Introduction to multi-messenger astrophysics

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Niels Bohr Institute, University of Copenhagen

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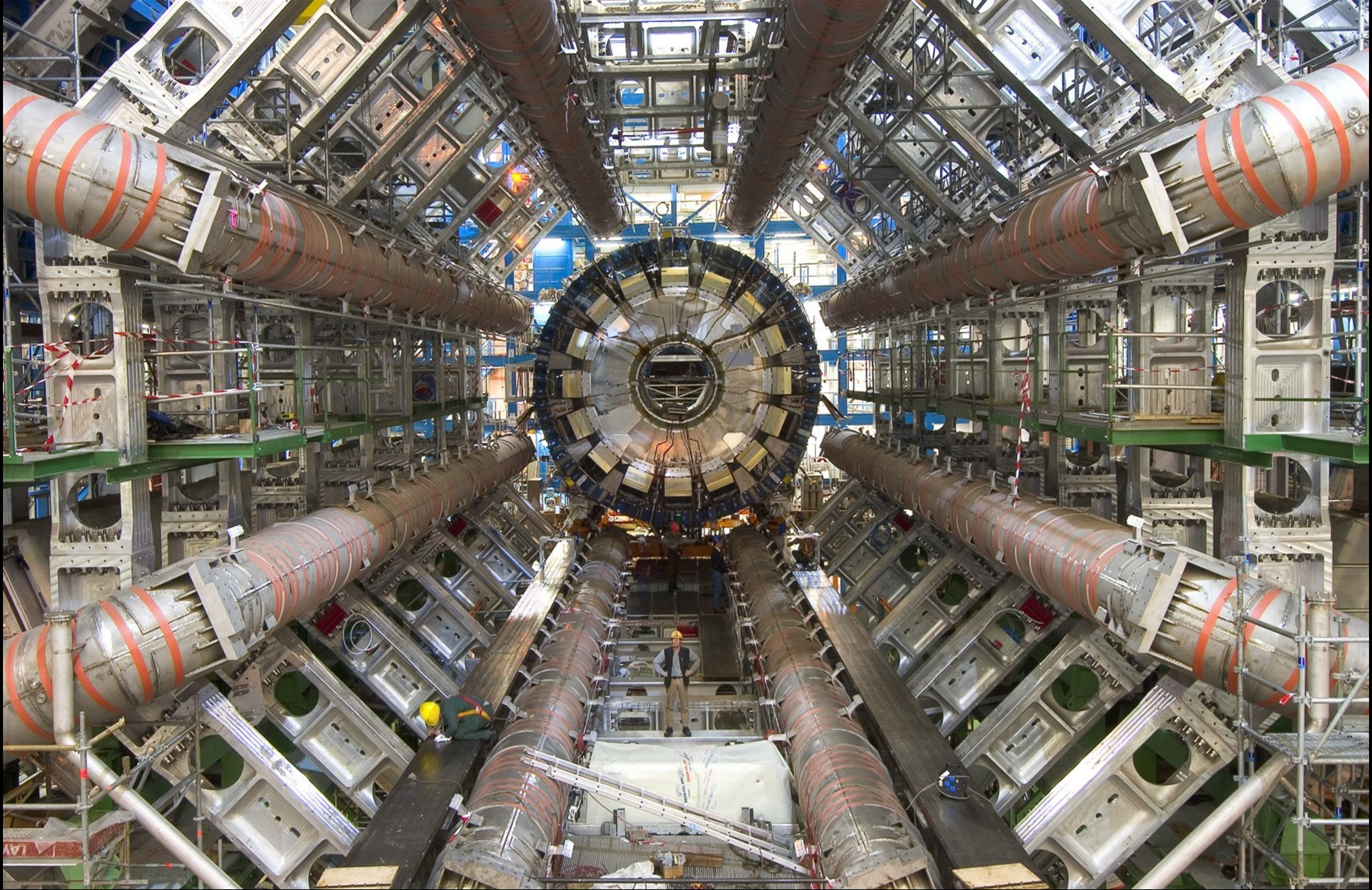
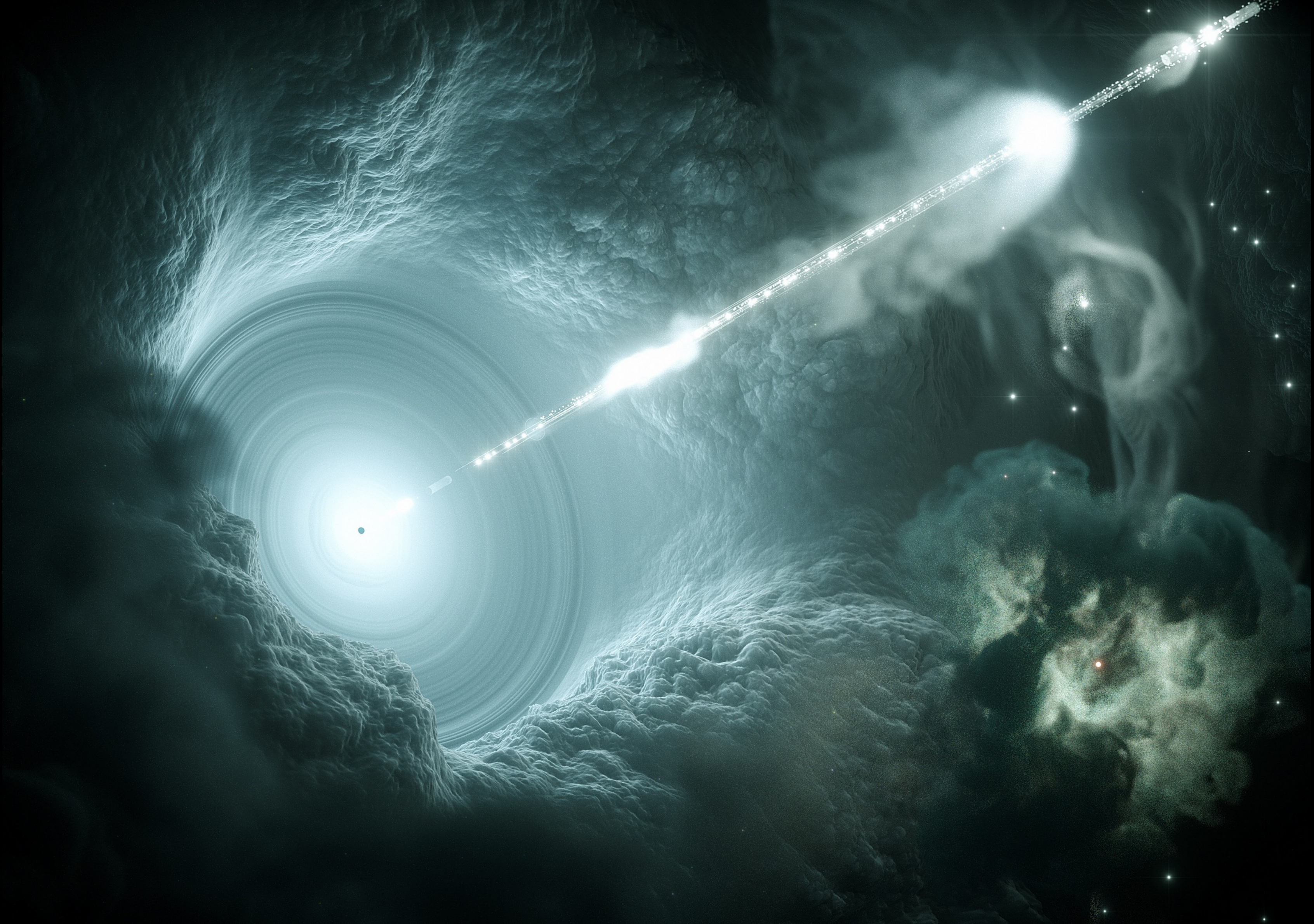
UNIVERSITY OF
COPENHAGEN

VILLUM FONDEN

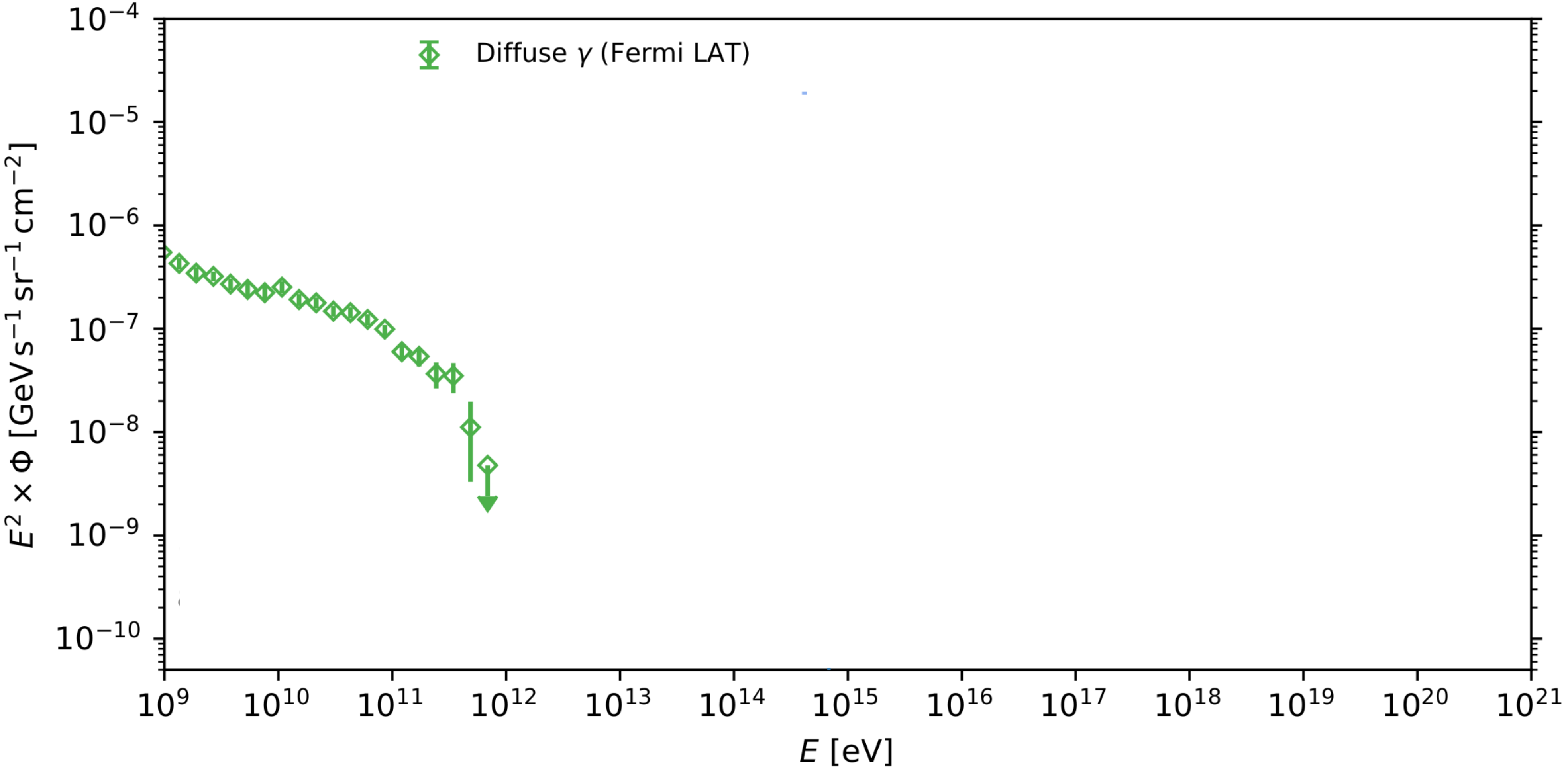


ATLAS



DESY

Gamma rays Neutrinos Cosmic rays



M. Ackermann, **MB**, *et al.*, *JHEAp* 35, 55 (2022) [2203.08096]

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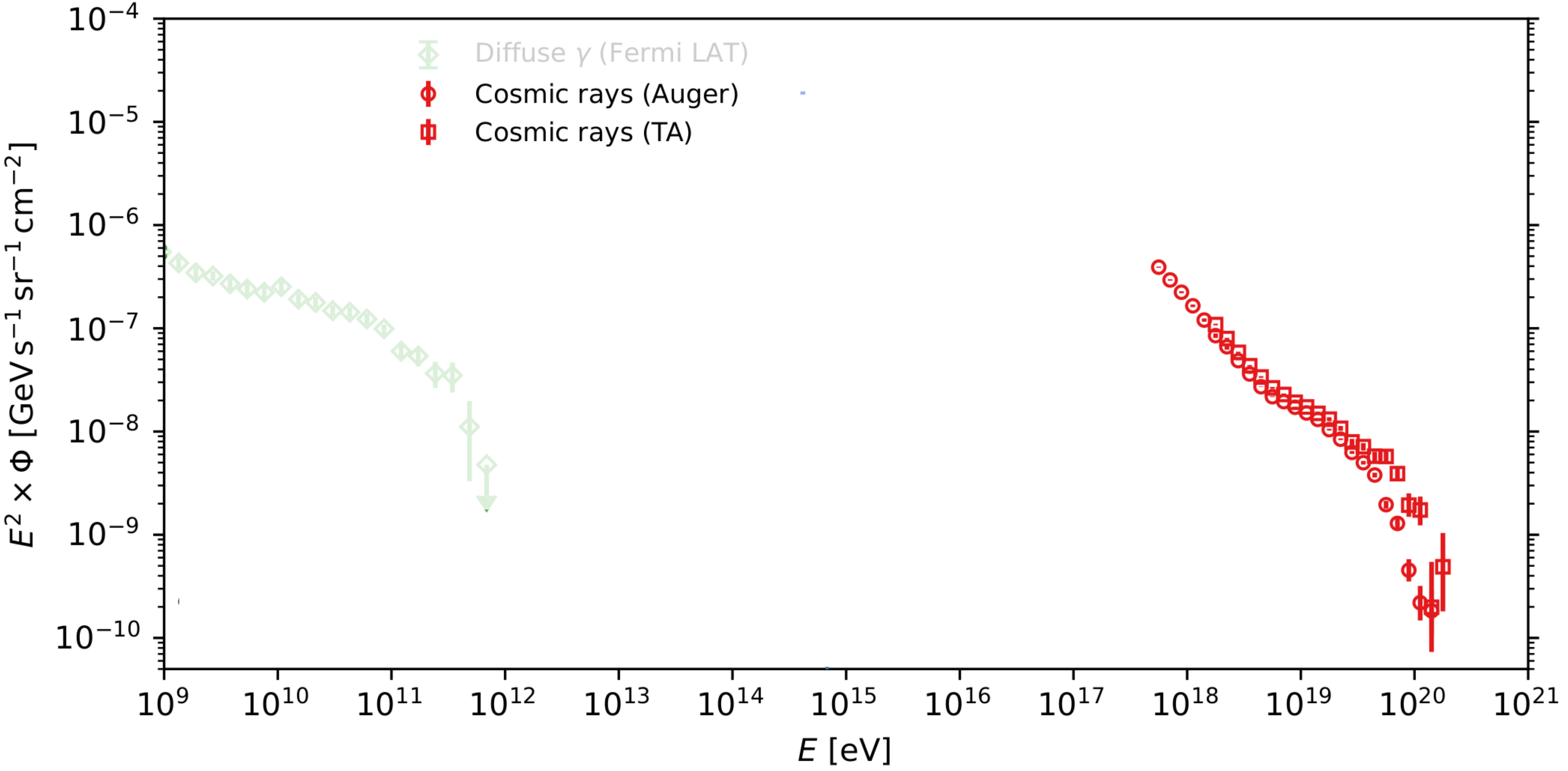

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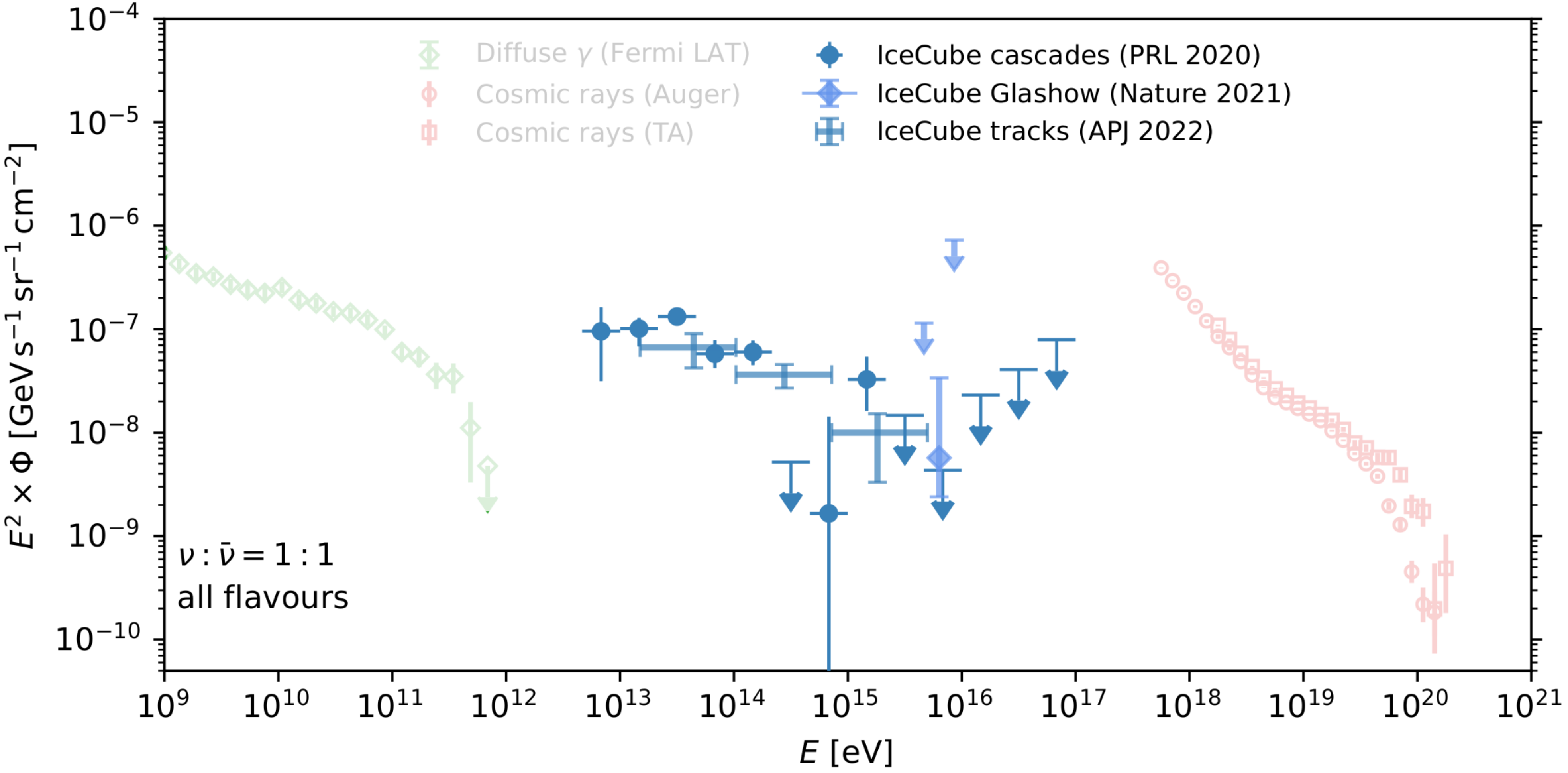

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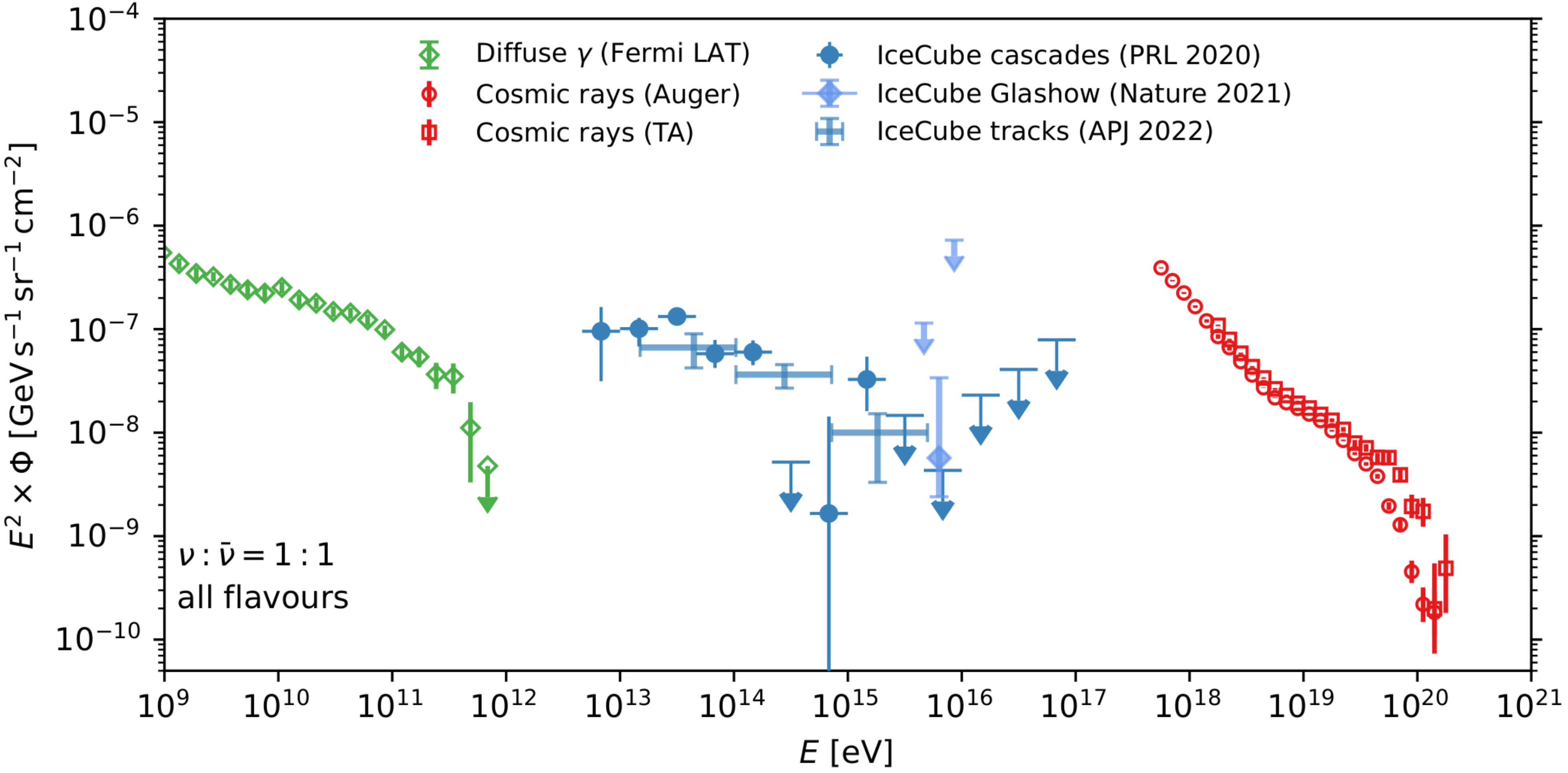

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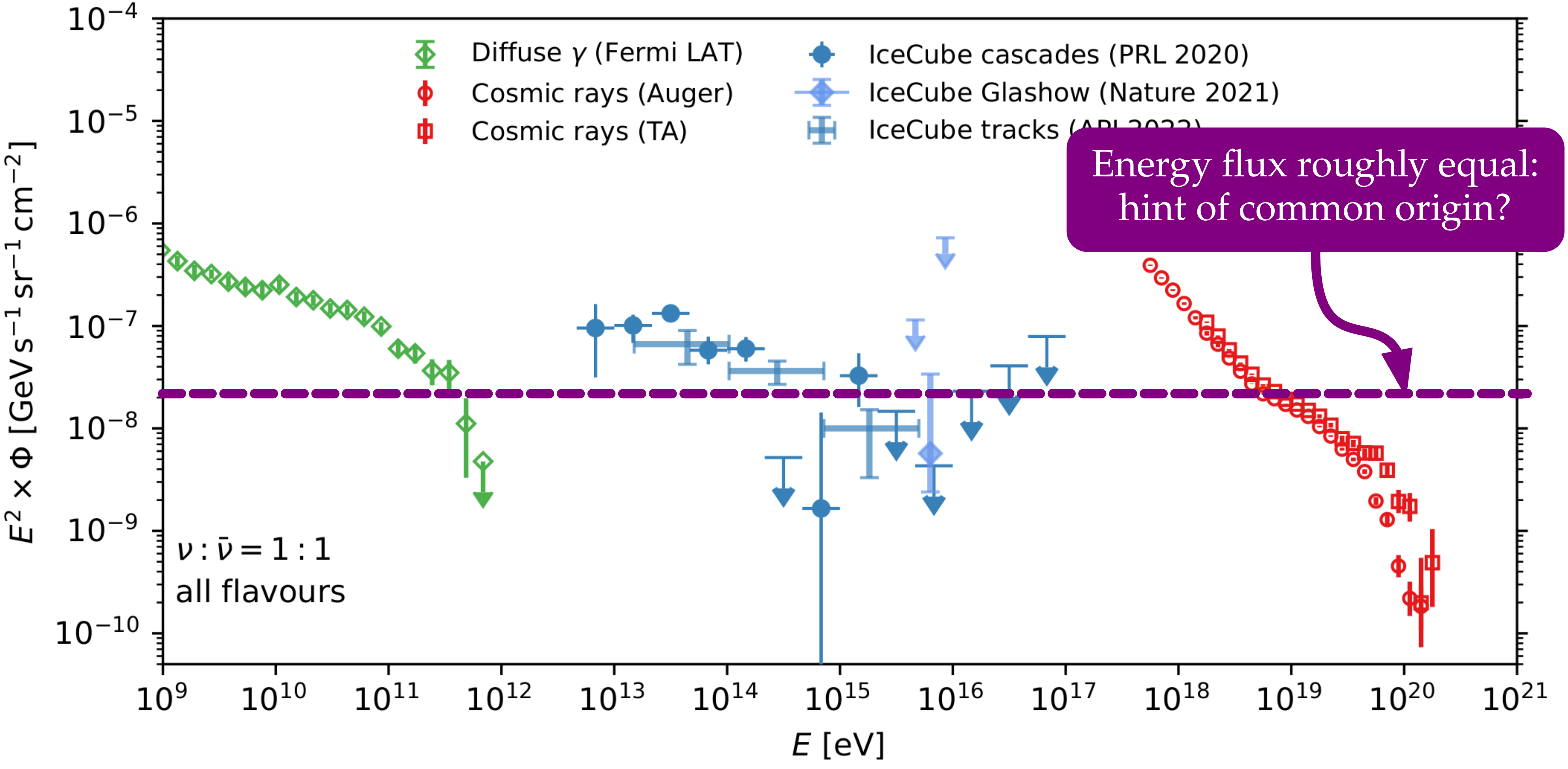

Energy flux roughly equal:
hint of common origin?

M. Ackermann, **MB**, *et al.*, *JHEAp* 35, 55 (2022) [2203.08096]

The multi-messenger connection: a simple picture

$$p + \gamma_{\mathrm{target}} \to \Delta^{+} \to \begin{cases} p + \pi^{0}, & \mathrm{Br} = 2/3 \\ n + \pi^{+}, & \mathrm{Br} = 1/3 \end{cases}$$

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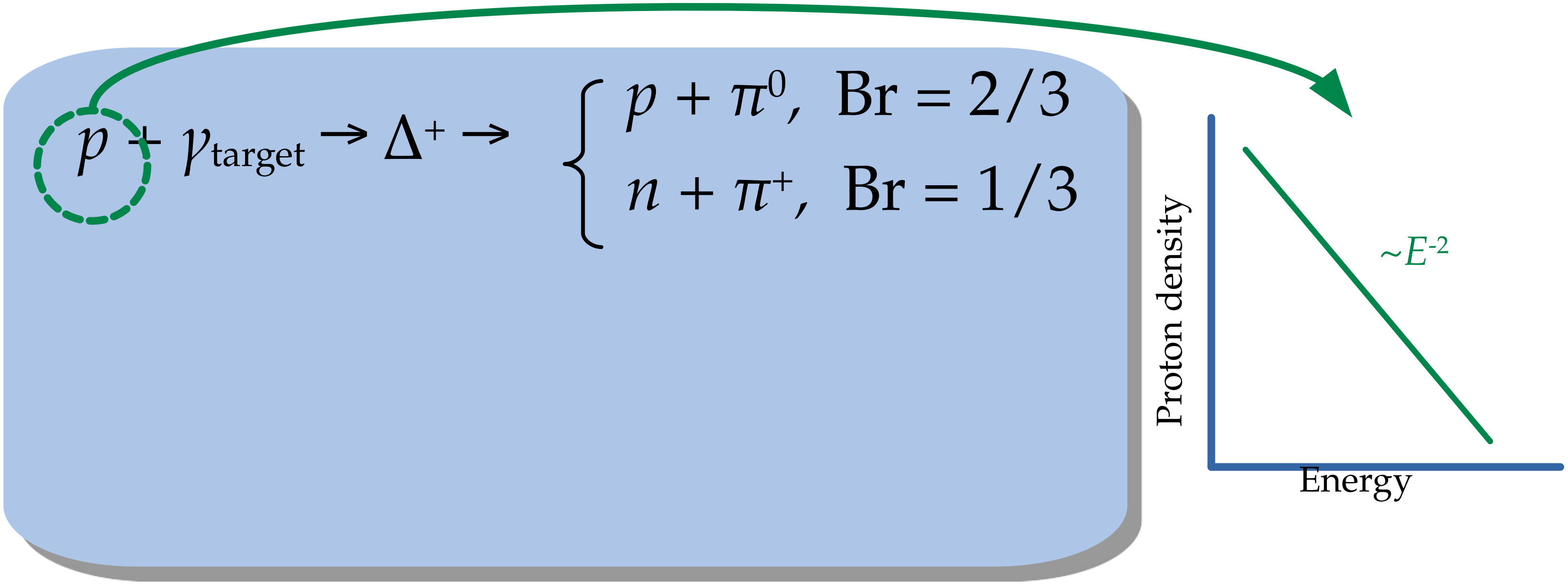

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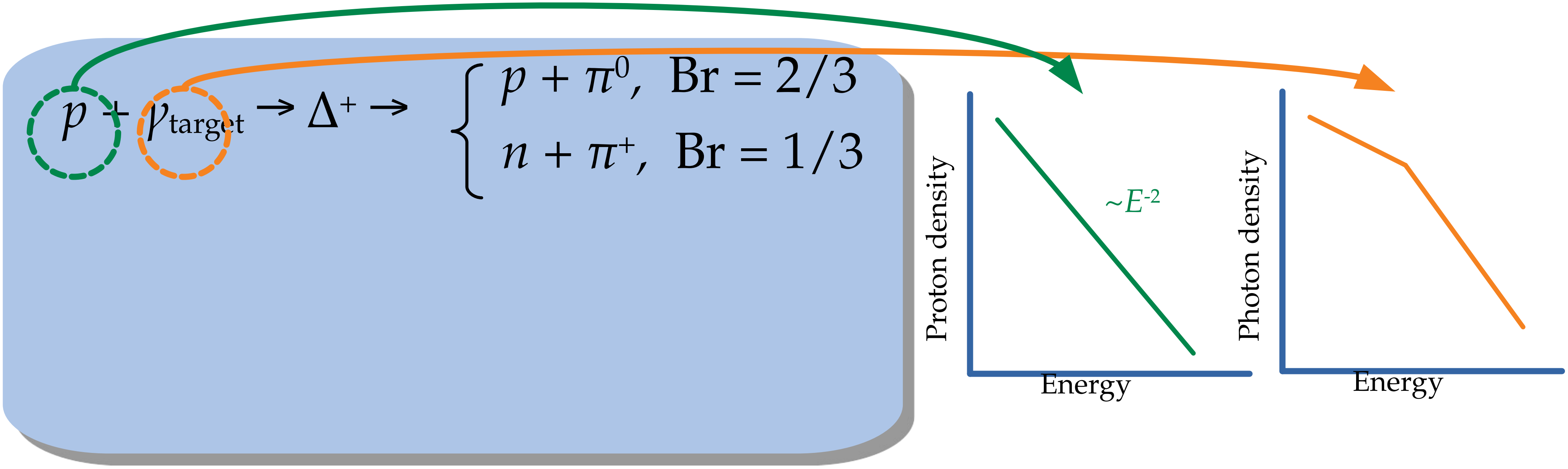

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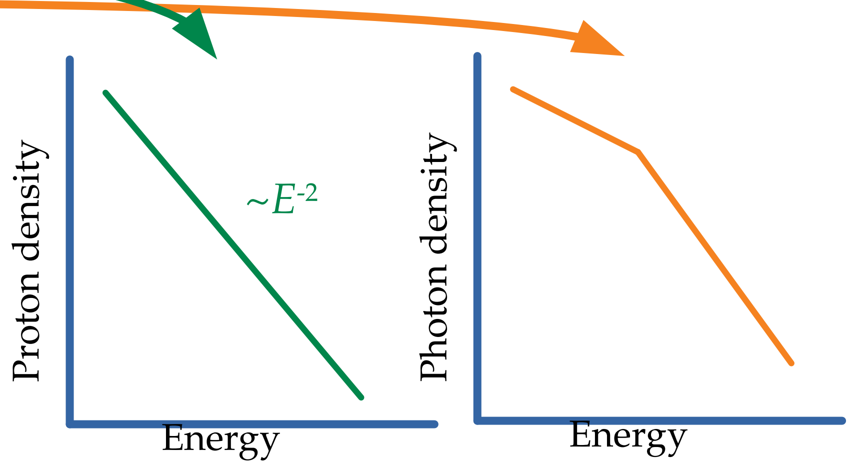
$$\pi^0 \to \gamma + \gamma$$

$$\pi^+ \to \mu^+ + \nu_\mu \to \bar{\nu}_\mu + e^+ + \nu_e + \nu_\mu$$

$$n \text{ (escapes)} \to p + e^- + \bar{\nu}_e$$



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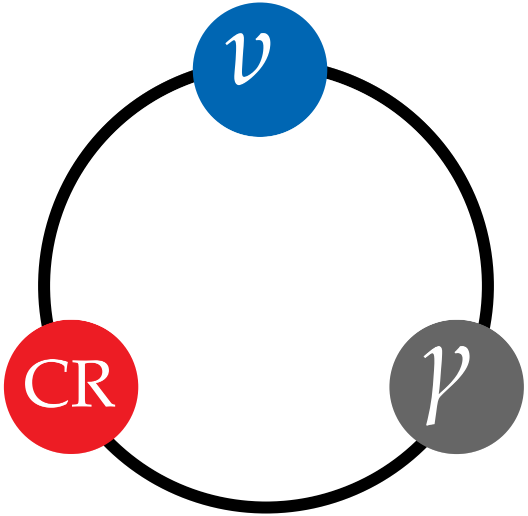

Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10

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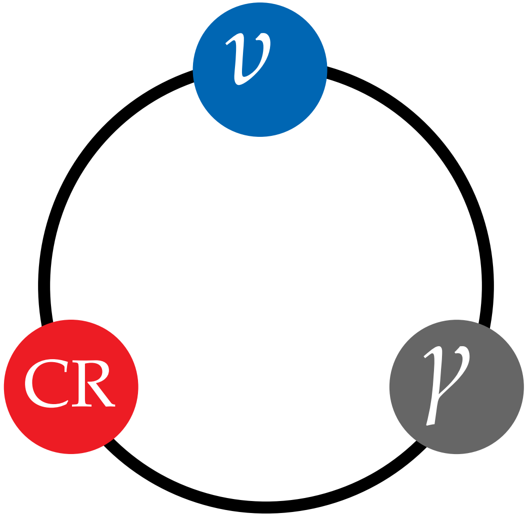

1 PeV 20 PeV

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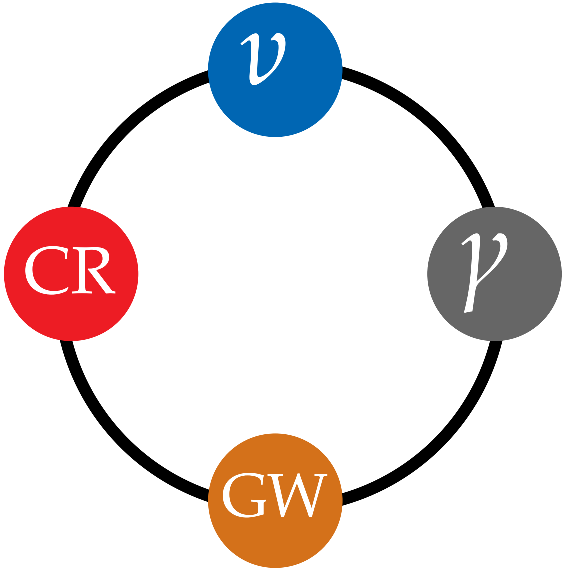

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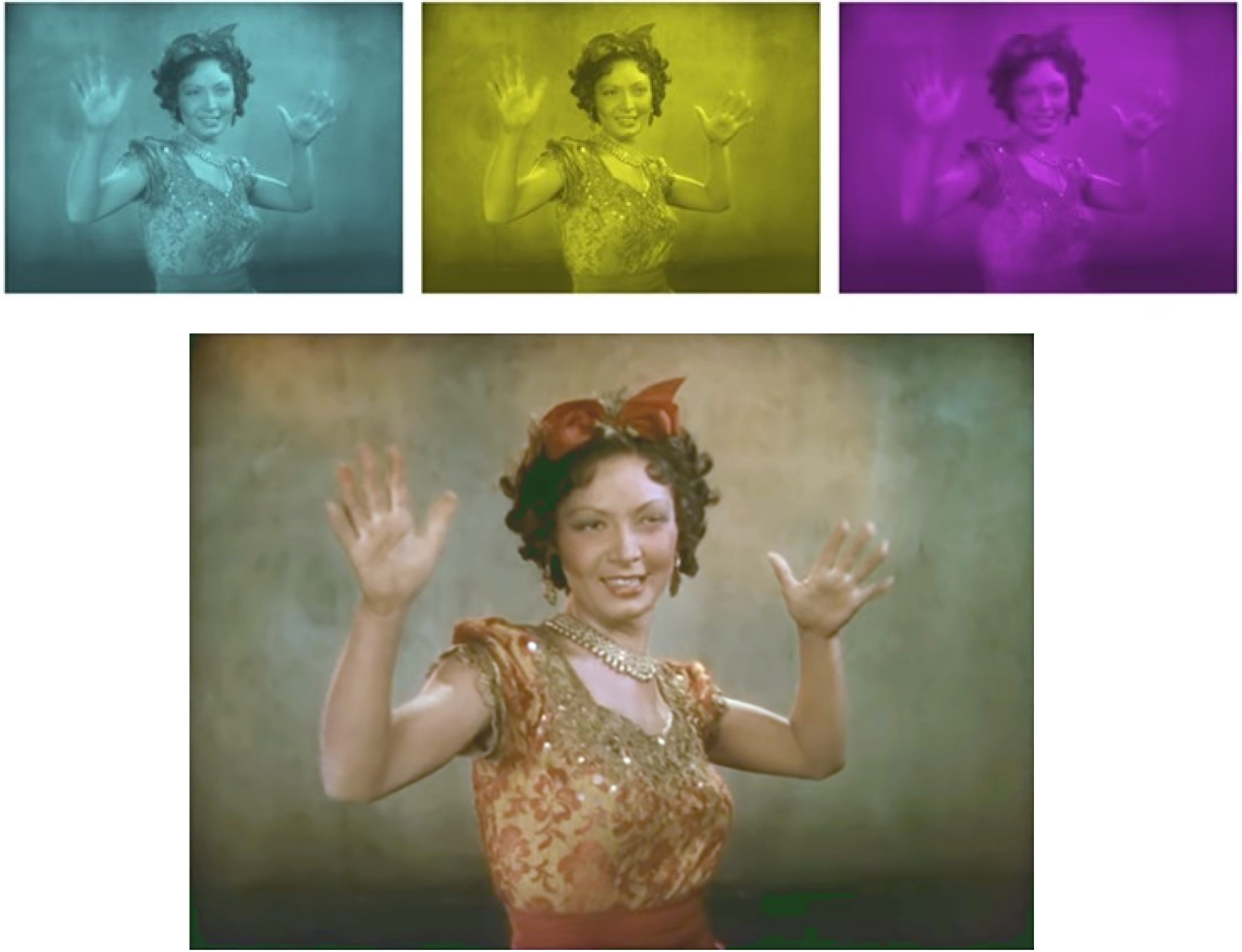
YouTube



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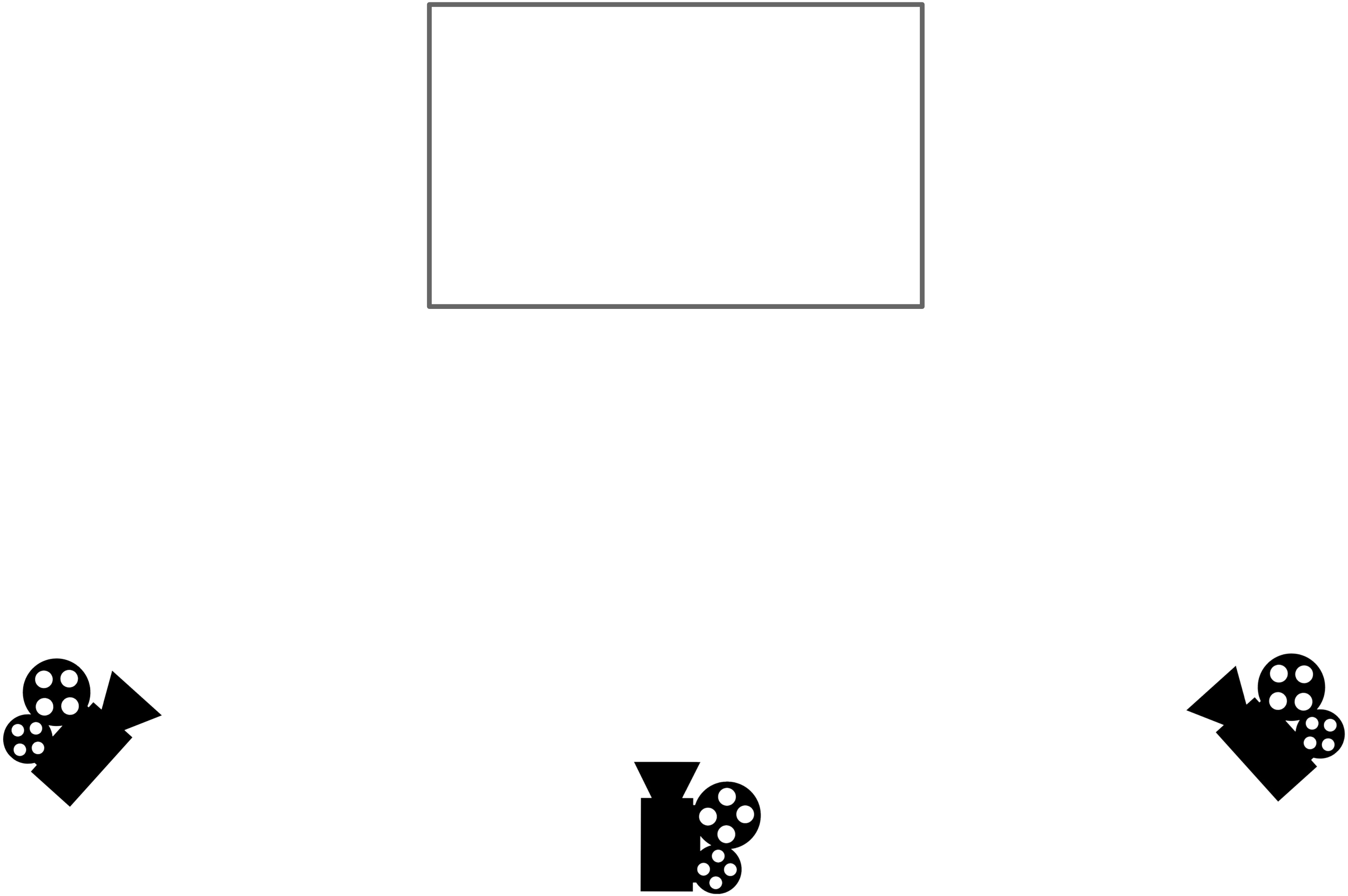
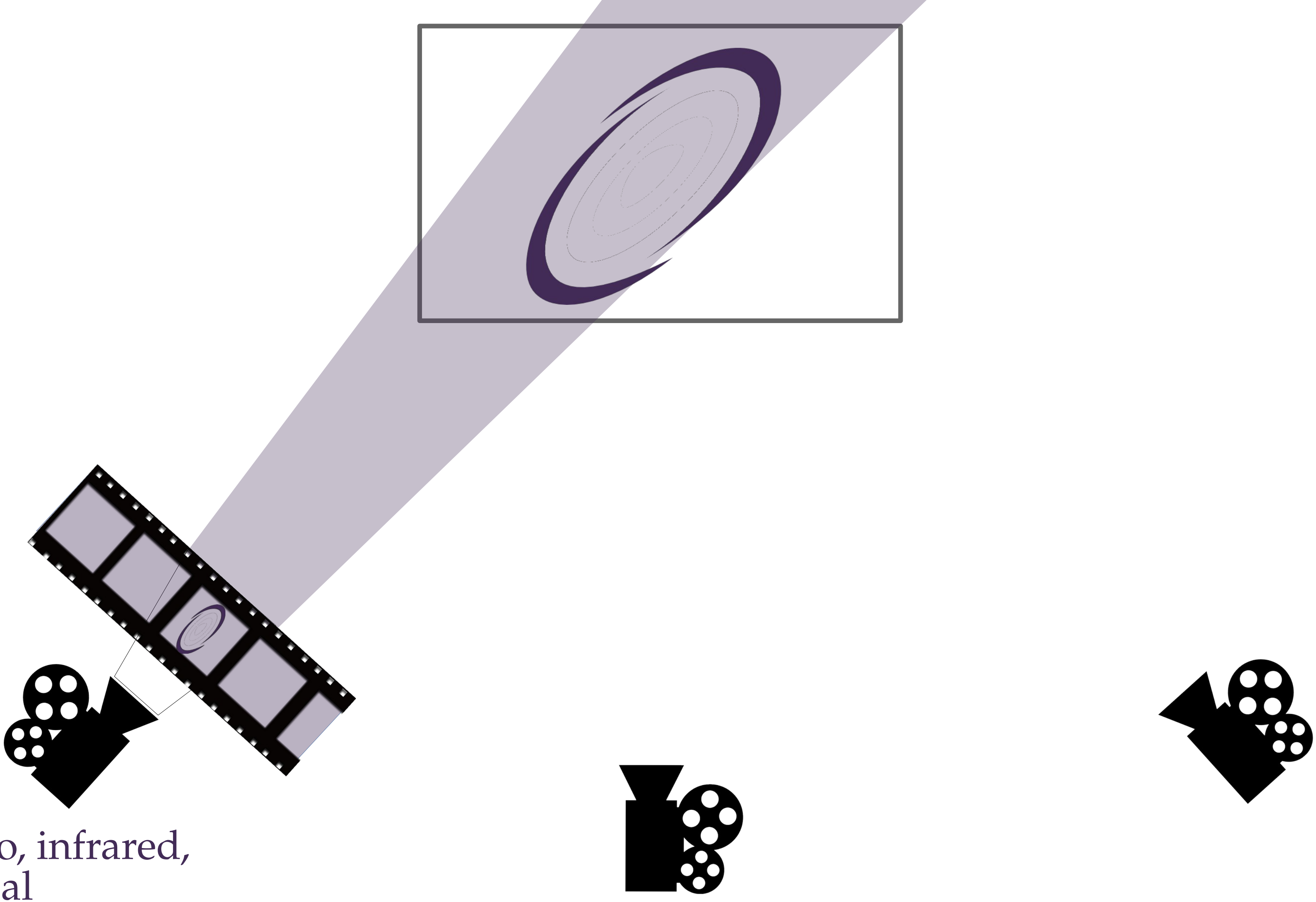
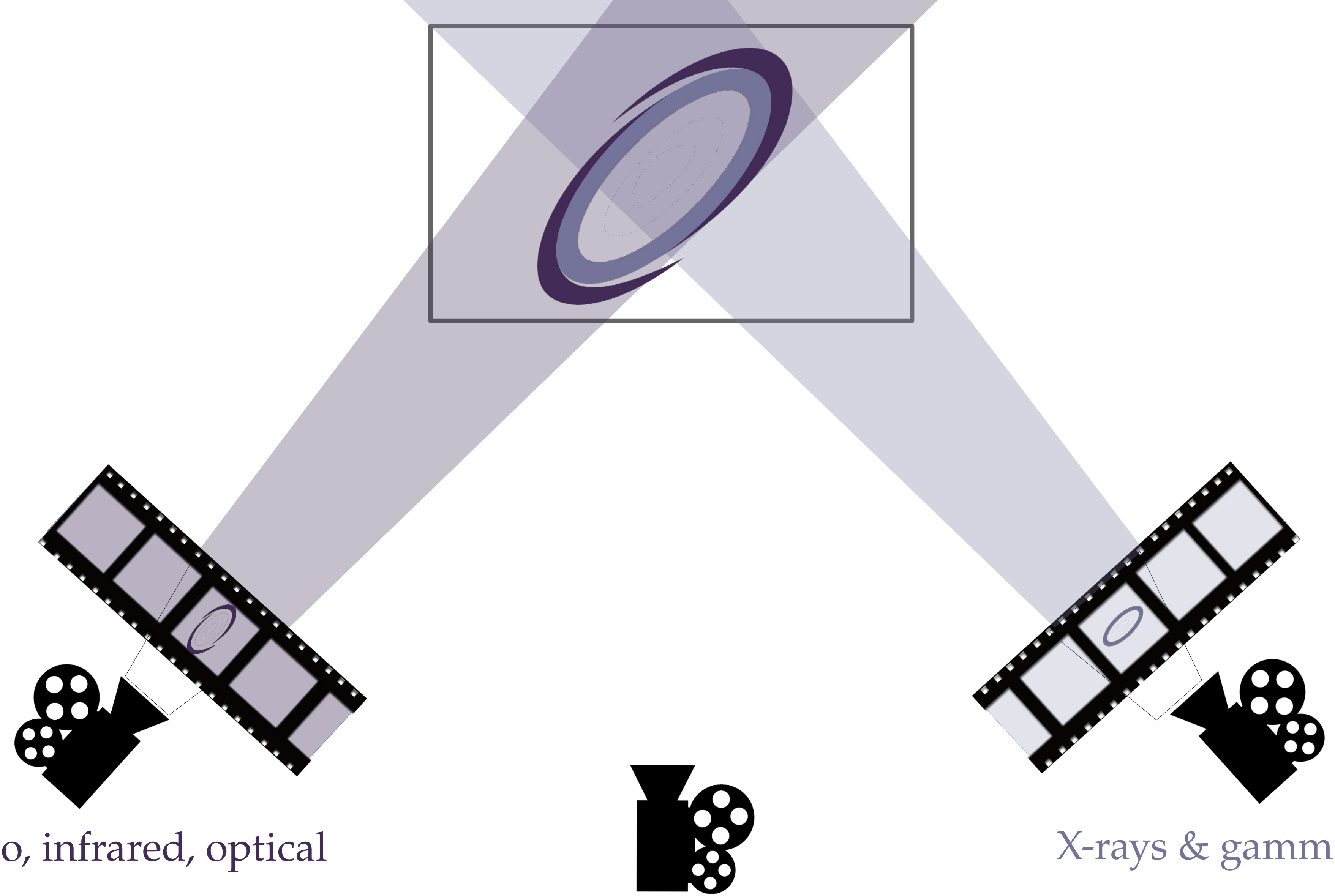
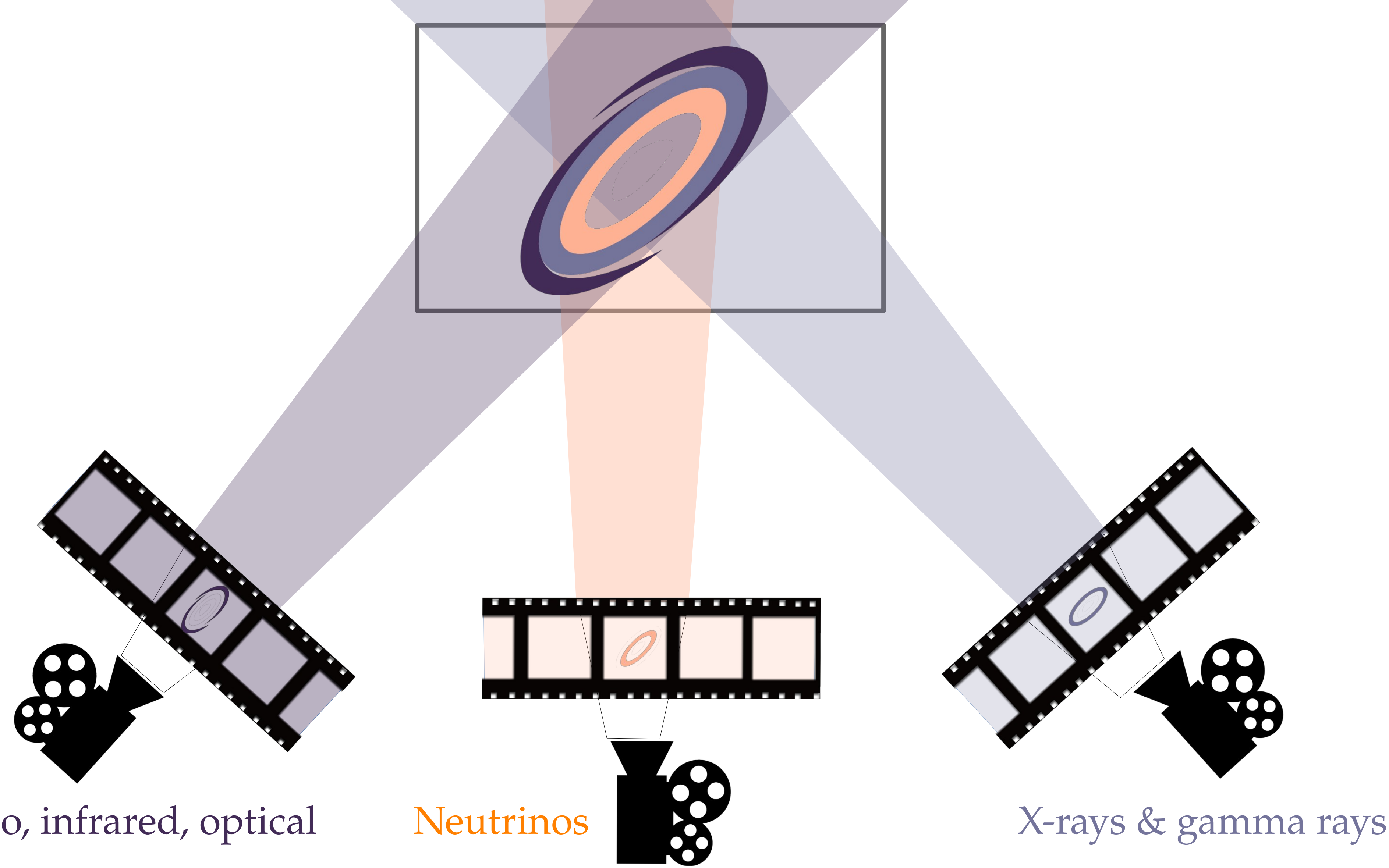
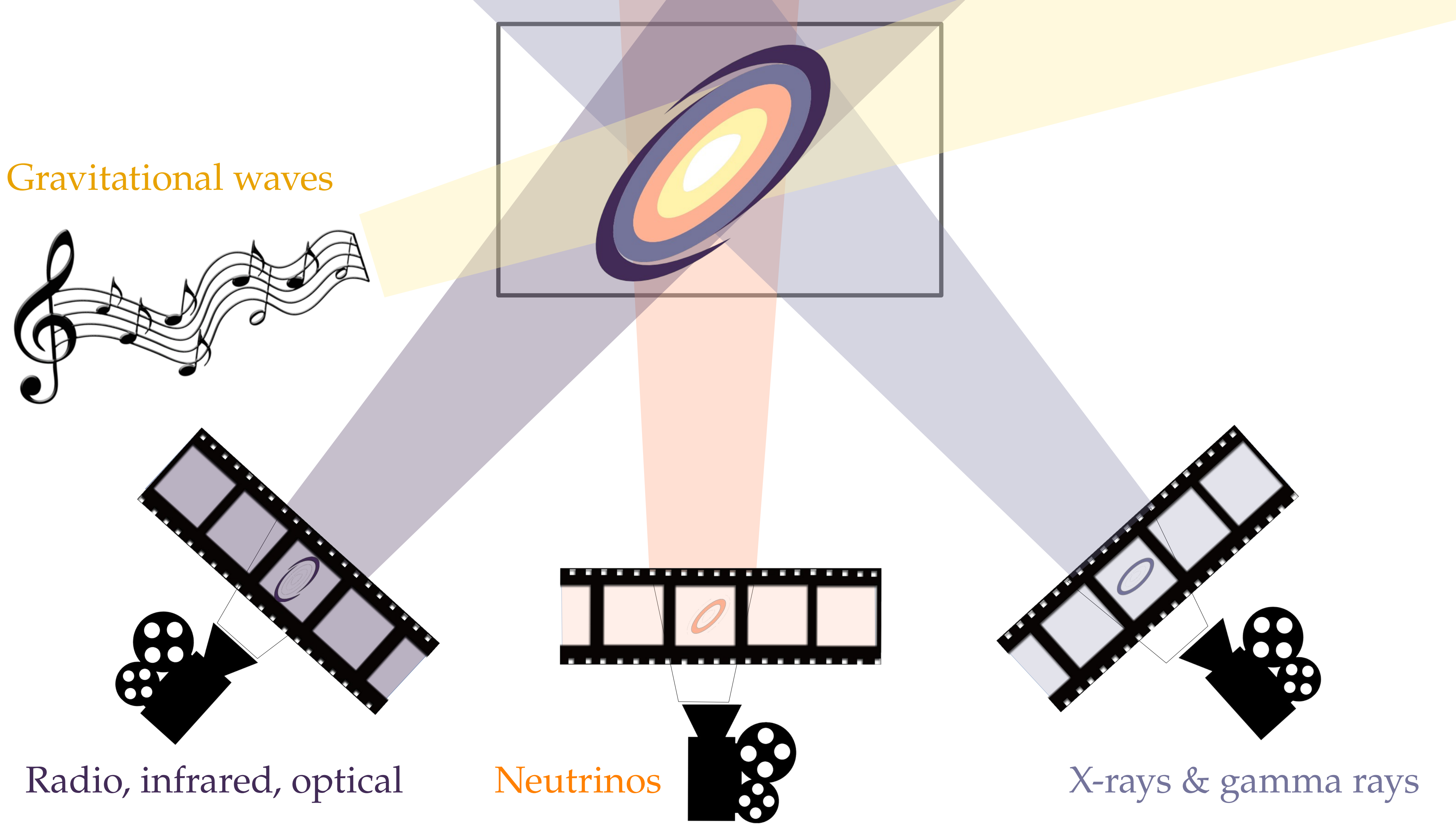




Radio, infrared, optical


Radio, infrared, optical
X-rays & gamma rays


Radio, infrared, optical
Neutrinos
X-rays & gamma rays


Gravitational waves
Radio, infrared, optical
Neutrinos
X-rays & gamma rays

Gamma rays Neutrinos UHE cosmic rays

Note: This is a simplified view

	Gamma rays	Neutrinos	UHE cosmic rays
Point back at sources	Yes	Yes	No

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Size of horizon	10 kpc (at PeV)	Size of the Universe	100 Mpc (> 40 EeV)

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Energy degradation	Severe	Tiny	Severe
Relative ease to detect	Easy	Hard	Easy

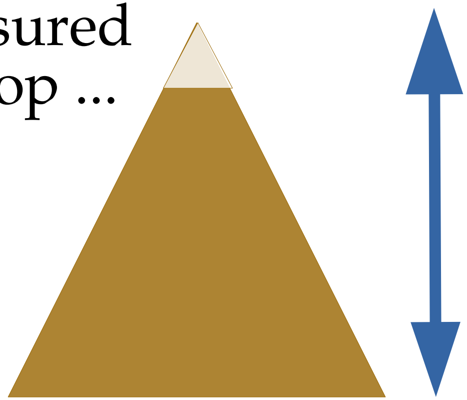
Note: This is a simplified view

Ultra-high-energy cosmic rays

Cosmic rays discovered

The state at the beginning of the 20th century:

(1) ambient radiation was already known to exist
(2) believed to be mainly coming from the ground



ambient radiation measured
to be lower at the top ...

… than at ground level

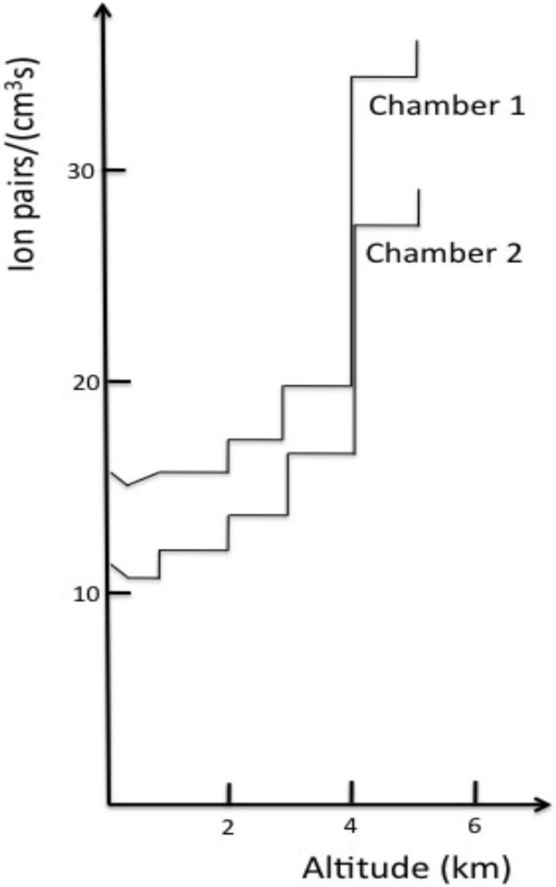
1 km tall mountain

(badly drawn)

Problem: they had measured *only* up to ~1 km of altitude

Physics is a risky business

Victor Hess – 1911-1913, balloon flights up to 5.3 km



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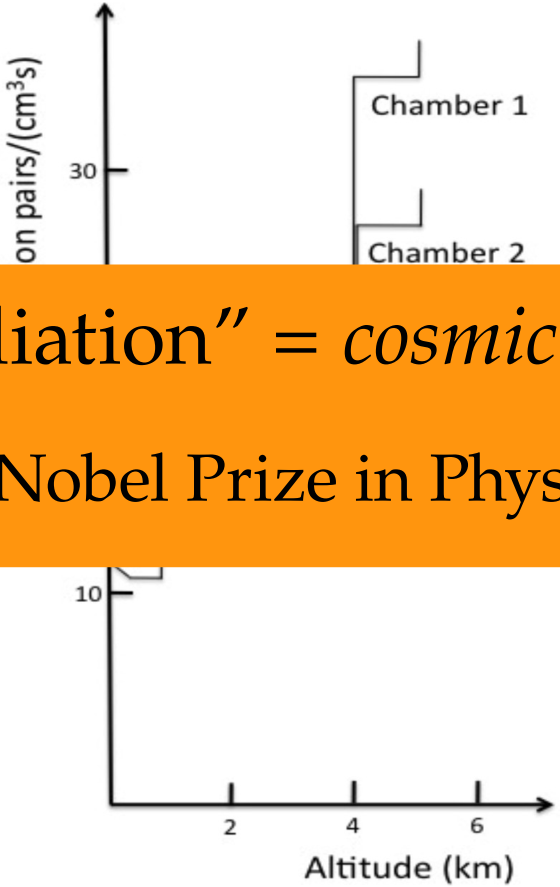
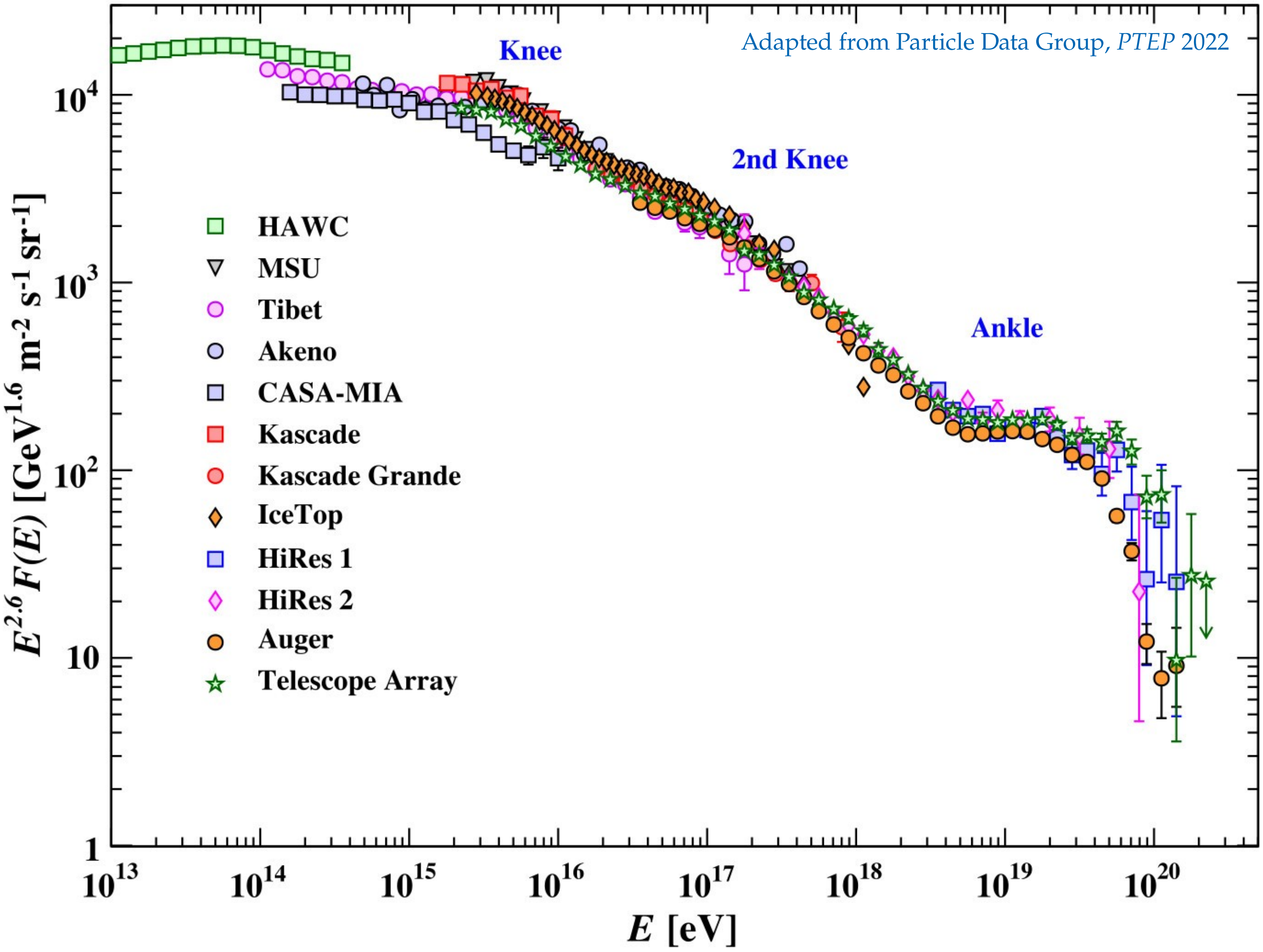


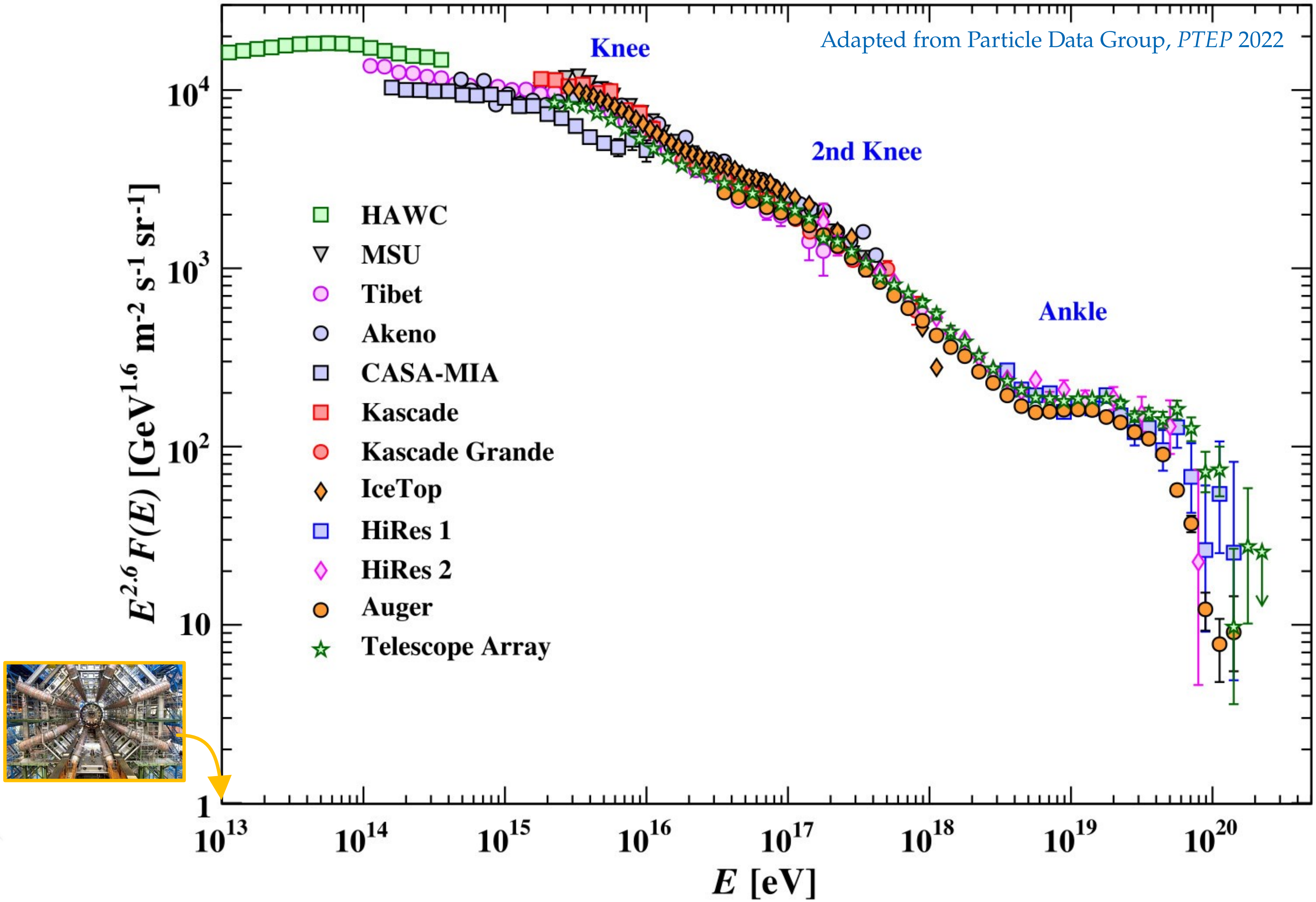
“Unknown penetrating radiation” = *cosmic rays*

… and that's one way to get a Nobel Prize in Physics

1962: First cosmic rays with $>10^{20}$ eV



Adapted from Particle Data Group, *PTEP* 2022



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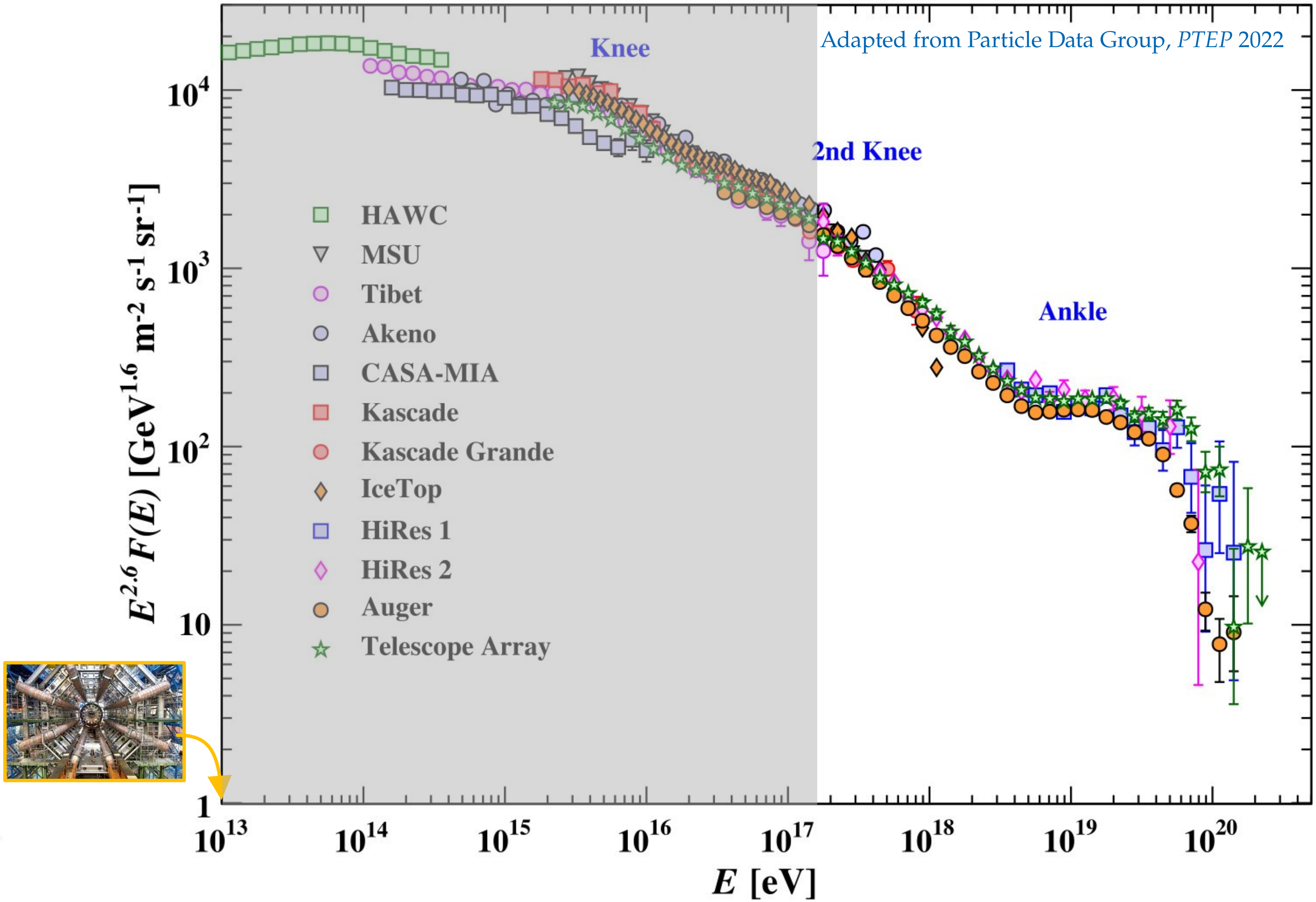
10^{12} eV

6×10^{20} eV

From the Milky Way

10^12 eV

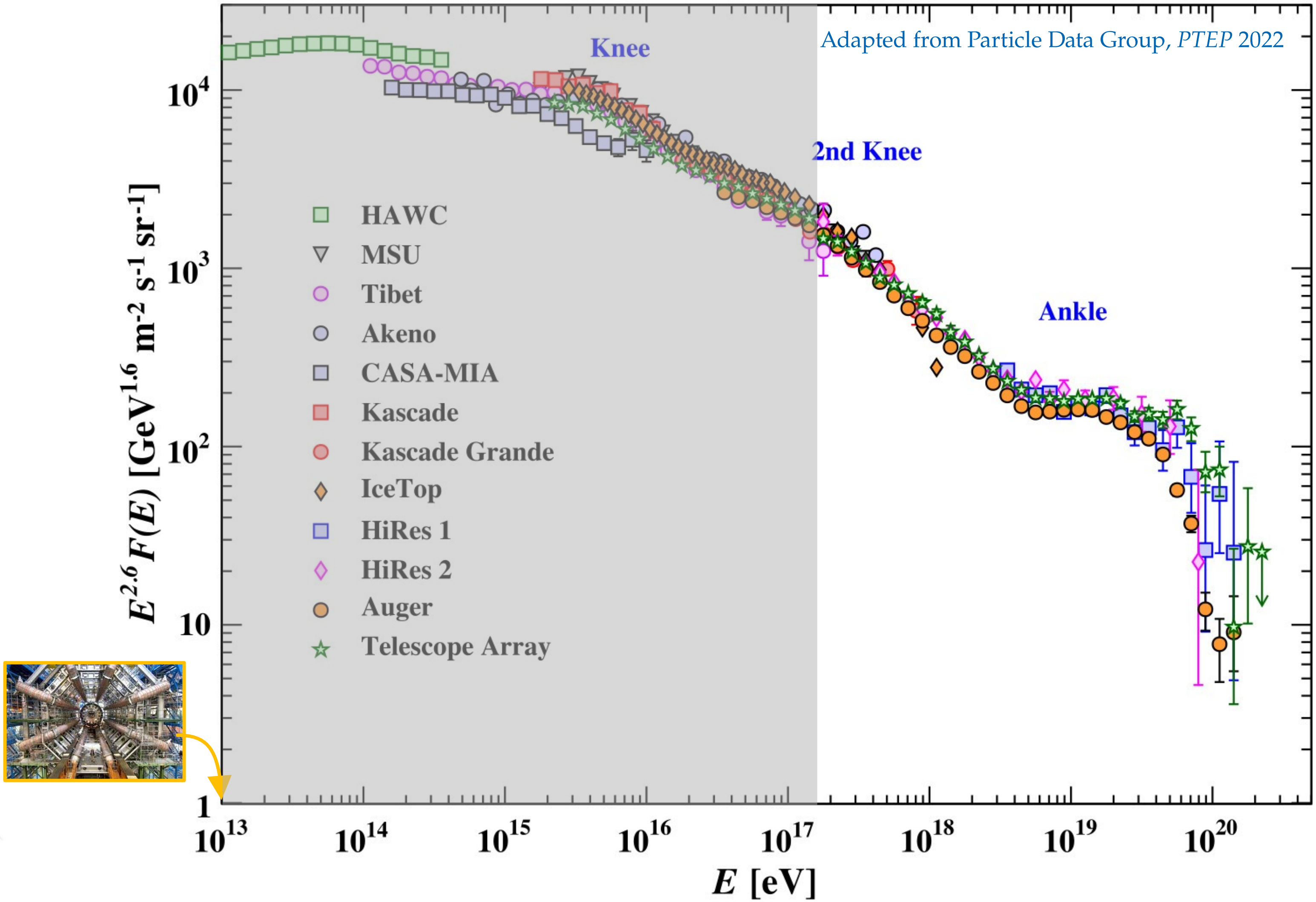


Adapted from Particle Data Group, *PTEP* 2022

6 × 10^20 eV

From the Milky Way

From outside the Milky Way



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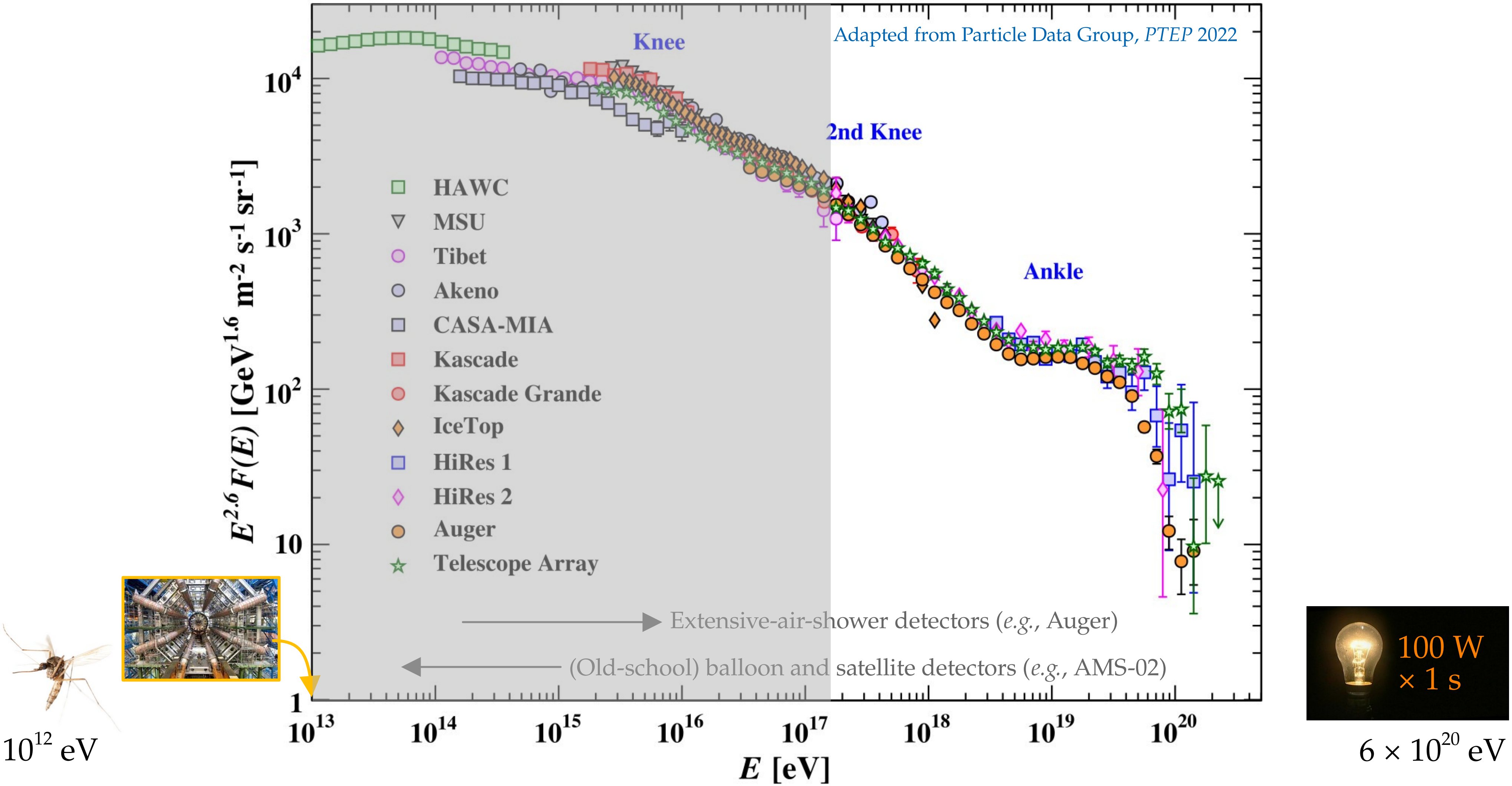
10^{12} eV

6×10^{20} eV

From the Milky Way From outside the Milky Way

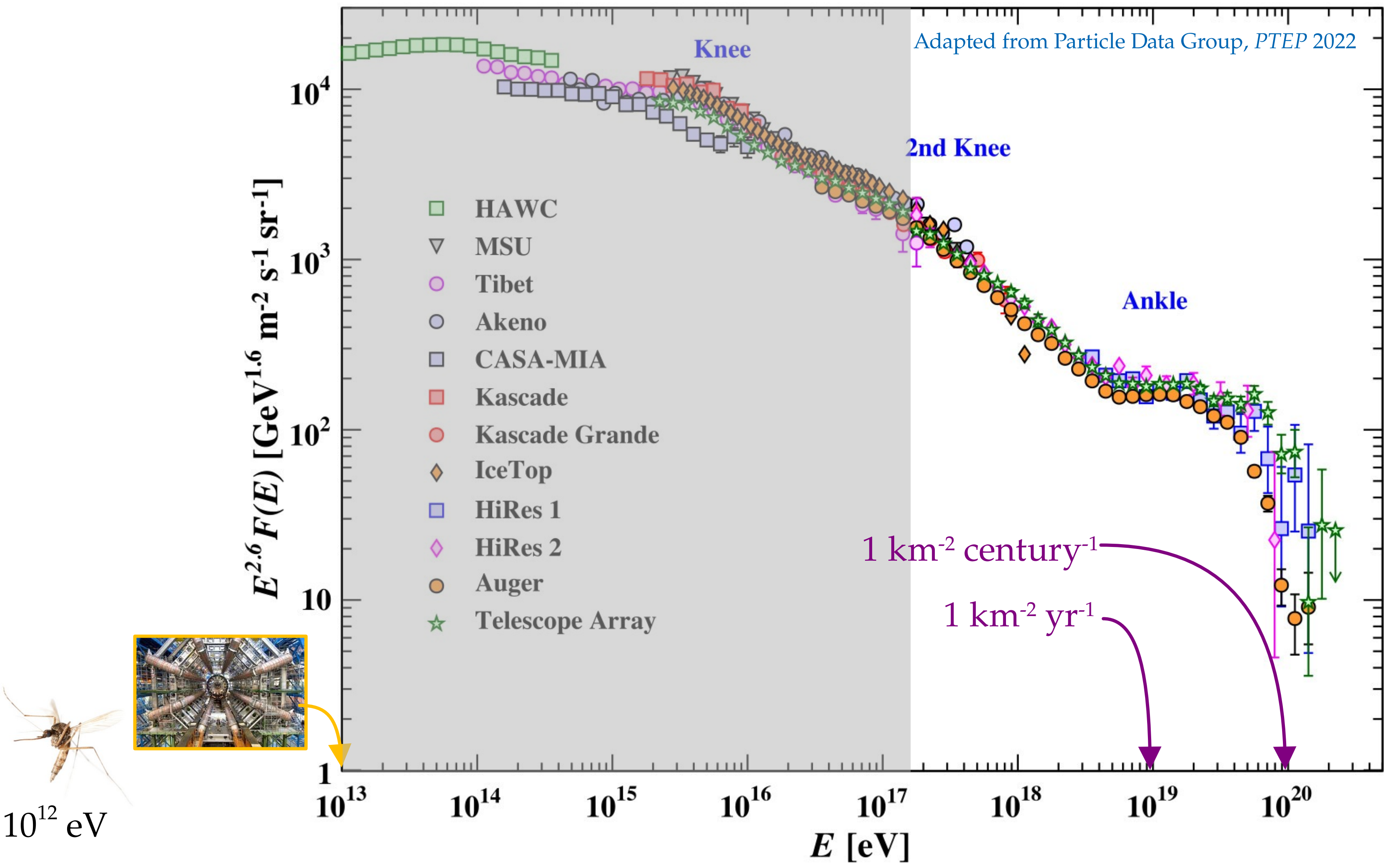


Adapted from Particle Data Group, *PTEP* 2022

Extensive-air-shower detectors (*e.g.*, Auger)

(Old-school) balloon and satellite detectors (*e.g.*, AMS-02)

From the Milky Way From outside the Milky Way



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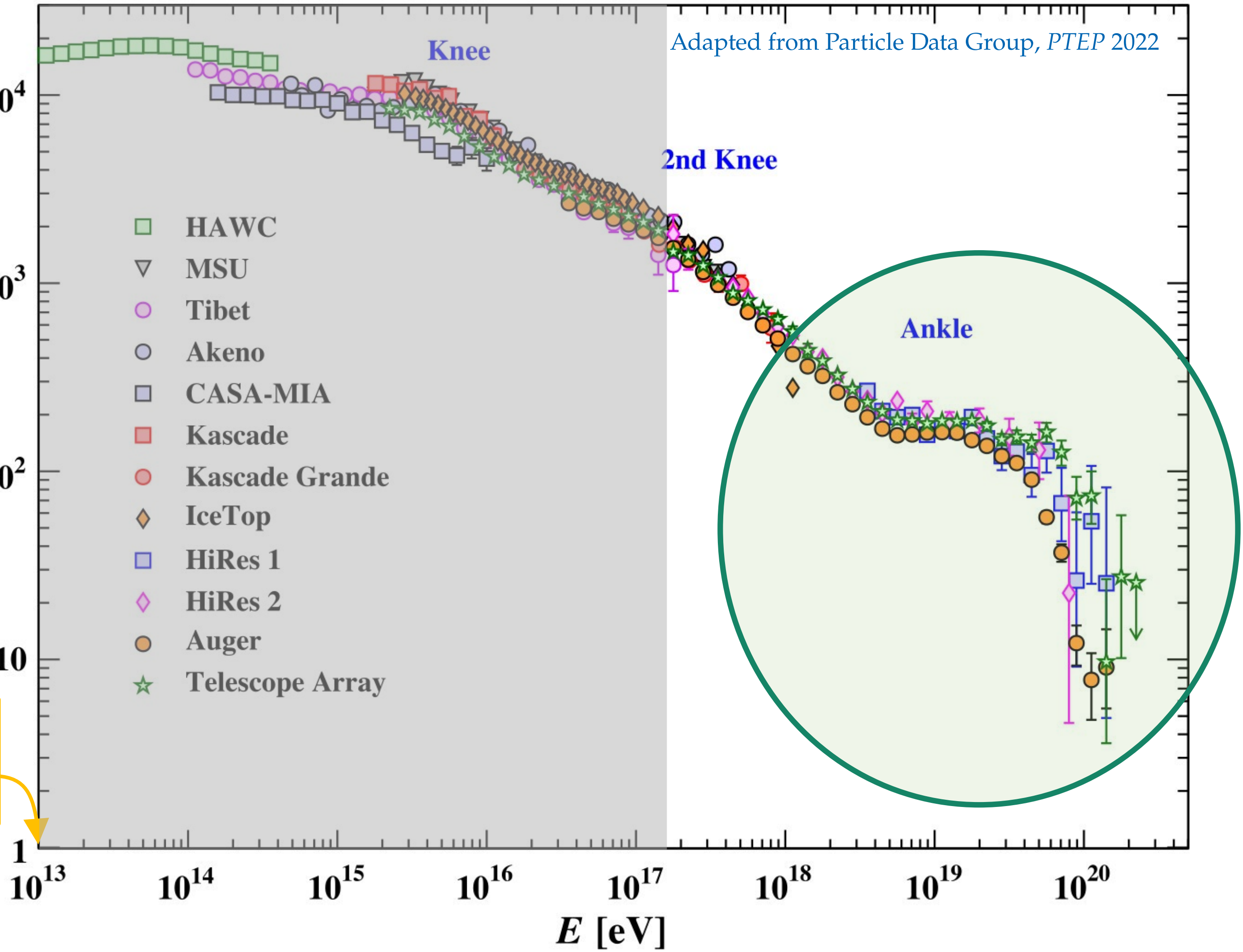
6×10^{20} eV

From the Milky Way

From outside the Milky Way



Let’s talk about these energies

10^{12} eV

6×10^{20} eV

What are they?

Protons and nuclei with energies above 10^{17} eV

Is that a lot?

Yes.

10^5–10^8 times higher than LHC protons

A 10^{20}-eV proton has the kinetic energy of a kicked football

We know no particles more energetic than UHECRs

So what's making them?

Good question. We don't know.

Whatever it is, it is one of the most violent processes in the Universe

(Ok, fine: extragalactic non-thermal astrophysical sources that act as cosmic particle accelerators)

Why is it so hard?

UHECRs don't travel in straight lines

(the Universe is magnetized)

+

UHECRs are rare

(the Universe is opaque to them)

Are we getting closer?

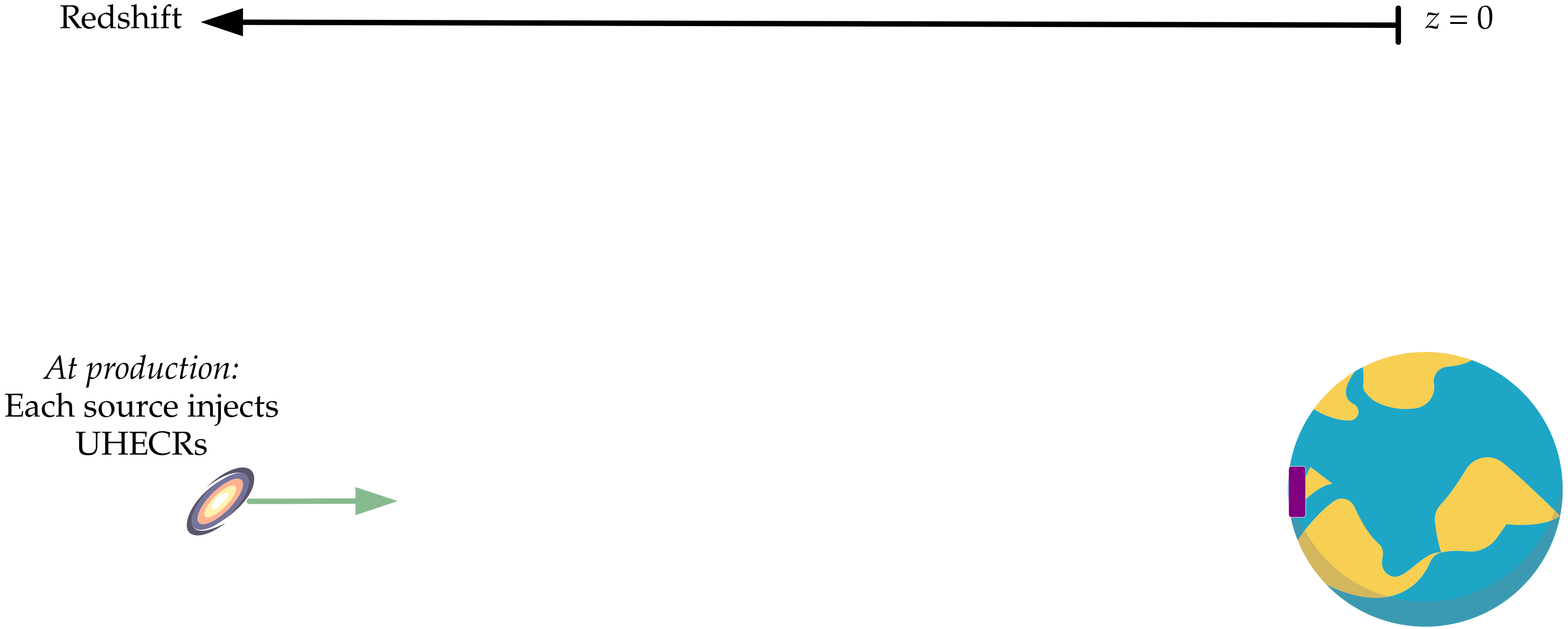
Yes.

We detect a growing number of UHECRs

and

we can use neutrinos, too

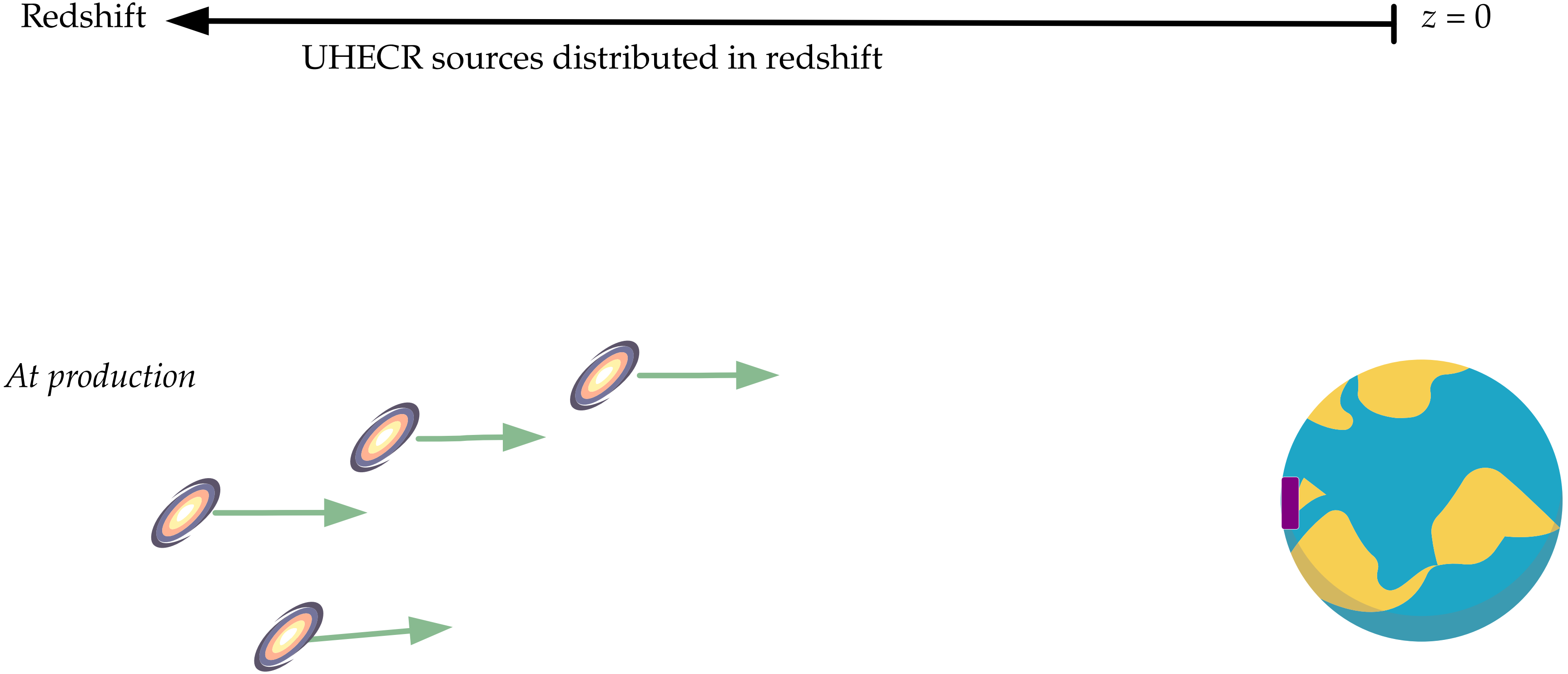
(more on this later)



Redshift

$z = 0$

At production:
Each source injects
UHECRs

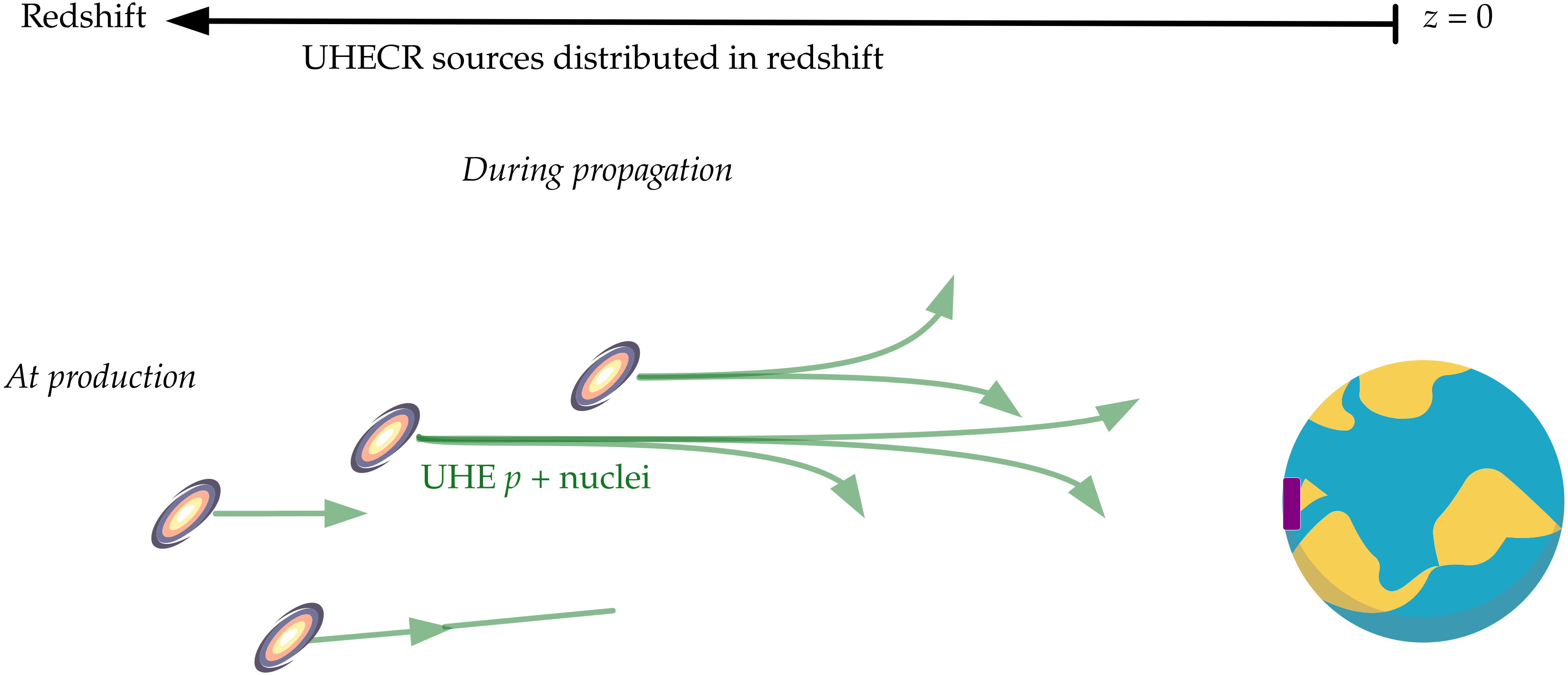


Redshift

$z = 0$

UHECR sources distributed in redshift

At production



Redshift

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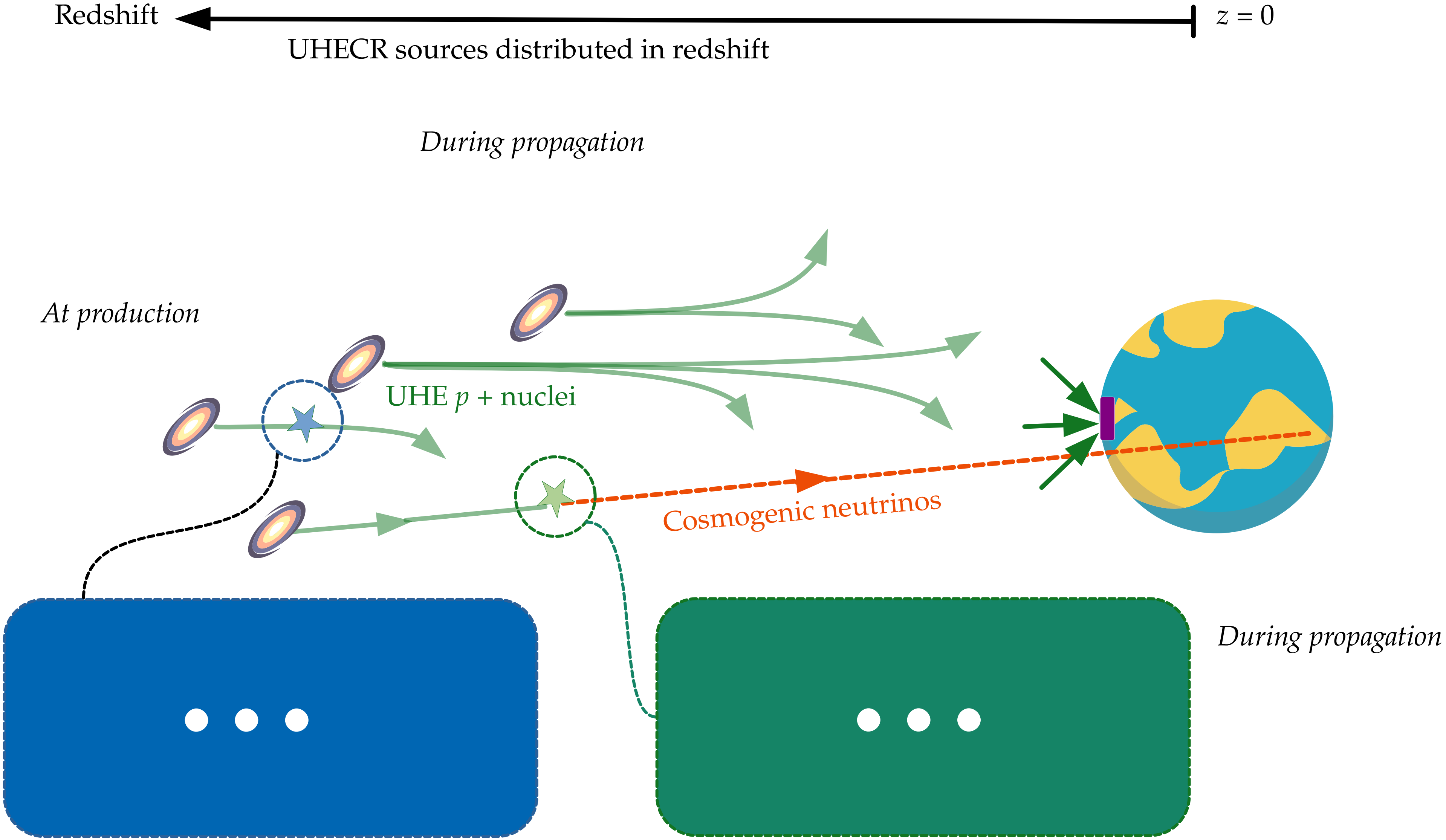
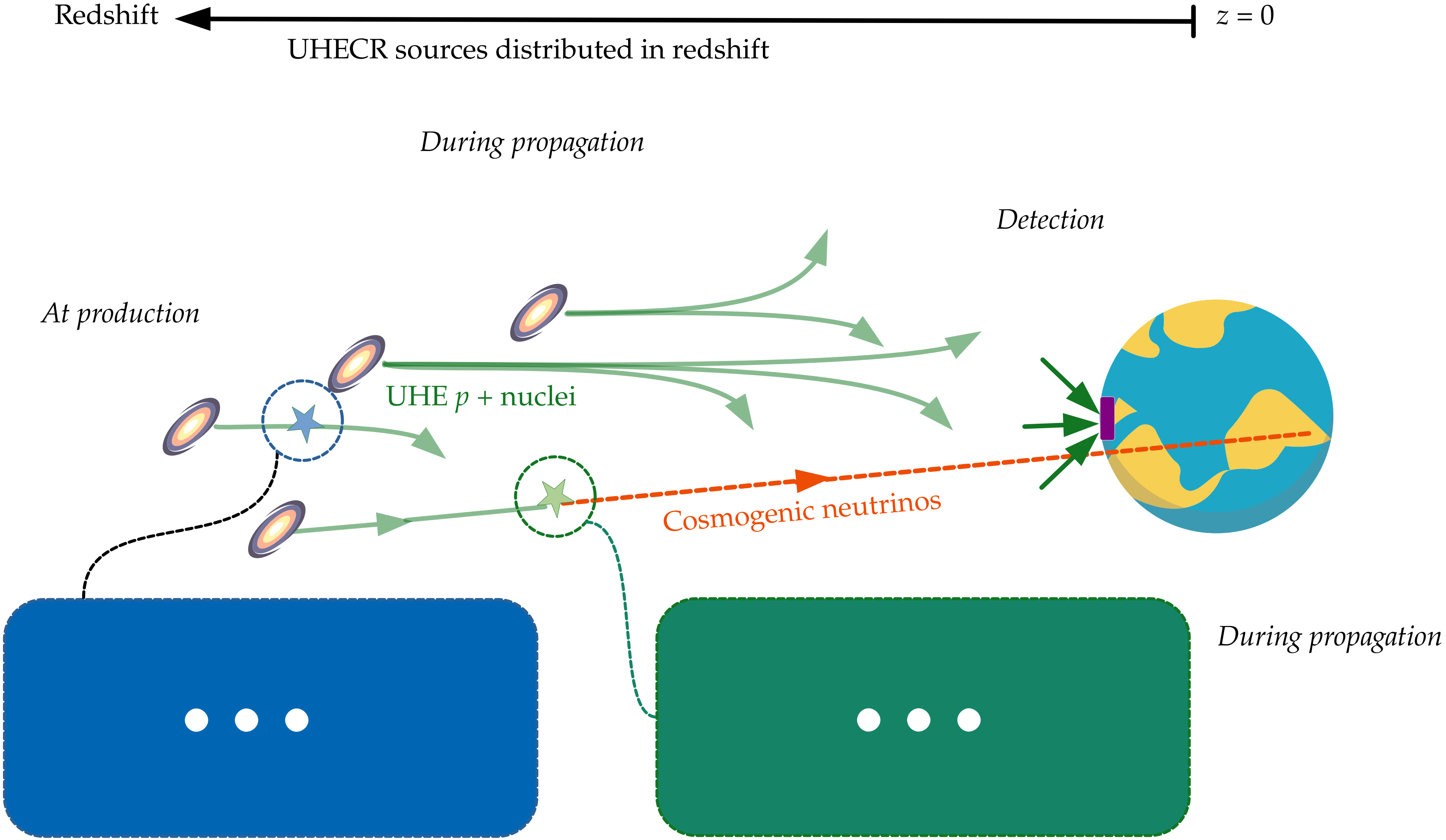
UHECR sources distributed in redshift

During propagation

At production

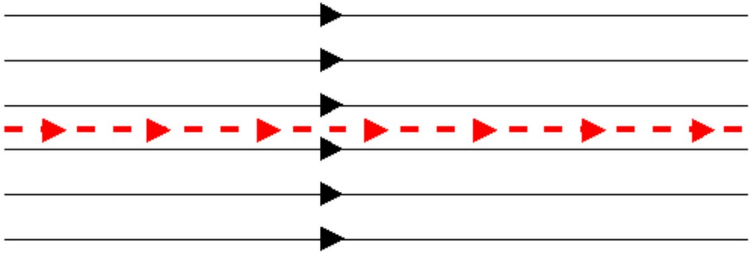
UHE p + nuclei

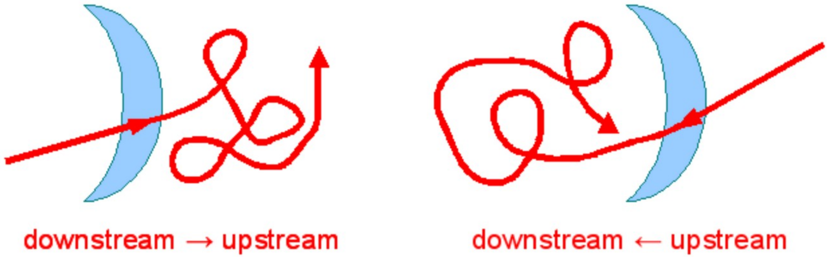

Redshift
z = 0
UHECR sources distributed in redshift
During propagation
At production
UHE p + nuclei
Cosmogenic neutrinos
During propagation


Redshift
z = 0
UHECR sources distributed in redshift
During propagation
Detection
At production
UHE p + nuclei
Cosmogenic neutrinos
During propagation

UHECR production

UHECR sources are messy





	Man-made accelerators	Astrophysical accelerators
Acceleration	In vacuum	In a medium
E.m. fields	Ordered	Messy
Beam dumps	Precisely regulated	Fully unregulated

Astrophysical accelerators *inevitably* make high-energy secondaries

How are cosmic rays made?

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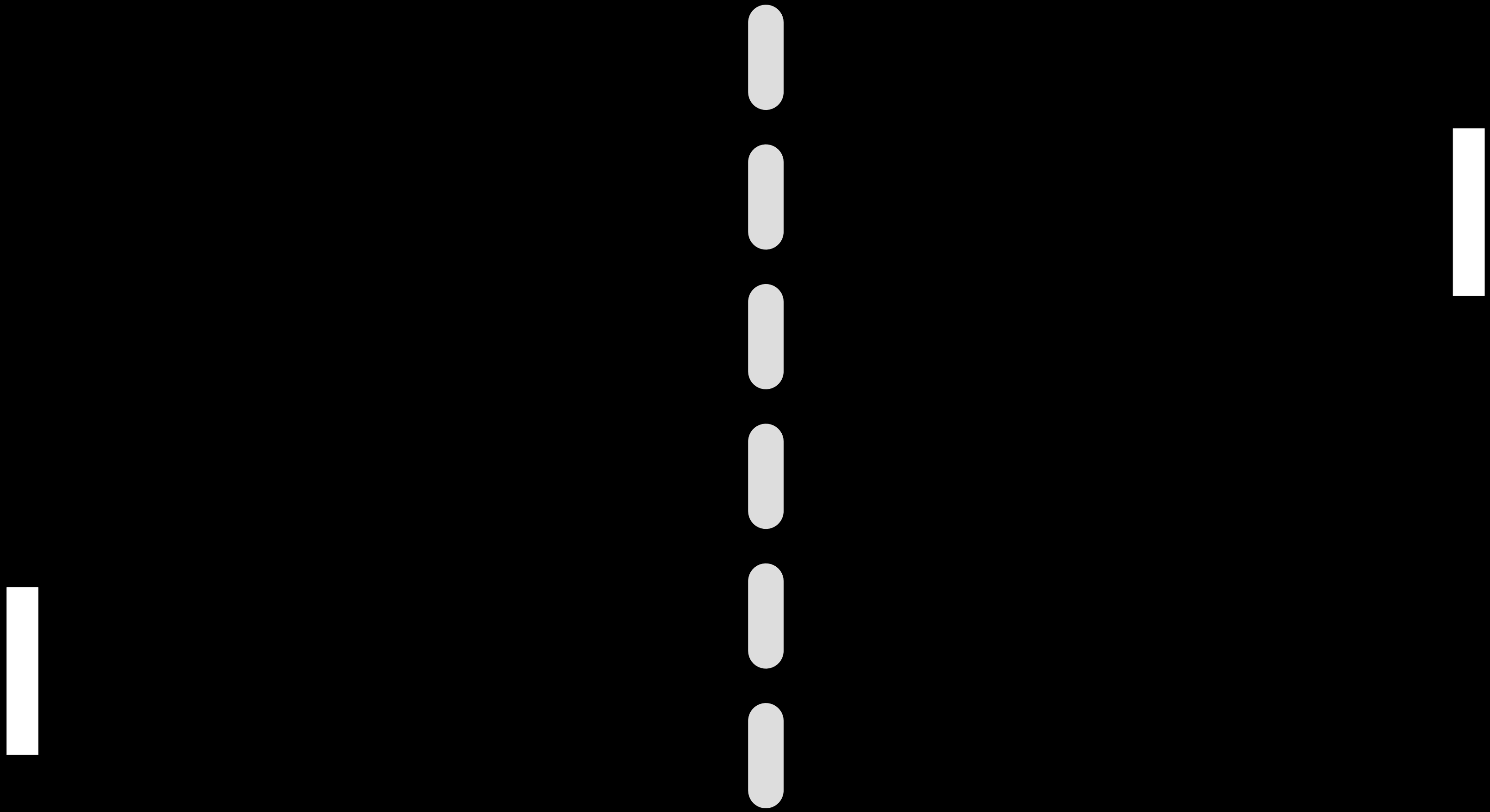

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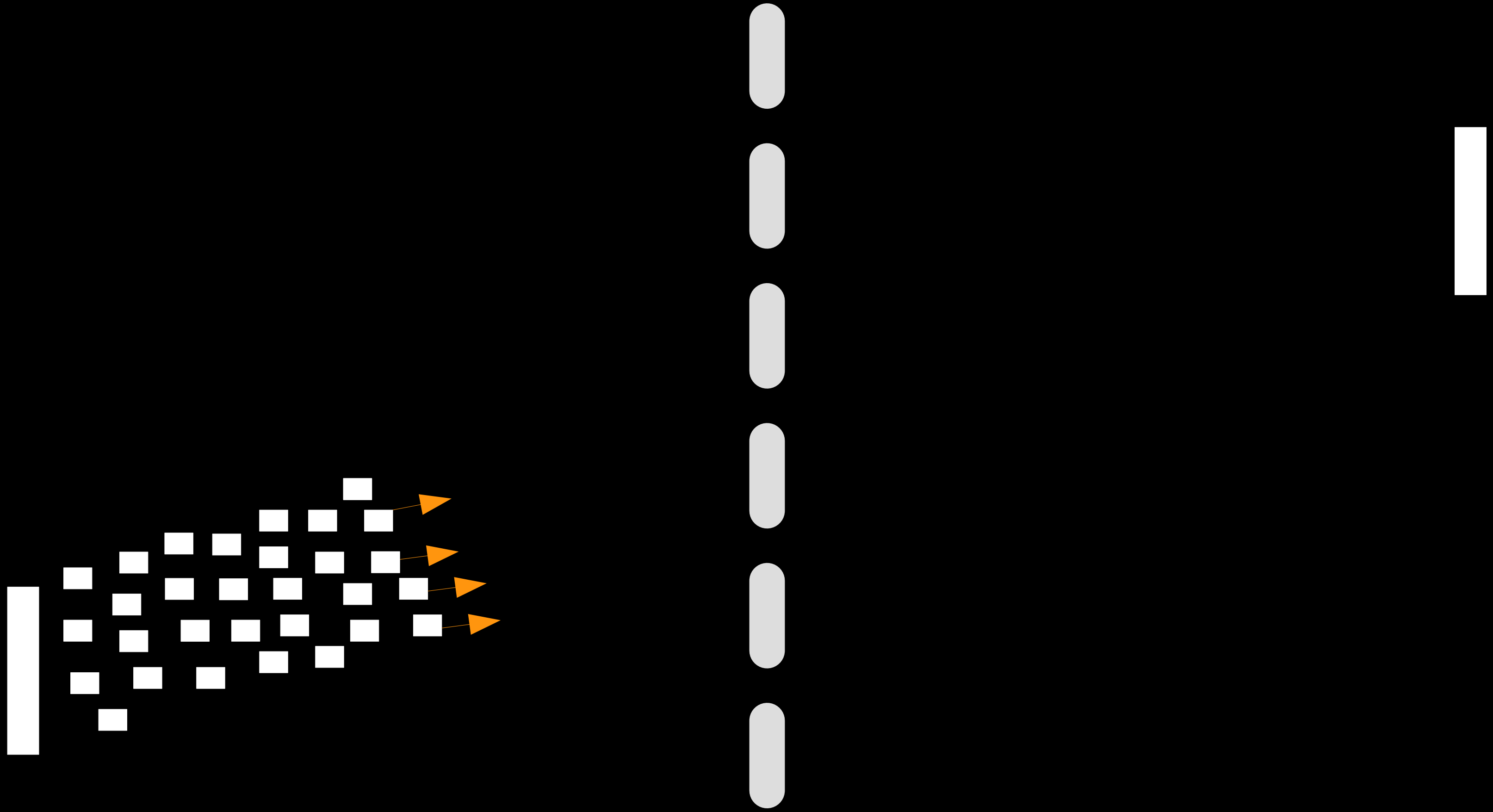

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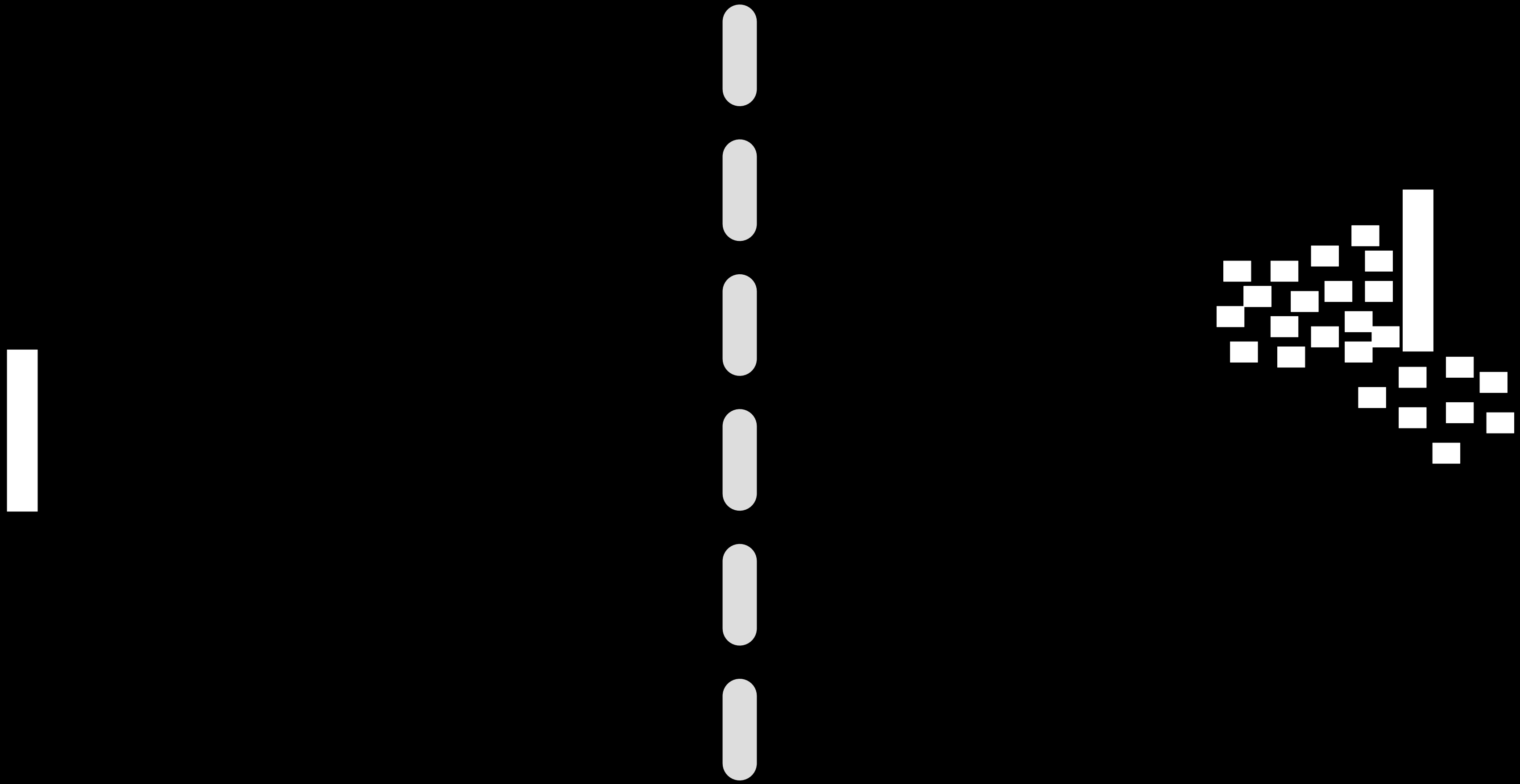

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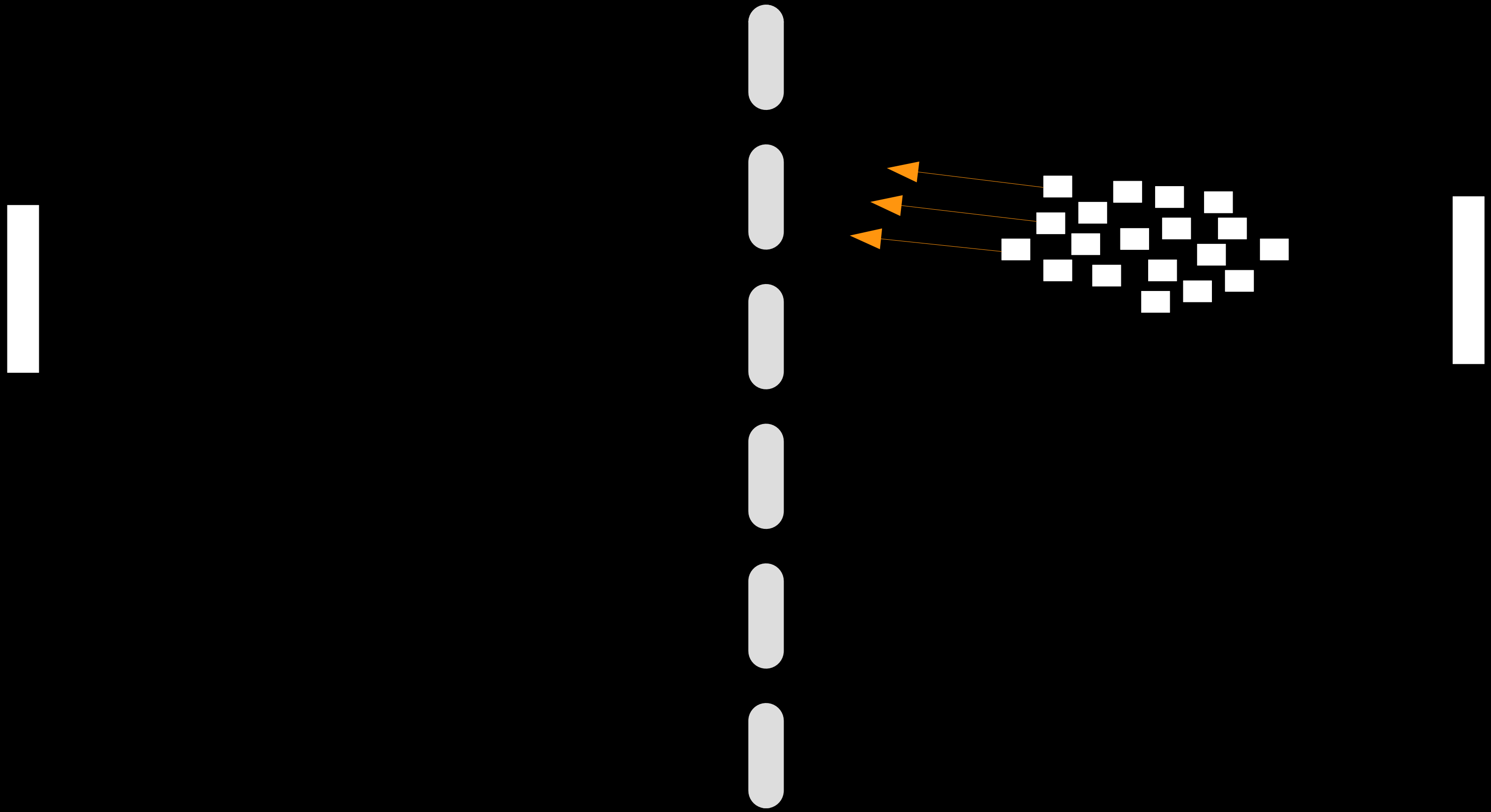

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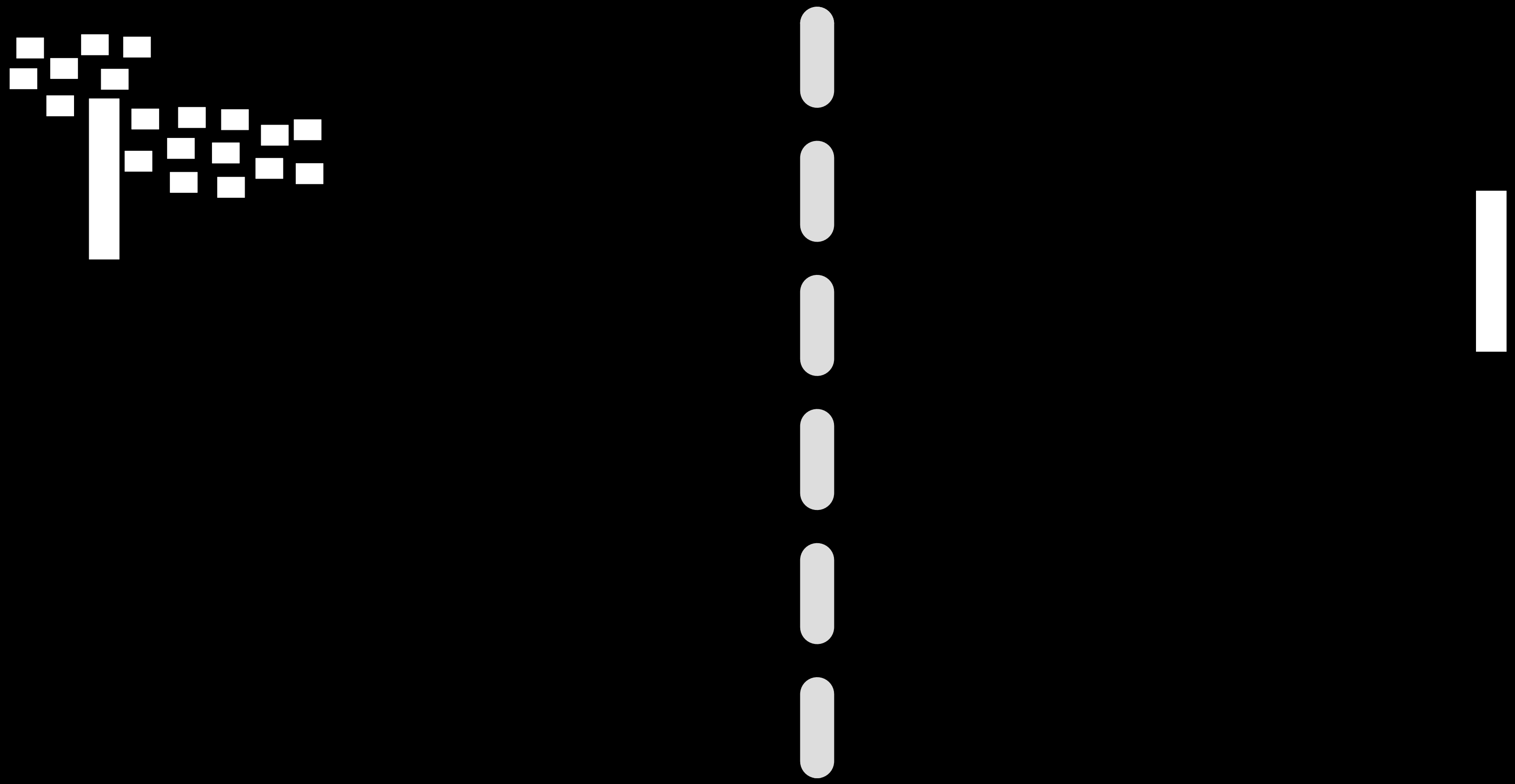

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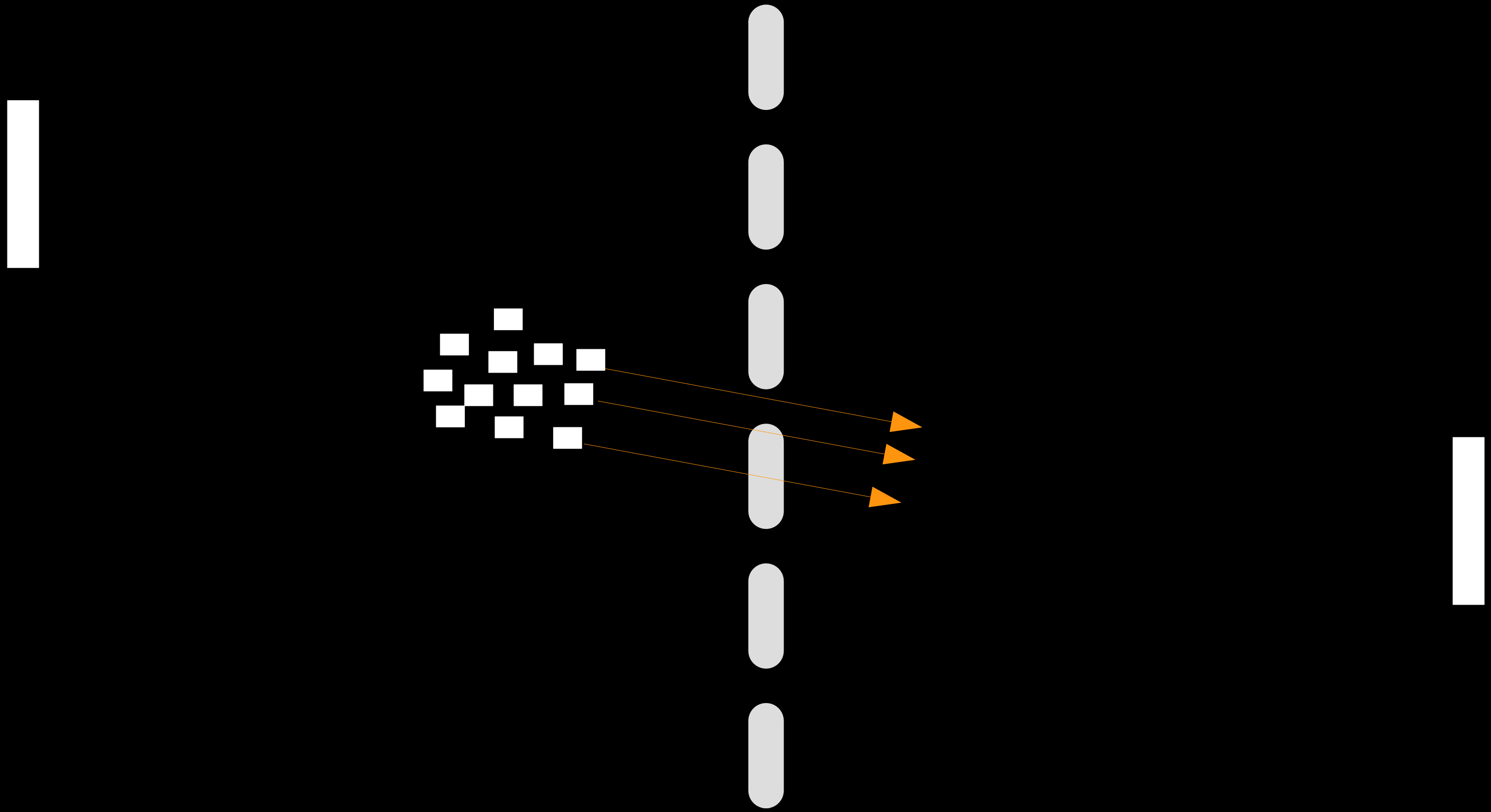
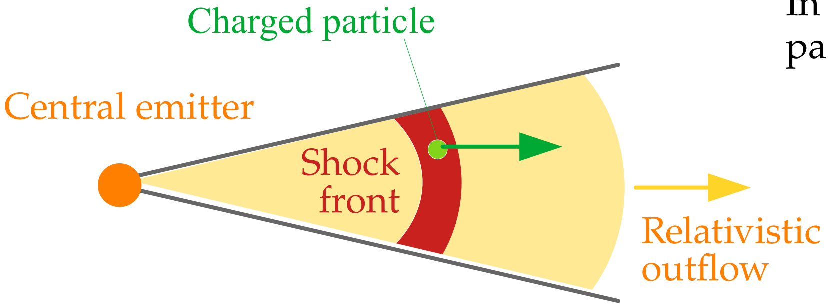
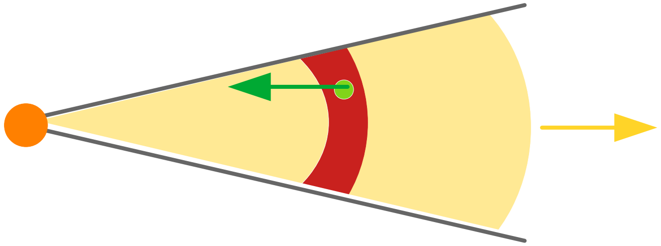


Fermi acceleration

Upstream to downstream



Downstream to upstream



In each crossing, the particle gains energy $\Delta E \propto v_{\text{shock}}$

Average energy of a particle after one crossing: $E = k\,E_0$

Probability that the particle remains in the acceleration region after one crossing: P

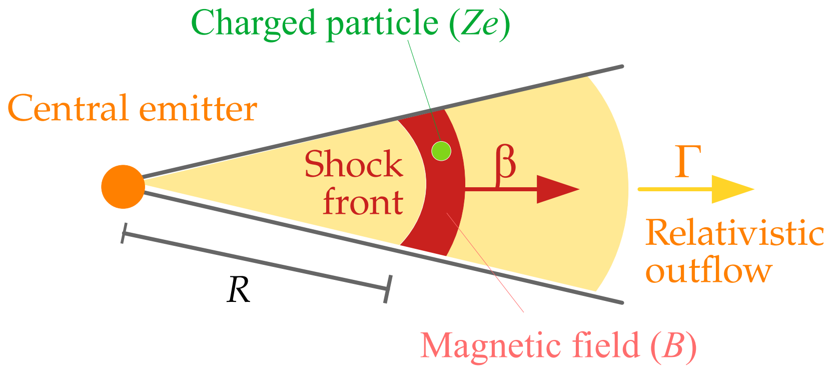
After n collisions, $N = N_0\,P^n$ particle remain, with energy $E = E_0\,k^n$

Energy spectrum: $N(E)dE \propto E^{-1+\frac{\ln P}{\ln k}}dE$

$$\left\langle \frac{\Delta E}{E} \right\rangle = \frac{4}{3}\left(\frac{v}{c}\right) \quad \text{and} \quad P = 1 - P_{\text{esc}} = 1 - \frac{4}{3}\left(\frac{v}{c}\right) \;\Rightarrow N(E)dE \propto E^{-2}dE$$

Hillas criterion

A necessary condition to accelerate charged particles is confinement within the acceleration region.



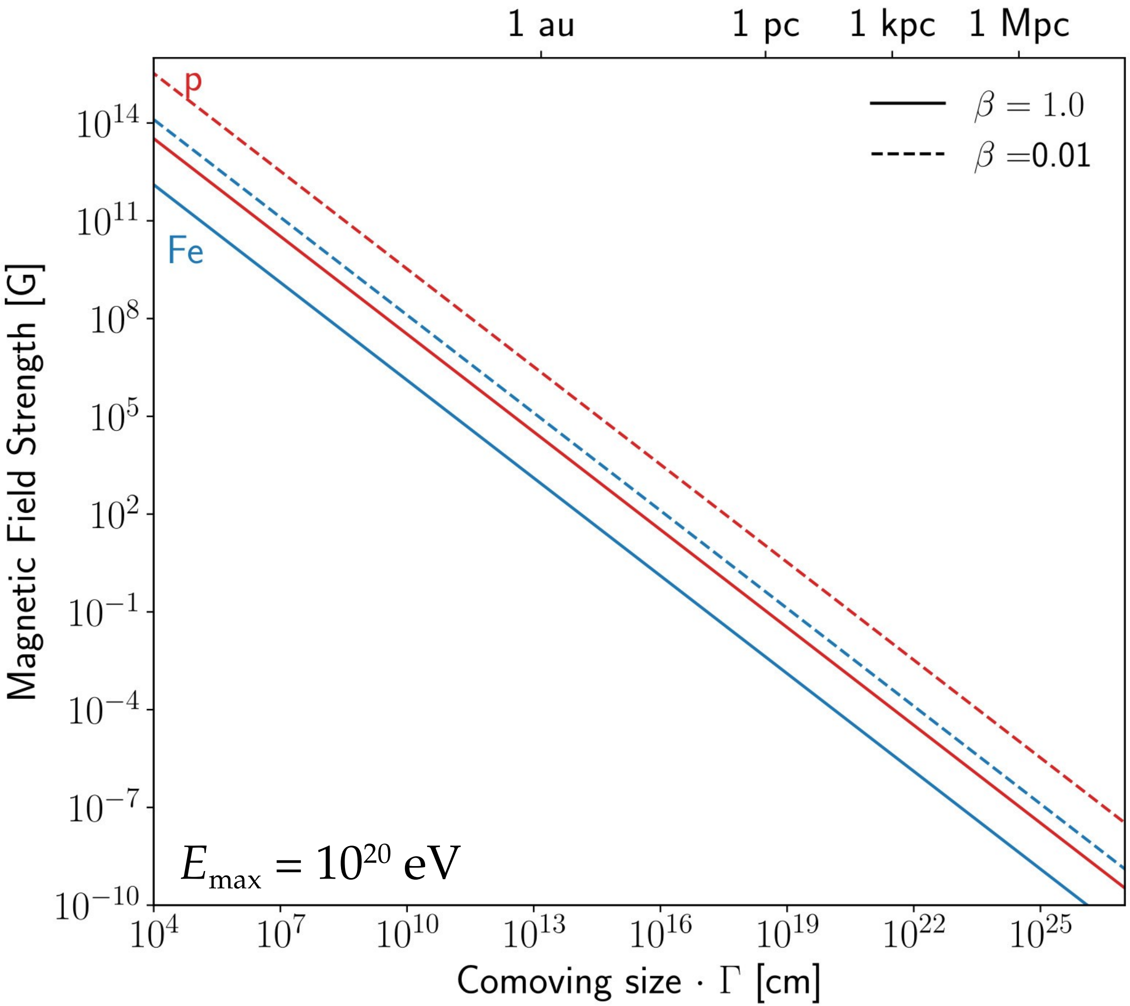
Confinement holds until

Larmor radius (R_L) = Size of region (R)

$$\frac{E_{\max}}{ZeB} = \beta\Gamma R$$

$$\Rightarrow E_{\max} = \eta^{-1}\beta\Gamma ZeBR$$

Acceleration efficiency



Hillas, *Ann. Rev. Astron. Astrophys.* 1984

Alves Batista *et al.* (inc. **MB**), *Front. Astron. Space Sci.* 2019

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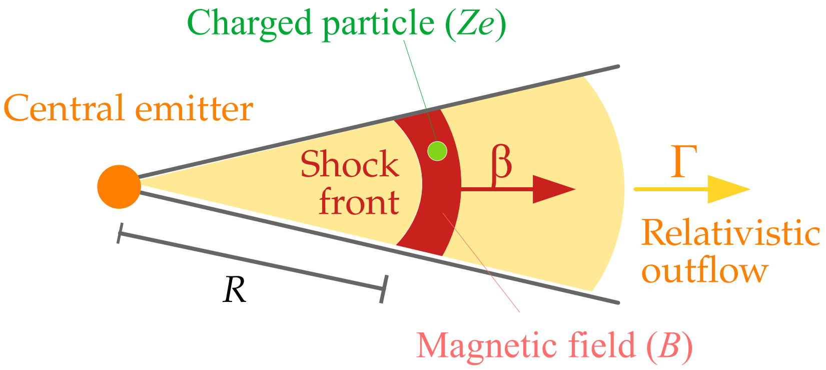

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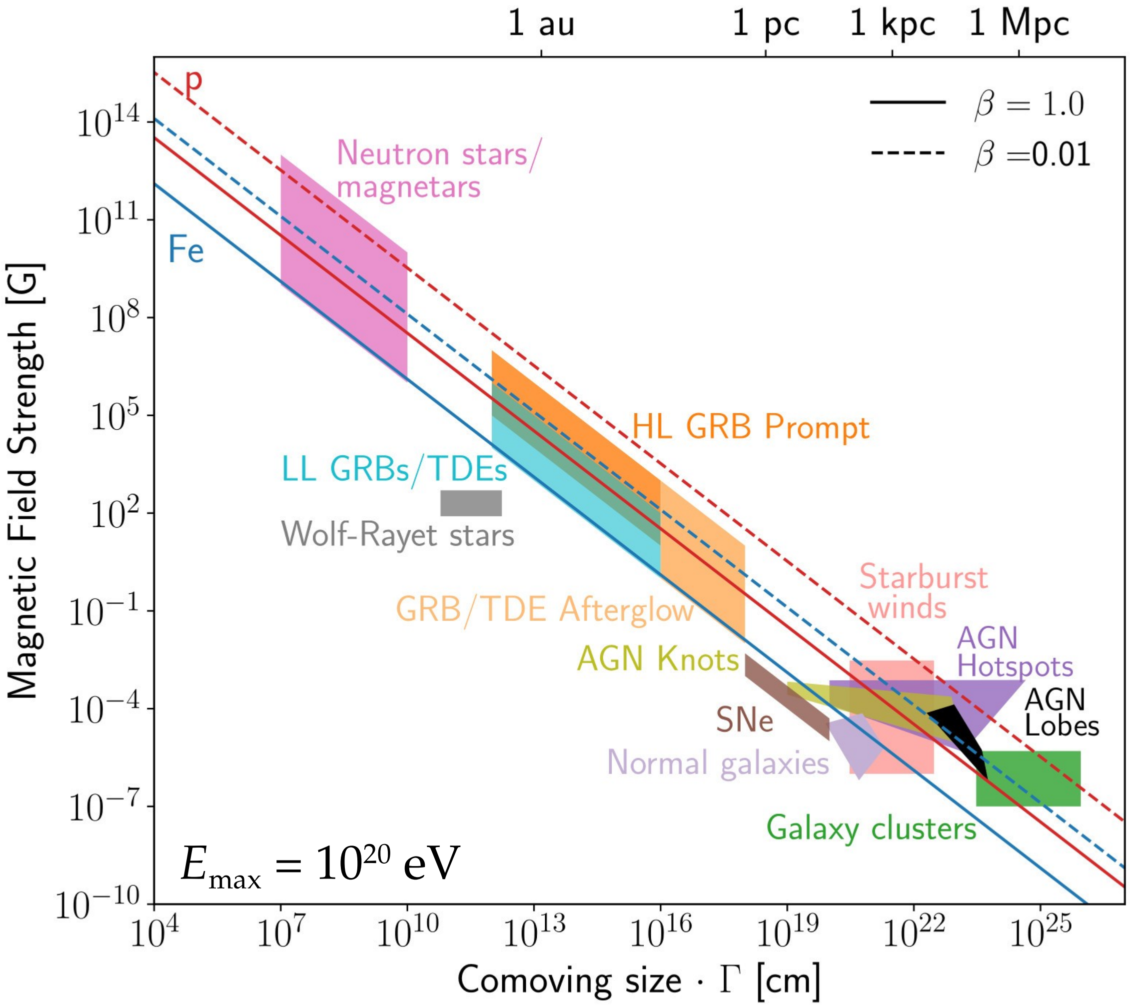
Acceleration efficiency



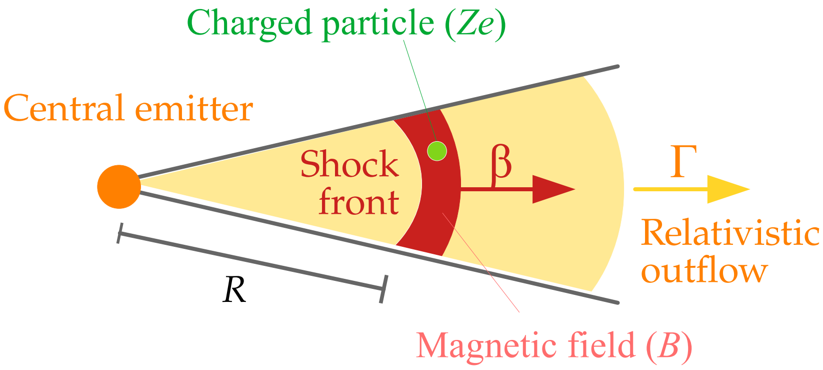
Hillas, *Ann. Rev. Astron. Astrophys.* 1984

Alves Batista *et al.* (inc. **MB**), *Front. Astron. Space Sci.* 2019

Hillas criterion

But not sufficient!

A necessary condition to accelerate charged particles is confinement within the acceleration region



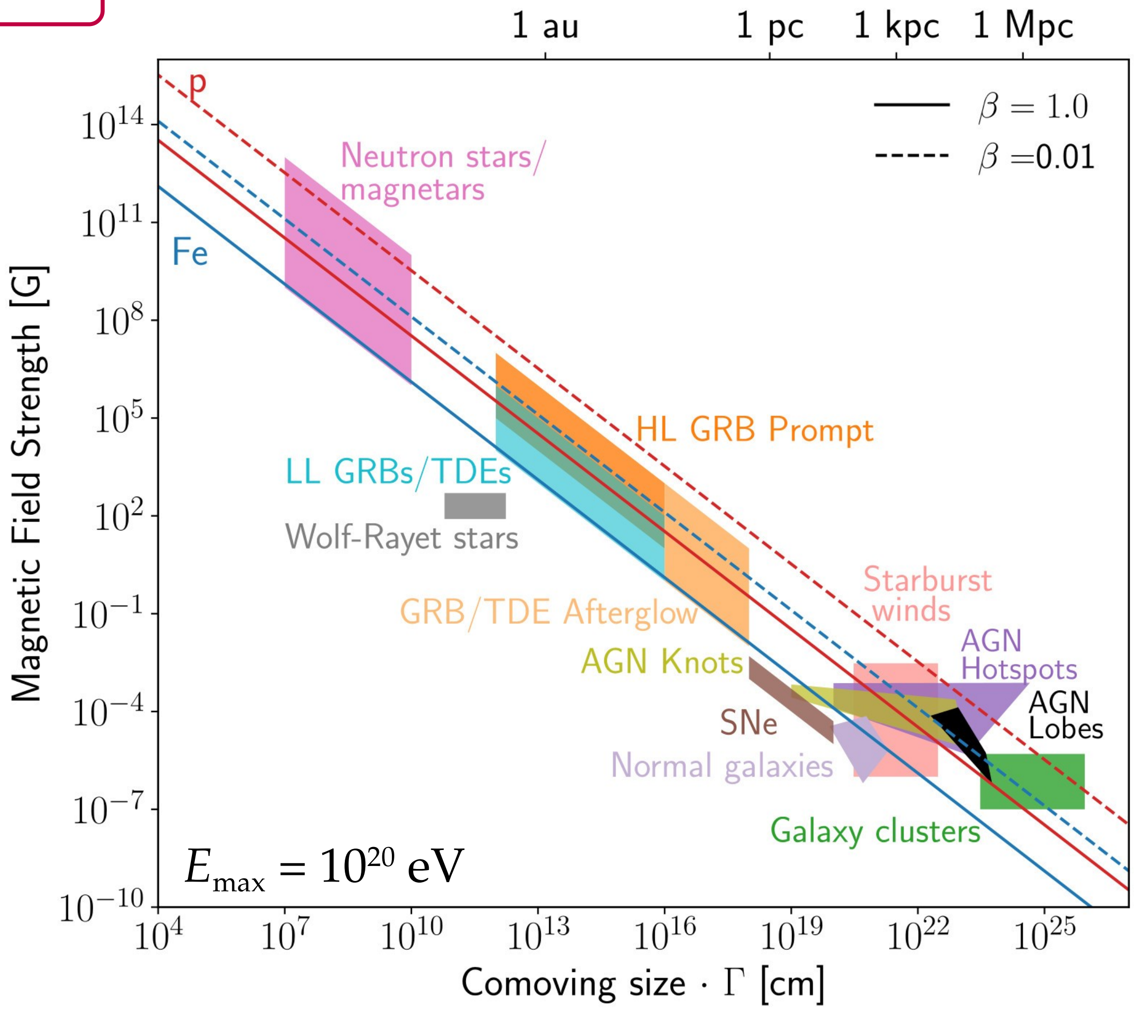
Confinement holds until

Larmor radius (R_L) = Size of region (R)

$$\frac{E_{\max}}{ZeB} = \beta\Gamma R$$

$$\Rightarrow E_{\max} = \eta^{-1}\beta\Gamma ZeBR$$

Acceleration efficiency



Hillas, *Ann. Rev. Astron. Astrophys.* 1984

Alves Batista *et al.* (inc. **MB**), *Front. Astron. Space Sci.* 2019

UHECR anisotropy

How do we know that UHECRs have an extragalactic origin?

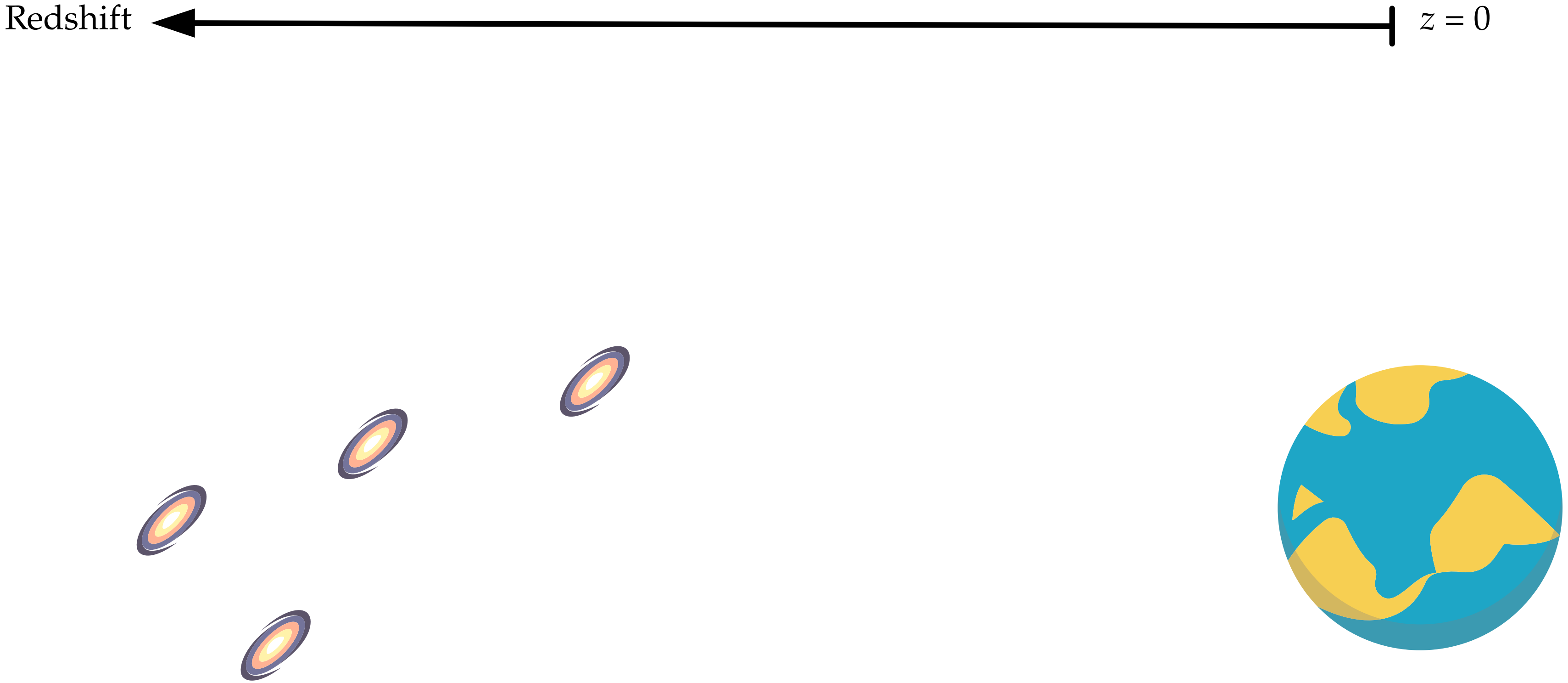
① Their energies are so large that their Larmor radius cannot be contained by the Milky Way

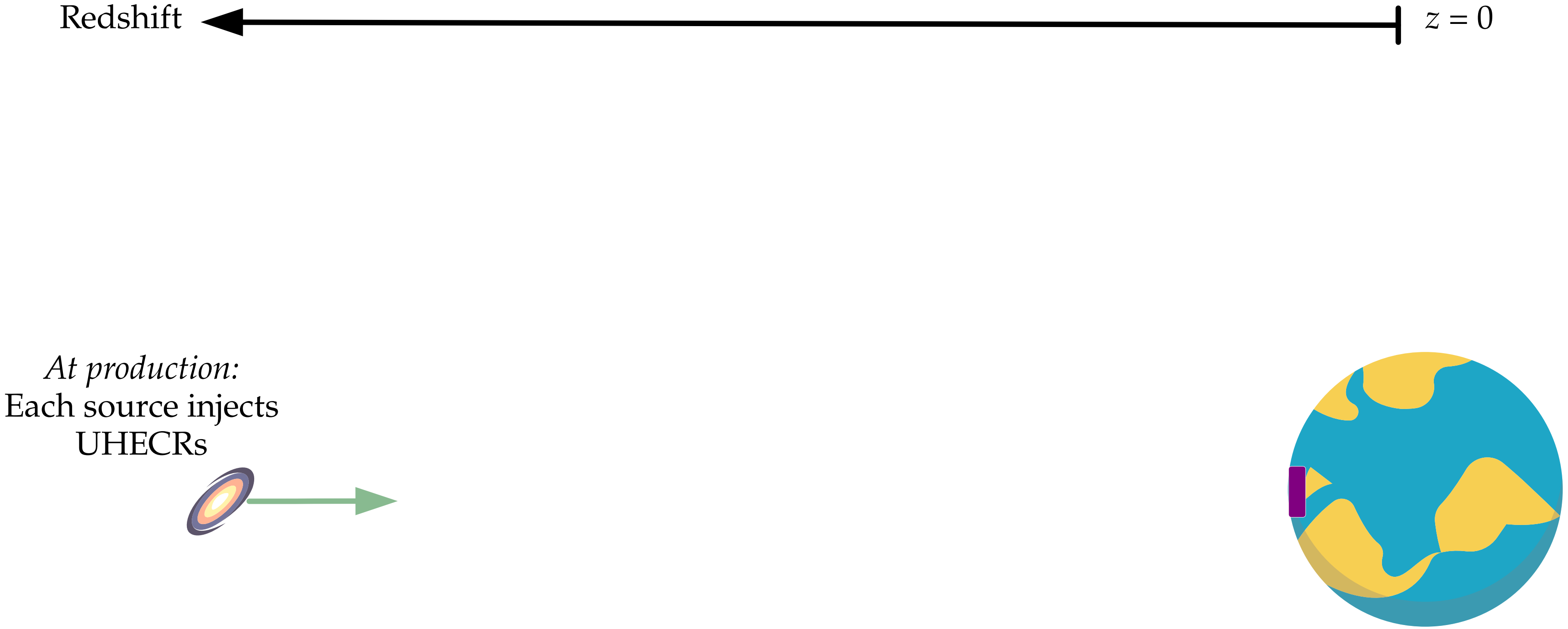
$$R_L = \frac{E_p}{eB} \approx \frac{10^{18}\ \mathrm{eV}}{e \times 1\ \mu\mathrm{G}} \gg 100\ \mathrm{kpc}$$

② We can look at the distribution of arrival directions of UHECRs (more on this later!)

