Neutrino physics at the highest energies today and in the future

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Niels Bohr Institute, University of Copenhagen

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Heidelberg, January 30, 2023

UNIVERSITY OF COPENHAGEN

VILLUM FONDEN

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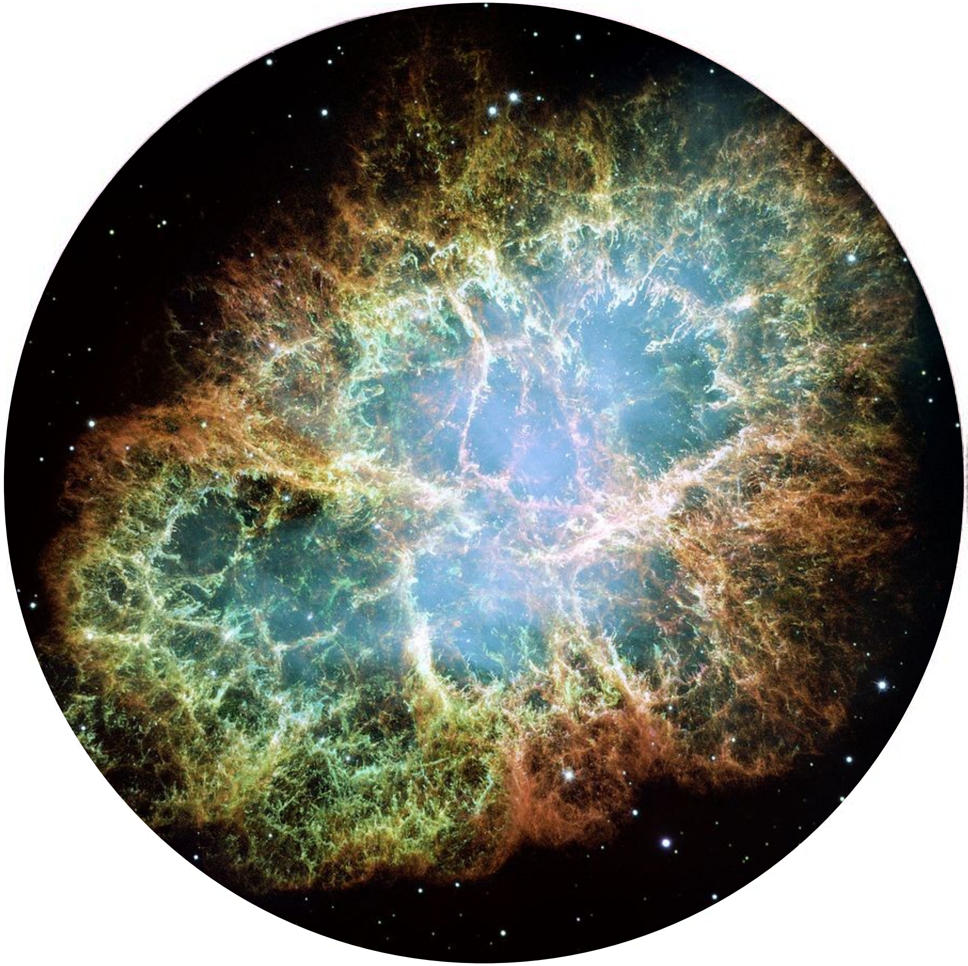


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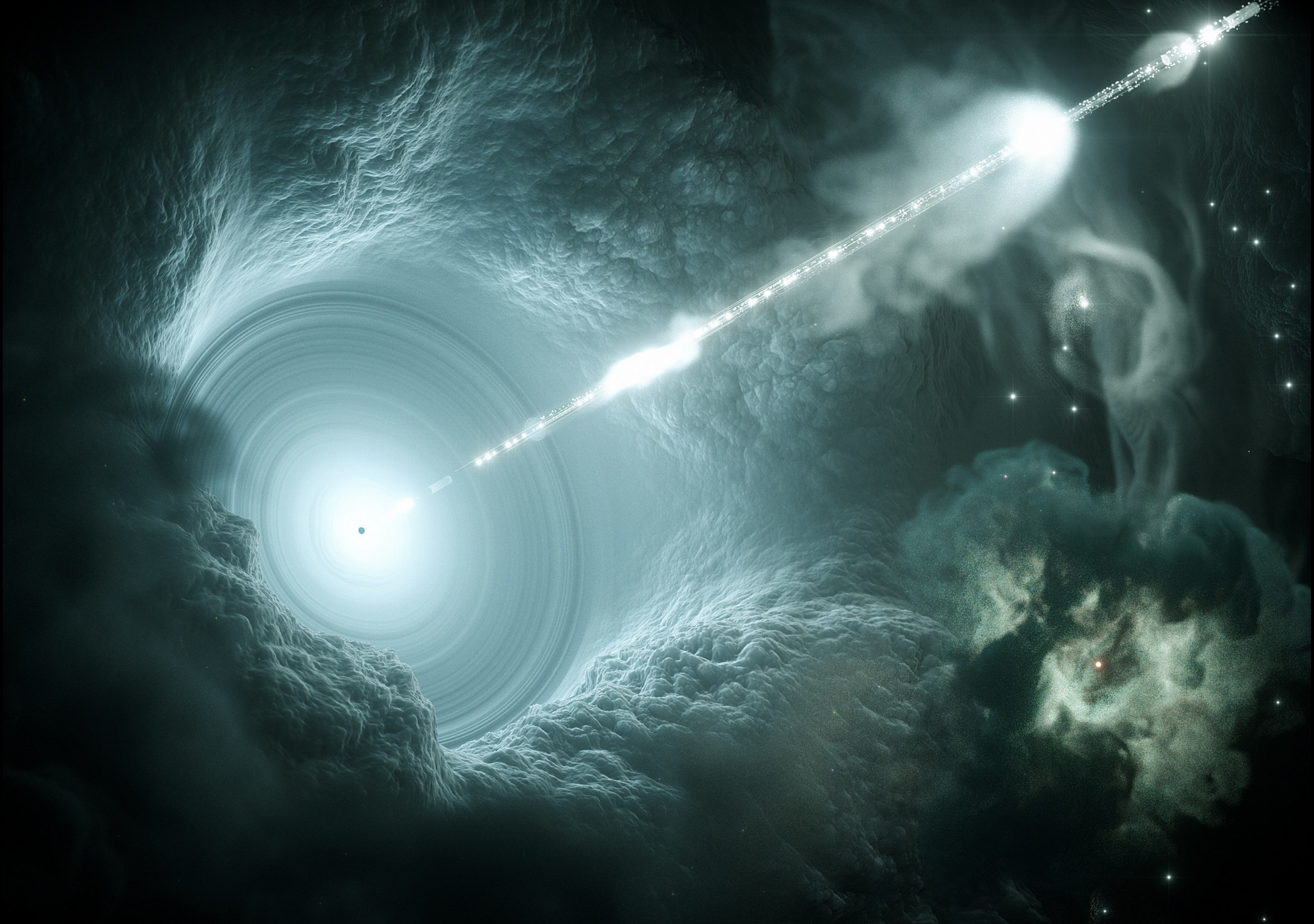

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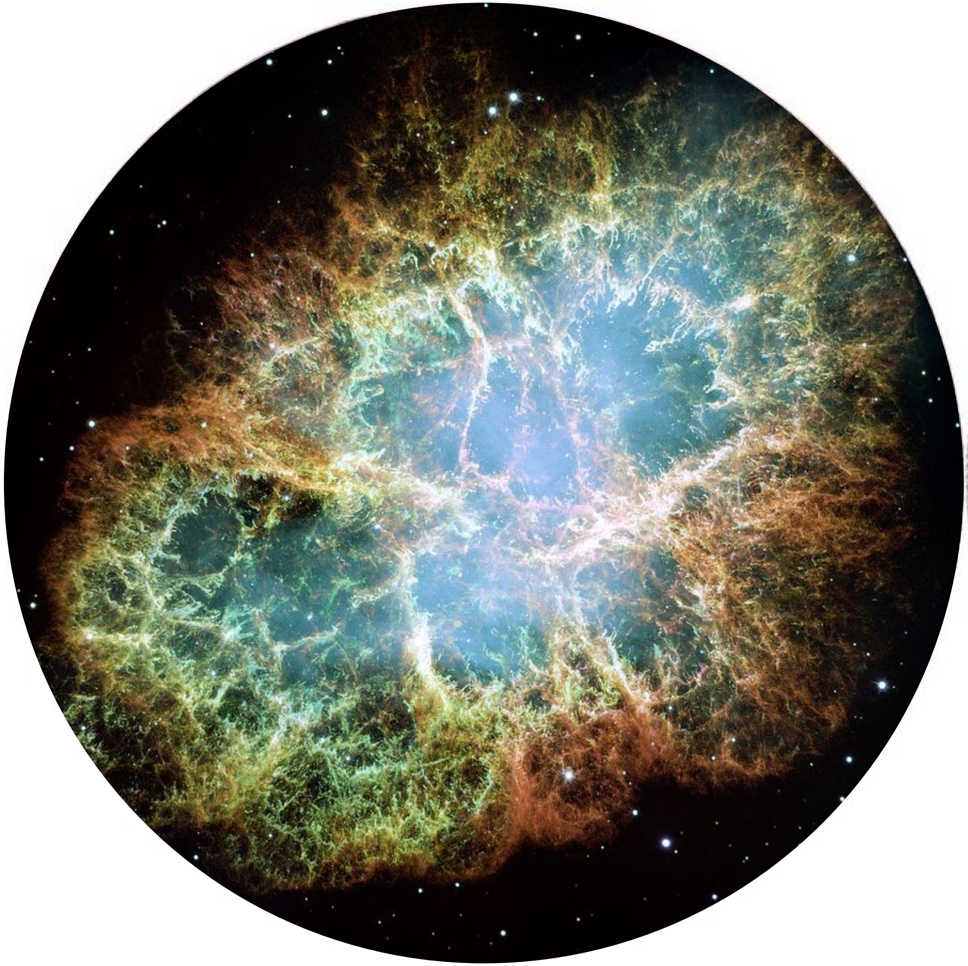

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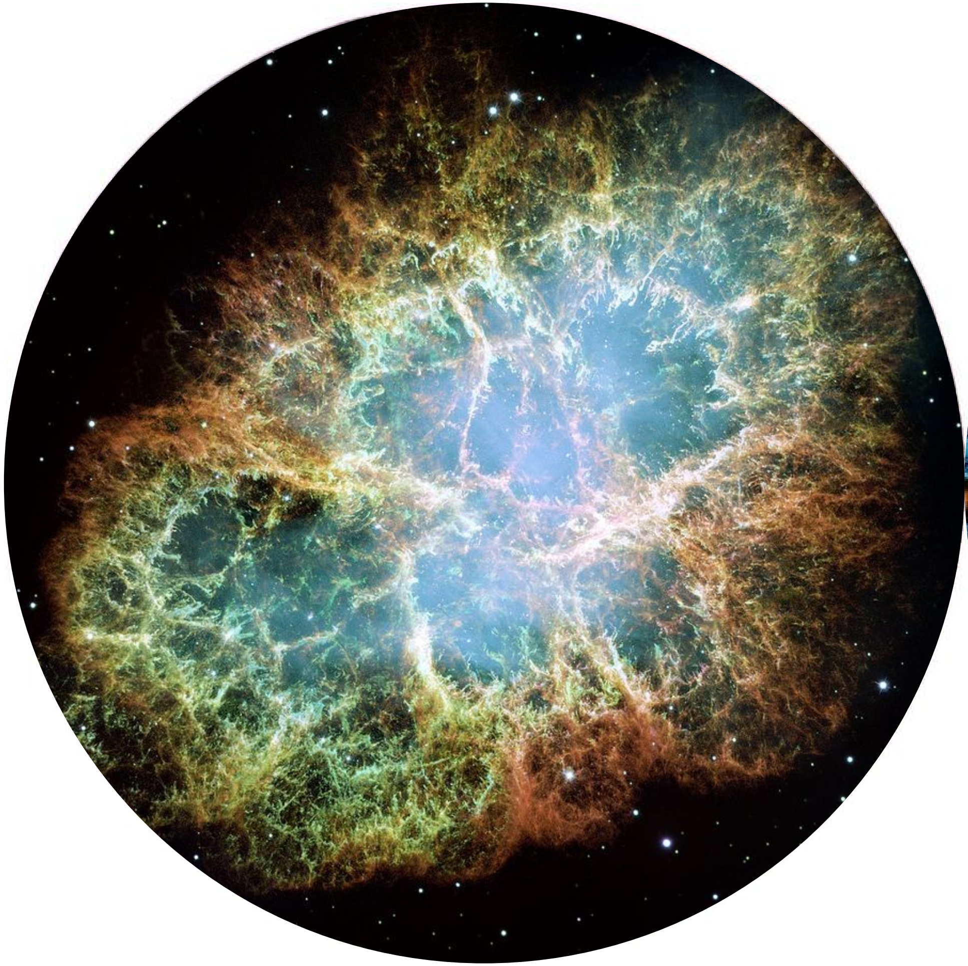

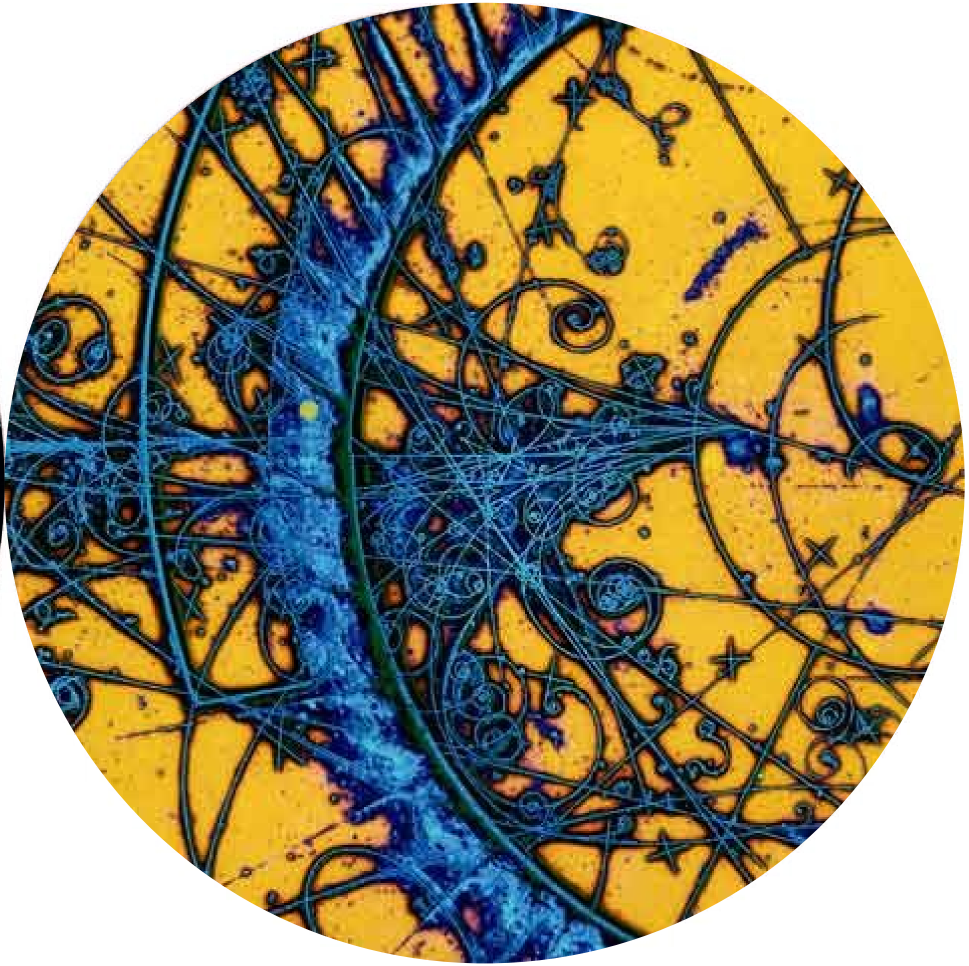

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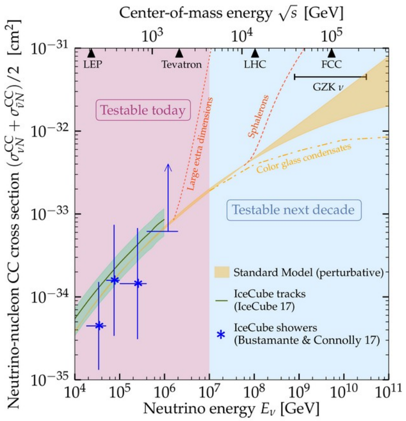
TeV–EeV ν cross sections



MB & Connolly, *PRL* 2019

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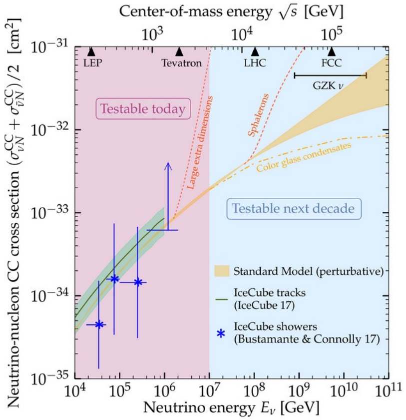

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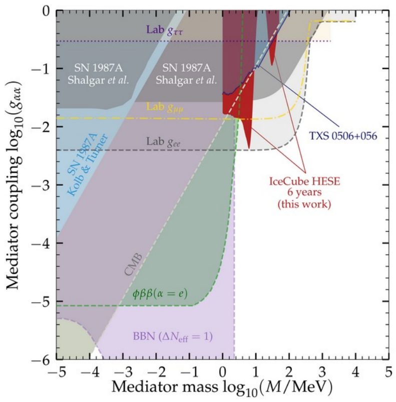
ν self-interactions



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

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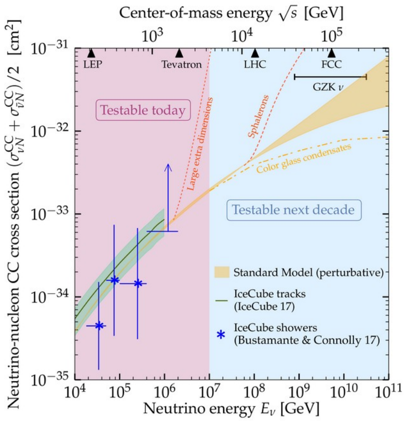

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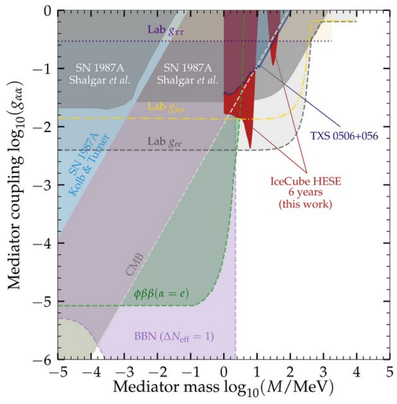

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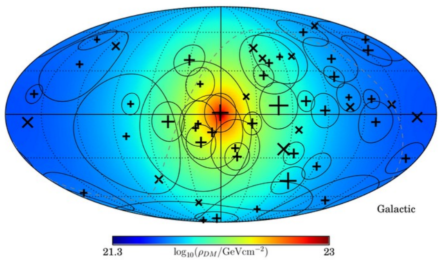
ν scattering on Galactic DM



Argüelles, Kheirandish, Vincent, *PRL* 2017

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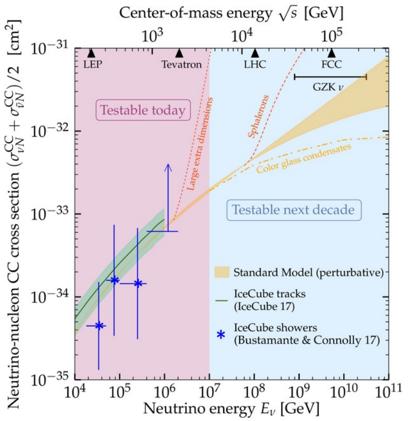

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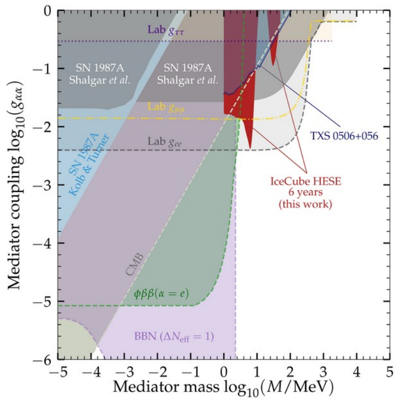

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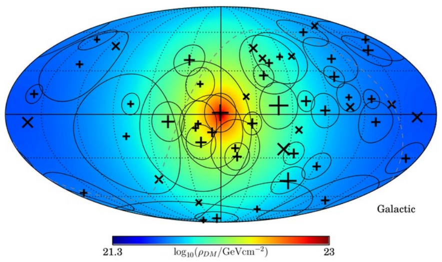

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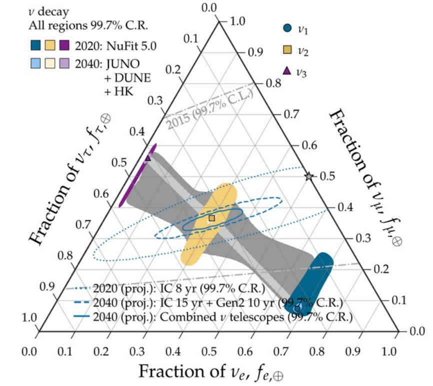

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

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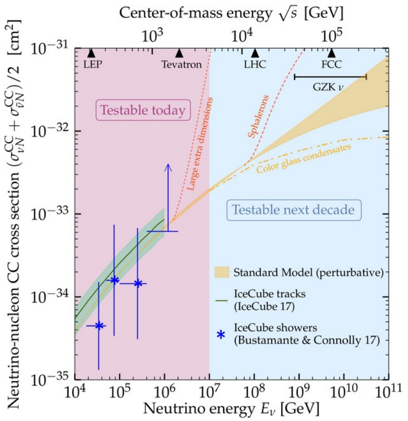

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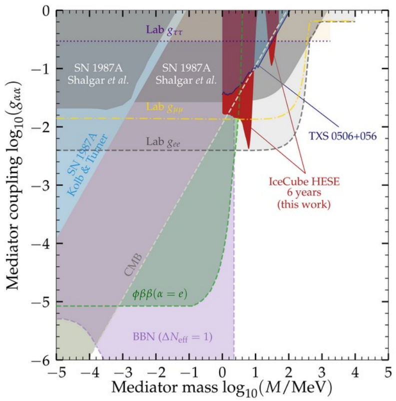

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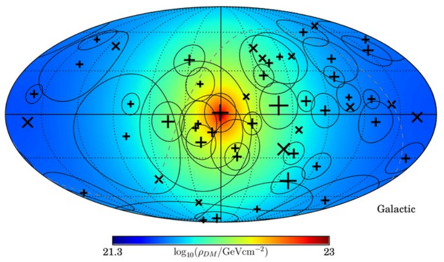

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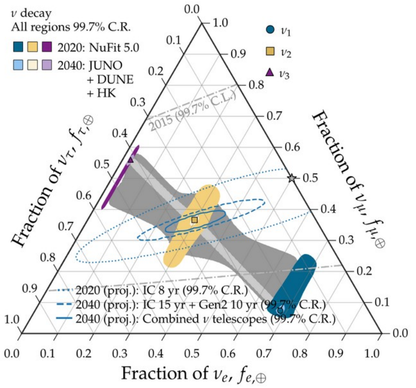

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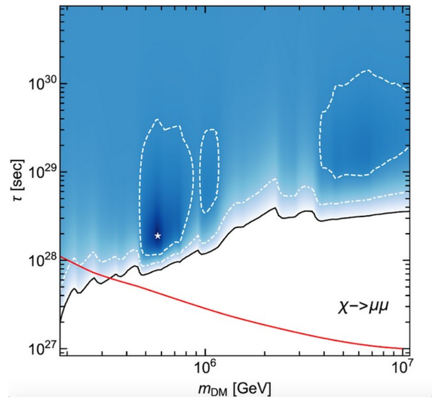
Dark matter decay



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

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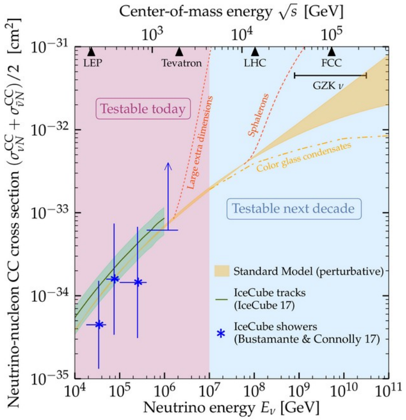

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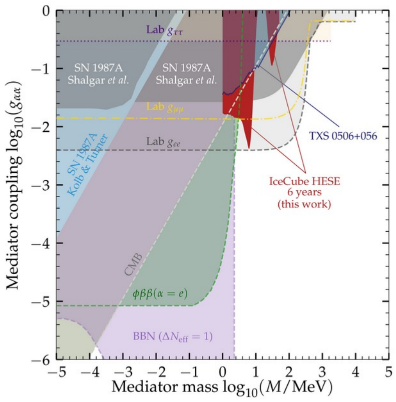

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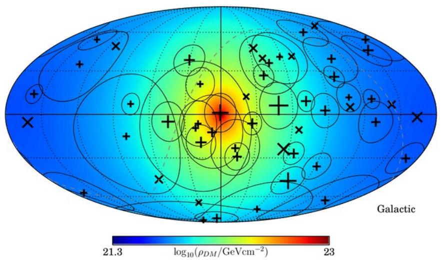

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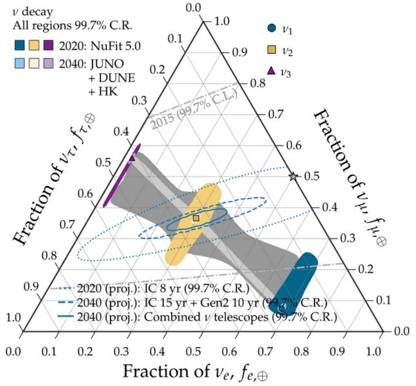

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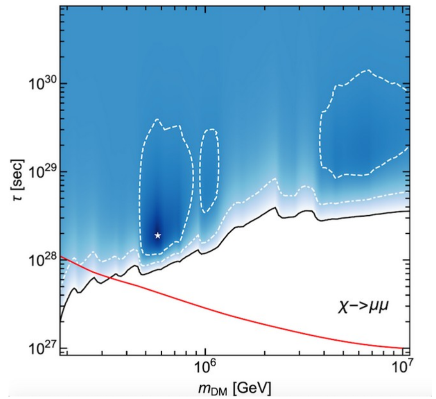

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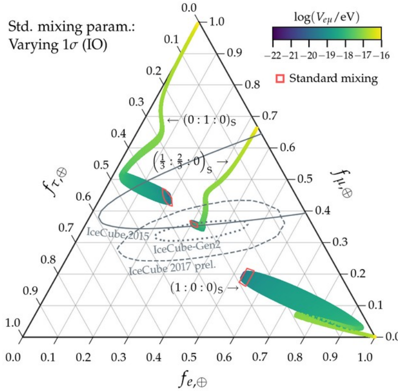
ν-electron interaction



MB & Agarwalla, *PRL* 2019

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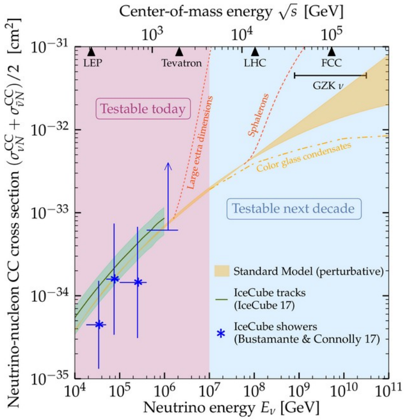

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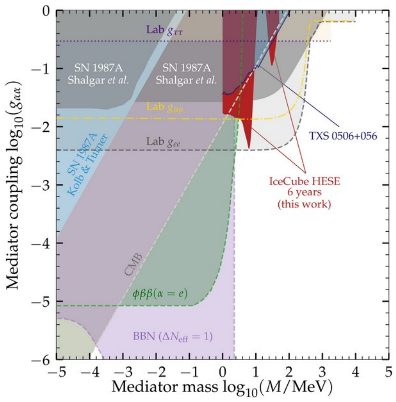

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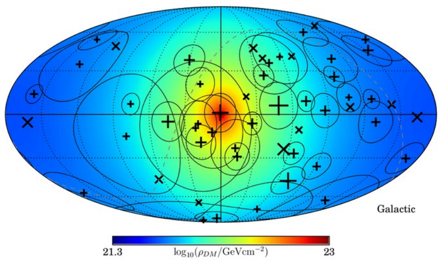

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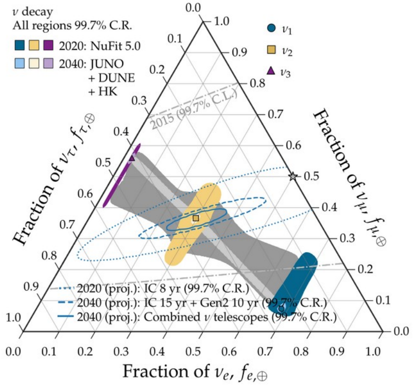

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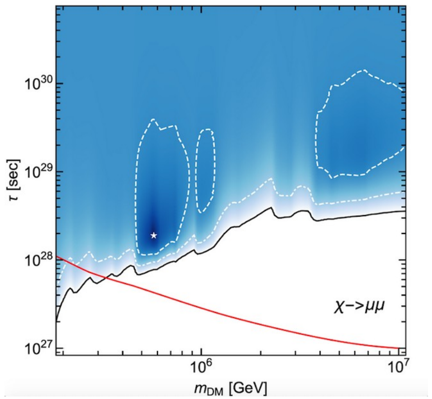

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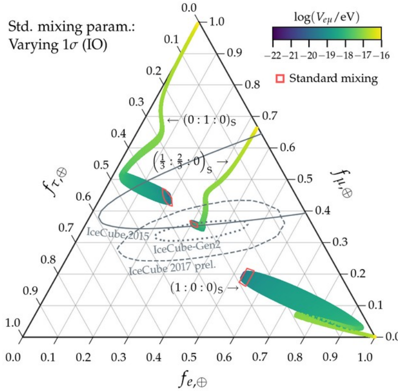
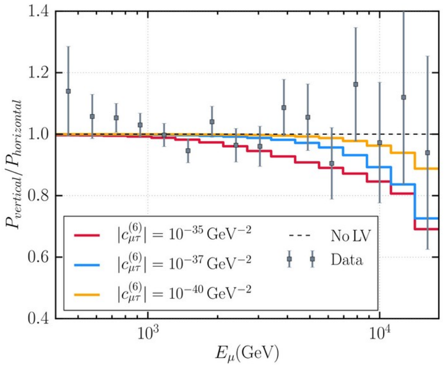


MB & Agarwalla, *PRL* 2019

Lorentz-invariance violation



IceCube, *Nature Phys.* 2018

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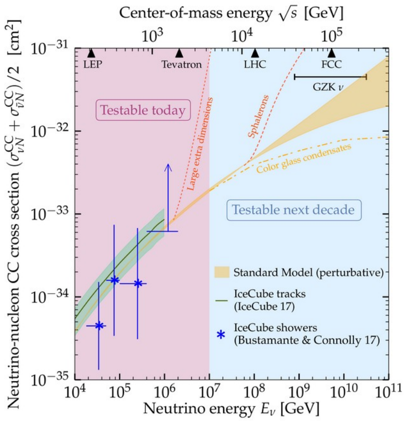

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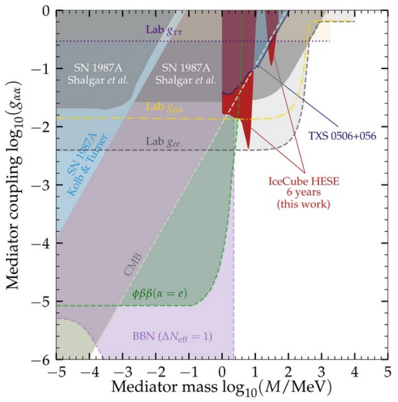

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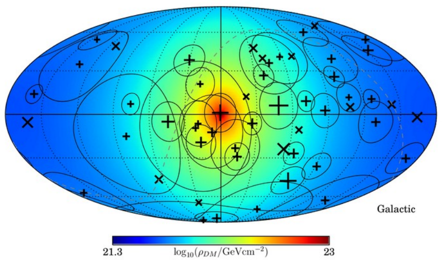

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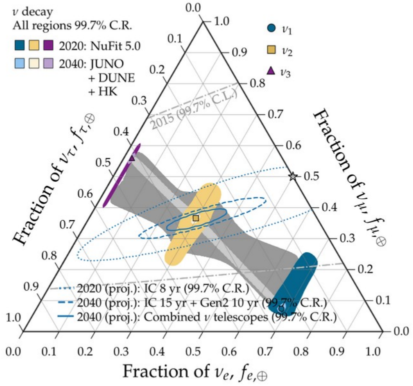

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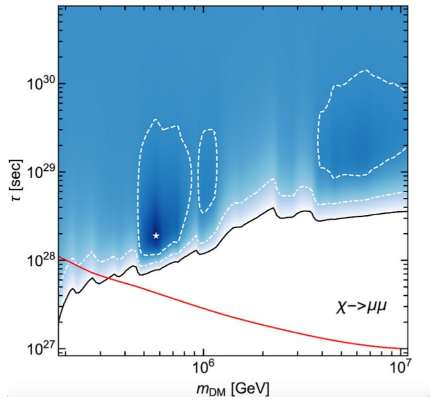

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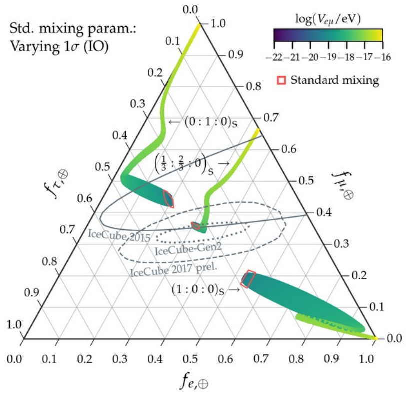

