Astrophysics and particle physics with high-energy cosmic neutrinos *today and in the future*

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Niels Bohr Institute, University of Copenhagen

Michigan State Astronomy Seminar
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UNIVERSITY OF COPENHAGEN

VILLUM FONDEN

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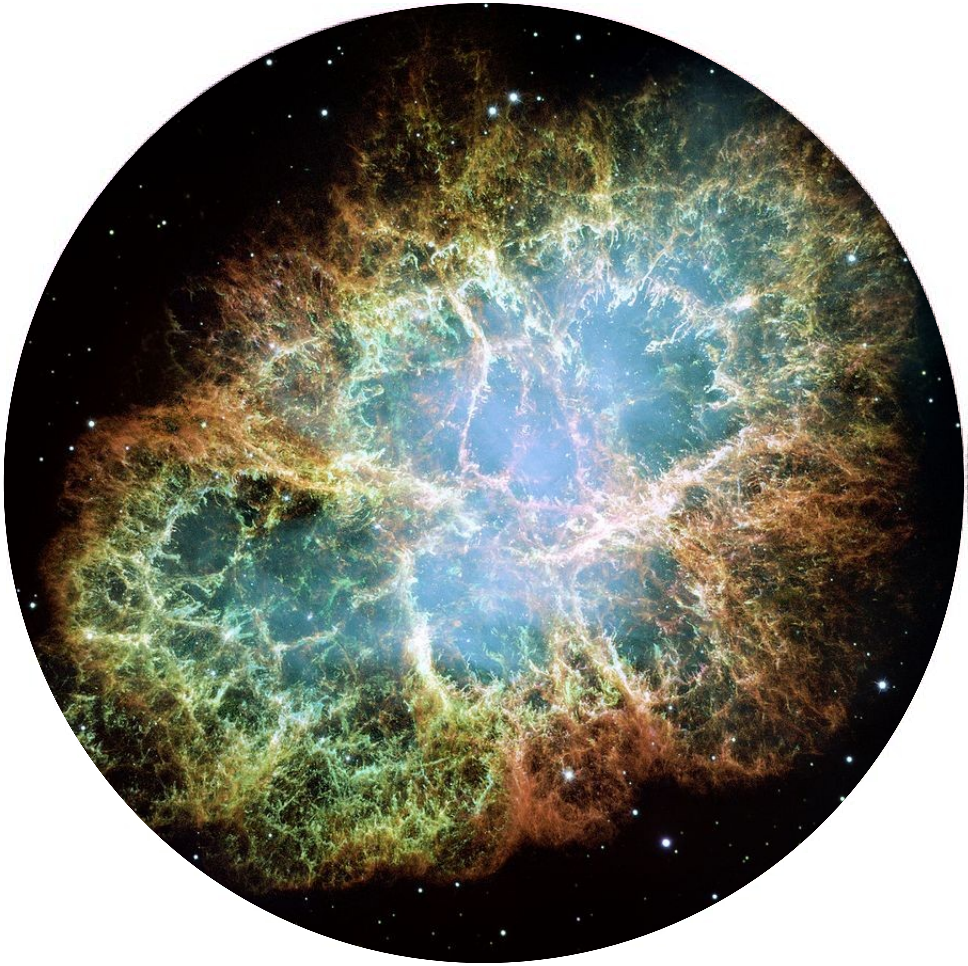

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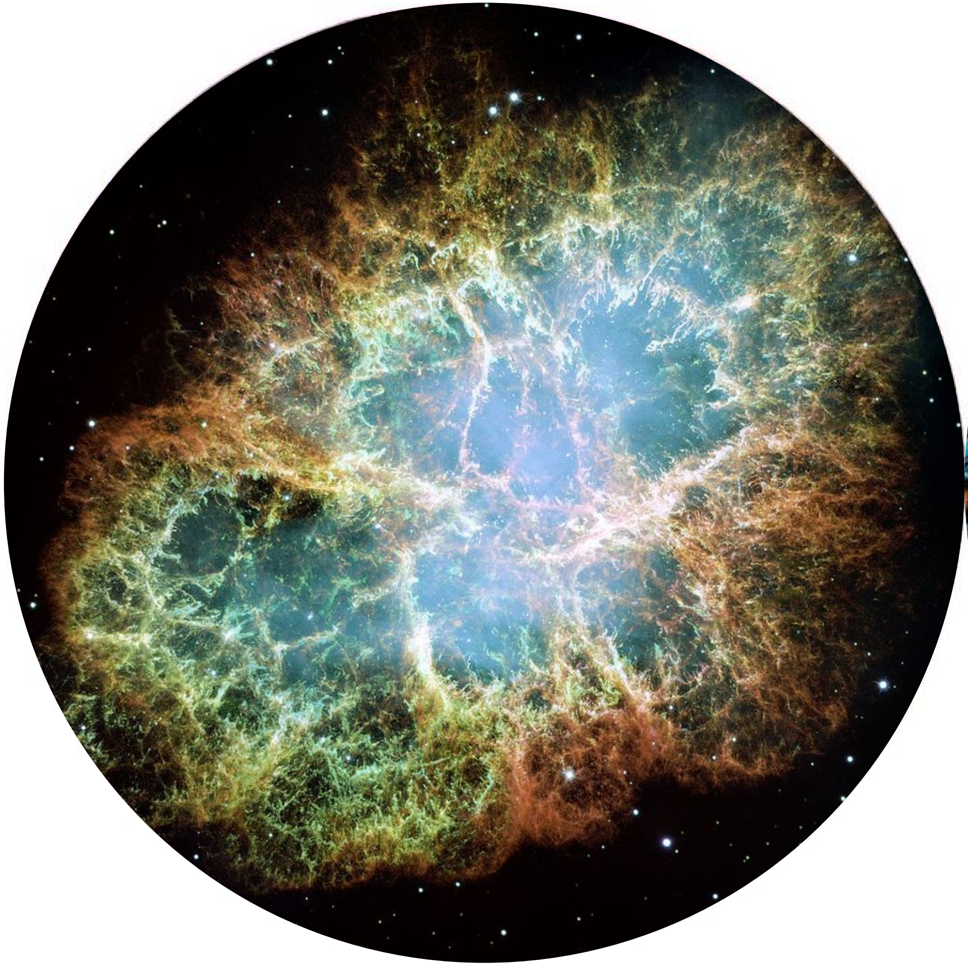
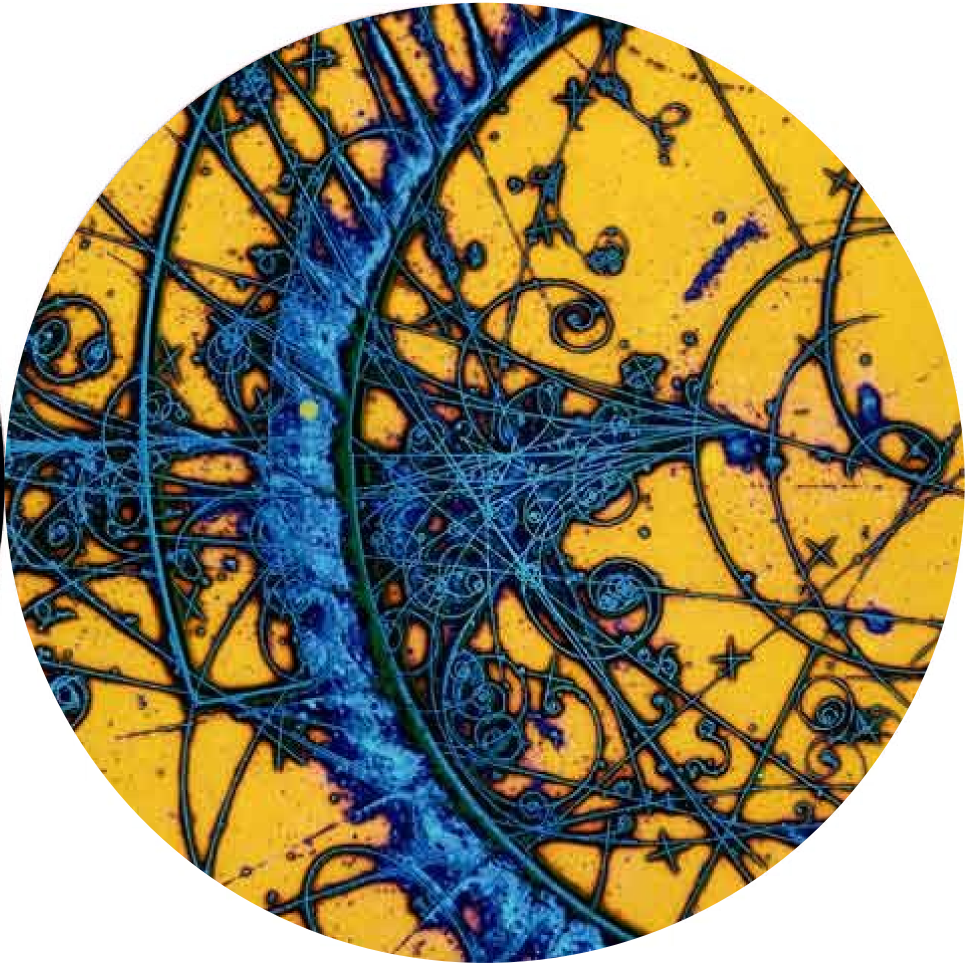

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   Astro: Probe the highest-energy non-thermal astrophysical sources

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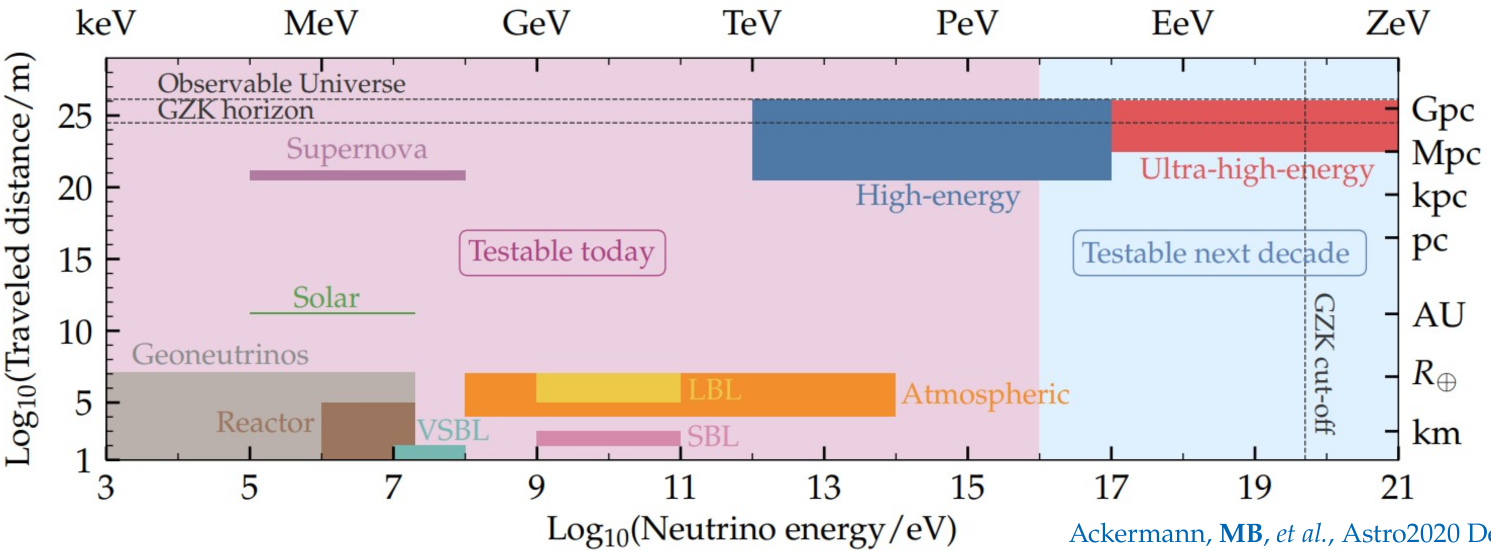

Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333)

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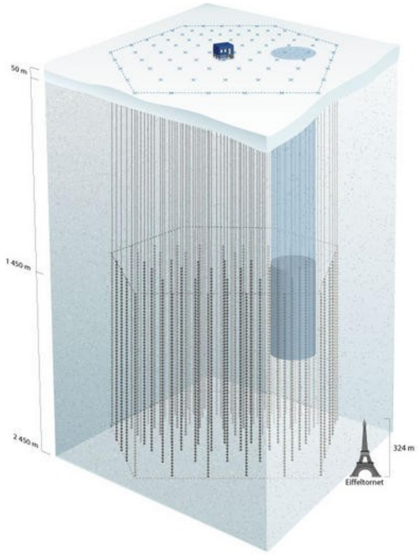
4 Neutrinos have a unique quantum number: flavor

Particle: Versatile probe of flavor-sensitive new physics

Astro: Can reveal the neutrino production mechanism

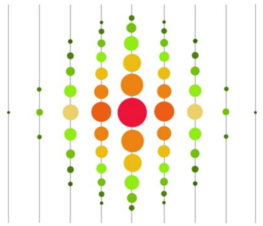
IceCube (~8 years)

km³ in-ice
Cherenkov detector



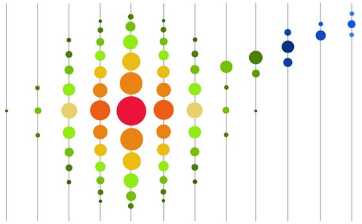
Showers

(mostly from ν_e, ν_τ)

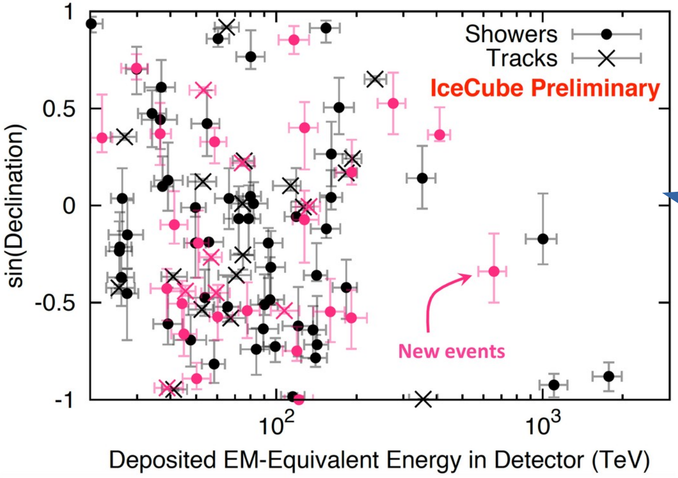


Tracks

(from ν_μ)



~100 contained events, 15 TeV–2 PeV



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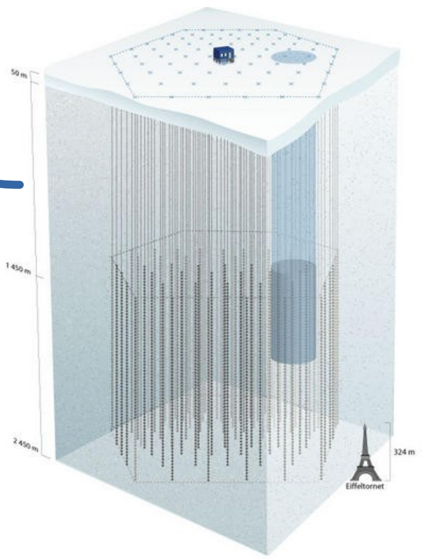

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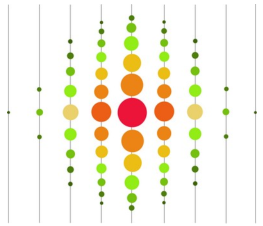

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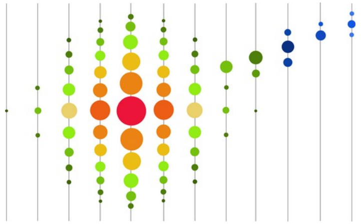

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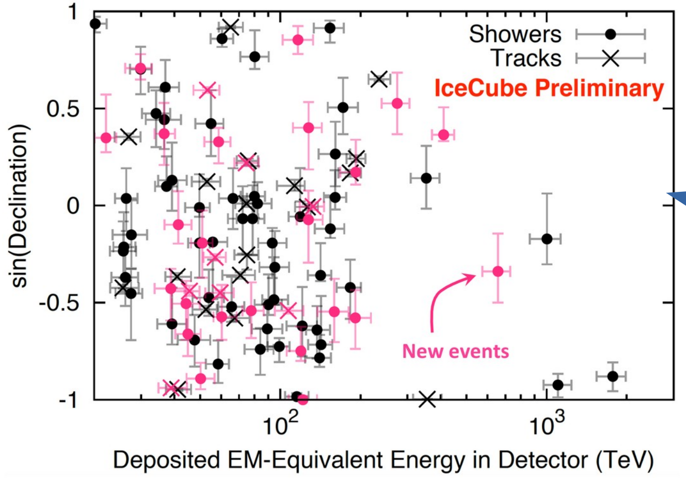

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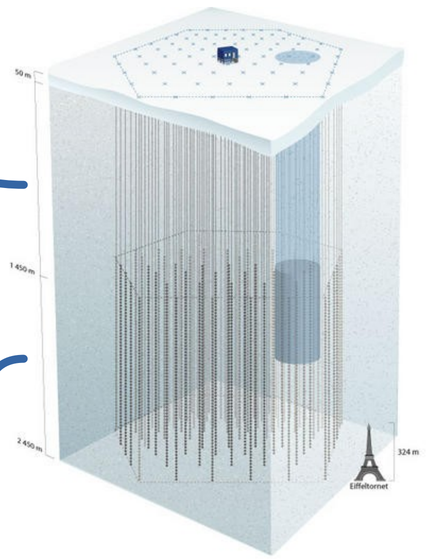
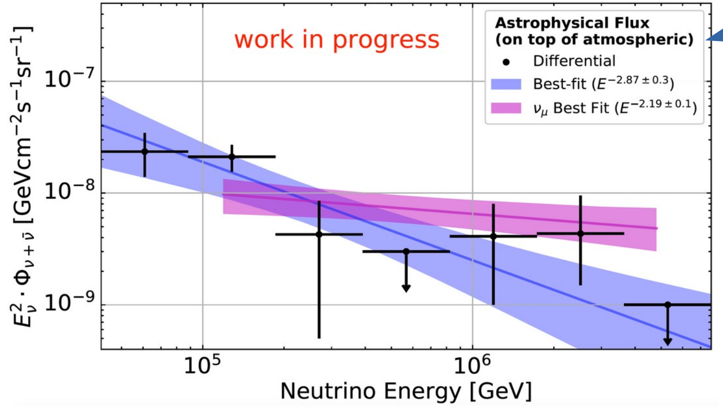


Astrophysical ν flux detected at > 7σ



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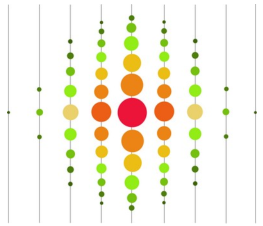

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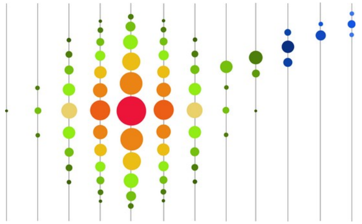

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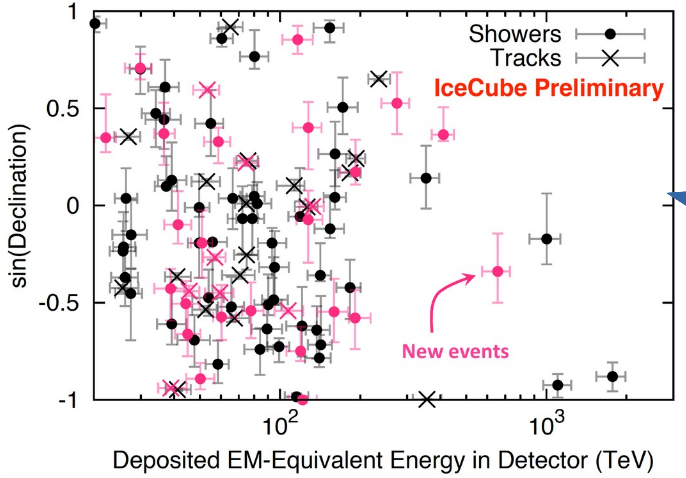

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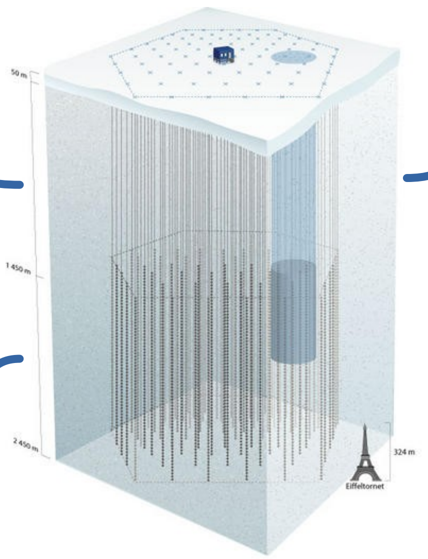
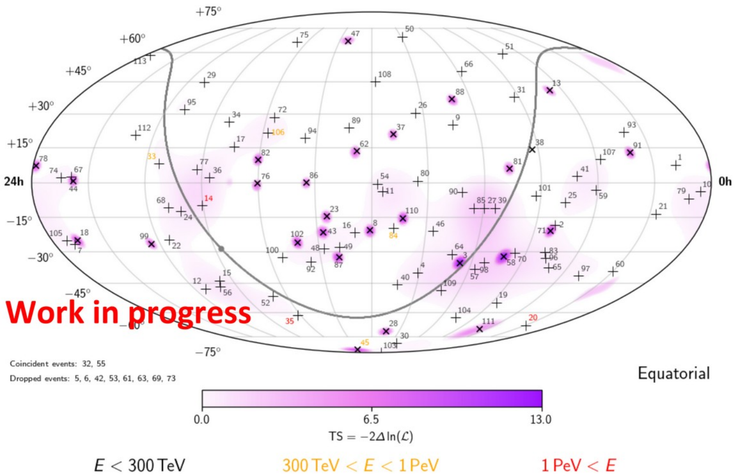


Arrival directions compatible with isotropy



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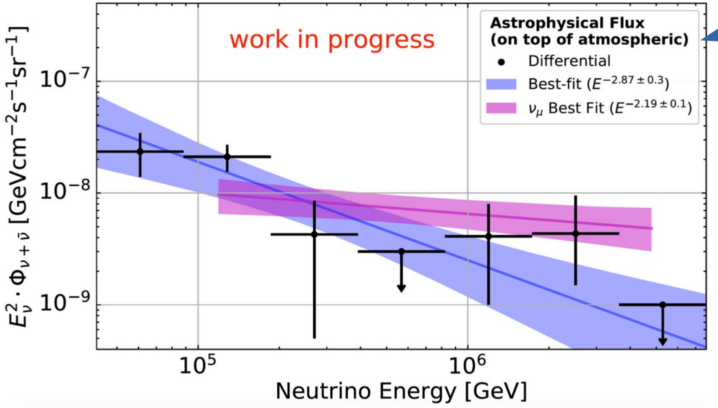

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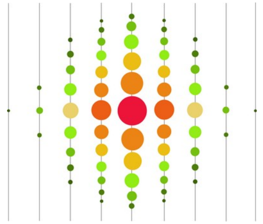

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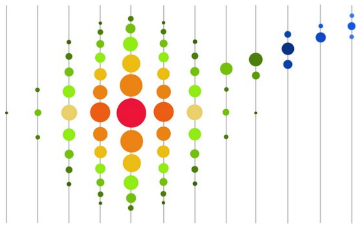

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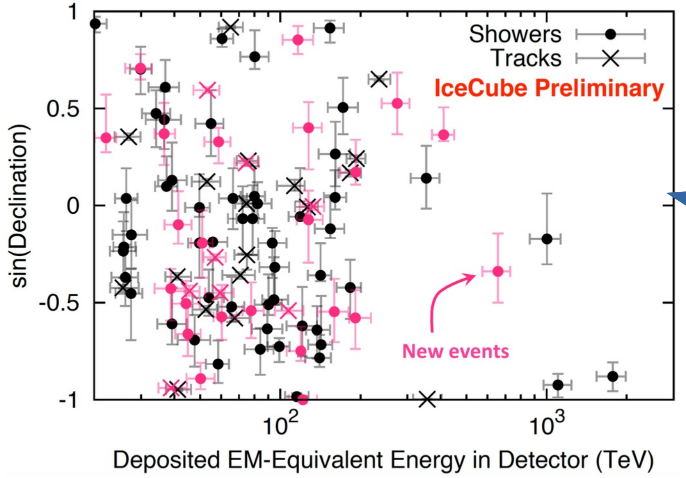

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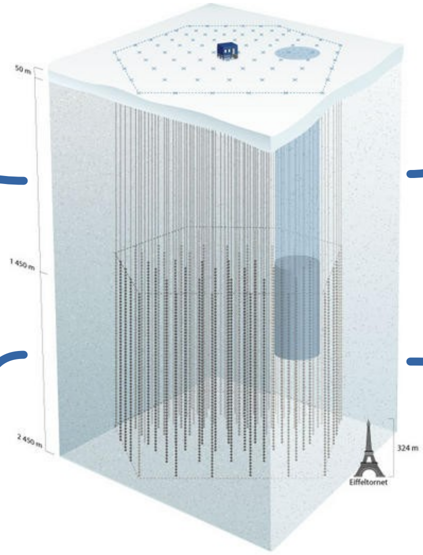

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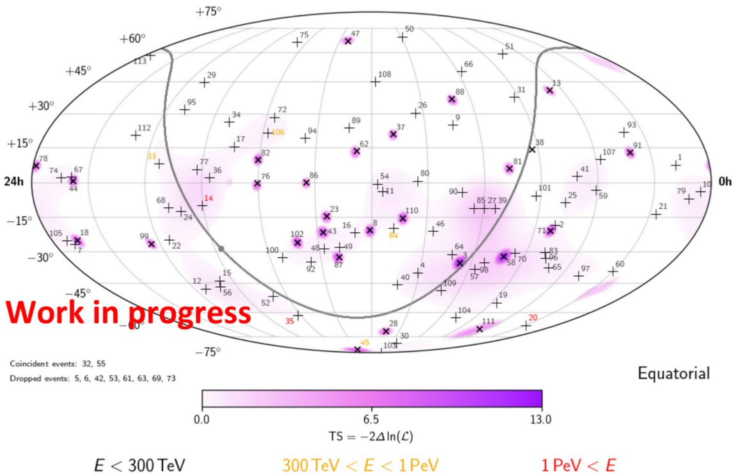

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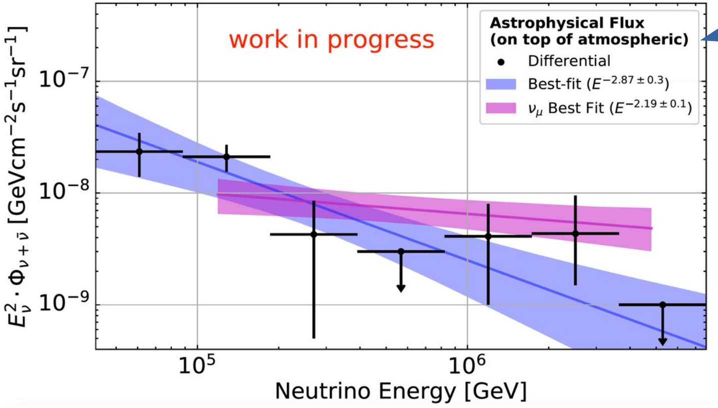

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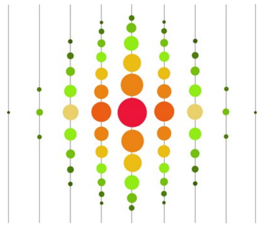

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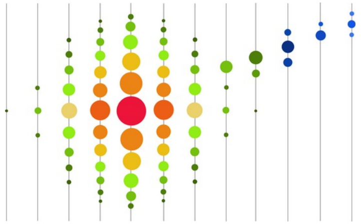
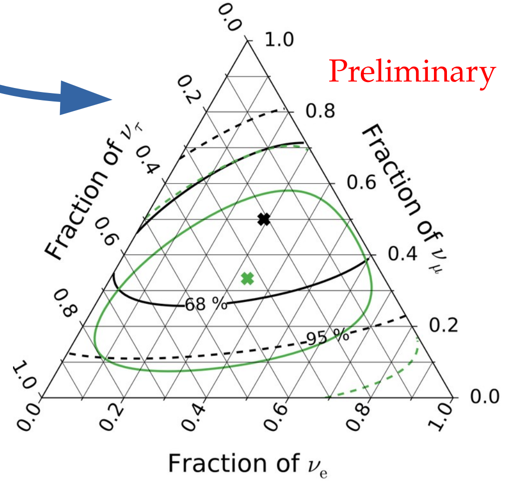


Flavor composition



Status quo of high-energy cosmic neutrinos

What we know

- Isotropic distribution of sources
- Spectrum is a power law $\propto E^{-p}$
- At least some sources are gamma-ray transients
- No correlation between directions of cosmic rays and neutrinos
- Flavor composition: compatible with equal number of ν_e, ν_μ, ν_τ
- No evident new physics

What we don't know

- The sources of the diffuse ν flux
- The ν production mechanism
- The spectral index of the spectrum
- A spectral cut-off at a few PeV?
- Are there Galactic ν sources?
- The precise flavor composition
- Is there new physics?

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But we have solid theory expectations
+ fast experimental progress

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I.
The basics (and hot news)

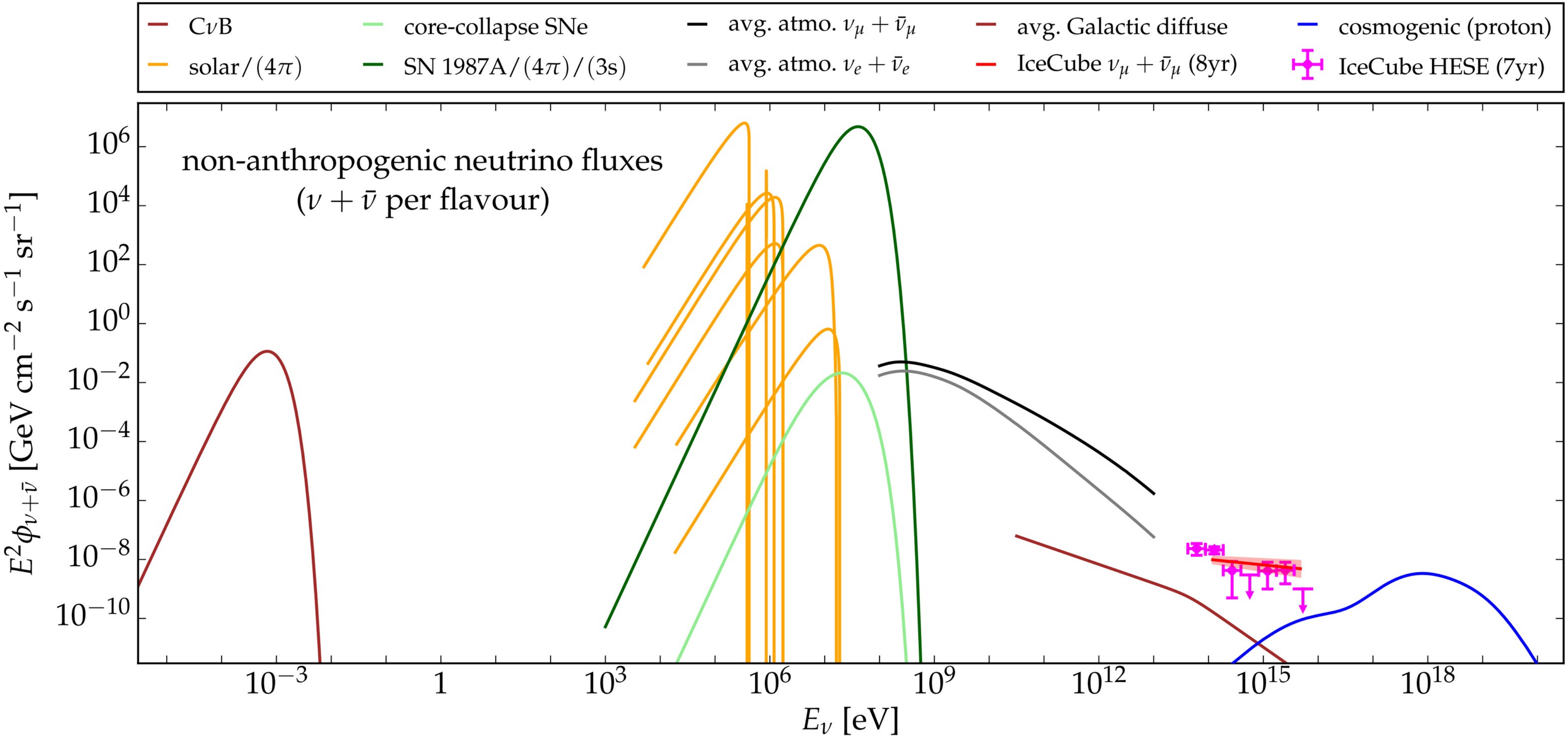
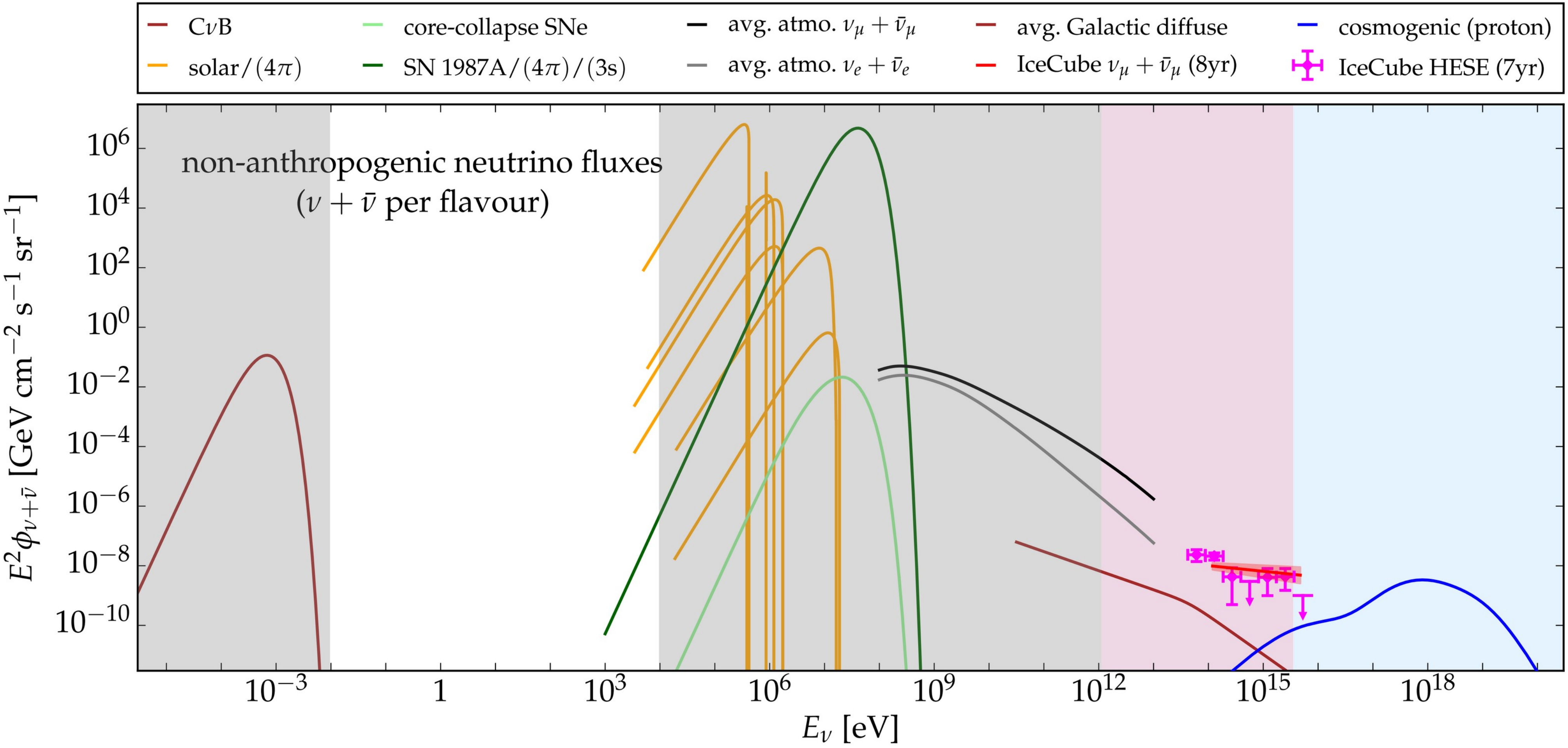


Figure courtesy of Markus Ahlers
Also in: Van Elewyck *et al.*, PoS(ICRC2019), 1023



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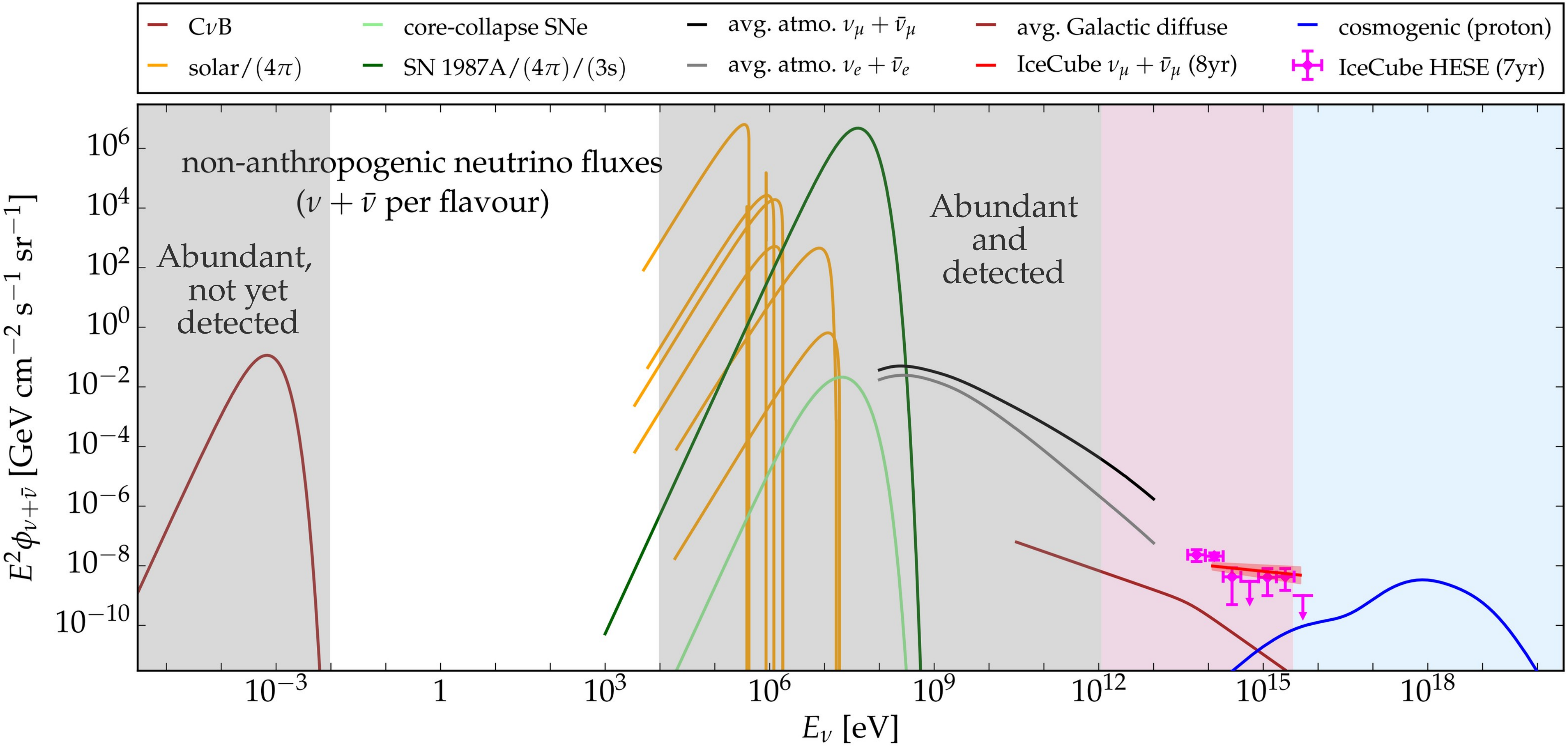

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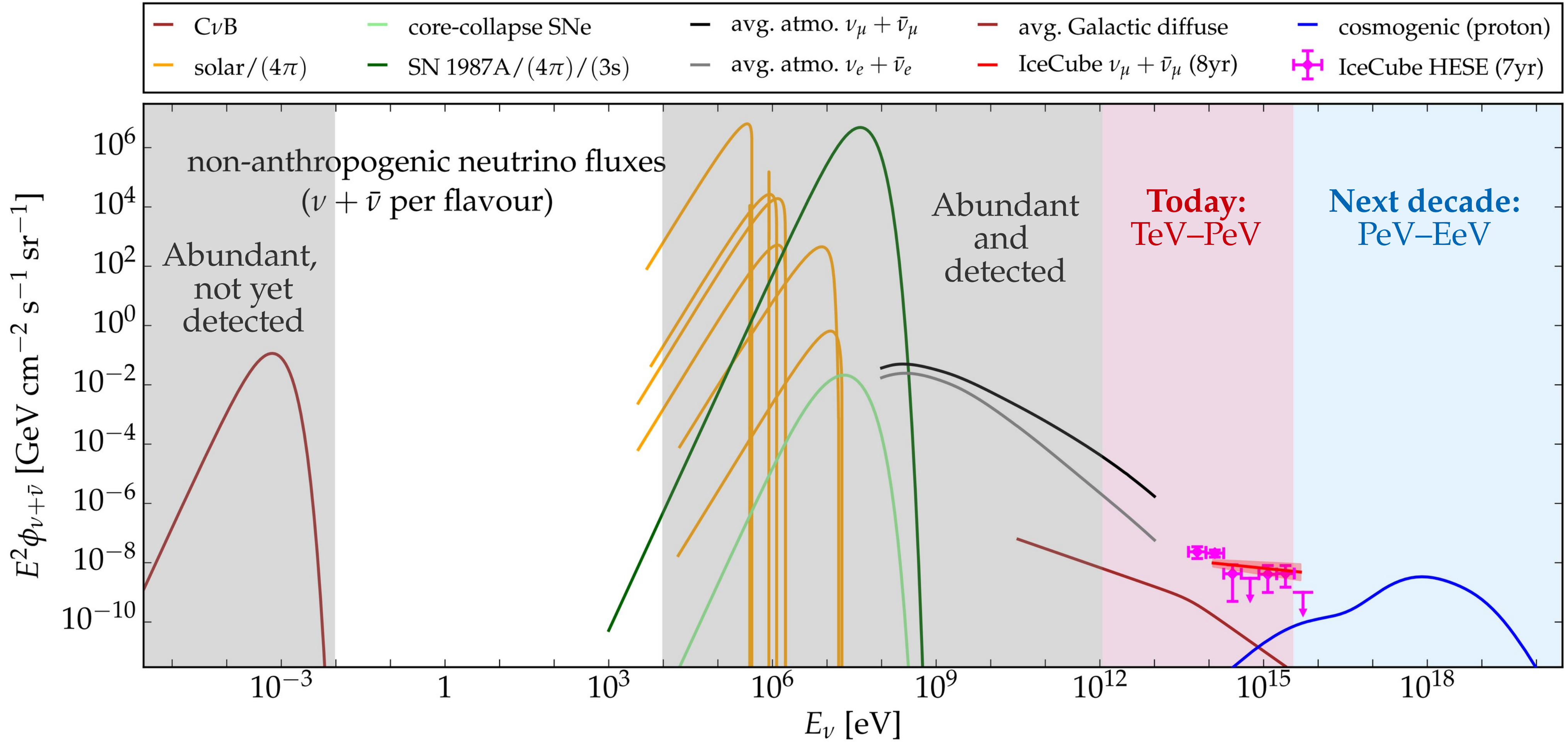

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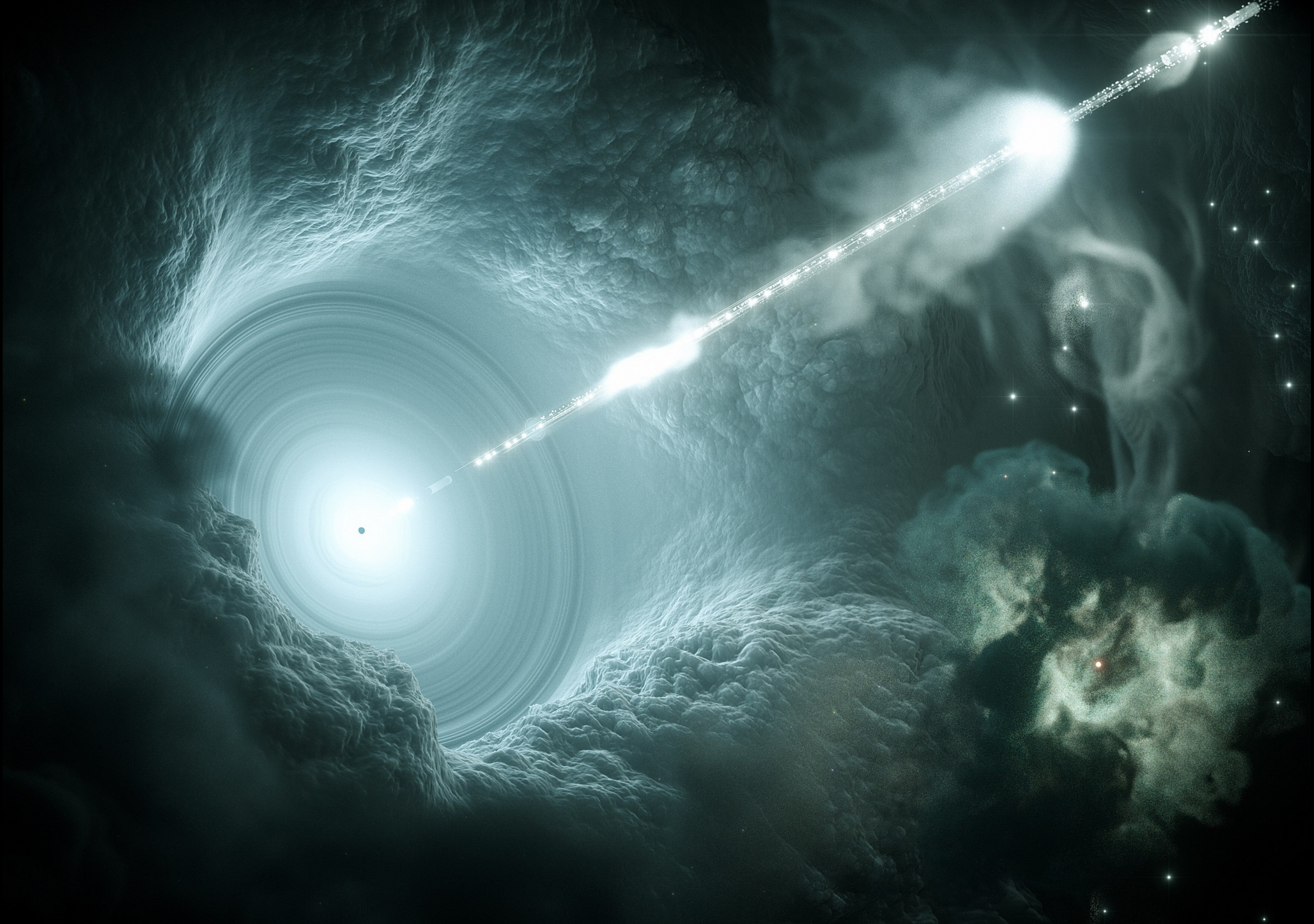
DESY

DESY

The multi-messenger connection: a simple picture

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

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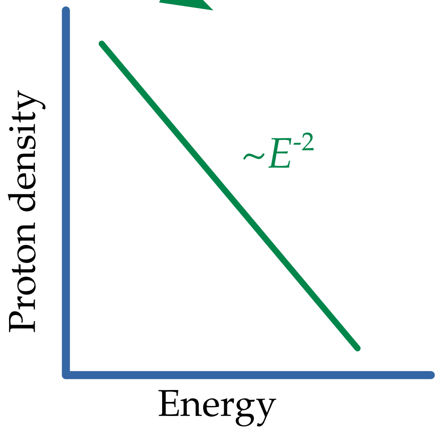

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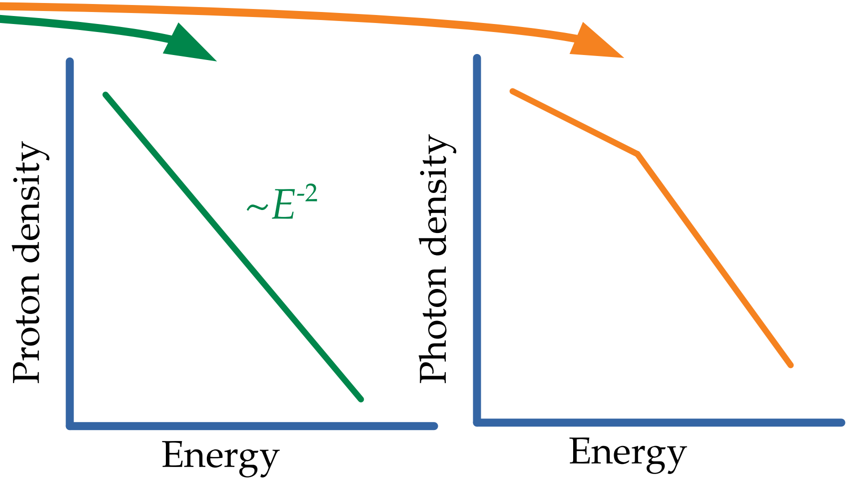

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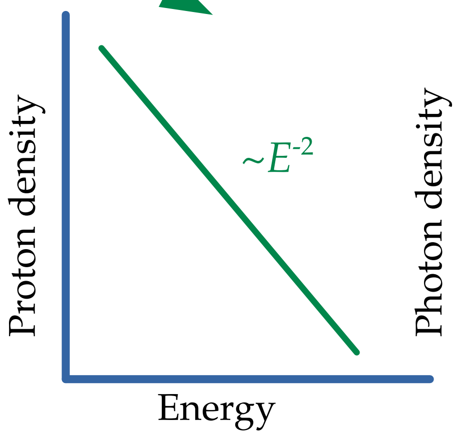
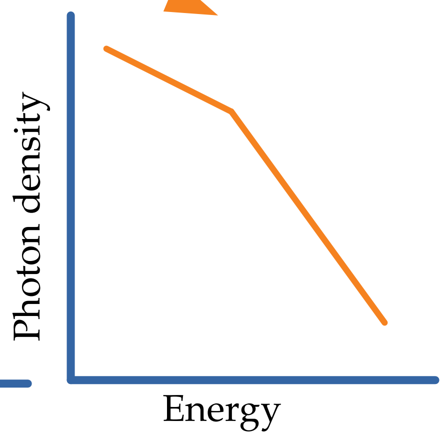
$$\pi^{0} \rightarrow \gamma + \gamma$$

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

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





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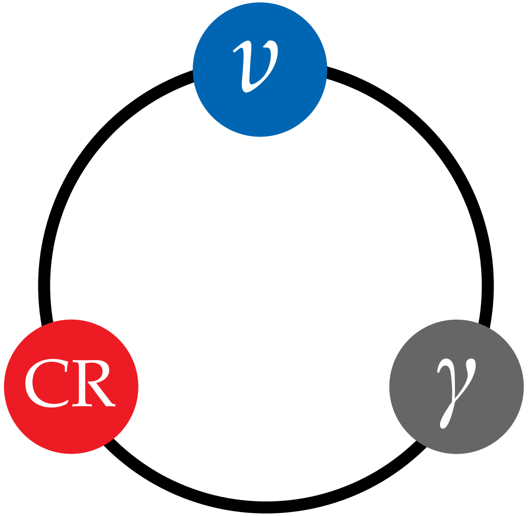

Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10

The multi-messenger connection: a simple picture

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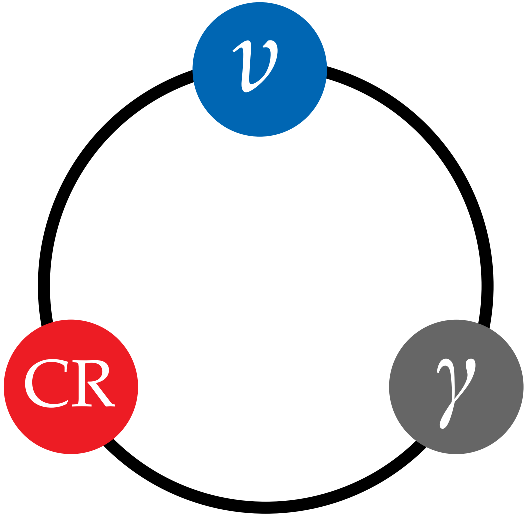

1 PeV 20 PeV

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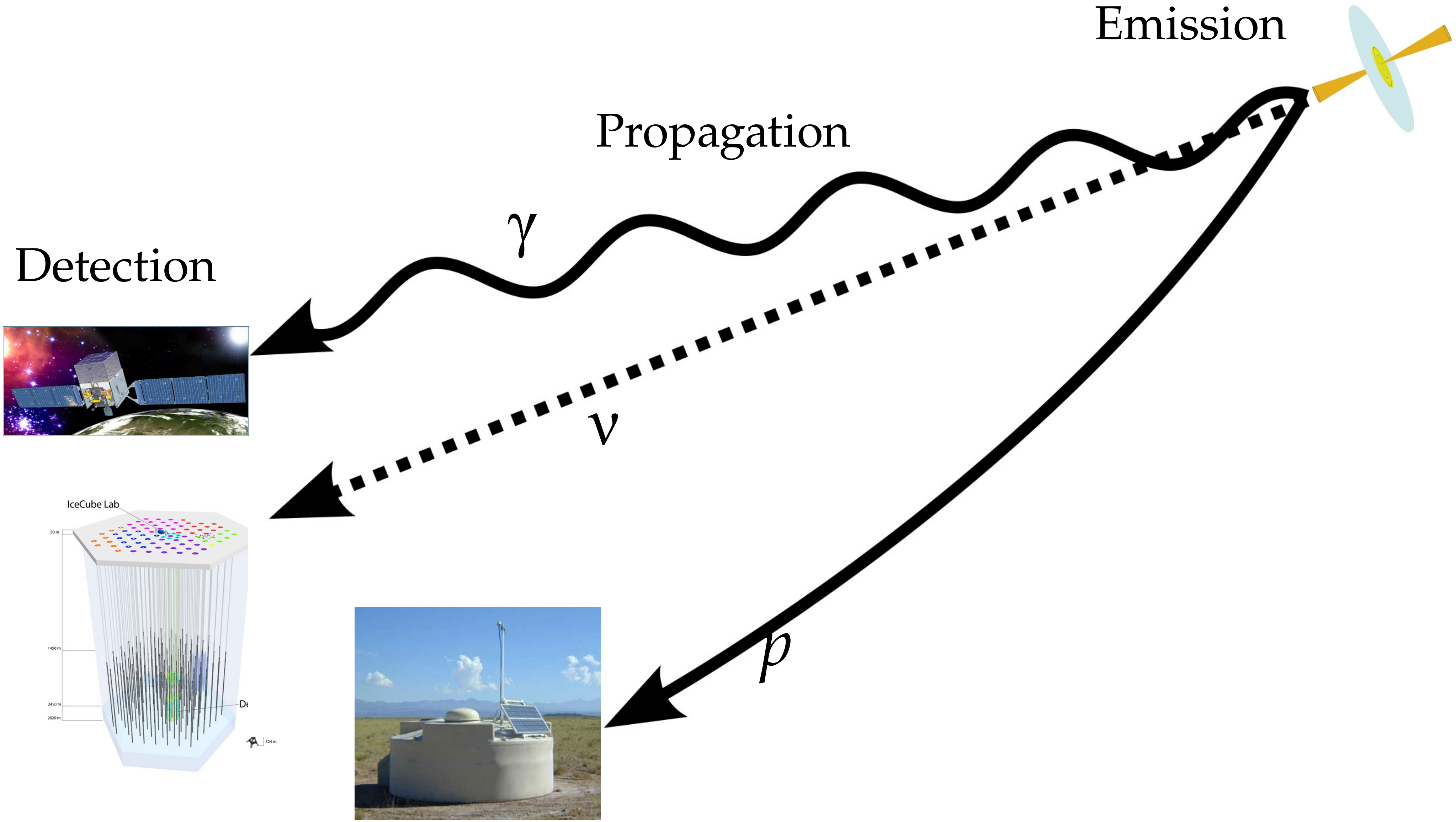
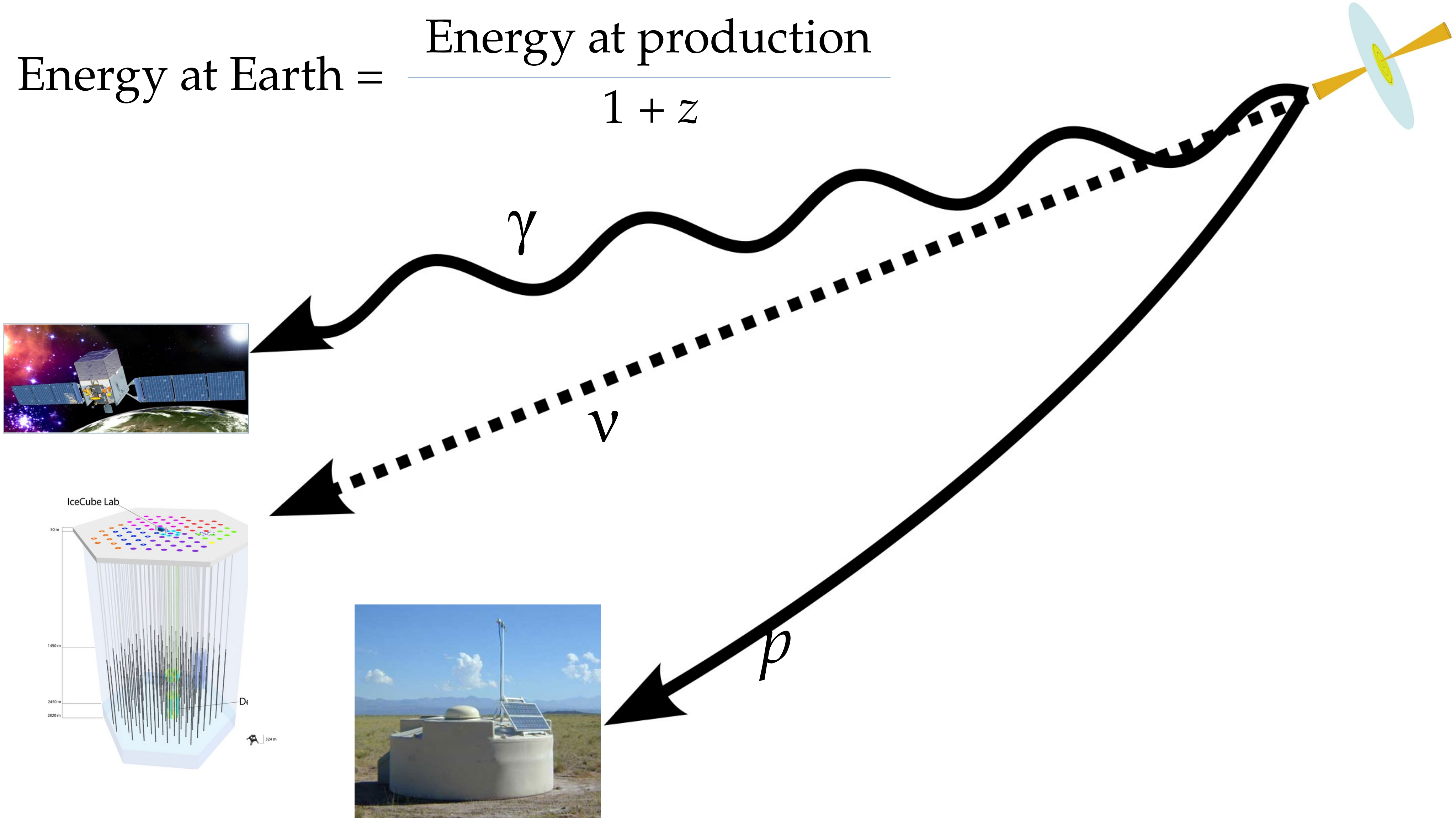
Gamma-ray energy = Proton energy / 10


Emission
Propagation
γ
ν
p
Detection
IceCube Lab

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



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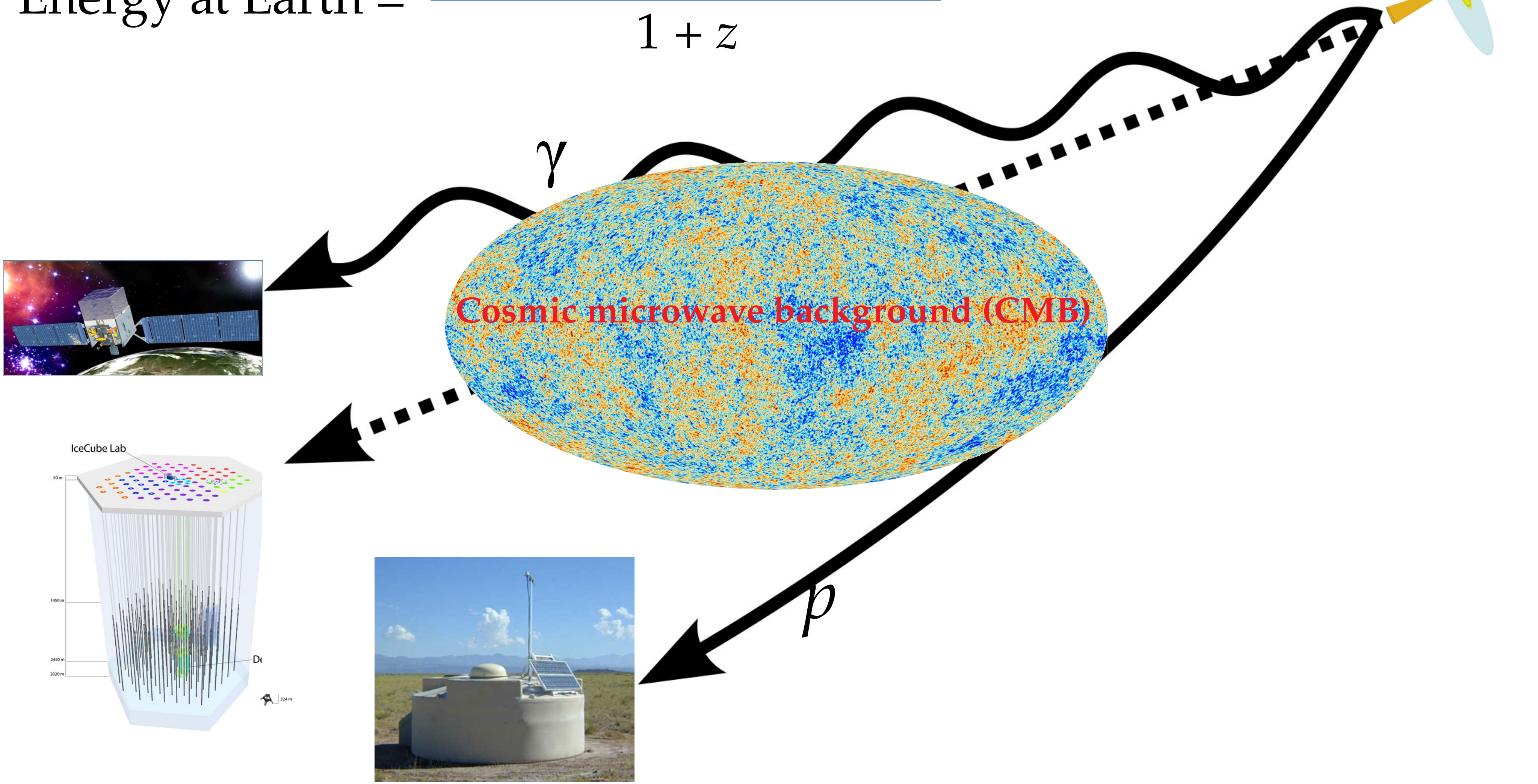
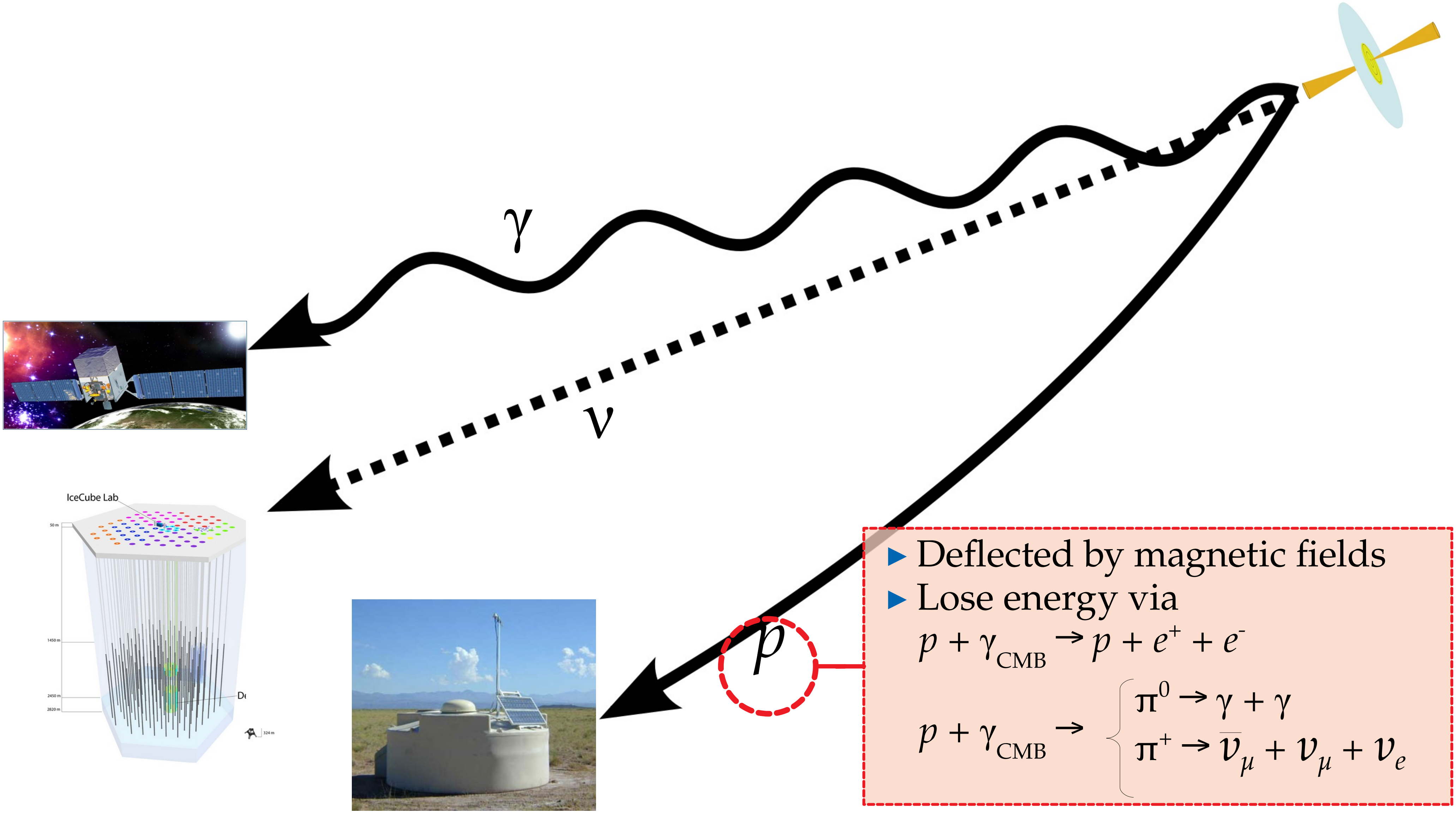
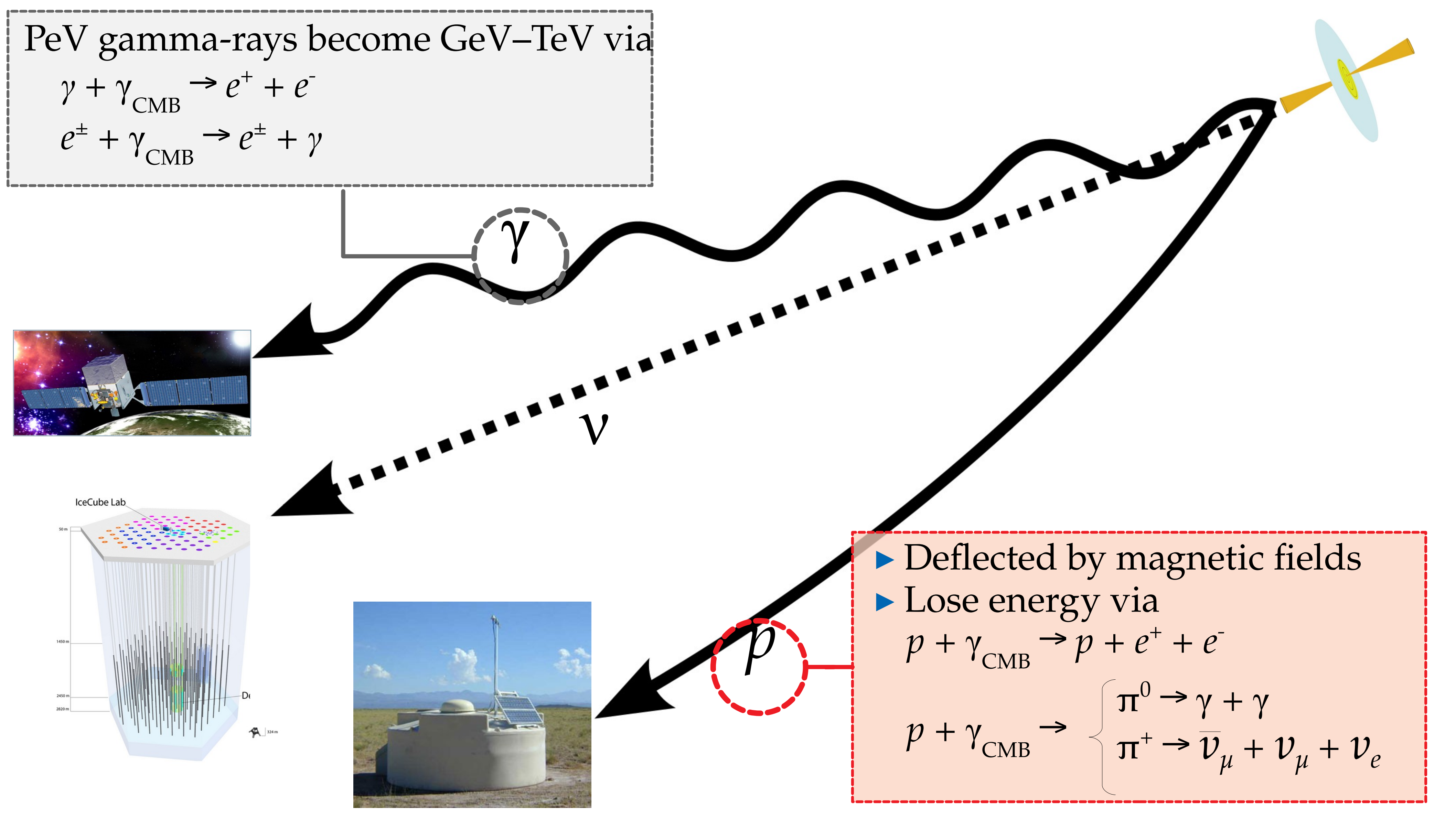




γ
ν
IceCube Lab
p
Deflected by magnetic fields
Lose energy via
$p + \gamma_{CMB} \rightarrow p + e^{+} + e^{-}$
$p + \gamma_{CMB} \rightarrow \begin{cases} \pi^{0} \rightarrow \gamma + \gamma \\ \pi^{+} \rightarrow \bar{\nu}_{\mu} + \nu_{\mu} + \nu_{e} \end{cases}$



PeV gamma-rays become GeV–TeV via
$\gamma + \gamma_{\mathrm{CMB}} \rightarrow e^{+} + e^{-}$
$e^{\pm} + \gamma_{\mathrm{CMB}} \rightarrow e^{\pm} + \gamma$
γ
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IceCube Lab
p
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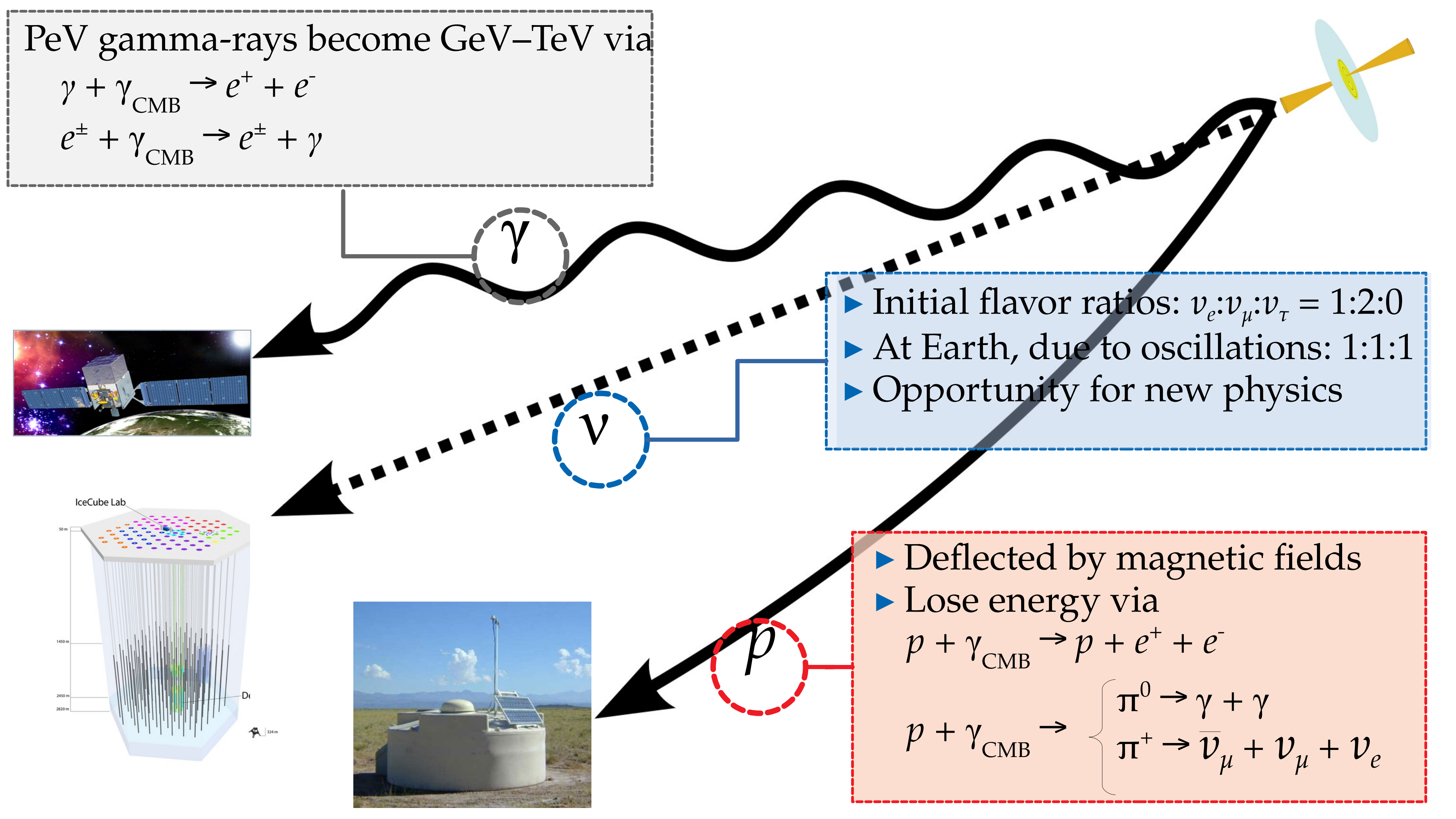

PeV gamma-rays become GeV–TeV via
$\gamma + \gamma_{CMB} \rightarrow e^+ + e^-$
$e^\pm + \gamma_{CMB} \rightarrow e^\pm + \gamma$
γ
ν
p
Initial flavor ratios: $\nu_e:\nu_\mu:\nu_\tau$ = 1:2:0
At Earth, due to oscillations: 1:1:1
Opportunity for new physics
IceCube Lab
Deflected by magnetic fields
Lose energy via
$p + \gamma_{CMB} \rightarrow p + e^+ + e^-$
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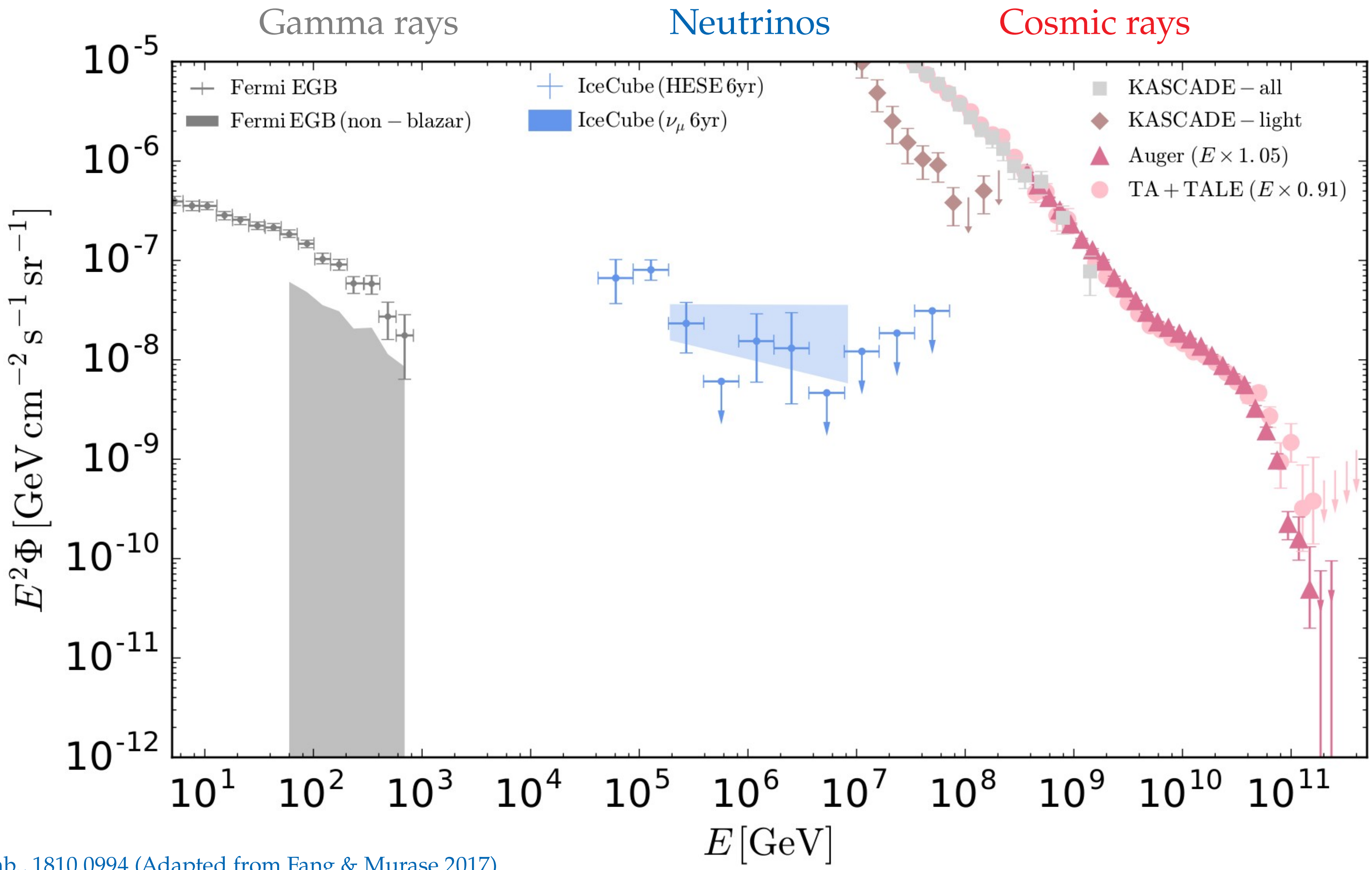
Fluxes at Earth



GRAND Collab., 1810.0994 (Adapted from Fang & Murase 2017)

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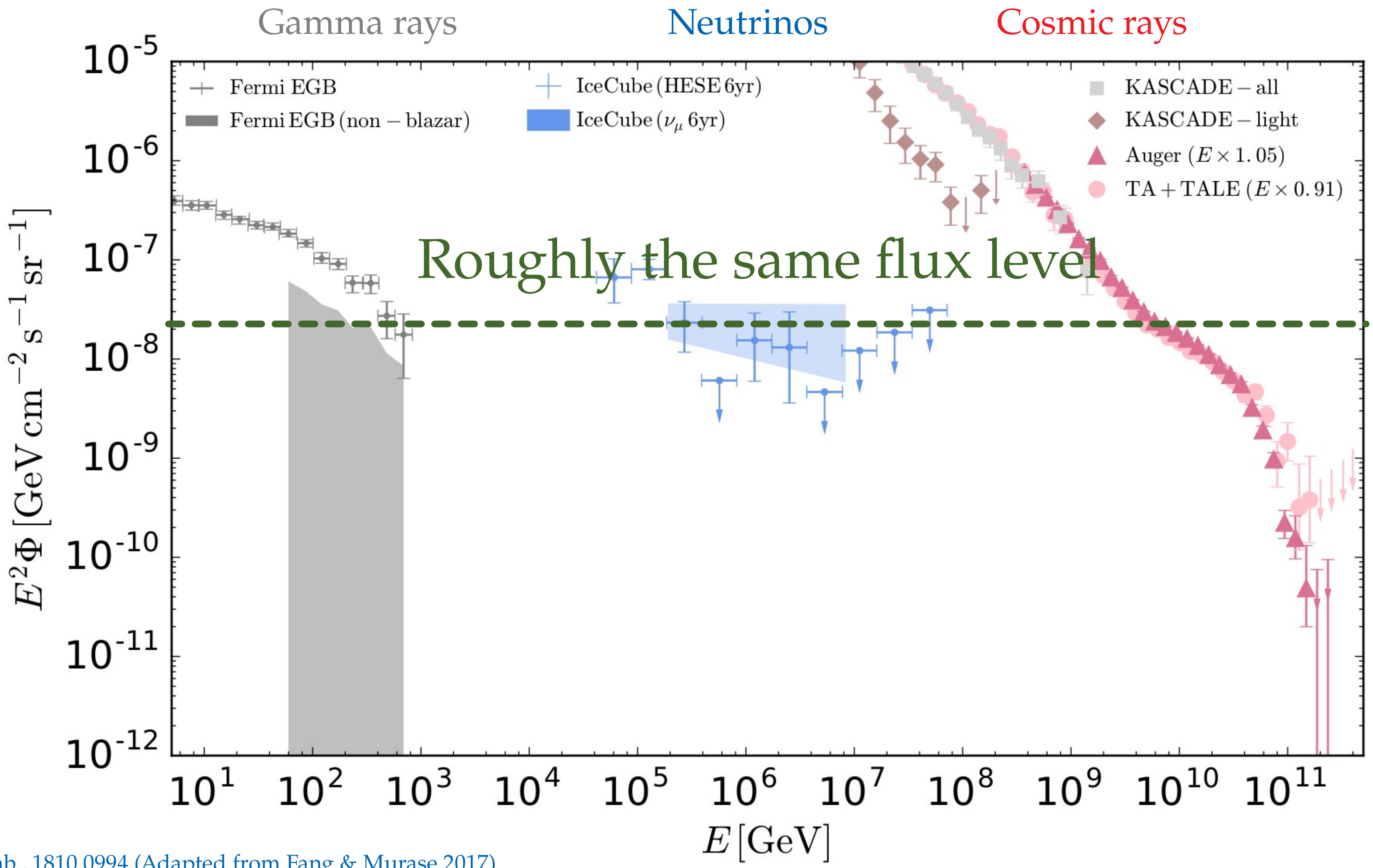

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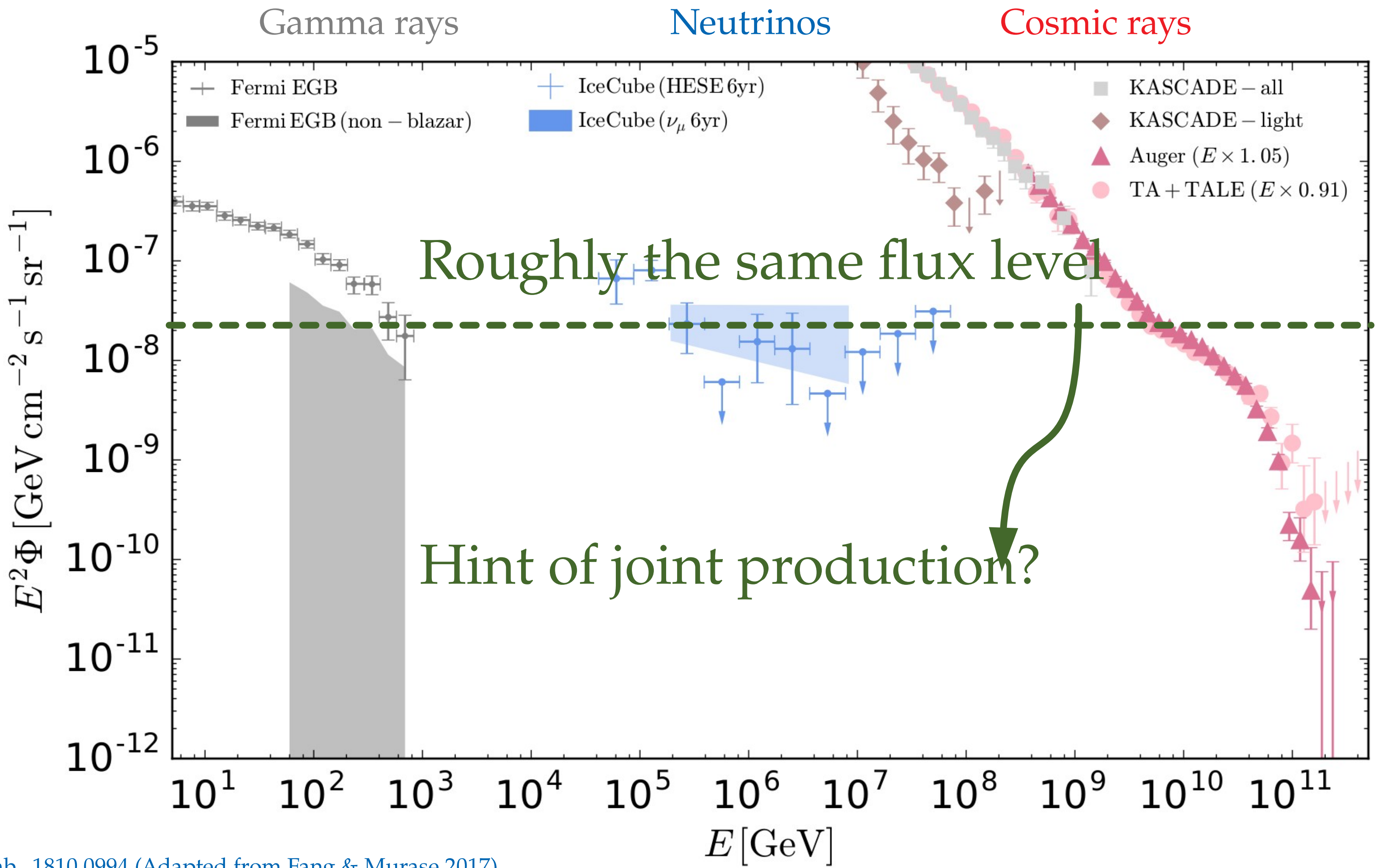

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Neutrinos – The ultimate smoking gun of cosmic accelerators

	Gamma rays	Neutrinos	UHE Cosmic rays
Point back at sources			
Size of horizon			
Energy degradation			
Relative ease to detect			

Note: This is a simplified view

Neutrinos – The ultimate smoking gun of cosmic accelerators

	Gamma rays	Neutrinos	UHE Cosmic rays
Point back at sources	Yes	Yes	No
Size of horizon			
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Neutrinos – The ultimate smoking gun of cosmic accelerators

	Gamma rays	Neutrinos	UHE Cosmic rays
Point back at sources	Yes	Yes	No
Size of horizon	10 Mpc (at EeV)	Size of the Universe	100 Mpc (> 40 EeV)
Energy degradation			
Relative ease to detect			

Note: This is a simplified view

Neutrinos – The ultimate smoking gun of cosmic accelerators

	Gamma rays	Neutrinos	UHE Cosmic rays
Point back at sources	Yes	Yes	No
Size of horizon	10 Mpc (at EeV)	Size of the Universe	100 Mpc (> 40 EeV)
Energy degradation	Severe	Tiny	Severe
Relative ease to detect			

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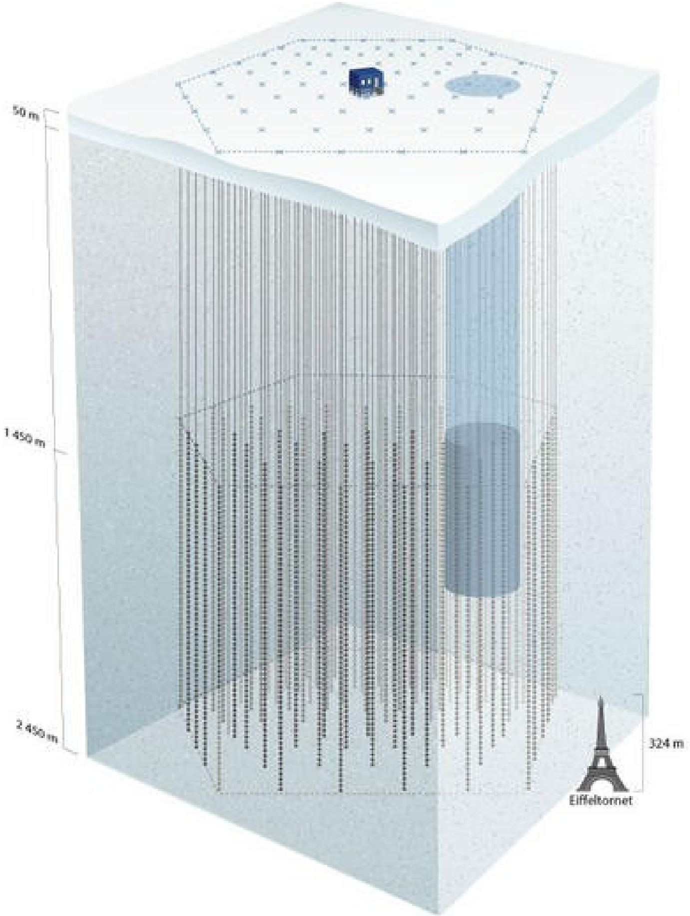
Note: This is a simplified view

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

How does IceCube see TeV–PeV neutrinos?

Deep inelastic neutrino-nucleon scattering

Neutral current (NC)

$$\nu_x + N \rightarrow \nu_x + X$$

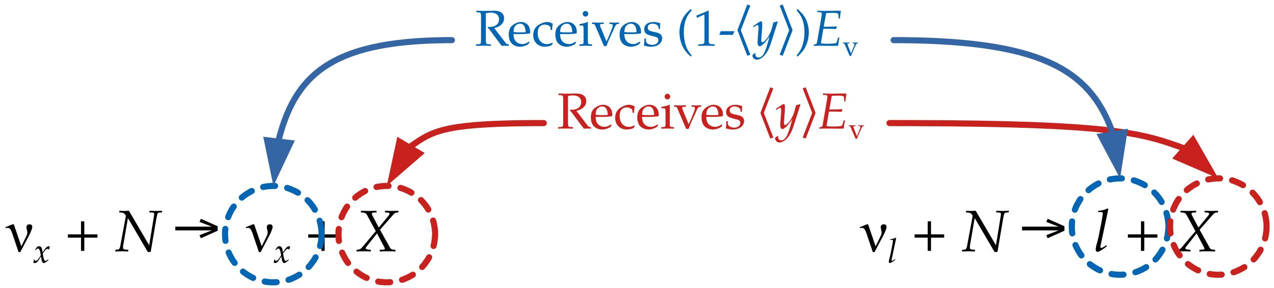
Charged current (CC)

$$\nu_l + N \rightarrow l + X$$

How does IceCube see TeV–PeV neutrinos?

Deep inelastic neutrino-nucleon scattering

Neutral current (NC) | Charged current (CC)



At TeV–PeV, the average inelasticity $\langle y \rangle = 0.25–0.30$

How does IceCube see TeV–PeV neutrinos?

Deep inelastic neutrino-nucleon scattering

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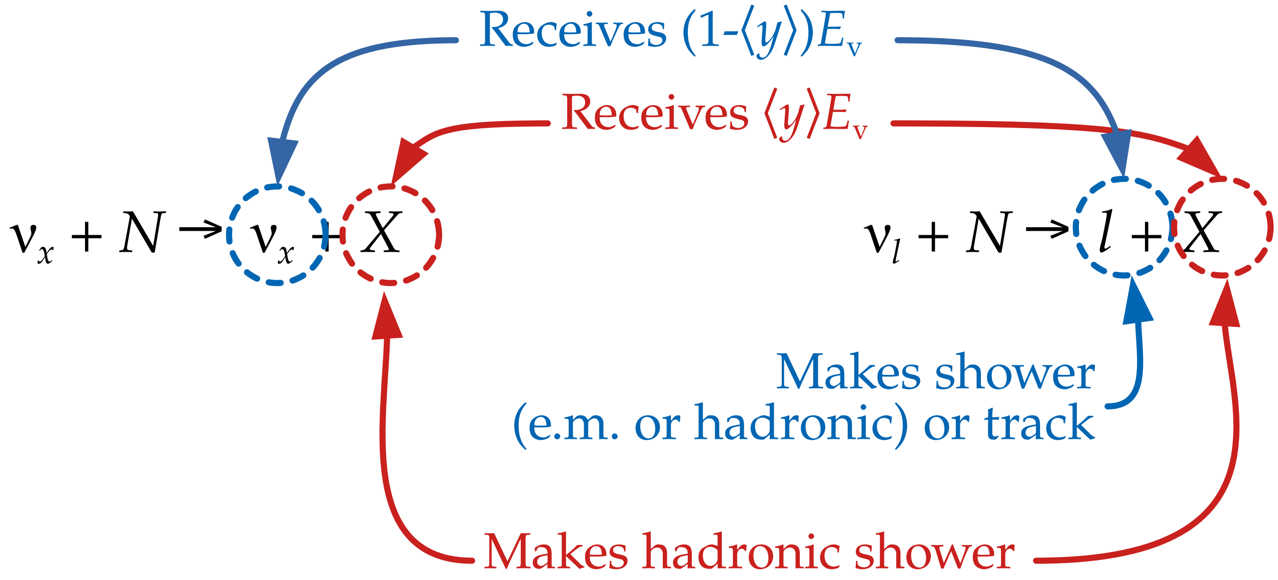
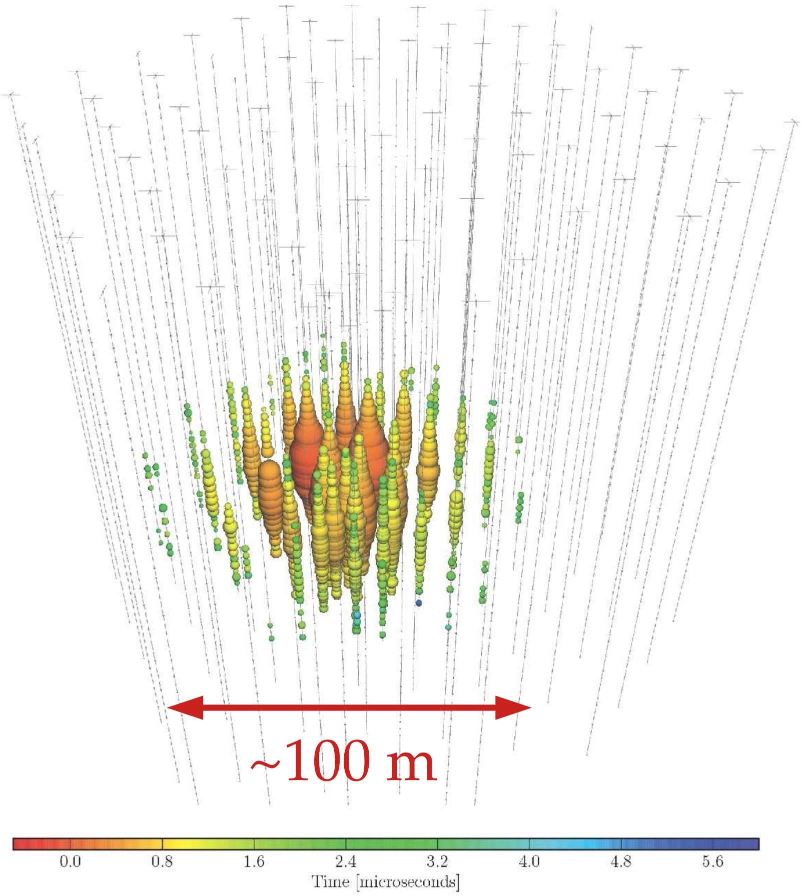


At TeV–PeV, the average inelasticity $\langle y \rangle$ = 0.25–0.30

Shower

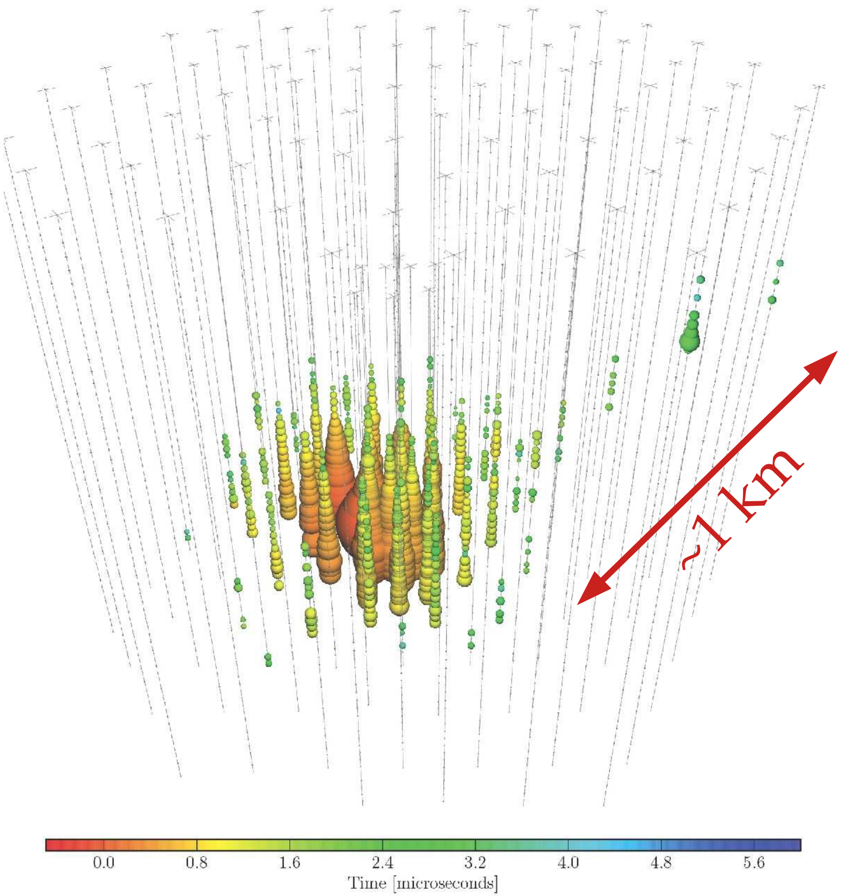
(mainly from ν_e and ν_τ)



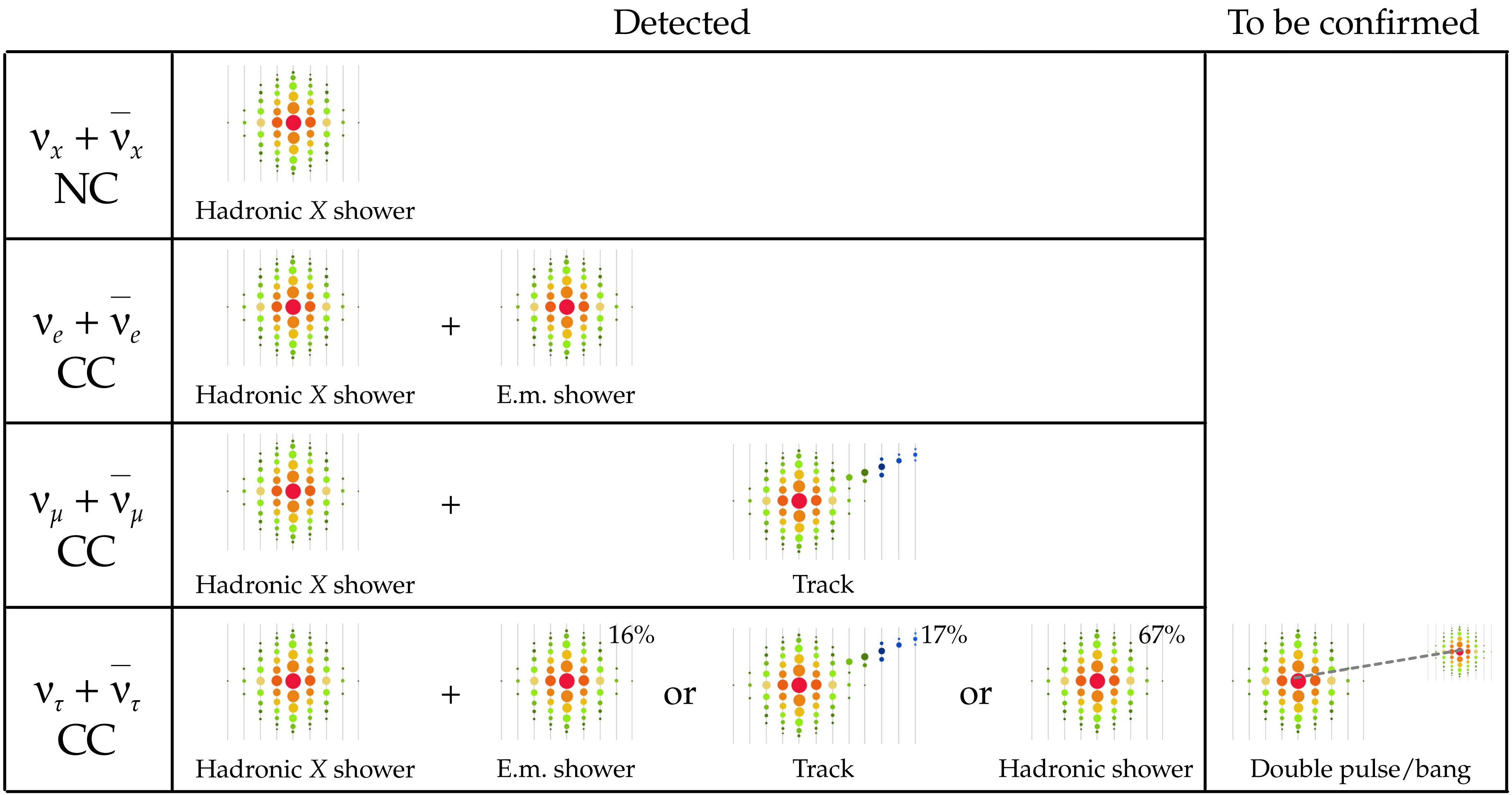
Poor angular resolution: ~10°

Track

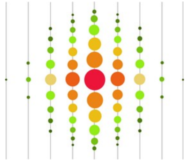
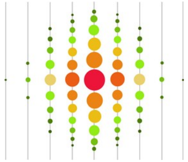
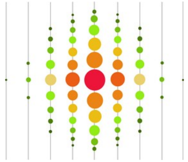
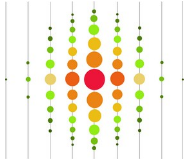
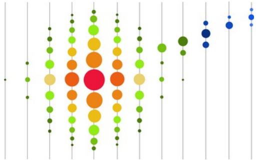
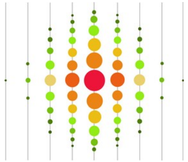
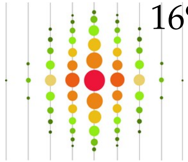
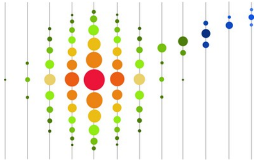
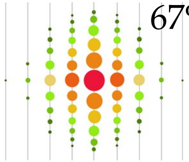
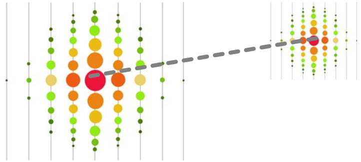
(mainly from ν_μ)



Angular resolution: < 1°

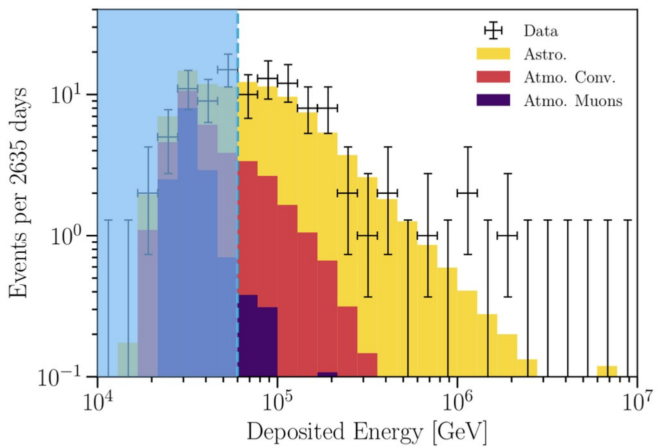


Detected
To be confirmed
$\nu_x + \bar{\nu}_x$ NC
Hadronic X shower
$\nu_e + \bar{\nu}_e$ CC
Hadronic X shower
+
E.m. shower
$\nu_\mu + \bar{\nu}_\mu$ CC
Hadronic X shower
+
Track
$\nu_\tau + \bar{\nu}_\tau$ CC
Hadronic X shower
+
16%
E.m. shower
or
17%
Track
or
67%
Hadronic shower
Double pulse/bang

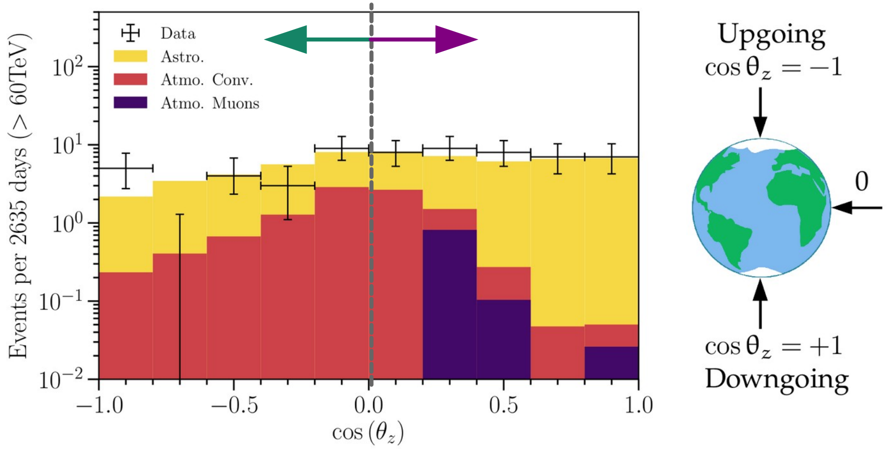
	Detected	~~To be confirmed~~ Confirmed (more later)
$\nu_x + \bar{\nu}_x$ NC	 Hadronic X shower	
$\nu_e + \bar{\nu}_e$ CC	 Hadronic X shower +  E.m. shower	
$\nu_\mu + \bar{\nu}_\mu$ CC	 Hadronic X shower +  Track	
$\nu_\tau + \bar{\nu}_\tau$ CC	 Hadronic X shower +  16% E.m. shower or  17% Track or  67% Hadronic shower	 Double pulse/bang

New (IC 7.5 yr): Neutrino energy spectrum

100+ contained events above 60 TeV:

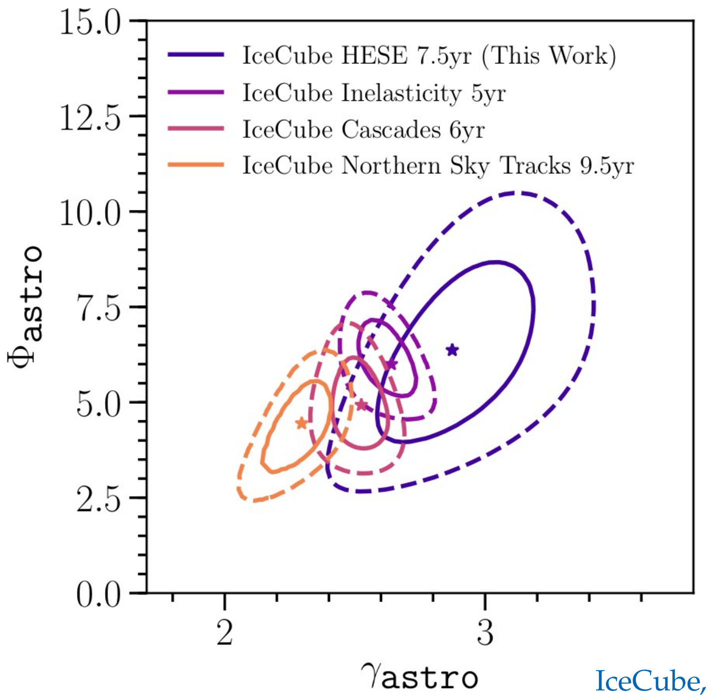


ν attenuated by Earth   Atm. ν and μ vetoed



Data is fit well by a single power law:

$$\frac{d\Phi_{6\nu}}{dE_\nu} = \Phi_{\text{astro}} \left(\frac{E_\nu}{100\ \text{TeV}} \right)^{-\gamma_{\text{astro}}} \cdot 10^{-18}\ \text{GeV}^{-1}\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$$



IceCube, 2011.03545

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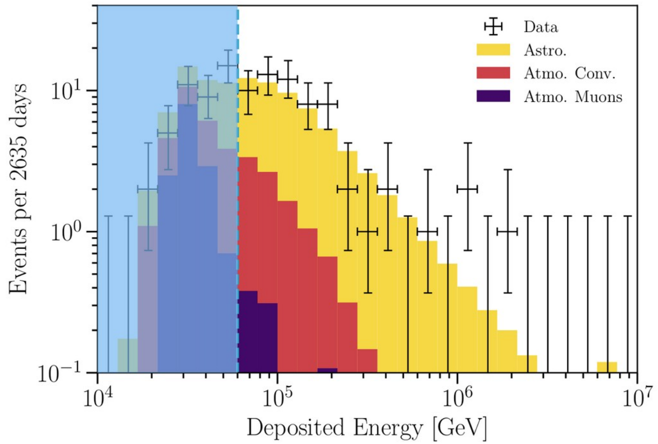

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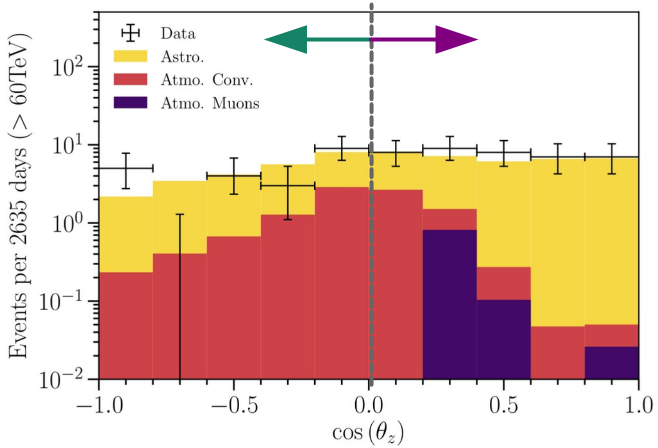

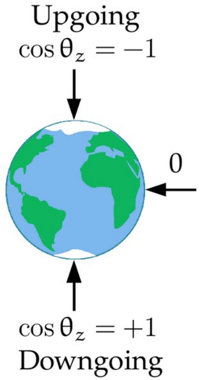

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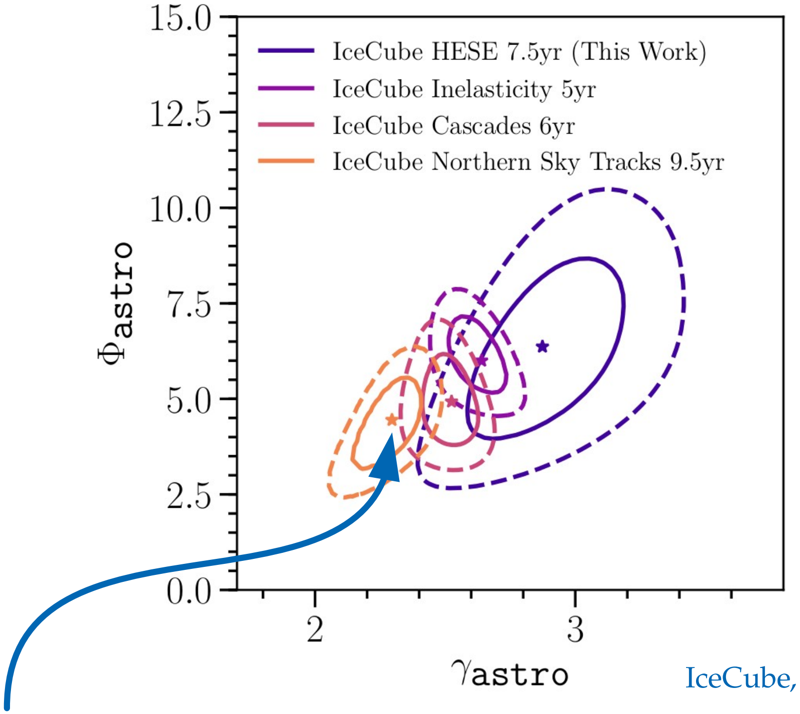
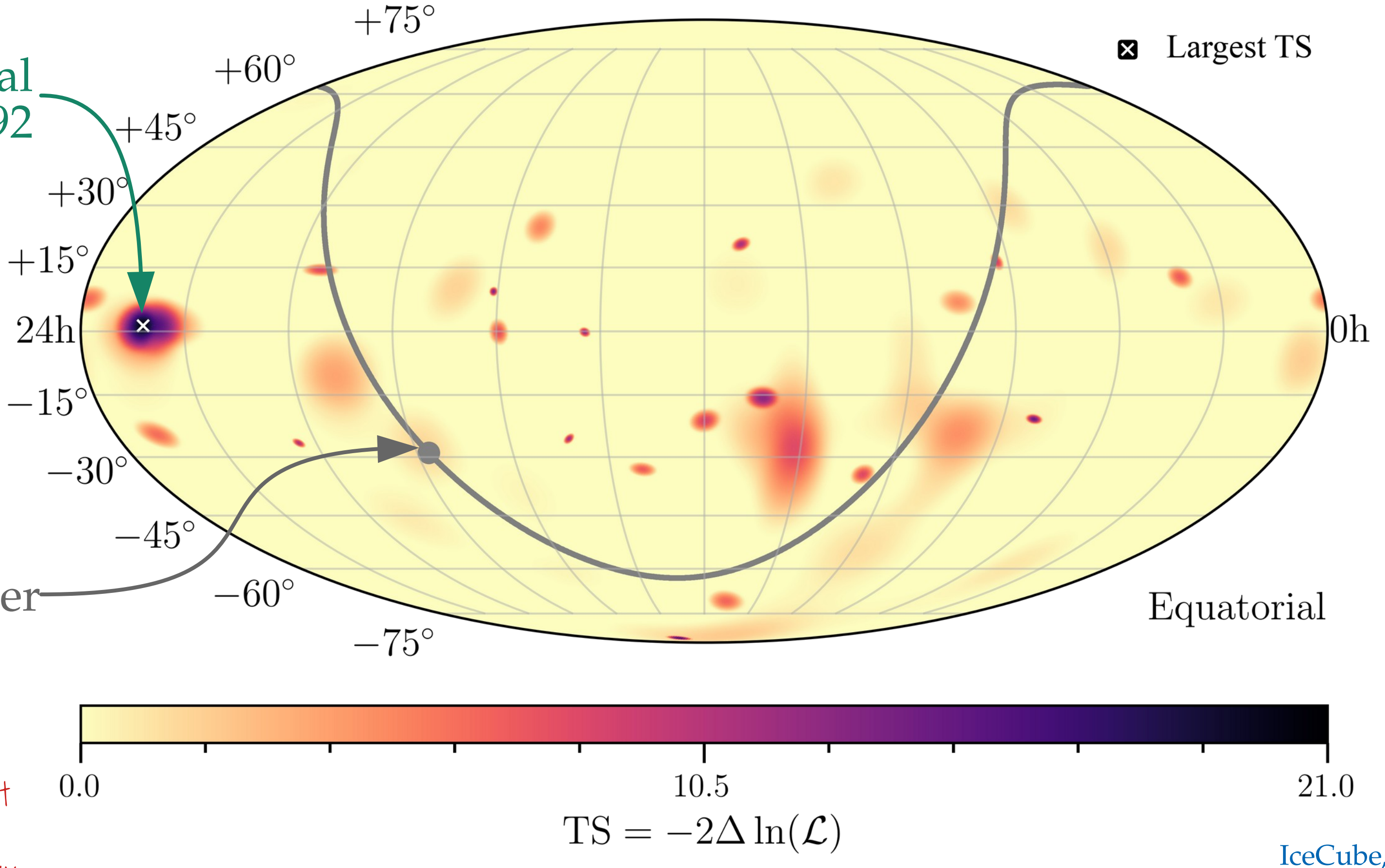