UHECR
propagation

Calculating the UHECR flux at Earth

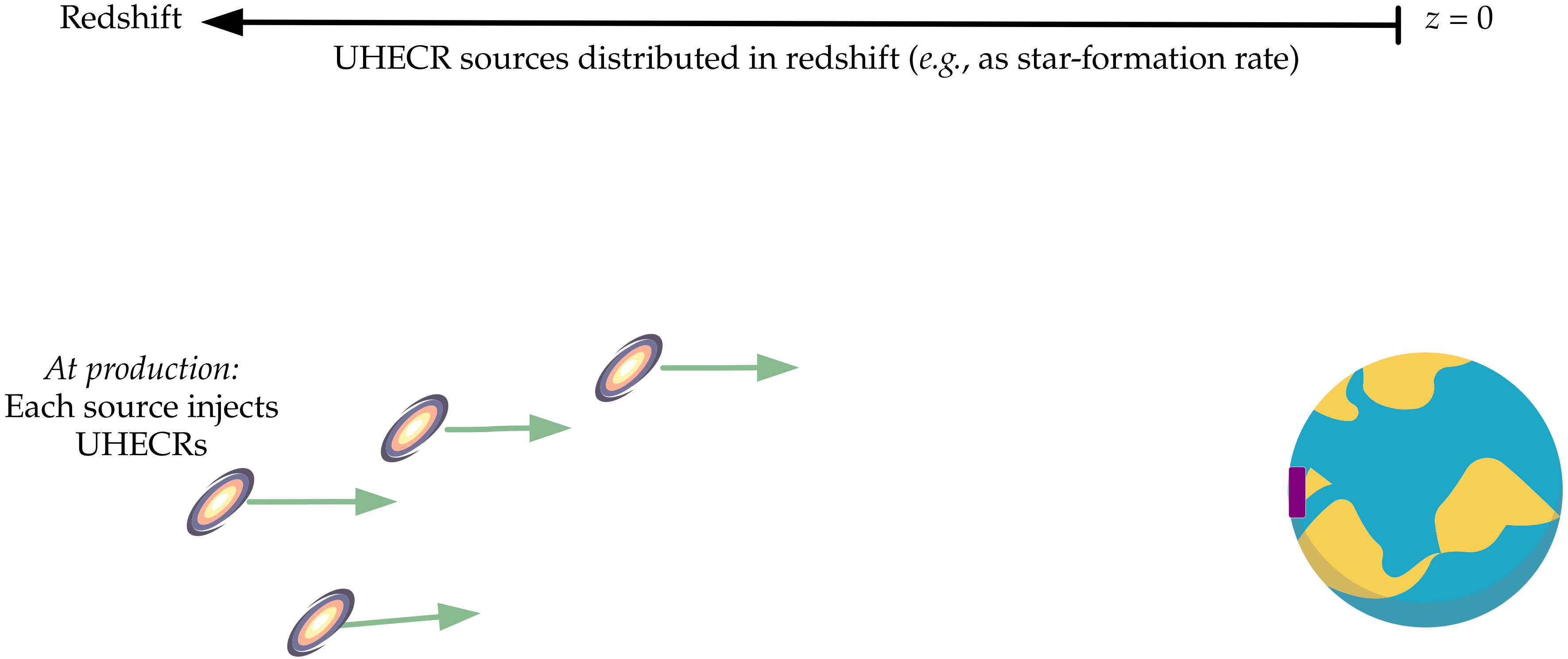

Redshift
$z = 0$



Redshift

$z = 0$

At production:
Each source injects
UHECRs

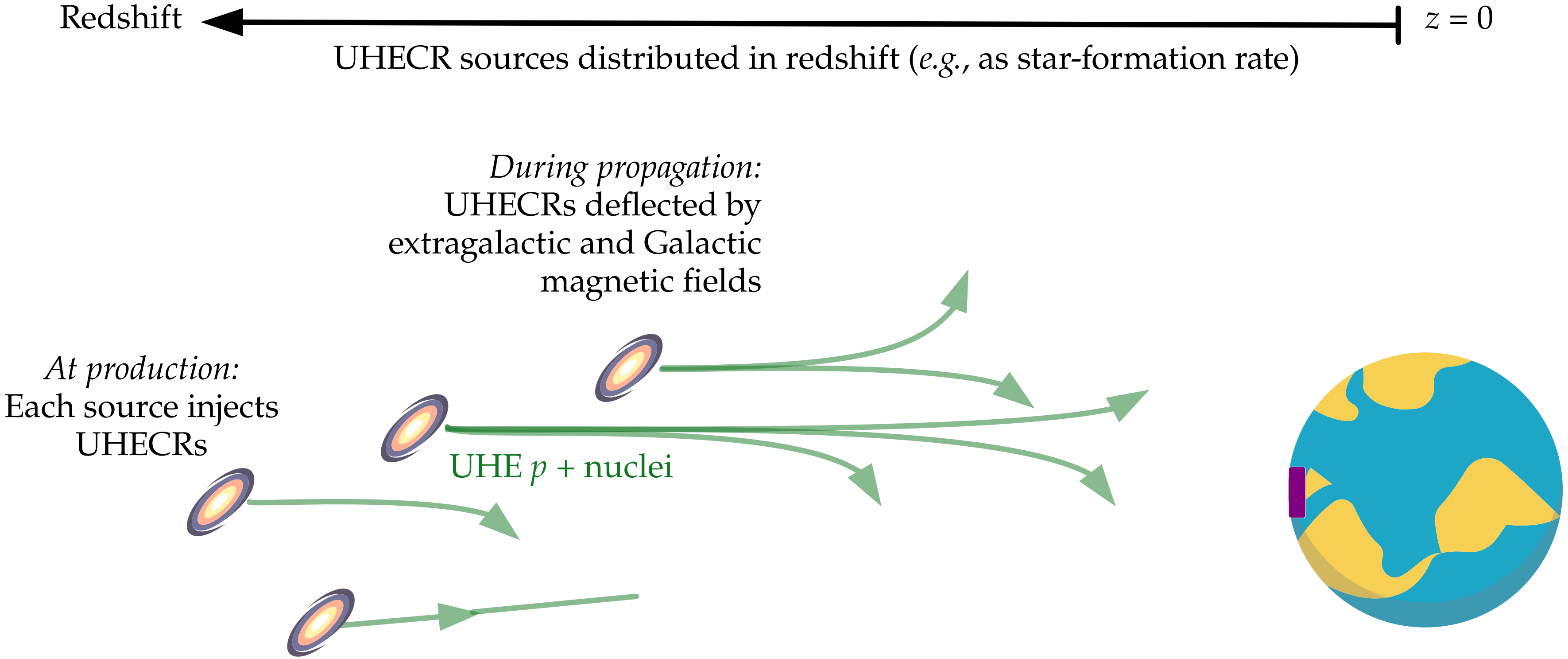


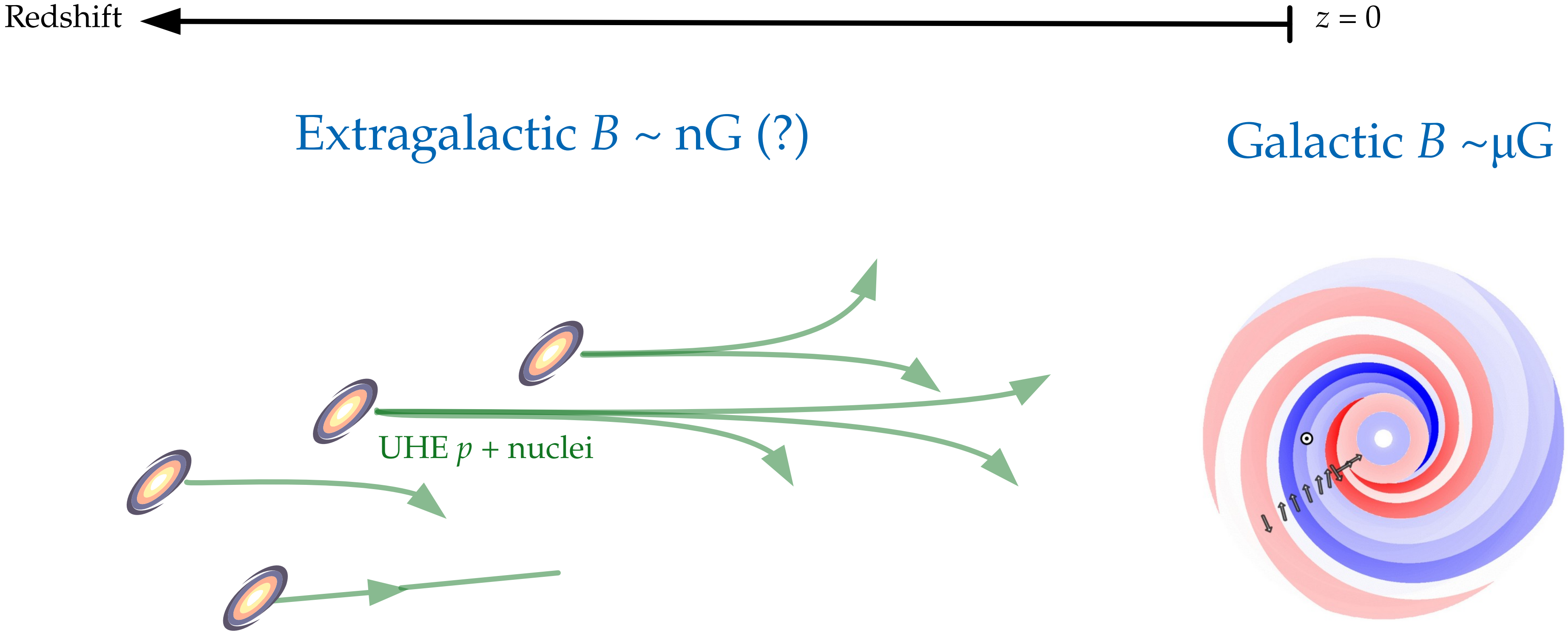
Redshift

$z = 0$

UHECR sources distributed in redshift (*e.g.*, as star-formation rate)

At production:
Each source injects
UHECRs


Redshift
$z = 0$
UHECR sources distributed in redshift (*e.g.*, as star-formation rate)
During propagation:
UHECRs deflected by
extragalactic and Galactic
magnetic fields
At production:
Each source injects
UHECRs
UHE p + nuclei



Redshift

$z = 0$

Extragalactic B ~ nG (?)

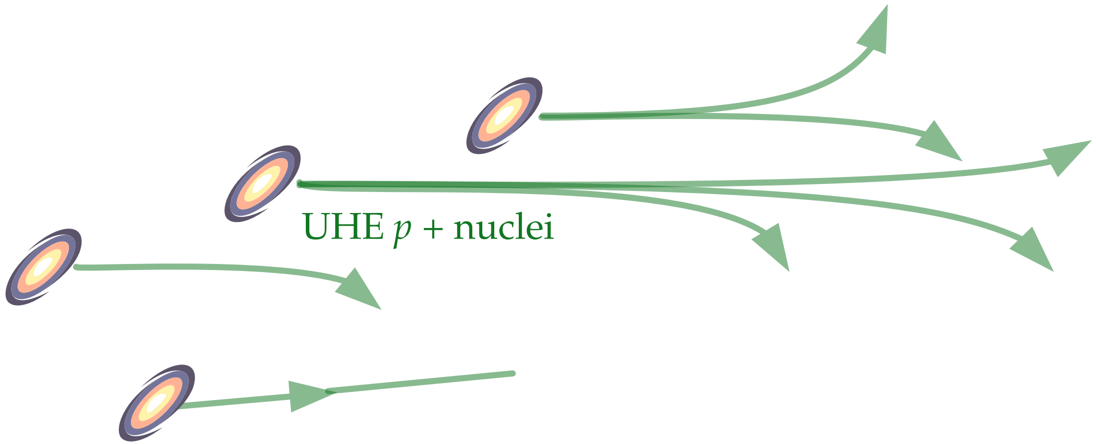
Galactic B ~μG

UHE p + nuclei

Not to scale

Redshift ← $z = 0$

Extragalactic B ~ nG (?)



Larger charge bends more

Longer trajectories bend more

Magnetic field intensity

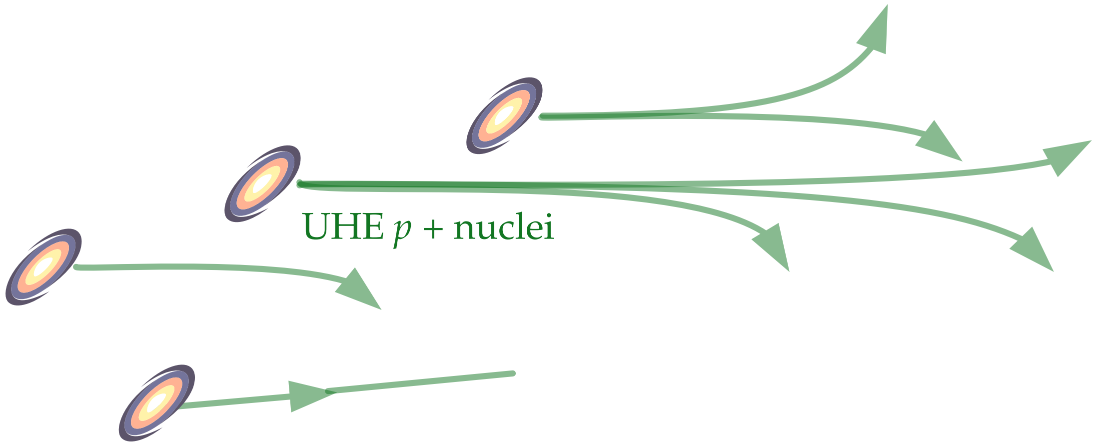
$$\delta_{\rm rms} \approx 0.8^\circ Z \left(\frac{10\ \text{EeV}}{E}\right)\left(\frac{L}{10\ \text{Mpc}}\right)^{1/2}\left(\frac{L_c}{\text{Mpc}}\right)^{1/2}\left(\frac{B_{\rm rms}}{n\text{G}}\right)$$

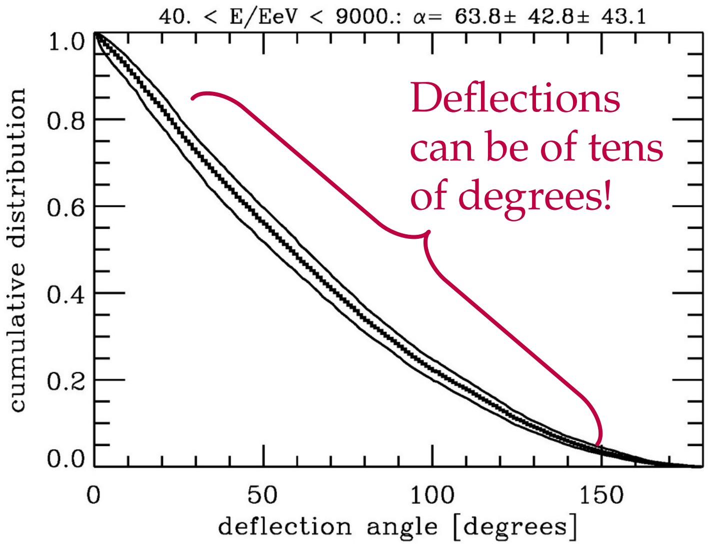
Larger charge bends more

L_c: field coherence length

Sigl, Miniati, Ensslin, *PRD* 2004

Extragalactic B ~ nG (?)





Deflections can be of tens of degrees!

Larger charge bends more

Longer trajectories bend more

Magnetic field intensity

$$\delta_{\rm rms} \approx 0.8^\circ Z \left(\frac{10\ \mathrm{EeV}}{E}\right)\left(\frac{L}{10\ \mathrm{Mpc}}\right)^{1/2}\left(\frac{L_c}{\mathrm{Mpc}}\right)^{1/2}\left(\frac{B_{\rm rms}}{n\mathrm{G}}\right)$$

Larger charge bends more

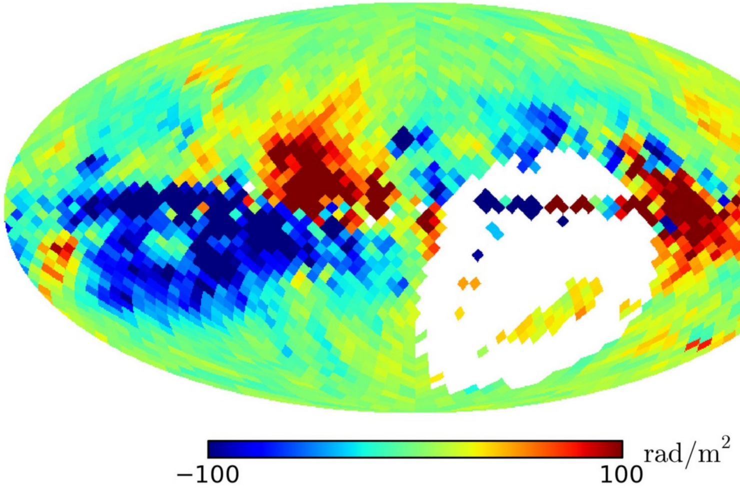
L_c: field coherence length

Sigl, Miniati, Ensslin, *PRD* 2004

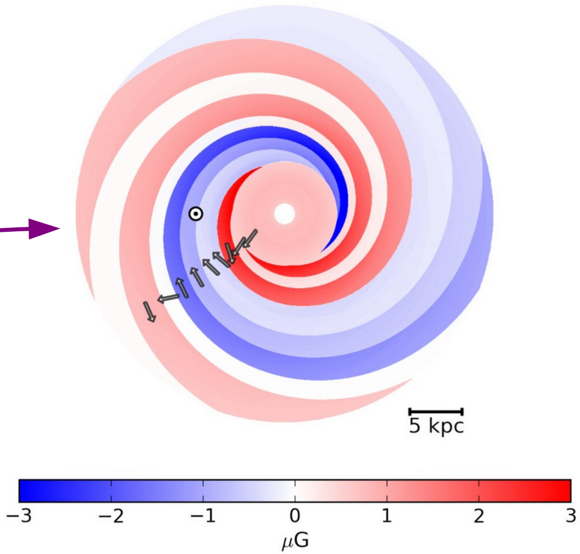
Scattering on magnetic fields

Faraday rotation: Polarization of e.m. waves
by magnetized plasma

$$\Delta\Psi = \mathrm{RM} \cdot \lambda^2$$



Galactic B ~μG



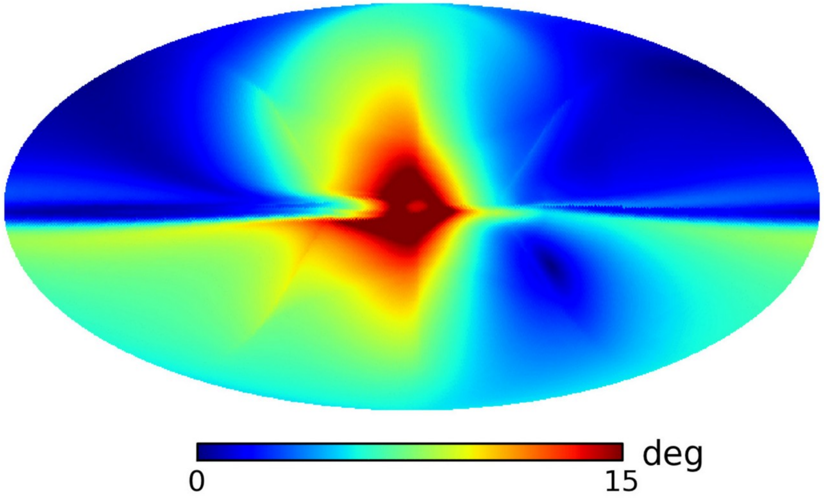
Milky Way electron density

$$\mathrm{RM} \simeq 0.81 \int_0^L \left(\frac{n_e(l)}{\mathrm{cm}^{-3}}\right)\left(\frac{B(l)}{\mu\mathrm{G}}\right)\left(\frac{dl}{\mathrm{pc}}\right)$$

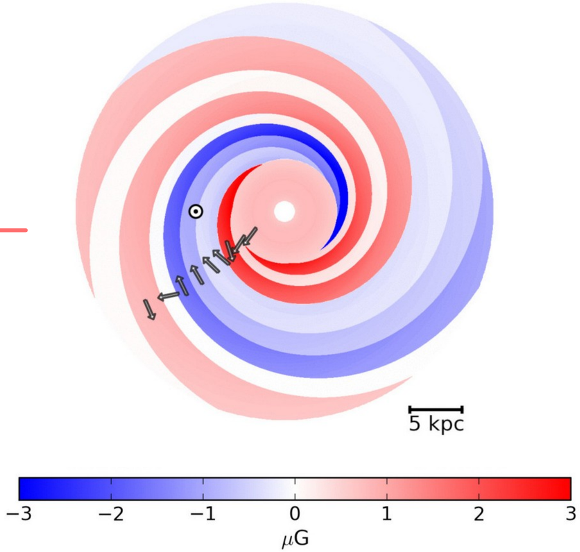
Jansson & Farrar, *ApJ* 2012

Scattering on magnetic fields

Galactic deflections of 60-EeV protons



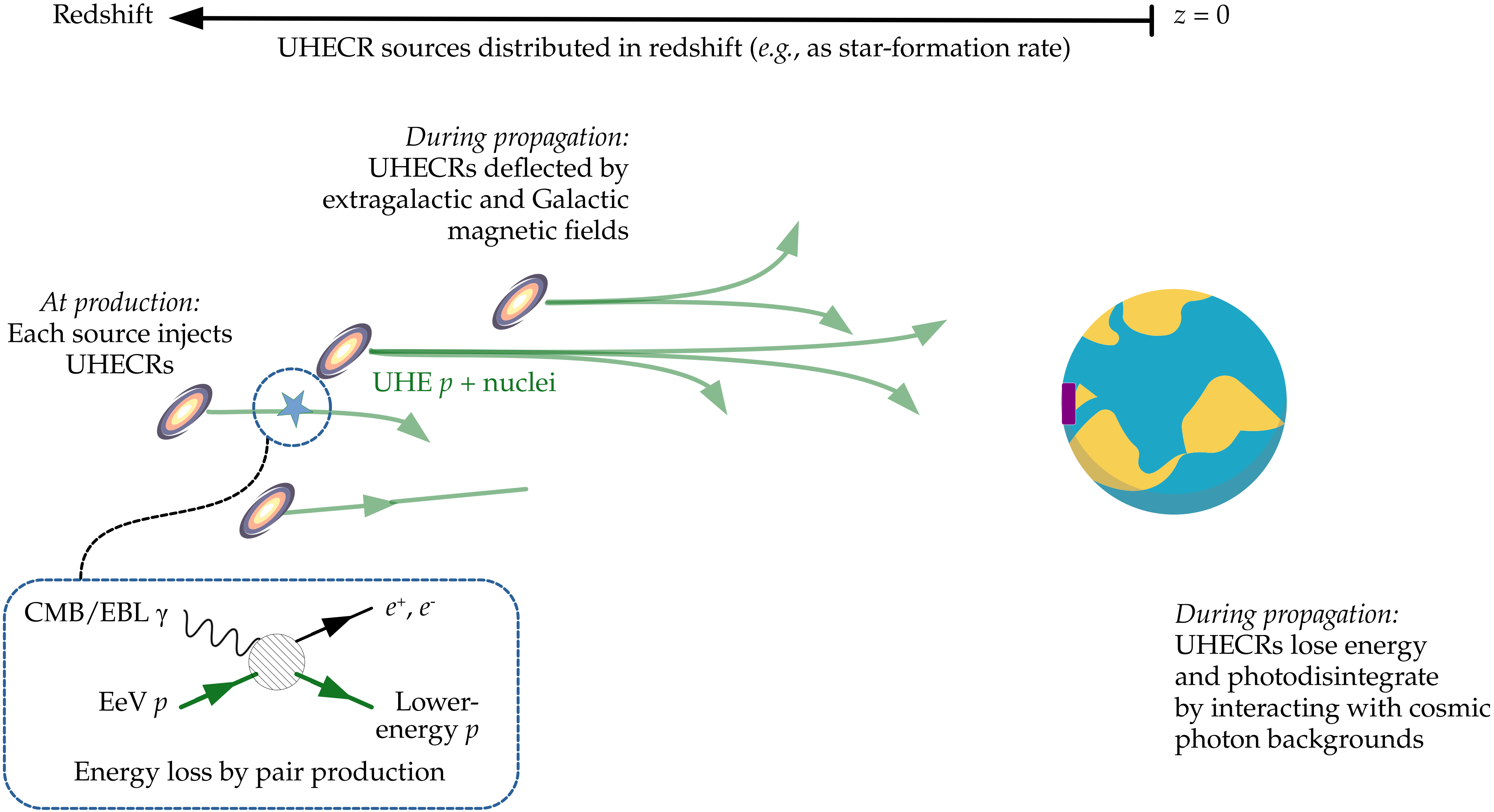
Galactic B ~μG

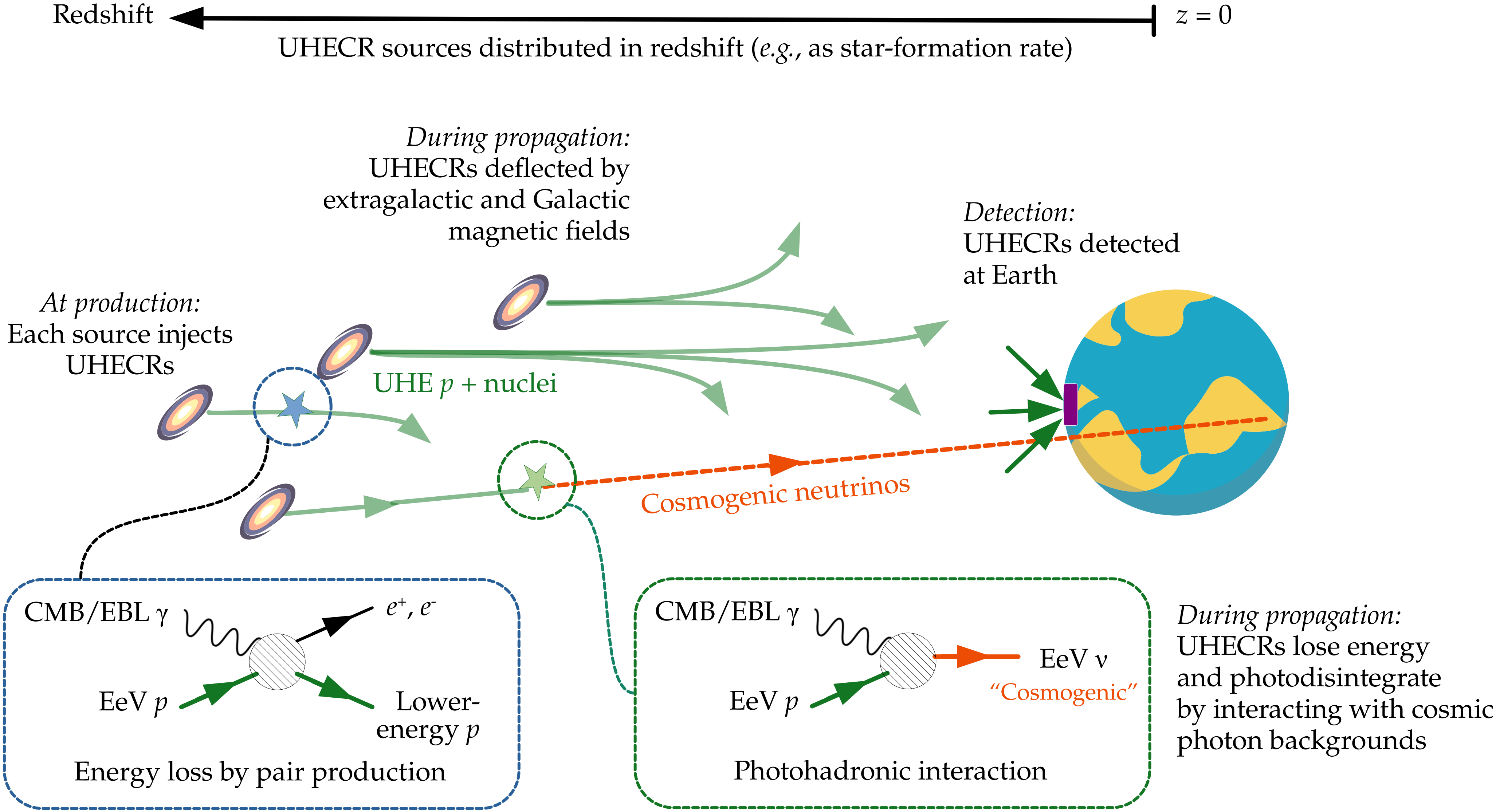


$$\delta \approx 16^\circ Z \left(\frac{20\ \mathrm{EeV}}{E}\right) \int_0^L \frac{dL}{3\ \mathrm{kpc}} \left(\frac{B}{2\ \mu\mathrm{G}}\right)$$

Auger Collab., *Astropart. Phys.* 2007

Jansson & Farrar, *ApJ* 2012


Redshift
$z = 0$
UHECR sources distributed in redshift (*e.g.*, as star-formation rate)
During propagation:
UHECRs deflected by
extragalactic and Galactic
magnetic fields
At production:
Each source injects
UHECRs
UHE p + nuclei
CMB/EBL γ
e^+, e^-
EeV p
Lower-
energy p
Energy loss by pair production
During propagation:
UHECRs lose energy
and photodisintegrate
by interacting with cosmic
photon backgrounds


Redshift
z = 0
UHECR sources distributed in redshift (e.g., as star-formation rate)
During propagation:
UHECRs deflected by extragalactic and Galactic magnetic fields
Detection:
UHECRs detected at Earth
At production:
Each source injects UHECRs
UHE p + nuclei
Cosmogenic neutrinos
CMB/EBL γ
e⁺, e⁻
EeV p
Lower-energy p
Energy loss by pair production
CMB/EBL γ
EeV ν
"Cosmogenic"
EeV p
Photohadronic interaction
During propagation:
UHECRs lose energy and photodisintegrate by interacting with cosmic photon backgrounds

Calculating the UHECR flux at Earth

a: Scale factor

n_p: Real number density

Comoving number density of protons (GeV^{-1} cm^{-3}): $Y_p(E,z) = a^3(z)n_p(E,z) = \frac{1}{(1+z)^3}n_p(E,z)$

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Solve a propagation equation:

$$\dot{Y}_p = \partial_E(HEY_p) + \partial_E(b_{e^+e^-}Y_p) + \partial_E(b_{p\gamma}Y_p) + \mathcal{L}_{\mathrm{CR}}$$

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Solve a propagation equation:

$$\dot{Y}_p = \underbrace{\partial_E(HEY_p)}_{\text{Energy loss due to adiabatic cosmological expansion}} + \partial_E(b_{e^+e^-} Y_p) + \partial_E(b_{p\gamma} Y_p) + \mathcal{L}_{\rm CR}$$

Calculating the UHECR flux at Earth

a: Scale factor

n_p: Real number density

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Solve a propagation equation:

Energy loss rates: $b \equiv -\frac{dE}{dt}$

$$\dot{Y}_p = \underbrace{\partial_E(HEY_p)}_{} + \partial_E(b_{e^+e^-}Y_p) + \partial_E(b_{p\gamma}Y_p) + \mathcal{L}_{\rm CR}$$

Energy loss due to adiabatic cosmological expansion

Calculating the UHECR flux at Earth

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Energy loss due to adiabatic cosmological expansion

Energy loss due to pair production:
$p + \gamma \rightarrow p + e^+ + e^-$

Calculating the UHECR flux at Earth

a: Scale factor

n_p: Real number density

Comoving number density of protons (GeV^{-1} cm^{-3}): $Y_p(E,z) = a^3(z)\,n_p(E,z) = \frac{1}{(1+z)^3}\,n_p(E,z)$

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Energy loss due to adiabatic
cosmological expansion

Energy loss due to
pair production:
$p + \gamma \rightarrow p + e^+ + e^-$

Energy loss due
to photohadronic int.:
$p + \gamma \rightarrow p + \pi^0$
$p + \gamma \rightarrow n + \pi^+$
+ other process
+ n beta-decay into p

Calculating the UHECR flux at Earth

a: Scale factor

n_p: Real number density

Comoving number density of protons (GeV^{-1} cm^{-3}): $Y_p(E,z) = a^3(z)n_p(E,z) = \frac{1}{(1+z)^3}n_p(E,z)$

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Energy loss due to adiabatic cosmological expansion

Energy loss due to pair production:

$p + \gamma \rightarrow p + e^+ + e^-$

Energy loss due to photohadronic int.:

$p + \gamma \rightarrow p + \pi^0$

$p + \gamma \rightarrow n + \pi^+$

+ other process

+ n beta-decay into p

Cosmic-ray injection by UHECR sources

Calculating the UHECR flux at Earth

a: Scale factor n_p: Real number density

Comoving number density of protons (GeV^{-1} cm^{-3}): $Y_p(E,z) = a^3(z) n_p(E,z) = \frac{1}{(1+z)^3} n_p(E,z)$

Solve a propagation equation:

$$\dot{Y}_p = \partial_E(HEY_p) + \partial_E(b_{e^+e^-} Y_p) + \partial_E(b_{p\gamma} Y_p) + \mathcal{L}_{\rm CR}$$

Recast in terms of redshift using

$$\frac{dz}{dt} = -(1+z)H(z)$$

with Hubble parameter

$$H(z) = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}$$

Calculating the UHECR flux at Earth

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$$H(z) = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}$$

$$\partial_z Y_p(E,z) = \frac{-1}{(1+z)H(z)}\{\partial_E(H(z)EY_p(E,z)) + \partial_E(b_{e^+e^-}(E,z)Y_p(E,z)) + \partial_E(b_{p\gamma}(E,z)Y_p(E,z)) + \mathcal{L}_{\mathrm{CR}}(E,z)\}$$

Calculating the UHECR flux at Earth

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n_p: Real number density

Comoving number density of protons (GeV^{-1} cm^{-3}): $Y_p(E,z) = a^3(z) n_p(E,z) = \frac{1}{(1+z)^3} n_p(E,z)$

Solve a propagation equation:

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Evolve this equation from $z_{\mathrm{max}} \sim 4$ to Earth ($z = 0$)

Calculating the UHECR flux at Earth

$$\partial_z Y_p(E,z) = \frac{-1}{(1+z)H(z)}\{\partial_E(H(z)EY_p(E,z)) + \partial_E(b_{e^+e^-}(E,z)Y_p(E,z)) + \partial_E(b_{p\gamma}(E,z)Y_p(E,z)) + \mathcal{L}_{\mathrm{CR}}(E,z)\}$$

Cosmic-ray injection by UHECR sources

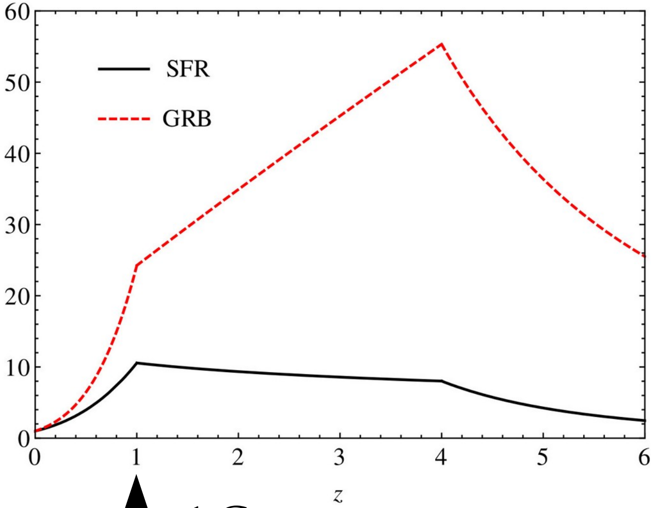
Each source injects UHECRs with a spectrum (GeV^{-1} s^{-1})

$$Q_{\mathrm{CR}}(E) \propto E^{-\gamma} e^{-E/E_{\max}}$$

$$\mathcal{L}_{\mathrm{CR}} = Q_{\mathrm{CR}}(E(1+z))\mathcal{H}_{\mathrm{CR}}(z)$$

The number density of sources evolves with redshift (Mpc^{-3})

$\mathcal{H}_{\mathrm{CR}}(z)$



~1 Gpc

Calculating the UHECR flux at Earth

$$\partial_z Y_p(E,z) = \frac{-1}{(1+z)H(z)}\{\partial_E(H(z)EY_p(E,z)) + \partial_E(b_{e^+e^-}(E,z)Y_p(E,z)) + \partial_E(b_{p\gamma}(E,z)Y_p(E,z)) + \mathcal{L}_{\mathrm{CR}}(E,z)\}$$

Adiabatic cosmological expansion

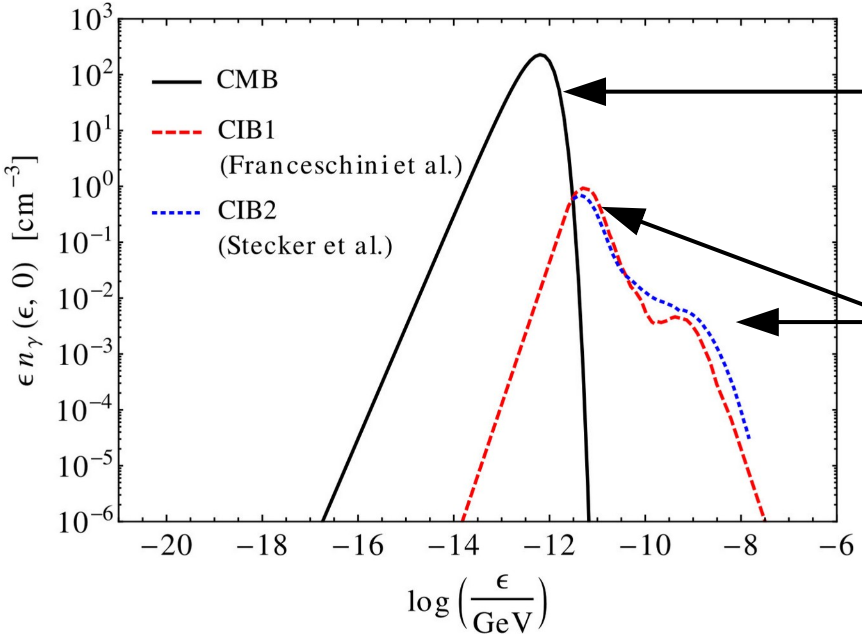
$$\text{Energy at Earth} = \frac{\text{Energy at production}}{1+z}$$

Calculating the UHECR flux at Earth

$$\partial_z Y_p(E,z) = \frac{-1}{(1+z)H(z)} \{\partial_E(H(z)EY_p(E,z)) + \partial_E(b_{e^+e^-}(E,z)Y_p(E,z)) + \partial_E(b_{p\gamma}(E,z)Y_p(E,z)) + \mathcal{L}_{\mathrm{CR}}(E,z)\}$$

Interaction with cosmological backgrounds
(pair production + photohadronic)

$p + \gamma \to \Delta$



Blackbody spectrum

Optical/UV emission from stars, reprocessed into infrared by dust

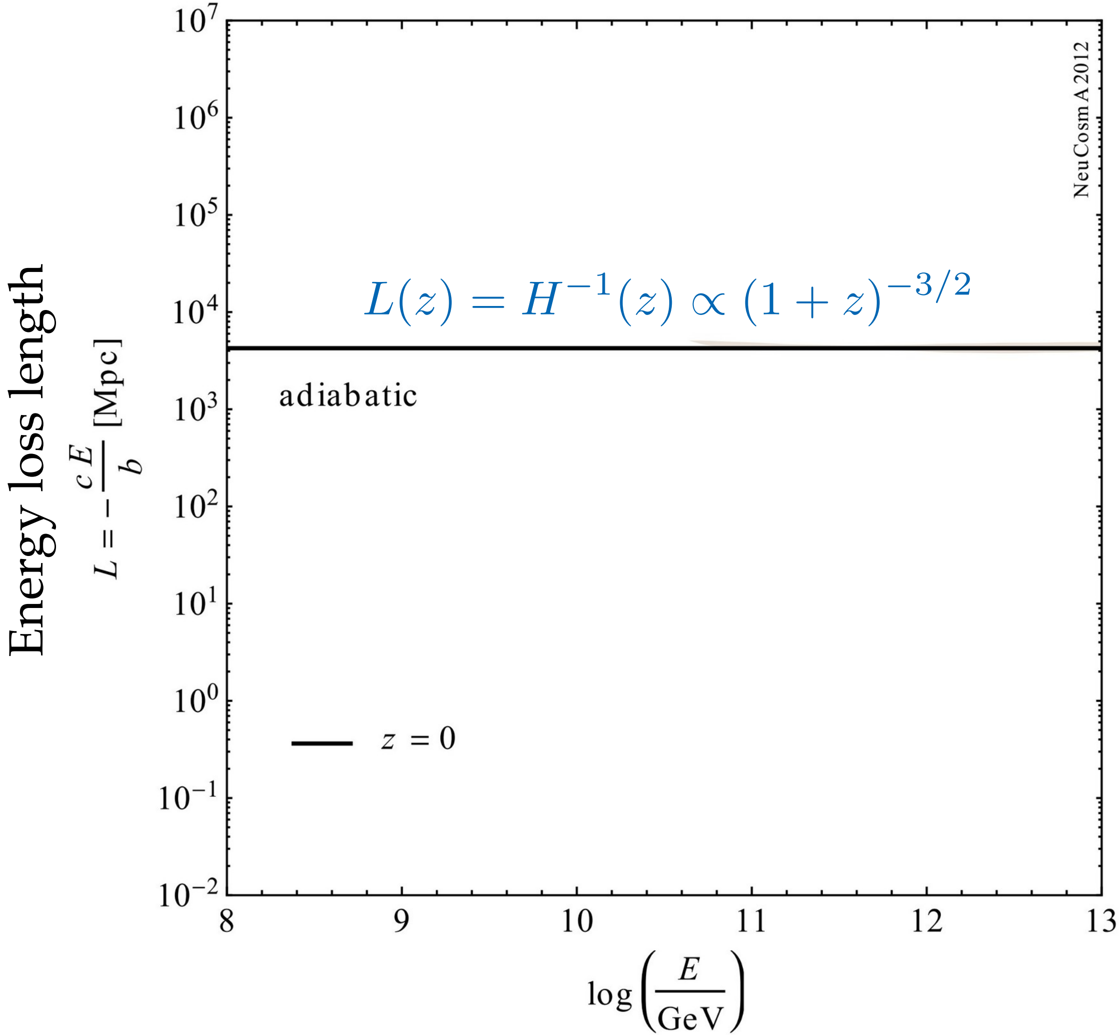
Energy threshold to produce a Δ(1232) resonance:

$$p_p + p_\gamma = p_\Delta$$

$$E_p E_\gamma \approx 0.16\ \mathrm{GeV}^2$$

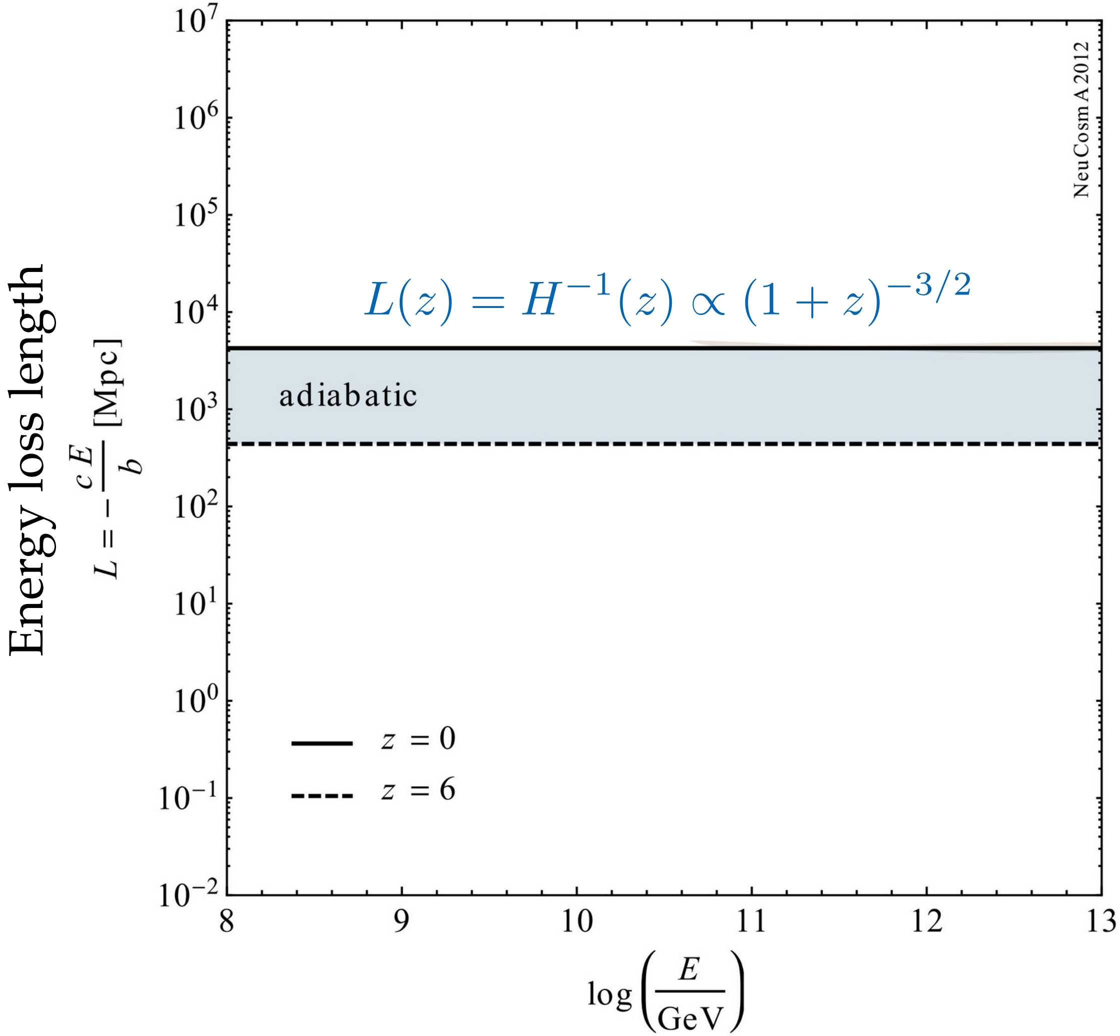
(We will use this later, too)

Calculating the UHECR flux at Earth

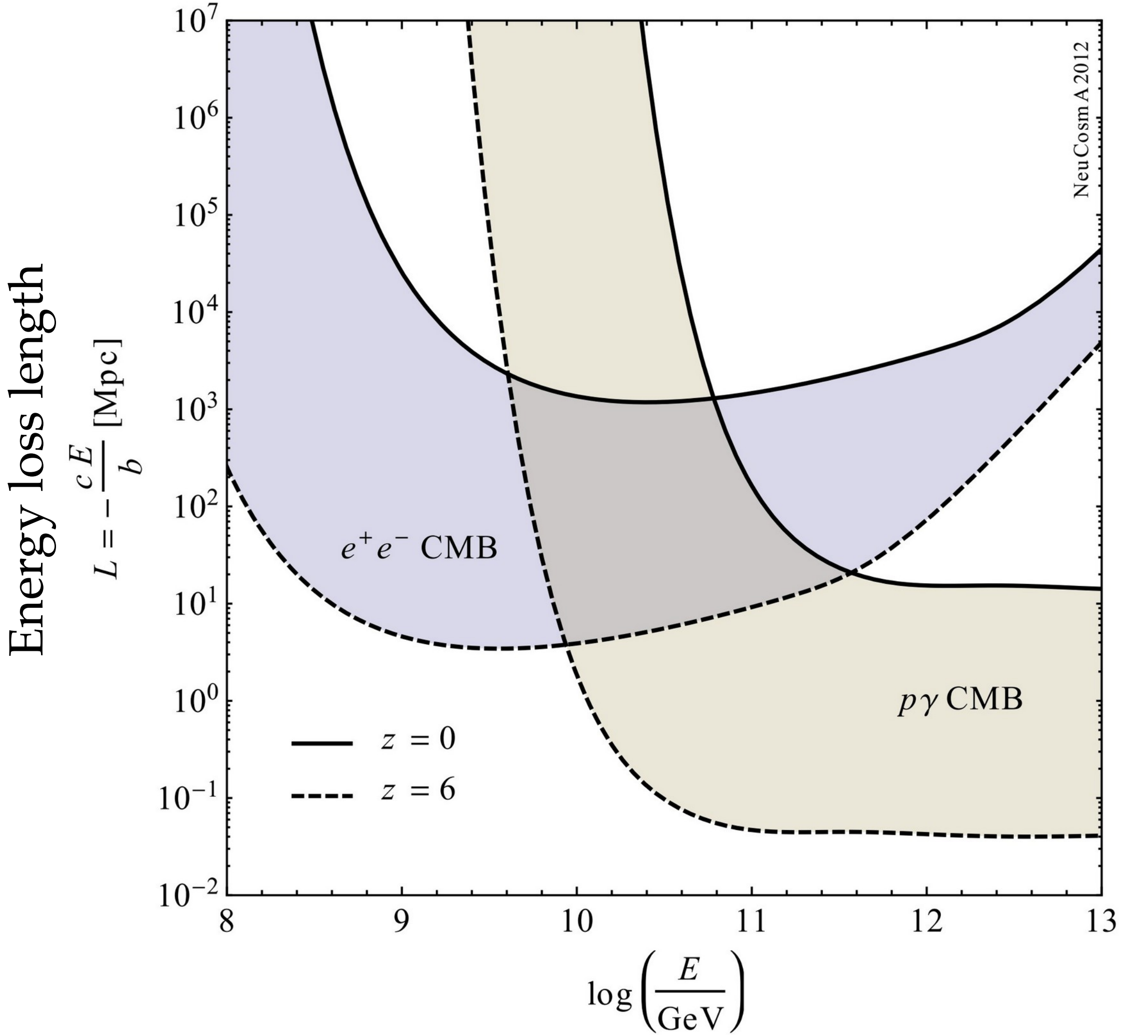


$$L(z) = H^{-1}(z) \propto (1+z)^{-3/2}$$

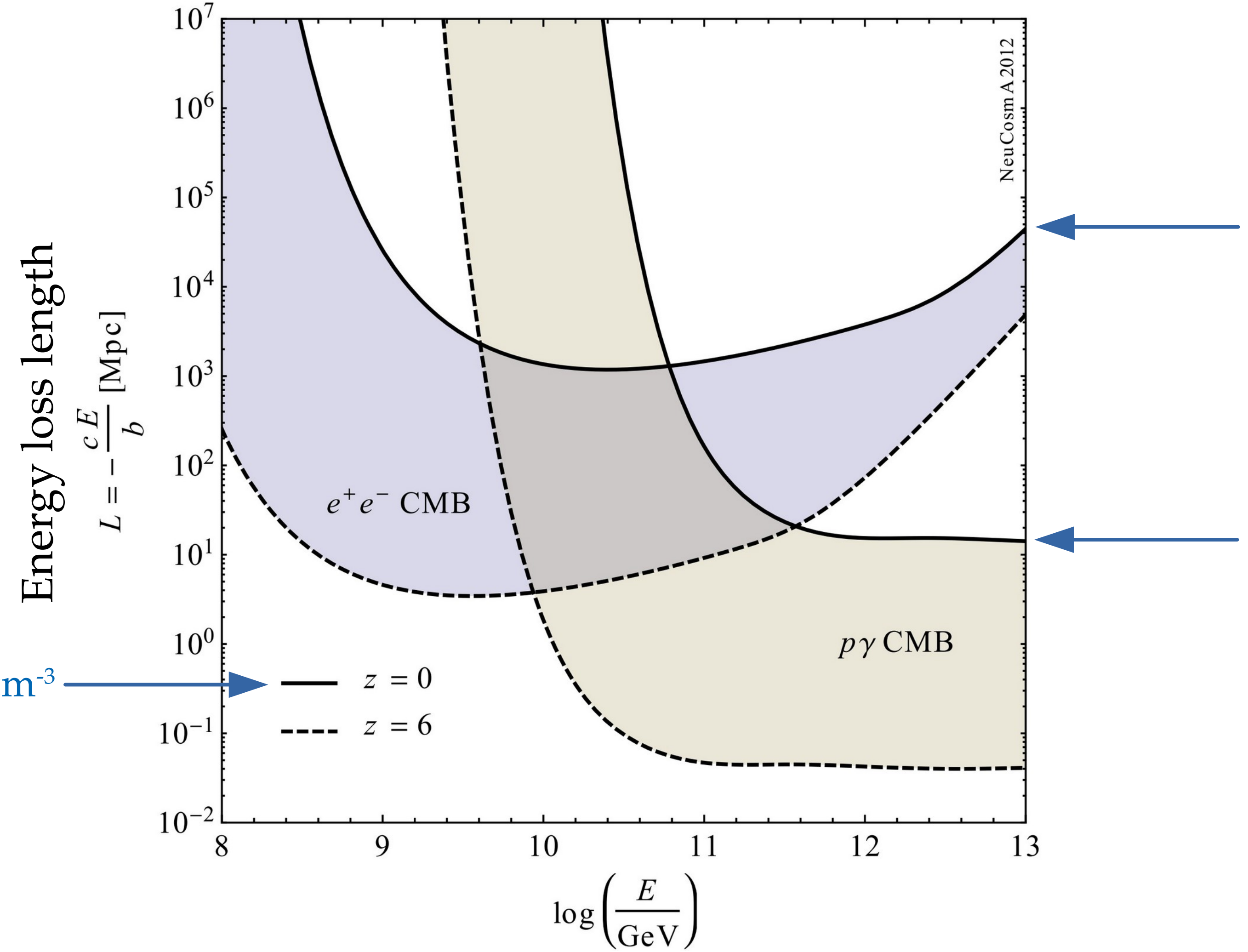
Calculating the UHECR flux at Earth



Calculating the UHECR flux at Earth

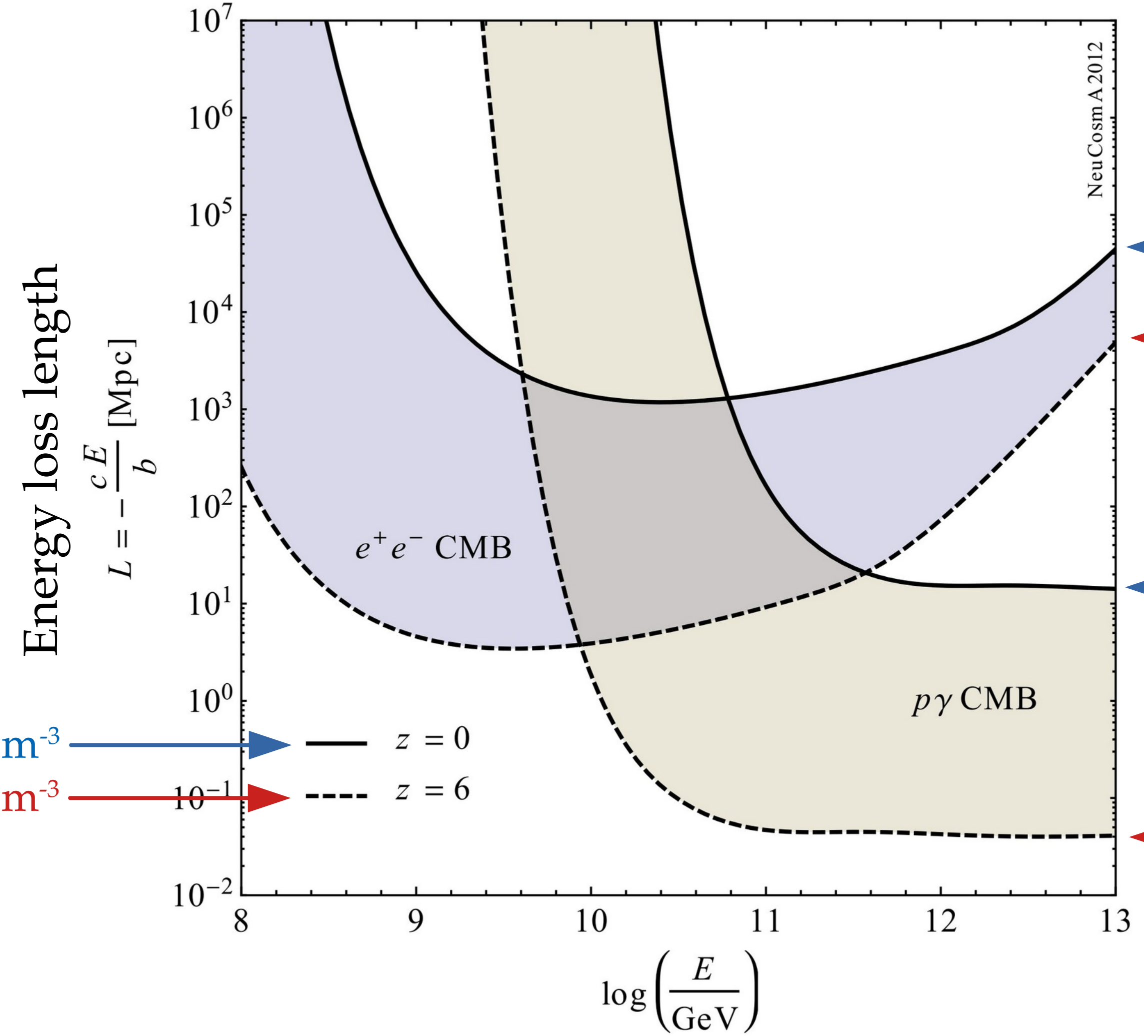


Calculating the UHECR flux at Earth



~400 CMB photons cm^{-3}

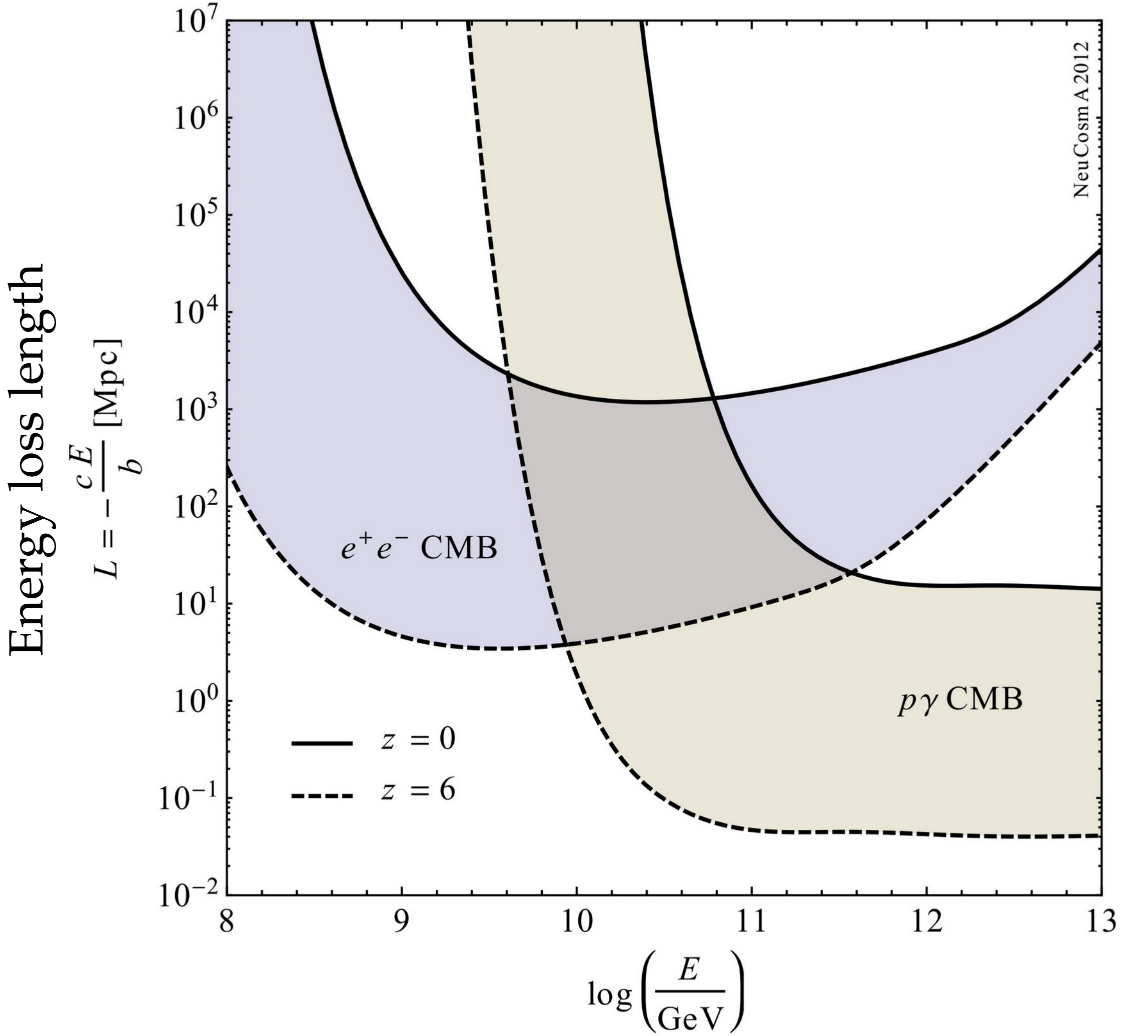
Calculating the UHECR flux at Earth



~400 CMB photons cm^{-3}

~400×$(1+z)^{3}$ cm^{-3}

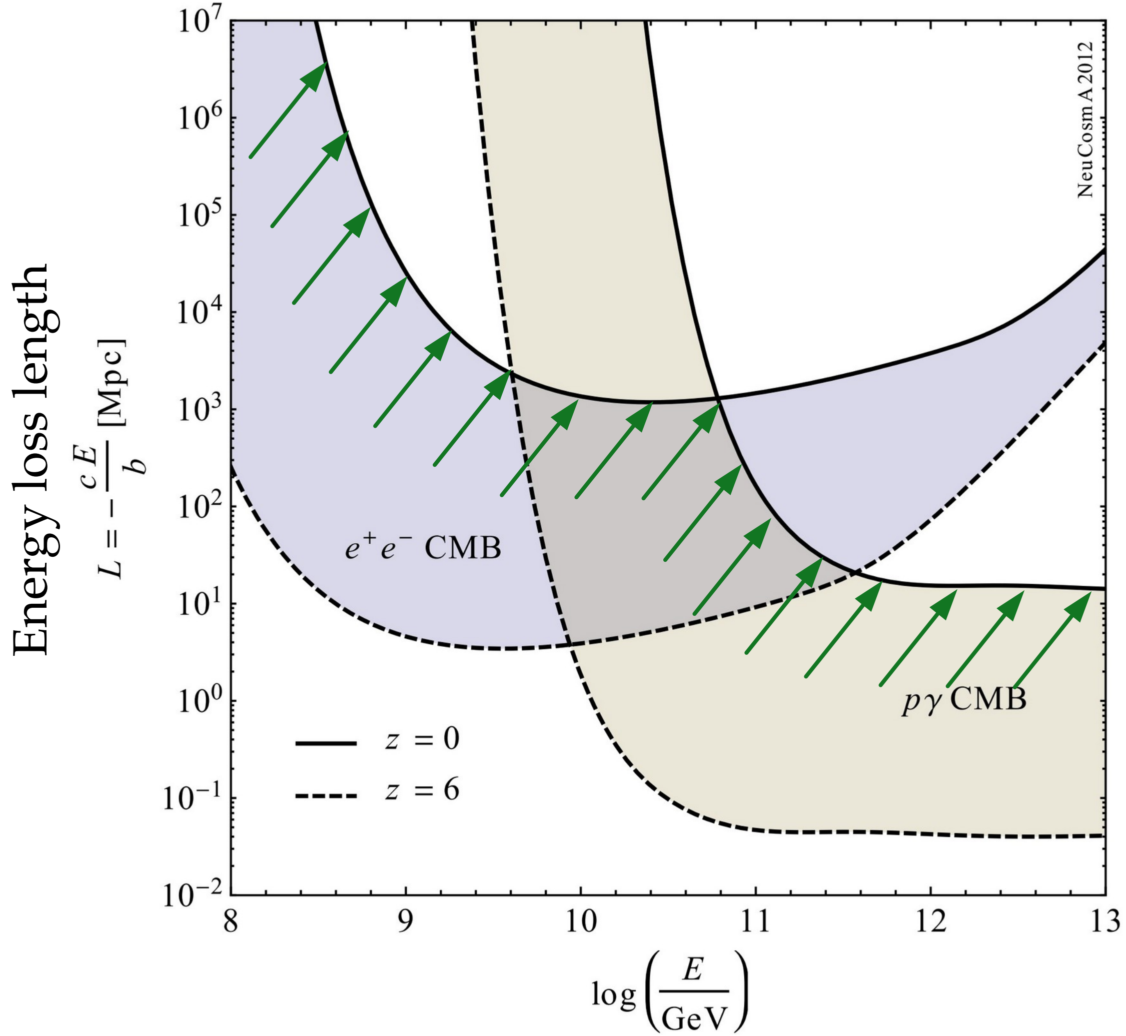
Calculating the UHECR flux at Earth



1

The shorter the energy loss length, the faster the UHECR proton loses energy during propagation

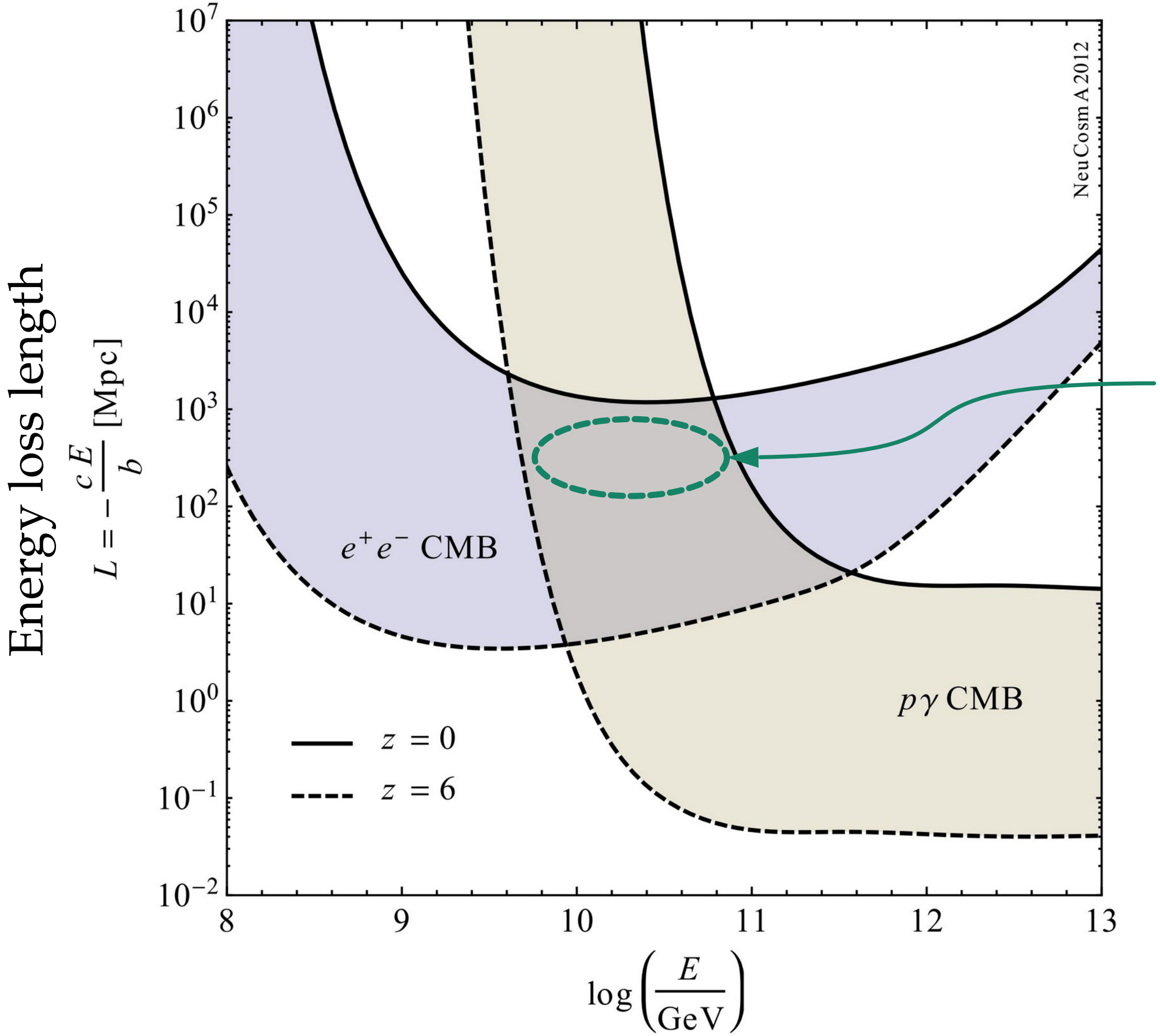
Calculating the UHECR flux at Earth



②

At each energy, the energy loss length is dominated by the fastest energy-loss process

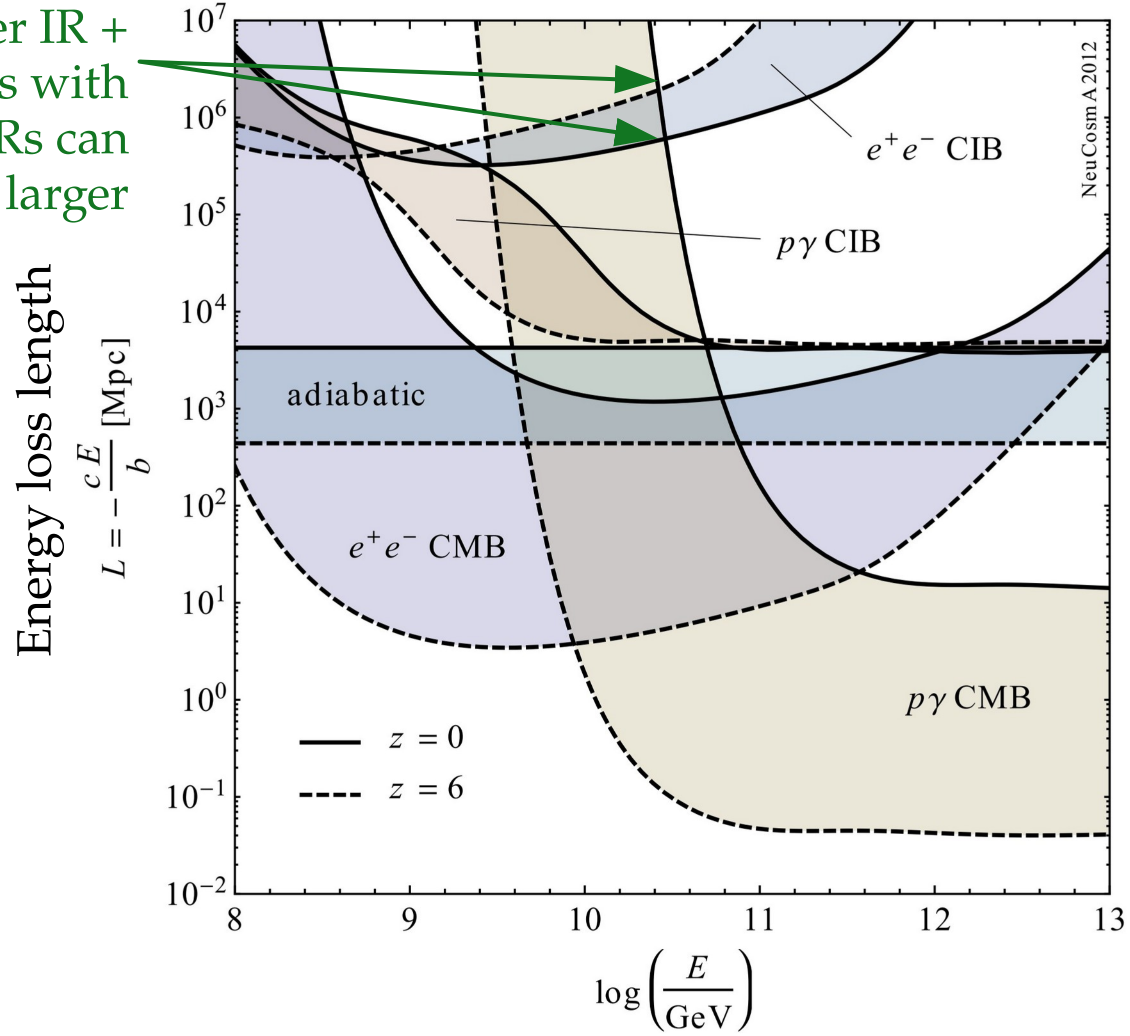
Calculating the UHECR flux at Earth



3

Greisen-Zatsepin-Kuzmin (GZK) cut-off is ~100 Mpc

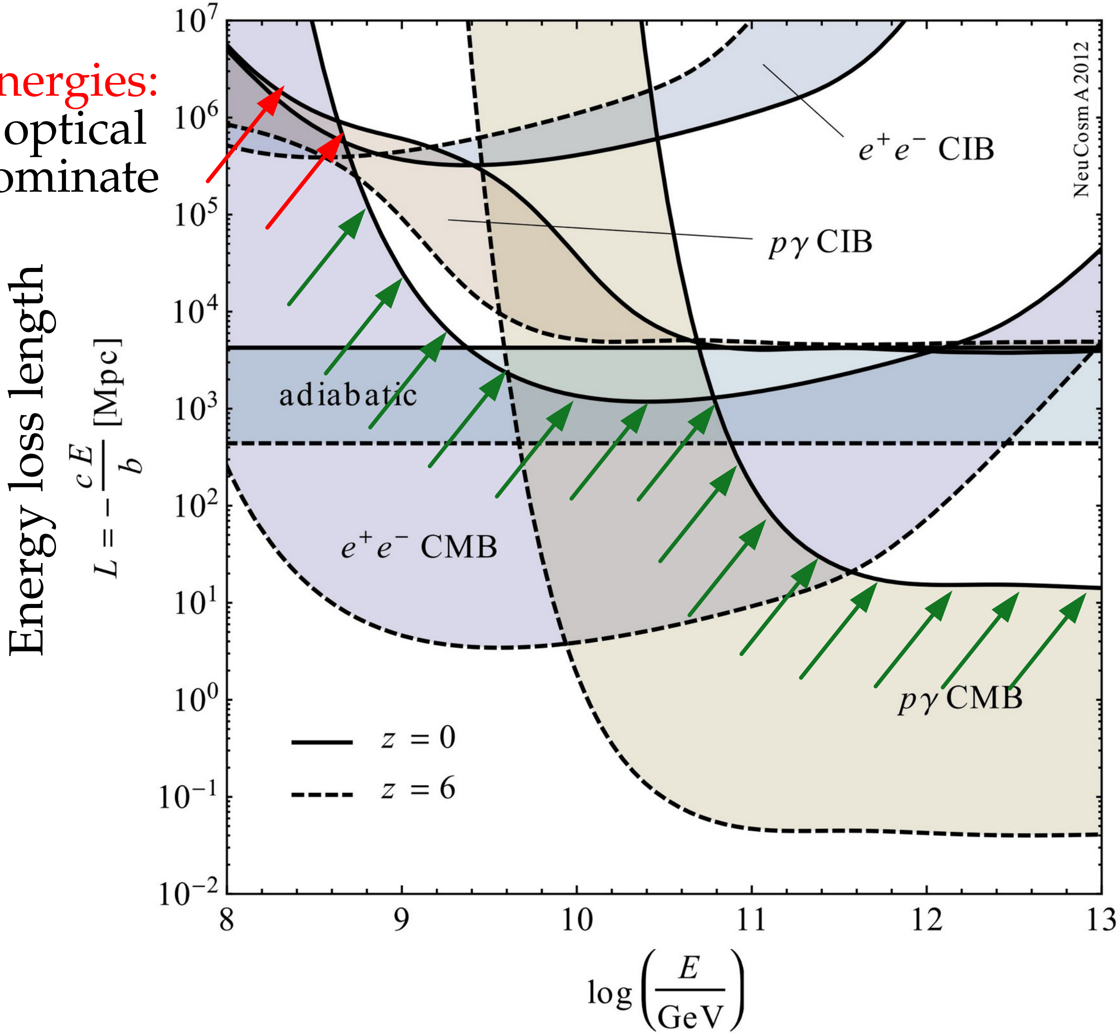
Calculating the UHECR flux at Earth



There are fewer IR + optical photons with which UHECRs can interact, so L is larger

Calculating the UHECR flux at Earth

Low energies:
Losses on IR + optical photons dominate



High energies:
Losses on CMB photons dominate

The Universe is opaque to UHECRs

Photohadronic processes:

$$p + \gamma \longrightarrow \Delta \longrightarrow \left\{\begin{array}{ll} & \Rsh\ \gamma + \gamma \\ p + \pi^0 & \\ n + \pi^+ & \\ & \hookrightarrow \nu_\mu + \bar{\nu}_\mu + \nu_e + e^+ \end{array}\right.$$

Pair production:

$$p + \gamma \longrightarrow p + e^- + e^+$$

Greisen *PRL* 1966; Zatsepin & Kuzmin, *JETP* 1966

The Universe is opaque to UHECRs

Photohadronic processes:

$$\begin{array}{l} \qquad\qquad\qquad\qquad\qquad\quad \Rsh\ \gamma + \gamma \\ p + \gamma \longrightarrow \Delta \longrightarrow \begin{cases} p + \pi^0 \\ n + \pi^+ \end{cases} \\ \qquad\qquad\qquad\qquad\qquad\quad \hookrightarrow \nu_\mu + \bar{\nu}_\mu + \nu_e + e^+ \end{array}$$

Pair production:

$$p + \gamma \longrightarrow p + e^- + e^+$$

Greisen-Zatsepin-Kuzmin (GZK) cut-off:

$$E_p \approx \frac{0.16\ \mathrm{GeV}^2}{0.66\ \mathrm{meV}} \approx 2 \cdot 10^{11}\ \mathrm{GeV}$$

Mean CMB photon energy

(Assuming only photohadronic interaction)

Greisen *PRL* 1966; Zatsepin & Kuzmin, *JETP* 1966

The Universe is opaque to UHECRs

Photohadronic processes:

$$\begin{array}{l} \qquad\qquad\qquad\qquad\quad \Rsh\ \gamma + \gamma \\ p + \gamma \longrightarrow \Delta \longrightarrow \begin{cases} p + \pi^0 \\ n + \pi^+ \end{cases} \\ \qquad\qquad\qquad\qquad\quad \hookrightarrow \nu_\mu + \bar{\nu}_\mu + \nu_e + e^+ \end{array}$$

Pair production:

$$p + \gamma \longrightarrow p + e^- + e^+$$

Greisen-Zatsepin-Kuzmin (GZK) cut-off:

$$E_p \approx \frac{0.16\ \mathrm{GeV}^2}{0.66\ \mathrm{meV}} \approx 2 \cdot 10^{11}\ \mathrm{GeV}$$

Mean CMB photon energy

(Assuming only photohadronic interaction)

Accounting also for pair production and CMB width:

$$E_p \approx 5 \cdot 10^{10}\ \mathrm{GeV}$$

Greisen *PRL* 1966; Zatsepin & Kuzmin, *JETP* 1966

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$$L_{\mathrm{GZK}} \approx 100\ \mathrm{Mpc}$$

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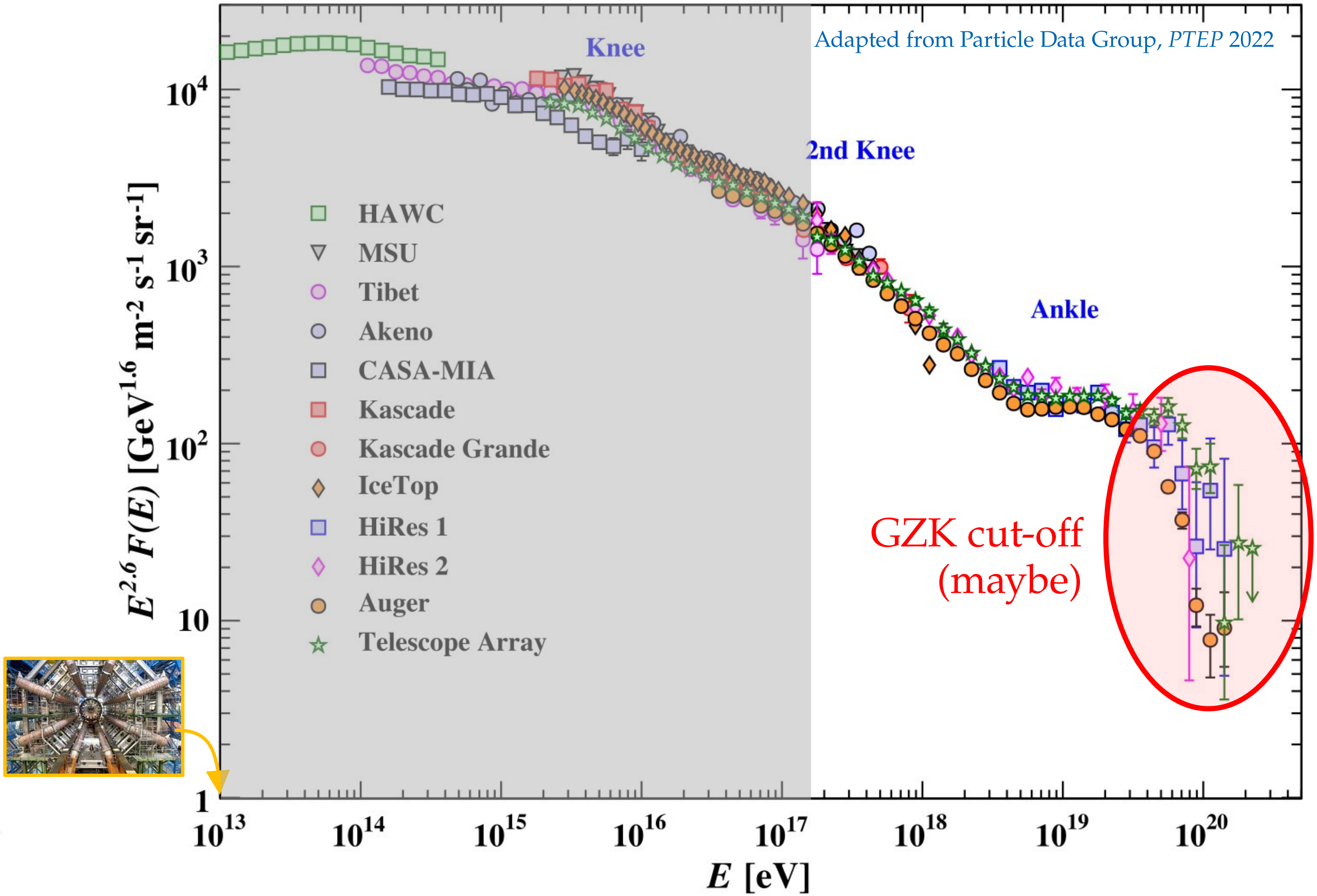
10^{12} eV



Adapted from Particle Data Group, *PTEP* 2022

GZK cut-off
(maybe)

100 W
× 1 s

6 × 10^{20} eV

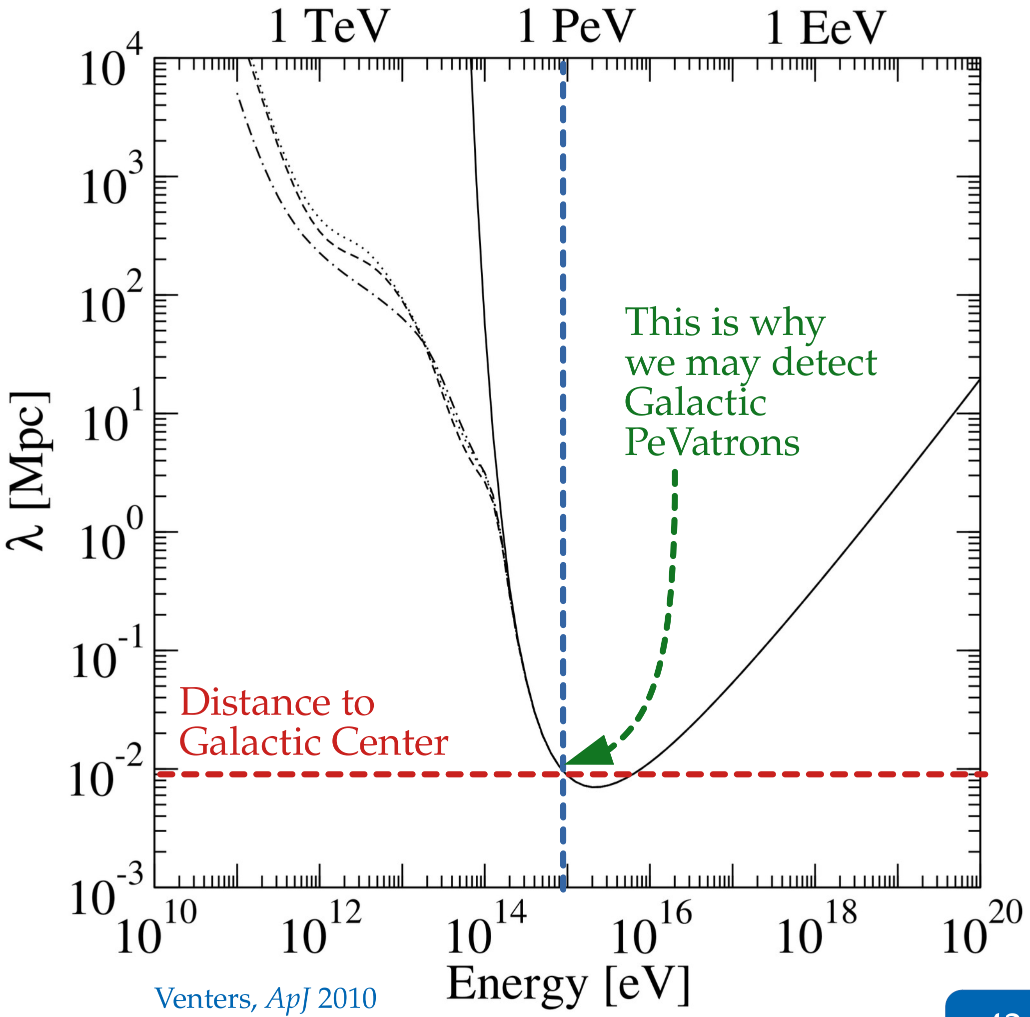
The Universe is *also* opaque to PeV gamma rays

Pair production:

$$\gamma_{\text{astro}} + \gamma_{\text{cosmo}} \rightarrow e^- + e^+$$

Inverse Compton scattering:

$$e^\pm + \gamma_{\text{cosmo}} \rightarrow e^\pm + \gamma$$



This is why we may detect Galactic PeVatrons

Distance to Galactic Center

Venters, *ApJ* 2010

Fermi-LAT, *ApJ* 2015

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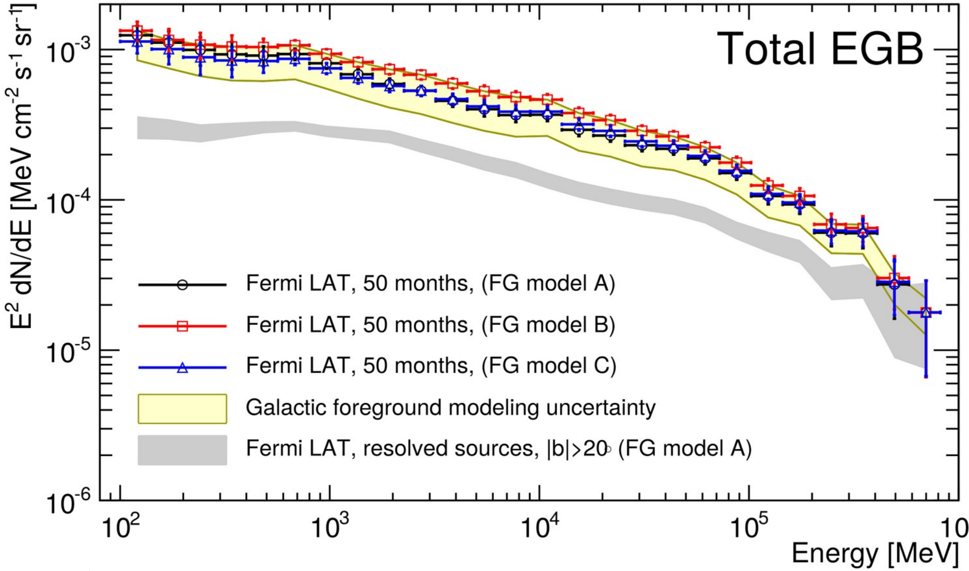
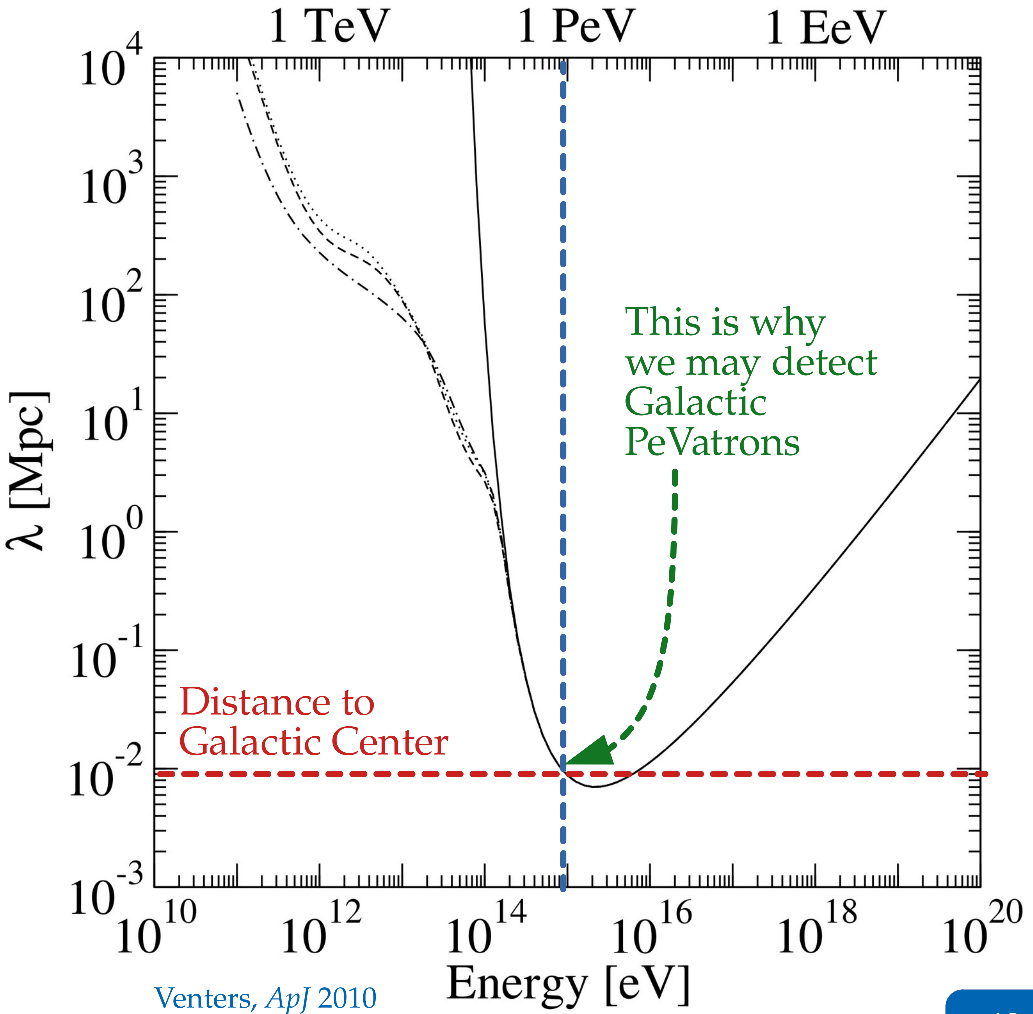
PeV gamma rays cascade down to MeV–GeV:



Fermi-LAT, *ApJ* 2015



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Venters, *ApJ* 2010

Calculating the UHECR flux at Earth

Putting it all together…

$$\partial_z Y_p(E,z) = \frac{-1}{(1+z)H(z)} \{\partial_E(H(z)EY_p(E,z)) + \partial_E(b_{e^+e^-}(E,z)Y_p(E,z)) + \partial_E(b_{p\gamma}(E,z)Y_p(E,z)) + \mathcal{L}_{\rm CR}(E,z)\}$$

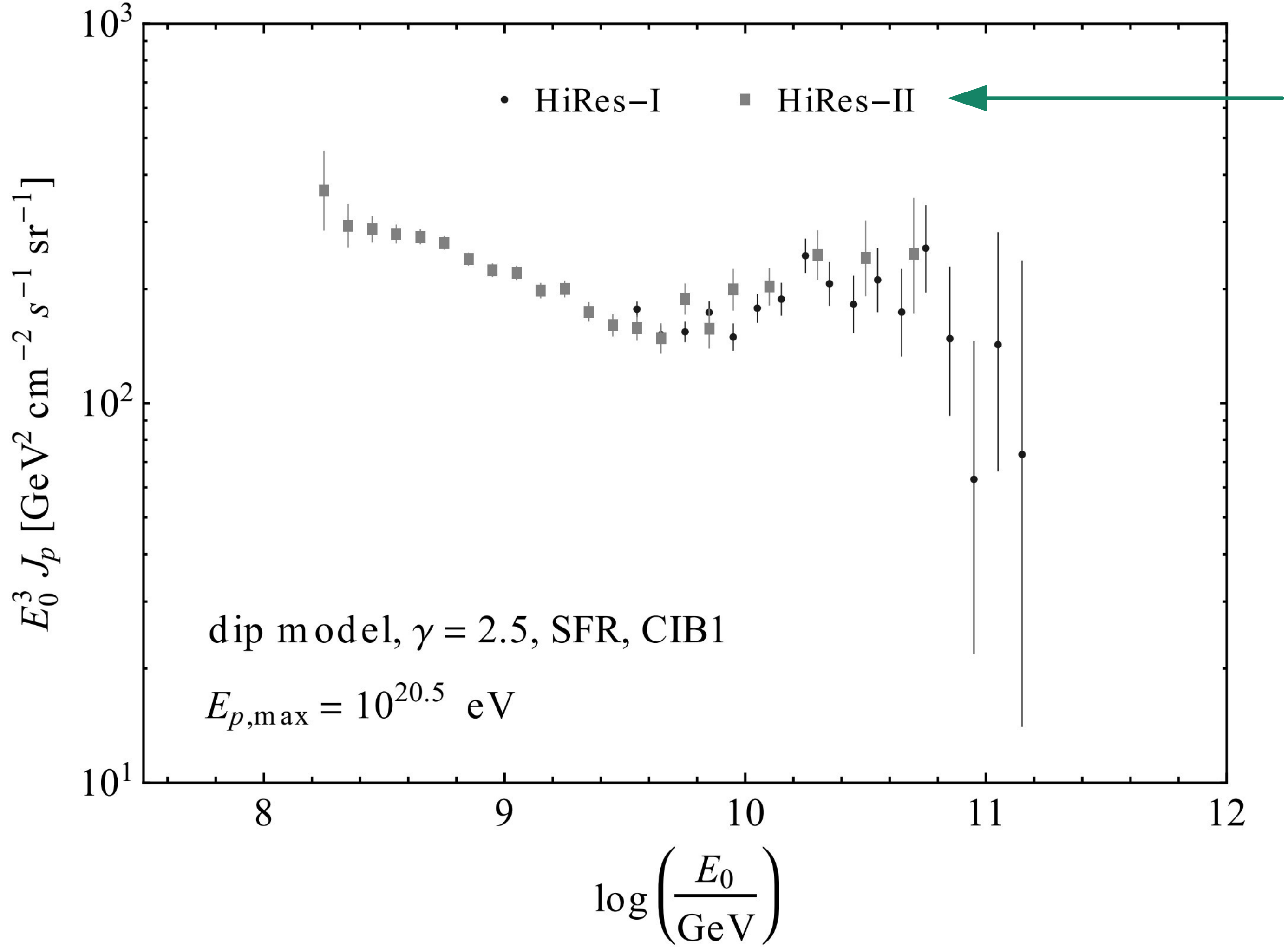
Evolve numerically from $z_{\rm max} \sim 4$ to Earth ($z = 0$)

Diffuse UHECR proton flux at Earth (GeV^{-1} cm^{-2} s^{-1} sr^{-1}):

$$J_p(E) = \underbrace{\frac{c}{4\pi}} n_p(E, z=0)$$

This factor converts density to flux

Calculating the UHECR flux at Earth



Old UHECR data (just as example)

Calculating the UHECR flux at Earth

Compare our predicted flux to the measured flux:

$$\chi^2(\overbrace{J_{p,0}}^{\text{Flux normalization}}, \underbrace{\delta_E}_{\text{Energy shift (nuisance)}}) = \sum_i^{\text{data}} \left(\frac{E^3 J_p(J_{p,0}) - \overbrace{(E^3 J_p)_i^{\text{HiRes}}}^{\text{Flux data points}}}{\underbrace{\sigma_i}_{\text{Uncertainty of } i\text{-th data point}}} \right)^2 + \underbrace{\left(\frac{\delta_E}{\sigma_E}\right)}_{\text{Systematic energy uncertainty}}^2$$

Minimize the function with respect to $J_{p,0}$ and δ_E

Note: This is a simplified setup; in reality, many flux parameters are jointly varied

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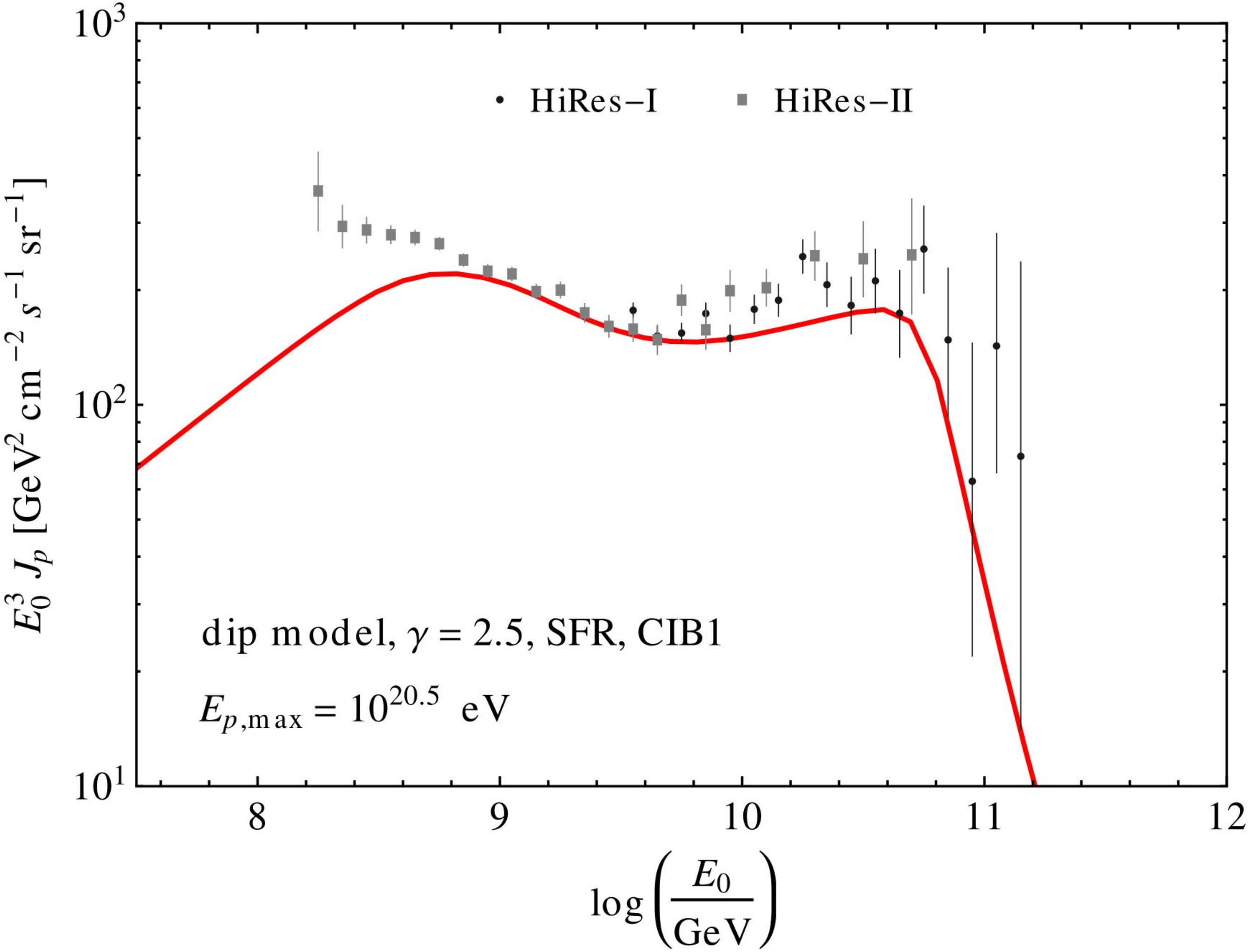
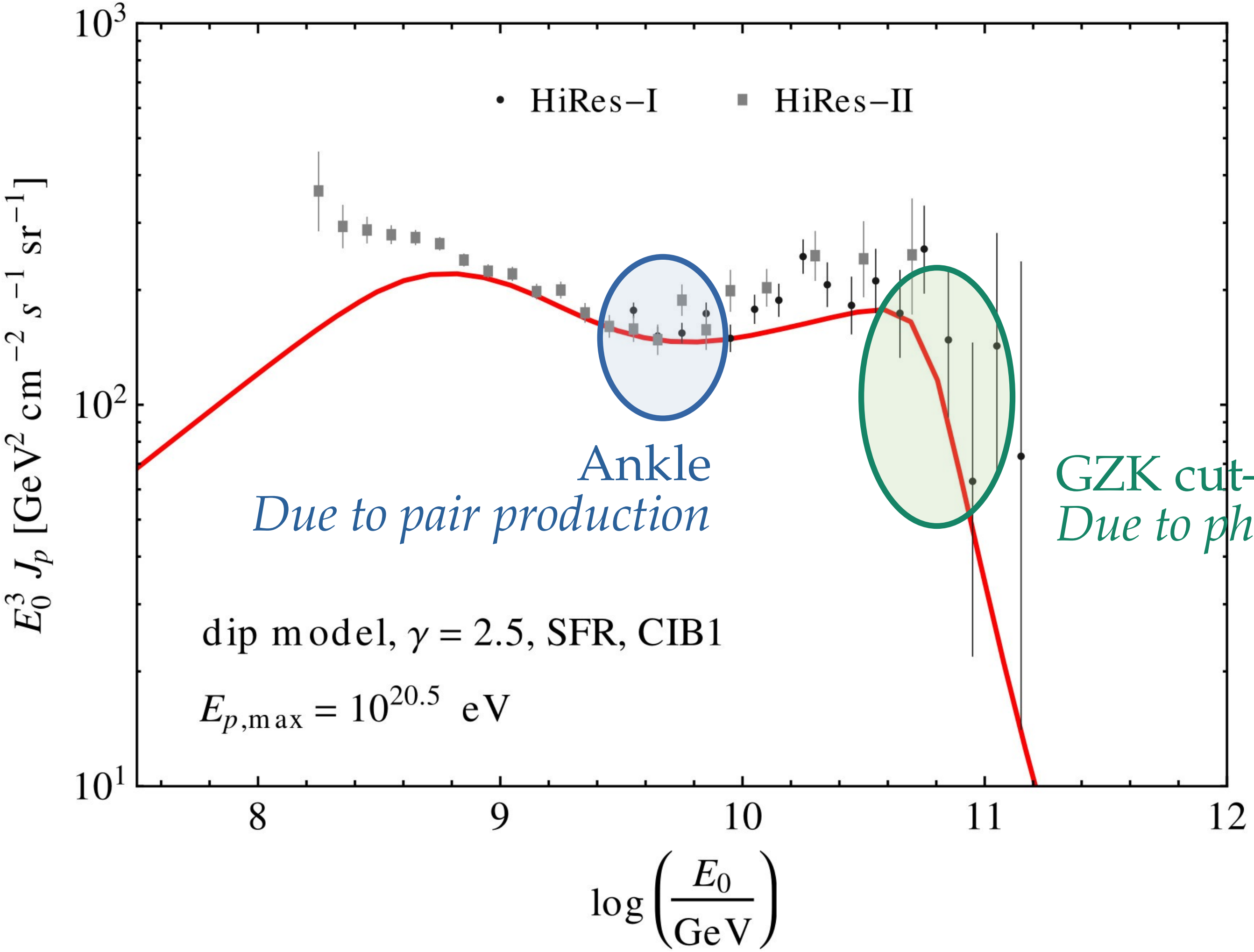
Calculating the UHECR flux at Earth



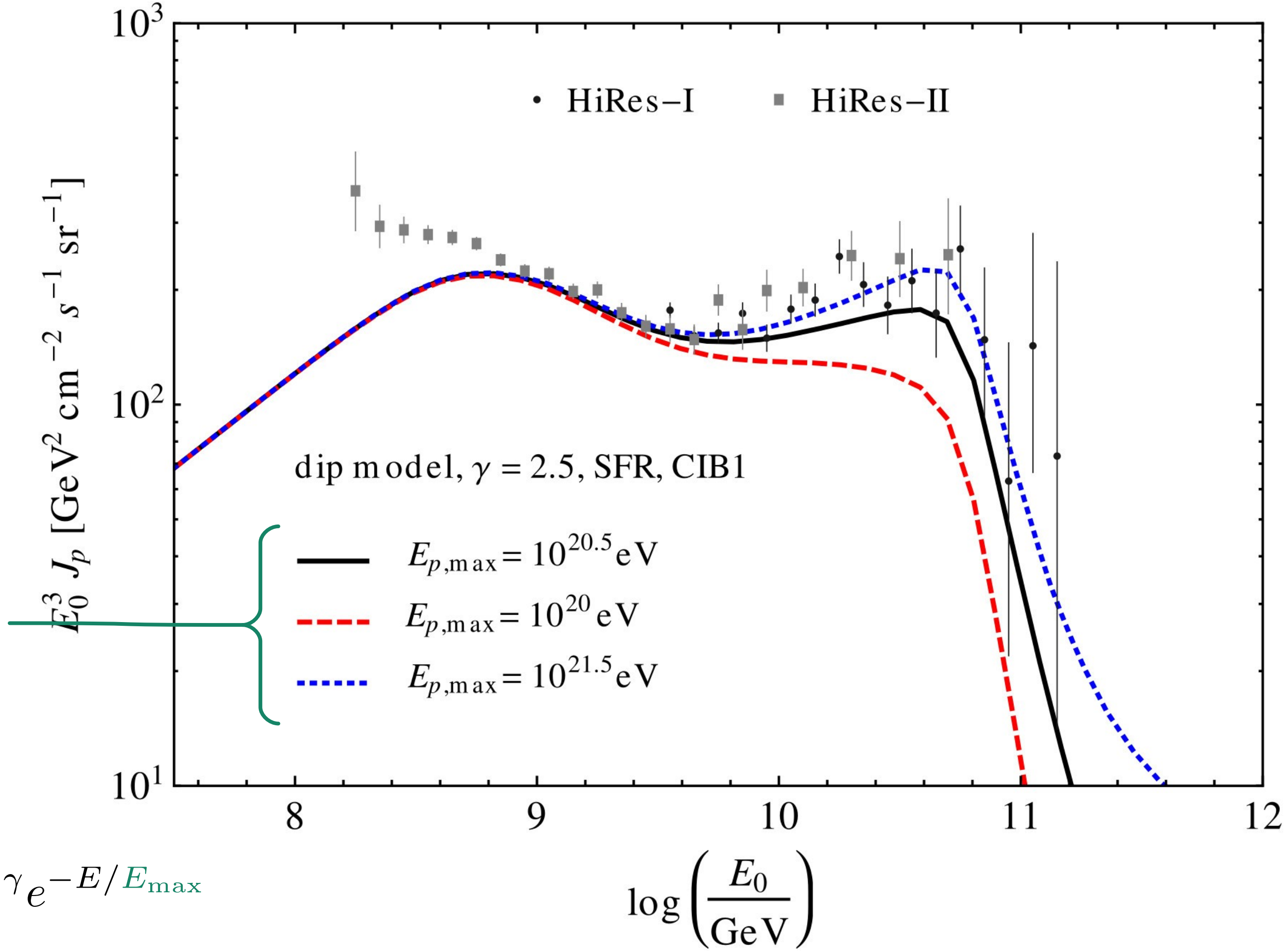
Calculating the UHECR flux at Earth



Ankle
Due to pair production

GZK cut-off
Due to photoproduction

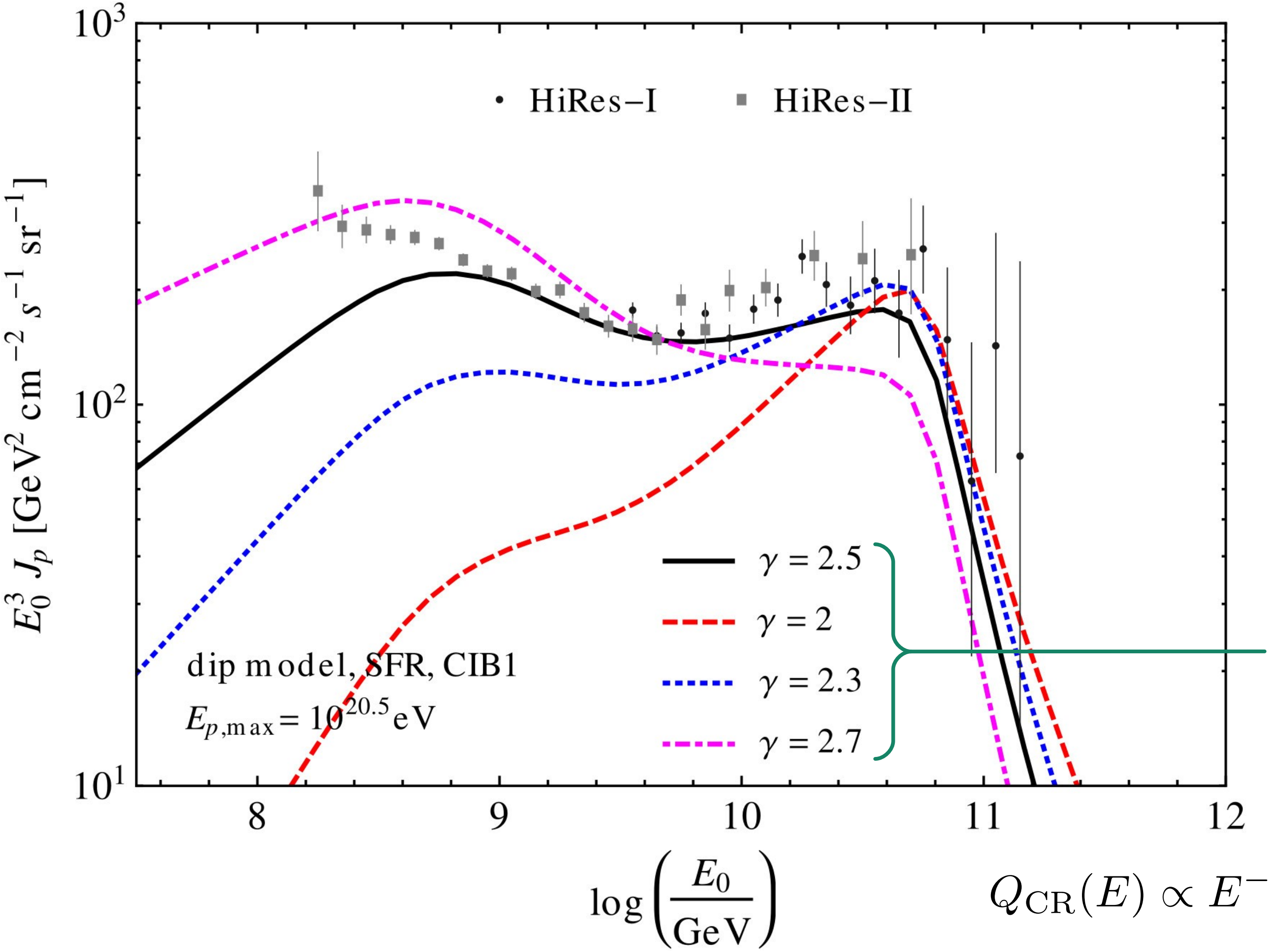
Calculating the UHECR flux at Earth



Varying the maximum proton energy

$$Q_{\text{CR}}(E) \propto E^{-\gamma} e^{-E/E_{\max}}$$

Calculating the UHECR flux at Earth



Varying the proton spectral index

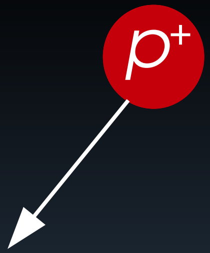
$$Q_{\mathrm{CR}}(E) \propto E^{-\gamma} e^{-E/E_{\max}}$$

UHECR
detection

Space

Atmosphere

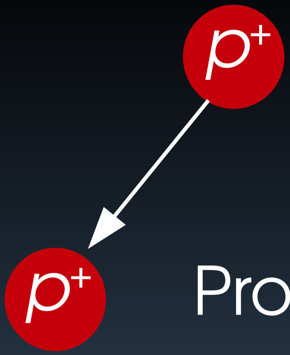
Space



Incoming cosmic ray

Atmosphere

Space

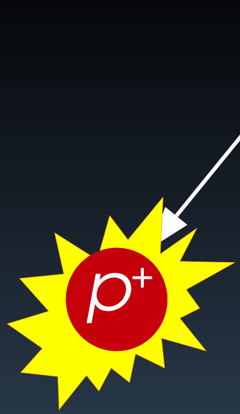


Incoming cosmic ray

Proton in the air

Atmosphere

Space

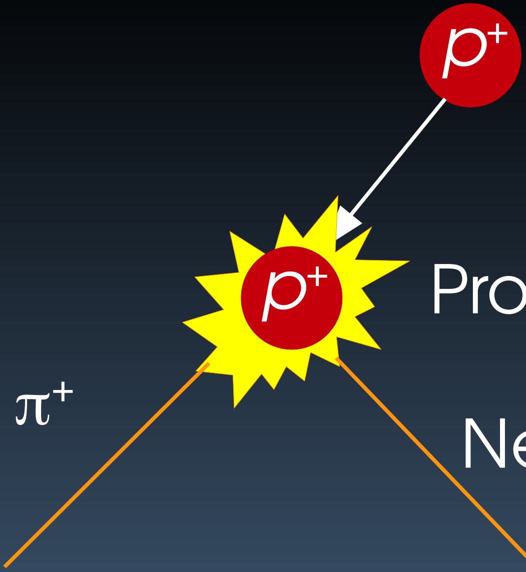


Incoming cosmic ray

Proton in the air

Atmosphere

Space



Incoming cosmic ray

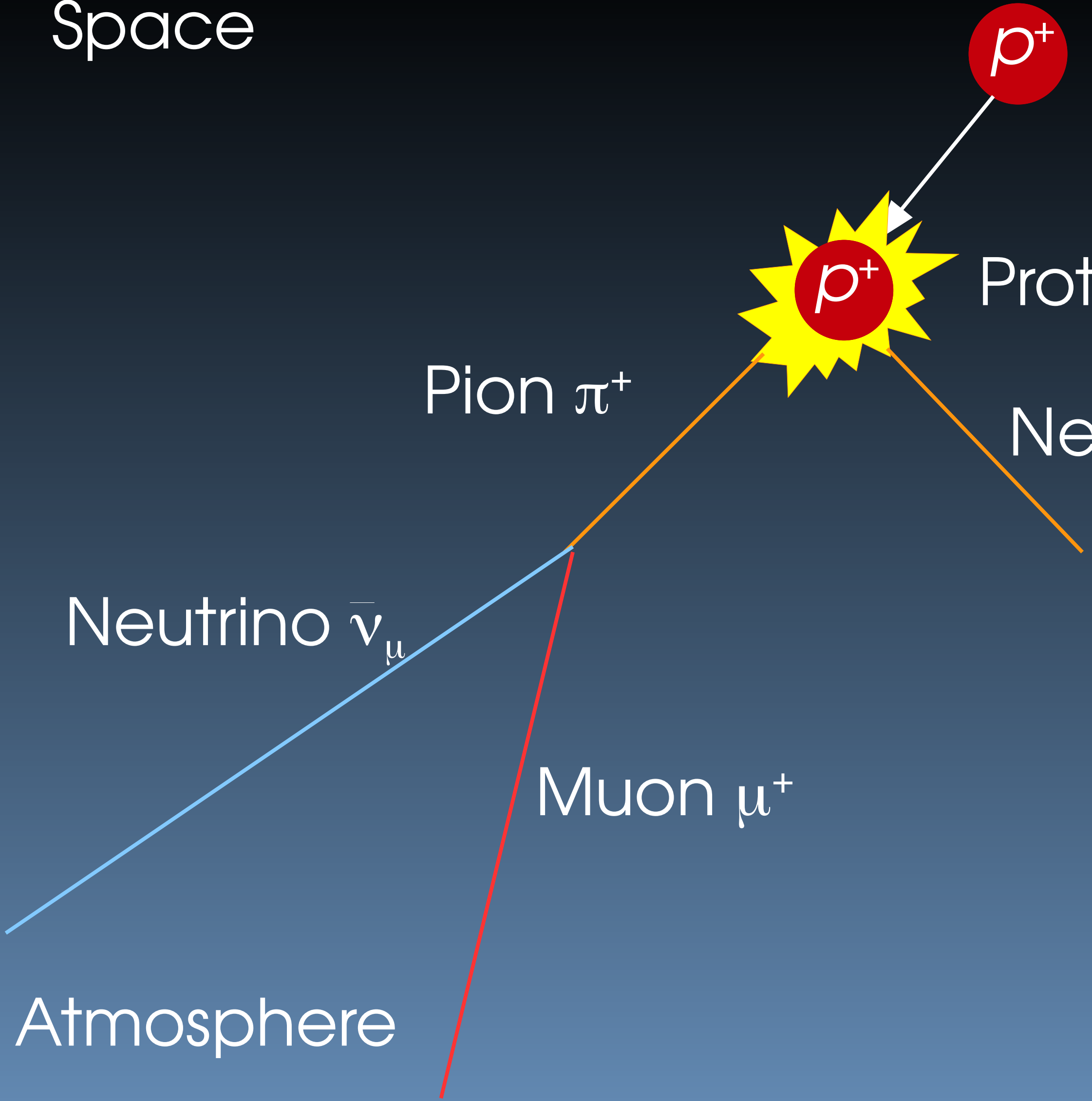
Proton in the air

Pion π^+

Neutron n

Atmosphere

Space



Incoming cosmic ray

Proton in the air

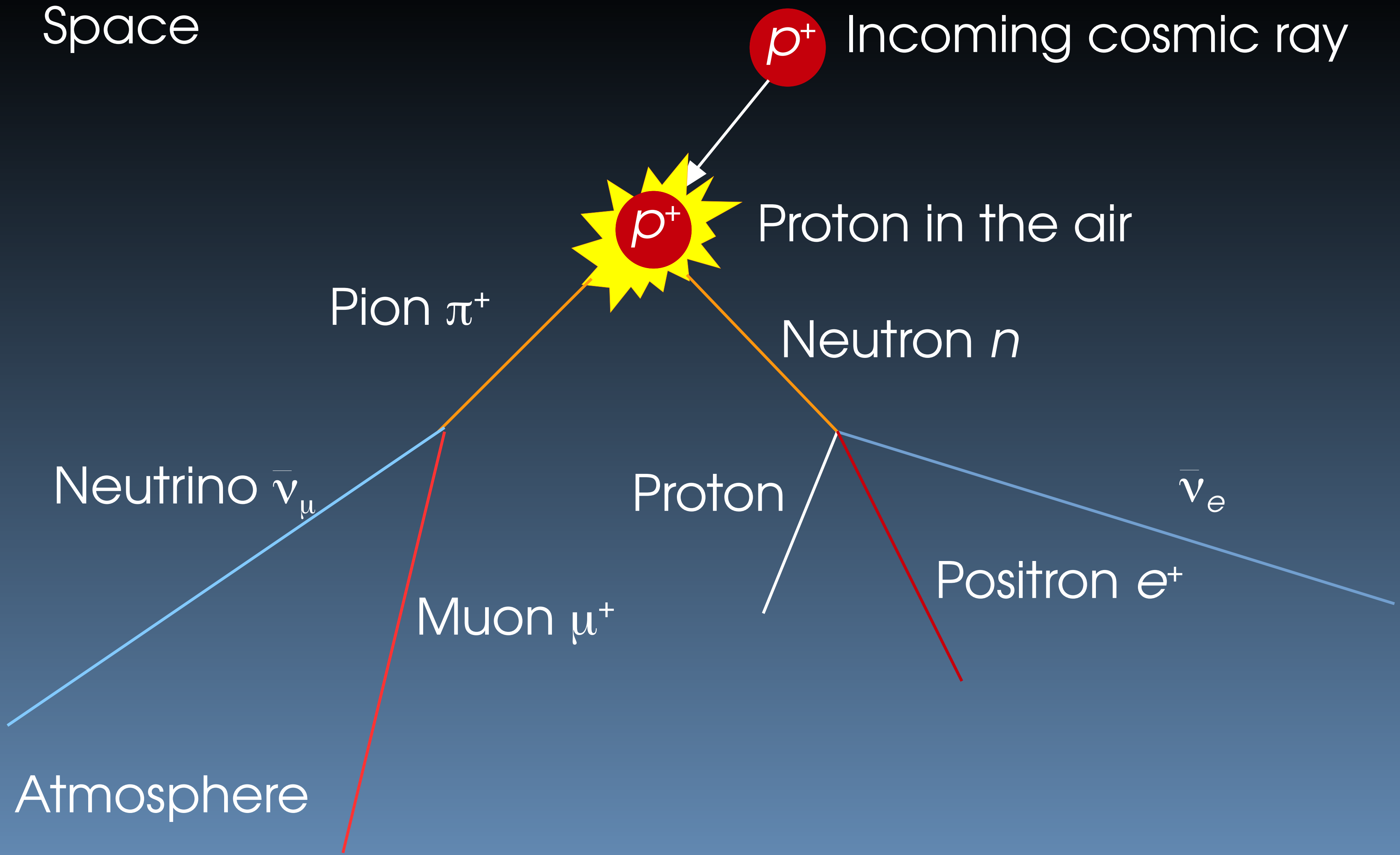
Pion π^+

Neutron *n*

Neutrino $\bar{\nu}_\mu$

Muon μ^+

Atmosphere



Space

p^+ Incoming cosmic ray

p^+ Proton in the air

Pion π^+

Neutron n

Neutrino $\bar{\nu}_\mu$

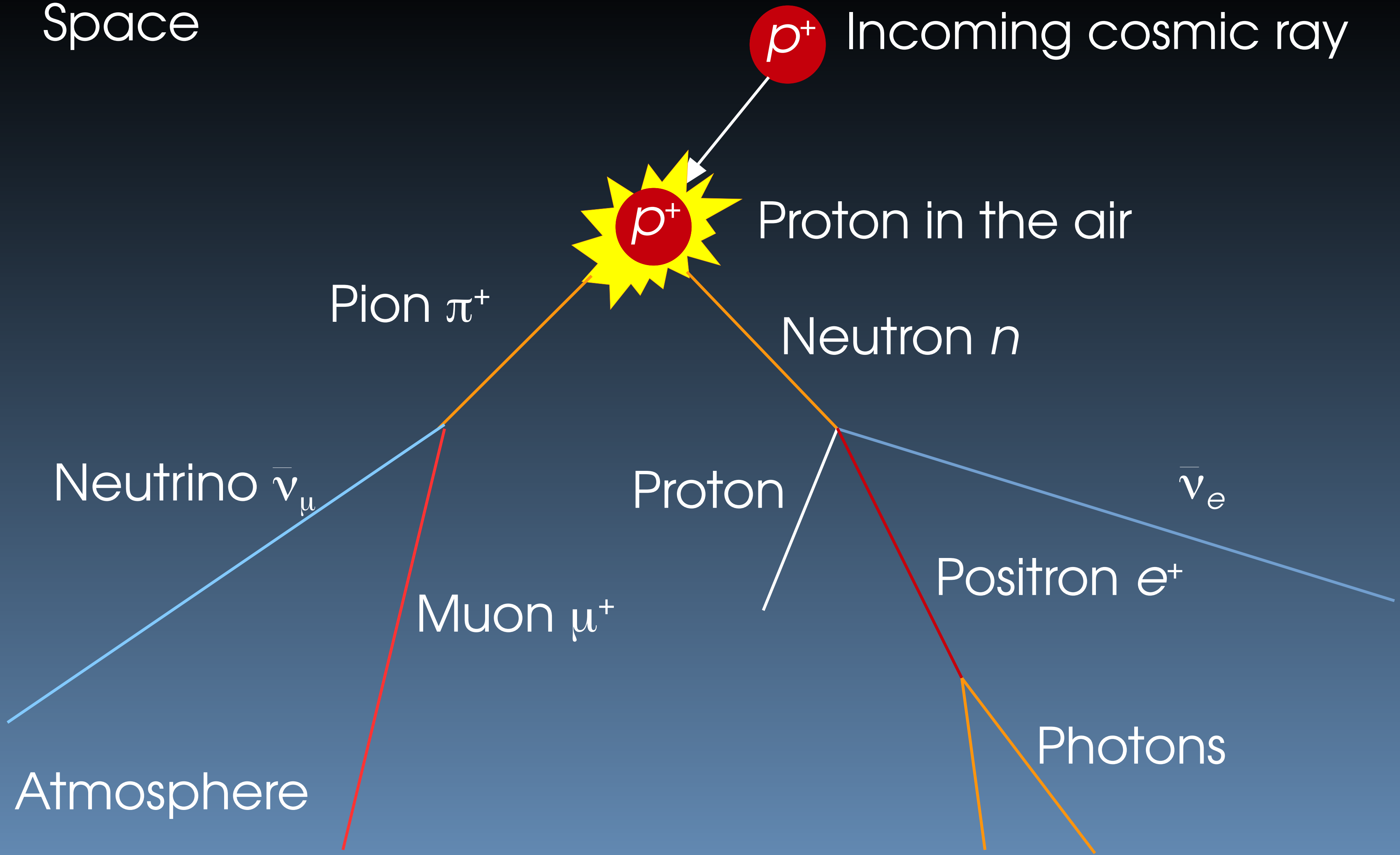
Proton

$\bar{\nu}_e$

Positron e^+

Muon μ^+

Atmosphere



Space

p^+ Incoming cosmic ray

p^+ Proton in the air

Pion π^+

Neutron n

Neutrino $\bar{\nu}_\mu$

Proton

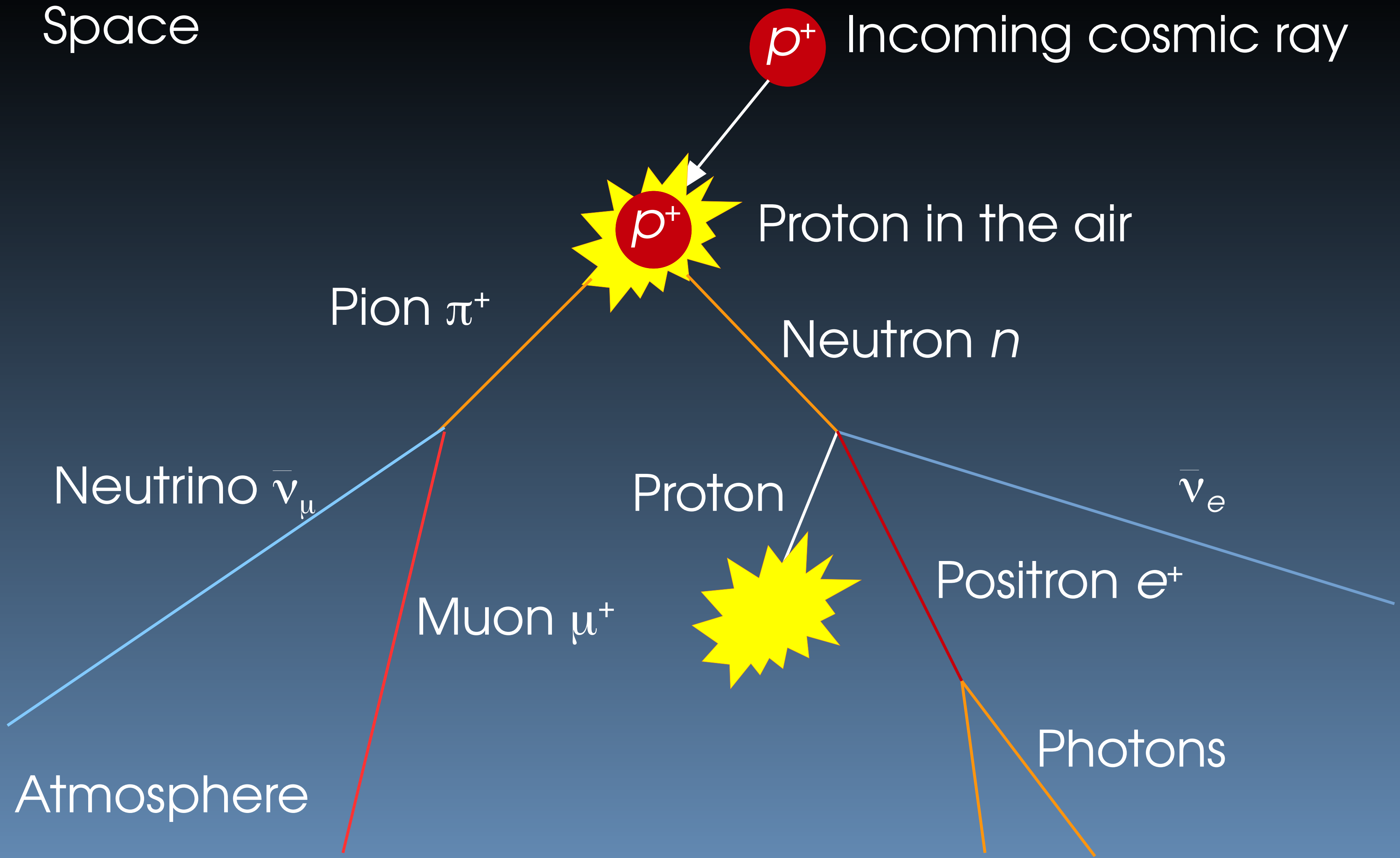
$\bar{\nu}_e$

Muon μ^+

Positron e^+

Photons

Atmosphere



Space

p^+ Incoming cosmic ray

p^+ Proton in the air

Pion π^+

Neutron n

Neutrino $\bar{\nu}_\mu$

Proton

$\bar{\nu}_e$

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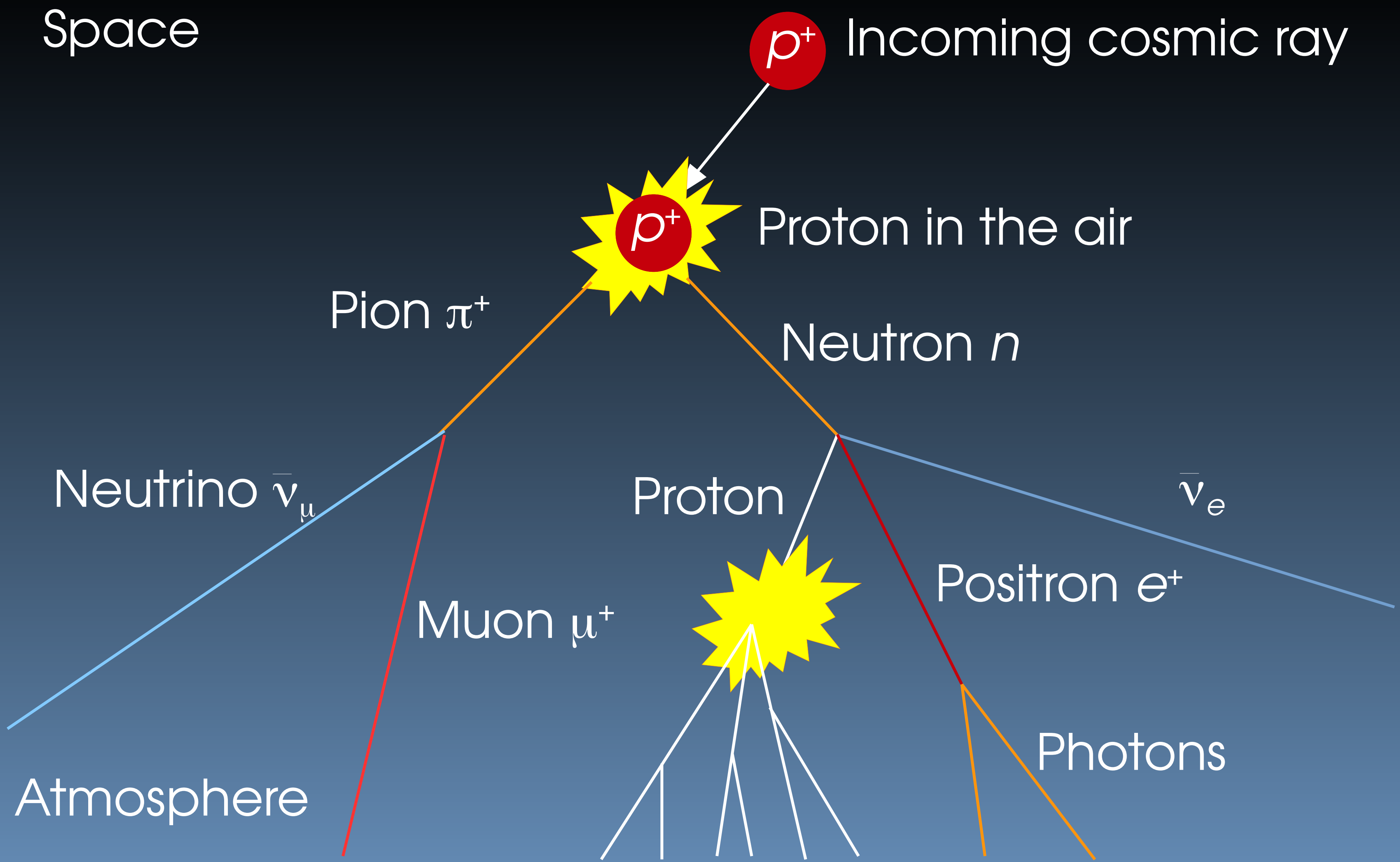
Muon μ^+

Photons

Atmosphere



Space

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p^+ Proton in the air

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Neutron n

Neutrino $\bar{\nu}_\mu$

Proton

$\bar{\nu}_e$

Muon μ^+

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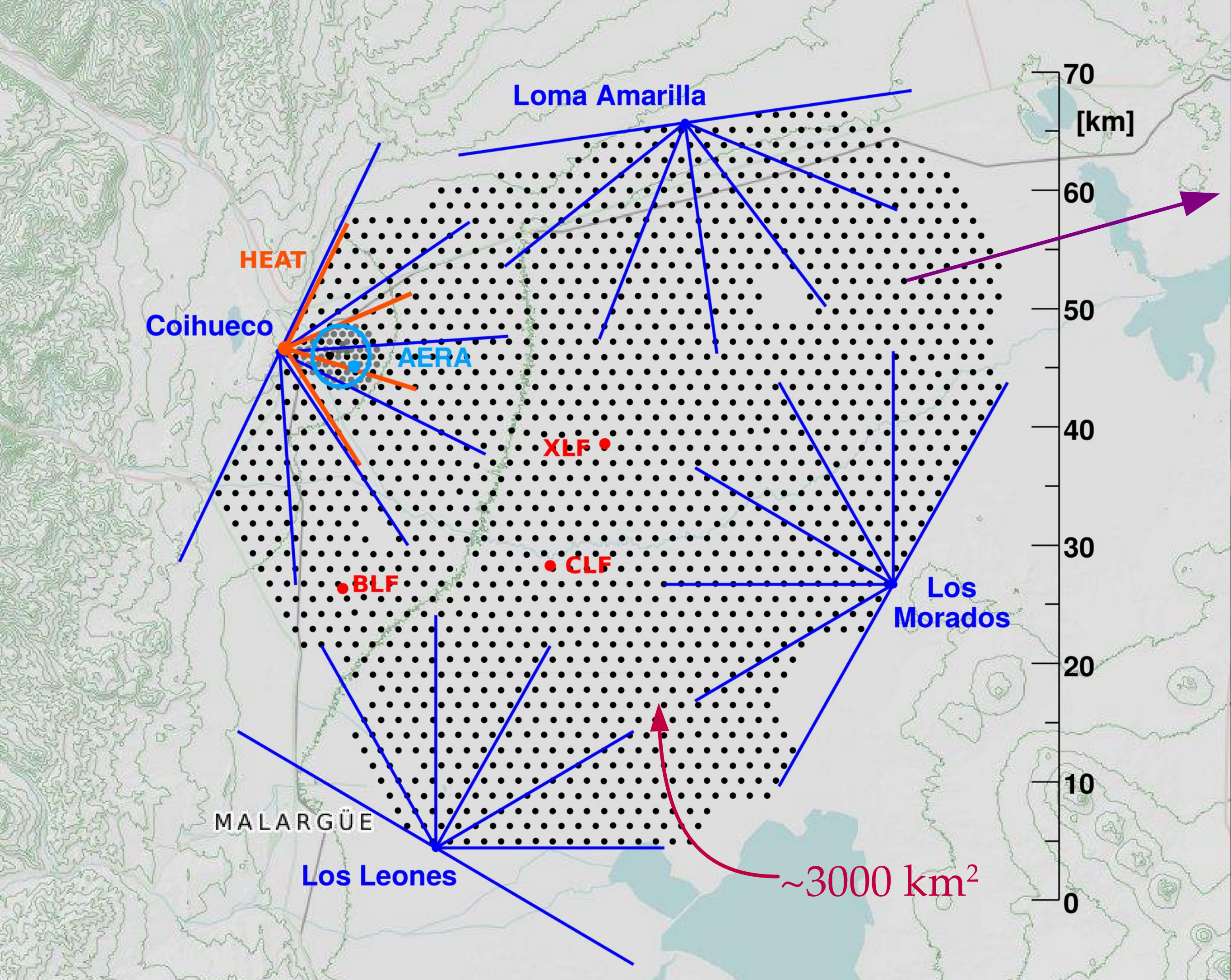
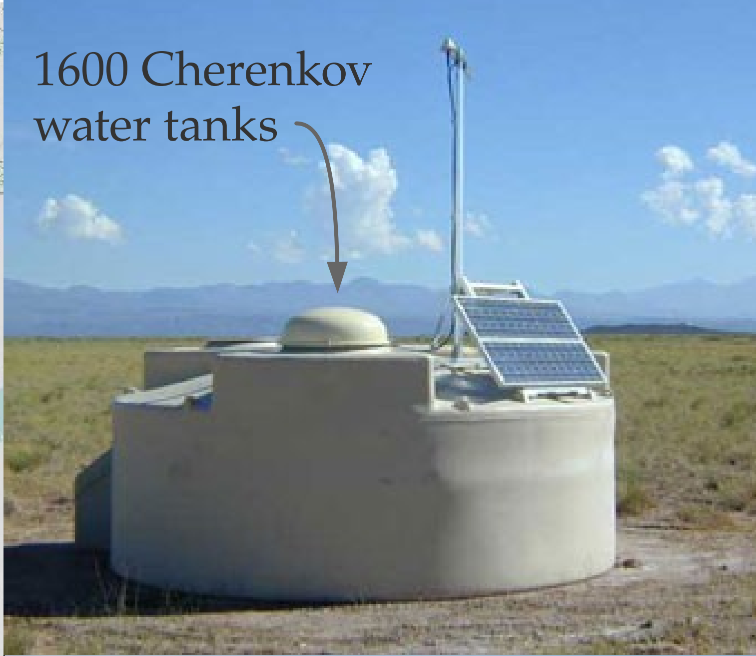
Photons

Atmosphere

Pierre Auger Observatory (Malargüe, Argentina)

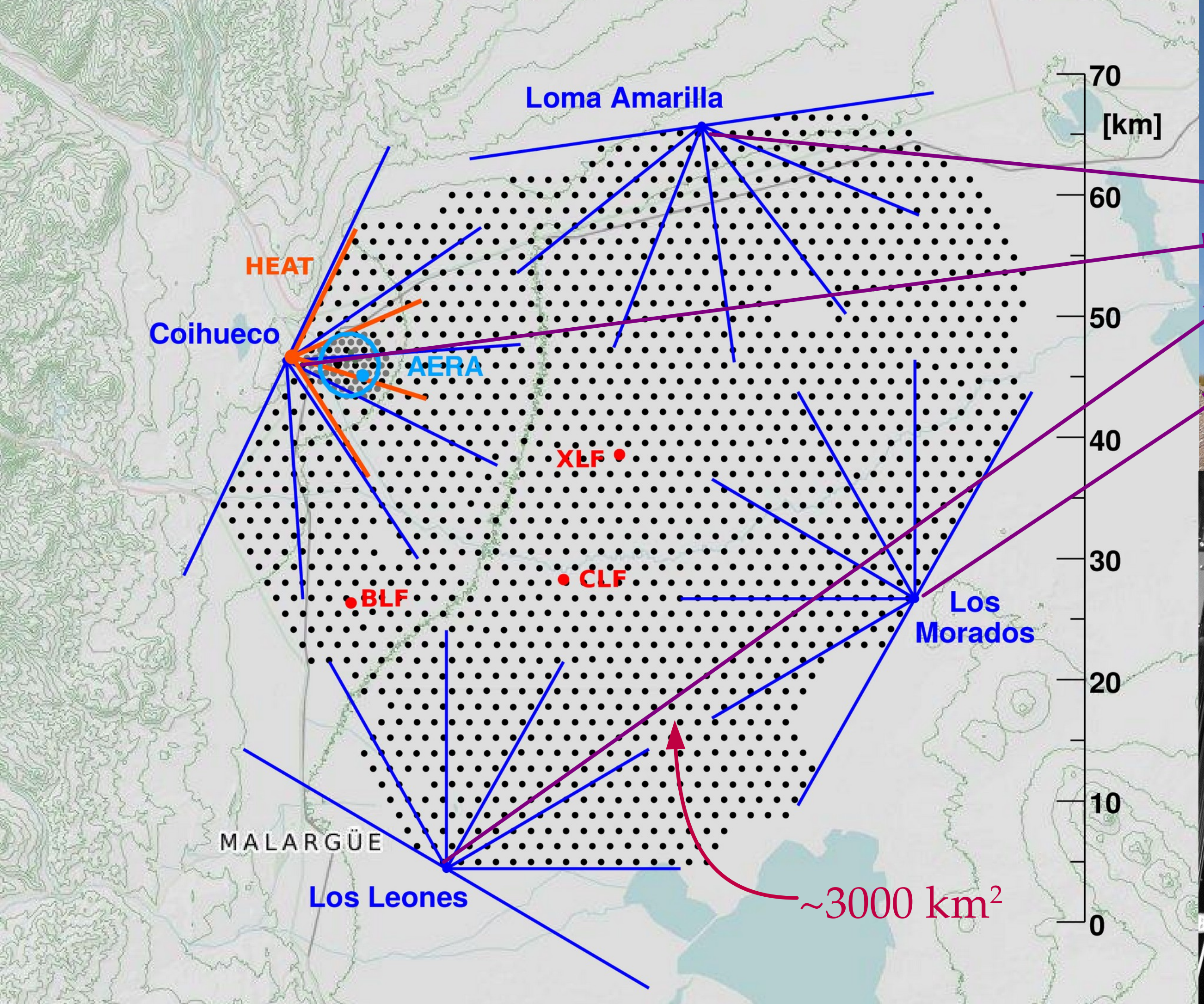


~3000 km²

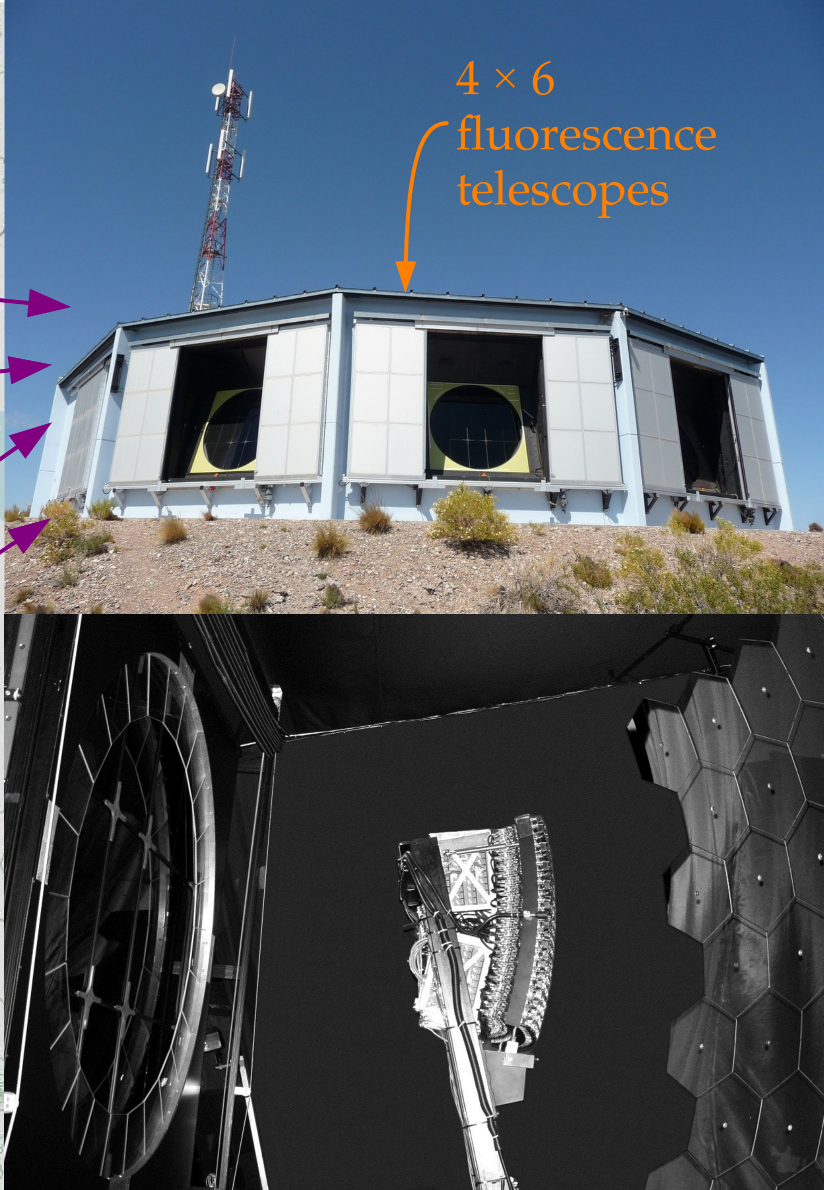


1600 Cherenkov water tanks

Pierre Auger Observatory (Malargüe, Argentina)



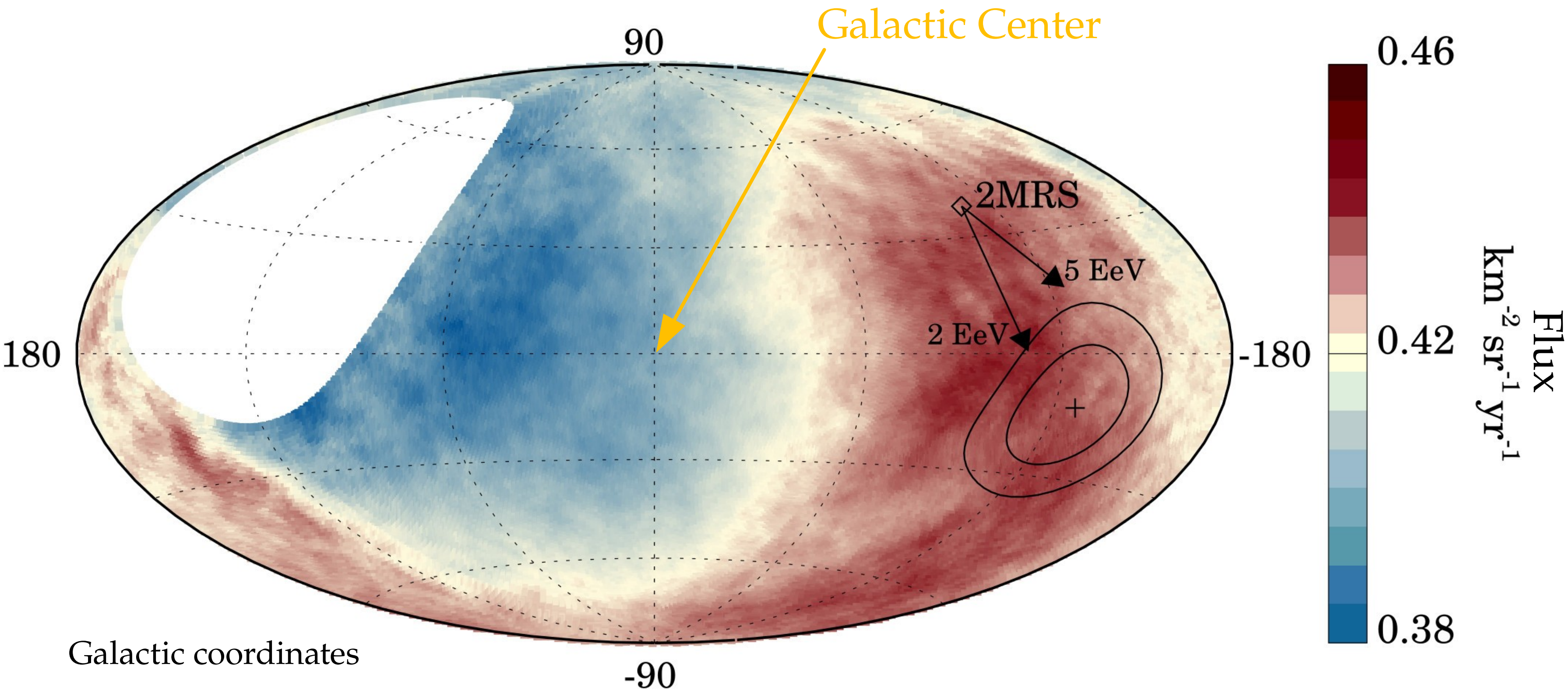
~3000 km^2



4 × 6 fluorescence telescopes

UHECR anisotropy

Flux of UHECRs > 8 EeV (Auger, 12 years of data):



Auger Collab., *Science* 2017

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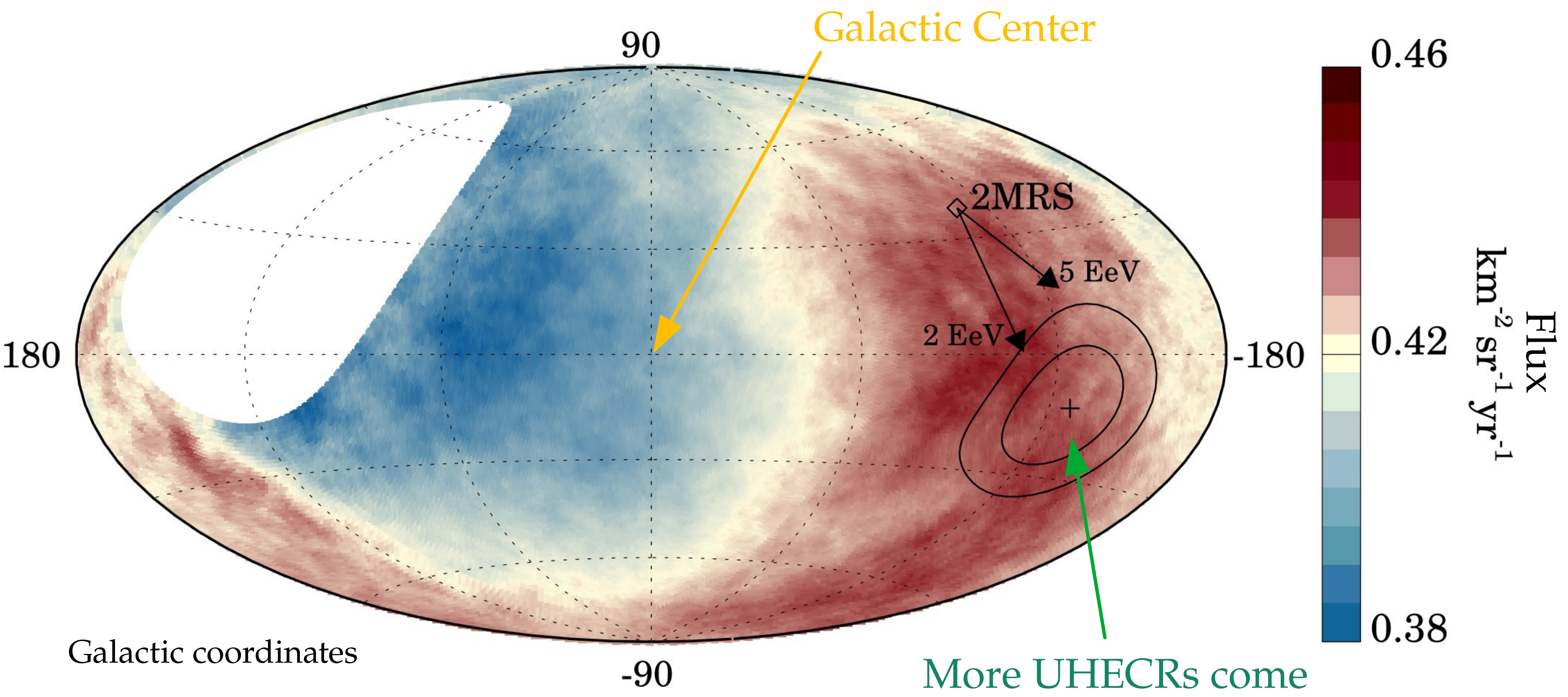

More UHECRs come from this direction: *away from the GC!*

Auger Collab., *Science* 2017

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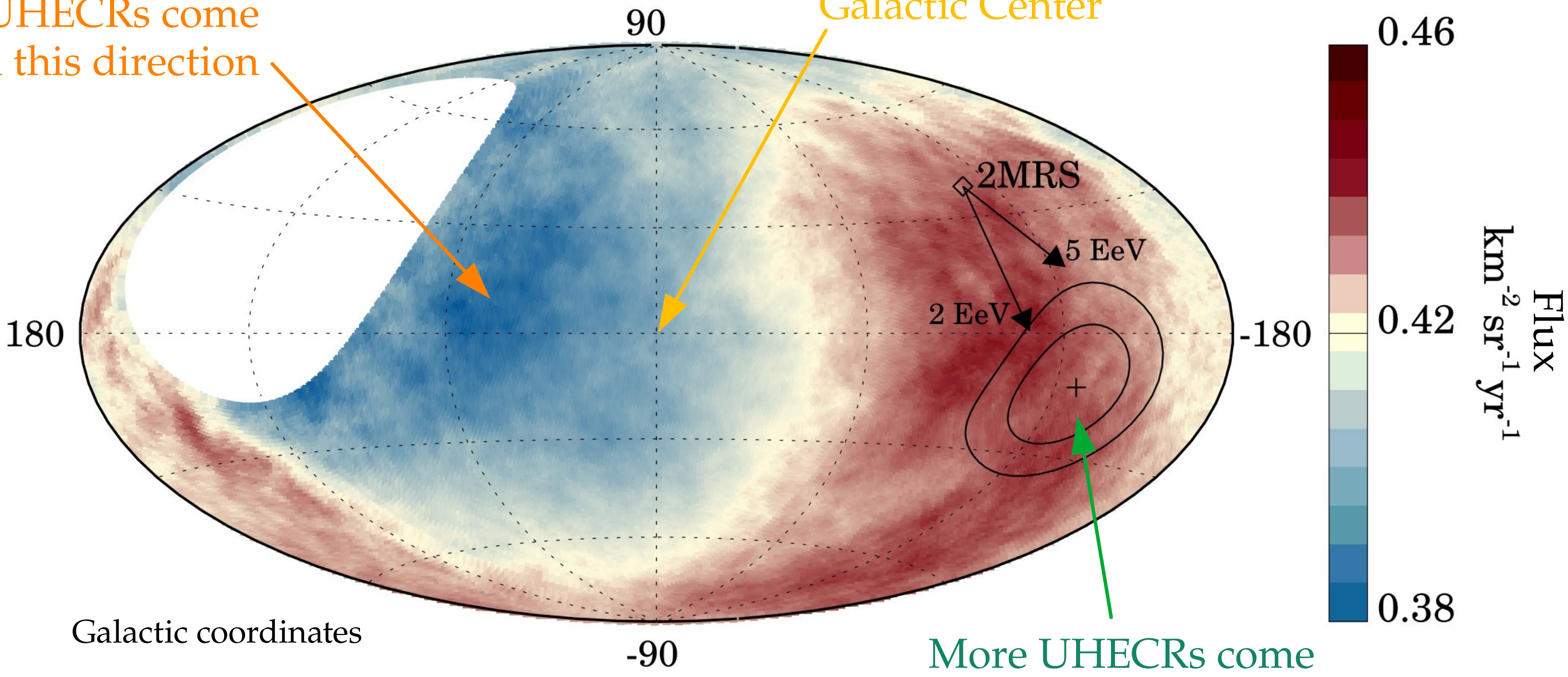

Fewer UHECRs come from this direction

Galactic Center

Galactic coordinates

More UHECRs come from this direction: *away from the GC!*

Auger Collab., *Science* 2017

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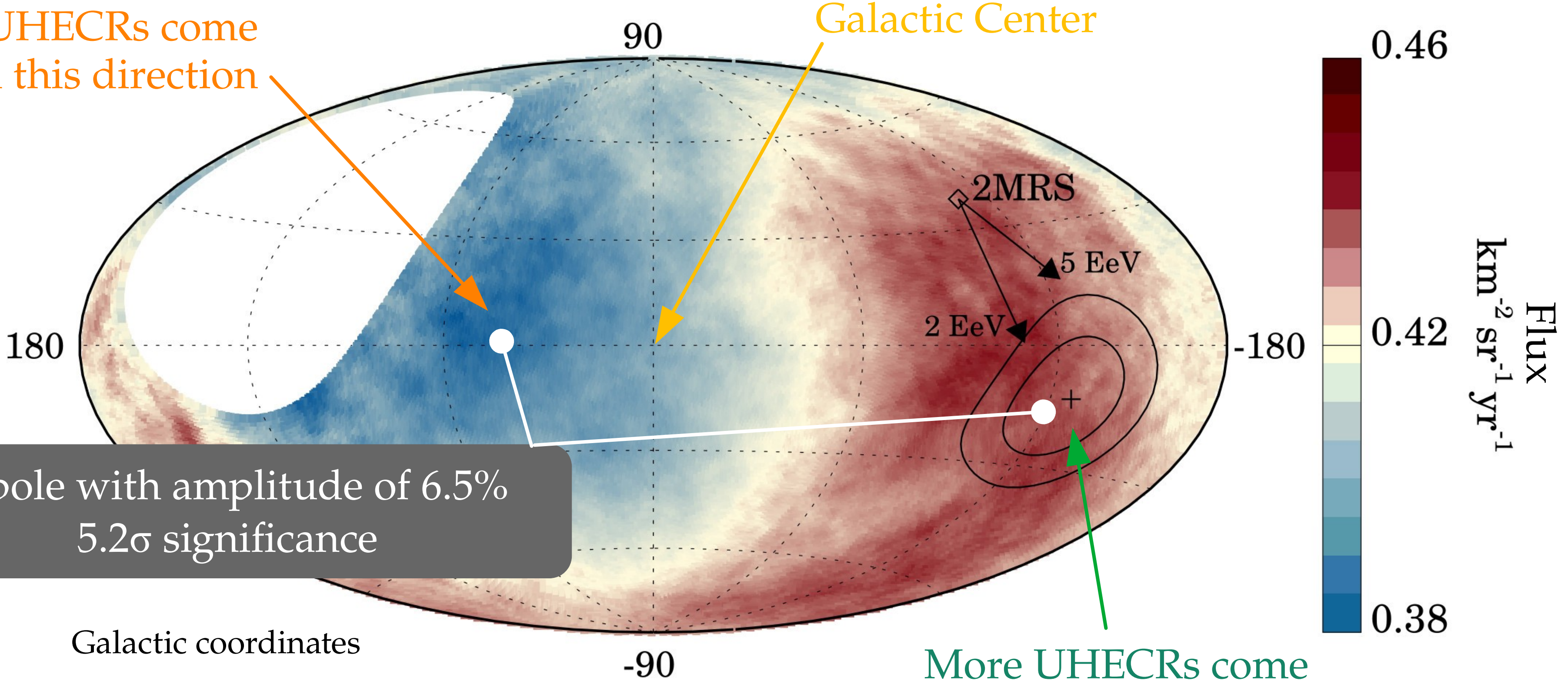


Fewer UHECRs come from this direction

Galactic Center

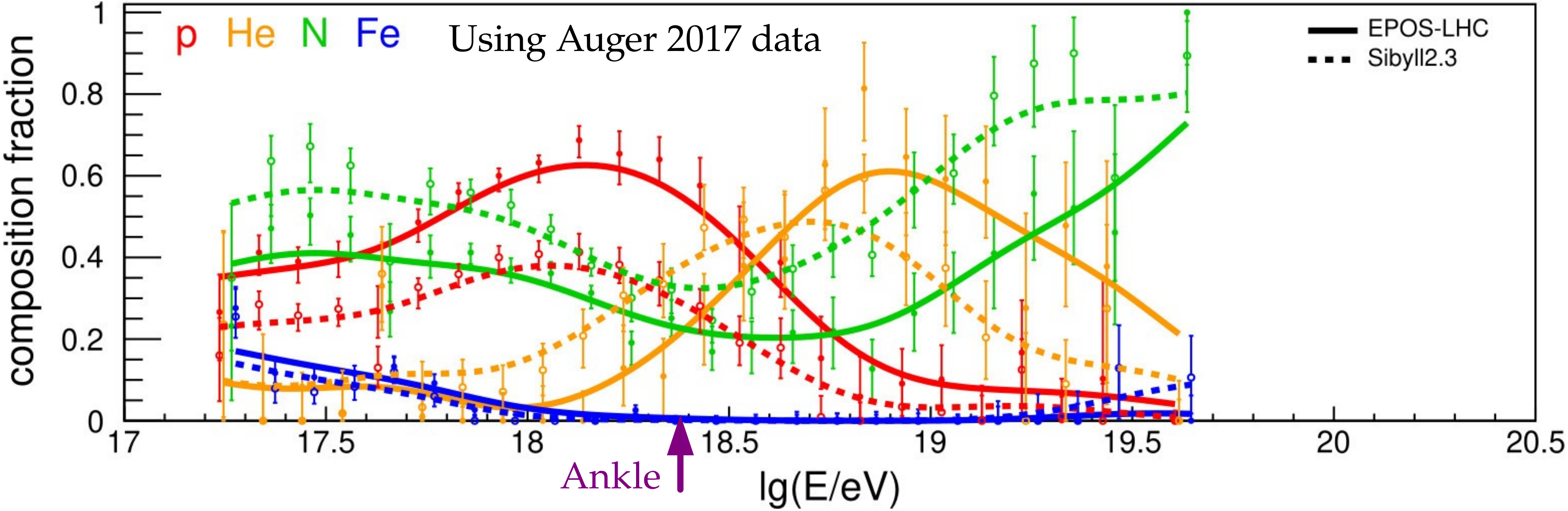
Dipole with amplitude of 6.5%
5.2σ significance

Galactic coordinates

More UHECRs come from this direction: *away from the GC!*

Auger Collab., *Science* 2017

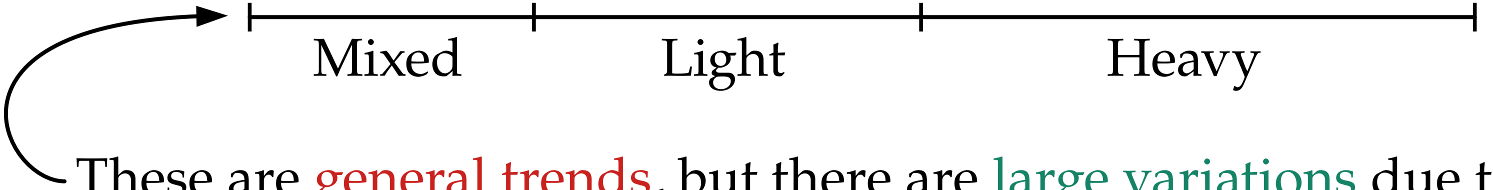
$X_{\max}$ and UHECR mass composition



Alves Batista *et al.* (inc. **MB**), *Front. Astron. Space Sci.* 2019

Using Auger 2017 data

Ankle



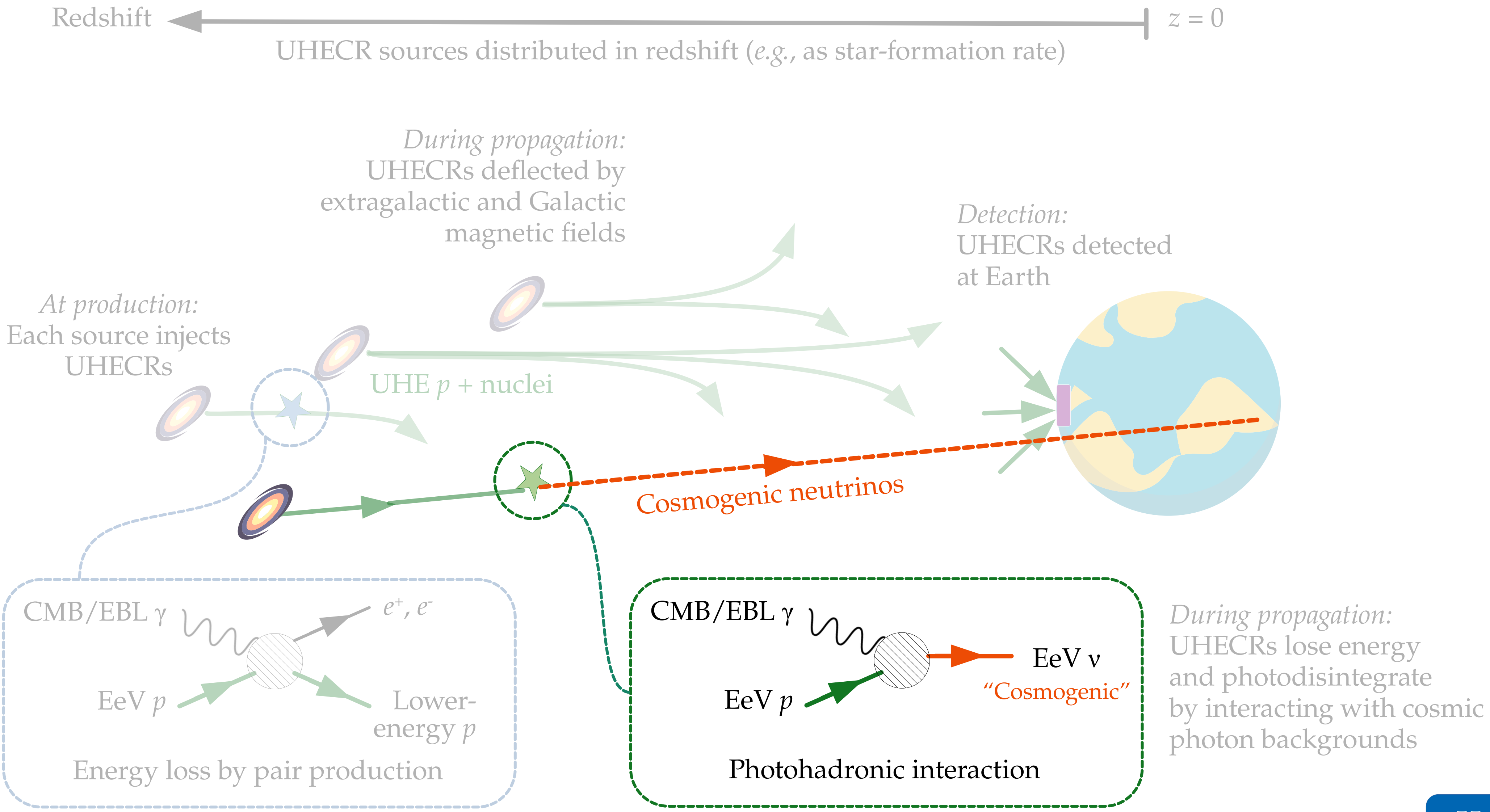
Mixed

Light

Heavy

These are general trends, but there are large variations due to systematic and statistical errors (also other experiments differ, *e.g.*, Telescope Array)

High-energy cosmic neutrinos



Redshift

$z = 0$

UHECR sources distributed in redshift (*e.g.*, as star-formation rate)

During propagation:
UHECRs deflected by
extragalactic and Galactic
magnetic fields

Detection:
UHECRs detected
at Earth

At production:
Each source injects
UHECRs

UHE p + nuclei

Cosmogenic neutrinos

CMB/EBL γ

e^+, e^-

EeV p

Lower-energy p

Energy loss by pair production

CMB/EBL γ

EeV ν

"Cosmogenic"

EeV p

Photohadronic interaction

During propagation:
UHECRs lose energy
and photodisintegrate
by interacting with cosmic
photon backgrounds

What about the cosmogenic neutrinos?