MB & Agarwalla, *PRL* 2019

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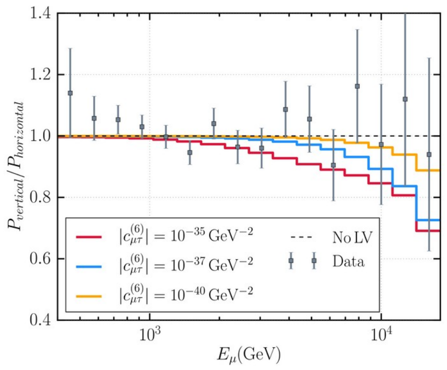
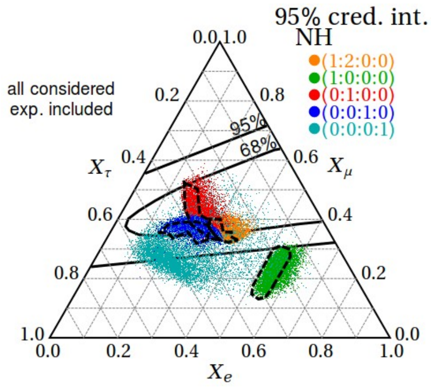
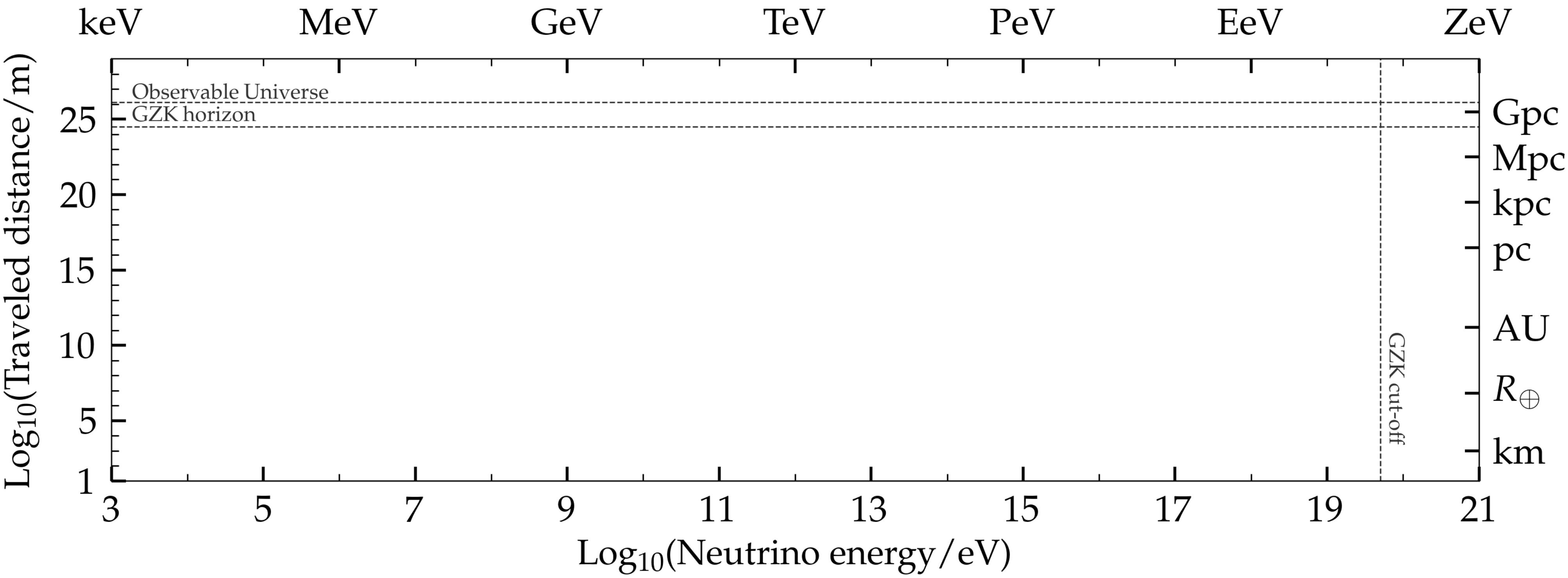


IceCube, *Nature Phys.* 2018

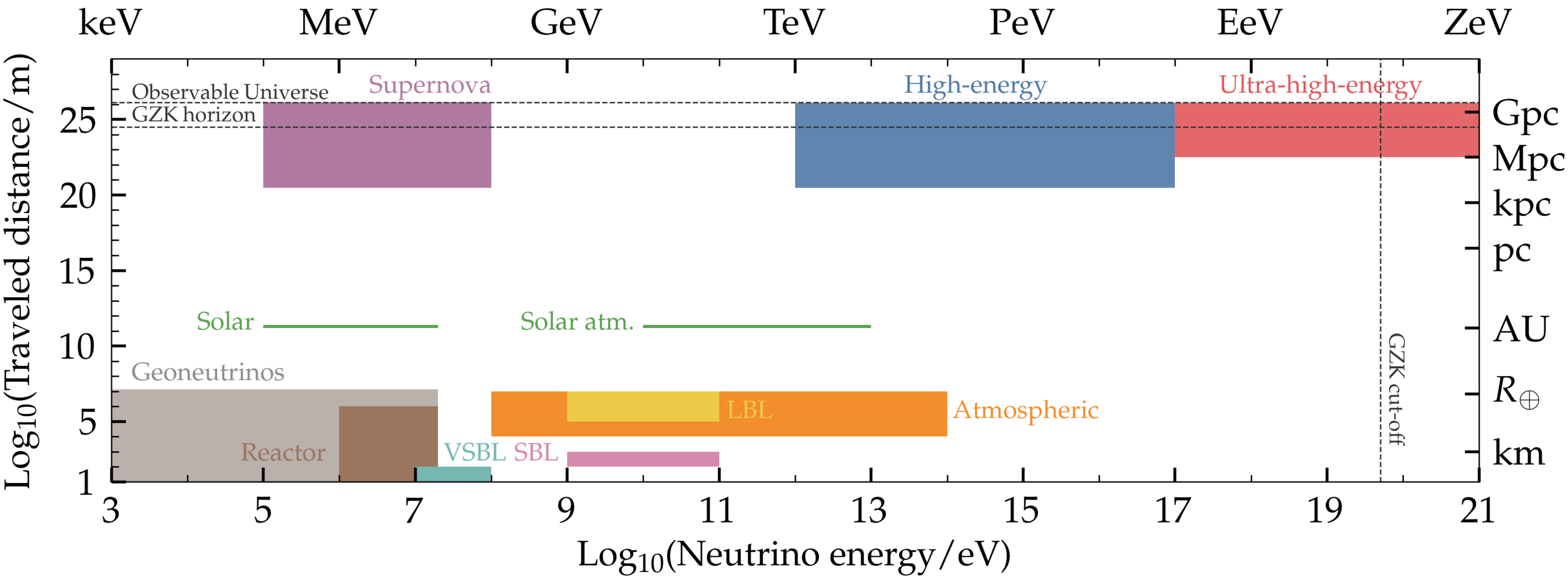
Sterile neutrinos



Brdar, Kopp, Wang, *JCAP* 2017



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



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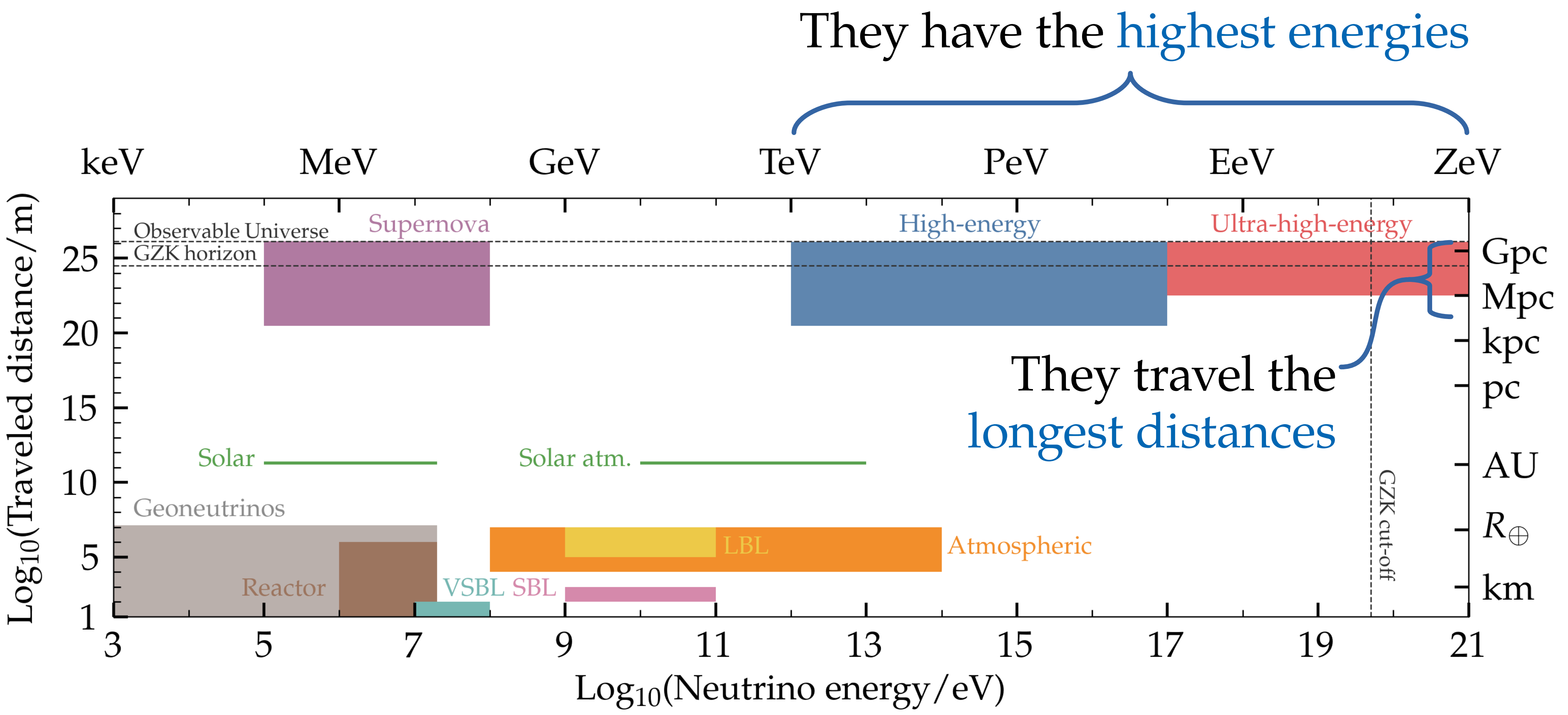

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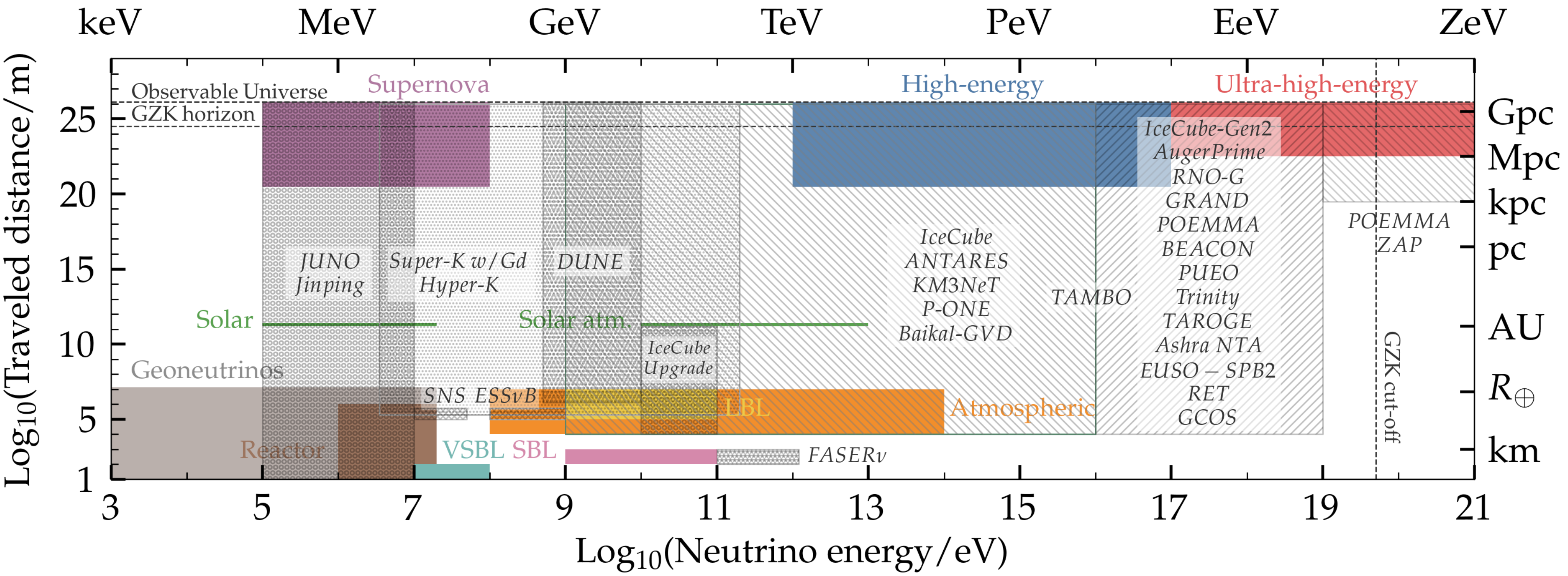

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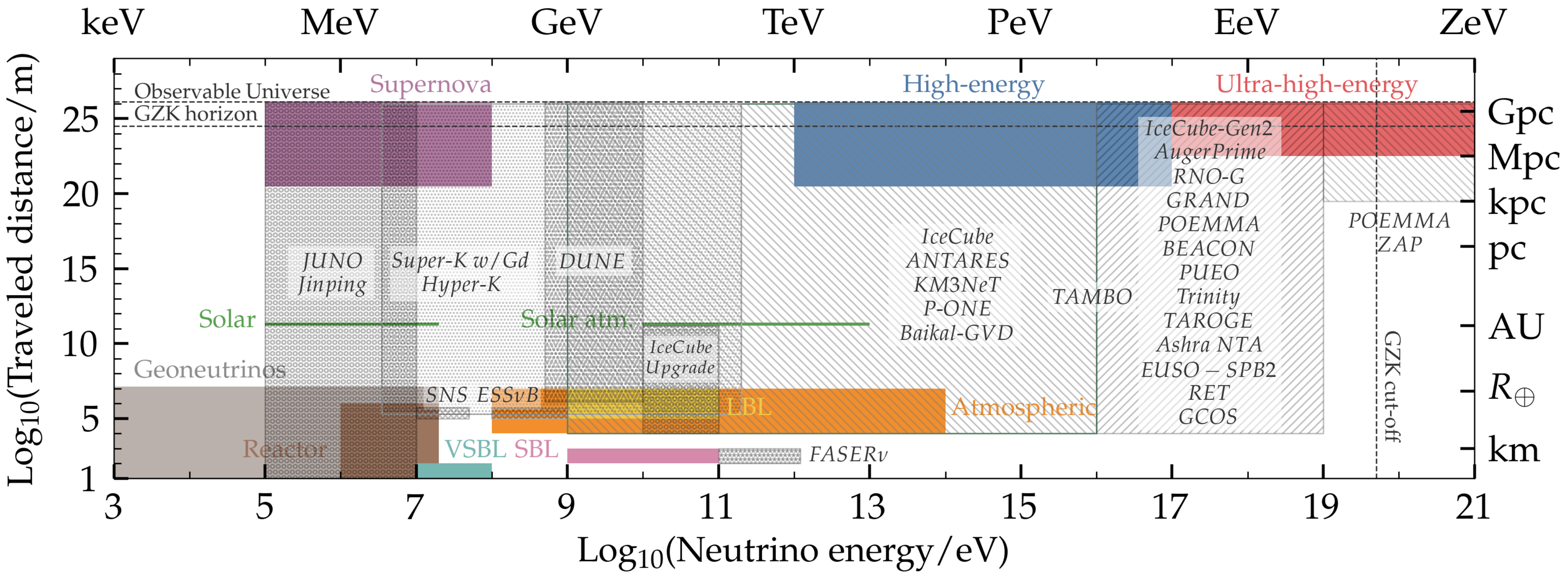
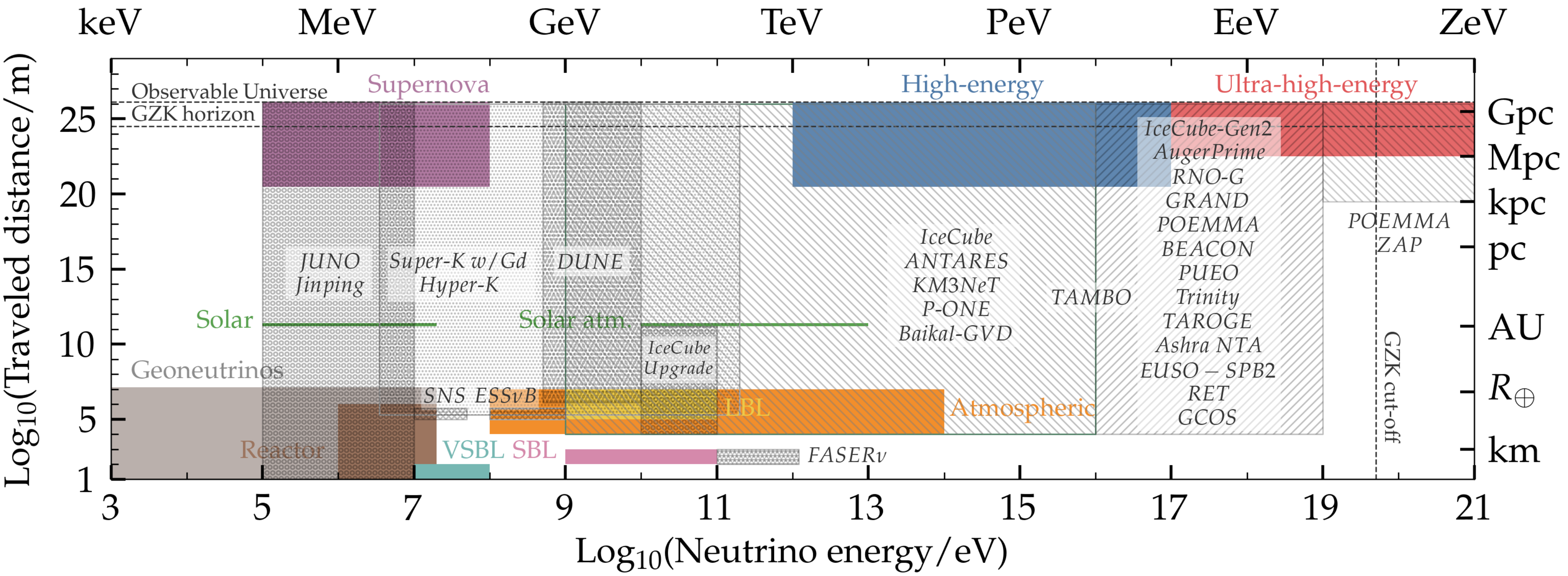


Synergies with lower energies

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

Discovered in 2013 by IceCube



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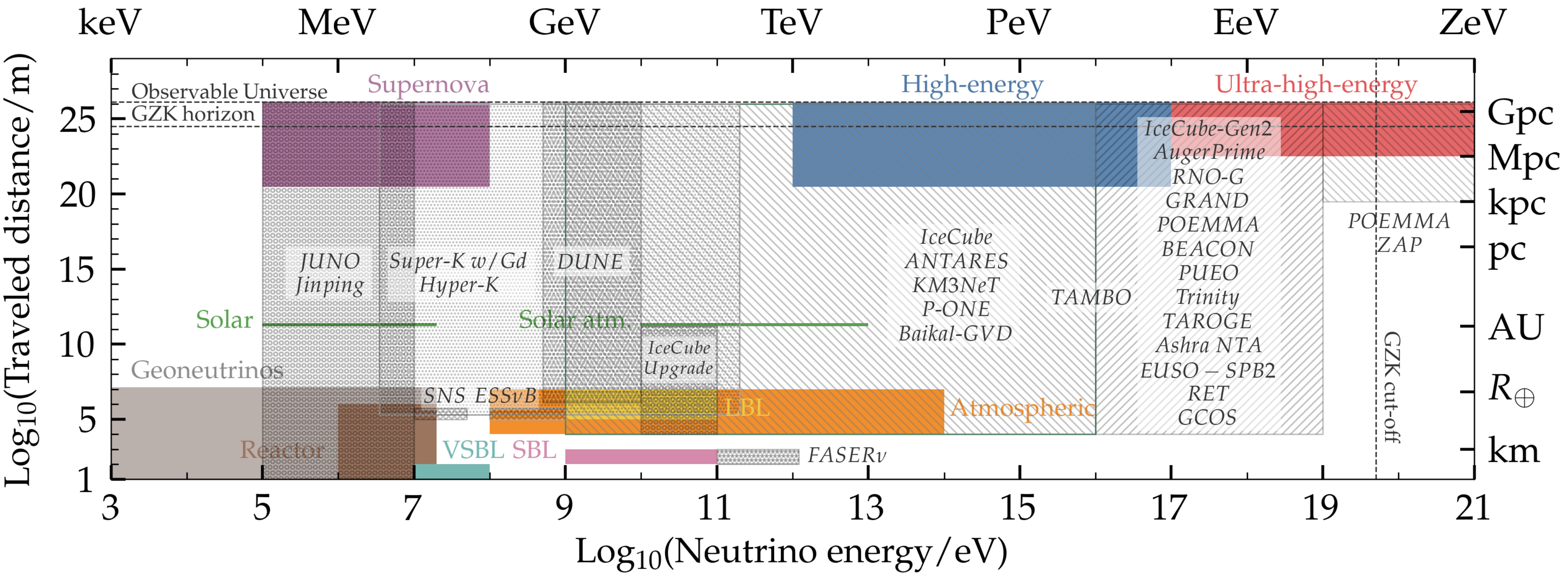

Synergies with lower energies

Increase TeV–PeV
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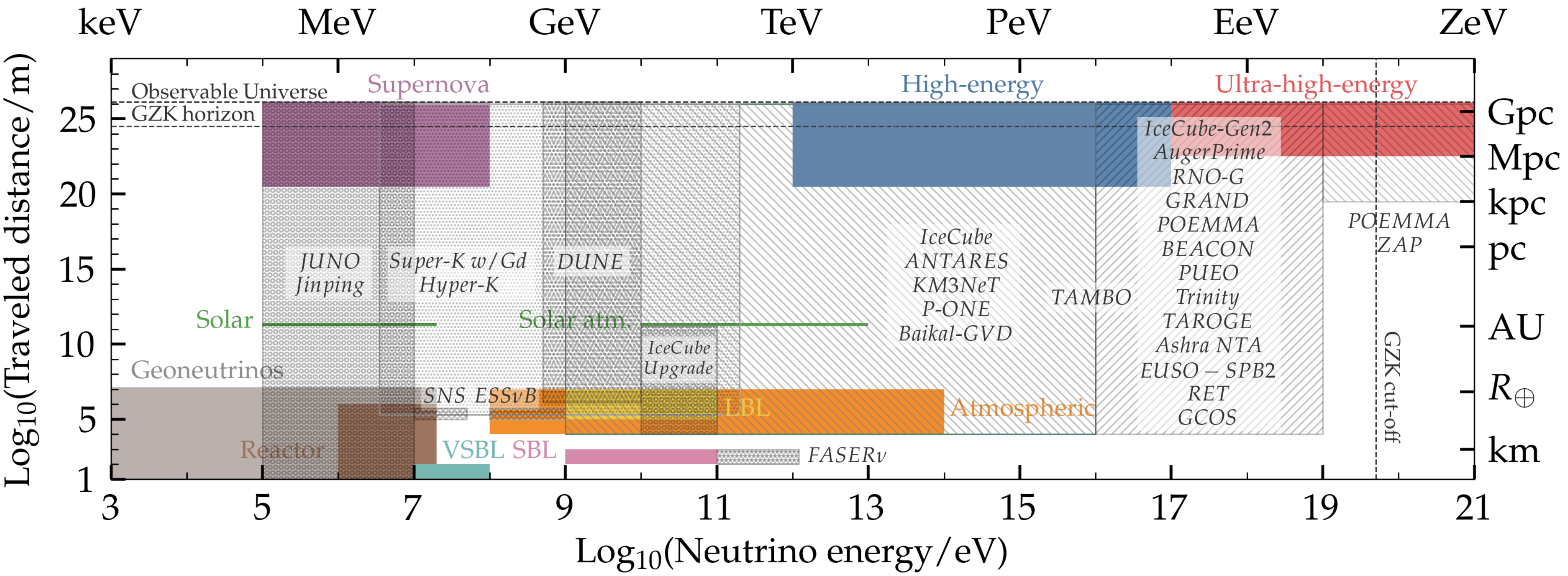

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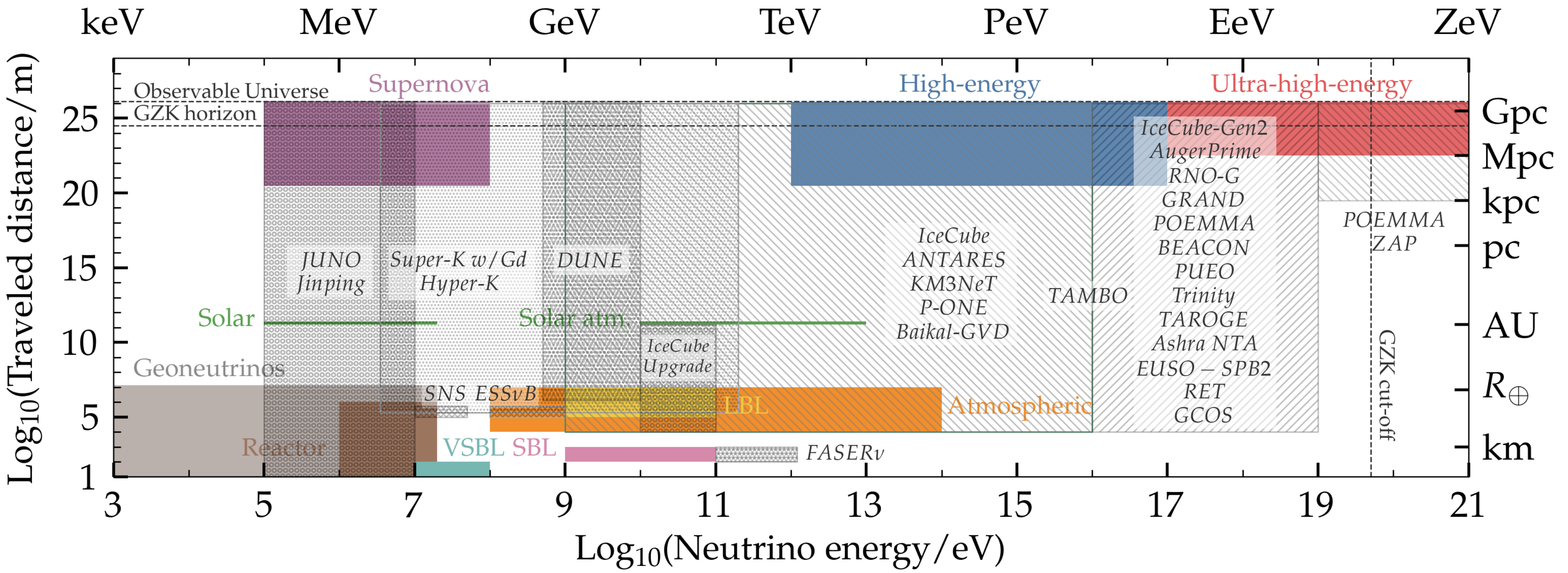

Synergies with lower energies

Increase TeV–PeV ν statistics

Discover > EeV ν

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

Fundamental physics with high-energy cosmic neutrinos

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

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

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

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

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

High-energy cosmic neutrinos:
Basics and current status

Making high-energy astrophysical neutrinos: a toy model

(or $p + p$)

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

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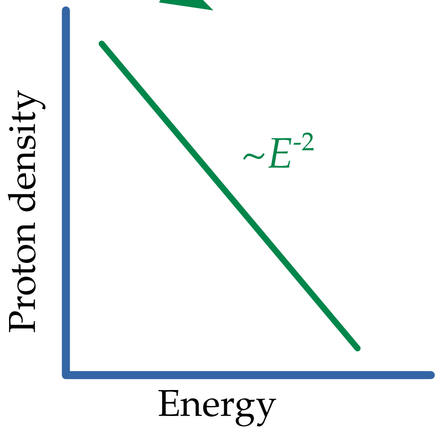

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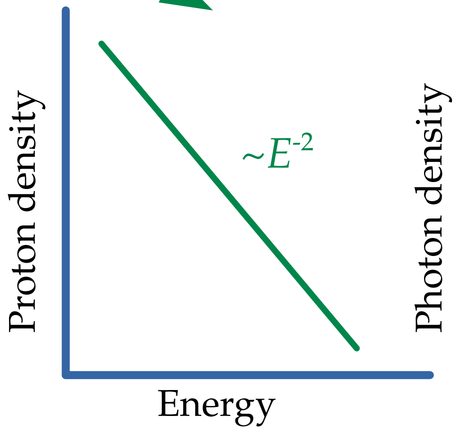

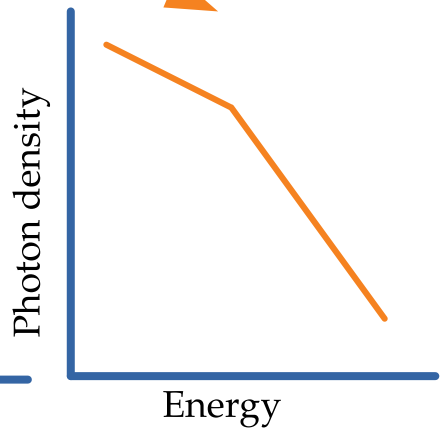

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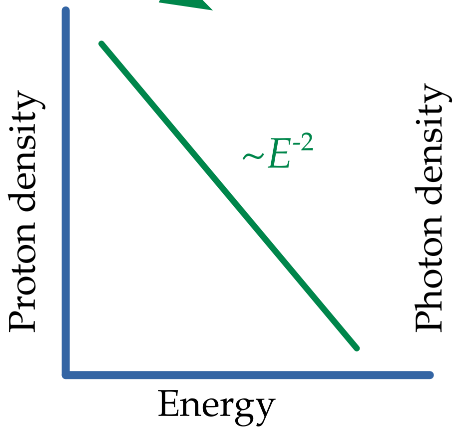
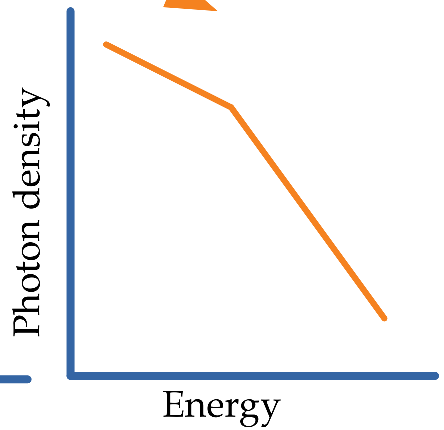
$$\pi^0 \longrightarrow \gamma + \gamma$$

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

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





Making high-energy astrophysical neutrinos: a toy model

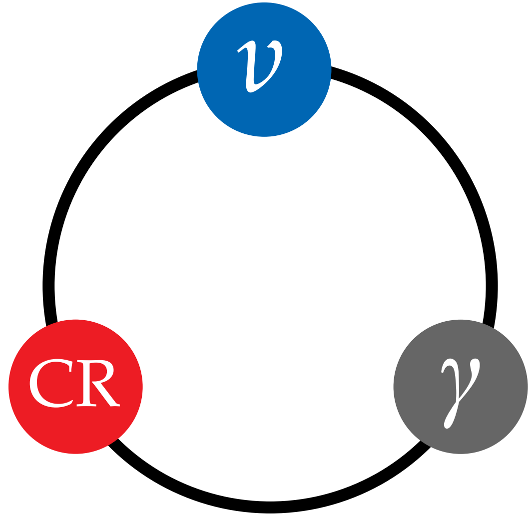
(or $p + p$)

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

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

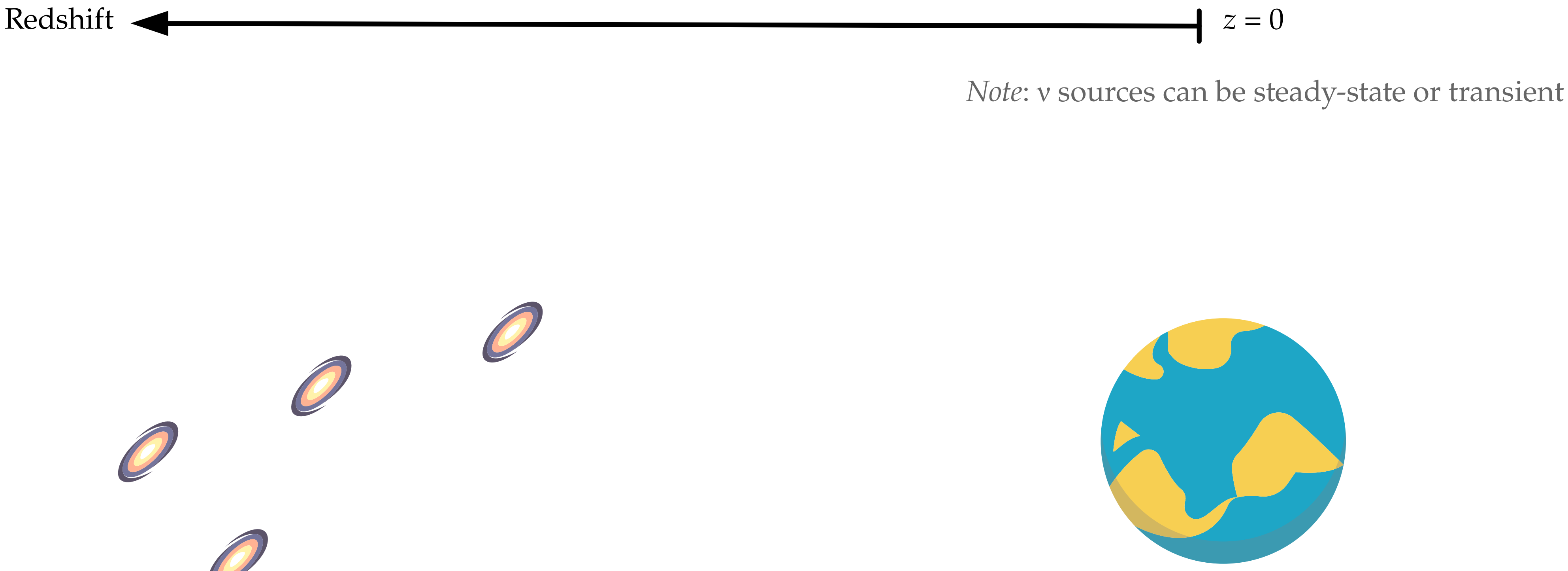
$$\pi^+ \longrightarrow \mu^+ + \nu_\mu \longrightarrow \bar{\nu}_\mu + e^+ + \nu_e + \nu_\mu$$