IceCube, 2011.03545

Spectrum looks harder for through-going ν_μ

New (IC 7.5 yr): Distribution of arrival directions

Distribution of arrival directions (7.5 yr) shows no significant excess:

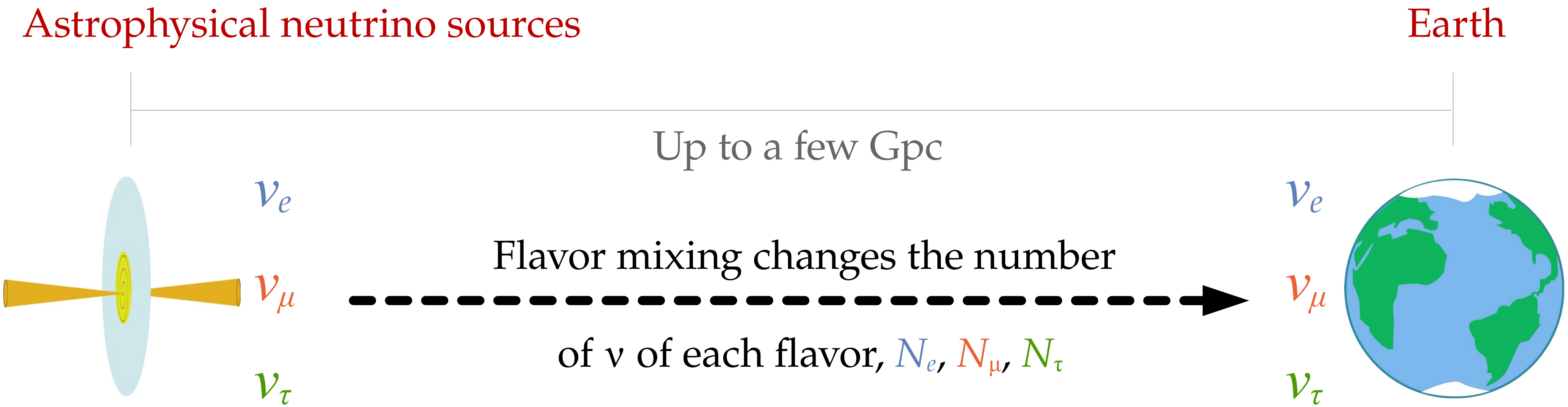


Milky Way sources?
They only contribute, at most, a few times 10% of the total diffuse flux

IceCube, 2011.03545

See also: Ackermann, **MB** *et al.*, Astro2020 Decadal Survey (1903.04334)

Flavor composition



- Different processes yield different ratios of neutrinos of each flavor:

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

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

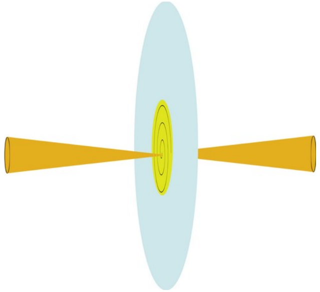
$$f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} P_{\nu_\beta \to \nu_\alpha} f_{\beta,\mathrm{S}}$$

Flavor composition

Astrophysical neutrino sources

Earth

Up to a few Gpc



ν_e

ν_μ

ν_τ

Flavor mixing changes the number

of ν of each flavor, N_e, N_μ, N_τ

ν_e

ν_μ

ν_τ

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

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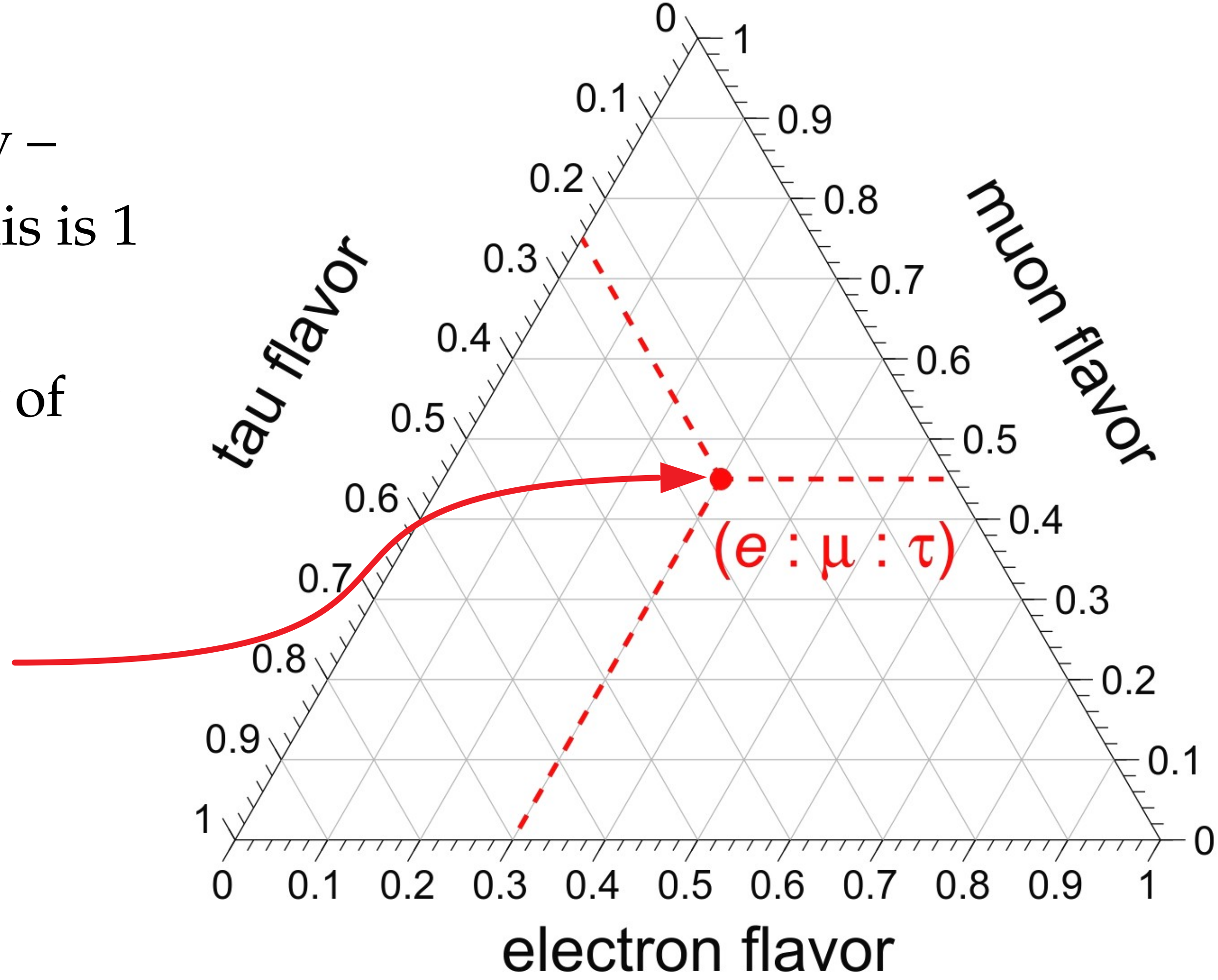
Standard oscillations
or
new physics

Reading 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, *e.g.*,

$(e : \mu : \tau) = (0.30 : 0.45 : 0.25)$



One likely TeV–PeV ν production scenario:

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

Full π decay chain

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

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

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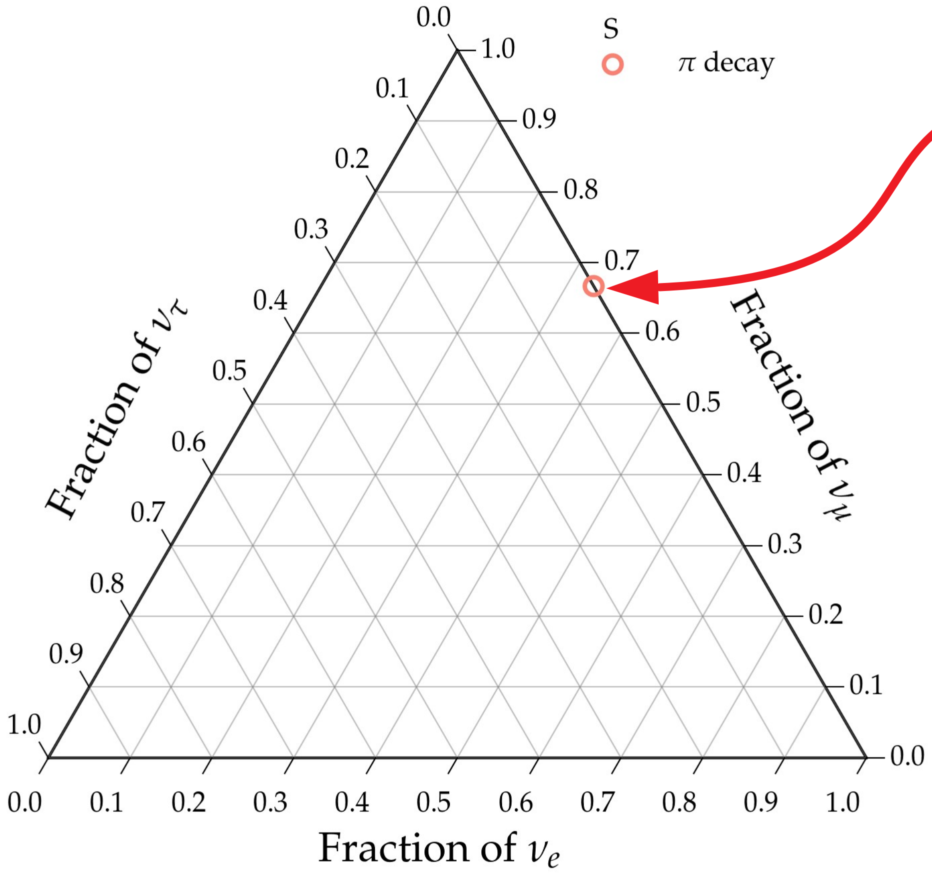

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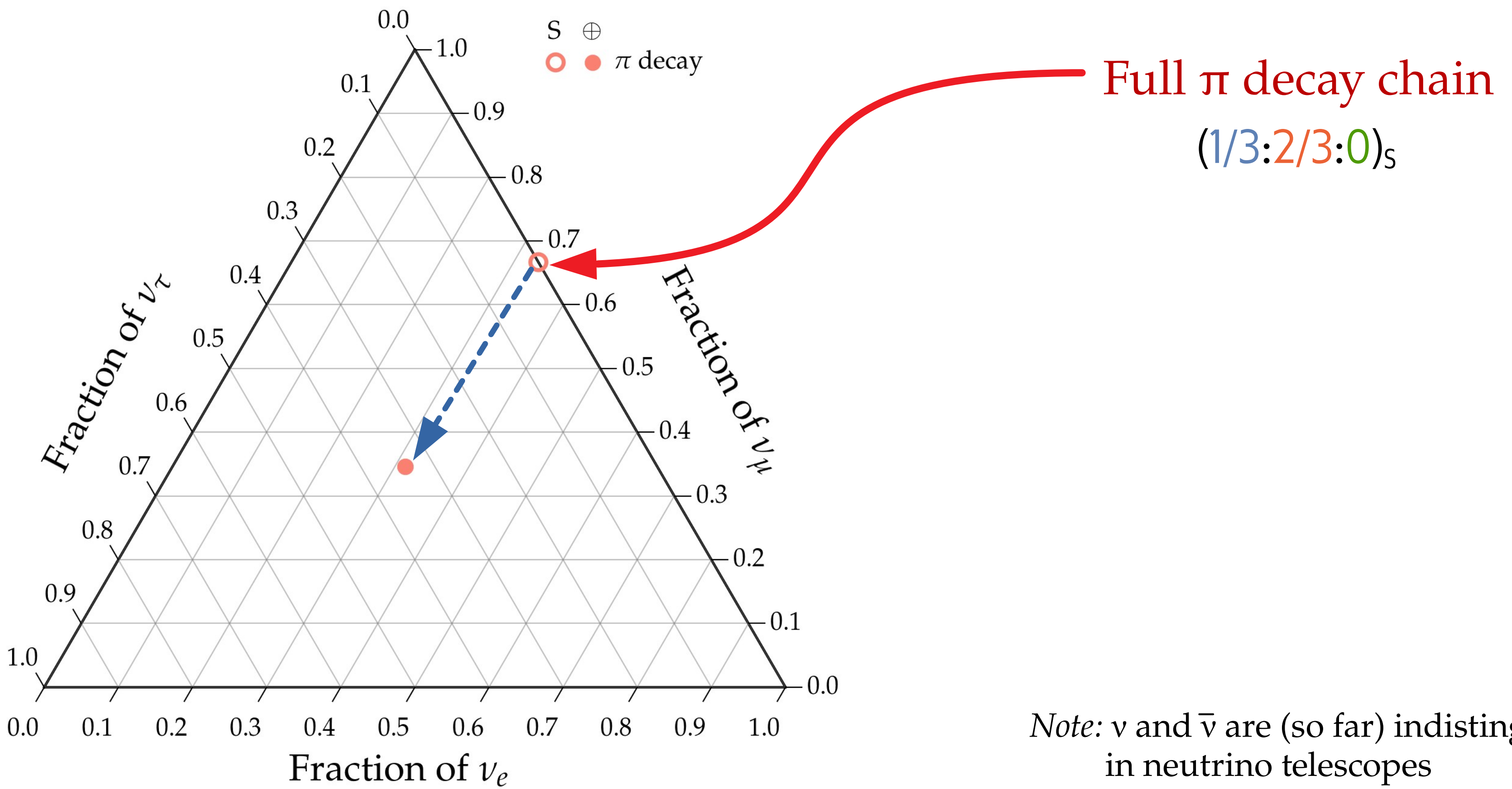

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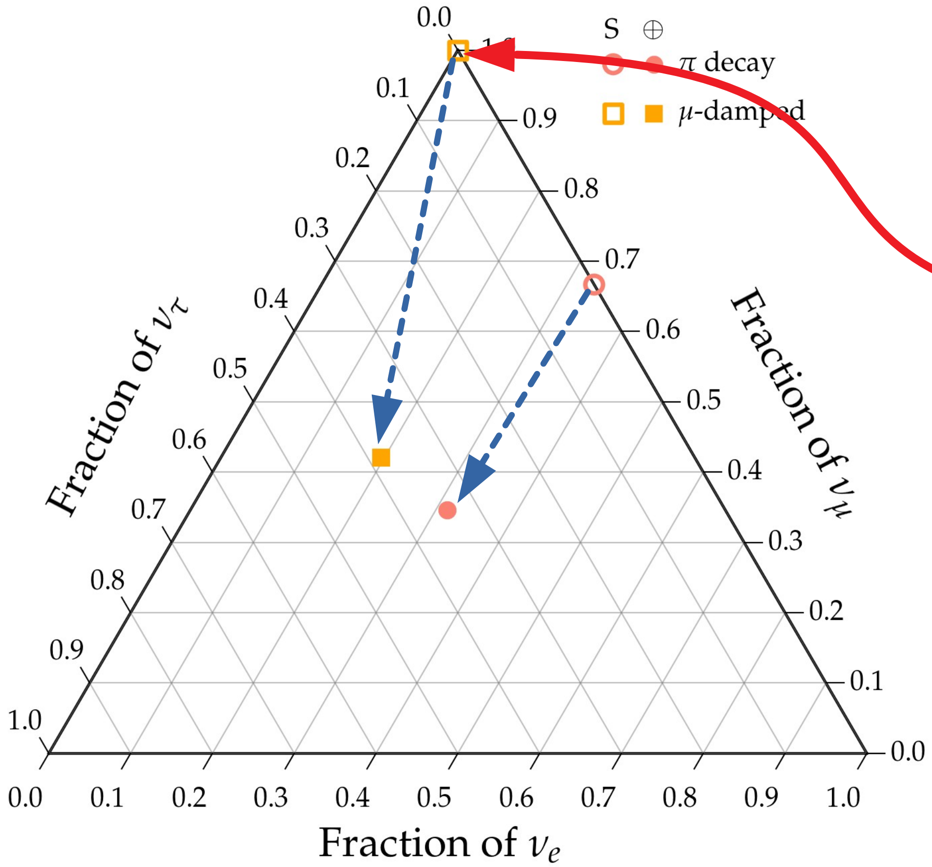

Full π decay chain

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

Muon damped

$(0:1:0)_S$

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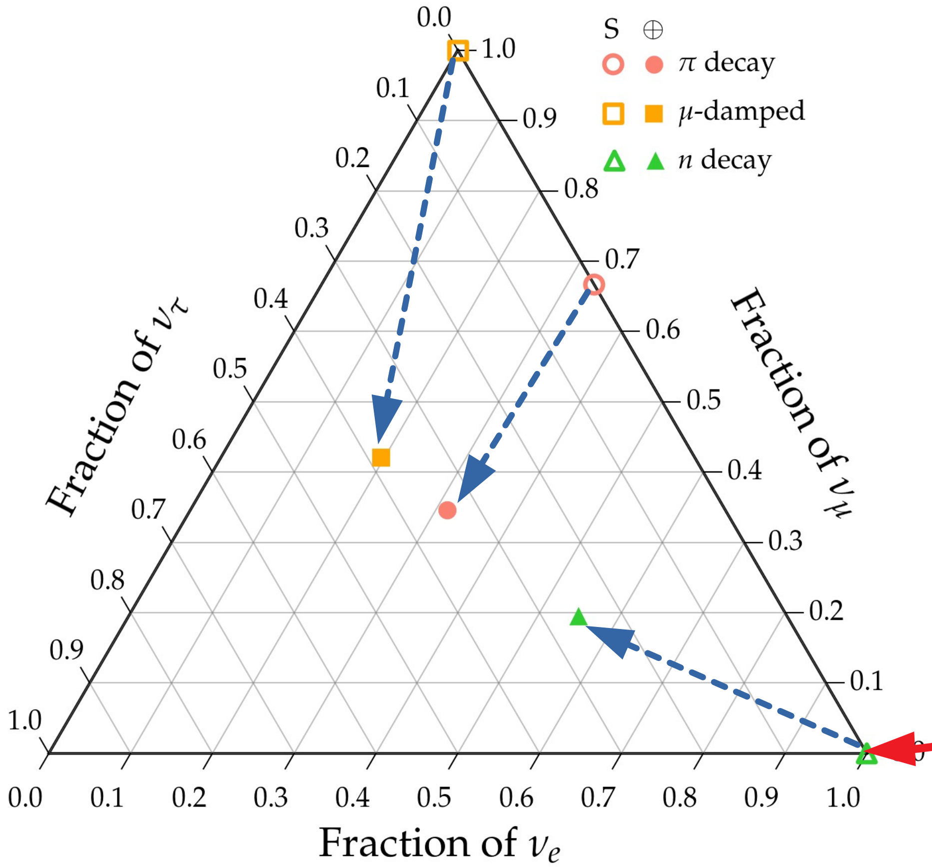

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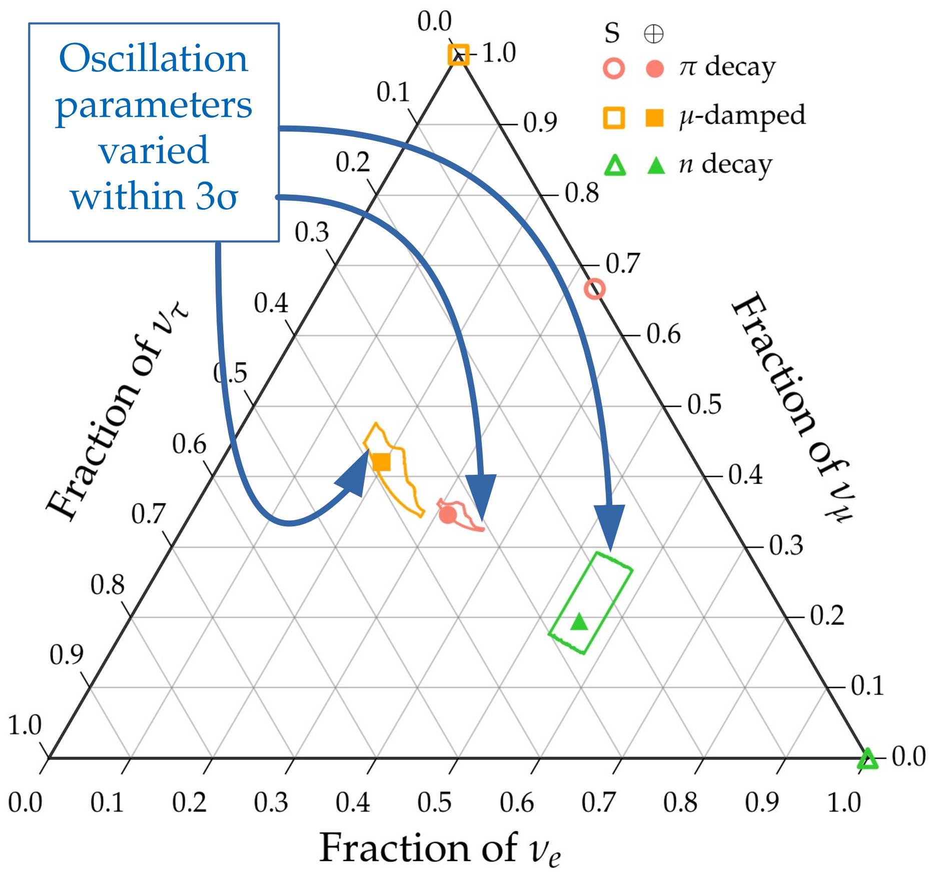

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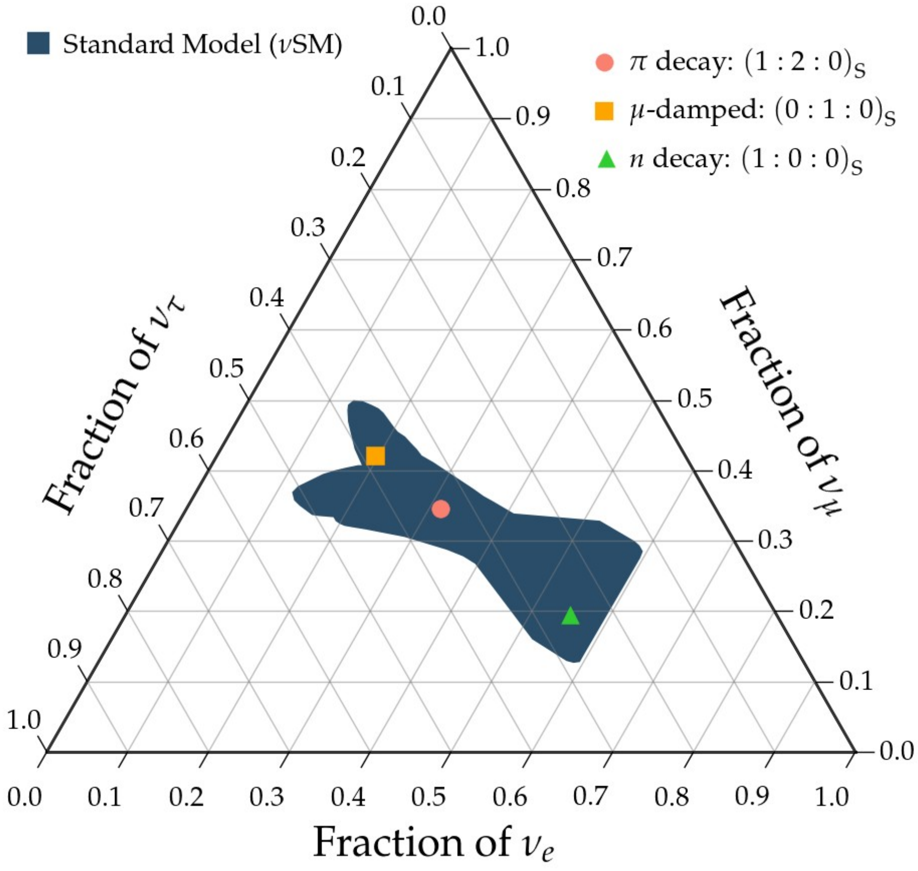


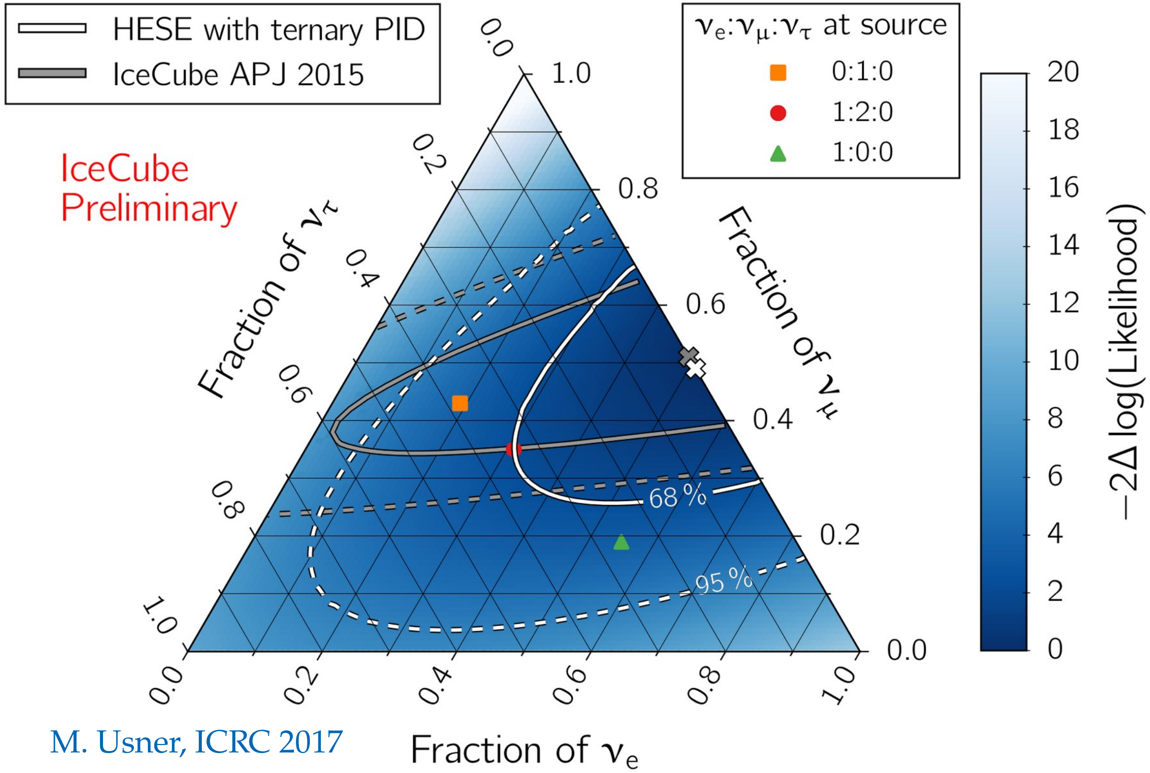
All possible flavor ratios at the sources

+

Vary oscillation parameters within 3σ

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

IceCube results: Flavor composition



M. Usner, ICRC 2017

- Compare number of tracks (ν_μ) *vs.* showers (all flavors)
- Best fit: $(f_e : f_\mu : f_\tau)_\oplus = (0.5 : 0.5 : 0)_\oplus$
- Compatible with standard source compositions
- Lots of room for improvement: more statistics, better flavor-tagging

Li, **MB**, Beacom *PRL* 2019

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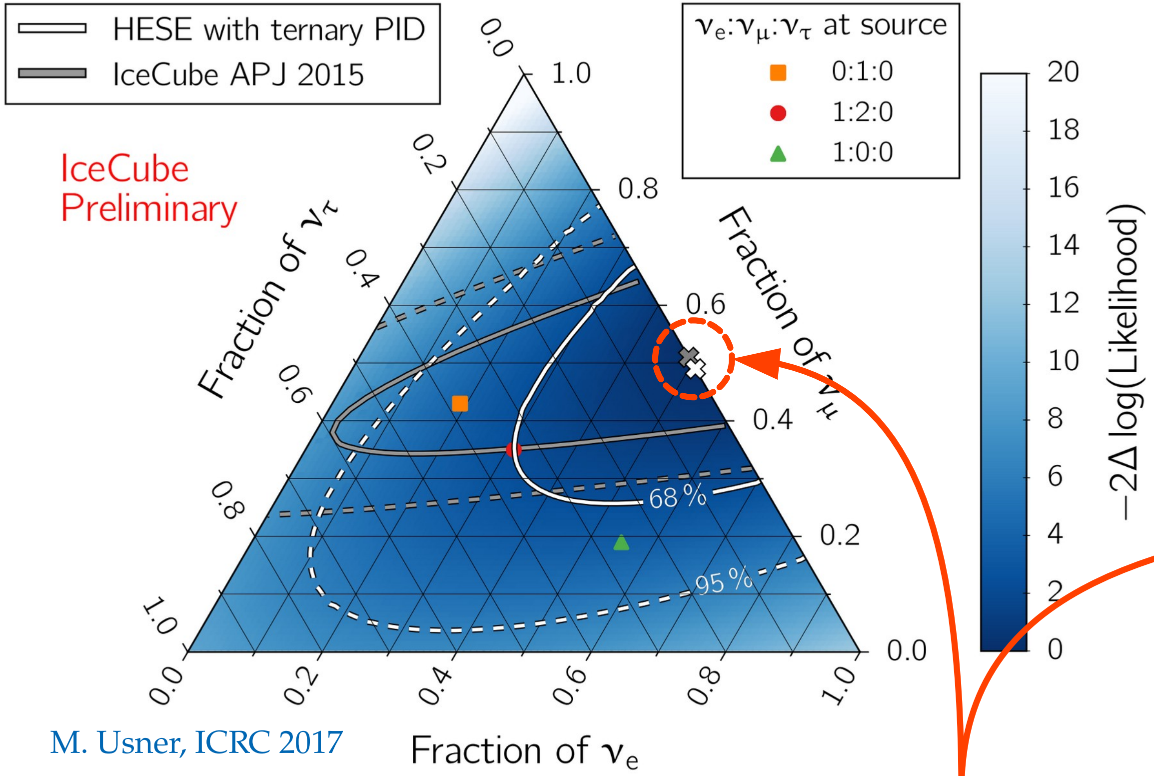

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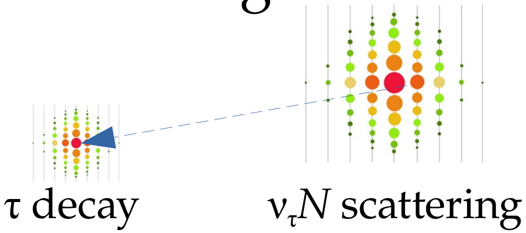
Li, **MB**, Beacom *PRL* 2019

Until yesterday!

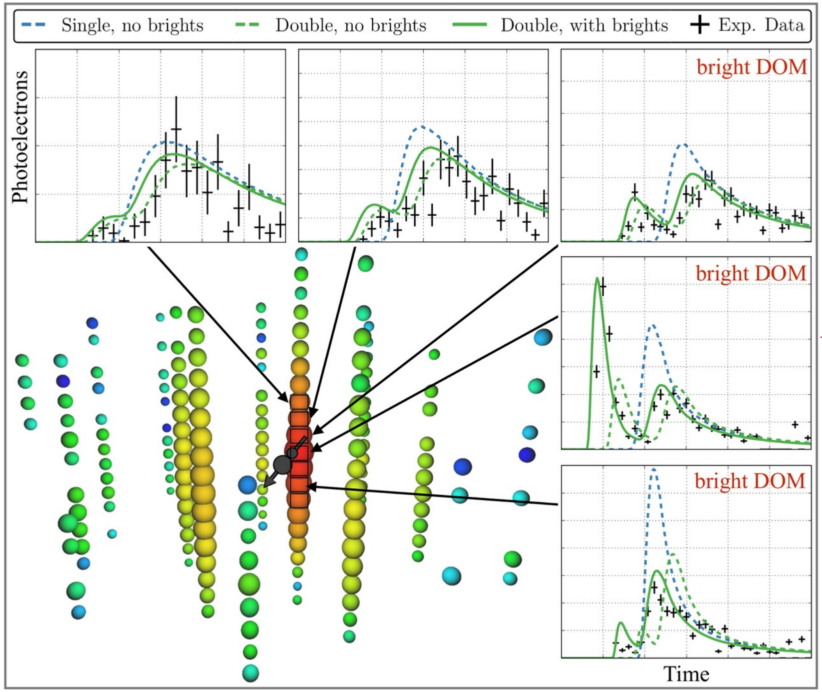
New (IC 7.5 yr): First identified high-energy astrophysical ν_τ

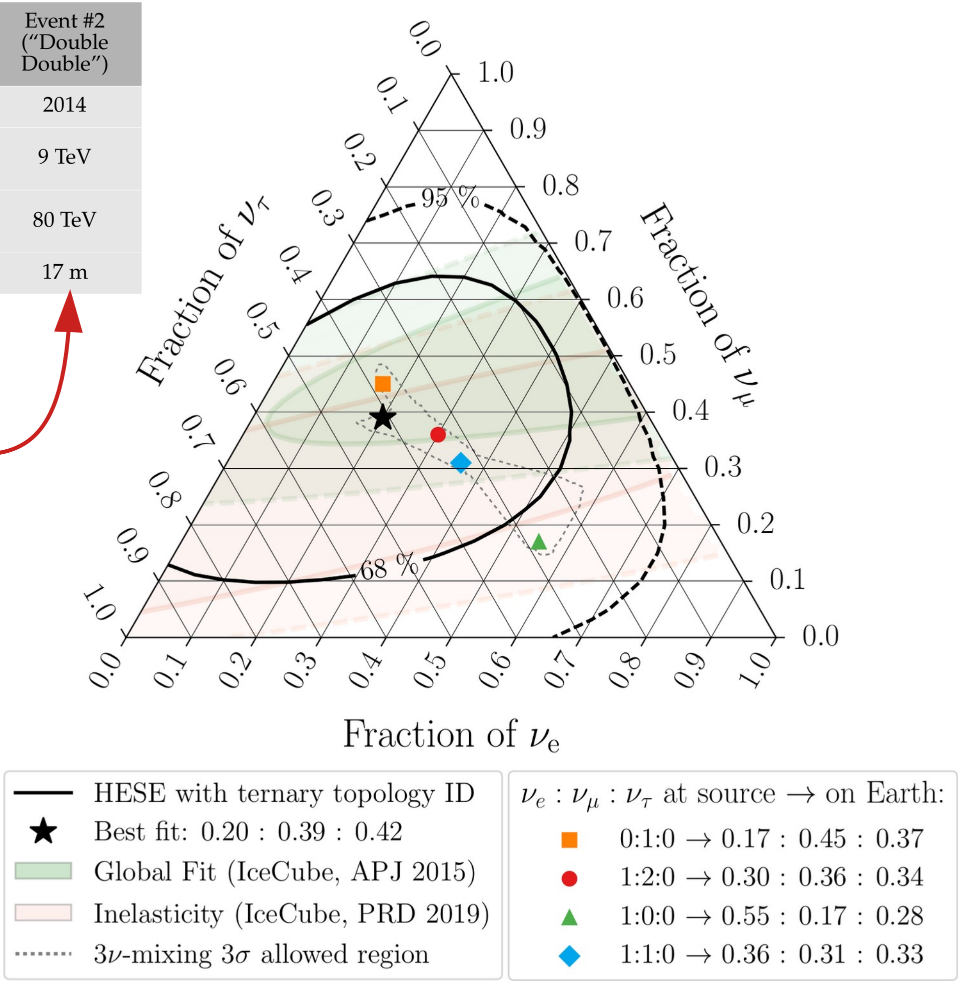
Double bang:



	Event #1 ("Big Bird")	Event #2 ("Double Double")
Year	2012	2014
Energy 1st cascade	1.2 PeV	9 TeV
Energy 2nd cascade	0.6 PeV	80 TeV
Length	16 m	17 m

Most likely to be a ν_τ





IceCube, 2011.03561

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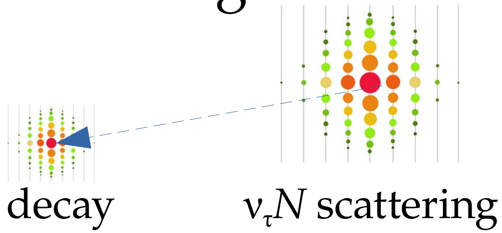

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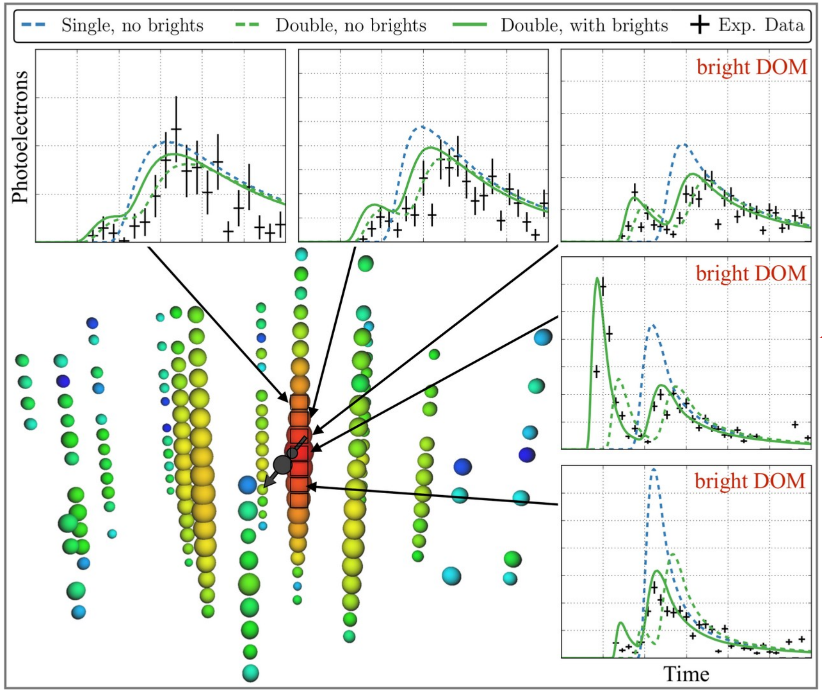
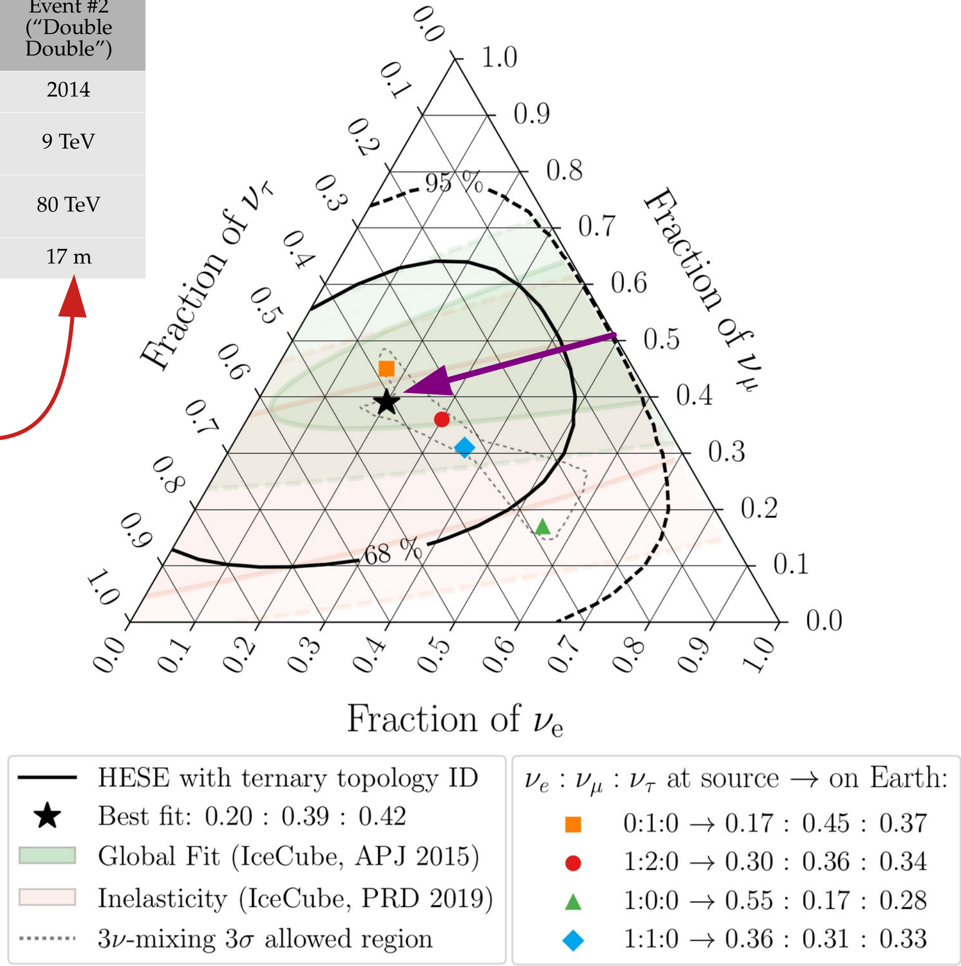




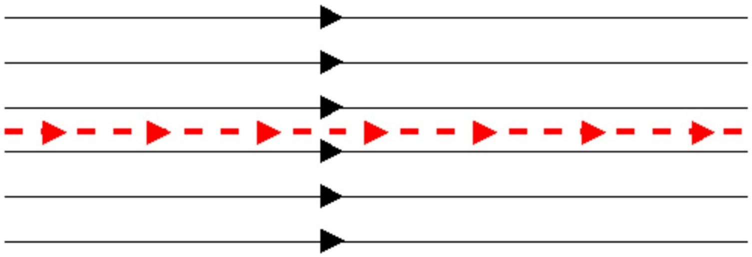
IceCube, 2011.03561

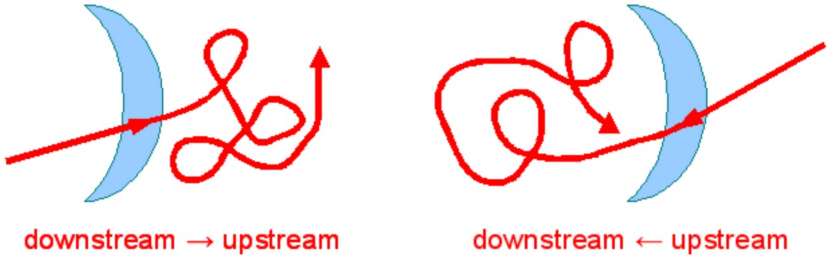
II.
Astrophysics with high-energy cosmic neutrinos

Jellyfish Nebula ,
NASA

Luckily, UHECR Sources Should Be Wasteful…

	Man-made accelerators	Astrophysical accelerators





	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

The Hillas criterion

- Necessary condition for a source to accelerate cosmic rays

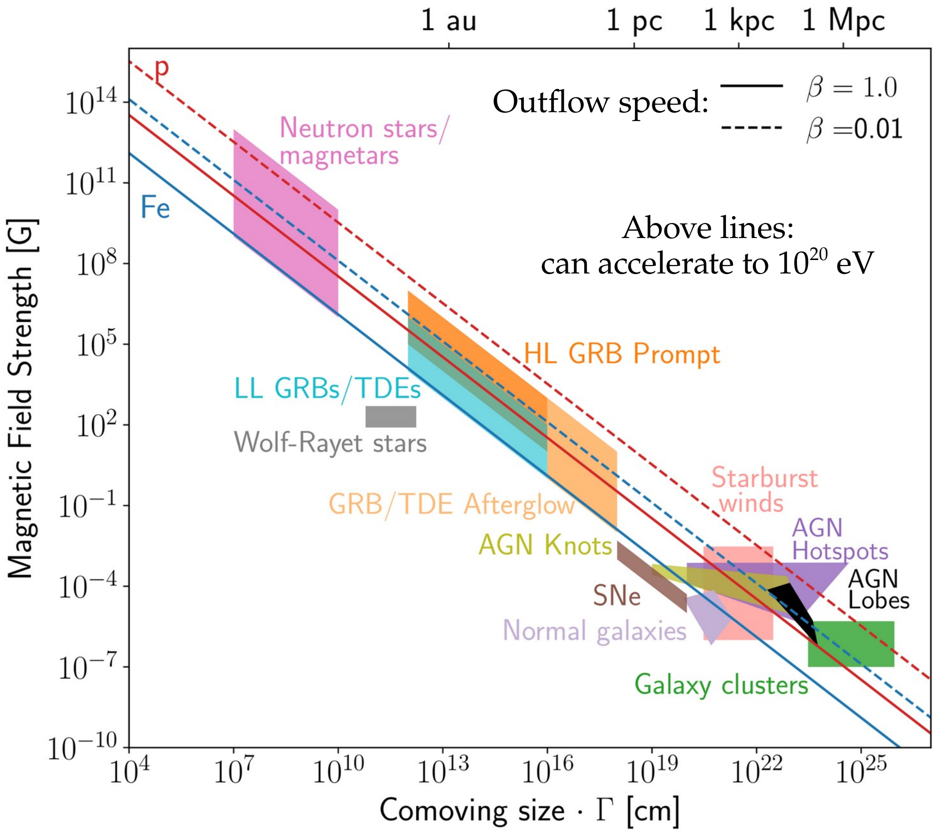
- Particles must stay confined:

Larmor radius < Size of acceleration region

$$R_L = E/(Z\,e\,B) < (R\,\Gamma)$$

- Maximum energy:

$$E_{\max} \approx \left(3 \cdot 10^{20}\ \mathrm{eV}\right) \eta^{-1} \beta_{\rm sh} Z \left(\frac{\Gamma R}{10^{16}\ \mathrm{cm}}\right) \left(\frac{B}{100\ \mathrm{G}}\right)$$



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

Alves Batista, **MB** *et al.*, *Frontiers* 2019
See also: Winter, *PRD* 2011

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Bulk Lorentz factor of accelerating region

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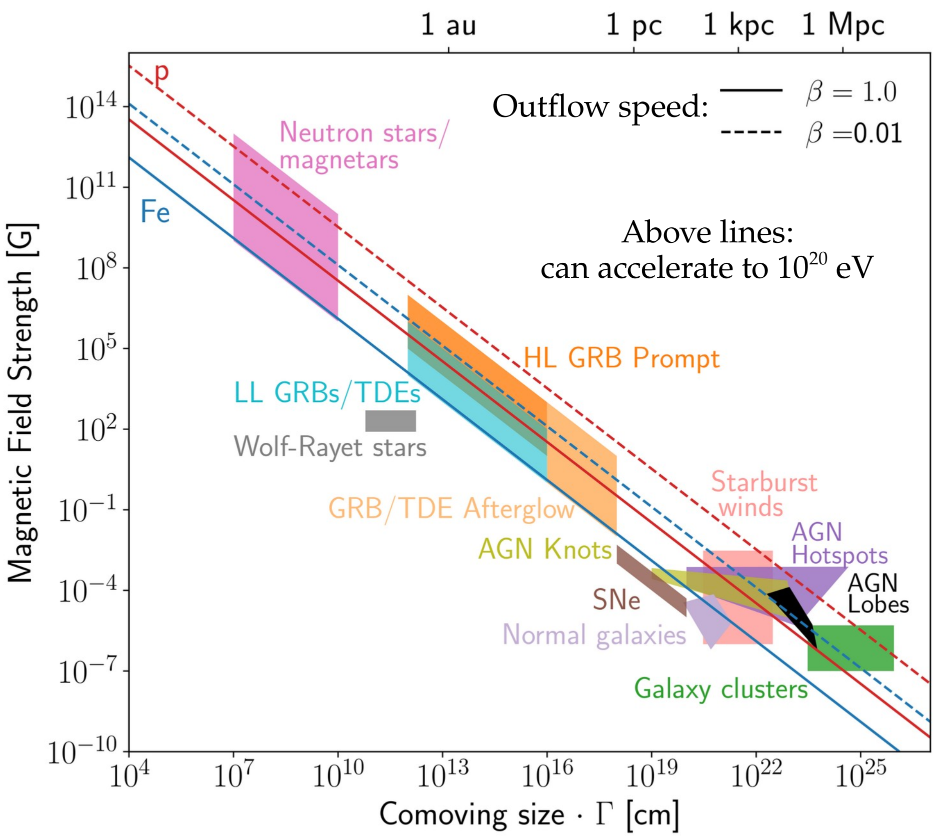

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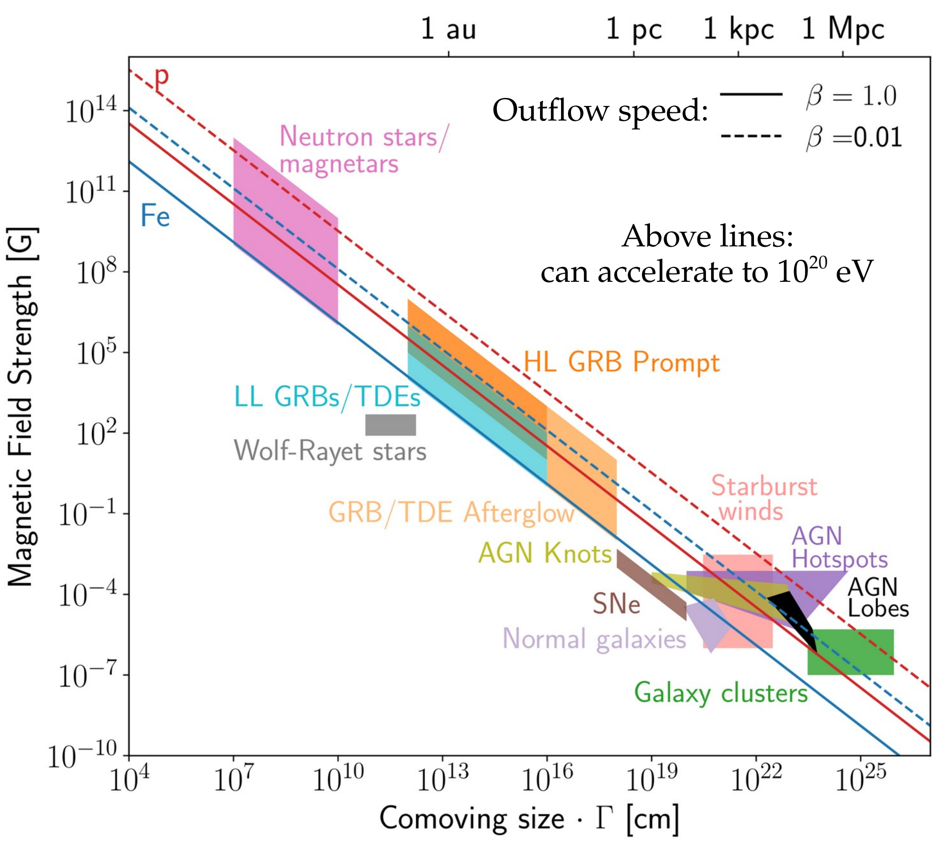
Bulk Lorentz factor of accelerating region

- Maximum energy:

Acceleration efficiency ($\eta = 1$ for perfect efficiency)

$$E_{\rm max} \approx \left(3 \cdot 10^{20}~{\rm eV}\right) \eta^{-1} \beta_{\rm sh} Z \left(\frac{\Gamma R}{10^{16}~{\rm cm}}\right) \left(\frac{B}{100~{\rm G}}\right)$$

Speed $v_{\rm sh}/c$ of the outflow



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

Alves Batista, **MB** *et al.*, *Frontiers* 2019
See also: Winter, *PRD* 2011

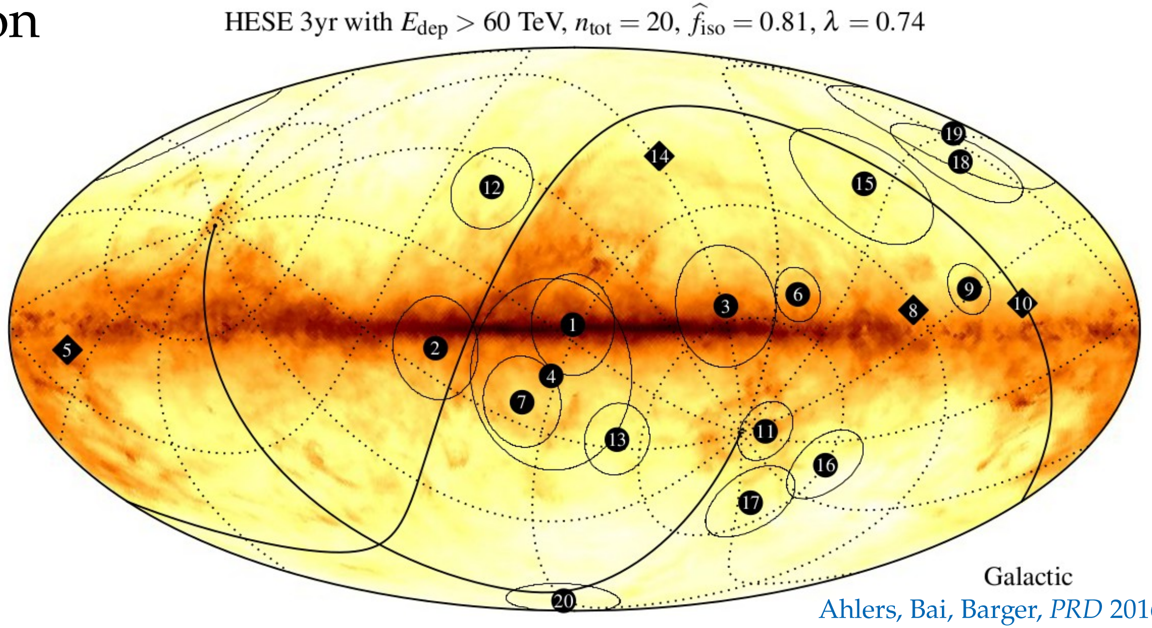
Three strategies to reveal sources of TeV–PeV ν

- **Look at bright e.m. point sources**
  - Examine single sources → No evident single steady source, *one* transient source
  - Stack several similar sources → Ruled out gamma-ray bursts, blazars as dominant
- **Look for neutrino multiplets**
  - Clustered in direction → Placed generic limits on source number density and luminosity
  - Clustered in direction *and* time → Used to trigger follow-ups by other detectors
- **Use the diffuse neutrino flux** → Any population of candidate sources must account for all or part of it

PeV neutrino sources in the Milky Way?

Candidates for full or partial contribution:

- ▶ Diffuse Galactic gamma-ray emission
- ▶ Unidentified gamma-ray sources
- ▶ Fermi bubbles
- ▶ Supernova remnants
- ▶ Pulsars
- ▶ Microquasars
- ▶ Sagitarius A*
- ▶ Galactic halo
- ▶ Heavy dark matter decay

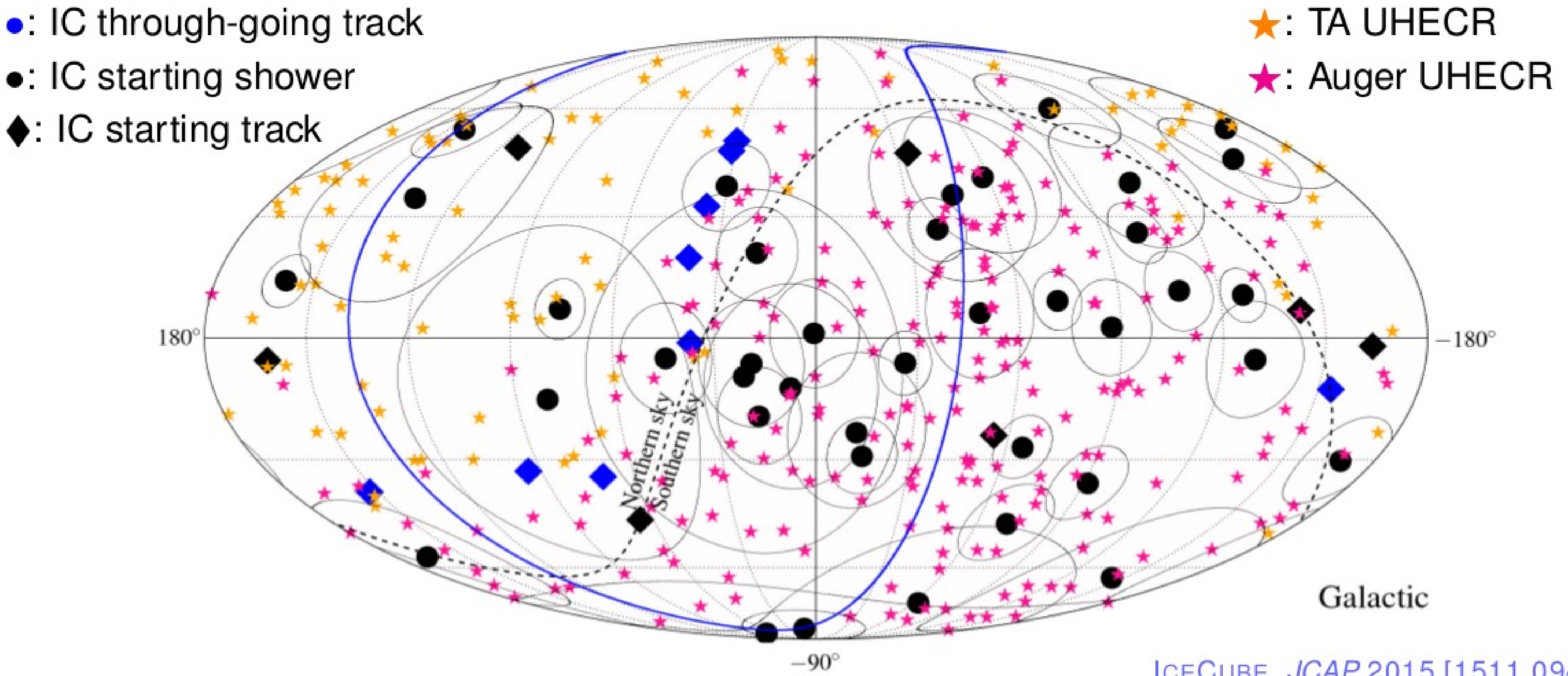


Ahlers, Bai, Barger, *PRD* 2016

Contribution from Galactic sources: < 14%

IceCube, *ApJ* 2017

Neutrino–UHECR angular correlation?



IceCube, *JCAP* 2015 [1511.09408]

No significant correlation with UHECRs (<3.3σ)

Bright in gamma rays, bright in high-energy neutrinos

Energy in neutrinos ∝ energy in gamma rays

$$\int_0^\infty \mathrm{d}E_\nu E_\nu F_\nu(E_\nu) = \frac{1}{8}\left[1 - \left(1 - \langle x_{p\to\pi}\rangle\right)^{\tau_{p\gamma}}\right] \frac{f_p}{f_e} \int_{1\ \mathrm{keV}}^{10\ \mathrm{MeV}} \mathrm{d}E_\gamma E_\gamma F_\gamma(E_\gamma)$$

E. Waxman & J. Bahcall, *PRL* 1997
D. Guetta *et al.*, *Astropart. Phys.* 2004

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Fraction of total p energy given to pions

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Baryonic loading

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Fraction of total p energy given to pions

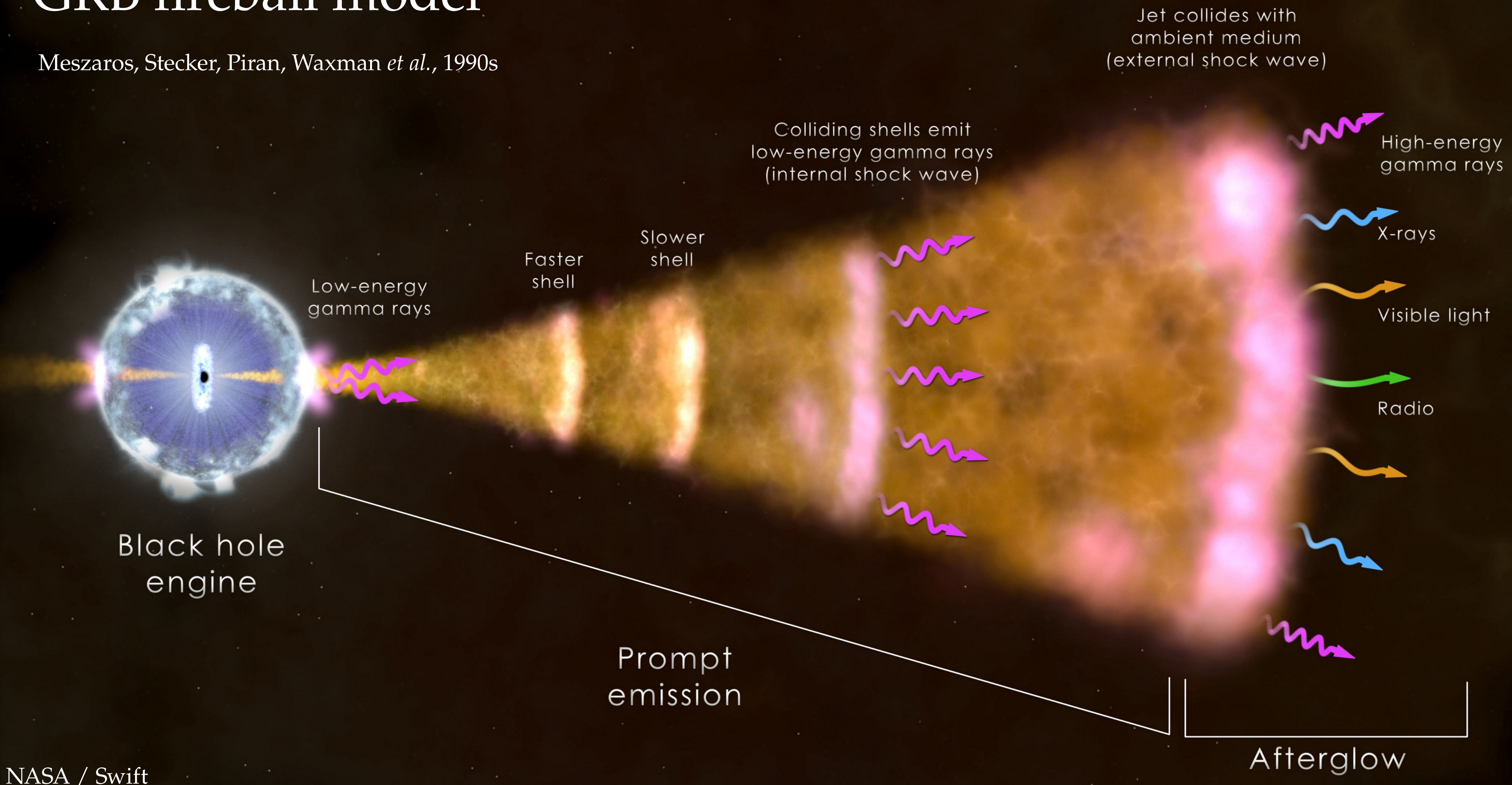
Baryonic loading

Optical depth to $p\gamma$: $$\tau_{p\gamma} = \left(\frac{L_\gamma^{\mathrm{iso}}}{10^{52} \mathrm{erg s}^{-1}}\right)\left(\frac{0.01}{t_\mathrm{v}}\right)\left(\frac{300}{\Gamma}\right)^4\left(\frac{\mathrm{MeV}}{\epsilon_{\gamma,\mathrm{break}}}\right)$$

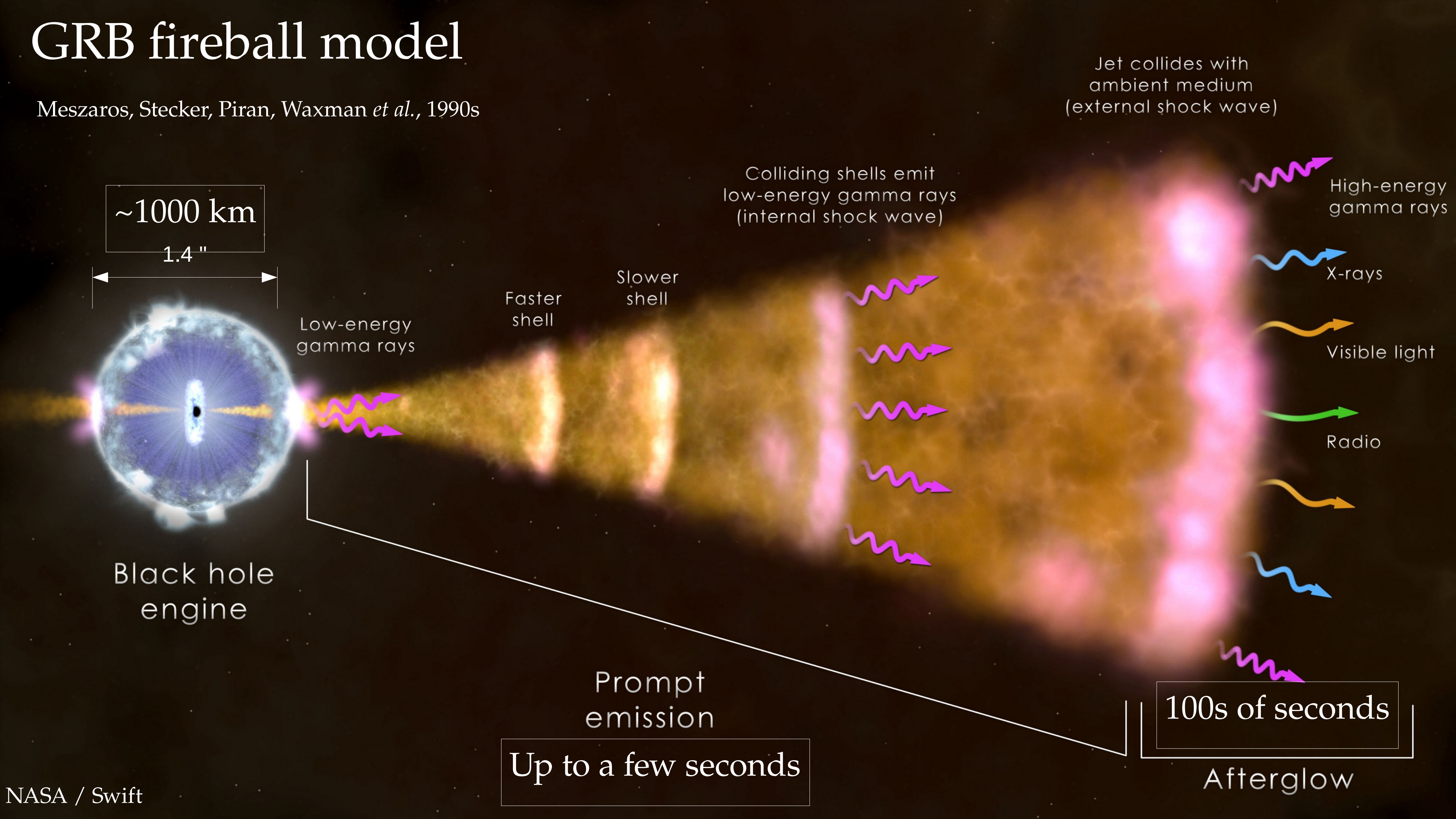
E. Waxman & J. Bahcall, *PRL* 1997
D. Guetta *et al.*, *Astropart. Phys.* 2004

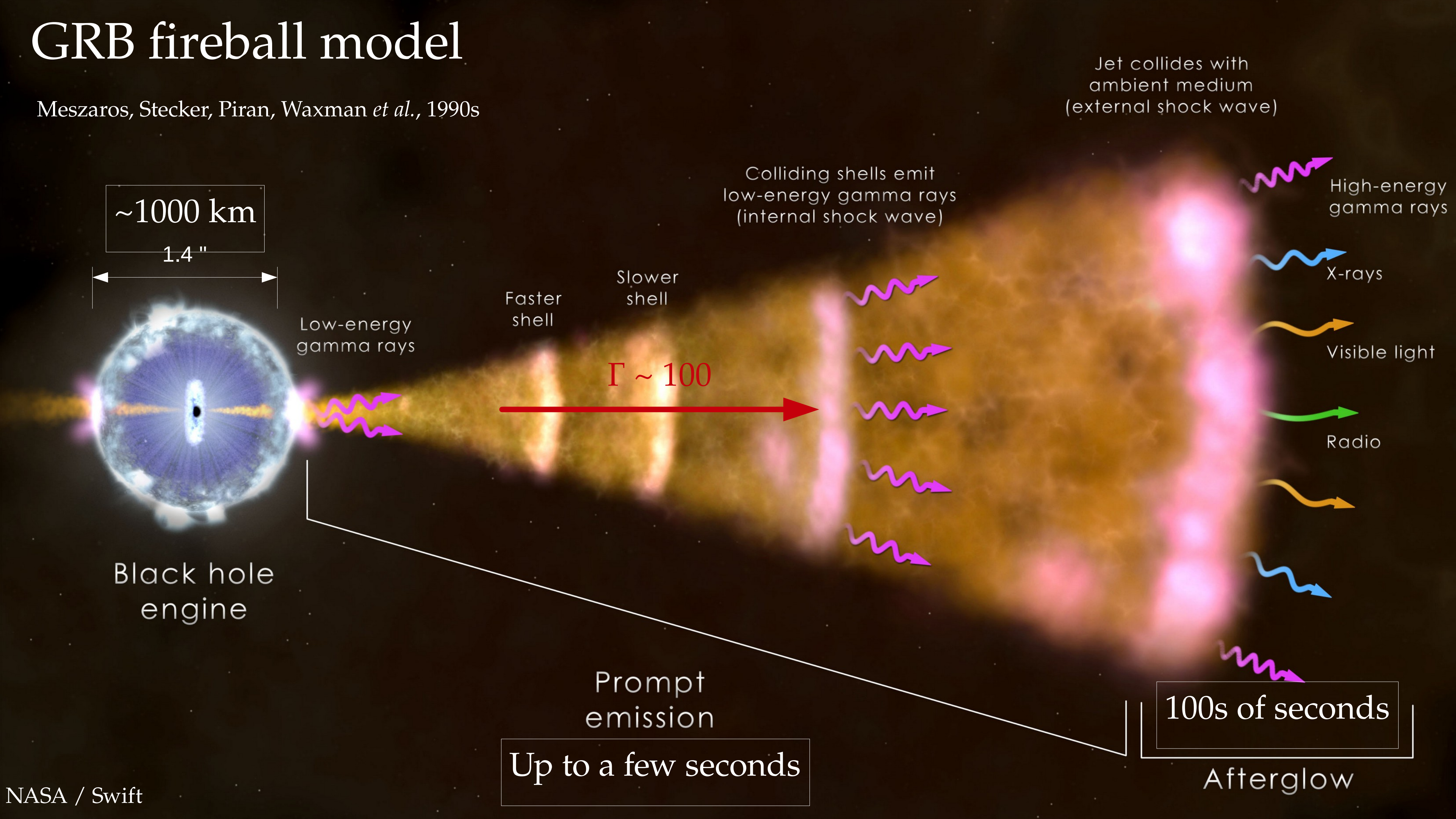
GRB fireball model

Meszaros, Stecker, Piran, Waxman *et al.*, 1990s



NASA / Swift


GRB fireball model
Meszaros, Stecker, Piran, Waxman *et al.*, 1990s
~1000 km
1.4 "
Black hole engine
Low-energy gamma rays
Faster shell
Slower shell
Colliding shells emit low-energy gamma rays (internal shock wave)
Jet collides with ambient medium (external shock wave)
High-energy gamma rays
X-rays
Visible light
Radio
Prompt emission
Up to a few seconds
100s of seconds
Afterglow
NASA / Swift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Faster shell
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Γ ~ 100
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Jet collides with ambient medium (external shock wave)
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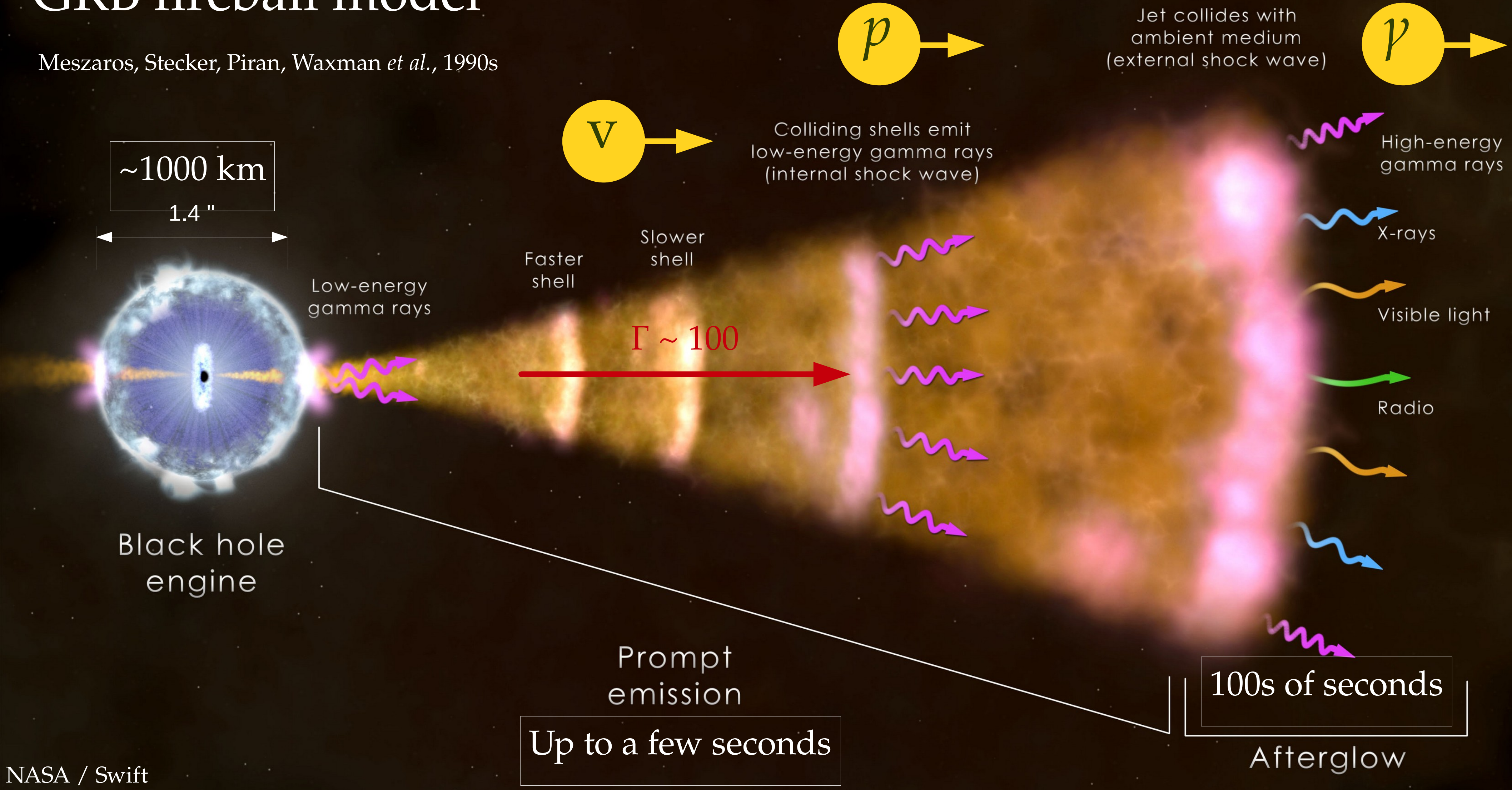
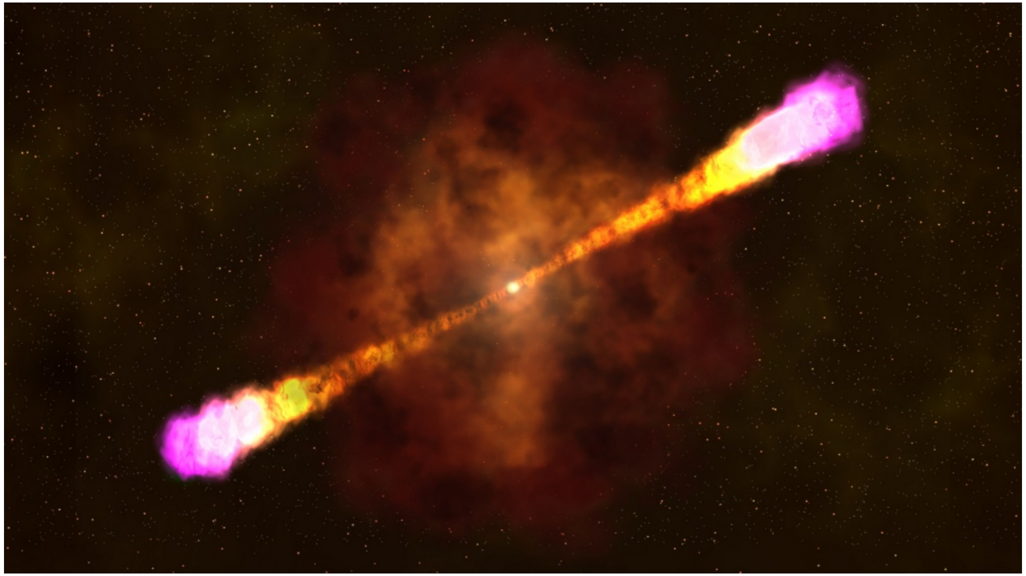


NASA / Swift

Gamma-ray bursts and blazars – *not* dominant

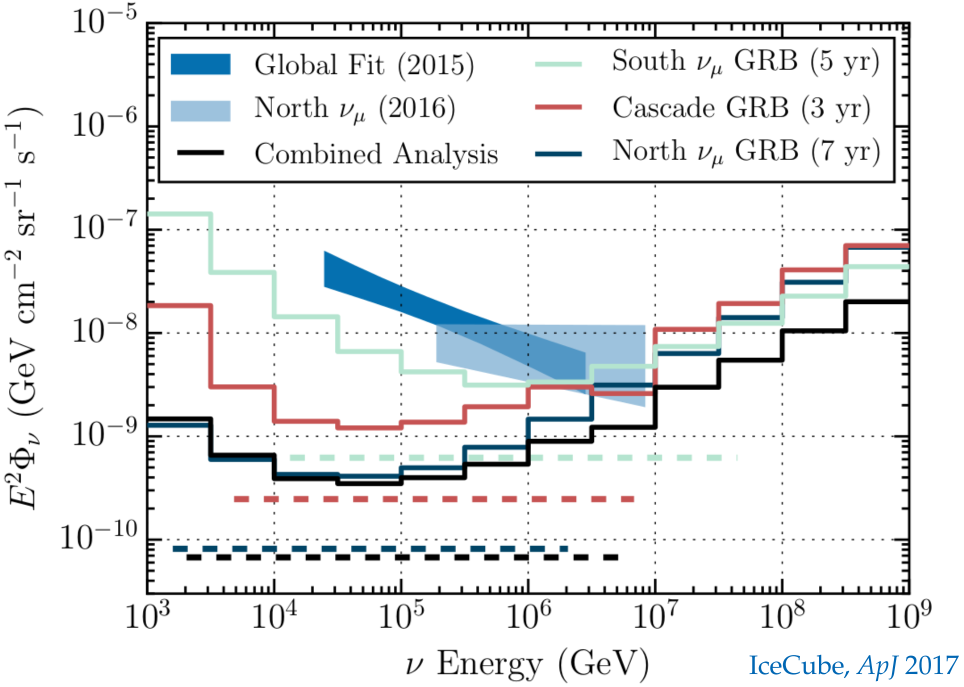
Gamma-ray bursts



Blazars

Gamma-ray bursts and blazars – *not* dominant

Gamma-ray bursts

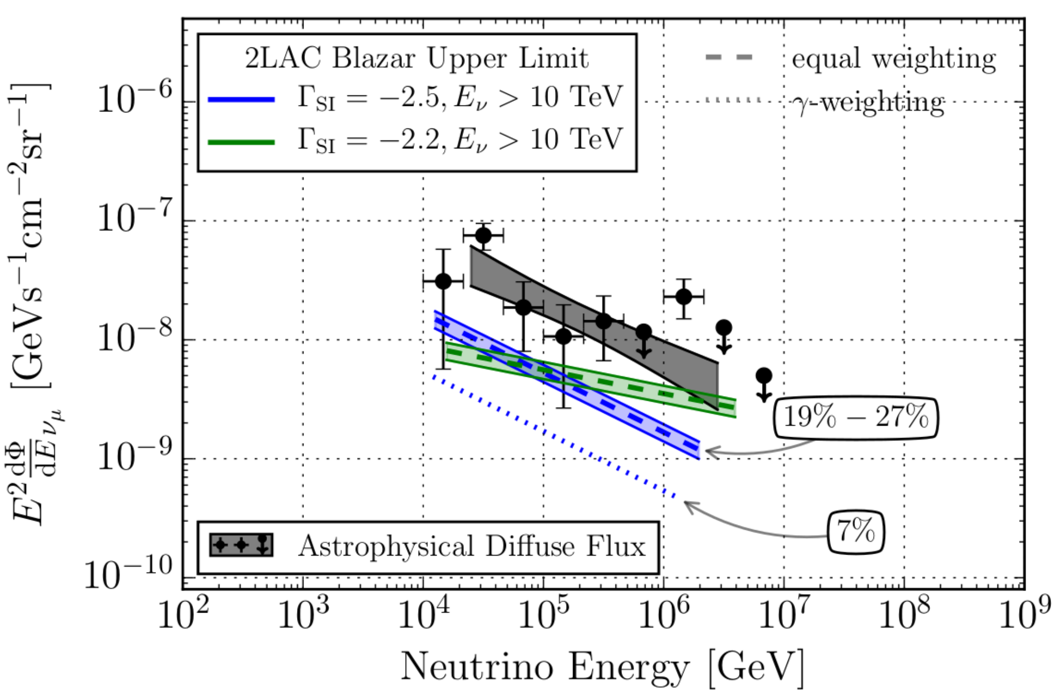


IceCube, *ApJ* 2017

1172 GRBs inspected, no correlation found

< 1% contribution to diffuse flux

Blazars



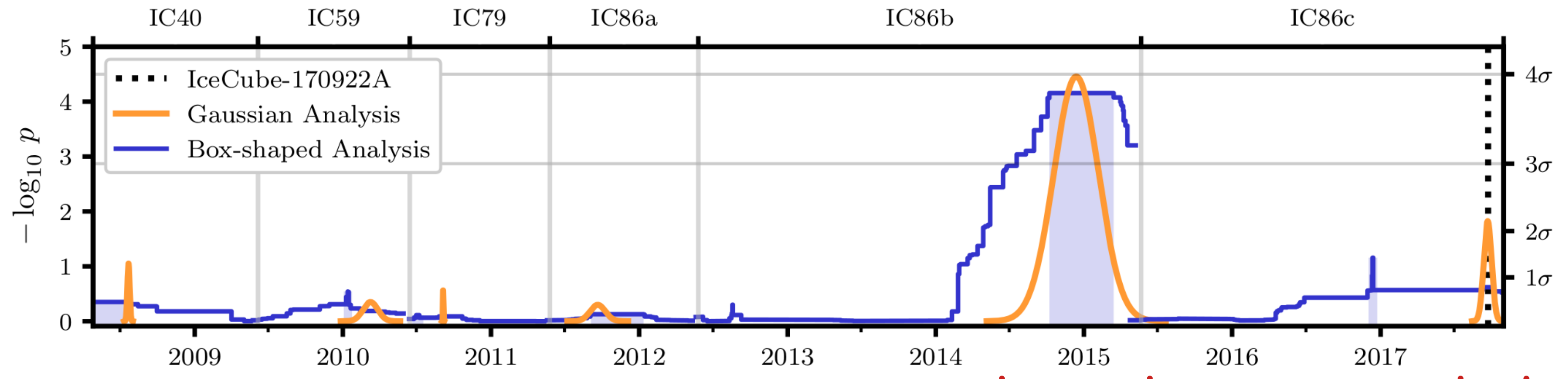
862 blazars inspected, no correlation found

< 27% contribution to diffuse flux

… but we have seen *one* blazar neutrino flare!

Recent news:
The starburst Seyfert galaxy NGC 1068 is also a potential neutrino source candidate (1908.05993)

Blazar TXS 0506+056:



Important:
If every blazar produced neutrinos as TXS 0506+056, the diffuse neutrino flux would be 20x higher than observed!

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

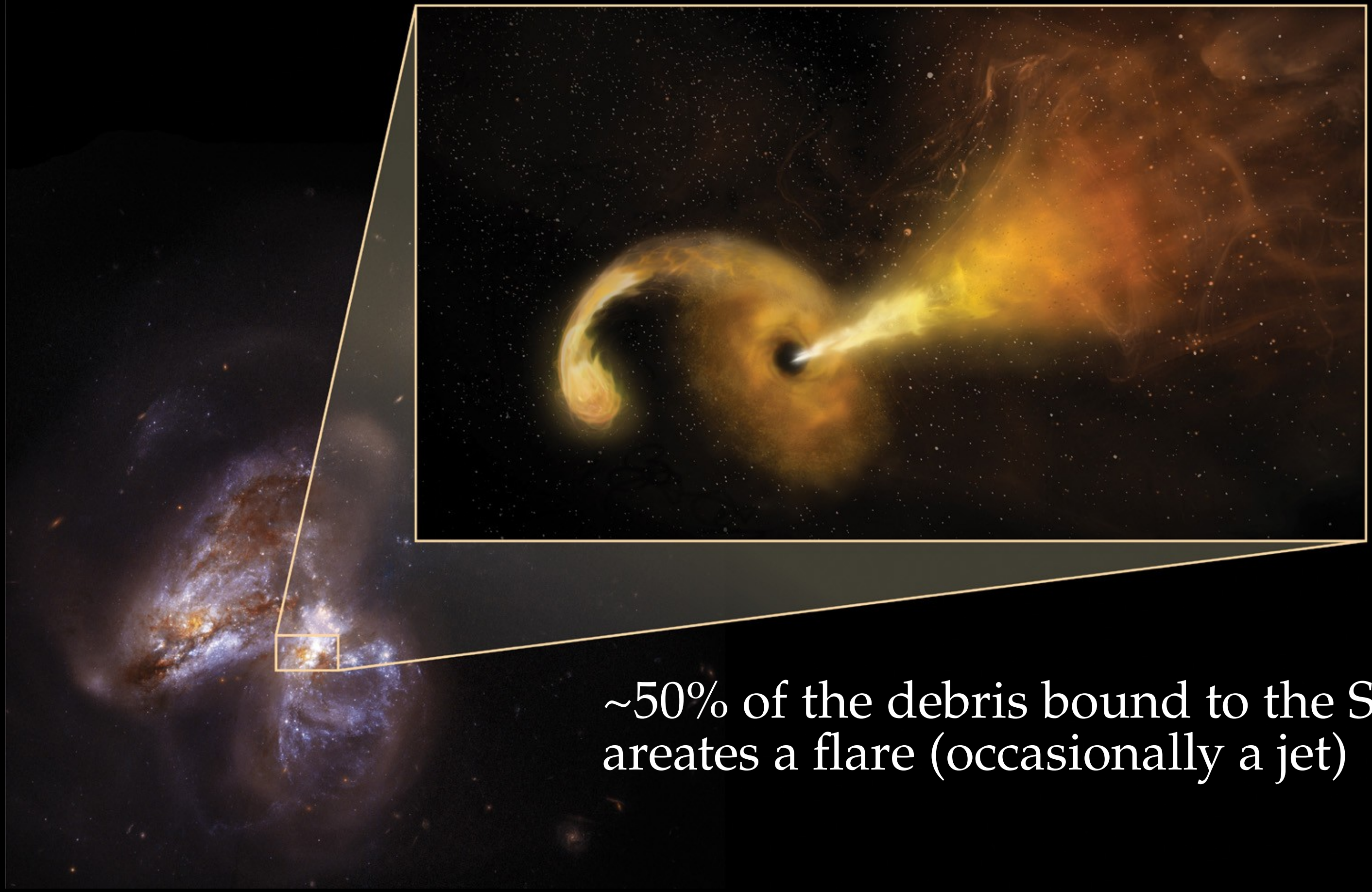
Combined (pre-trial): 4.1σ

Hard fluence: $E^2 J_{100} = 2.1^{+0.9}_{-0.7} \left(\frac{E}{100\ \mathrm{TeV}}\right)^{-2.1\pm0.2}\ \mathrm{TeV\ cm^{-2}}$

Joint modeling of the two periods is challenging; see ICRC 2019 talk by Walter Winter

Tidal disruption events

Solar-mass star disrupted by SMBH (>10^5 $M_\odot$)



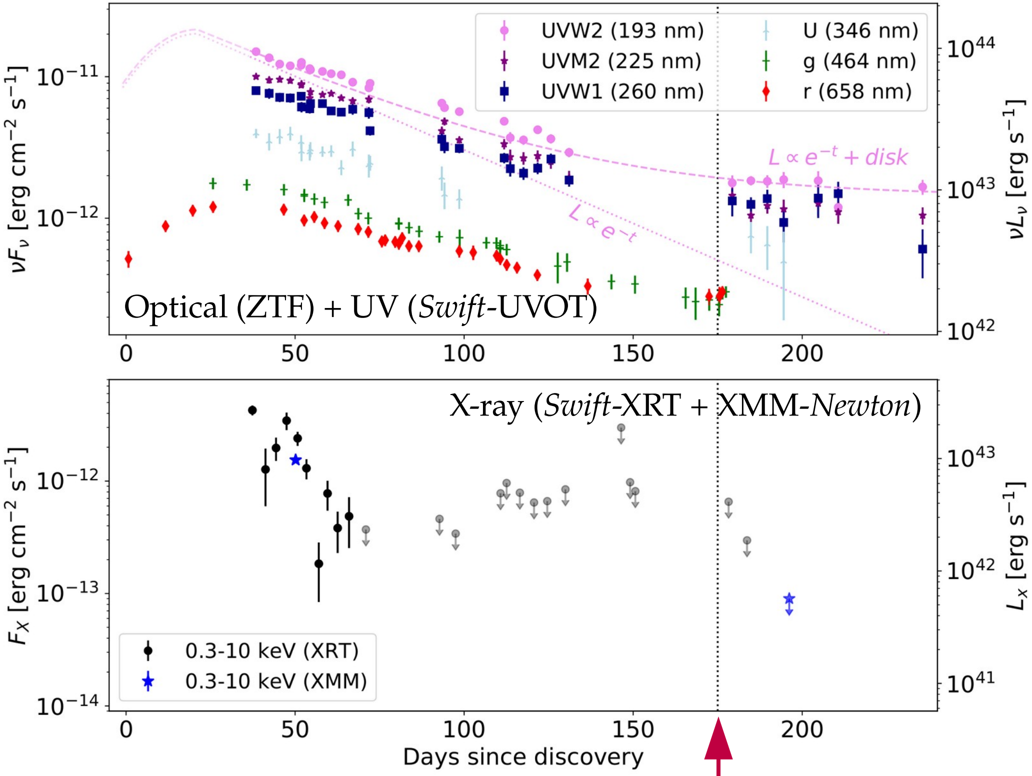
~50% of the debris bound to the SMBH, areates a flare (occasionally a jet)

NASA

An apparent TDE neutrino source

Radio-emitting TDE AT2019dsg coincident with neutrino event IC191001A:

AT2019dsg: Apr 9, 2019 / $z = 0.051$ (230 Mpc) / $M_{BH} = 3 \times 10^7 M_\odot$

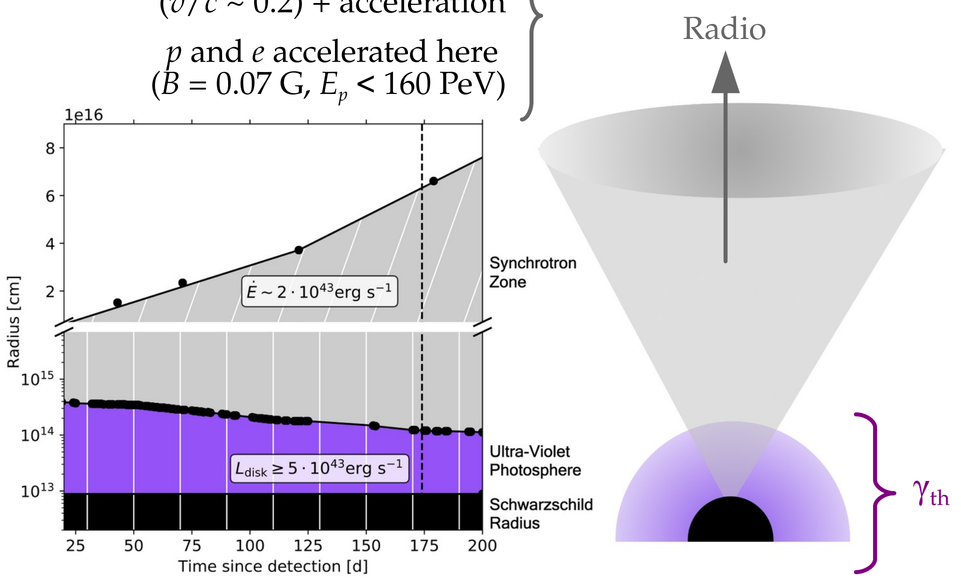


IC191001A, ~200 TeV

Multi-zone model:

From radio:
mildly relativistic expansion
($v/c \sim 0.2$) + acceleration

p and e accelerated here
($B = 0.07$ G, $E_p < 160$ PeV)



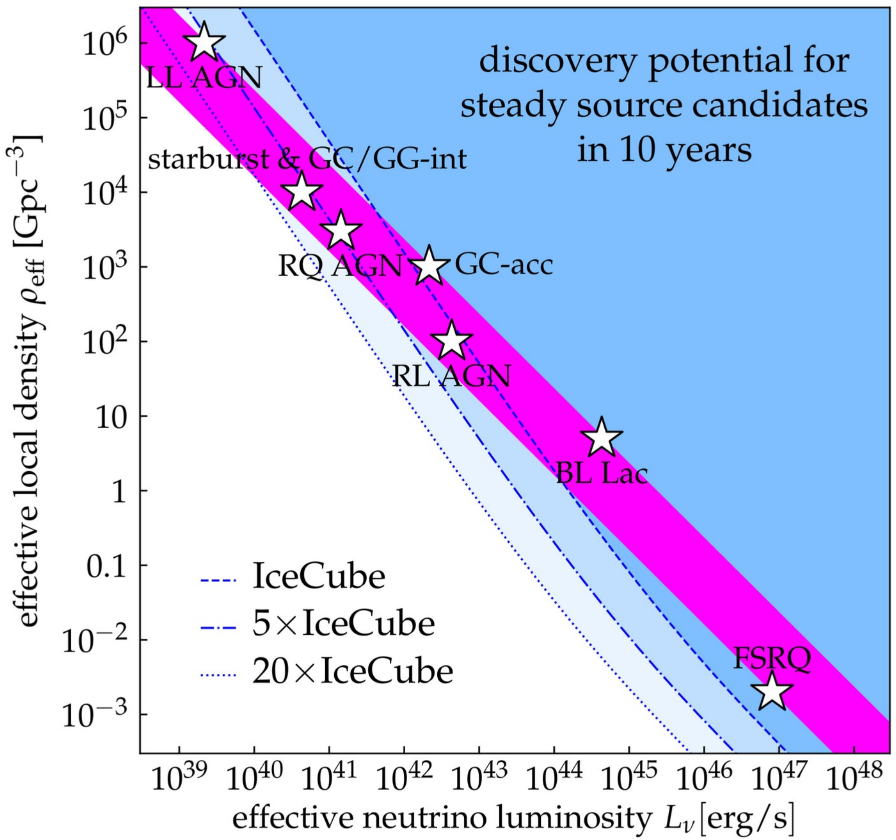
$p + \gamma_{th}$ (or p) $\rightarrow \nu$

Stein *et al.*, 2005.05340 – See also: Winter & Lunardini, 2005.06097; Murase *et al.*, 2005.08937

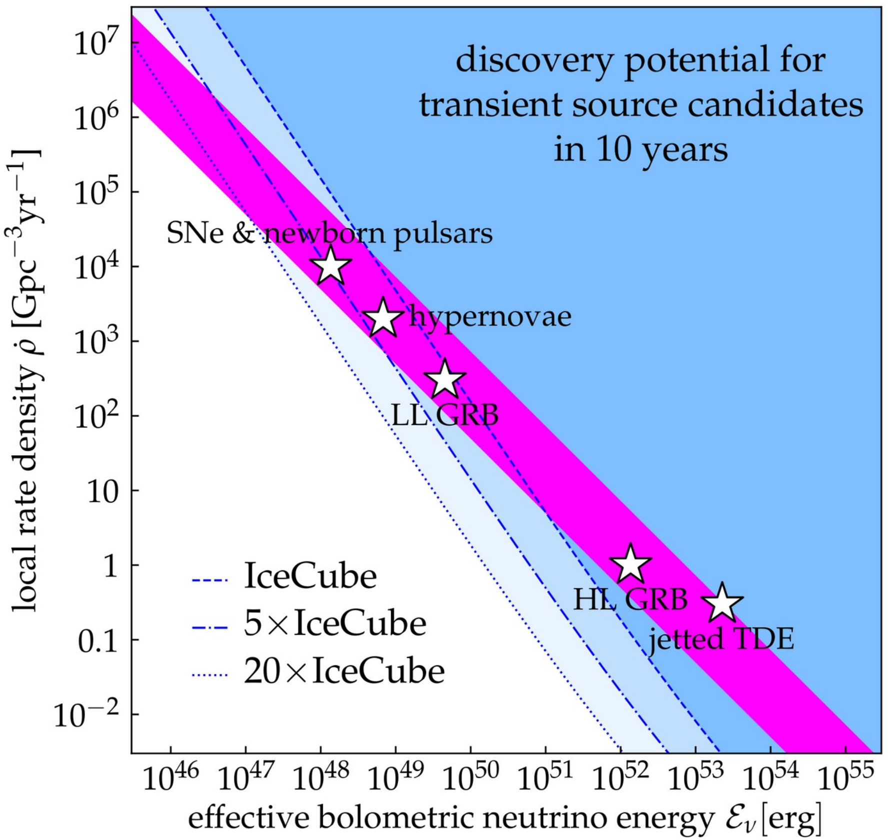
Source discovery potential: today and in the future

Accounts for the observed diffuse ν flux (lower/upper edge: rapid/no redshift evolution)

Closest source with $E^2\Phi_{\nu_\mu+\bar{\nu}_\mu} = 10^{-12}$ TeV cm^{-2} s^{-1}



Closest source with $E^2F_{\nu_\mu+\bar{\nu}_\mu} = 0.1$ GeV cm^{-2}



Ackermann, **MB** *et al.*, Astro2020 Survey (1903.04333) – See also: Silvestri & Barwick, *PRD* 2010; Murase & Waxman, *PRD* 2016

Using high-energy neutrinos as magnetometers

If sources have strong magnetic fields, charged particles cool via synchrotron:

$$p + \gamma(p) \to \pi^{+} \to \mu^{+} + \nu_{\mu}$$
$$\hookrightarrow \bar{\nu}_{\mu} + e^{+} + \nu_{e}$$

MB, I. Tamborra, 2009.01306 (to appear in *PRD*)

Using high-energy neutrinos as magnetometers

If sources have strong magnetic fields, charged particles cool via synchrotron:

Proton cooling

Induce a high-energy cut-off in the emitted ν spectrum:

$$E_\nu'^2 \frac{dN_\nu}{dE_\nu'} \propto E_\nu'^{2-\alpha_\nu} e^{-E_\nu'/E_\nu'^{\max}}$$

$$E_\nu^{\max} \approx \frac{10^{10}\Gamma \text{ GeV}}{\sqrt{B'/\text{G}}}$$

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Muon cooling

Change flavor composition:

$$(f_{e,\text{S}}, f_{\mu,\text{S}}, f_{\tau,\text{S}}) = \begin{cases} (\frac{1}{3}, \frac{2}{3}, 0), & \text{if } E_\nu < E_{\nu,\mu}^{\text{sync}} \\ (0, 1, 0), & \text{if } E_\nu \geq E_{\nu,\mu}^{\text{sync}} \end{cases}$$

$$E_{\nu,\mu}^{\text{sync}} \approx 10^9 \Gamma \frac{\text{G}}{B'} \text{ GeV}$$

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$$p + \gamma(p) \rightarrow \pi^+ \rightarrow \mu^+ + \nu_\mu$$

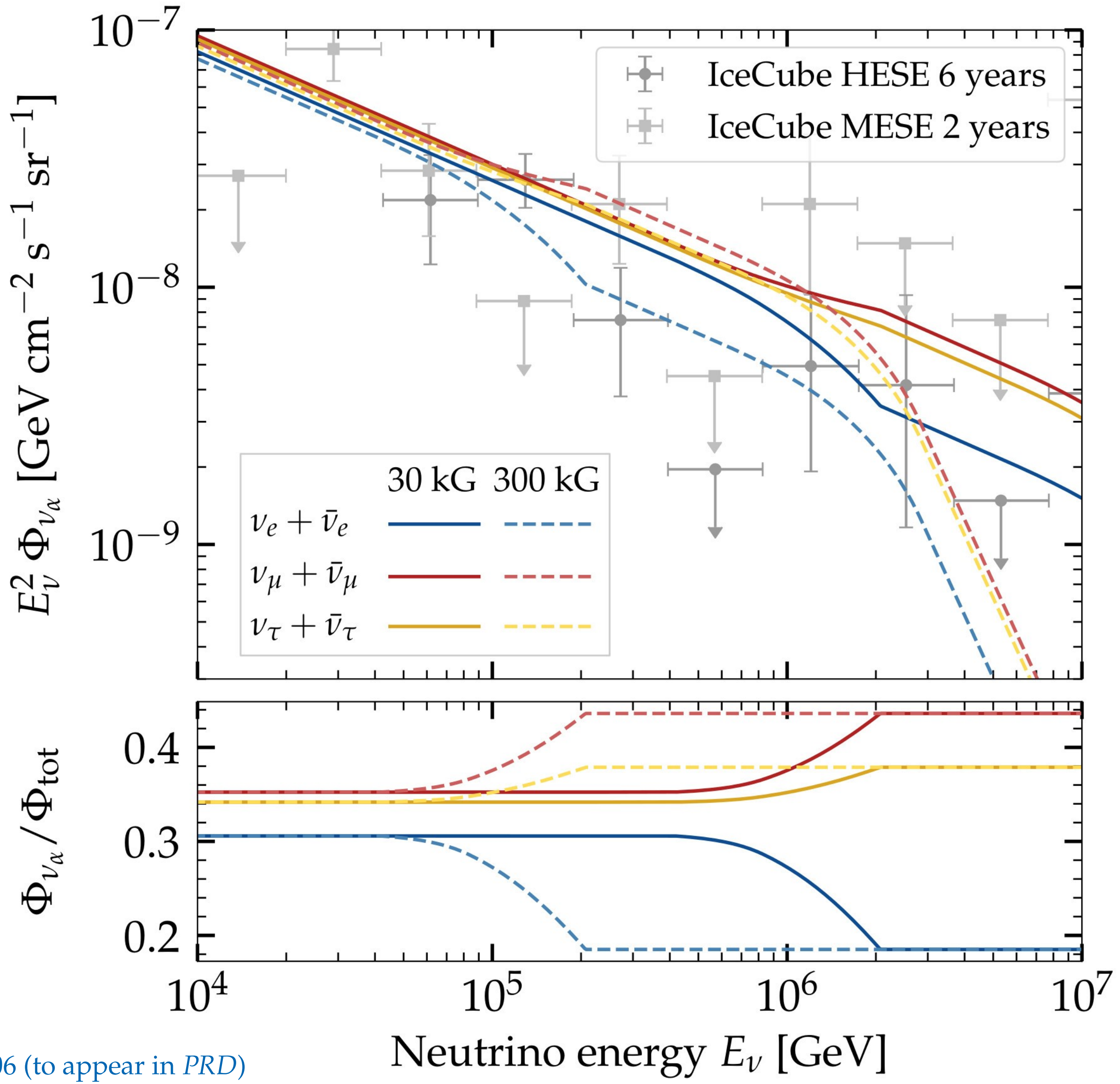
$$\mu^+ \rightarrow \bar{\nu}_\mu + e^+ + \nu_e$$

Pion cooling

Steepen the ν spectrum: $\alpha_\nu = \begin{cases} \gamma, & \text{if } E_\nu < E_{\nu,\pi}^{\text{sync}} \\ \gamma + 2, & \text{if } E_\nu \geq E_{\nu,\pi}^{\text{sync}} \end{cases}$

$$E_{\nu,\pi}^{\text{sync}} \approx 10^{10} \Gamma \frac{\text{G}}{B'} \text{ GeV}$$

MB, I. Tamborra, 2009.01306 (to appear in *PRD*)



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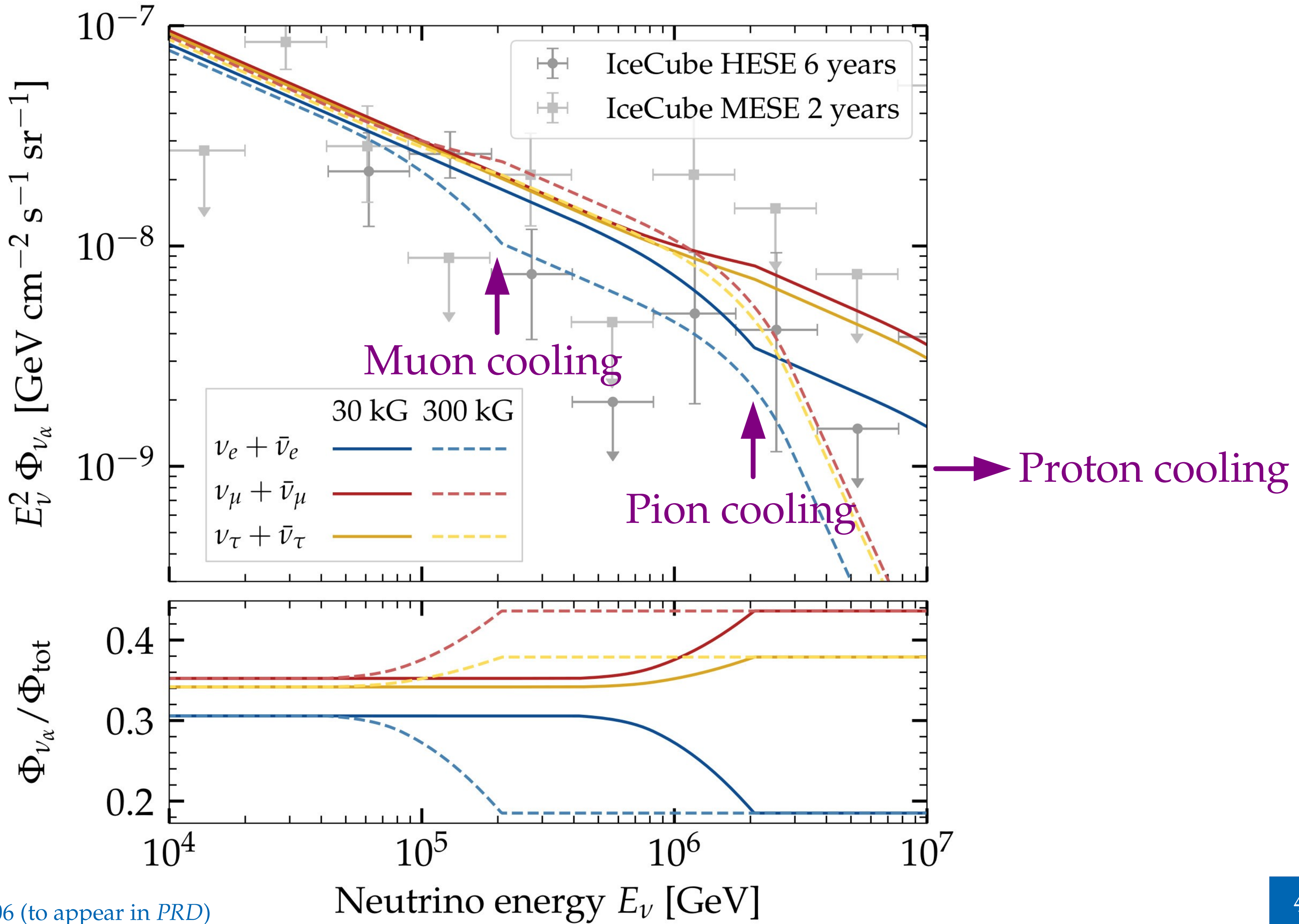
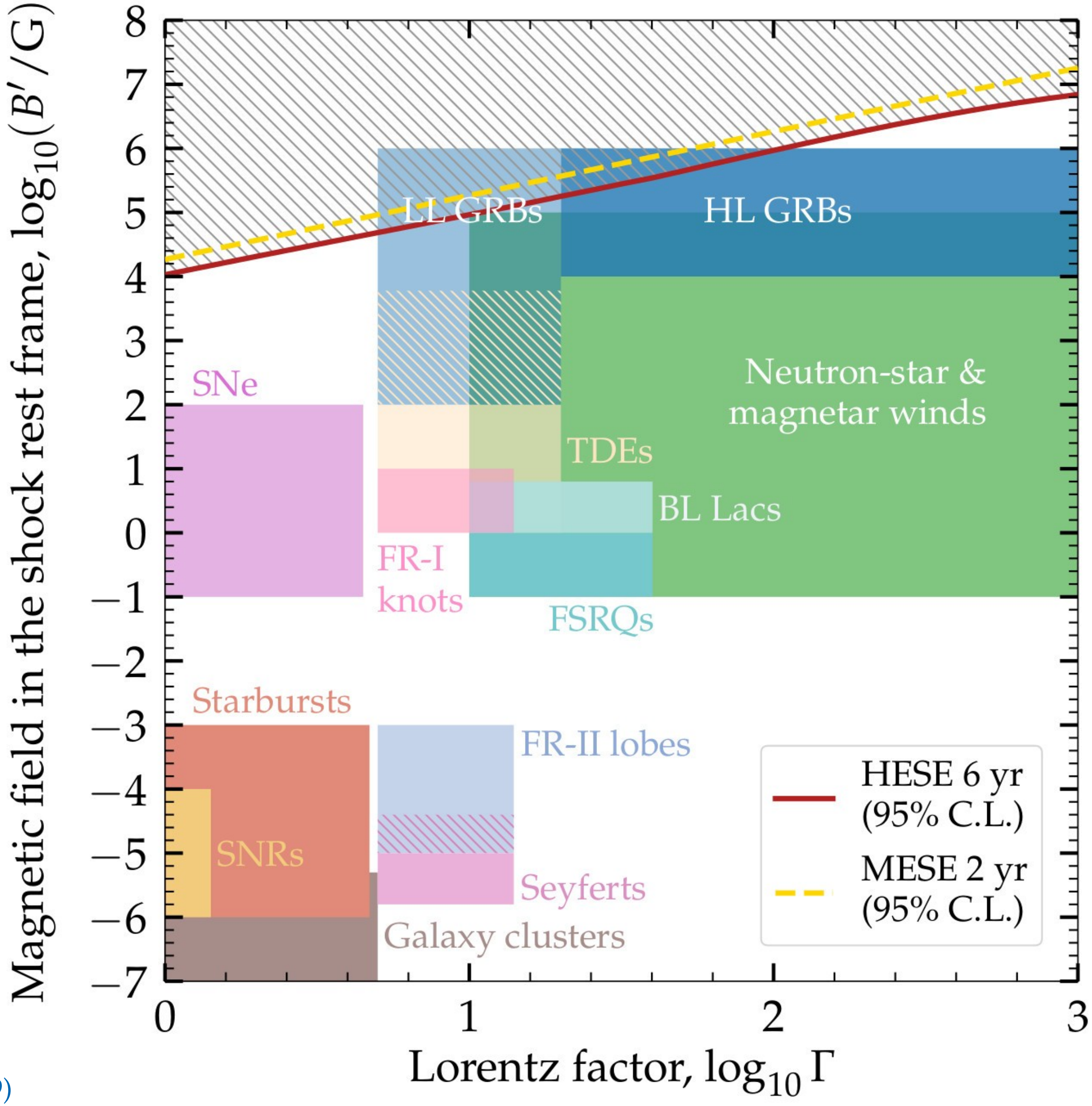


MB, I. Tamborra, 2009.01306 (to appear in *PRD*)

ν sources with strong B′ are likely not dominant

Average B' must be < 10kG–10 MG



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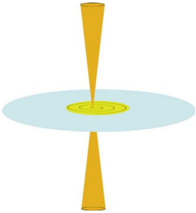
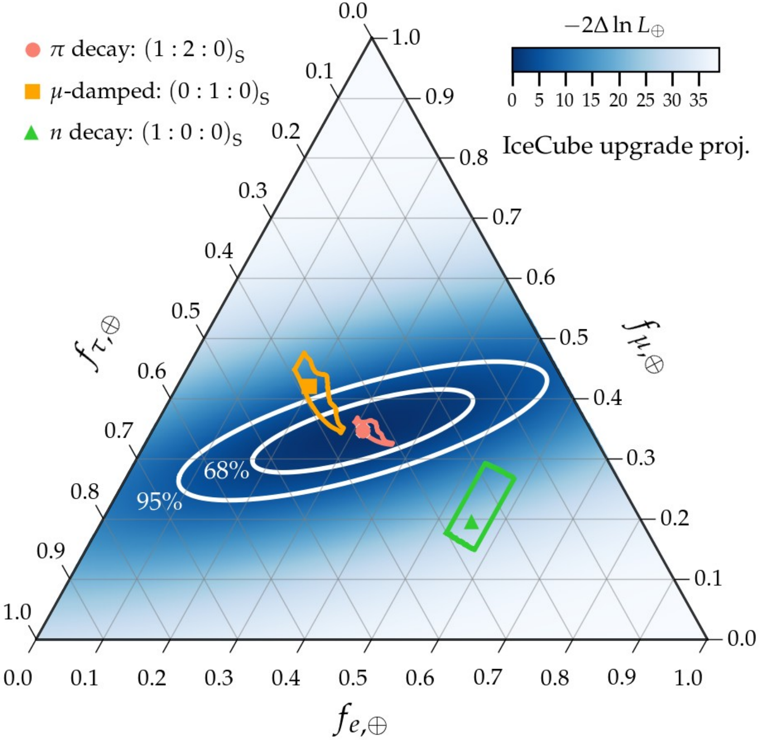
Inferring the flavor composition at the sources

Measured:
Flavor ratios at Earth

Invert flavor oscillations



Inferred:
Flavor ratios at astrophysical sources



MB & Ahlers, *PRL* 2019

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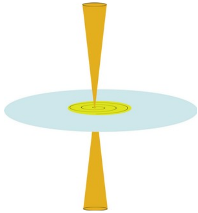

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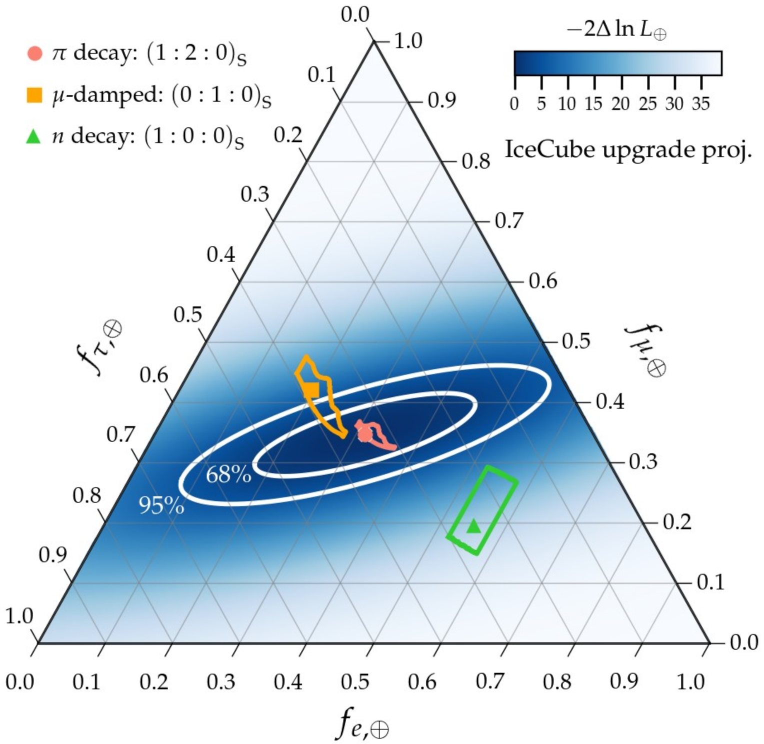

?

