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

Mauricio Bustamante

Niels Bohr Institute, University of Copenhagen

Institut d'Astrophysique de Paris
February 17, 2023

UNIVERSITY OF COPENHAGEN

VILLUM FONDEN

Optical light

Mycelia muralis by Bjørn Rørsletr / NN, naturfotograf.com

Optical light

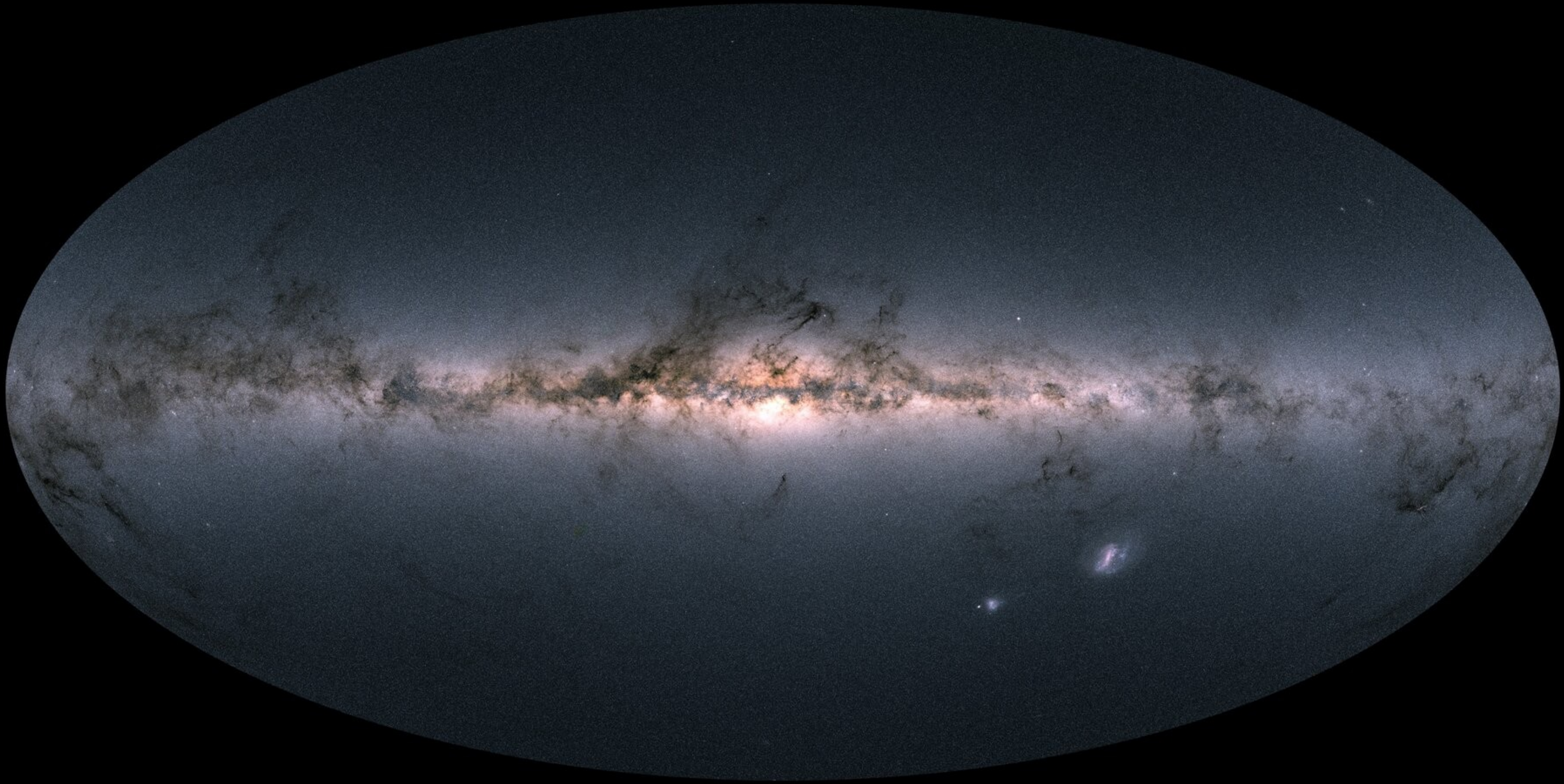
Mycelia muralis by Bjørn Rørsletr / NN, naturfotograf.com

Optical light

Ultraviolet light

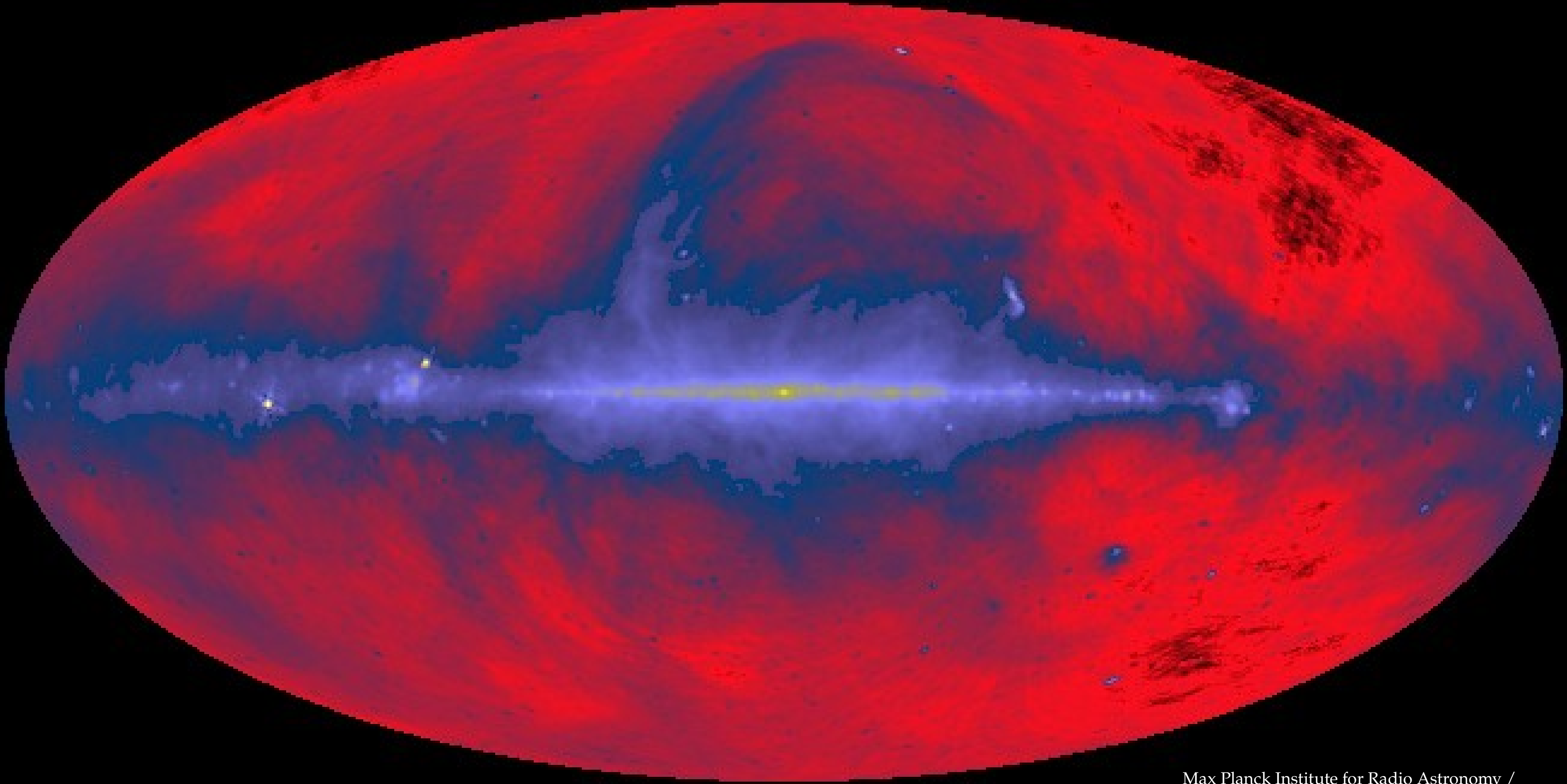
Mycelia muralis by Bjørn Rørsletr / NN, naturfotograf.com

Optical light



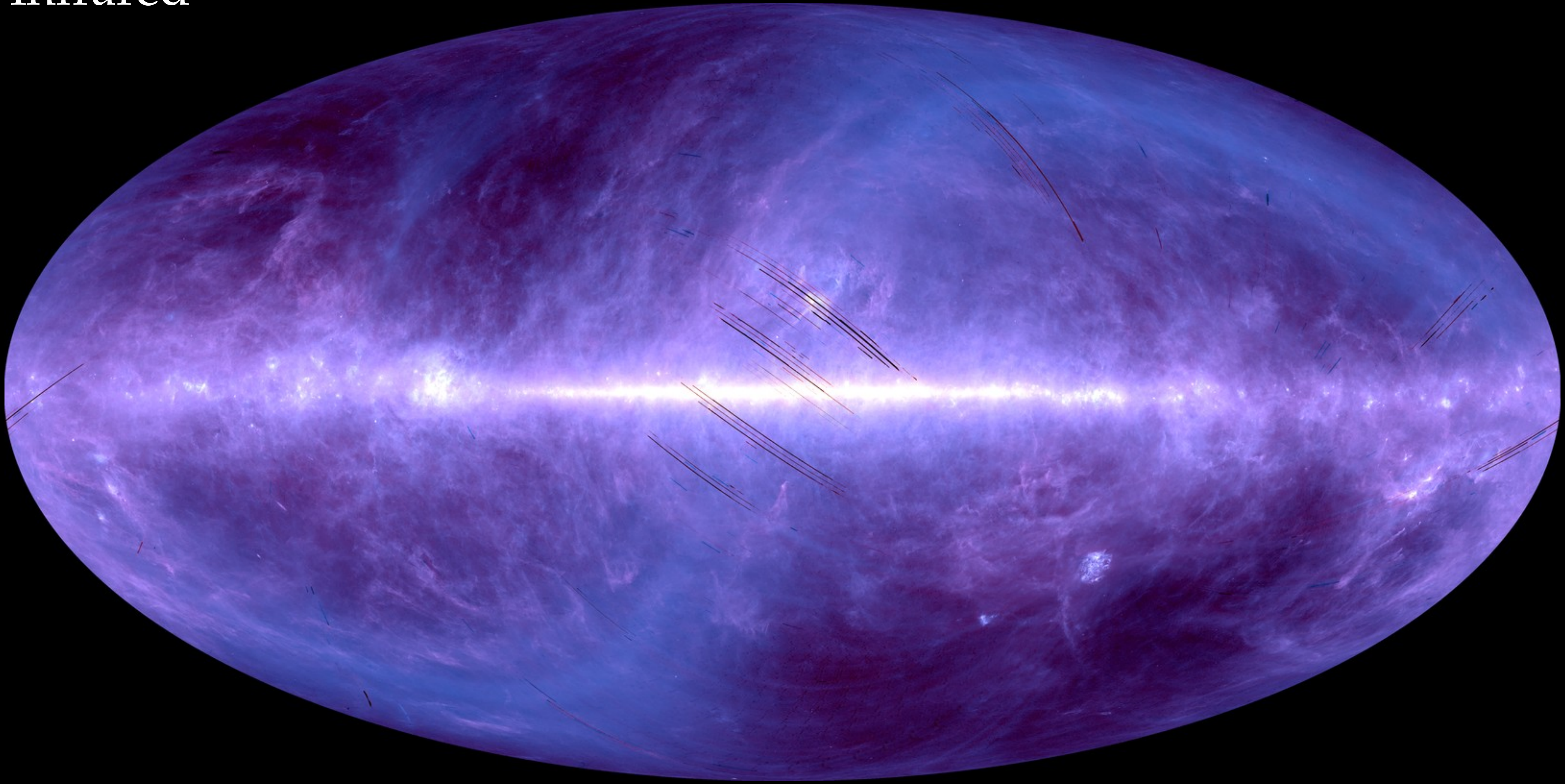
Gaia

Radio waves



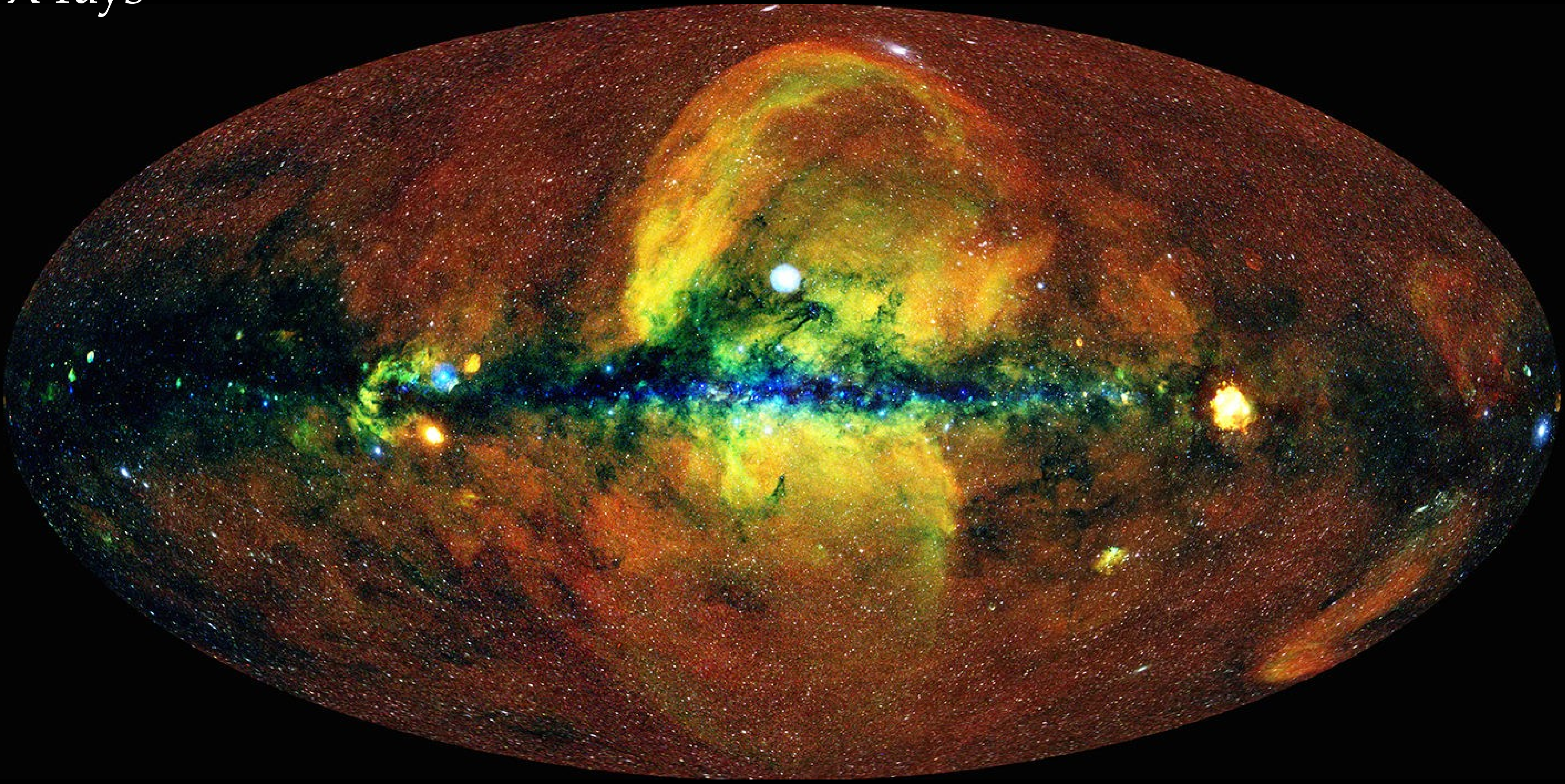
Max Planck Institute for Radio Astronomy /
Glyn Haslam / Jodrell Bank / Effelsberg / Parkes

Infrared



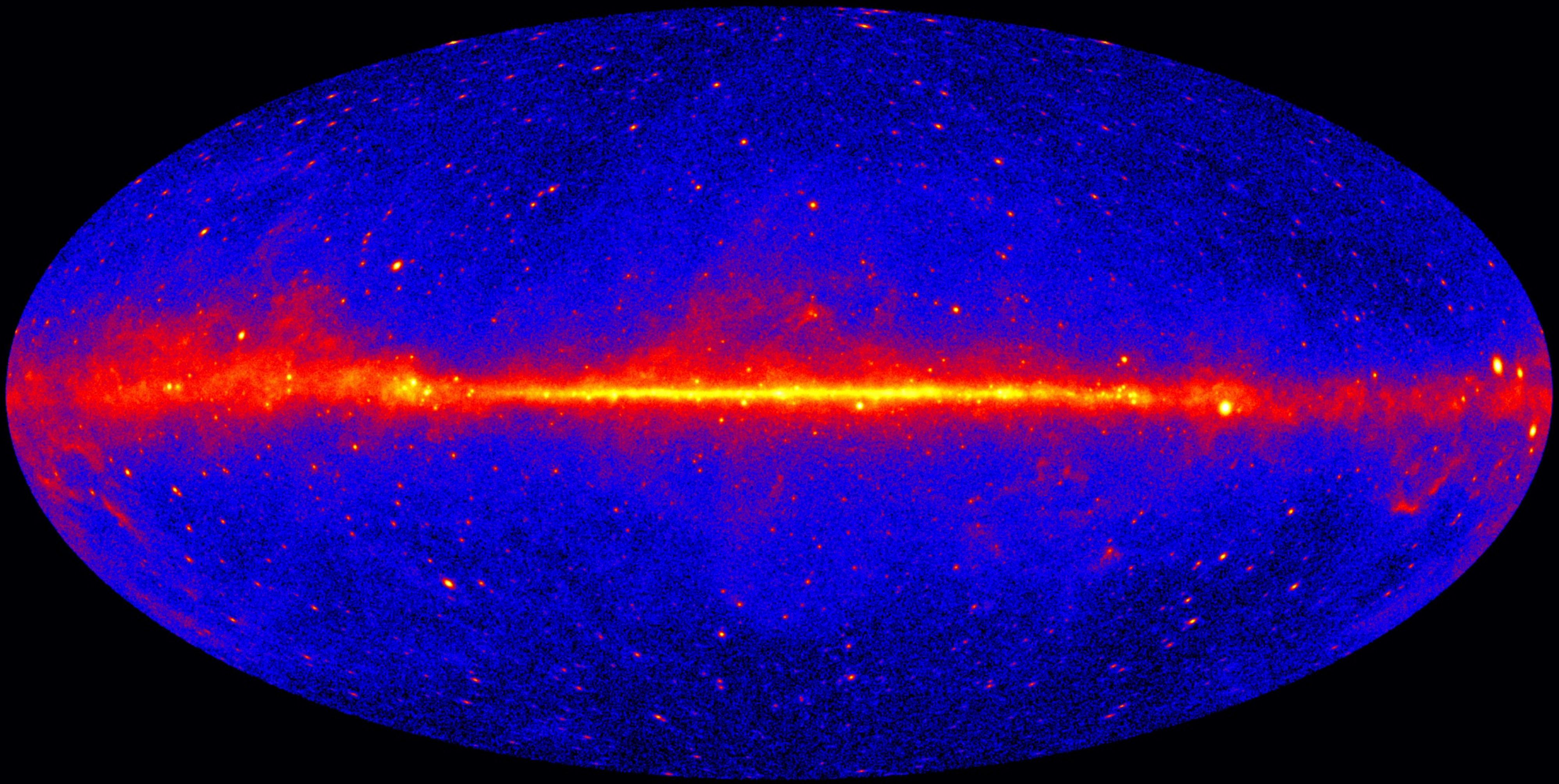
AKARI

X-rays



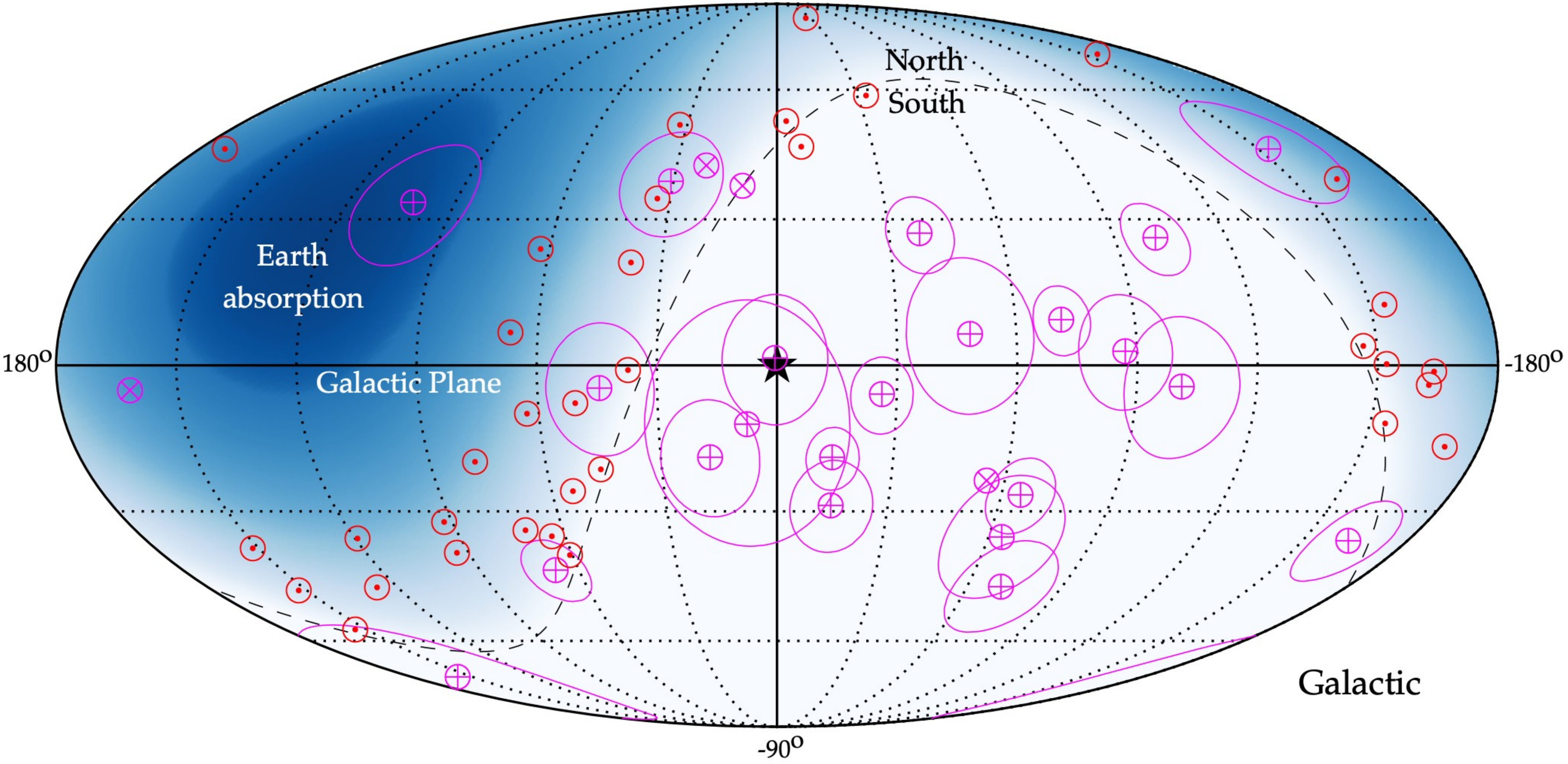
eRosita

Gamma rays

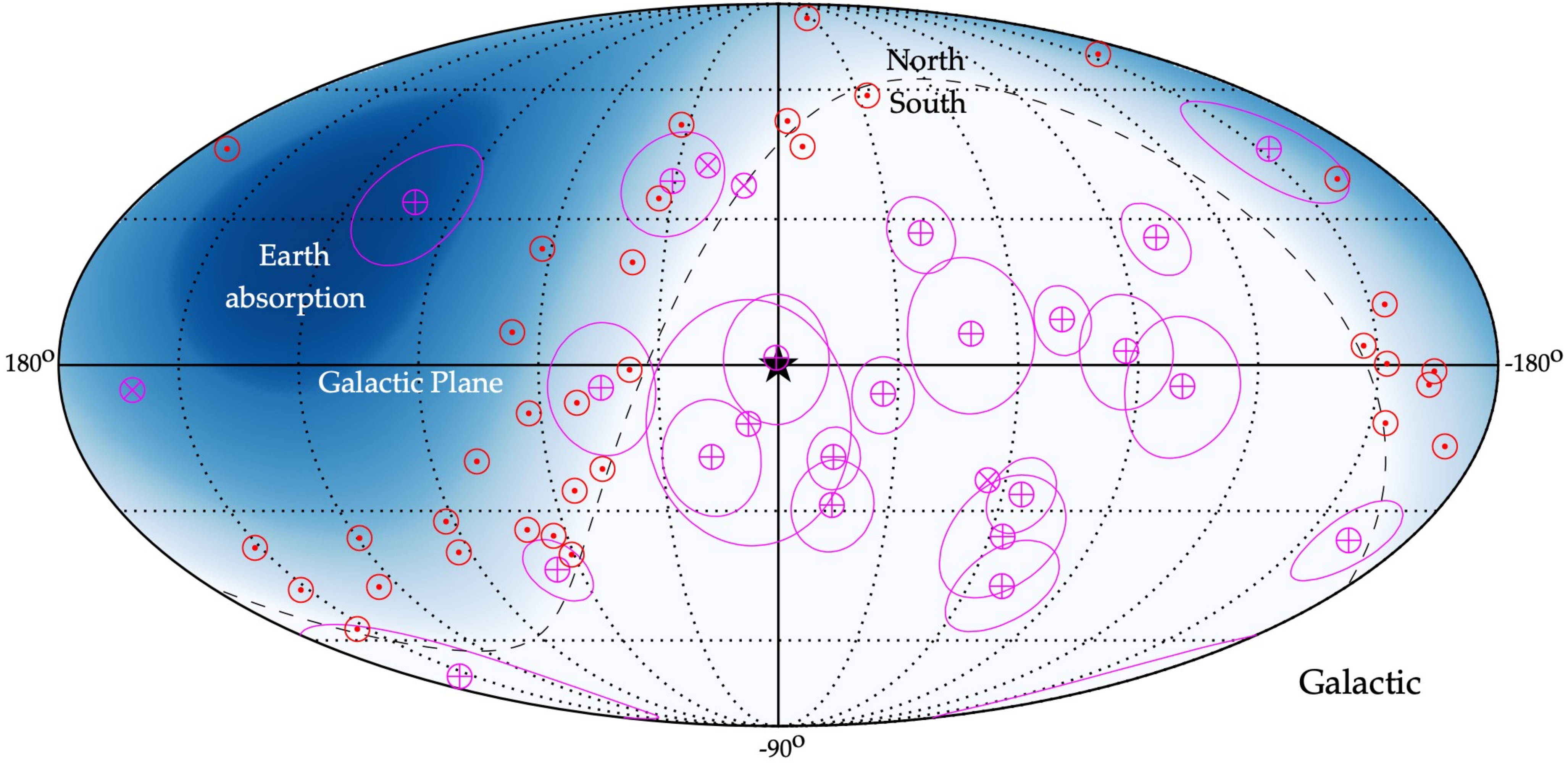


Fermi

??????????????


North
South
Earth
absorption
180°
-180°
Galactic Plane
-90°
Galactic

Neutrinos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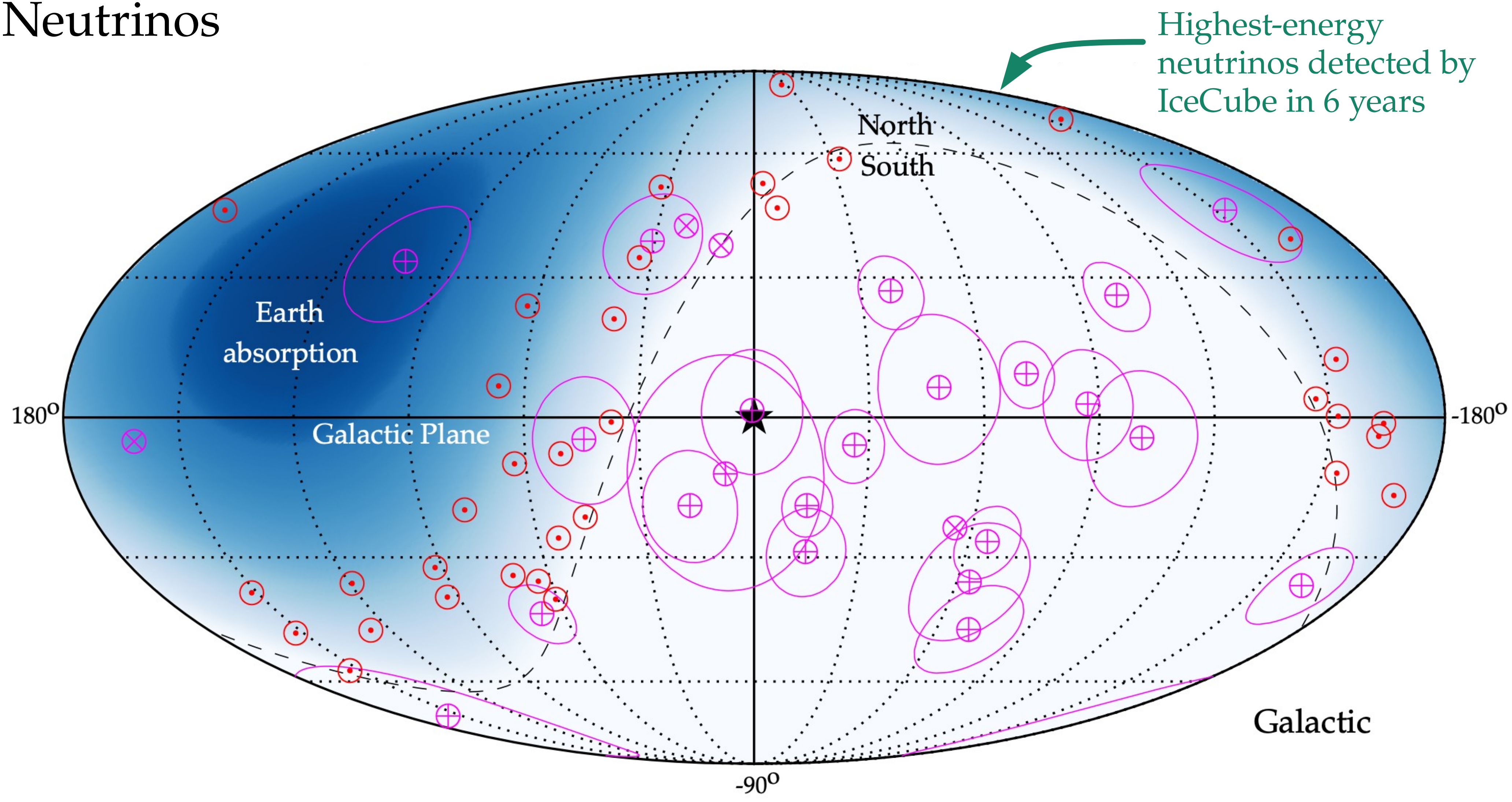
Highest-energy neutrinos detected by IceCube in 6 years
North
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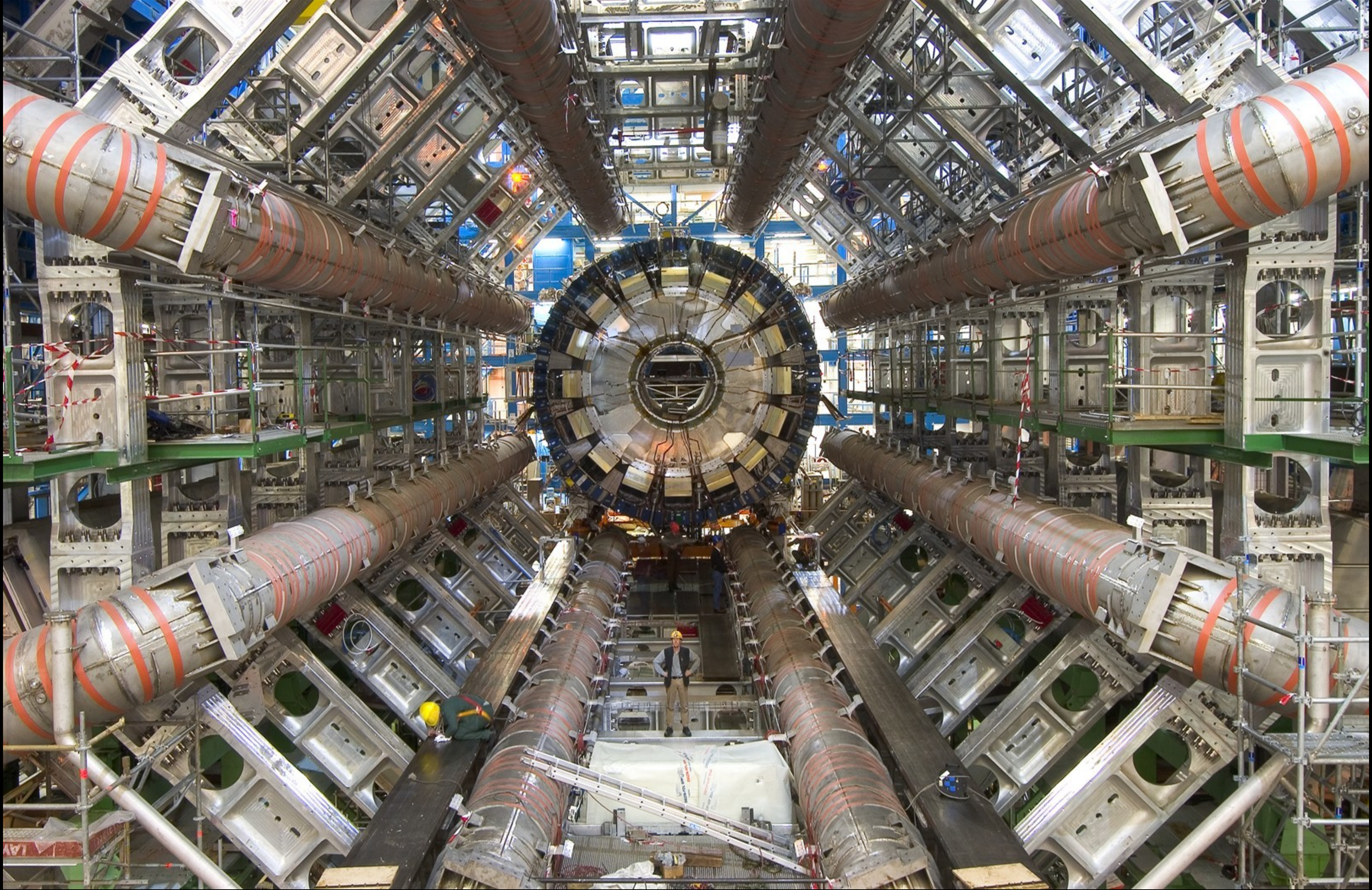
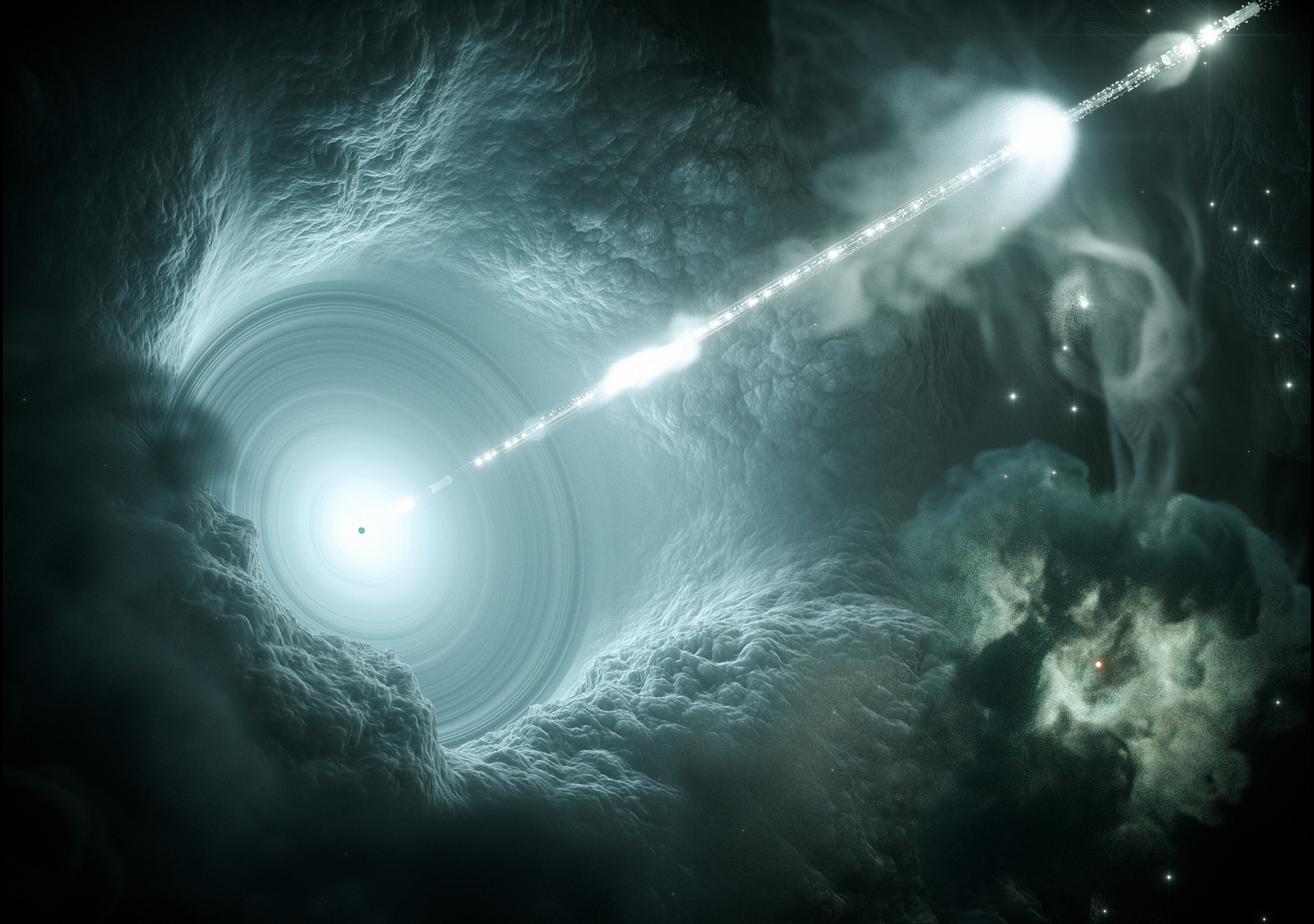


ATLAS



DESY

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Neutrinos are elementary particles,

electrically neutral,

very light,

and superbly antisocial

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and $\underbrace{\text{superbly antisocial}}_{= \textit{barely interact with matter}}$

Neutrinos are quintessential quantum particles

There are three types, or *flavors*, of neutrinos:

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ν_e

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e

electron

ν_e

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ν_e

electron
neutrino

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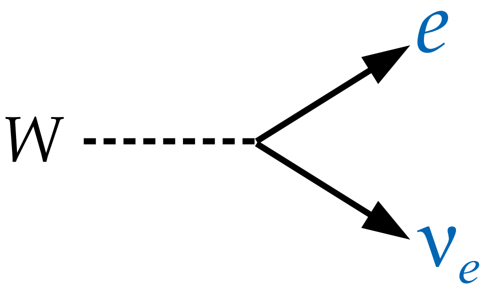
e

electron

ν_e

electron neutrino



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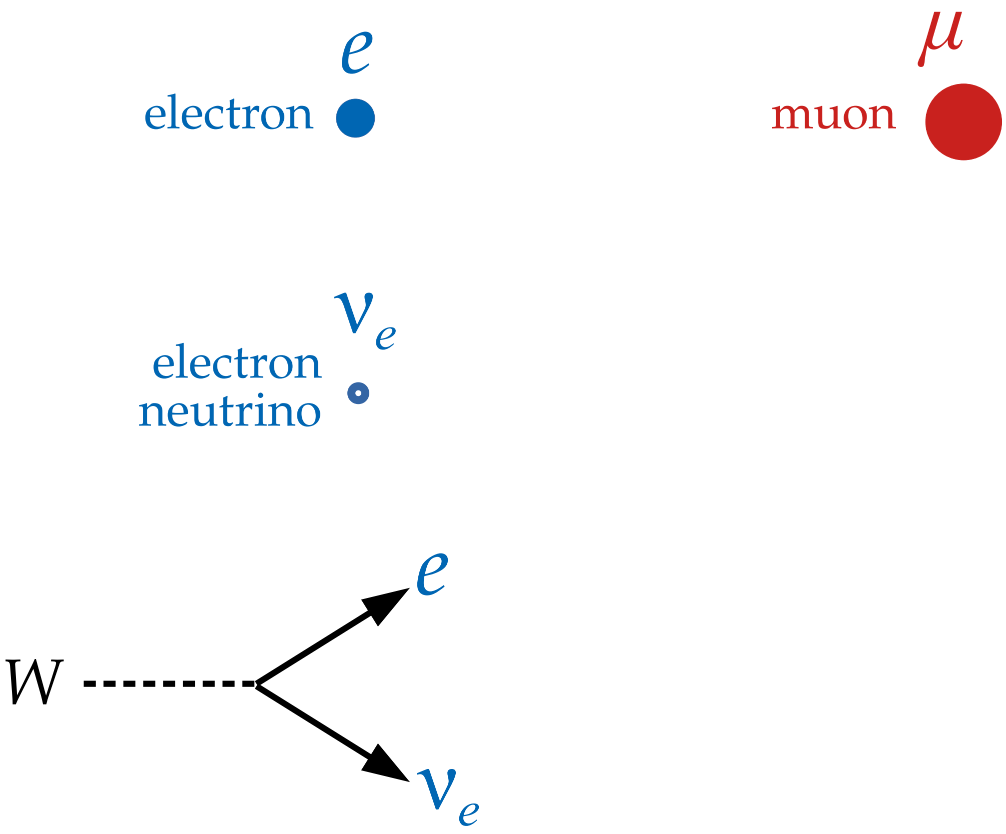

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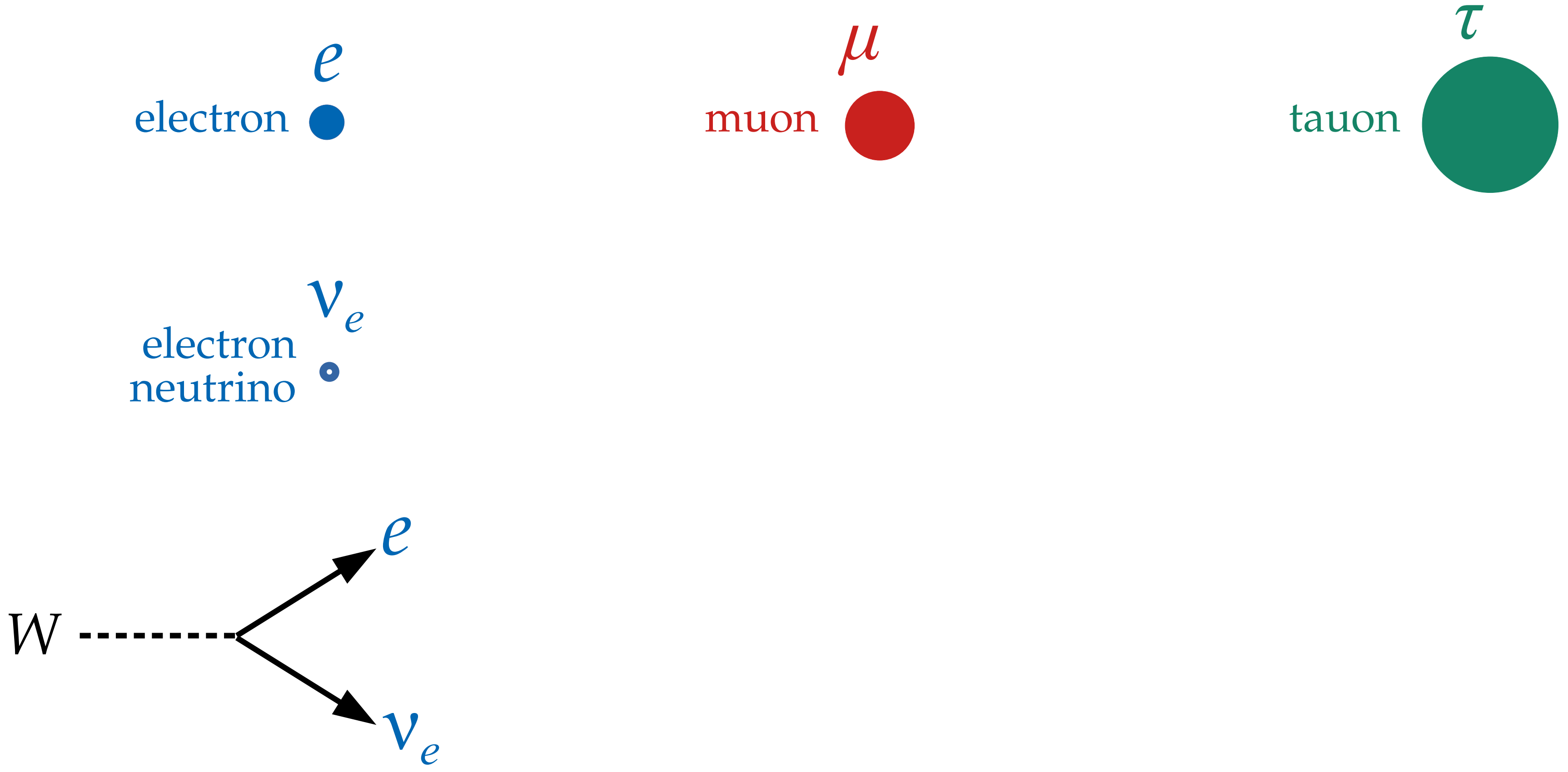

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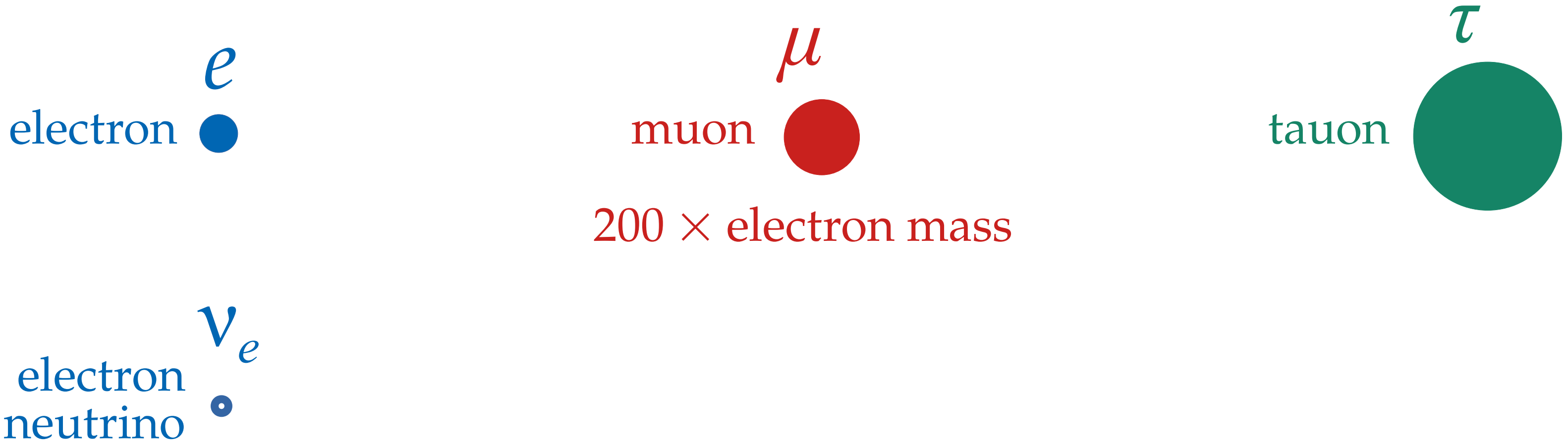

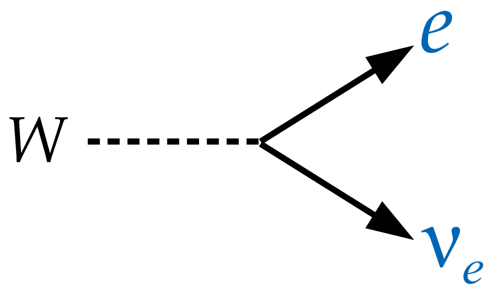

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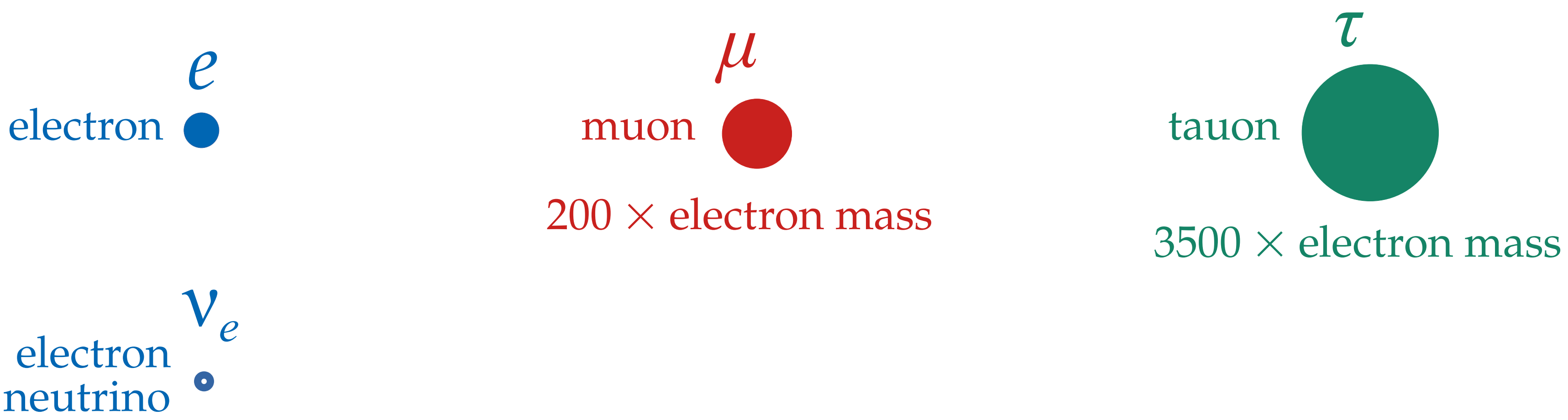

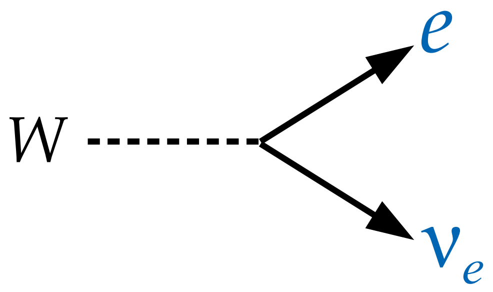

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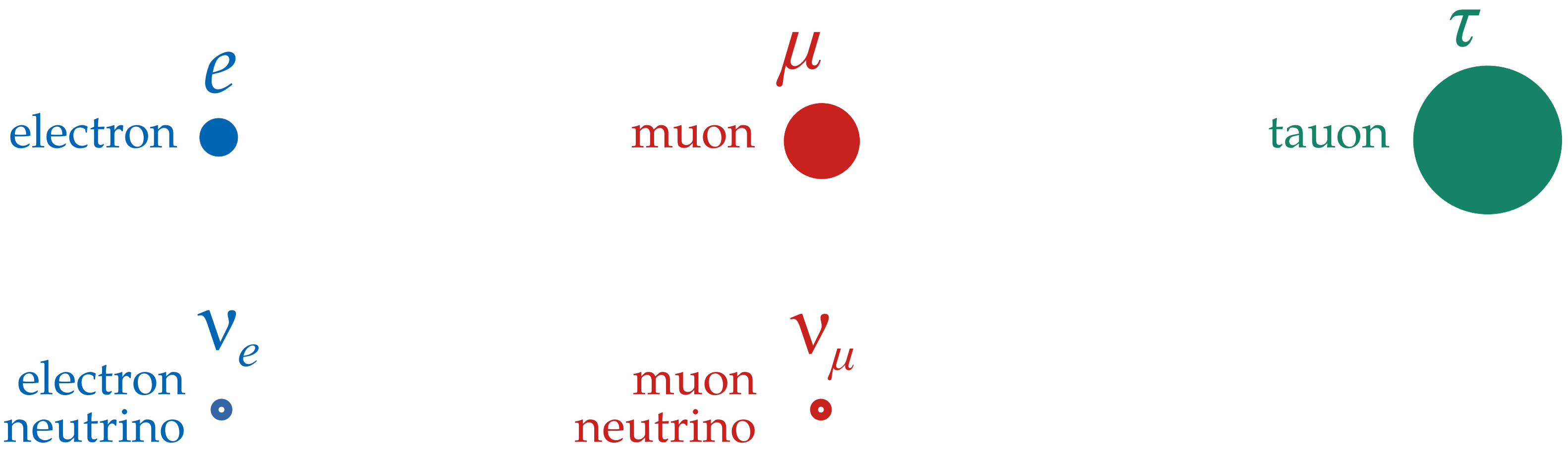

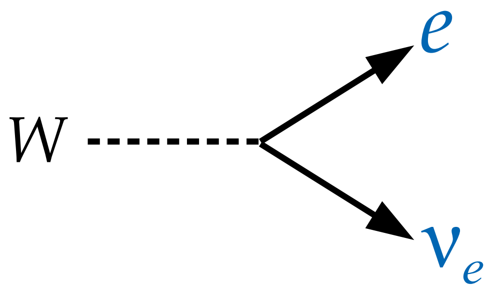

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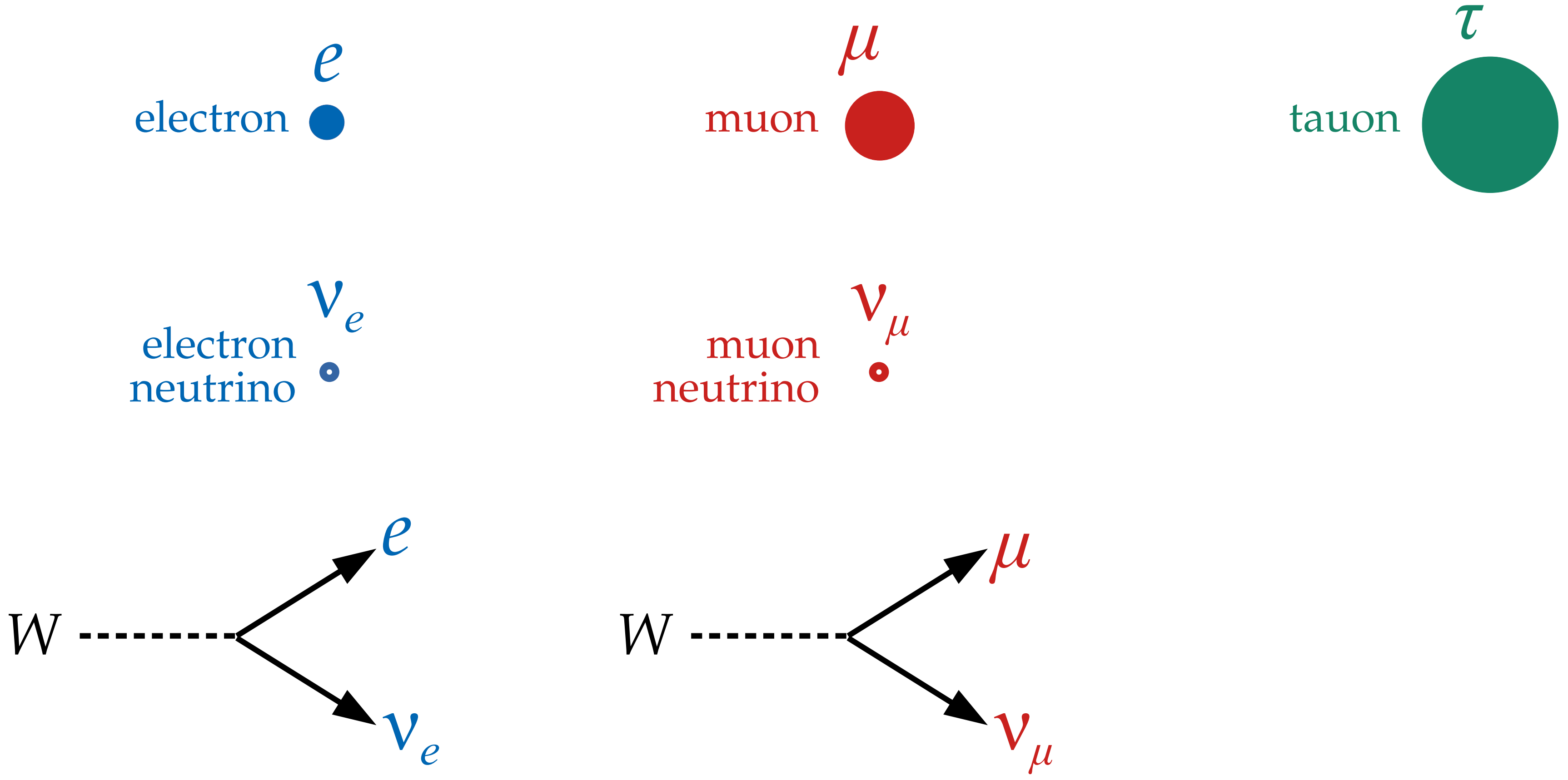

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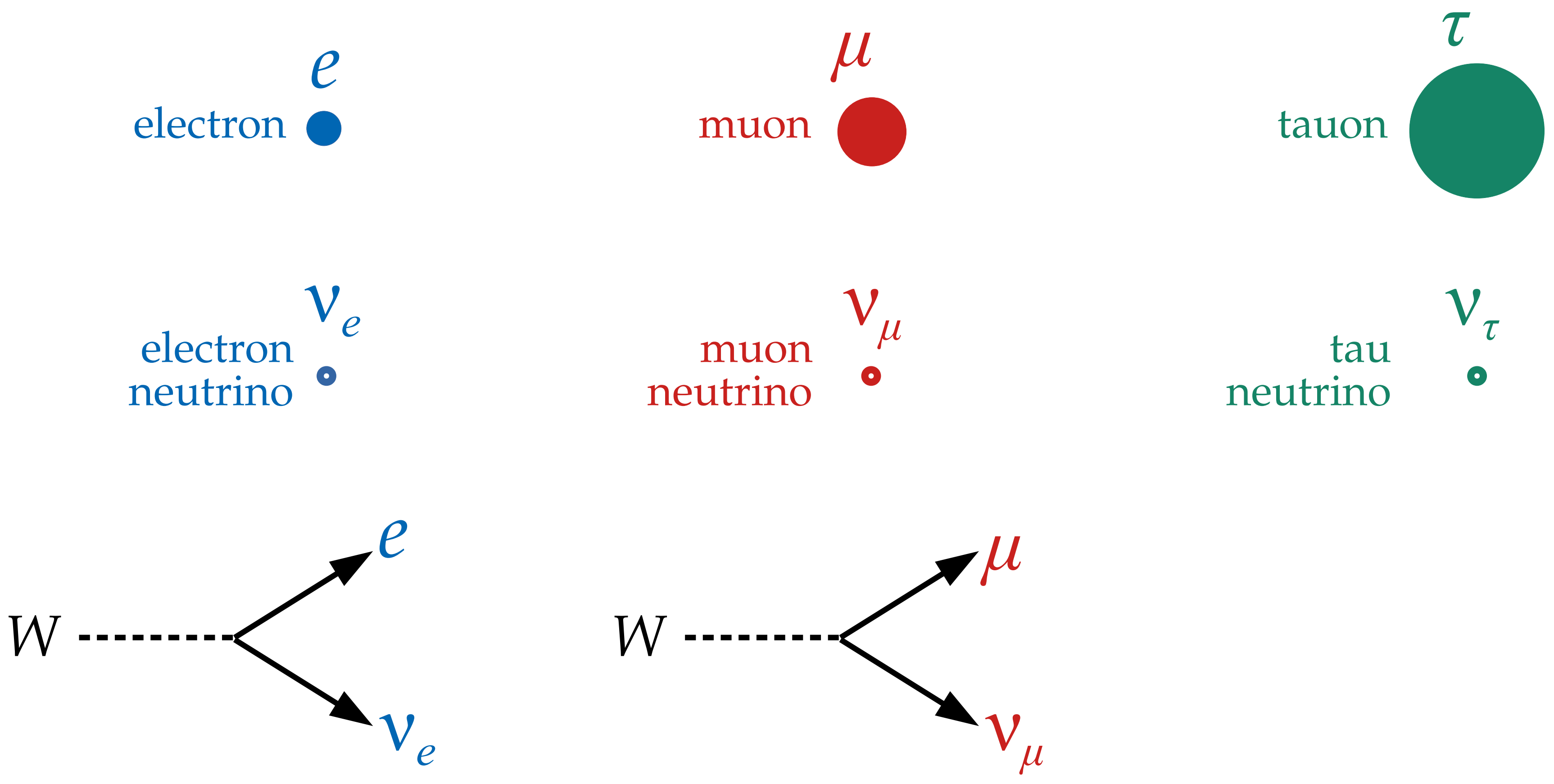

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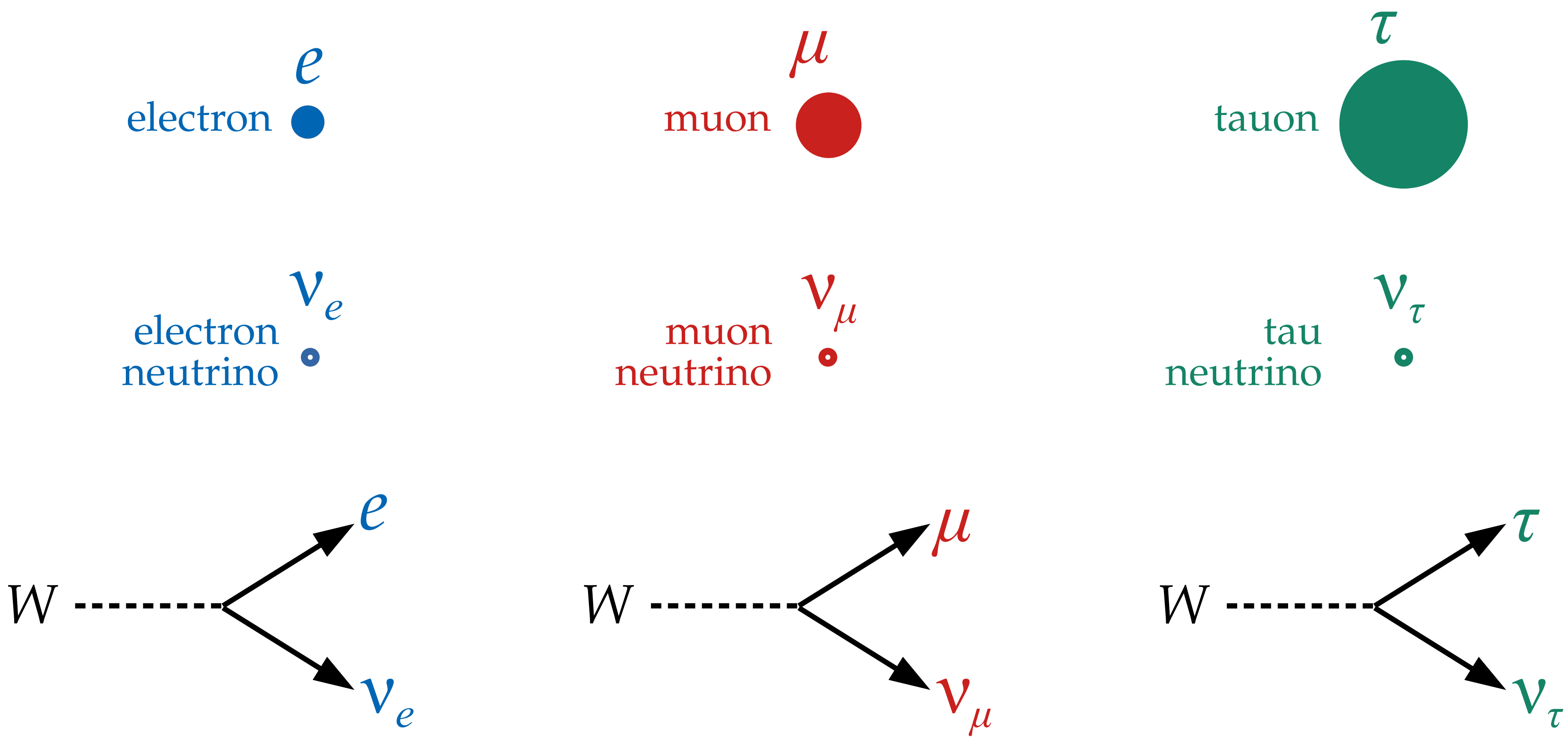

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ν_e

Neutrino source

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It travels a long
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But may be detected with a
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ν_e or ν_μ or ν_τ

Neutrino detector

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(Nobel Prize 2002, 2015)

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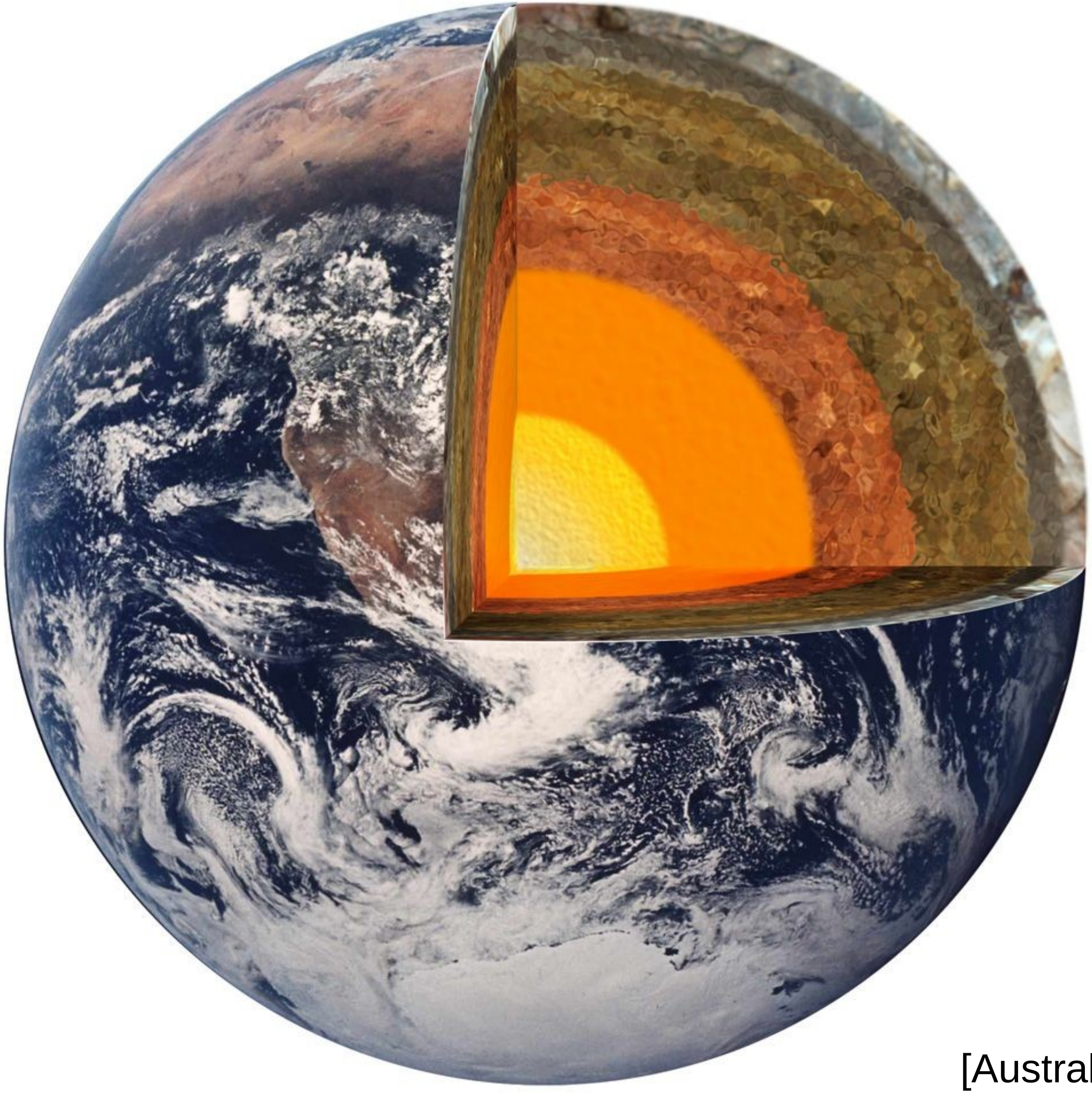
Neutrino source

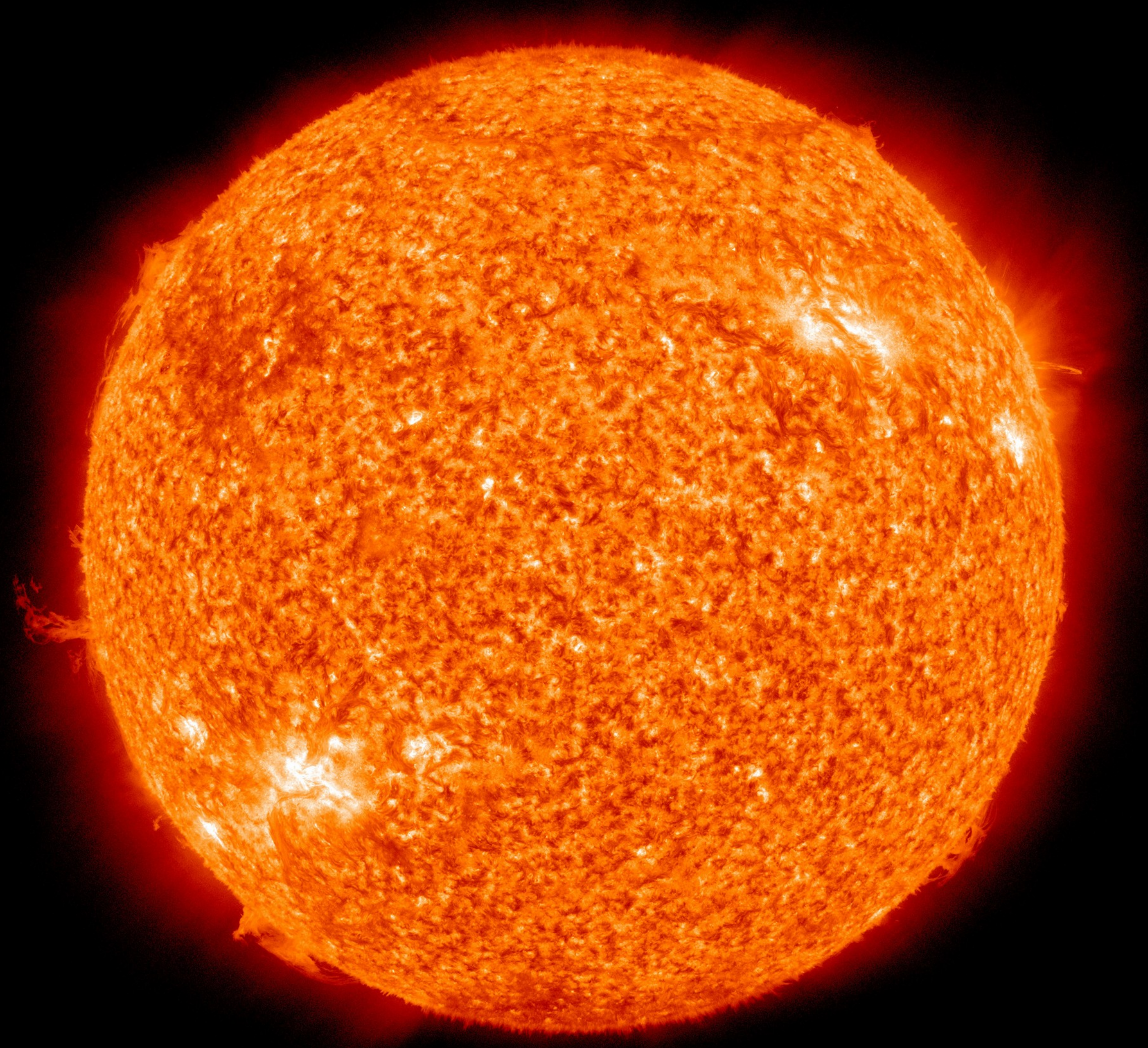
Neutrino detector

We use quantum mechanics to compute probabilities over *macroscopic* distances!

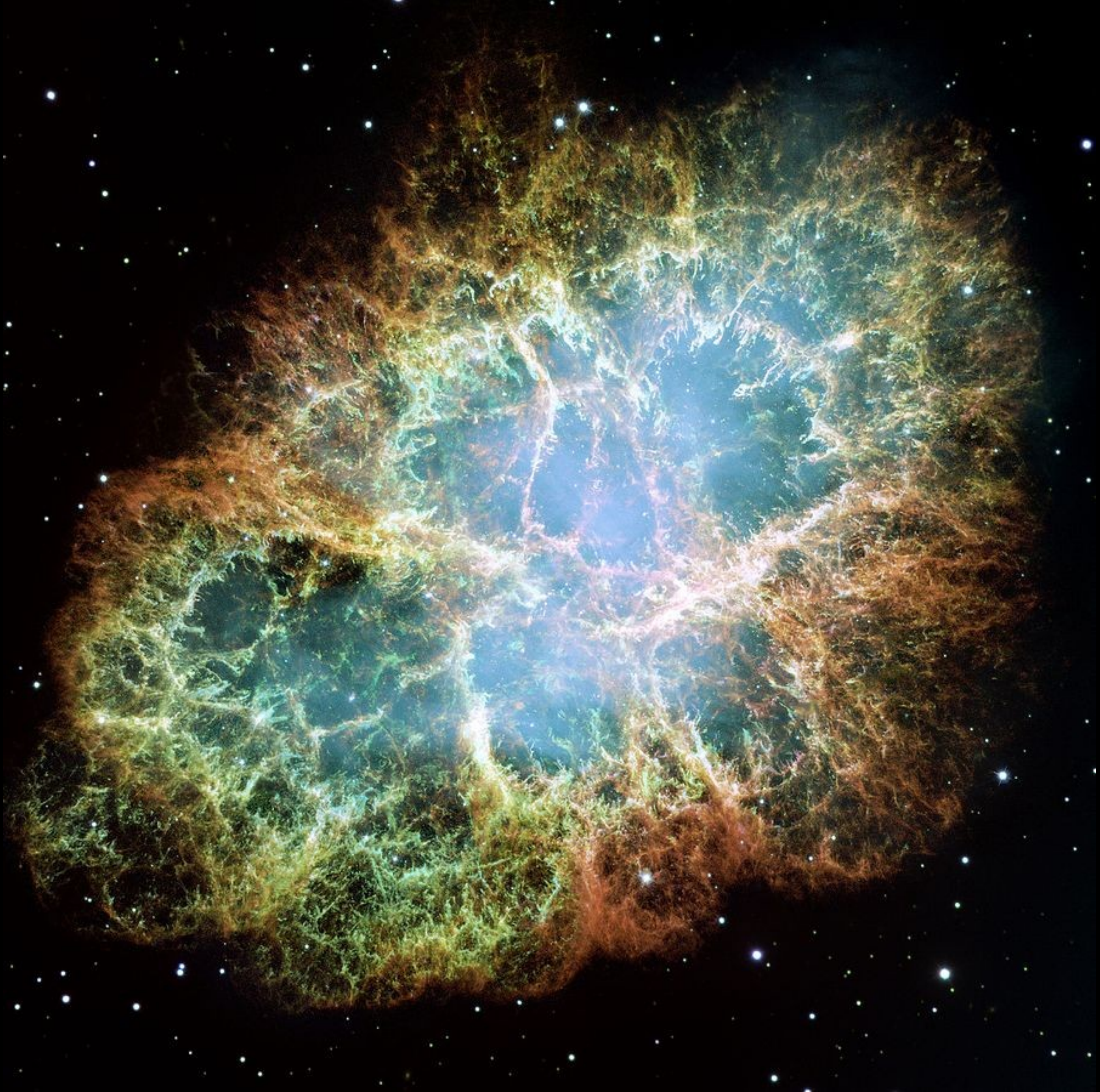

[Avda]



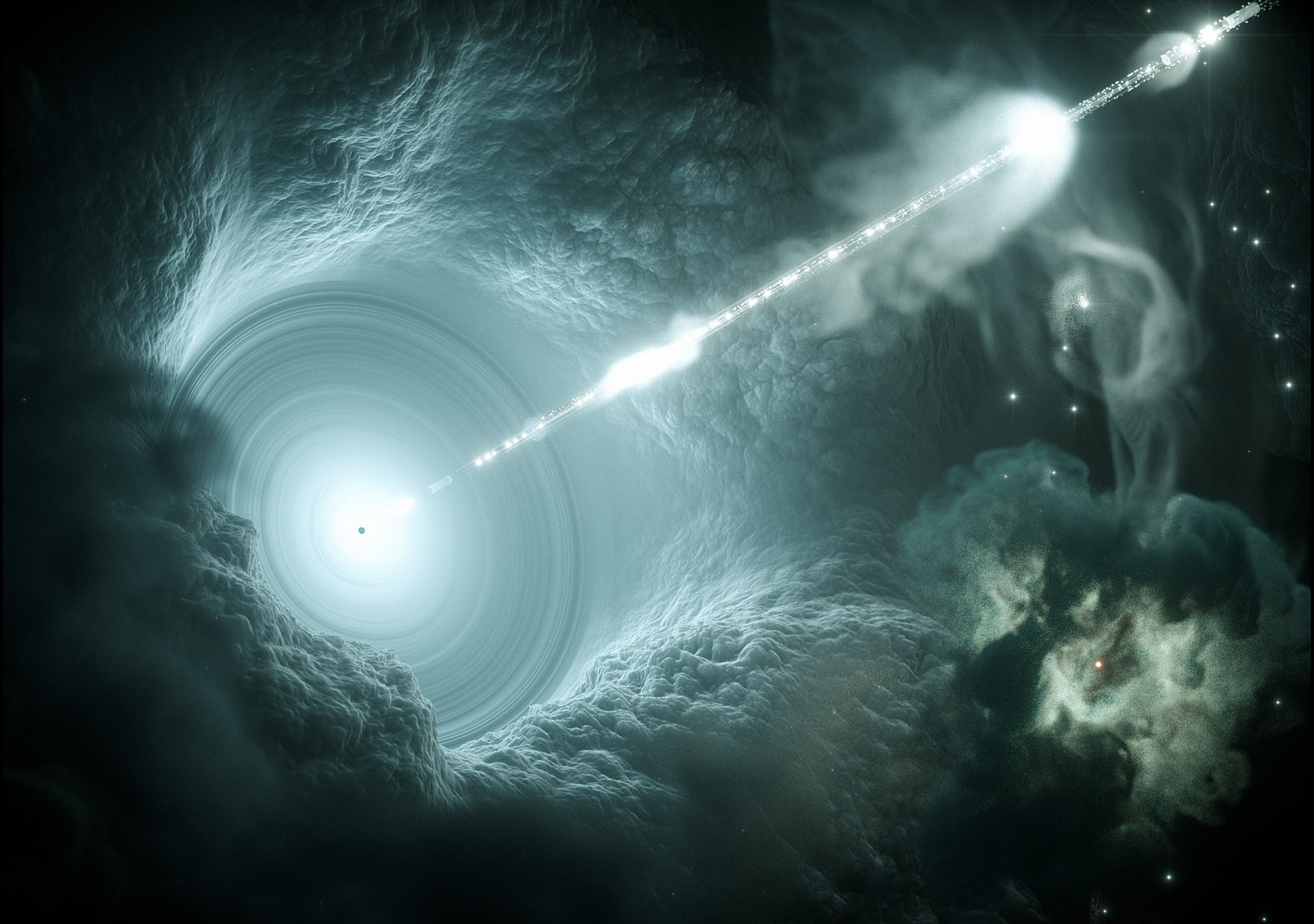
[Australian National University]



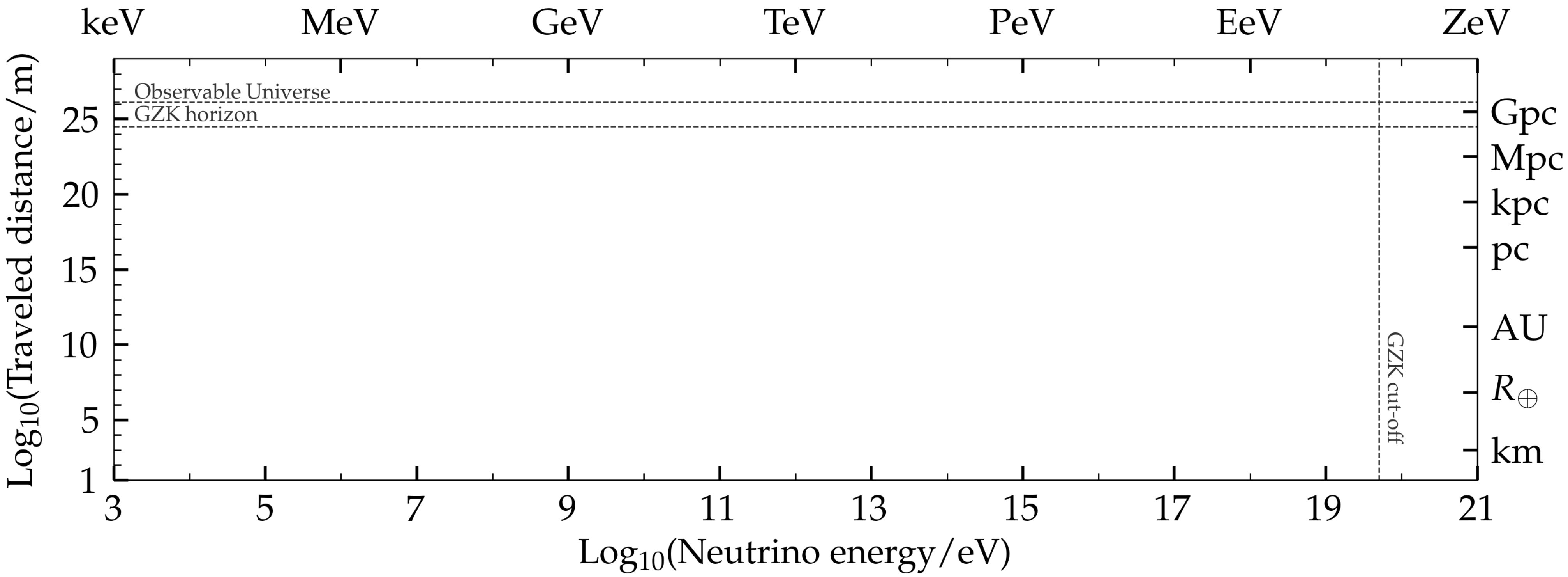
[NASA]



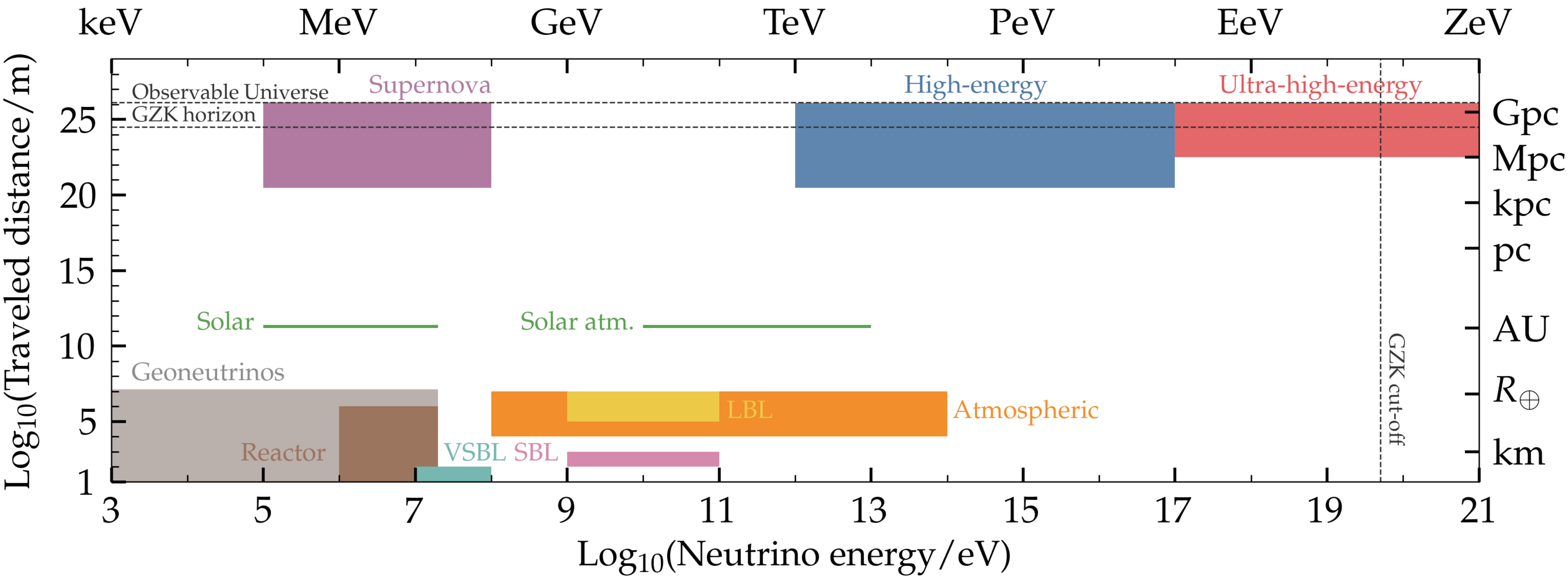
[NASA, ESA]



DESY



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



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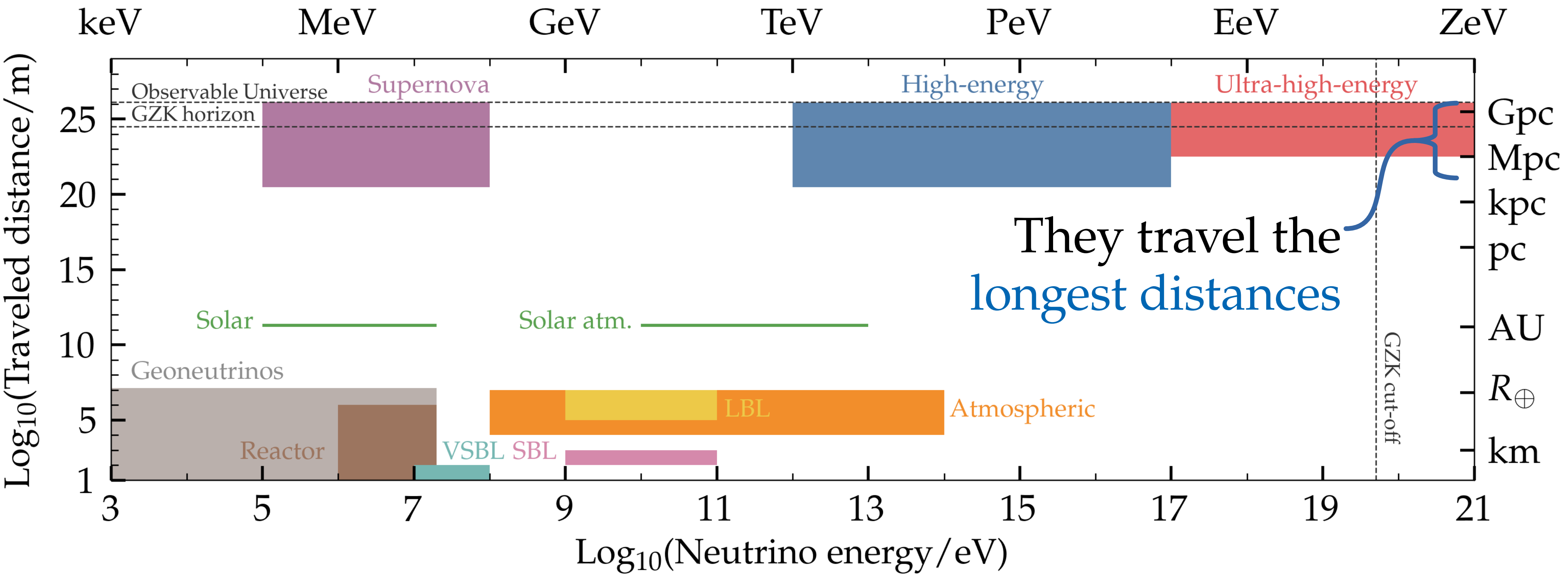
They have the highest energies



They travel the longest distances

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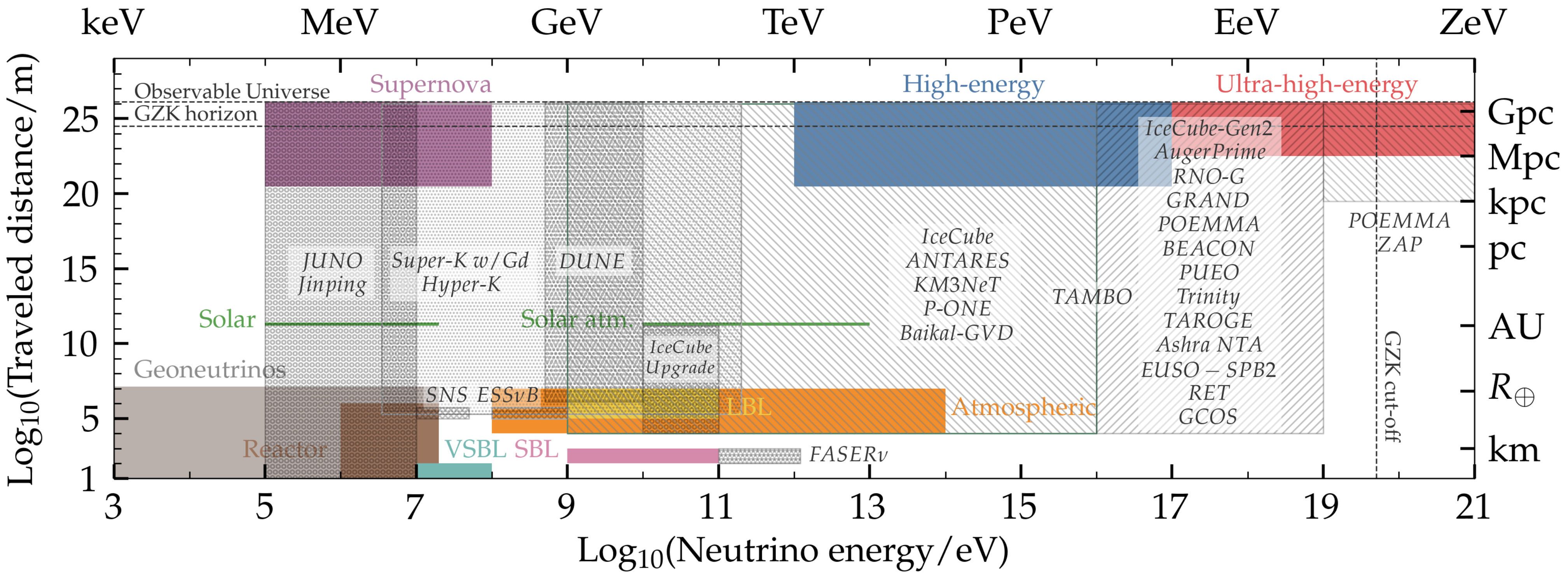

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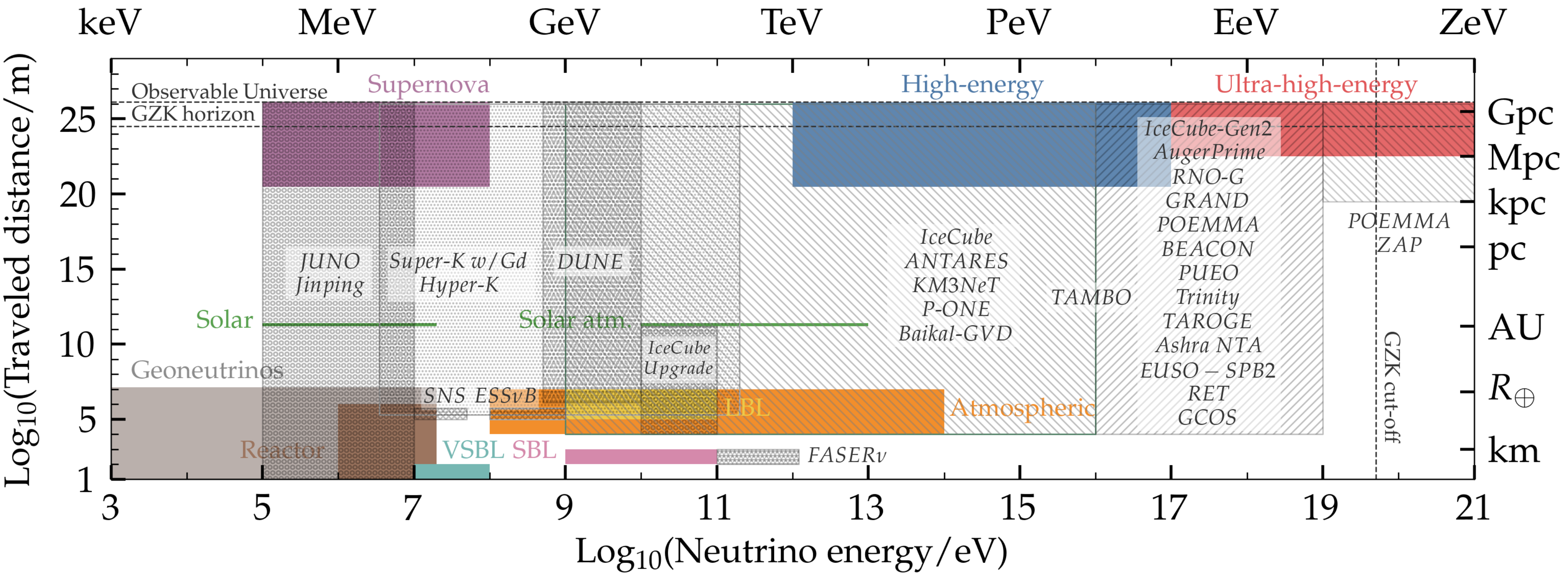
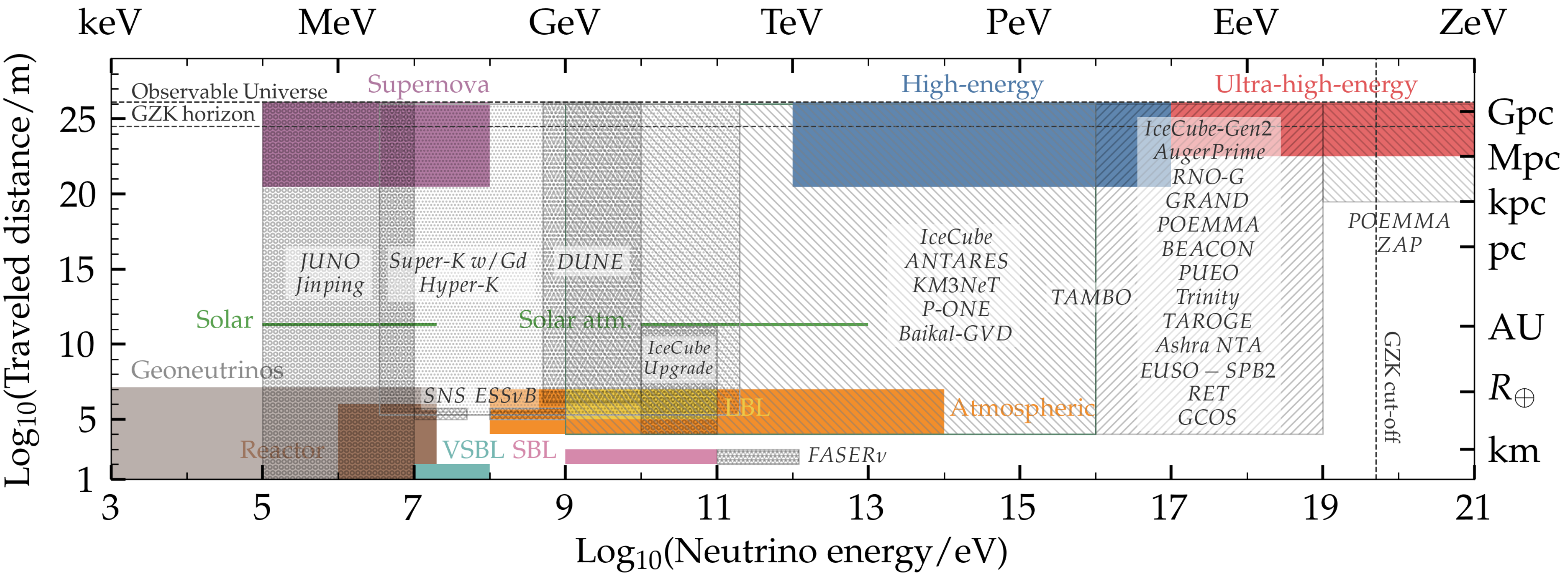


Synergies with lower energies

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

Discovered in 2013
by IceCube



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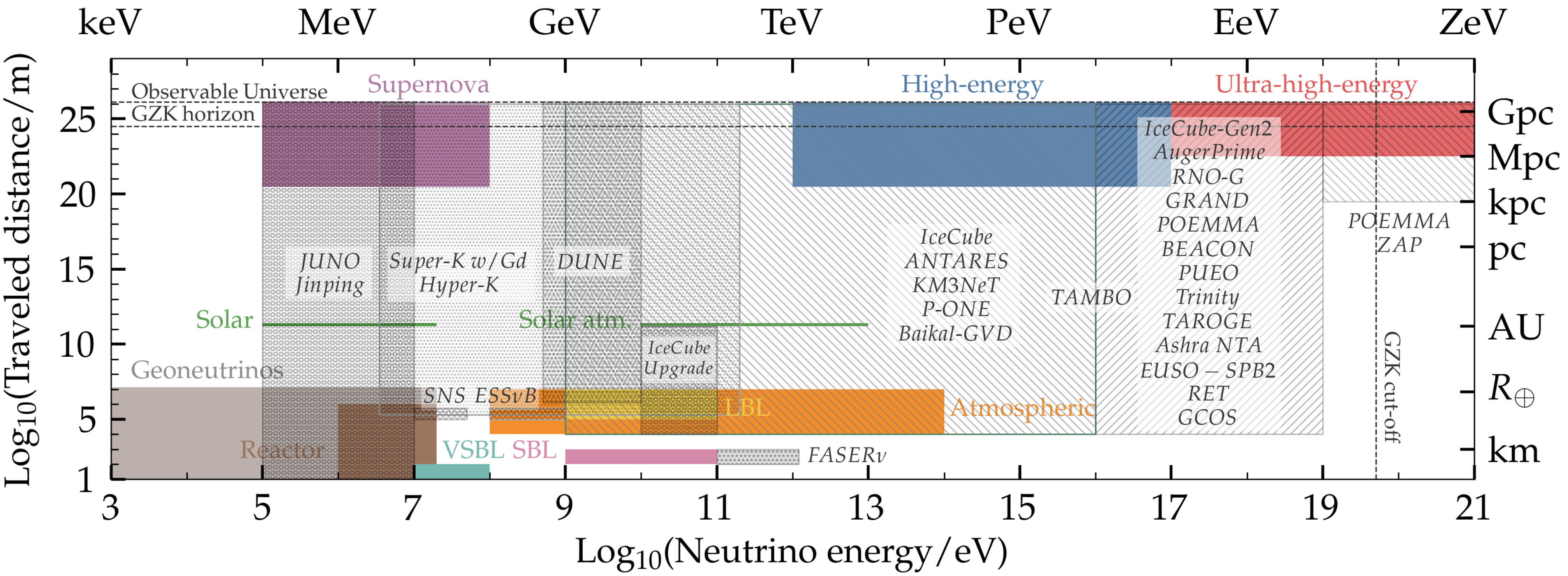


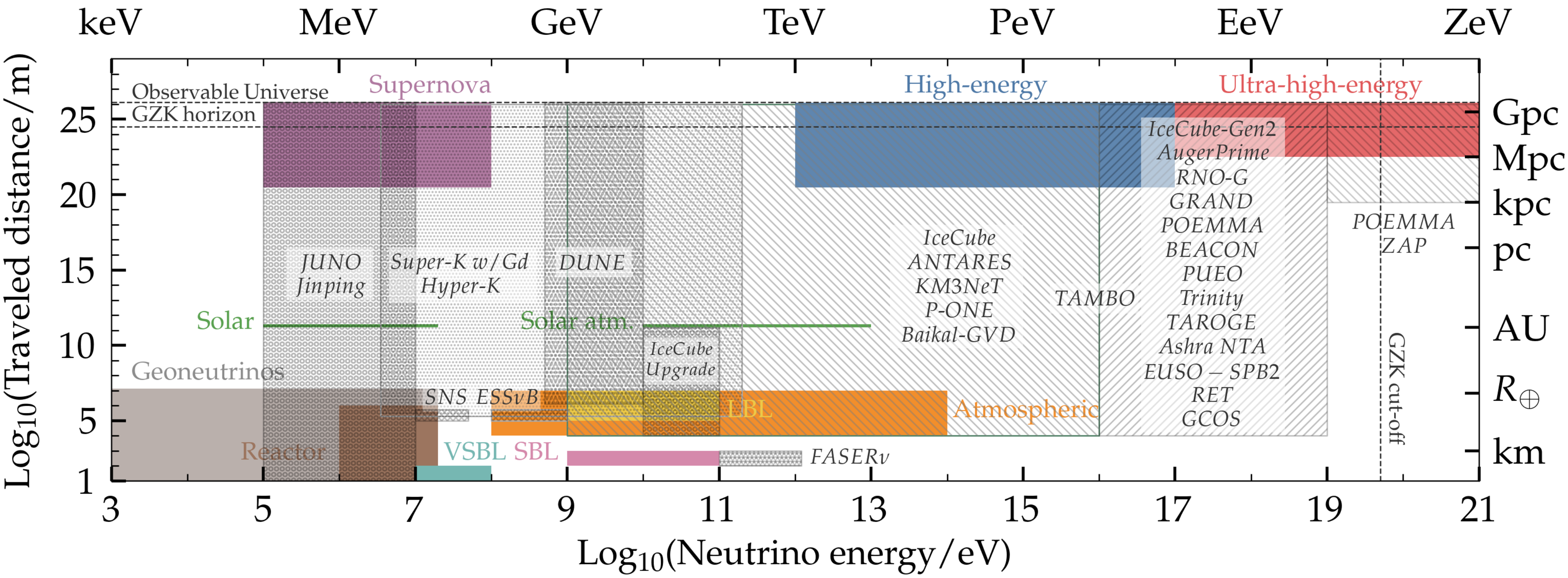
Synergies with lower energies

Increase TeV–PeV
ν statistics

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

Discovered in 2013 by IceCube

Predicted in 1969 by Berezinksy



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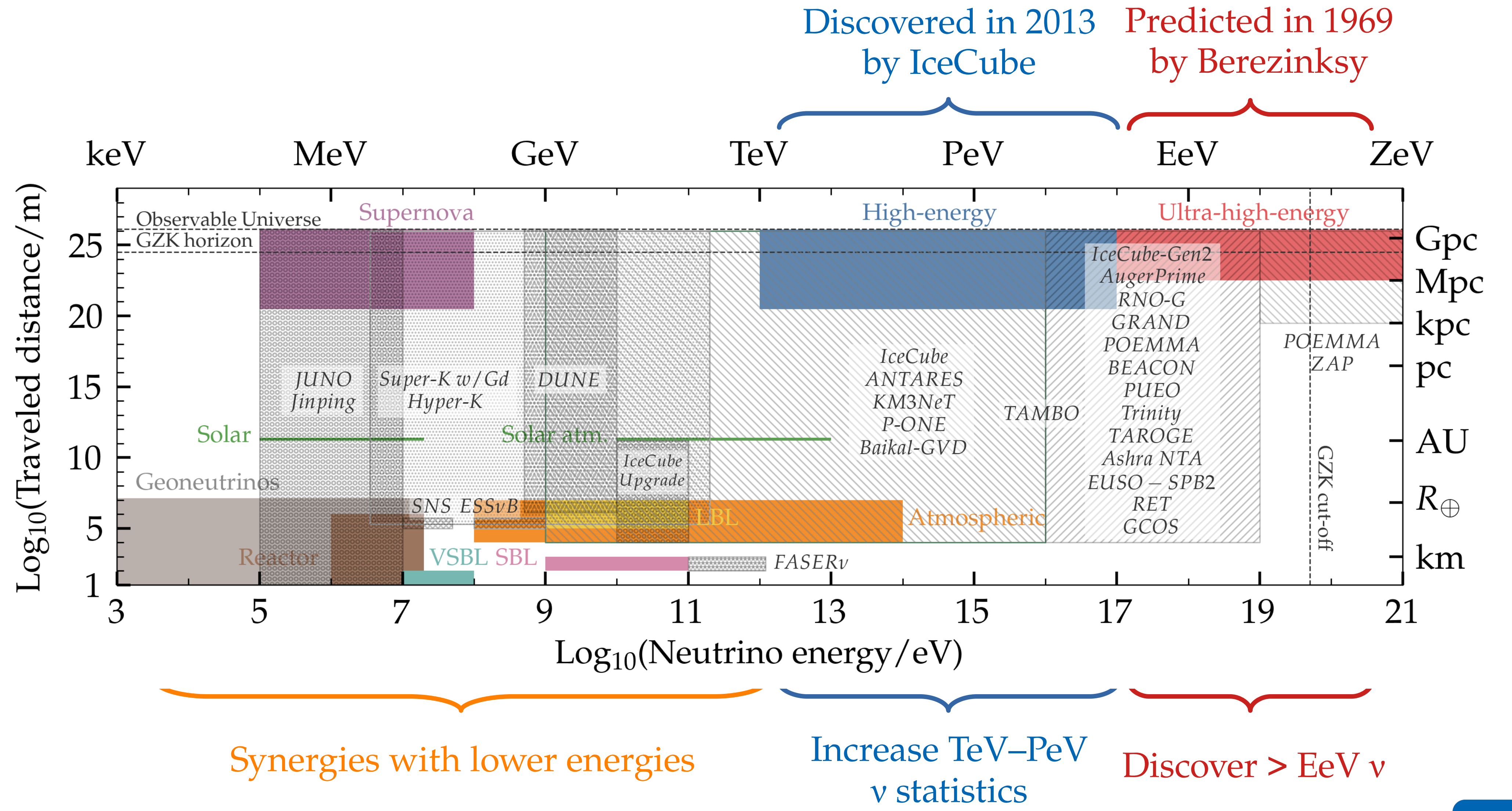

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Today

TeV–PeV ν

Next decade

$>$ 100-PeV ν

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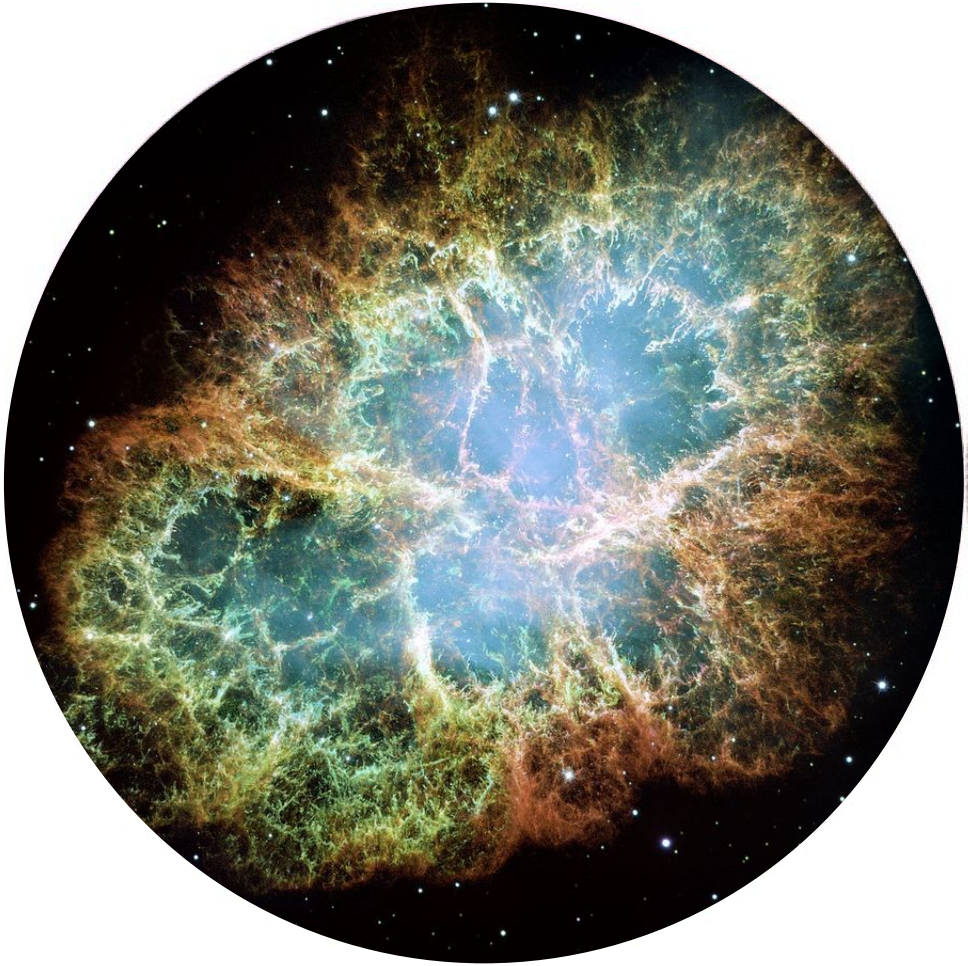
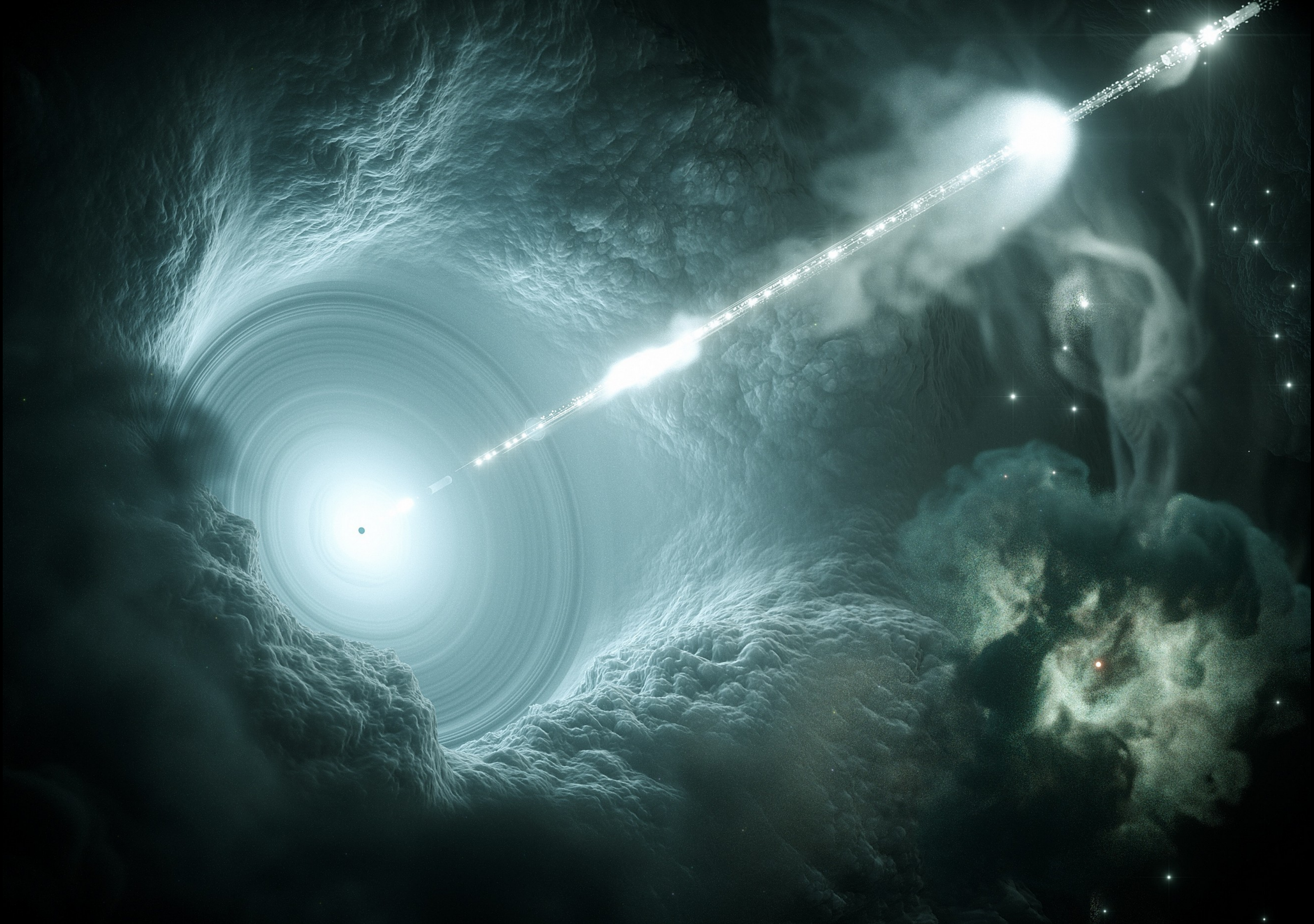