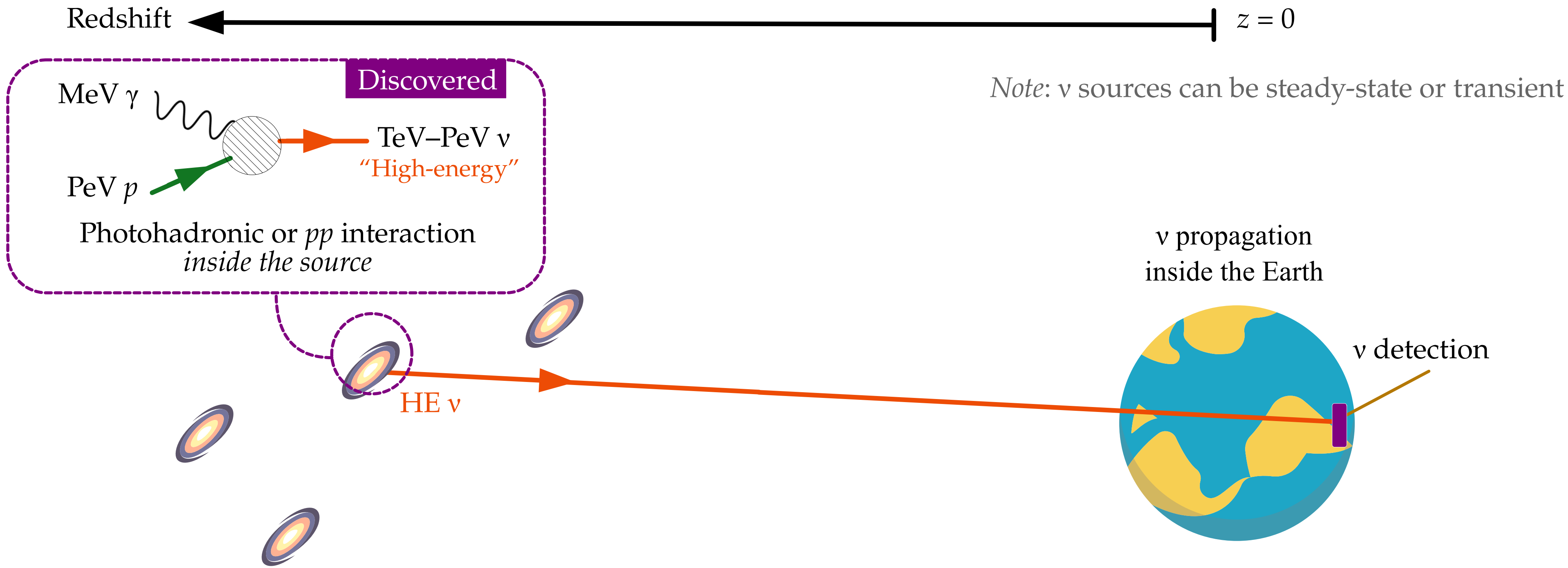
$$n \text{ (escapes)} \longrightarrow p + e^- + \bar{\nu}_e$$

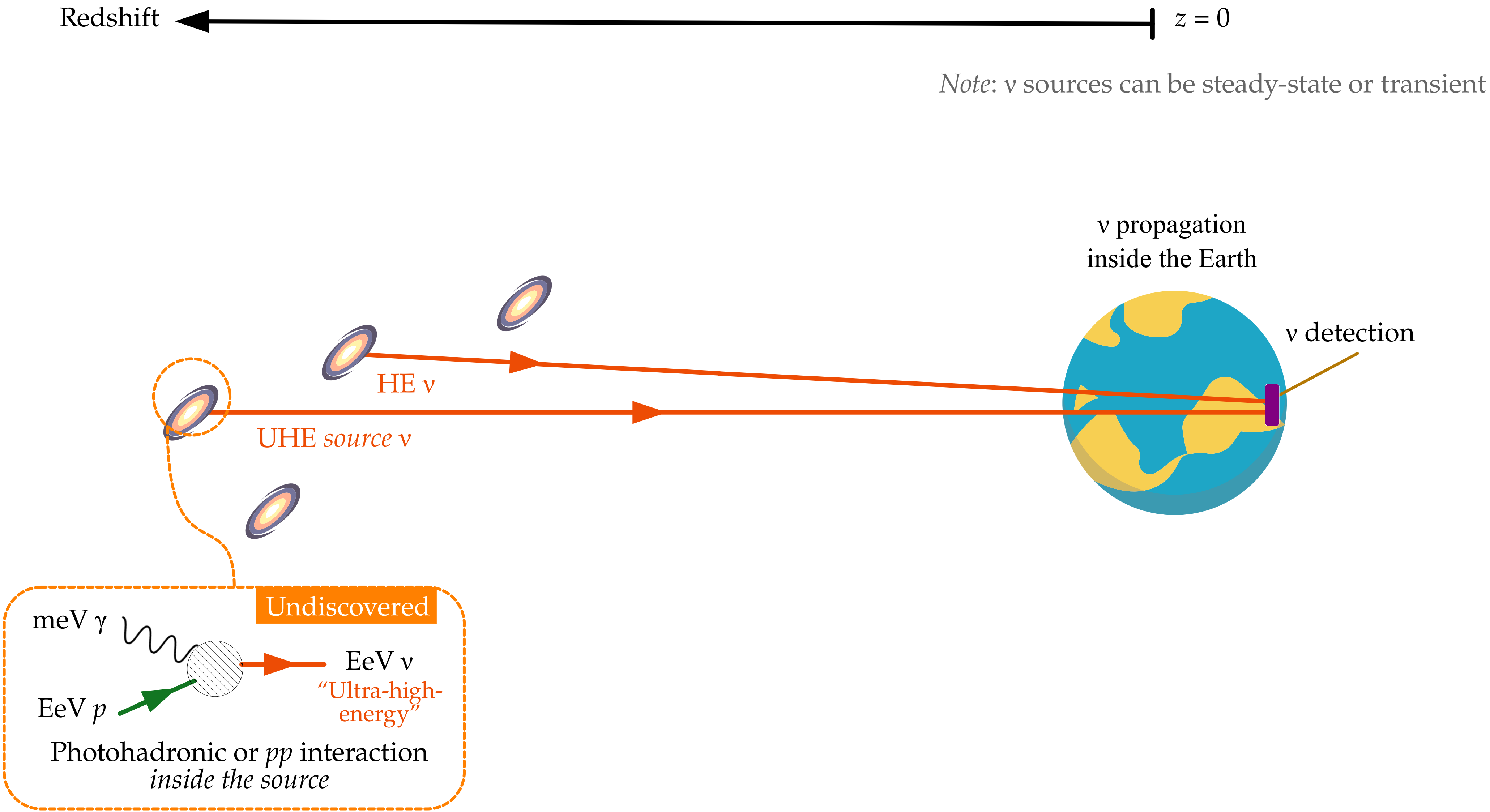


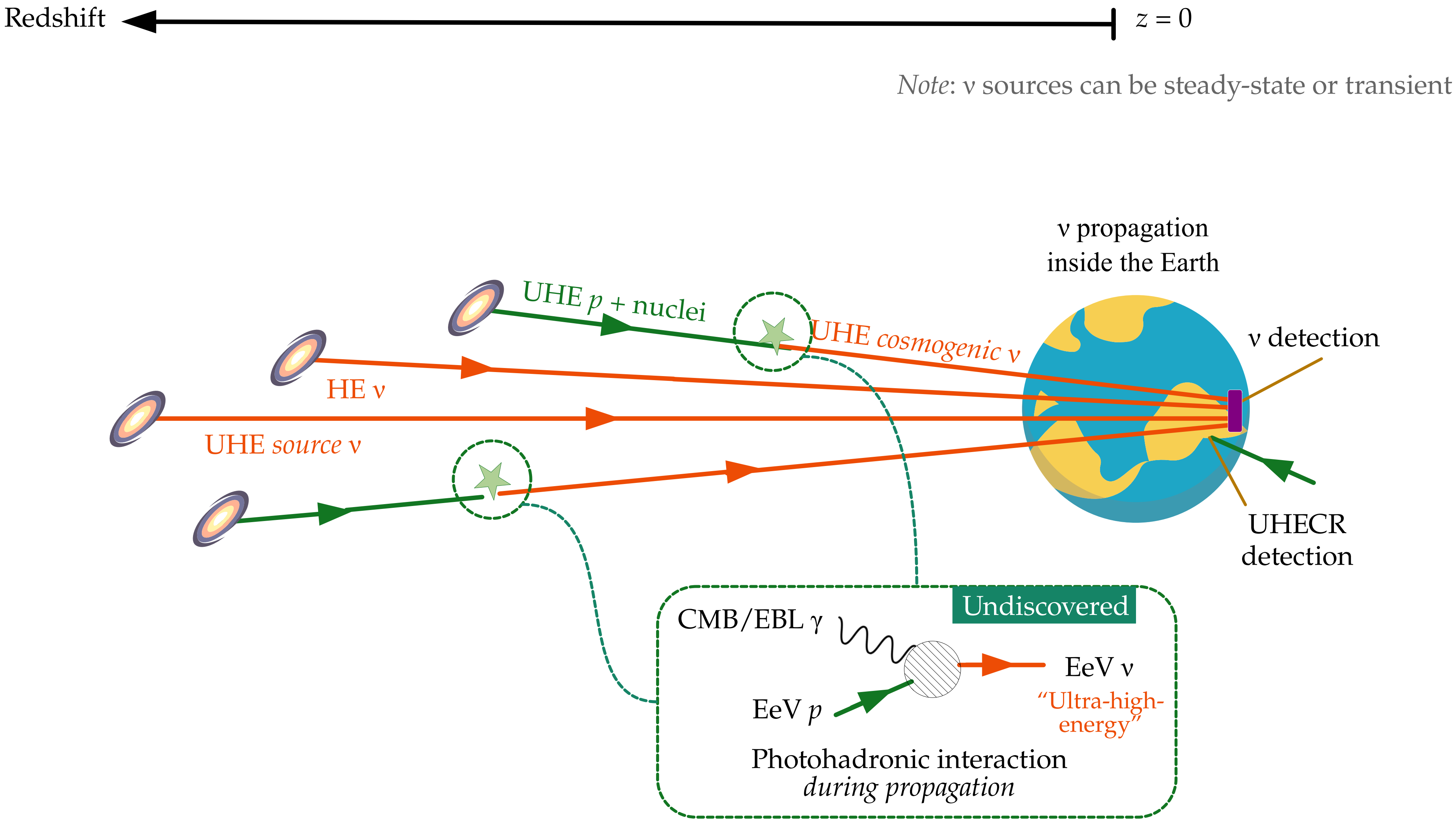
Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10

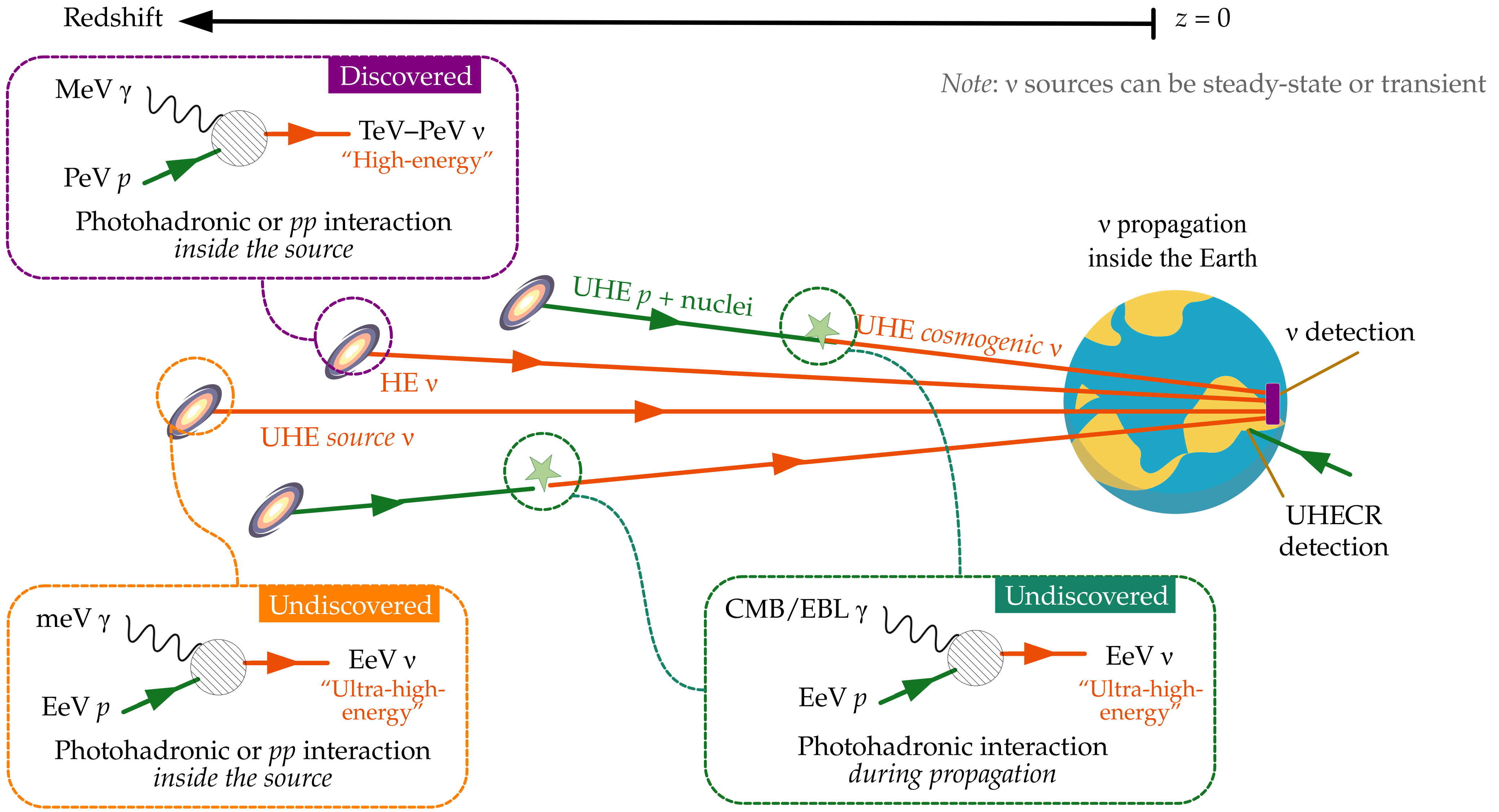

Redshift
$z = 0$
Note: ν sources can be steady-state or transient


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
"Ultra-high-
energy"
EeV p
Photohadronic interaction
during propagation



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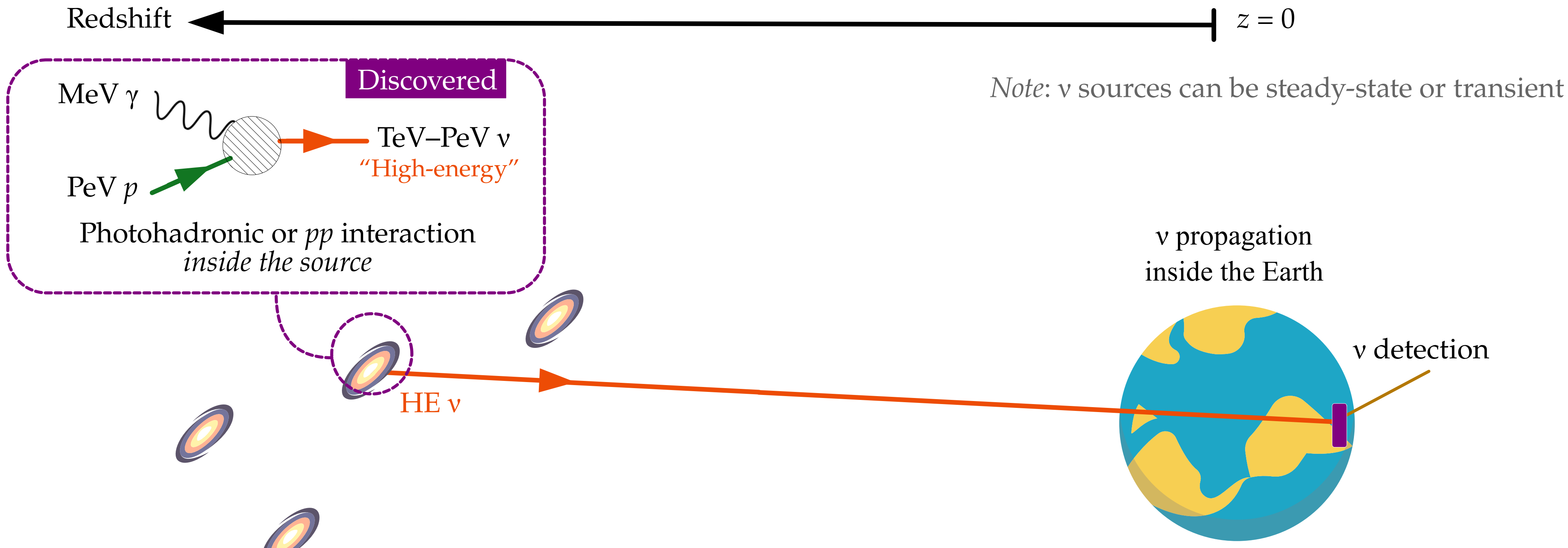
Redshift
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MeV γ
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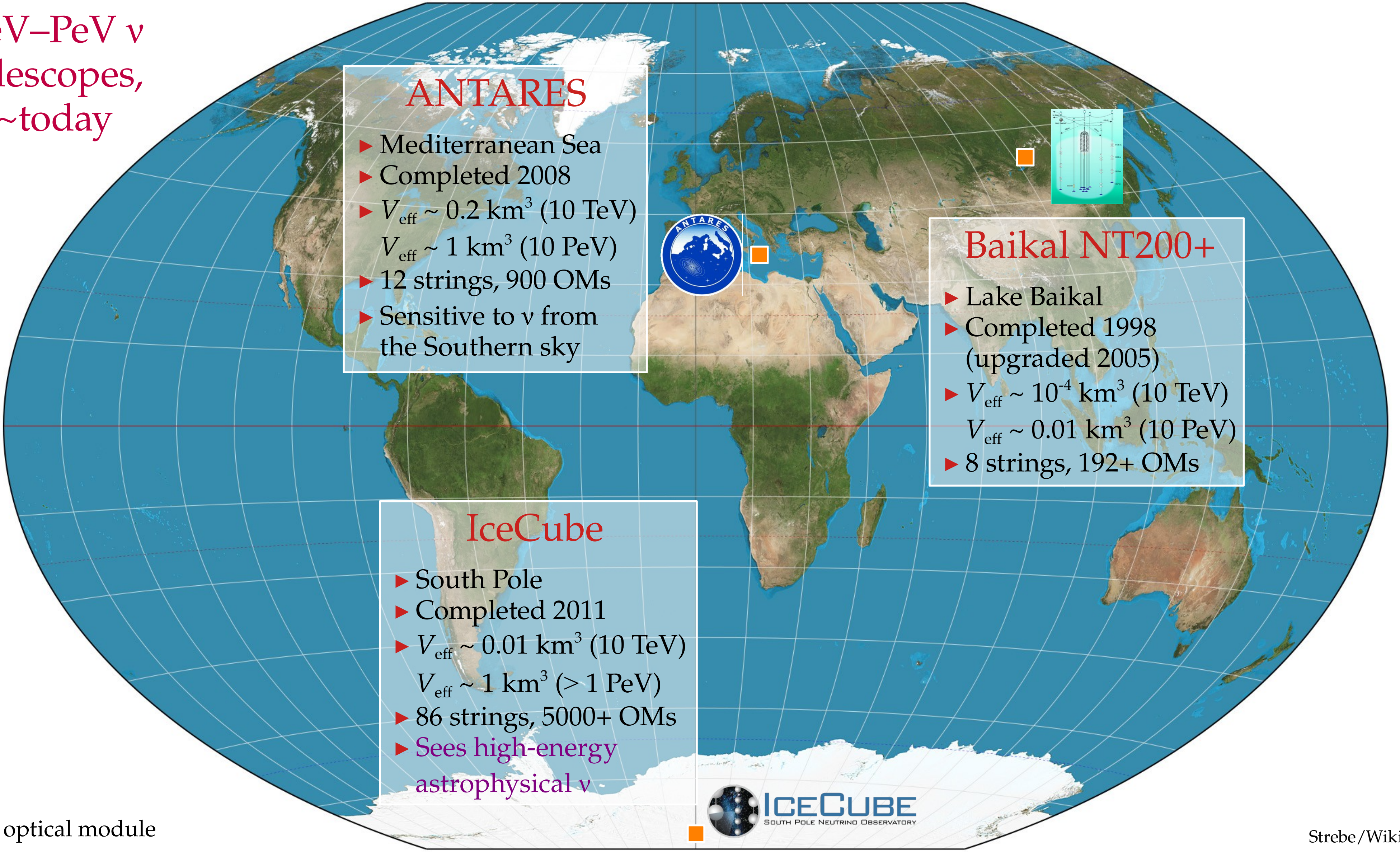
Note: ν sources can be steady-state or transient
ν propagation
inside the Earth
ν detection
HE ν

TeV–PeV ν telescopes, ~today



ANTARES

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

Baikal NT200+

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

IceCube

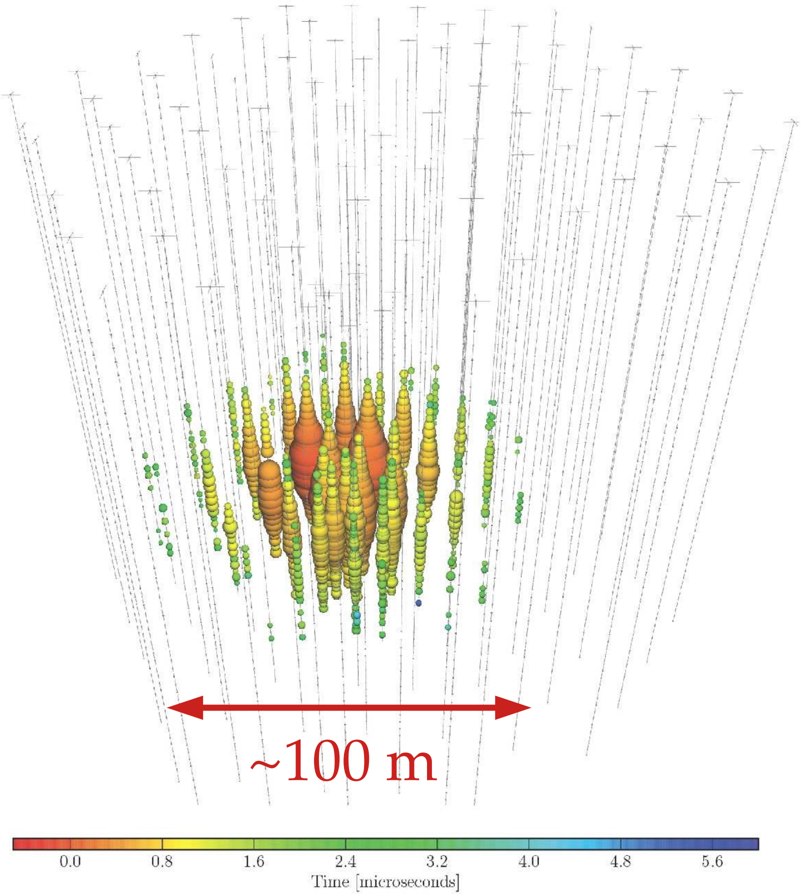
- South Pole
- Completed 2011
- $V_{\mathrm{eff}} \sim 0.01\ \mathrm{km}^3$ (10 TeV)
  $V_{\mathrm{eff}} \sim 1\ \mathrm{km}^3$ (> 1 PeV)
- 86 strings, 5000+ OMs
- Sees high-energy astrophysical ν

OM: optical module

Strebe/Wikipedia

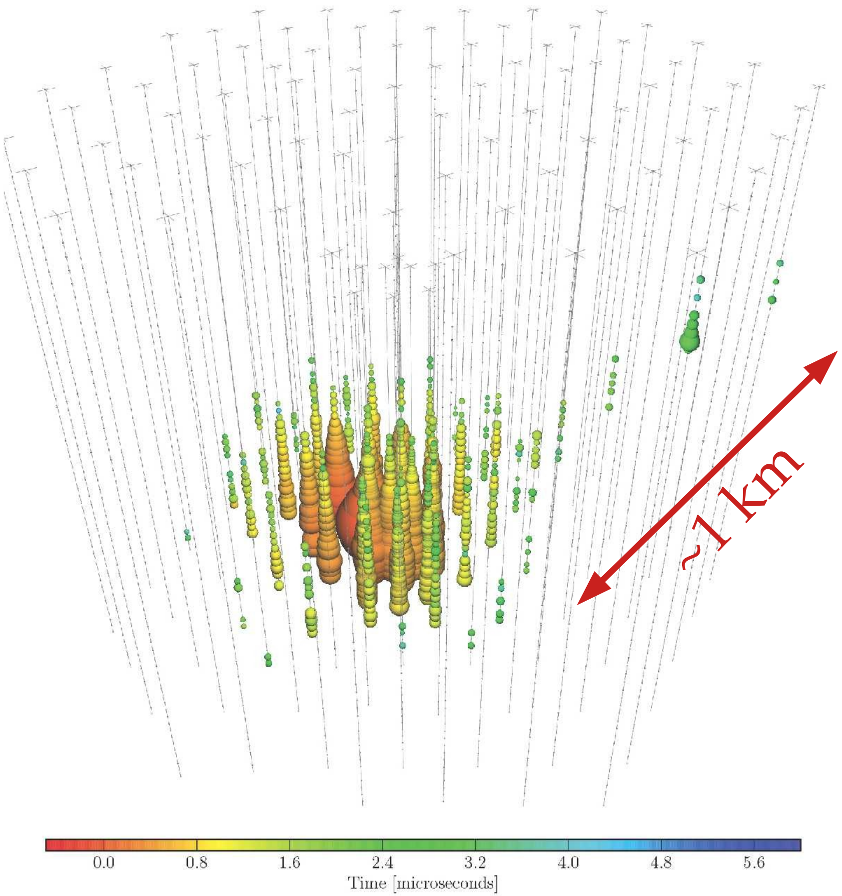
Yuya Makino, IceCube/NSF

Shower (mainly from ν_e and ν_τ)

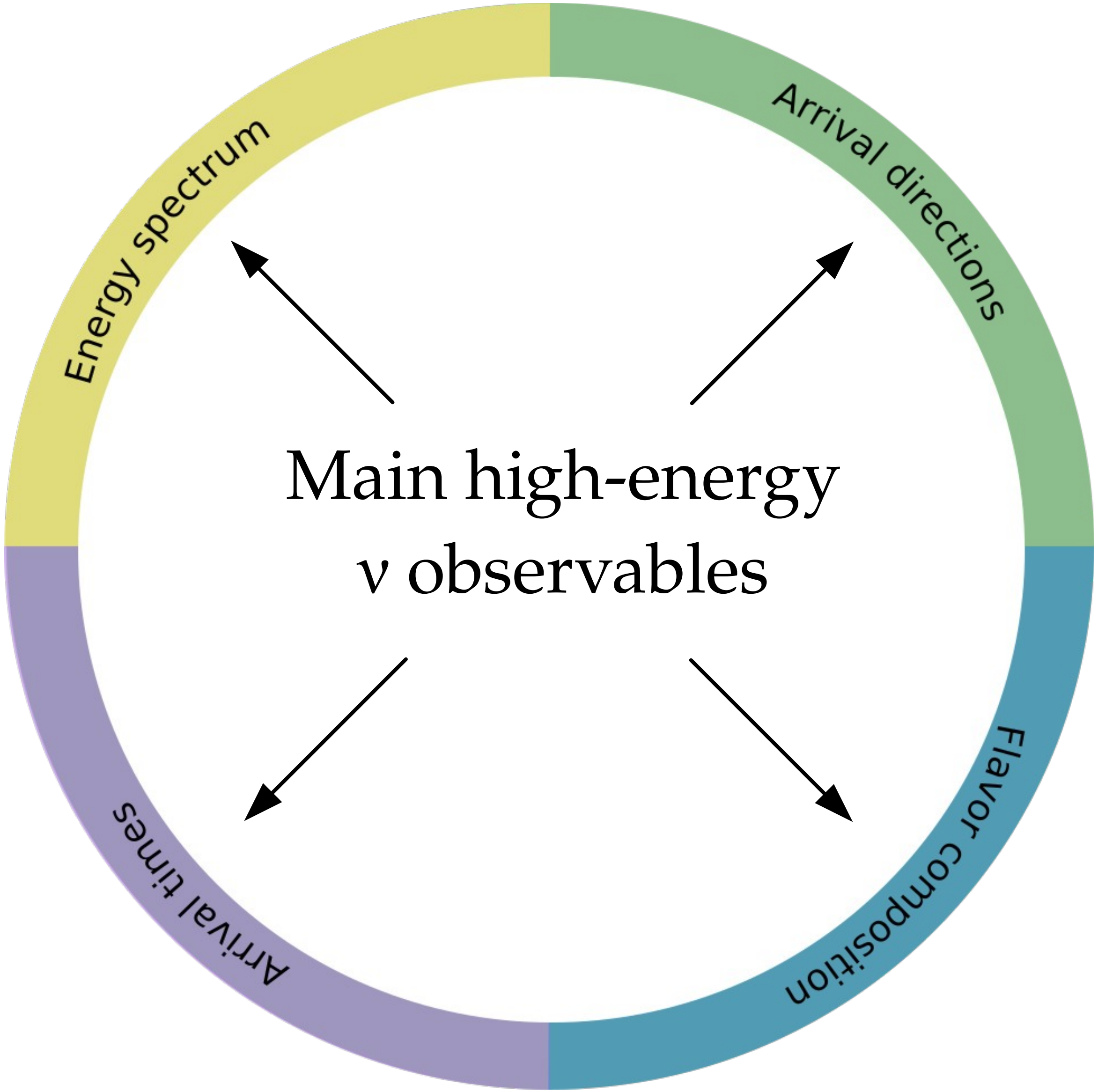


Poor angular resolution: ~10°

Track (mainly from ν_μ)

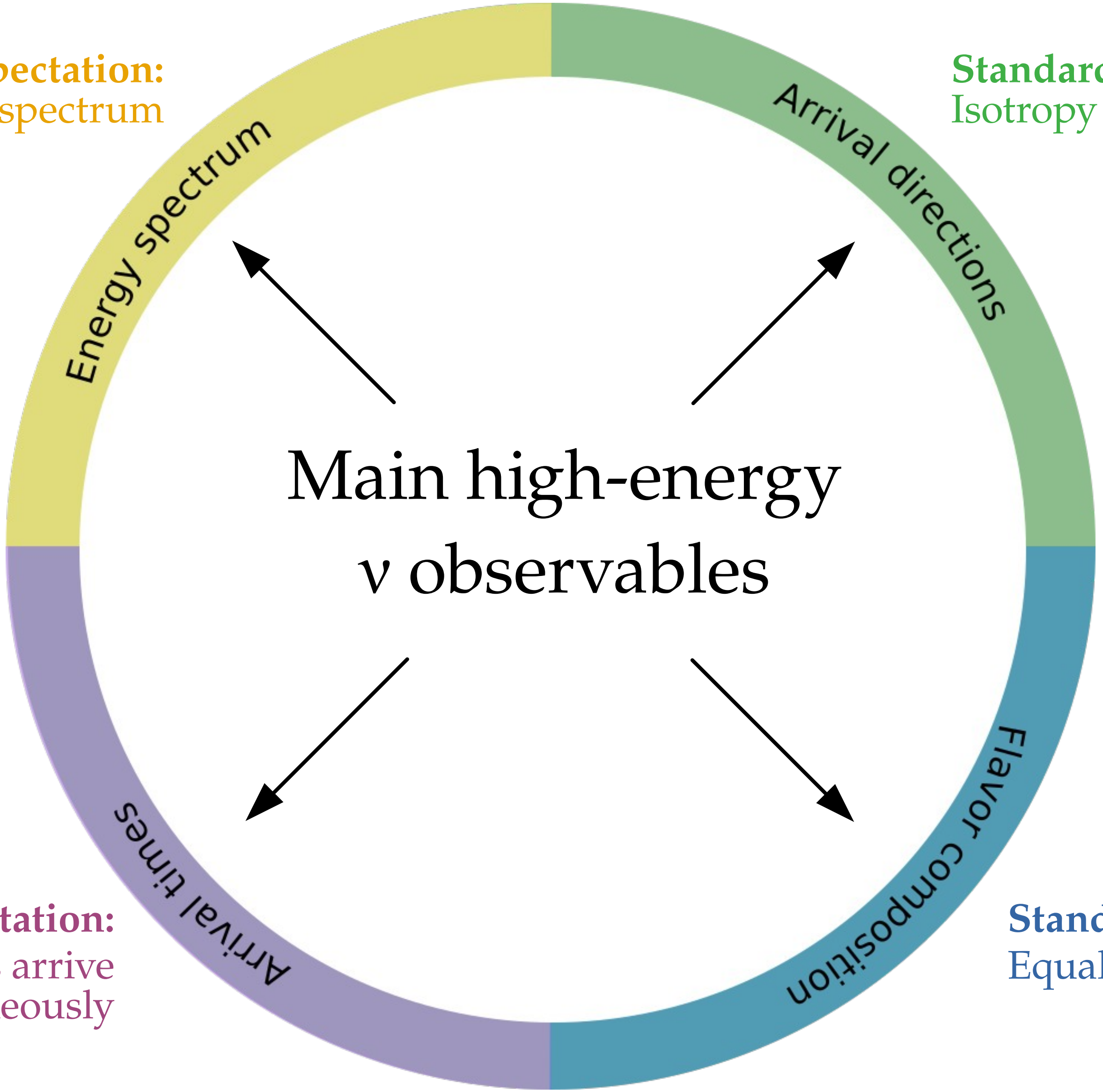


Angular resolution: < 1°


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

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)