MB & Ahlers, *PRL* 2019

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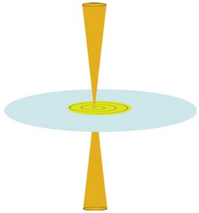

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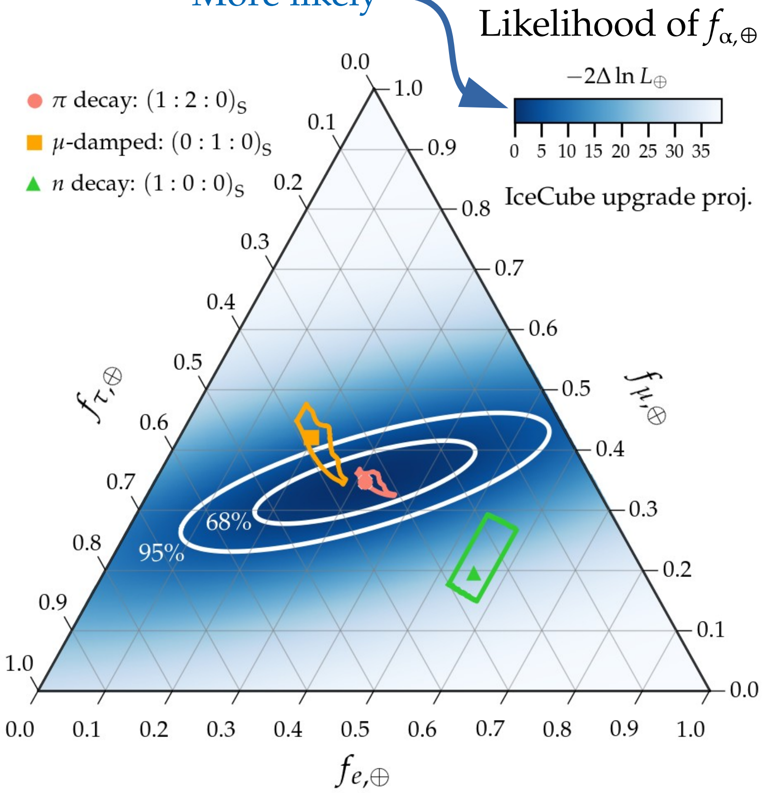
More likely



MB & Ahlers, *PRL* 2019

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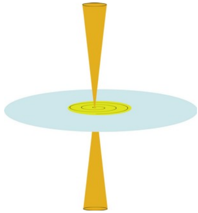

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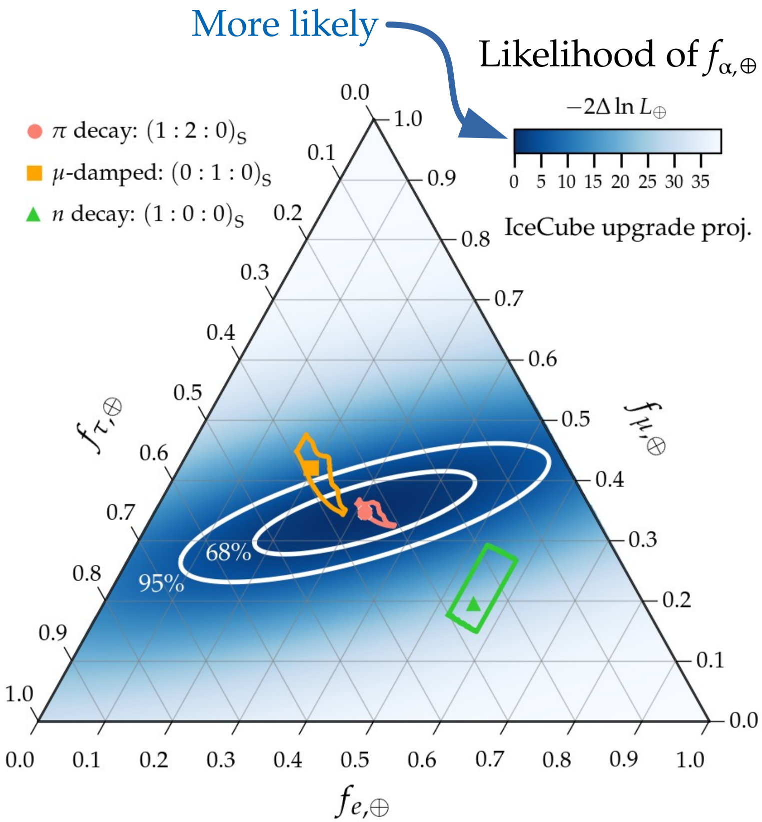

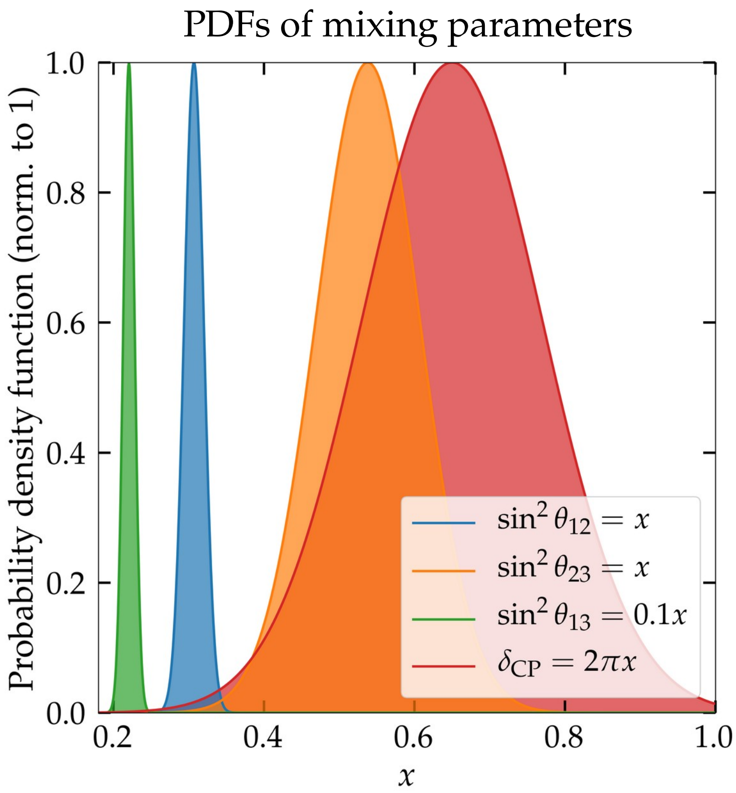

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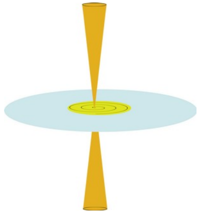

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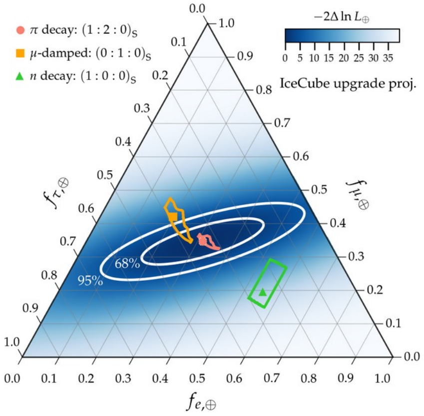
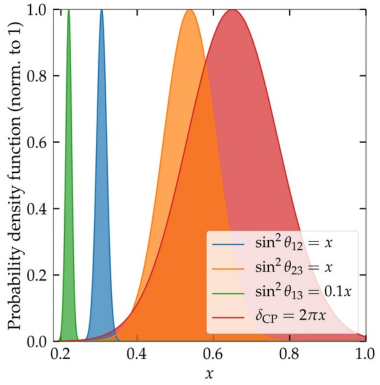


Posterior probability density of $f_{\alpha,S}$ being the flavor ratios at the sources:

$$\mathcal{P}\left(f_{\alpha,\mathrm{S}}\right) \equiv \int \mathrm{d}\boldsymbol{\theta} \frac{\mathcal{P}(\boldsymbol{\theta})}{\mathcal{N}(\boldsymbol{\theta})} \mathcal{L}_\oplus \left[f_{e,\oplus}(f_{\alpha,\mathrm{S}}, \boldsymbol{\theta}), f_{\mu,\oplus}(f_{\alpha,\mathrm{S}}, \boldsymbol{\theta})\right]$$

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

$$\left[\text{Normalization: } \mathcal{N}(\boldsymbol{\theta}) \equiv \int_0^1 \mathrm{d}f_{e,\mathrm{S}} \int_0^{1-f_{e,\mathrm{S}}} \mathrm{d}f_{\mu,\mathrm{S}}\; \mathcal{L}_\oplus \left[f_{e,\oplus}(f_{\alpha,\mathrm{S}}, \boldsymbol{\theta}), f_{\mu,\oplus}(f_{\alpha,\mathrm{S}}, \boldsymbol{\theta})\right]\right]$$



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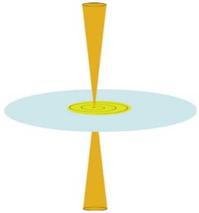

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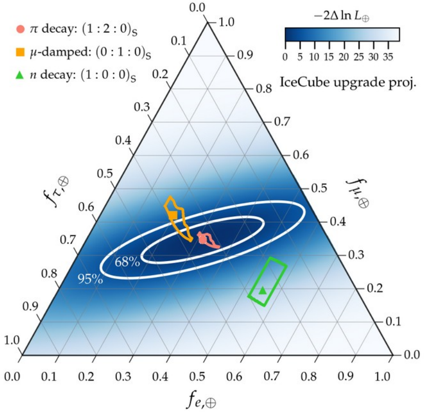
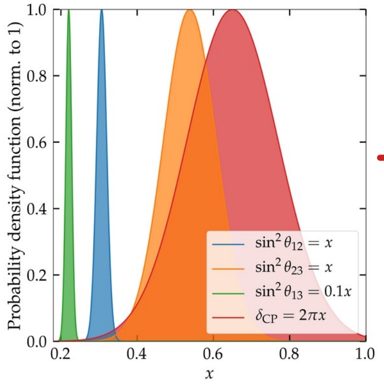




Posterior probability density of $f_{\alpha,\mathrm{S}}$ being the flavor ratios at the sources:

$$\mathcal{P}\left(f_{\alpha,\mathrm{S}}\right) \equiv \int \mathrm{d}\boldsymbol{\theta} \frac{\mathcal{P}(\boldsymbol{\theta})}{\mathcal{N}(\boldsymbol{\theta})} \mathcal{L}_{\oplus}\left[f_{e,\oplus}(f_{\alpha,\mathrm{S}},\boldsymbol{\theta}), f_{\mu,\oplus}(f_{\alpha,\mathrm{S}},\boldsymbol{\theta})\right]$$

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

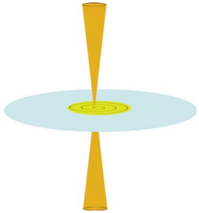
Normalization: $\mathcal{N}(\boldsymbol{\theta}) \equiv \int_0^1 \mathrm{d}f_{e,\mathrm{S}} \int_0^{1-f_{e,\mathrm{S}}} \mathrm{d}f_{\mu,\mathrm{S}}\ \mathcal{L}_{\oplus}\left[f_{e,\oplus}(f_{\alpha,\mathrm{S}},\boldsymbol{\theta}), f_{\mu,\oplus}(f_{\alpha,\mathrm{S}},\boldsymbol{\theta})\right]$

MB & Ahlers, *PRL* 2019

Inferring the flavor composition at the sources

Measured:
Flavor ratios at Earth

Invert flavor oscillations



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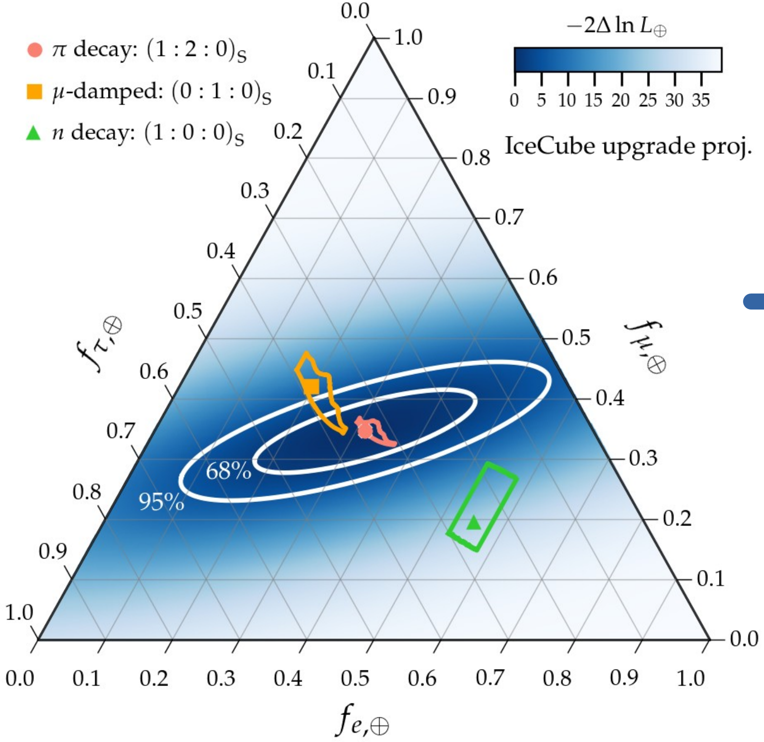

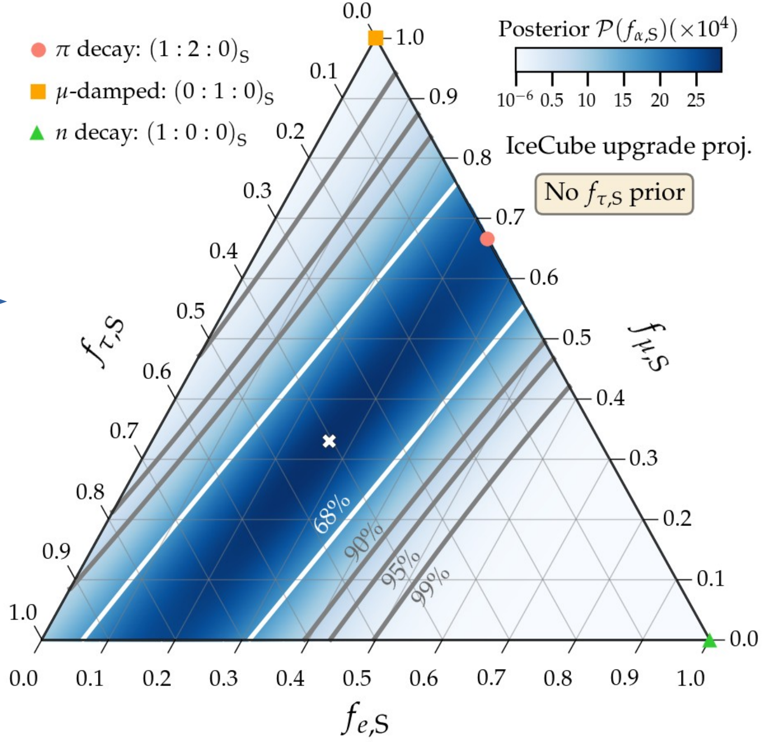

MB & Ahlers, *PRL* 2019

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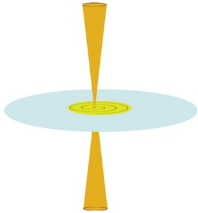

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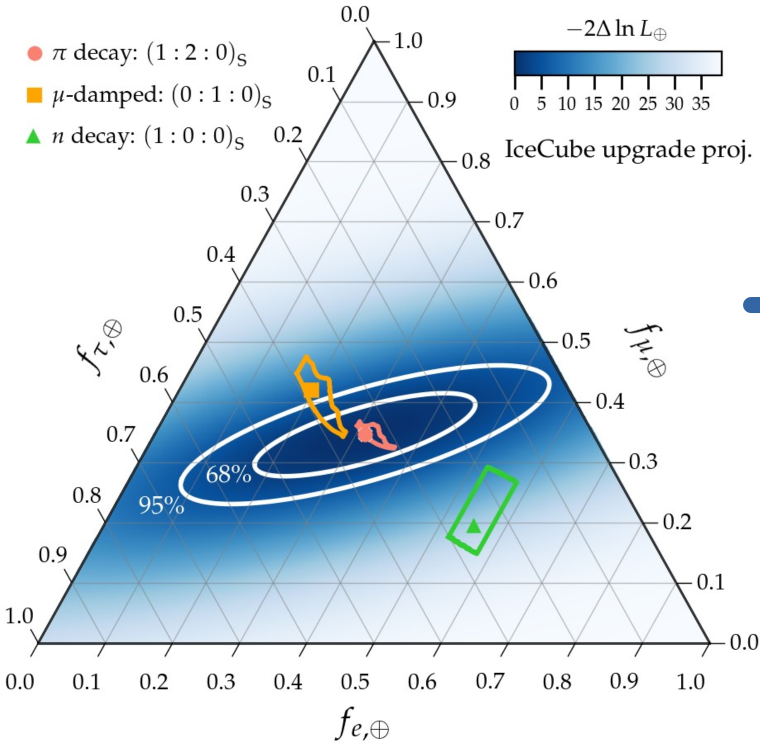

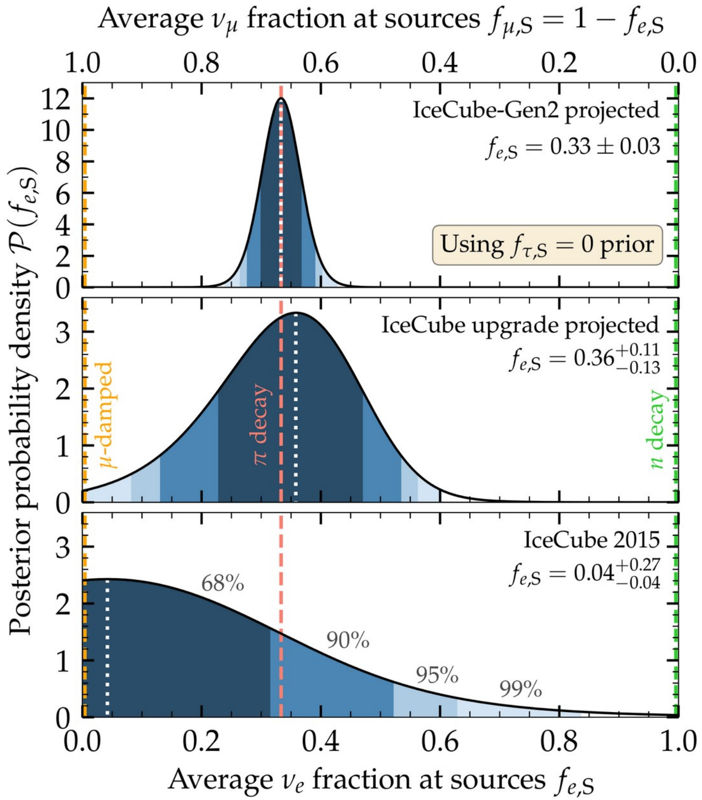

MB & Ahlers, *PRL* 2019

III.
Particle physics with high-energy cosmic neutrinos

In the face of astrophysical unknowns,
can we extract fundamental TeV–PeV ν physics?

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can we extract fundamental TeV–PeV ν physics?

Yes.

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Yes.

Already today.


Neutrino physicist

Note: Not an exhaustive list

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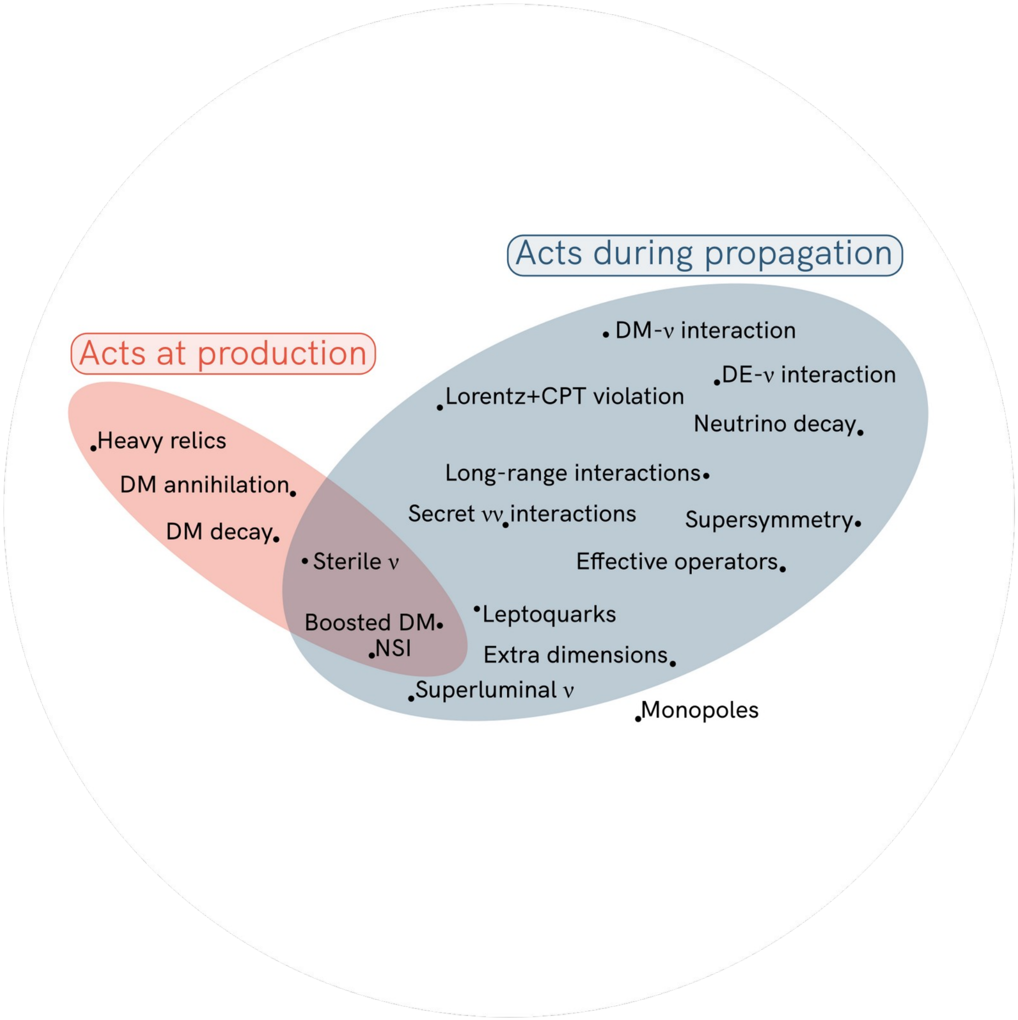

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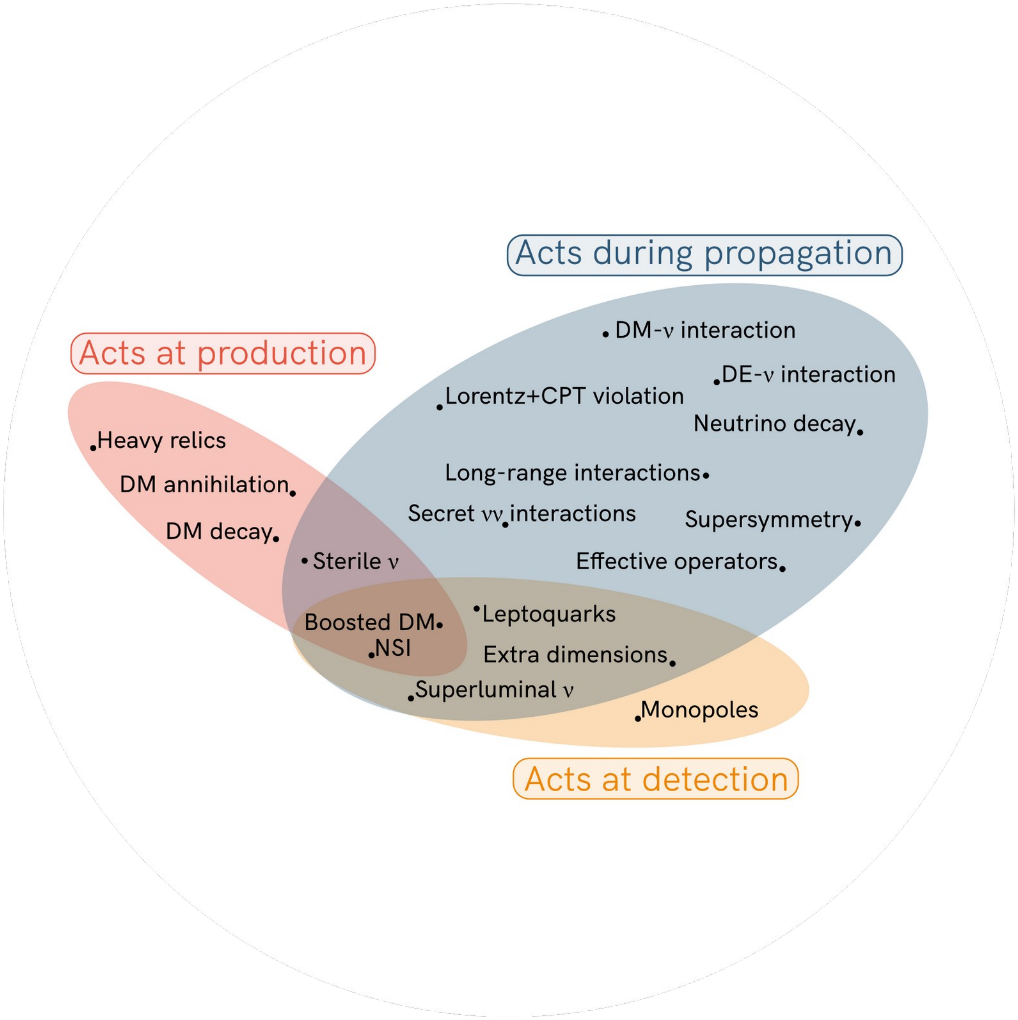

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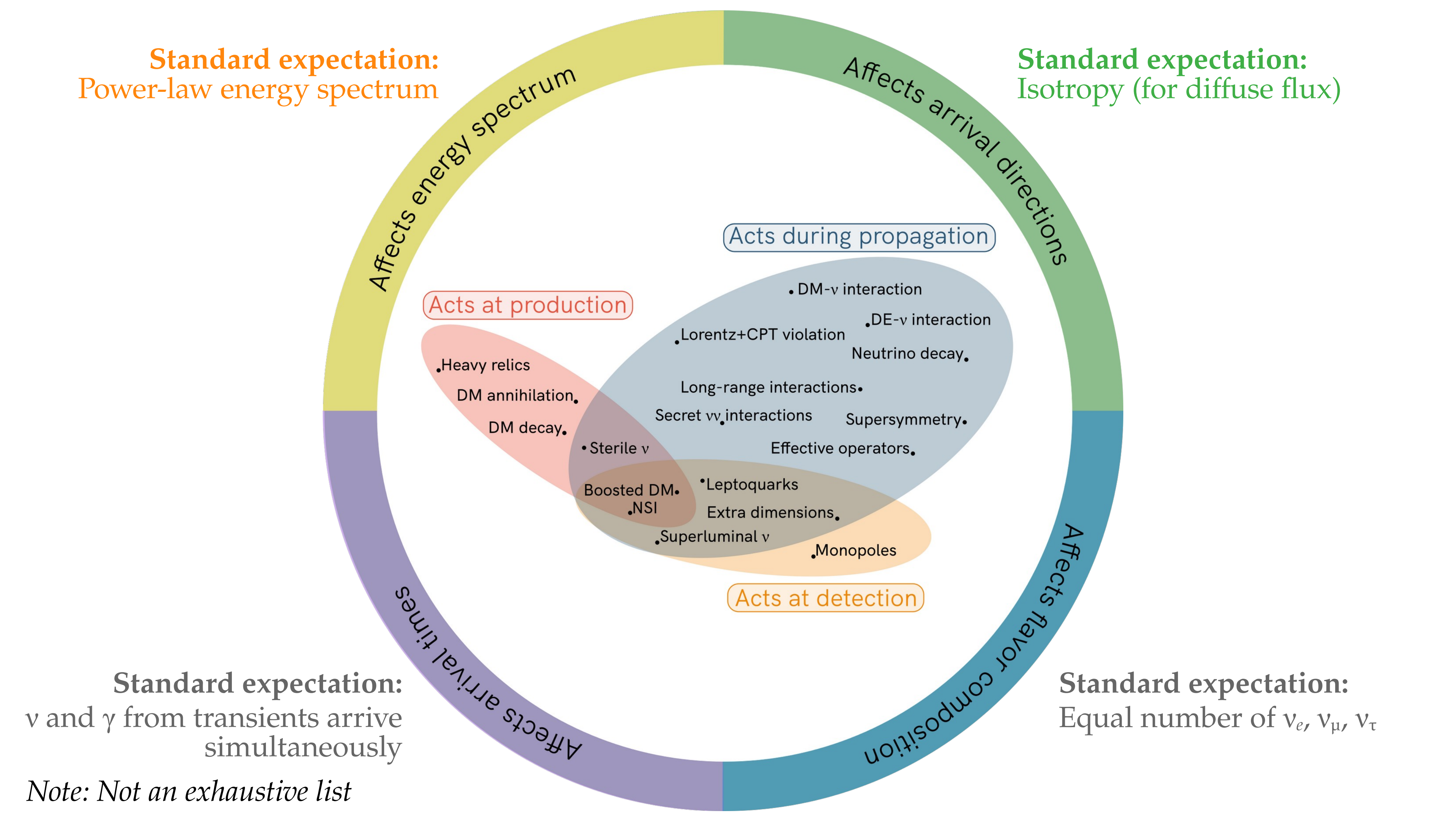
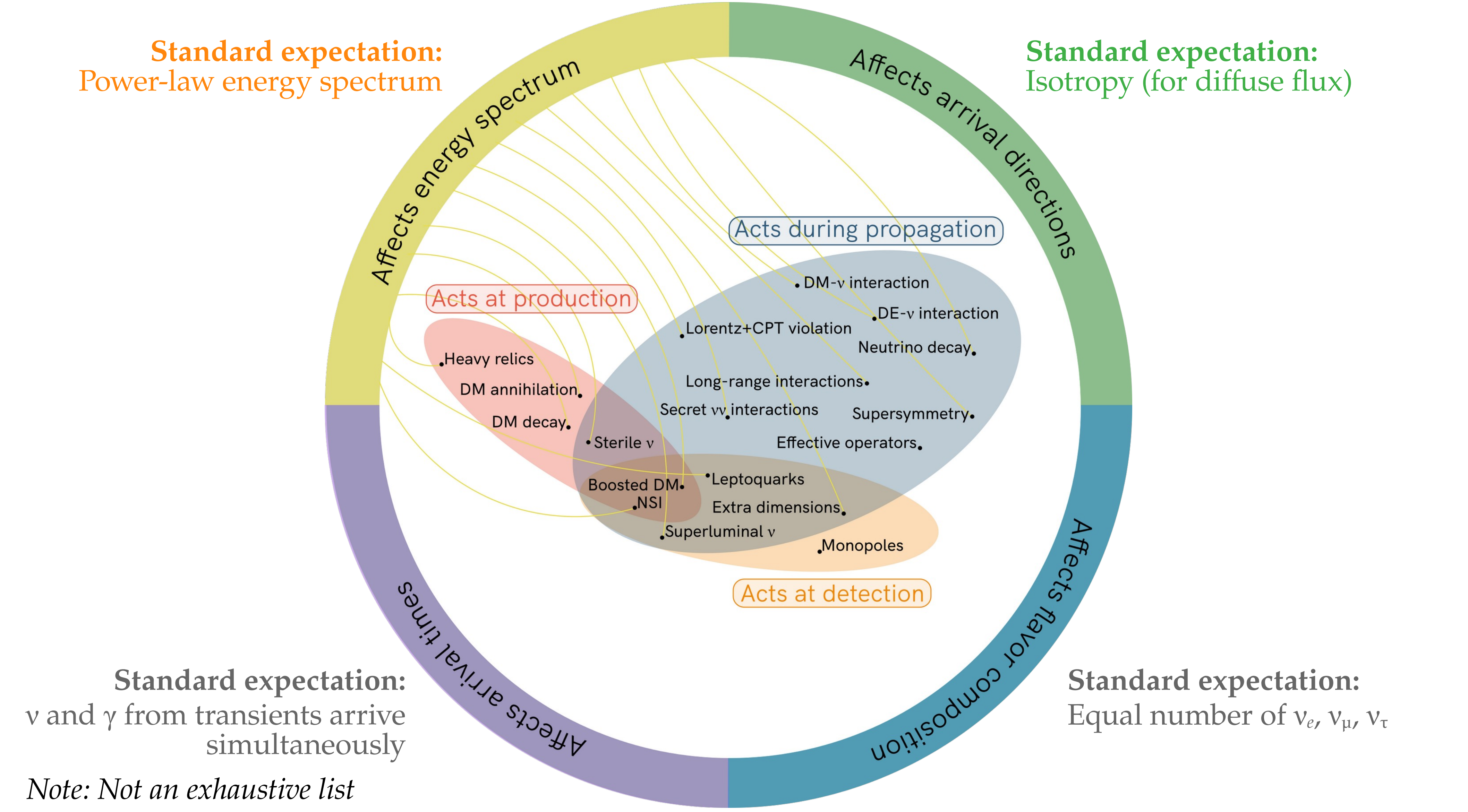


Standard expectation:
Power-law energy spectrum
Standard expectation:
Isotropy (for diffuse flux)
Affects energy spectrum
Affects arrival directions
Acts during propagation
Acts at production
DM-ν interaction
DE-ν interaction
Lorentz+CPT violation
Neutrino decay
Heavy relics
DM annihilation
DM decay
Long-range interactions
Secret νν interactions
Supersymmetry
Sterile ν
Effective operators
Boosted DM
NSI
Leptoquarks
Extra dimensions
Superluminal ν
Monopoles
Acts at detection
Affects arrival times
Affects flavor composition
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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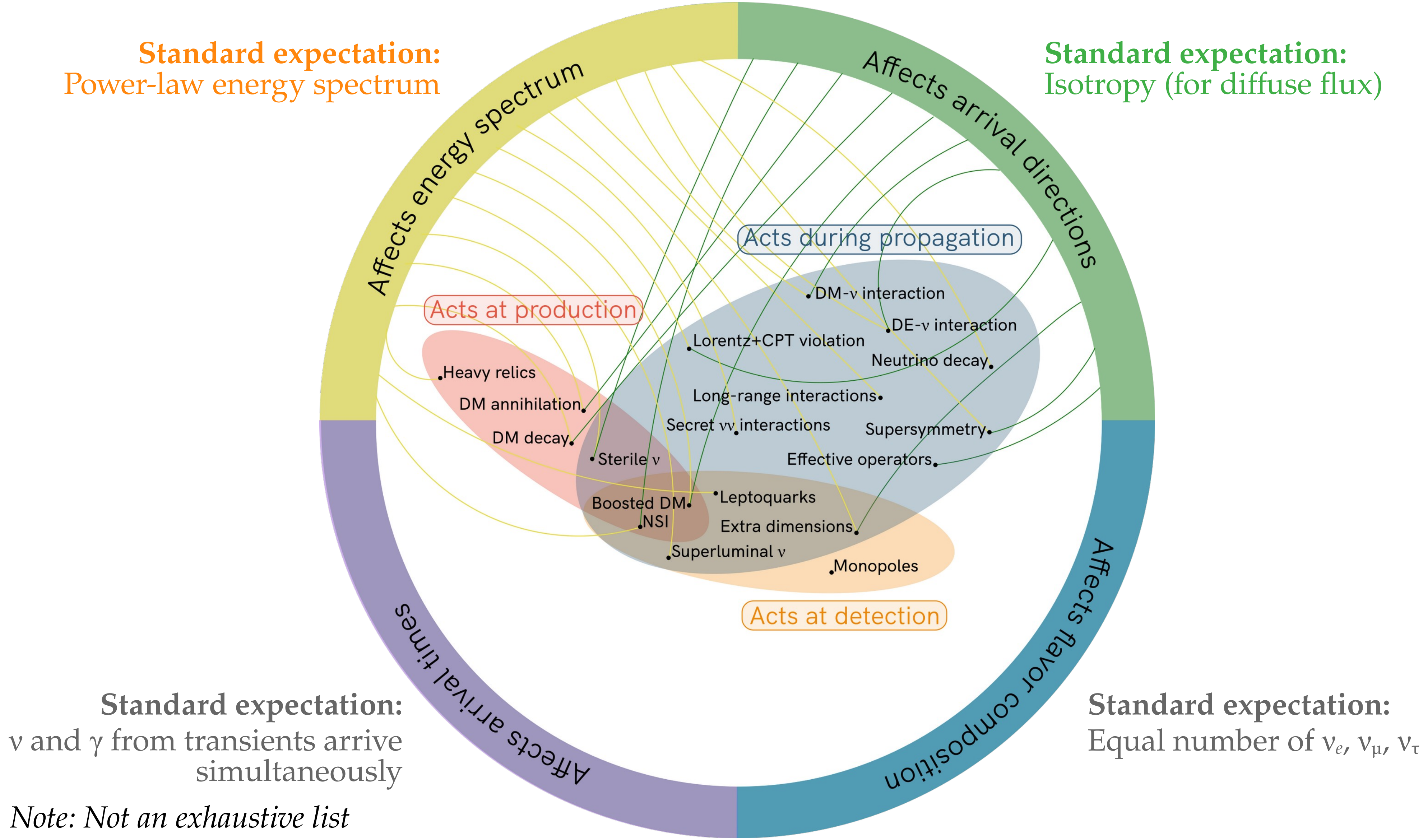
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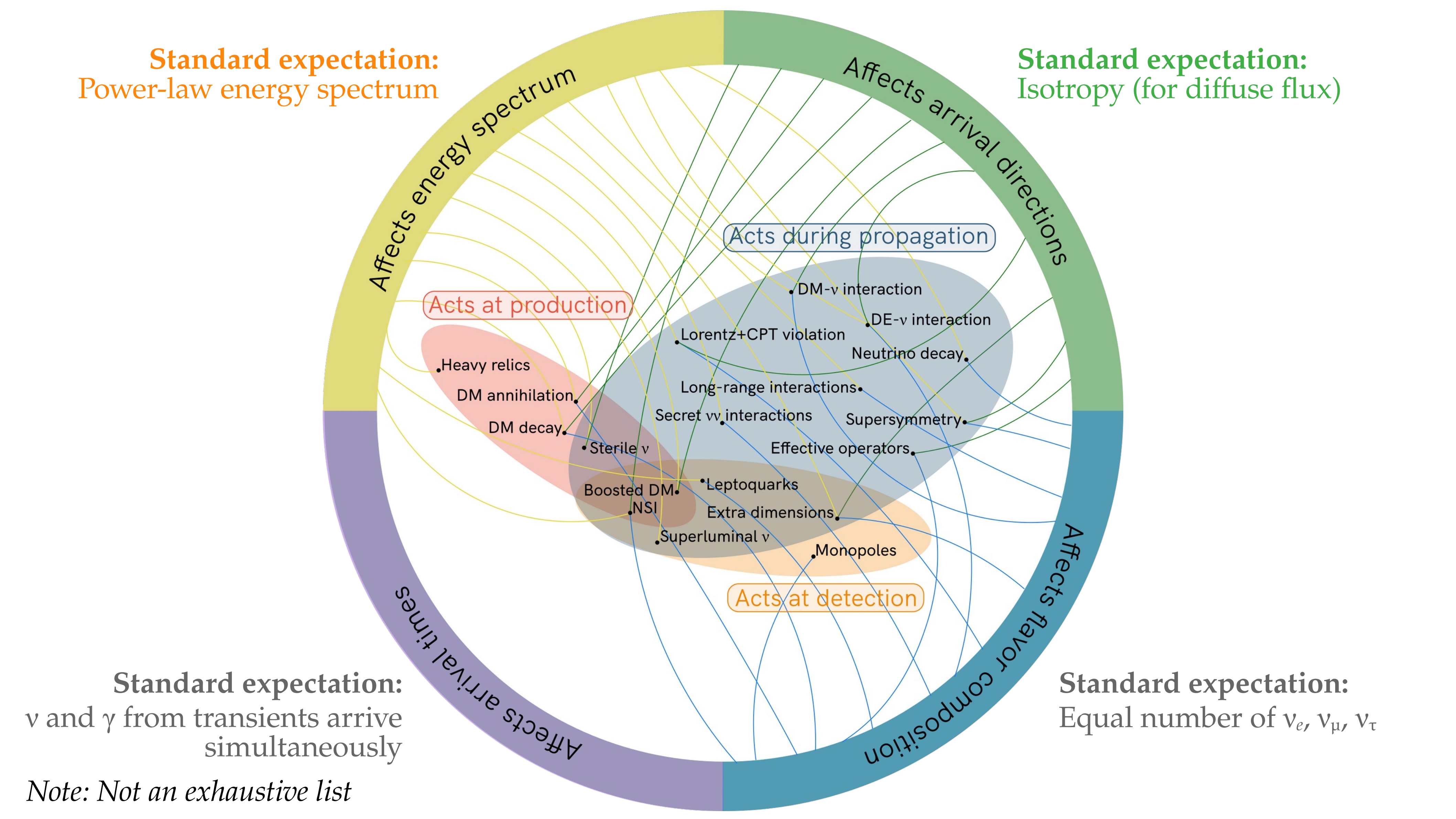

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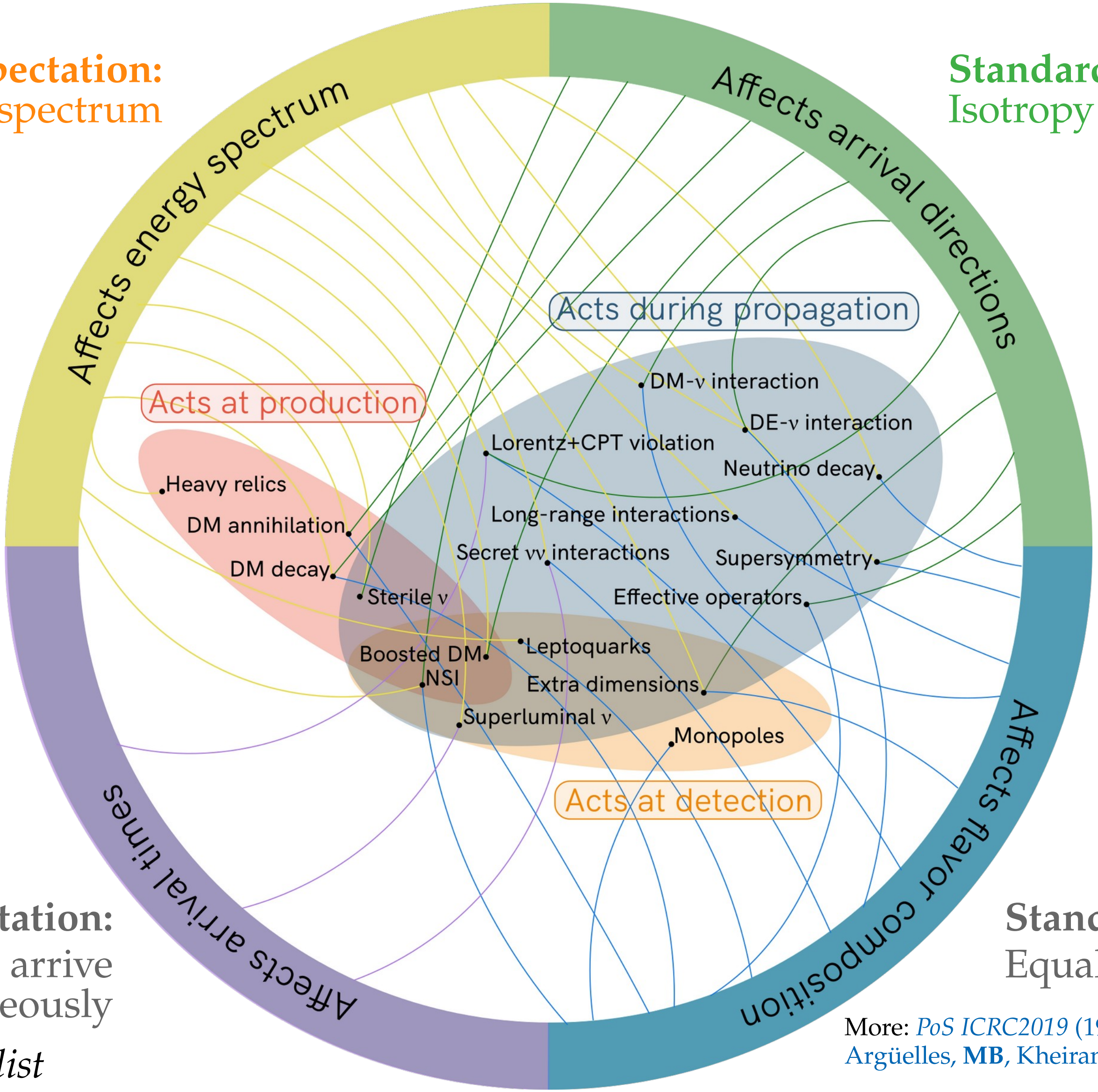

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More: *PoS ICRC2019* (1907.08690)
Argüelles, **MB**, Kheirandish, Palomares-Ruiz, Salvadó, Vincent

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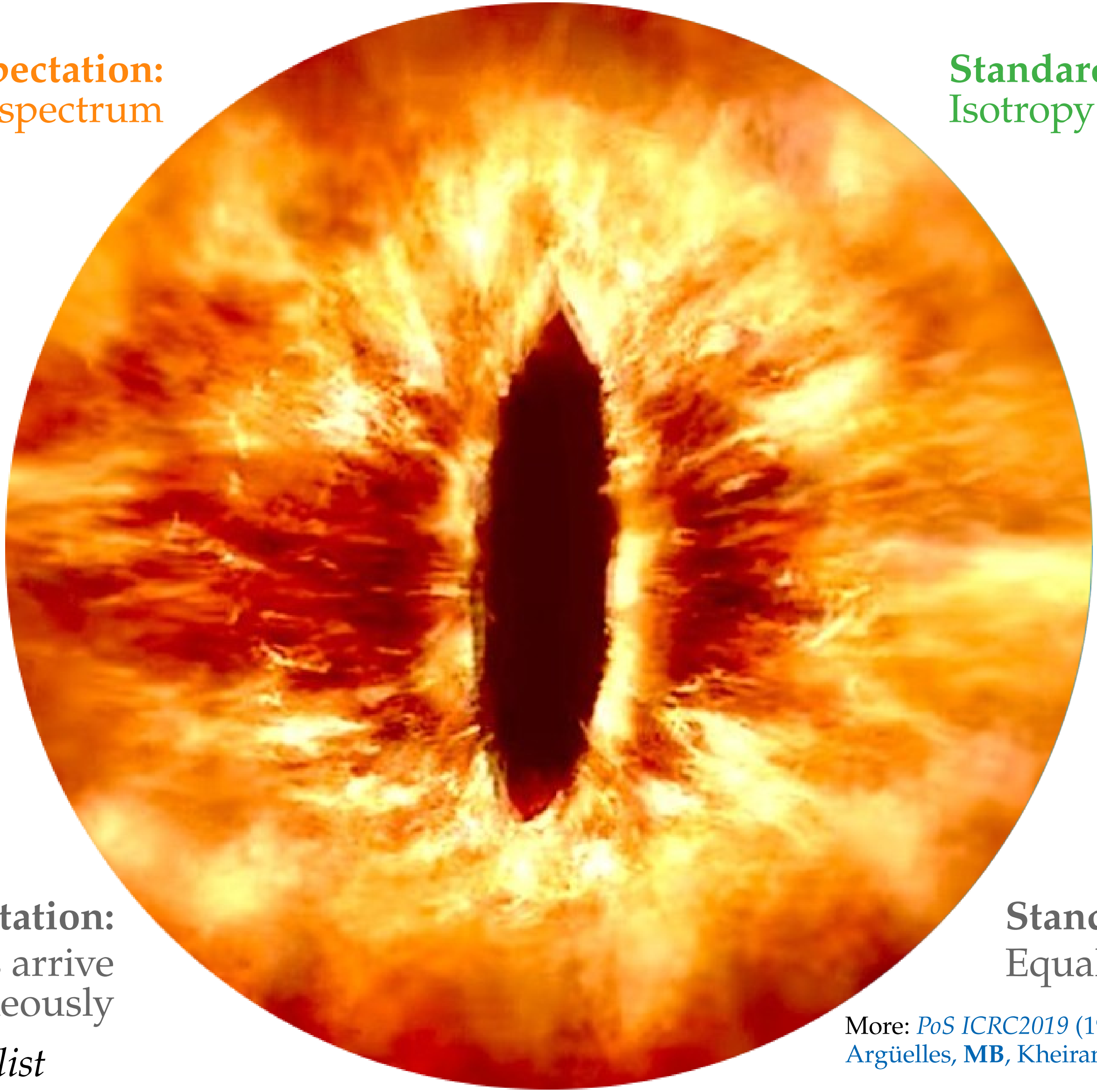

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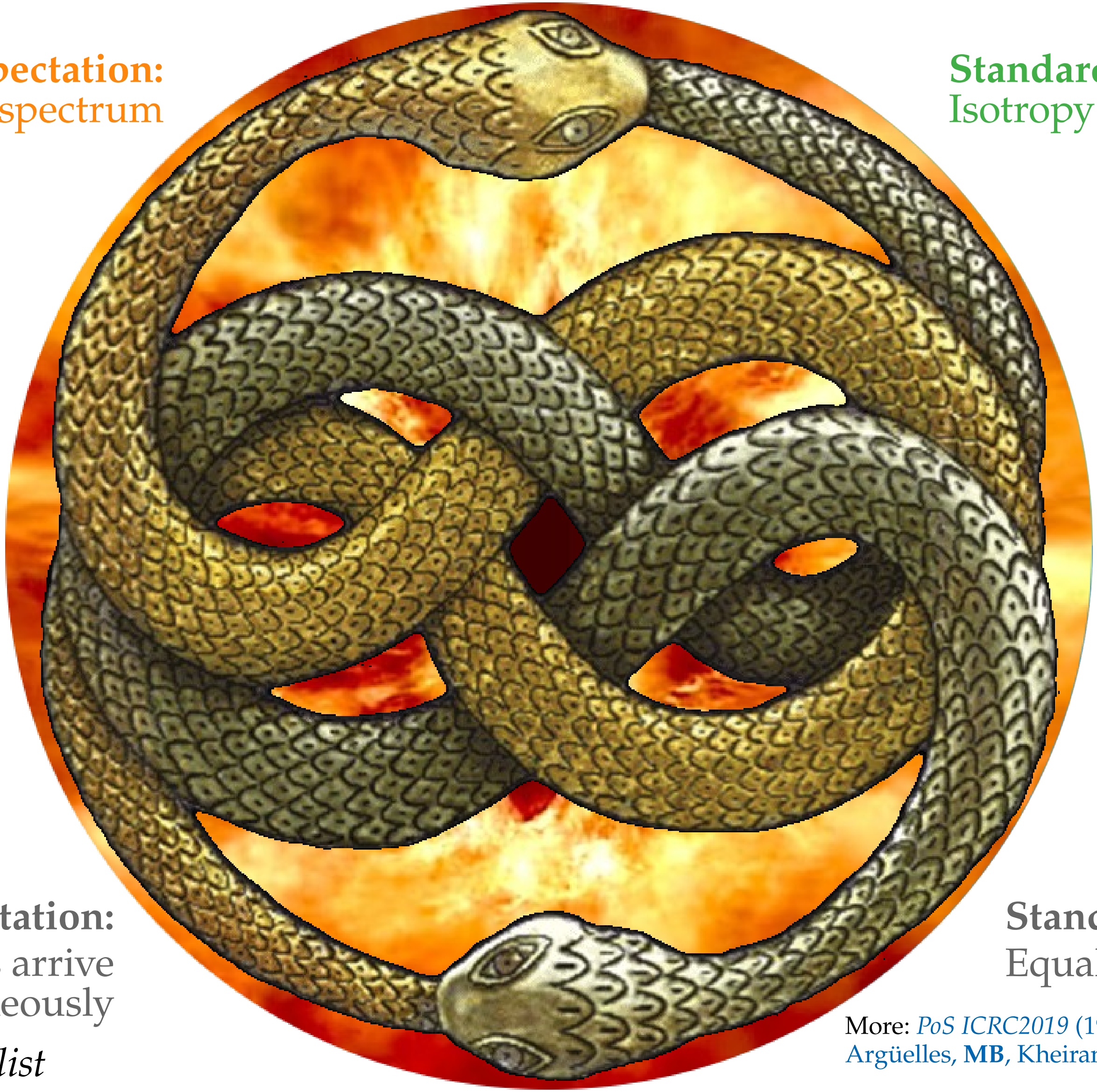

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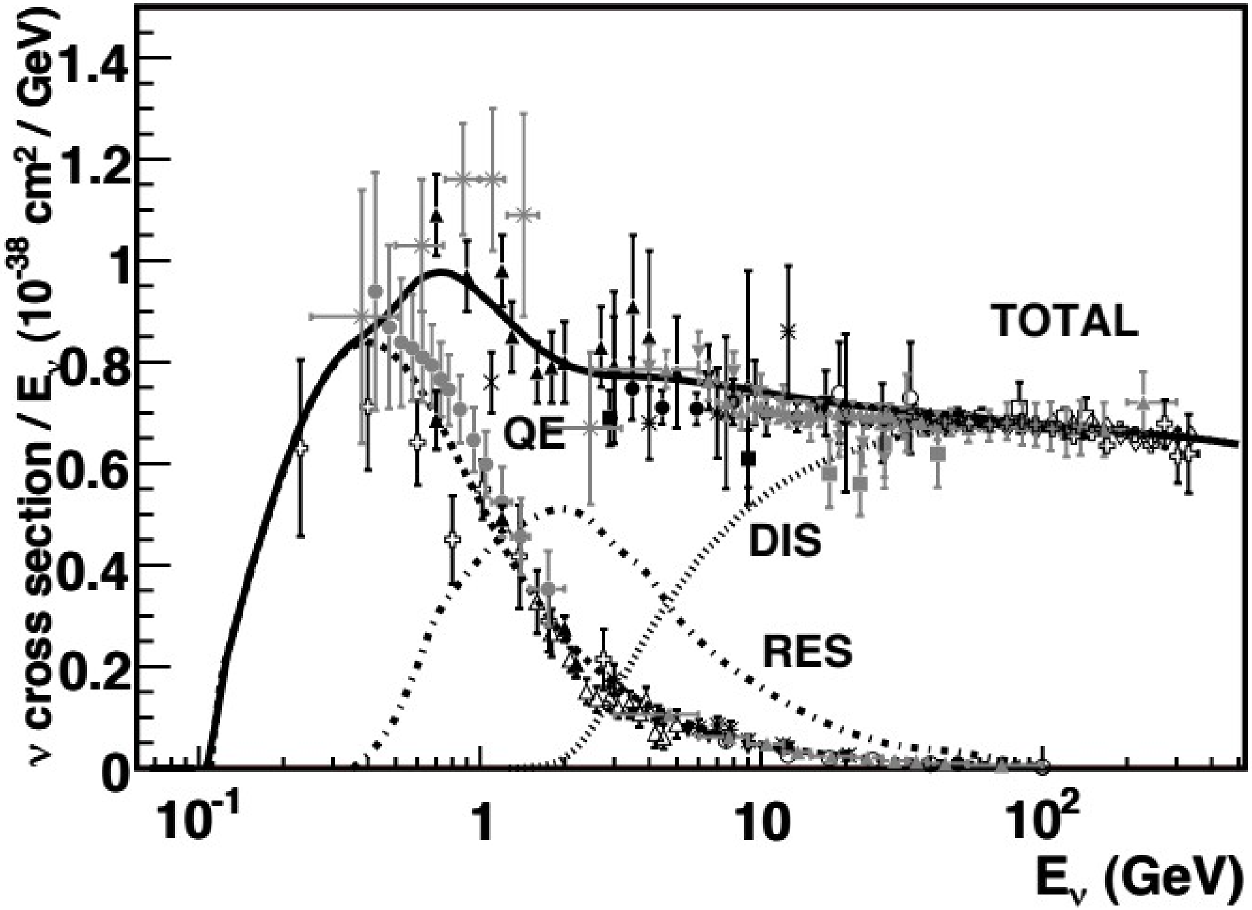
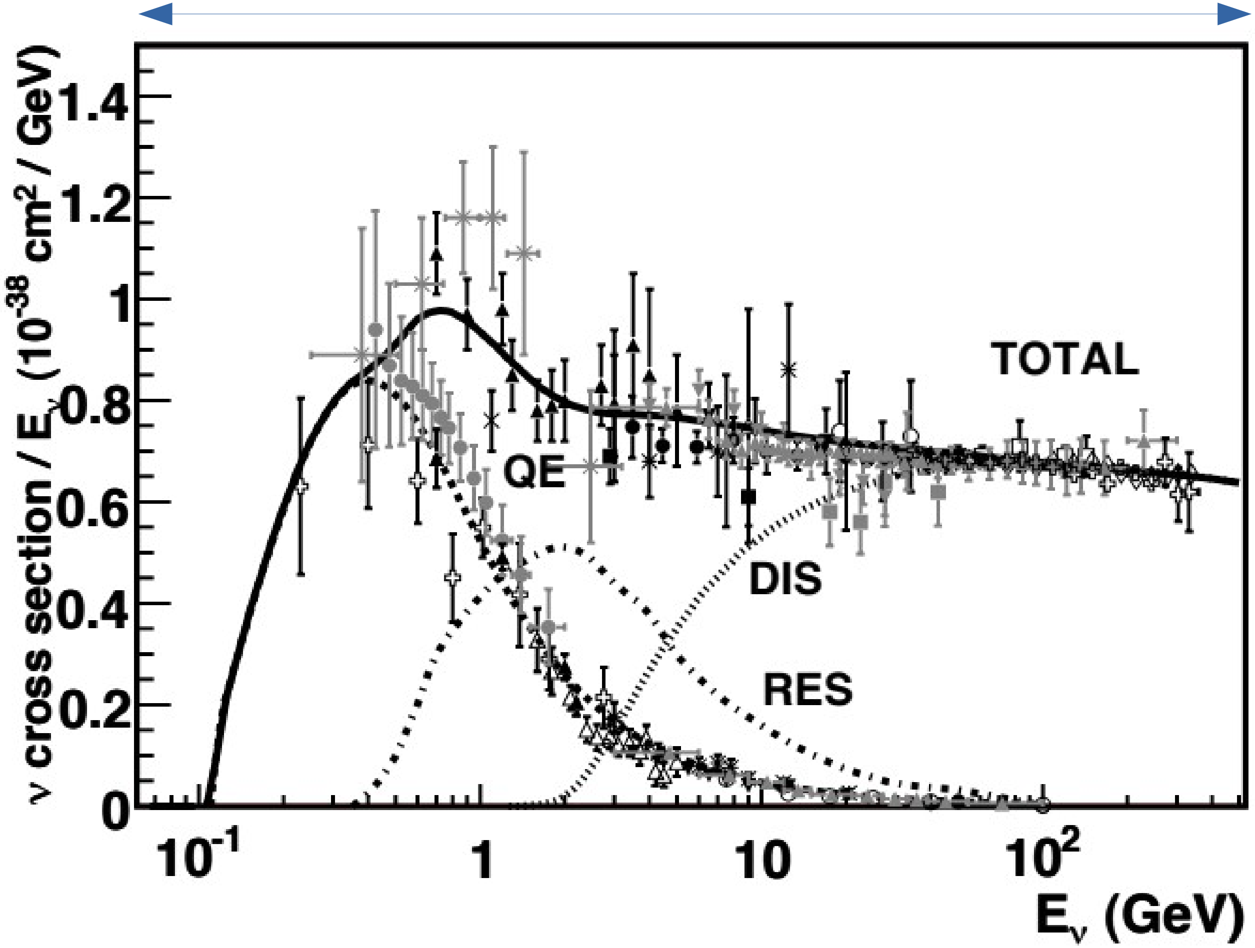
Example 1:
Measuring TeV–PeV ν cross sections



Particle Data Group

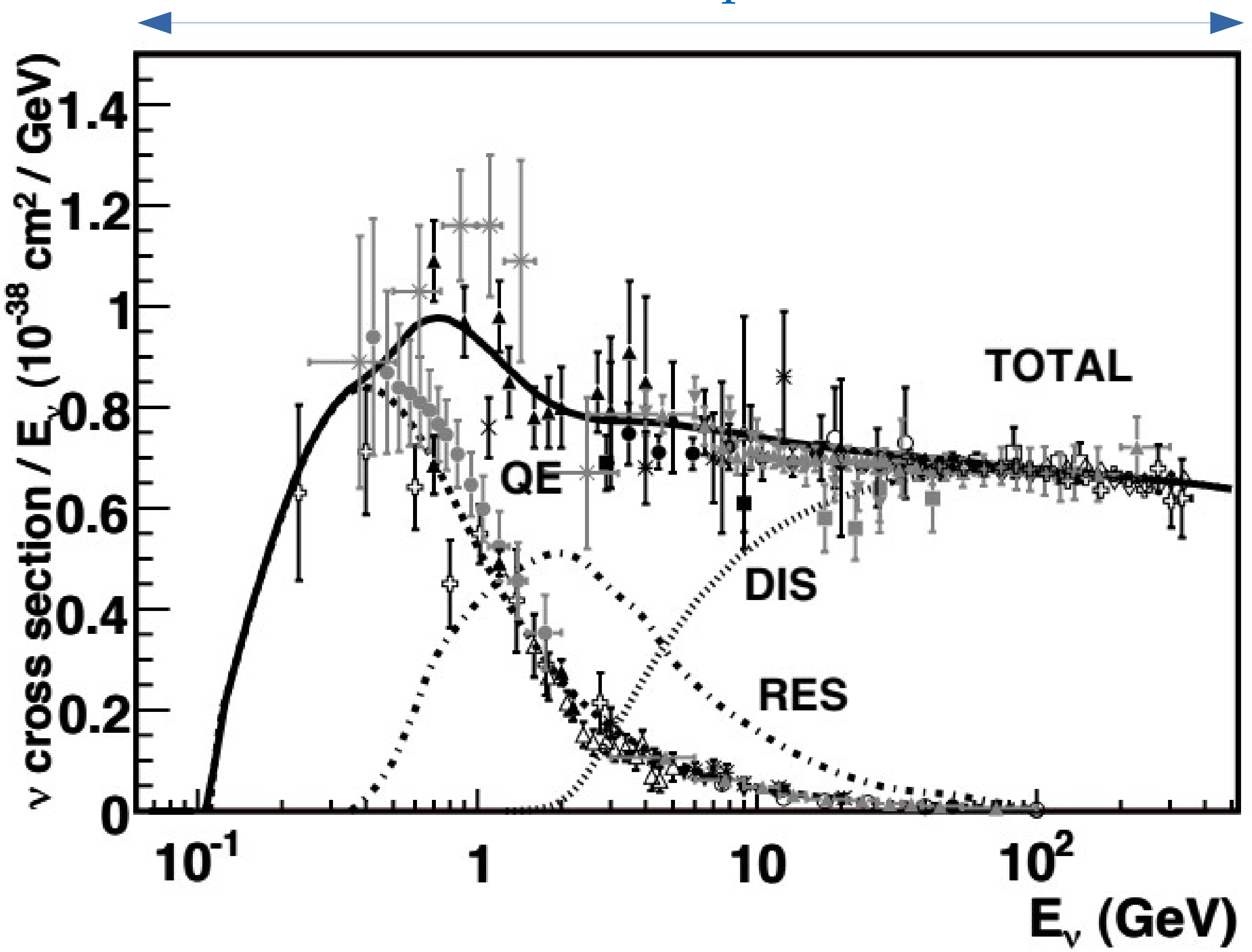
Accelerator experiments



Particle Data Group

Accelerator experiments

One recent measurement (COHERENT)



Particle Data Group

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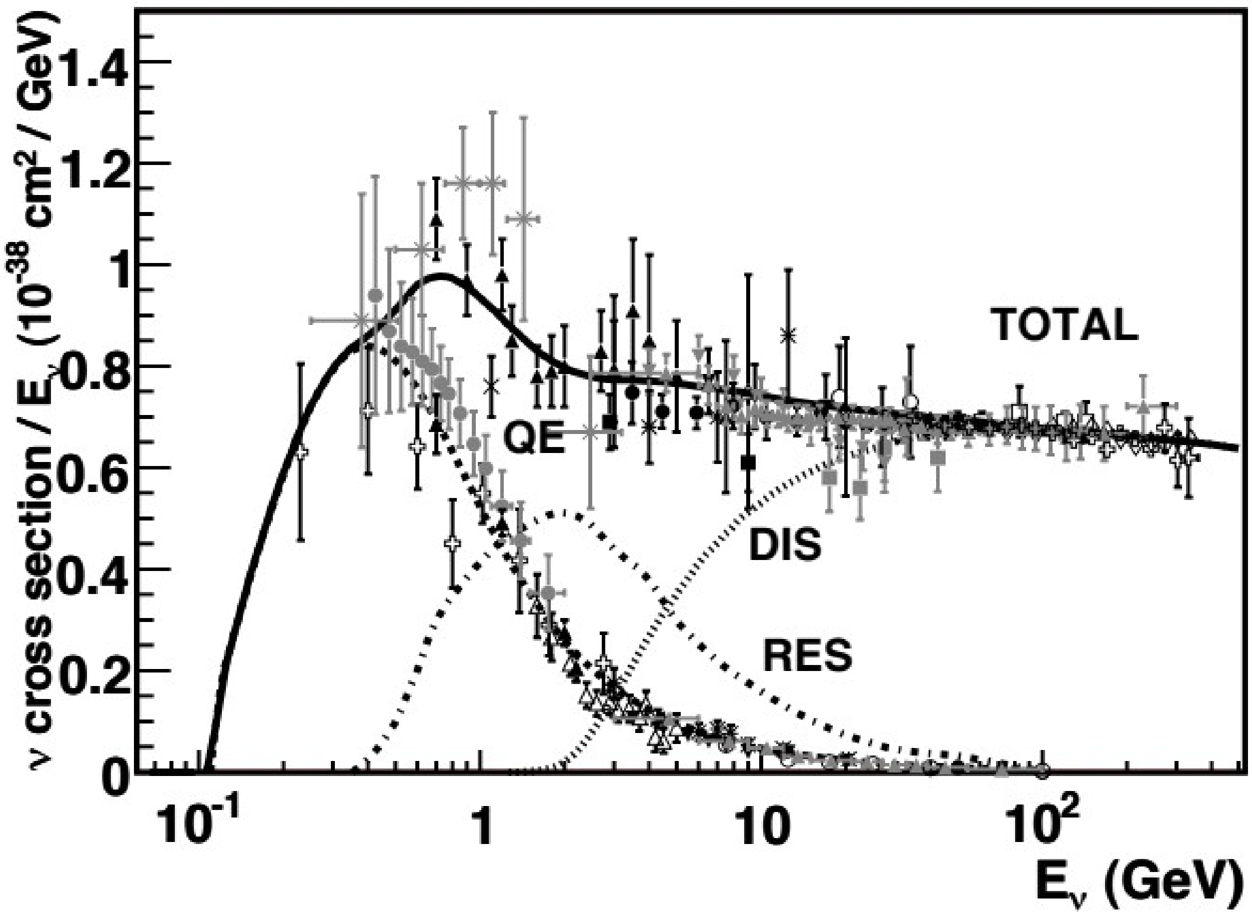

No measurements … until recently!

Particle Data Group

Accelerator experiments

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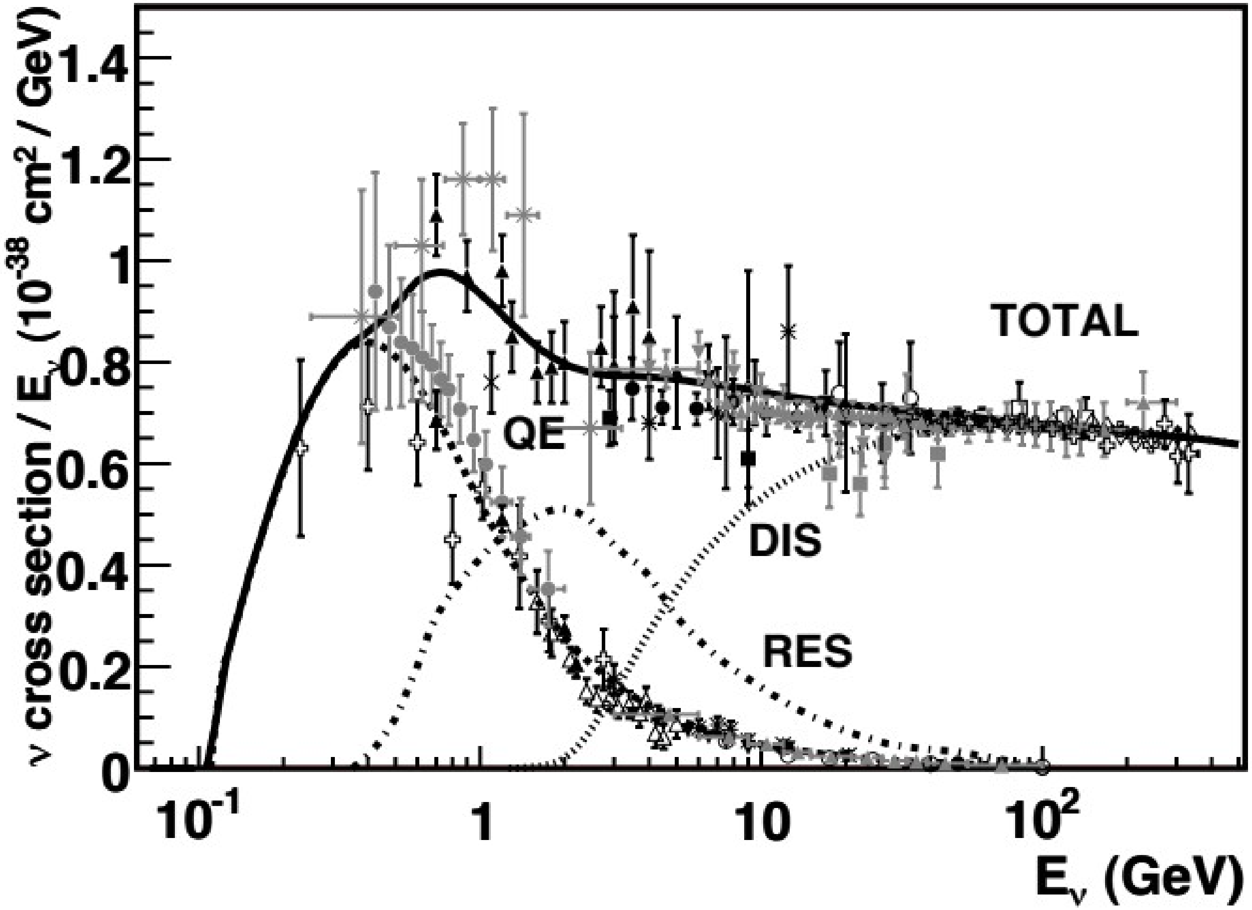
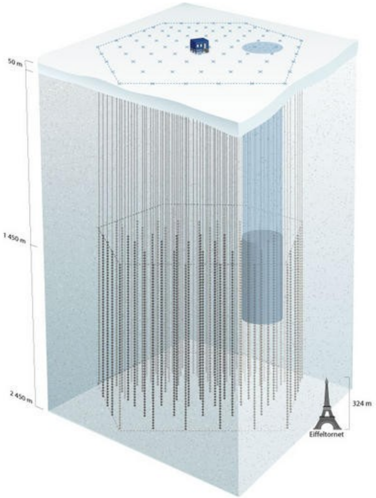
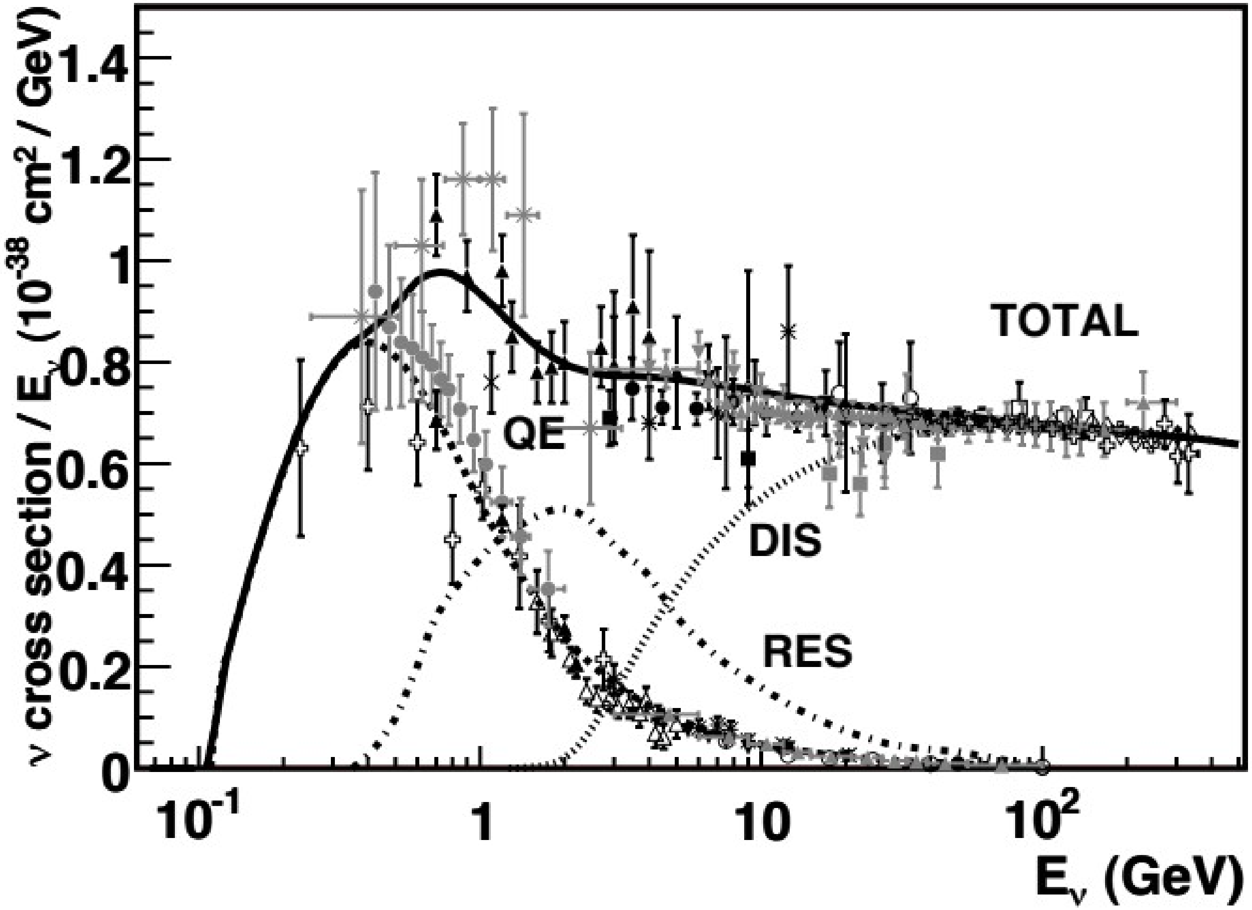


Particle Data Group



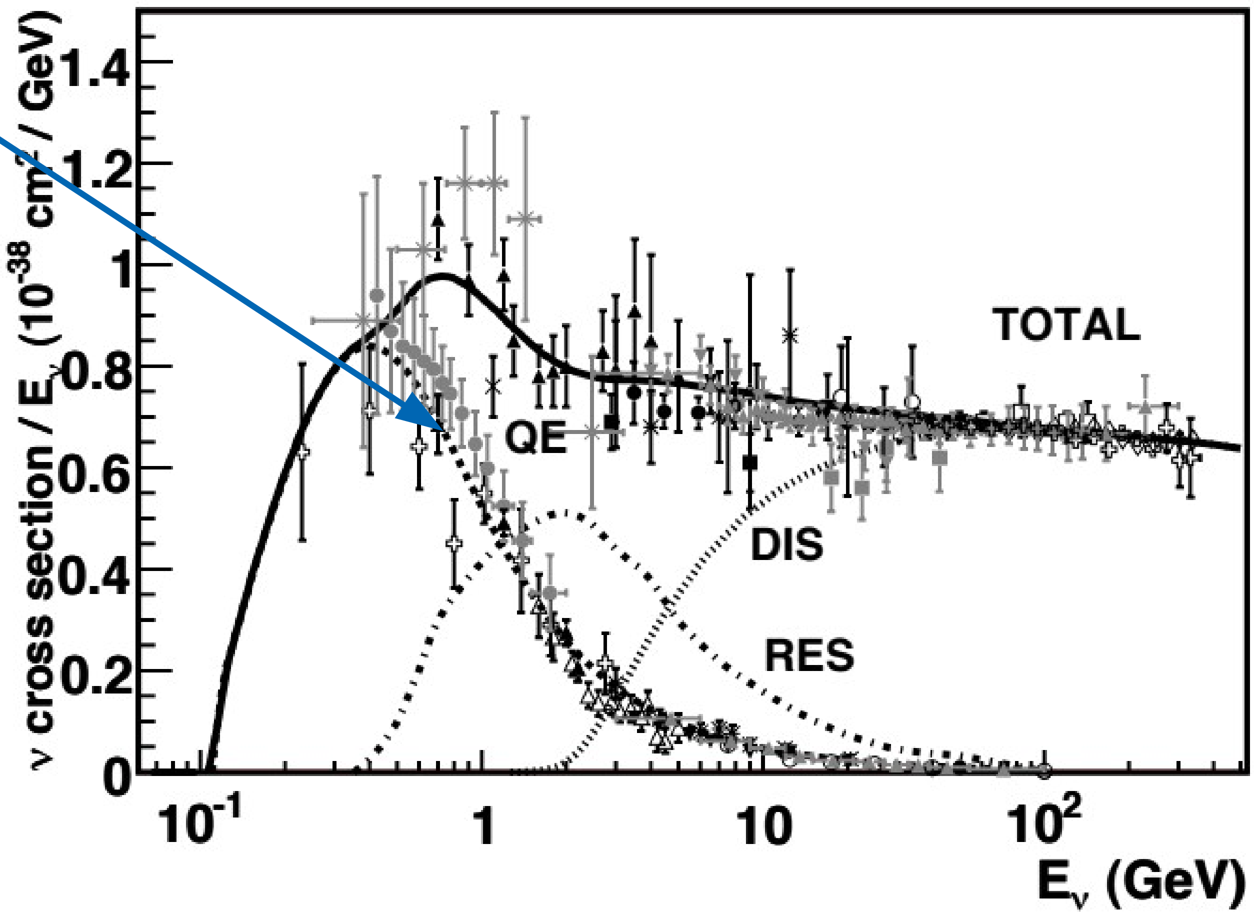


Particle Data Group

Quasi-elastic scattering:

$\nu_l + n \rightarrow l^- + p$

$\bar{\nu}_l + p \rightarrow l^+ + n$



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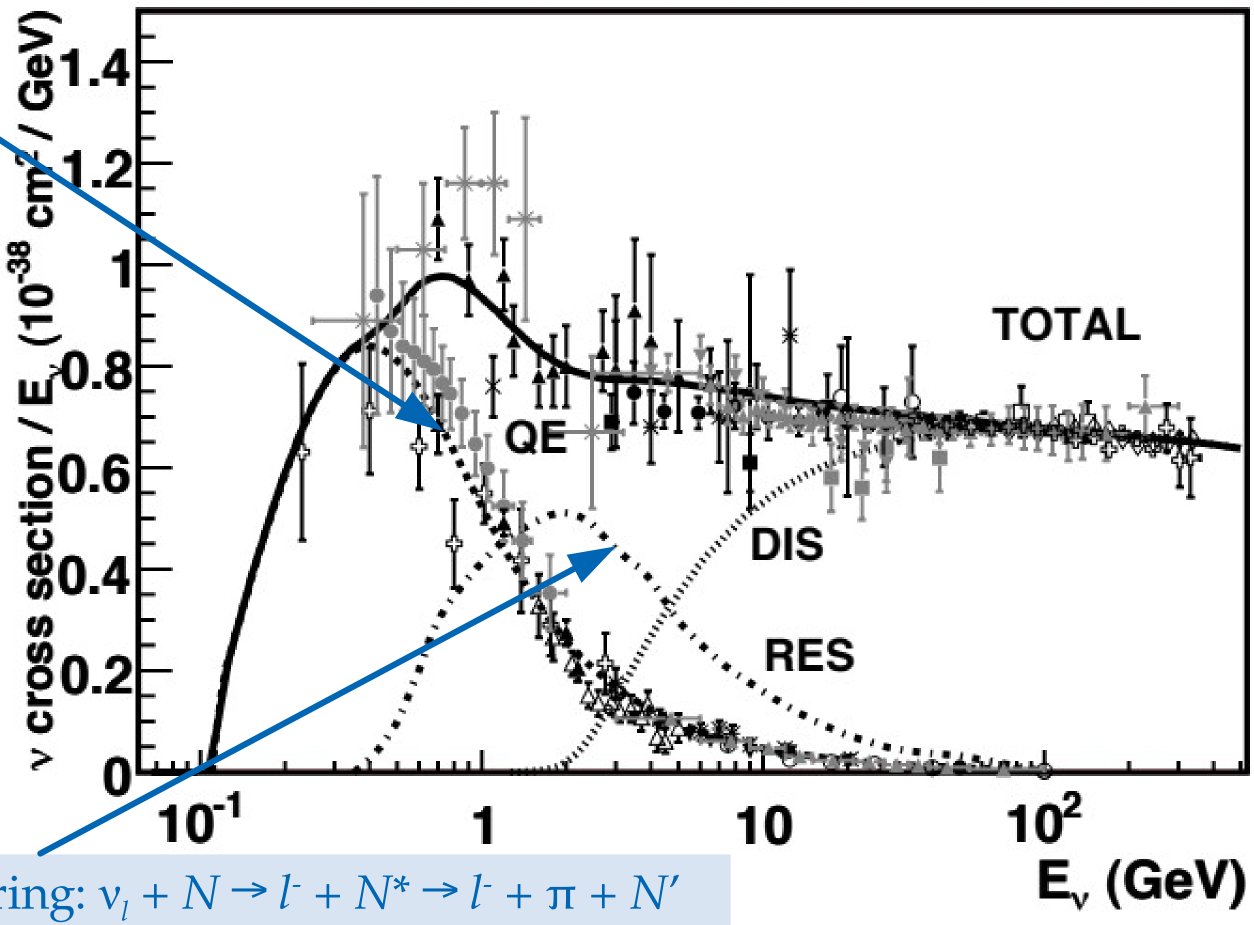

Resonant scattering: $\nu_l + N \rightarrow l^- + N^* \rightarrow l^- + \pi + N'$

Particle Data Group

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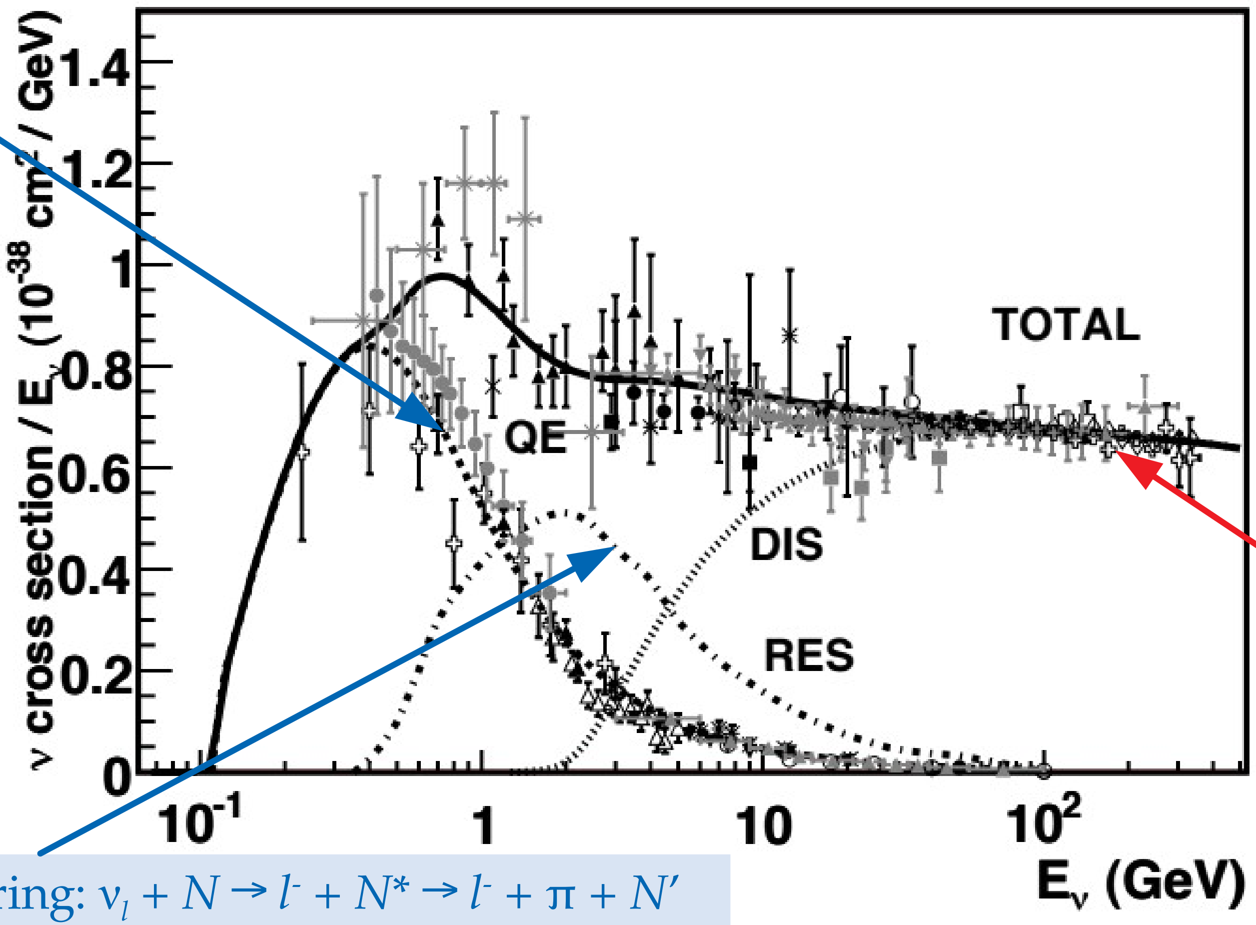


Resonant scattering: $\nu_l + N \rightarrow l^- + N^* \rightarrow l^- + \pi + N'$

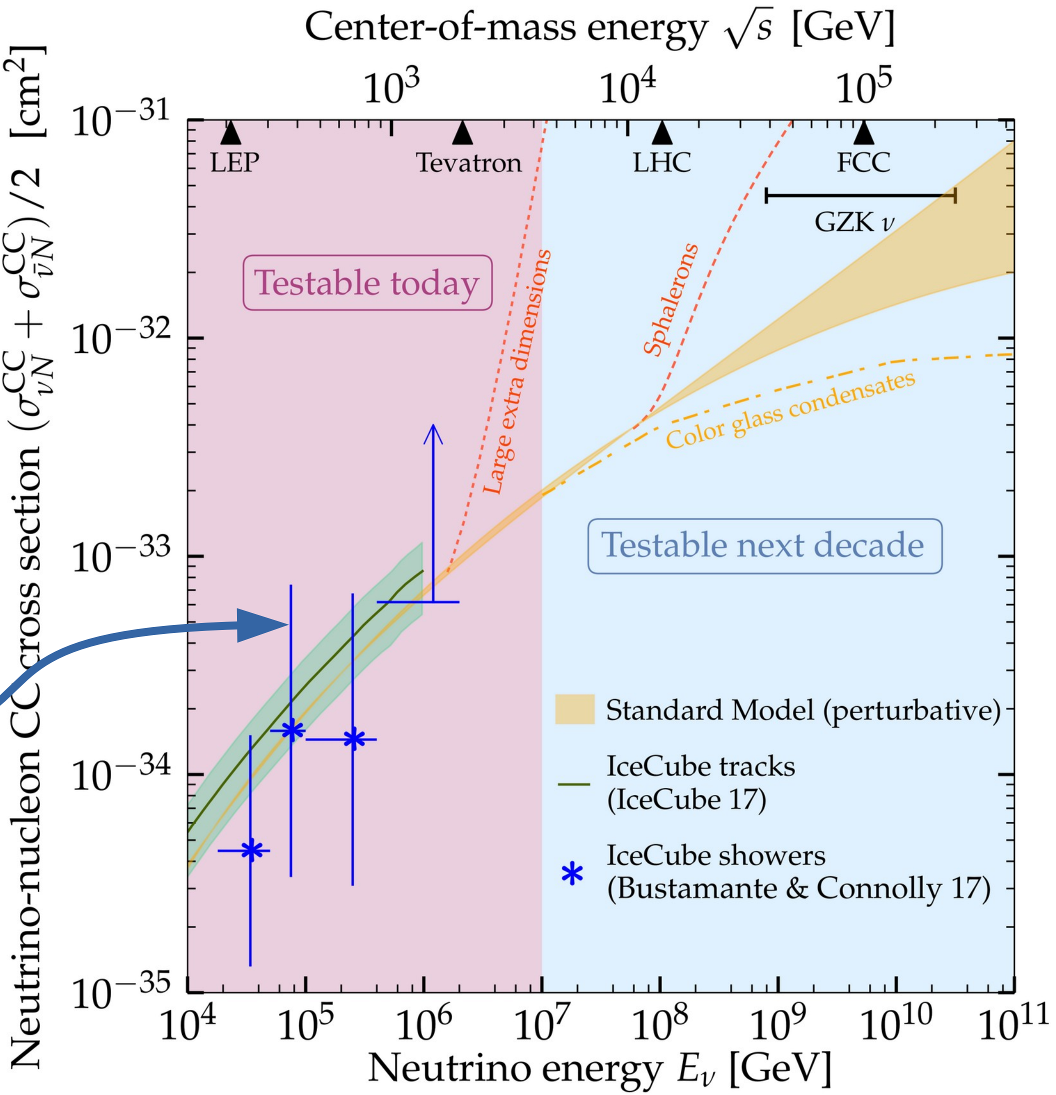
Deep inelastic scattering:

$\nu_l + N \rightarrow l^- + X$

$\bar{\nu}_l + N \rightarrow l^+ + X$

Particle Data Group

- Fold in astrophysical unknowns (spectral index, normalization)
- Compatible with SM predictions
- Still room for new physics
- Today, using IceCube:
  - Extracted from ~60 showers in 6 yr
  - Limited by statistics
- Future, using IceCube-Gen2:
  - × 5 volume ⇒ 300 showers in 6 yr
  - Reduce statistical error by 40%



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

Cross sections from:
MB & Connolly, *PRL* 2019
IceCube, *Nature* 2017

UHE uncertainties are actually smaller:
Cooper-Sarkar, Mertsch, Sarkar *et al.*, *JHEP* 2011

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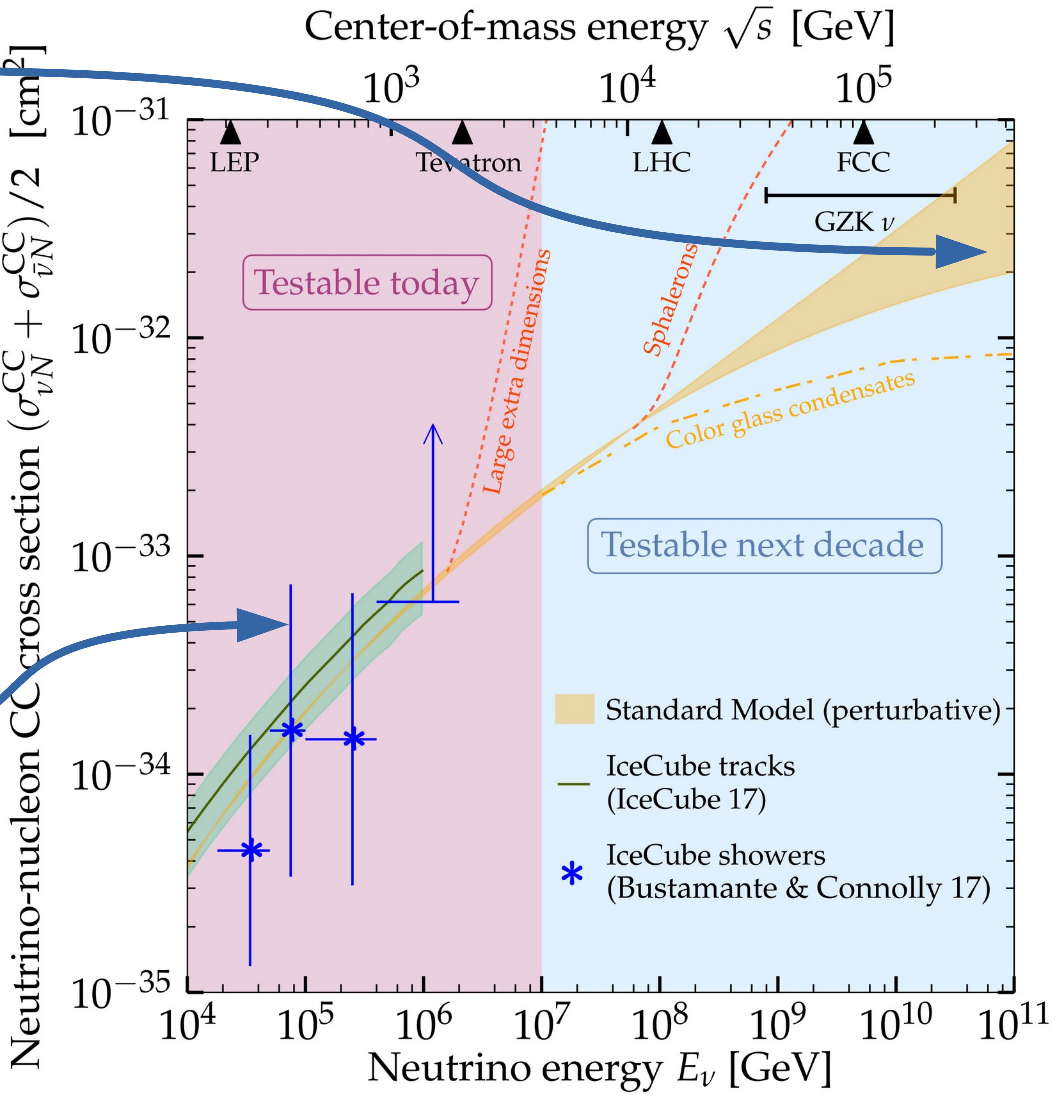

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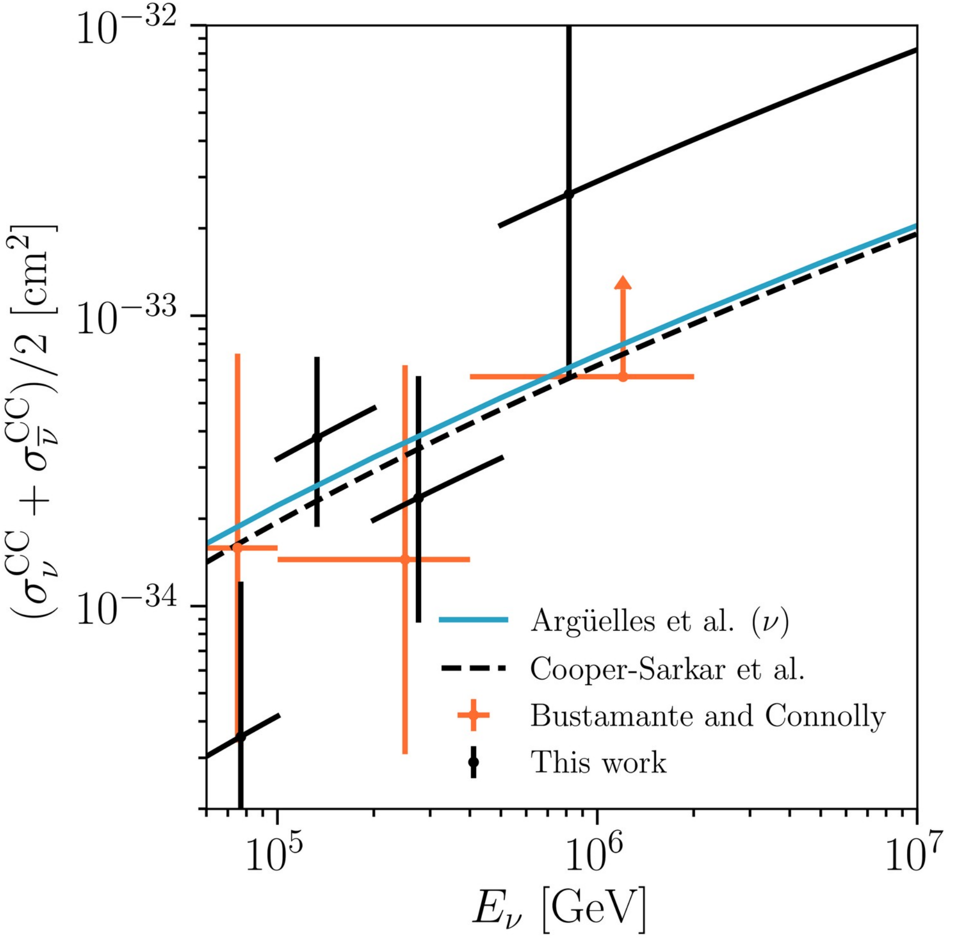
Cross sections from:
MB & Connolly, *PRL* 2019
IceCube, *Nature* 2017

New (IC 7.5 yr): Updated cross section measurement

- Uses 7.5 years of IceCube data
- Uses starting showers + tracks
  - *Vs.* starting showers only in Bustamante & Connolly 2017
  - *Vs.* throughgoing muons in IceCube 2017
- Extends measurement to 10 PeV
- Still compatible with Standard Model predictions
- Higher energies? Work in progress by Valera & Bustamante



IceCube, 2011.03560

Example 2:
Secret neutrino interactions

Astrophysical neutrino sources

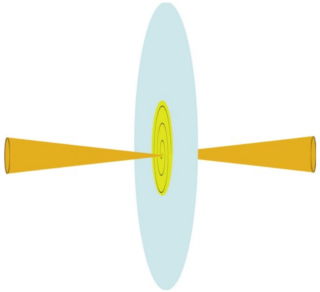
Earth

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

Astrophysical neutrino sources

Earth

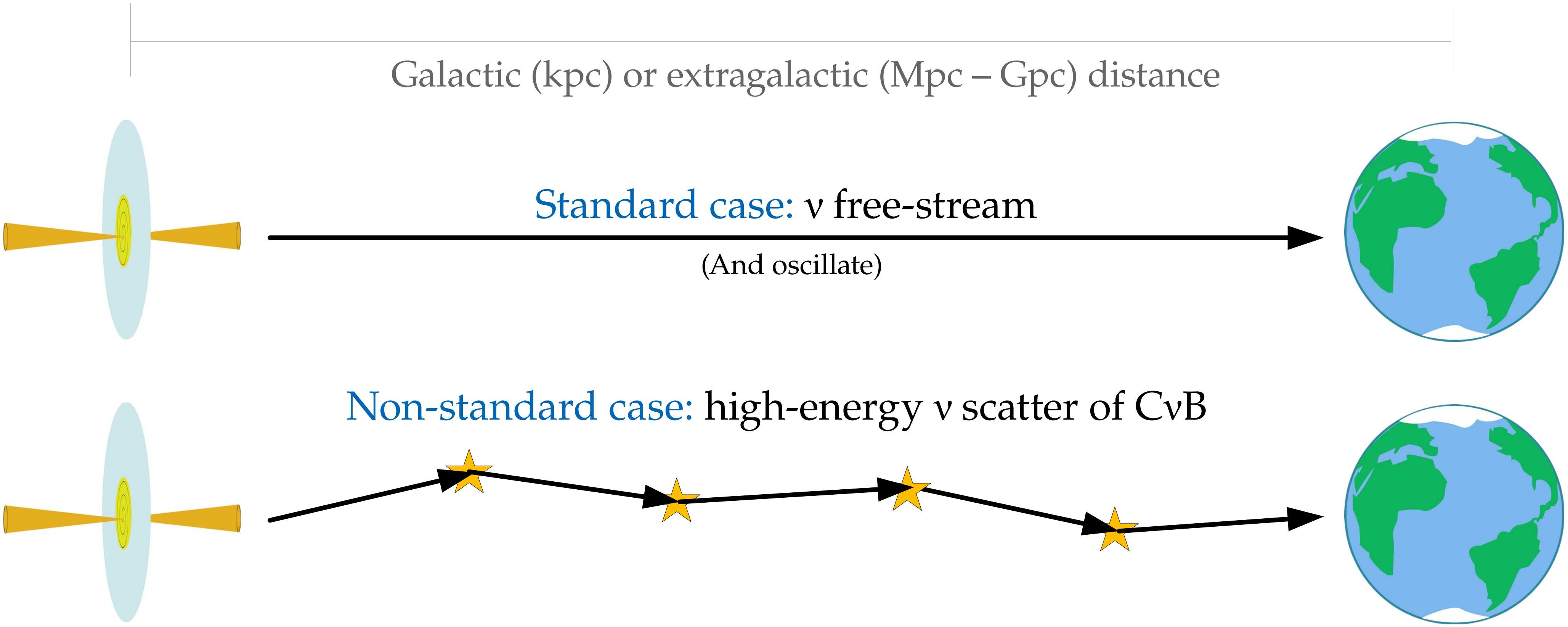
Galactic (kpc) or extragalactic (Mpc – Gpc) distance

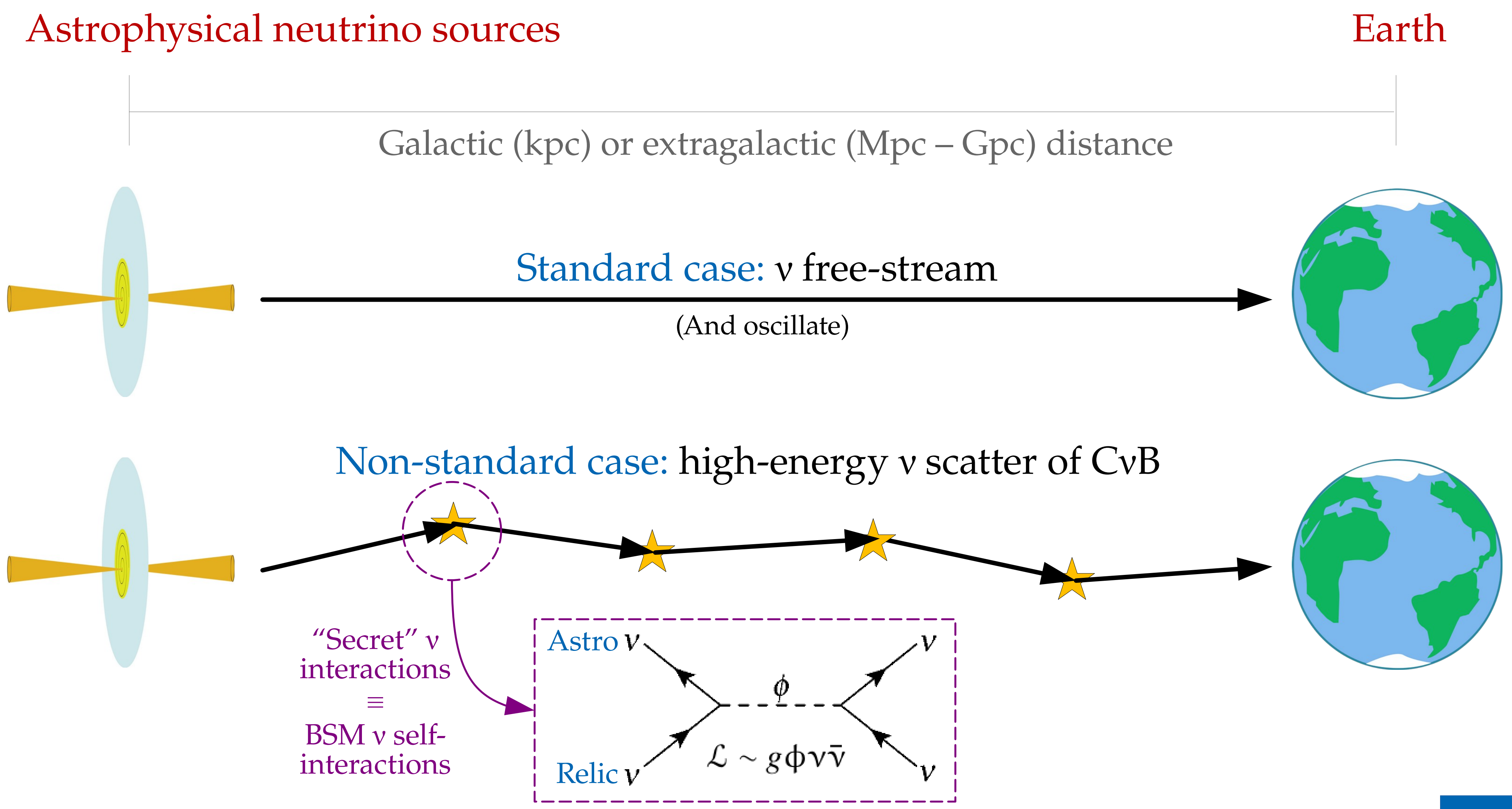


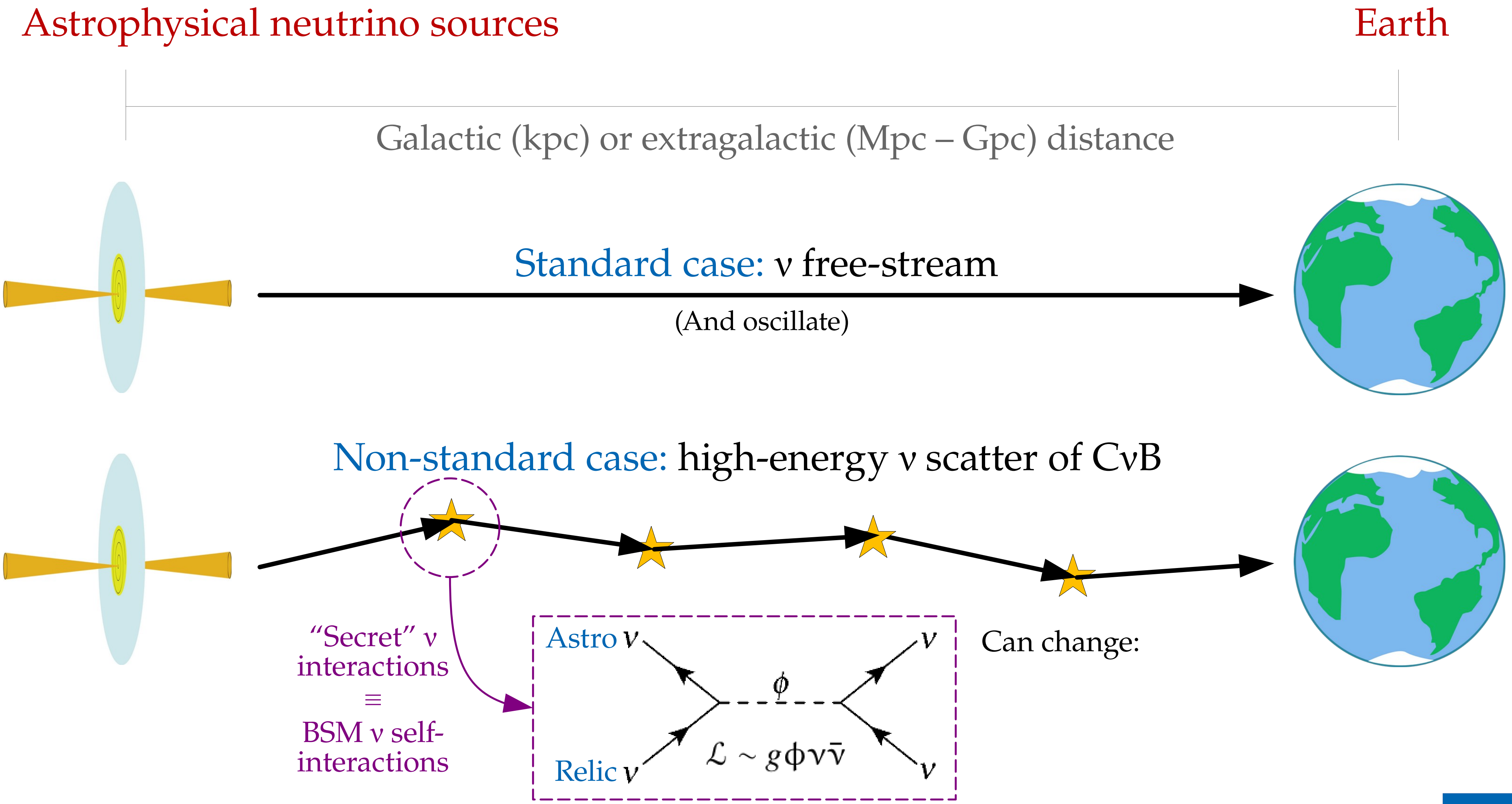
Standard case: ν free-stream

(And oscillate)

Astrophysical neutrino sources Earth




Astrophysical neutrino sources
Earth
Galactic (kpc) or extragalactic (Mpc – Gpc) distance
Standard case: ν free-stream
(And oscillate)
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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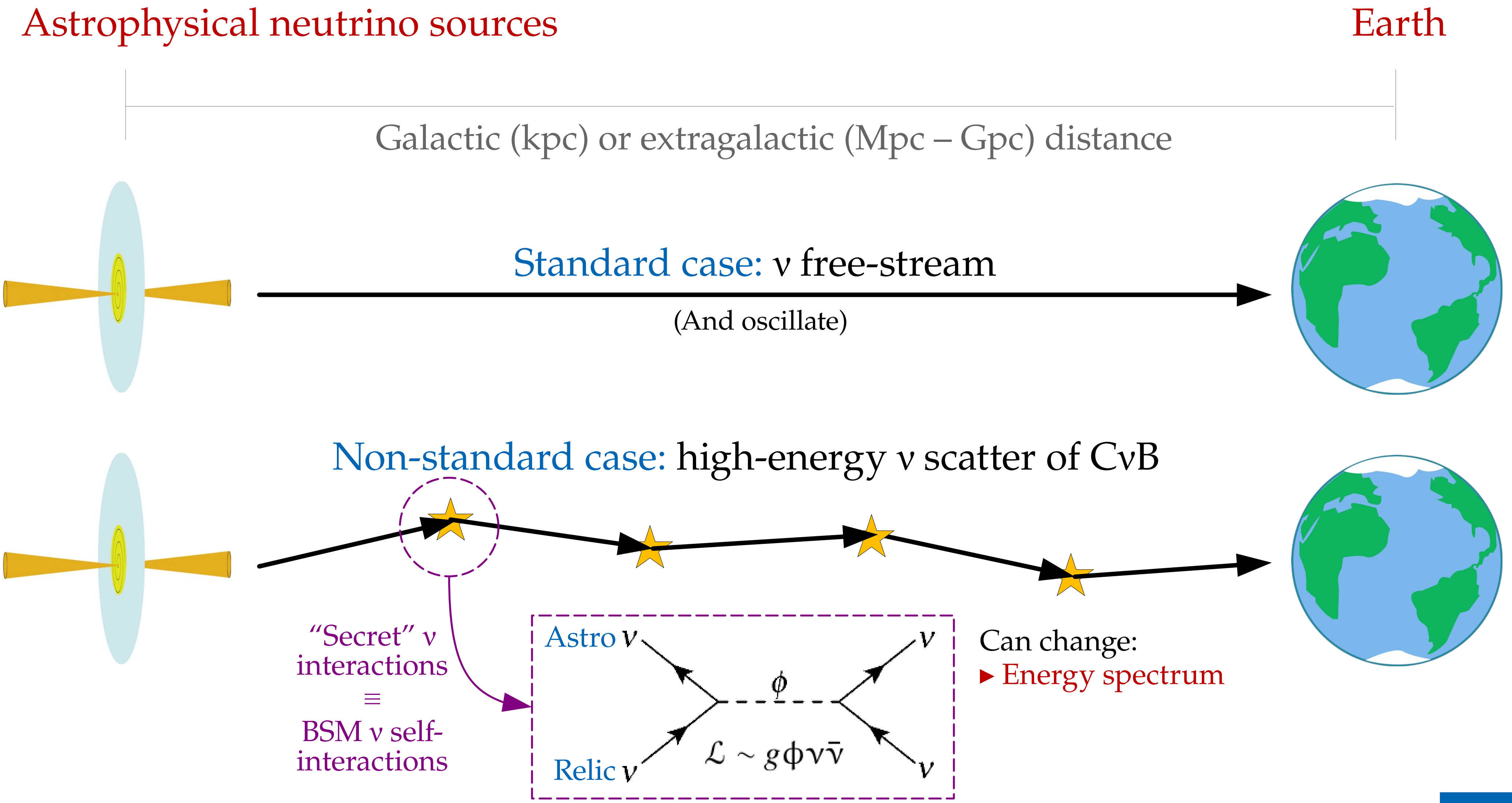
ℒ ~ gϕνν̄
Can change: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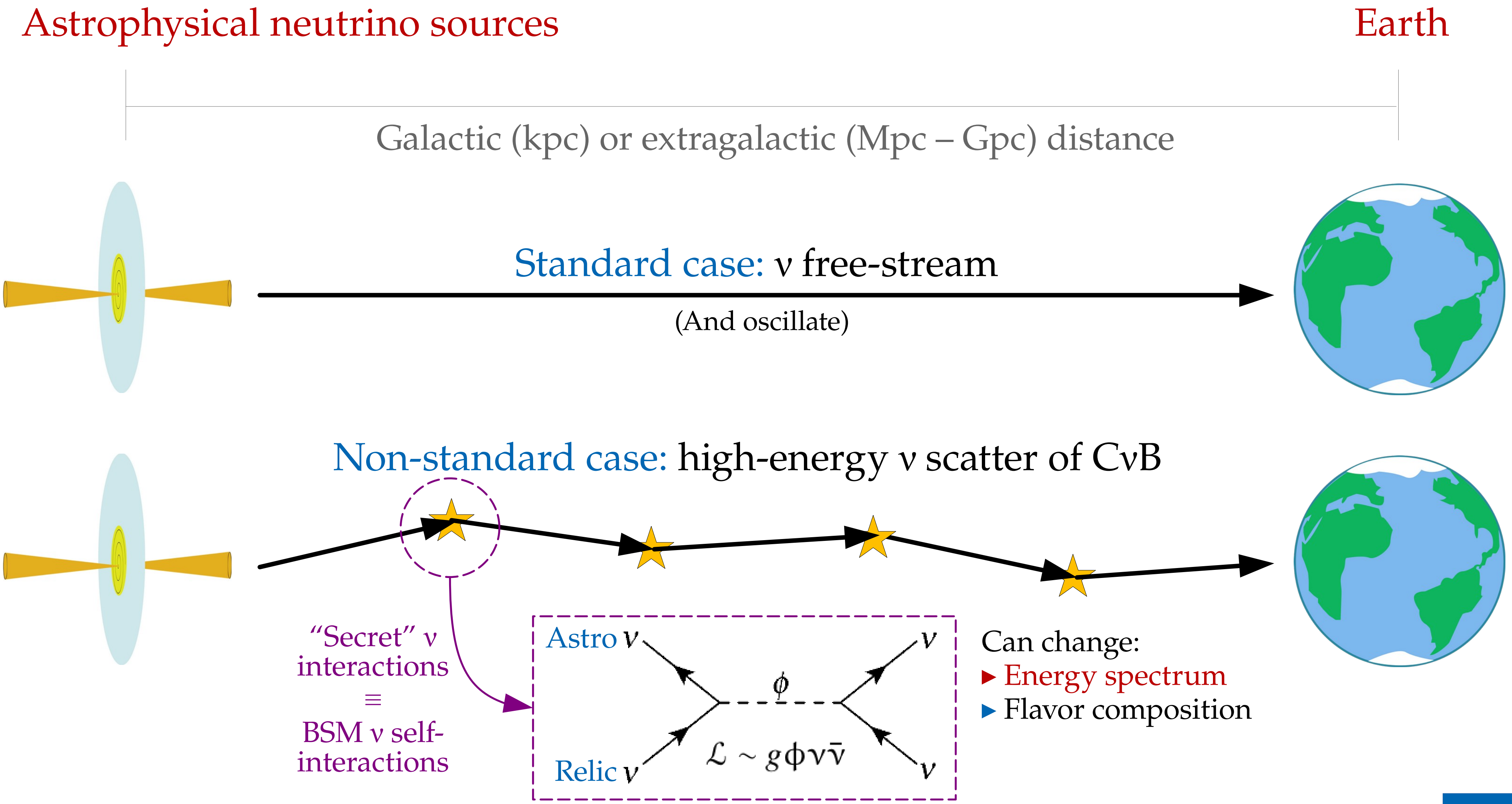
Can change:
▸ Energy spectrum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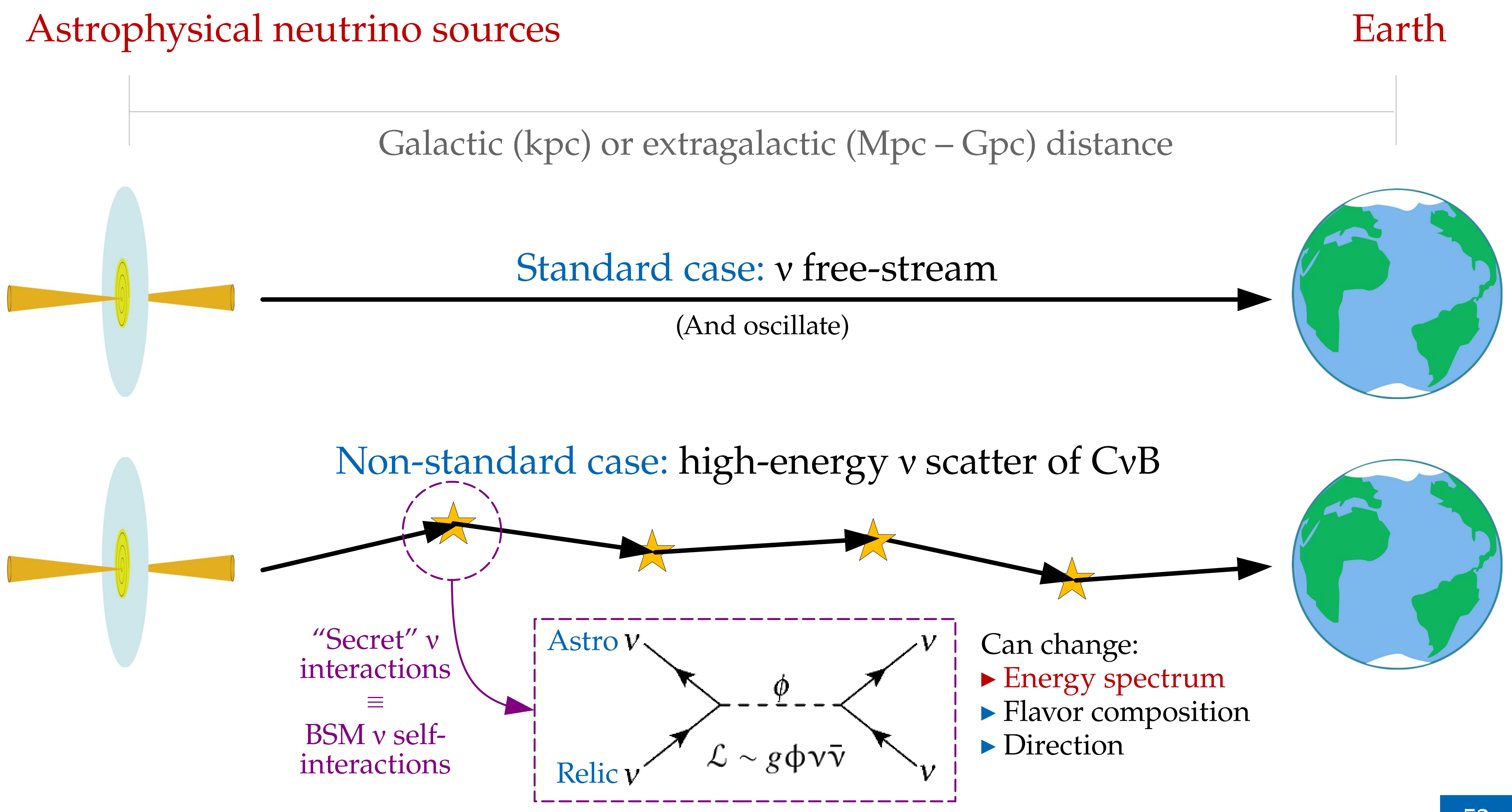
Can change:
Energy spectrum
Flavor composition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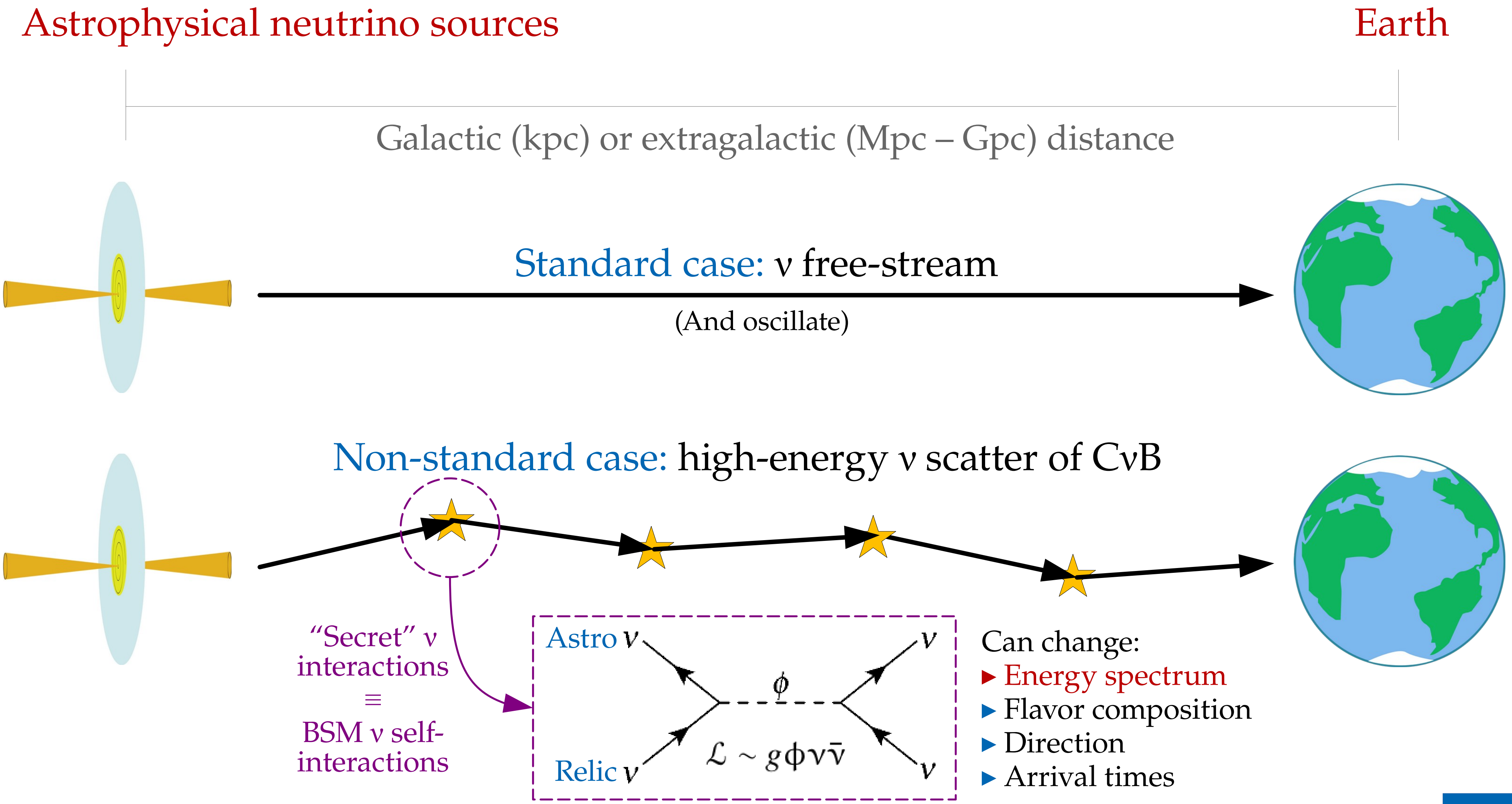
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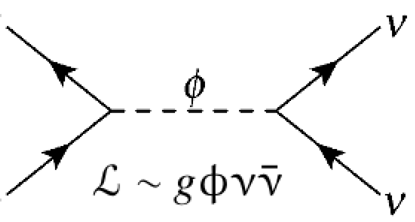
Flavor composition
Direction
Arrival times