Banco Central de Reserva del Perú / NASA / ESA / CERN / Symmetry Magazine



DESY

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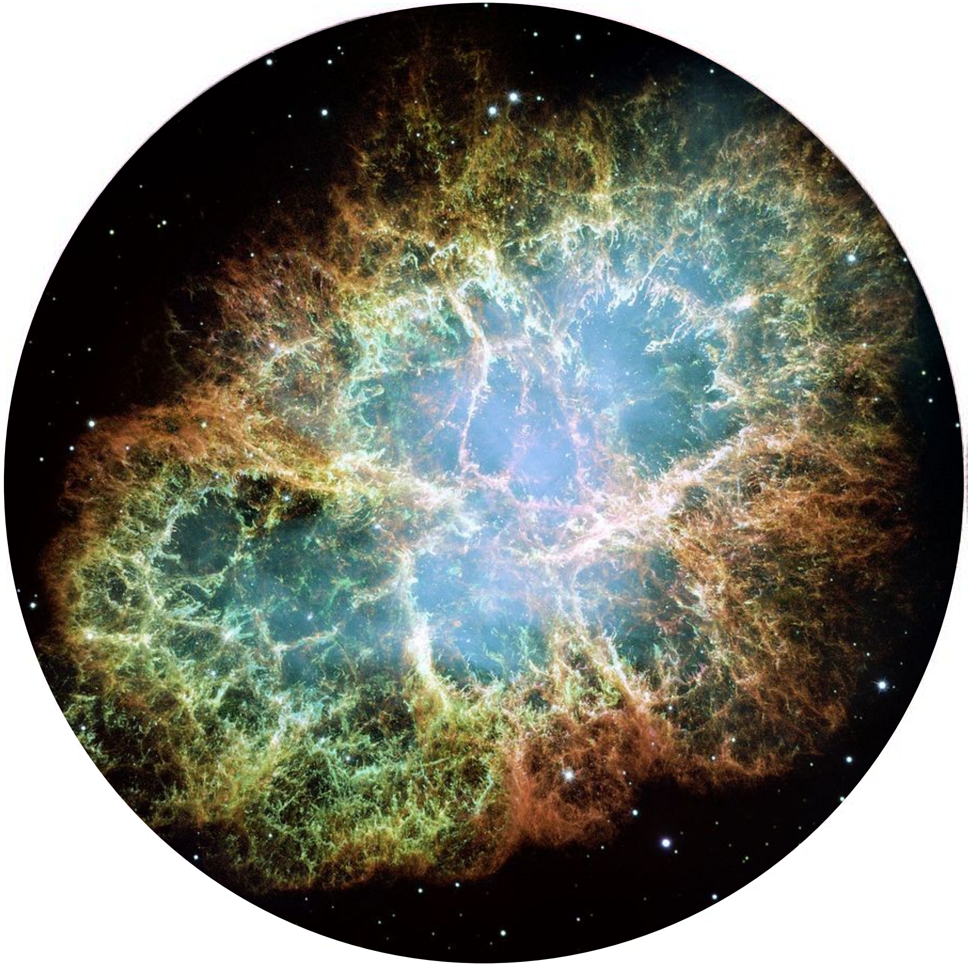

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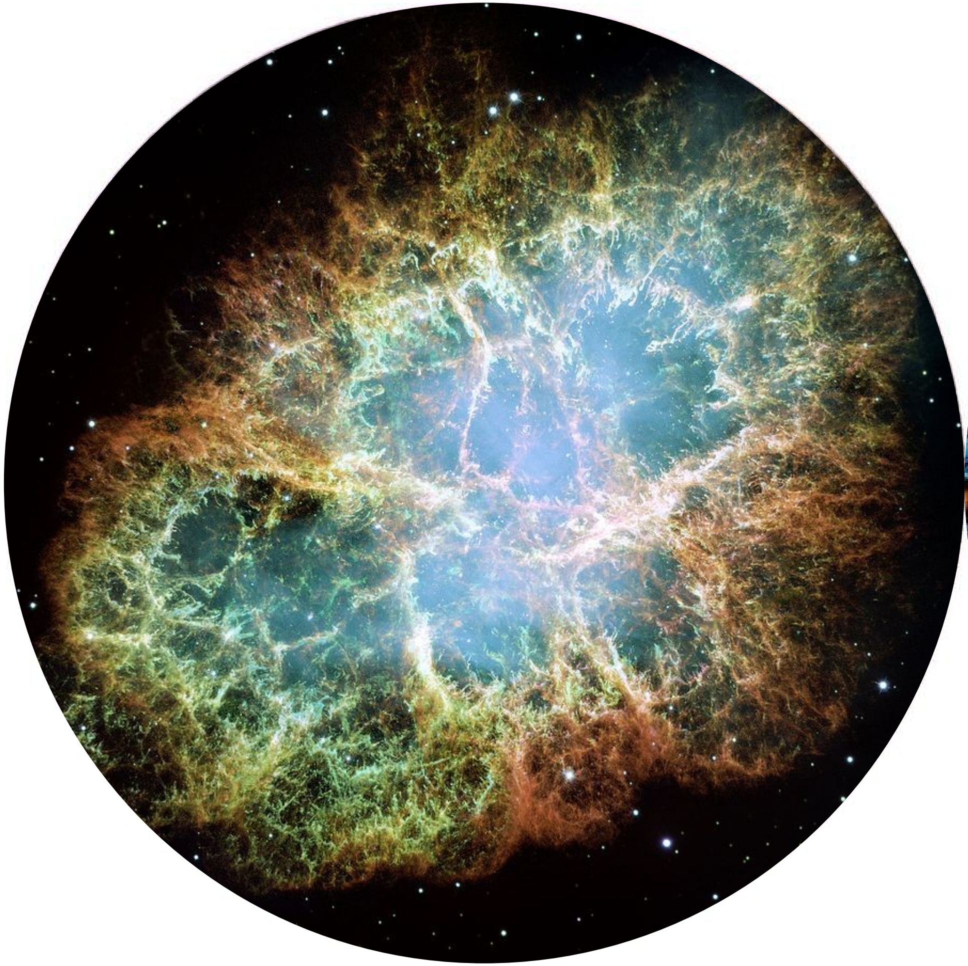

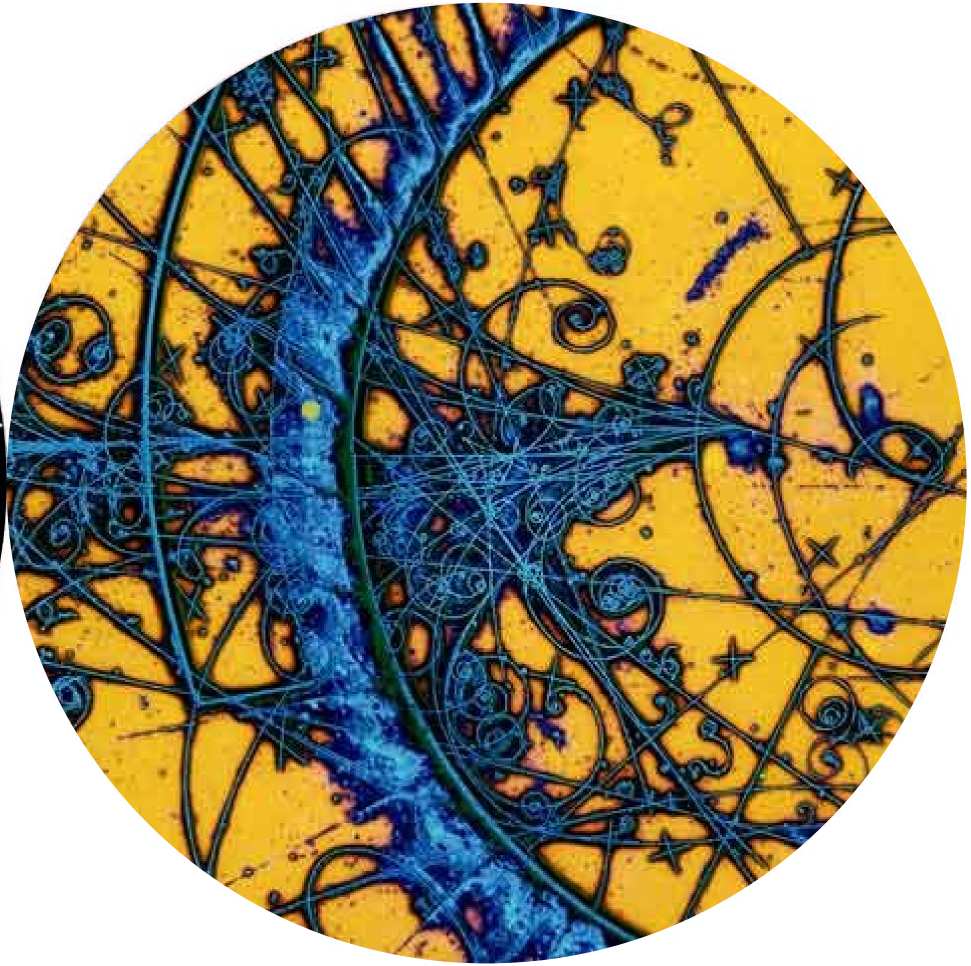

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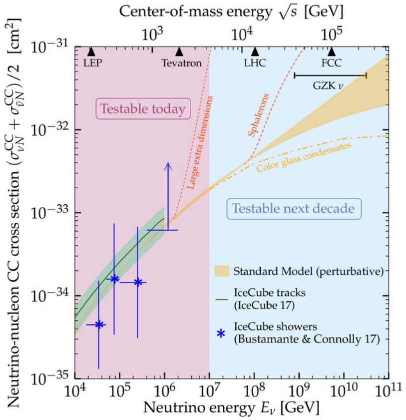
TeV–EeV ν cross sections



MB & Connolly, *PRL* 2019

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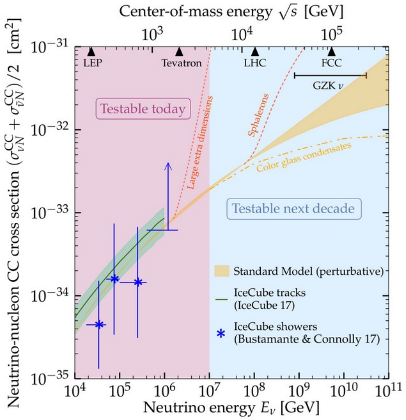
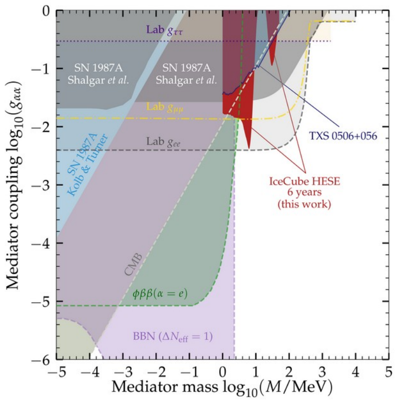


MB & Connolly, *PRL* 2019

ν self-interactions



MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

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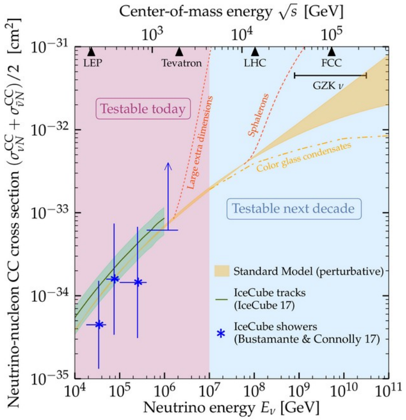

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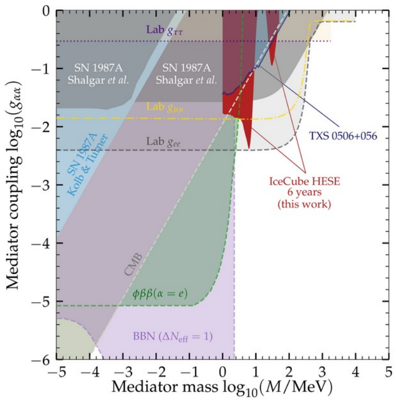
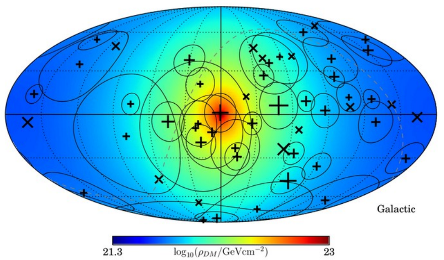


MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

ν scattering on Galactic DM



Argüelles, Kheirandish, Vincent, *PRL* 2017

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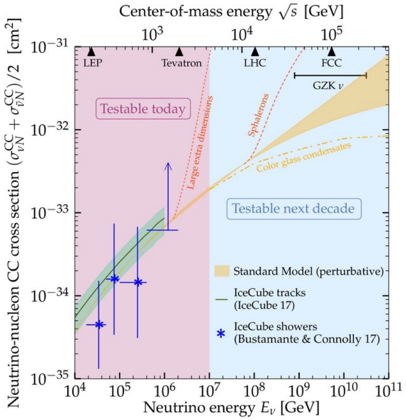

MB & Connolly, *PRL* 2019

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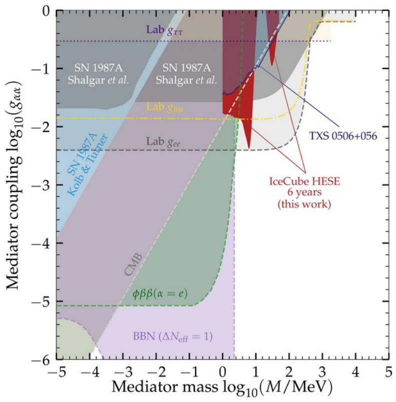

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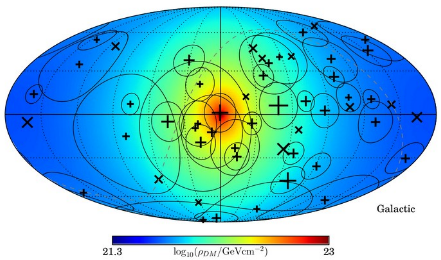
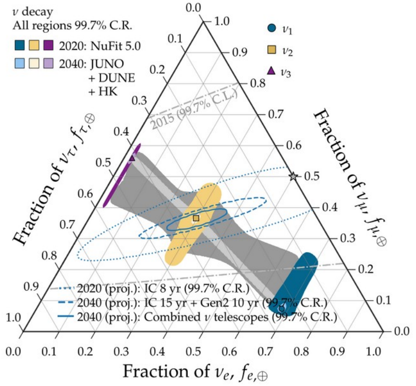


Argüelles, Kheirandish, Vincent, *PRL* 2017

ν decay



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

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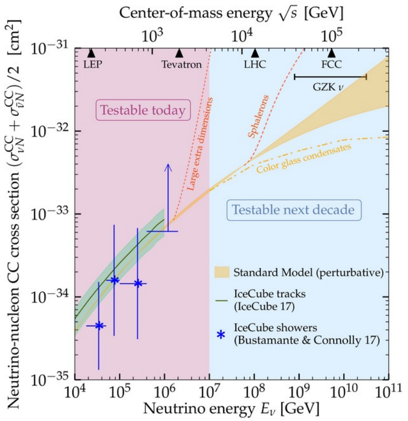

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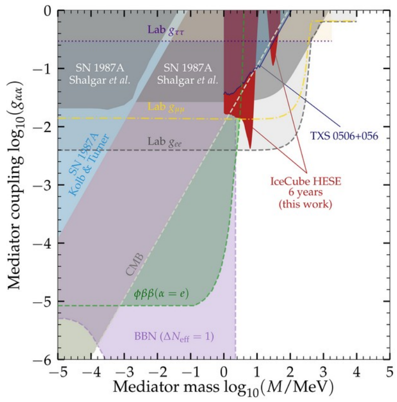

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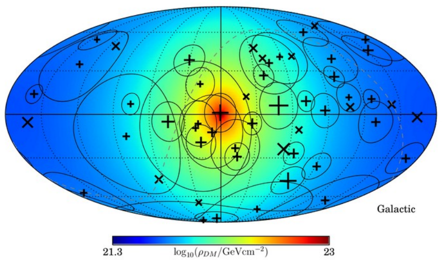

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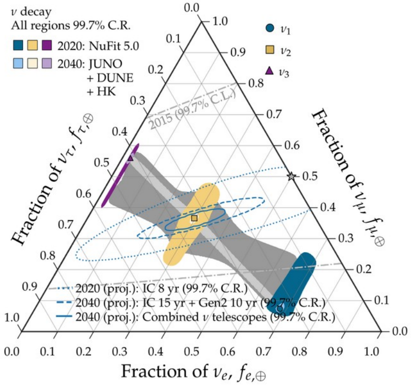
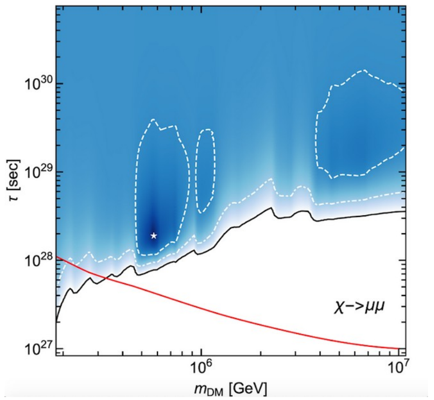


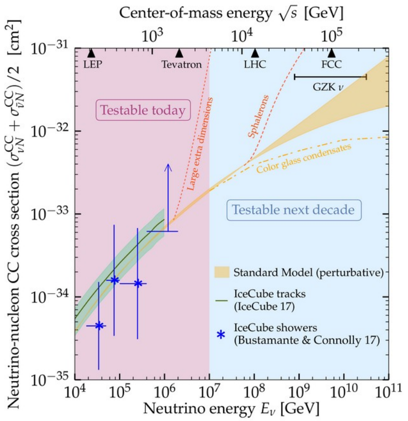
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Dark matter decay



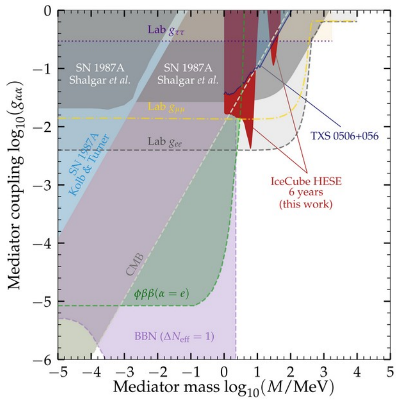
Chianese, Fiorillo, Miele, Morisi, Pisanti, *JCAP* 2019

TeV–EeV ν cross sections



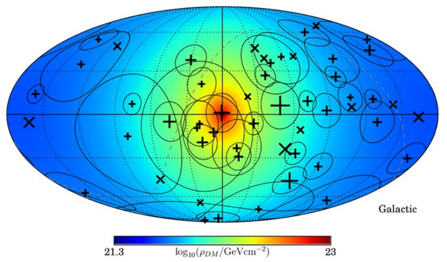
MB & Connolly, *PRL* 2019

ν self-interactions



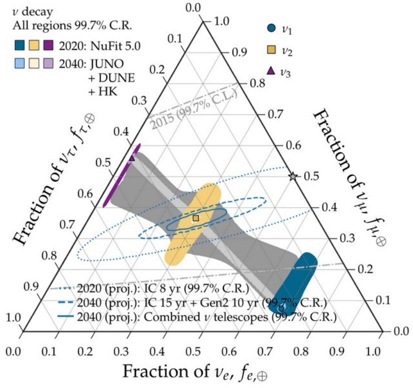
MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

ν scattering on Galactic DM



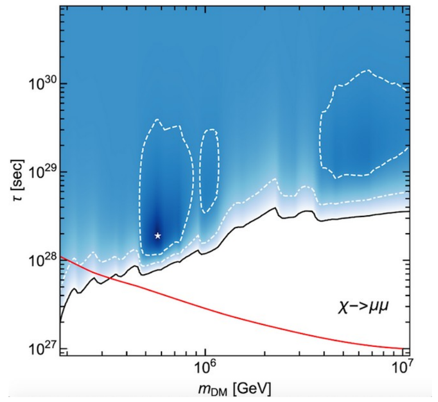
Argüelles, Kheirandish, Vincent, *PRL* 2017

ν decay



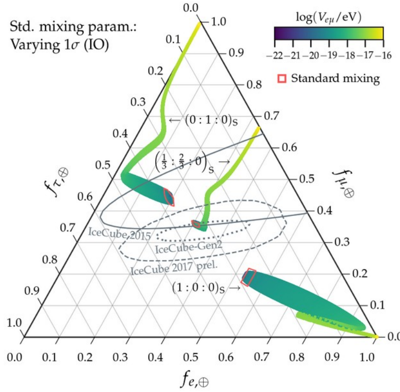
Song, Li, Argüelles, MB, Vincent, *JCAP* 2021

Dark matter decay



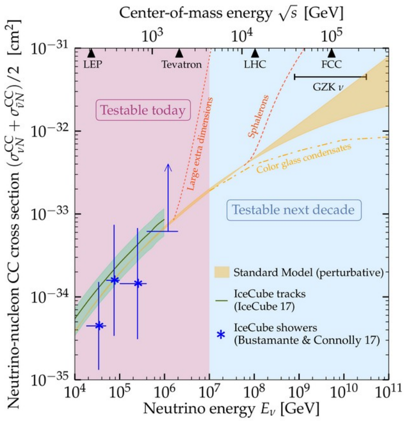
Chianese, Fiorillo, Miele, Morisi, Pisanti, *JCAP* 2019

ν-electron interaction



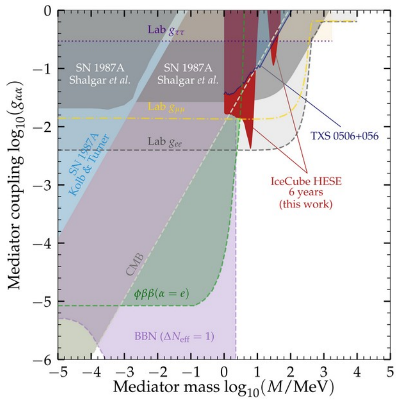
MB & Agarwalla, *PRL* 2019

ν TeV–EeV ν cross sections



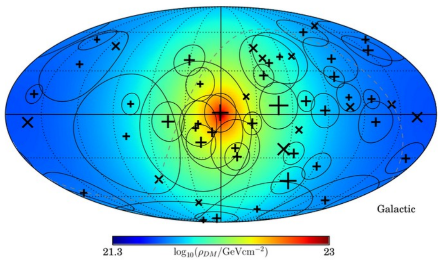
MB & Connolly, *PRL* 2019

ν self-interactions



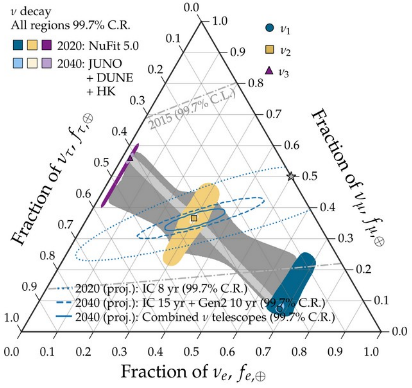
MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

ν scattering on Galactic DM



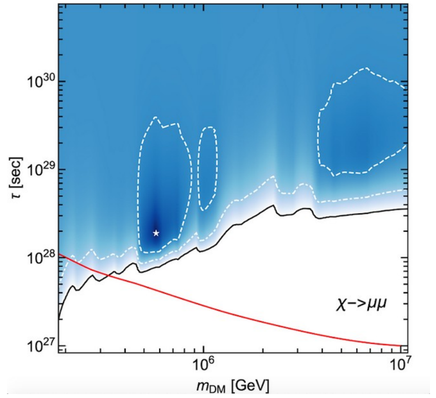
Argüelles, Kheirandish, Vincent, *PRL* 2017

ν decay



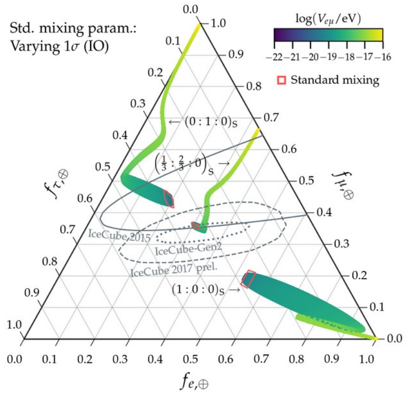
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Dark matter decay



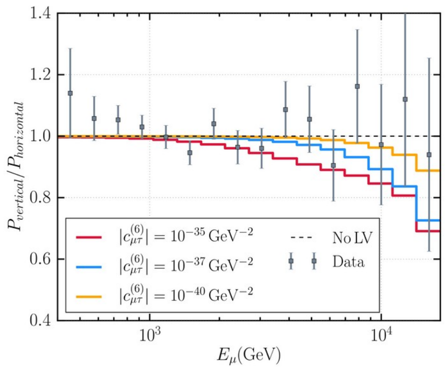
Chianese, Fiorillo, Miele, Morisi, Pisanti, *JCAP* 2019

ν-electron interaction



MB & Agarwalla, *PRL* 2019

Lorentz-invariance violation



IceCube, *Nature Phys.* 2018

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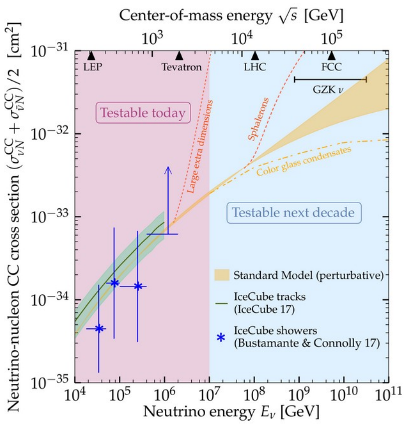
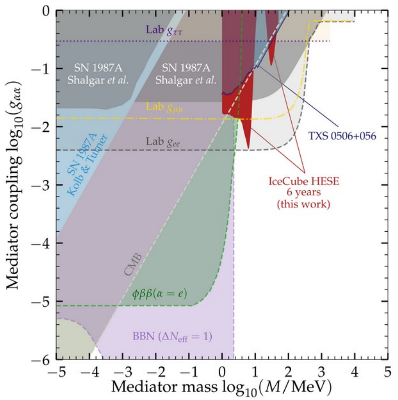


MB & Connolly, *PRL* 2019

ν self-interactions



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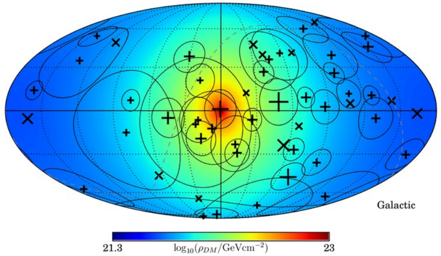
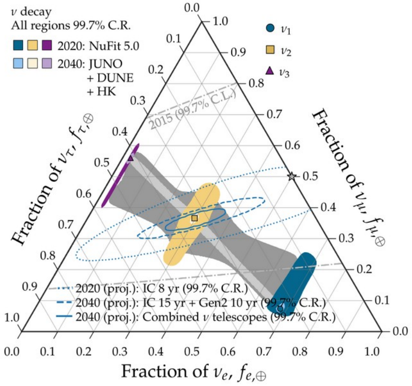


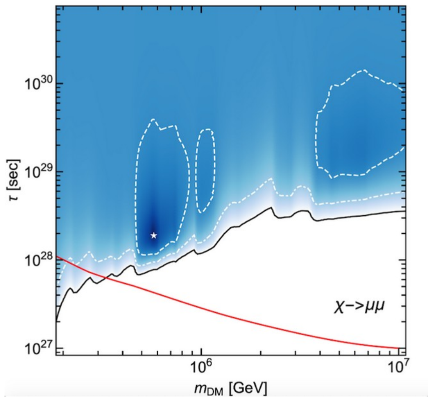
Argüelles, Kheirandish, Vincent, *PRL* 2017

ν decay



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

Dark matter decay



Chianese, Fiorillo, Miele, Morisi, Pisanti, *JCAP* 2019

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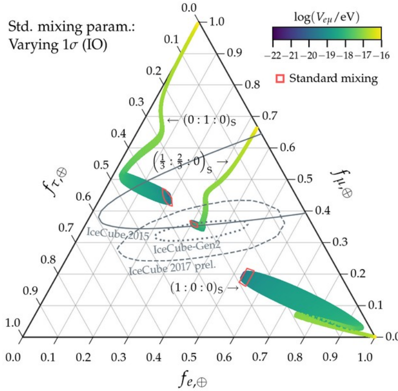
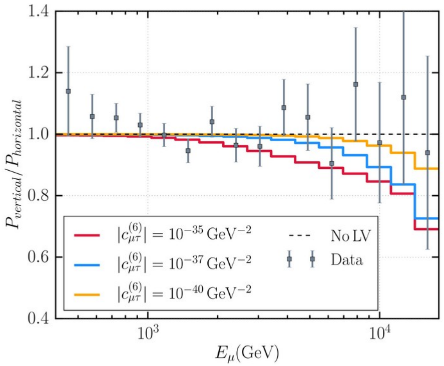


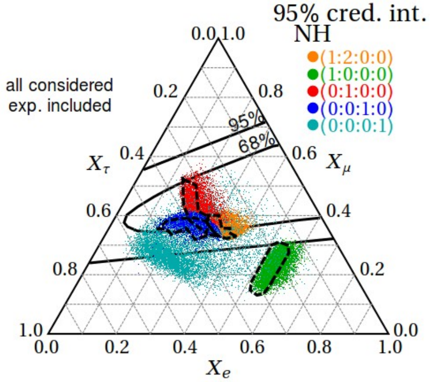
MB & Agarwalla, *PRL* 2019

Lorentz-invariance violation



IceCube, *Nature Phys.* 2018

Sterile neutrinos



Brdar, Kopp, Wang, *JCAP* 2017

I.
High-energy cosmic neutrinos:
The story so far

Making high-energy astrophysical neutrinos: a toy model

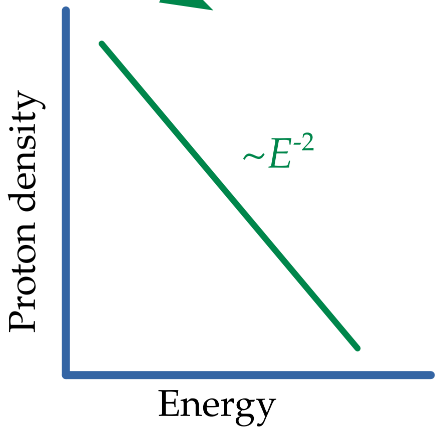
(or $p + p$)

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

Making high-energy astrophysical neutrinos: a toy model

(or $p + p$)

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



Making high-energy astrophysical neutrinos: a toy model

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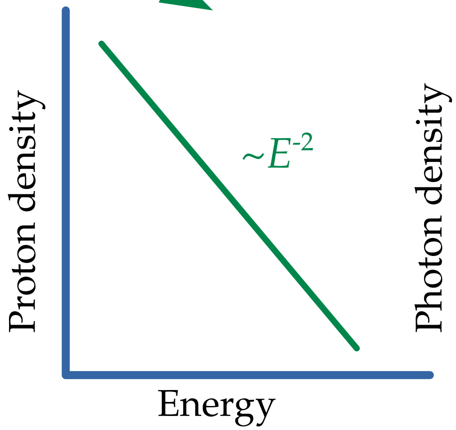
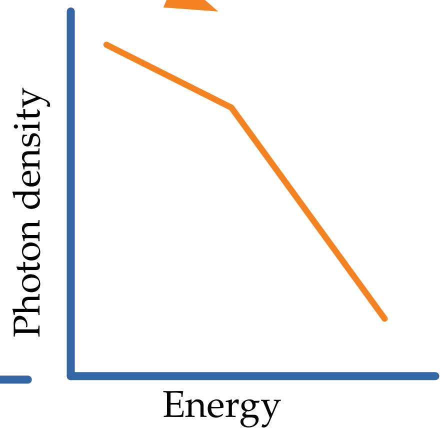




Making high-energy astrophysical neutrinos: a toy model

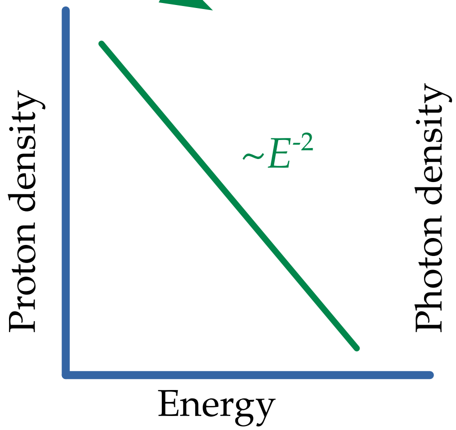
(or $p + p$)

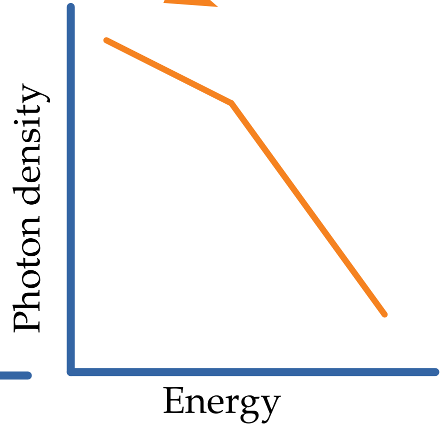
$$p + \gamma_{\text{target}} \longrightarrow \Delta^+ \longrightarrow \begin{cases} p + \pi^0, & \text{Br} = 2/3 \\ n + \pi^+, & \text{Br} = 1/3 \end{cases}$$

$$\pi^0 \longrightarrow \gamma + \gamma$$

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

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





Making high-energy astrophysical neutrinos: a toy model

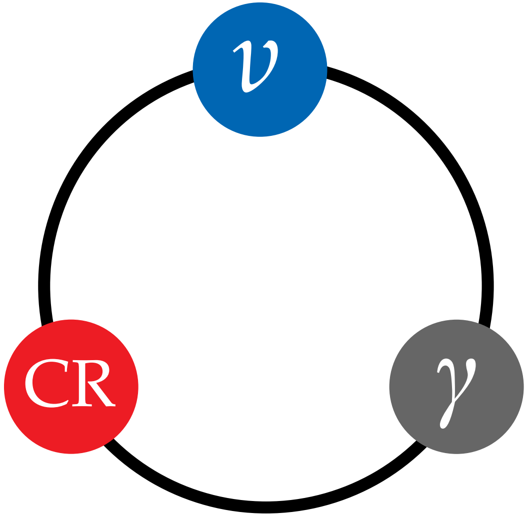
(or $p + p$)

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

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

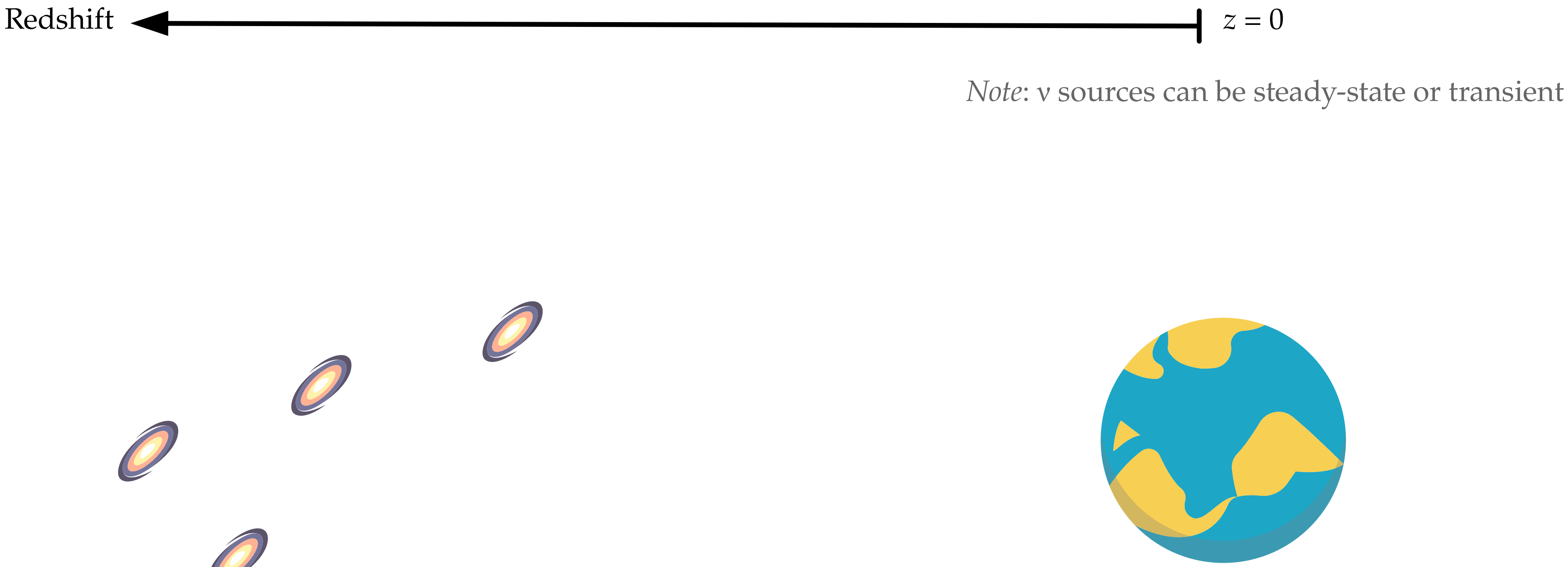
$$\pi^{+} \longrightarrow \mu^{+} + \nu_{\mu} \longrightarrow \bar{\nu}_{\mu} + e^{+} + \nu_{e} + \nu_{\mu}$$

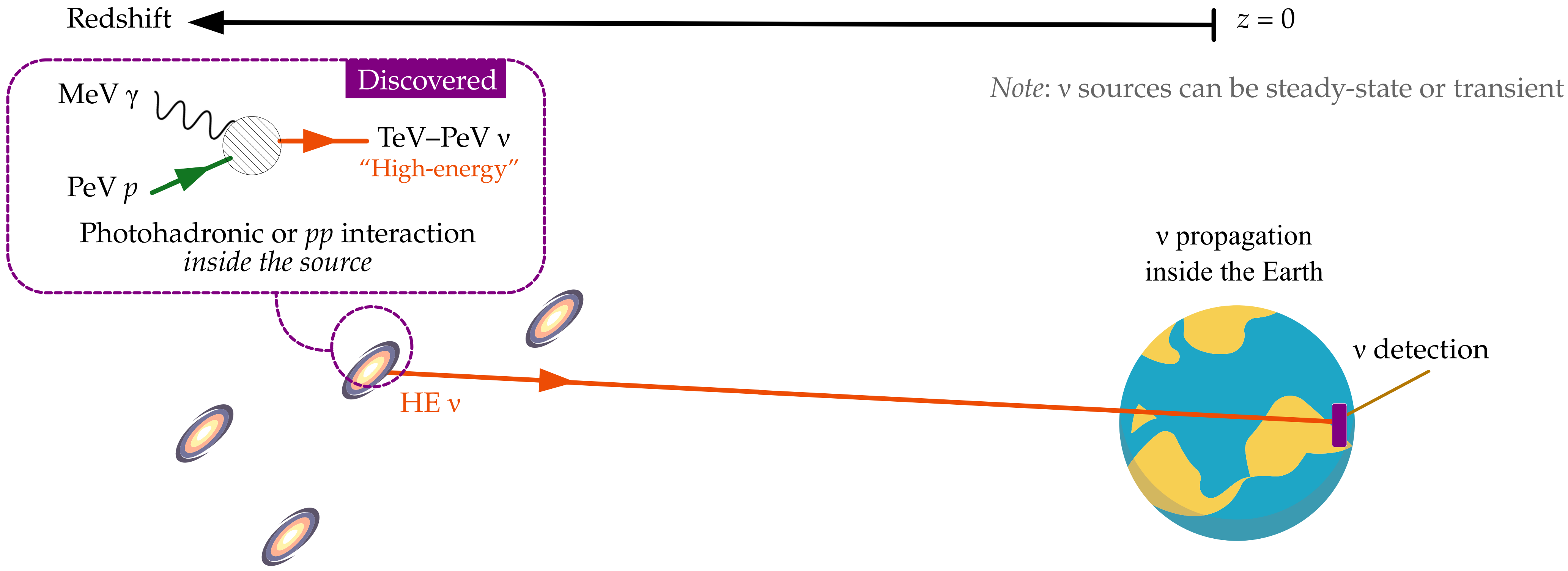
$$n \text{ (escapes)} \longrightarrow p + e^{-} + \bar{\nu}_{e}$$

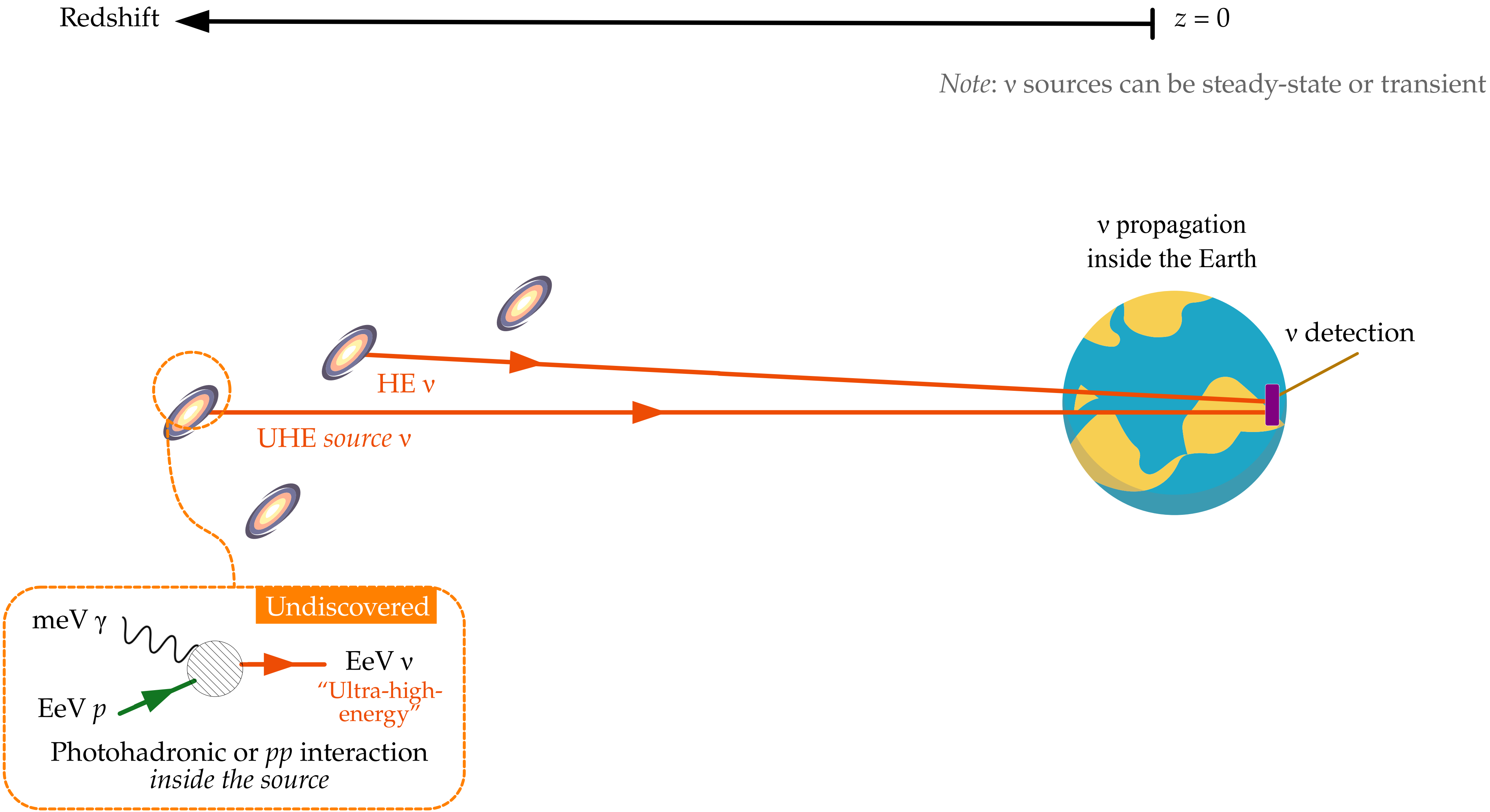


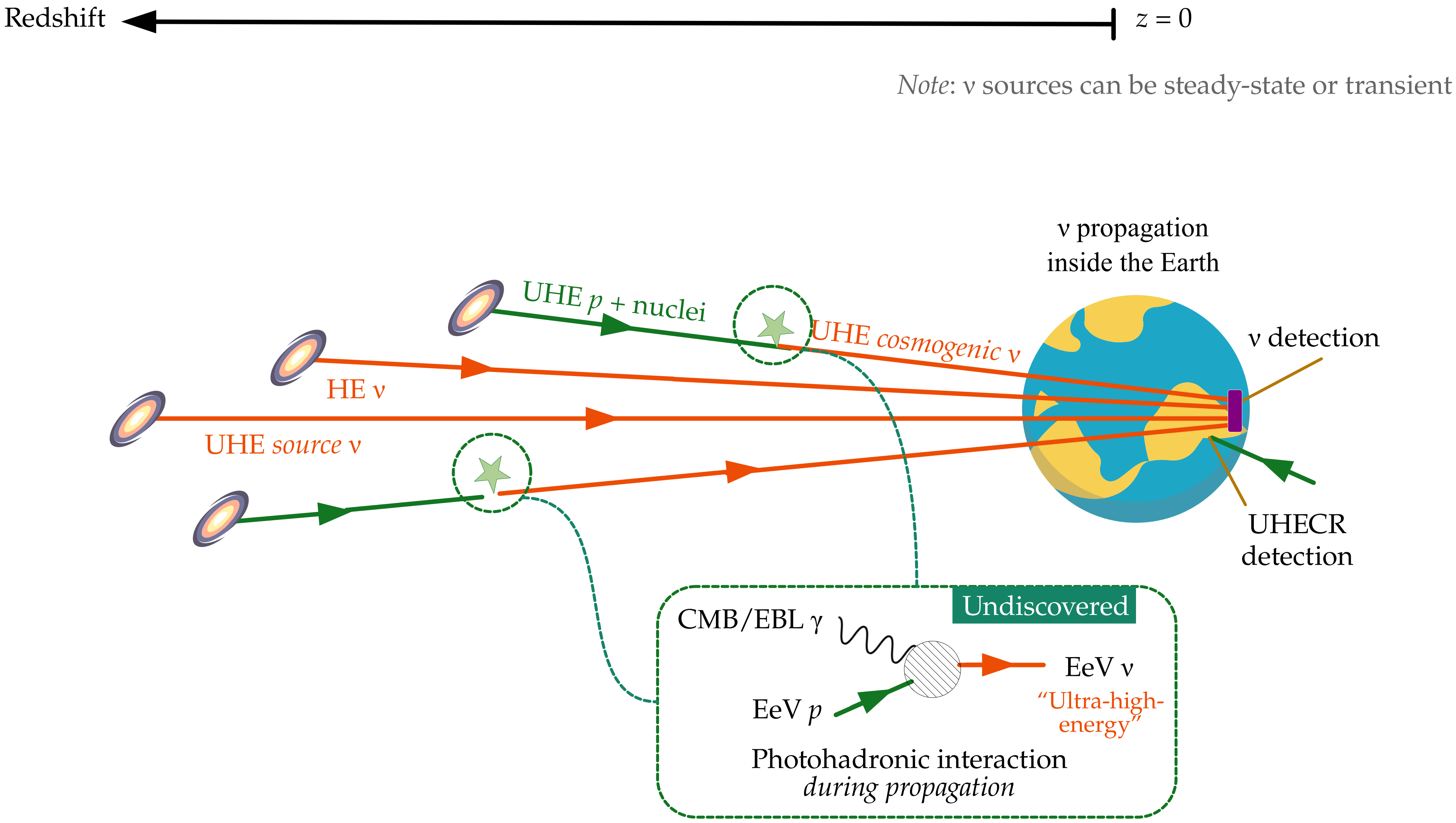
Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10

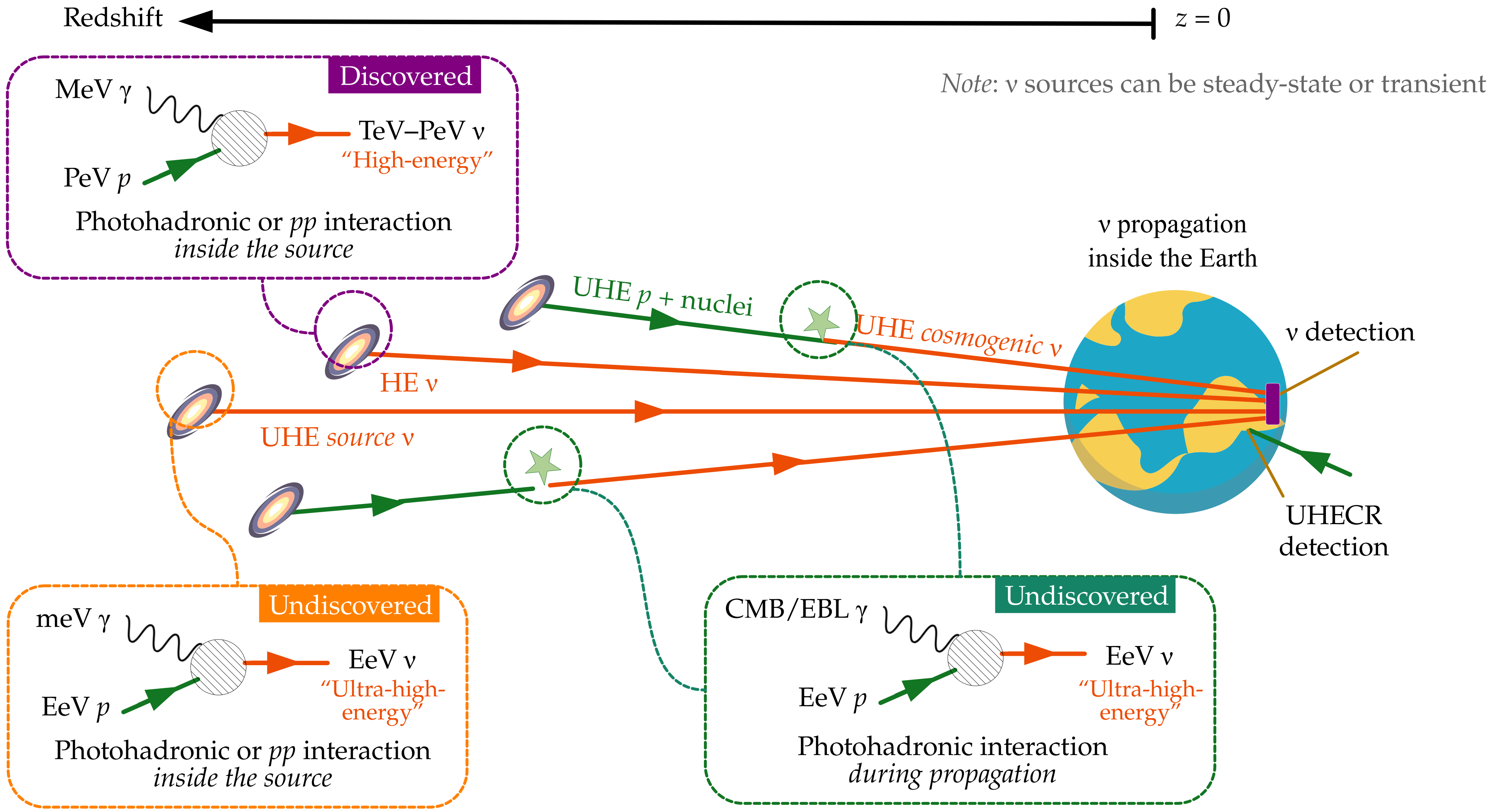

Redshift
$z = 0$
Note: ν sources can be steady-state or transient


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


Redshift
$z = 0$
Note: ν sources can be steady-state or transient
ν propagation inside the Earth
ν detection
HE ν
UHE *source* ν
Undiscovered
meV γ
EeV ν
"Ultra-high-energy"
EeV *p*
Photohadronic or *pp* interaction *inside the source*



Redshift
$z = 0$
Note: ν sources can be steady-state or transient
ν propagation inside the Earth
UHE p + nuclei
UHE *cosmogenic* ν
ν detection
HE ν
UHE *source* ν
UHECR detection
Undiscovered
CMB/EBL γ
EeV ν
EeV p
"Ultra-high-energy"
Photohadronic interaction
during propagation



Redshift
$z = 0$
Note: ν sources can be steady-state or transient
Discovered
MeV γ
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PeV p
Photohadronic or pp interaction
inside the source
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UHE cosmogenic ν
HE ν
UHE source ν
ν propagation
inside the Earth
ν detection
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detection
Undiscovered
meV γ
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"Ultra-high-energy"
EeV p
Photohadronic or pp interaction
inside the source
CMB/EBL γ
Undiscovered
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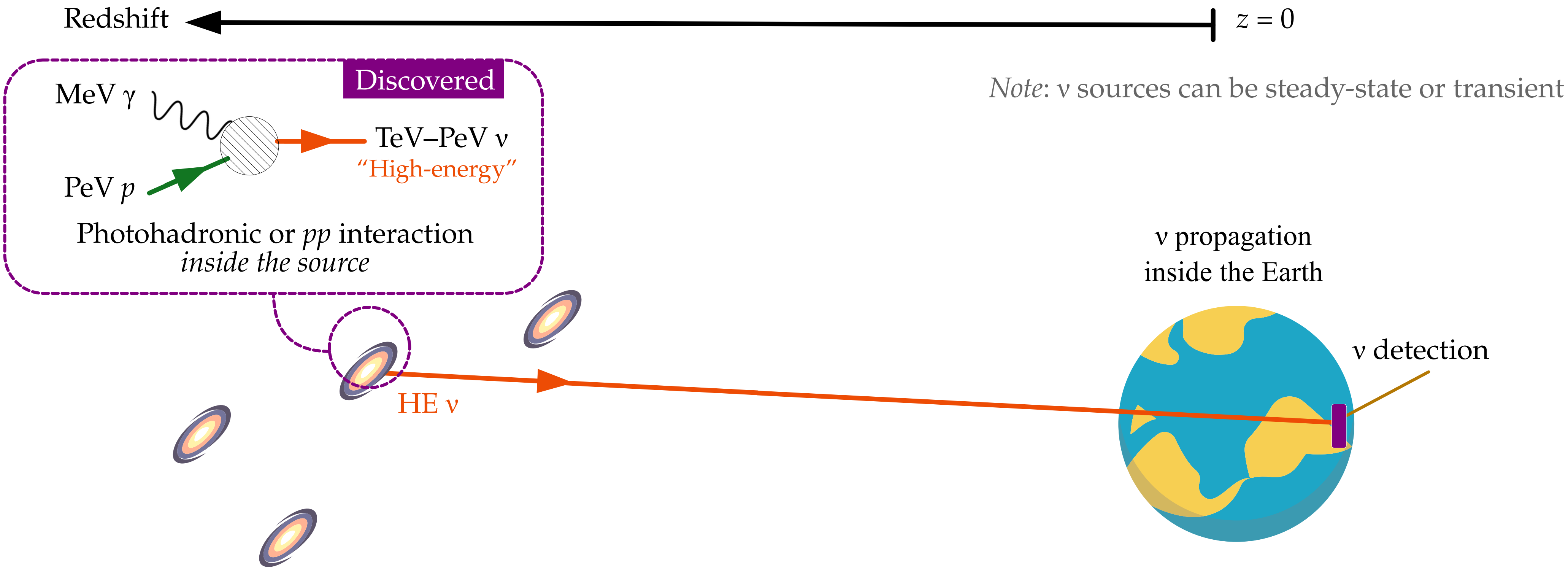
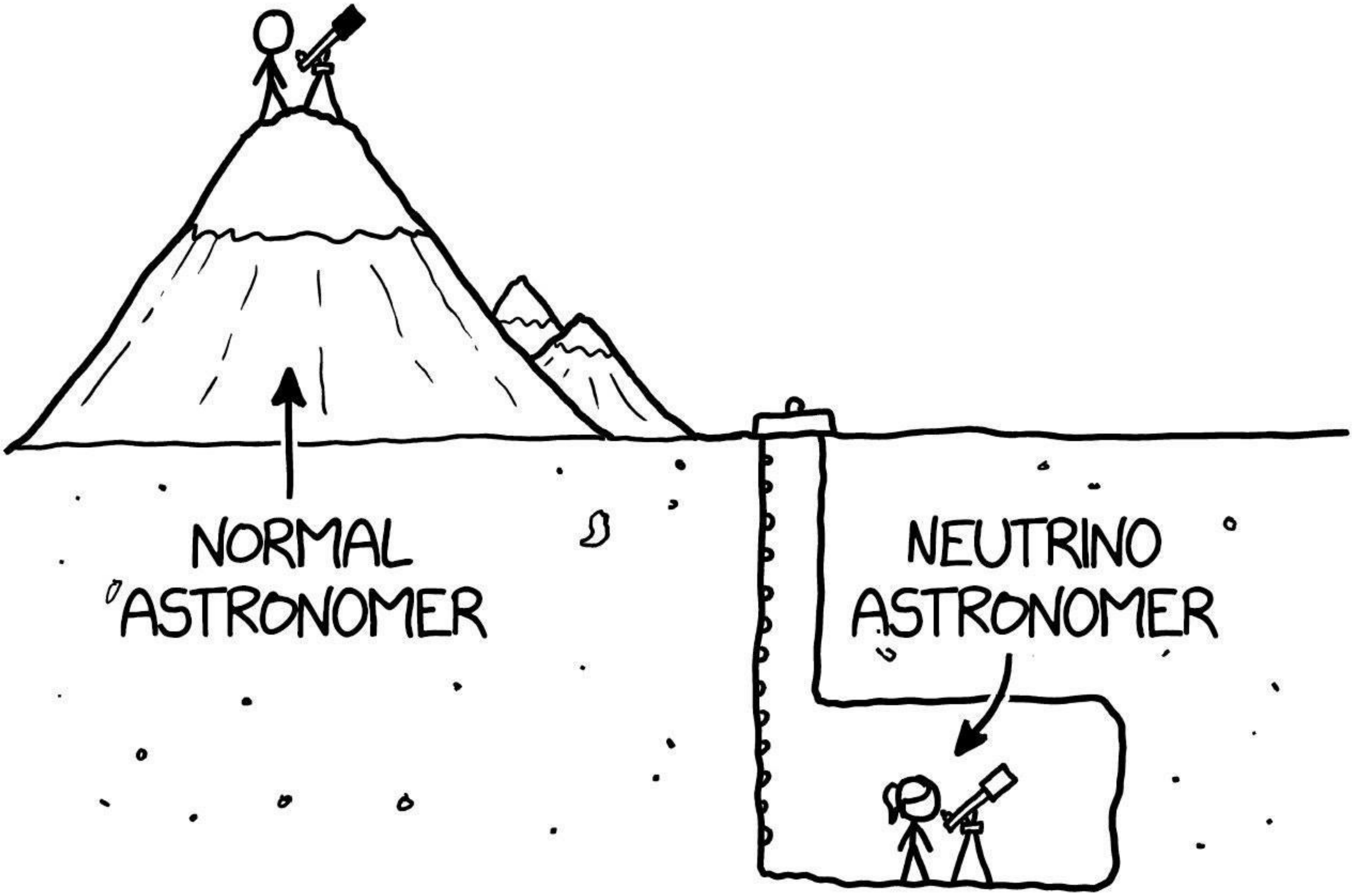
"Ultra-high-energy"
EeV p
Photohadronic interaction
during propagation

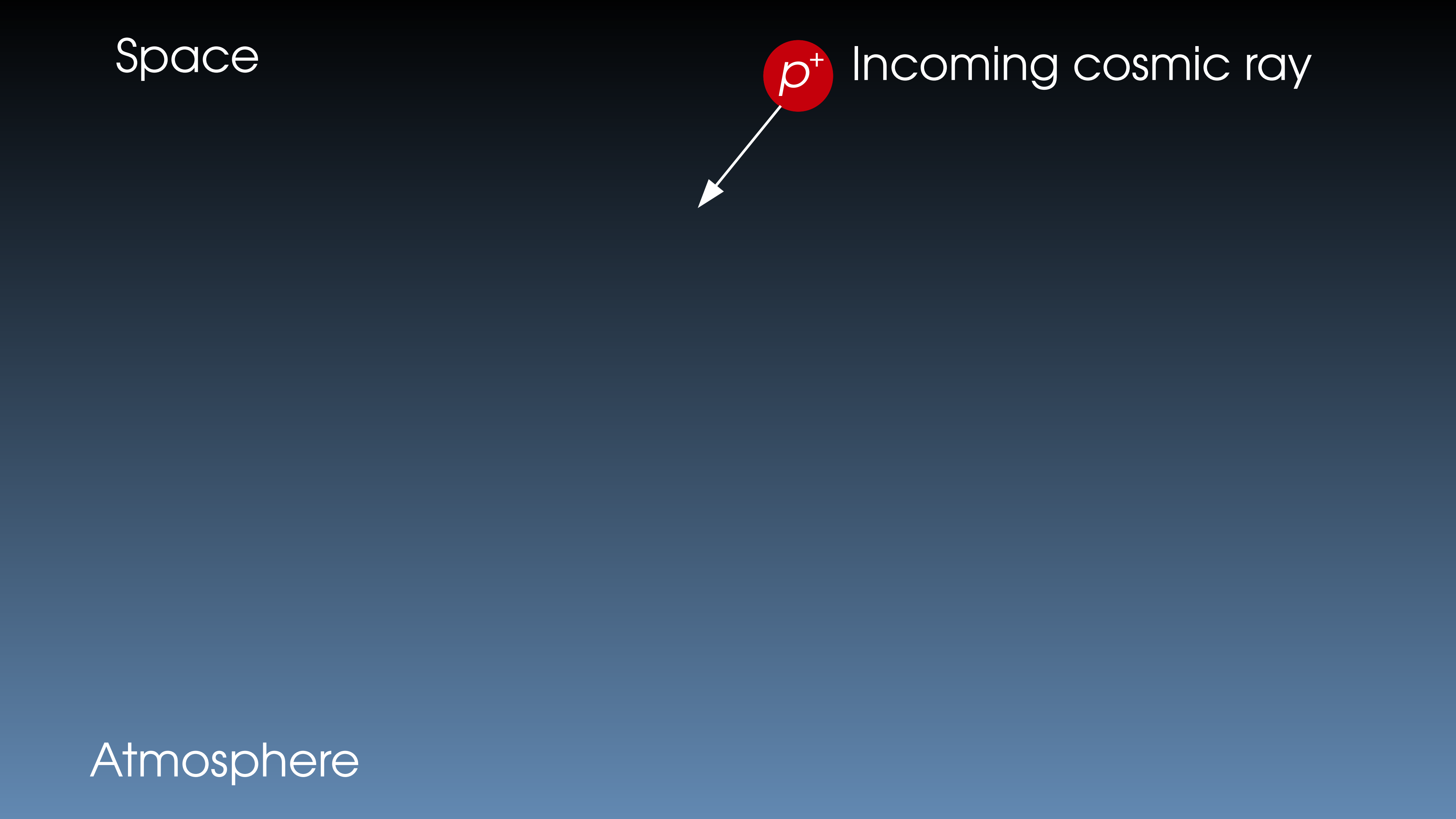

Redshift
$z = 0$
Discovered
MeV γ
TeV–PeV ν
"High-energy"
PeV p
Photohadronic or *pp* interaction
inside the source
Note: ν sources can be steady-state or transient
ν propagation
inside the Earth
ν detection
HE ν

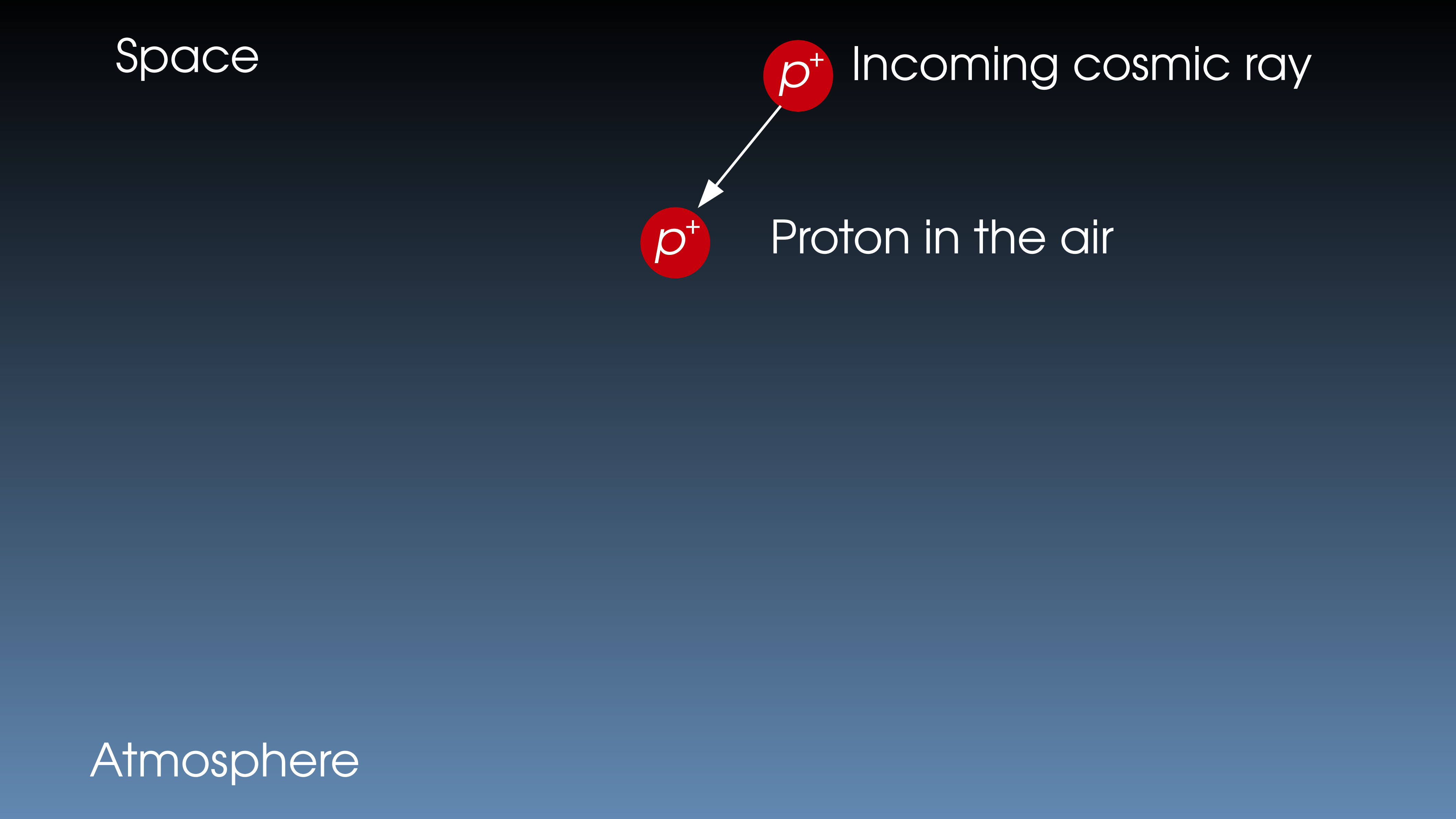


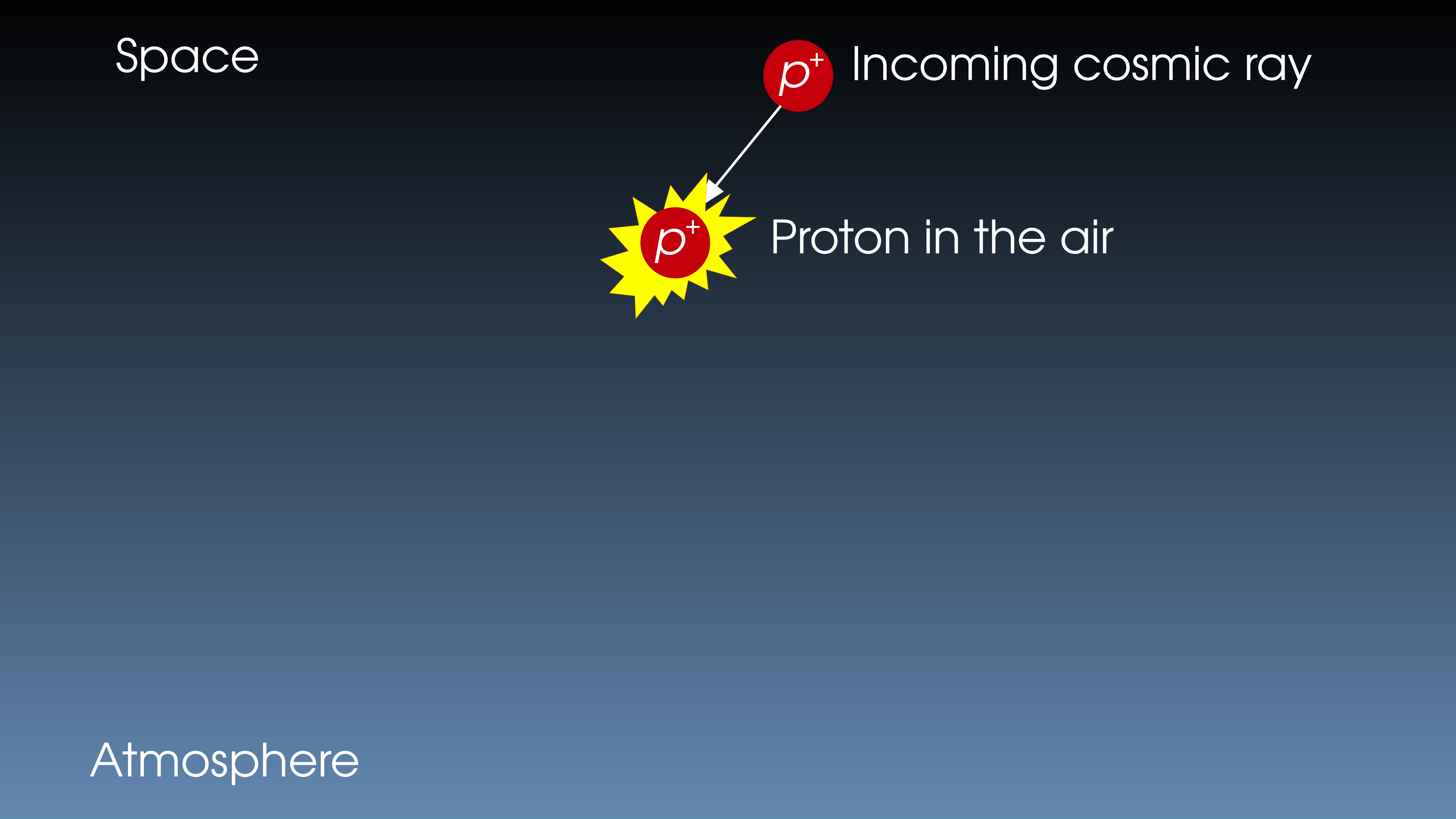
xkcd

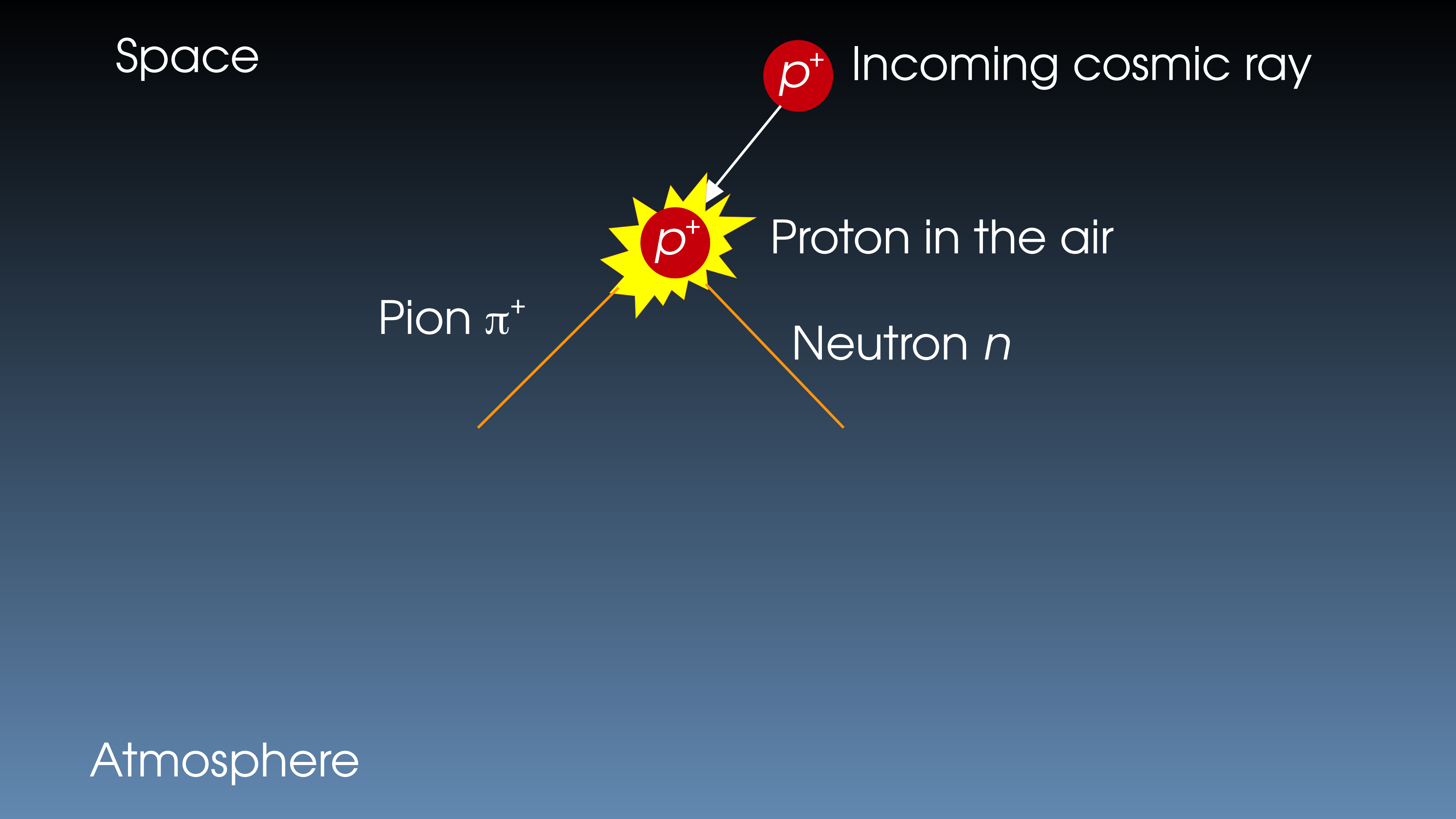
Space

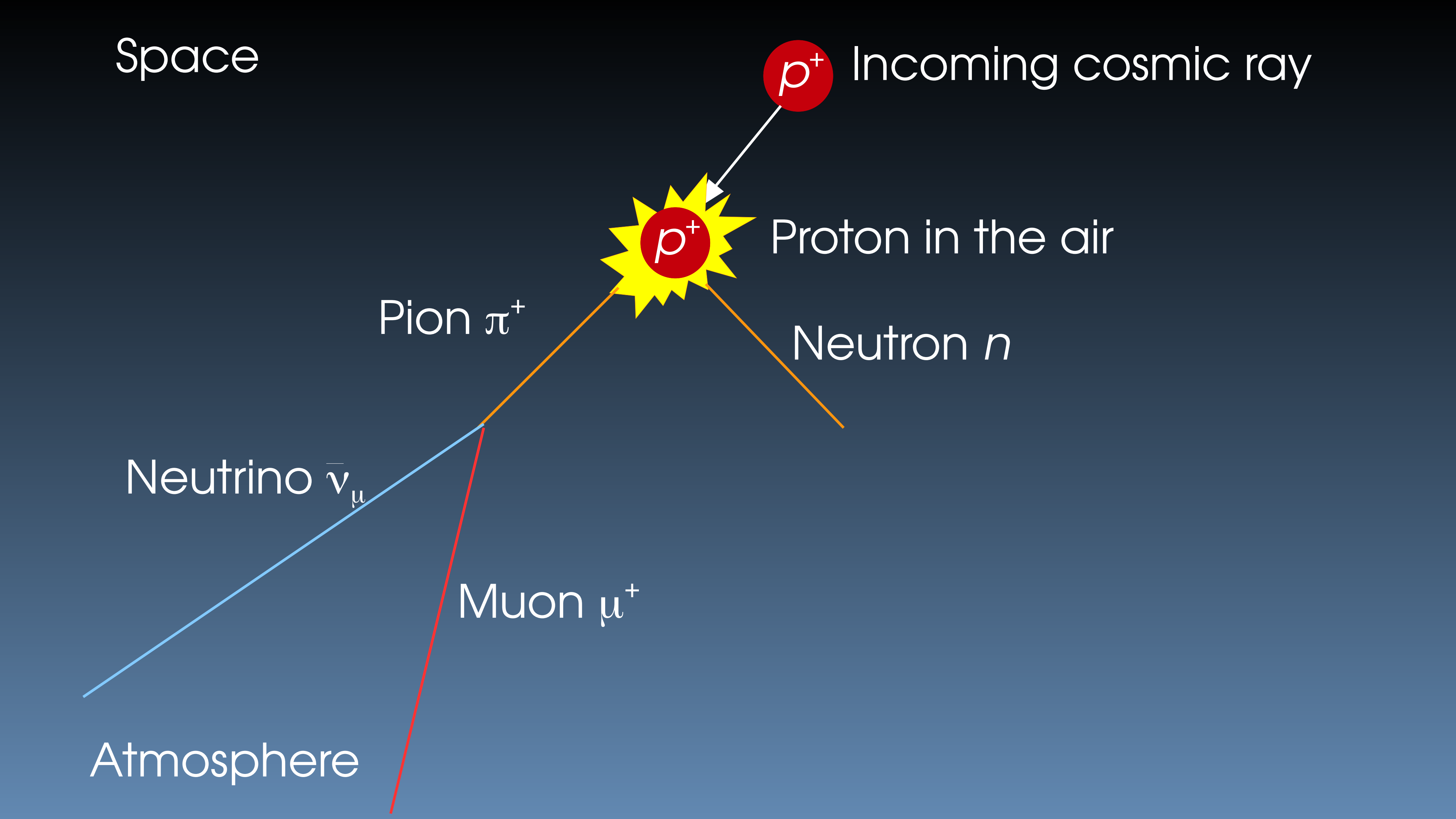
Atmosphere

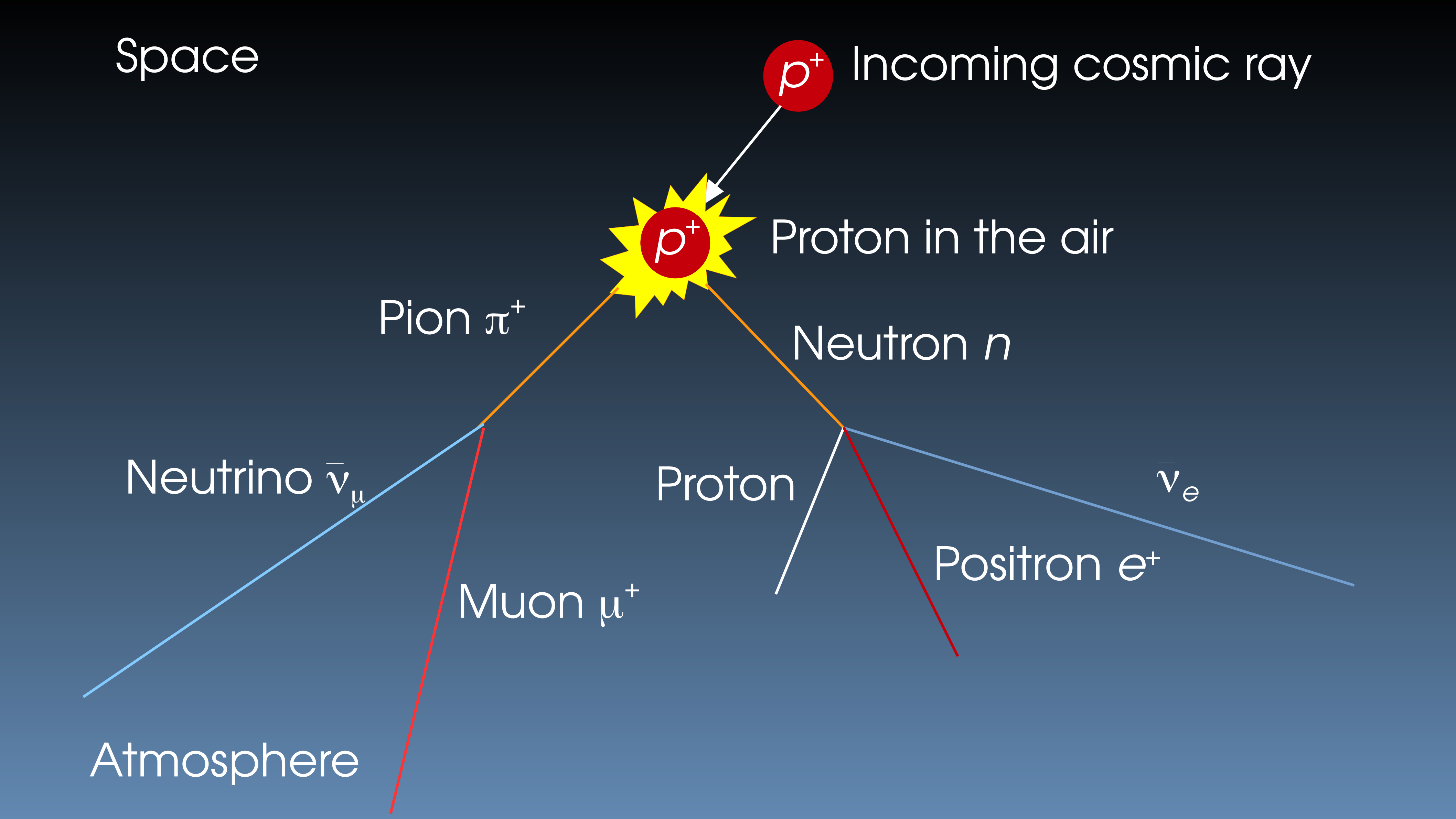

Space
p^+
Incoming cosmic ray
Atmosphere

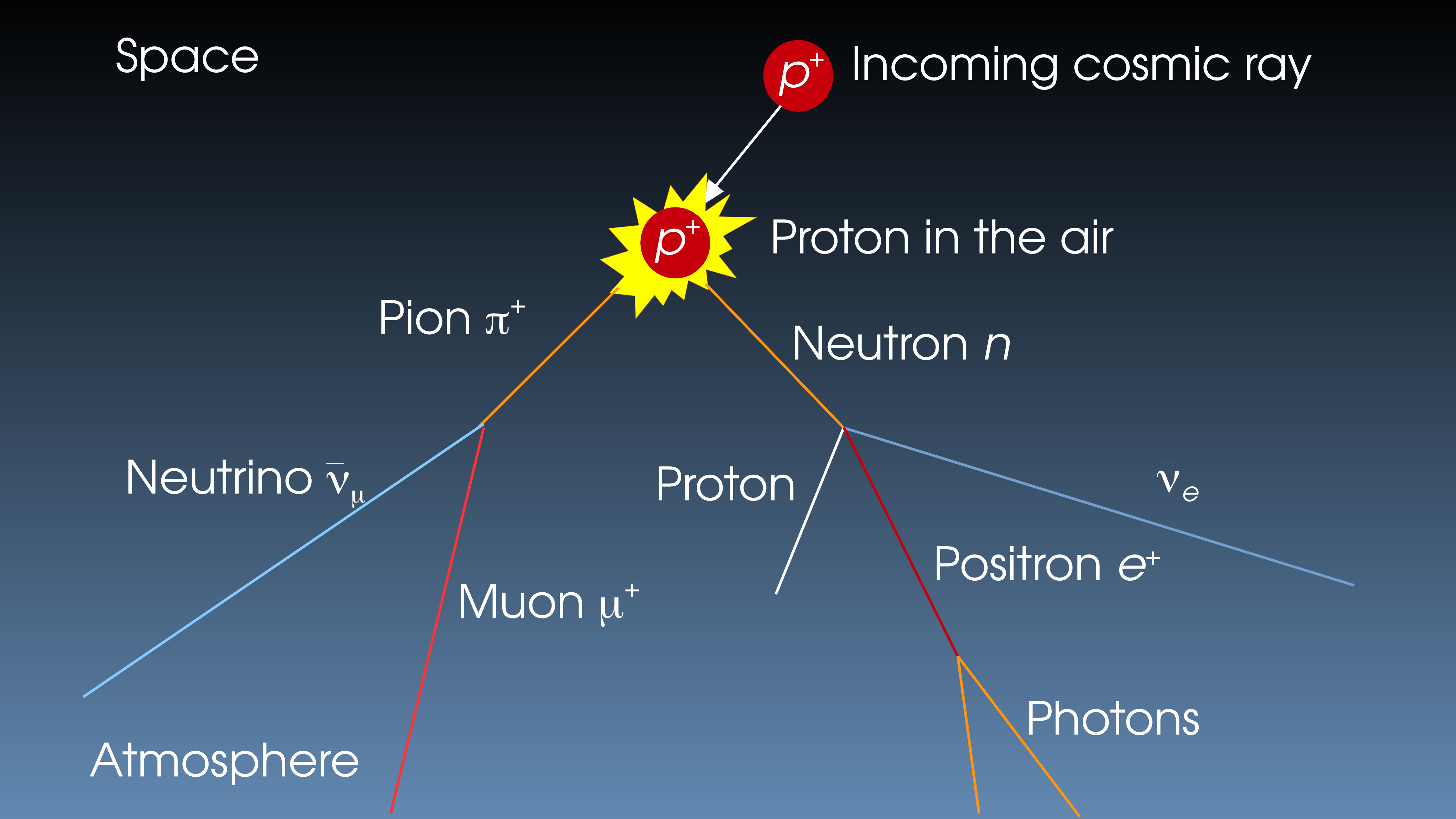

Space
p^+
Incoming cosmic ray
p^+
Proton in the air
Atmosphere

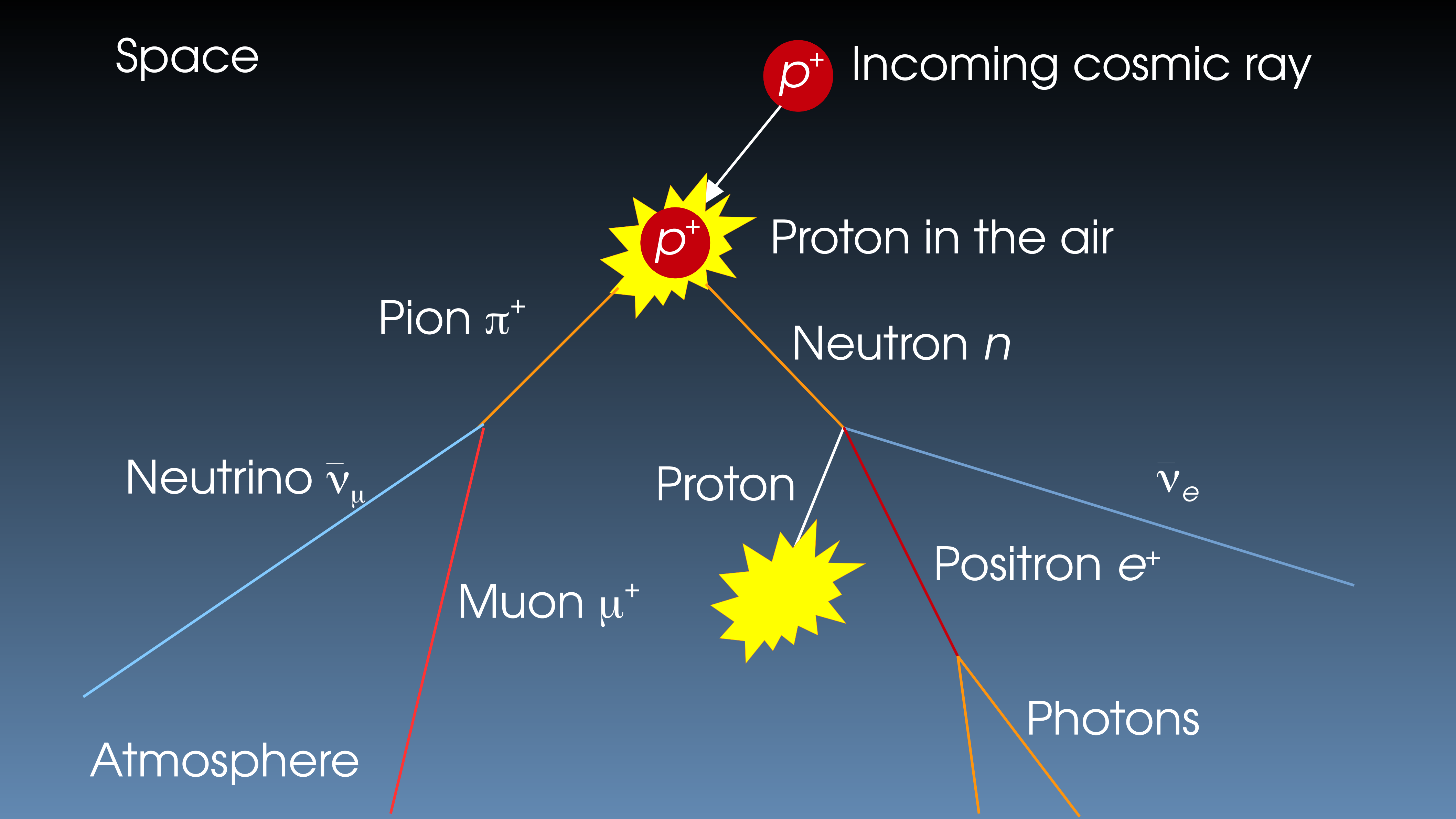

Space
p^+
Incoming cosmic ray
p^+
Proton in the air
Atmosphere


Space
p^+
Incoming cosmic ray
p^+
Proton in the air
Pion π^+
Neutron n
Atmosphere


Space
p^+ Incoming cosmic ray
p^+ Proton in the air
Pion π^+
Neutron n
Neutrino $\bar{\nu}_\mu$
Muon μ^+
Atmosphere


Space
p^+
Incoming cosmic ray
p^+
Proton in the air
Pion π^+
Neutron n
Neutrino $\bar{\nu}_\mu$
Proton
$\bar{\nu}_e$
Positron e^+
Muon μ^+
Atmosphere


Space
p^+ Incoming cosmic ray
p^+ Proton in the air
Pion π^+
Neutron n
Neutrino $\bar{\nu}_\mu$
Proton
$\bar{\nu}_e$
Positron e^+
Muon μ^+
Photons
Atmosphere


Space
p^+
Incoming cosmic ray
p^+
Proton in the air
Pion π^+
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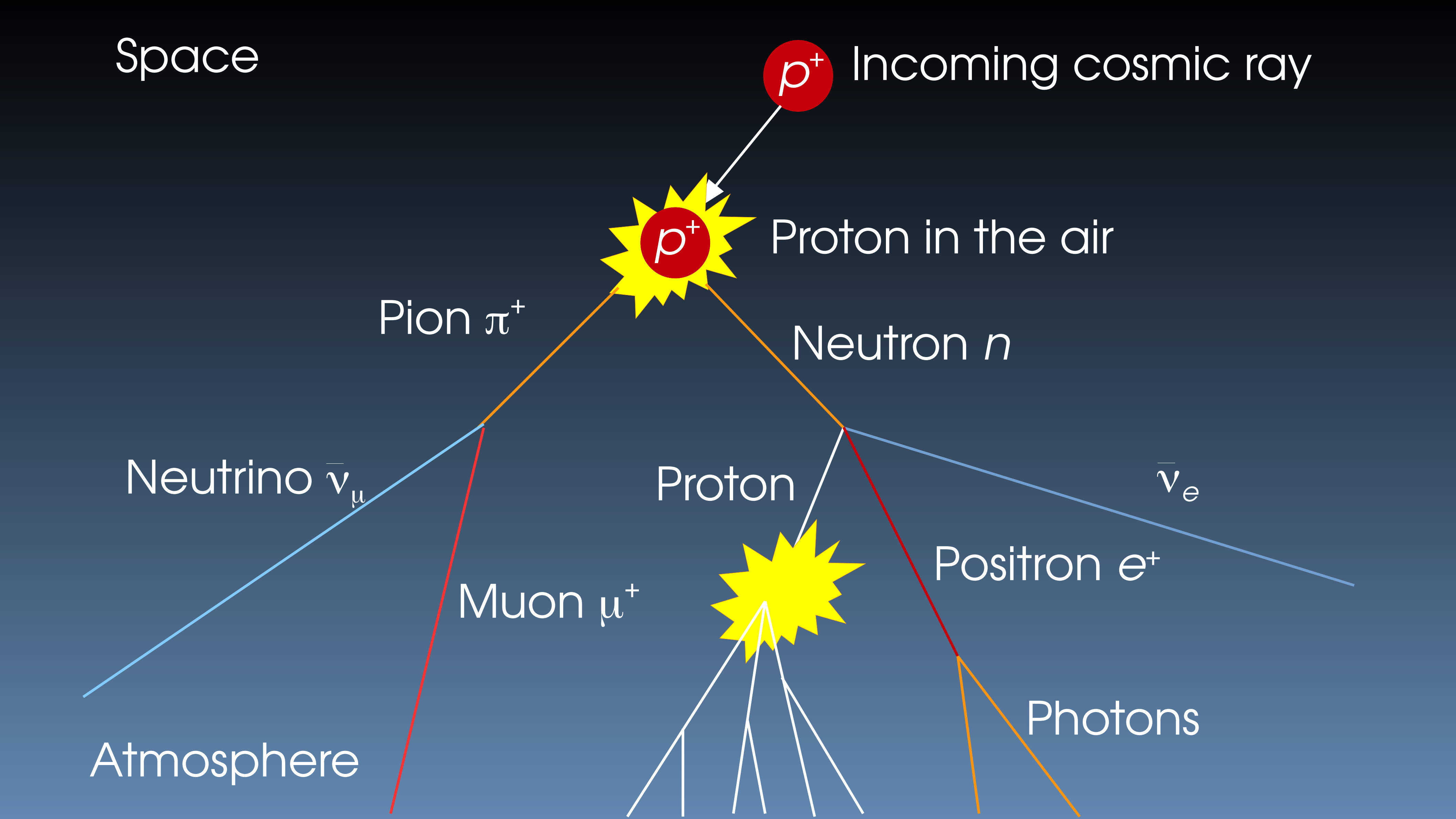
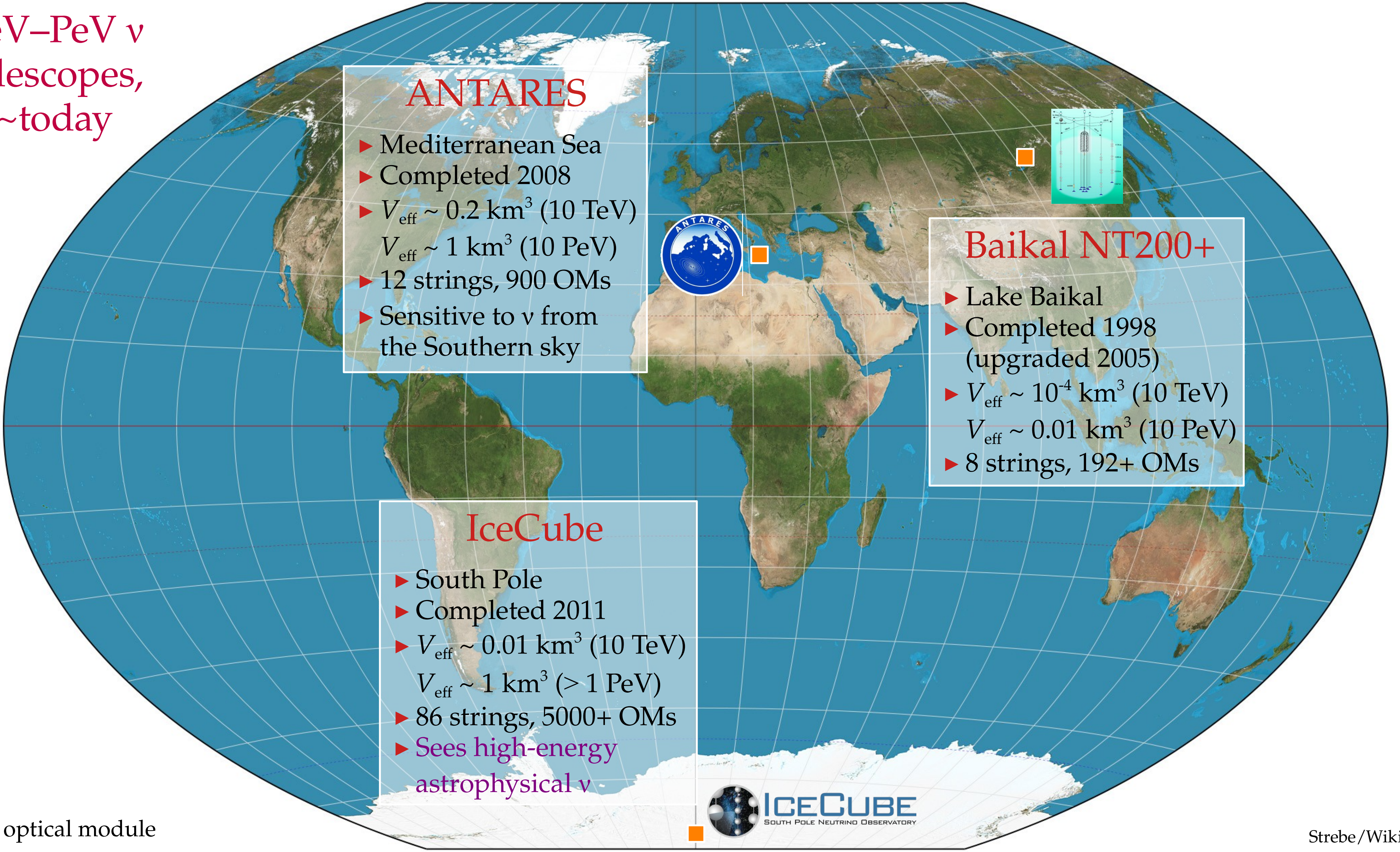
Proton
$\bar{\nu}_e$
Positron e^+
Muon μ^+
Photons
Atmosphere



Space
p^+
Incoming cosmic ray
p^+
Proton in the air
Pion π^+
Neutron n
Neutrino $\bar{\nu}_\mu$
Proton
$\bar{\nu}_e$
Positron e^+
Muon μ^+
Photons
Atmosphere

TeV–PeV ν telescopes, ~today



ANTARES

- Mediterranean Sea
- Completed 2008
- $V_{\text{eff}} \sim 0.2$ km^3 (10 TeV)
  $V_{\text{eff}} \sim 1$ km^3 (10 PeV)
- 12 strings, 900 OMs
- Sensitive to ν from the Southern sky

Baikal NT200+

- Lake Baikal
- Completed 1998 (upgraded 2005)
- $V_{\text{eff}} \sim 10^{-4}$ km^3 (10 TeV)
  $V_{\text{eff}} \sim 0.01$ km^3 (10 PeV)
- 8 strings, 192+ OMs

IceCube

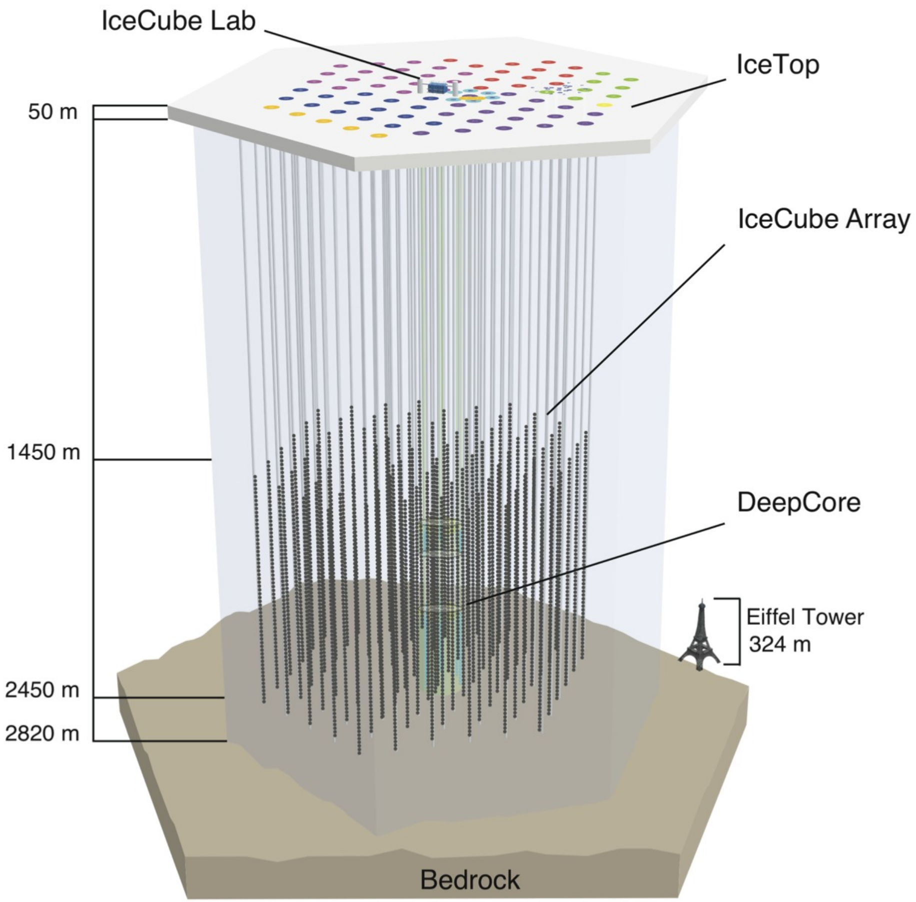
- South Pole
- Completed 2011
- $V_{\text{eff}} \sim 0.01$ km^3 (10 TeV)
  $V_{\text{eff}} \sim 1$ km^3 (> 1 PeV)
- 86 strings, 5000+ OMs
- Sees high-energy astrophysical ν

OM: optical module

Strebe/Wikipedia

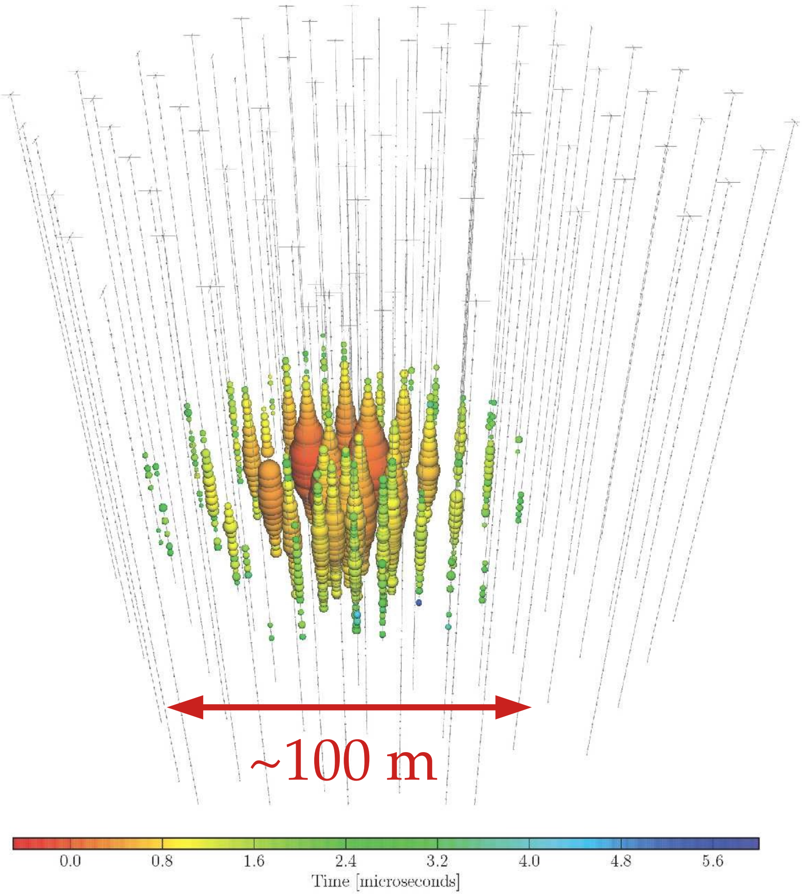
Yuya Makino, IceCube/NSF

IceCube – What is it?