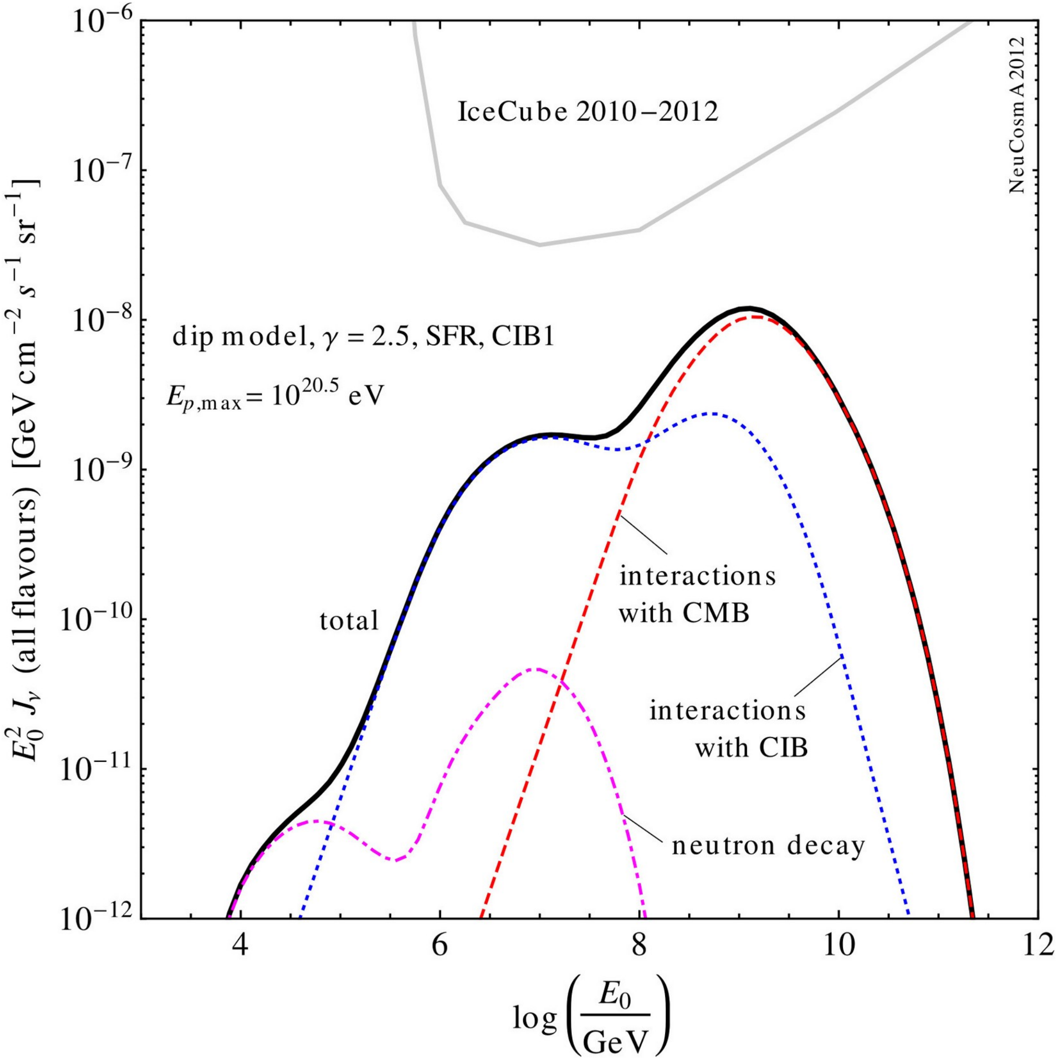
Co-evolve UHECRs and cosmogenic neutrinos:

$$\textbf{UHECRs:}\quad \partial_z Y_p(E,z) = \frac{-1}{(1+z)H(z)}\{\partial_E(H(z)EY_p(E,z)) + \partial_E(b_{e^+e^-}(E,z)Y_p(E,z)) \\ + \partial_E(b_{p\gamma}(E,z)Y_p(E,z)) + \mathcal{L}_{\mathrm{CR}}(E,z)\}$$

$$\textbf{Neutrinos:}\ \partial_z Y_\nu(E,z) = \frac{-1}{(1+z)H(z)}\{\partial_E(H(z)EY_\nu(E,z)) + \mathcal{L}_\nu(E,z)\}$$

Note: We can propagate gamma rays by adding an additional equation for them

Cosmogenic neutrinos



The position of the ν bump is determined by the Δ-resonance production threshold,

$$E_p E_\gamma \approx 0.2\ \text{GeV}^2\ ,$$

and the relation between neutrino energy and proton energy,

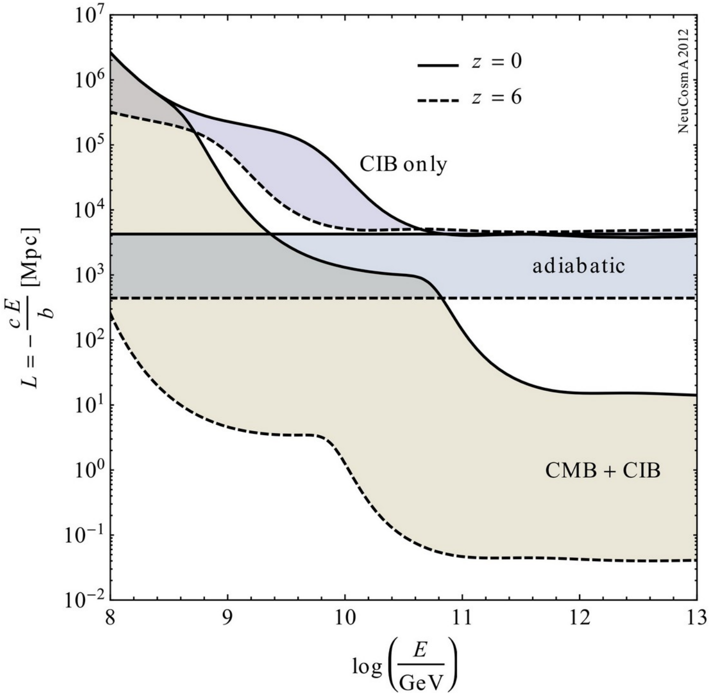
$$E_\nu \approx E_p/20\,.$$

So the neutrino spectrum peaks at

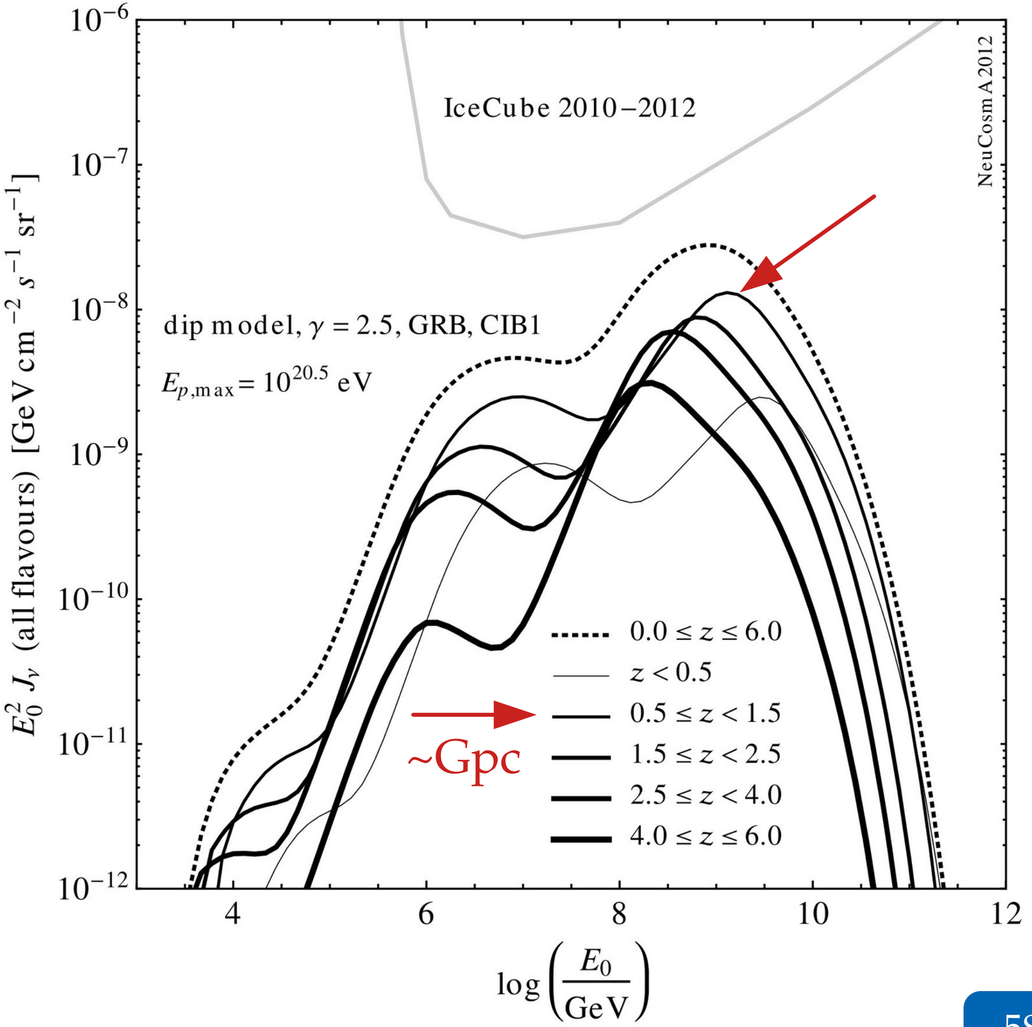
$$E_\nu \approx \frac{0.01\ \text{GeV}}{E_\gamma/\text{GeV}}$$

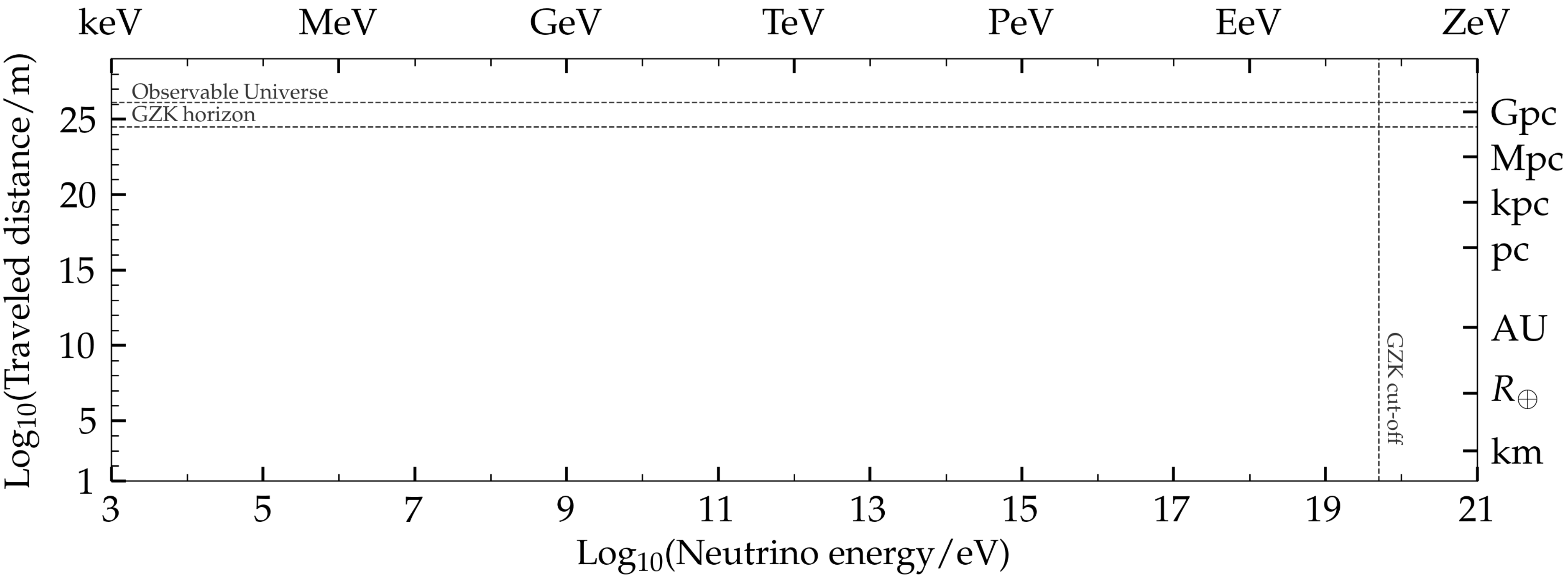
Cosmogenic neutrinos—they come from afar

UHECRs cannot travel farther than the GZK horizon (~100 Mpc)

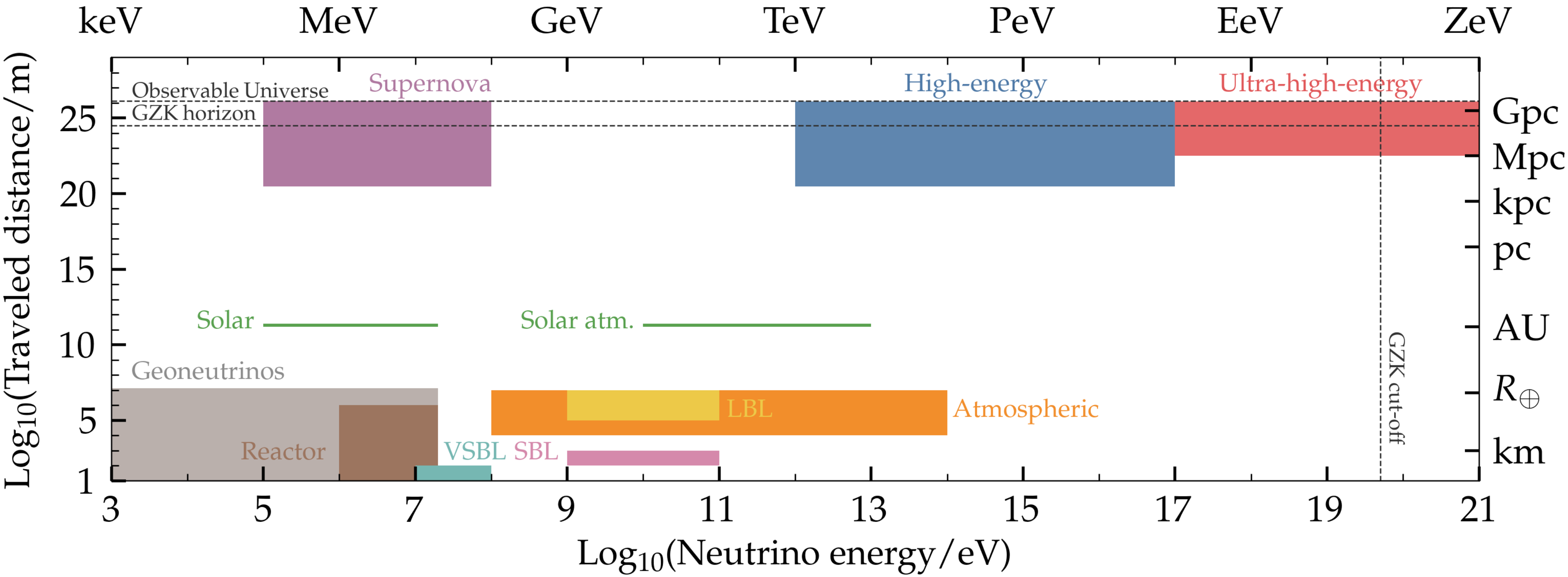


But neutrinos can!



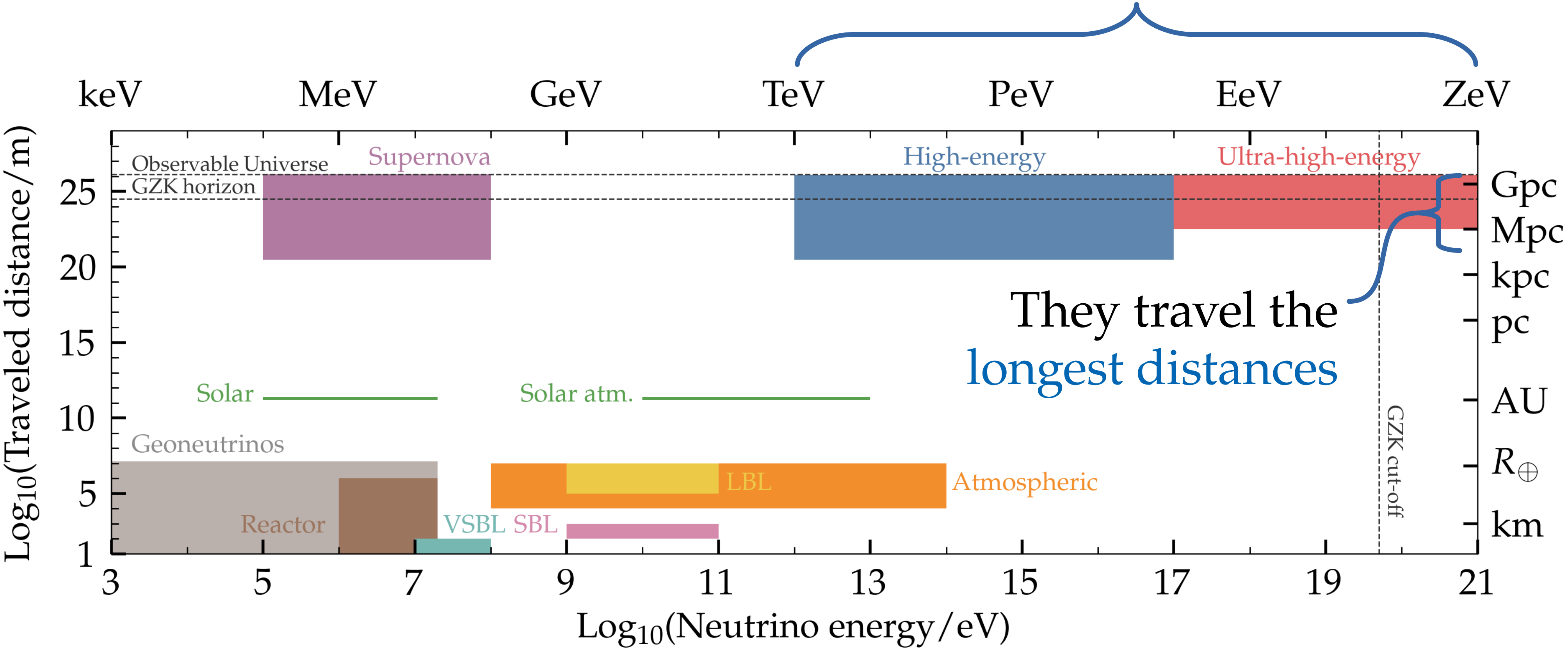


Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted



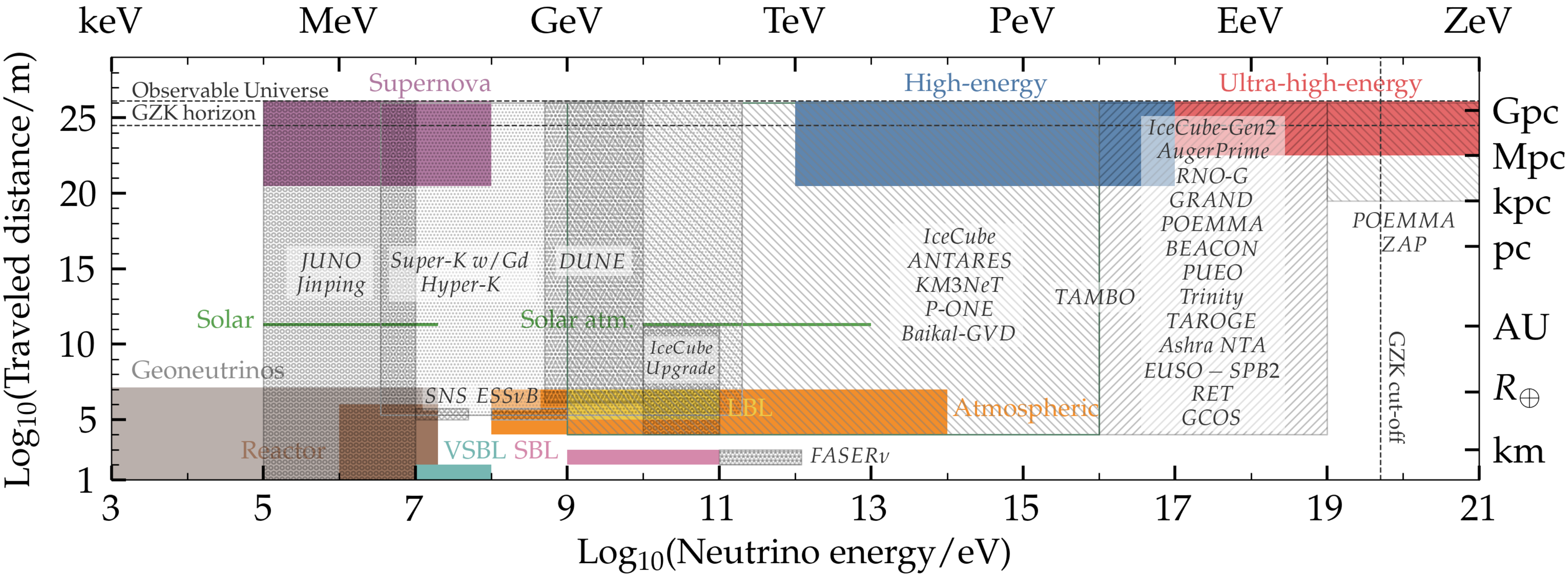
Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted

They have the highest energies



They travel the longest distances

Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted



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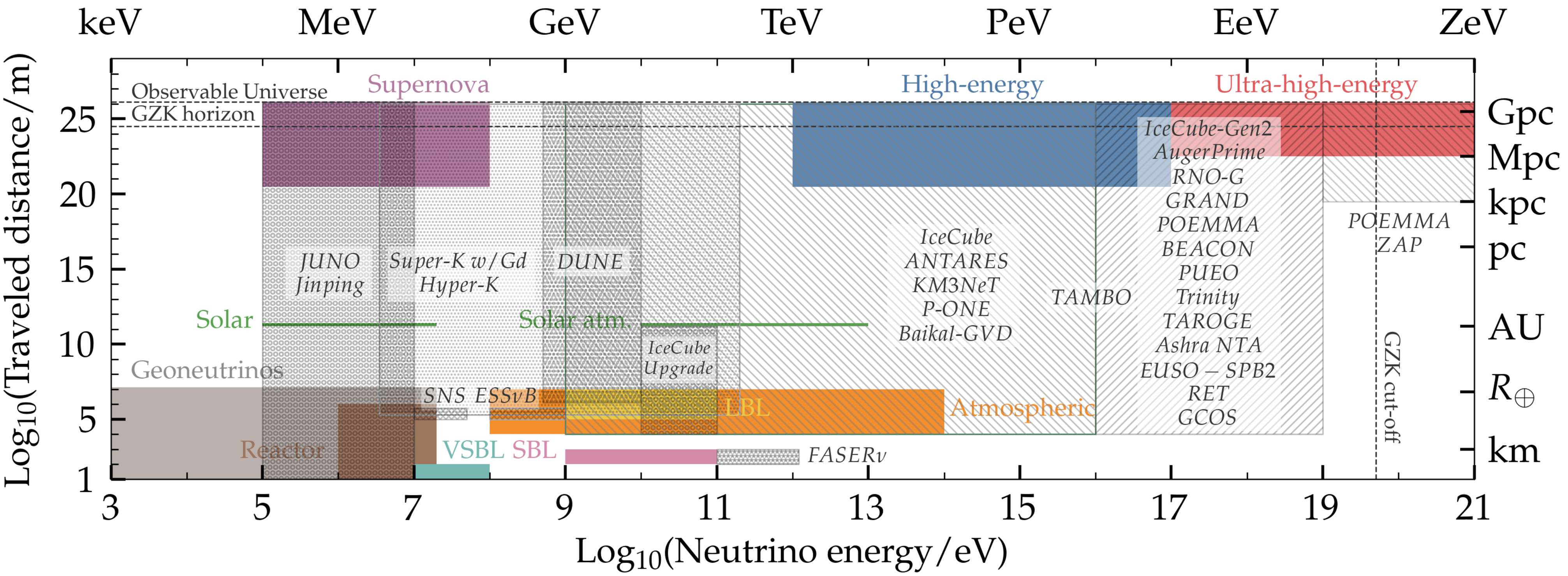
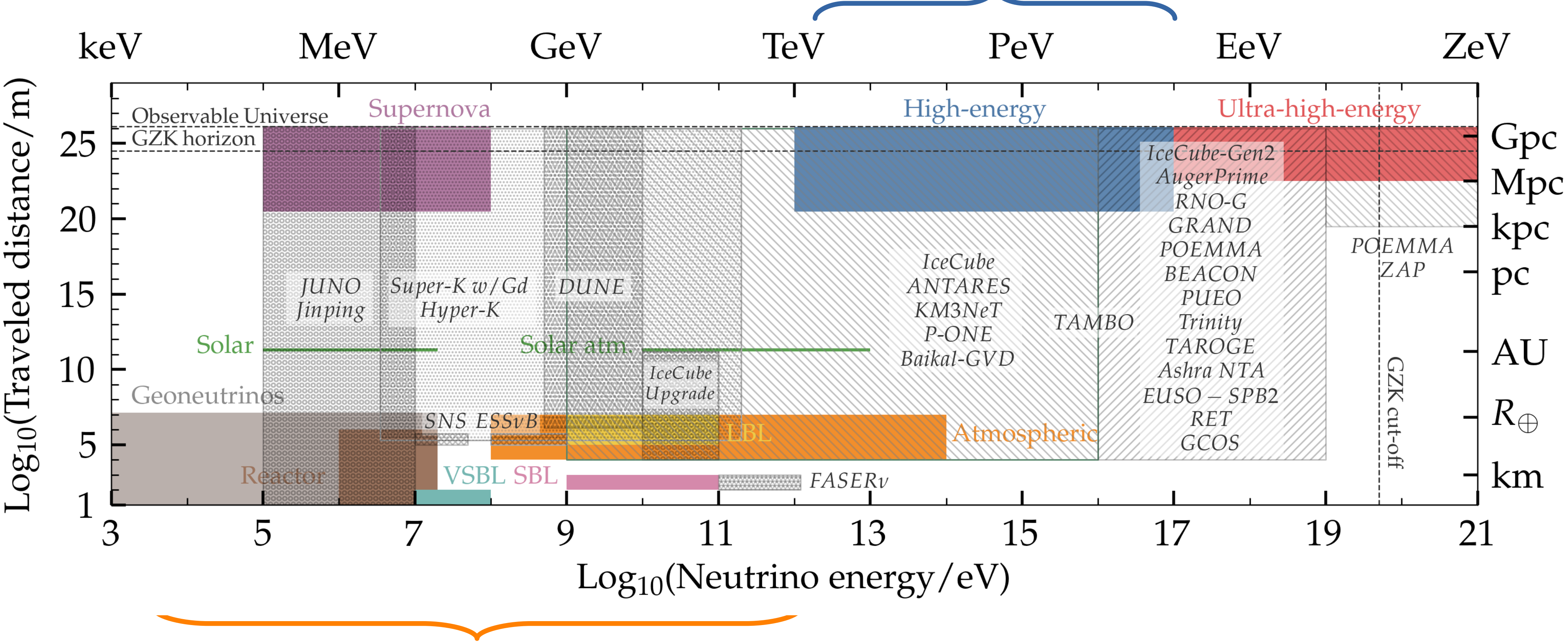


Synergies with lower energies

Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted

Discovered in 2013
by IceCube



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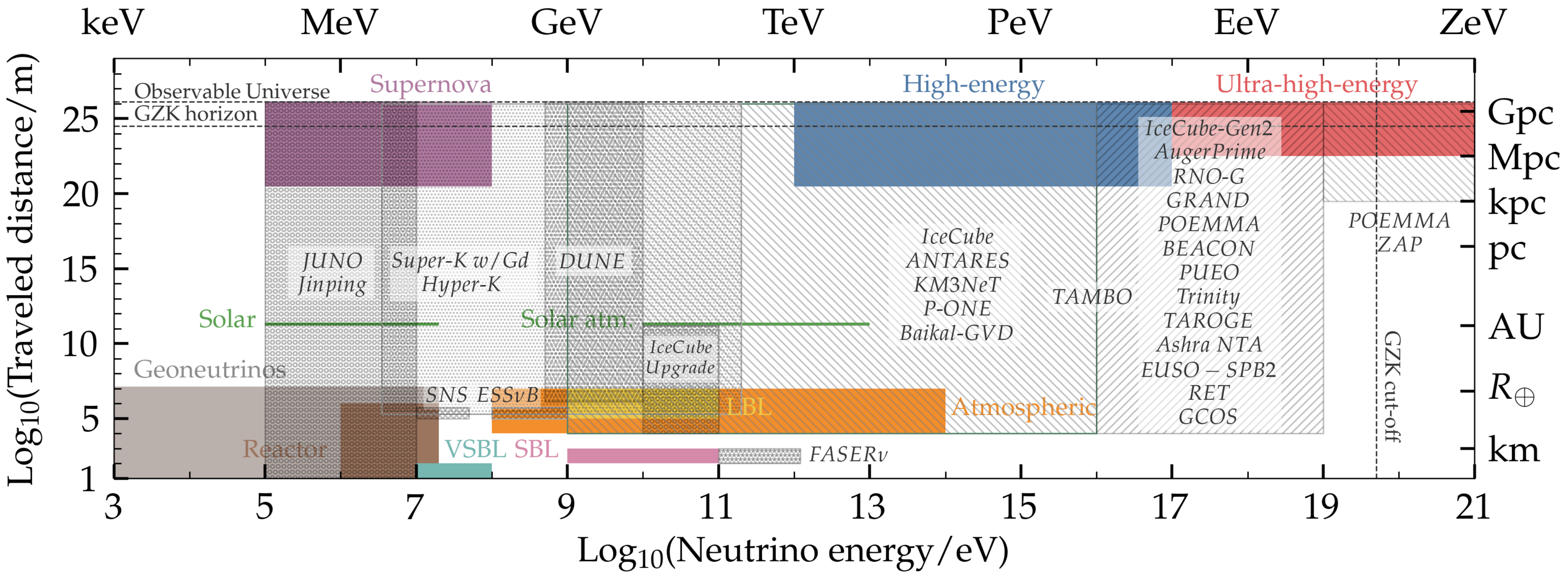

Synergies with lower energies

Increase TeV–PeV
ν statistics

Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted

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Predicted in 1969
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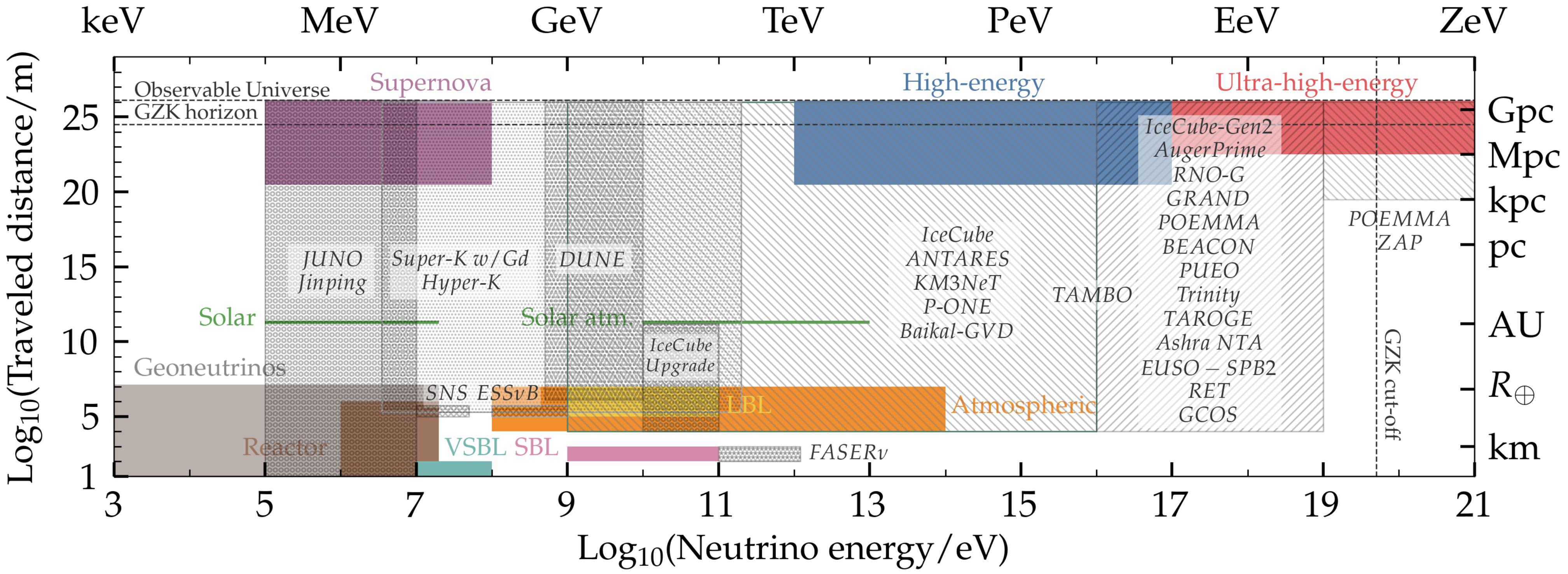

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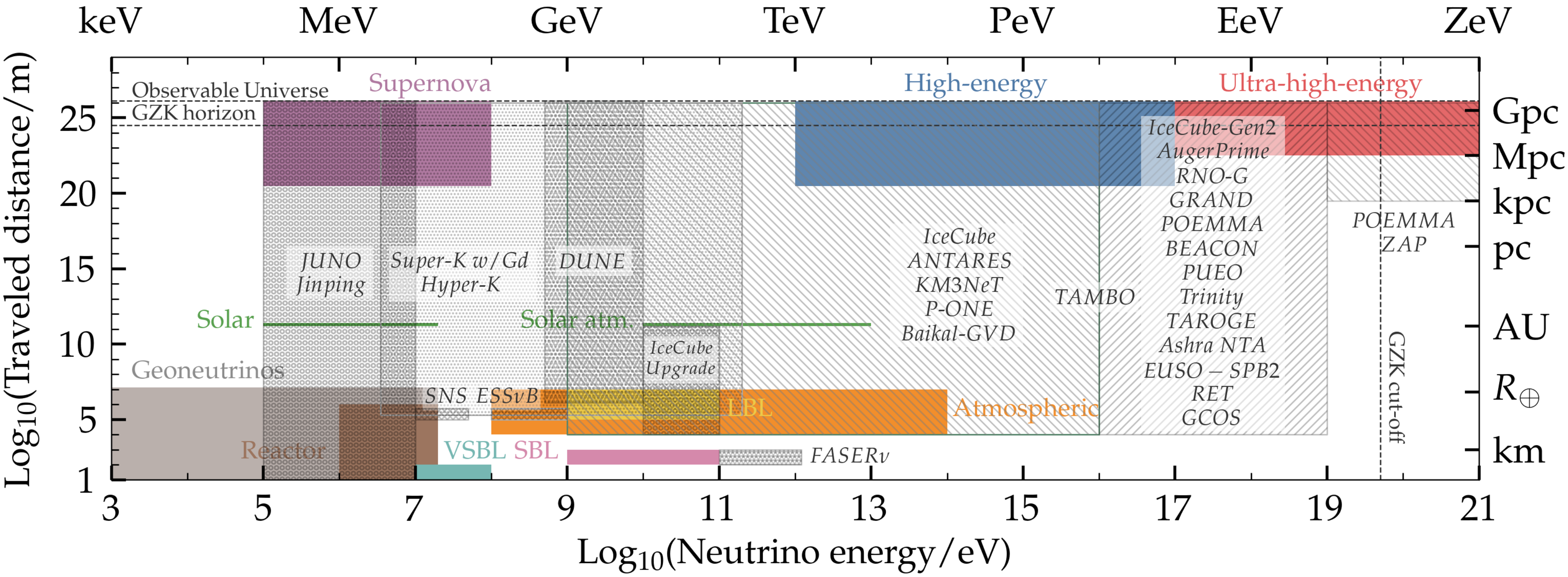


Synergies with lower energies

Increase TeV–PeV
ν statistics

Discover > EeV ν

Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted

Today

TeV–PeV ν

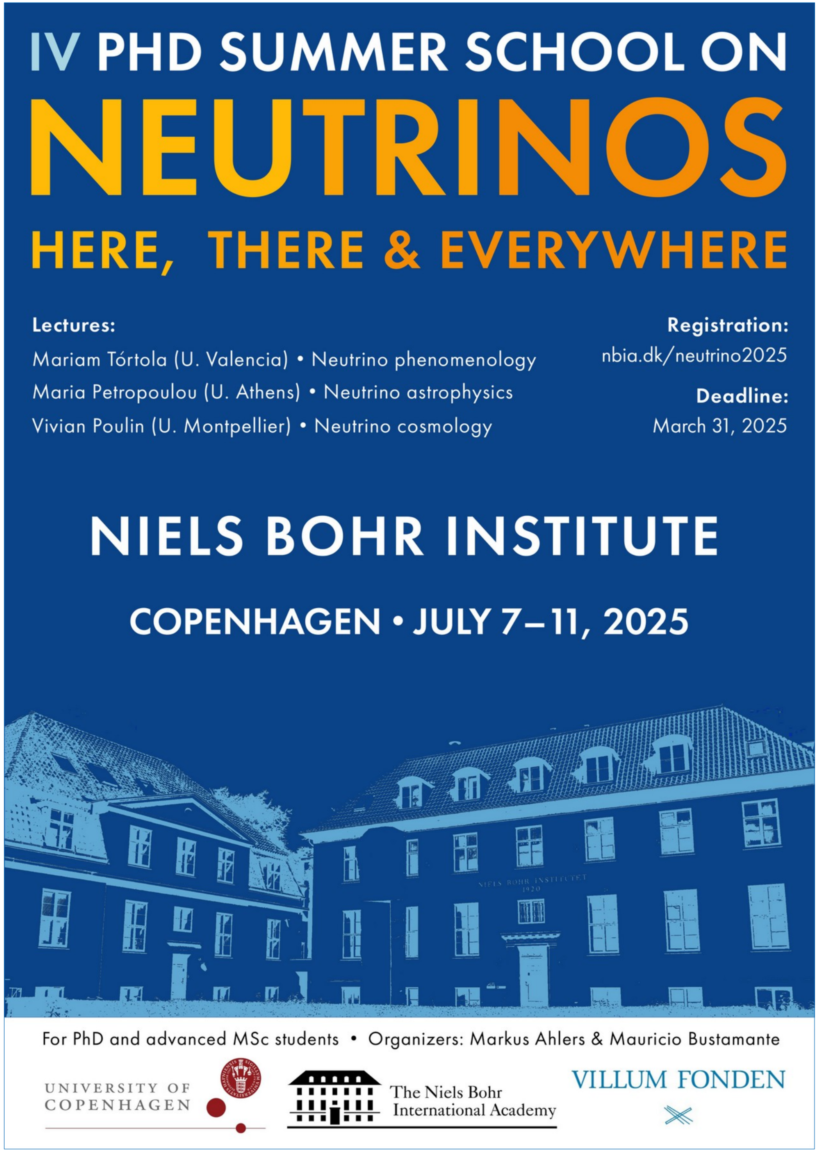
Astro: Find & understand sources

Particle: Turn predictions into tests

Next decade

$>$ 100-PeV ν

Make predictions for
a new energy regime



IV PHD SUMMER SCHOOL ON

NEUTRINOS

HERE, THERE & EVERYWHERE

Lectures:

Mariam Tórtola (U. Valencia) • Neutrino phenomenology

Maria Petropoulou (U. Athens) • Neutrino astrophysics

Vivian Poulin (U. Montpellier) • Neutrino cosmology

Registration:
nbia.dk/neutrino2025

Deadline:
March 31, 2025

NIELS BOHR INSTITUTE

COPENHAGEN • JULY 7–11, 2025

For PhD and advanced MSc students • Organizers: Markus Ahlers & Mauricio Bustamante

UNIVERSITY OF COPENHAGEN

The Niels Bohr International Academy

VILLUM FONDEN

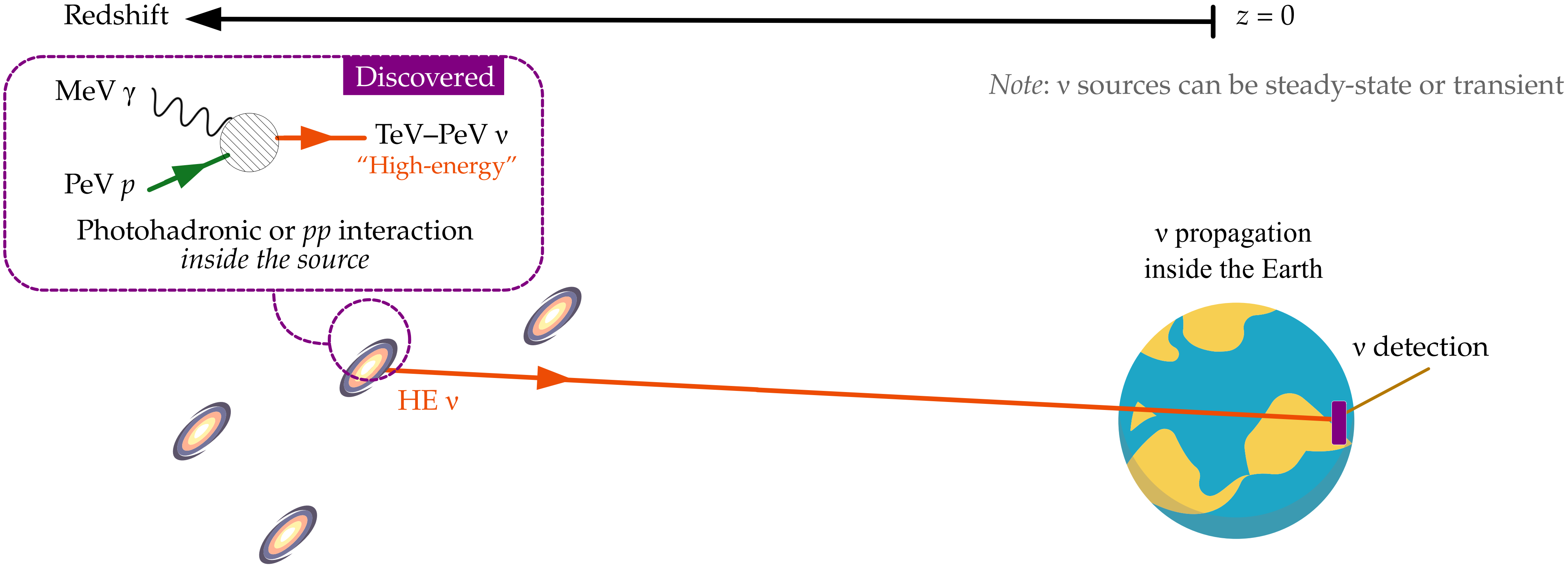
- Three tracks:
  - Neutrino phenomenology:
    Mariam Tórtola (Valencia)
  - Neutrino astrophysics:
    Maria Petropoulou (Athens)
  - Neutrino cosmology:
    Vivian Poulin (Montpellier)
- Plus topical seminars & student talks
- Registration open (deadline: March 31)

nbia.dk/neutrino2025

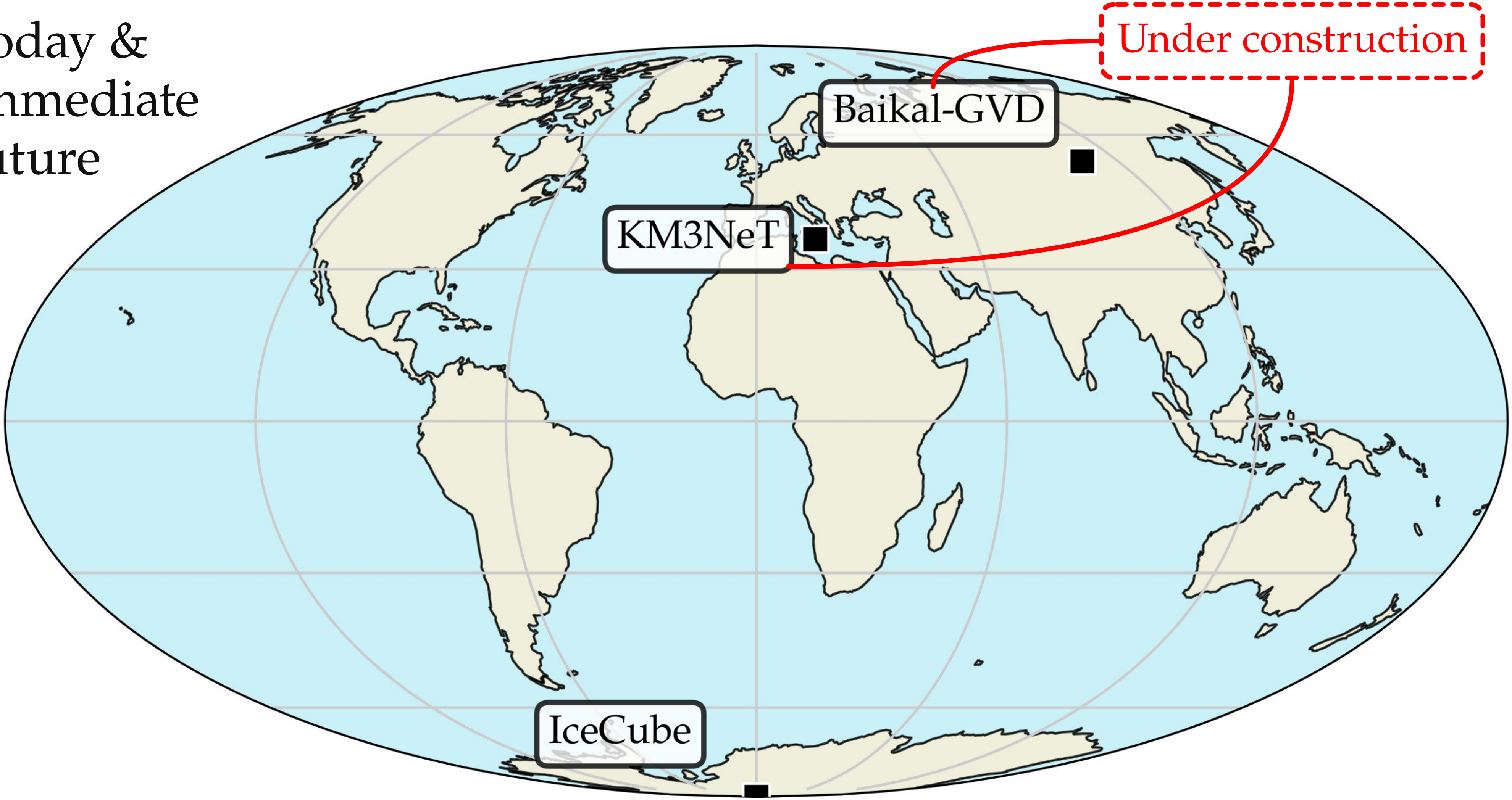
The story so far

Redshift ← $z = 0$

Note: ν sources can be steady-state or transient

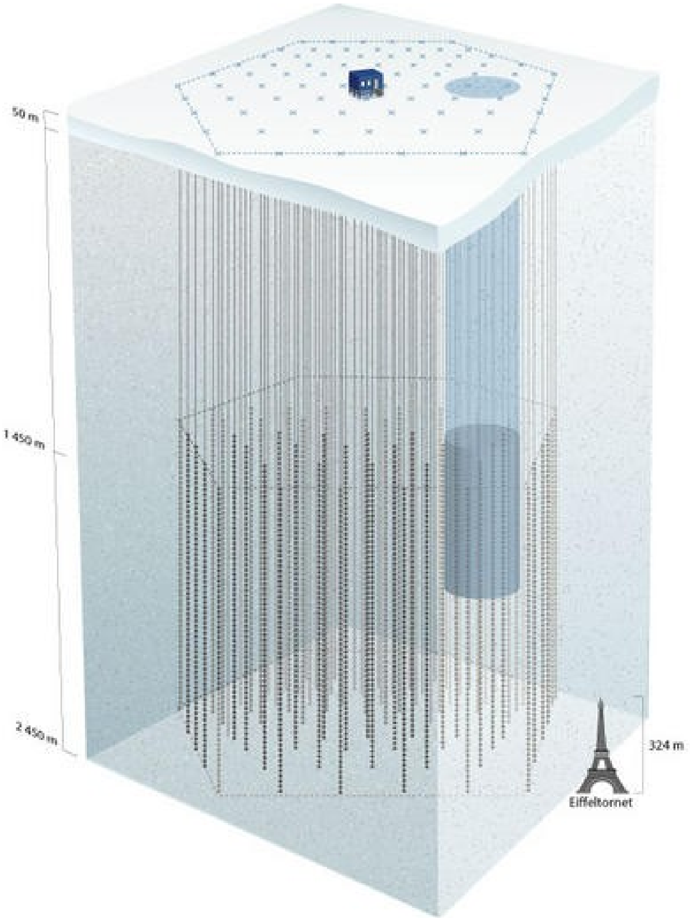

Redshift
$z = 0$
Discovered
MeV γ
TeV–PeV ν
"High-energy"
PeV p
Photohadronic or pp interaction
inside the source
Note: ν sources can be steady-state or transient
ν propagation
inside the Earth
ν detection
HE ν

Today & immediate future



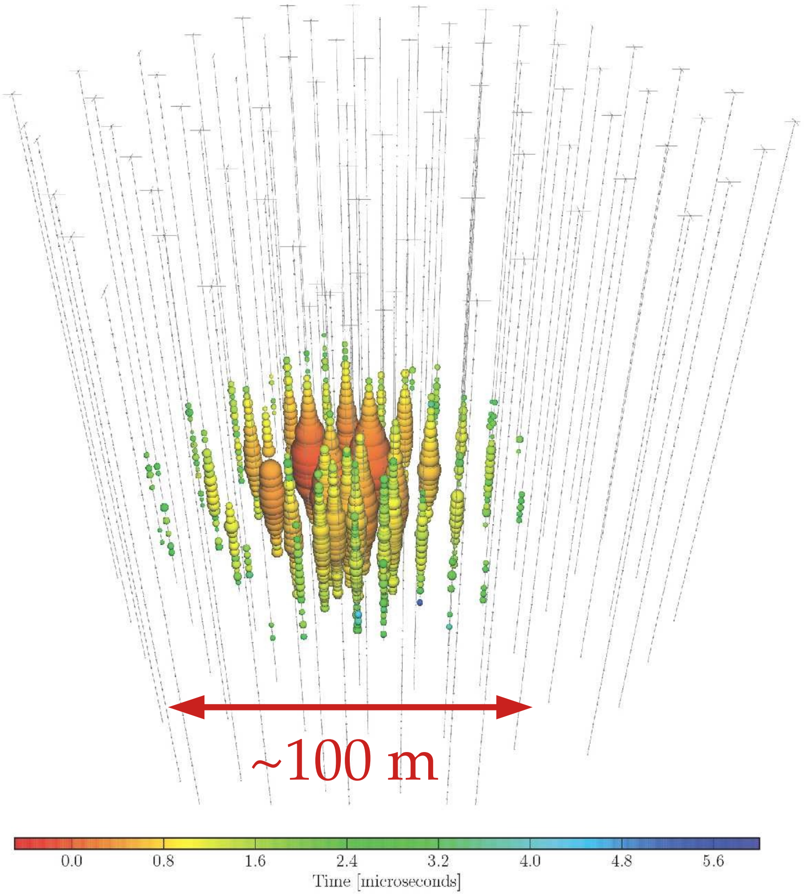
Schumacher, Agostini, **MB**, Oikonomou, Resconi, *In prep.*

IceCube – What is it?



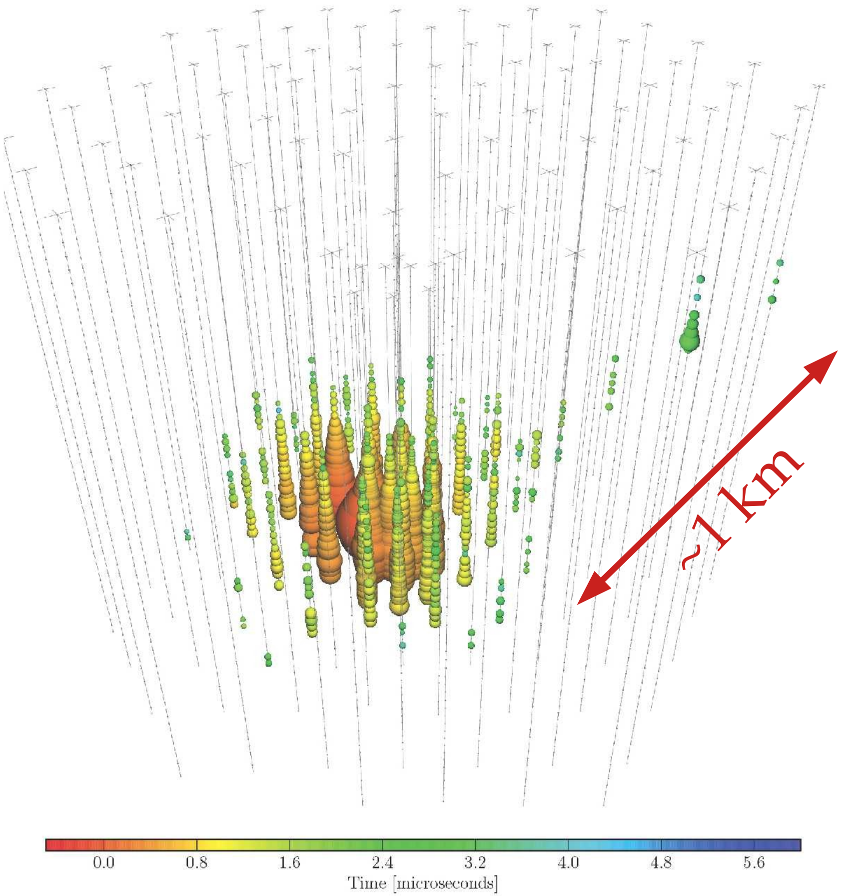
- Km^3 in-ice Cherenkov detector in Antarctica
- $>$ 5000 PMTs at 1.5–2.5 km of depth
- Sensitive to neutrino energies $>$ 10 GeV

Shower
(mainly from ν_e and ν_τ)

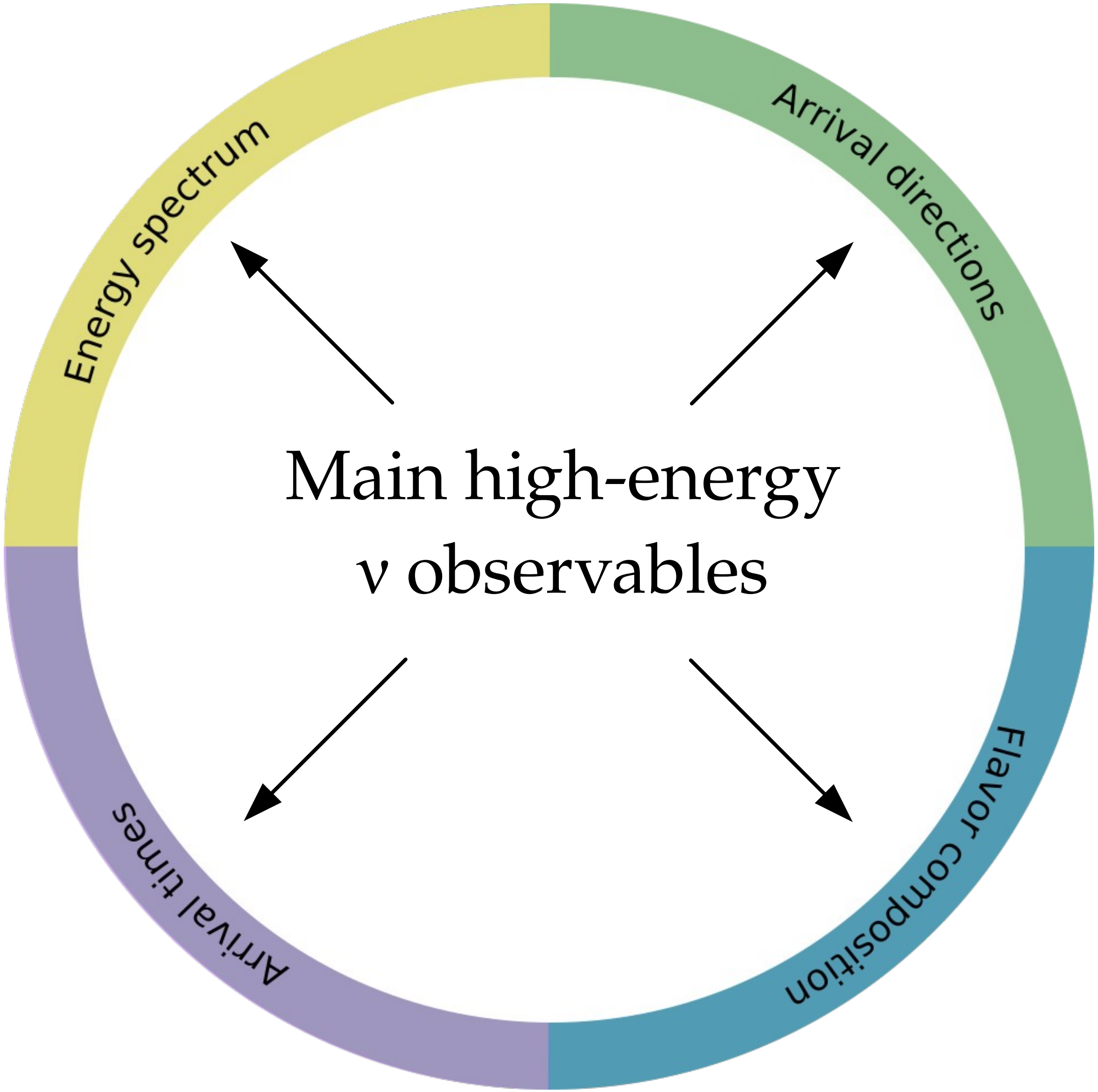


Poor angular resolution: ≥ 5°

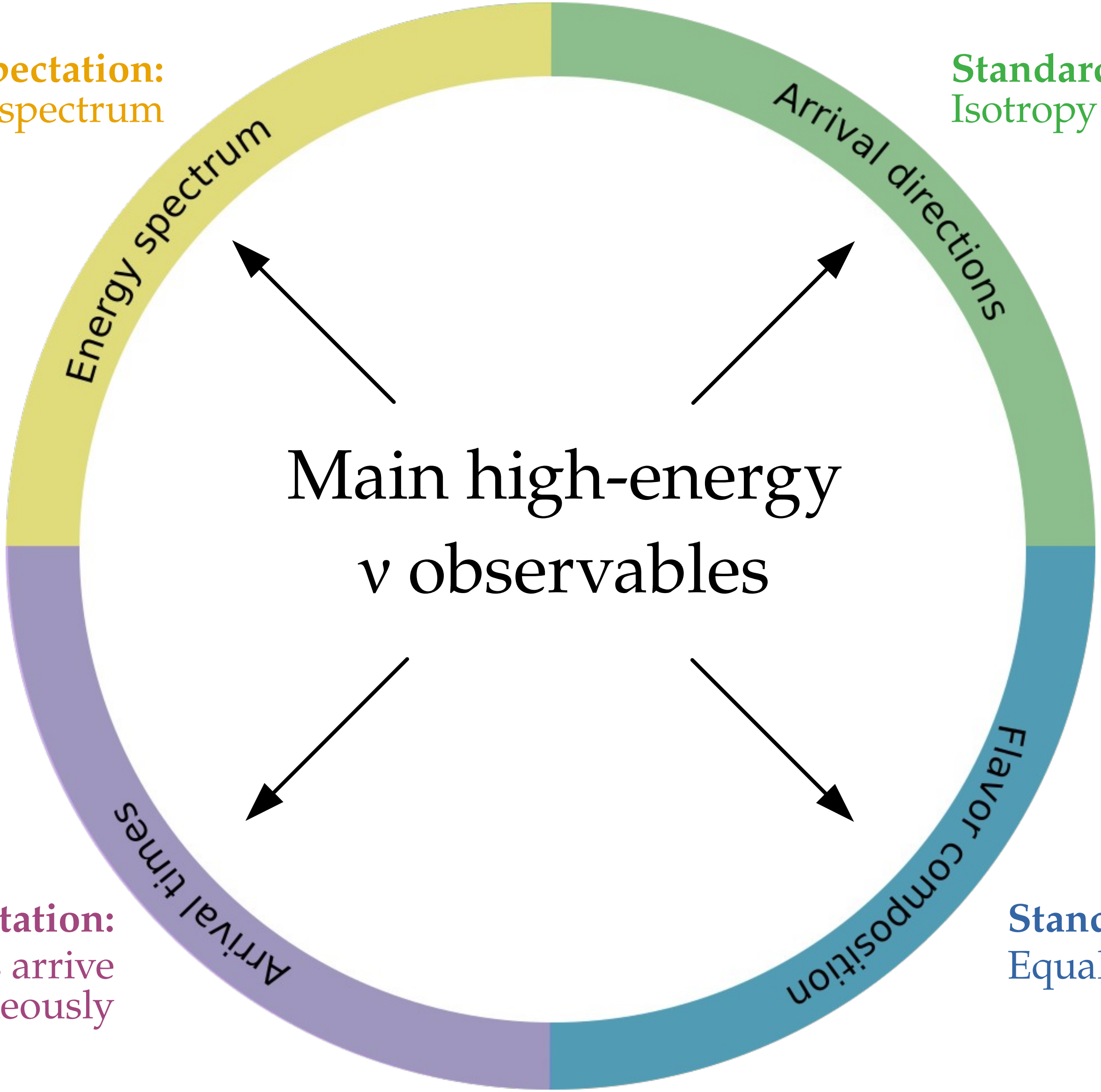
Track
(mainly from ν_μ)



Angular resolution: < 1°



Main high-energy
ν observables



Main high-energy ν observables

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)

Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

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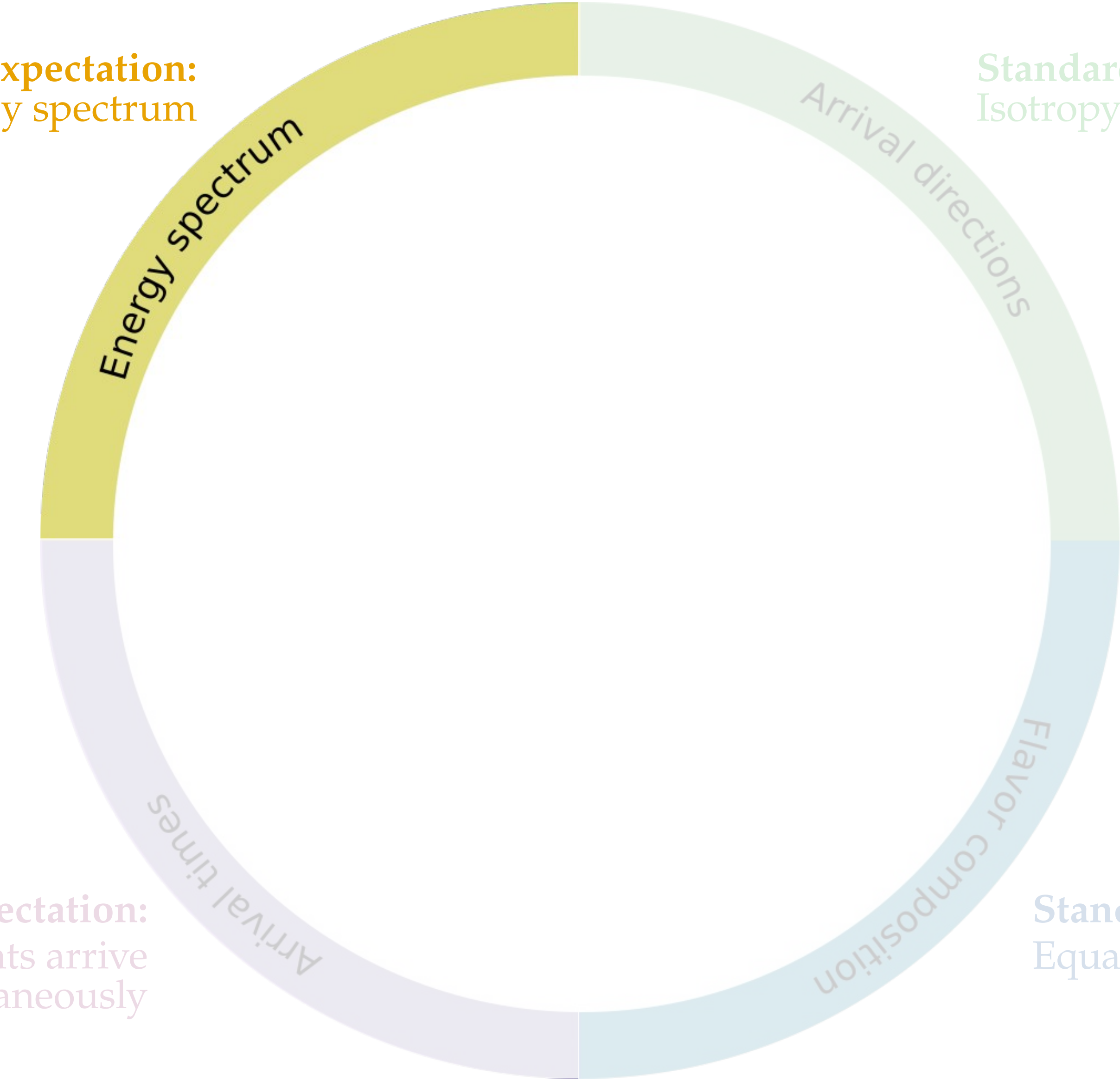

Standard expectation:
ν and γ from transients arrive simultaneously

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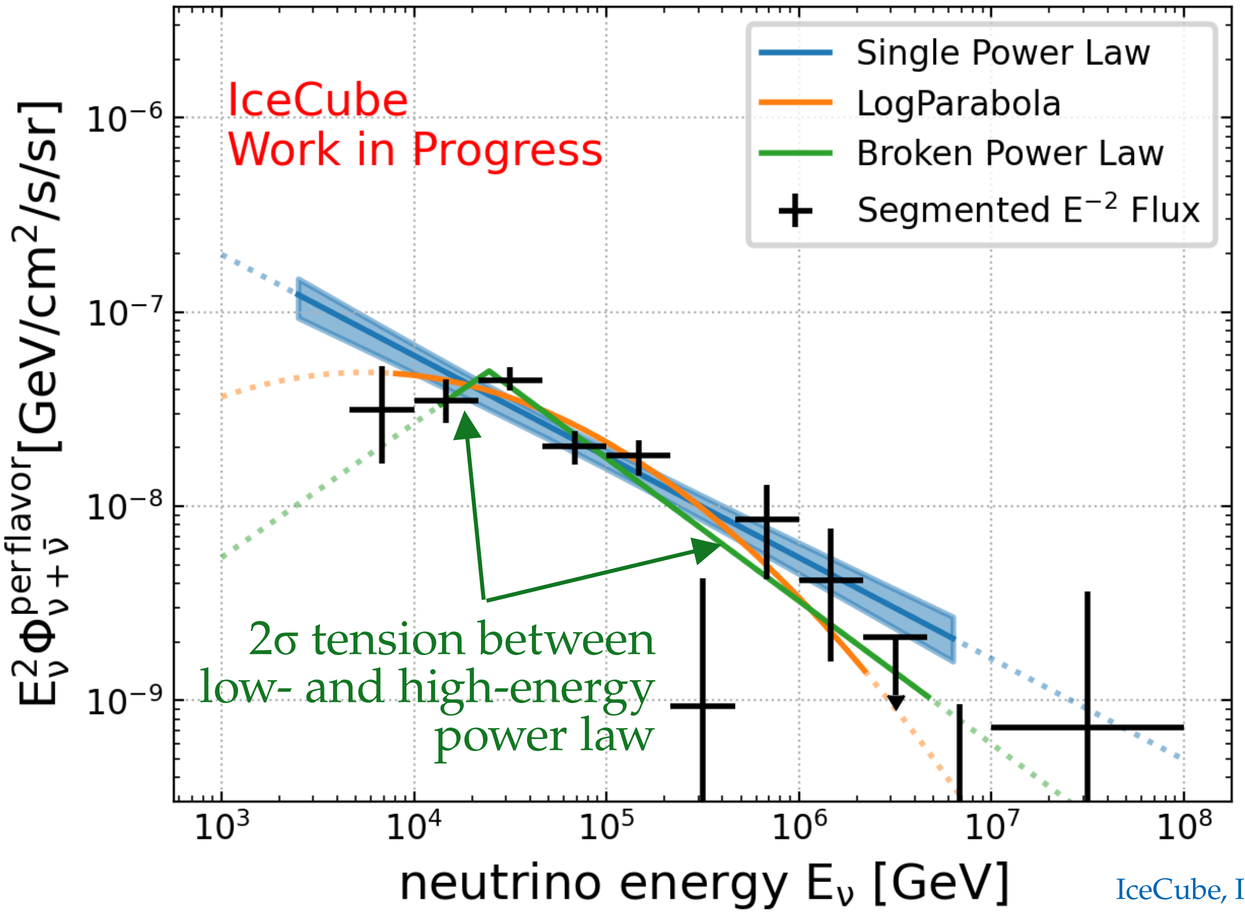
Neutrino energy spectrum

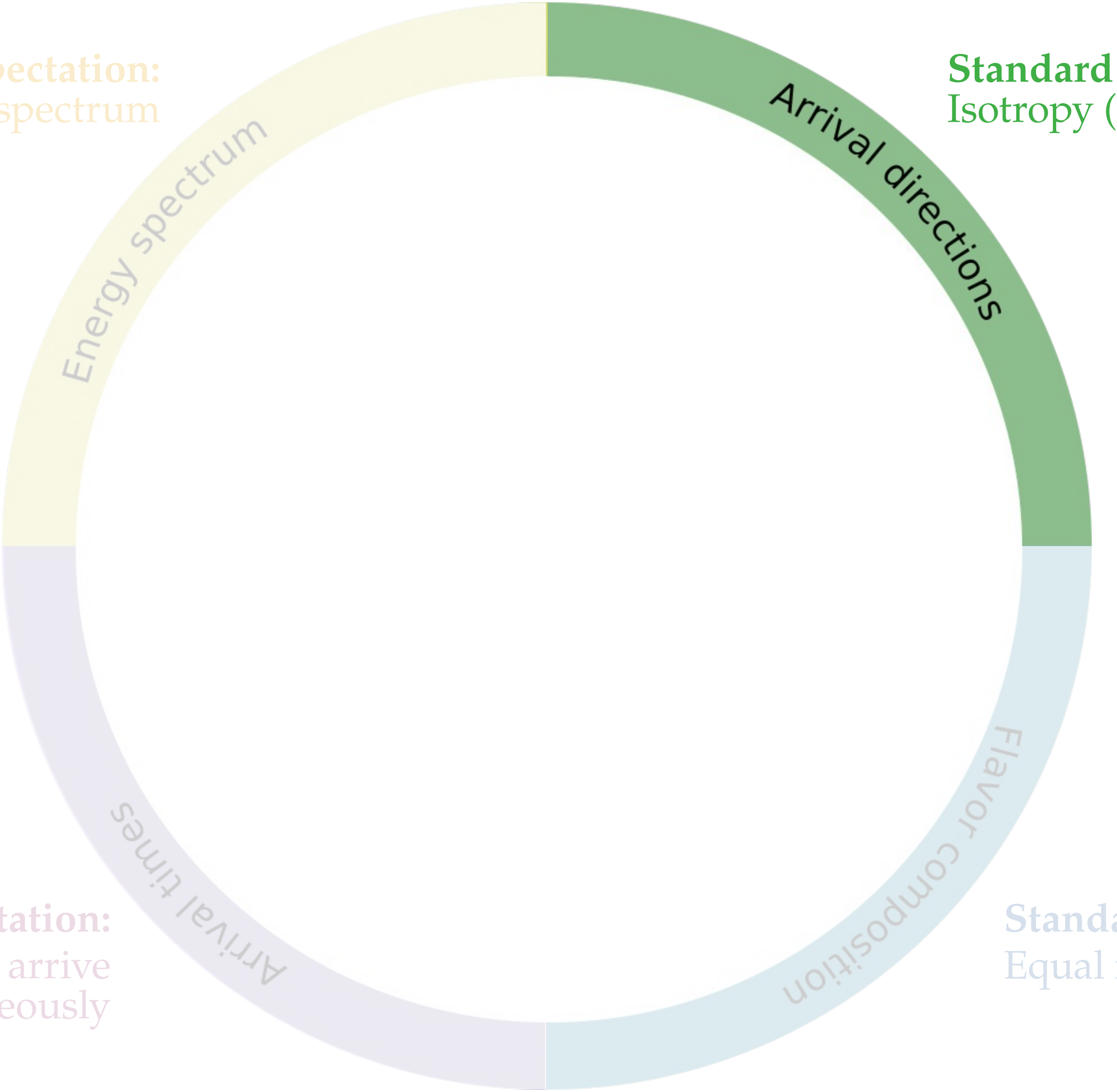
With > 10 years of data, deviations from a power law start to be testable:



2σ tension between low- and high-energy power law

Different spectra might reflect different source populations

IceCube, ICRC 2023



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Standard expectation:
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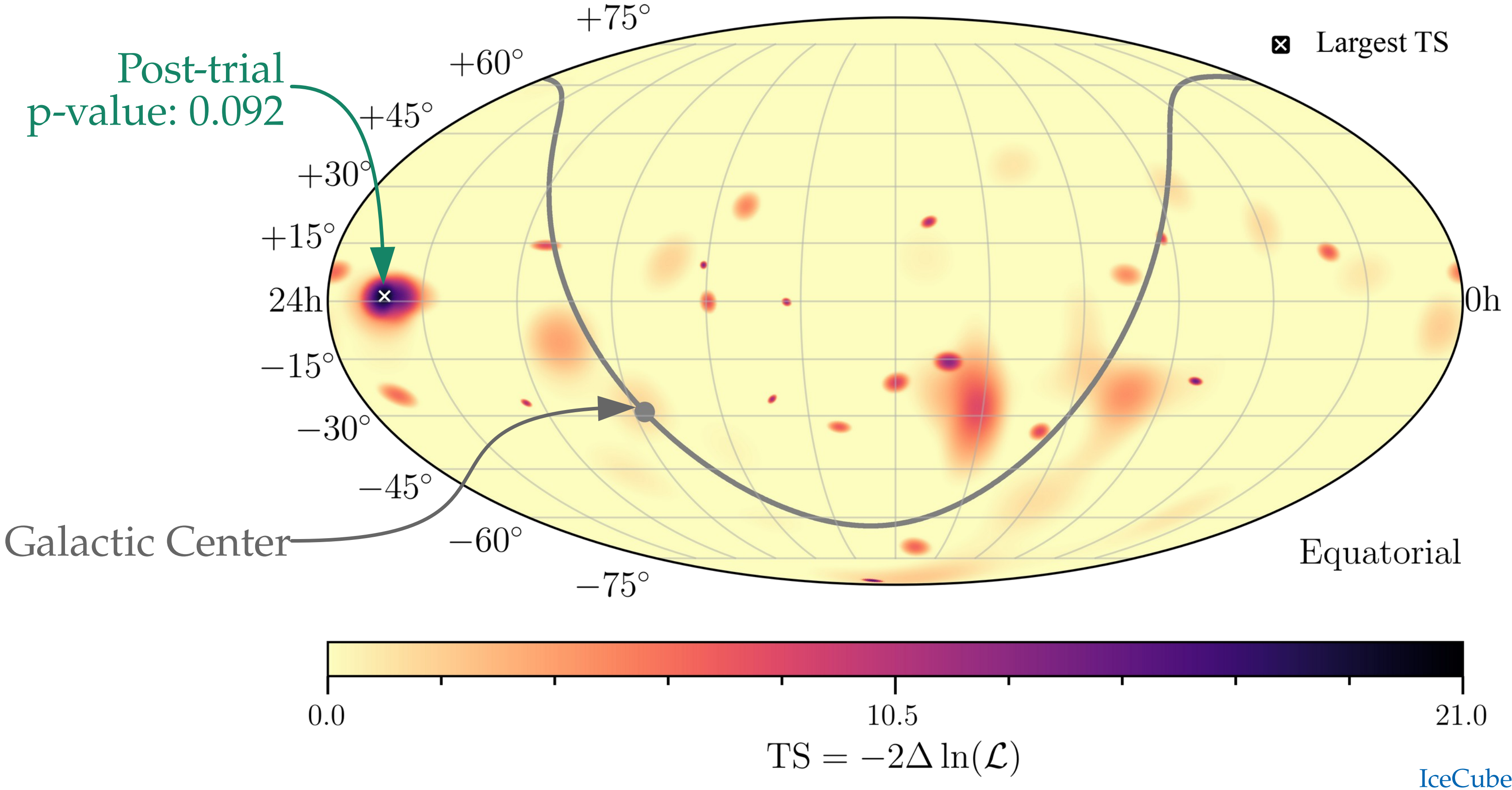
Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

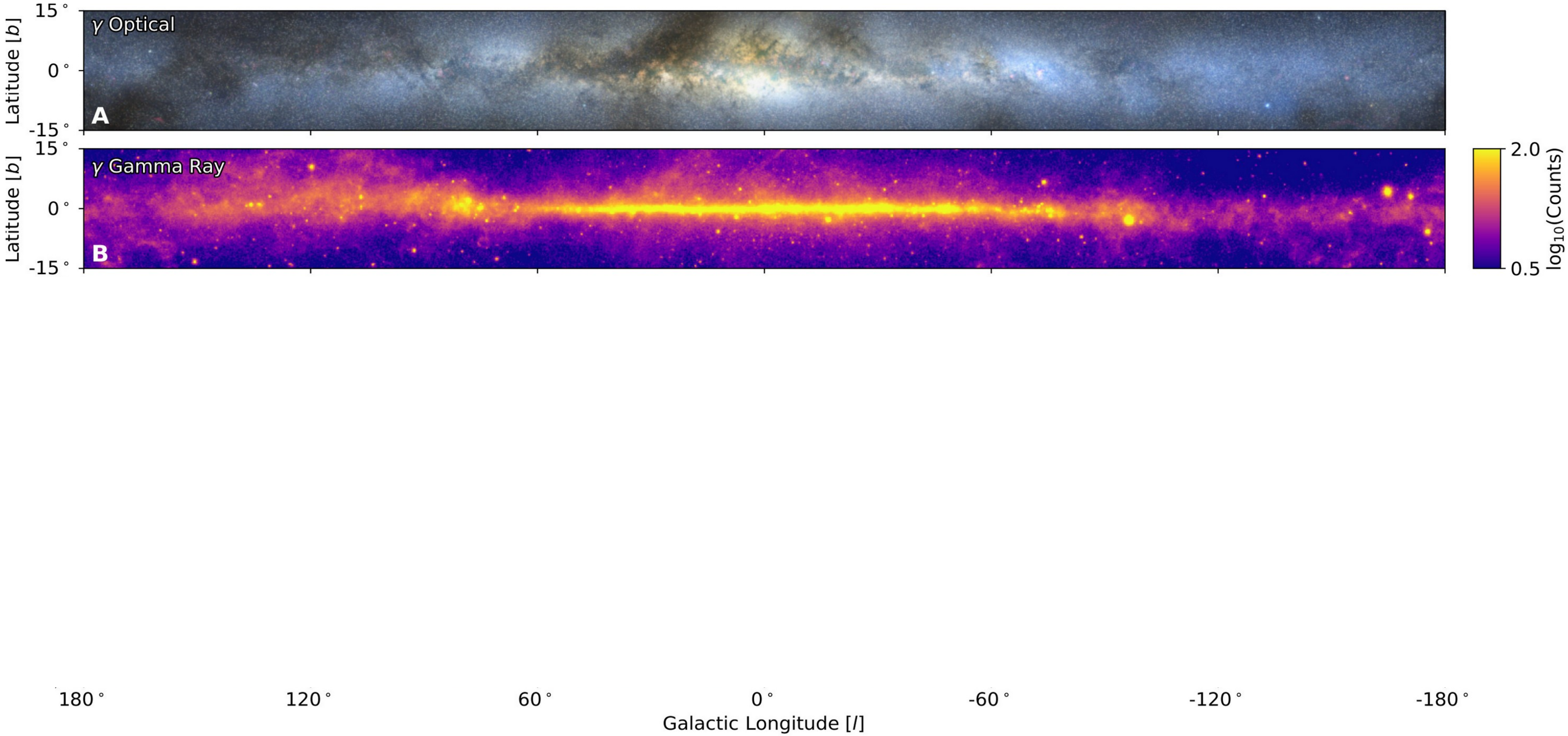
Distribution of arrival directions (7.5 yr)

No significant excess in the neutrino skymap:



IceCube, 2011.03545

High-energy neutrinos from the Galactic Plane



IceCube Collab., *Science* 2023

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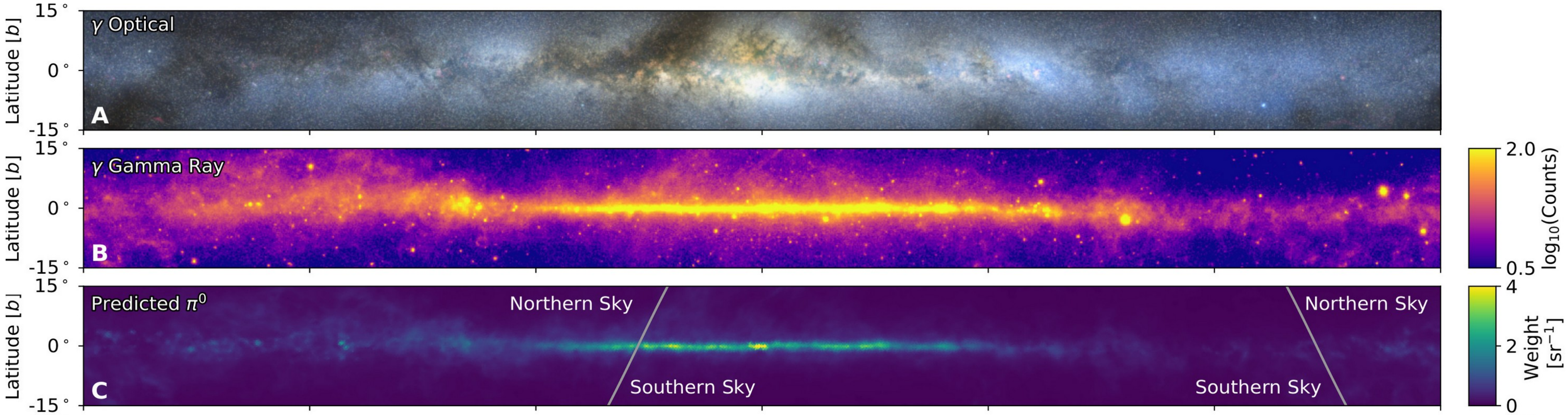


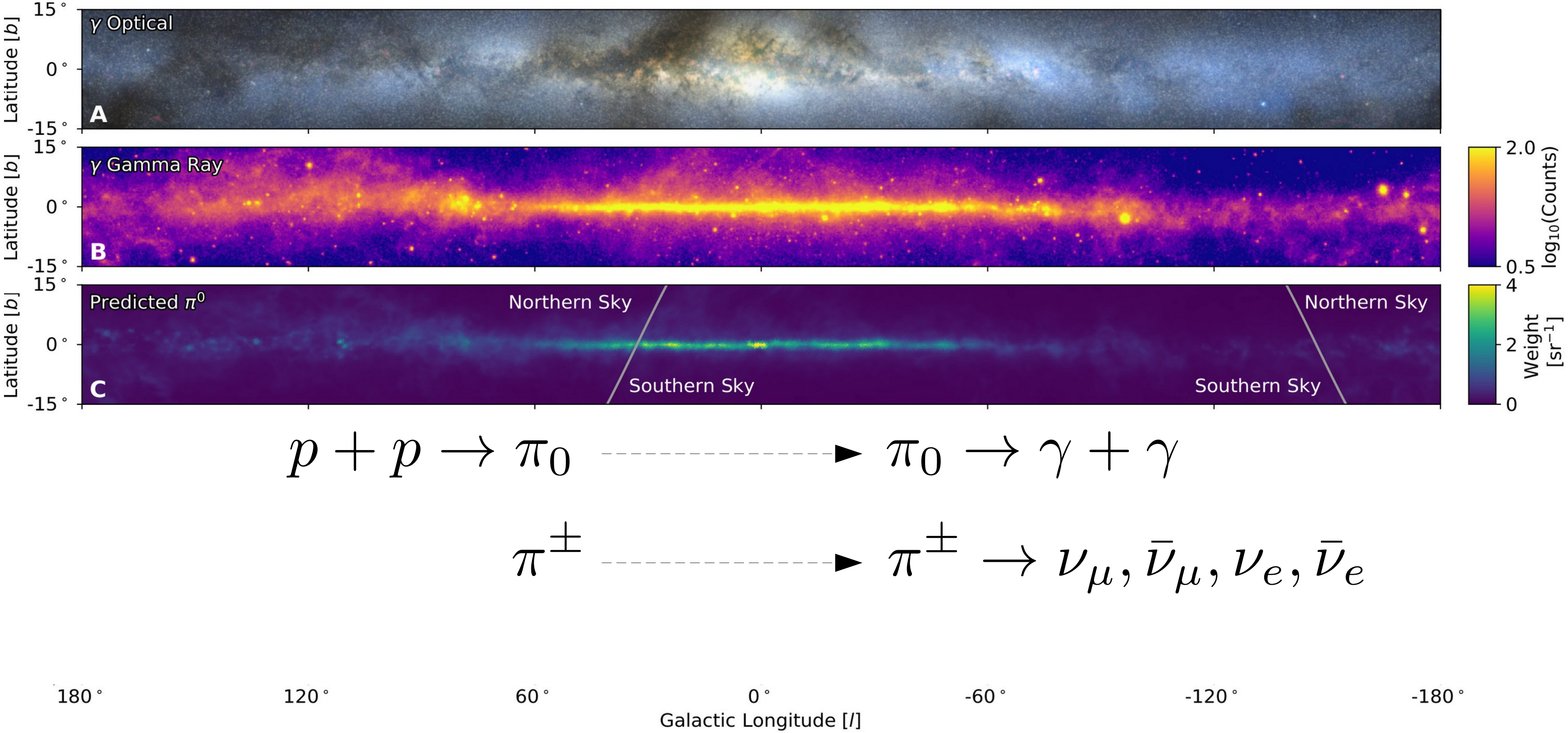
$$p + p \rightarrow \pi_0 \dashrightarrow \pi_0 \rightarrow \underbrace{\gamma + \gamma}_{\text{Gamma rays from the GP}}$$

Cosmic rays

Interstellar medium (aligned with GP)

IceCube Collab., *Science* 2023

High-energy neutrinos from the Galactic Plane

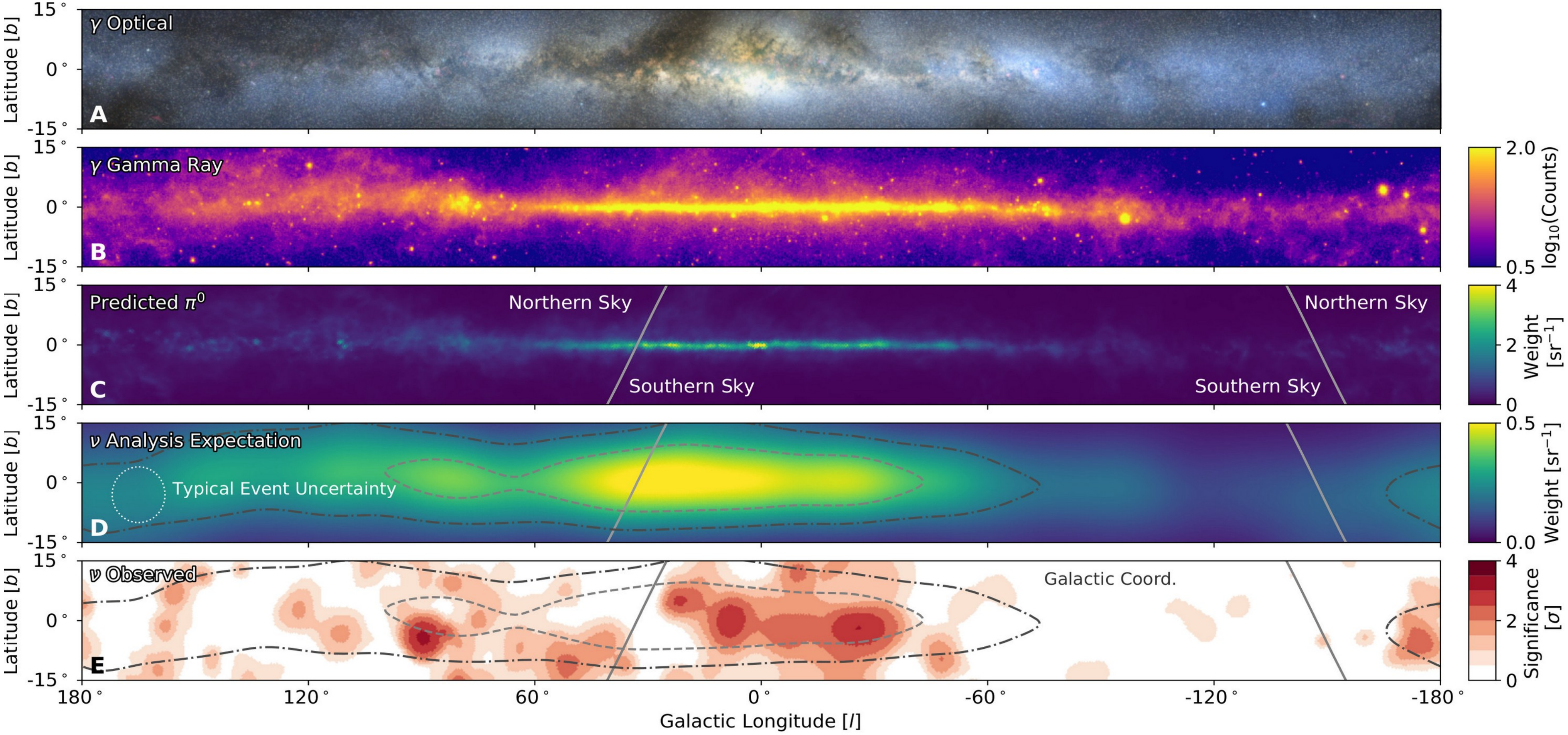


$$p + p \rightarrow \pi_0 \dashrightarrow \pi_0 \rightarrow \gamma + \gamma$$

$$\pi^{\pm} \dashrightarrow \pi^{\pm} \rightarrow \nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$$

IceCube Collab., *Science* 2023

High-energy neutrinos from the Galactic Plane



IceCube Collab., *Science* 2023

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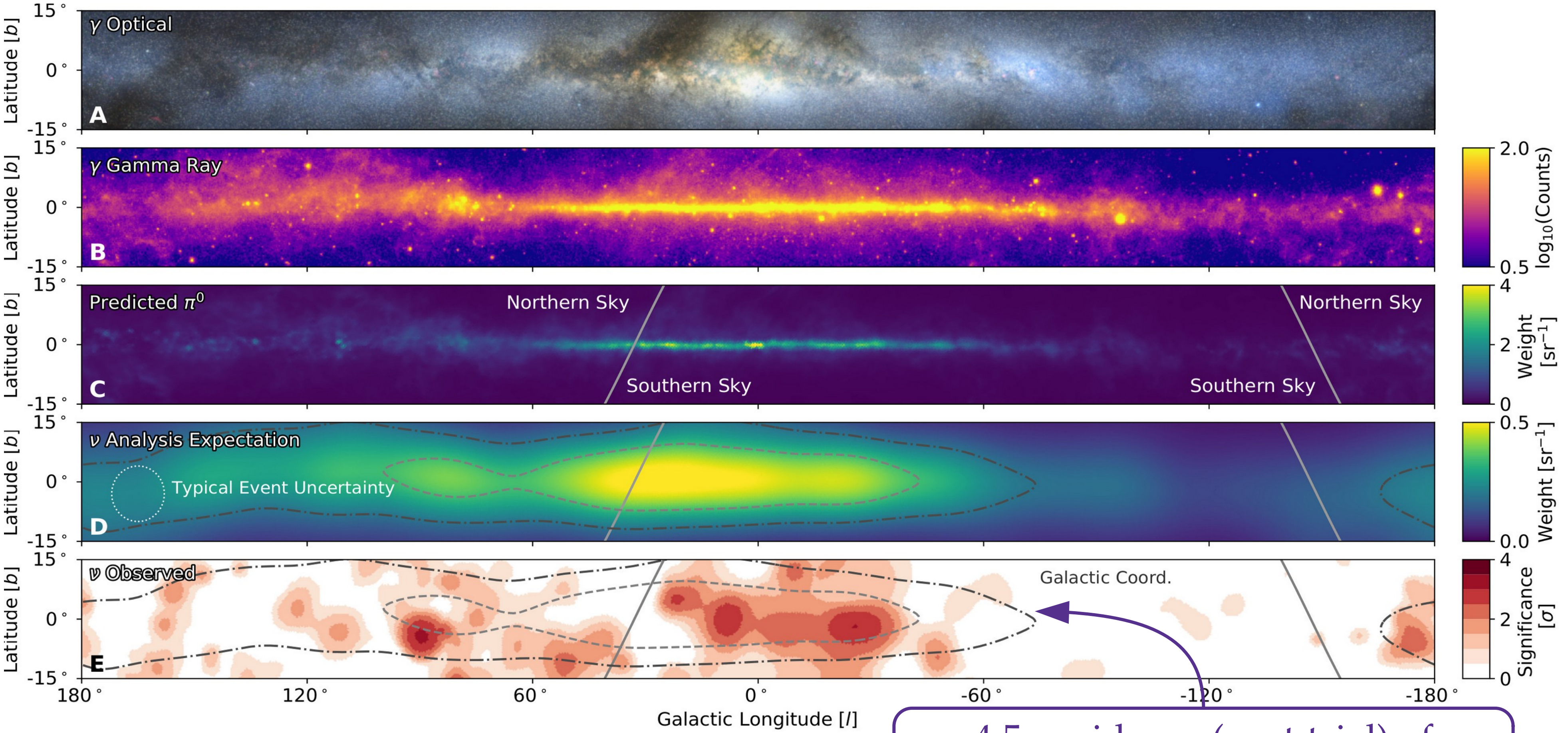

4.5σ evidence (post-trial) of diffuse flux of > TeV ν from the GP

IceCube Collab., *Science* 2023

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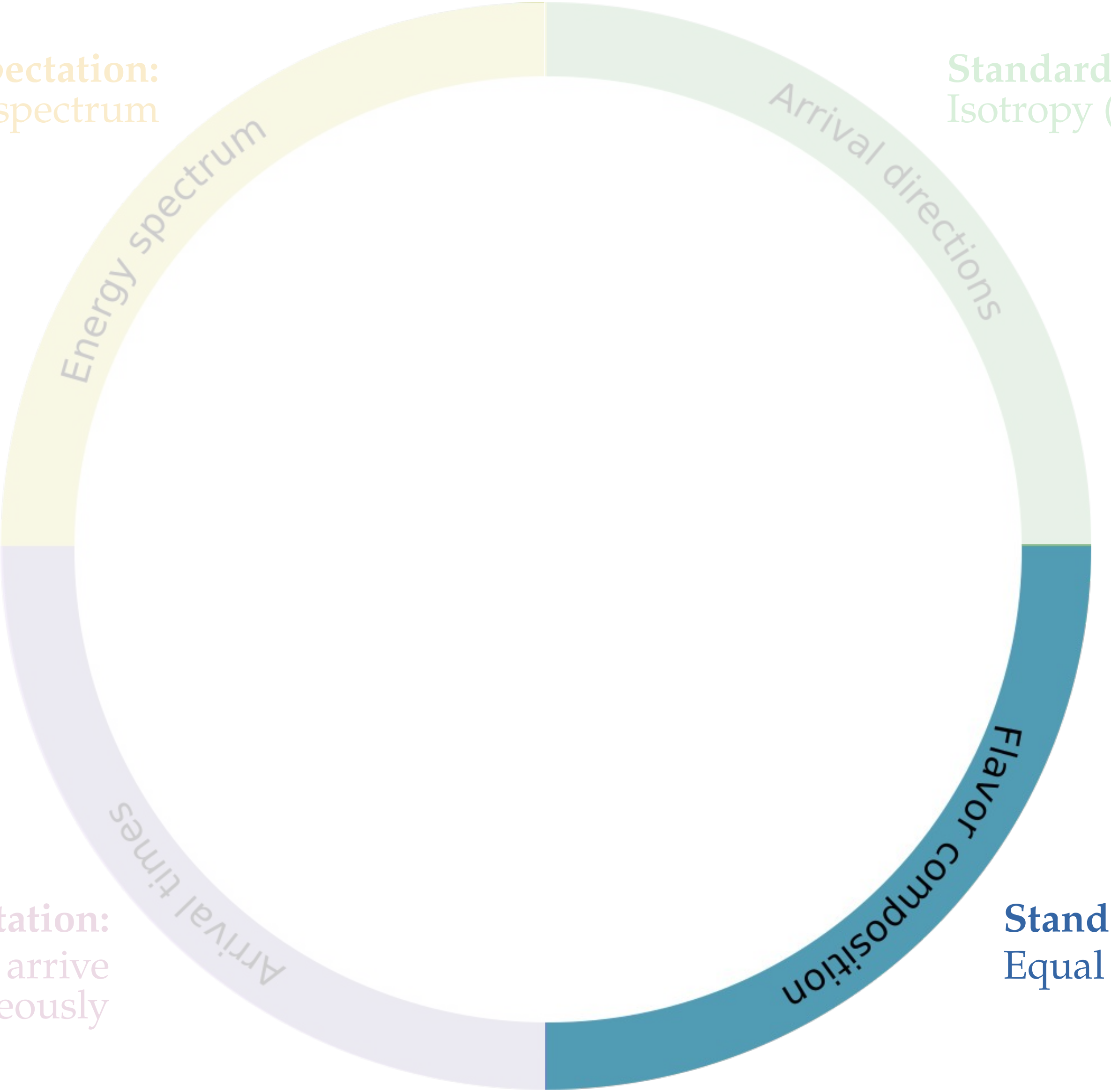

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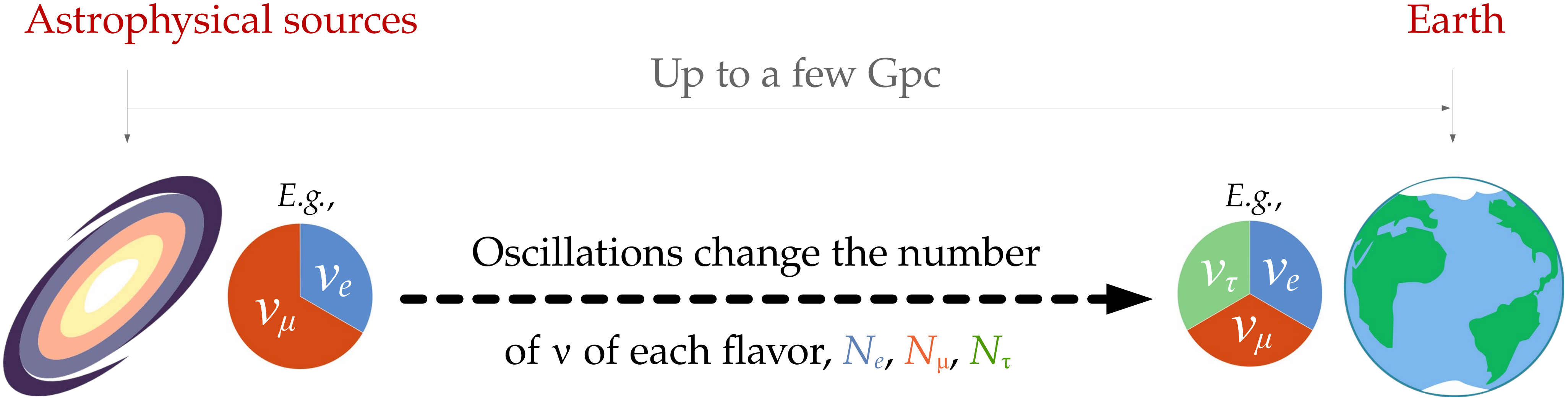


Astrophysical sources

Earth

Up to a few Gpc

Oscillations change the number

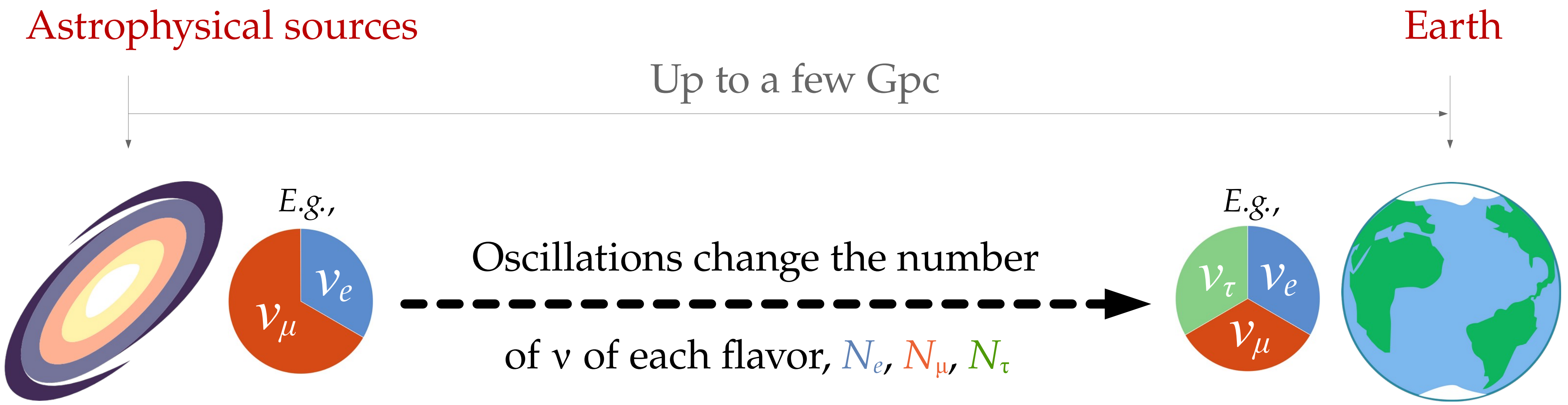
of ν of each flavor, N_e, N_μ, N_τ

Different production mechanisms yield different flavor ratios:

$$(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}}) \equiv (N_{e,\mathrm{S}}, N_{\mu,\mathrm{S}}, N_{\tau,\mathrm{S}})/N_{\mathrm{tot}}$$

Flavor ratios at Earth ($\alpha = e, \mu, \tau$):

$$f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} P_{\nu_\beta\to\nu_\alpha} f_{\beta,\mathrm{S}}$$



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Standard oscillations
or
new physics

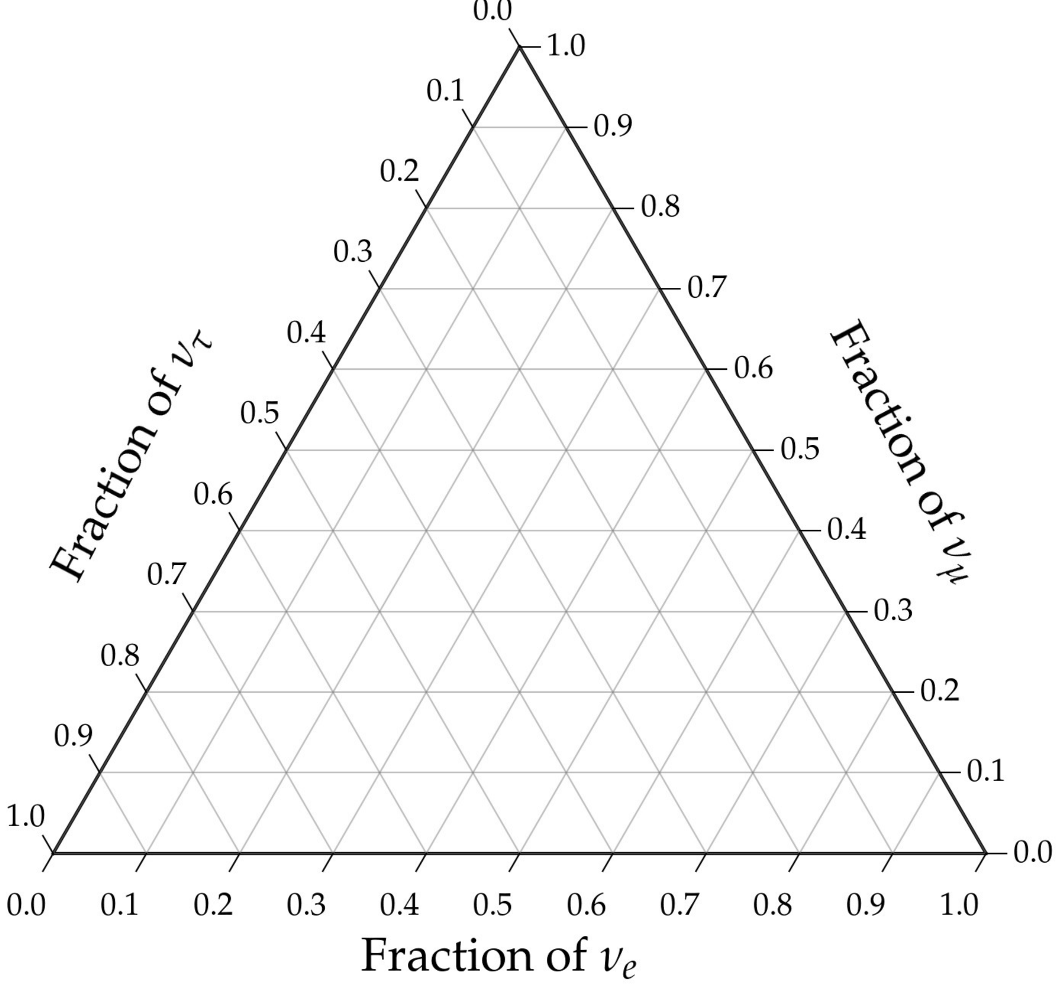
Quick aside: how to read a ternary plot

Assumes underlying unitarity – sum of projections on each axis is 1

How to read it:

Follow the tilt of the tick marks

Always in this order: (f_e, f_μ, f_τ)



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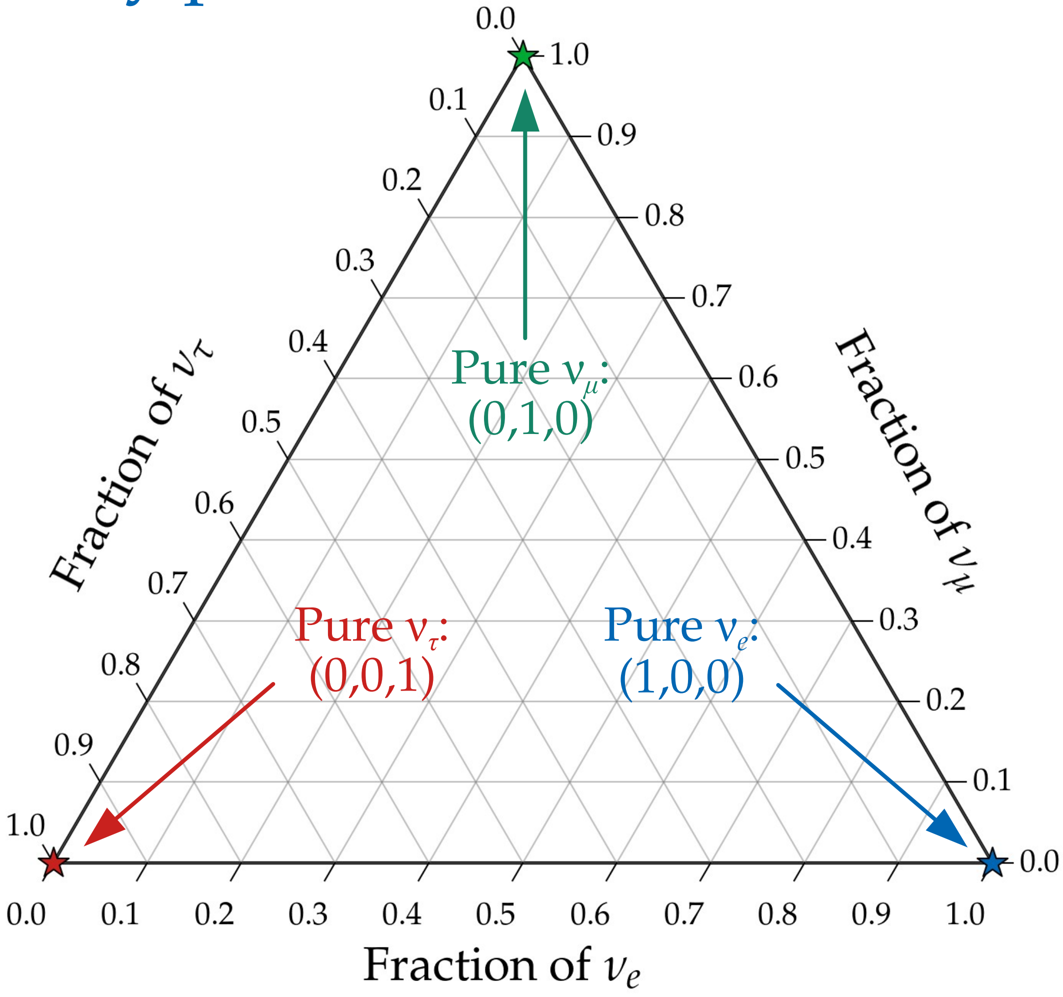

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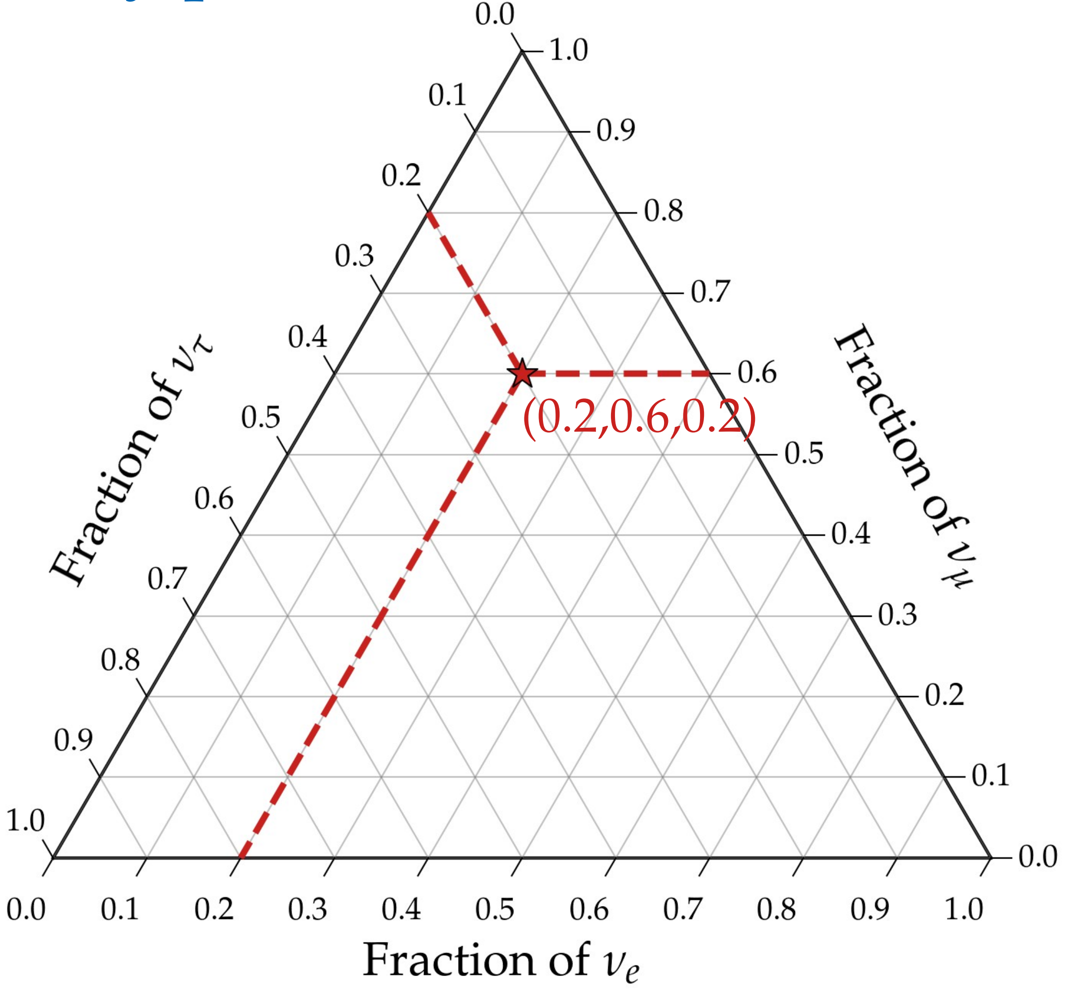

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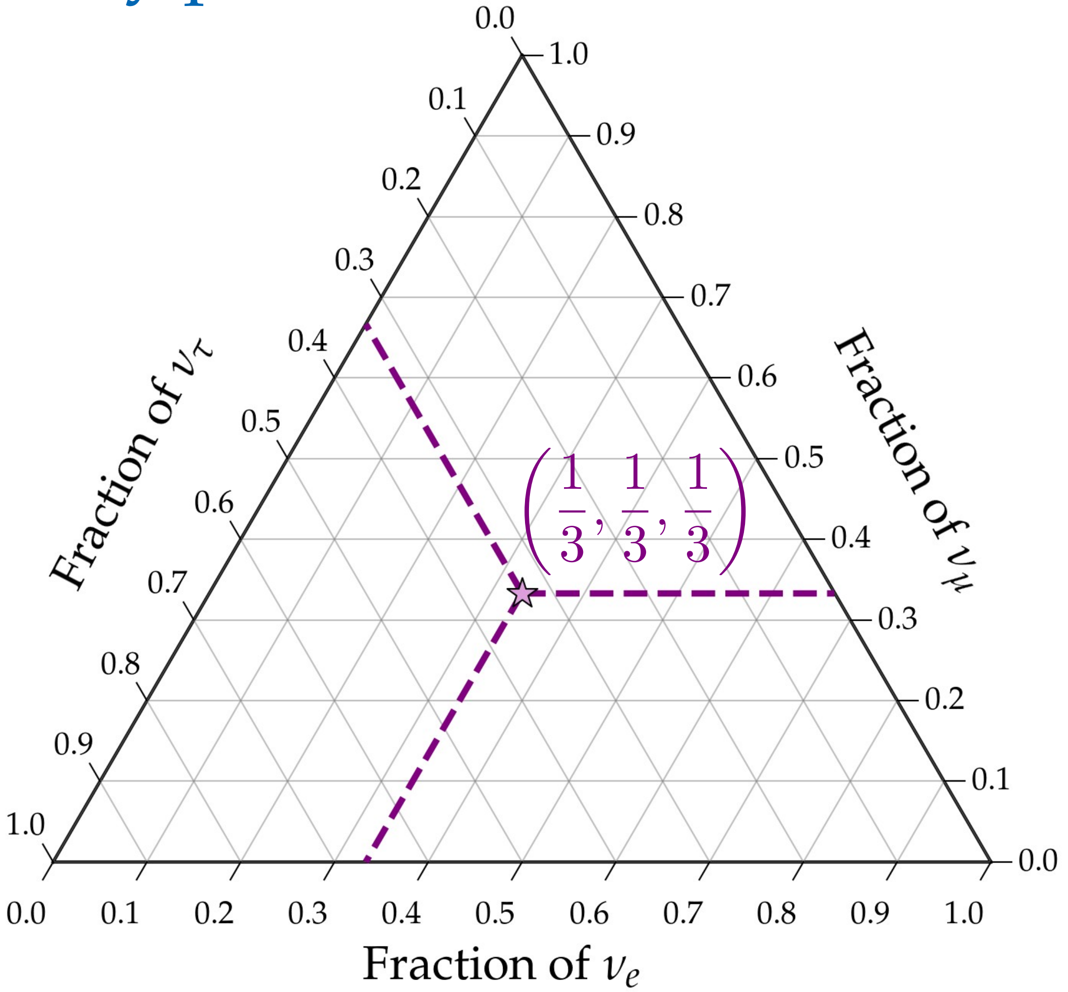
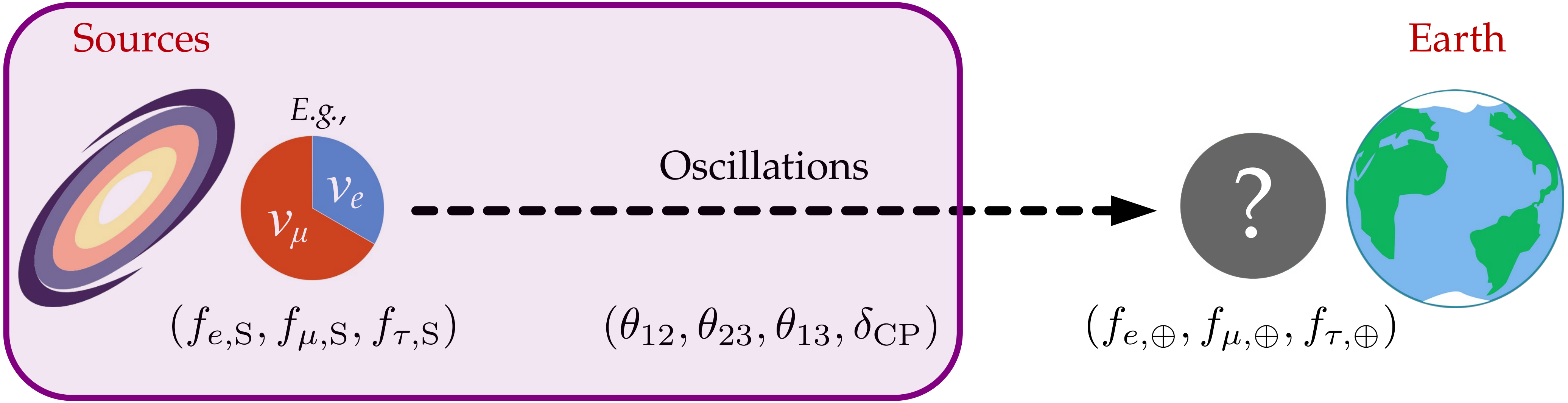


From sources to Earth: we learn what to expect when measuring $f_{\alpha,\oplus}$



Sources

E.g.,

$(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}})$

Oscillations

$(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\mathrm{CP}})$

Earth

$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$

One likely TeV–PeV ν production scenario:

$p + \gamma \longrightarrow \pi^+ \longrightarrow \mu^+ + \nu_\mu$ followed by $\mu^+ \longrightarrow e^+ + \nu_e + \bar{\nu}_\mu$

Full π decay chain

$(1/3 : 2/3 : 0)_\mathrm{S}$

Note: ν and $\bar{\nu}$ are (so far) indistinguishable
in neutrino telescopes

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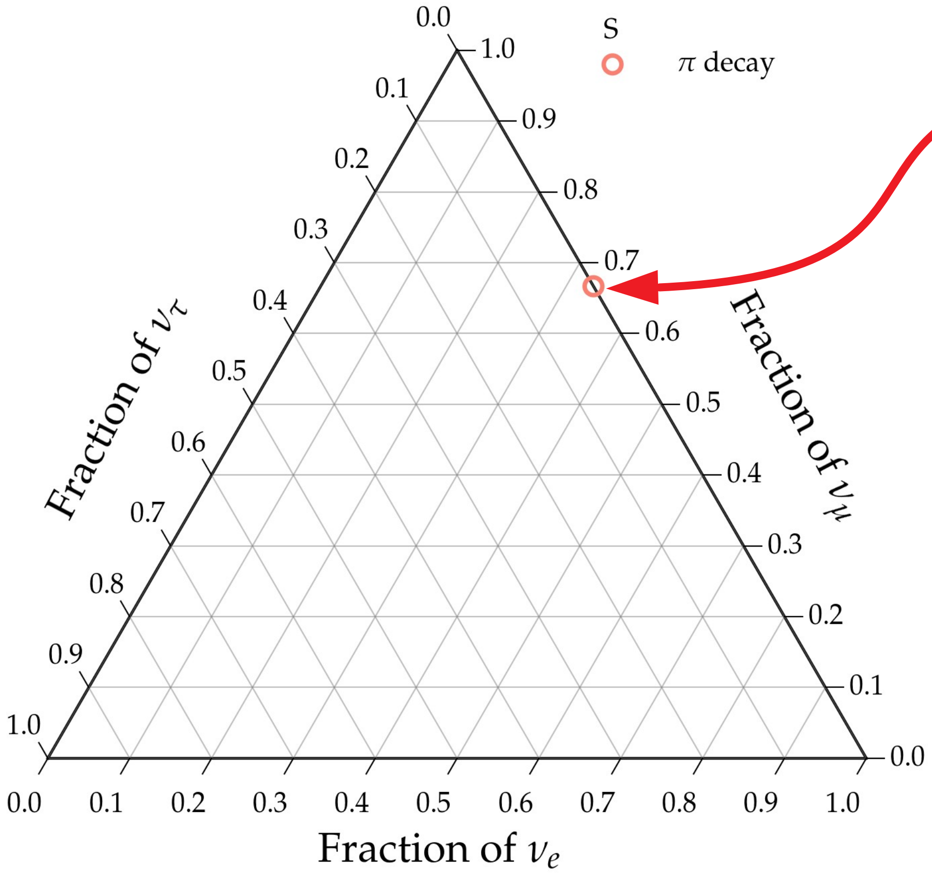

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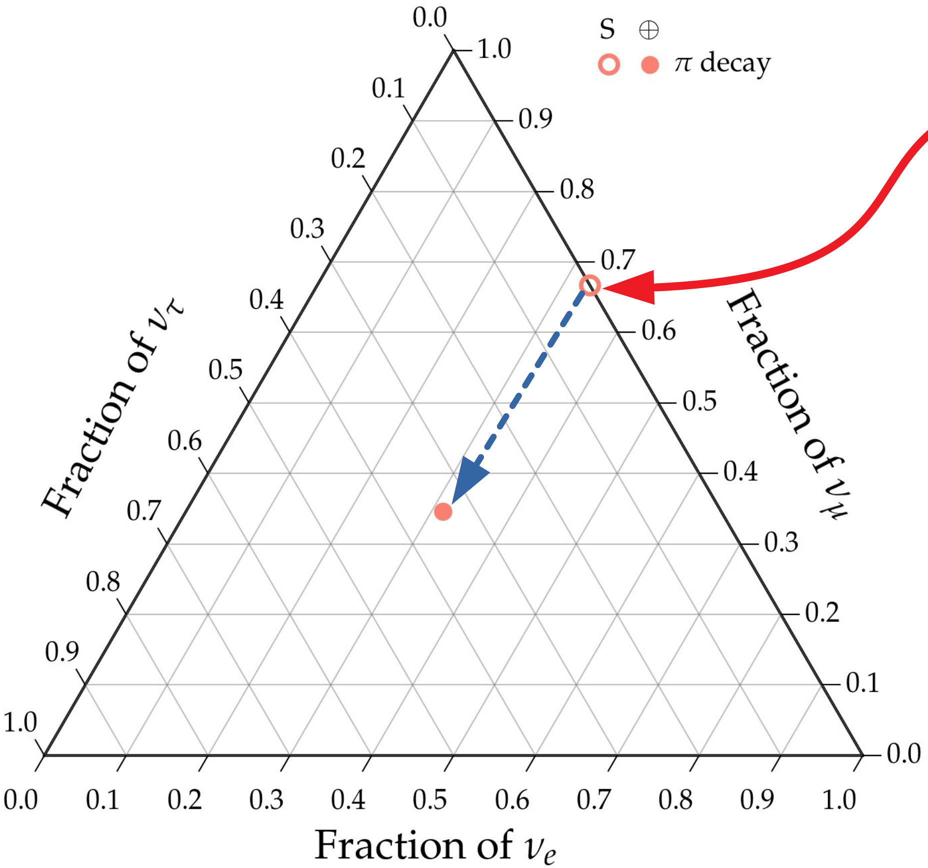

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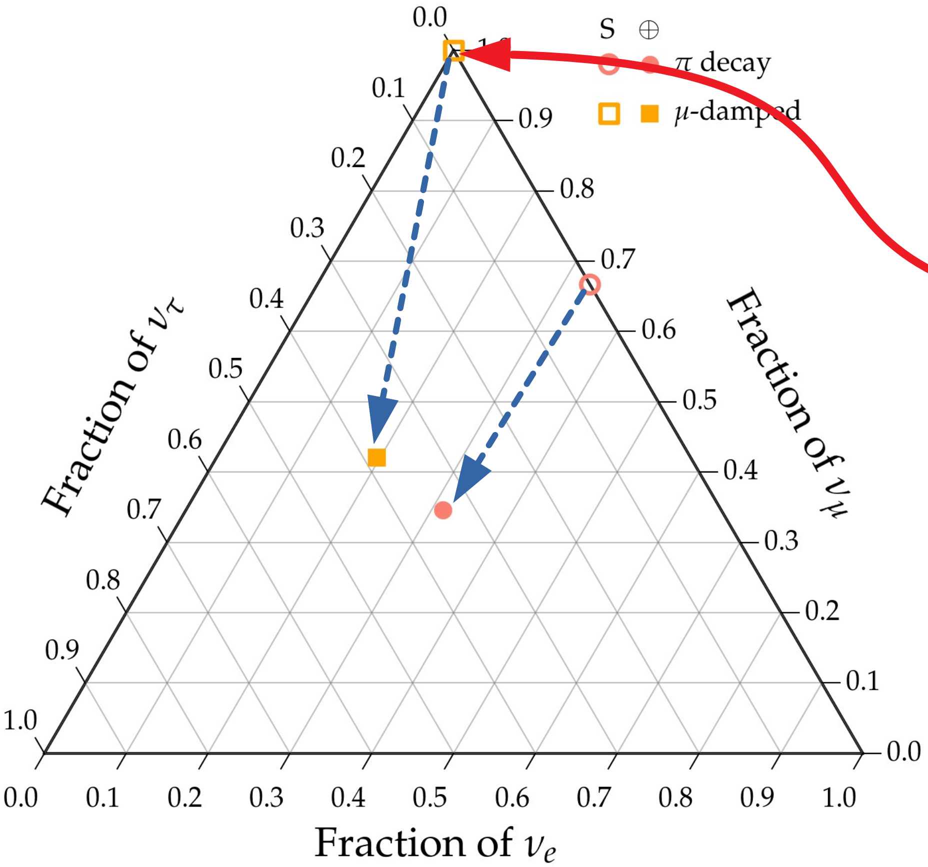

Full π decay chain

$(1/3:2/3:0)_\mathrm{S}$

Muon damped

$(0:1:0)_\mathrm{S}$

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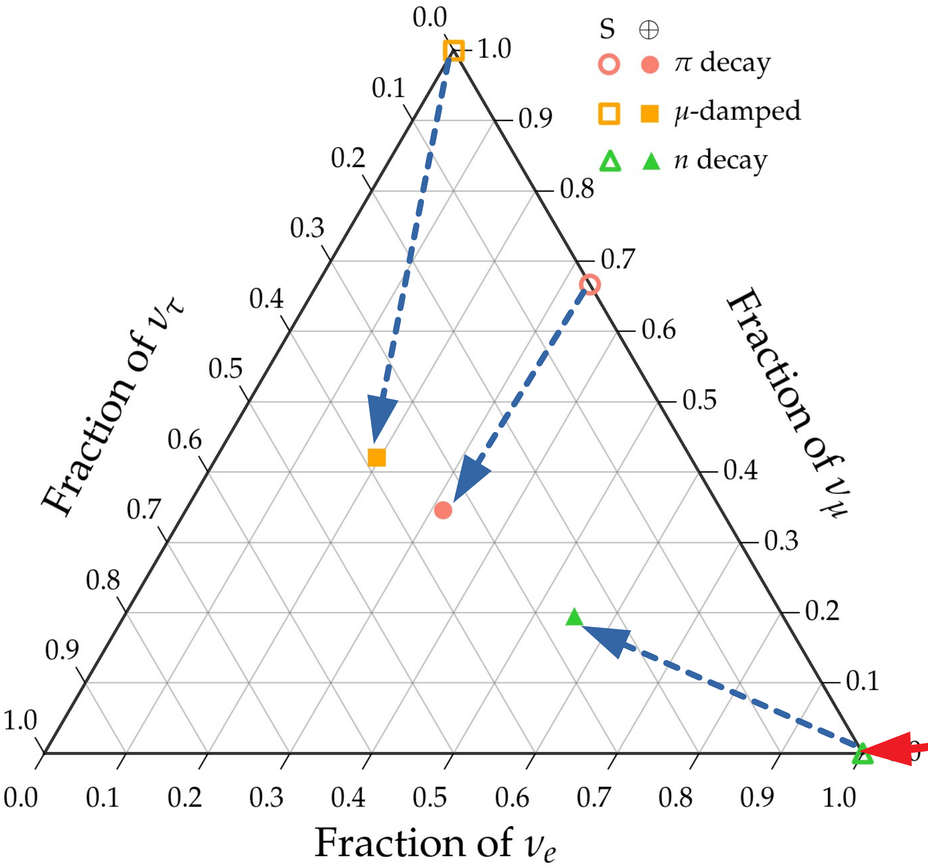


Full π decay chain

(1/3:2/3:0)$_S$

Muon damped

(0:1:0)$_S$

Neutron decay

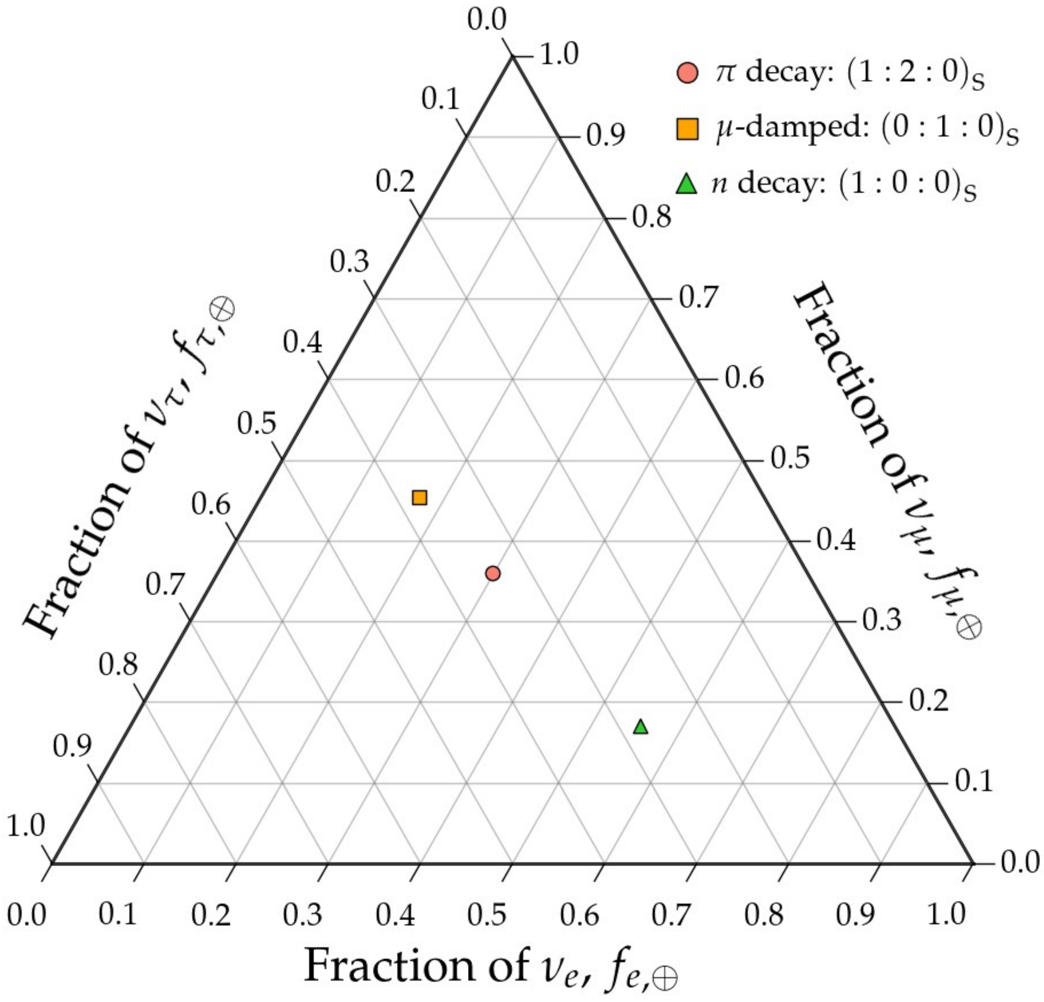
(1:0:0)$_S$

Note: ν and $\bar{\nu}$ are (so far) indistinguishable in neutrino telescopes

Measuring flavor composition: 2015–2020

IceCube Collab., *EPJC* 2022
IceCube Collab., *PRD* 2019
IceCube Collab., *ApJ* 2015

Measuring flavor composition: 2015–2020



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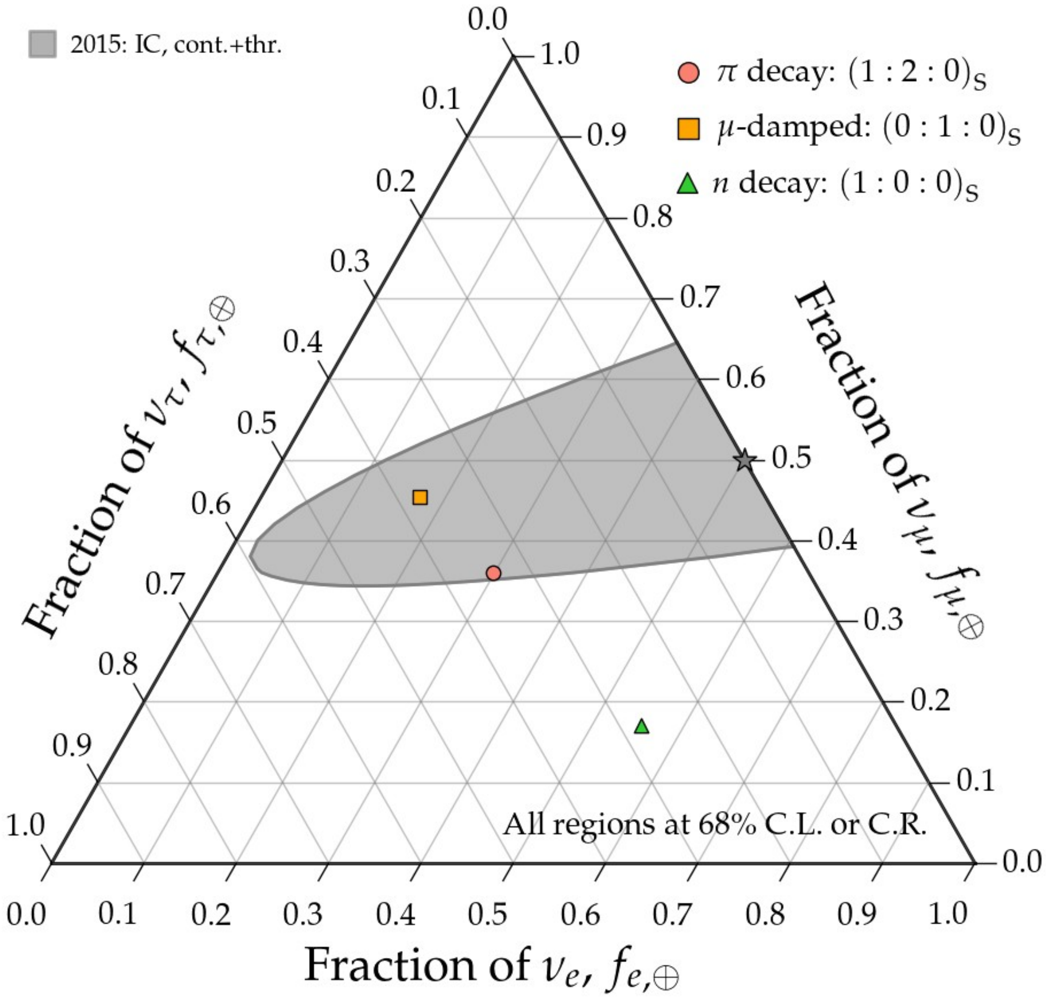