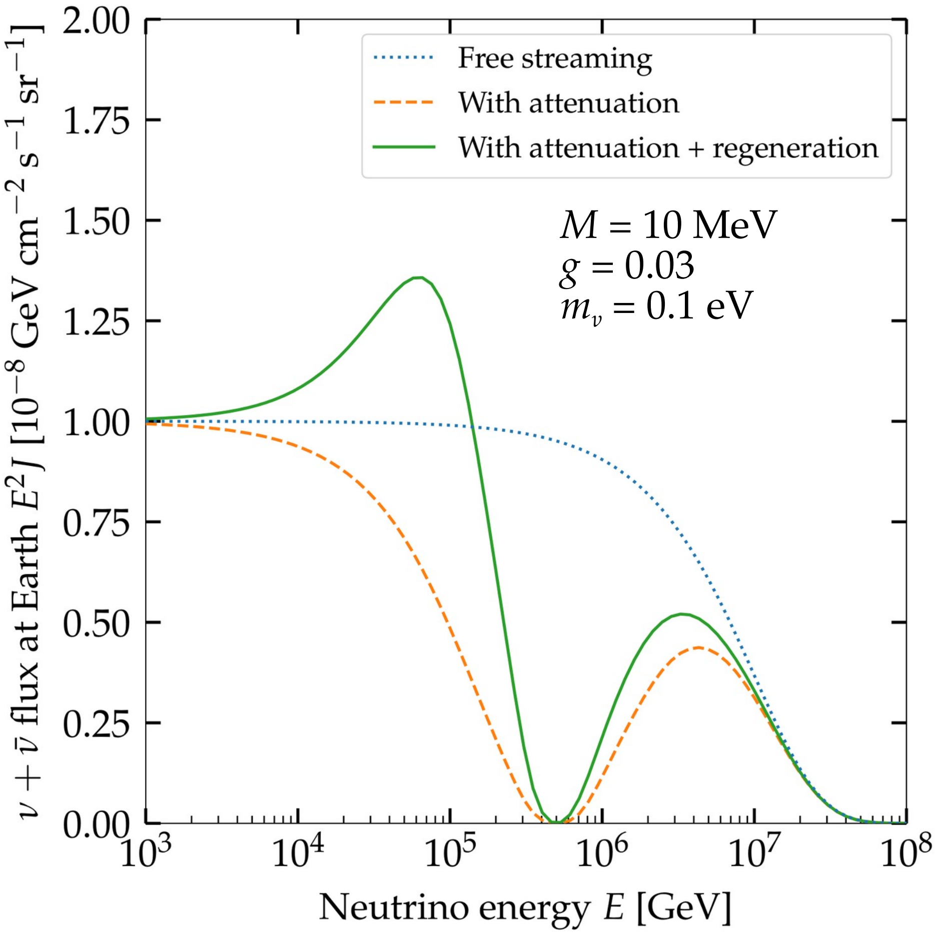
Secret interactions of high-energy astrophysical neutrinos

"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: $E_{\rm res} = \frac{M^2}{2m_\nu}$



MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020
See also: Ng & Beacom, *PRD* 2014
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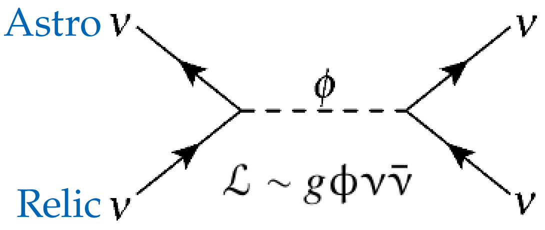
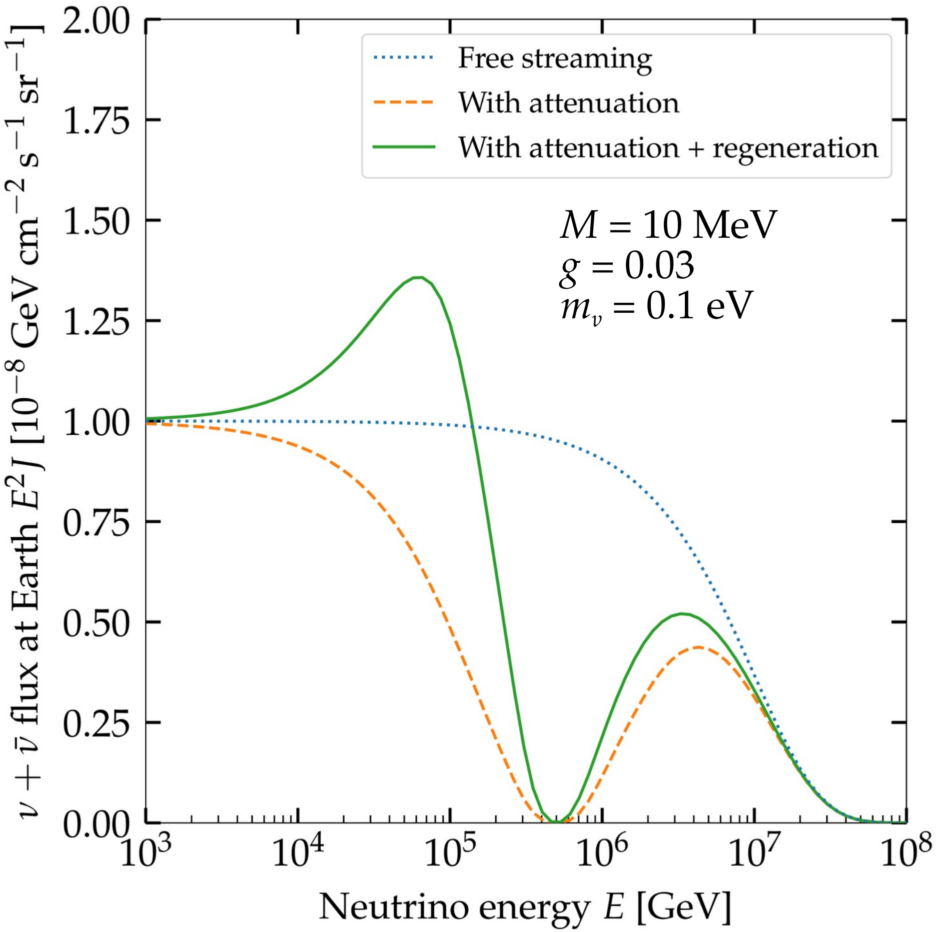


New coupling

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

Mediator mass

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



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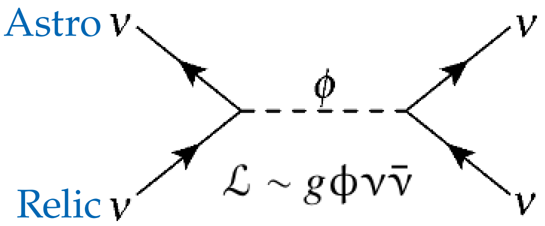
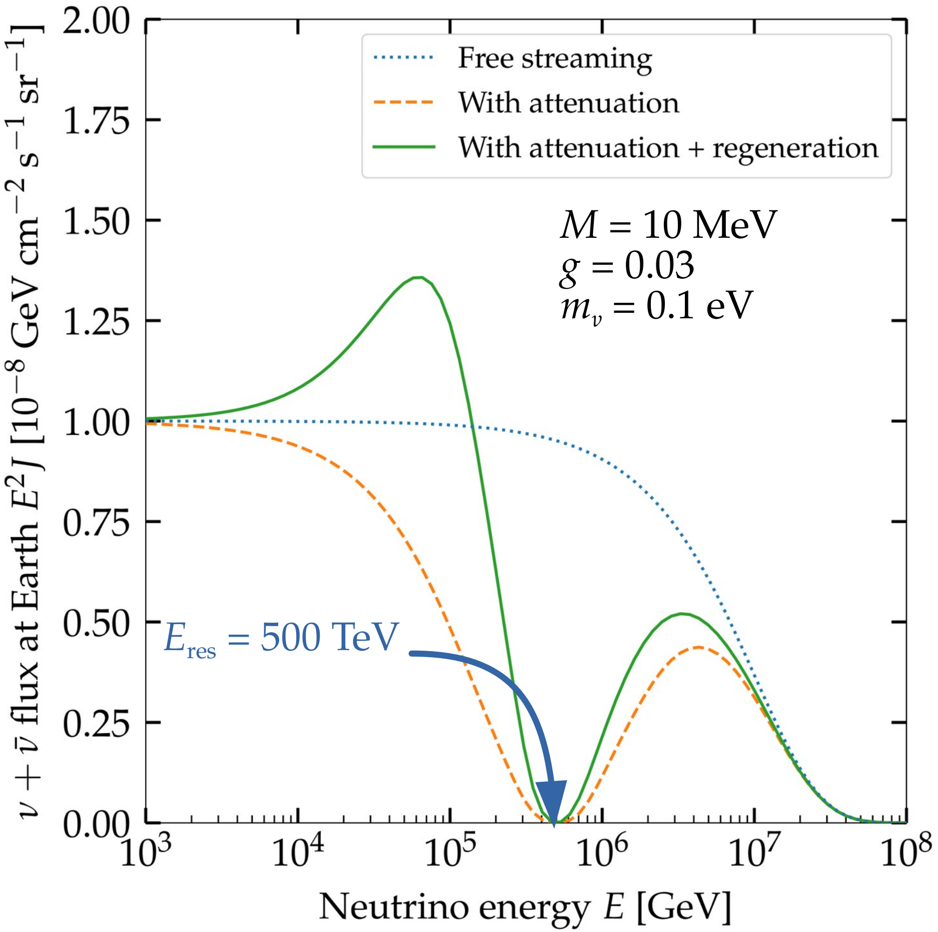


New coupling

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

Mediator mass

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



MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020
See also: Ng & Beacom, *PRD* 2014
Cherry, Friedland, Shoemaker, 1411.1071
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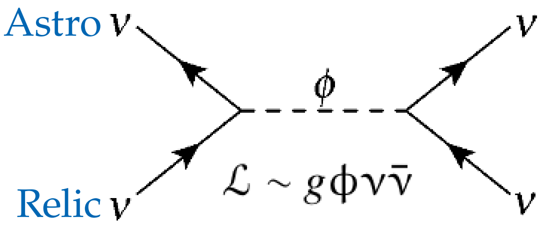

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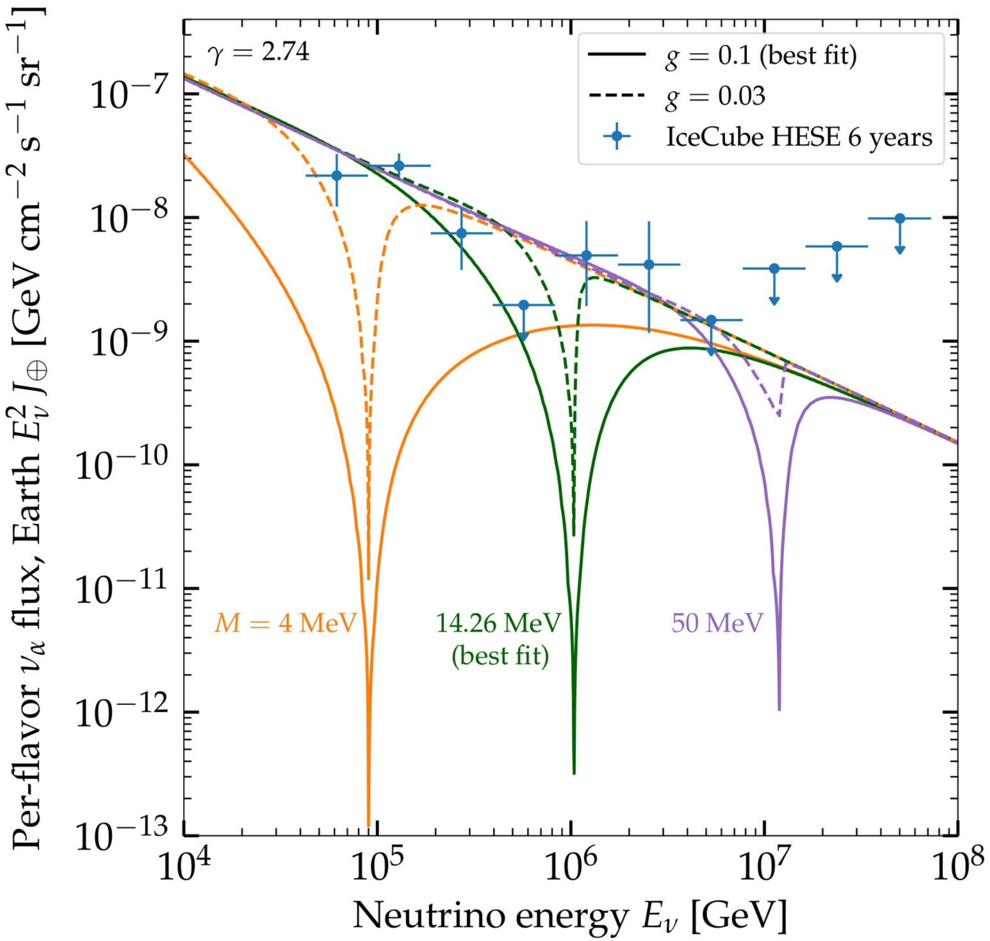

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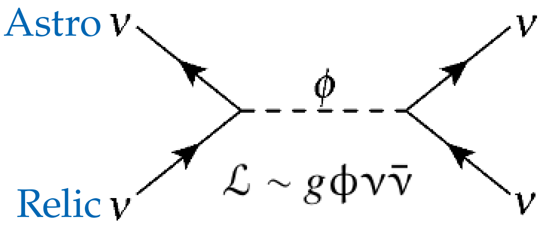

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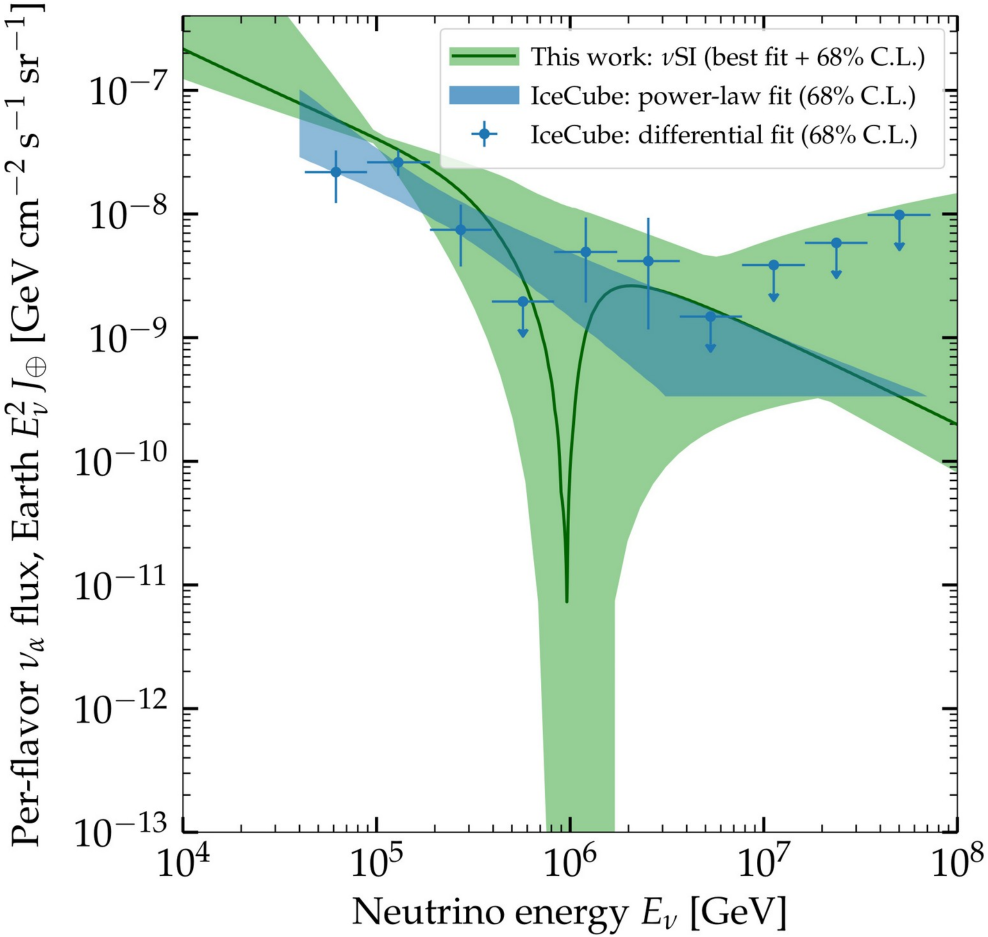
Looking for evidence of νSI

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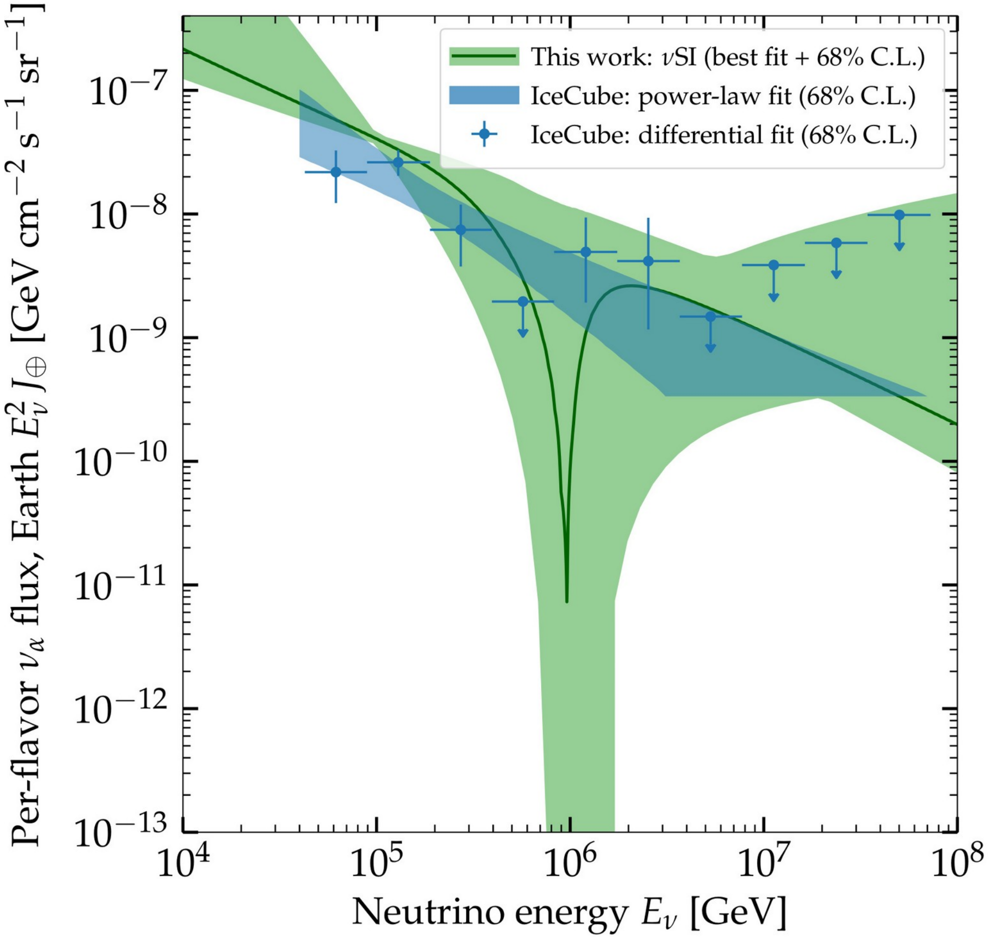
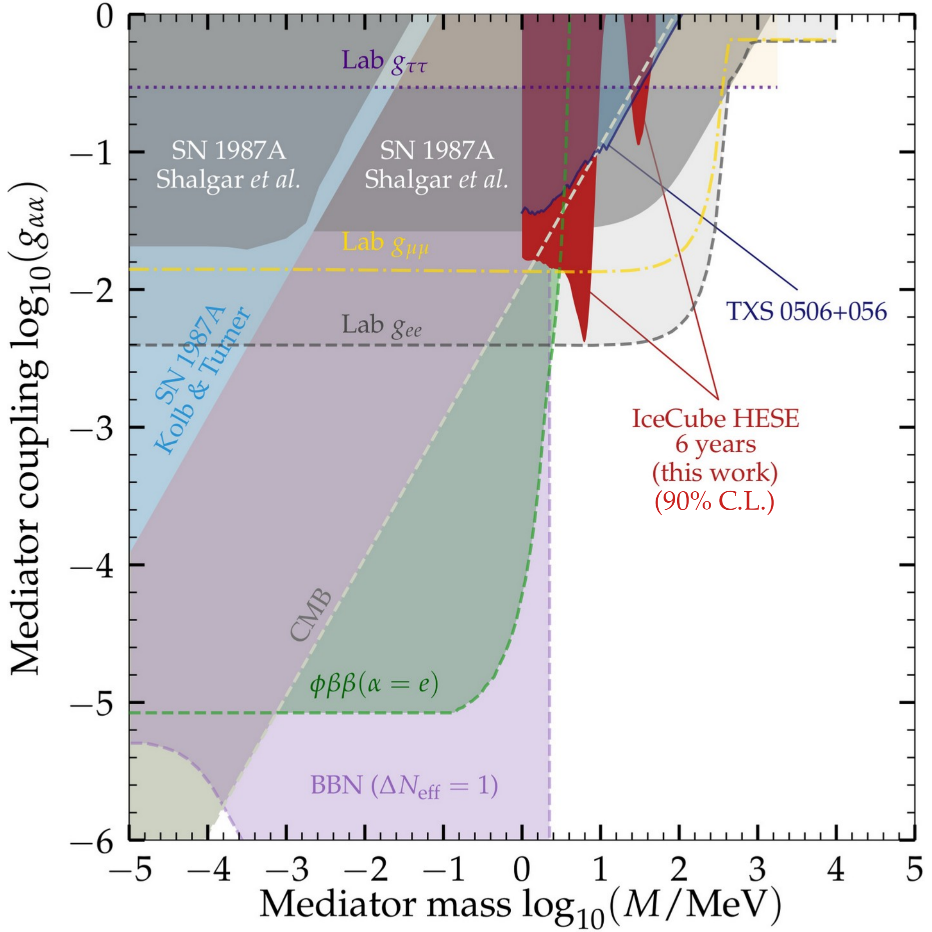
No significant (> 3σ) evidence for a spectral dip … … so we set upper limits on the coupling g





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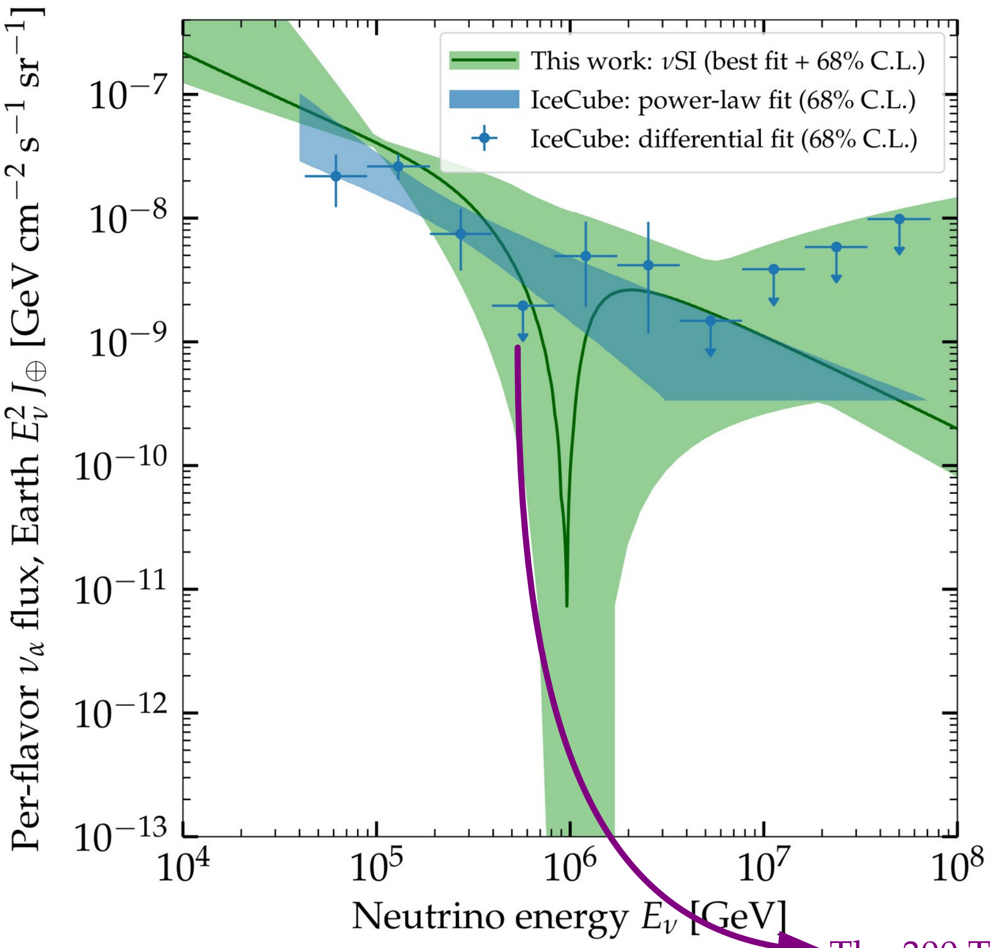
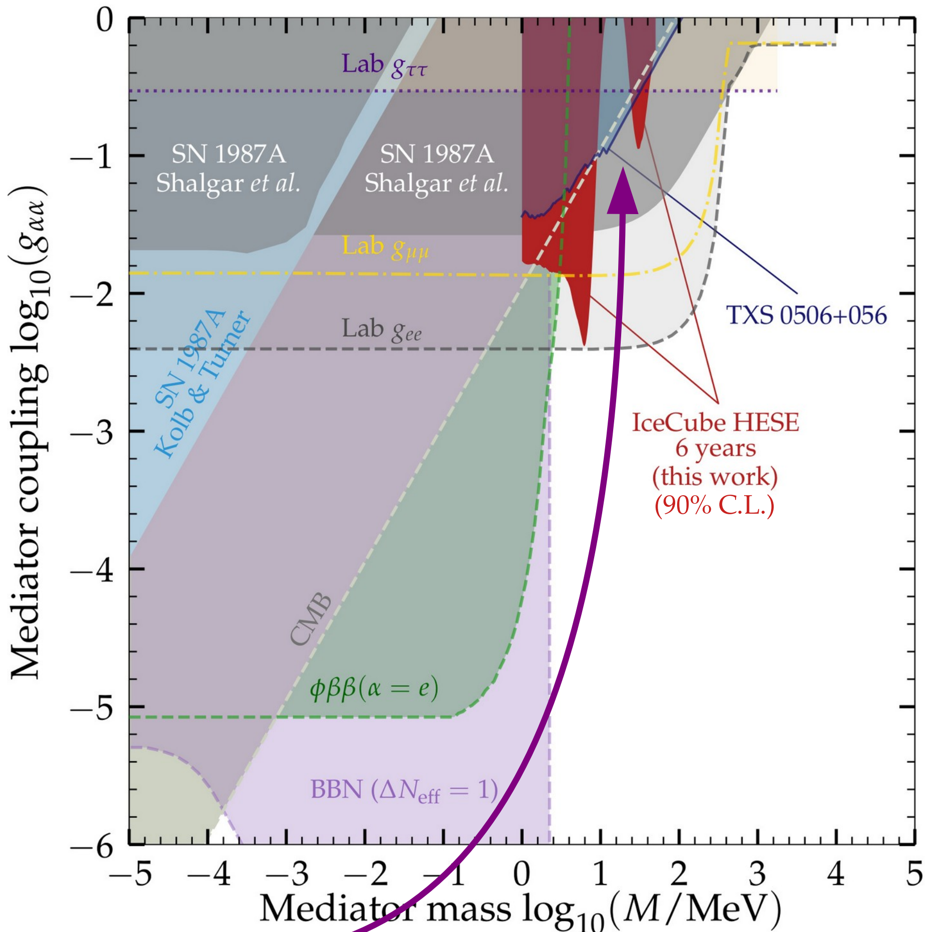




The 300 TeV–1 PeV "gap" degrades the limit at ~10 MeV

MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020
See also: Shalgar, **MB**, Tamborra, 1912.09115

IV.
The future

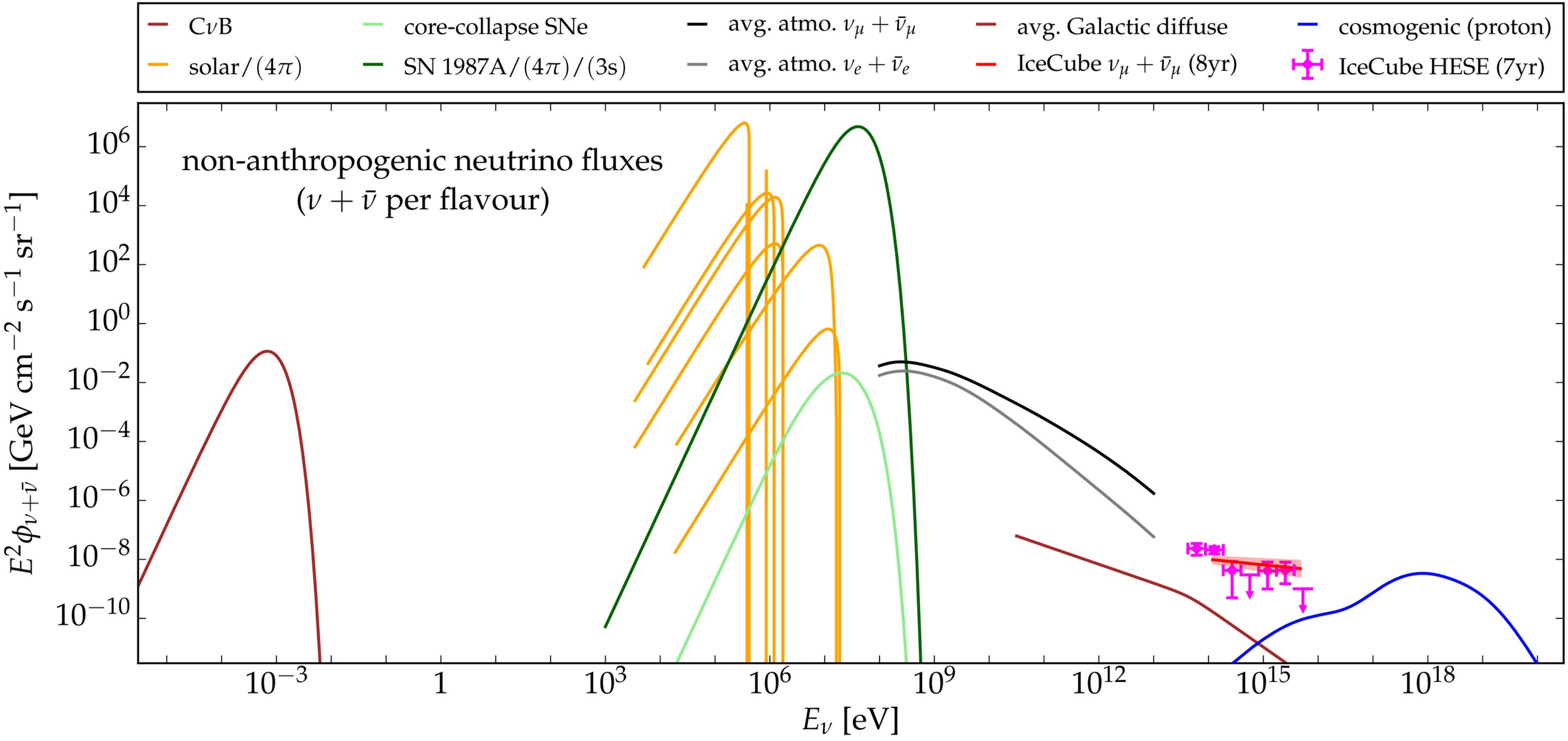
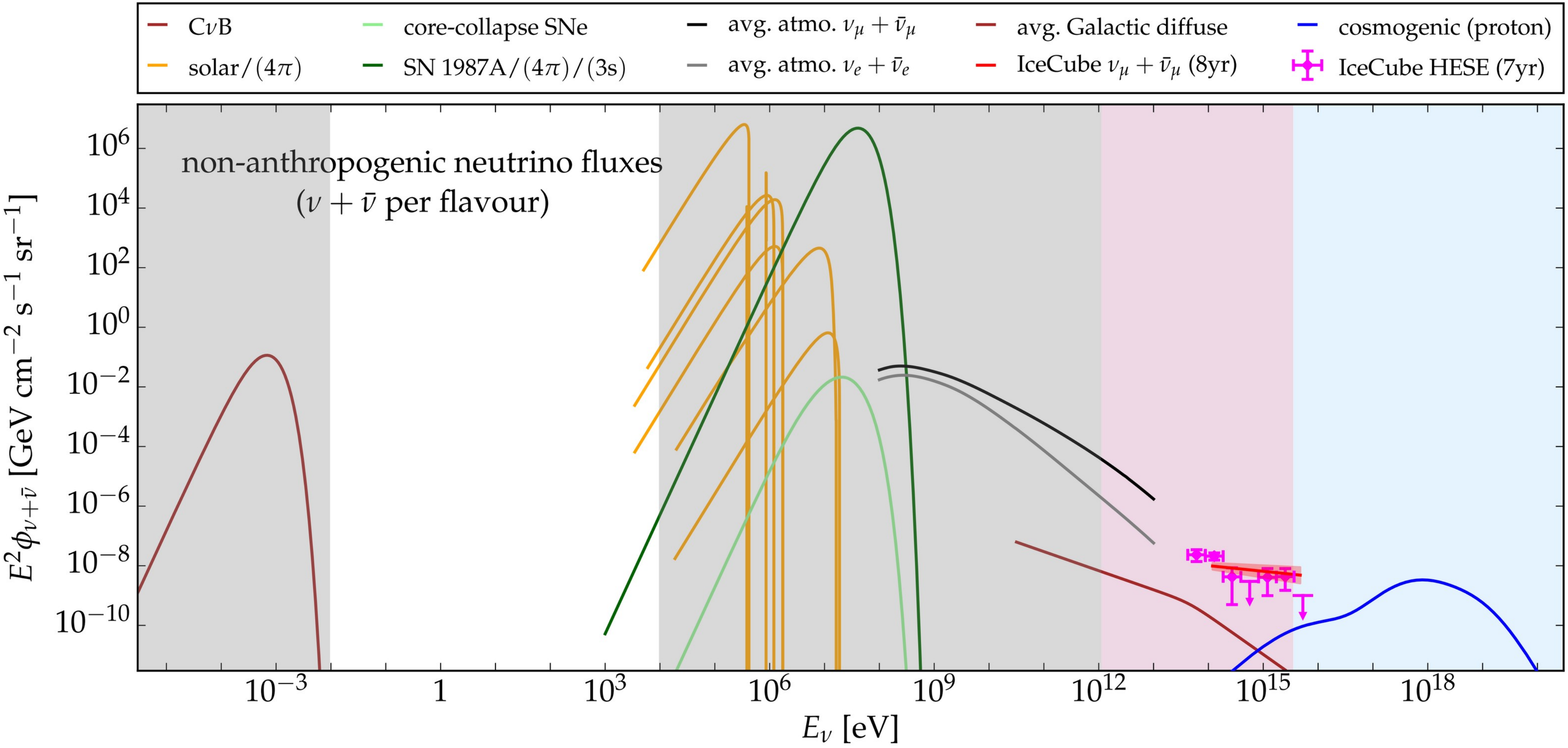


Figure courtesy of Markus Ahlers
Also in: Van Elewyck *et al.*, PoS(ICRC2019), 1023



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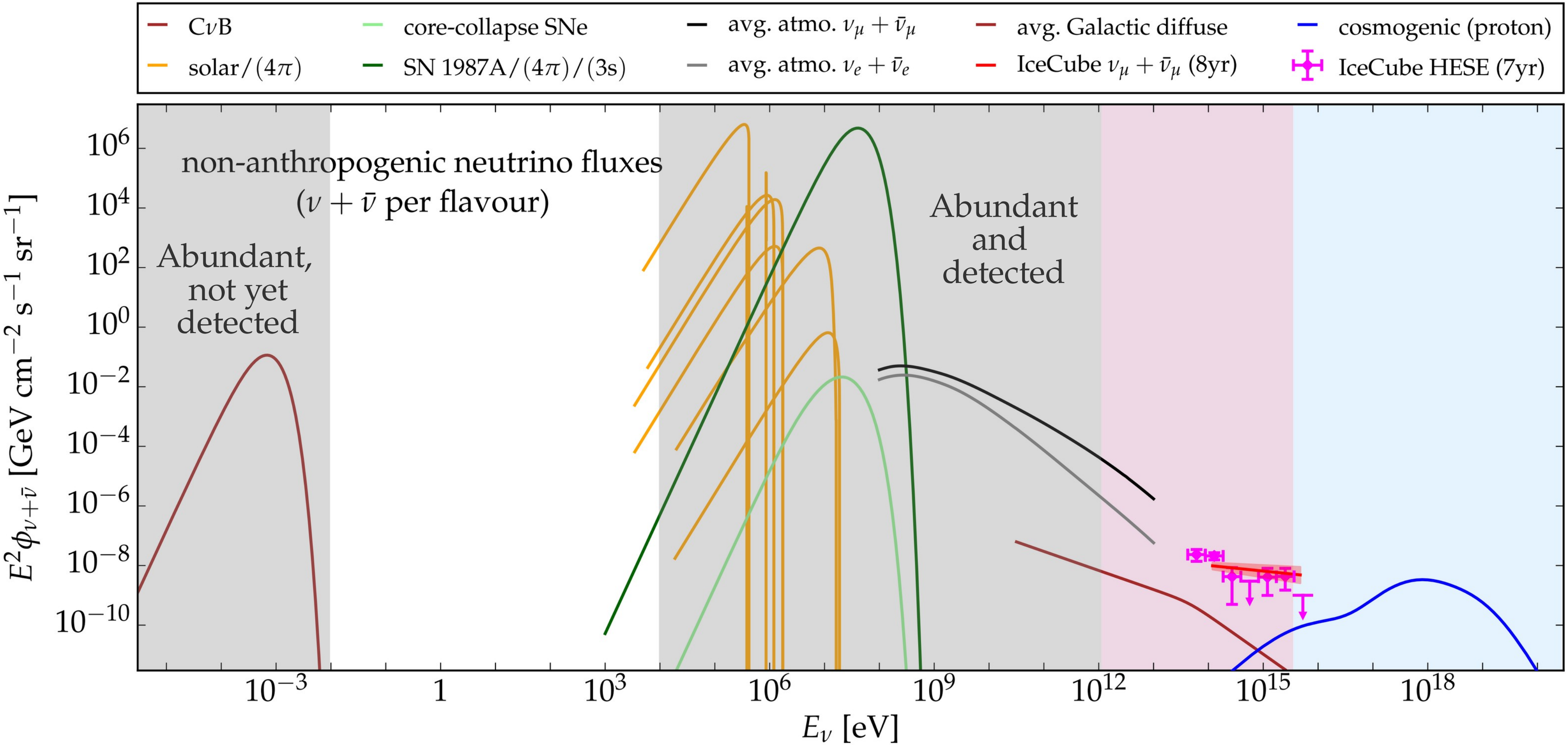

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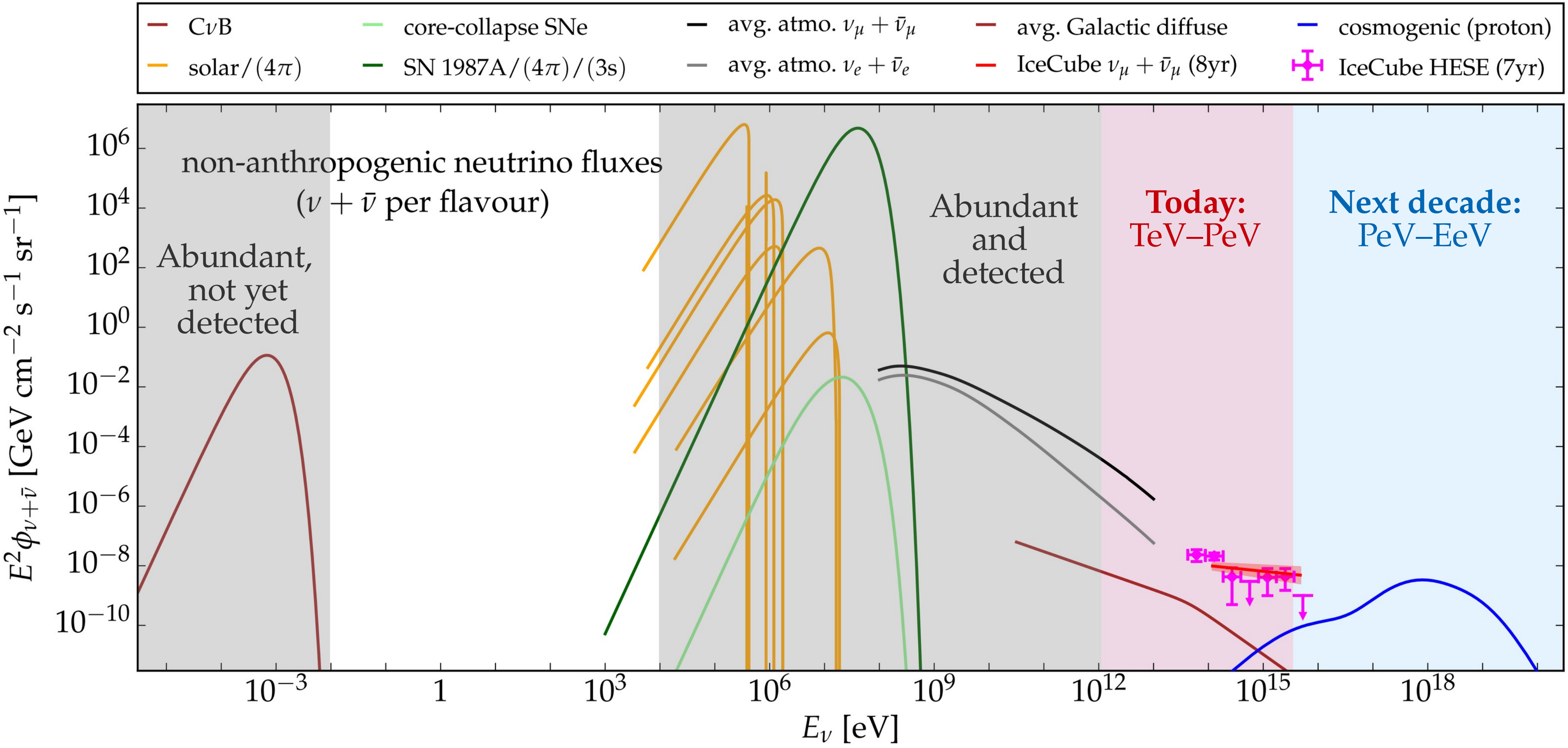

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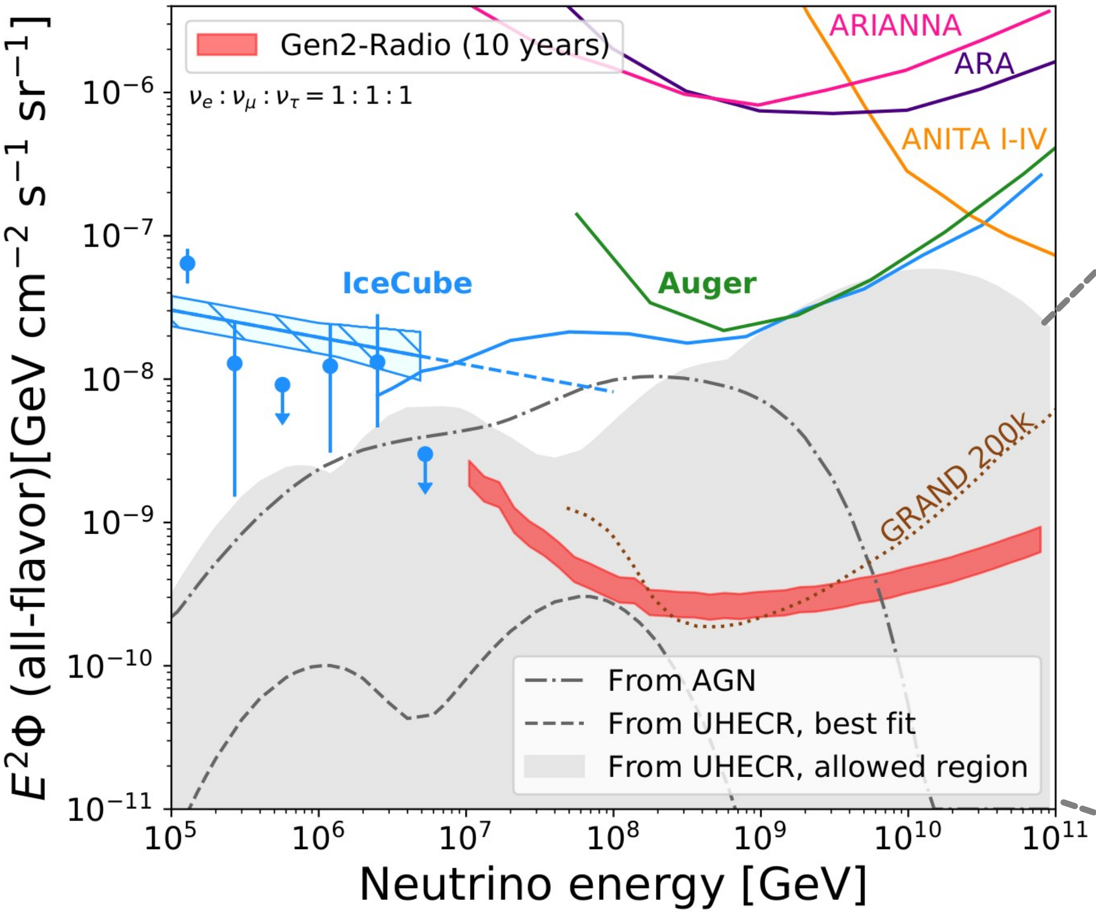
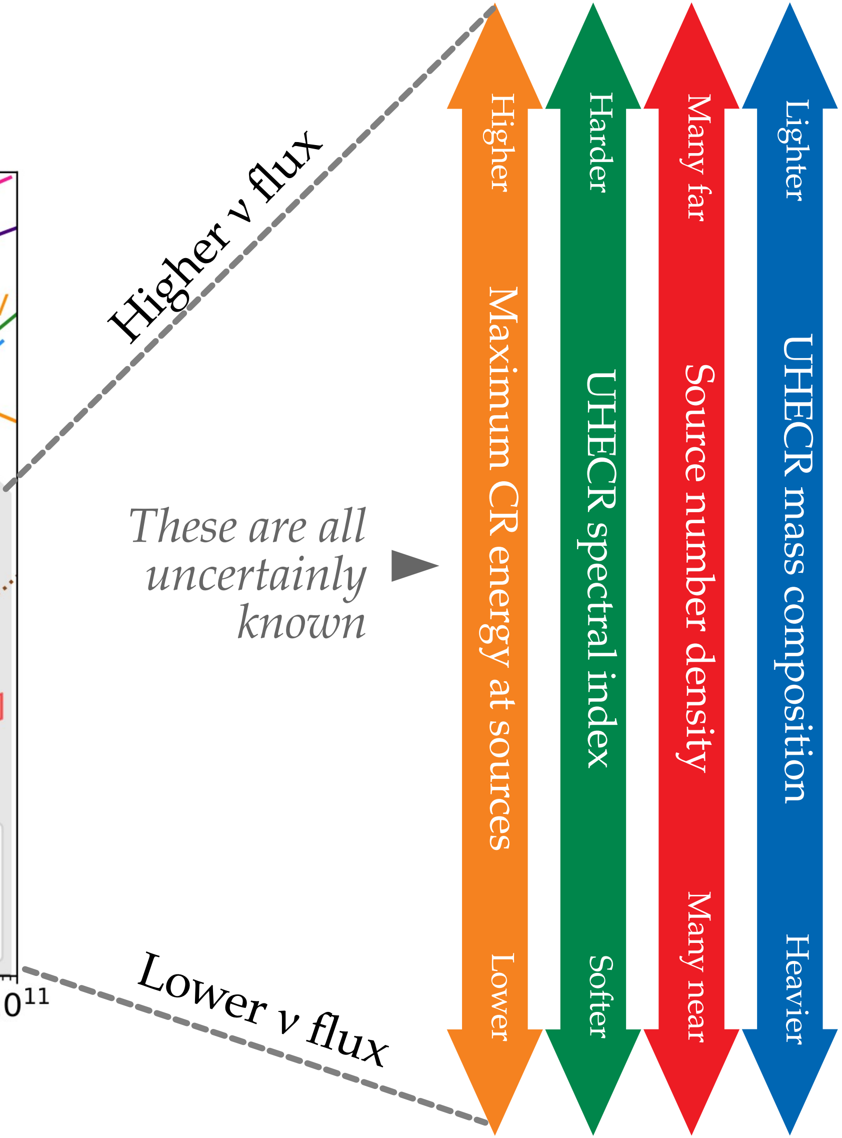
Cosmogenic ν flux: how low?

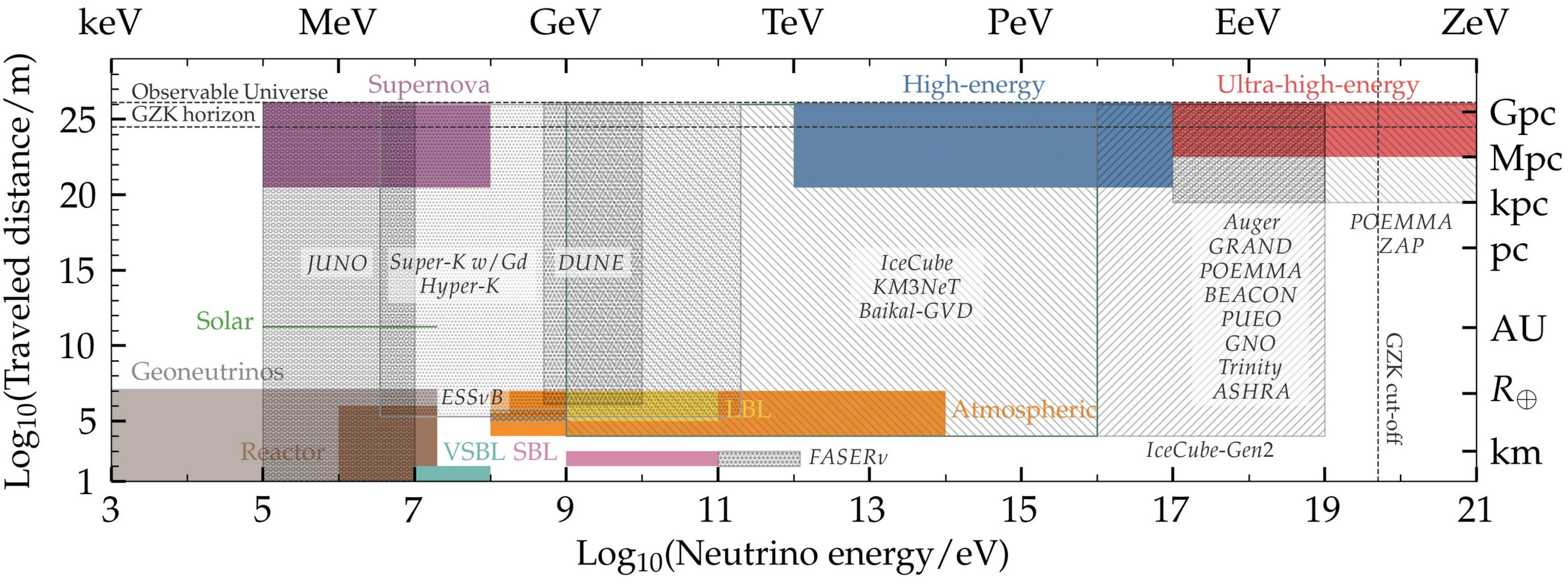


These are all uncertainly known



IceCube-Gen2, 2008.04323

Next decade: a host of planned neutrino detectors



MB *et al.*, Snowmass 20201 Letter of interest

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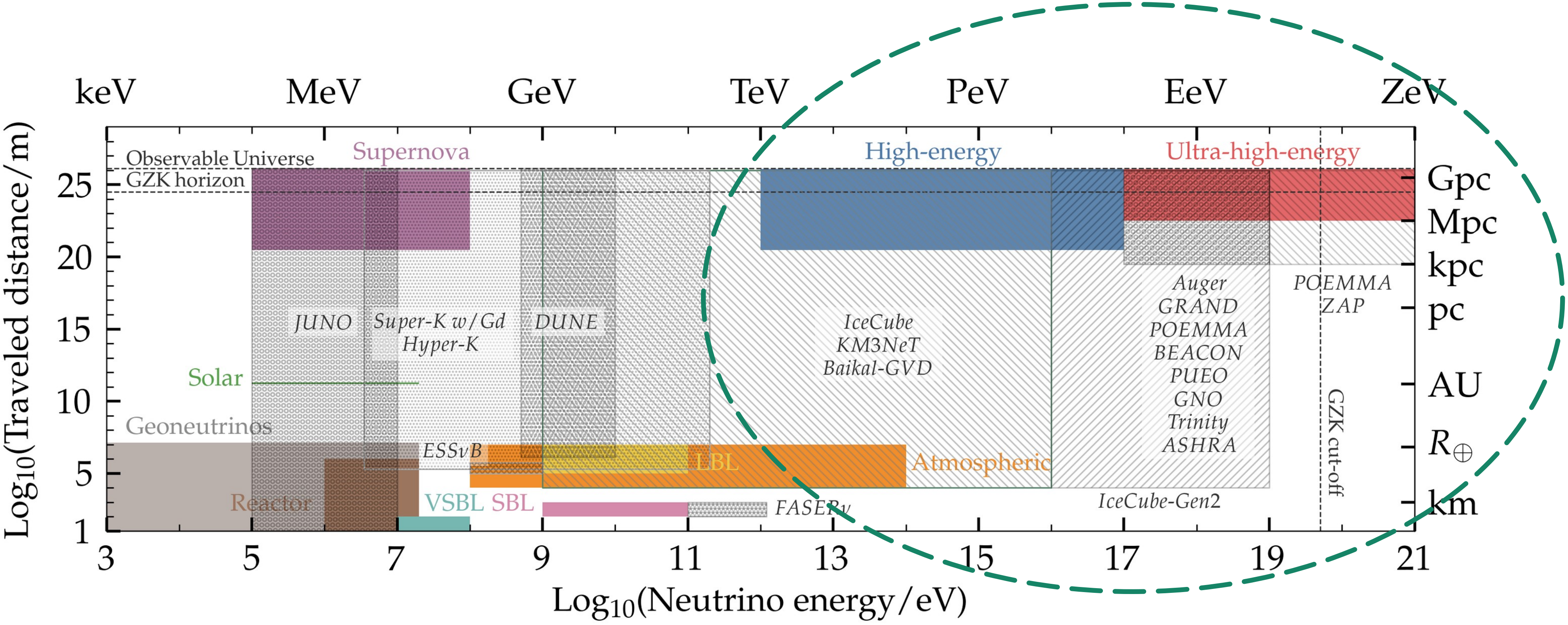

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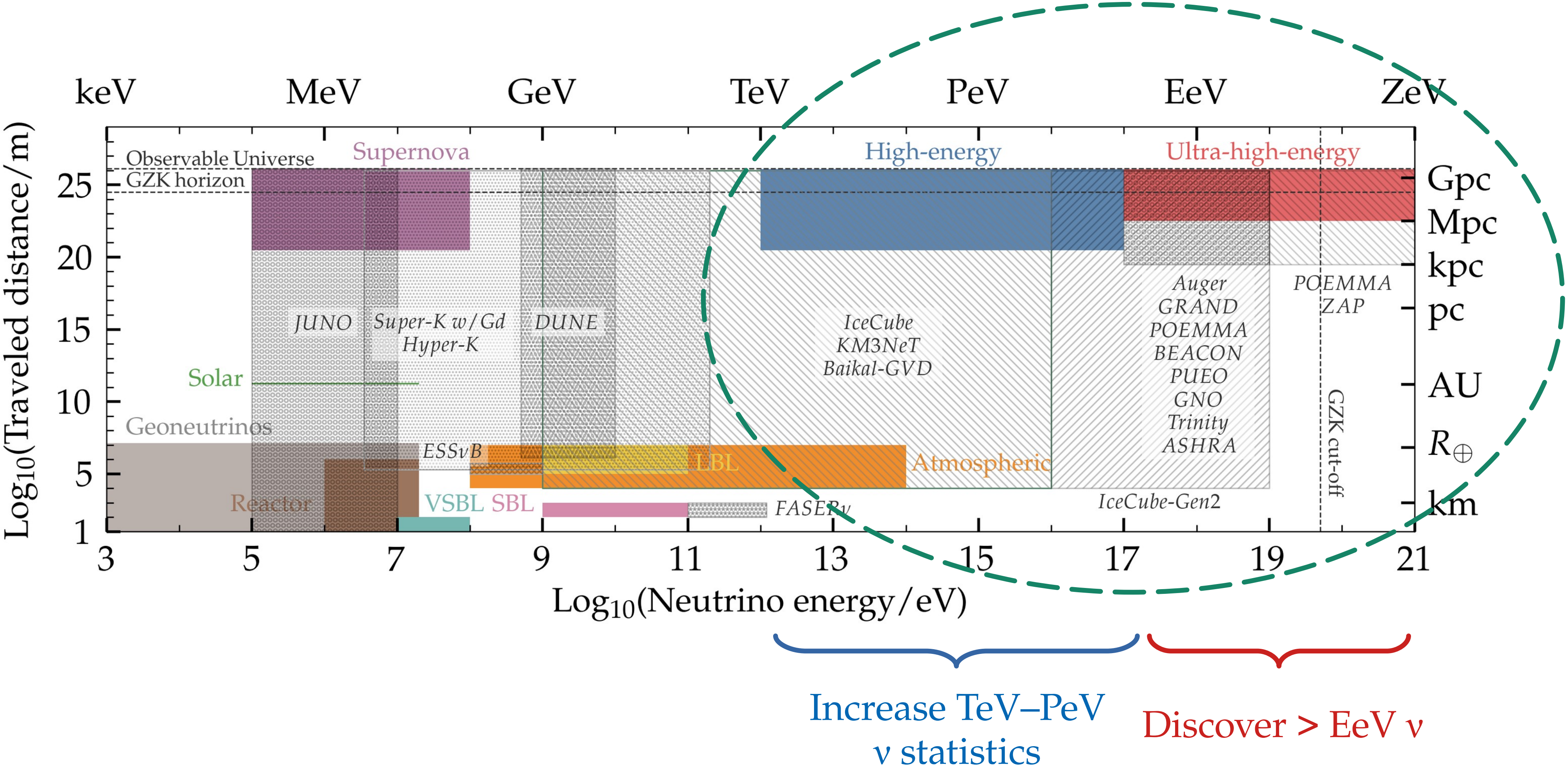

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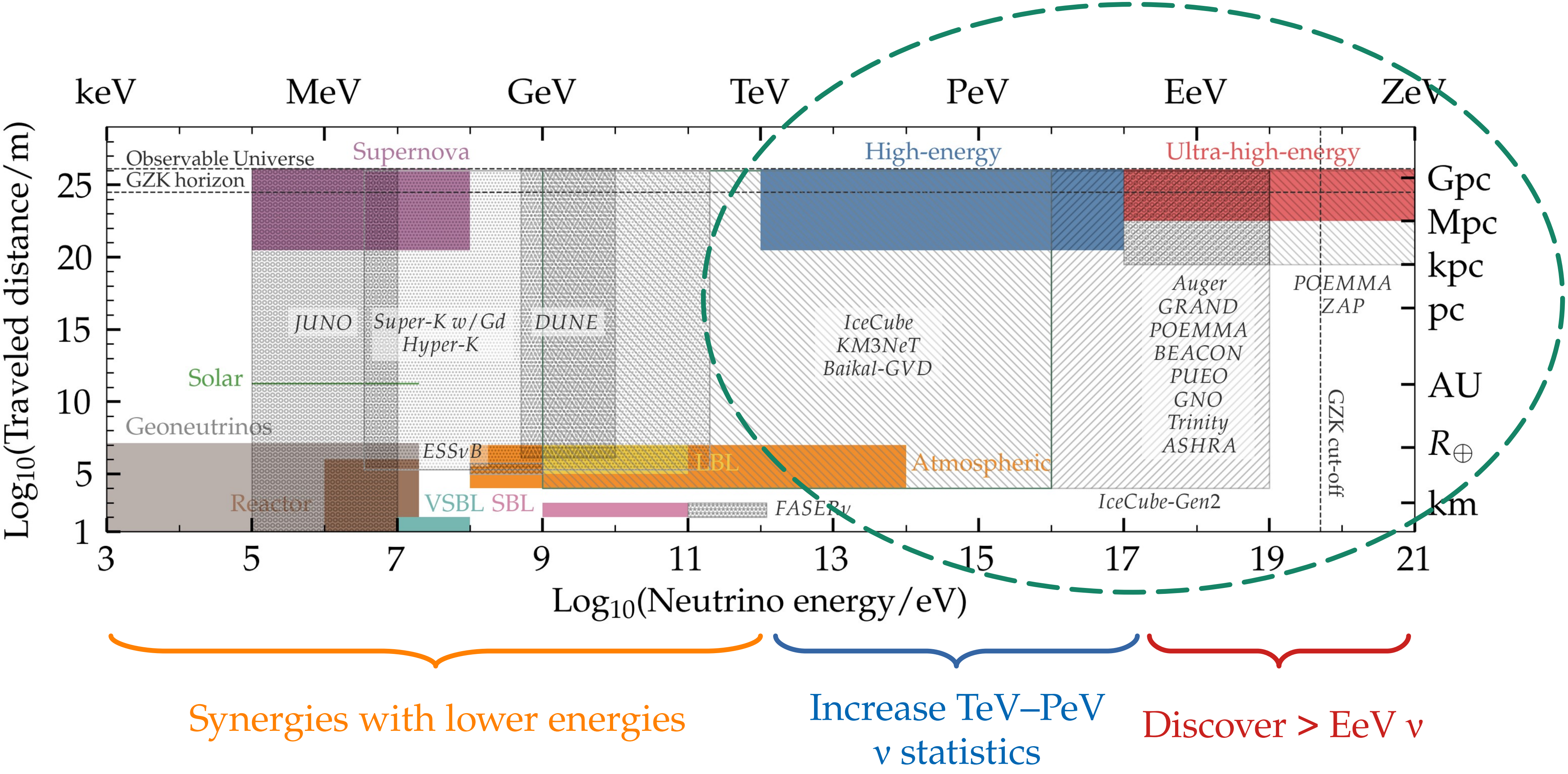

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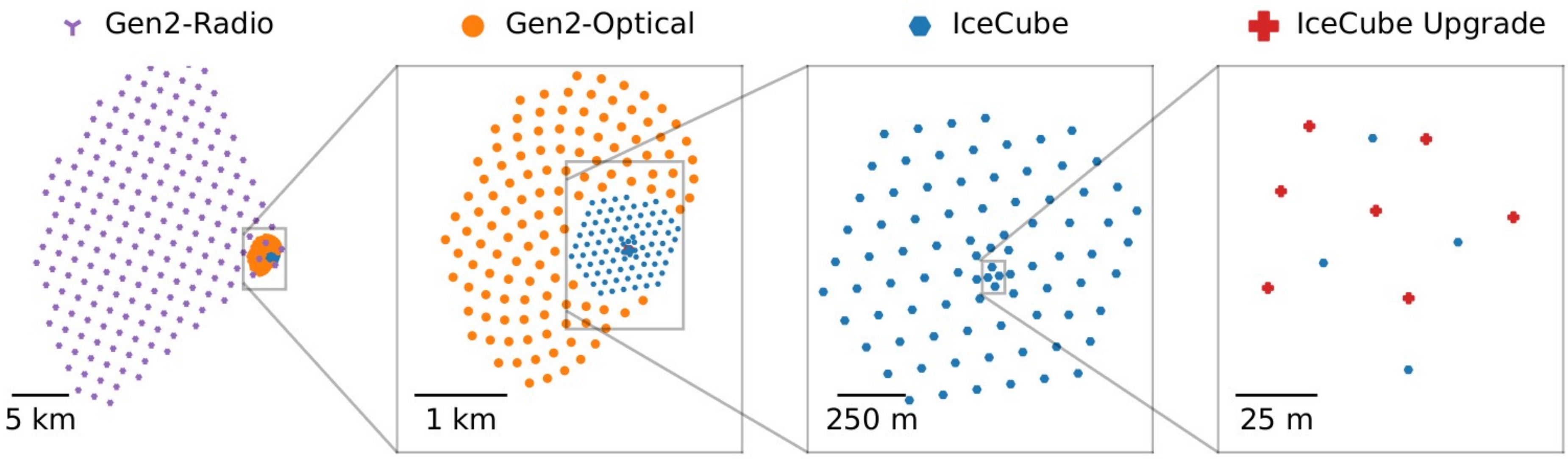
IceCube-Gen2



~2040		Today	2023
10s km^3	~8 km^3	1 km^3	7 new strings
> 100 PeV ν	TeV–10 PeV ν	TeV–few PeV ν	GeV–TeV ν

IceCube-Gen2, 2008.04323

What are you taking home?

- Cosmic TeV–PeV neutrinos are firmly detected:
  Powerful probes of the non-thermal Universe and high-energy particle physics

- We have detected two *tentative* sources — but it is challenging to understand them

- Still unknown, but getting there:
  - Where do most neutrinos come from?
  - What are, precisely, their spectrum, arrival directions, flavor composition?

- Exciting prospects: larger statistics, better reconstruction, higher energies

Want more? Here is a start:

- *Astro2020: Fundamental physics with high-energy cosmic neutrinos*, 1903.04333
- *Astro2020: Astrophysics uniquely enabled by observations of high-energy cosmic neutrinos*, 1903.04334

Postdoctoral Position in High-Energy Cosmic Neutrino Physics at NBIA

Bohr Inst. • Europe

astro-ph hep-ph PostDoc

Deadline on Nov 20, 2020

Contact:
Mauricio Bustamante (Niels Bohr Institute)
mbustamante@nbi.ku.dk

Job description:
The Niels Bohr International Academy invites applications for a postdoctoral researcher position in high-energy neutrino physics using cosmic neutrinos. We encourage applications from motivated, outstanding candidates with expertise in the theory and phenomenology of neutrino astrophysics and physics, in analytical and numerical methods.

About the position
The successful applicant will explore the vast potential of high-energy cosmic neutrinos to test particle physics at the highest energies, including tests of Standard-Model predictions and of physics beyond the Standard Model. The work will be geared along two directions: using the TeV-PeV neutrinos detected by IceCube and making predictions for the potential of EeV neutrinos to test particle physics in upcoming experiments. The work will be part of the project "Pushing Neutrino Physics to the Cosmic Frontier", funded by the Villum Fonden (project no. 29388).

The duration of the position is 2 years, starting in Fall of 2021. Postdoctoral researchers receive a competitive salary (including pension) and funds for travel and computing. Generous parental leave, state-subsidized childcare, vacation, and full medical care are provided to employees in Denmark. A favorable tax scheme is generally granted to international researchers.

Application requirements
The applicant must hold a PhD degree in particle or astroparticle physics by the start of the appointment. When assessing the qualifications of the applicant, we will evaluate relevant work experience and publications. The applicant must have good English skills. The application, in English, must be submitted electronically via AcademicJobsOnline at this link.

The application documents must include:
- Cover letter, max. 1 page (your motivation and background for applying to this position)
- Curriculum vitae
- Research statement, max. 4 pages (detailing your research experience and research interests for the future)
- Publication list
- Three reference letters

To receive full consideration, complete applications should be received by **November 20, 2020**. Later applications will be considered until the position is filled.

Backup slides

Fundamental physics with HE cosmic neutrinos

- Numerous new-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 can be extracted from four neutrino observables:
  - Spectral shape
  - Angular distribution
  - Flavor composition
  - Timing

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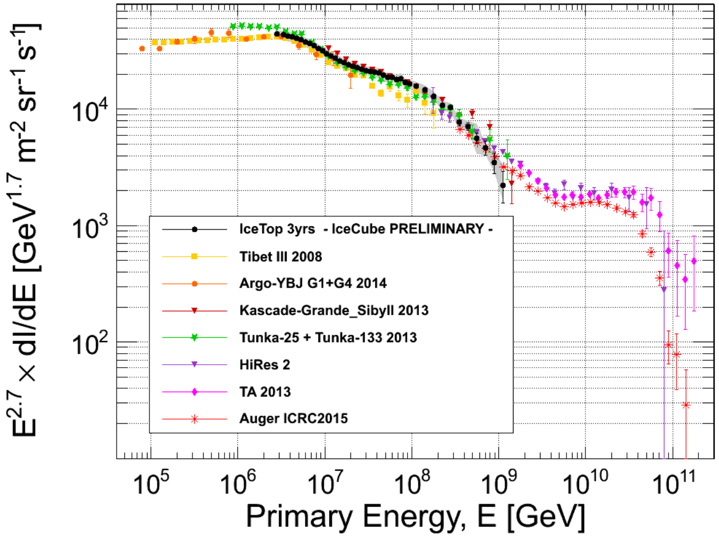
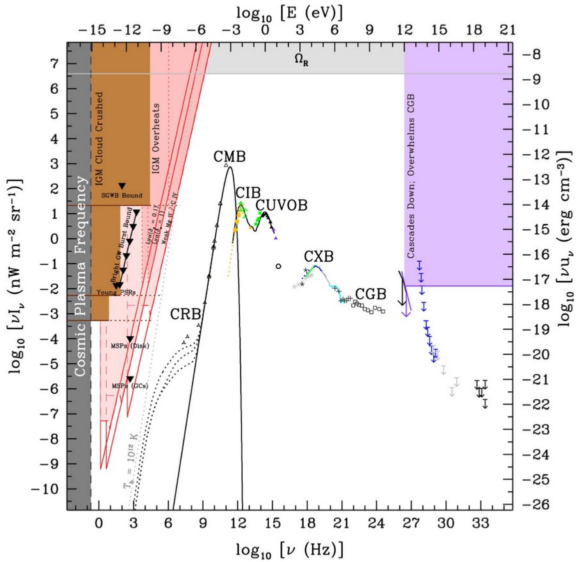
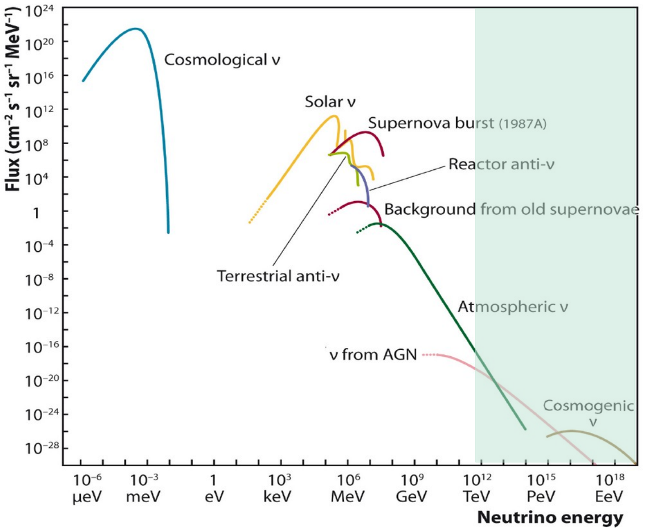
  - Timing

  In spite of
  poor energy, angular, flavor reconstruction
  & astrophysical unknowns



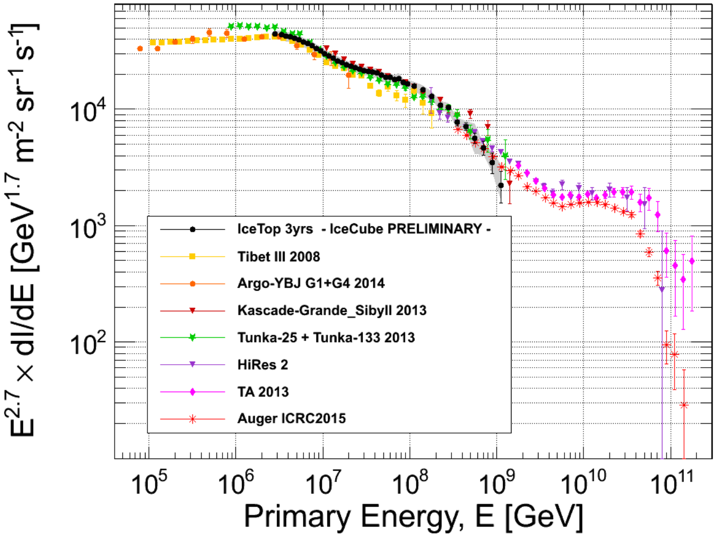


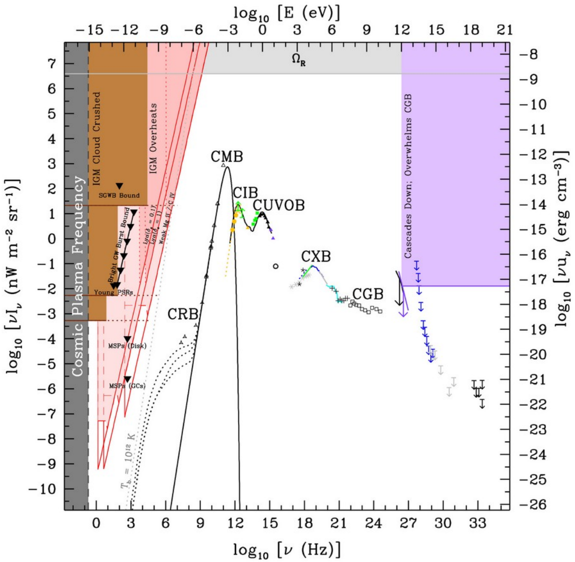


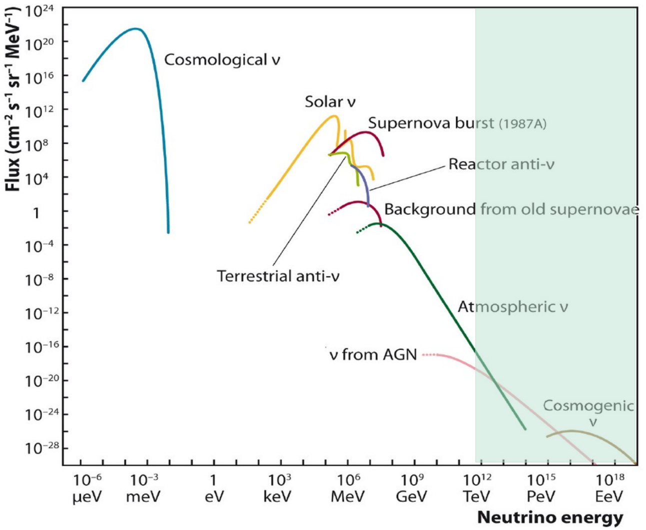
UHE cosmic rays + Photons → Neutrinos

In sources:

Propagation:



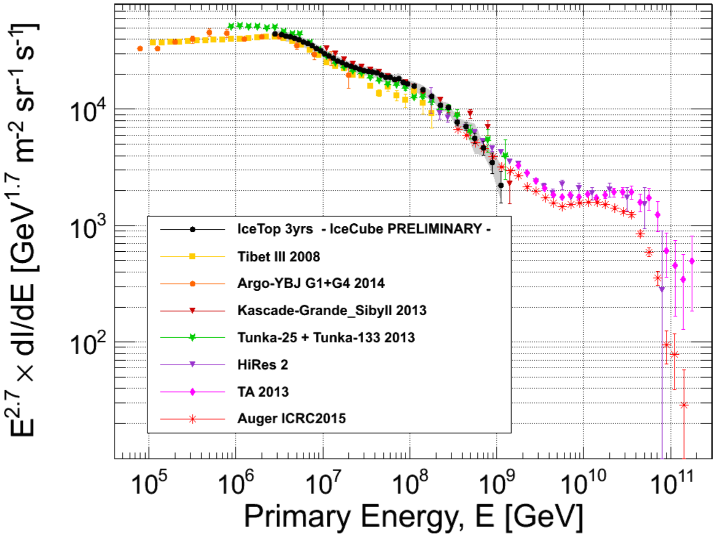


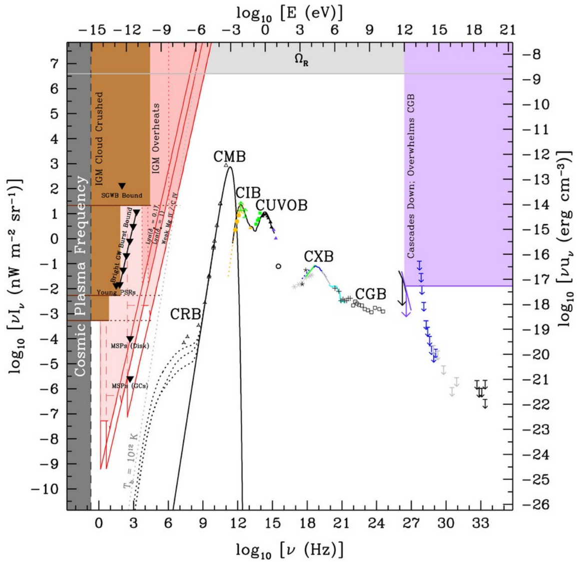


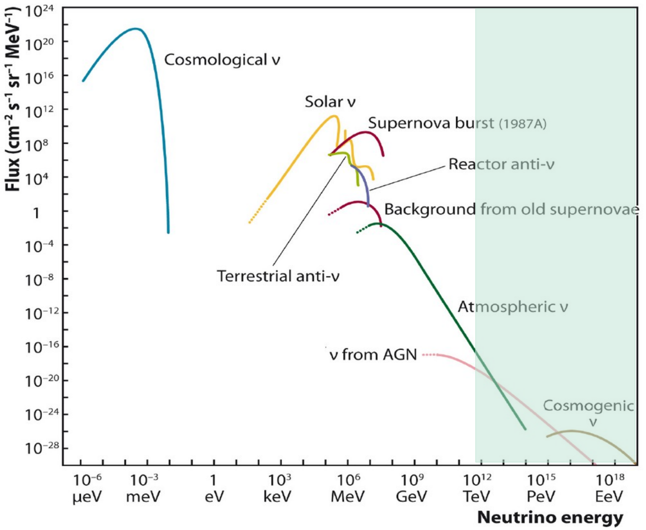
UHE cosmic rays + Photons → Neutrinos

In sources: 0.1–100 PeV .... MeV .... TeV–PeV

Propagation: EeV–ZeV .... meV .... 1–100 EeV







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In sources: 0.1–100 PeV .... MeV .... TeV–PeV

Propagation: EeV–ZeV .... meV .... 1–100 EeV ✗

Flavor-transition probability: the quick and dirty of it

- In matrix form: $$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1}^* & U_{e2}^* & U_{e3}^* \\ U_{\mu 1}^* & U_{\mu 2}^* & U_{\mu 3}^* \\ U_{\tau 1}^* & U_{\tau 2}^* & U_{\tau 3}^* \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- Pontecorvo-Maki-Nakagawa-Sakata matrix ($c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$):

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{Atmospheric}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}}_{\text{Cross mixing}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar}} \underbrace{\begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Majorana CP phases}}$$

- Probability for $\nu_\alpha \to \nu_\beta$: $$P_{\nu_\alpha \to \nu_\beta} = \delta_{\alpha\beta} - 4 \sum_{i>j} \mathrm{Re}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin^2\left(\Delta m_{ij}^2 \frac{L}{4E}\right) + 2 \sum_{i>j} \mathrm{Im}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin\left(\Delta m_{ij}^2 \frac{L}{2E}\right)$$

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$\theta_{23} \approx 48°$
$\theta_{13} \approx 9°$
$\theta_{12} \approx 34°$
$\delta \approx 222°$

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Atmospheri c | Cross mixing | Solar | Majorana CP phases

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… But high-energy neutrinos oscillate *fast*

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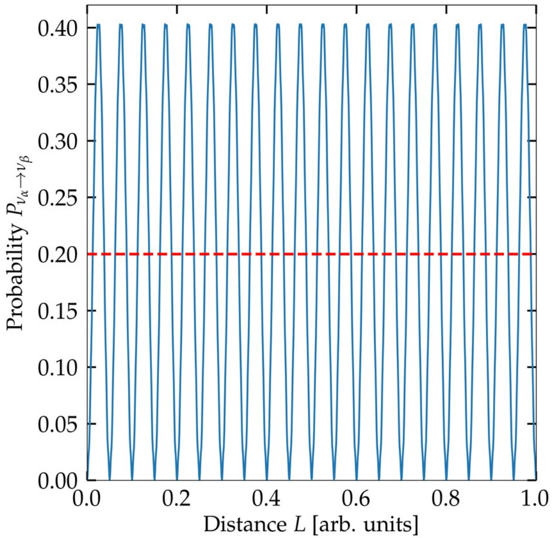

Oscillation length for 1-TeV ν: $2\pi \times 2E/\Delta m^2 \sim 0.1$ pc

~ 8% of the way to Proxima Centauri
≪ Distance to Galactic Center (8 kpc)
≪ Distance to Andromeda (1 Mpc)
≪ Cosmological distances (few Gpc)

We cannot resolve oscillations, so we use instead the average probability:

$$\langle P_{\nu_\alpha \to \nu_\beta} \rangle = \sum_{i=1}^{3} |U_{\alpha i}|^2 |U_{\beta i}|^2$$

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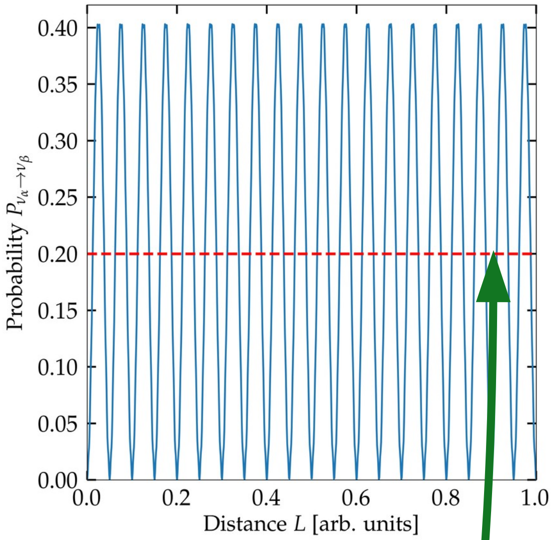

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How many neutrinos? The Waxman-Bahcall bound

- Energy production rate of extragalactic cosmic-ray protons in the energy range 10^{19}–10^{20} eV:

$$\dot{\varepsilon}_{\rm CR}^{[10^{19},10^{21}]} \sim 5 \cdot 10^{44}\ {\rm erg\ Mpc}^{-3}\ {\rm yr}^{-1}$$

- So, the energy-dependent generation rate of cosmic rays is $E_{\rm CR}^2 \frac{d\dot{N}_{\rm CR}}{dE_{\rm CR}} = \frac{\dot{\varepsilon}_{\rm CR}^{[10^{19},10^{21}]}}{\ln(10^{21}/10^{19})} \approx 10^{44}\ {\rm erg\ Mpc}^{-3}\ {\rm yr}^{-1}$

- Protons lose a fraction $\epsilon < 1$ in photohadronic production of pions in the sources

- Present-day energy density of $\nu_\mu + \bar{\nu}_\mu$: $E_\nu^2 \frac{dN_\nu}{dE_\nu} \approx \frac{1}{4} \epsilon\ t_{\rm H}\ E_{\rm CR}^2 \frac{d\dot{N}_{\rm CR}}{dE_{\rm CR}}$

$\mathrm{Br}(p+\gamma \to \pi^+) = 0.5$ × Fraction of π energy going to $\nu_\mu + \bar{\nu}_\mu$

Hubble time: $t_{\rm H} \sim 10^{10}$ yr

- Maximum neutrino intensity is for $\epsilon = 1$: $I_{\rm max} \approx \frac{1}{4}\,\xi_z\,t_{\rm H}\,\frac{c}{4\pi} E_{\rm CR}^2 \frac{d\dot{N}_{\rm CR}}{dE_{\rm CR}} \approx 1.5 \cdot 10^{-8} \xi_z\ {\rm GeV\ cm}^{-2}\ {\rm s}^{-1}\ {\rm sr}^{-1}$

- So the expected neutrino flux is $E_\nu^2 \Phi_{\nu_\mu} \equiv \frac{c}{4\pi} E_\nu^2 \frac{dN_\nu}{dE_\nu} = \frac{1}{2} \epsilon I_{\rm max}$

Waxman & Bahcall, *PRD* 1999

Waxman-Bahcall bound: $E_\nu^2 \Phi_{\nu_\mu} \approx 0.75 \cdot 10^{-8} \xi_z\ \epsilon\ {\rm GeV\ cm}^{-2}\ {\rm s}^{-1}\ {\rm sr}^{-1}$

The need for km-scale detectors

Predicted by Waxman-Bahcall 1998

- Neutrino flux at TeV–PeV: $E^2 \cdot \Phi \sim 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}

At center-of-mass energy of 1 GeV:
$\sigma_{pp} \sim 10^{-28}$ cm^2
$\sigma_{\gamma p} \sim 10^{-29}$ cm^2

- Neutrino-nucleon cross section: $\sigma_{\nu p} \sim 10^{-35}\ \text{cm}^2\ (E/\text{GeV})^{0.36}$

- Number of detected neutrinos from half the sky in 1 yr:

$$N = (n_{\text{nucl}} \cdot V_{\text{det}}) \cdot (2\pi) \cdot (1\ \text{yr}) \cdot \int_{100\ \text{TeV}} \Phi(E) \cdot \sigma_{\nu p}(E)\, \mathrm{d}E$$

- To detect $N > 10$ neutrino, we needed

$$V_{\text{det}} > 1\ \text{km}^3$$

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Number density of nucleons: $\sim N_{\rm Av}$ cm^3

Detector volume

- To detect $N > 10$ neutrino, we needed

$$V_{\rm det} > 1\ \text{km}^3$$

Kinematics of high-energy neutrino production (1/2)

- What are the proton and photon energies needed for $p + \gamma \to \Delta$?

Four-vectors

$$\left(p_p + p_\gamma\right)^2 = p_\Delta^2 \Rightarrow p_p^2 + p_\gamma^2 + 2p_p \cdot p_\gamma = p_\Delta^2$$

But $p^2 = m^2$ for massive particles, so $m_p^2 + 2p_p \cdot p_\gamma = m_\Delta^2$.

Now, $p_p \cdot p_\gamma = E_p E_\gamma - \bar{p}_p \cdot \bar{p}_\gamma = E_p E_\gamma - |\bar{p}_p| \cdot |\bar{p}_\gamma| \cos\theta_{p\gamma}$.

For the photon, $|\bar{p}_\gamma| = E_\gamma$. For the high-energy proton, $|\bar{p}_p| = \sqrt{E_p^2 - m_p^2} \approx E_p$.

So, $p_p \cdot p_\gamma = E_p E_\gamma \left(1 - \cos\theta_{p\gamma}\right)$. Plugging this back yields $E_p E_\gamma = \dfrac{m_\Delta^2 - m_p^2}{2\left(1 - \cos\theta_{p\gamma}\right)}$.

- For a head-on collision ($\cos\theta_{p\gamma} = -1$):

$$E_p E_\gamma = \frac{(1.232\ \text{GeV})^2 - (0.938\ \text{GeV})^2}{4} \approx 0.16\ \text{GeV}^2$$

Kinematics of high-energy neutrino production (2/2)

- What are the energies of the neutrinos produced?
- In a $p + \gamma \to \pi^+$ interaction, the average pion energy is $E_\pi = E_p/5$
- In each decay $\pi^+ \to \nu_\mu + \bar{\nu}_\mu + \nu_e + e^+$, the average $\nu_\mu + \bar{\nu}_\mu$ energy is $E_\nu = E_\pi/4$
- Therefore, each neutrino takes an average fraction of proton energy

$$E_\nu/E_p = 1/20 = 5\%$$

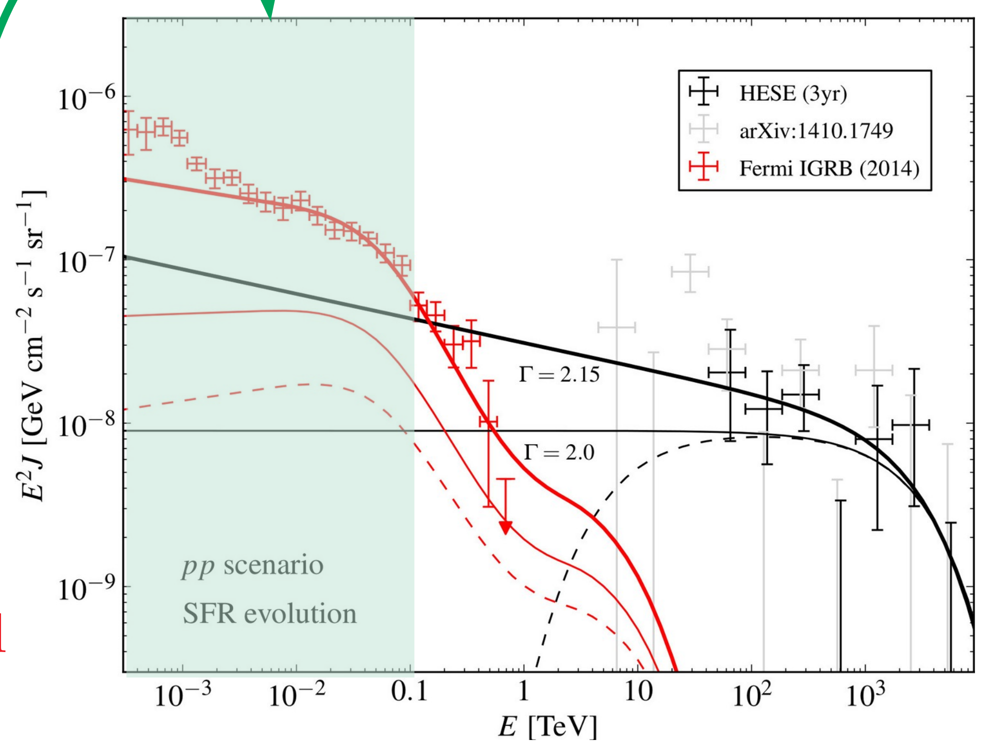
- So:

If we see ν with energy…	**… they were made by *p* with energy**
PeV ($\equiv 10^{15}$ eV)	20 PeV (these reach Earth)
10 EeV ($\equiv 10^{19}$ eV)	200 EeV (these do not!)

Constraints from the gamma-ray background

- Production via *pp*: ν and gamma-ray spectra follow the CR spectrum $E^{-\Gamma}$
- Gamma-ray interactions on the CMB make them pile up at GeV
- *Fermi* gamma-ray background is not exceeded only if Γ < 2.2
- But IceCube found Γ = 2.5–2.7
- Therefore, production via *pp* is disfavored between 10–100 TeV

Murase, Ahlers, Lacki, *PRD* 2013



The Hillas criterion

- Necessary condition for a source to accelerate cosmic rays

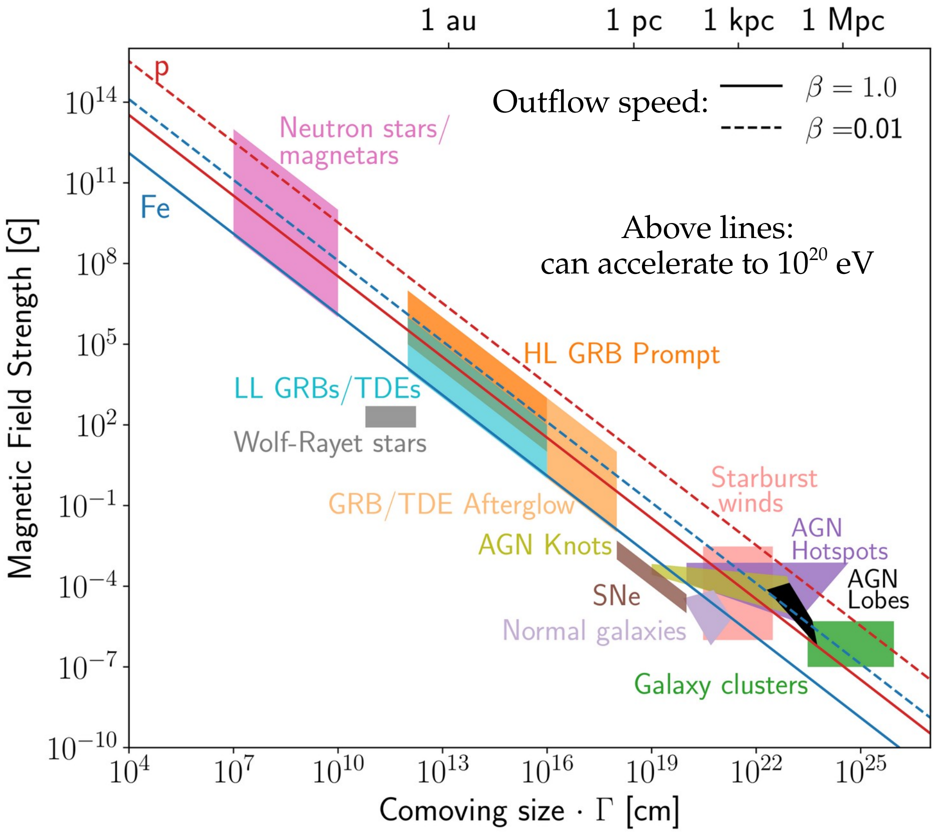
- Particles must stay confined:

Larmor radius < Size of acceleration region

$$R_L = E/(Z\,e\,B) < (R\,\Gamma)$$

- Maximum energy:

$$E_{\rm max} \approx \left(3 \cdot 10^{20}\ \mathrm{eV}\right) \eta^{-1} \beta_{\rm sh} Z \left(\frac{\Gamma R}{10^{16}\ \mathrm{cm}}\right) \left(\frac{B}{100\ \mathrm{G}}\right)$$



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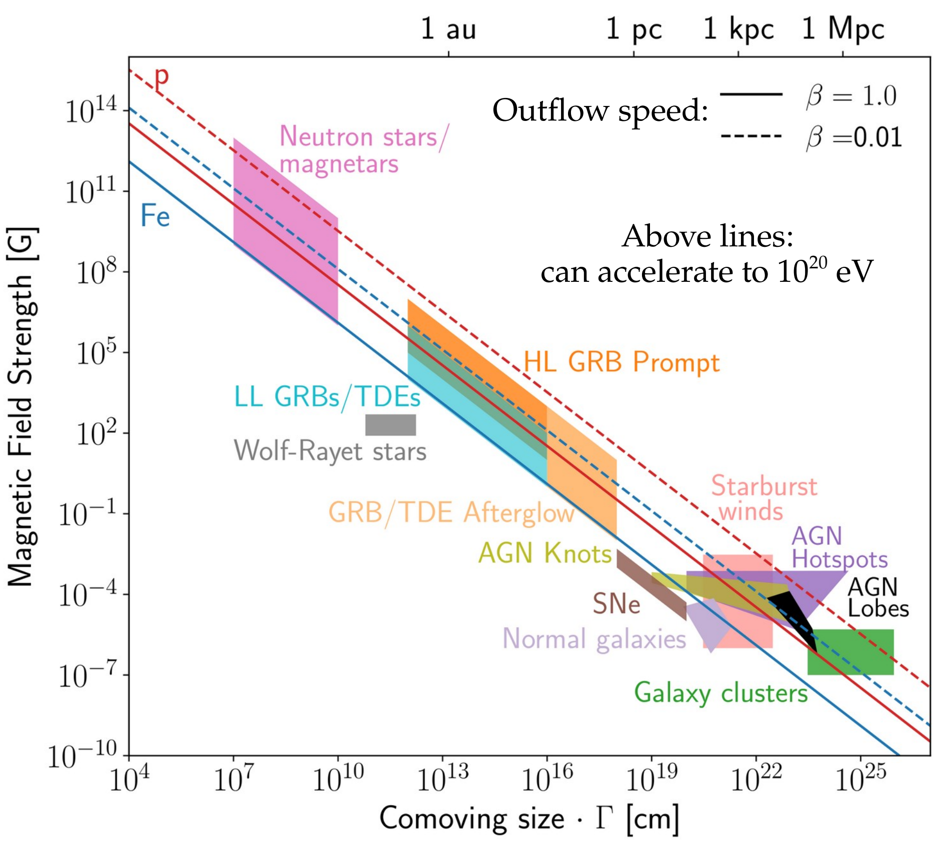

Hillas, *Ann. Rev. Astron. Astrophys.* 1984

Alves Batista, **MB** *et al.*, *Frontiers* 2019
See also: Winter, *PRD* 2011

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Electric charge of the particle

$$R_L = E/(Z e B) < (R \Gamma)$$

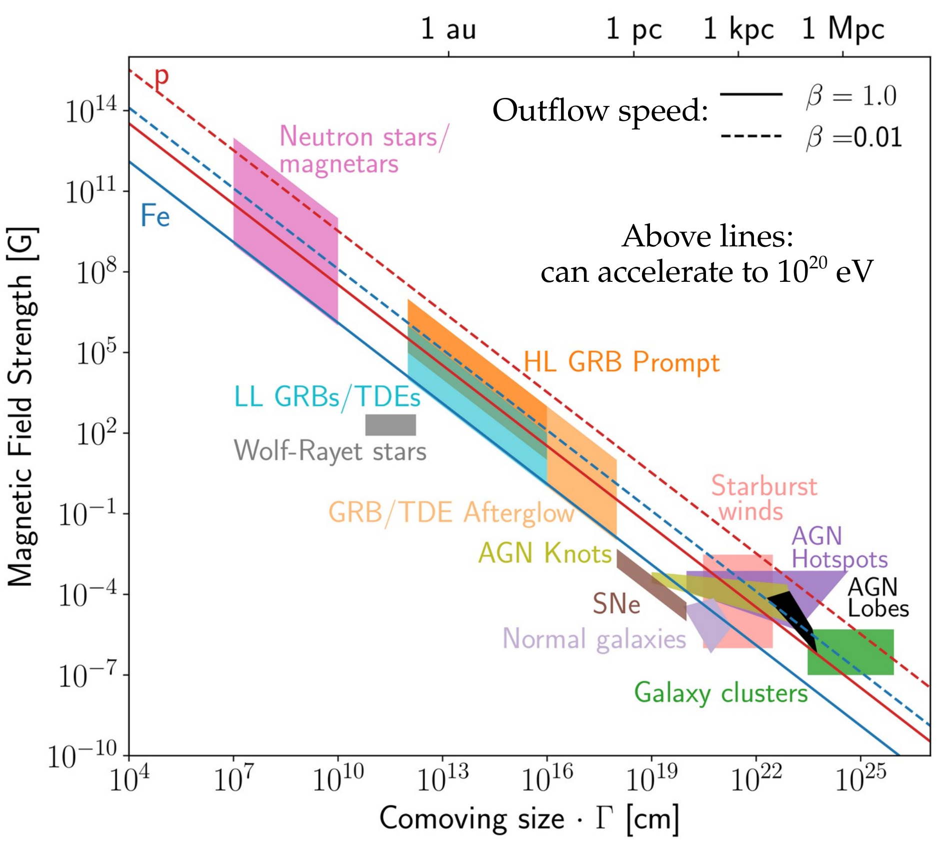
Bulk Lorentz factor of accelerating region

- Maximum energy:

Acceleration efficiency ($\eta = 1$ for perfect efficiency)

$$E_{\max} \approx \left(3 \cdot 10^{20}\ \mathrm{eV}\right) \eta^{-1} \beta_{\mathrm{sh}} Z \left(\frac{\Gamma R}{10^{16}\ \mathrm{cm}}\right) \left(\frac{B}{100\ \mathrm{G}}\right)$$

Speed v_{sh}/c of the outflow



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

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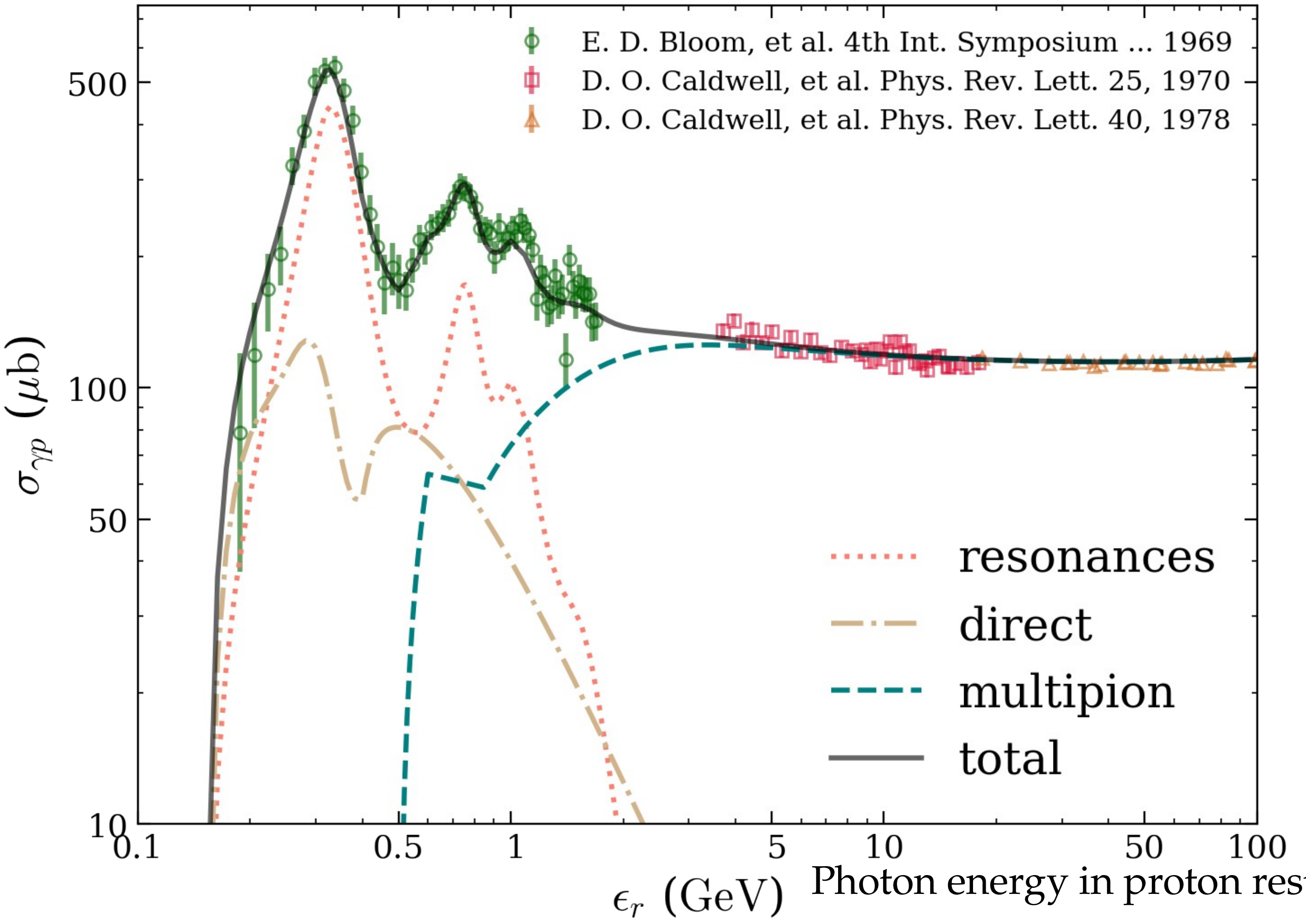
Beyond the Δ resonance (1/2)

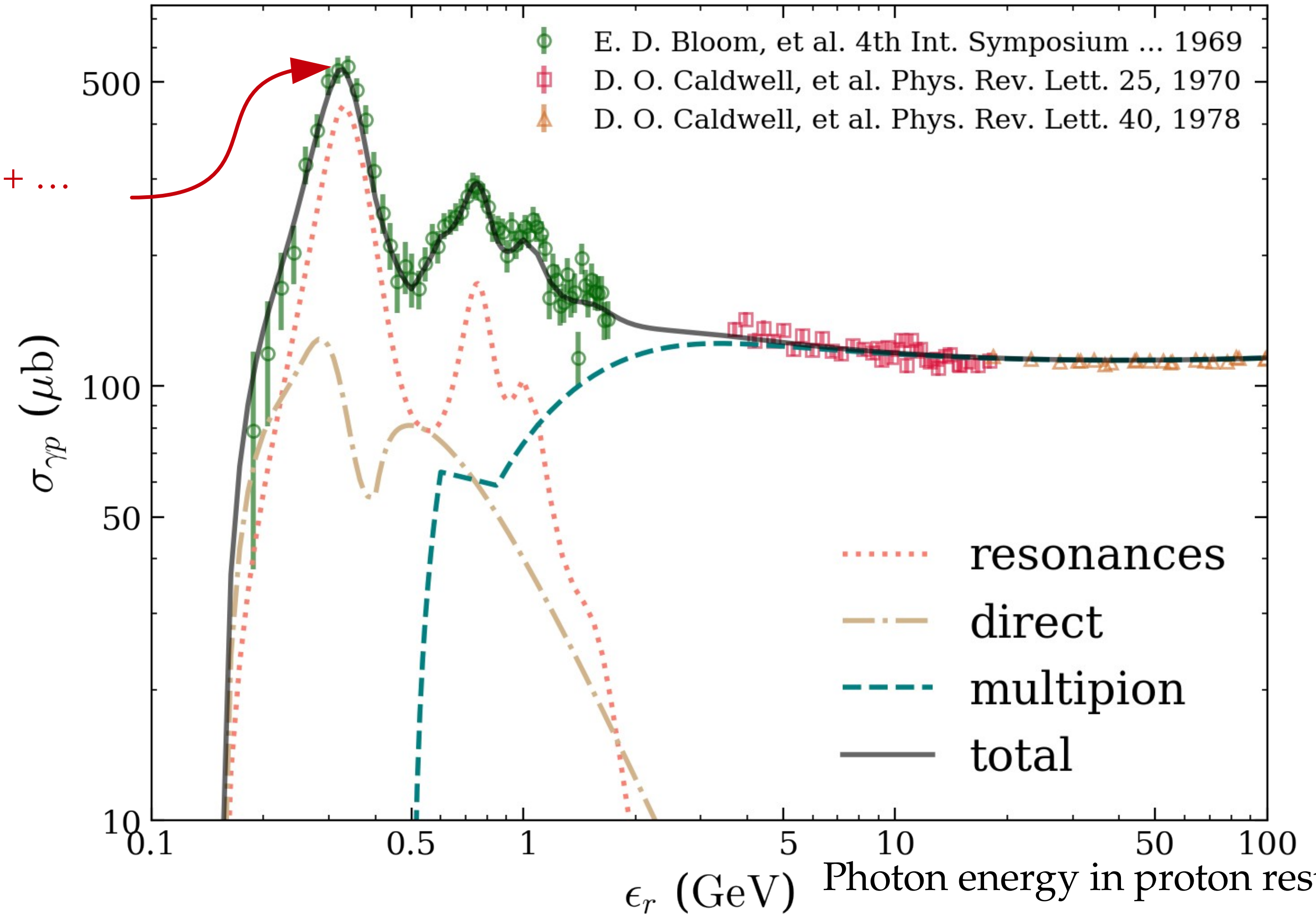


Photon energy in proton rest frame

Morejón *et al.*, 1904.07999

Beyond the Δ resonance (1/2)

Delta resonance:
$p + \gamma \rightarrow \Delta \rightarrow \pi^+ \rightarrow 3\nu + \ldots$



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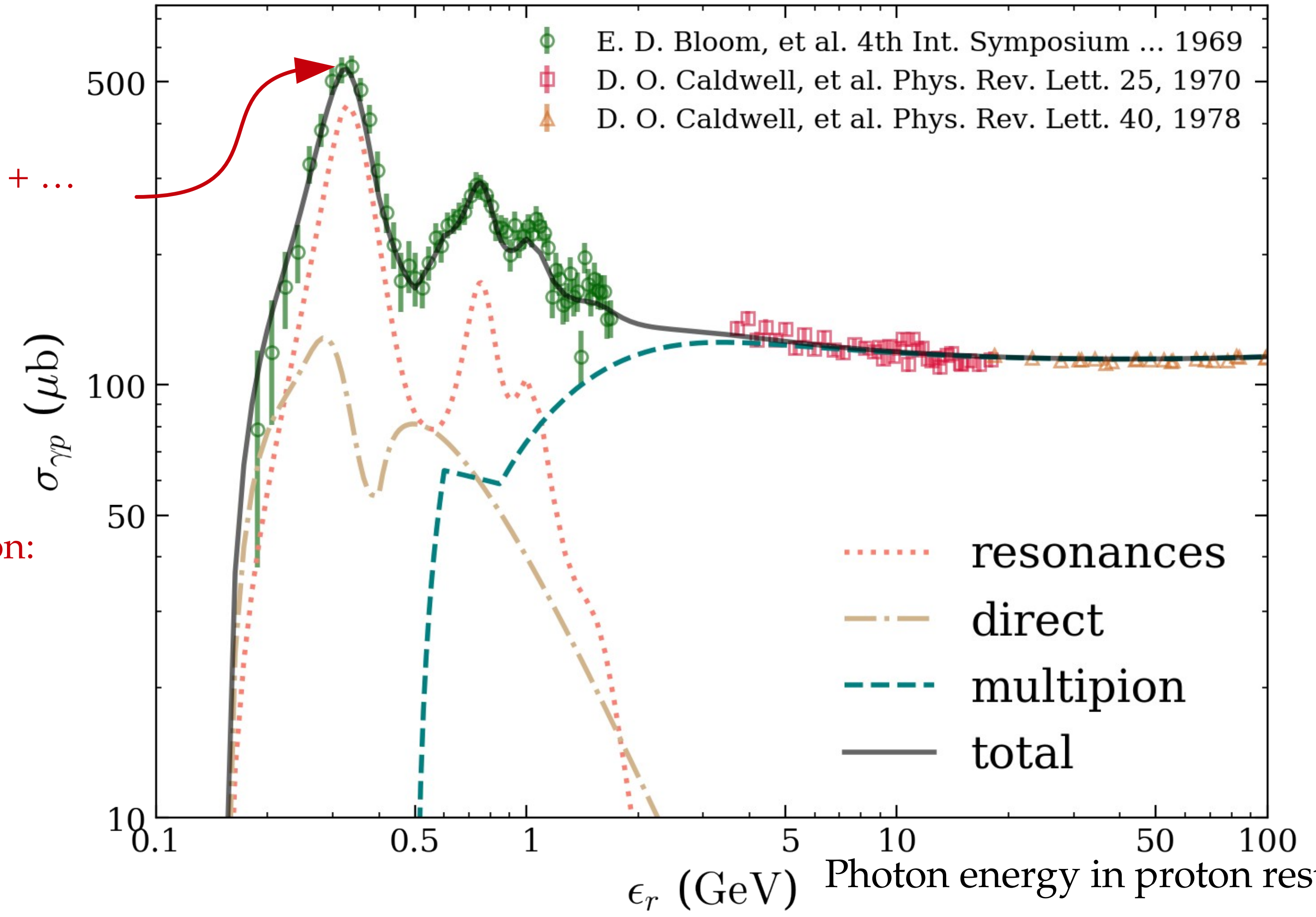
Morejón *et al.*, 1904.07999

Beyond the Δ resonance (1/2)

Delta resonance:
$p + \gamma \rightarrow \Delta \rightarrow \pi^+ \rightarrow 3\nu + \ldots$

Resonance condition:
$E_p \times E_\nu \sim 0.2\ \mathrm{GeV}^2$



Photon energy in proton rest frame

Morejón *et al.*, 1904.07999

Beyond the Δ resonance (2/2)

(1) Δ-resonance region

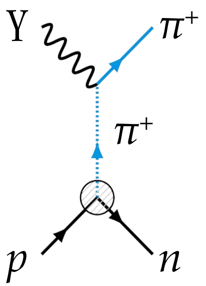
$$p + \gamma \xrightarrow{\Delta(1232)} p' + \pi$$

(2) Higher resonances

$$p + \gamma \xrightarrow{\Delta, N} \Delta' + \pi \;, \quad \Delta' \rightarrow p' + \pi$$

(3) Direct production (t channel)