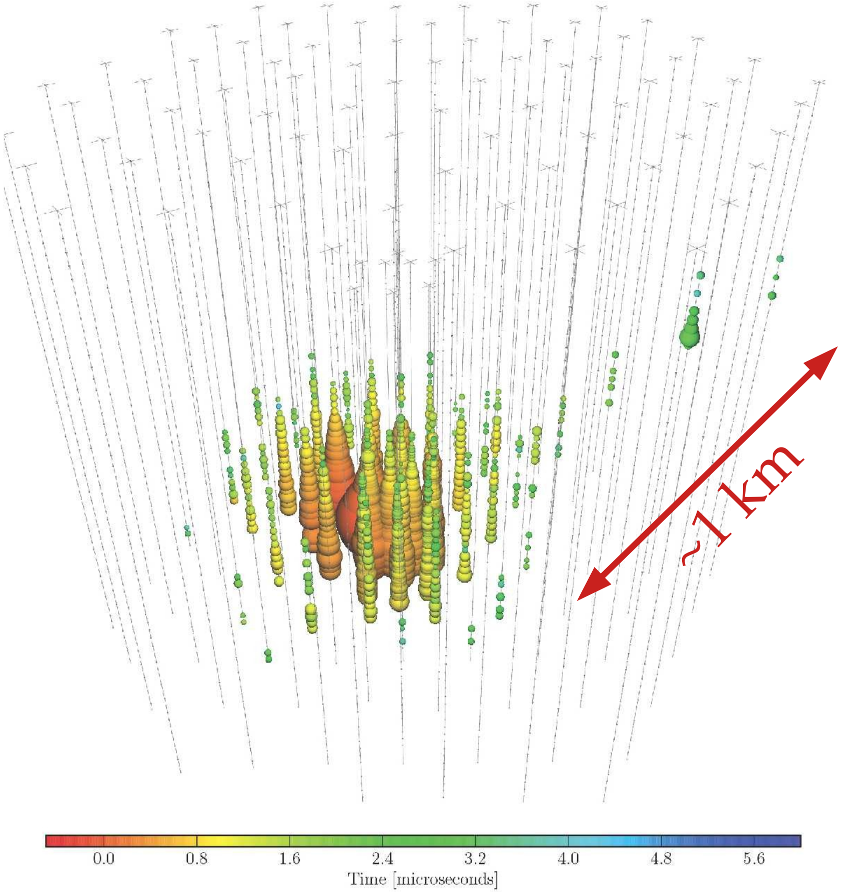
- Km^3 in-ice Cherenkov detector in Antarctica
- > 5000 PMTs at 1.5–2.5 km of depth
- Sensitive to neutrino energies > 10 GeV

Shower
(mainly from ν_e and ν_τ)

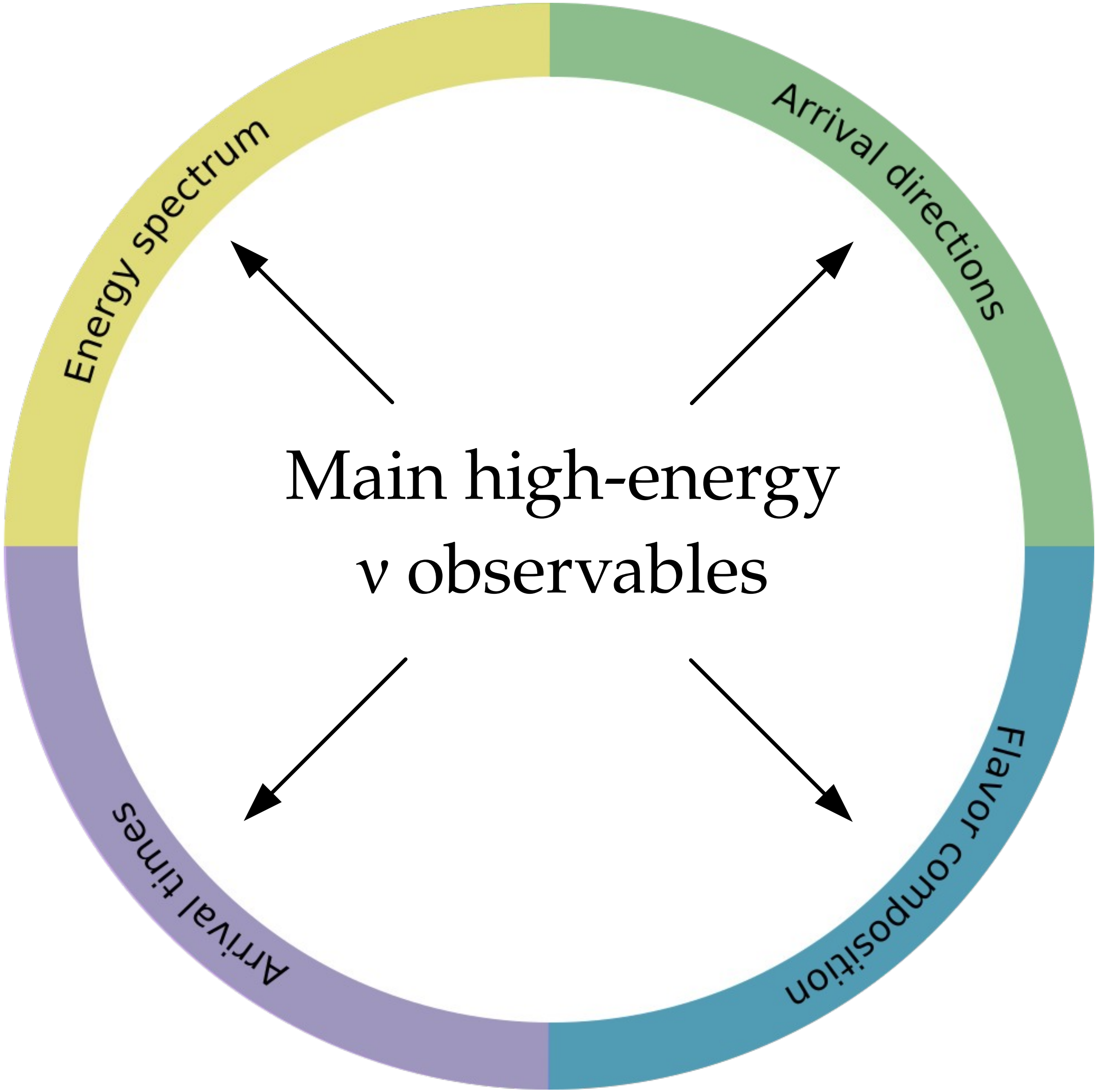


Poor angular resolution: ~10°

Track
(mainly from ν_μ)



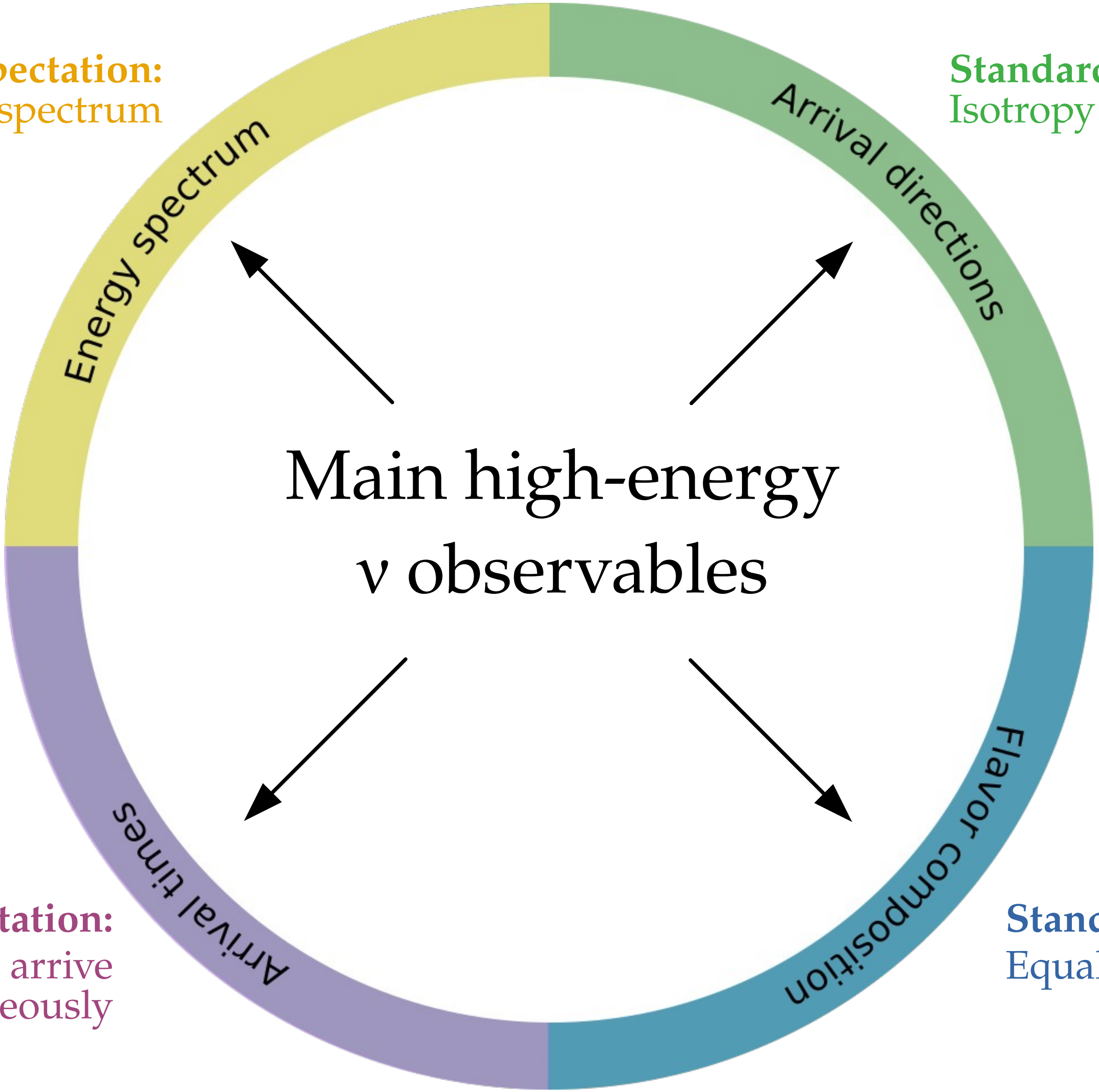
Angular resolution: < 1°



Main high-energy ν observables
Energy spectrum
Arrival directions
Flavor composition
Arrival times

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



Standard expectation:
ν and γ from transients arrive simultaneously

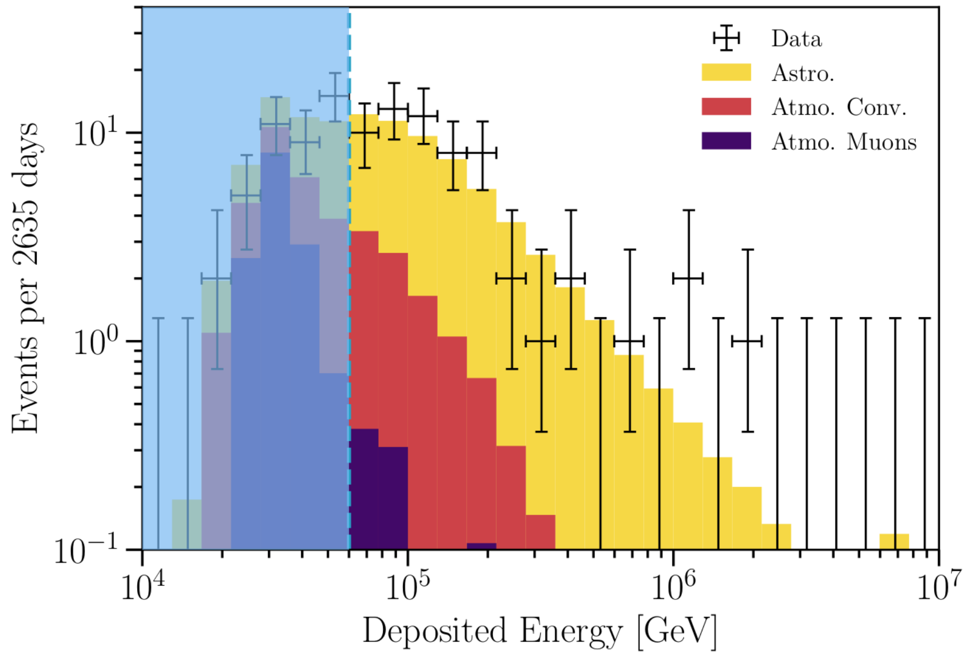
Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

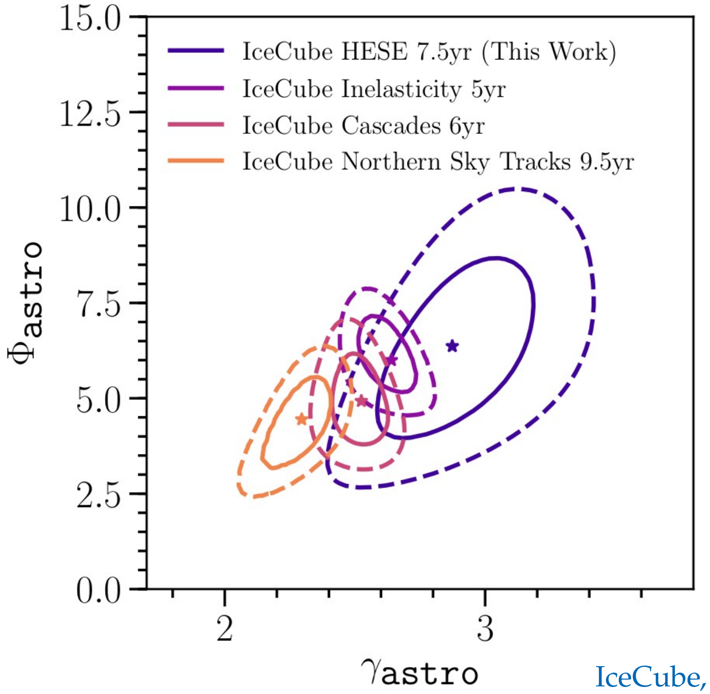
Energy spectrum (IceCube, 7.5 yr)

Data is fit well by a single power law:

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

100+ contained events above 60 TeV:





IceCube, 2011.03545

Energy spectrum (IceCube, 7.5 yr)

Data is fit well by a single power law:

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

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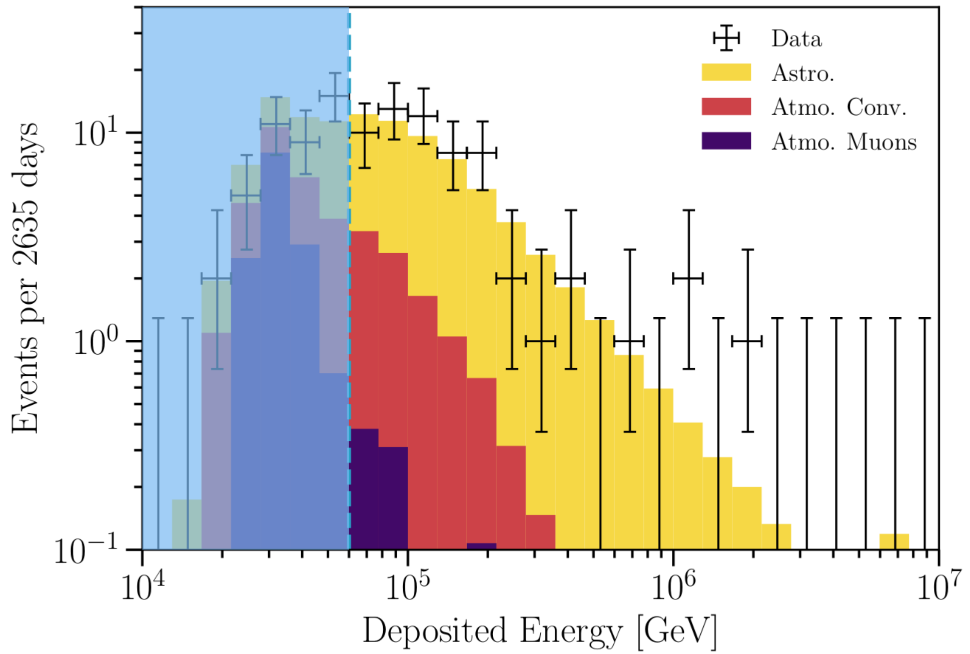
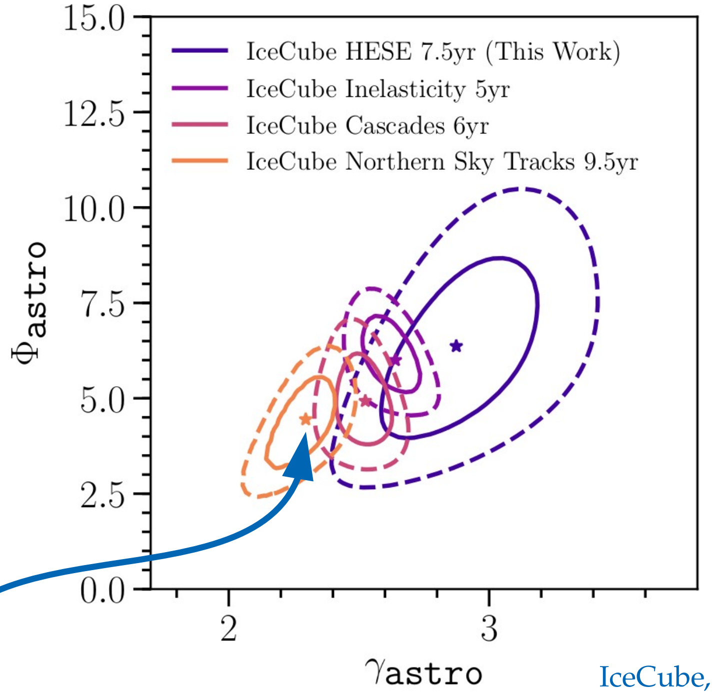
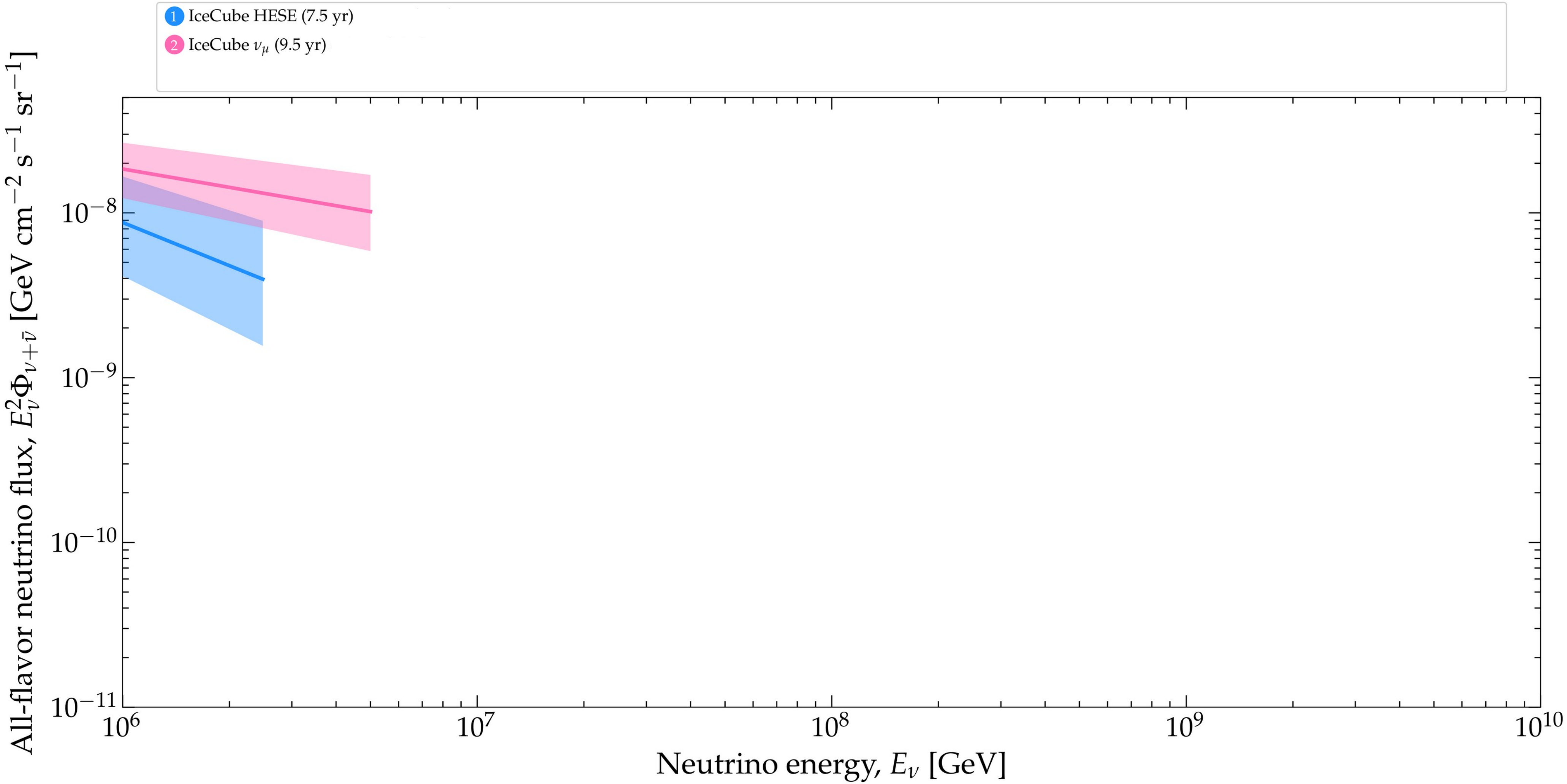




IceCube, 2011.03545

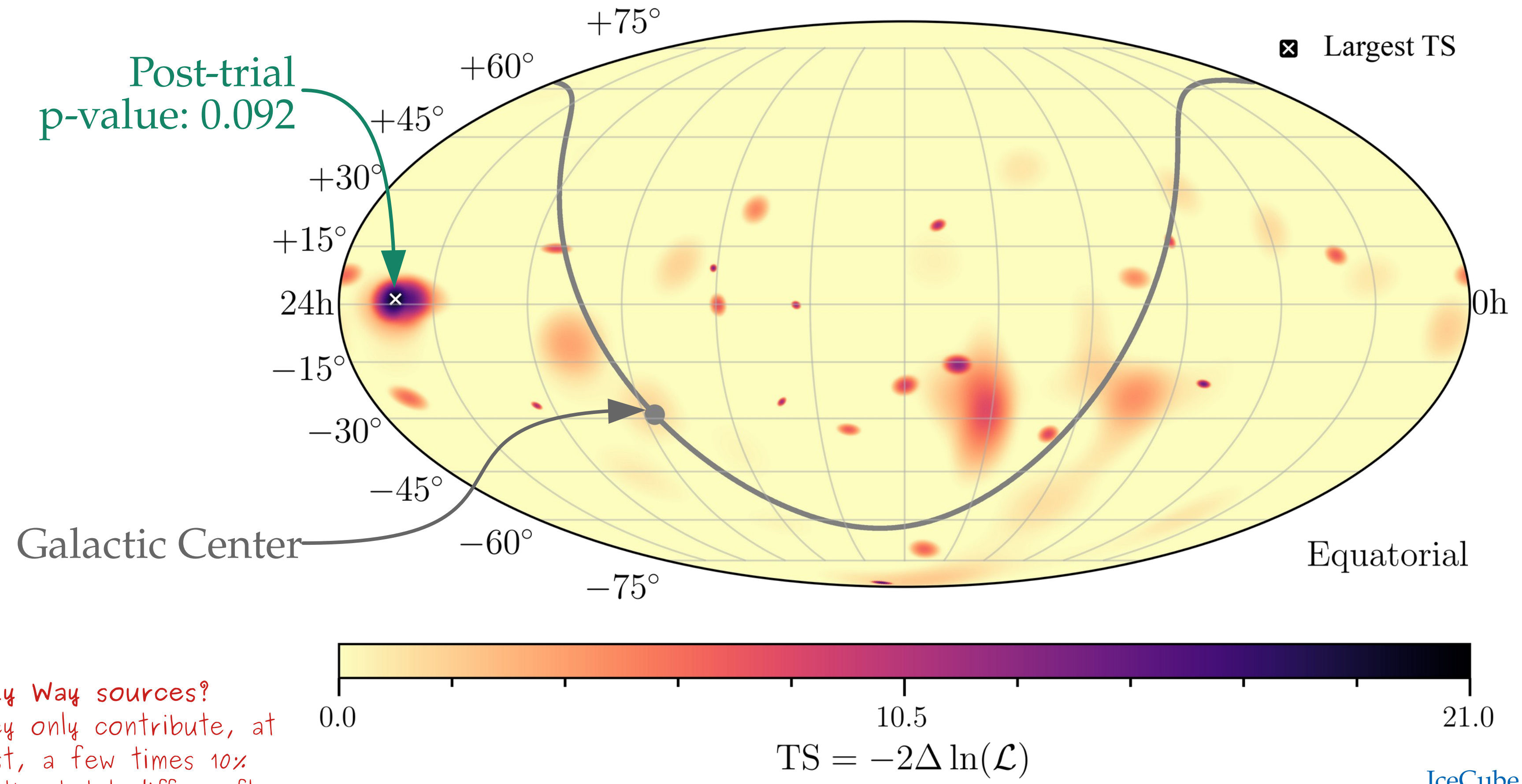
Spectrum looks harder for (lower-energy) through-going ν_μ



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

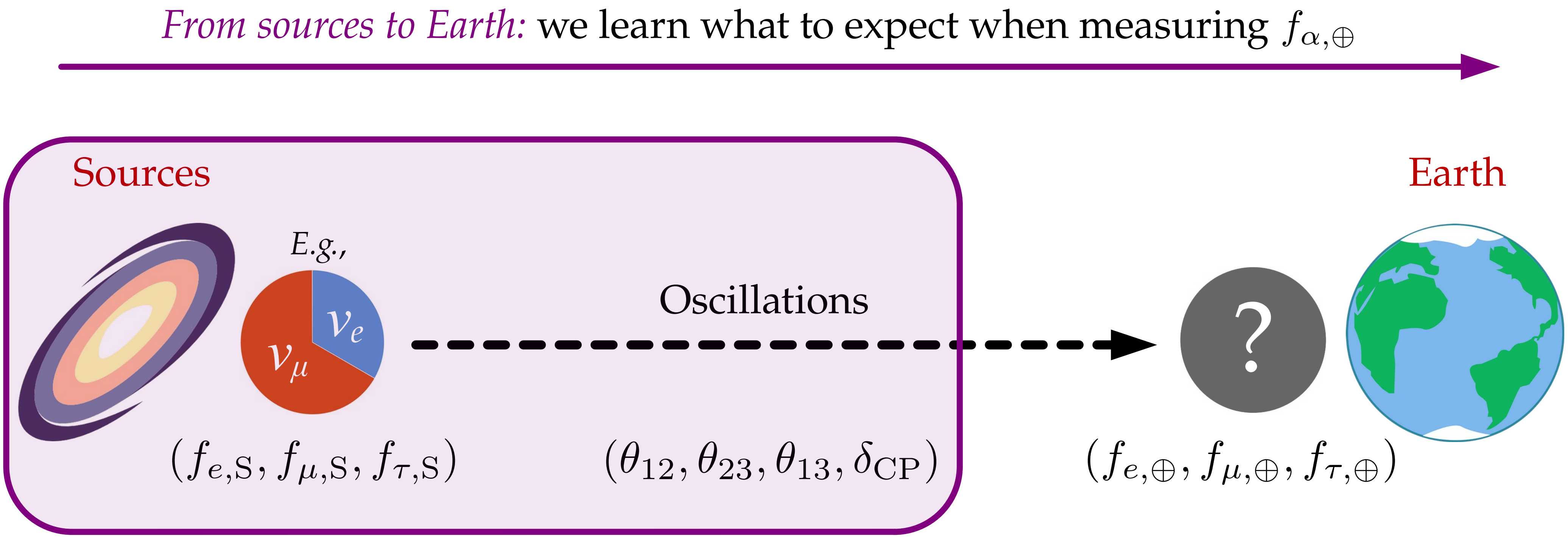
Arrival directions (7.5 yr)

No significant excess in the neutrino sky map:



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

IceCube, 2011.03545


From sources to Earth: we learn what to expect when measuring $f_{\alpha,\oplus}$
Sources
Earth
E.g.,
ν_e
ν_μ
Oscillations
?
$(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}})$
$(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\mathrm{CP}})$
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$

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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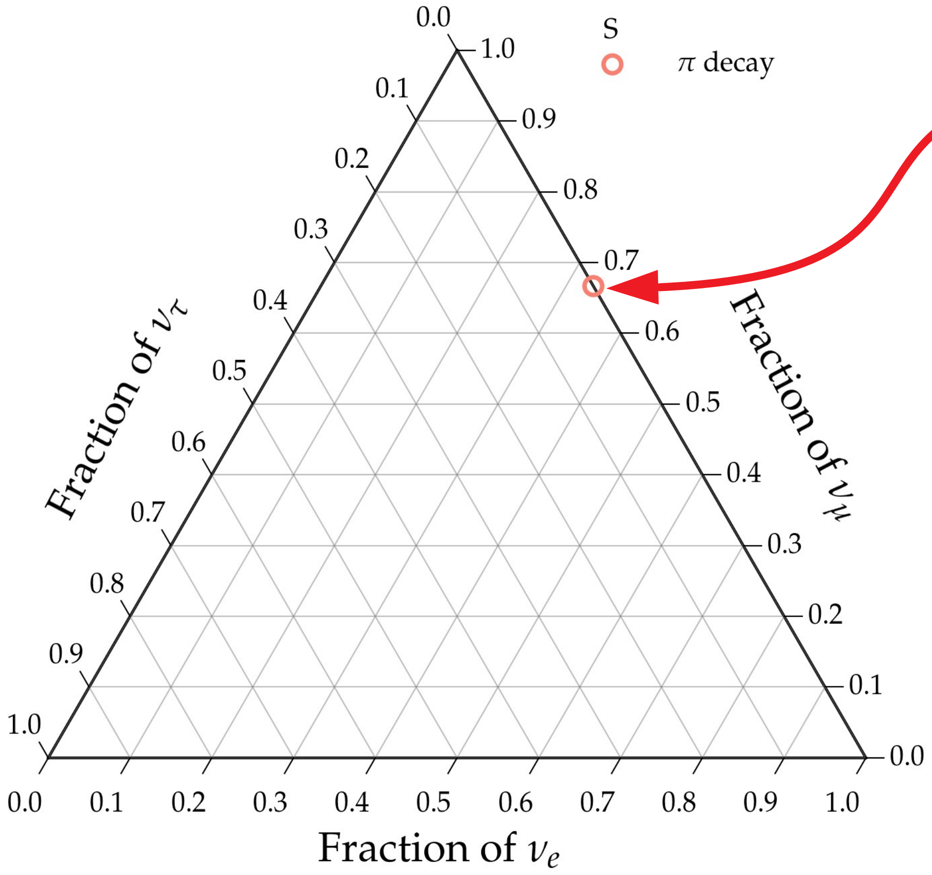

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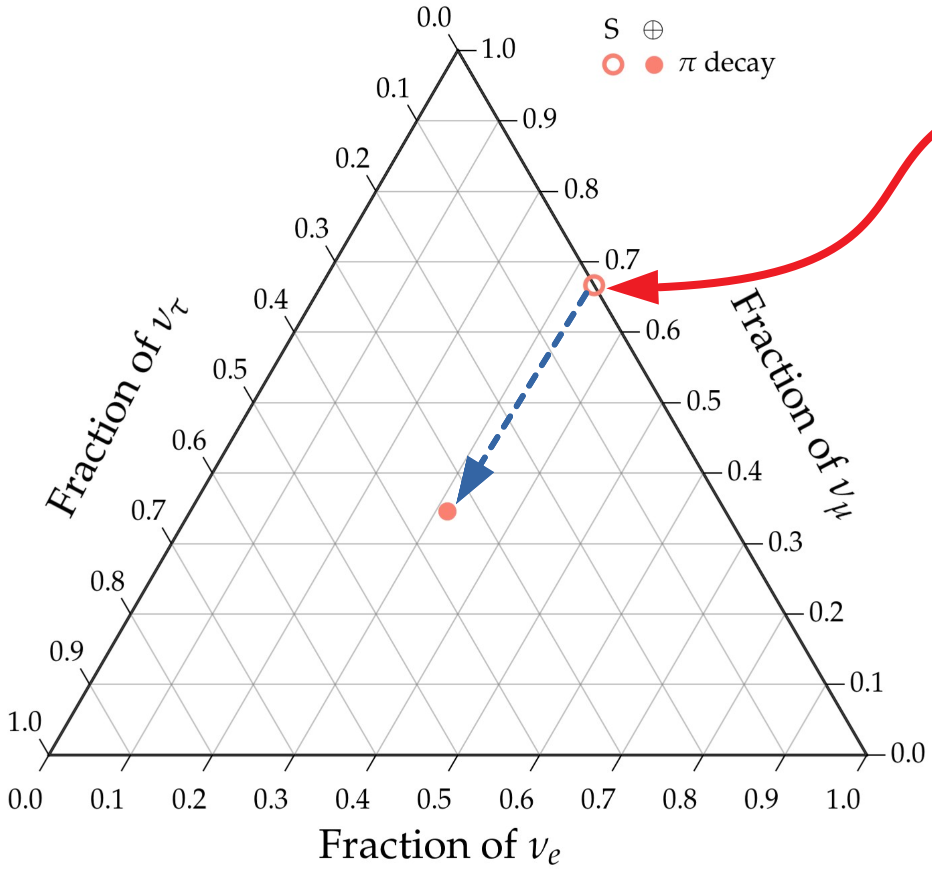

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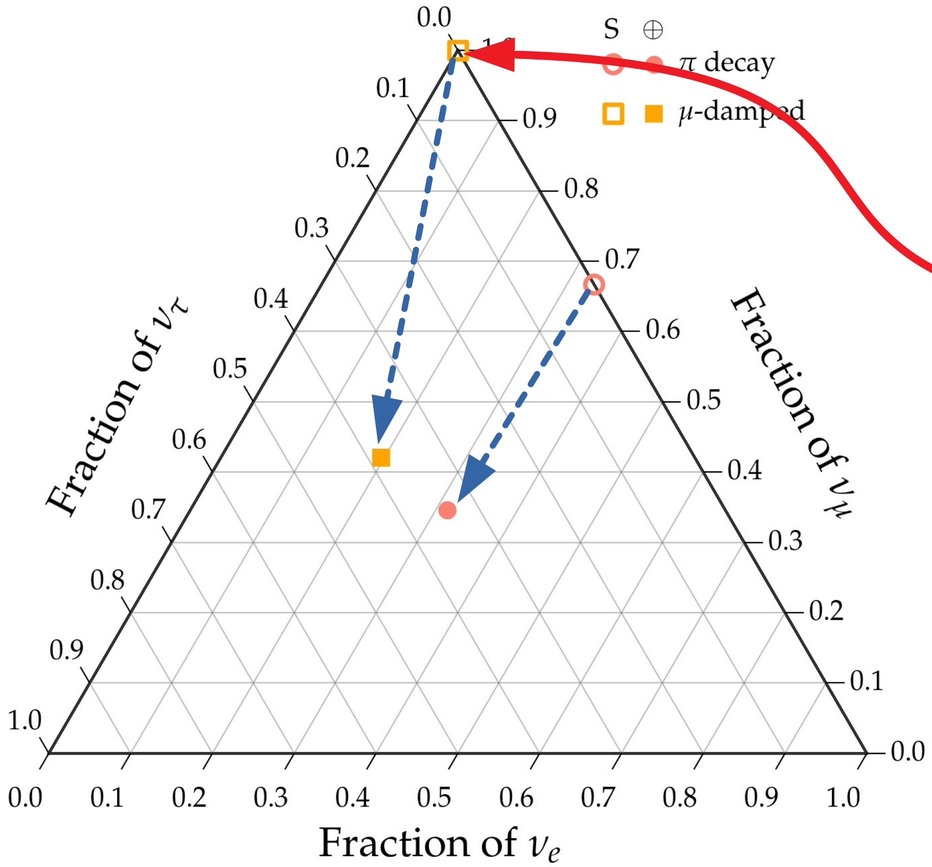

Full π decay chain

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

Muon damped

$(0:1:0)_S$

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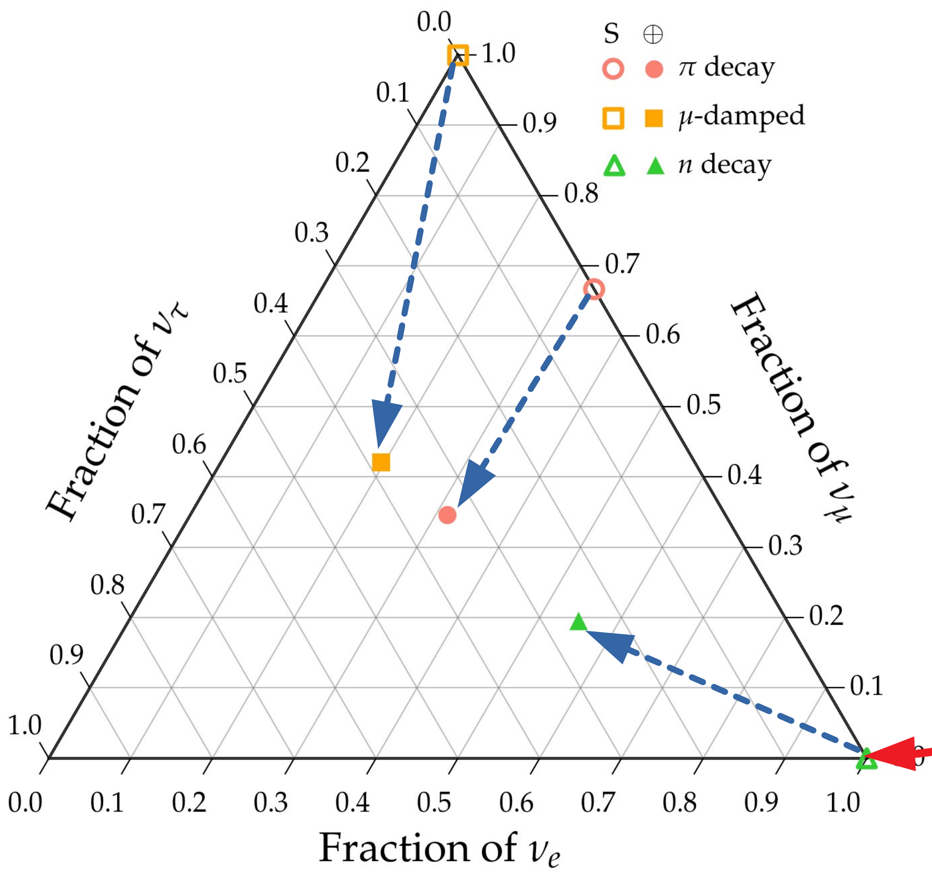

Full π decay chain
$(1/3:2/3:0)_S$

Muon damped
$(0:1:0)_S$

Neutron decay
$(1:0:0)_S$

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

Measuring flavor composition: 2015–2020

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
IceCube, *PRL* 2015, *ApJ* 2015, *PRD* 2019, *J. Phys. G* 2021, 2011.03561

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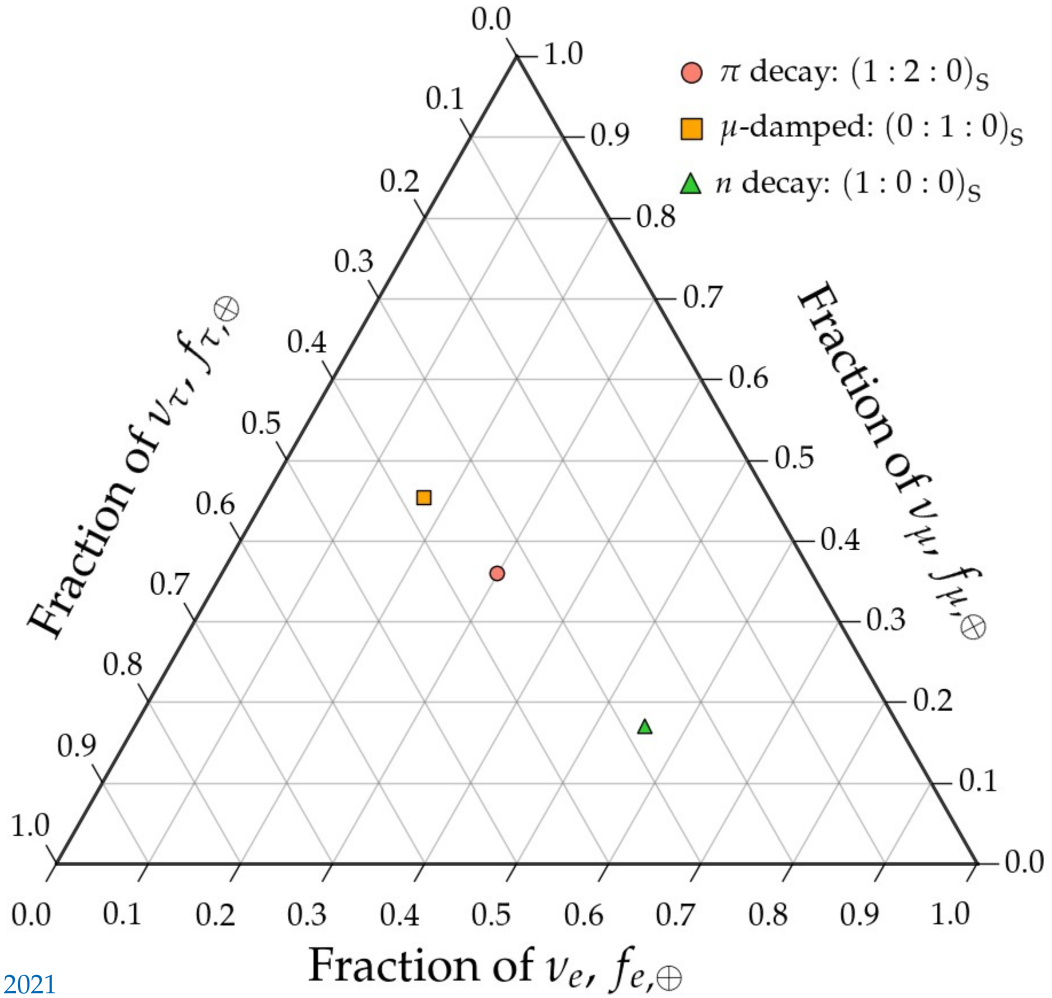

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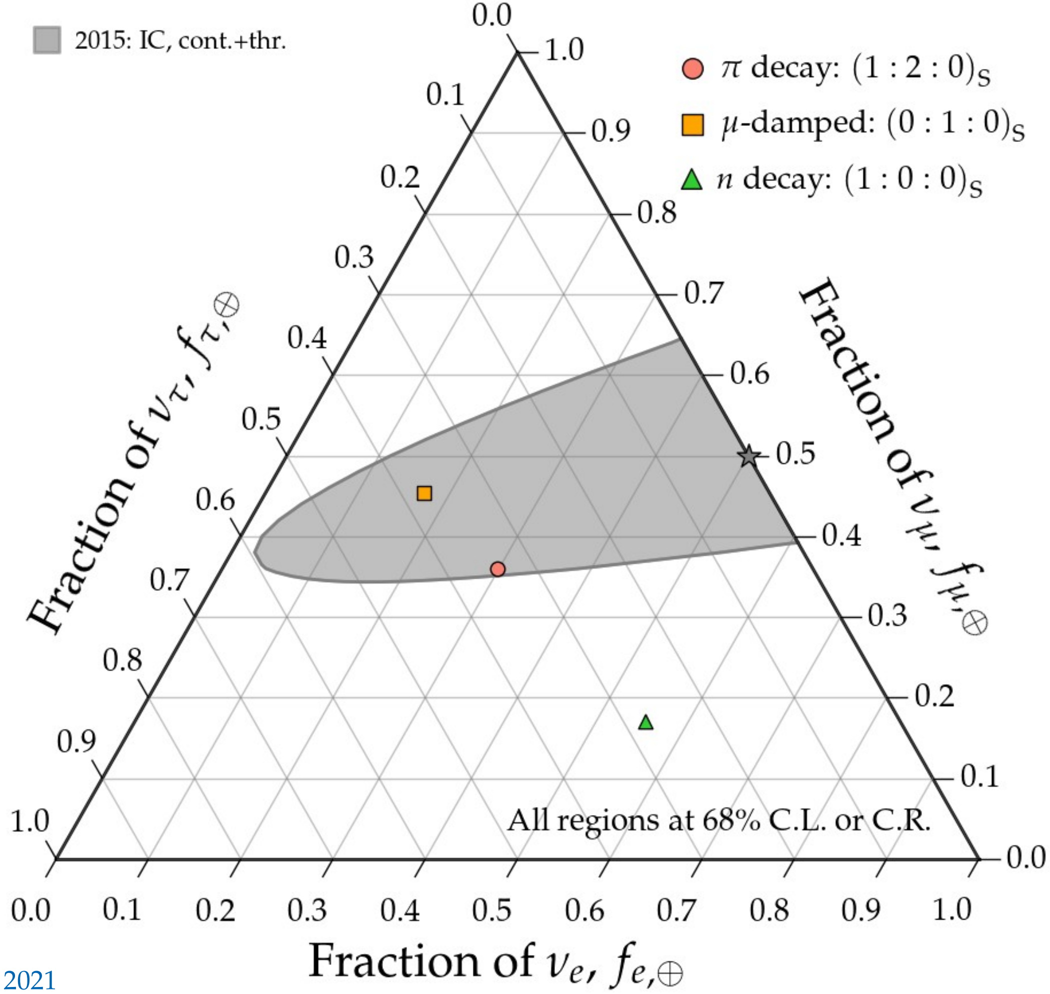

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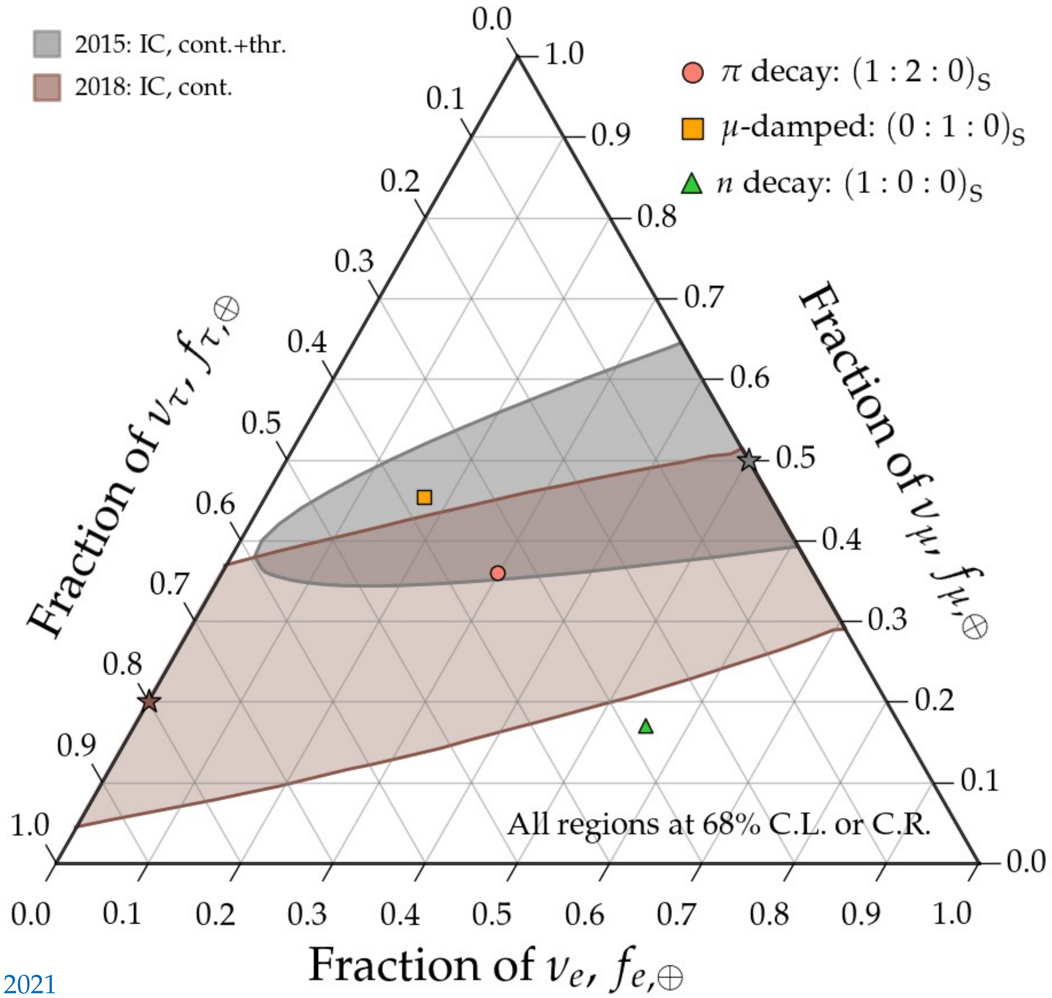

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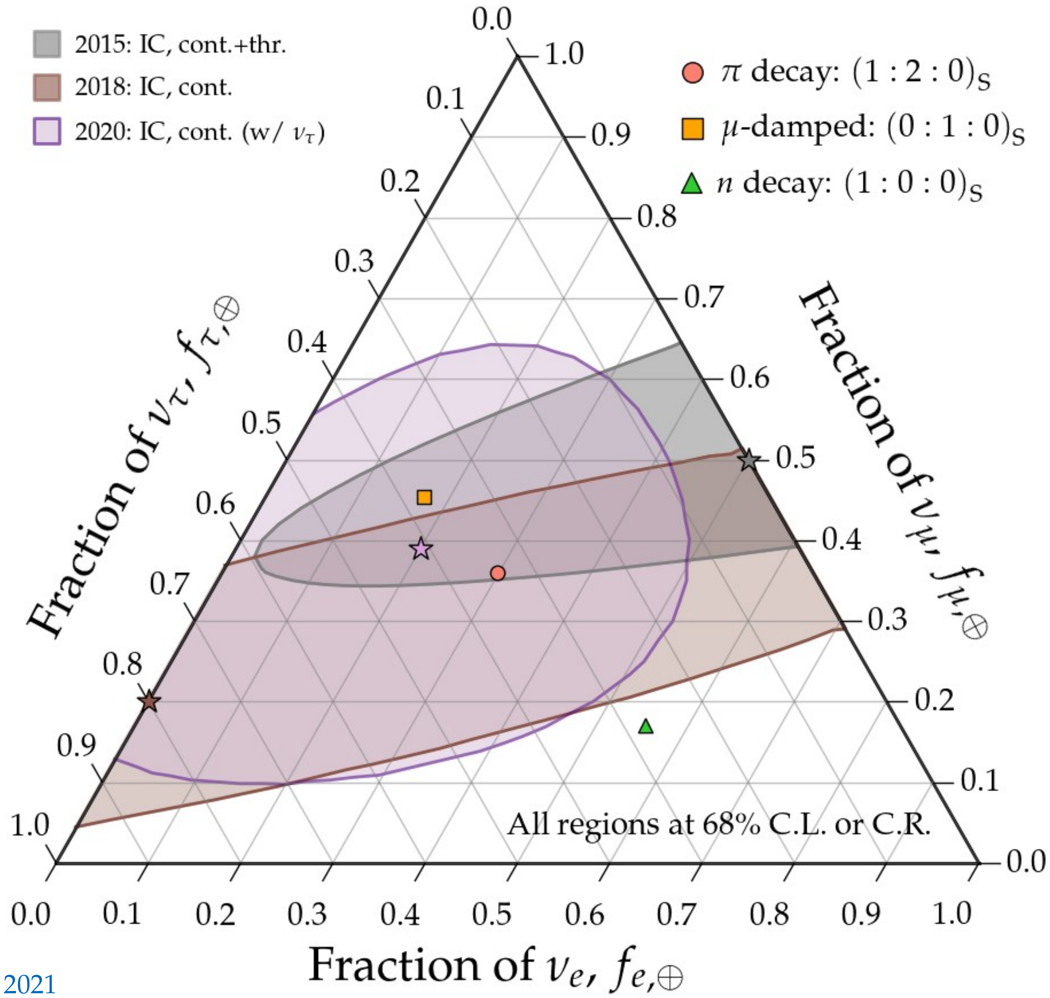

Status today:
Measurements are compatible with standard expectations (but errors are large!)

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Today

TeV–PeV ν

Today

TeV–PeV ν

Turn predictions
into data-driven tests

Today

TeV–PeV ν

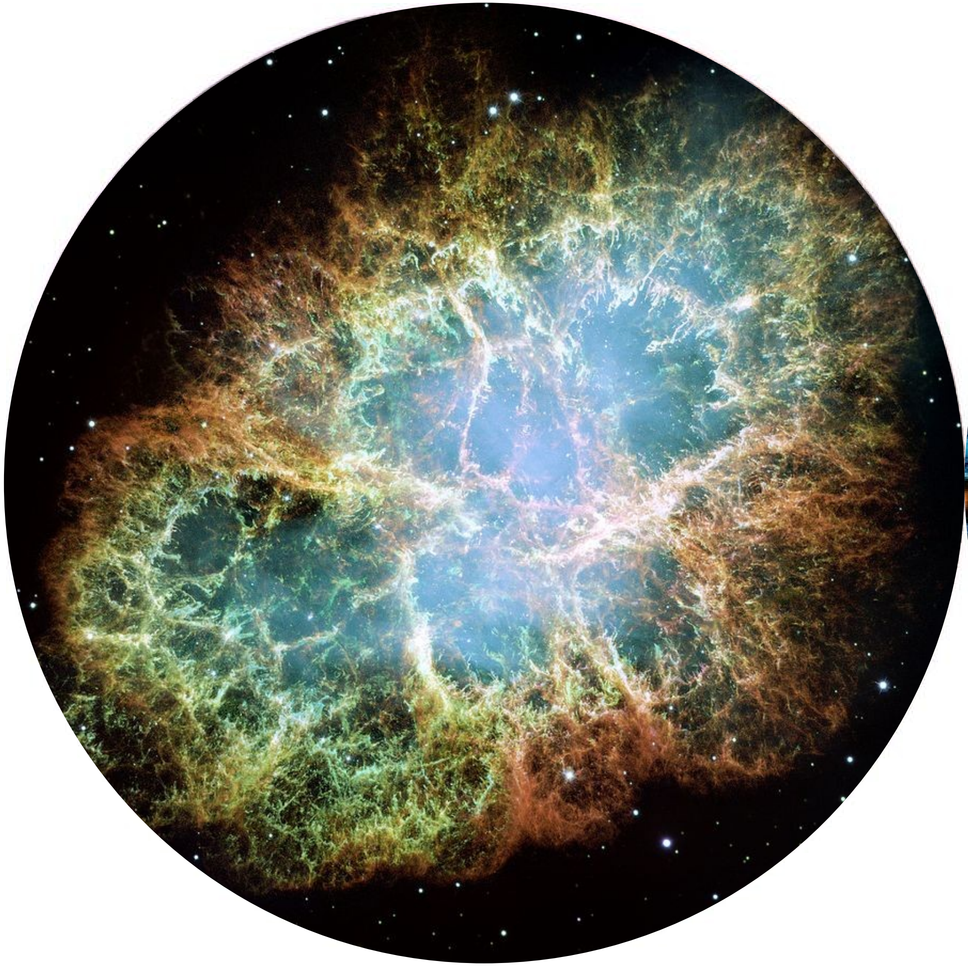
Turn predictions
into data-driven tests

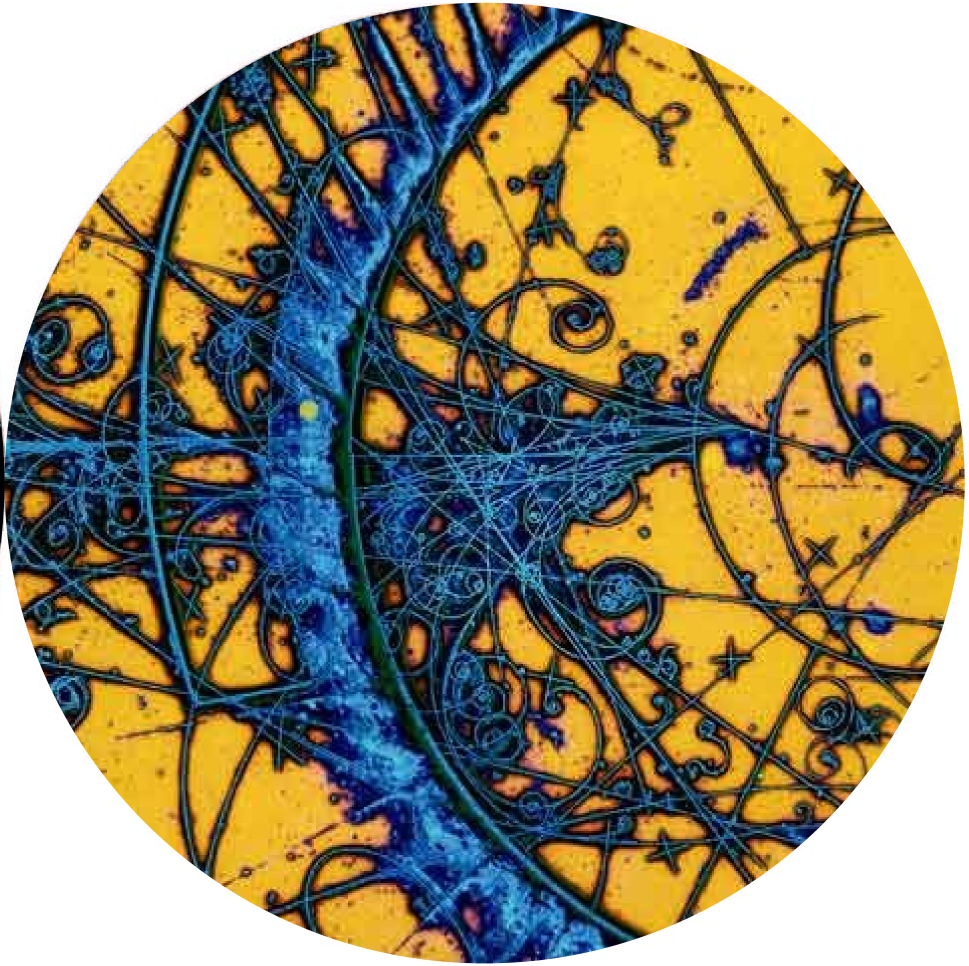
<u>Key developments</u>:

Bigger detectors → larger statistics

Better reconstruction

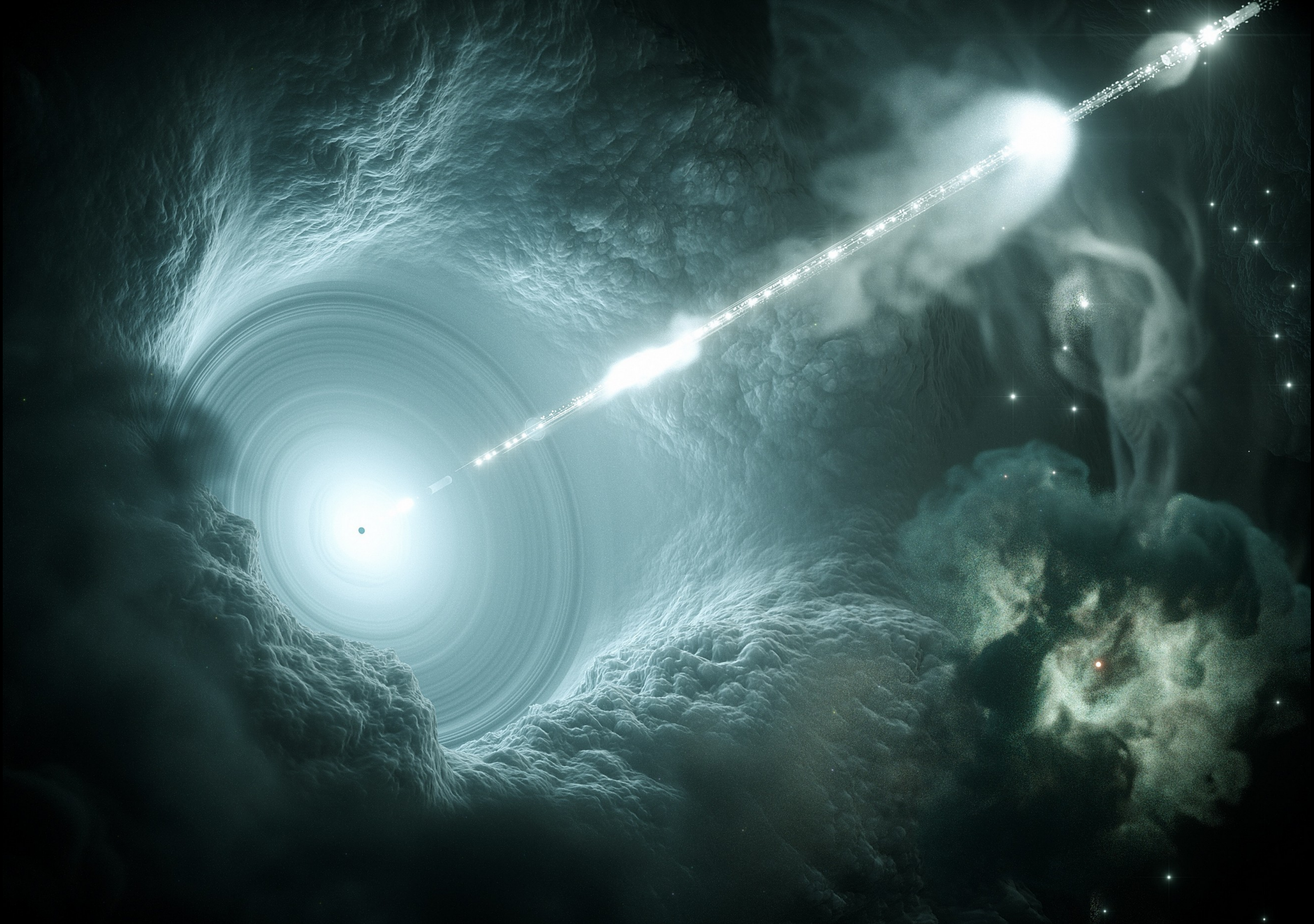
Smaller astrophysical uncertainties





Banco Central de Reserva del Perú / NASA / ESA / CERN / Symmetry Magazine

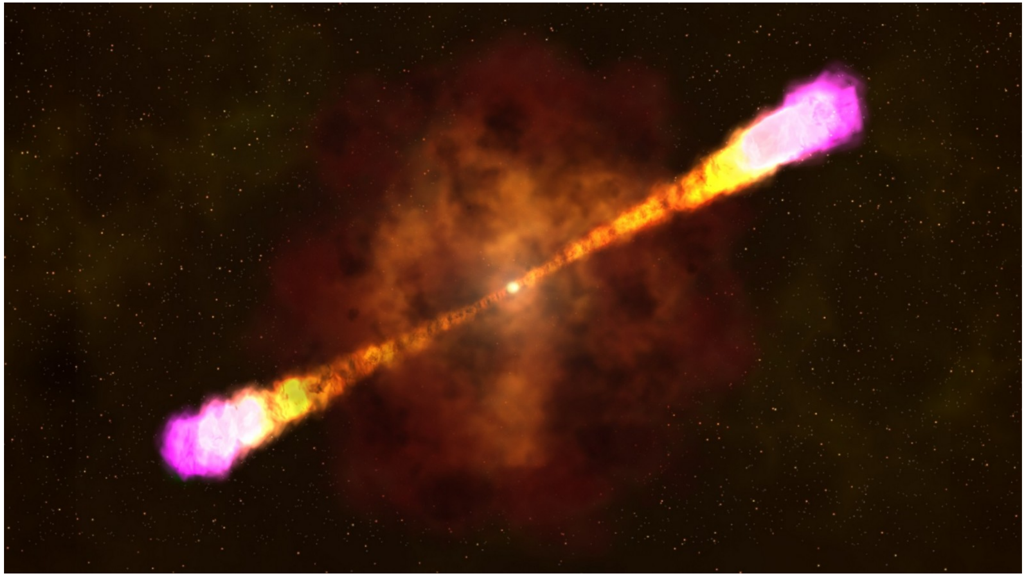
II.
What have we learned about *astrophysics*



DESY

Gamma-ray bursts and blazars – *not* dominant

Gamma-ray bursts



Blazars

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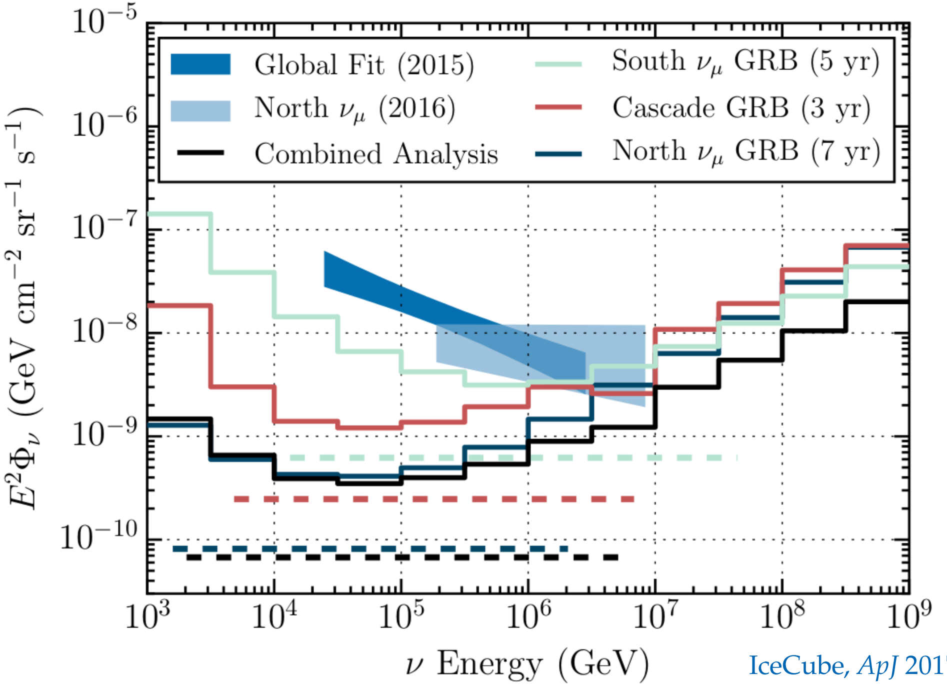
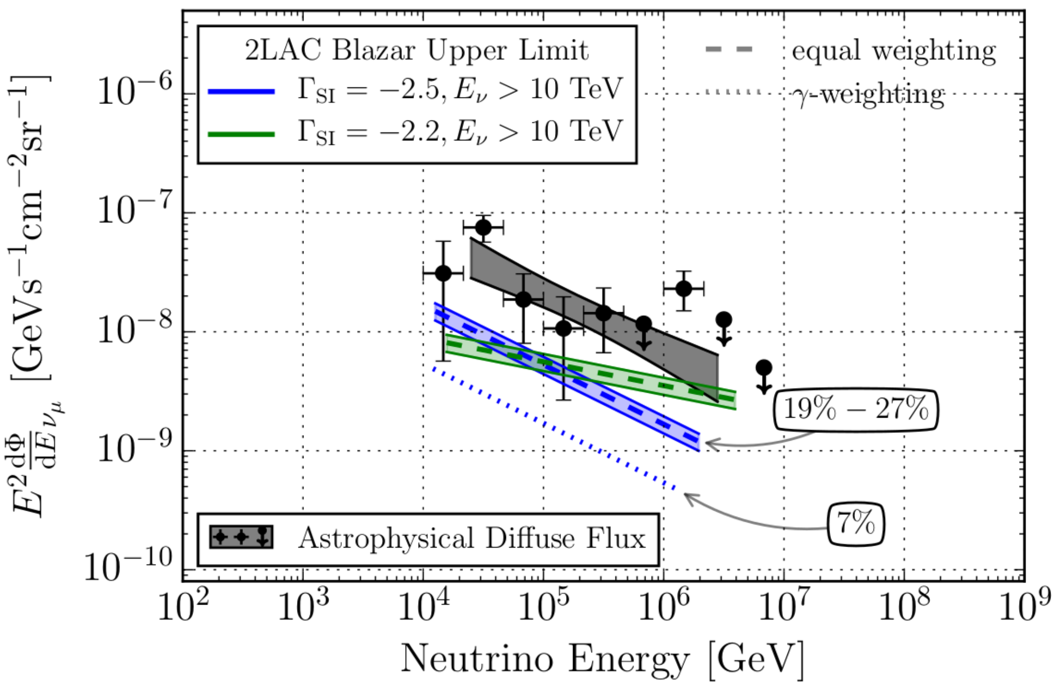


IceCube, *ApJ* 2017

1172 GRBs inspected, no correlation found

< 1% contribution to diffuse flux

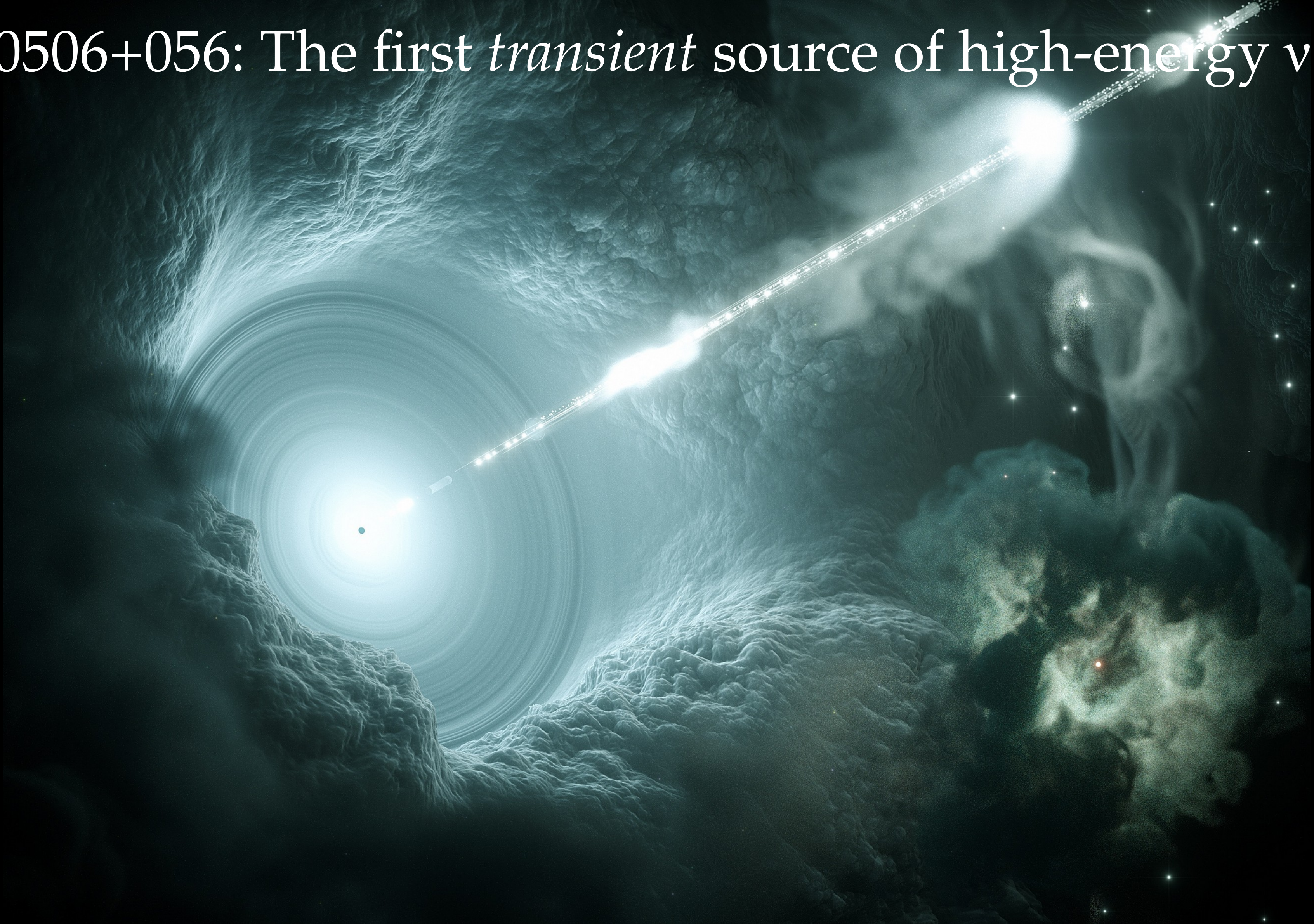
Blazars



862 blazars inspected, no correlation found

< 27% contribution to diffuse flux

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



DESY

Tidal disruption events

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

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

NASA

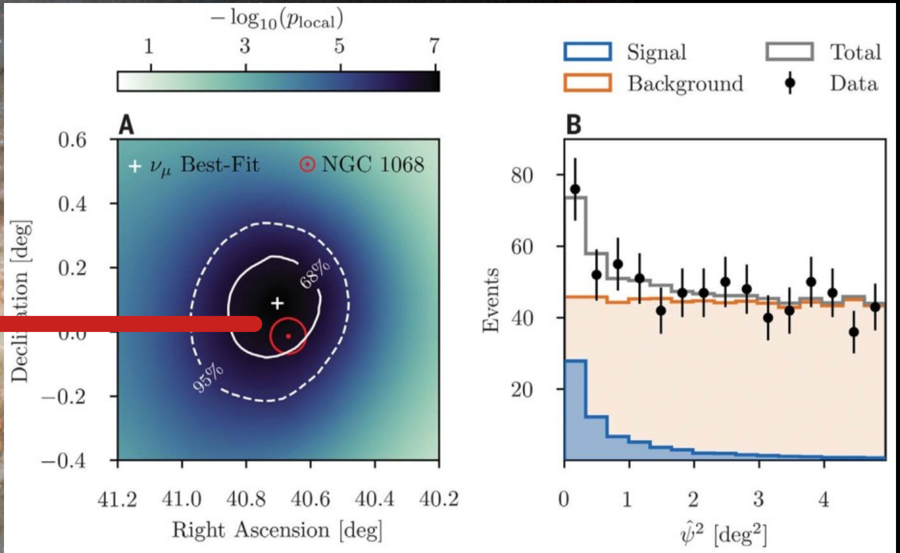
NGC1068: The first *steady-state* source of high-energy ν

Active galactic nucleus

Brightest type-2 Seyfert

79^{+22}_{-20} ν of TeV energy

Significance: 4.2σ (global)



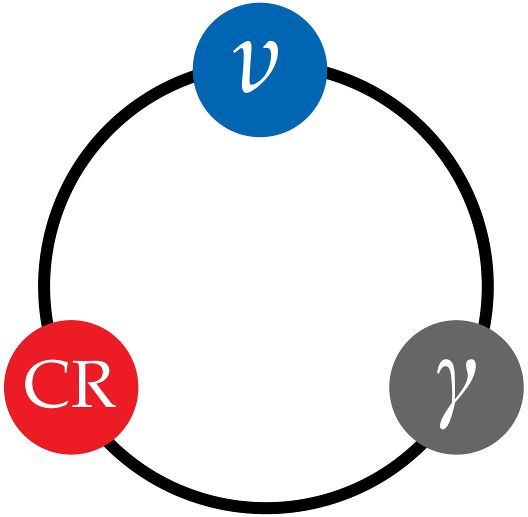
IceCube Collab., *Science* 378, 538 (2022)

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

Bright in gamma rays, bright in high-energy neutrinos?

Energy in neutrinos $\propto$ energy in gamma rays

Waxman & Bahcall, *PRL* 1997



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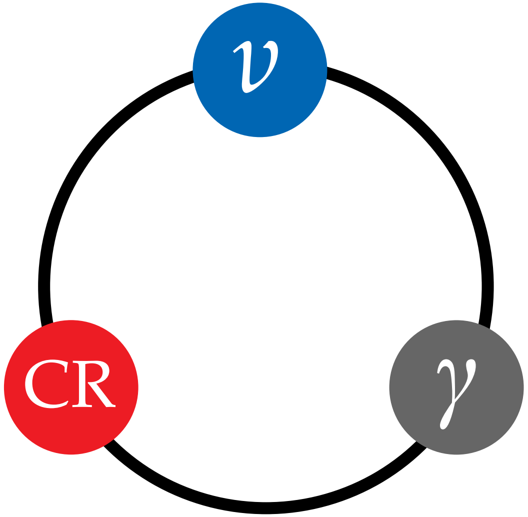
Fudge factors:

Source properties (*e.g.*, baryonic loading)

Particle effects (*e.g.*, ν-producing channels)



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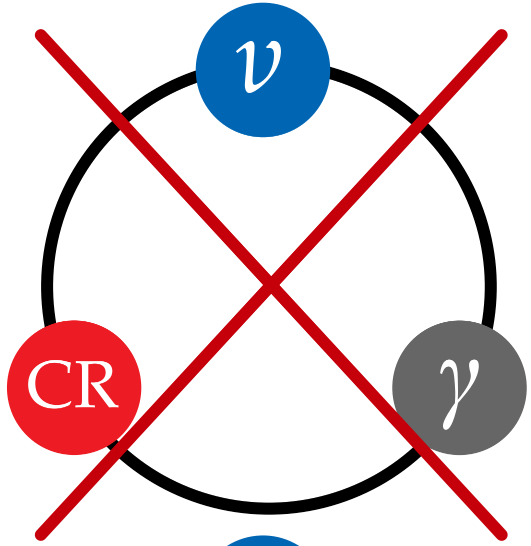
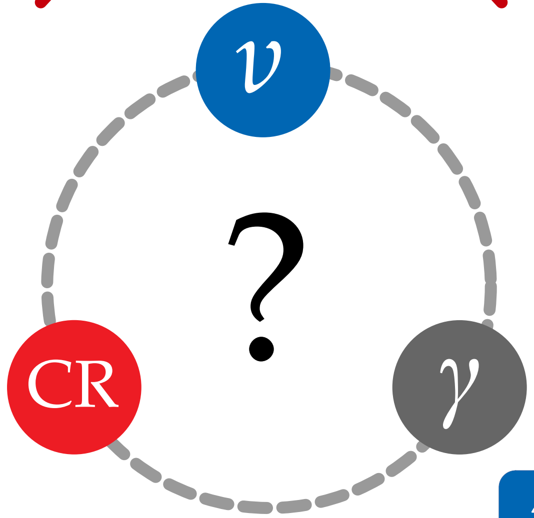


But the correlation between ν and γ may be more nuanced:

Gao, Pohl, Winter, *ApJ* 2017



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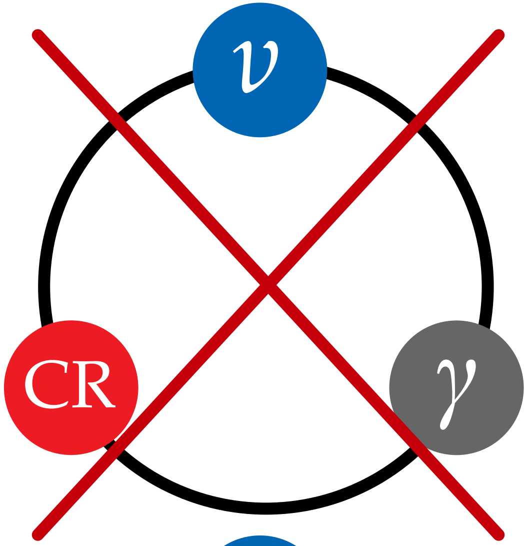

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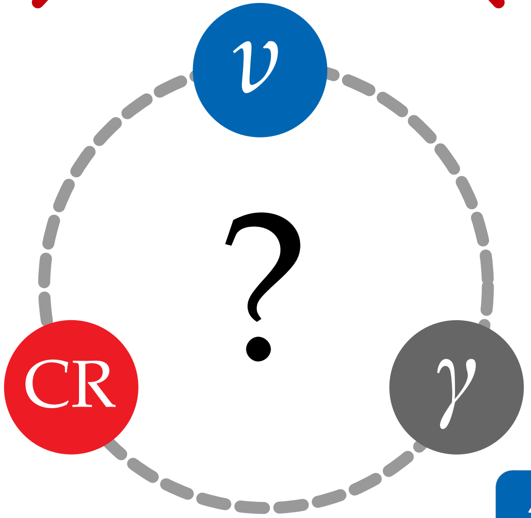
Sources that make neutrinos via *p*γ
may be opaque to 1–100 MeV gamma rays

Murase, Guetta, Ahlers, *PRL* 2016

Modeling of *p*γ interactions & nuclear cascading
in the sources is complex and uncertain

Morejon, Fedynitch, Boncioli, Winter, *JCAP* 2019
Boncioli, Fedynitch, Winter, *Sci. Rep.* 2017



Using high-energy neutrinos as magnetometers

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

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

$$\pi^0 \longrightarrow \gamma + \gamma$$

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

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

MB, Tamborra, *PRD* 2020
Winter, *PRD* 2013

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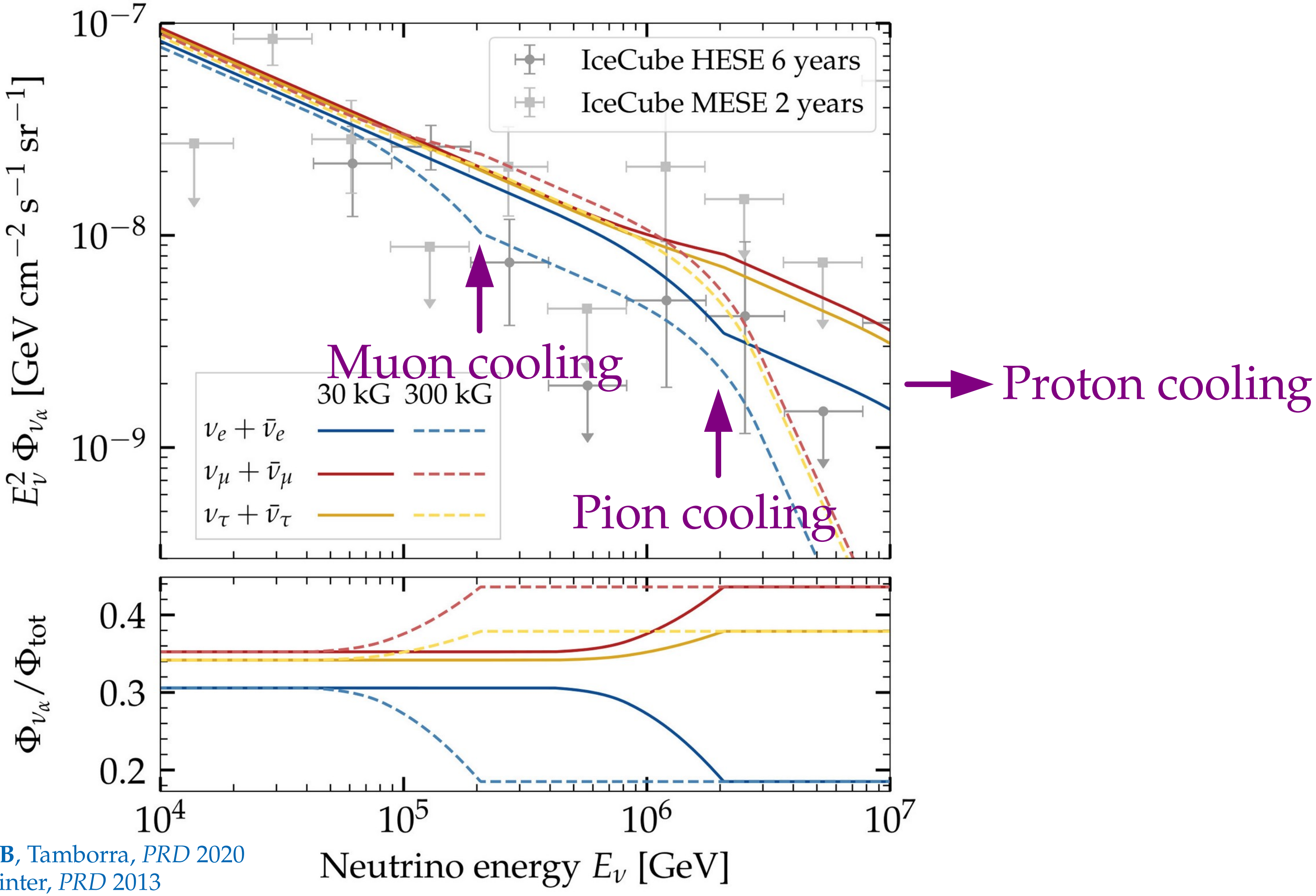

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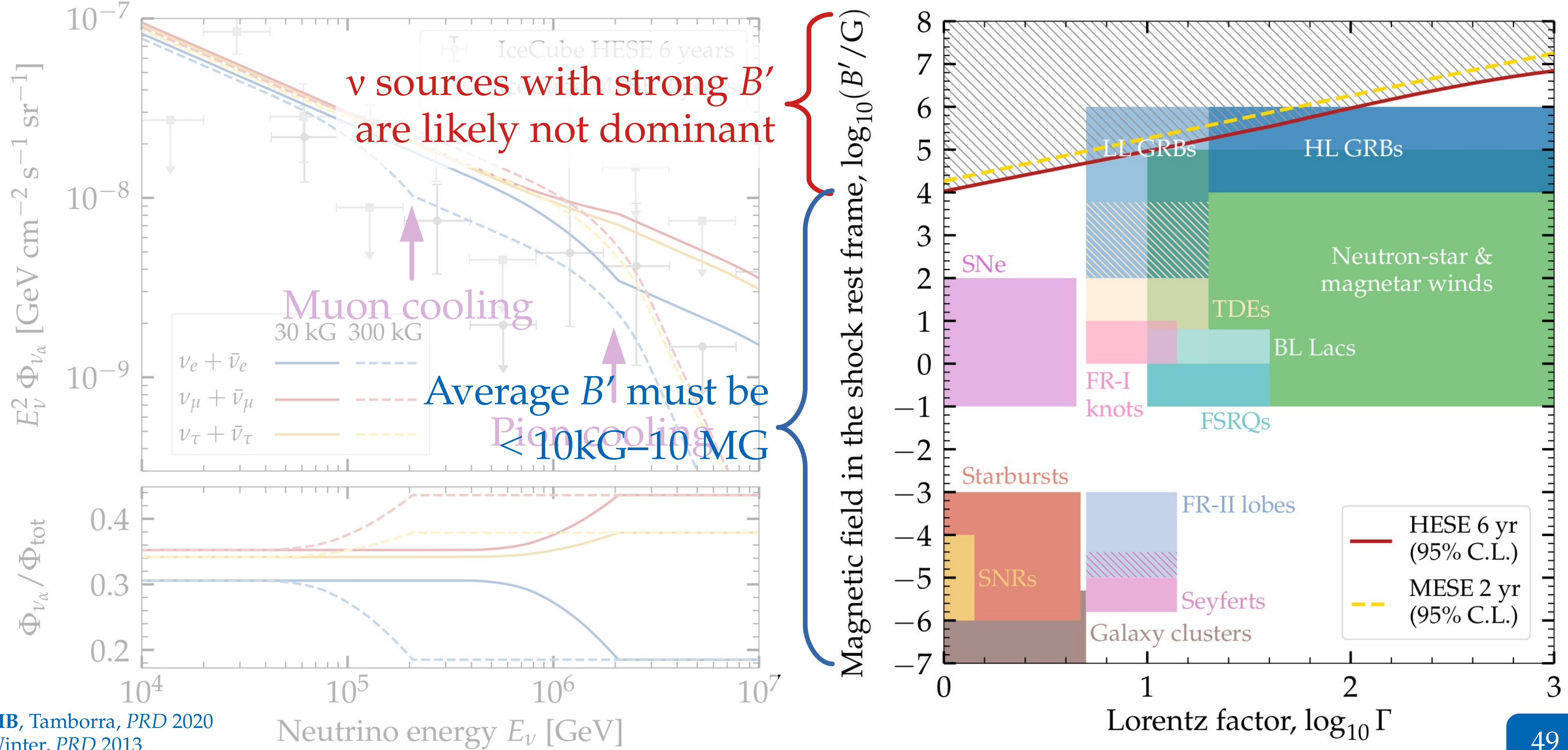
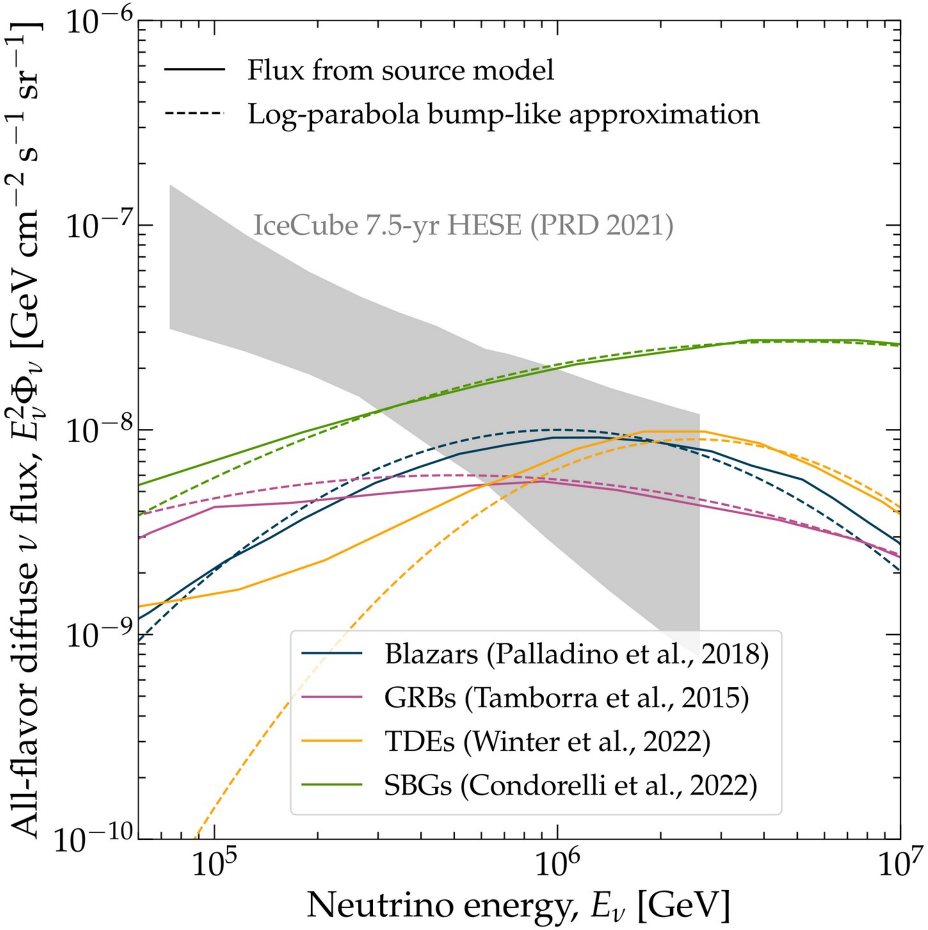


MB, Tamborra, *PRD* 2020
Winter, *PRD* 2013

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

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



Fiorillo, **MB**, 2301.00024

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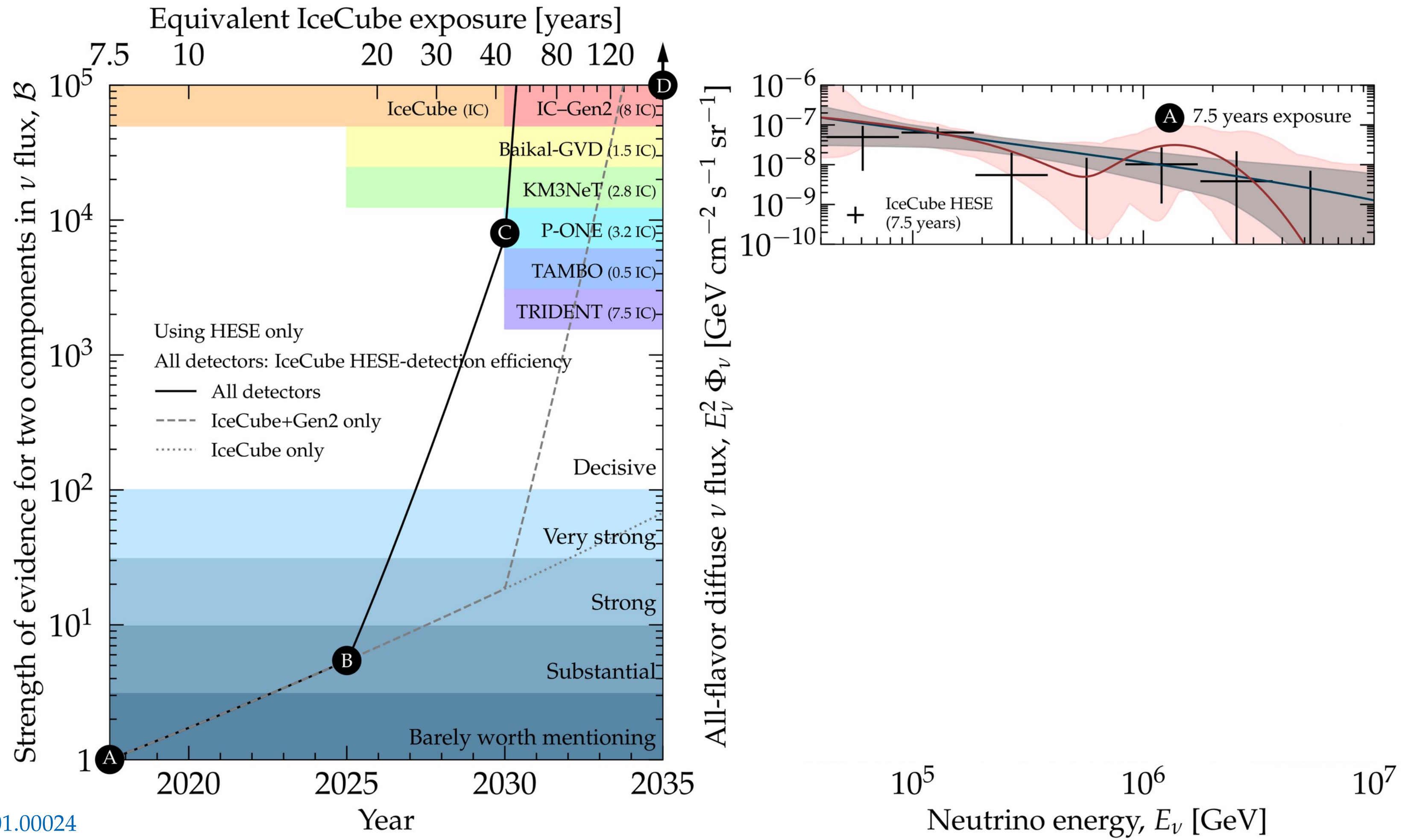

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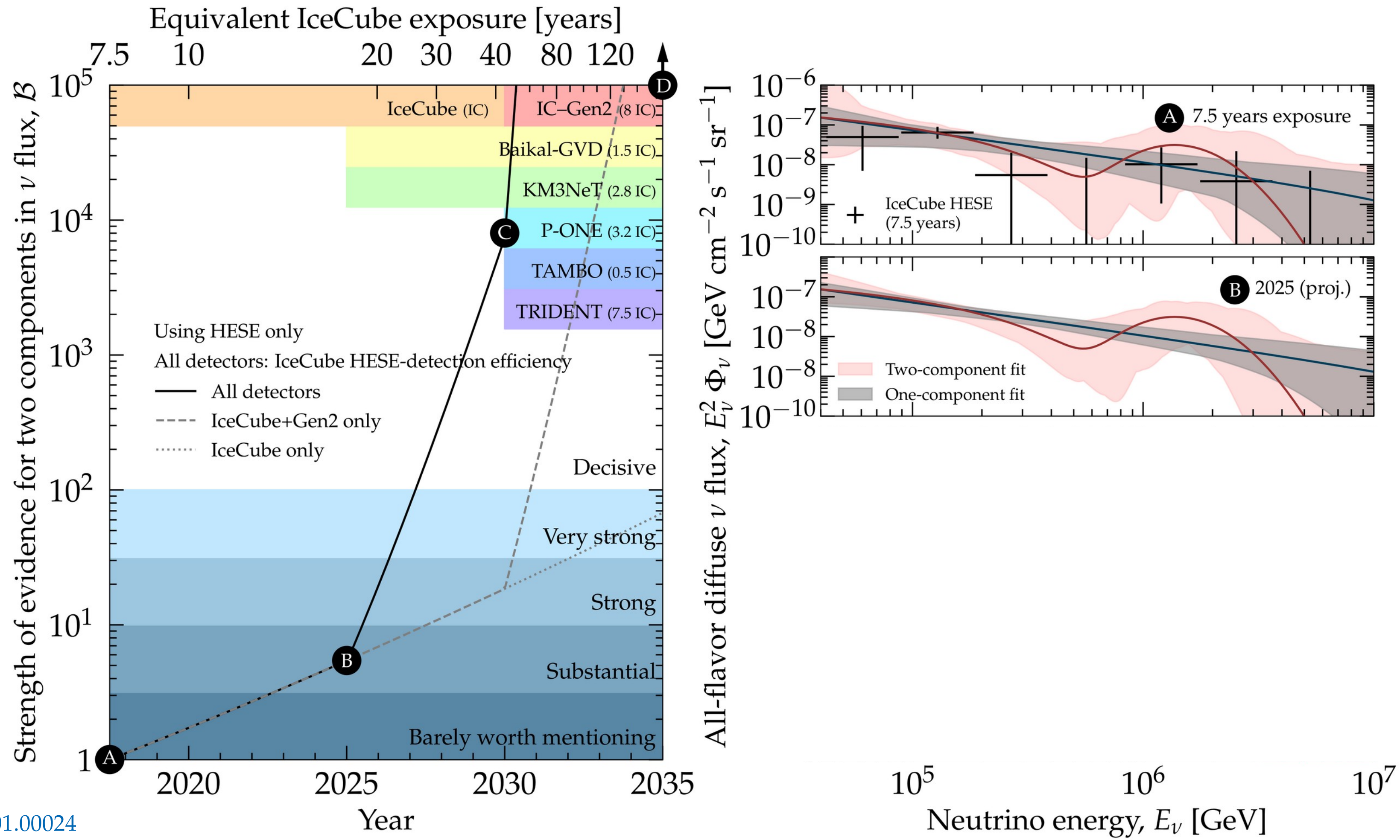

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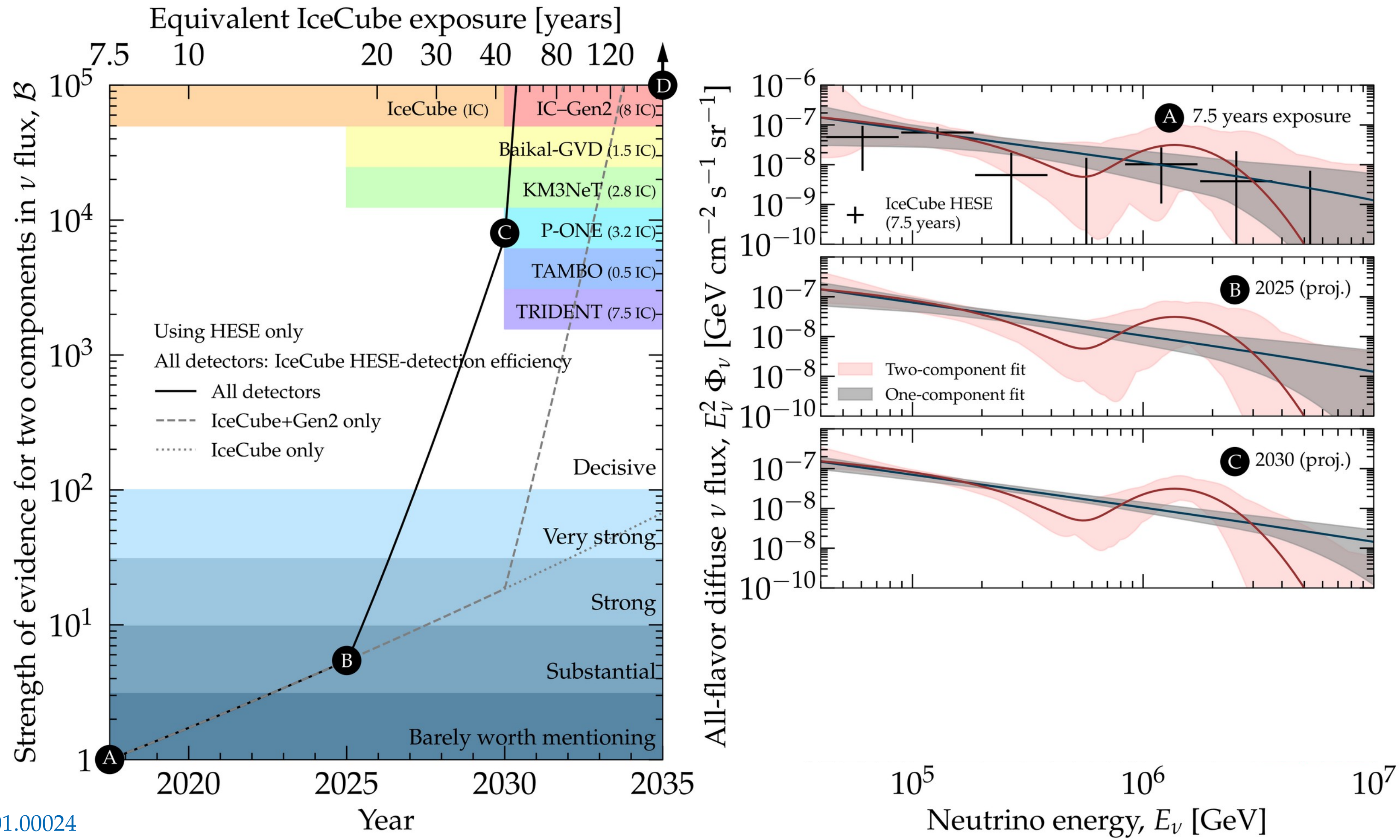

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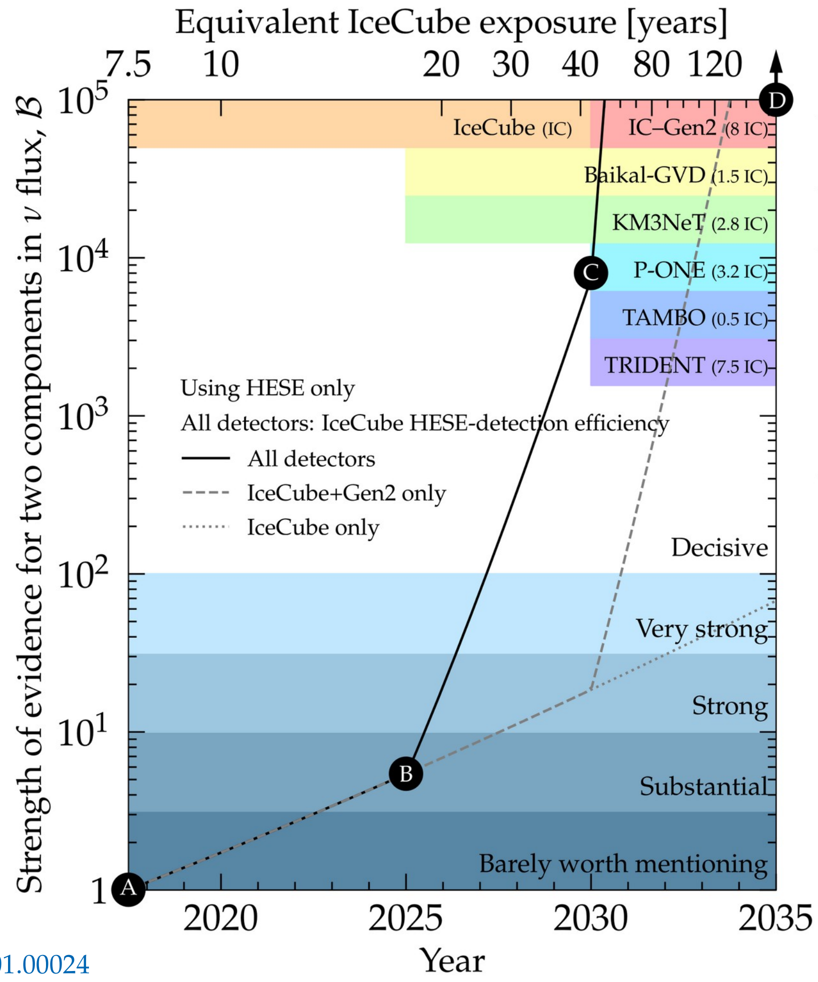
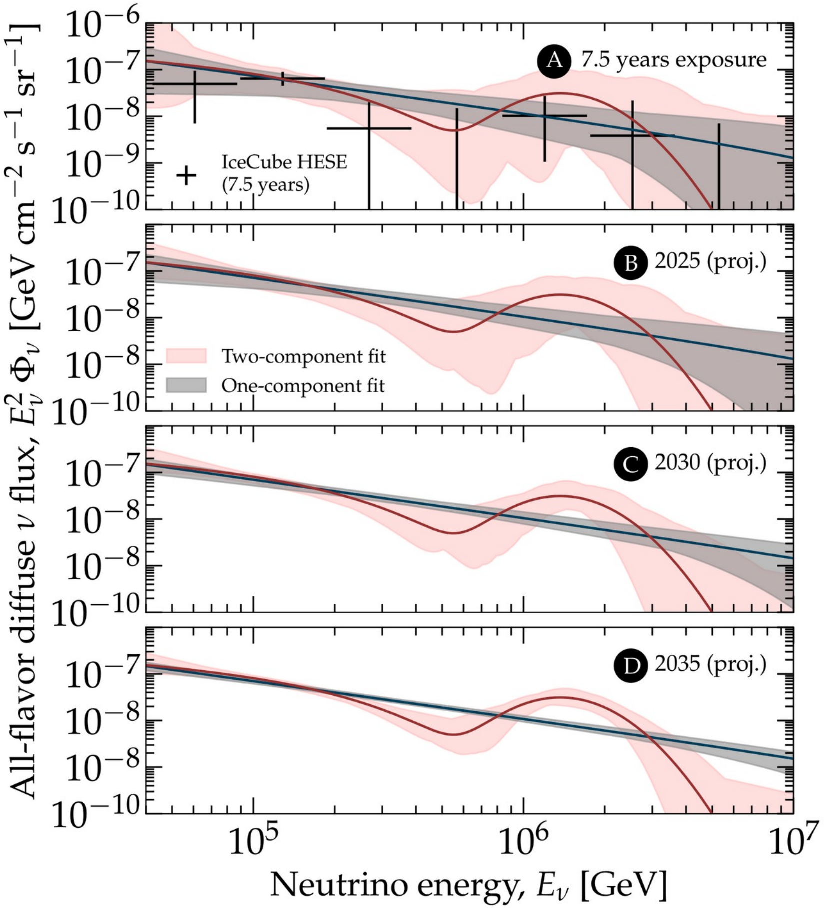
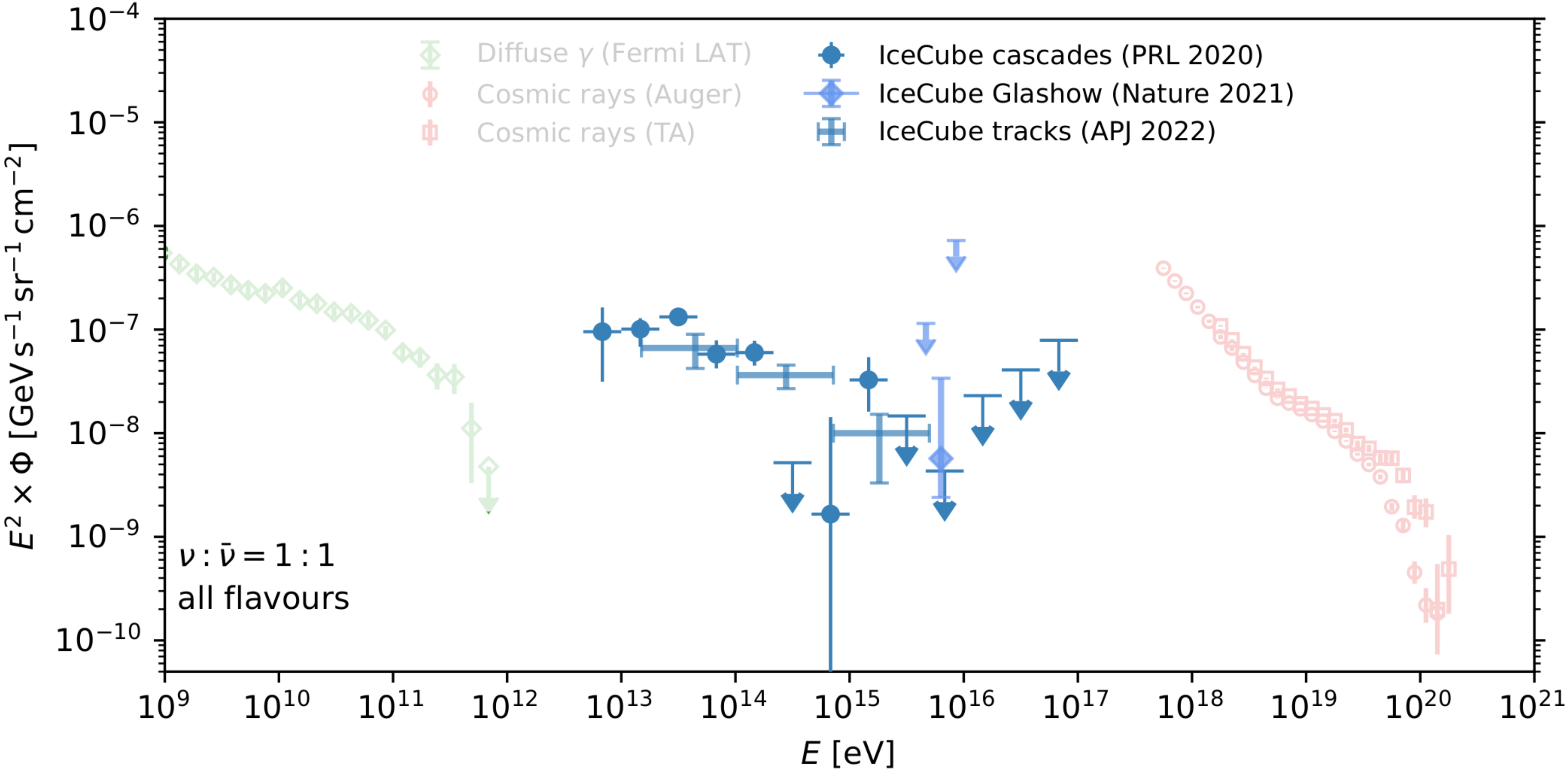