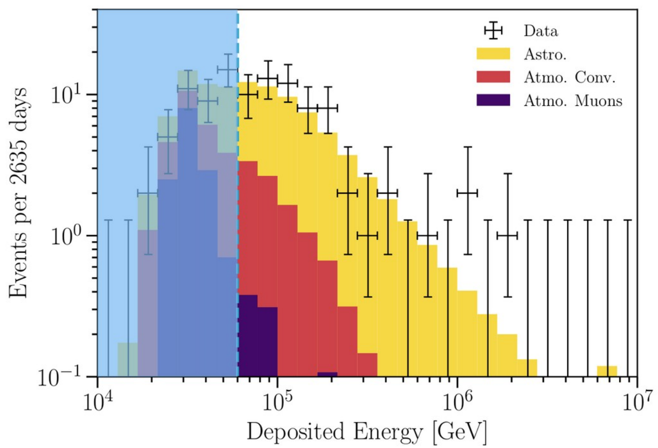


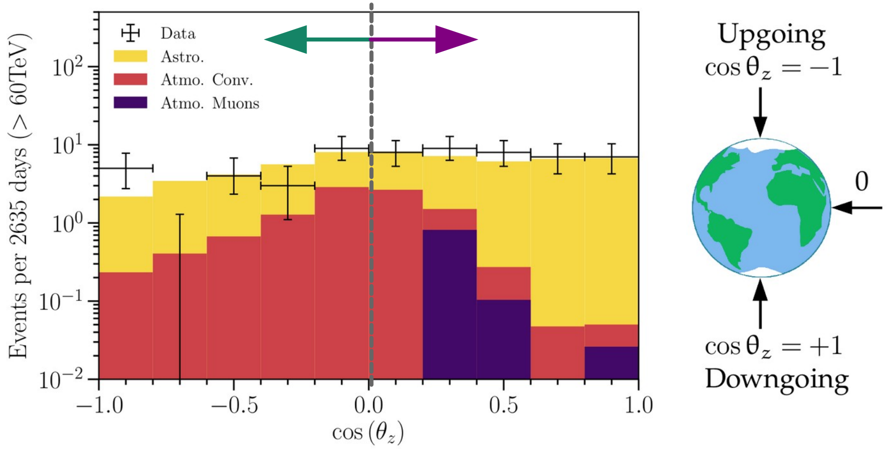
Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Energy spectrum (7.5 yr)

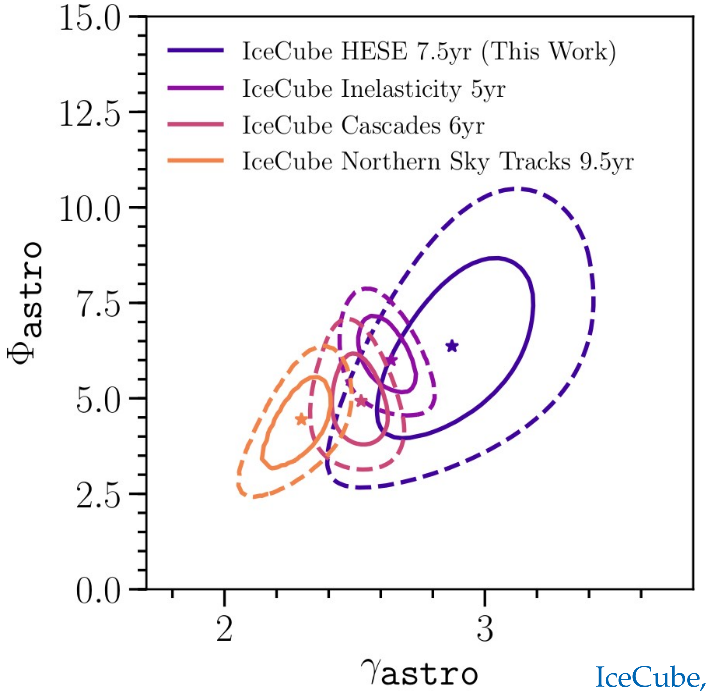
100+ contained events above 60 TeV:





Data is fit well by a single power law:

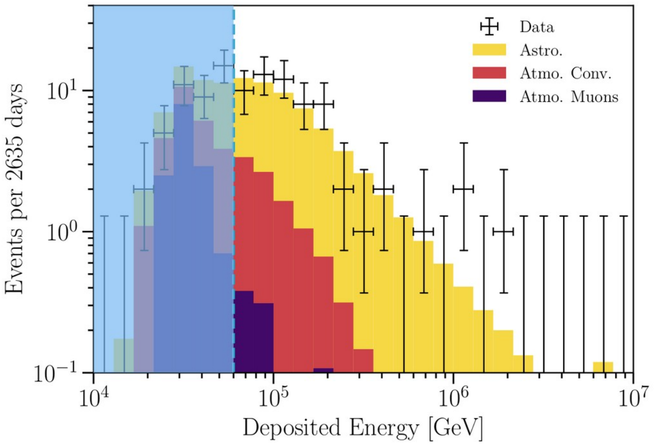
$$\frac{d\Phi_{6\nu}}{dE_\nu} = \Phi_{\text{astro}} \left(\frac{E_\nu}{100\ \text{TeV}} \right)^{-\gamma_{\text{astro}}} \cdot 10^{-18}\ \text{GeV}^{-1}\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$$



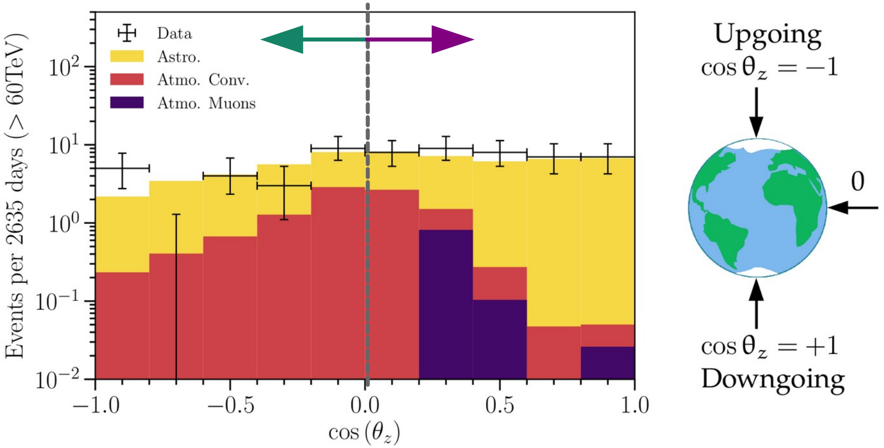
IceCube, 2011.03545

Energy spectrum (7.5 yr)

100+ contained events above 60 TeV:



ν attenuated by Earth   Atm. ν and μ vetoed



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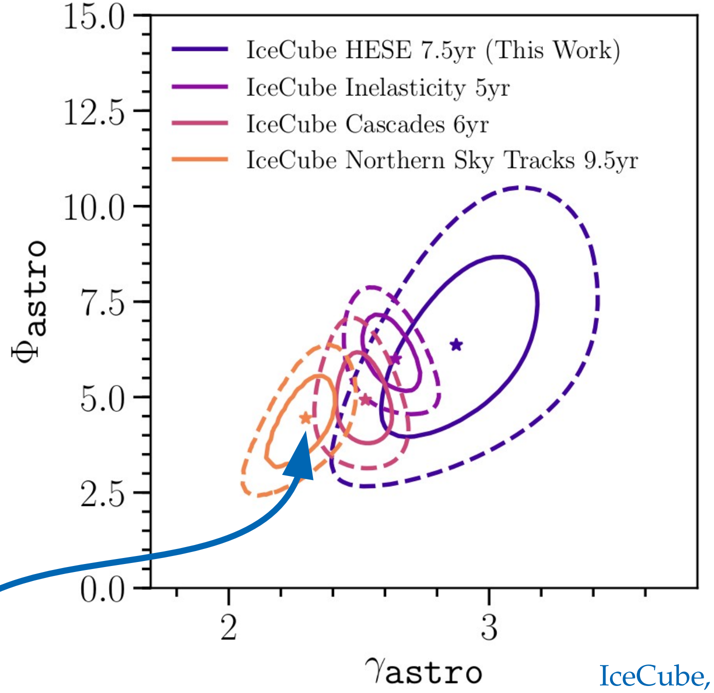
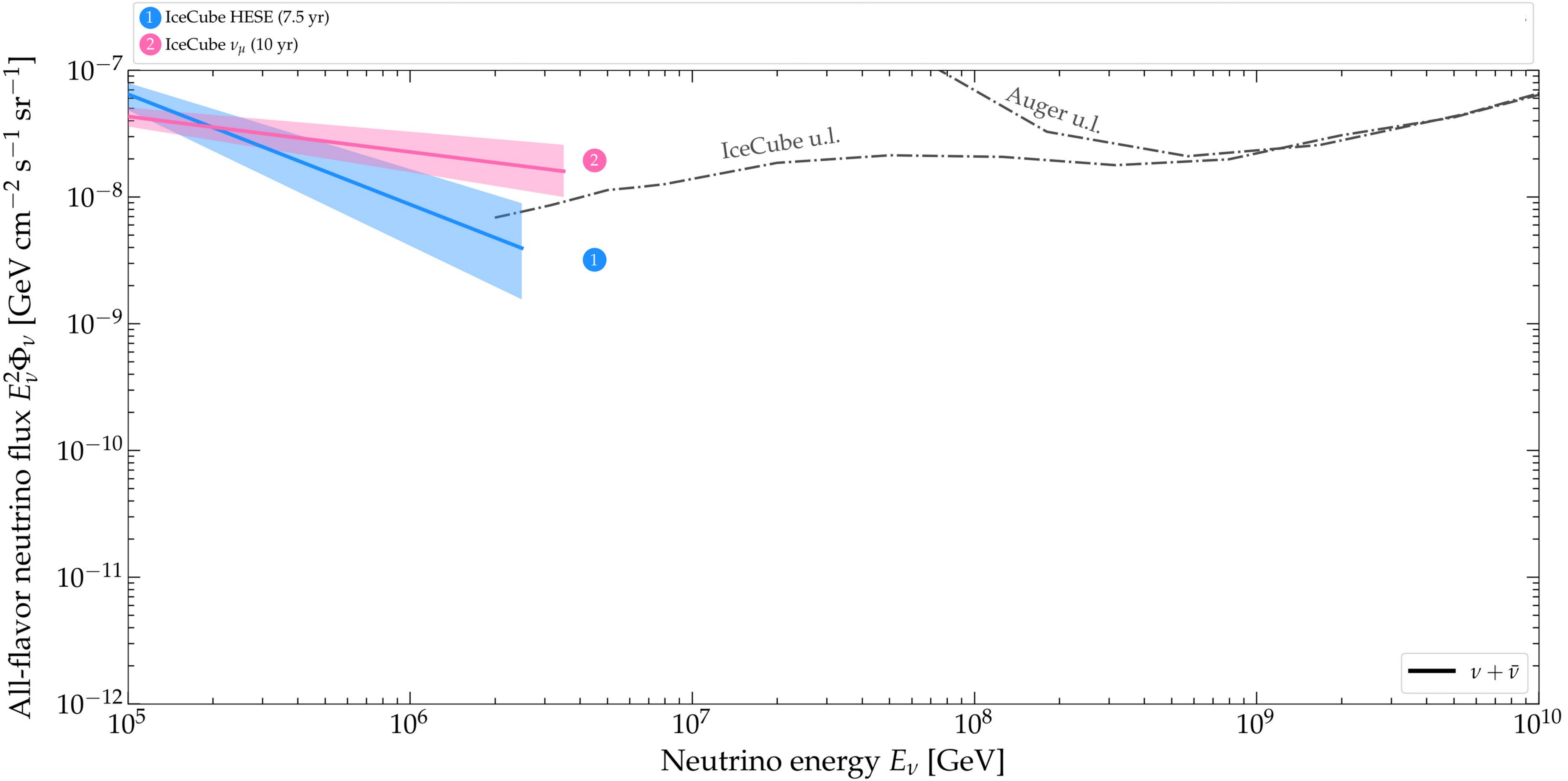


IceCube, 2011.03545

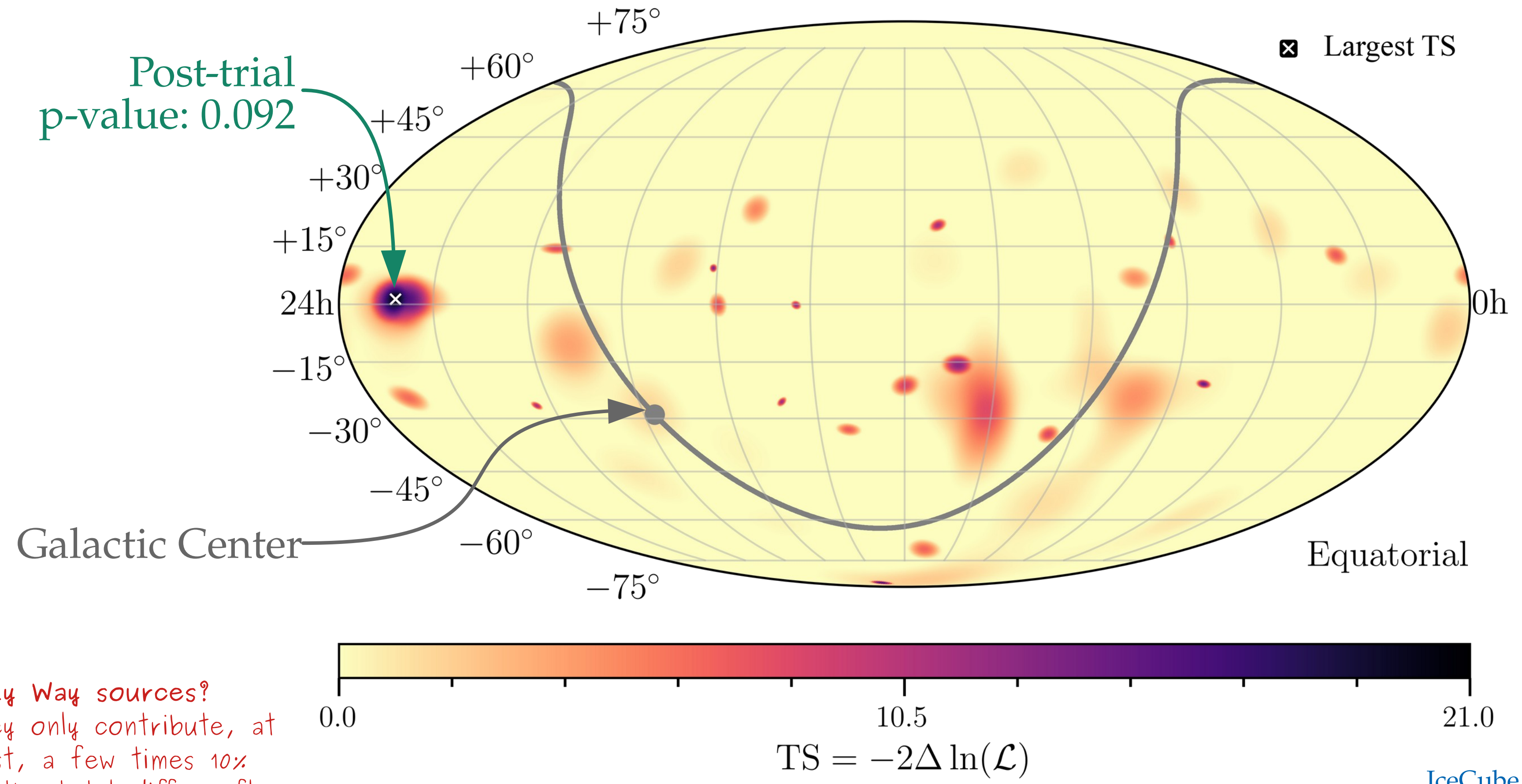
Spectrum looks harder for through-going ν_μ



1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (10 yr)
Auger u.l.
IceCube u.l.
$\nu + \bar{\nu}$
All-flavor neutrino flux $E_\nu^2\Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy E_ν [GeV]

Arrival directions (7.5 yr)

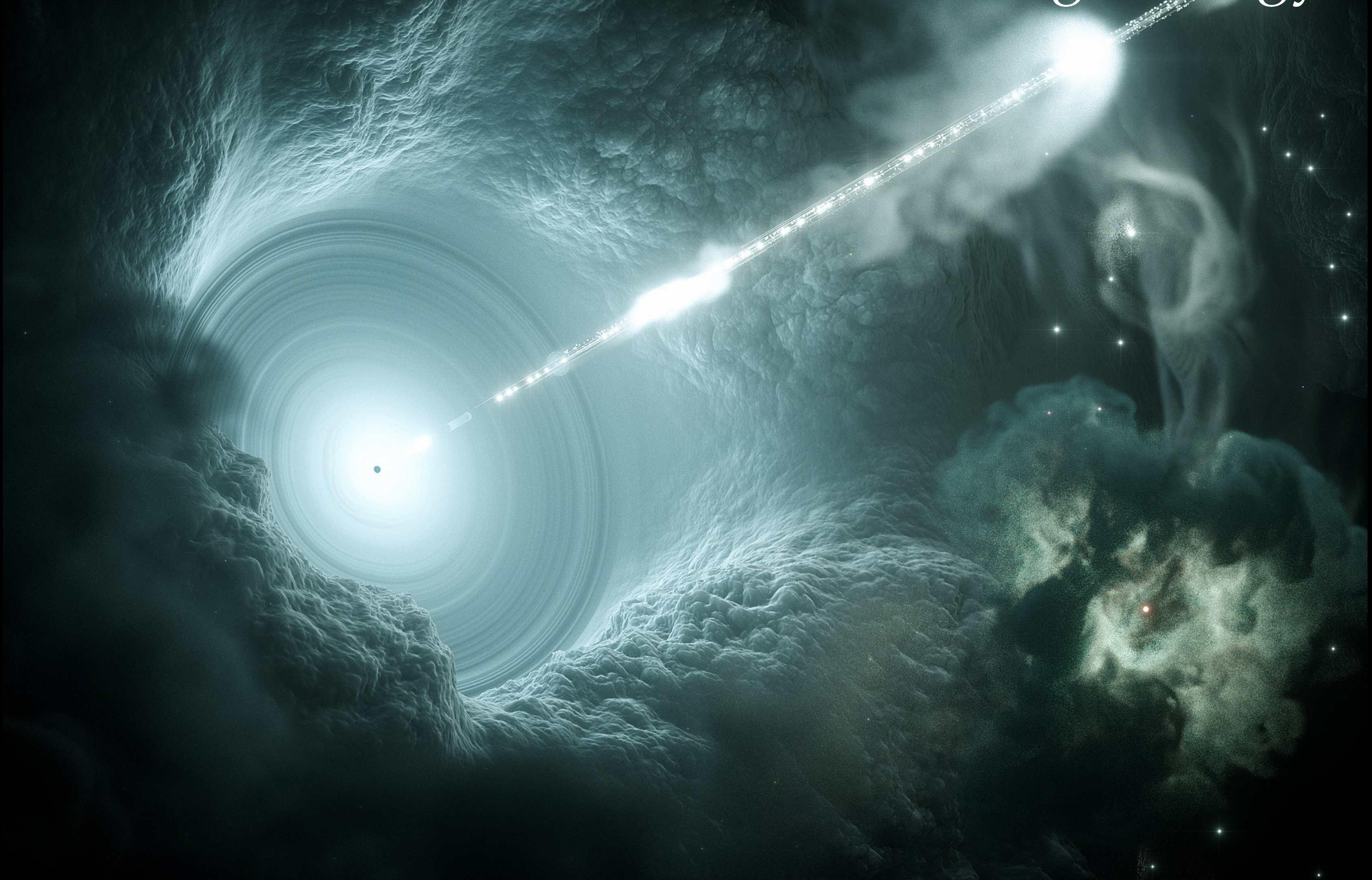
No significant excess in the neutrino sky map:



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

IceCube, 2011.03545

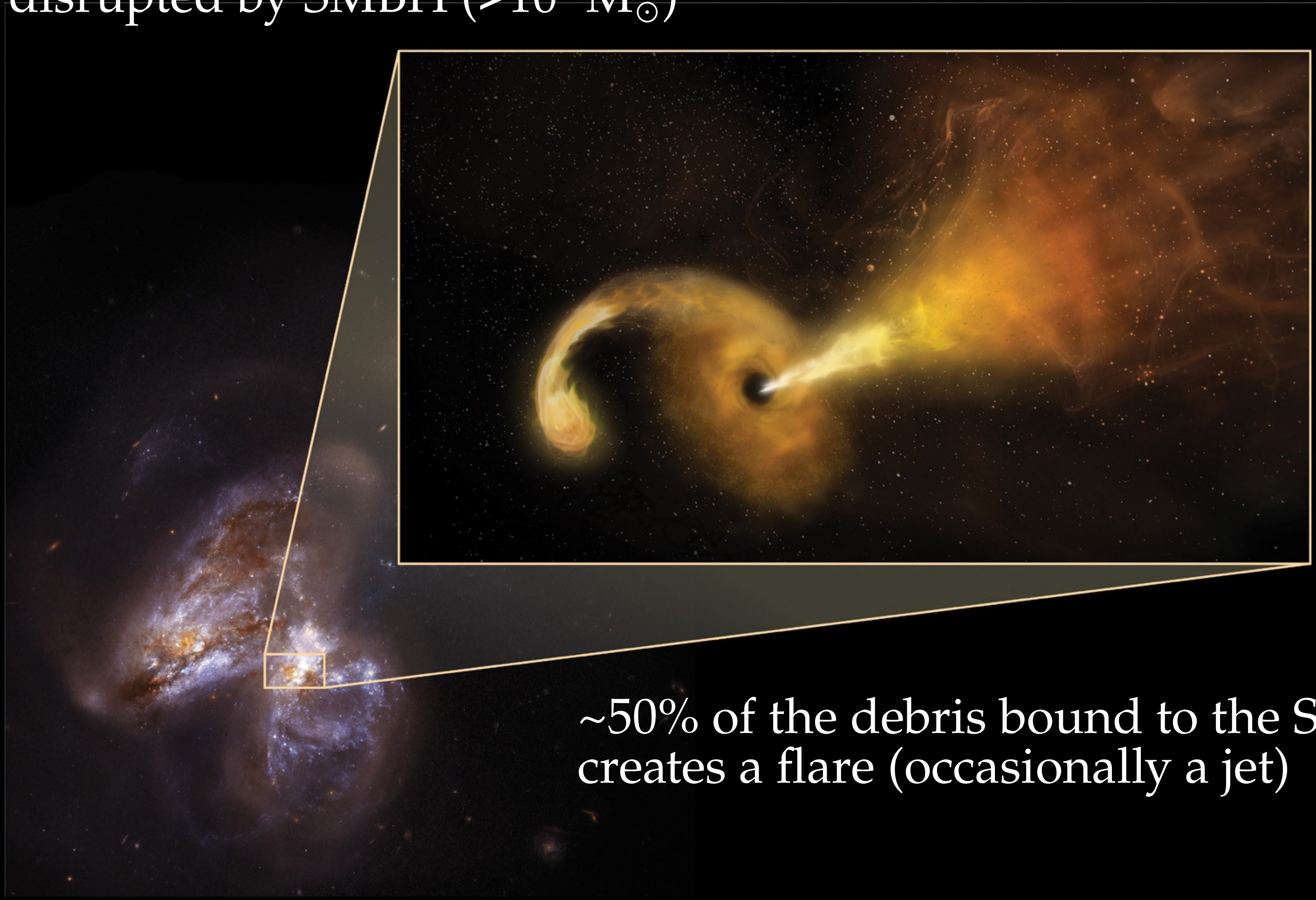
TXS 0506+056: The first *transient* source of high-energy ν



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

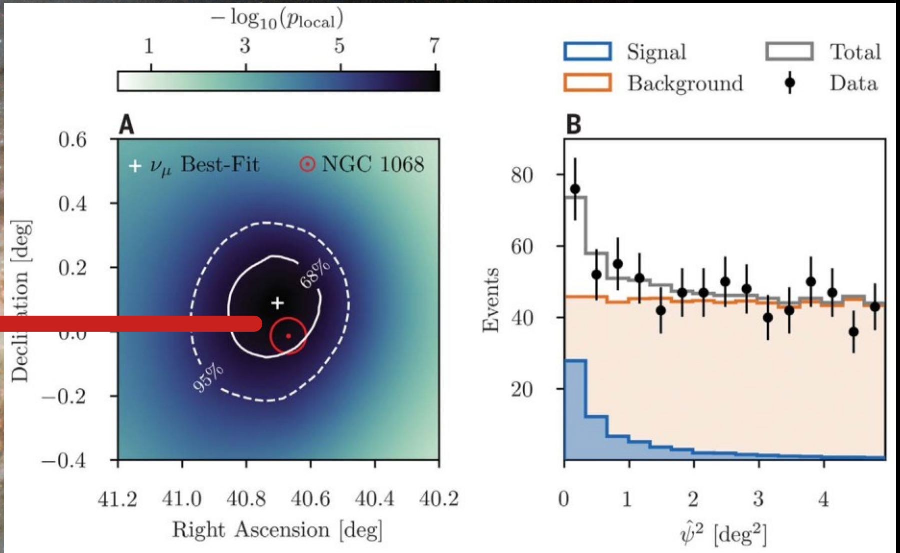
NGC1068: The first *steady-state* source of high-energy ν

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

Today

TeV–PeV ν

Today

TeV–PeV ν

Turn predictions
into data-driven tests

Today

TeV–PeV ν

Turn predictions
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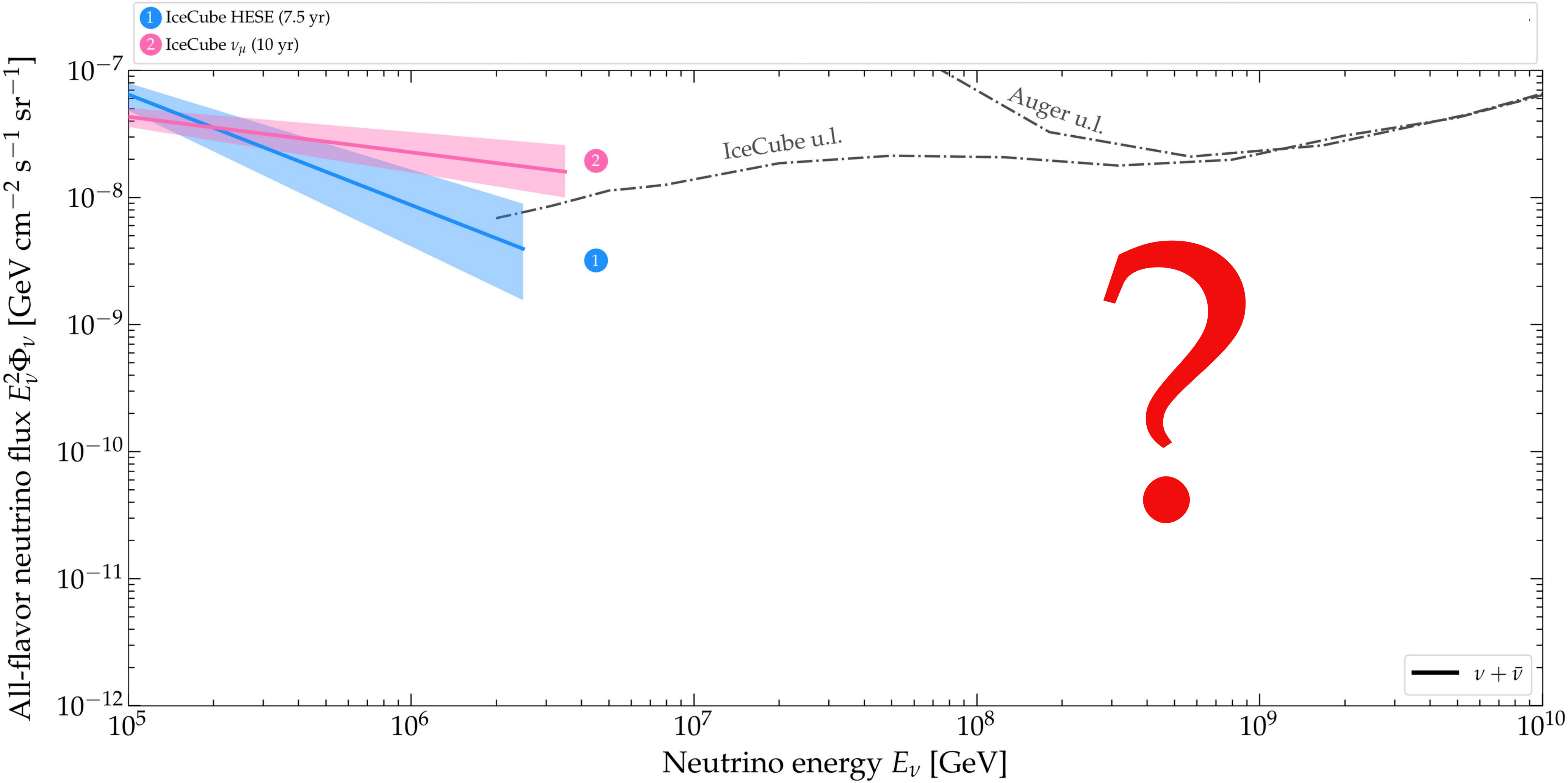
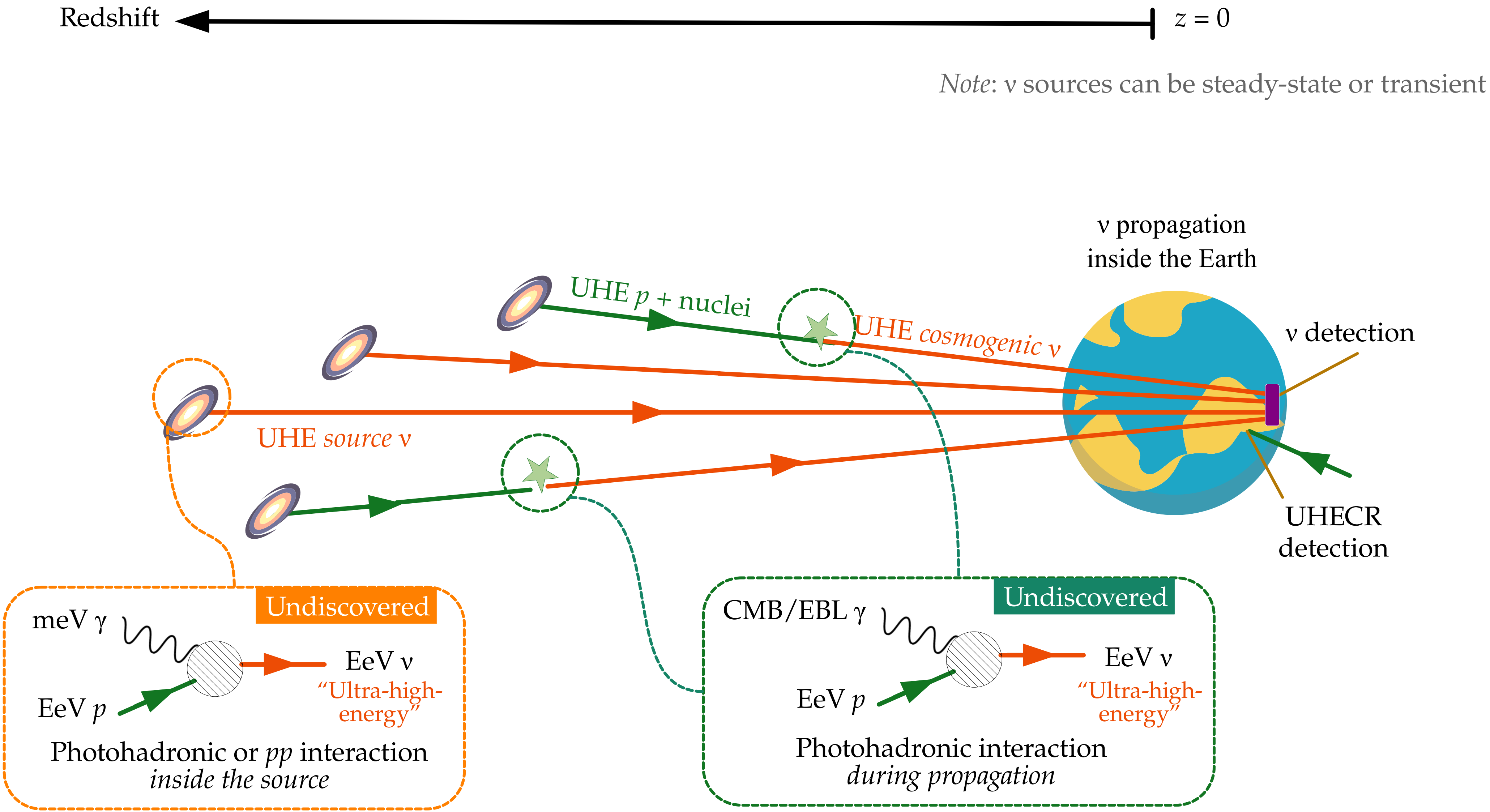
<u>Key developments</u>:
Bigger detectors $\rightarrow$ larger statistics
Better reconstruction
Smaller astrophysical uncertainties