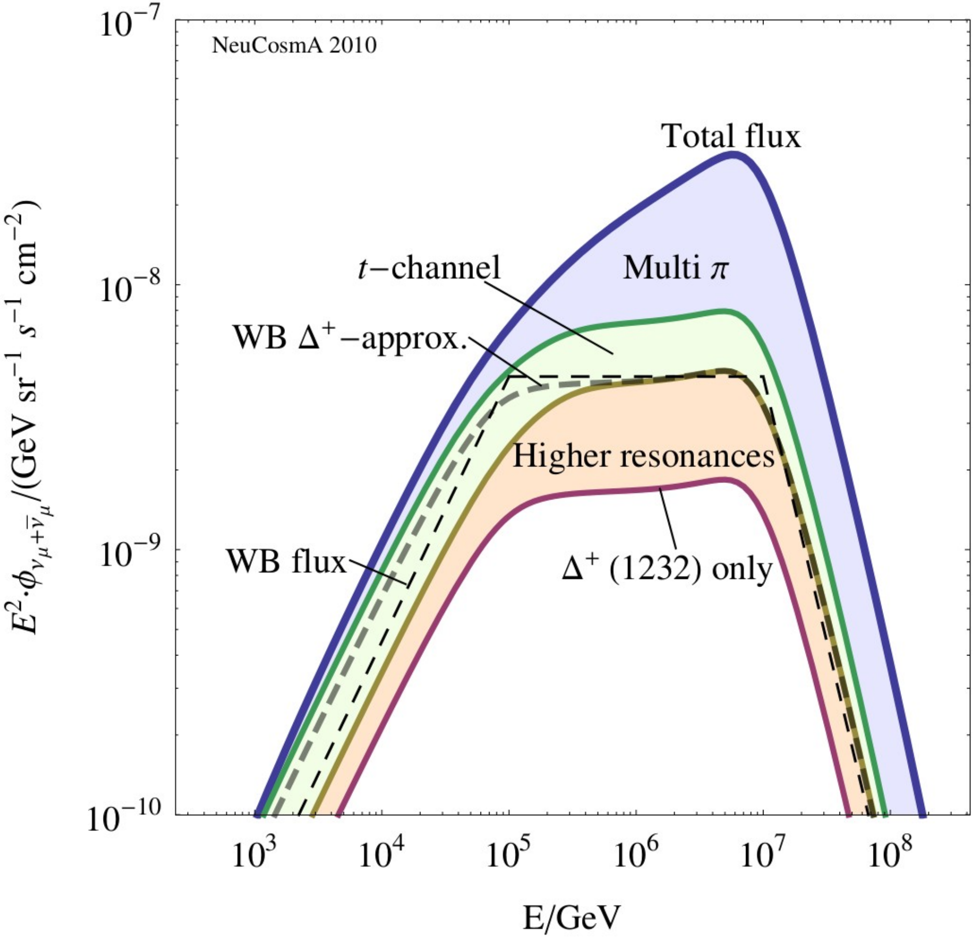
Same as (1) and (2), but in the
t channel, *i.e.*,
with a virtual pion



(4) Multi-pion production

Statistical production of two or more pions

E.g., neutrinos from a gamma-ray burst:



Mücke *et al.*, *Comput. Phys. Comm.* 2000
Hümmer *et al.*, *ApJ* 2010; Baerwald, Hümmer, Winter, *PRD* 2011

The Universe is opaque to UHECRs

Photohadronic processes:

$$p + \gamma \rightarrow \Delta \rightarrow \begin{cases} p + \pi^0 \quad (\rightarrow \gamma + \gamma) \\ n + \pi^+ \quad (\rightarrow \nu_\mu + \bar{\nu}_\mu + \nu_e + e^+) \end{cases}$$

Pair production:

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

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

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

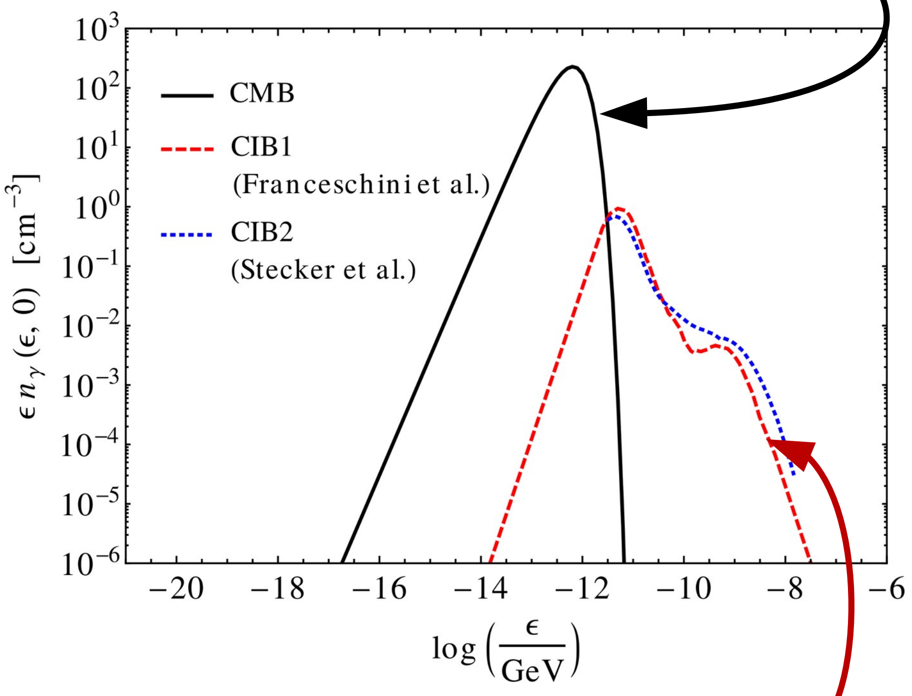
(Assuming only photohadronic interaction)

Accounting also for pair production and CMB width:

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

Target photon spectra (at $z = 0$):

CMB: Microwave (black body, <ϵ> ~ 0.66 meV)



CIB: optical (stars) + infrared (dust remission)

$n_\gamma(z) = (1+z)^3\, n_\gamma(z=0)$ (exact only for CMB)

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

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Mean free path:

$$(n_\gamma \langle\sigma\rangle_{p\gamma})^{-1} = (413 \text{ cm}^{-3} \times 200 \text{ µbarn})^{-1} \approx 10^{25} \text{ cm} \approx 4 \text{ Mpc}$$

Energy-loss scale:

$$L = (E/\Delta E)(n_\gamma \langle\sigma\rangle_{p\gamma})^{-1} \approx (1/0.2) \times 4 \text{ Mpc} \approx 20 \text{ Mpc}$$

A more detailed calculation yields

$$L_{\text{GZK}} = 50 \text{ Mpc}$$

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

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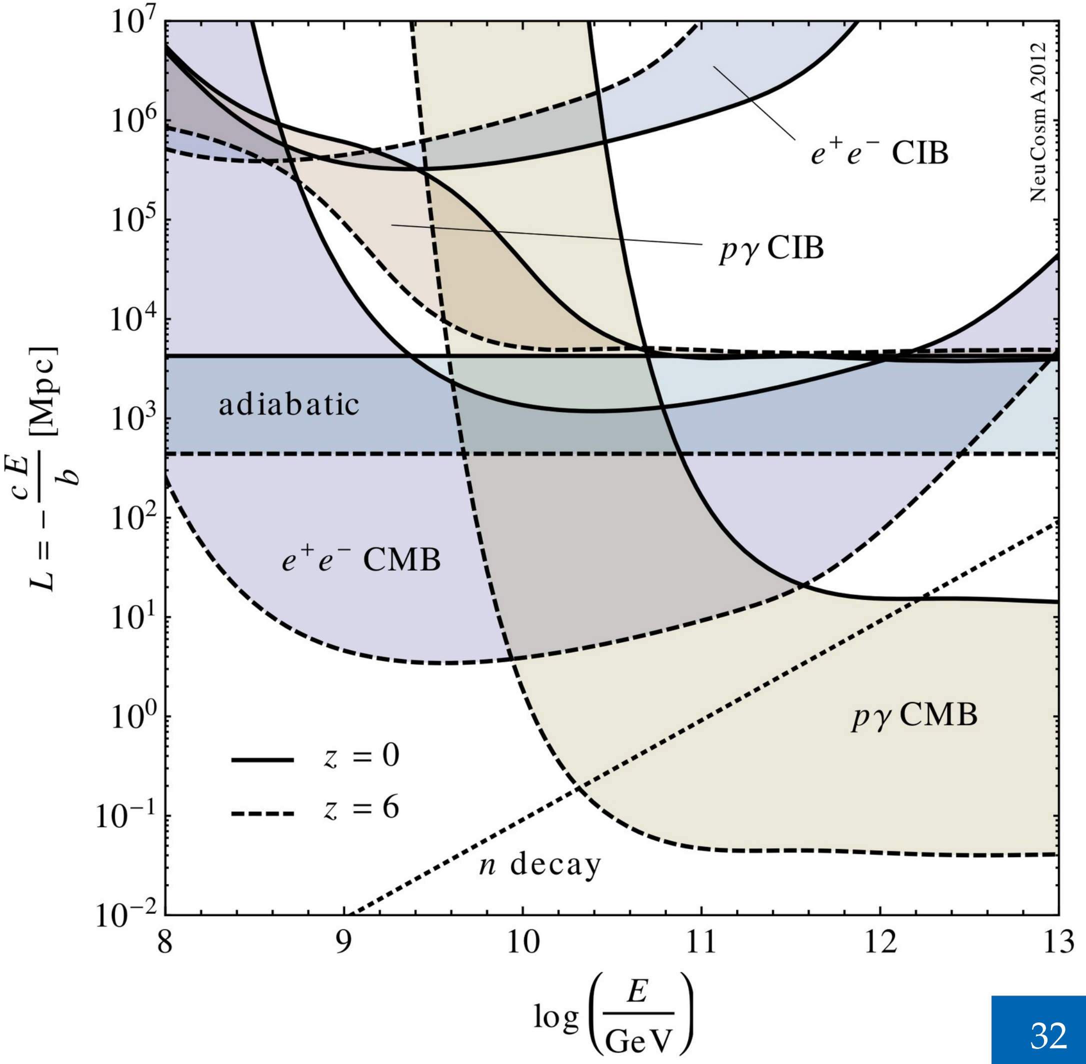


Greisen *PRL* 1966; Zatsepin & Kuzmin, *JETP* 1966

The Universe is *also* opaque to PeV gamma rays

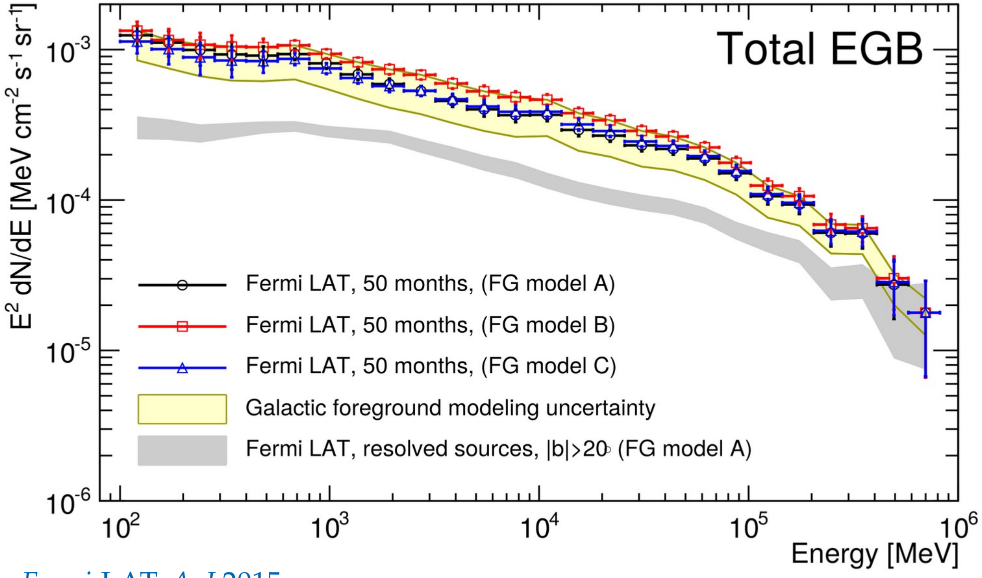
Pair production:

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

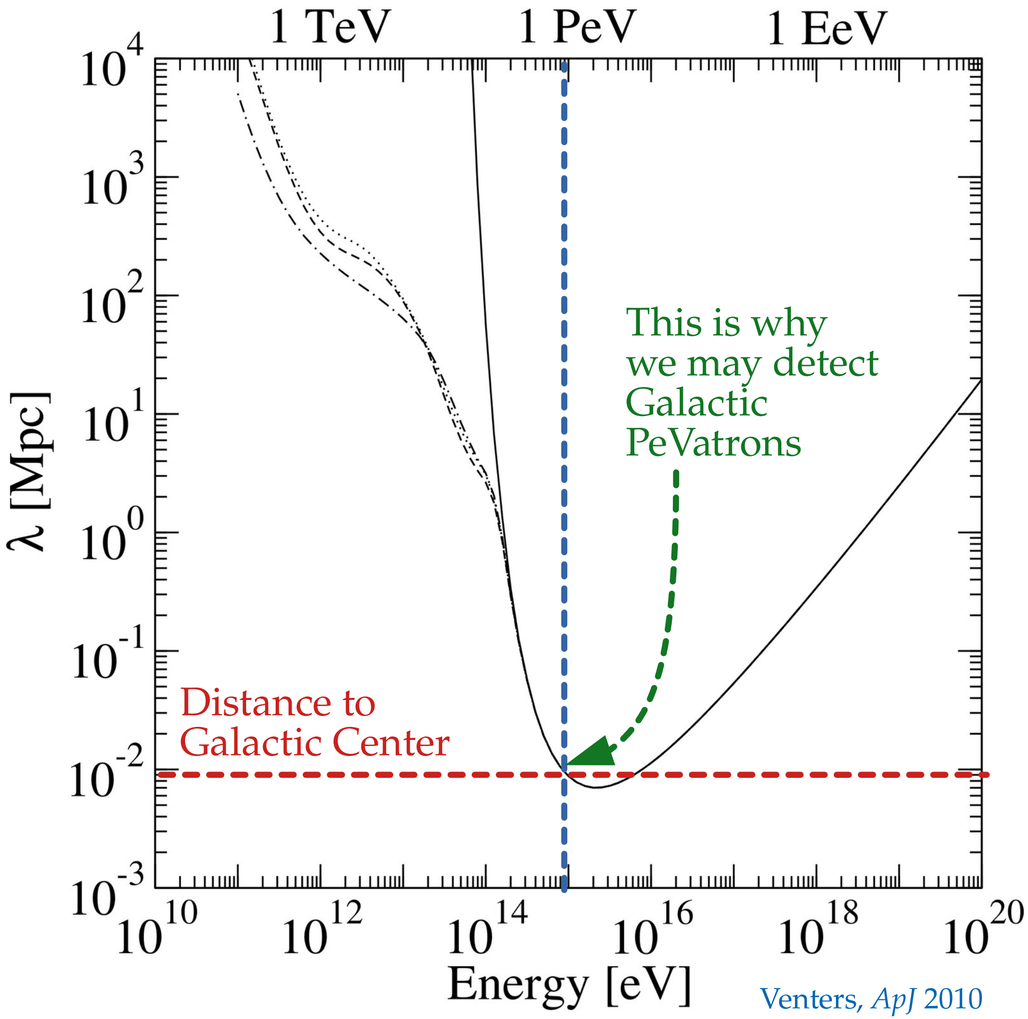
Inverse Compton scattering:

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

PeV gamma rays cascade down to MeV–GeV:



Fermi-LAT, *ApJ* 2015



Venters, *ApJ* 2010

$$p + \gamma(p) \rightarrow \pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow \bar{\nu}_\mu + e^+ + \nu_e$$

$$p + \gamma(p) \to \pi^+ \to \mu^+ + \nu_\mu$$
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Protons

Acceleration time scale: $t'_{\rm acc} \propto \frac{E'_p}{B'}$

Synchrotron-loss time scale: $t'_{\rm sync} \propto \frac{m_p^4}{B'^2 E'_p}$

Maximum neutrino energy:

$$t'_{\rm acc} = t'_{\rm sync}$$

$$E_\nu^{\rm max} = E_p^{\rm max}/20 \approx \frac{10^{10}\Gamma \ {\rm GeV}}{\sqrt{B'/{\rm G}}}$$

Effect: Induce a high-energy cut-off in the emitted ν spectrum, *i.e.*,

$$E_\nu'^2 \frac{dN_\nu}{dE'_\nu} \propto E_\nu'^{2-\alpha_\nu} e^{-E'_\nu/E_\nu'^{\,\rm max}}$$

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Pions

Decay time scale: $t'_{\rm dec} = \frac{\tau_\pi E'_\pi}{m_\pi}$

$$t'_{\rm sync} \propto \frac{m_\pi^4}{B'^2 E'_\pi}$$

Synchrotron relevant above

$$t'_{\rm dec} = t'_{\rm sync}$$

$$E_{\nu,\pi}^{\rm sync} \approx 10^{10}\Gamma \frac{\text{G}}{B'} \ \text{GeV}$$

Effect: Steepen the ν spectrum

$$\alpha_\nu = \begin{cases} \gamma, & \text{if } E_\nu < E_{\nu,\pi}^{\rm sync} \\ \gamma + 2, & \text{if } E_\nu \geq E_{\nu,\pi}^{\rm sync} \end{cases}$$

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Effect: Steepen the ν spectrum

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Muons

$$t'_{\rm dec} = \frac{\tau_\mu E'_\mu}{m_\mu}$$

$$t'_{\rm sync} \propto \frac{m_\mu^4}{B'^2 E'_\mu}$$

$$E^{\rm sync}_{\nu,\mu} \approx 10^{9}\Gamma \frac{\rm G}{B'}~{\rm GeV}$$

Effect: Change flavor composition

$$(f_{e,{\rm S}}, f_{\mu,{\rm S}}, f_{\tau,{\rm S}}) = \begin{cases} (\frac{1}{3}, \frac{2}{3}, 0), & \text{if } E_\nu < E_{\nu,\mu} \\ (0, 1, 0), & \text{if } E_\nu \geq E_{\nu,\mu} \end{cases}$$

Statistical analysis

We look for synchrotron effects in two public IceCube data sets:

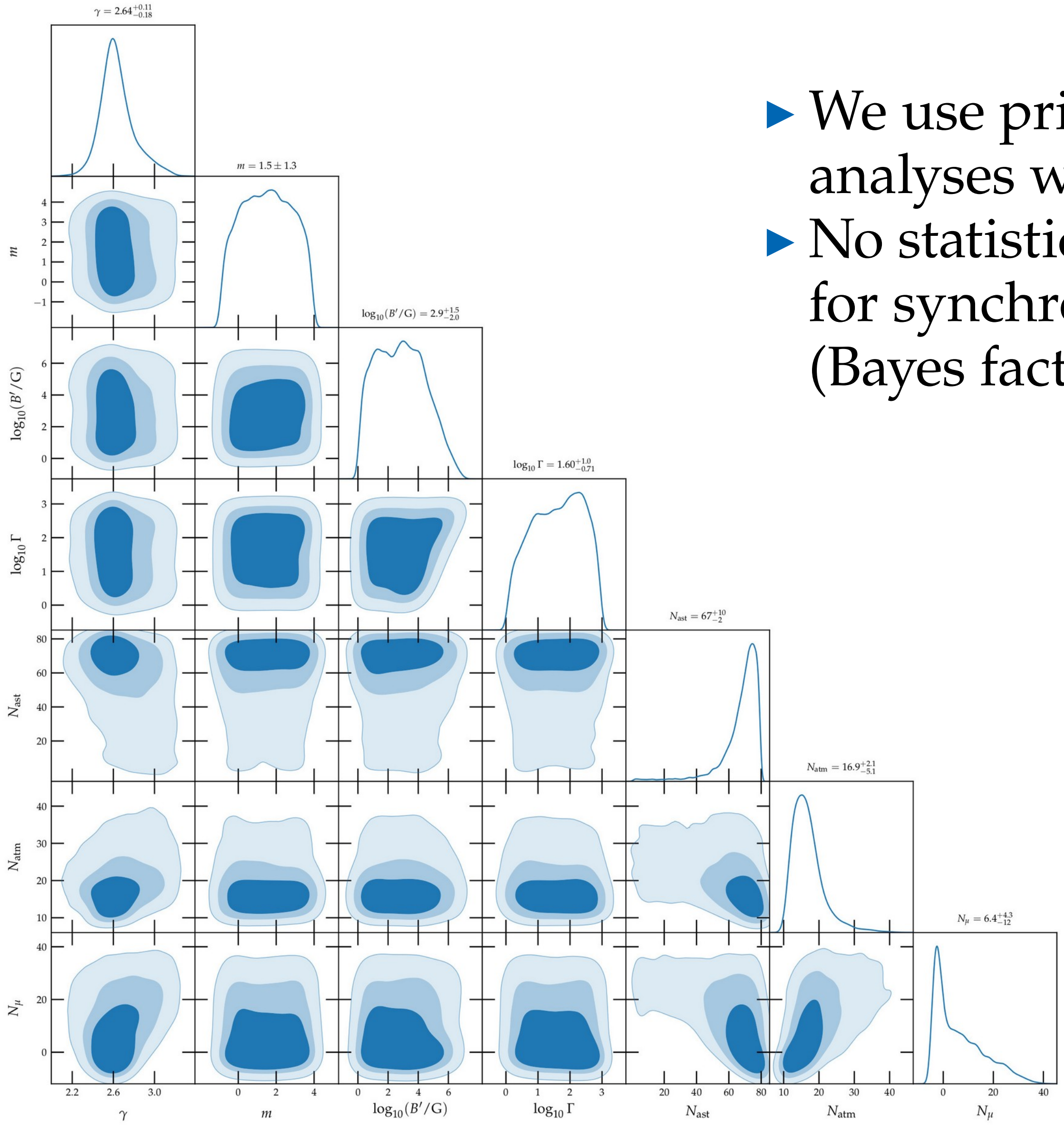
- 6 years of High Energy Starting Events (HESE): 80 events
- 2 years of Medium Energy Starting Events (HESE): 54 events

Bayesian analysis with likelihood function

$$\mathcal{L}(\gamma, m, \Gamma, B', N_{\rm ast}, N_{\rm atm}, N_\mu) = e^{-N_{\rm ast} - N_{\rm atm} - N_\mu} \prod_{i=1}^{N_{\rm obs}} \mathcal{L}_i(\gamma, m, \Gamma, B', N_{\rm ast}, N_{\rm atm}, N_\mu)$$

Partial likelihood: $\mathcal{L}_i = N_{\rm ast} \mathcal{P}_{i,{\rm ast}}(\gamma, m, \Gamma, B') + N_{\rm atm} \mathcal{P}_{i,{\rm atm}} + N_\mu \mathcal{P}_{i,\mu}$

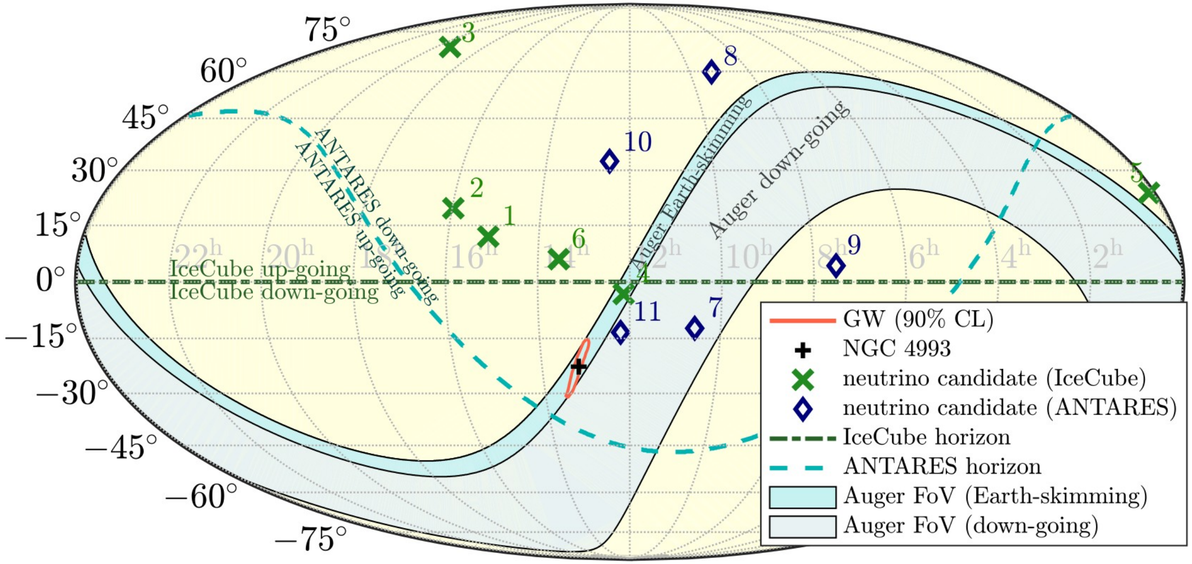
Probability distribution function, *e.g.*, $\mathcal{P}_{i,{\rm ast}} = \dfrac{dN_i/dE_{\rm dep}}{\int dE_{\rm dep} dN_i/dE_{\rm dep}}$

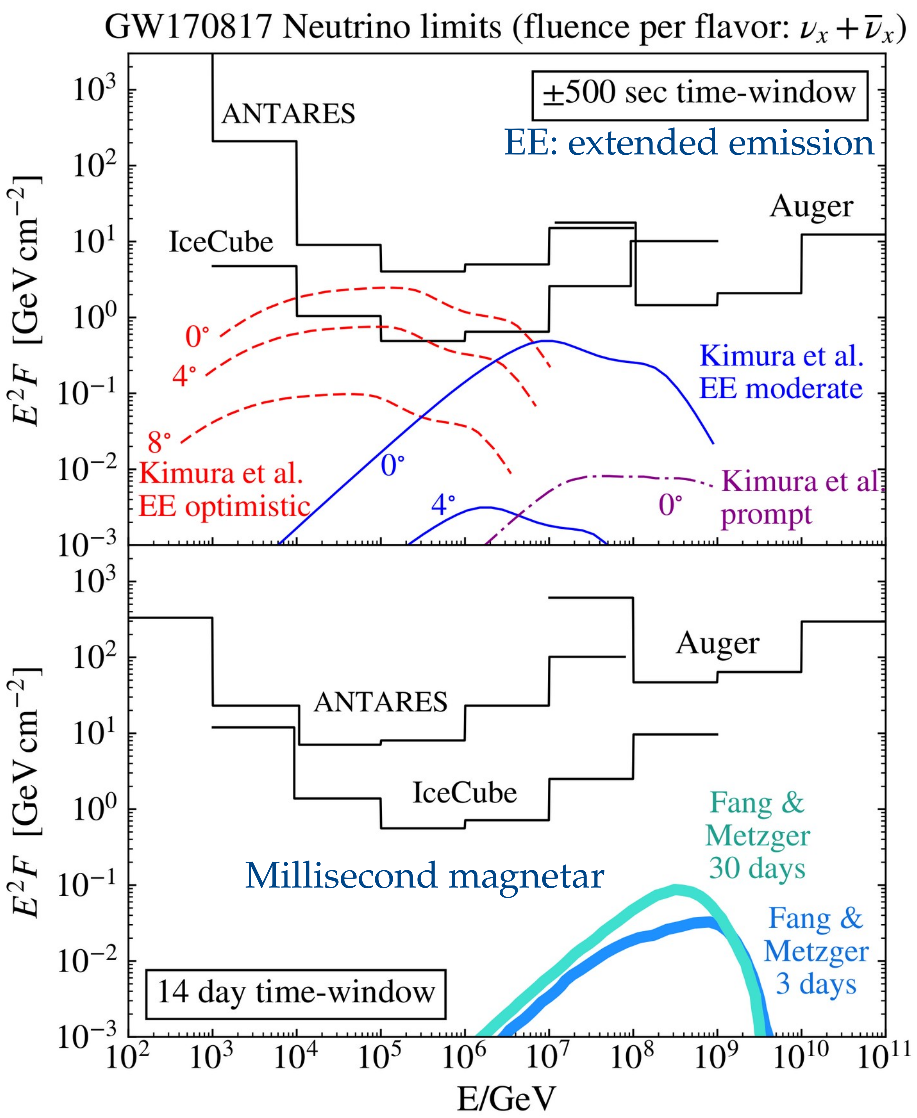


- We use priors informed by IceCube analyses when possible
- No statistically significant evidence for synchrotron-loss features (Bayes factor ~ 2)

GW170817 (NS-NS merger)

- Short GRB seen in *Fermi*-GBM, INTEGRAL
- Neutrino search by IceCube, ANTARES, and Auger
- MeV–EeV neutrinos, 14-day window
- Non-detection consistent with off-axis





ANTARES, IceCube, Pierre Auger Collab., *ApJL* 2017

Are GRBs still good UHECR source candidates?

- High-luminosity bursts: Not so much
- Low-luminosity bursts: Yes!

	HL GRBs	LL GRBs
Luminosity (erg s^{-1})	$> 10^{49}$	$< 10^{49}$
Rate (Gpc^{-3} yr^{-1})	1	300 (predicted)
Survival of heavy nuclei in jet?	Unlikely	Likely
Can explain IceCube ν?	No	Yes

D. Boncioli, D. Biehl, & W. Winter, *ApJ* 2019; B.T. Zhang *et al.*, *PRD* 2018

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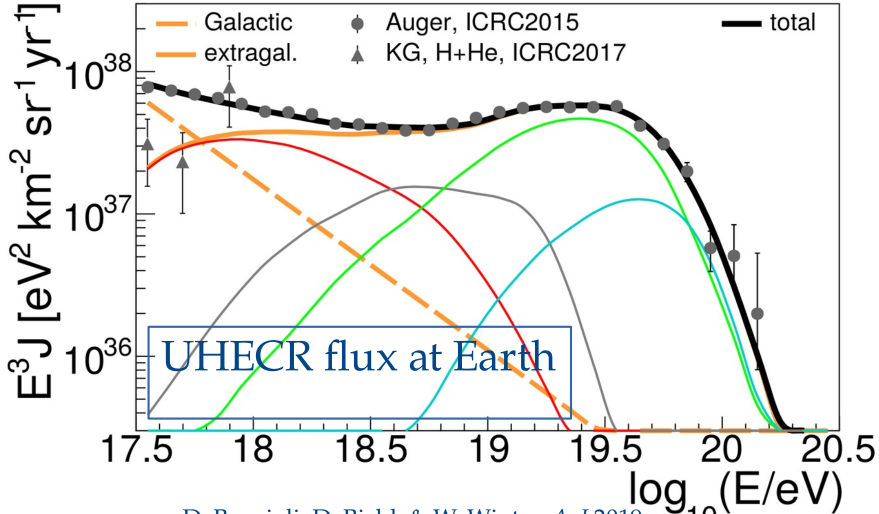

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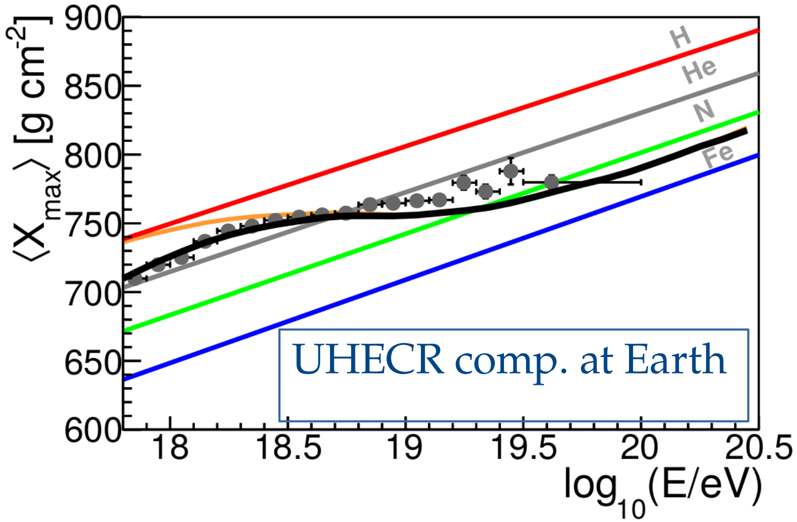

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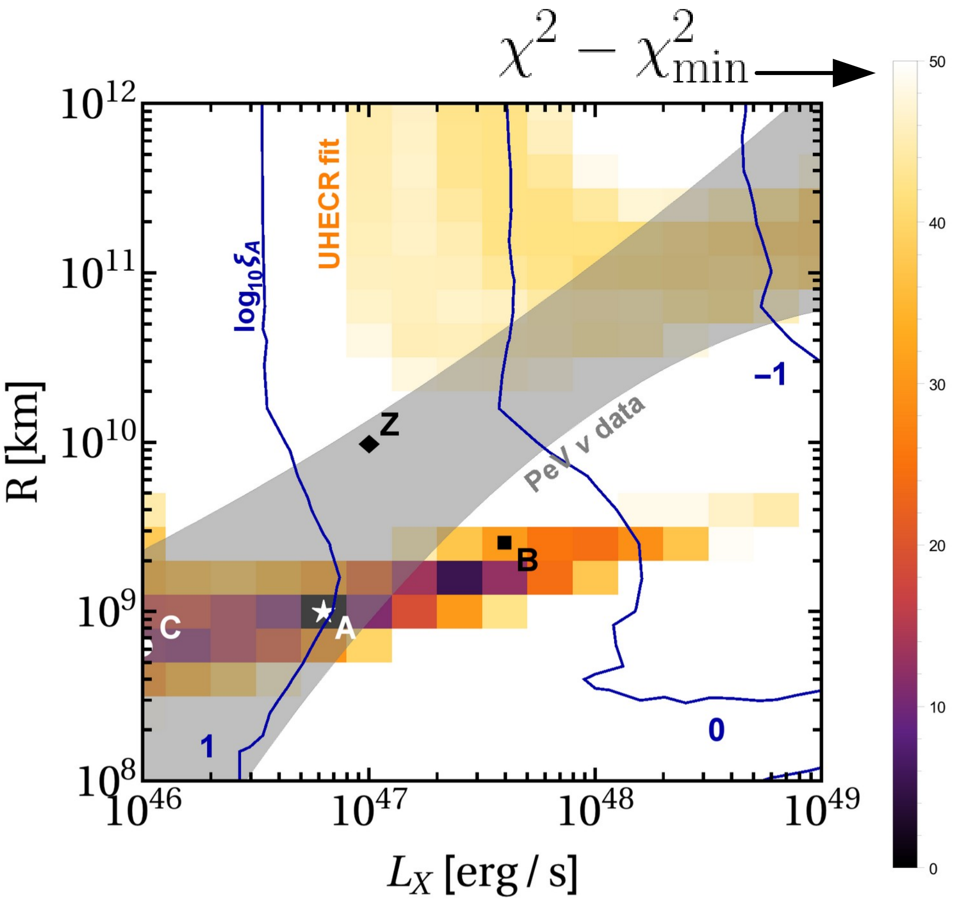
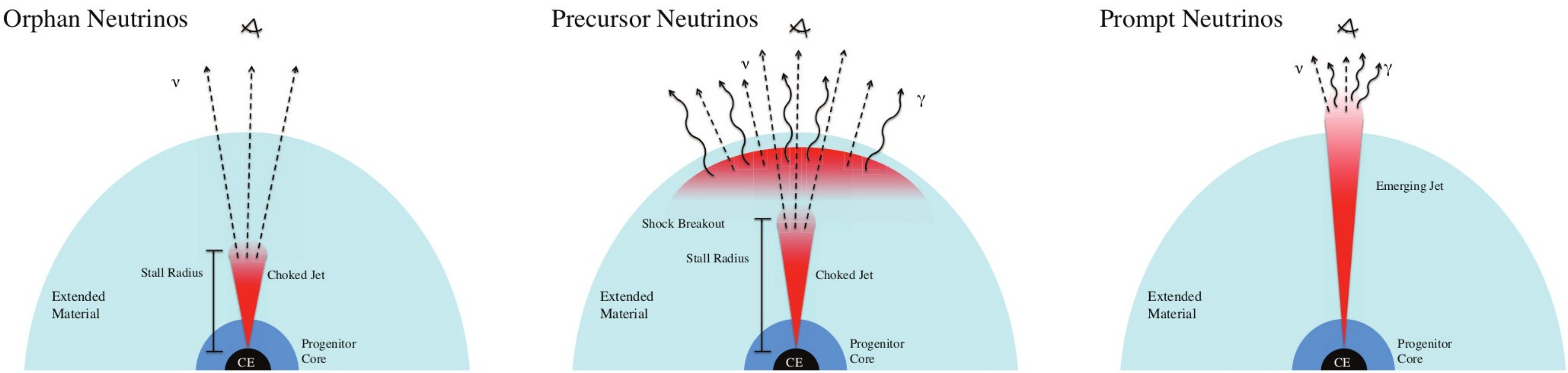


D. Boncioli, D. Biehl, & W. Winter, *ApJ* 2019; B.T. Zhang *et al.*, *PRD* 2018

Low-luminosity and dark GRBs

In jetted supernovae, the jet might be choked —



N. Senno, K. Murase, & P. Meszaros, *PRD* 2016

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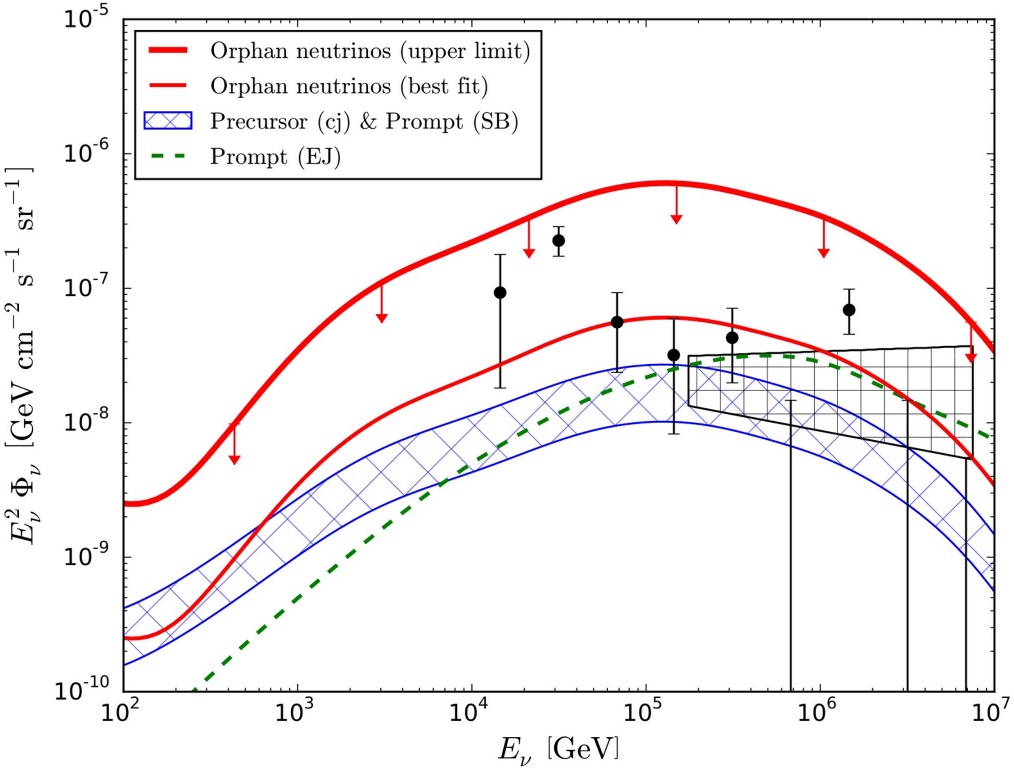
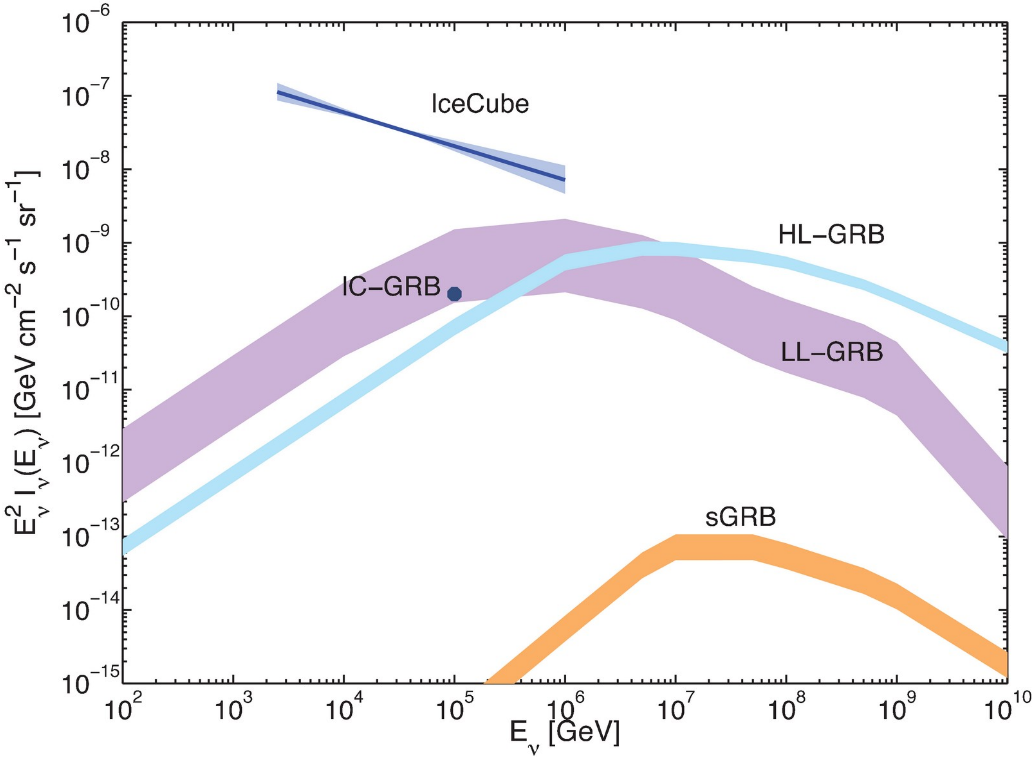


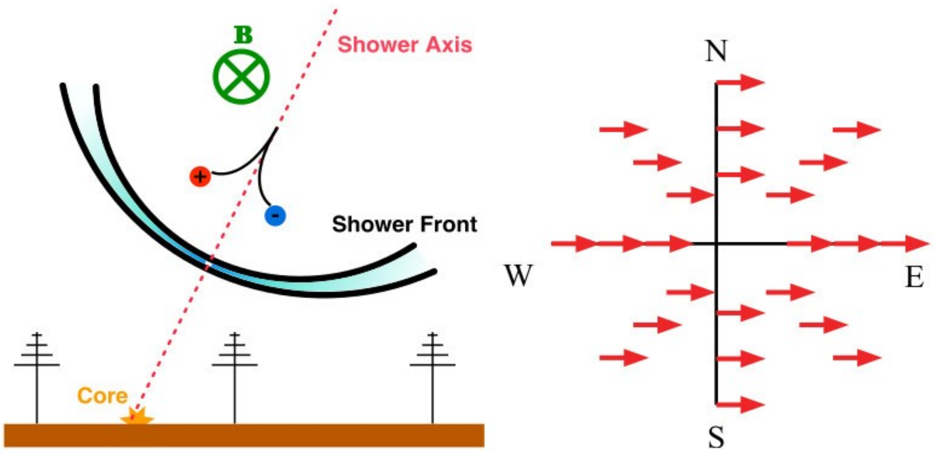
N. Senno, K. Murase, & P. Meszaros, *PRD* 2016



I. Tamborra & S. Ando, *JCAP* 2015

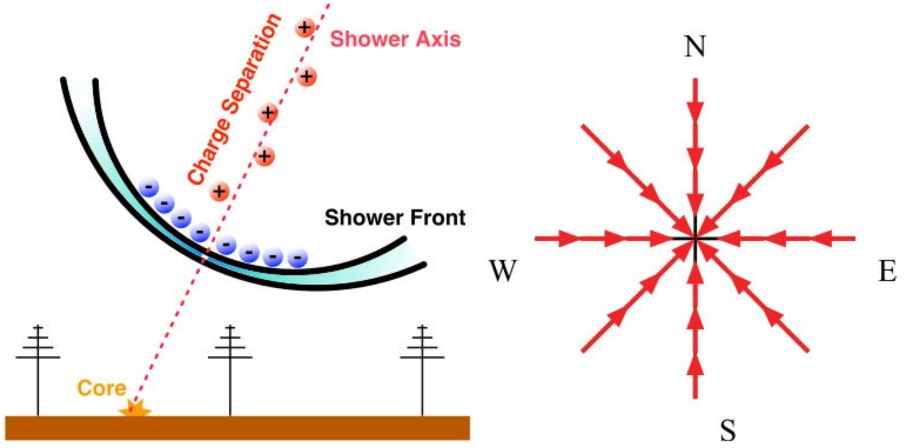
Radio emission: geomagnetic and Askaryan

Geomagnetic



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

Askaryan



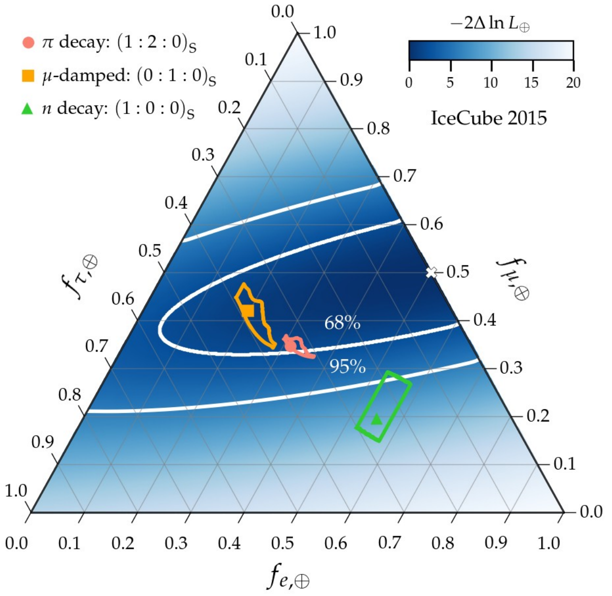
- Time-varying negative-charge ~20% excess
- Linearly polarized towards axis
- Sub-dominant in air showers

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

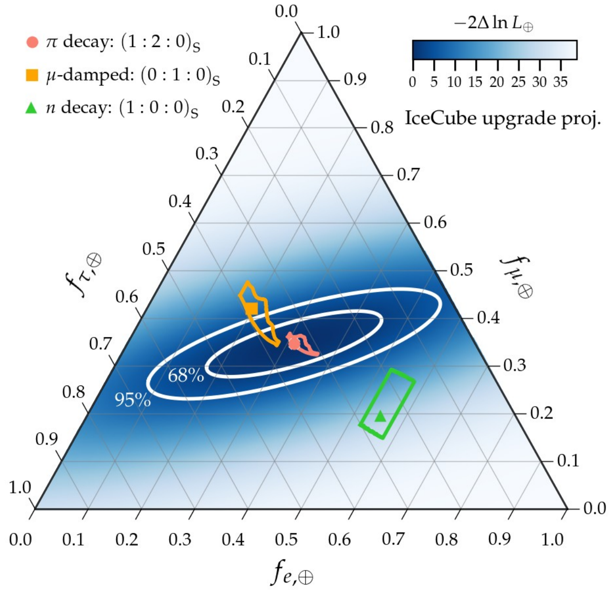
Radio emission: geomagnetic and Askaryan

IceCube flavor composition

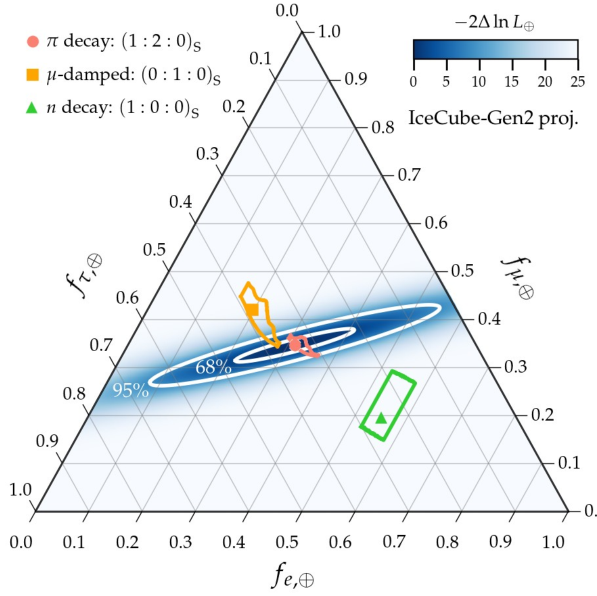
Today
IceCube



Near future (2022)
IceCube upgrade



In 10 years (2030s)
IceCube-Gen2



- Best fit:
  $(f_e : f_\mu : f_\tau)_\oplus = (0.49 : 0.51 : 0)_\oplus$
- Compatible with standard source compositions
- Hints of one ν_τ (not shown)

Assuming production by the full pion decay chain

Plus possibly better flavor-tagging, *e.g.*, muon and neutron echoes

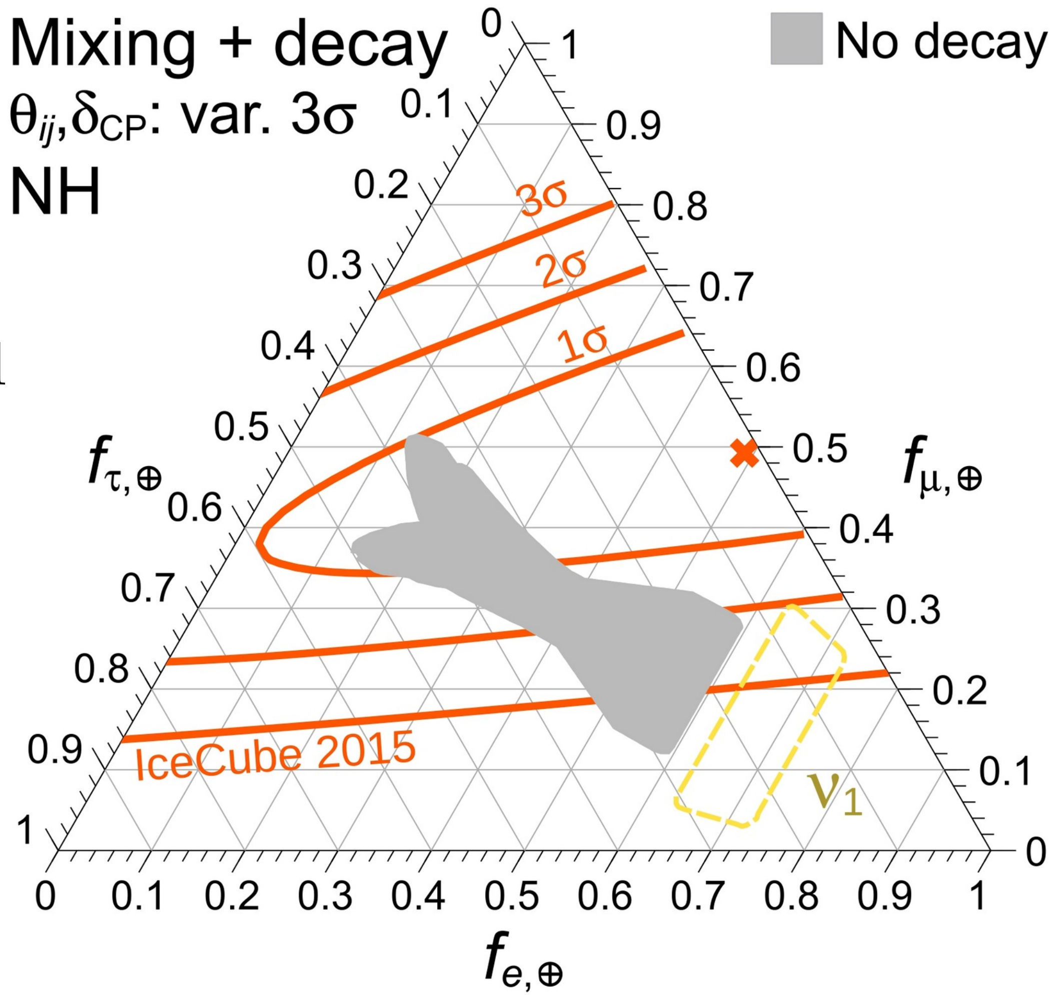
[Li, **MB**, Beacom *PRL* 2019]

Measuring the neutrino lifetime

Find the value of *D* so that decay is complete, *i.e.*, $f_{\alpha,\oplus} = |U_{\alpha 1}|^2$, for

- Any value of mixing parameters; and
- Any flavor ratios at the sources

(Assume equal lifetimes of ν_2, ν_3)



MB, Beacom, Murase, *PRD* 2017
Baerwald, **MB**, Winter, *JCAP* 2012

Measuring the neutrino lifetime

Fraction of ν_2, ν_3 remaining at Earth

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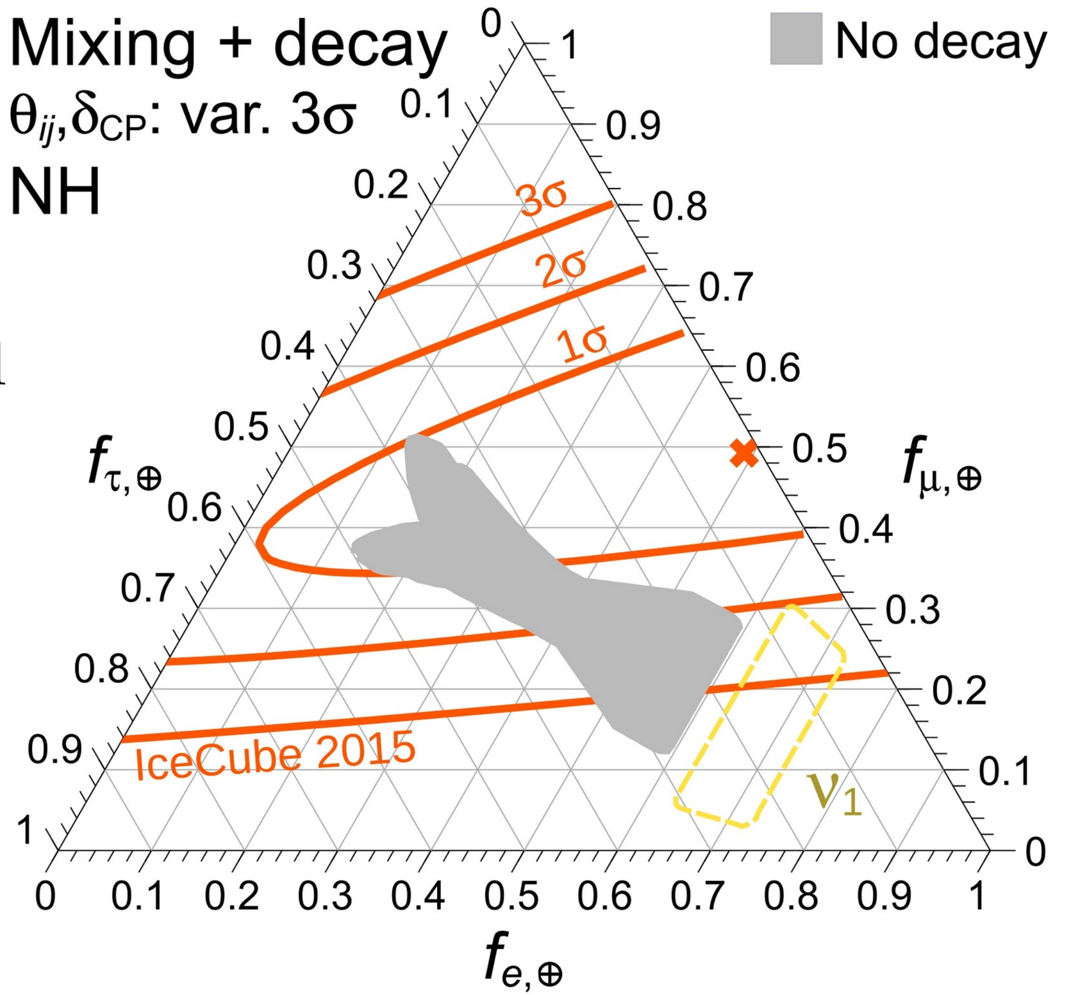

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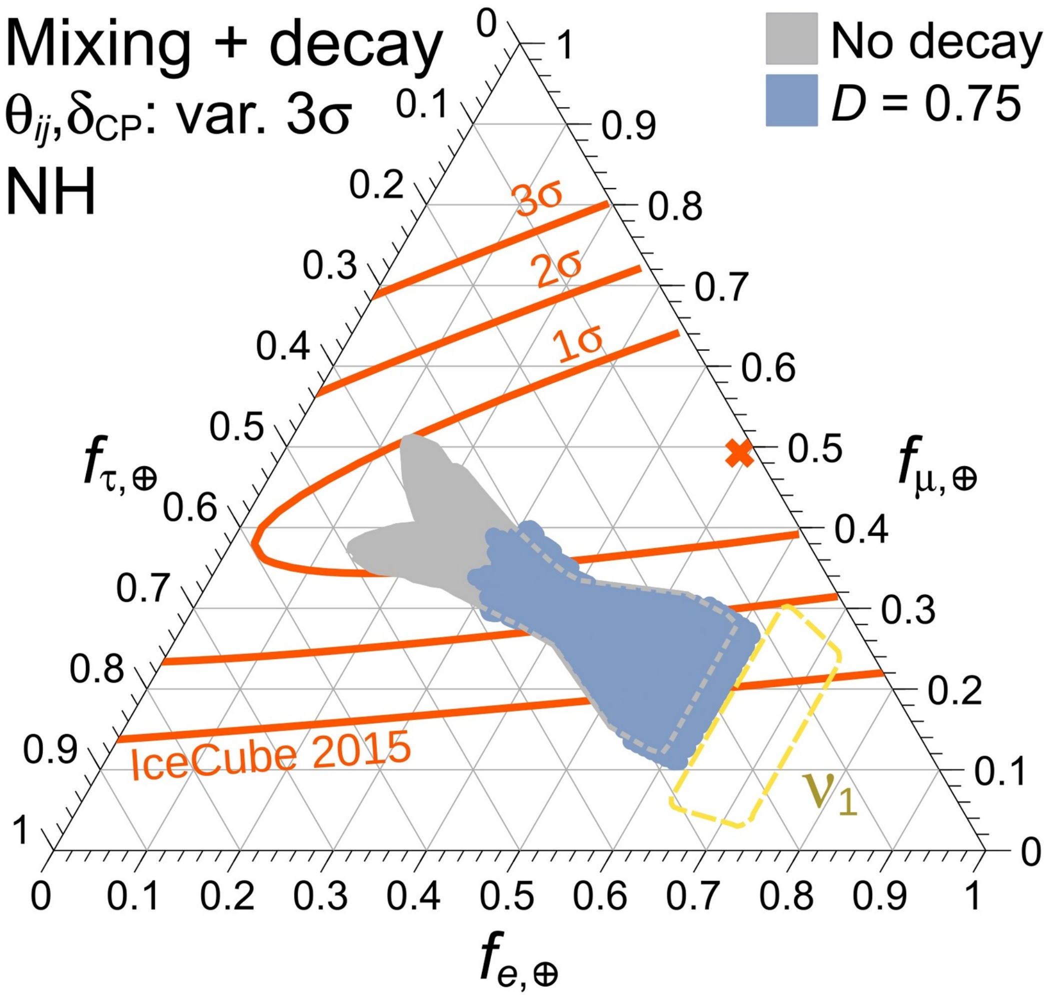

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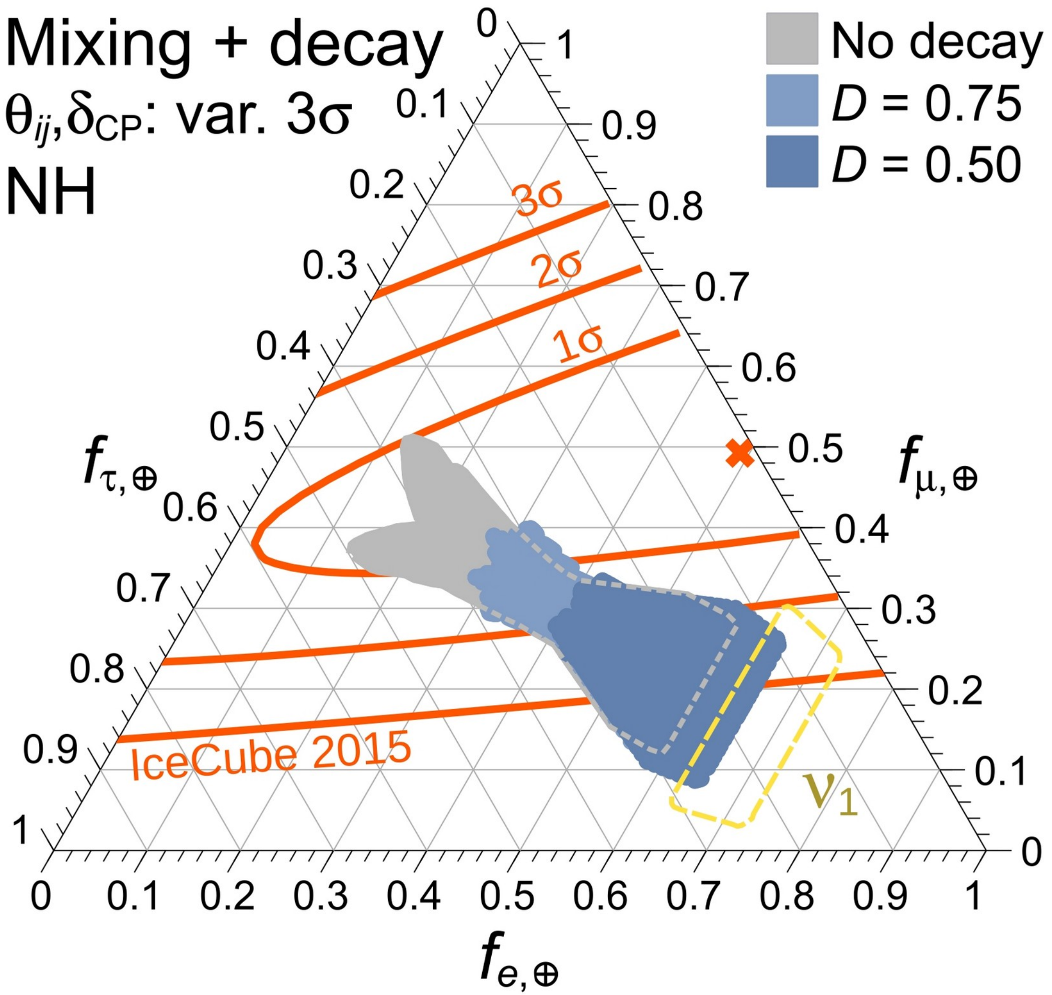

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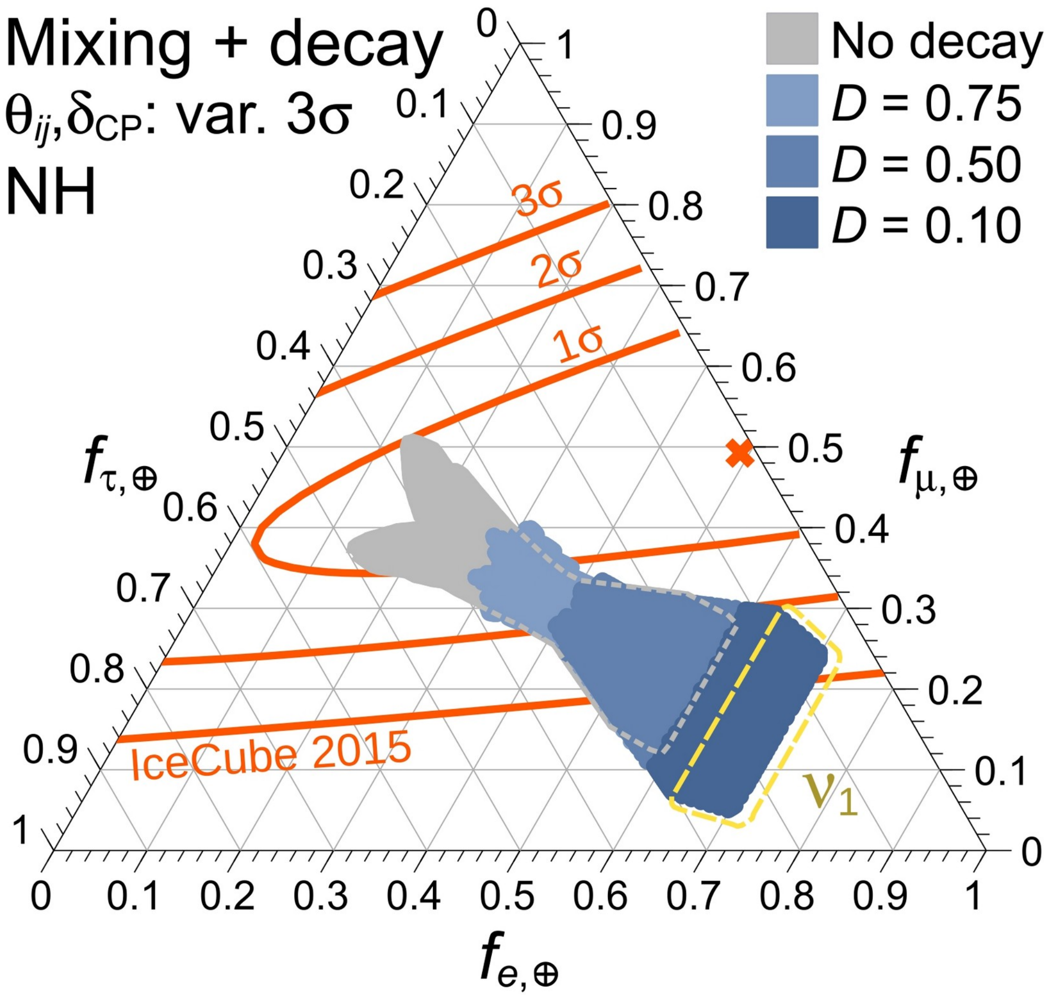

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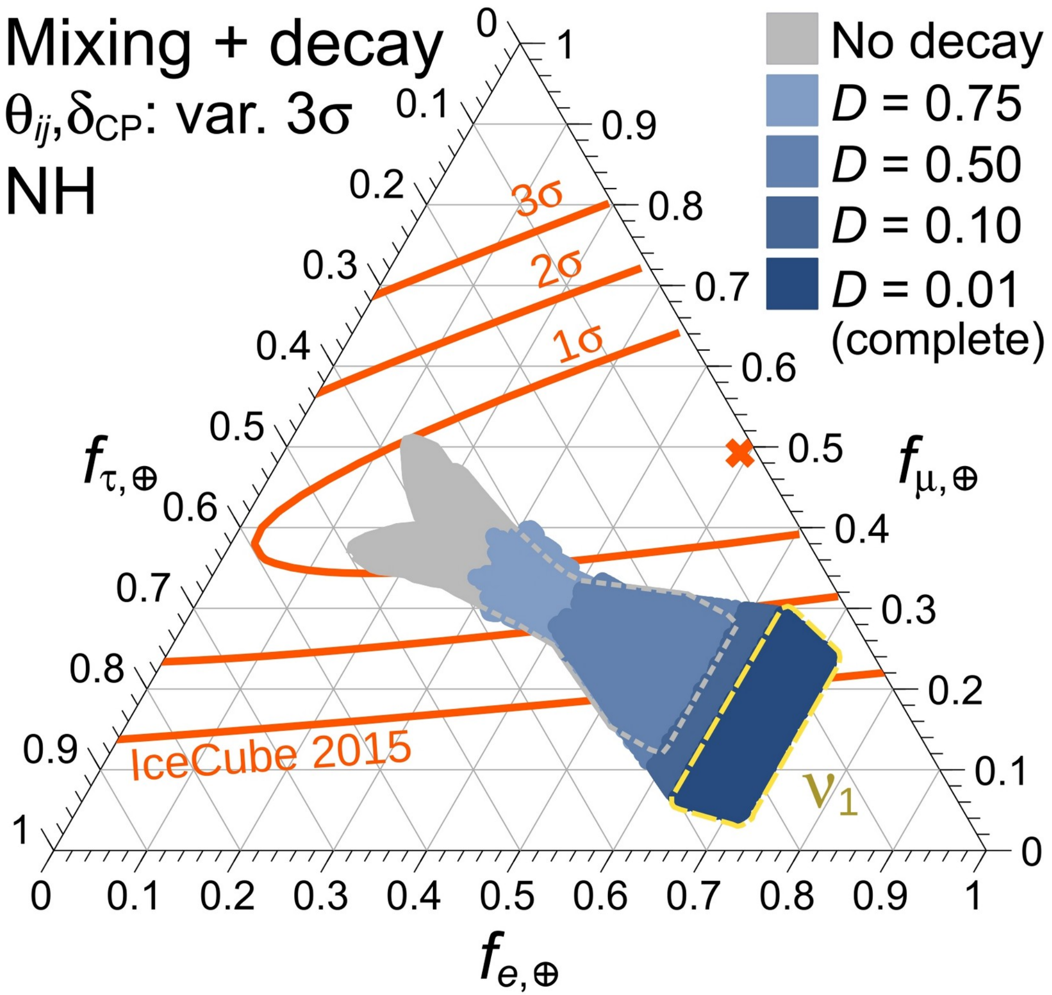

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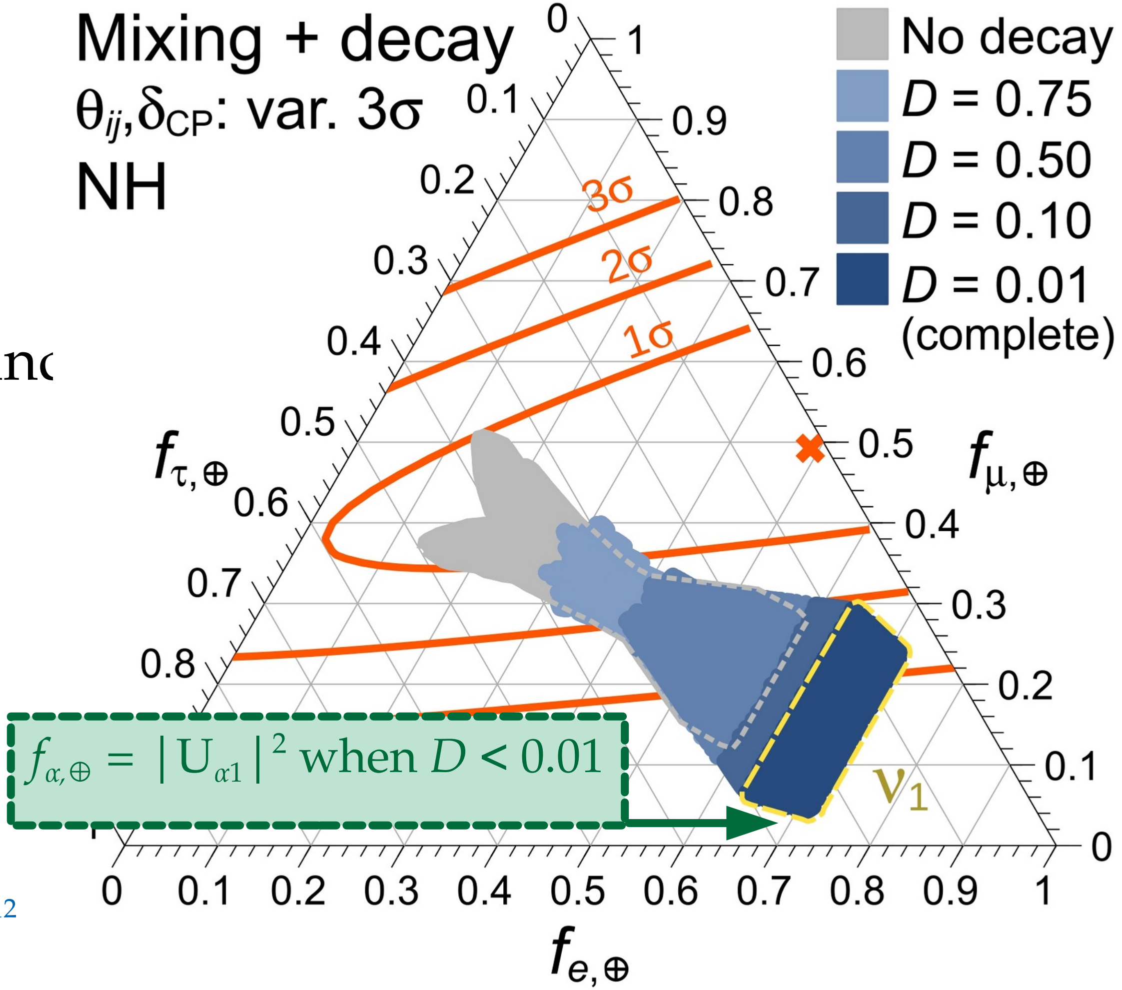

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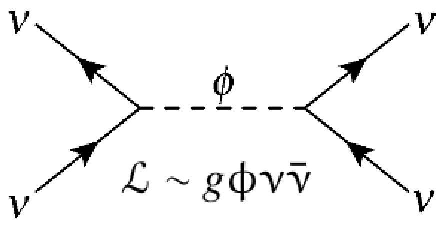
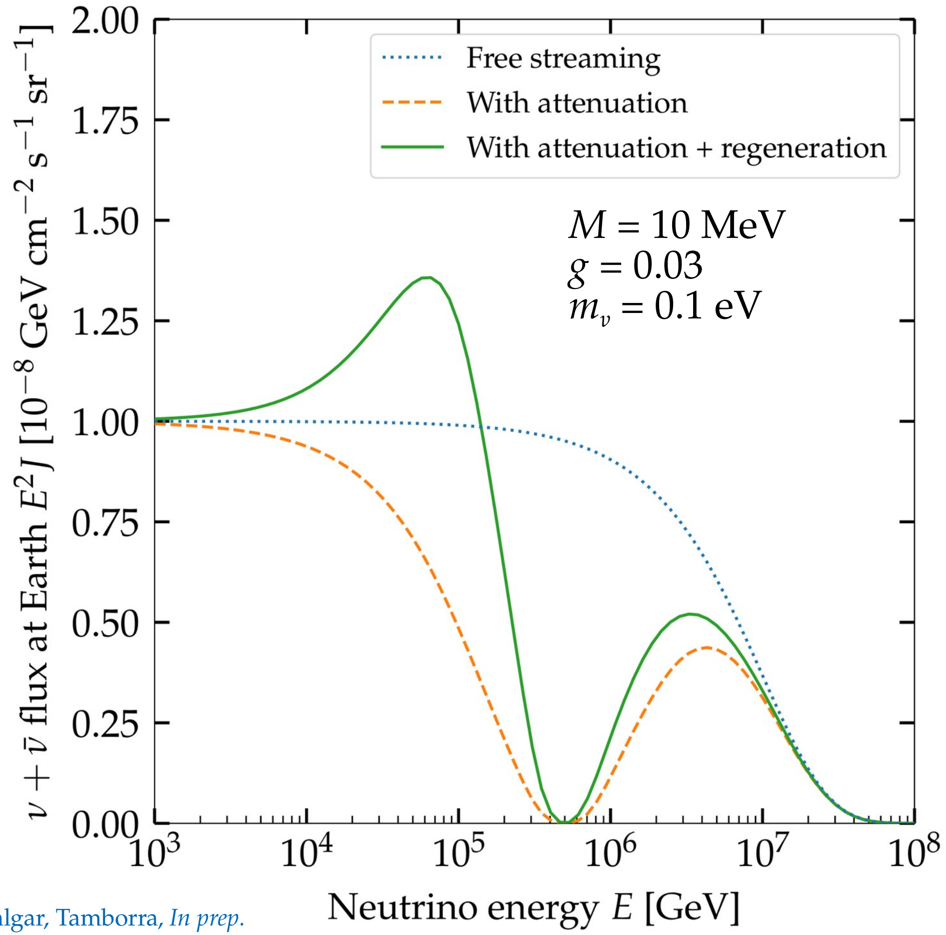
New physics in the spectral shape: νν interactions

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



MB, Rosenstroem, Shalgar, Tamborra, *In prep.*
Ng & Beacom, *PRD* 2014
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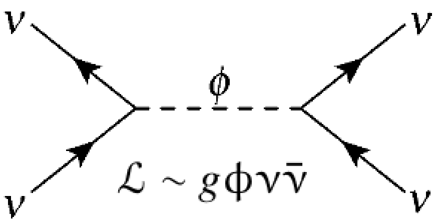
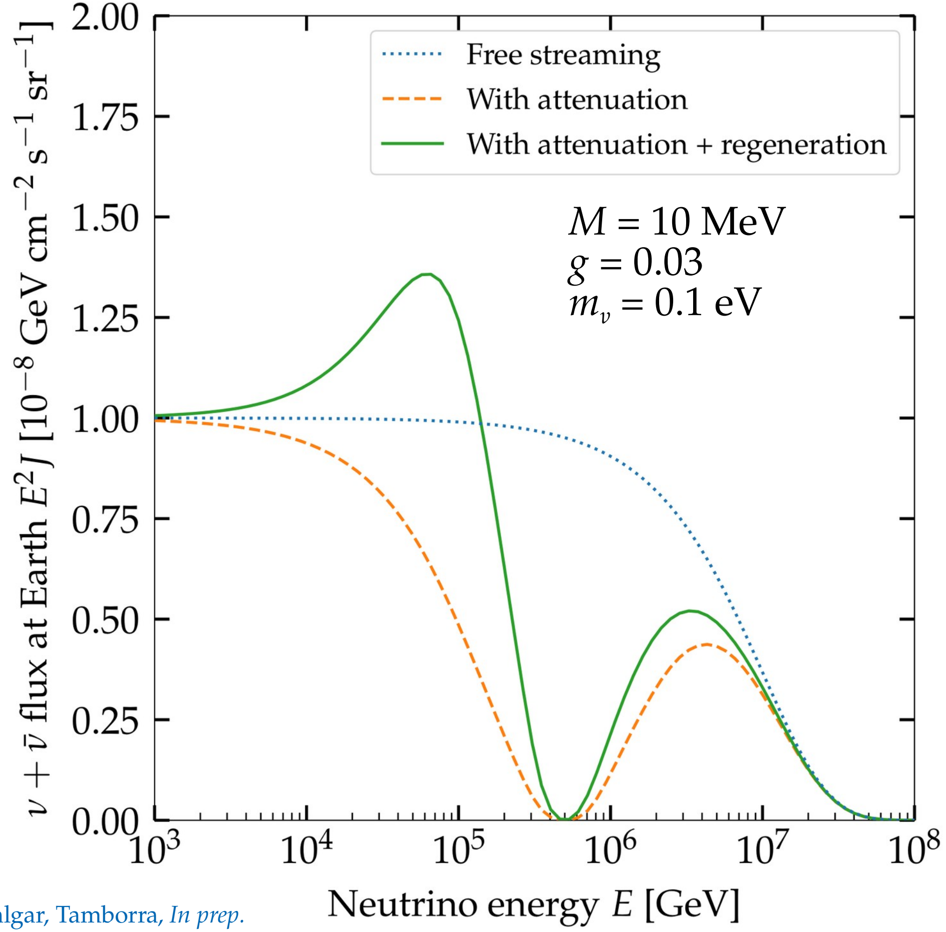


New coupling

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

Mediator mass

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



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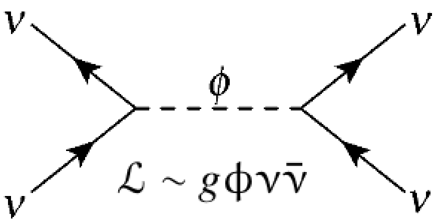

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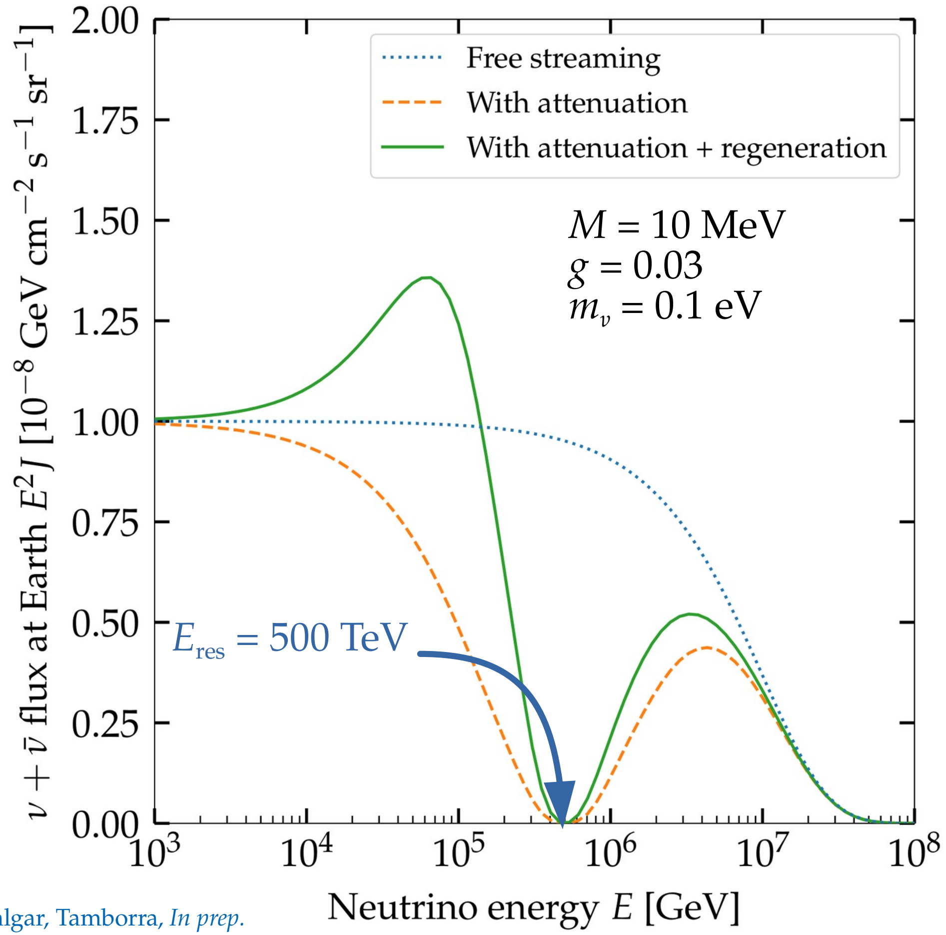

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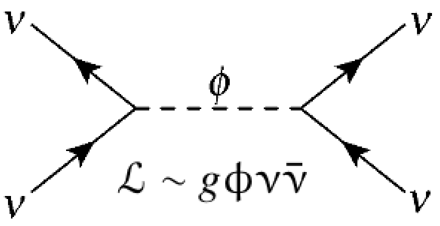

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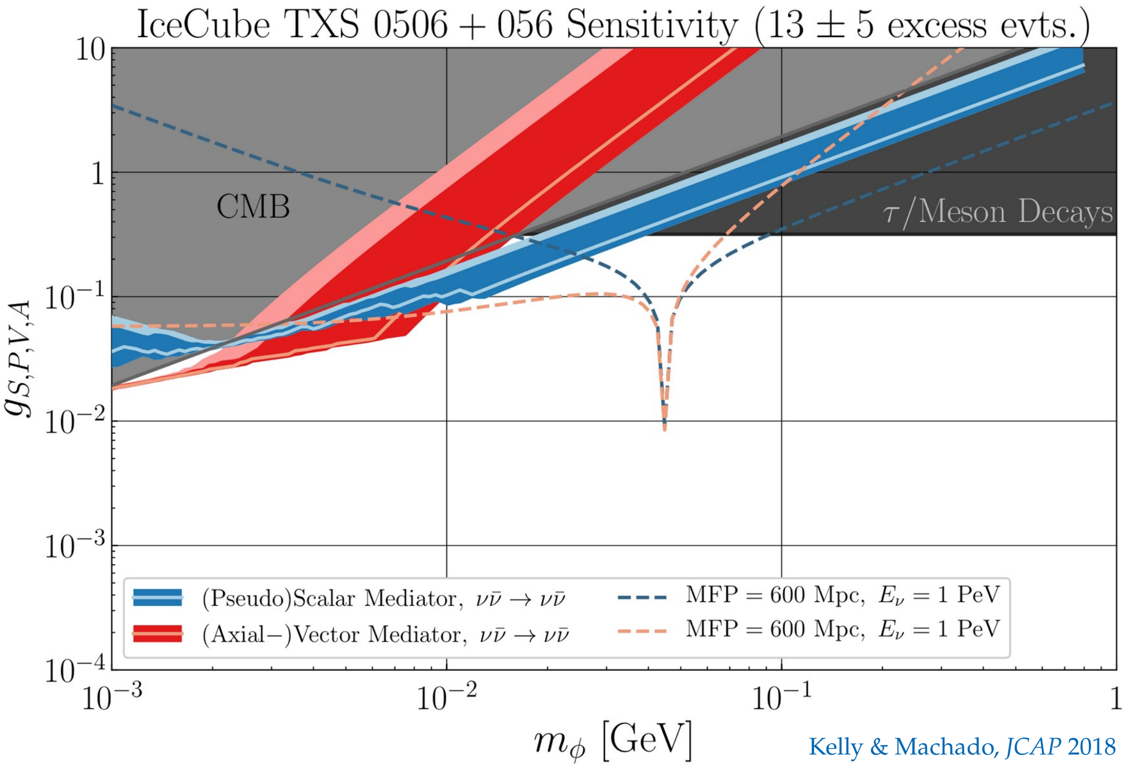
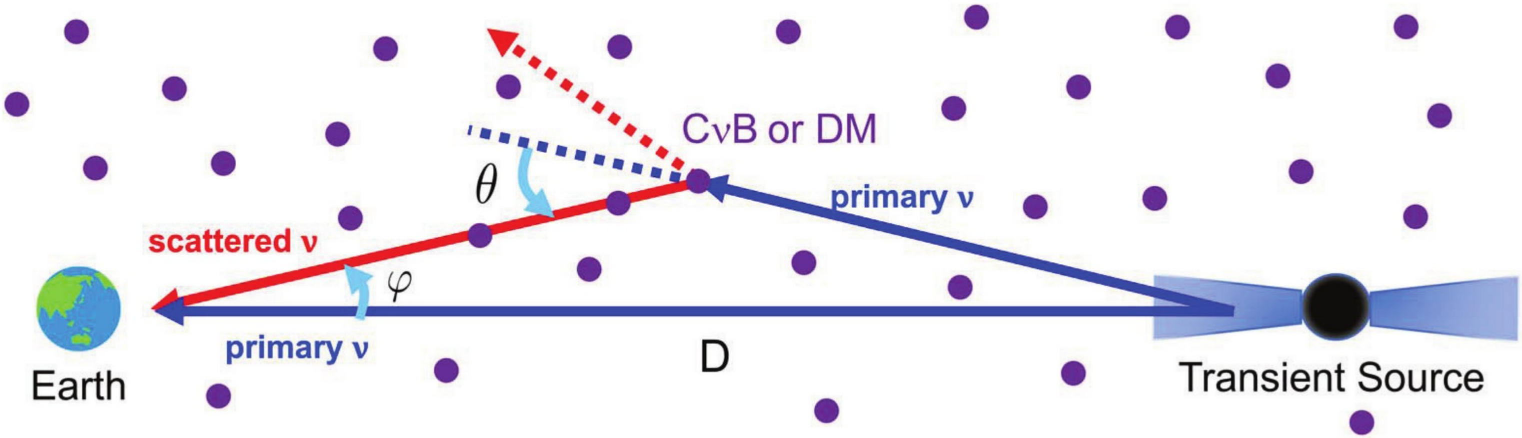


Kelly & Machado, *JCAP* 2018

Delays from secret interactions

Multiple secret νν scatterings may delay the arrival of neutrinos from a transient



Shoemaker & Murase, *PRL* 2019

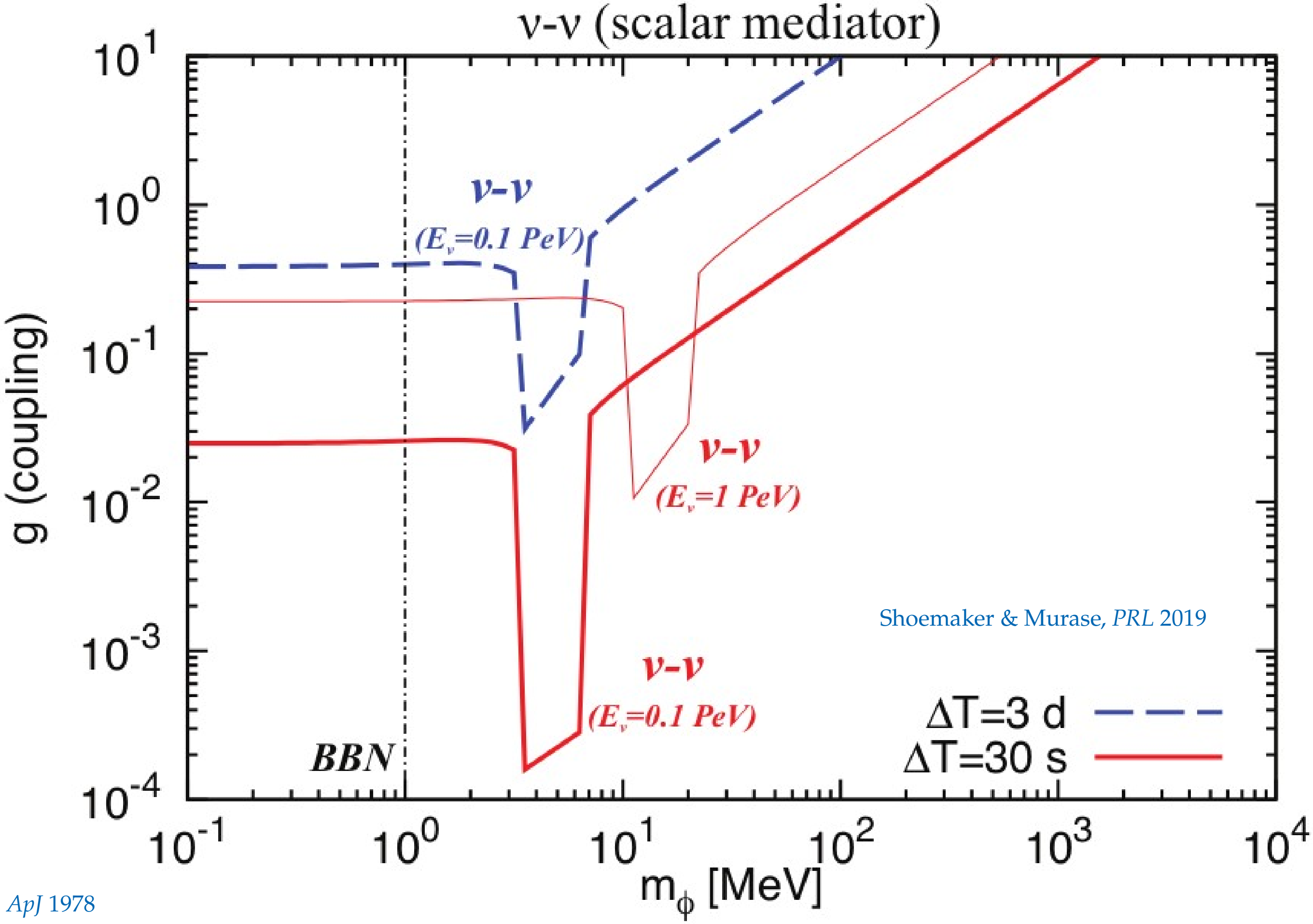
Characteristic time delay —

Optical depth to νν: $\tau_{\nu\nu} = n_\nu \sigma_{\nu\nu} D$

$$\Delta t \approx 1500\,\mathrm{s} \left(\frac{\tau_{\nu\nu}}{30}\right) \left(\frac{D}{3\ \mathrm{Gpc}}\right) \left(\frac{m_\nu}{0.1\ \mathrm{eV}}\right) \left(\frac{0.1\ \mathrm{PeV}}{E_\nu}\right)$$

See also: Alcock & Hatchett, *ApJ* 1978

Delays from secret interactions



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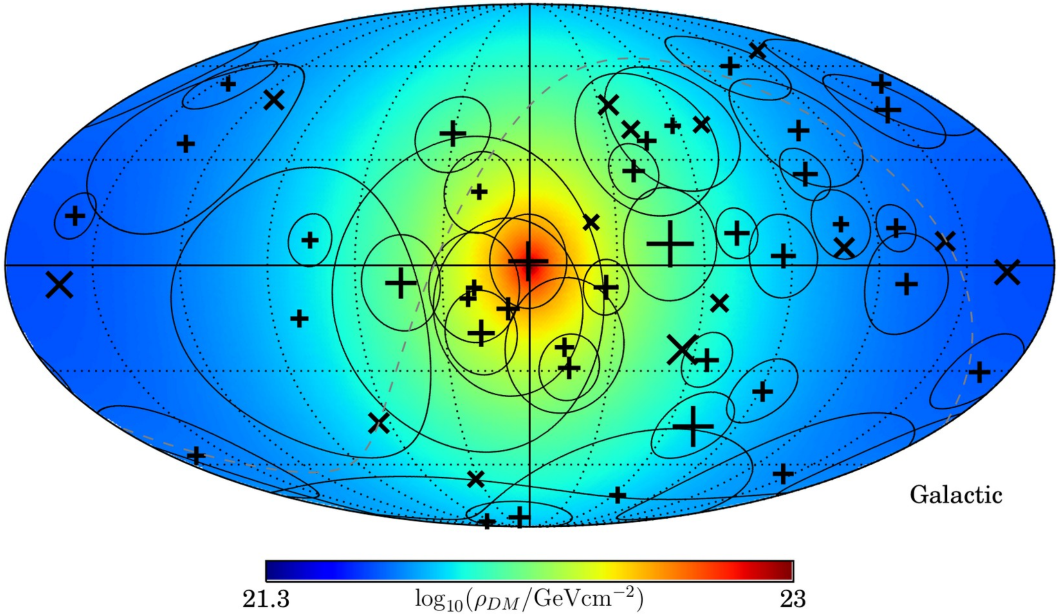
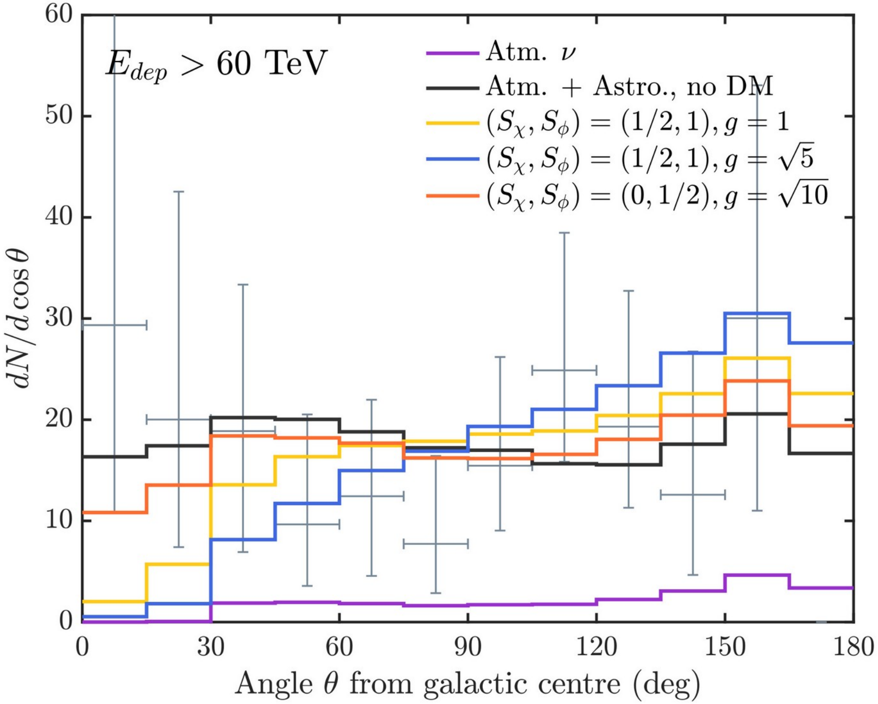
New physics in the angular distribution: ν-DM interactions

Interaction between astrophysical neutrinos and the Galactic dark matter profile –





Expected: Fewer neutrinos coming from the Galactic Center

Observed: Isotropy

Argüelles, Kheirandish, Vincent, *PRL* 2017

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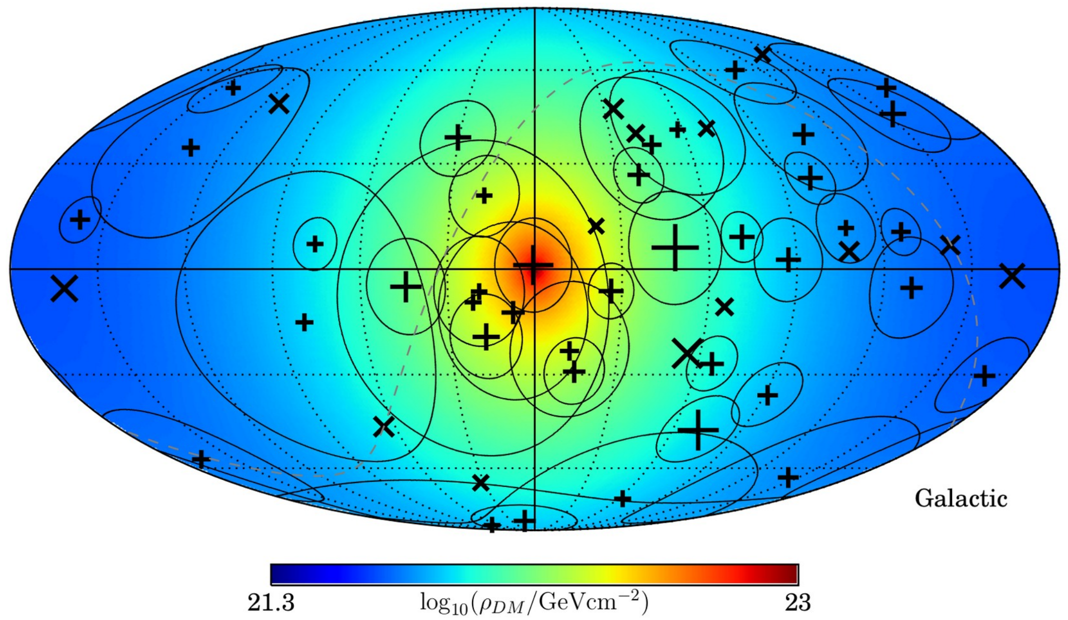

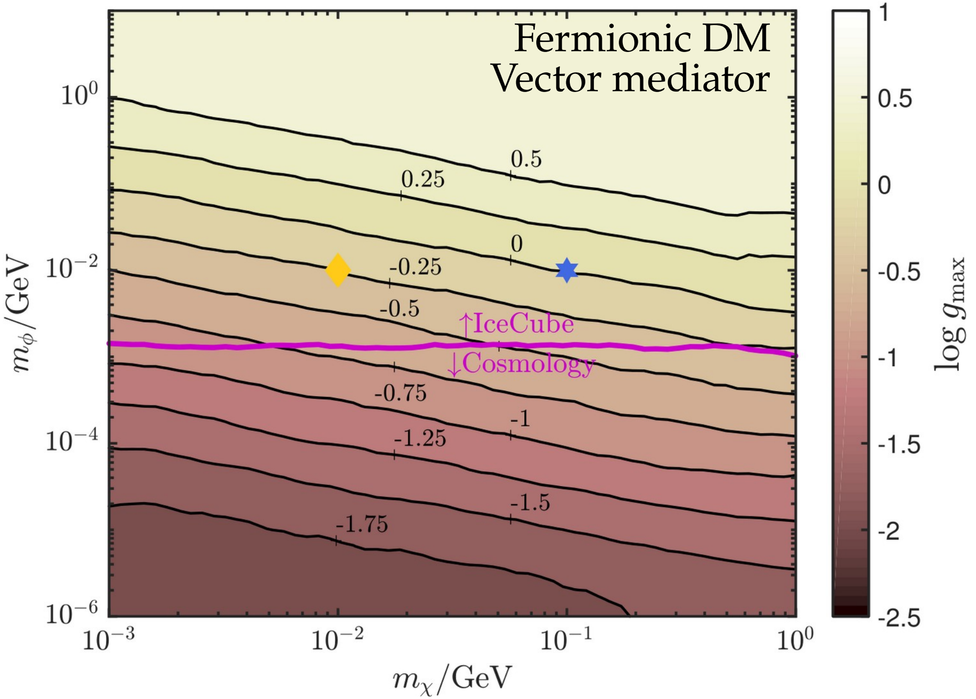

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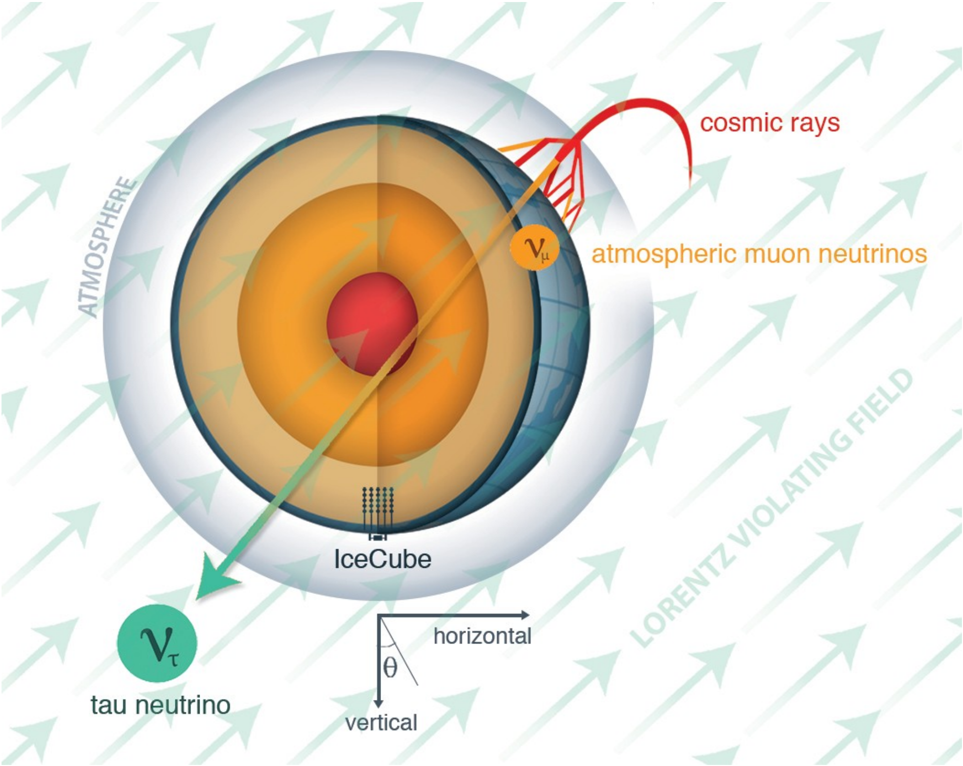
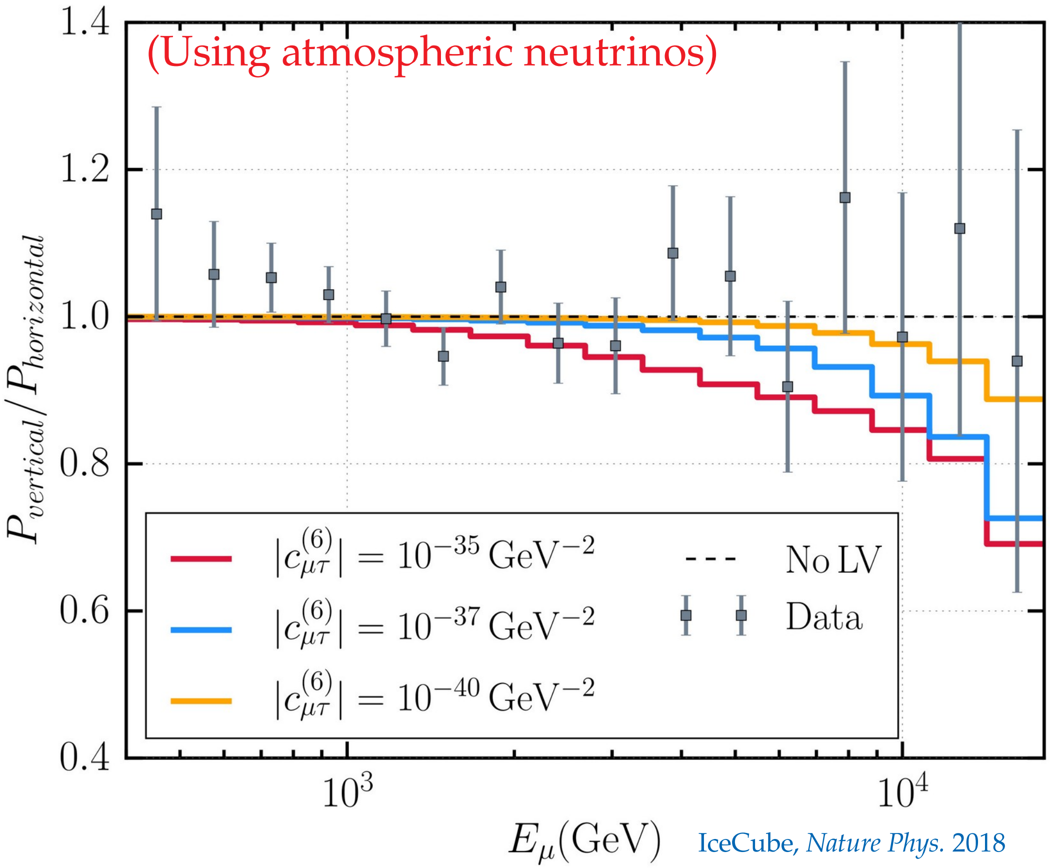
New physics in the energy & angular distribution

Lorentz invariance violation – Hamiltonian: $H \sim m^2/(2E) + a^{(3)} - E \cdot c^{(4)} + E^2 \cdot a^{(5)} - E^3 \cdot c^{(6)}$



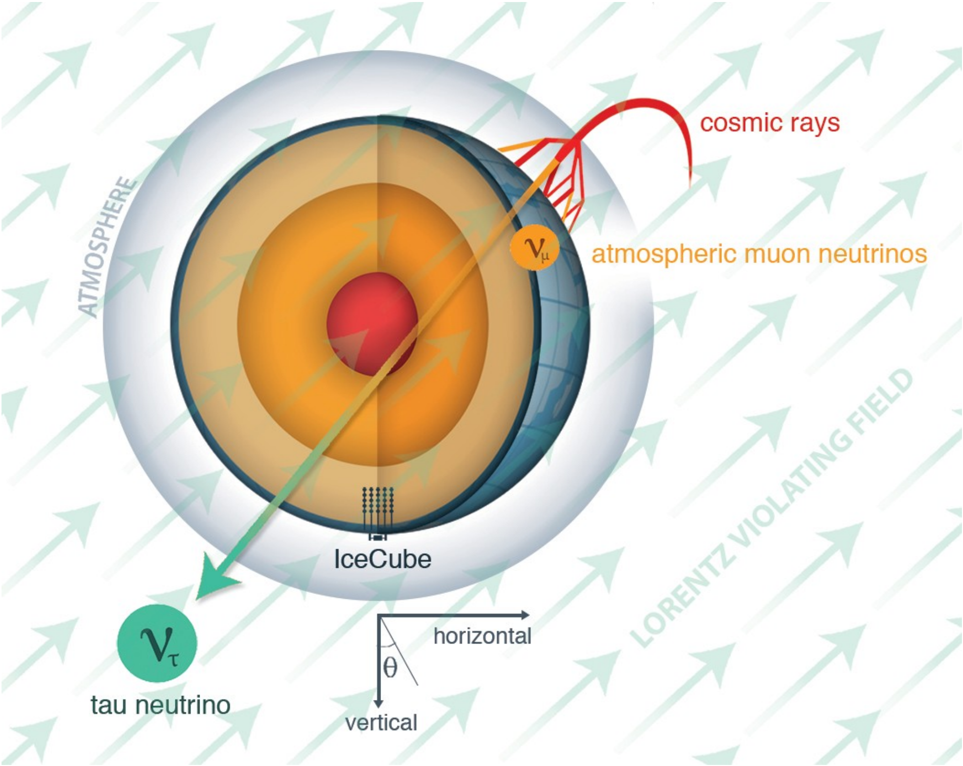


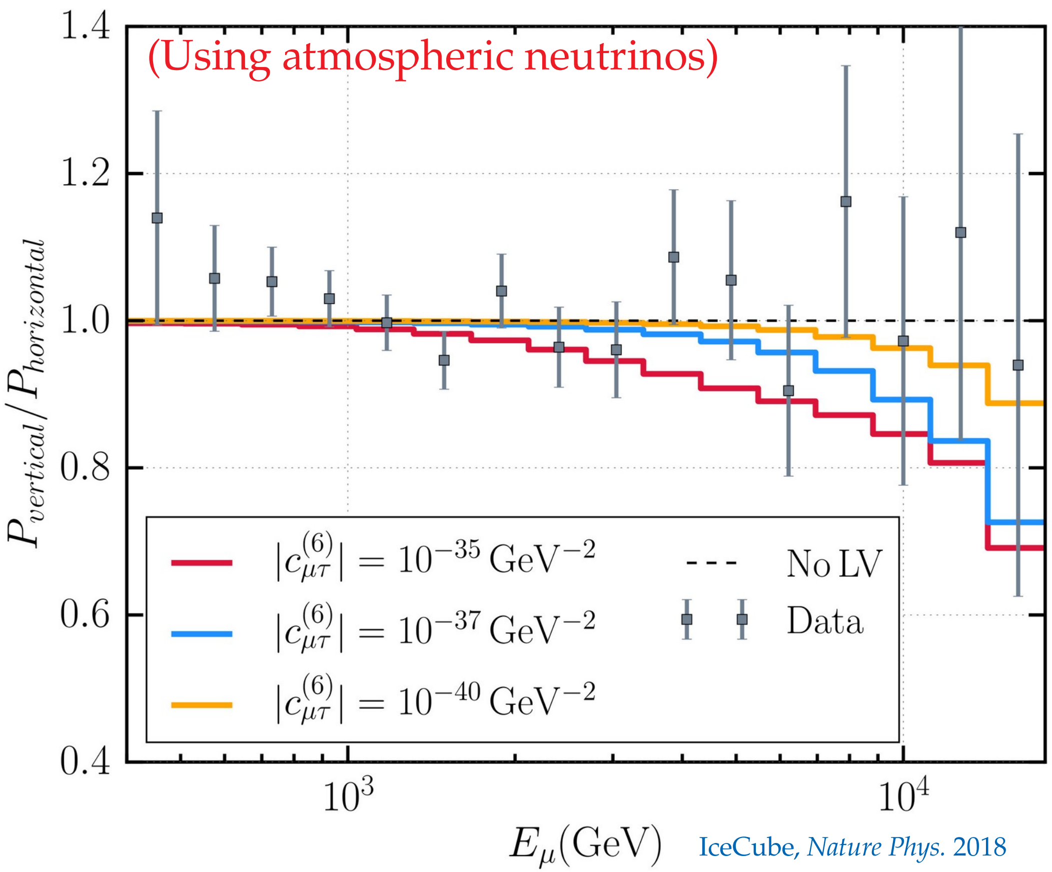
IceCube, *Nature Phys.* 2018

New physics in the energy & angular distribution

Standard oscillations — Lorentz violation

Lorentz invariance violation – Hamiltonian: $H \sim m^2/(2E) + \mathring{a}^{(3)} - E \cdot \mathring{c}^{(4)} + E^2 \cdot \mathring{a}^{(5)} - E^3 \cdot \mathring{c}^{(6)}$





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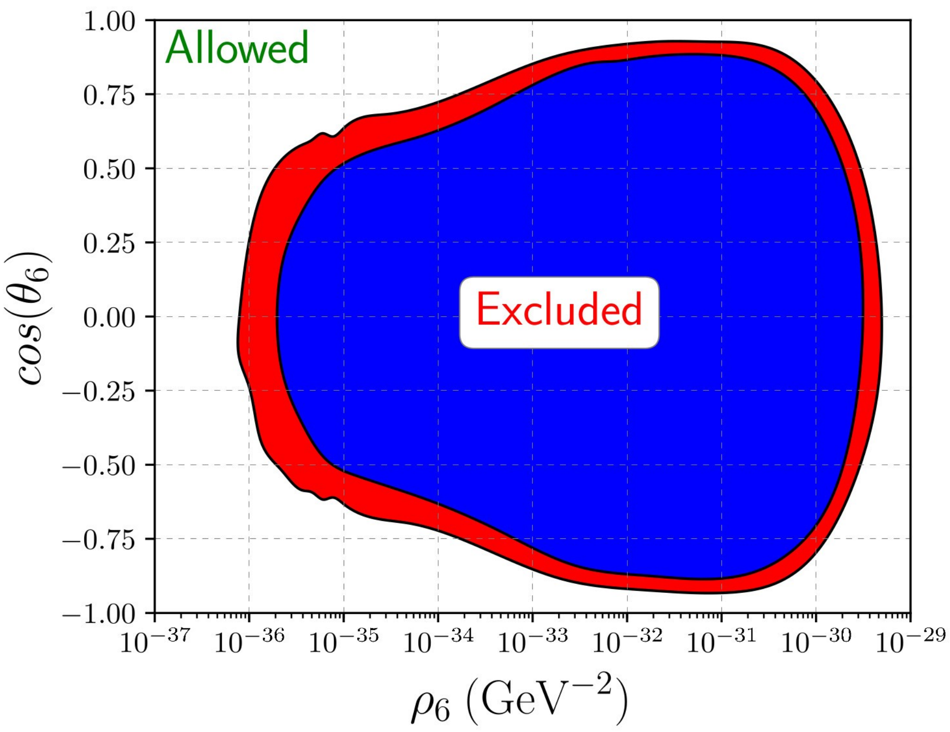
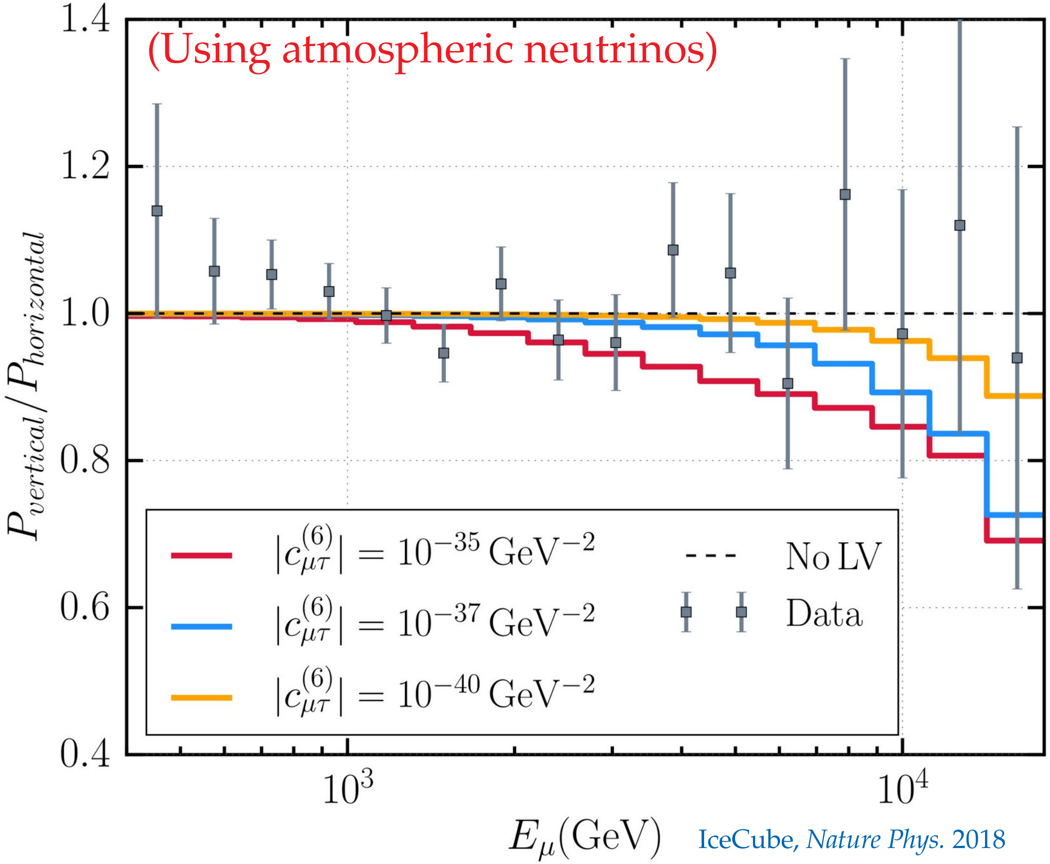
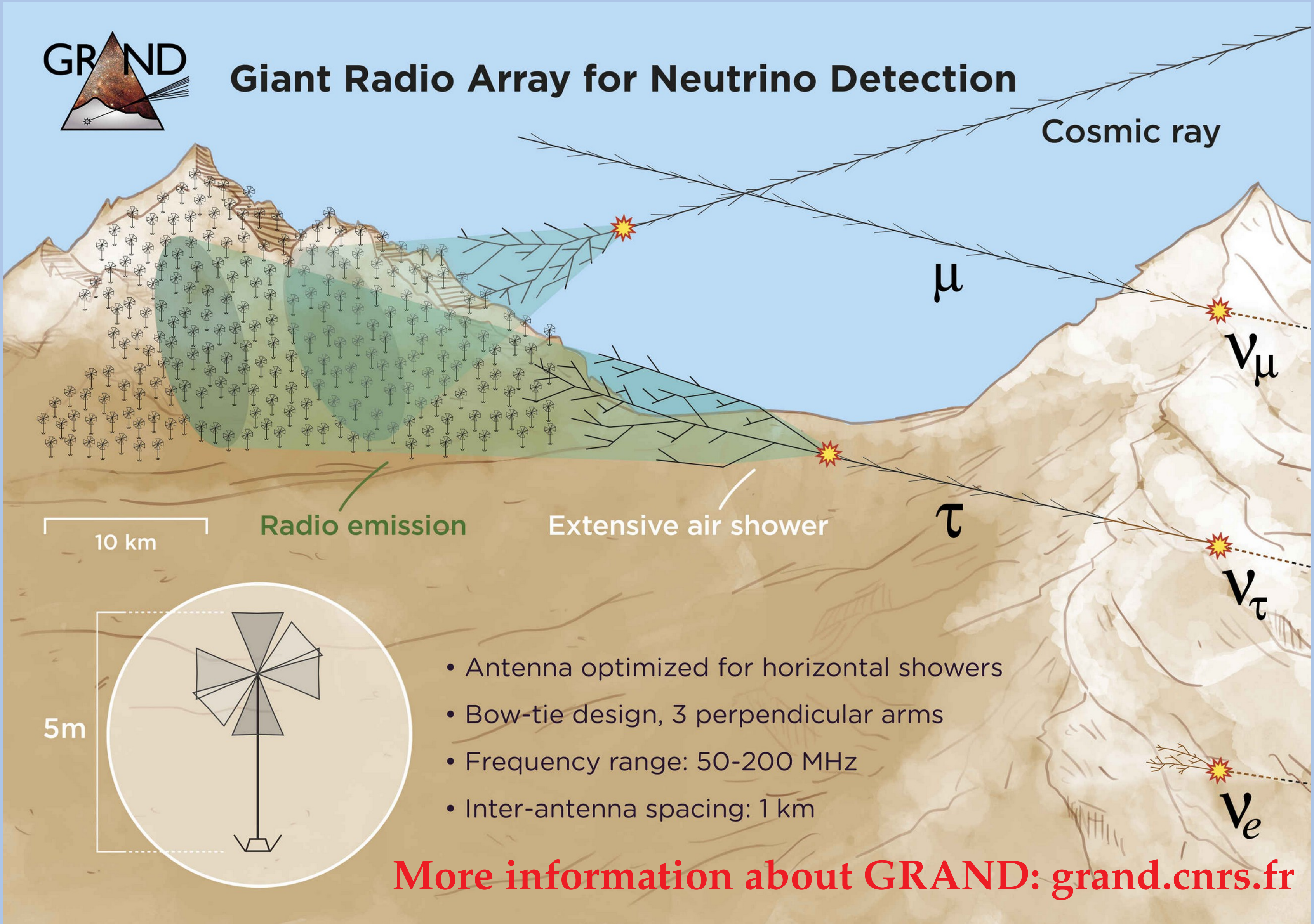
Best bounds come from IceCube





IceCube, *Nature Phys.* 2018

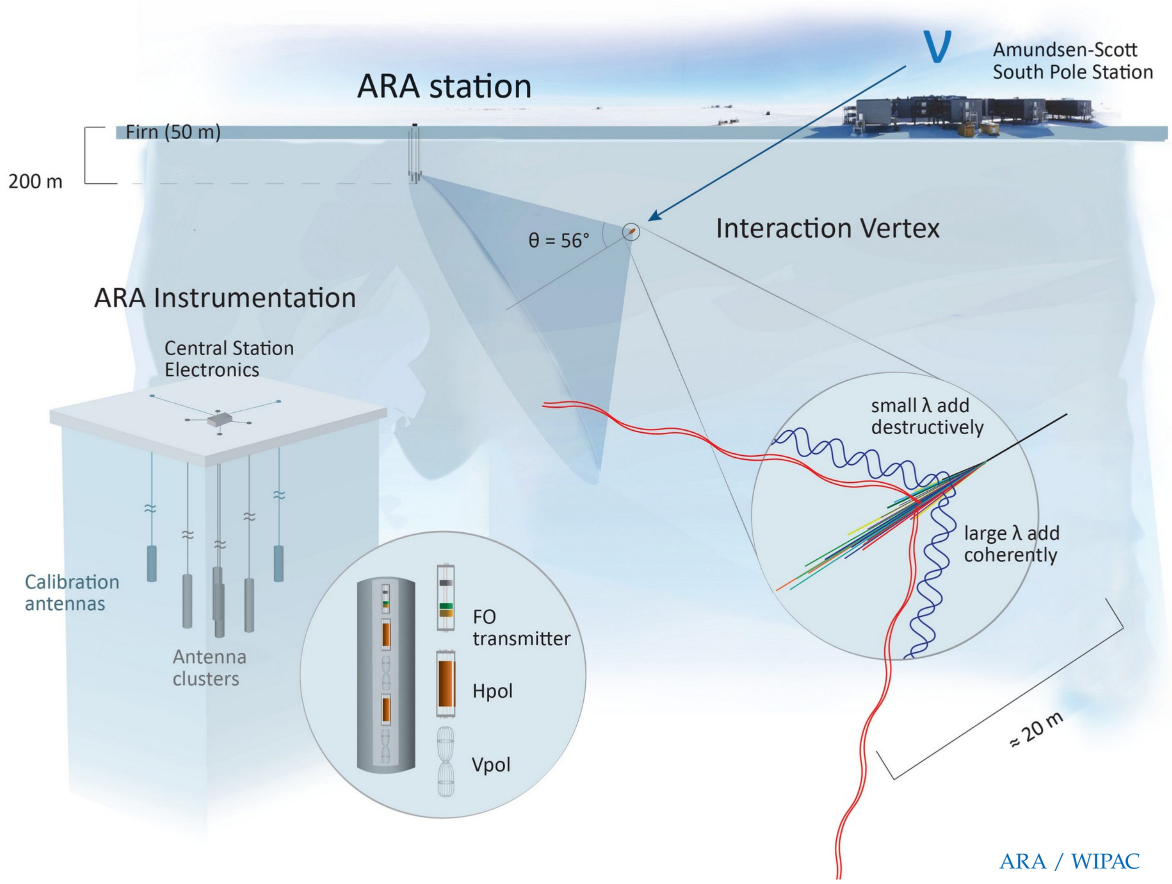

GRAND
Giant Radio Array for Neutrino Detection
Cosmic ray
μ
νμ
τ
ντ
νe
10 km
Radio emission
Extensive air shower
5m
• Antenna optimized for horizontal showers
• Bow-tie design, 3 perpendicular arms
• Frequency range: 50-200 MHz
• Inter-antenna spacing: 1 km
More information about GRAND: grand.cnrs.fr

Radio-detection of UHE neutrinos in ice

- Radio attenuation length in ice: few km (*vs.* 100 m for light)
- Larger monitored volume than IceCube
- ARA, ARIANNA: antennas buried in ice
- ANITA: antennas mounted on a balloon

No ν detected yet

(But UHECRs detected regularly!)