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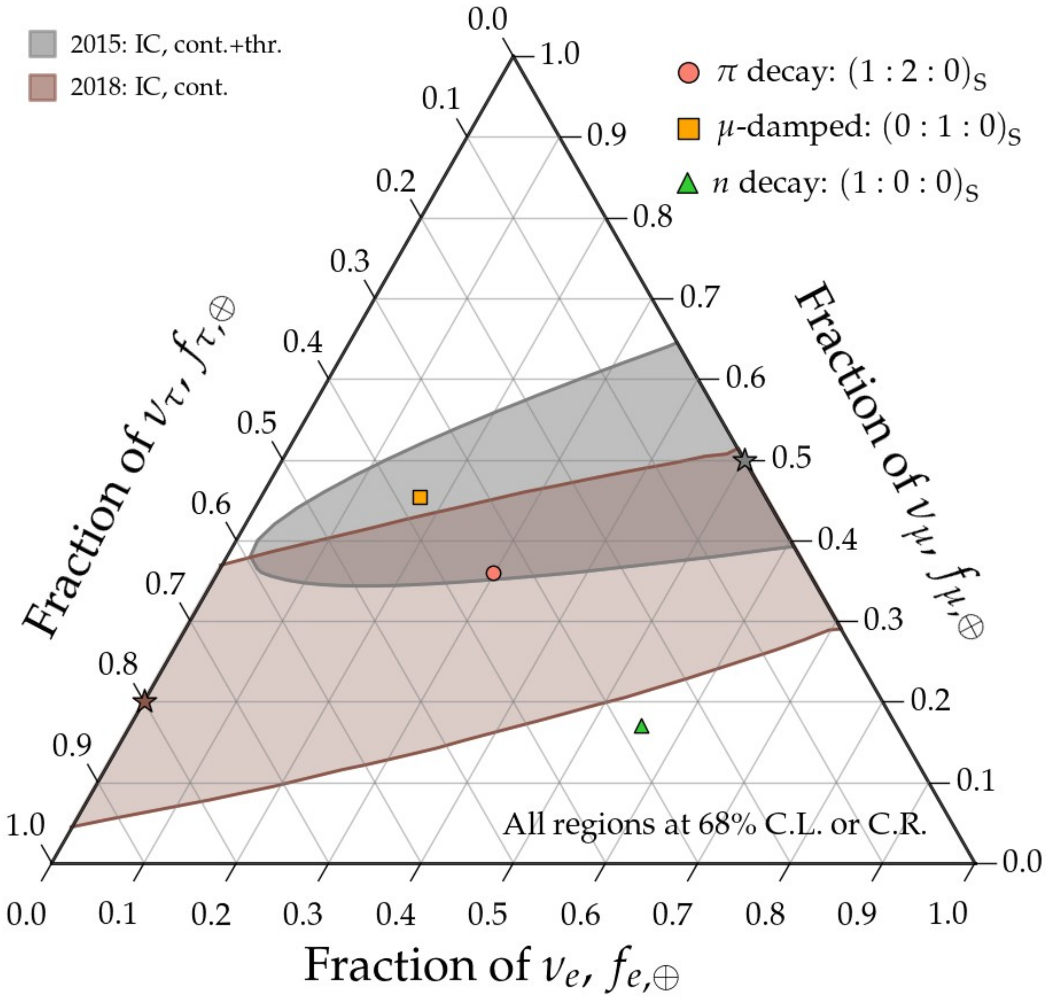

IceCube Collab., *EPJC* 2022
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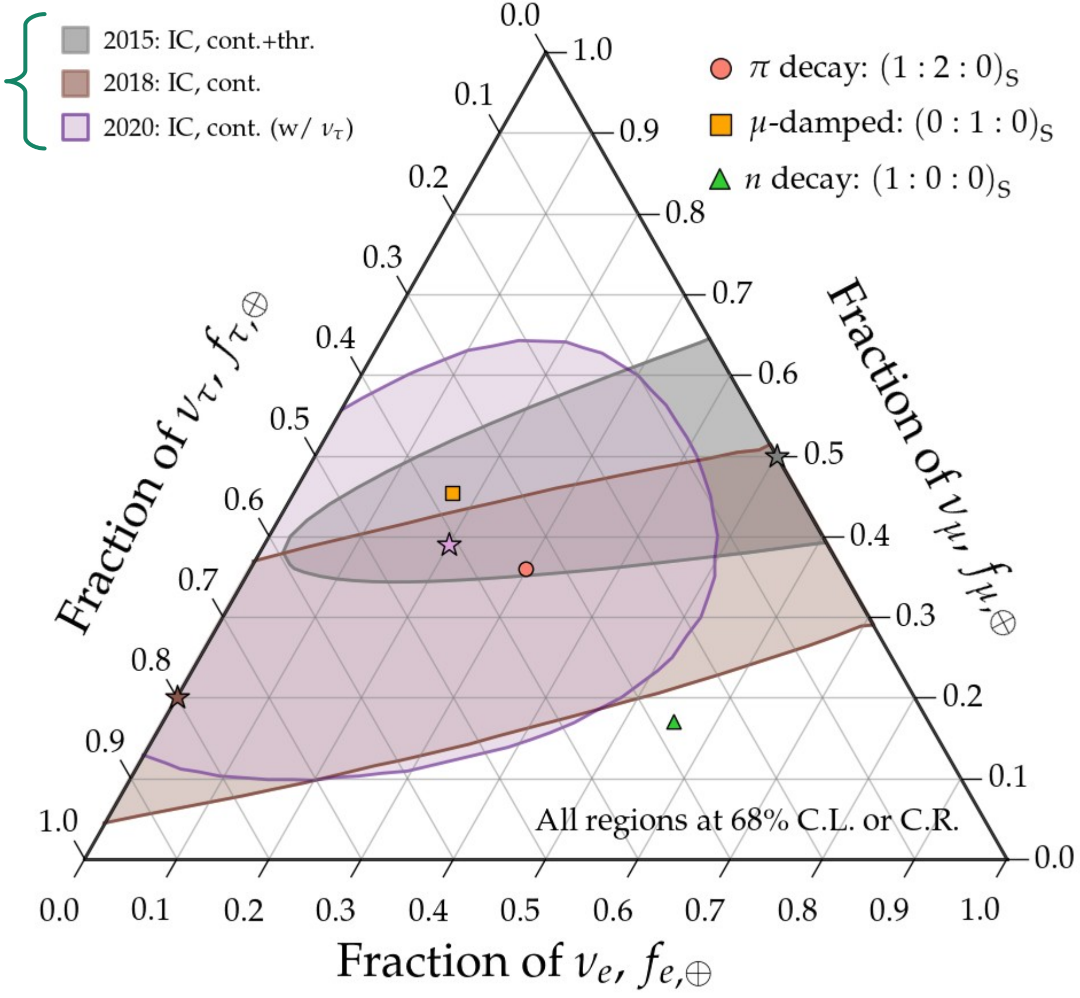
IceCube Collab., *ApJ* 2015

Measuring flavor composition: 2015–2020

Based on real data



IceCube Collab., *EPJC* 2022
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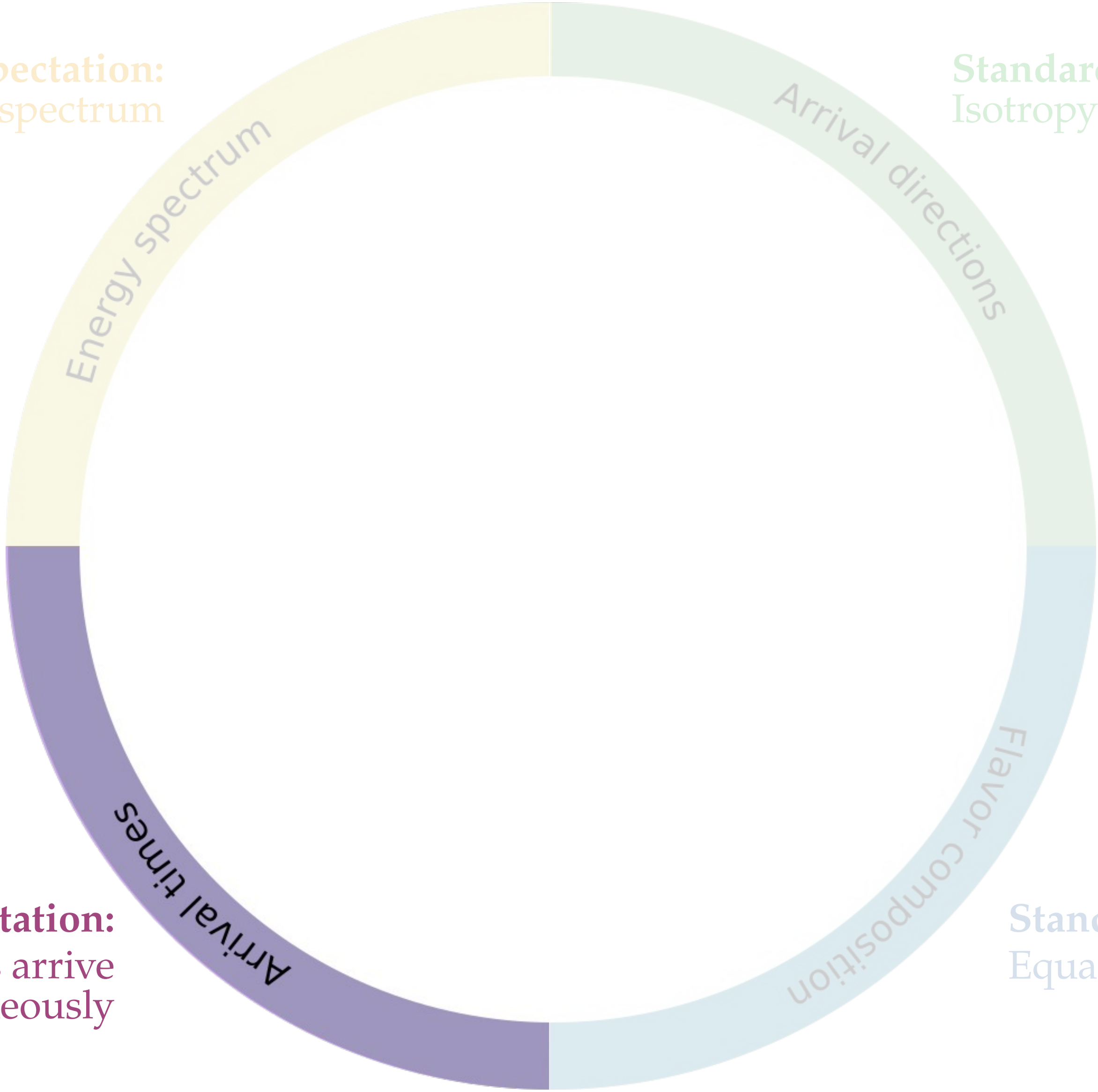

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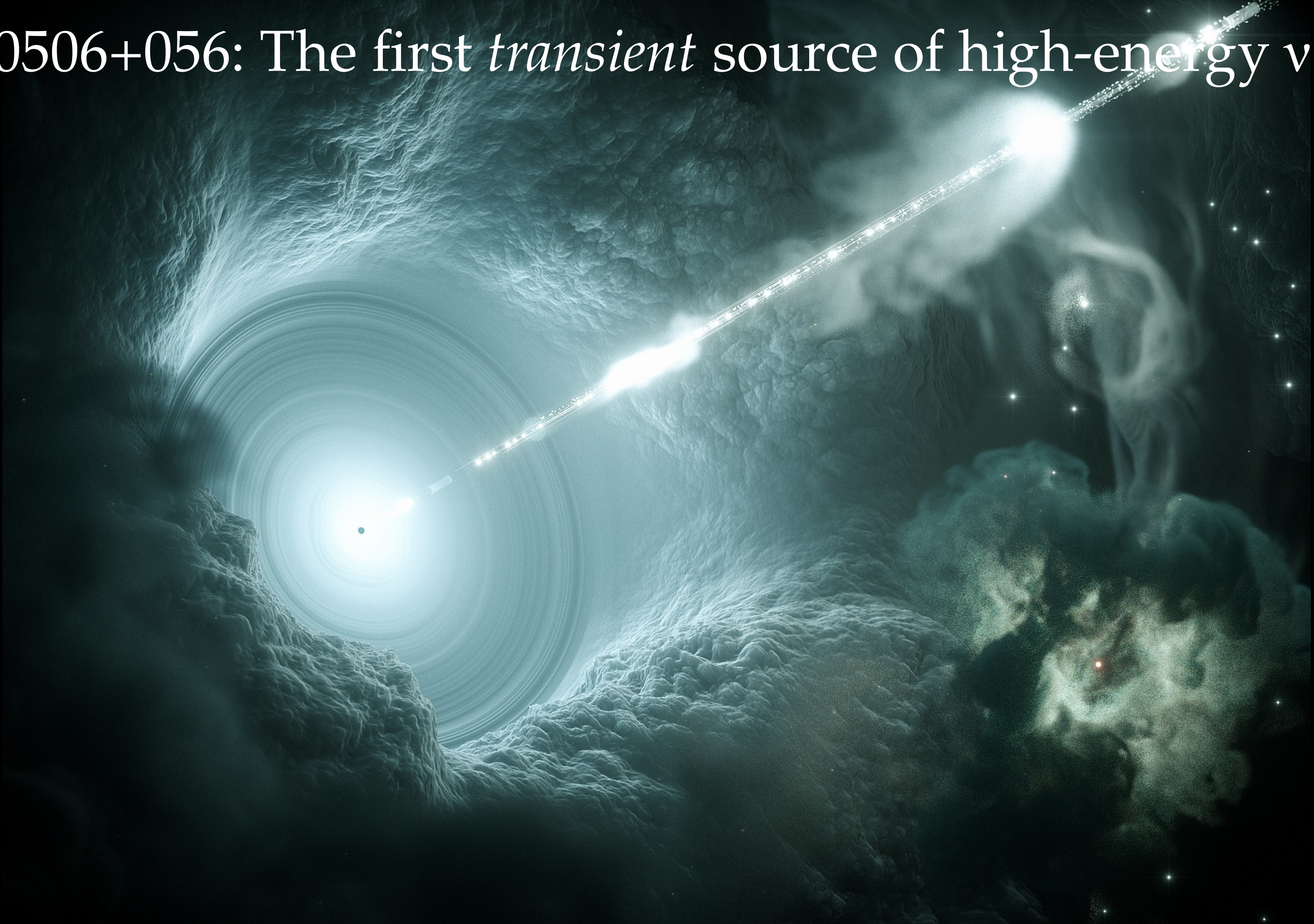
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

TXS 0506+056: The first *transient* source of high-energy ν

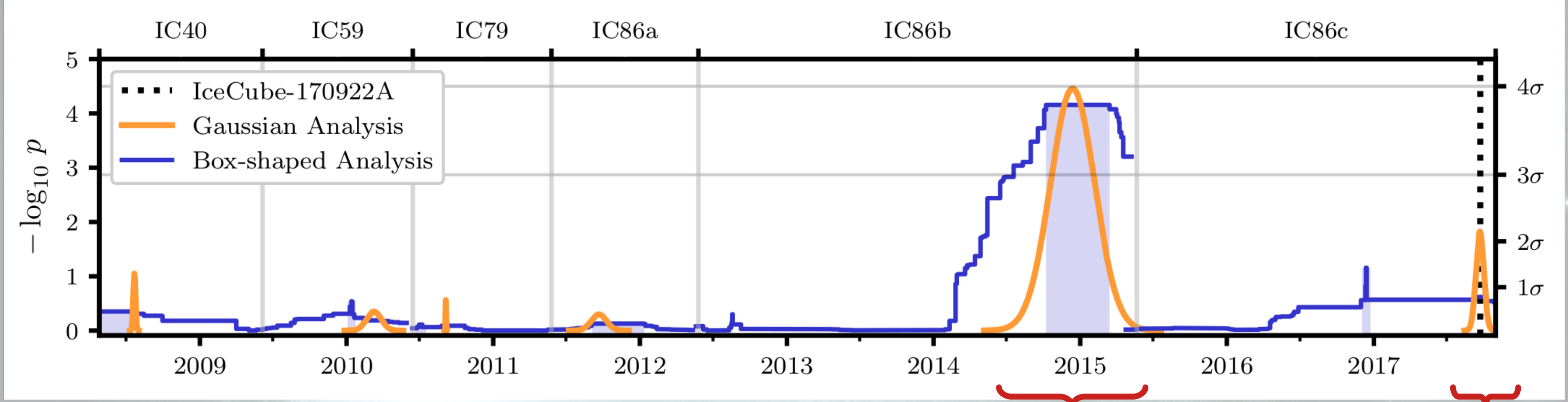


DESY

TXS 0506+056: The first *transient* source of high-energy ν

Blazar TXS 0506+056:

IceCube, *Science* 2018



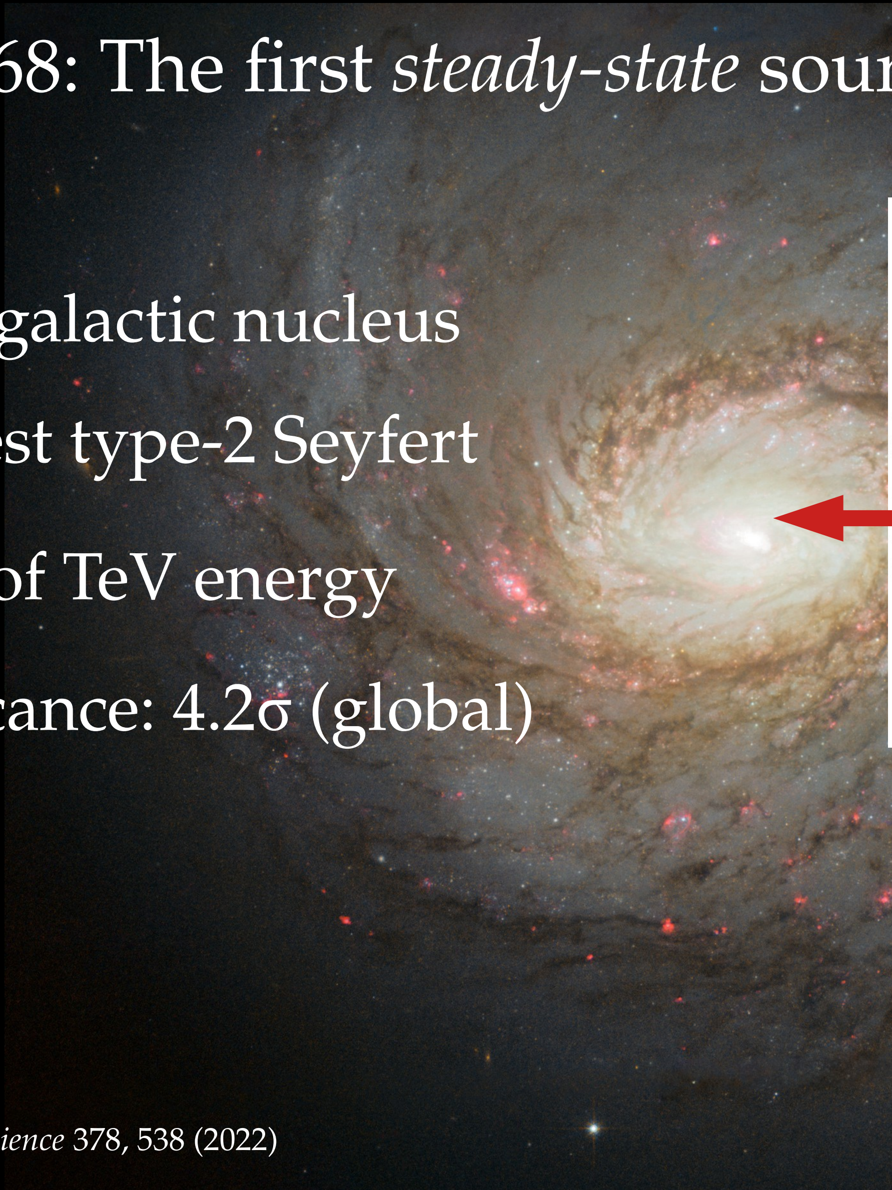
After re-analysis (2101.09836),
significance dropped
from $p=7\times10^{-5}$ to $p=8\times10^{-3}$

2014–2015: 13±5 ν flare, no X-ray flare
3.5σ significance of correlation (post-trial)

2017: one 290-TeV ν + X-ray flare
1.4σ significance of correlation

Combined (pre-trial): 4.1σ

NGC1068: The first *steady-state* source of high-energy ν

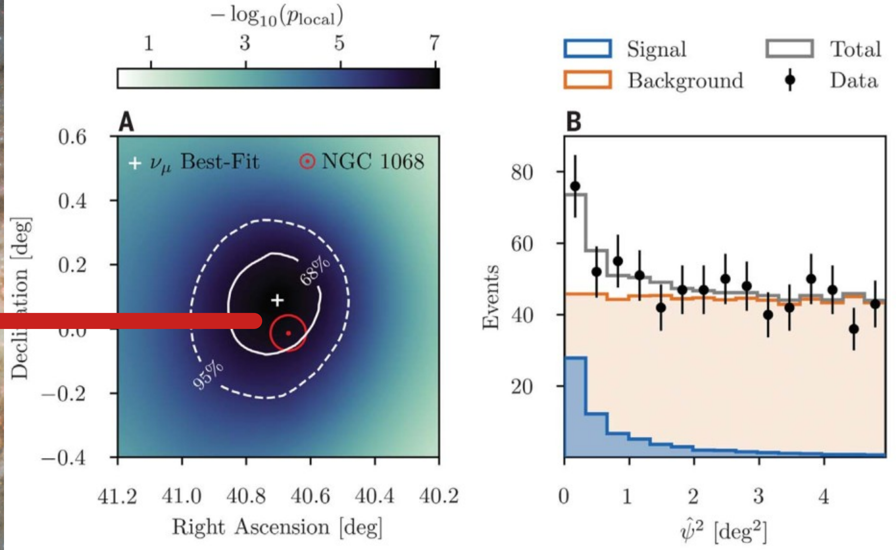


Active galactic nucleus

Brightest type-2 Seyfert

79^{+22}_{-20} ν of TeV energy

Significance: 4.2σ (global)



IceCube Collab., *Science* 378, 538 (2022)

Hubble Space Telescope,
NASA, ESA & A. van der Hoeven

Today
TeV–PeV ν

Astro: Find & understand sources

Particle: Turn predictions into tests

Key developments:

Larger statistics

Better reconstruction

Smaller astrophysical uncertainties

High-energy neutrino physics

today

Fundamental physics with high-energy cosmic neutrinos

- Numerous new ν physics effects grow as $\sim \kappa_n \cdot E^n \cdot L$

- So we can probe $\kappa_n \sim 4 \cdot 10^{-47}\, (E/\mathrm{PeV})^{-n}\, (L/\mathrm{Gpc})^{-1}\, \mathrm{PeV}^{1-n}$

- Improvement over limits using atmospheric ν: $\kappa_0 < 10^{-29}$ PeV, $\kappa_1 < 10^{-33}$

Fundamental physics with high-energy cosmic neutrinos

- Numerous new ν physics effects grow as $\sim \kappa_n \cdot E^n \cdot L$ $\Bigg\}$

  E.g.,
  n = -1: neutrino decay
  n = 0: CPT-odd Lorentz violation
  n = +1: CPT-even Lorentz violation

- So we can probe $\kappa_n \sim 4 \cdot 10^{-47}\,(E/\mathrm{PeV})^{-n}\,(L/\mathrm{Gpc})^{-1}\,\mathrm{PeV}^{1-n}$

- Improvement over limits using atmospheric ν: $\kappa_0 < 10^{-29}$ PeV, $\kappa_1 < 10^{-33}$

DM-ν interaction
DE-ν interaction
Lorentz+CPT violation
Neutrino decay
Heavy relics
Long-range interactions
DM annihilation
Secret νν interactions
Supersymmetry
DM decay
Sterile ν
Effective operators
Leptoquarks
Boosted DM
NSI
Extra dimensions
Superluminal ν
Monopoles

Note: Not an exhaustive list

Acts at production

- Heavy relics
- DM annihilation
- DM decay
- Sterile ν
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- NSI

- DM-ν interaction
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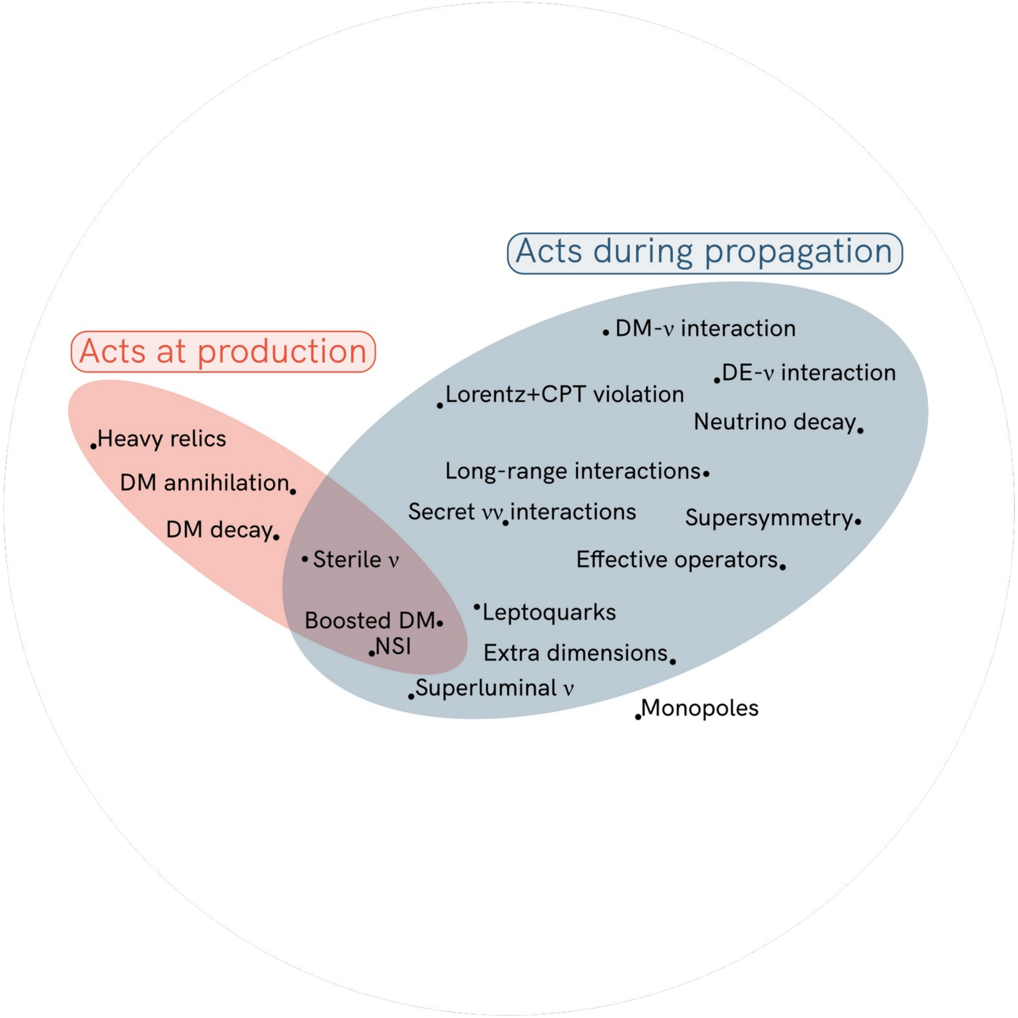

Acts at production

Acts during propagation

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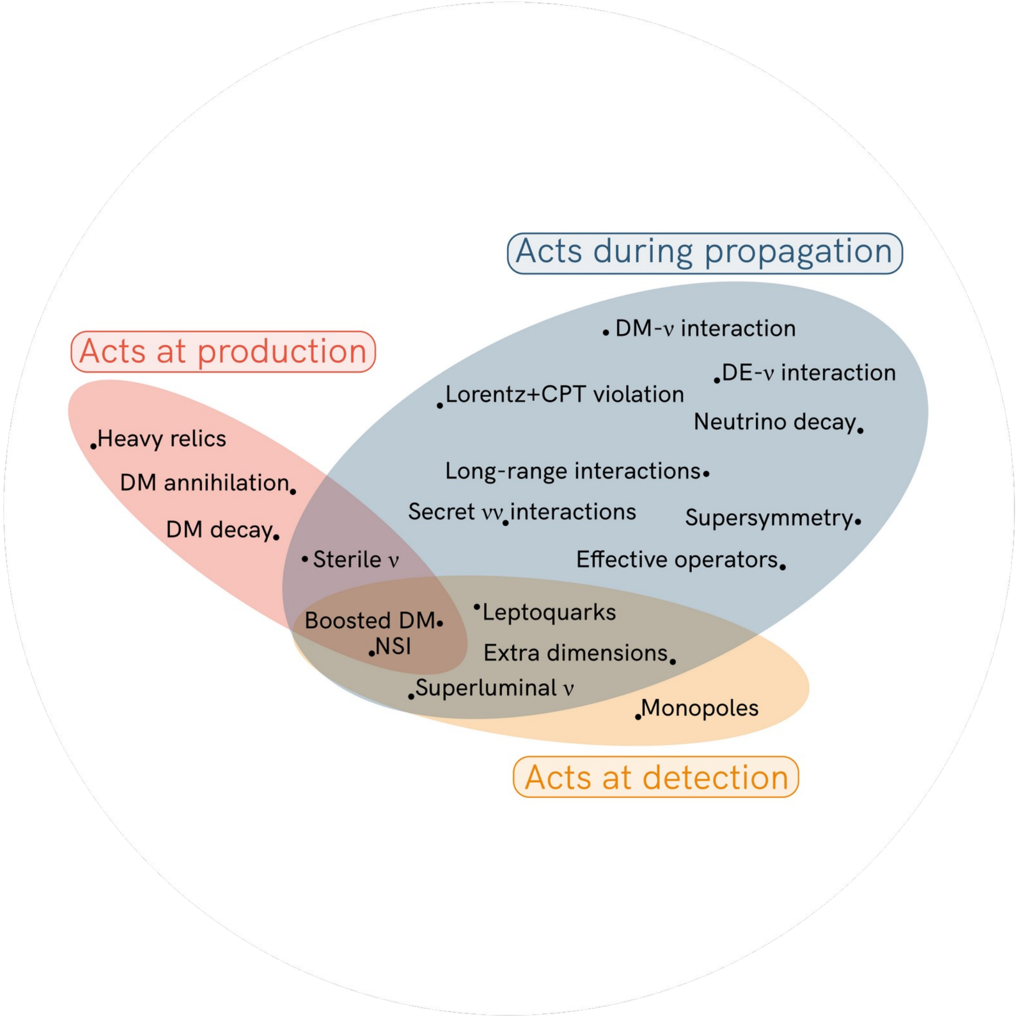
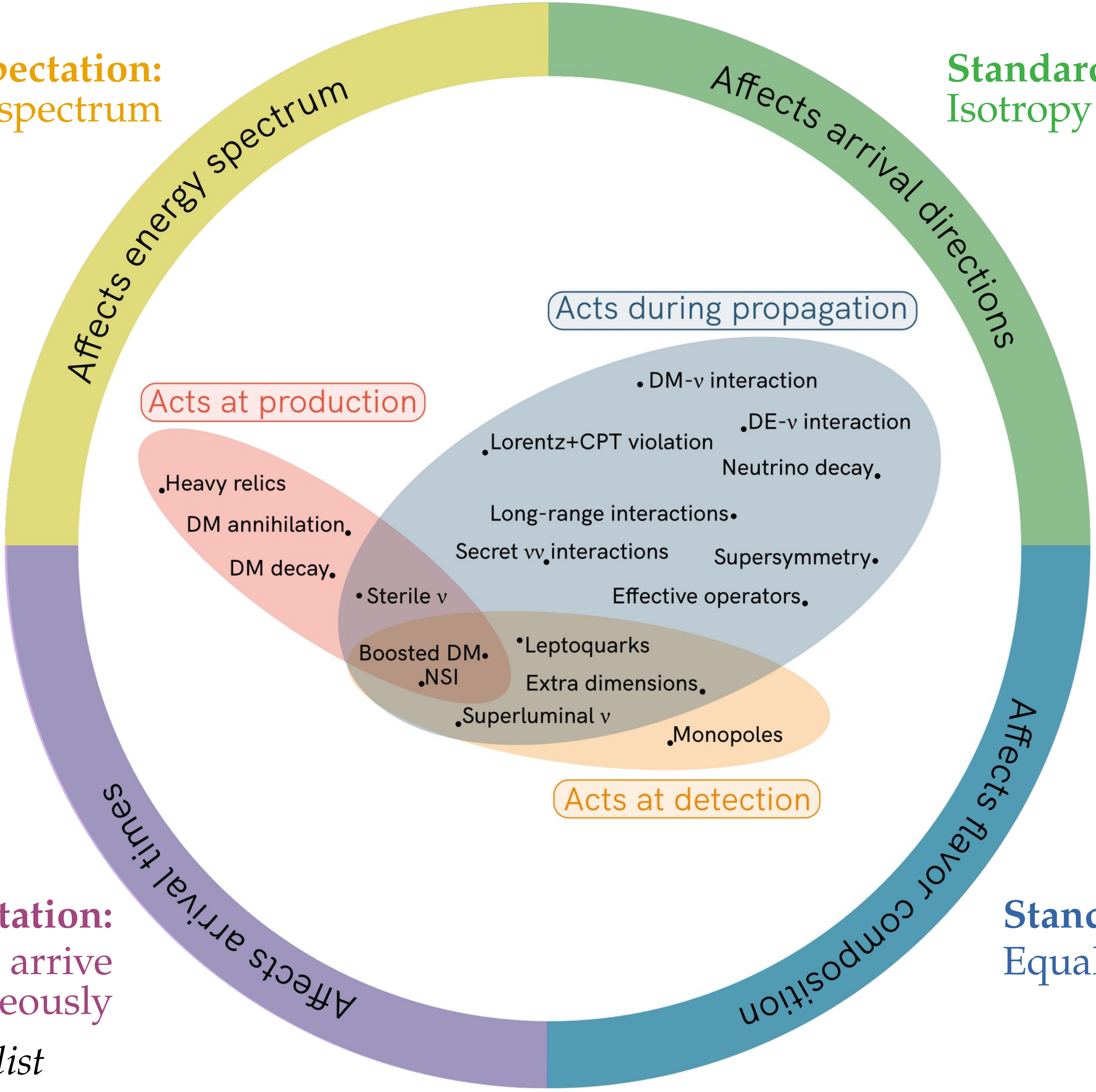


Note: Not an exhaustive list

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



Affects energy spectrum

Affects arrival directions

Affects flavor composition

Affects arrival times

Acts during propagation

Acts at production

Acts at detection

- DM-ν interaction
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ν and γ from transients arrive simultaneously

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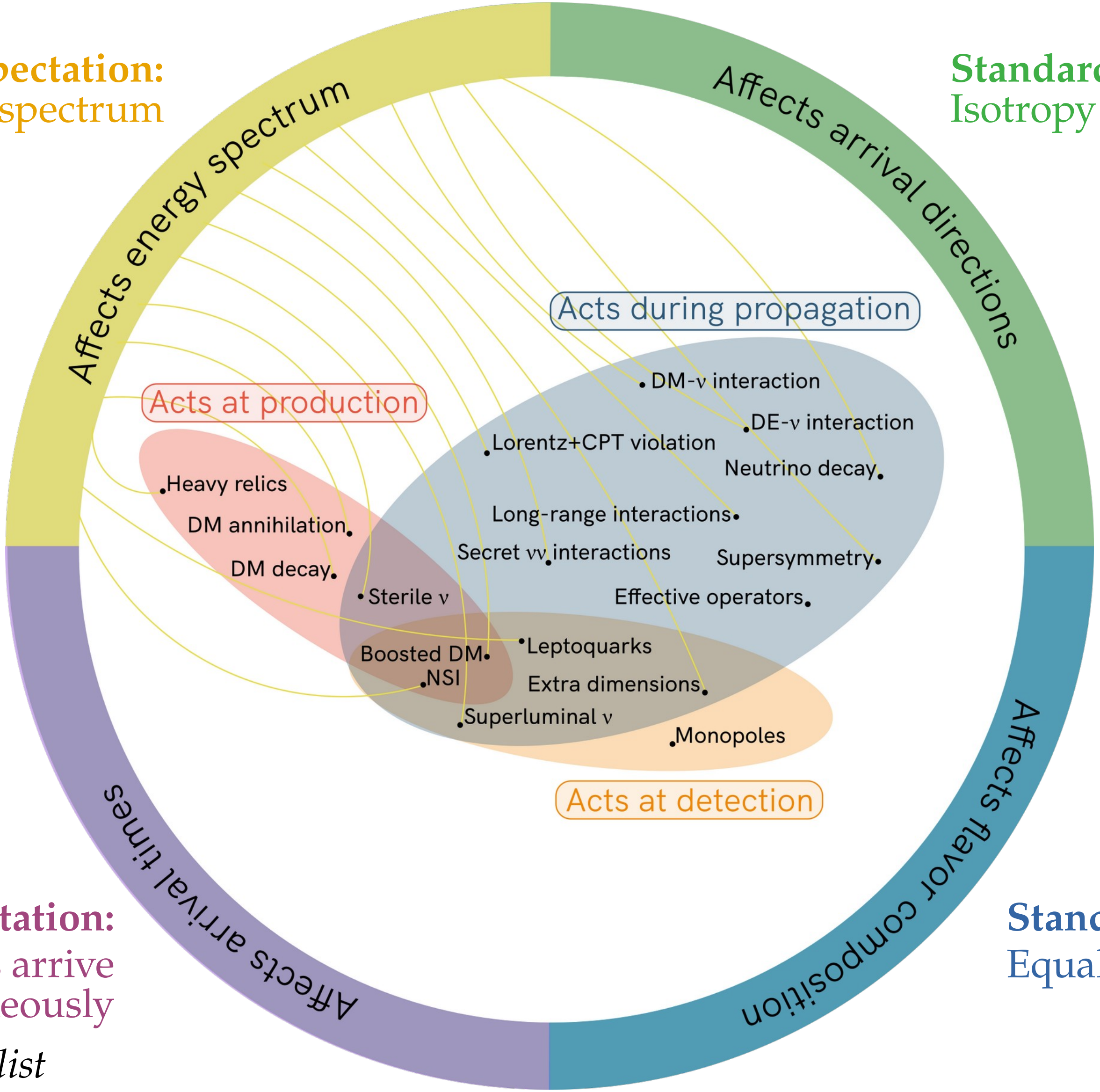

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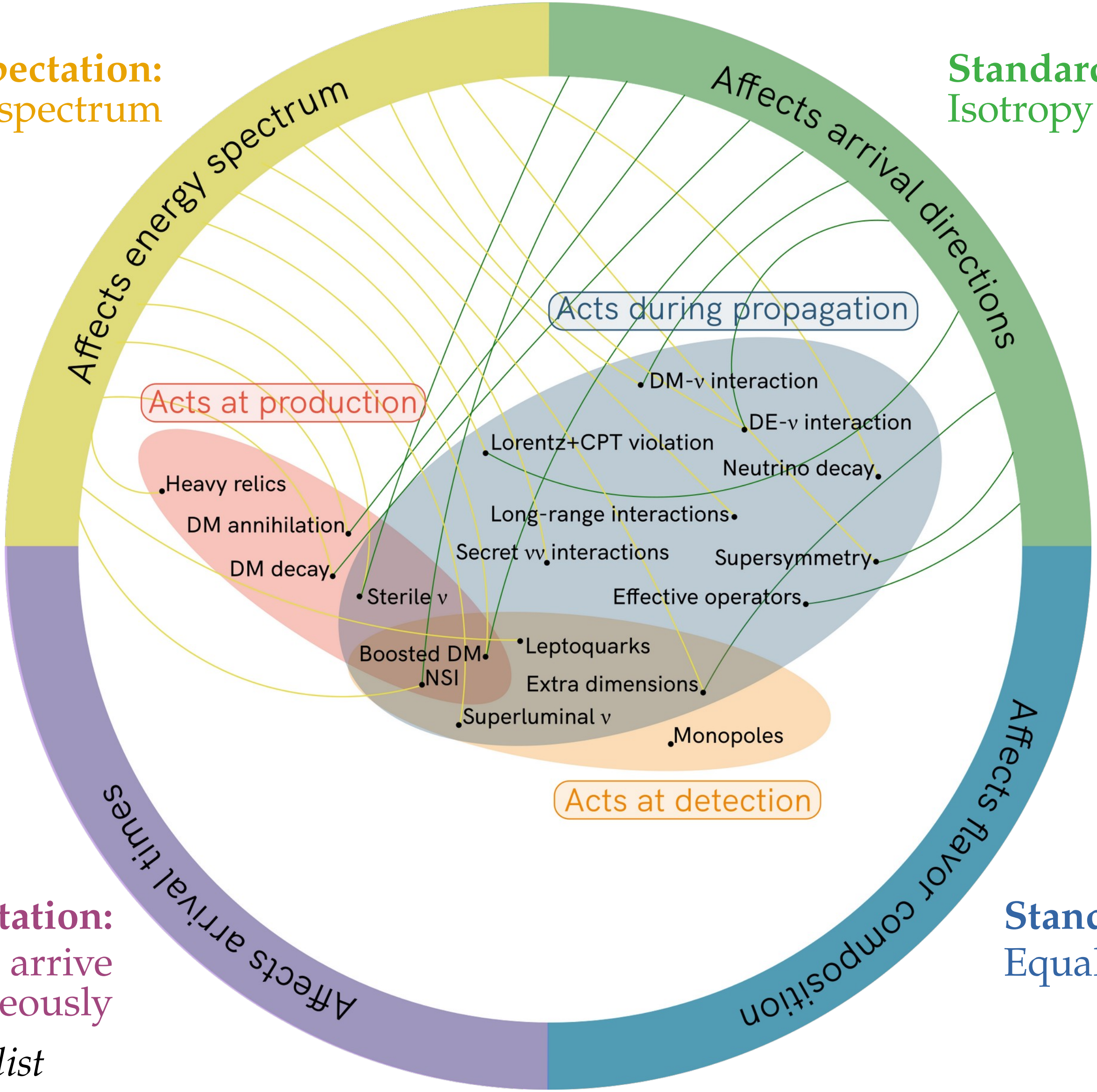

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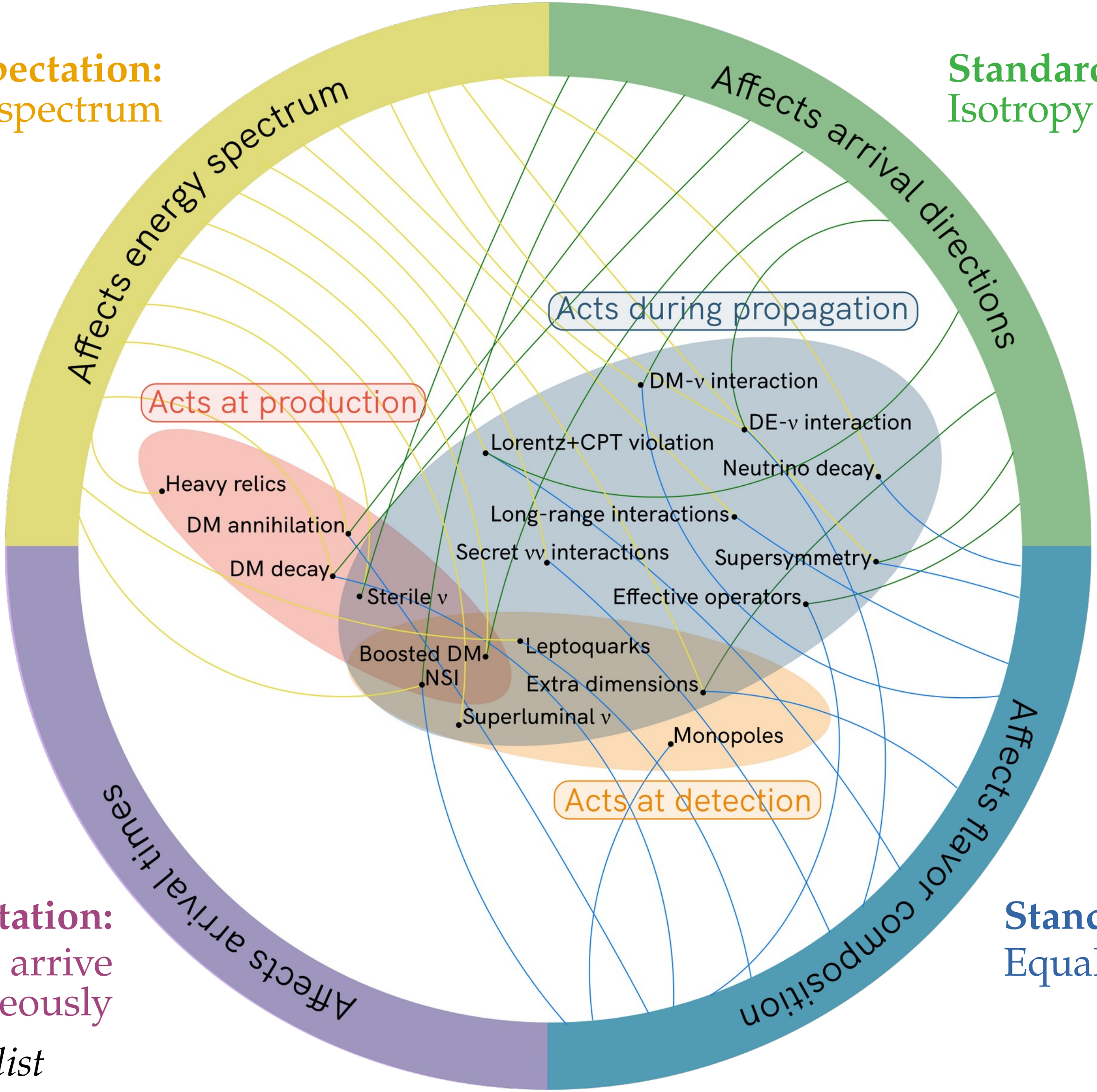

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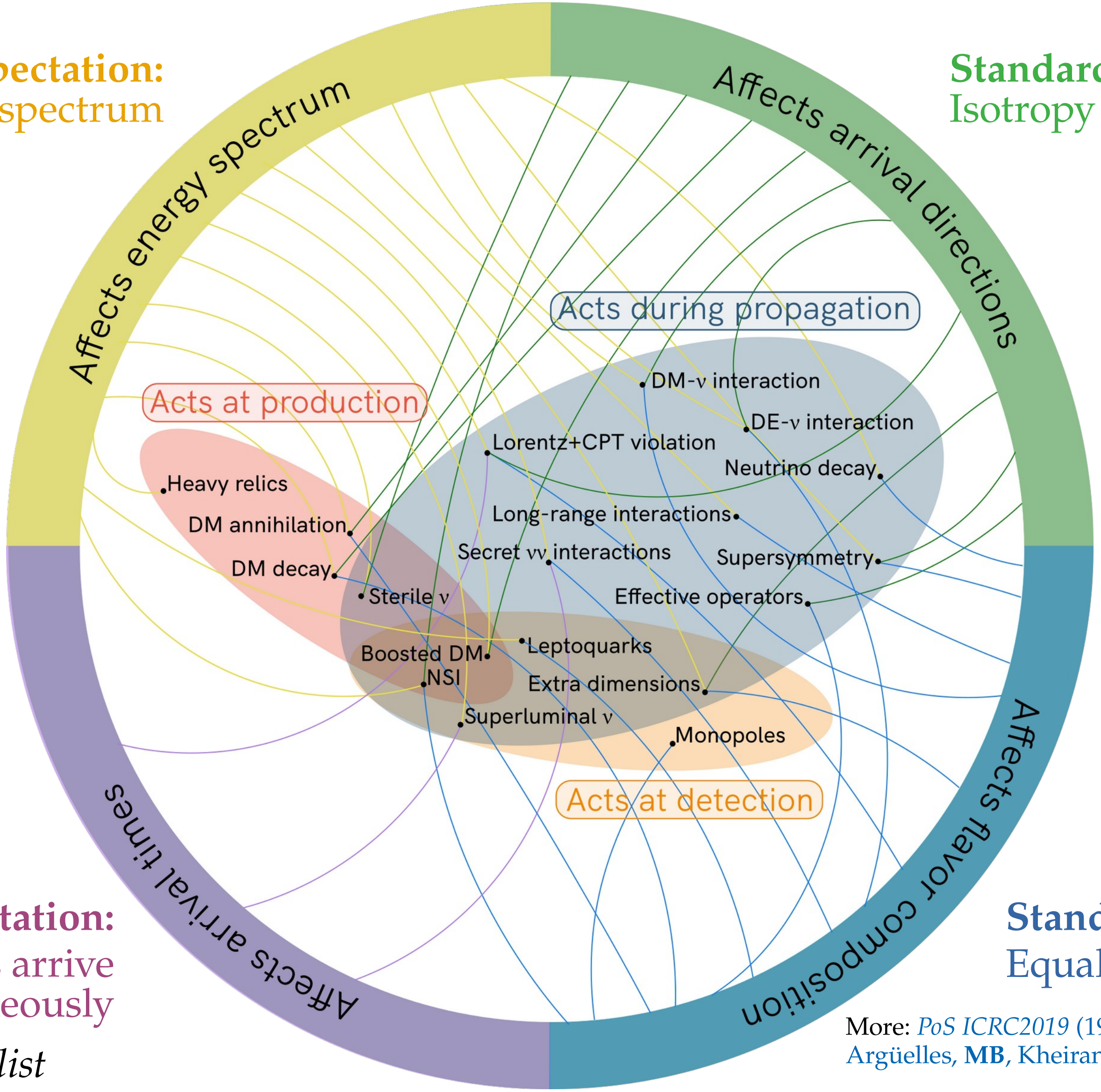

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More: *PoS ICRC2019* (1907.08690)
Argüelles, **MB**, Kheirandish, Palomares-Ruiz, Salvadó, Vincent

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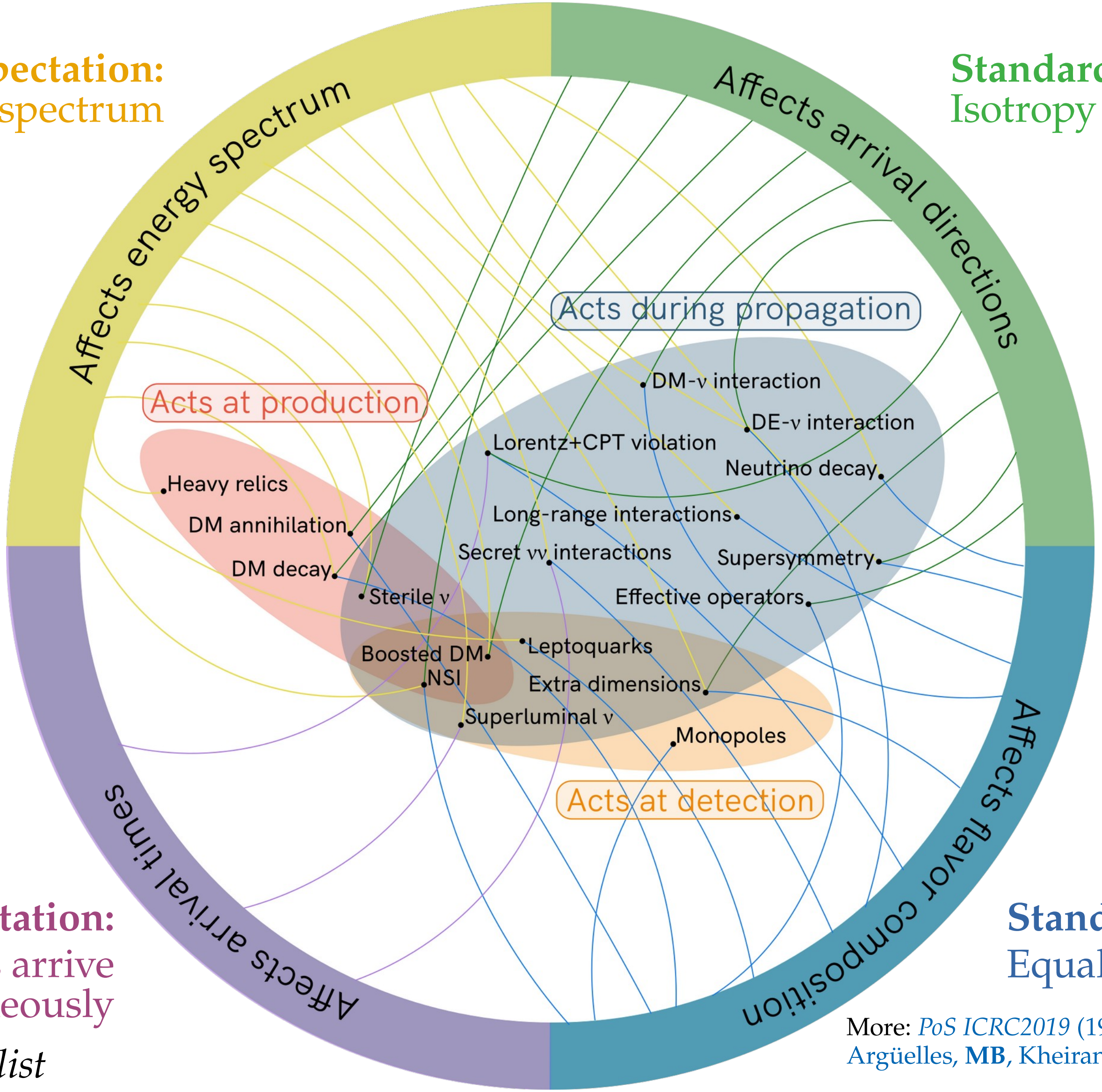

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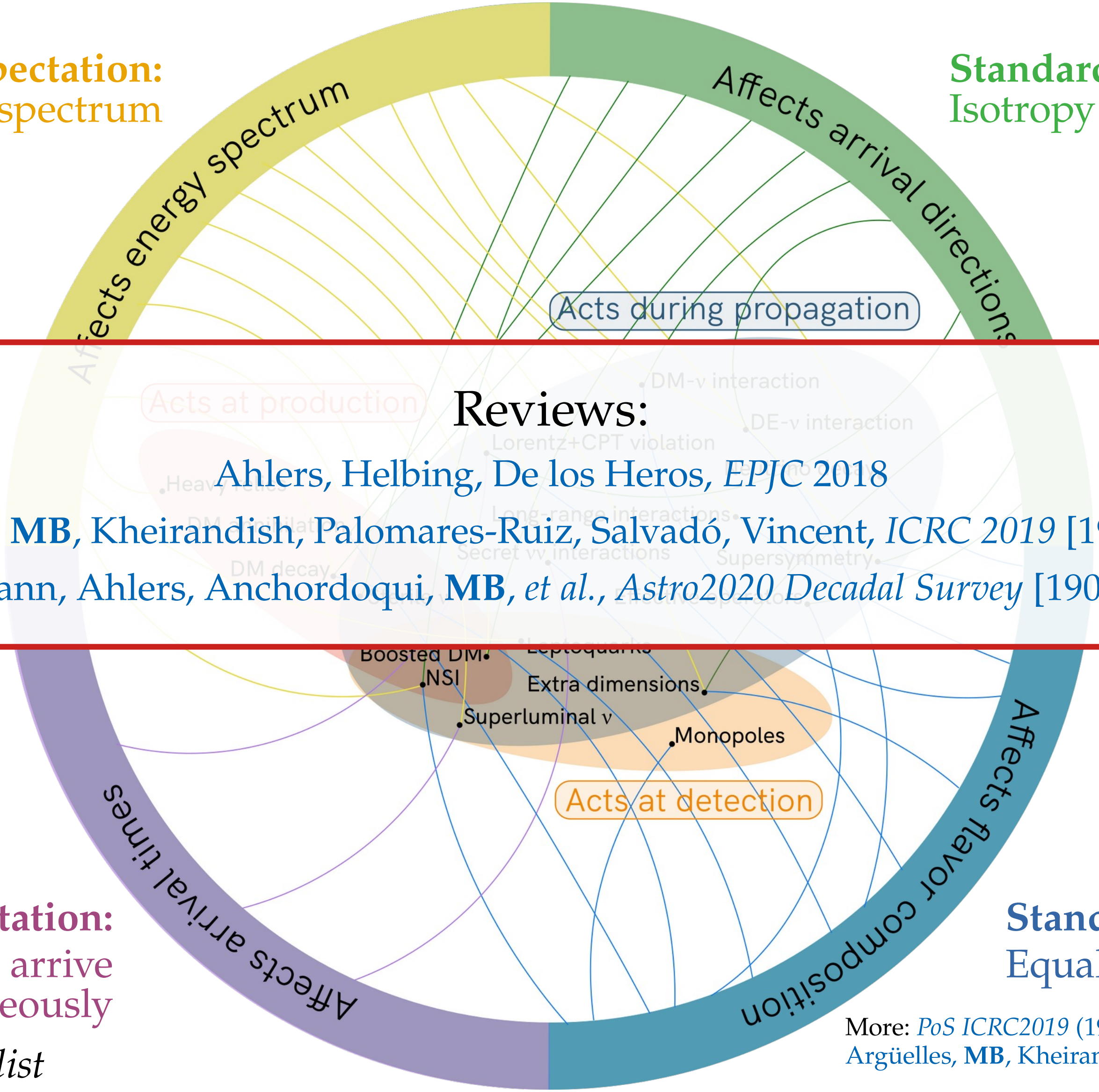

Reviews:

Ahlers, Helbing, De los Heros, *EPJC* 2018

Argüelles, **MB**, Kheirandish, Palomares-Ruiz, Salvadó, Vincent, *ICRC 2019* [1907.08690]

Ackermann, Ahlers, Anchordoqui, **MB**, *et al.*, *Astro2020 Decadal Survey* [1903.04333]

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A selection of neutrino physics

1. Discovering the Glashow resonance
2. Neutrino-matter cross section
3. Flavor physics
4. Dark matter
5. Secret neutrino interactions
6. Neutrino decay

$\left.\begin{array}{l}4\\5\\6\end{array}\right\}$ Find this in the backup slides

1. Glashow resonance:

Long-sought, finally seen

First observation of a Glashow resonance

Predicted in 1960:

IceCube, *Nature* 2021
Glashow, *PR* 1960

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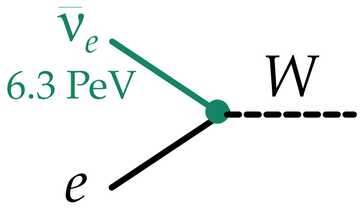

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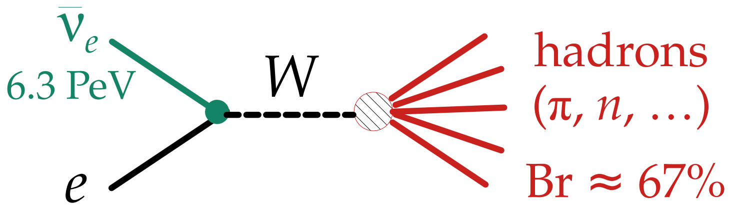

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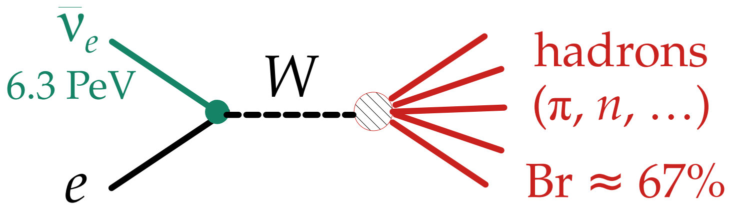
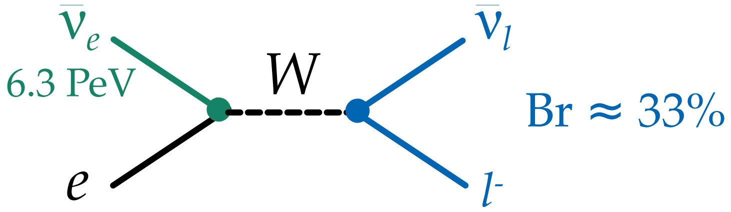


hadrons
(π, n, …)
Br ≈ 67%



Br ≈ 33%

IceCube, *Nature* 2021
Glashow, *PR* 1960

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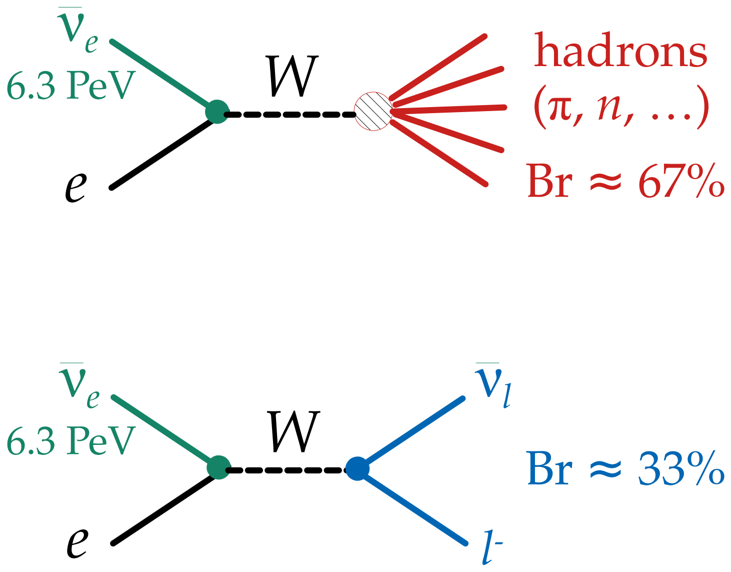
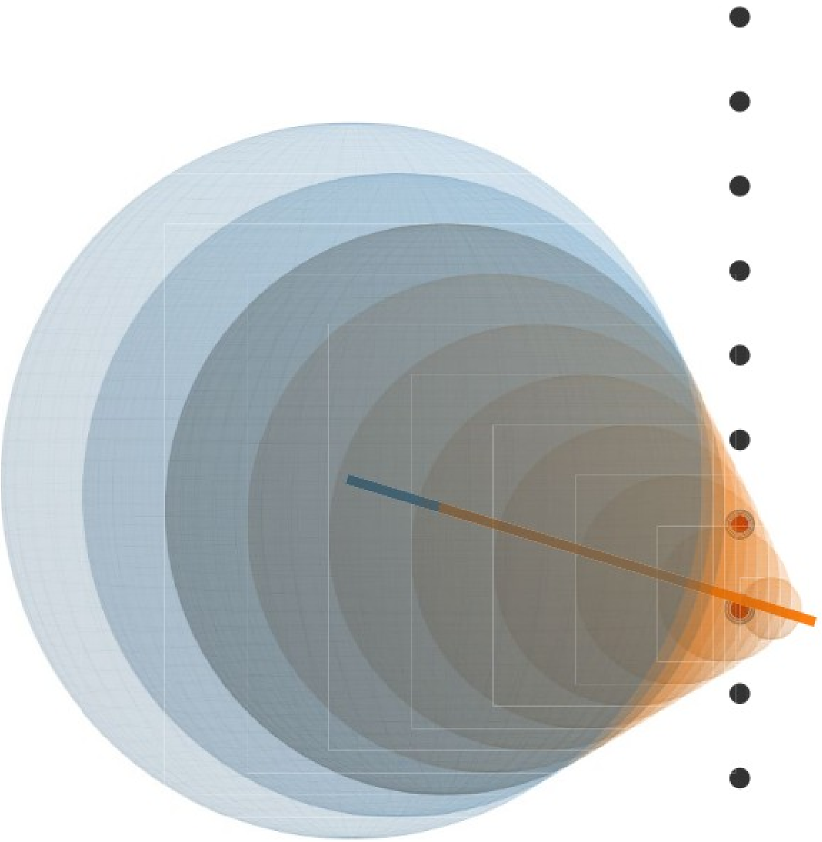


First reported by IceCube in 2021:



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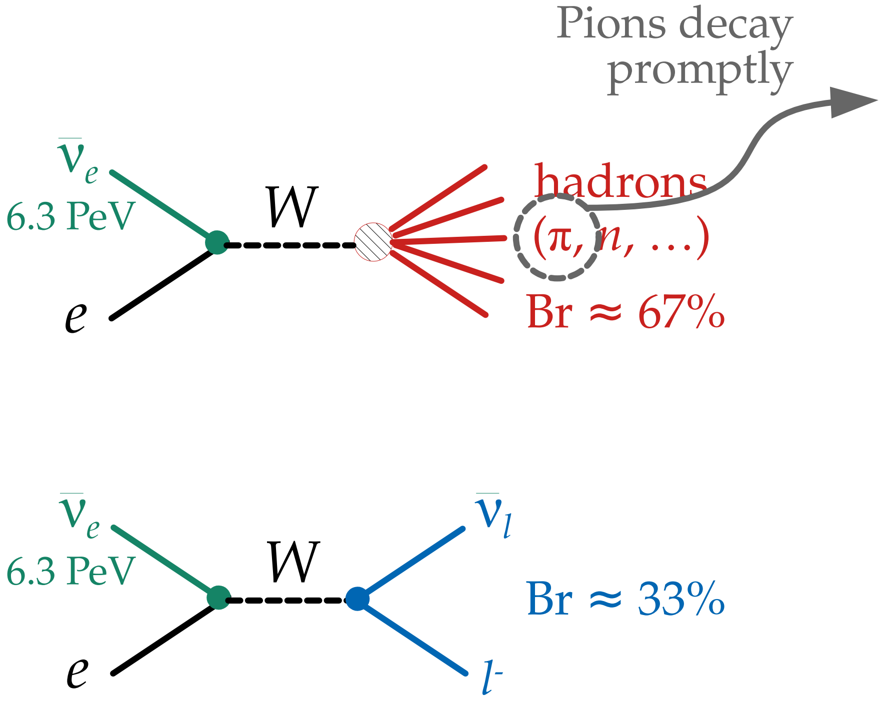
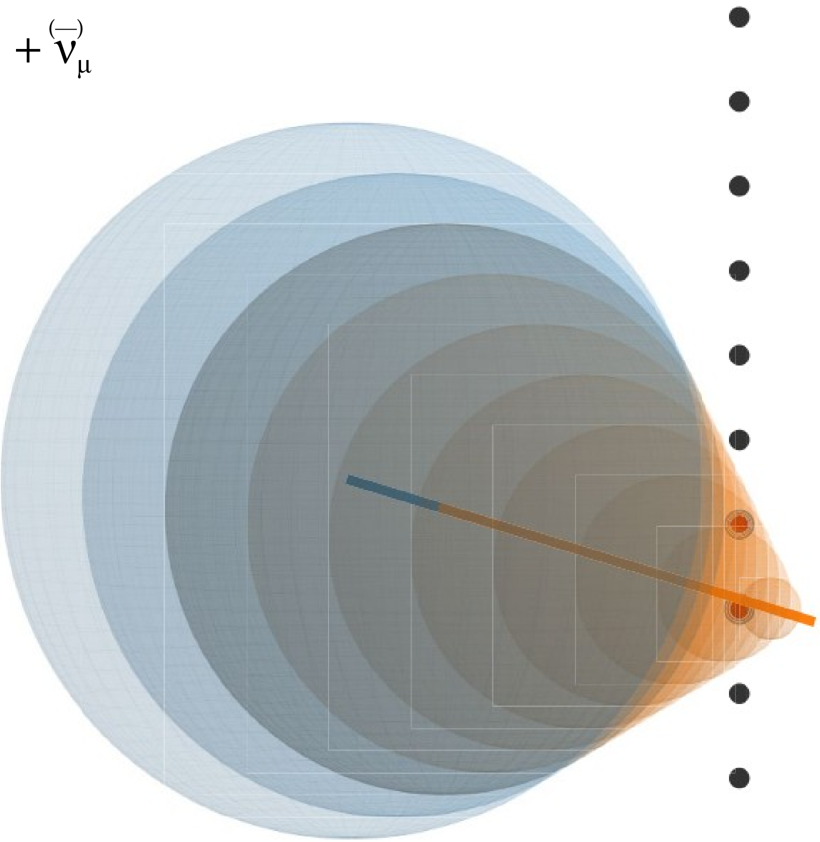


$$\pi^{\pm} \longrightarrow \mu^{\pm} + \overset{(-)}{\nu}_{\mu}$$

First reported by IceCube in 2021:



IceCube, *Nature* 2021
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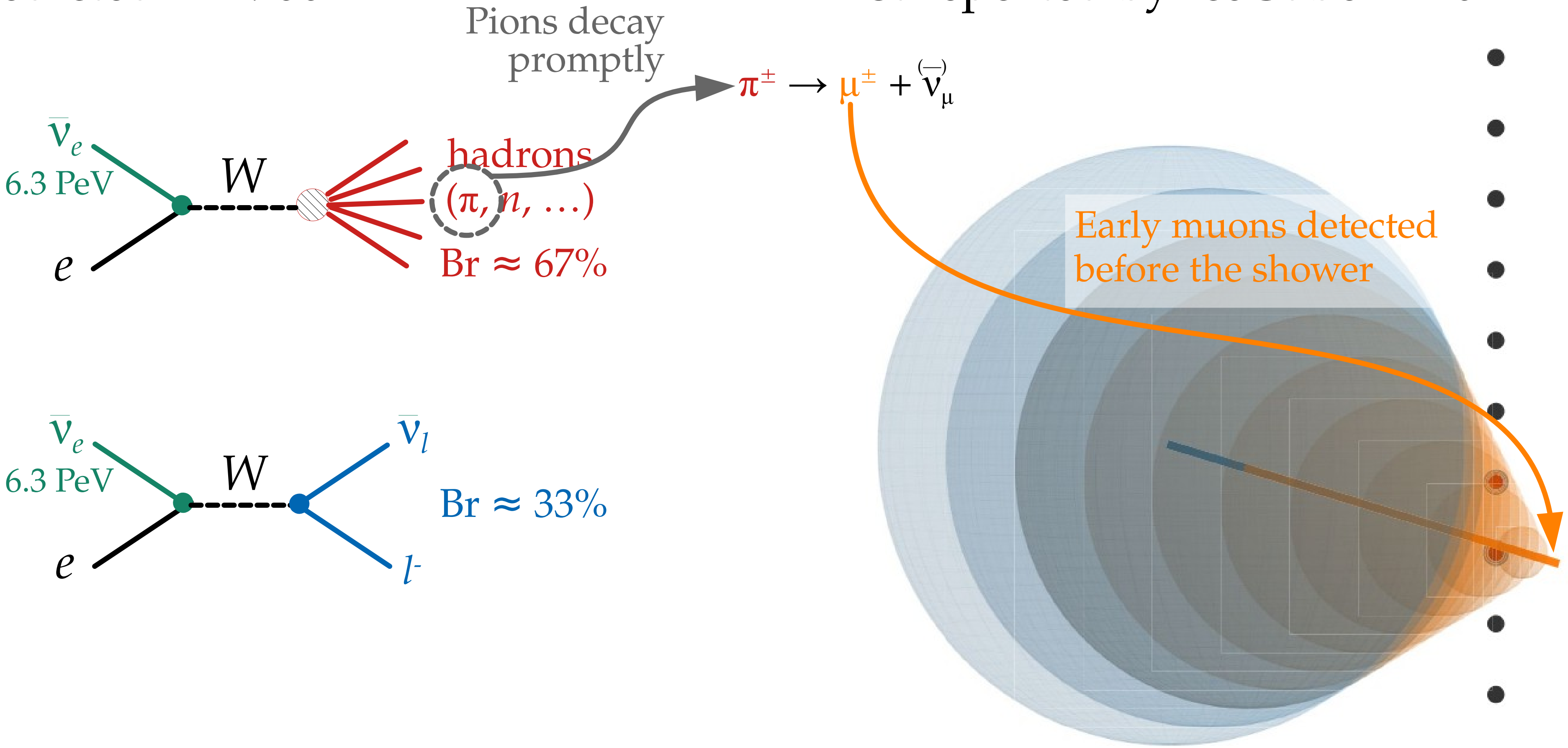


Pions decay promptly

$\pi^\pm \longrightarrow \mu^\pm + \overset{(-)}{\nu}_\mu$

hadrons

$(\pi, n, \ldots)$

Br ≈ 67%

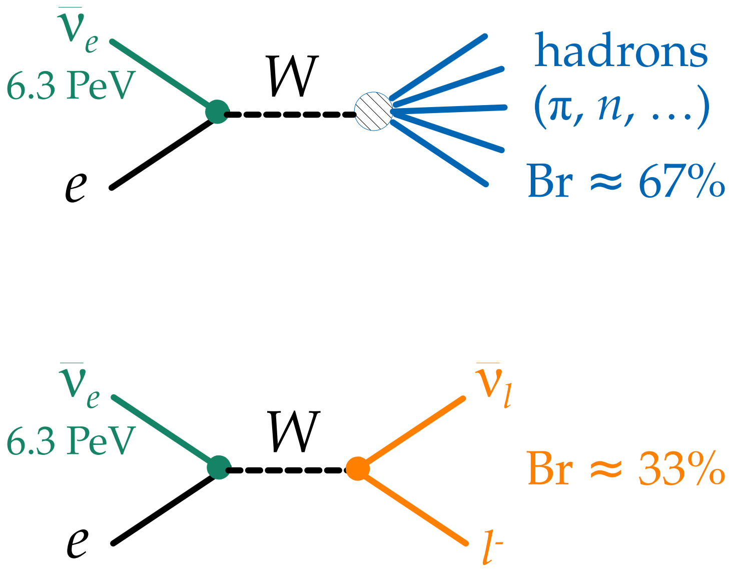
Br ≈ 33%

Early muons detected before the shower

IceCube, *Nature* 2021
Glashow, *PR* 1960

First observation of a Glashow resonance

Predicted in 1960:



$\bar{\nu}_e$

6.3 PeV

W

e

hadrons

$(\pi, n, \ldots)$

Br ≈ 67%

$\bar{\nu}_e$

6.3 PeV

W

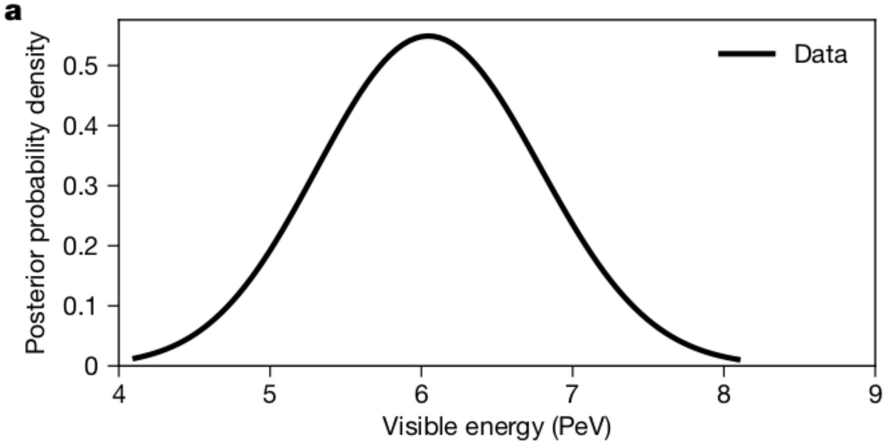
e

$\bar{\nu}_l$

Br ≈ 33%

l^-

First reported by IceCube in 2021:



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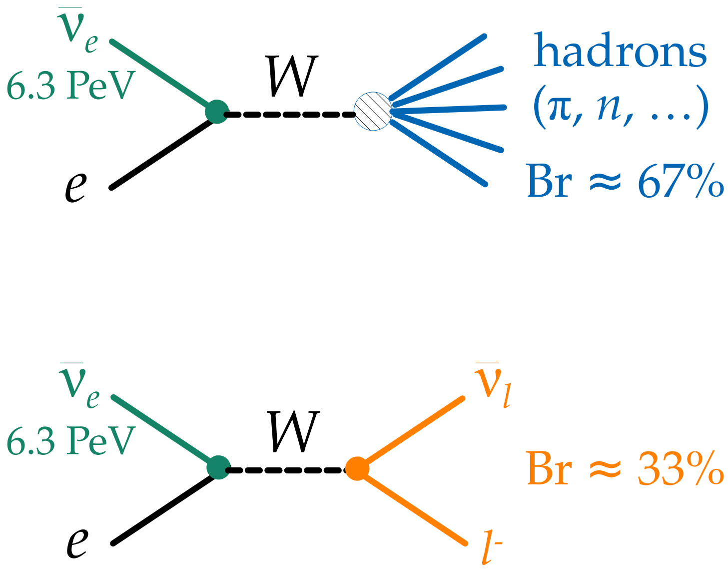

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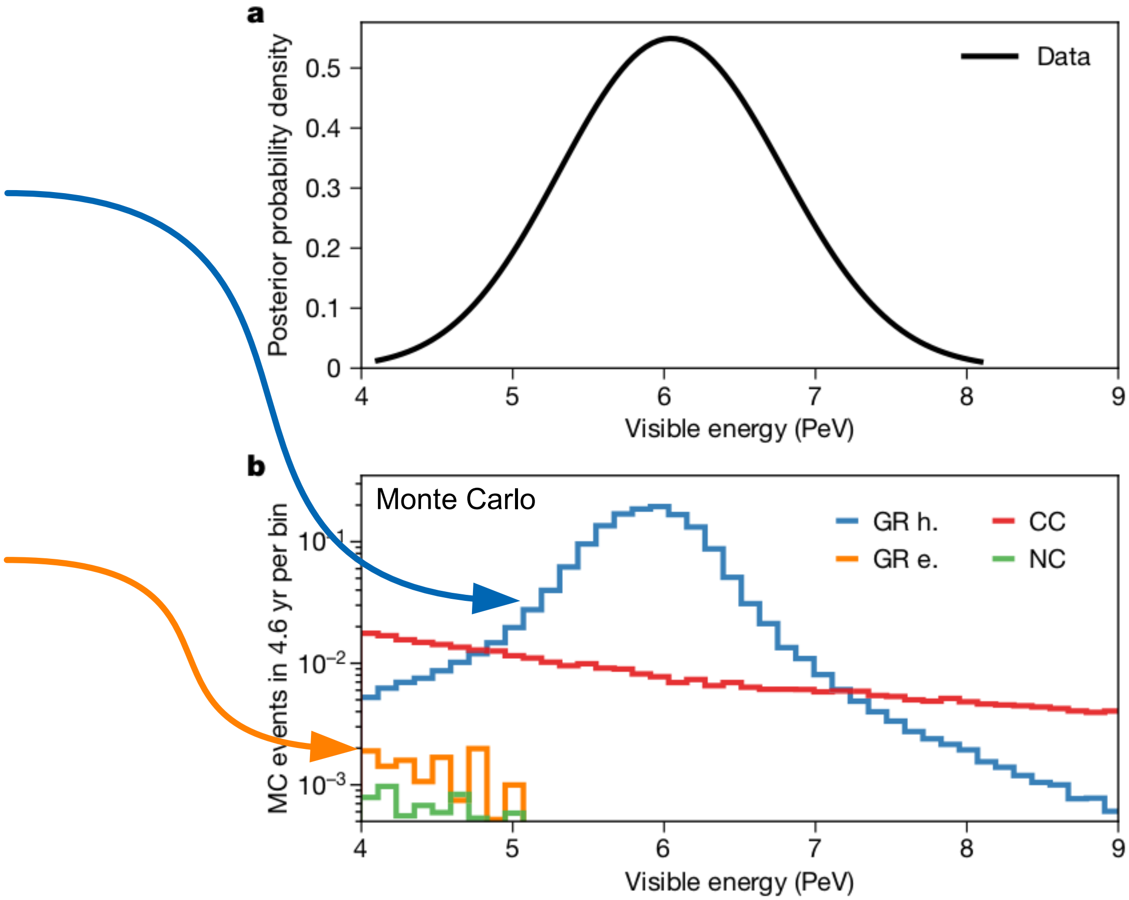
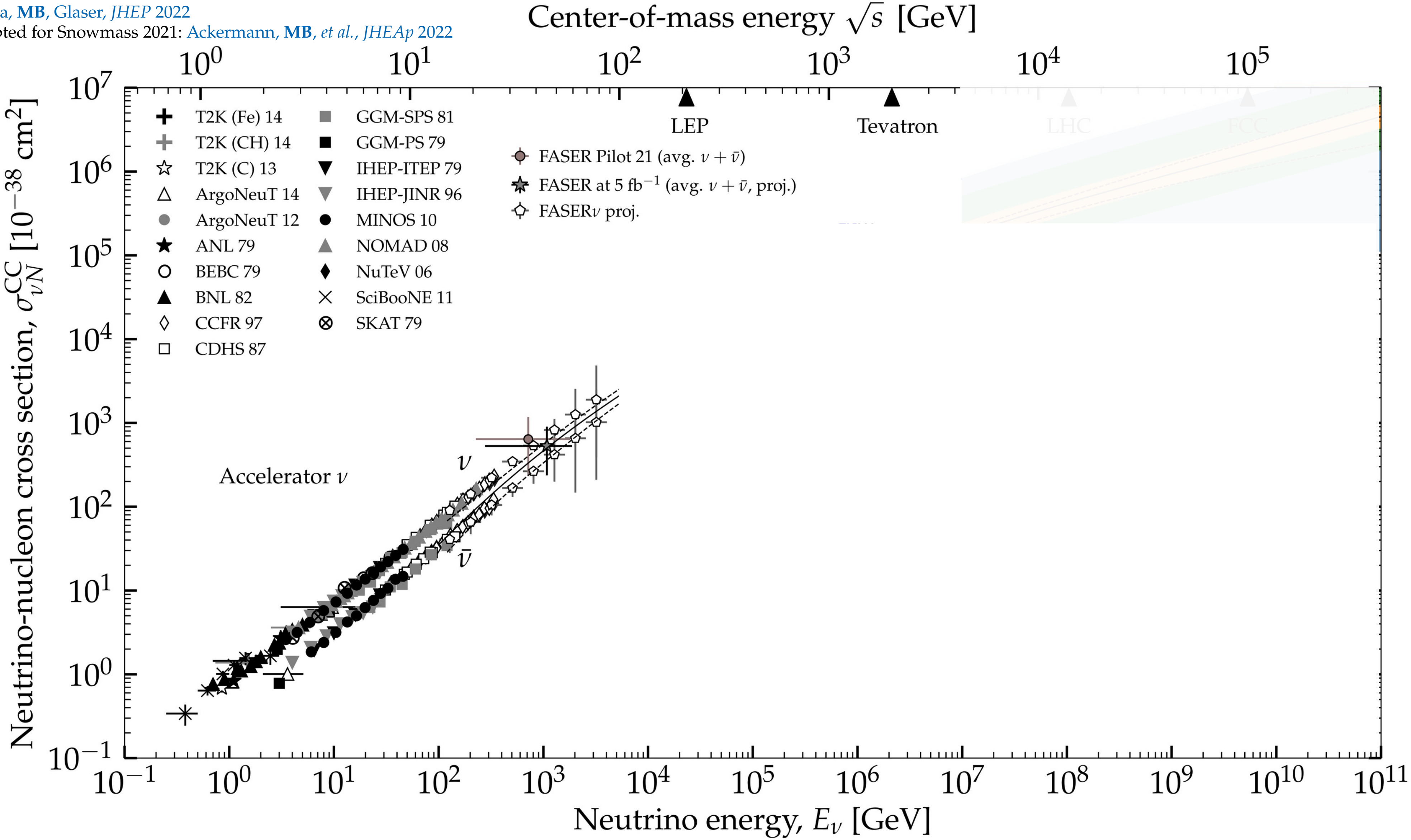


IceCube, *Nature* 2021
Glashow, *PR* 1960

2. Neutrino-matter cross section:

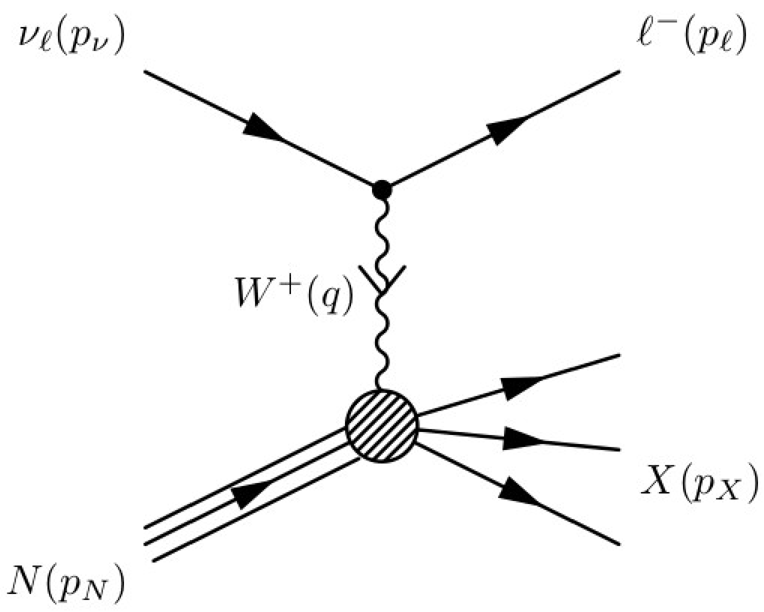
From TeV to PeV

Valera, **MB**, Glaser, *JHEP* 2022
Adapted for Snowmass 2021: Ackermann, **MB**, *et al.*, *JHEAp* 2022

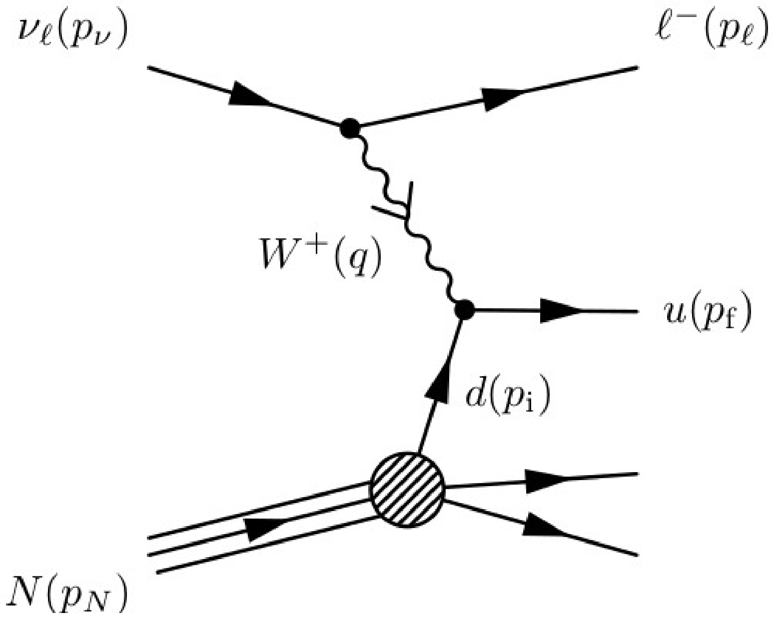


How does DIS probe nucleon structure?

What you see



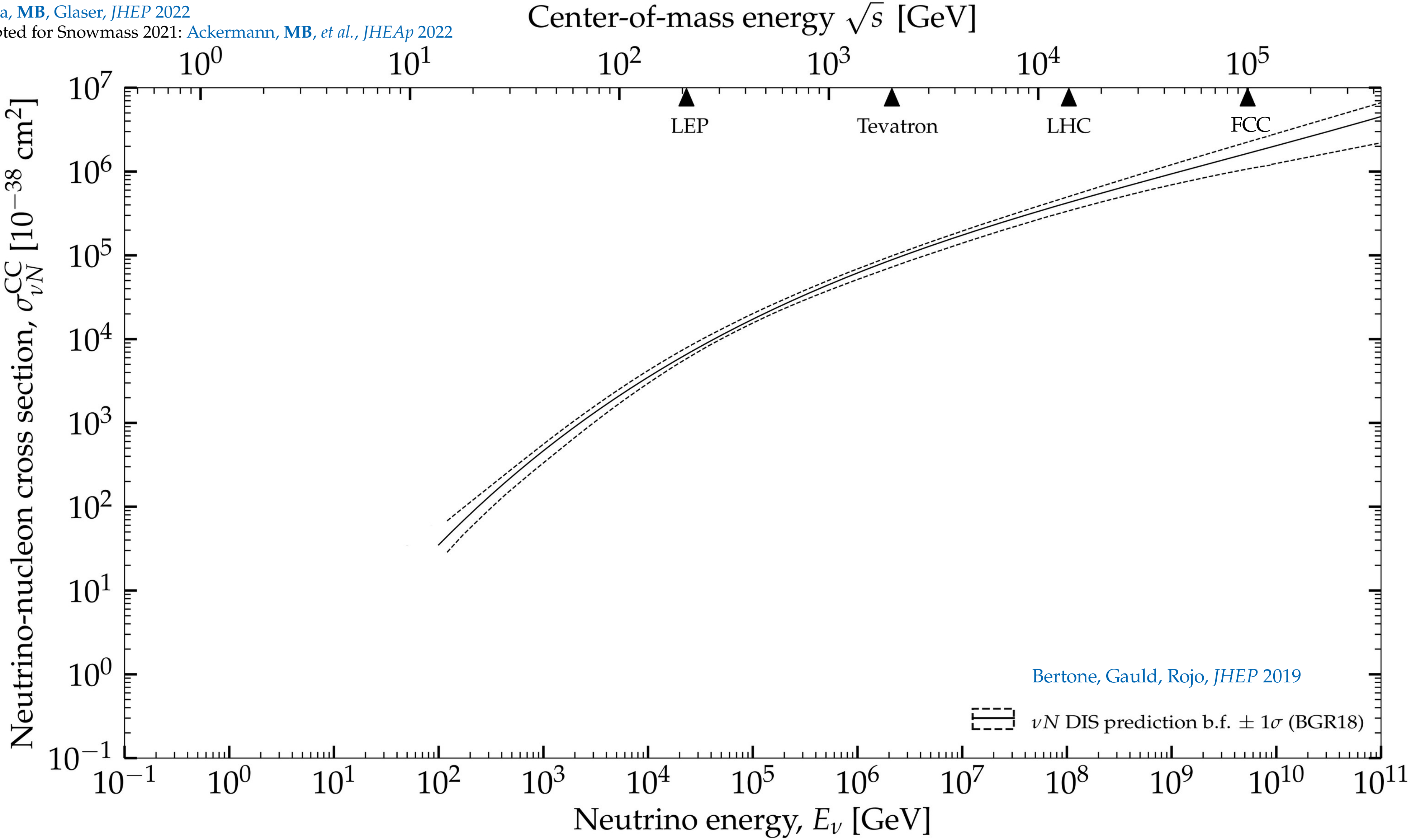
Beneath the hood



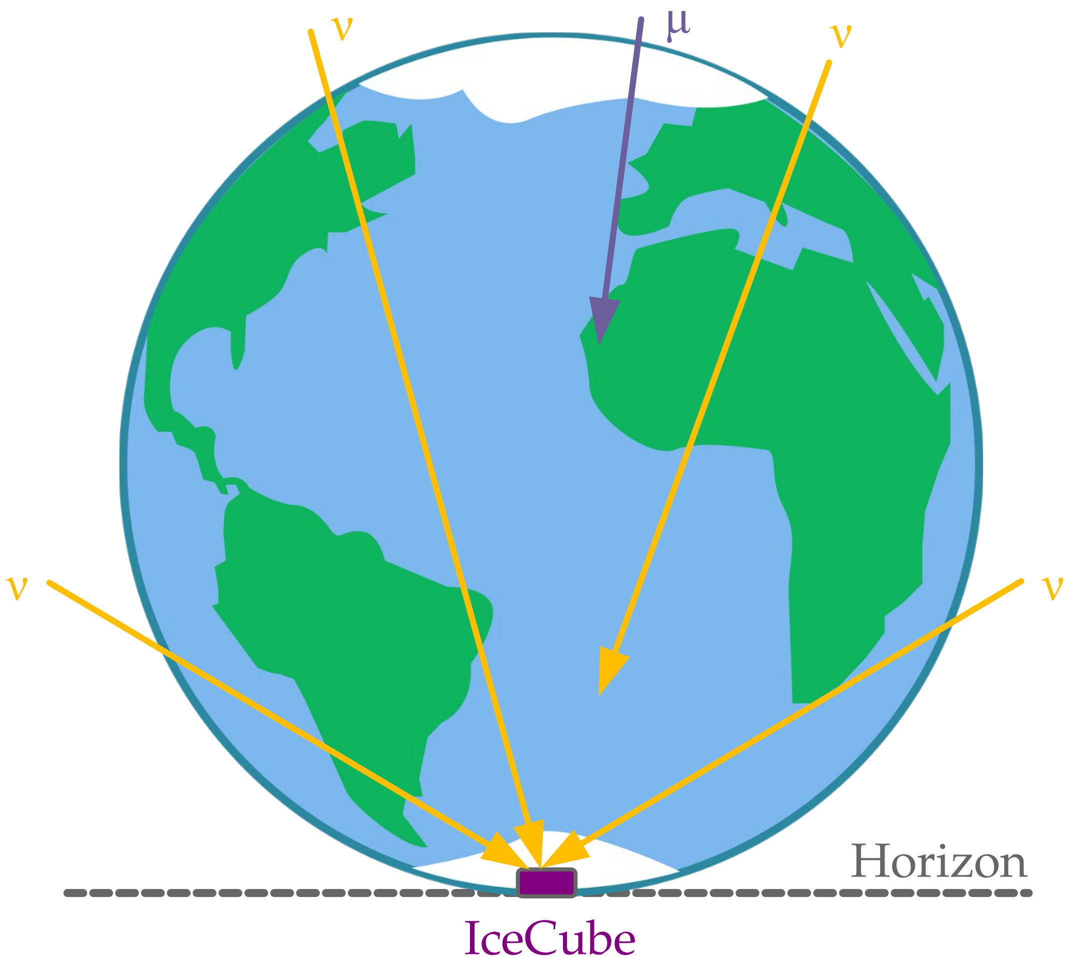
(Plus the equivalent neutral-current process (Z-exchange))

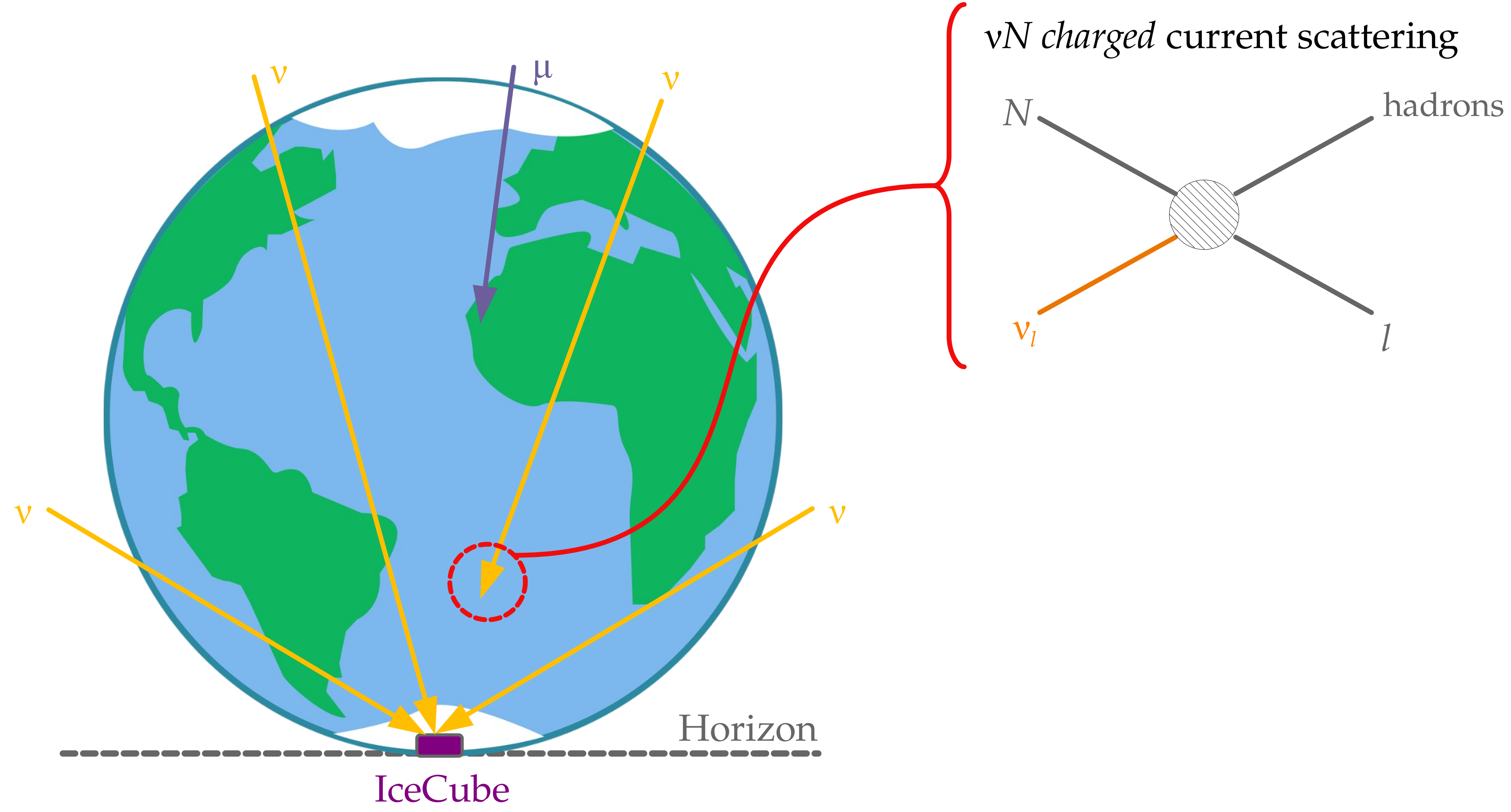
Giunti & Kim, *Fundamentals of Neutrino Physics & Astrophysics*

Valera, **MB**, Glaser, *JHEP* 2022
Adapted for Snowmass 2021: Ackermann, **MB**, *et al.*, *JHEAp* 2022

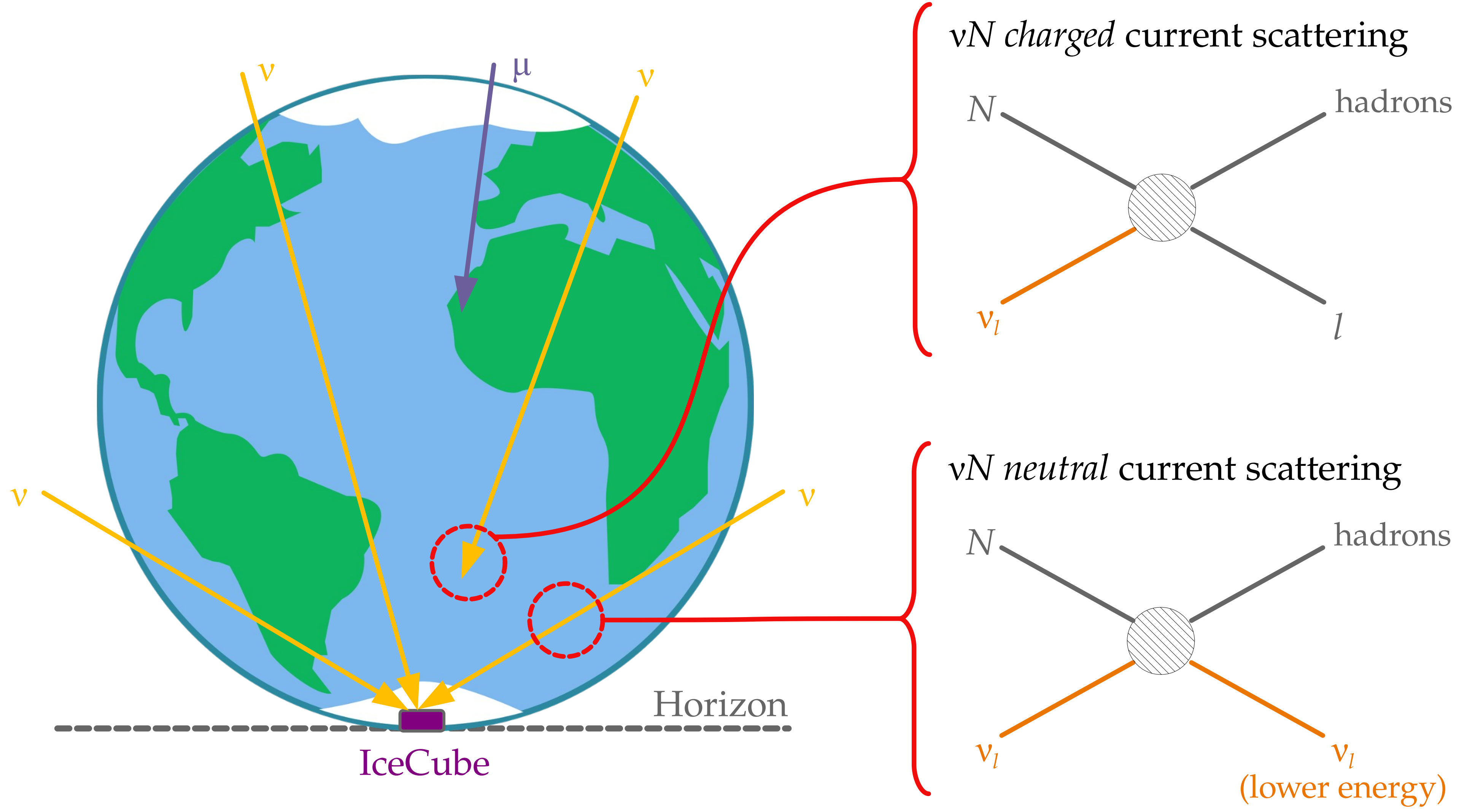


Bertone, Gauld, Rojo, *JHEP* 2019


ν
μ
ν
ν
ν
Horizon
IceCube

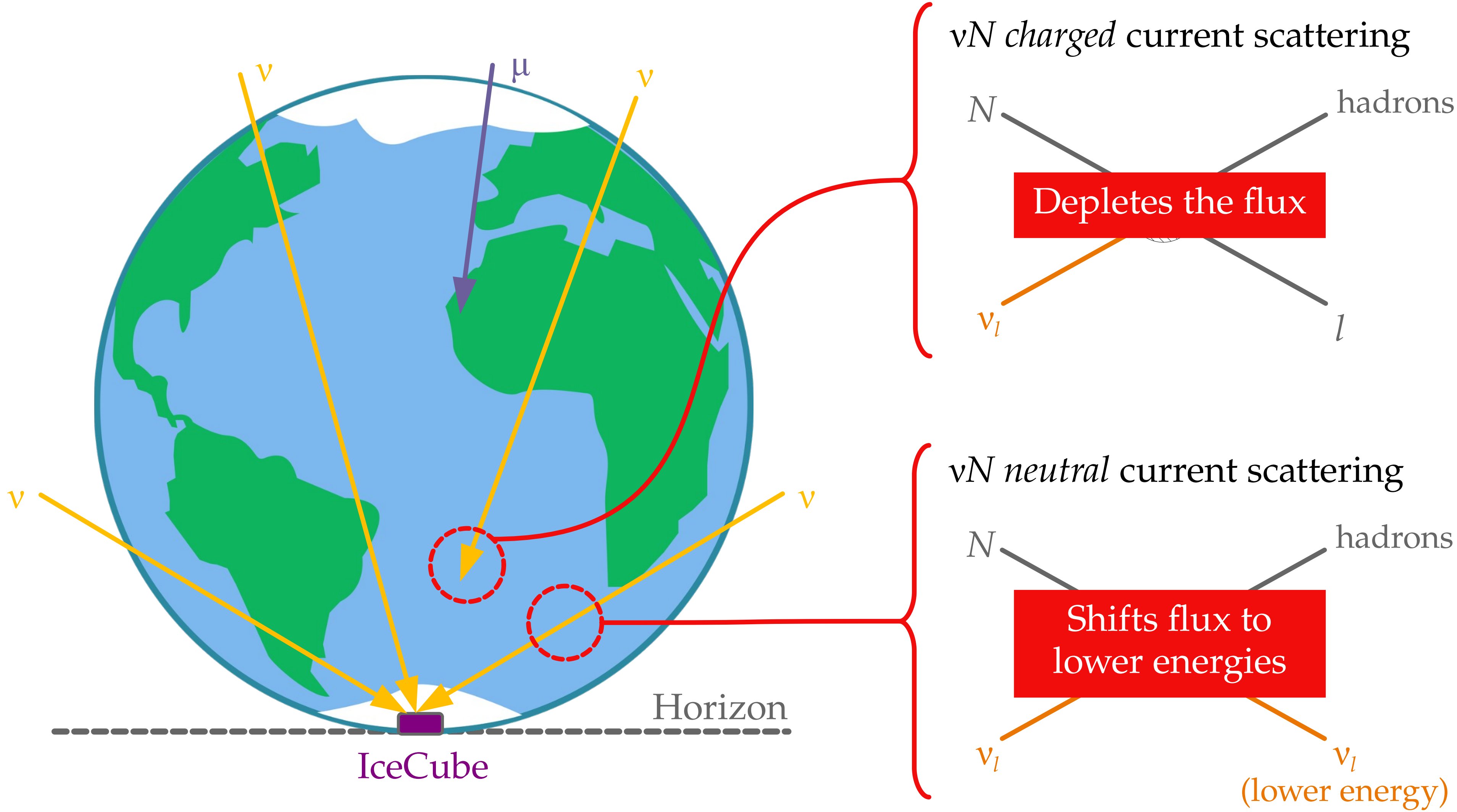


νN *charged* current scattering



νN *charged* current scattering

νN *neutral* current scattering



νN *charged* current scattering

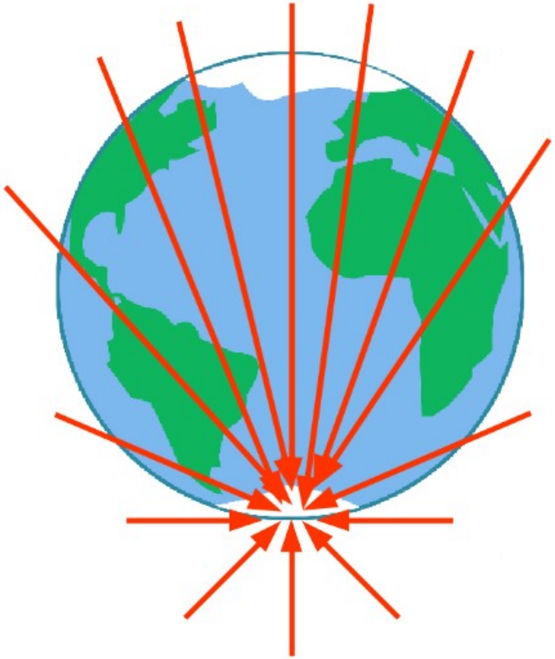
Depletes the flux

νN *neutral* current scattering

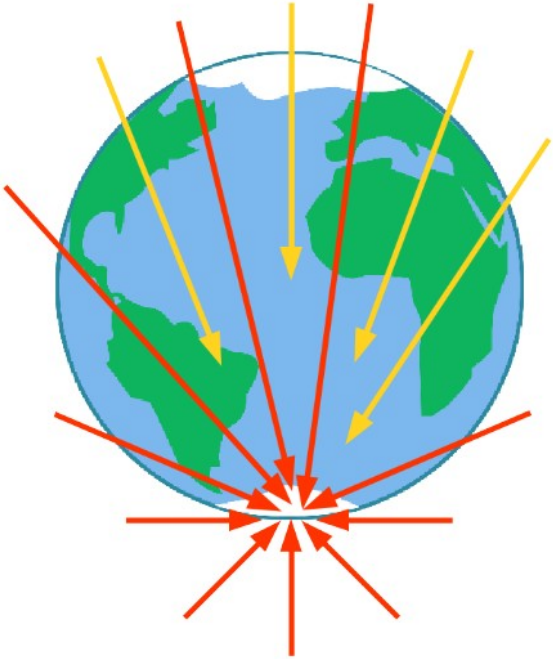
Shifts flux to lower energies

Measuring the high-energy νN cross section

Below ~ 10 TeV: Earth is transparent

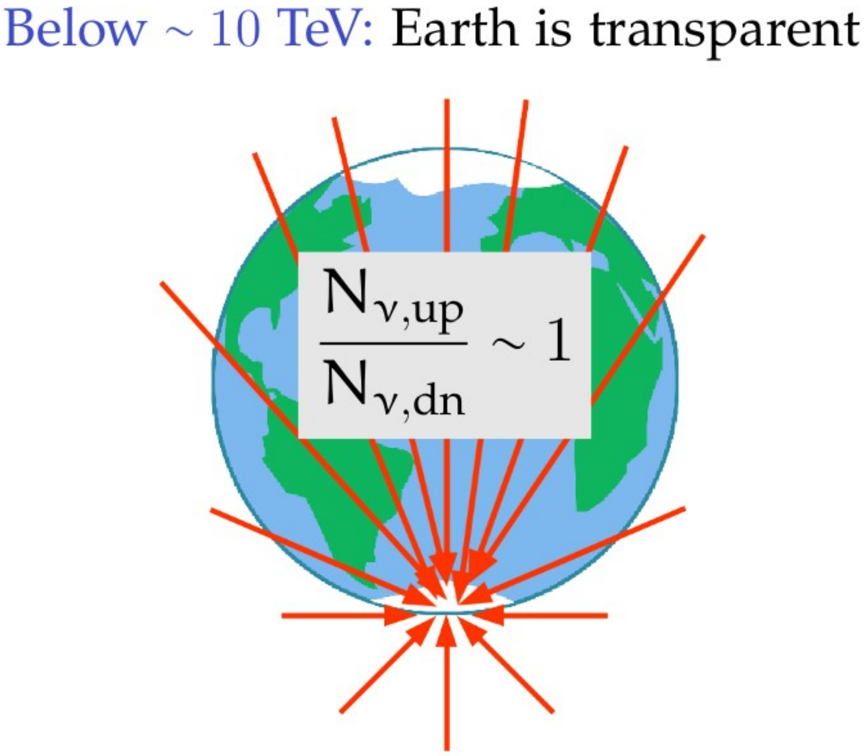


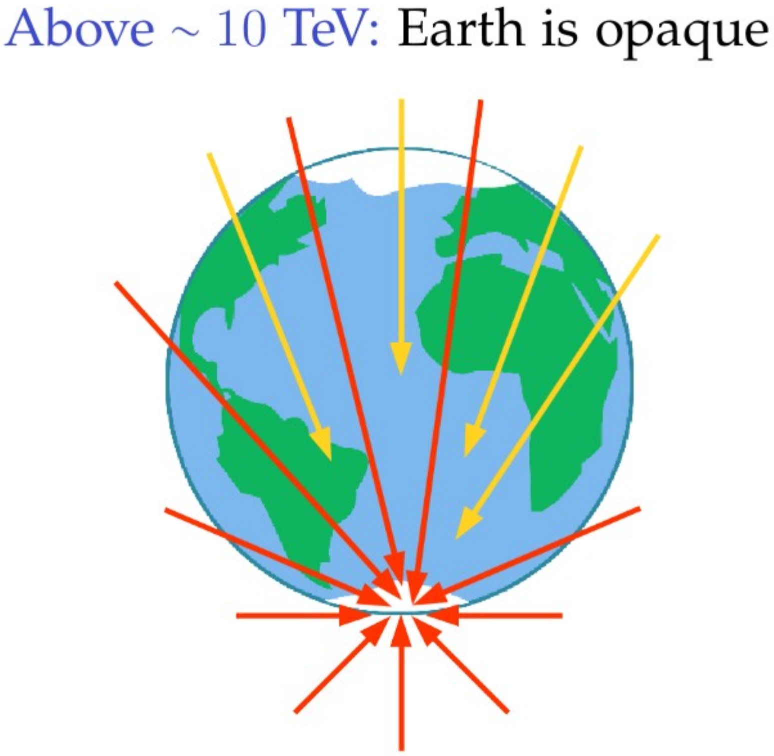
Above ~ 10 TeV: Earth is opaque



Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
Hussain, Mafatia, McKay, *PRD* 2008; Connolly, Thorne, Waters, *PRD* 2011; Marfatia, McKay, Weiler, *PLB* 2015

Measuring the high-energy *νN* cross section





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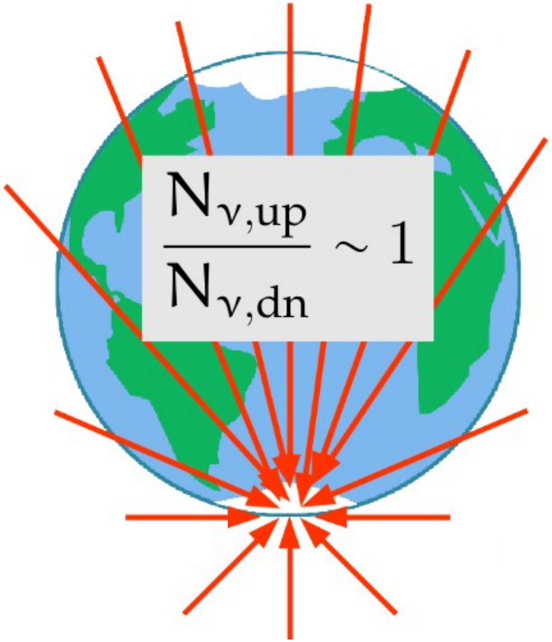
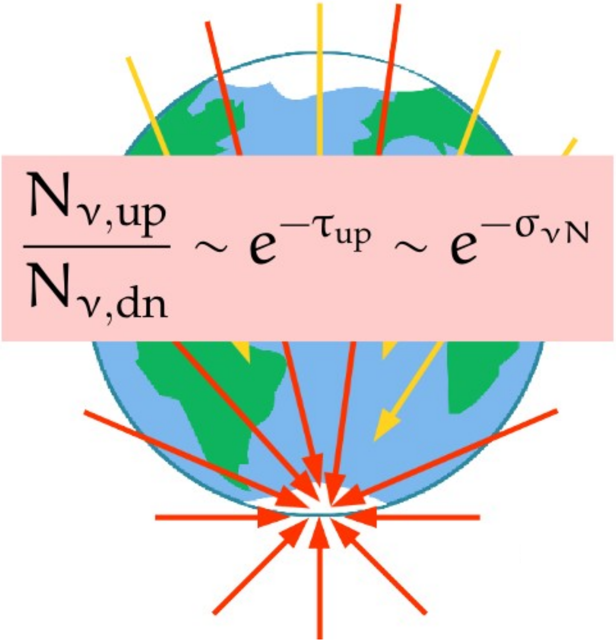


$$\frac{N_{\nu,\mathrm{up}}}{N_{\nu,\mathrm{dn}}} \sim 1$$

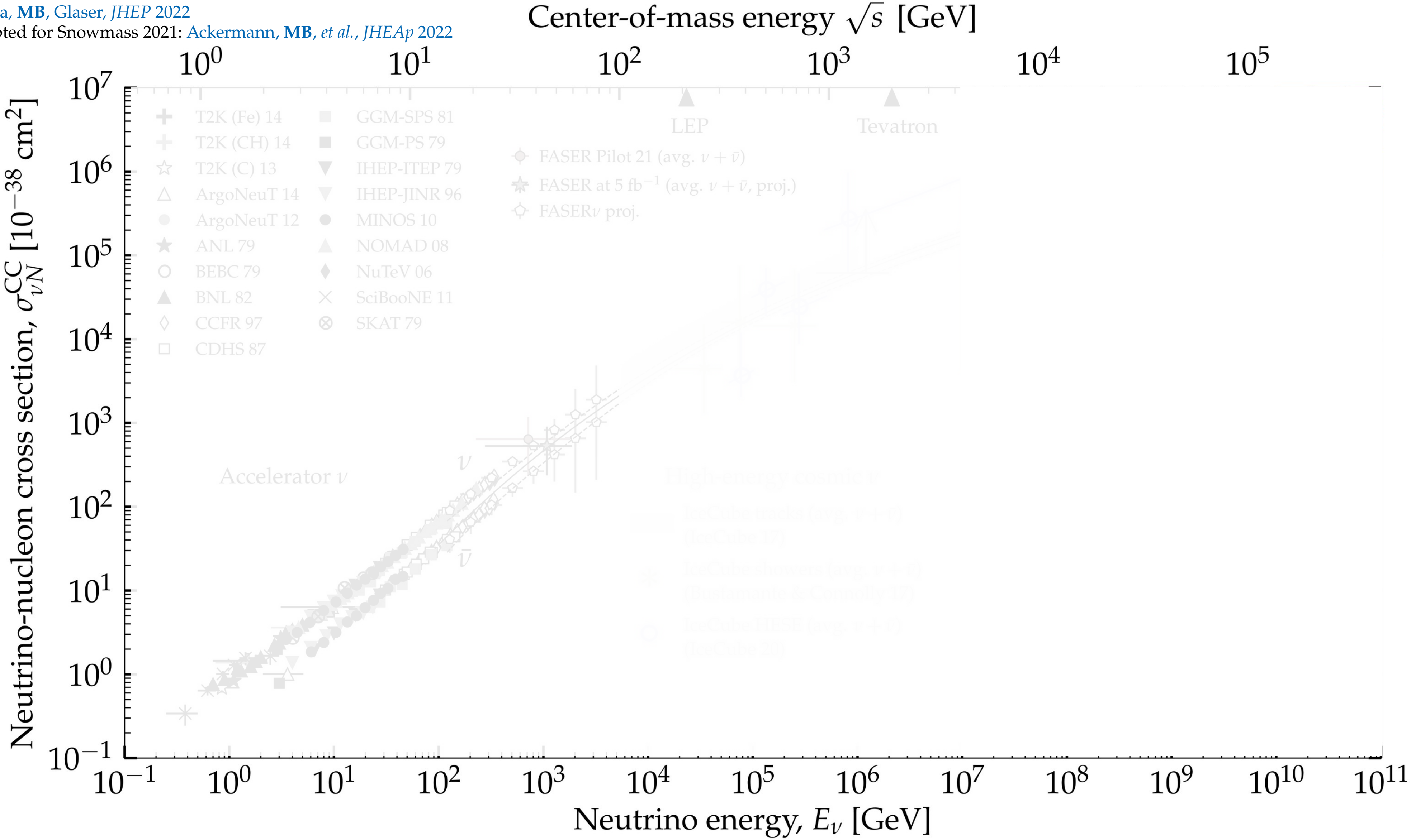
Above ~ 10 TeV: Earth is opaque



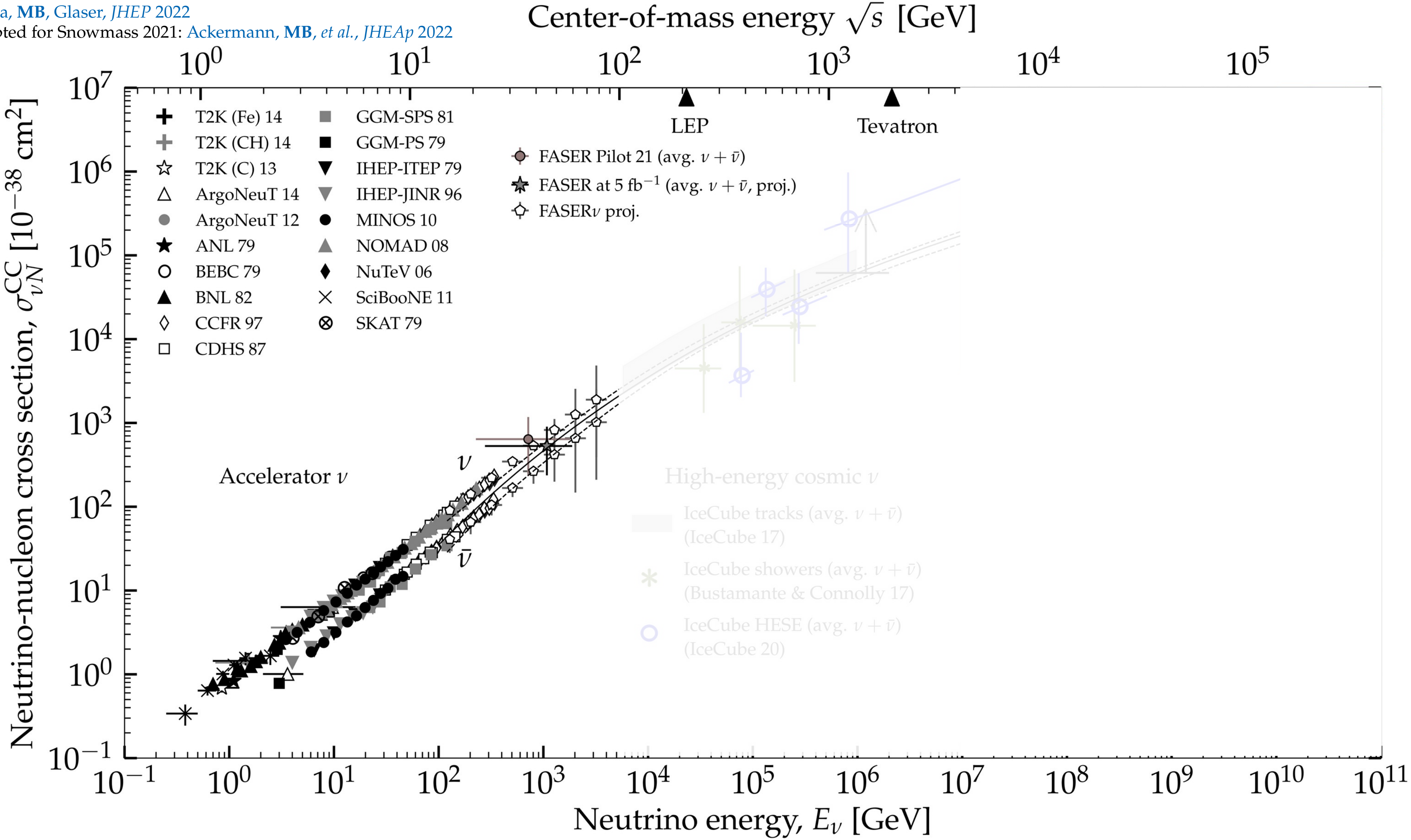
$$\frac{N_{\nu,\mathrm{up}}}{N_{\nu,\mathrm{dn}}} \sim e^{-\tau_{\mathrm{up}}} \sim e^{-\sigma_{\nu N}}$$

Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
Hussain, Mafatia, McKay, *PRD* 2008; Connolly, Thorne, Waters, *PRD* 2011; Marfatia, McKay, Weiler, *PLB* 2015

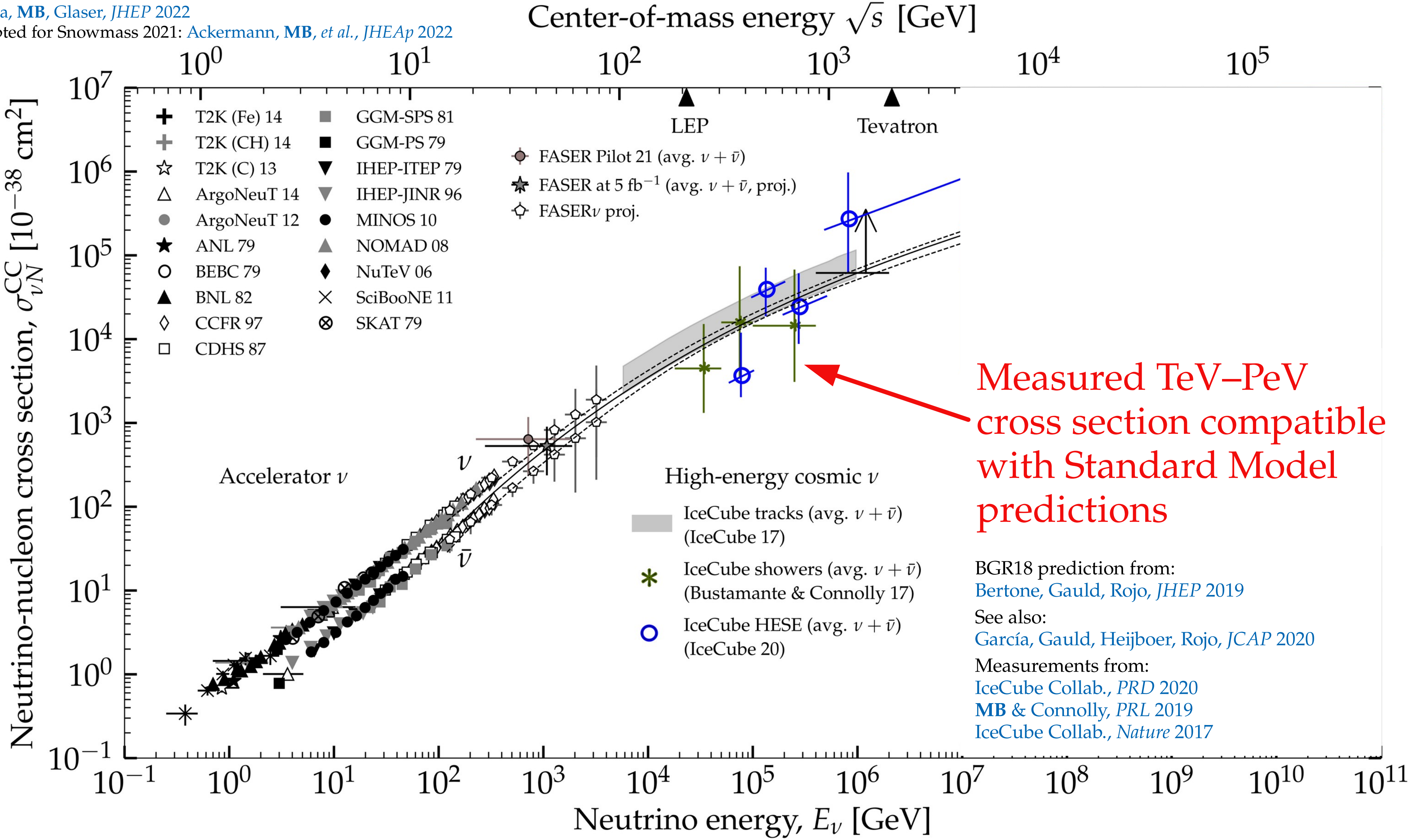
Valera, **MB**, Glaser, *JHEP* 2022
Adapted for Snowmass 2021: Ackermann, **MB**, *et al.*, *JHEAp* 2022



Valera, **MB**, Glaser, *JHEP* 2022
Adapted for Snowmass 2021: Ackermann, **MB**, *et al.*, *JHEAp* 2022



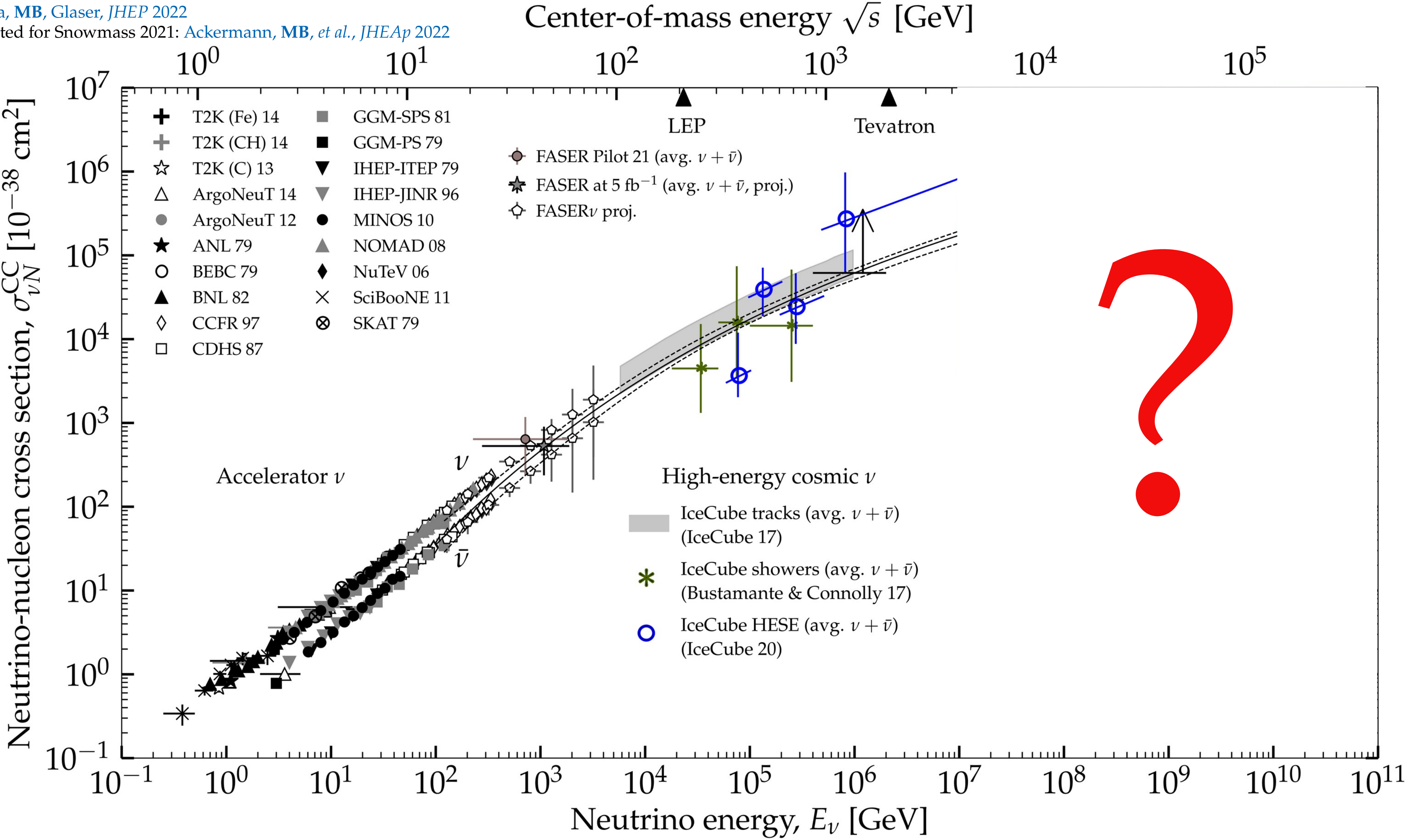
Valera, **MB**, Glaser, *JHEP* 2022
Adapted for Snowmass 2021: Ackermann, **MB**, *et al.*, *JHEAp* 2022



Measured TeV–PeV cross section compatible with Standard Model predictions

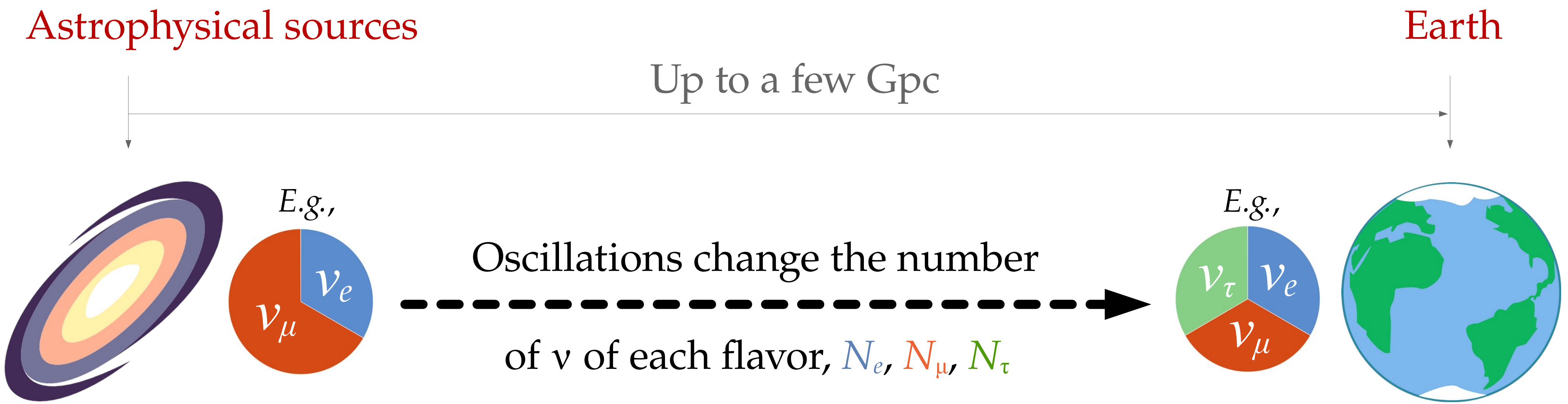
BGR18 prediction from:
Bertone, Gauld, Rojo, *JHEP* 2019
See also:
García, Gauld, Heijboer, Rojo, *JCAP* 2020
Measurements from:
IceCube Collab., *PRD* 2020
MB & Connolly, *PRL* 2019
IceCube Collab., *Nature* 2017

Valera, **MB**, Glaser, *JHEP* 2022
Adapted for Snowmass 2021: Ackermann, **MB**, *et al.*, *JHEAp* 2022



3. New physics via flavor

Hard to do, but worth it



Astrophysical sources

Earth

Up to a few Gpc

Oscillations change the number

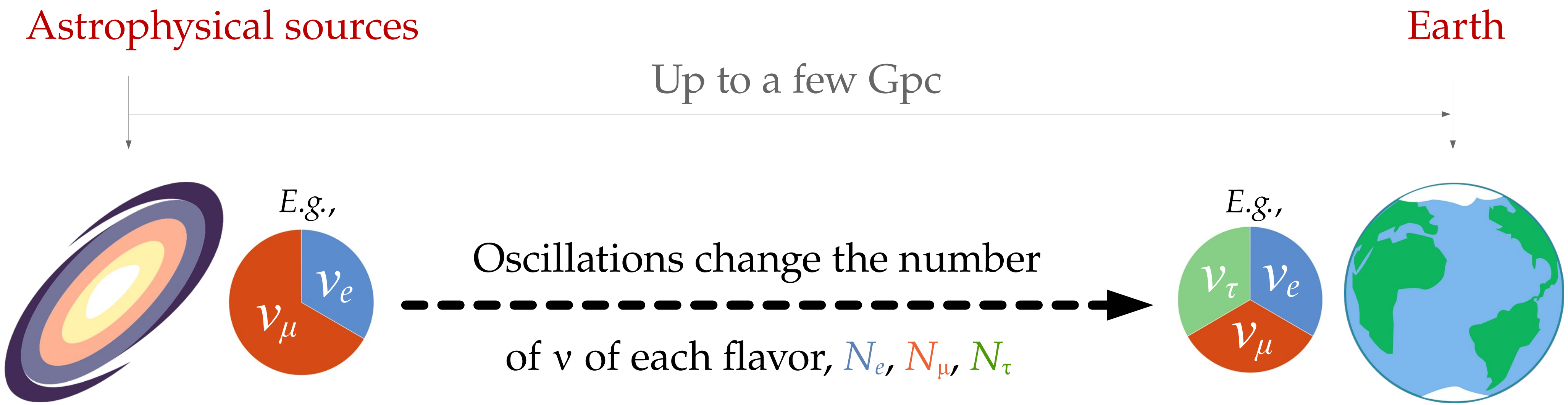
of ν of each flavor, N_e, N_μ, N_τ

Different production mechanisms yield different flavor ratios:

$$(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}}) \equiv (N_{e,\mathrm{S}}, N_{\mu,\mathrm{S}}, N_{\tau,\mathrm{S}})/N_{\mathrm{tot}}$$

Flavor ratios at Earth ($\alpha = e, \mu, \tau$):

$$f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} P_{\nu_\beta \to \nu_\alpha} f_{\beta,\mathrm{S}}$$



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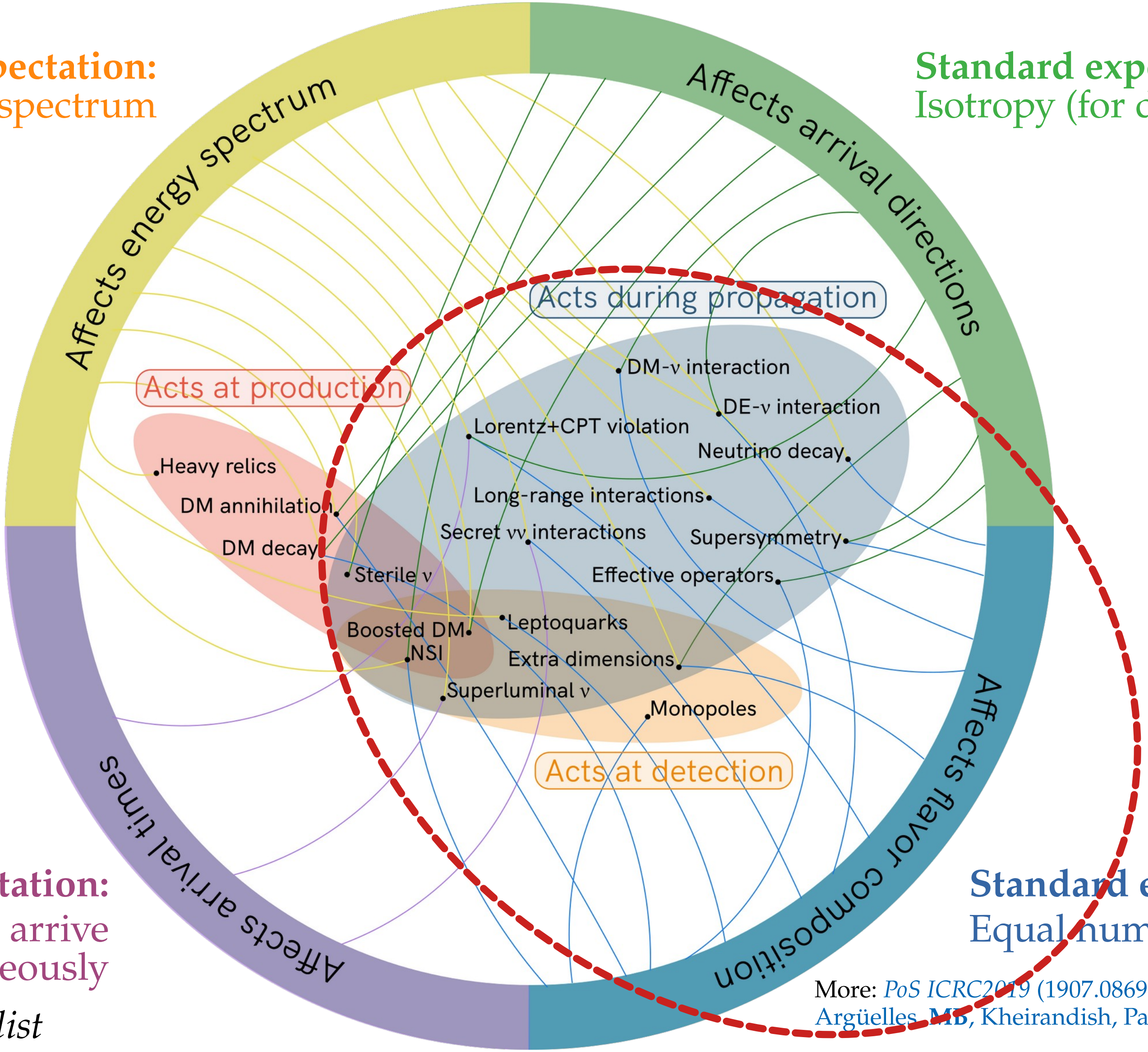
Flavor ratios at Earth ($\alpha = e, \mu, \tau$):

$$f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} P_{\nu_\beta \to \nu_\alpha} f_{\beta,\mathrm{S}}$$

Standard oscillations
or
new physics

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Note: Not an exhaustive list

More: *PoS ICRC2019* (1907.08690)
Argüelles, **MB**, Kheirandish, Palomares-Ruiz, Salvadó, Vincent

New physics in flavor composition

Repurpose the flavor sensitivity to test new physics:

New physics in flavor composition

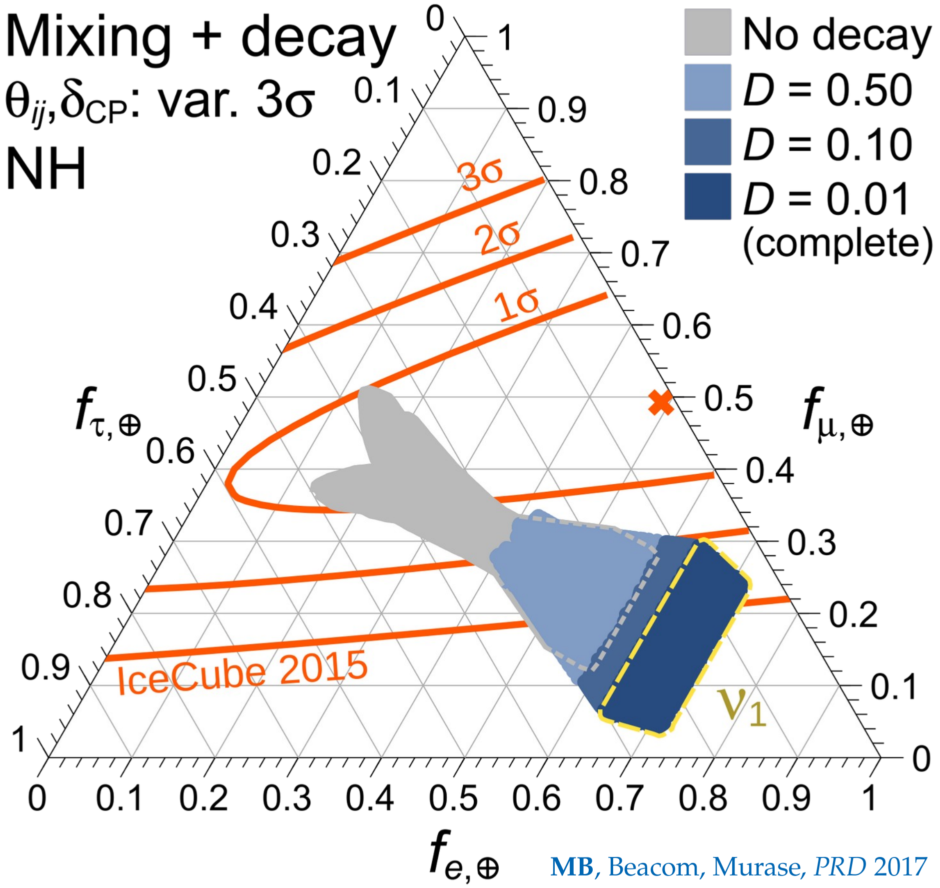
Repurpose the flavor sensitivity to test new physics:

Reviews:
Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017

New physics in flavor composition

Repurpose the flavor sensitivity to test new physics:

- Neutrino decay
  [Beacom *et al.*, *PRL* 2003; Baerwald, **MB**, Winter, JCAP 2010; **MB**, Beacom, Winter, *PRL* 2015; **MB**, Beacom, Murase, *PRD* 2017]



MB, Beacom, Murase, *PRD* 2017

Reviews:
Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017

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  [Xu, He, Rodejohann, *JCAP* 2014; Ahlers, **MB**, Mu, *PRD* 2018;
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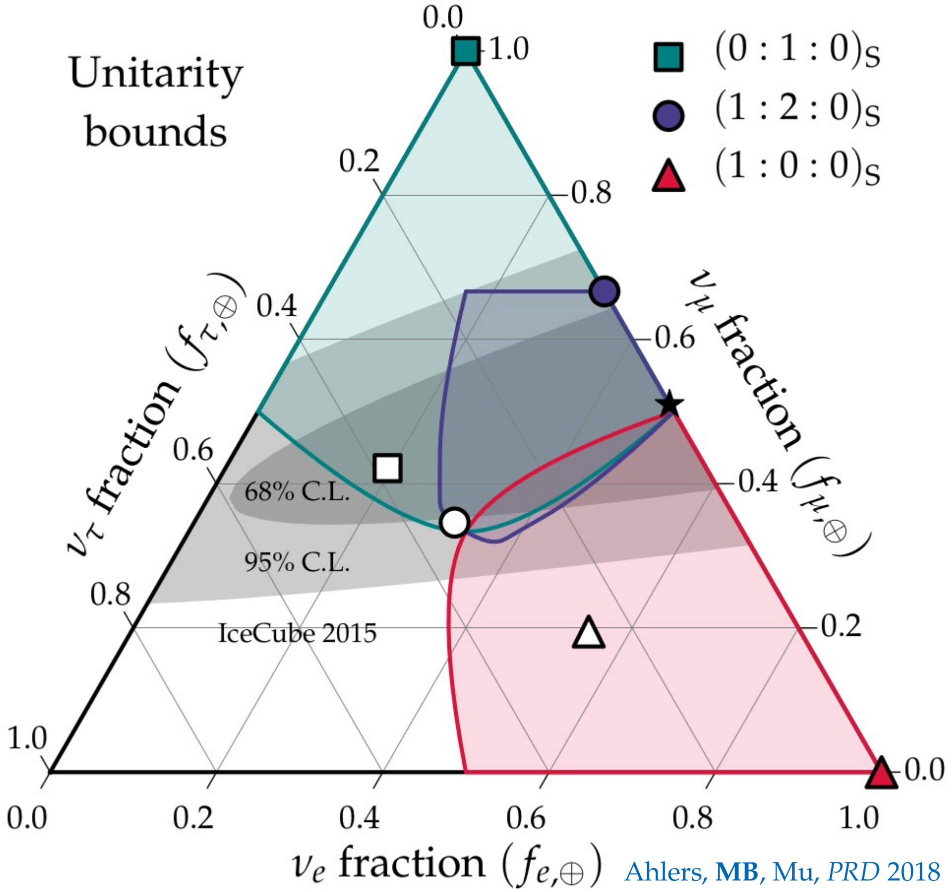

Ahlers, **MB**, Mu, *PRD* 2018

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Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017

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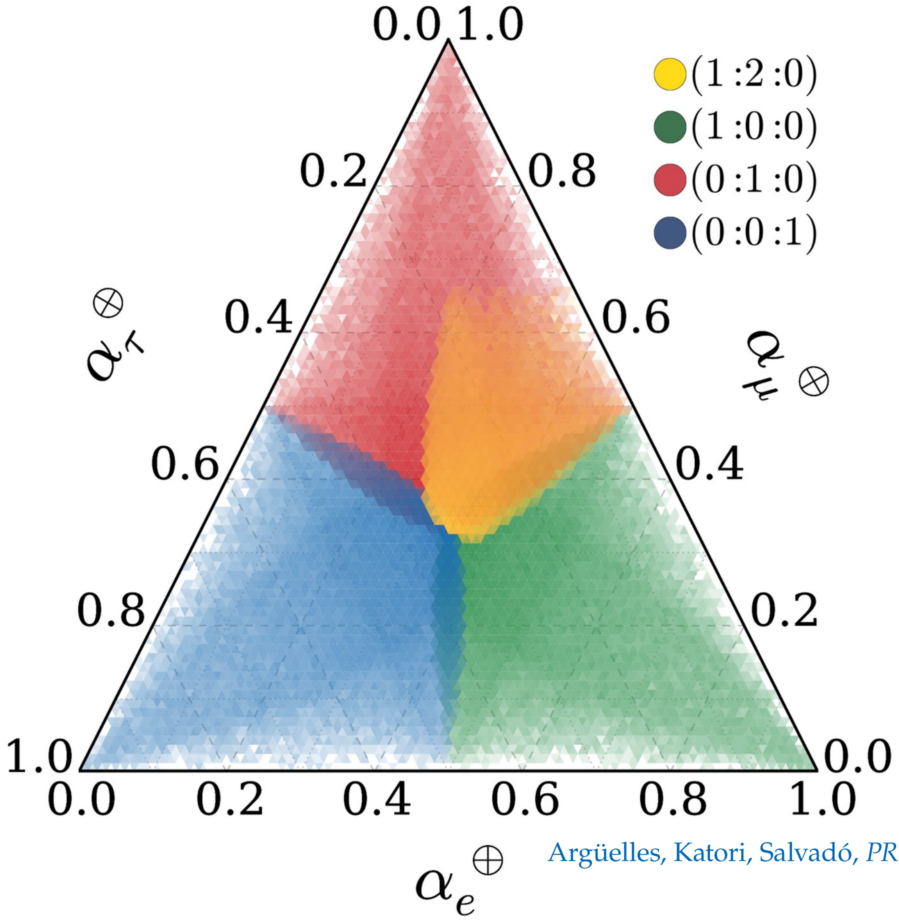

Argüelles, Katori, Salvadó, *PRL* 2015

Reviews:
Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017

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  [González-García *et al.*, *Astropart. Phys.* 2016;
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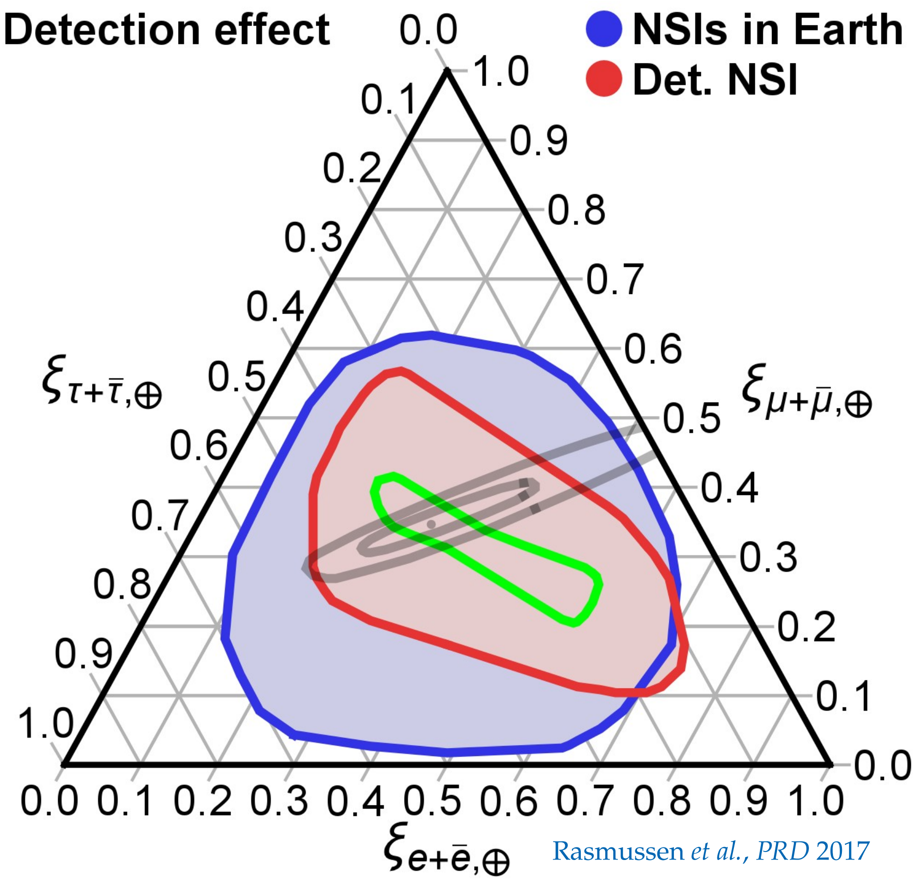

Rasmussen *et al.*, *PRD* 2017

Reviews:
Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017

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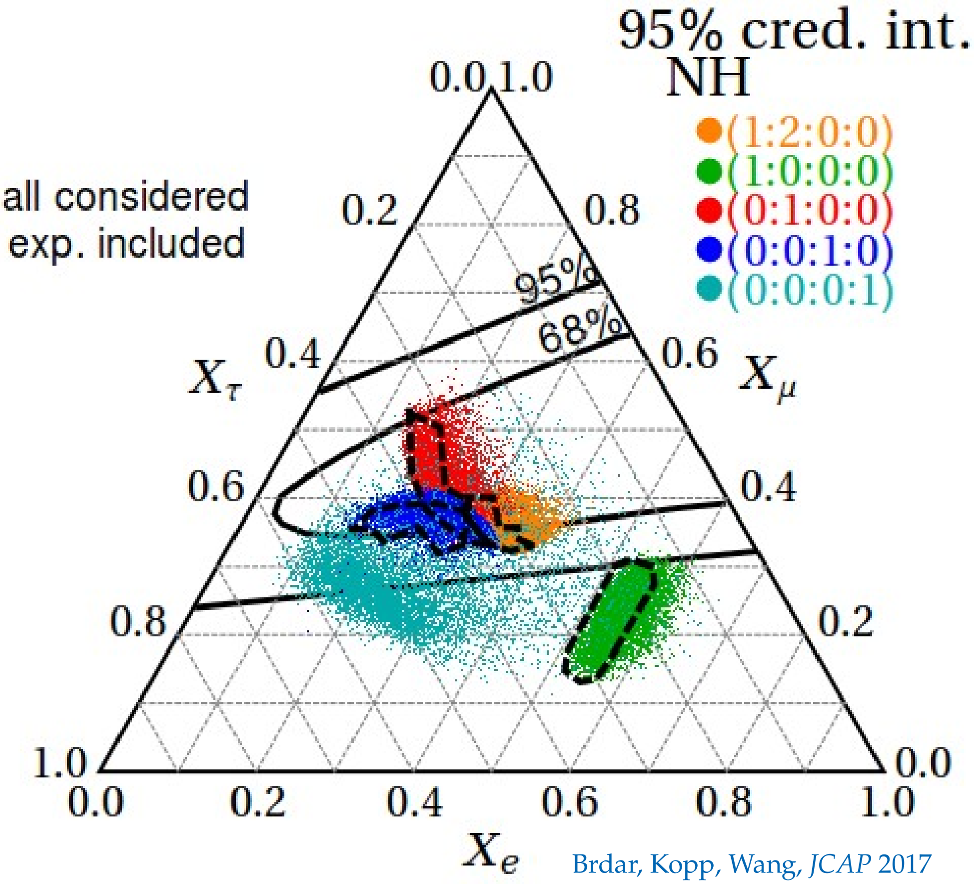
- Non-standard interactions
  [González-García *et al.*, *Astropart. Phys.* 2016; Rasmussen *et al.*, *PRD* 2017]
- Active-sterile ν mixing
  [Aeikens *et al.*, *JCAP* 2015; Brdar, Kopp, Wang, *JCAP* 2017; Argüelles *et al.*, *JCAP* 2020; Ahlers, **MB**, *JCAP* 2021]