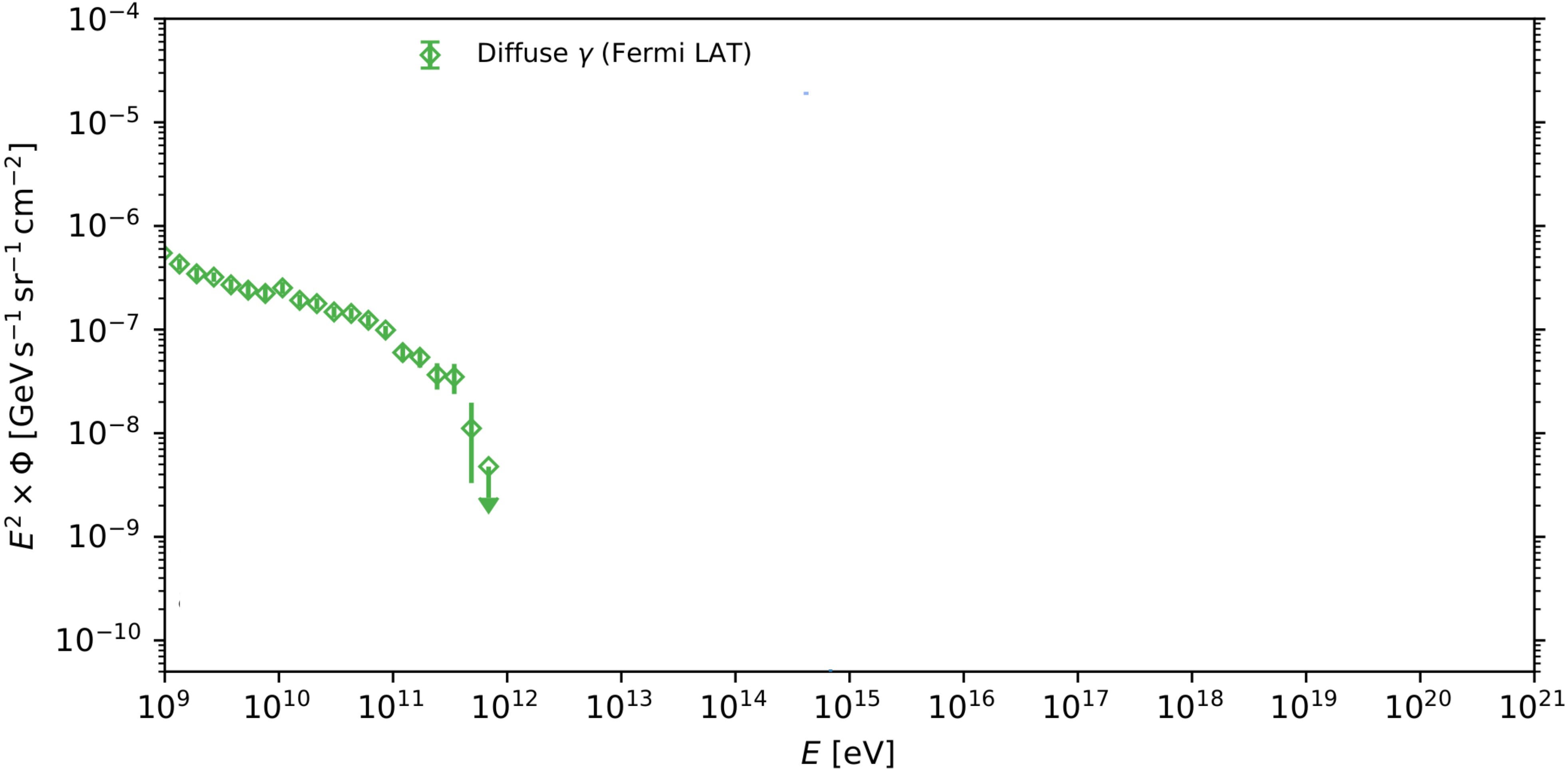


Gamma rays Neutrinos Cosmic rays



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

Gamma rays Neutrinos Cosmic rays



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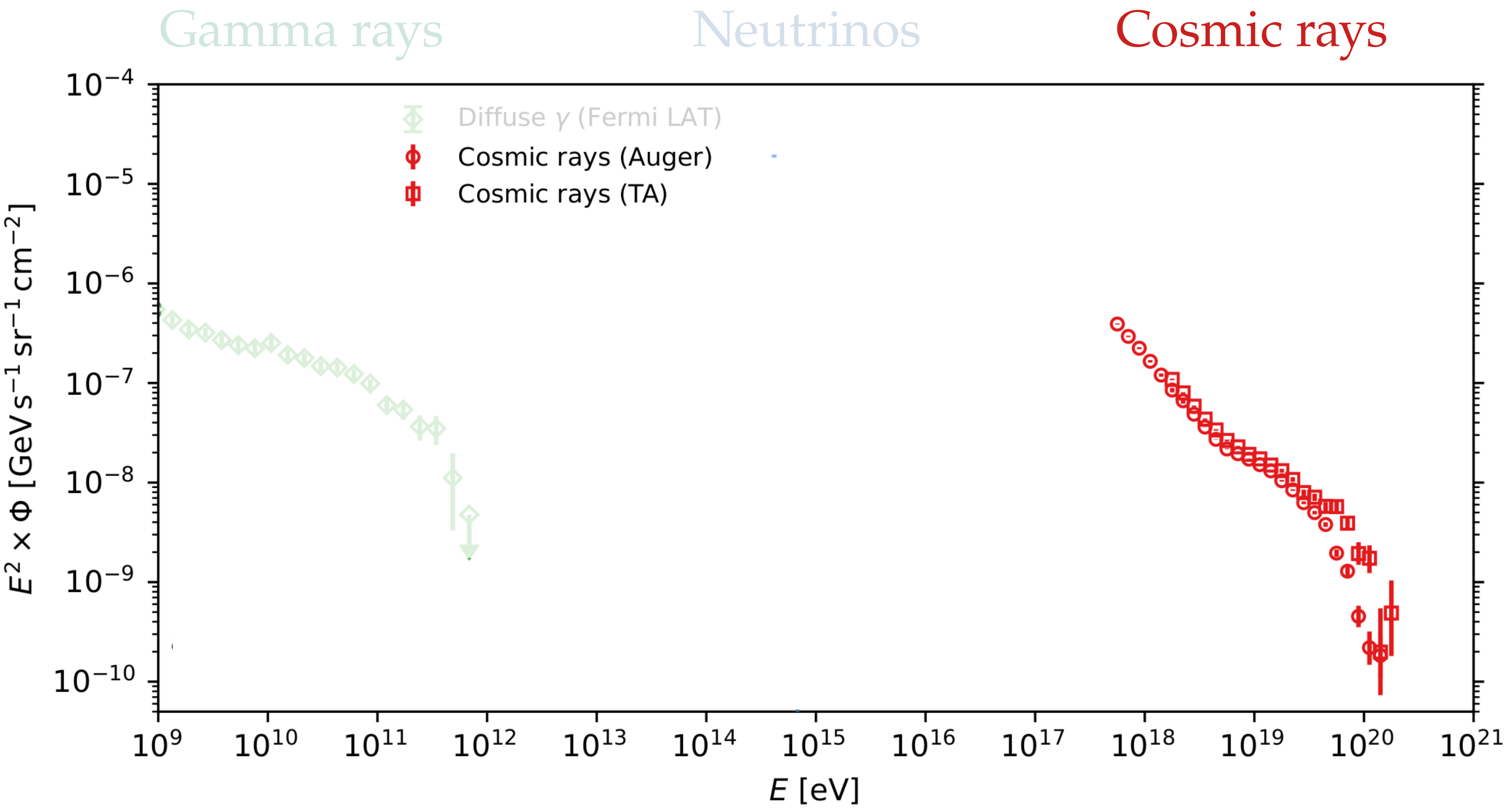

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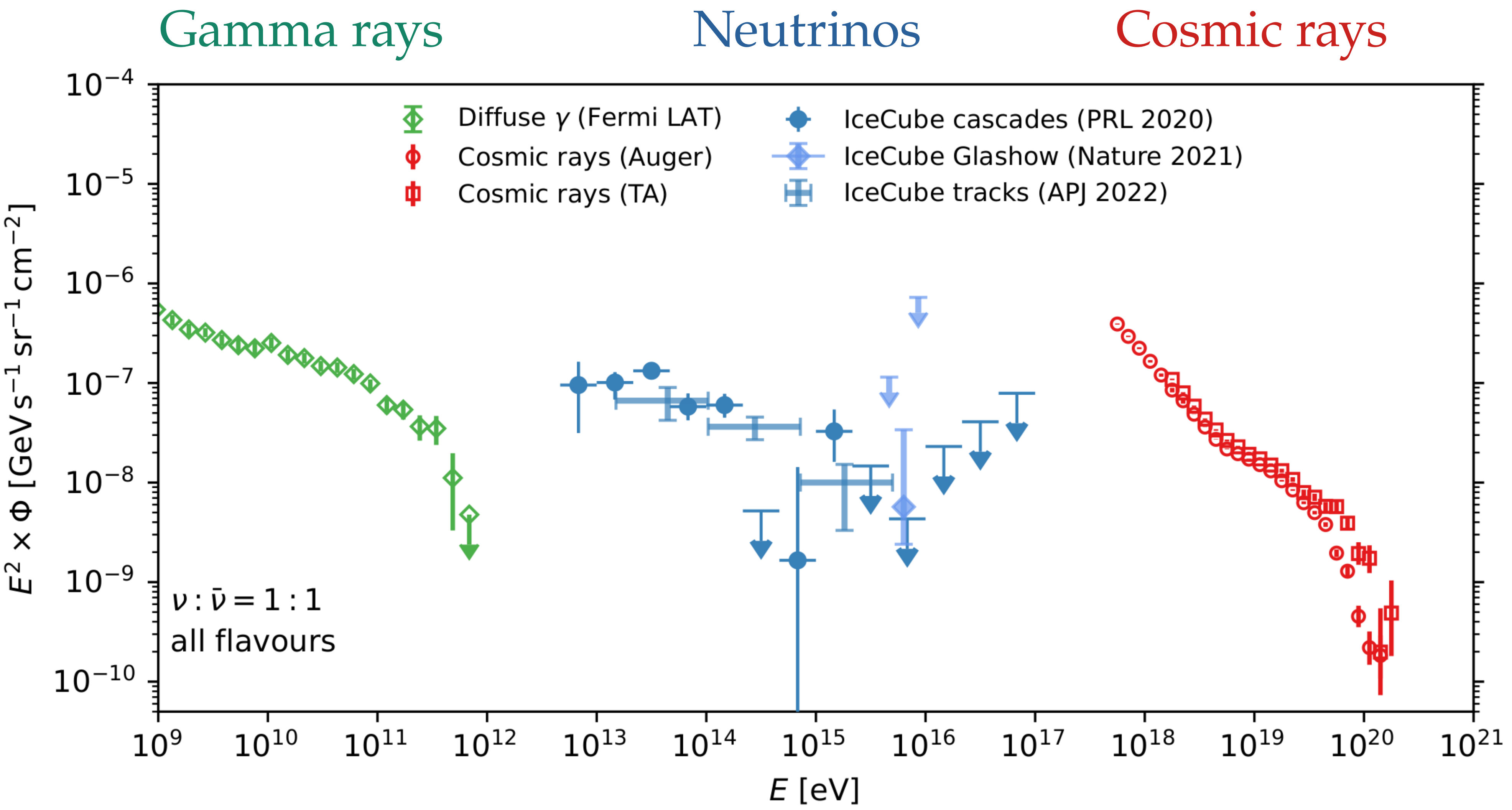

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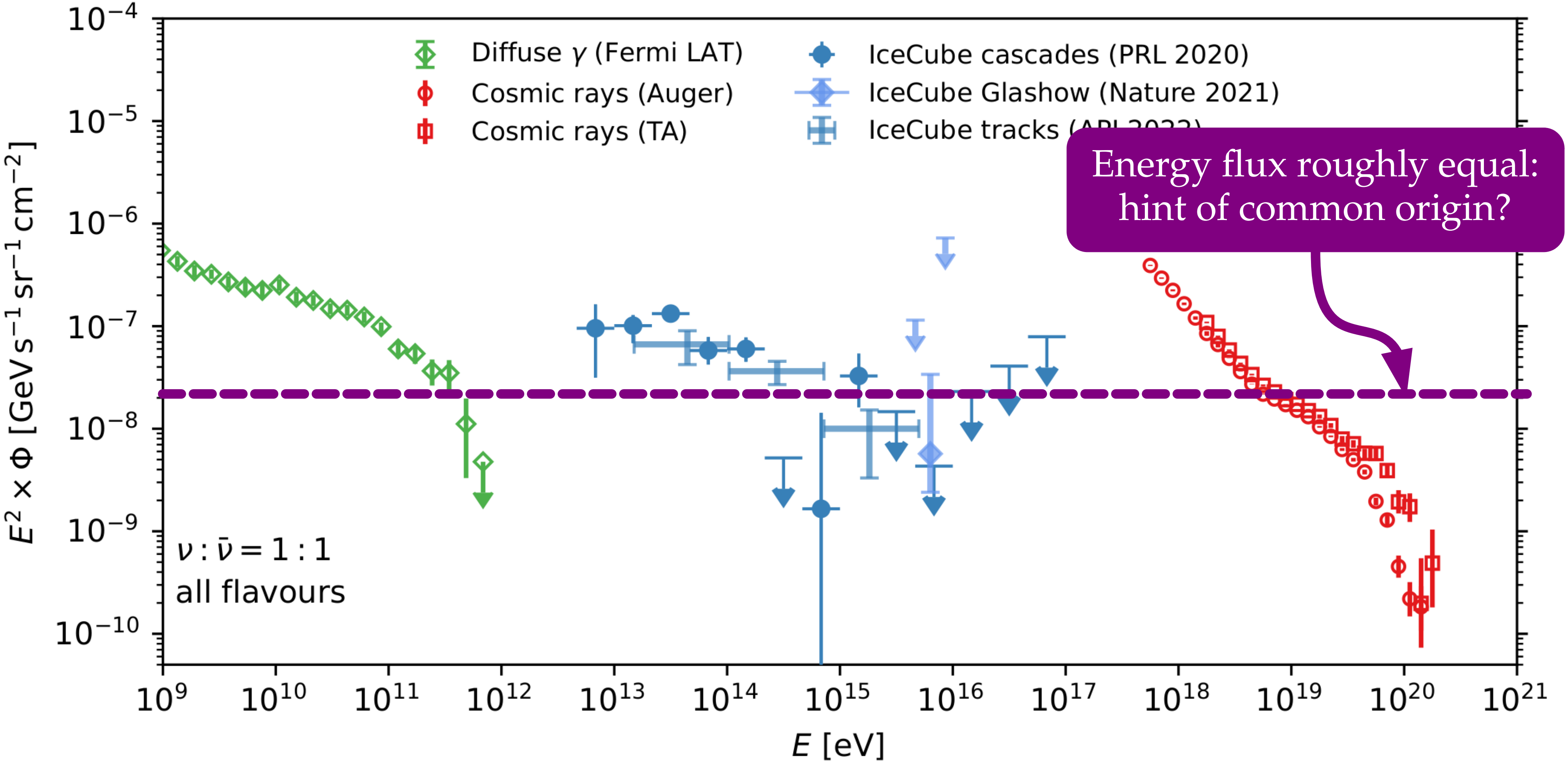
Gamma rays Neutrinos Cosmic rays



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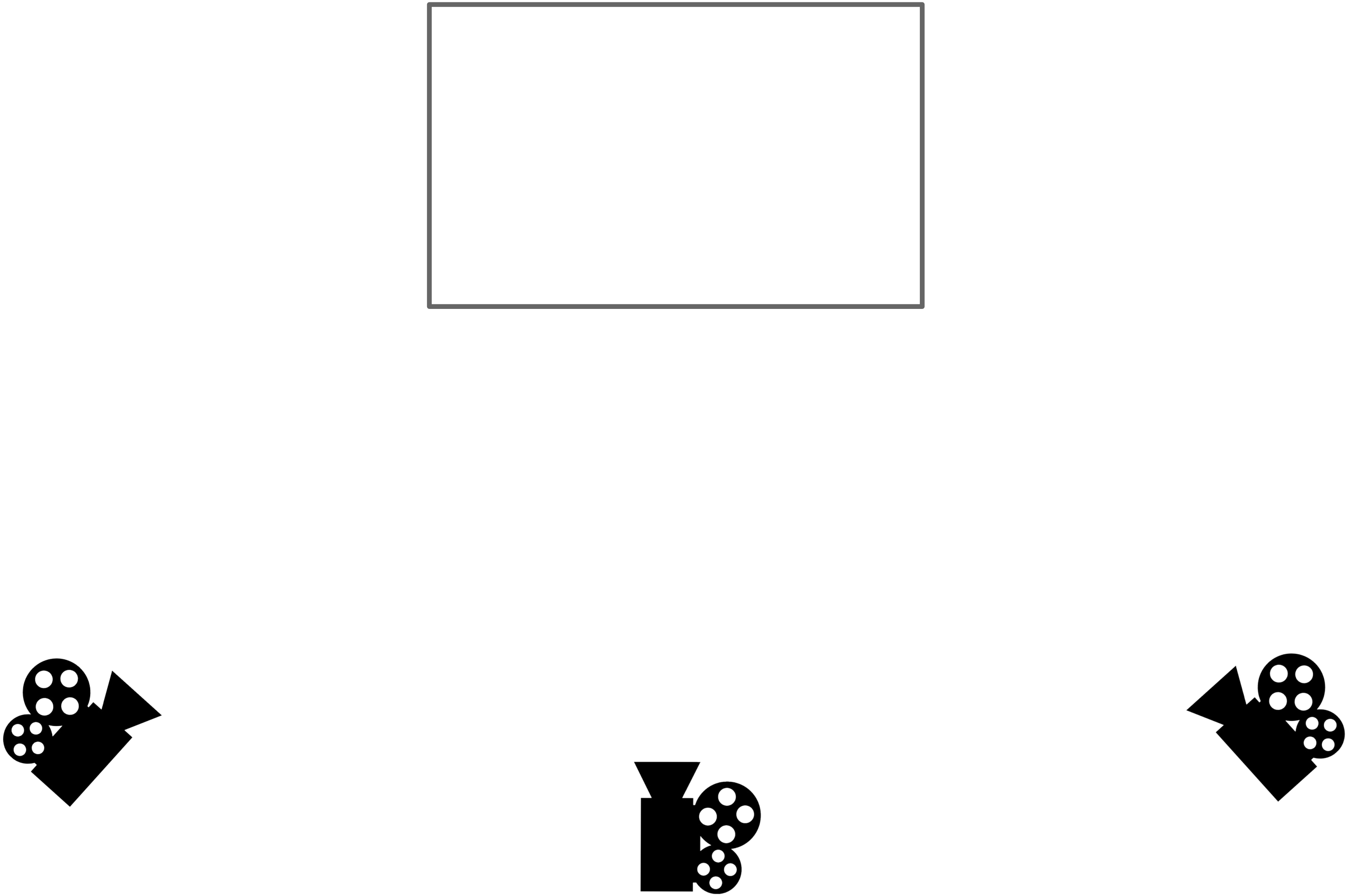
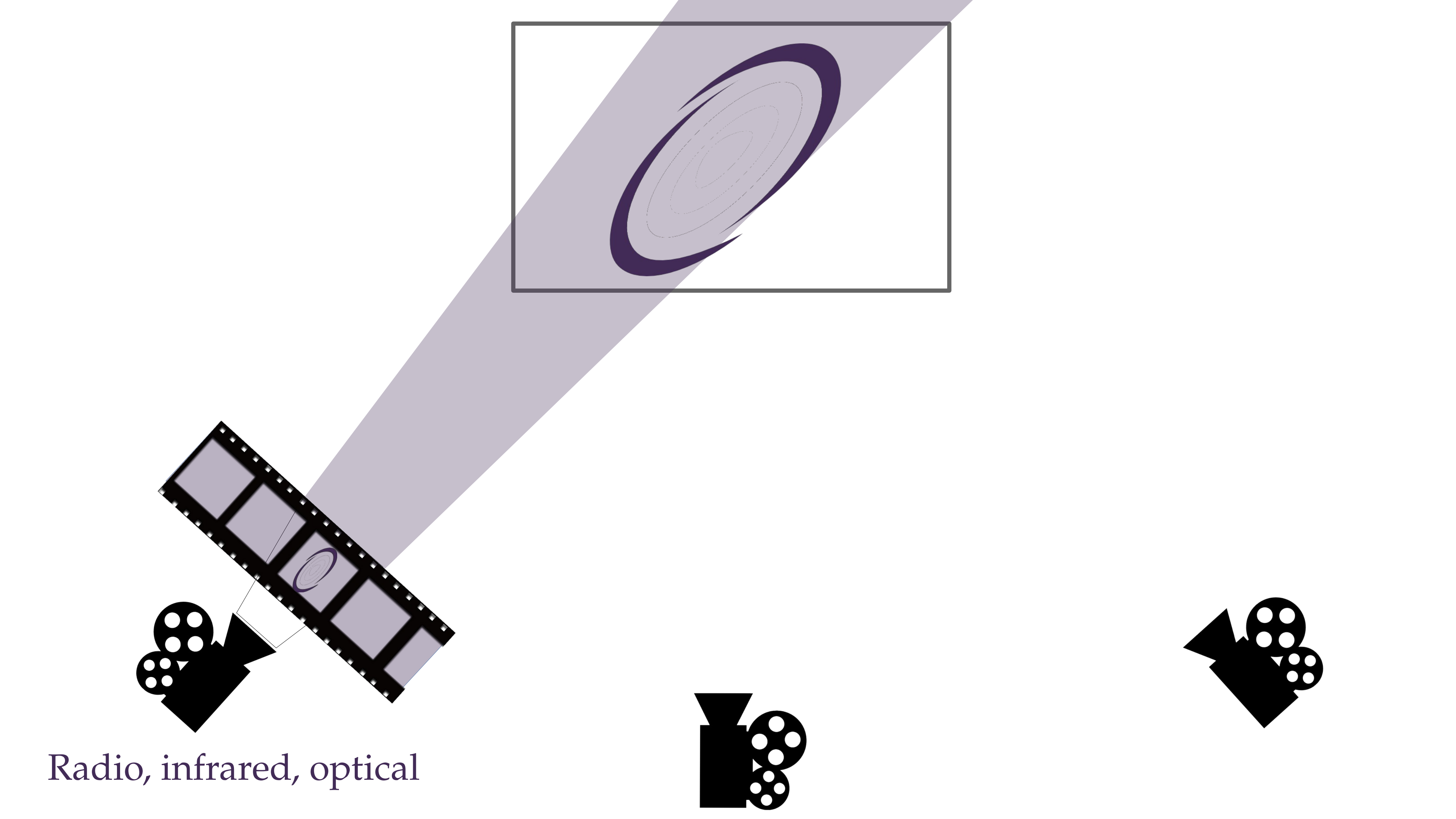
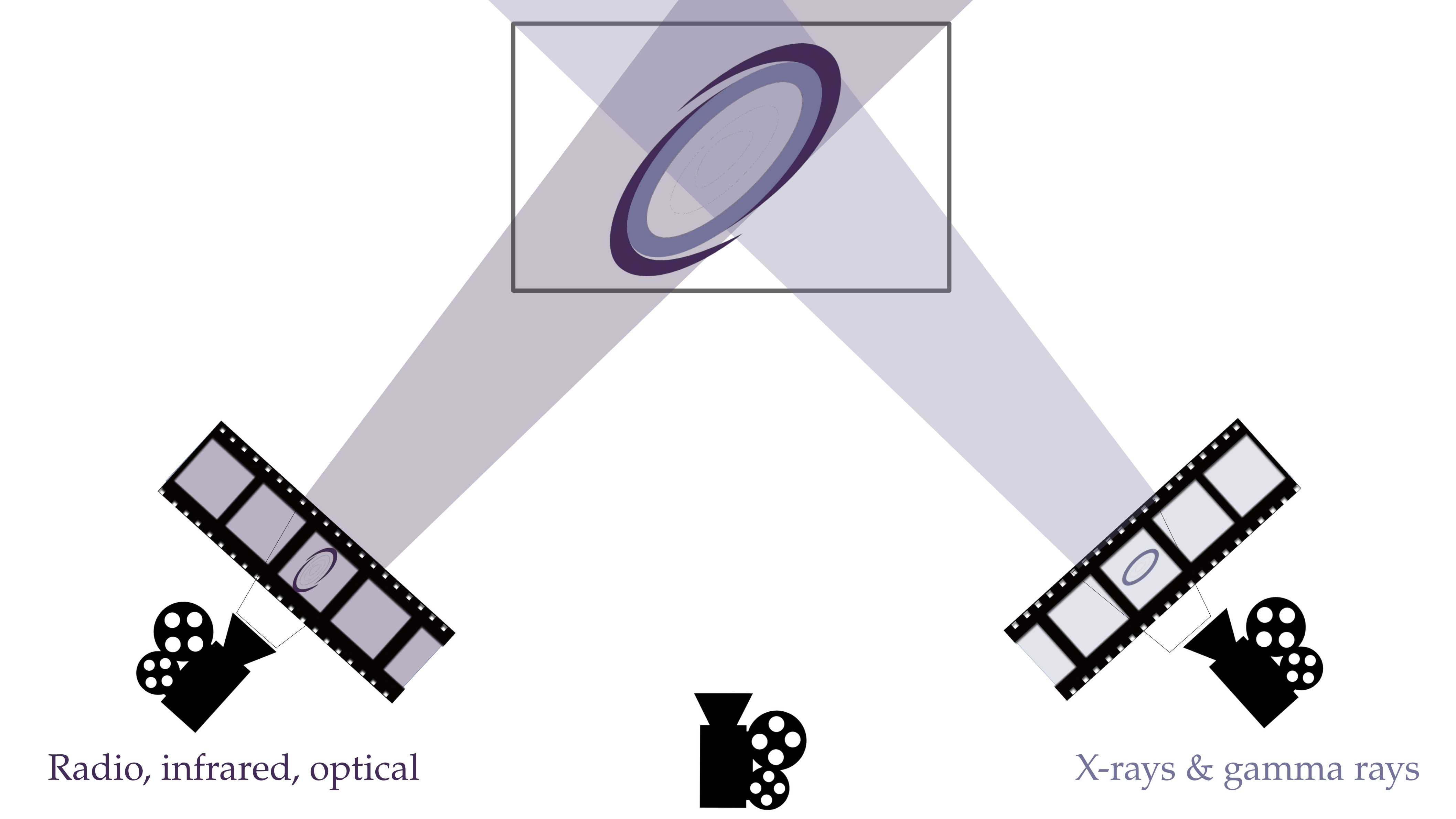
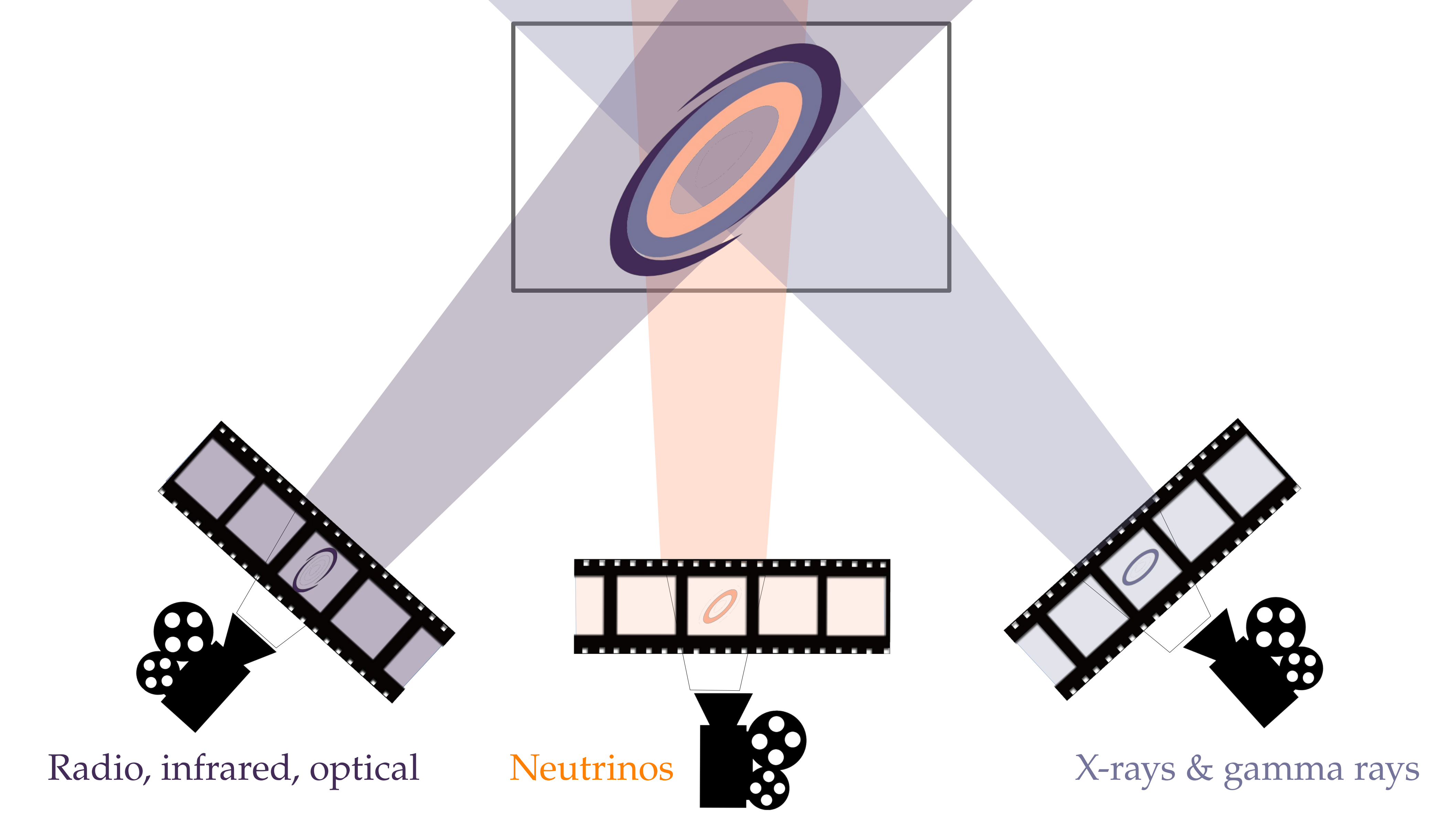



Radio, infrared, optical


Radio, infrared, optical
X-rays & gamma rays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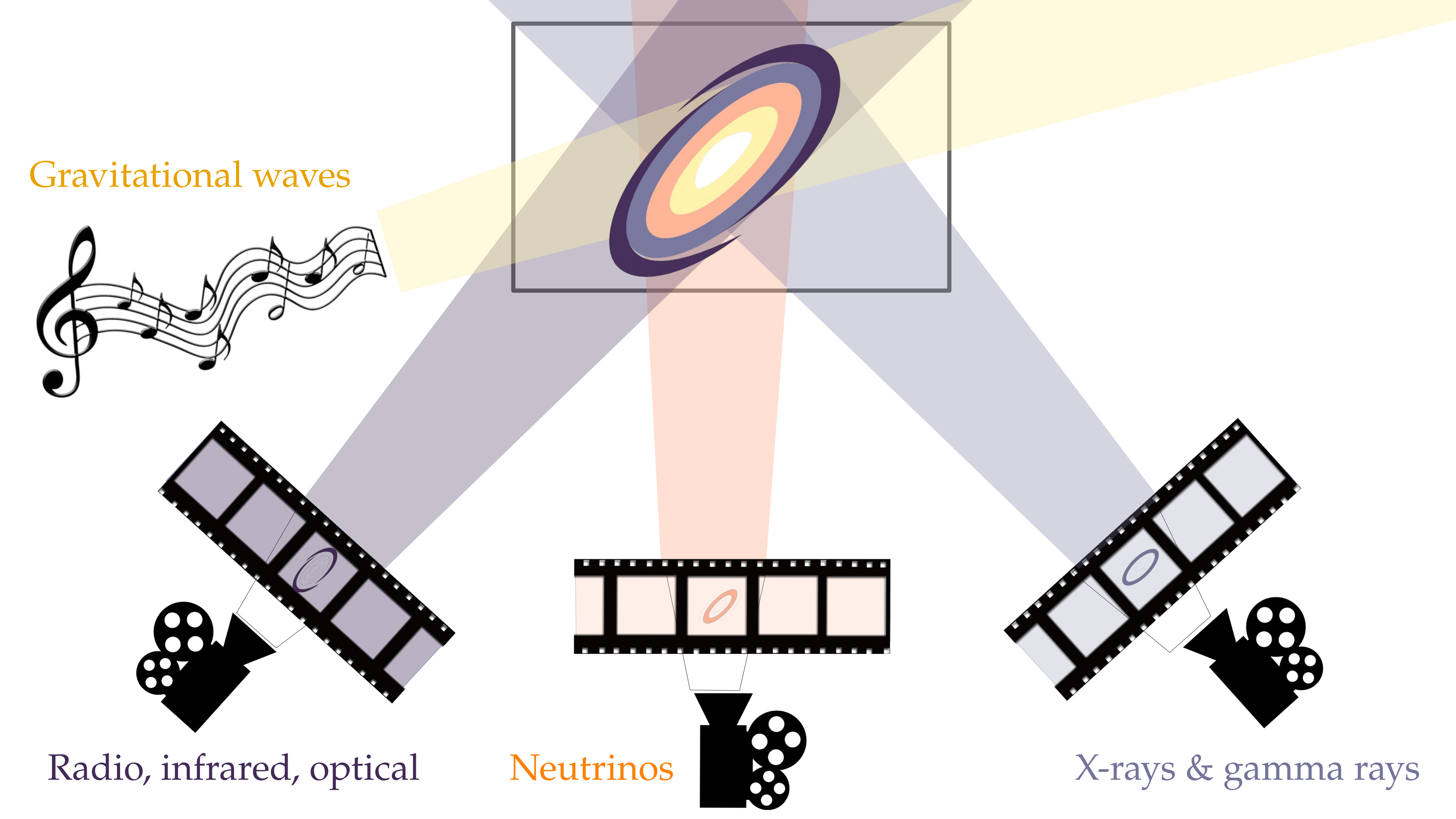
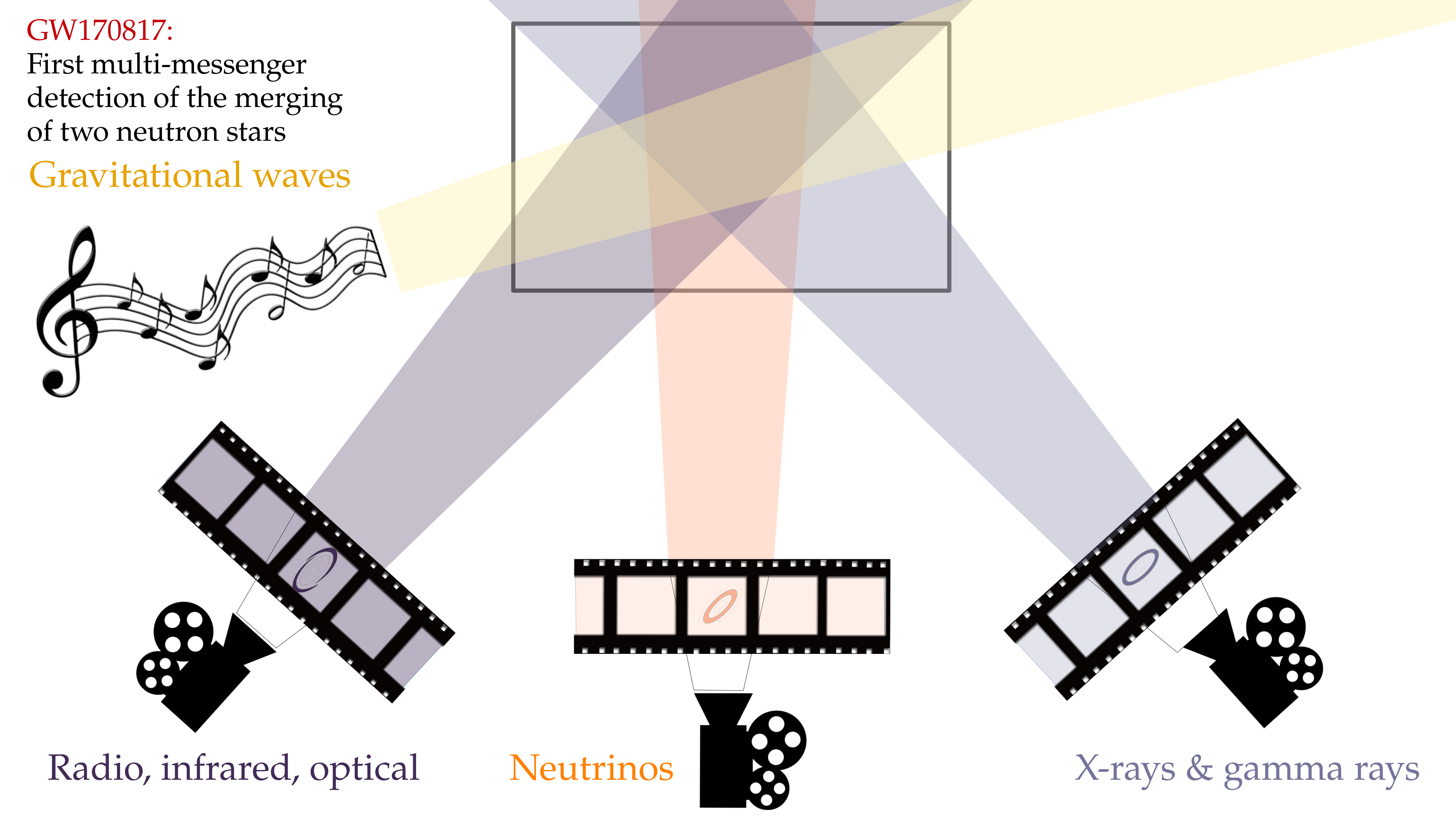
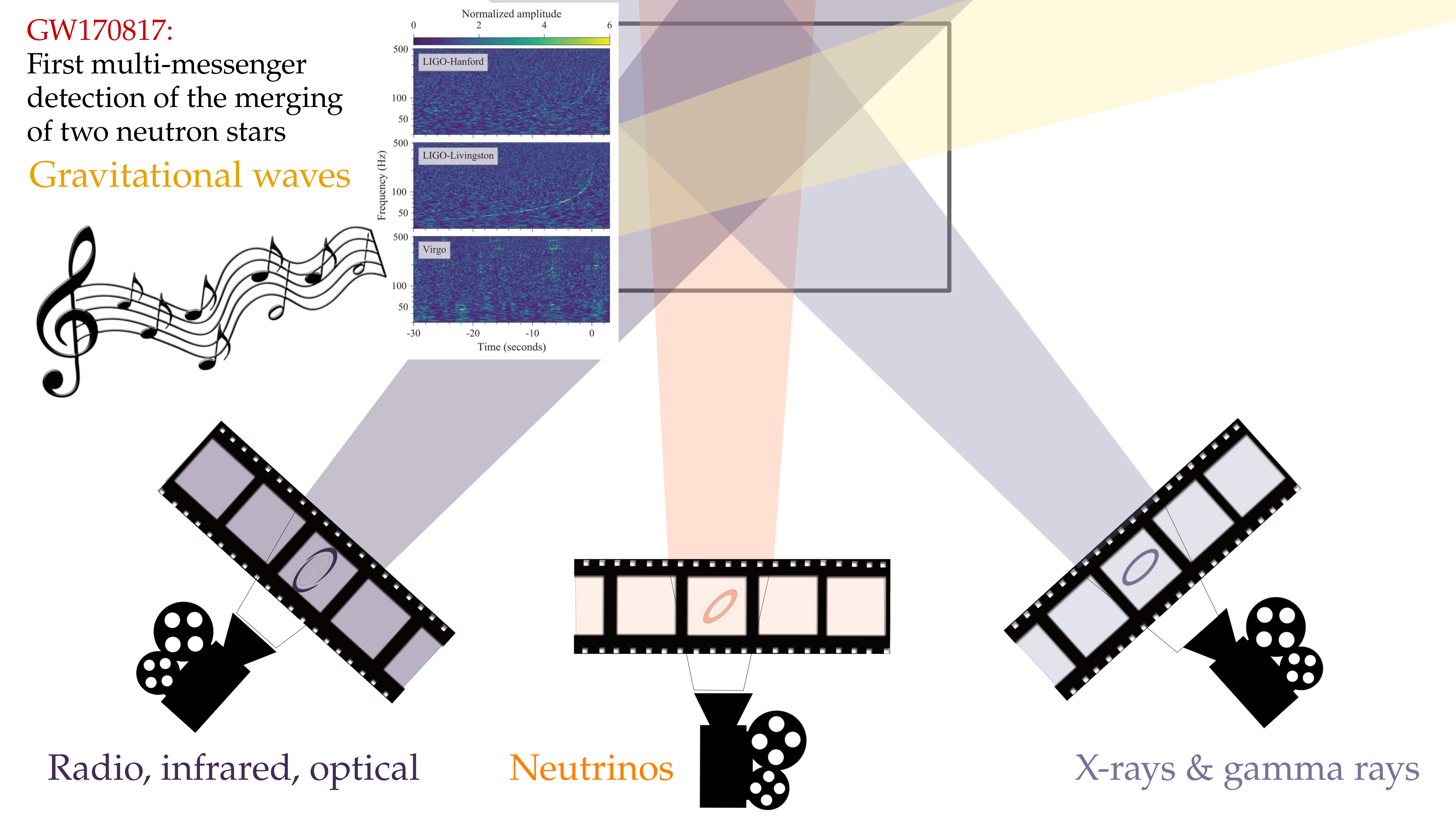
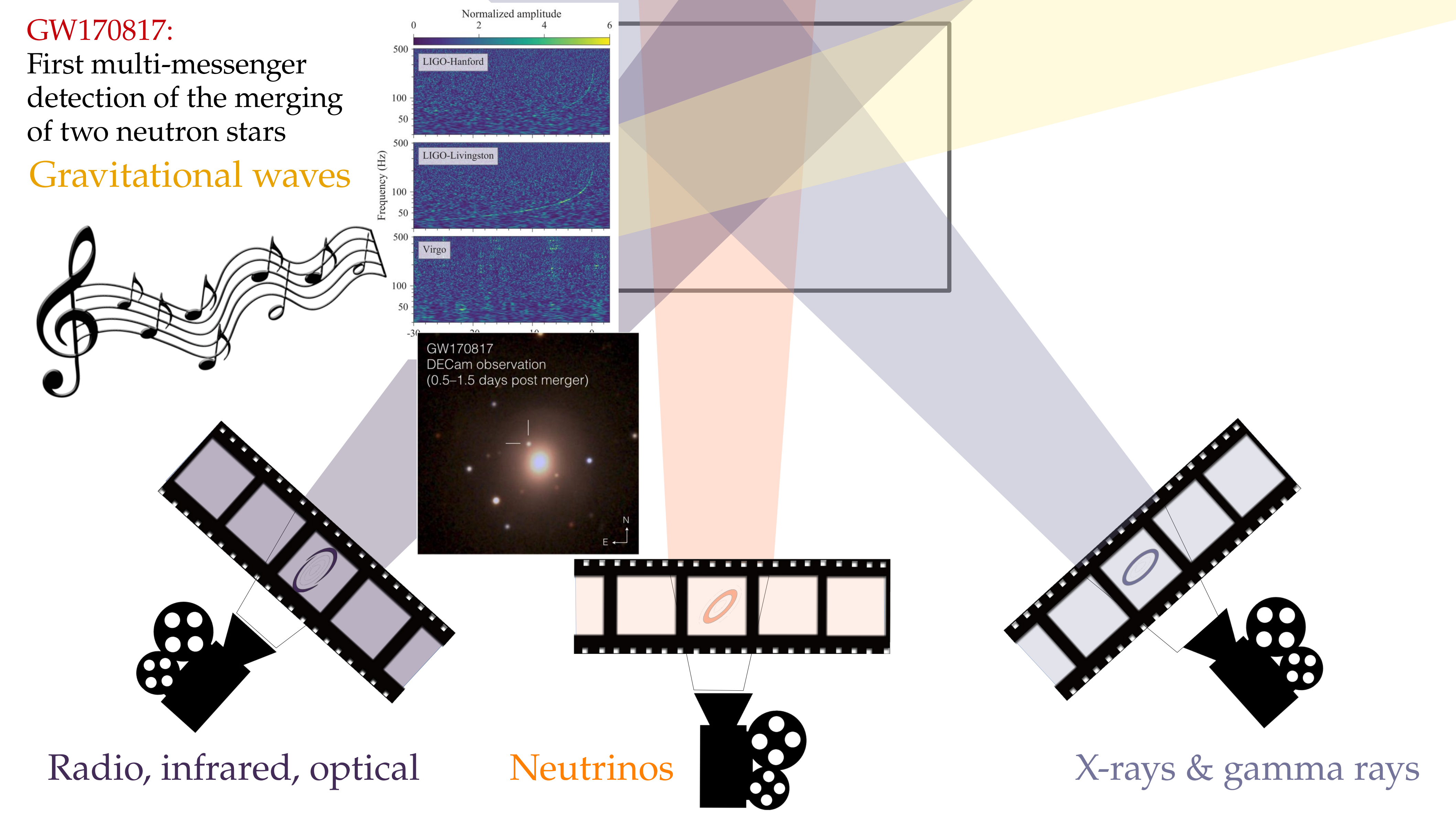
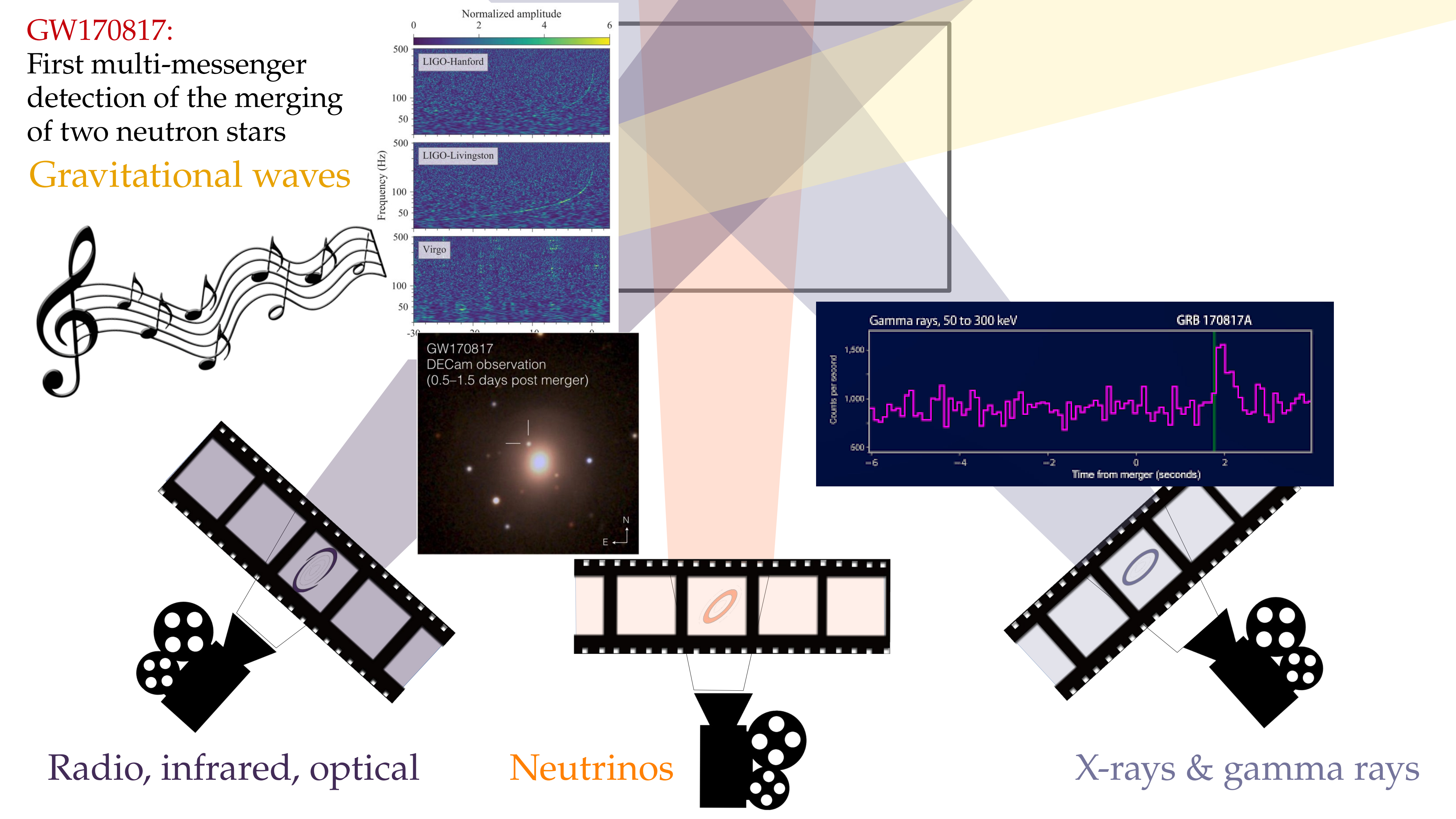
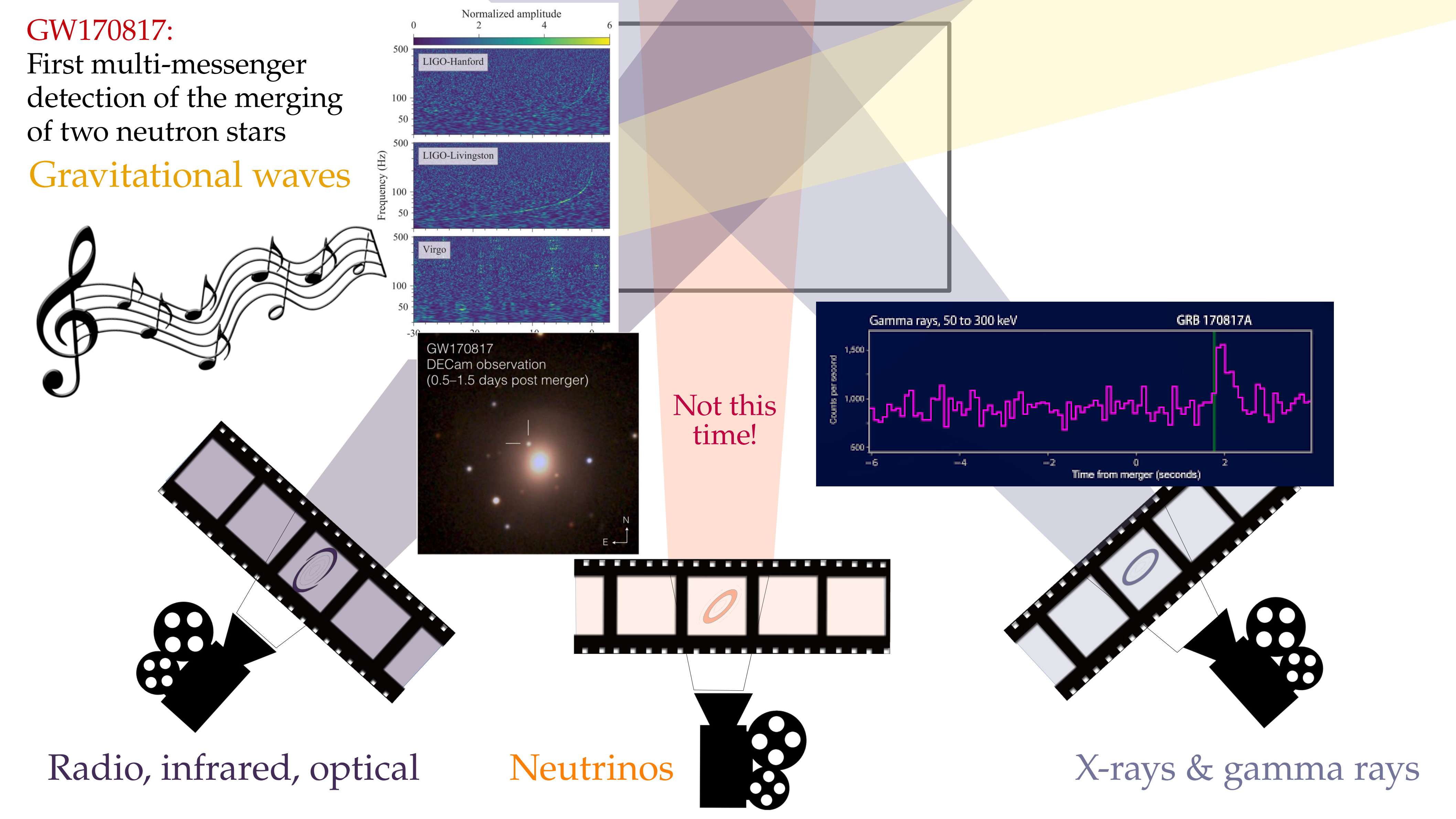

Gravitational waves
Radio, infrared, optical
Neutrinos
X-rays & gamma rays


GW170817:
First multi-messenger detection of the merging of two neutron stars
Gravitational waves
Radio, infrared, optical
Neutrinos
X-rays & gamma rays


GW170817:
First multi-messenger detection of the merging of two neutron stars
Gravitational waves
Normalized amplitude
0
2
4
6
LIGO-Hanford
LIGO-Livingston
Virgo
Frequency (Hz)
500
100
50
-30
-20
-10
0
Time (seconds)
Radio, infrared, optical
Neutrinos
X-rays & gamma rays


GW170817:
First multi-messenger detection of the merging of two neutron stars
Gravitational waves
Normalized amplitude
0 2 4 6
LIGO-Hanford
LIGO-Livingston
Virgo
Frequency (Hz)
500
100
50
GW170817
DECam observation
(0.5–1.5 days post merger)
N
E
Radio, infrared, optical
Neutrinos
X-rays & gamma rays


GW170817:
First multi-messenger detection of the merging of two neutron stars
Gravitational waves
Normalized amplitude
0 2 4 6
LIGO-Hanford
LIGO-Livingston
Virgo
Frequency (Hz)
500
100
50
GW170817
DECam observation
(0.5–1.5 days post merger)
N
E
Gamma rays, 50 to 300 keV
GRB 170817A
Counts per second
1,500
1,000
Time from merger (seconds)
−6 −4 −2 0 2
Radio, infrared, optical
Neutrinos
X-rays & gamma rays



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Virgo
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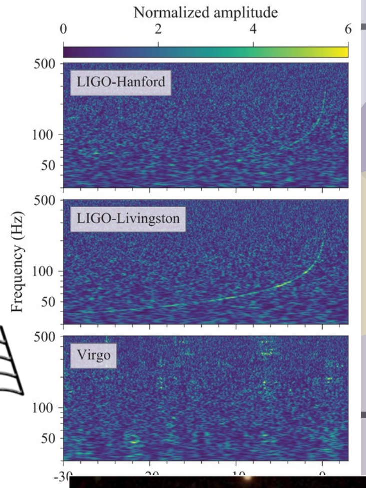
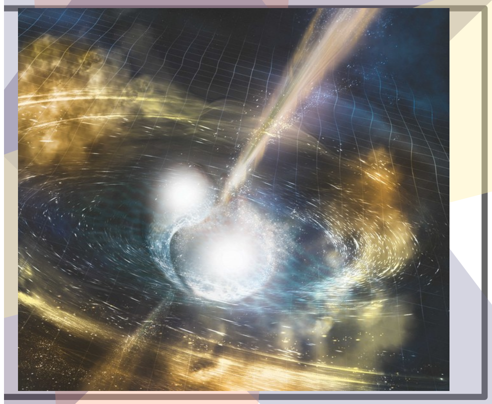
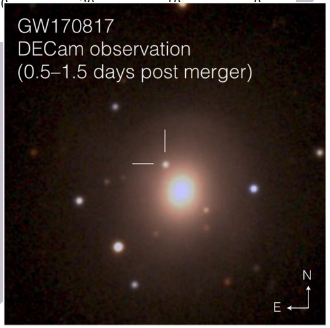
DECam observation
(0.5–1.5 days post merger)
N
E
Not this time!
Gamma rays, 50 to 300 keV
GRB 170817A
Counts per second
1,500
1,000
600
−6
−4
−2
0
2
Time from merger (seconds)
Radio, infrared, optical
Neutrinos
X-rays & gamma rays

GW170817:
First multi-messenger detection of the merging of two neutron stars

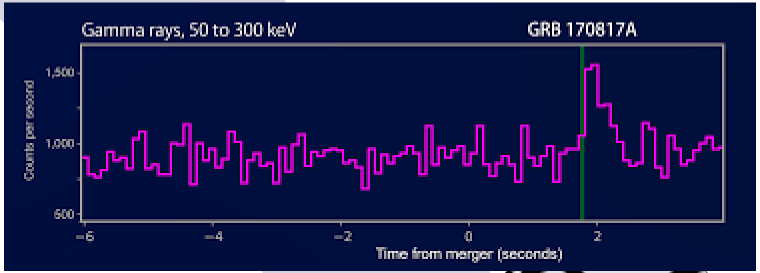
Gravitational waves

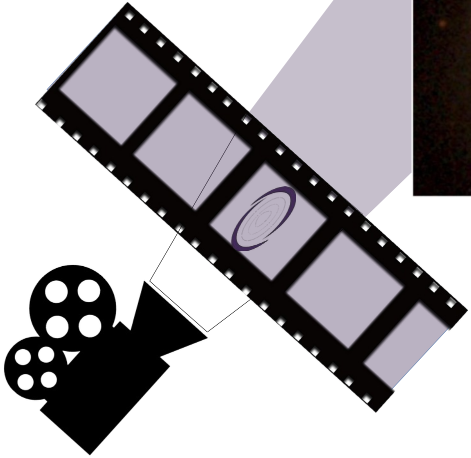


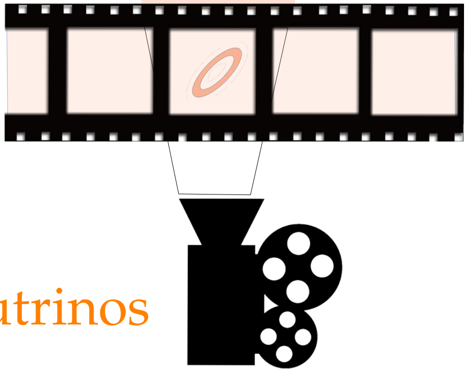


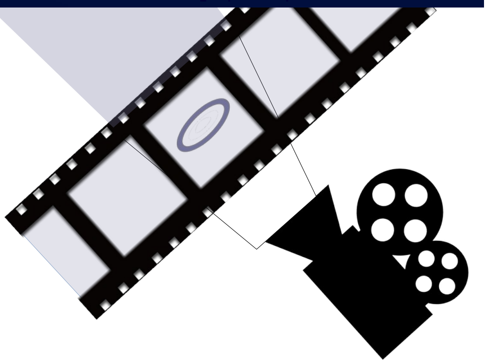


Not this time!









Radio, infrared, optical

Neutrinos

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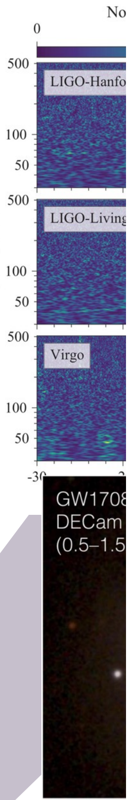
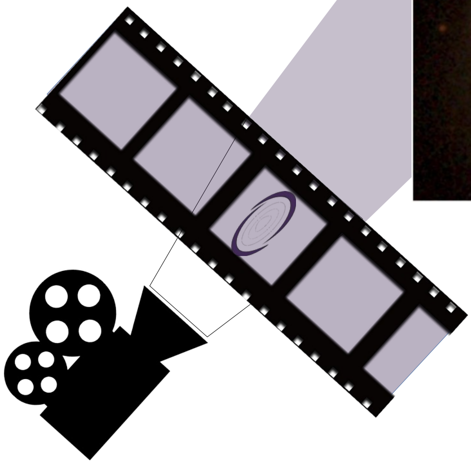
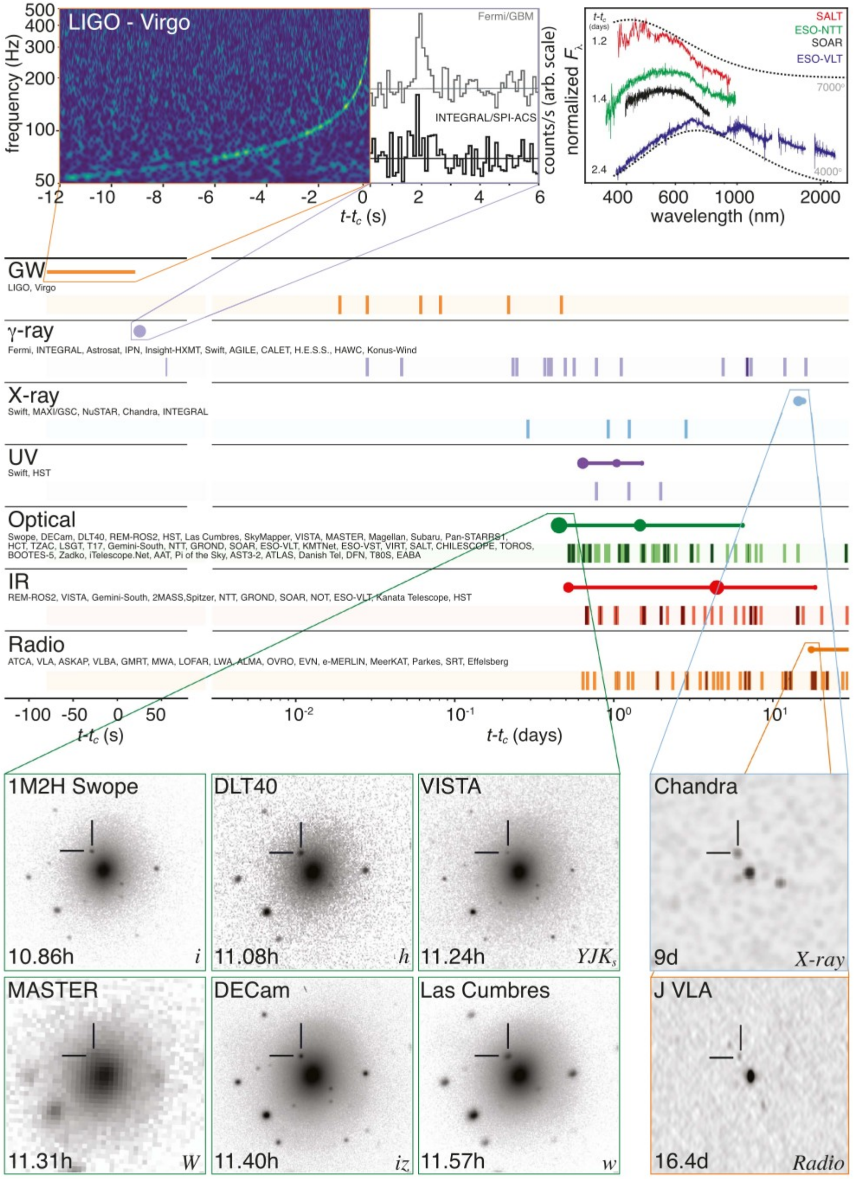
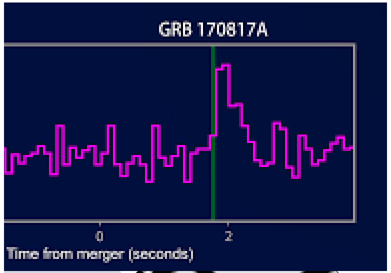
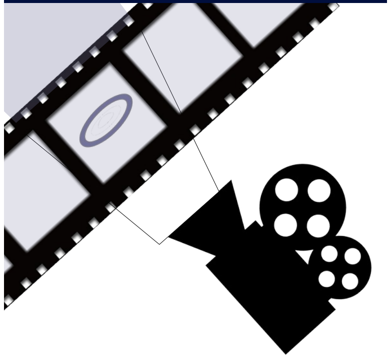
Gravitational waves









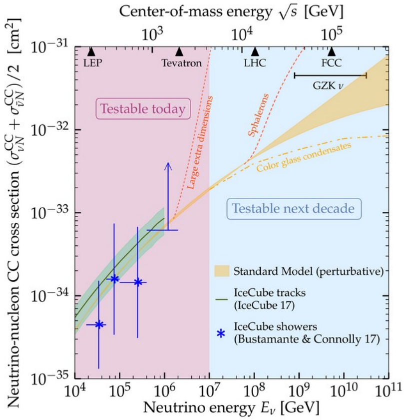


Radio, infrared, optical

X-rays & gamma rays

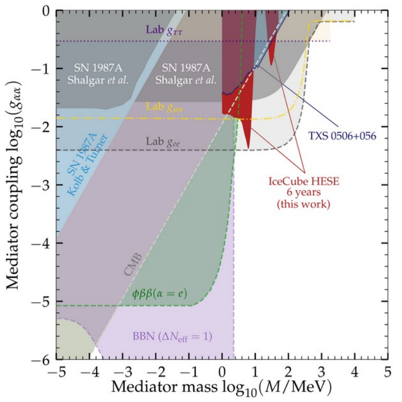
III.
What have we learned about *particle physics*

TeV–EeV ν cross sections



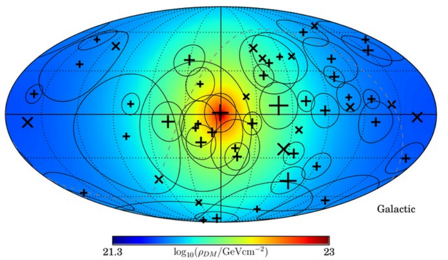
MB & Connolly, *PRL* 2019

ν self-interactions



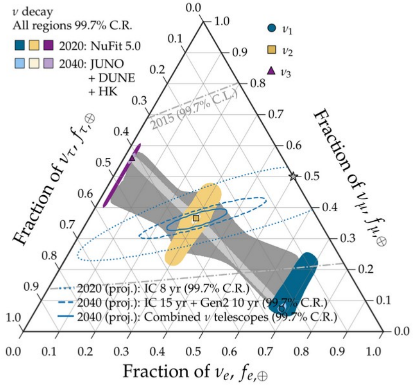
MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

ν scattering on Galactic DM



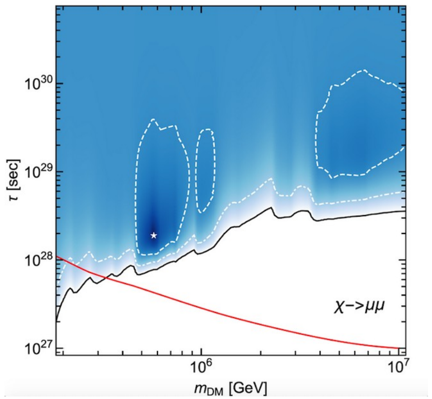
Argüelles, Kheirandish, Vincent, *PRL* 2017

ν decay



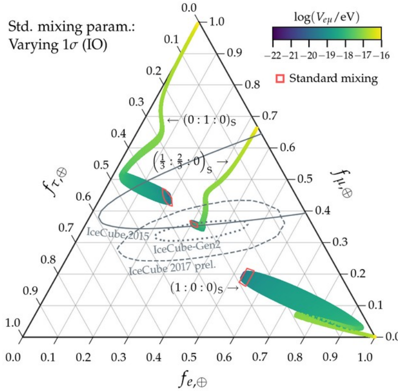
Song, Li, Argüelles, MB, Vincent, *JCAP* 2021

Dark matter decay



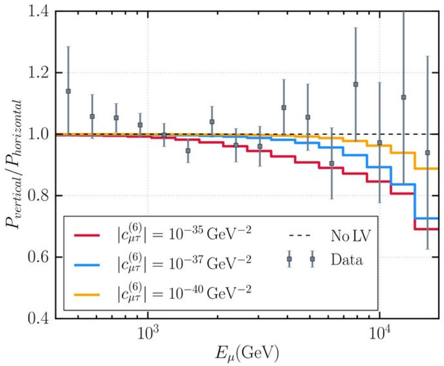
Chianese, Fiorillo, Miele, Morisi, Pisanti, *JCAP* 2019

ν-electron interaction



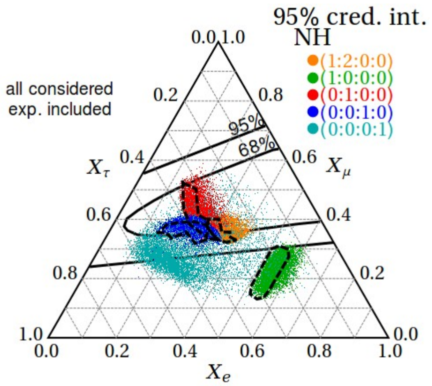
MB & Agarwalla, *PRL* 2019

Lorentz-invariance violation



IceCube, *Nature Phys.* 2018

Sterile neutrinos



Brdar, Kopp, Wang, *JCAP* 2017

Note: Not an exhaustive list

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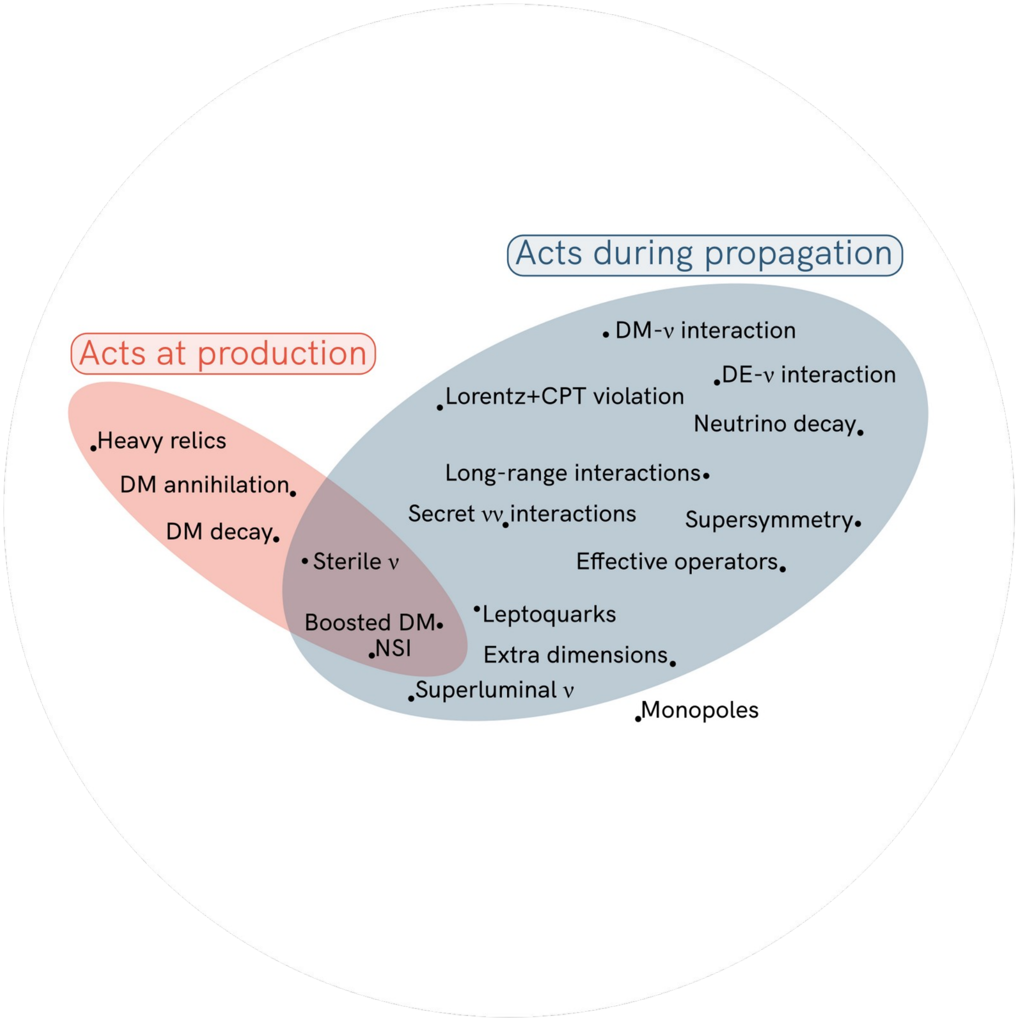
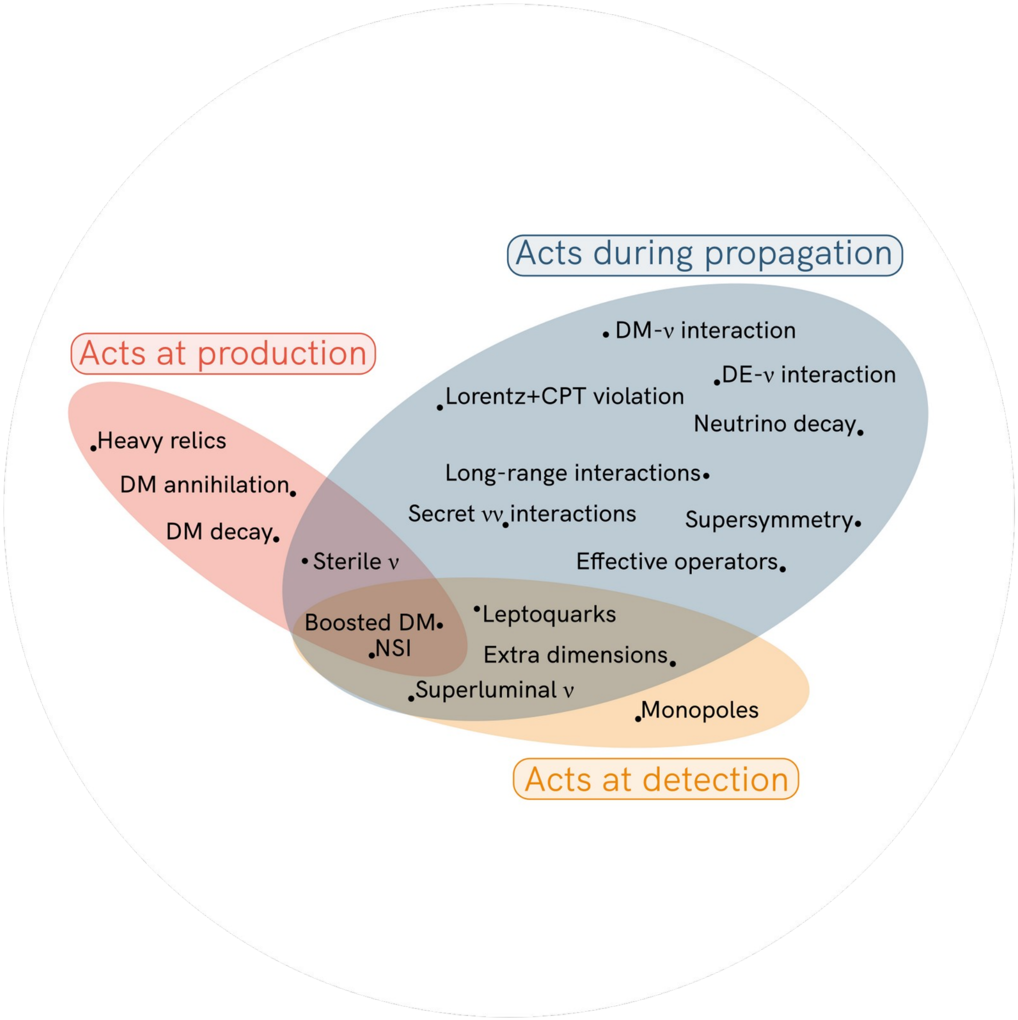
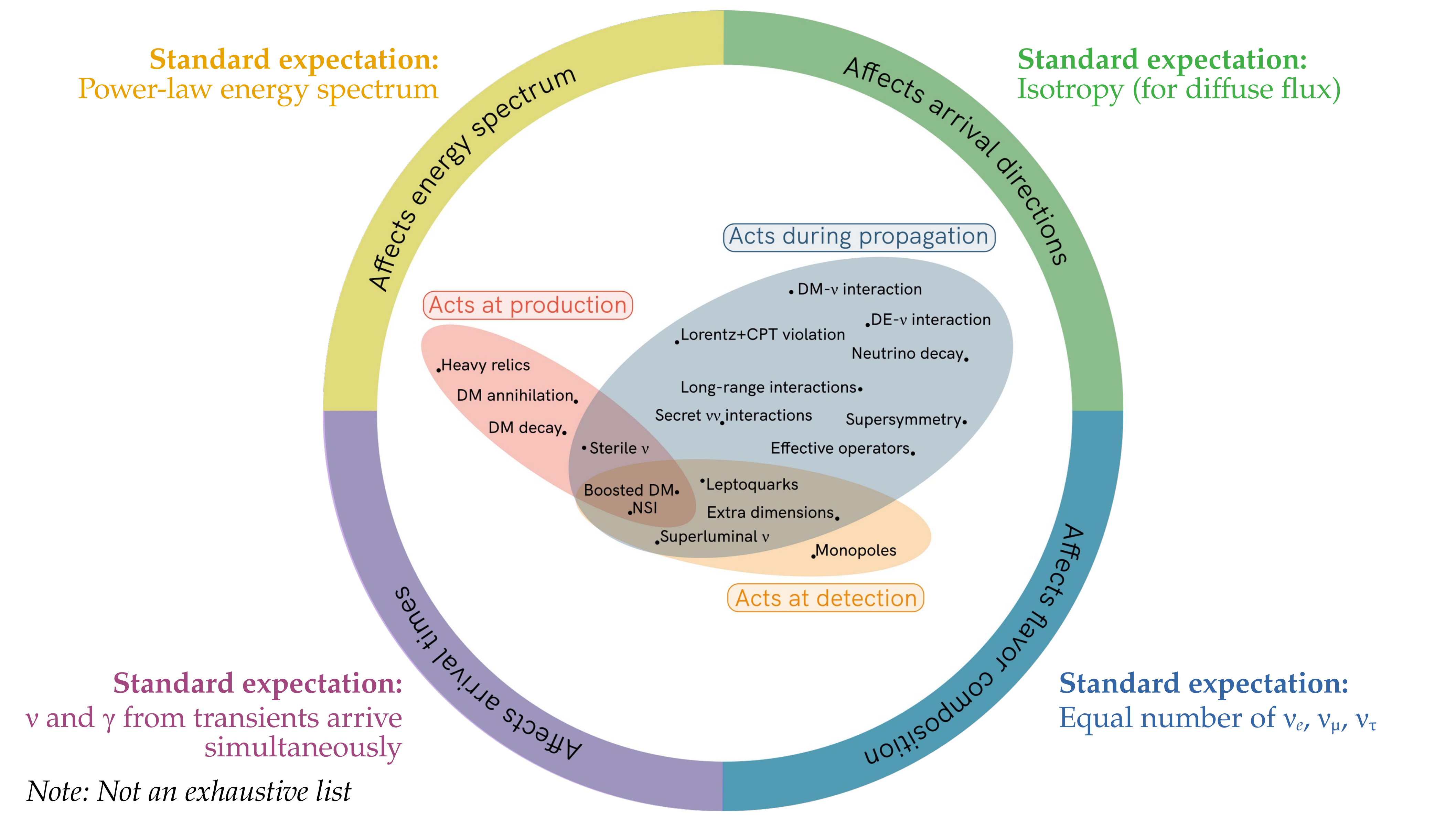
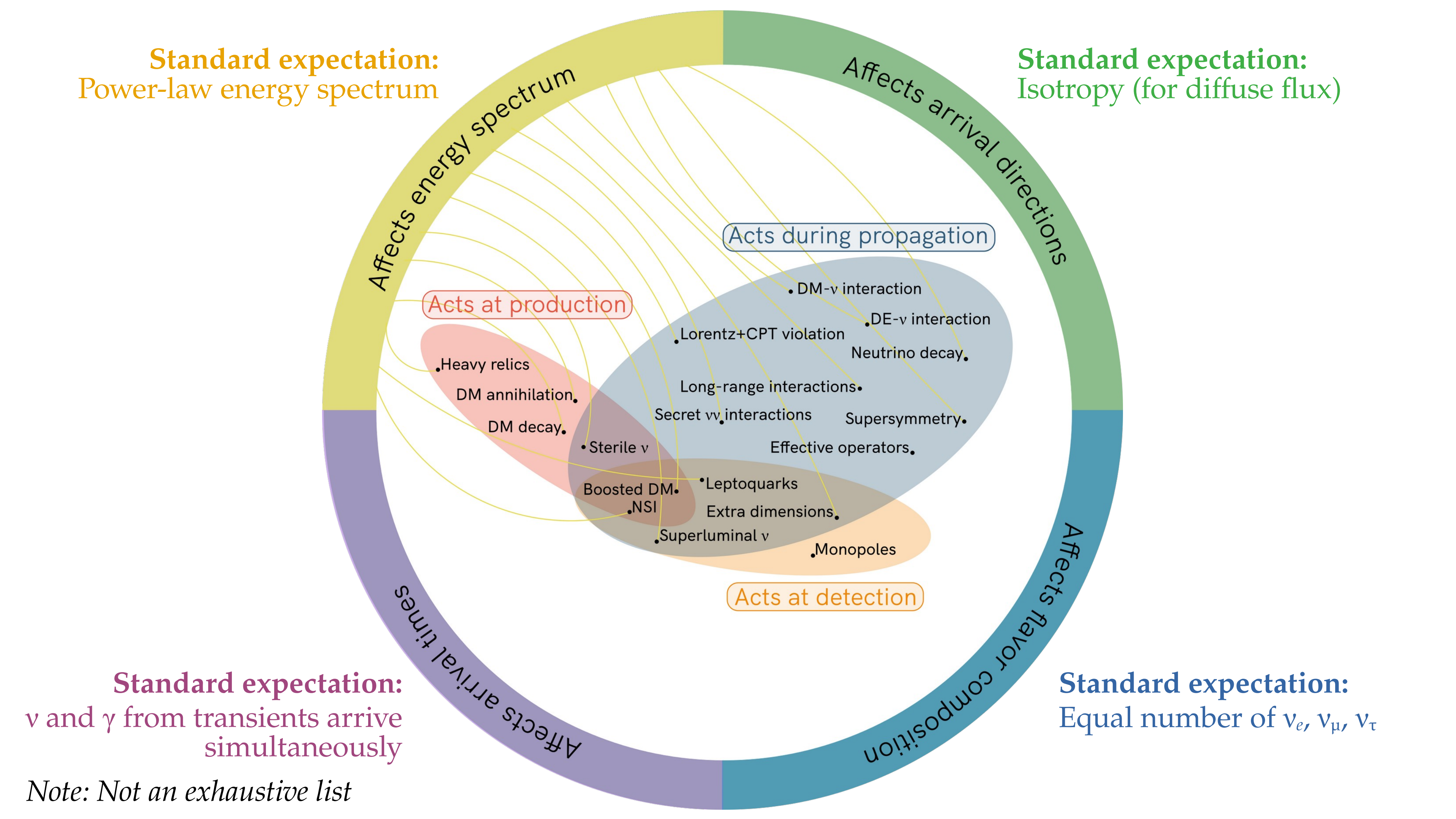


Note: Not an exhaustive list



Note: Not an exhaustive list


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
Long-range interactions
Secret νν interactions
Supersymmetry
DM decay
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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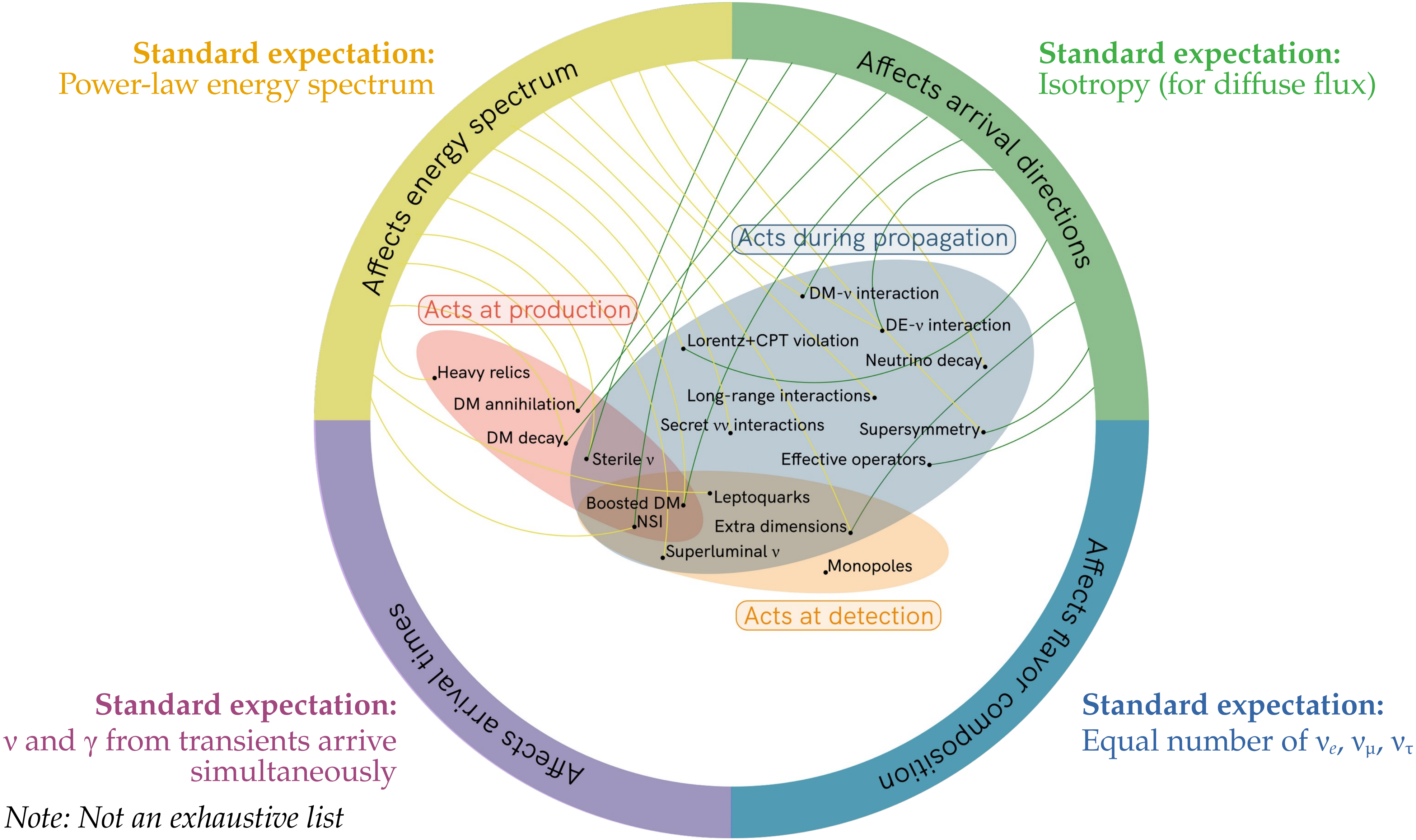

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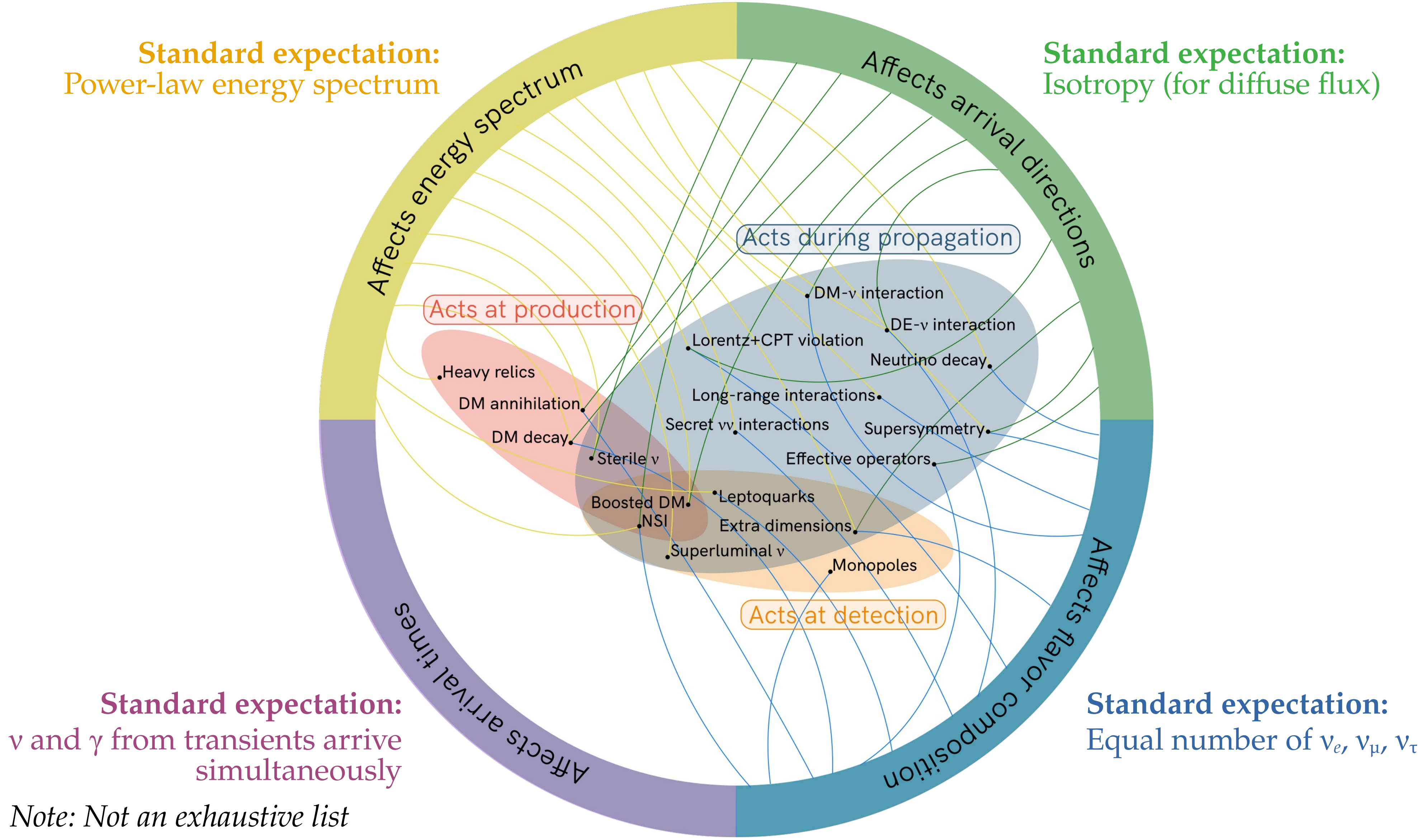
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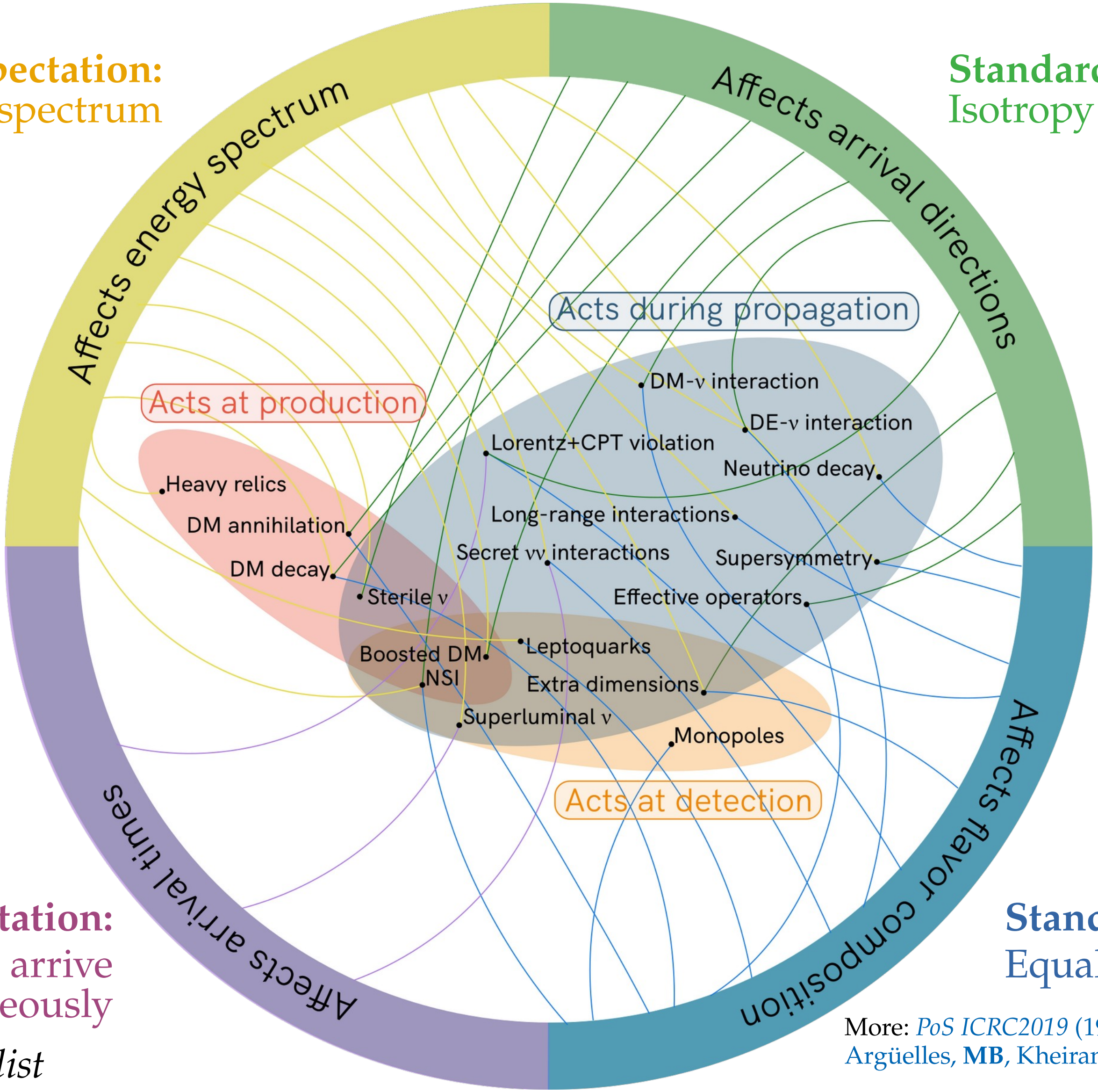

Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
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Note: Not an exhaustive list

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

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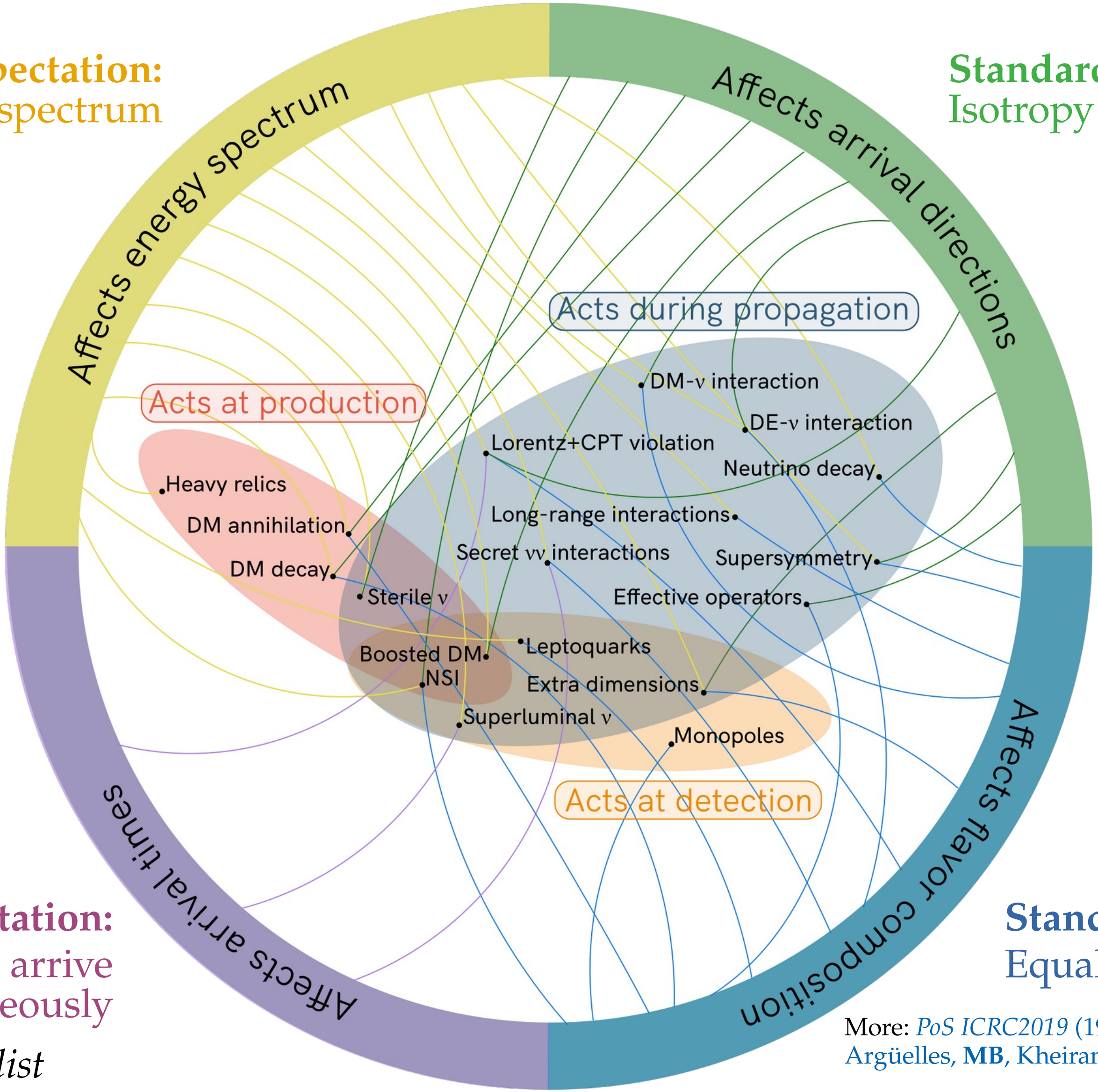
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



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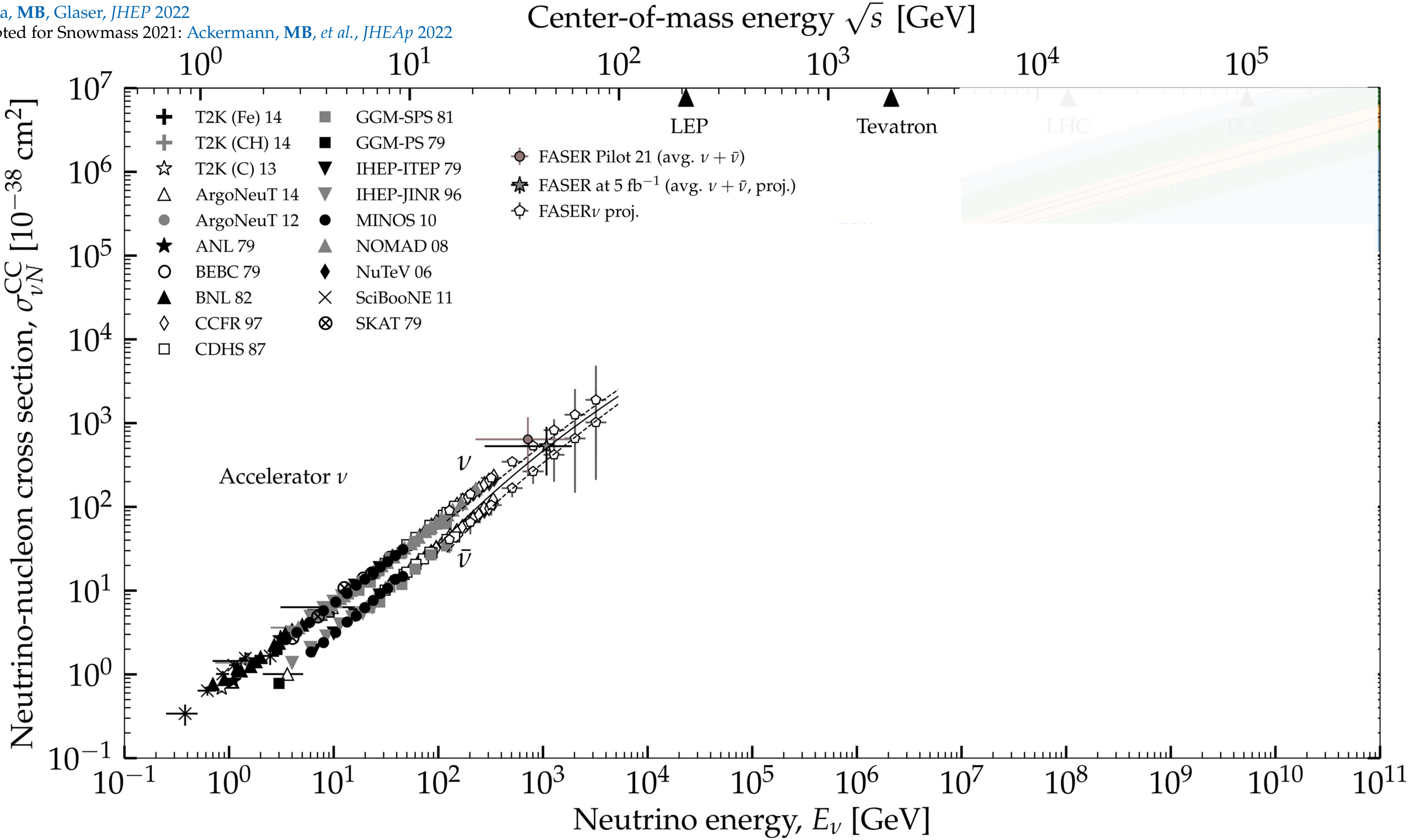
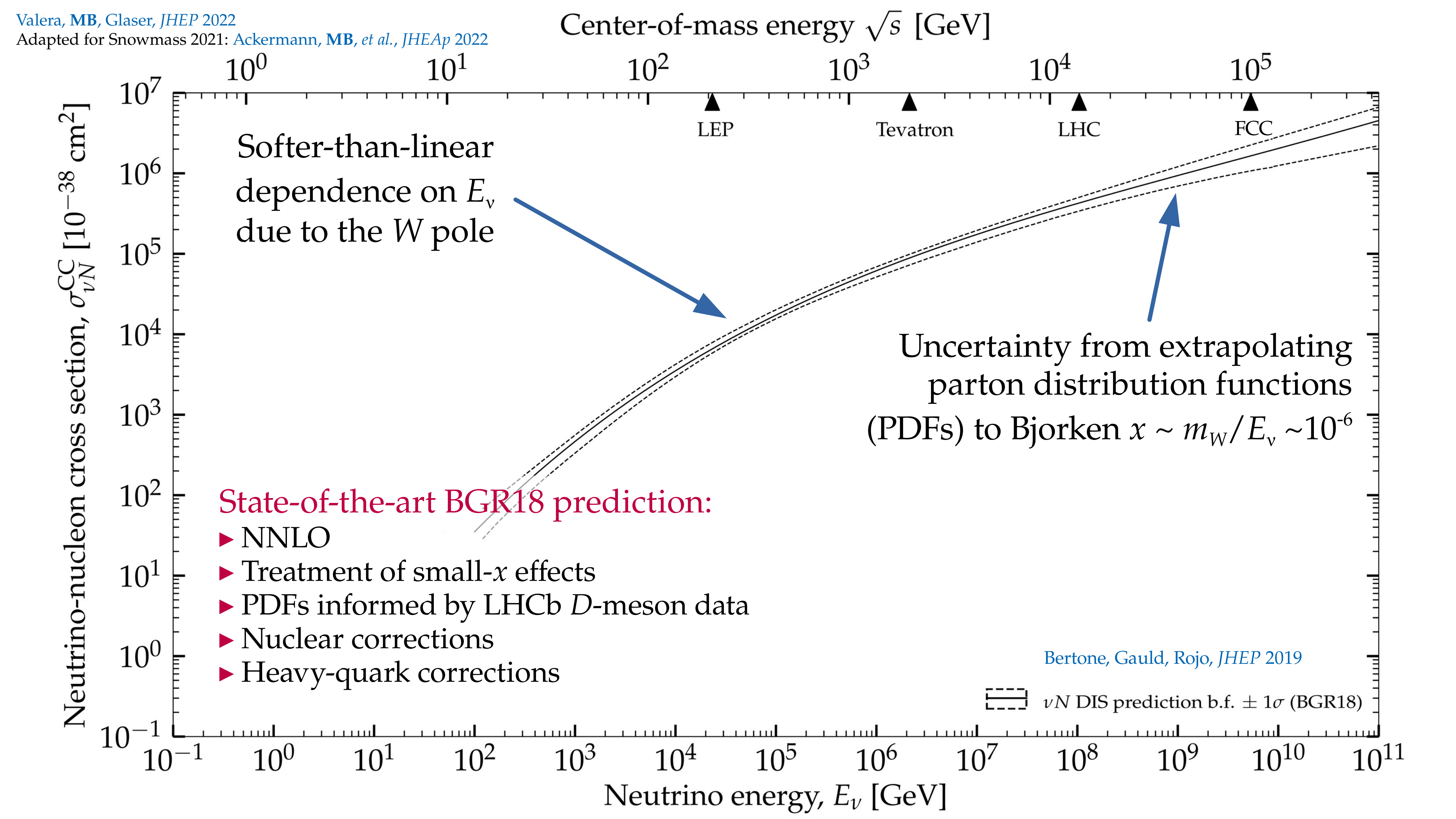
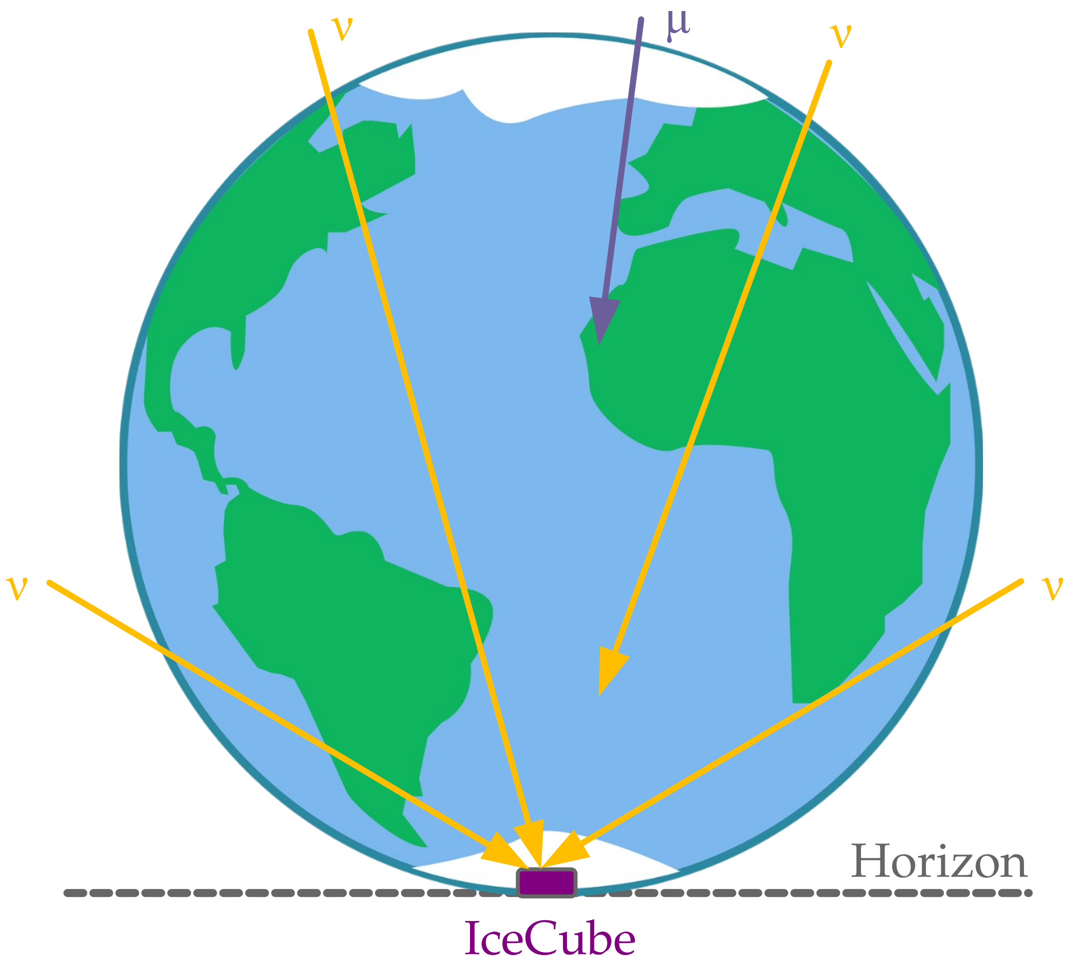
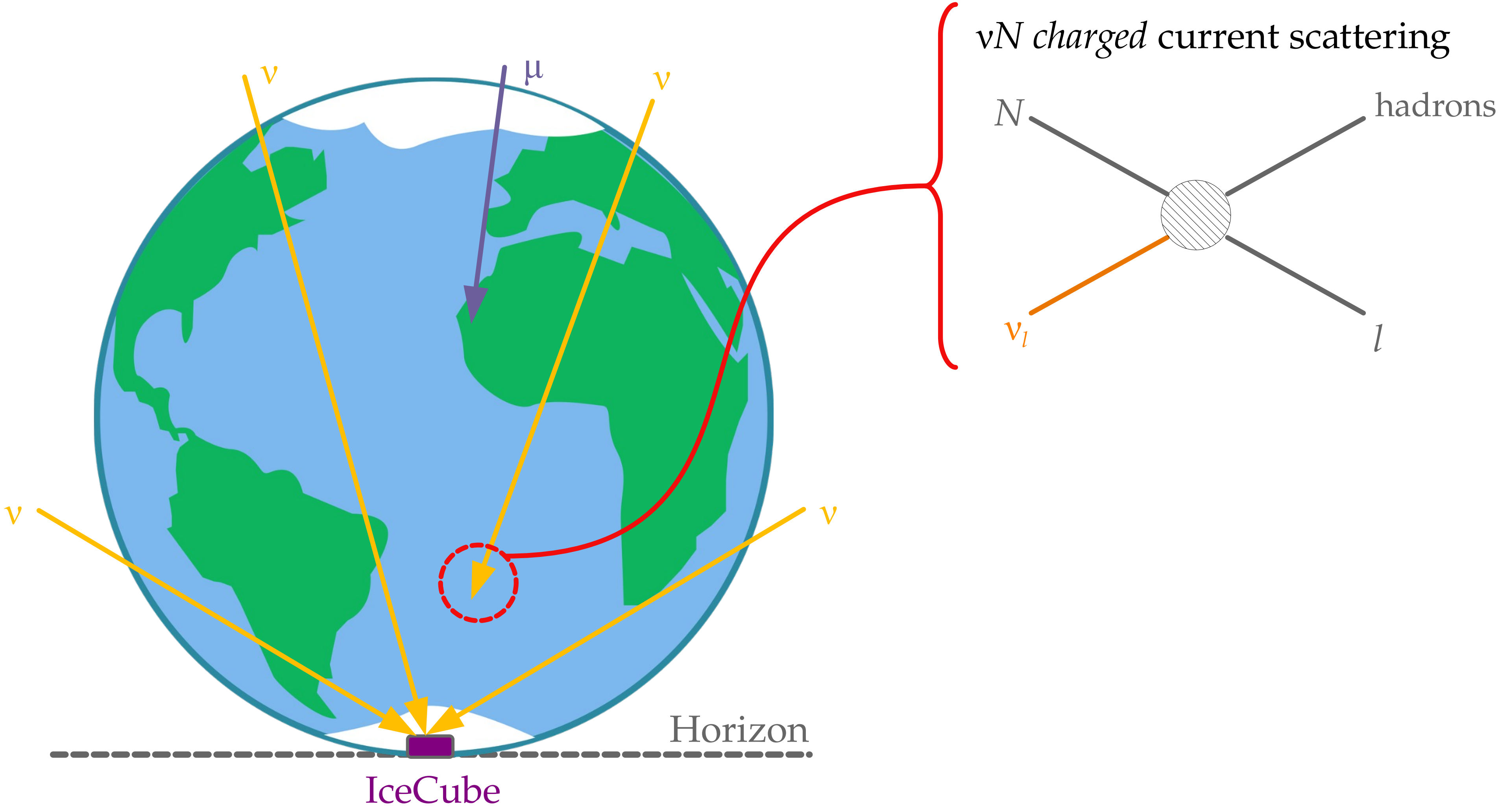
Argüelles, **MB**, Kheirandish, Palomares-Ruiz, Salvadó, Vincent