ARA / WIPAC

Flavor-transition probability: the quick and dirty of it

- In matrix form: $$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}U^*_{e1} & U^*_{e2} & U^*_{e3}\\ U^*_{\mu1} & U^*_{\mu2} & U^*_{\mu3}\\ U^*_{\tau1} & U^*_{\tau2} & U^*_{\tau3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

- Pontecorvo-Maki-Nakagawa-Sakata matrix ($c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$):

$$U = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}}_{\text{Atmospheric}} \underbrace{\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}}_{\text{Cross mixing}} \underbrace{\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\text{Solar}} \underbrace{\begin{pmatrix}e^{i\alpha_1/2} & 0 & 0\\ 0 & e^{i\alpha_2/2} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\text{Majorana CP phases}}$$

- Probability for $\nu_\alpha \to \nu_\beta$: $$P_{\nu_\alpha\to\nu_\beta} = \delta_{\alpha\beta} - 4\sum_{i>j}\text{Re}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2\left(\Delta m^2_{ij}\frac{L}{4E}\right) + 2\sum_{i>j}\text{Im}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin\left(\Delta m^2_{ij}\frac{L}{2E}\right)$$

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- $\theta_{23} \approx 48°$
- $\theta_{13} \approx 9°$
- $\theta_{12} \approx 34°$
- $\delta \approx 222°$

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… But high-energy neutrinos oscillate *fast*

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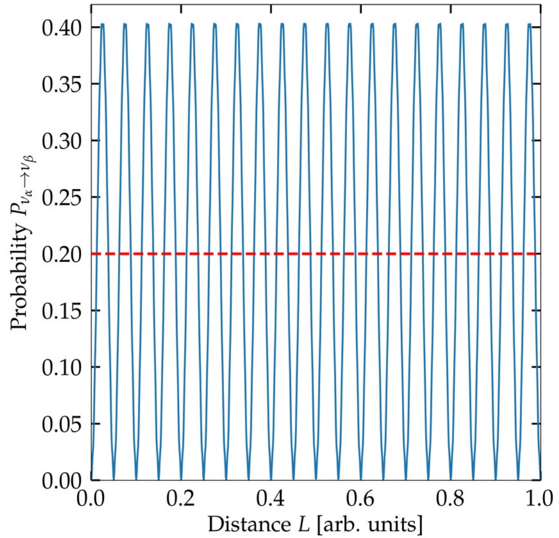

Oscillation length for 1-TeV ν: $2\pi \times 2E/\Delta m^2 \sim 0.1$ pc

~ 8% of the way to Proxima Centauri
⋘ Distance to Galactic Center (8 kpc)
⋘ Distance to Andromeda (1 Mpc)
⋘ Cosmological distances (few Gpc)

We cannot resolve oscillations, so we use instead the average probability:

$$\langle P_{\nu_\alpha \to \nu_\beta} \rangle = \sum_{i=1}^{3} |U_{\alpha i}|^2 |U_{\beta i}|^2$$

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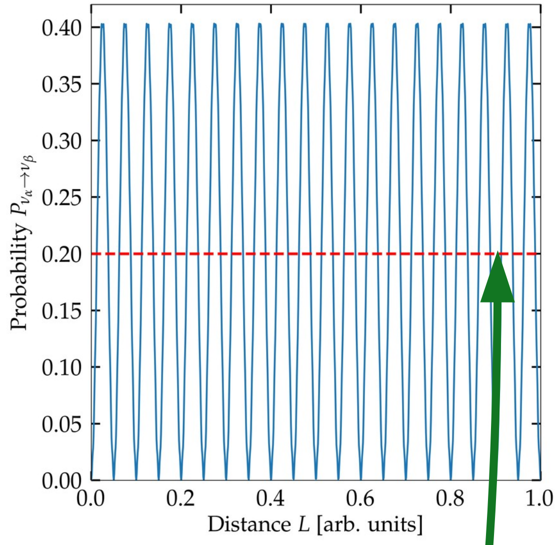

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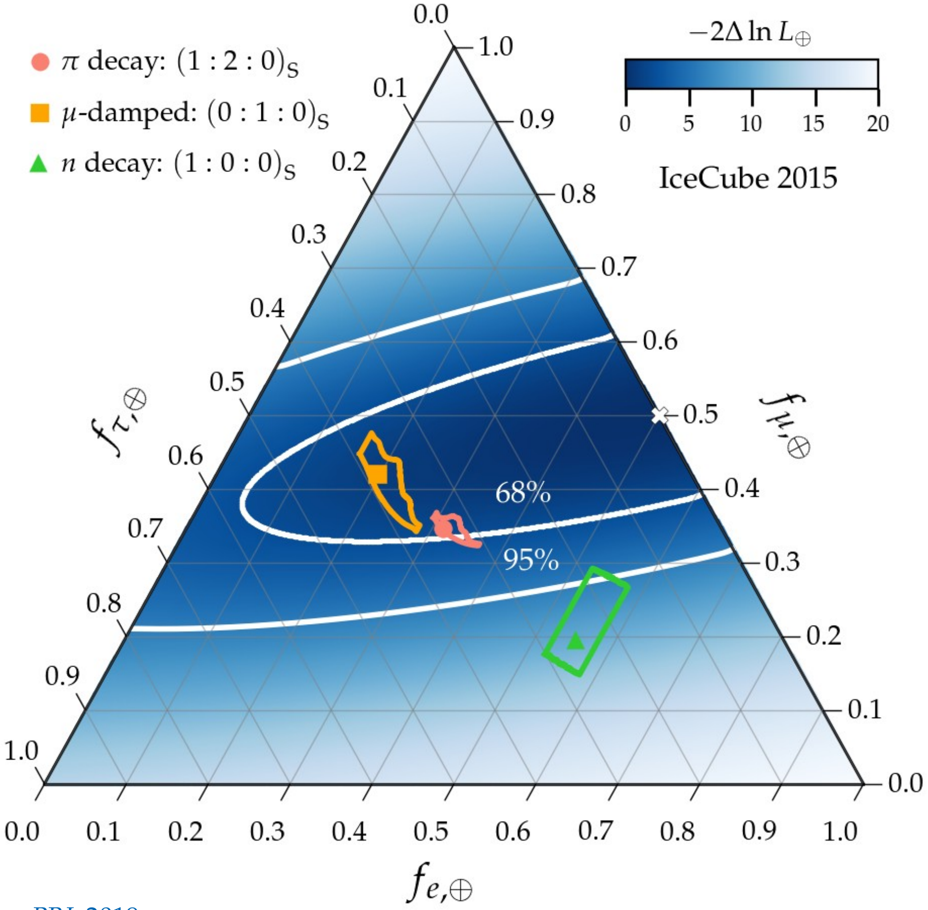
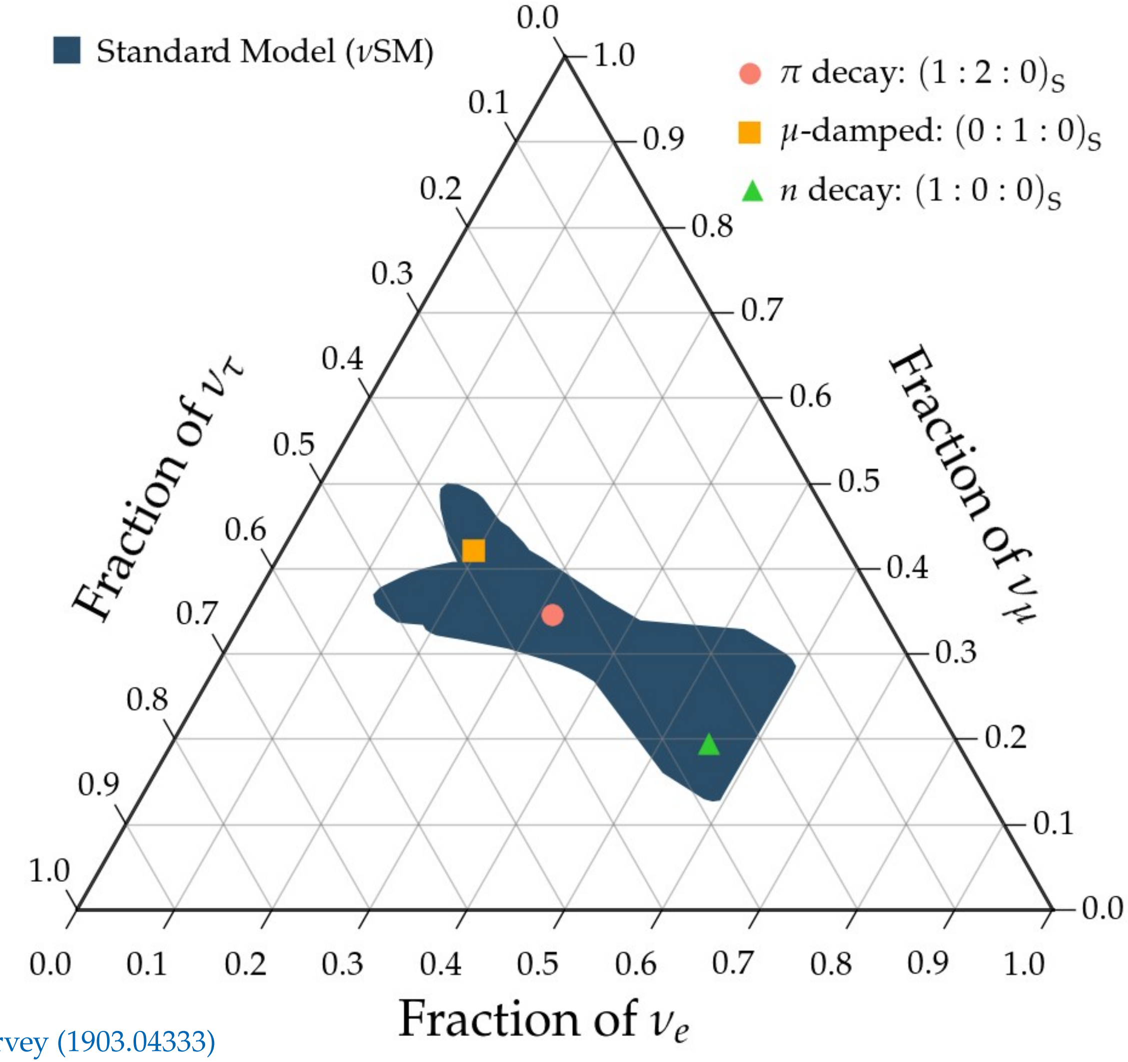
The TeV–PeV ν flavor composition

IceCube flavor composition

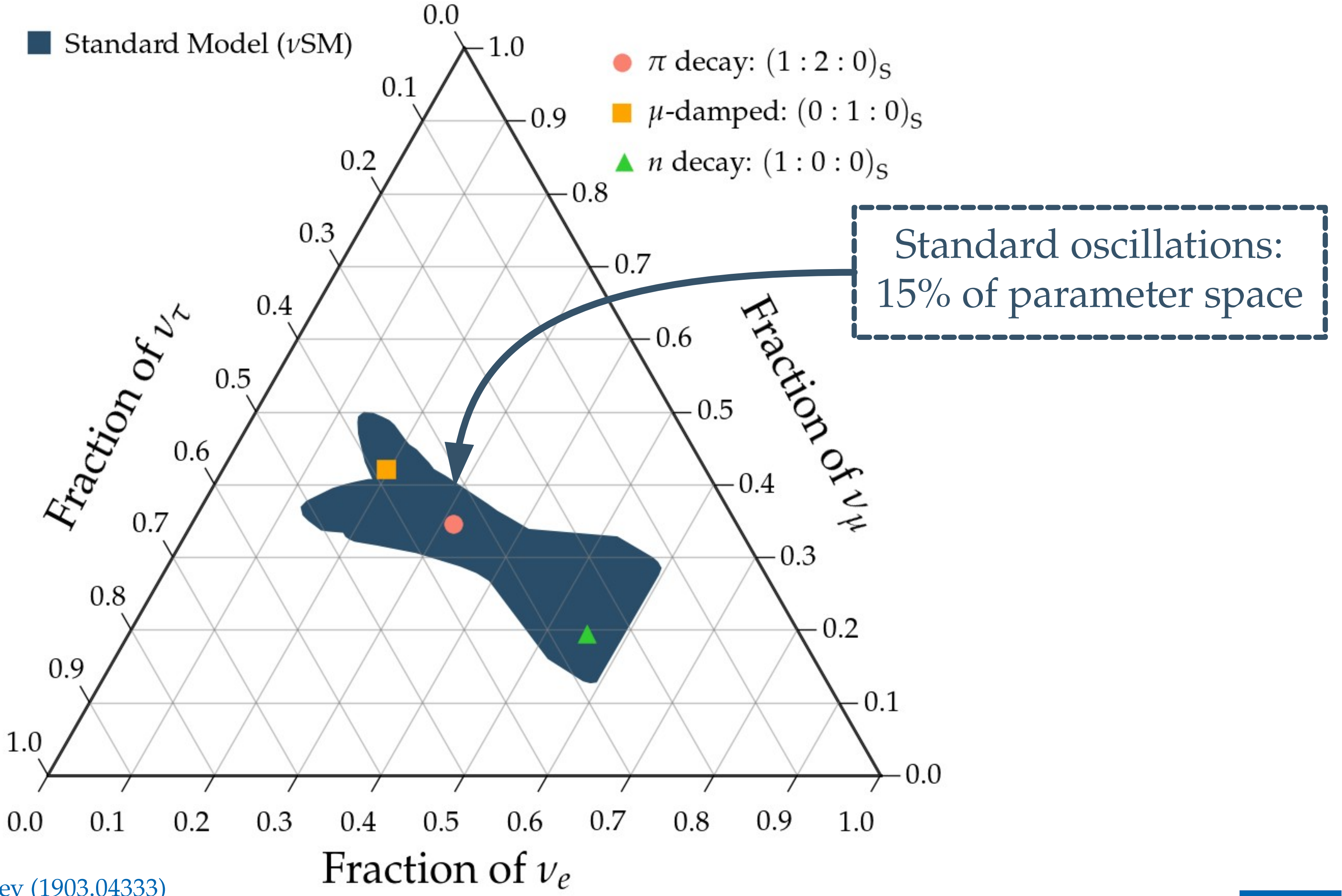


- Compare number of tracks (ν_μ) *vs.* showers (all flavors)
- Best fit: $(f_e : f_\mu : f_\tau)_\oplus = (0.5 : 0.5 : 0)_\oplus$
- Compatible with standard source compositions
- Lots of room for improvement: more statistics, better flavor-tagging

MB & Ahlers, *PRL* 2019
Adapted from: IceCube, *ApJ* 2015



Ackermann, **MB**, *et al.*, Astro2020 Survey (1903.04333)
Based on: **MB**, Beacom, Winter *PRL* 2015



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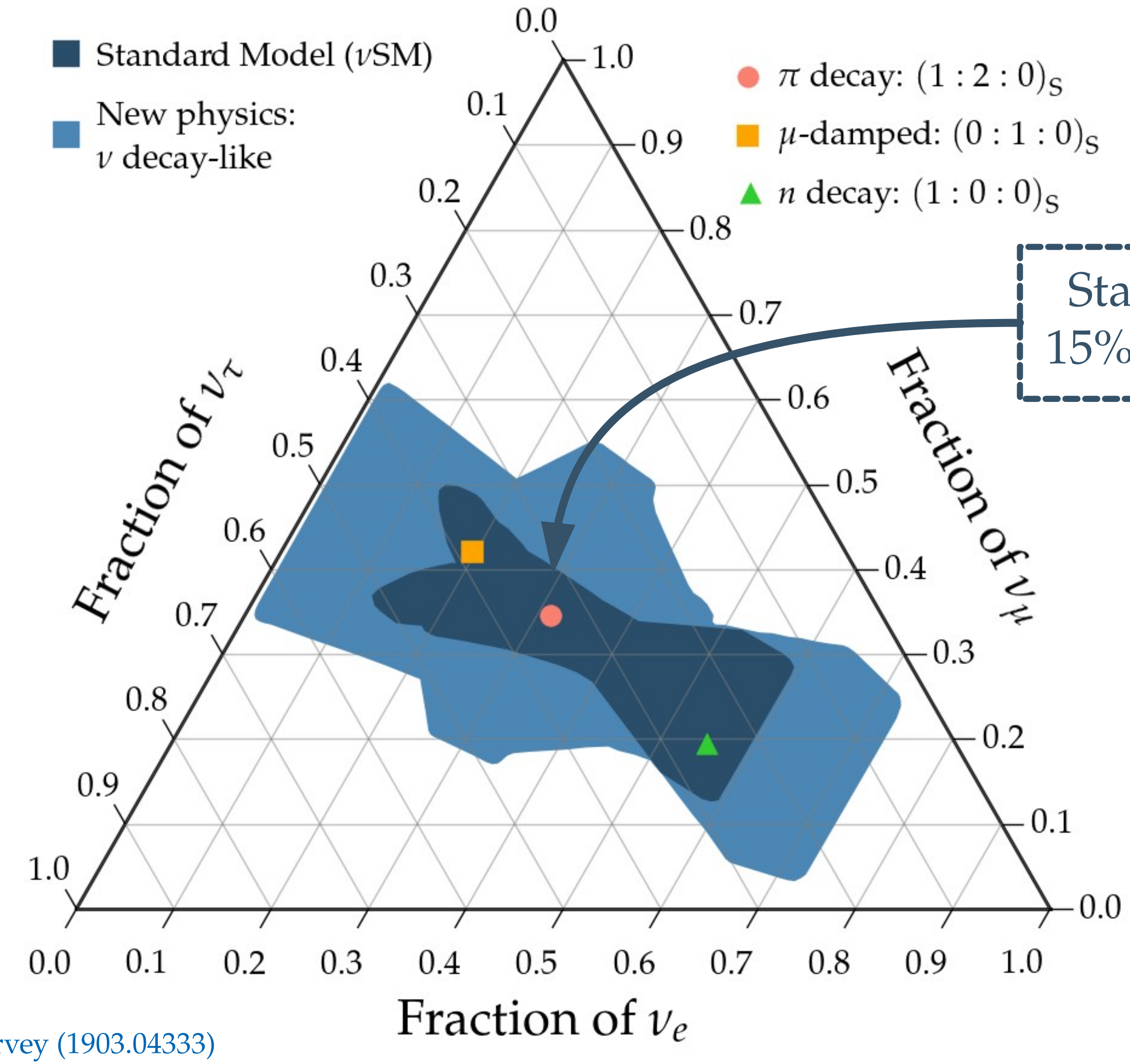

Standard oscillations:
15% of parameter space

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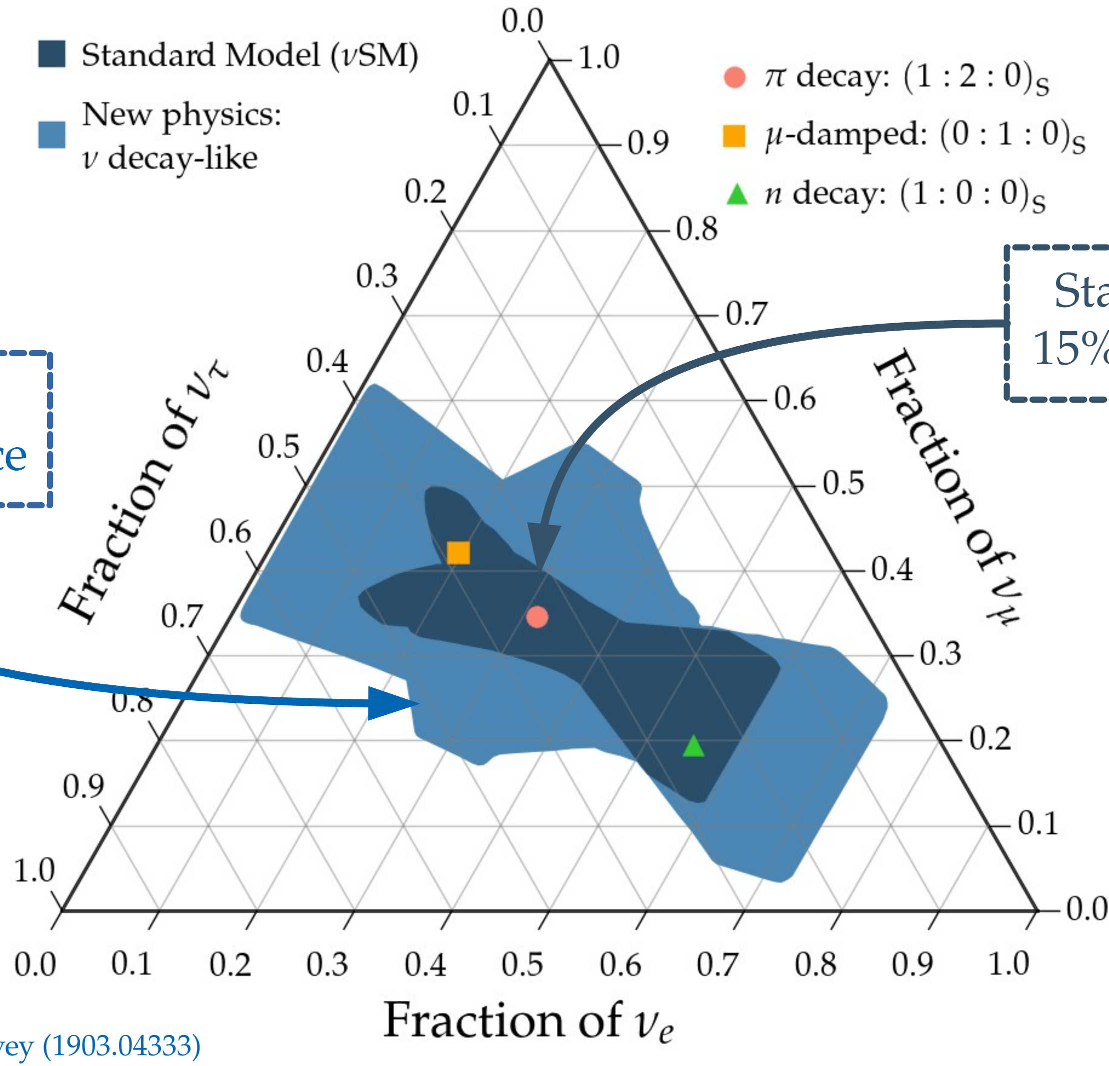

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Neutrino decay
30% of parameter space

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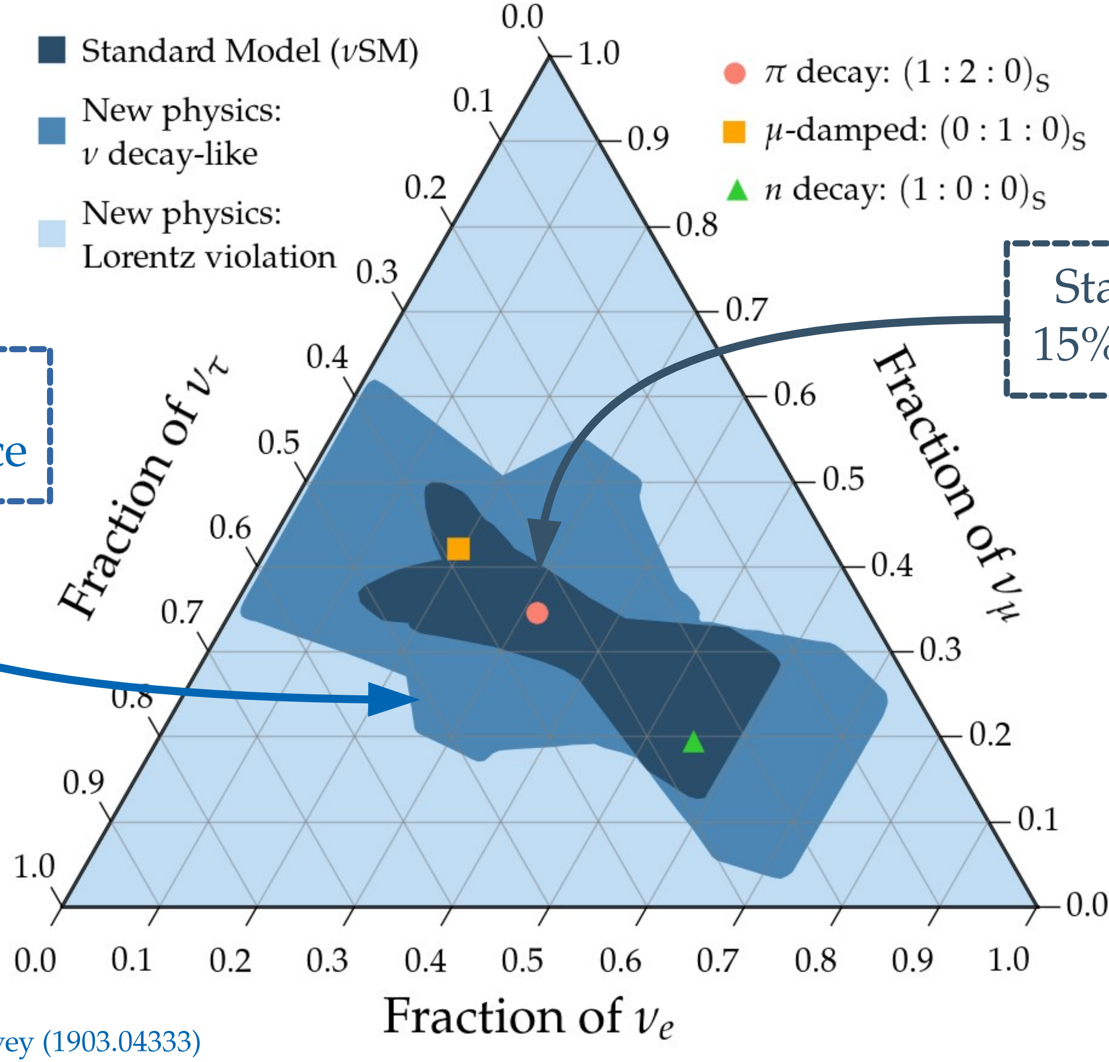

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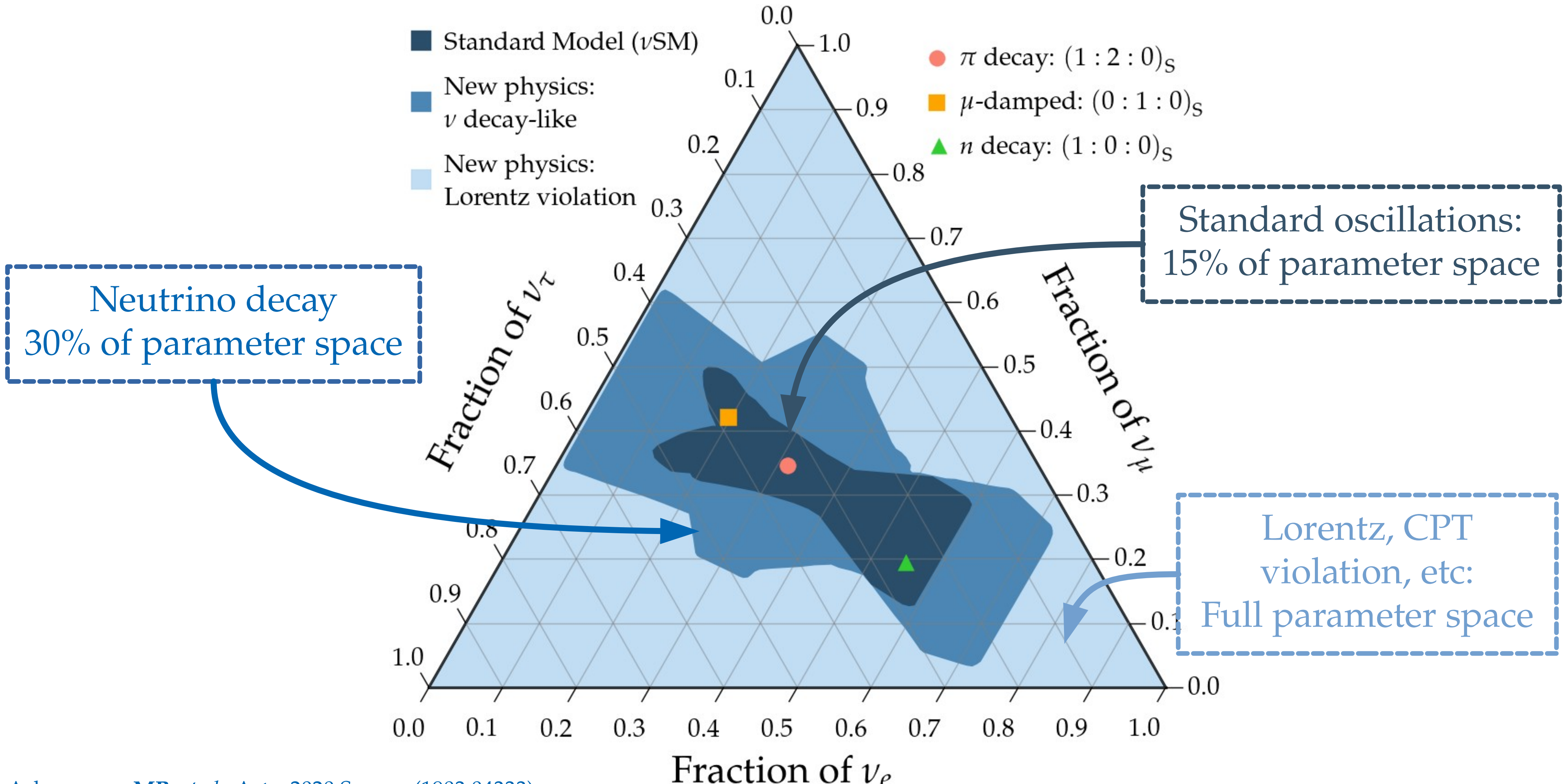

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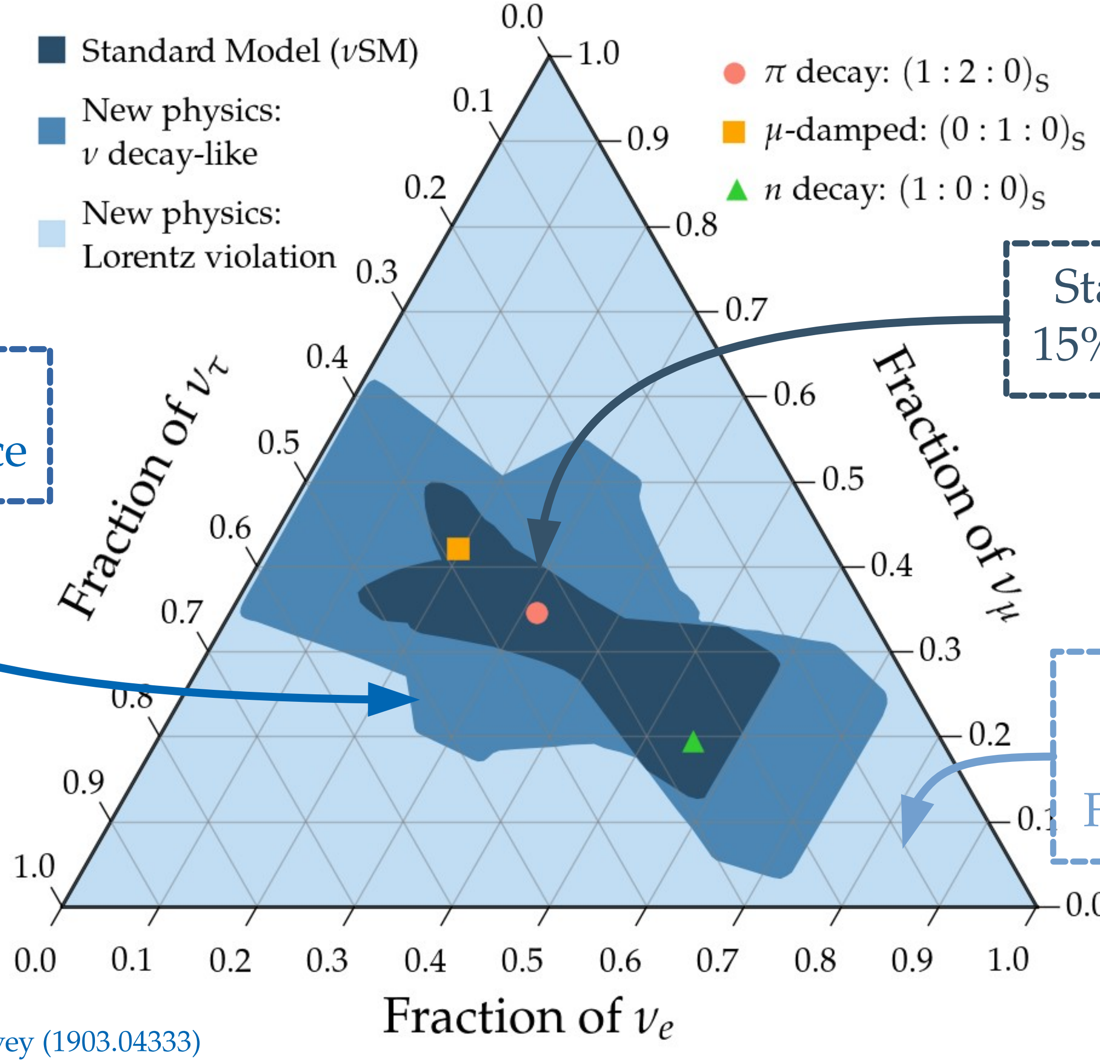
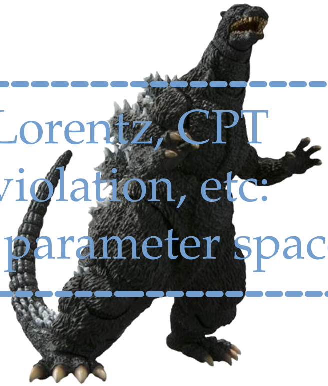




Lorentz, CPT
violation, etc:
Full parameter space

Ackermann, **MB**, *et al.*, Astro2020 Survey (1903.04333)
Based on: **MB**, Beacom, Winter *PRL* 2015

There be dragons

- High-energy effective field theories
  - Violation of Lorentz and CPT invariance
    [Barenboim & Quigg, *PRD* 2003; **MB**, Gago, Peña-Garay, *JHEP* 2010; Kostelecky & Mewes 2004]
  - Violation of equivalence principle
    [Gasperini, *PRD* 1989; Glashow *et al.*, *PRD* 1997]
  - Coupling to a gravitational torsion field
    [De Sabbata & Gasperini, *Nuovo Cim.* 1981]
  - Renormalization-group-running of mixing parameters
    [**MB**, Gago, Jones, *JHEP* 2011]
  - General non-unitary propagation
    [Ahlers, **MB**, Mu, *PRD* 2018]
- Active-sterile mixing
  [Aeikens *et al.*, *JCAP* 2015; Brdar, *JCAP* 2017]
- Flavor-violating physics
  - New neutrino-electron interactions
    [**MB** & Agarwalla, *PRL* 2019]
  - New νν interactions
    [**MB** *et al.*, *PRD* 2020; Ng & Beacom, *PRD* 2014; Cherry, Friedland, Shoemaker, 1411.1071; Blum, Hook, Murase, 1408.3799]
- …

Toho Company Ltd.

How to fill out the flavor triangle?

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

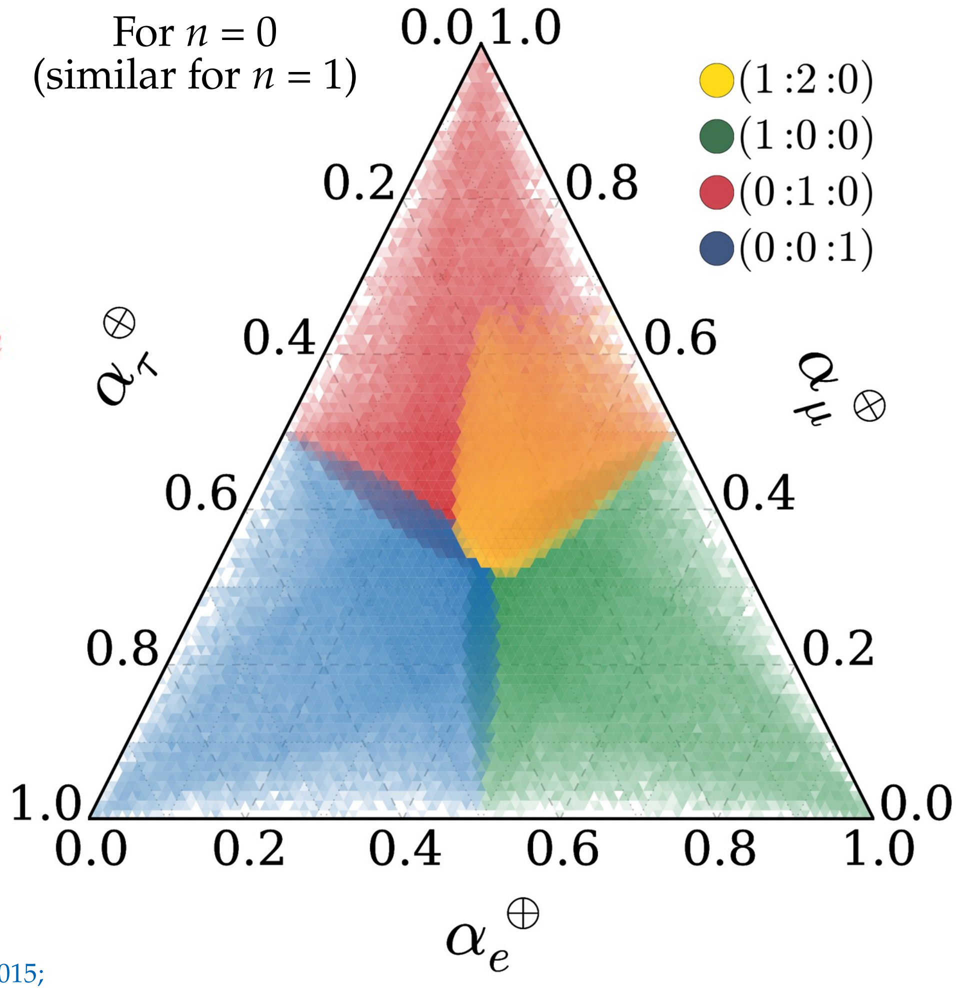
$$H_{\text{std}} = \frac{1}{2E} U^\dagger_{\text{PMNS}} \, \text{diag}\left(0, \Delta m^2_{21}, \Delta m^2_{31}\right) U_{\text{PMNS}}$$

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

This can populate *all* of the triangle –

- Use current atmospheric bounds on $O_{n,i}$:
  $O_0 < 10^{-23}$ GeV, $O_1/\Lambda_1 < 10^{-27}$ GeV
- Sample the unknown new mixing angles

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



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

Argüelles, Katori, Salvadó, *PRL* 2015

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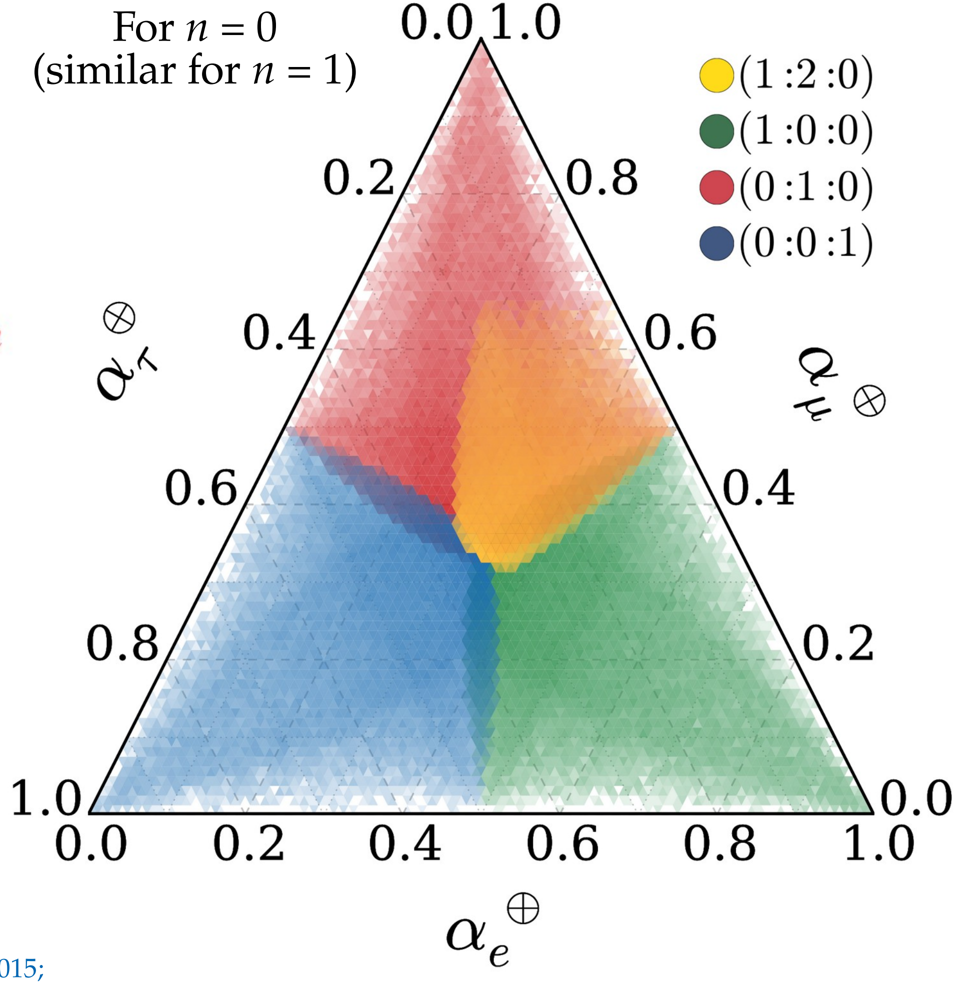


Argüelles, Katori, Salvadó, *PRL* 2015

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

Neutrino decay

Are neutrinos forever?

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

  » Age of Universe (~ 14.5 Gyr)

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

- φ: Nambu-Goldstone boson of a broken symmetry (*e.g.*, Majoron)

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

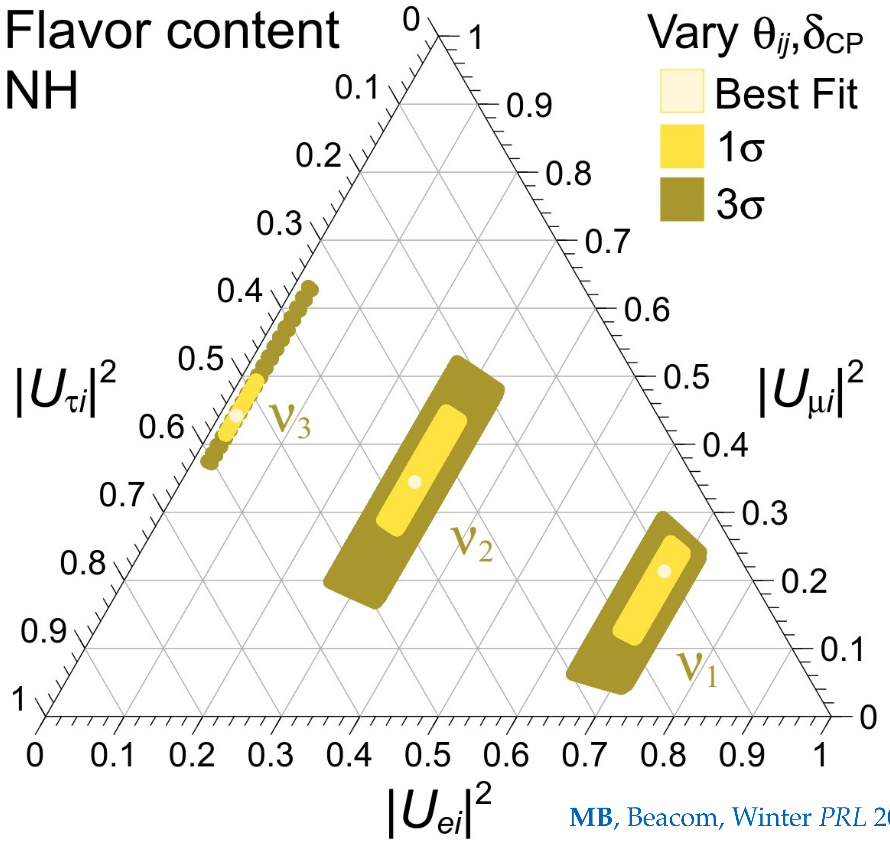
Flavor content of neutrino mass eigenstates

Known to within 2%

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

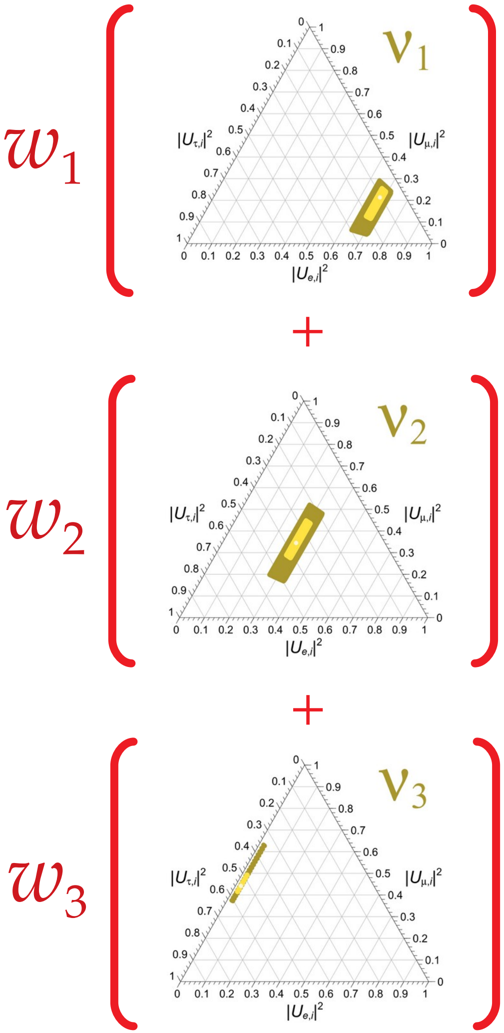
Known to within 8%

Known to within 20%
(or worse)

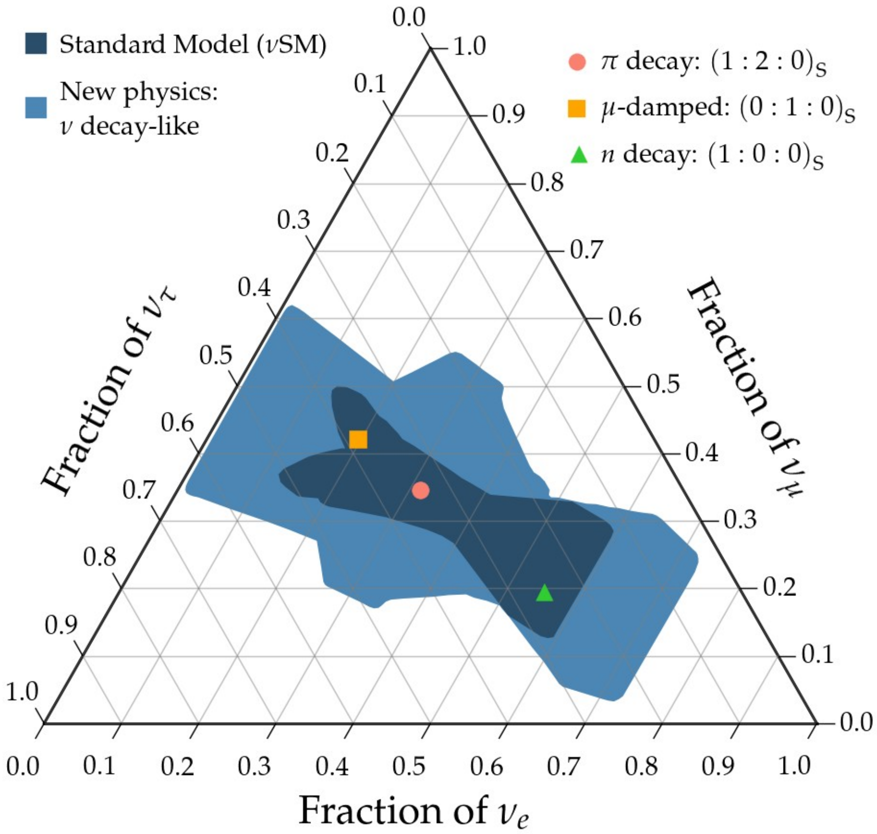


MB, Beacom, Winter *PRL* 2015

Neutrinos propagate as an incoherent mix of ν_1, ν_2, ν_3 —



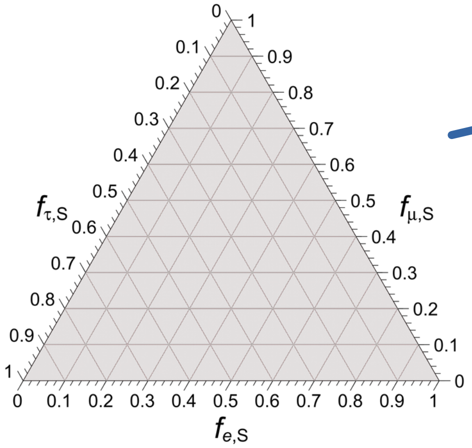
Varying all possible combinations of weights w_i and mixing parameters



Complete decay selects particular weights with striking consequences for flavor ▸

Measuring the neutrino lifetime

Sources



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

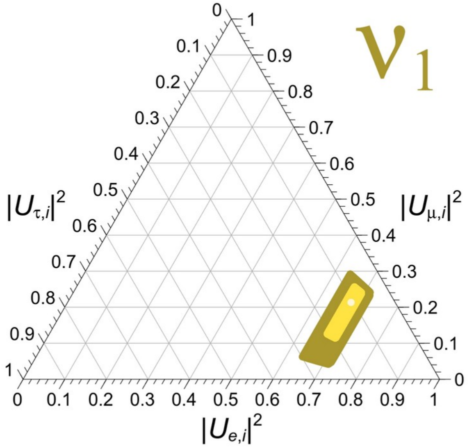
ν_1 lightest and stable
(normal mass ordering)

If all unstable
neutrinos decay

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

ν_3 lightest and stable
(inverted mass ordering)

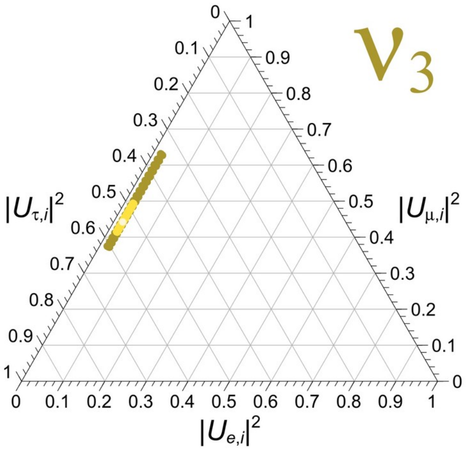
Earth



ν_1

$$f_{\alpha,\oplus} = |U_{\alpha 1}|^2$$

$(w_1 \sim 1; w_2, w_3 \sim 0)$



ν_3

$$f_{\alpha,\oplus} = |U_{\alpha 3}|^2$$

$(w_3 \sim 1; w_1, w_2 \sim 0)$

Measuring the neutrino lifetime

Earth

Sources

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

ν_1 lightest and stable
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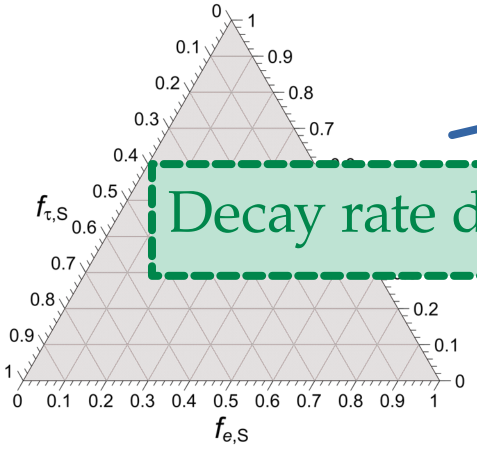
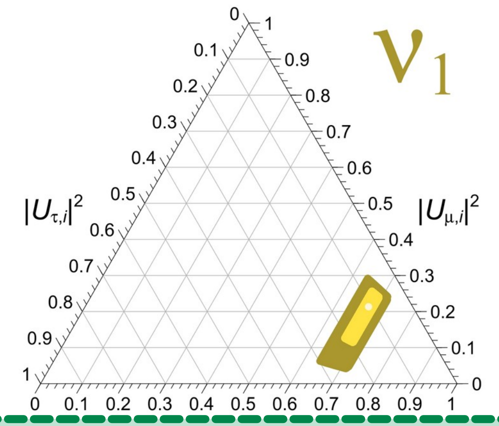
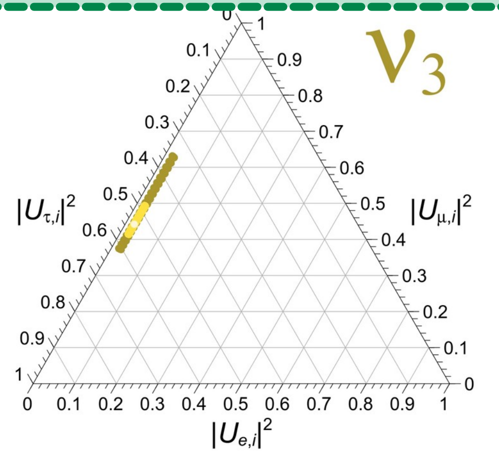




$f_{\alpha,\oplus} = |U_{\alpha 1}|^2$
$(w_1 \sim 1; w_2, w_3 \sim 0)$

Decay rate depends on $\exp[-\, t\,/\,(\gamma\, \tau_i)] = \exp[-\,(L/E) \cdot (m_i/\tau_i)]$



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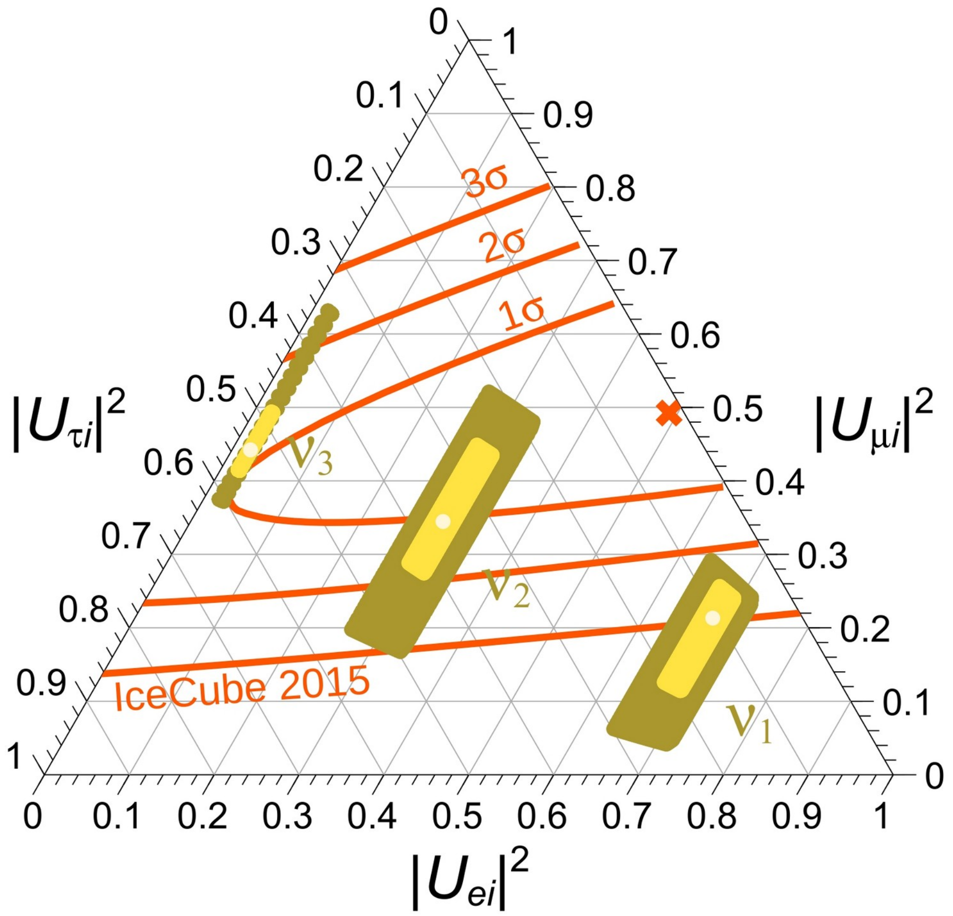
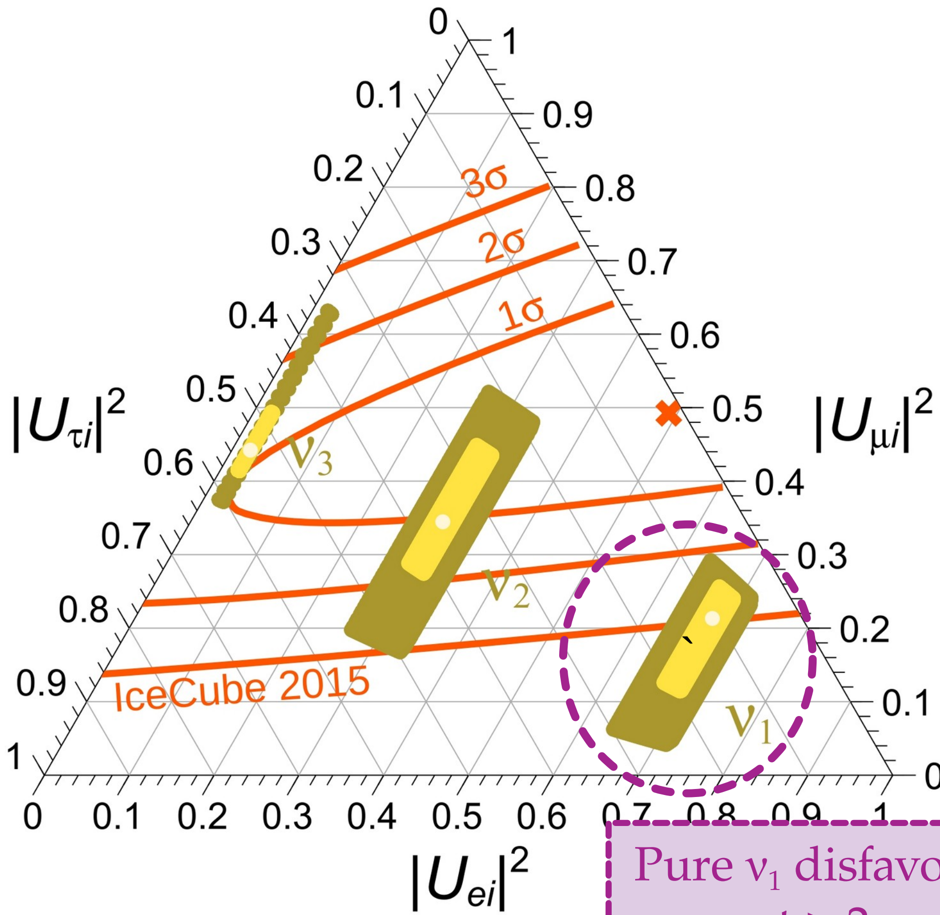


MB, Beacom, Murase, *PRD* 2017

Baerwald, **MB**, Winter, *JCAP* 2012

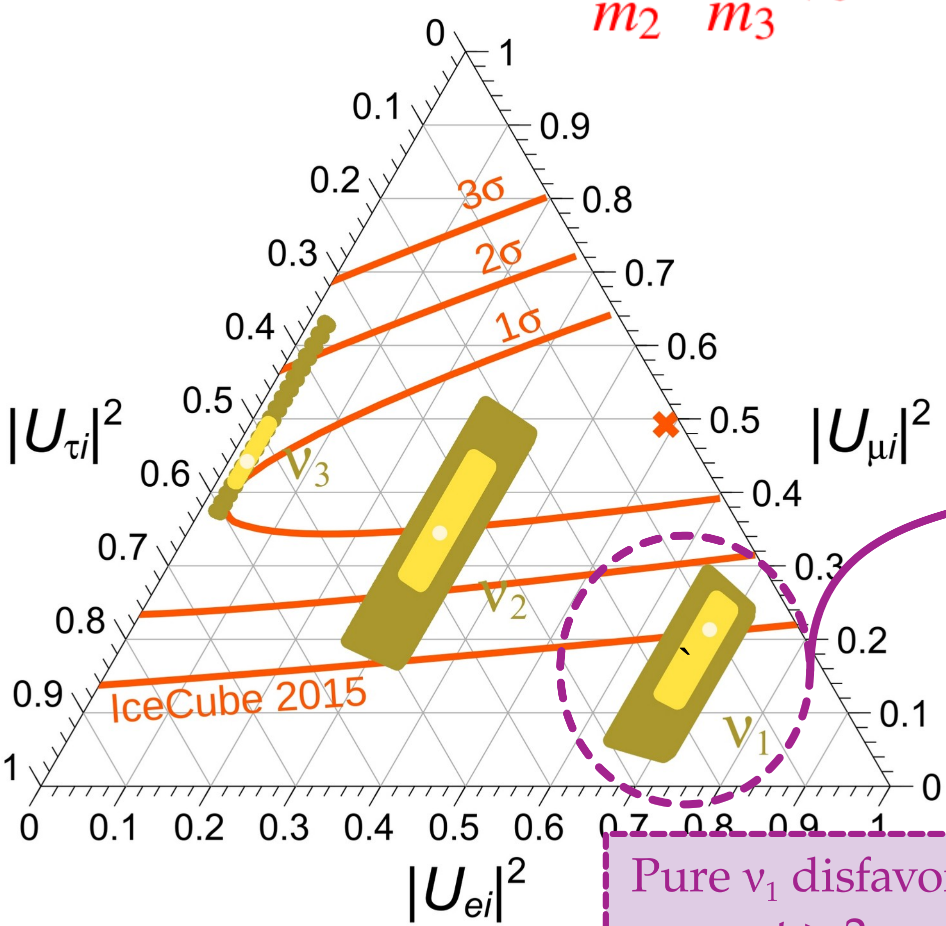


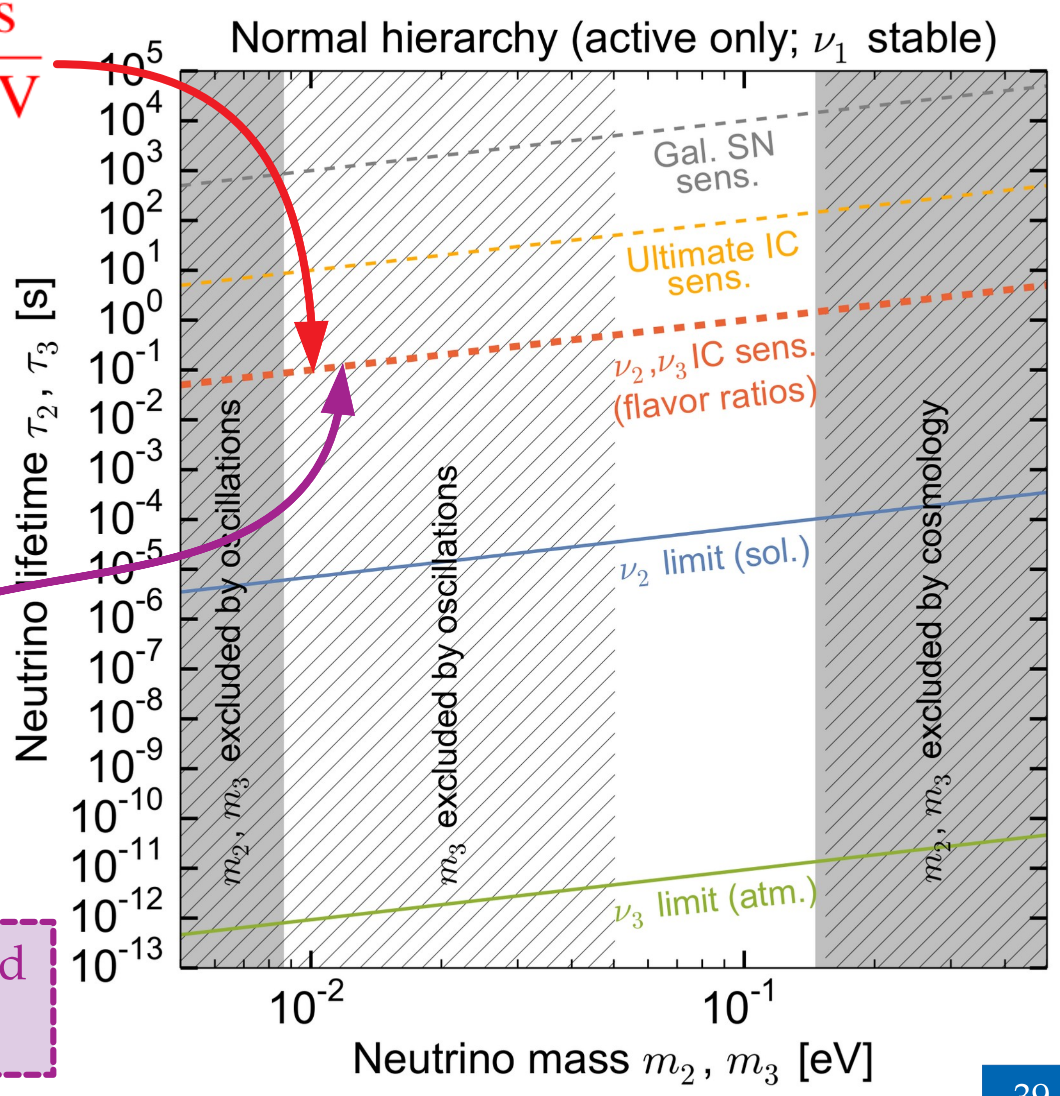
Pure ν_1 disfavored at > 2σ

MB, Beacom, Murase, *PRD* 2017

Baerwald, **MB**, Winter, *JCAP* 2012

$$\frac{\tau_2}{m_2}, \frac{\tau_3}{m_3} \gtrsim 10 \frac{\text{s}}{\text{eV}}$$





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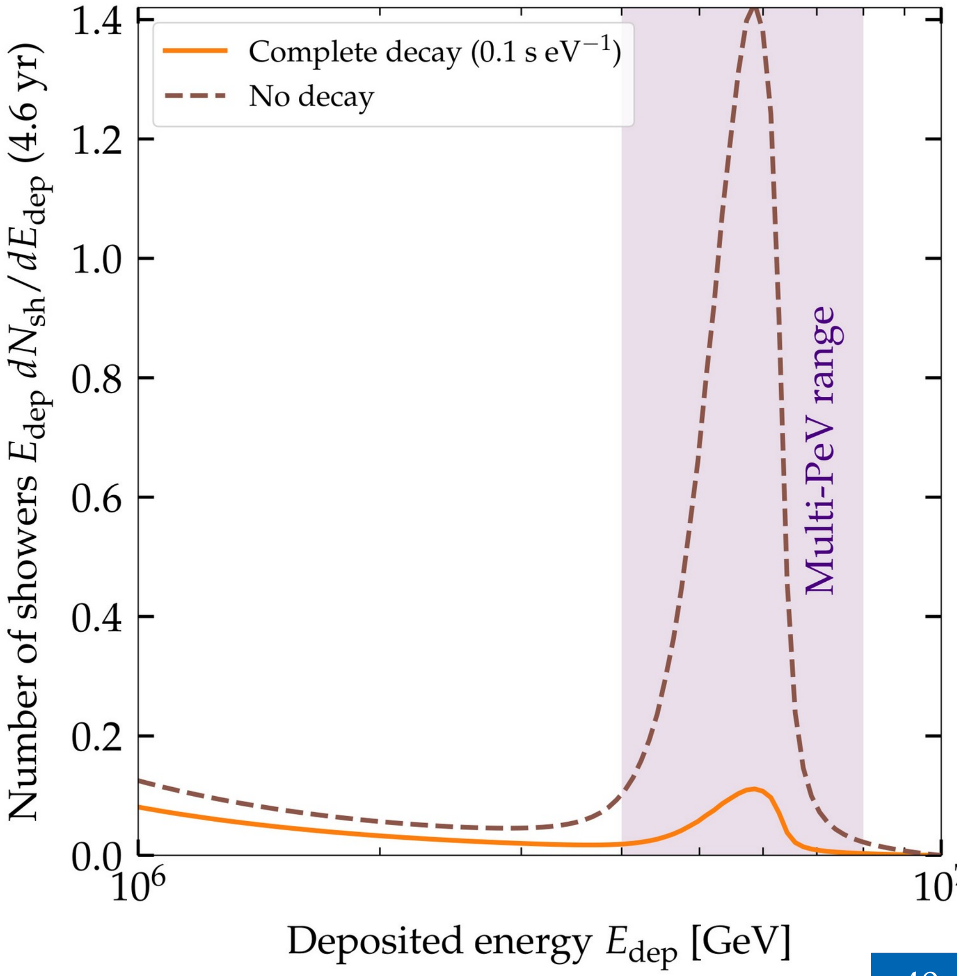
Using the Glashow resonance to test decay

- At 6.3 PeV, the Glashow resonance ($\bar{\nu}_e + e \to W$) should trigger showers in IceCube
- … unless ν_1, ν_2 decay to ν_3 en route to Earth (the surviving ν_3 have little electron content)
- IceCube has seen 1 shower in the 4–8 PeV range, so ν_1, ν_2 *must* make it to Earth
- So we set *lower* limits on their lifetimes (in the inverted mass ordering)
- Translated into *upper* limits on coupling



MB, 2004.06844
See also: **MB**, Beacom, Murase, *PRD* 2017

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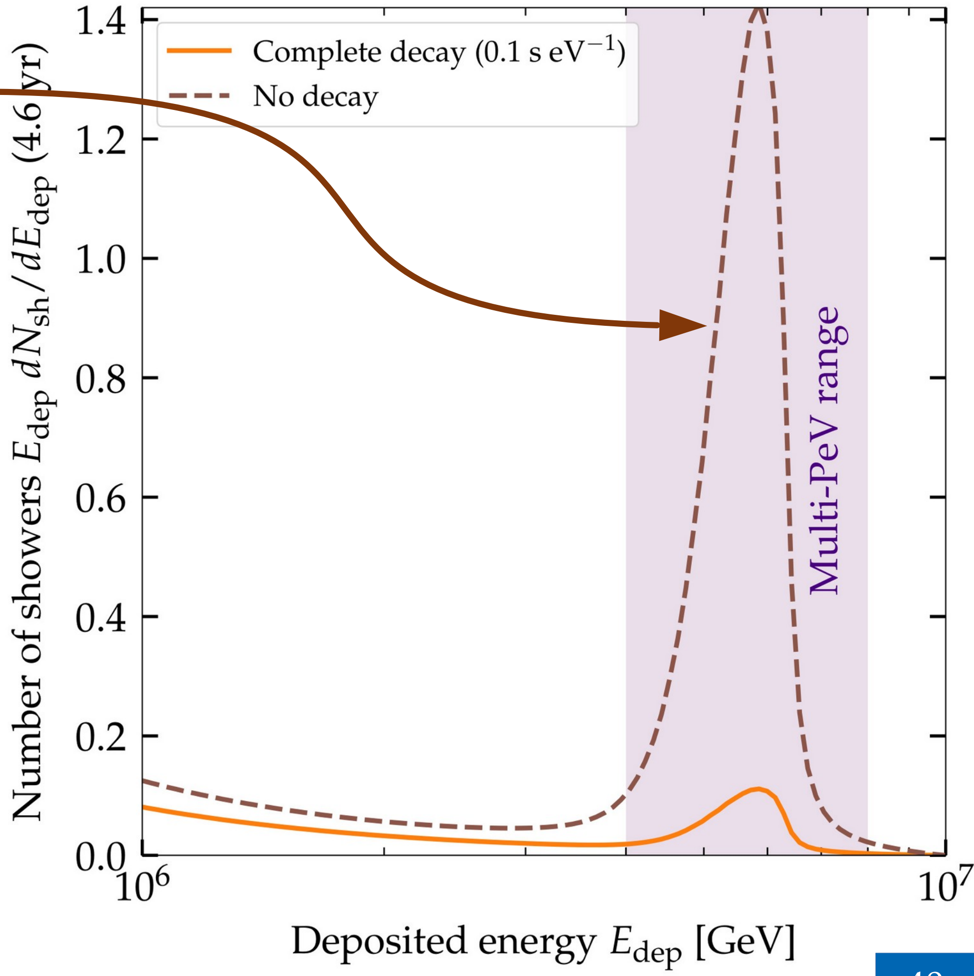

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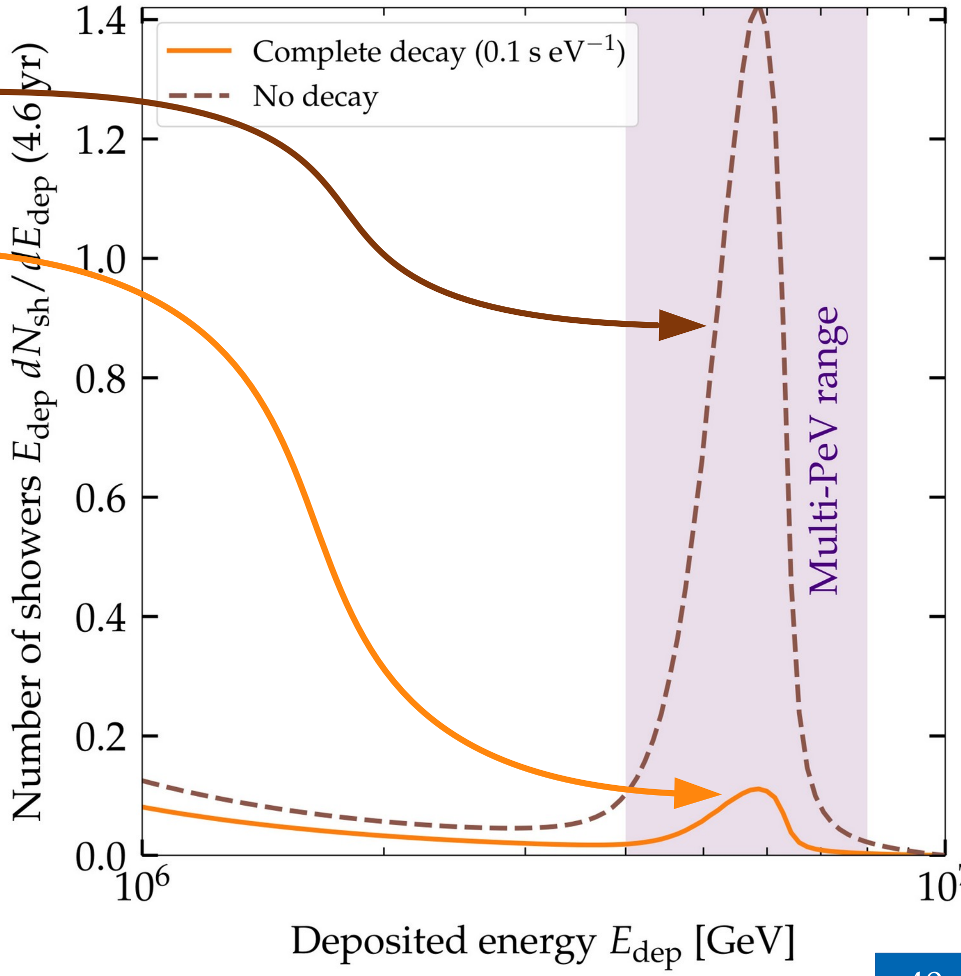

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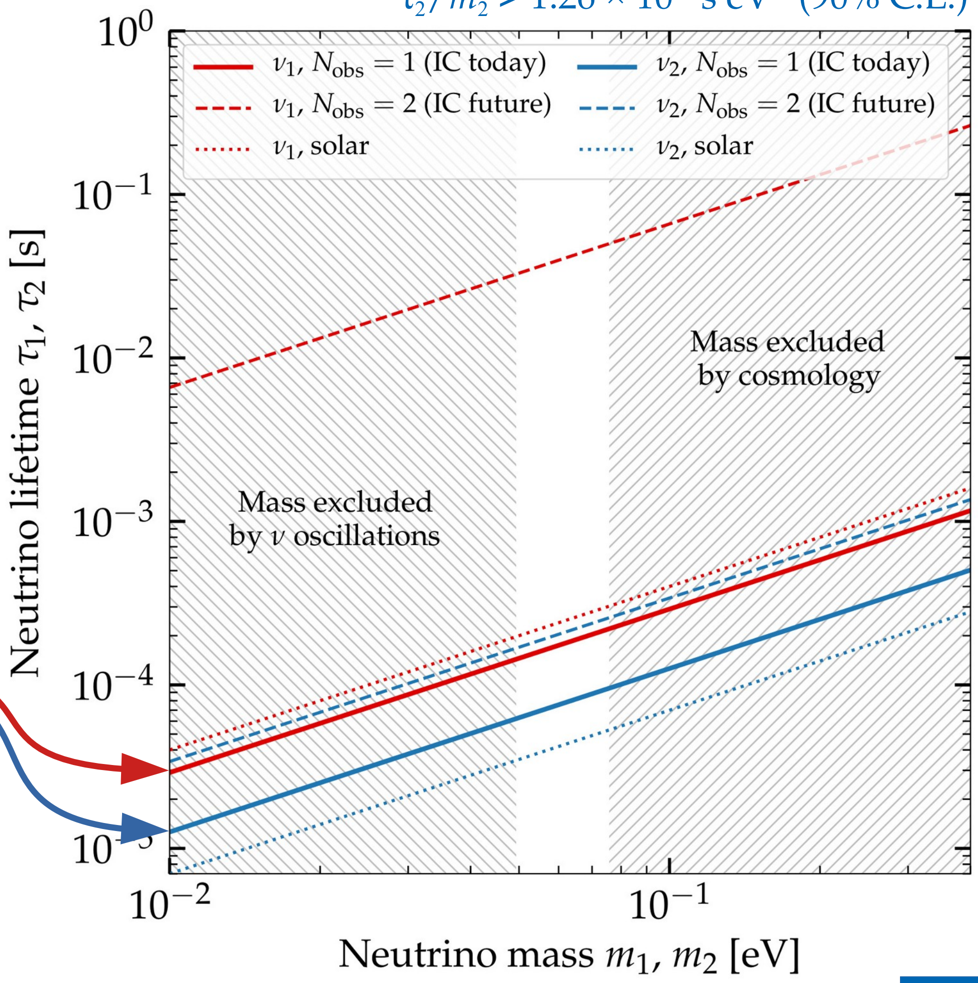
$\tau_1/m_1 > 2.91 \times 10^{-3}$ s eV^{-1} (90% C.L.)

$\tau_2/m_2 > 1.26 \times 10^{-3}$ s eV^{-1} (90% C.L.)



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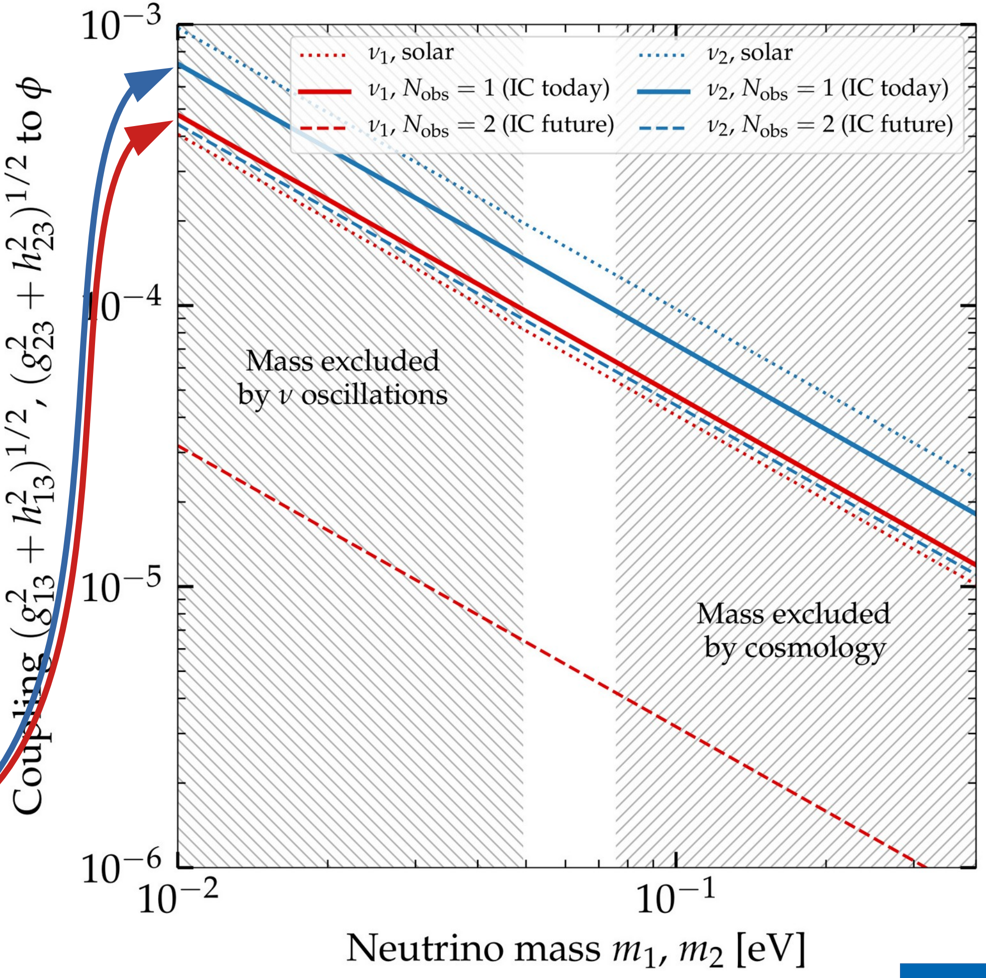
$$\mathcal{L} = g_{ij}\bar{\nu}_i\nu_j\phi + h_{ij}\bar{\nu}_i\gamma_5\nu_j\phi + \text{h.c.}$$

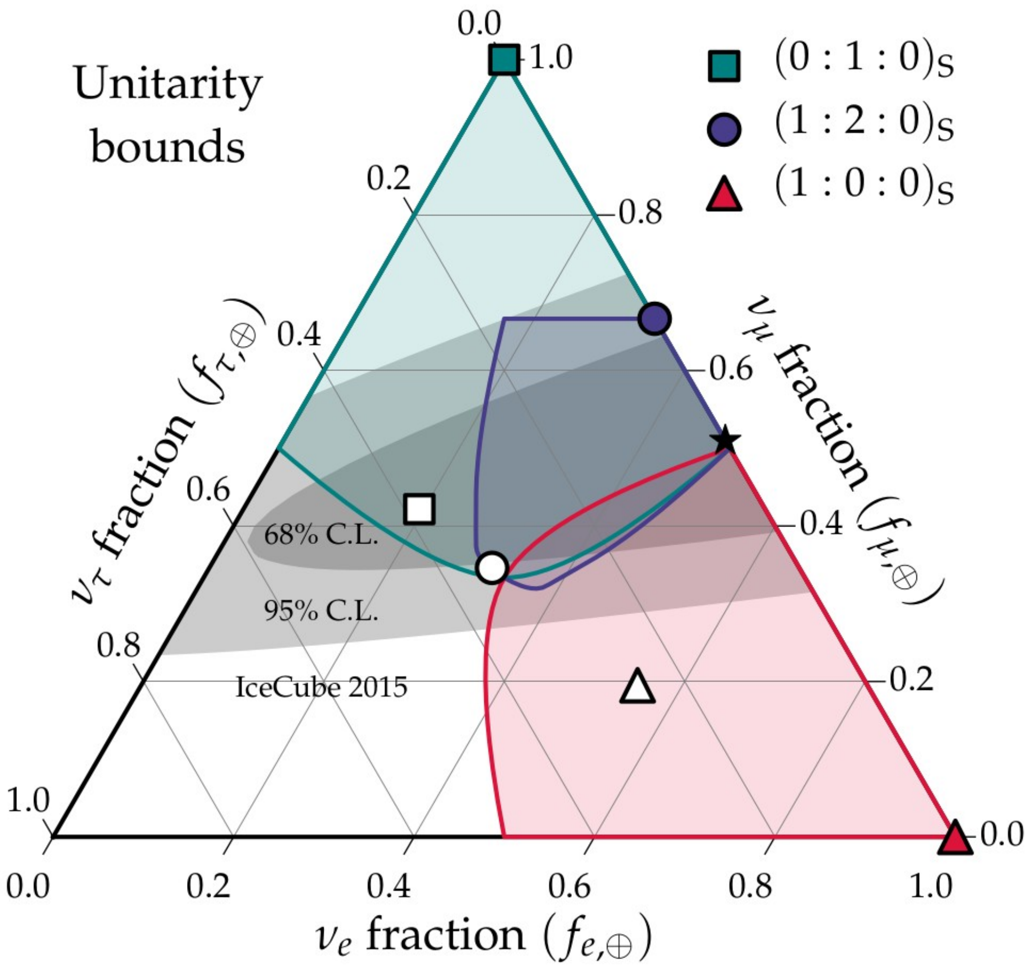


MB, 2004.06844
See also: **MB**, Beacom, Murase, *PRD* 2017

Using unitarity to constrain new physics

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

- New mixing angles unconstrained
- Use unitarity ($U_{NP}U_{NP}^{\dagger} = 1$) to bound all possible flavor ratios at Earth
- Can be used as prior in new-physics searches in IceCube



Ahlers, **MB**, Mu, *PRD* 2018
See also: Xu, He, Rodejohann, *JCAP* 2014

Ultra-long-range flavorful interactions

- Simple extension of the SM: Promote the global lepton-number symmetries L_e-L_μ, L_e-L_τ to local symmetries

- They introduce new interaction between electrons and ν_e and ν_μ or ν_τ mediated by a new neutral vector boson (Z'):
  - Affects oscillations
  - If the Z' is *very* light, *many* electrons can contribute

X.-G. He, G.C. Joshi, H. Lew, R. R. Volkas, *PRD* 1991 / R. Foot, X.-G. He, H. Lew, R. R. Volkas, *PRD* 1994
A. Joshipura, S. Mohanty, *PLB* 2004 / J. Grifols & E. Massó, PLB 2004 / A. Bandyopadhyay, A. Dighe, A. Joshipura, *PRD* 2007
M.C. González-García, P..C. de Holanda, E. Massó, R. Zukanovich Funchal, *JCAP* 2007 / A. Samanta, *JCAP* 2011
S.-S. Chatterjee, A. Dasgupta, S. Agarwalla, *JHEP* 2015

The new potential sourced by an electron

Under the L_e-L_μ or L_e-L_τ symmetry, an electron sources a Yukawa potential —

$$V \sim \frac{{g'}_{e\beta}^{2}}{r} e^{-m'_{e\beta} r}$$

A neutrino "feels" all the electrons within the interaction range $\sim(1/m')$

The new potential sourced by an electron

Under the L_e-L_μ or L_e-L_τ symmetry, an electron sources a Yukawa potential —

Z' coupling

Z' mass

$$V \sim \frac{g'^{2}_{e\beta}}{r} e^{-m'_{e\beta} r}$$

Distance to neutrino

A neutrino "feels" all the electrons within the interaction range ~$(1/m')$

Electron-neutrino interactions can kill oscillations

Electron-neutrino interactions can kill oscillations

$$\mathrm{H_{tot}} = \underbrace{\mathrm{H_{vac}}}$$

Standard oscillations:
Neutrinos change flavor
because this is non-diagonal

Electron-neutrino interactions can kill oscillations

$$\mathrm{H}_{\mathrm{tot}} = \underbrace{\mathrm{H}_{\mathrm{vac}}}$$

Standard oscillations:
Neutrinos change flavor
because this is non-diagonal

↓

$$P_{\nu_\alpha \to \nu_\beta}\left(\theta_{ij}, \delta_{\mathrm{CP}}\right)$$

Electron-neutrino interactions can kill oscillations

$$= \mathrm{diag}(V_{e\mu}, -V_{e\mu}, 0)$$

$$\mathrm{H}_{\mathrm{tot}} = \mathrm{H}_{\mathrm{vac}} + \underbrace{\mathrm{V}_{e\beta}}$$

New neutrino-electron interaction:
This is diagonal

Electron-neutrino interactions can kill oscillations

$$= \mathrm{diag}(V_{e\mu}, -V_{e\mu}, 0)$$

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New neutrino-electron interaction:
This is diagonal

Z' parameters

$$P_{\nu_\alpha \to \nu_\beta}\left(\theta_{ij}, \delta_{\mathrm{CP}}, \Delta m^2_{ij}, E_\nu, g'_{e\mu}, m'_{e\mu}\right)$$

Electron-neutrino interactions can kill oscillations

$$\mathrm{H_{tot} = H_{vac} + V}_{e\beta} \quad = \mathrm{diag}(V_{e\mu}, -V_{e\mu}, 0)$$

New neutrino-electron interaction:
This is diagonal

Z′ parameters

$$P_{\nu_\alpha \to \nu_\beta}\left(\theta_{ij}, \delta_{\mathrm{CP}}, \Delta m^2_{ij}, E_\nu, g'_{e\mu}, m'_{e\mu}\right)$$

If $V_{e\beta}$ dominates ($g' \gg 1$, $m' \ll 1$), oscillations turn off

Electron-neutrino interactions can kill oscillations

$$\mathrm{H}_{\mathrm{tot}} = \mathrm{H}_{\mathrm{vac}} + \mathrm{V}_{e\beta}$$

Electron-neutrino interactions can kill oscillations

$$\mathrm{H}_{\mathrm{tot}} = \mathrm{H}_{\mathrm{vac}} + \mathrm{V}_{e\beta}$$

$\sim 1/E$

Energy-independent

Electron-neutrino interactions can kill oscillations

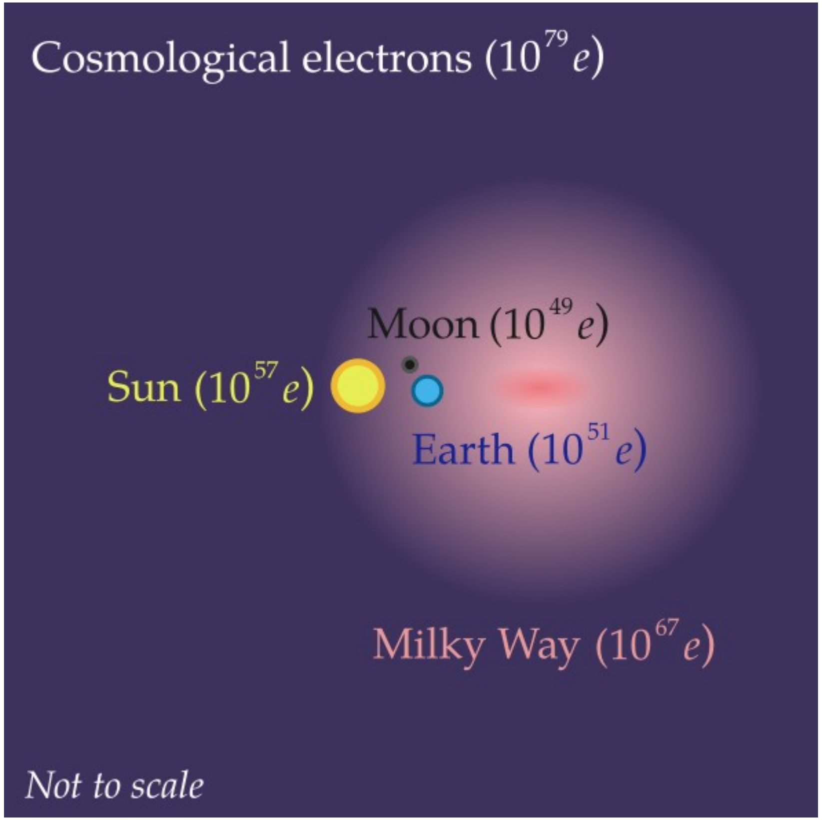
$$\mathrm{H}_{\mathrm{tot}} = \mathrm{H}_{\mathrm{vac}} + \mathrm{V}_{e\beta}$$

$\sim 1/E$

Energy-independent

∴ We can use high-energy astrophysical neutrinos

The total potential



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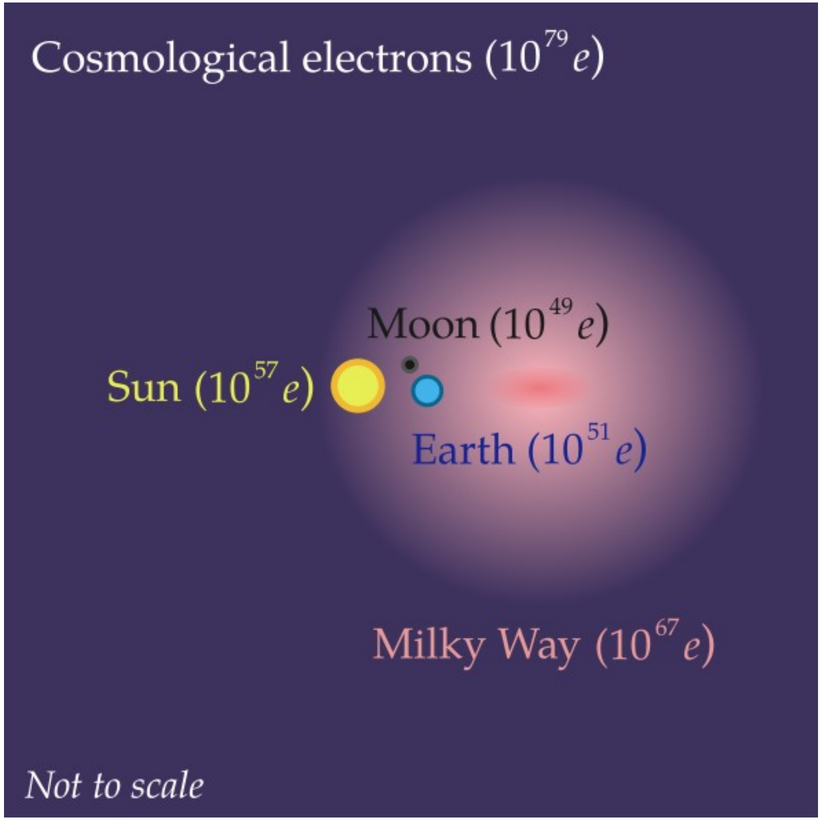
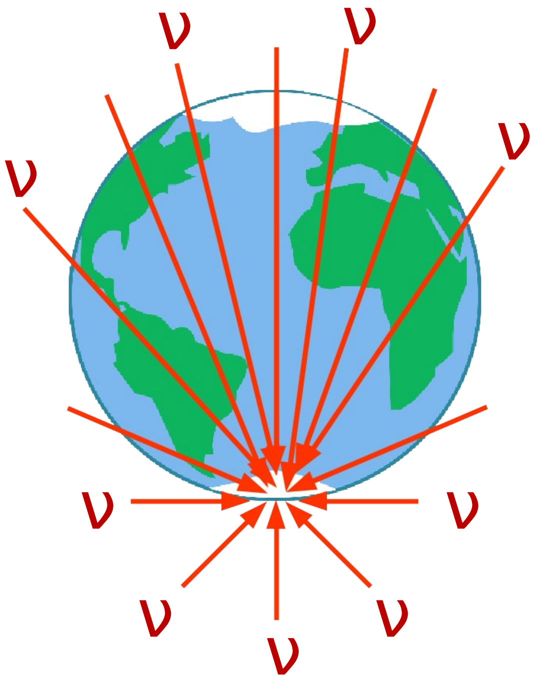


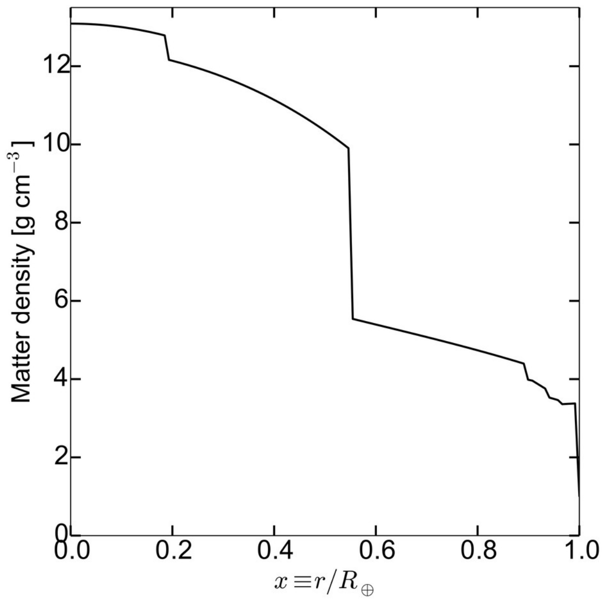
$$V_{e\beta} = V_{e\beta}^{\oplus}$$

Earth:



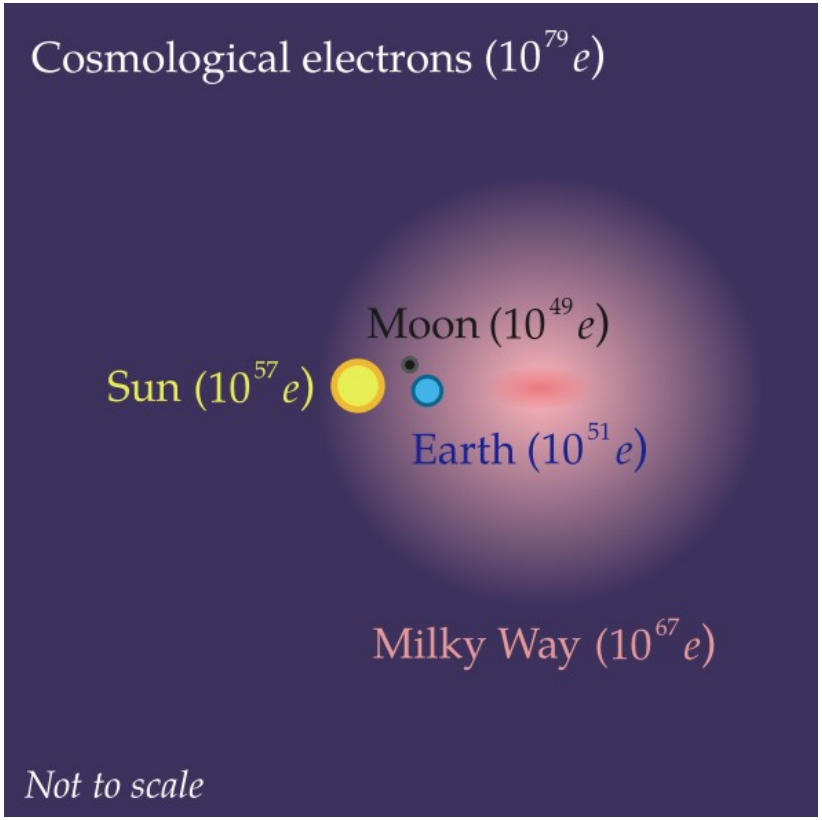
Preliminary Reference Earth Model

Dziewonski & Anderson 1981

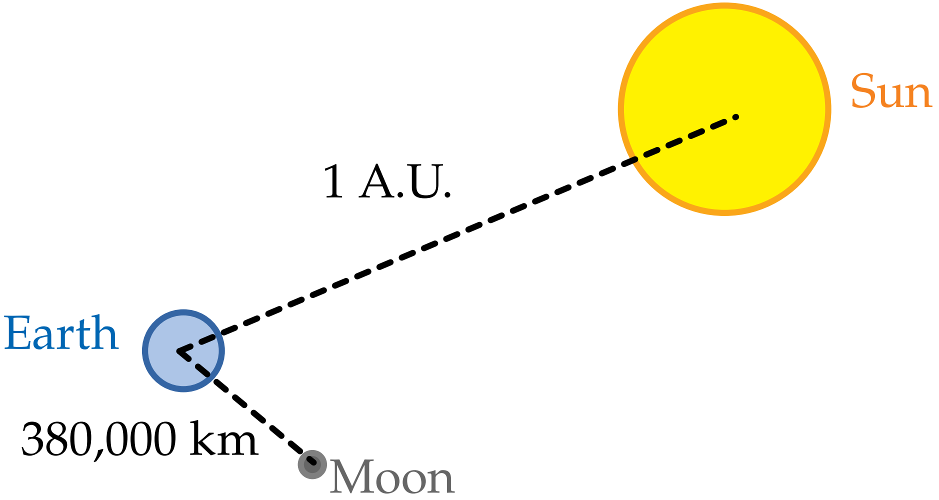


Neutrinos traverse different electron column depths

The total potential



Moon and Sun:



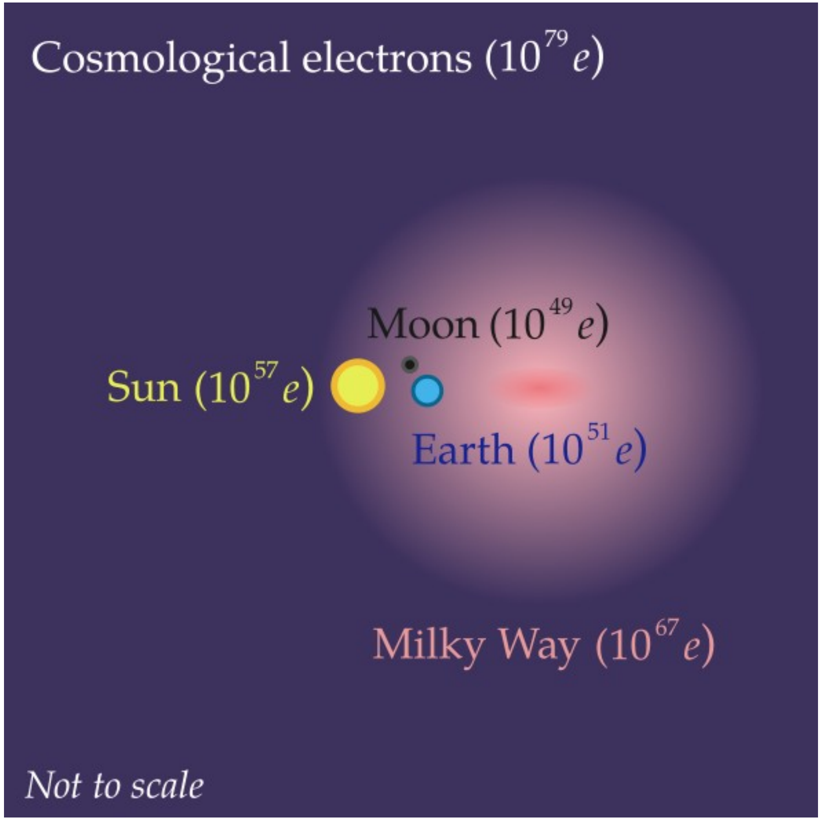
Treated as point sources of electrons

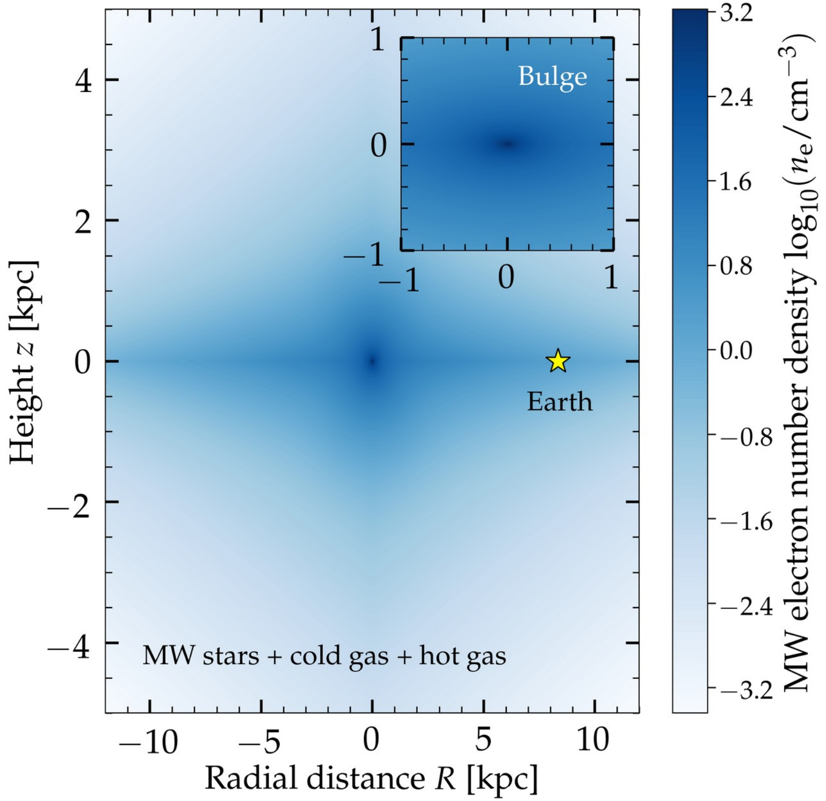
$$V_{e\beta} = V_{e\beta}^{\oplus} + V_{e\beta}^{\text{Moon}} + V_{e\beta}^{\odot}$$

The total potential

Milky Way:

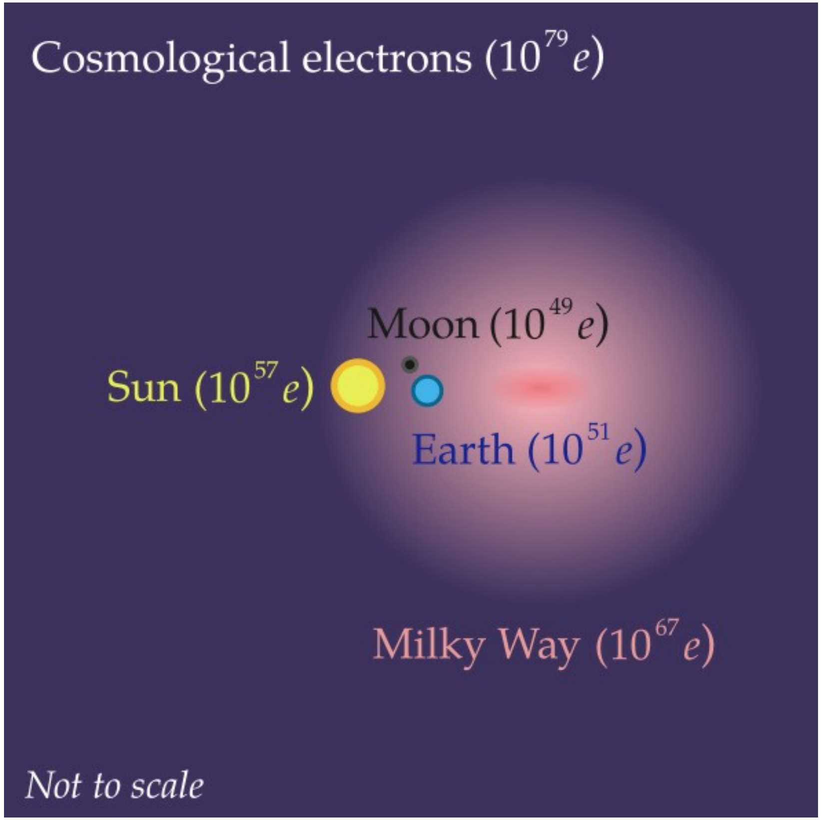
P. McMillan 2011
M.J. Miller & J.N. Bregman 2013





$$V_{e\beta} = V_{e\beta}^{\oplus} + V_{e\beta}^{\mathrm{Moon}} + V_{e\beta}^{\odot} + V_{e\beta}^{\mathrm{MW}}$$

The total potential



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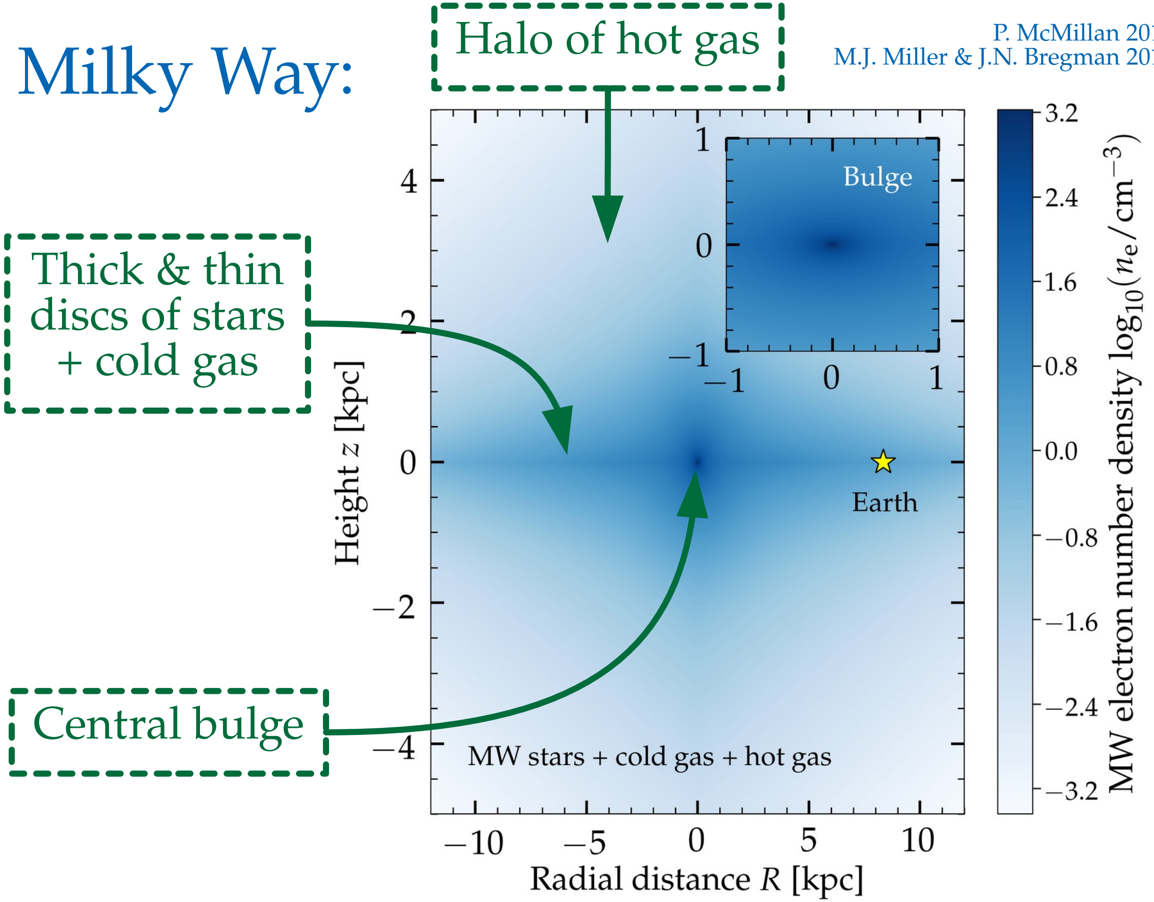