Brdar, Kopp, Wang, *JCAP* 2017

Reviews:
Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017

New physics in flavor composition

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  MB, Beacom, Winter, *PRL* 2015; **MB**, Beacom, Murase, *PRD* 2017]
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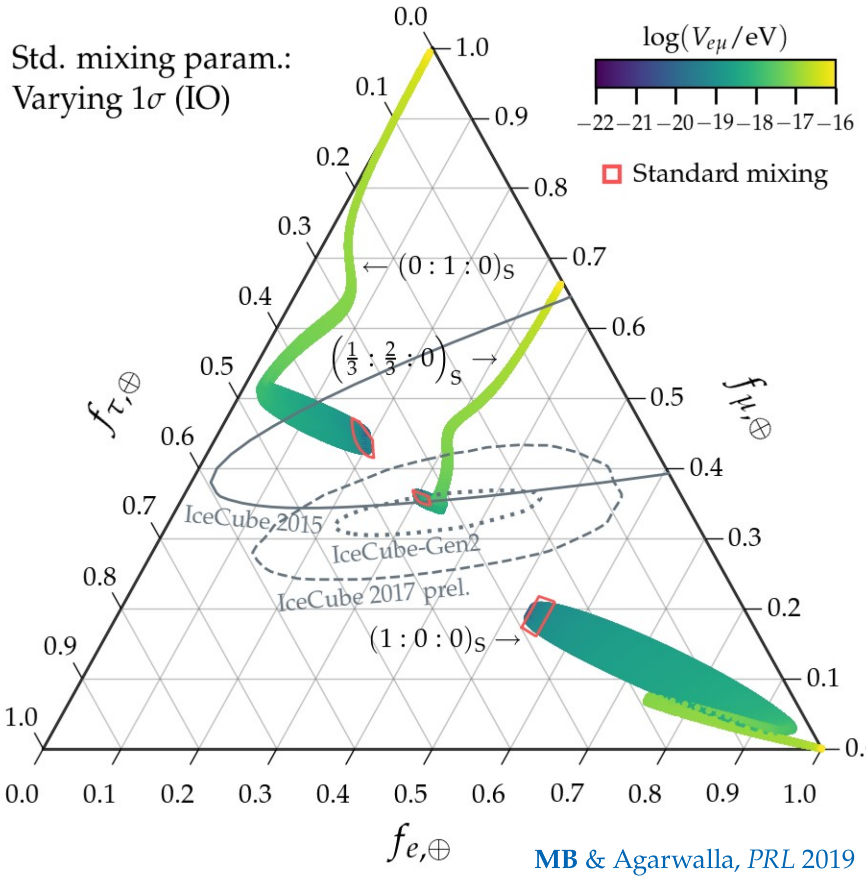
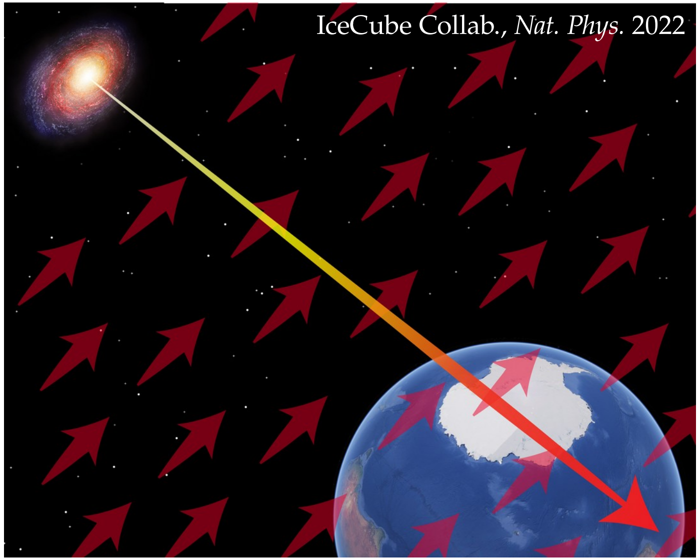
  Argüelles *et al.*, *JCAP* 2020; Ahlers, **MB**, *JCAP* 2021]
- Long-range *e*ν interactions
  [**MB** & Agarwalla, *PRL* 2019]

Reviews:
Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017



MB & Agarwalla, *PRL* 2019

Lorentz-invariance violation can fill up the flavor triangle

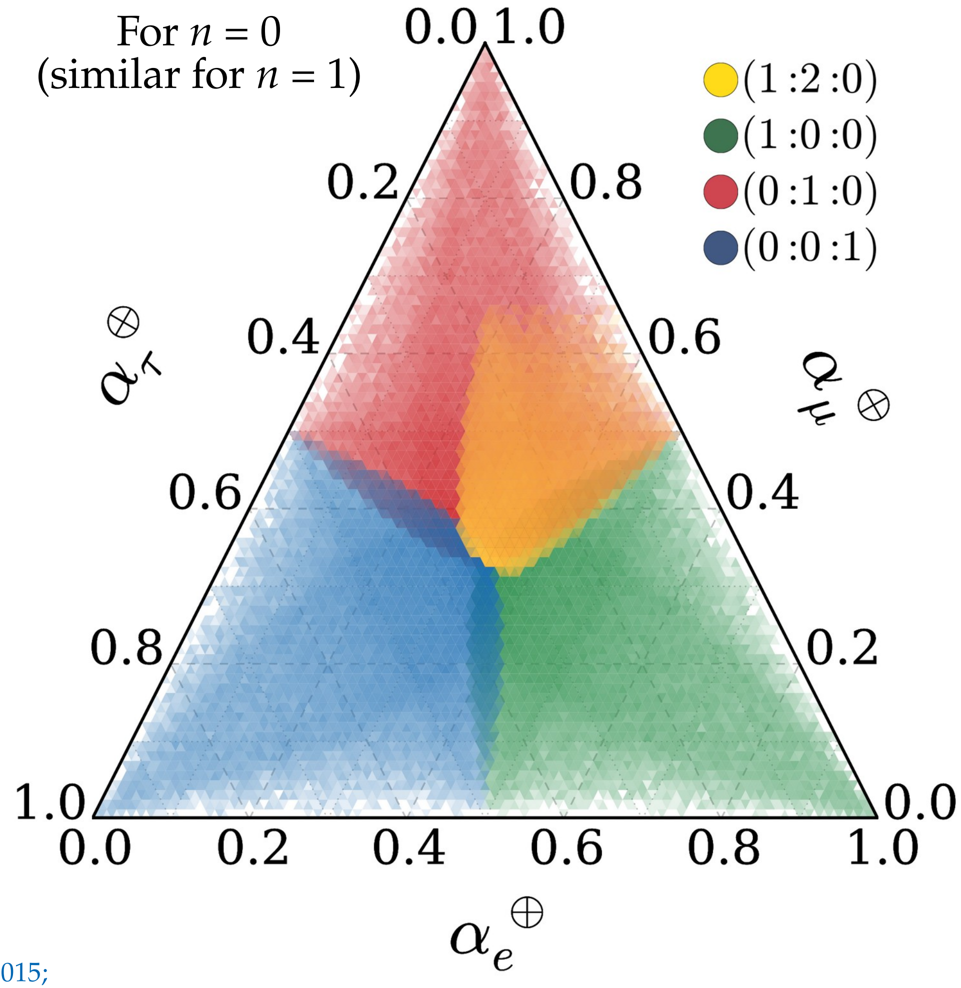

IceCube Collab., *Nat. Phys.* 2022

$$H_{\text{tot}} = H_{\text{std}} + H_{\text{NP}}$$

$$H_{\text{std}} = \frac{1}{2E} U^{\dagger}_{\text{PMNS}} \, \text{diag}\left(0, \Delta m^2_{21}, \Delta m^2_{31}\right) U_{\text{PMNS}}$$

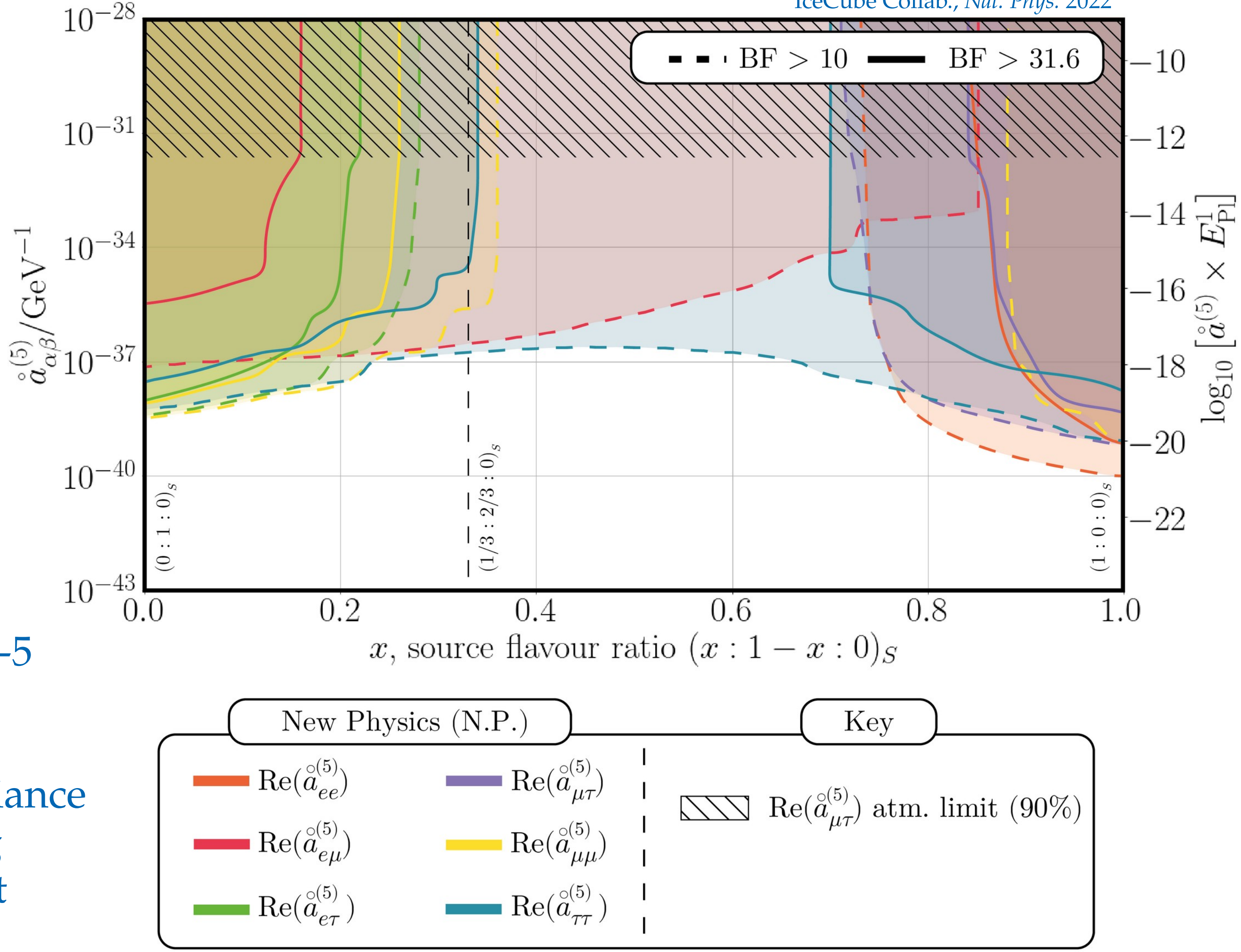
$$H_{\text{NP}} = \sum_{n} \left(\frac{E}{\Lambda_n}\right)^{n} U^{\dagger}_{n} \, \text{diag}\left(O_{n,1}, O_{n,2}, O_{n,3}\right) U_{n}$$

See also: Ahlers, **MB**, Mu, *PRD* 2018; Rasmusen *et al.*, *PRD* 2017; **MB**, Beacom, Winter *PRL* 2015; **MB**, Gago, Peña-Garay *JCAP* 2010; Bazo, **MB**, Gago, Miranda *IJMPA* 2009; + many others


For $n = 0$
(similar for $n = 1$)

Argüelles, Katori, Salvadó, *PRL* 2015

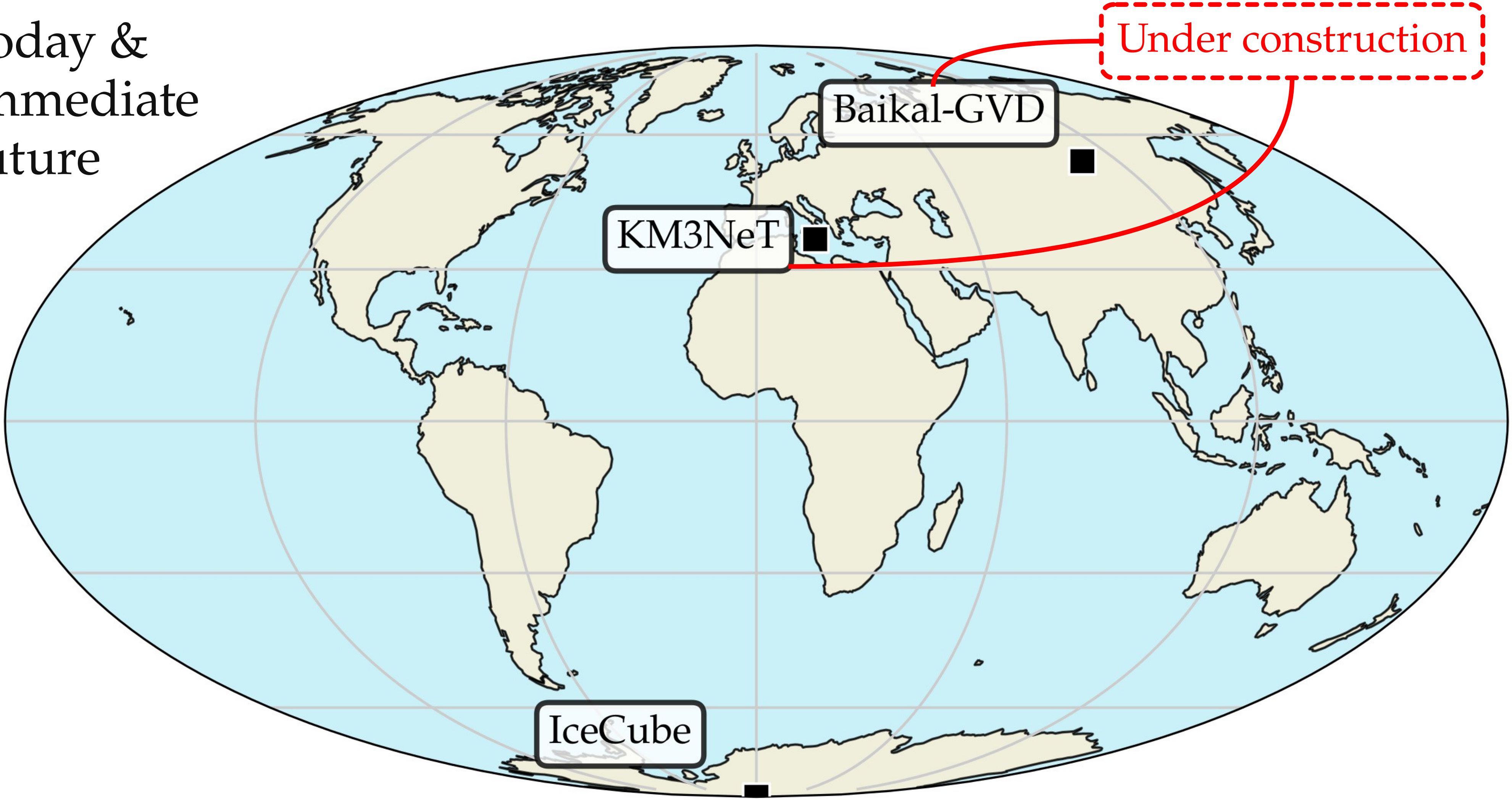
IceCube Collab., *Nat. Phys.* 2022



Dimension-5
CPT-odd
Isotropic
Lorentz-invariance
-violating
coefficient

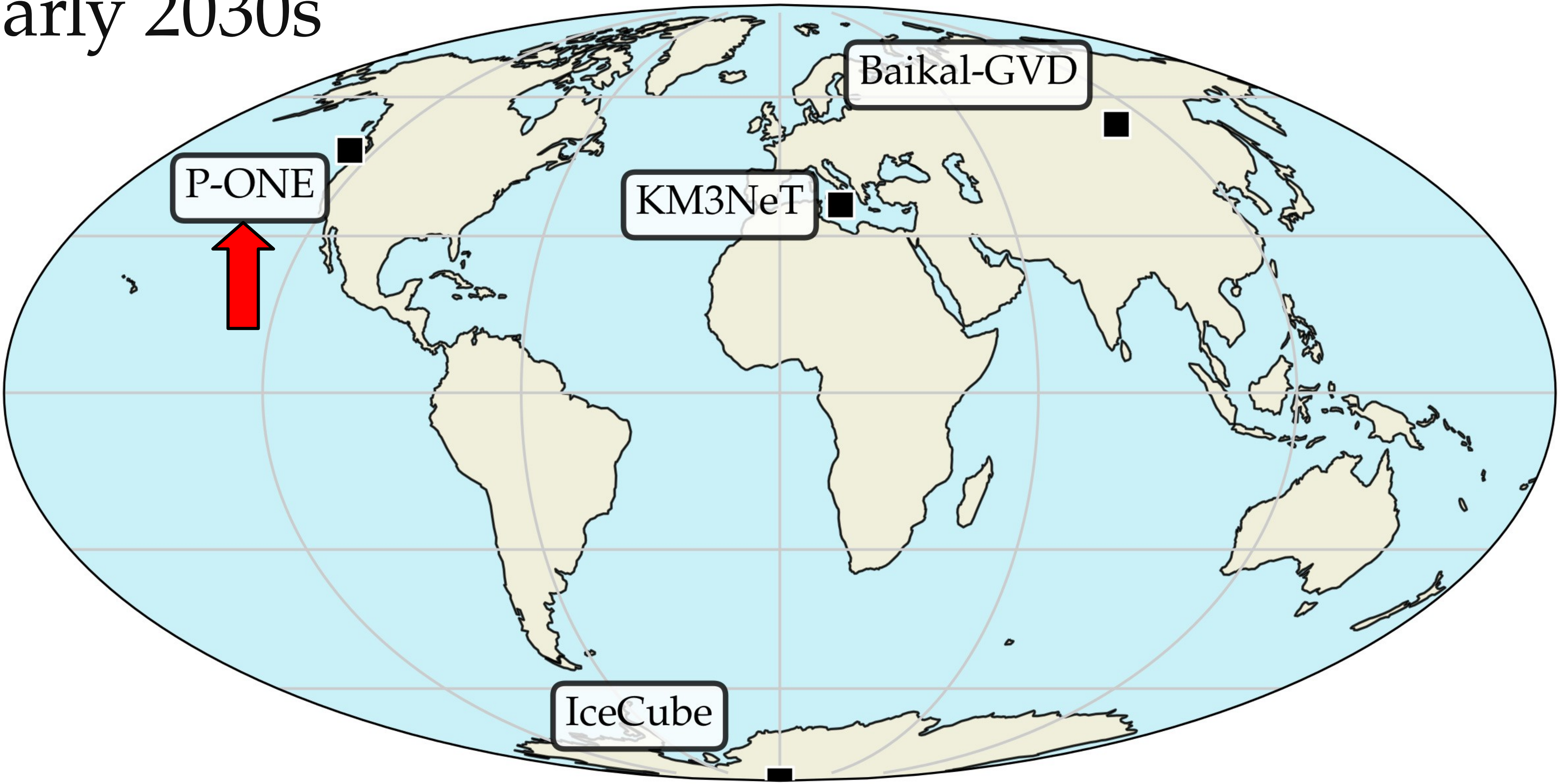
The future

Today & immediate future



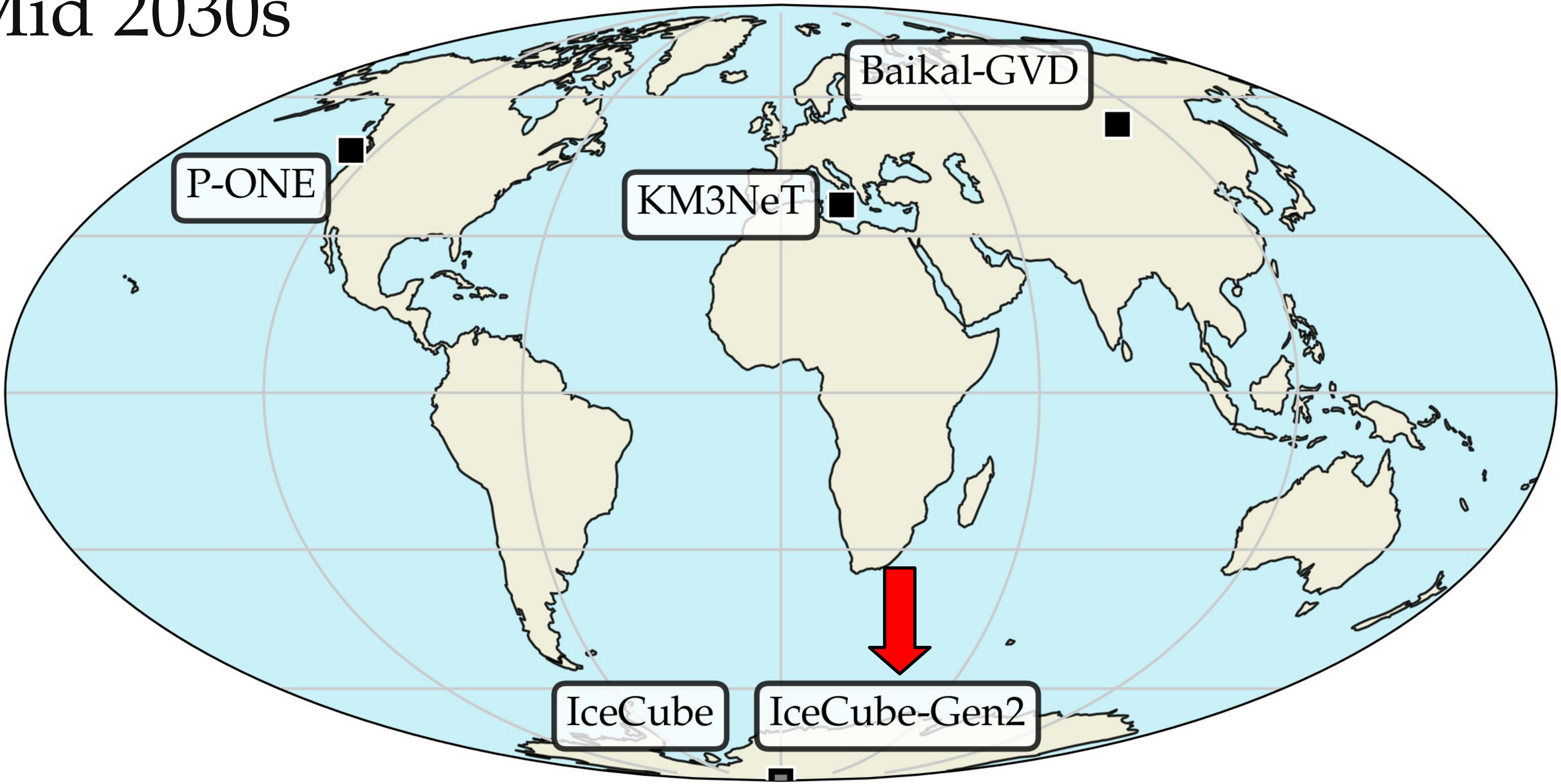
Schumacher, Agostini, **MB**, Oikonomou, Resconi, *In prep.*

Early 2030s



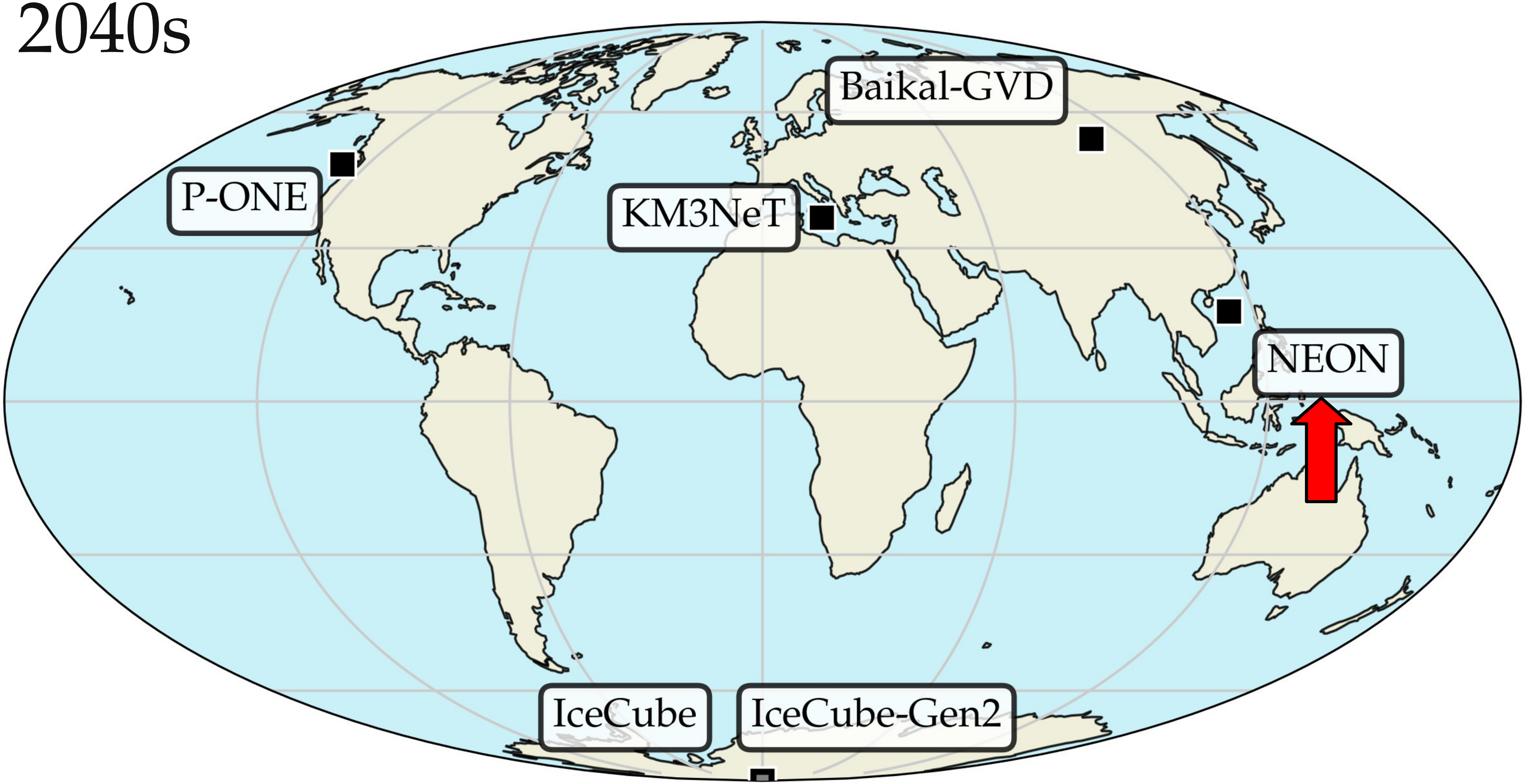
Schumacher, Agostini, **MB**, Oikonomou, Resconi, *In prep.*

Mid 2030s



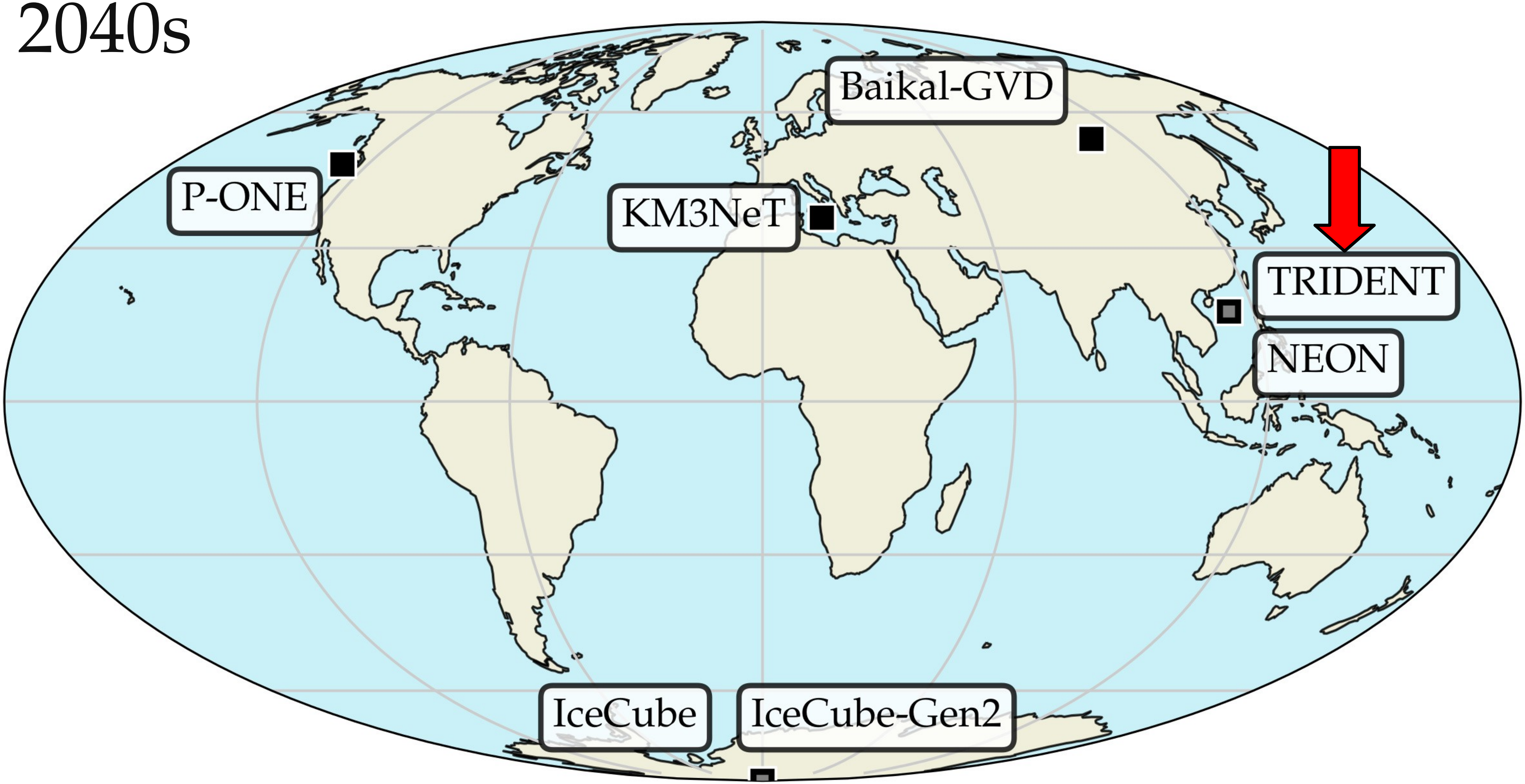
Schumacher, Agostini, **MB**, Oikonomou, Resconi, *In prep.*

2040s

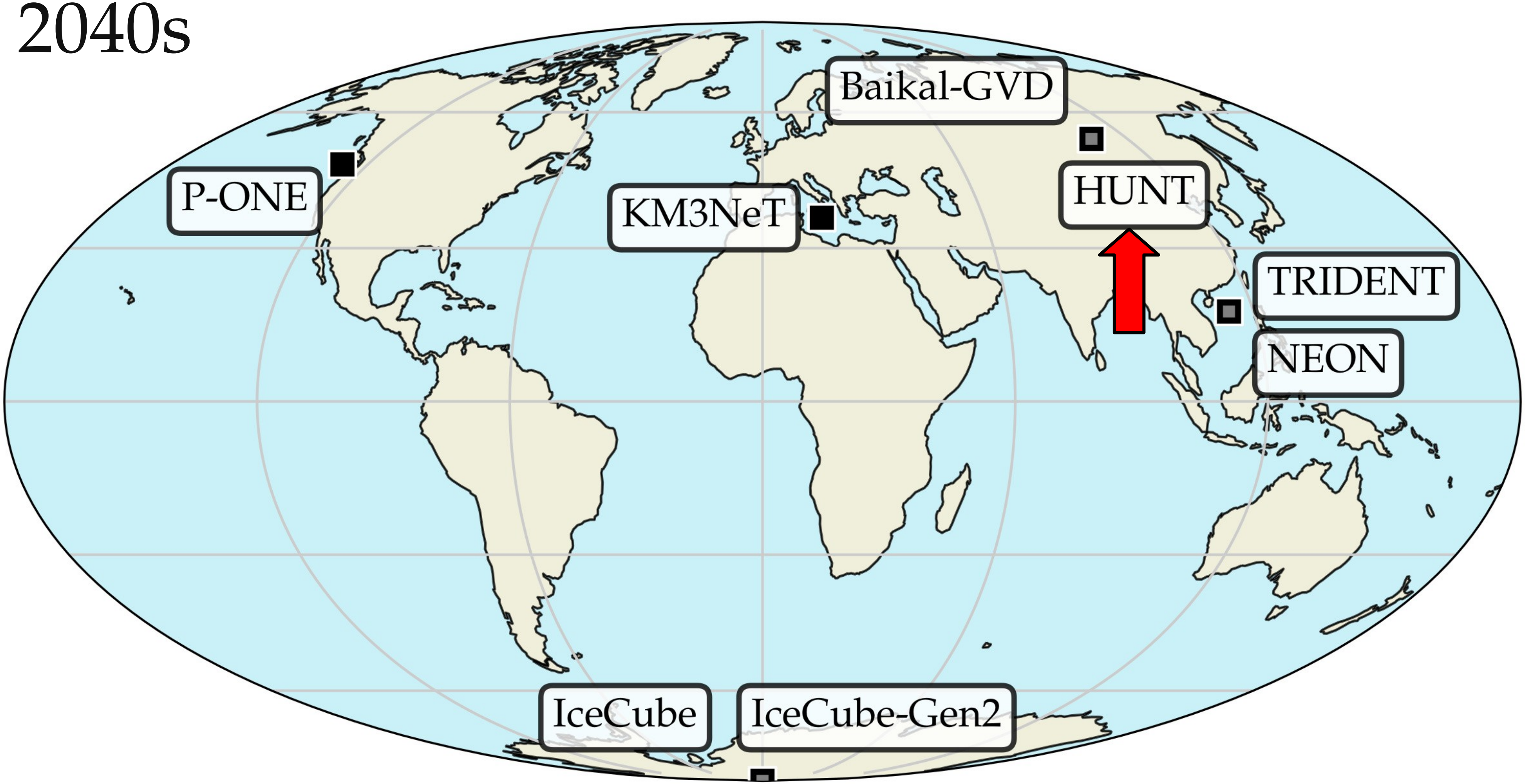


Schumacher, Agostini, **MB**, Oikonomou, Resconi, *In prep.*

2040s

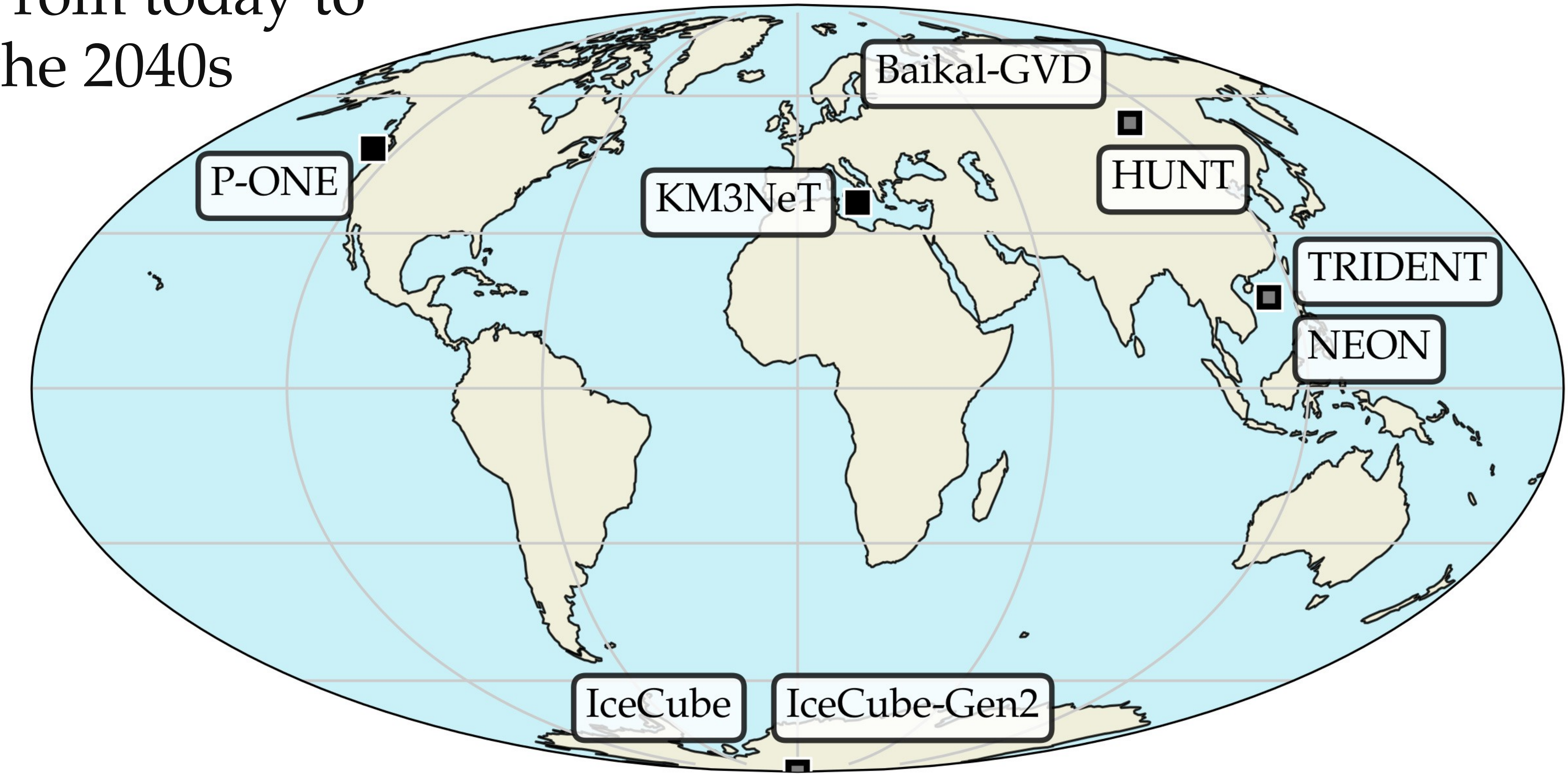


2040s



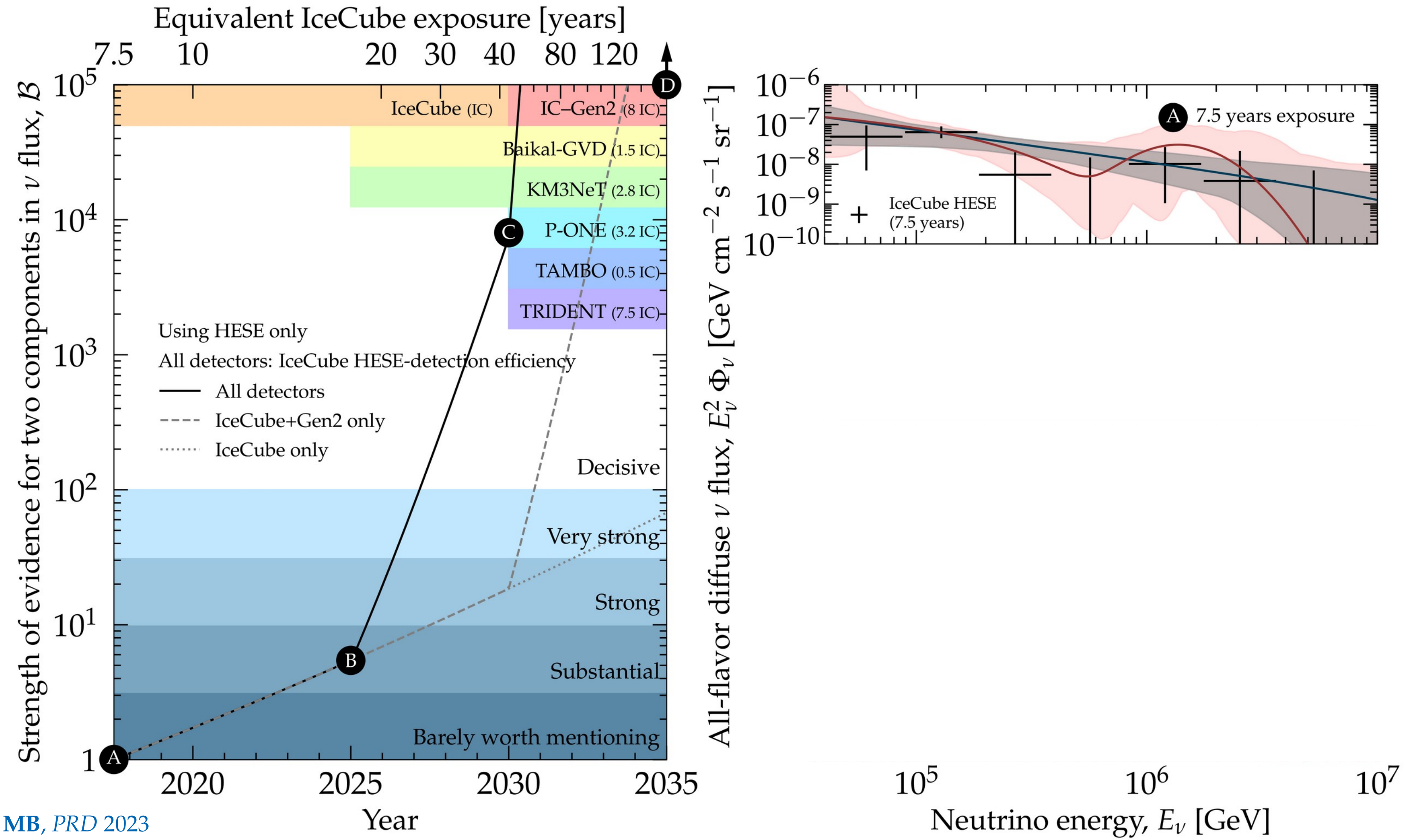
Schumacher, Agostini, **MB**, Oikonomou, Resconi, *In prep.*

From today to the 2040s



Bump-hunting in the diffuse flux of high-energy neutrinos

Bump-like spectra can reveal the presence of ν production via $p\gamma$:



D. F. G. Fiorillo, **MB**, *PRD* 2023

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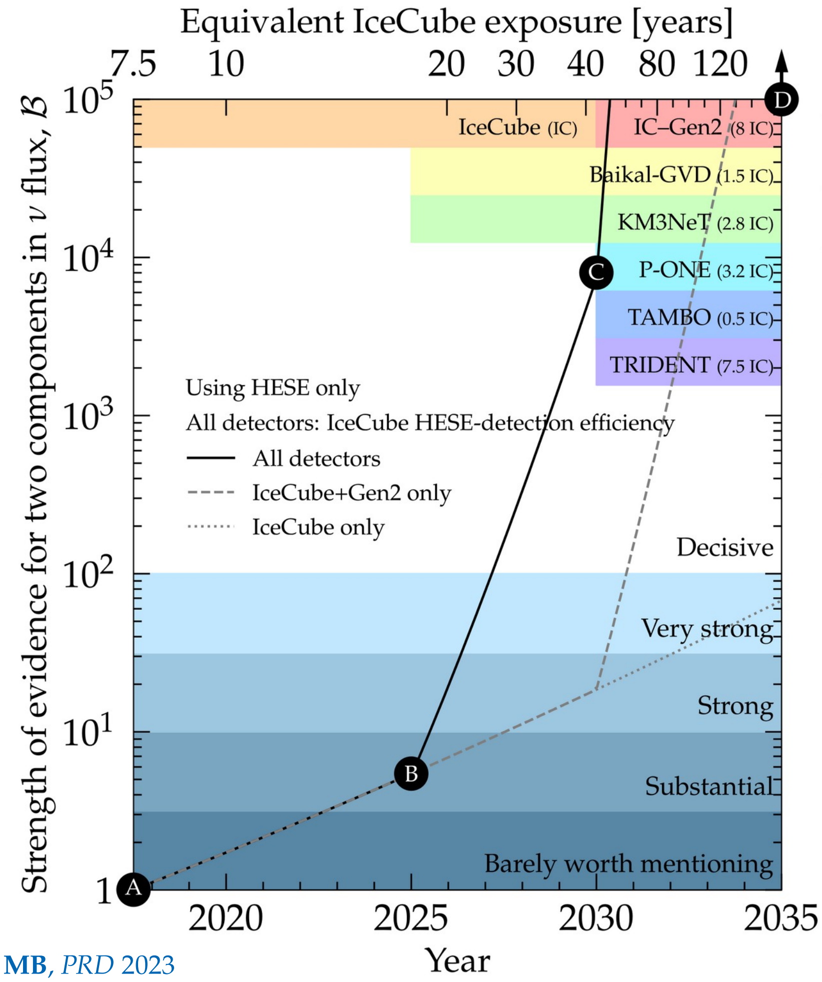

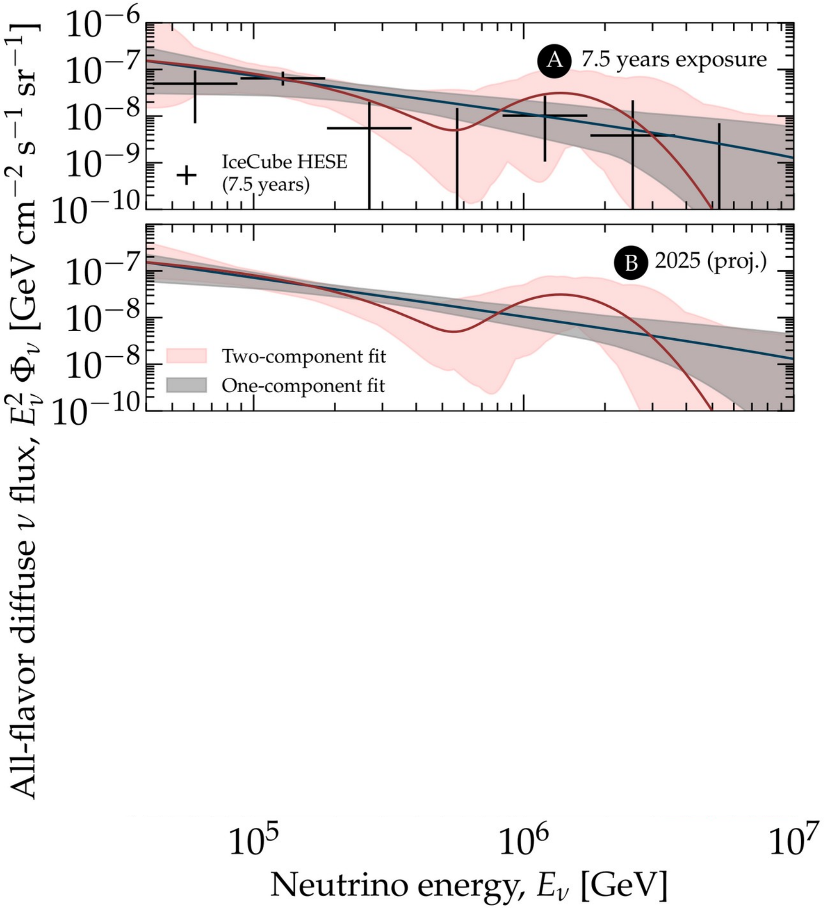

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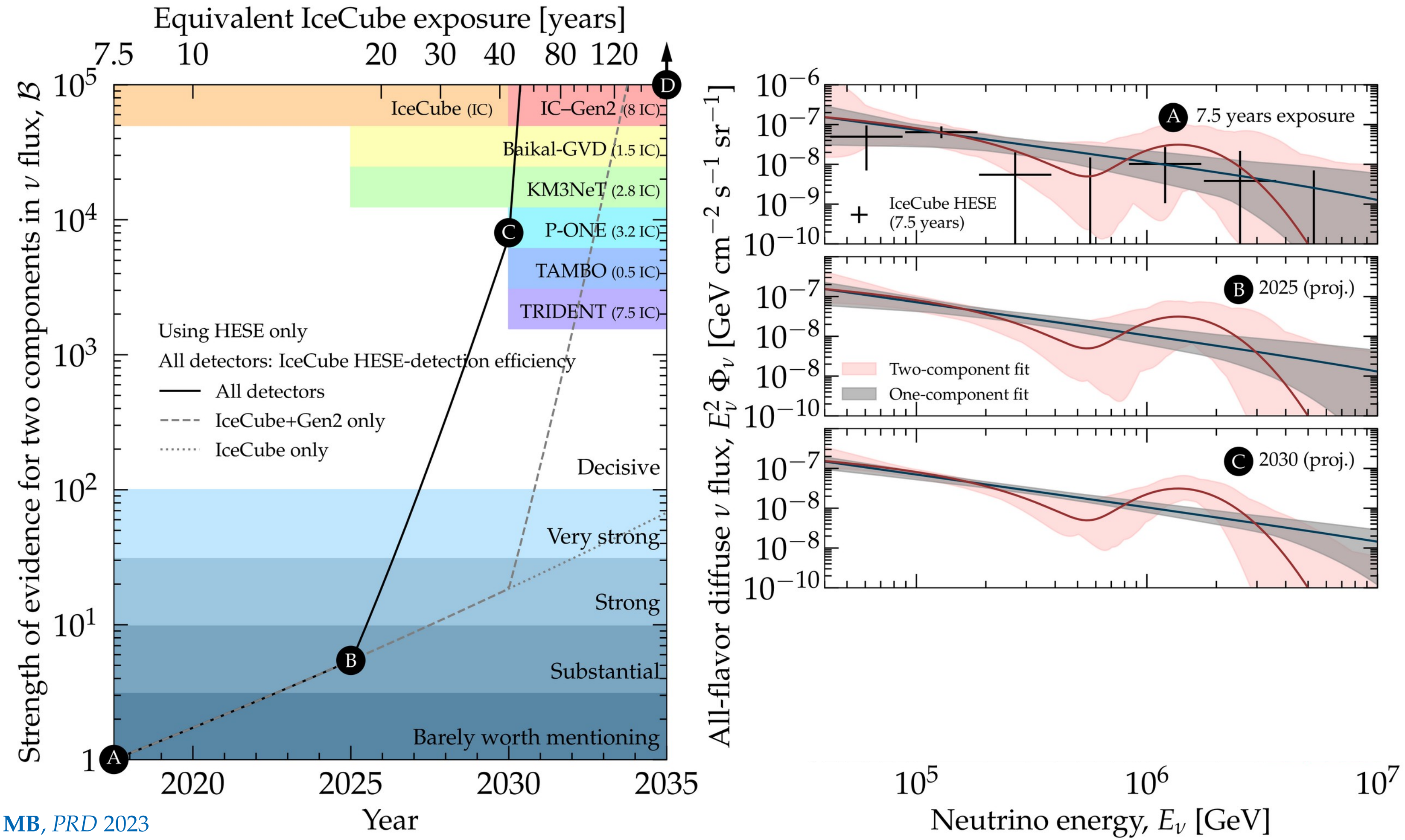

D. F. G. Fiorillo, **MB**, *PRD* 2023

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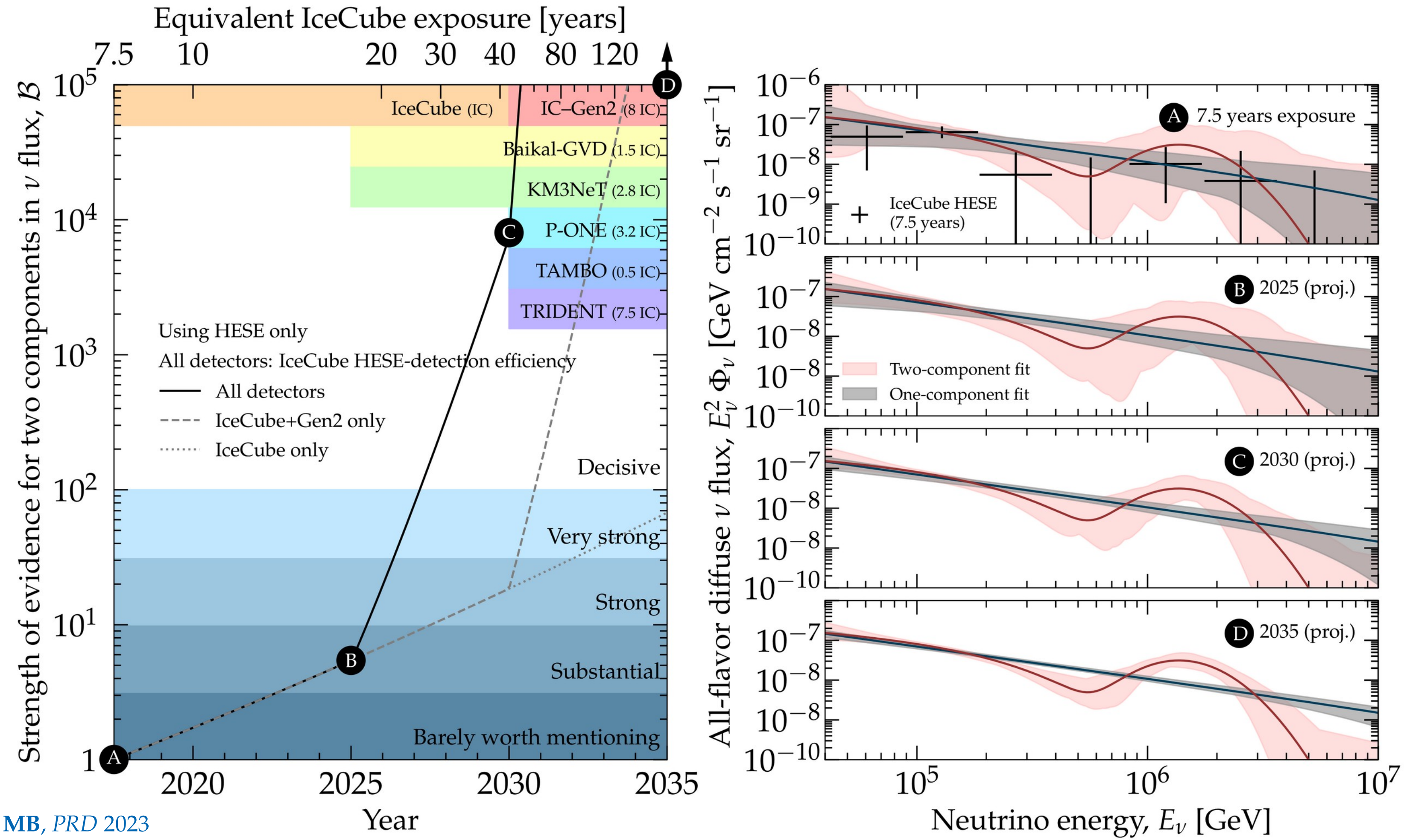

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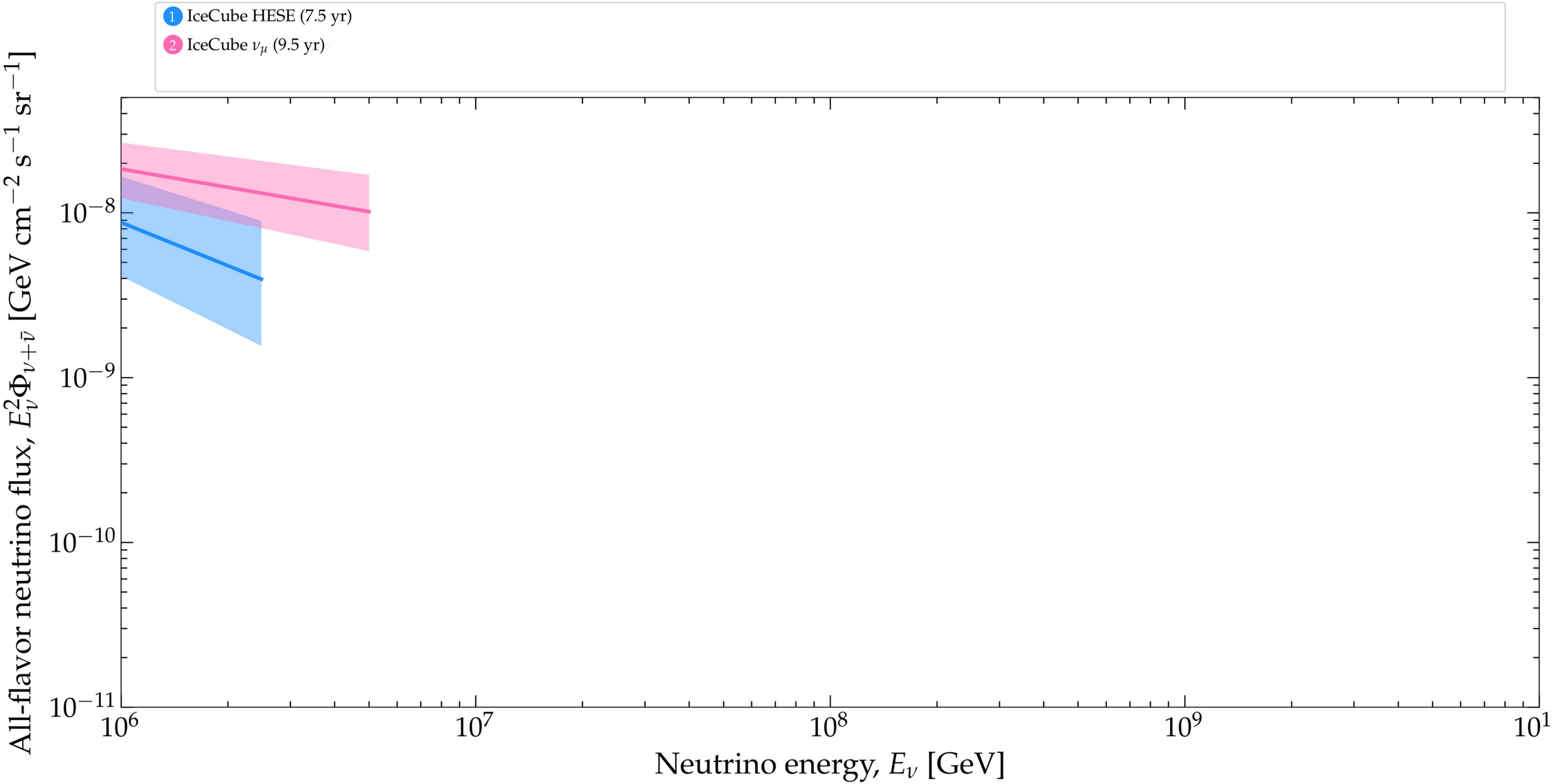
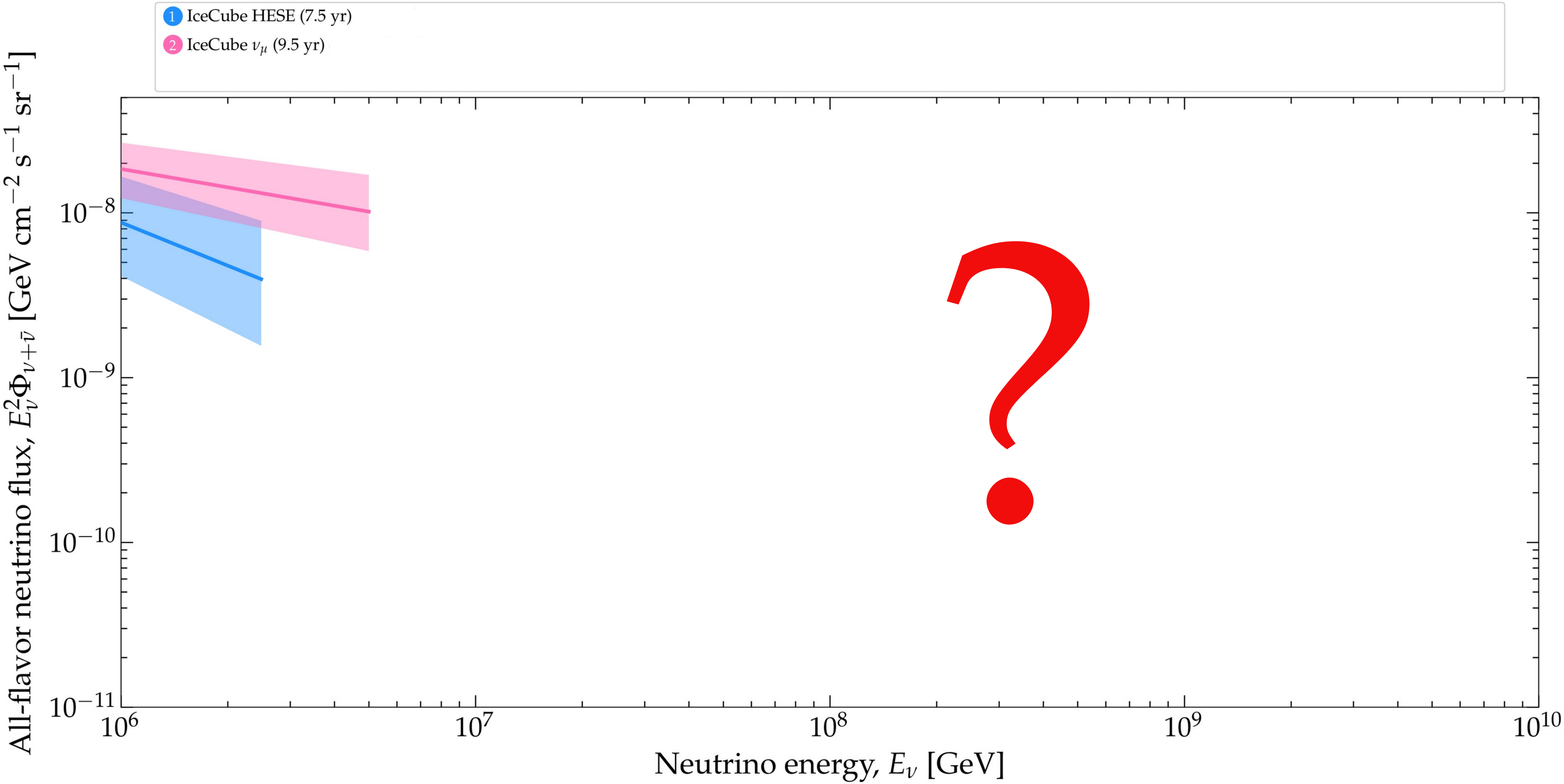

1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (9.5 yr)
All-flavor neutrino flux, $E_\nu^2\Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]



① IceCube HESE (7.5 yr)
② IceCube ν_μ (9.5 yr)
?
All-flavor neutrino flux, $E_\nu^2\Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
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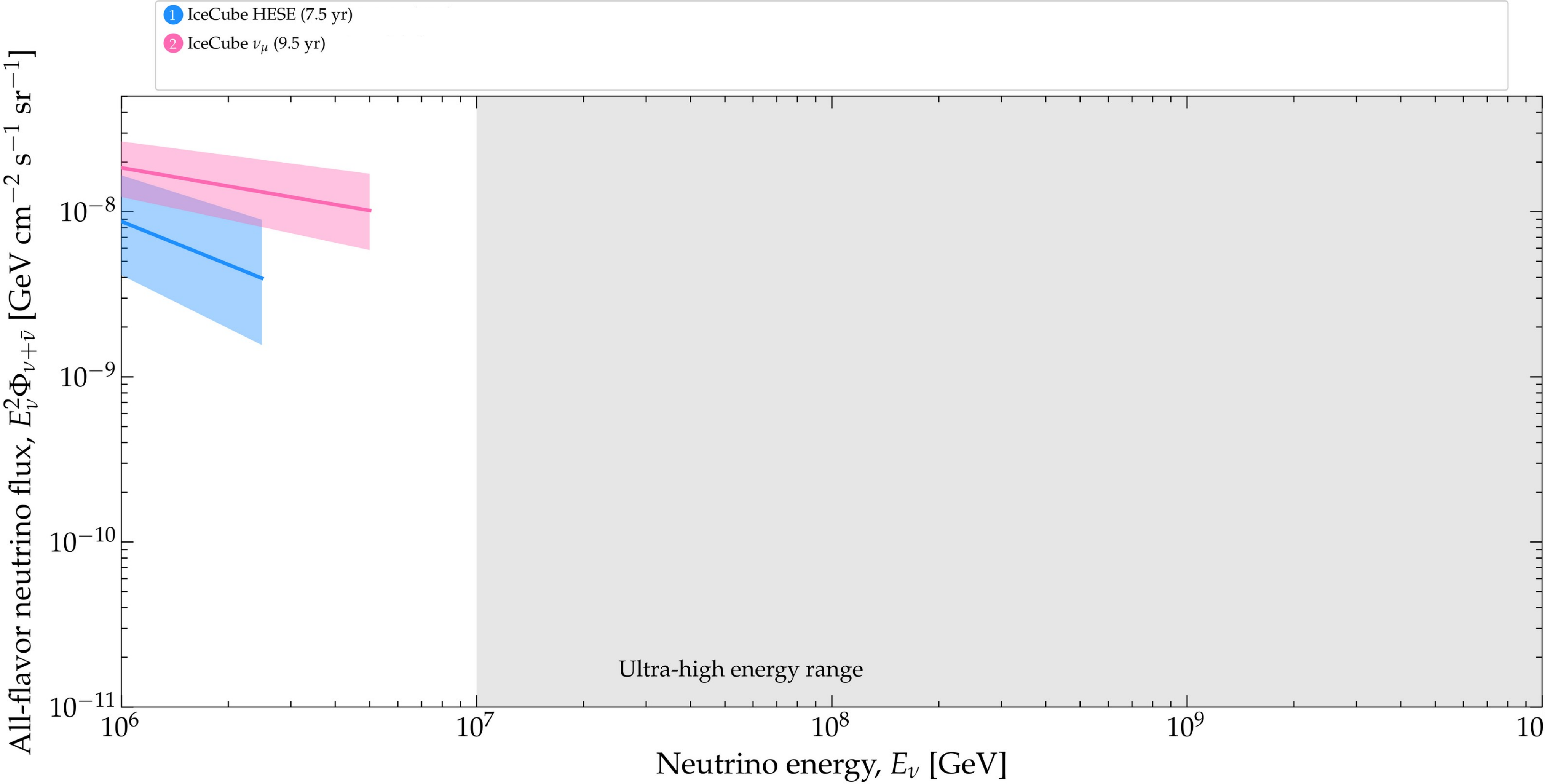
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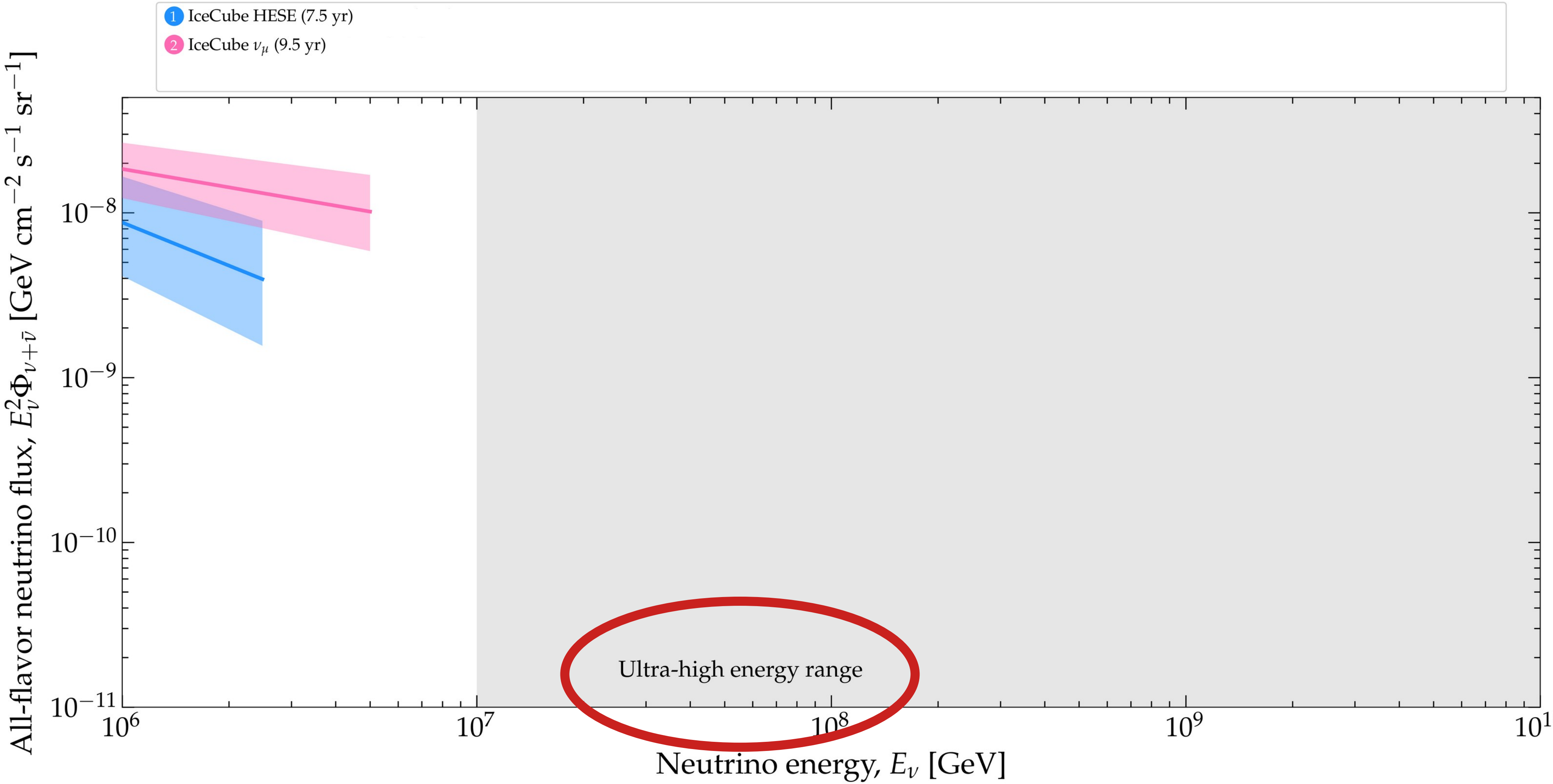
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Ultra-high energy range
Neutrino energy, E_ν [GeV]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10^{-8}
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10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
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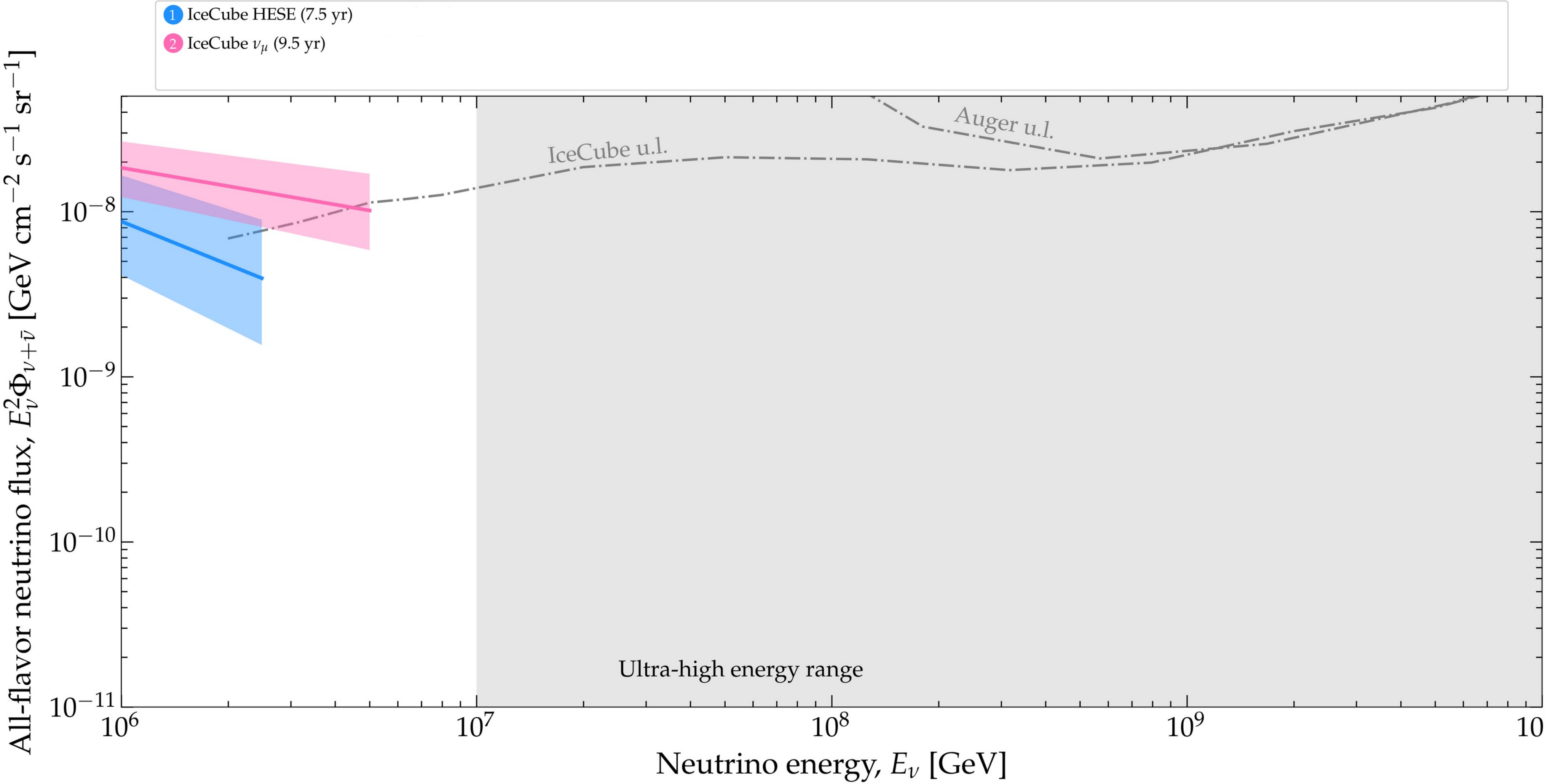
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② IceCube ν_μ (9.5 yr)
IceCube u.l.
Auger u.l.
Ultra-high energy range
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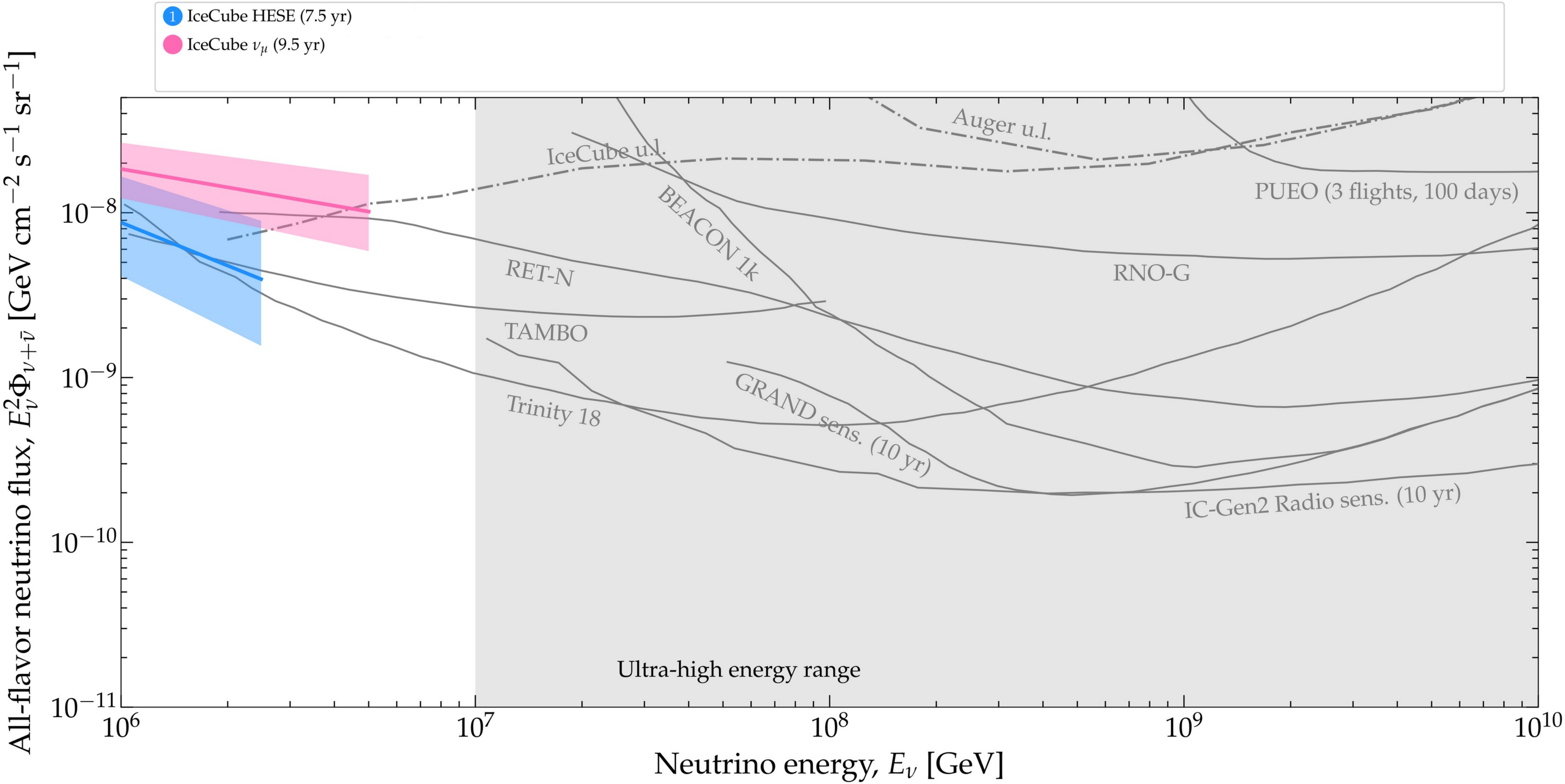
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
Neutrino energy, E_ν [GeV]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IceCube HESE (7.5 yr)
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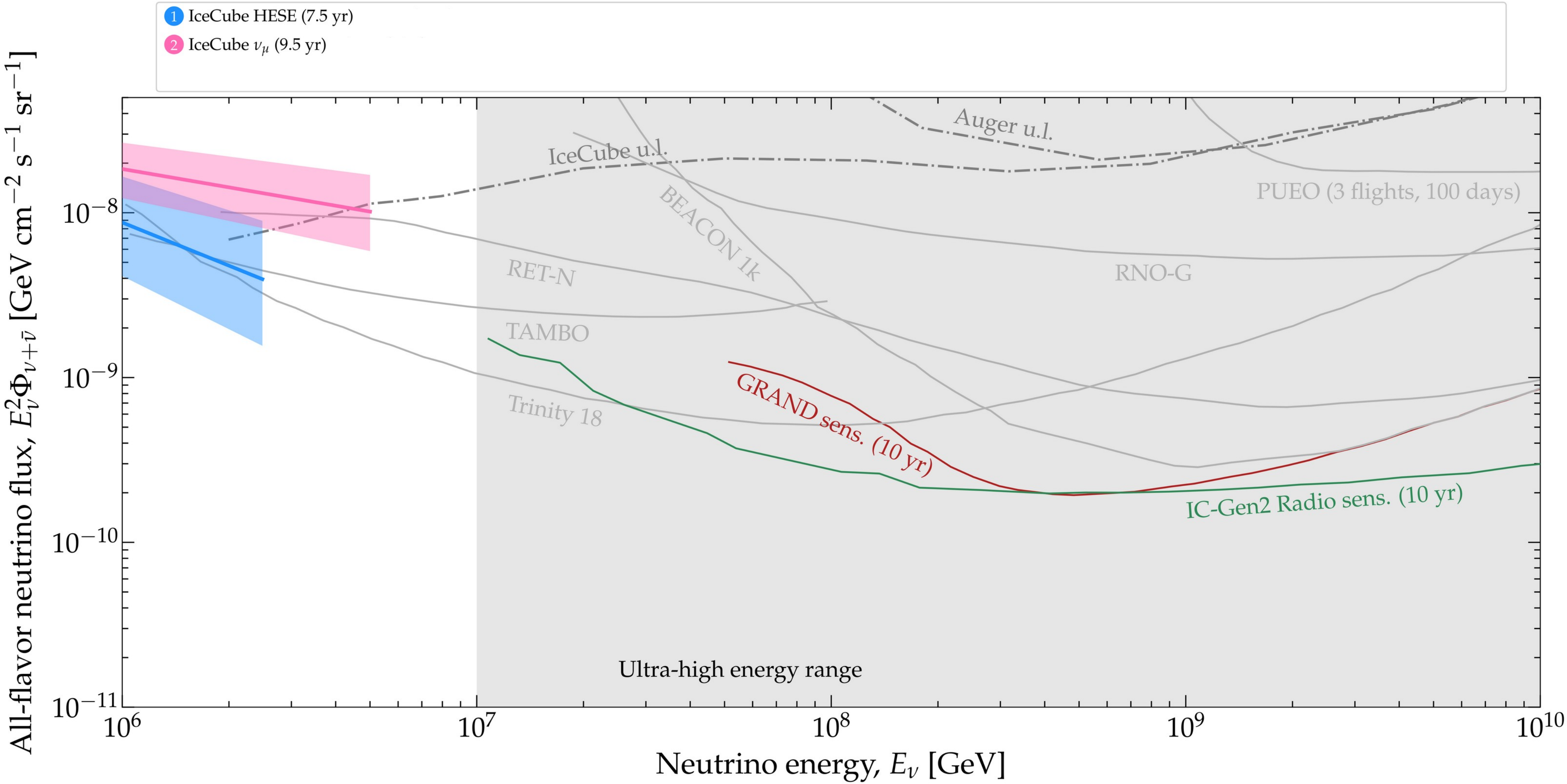
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]
Auger u.l.
IceCube u.l.
PUEO (3 flights, 100 days)
BEACON 1k
RET-N
RNO-G
TAMBO
GRAND sens. (10 yr)
Trinity 18
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range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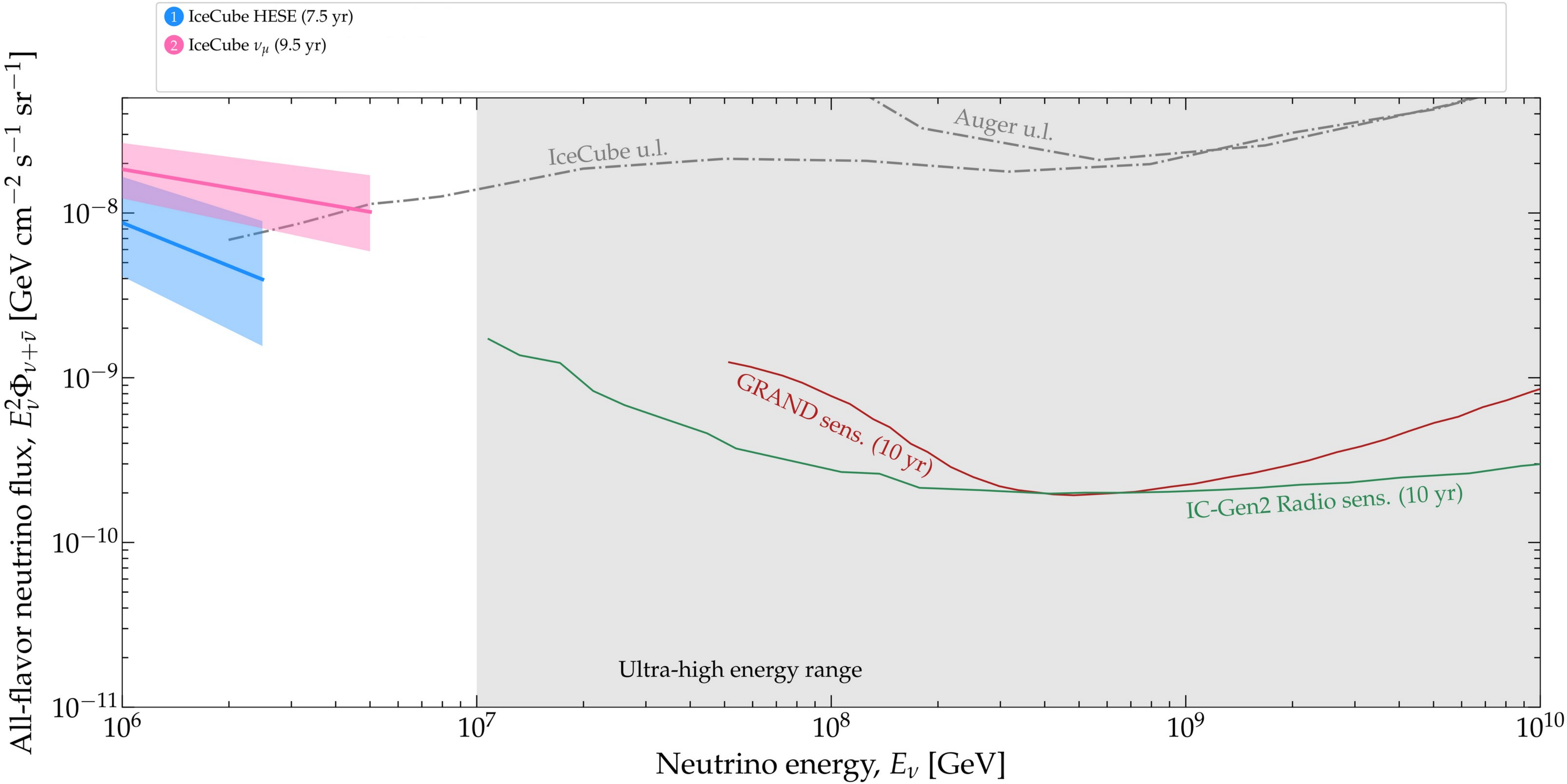
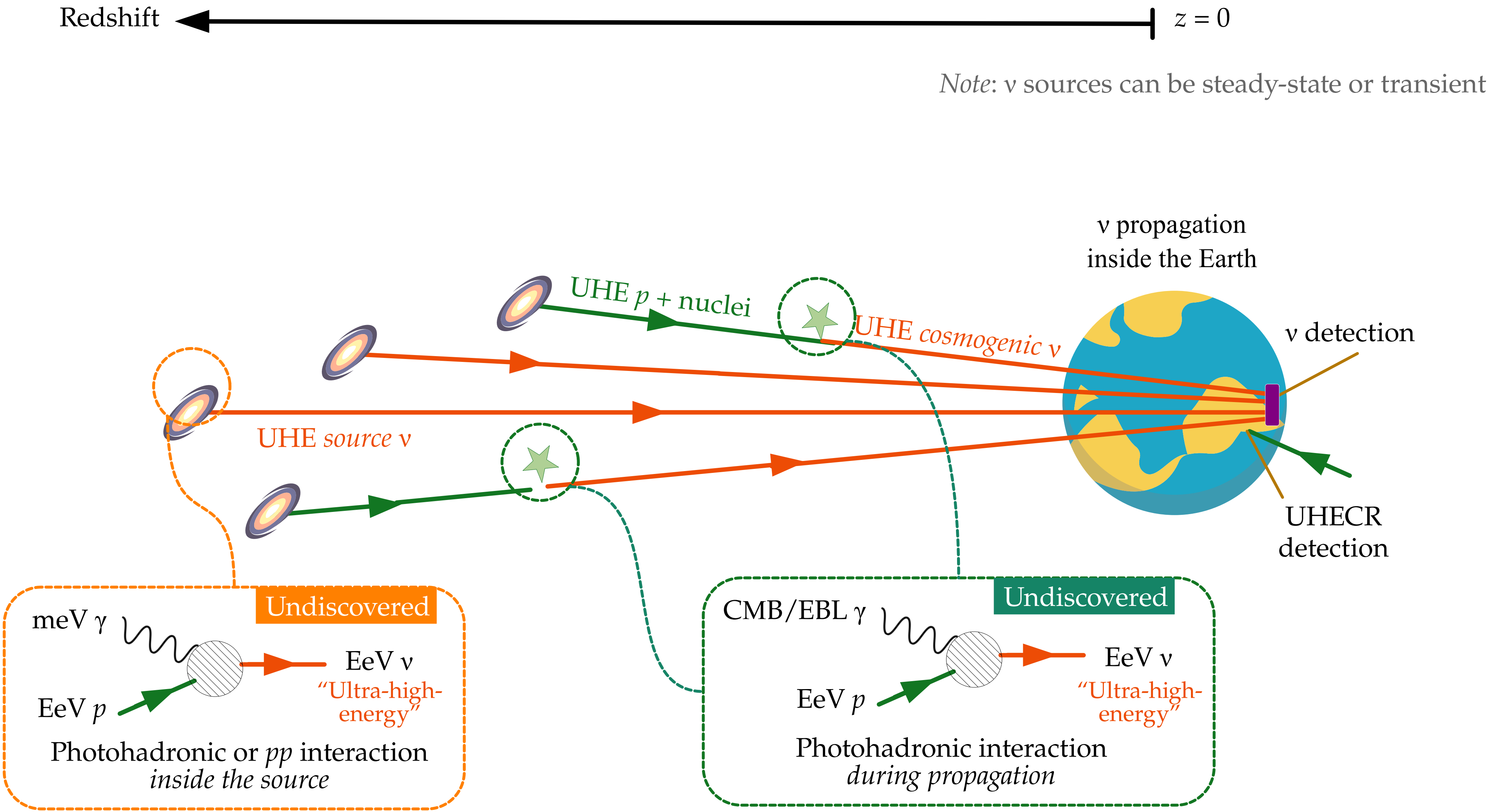
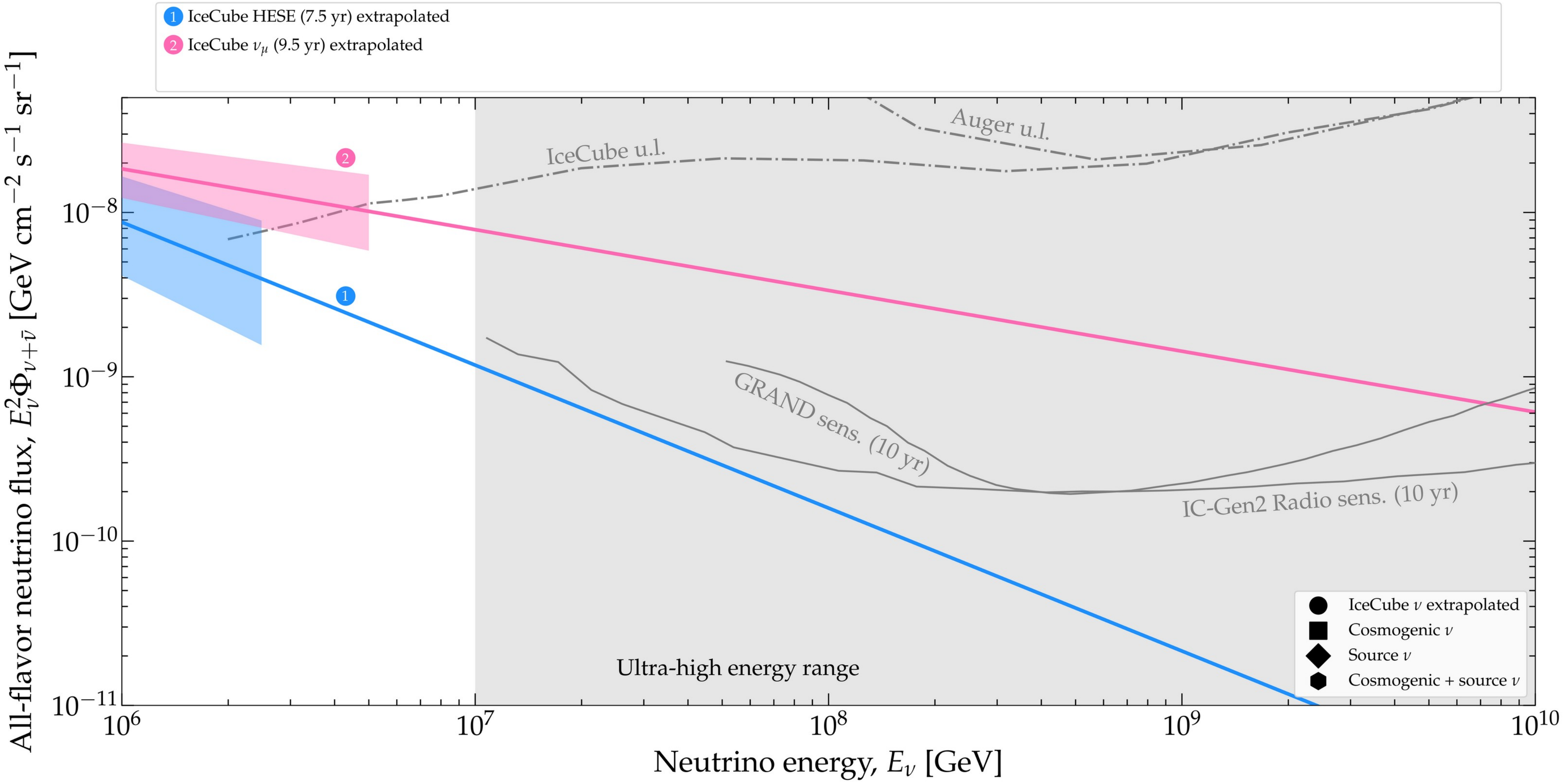
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Auger u.l.
IceCube u.l.
PUEO (3 flights, 100 days)
BEACON 1k
RET-N
RNO-G
TAMBO
Trinity 18
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range


① IceCube HESE (7.5 yr)
② IceCube ν_μ (9.5 yr)
Auger u.l.
IceCube u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]


Redshift
$z = 0$
Note: ν sources can be steady-state or transient
ν propagation
inside the Earth
UHE p + nuclei
UHE *cosmogenic* ν
ν detection
UHE *source* ν
UHECR
detection
meV γ
Undiscovered
EeV ν
EeV p
"Ultra-high-
energy"
Photohadronic or pp interaction
inside the source
CMB/EBL γ
Undiscovered
EeV ν
EeV p
"Ultra-high-
energy"
Photohadronic interaction
during propagation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Auger u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
● IceCube ν extrapolated
■ Cosmogenic ν
◆ Source ν
⬢ Cosmogenic + source ν
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10^{-11}
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10^7
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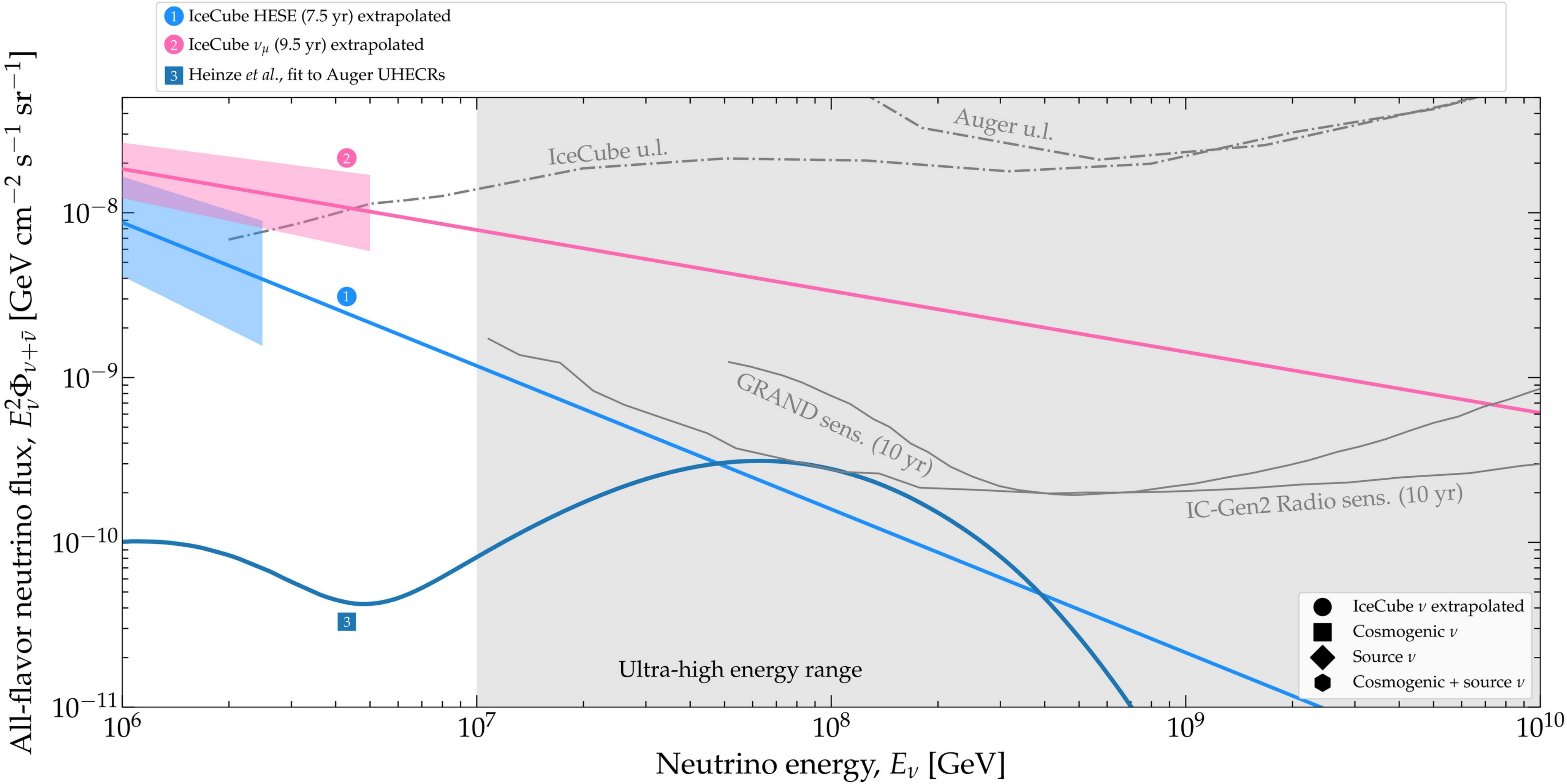
10^9
10^{10}
Neutrino energy, E_ν [GeV]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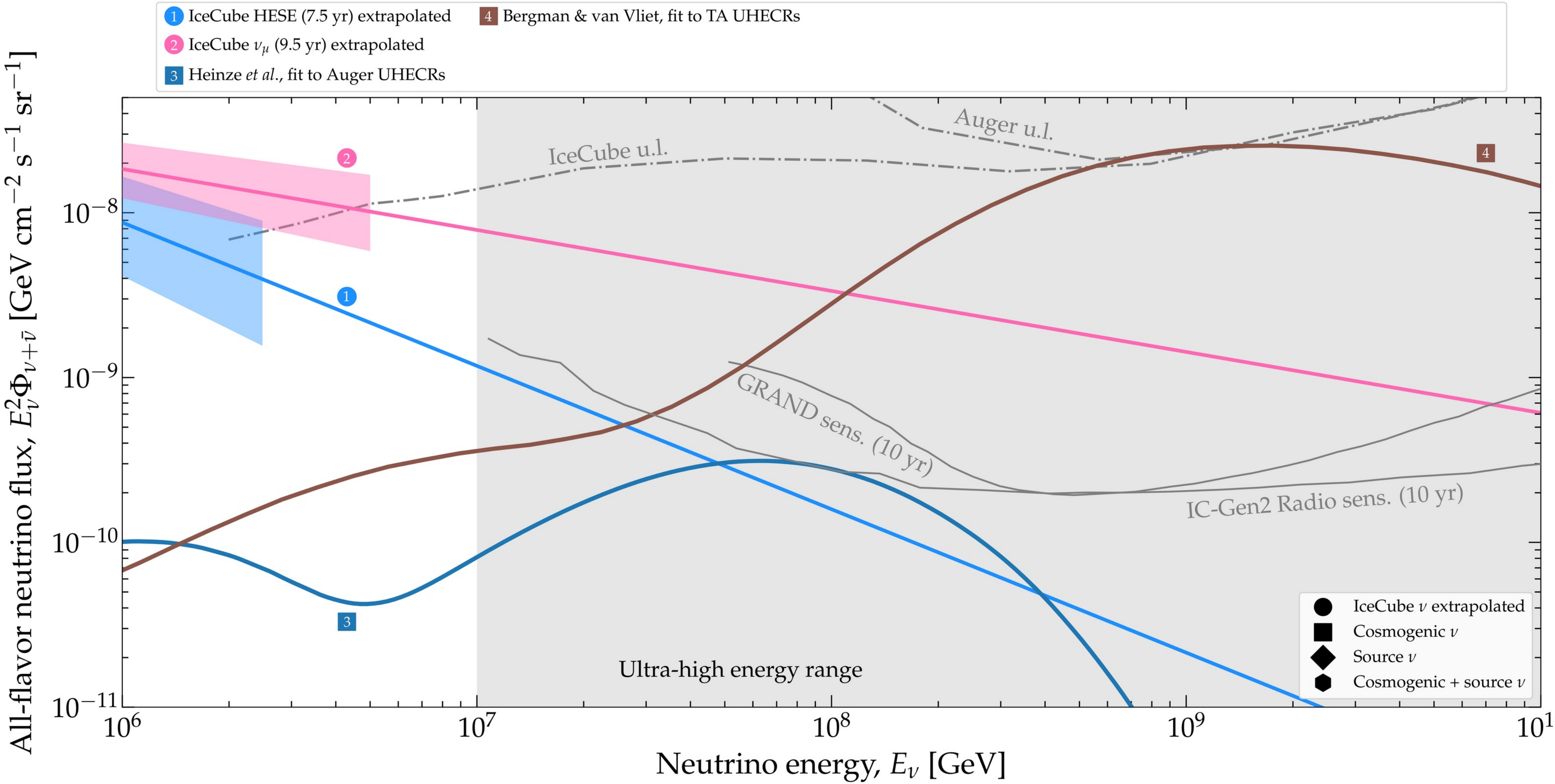
10^{-10}
10^{-11}
Neutrino energy, E_ν [GeV]
10^6
10^7
10^8
10^9
10^{10}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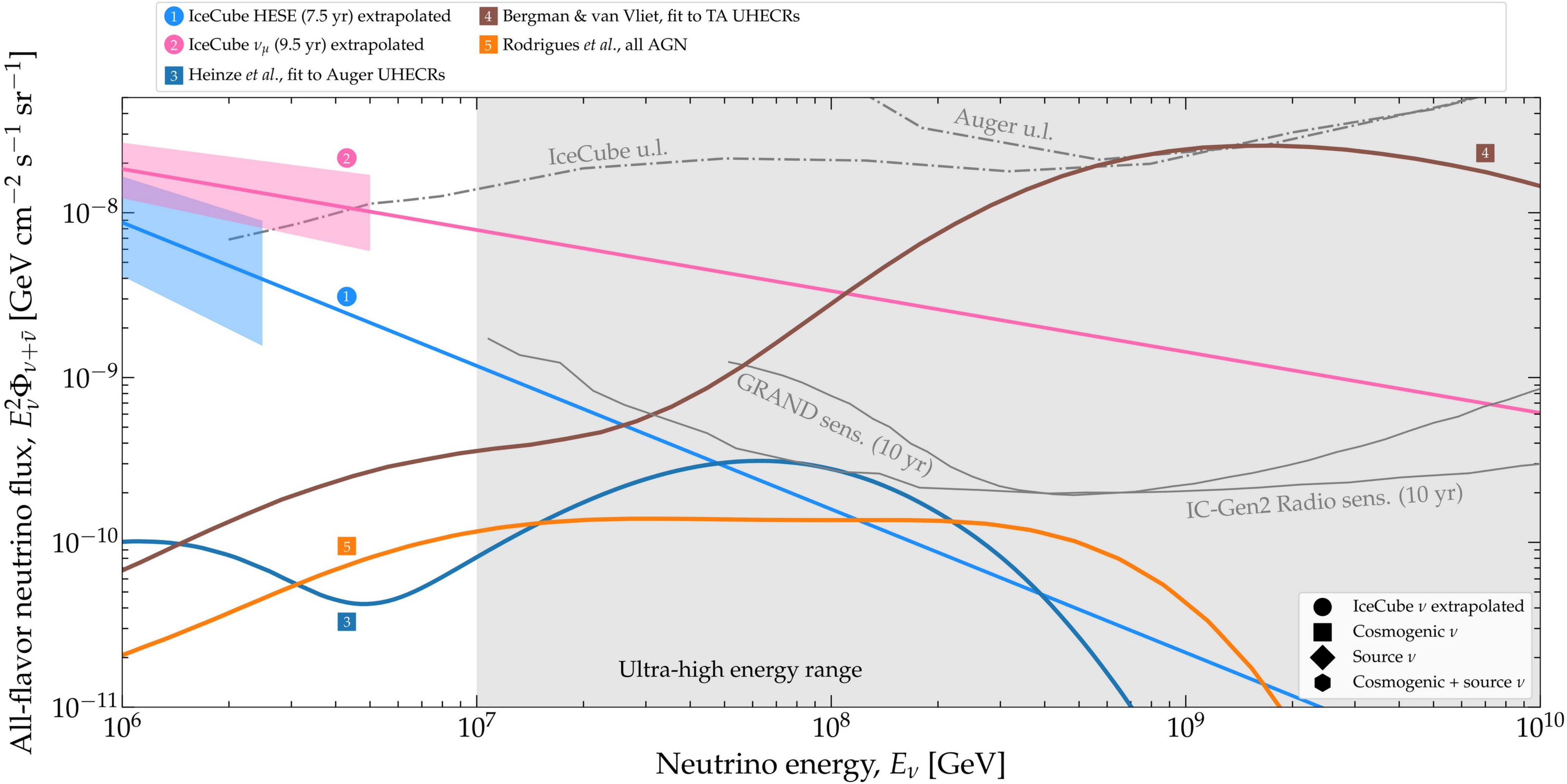
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Neutrino energy, E_ν [GeV]
10^6
10^7
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10^{10}
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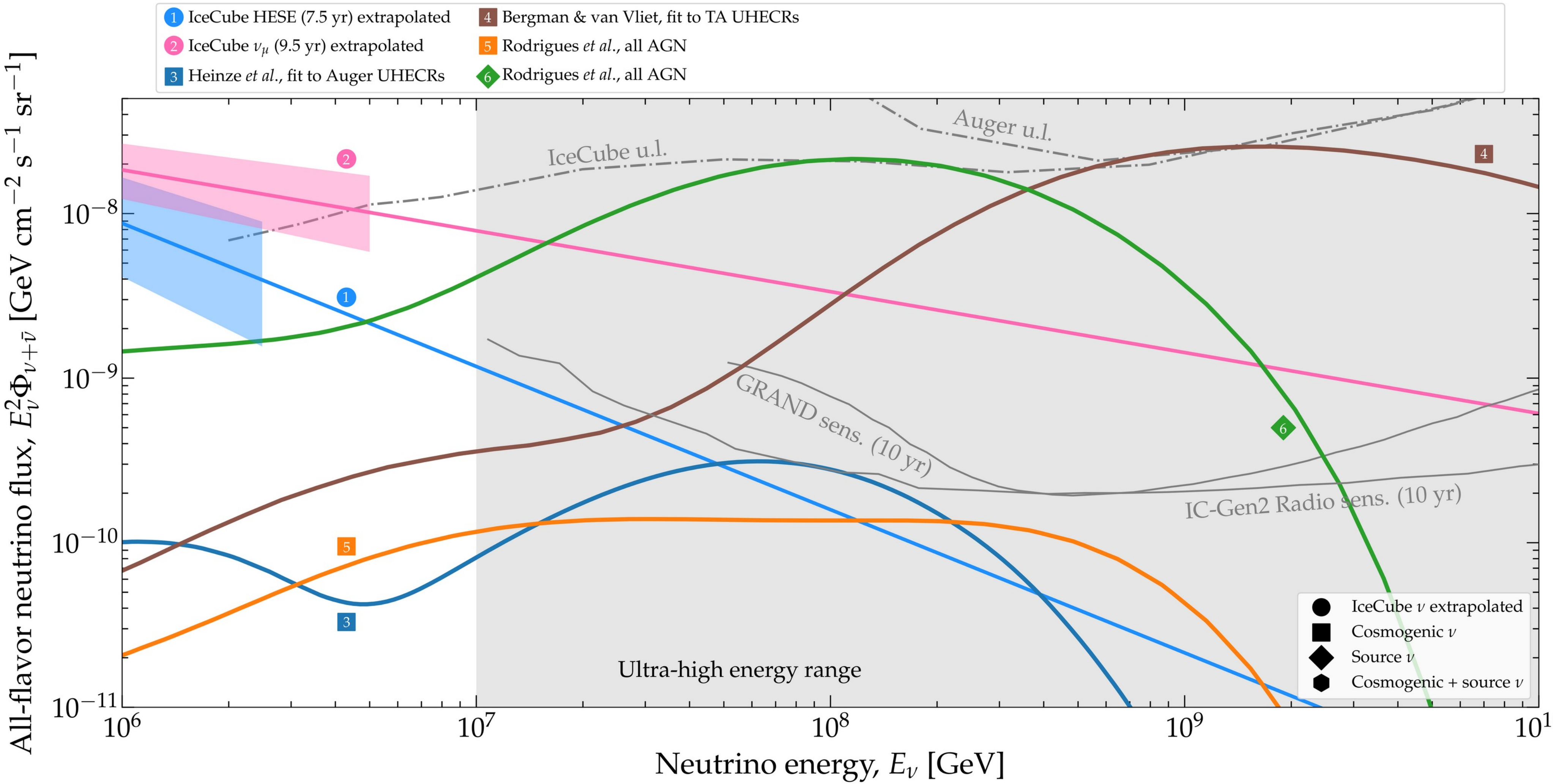
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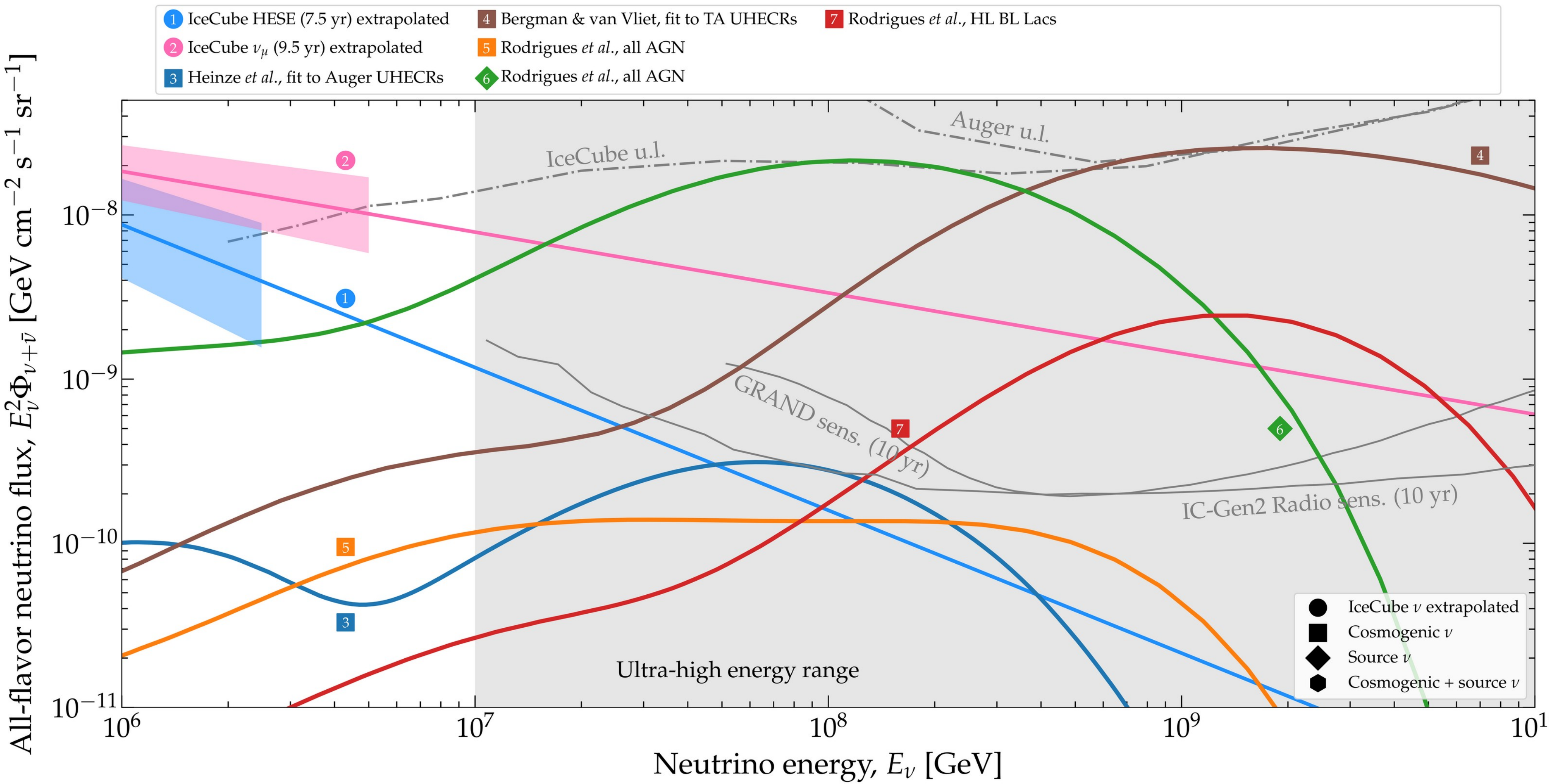
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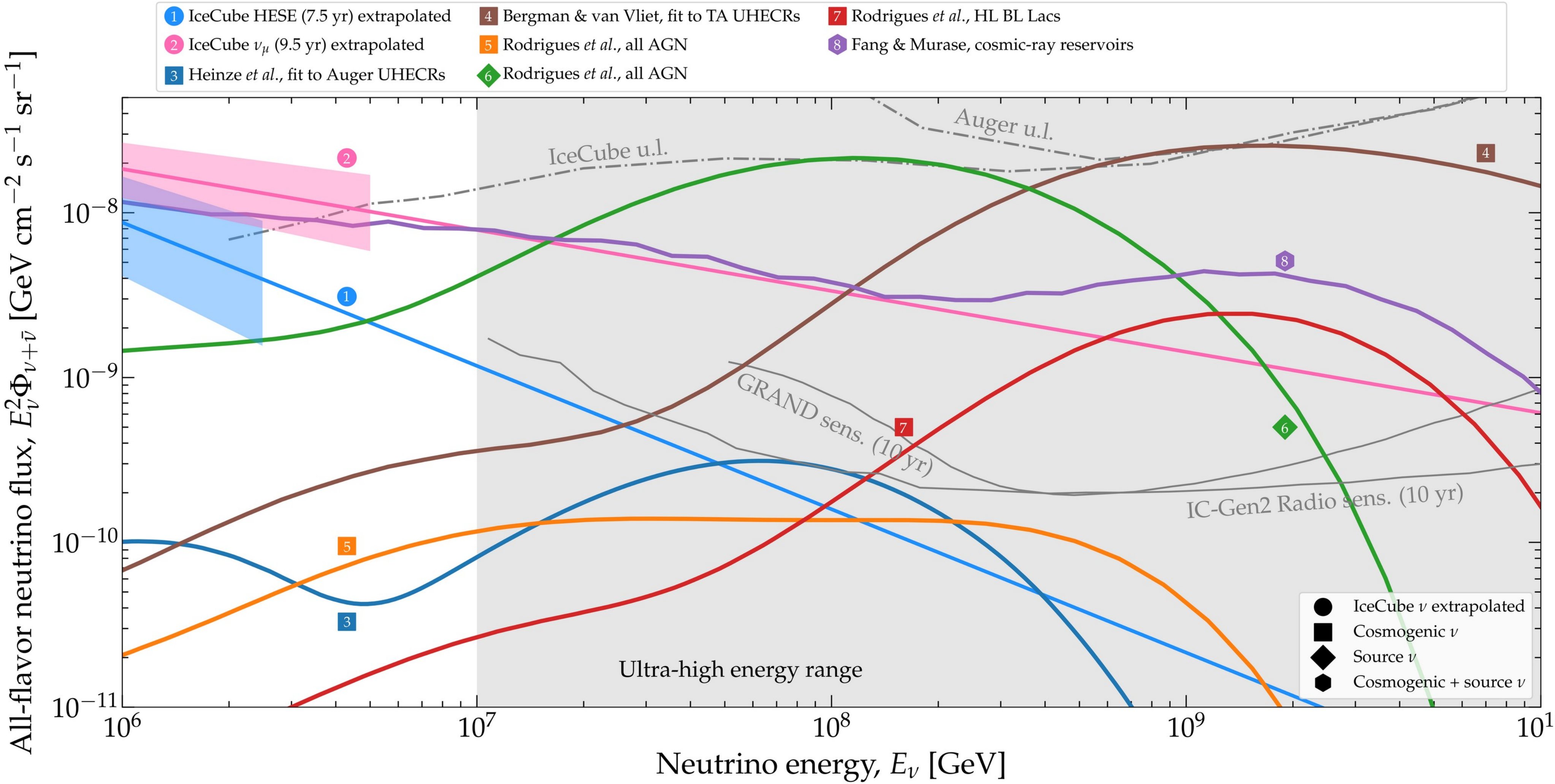

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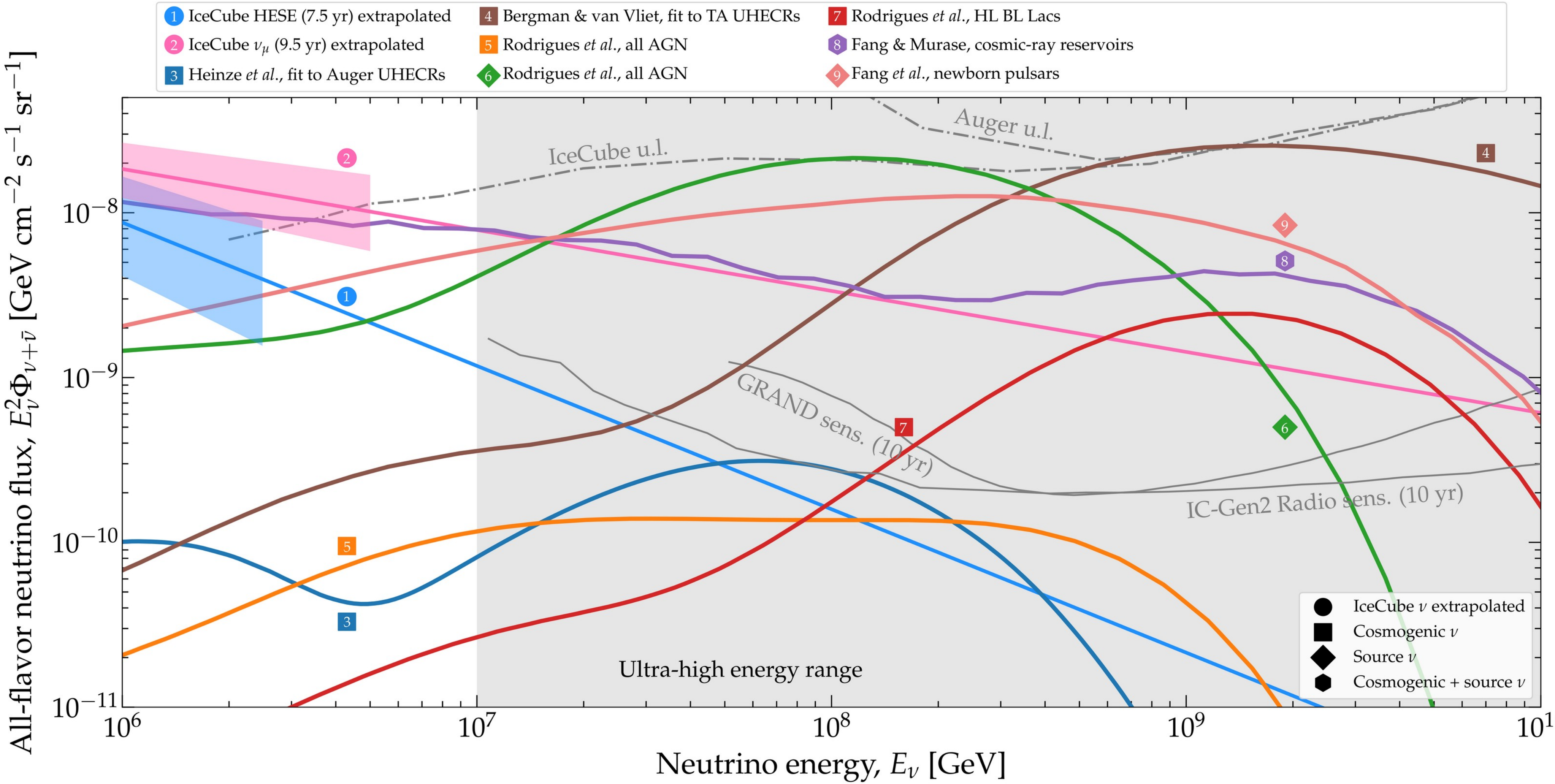
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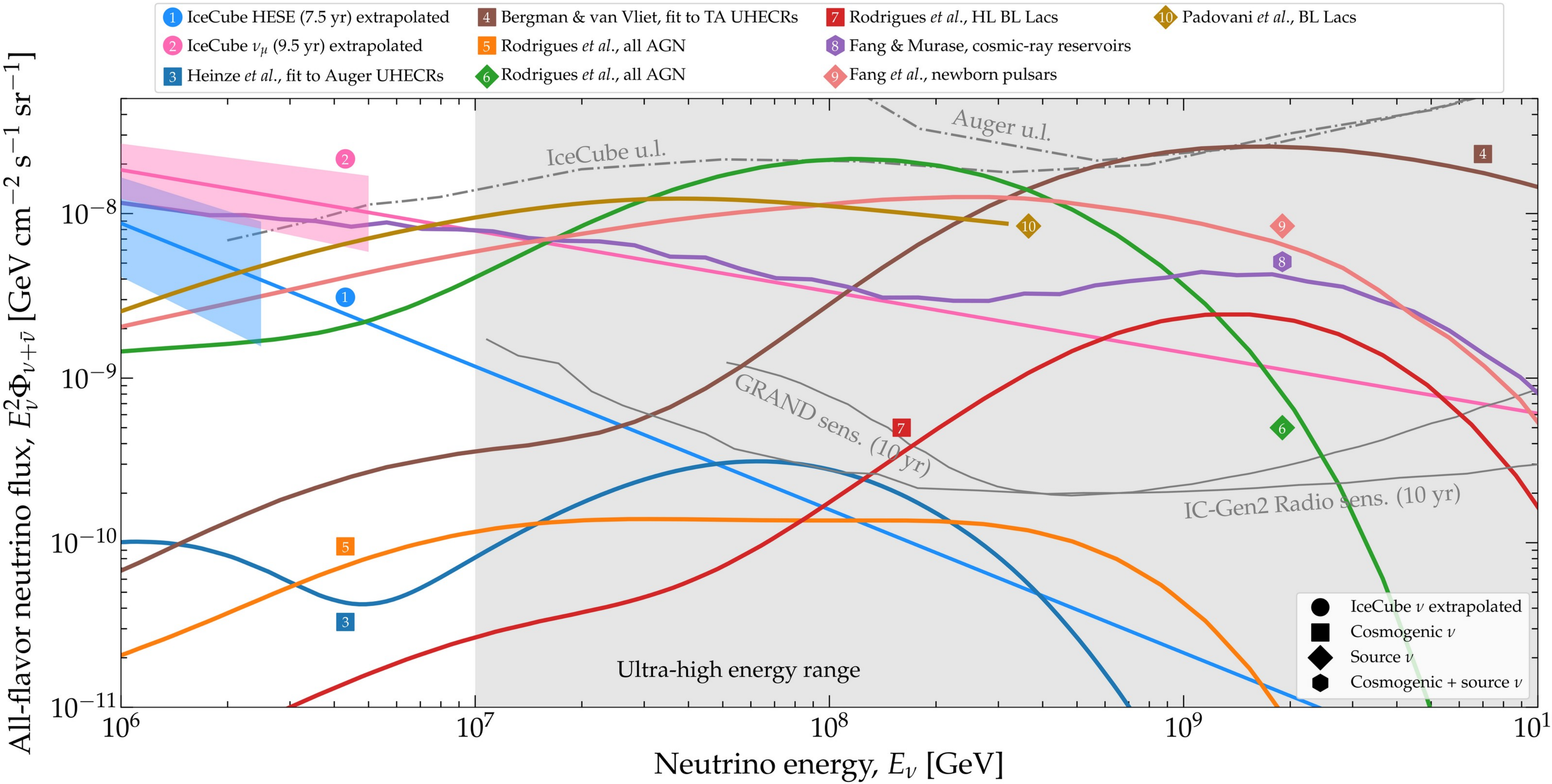
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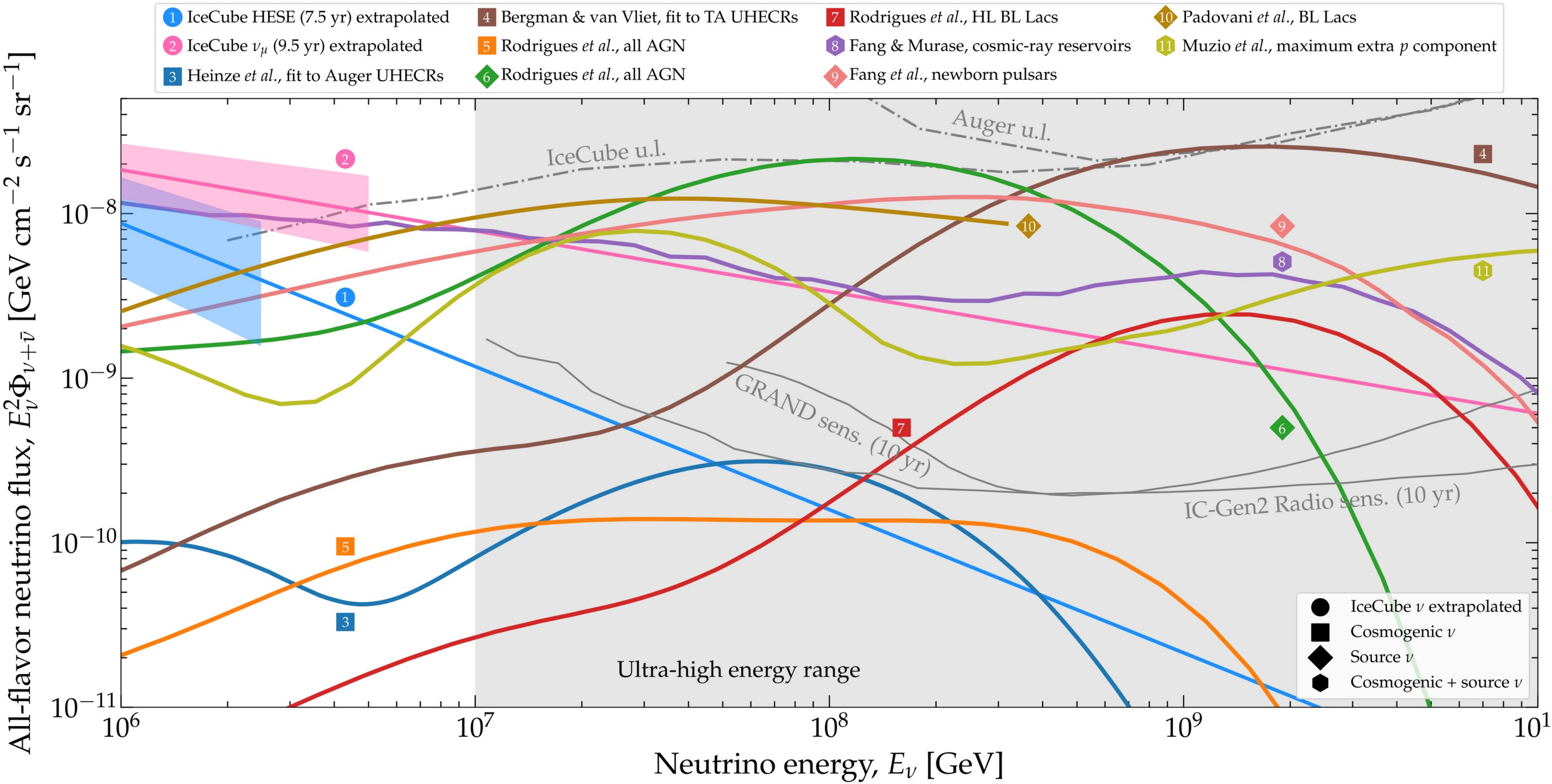
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IceCube u.l.
Auger u.l.
GRAND sens. (10 yr)
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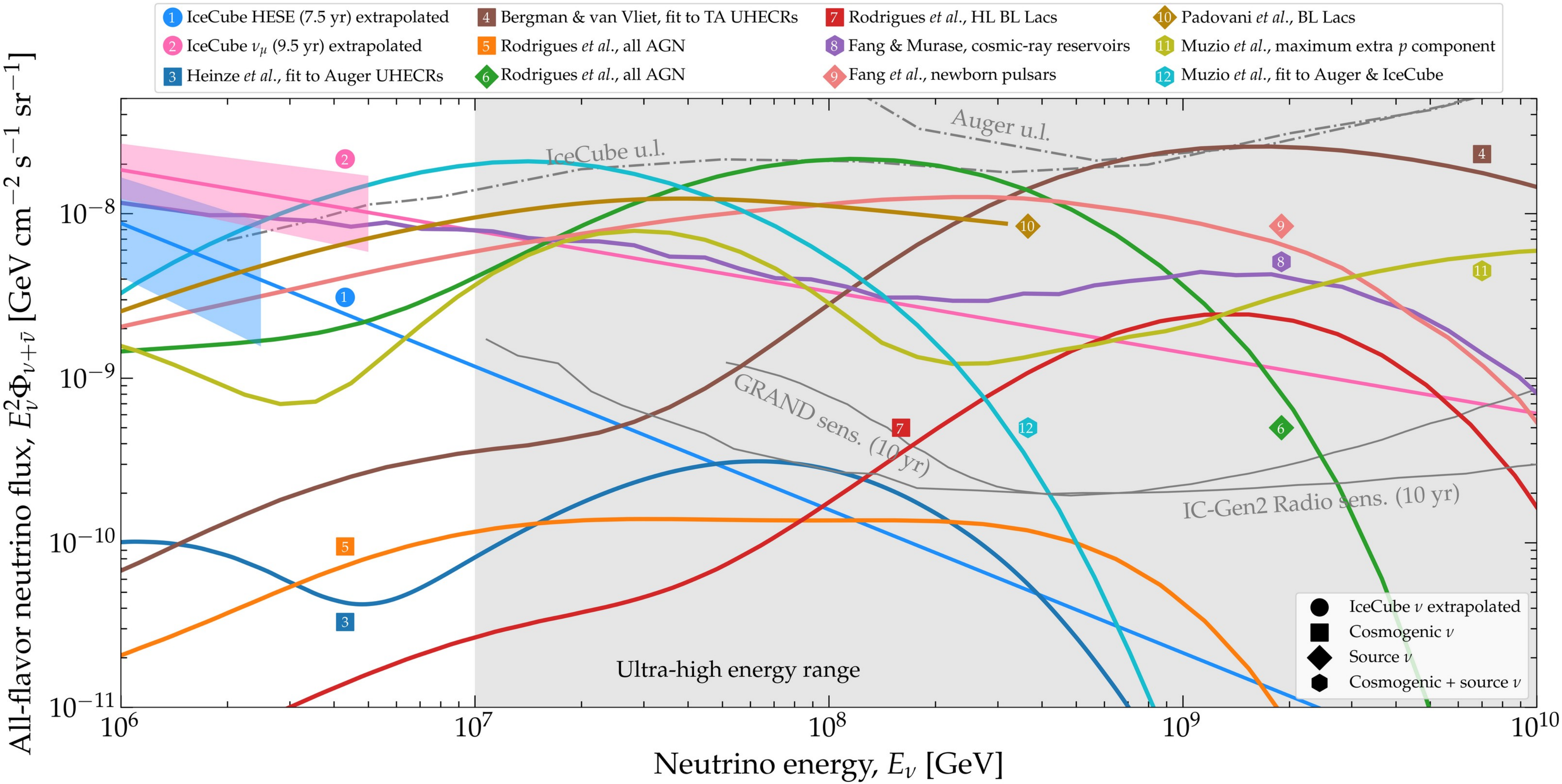

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IceCube u.l.
Auger u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
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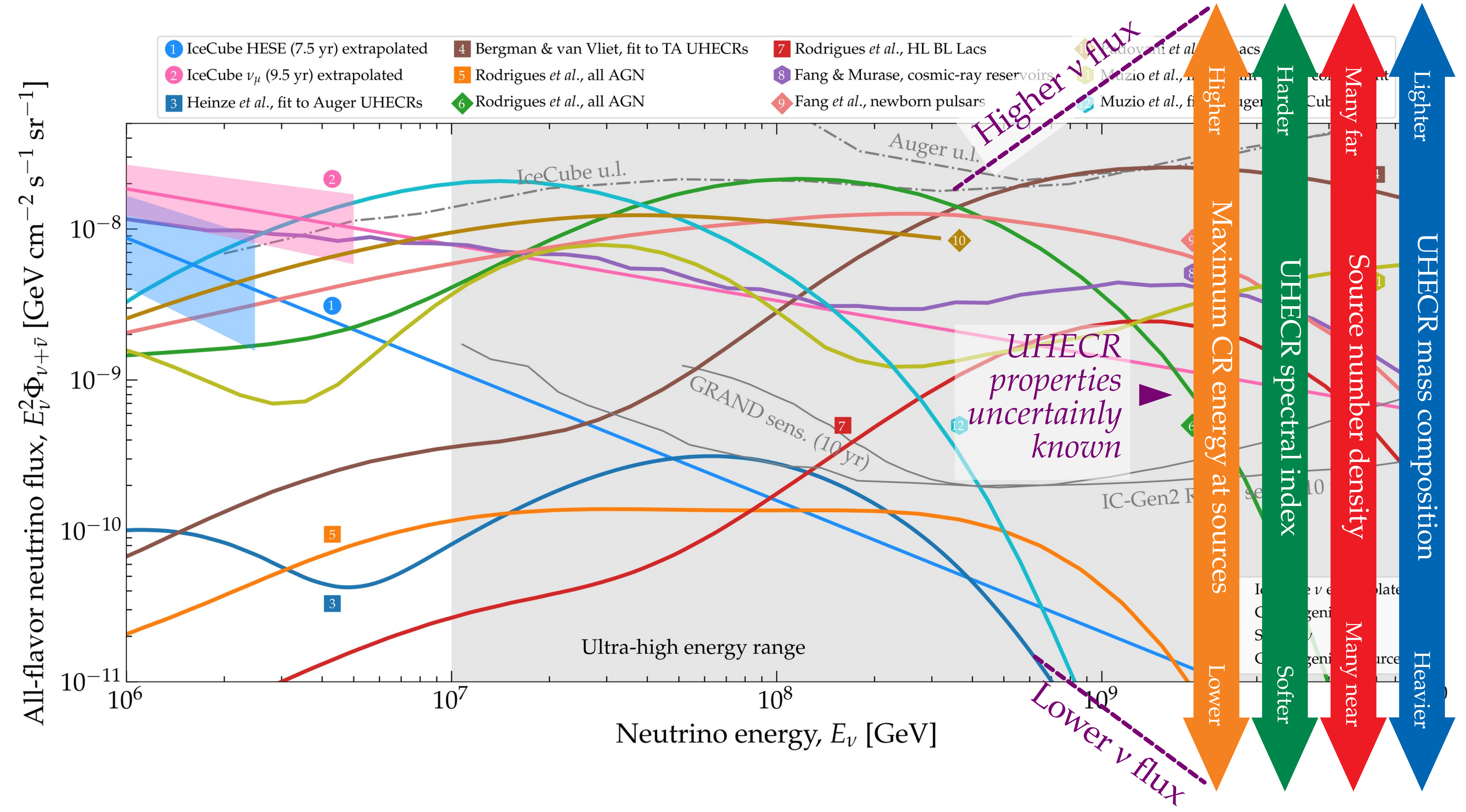
Neutrino energy, E_ν [GeV]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Lacs
11 Muzio *et al.*,
12 Muzio *et al.*, fi
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IceCube u.l.
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GRAND sens. (10 yr)
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Ultra-high energy range
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10^6
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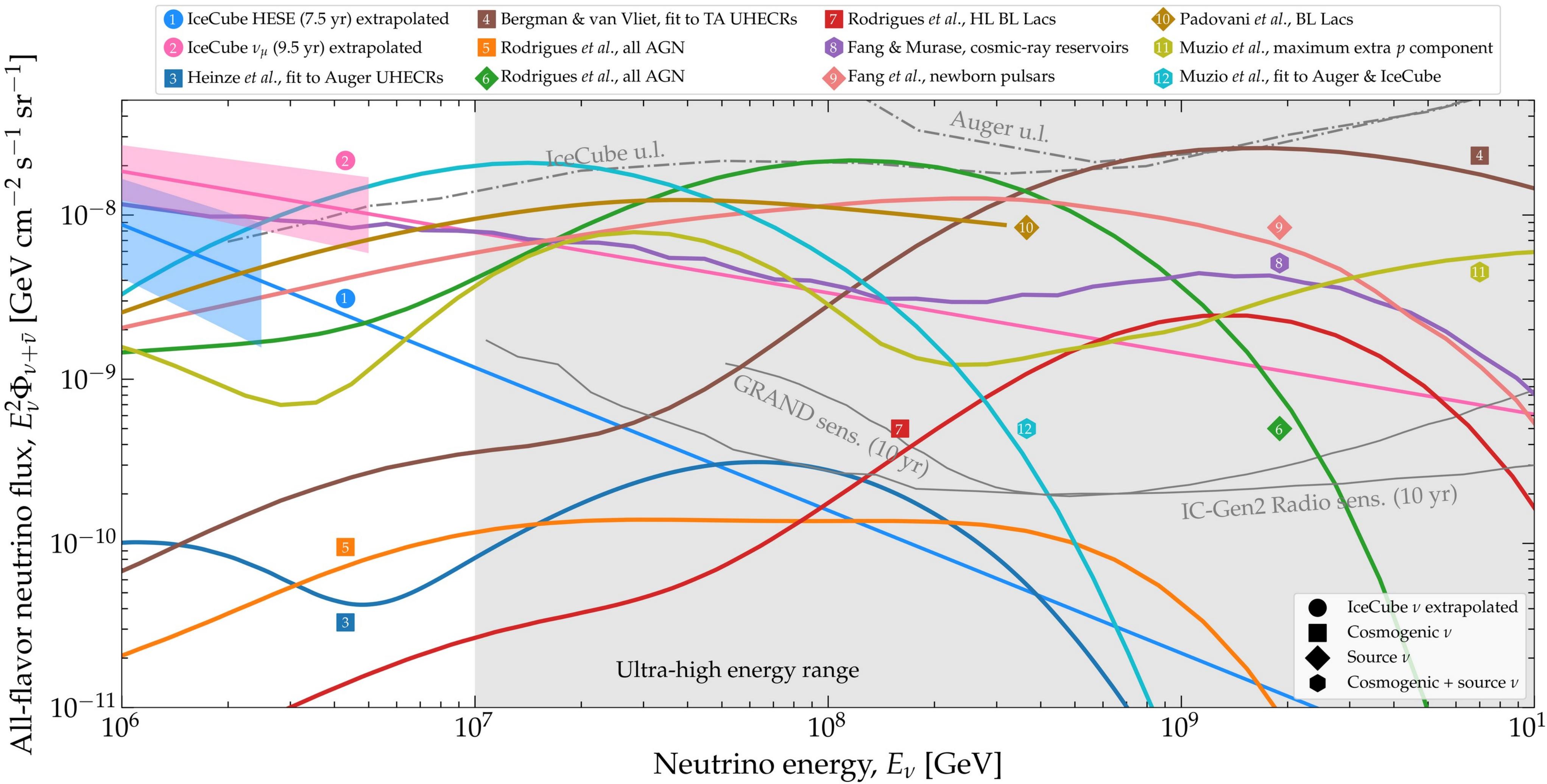
10^9
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy, E_ν [GeV]
Higher ν flux
Lower ν flux
UHECR properties uncertainly known
Higher
Maximum CR energy at sources
Lower
Harder
UHECR spectral index
Softer
Many far
Source number density
Many near
Lighter
UHECR mass composition
Heavier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Neutrino energy, E_ν [GeV]
IceCube u.l.
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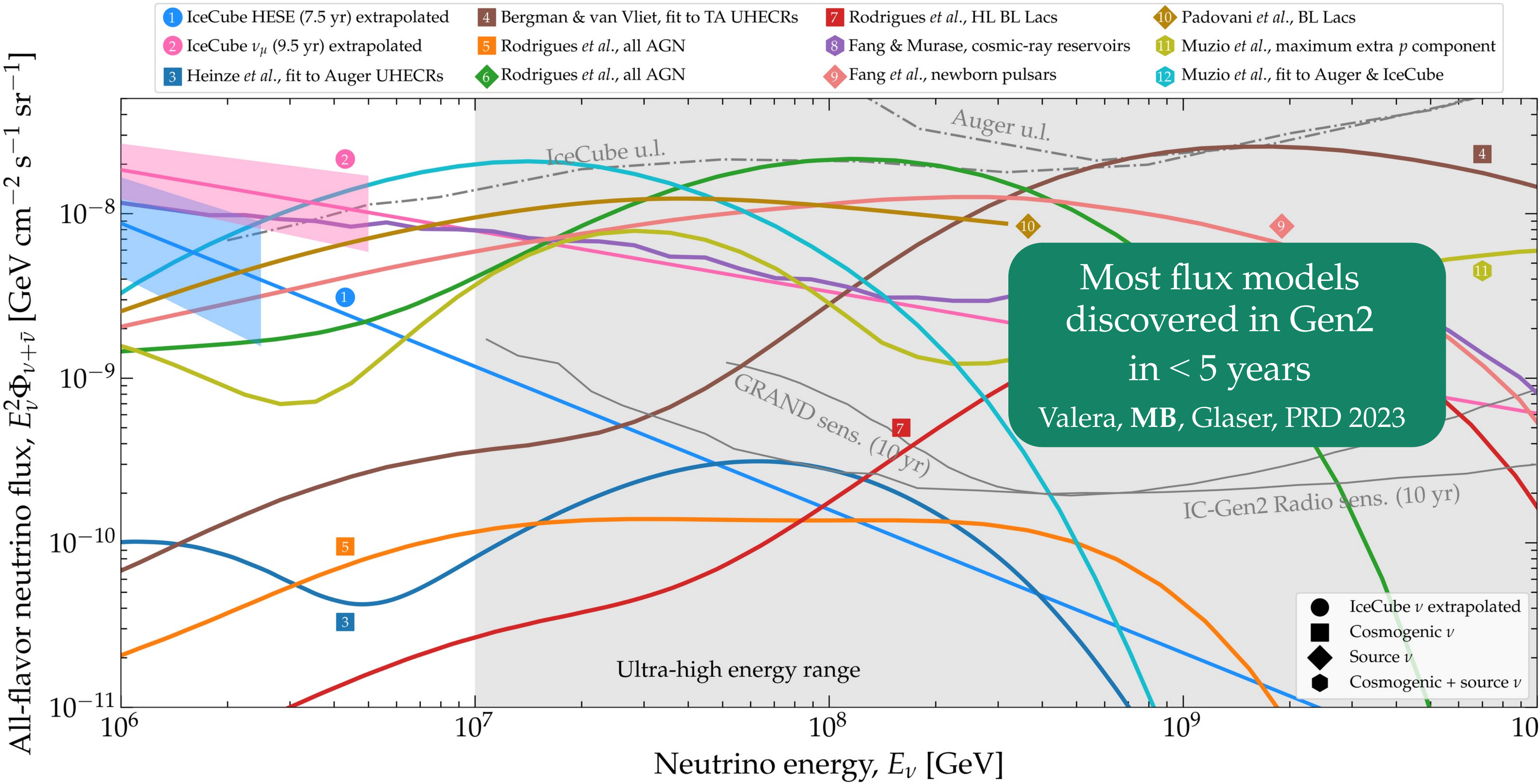
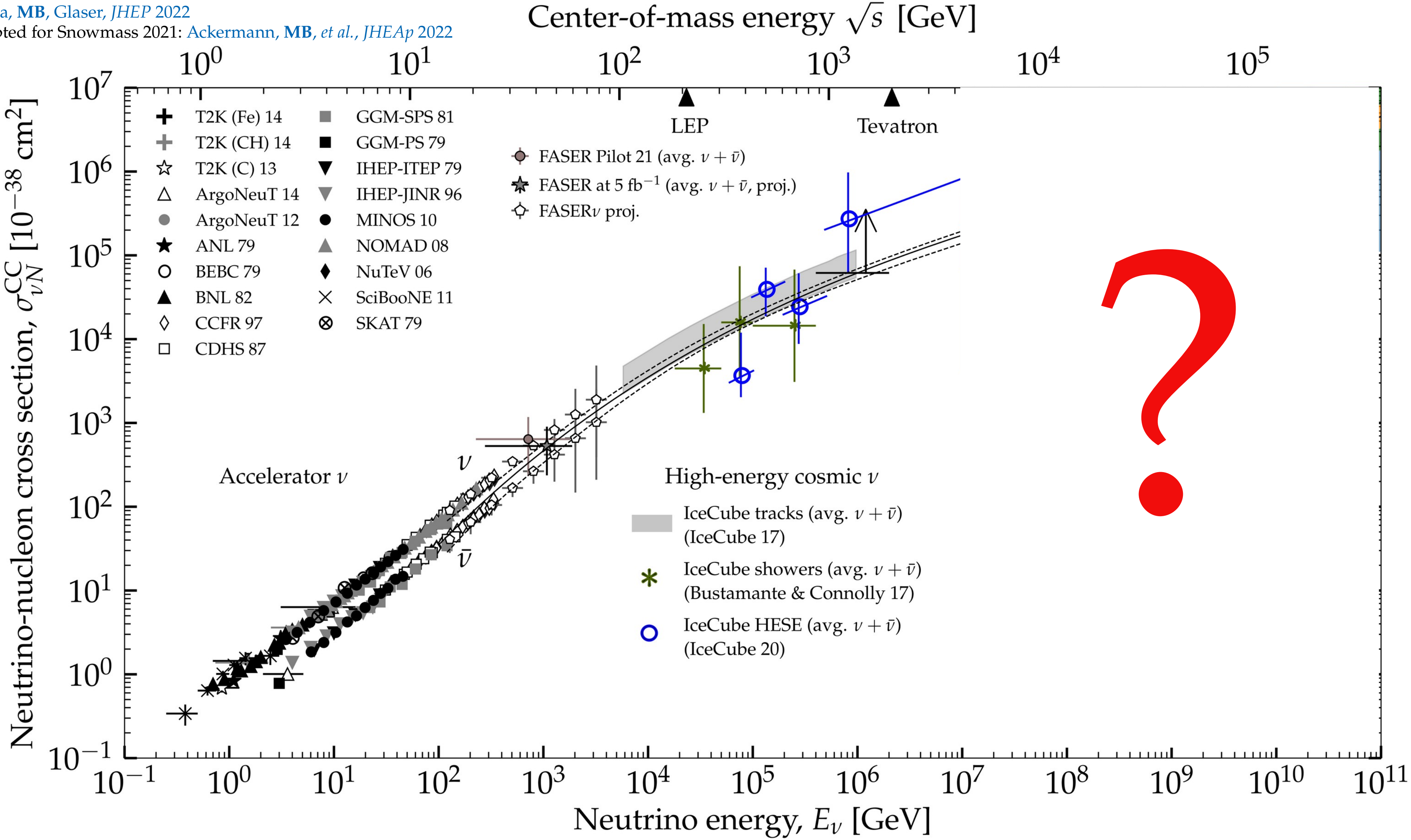


Most flux models discovered in Gen2 in < 5 years

Valera, **MB**, Glaser, PRD 2023

Valera, **MB**, Glaser, *JHEP* 2022
Adapted for Snowmass 2021: Ackermann, **MB**, *et al.*, *JHEAp* 2022



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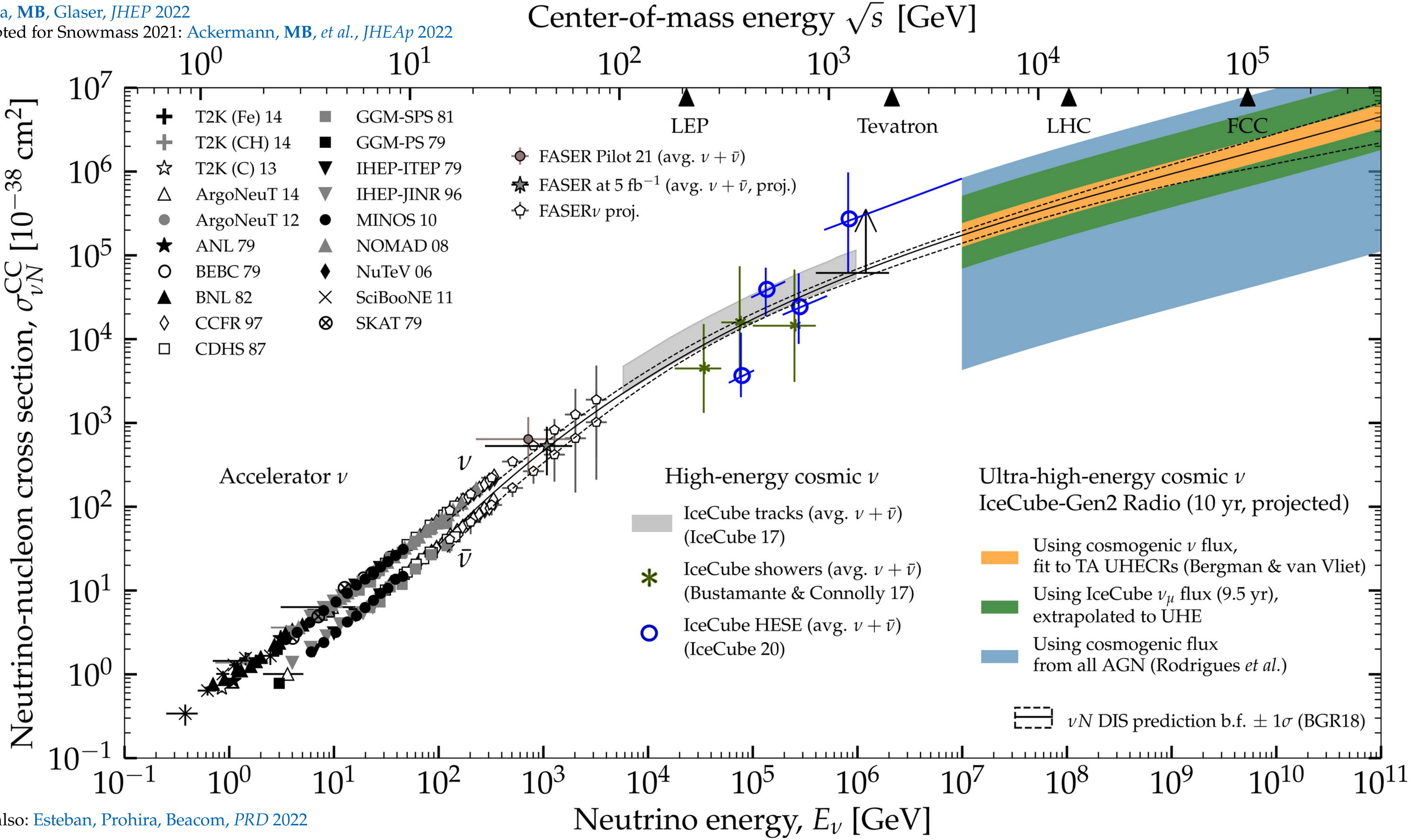

See also: Esteban, Prohira, Beacom, *PRD* 2022

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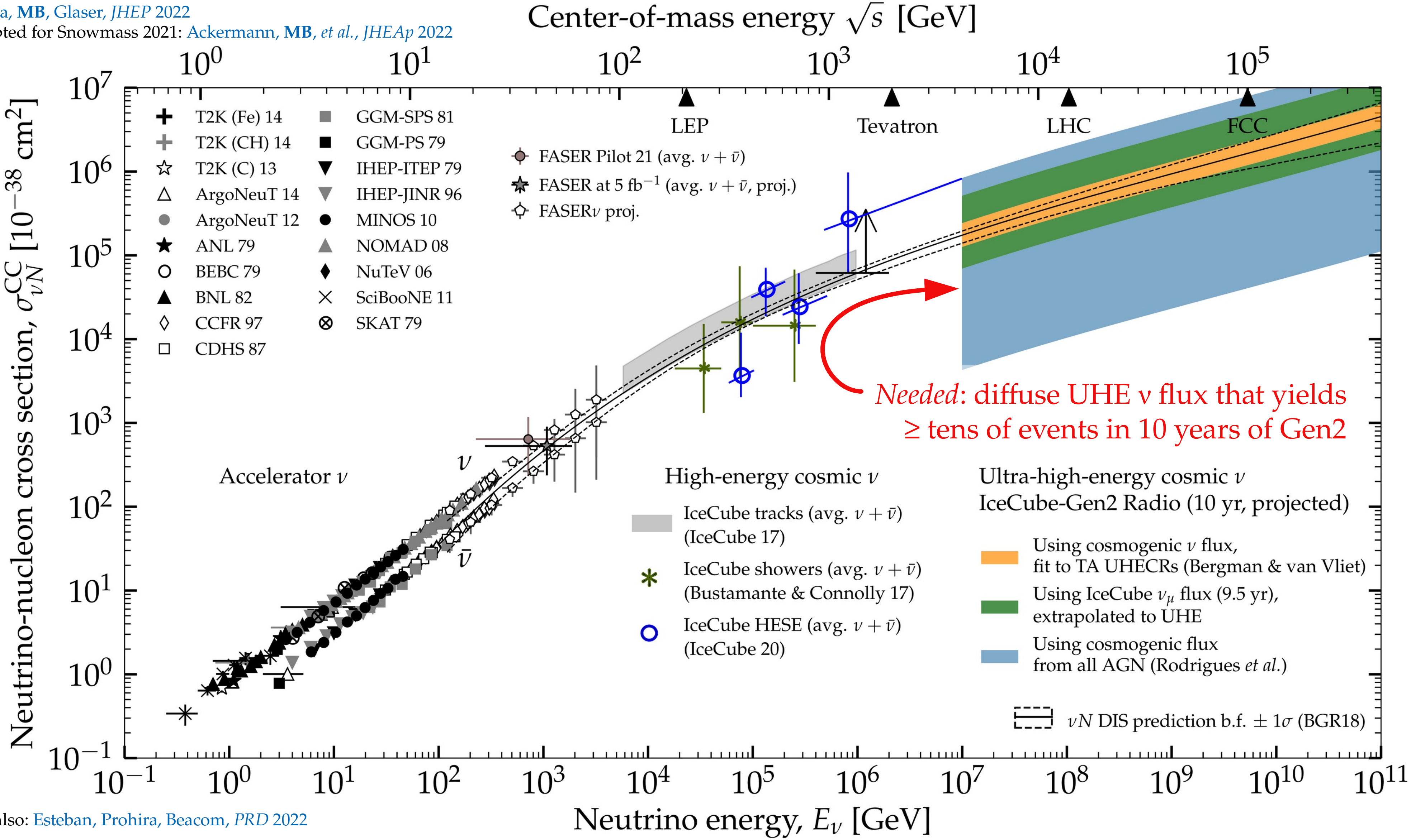

Needed: diffuse UHE ν flux that yields
≥ tens of events in 10 years of Gen2

See also: Esteban, Prohira, Beacom, *PRD* 2022

Today

TeV–PeV ν

Turn predictions
into data-driven tests

Key developments:

Bigger detectors → larger statistics

Better reconstruction

Smaller astrophysical uncertainties

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Next decade
> 100-PeV ν

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Make predictions for
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Key developments:
Discovery
New detection techniques
Better UHE ν flux predictions

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<u>Key developments</u>:
Discovery
New detection techniques
Better UHE ν flux predictions

Made robust and meaningful by accounting
for all relevant particle and astrophysics uncertainties

Today

TeV–PeV ν

Turn predictions
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Key developments:
Bigger detectors → larger statistics
Better reconstruction
Smaller astrophysical uncertainties

Next decade

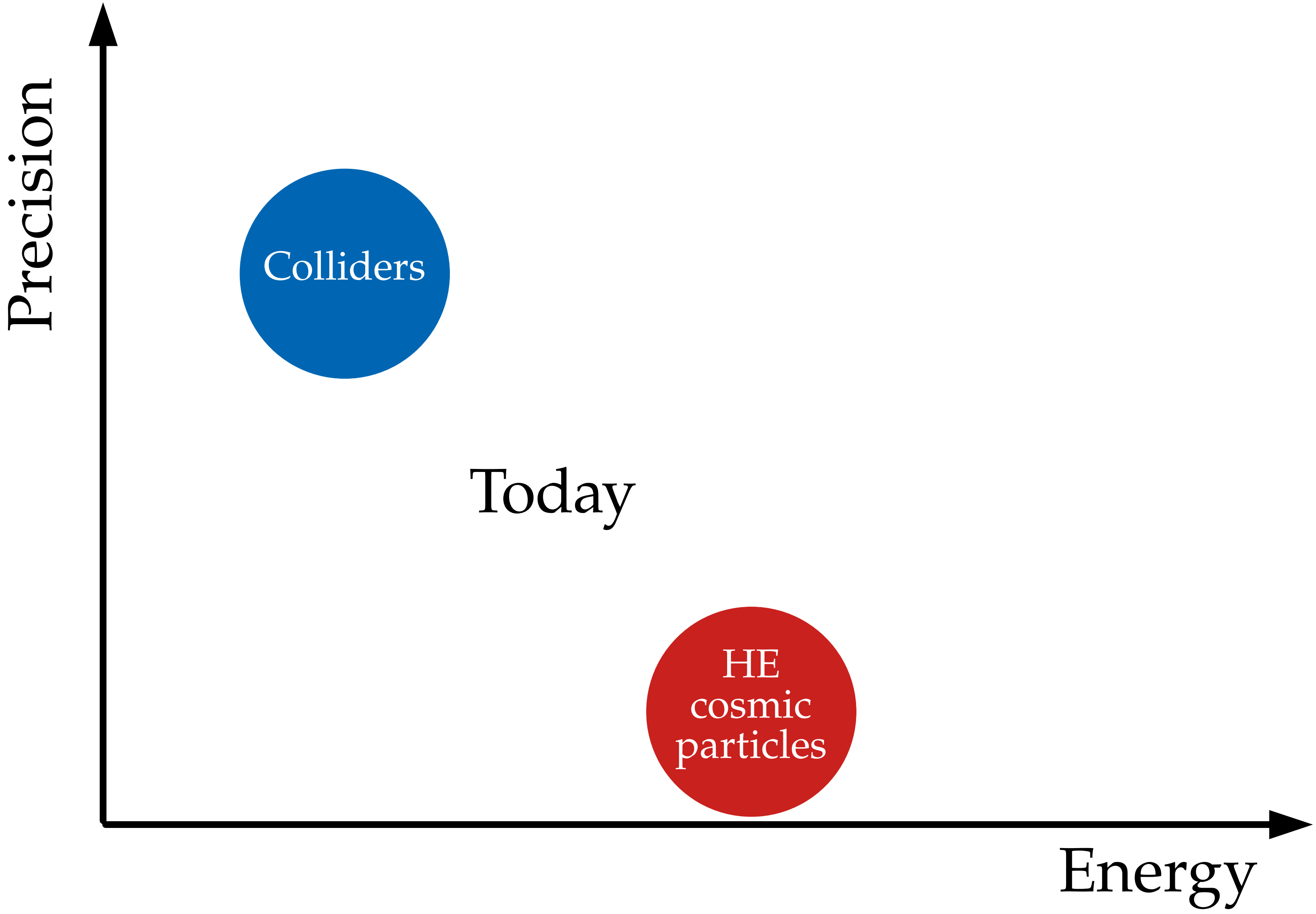
> 100-PeV ν

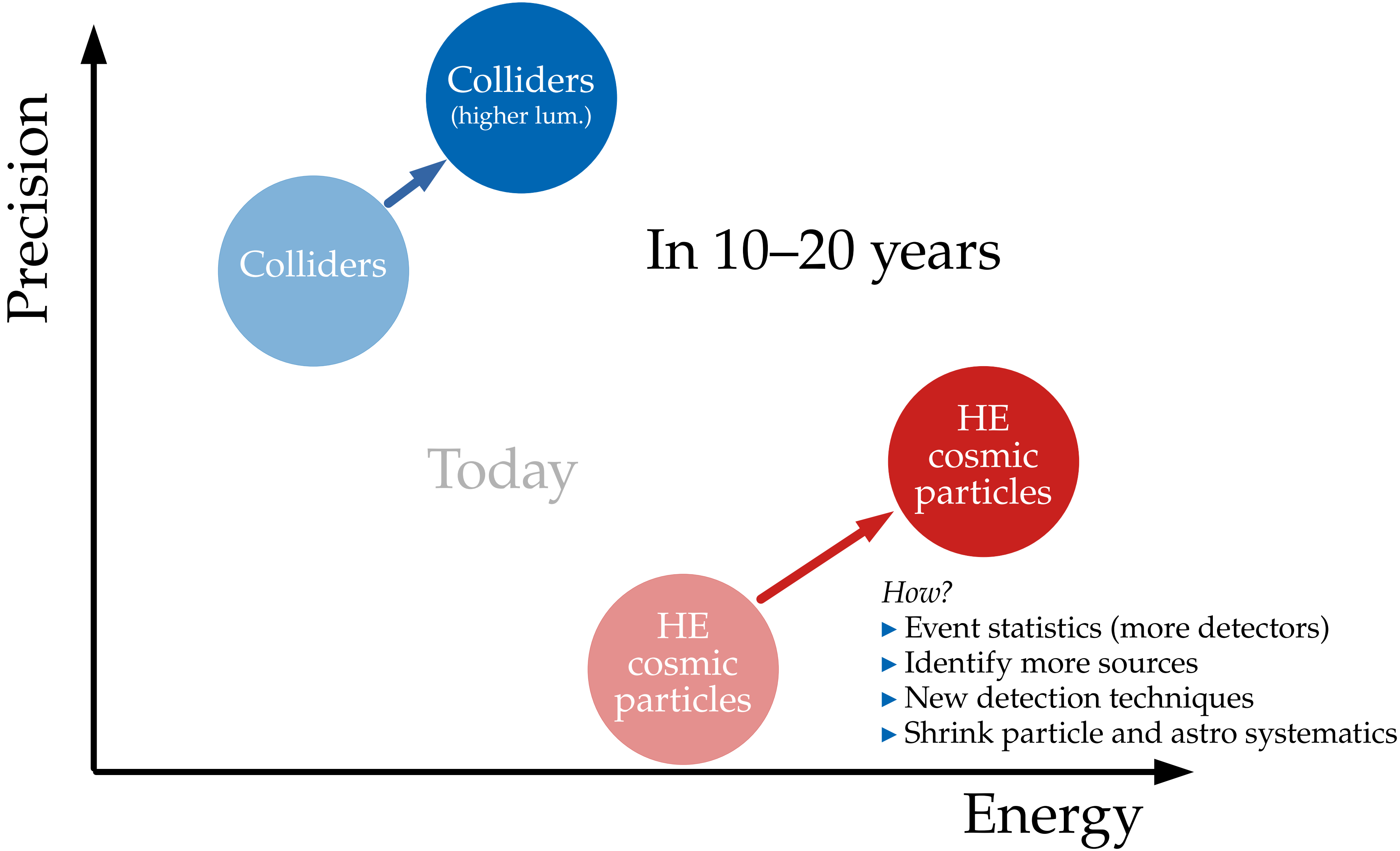
Make predictions for
a new energy regime

Key developments:
Discovery
New detection techniques
Better UHE ν flux predictions

Similar to the evolution of cosmology to a high-precision field in the 1990s

Made robust and meaningful by accounting
for all relevant particle and astrophysics uncertainties


Precision
Colliders
Today
HE cosmic particles
Energy



How?