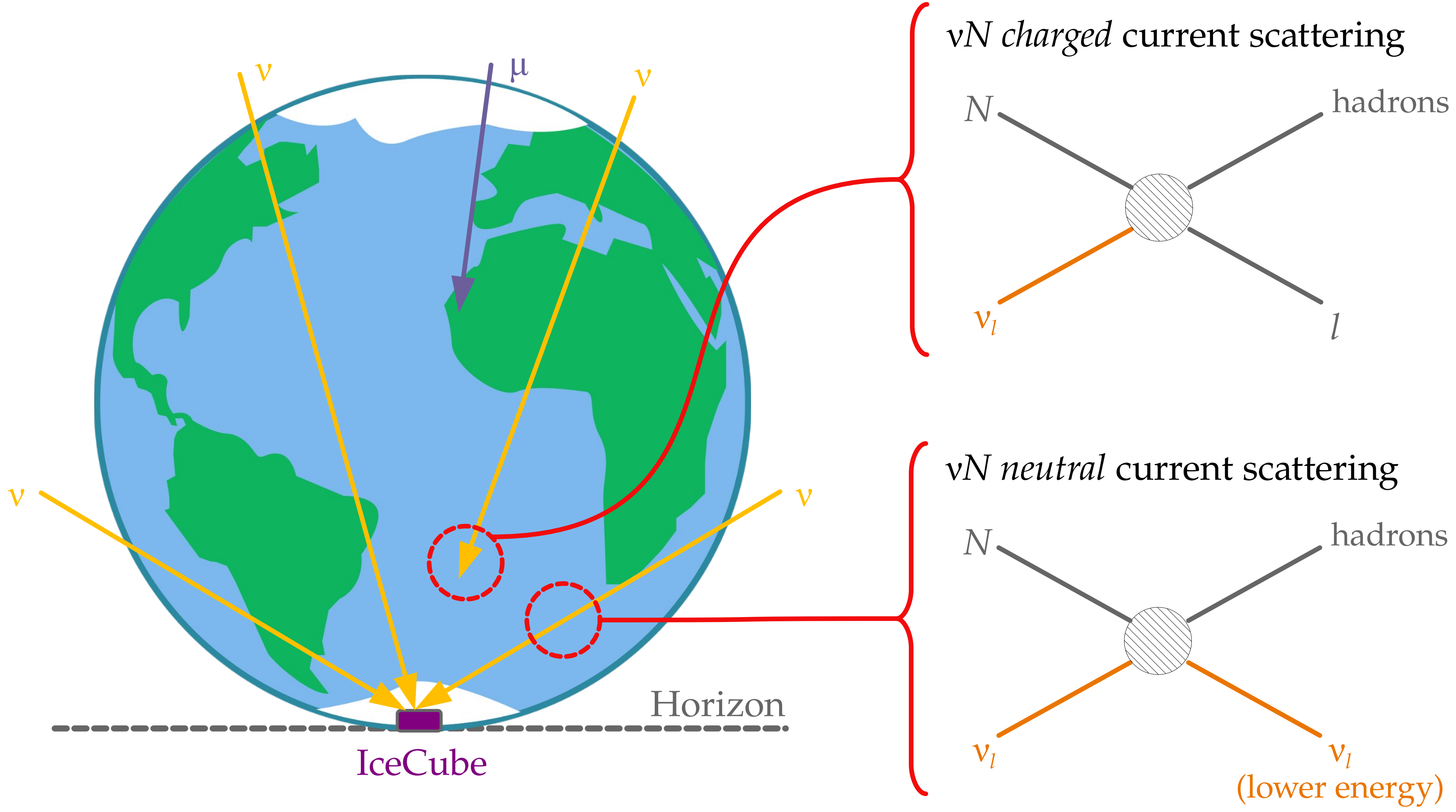
Valera, **MB**, Glaser, *JHEP* 2022
Adapted for Snowmass 2021: Ackermann, **MB**, *et al.*, *JHEAp* 2022



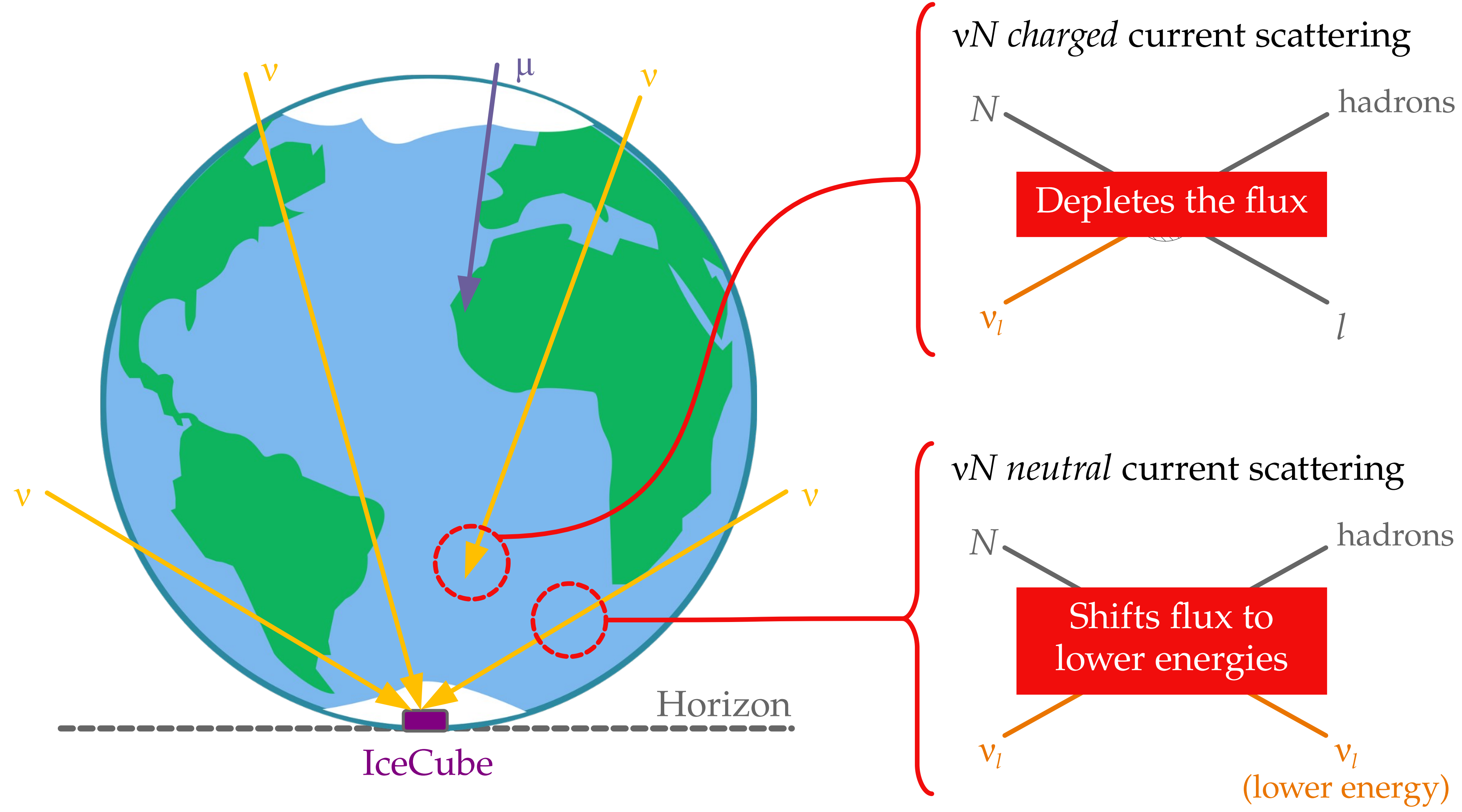

Valera, MB, Glaser, JHEP 2022
Adapted for Snowmass 2021: Ackermann, MB, et al., JHEAp 2022
Center-of-mass energy $\sqrt{s}$ [GeV]
LEP
Tevatron
LHC
FCC
Softer-than-linear dependence on E_ν due to the W pole
Uncertainty from extrapolating parton distribution functions (PDFs) to Bjorken $x \sim m_W/E_\nu \sim 10^{-6}$
State-of-the-art BGR18 prediction:
▸ NNLO
▸ Treatment of small-x effects
▸ PDFs informed by LHCb D-meson data
▸ Nuclear corrections
▸ Heavy-quark corrections
Bertone, Gauld, Rojo, JHEP 2019
νN DIS prediction b.f. $\pm 1\sigma$ (BGR18)
Neutrino-nucleon cross section, $\sigma_{\nu N}^{\rm CC}$ [10^{-38} cm^2]
Neutrino energy, E_ν [GeV]


ν
μ
ν
ν
ν
Horizon
IceCube


νN *charged* current scattering
N
hadrons
ν_l
l
ν
μ
ν
ν
ν
Horizon
IceCube



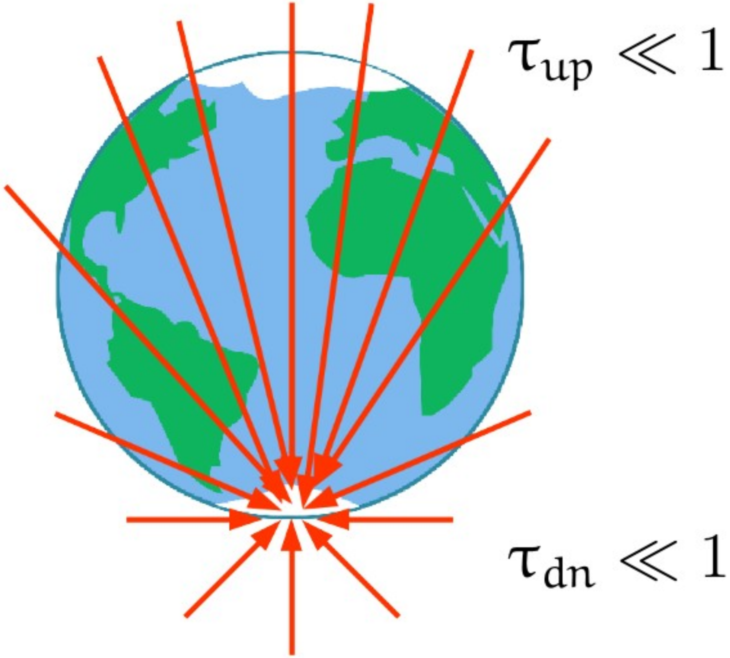
ν
μ
ν
ν
ν
Horizon
IceCube
νN charged current scattering
N
hadrons
ν_l
l
νN neutral current scattering
N
hadrons
ν_l
ν_l
(lower energy)


νN charged current scattering
N
hadrons
Depletes the flux
ν_l
l
νN neutral current scattering
N
hadrons
Shifts flux to
lower energies
ν_l
ν_l
(lower energy)
ν
μ
ν
ν
ν
Horizon
IceCube

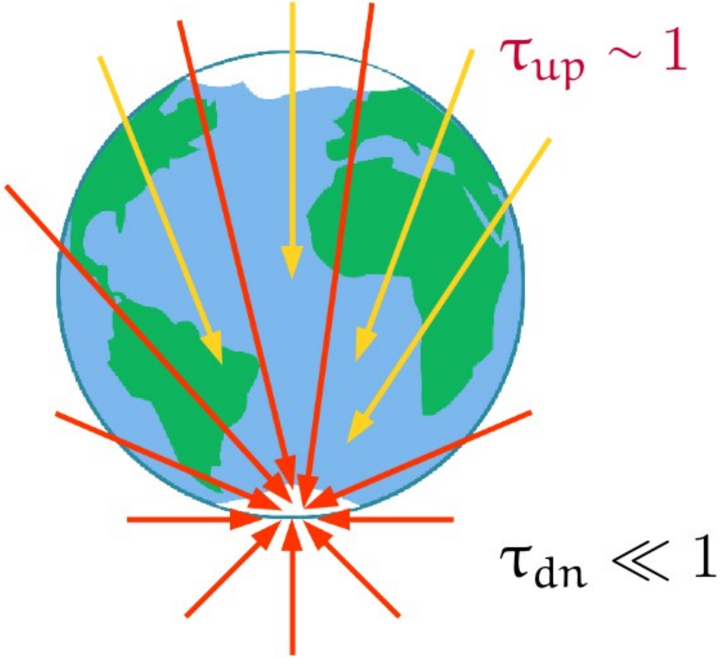
Measuring the high-energy νN cross section

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

Below ~ 10 TeV: Earth is transparent



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

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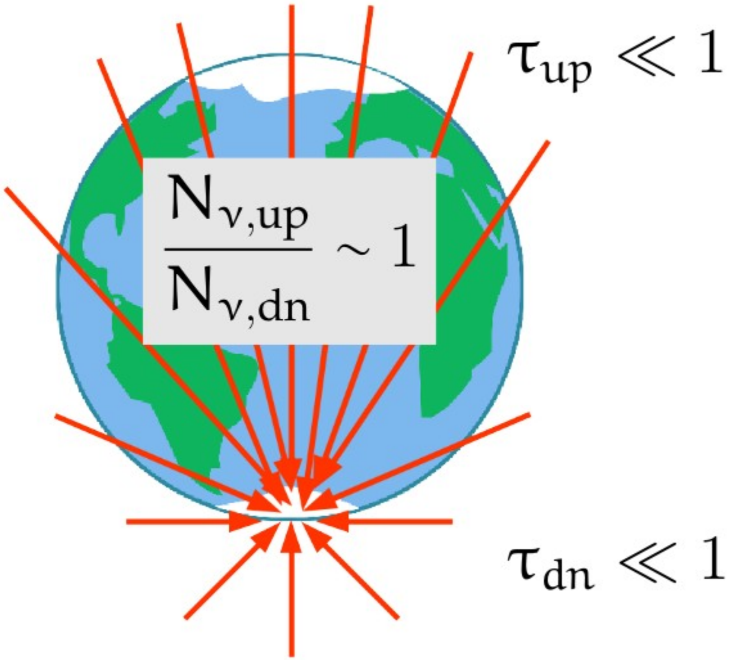

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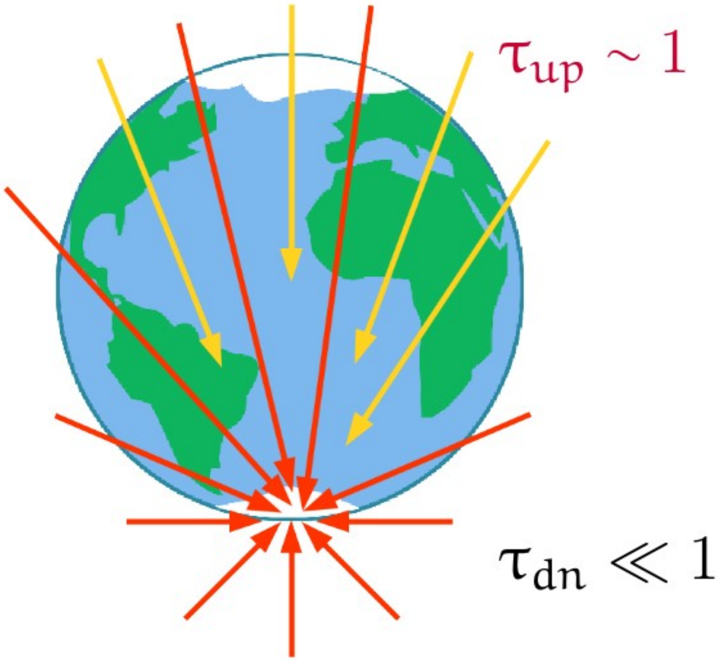

Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
Hussain, Mafatia, McKay, *PRD* 2008 Connolly, Thorne, Waters, *PRD* 2011; Marfatia, McKay, Weiler, *PLB* 2015

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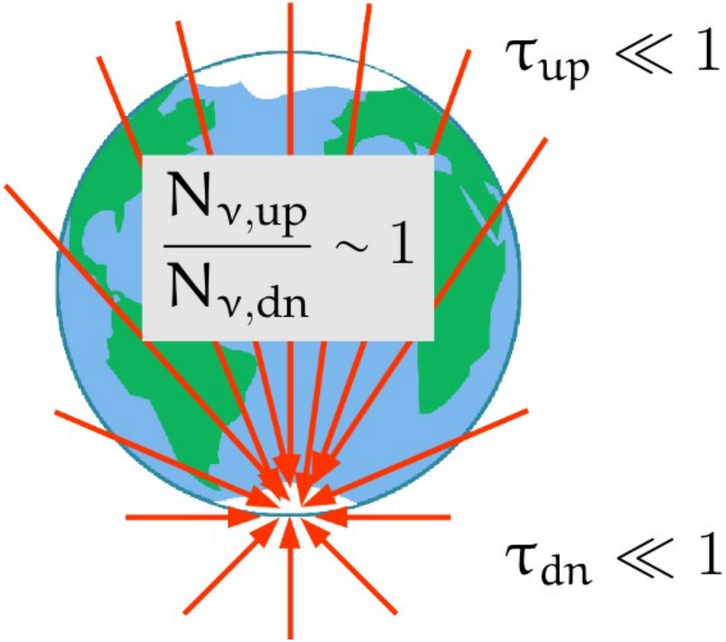

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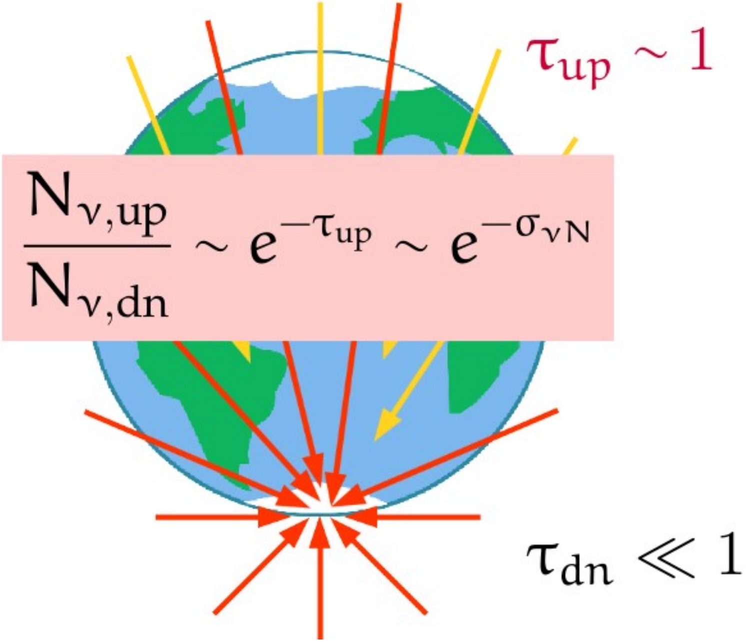
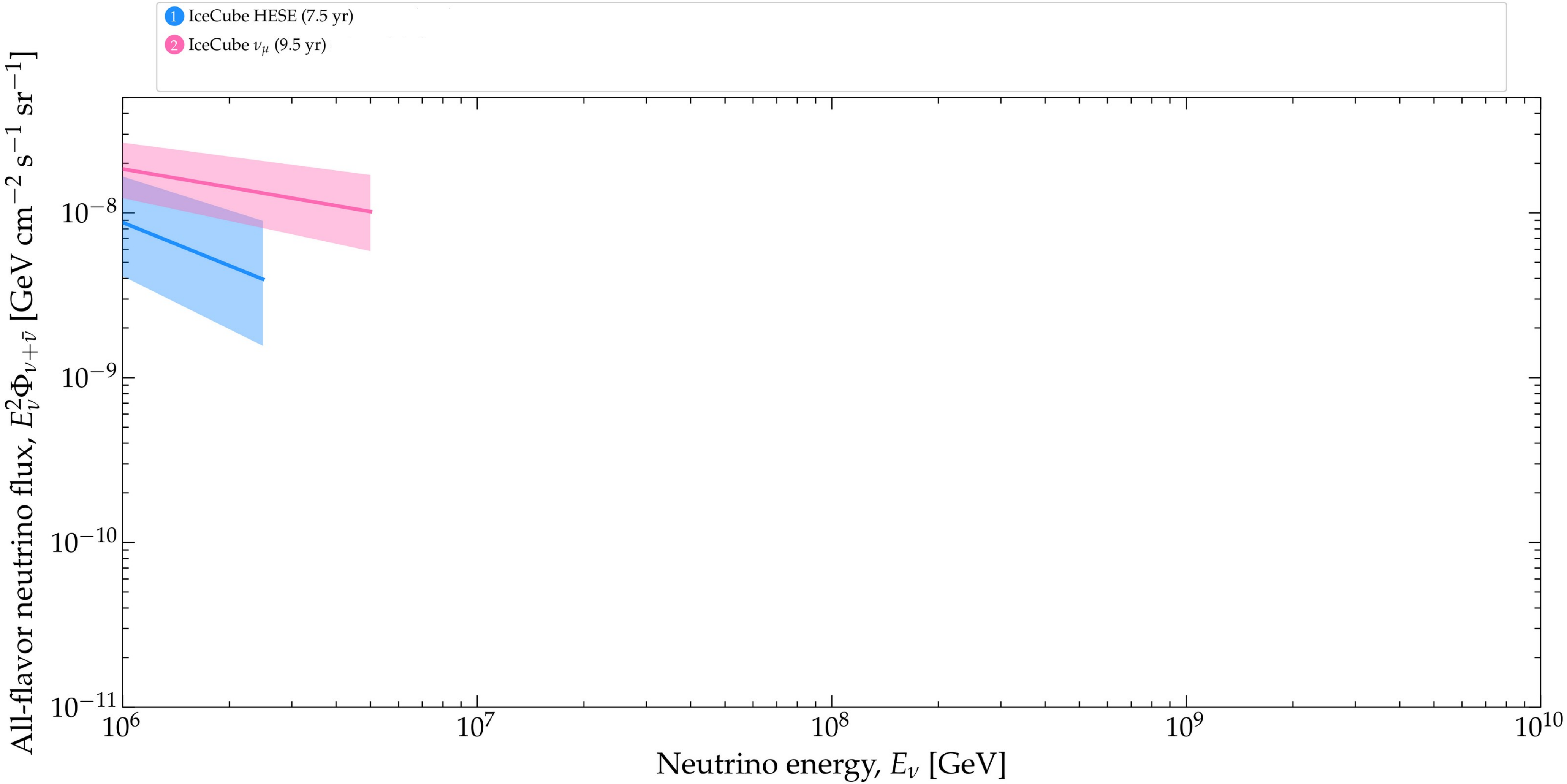
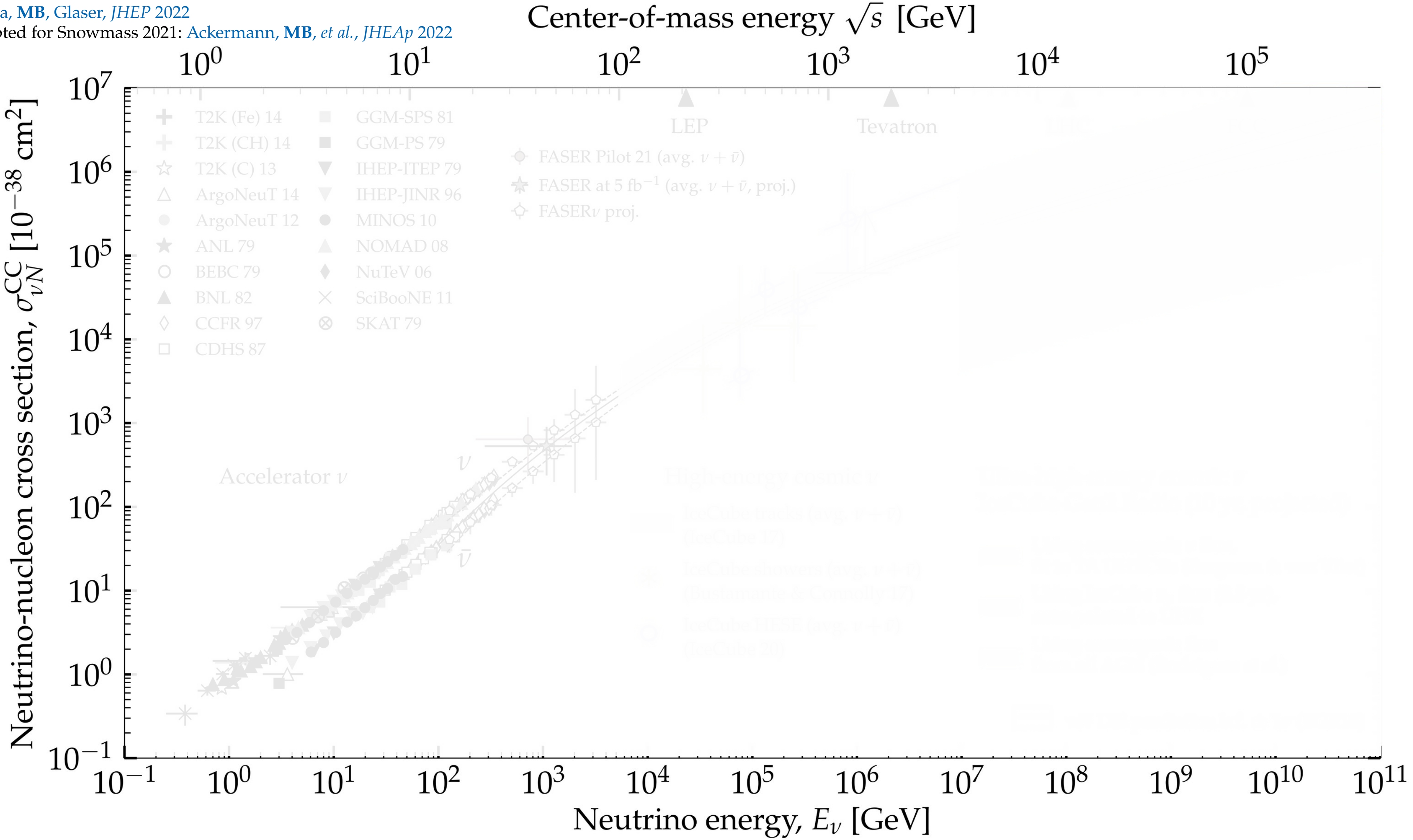


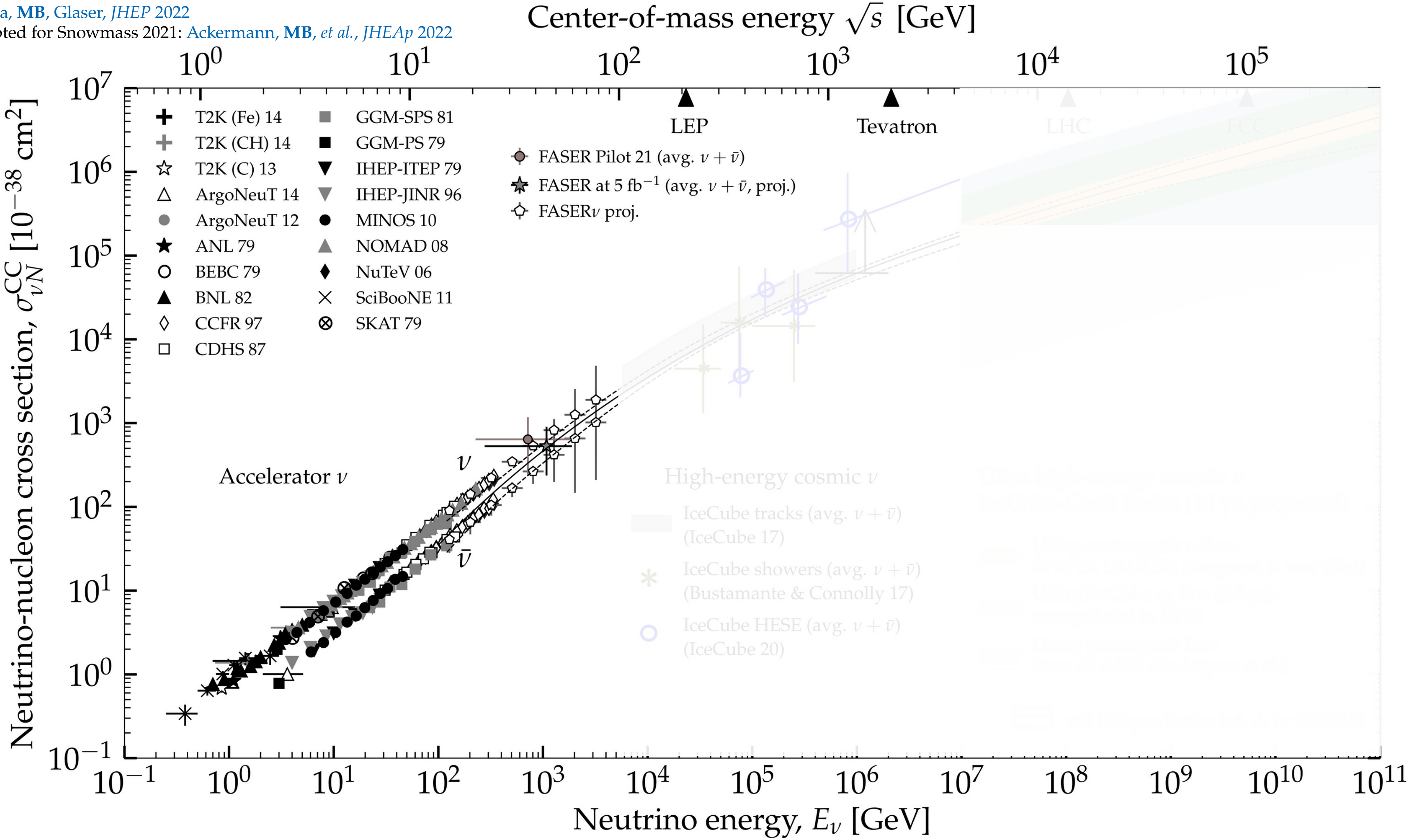
Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
Hussain, Mafatia, McKay, *PRD* 2008 Connolly, Thorne, Waters, *PRD* 2011; Marfatia, McKay, Weiler, *PLB* 2015


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

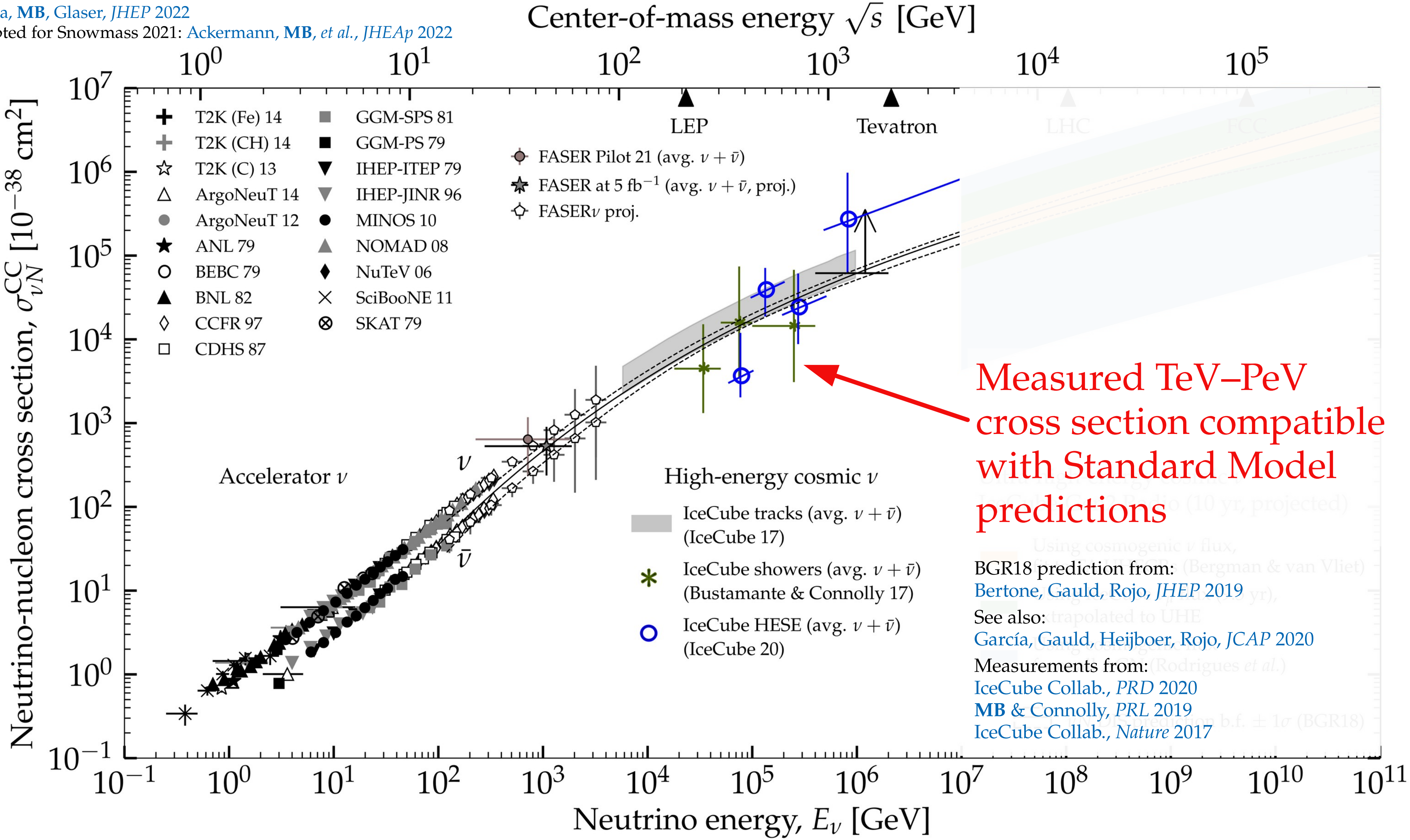
Valera, **MB**, Glaser, *JHEP* 2022
Adapted for Snowmass 2021: Ackermann, **MB**, *et al.*, *JHEAp* 2022



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



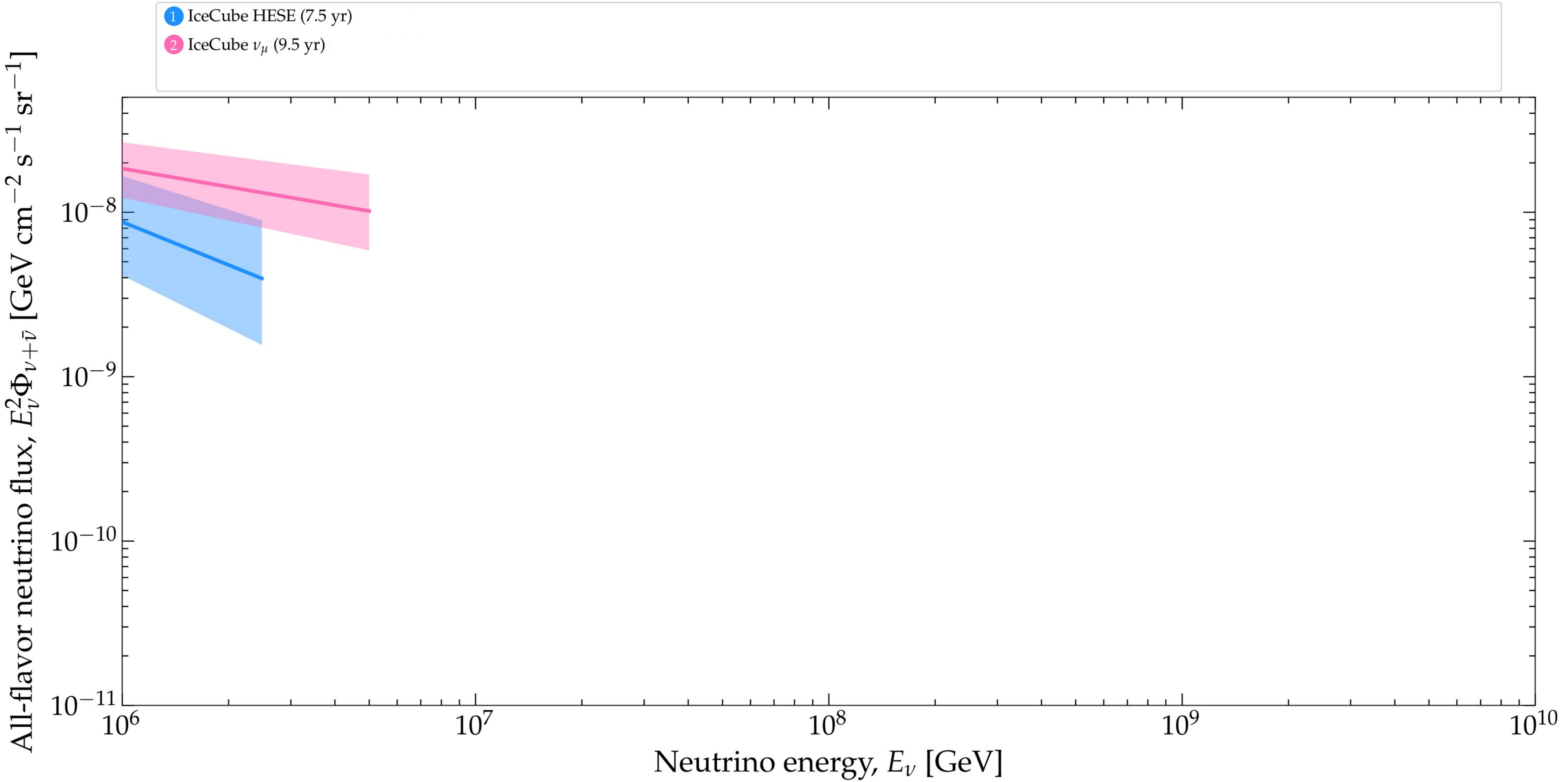
Valera, **MB**, Glaser, *JHEP* 2022
Adapted for Snowmass 2021: Ackermann, **MB**, *et al.*, *JHEAp* 2022



Measured TeV–PeV cross section compatible with Standard Model predictions

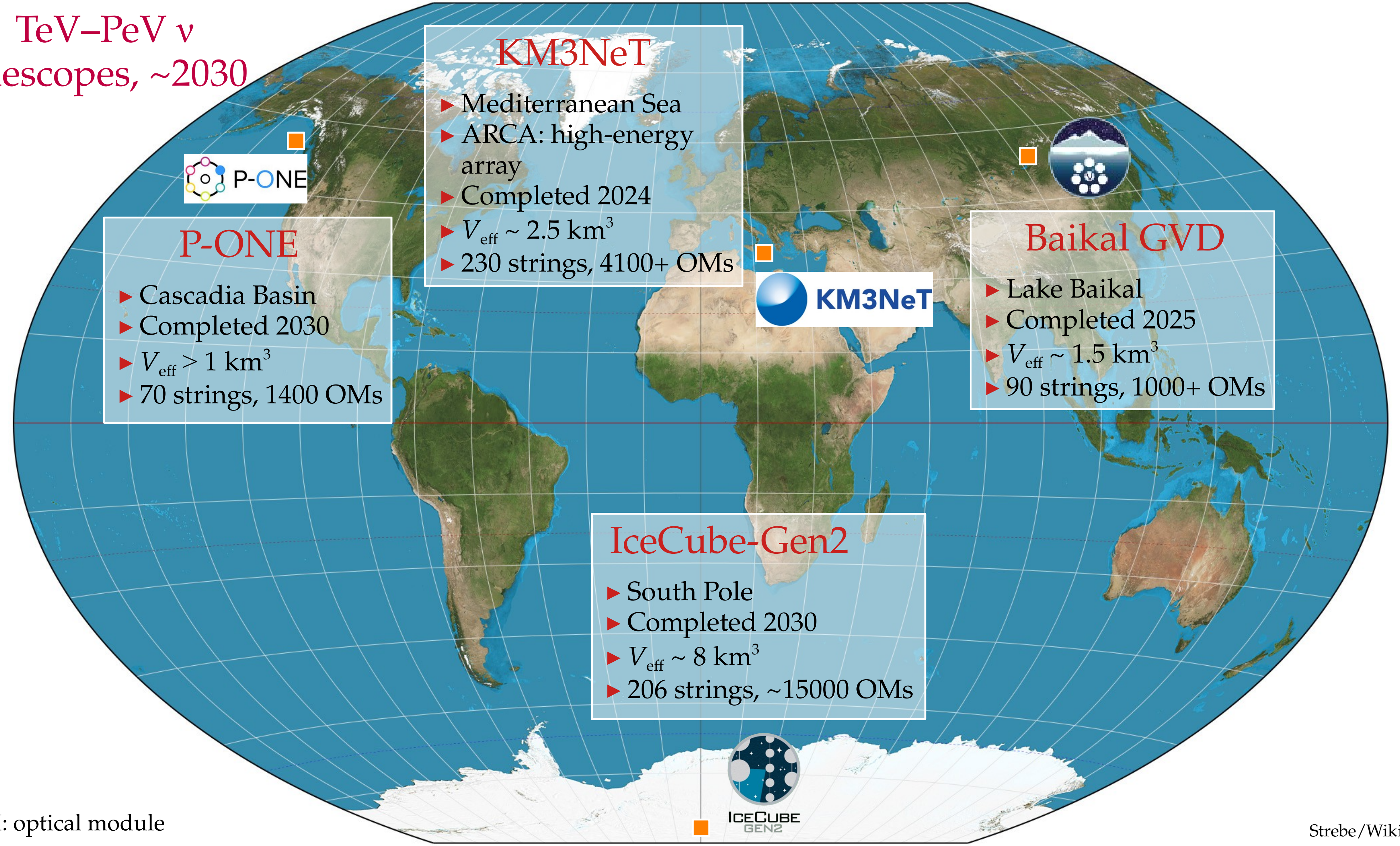
BGR18 prediction from:
Bertone, Gauld, Rojo, *JHEP* 2019
See also:
García, Gauld, Heijboer, Rojo, *JCAP* 2020
Measurements from:
IceCube Collab., *PRD* 2020
MB & Connolly, *PRL* 2019
IceCube Collab., *Nature* 2017

IV.
The future



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

TeV–PeV ν telescopes, ~2030



KM3NeT

- Mediterranean Sea
- ARCA: high-energy array
- Completed 2024
- $V_{\mathrm{eff}} \sim 2.5\ \mathrm{km}^3$
- 230 strings, 4100+ OMs

P-ONE

- Cascadia Basin
- Completed 2030
- $V_{\mathrm{eff}} > 1\ \mathrm{km}^3$
- 70 strings, 1400 OMs

Baikal GVD

- Lake Baikal
- Completed 2025
- $V_{\mathrm{eff}} \sim 1.5\ \mathrm{km}^3$
- 90 strings, 1000+ OMs

IceCube-Gen2

- South Pole
- Completed 2030
- $V_{\mathrm{eff}} \sim 8\ \mathrm{km}^3$
- 206 strings, ~15000 OMs

OM: optical module

Strebe/Wikipedia

TeV–PeV ν telescopes, ~2030

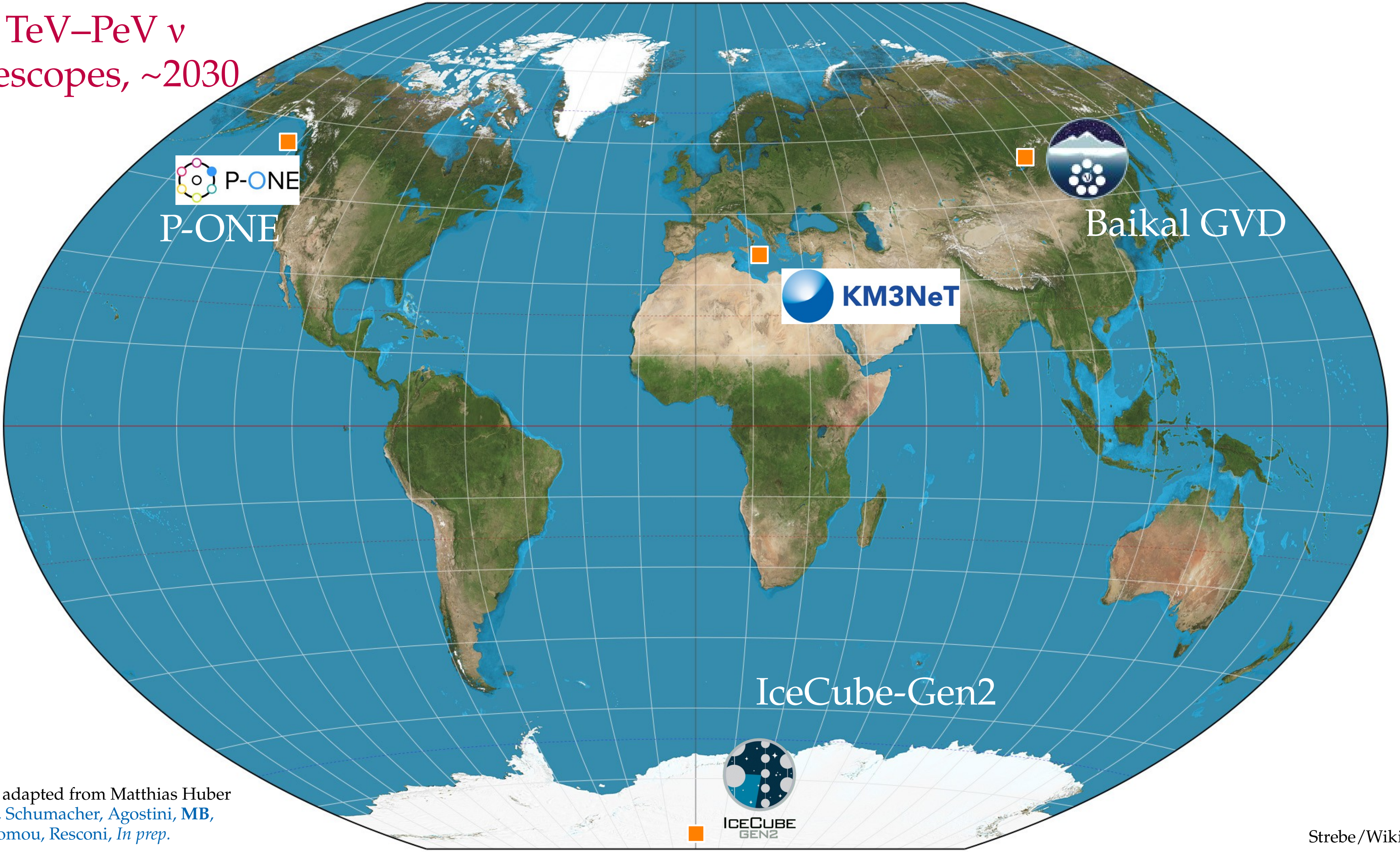


Figure adapted from Matthias Huber
Huber, Schumacher, Agostini, **MB**, Oikonomou, Resconi, *In prep.*

Strebe/Wikipedia

TeV–PeV ν telescopes, ~2030

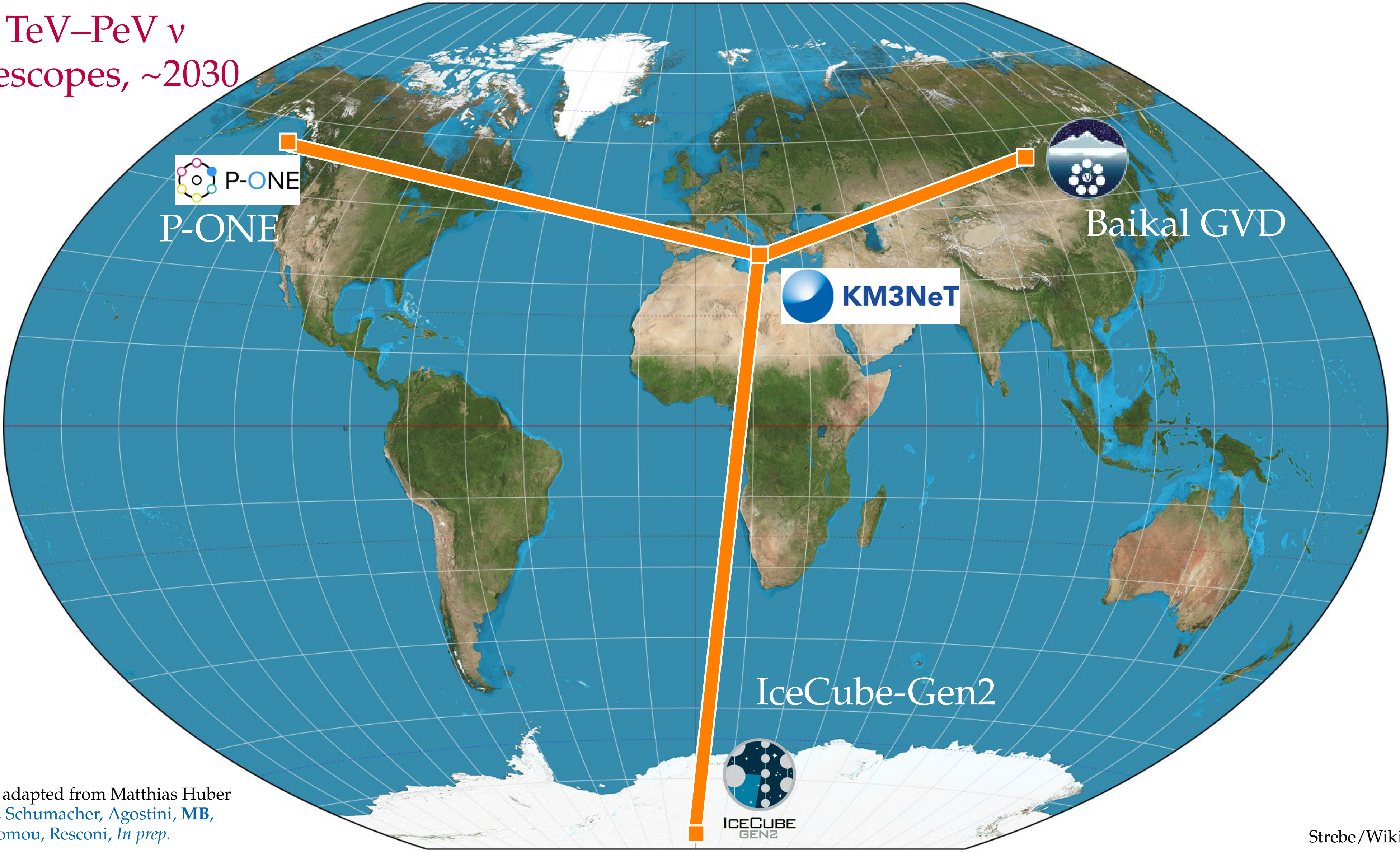
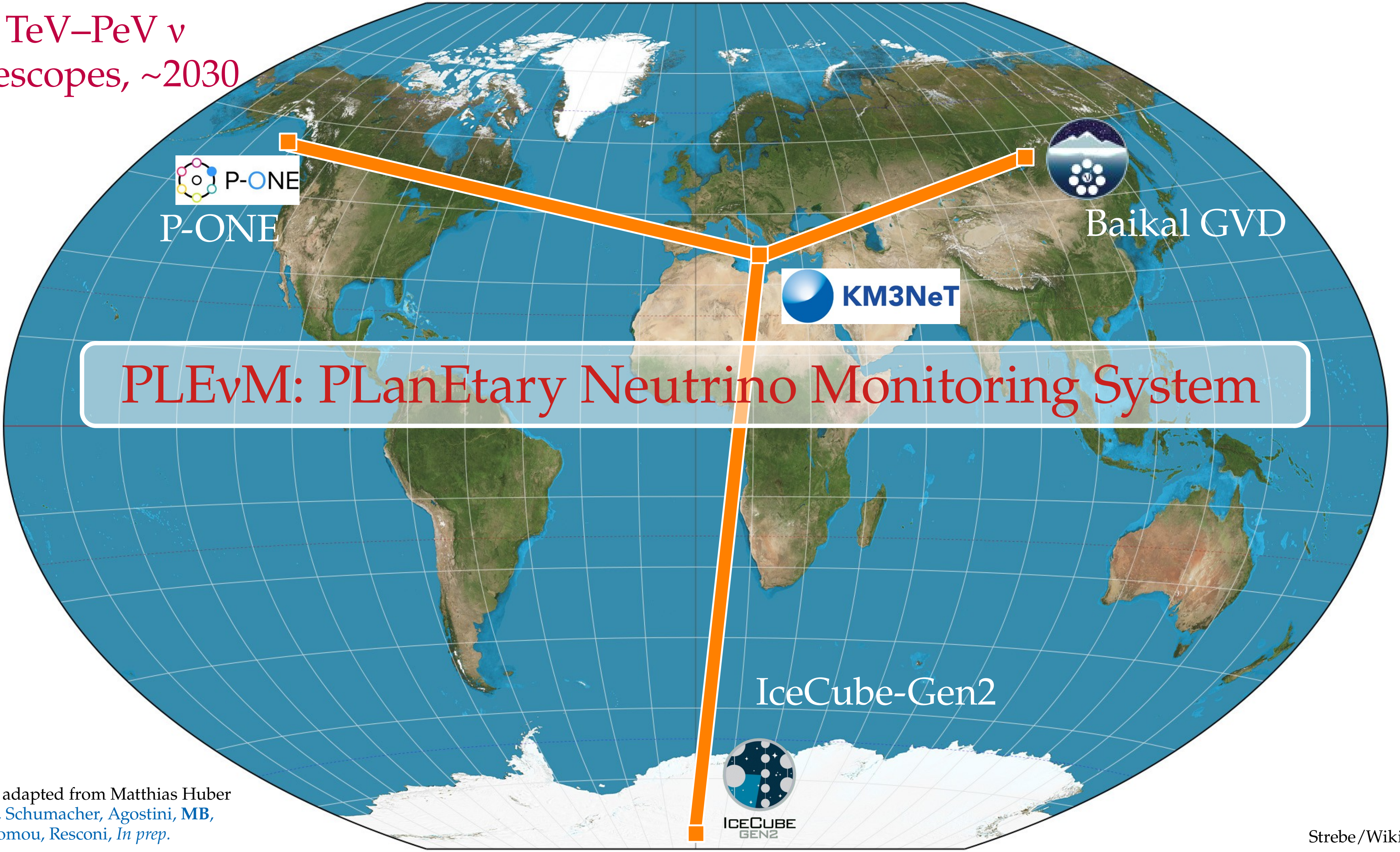


Figure adapted from Matthias Huber
Huber, Schumacher, Agostini, **MB**, Oikonomou, Resconi, *In prep.*

Strebe/Wikipedia

TeV–PeV ν telescopes, ~2030



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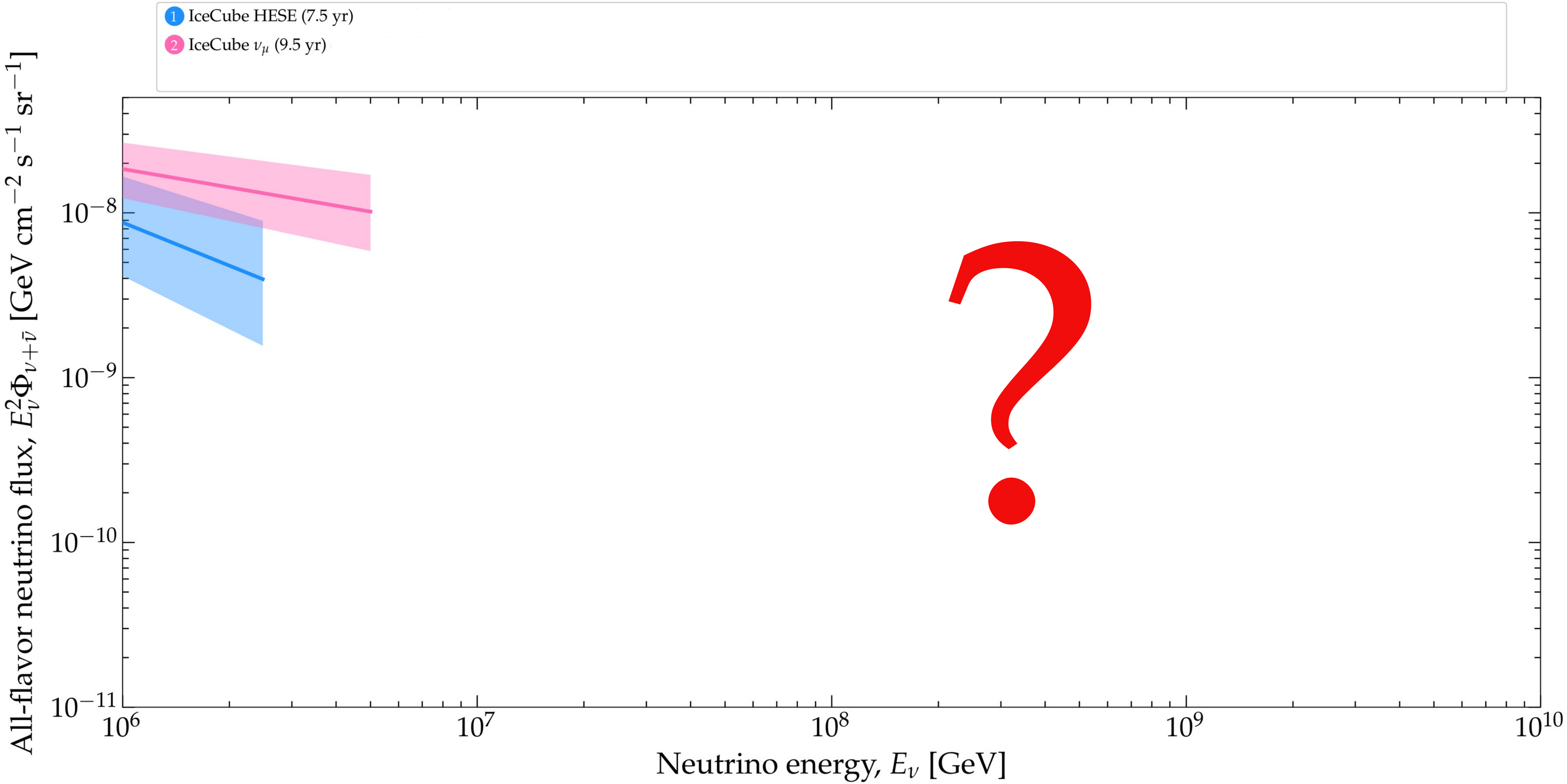
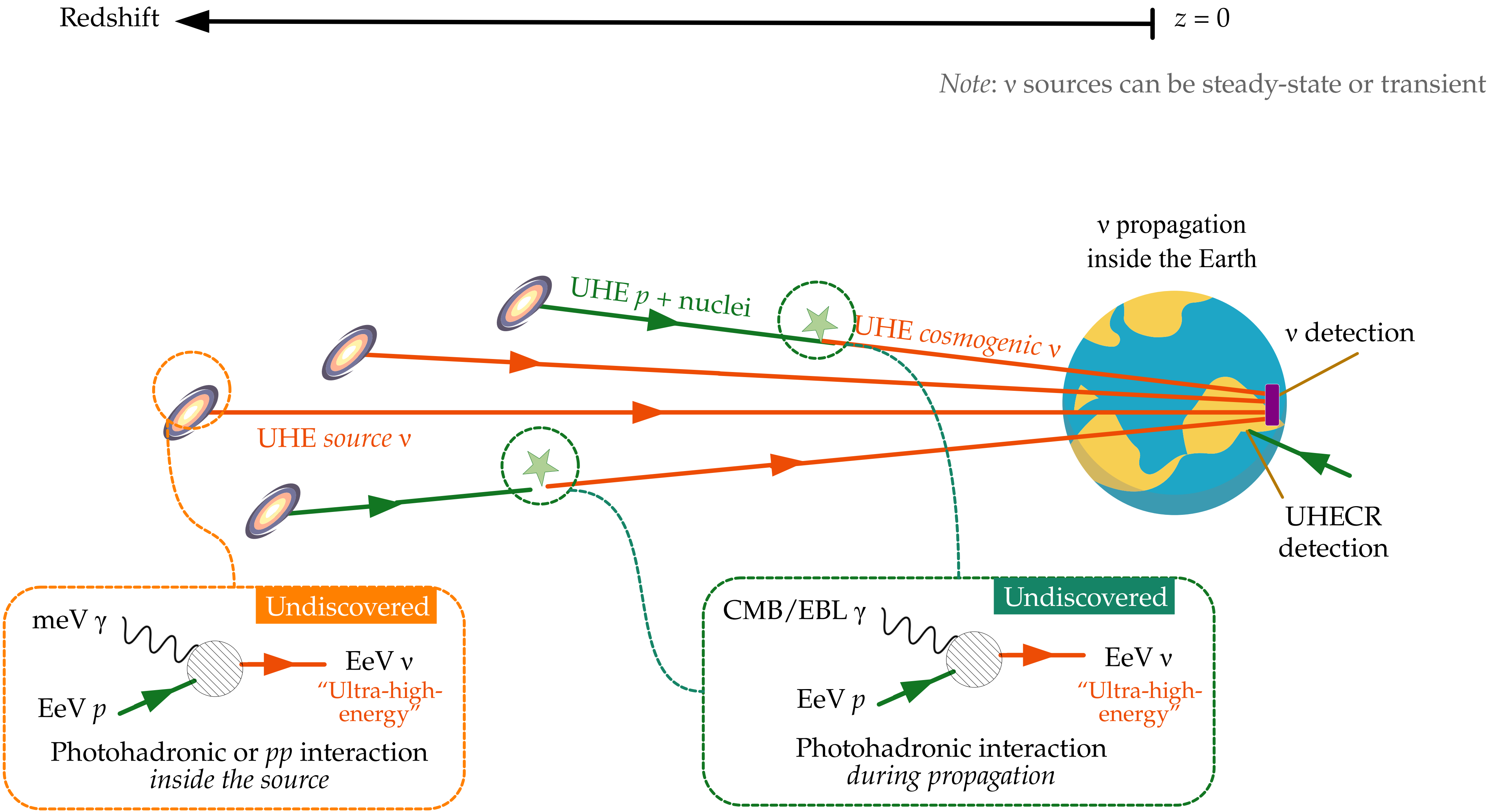
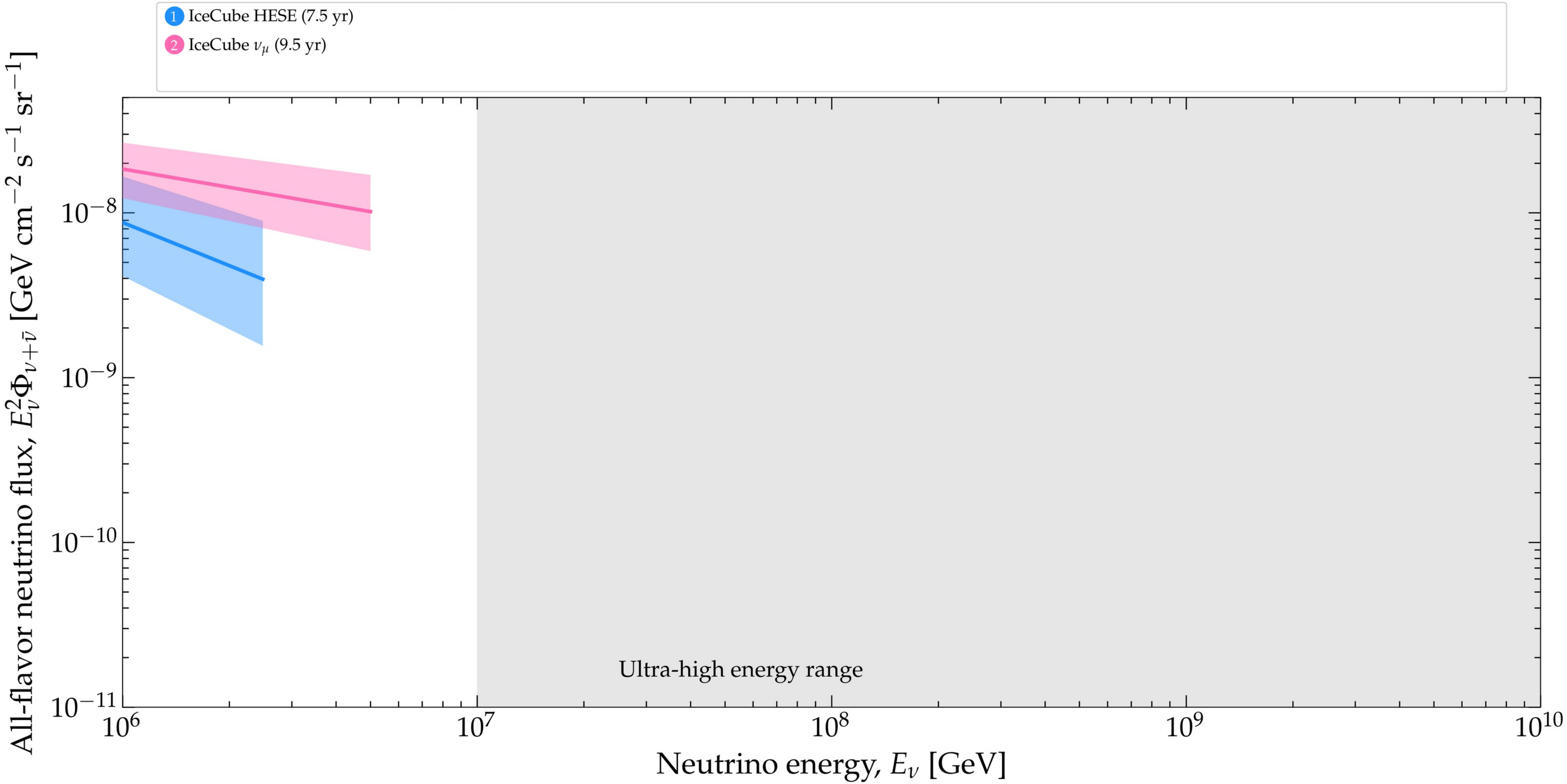


1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (9.5 yr)
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
Neutrino energy, E_ν [GeV]
?


Redshift
$z = 0$
Note: ν sources can be steady-state or transient
ν propagation inside the Earth
UHE p + nuclei
UHE *cosmogenic* ν
ν detection
UHE *source* ν
UHECR detection
Undiscovered
meV γ
EeV ν
"Ultra-high-energy"
EeV p
Photohadronic or pp interaction *inside the source*
Undiscovered
CMB/EBL γ
EeV ν
"Ultra-high-energy"
EeV p
Photohadronic interaction *during propagation*



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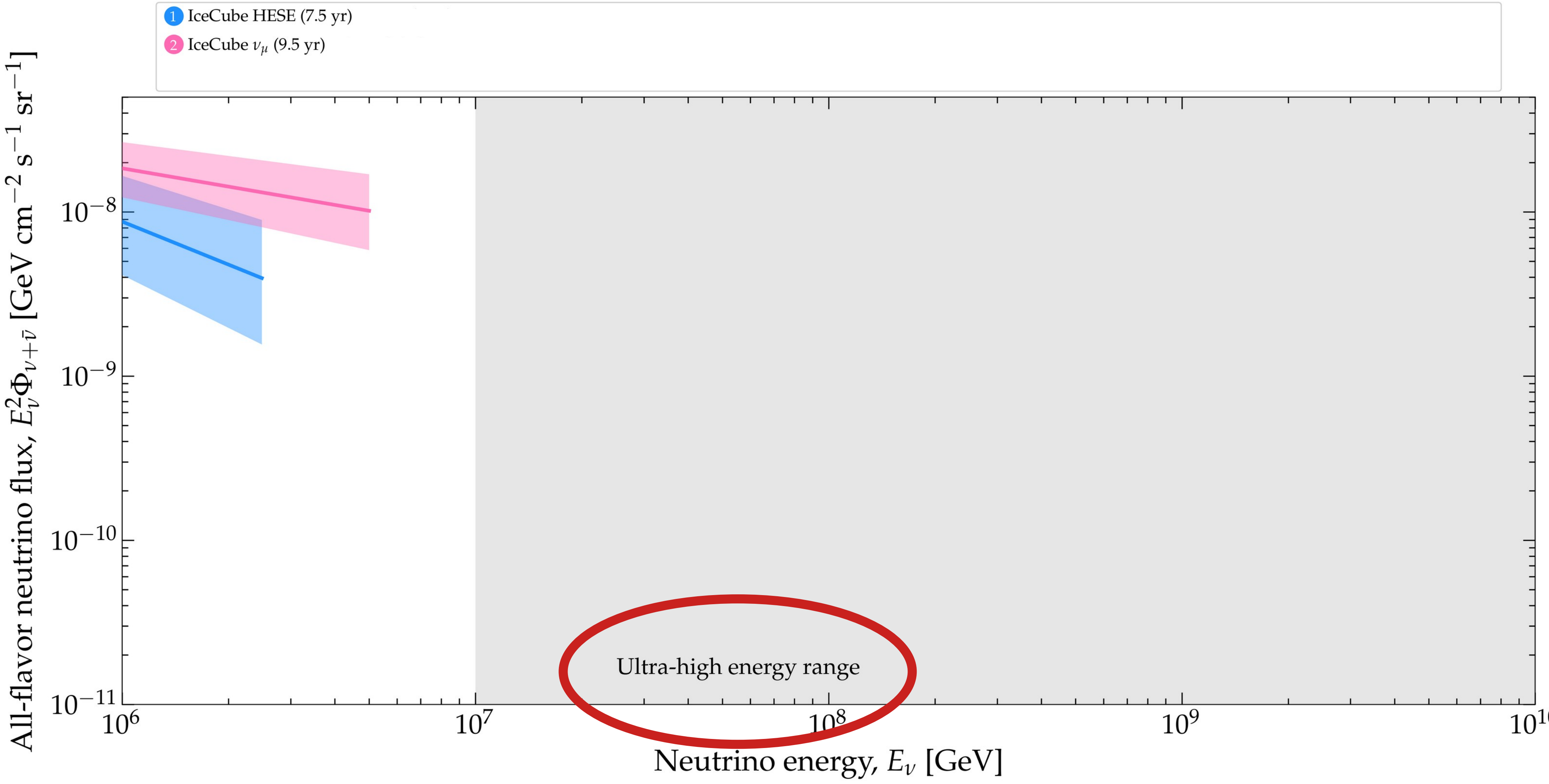
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Ultra-high energy range
Neutrino energy, E_ν [GeV]



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All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
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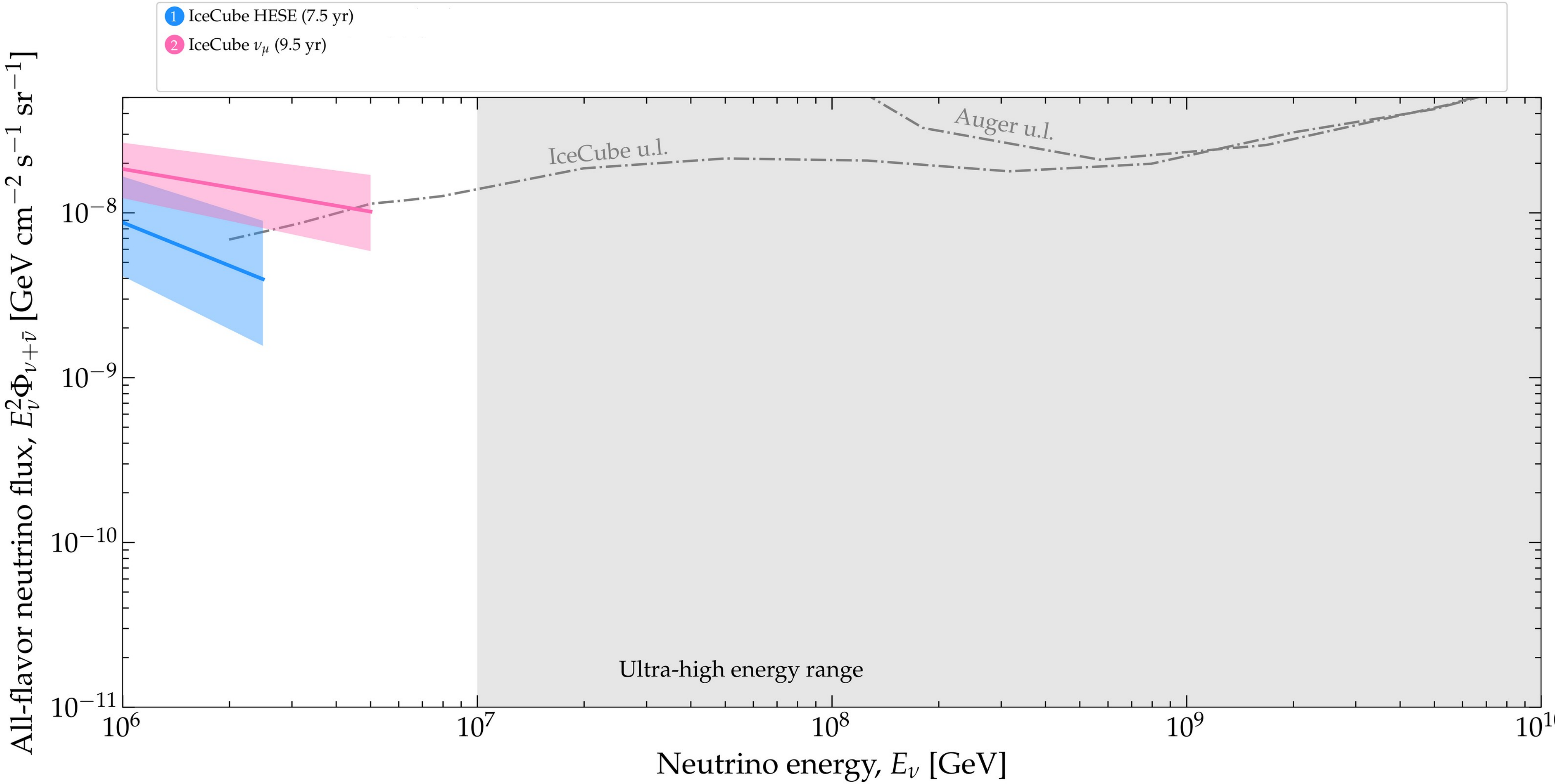
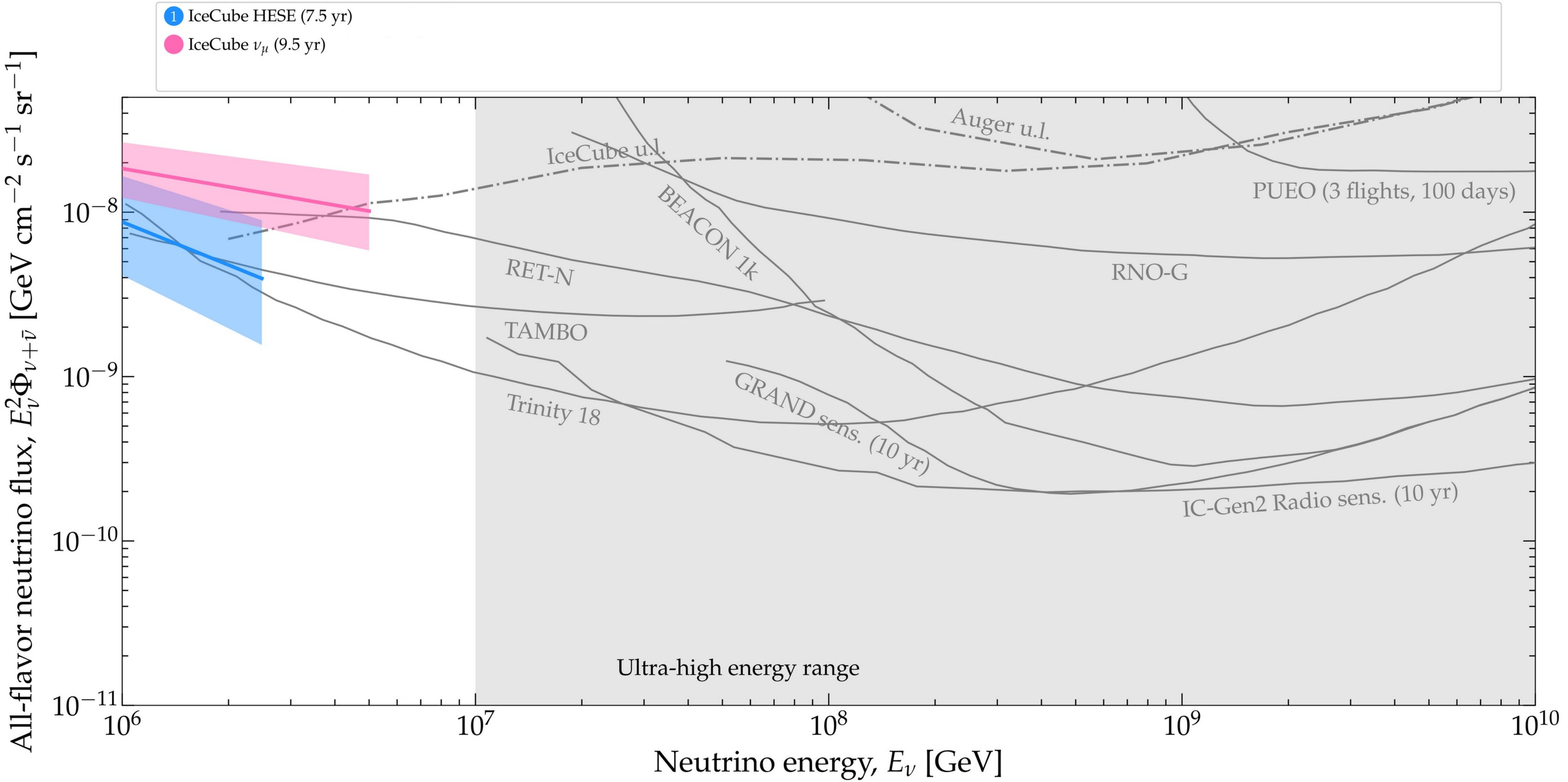
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Ultra-high energy range
Neutrino energy, E_ν [GeV]


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



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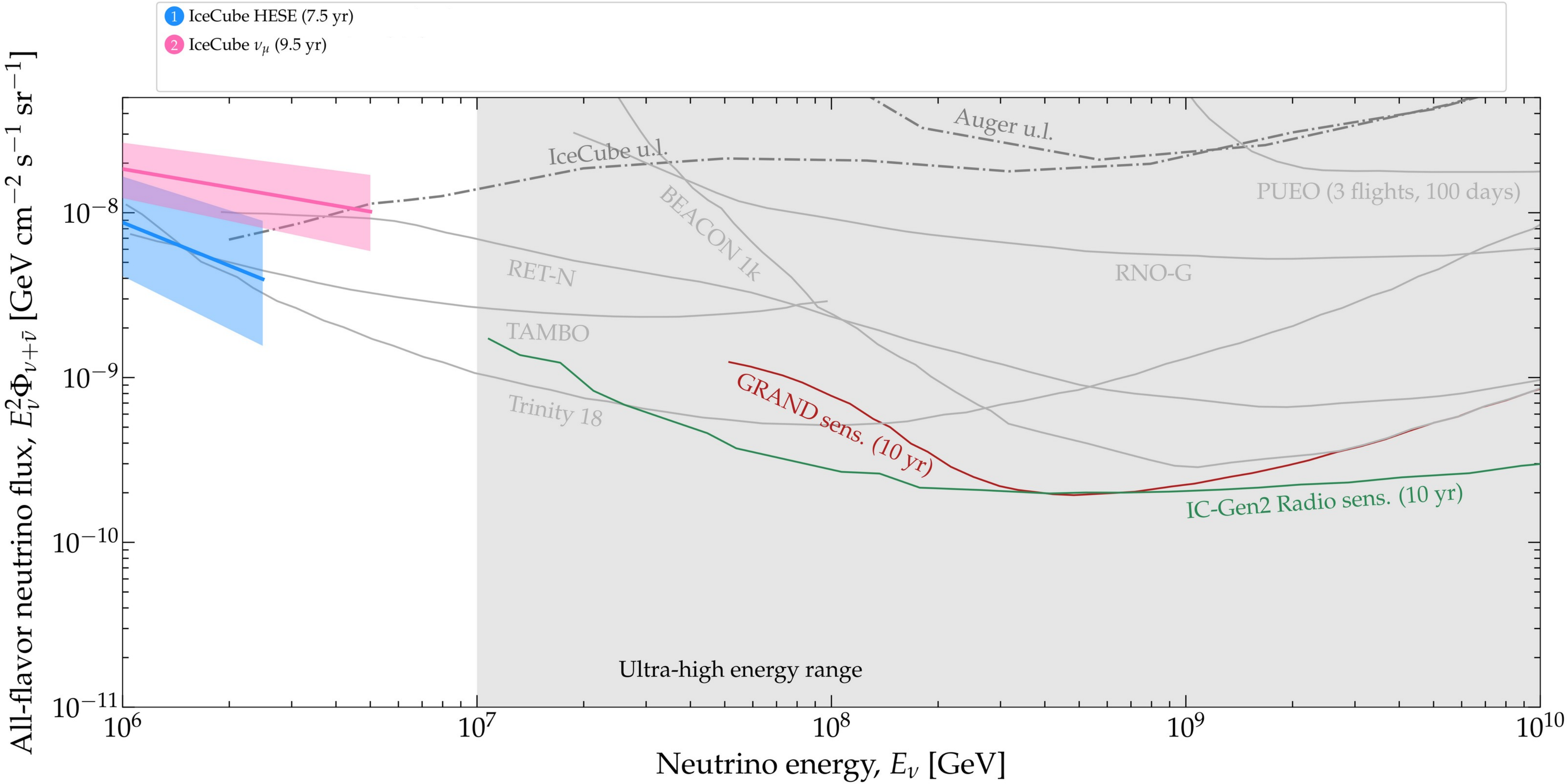
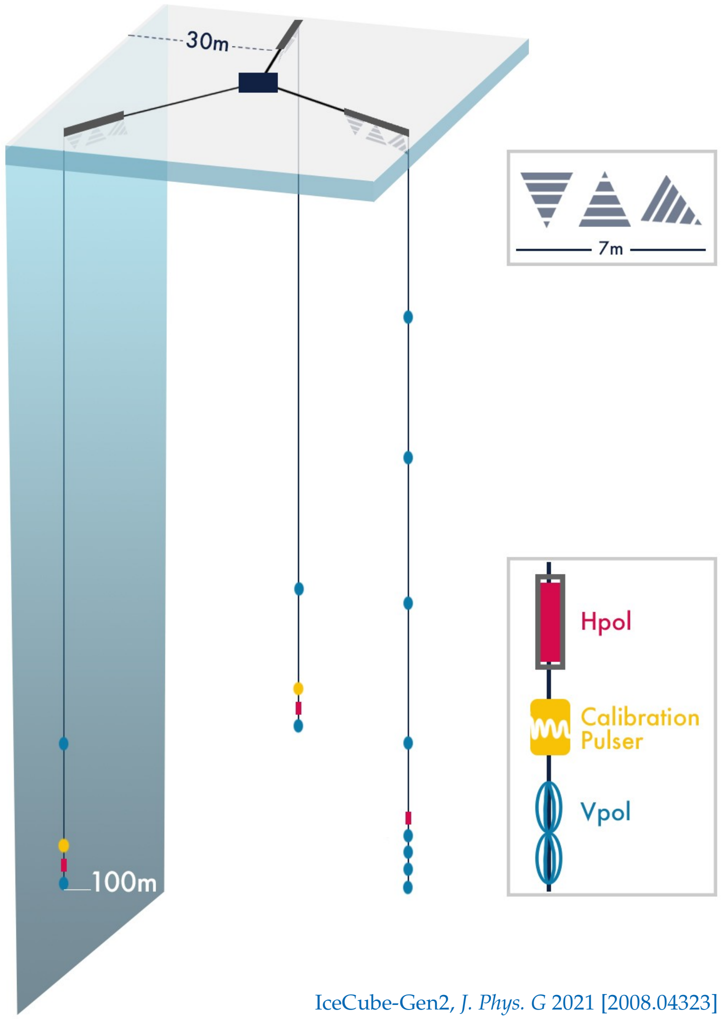
IceCube ν_μ (9.5 yr)
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
Auger u.l.
IceCube u.l.
PUEO (3 flights, 100 days)
BEACON 1k
RET-N
RNO-G
TAMBO
GRAND sens. (10 yr)
Trinity 18
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range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

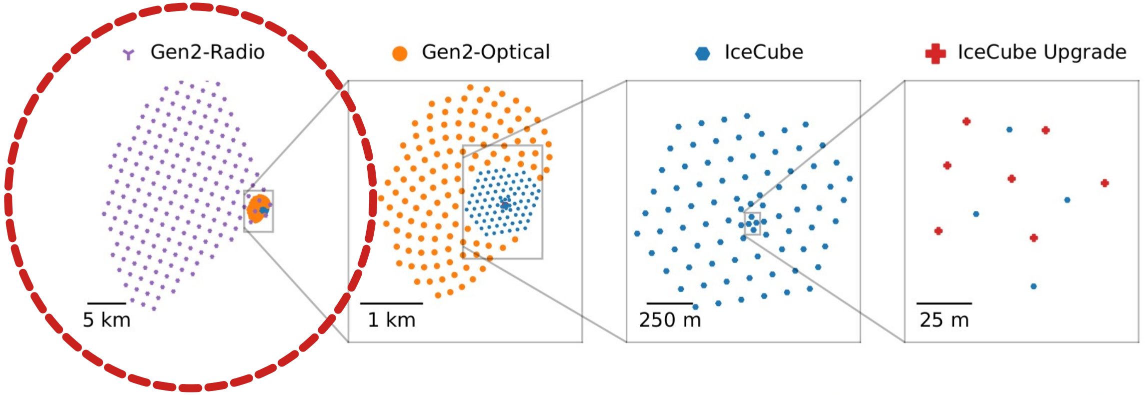


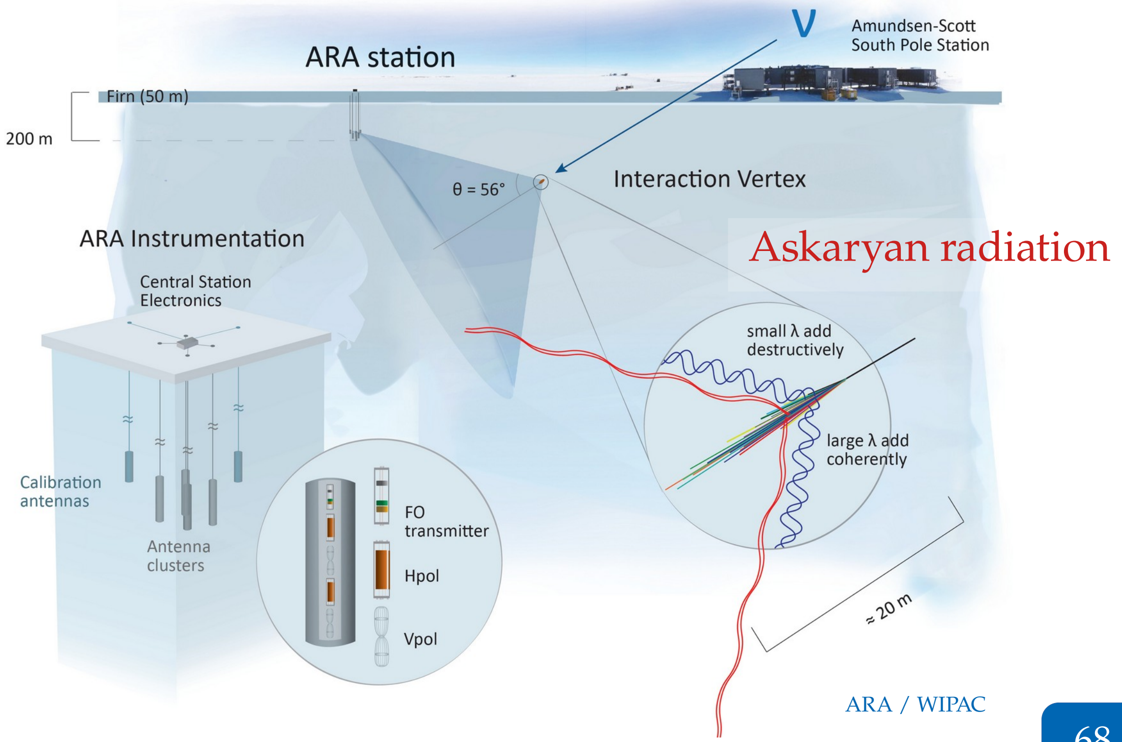
IceCube HESE (7.5 yr)
IceCube ν_μ (9.5 yr)
Auger u.l.
IceCube u.l.
PUEO (3 flights, 100 days)
BEACON 1k
RET-N
RNO-G
TAMBO
GRAND sens. (10 yr)
Trinity 18
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy,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

IceCube-Gen2 Radio

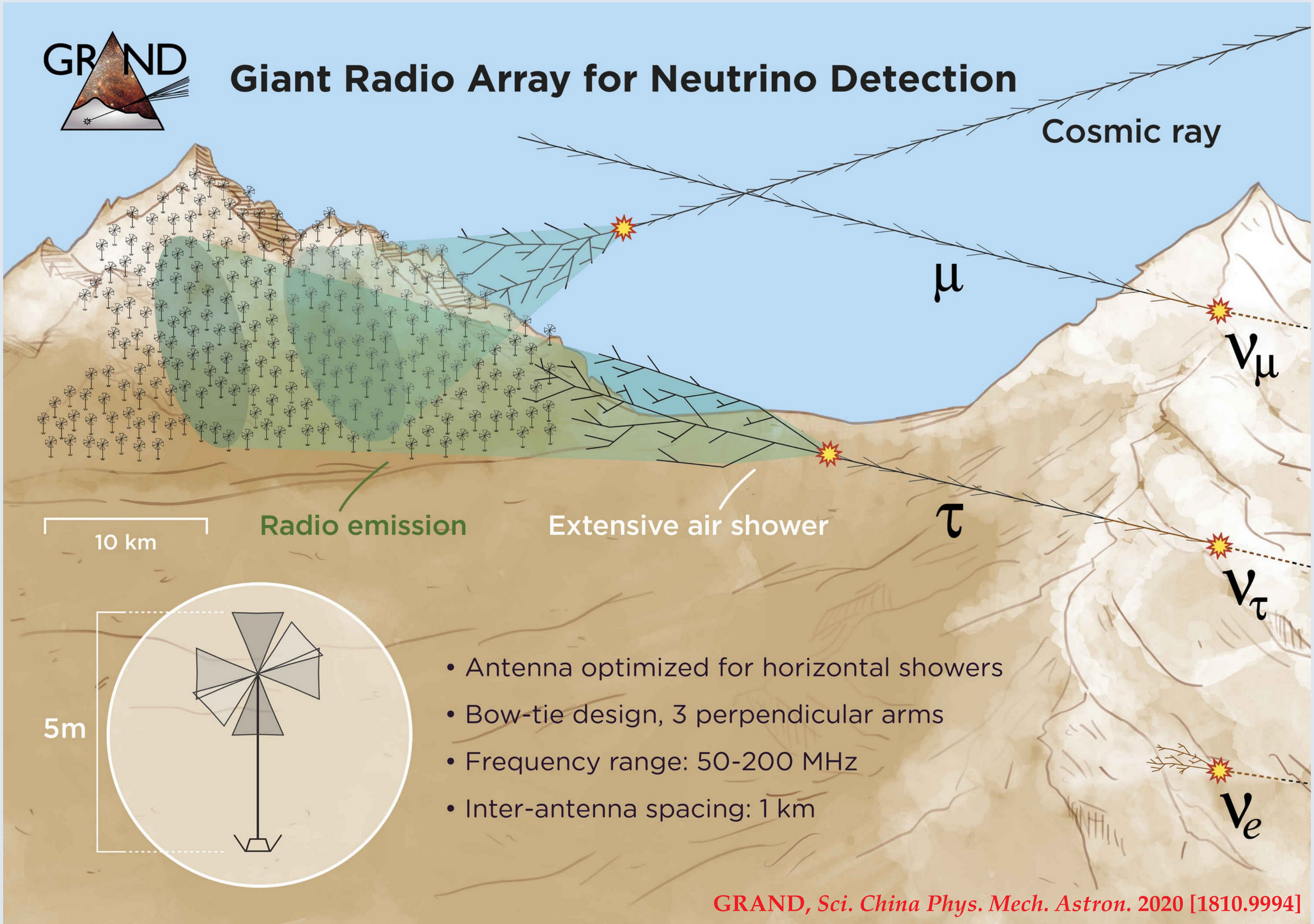


IceCube-Gen2, *J. Phys. G* 2021 [2008.04323]





ARA / WIPAC


GRAND
Giant Radio Array for Neutrino Detection
Cosmic ray
μ
ν_μ
τ
ν_τ
ν_e
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
GRAND, *Sci. China Phys. Mech. Astron.* 2020 [1810.9994]

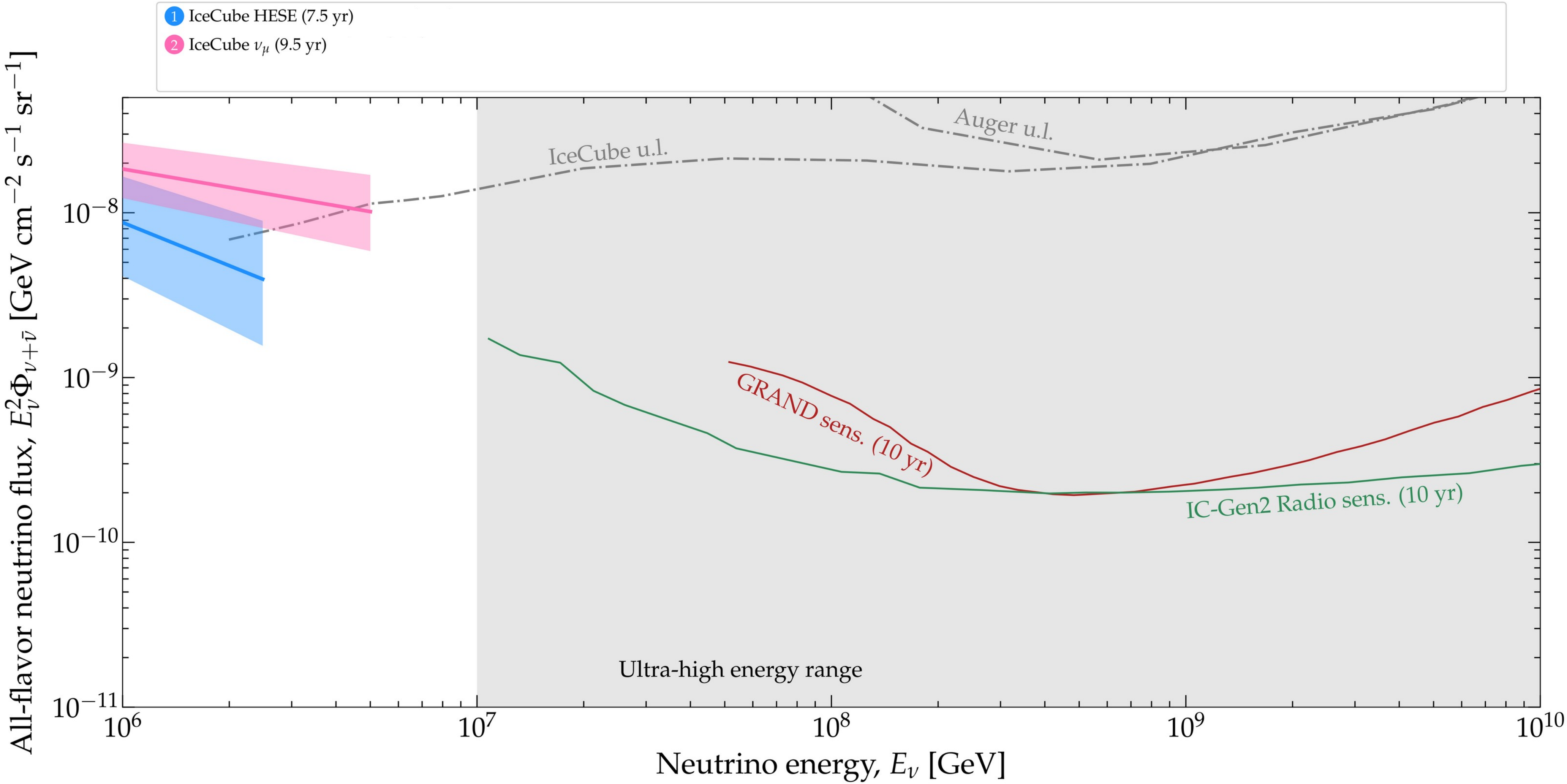
GRANDProto300@China

GRAND@Nançay

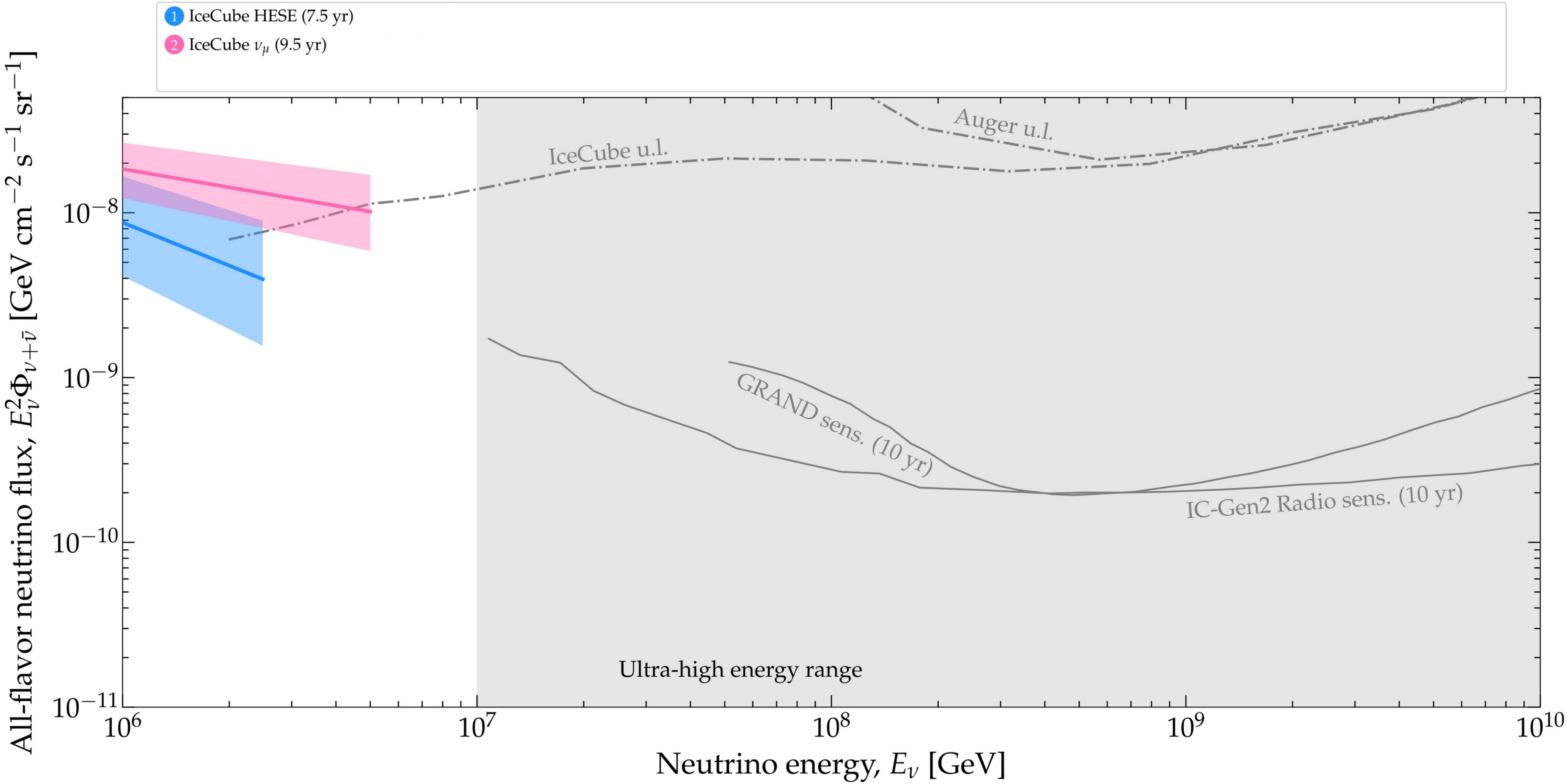
GRAND@Auger

Local development at IAP and LPNHE!