1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (10 yr)
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
Auger u.l.
IceCube u.l.
?
$\nu + \bar{\nu}$
10^5
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
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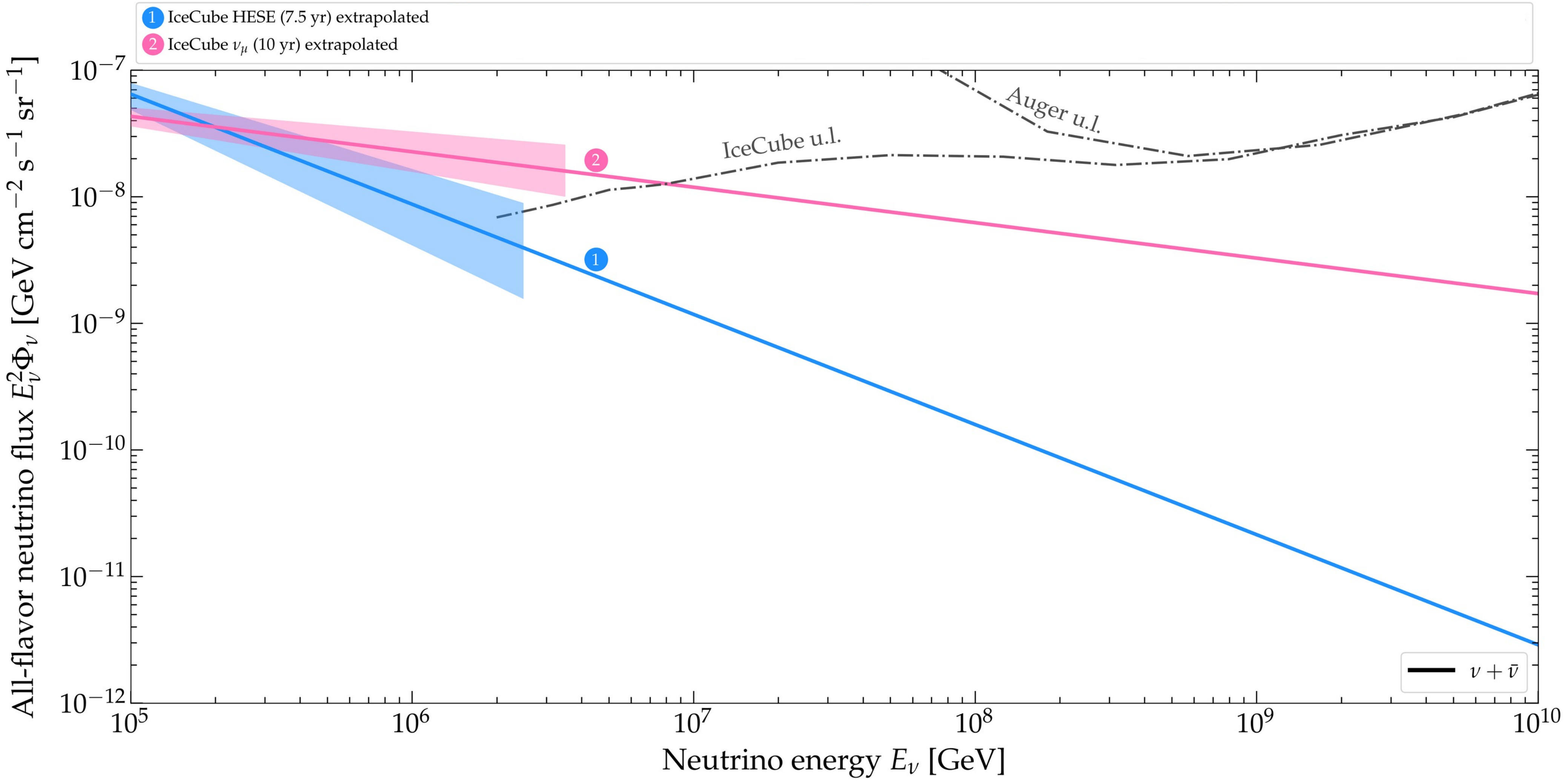
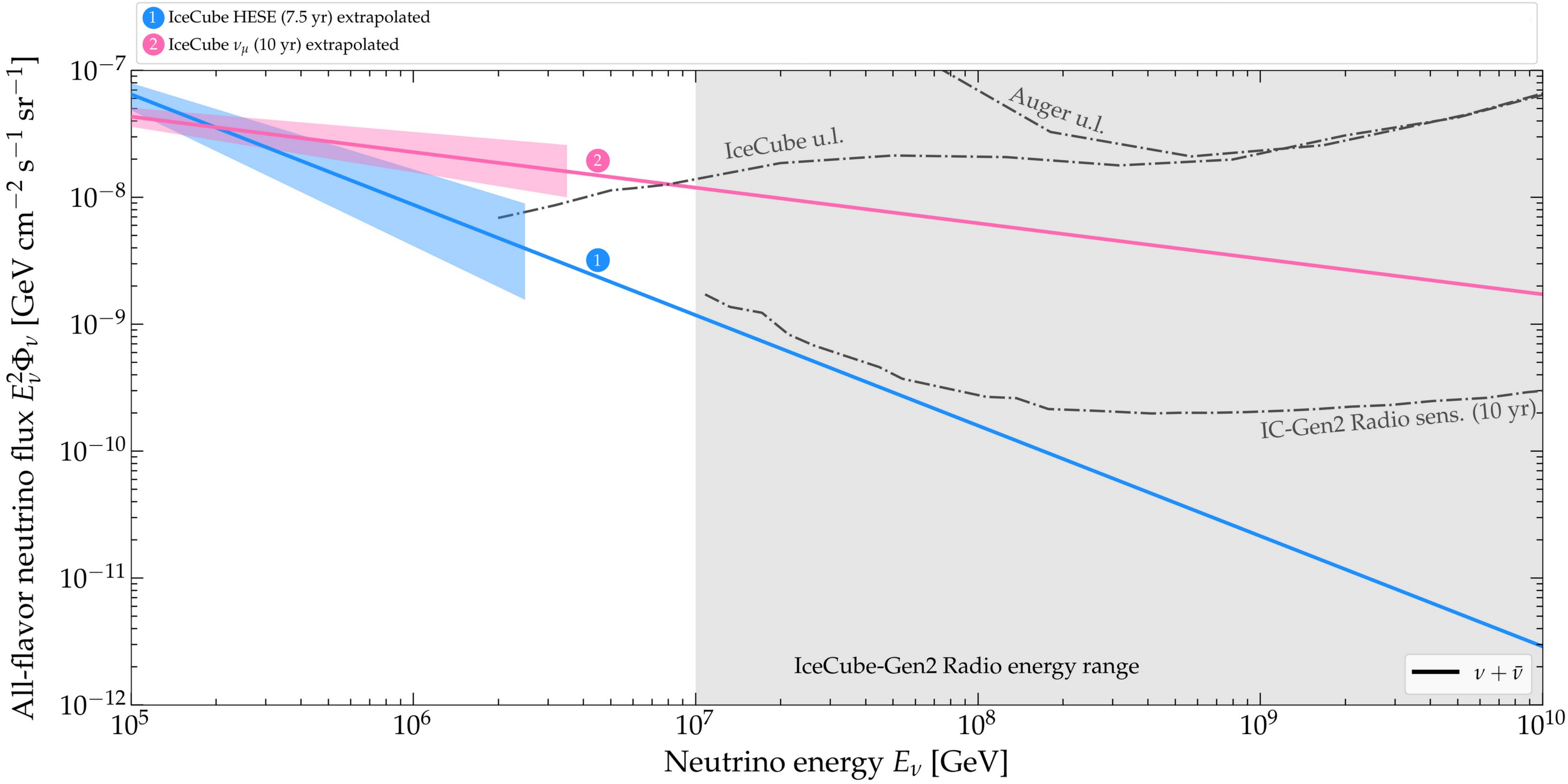
EeV p
Photohadronic interaction
during propagation



1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (10 yr) extrapolated
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
Auger u.l.
IceCube u.l.
1
2
$\nu + \bar{\nu}$
10^5
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy E_ν [GeV]



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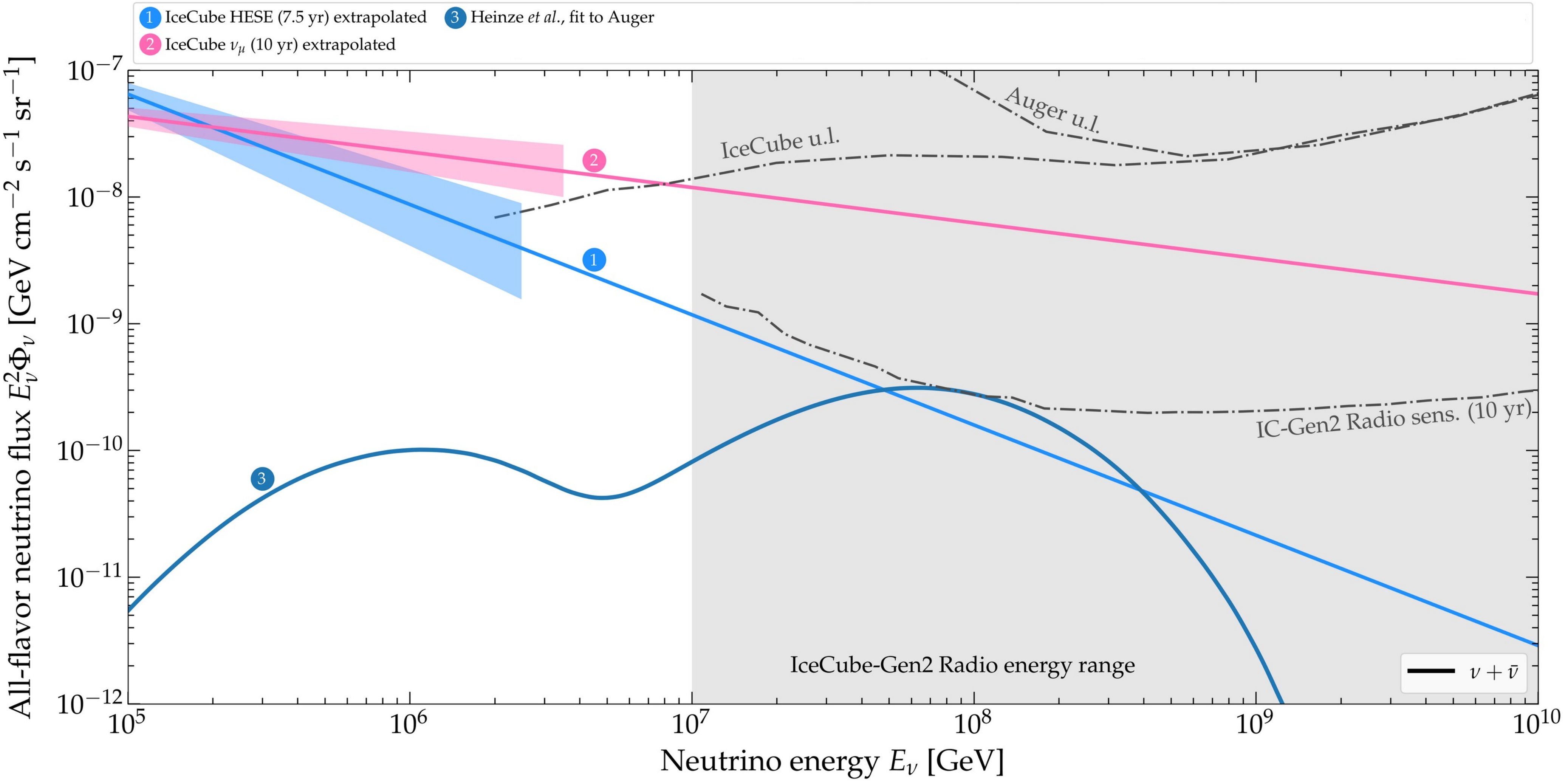
2 IceCube ν_μ (10 yr) extrapolated
All-flavor neutrino flux $E_\nu^2\Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
Auger u.l.
IceCube u.l.
IC-Gen2 Radio sens. (10 yr)
IceCube-Gen2 Radio energy range
$\nu + \bar{\nu}$
10^5
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy E_ν [GeV]



1 IceCube HESE (7.5 yr) extrapolated
3 Heinze *et al.*, fit to Auger
2 IceCube ν_μ (10 yr) extrapolated
All-flavor neutrino flux $E_\nu^2\Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-7}
10^{-8}
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10^6
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10^8
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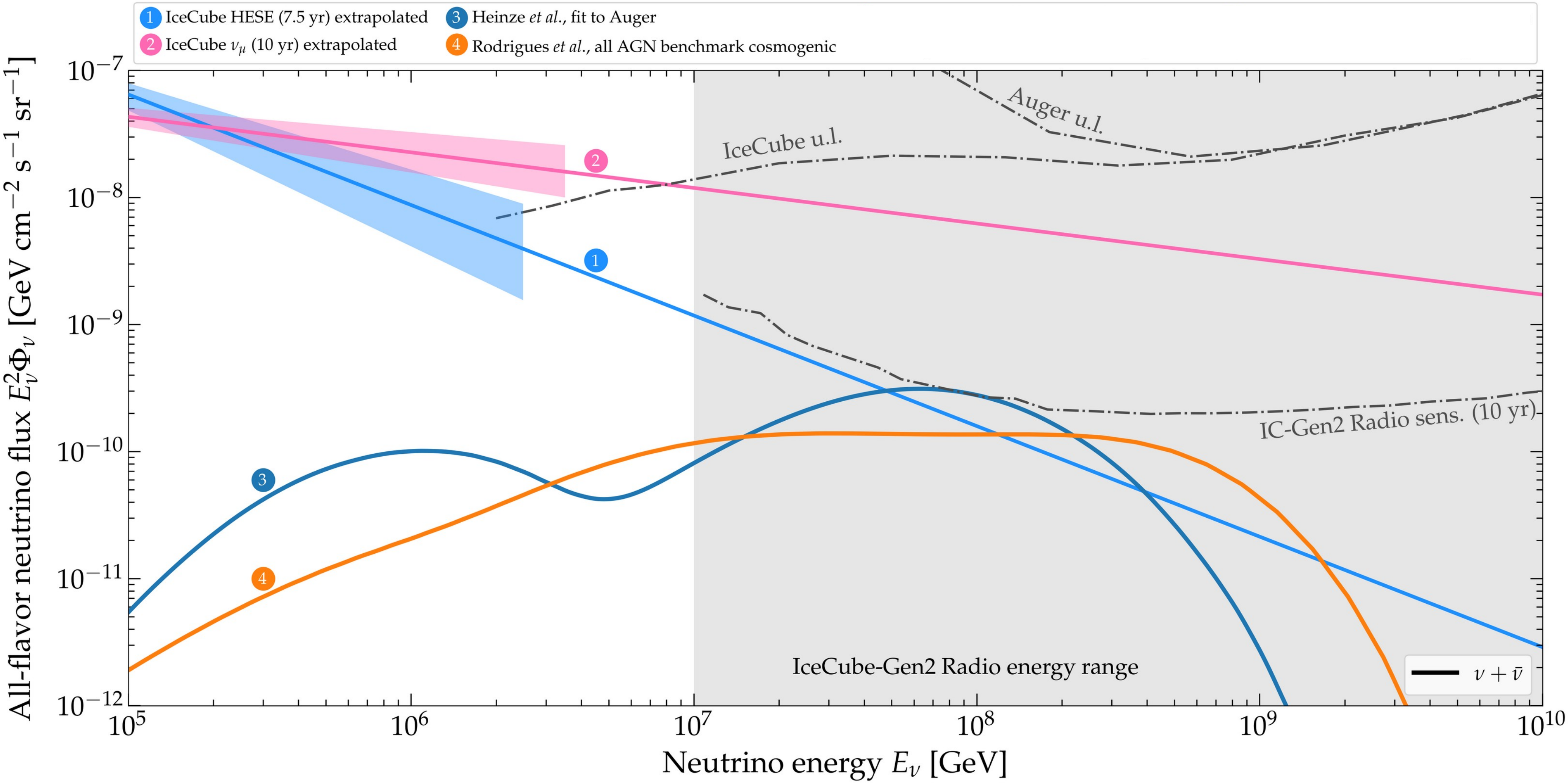
Neutrino energy E_ν [GeV]



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4 Rodrigues *et al.*, all AGN benchmark cosmogenic
All-flavor neutrino flux $E_\nu^2\Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-7}
10^{-8}
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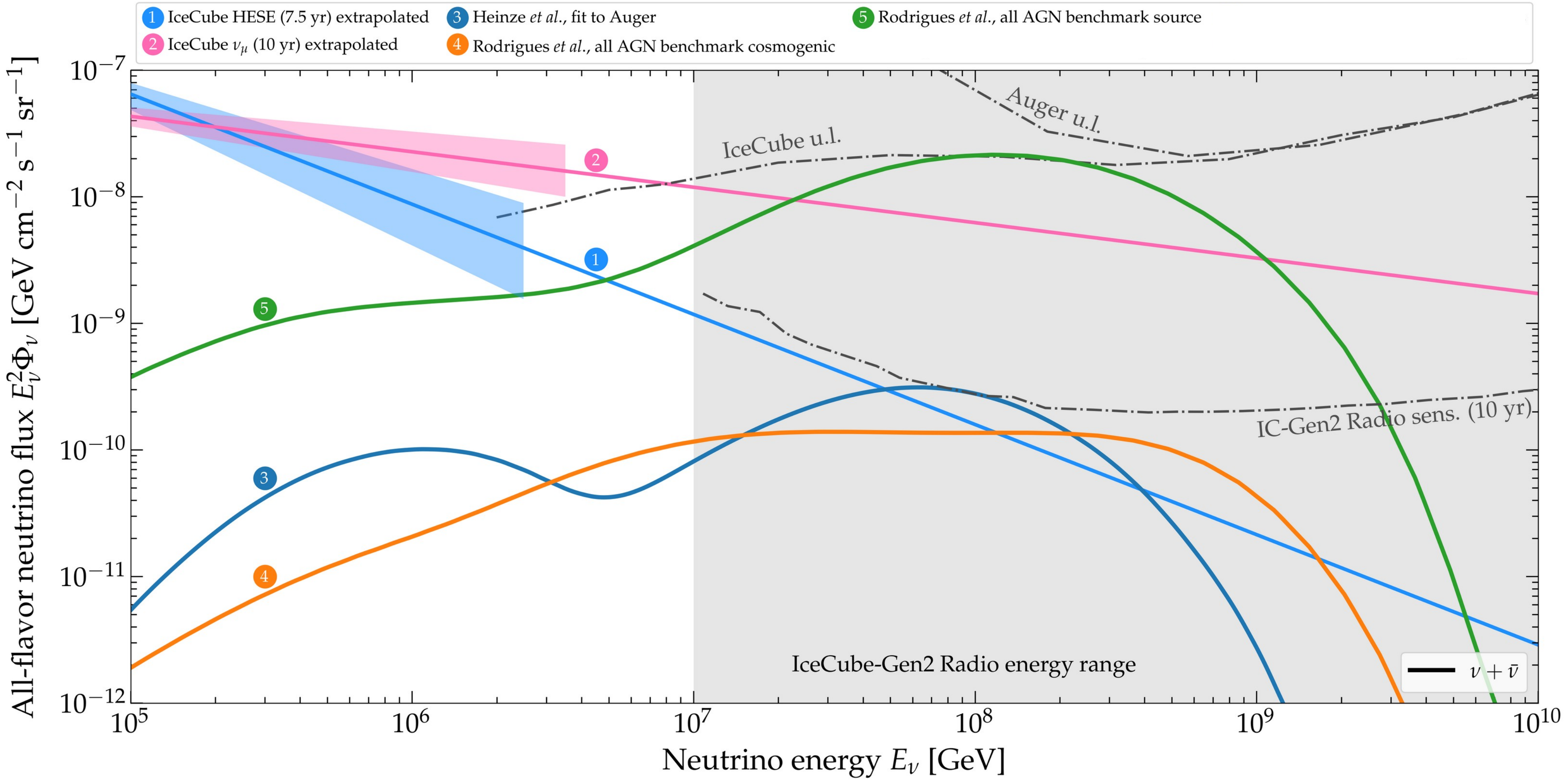
10^{-10}
10^{-11}
10^{-12}
Auger u.l.
IceCube u.l.
IC-Gen2 Radio sens. (10 yr)
IceCube-Gen2 Radio energy range
$\nu + \bar{\nu}$
10^5
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy E_ν [GeV]



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Auger u.l.
IceCube u.l.
IC-Gen2 Radio sens. (10 yr)
IceCube-Gen2 Radio energy range
$\nu + \bar{\nu}$
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
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10^{-7}
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10^{-10}
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10^5
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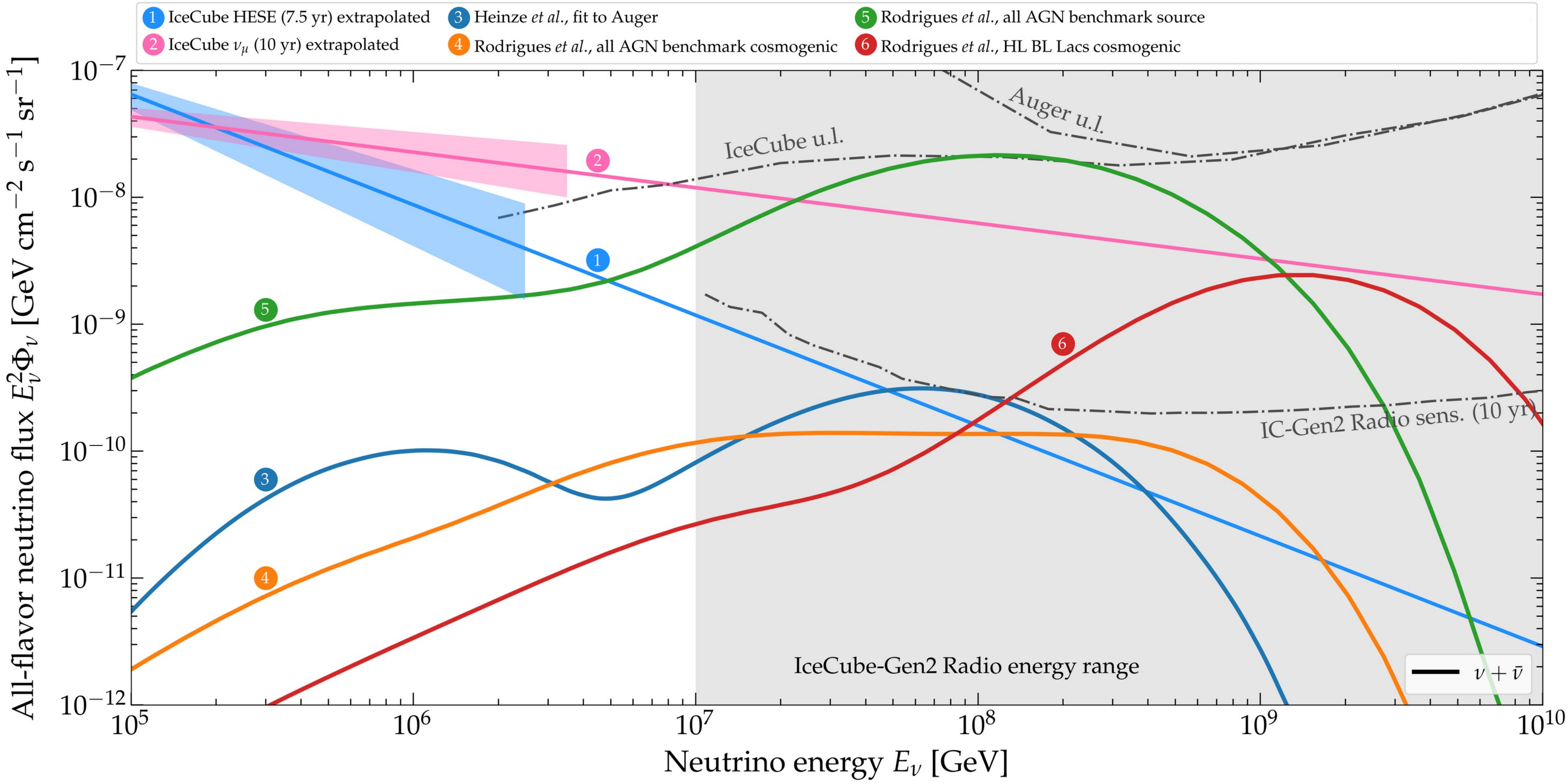
10^8
10^9
10^{10}



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4 Rodrigues *et al.*, all AGN benchmark cosmogenic
5 Rodrigues *et al.*, all AGN benchmark source
6 Rodrigues *et al.*, HL BL Lacs cosmogenic
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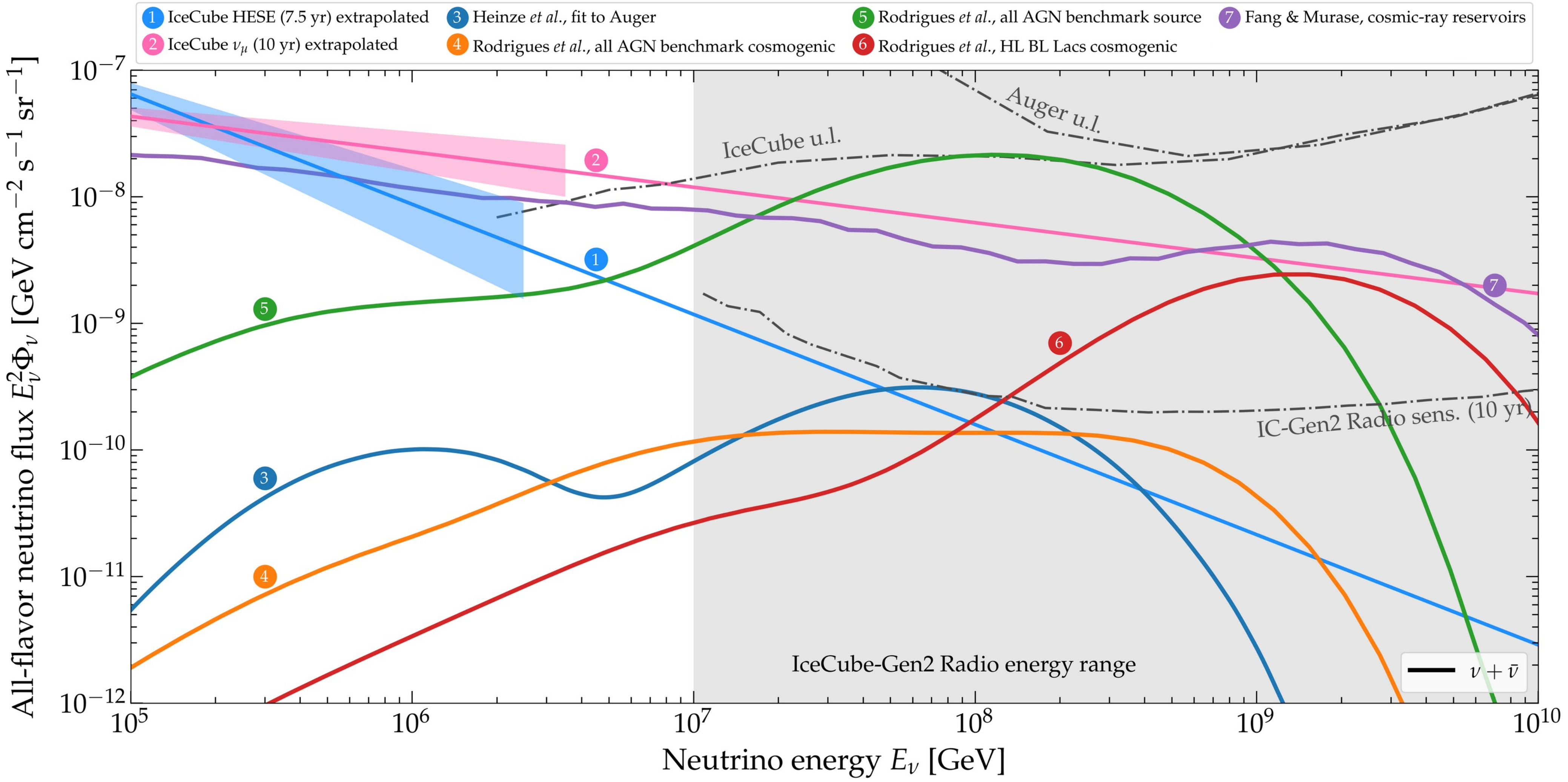
IC-Gen2 Radio sens. (10 yr)
IceCube-Gen2 Radio energy range
$\nu + \bar{\nu}$



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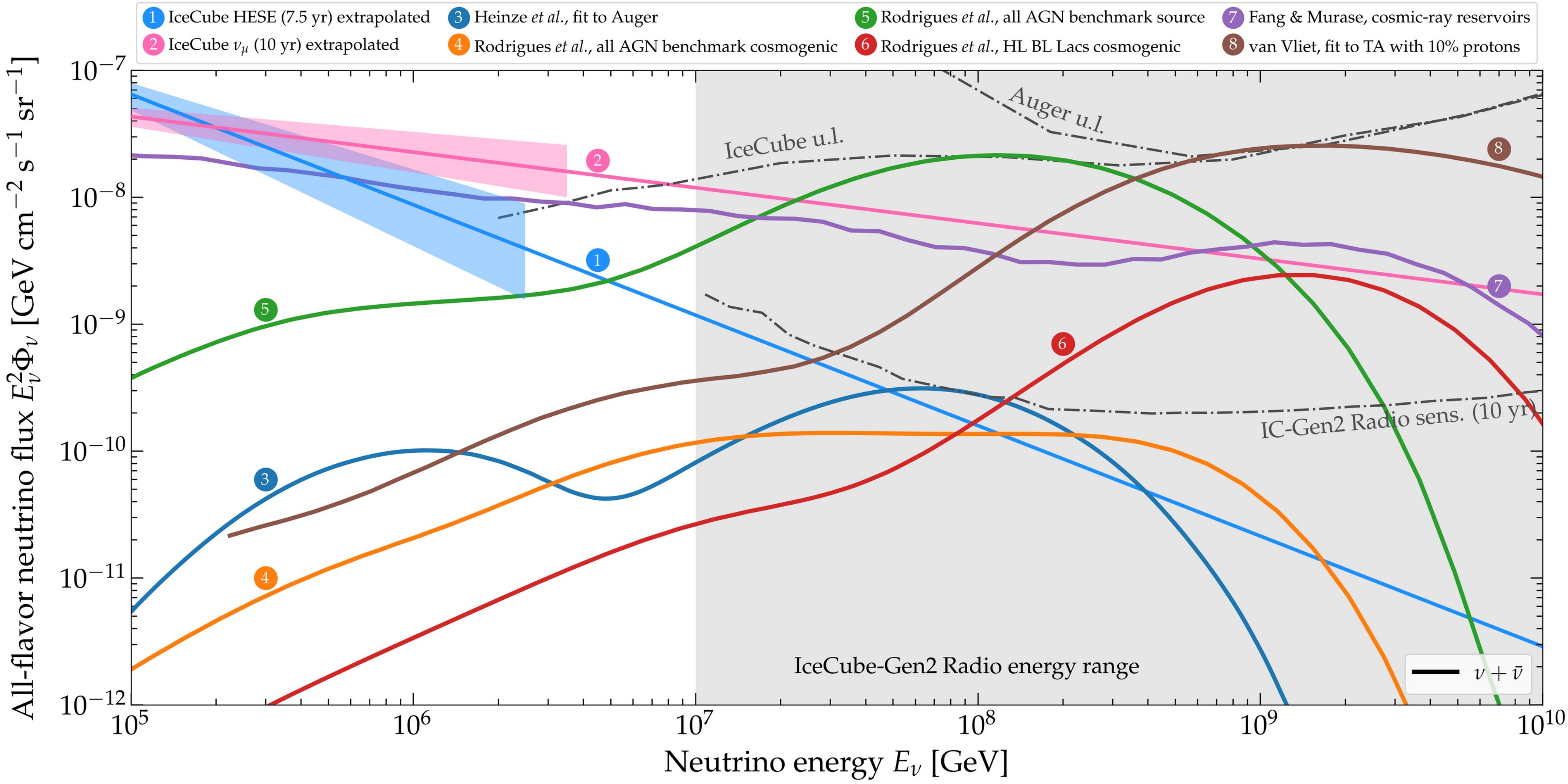
4 Rodrigues et al., all AGN benchmark cosmogenic
5 Rodrigues et al., all AGN benchmark source
6 Rodrigues et al., HL BL Lacs cosmogenic
7 Fang & Murase, cosmic-ray reservoirs
Auger u.l.
IceCube u.l.
IC-Gen2 Radio sens. (10 yr)
IceCube-Gen2 Radio energy range
$\nu + \bar{\nu}$
All-flavor neutrino flux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



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4 Rodrigues et al., all AGN benchmark cosmogenic
5 Rodrigues et al., all AGN benchmark source
6 Rodrigues et al., HL BL Lacs cosmogenic
7 Fang & Murase, cosmic-ray reservoirs
8 van Vliet, fit to TA with 10% protons
Auger u.l.
IceCube u.l.
IC-Gen2 Radio sens. (10 yr)
IceCube-Gen2 Radio energy range
$\nu + \bar{\nu}$
All-flavor neutrino flux $E_\nu^2\Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
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10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^5
10^6
10^7
10^8
10^9
10^{10}

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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Next decade

> 100-PeV ν

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Key developments:

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Better reconstruction

Smaller astrophysical uncertainties

Next decade

$>$ 100-PeV ν

Make predictions for
a new energy regime

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Make predictions for
a new energy regime

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

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a new energy regime

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

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

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TeV–PeV ν

Turn predictions
into data-driven tests

Key developments:
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Better reconstruction
Smaller astrophysical uncertainties