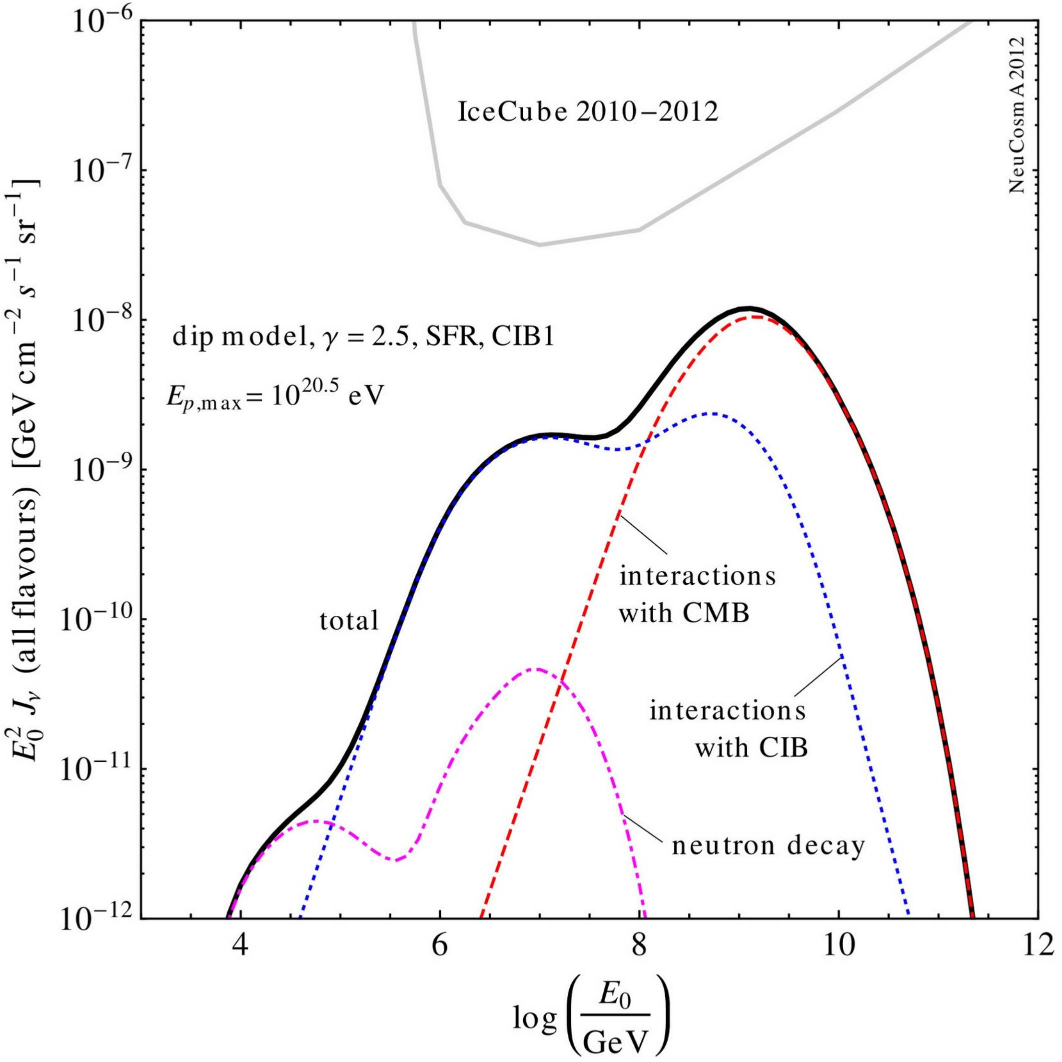
- ▸ Event statistics (more detectors)
- ▸ Identify more sources
- ▸ New detection techniques
- ▸ Shrink particle and astro systematics

Thanks!

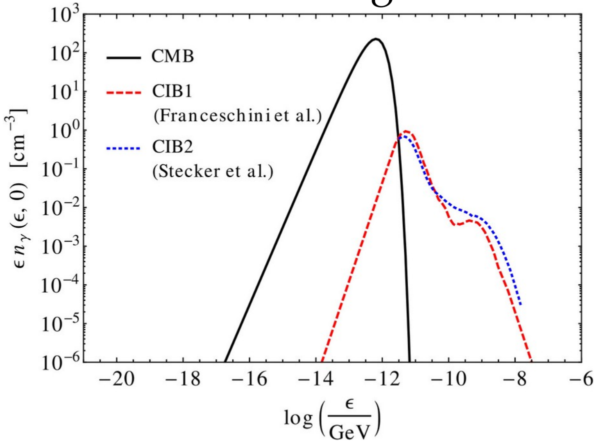
Backup slides

UHECRs

Cosmogenic neutrinos



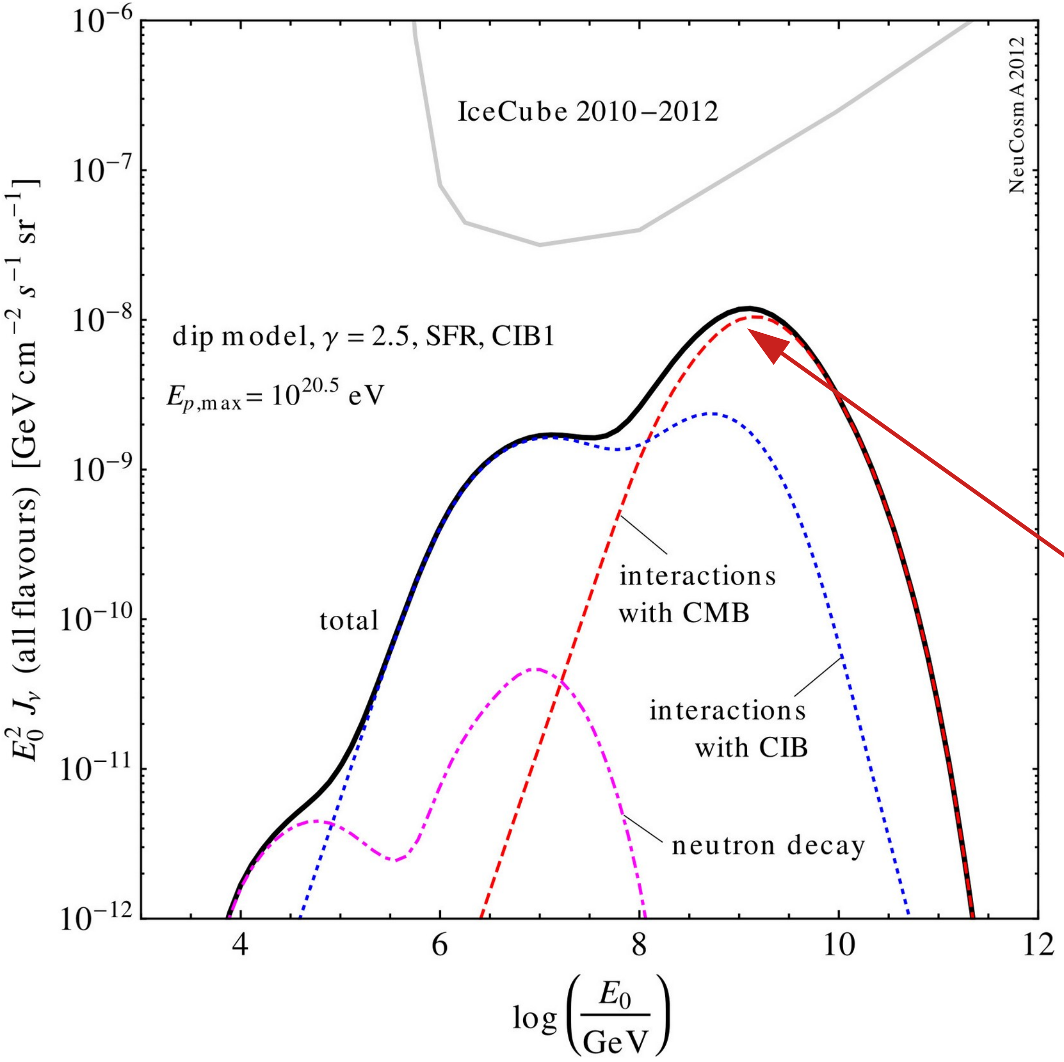
Photon backgrounds



Position of the ν bump from $p\gamma$:

$$E_\nu \approx \frac{0.01\ \text{GeV}}{E_\gamma/\text{GeV}}$$

Cosmogenic neutrinos



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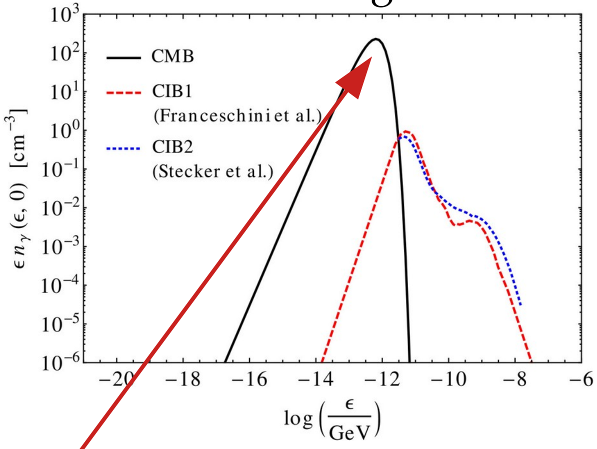
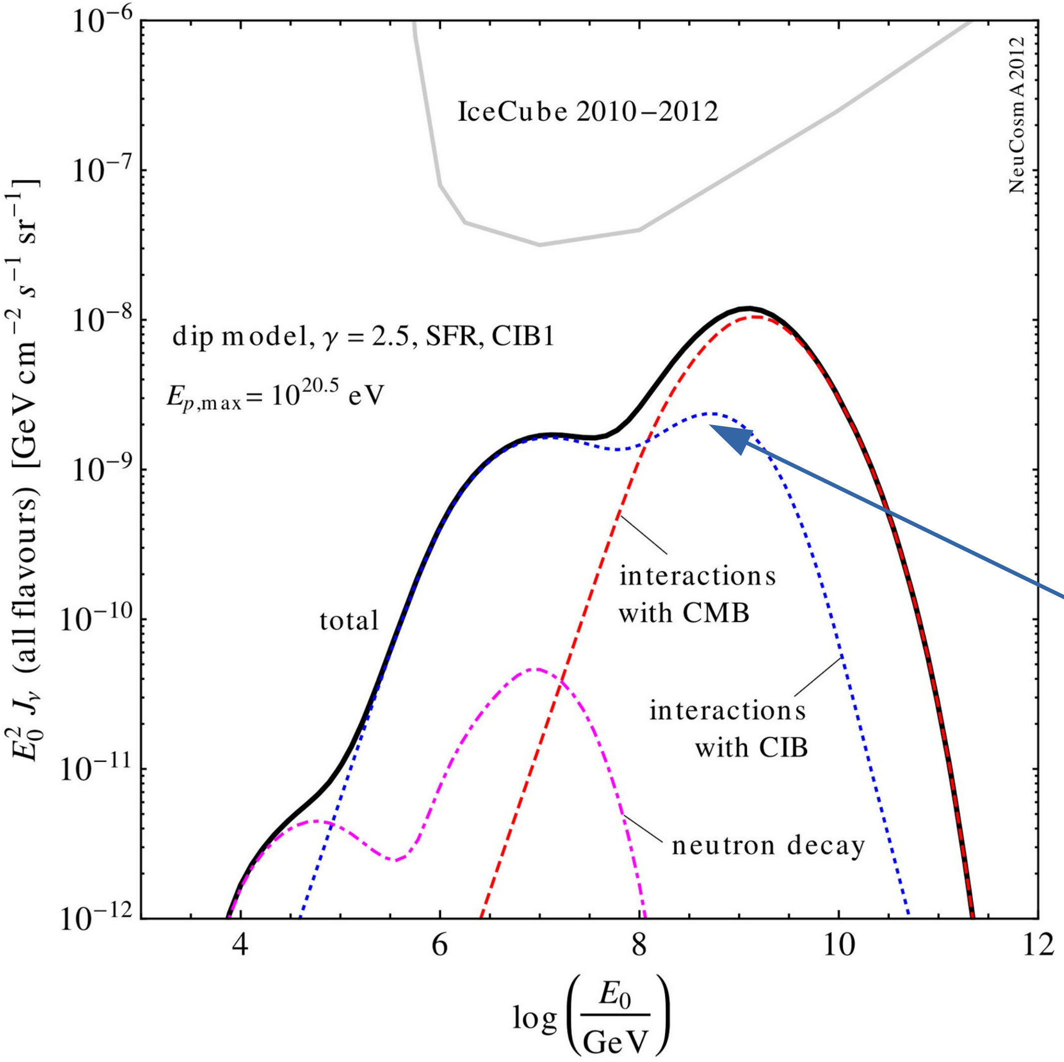


Position of the ν bump from $p\gamma$:

$$E_\nu \approx \frac{0.01\ \mathrm{GeV}}{E_\gamma/\mathrm{GeV}}$$

ν from CMB: $E_\nu \approx \frac{0.01\ \mathrm{GeV}}{10^{-12}} = 10^{10}\ \mathrm{GeV}$

Cosmogenic neutrinos



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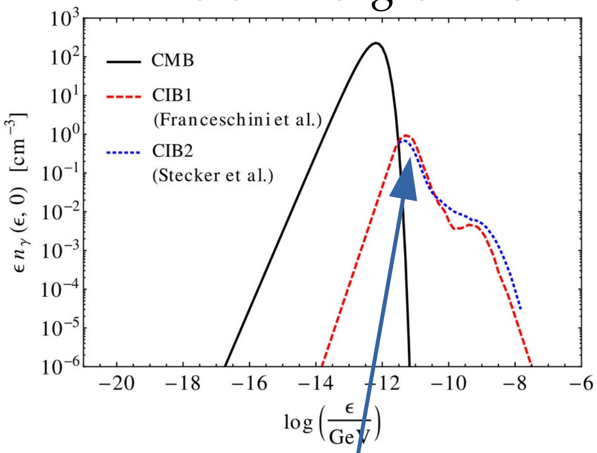


Position of the ν bump from $p\gamma$:

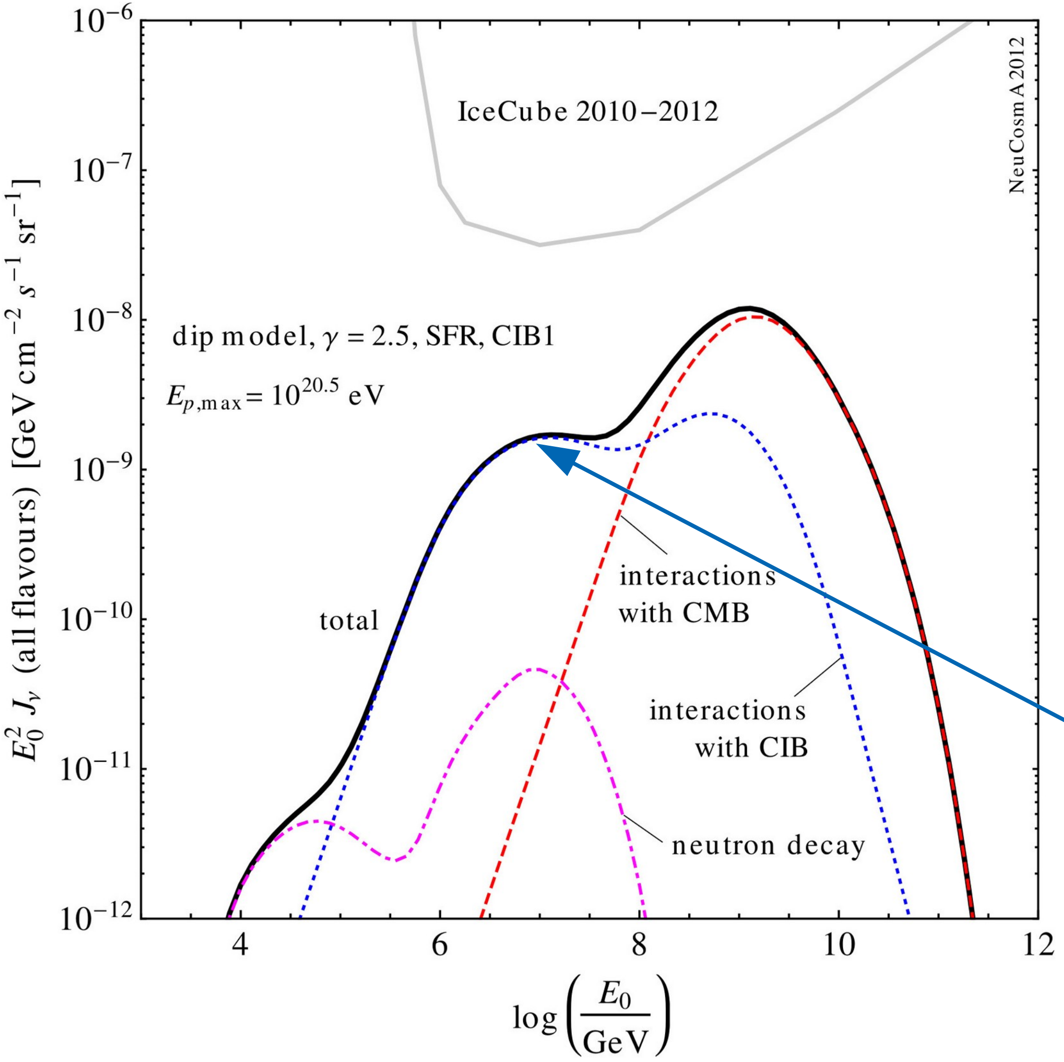
$$E_\nu \approx \frac{0.01\ \mathrm{GeV}}{E_\gamma/\mathrm{GeV}}$$

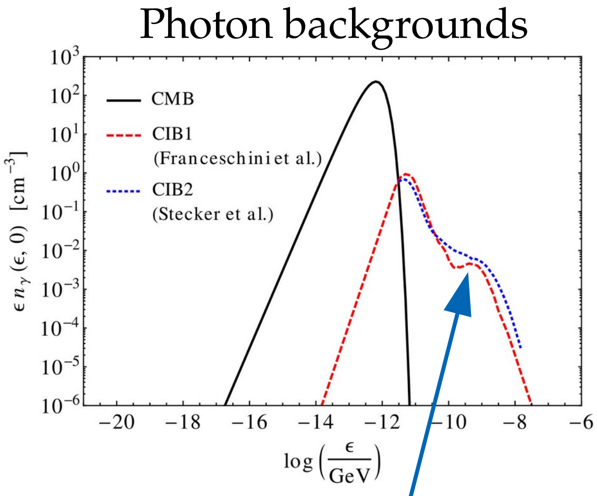
ν from CMB: $E_\nu \approx \dfrac{0.01\ \mathrm{GeV}}{10^{-12}} = 10^{10}\ \mathrm{GeV}$

$$E_\nu \approx \frac{0.01\ \mathrm{GeV}}{10^{-11}} = 10^{9}\ \mathrm{GeV}$$

ν from CIB:

Cosmogenic neutrinos





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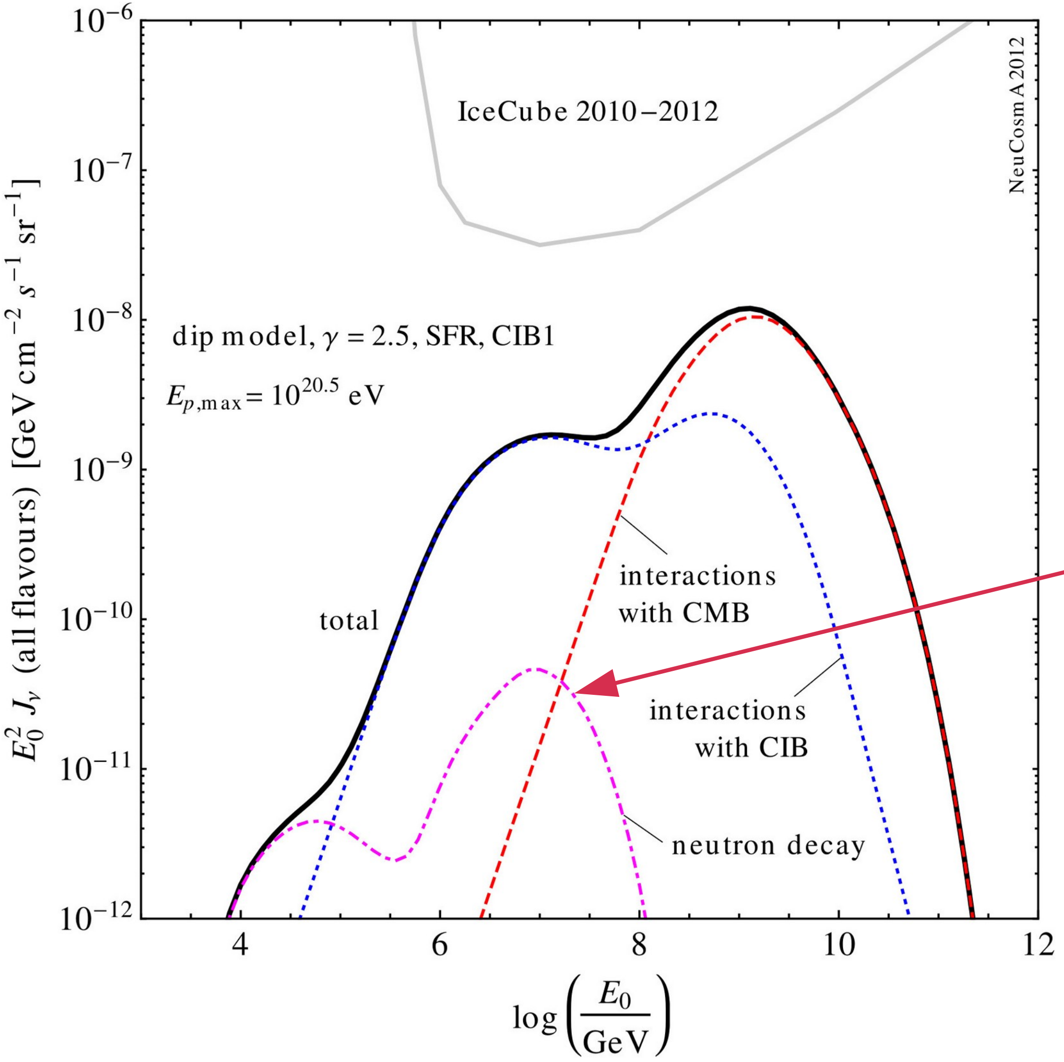
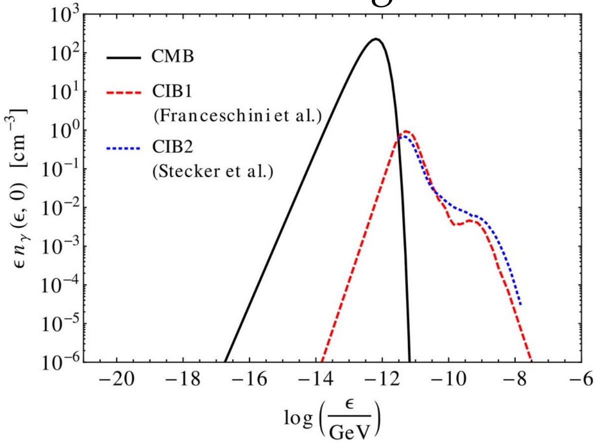
$$E_\nu \approx \frac{0.01\ \text{GeV}}{10^{-9}} = 10^{7}\ \text{GeV}$$

Cosmogenic neutrinos



Photon backgrounds



Position of the ν bump from $p\gamma$:

$$E_\nu \approx \frac{0.01\ \mathrm{GeV}}{E_\gamma/\mathrm{GeV}}$$

Why are ν from n decay lower-energy?

$$n \to p + e^- + \bar{\nu}_e$$

The n and p mass are very similar …

… so there is little energy left for e, ν

UHECRs: more sophisticated models

Use more data:

Spectrum + mass composition (X_{max})

Five mass groups:

H, He, N, Si, Fe

Common maximum rigidity:

Max. rigidity is $R_{\mathrm{max}} = E_{\mathrm{max}}/Z$

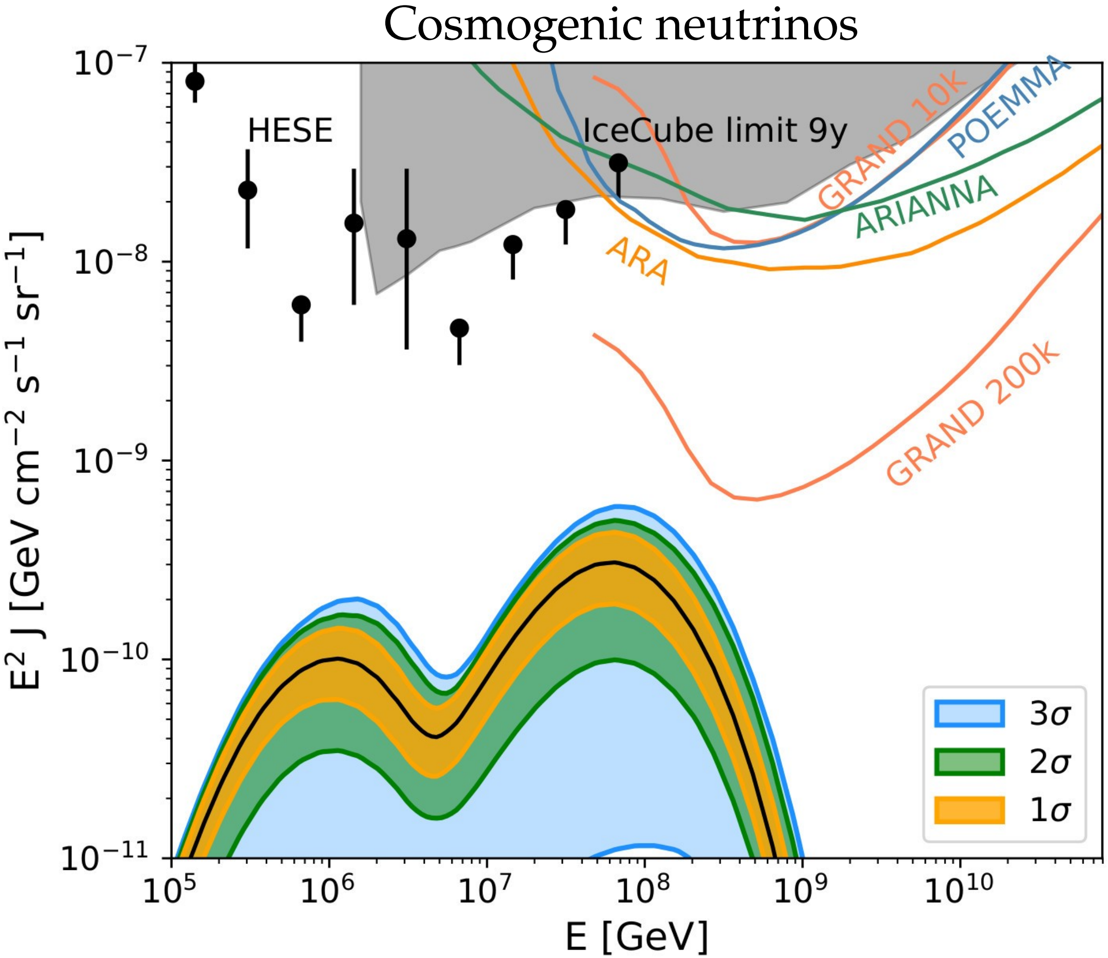
$$Q_Z(E) \propto E^{-\gamma} e^{-E/(ZR_{\mathrm{max}})}$$

"Peters cycle"

Add nuclei photodisintegration:

During propagation, interaction of nuclei on CMB or EBL breaks them up,

$$A + \gamma \to (A-1) + \gamma$$



See also: Romero-Wolf & Ave, *JCAP* 2018
Alves Batista, Almeida, Lago, Kotera, *JCAP* 2019

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"Peters cycle"

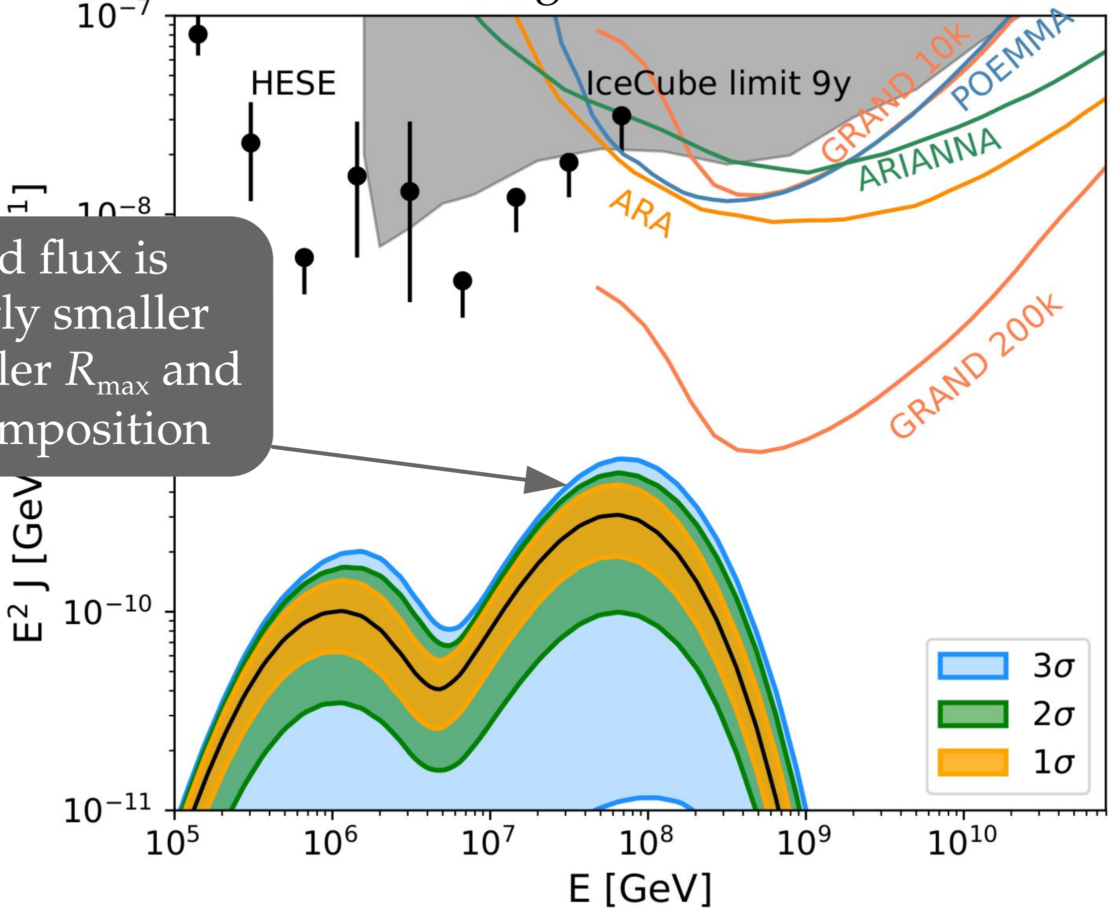
Add nuclei photodisintegration:

During propagation, interaction of nuclei on CMB or EBL breaks them up,

$$A + \gamma \to (A-1) + \gamma$$

Predicted flux is significantly smaller due to smaller R_{max} and heavier composition

Cosmogenic neutrinos



See also: Romero-Wolf & Ave, *JCAP* 2018
Alves Batista, Almeida, Lago, Kotera, *JCAP* 2019

The UHECR all-particle spectrum – more features!

15 years of Auger data (2004–2019)!

~215k events above 2.5 × 10^{18} eV

Use *hybrid* events detected by surface + fluorescence detectors to calibrate

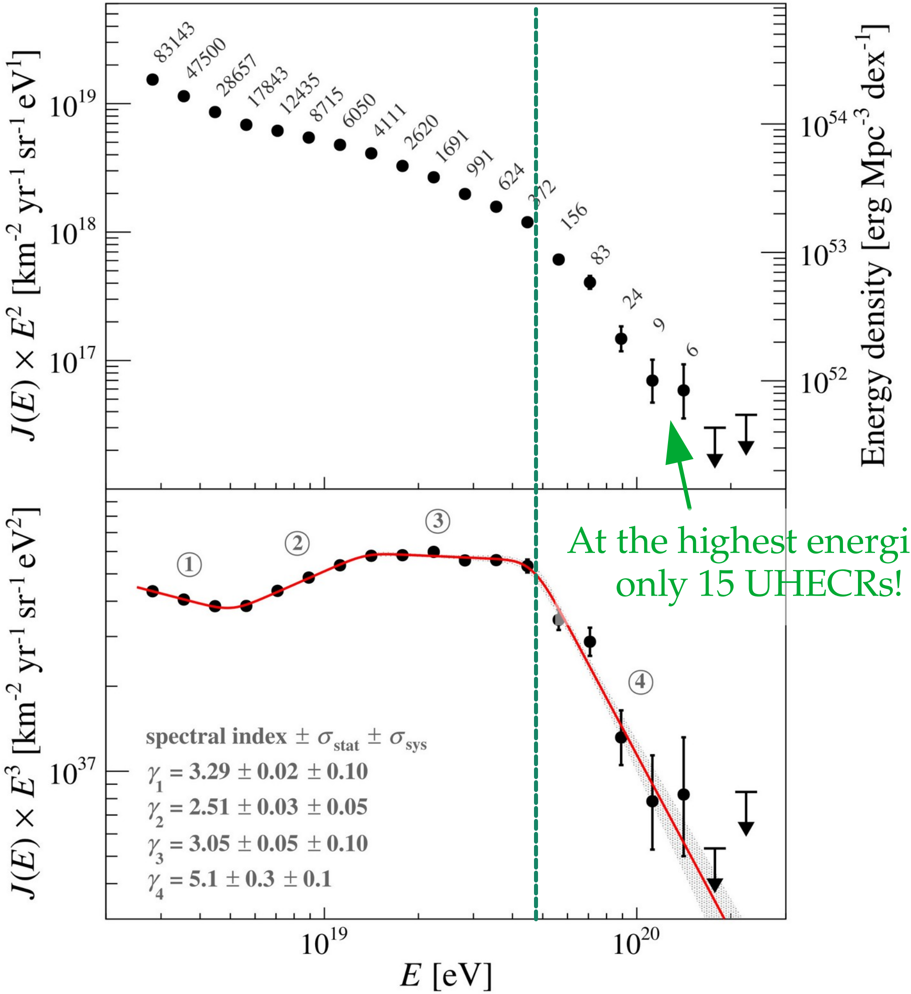
—Allows us to measure energies of other events robustly

CR luminosity density above 5 × 10^{18} eV:

6×10^{44} erg Mpc^{-3} yr^{-1}

(could be AGN or starburst galaxies)

$$\ln(10)\frac{4\pi}{c}E^2J(E)$$



At the highest energies, only 15 UHECRs!

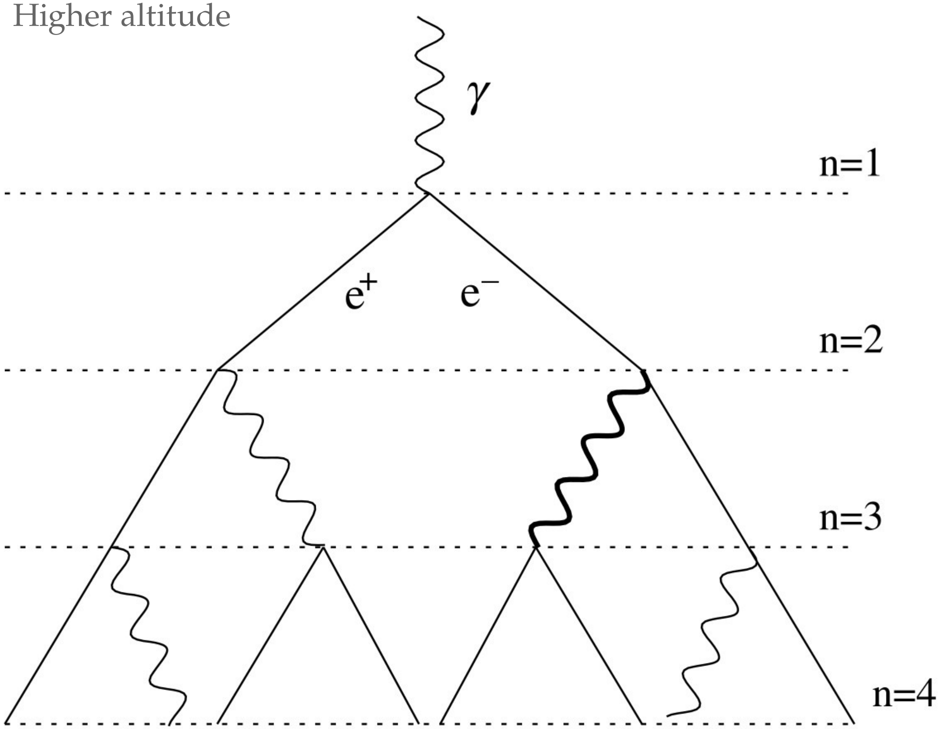
Auger Collab., *PRL* 2020
See also: Auger Collab., PRD 2020

UHECR
shower development

Shower development in the atmosphere

Heitler model—simple, but illustrative:

Higher altitude



Lower altitude

Heitler, *The Quantum Theory of Radiation*, 1954
Matthews, *Astropart. Phys.* 2005

Shower development in the atmosphere

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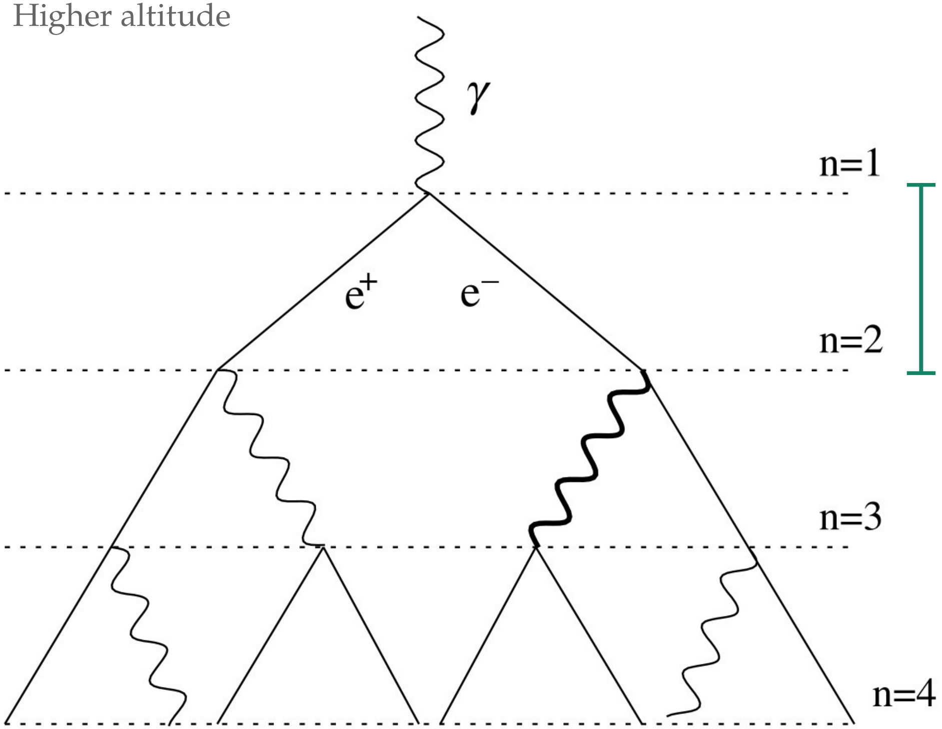

Electron splitting length, $d = \lambda_\Gamma \ln 2$

Lower altitude

Heitler, *The Quantum Theory of Radiation*, 1954
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Shower development in the atmosphere

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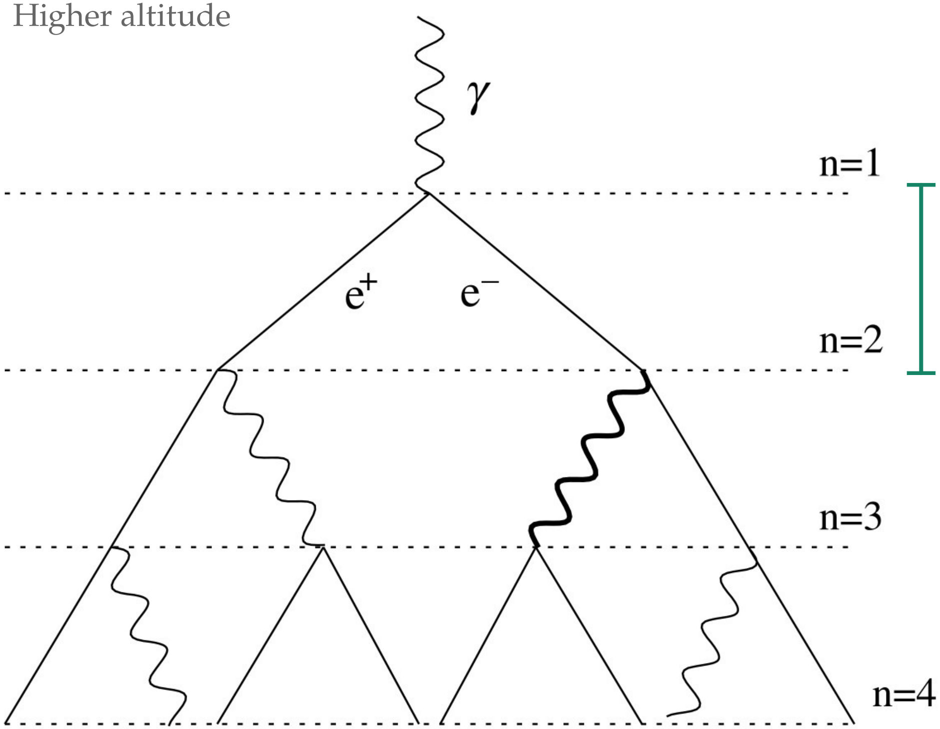

Lower altitude

Electron
splitting
length,
$d = \lambda_\Gamma \ln 2$

Radiation
length
(g cm^{-2})

Heitler, *The Quantum Theory of Radiation*, 1954
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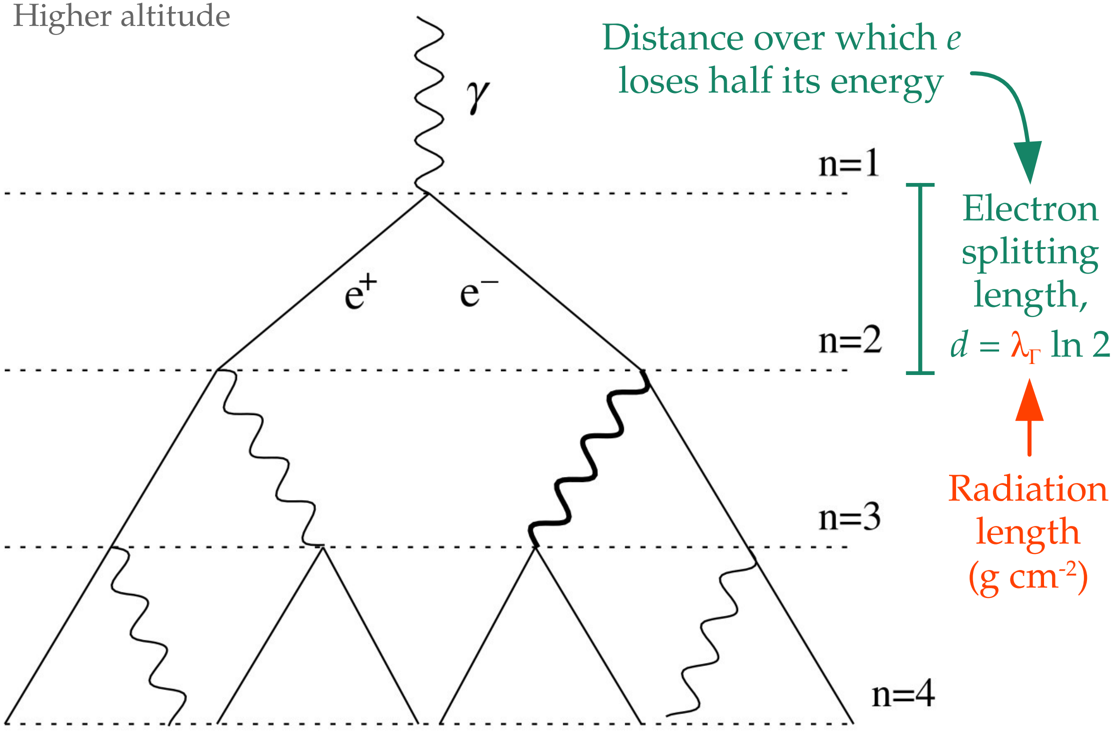


Distance over which *e* loses half its energy

Electron splitting length, $d = \lambda_r \ln 2$

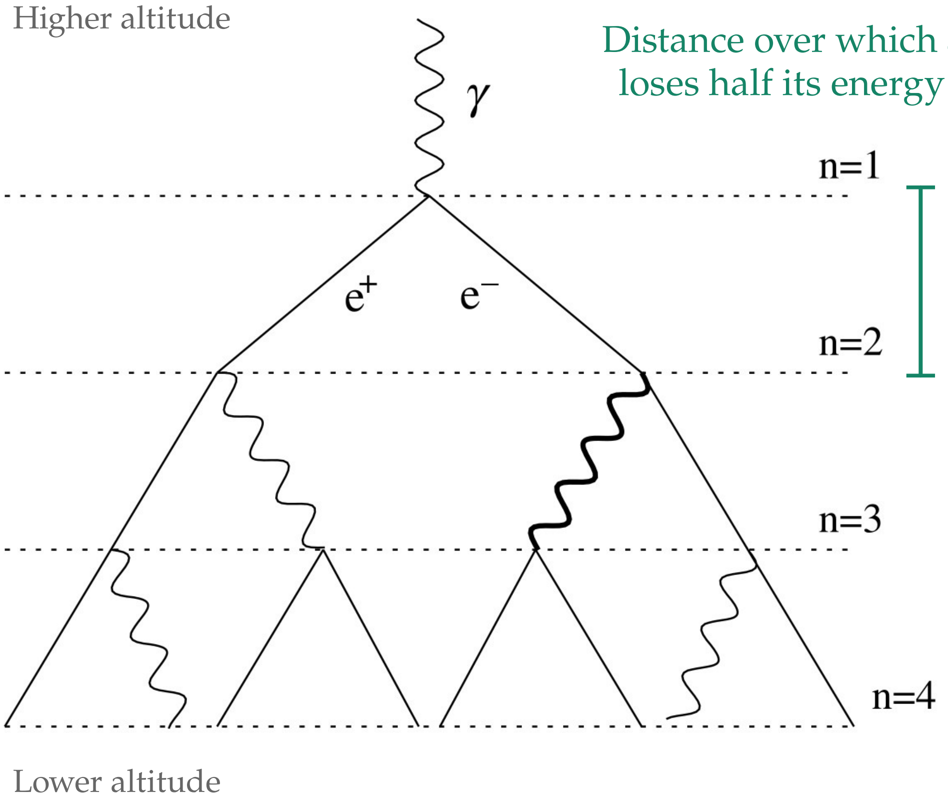
Radiation length (g cm^{-2})

Lower altitude

Heitler, *The Quantum Theory of Radiation*, 1954
Matthews, *Astropart. Phys.* 2005

Shower development in the atmosphere

Heitler model—simple, but illustrative:



Distance over which *e* loses half its energy

Electron splitting length,
$d = \lambda_\Gamma \ln 2$

Radiation length
(g cm^{-2})

After n splitting lengths,

Depth traveled:
$x = n\,\lambda_\Gamma \ln 2$

Number of particles ($e + \gamma$):
$N = 2^n = e^{x/\lambda_\Gamma}$

Heitler, *The Quantum Theory of Radiation*, 1954
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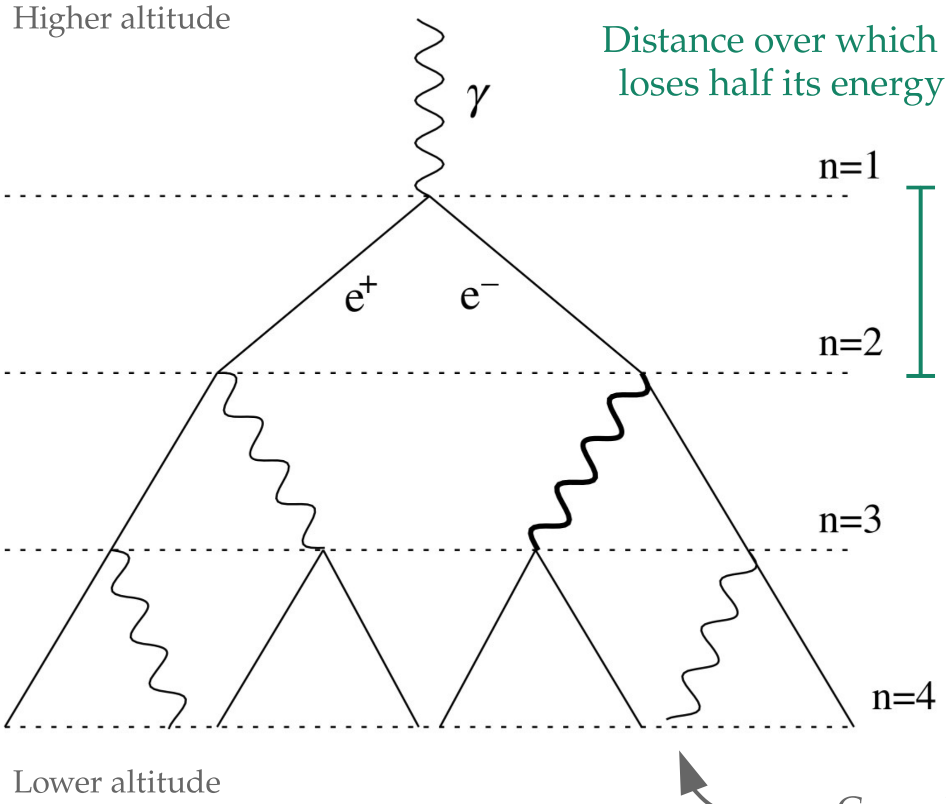

Distance over which *e* loses half its energy

Electron splitting length,
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Radiation length (g cm^{-2})

After *n* splitting lengths,

Depth traveled:
$x = n\,\lambda_\Gamma \ln 2$

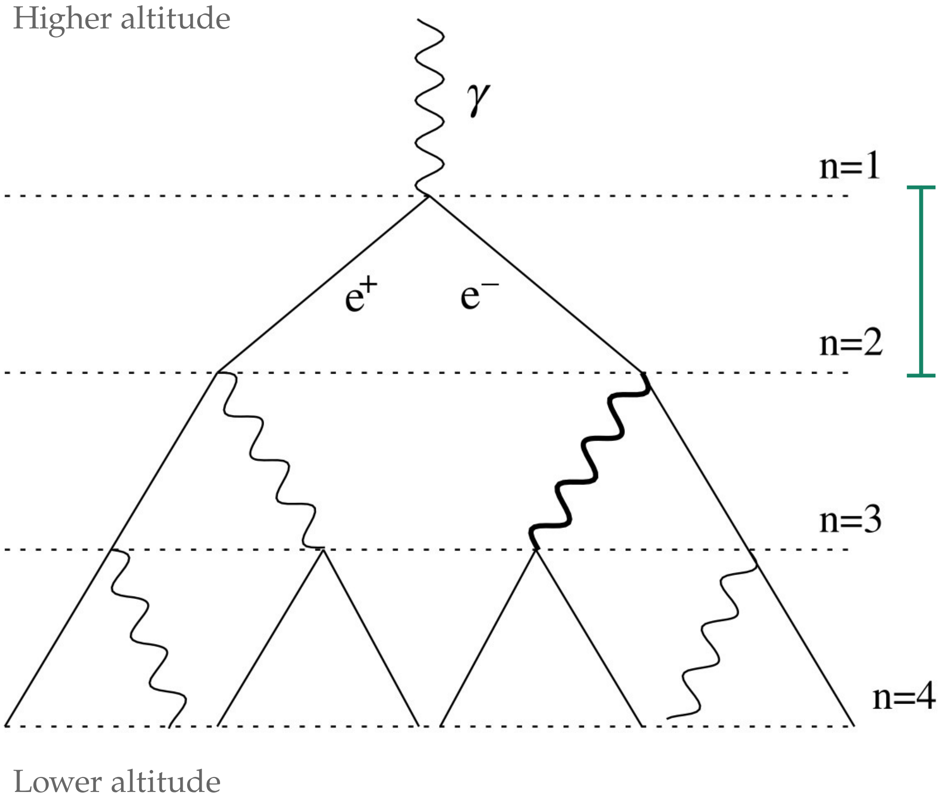
Number of particles ($e + \gamma$):
$N = 2^n = e^{x/\lambda_\Gamma}$

Cascade development stops after n_C splittings, when the particle energies are too low for pair production or bremsstrahlung

Heitler, *The Quantum Theory of Radiation*, 1954
Matthews, *Astropart. Phys.* 2005

Shower development in the atmosphere

Heitler model—simple, but illustrative:



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After *n* splitting lengths,

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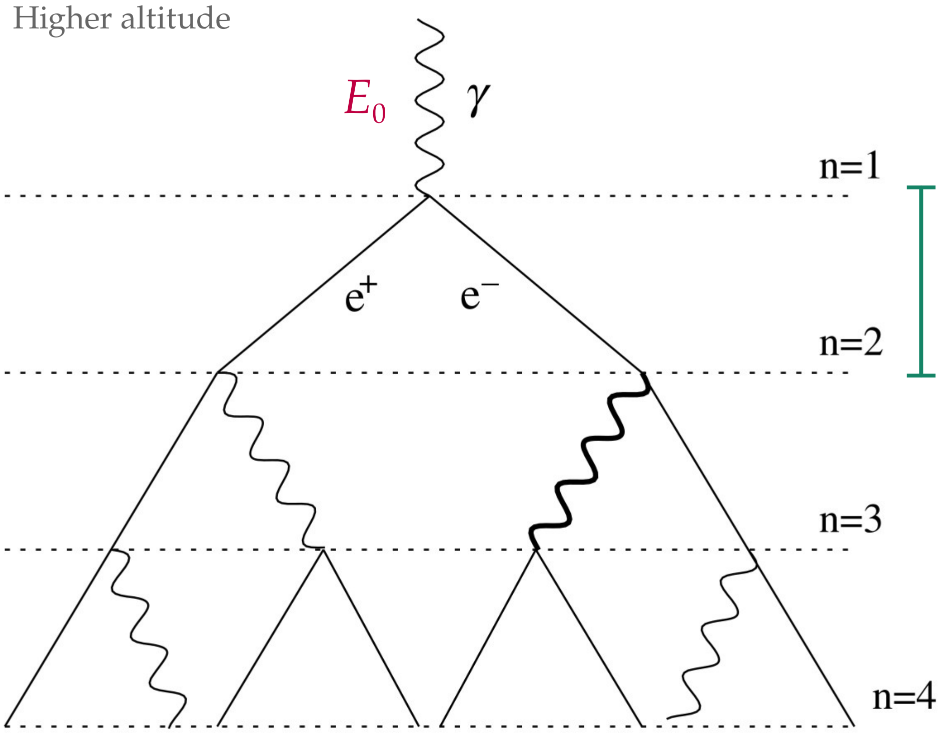

Electron splitting length,
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Radiation length
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After n splitting lengths,

Depth traveled:
$x = n\,\lambda_\Gamma \ln 2$

Number of particles ($e + \gamma$):
$N = 2^n = e^{x/\lambda_\Gamma}$

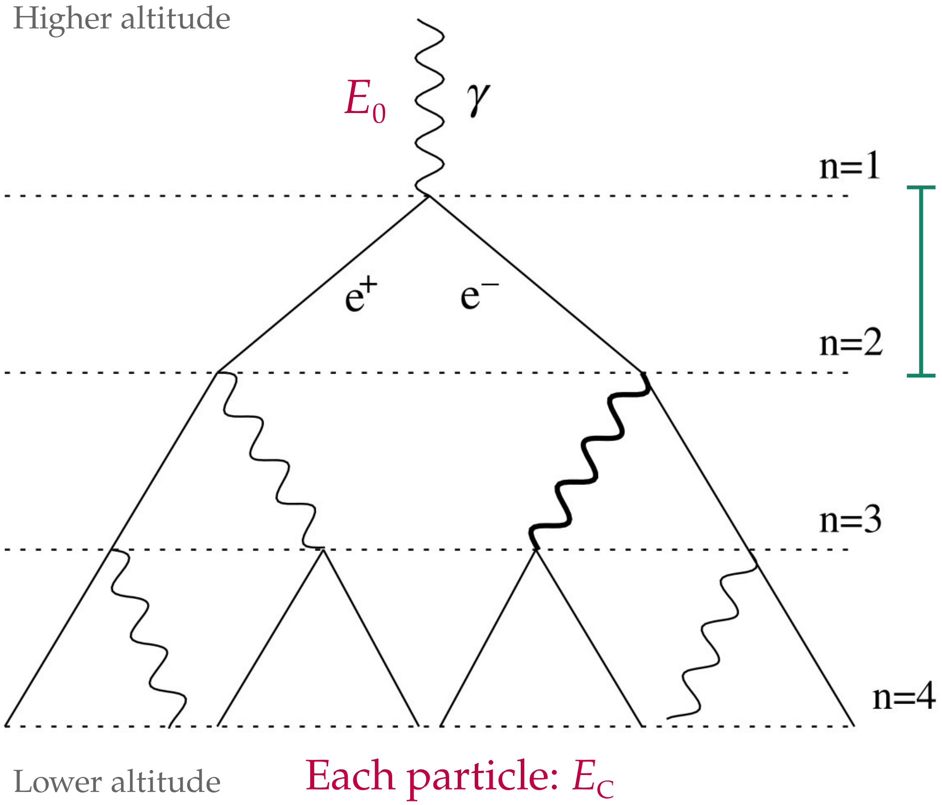
Lower altitude

Each particle: E_C
($\approx$ 85 MeV in air)

Heitler, *The Quantum Theory of Radiation*, 1954
Matthews, *Astropart. Phys.* 2005

Shower development in the atmosphere

Heitler model—simple, but illustrative:



Each particle: E_C

($\approx$ 85 MeV in air)

Electron splitting length, $d = \lambda_\Gamma \ln 2$

Radiation length (g cm^{-2})

After n splitting lengths,

Depth traveled: $x = n\,\lambda_\Gamma \ln 2$

Number of particles ($e + \gamma$): $N = 2^n = e^{x/\lambda_\Gamma}$

The cascade reaches its maximum size $N = N_{\text{max}}$ when all particles have energy E_C so that

$$E_0 = E_C\, N_{\text{max}} \;.$$

But $N_{\text{max}} = 2^{n_C}$, so

$$n_C = \ln(E_0/E_C)/\ln 2$$

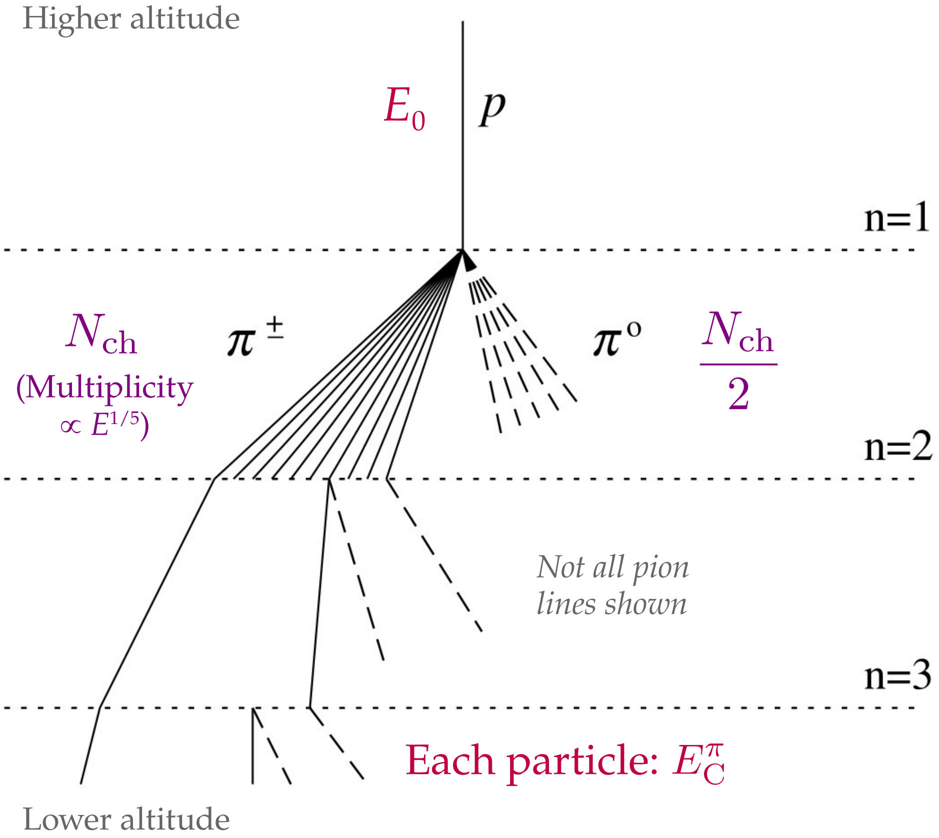
And $X_{\text{max}} = n_C\, d$ is

$$X_{\text{max}} = \lambda_\Gamma \ln(E_0/E_C)$$

Heitler, *The Quantum Theory of Radiation*, 1954
Matthews, *Astropart. Phys.* 2005

Shower development in the atmosphere

Heitler model—simple, but illustrative:



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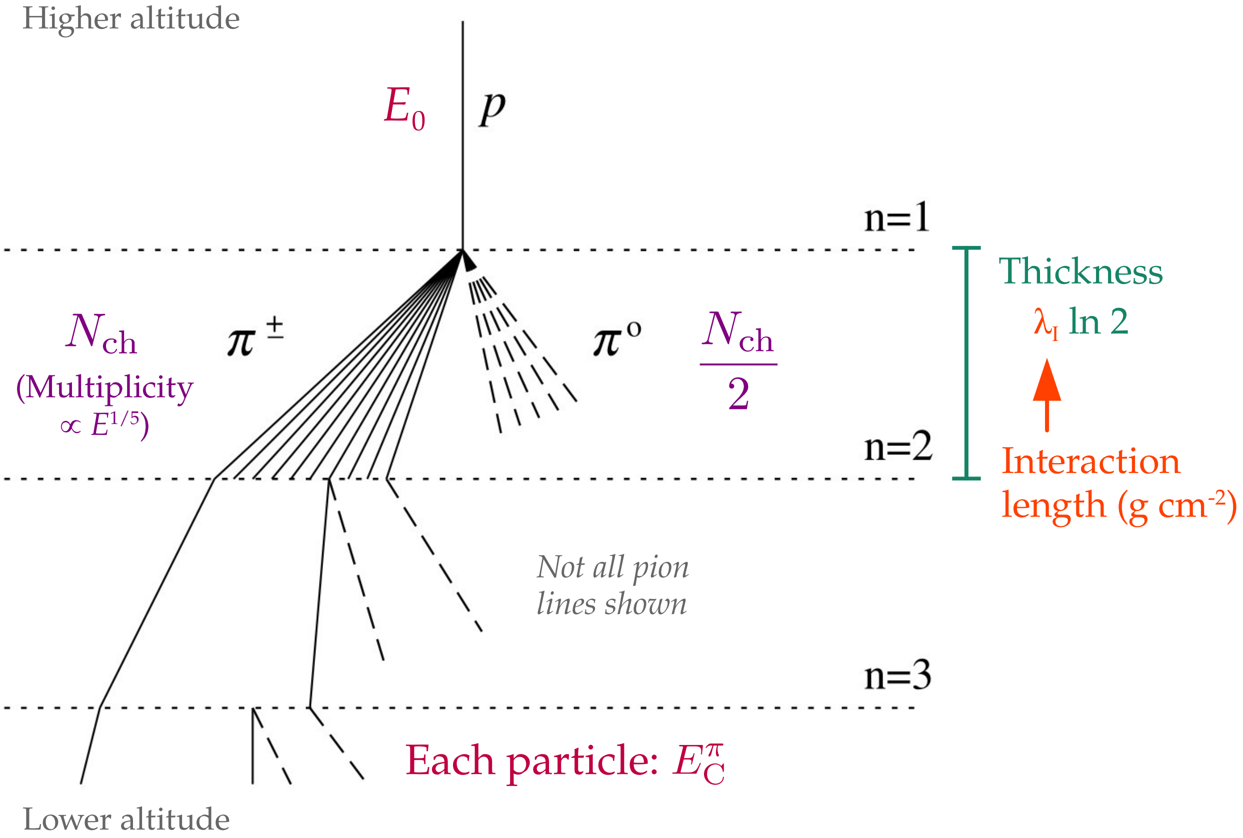

Higher altitude

E_0 p

n=1

n=2

n=3

N_{ch}
(Multiplicity
$\propto E^{1/5}$)

$\pi^{\pm}$

π^{o} $\frac{N_{\mathrm{ch}}}{2}$

Thickness
λ_{I} ln 2

Interaction
length (g cm^{-2})

Not all pion
lines shown

Each particle: E_{C}^{π}

Lower altitude

Heitler, *The Quantum Theory of Radiation*, 1954
Matthews, *Astropart. Phys.* 2005

Shower development in the atmosphere

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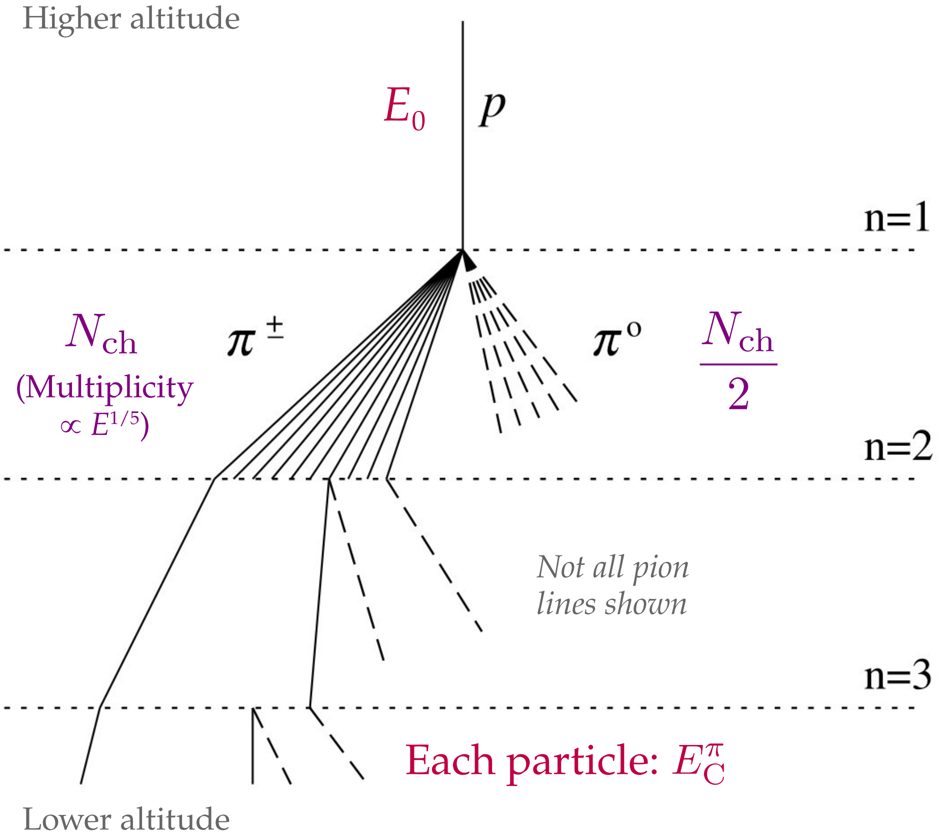

Not all pion lines shown

Each particle: E_{C}^{π}

Thickness $\lambda_{\text{I}} \ln 2$

Interaction length (g cm^{-2})

After n lengths,

Number of $\pi^{\pm}$:

$$N_\pi = N_{\text{ch}}^n$$

Total energy in $\pi^{\pm}$:

$$(2/3)^n \, E_0$$

Per $\pi^{\pm}$:

$$E_\pi = \frac{E_0}{\left(\frac{3}{2}N_{\text{ch}}\right)^n}$$

Heitler, *The Quantum Theory of Radiation*, 1954
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Shower development in the atmosphere

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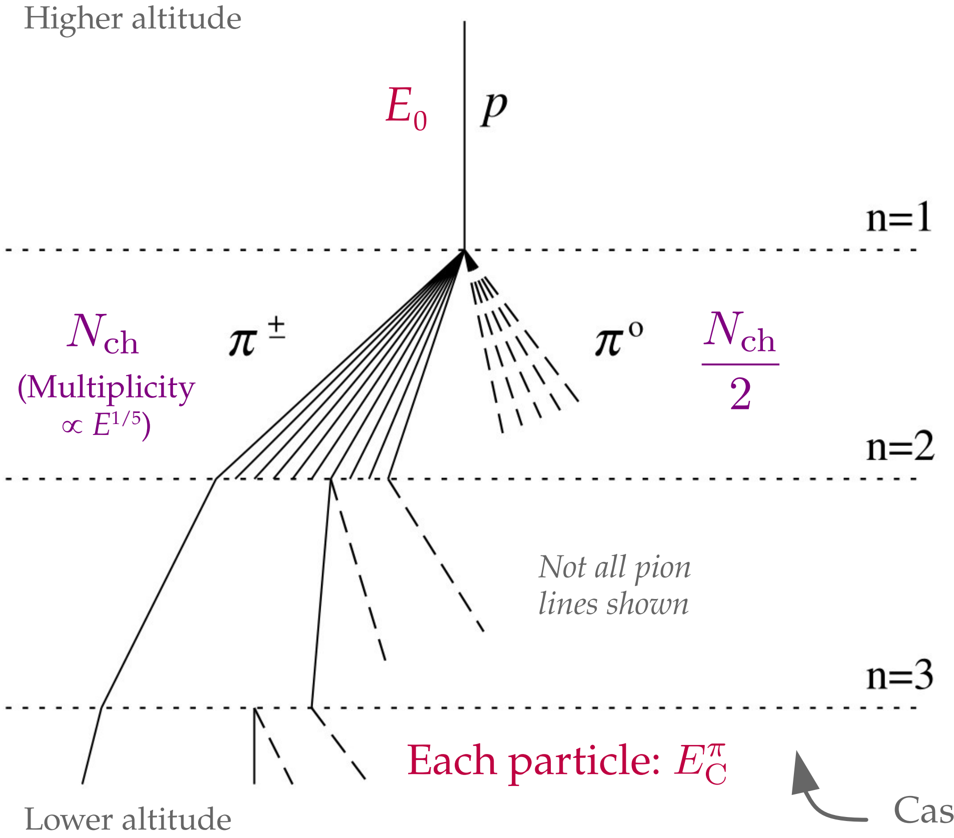

Each particle: E_C^π

Thickness $\lambda_I \ln 2$

Interaction length (g cm^{-2})

After n lengths,

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Total energy in $\pi^\pm$:

$$(2/3)^n E_0$$

Per $\pi^\pm$:

$$E_\pi = \frac{E_0}{\left(\frac{3}{2}N_{\text{ch}}\right)^n}$$

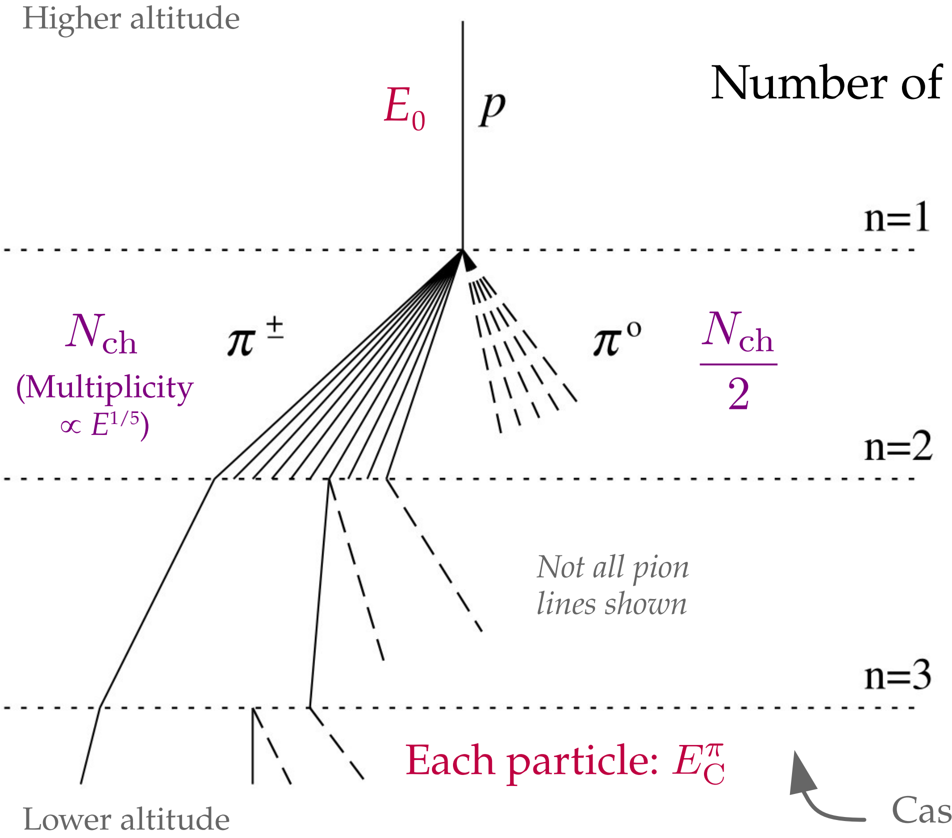
Cascade development stops after n_C lengths, when the average pion energy E_C is such that the decay length of $\pi^\pm$ is < λ_I

Heitler, *The Quantum Theory of Radiation*, 1954
Matthews, *Astropart. Phys.* 2005

Shower development in the atmosphere

Heitler model—simple, but illustrative:

Number of interactions to reach $E_\pi = E_\mathrm{C}^\pi$: $n_\mathrm{C} = \dfrac{\ln(E_0/E_\mathrm{C}^\pi)}{\ln(\frac{3}{2}N_\mathrm{ch})}$



Thickness
$\lambda_\mathrm{I} \ln 2$

Interaction length (g cm^{-2})

After n lengths,

Number of $\pi^\pm$:
$N_\pi = N_\mathrm{ch}^n$

Total energy in $\pi^\pm$:
$(2/3)^n E_0$

Per $\pi^\pm$:
$E_\pi = \dfrac{E_0}{\left(\frac{3}{2}N_\mathrm{ch}\right)^n}$

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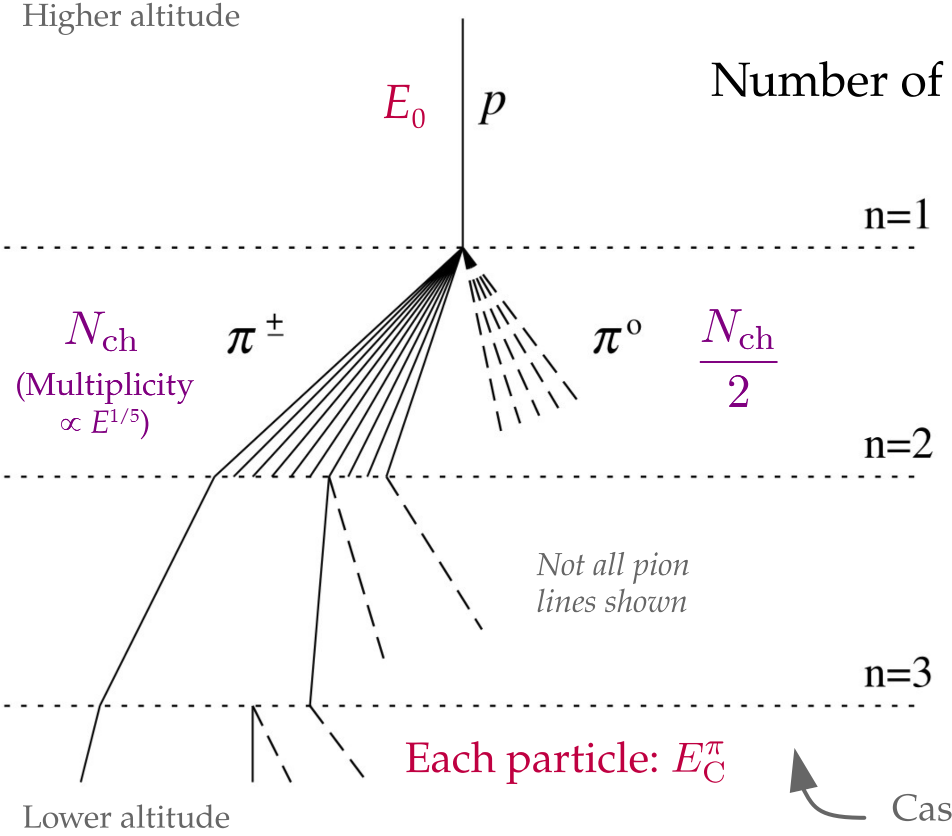


Each particle: E_C^π

Number of interactions to reach $E_\pi = E_C^\pi$: $n_C = \dfrac{\ln(E_0/E_C^\pi)}{\ln(\frac{3}{2}N_{\text{ch}})}$

Thickness $\lambda_I \ln 2$

Interaction length (g cm^{-2})

After n lengths,

Number of $\pi^\pm$:

$N_\pi = N_{\text{ch}}^n$

Total energy in $\pi^\pm$:

$(2/3)^n E_0$

Per $\pi^\pm$:

$$E_\pi = \frac{E_0}{\left(\frac{3}{2}N_{\text{ch}}\right)^n}$$

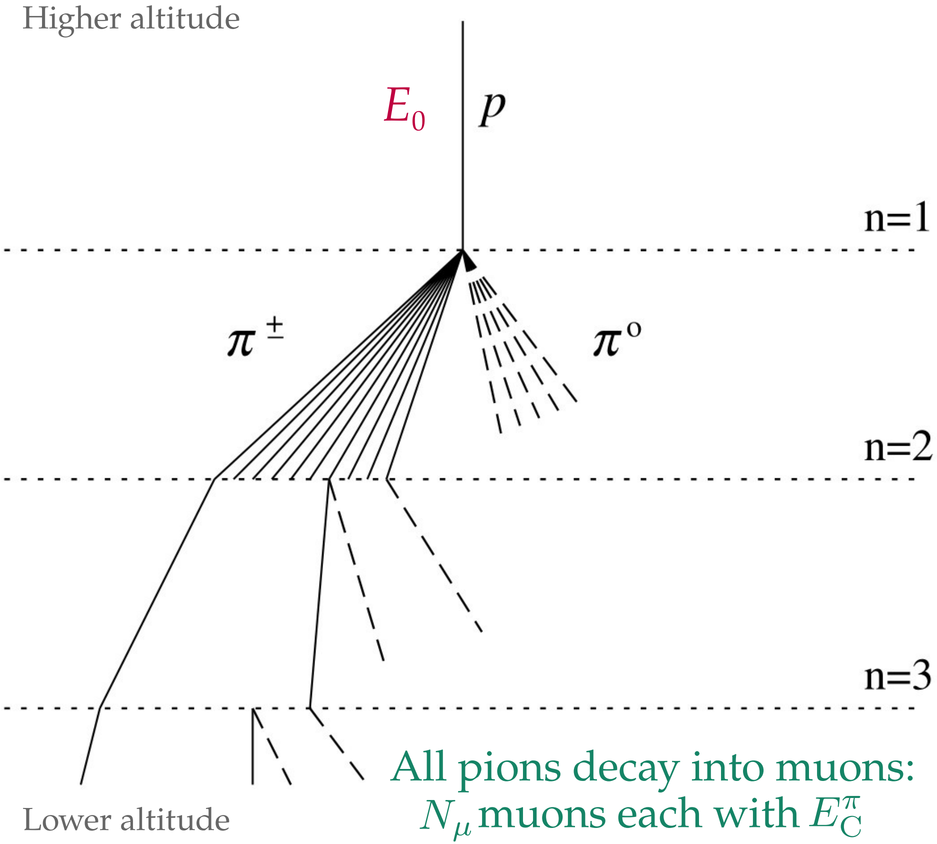
Let's put this all together to infer E_0 and $X_{\max}$ from measured quantities (*simplified calculations*)

Cascade development stops after n_C lengths, when the average pion energy E_C is such that the decay length of $\pi^\pm$ is < λ_I

Heitler, *The Quantum Theory of Radiation*, 1954
Matthews, *Astropart. Phys.* 2005

Shower development in the atmosphere

Inferring the primary UHECR energy:

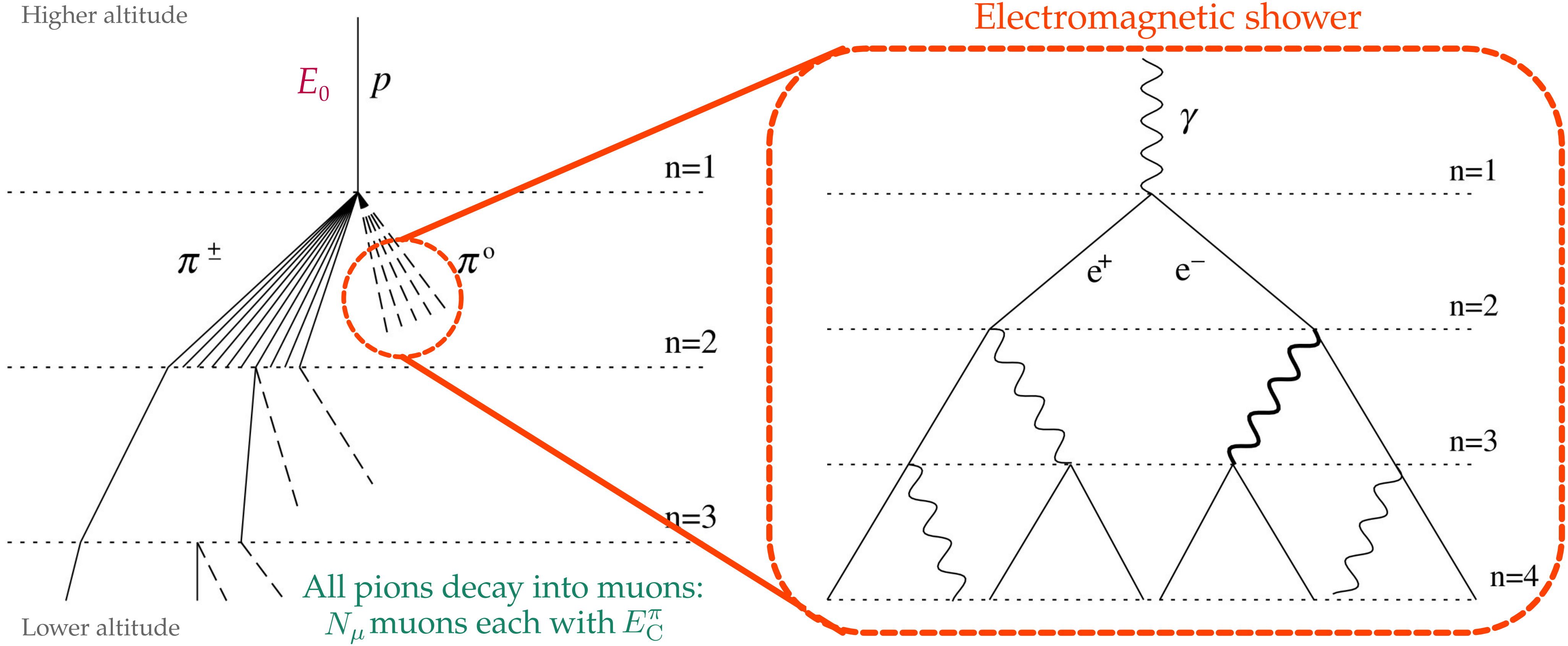


All pions decay into muons:
N_μ muons each with E_C^π

Heitler, *The Quantum Theory of Radiation*, 1954
Matthews, *Astropart. Phys.* 2005

Shower development in the atmosphere

Inferring the primary UHECR energy:



Electromagnetic shower

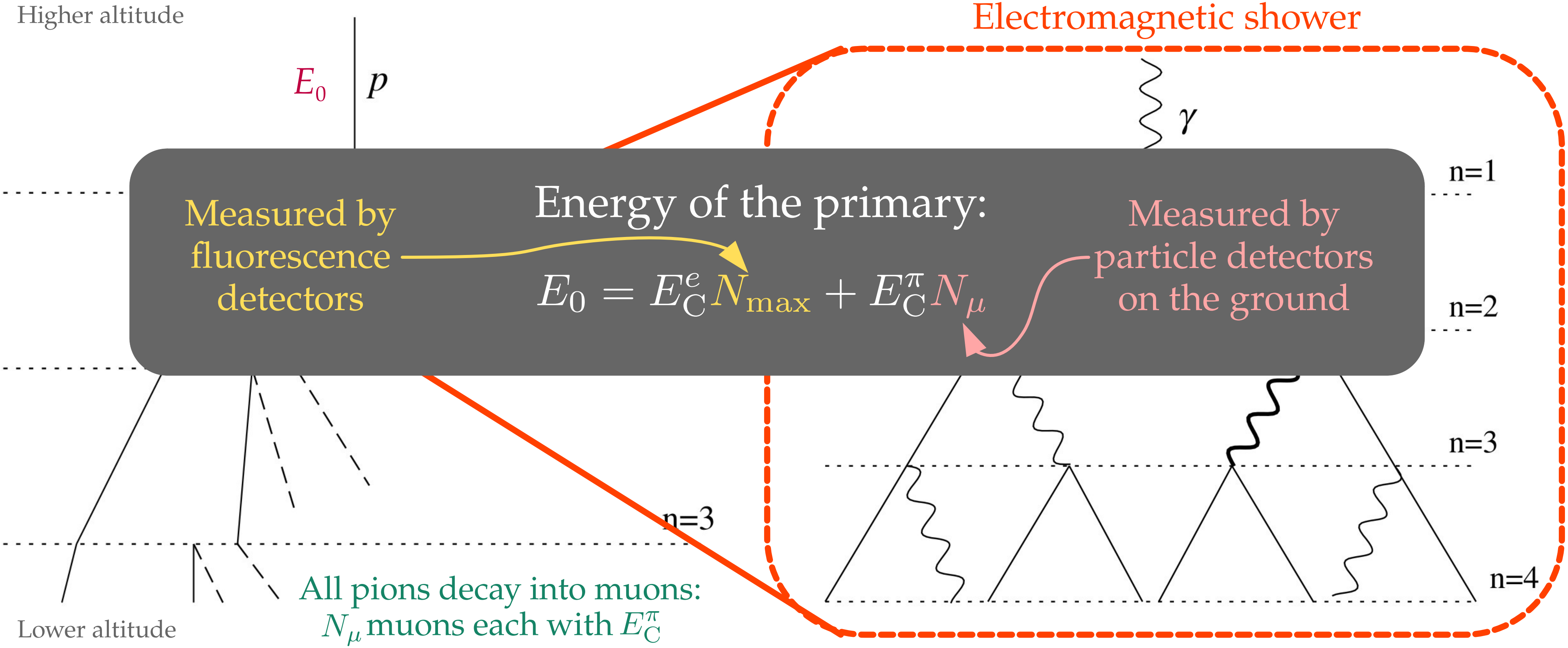
All pions decay into muons:
N_μ muons each with E_C^π

At maximum: N_{max} particles each with E_C^π

Heitler, *The Quantum Theory of Radiation*, 1954
Matthews, *Astropart. Phys.* 2005

Shower development in the atmosphere

Inferring the primary UHECR energy:



Electromagnetic shower

Measured by fluorescence detectors

Energy of the primary:

$$E_0 = E_{\mathrm{C}}^{e} N_{\mathrm{max}} + E_{\mathrm{C}}^{\pi} N_{\mu}$$

Measured by particle detectors on the ground

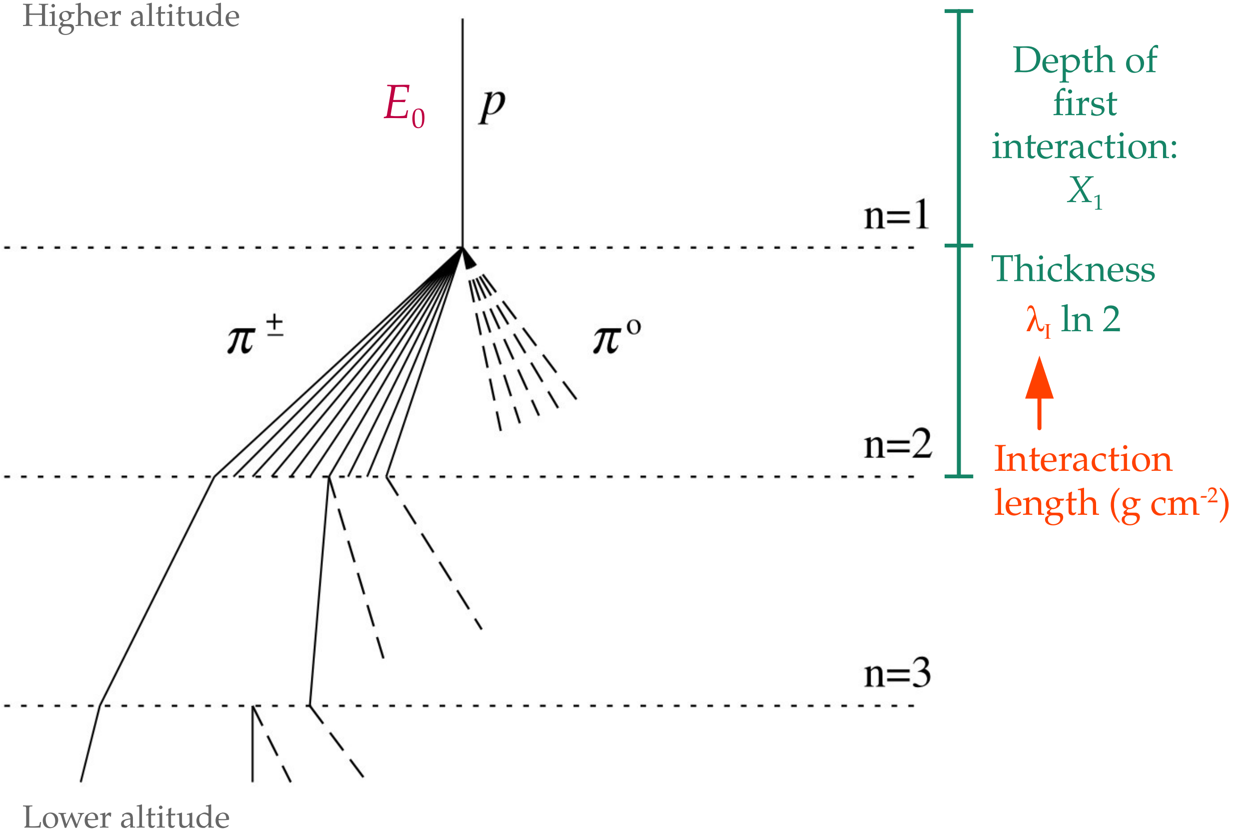
All pions decay into muons:
N_μ muons each with E_{C}^{π}

At maximum: N_{max} particles each with

Heitler, *The Quantum Theory of Radiation*, 1954
Matthews, *Astropart. Phys.* 2005

Shower development in the atmosphere

Inferring X_{max}:



Depth of first interaction: X_1

Thickness $\lambda_I \ln 2$

Interaction length (g cm^{-2})

Proton-air interaction length:

$$\lambda_{\text{I}} = \sigma_{p-\text{air}} \langle m_{\text{air}} \rangle$$

Hard

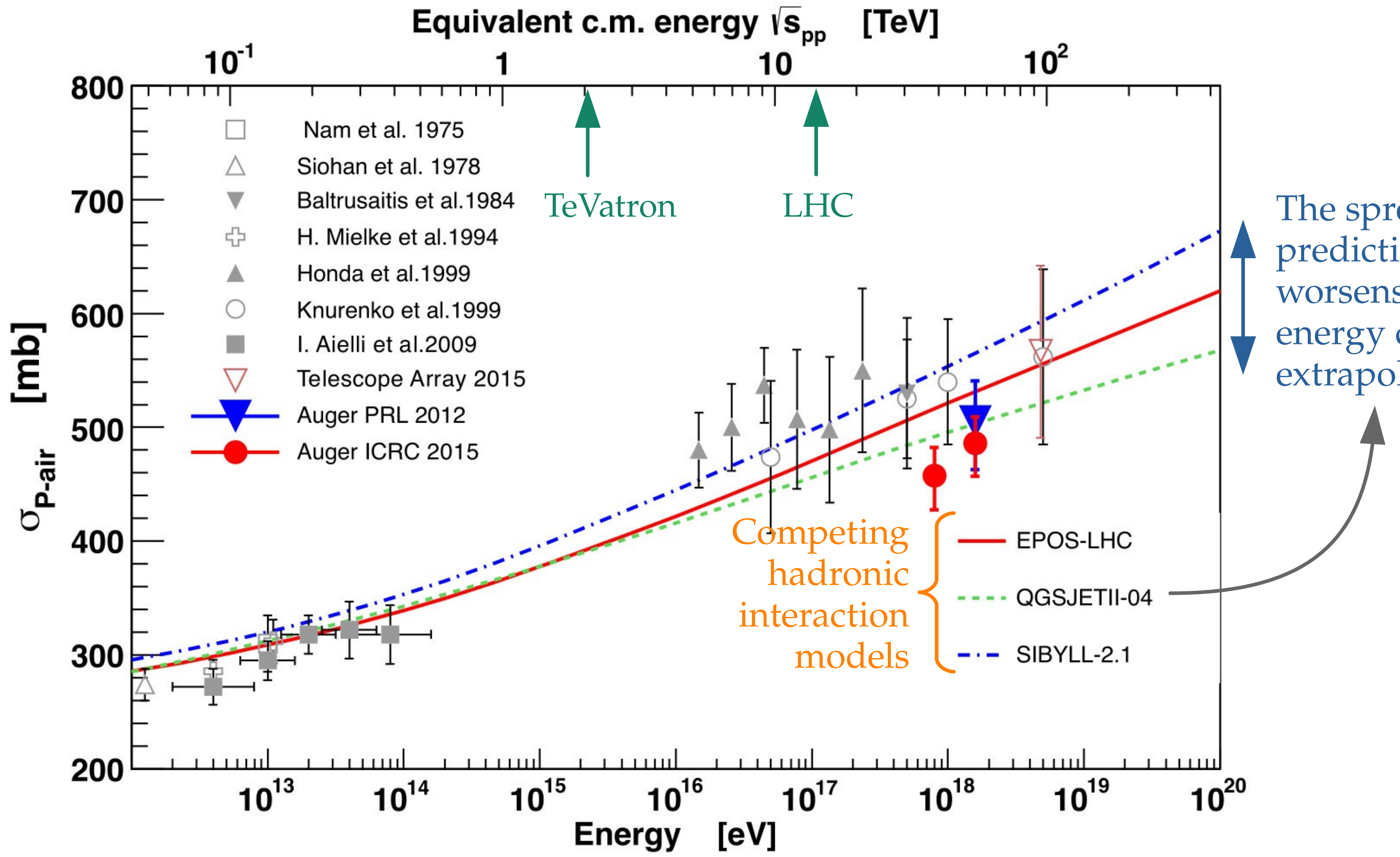
High-energy proton-air cross section

Easy

Average target mass of air (needs model of density profile of atmosphere)

Heitler, *The Quantum Theory of Radiation*, 1954
Matthews, *Astropart. Phys.* 2005

Shower development in the atmosphere



TeVatron

LHC

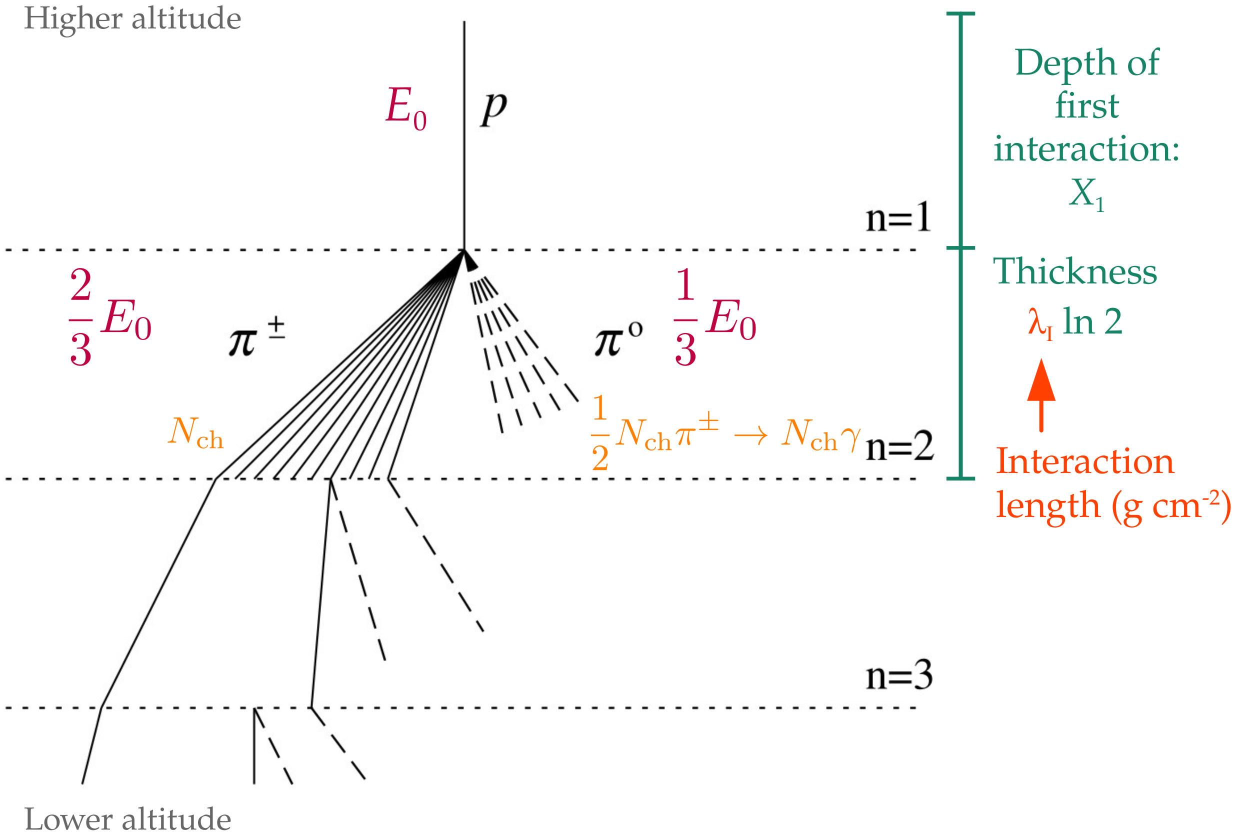
Competing hadronic interaction models

The spread in predictions worsens with energy due to extrapolation

Ulrich (for Auger Collab.), *PoS* ICRC2015

Shower development in the atmosphere

Inferring X_{max}:



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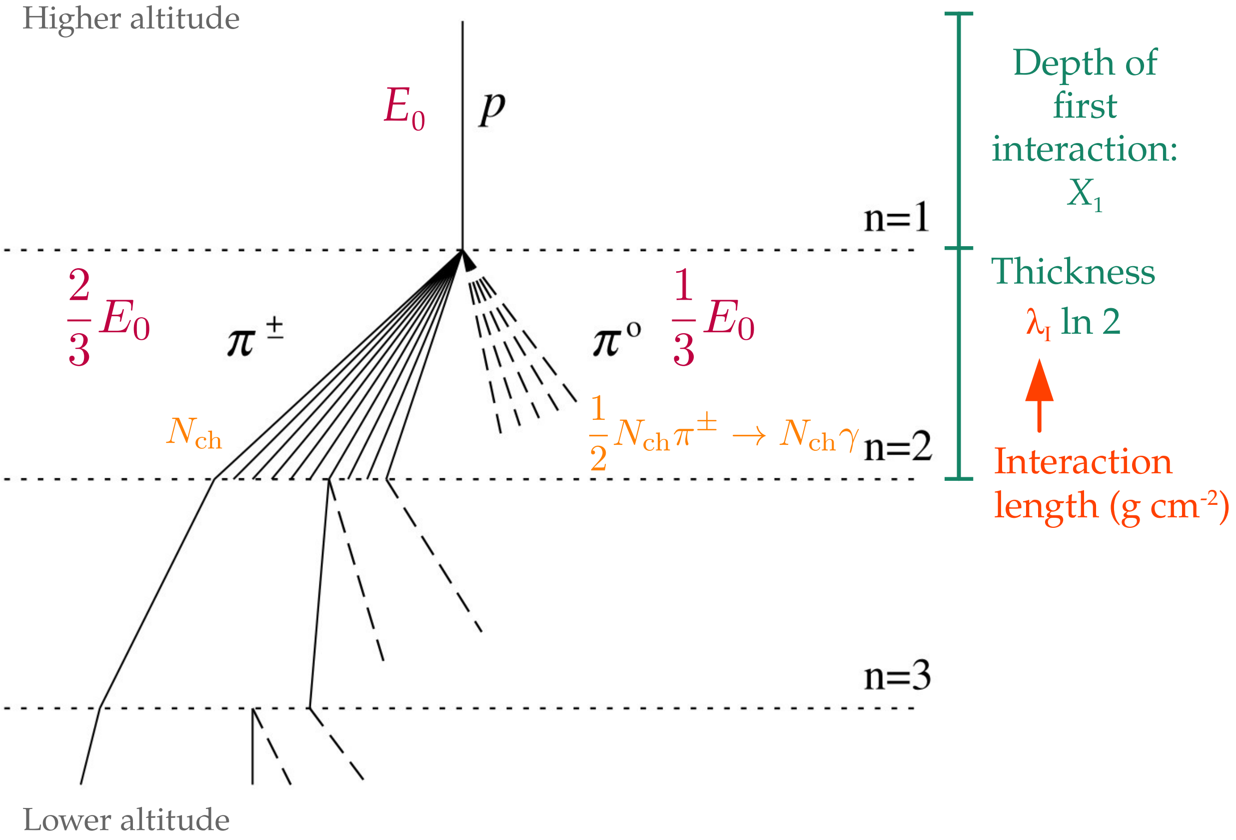
Heitler, *The Quantum Theory of Radiation*, 1954
Matthews, *Astropart. Phys.* 2005

Shower development in the atmosphere

Inferring $X_{\max}$:



Proton-air interaction length:

$$\lambda_{\mathrm{I}} = \sigma_{p-\mathrm{air}} \langle m_{\mathrm{air}} \rangle$$

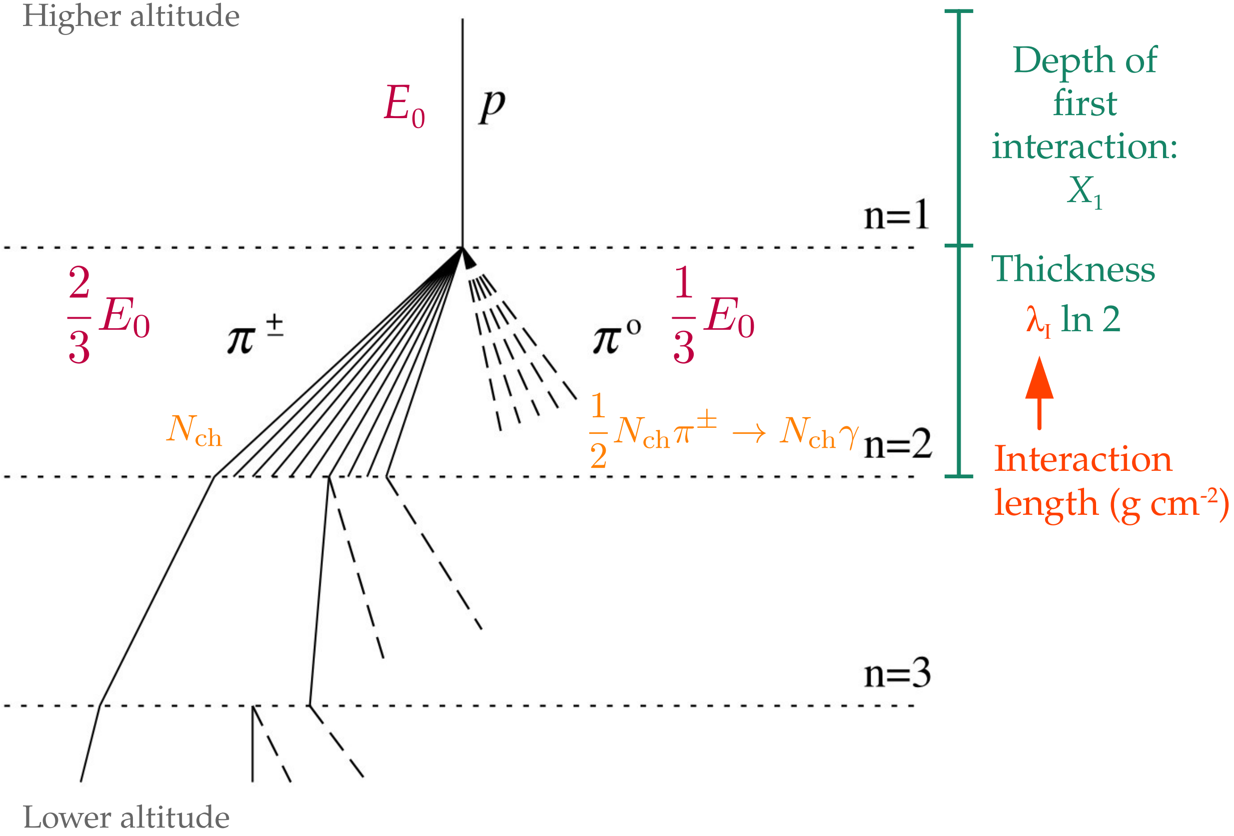
Depth of first interaction:

$$X_1 = \lambda_{\mathrm{I}} \ln 2$$

Heitler, *The Quantum Theory of Radiation*, 1954
Matthews, *Astropart. Phys.* 2005

Shower development in the atmosphere

Inferring $X_{\max}$:



Depth of first interaction: X_1

Thickness λ_I ln 2

Interaction length (g cm^{-2})

Proton-air interaction length:

$$\lambda_{\mathrm{I}} = \sigma_{p-\mathrm{air}} \langle m_{\mathrm{air}} \rangle$$

Depth of first interaction:

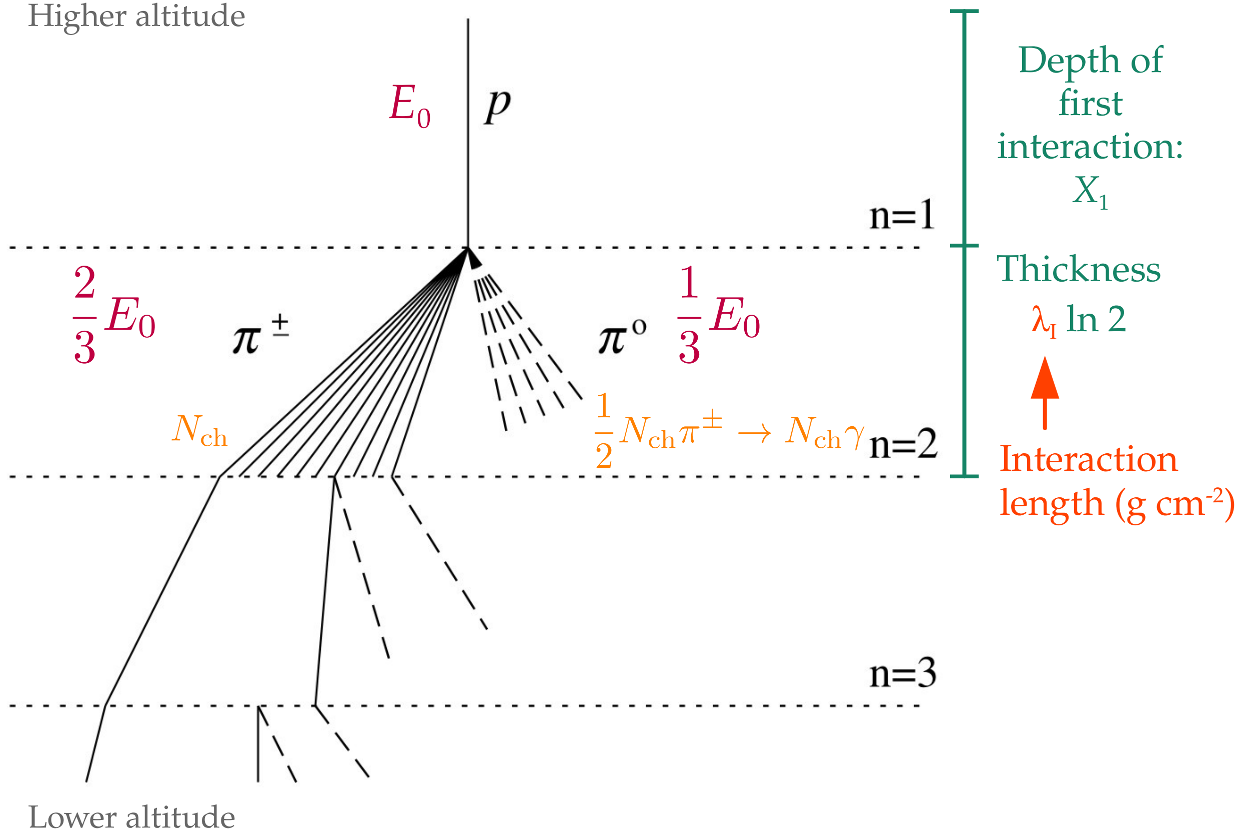
$$X_1 = \lambda_{\mathrm{I}} \ln 2$$

Each photon from π^0 decay starts a shower of energy $(E_0/3)/N_{\mathrm{ch}}$

Heitler, *The Quantum Theory of Radiation*, 1954
Matthews, *Astropart. Phys.* 2005

Shower development in the atmosphere

Inferring X_{max}:



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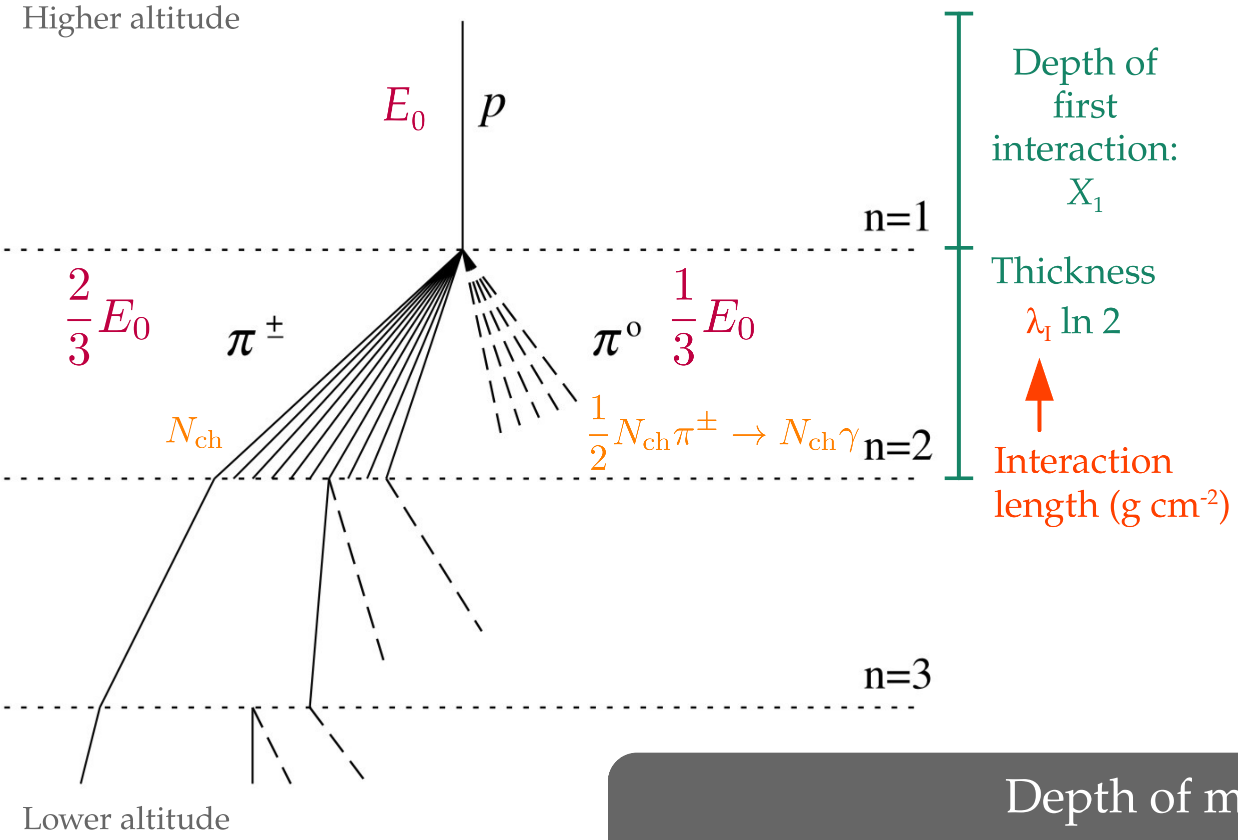
Each photon from π^0 decay starts a shower of energy $(E_0/3)/N_{\mathrm{ch}}$

Each e.m. shower reaches maximum at $\lambda_\Gamma \ln[E_0/(3N_{\mathrm{ch}})/E^e_{\mathrm{C}}]$

Heitler, *The Quantum Theory of Radiation*, 1954
Matthews, *Astropart. Phys.* 2005

Shower development in the atmosphere

Inferring X_{max}:



Heitler, *The Quantum Theory of Radiation*, 1954
Matthews, *Astropart. Phys.* 2005

Proton-air interaction length:

$$\lambda_{\text{I}} = \sigma_{p-\text{air}} \langle m_{\text{air}} \rangle$$

Depth of first interaction:

$$X_1 = \lambda_{\text{I}} \ln 2$$

Each photon from π^0 decay starts a shower of energy $(E_0/3)/N_{\text{ch}}$

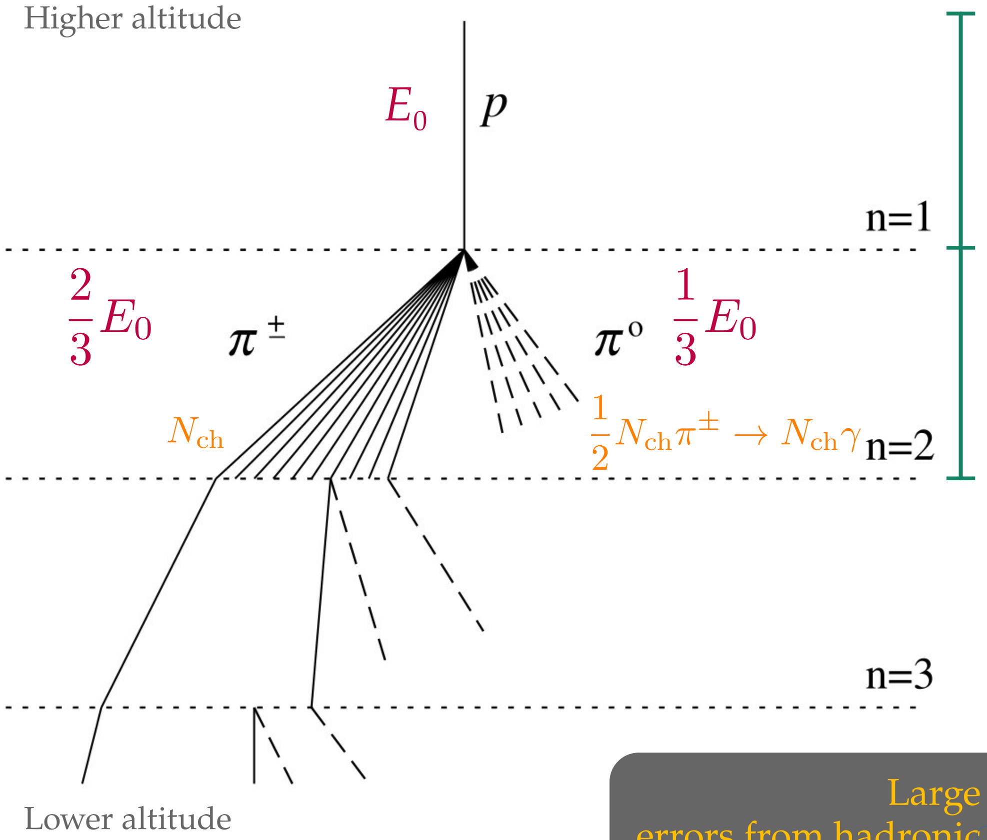
Each e.m. shower reaches maximum at $\lambda_\Gamma \ln[E_0/(3N_{\text{ch}})/E_{\text{C}}^e]$

Depth of maximum of the *p*-initiated shower:

$$X_{\text{max}}^p = X_1 + \lambda_\Gamma \ln[E_0/(3N_{\text{ch}} E_{\text{C}}^e)]$$

Shower development in the atmosphere

Inferring $X_{\max}$:



Depth of first interaction: X_1

Thickness $\lambda_I \ln 2$

Interaction length (g cm^{-2})

Proton-air interaction length:

$$\lambda_{\mathrm{I}} = \sigma_{p-\mathrm{air}} \langle m_{\mathrm{air}} \rangle$$

Depth of first interaction:

$$X_1 = \lambda_{\mathrm{I}} \ln 2$$

Each photon from π^0 decay starts a shower of energy $(E_0/3)/N_{\mathrm{ch}}$

Each e.m. shower reaches maximum at $\lambda_\Gamma \ln[E_0/(3N_{\mathrm{ch}})/E_{\mathrm{C}}^e]$

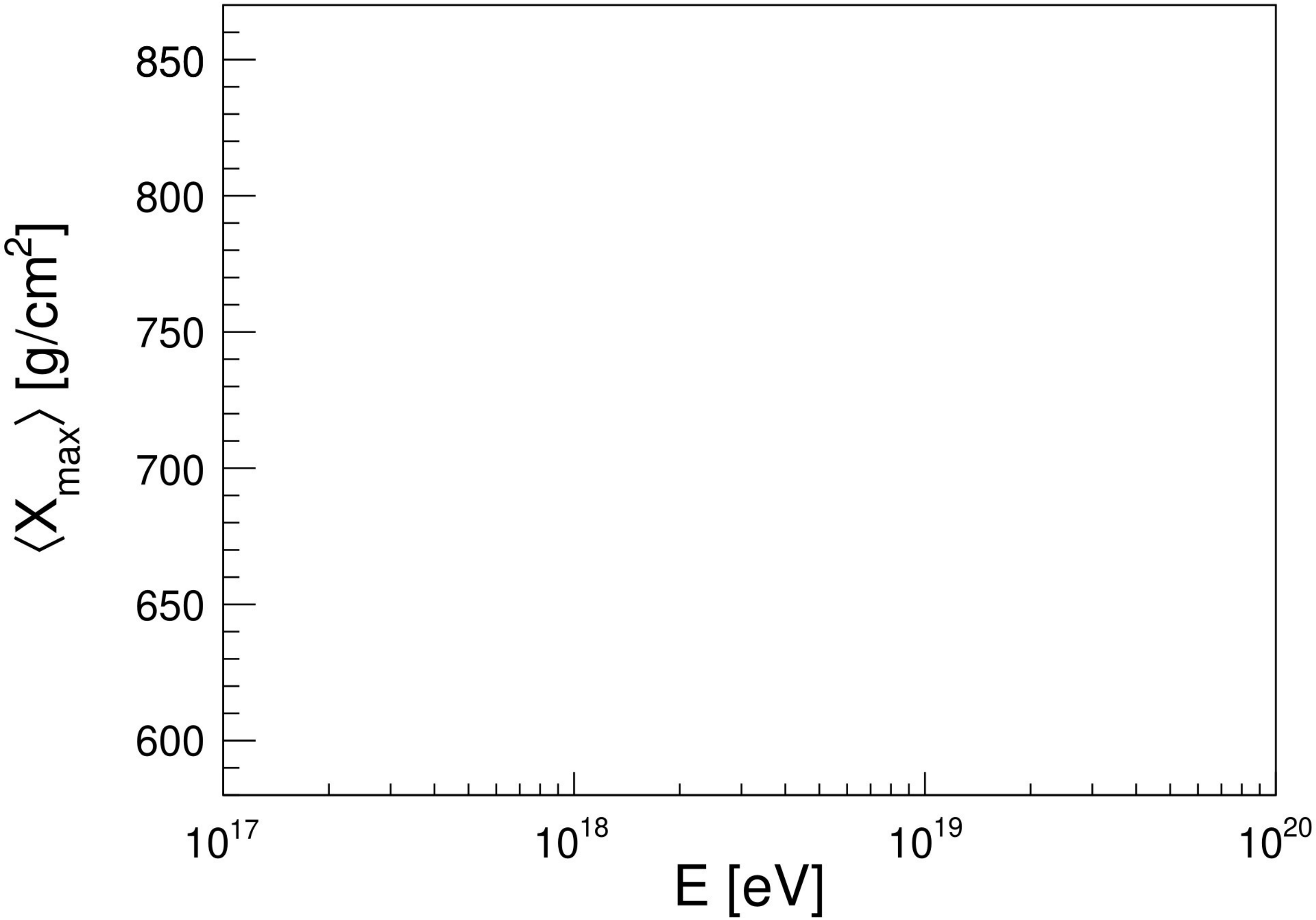
Depth of maximum of the *p*-initiated shower:

$$X_{\max}^p = X_1 + \lambda_\Gamma \ln[E_0/(3N_{\mathrm{ch}}E_{\mathrm{C}}^e)]$$

Large errors from hadronic interaction models

Heitler, *The Quantum Theory of Radiation*, 1954
Matthews, *Astropart. Phys.* 2005

X_{max} and UHECR mass composition



Alves Batista *et al.* (inc. **MB**), *Front. Astron. Space Sci.* 2019

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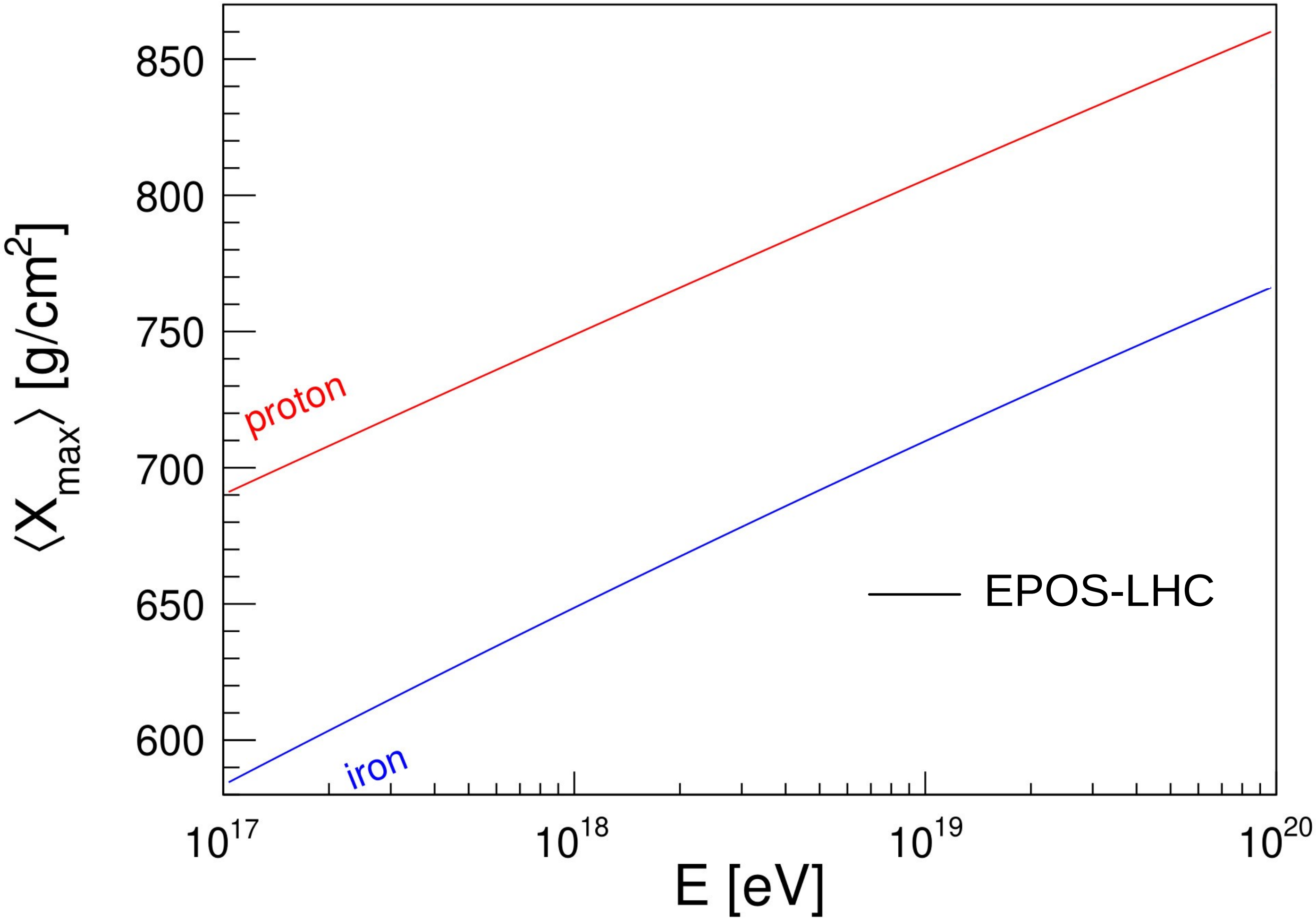

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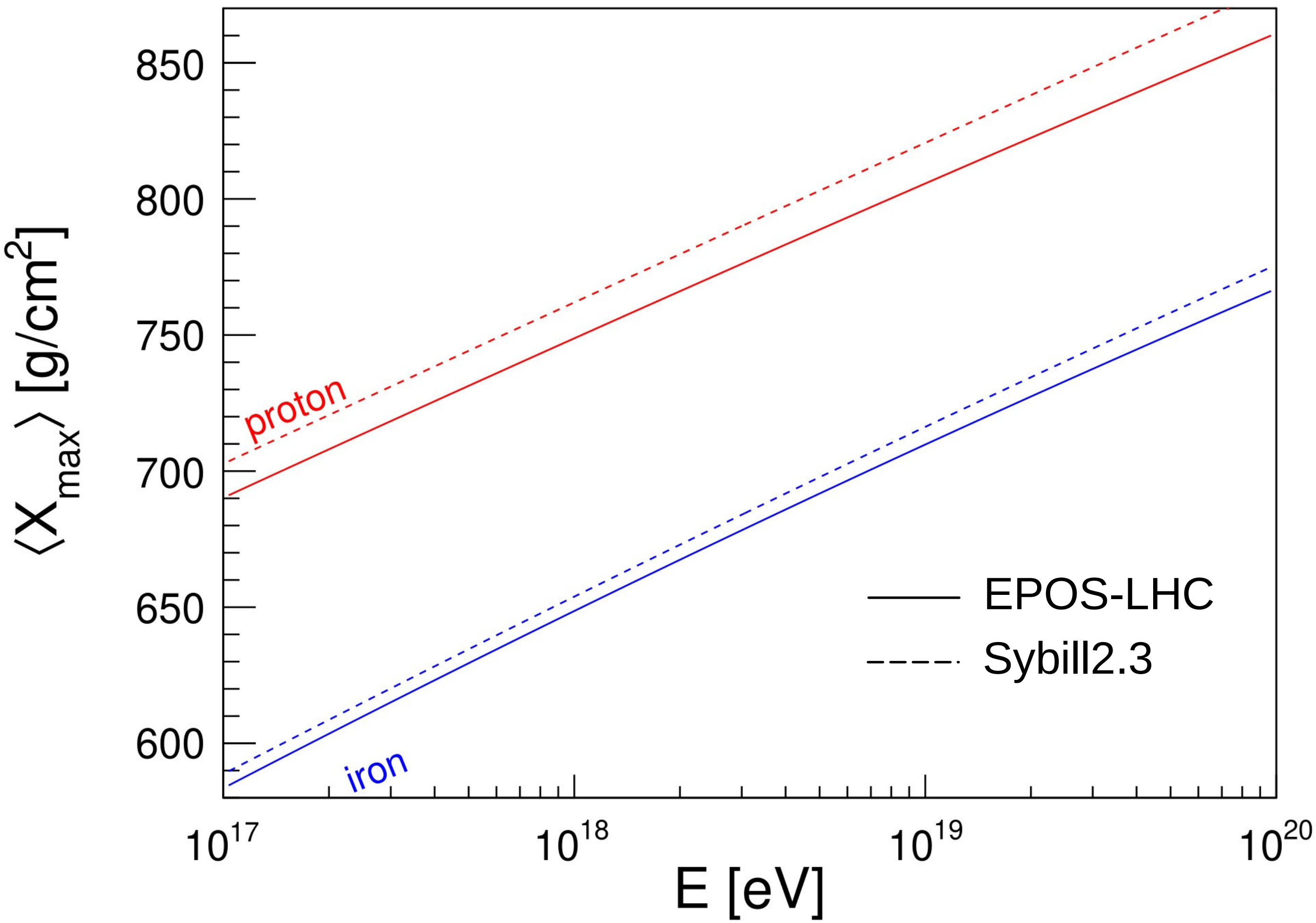

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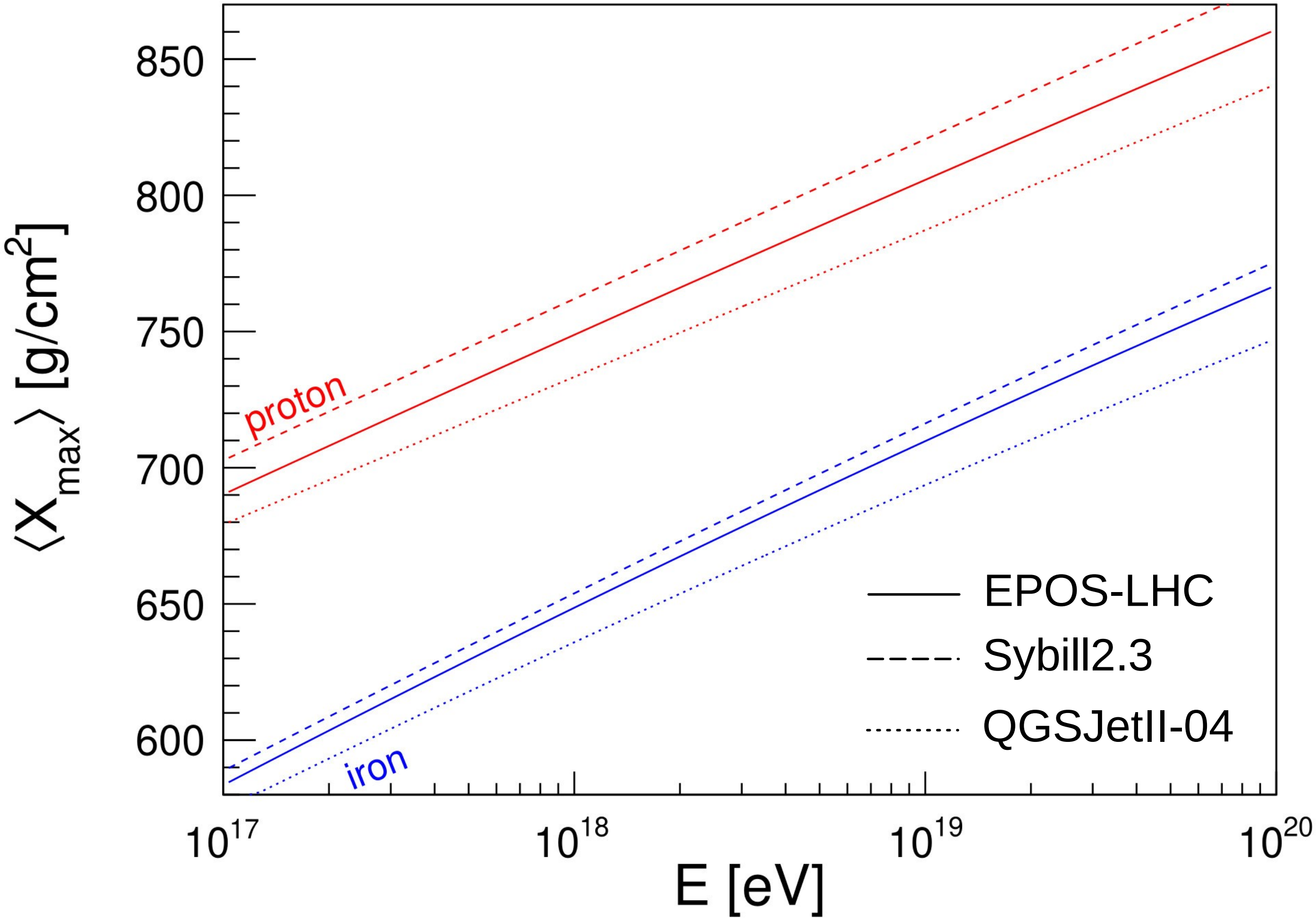

Alves Batista *et al.* (inc. **MB**), *Front. Astron. Space Sci.* 2019

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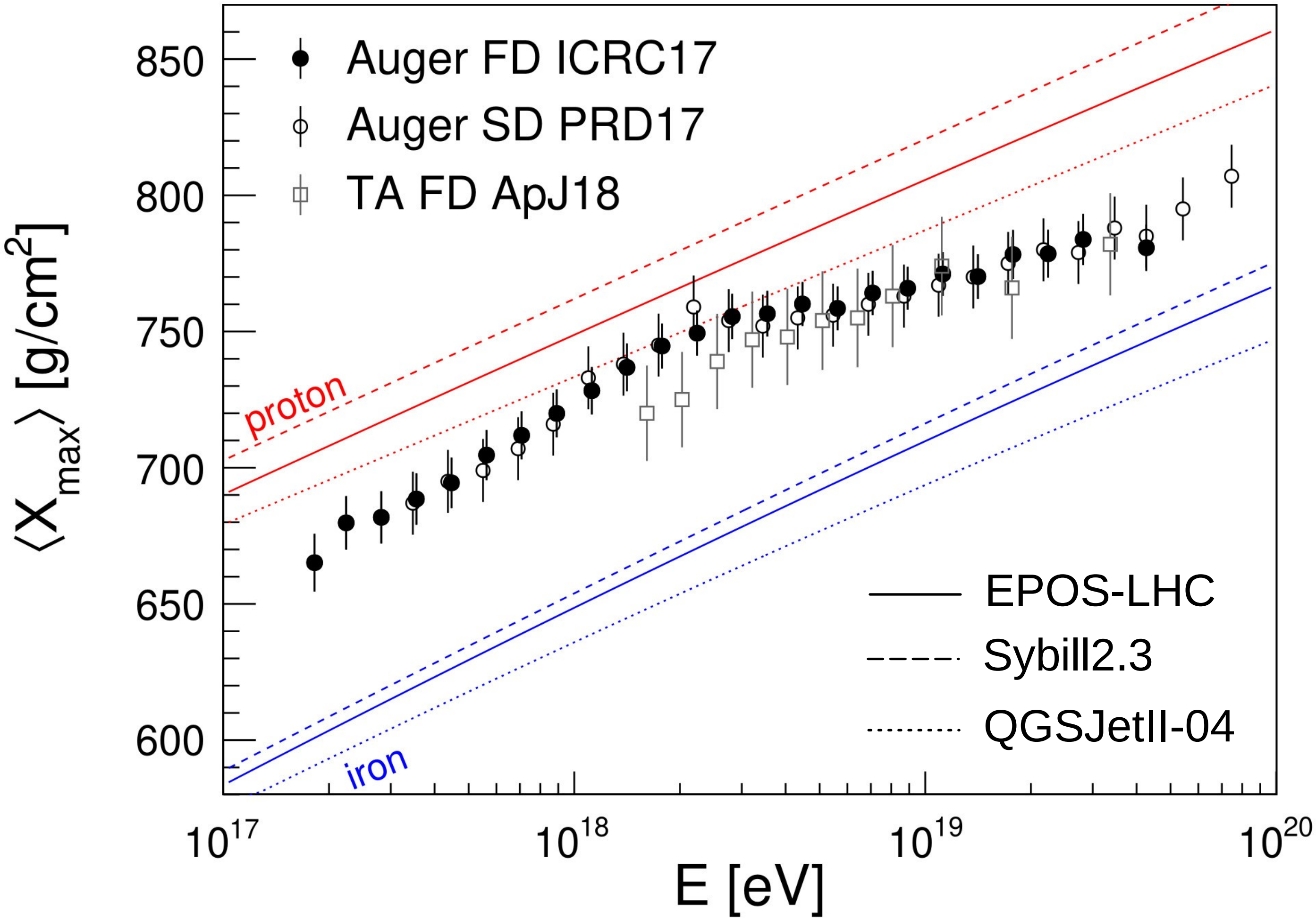

Alves Batista *et al.* (inc. **MB**), *Front. Astron. Space Sci.* 2019

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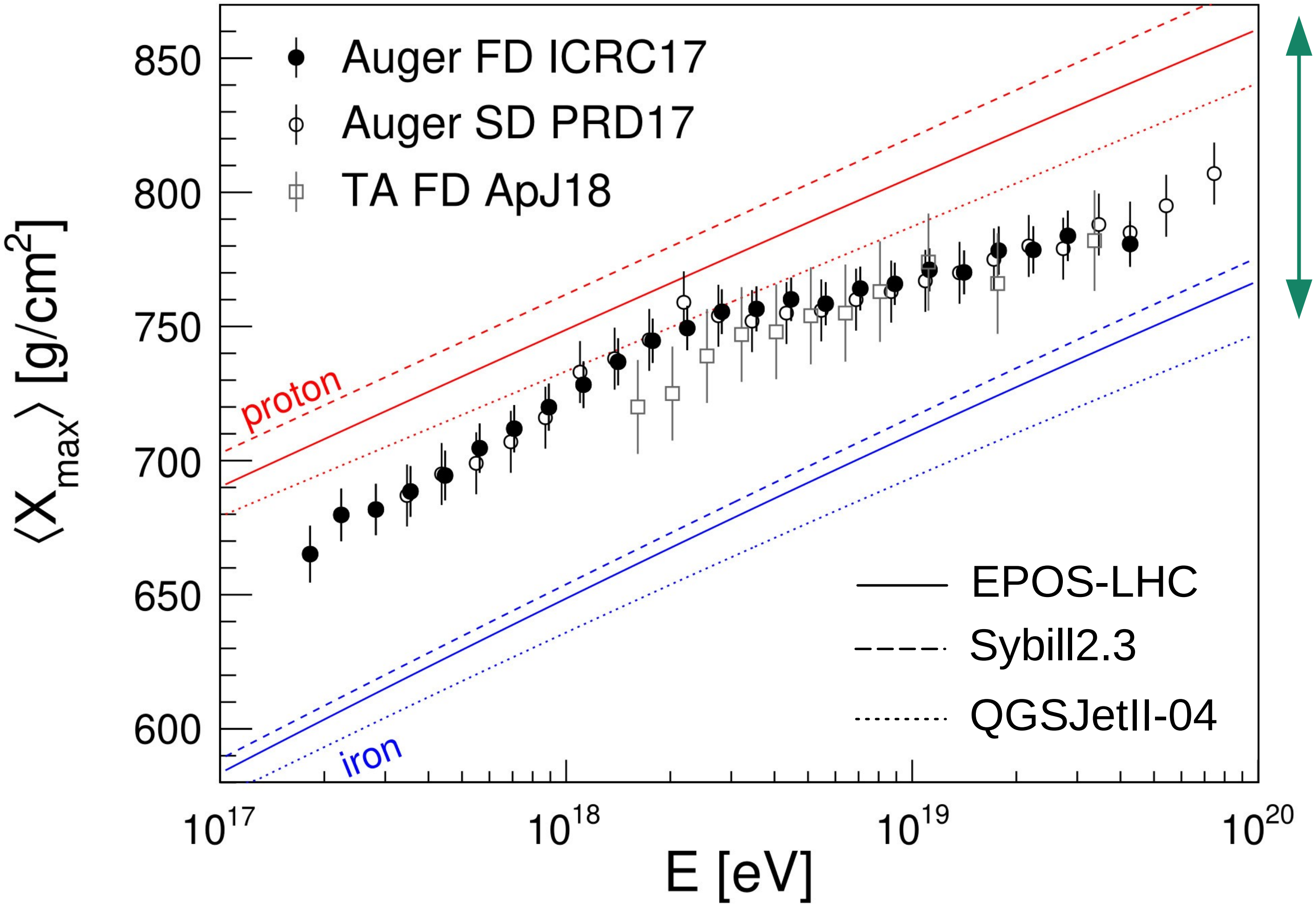
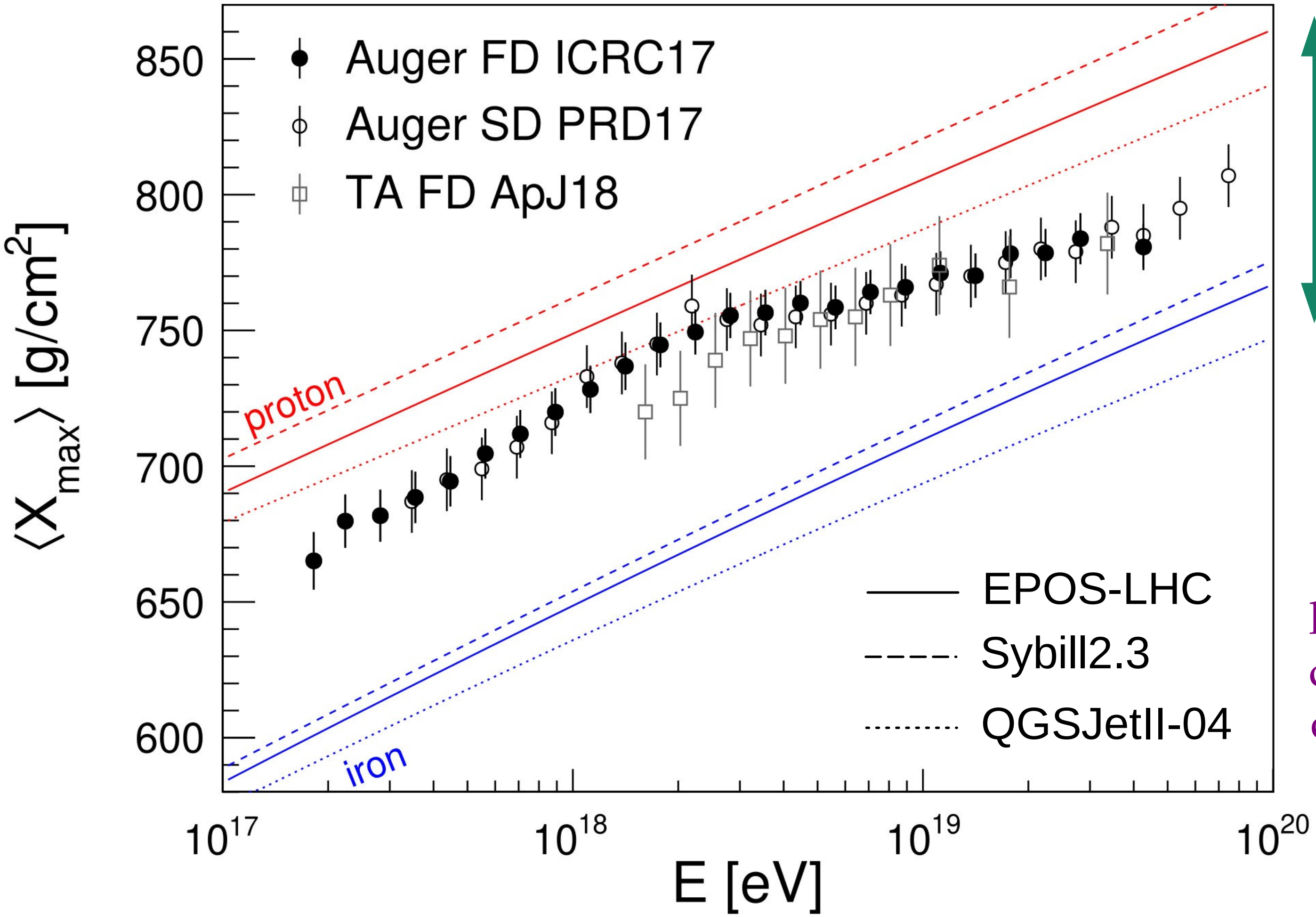


Other mass groups lie within this band (He, N, Si)

Alves Batista *et al.* (inc. **MB**), *Front. Astron. Space Sci.* 2019

X_{max} and UHECR mass composition



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This is why it's hard to suss out contributions of different nuclei!