GRAND, *Sci. China Phys. Mech. Astron.* 2020 [1810.9994]



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



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Auger u.l.
IceCube u.l.
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10^{9}
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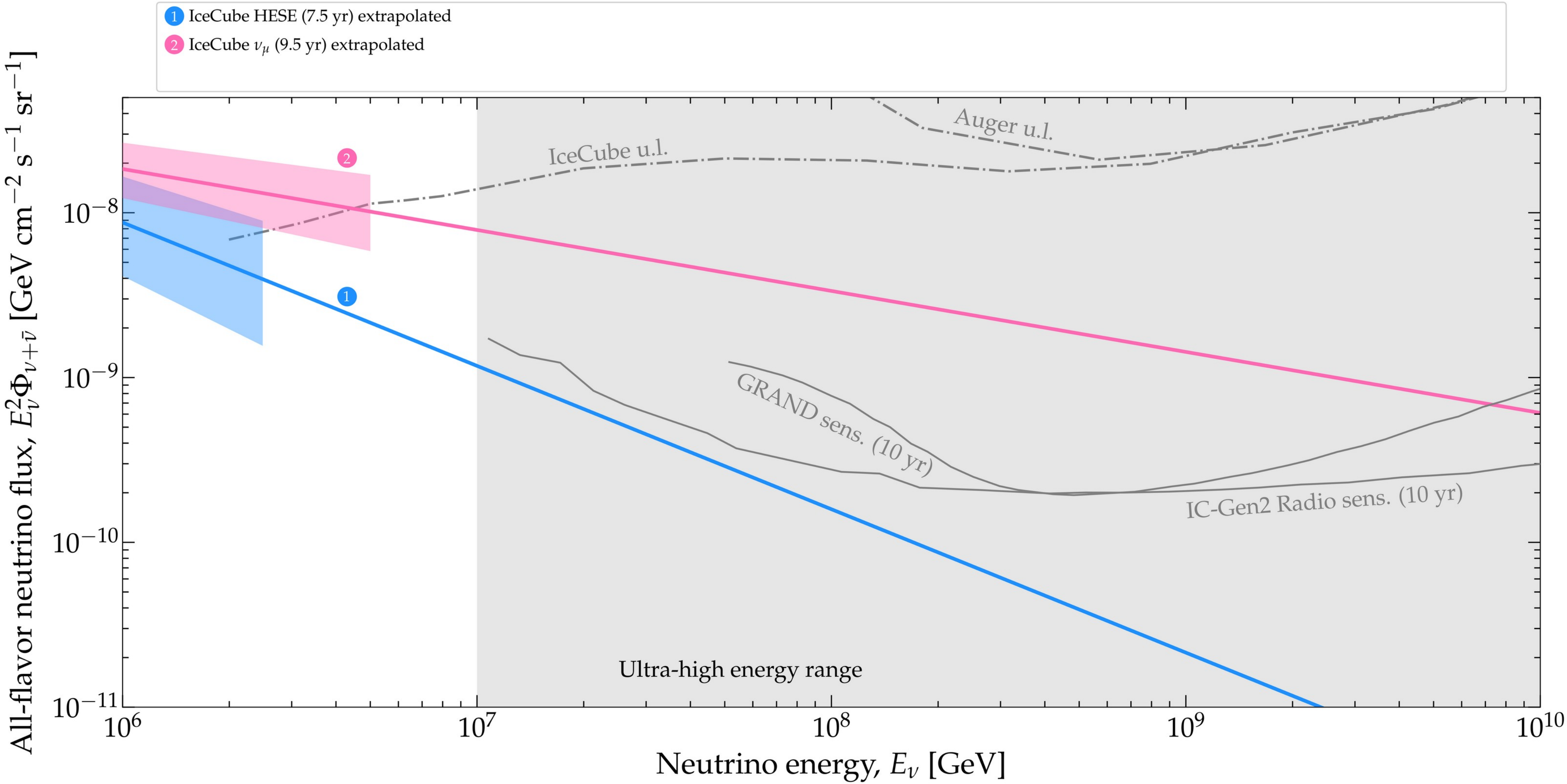

1 IceCube HESE (7.5 yr) extrapolated
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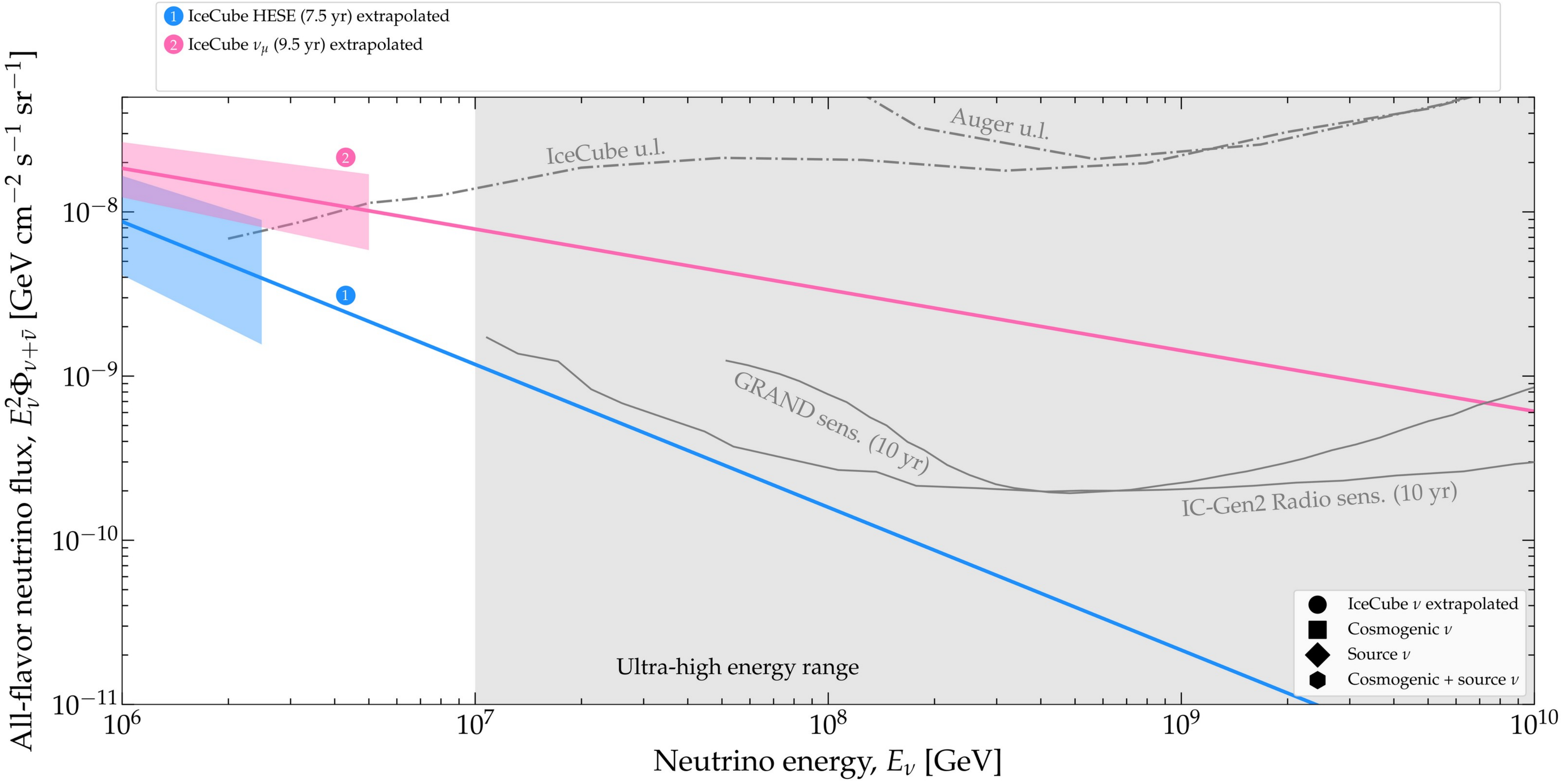
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy, E_ν [GeV]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
IceCube u.l.
Auger u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range



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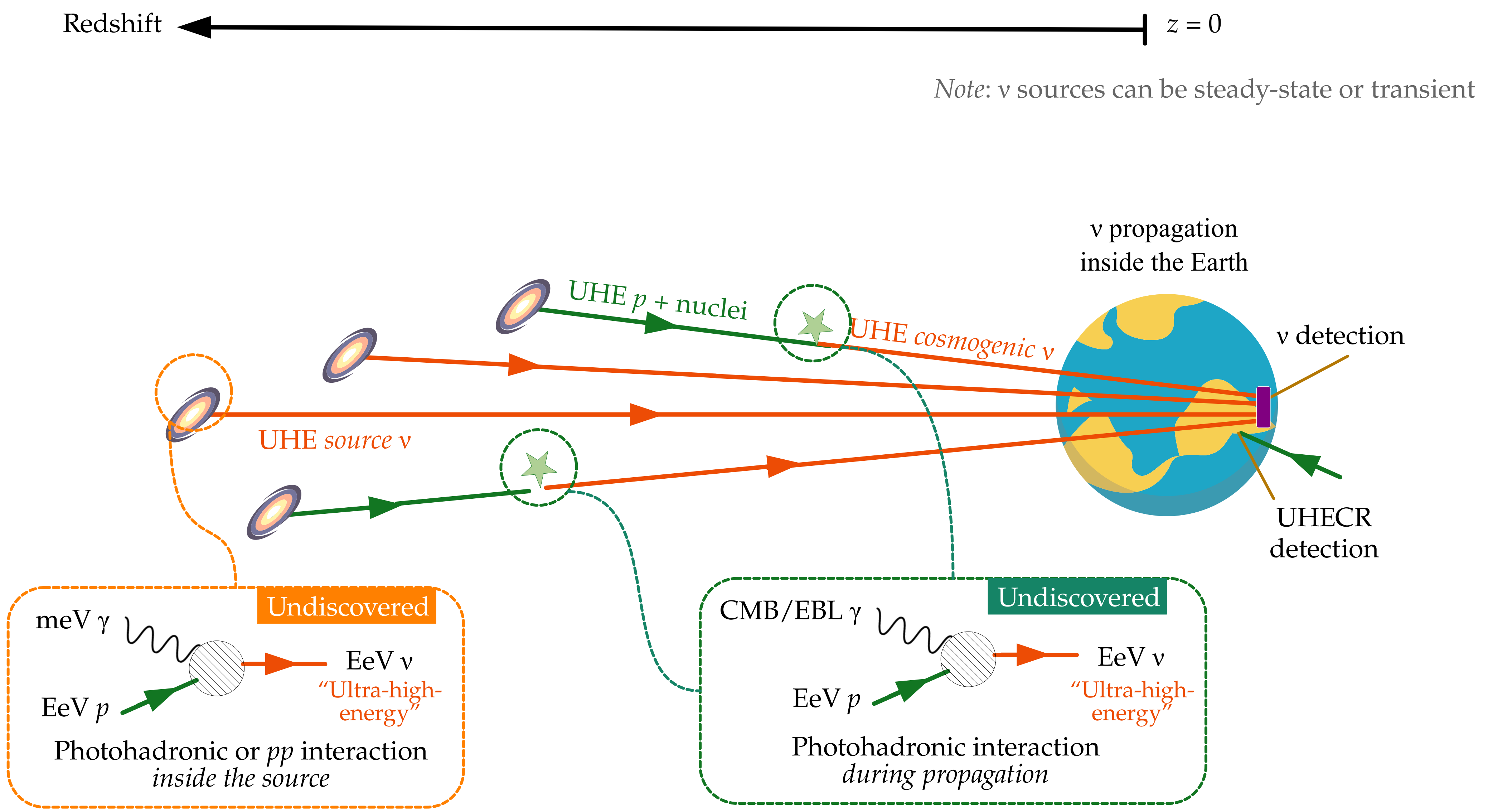
All-flavor neutrino flux, $E_\nu^2\Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
Neutrino energy, E_ν [GeV]
IceCube u.l.
Auger u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
IceCube ν extrapolated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


Redshift
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Note: ν sources can be steady-state or transient
ν propagation inside the Earth
UHE p + nuclei
UHE *cosmogenic* ν
ν detection
UHE *source* ν
UHECR detection
Undiscovered
meV γ
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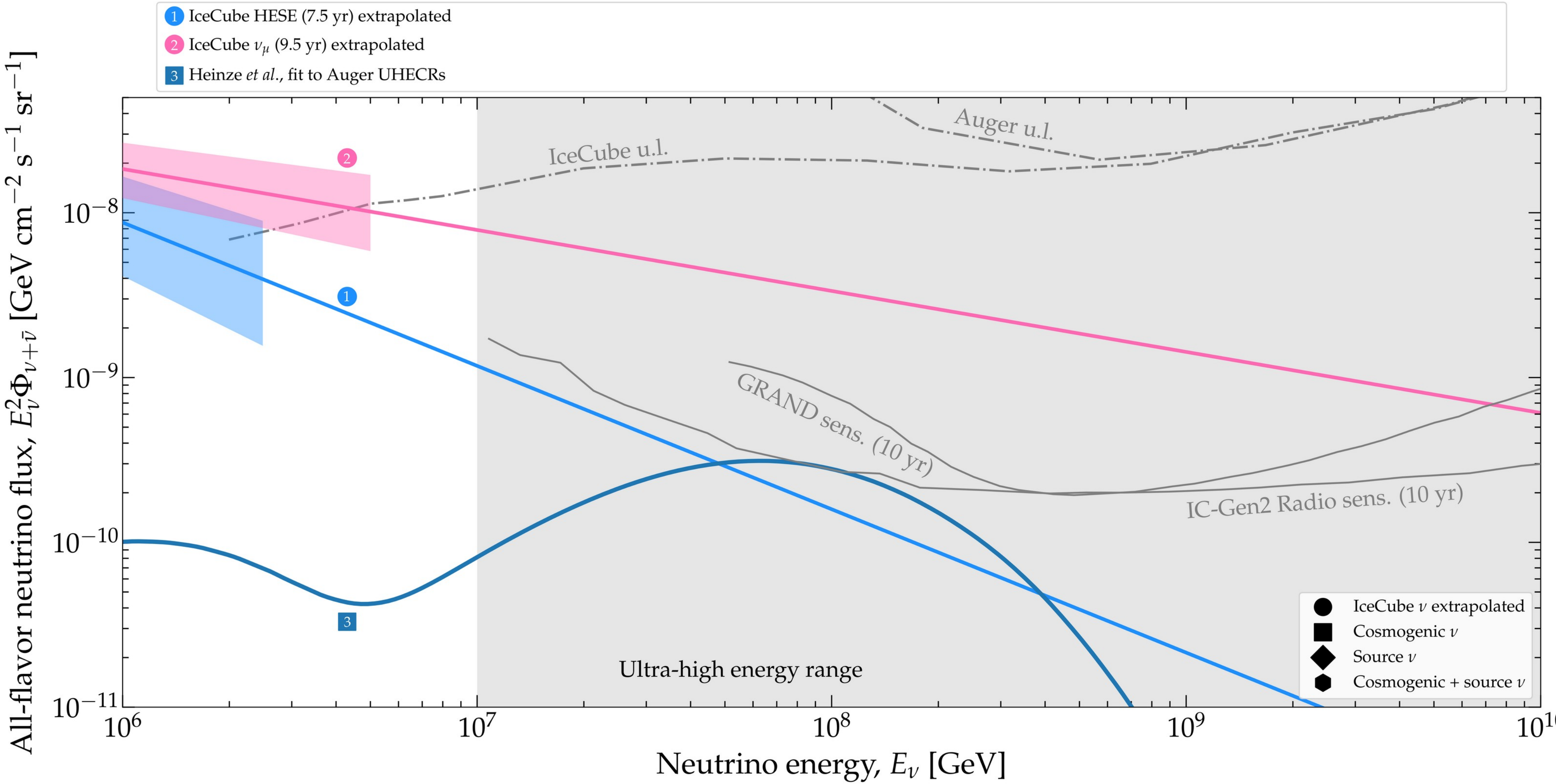
EeV p
Photohadronic or pp interaction *inside the source*
Undiscovered
CMB/EBL γ
EeV ν
"Ultra-high-energy"
EeV p
Photohadronic interaction *during propagation*



1 IceCube HESE (7.5 yr) extrapolated
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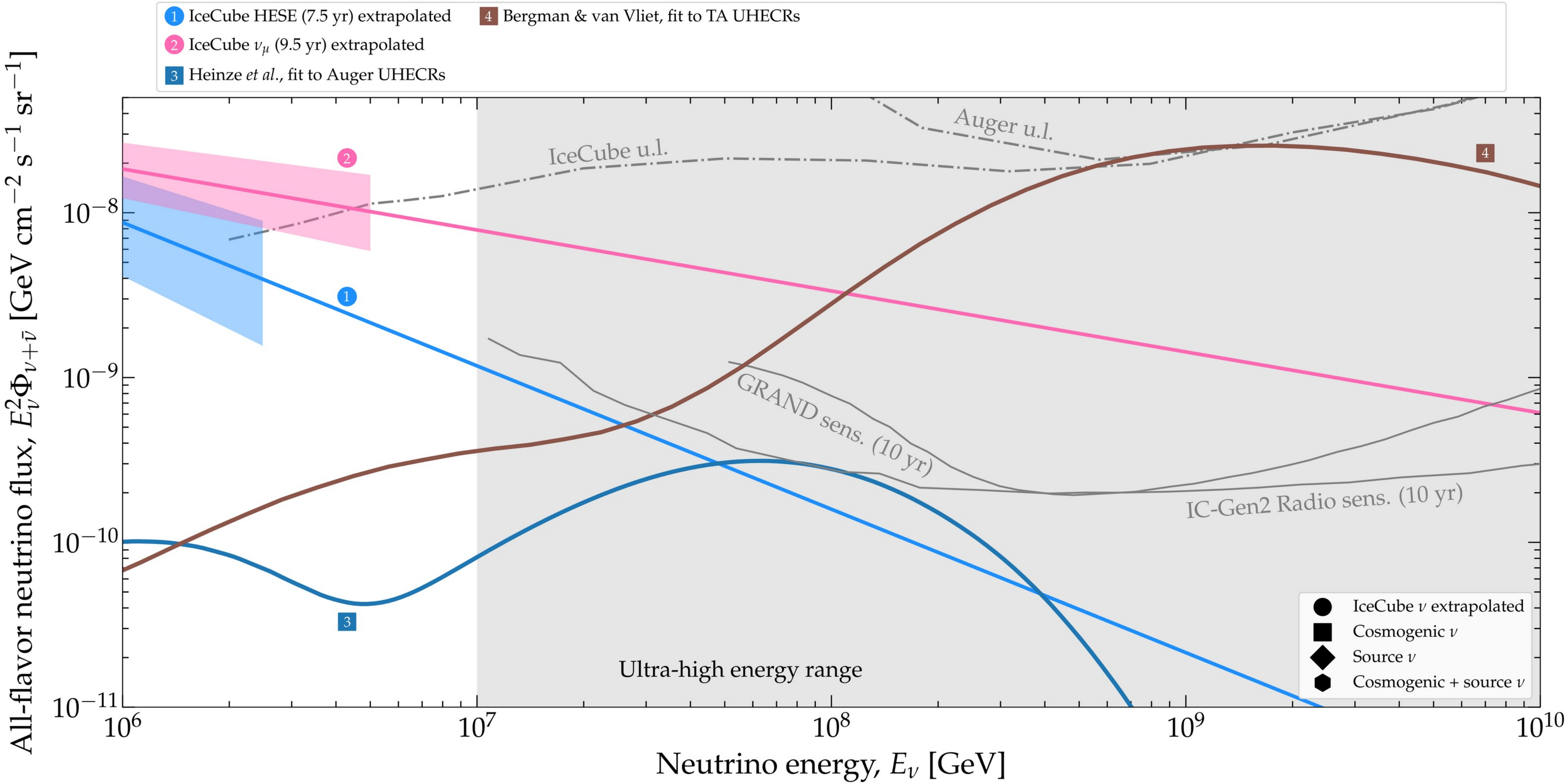
3 Heinze *et al.*, fit to Auger UHECRs
Auger u.l.
IceCube u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
IceCube ν extrapolated
Cosmogenic ν
Source ν
Cosmogenic + source ν
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy, E_ν [GeV]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}



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Auger u.l.
IceCube u.l.
GRAND sens. (10 yr)
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Ultra-high energy range
IceCube ν extrapolated
Cosmogenic ν
Source ν
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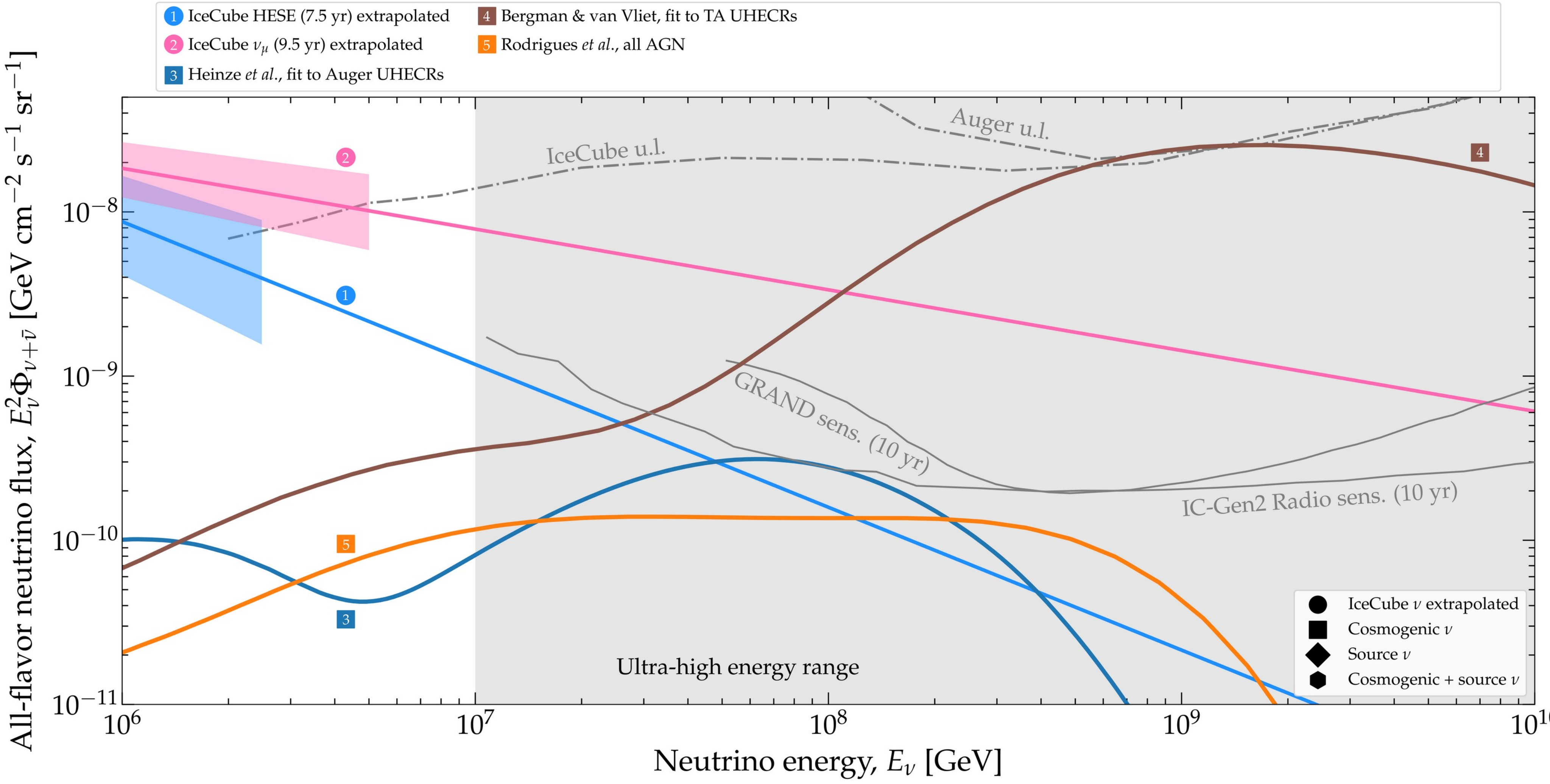

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Auger u.l.
IceCube u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
IceCube ν extrapolated
Cosmogenic ν
Source ν
Cosmogenic + source ν
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10^{-8}
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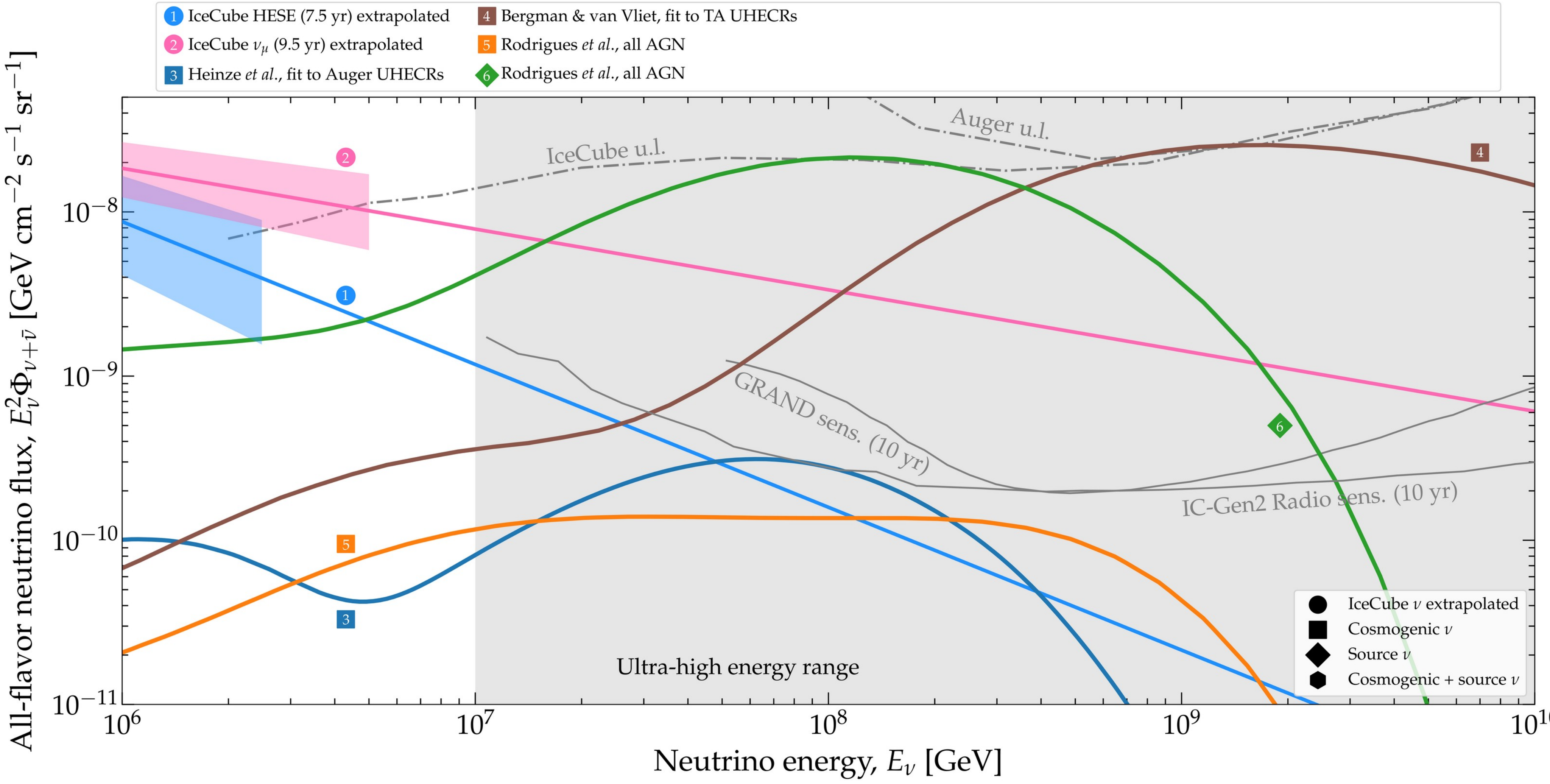
10^9
10^{10}



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Auger u.l.
IceCube u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
IceCube ν extrapolated
Cosmogenic ν
Source ν
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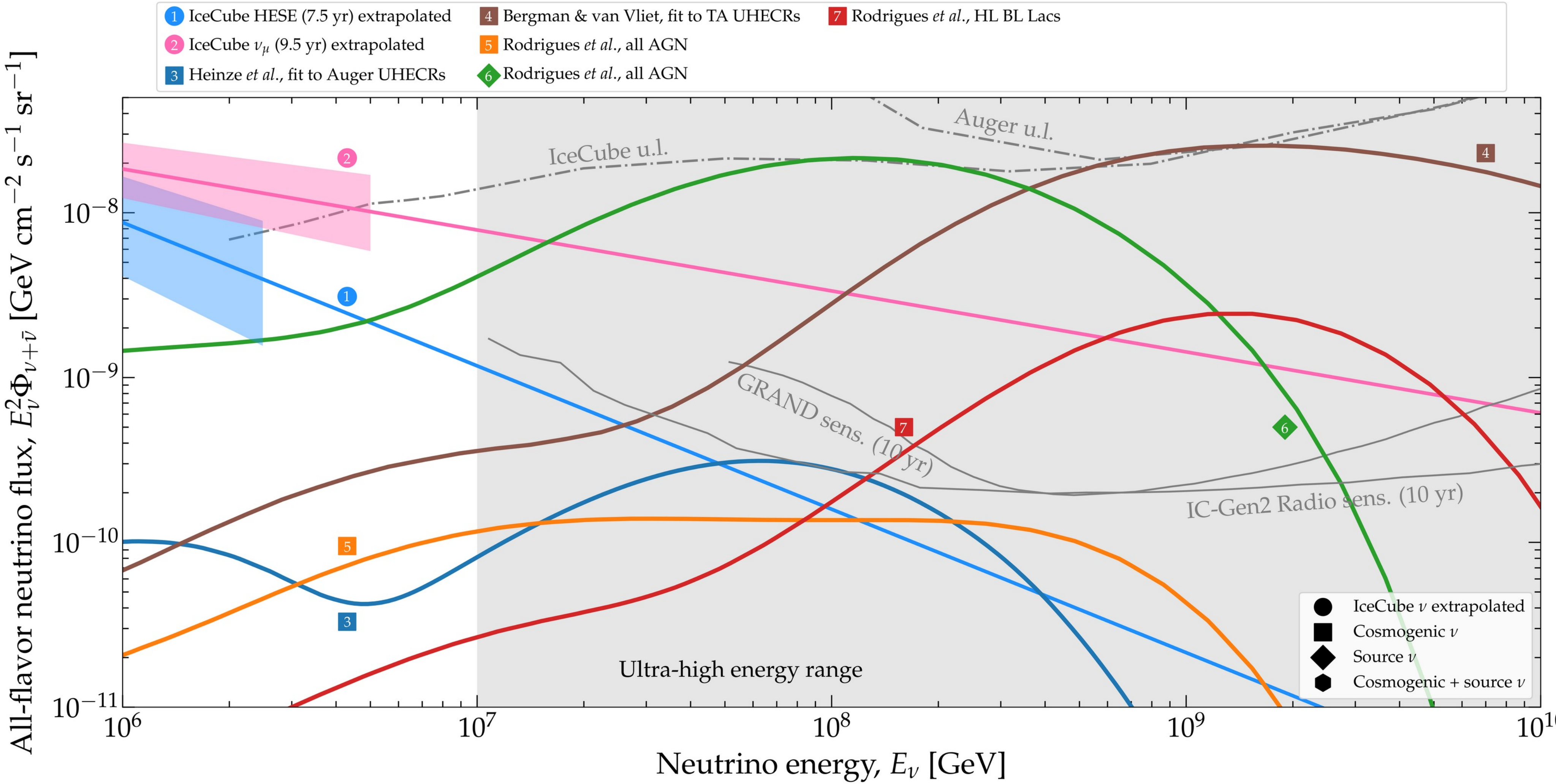
10^{10}



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5 Rodrigues *et al.*, all AGN
6 Rodrigues *et al.*, all AGN
7 Rodrigues *et al.*, HL BL Lacs
Auger u.l.
IceCube u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
IceCube ν extrapolated
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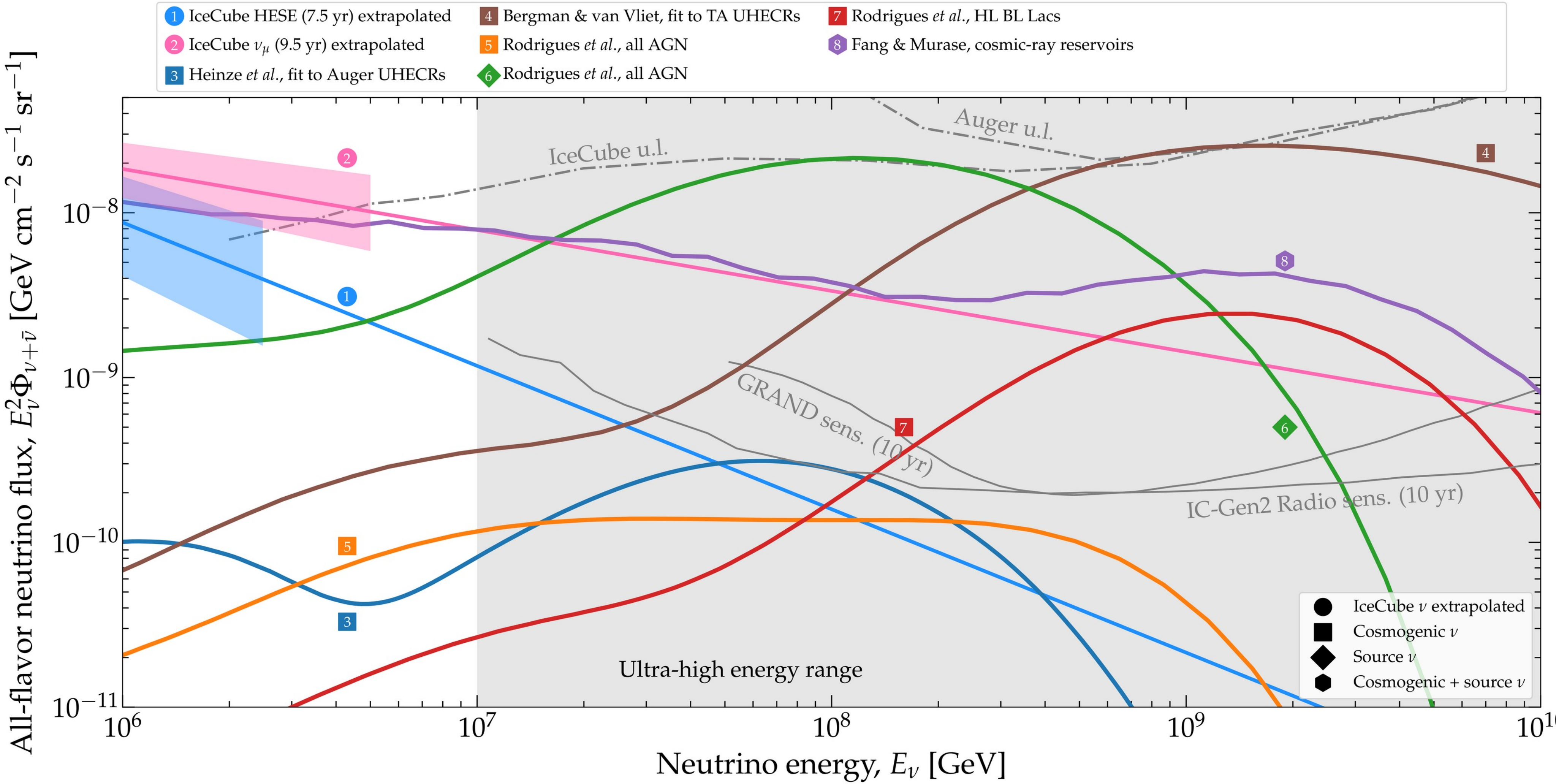
10^9
10^{10}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6 Rodrigues et al., all AGN
7 Rodrigues et al., HL BL Lacs
8 Fang & Murase, cosmic-ray reservoirs
Auger u.l.
IceCube u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
IceCube ν extrapolated
Cosmogenic ν
Source ν
Cosmogenic + source ν
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy, E_ν [GeV]
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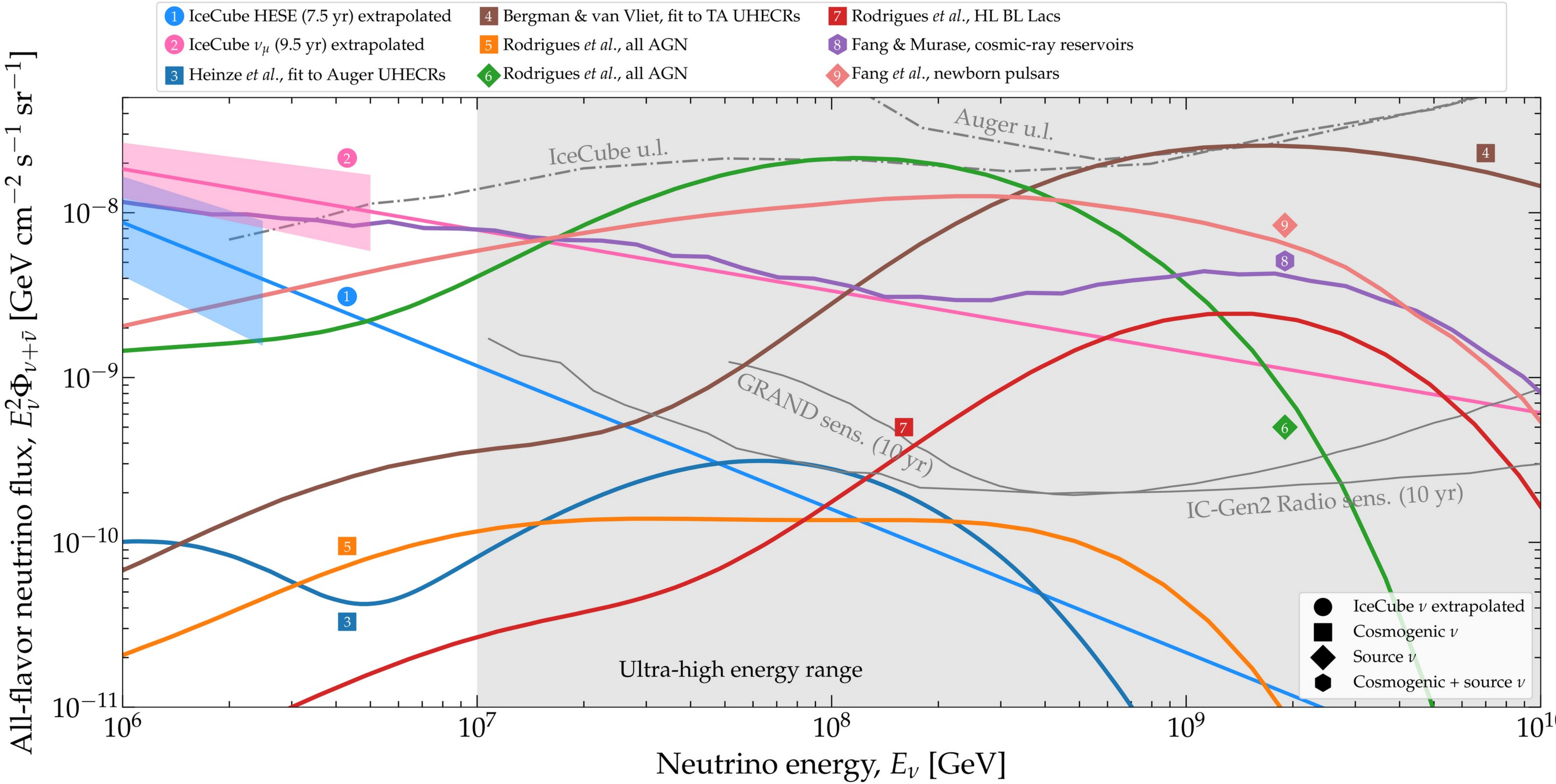
10^8
10^9
10^{10}



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7 Rodrigues *et al.*, HL BL Lacs
8 Fang & Murase, cosmic-ray reservoirs
9 Fang *et al.*, newborn pulsars
Auger u.l.
IceCube u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
IceCube ν extrapolated
Cosmogenic ν
Source ν
Cosmogenic + source ν
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
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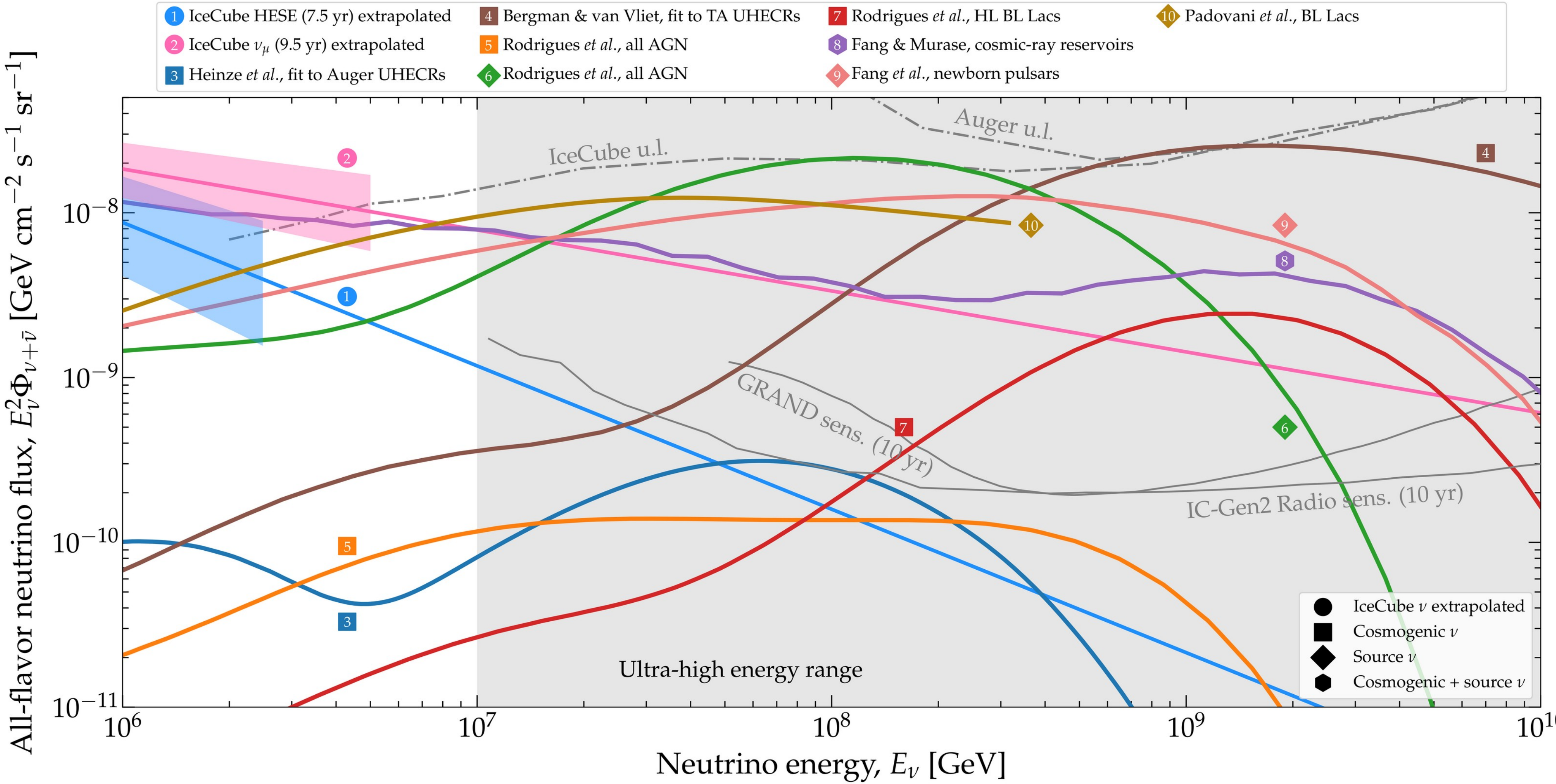
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]



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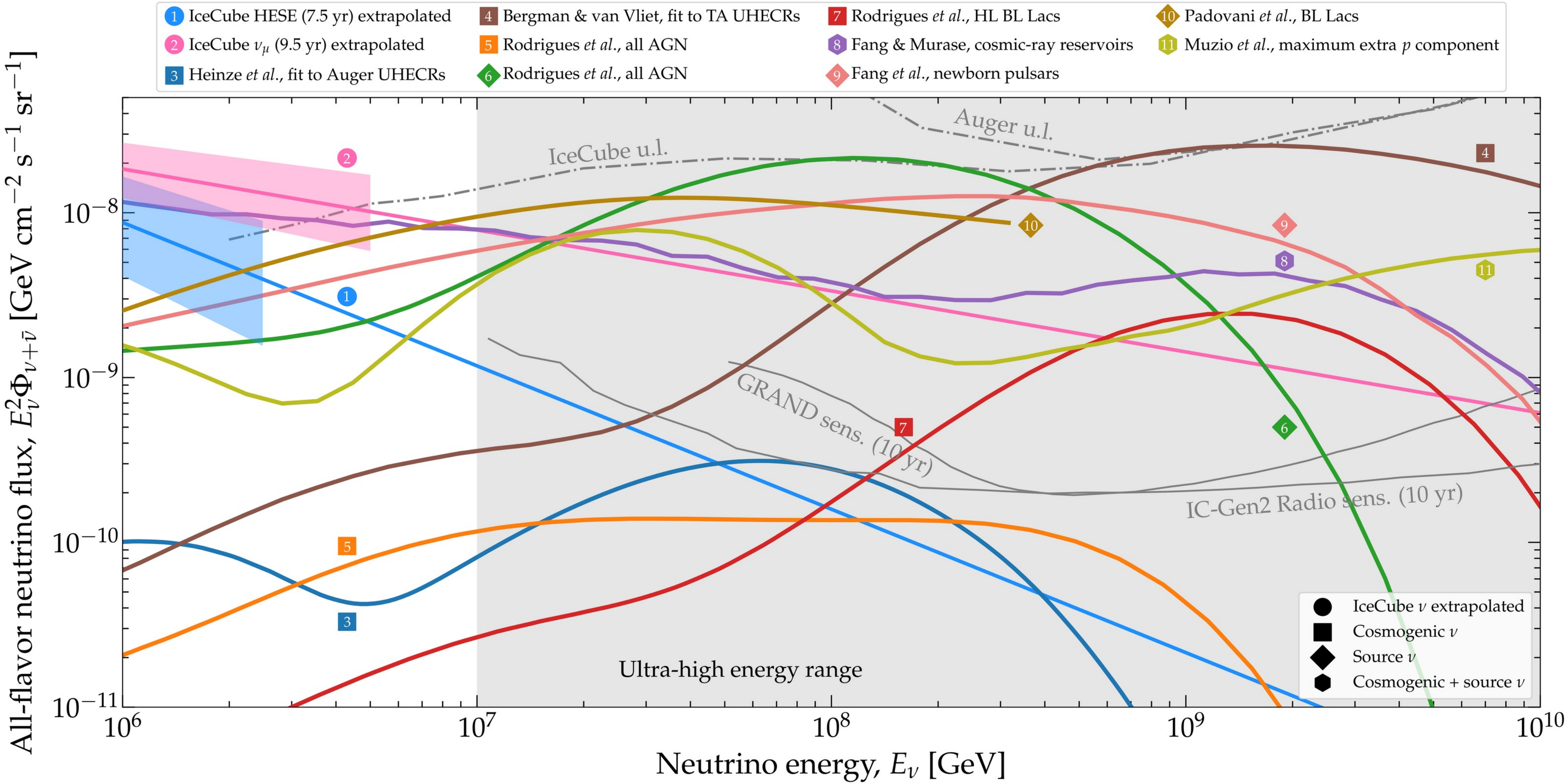
Auger u.l.
IceCube u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
IceCube ν extrapolated
Cosmogenic ν
Source ν
Cosmogenic + source ν
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9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



1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (9.5 yr) extrapolated
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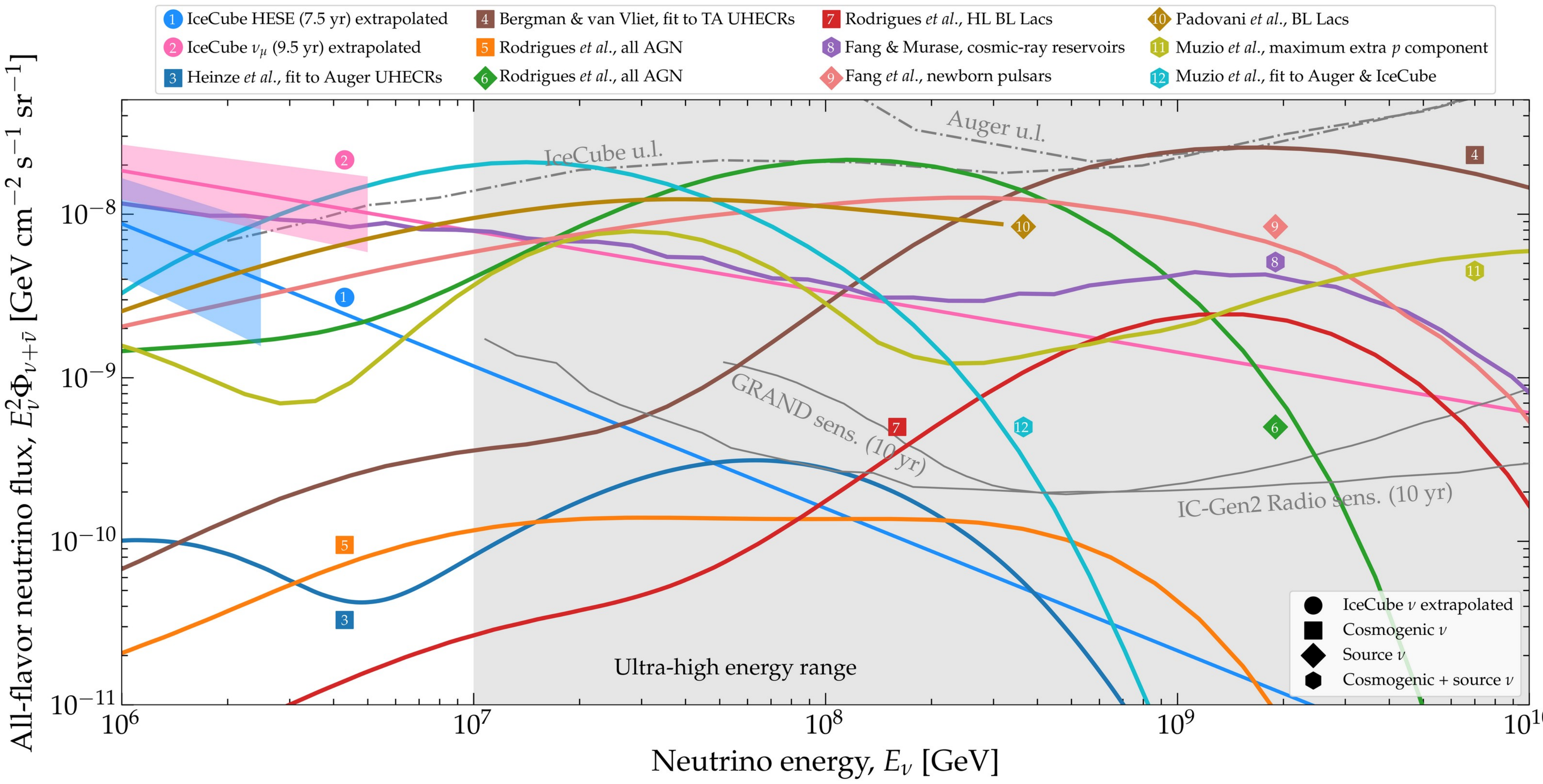

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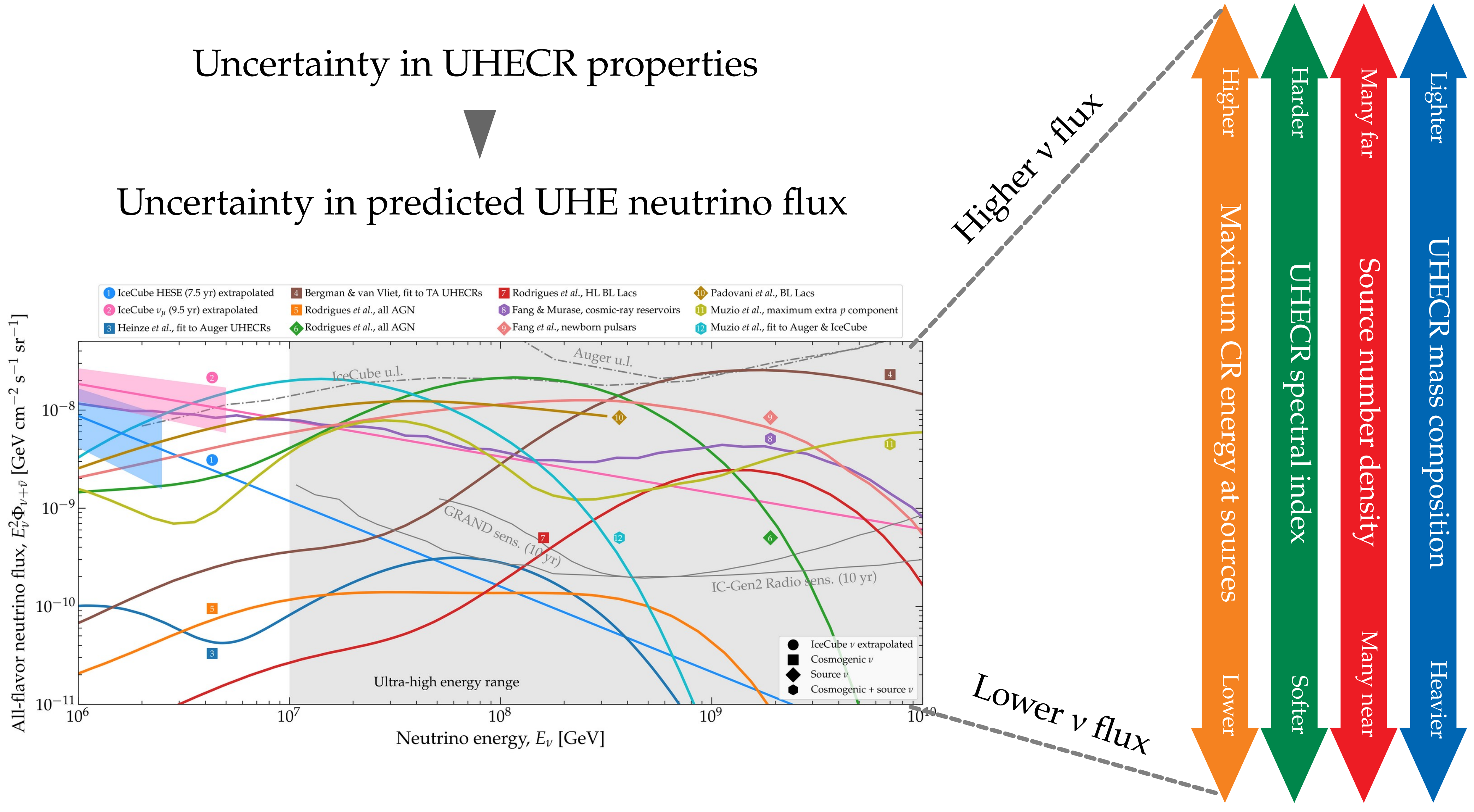

Uncertainty in UHECR properties
Uncertainty in predicted UHE neutrino flux
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10^{7}
10^{8}
10^{9}
10^{10}
Higher ν flux
Lower ν flux
Higher
Maximum CR energy at sources
Lower
Harder
UHECR spectral index
Softer
Many far
Source number density
Many near
Lighter
UHECR mass composition
Heavier

Today

TeV–PeV ν

Turn predictions
into data-driven tests

<u>Key developments</u>:

Bigger detectors → larger statistics

Better reconstruction

Smaller astrophysical uncertainties

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$>$ 100-PeV ν

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Better UHE ν flux predictions

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

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Next decade

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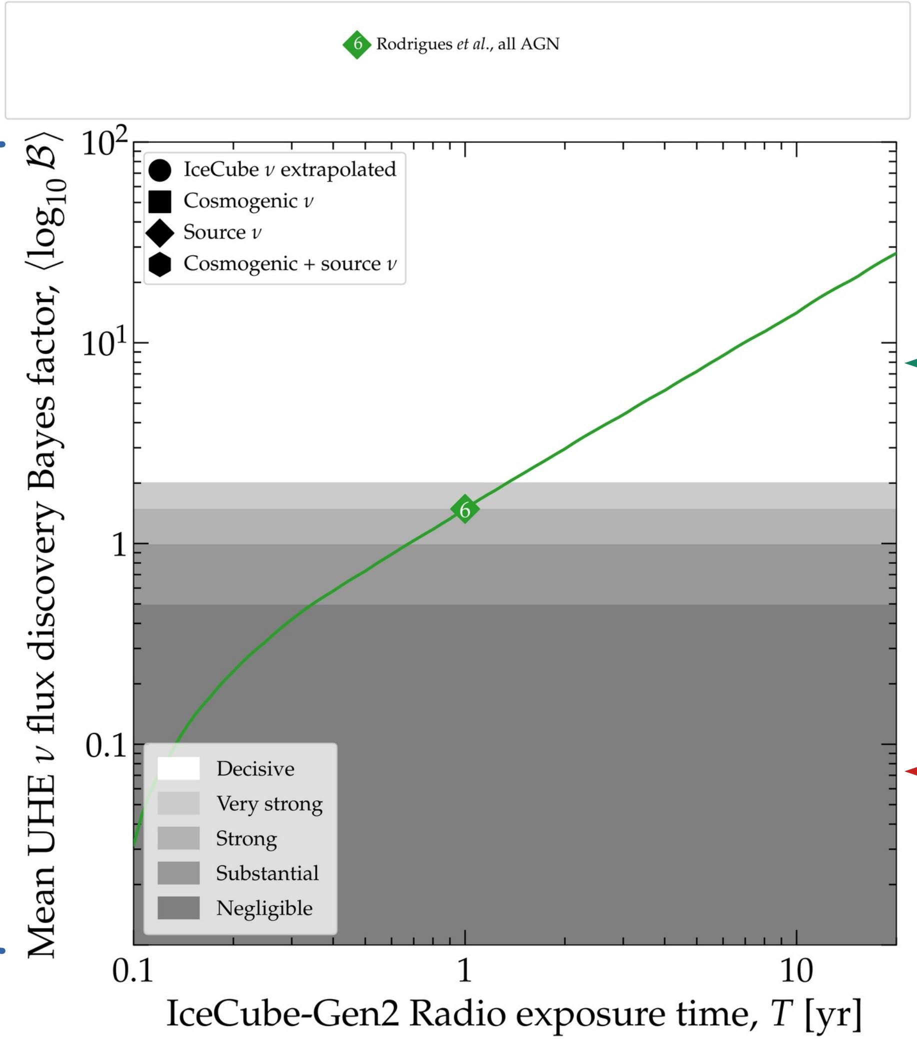
<u>Key developments</u>:
Discovery
New detection techniques
Better UHE ν flux predictions

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

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

Discovering the diffuse flux of UHE neutrinos

Bayes factor compares signal+bkg. *vs.* bkg.-only



High Bayes factor
→ Decisive flux discovery

Low Bayes factor
→ No flux discovered

Valera, **MB**, Glaser, *PRD* 2023 (to appear) [2210.03756]

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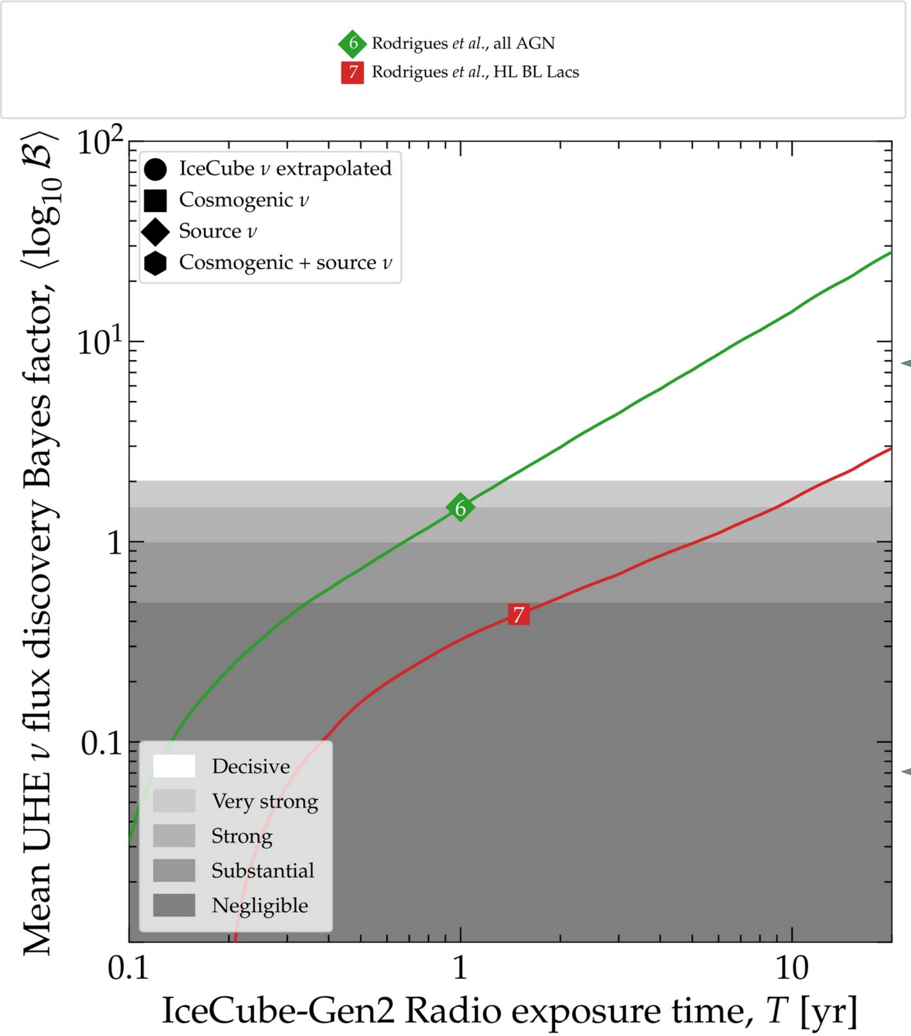

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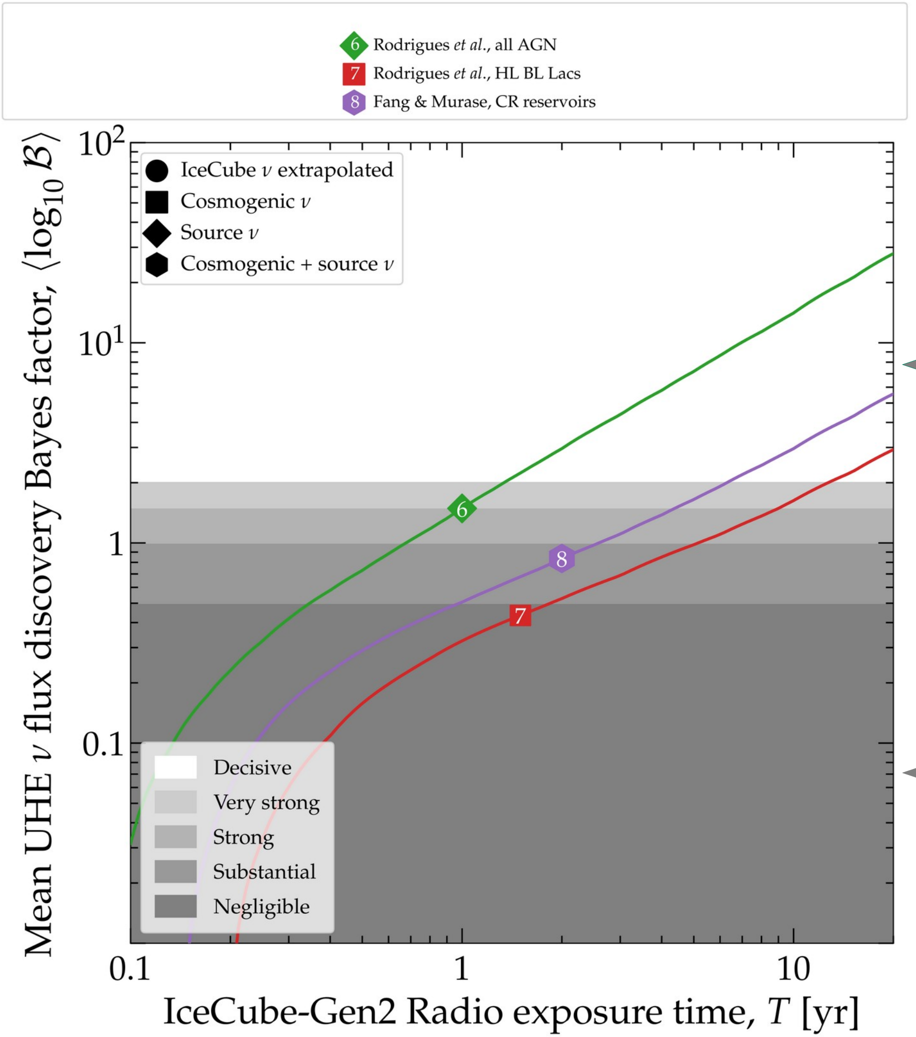

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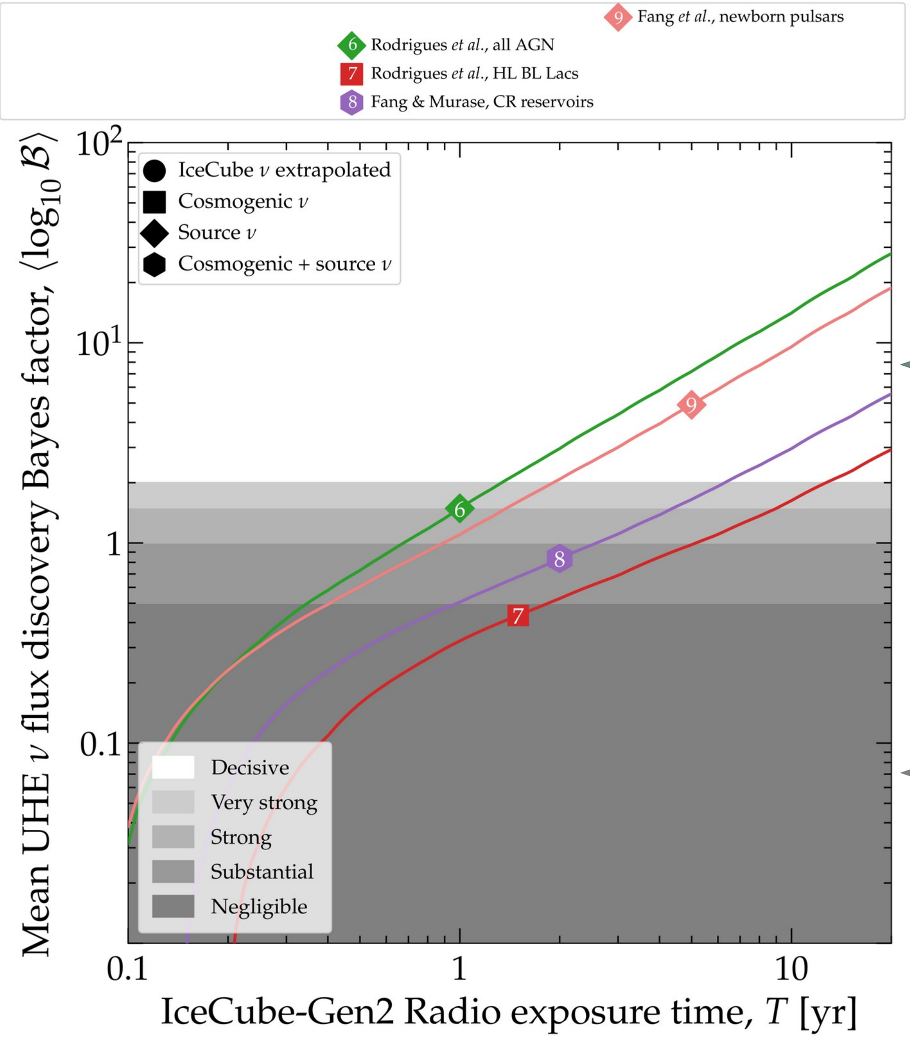

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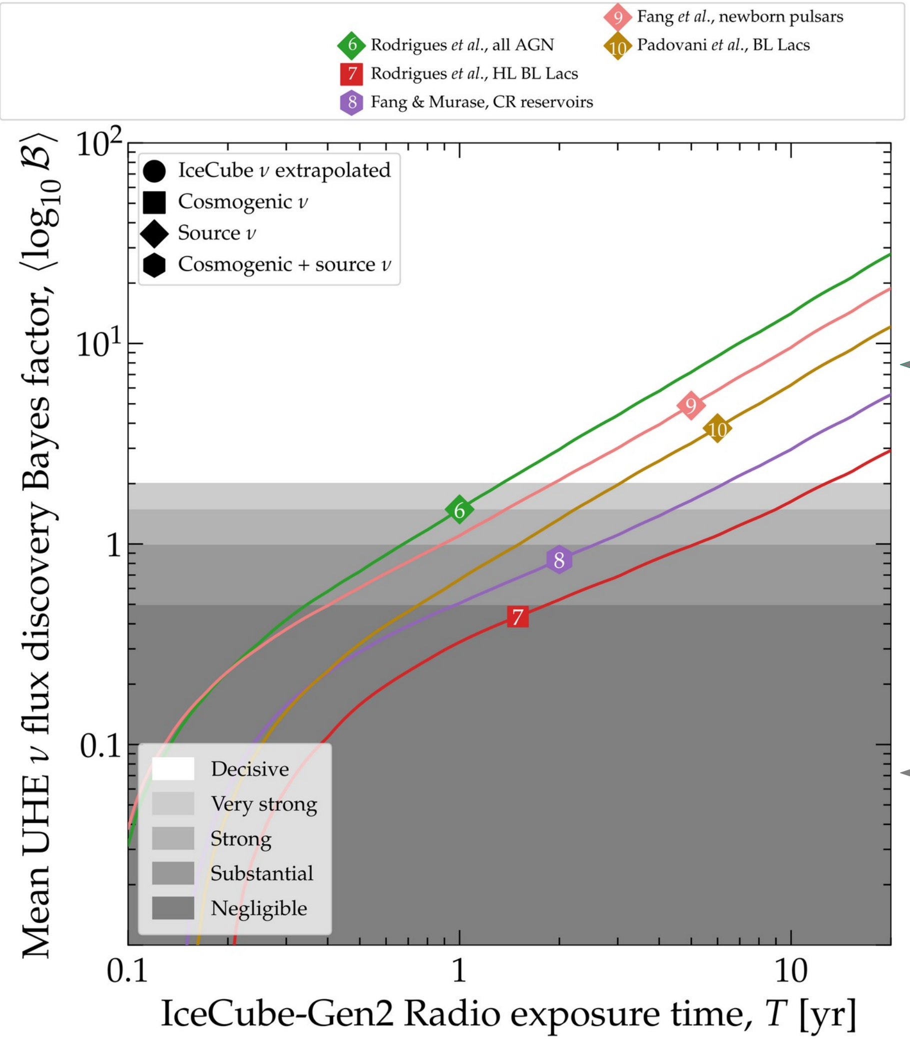

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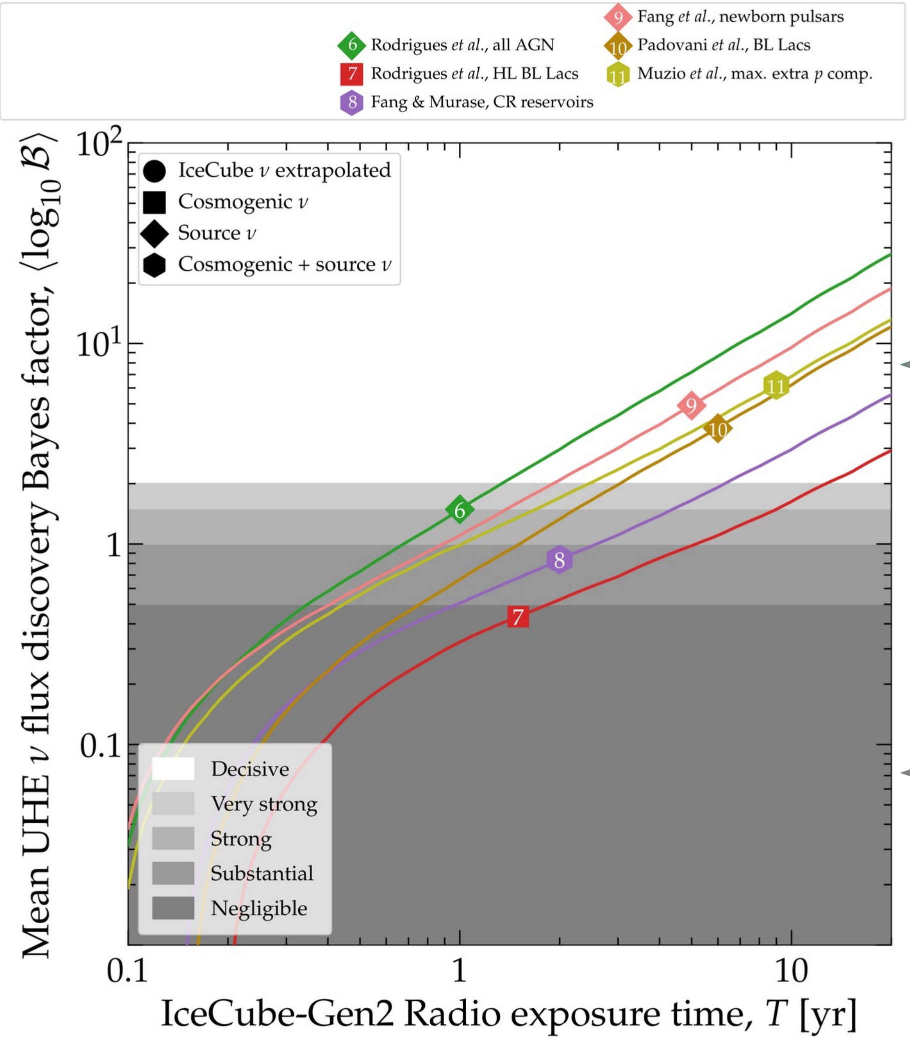

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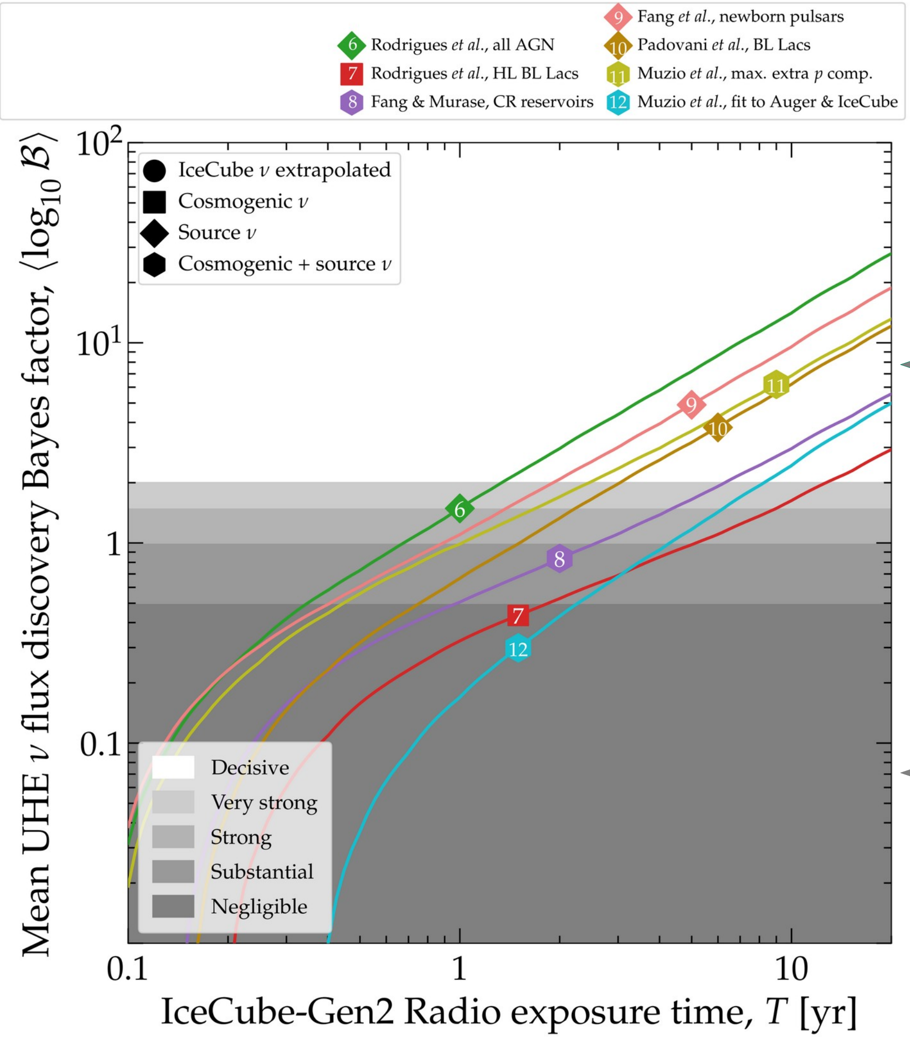

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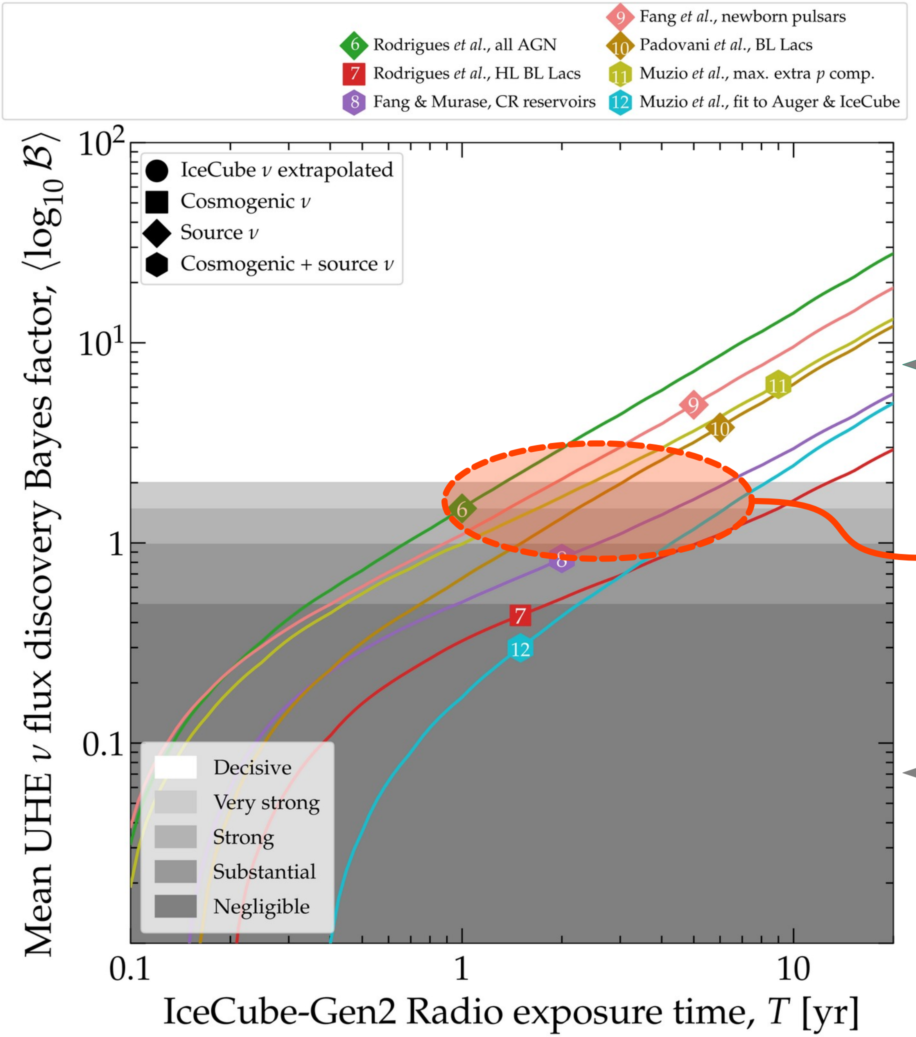

High Bayes factor
→ Decisive flux discovery

Most flux models are discoverable within a few years

Low Bayes factor
→ No flux discovered

Valera, **MB**, Glaser,
PRD 2023 (to appear) [2210.03756]

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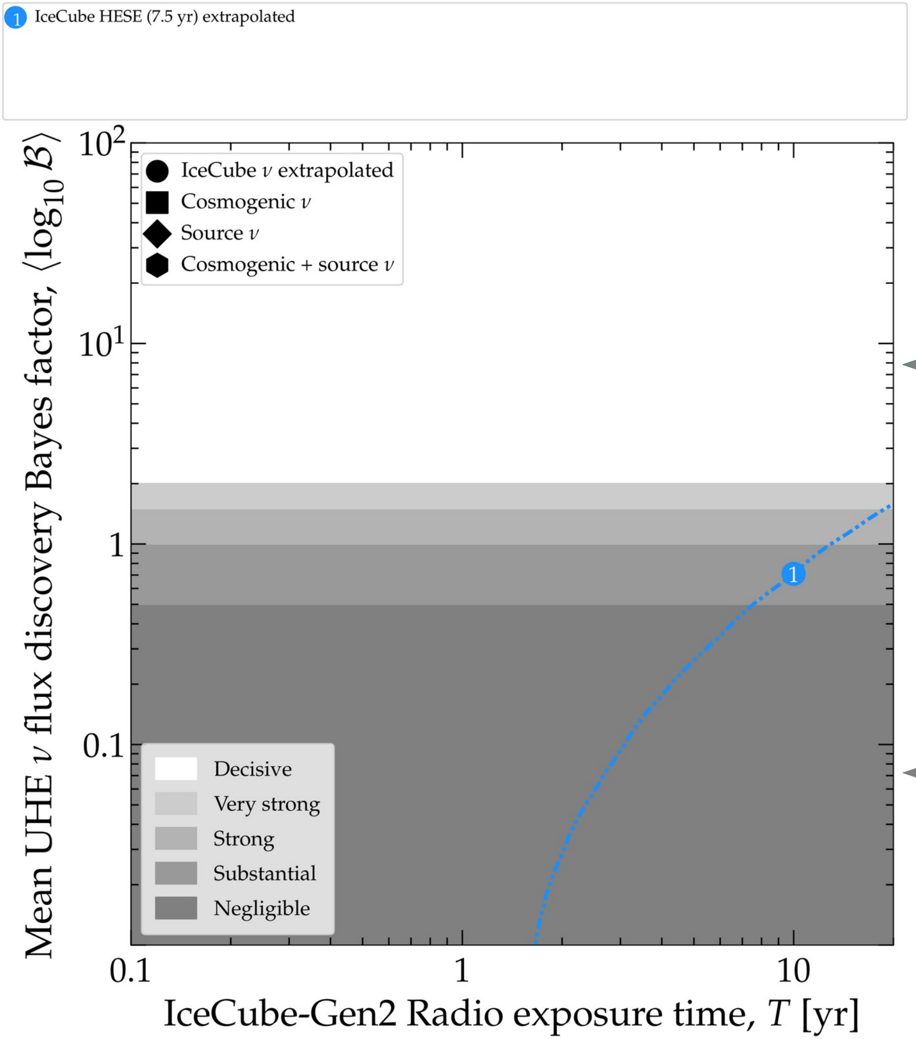

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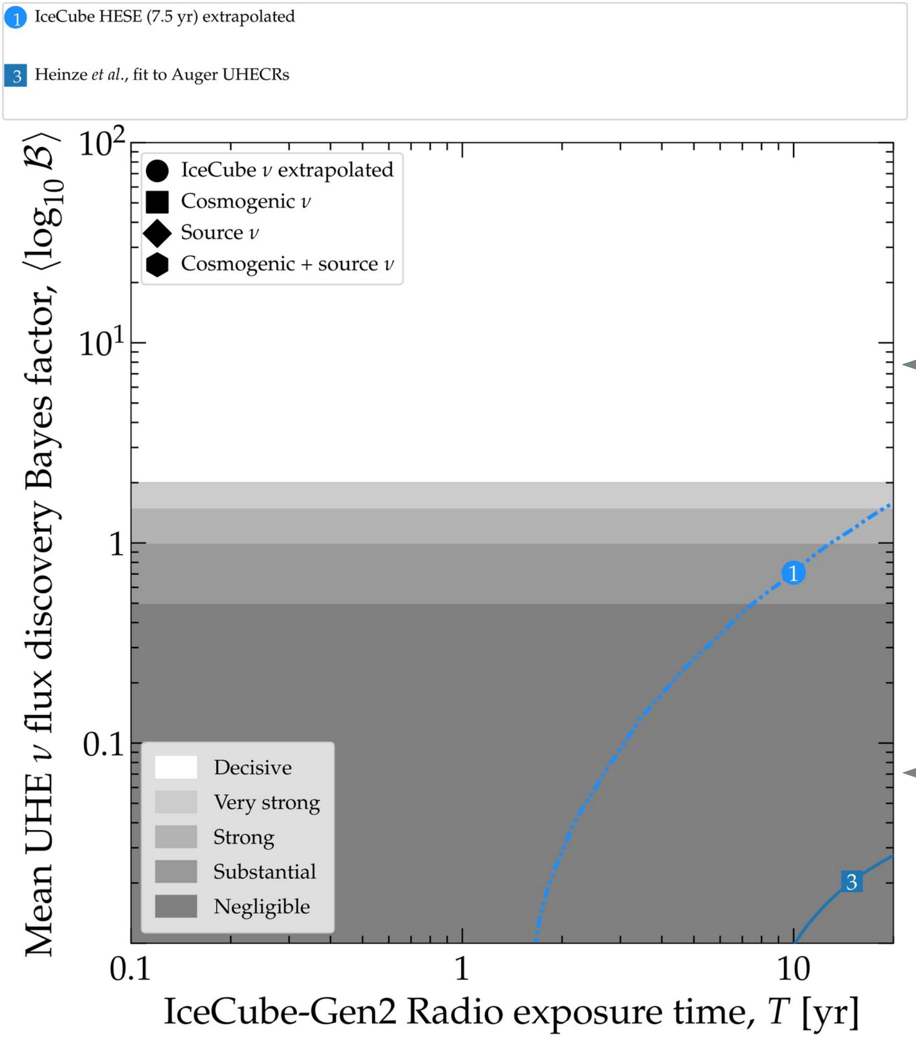

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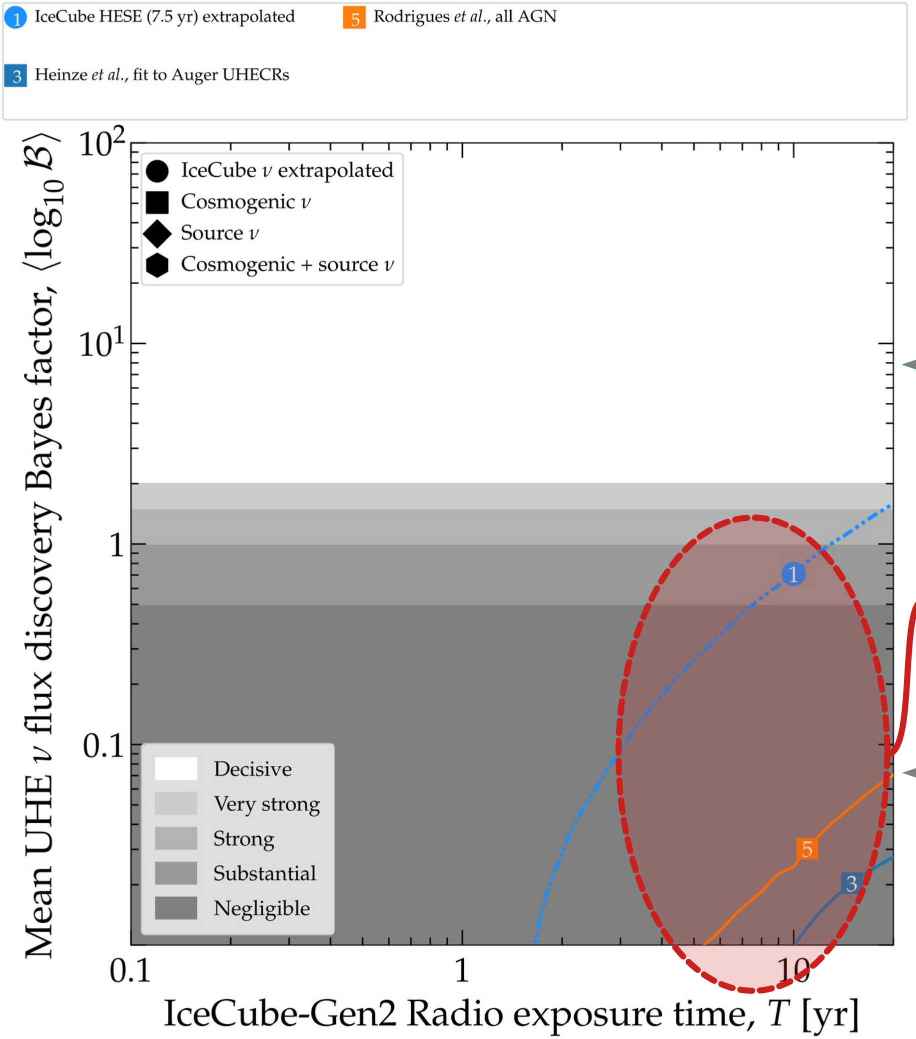

High Bayes factor → Decisive flux discovery

Some models will *not* be discovered

Low Bayes factor → No flux discovered

Valera, **MB**, Glaser, *PRD* 2023 (to appear) [2210.03756]

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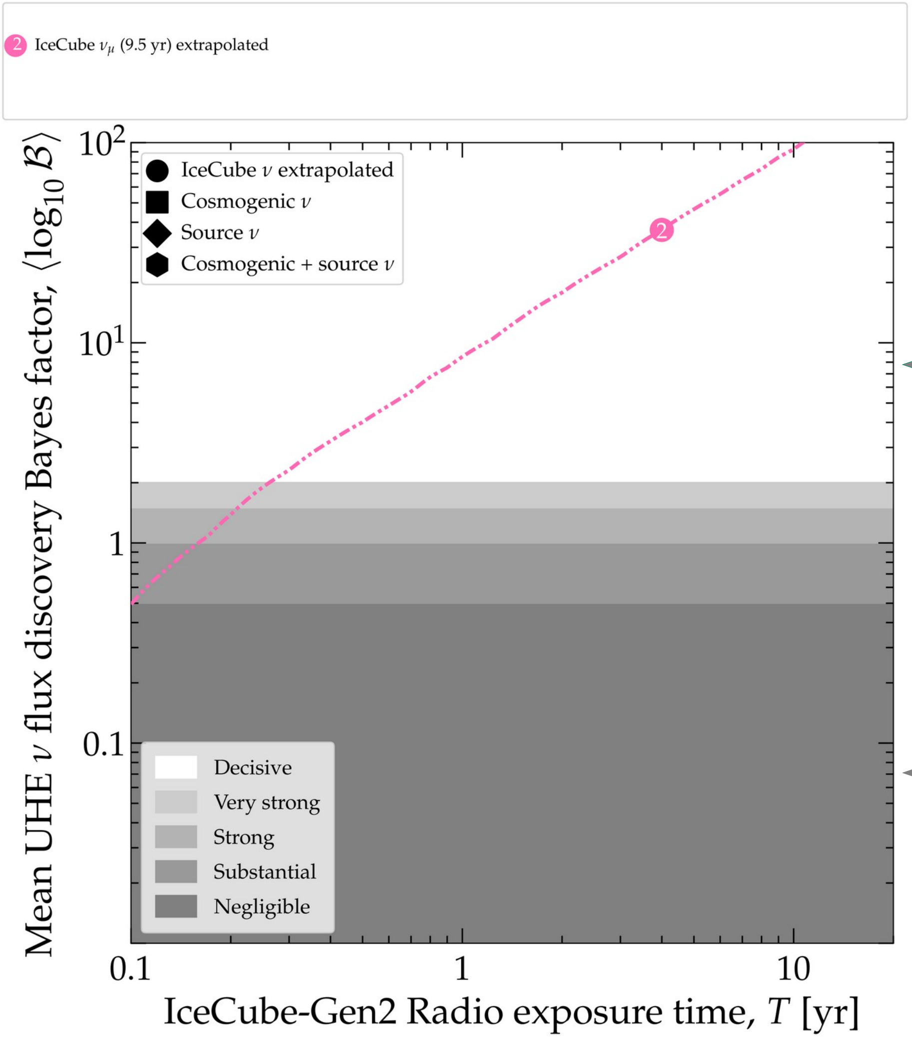

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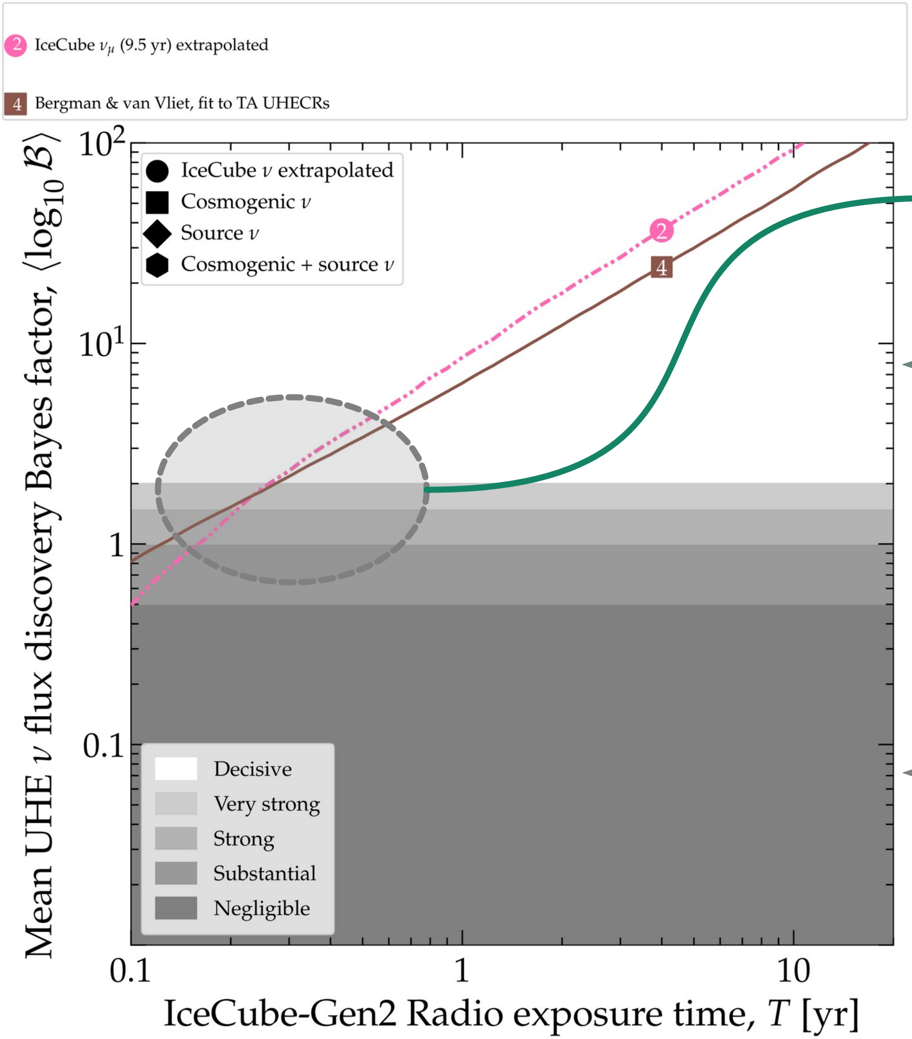

Some models will be discovered right away

High Bayes factor
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Low Bayes factor
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Valera, **MB**, Glaser,
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Discovering the diffuse flux of UHE neutrinos

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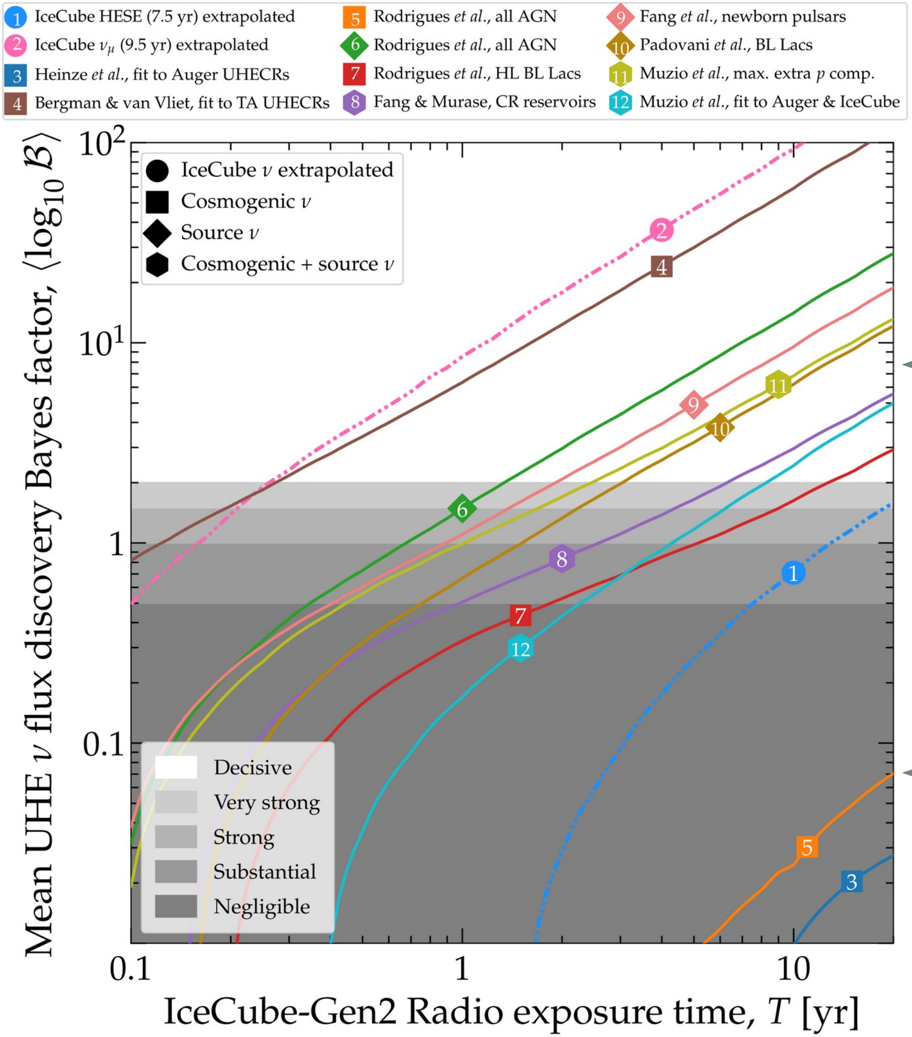

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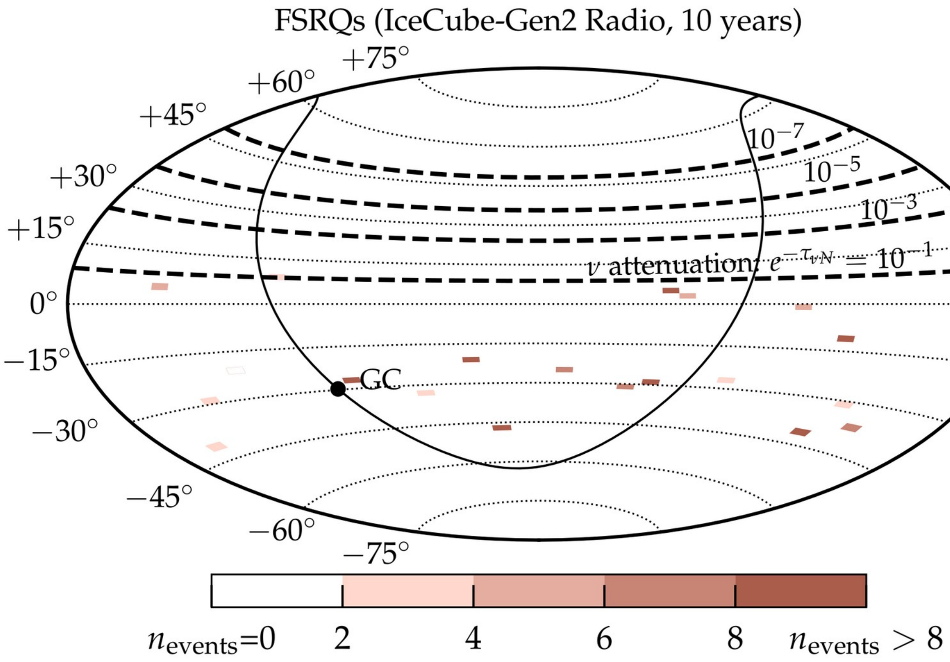
Work led by Víctor Valera

Valera, **MB**, Glaser, *PRD* 2023 (to appear) [2210.03756]

Discovering point sources of UHE neutrinos

Number of events detected
from a population of sources



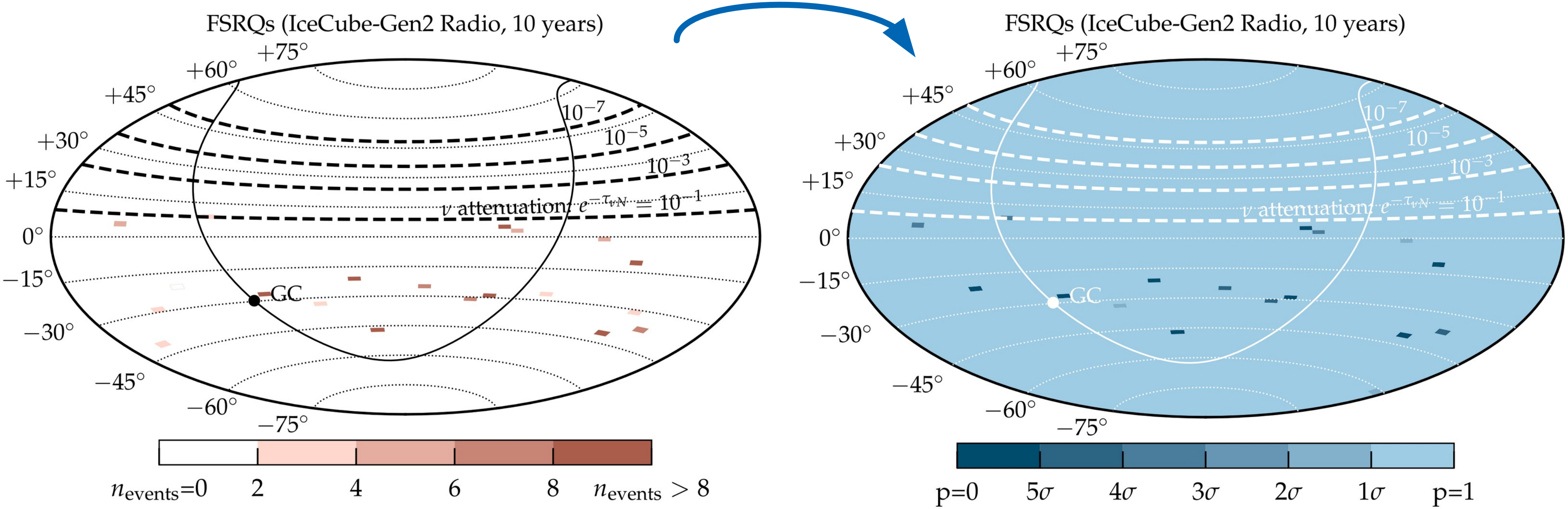
Above: angular resolution of 2° → GRAND aims for ~0.1°!

Fiorillo, **MB**, Valera,
JCAP 2023 (to appear) [2205.15985]

Discovering point sources of UHE neutrinos

Number of events detected from a population of sources

(Global) significance of a point-source discovery



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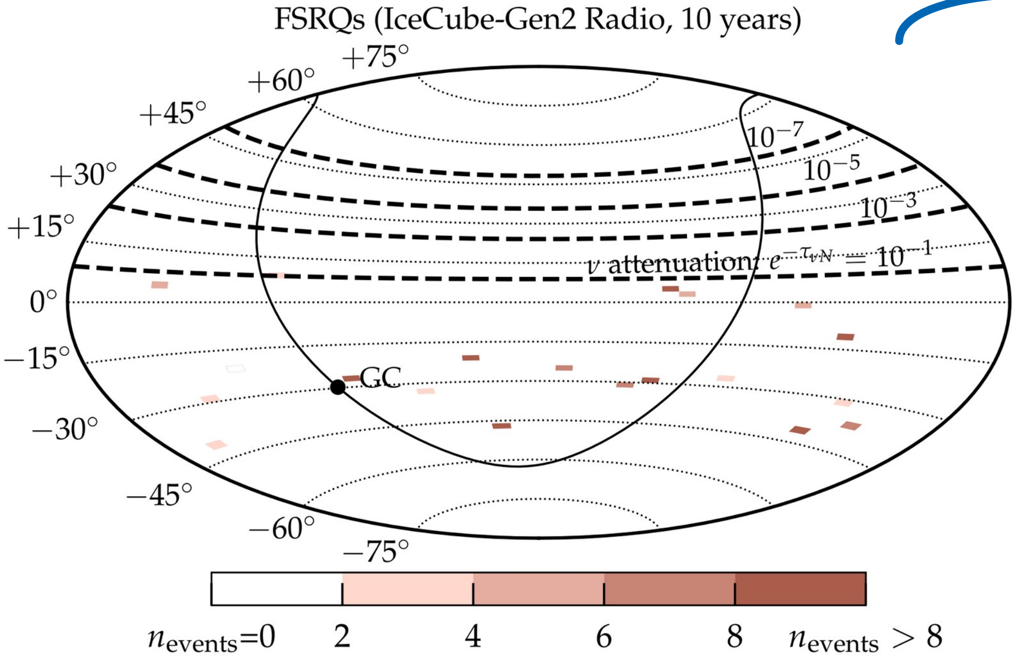

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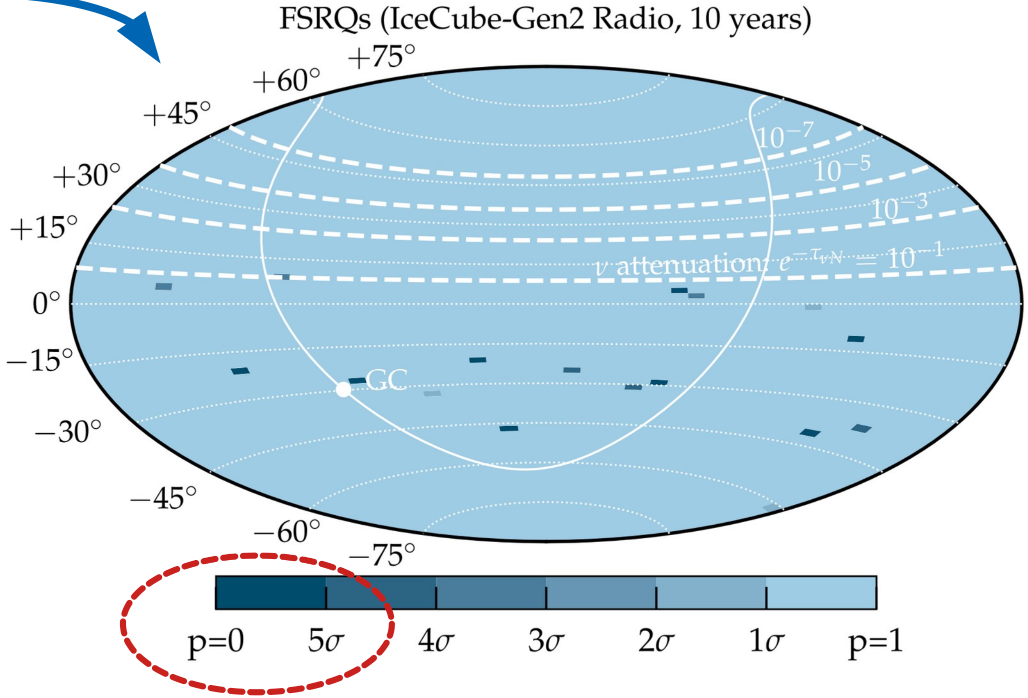

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Fiorillo, **MB**, Valera,
JCAP 2023 (to appear) [2205.15985]

Discovering point sources of UHE neutrinos

Work led by
Damiano Fiorillo & Víctor Valera

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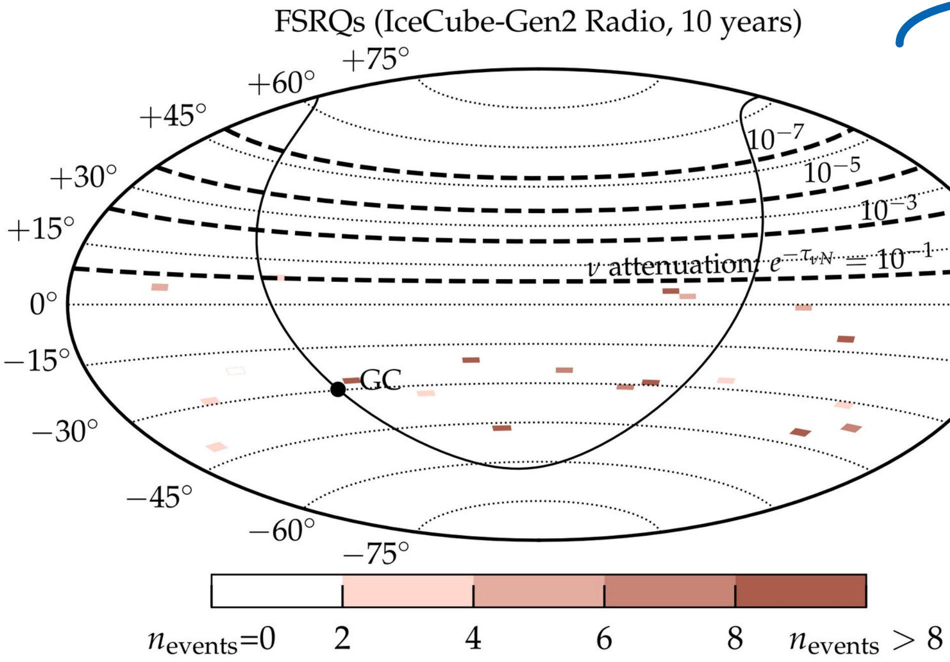
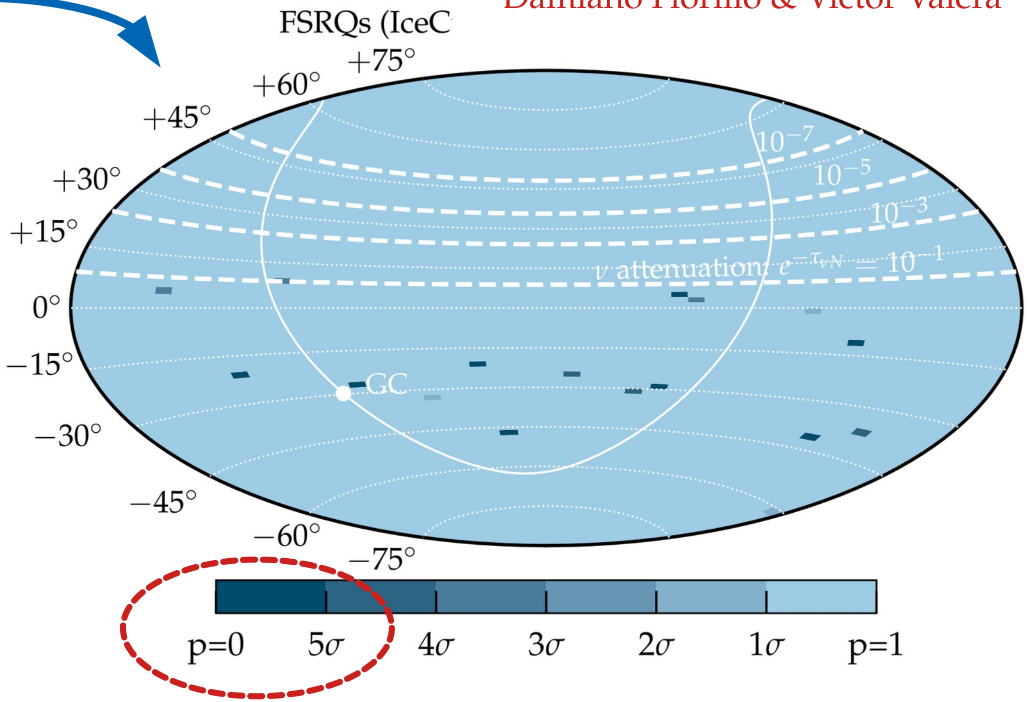


(Global) s
point-so



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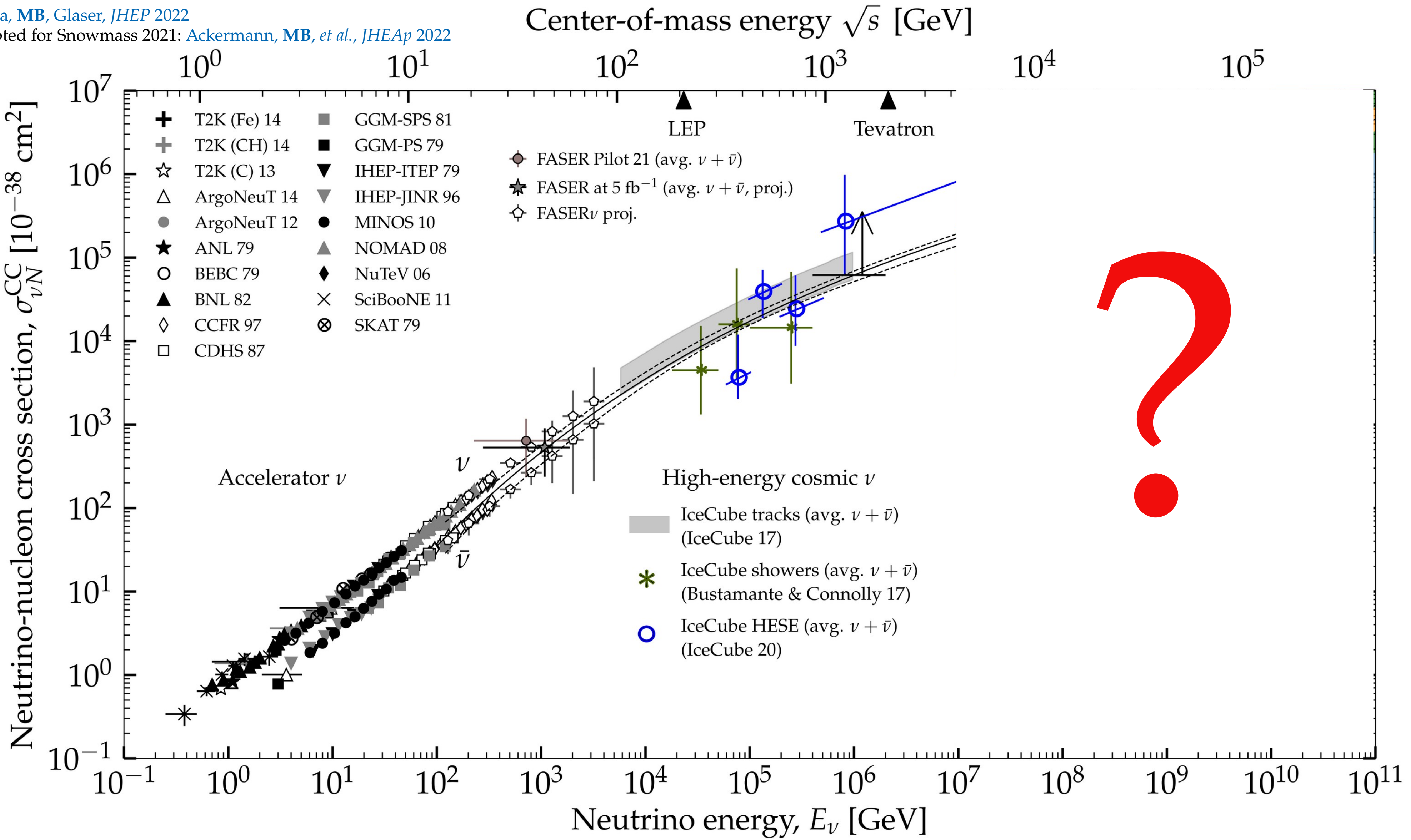
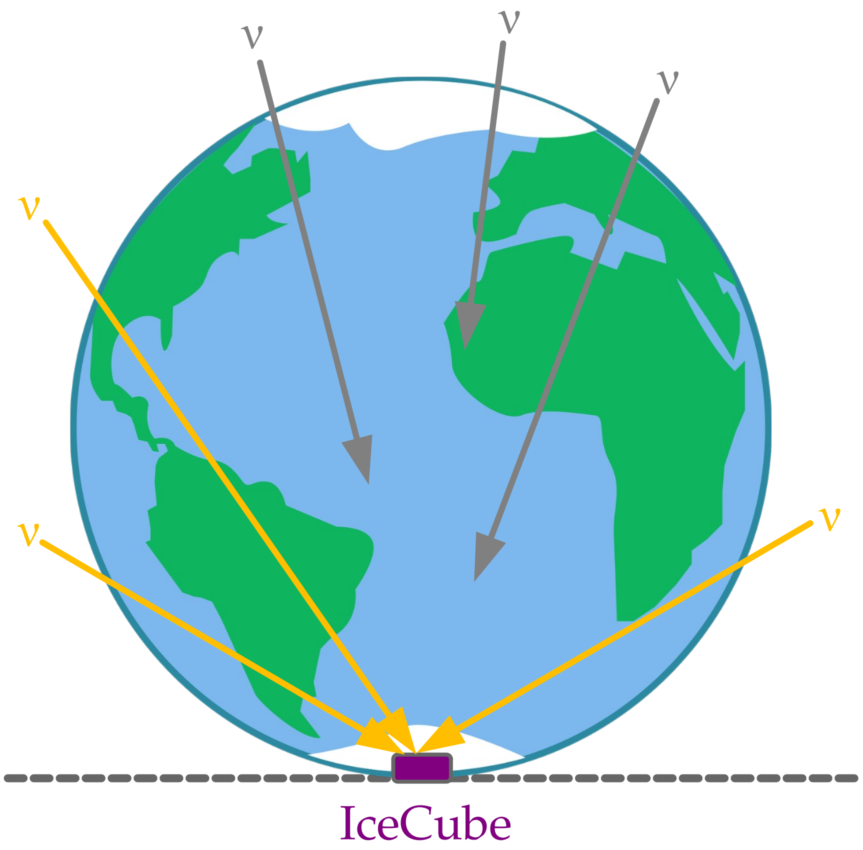
Adapted for Snowmass 2021: Ackermann, **MB**, *et al.*, *JHEAp* 2022



TeV–PeV:



Earth is *almost fully* opaque,
some upgoing ν still make it through

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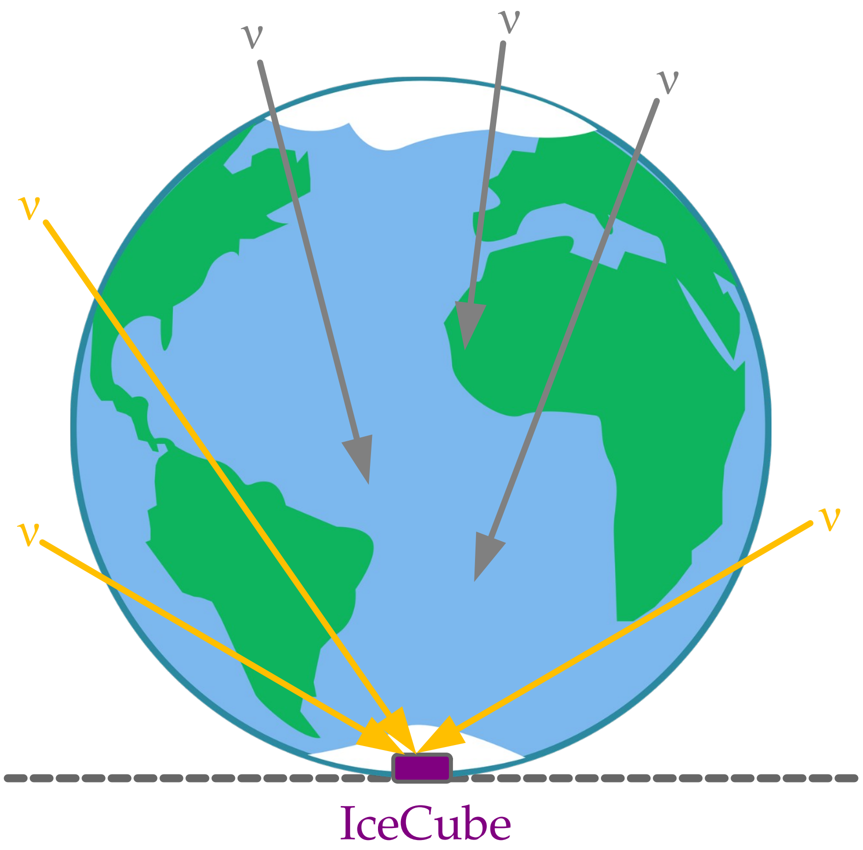