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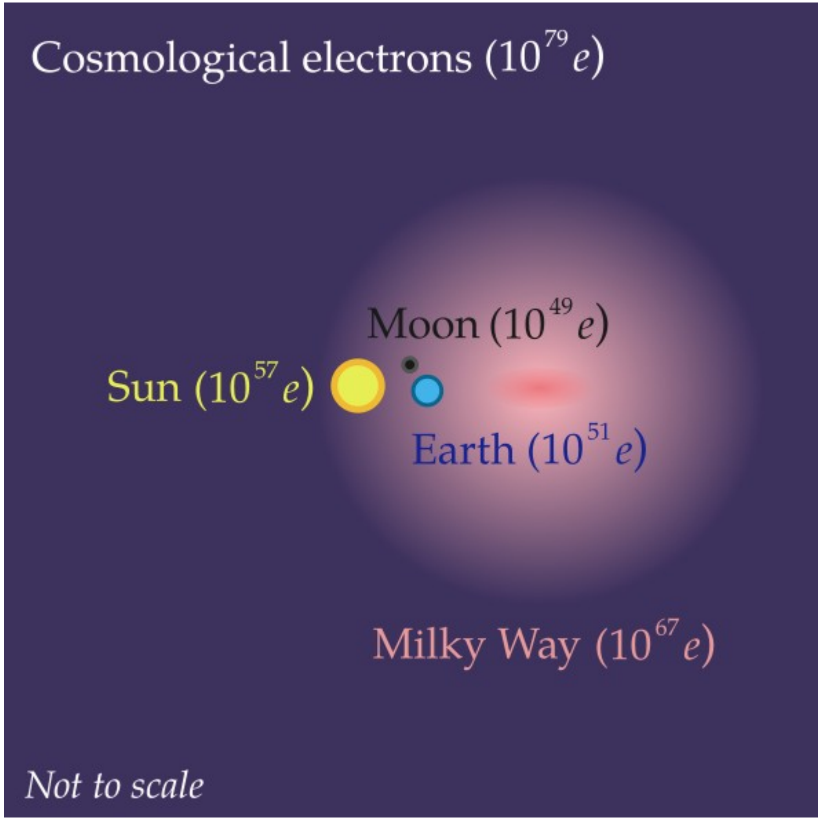
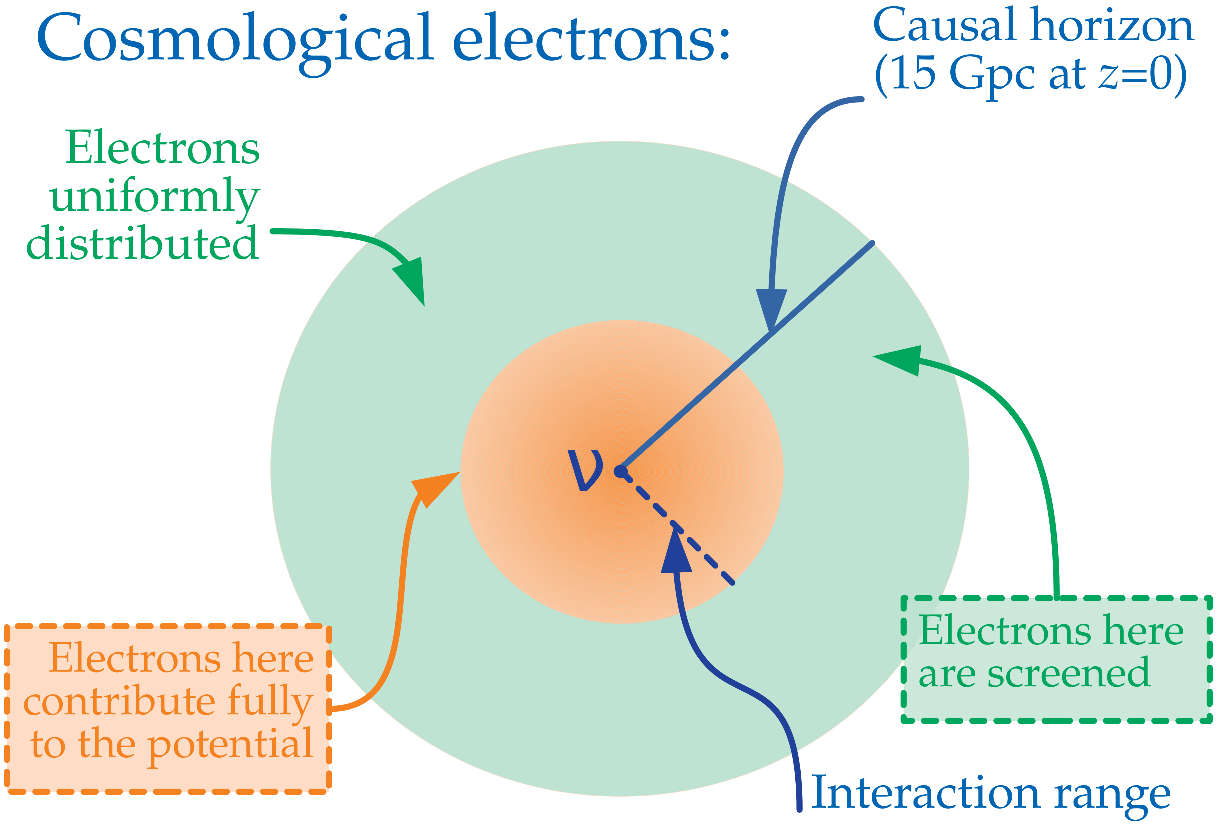


Cosmological electrons:



$$V_{e\beta} = V_{e\beta}^{\oplus} + V_{e\beta}^{\mathrm{Moon}} + V_{e\beta}^{\odot} + V_{e\beta}^{\mathrm{MW}} + V_{e\beta}^{\cos}$$

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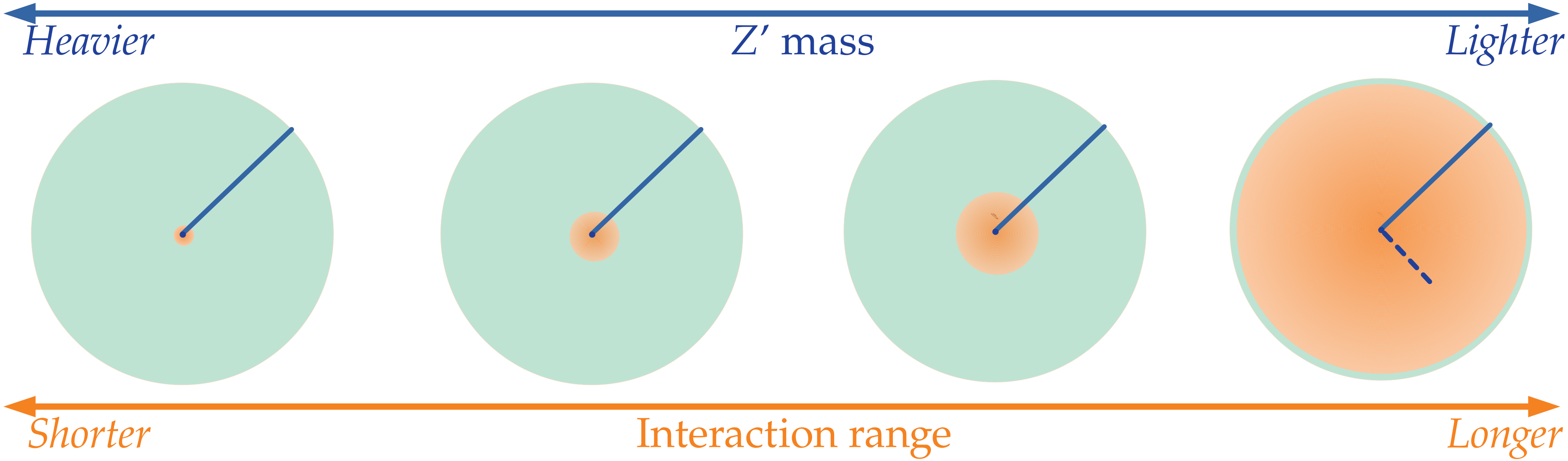

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Electrons in the local and distant Universe

Potential:

$$V_{e\beta} \propto \frac{1}{r} e^{-m'_{e\beta} r}$$

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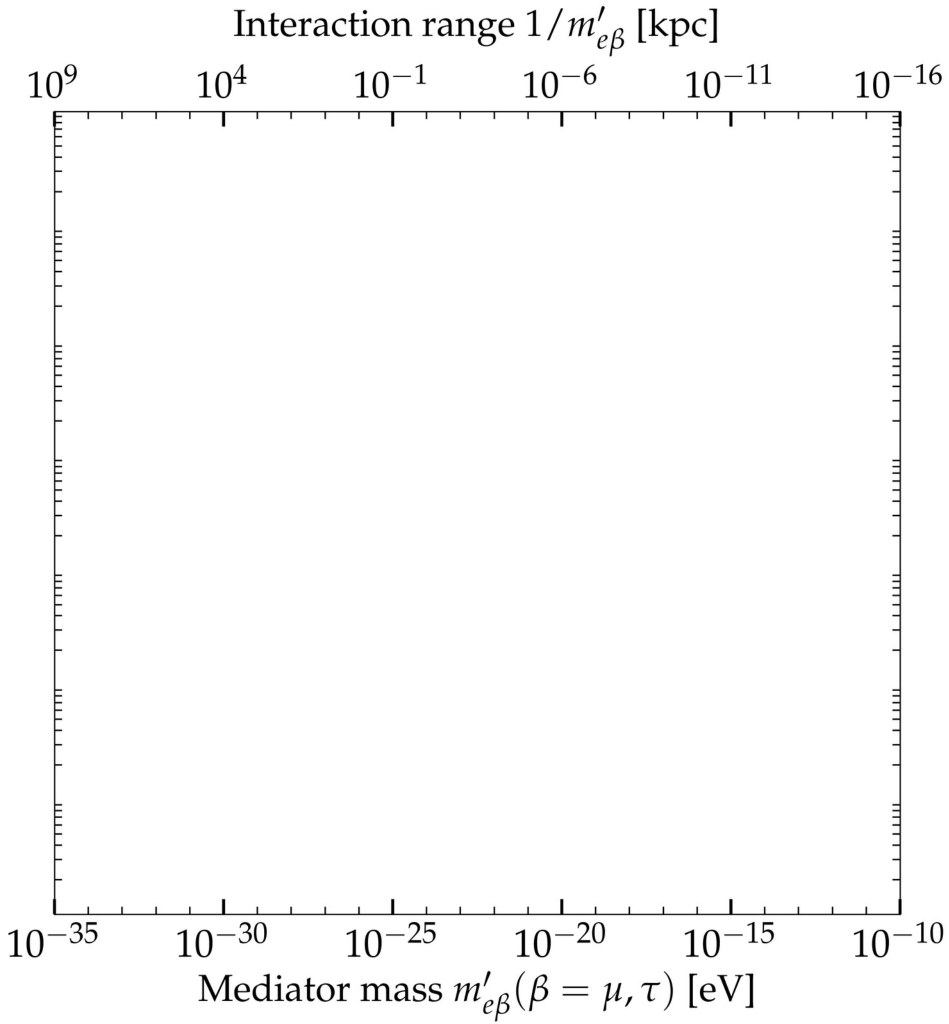

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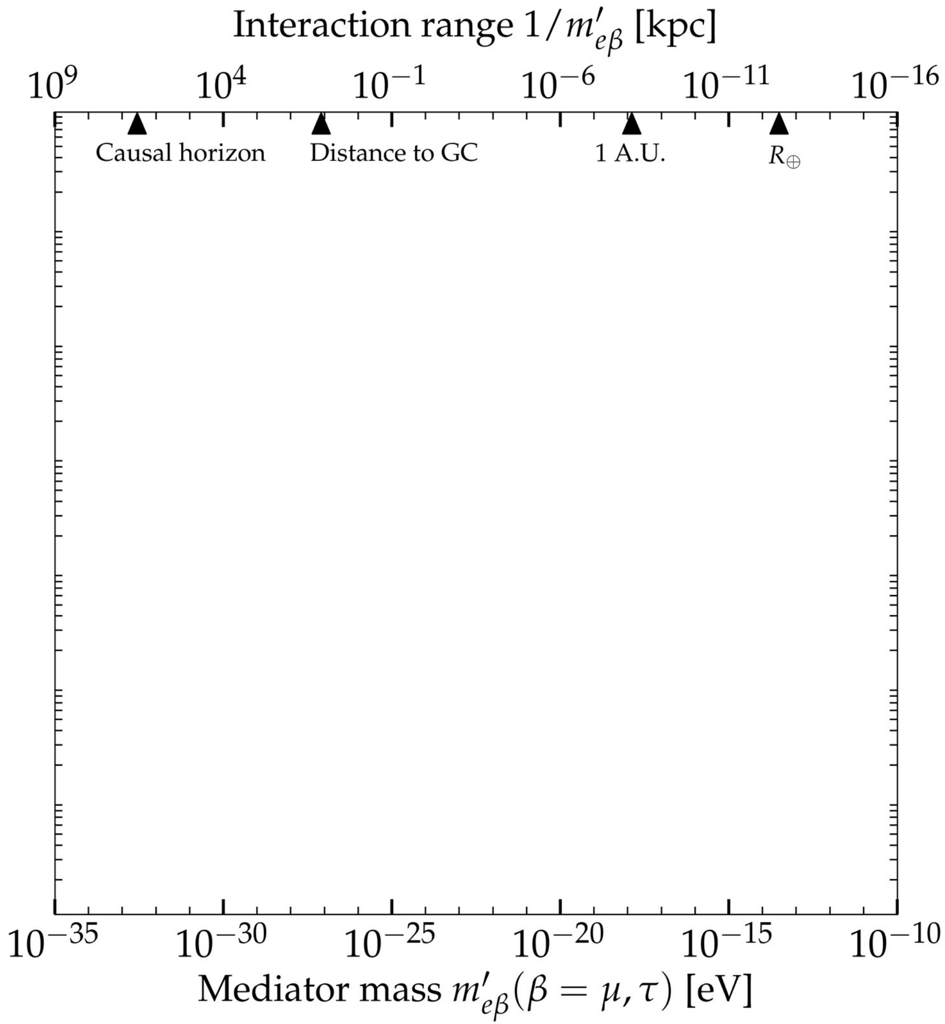

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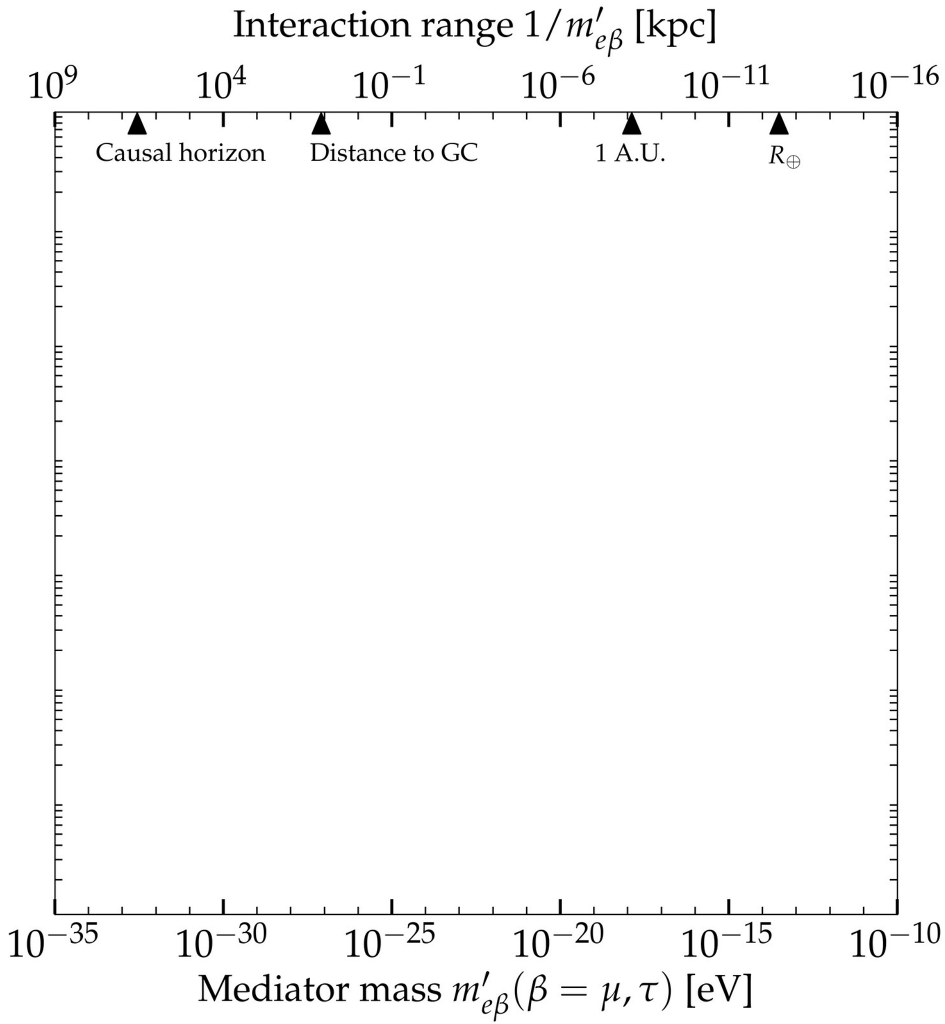

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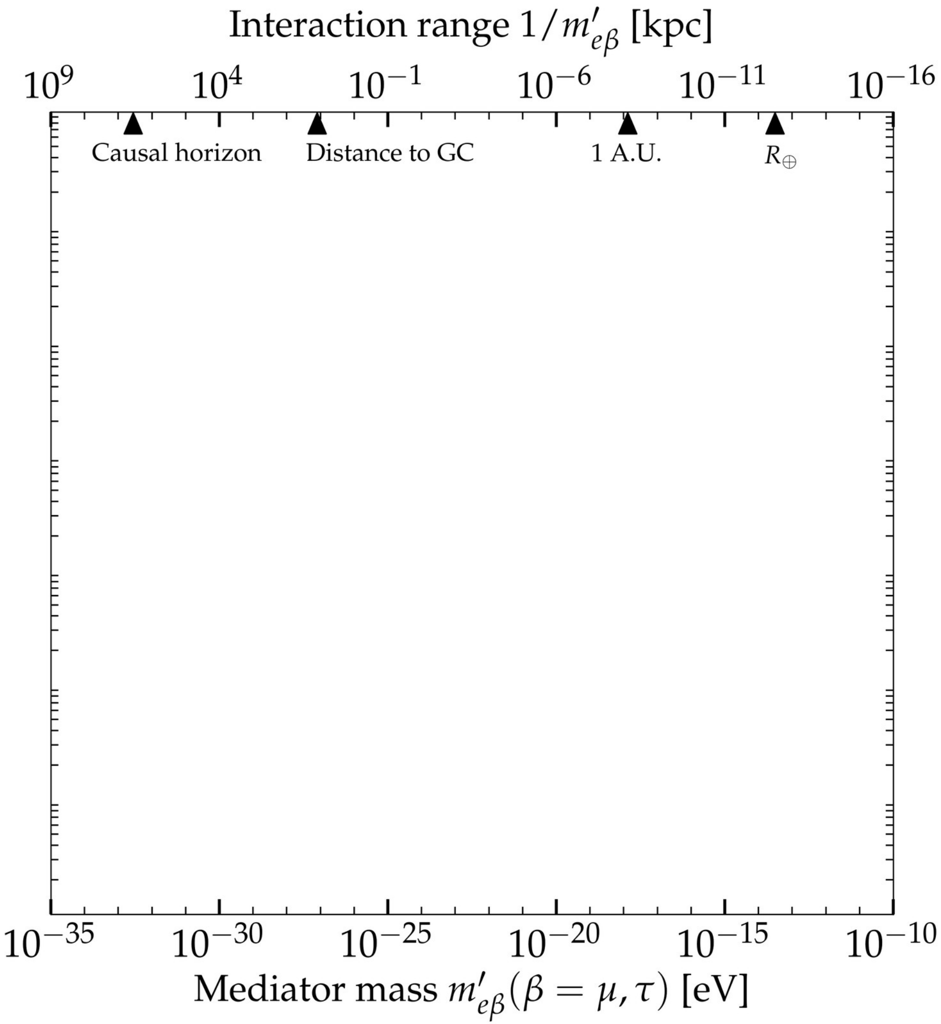
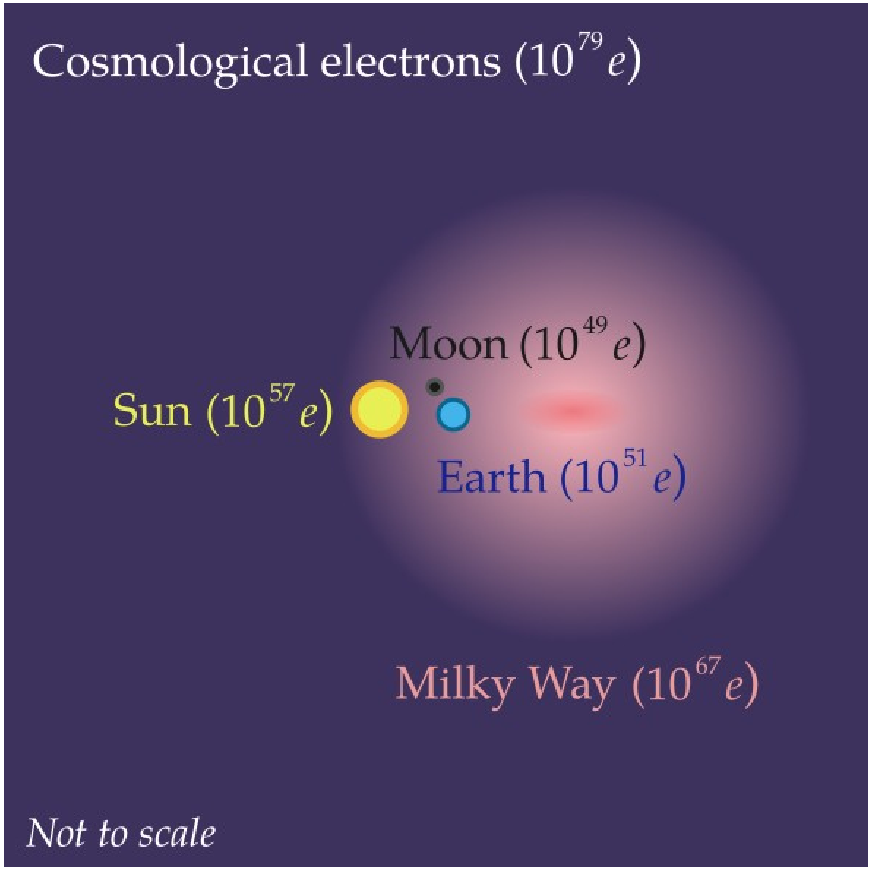
Light mediators
⇒ Long interaction ranges

Electrons in the local and distant Universe





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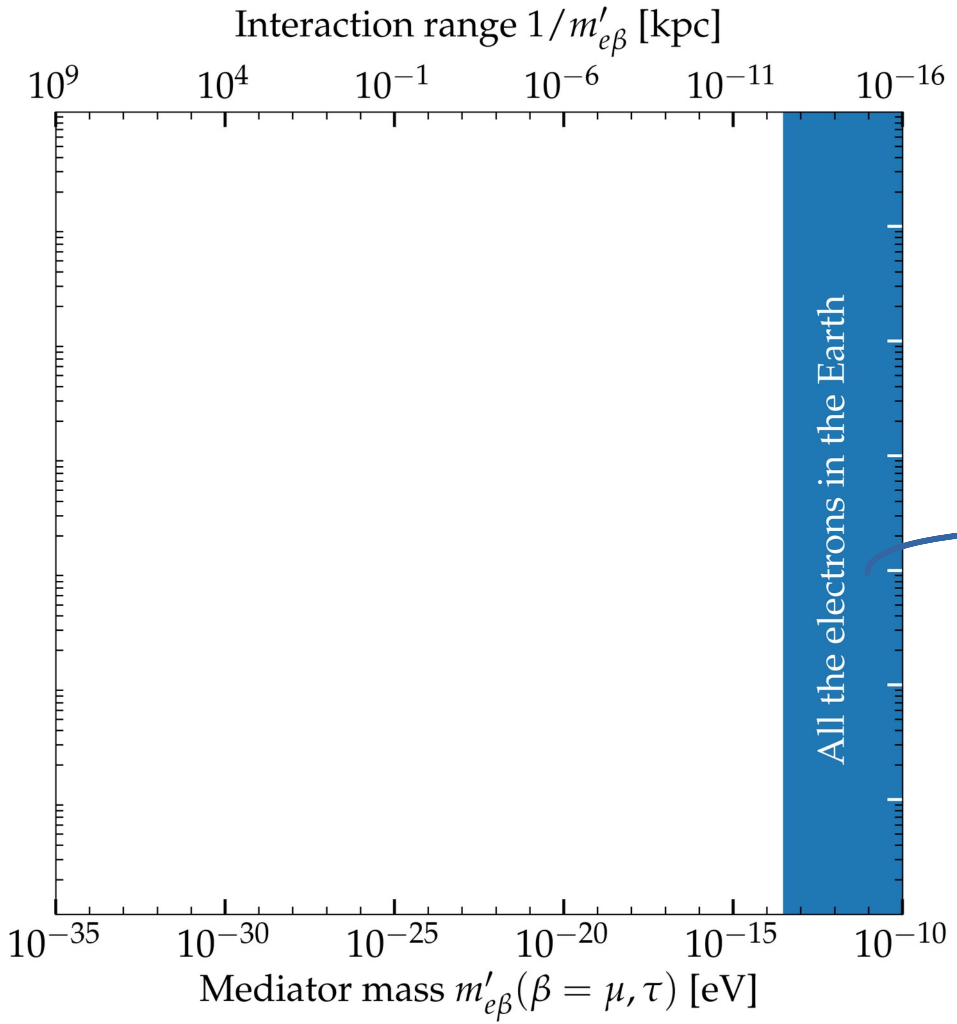

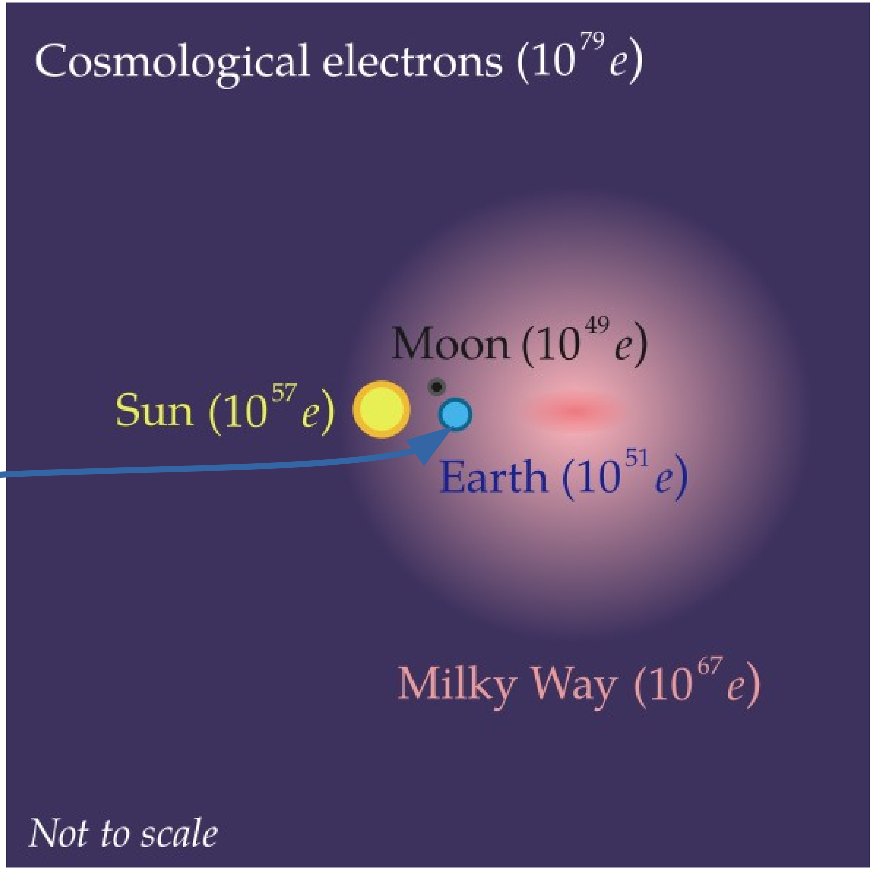

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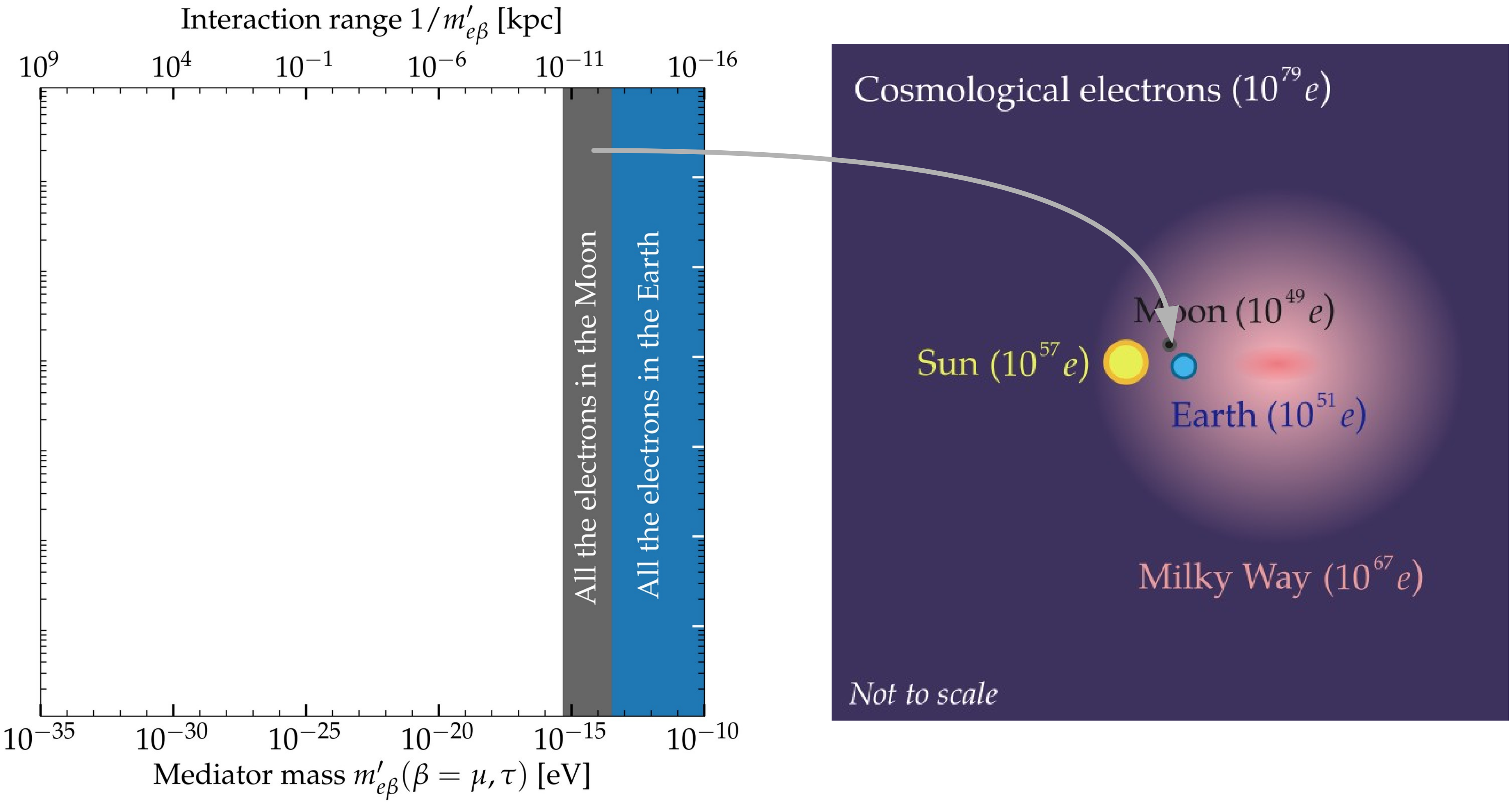

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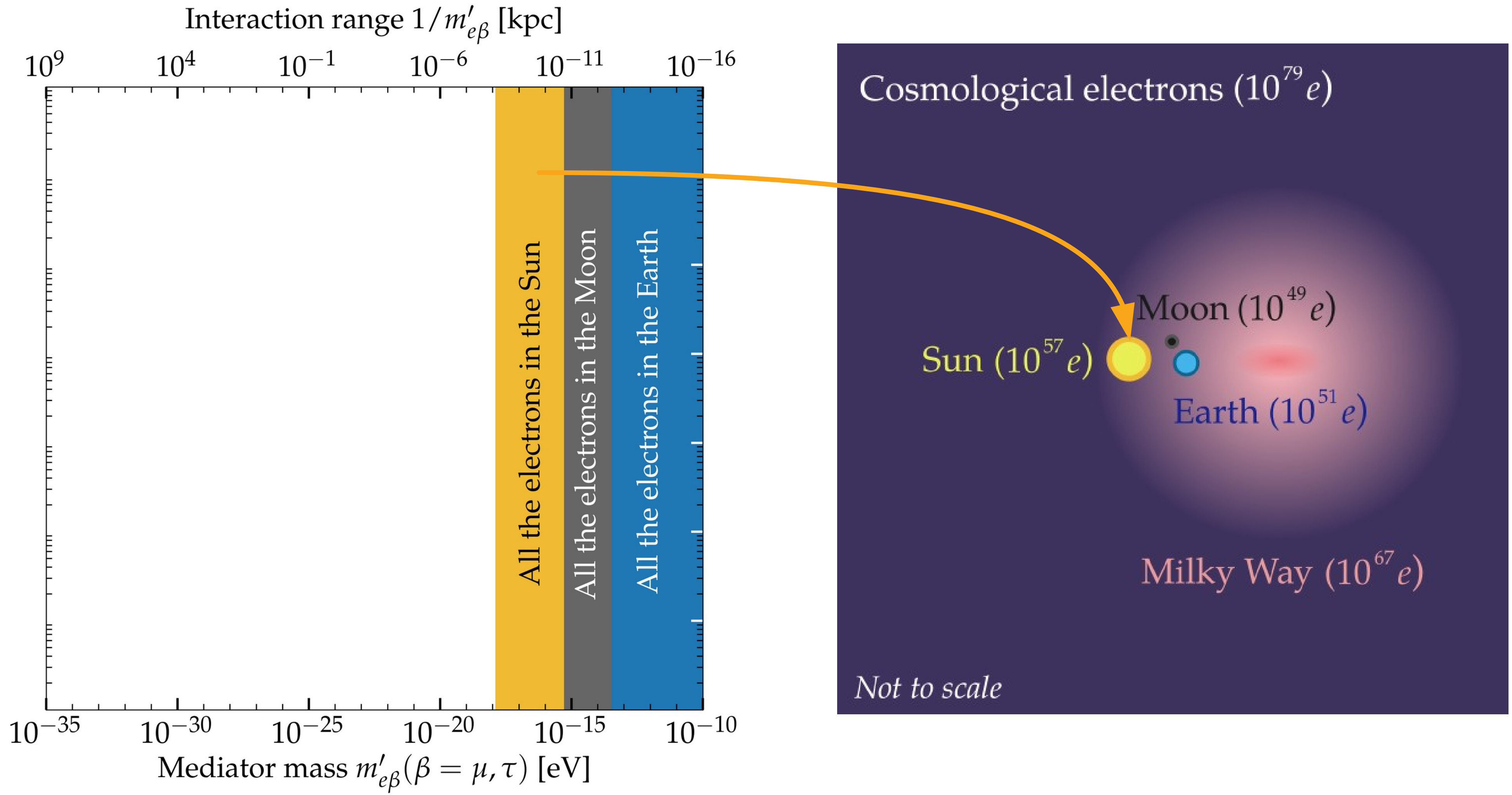

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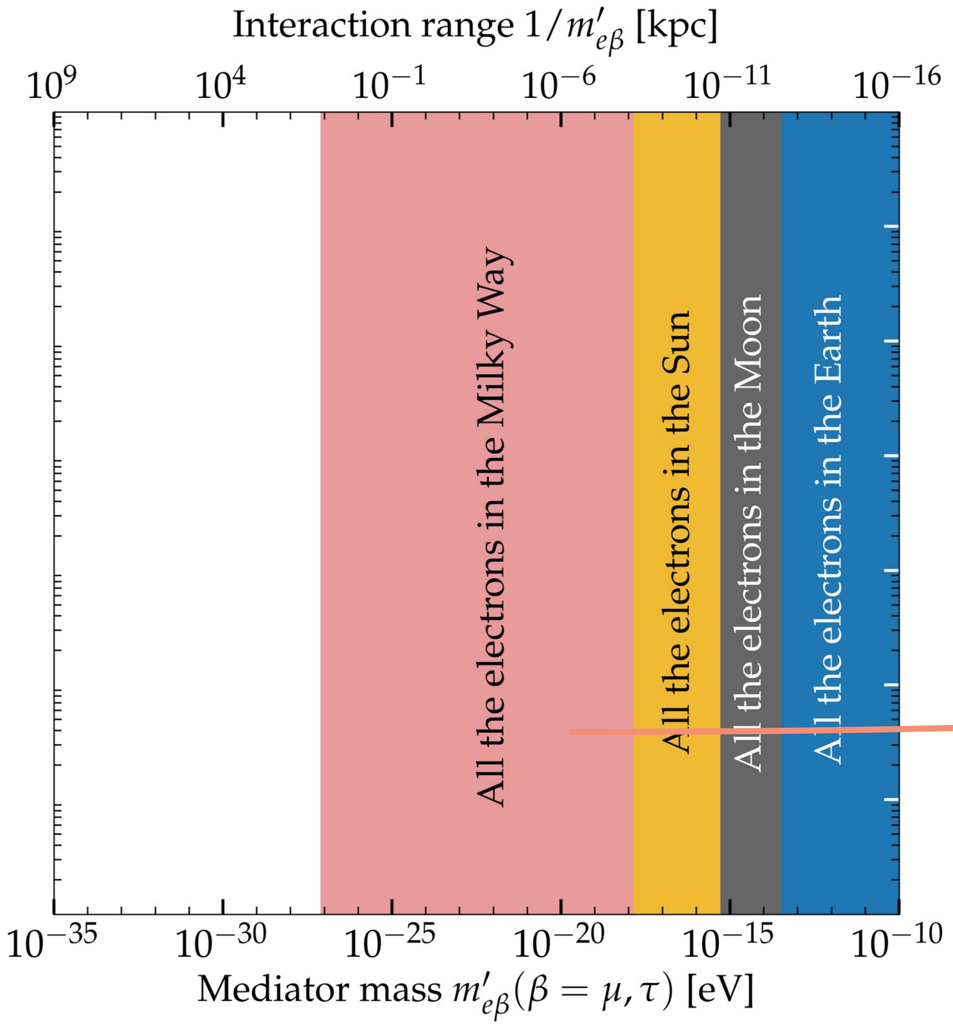

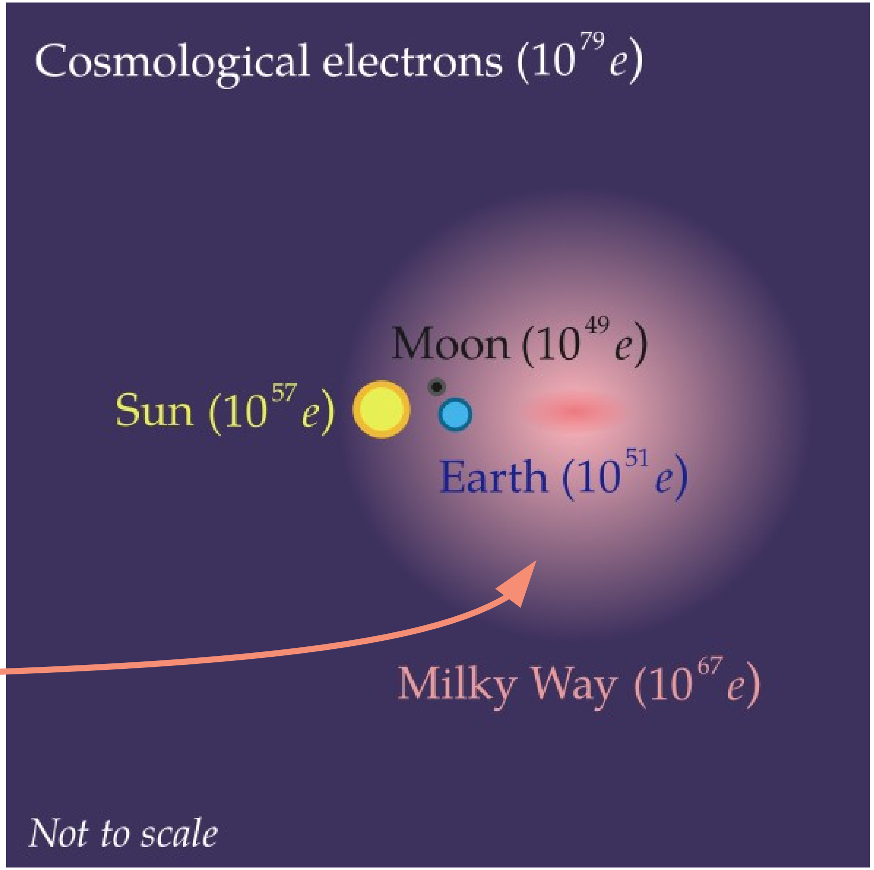

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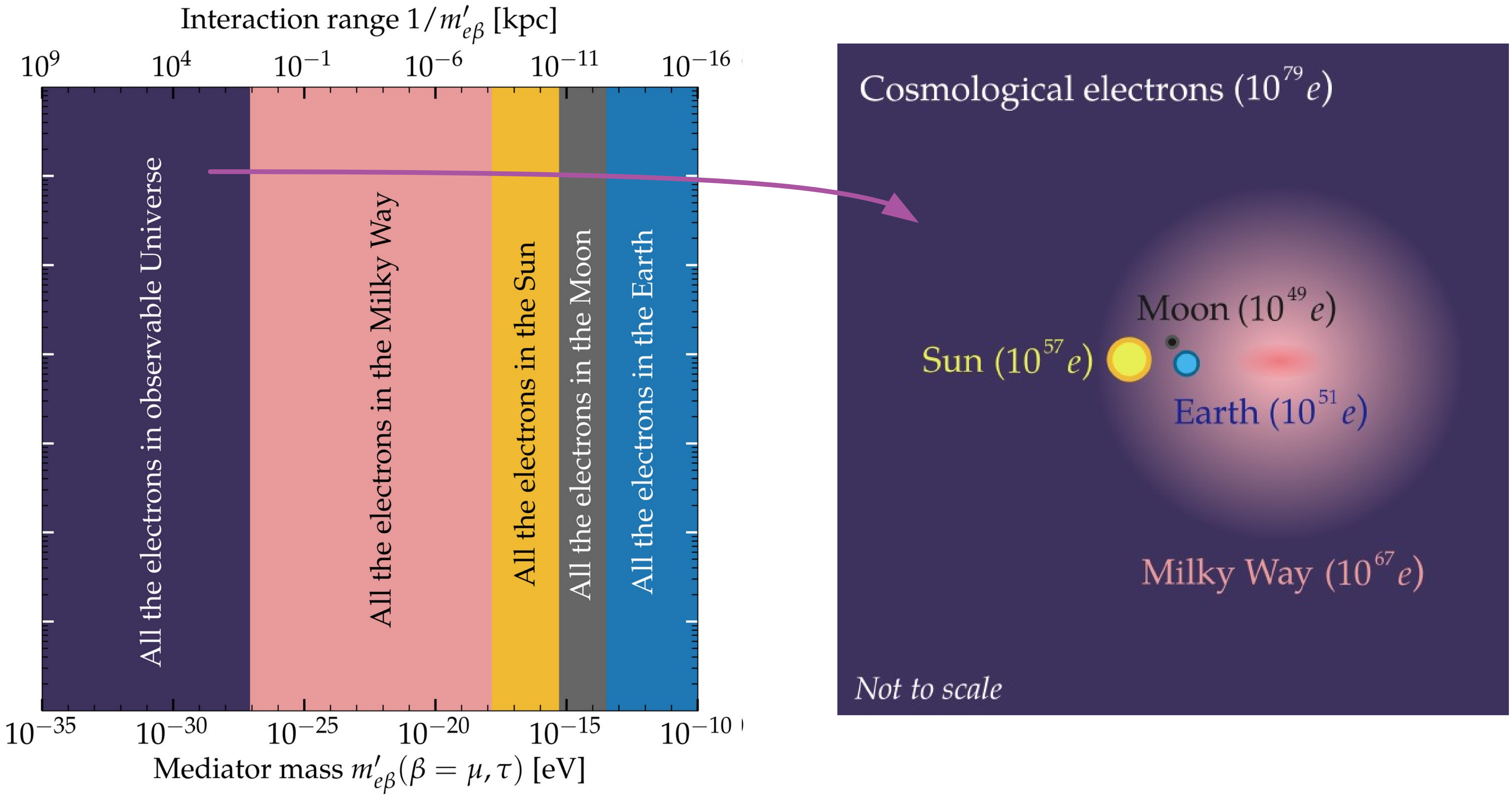

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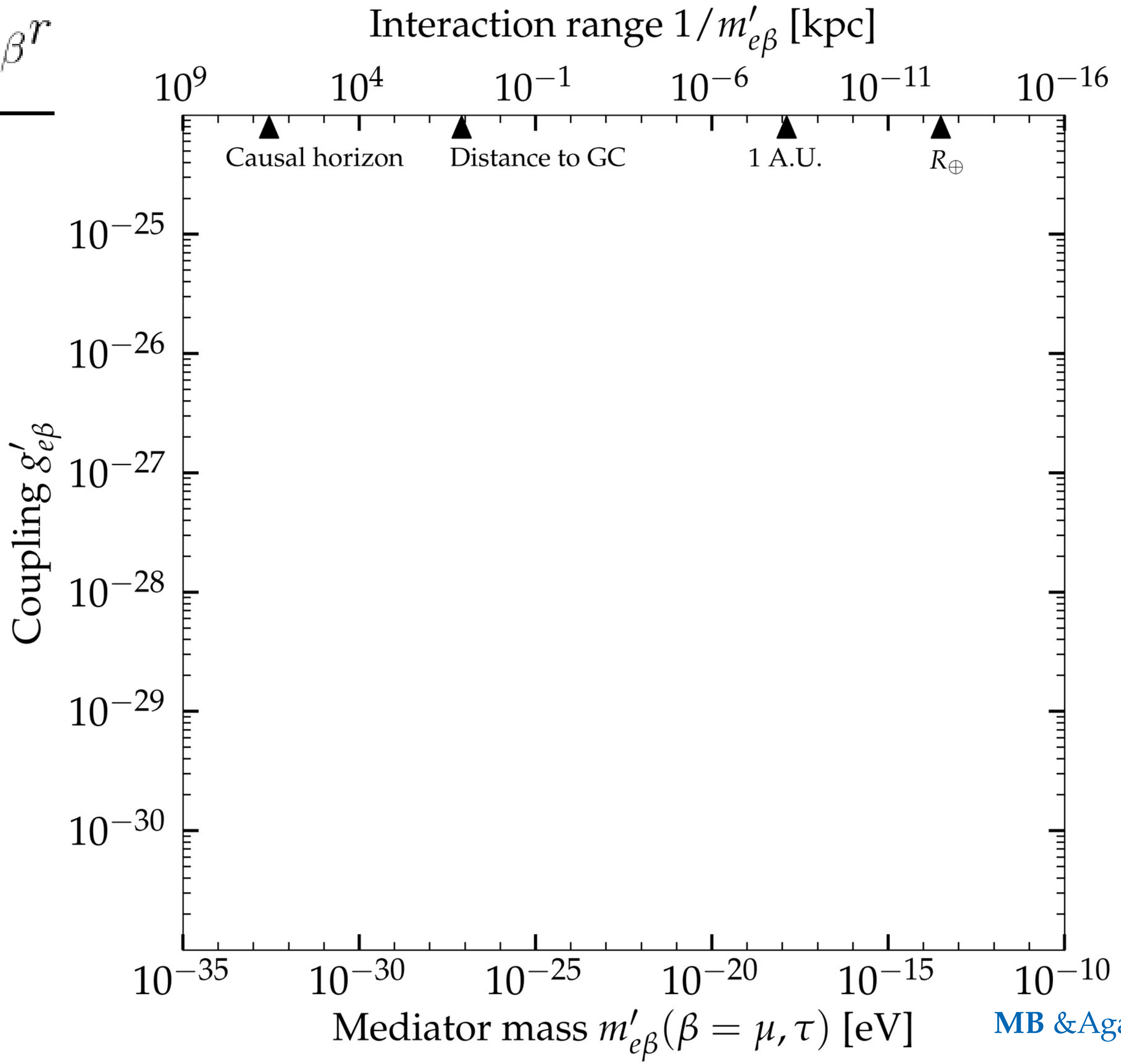

MB &Agarwalla, *PRL* 2019

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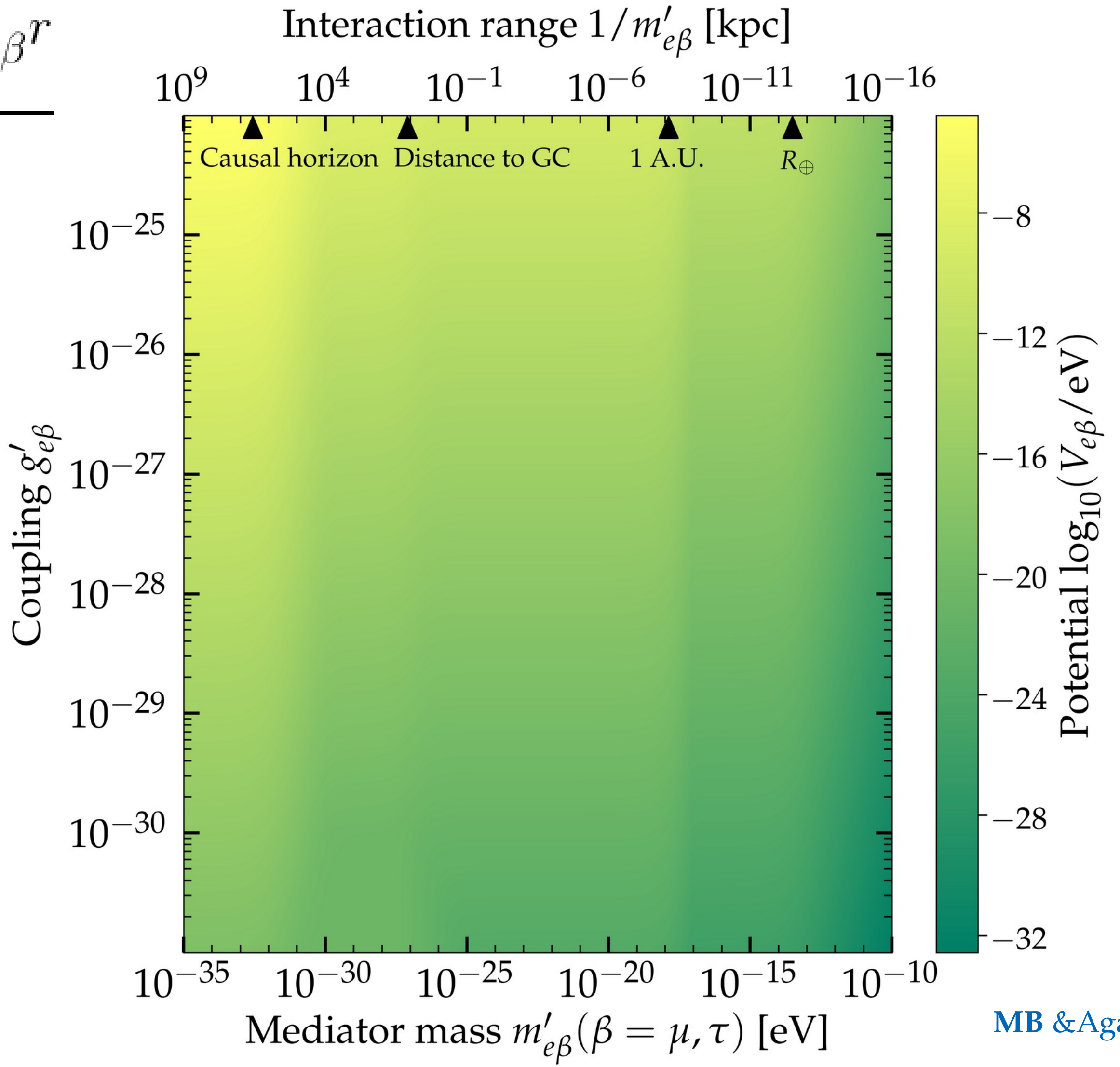
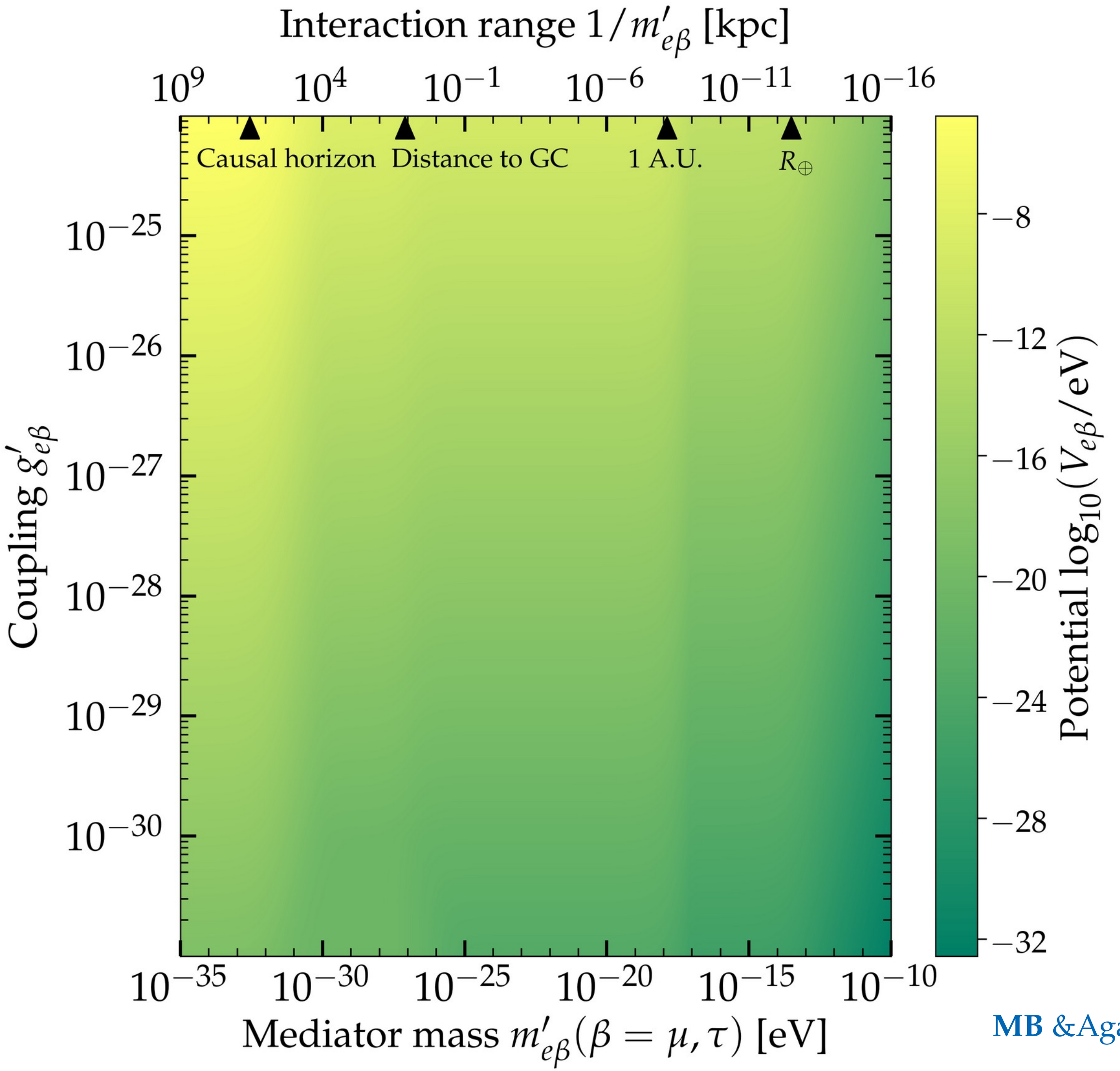


MB &Agarwalla, *PRL* 2019

$g_{strong} \sim 13.5$
$g_{e.m.} \sim 0.3$
$g_{weak} \sim 0.01$
$g_{gravity} \sim 10^{-19}$



MB &Agarwalla, *PRL* 2019

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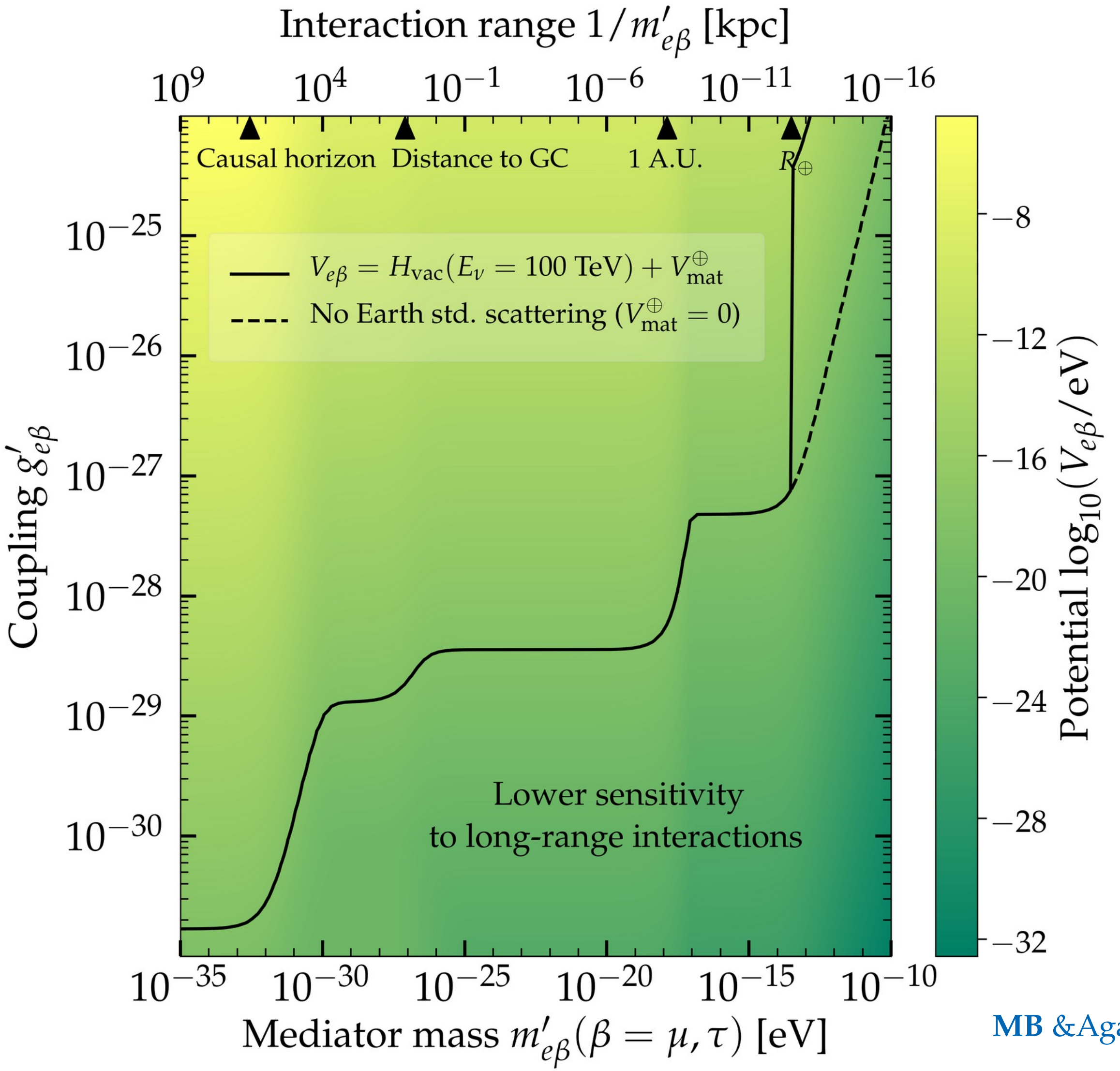
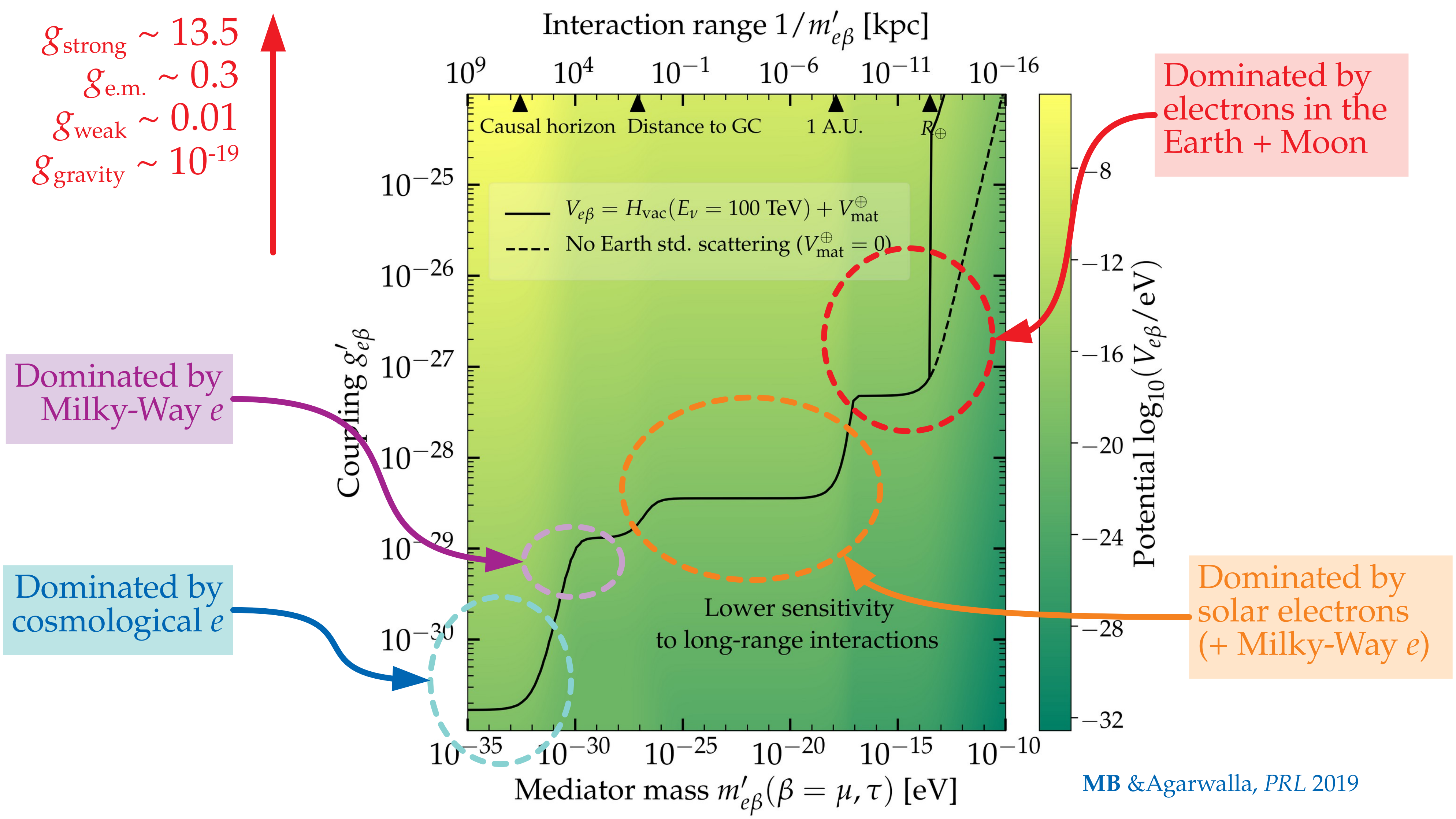


MB &Agarwalla, *PRL* 2019



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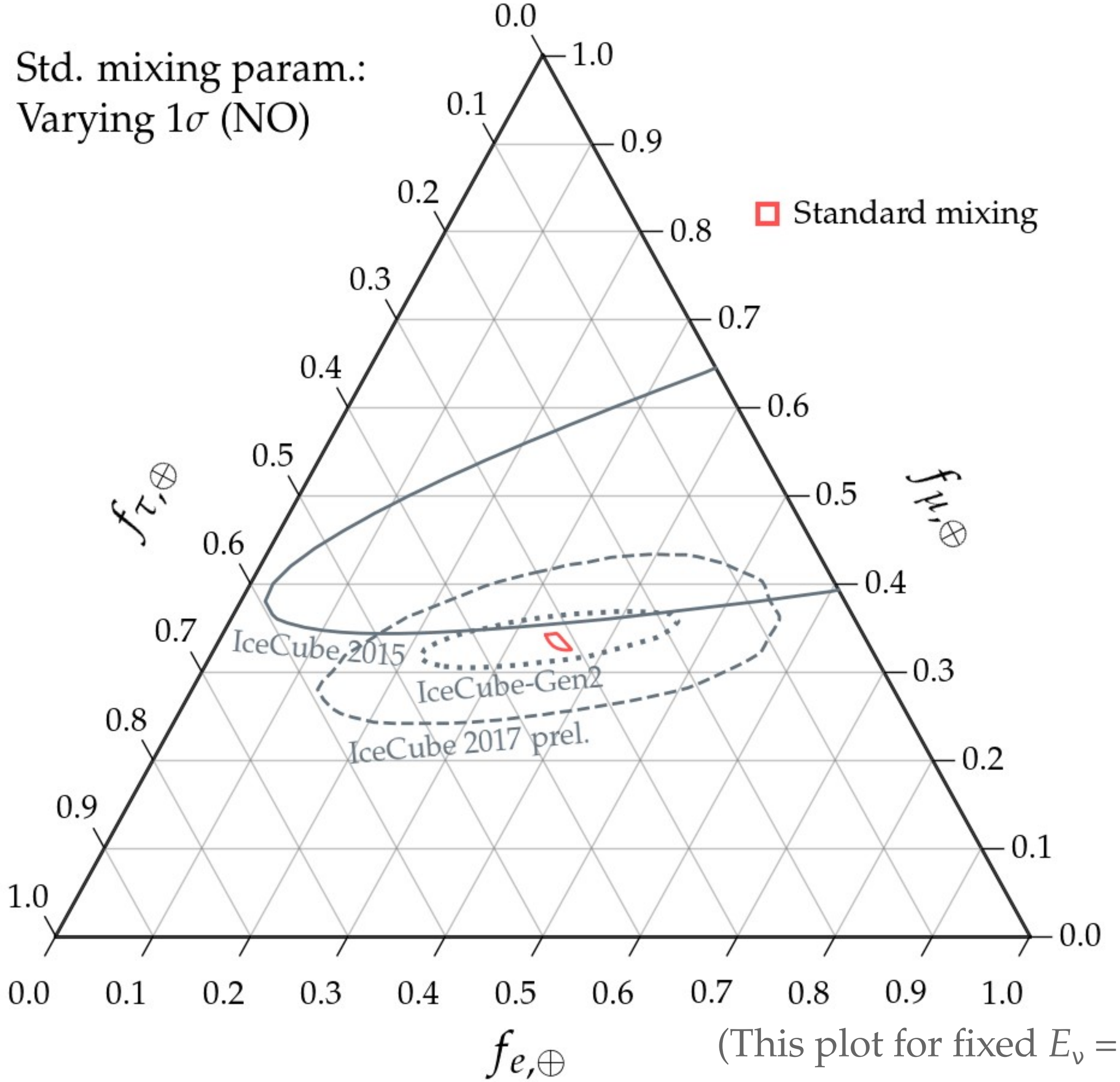
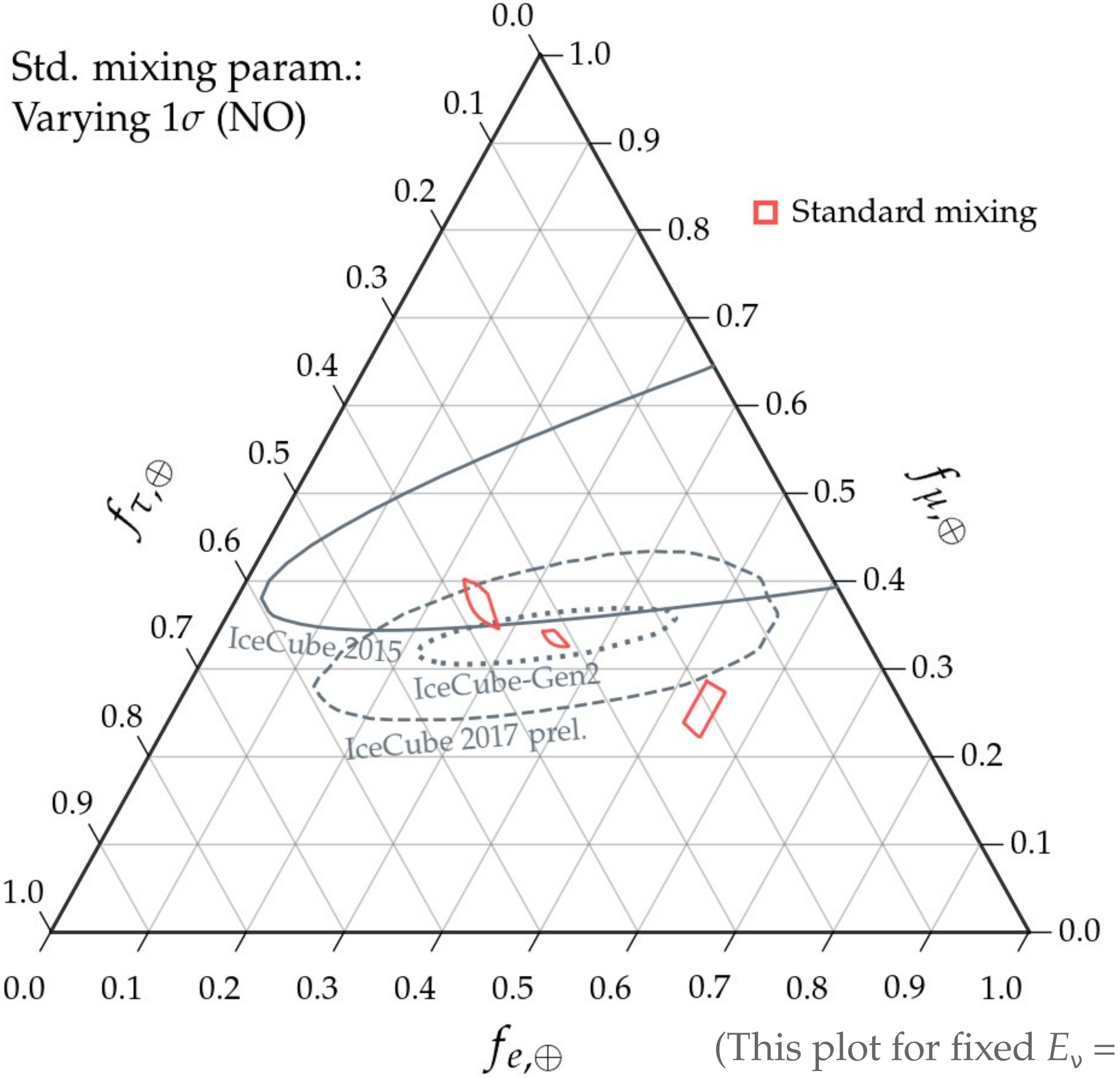


MB & Agarwalla, *PRL* 2019

(This plot for fixed E_ν = 100 TeV)



MB & Agarwalla, *PRL* 2019

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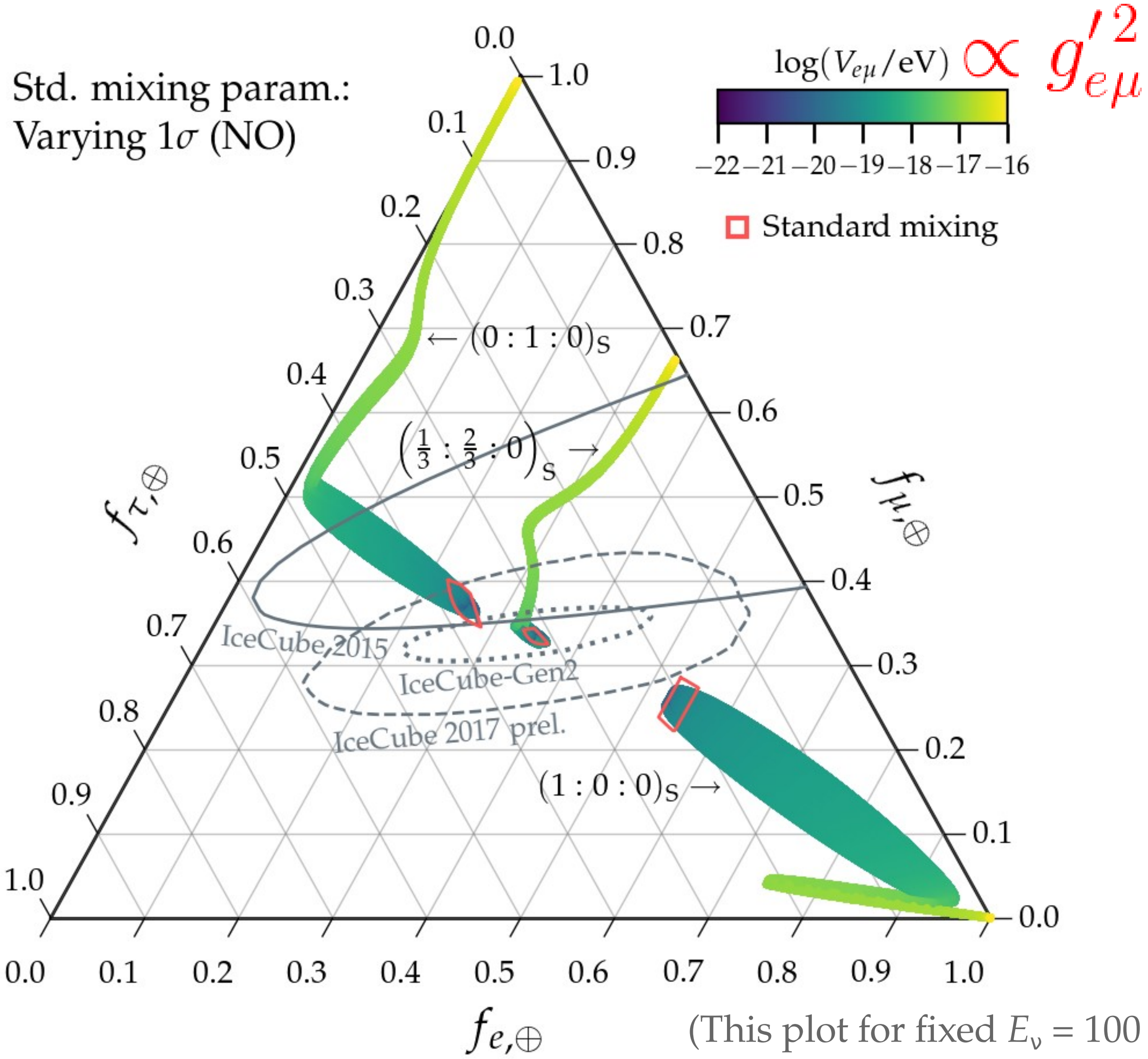

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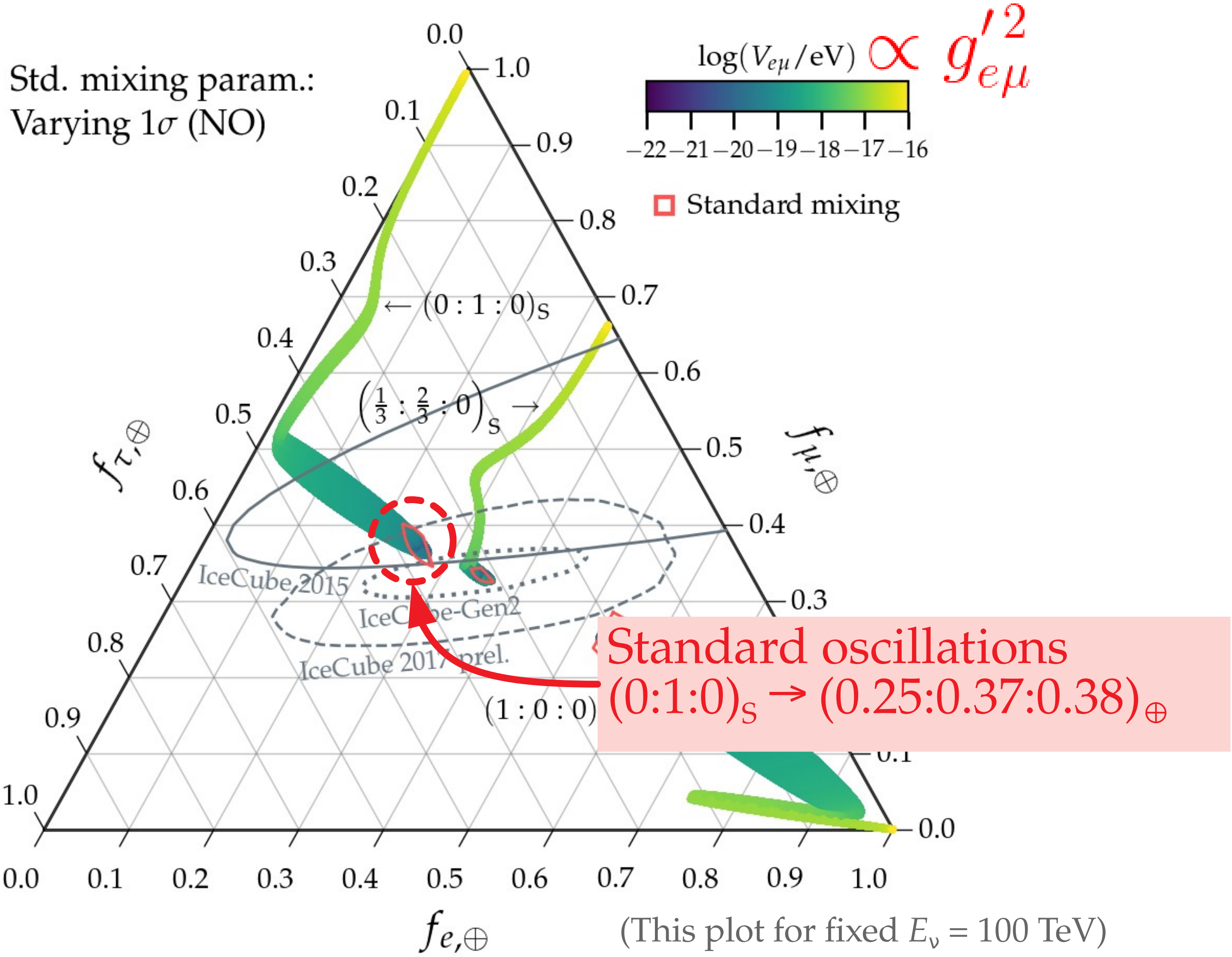

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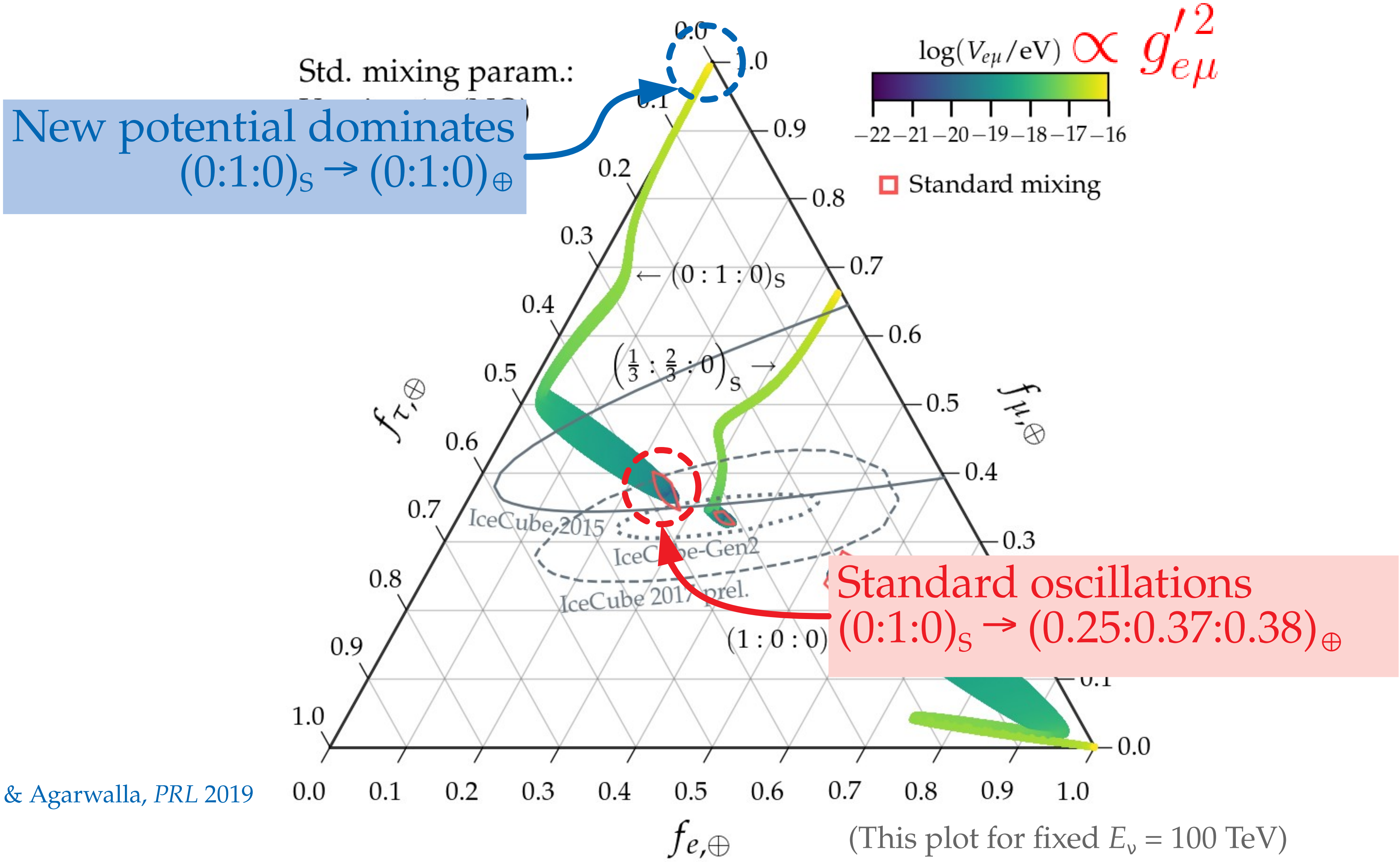

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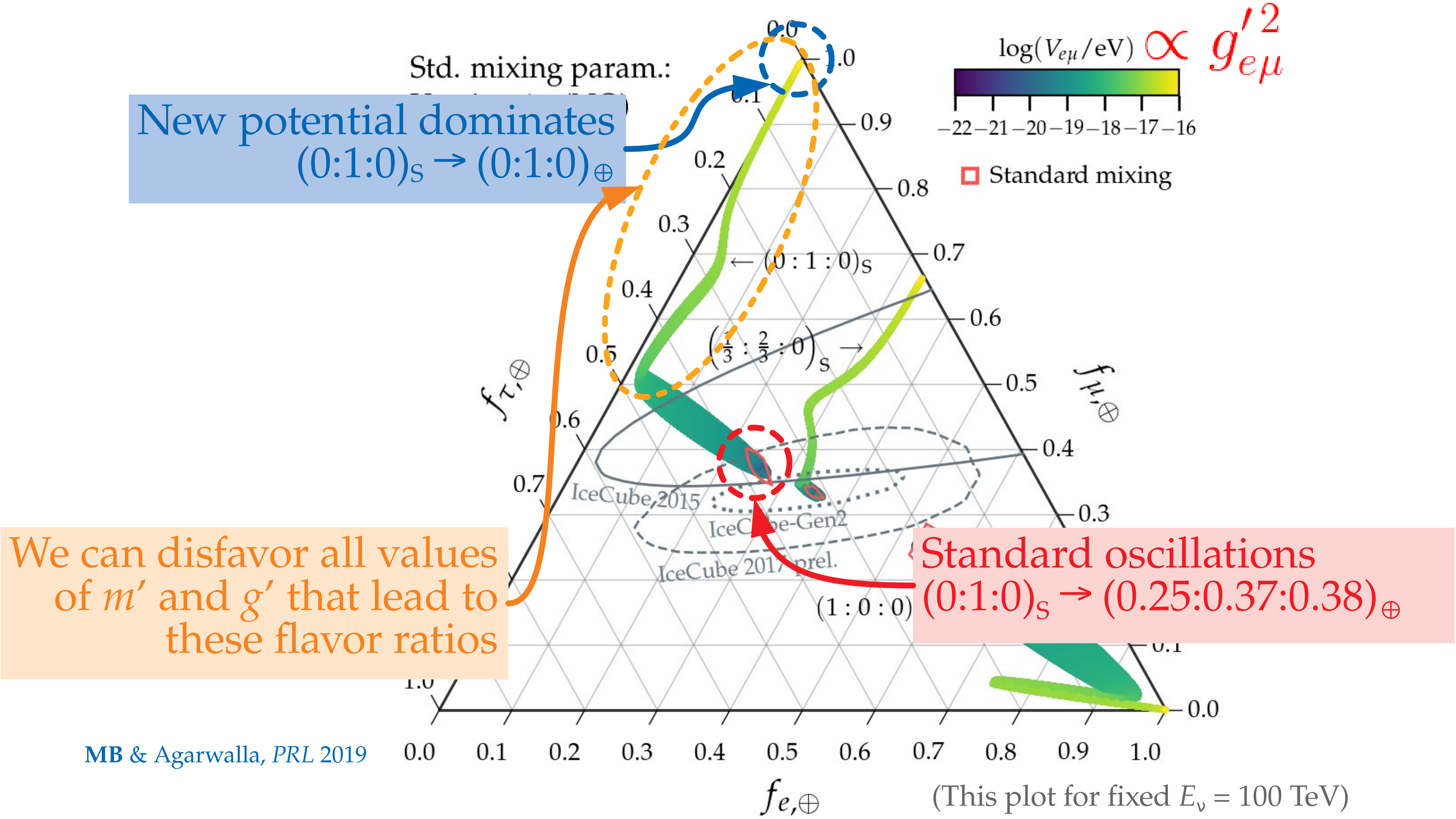

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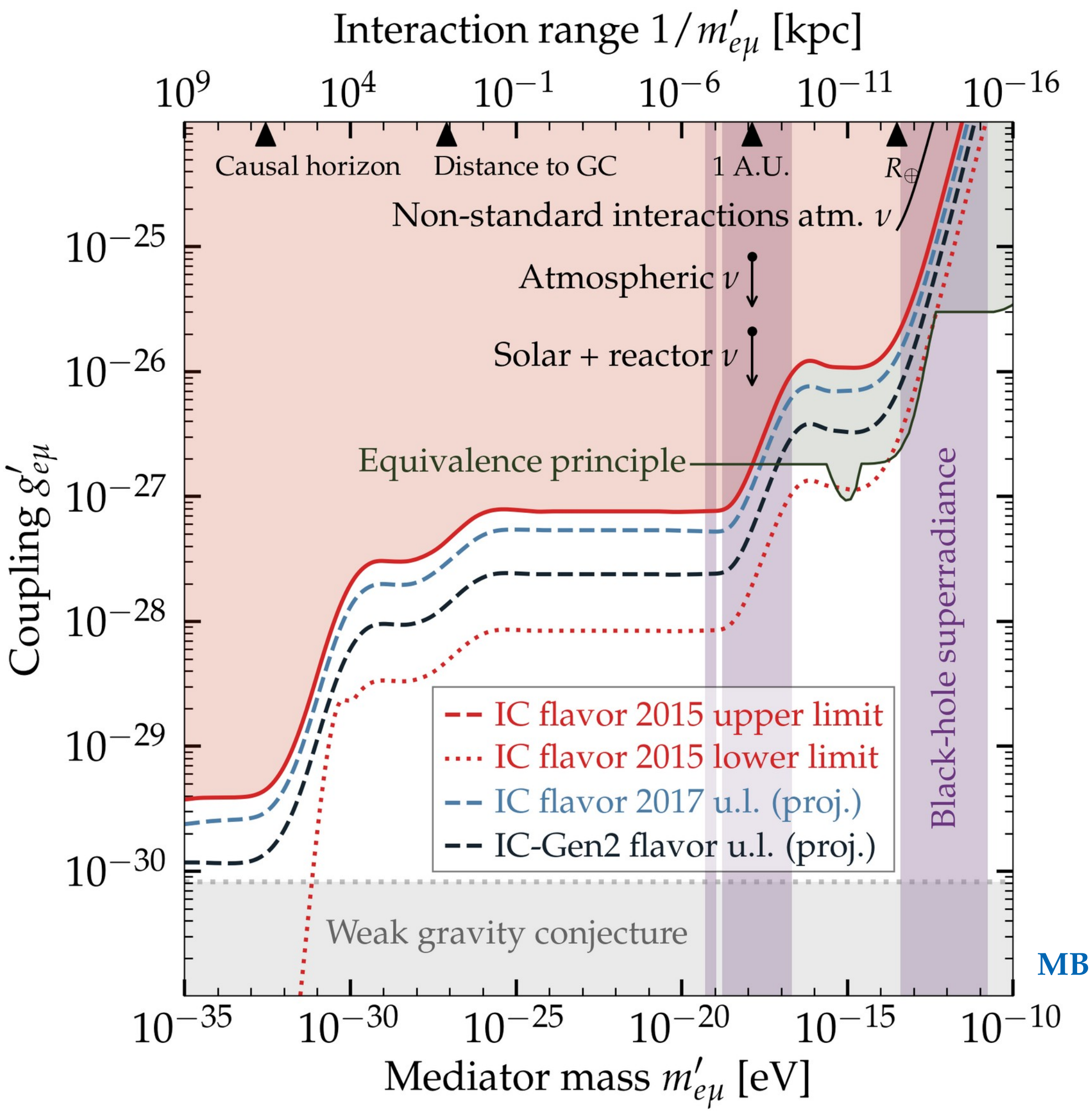

MB &Agarwalla, *PRL* 2019

Extrapolating the cross section to high energies

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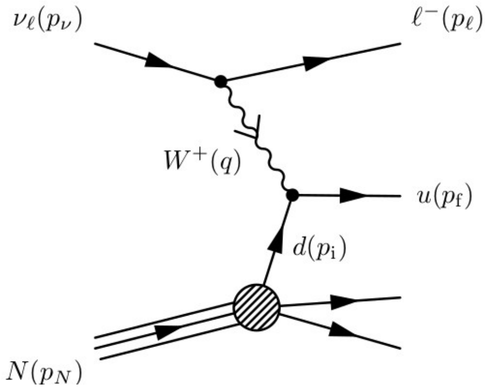
SM



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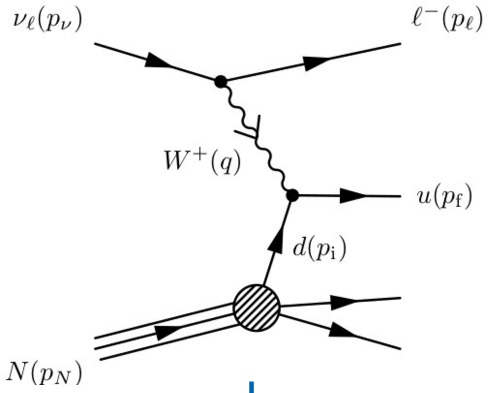

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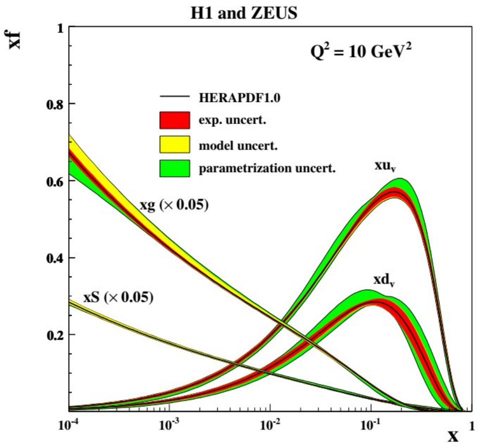
PDFs



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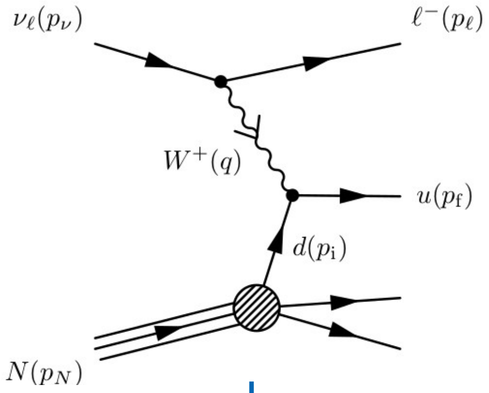

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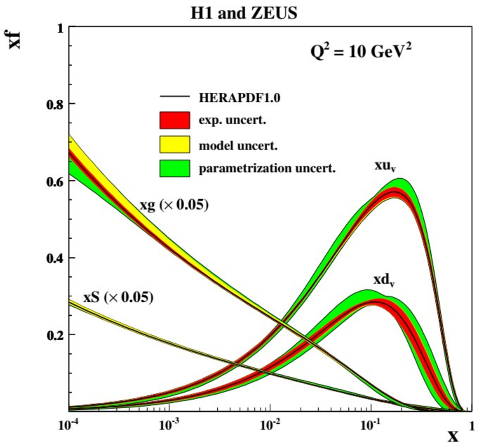

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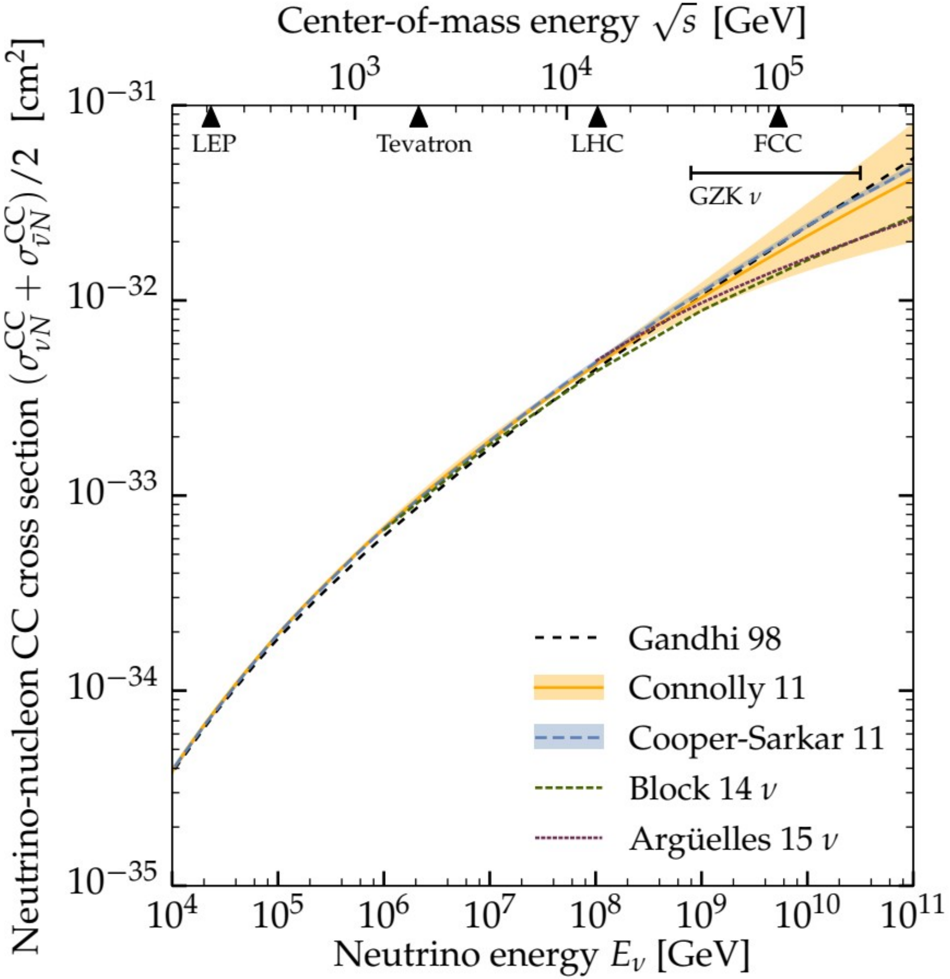

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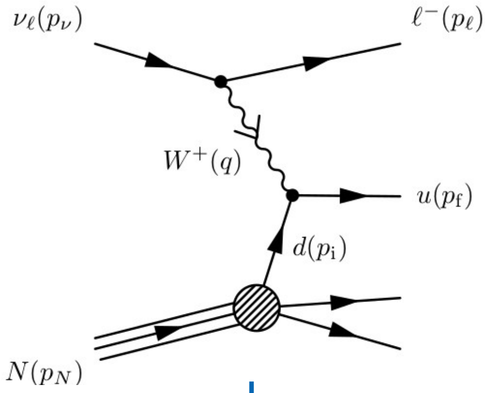

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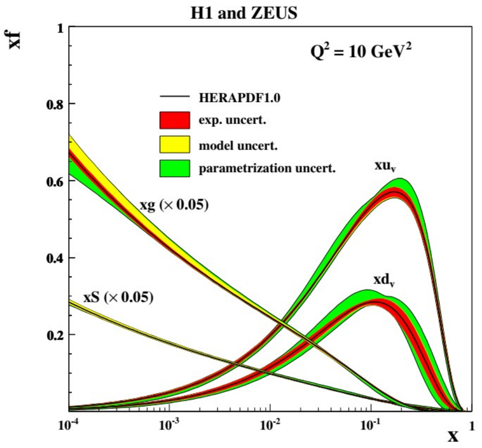

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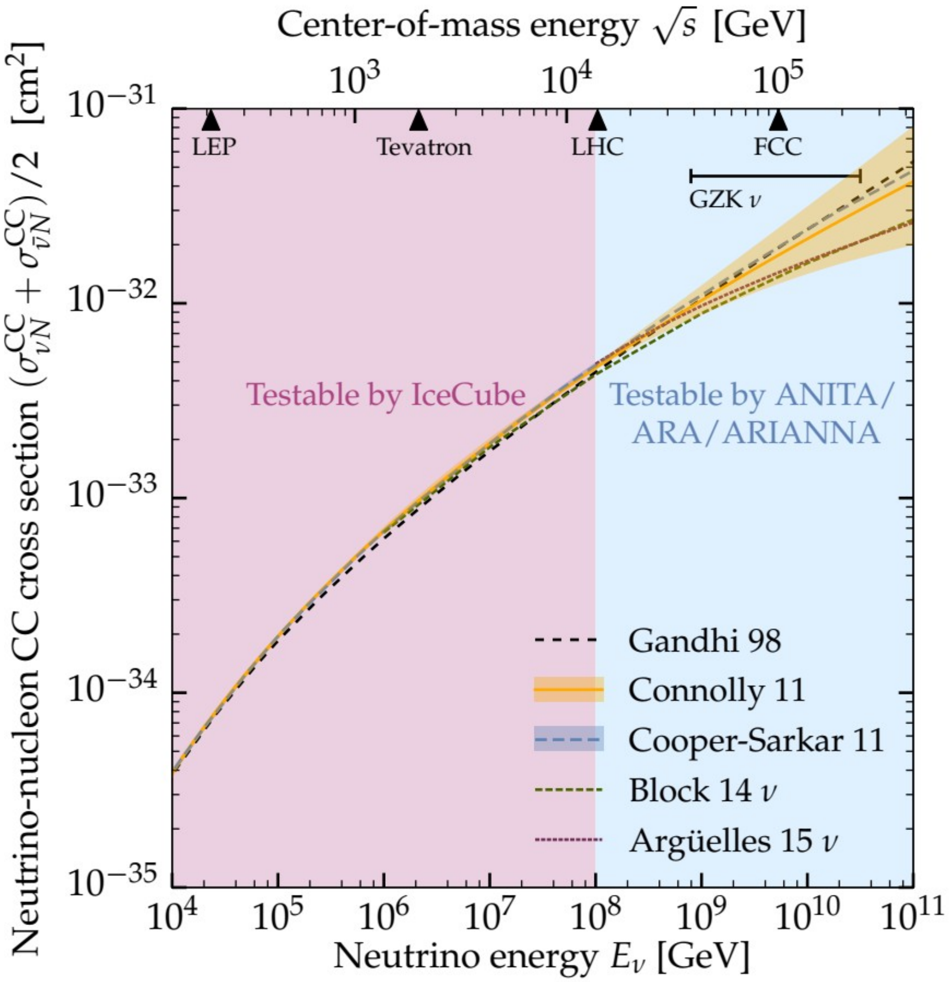


Bonus: Measuring the inelasticity $\langle y \rangle$

- Inelasticity in CC ν_μ interaction $\nu_\mu + N \rightarrow \mu + X$:

  $E_X = y\, E_\nu$ and $E_\mu = (1-y)\, E_\nu \Rightarrow y = (1 + E_\mu/E_X)^{-1}$

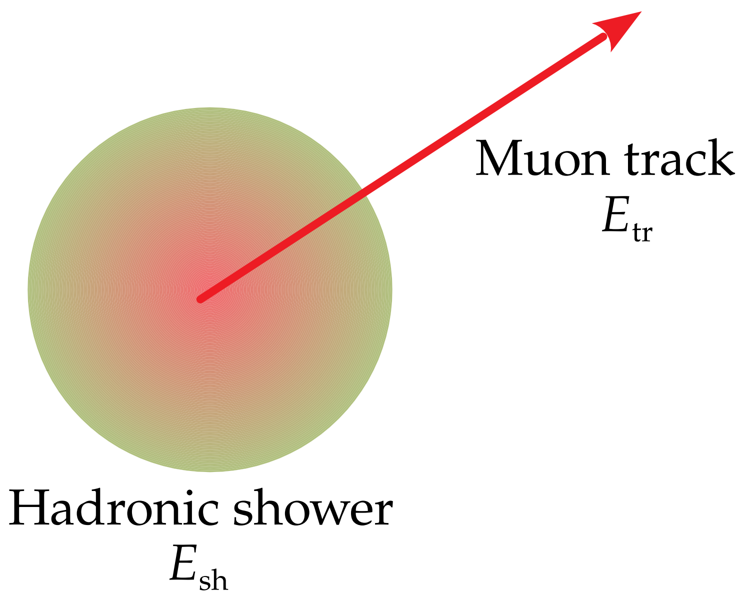
- The value of y follows a distribution $d\sigma/dy$

- In a HESE starting track:

  $E_X = E_{sh}$ (energy of shower)
  $E_\mu = E_{tr}$ (energy of track)

  $y = (1 + E_{tr}/E_{sh})^{-1}$

- New IceCube analysis:
  - 5 years of starting-track data (2650 tracks)
  - Machine learning separates shower from track
  - Different y distributions for ν and $\bar{\nu}$



IceCube, *PRD* 2019

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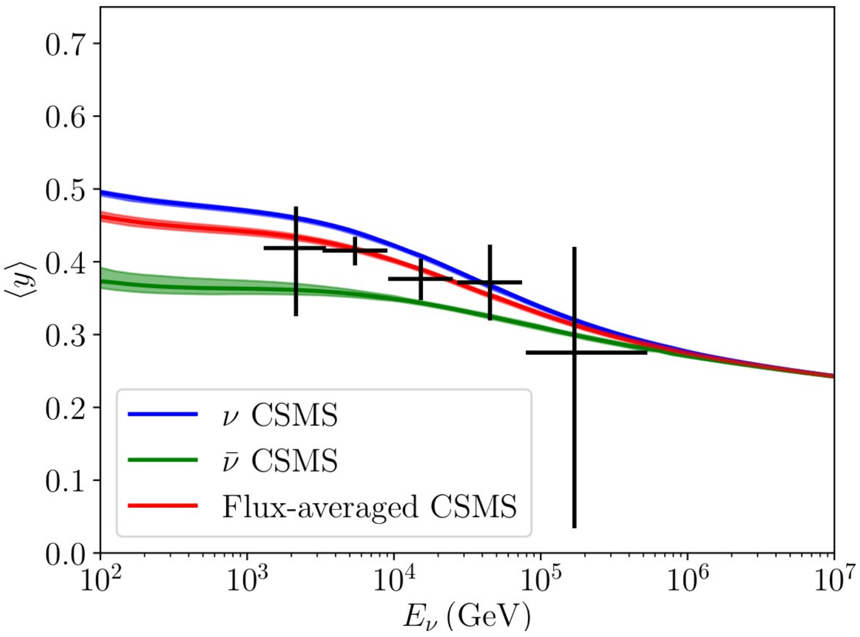
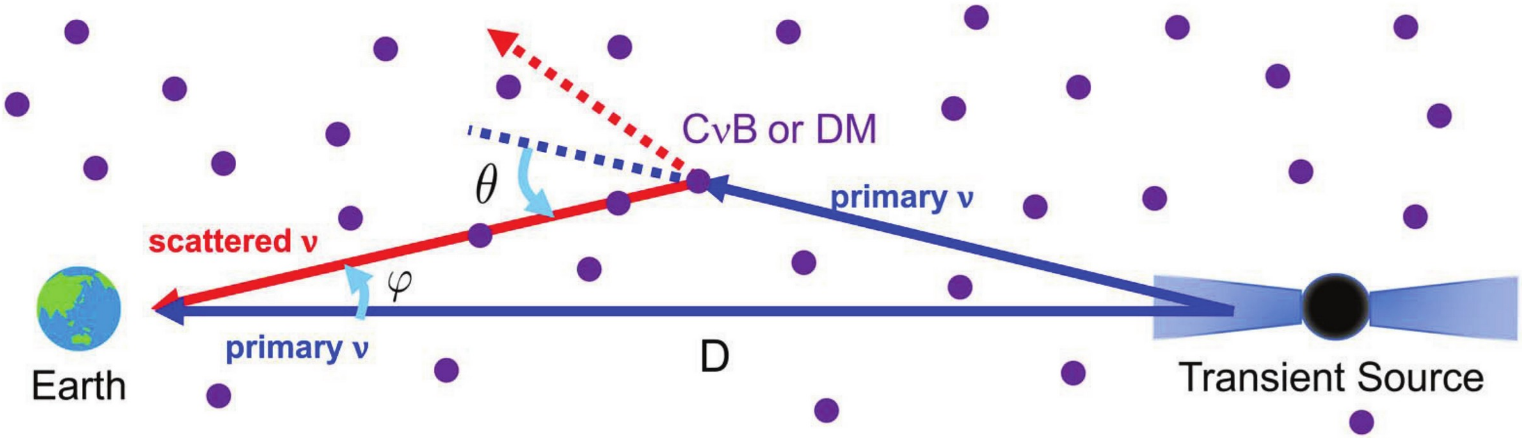


IceCube, *PRD* 2019

Delays from secret interactions

Multiple secret νν scatterings may delay the arrival of neutrinos from a transient



Shoemaker & Murase, *PRL* 2019

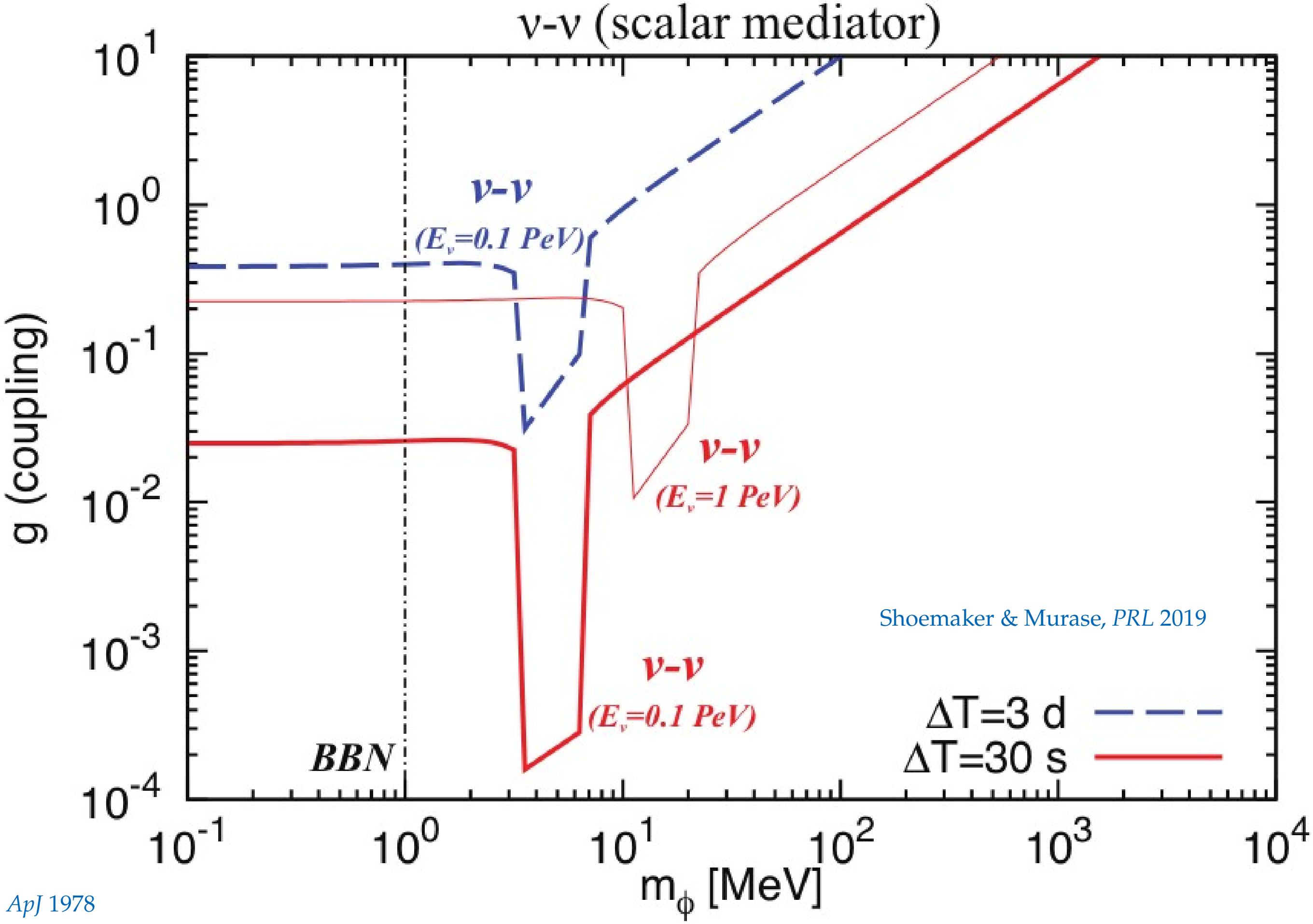
Characteristic time delay —

Optical depth to νν: $\tau_{\nu\nu} = n_\nu \sigma_{\nu\nu} D$

$$\Delta t \approx 1500\,\mathrm{s} \left(\frac{\tau_{\nu\nu}}{30}\right) \left(\frac{D}{3\ \mathrm{Gpc}}\right) \left(\frac{m_\nu}{0.1\ \mathrm{eV}}\right) \left(\frac{0.1\ \mathrm{PeV}}{E_\nu}\right)$$

See also: Alcock & Hatchett, *ApJ* 1978

Delays from secret interactions



See also: Alcock & Hatchett, *ApJ* 1978

Neutrino zenith angle distribution

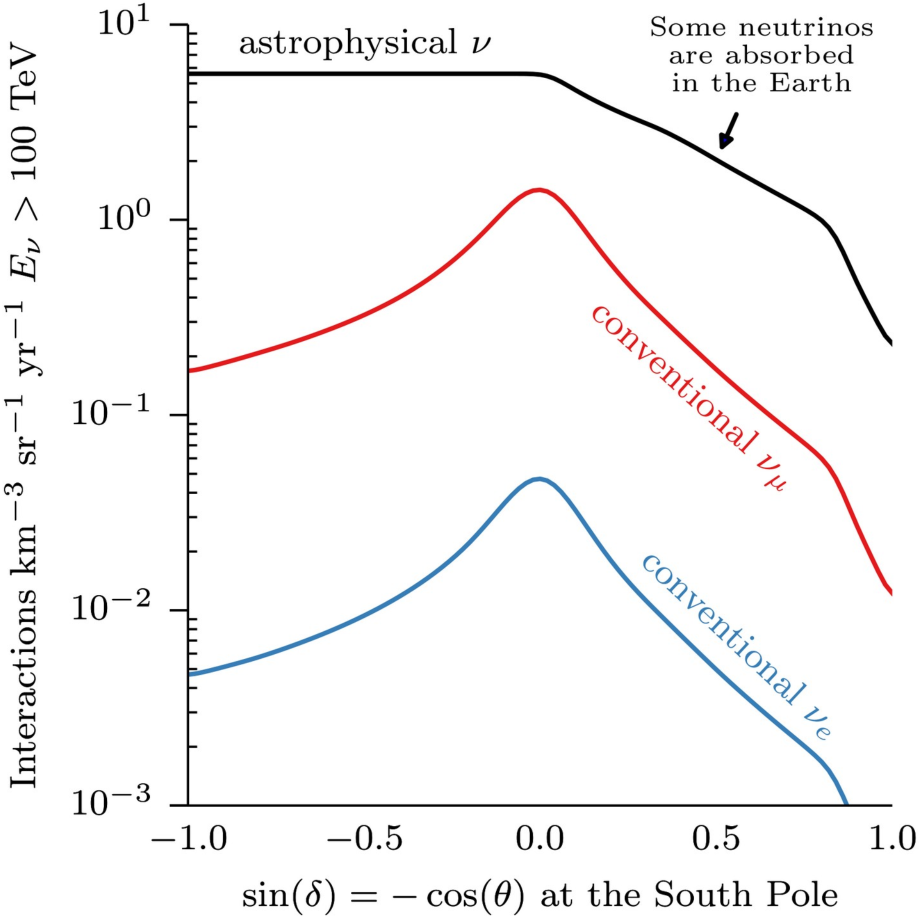
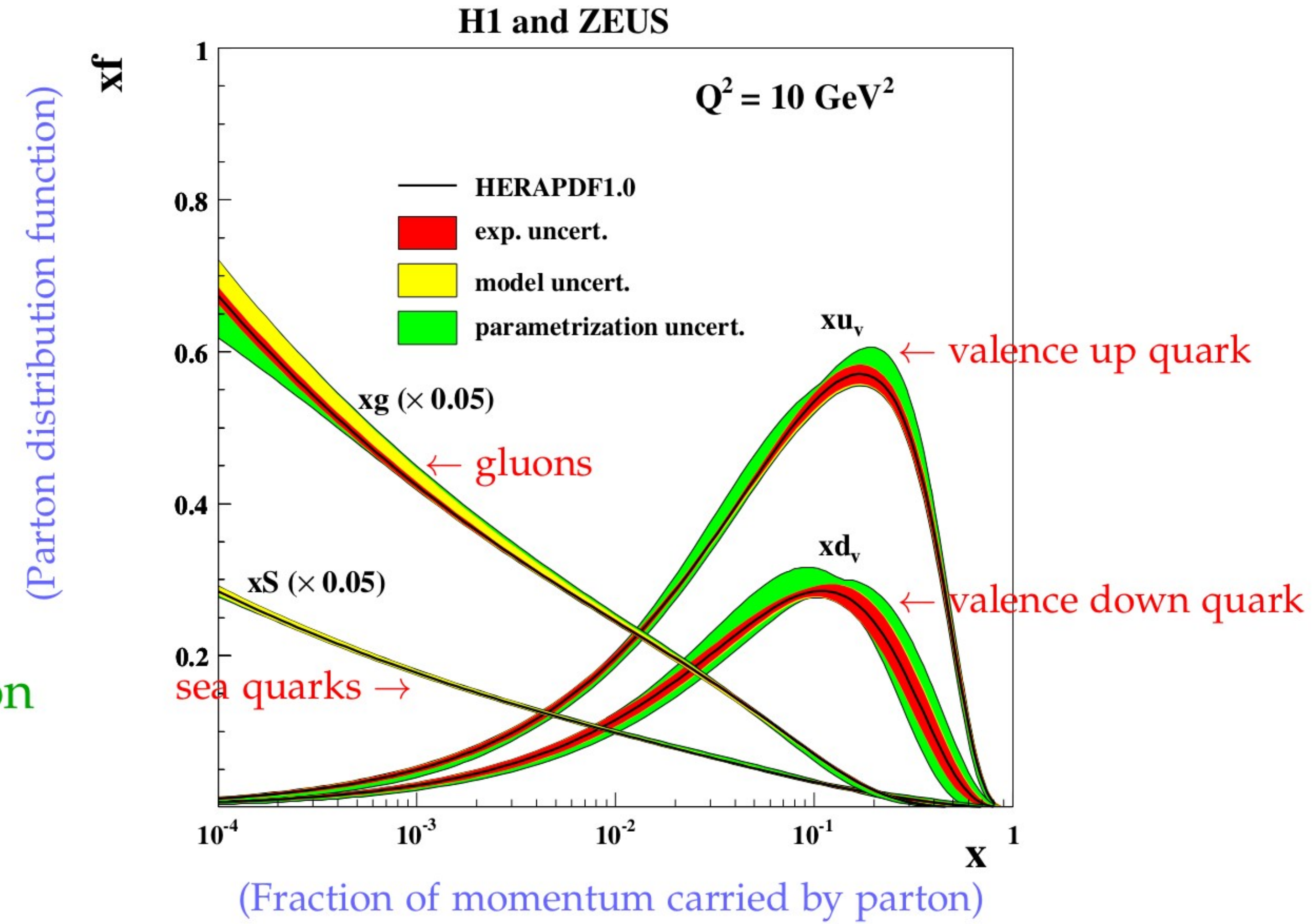