Alves Batista *et al.* (inc. **MB**), *Front. Astron. Space Sci.* 2019

UHECRs: more sophisticated models

Use more data:

Spectrum + mass composition (X_{max})

Five mass groups:

H, He, N, Si, Fe

Common maximum rigidity:

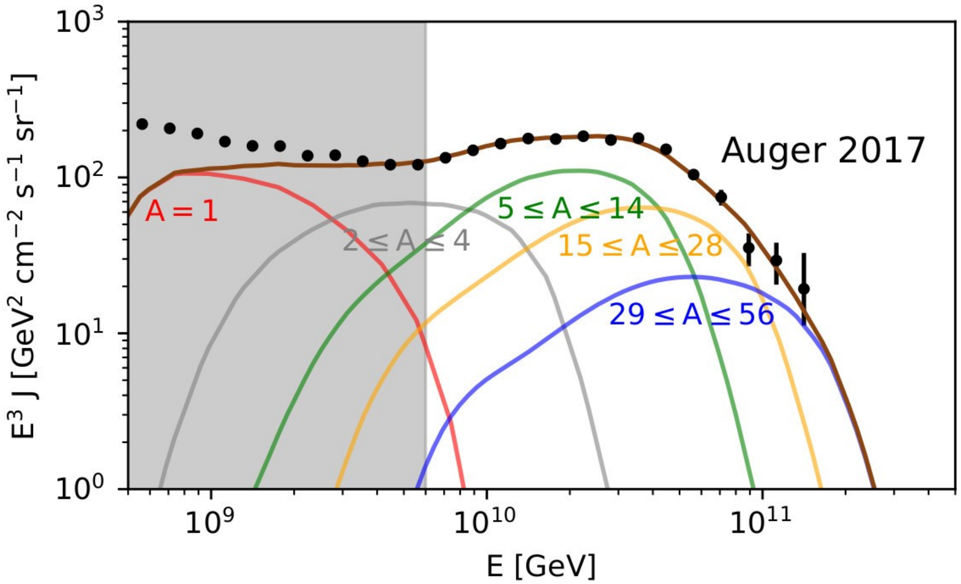
Max. rigidity is $R_{\text{max}} = E_{\text{max}}/Z$

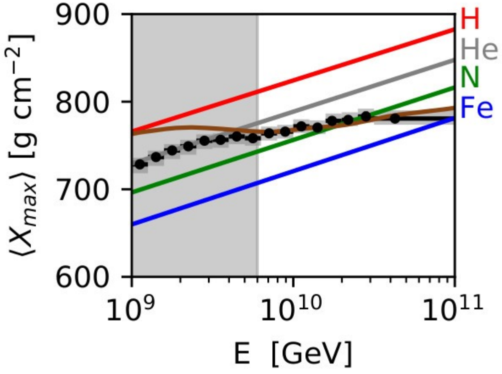
$$Q_Z(E) \propto E^{-\gamma} e^{-E/(ZR_{\text{max}})}$$

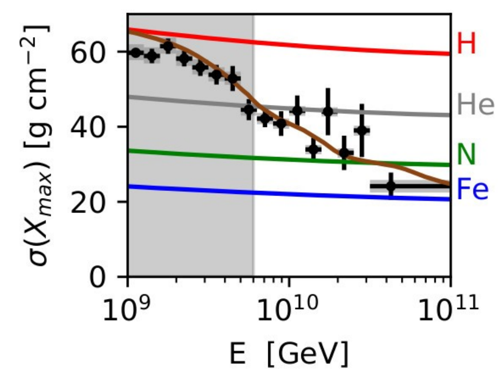
Add nuclei photodisintegration:

During propagation, interaction of nuclei on CMB or EBL breaks them up,

$$A + \gamma \to (A-1) + \gamma$$







Heinze, Fedynitch, Boncioli, Winter, *ApJ* 2019

See also: Romero-Wolf & Ave, *JCAP* 2018
Alves Batista, Almeida, Lago, Kotera, *JCAP* 2019

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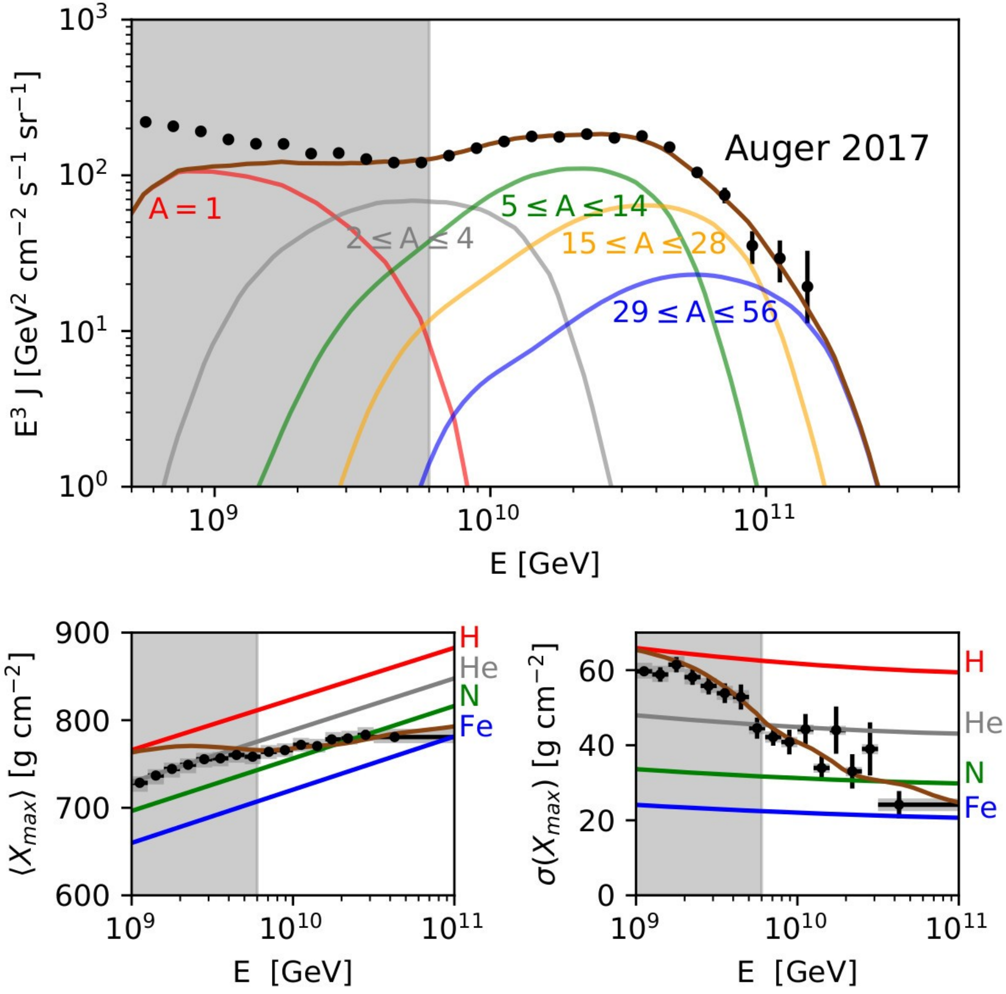

Heinze, Fedynitch, Boncioli, Winter, *ApJ* 2019

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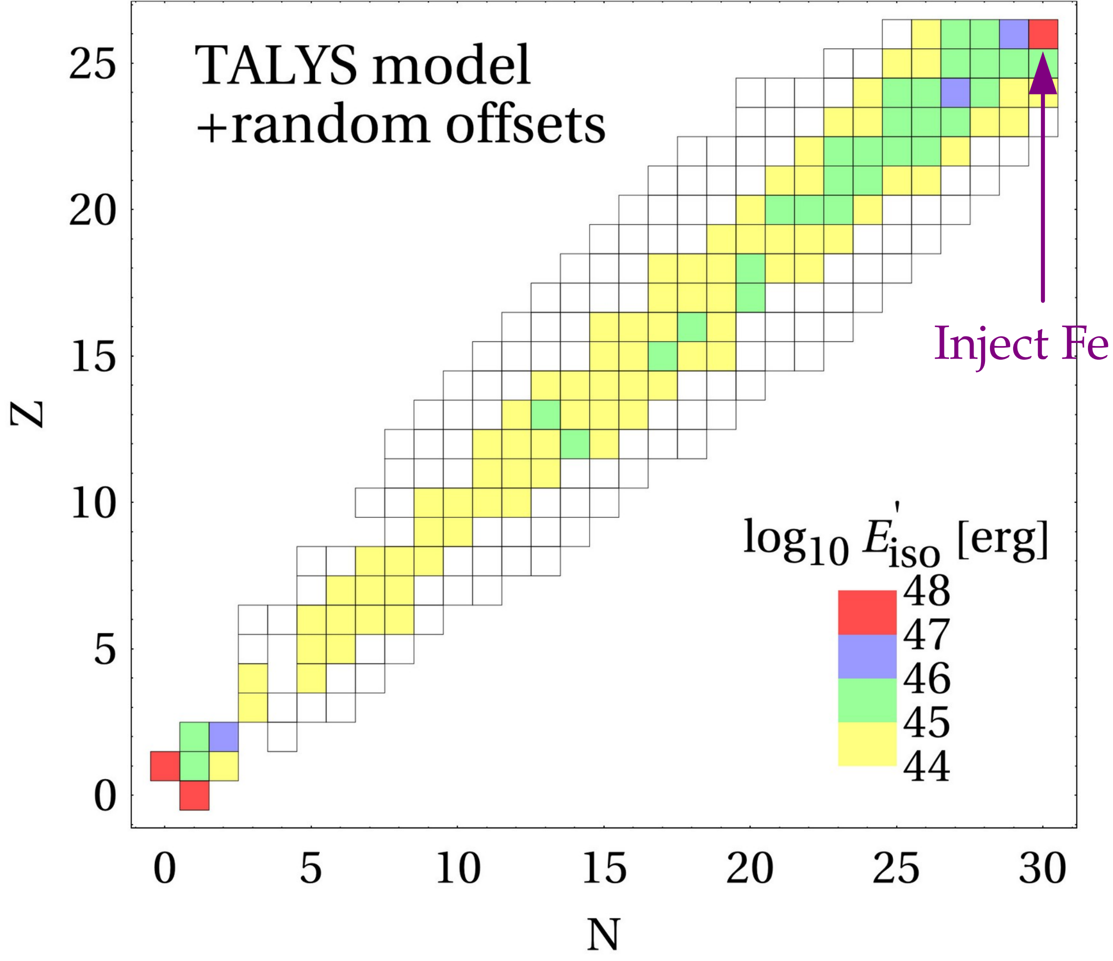
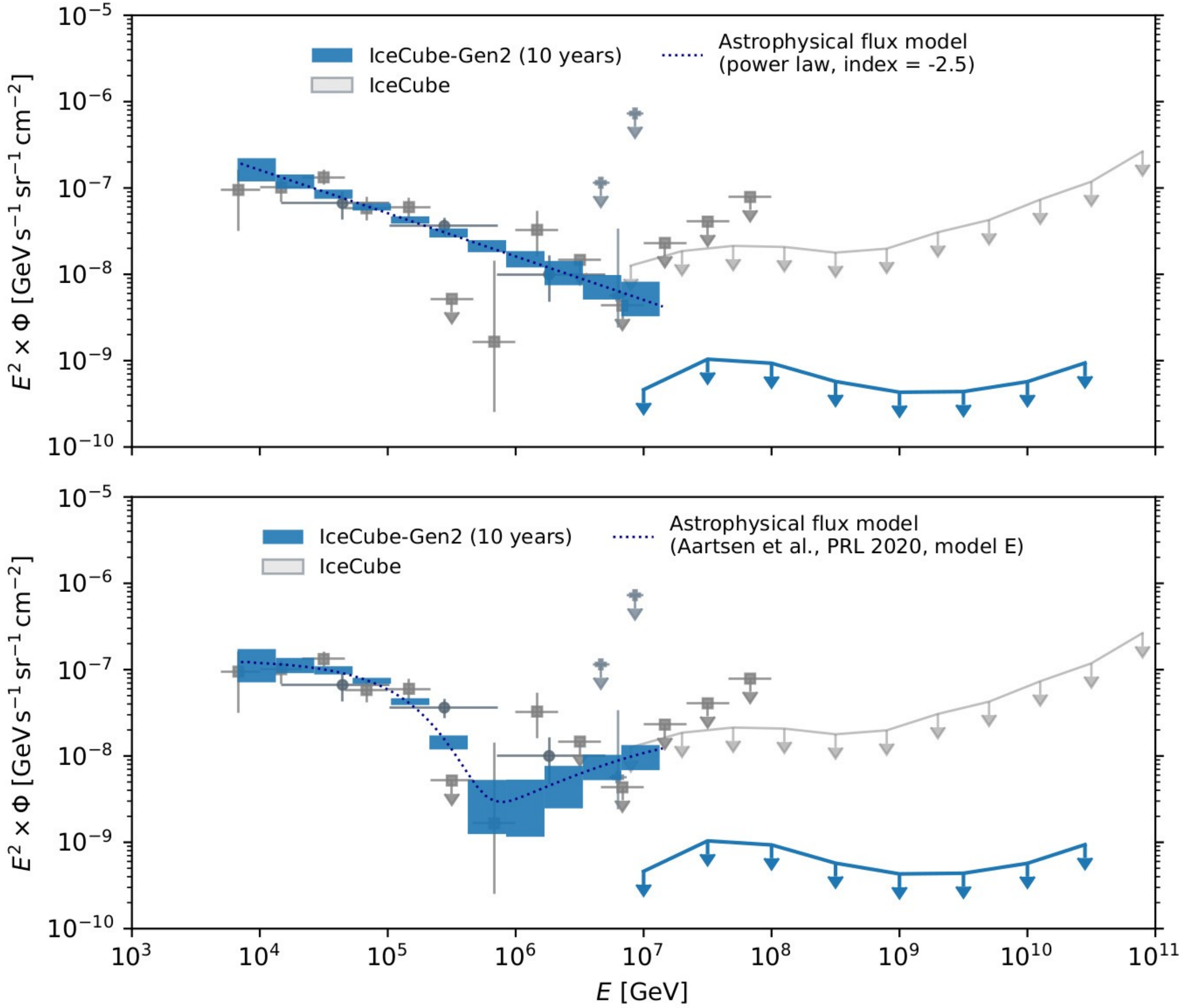
Fedynitch, Boncioli, Winter, *Sci. Rep.* 2017



See also: Romero-Wolf & Ave, *JCAP* 2018
Alves Batista, Almeida, Lago, Kotera, *JCAP* 2019

High-energy cosmic neutrinos

Measuring the diffuse flux *precisely*



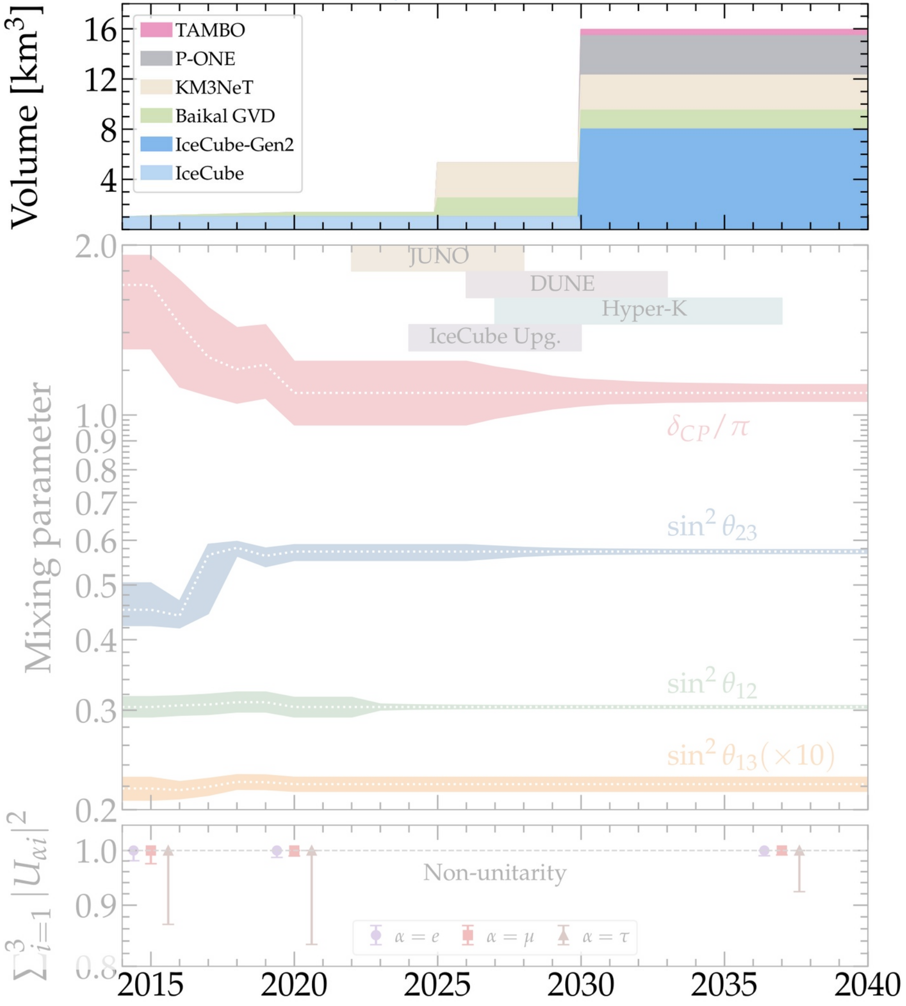
Assuming a power-law ν flux ∝ $E^{-2.5}$

Assuming a power-law ν flux with 100-TeV cut-off + *pγ* bump at tens of TeV

Ackermann, **MB** *et al.*, *JHEAp* 2022

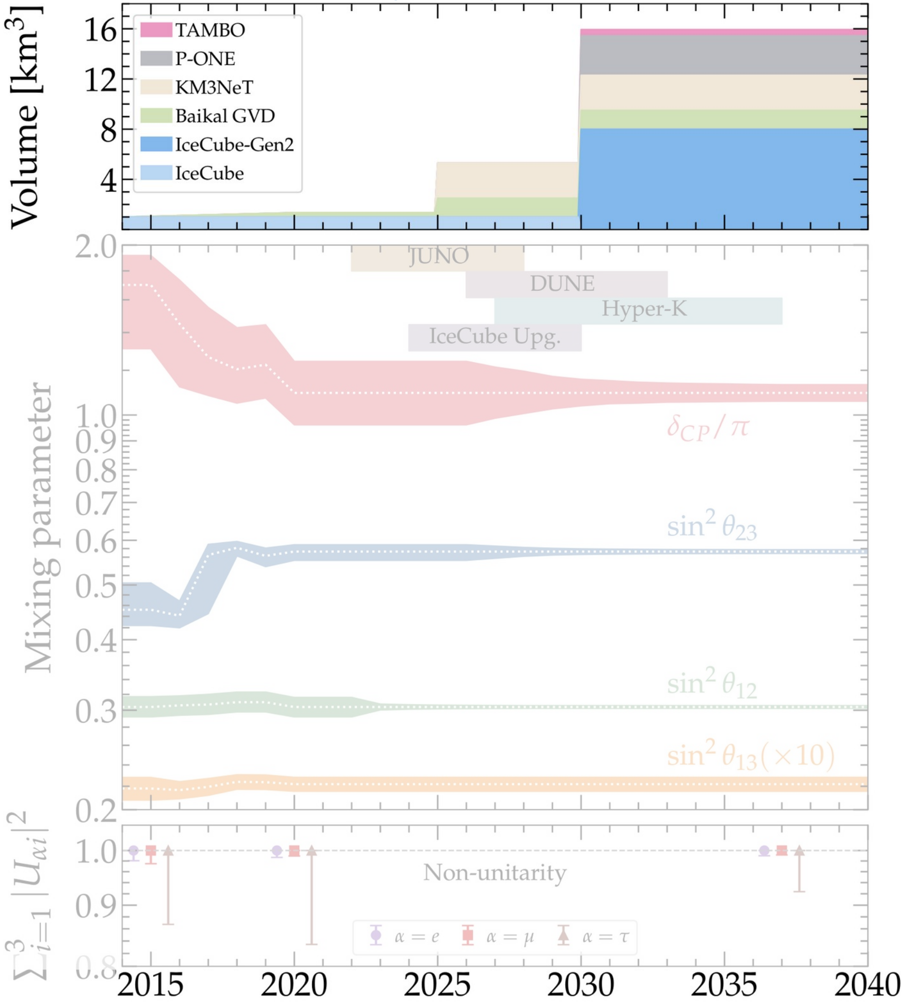
Measuring flavor composition: 2015–2040

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



Measuring flavor composition: 2015–2040

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



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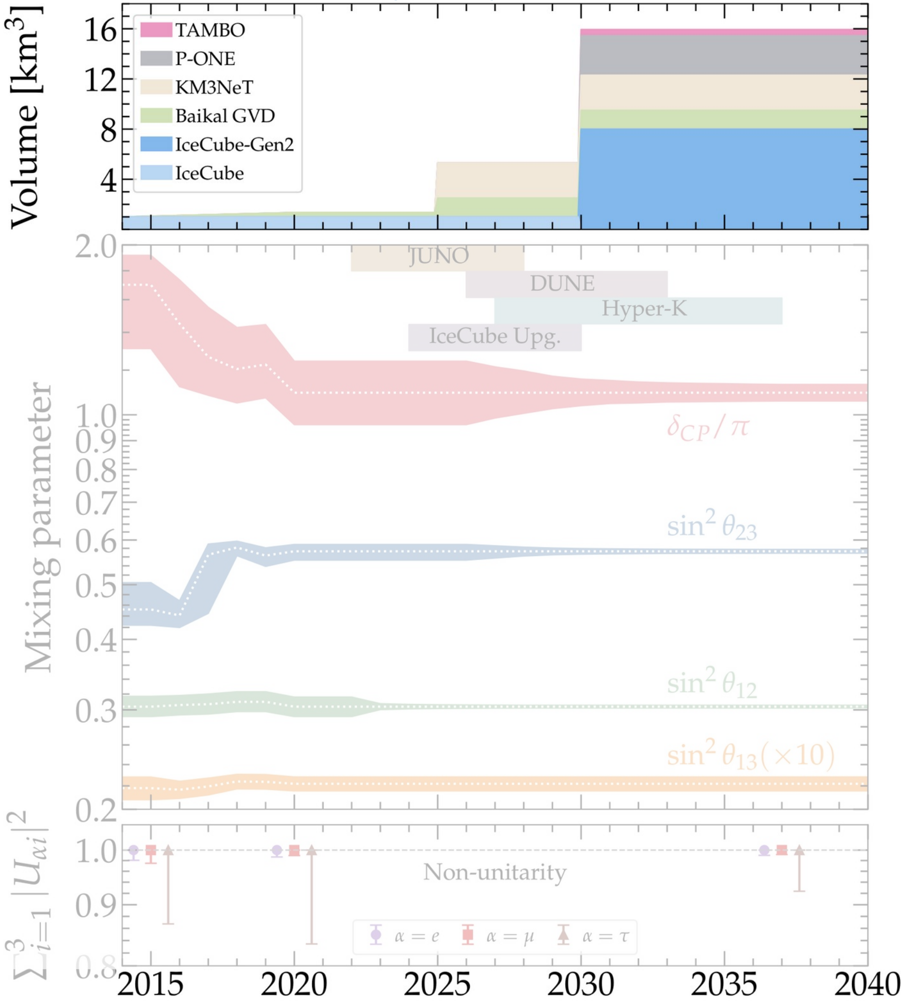

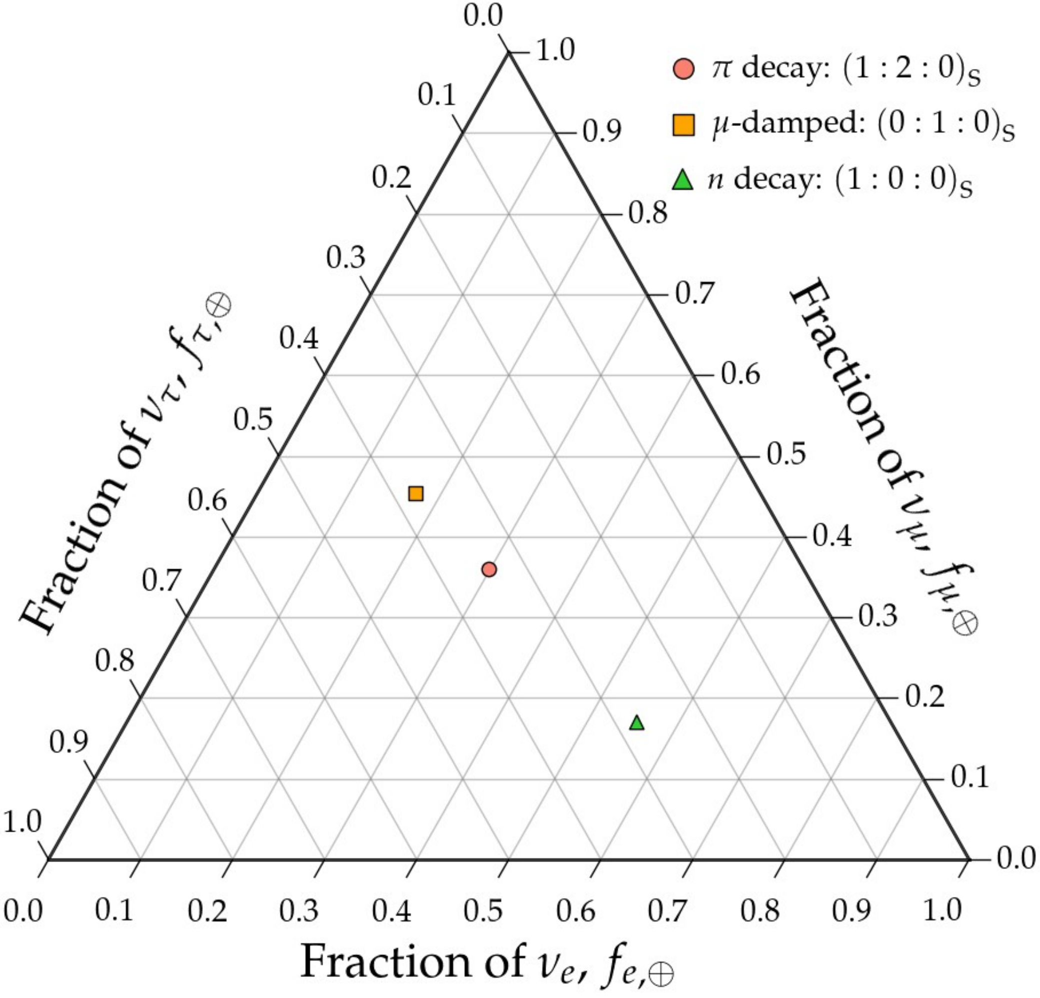

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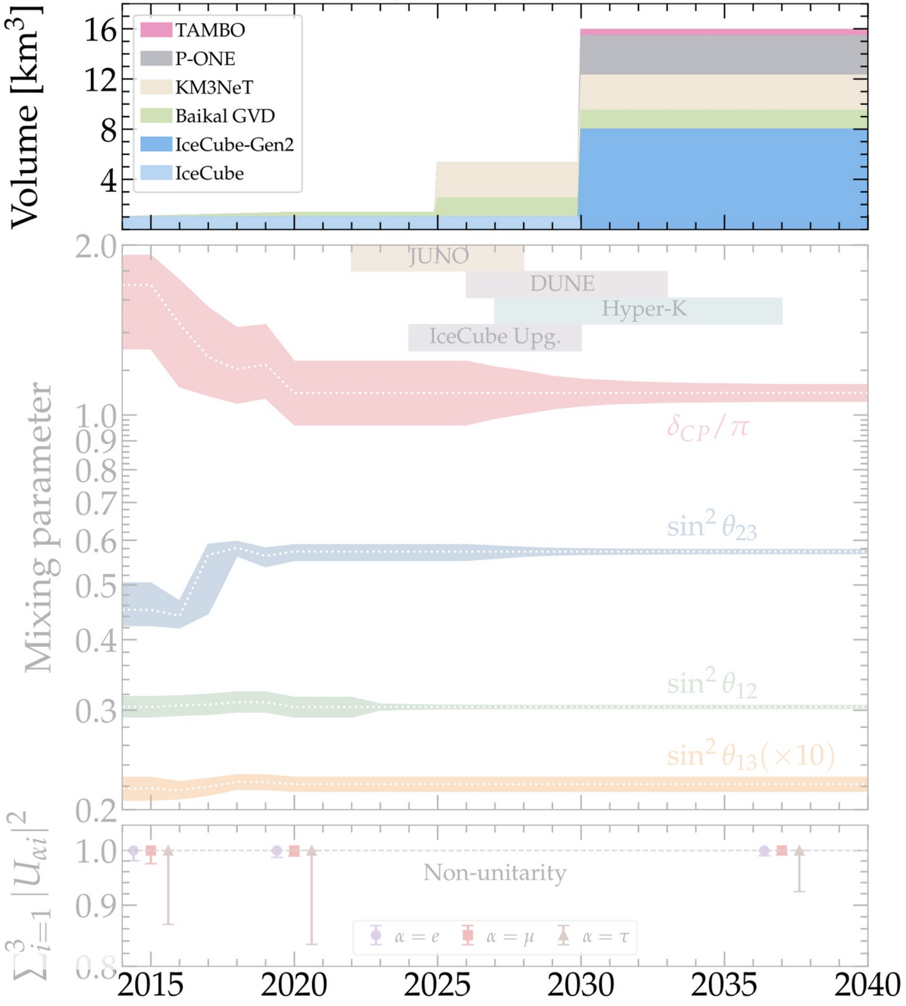
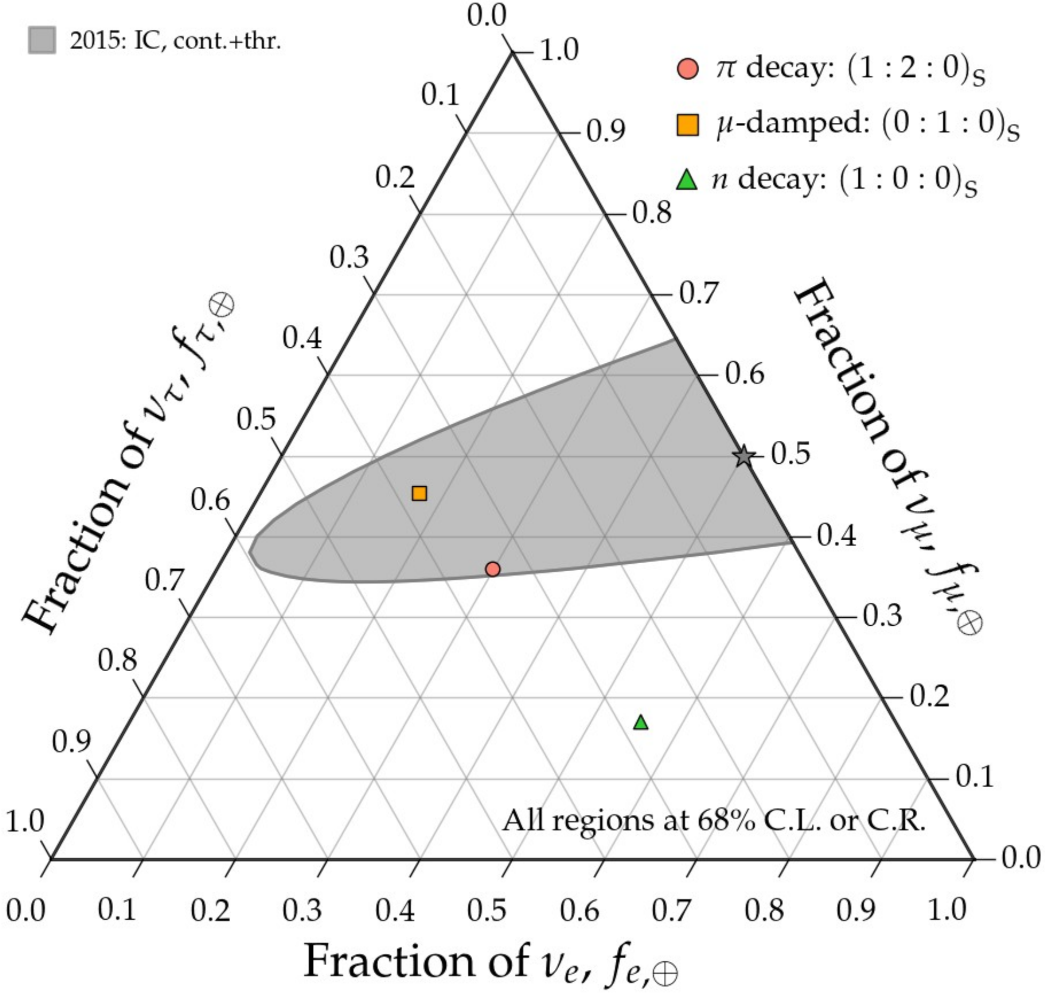
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021





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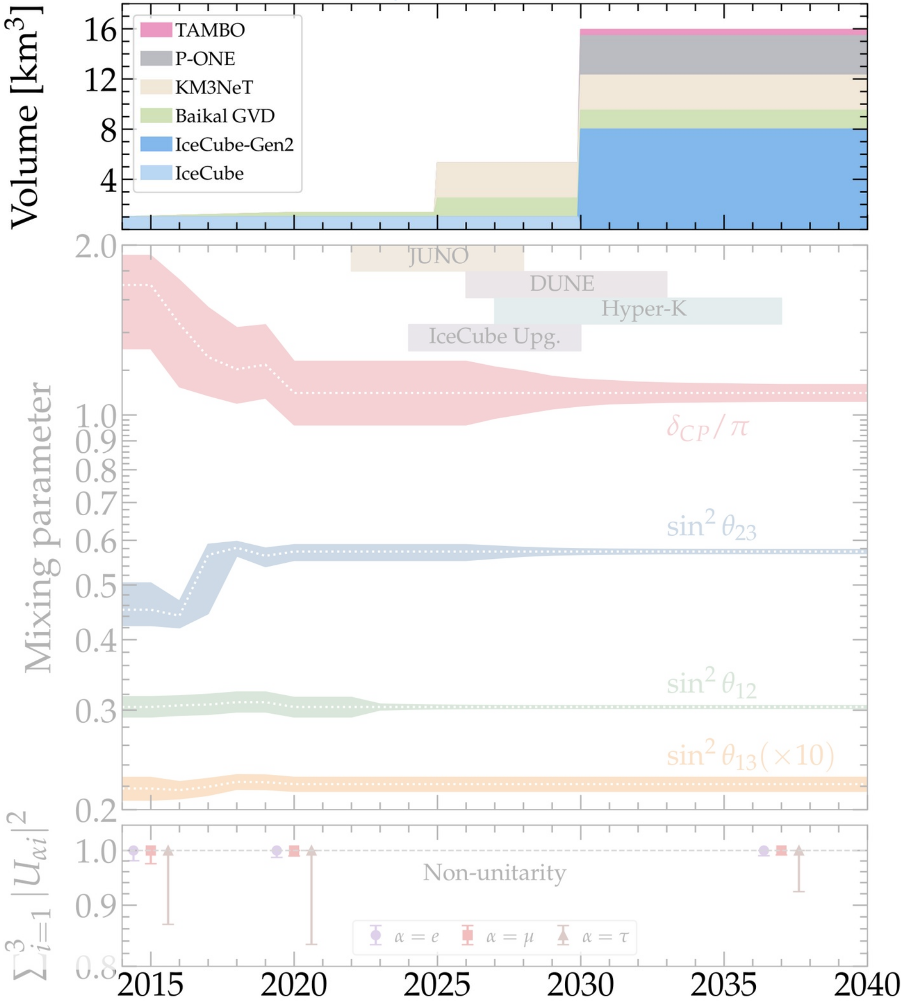

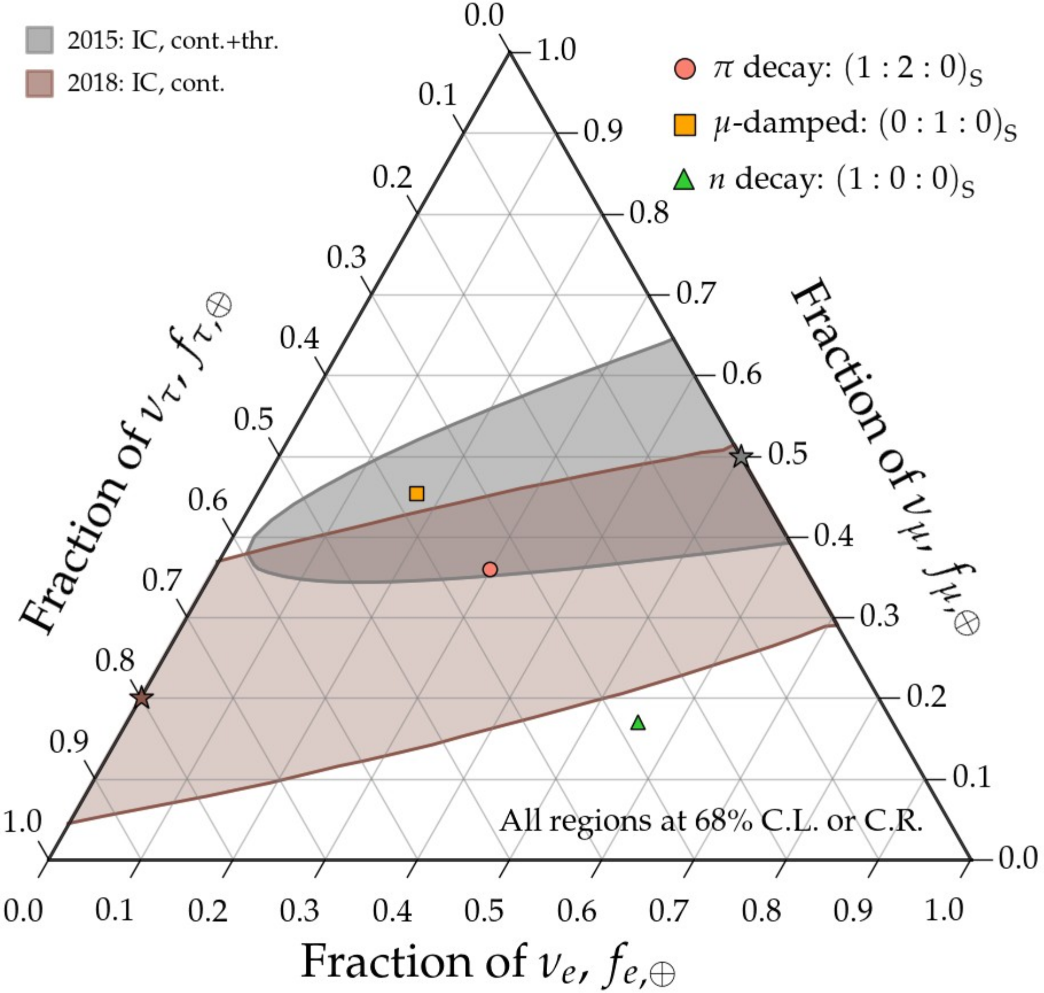

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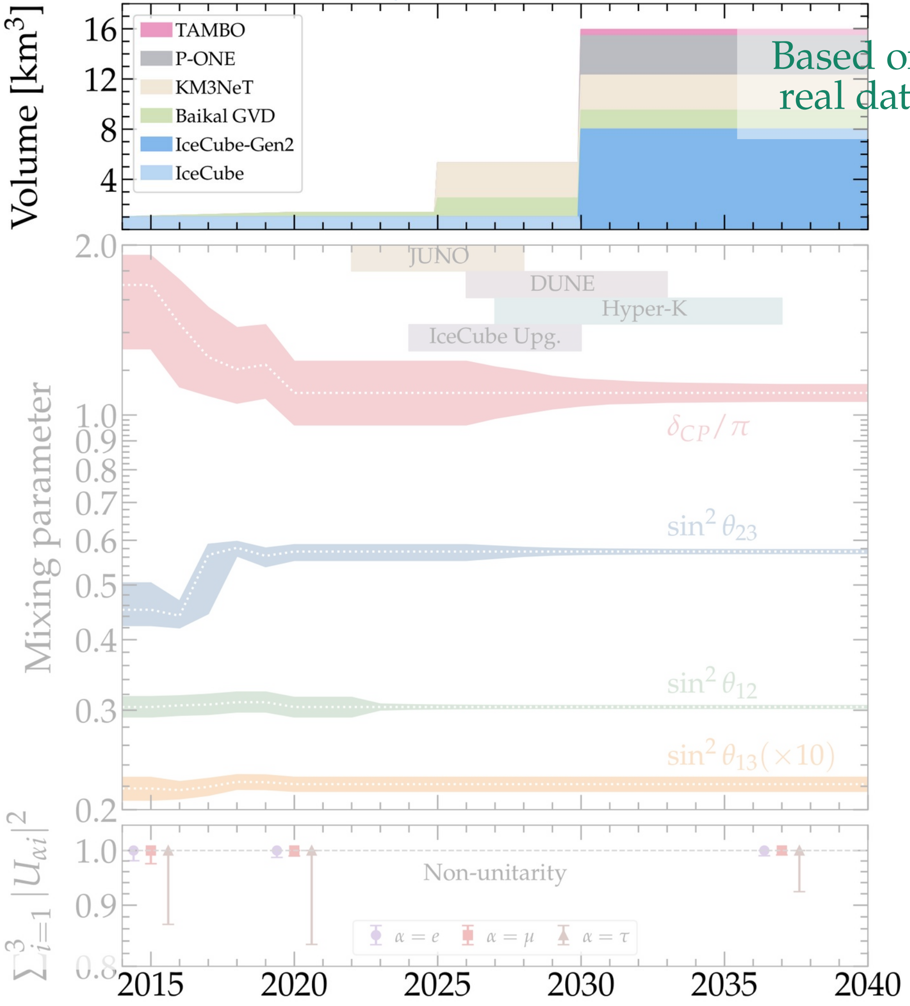
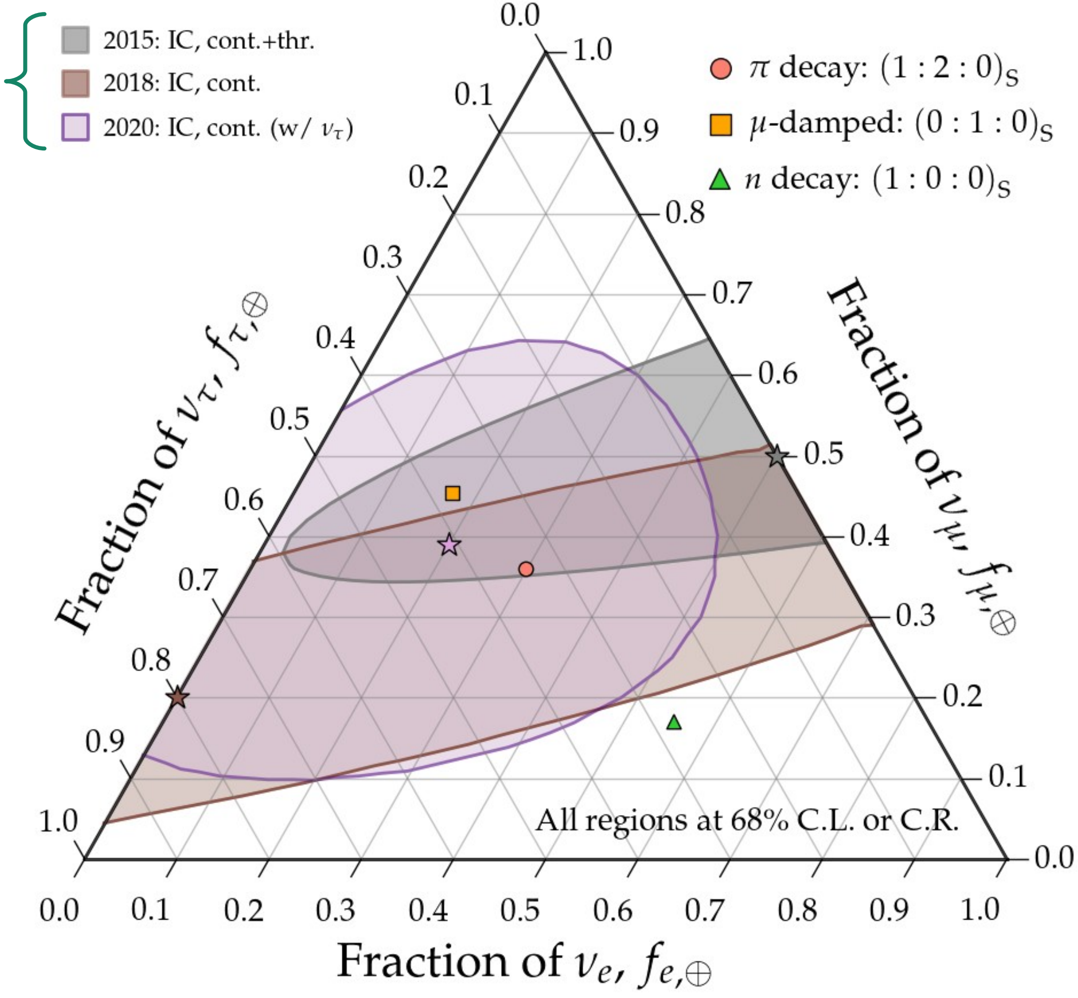


Based on real data



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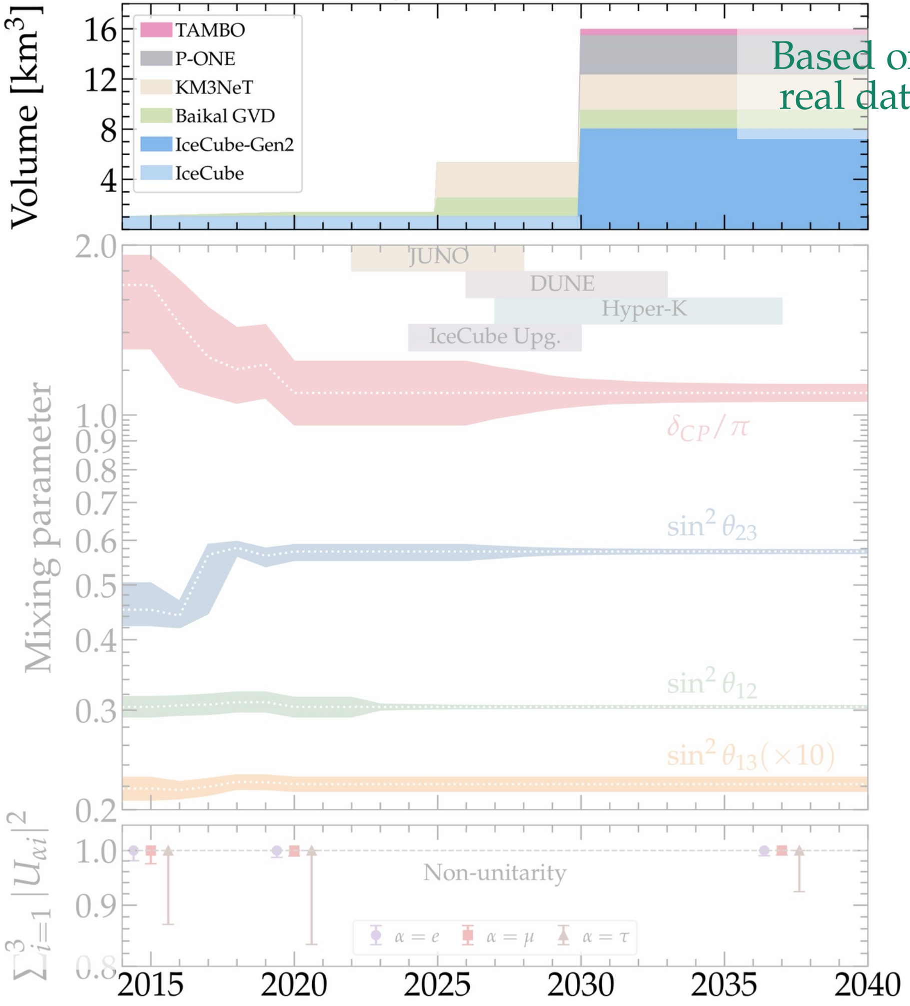

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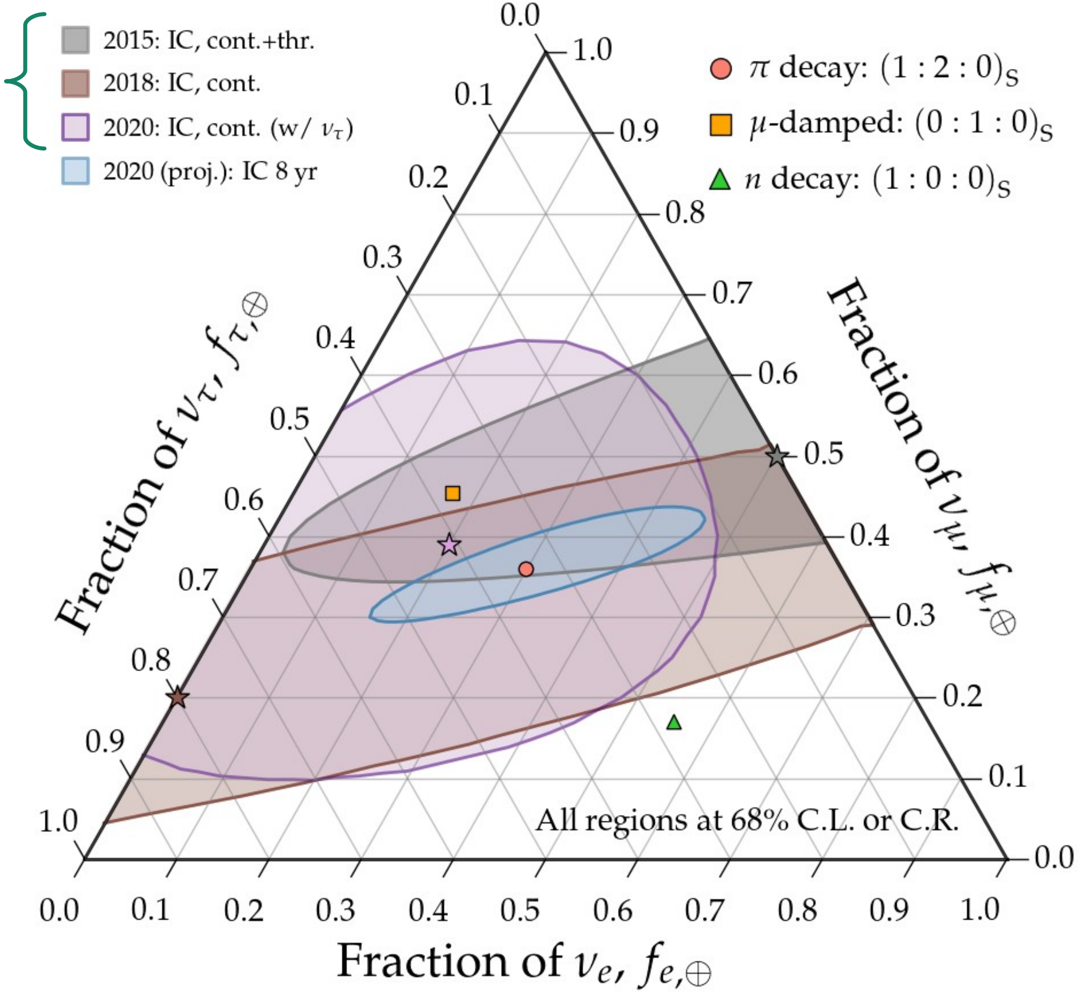

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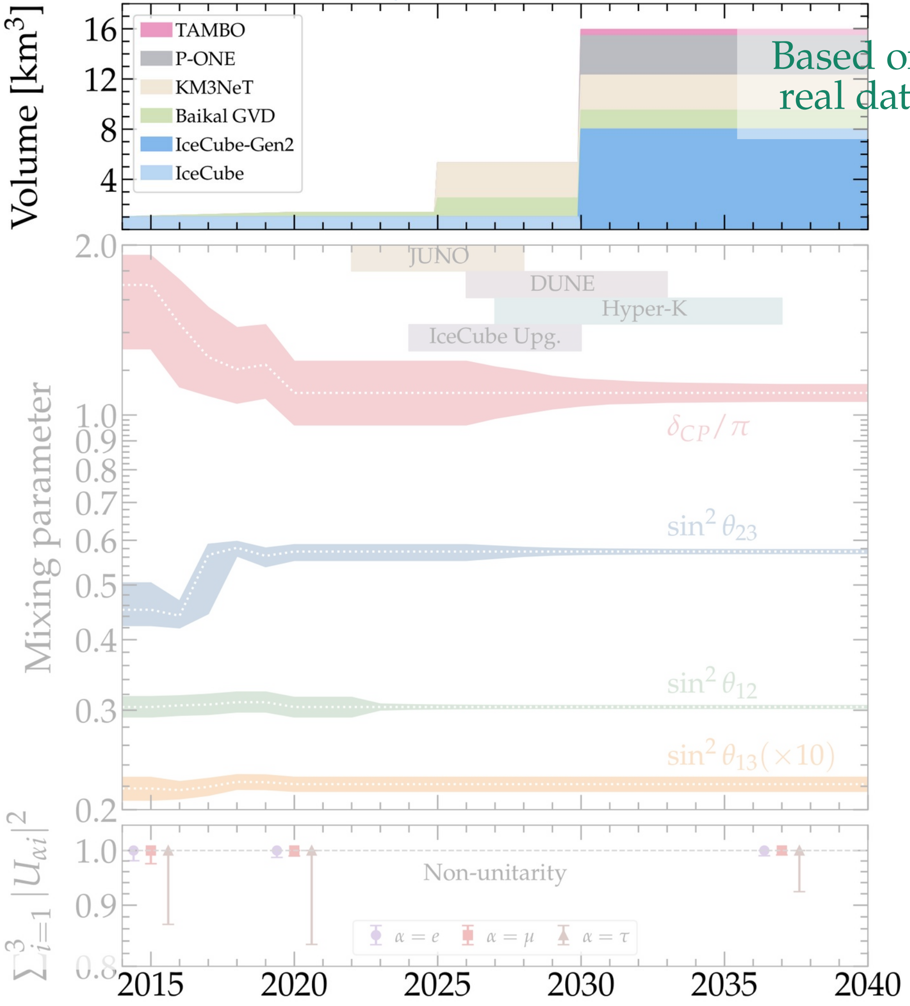

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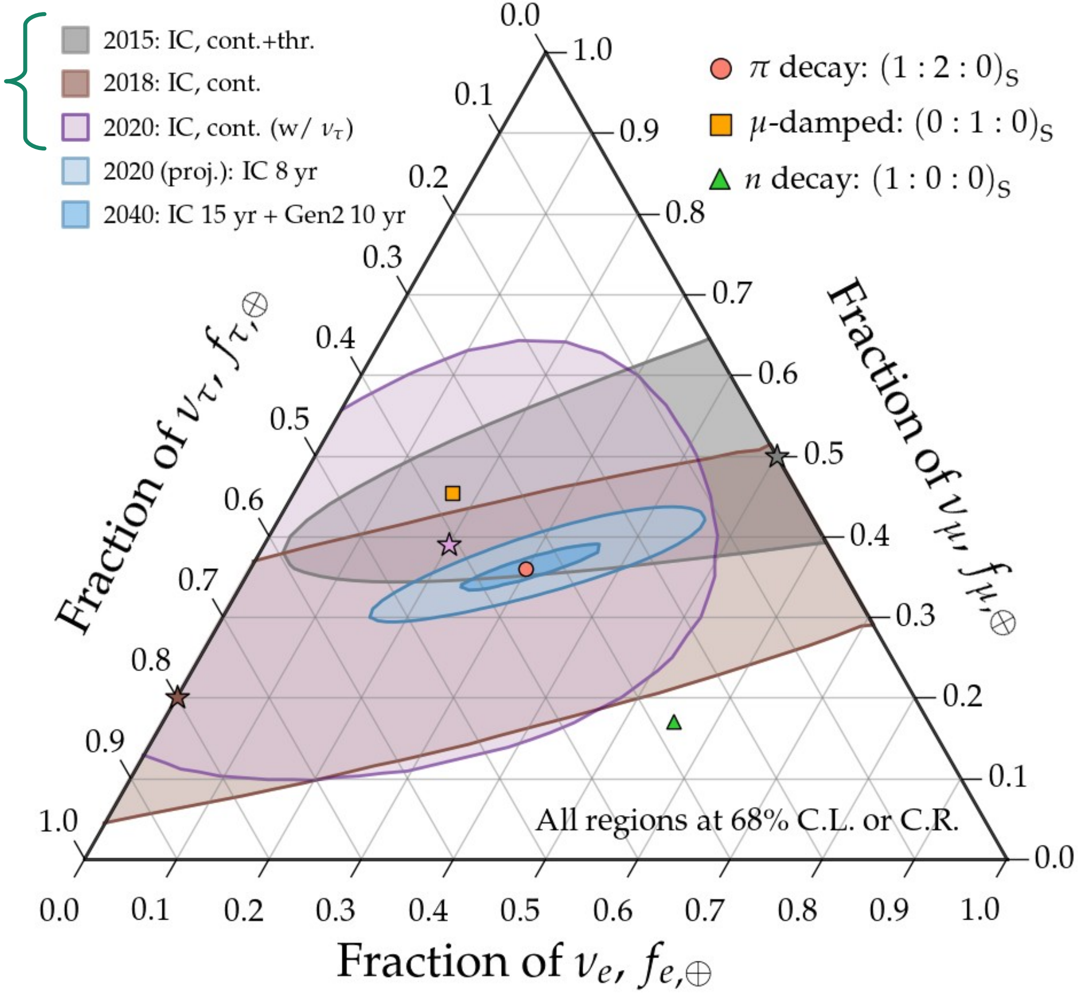

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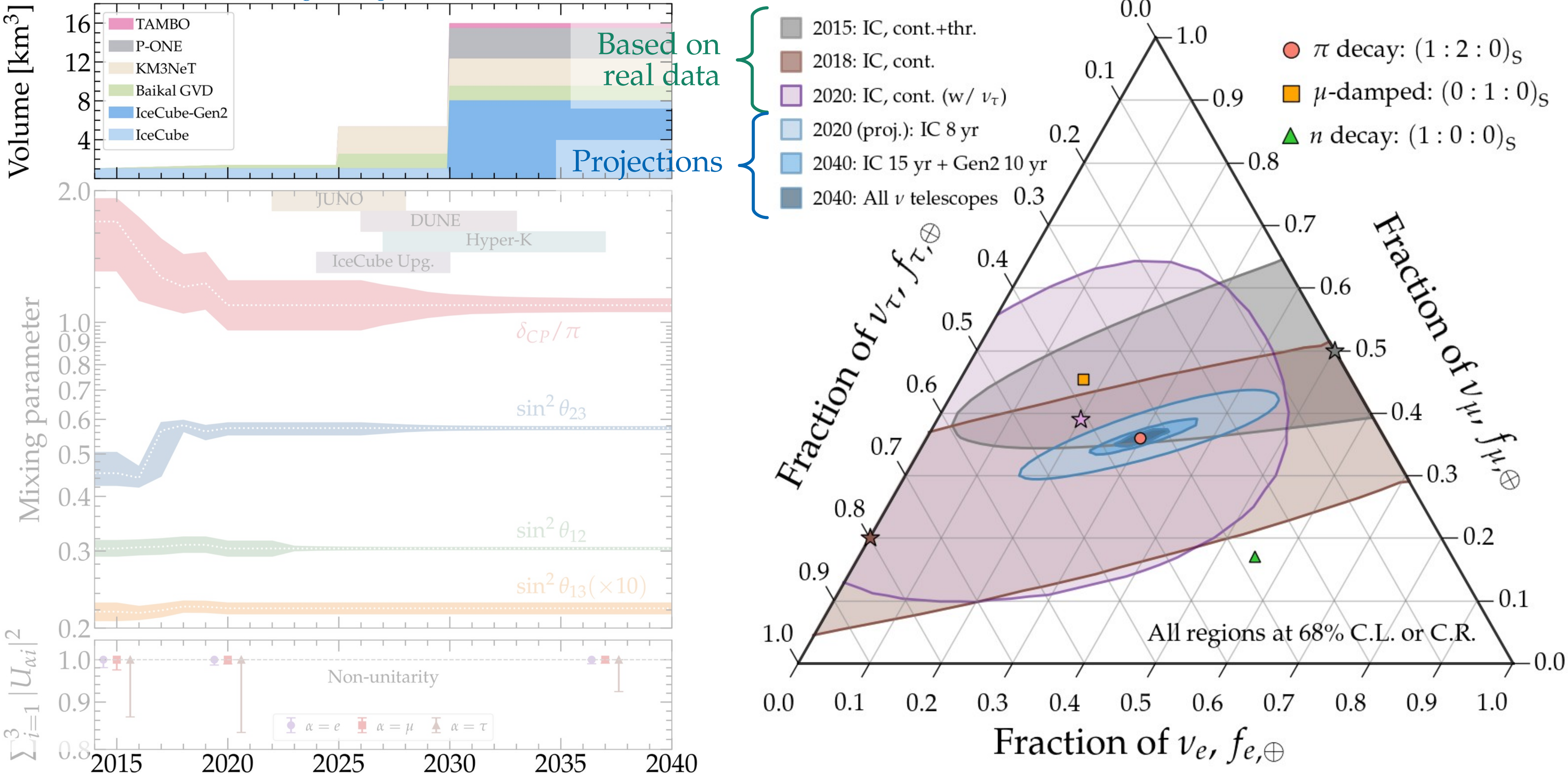
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



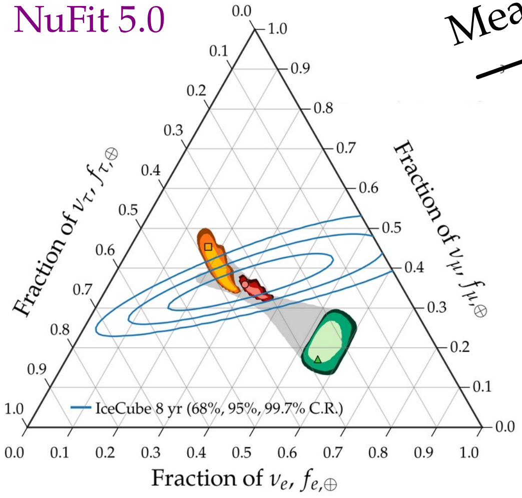
Based on real data

Projections

How knowing the mixing parameters better helps

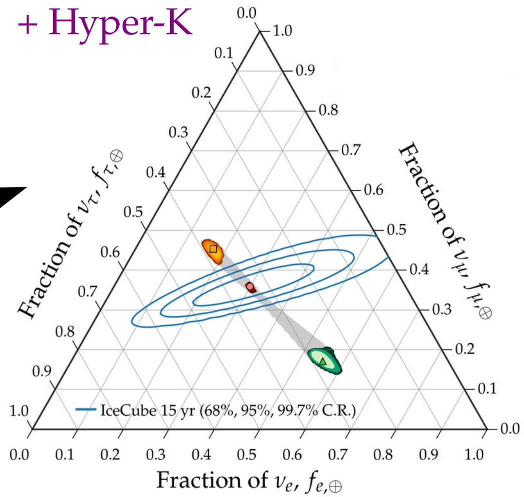
2020

NuFit 5.0

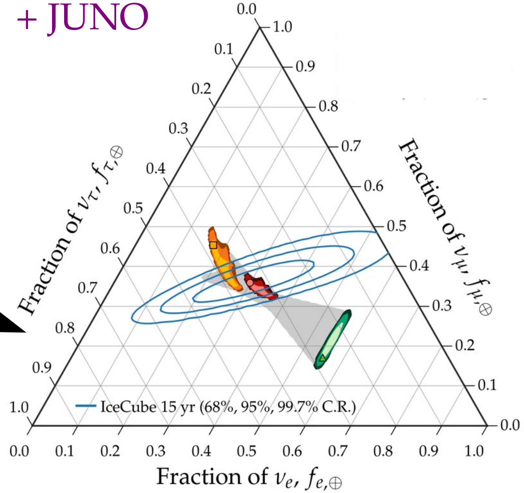


Measure θ_{23} better

+ Hyper-K



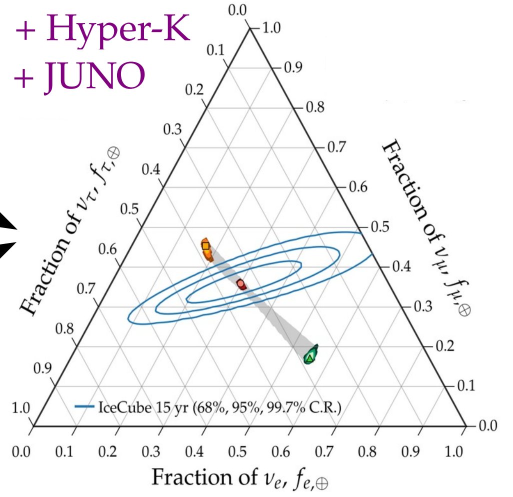
+ JUNO



Measure θ_{12} better

~2030

+ Hyper-K
+ JUNO

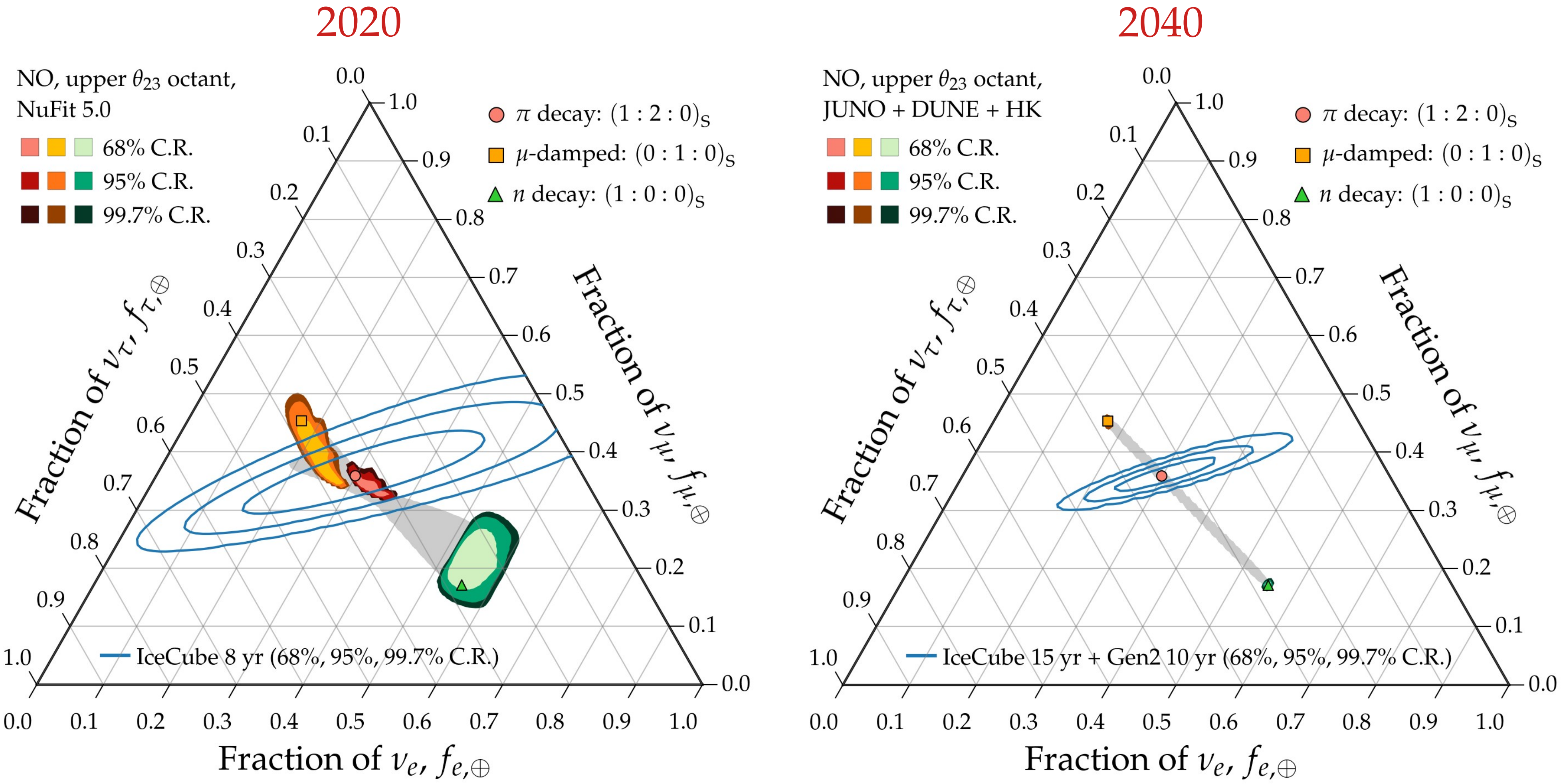


In our results:
JUNO + Hyper-K + DUNE

Marginal improvement til 2040

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Theoretically palatable regions: 2020 → 2040



Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Measuring the high-energy *νN* cross section

Number of detected neutrinos (simplified for presentation):

$$N \propto \underbrace{\Phi_\nu}_{\text{Neutrino flux}} \underbrace{\sigma_{\nu N}}_{\text{Cross section}} e^{-\tau_{\nu N}} = \Phi_\nu \sigma_{\nu N} e^{-L \sigma_{\nu N} n_N}$$

Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
Hussain, Mafatia, McKay, *PRD* 2008 Connolly, Thorne, Waters, *PRD* 2011; Marfatia, McKay, Weiler, *PLB* 2015

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Downgoing neutrinos
(*L* short → no matter)

$$N \propto \Phi_\nu \sigma_{\nu N}$$

Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
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$$N \propto \underbrace{\Phi_\nu \sigma_{\nu N}}_{\text{Degeneracy}}$$

Upgoing neutrinos
(L long → lots of matter)

$$N \propto \Phi_\nu \sigma_{\nu N} e^{-L\sigma_{\nu N} n_N}$$

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(*L* short → no matter)

$$N \propto \underbrace{\Phi_\nu \sigma_{\nu N}}_{\text{Degeneracy}}$$

Upgoing neutrinos
(*L* long → lots of matter)

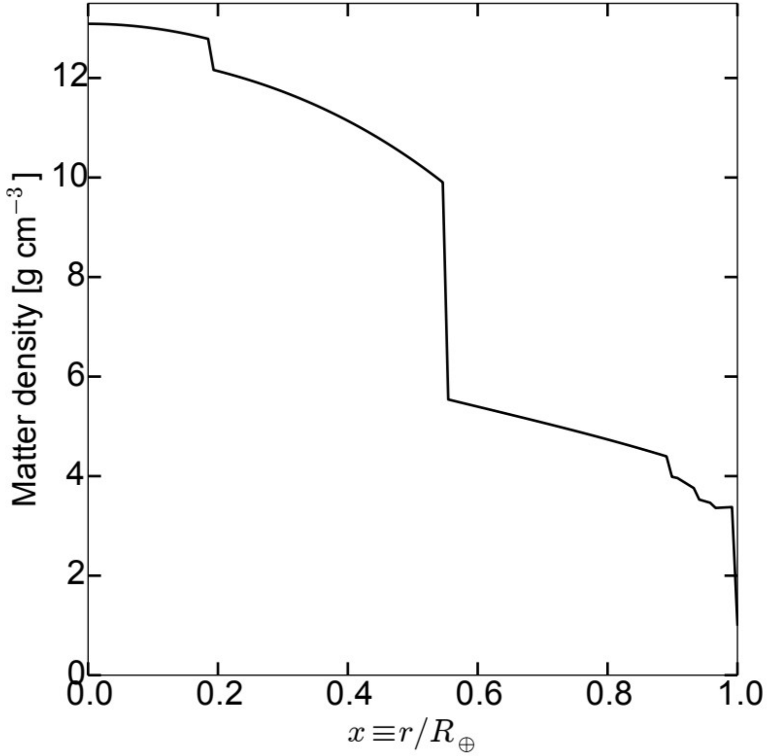
$$N \propto \Phi_\nu \sigma_{\nu N} \underbrace{e^{-L\sigma_{\nu N} n_N}}_{\text{Breaks the degeneracy}}$$

Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
Hussain, Mafatia, McKay, *PRD* 2008 Connolly, Thorne, Waters, *PRD* 2011; Marfatia, McKay, Weiler, *PLB* 2015

A feel for the in-Earth attenuation

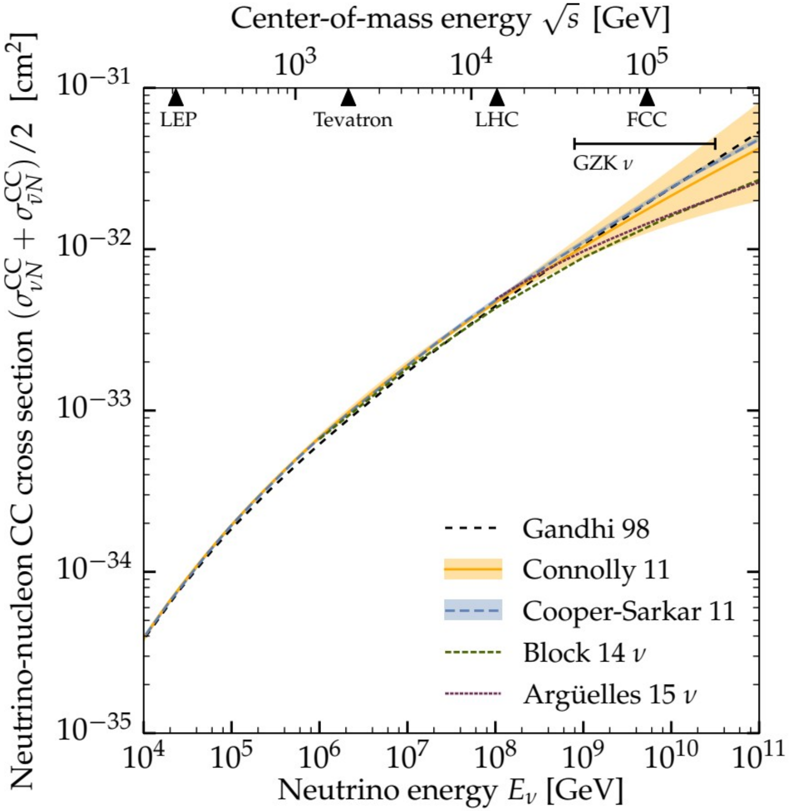
Earth matter density

(Preliminary Reference Earth Model)



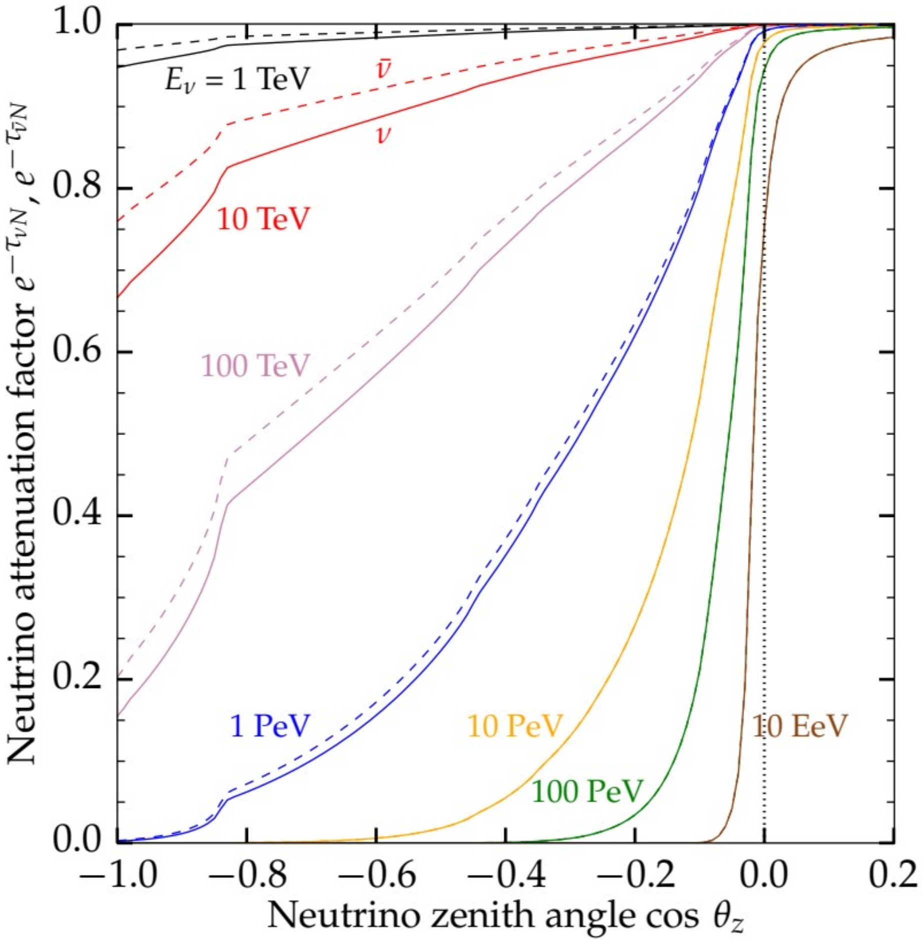
+

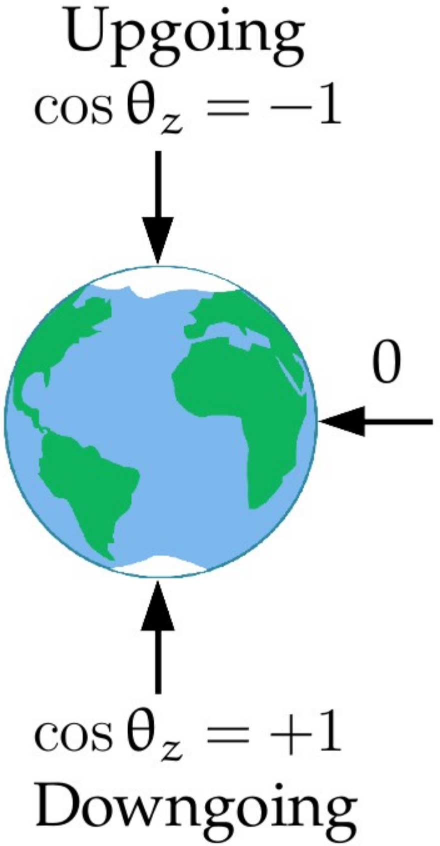
Neutrino-nucleon cross section



A feel for the in-Earth attenuation

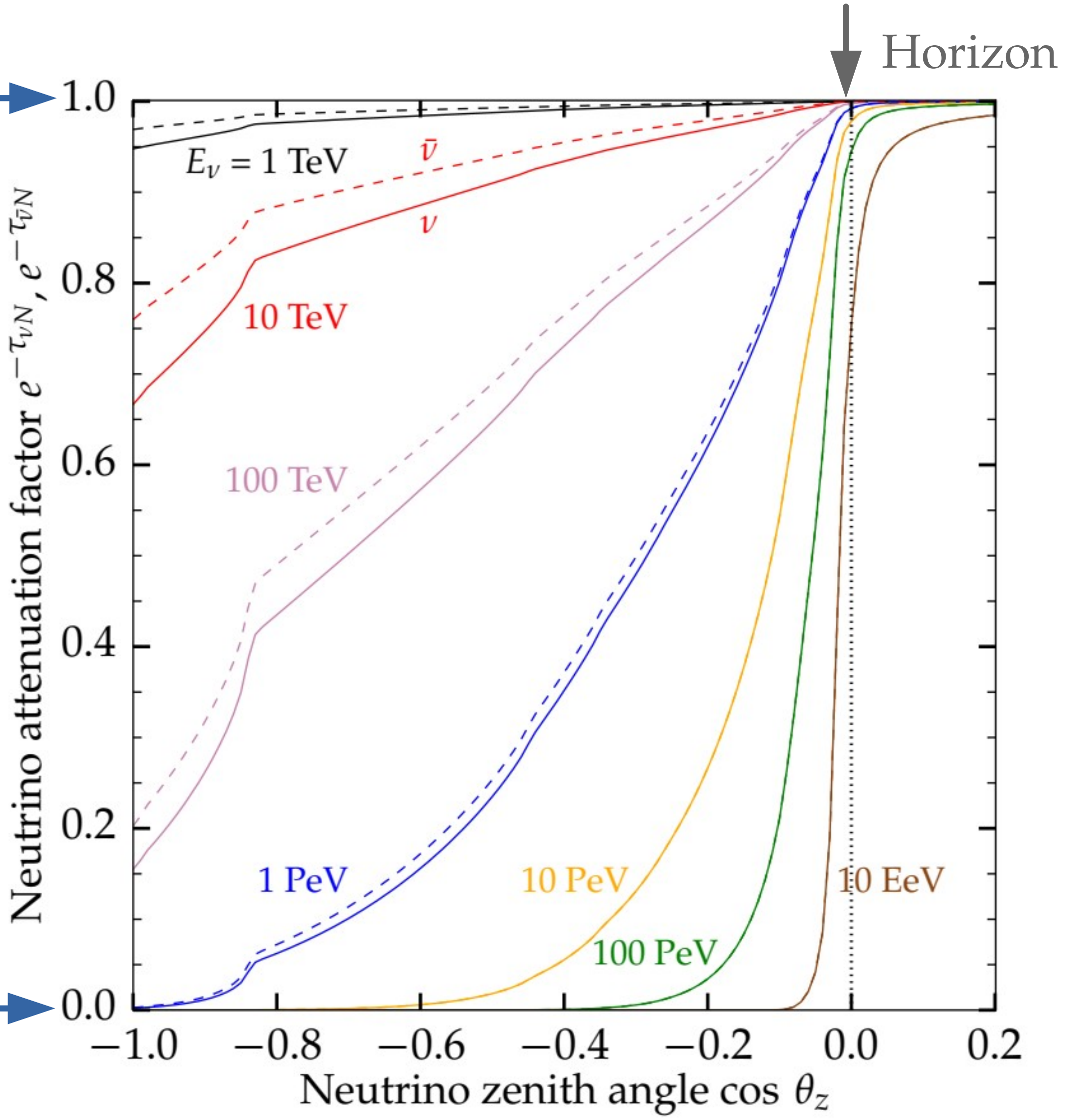
=

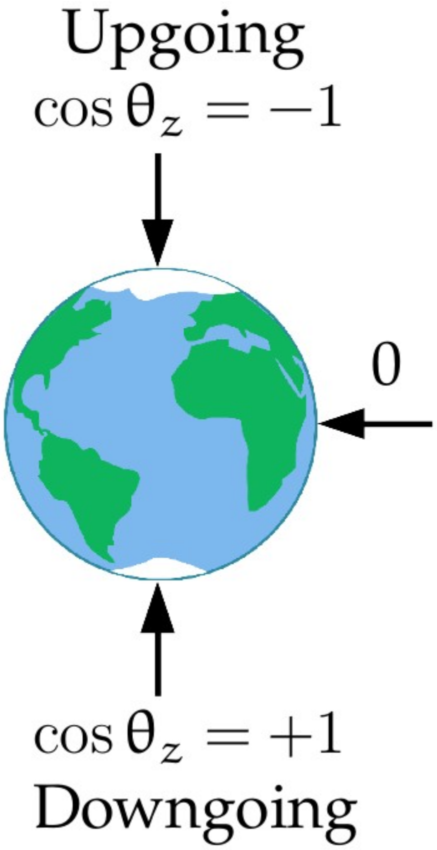




No attenuation

Full attenuation




Upgoing

$\cos\theta_z = -1$

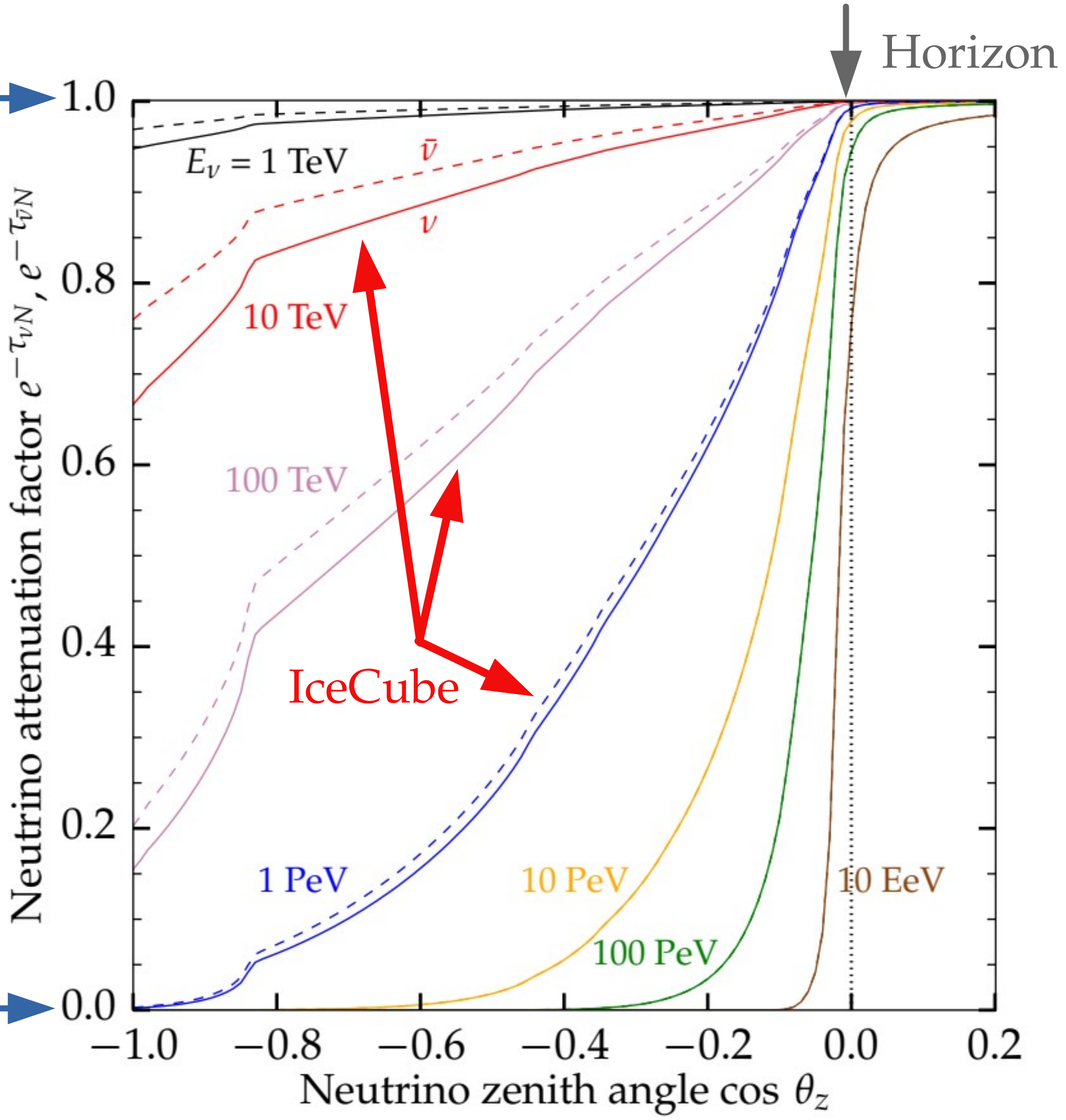
0

$\cos\theta_z = +1$

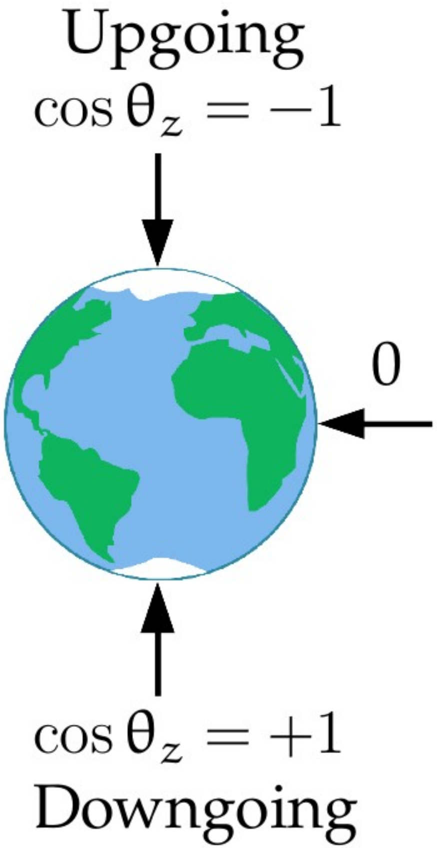
Downgoing

MB & Connolly, *PRL* 2019

No
attenuation



Full
attenuation



Upgoing
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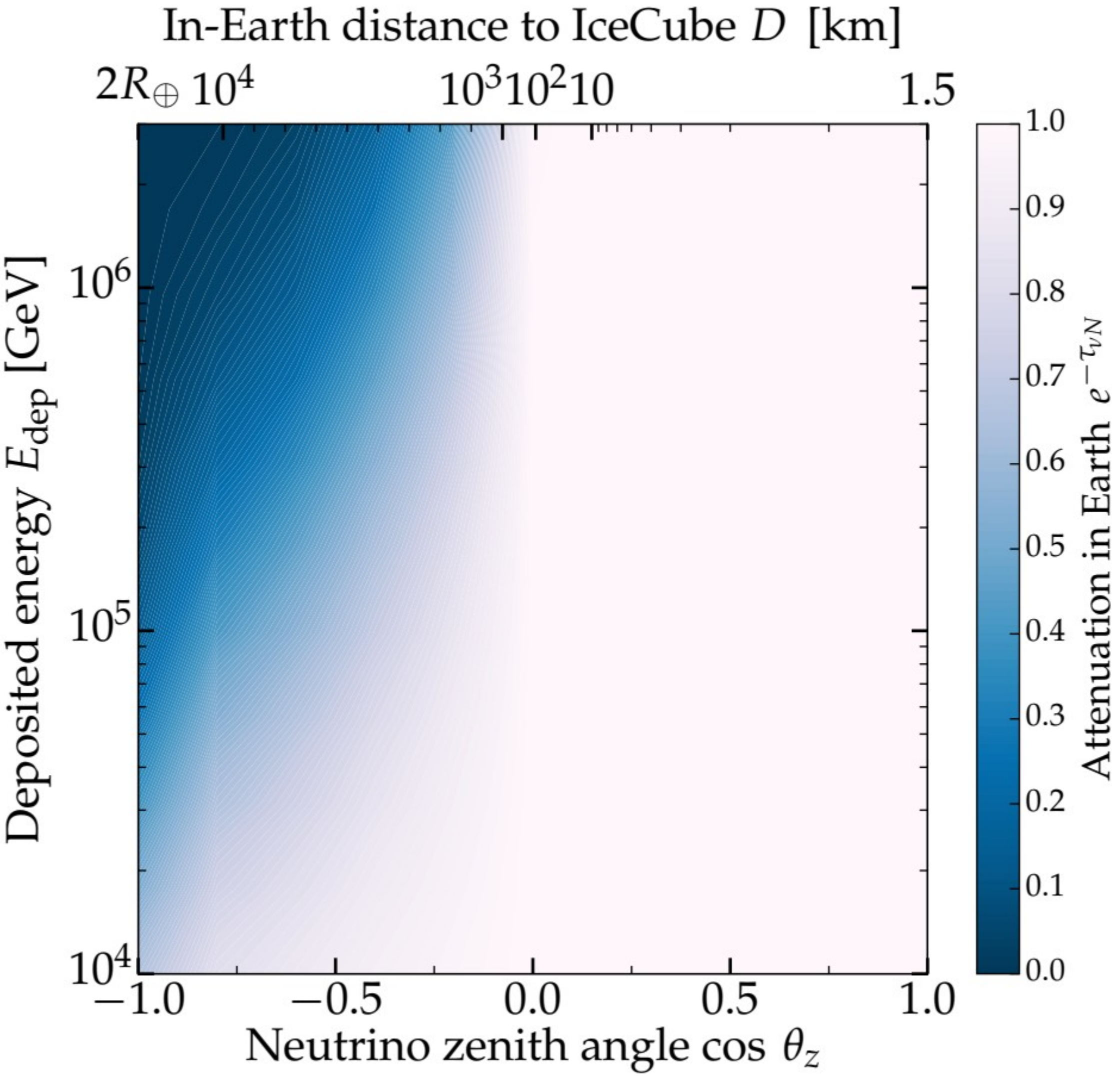
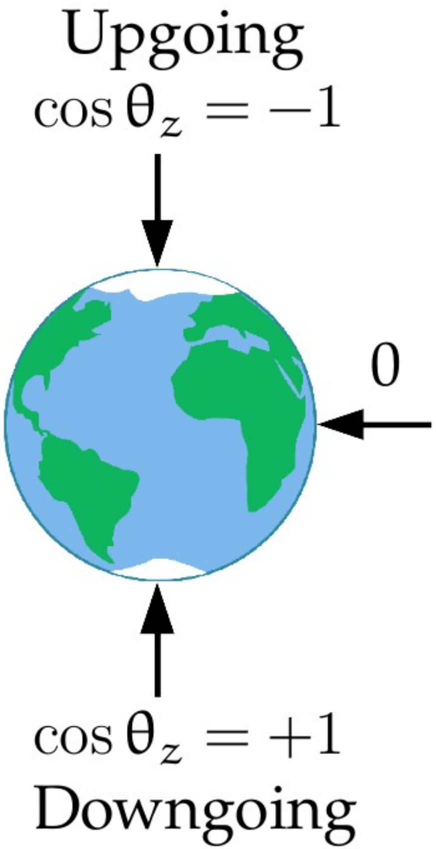
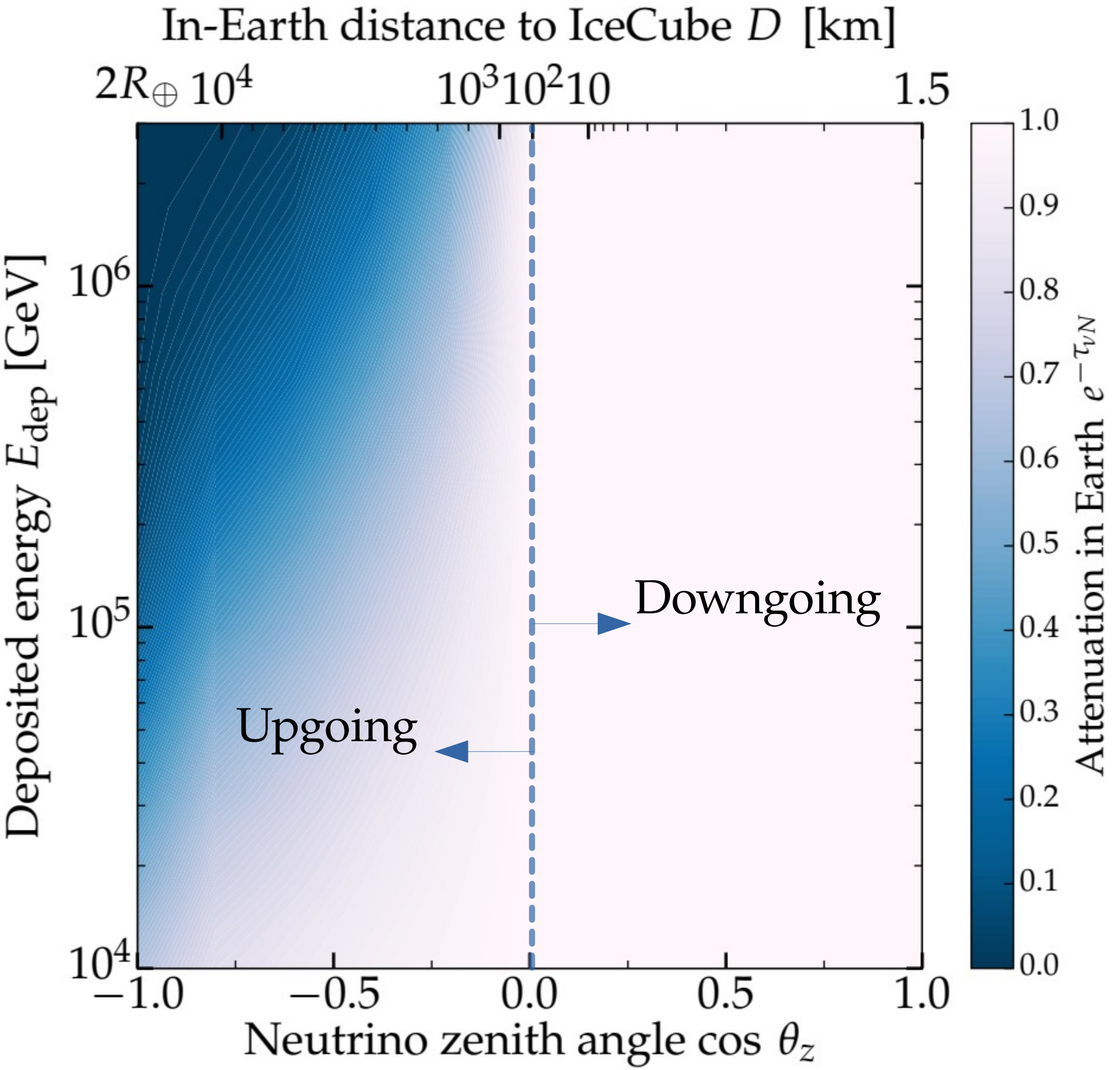
Downgoing

MB & Connolly, *PRL* 2019


In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4
10^3 10^2 10
1.5
Deposited energy E_{dep} [GeV]
10^6
10^5
10^4
−1.0
−0.5
0.0
0.5
1.0
Neutrino zenith angle cos θ_z
Attenuation in Earth $e^{-\tau_{\nu N}}$
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0


Upgoing
$\cos\theta_z = -1$
0
$\cos\theta_z = +1$
Downgoing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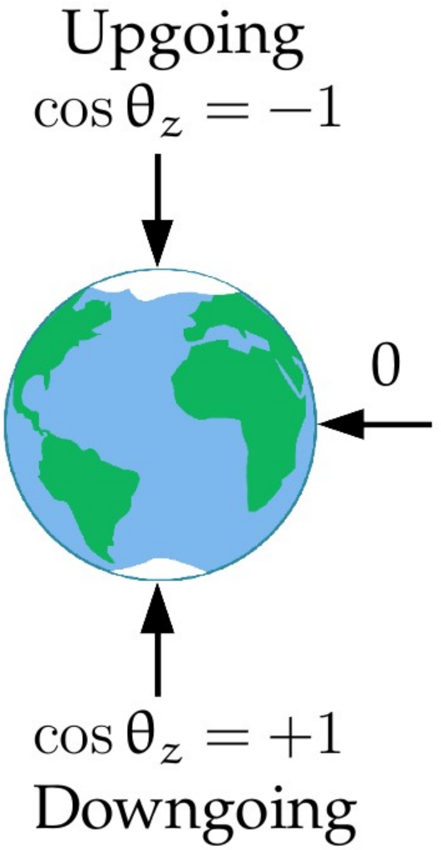
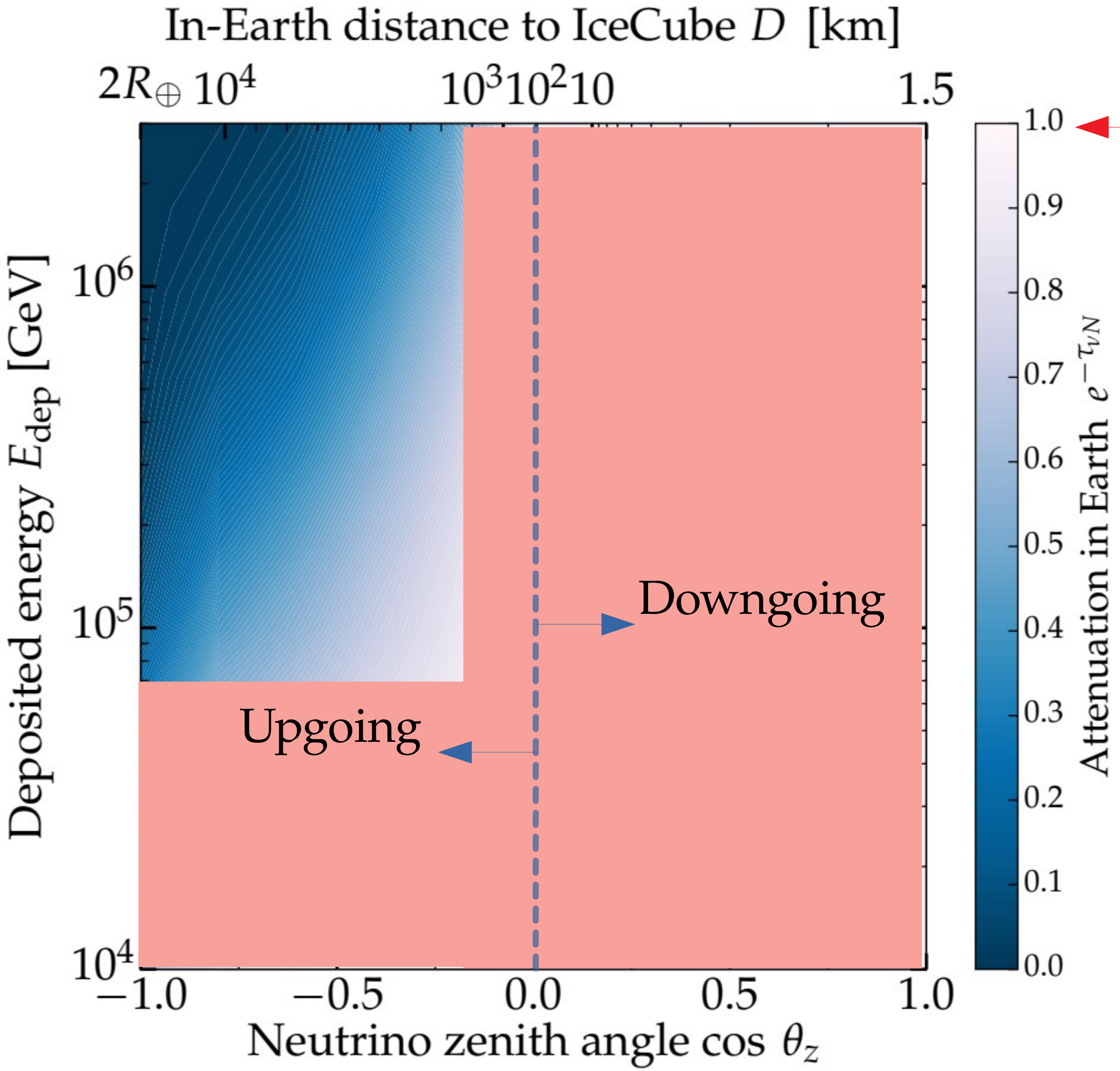
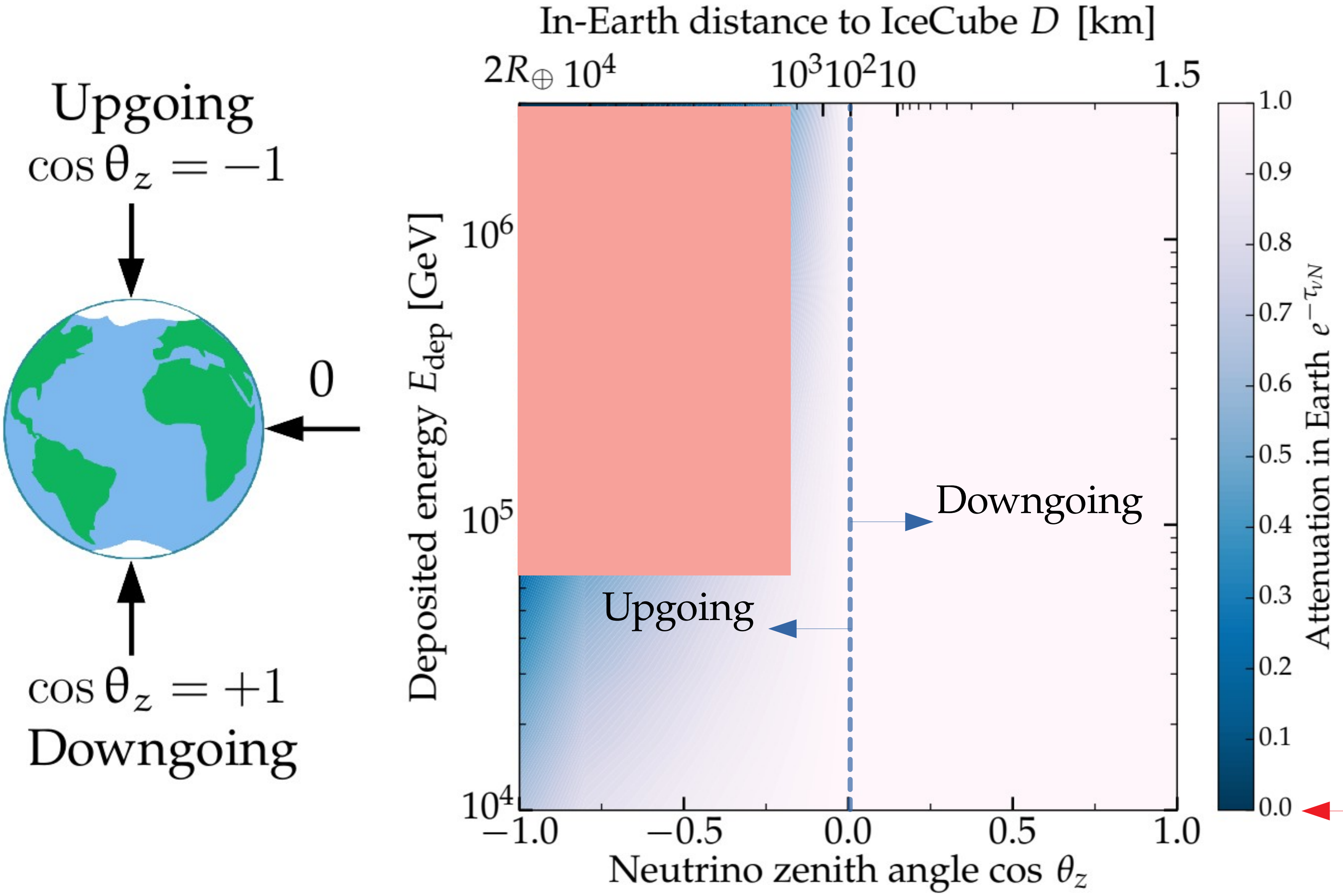
$2R_\oplus$
10^4
10^3
10^2
10
1.5
Deposited energy $E_{\rm dep}$ [GeV]
10^6
10^5
10^4
Downgoing
Upgoing
−1.0
−0.5
0.0
0.5
1.0
Neutrino zenith angle $\cos\,\theta_z$
Attenuation in Earth $e^{-\tau_{\nu N}}$
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0



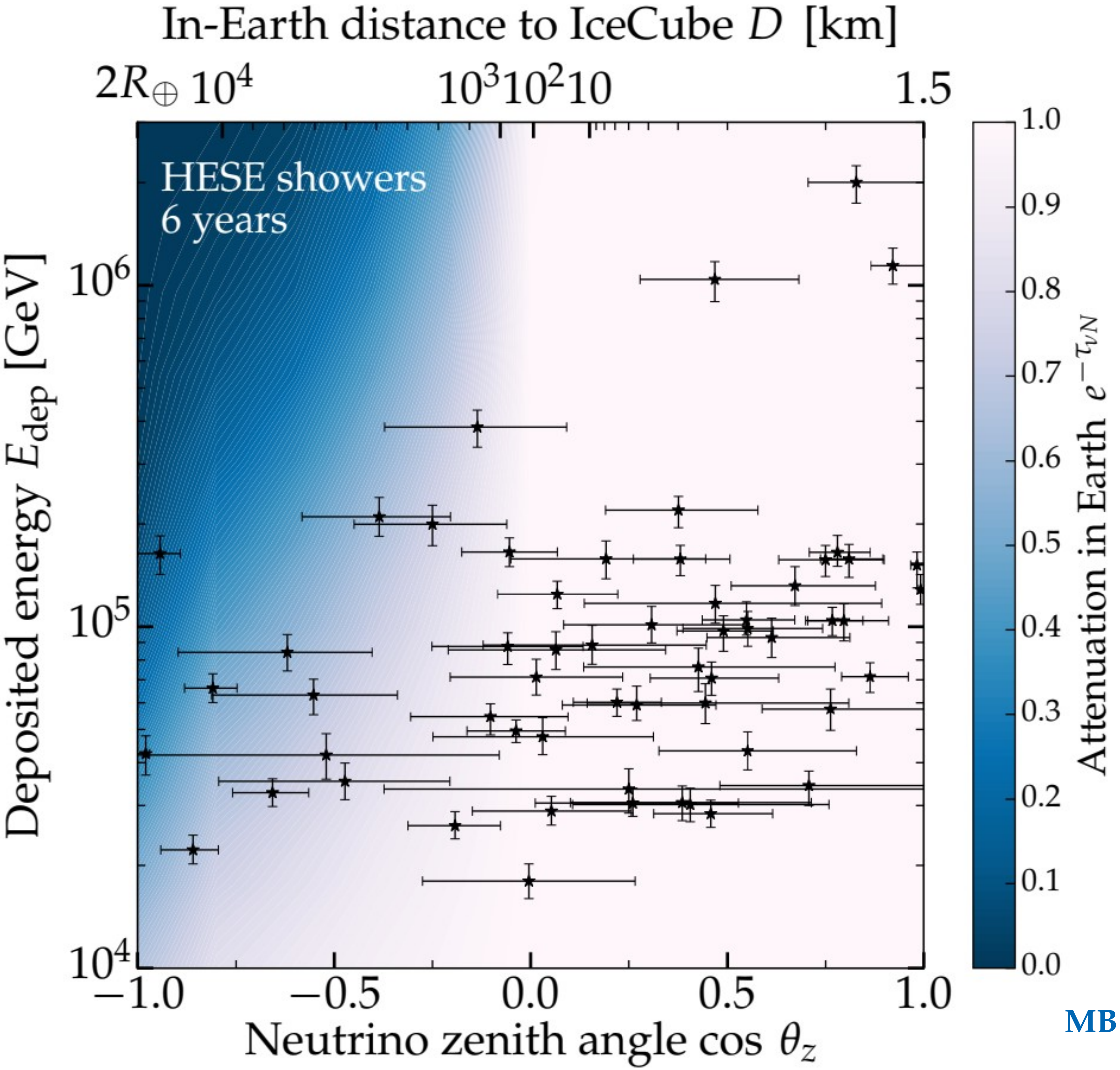


Transparent Earth

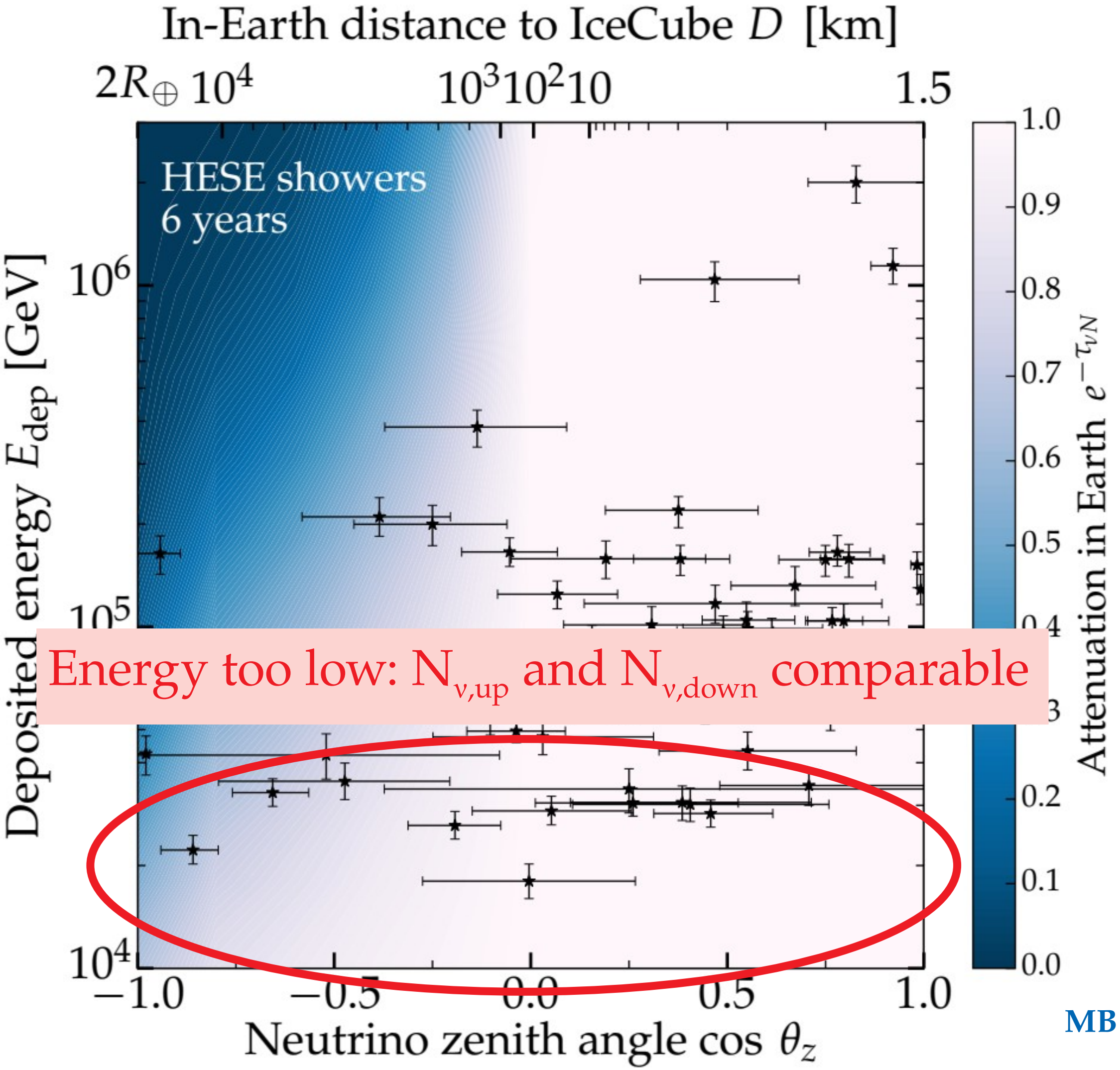
$e^{-\tau} \sim 1$



Opaque Earth
$e^{-\tau} \sim 0$

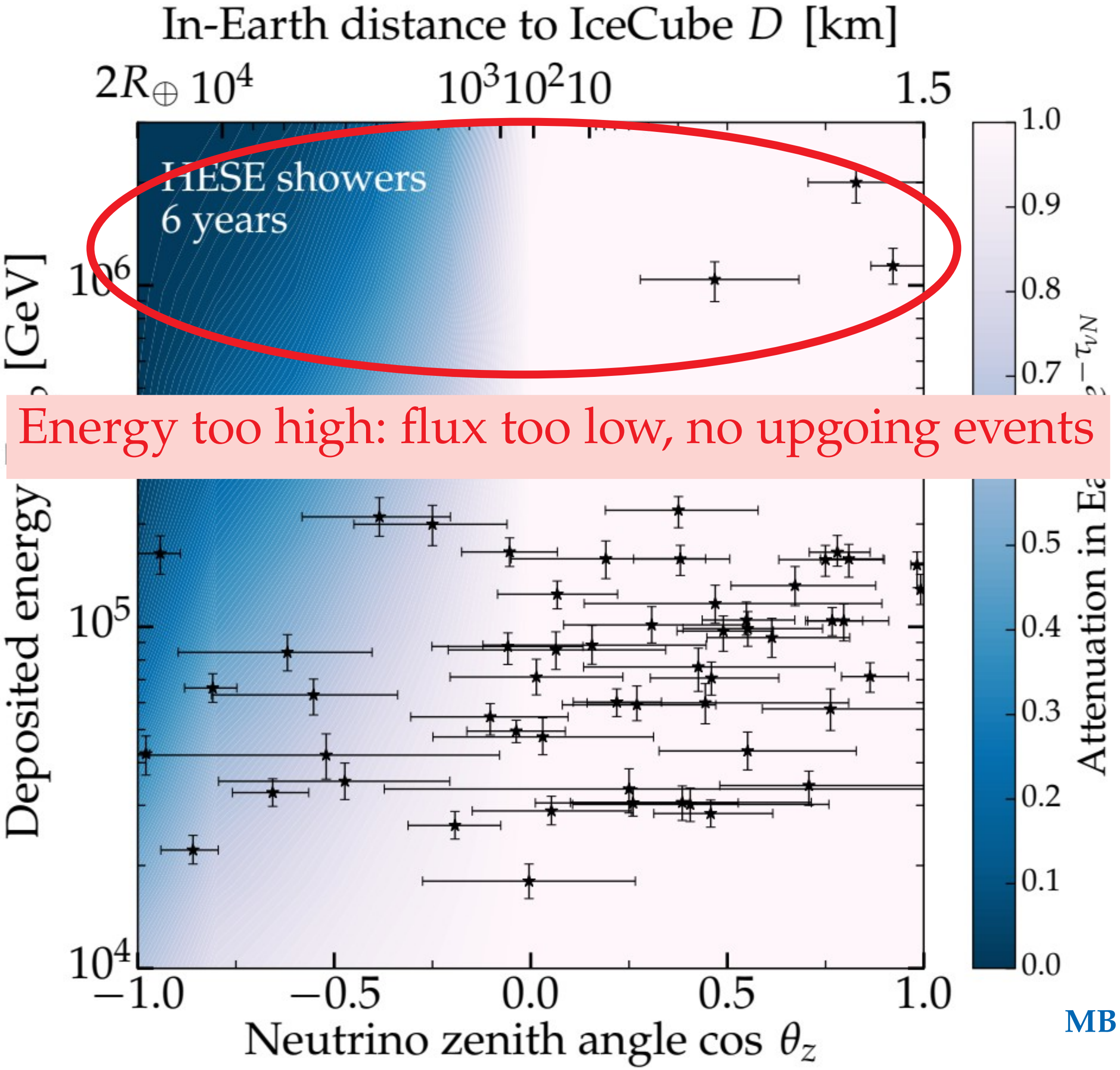


MB & Connolly, *PRL* 2019



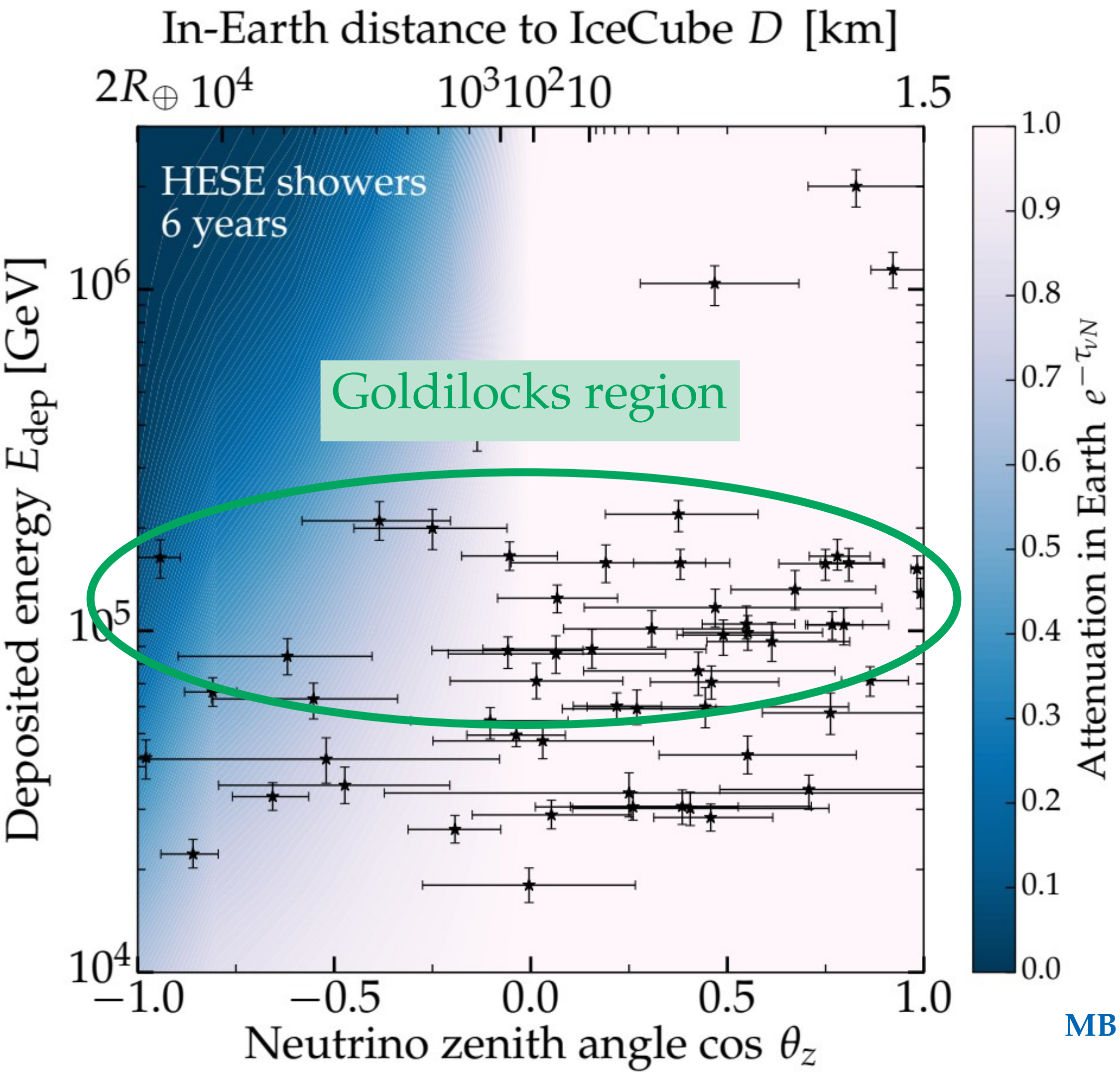
Energy too low: $N_{\nu,\rm up}$ and $N_{\nu,\rm down}$ comparable

MB & Connolly, *PRL* 2019



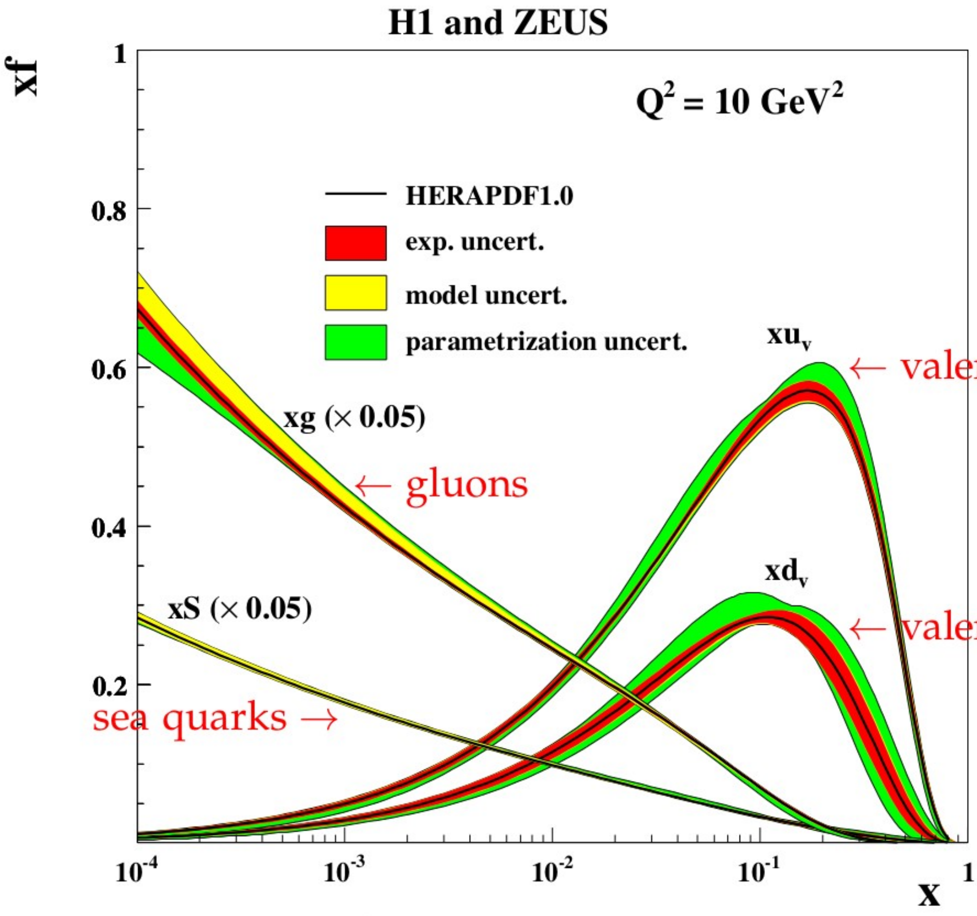
Energy too high: flux too low, no upgoing events

MB & Connolly, *PRL* 2019



MB & Connolly, *PRL* 2019

Peeking inside a proton



(Parton distribution function)

← valence up quark

← gluons

← valence down quark

sea quarks →

← Extrapolation

(Fraction of momentum carried by parton)

4. Dark matter:

Annihilation and decay into ν

High-energy neutrinos from dark matter

Dark matter co-annihilation:

$$\chi + \chi \to \nu + \bar{\nu}$$

$$\chi + \chi \to \ldots \to \nu + \bar{\nu} + \ldots$$

$$E_{\max} = m_\chi$$

Dark matter decay:

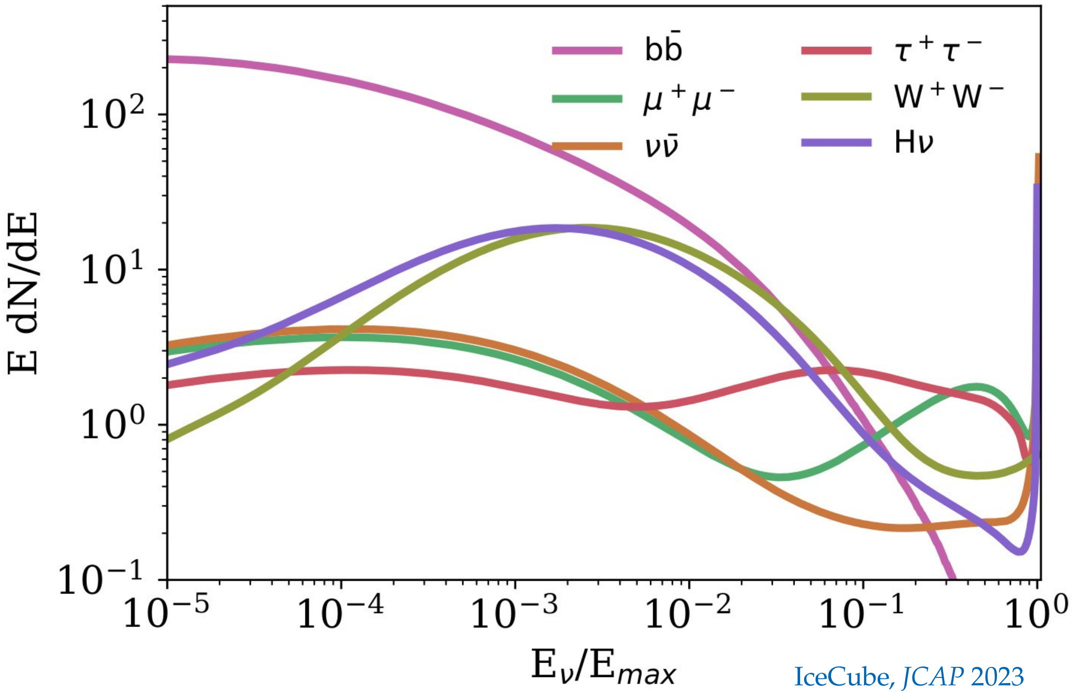
$$\chi \to \nu + \bar{\nu}$$

$$\chi \to \ldots \to \nu + \bar{\nu} + \ldots$$

$$E_{\max} = m_\chi / 2$$

Electroweak corrections (off-shell *W* and *Z* emission) broaden the ν spectrum

$\nu + \bar{\nu}$ yield from DM (at source)

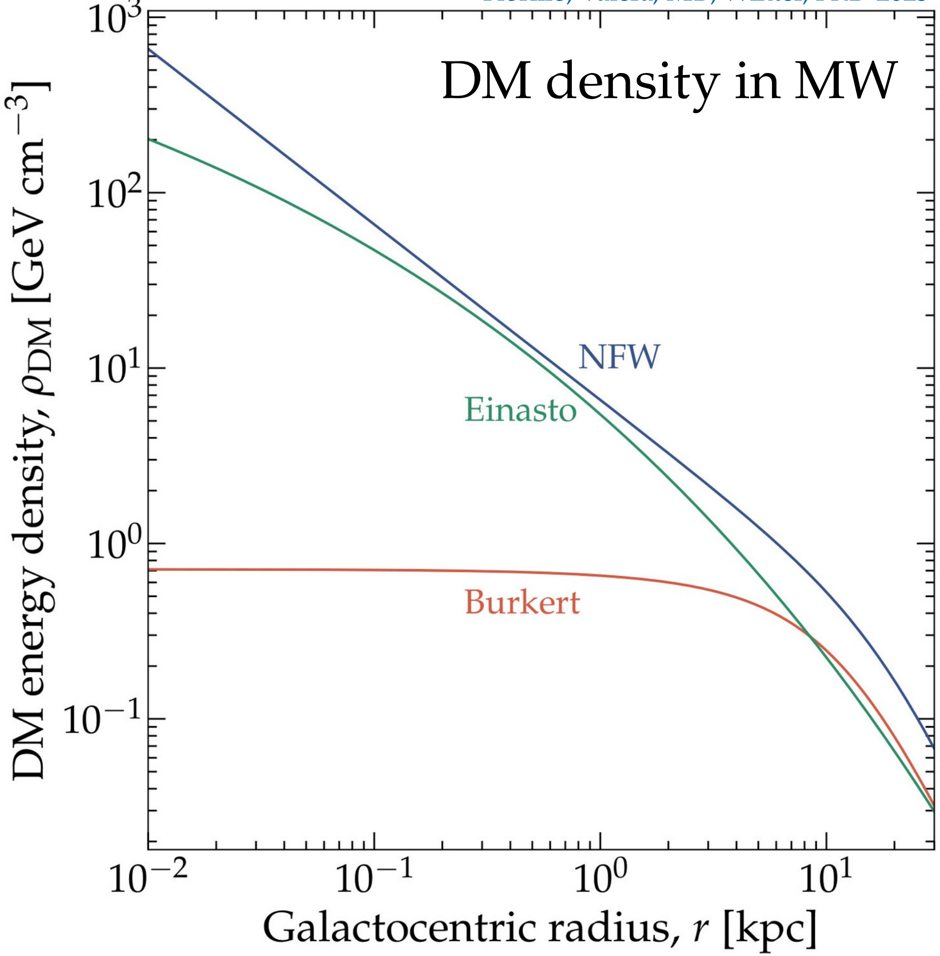


IceCube, *JCAP* 2023

Approximate independence on m_χ valid for $m_\chi \approx$ 100 TeV–10 PeV

Dark matter in the Milky Way

Fiorillo, Valera, **MB**, Winter, *PRD* 2023



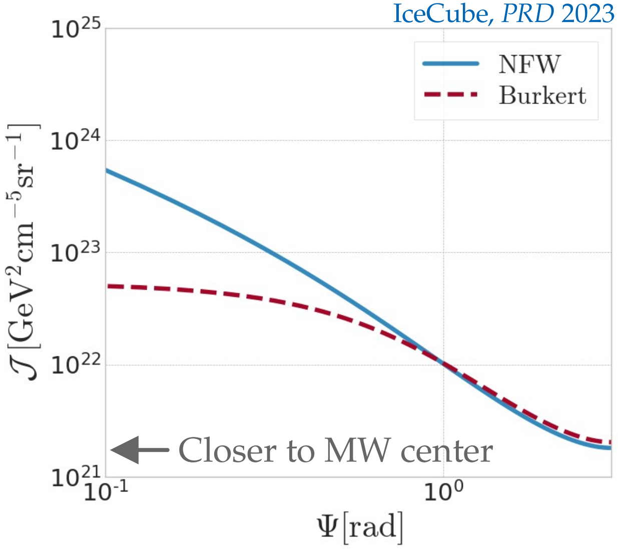
DM annihilation

$\Phi_\nu \propto \mathcal{I} \propto \rho_{\rm DM}^2$

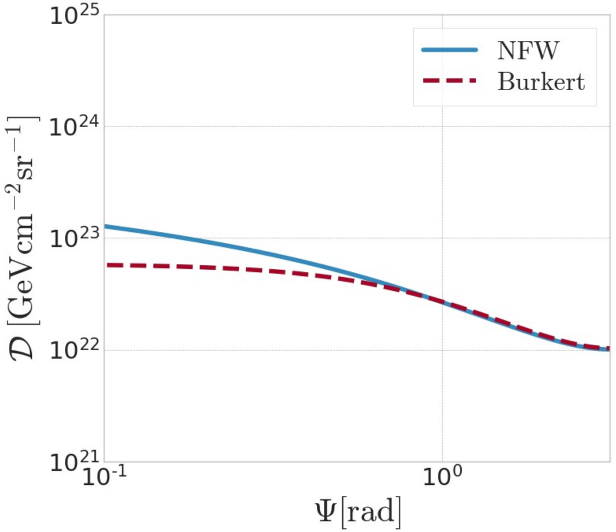
DM decay

$\Phi_\nu \propto \mathcal{D} \propto \rho_{DM}$

IceCube, *PRD* 2023



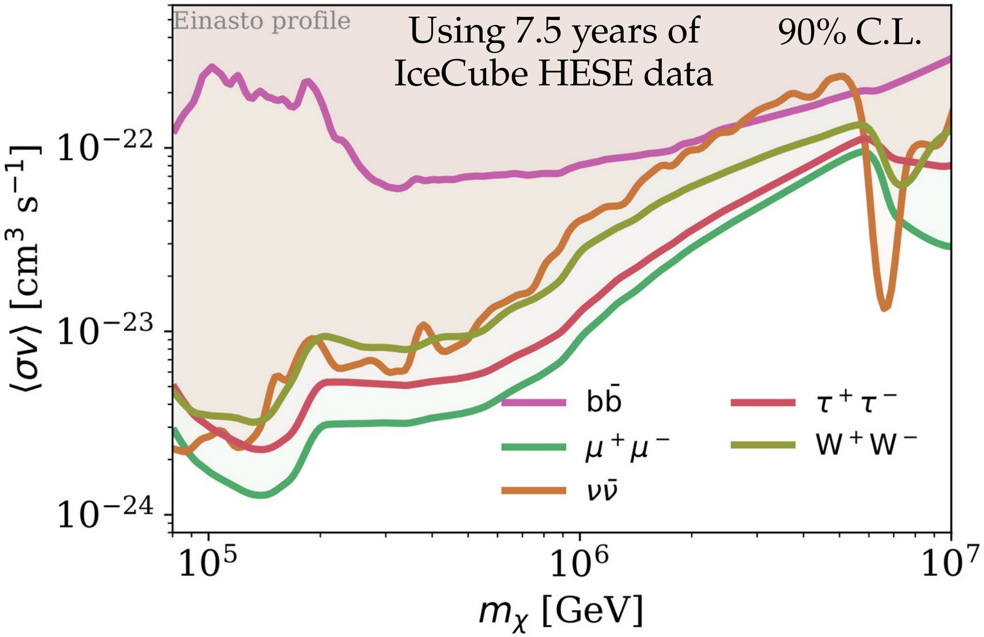
Closer to MW center



Limits on dark matter annihilation

Per annihilation channel

(assuming 100% branching ratio)



Two DM contributions: Galactic (anisotropic) + extragalactic (isotropic)

Plus background of atmospheric neutrinos (anisotropic, but different)

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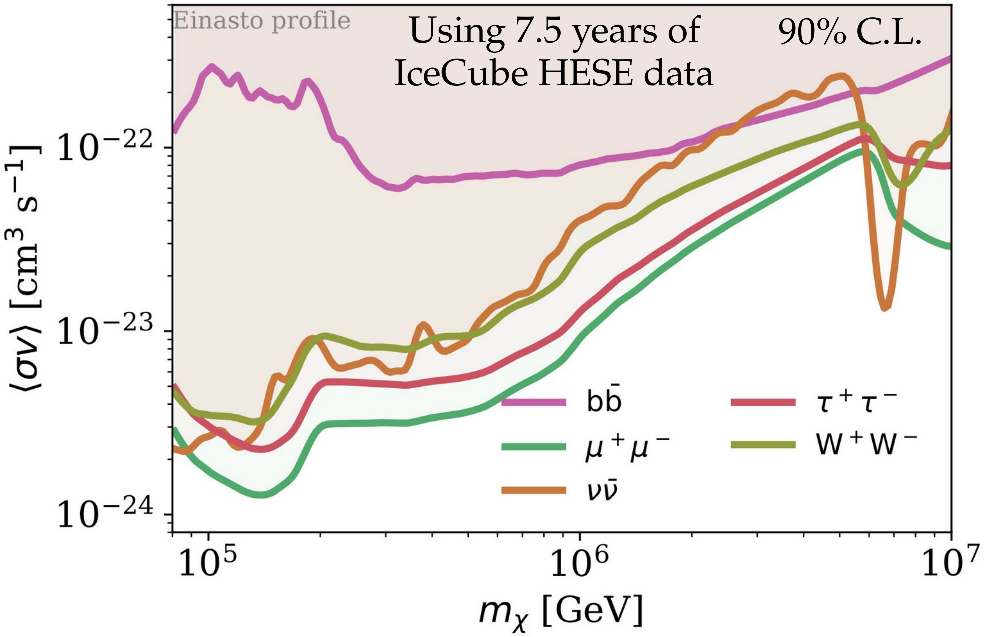
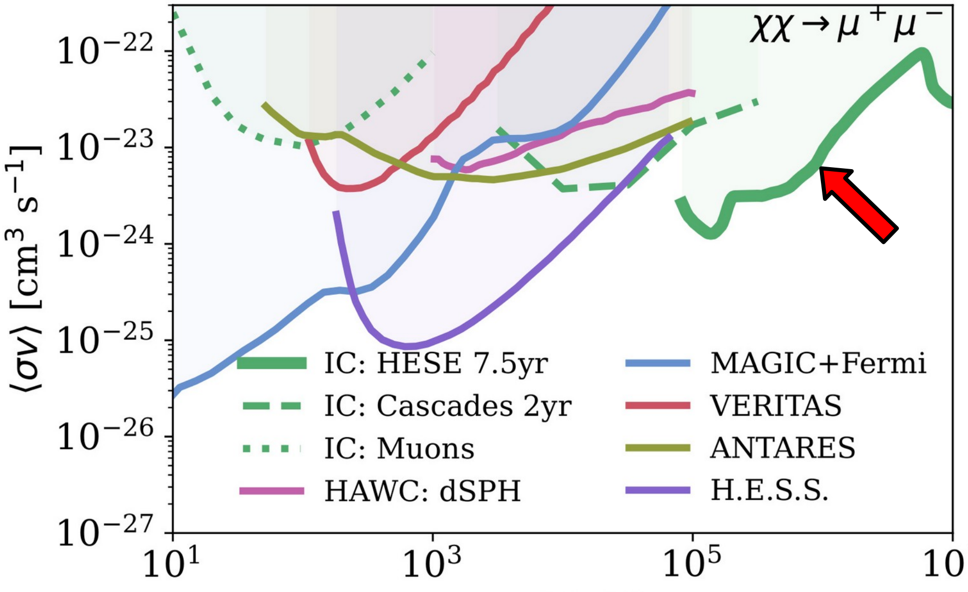
(assuming 100% branching ratio)



Compared to other limits

(assuming annihilation to muons)



IceCube, *JCAP* 2023

Two DM contributions: Galactic (anisotropic) + extragalactic (isotropic)

Plus background of atmospheric neutrinos (anisotropic, but different)

5. New neutrino interactions:

Are there secret νν interactions?