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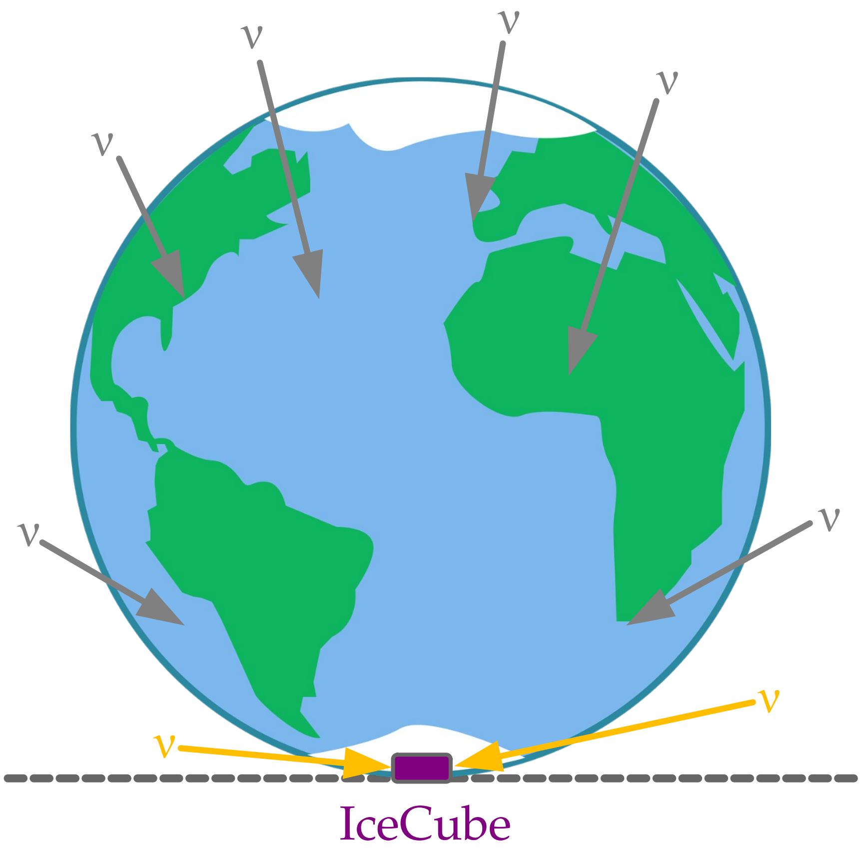
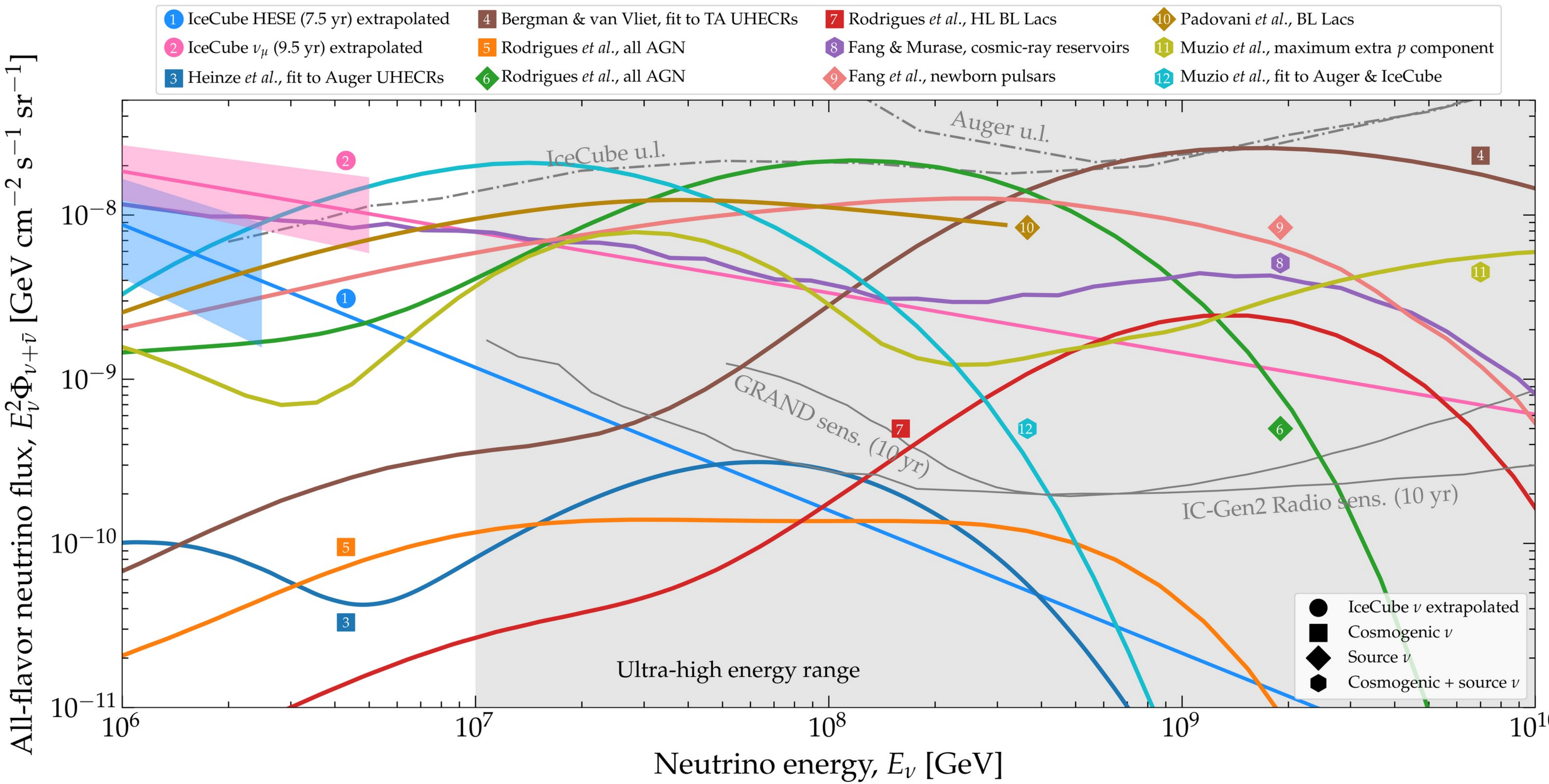
> 100 PeV:



Earth is *completely* opaque,
but horizontal ν still make it through



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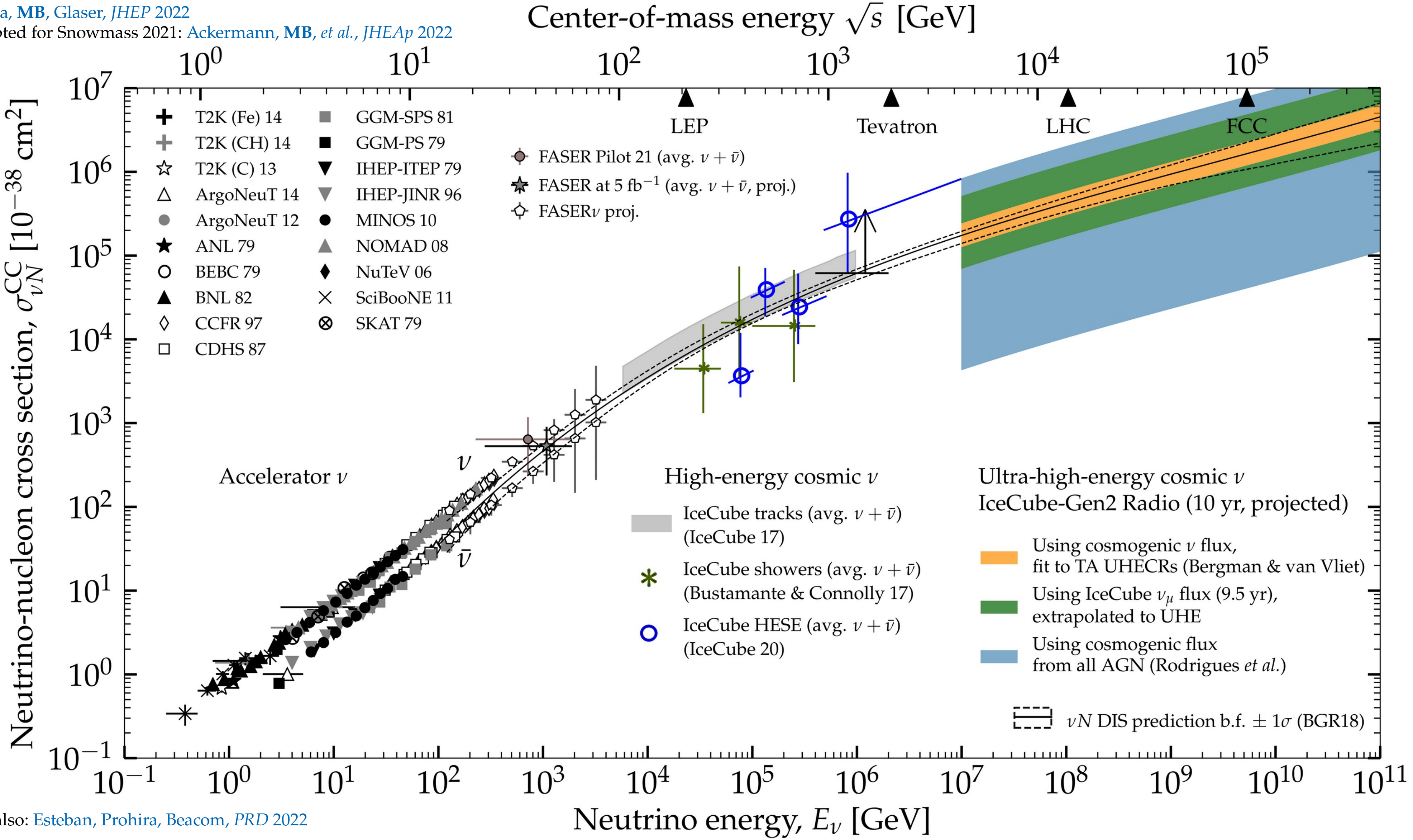
Valera, **MB**, Glaser, *JHEP* 2022
Adapted for Snowmass 2021: Ackermann, **MB**, *et al.*, *JHEAp* 2022



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

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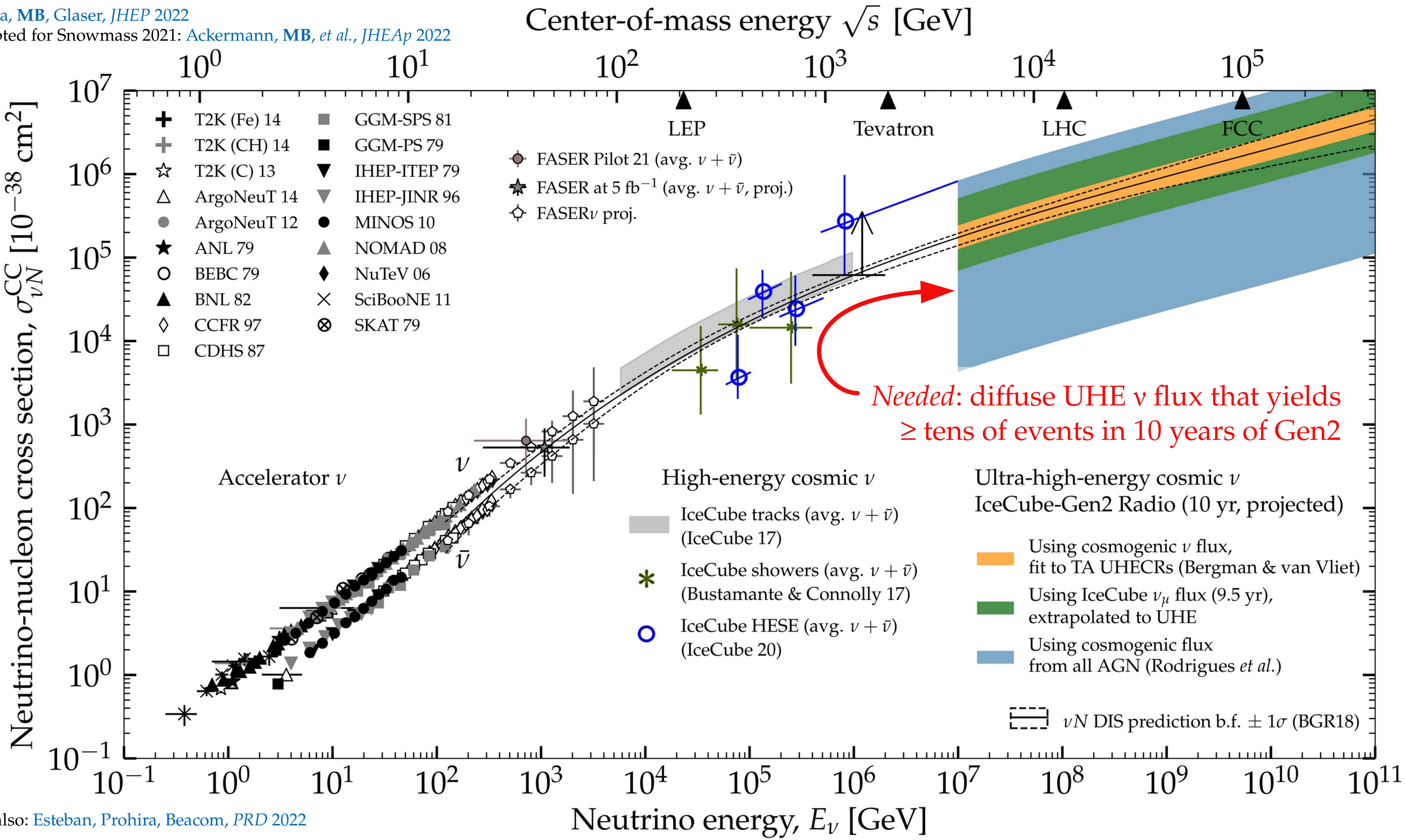

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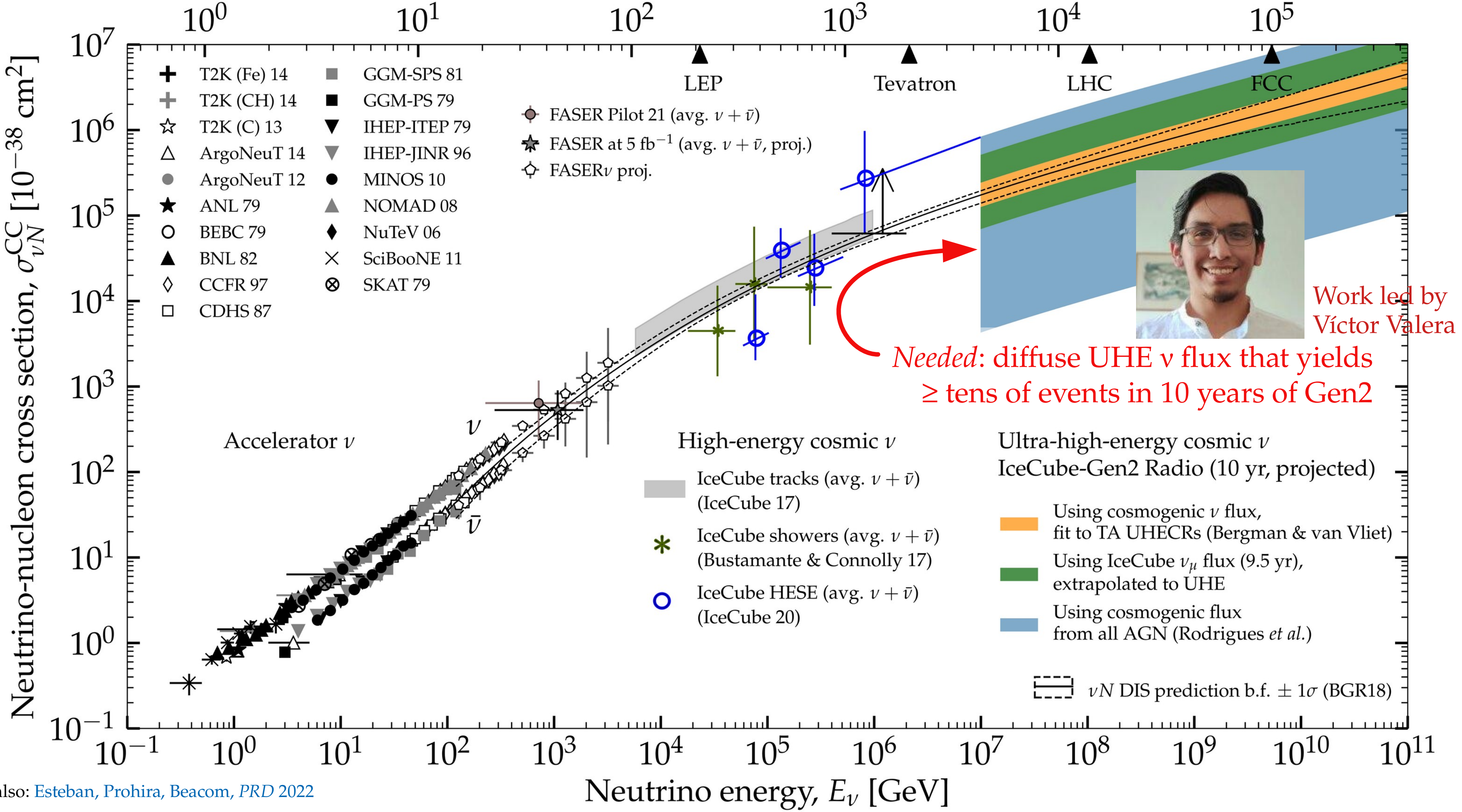

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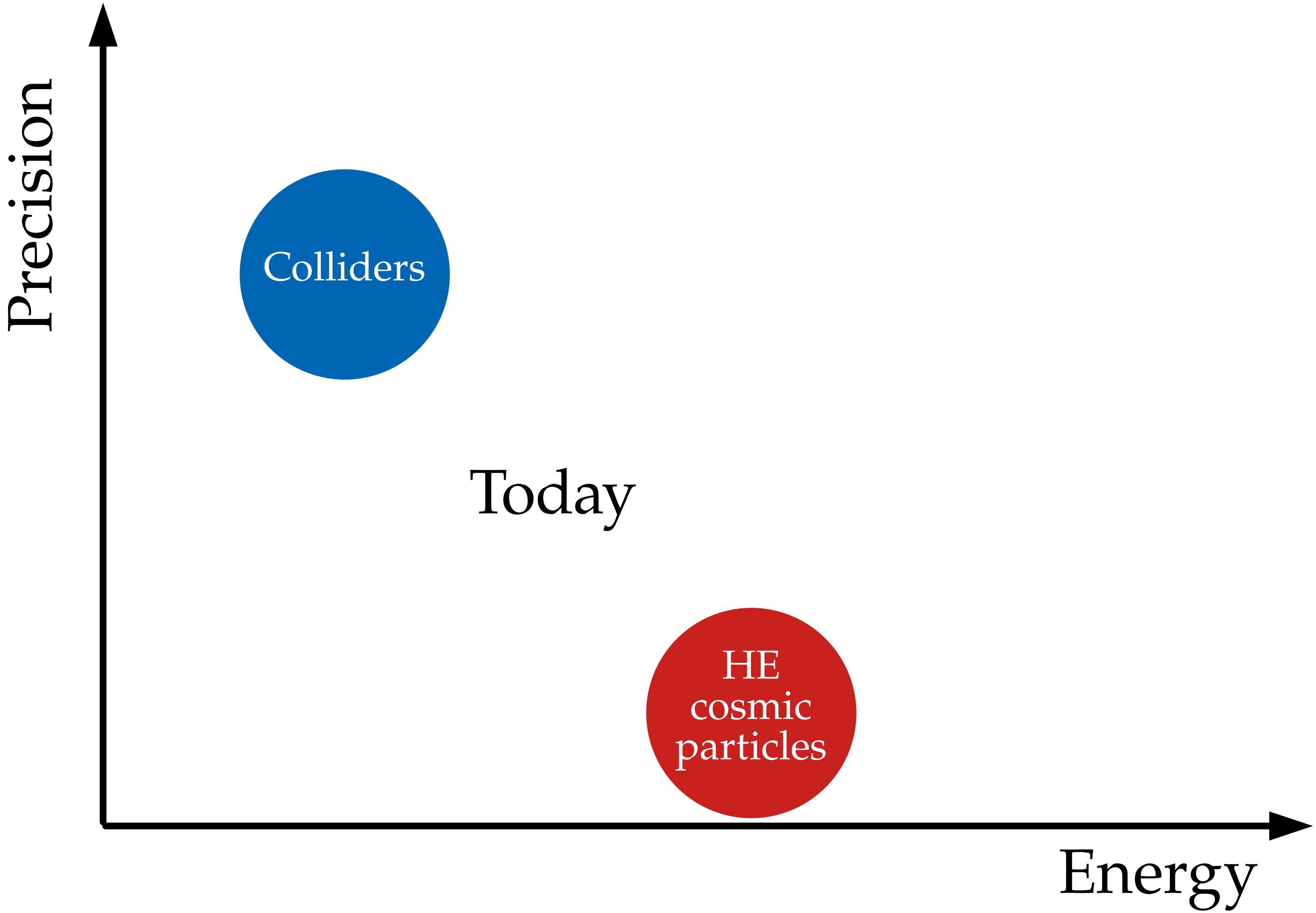
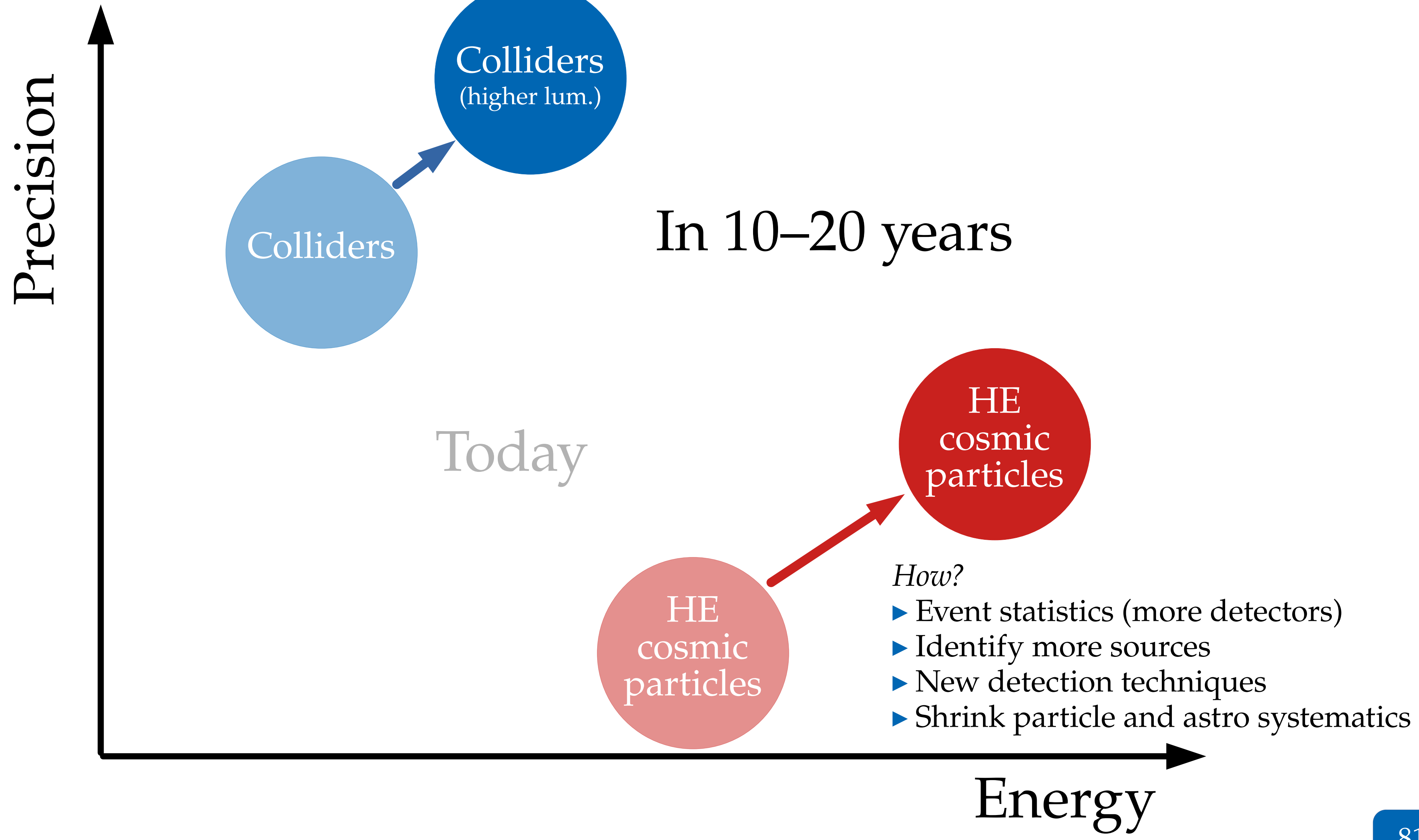
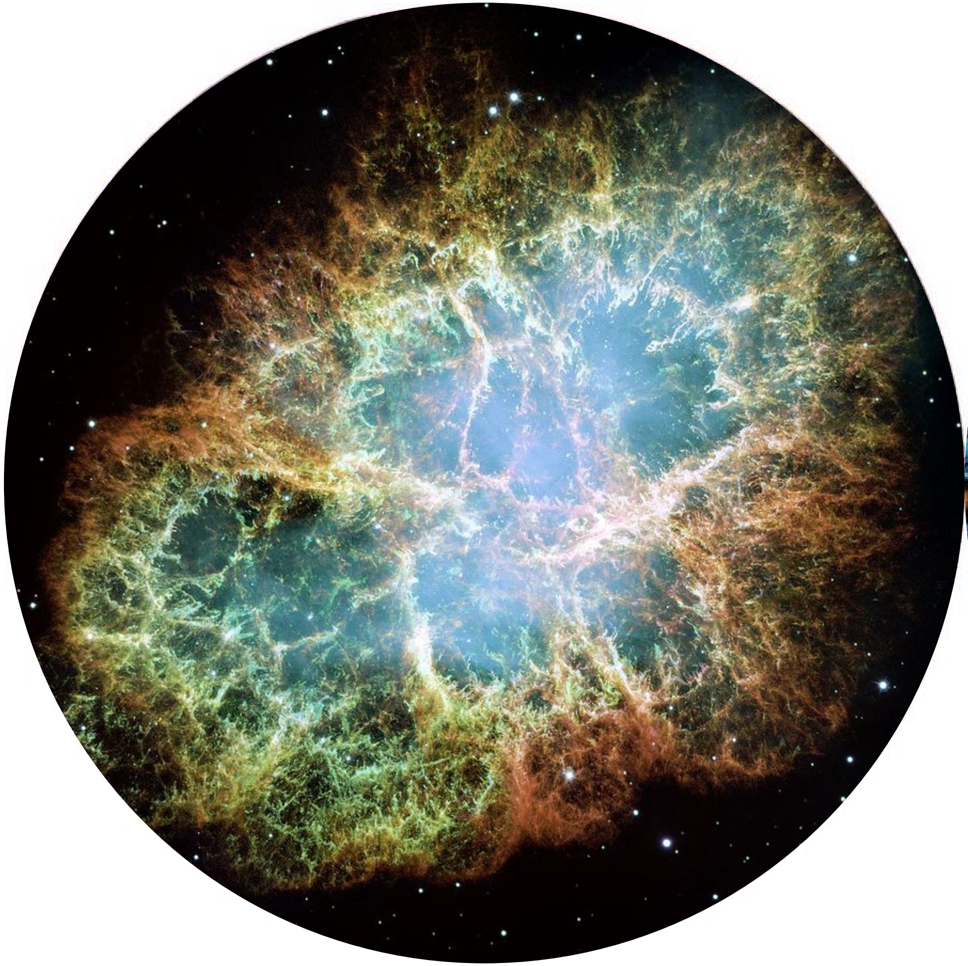
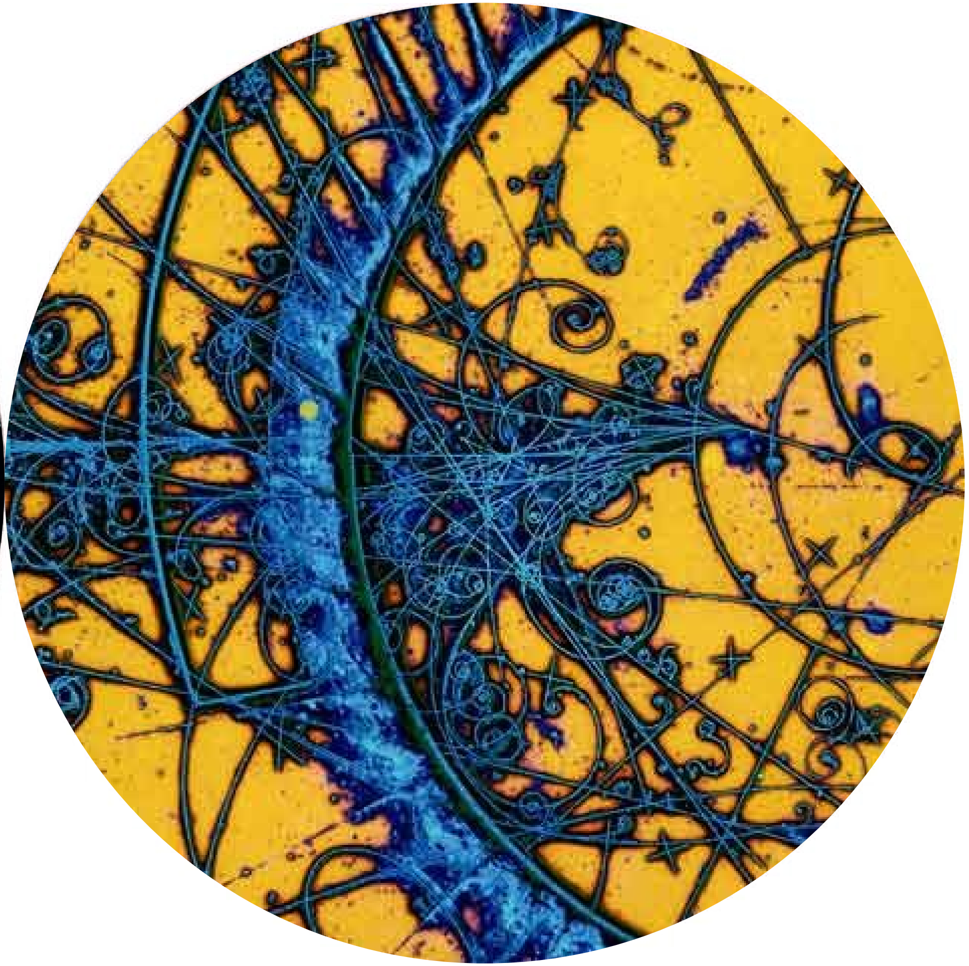
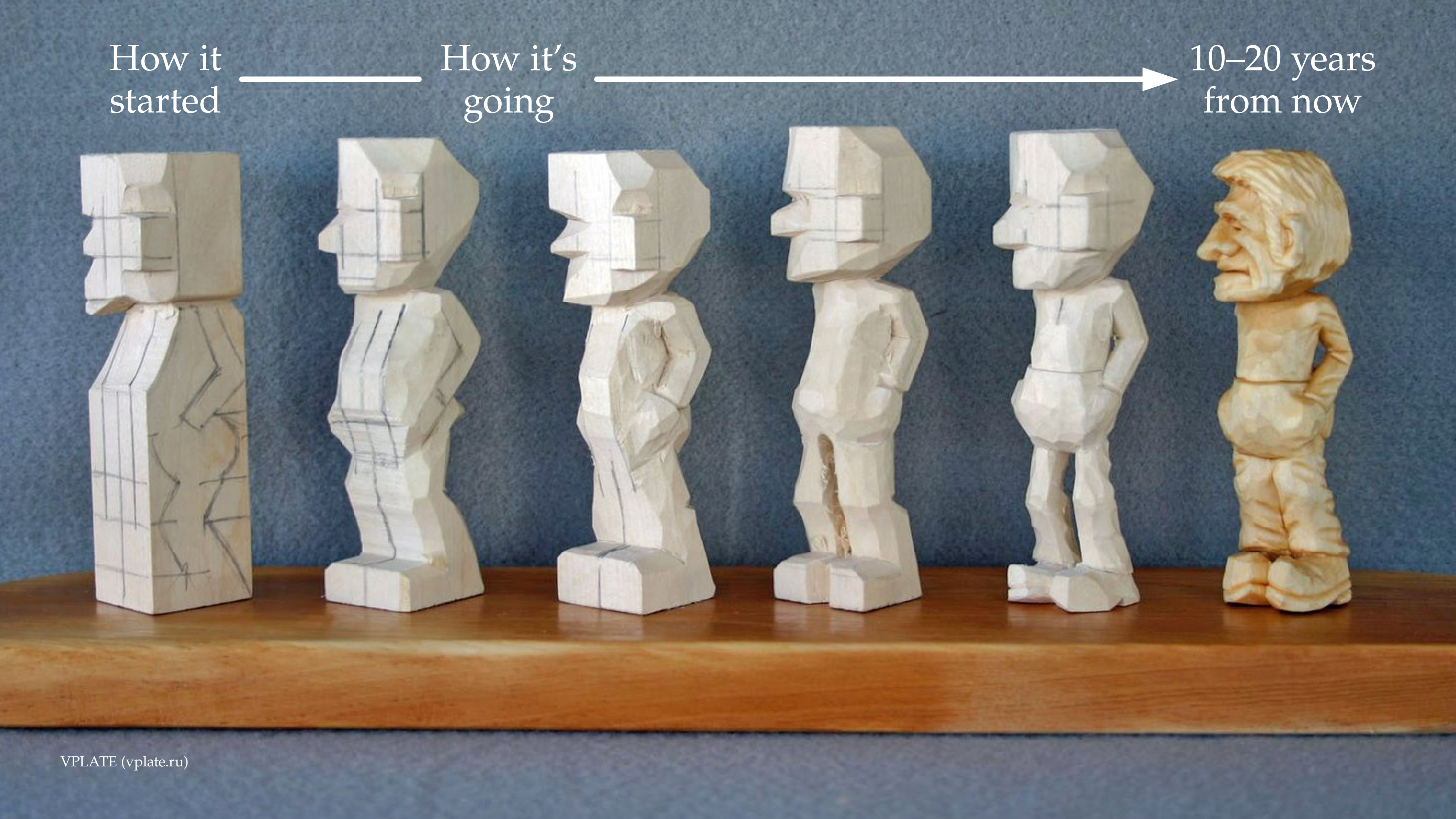

Precision
Colliders
Today
HE cosmic particles
Energy

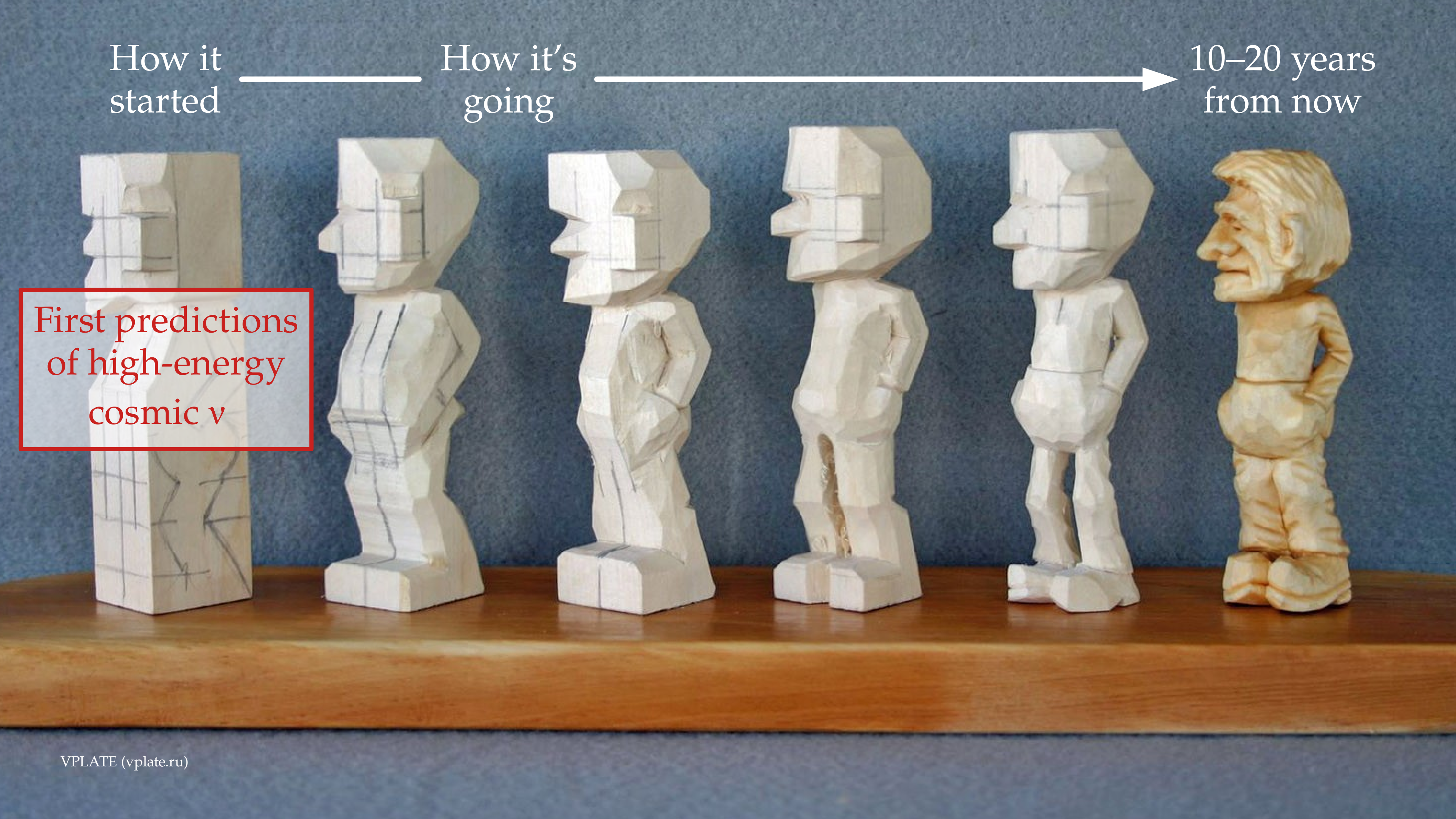

Precision
Colliders
(higher lum.)
Colliders
In 10–20 years
Today
HE cosmic particles
HE cosmic particles
How?
Event statistics (more detectors)
Identify more sources
New detection techniques
Shrink particle and astro systematics
Energy

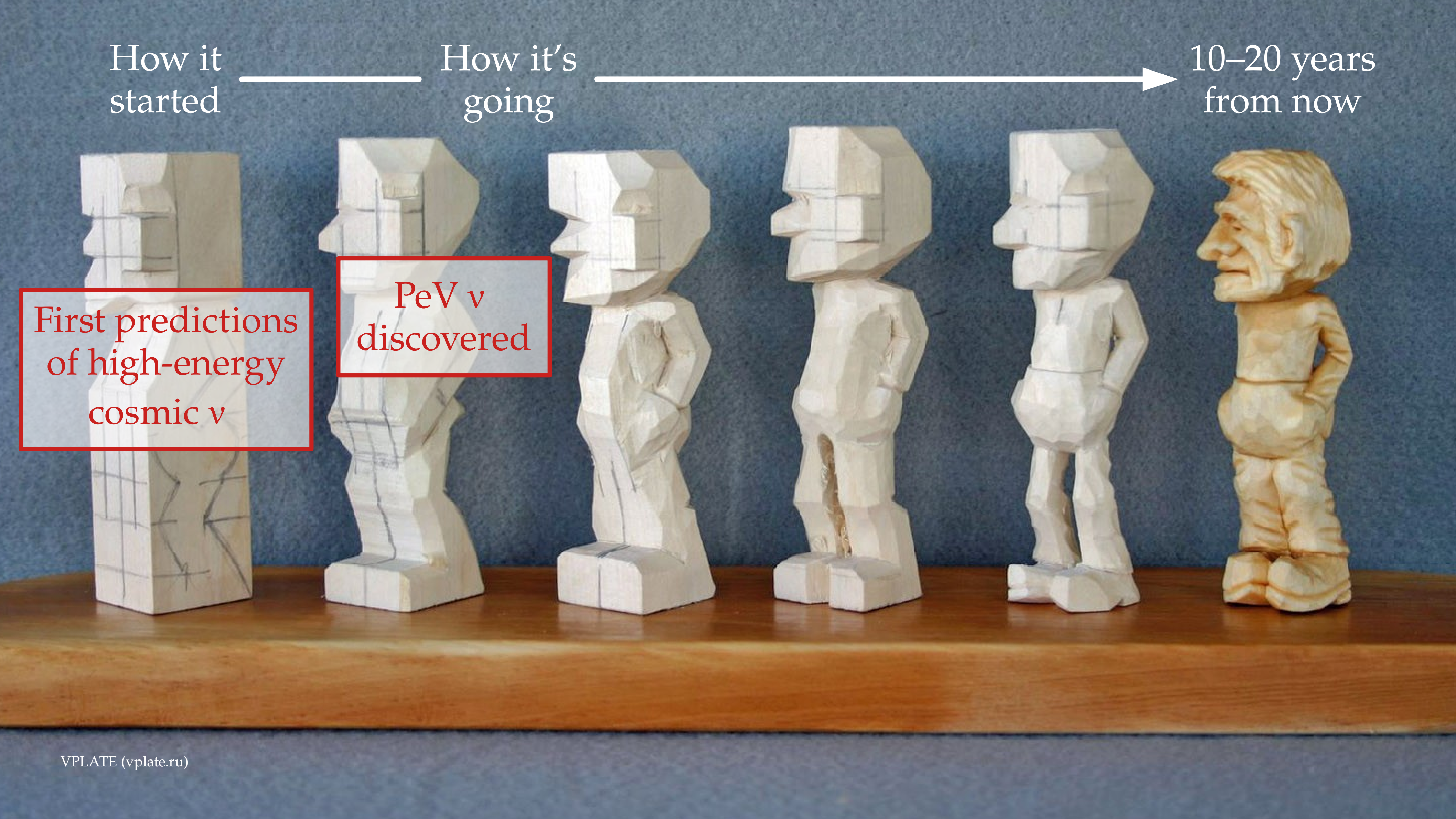




Banco Central de Reserva del Perú / NASA / ESA / CERN / Symmetry Magazine


How it started
How it's going
10–20 years from now
VPLATE (vplate.ru)


How it started
How it's going
10–20 years from now
First predictions of high-energy cosmic ν
VPLATE (vplate.ru)


How it started
How it's going
10–20 years from now
First predictions of high-energy cosmic ν
PeV ν discovered
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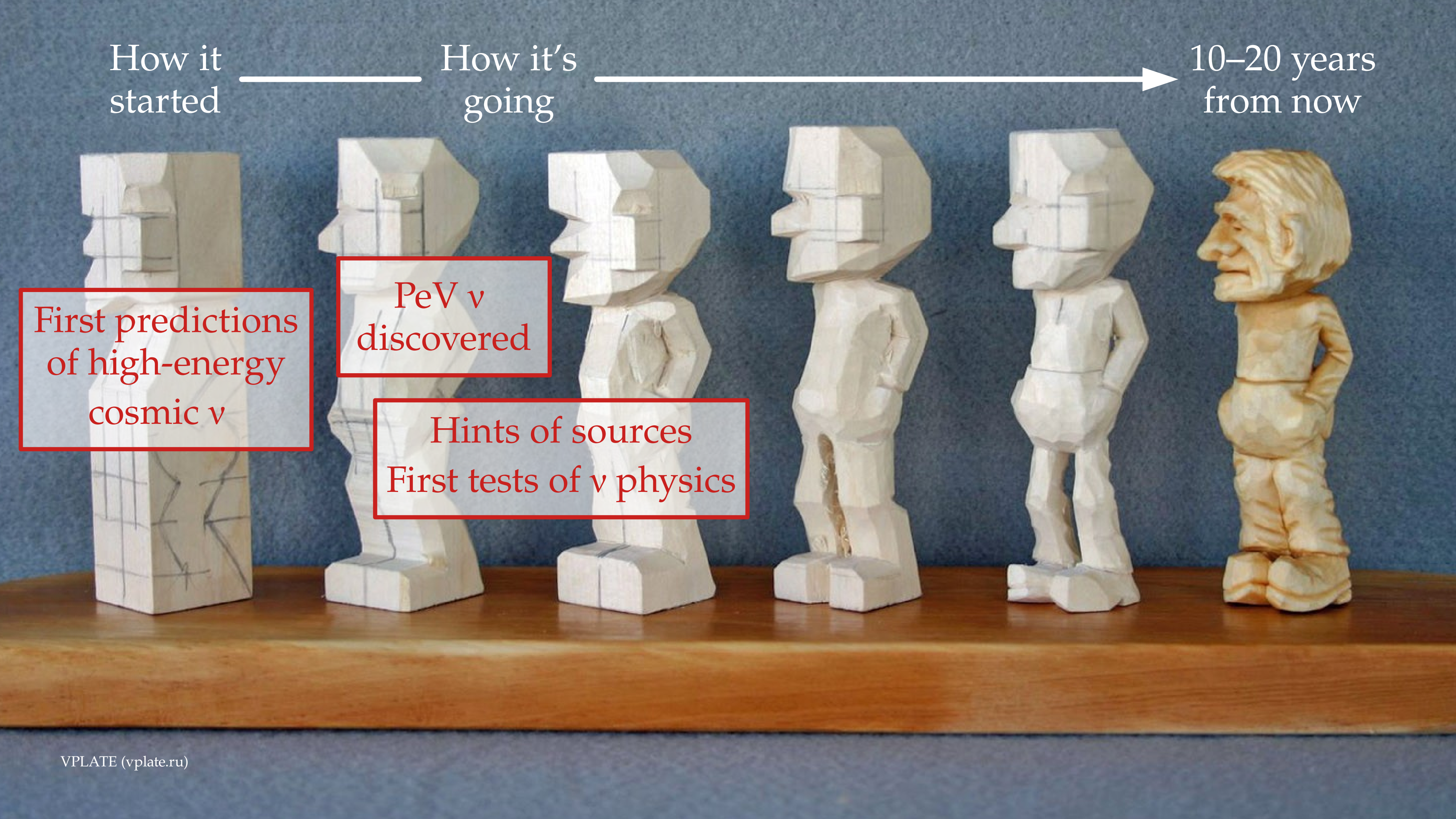
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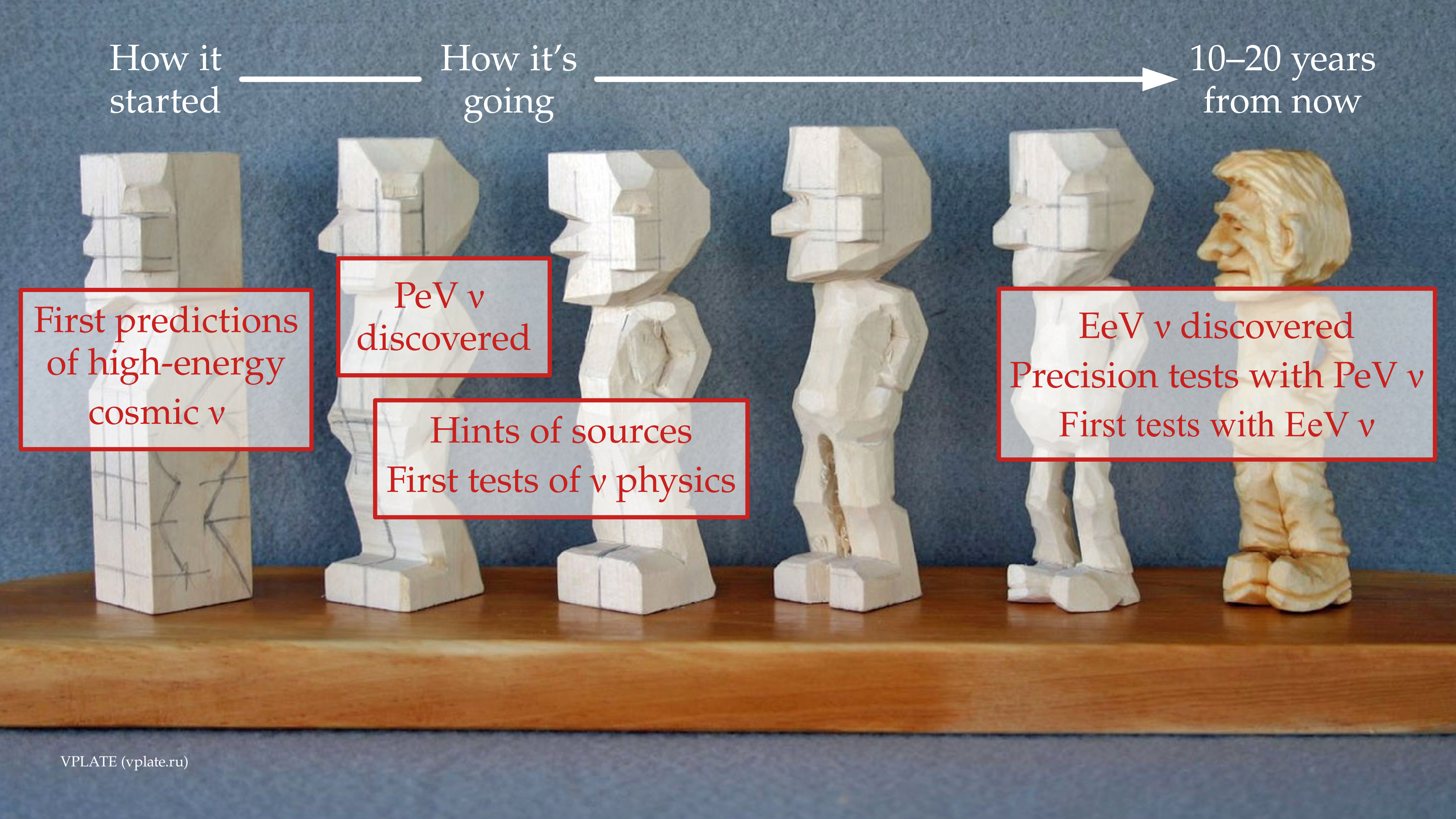
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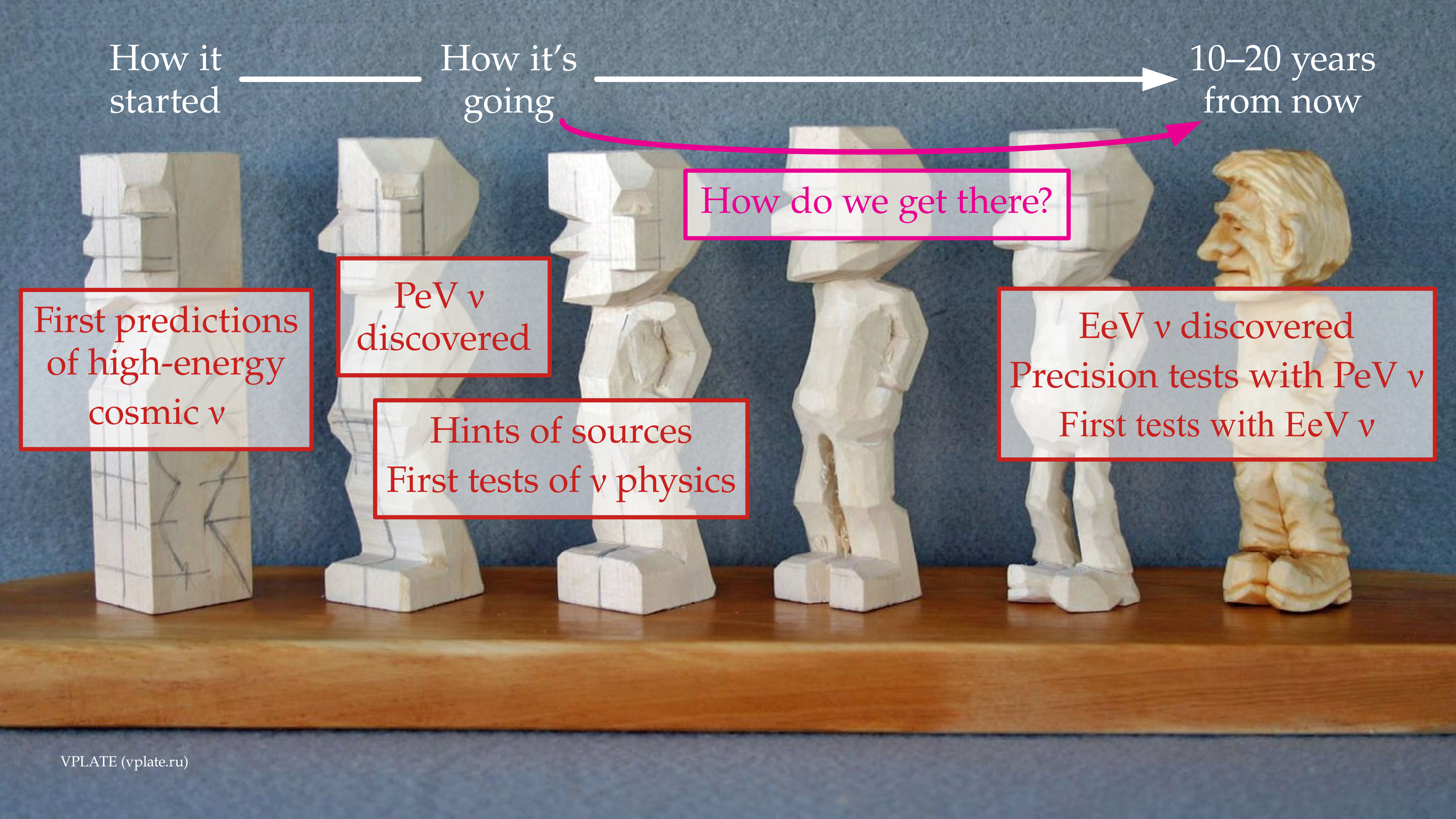

How it started
How it's going
10–20 years from now
How do we get there?
First predictions of high-energy cosmic ν
PeV ν discovered
Hints of sources
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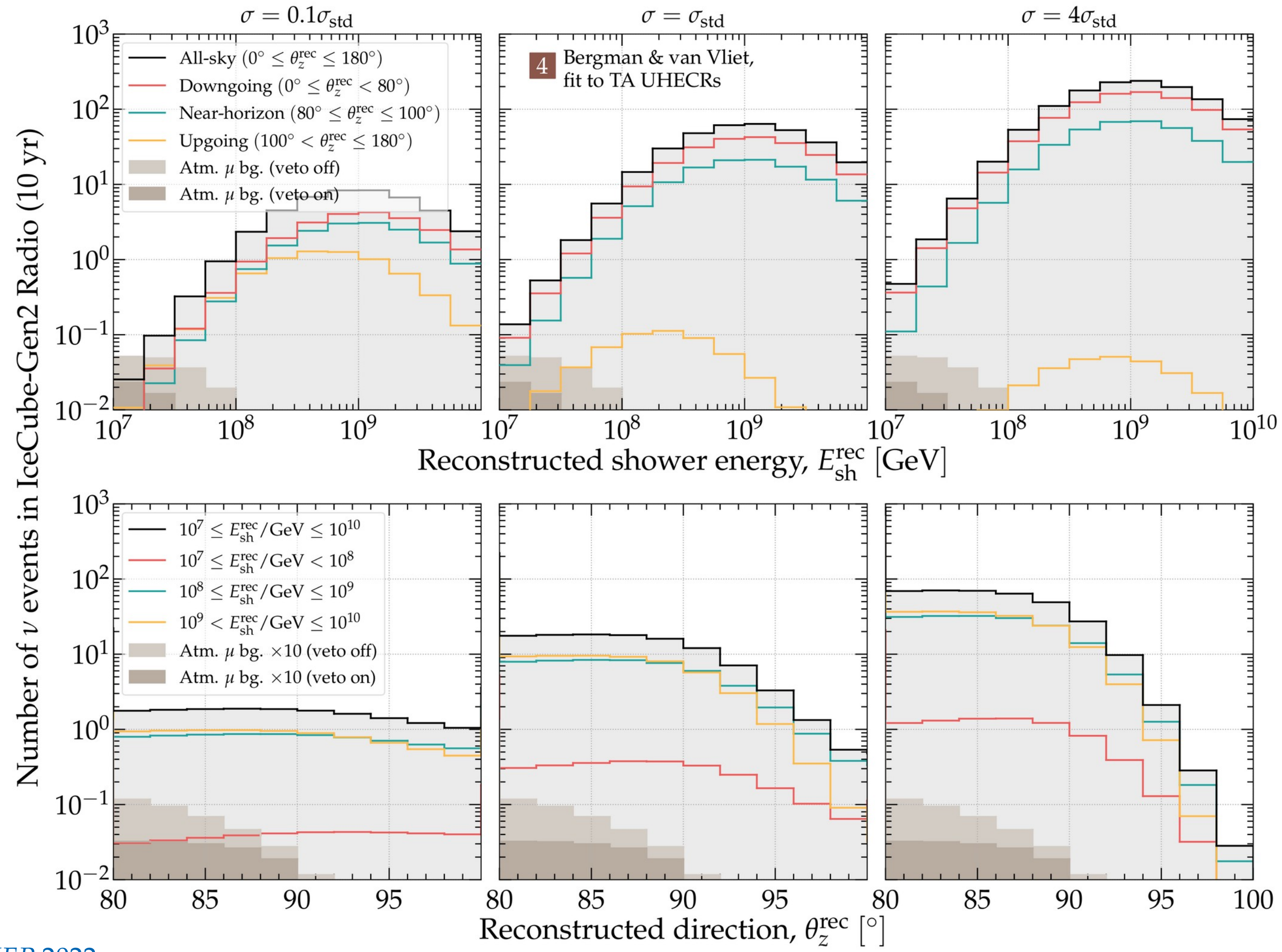
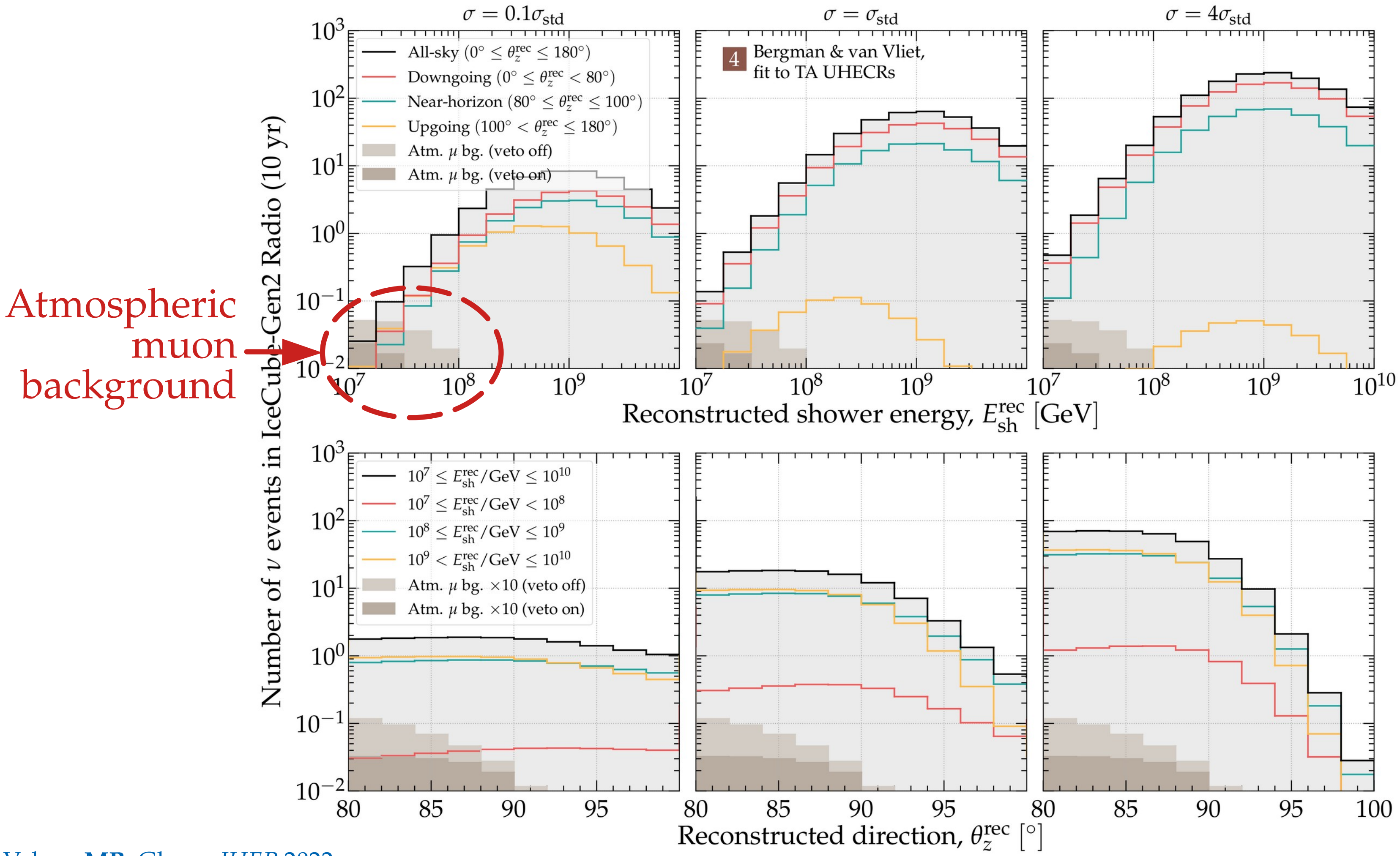
VPLATE (vplate.ru)

Thanks!

Backup slides

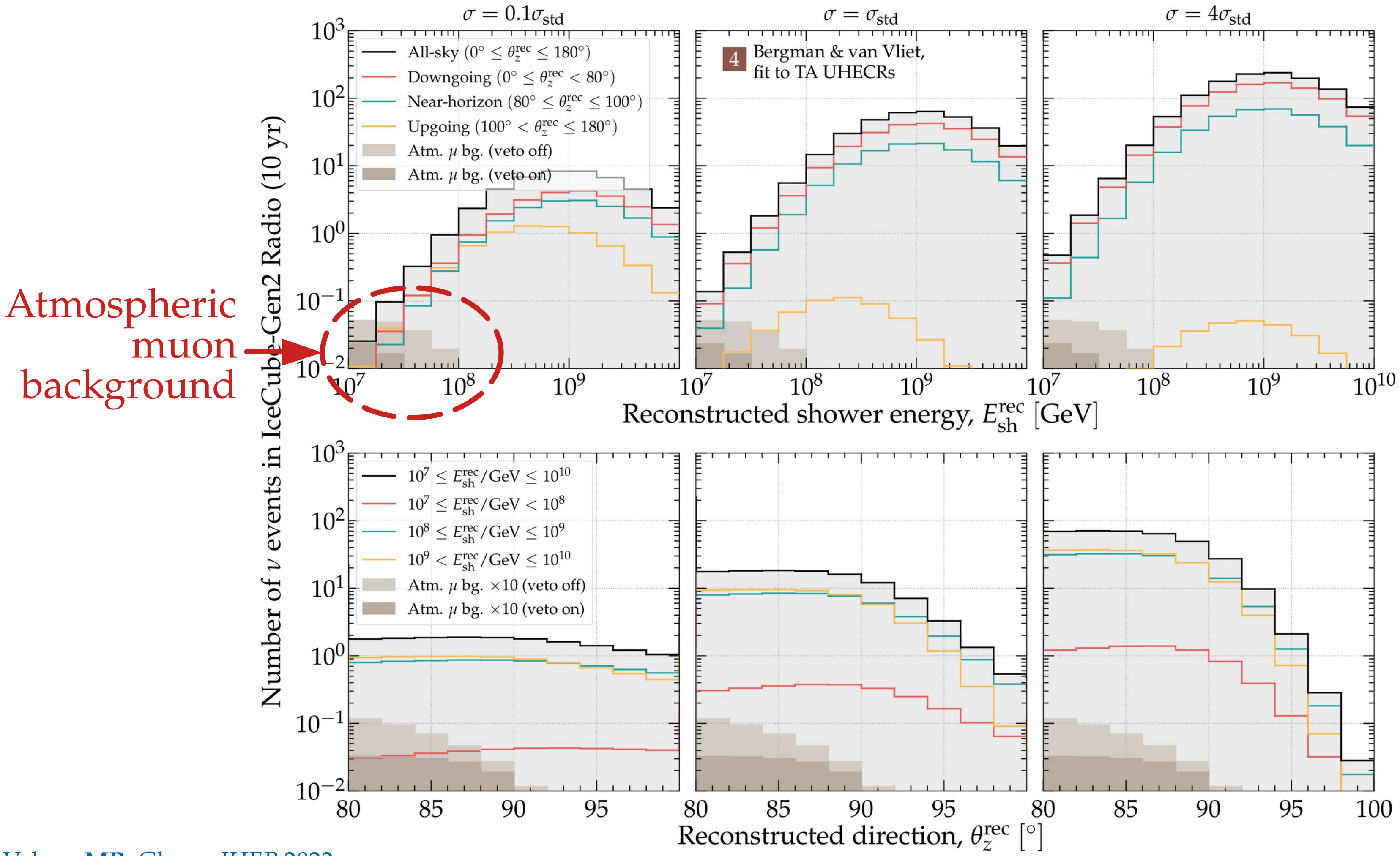


Valera, **MB**, Glaser, *JHEP* 2022



Valera, **MB**, Glaser, *JHEP* 2022

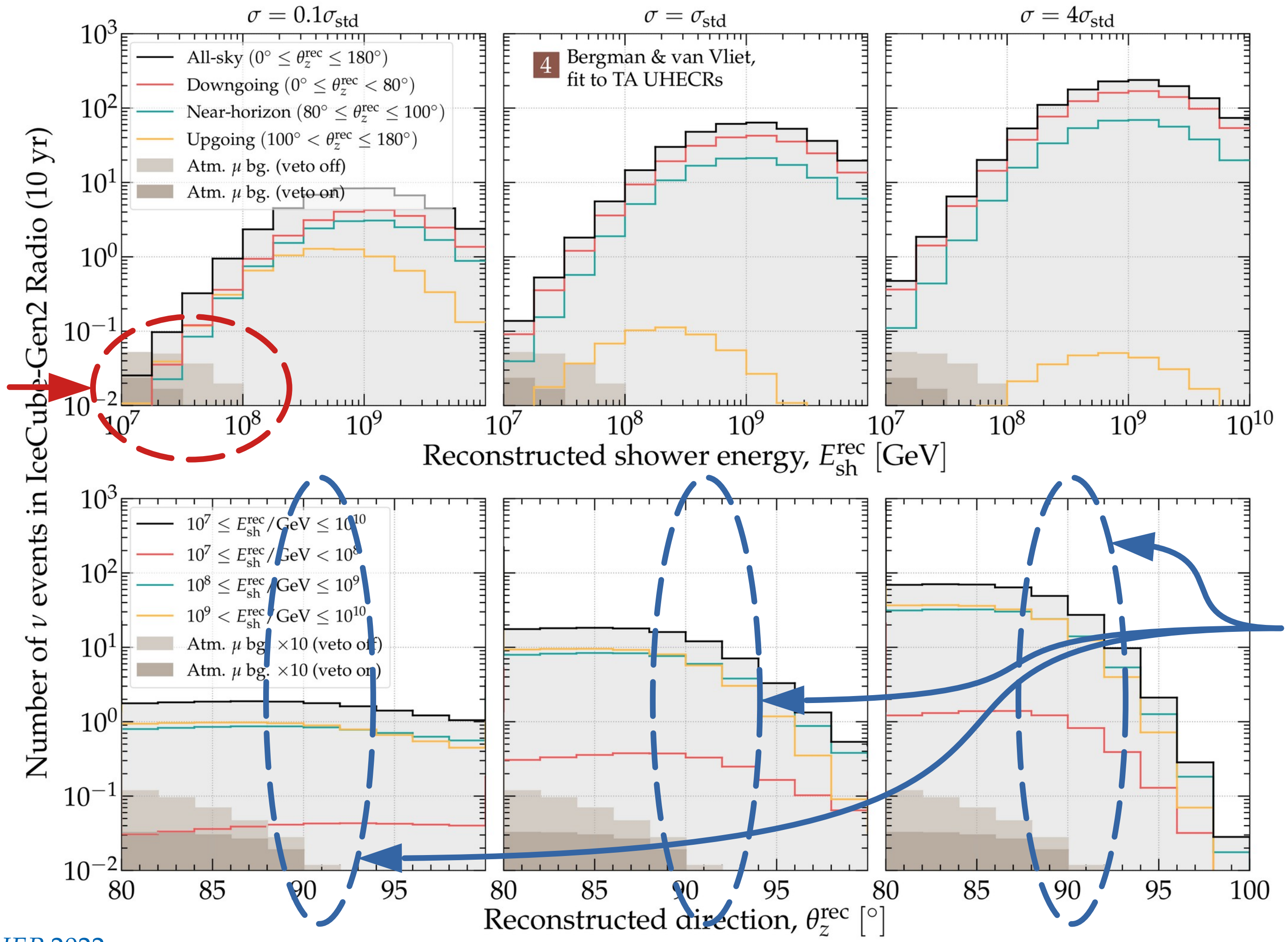
Larger neutrino-nucleon cross section



Valera, **MB**, Glaser, *JHEP* 2022

Larger neutrino-nucleon cross section

Atmospheric muon background



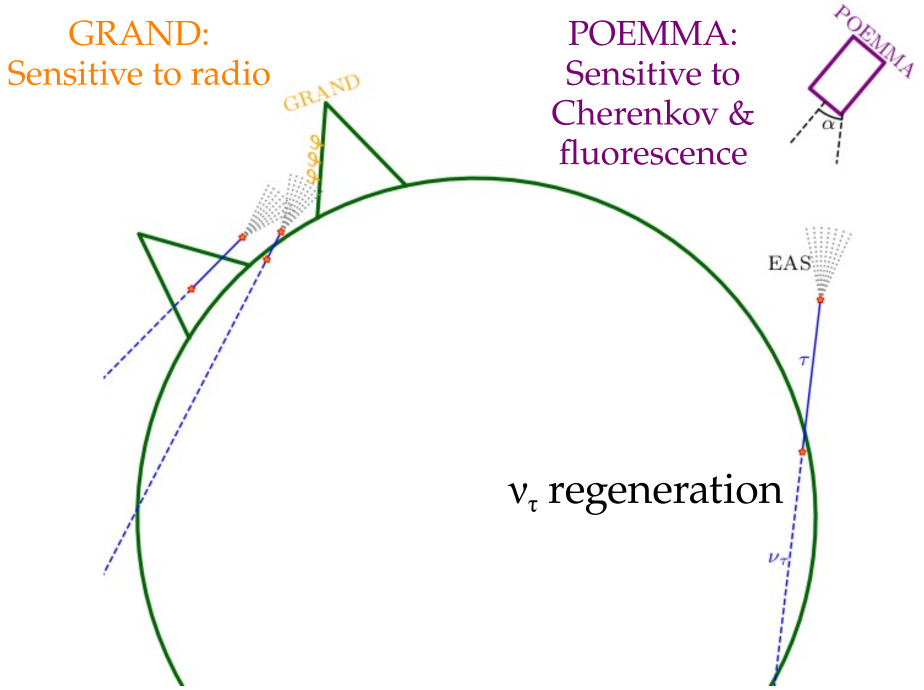
Sensitivity to cross section comes from horizontal neutrinos

Valera, **MB**, Glaser, *JHEP* 2022

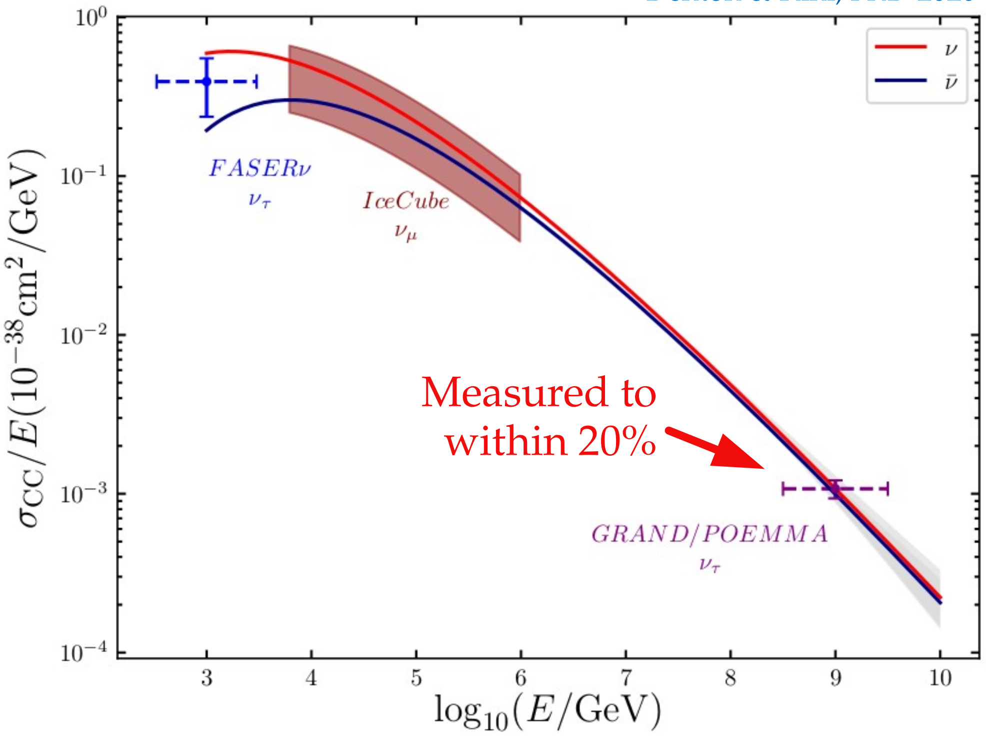
GRAND & POEMMA

Both sensitive to extensive air showers induced by Earth-skimming UHE ν_τ

If they see 100 events from ν_τ with initial energy of 10^9 GeV (pre-attenuation):



Denton & Kini, *PRD* 2020



Measuring the high-energy *νN* cross section

Number of detected neutrinos (simplified for presentation):

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

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

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Downgoing neutrinos
(L short → no matter)

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

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(L short $\rightarrow$ no matter)

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Upgoing neutrinos
(L long $\rightarrow$ lots of matter)

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Downgoing neutrinos
(L short → no matter)

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

Upgoing neutrinos
(L long → lots of matter)

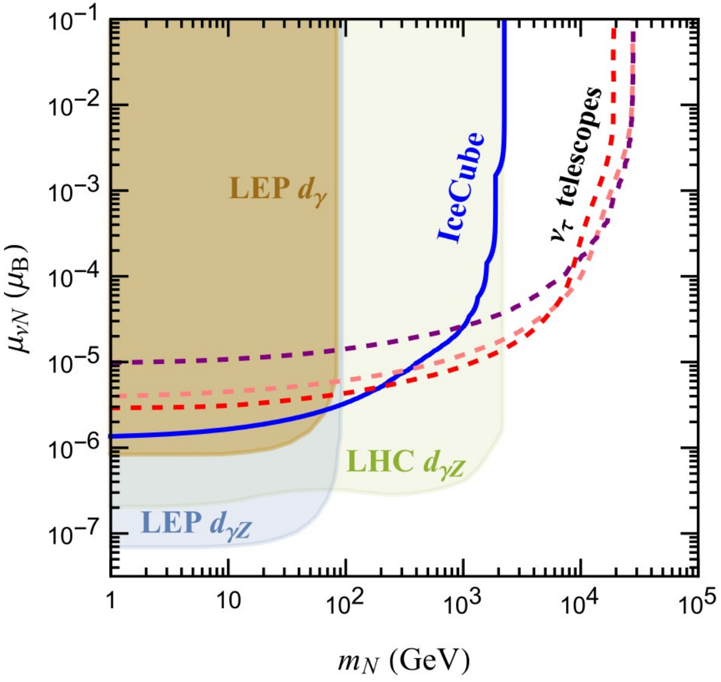
$$N \propto \Phi_\nu \sigma_{\nu N} \underbrace{e^{-L \sigma_{\nu N} n_N}}_{\text{Breaks the degeneracy}}$$

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

New physics in the UHE νN cross section

New physics in the UHE νN cross section

Heavy sterile neutrinos
via the dipole portal



Huang, Jana, Lindner, Rodejohann, 2204.10347

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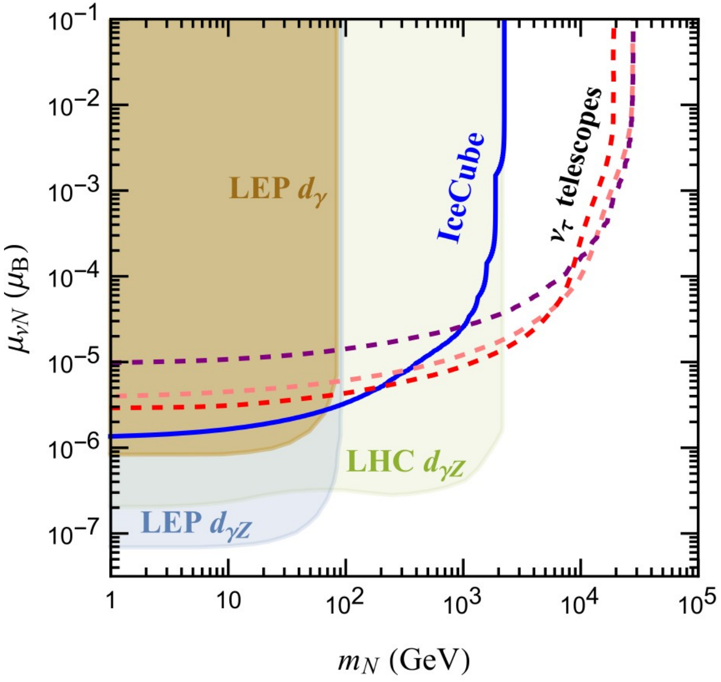
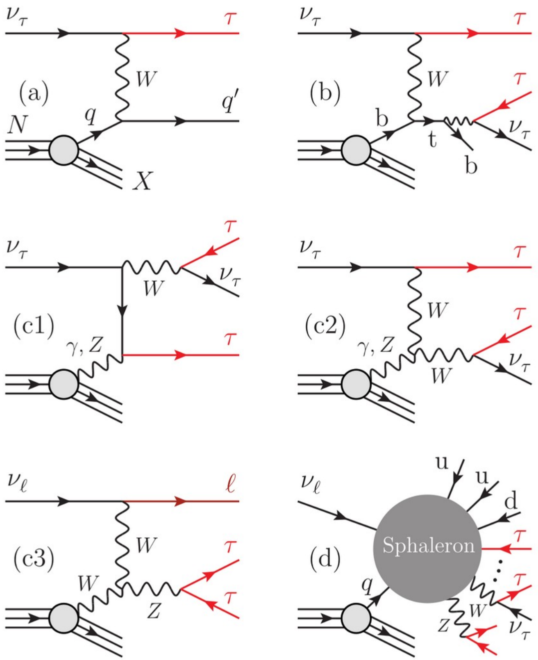


Huang, Jana, Lindner, Rodejohann, 2204.10347

Multiple ν_τ-induced bangs



Huang, *EPJC* 2022 [2207.02222]

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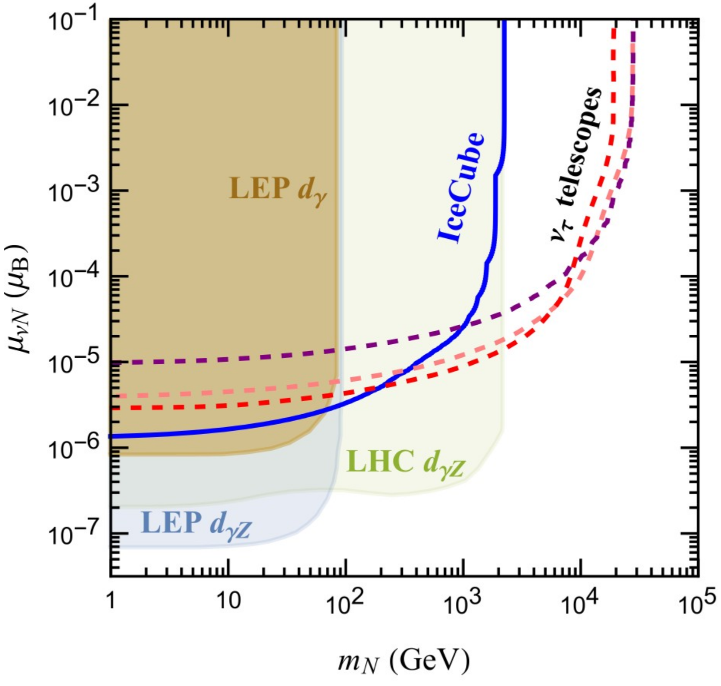

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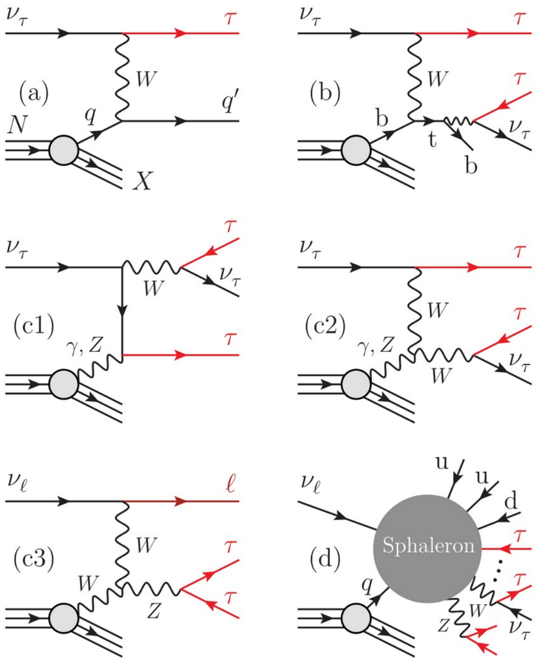
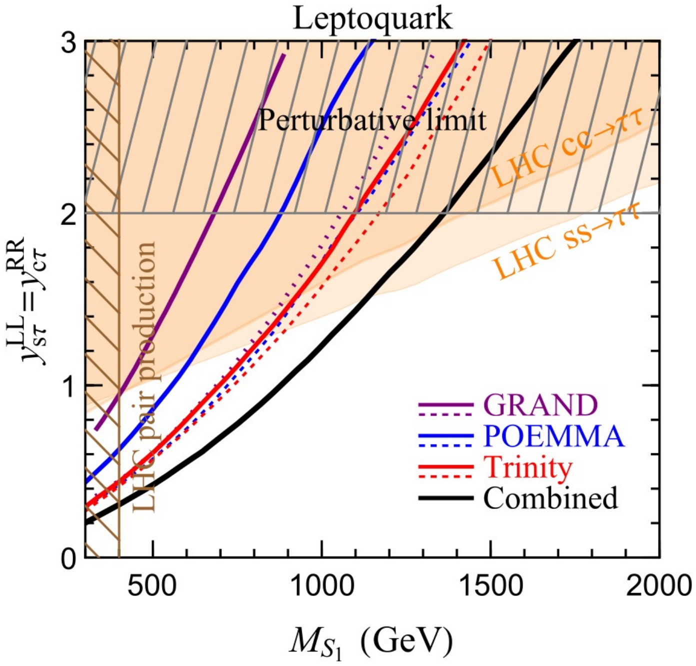
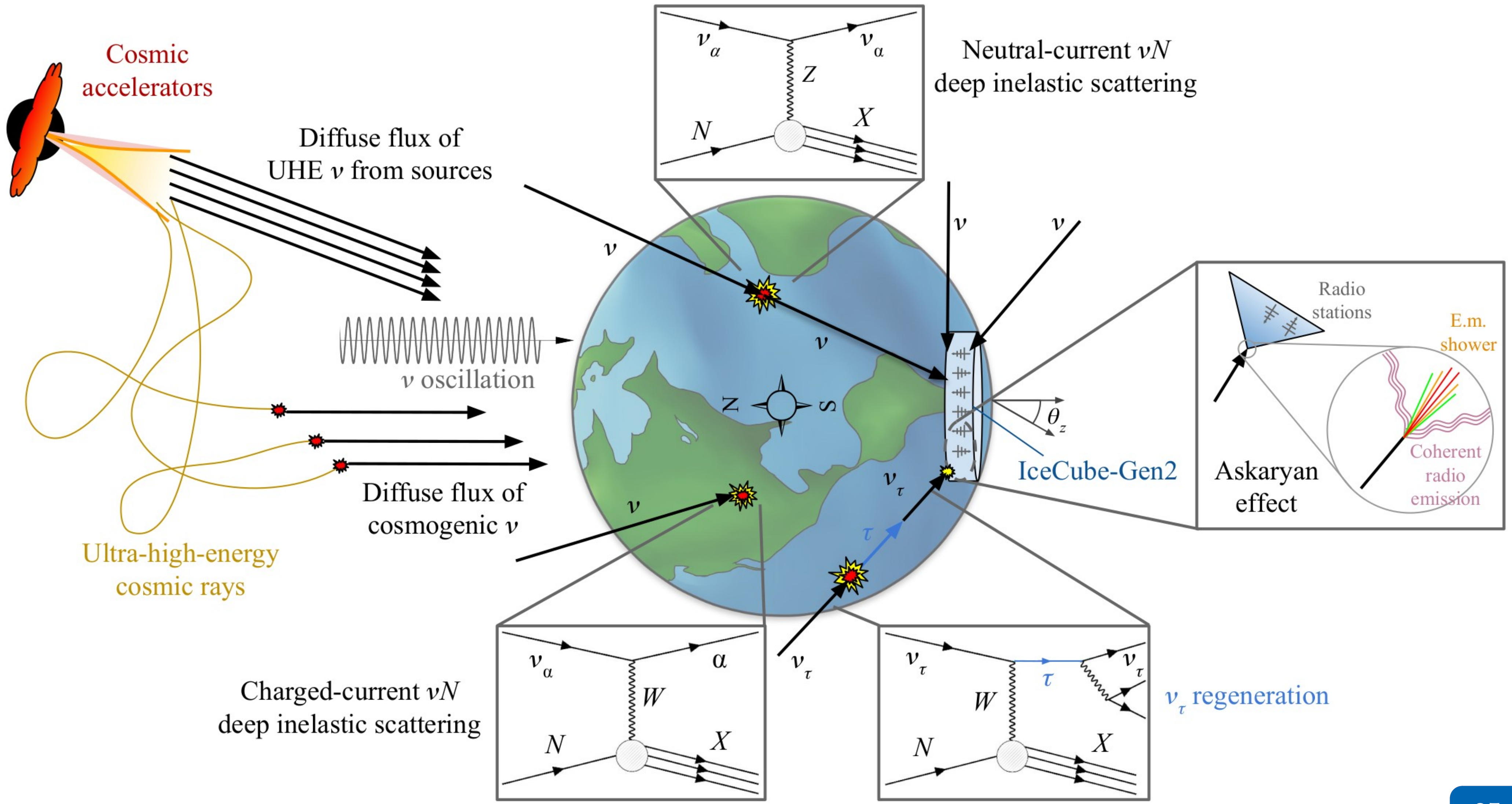


Huang, *EPJC* 2022 [2207.02222]

Leptoquarks, charged Higgs, *etc*.



Huang, Jana, Lindner, Rodejohann, *JCAP* 2022 [2112.09476]

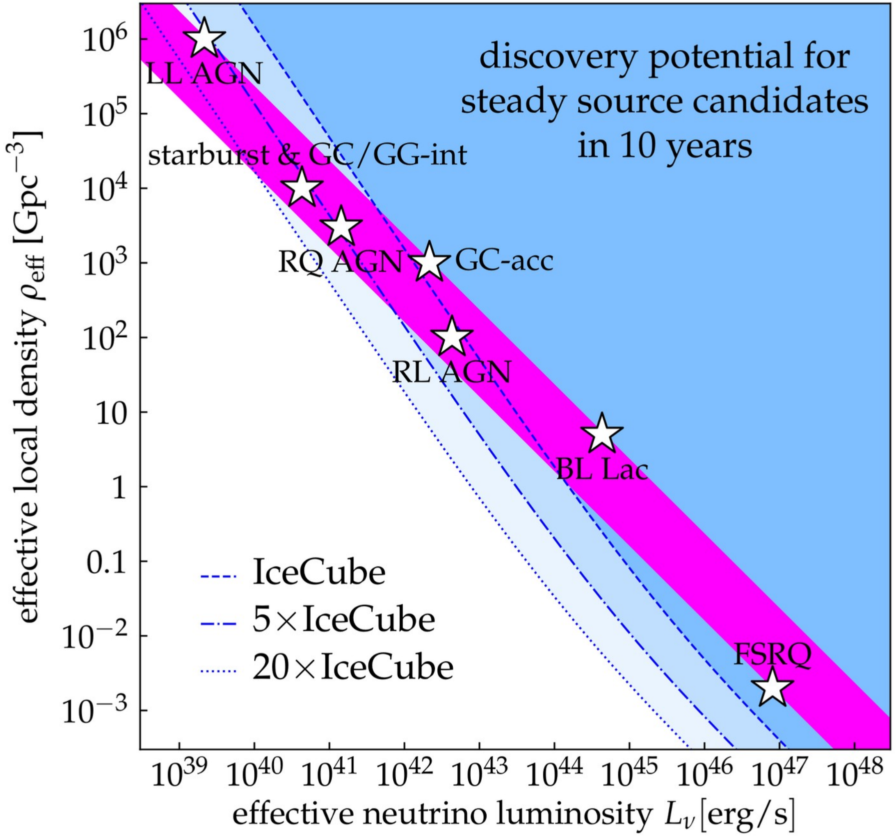


Valera, **MB**, Glaser, *JHEP* 2022 [2204.04237]

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 $E^2\phi_{\nu_\mu+\bar{\nu}_\mu} = 10^{-9}\ \mathrm{GeV cm^{-2} s^{-1}}$



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

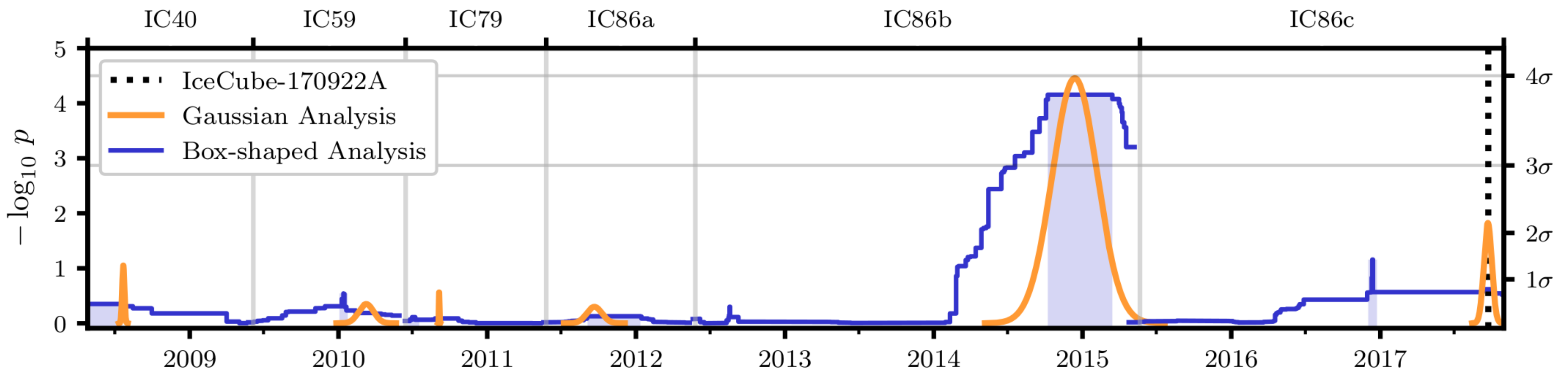
Many TeV–EeV
ν telescopes
in planning for
2020–2040

				Flavor		Technique			Neutrino Target					Geometry					
Experiments	Phase & Online Date	Energy Range	Site	Tau	All Flavor	Optical / UV	Radio	Showers	H_2O	Atmosphere	Earth's limb	Topography	Lunar Regolith	Embedded	Planar Arrays	Valley	Mountains	Balloon	Satellite
IceCube	2010	TeV-EeV	South Pole		✓	✓			✓					✓					
KM3NeT	2021	TeV-PeV	Mediteranean		✓	✓			✓					✓					
Baikal-GVD	2021	TeV-PeV	Lake Baikal		✓	✓			✓					✓					
P-ONE	2020	TeV-PeV	Pacific Ocean		✓	✓			✓					✓					
IceCube-Gen2	2030+	TeV-EeV	South Pole		✓	✓	✓		✓					✓					
ARIANNA	2014	>30 PeV	Moore's Bay		✓		✓		✓					✓					
ARA	2011	>30 PeV	South Pole		✓		✓		✓					✓					
RNO-G	2021	>30 PeV	Greenland		✓		✓		✓					✓					
RET-N	2024	PeV-EeV	Antarctica		✓		✓		✓					✓					
ANITA	2008,2014,2016	EeV	Antarctica	✓	✓		✓		✓		✓							✓	
PUEO	2024	EeV	Antarctica	✓	✓		✓		✓		✓							✓	
GRAND	2020	EeV	China / Worldwide	✓			✓			✓	✓	✓			✓		✓		
BEACON	2018	EeV	CA, USA/ Worldwide	✓			✓				✓	✓					✓		
TAROGE-M	2018	EeV	Antarctica	✓			✓				✓	✓					✓		
SKA	2029	>100 EeV	Australia		✓		✓						✓		✓				
Trinity	2022	PeV-EeV	Utah, USA	✓		✓					✓						✓		
POEMMA		>20 PeV	Satellite	✓	✓	✓				✓	✓								✓
EUSO-SPB	2022	EeV	New Zealand	✓		✓					✓							✓	
Pierre Auger	2008	EeV	Argentina	✓	✓			✓		✓	✓	✓			✓				
AugerPrime	2022	EeV	Argentina	✓	✓		✓	✓		✓	✓	✓			✓				
Telescope Array	2008	EeV	Utah, USA	✓	✓			✓		✓					✓				
TAx4		EeV	Utah, USA	✓	✓			✓											
TAMBO	2025-2026	PeV-EeV	Peru	✓				✓				✓				✓			

Operational	Date full operations began
Prototype	Date protoype operations began or begin
Planning	Projected full operations

Abraham *et al.* (inc. **MB**),
J. Phys. G: Nucl. Part. Phys. 59, 11 (2022) [2203.05591]

IceCube, *Science* 2018



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!