Figure by
Jakob Van Santen
ICRC 2017

Peeking inside a proton



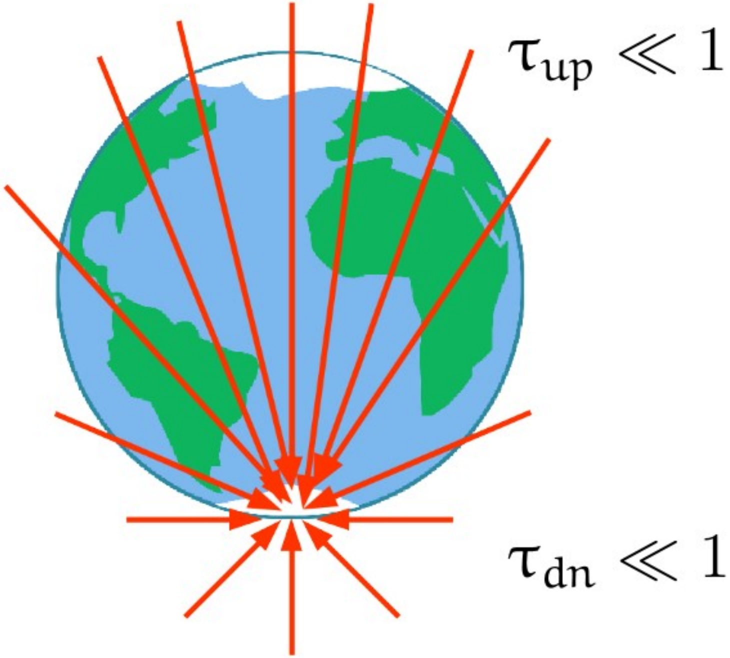
← Extrapolation

A. Cooper-Sarkar 2012

Measuring the high-energy cross section

$$\text{Optical depth to } \nu N \text{ int's} = \frac{\text{Distance from Earth's surface to IceCube}}{\text{Mean free path inside Earth}} \equiv \tau(E_\nu, \theta_z) \propto \sigma_{\nu N}$$

Below ~ 10 TeV: Earth is transparent



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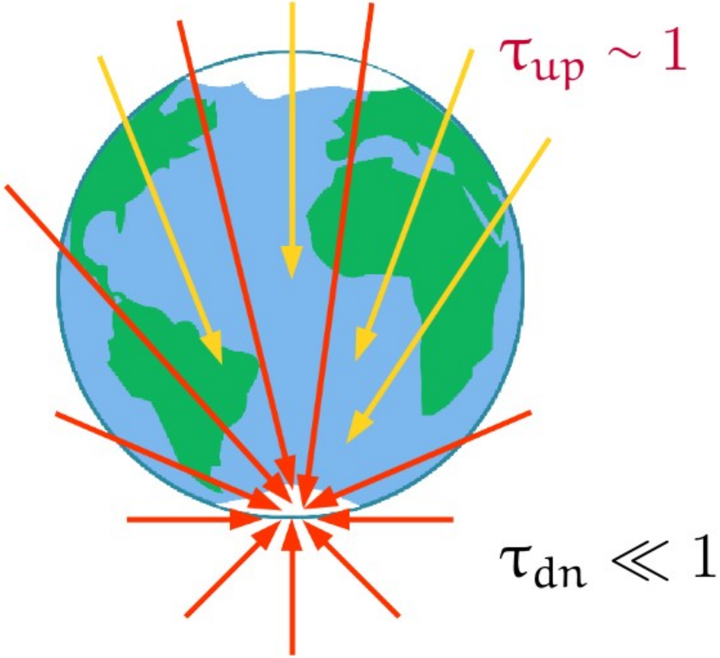

Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
Hussain, Mafatia, McKay, *PRD* 2008 Connolly, Thorne, Waters, *PRD* 2011; Marfatia, McKay, Weiler, *PLB* 2015

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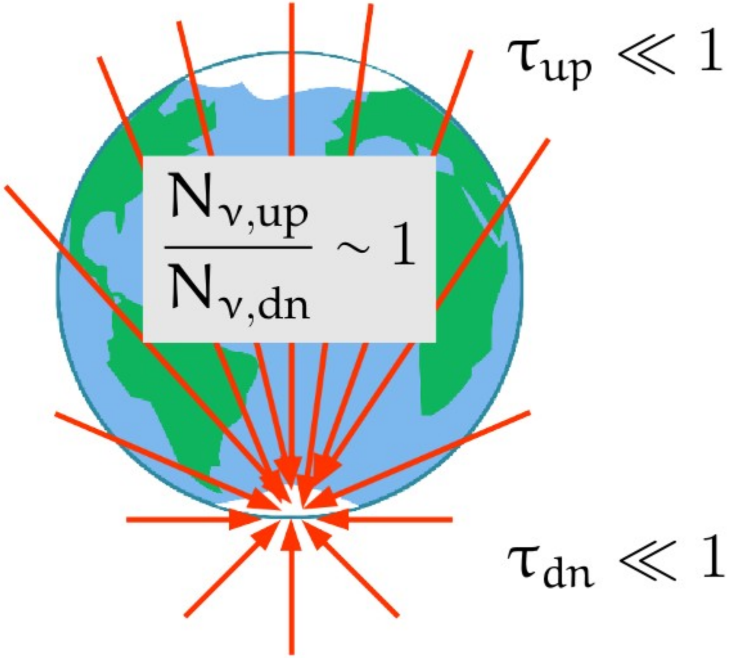

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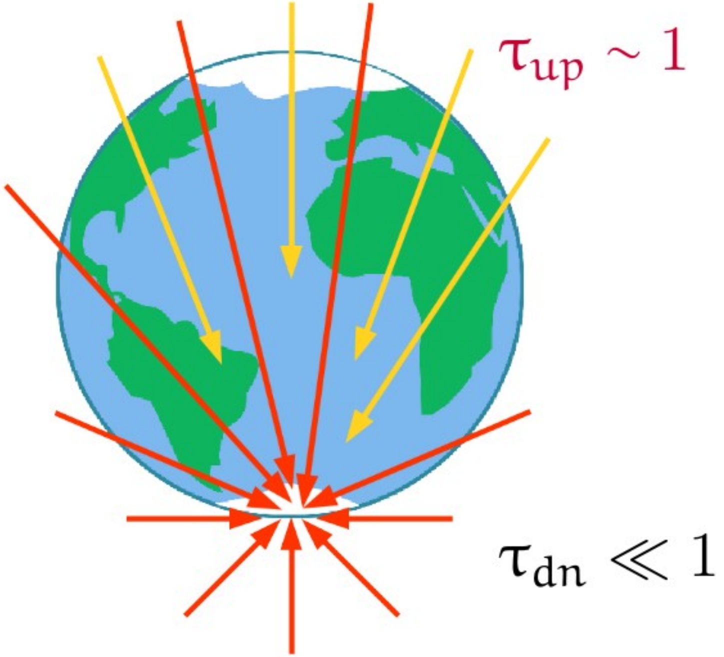

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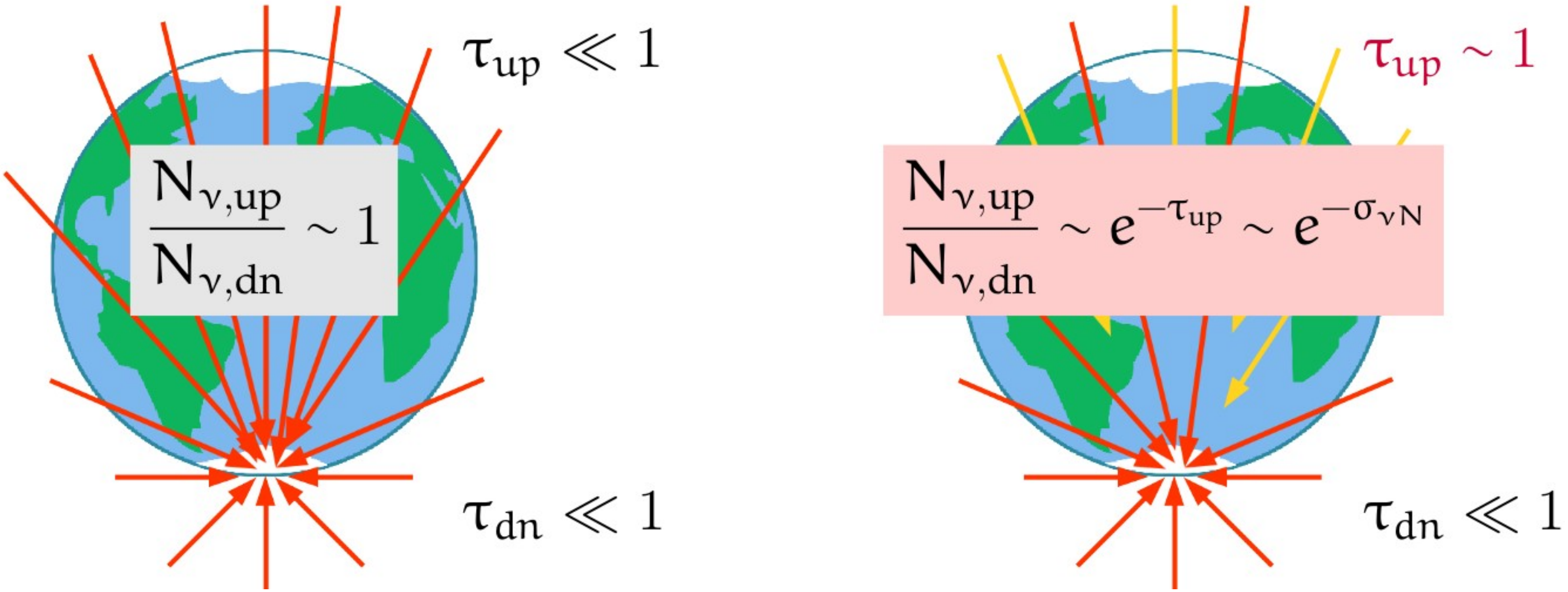
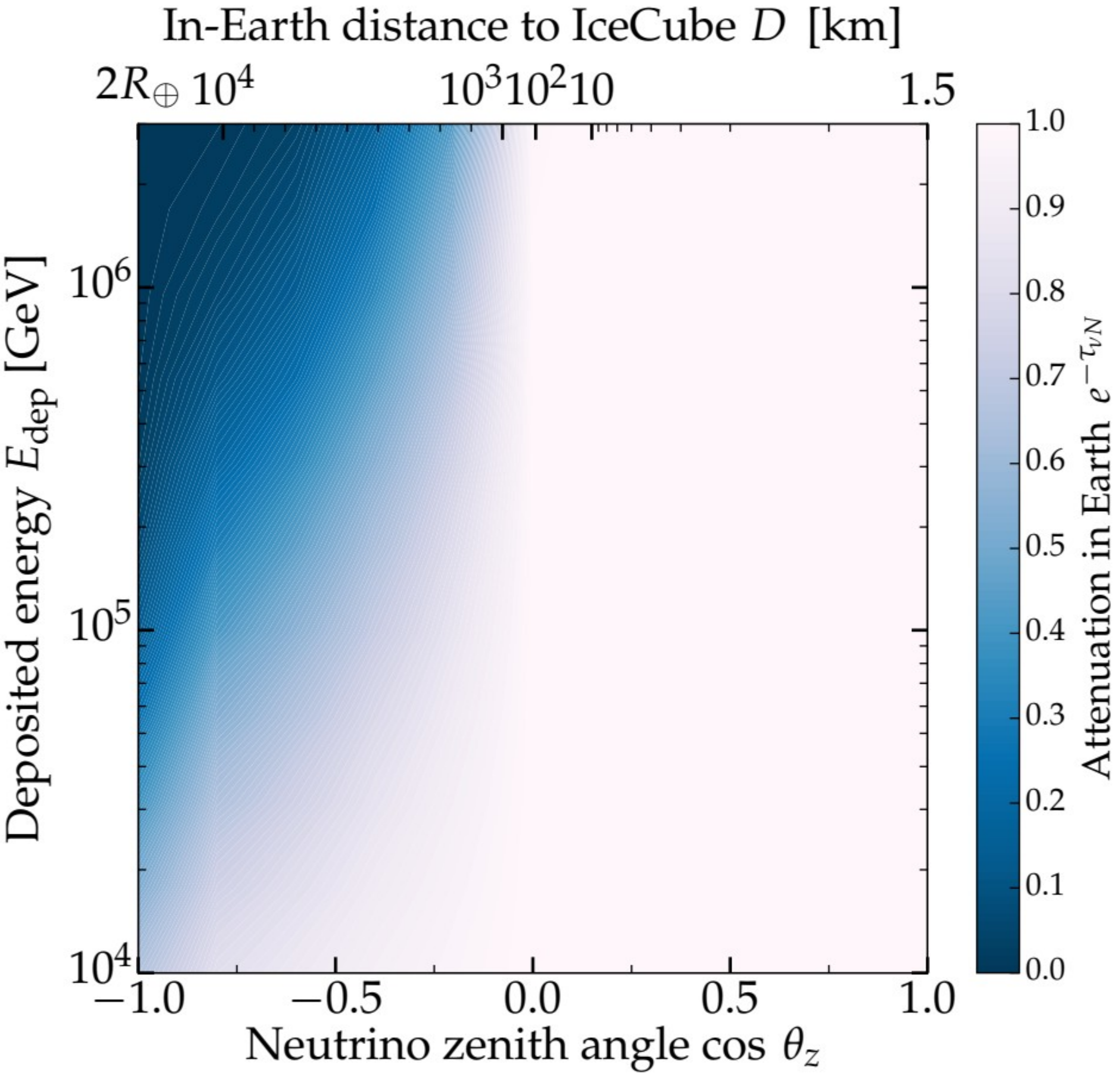
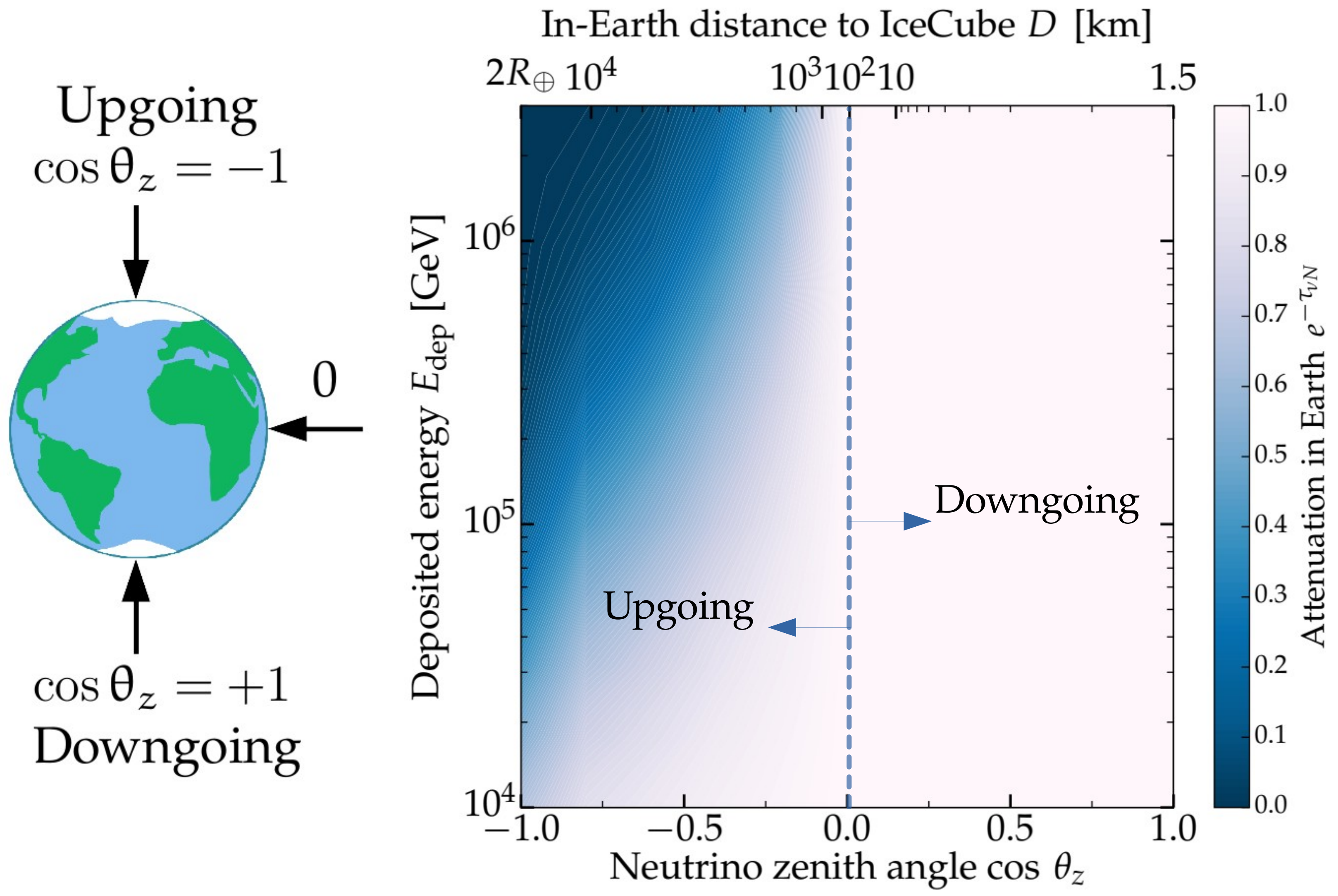
Above ~ 10 TeV: Earth is opaque



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



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
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
Downgoing
Upgoing
−1.0 −0.5 0.0 0.5 1.0
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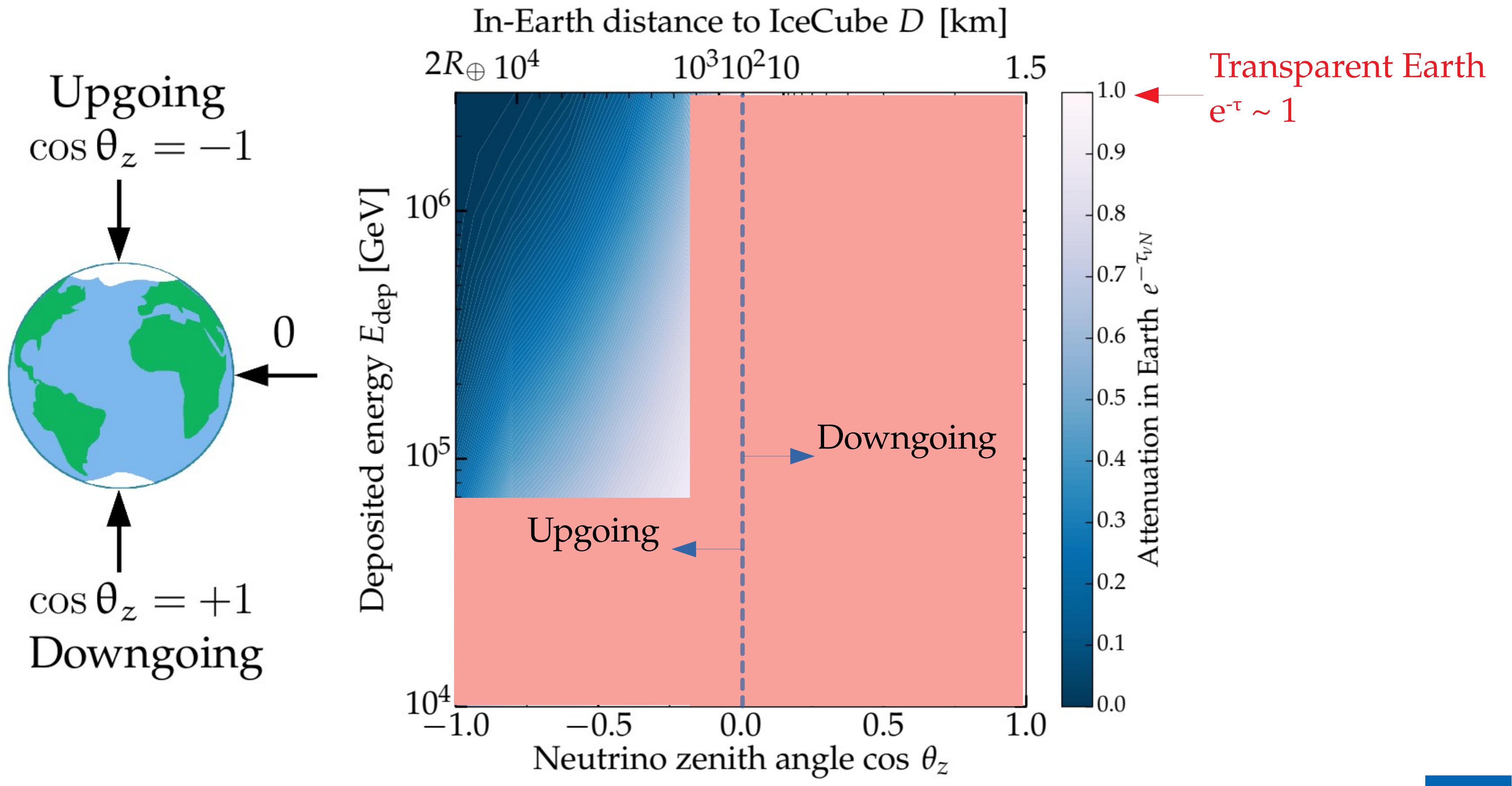
1.0 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.0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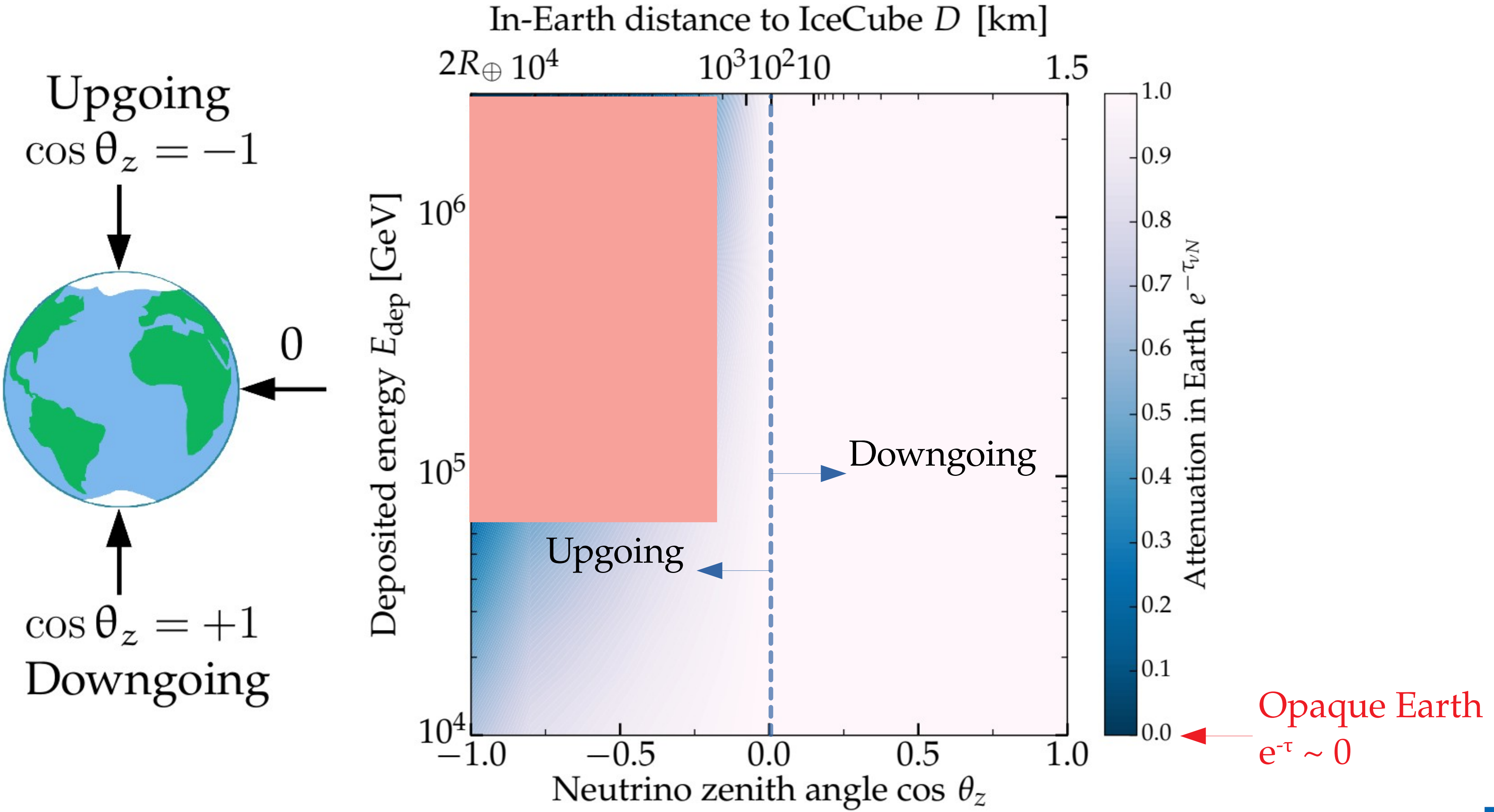
Downgoing
Upgoing
Attenuation in Earth $e^{-\tau_{\nu N}}$
1.0 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.0
Transparent Earth
$e^{-\tau} \sim 1$


Upgoing
$\cos\theta_z = -1$
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$2R_\oplus$ 10^4 10^3 10^2 10 1.5
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Downgoing
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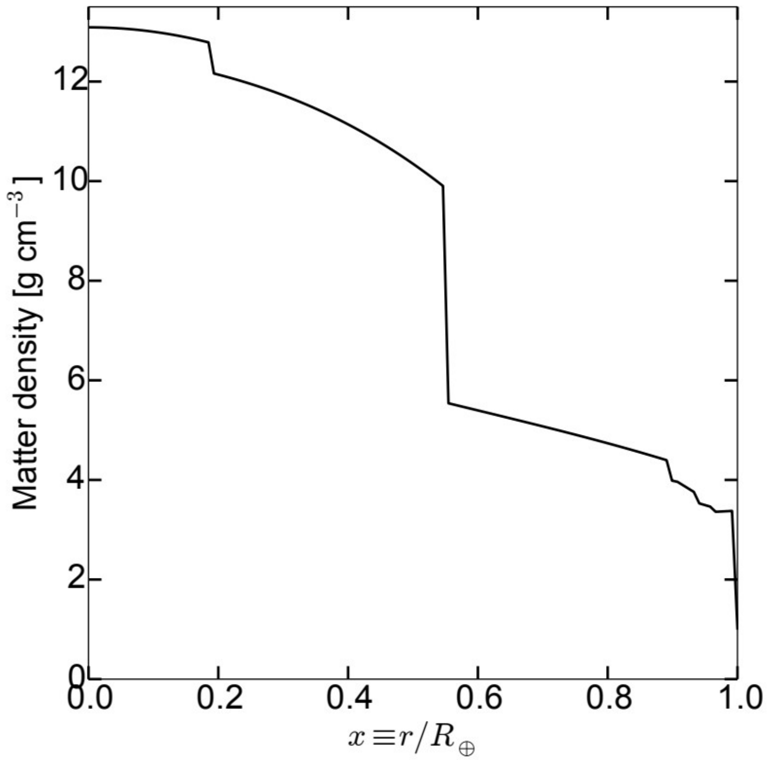
−1.0 −0.5 0.0 0.5 1.0
Neutrino zenith angle $\cos\theta_z$
Attenuation in Earth $e^{-\tau_{\nu N}}$
1.0 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.0
Opaque Earth
$e^{-\tau} \sim 0$

A feel for the in-Earth attenuation

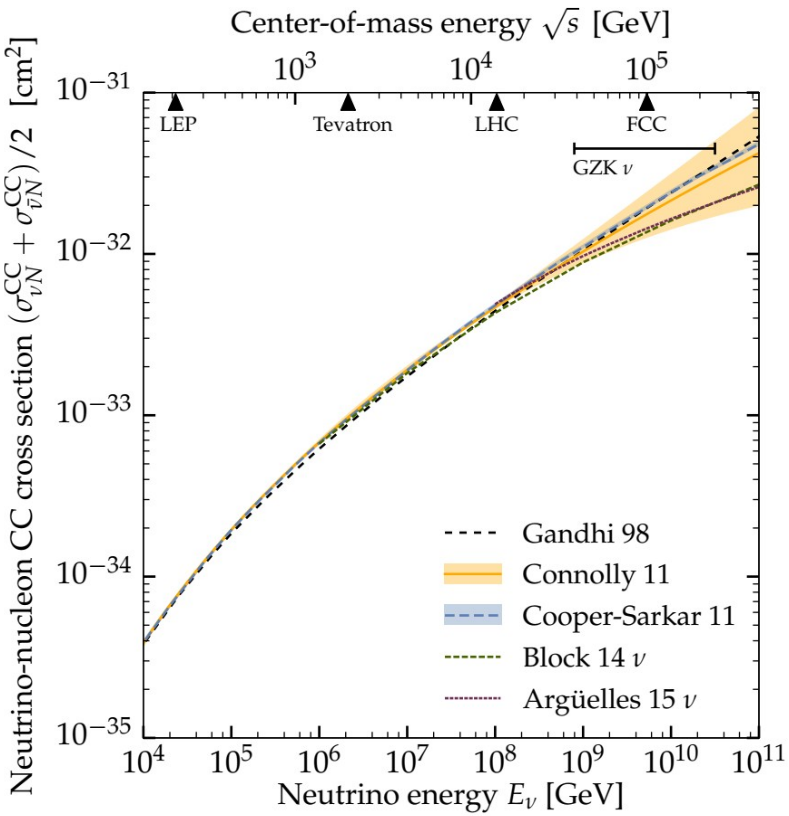
Earth matter density

(Preliminary Reference Earth Model)



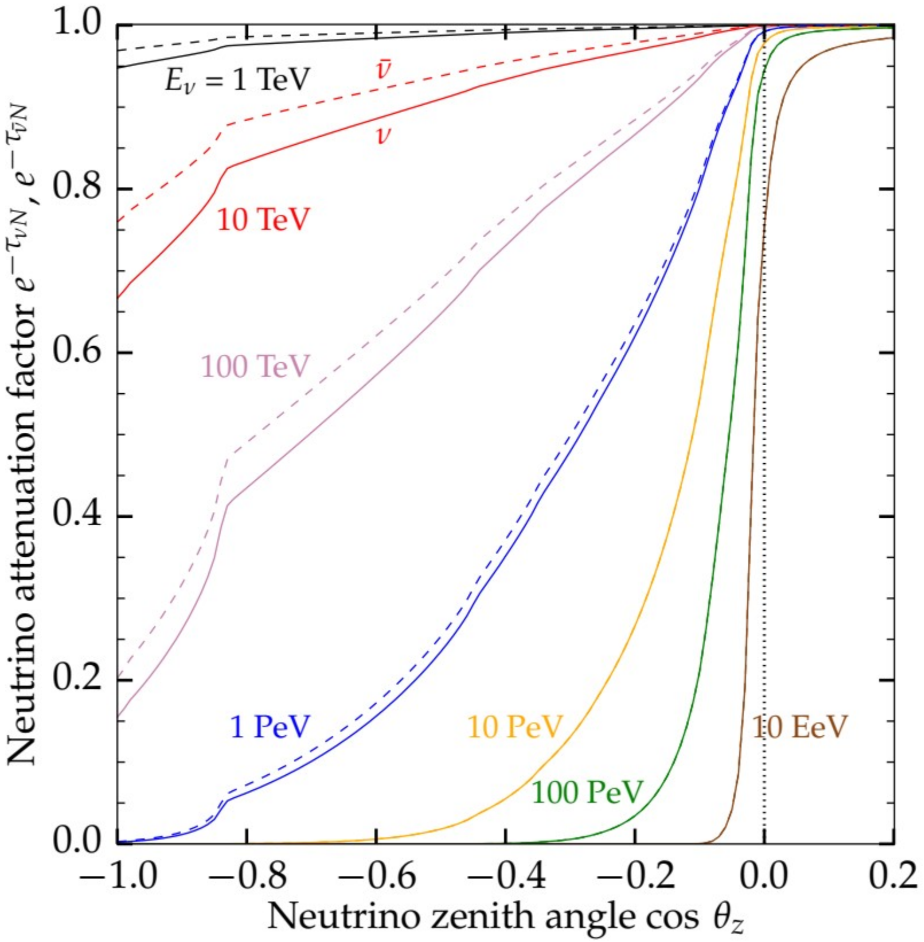
+

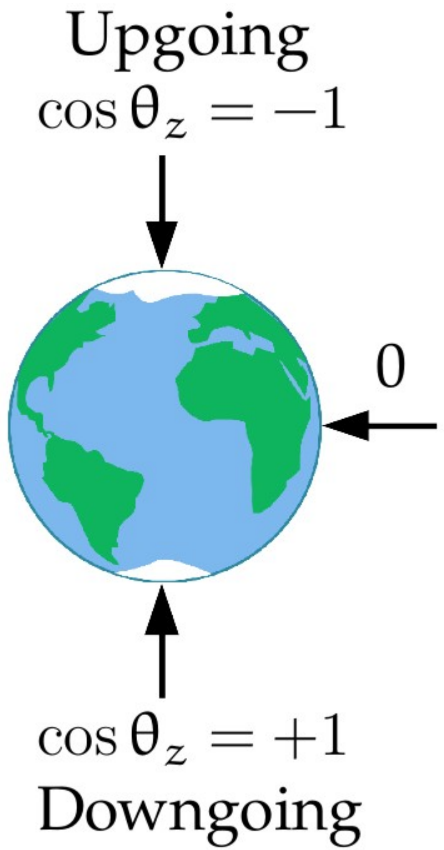
Neutrino-nucleon cross section

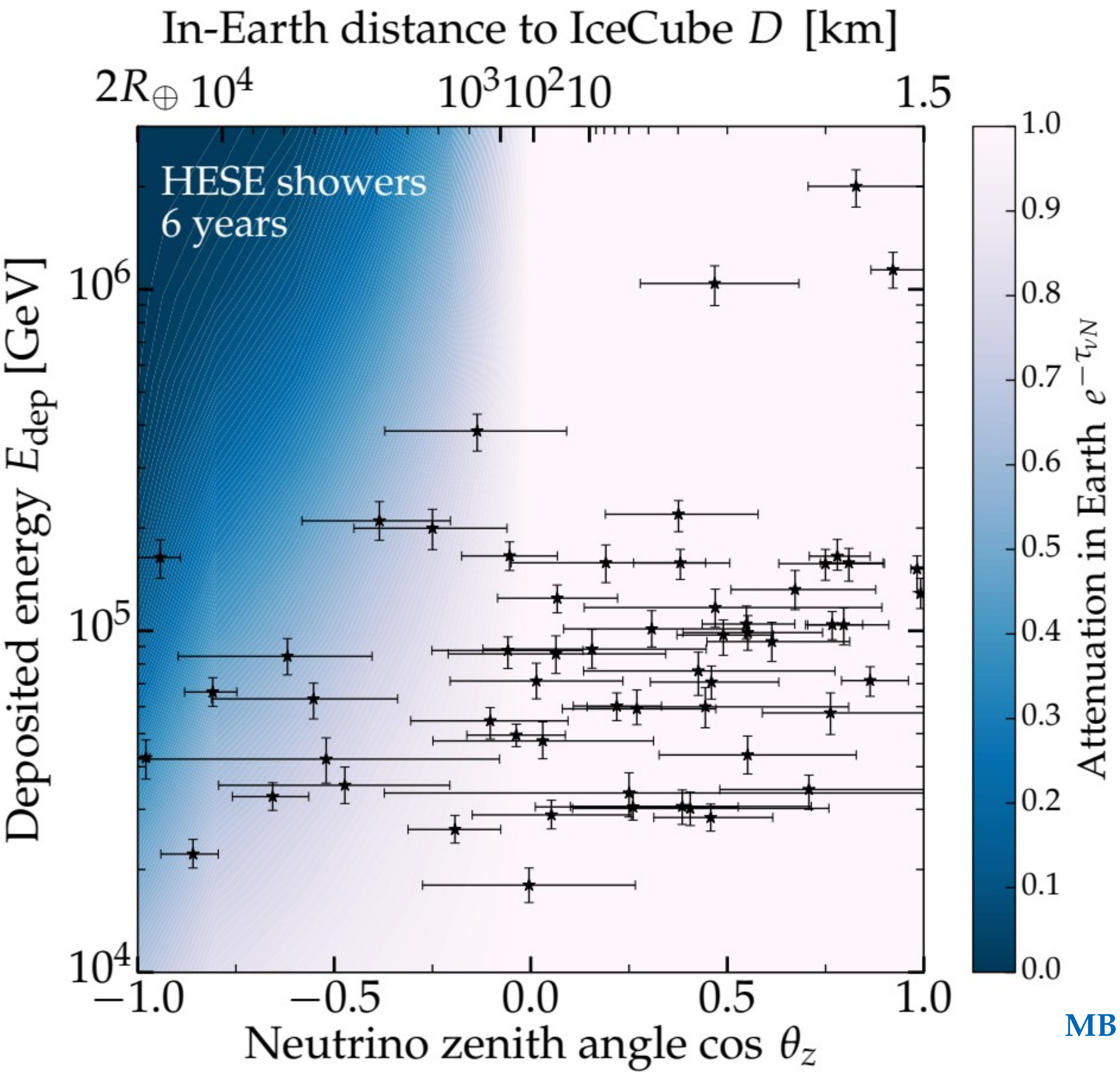


A feel for the in-Earth attenuation

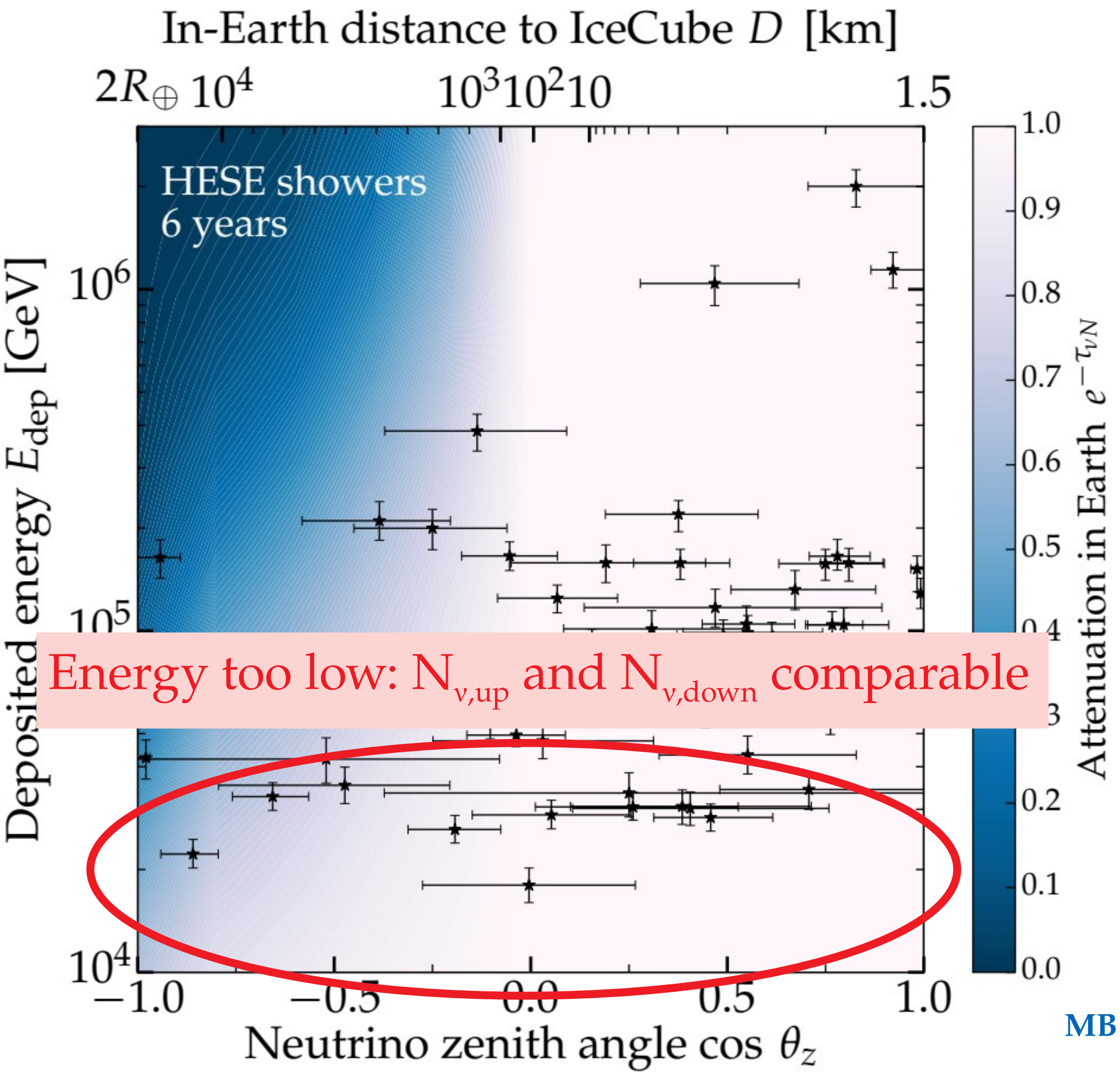
=



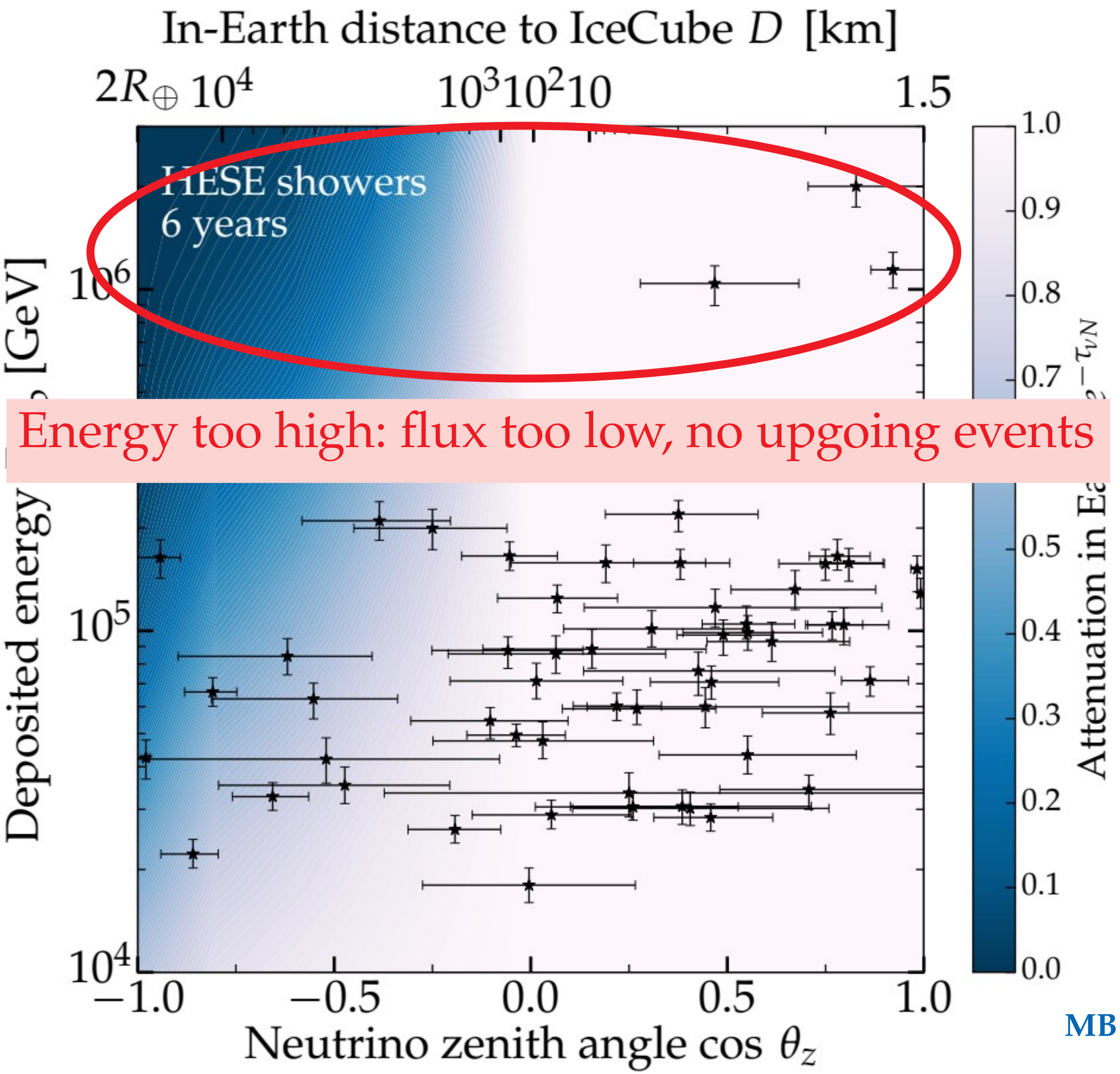




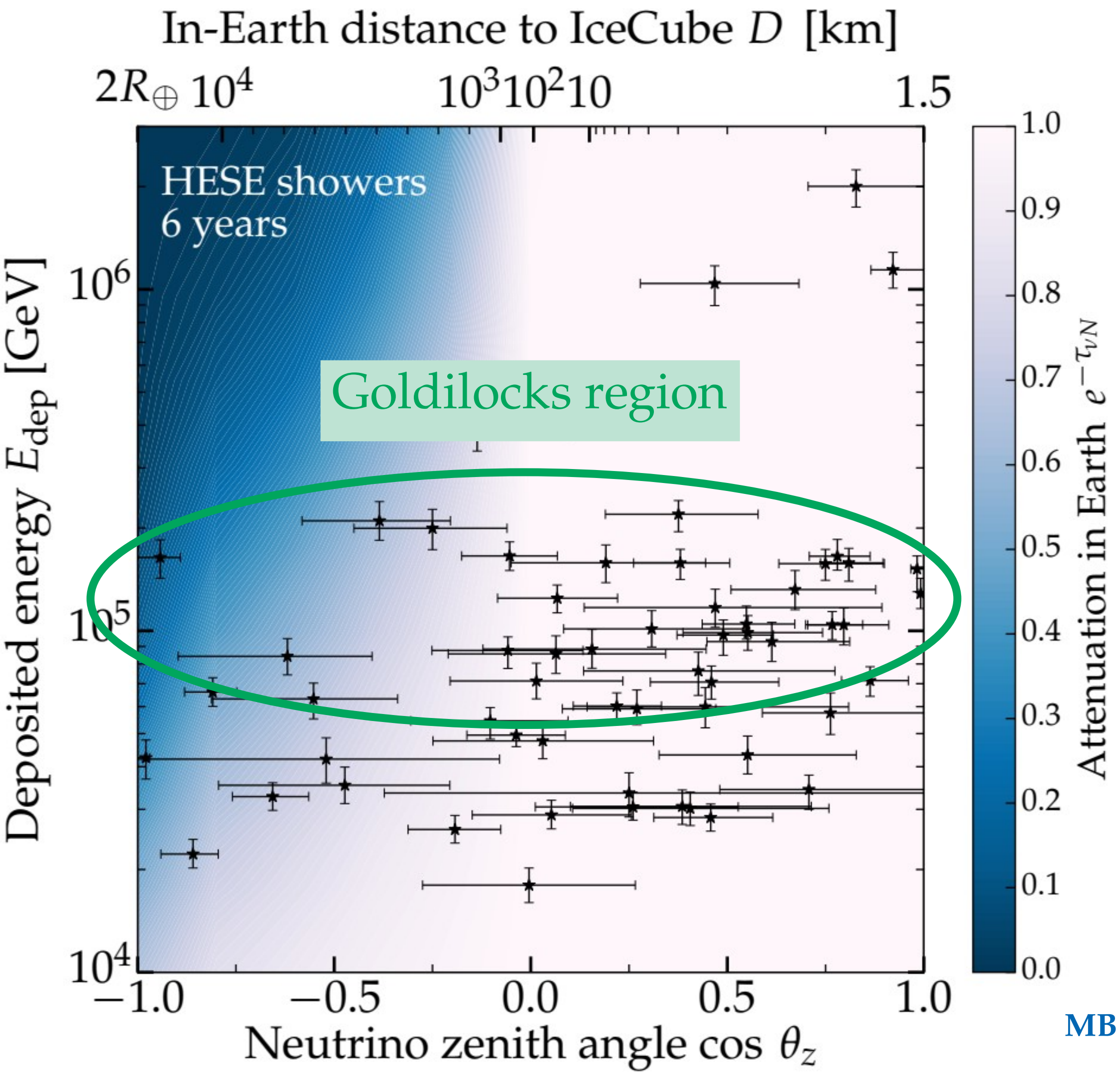
MB & Connolly, *PRL* 2019



MB & Connolly, *PRL* 2019



MB & Connolly, *PRL* 2019



MB & Connolly, *PRL* 2019

What goes into the (likelihood) mix?

- Inside each energy bin, we freely vary
  - N_{ast} (showers from astrophysical neutrinos)
  - N_{atm} (showers from atmospheric neutrinos)
  - γ (astrophysical spectral index)
  - σ_{CC} (neutrino-nucleon charged-current cross section)
- For each combination, we generate the angular and energy shower spectrum…
- … and compare it to the observed HESE spectrum via a likelihood
- Maximum likelihood yields σ_{CC} (marginalized over nuisance parameters)
- Bins are independent of each other – there are no (significant) cross-bin correlations

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Including detector resolution (10% in energy, 15° in direction)

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Marginalized cross section in each bin

TABLE I. Neutrino-nucleon charged-current inclusive cross sections, averaged between neutrinos ($\sigma_{\nu N}^{\rm CC}$) and anti-neutrinos ($\sigma_{\bar{\nu} N}^{\rm CC}$), extracted from 6 years of IceCube HESE showers. To obtain these results, we fixed $\sigma_{\bar{\nu} N}^{\rm CC} = \langle \sigma_{\bar{\nu} N}^{\rm CC} / \sigma_{\nu N}^{\rm CC} \rangle \cdot \sigma_{\nu N}^{\rm CC}$ — where $\langle \sigma_{\bar{\nu} N}^{\rm CC} / \sigma_{\nu N}^{\rm CC} \rangle$ is the average ratio of $\bar{\nu}$ to ν cross sections calculated using the standard prediction from Ref. [60] — and $\sigma_{\nu N}^{\rm NC} = \sigma_{\nu N}^{\rm CC}/3$, $\sigma_{\bar{\nu} N}^{\rm NC} = \sigma_{\bar{\nu} N}^{\rm CC}/3$. Uncertainties are statistical plus systematic, added in quadrature.

E_ν [TeV]	$\langle E_\nu \rangle$ [TeV]	$\langle \sigma_{\bar{\nu} N}^{\rm CC} / \sigma_{\nu N}^{\rm CC} \rangle$	$\log_{10}[\frac{1}{2}(\sigma_{\nu N}^{\rm CC} + \sigma_{\bar{\nu} N}^{\rm CC})/{\rm cm}^2]$
18–50	32	0.752	-34.35 ± 0.53
50–100	75	0.825	-33.80 ± 0.67
100–400	250	0.888	-33.84 ± 0.67
400–2004	1202	0.957	> -33.21 (1σ)

MB & A. Connolly, 1711.11043

Energy and angular shower spectra

Rate from all flavors, CC + NC:

$$\frac{d^2 N_{\rm sh}}{dE_{\rm sh} d\cos\theta_z} = \frac{d^2 N^{\rm CC}_{{\rm sh},e}}{dE_{\rm sh} d\cos\theta_z} + \underbrace{{\rm Br}_{\tau\to{\rm sh}}}_{= 0.83} \frac{d^2 N^{\rm CC}_{{\rm sh},\tau}}{dE_{\rm sh} d\cos\theta_z} + \sum_{l=e,\mu,\tau} \frac{d^2 N^{\rm NC}_{{\rm sh},l}}{dE_{\rm sh} d\cos\theta_z}$$

Contribution from one flavor CC:

$$\frac{d^2 N^{\rm CC}_{{\rm sh},l}}{dE_{\rm sh} d\cos\theta_z}(E_{\rm sh}, \cos\theta_z) \simeq -2\pi \rho_{\rm ice} N_A V T \left\{ \Phi_l(E_\nu) \sigma^{\rm CC}_{\nu N}(E_\nu) e^{-\tau_{\nu N}(E_\nu,\theta_z)} + \Phi_{\bar{l}}(E_\nu) \sigma^{\rm CC}_{\bar{\nu} N}(E_\nu) e^{-\tau_{\bar{\nu} N}(E_\nu,\theta_z)} \right\} \Big|_{E_\nu = E_{\rm sh}/f_{l,{\rm CC}}}$$

Conversion between shower energy and neutrino energy:

$$f_{l,t} \equiv \frac{E_{\rm sh}}{E_\nu} \simeq \begin{cases} 1 & \text{for } l = e \text{ and } t = {\rm CC} \\ [\langle y \rangle + 0.7\,(1 - \langle y \rangle)] \simeq 0.8 & \text{for } l = \tau \text{ and } t = {\rm CC} \\ \langle y \rangle \simeq 0.25 & \text{for } l = e, \mu, \tau \text{ and } t = {\rm NC} \end{cases}$$

MB & A. Connolly, 1711.11043

Detector resolution

Number of contained showers:

$$\frac{d^2 N_{\rm sh}}{dE_{\rm dep} d\cos\theta_z} = \int dE_{\rm sh} \int d\cos\theta'_z \frac{d^2 N_{\rm sh}}{dE_{\rm sh} d\cos\theta'_z} R_E(E_{\rm sh}, E_{\rm dep}, \sigma_E(E_{\rm sh})) R_\theta(\cos\theta'_z, \cos\theta_z, \sigma_{\cos\theta_z})$$

Energy resolution: [Palomares-Ruiz, Vincent, Mena *PRD* 2015; Vincent, Palomares-Ruiz, Mena *PRD* 2016; MB, Beacom. Murase, *PRD* 2016]

$$R_E(E_{\rm sh}, E_{\rm dep}, \sigma_E(E_{\rm sh})) = \frac{1}{\sqrt{2\pi\sigma_E^2(E_{\rm sh})}} \exp\left[-\frac{(E_{\rm sh} - E_{\rm dep})^2}{2\sigma_E^2(E_{\rm sh})}\right]$$ with $\sigma_E(E_{\rm sh}) = 0.1 E_{\rm sh}$

IceCube, *JINST* 2014

Angular resolution:

$$R_\theta(\cos\theta'_z, \cos\theta_z, \sigma_{\cos\theta_z}) = \frac{1}{\sqrt{2\pi\sigma^2_{\cos\theta_z}}} \exp\left[-\frac{(\cos\theta'_z - \cos\theta_z)^2}{2\sigma^2_{\cos\theta_z}}\right]$$

with $\sigma_{\cos\theta_z} \equiv \frac{1}{2}\left[\left|\cos(\theta_z + \sigma_{\theta_z}) - \cos\theta_z\right| + \left|\cos(\theta_z - \sigma_{\theta_z}) - \cos\theta_z\right|\right]$ and $\sigma_{\theta_z} = 15^\circ$

MB & A. Connolly, 1711.11043

Likelihood

In an energy bin containing $N_{\rm sh}^{\rm obs}$ observed showers, the likelihood is

Each energy bin is independent

$$\mathcal{L} = \frac{e^{-(N_{\rm sh}^{\rm atm}+N_{\rm sh}^{\rm ast})}}{N_{\rm sh}^{\rm obs}!} \prod_{i=1}^{N_{\rm sh}^{\rm obs}} \mathcal{L}_i$$

Partial likelihood, *i.e.*, relative probability of the *i*-th shower being from an atmospheric neutrino or an astrophysical neutrino:

Depends on $\sigma_{\nu N}$

$$\mathcal{L}_i = N_{\rm sh}^{\rm atm}\,\mathcal{P}_i^{\rm atm} + N_{\rm sh}^{\rm ast}\,\mathcal{P}_i^{\rm ast}$$

$$\mathcal{P}_i^{\rm atm} = \left(\int_{E_{\rm dep}^{\rm min}}^{E_{\rm dep}^{\rm max}} dE_{\rm dep} \int_{-1}^{1} d\cos\theta_z \frac{d^2N_{\rm sh}^{\rm atm}}{dE_{\rm dep}d\cos\theta_z}\right)^{-1} \left(\left.\frac{d^2N_{\rm sh}^{\rm atm}}{dE_{\rm dep}d\cos\theta_z}\right|_{E_{{\rm dep},i},\cos\theta_{z,i}}\right)$$

PDF for this shower to be made by an atmospheric ν

$$\mathcal{P}_i^{\rm ast} = \left(\int_{E_{\rm dep}^{\rm min}}^{E_{\rm dep}^{\rm max}} dE_{\rm dep} \int_{-1}^{1} d\cos\theta_z \frac{d^2N_{\rm sh}^{\rm ast}}{dE_{\rm dep}d\cos\theta_z}\right)^{-1} \left(\left.\frac{d^2N_{\rm sh}^{\rm ast}}{dE_{\rm dep}d\cos\theta_z}\right|_{E_{{\rm dep},i},\cos\theta_{z,i}}\right)$$

PDF for this shower to be made by an astrophysical ν

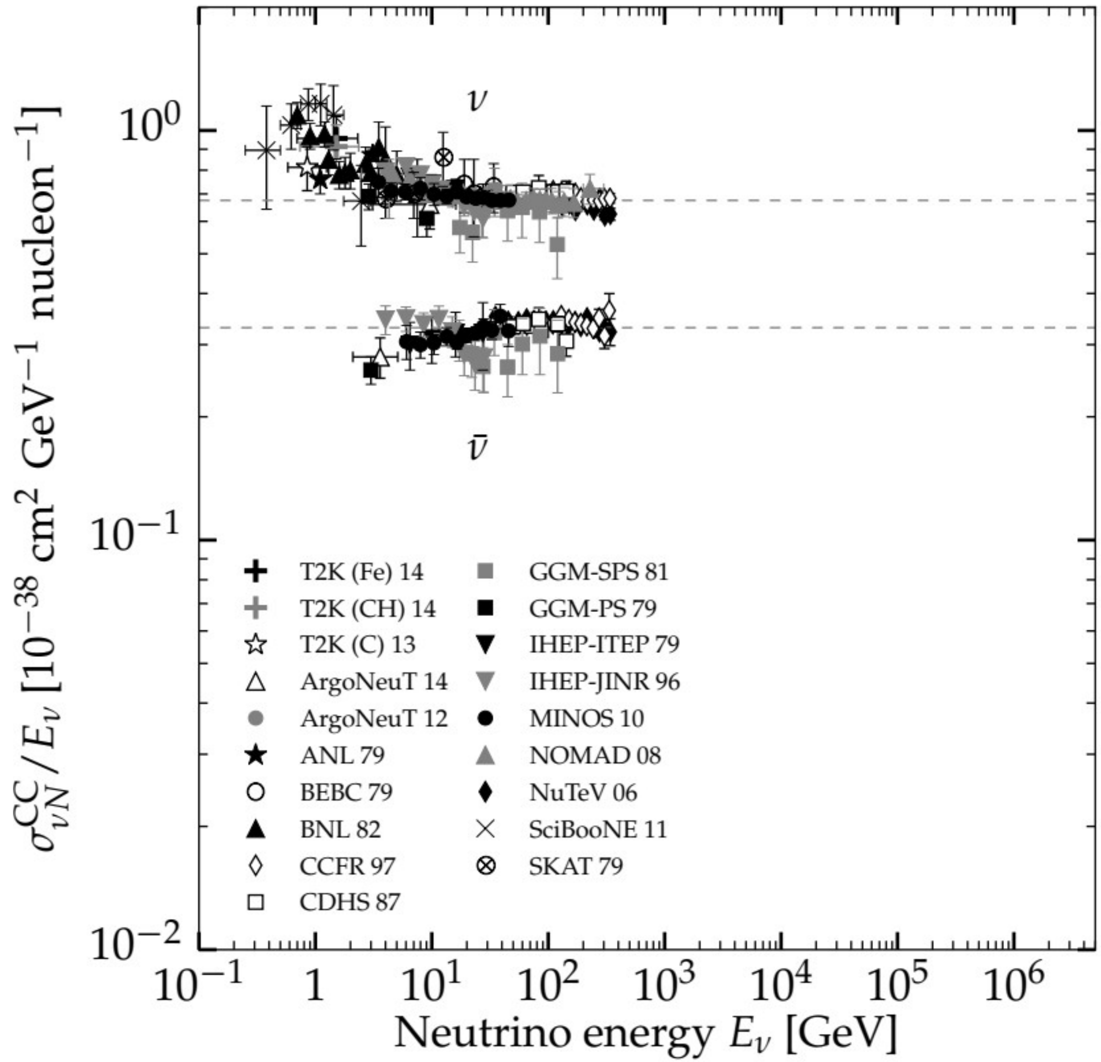
Depends on γ and $\sigma_{\nu N}$

MB & A. Connolly, 1711.11043

See also: Palomares-Ruiz, Vincent, Mena *PRD* 2015; Vincent, Palomares-Ruiz, Mena *PRD* 2016

The fine print

- High-energy ν's: astrophysical (isotropic) + atmospheric (**anisotropic**)
  ↦ We take into account the shape of the atmospheric contribution
- The shape of the astrophysical ν **energy spectrum** is still uncertain
  ↦ We take a $E^{-\gamma}$ spectrum in *narrow* energy bins
- **NC showers** are sub-dominant to **CC showers**, but they are indistinguishable
  ↦ Following Standard-Model predictions, we take $\sigma_{NC} = \sigma_{CC}/3$
- IceCube does not **distinguish ν from $\bar{\nu}$**, and their cross-sections are different
  ↦ We assume equal fluxes, expected from production via pp collisions
  ↦ We assume the avg. ratio $\langle\sigma_{\bar{\nu}N}/\sigma_{\nu N}\rangle$ in each bin known, from SM predictions
- The **flavor composition** of astrophysical neutrinos is still uncertain
  ↦ We assume equal flux of each flavor, compatible with theory and observations



MB & Connolly *PRL* 2019
See also: IceCube, *Nature* 2017

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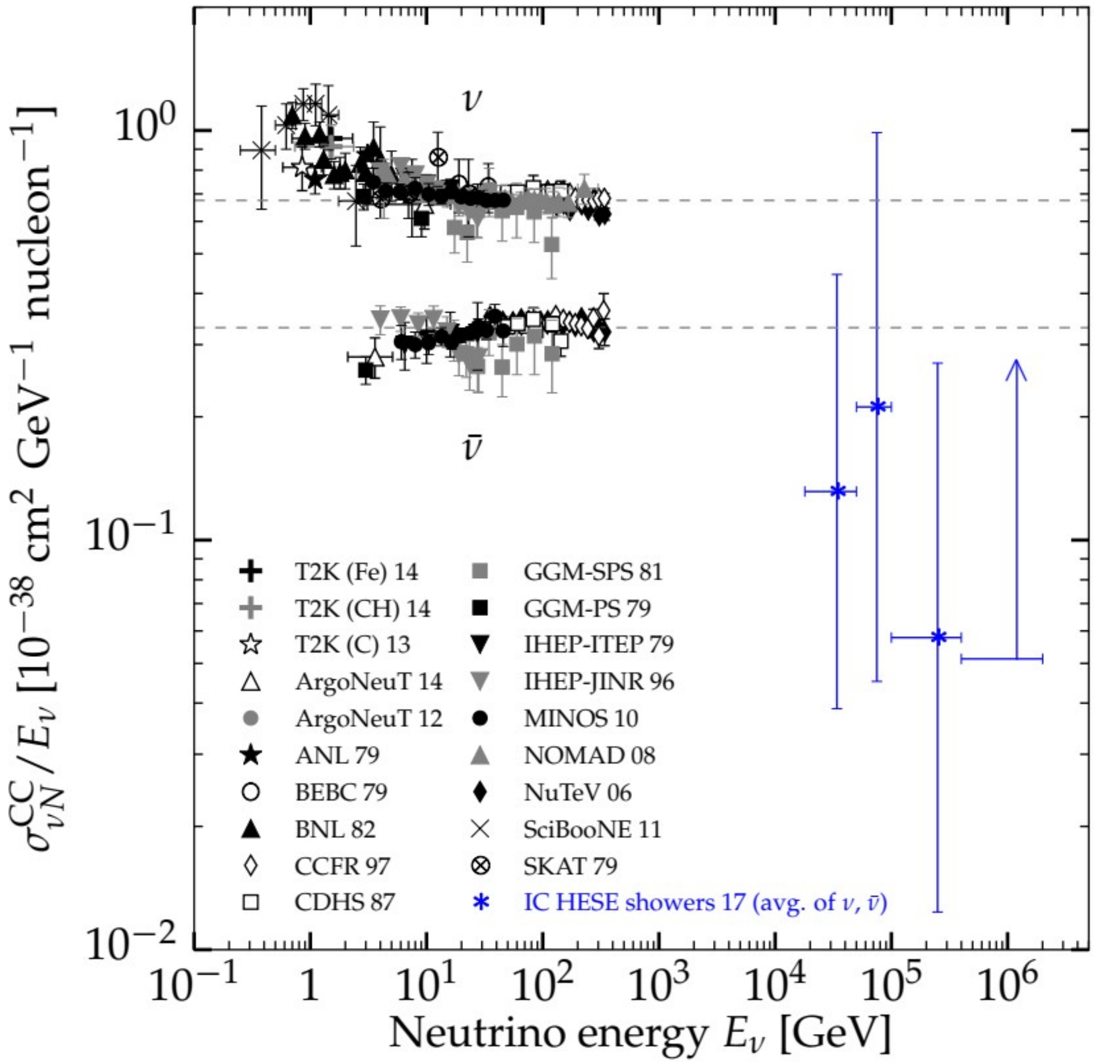
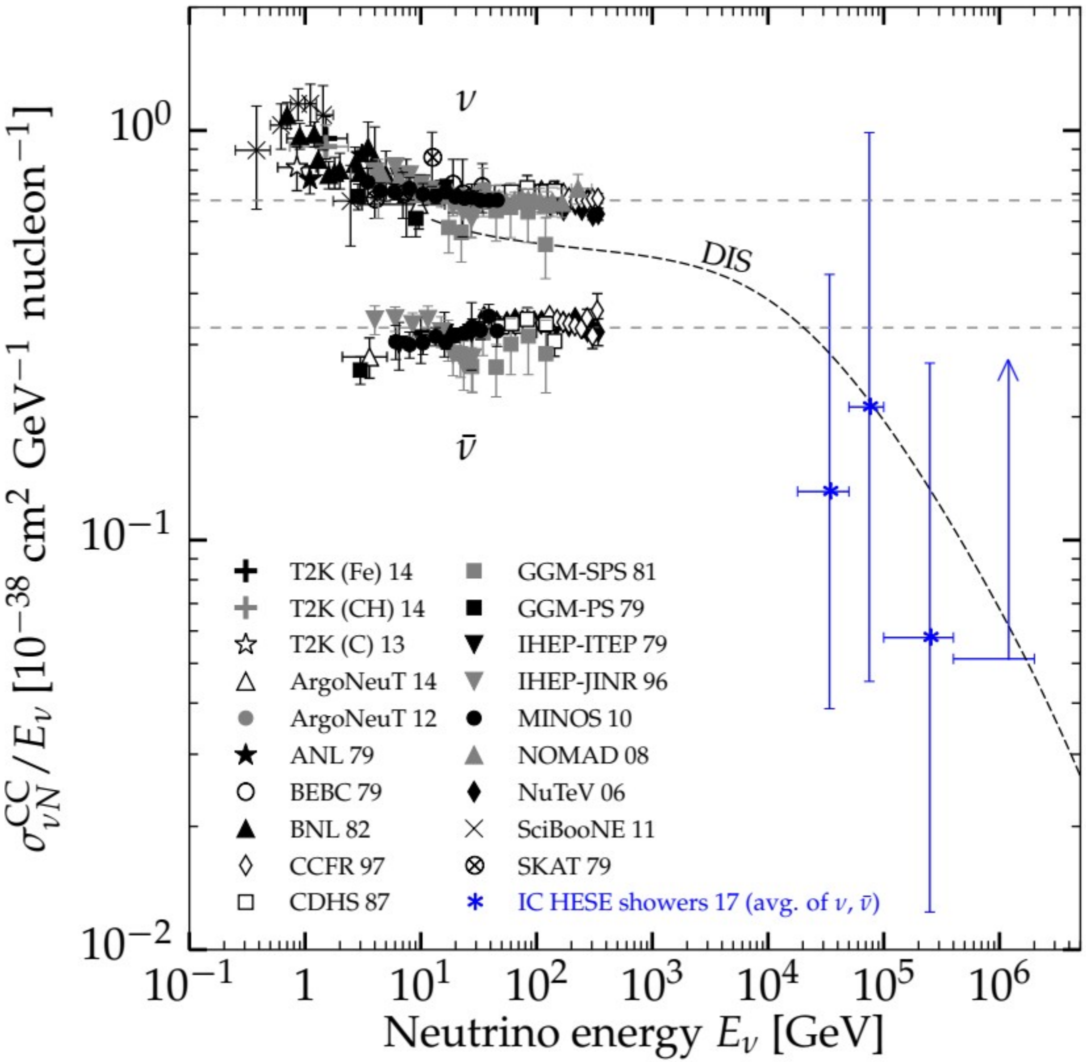
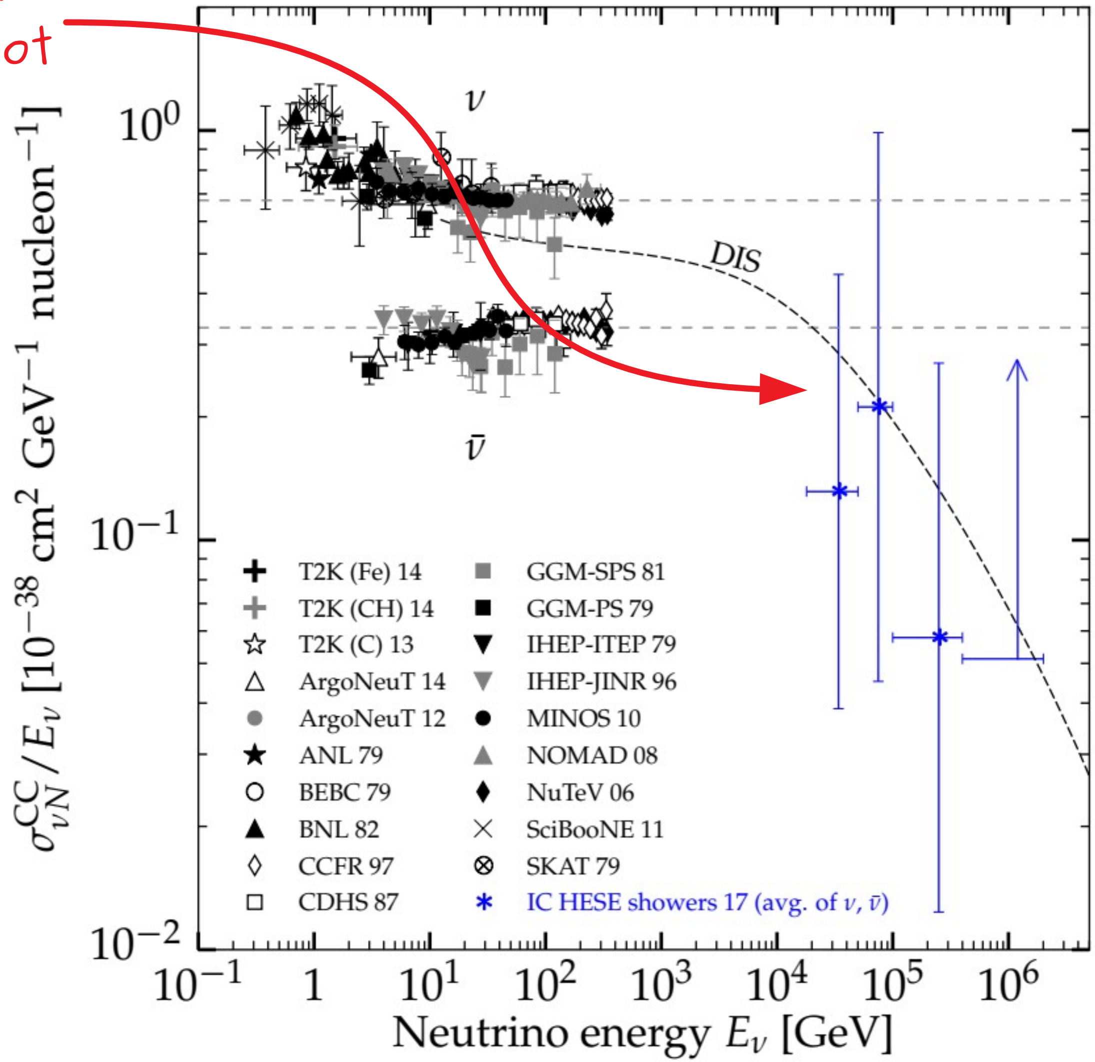


MB & Connolly *PRL* 2019
See also: IceCube, *Nature* 2017



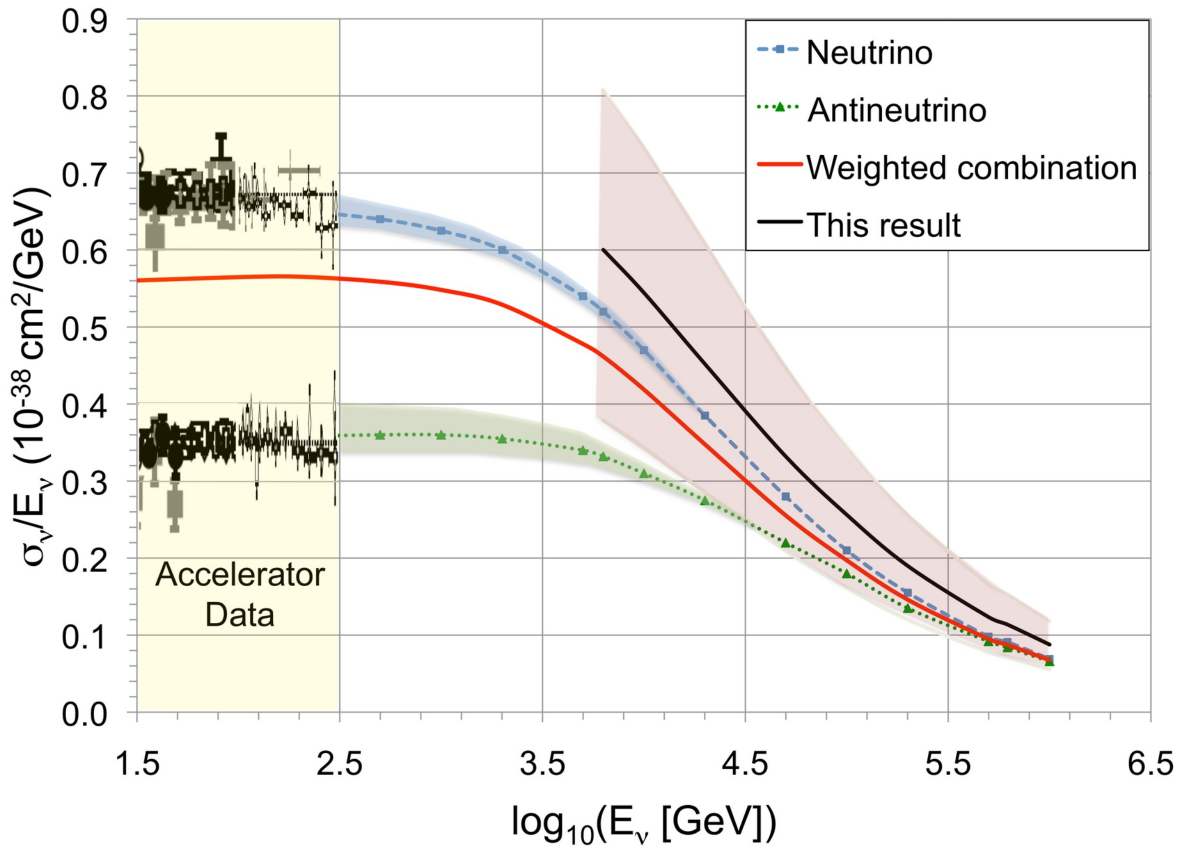
Extending the PDG cross-section plot

MB & Connolly *PRL* 2019
See also: IceCube, *Nature* 2017



Using through-going muons instead

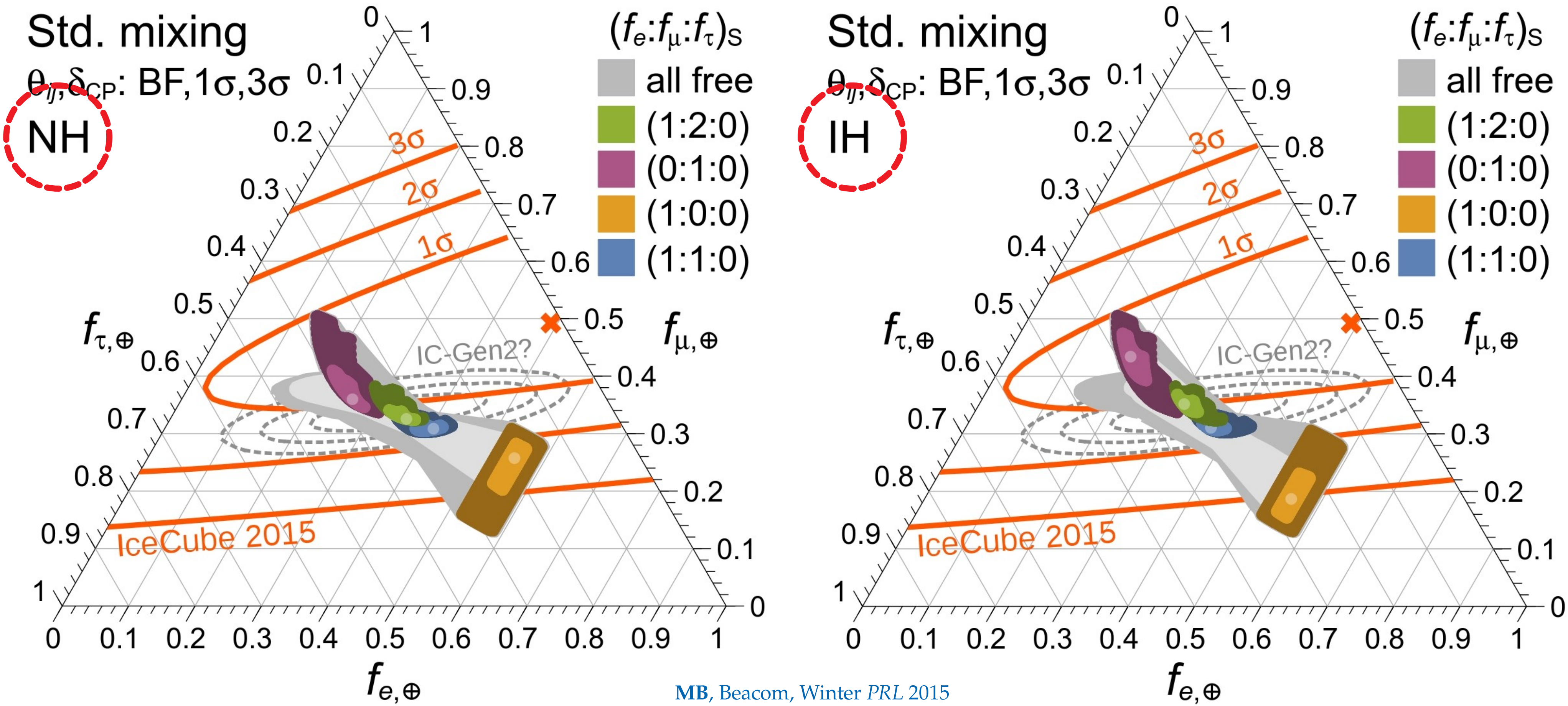
- Use ~10^4 through-going muons
- Measured: $\mathrm{d}E_\mu/\mathrm{d}x$
- Inferred: $E_\mu \approx \mathrm{d}E_\mu/\mathrm{d}x$
- From simulations (uncertain): most likely E_ν given E_μ
- Fit the ratio σ_{obs}/σ_{SM}
  $1.30\,^{+0.21}_{-0.19}\,(\text{stat.})\,^{+0.39}_{-0.43}\,(\text{syst.})$
- All events grouped in a single energy bin 6–980 TeV



IceCube, *Nature* 2017

Flavor composition – a few source choices

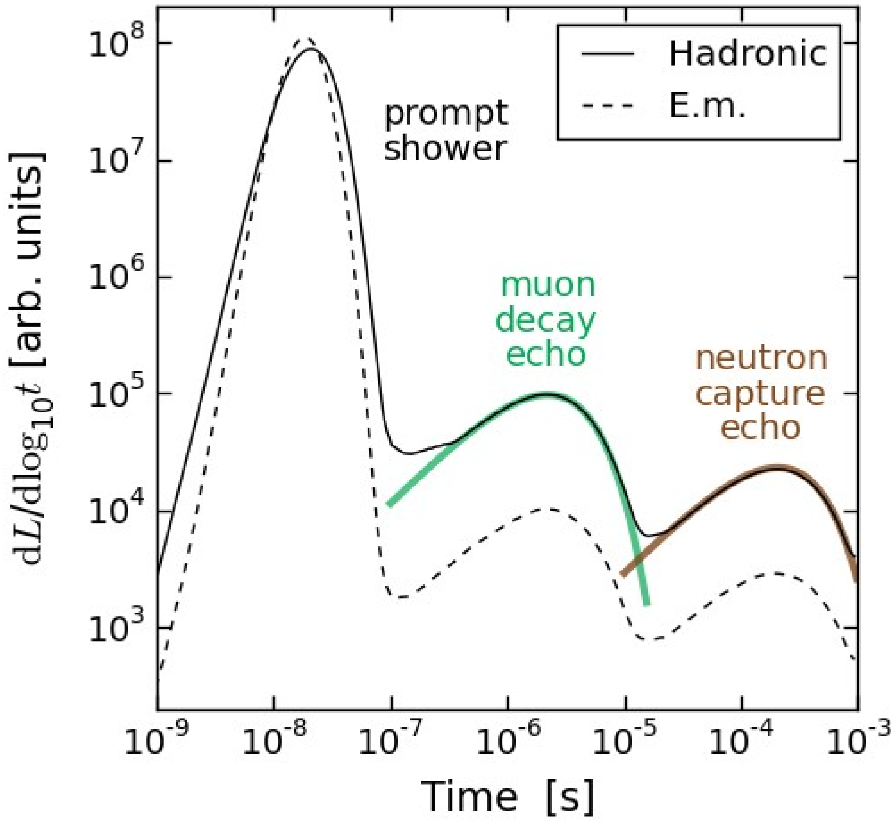
Flavor composition – a few source choices

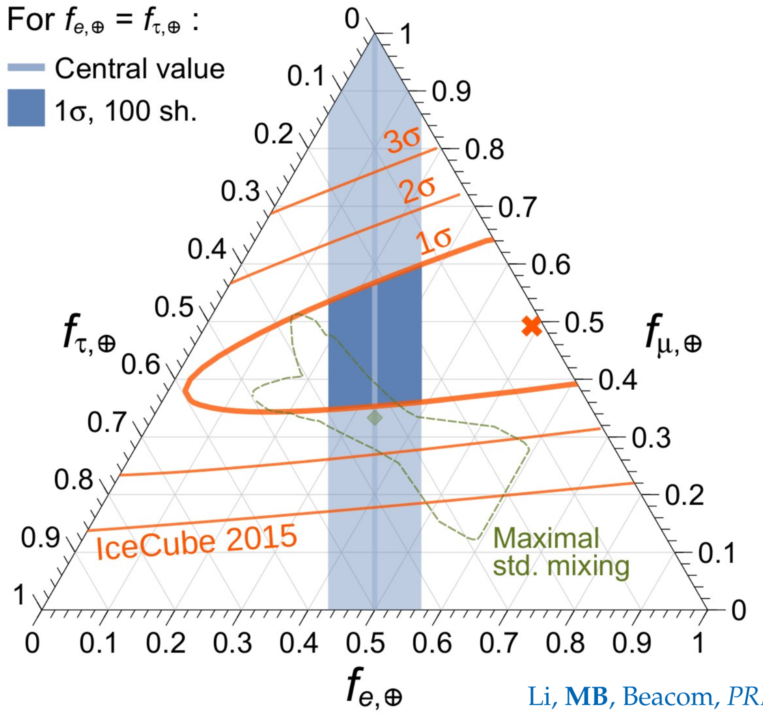


MB, Beacom, Winter *PRL* 2015

Side note: Improving flavor-tagging using *echoes*

Late-time light (*echoes*) from muon decays and neutron captures can separate showers made by ν_e and ν_τ –





Li, **MB**, Beacom, *PRL* 2019

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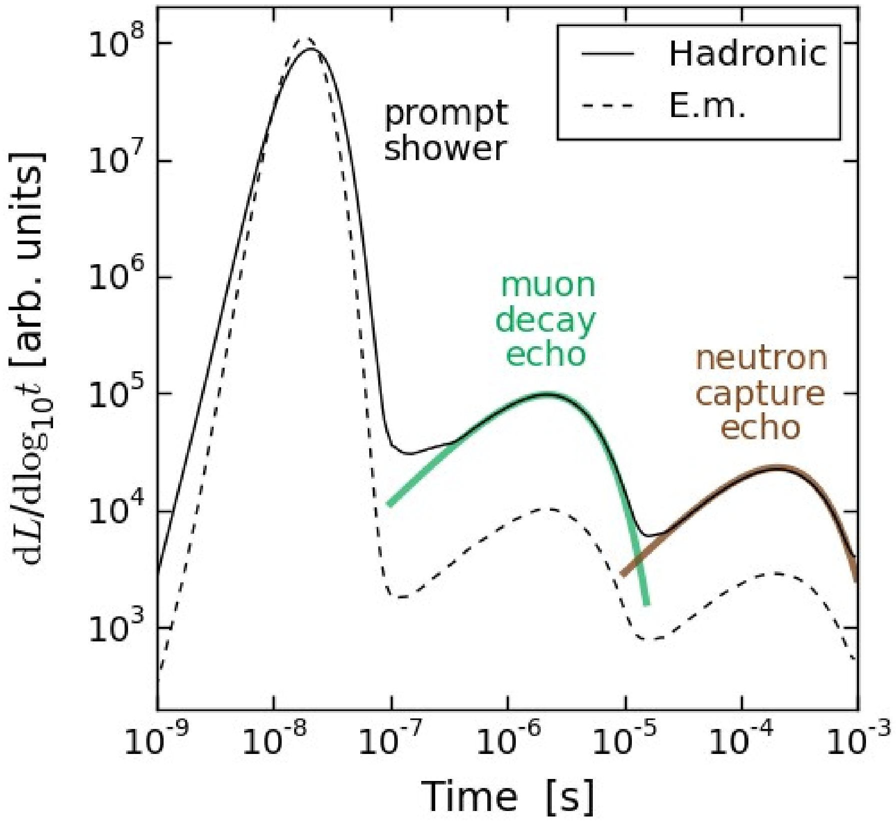
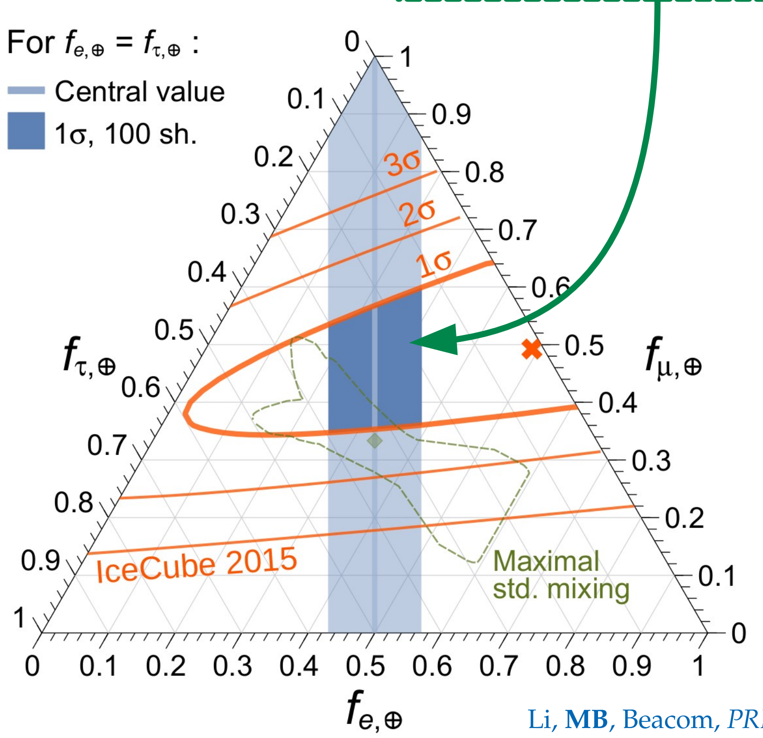


~10 × improvement over current measurement



Li, **MB**, Beacom, *PRL* 2019

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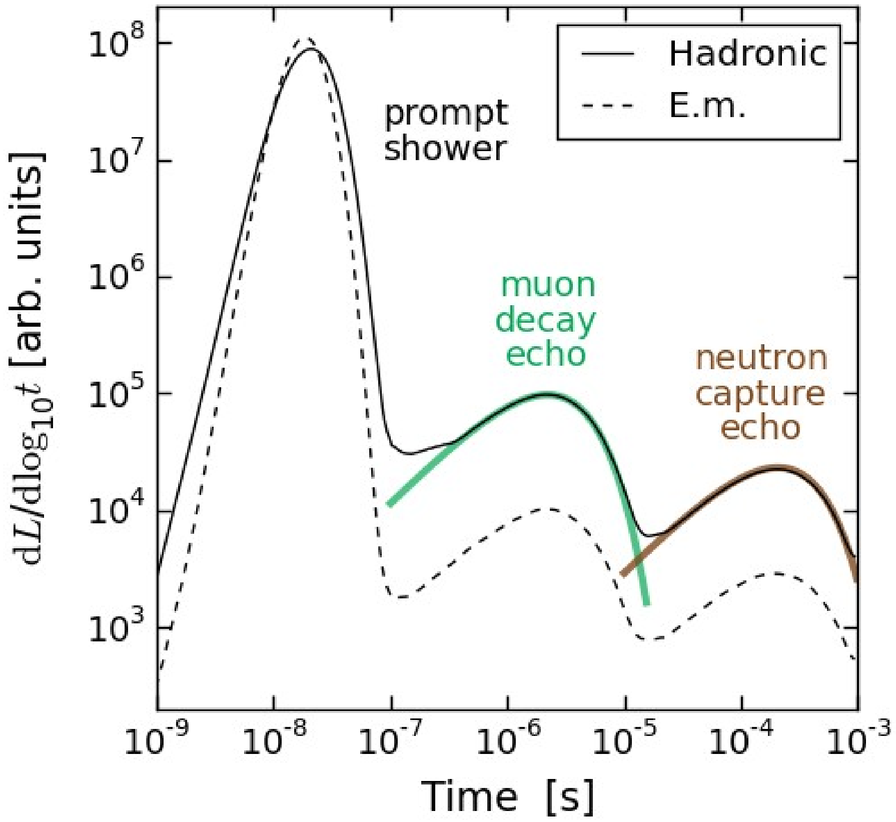

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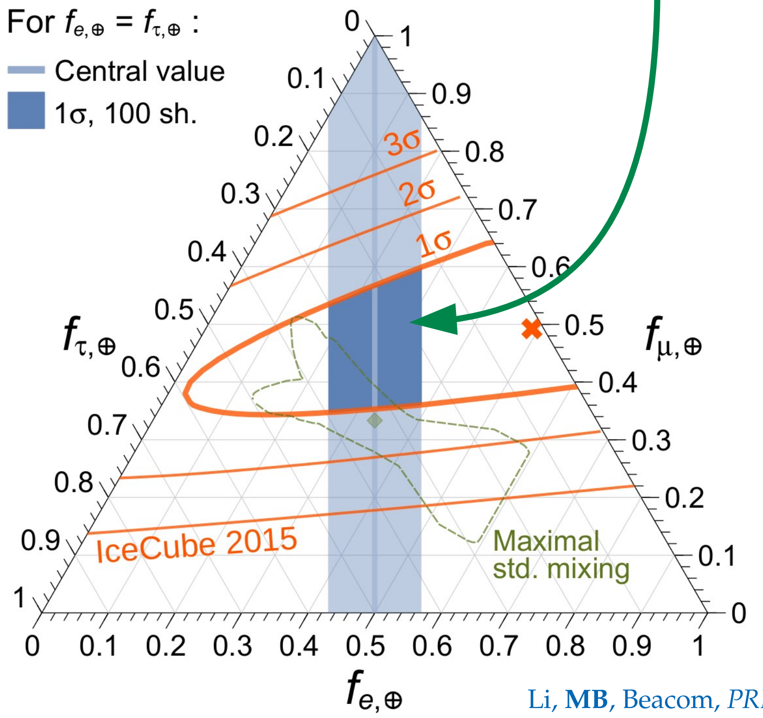
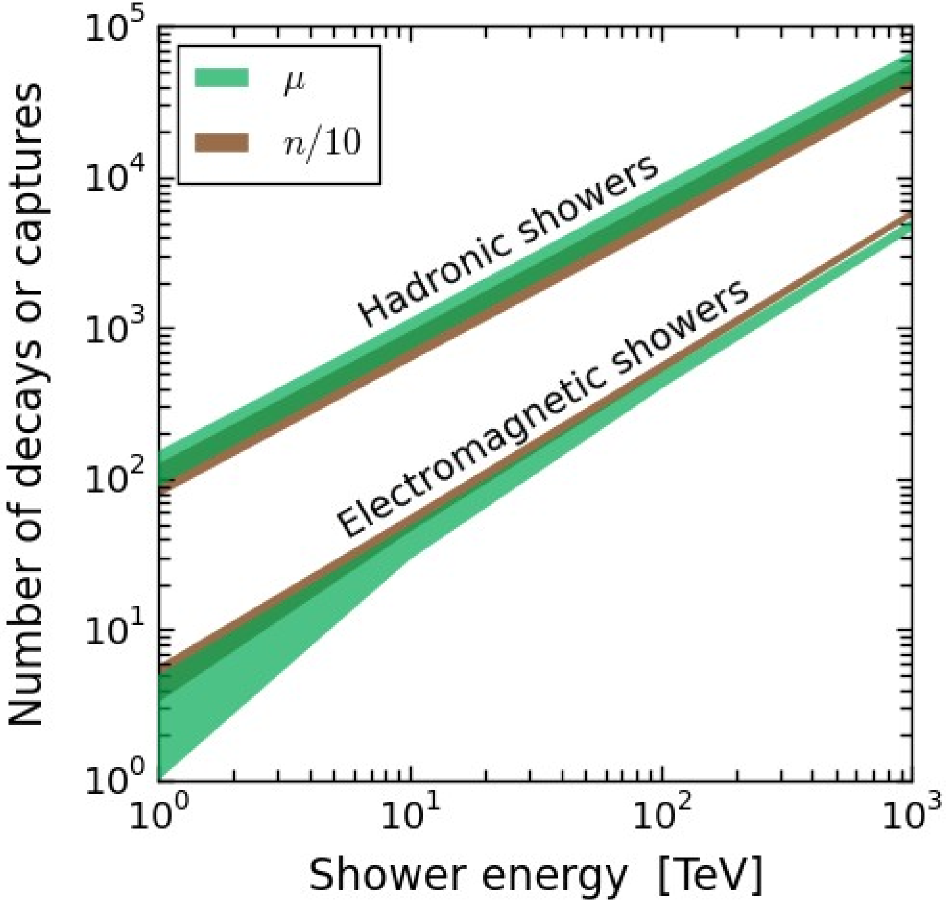
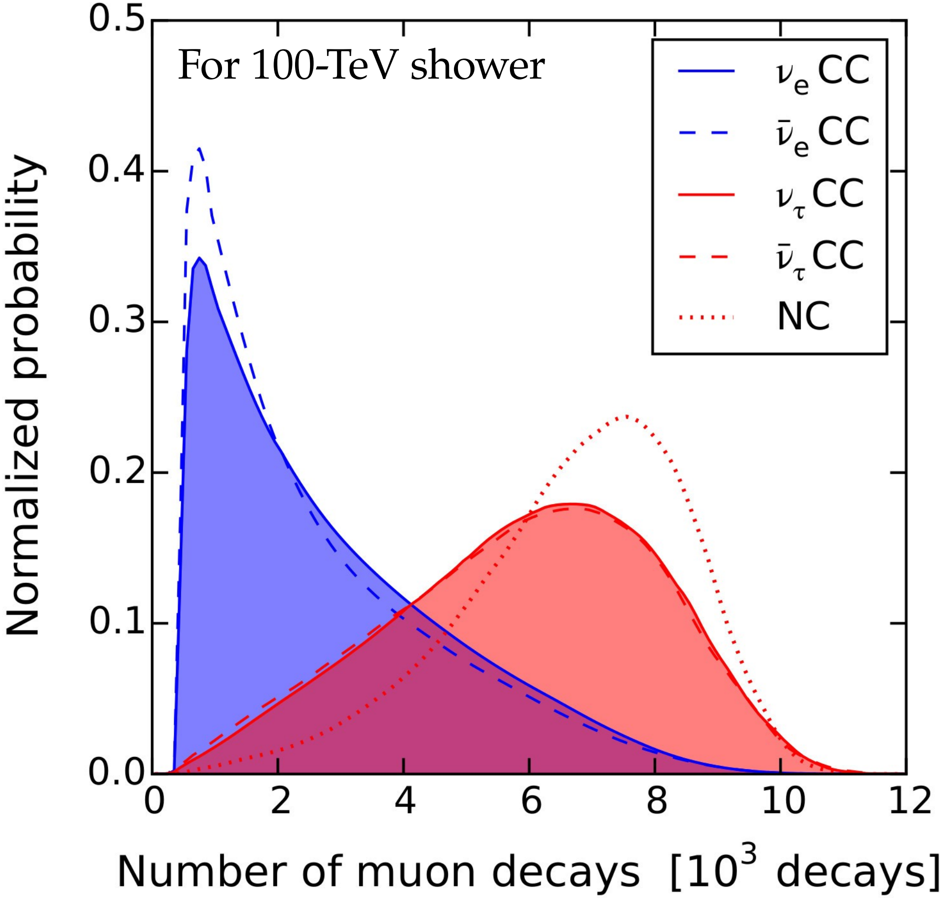


Li, **MB**, Beacom, *PRL* 2019

Hadronic *vs.* electromagnetic showers

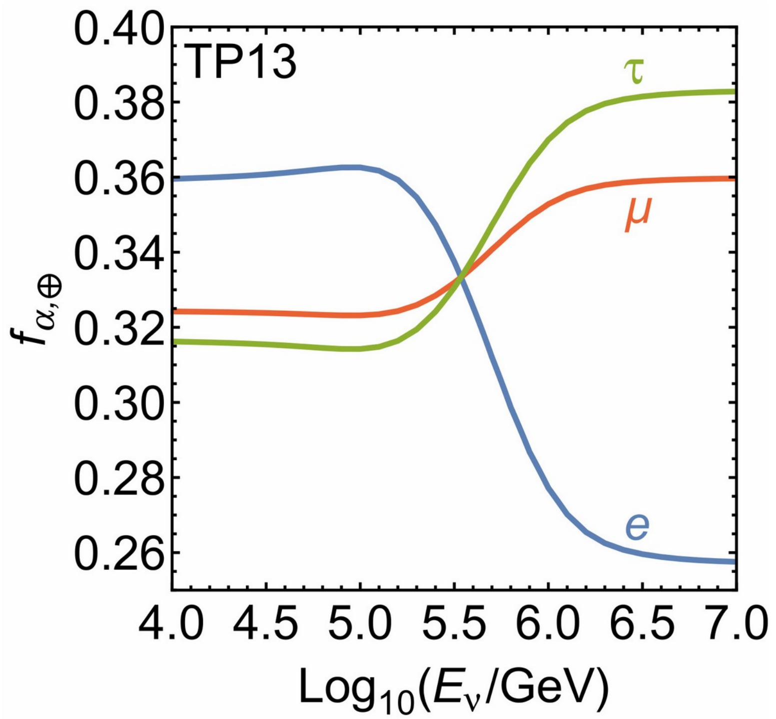


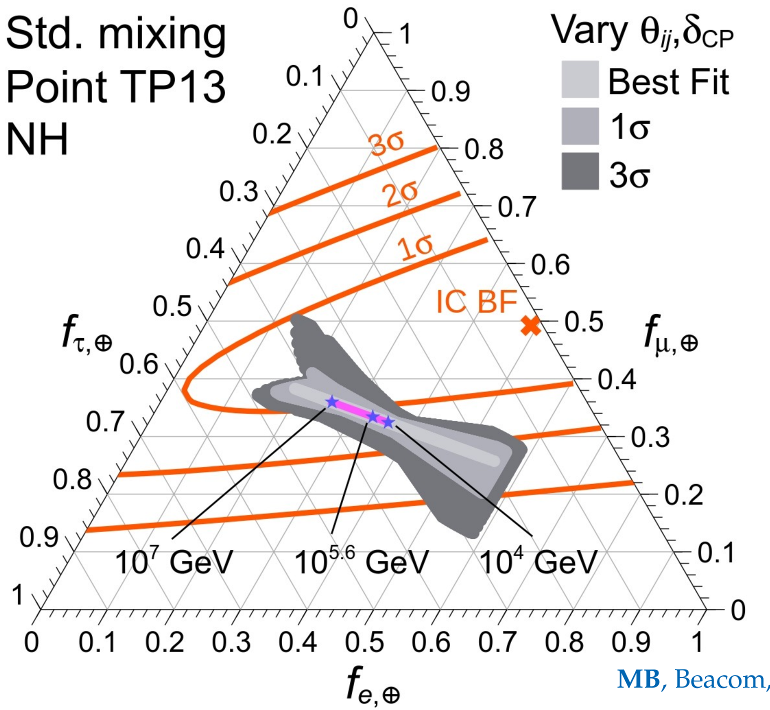


Li, **MB**, Beacom, *PRL* 2019

Energy dependence of the flavor composition?

Different neutrino production channels accessible at different energies –

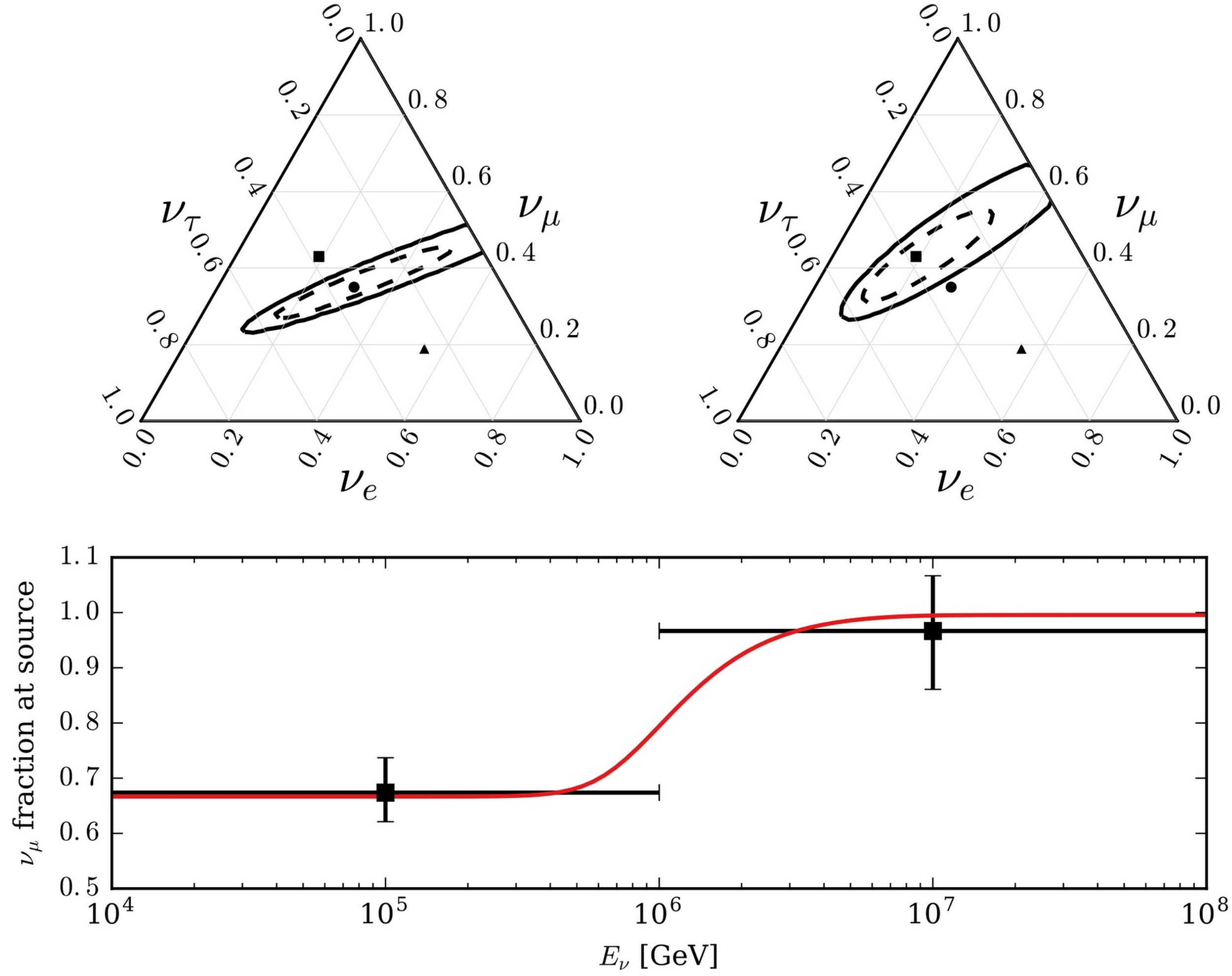




MB, Beacom, Winter *PRL* 2015

- TP13: $p\gamma$ model, target photons from electron-positron annihilation [Hümmer+, *Astropart. Phys.* 2010]
- Will be difficult to resolve [Kashti, Waxman, *PRL* 2005; Lipari, Lusignoli, Meloni, *PRD* 2007]

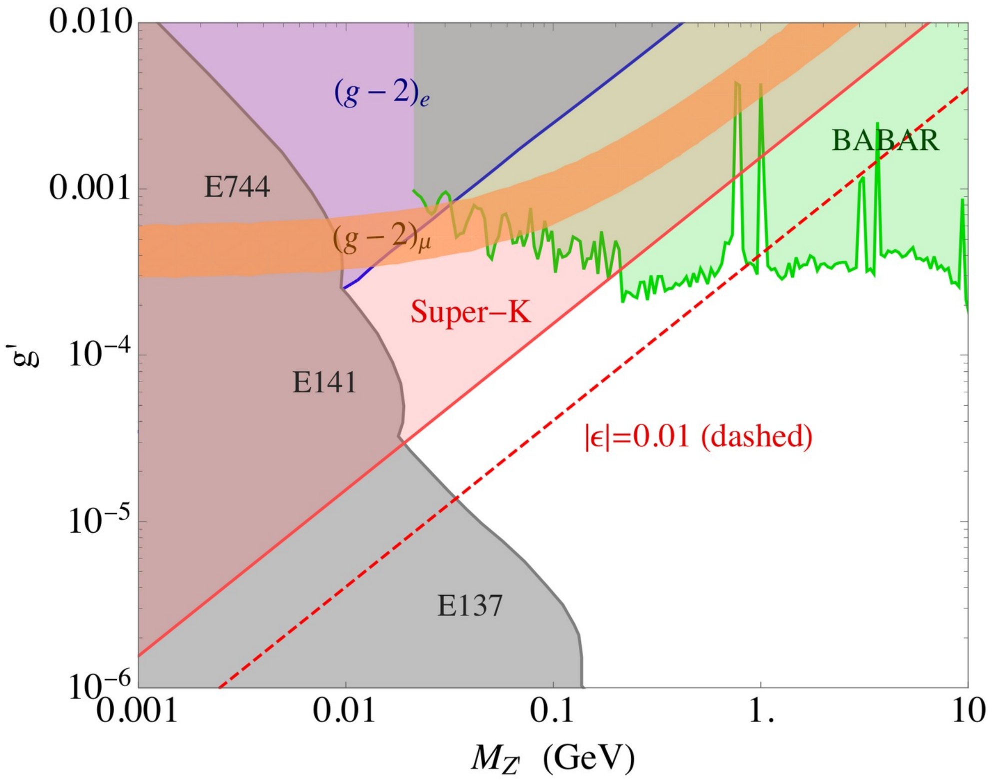
… Observable in IceCube-Gen2?



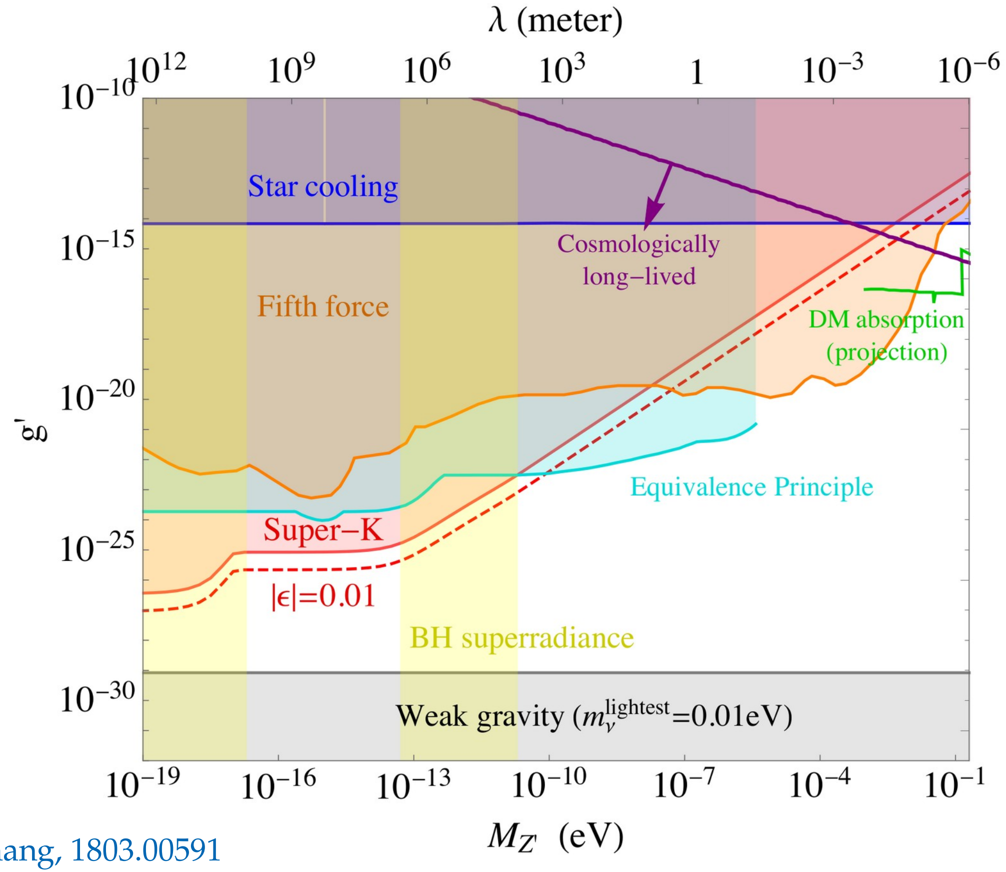
Borrowed from M. Kowalski

Current limits on the Z′

MeV–GeV masses



Sub-eV masses



M. Wise & Y. Zhang, 1803.00591

Connecting flavor-ratio predictions to experiment

1. Integrate potential in redshift, weighed by source number density
   ↦ Assume star formation rate

$$\langle V_{e\beta}^{\cos} \rangle \propto \int dz \; \rho_{\rm SFR}(z) \cdot \frac{dV_{\rm c}}{dz} \cdot V_{e\beta}^{\cos}(z)$$

Density of cosmological *e* grows with *z*

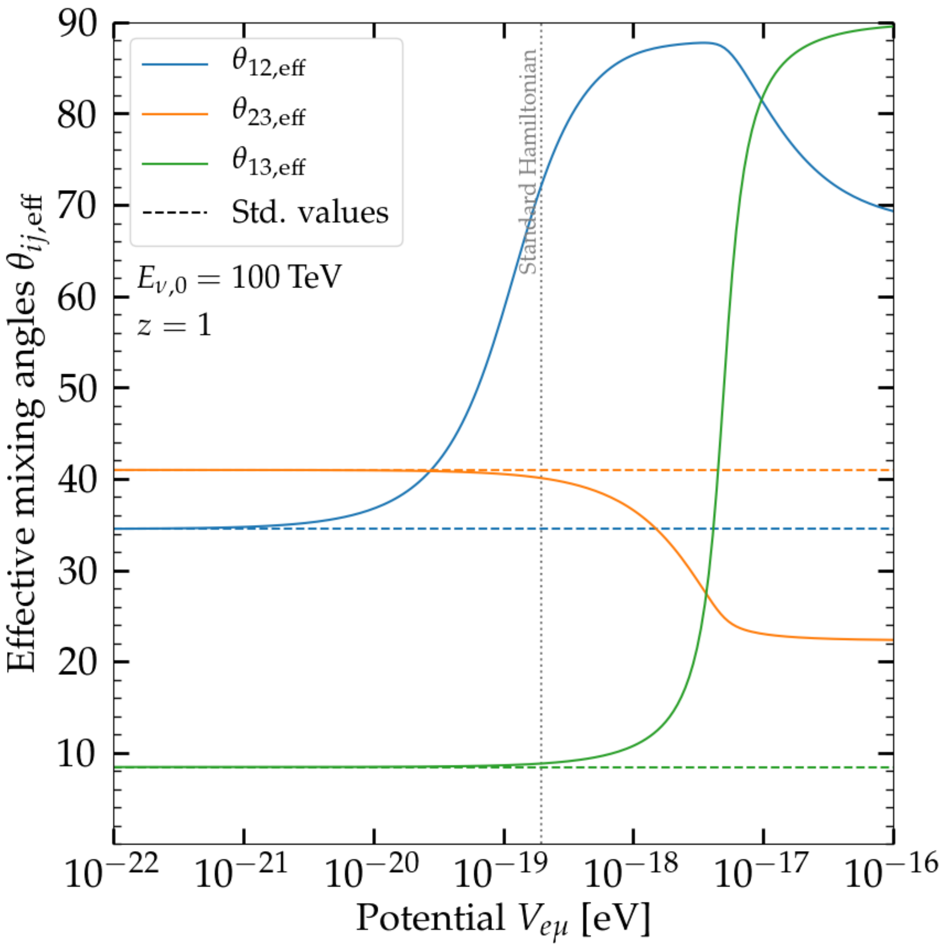
2. Convolve flavor ratios with observed neutrino energy spectrum
   ↦ Either $E^{-2.50}$ (combined analysis) or $E^{-2.13}$ (through-going muons)

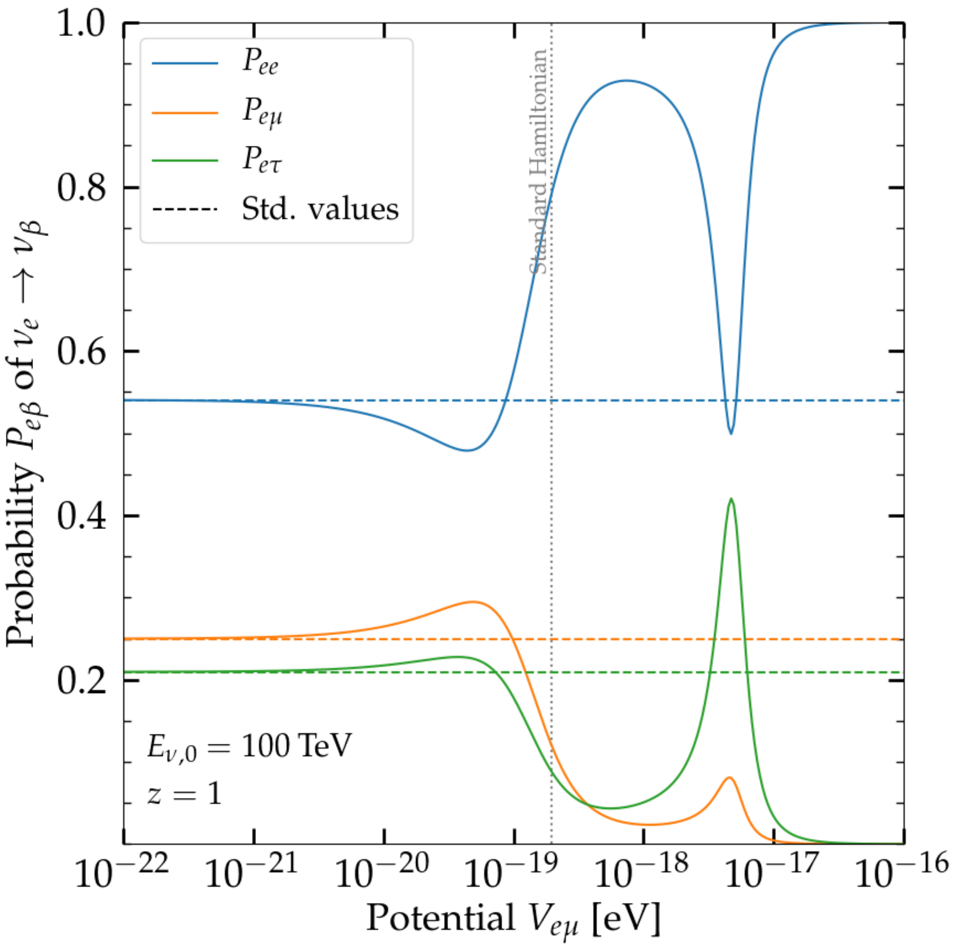
$$\langle \Phi_\alpha \rangle \propto \int dE_\nu \; f_{\alpha,\oplus}(E_\nu) \; E_\nu^{-\gamma} \quad \Rightarrow \quad \langle f_{\alpha,\oplus} \rangle \equiv \frac{\langle \Phi_\alpha \rangle}{\sum_{\beta=e,\mu,\tau} \langle \Phi_\beta \rangle}$$

Energy-averaged flux

Energy-averaged flavor ratios

Resonance due to the L_e-L_μ symmetry





Resonance due to the L_e-L_μ symmetry (*cont.*)