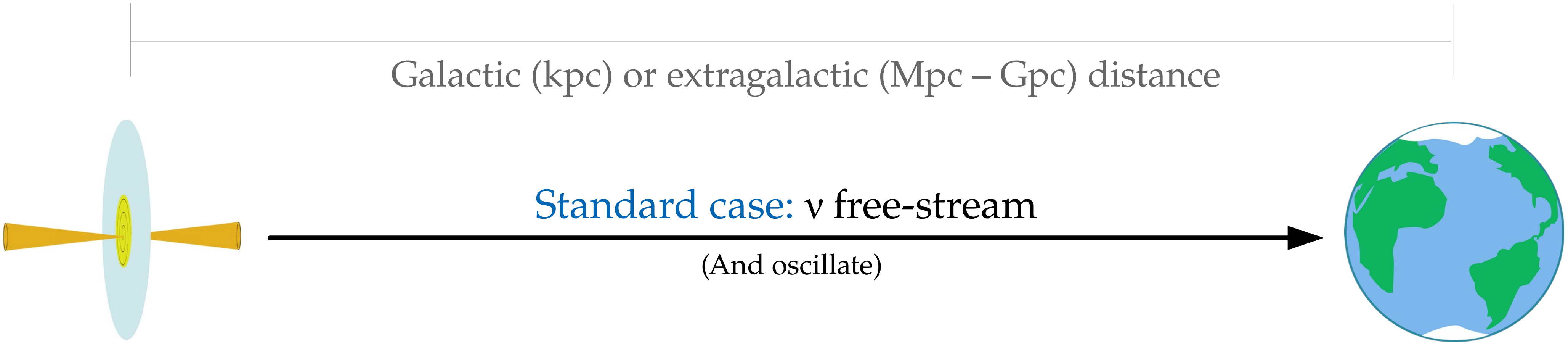
Astrophysical neutrino sources

Earth

Galactic (kpc) or extragalactic (Mpc – Gpc) distance

Astrophysical neutrino sources

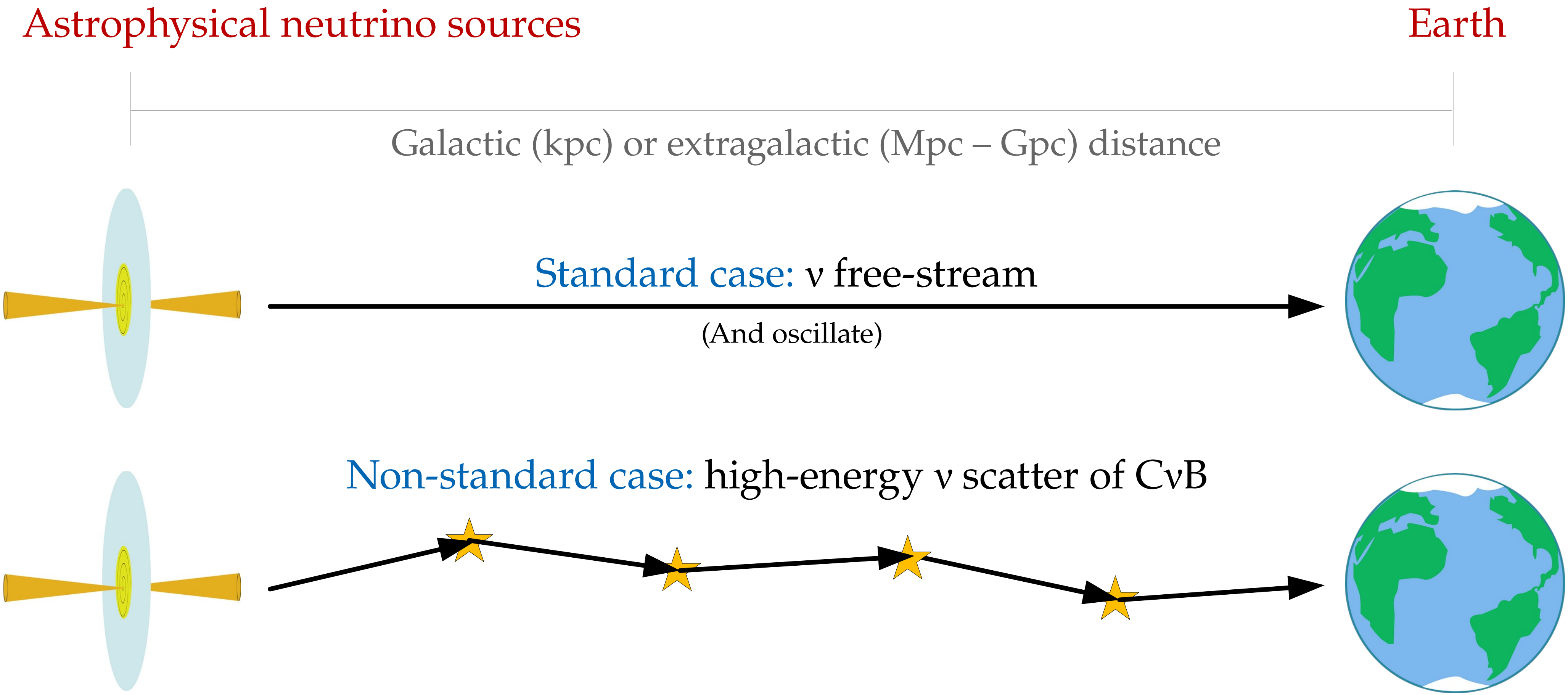
Earth



Galactic (kpc) or extragalactic (Mpc – Gpc) distance

Standard case: ν free-stream

(And oscillate)



Astrophysical neutrino sources

Earth

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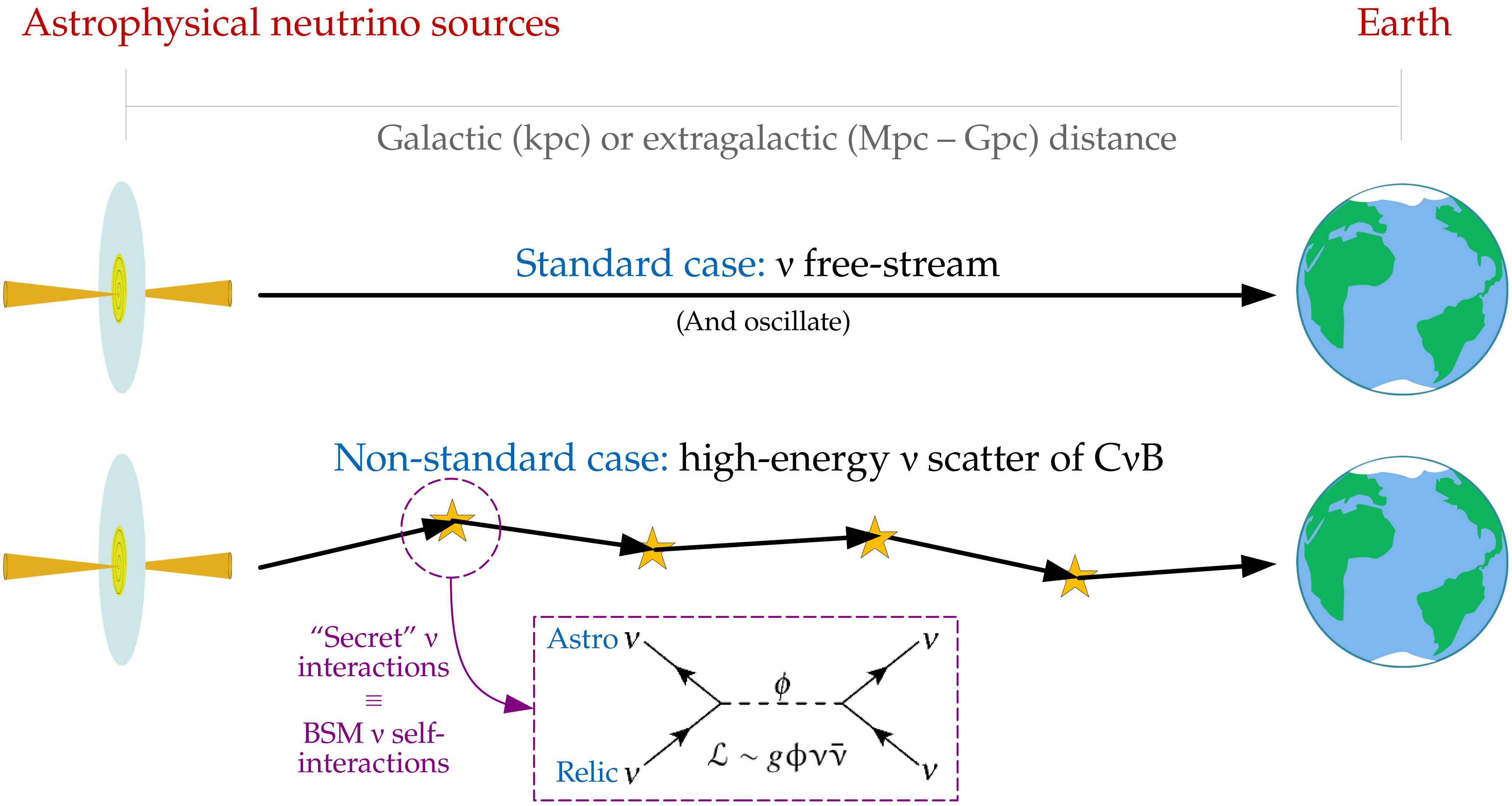
Non-standard case: high-energy ν scatter of CνB


Astrophysical neutrino sources
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Standard case: ν free-stream
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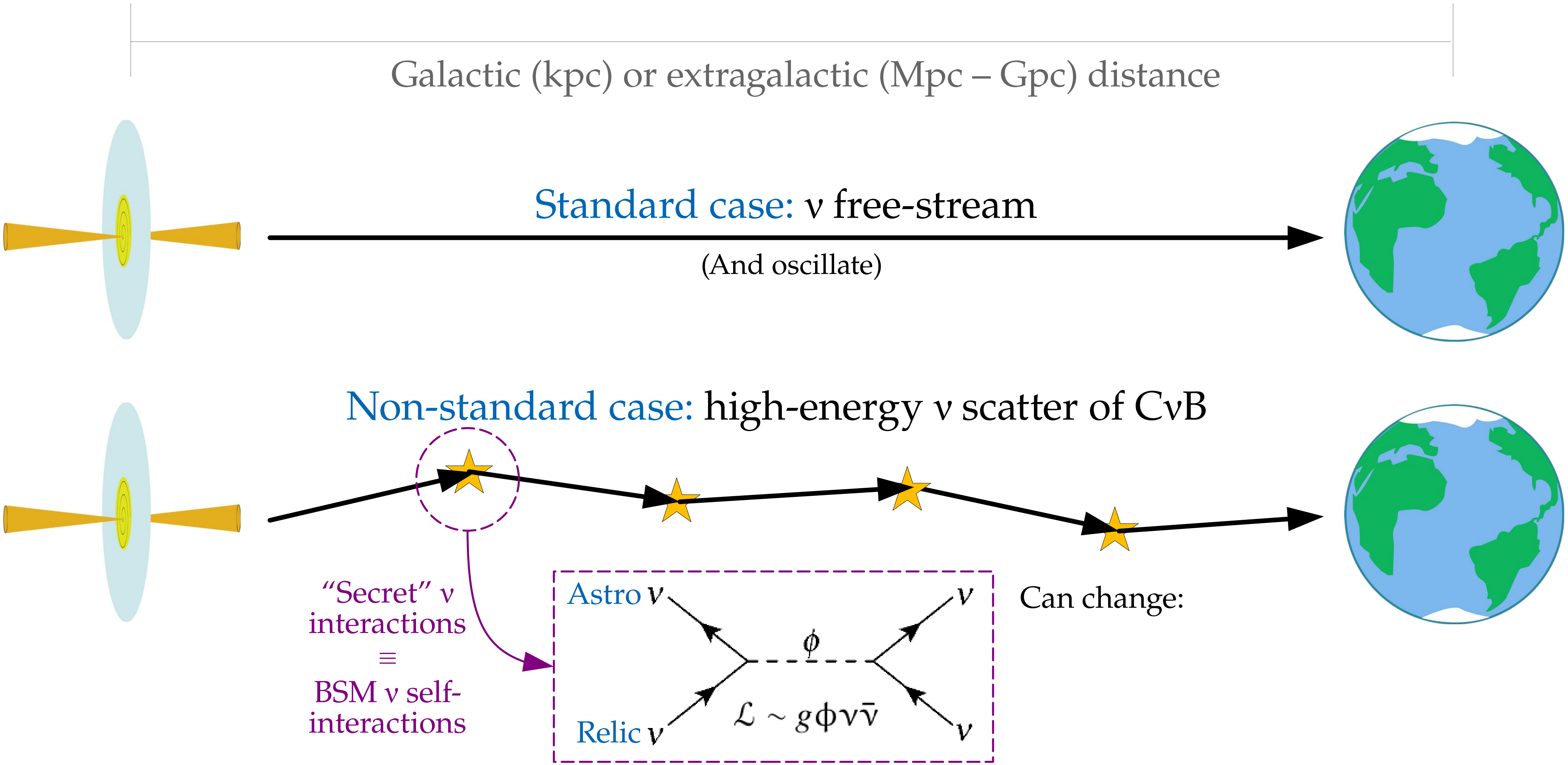
Non-standard case: high-energy ν scatter of CνB
"Secret" ν interactions ≡ BSM ν self-interactions
Astro ν
Relic ν
ν
ν
ϕ
$\mathcal{L} \sim g\phi\nu\bar{\nu}$



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Relic ν

ϕ

ν

ν

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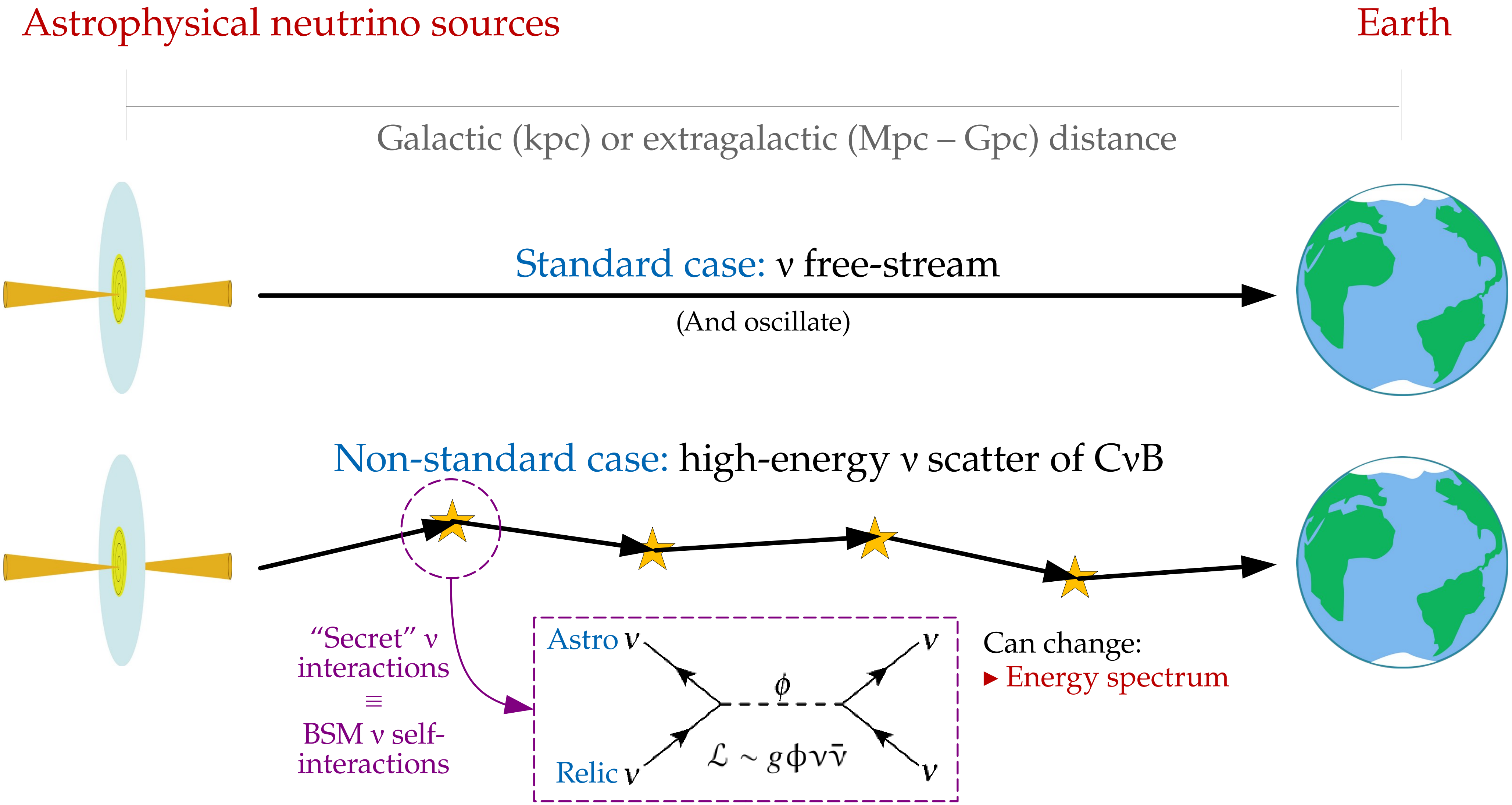
Can change:



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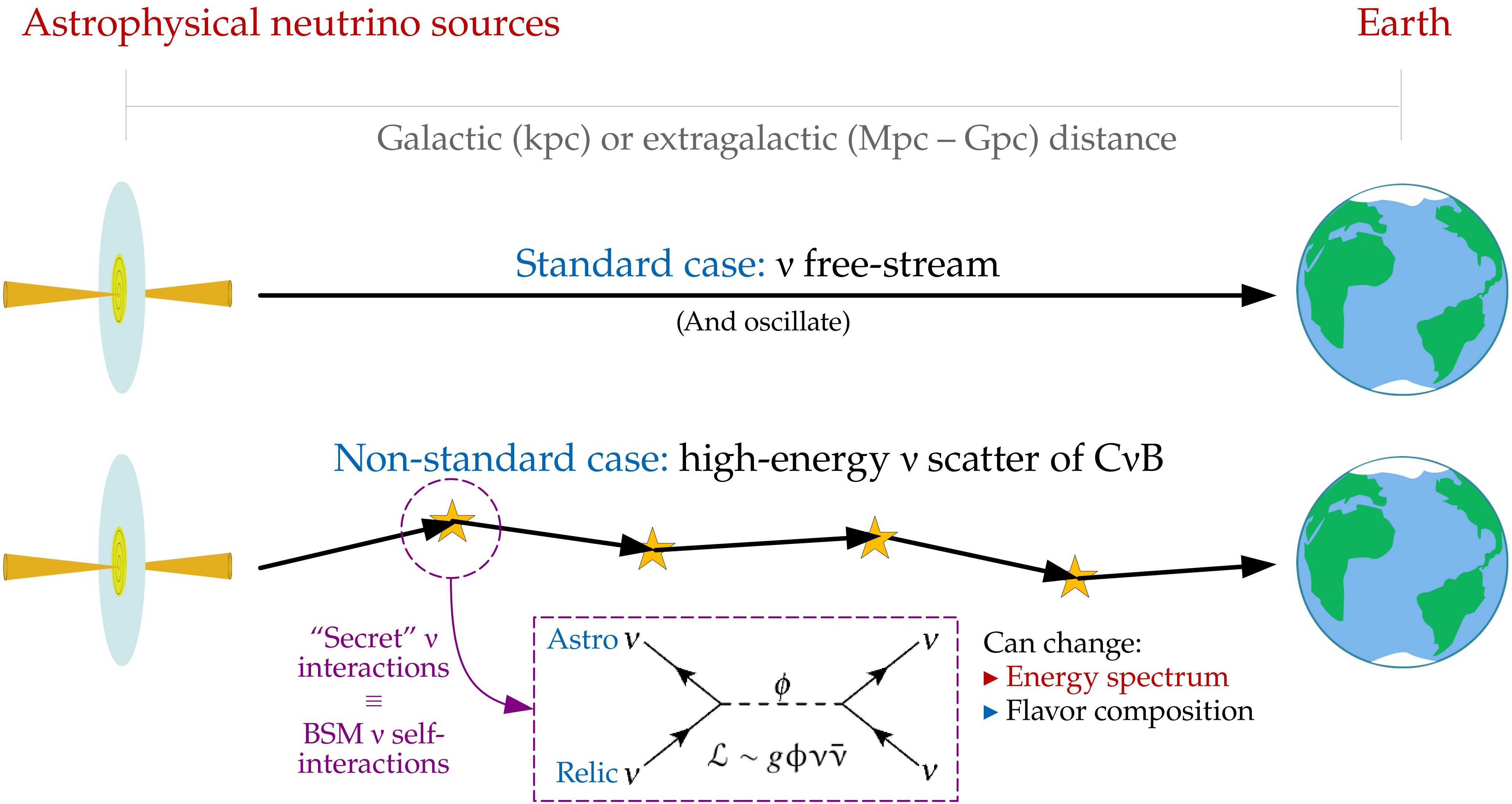
≡
BSM ν self-interactions

Can change:
- Energy spectrum



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ν

ν

ϕ

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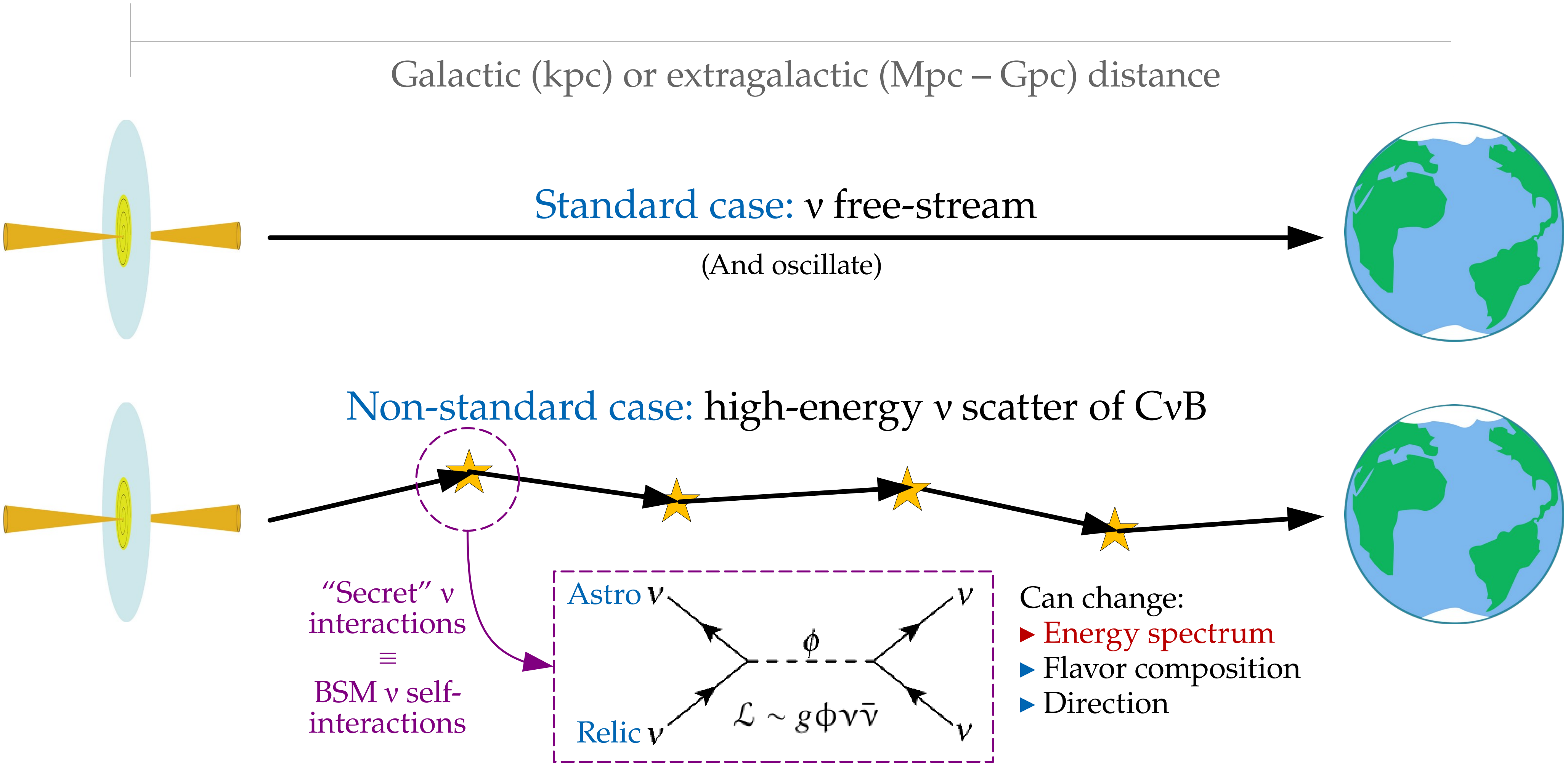
Can change:

- Energy spectrum
- Flavor composition



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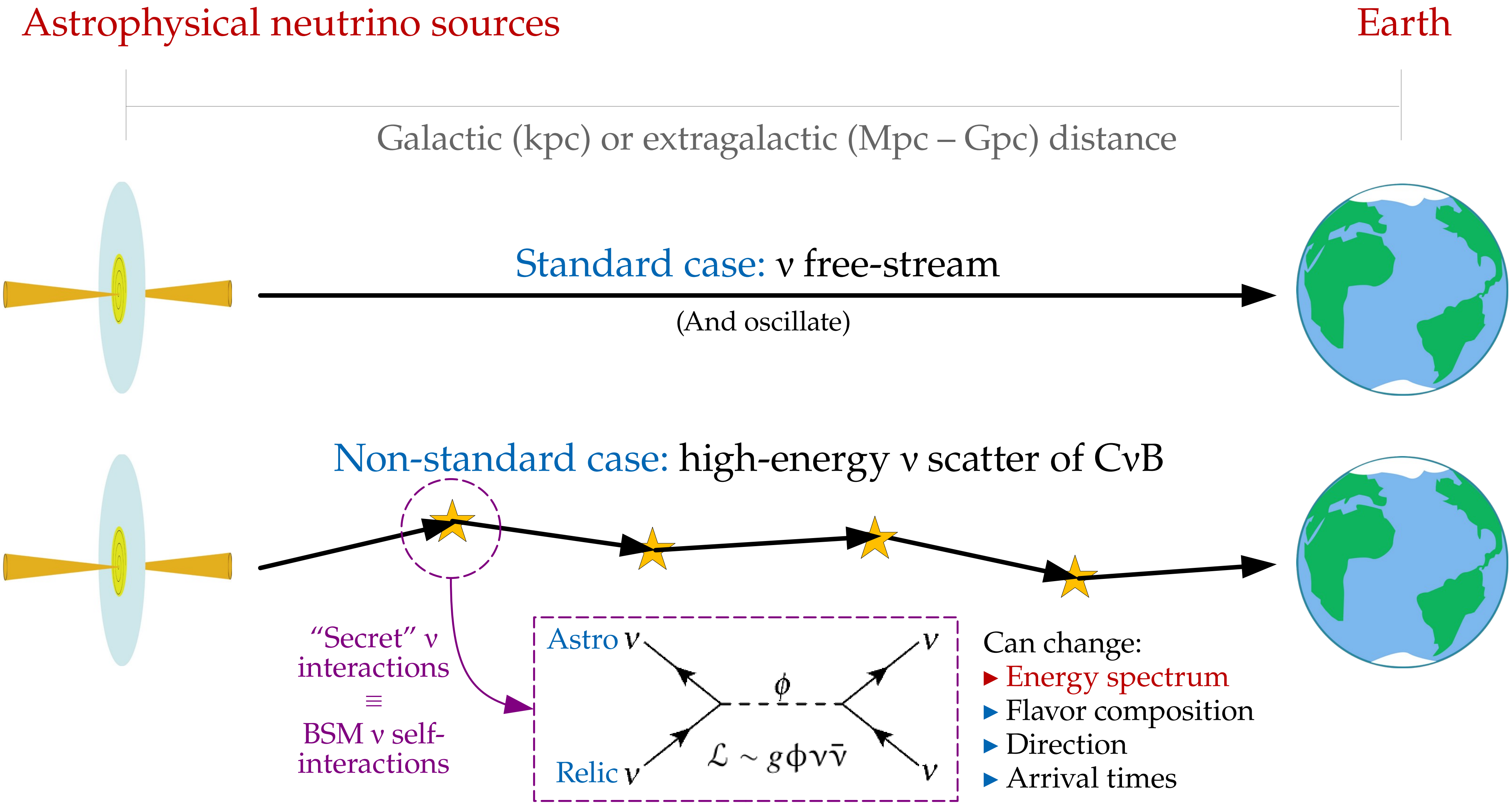
Can change:

- Energy spectrum
- Flavor composition
- Direction



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(And oscillate)

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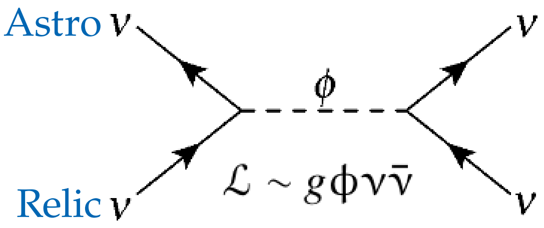
"Secret" ν interactions ≡ BSM ν self-interactions

Can change:

- Energy spectrum
- Flavor composition
- Direction
- Arrival times

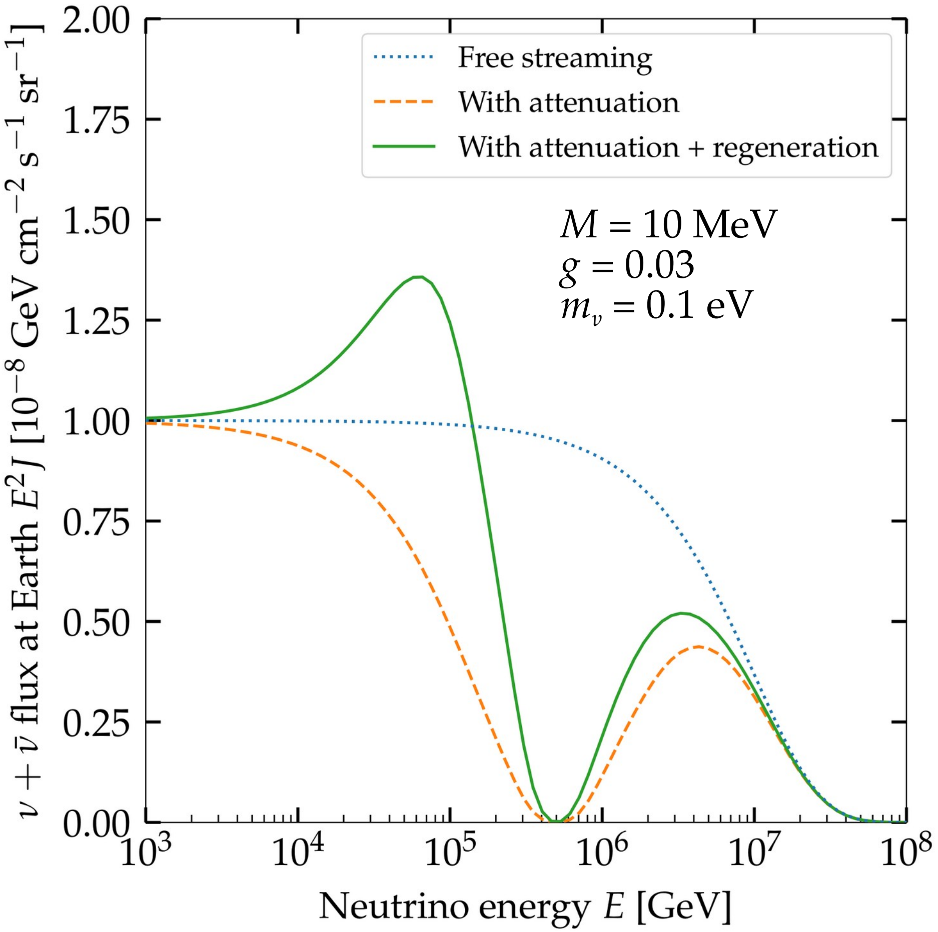
Secret interactions of high-energy astrophysical neutrinos

"Secret" neutrino interactions between astrophysical ν (PeV) and relic ν (0.1 meV):



Cross section: $\sigma = \frac{g^4}{4\pi} \frac{s}{(s - M^2)^2 + M^2\Gamma^2}$

Resonance energy: $E_{\mathrm{res}} = \frac{M^2}{2m_\nu}$



MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020
See also: Esteban, Pandey, Brdar, Beacom, *PRD* 2021
Creque-Sarbinowski, Hyde, Kamionkowski, *PRD* 2021
Ng & Beacom, *PRD* 2014
Cherry, Friedland, Shoemaker, 1411.1071
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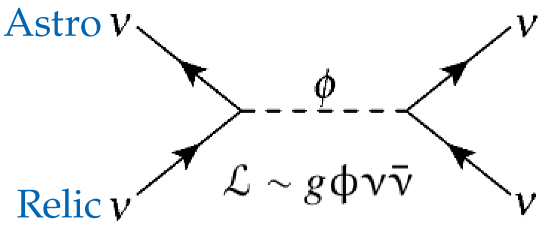

New coupling

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Mediator mass

Resonance energy: $$E_{\text{res}} = \frac{M^2}{2m_\nu}$$

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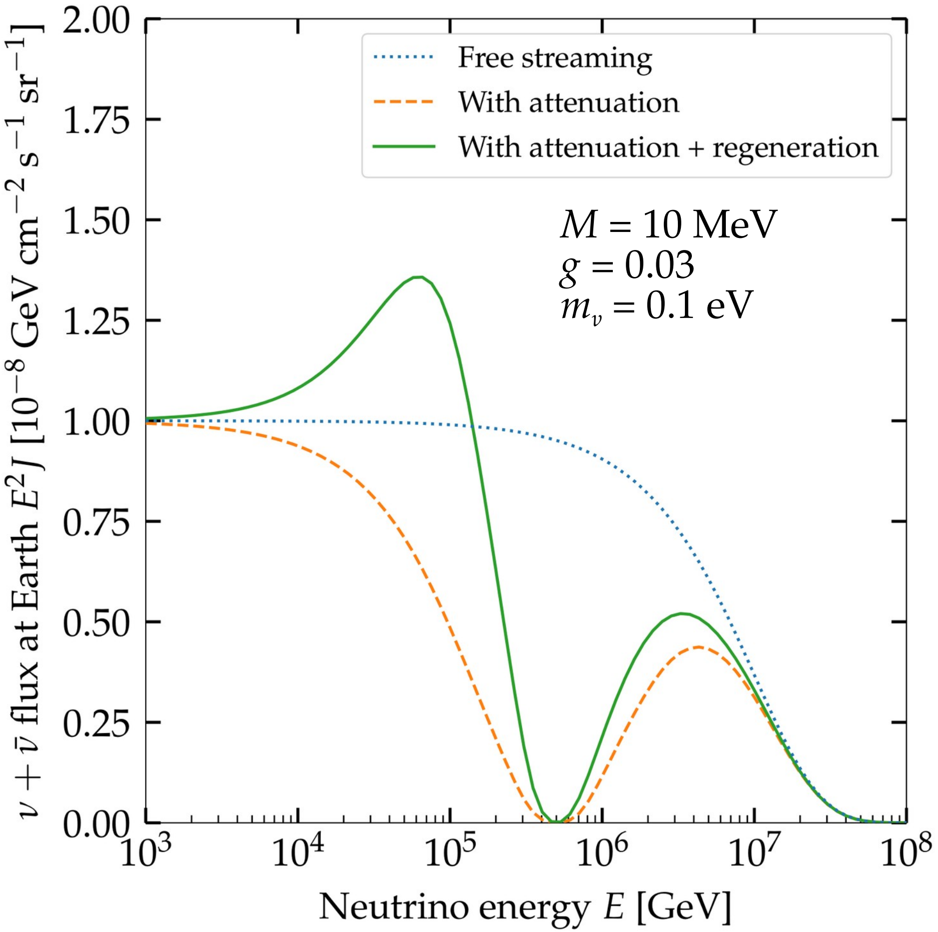

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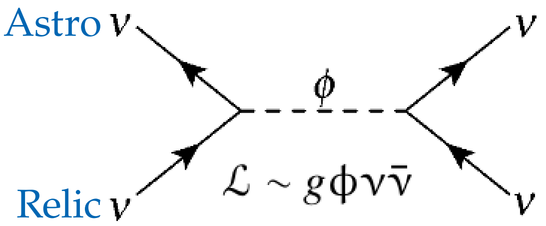

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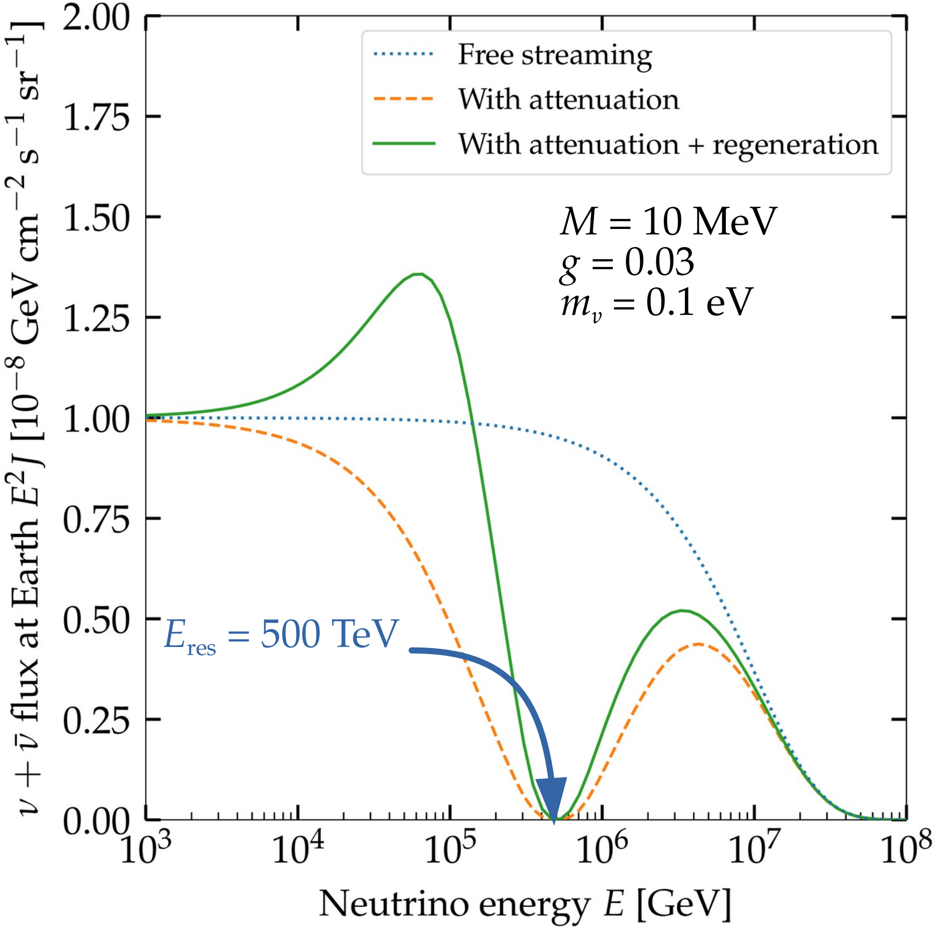

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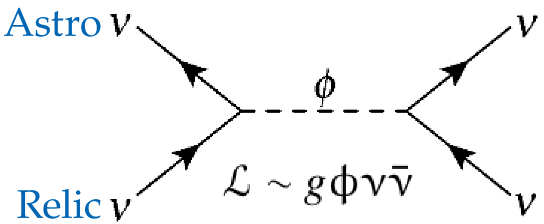

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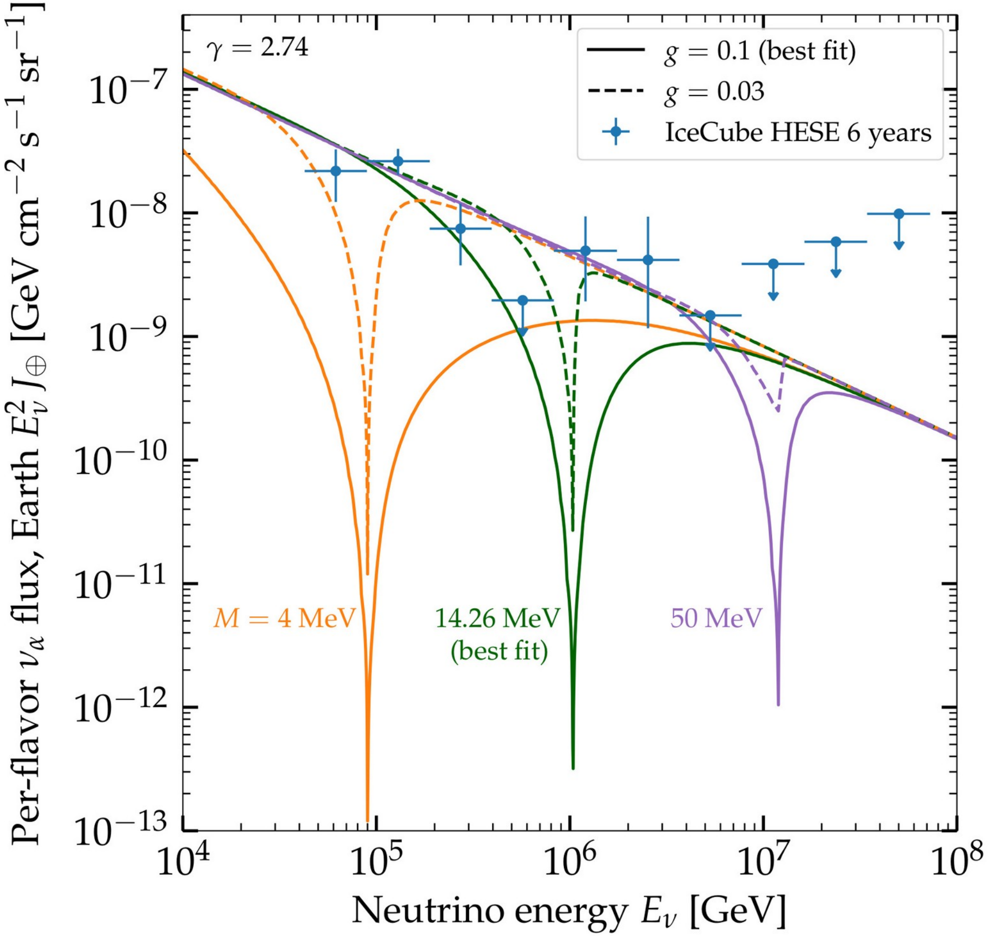

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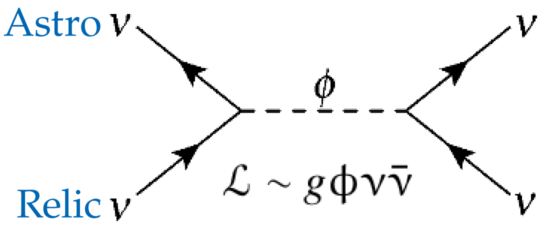

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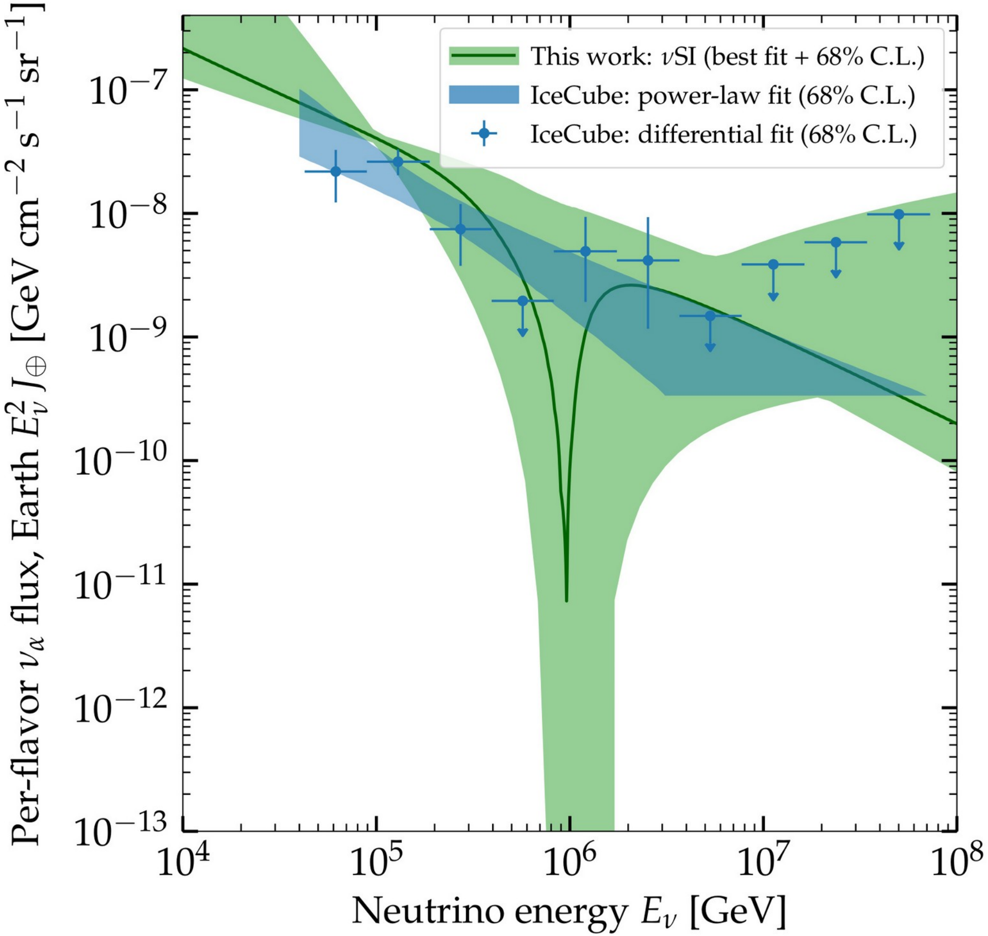
Looking for evidence of νSI

- Look for dips in 6 years of public IceCube data (HESE)
- 80 events, 18 TeV–2 PeV
- Assume flavor-diagonal and universal: $g_{\alpha\alpha} = g\,\delta_{\alpha\alpha}$
- Bayesian analysis varying M, g, shape of emitted flux (γ)
- Account for atmospheric ν, in-Earth propagation, detector uncertainties

No significant (> 3σ) evidence for a spectral dip …



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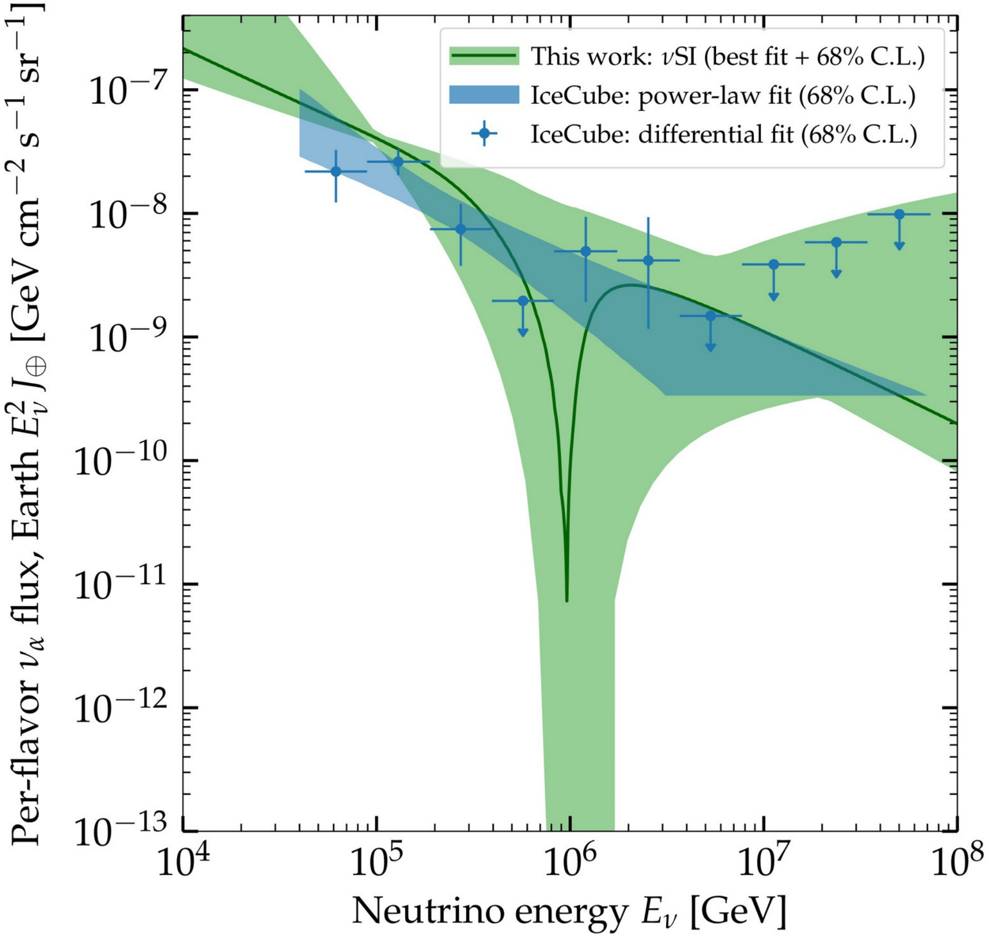
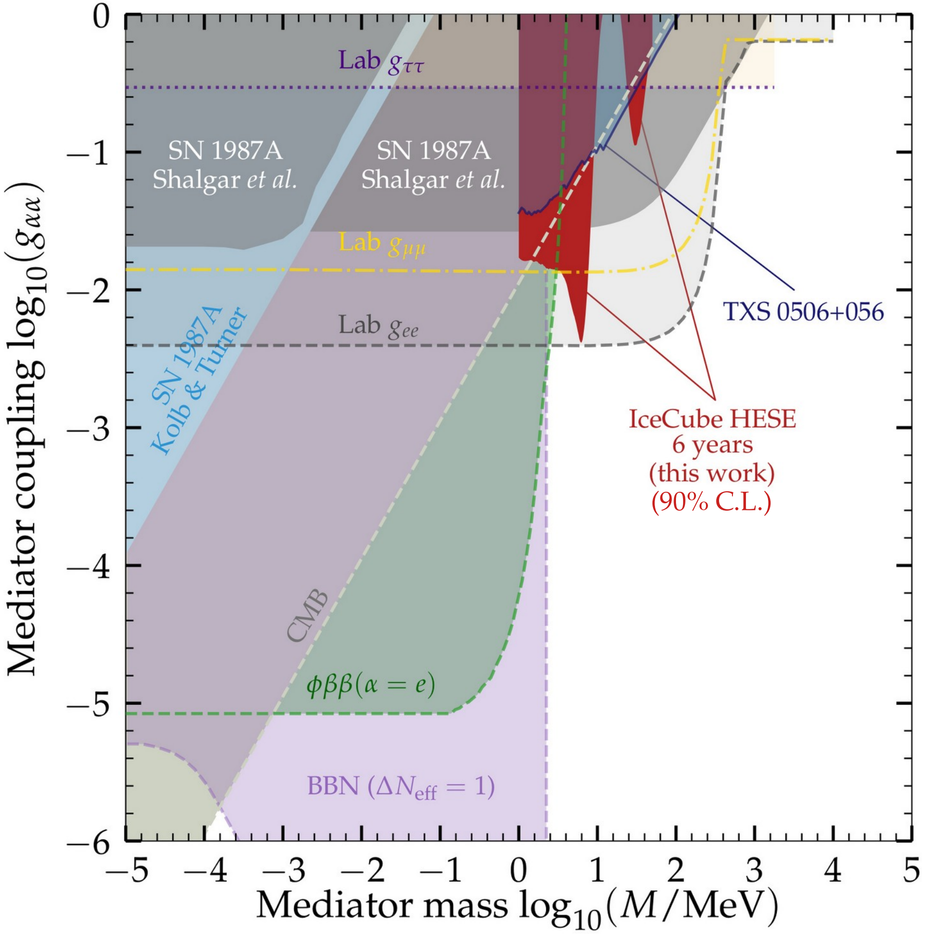
No significant (> 3σ) evidence for a spectral dip … … so we set upper limits on the coupling *g*





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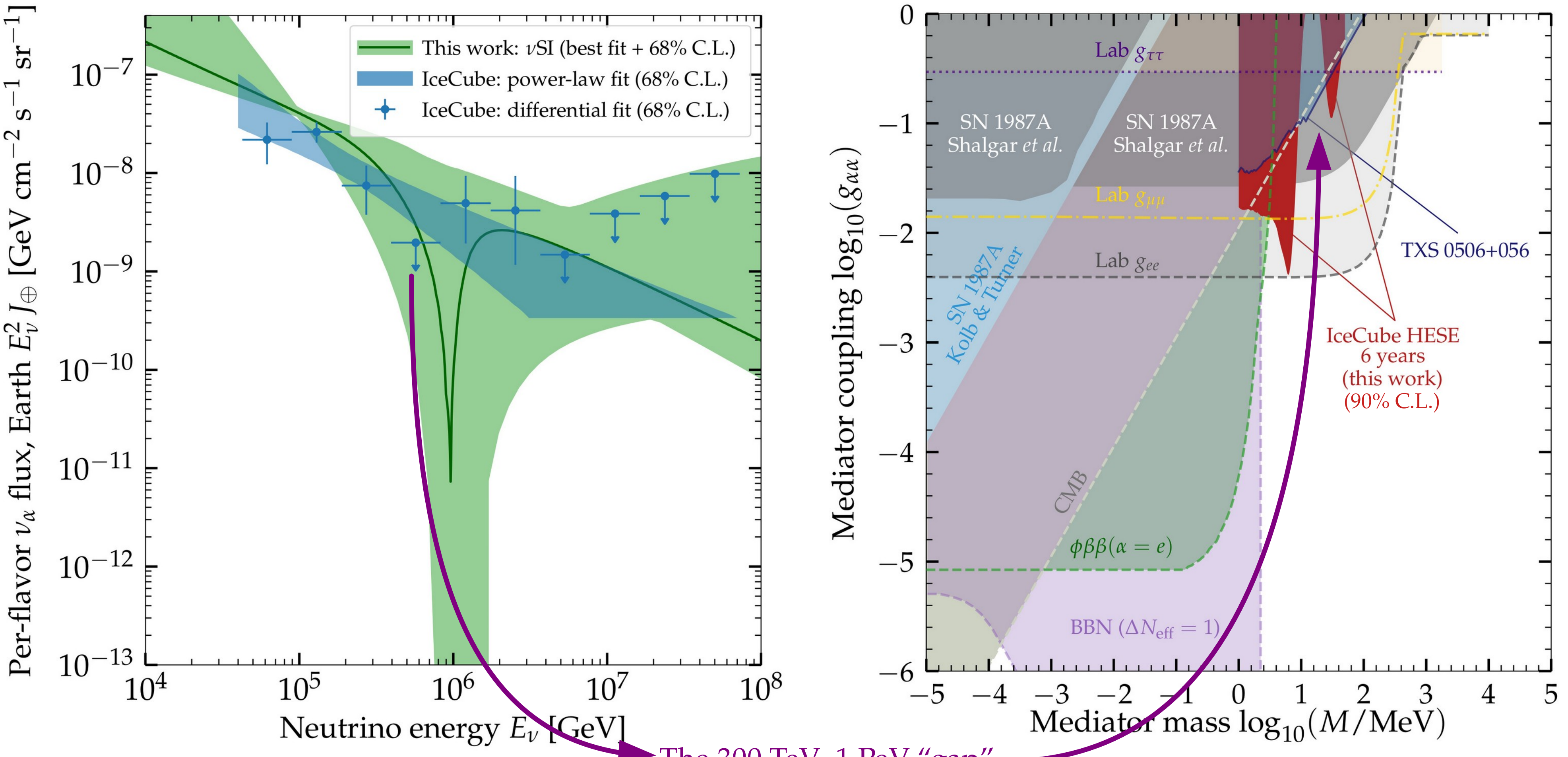

The 300 TeV–1 PeV "gap"
degrades the limit at ~10 MeV

MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020
See also: Shalgar, **MB**, Tamborra, *PRD* 2020

6. Unstable neutrinos:

Are neutrinos for ever?

Are neutrinos forever?

- In the Standard Model (νSM), neutrinos are essentially stable ($\tau > 10^{36}$ yr):
  - One-photon decay ($\nu_i \to \nu_j + \gamma$): $\tau > 10^{36}\,(m_i/\mathrm{eV})^{-5}$ yr
  - Two-photon decay ($\nu_i \to \nu_j + \gamma + \gamma$): $\tau > 10^{57}\,(m_i/\mathrm{eV})^{-9}$ yr
  - Three-neutrino decay ($\nu_i \to \nu_j + \nu_k + \bar{\nu}_k$): $\tau > 10^{55}\,(m_i/\mathrm{eV})^{-5}$ yr

» Age of Universe
(~ 14.5 Gyr)

- BSM decays may have significantly higher rates: $\nu_i \to \nu_j + \varphi$

- We work in a model-independent way:
  the nature of φ is unimportant if it is invisible to neutrino detectors

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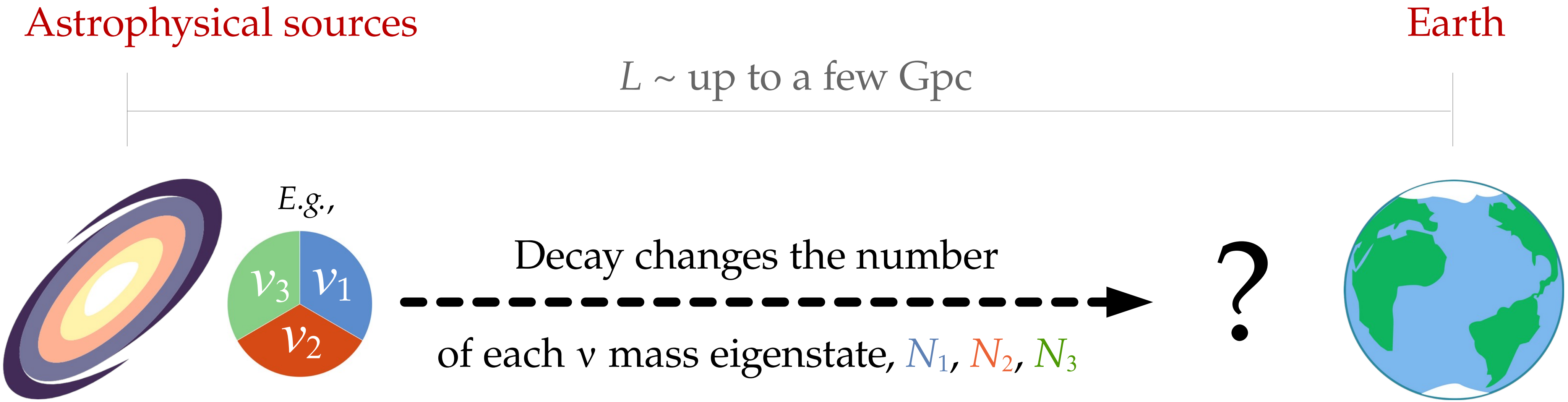
Nambu-Goldstone
boson of a broken
symmetry

- We work in a model-independent way:
  the nature of φ is unimportant if it is invisible to neutrino detectors



Astrophysical sources

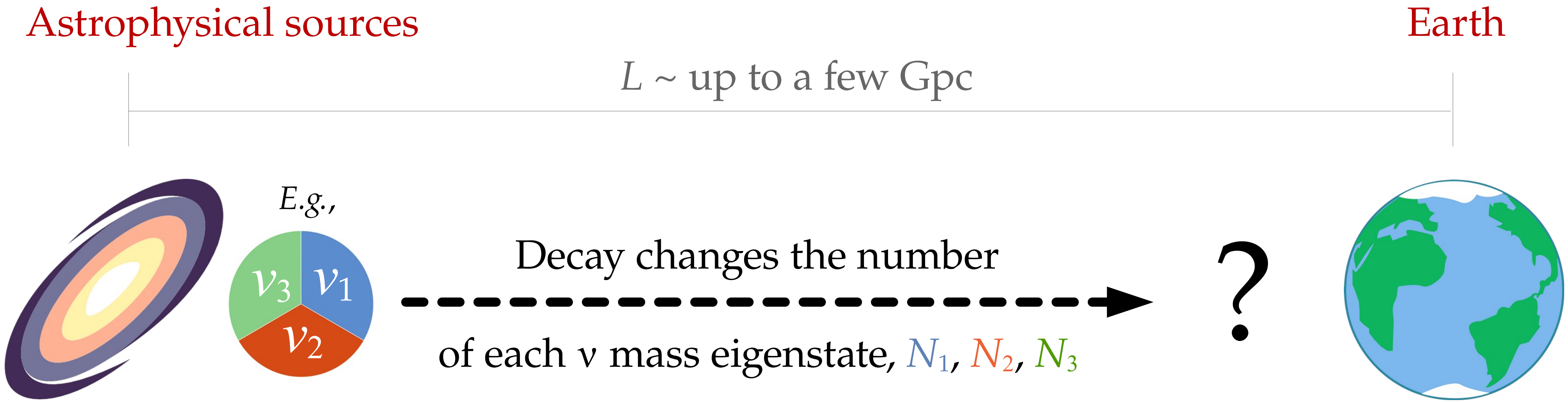
Earth

L ~ up to a few Gpc

E.g.,

Decay changes the number of each ν mass eigenstate, N_1, N_2, N_3

The flux of ν_i is attenuated by $\exp[-\,(L/E)\cdot(\underbrace{m_i}_{\text{Mass of }\nu_i}/\underbrace{\tau_i}_{\text{Lifetime of }\nu_i})]$



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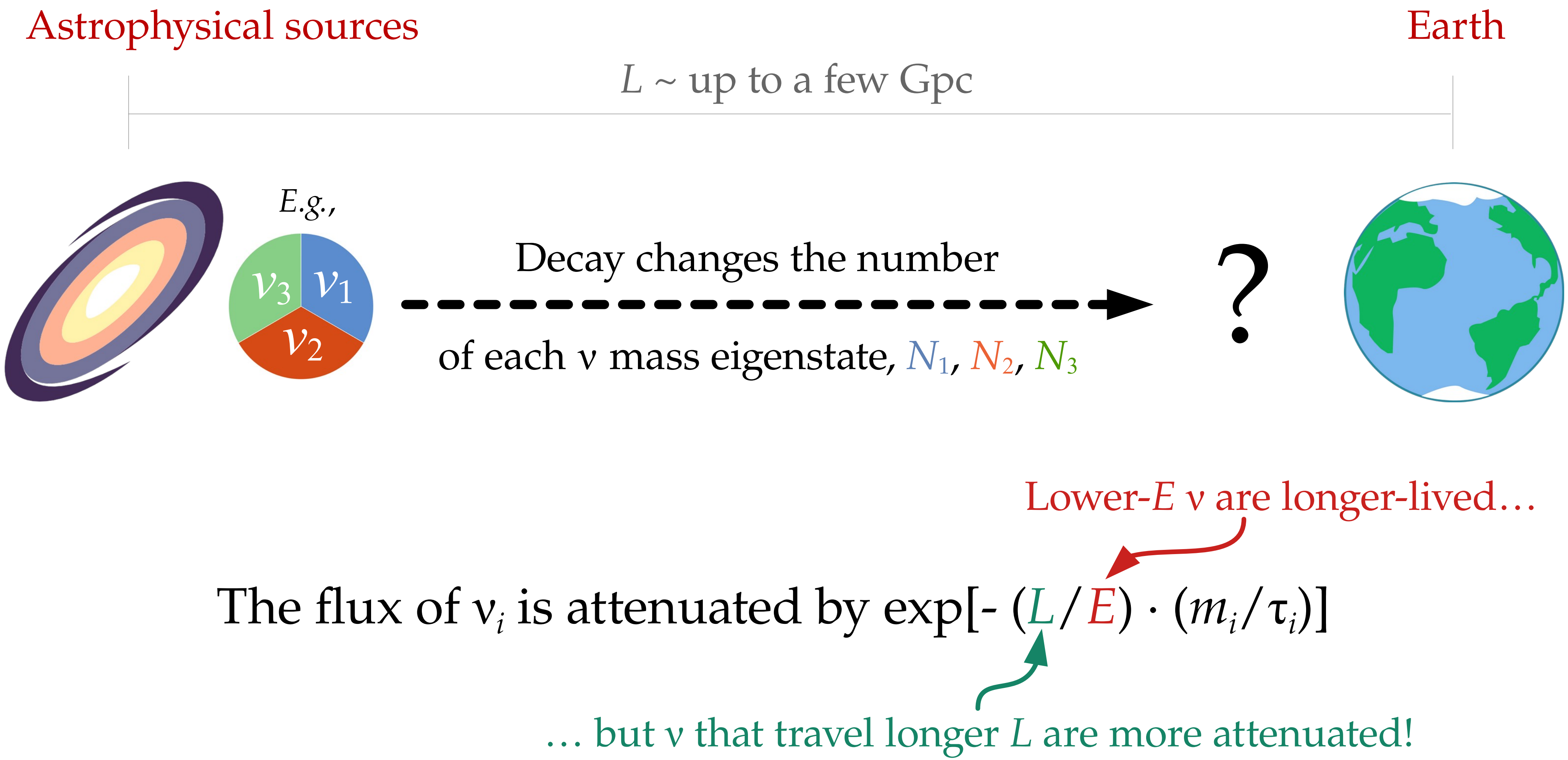


Astrophysical sources

Earth

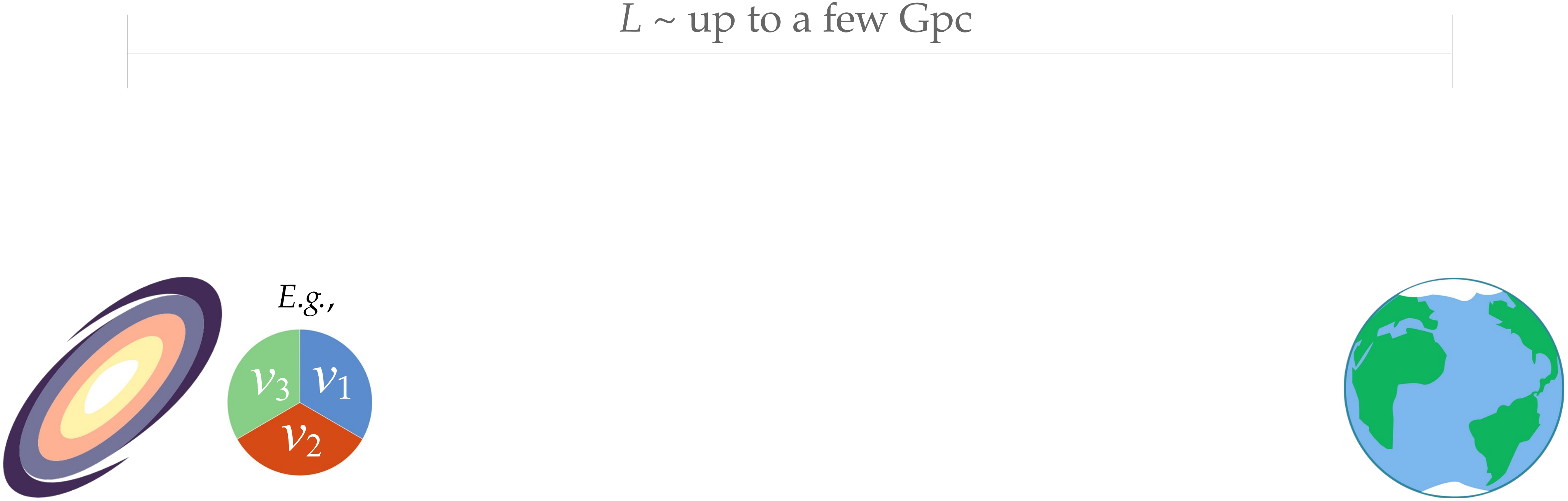
L ~ up to a few Gpc

Decay changes the number of each ν mass eigenstate, N_1, N_2, N_3

Lower-E ν are longer-lived…

The flux of ν_i is attenuated by $\exp[-(L/E)\cdot(m_i/\tau_i)]$

… but ν that travel longer L are more attenuated!



Astrophysical sources

Earth

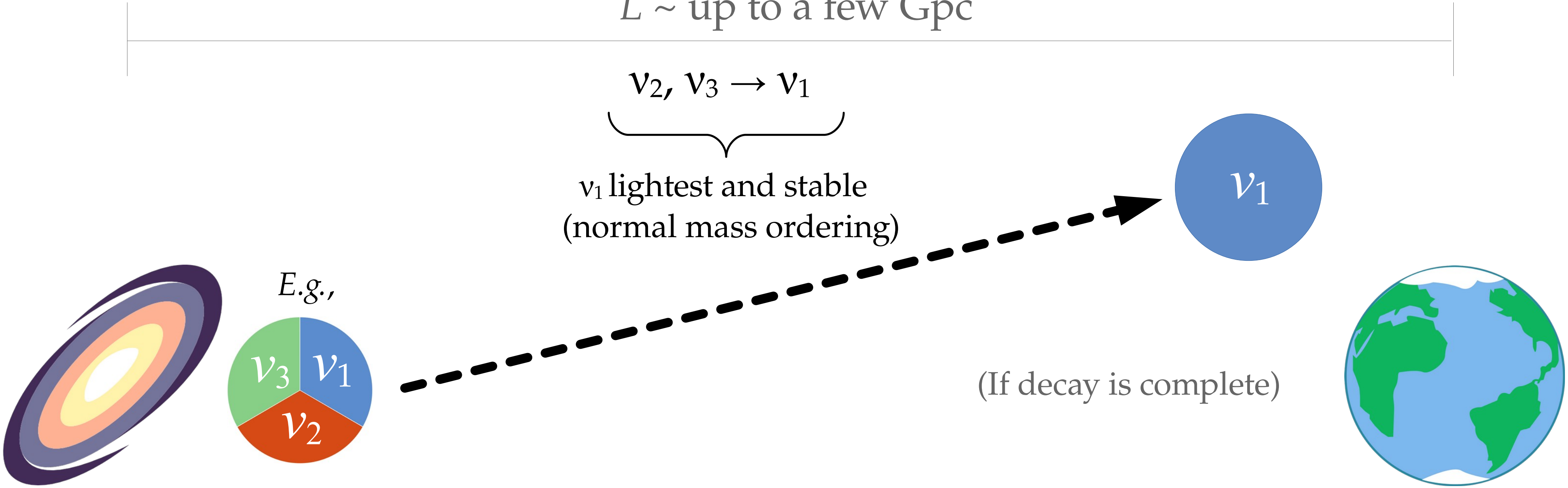
$L \sim$ up to a few Gpc

E.g.,

Astrophysical sources

Earth

L ~ up to a few Gpc

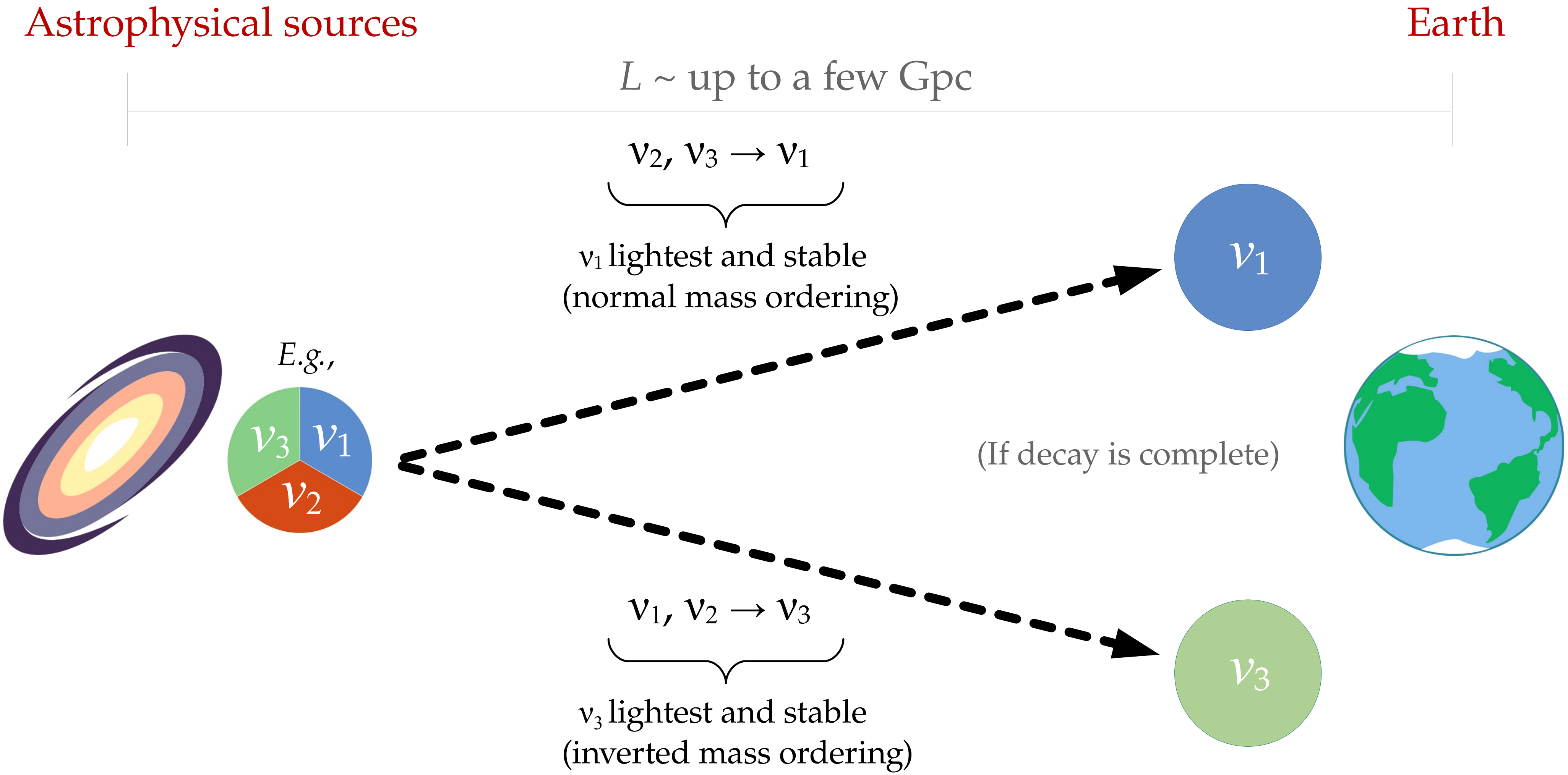


$$\underbrace{\nu_2, \nu_3 \rightarrow \nu_1}$$

ν_1 lightest and stable
(normal mass ordering)

E.g.,

(If decay is complete)


Astrophysical sources
Earth
L ~ up to a few Gpc
$\nu_2, \nu_3 \to \nu_1$
ν_1 lightest and stable
(normal mass ordering)
E.g.,
ν_3
ν_1
ν_2
ν_1
(If decay is complete)
$\nu_1, \nu_2 \to \nu_3$
ν_3 lightest and stable
(inverted mass ordering)
ν_3

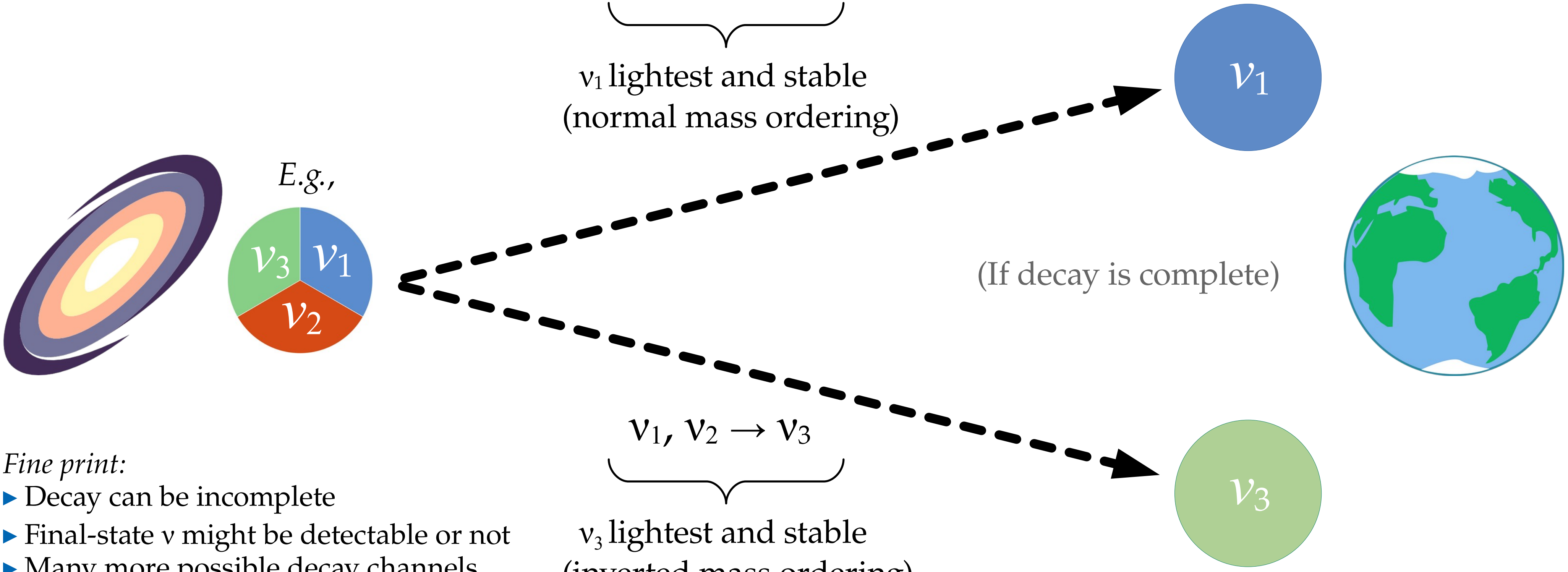
Astrophysical sources

Earth

$L \sim$ up to a few Gpc

$\underbrace{\nu_2, \nu_3 \to \nu_1}$

ν_1 lightest and stable
(normal mass ordering)



E.g.,

(If decay is complete)

$\underbrace{\nu_1, \nu_2 \to \nu_3}$

ν_3 lightest and stable
(inverted mass ordering)

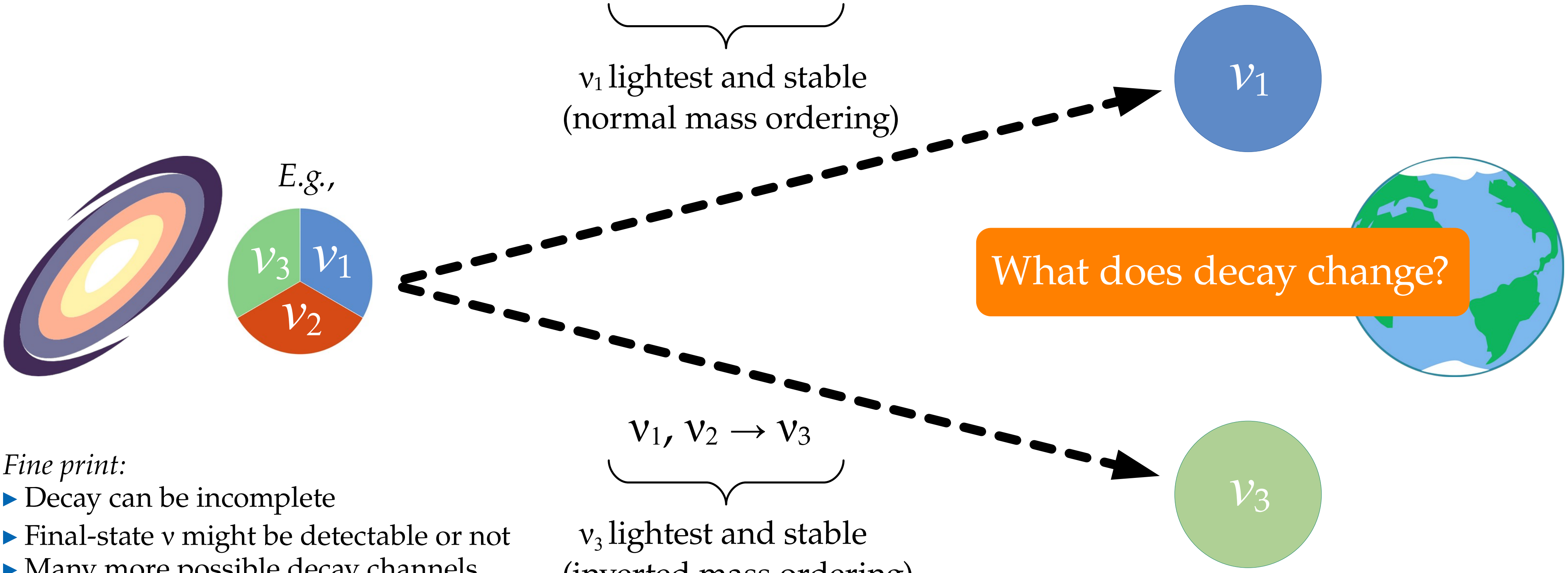
Fine print:

- Decay can be incomplete
- Final-state ν might be detectable or not
- Many more possible decay channels (see Winter & Mehta, *JCAP* 2011)

Astrophysical sources

Earth

L ~ up to a few Gpc



$$\underbrace{\nu_2, \nu_3 \rightarrow \nu_1}$$

ν_1 lightest and stable
(normal mass ordering)

What does decay change?

$$\underbrace{\nu_1, \nu_2 \rightarrow \nu_3}$$

ν_3 lightest and stable
(inverted mass ordering)

Fine print:

- Decay can be incomplete
- Final-state ν might be detectable or not
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What does neutrino decay change?

Flavor composition ⟺ Spectrum shape ⟺ Event rate

What does neutrino decay change?

Flavor composition ⟺ Spectrum shape ⟺ Event rate

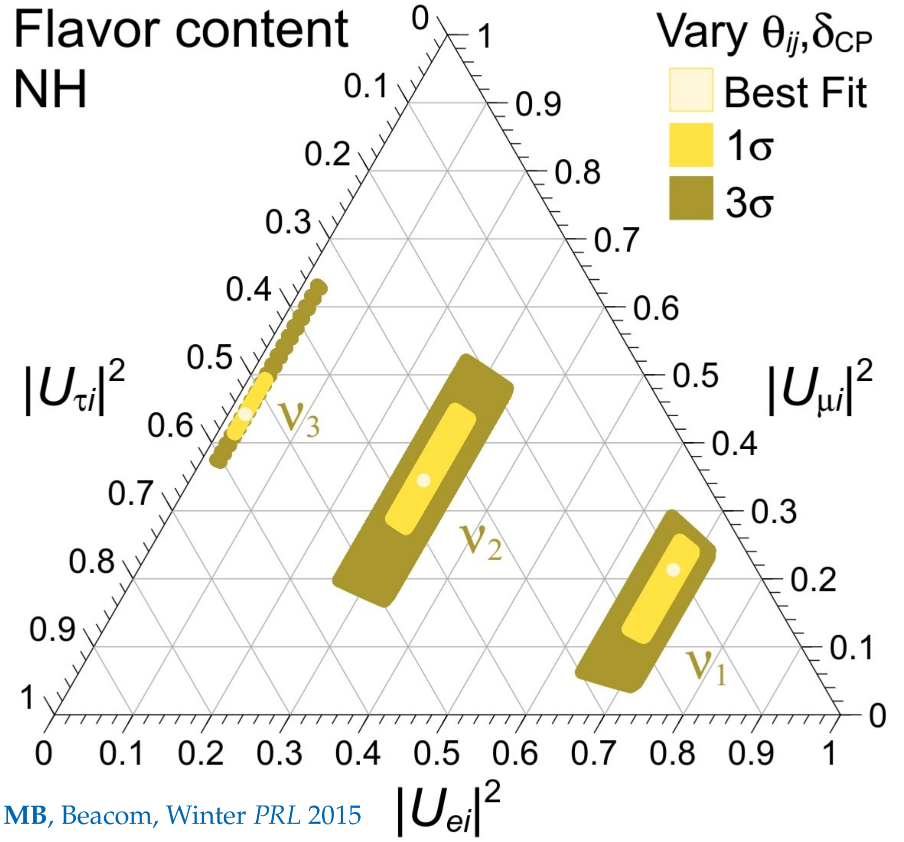
Flavor content of mass eigenstates:

Known to within 2%

$$|U_{\alpha i}|^2 = |U_{\alpha i}(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP})|^2$$

Known to within 8%

Known to within 20%
(or worse)



MB, Beacom, Winter *PRL* 2015

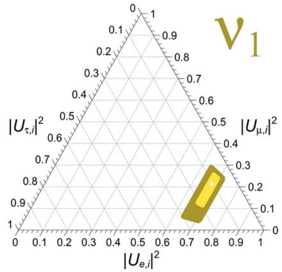
What does neutrino decay change?

Flavor composition ⟺ Spectrum shape ⟺ Event rate

E.g.,

$$\underbrace{\nu_2,\, \nu_3 \rightarrow \nu_1}$$

ν_1 lightest and stable
(normal mass ordering)



$$\underbrace{\nu_1,\, \nu_2 \rightarrow \nu_3}$$

ν_3 lightest and stable
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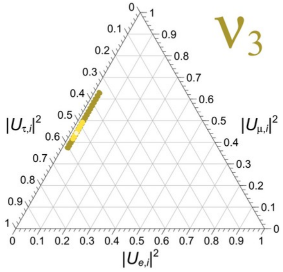


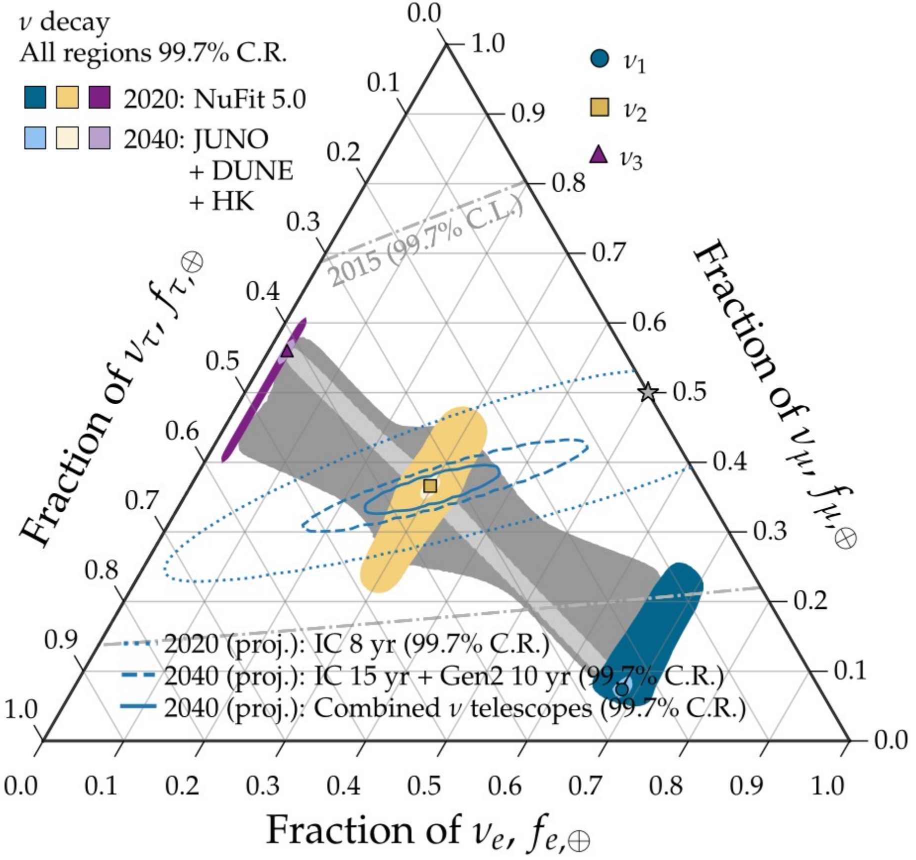
What does neutrino decay change?

See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / **MB**, 2004.06844

Flavor composition

Spectrum shape

Event rate



What does neutrino decay change?

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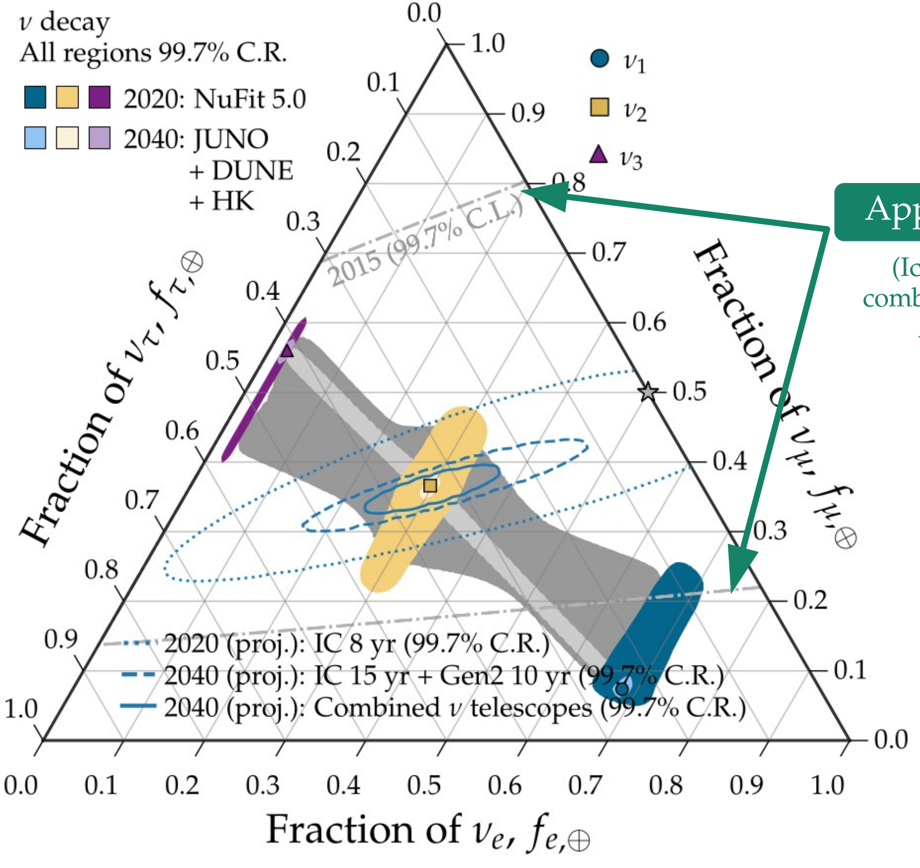
Flavor composition ⇔ Spectrum shape ⇔ Event rate



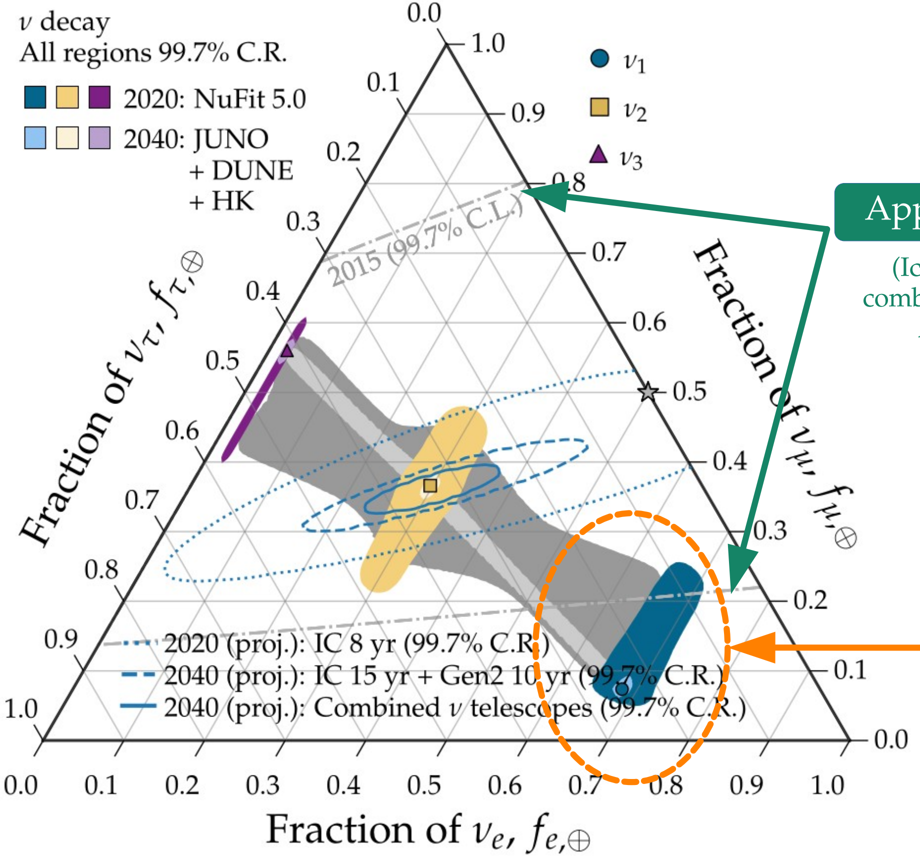
Approx. today

(IceCube 2015 combined analysis, *ApJ* 2015)

What does neutrino decay change?

See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / **MB**, 2004.06844

Flavor composition ⇔ Spectrum shape ⇔ Event rate



Approx. today

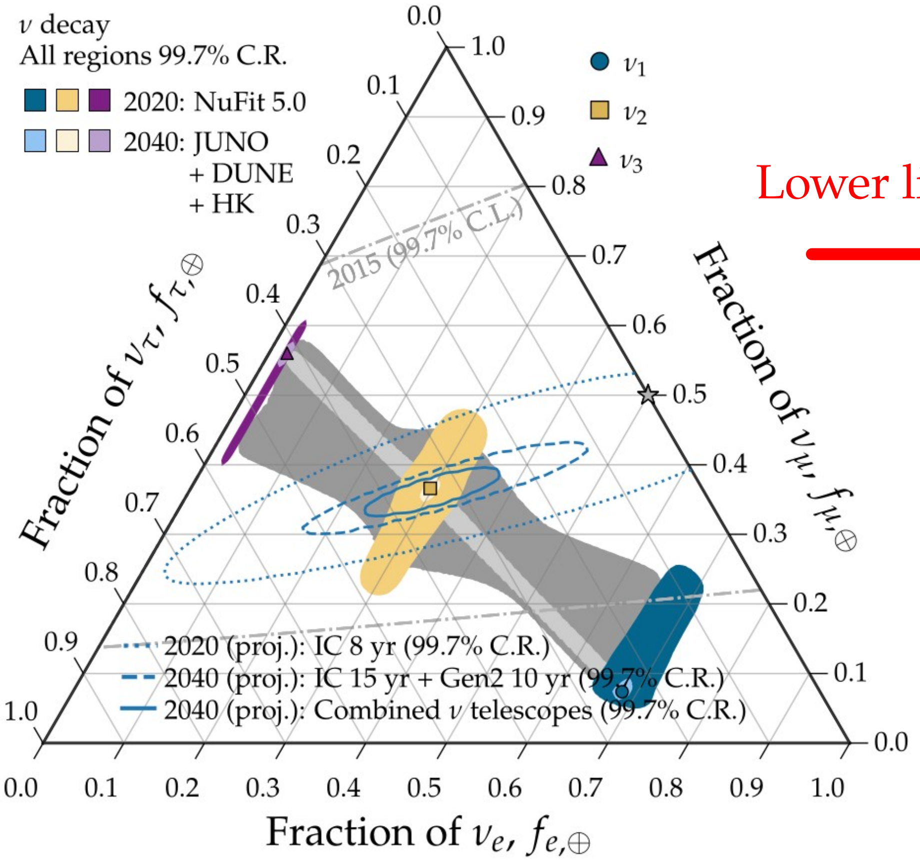
(IceCube 2015 combined analysis, *ApJ* 2015)

Complete decay into ν_1 disfavored by 2015 IceCube flavor measurement

What does neutrino decay change?

See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / **MB**, 2004.06844

Flavor composition ⇔ Spectrum shape ⇔ Event rate

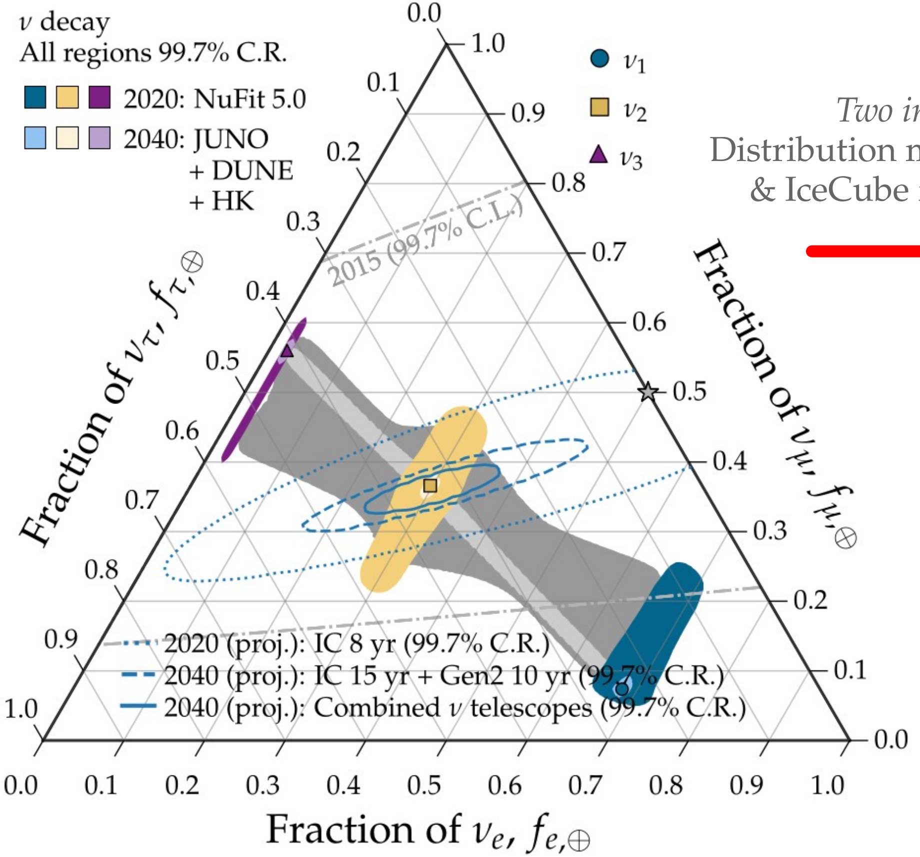


Lower limit on τ/m →

What does neutrino decay change?

See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / **MB**, 2004.06844

Flavor composition ⟺ Spectrum shape ⟺ Event rate

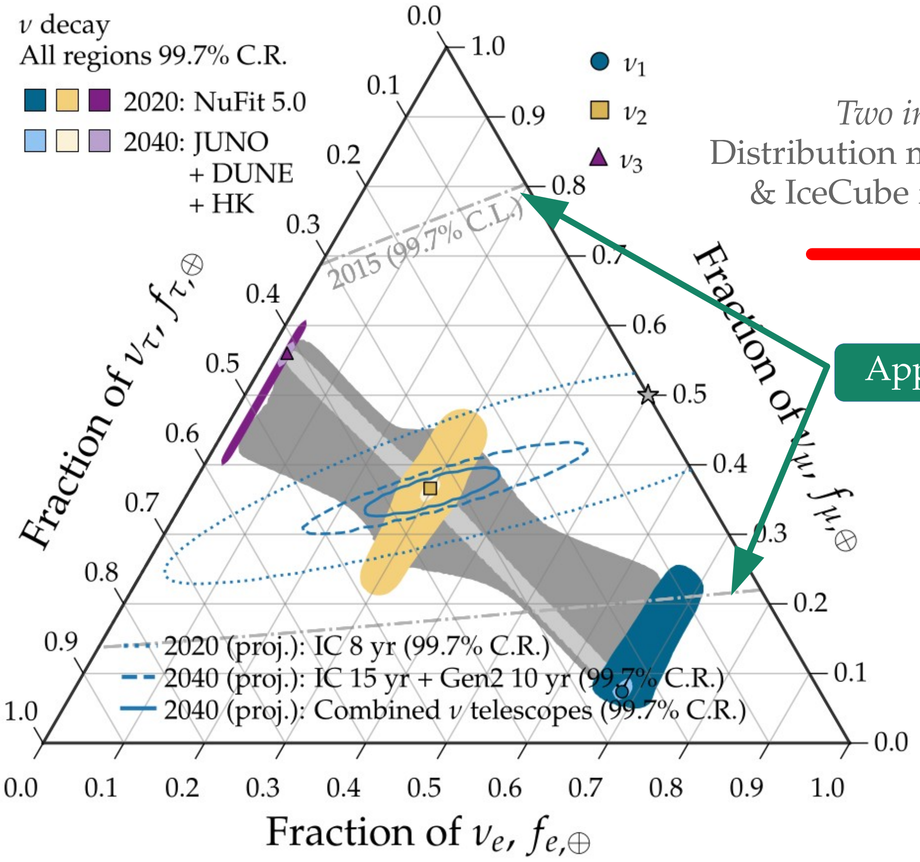


Two ingredients:
Distribution mixing parameters
& IceCube flavor posterior

What does neutrino decay change?

See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / **MB**, 2004.06844

Flavor composition ⇔ Spectrum shape ⇔ Event rate



Two ingredients:
Distribution mixing parameters
& IceCube flavor posterior

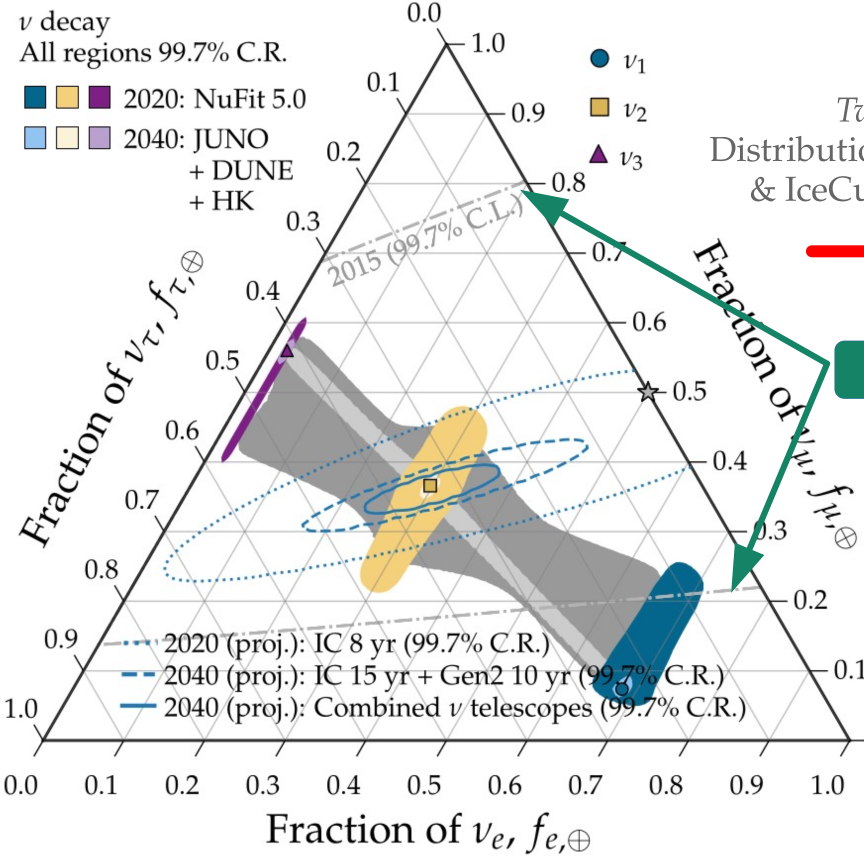
→

Approx. today

What does neutrino decay change?

See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / **MB**, 2004.06844

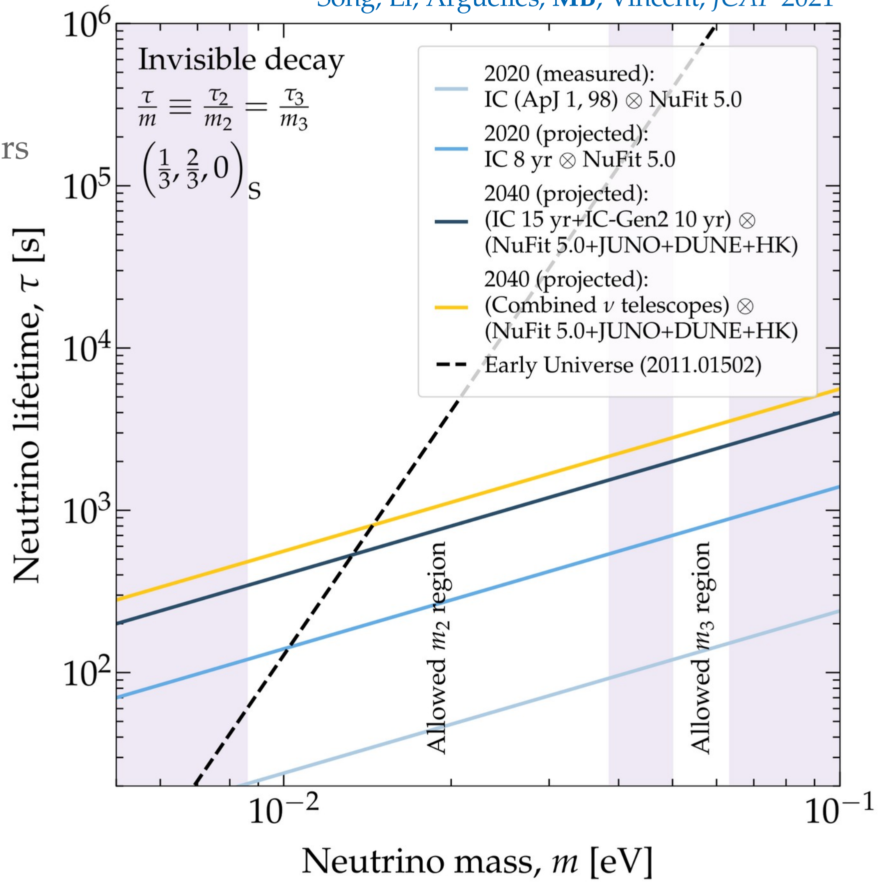
Flavor composition ⇔ Spectrum shape ⇔ Event rate



Approx. today

Two ingredients:
Distribution mixing parameters
& IceCube flavor posterior

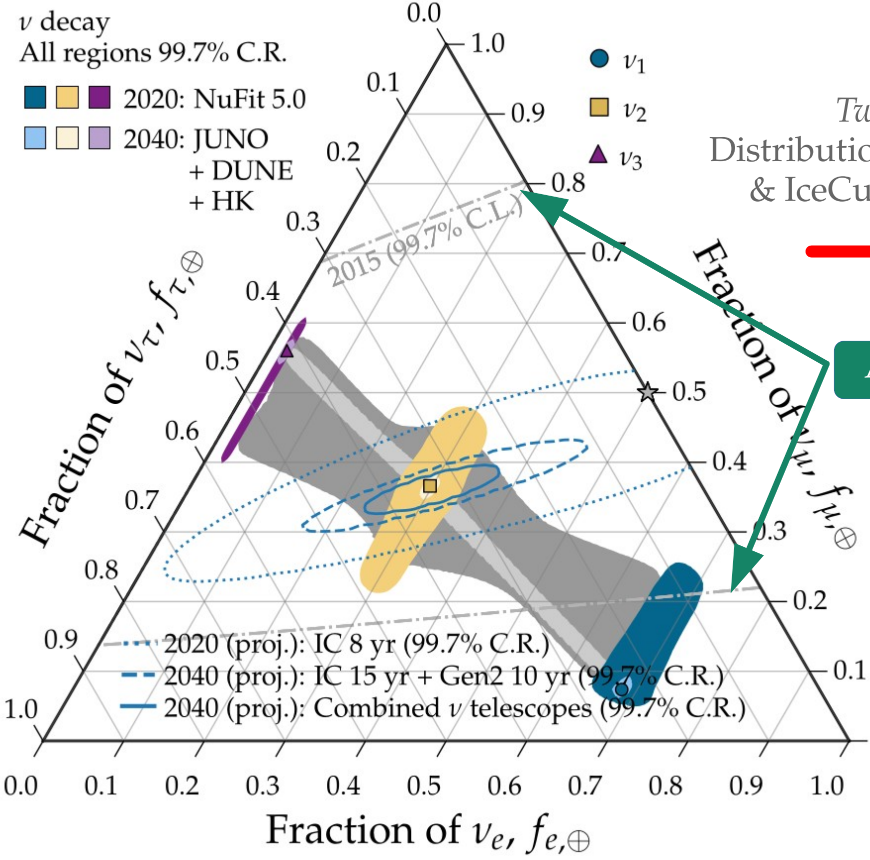
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



What does neutrino decay change?

See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / **MB**, 2004.06844

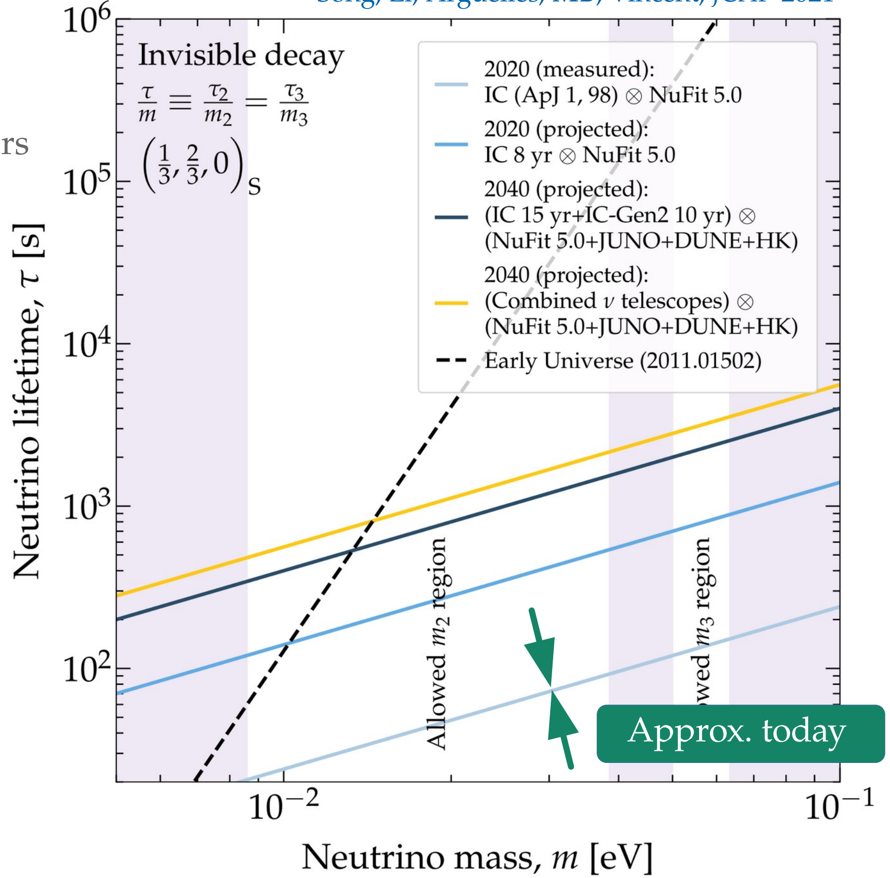
Flavor composition ⟺ Spectrum shape ⟺ Event rate



Two ingredients:
Distribution mixing parameters & IceCube flavor posterior

Approx. today

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

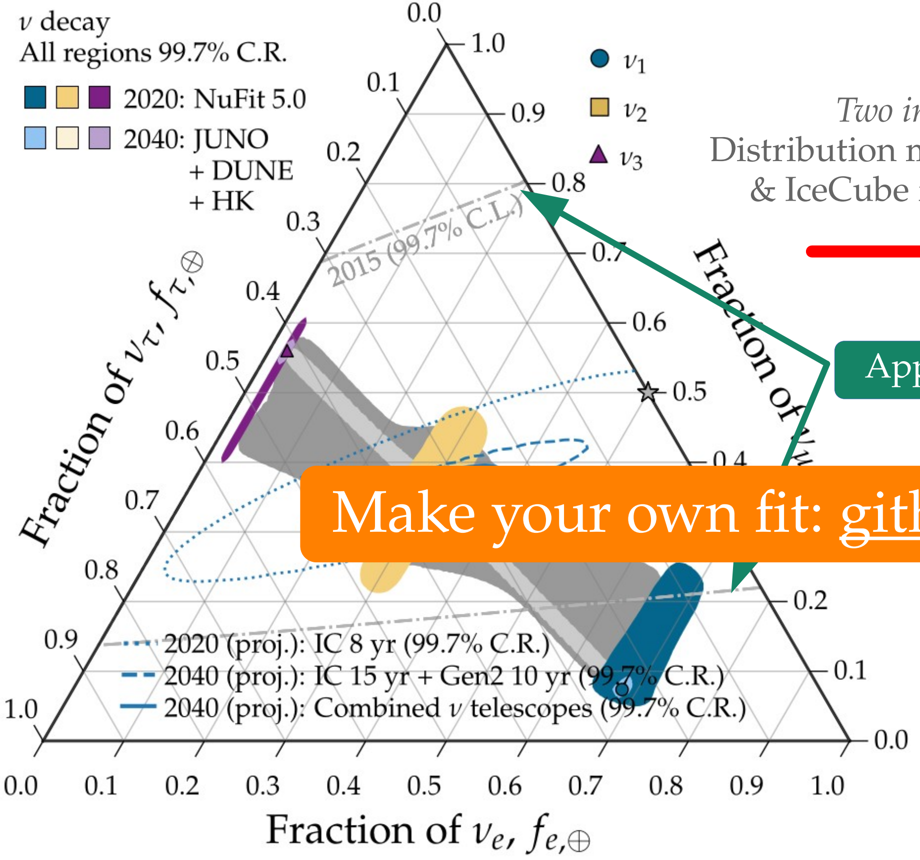


Approx. today

What does neutrino decay change?

See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / **MB**, 2004.06844

Flavor composition ⇔ Spectrum shape ⇔ Event rate



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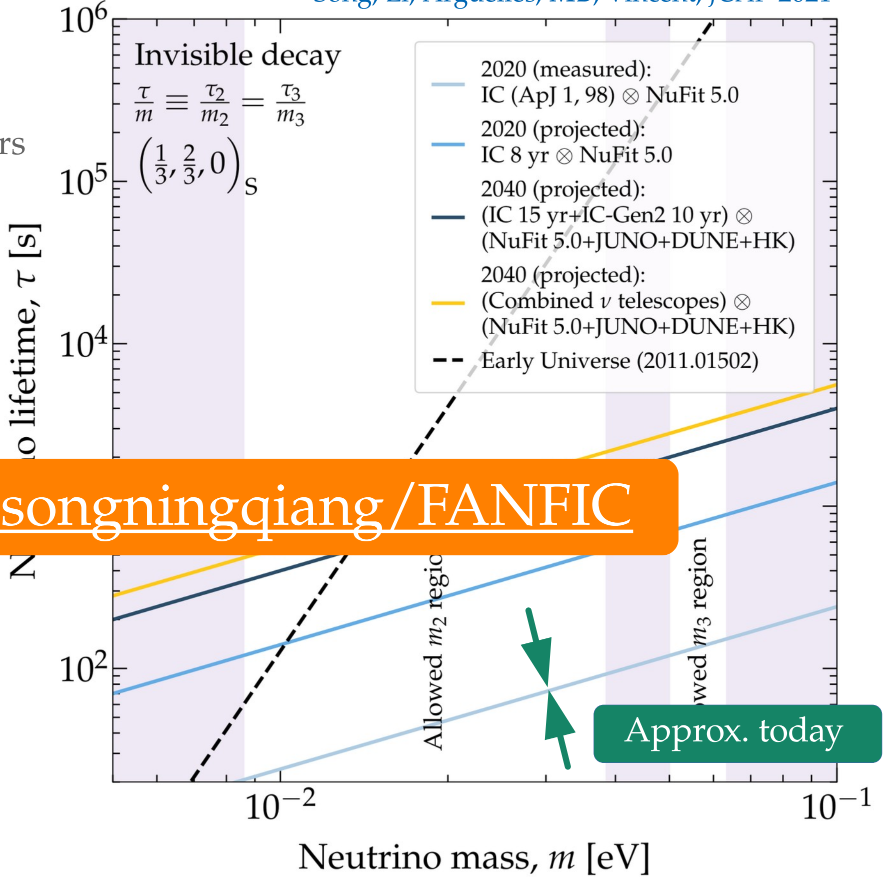
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

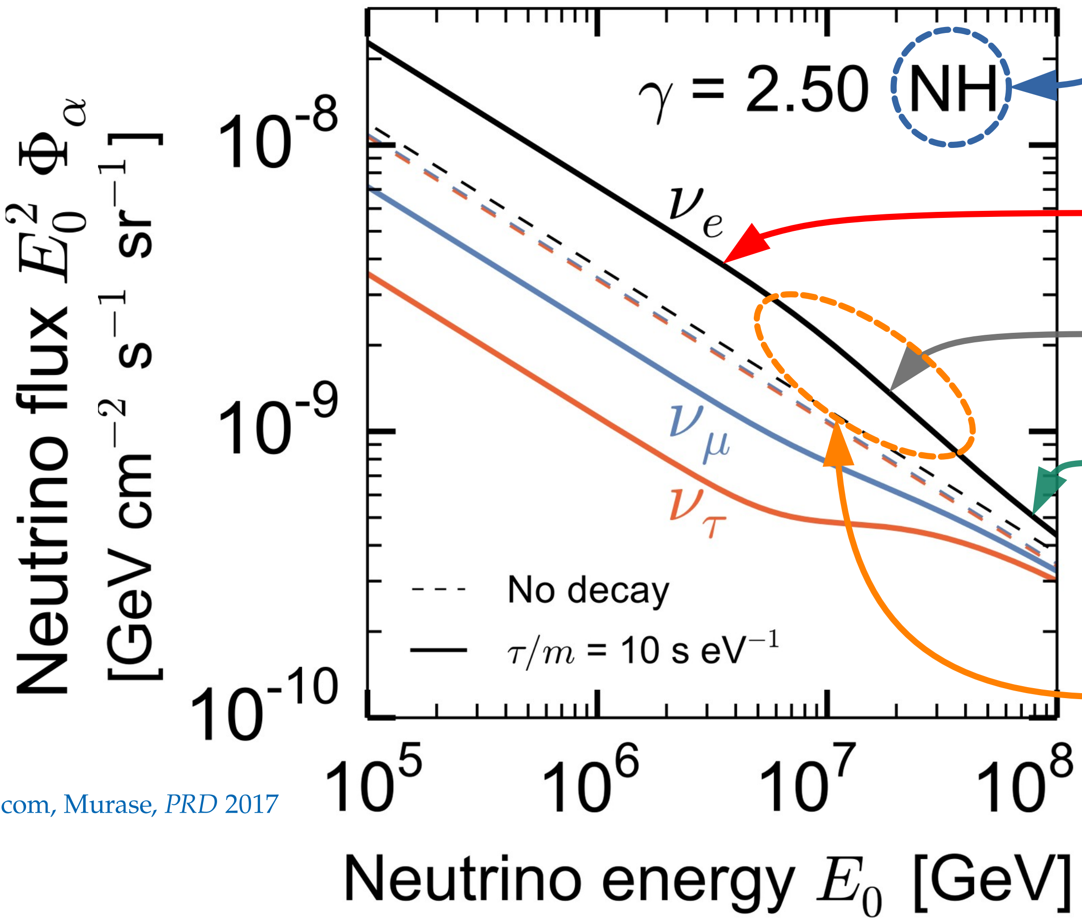


Make your own fit: github.com/songningqiang/FANFIC

What does neutrino decay change?

See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / **MB**, 2004.06844 / Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2020

Flavor composition ⇔ Spectrum shape ⇔ Event rate



$\nu_2, \nu_3 \to \nu_1$

Low energy: decay evident

Transition region

High energy: no decay

Look for sigmoid-like transition in spectrum: *challenging, but possible with more statistics!*

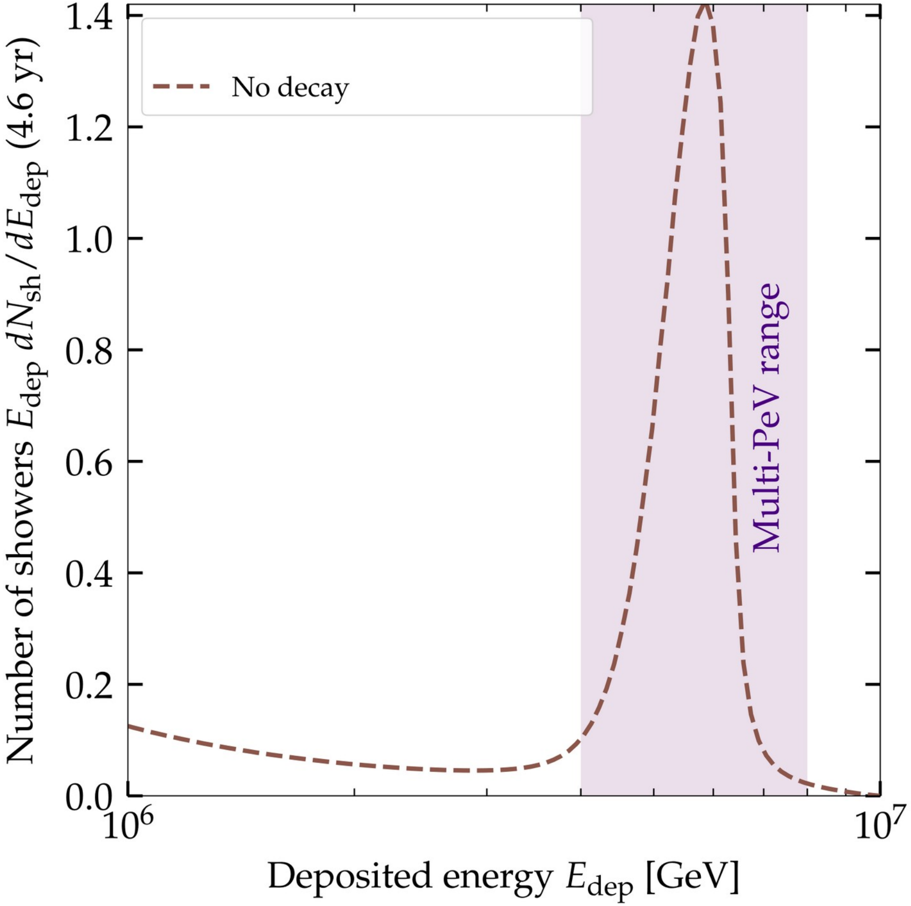
MB, Beacom, Murase, *PRD* 2017

What does neutrino decay change?

See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017/ Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2020

Flavor composition ⟺ Spectrum shape ⟺ Event rate

MB, 2004.06844

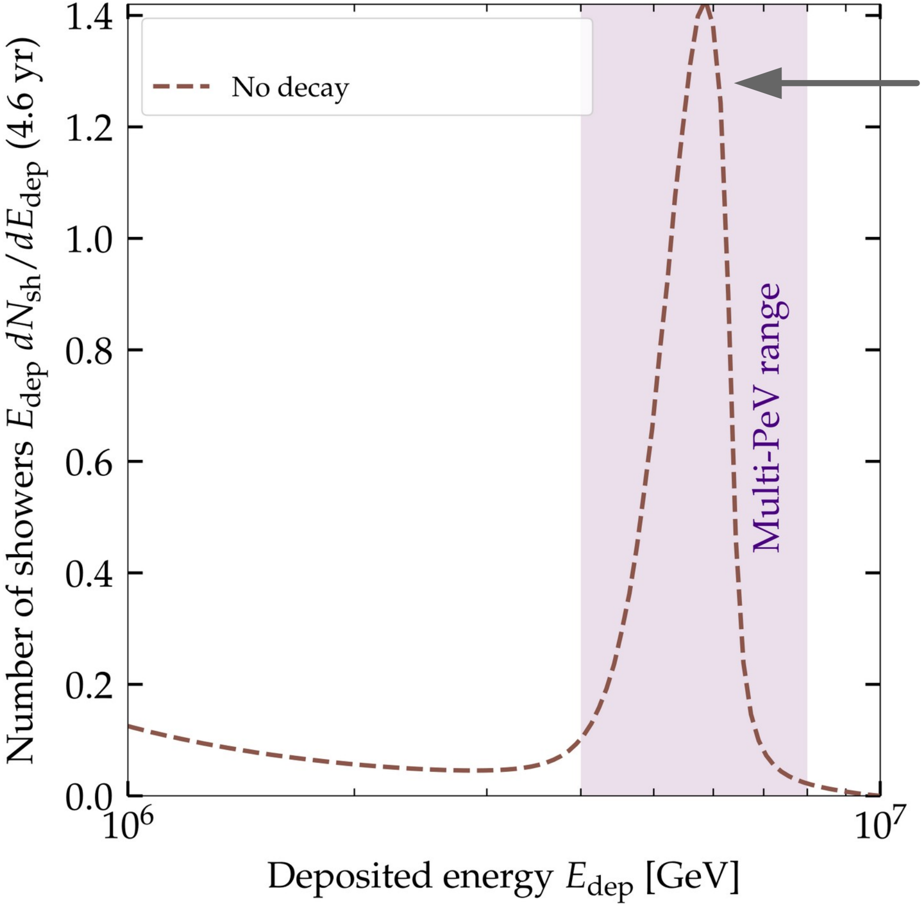


What does neutrino decay change?

See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017/ Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2020

Flavor composition ⟺ Spectrum shape ⟺ Event rate

MB, 2004.06844



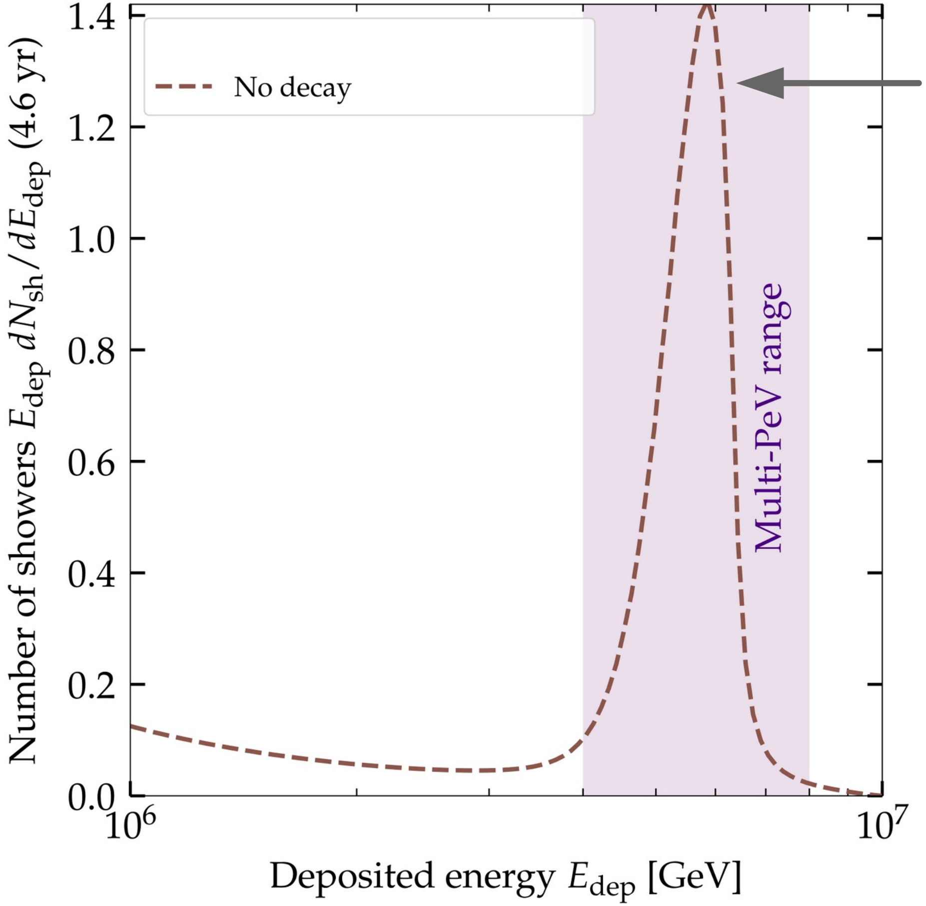
Glashow resonance (GR):
$\bar{\nu}_e + e \rightarrow W \rightarrow$ hadrons $\rightarrow$ shower

What does neutrino decay change?

See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017/ Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2020

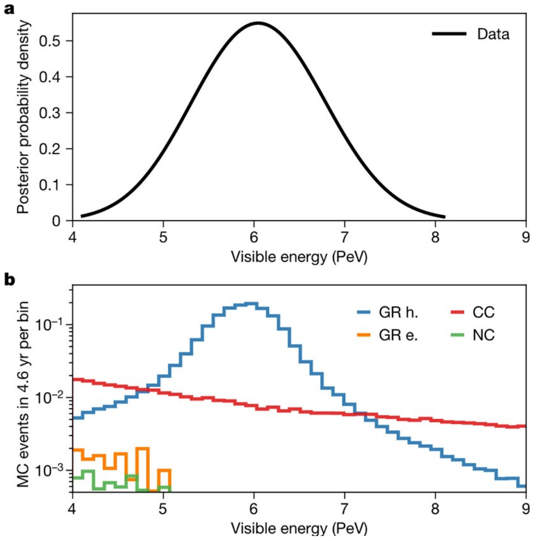
Flavor composition ⟺ Spectrum shape ⟺ Event rate

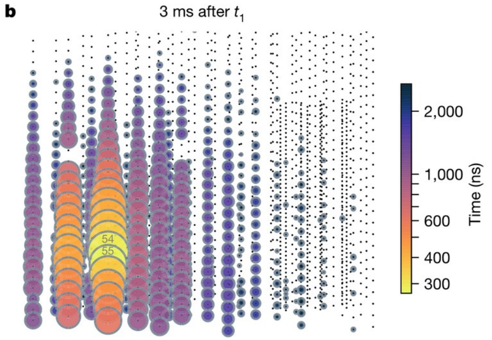
MB, 2004.06844



Glashow resonance (GR):
$\bar{\nu}_e + e \to W \to$ hadrons $\to$ shower

IceCube has seen one GR candidate in 4.6 years:





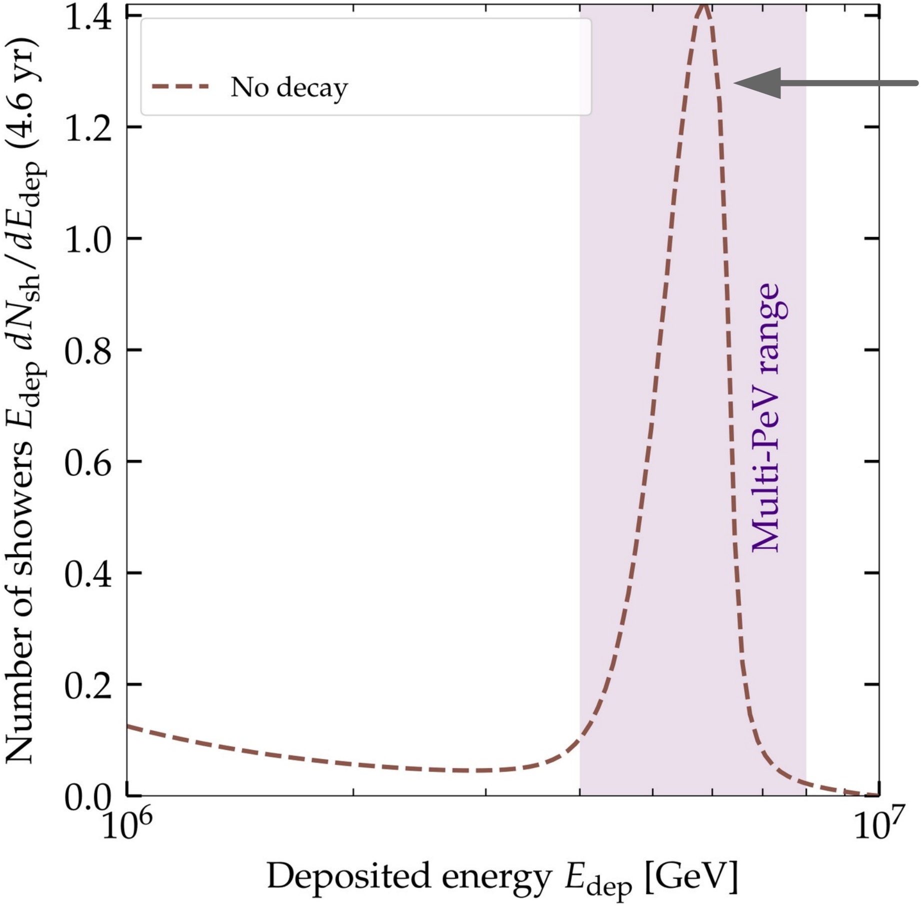
IceCube Collab., *Nature* 2021

What does neutrino decay change?

See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017/ Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2020

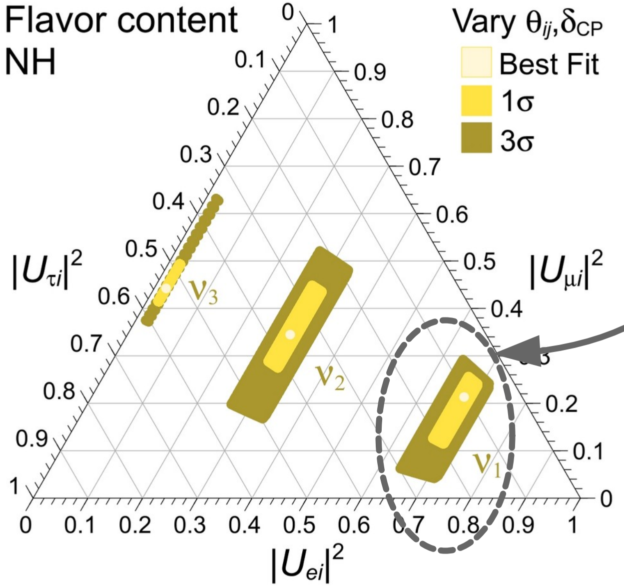
Flavor composition ↔ Spectrum shape ↔ Event rate

MB, 2004.06844



Glashow resonance (GR):
$\bar{\nu}_e + e \rightarrow W \rightarrow$ hadrons $\rightarrow$ shower

ν_1 is the mass eigenstate with the most e flavor

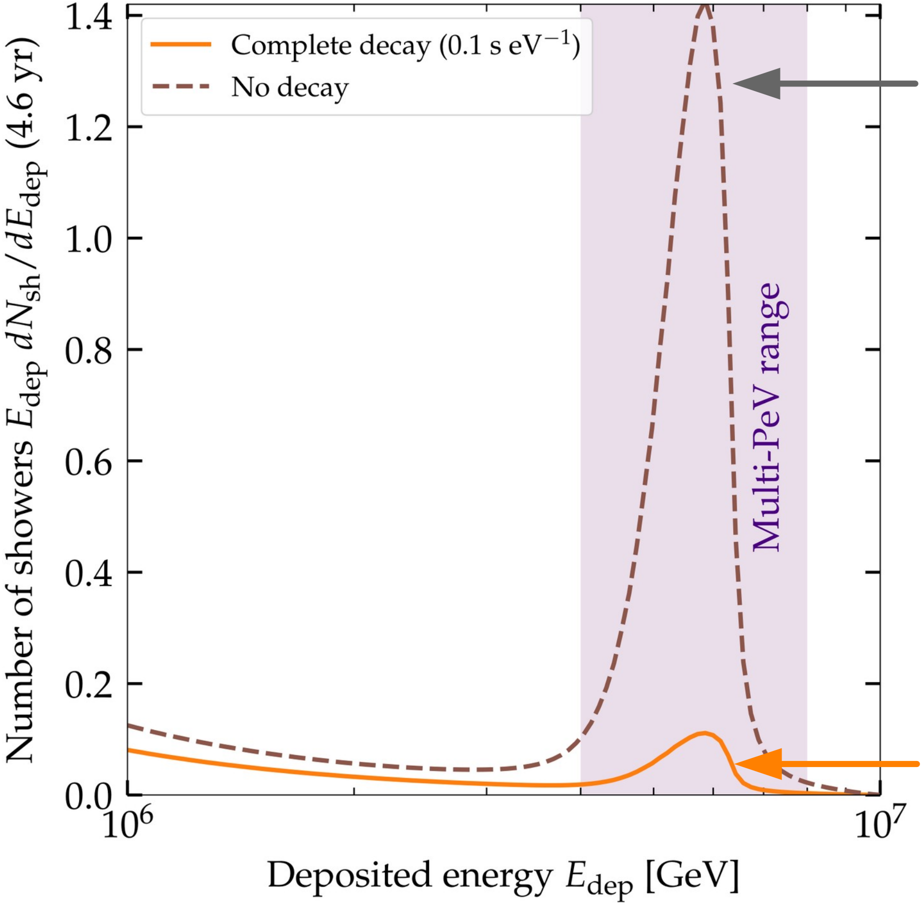


What does neutrino decay change?

See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017/ Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2020

Flavor composition ⟺ Spectrum shape ⟺ Event rate

MB, 2004.06844



Glashow resonance (GR):
$\bar{\nu}_e + e \to W \to$ hadrons $\to$ shower

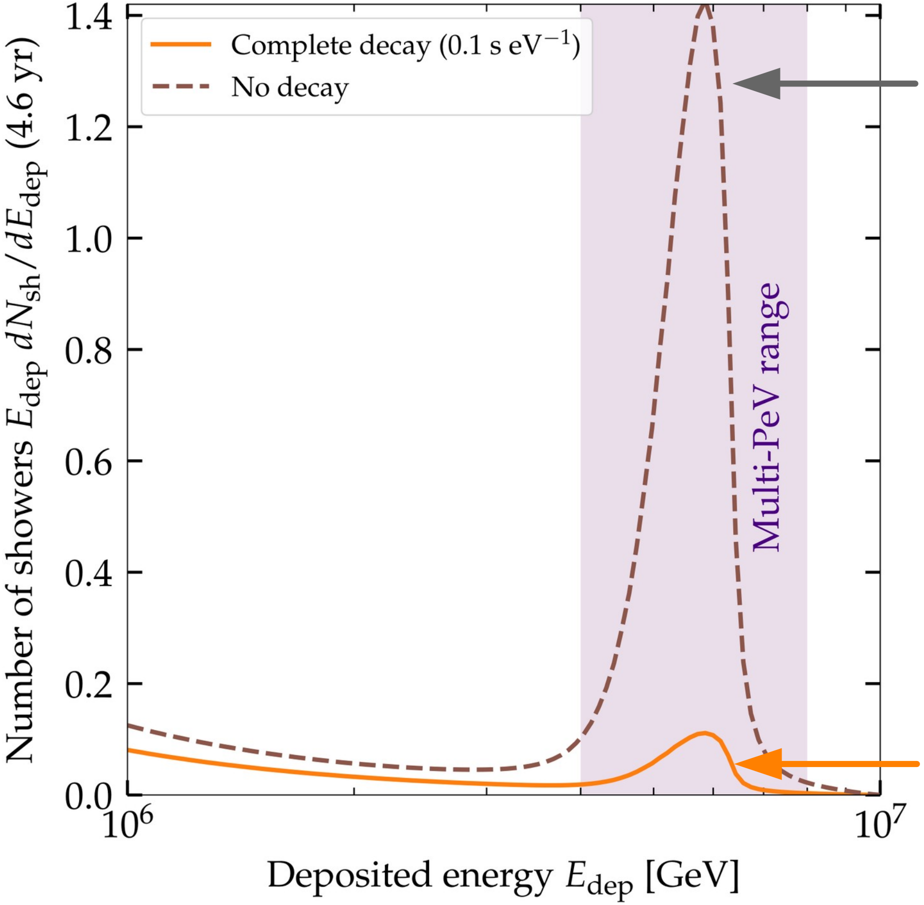
If $\bar{\nu}_1$ had decayed en route to Earth,
there would not have been $\bar{\nu}_e$ left to trigger a GR

What does neutrino decay change?

See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2020

Flavor composition ⟺ Spectrum shape ⟺ Event rate

MB, 2004.06844



Glashow resonance (GR):
$\bar{\nu}_e + e \rightarrow W \rightarrow$ hadrons $\rightarrow$ shower

So by having observed 1 GR event we can place a *lower* limit on the lifetime of $\bar{\nu}_1$ ($= \nu_1$)

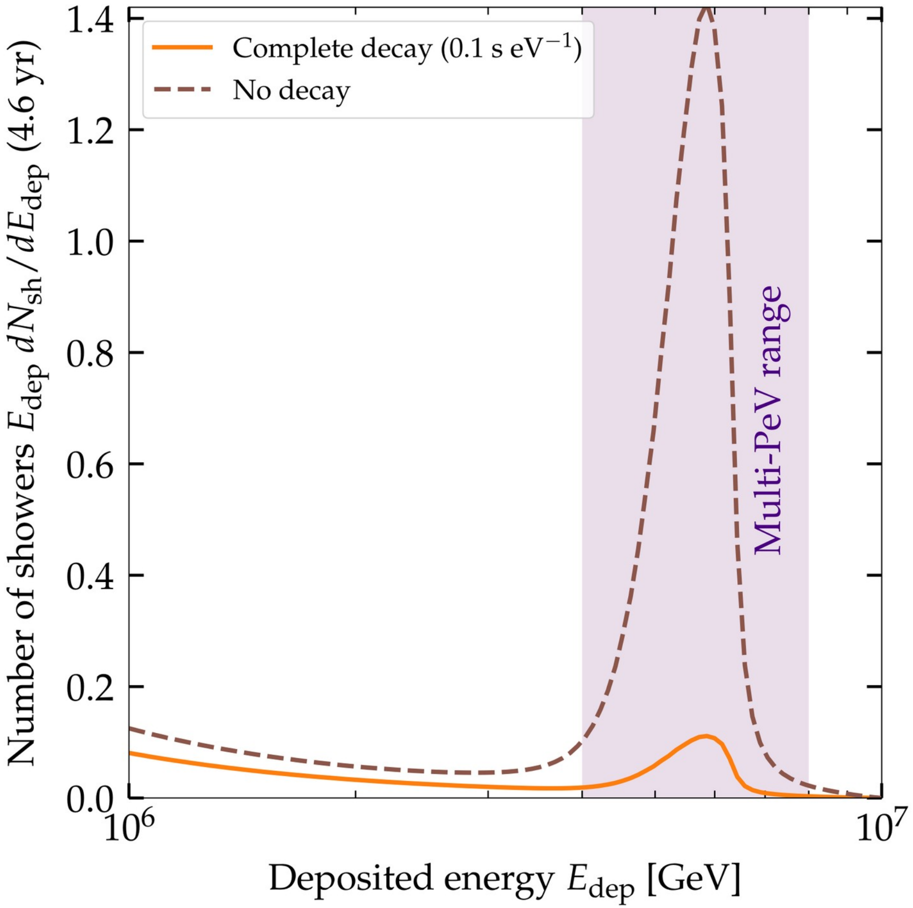
If $\bar{\nu}_1$ had decayed en route to Earth, there would not have been $\bar{\nu}_e$ left to trigger a GR

What does neutrino decay change?

See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017/ Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2020

Flavor composition ⟺ Spectrum shape ⟺ Event rate

MB, 2004.06844



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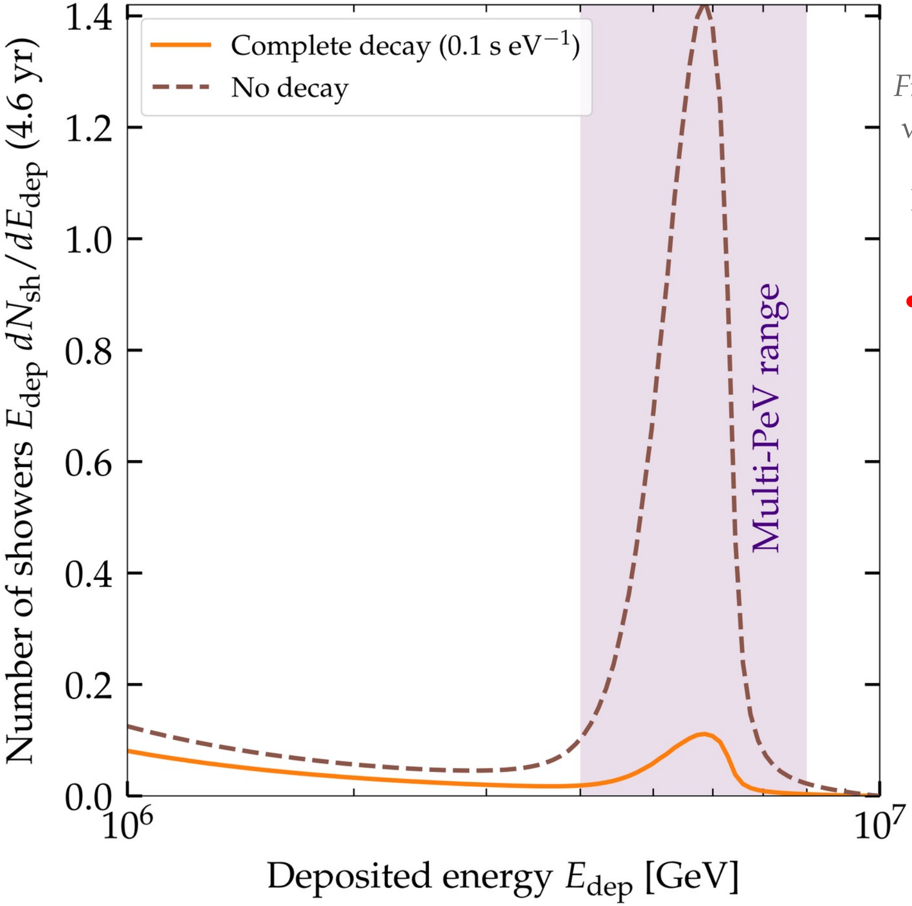
Flavor composition ⟺ Spectrum shape ⟺ Event rate

MB, 2004.06844



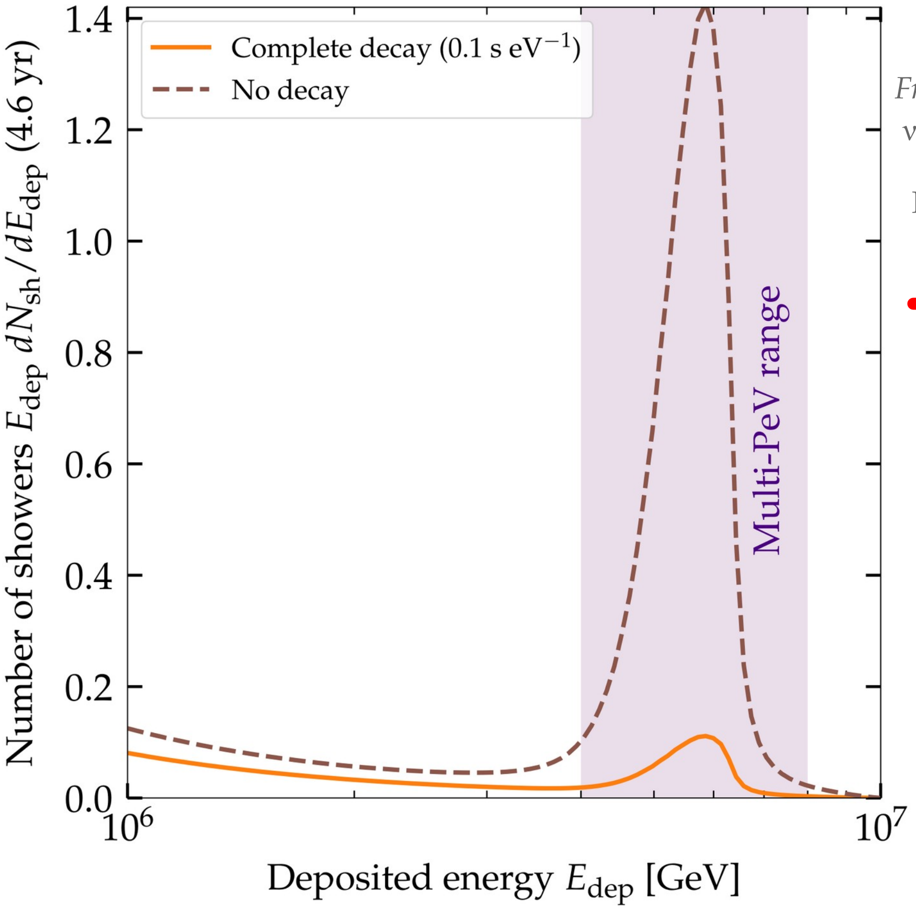
Free parameters:
ν_1, ν_2 lifetimes
Mix. par.
Flavor ratios
$\bar{\nu}/\nu$ ratio

→

What does neutrino decay change?

See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2020

Flavor composition ⟺ Spectrum shape ⟺ Event rate



Free parameters:

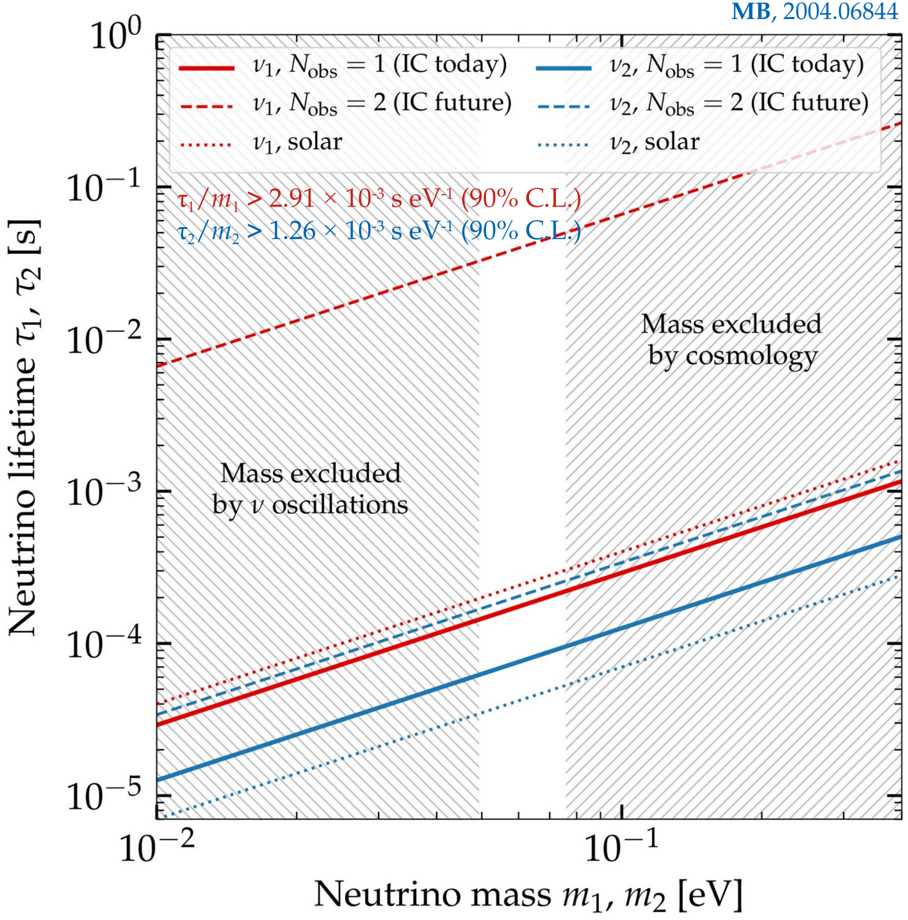
ν_1, ν_2 lifetimes

Mix. par.

Flavor ratios

$\bar{\nu}/\nu$ ratio

MB, 2004.06844



What does neutrino decay change?

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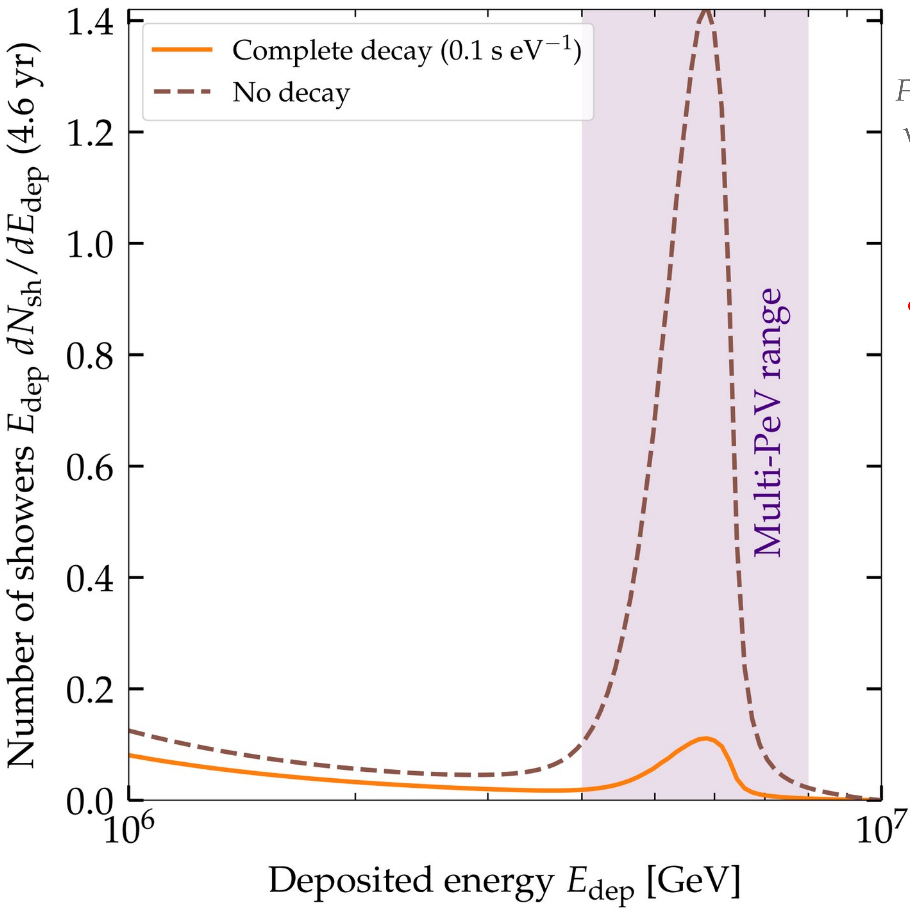
Flavor composition ⇔ Spectrum shape ⇔ Event rate



Free parameters:
ν_1, ν_2 lifetimes
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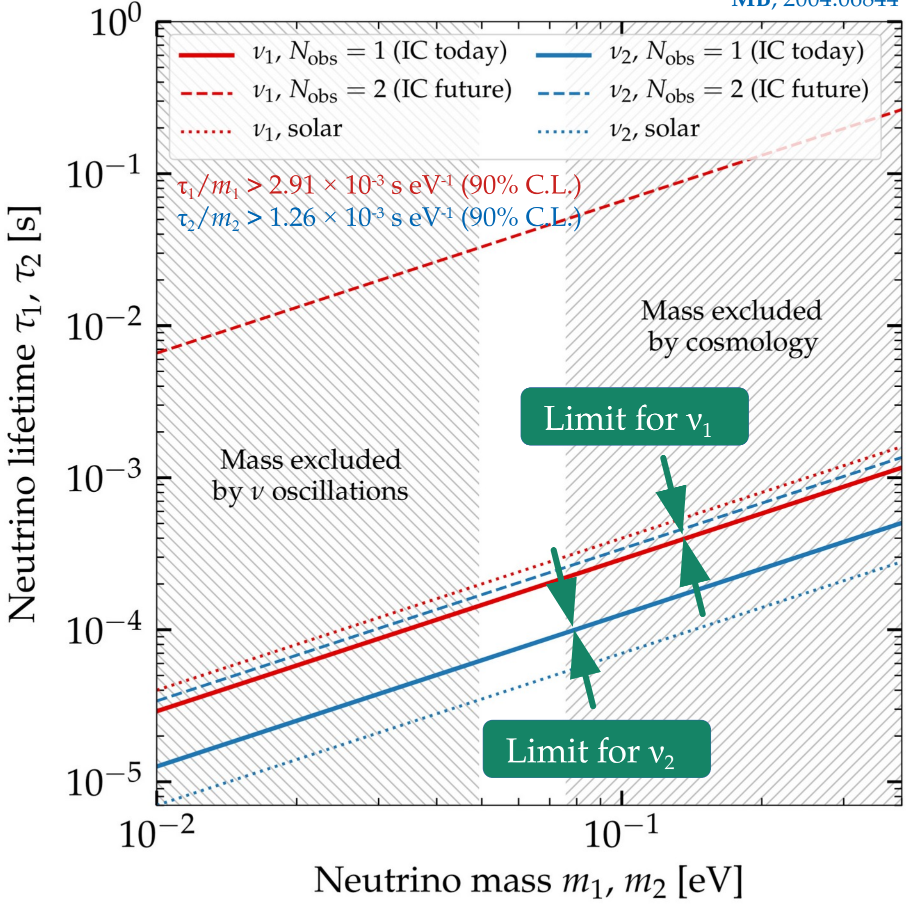
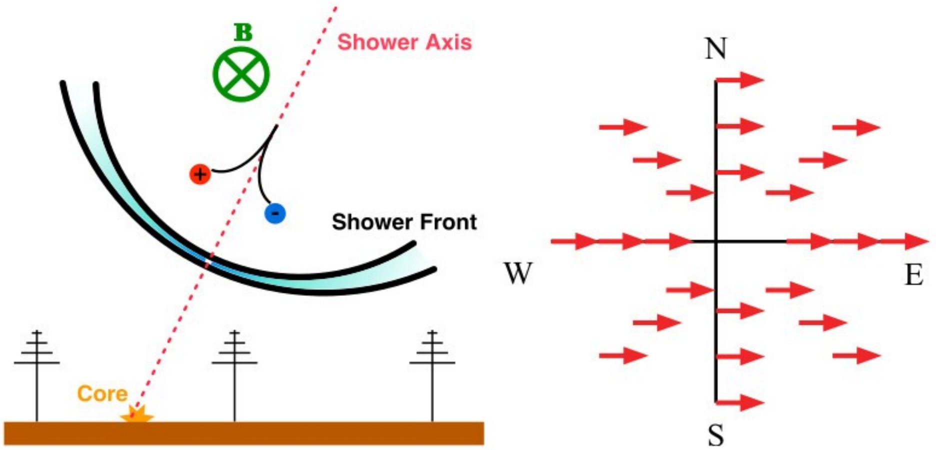


Neutrino radio-detection

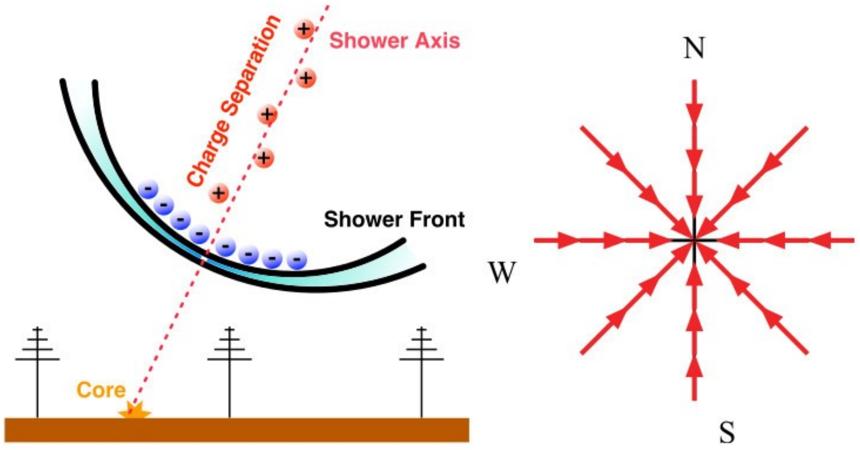
Radio emission: geomagnetic and Askaryan

Geomagnetic



- Time-varying transverse current
- Linearly polarized parallel to Lorentz force
- Dominant in air showers

Askaryan

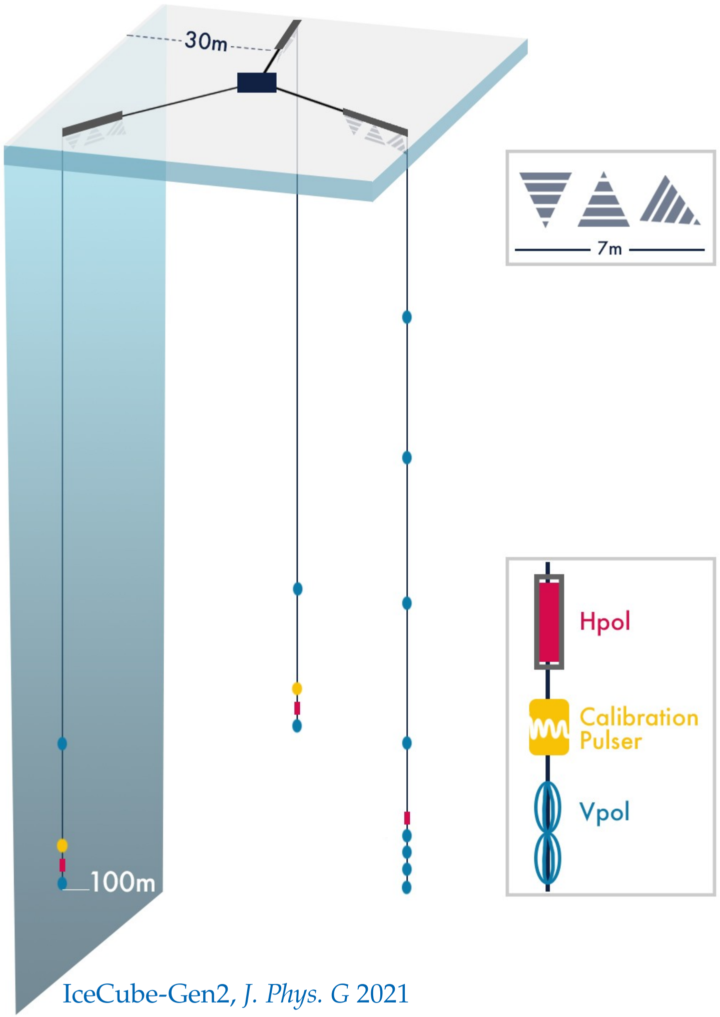


- Time-varying negative-charge ~20% excess
- Linearly polarized towards axis
- Sub-dominant in air showers

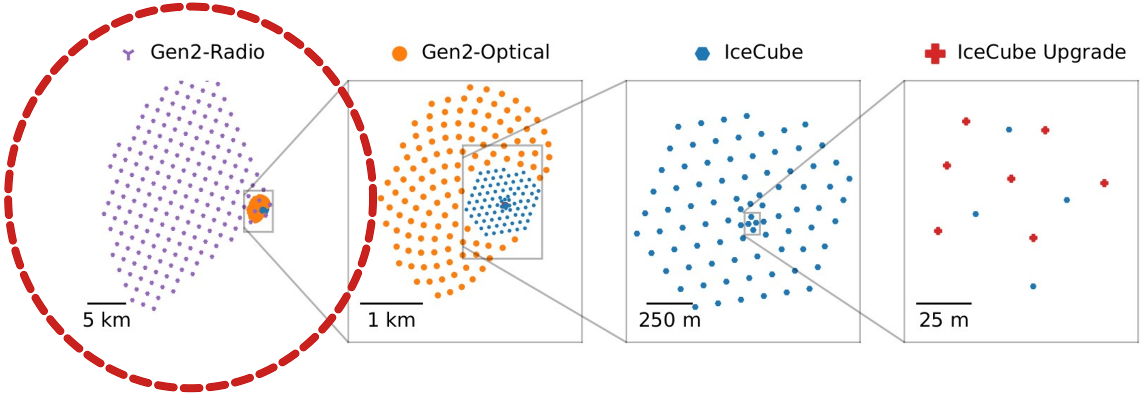
Figures by H. Schoorlemmer and K. D. de Vries

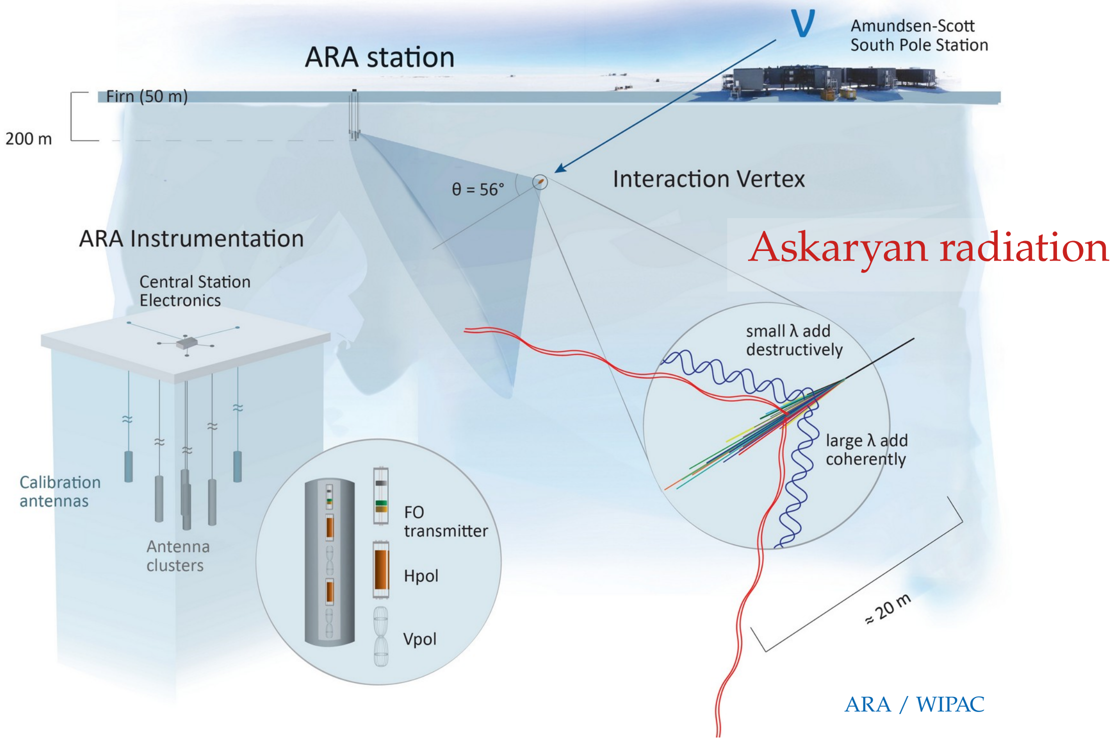
Radio emission: geomagnetic and Askaryan

IceCube-Gen2 Radio



IceCube-Gen2, *J. Phys. G* 2021

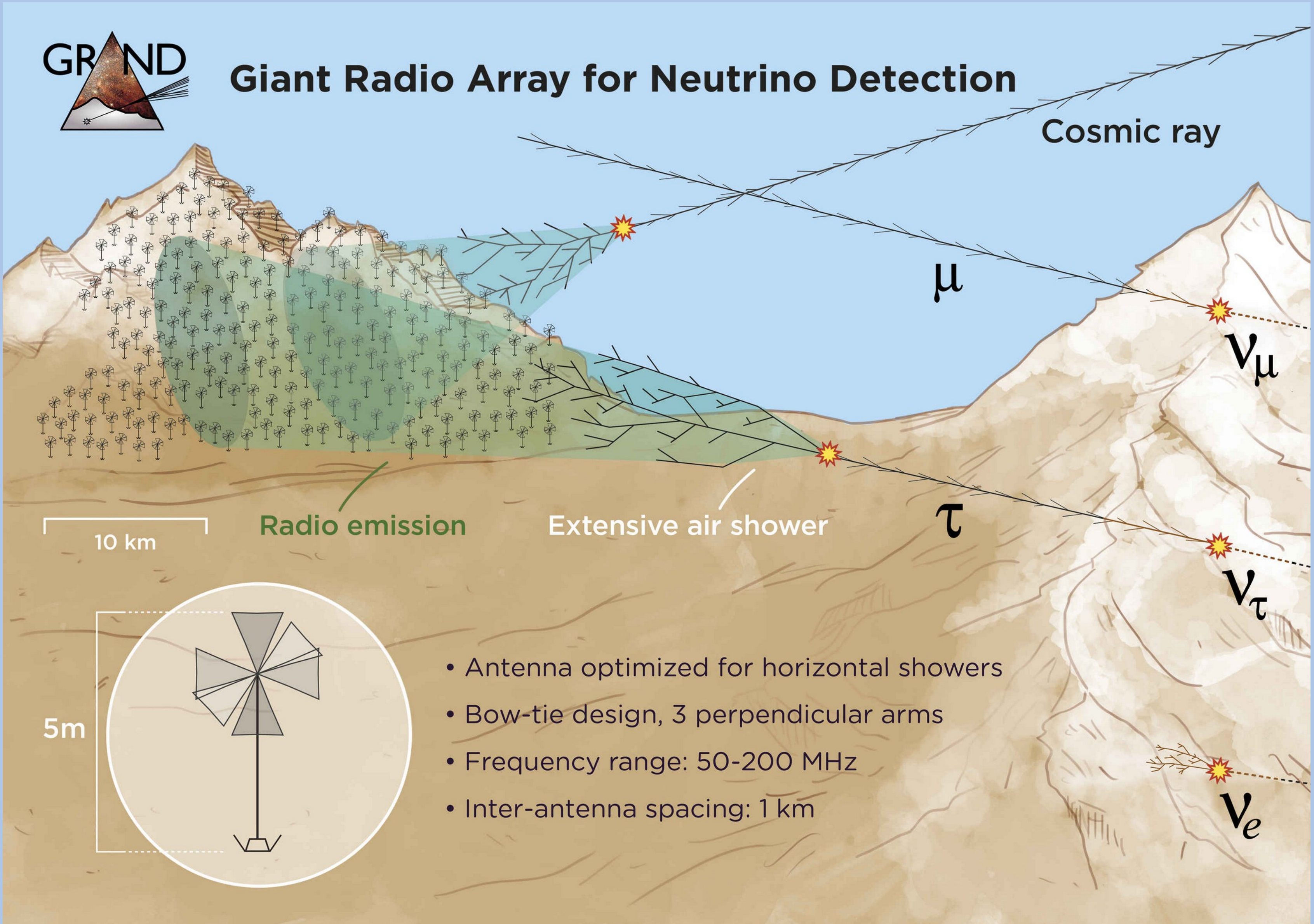




Askaryan radiation

ARA / WIPAC

Giant Radio Array for Neutrino Detection



- Antenna optimized for horizontal showers
- Bow-tie design, 3 perpendicular arms
- Frequency range: 50-200 MHz
- Inter-antenna spacing: 1 km