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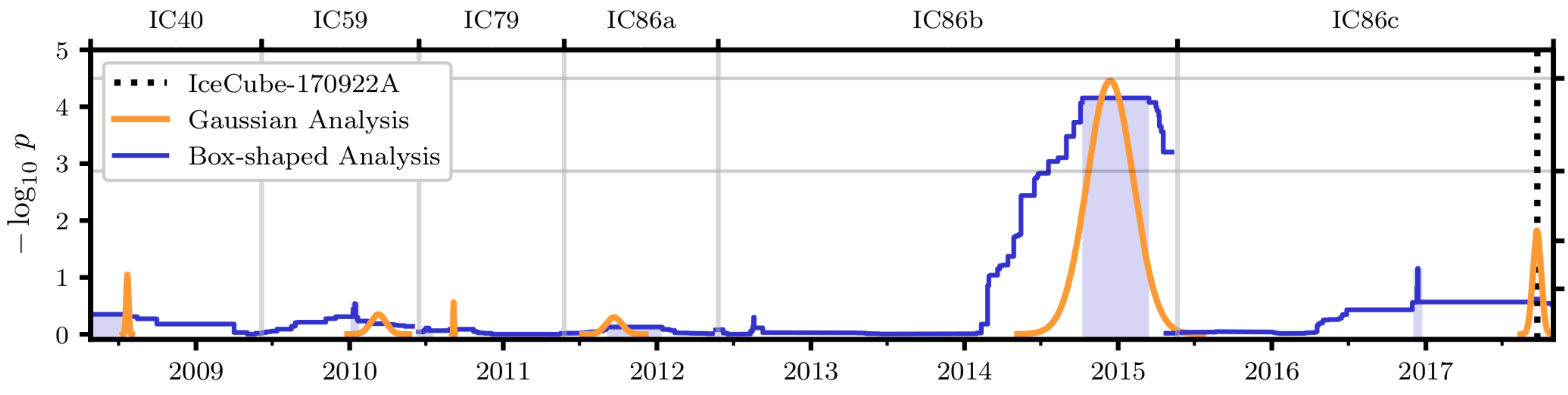

After re-analysis (2101.09836), significance dropped from $p=7\times10^{-5}$ to $p=8\times10^{-3}$

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3. Flavor:
Towards precision, finally

(with the help of lower-energy experiments)

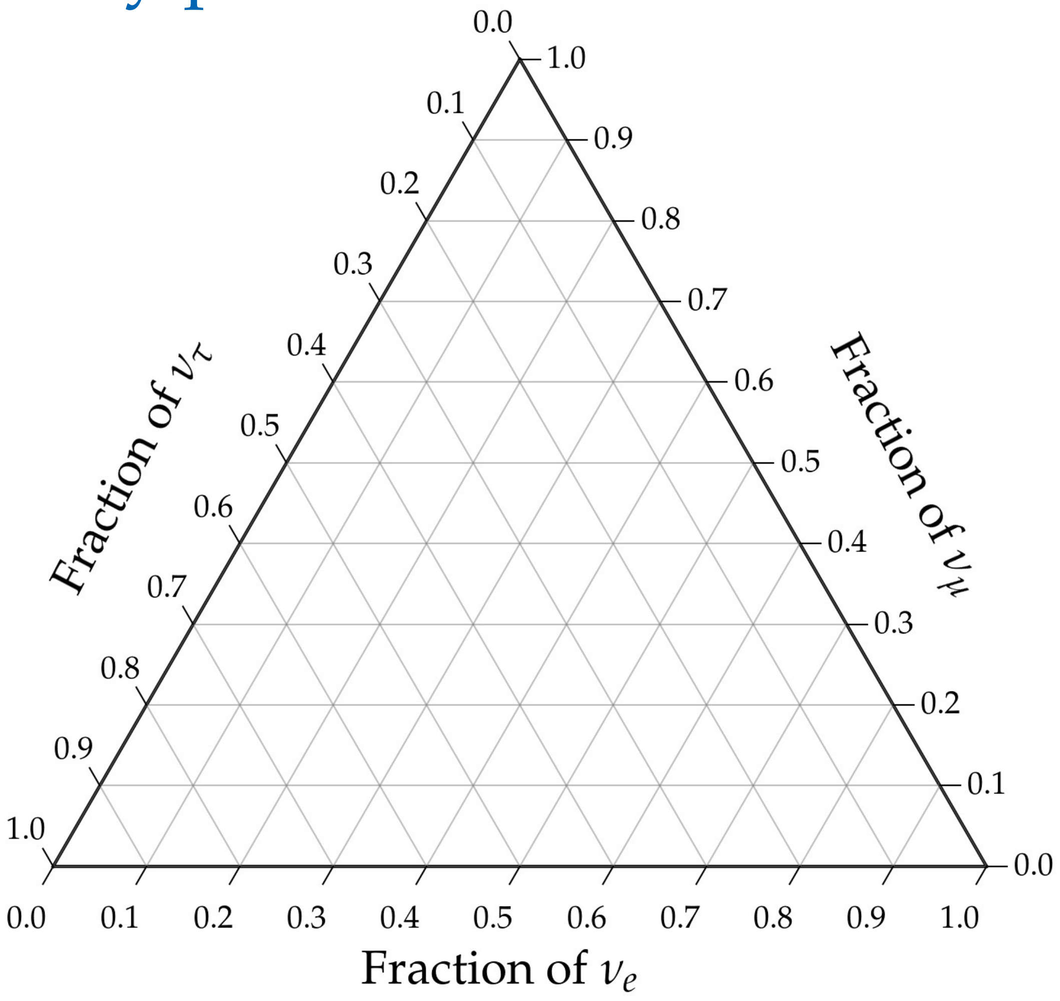
Quick aside: how to read a ternary plot

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

How to read it:

Follow the tilt of the tick marks

Always in this order: (f_e, f_μ, f_τ)



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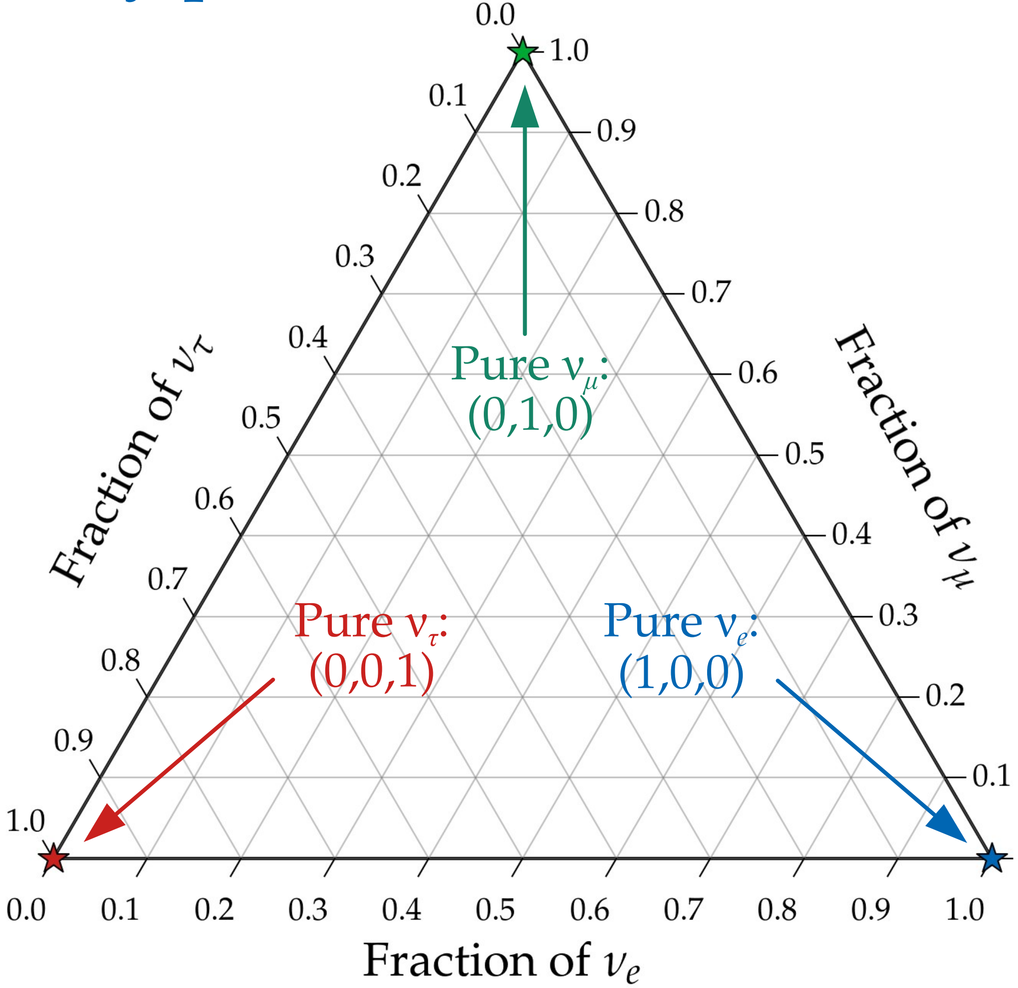

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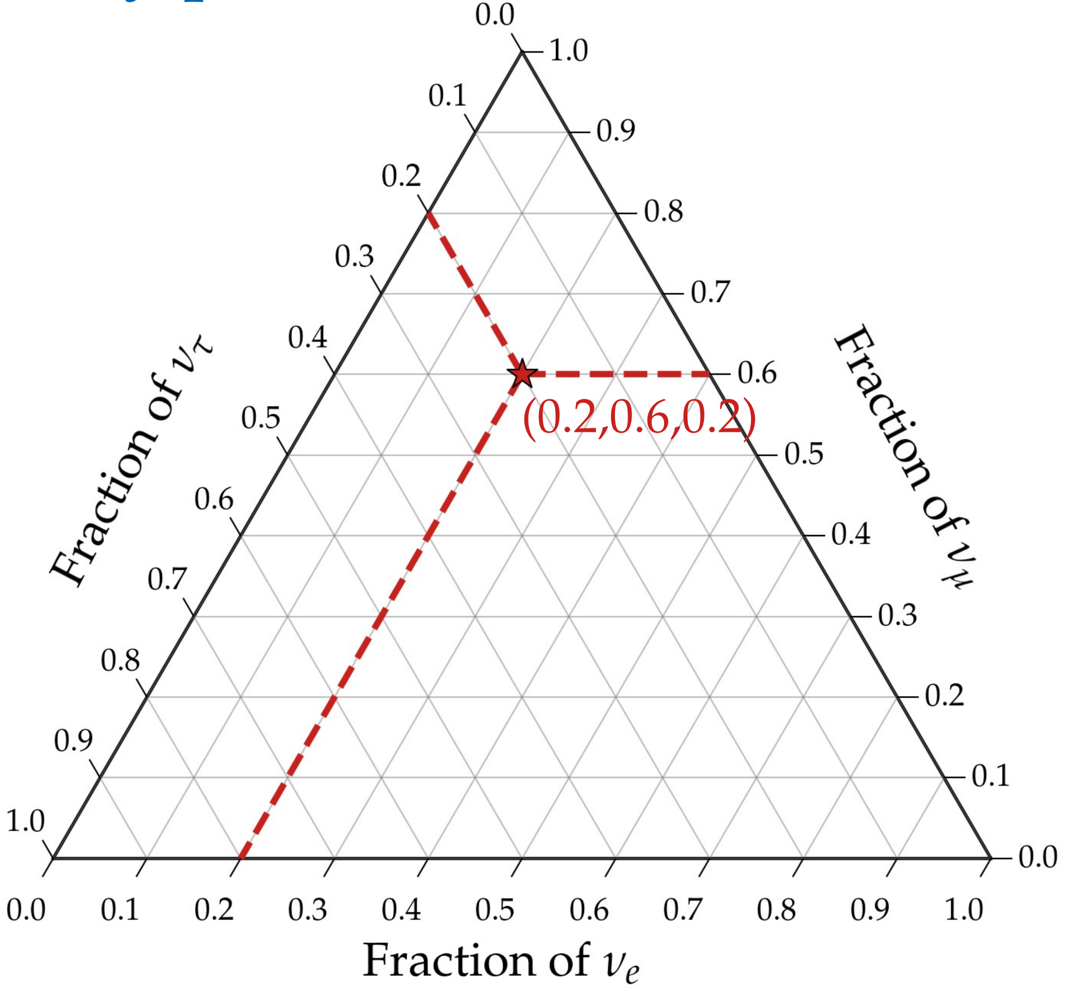

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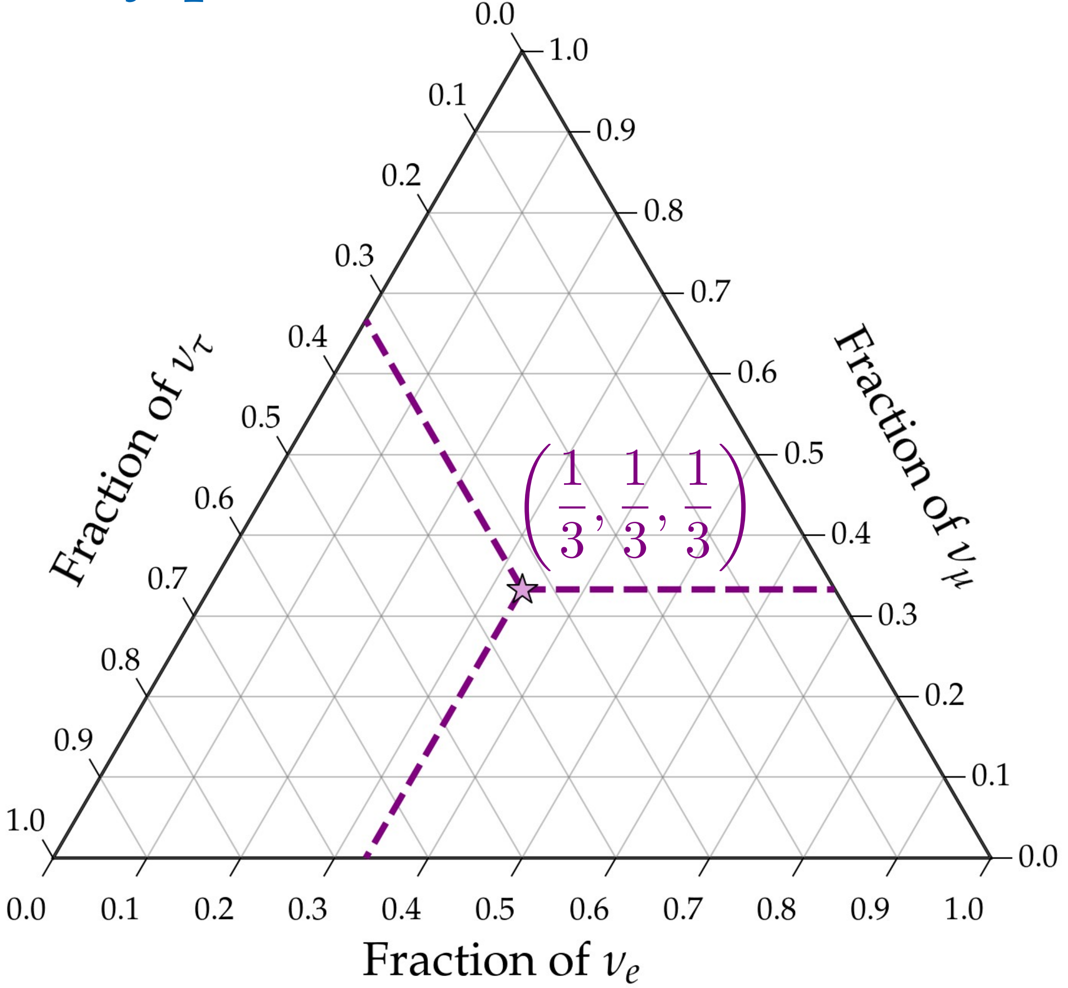
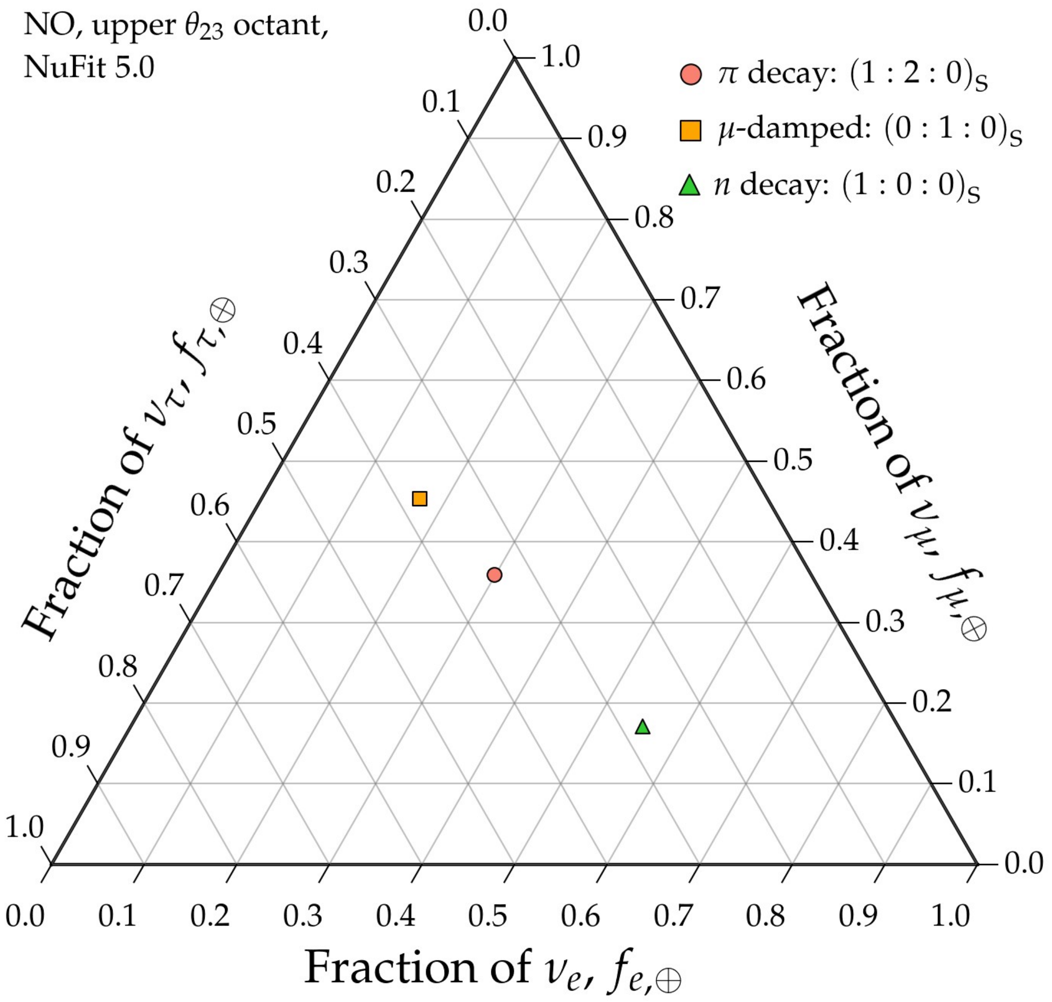


Theoretically palatable regions: today



Note:
All plots shown are for normal neutrino mass ordering (NO); inverted ordering looks similar

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

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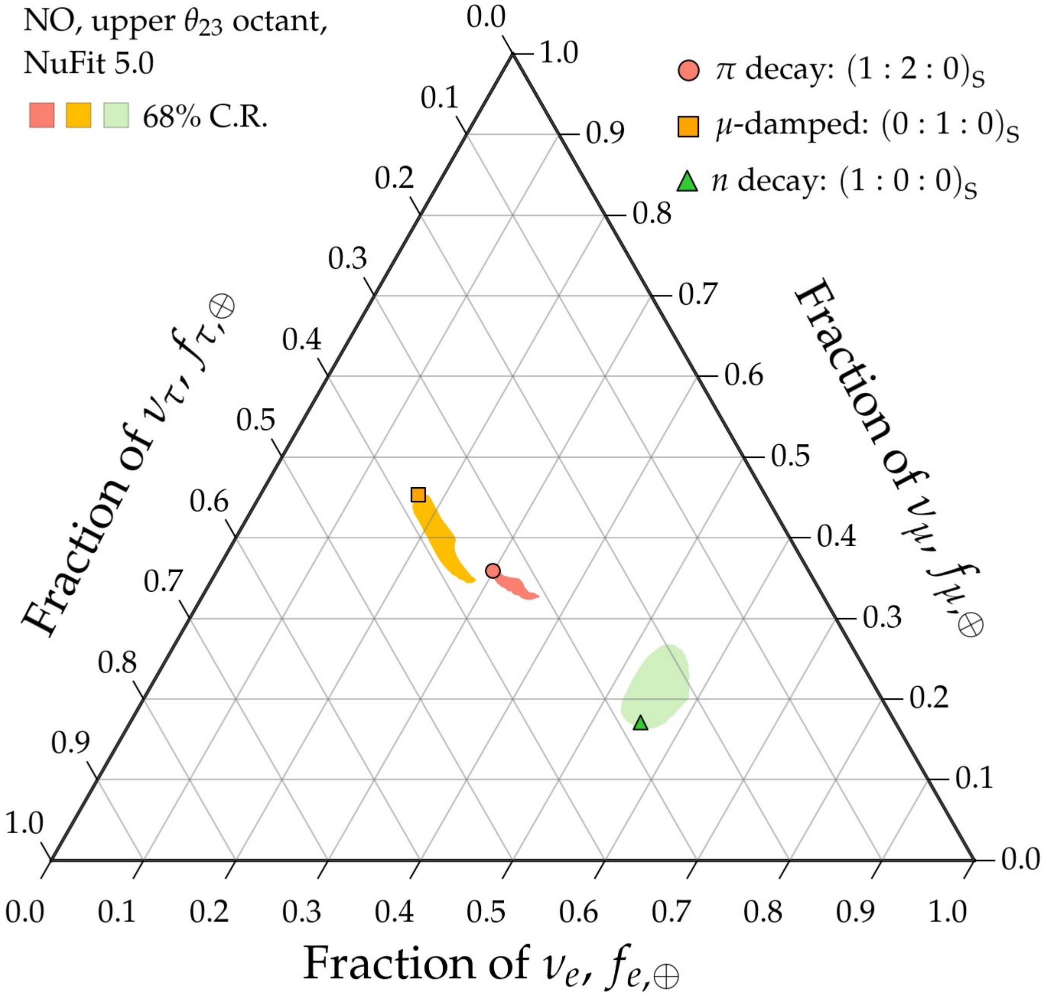

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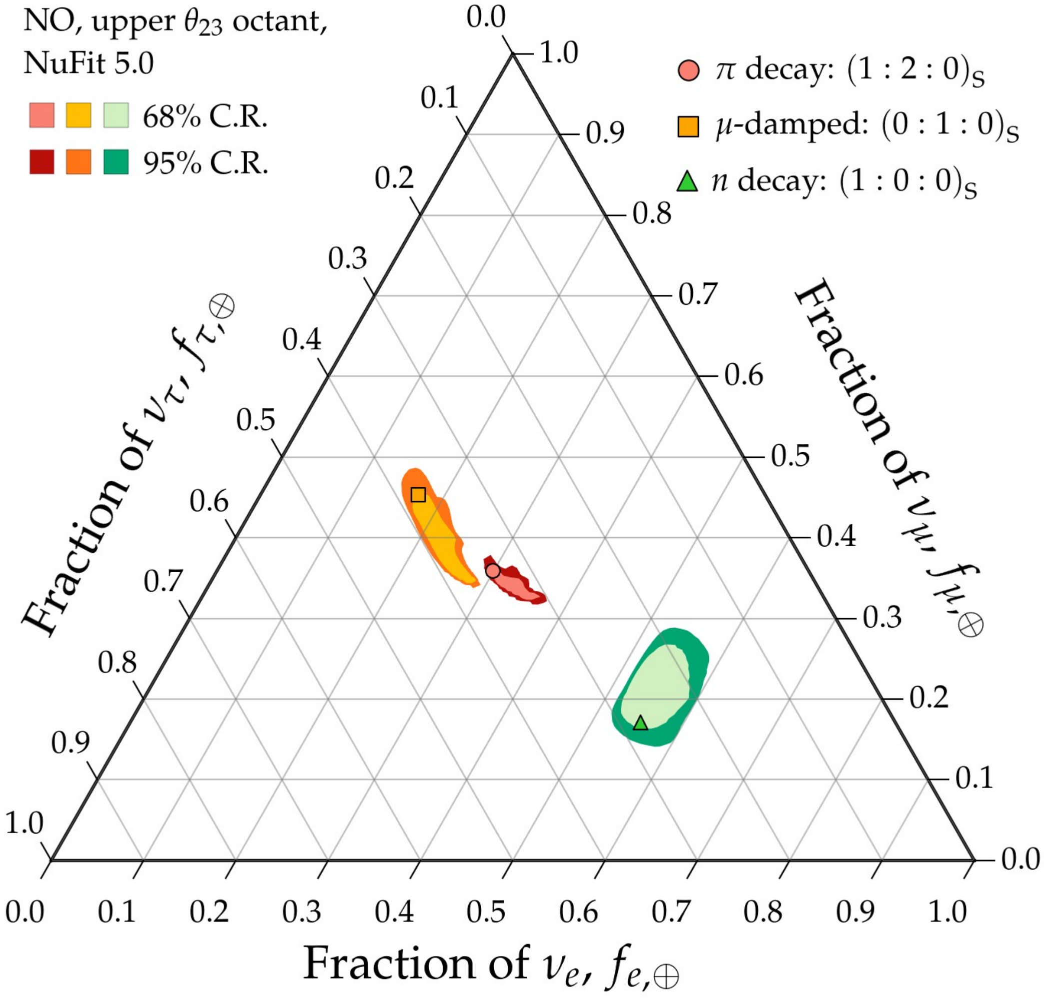

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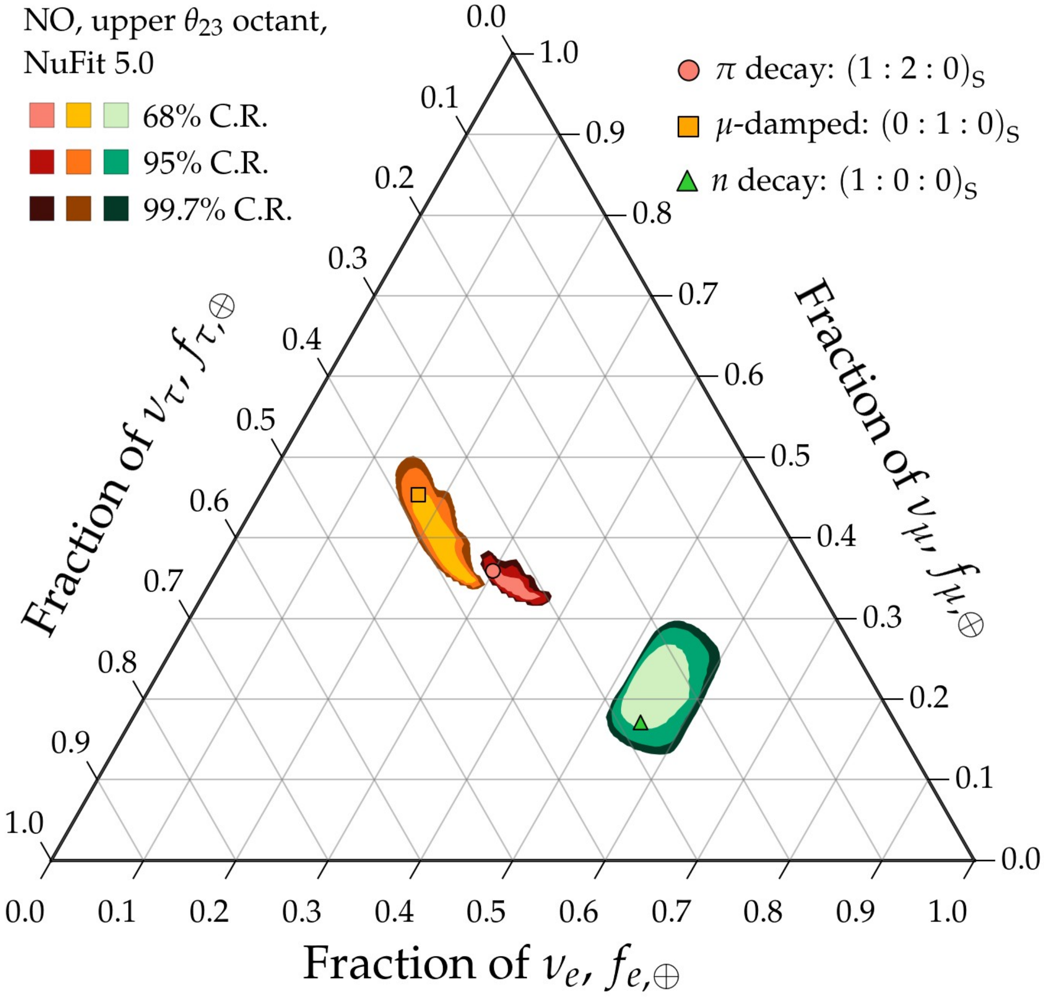

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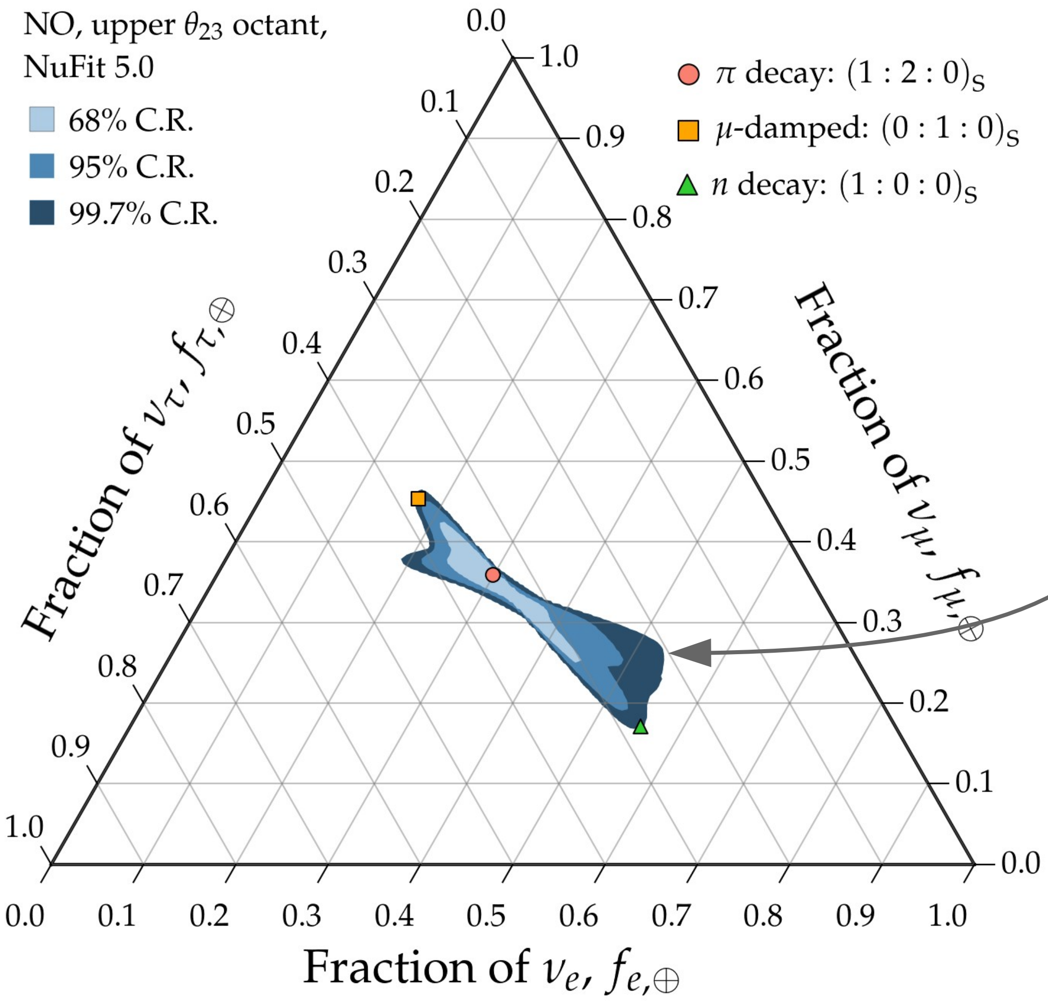

Varying over all possible flavor ratios at the source

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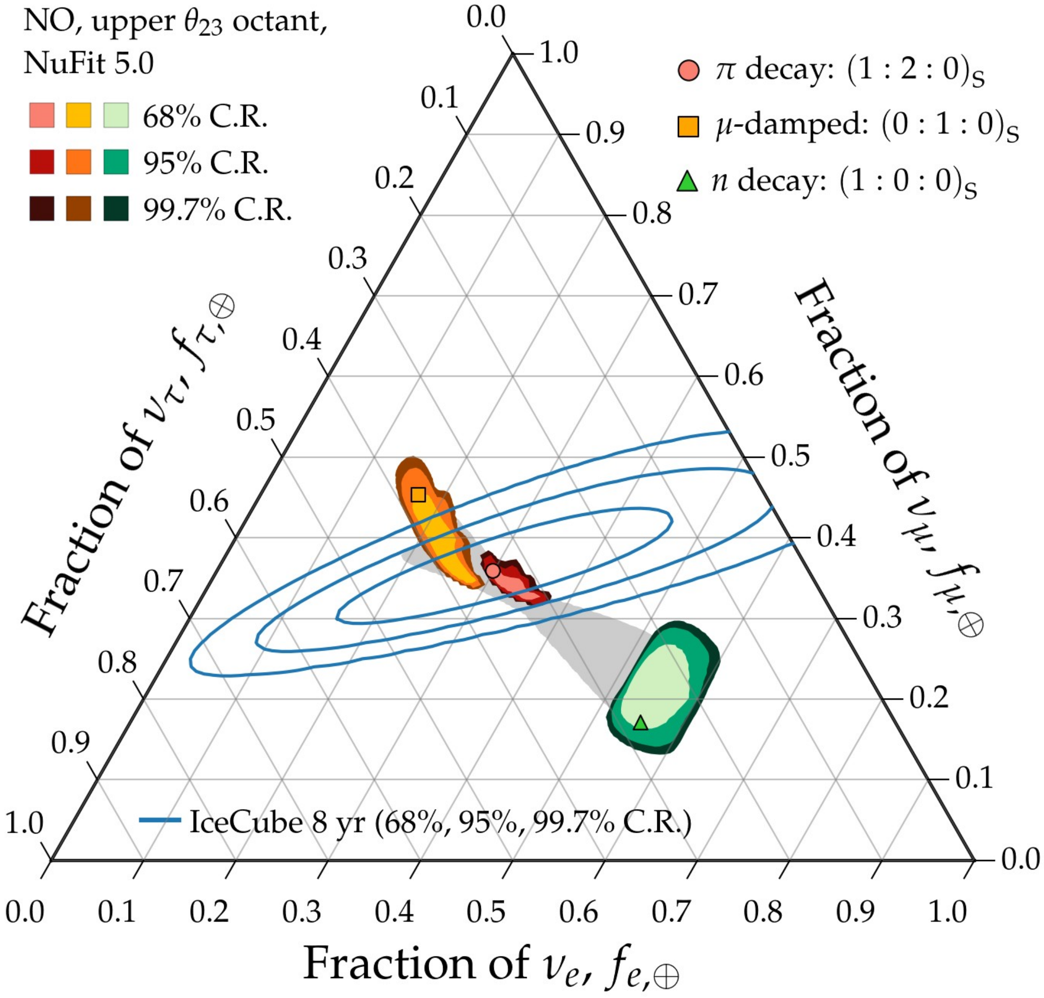
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Theoretically palatable regions: today



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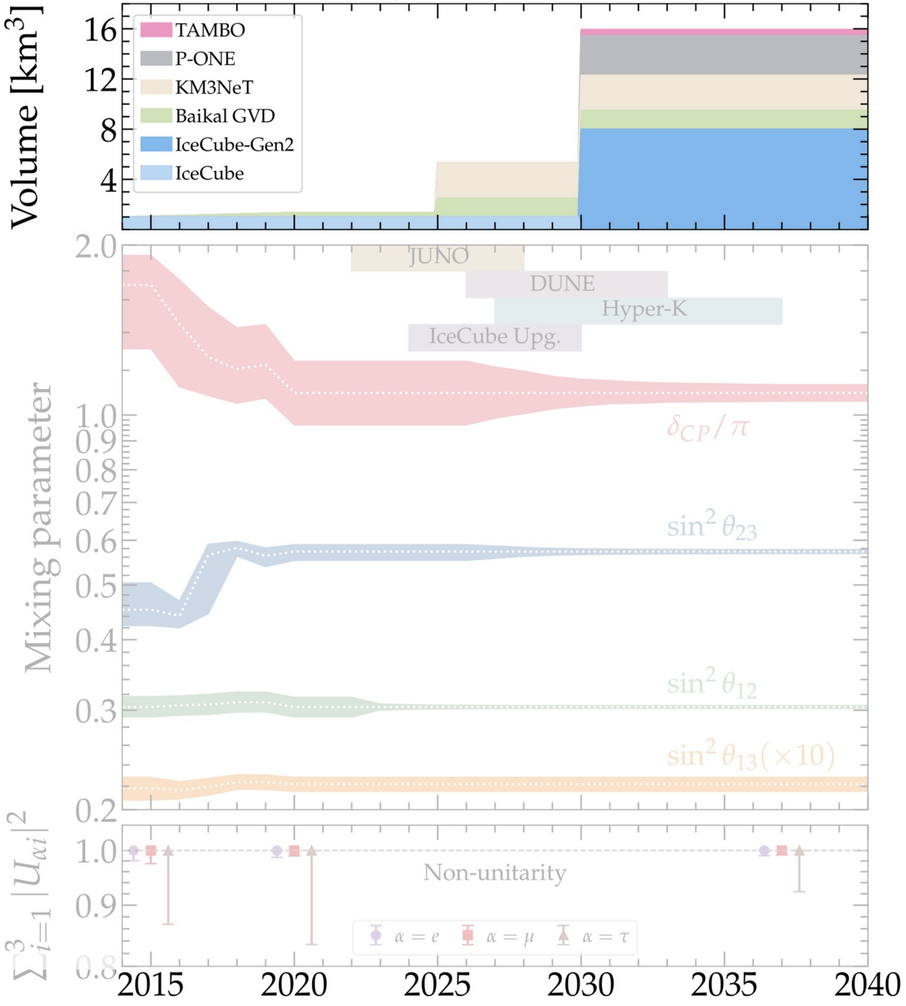
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Measuring flavor composition: 2015–2040

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



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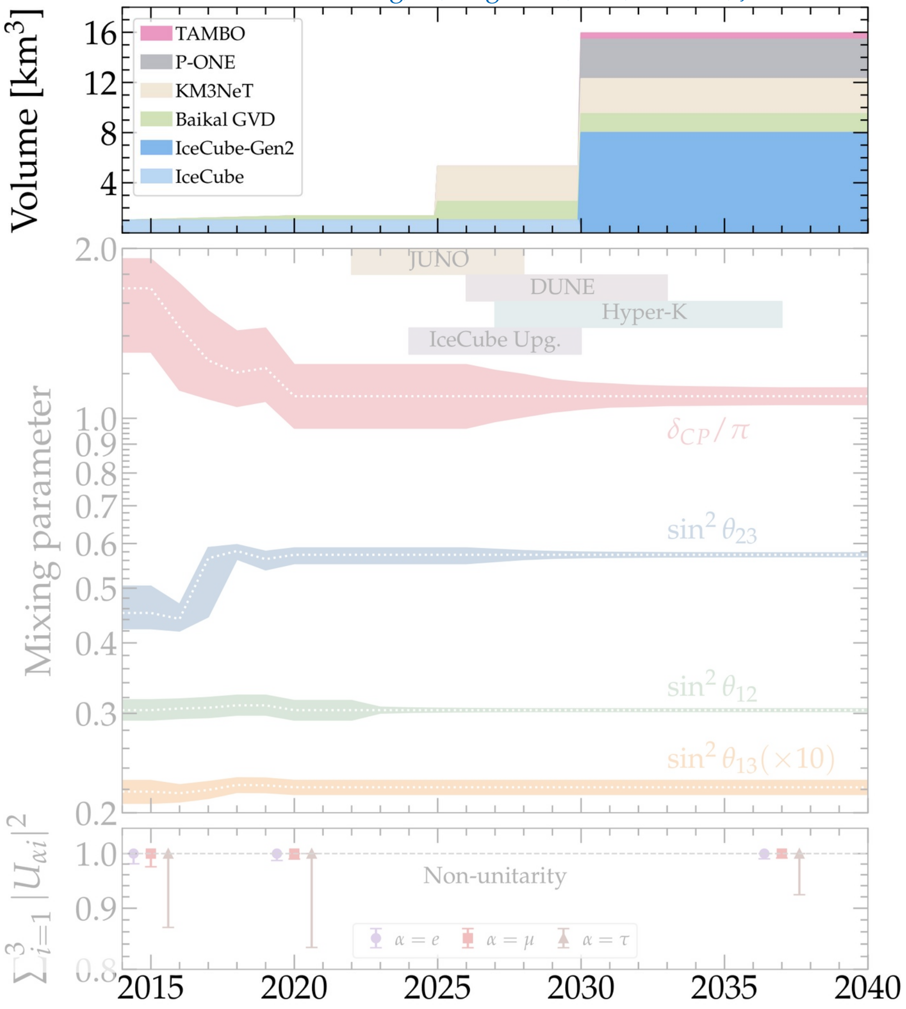
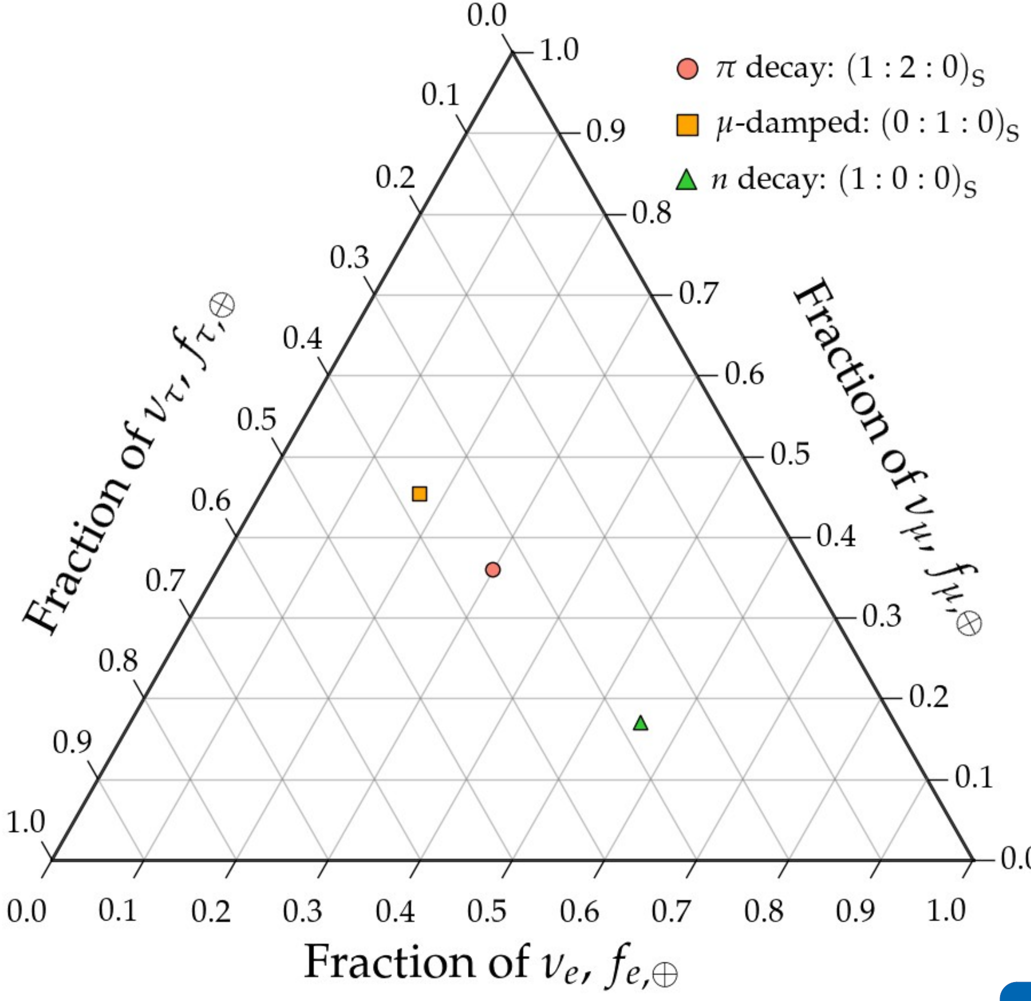
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021





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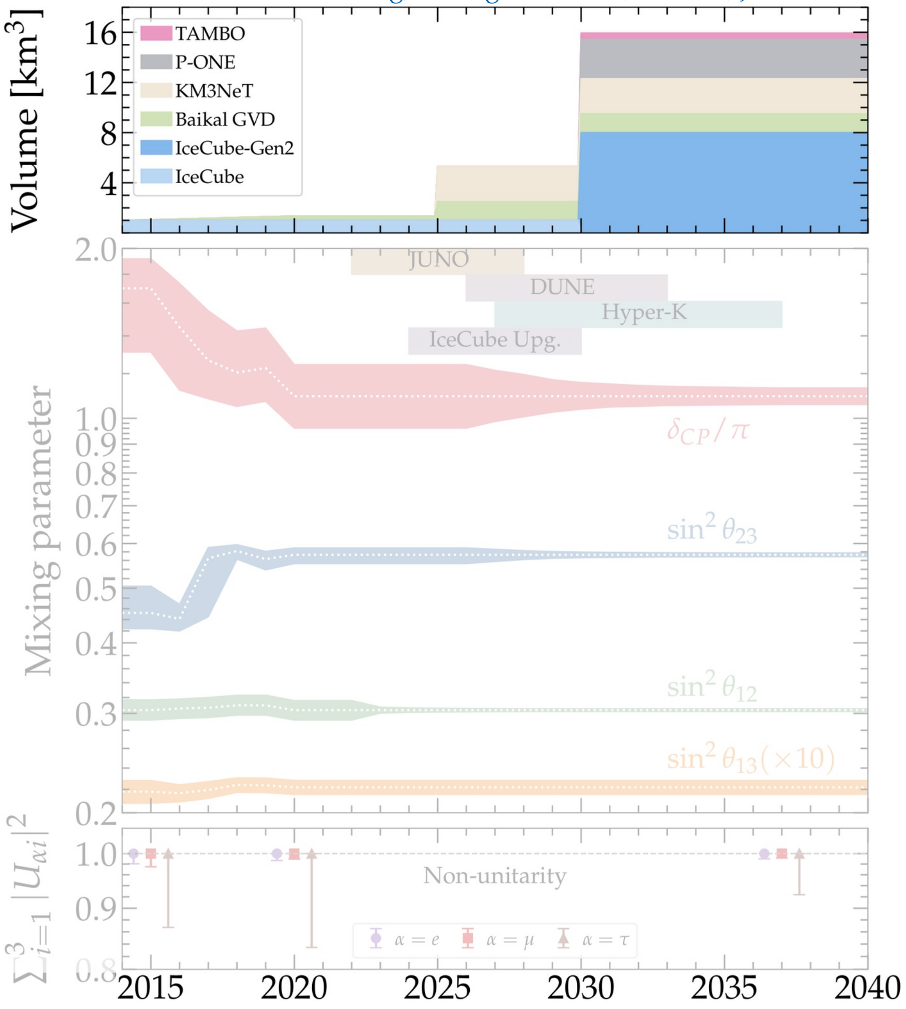

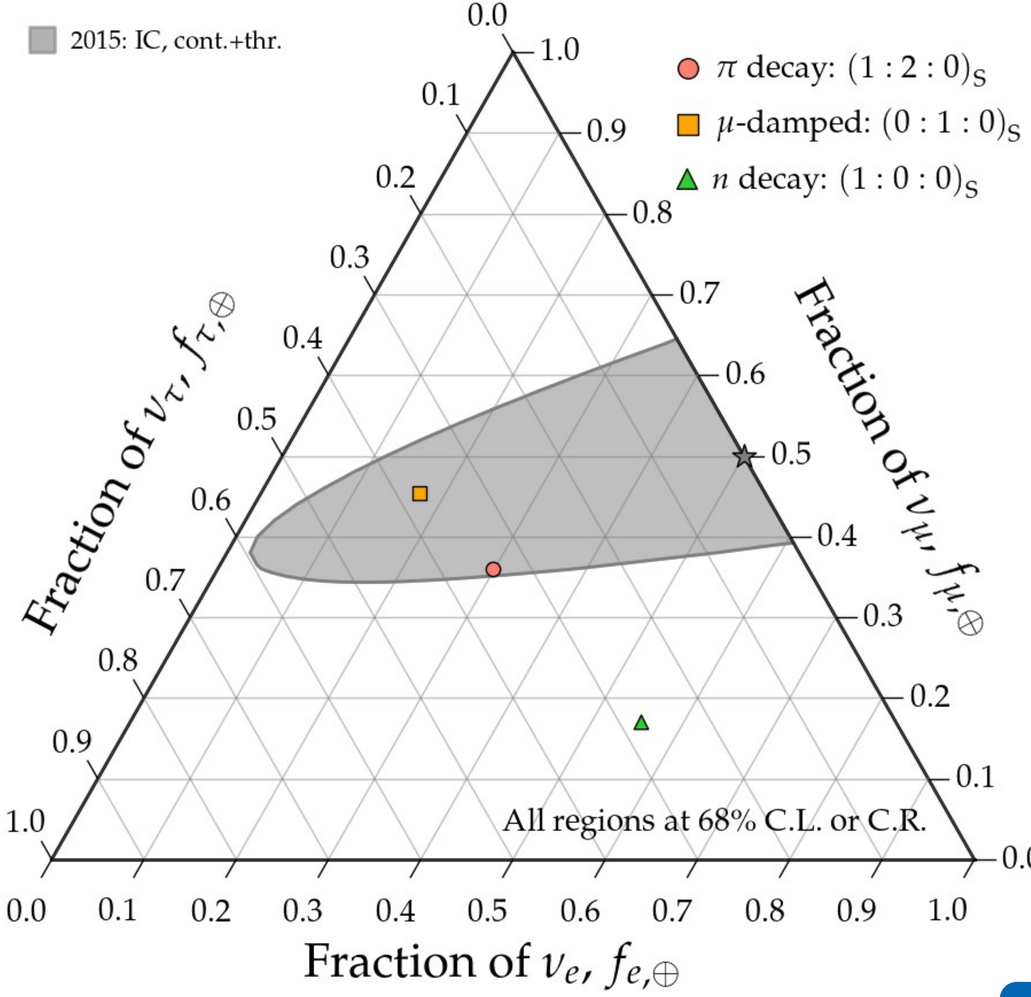

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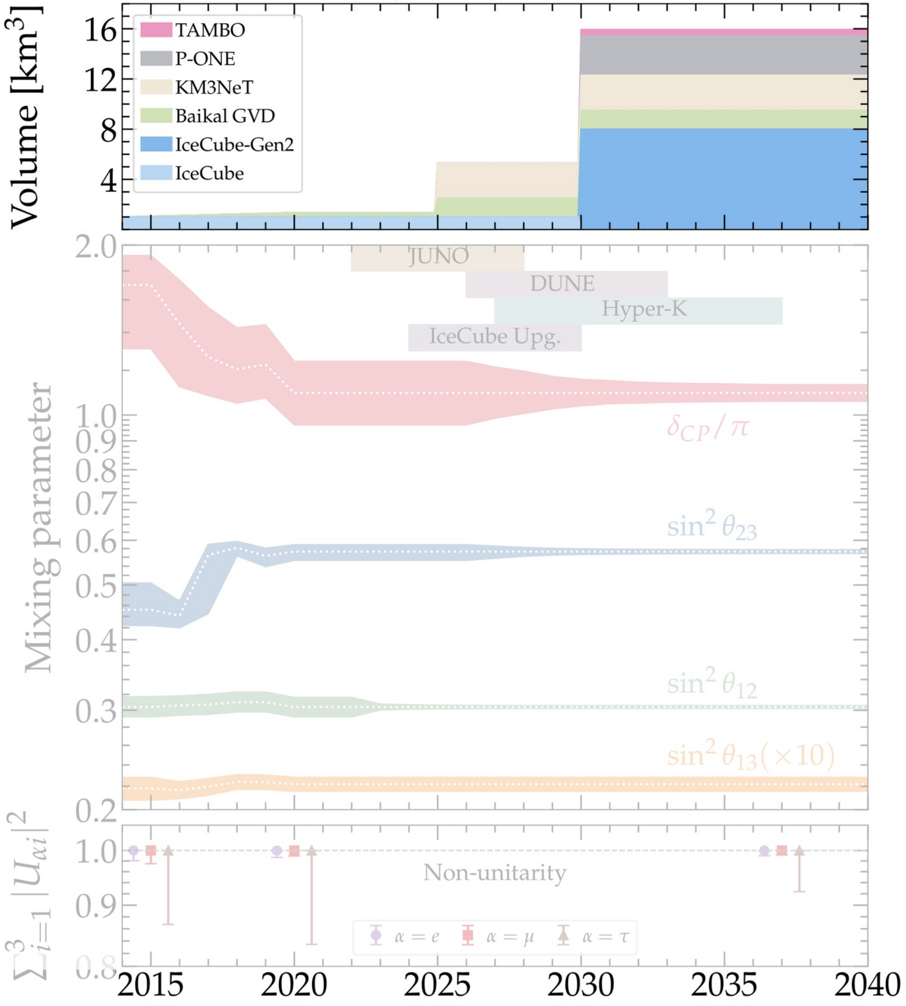
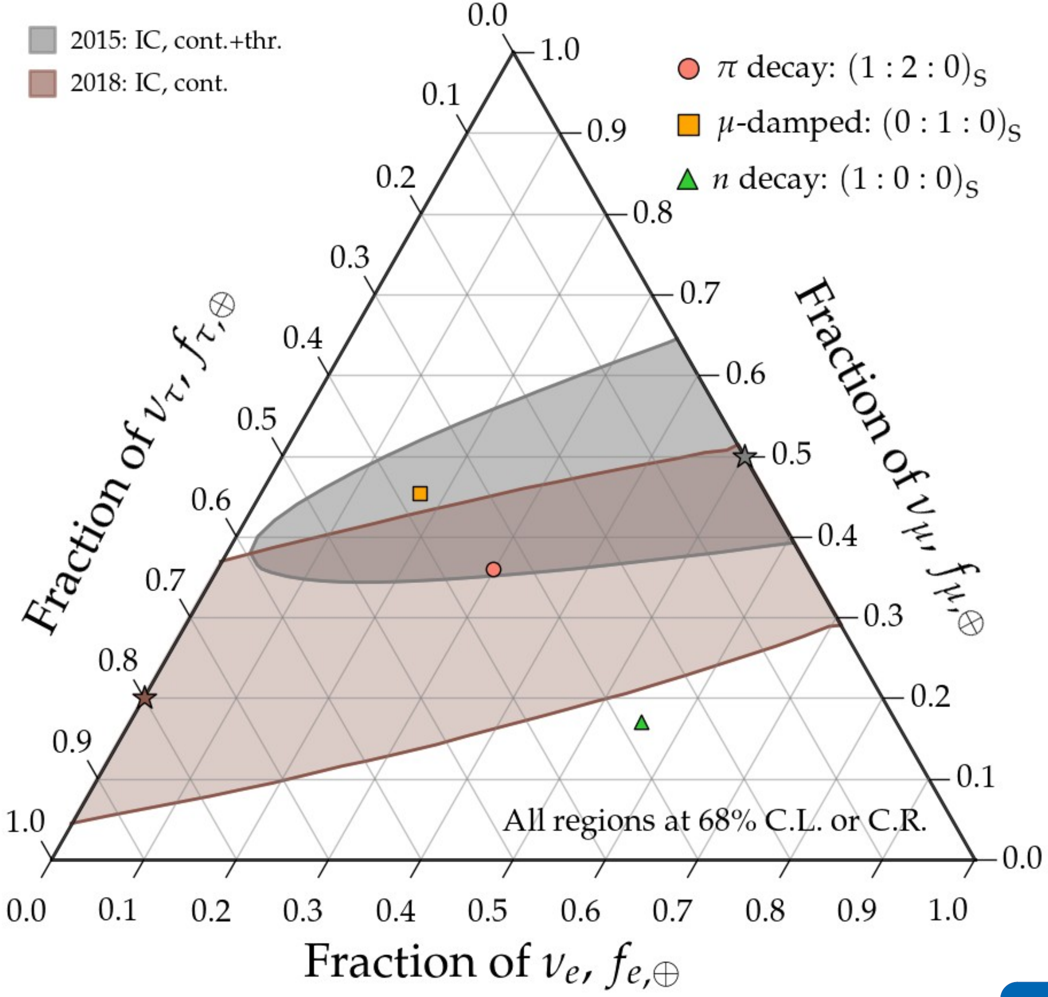
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021





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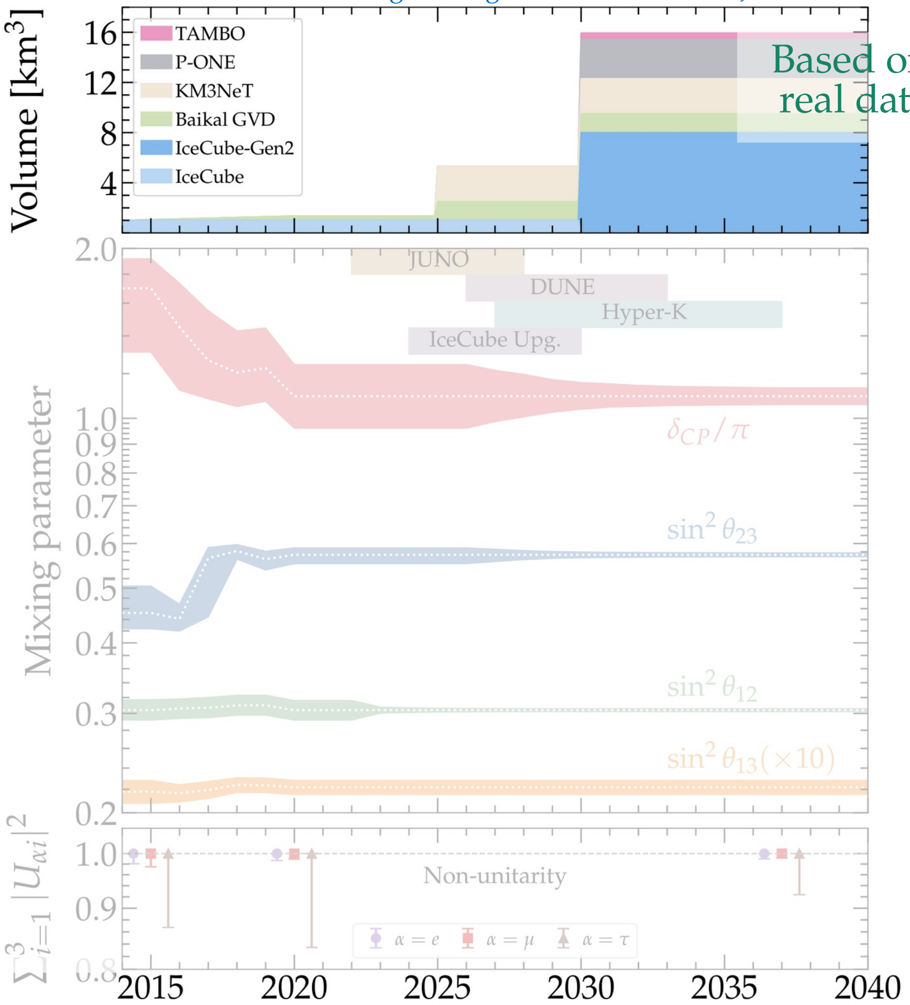
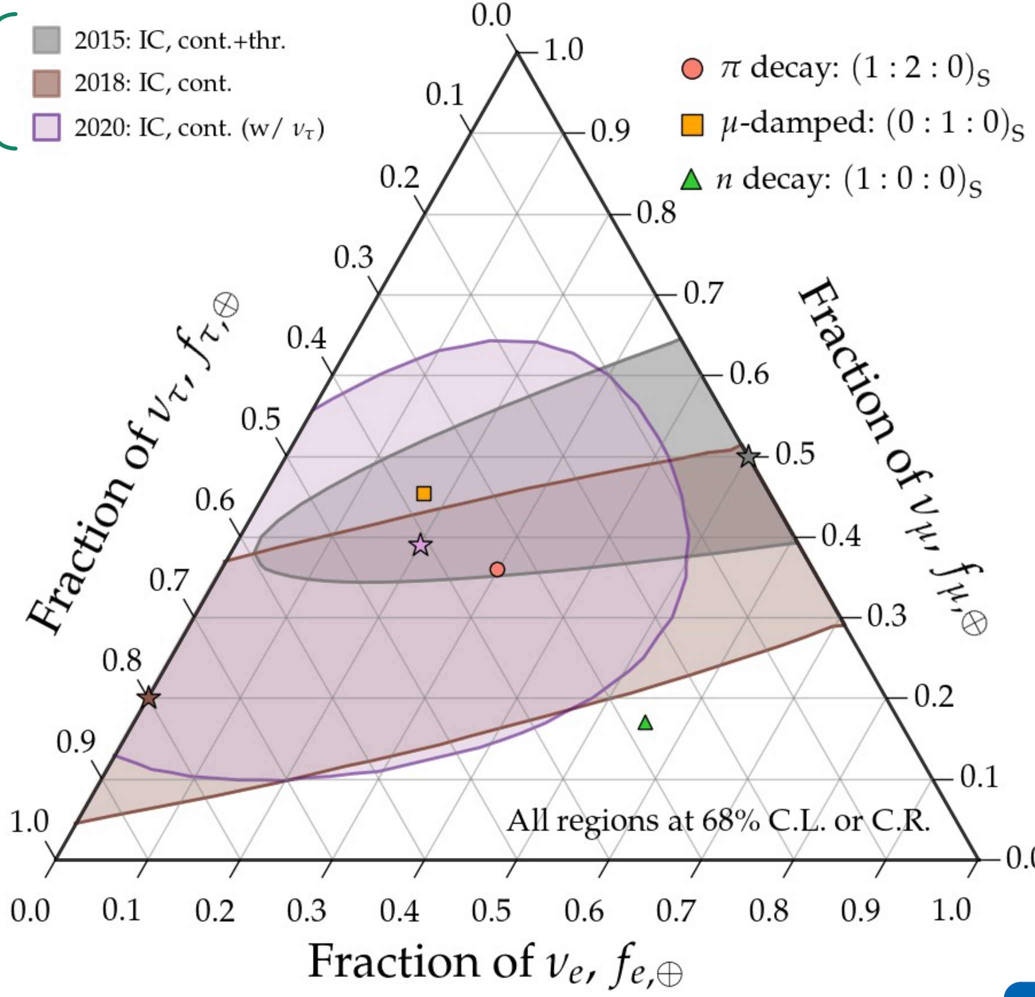
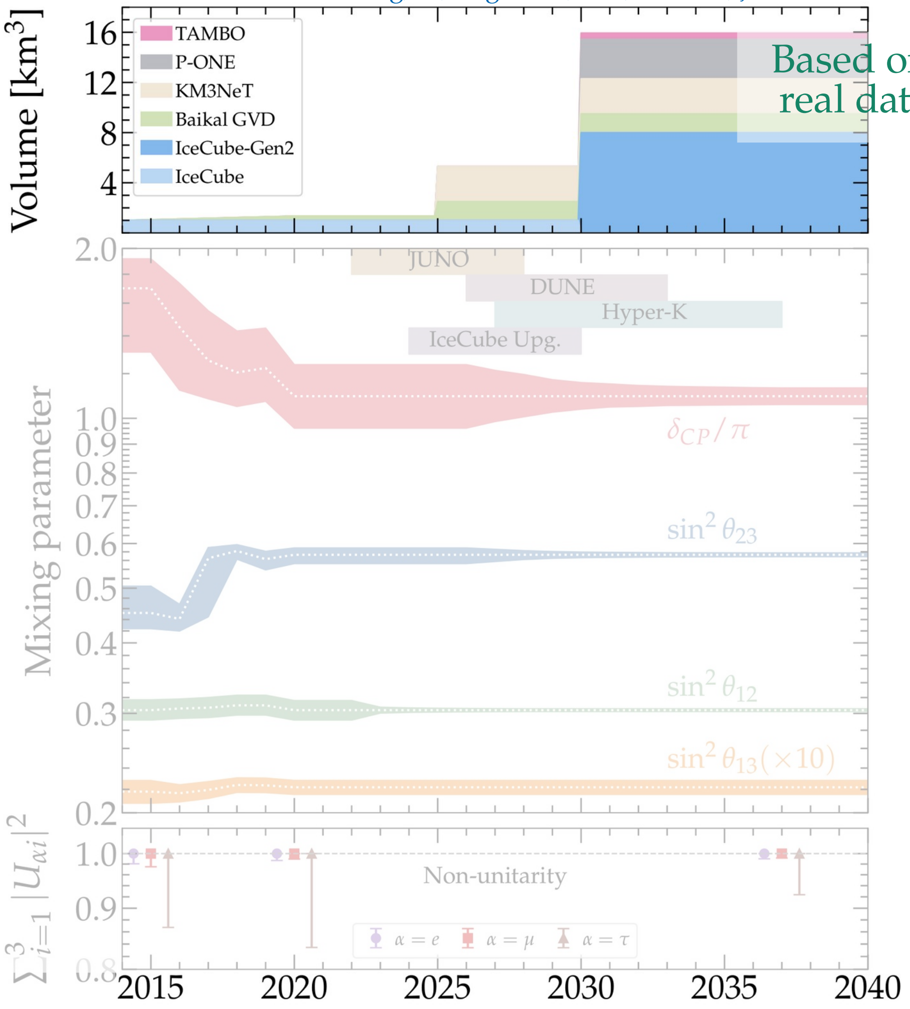


Based on real data

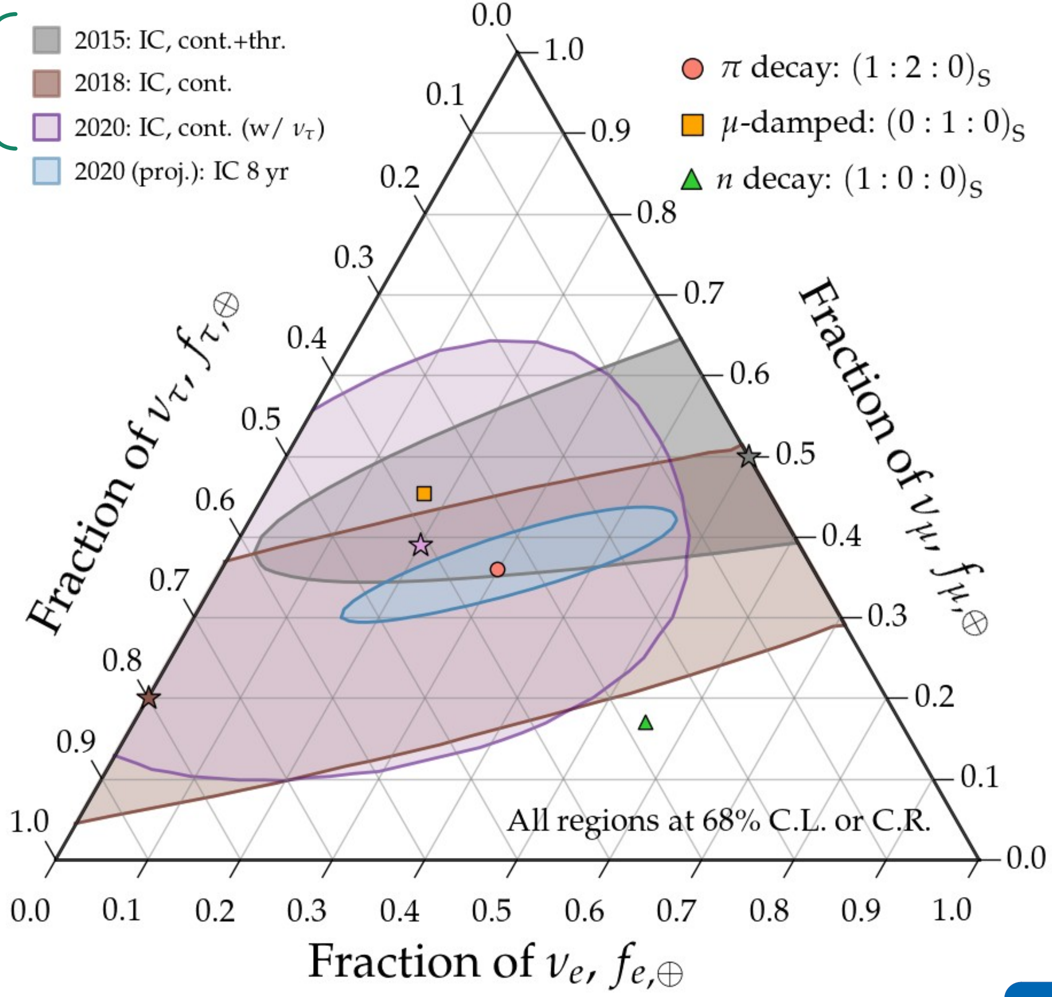


Measuring flavor composition: 2015–2040

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



Based on real data



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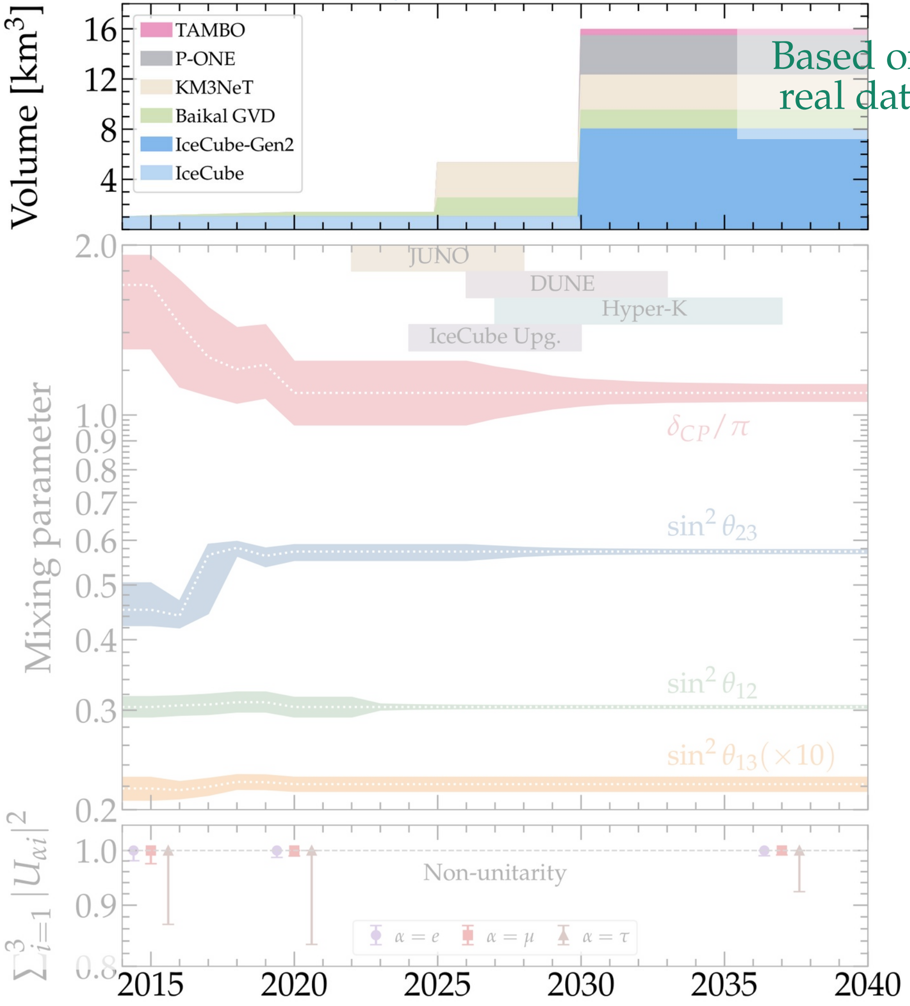

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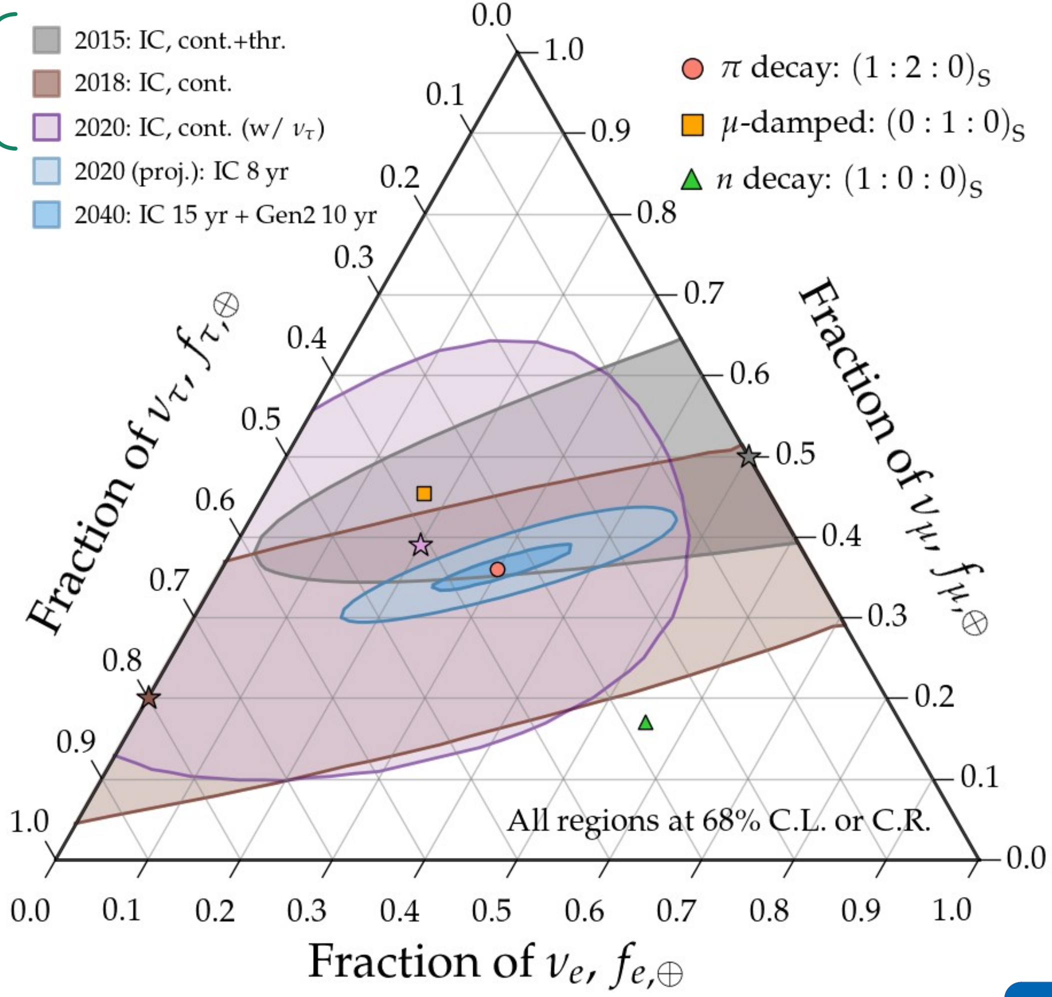

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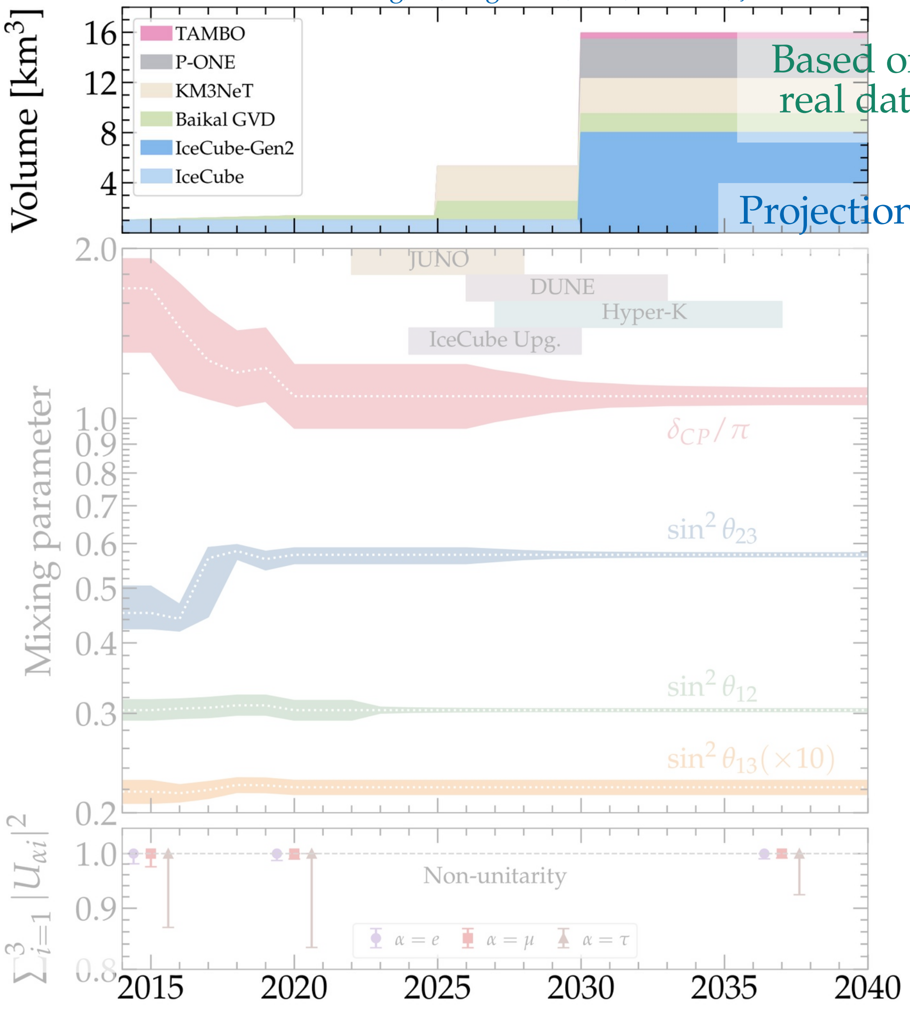
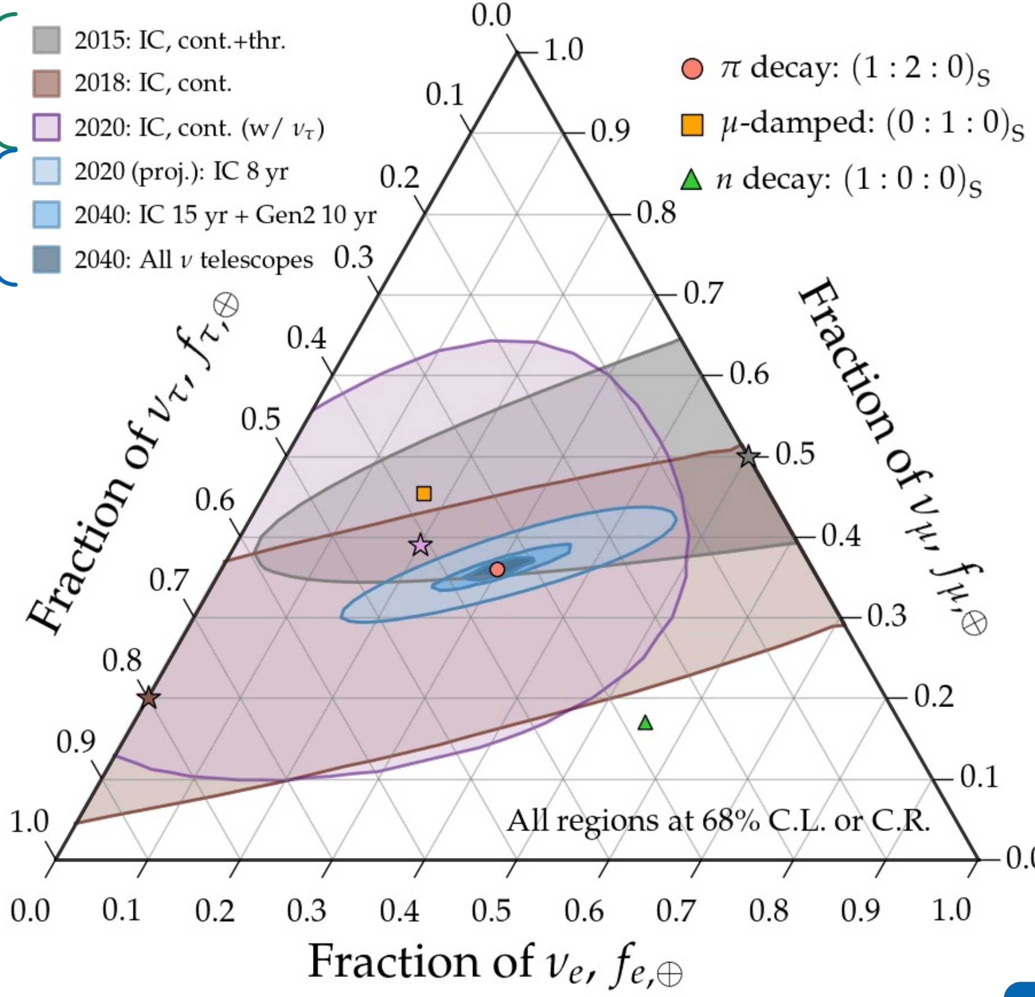
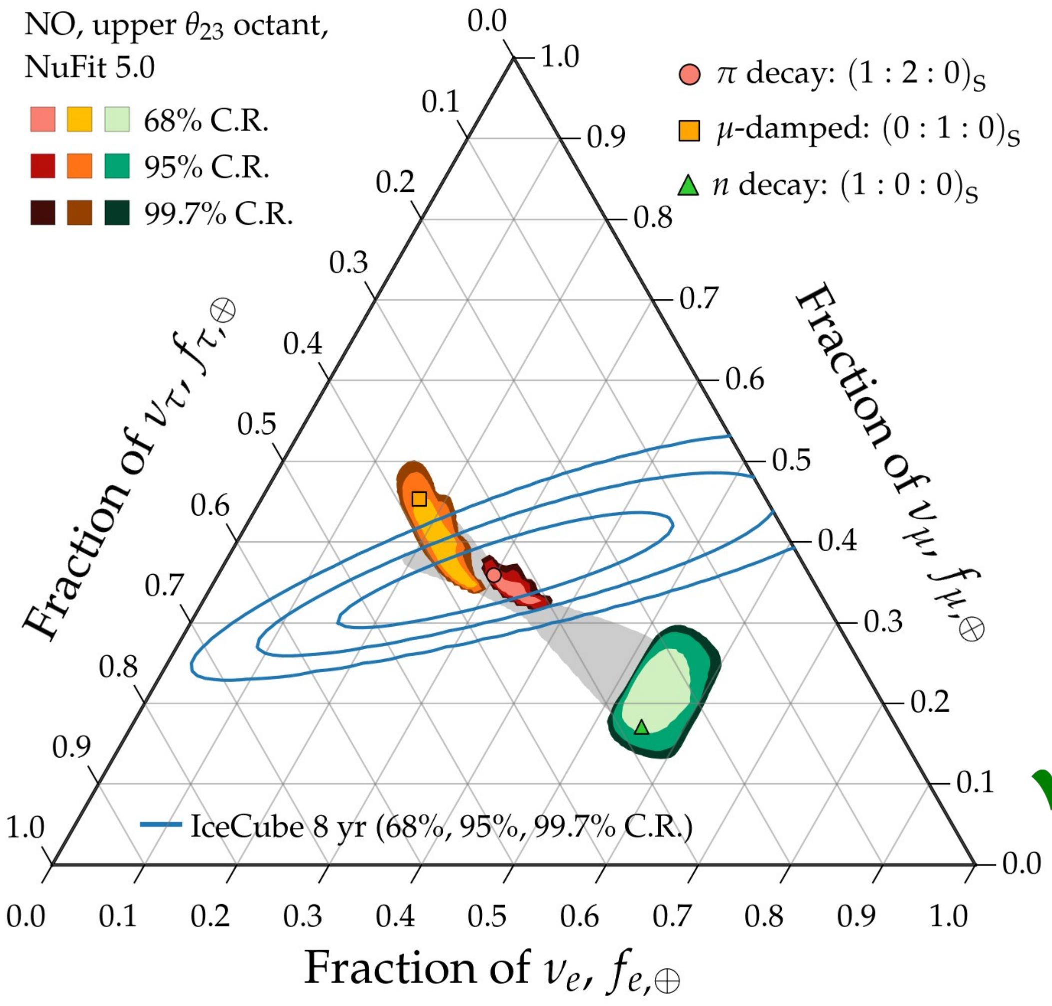


Based on real data

Projections



Theoretically palatable regions: today



Two limitations:

Allowed flavor regions overlap –
Insufficient precision in the mixing parameters

Will be overcome by 2030

Measurement of flavor ratios –
~~Cannot distinguish between pion-decay and muon-damped benchmarks even at 68% C.R. (1σ)~~

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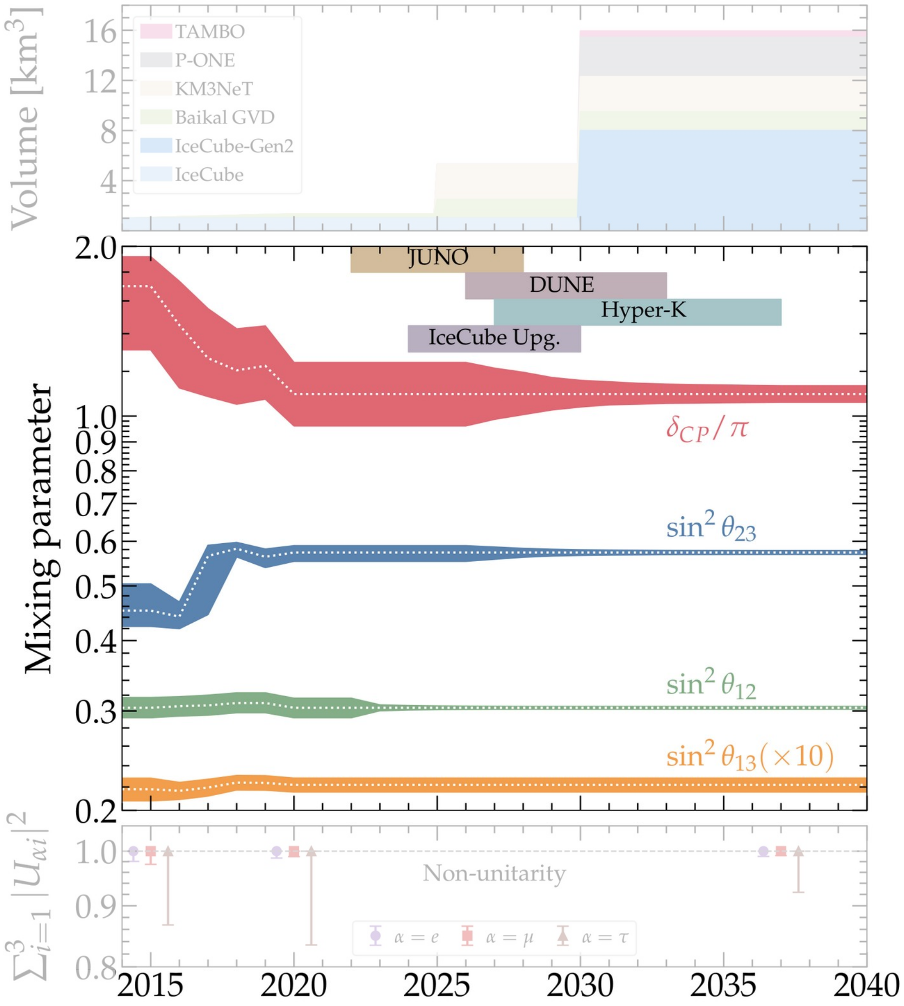
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

How knowing the mixing parameters better helps



We can compute the oscillation probability more precisely:

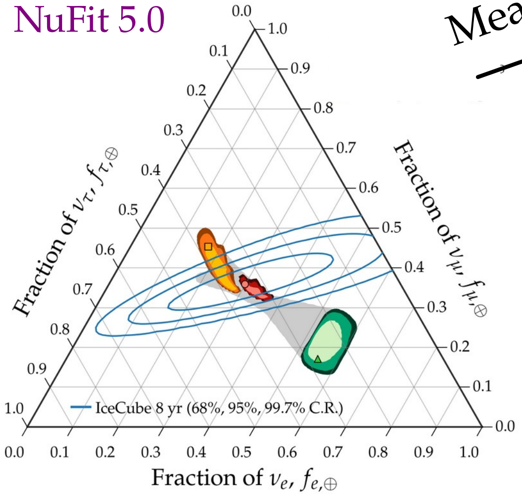
$$f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} P_{\beta\alpha} f_{\beta,\mathrm{S}}$$

So we can convert back and forth between source and Earth more precisely

How knowing the mixing parameters better helps

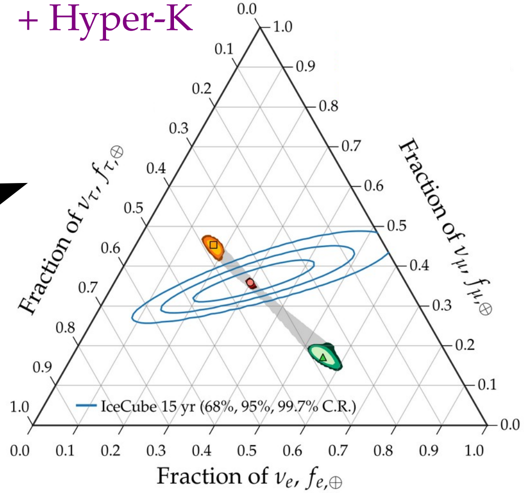
2020

NuFit 5.0



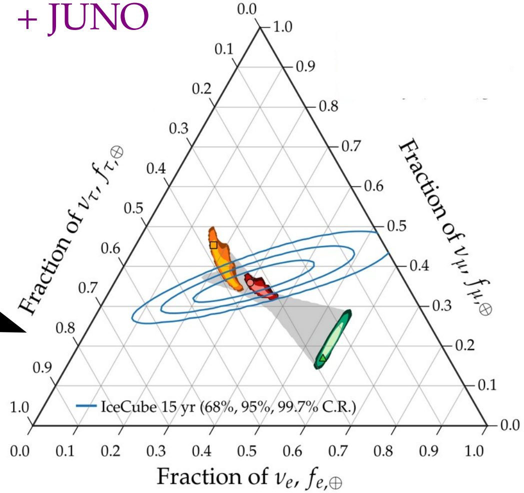
Measure θ_{23} better

+ Hyper-K



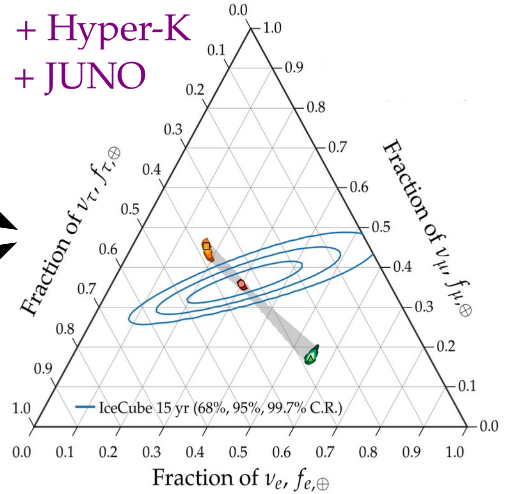
Measure θ_{12} better

+ JUNO



~2030

+ Hyper-K
+ JUNO



In our results:
JUNO + Hyper-K + DUNE

Marginal improvement til 2040

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

Theoretically palatable regions: 2020 → 2030 → 2040

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

Theoretically palatable regions: 2020 → 2030 → 2040

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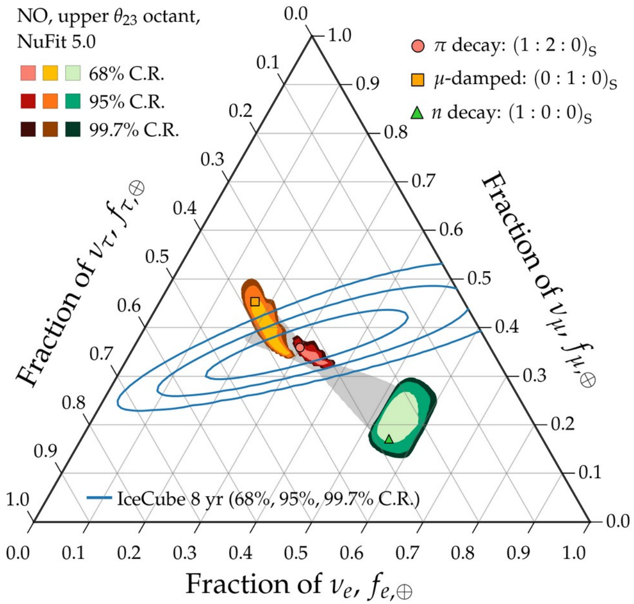

Allowed regions: overlapping

Measurement: imprecise

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

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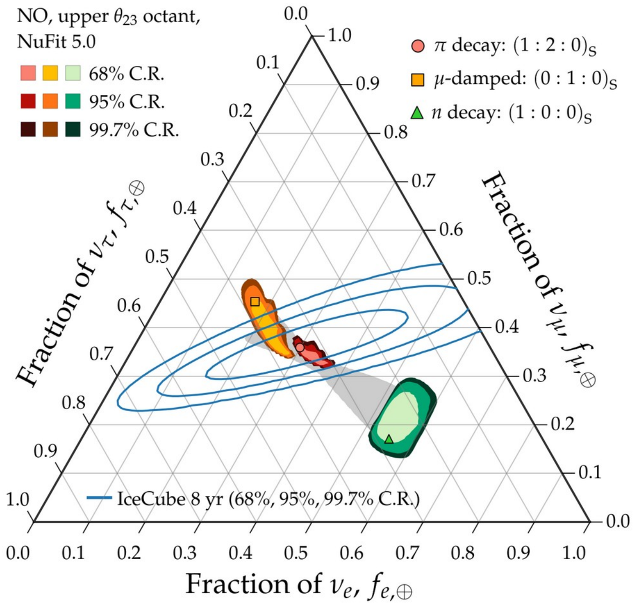

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Not ideal

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

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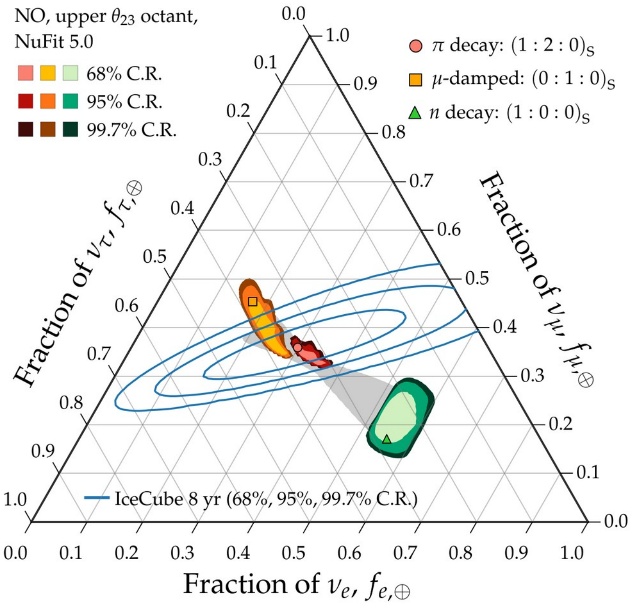

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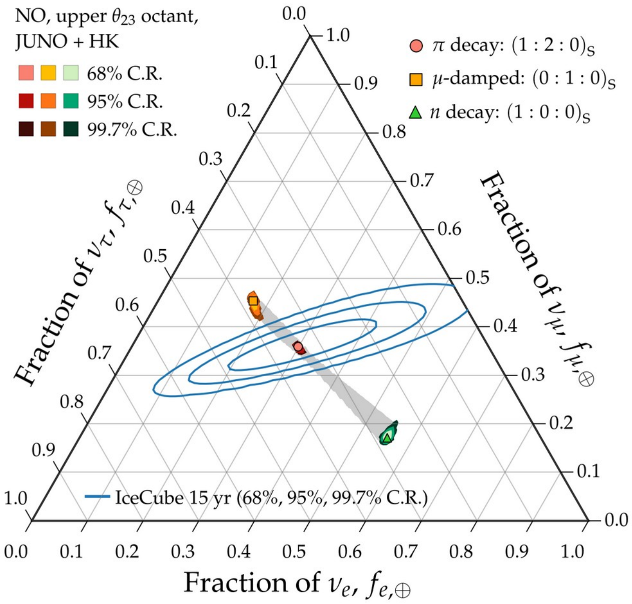
2030



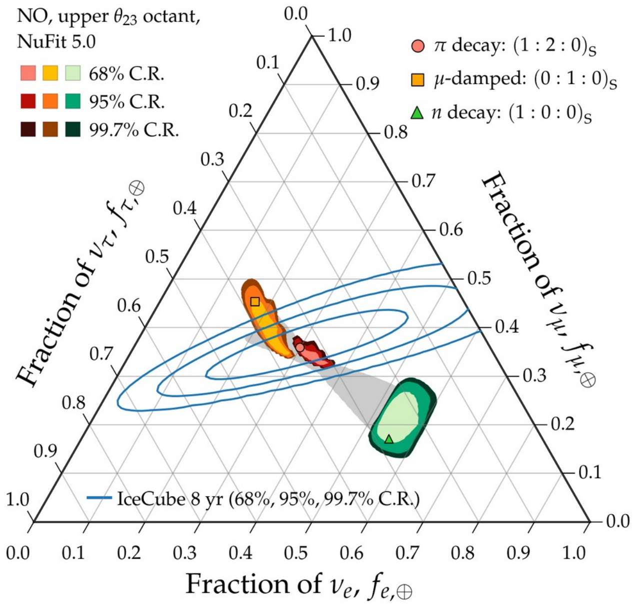
Allowed regions: well separated

Measurement: improving

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

Theoretically palatable regions: 2020 → 2030 → 2040

2020



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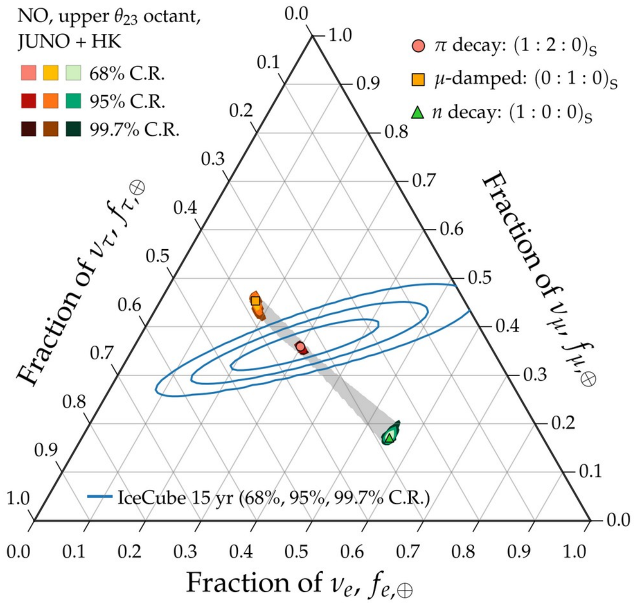

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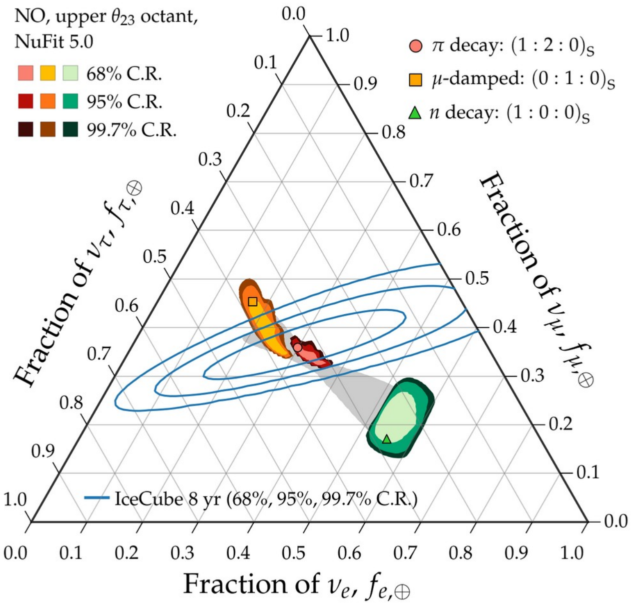
Nice

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

Theoretically palatable regions: 2020 → 2030 → 2040

2020



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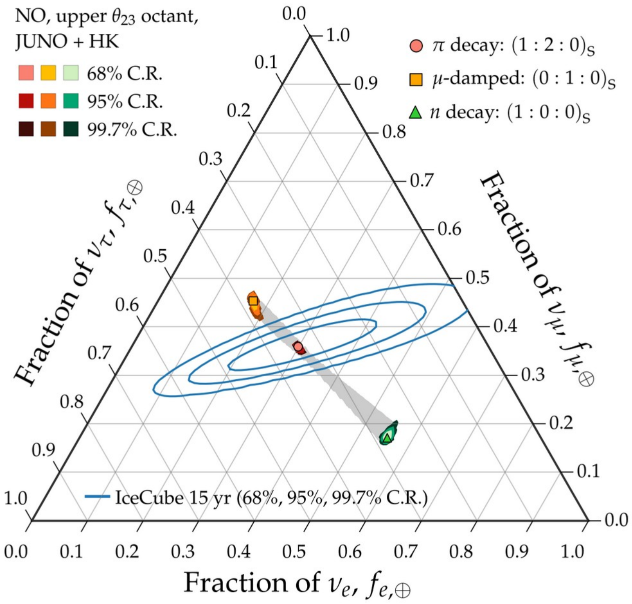
2030



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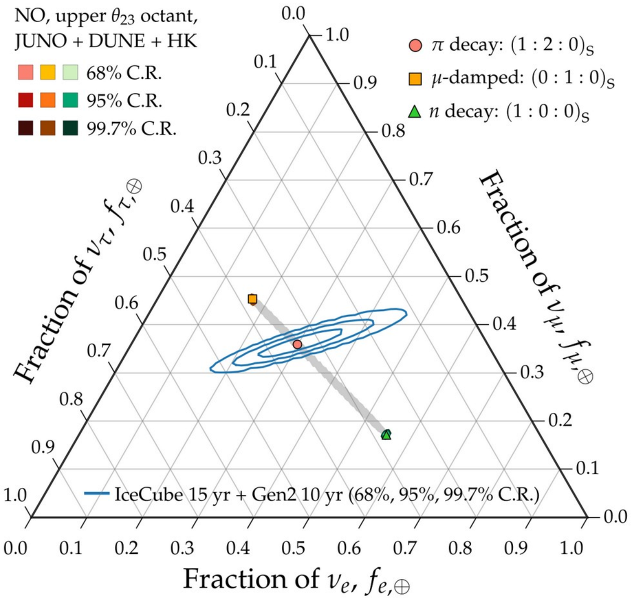
2040



Allowed regions: well separated

Measurement: precise

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

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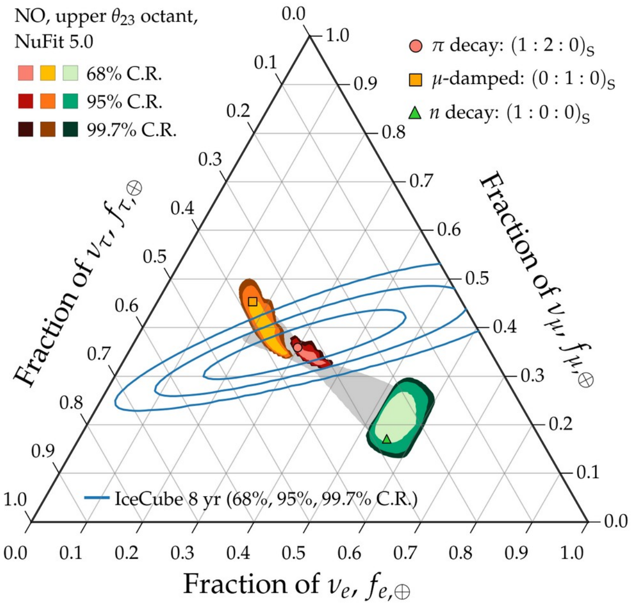
2020



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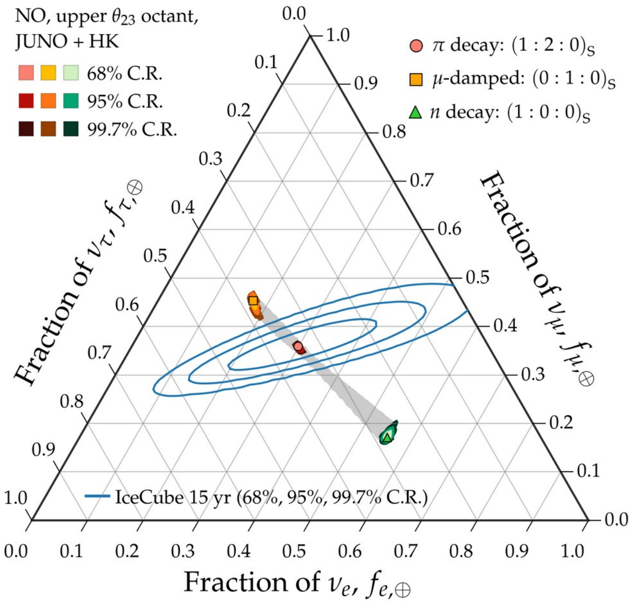
2030



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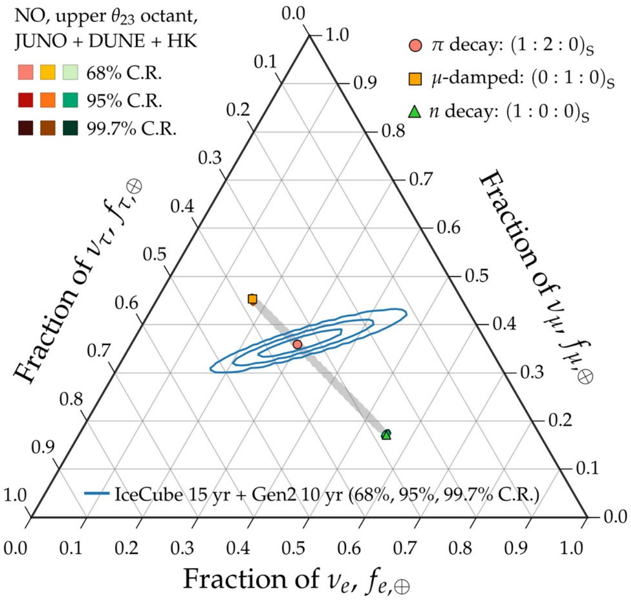
Nice

2040



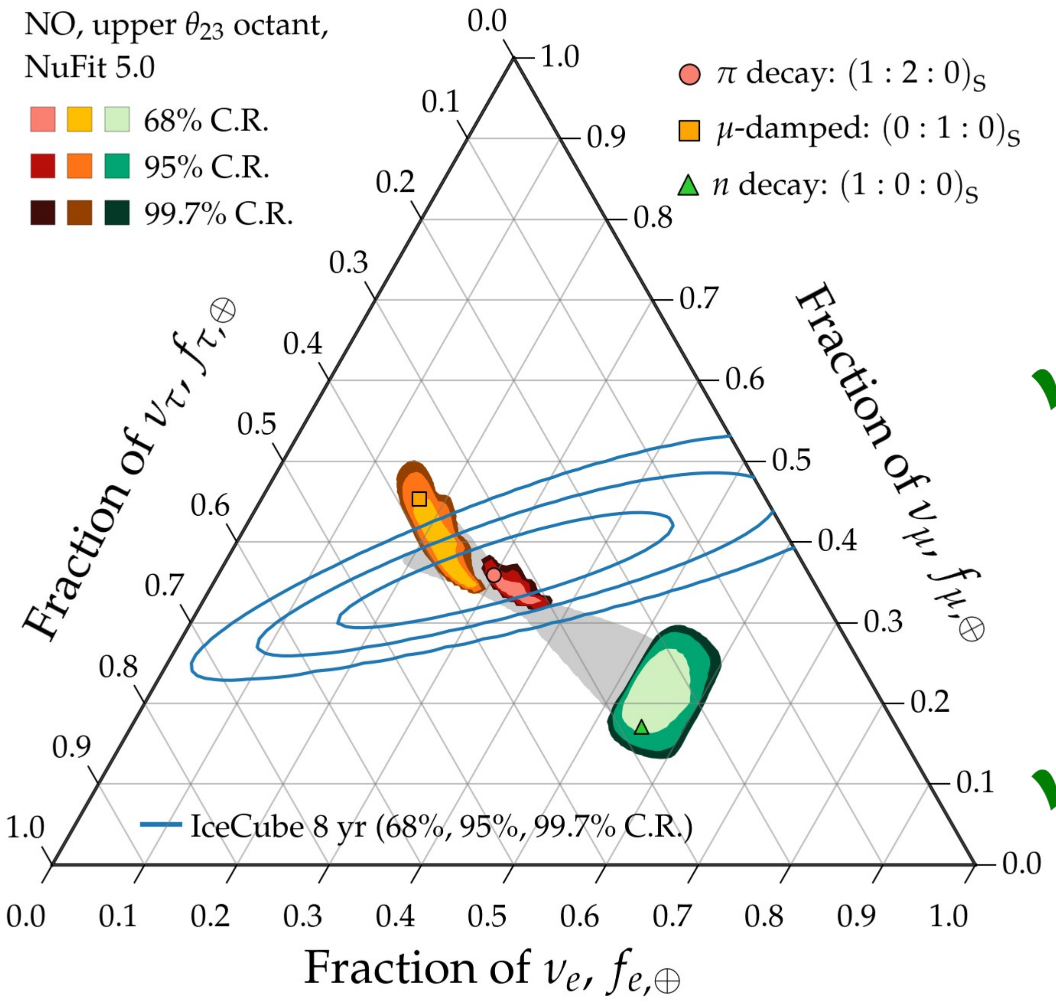
Allowed regions: well separated

Measurement: precise

Success

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

Theoretically palatable regions: today



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New physics in flavor composition

Repurpose the flavor sensitivity to test new physics:

New physics in flavor composition

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

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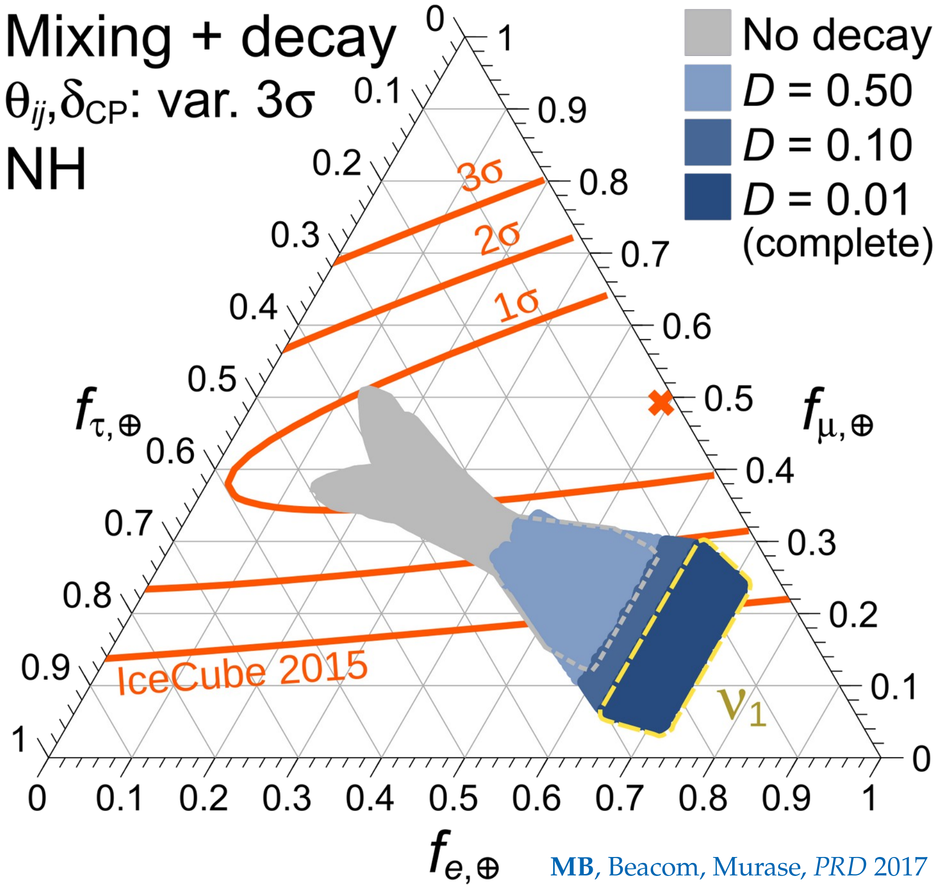
  [Beacom *et al.*, *PRL* 2003; Baerwald, **MB**, Winter, JCAP 2010; **MB**, Beacom, Winter, *PRL* 2015; **MB**, Beacom, Murase, *PRD* 2017]



MB, Beacom, Murase, *PRD* 2017

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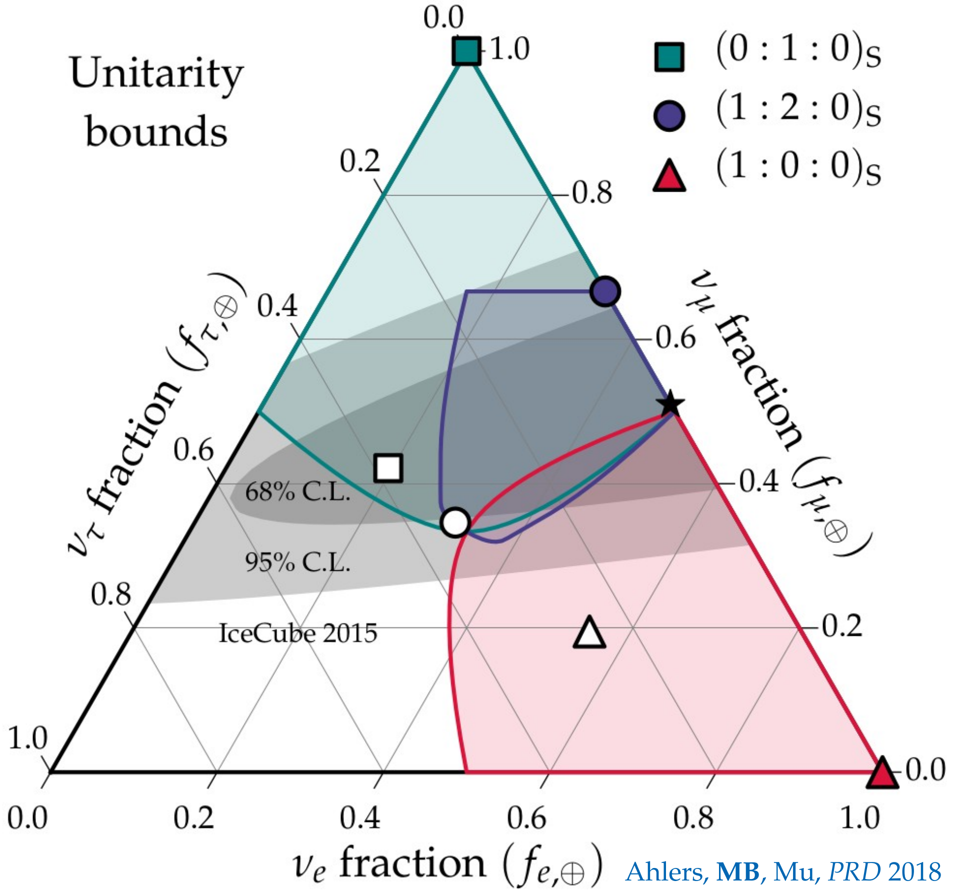

Ahlers, **MB**, Mu, *PRD* 2018

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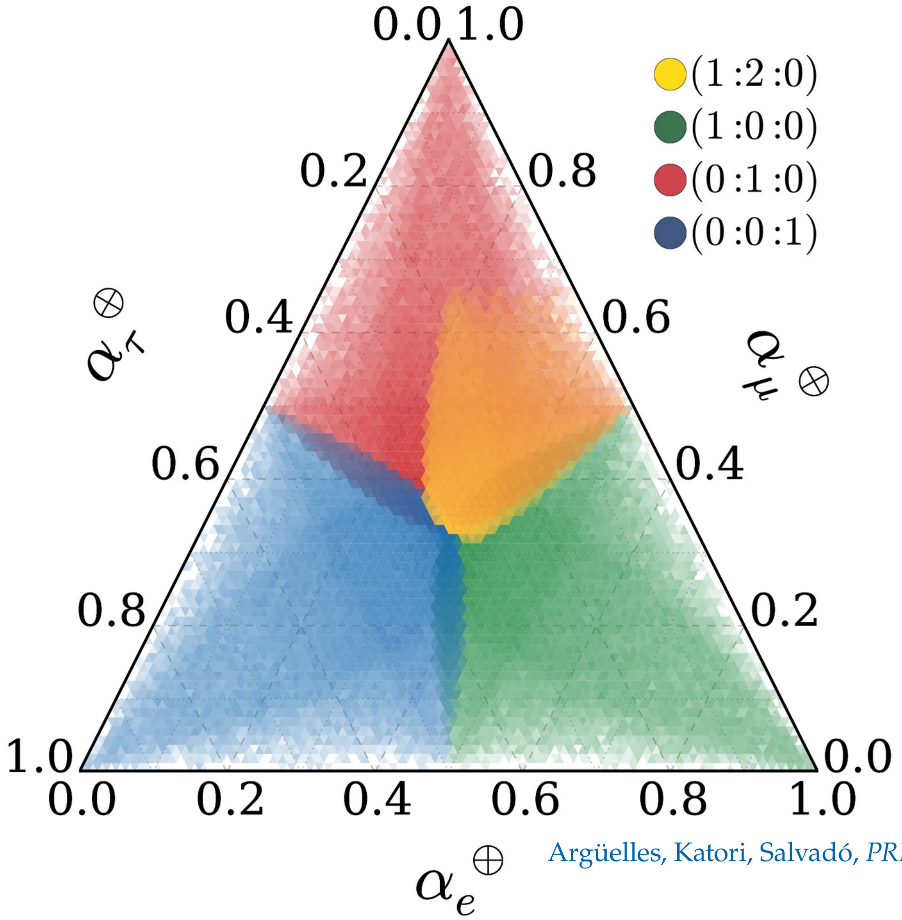

Argüelles, Katori, Salvadó, *PRL* 2015

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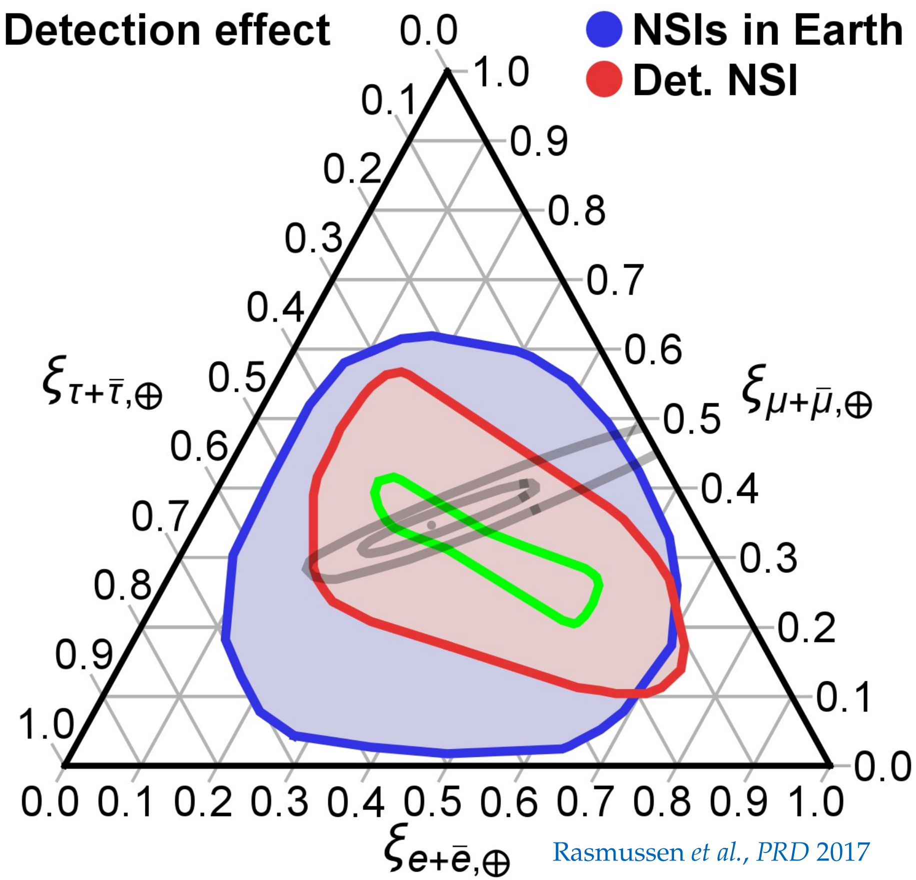

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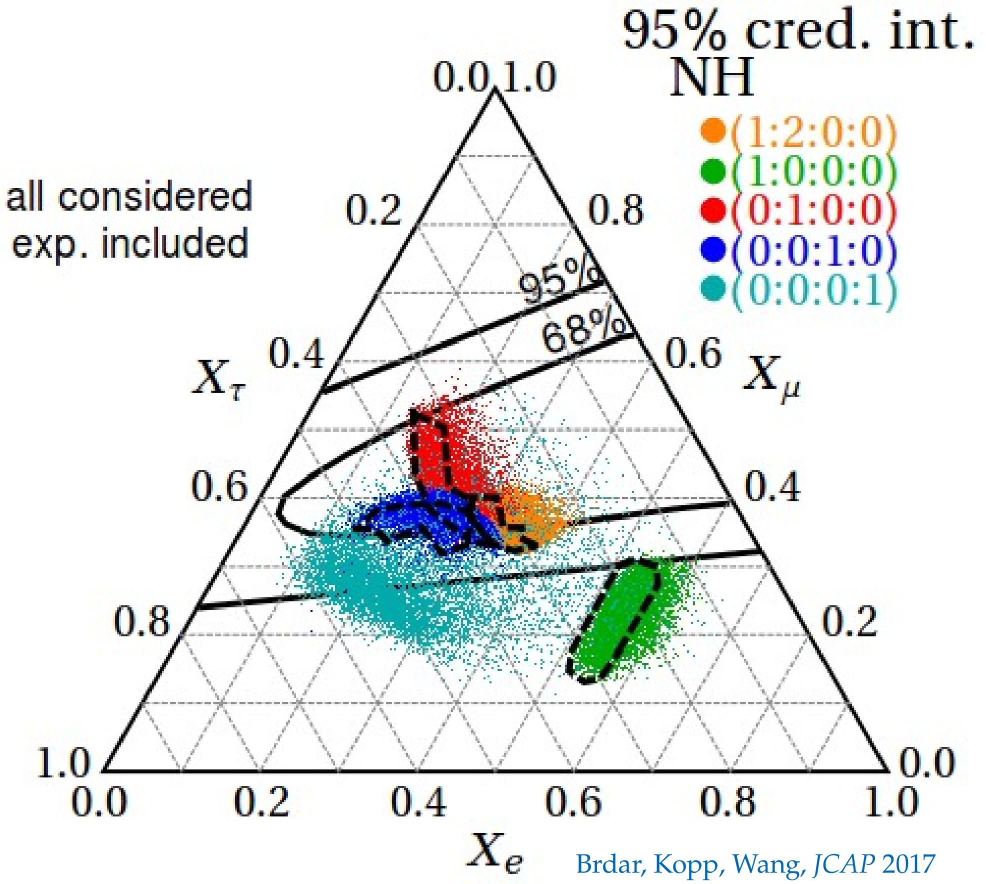

Brdar, Kopp, Wang, *JCAP* 2017

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- **Long-range *e*ν interactions**
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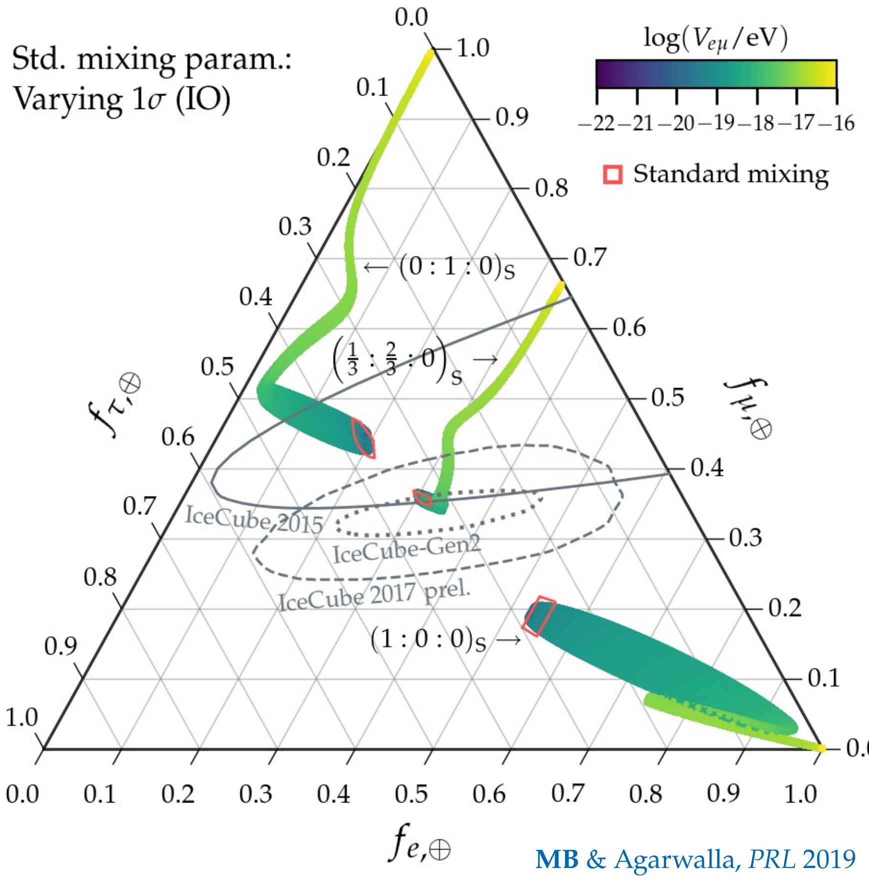

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