Next decade

$>$ 100-PeV ν

Make predictions for
a new energy regime

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

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

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

Note: Not an exhaustive list

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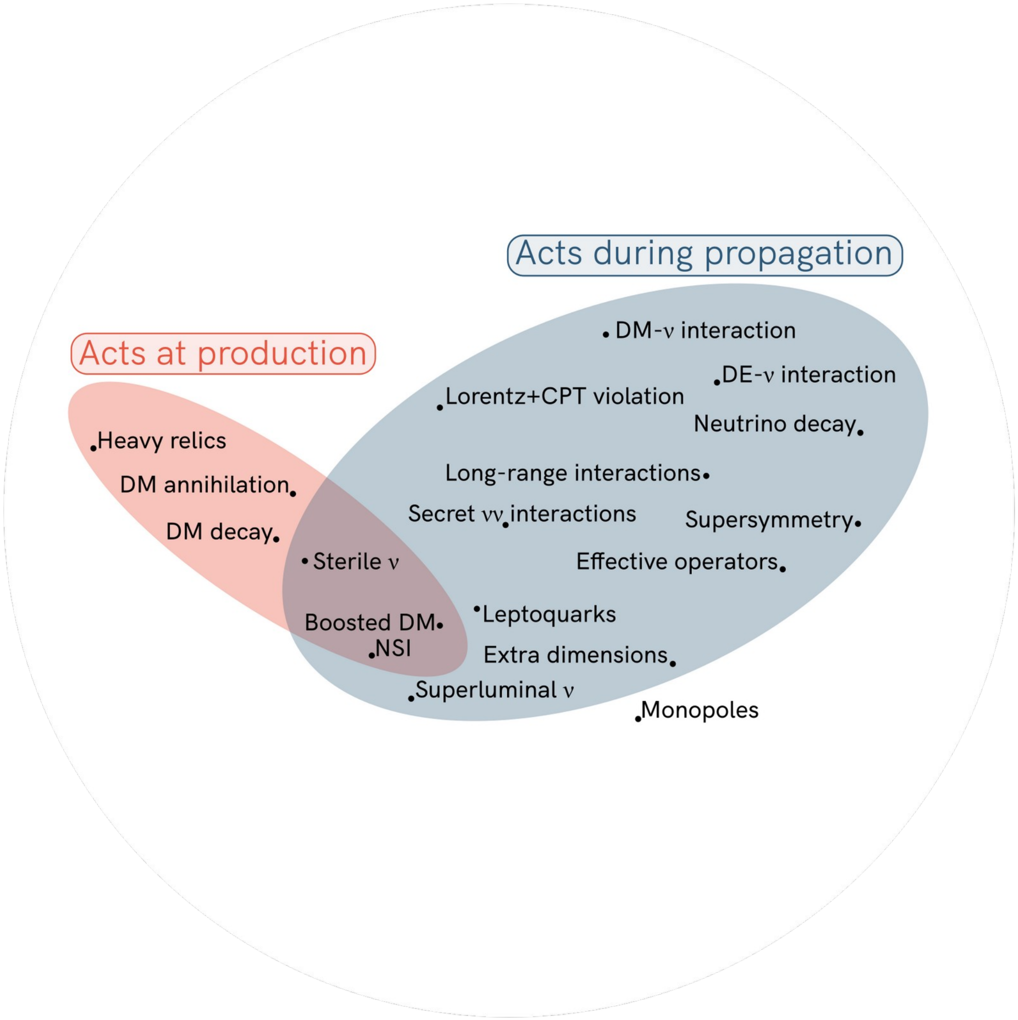
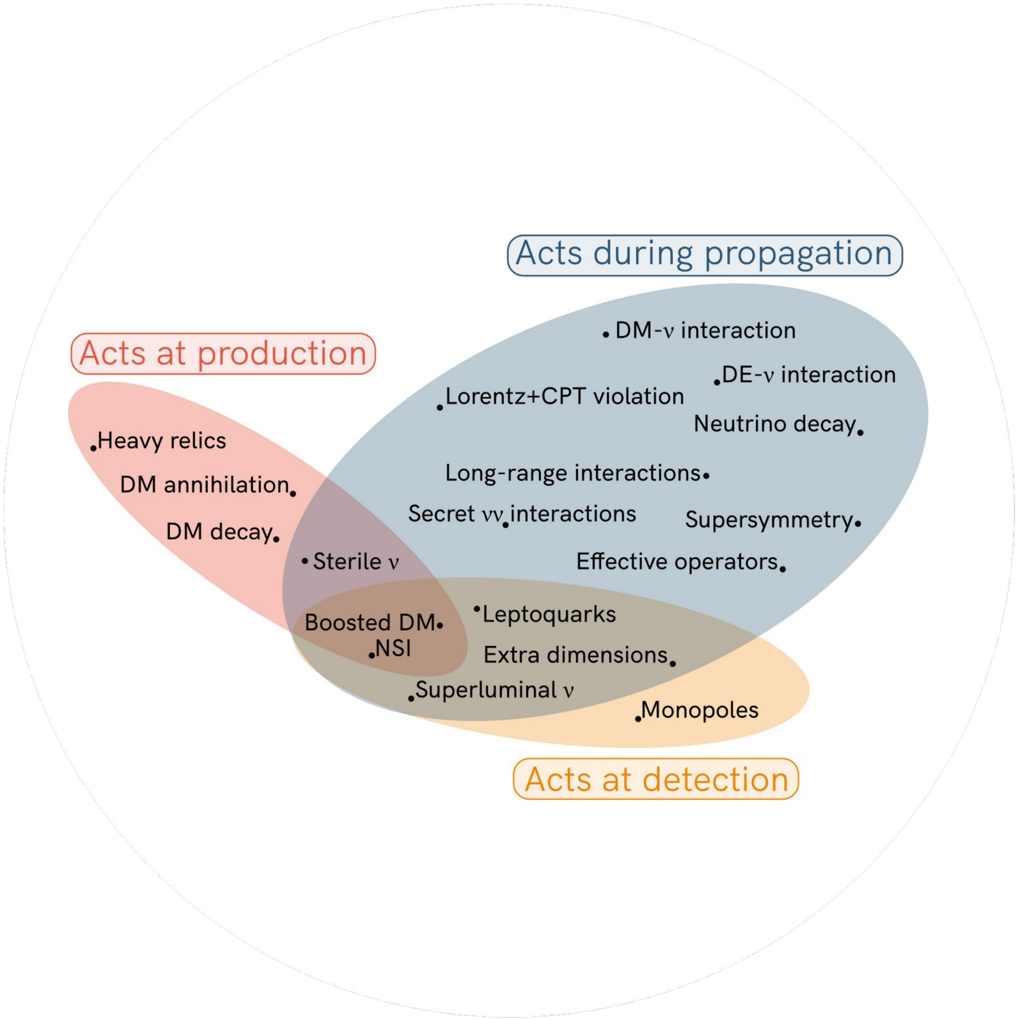
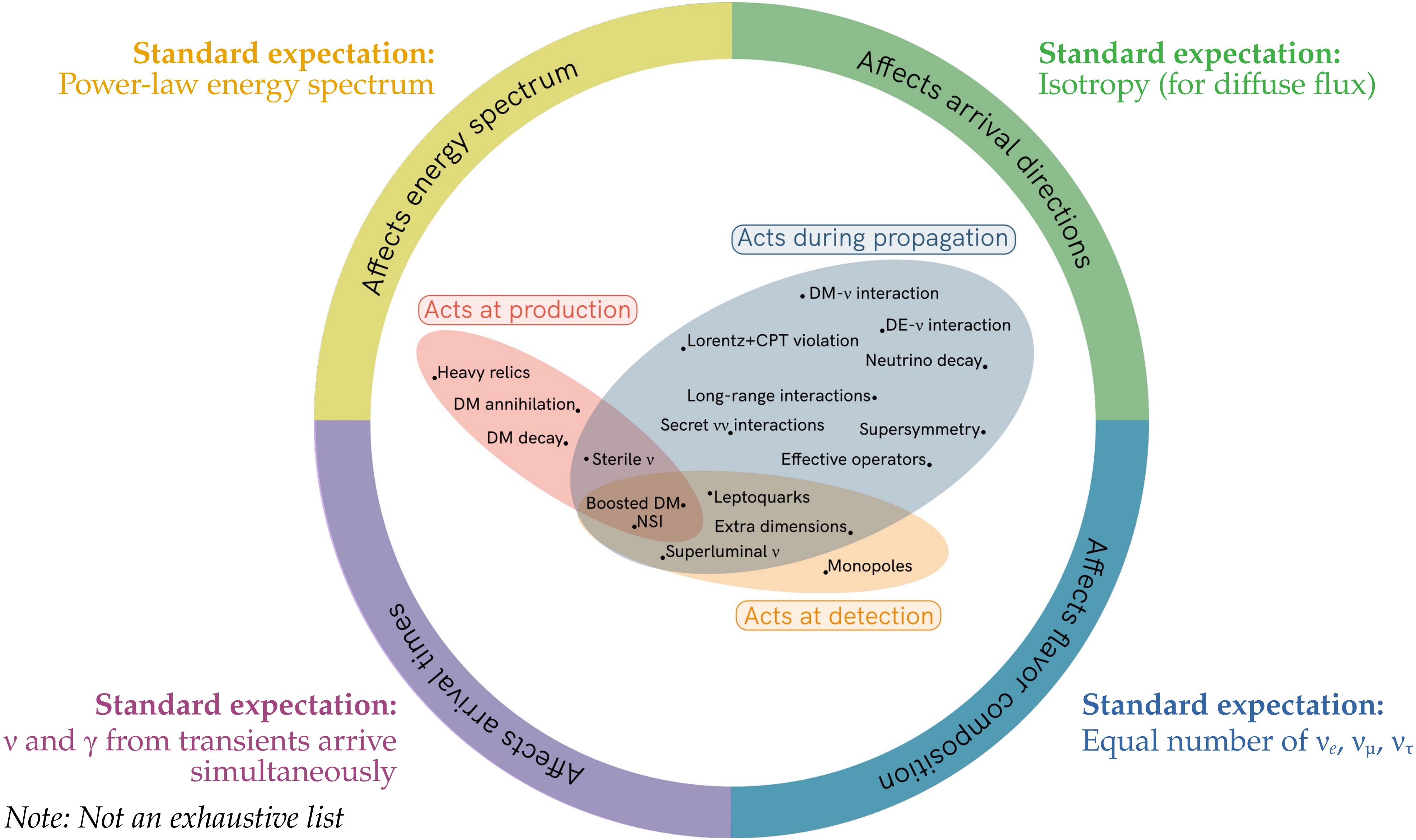
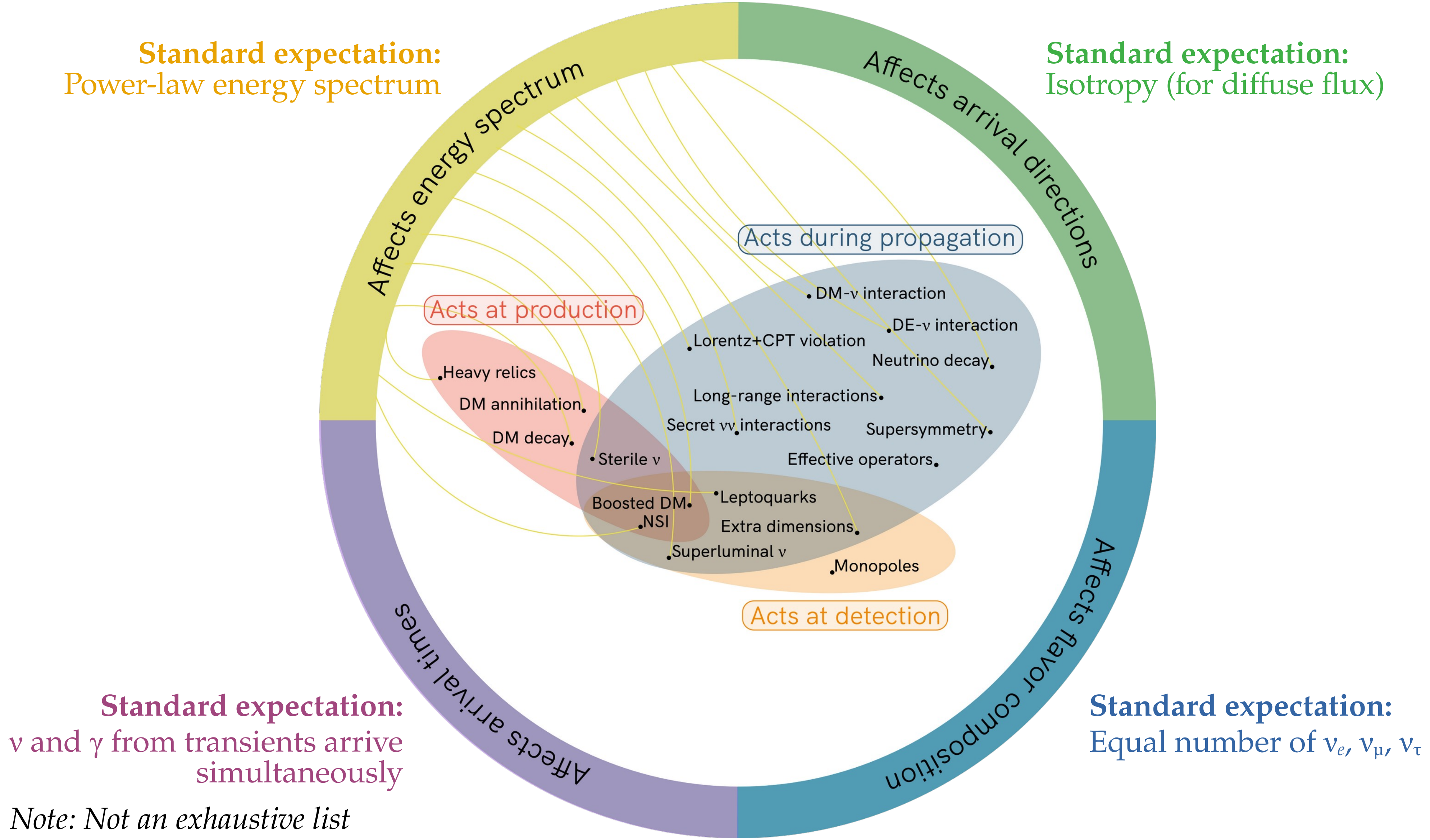


Note: Not an exhaustive list

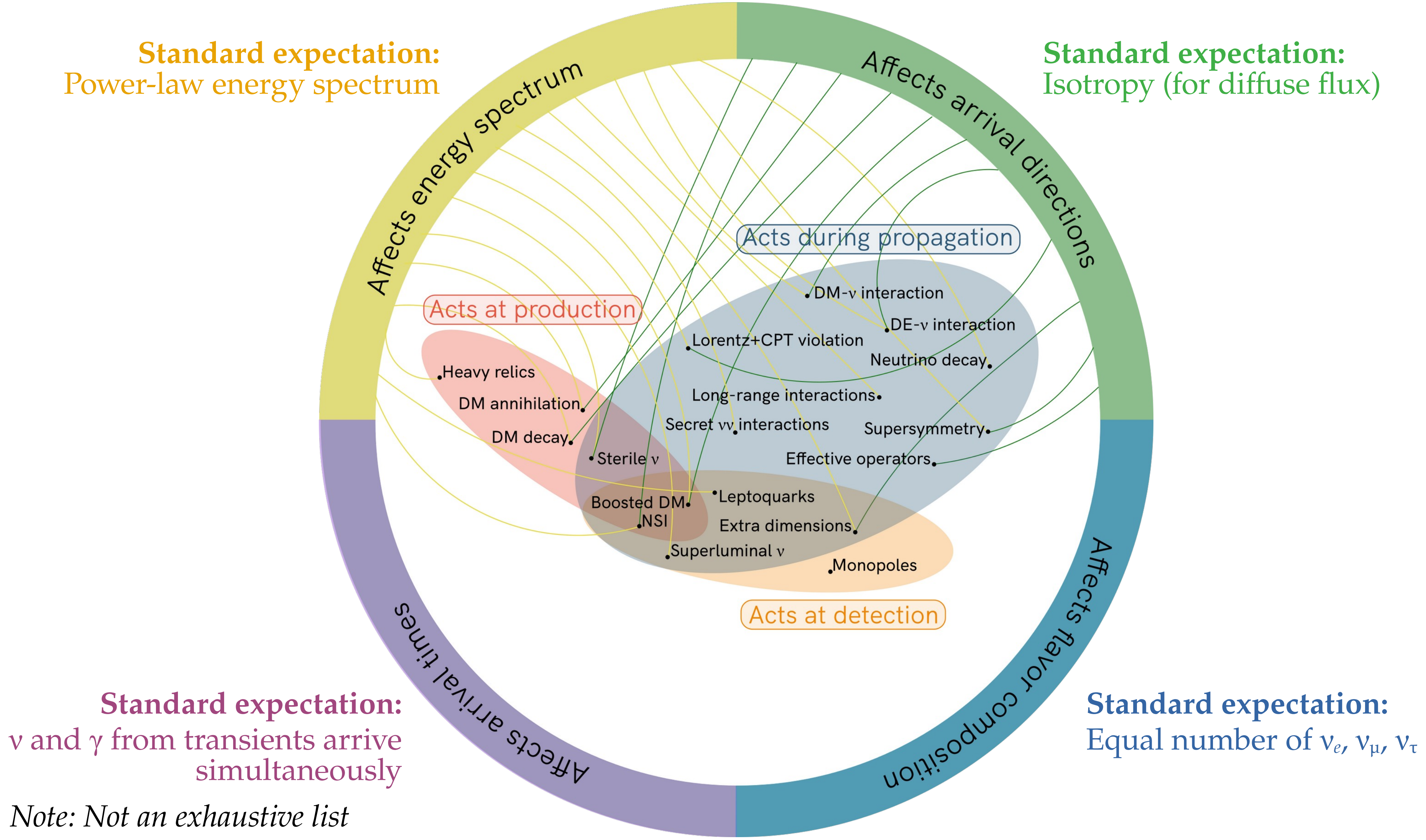


Note: Not an exhaustive list


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
DM decay
Long-range interactions
Secret νν interactions
Supersymmetry
Sterile ν
Effective operators
Boosted DM
NSI
Leptoquarks
Extra dimensions
Superluminal ν
Monopoles
Acts at detection
Affects arrival times
Affects flavor composition
Standard expectation:
ν and γ from transients arrive simultaneously
Standard expectation:
Equal number of ν_e, ν_μ, ν_τ
Note: Not an exhaustive list



Note: Not an exhaustive list



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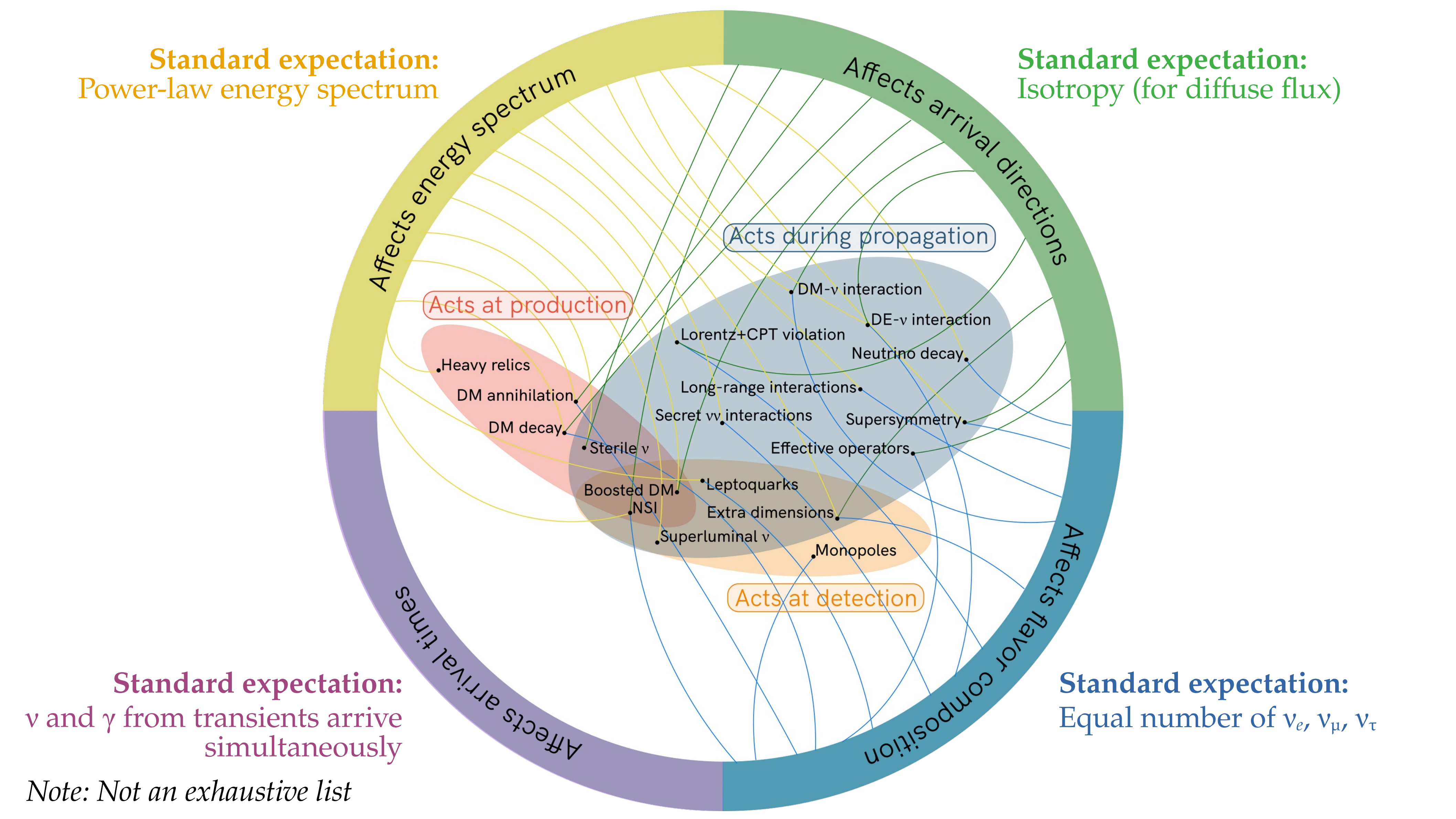
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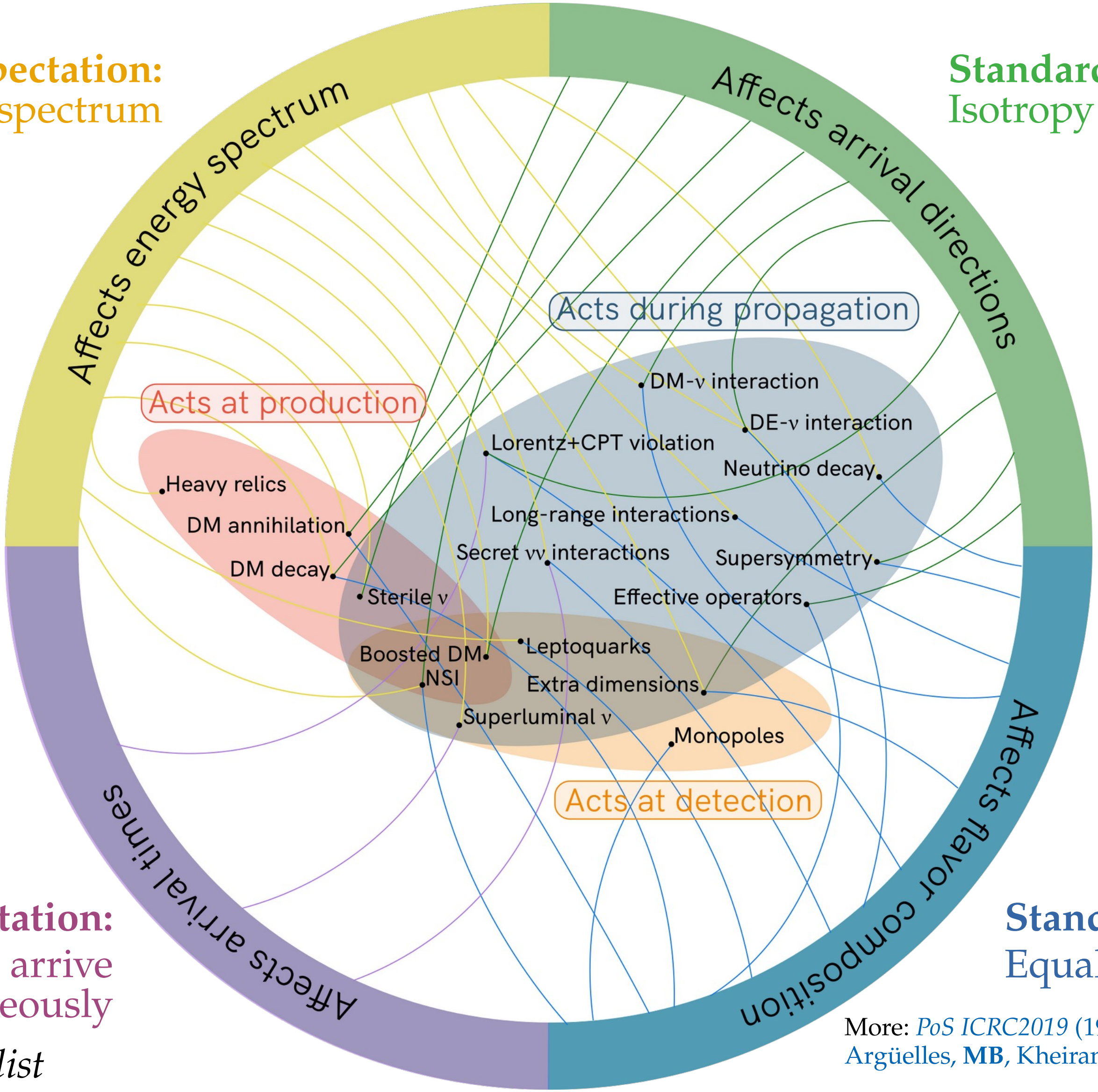

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Note: Not an exhaustive list

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

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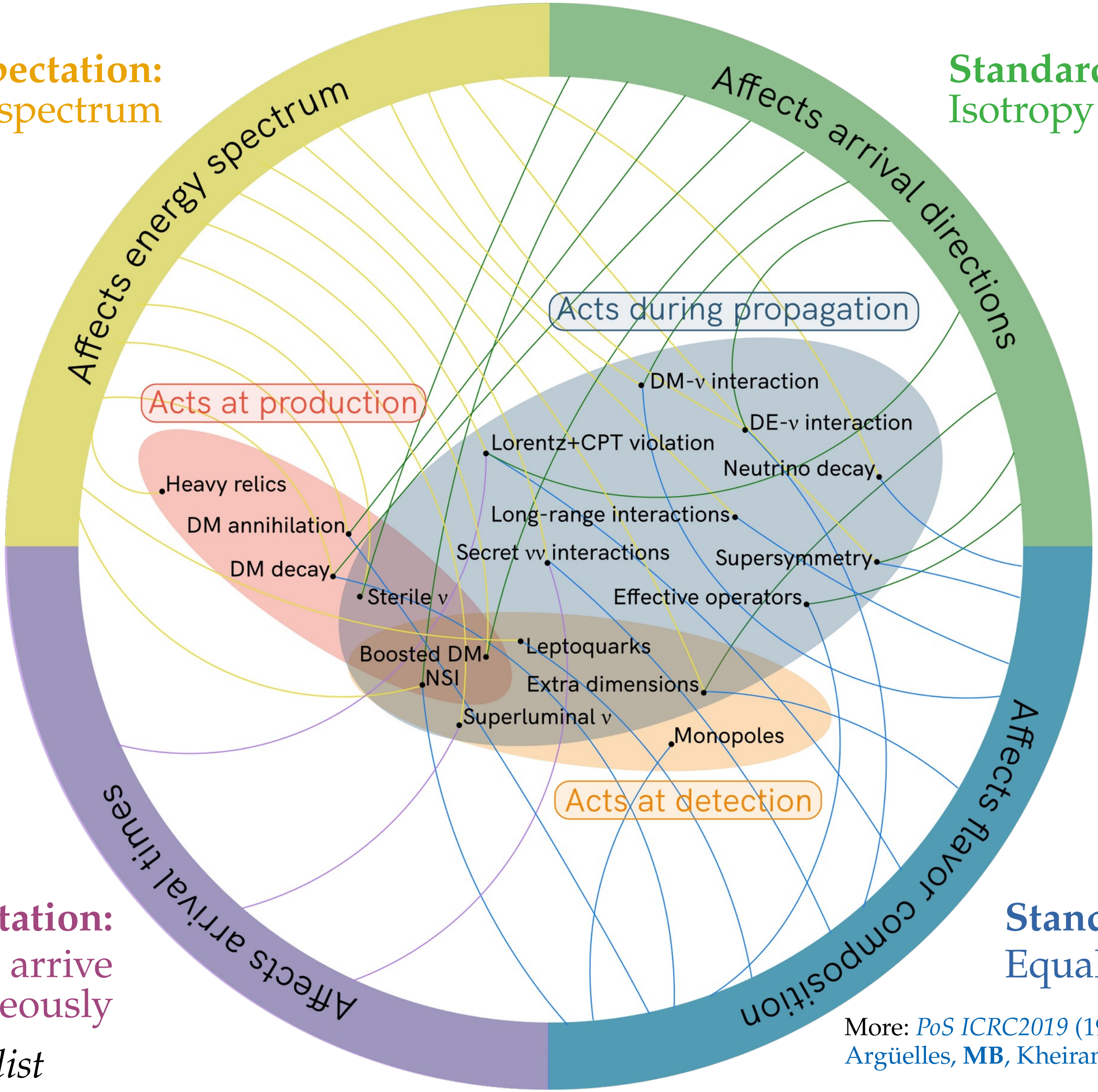

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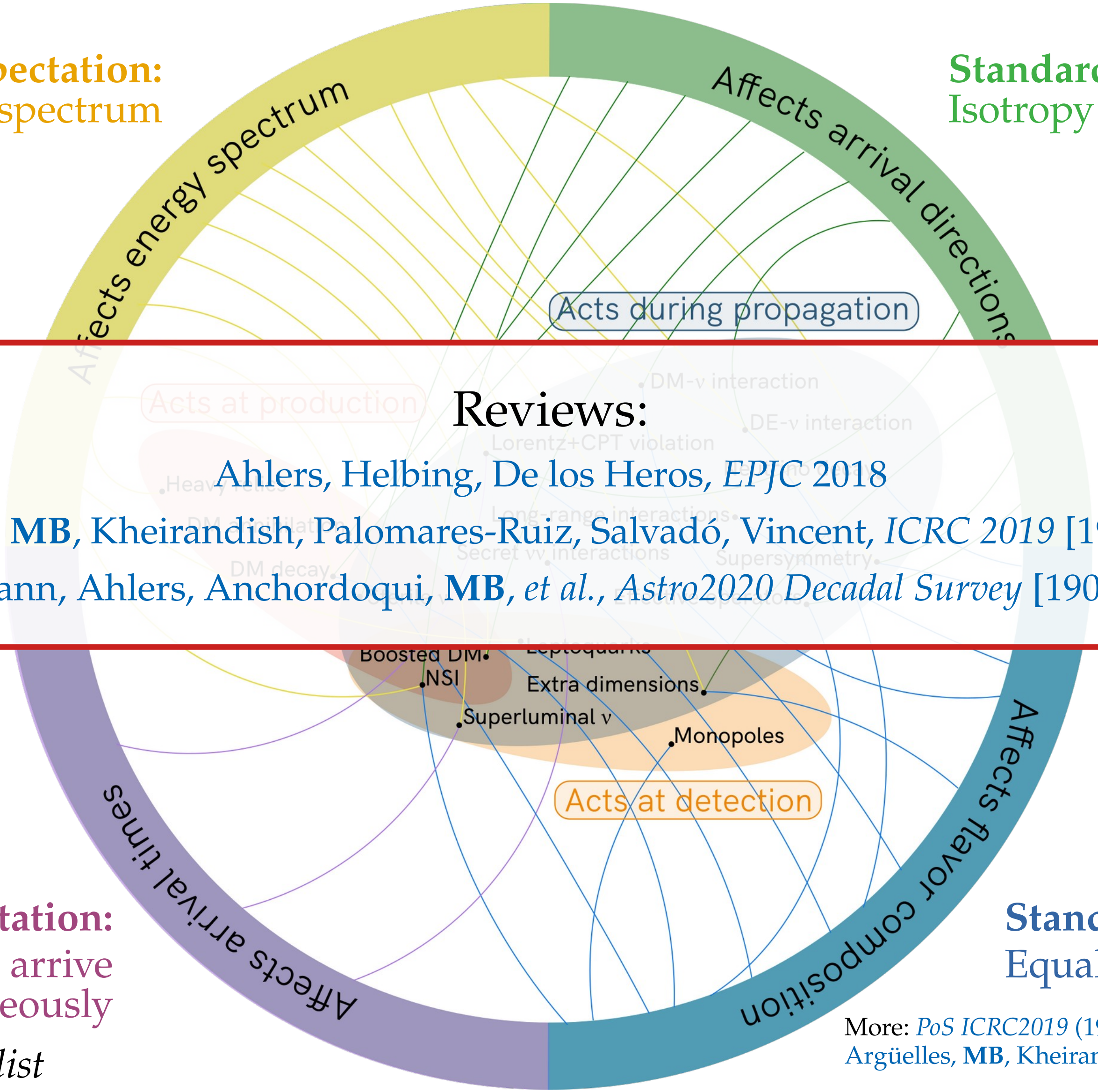

Reviews:

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

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

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

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A selection of neutrino physics

1. Discovering the Glashow resonance
2. Neutrino-matter cross section
3. New physics via flavor
4. Unstable neutrinos
   (If time allows)
5. New neutrino interactions
   (If time allows)

1. Glashow resonance:
Long-sought, finally seen

First observation of a Glashow resonance

Predicted in 1960:

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

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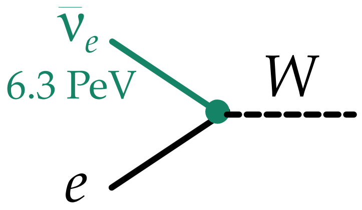

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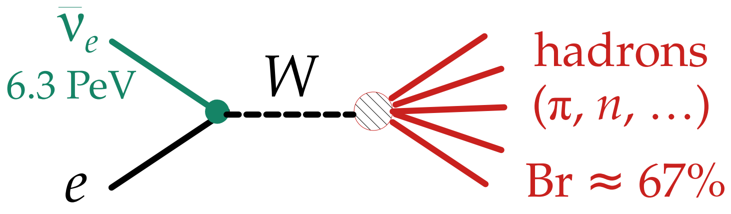

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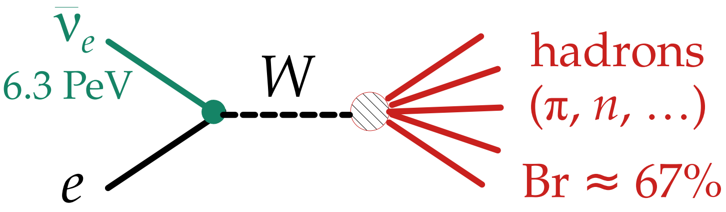

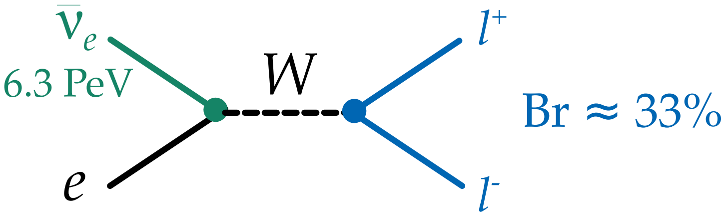

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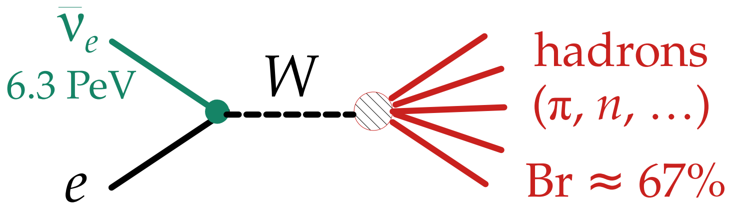
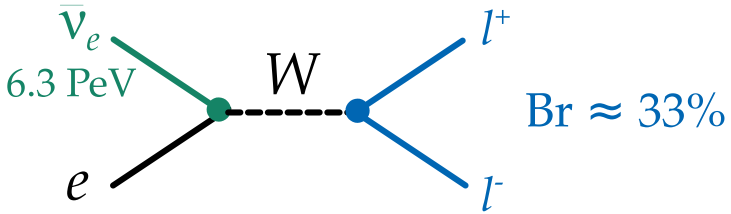
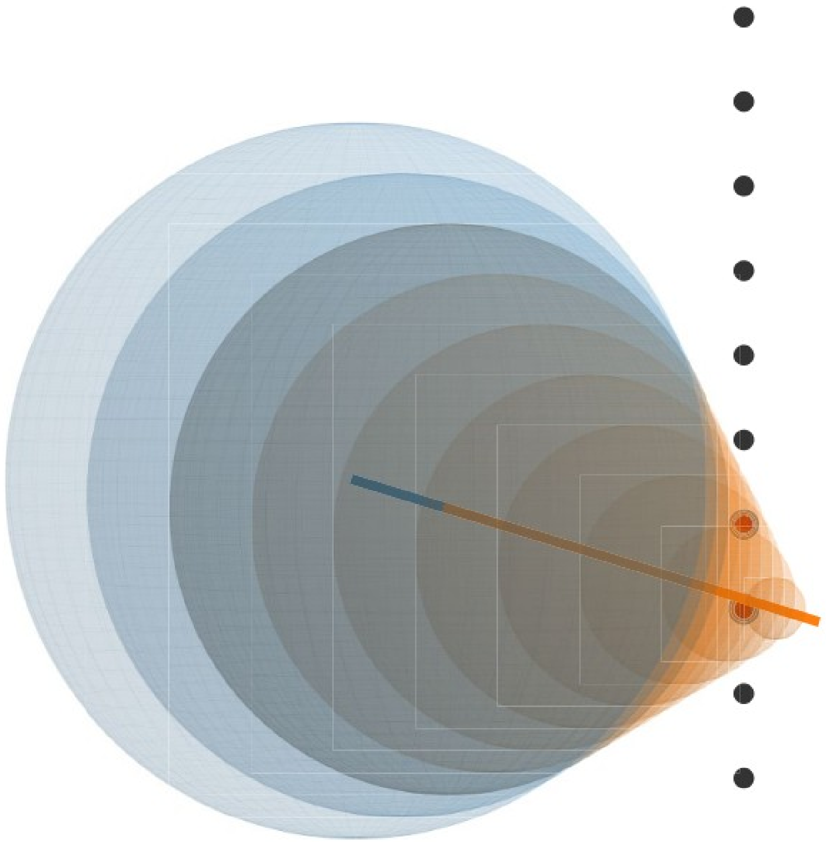




First reported by IceCube in 2021:



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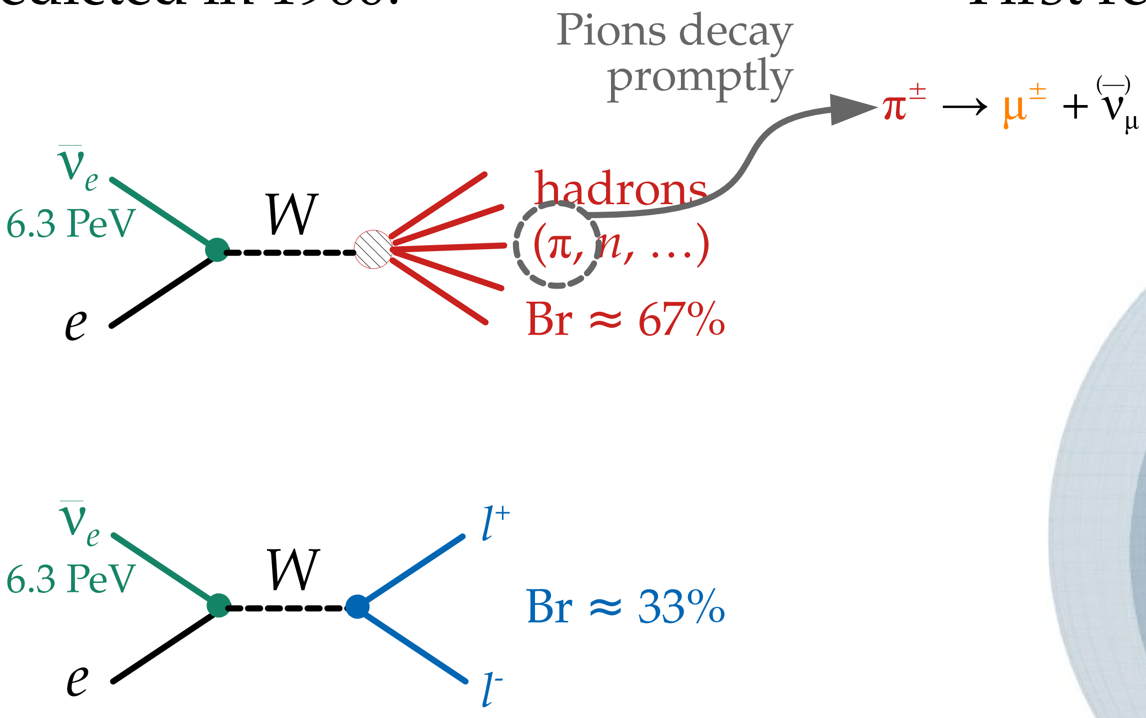

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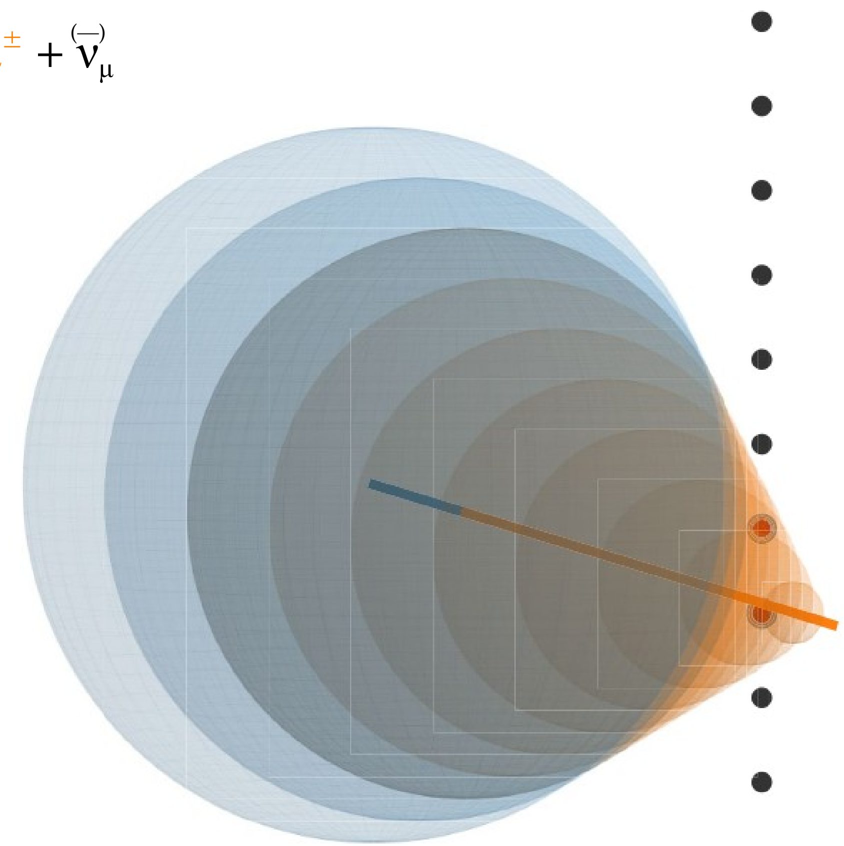

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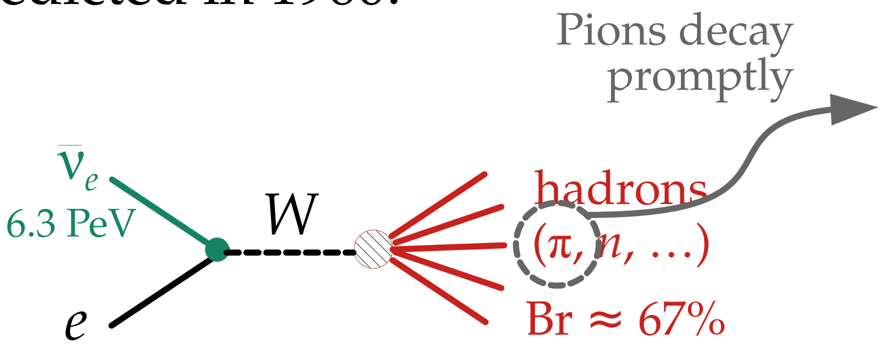
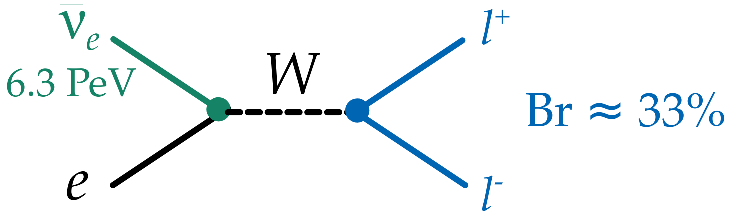


$\pi^{\pm} \longrightarrow \mu^{\pm} + \overset{(-)}{\nu}_{\mu}$



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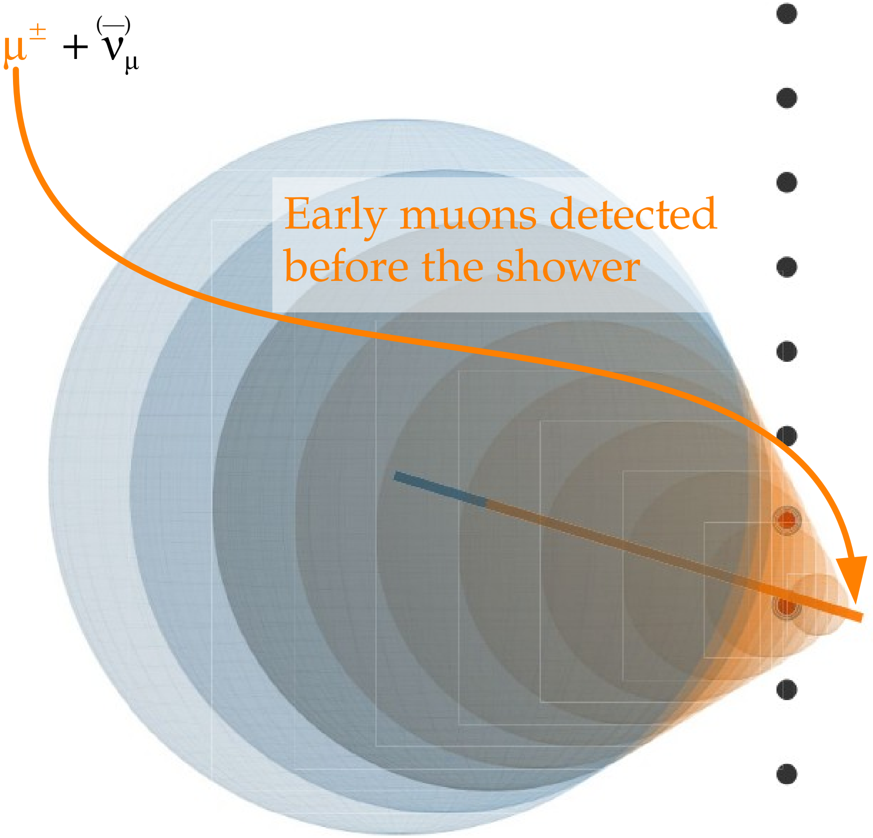

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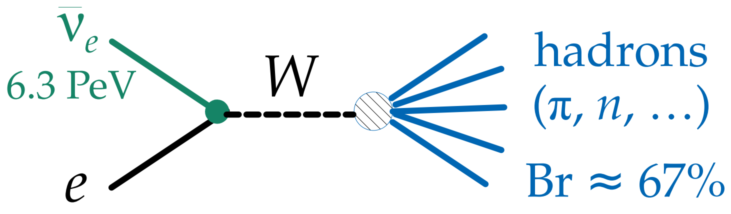

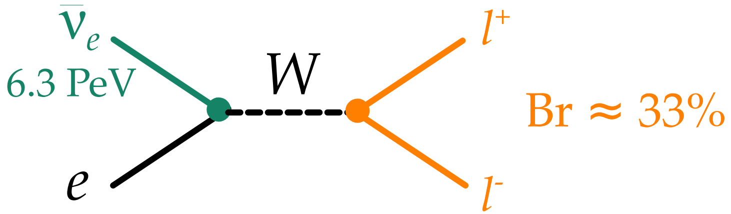

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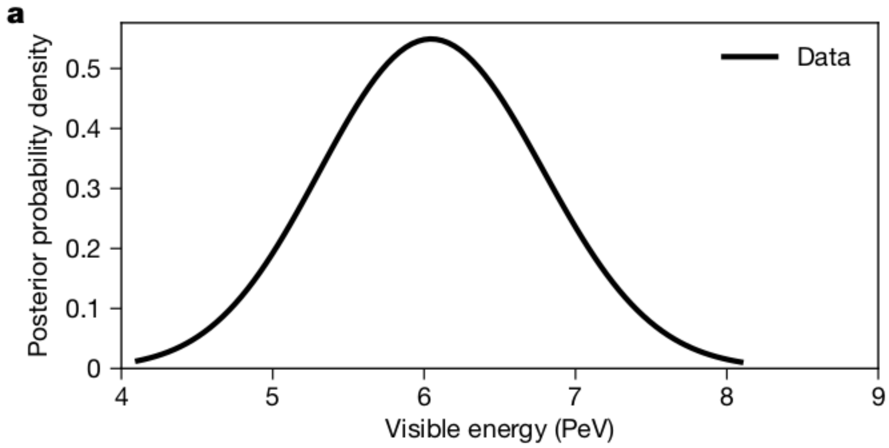

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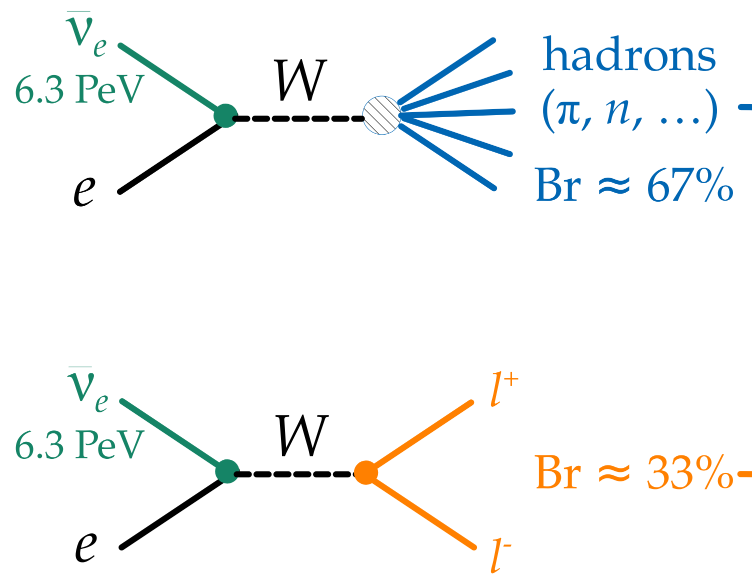

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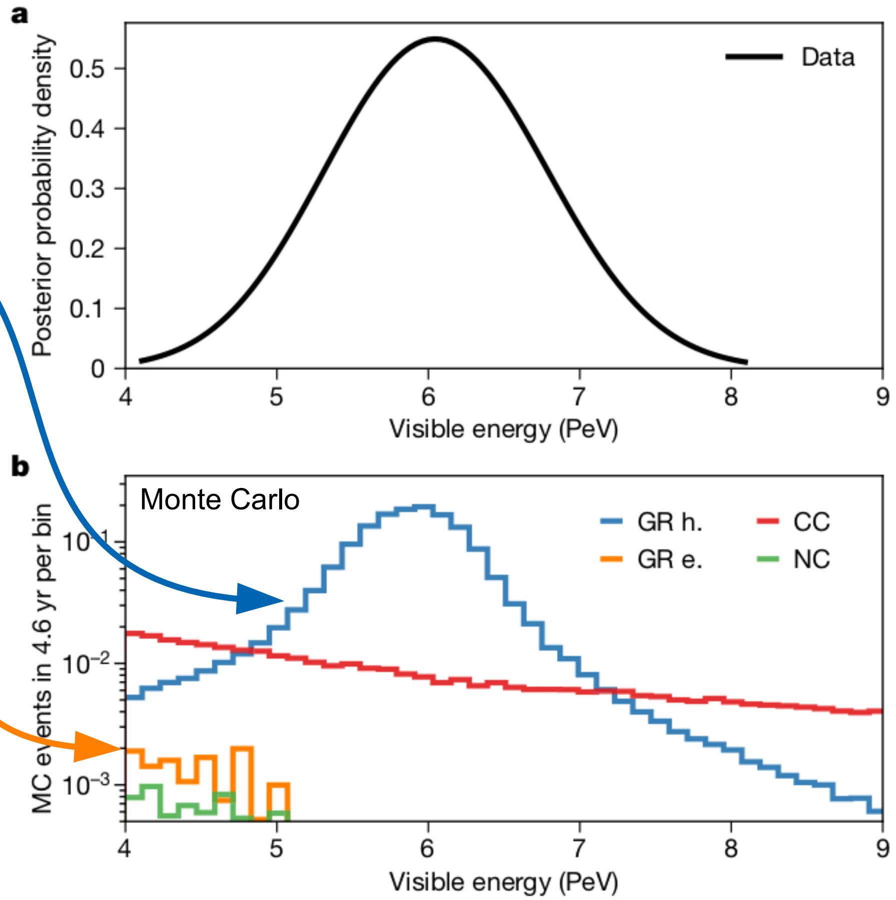
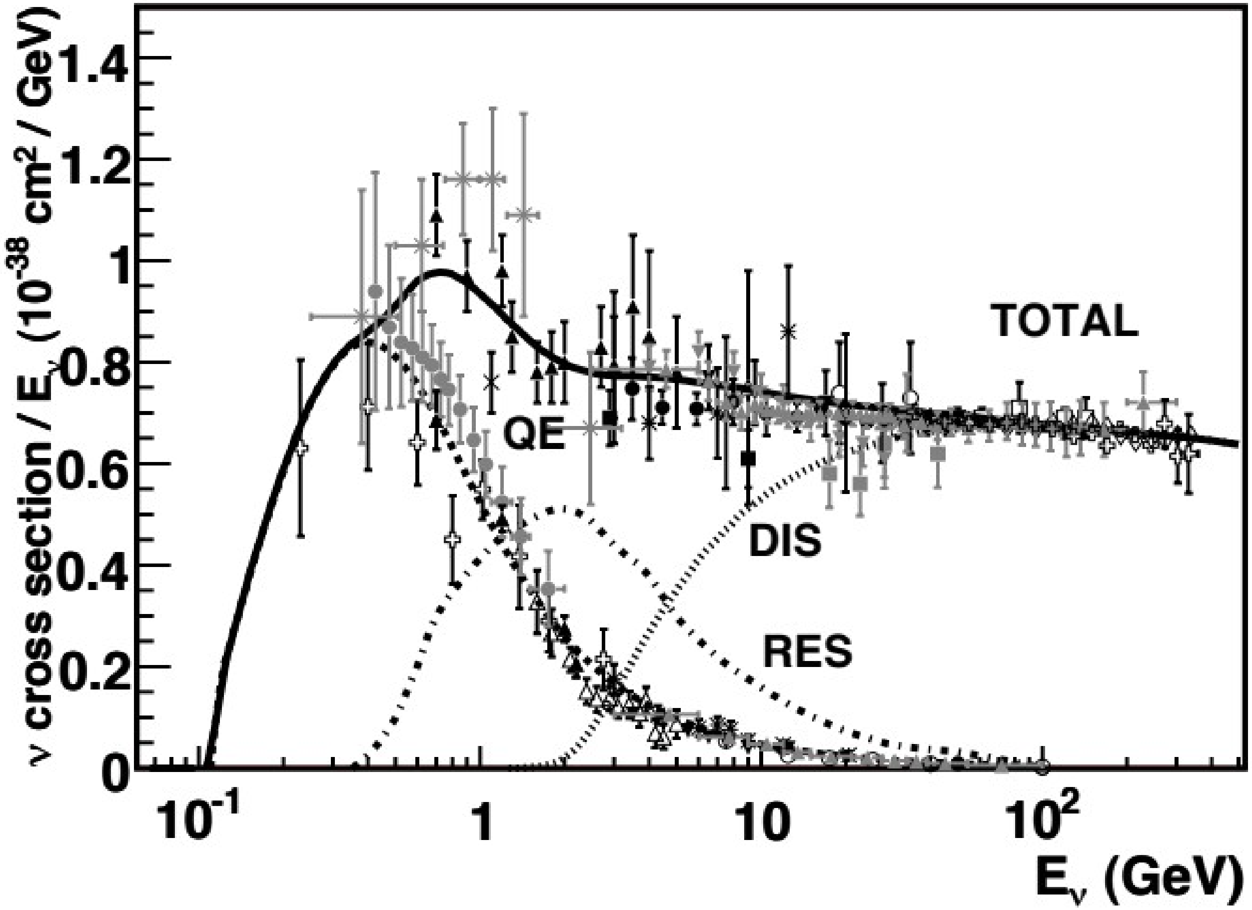


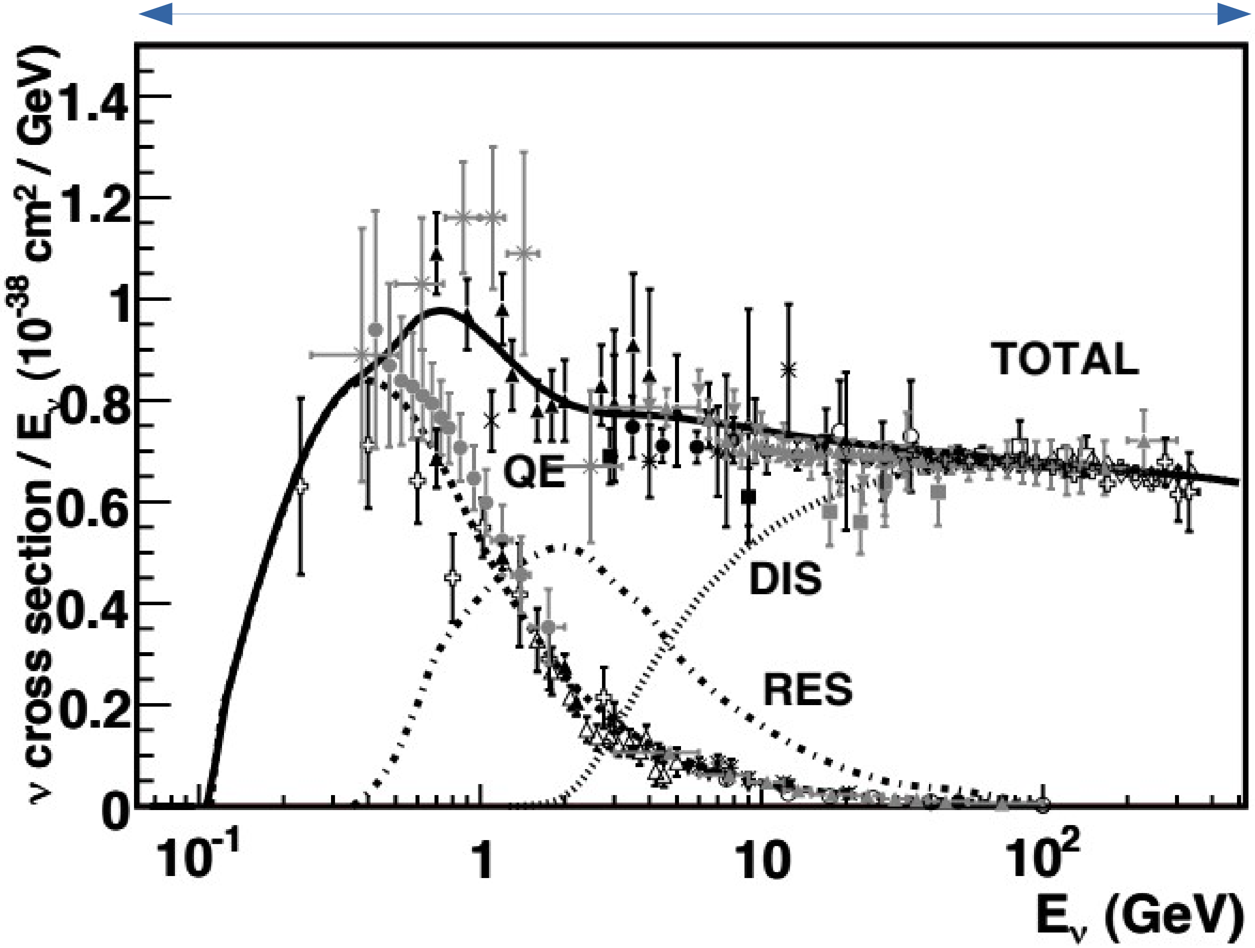
IceCube, *Nature* 2021
Glashow, *PR* 1960

2. Neutrino-matter cross section:
From TeV to EeV



Particle Data Group

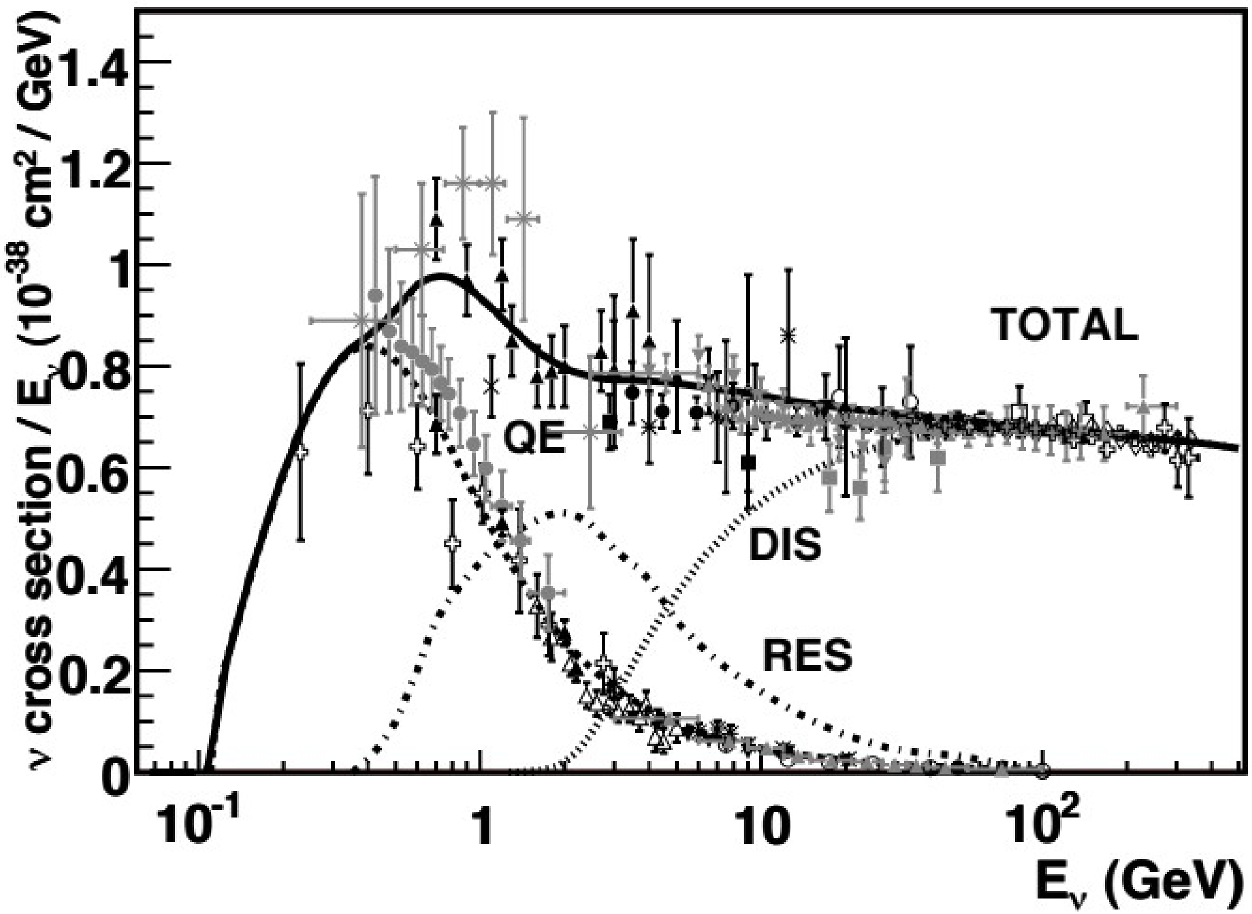
Accelerator experiments



Particle Data Group

Accelerator experiments

Coherent neutrino scattering



Particle Data Group

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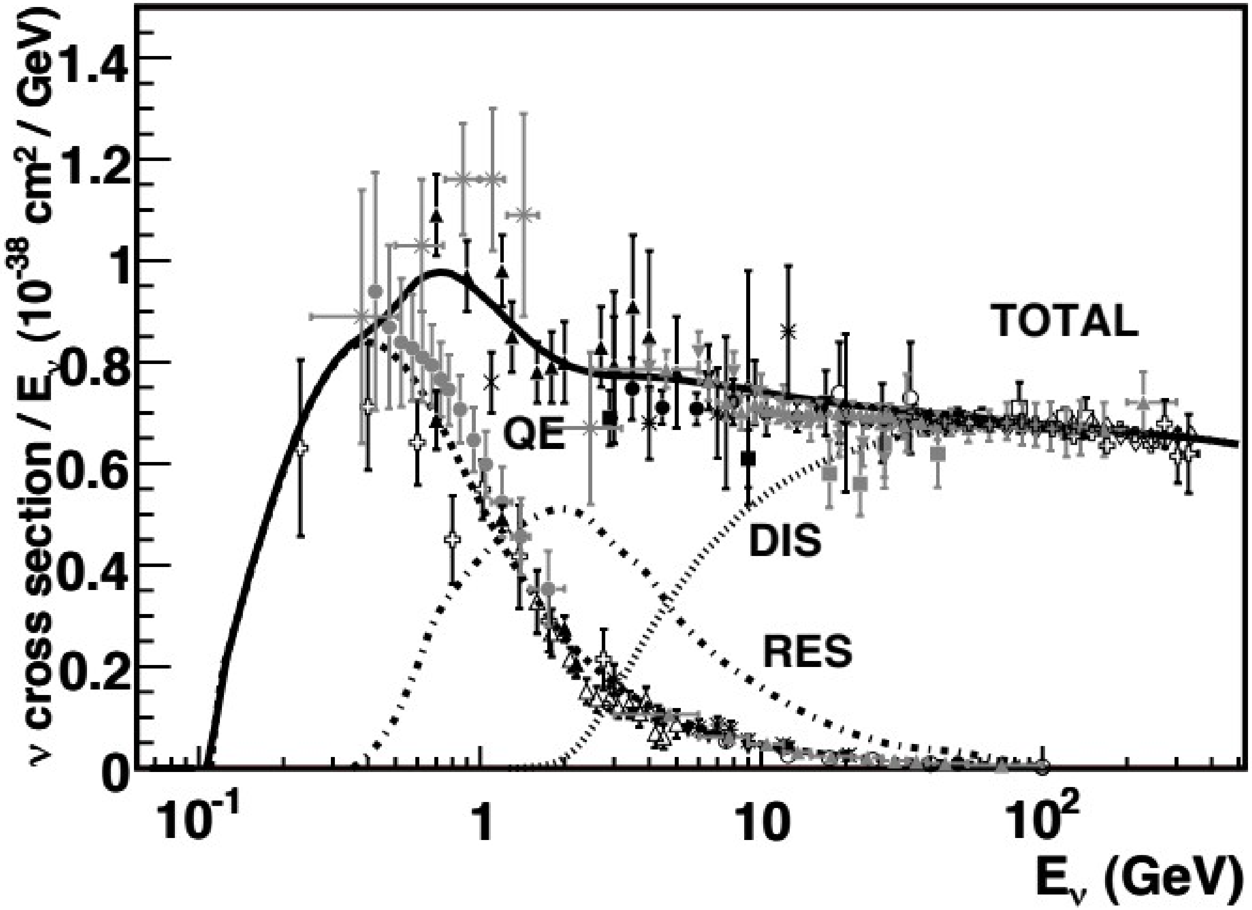
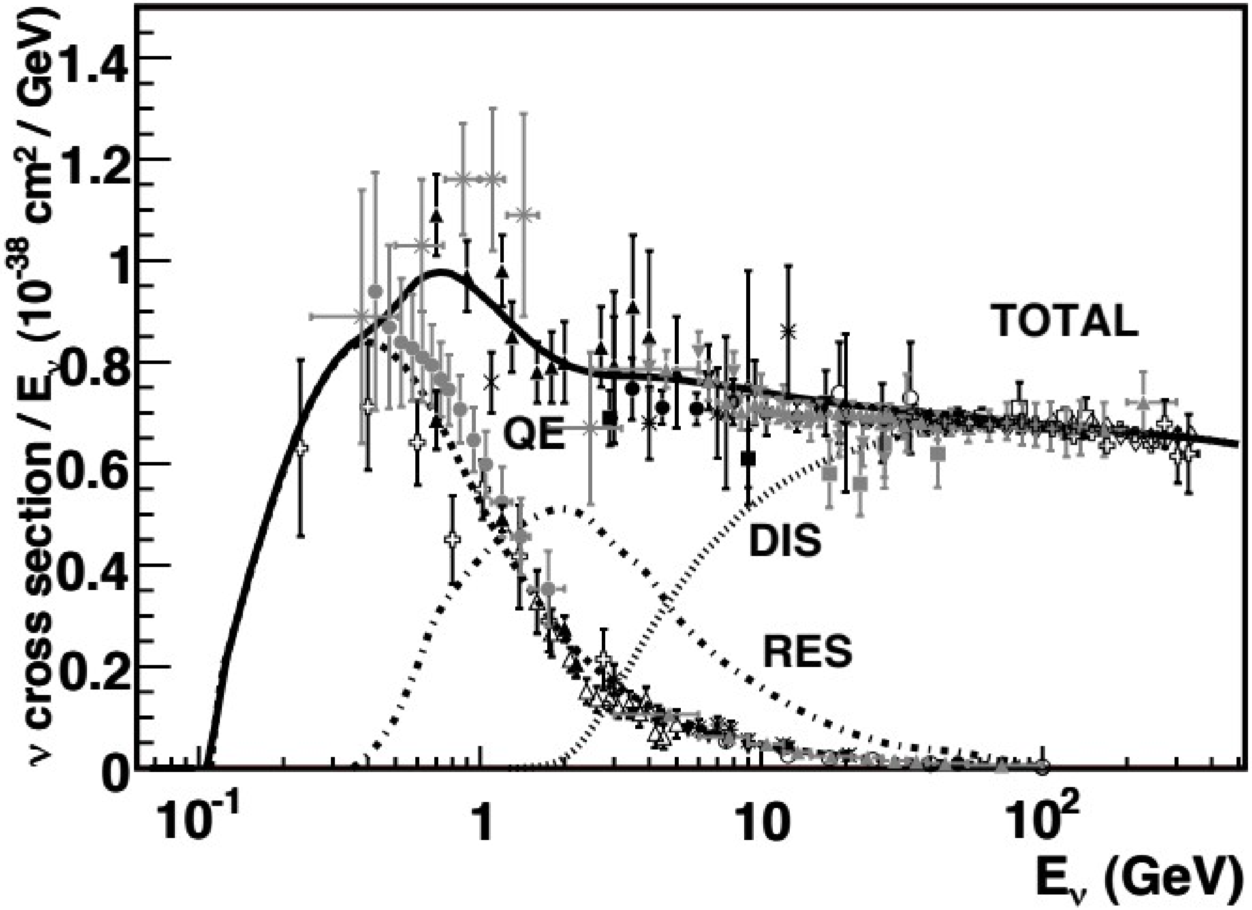


Particle Data Group

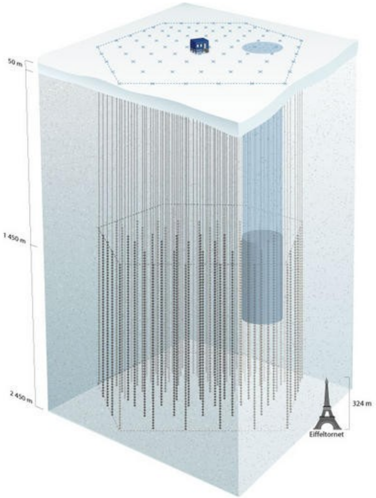
No measurements … until recently!

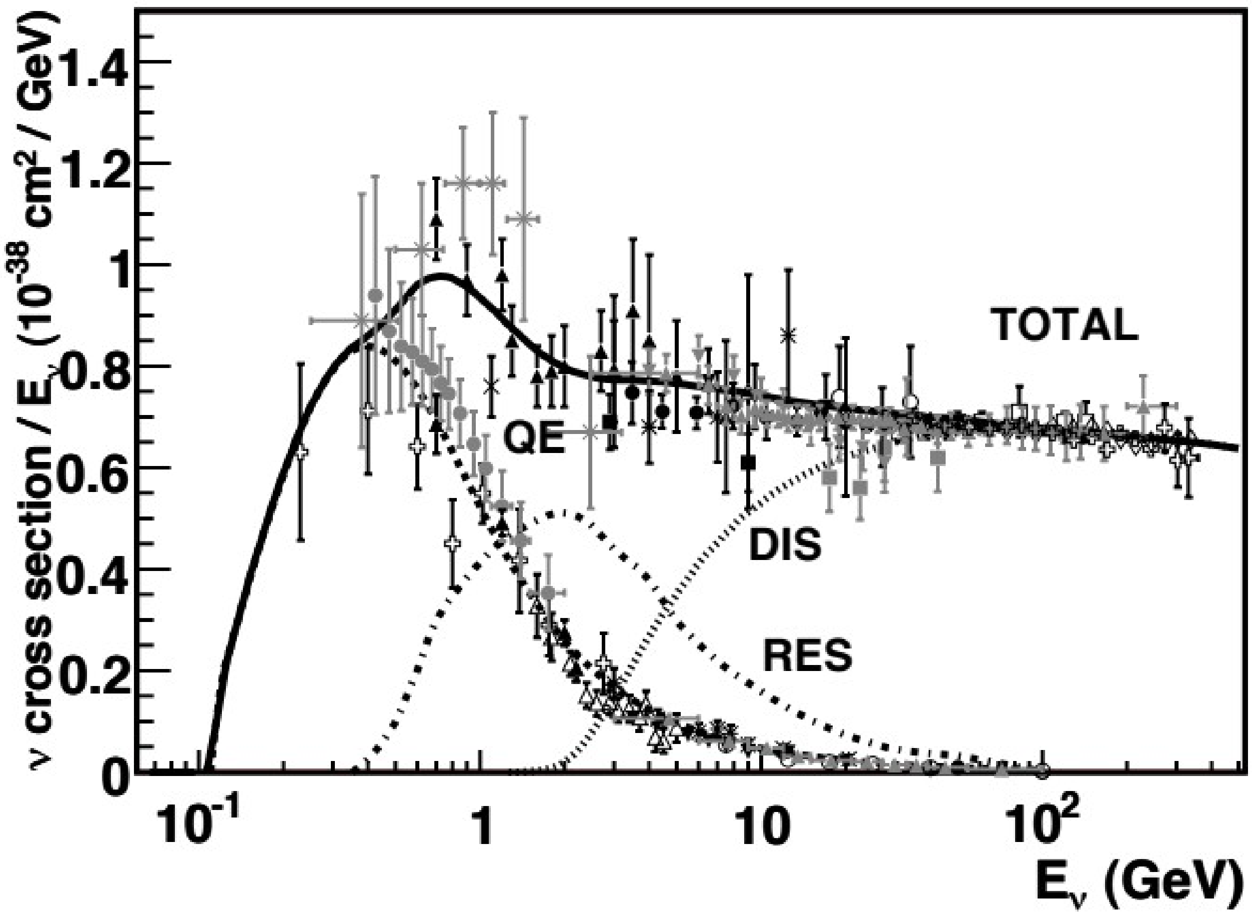
Accelerator experiments

Coherent neutrino scattering



Particle Data Group



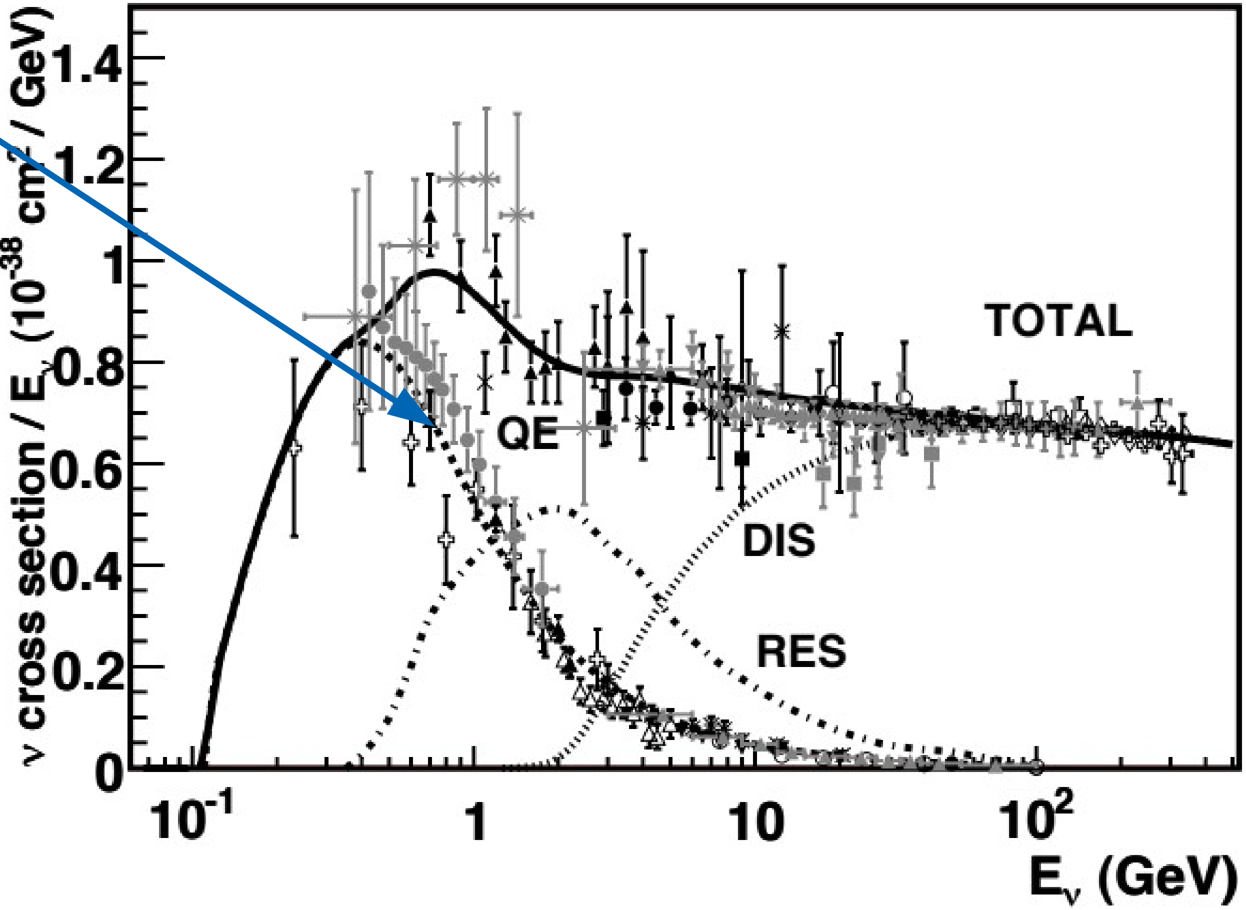


Particle Data Group

Quasi-elastic scattering:

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

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



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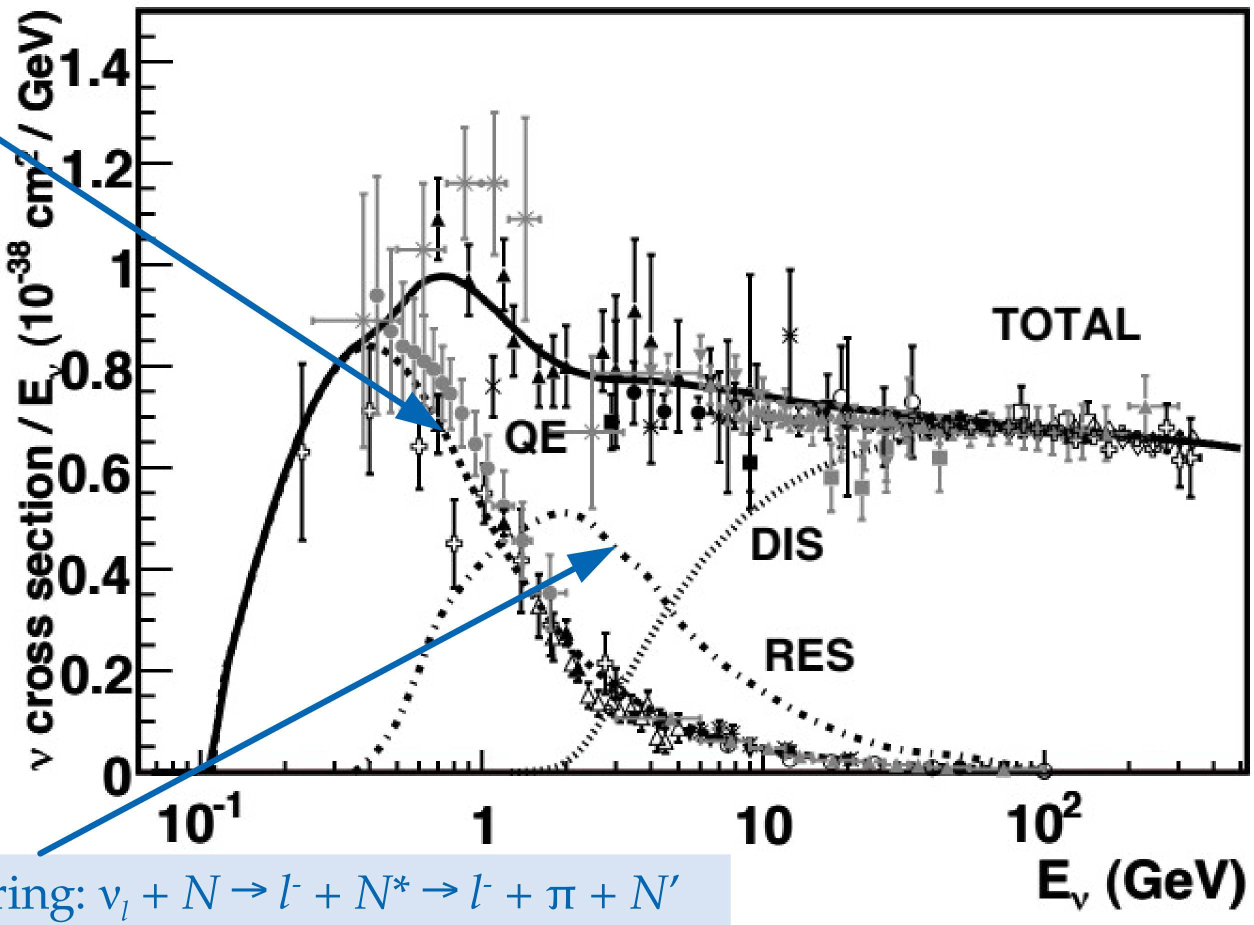

Resonant scattering: $\nu_l + N \rightarrow l^- + N^* \rightarrow l^- + \pi + N'$

Particle Data Group

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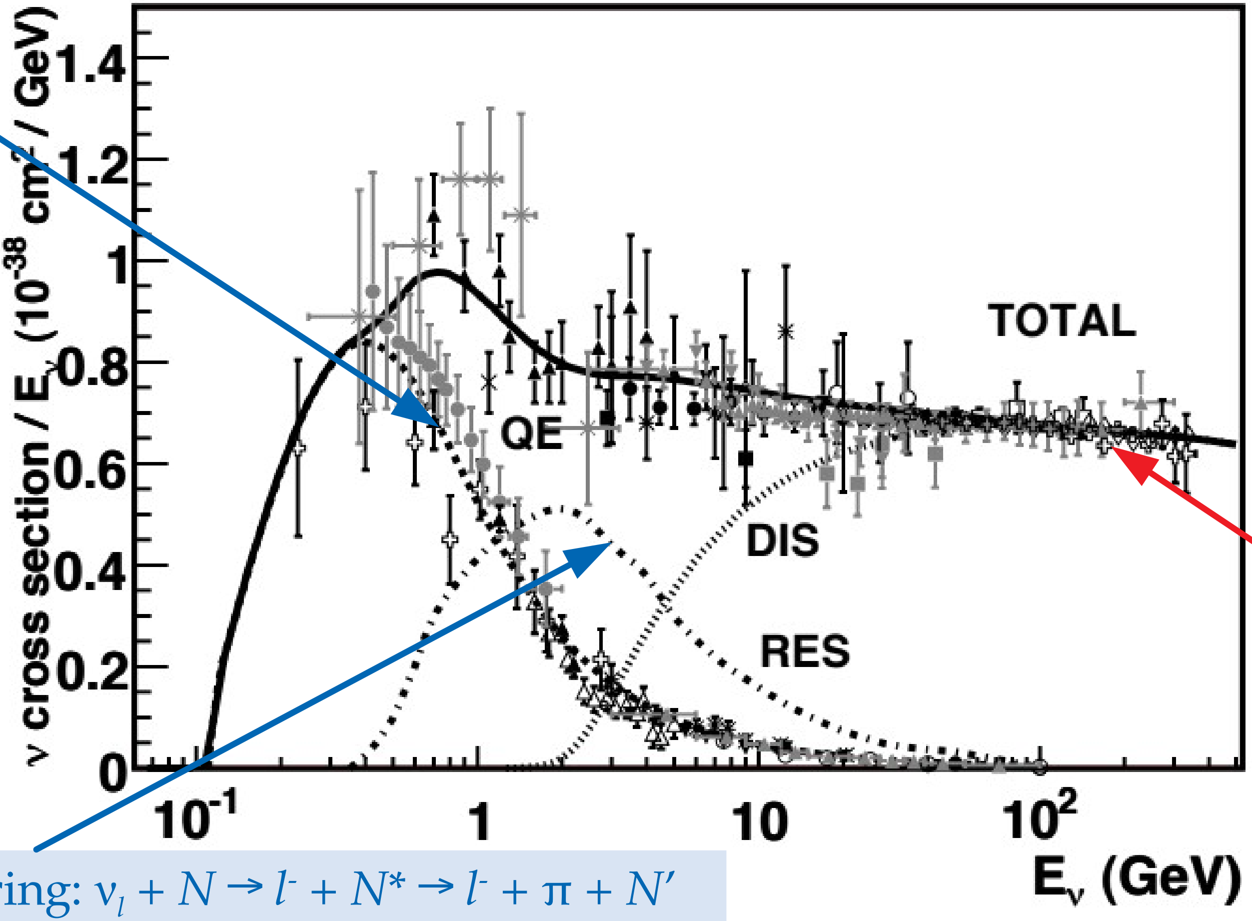


Deep inelastic scattering:

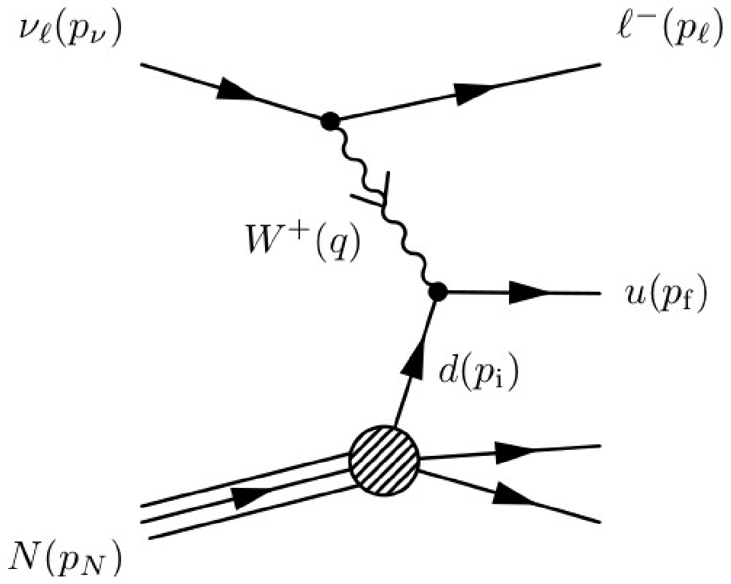
$\nu_l + N \rightarrow l^- + X$

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

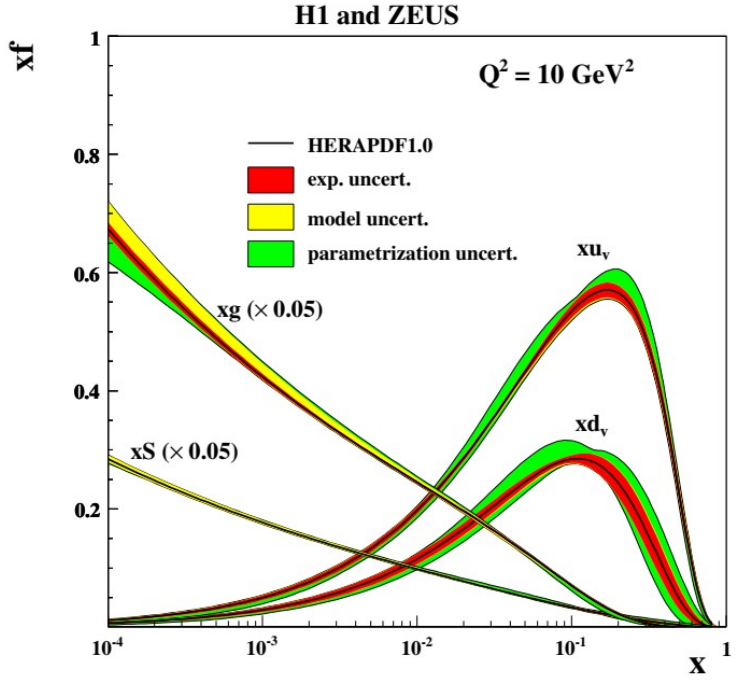
Resonant scattering: $\nu_l + N \rightarrow l^- + N^* \rightarrow l^- + \pi + N'$

Particle Data Group

Extrapolating the cross section to high energies

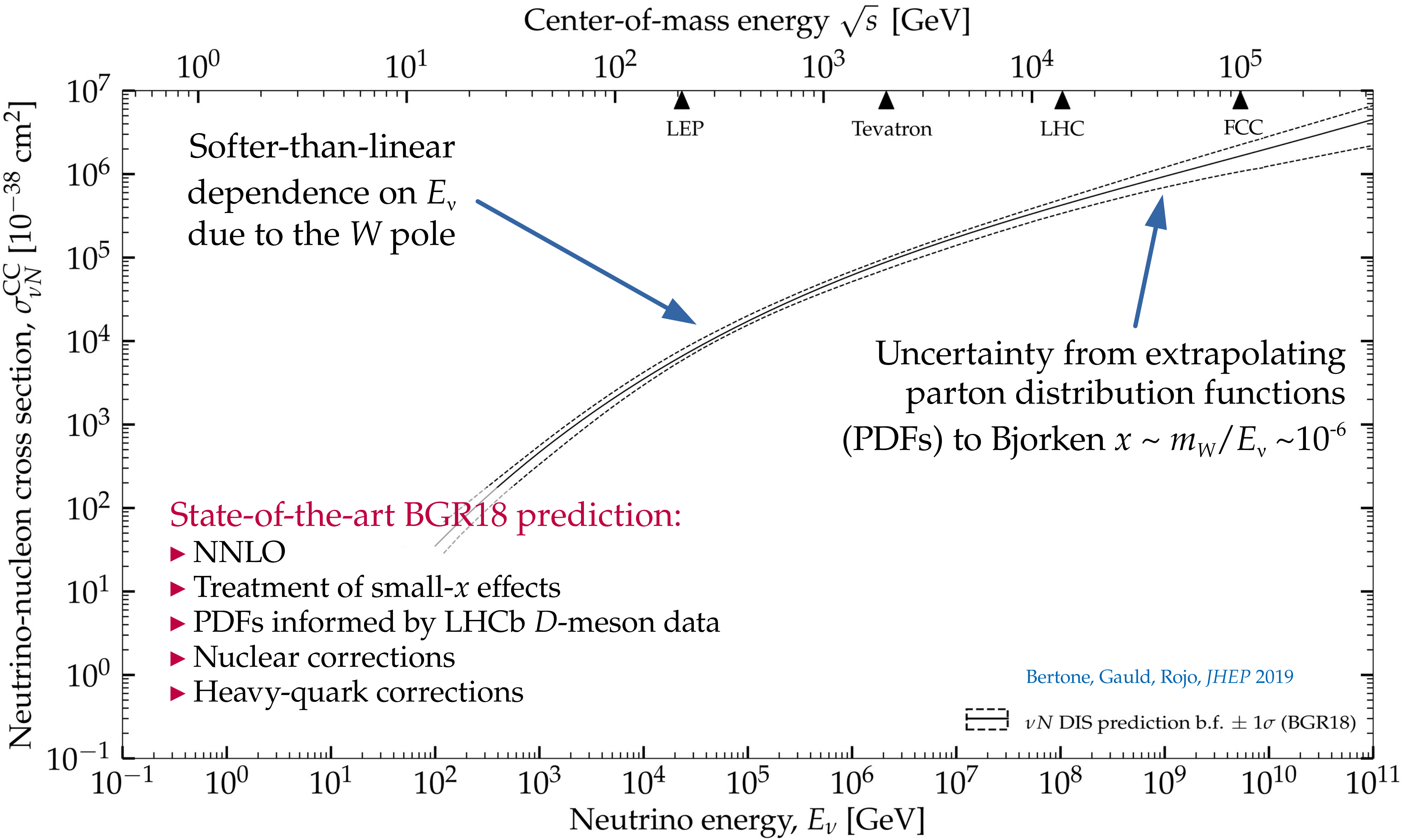


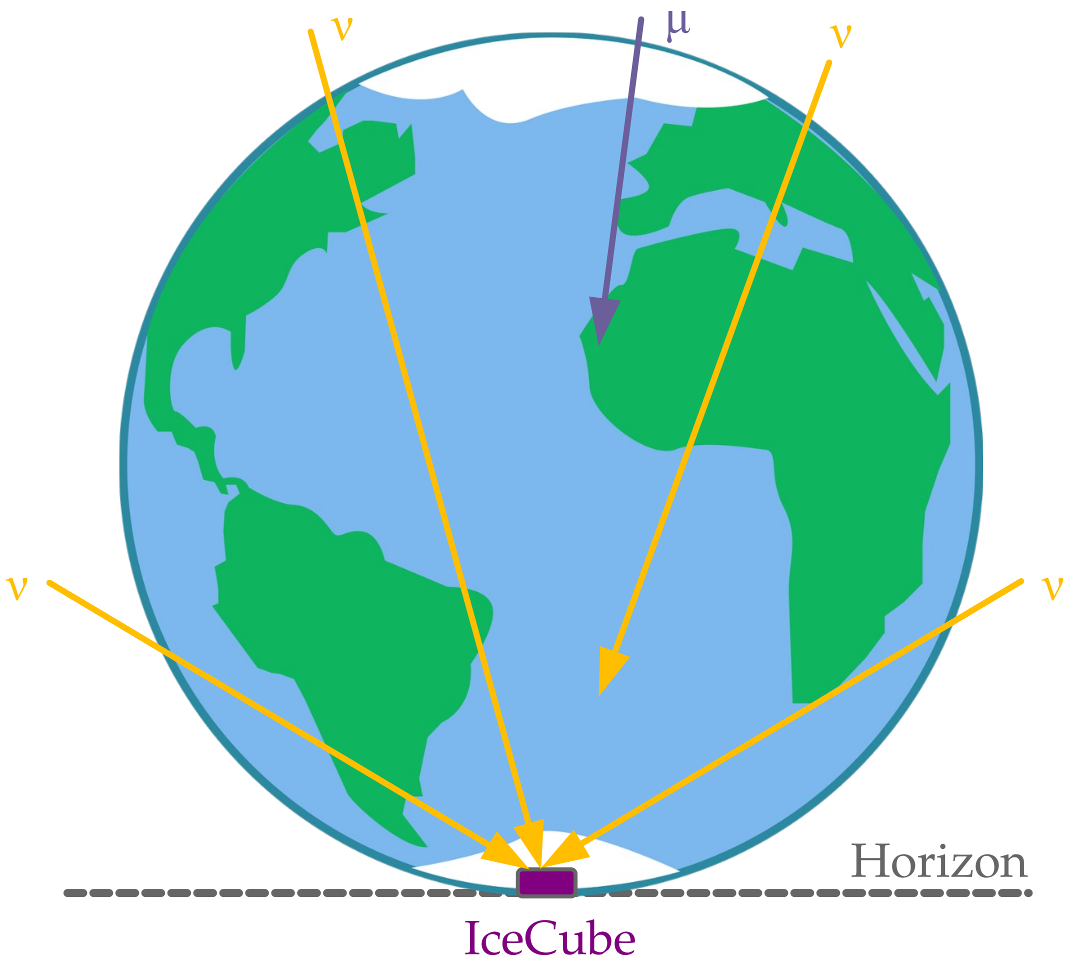
+

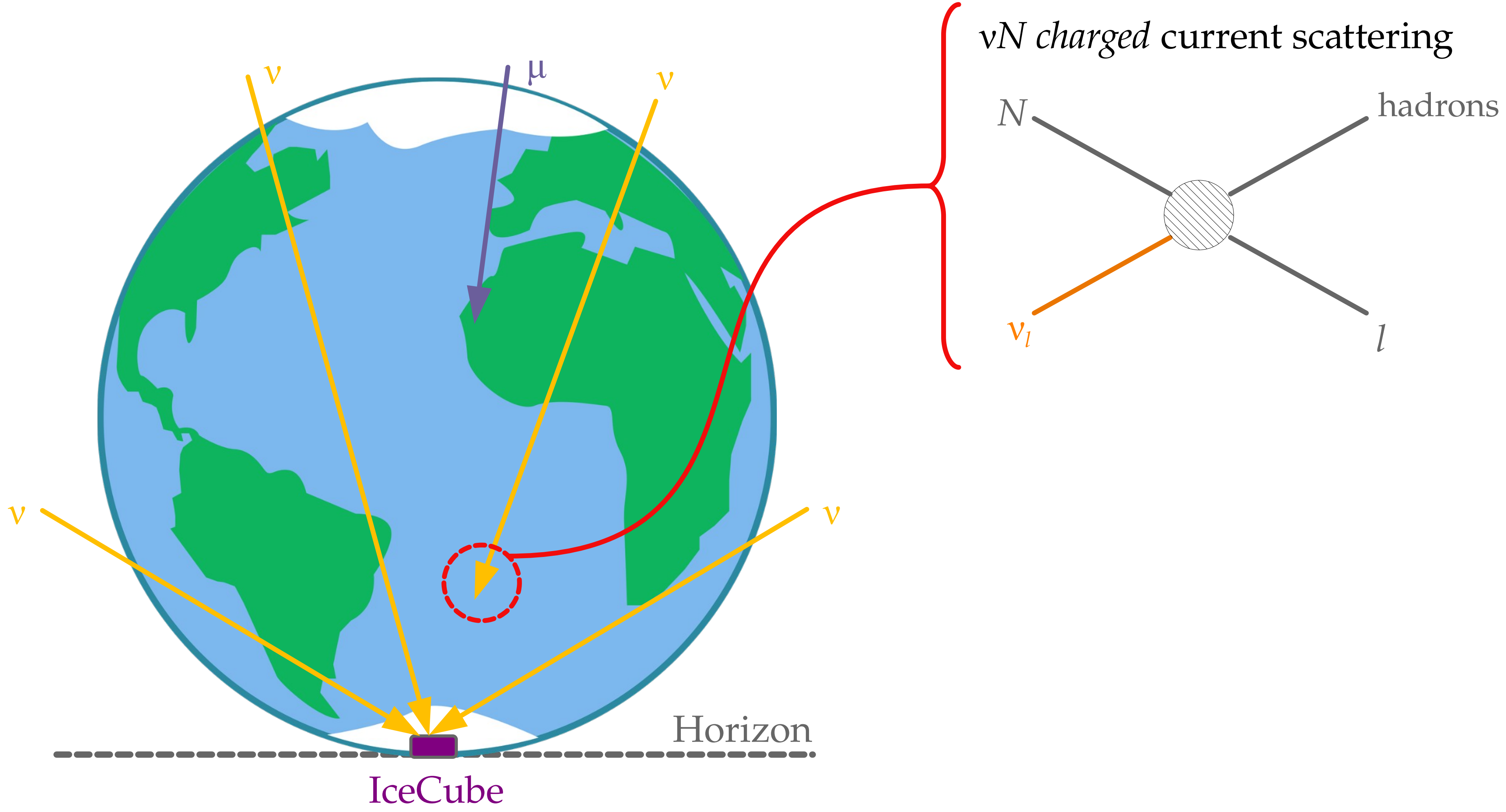


From theory:
Neutrino-quark cross section

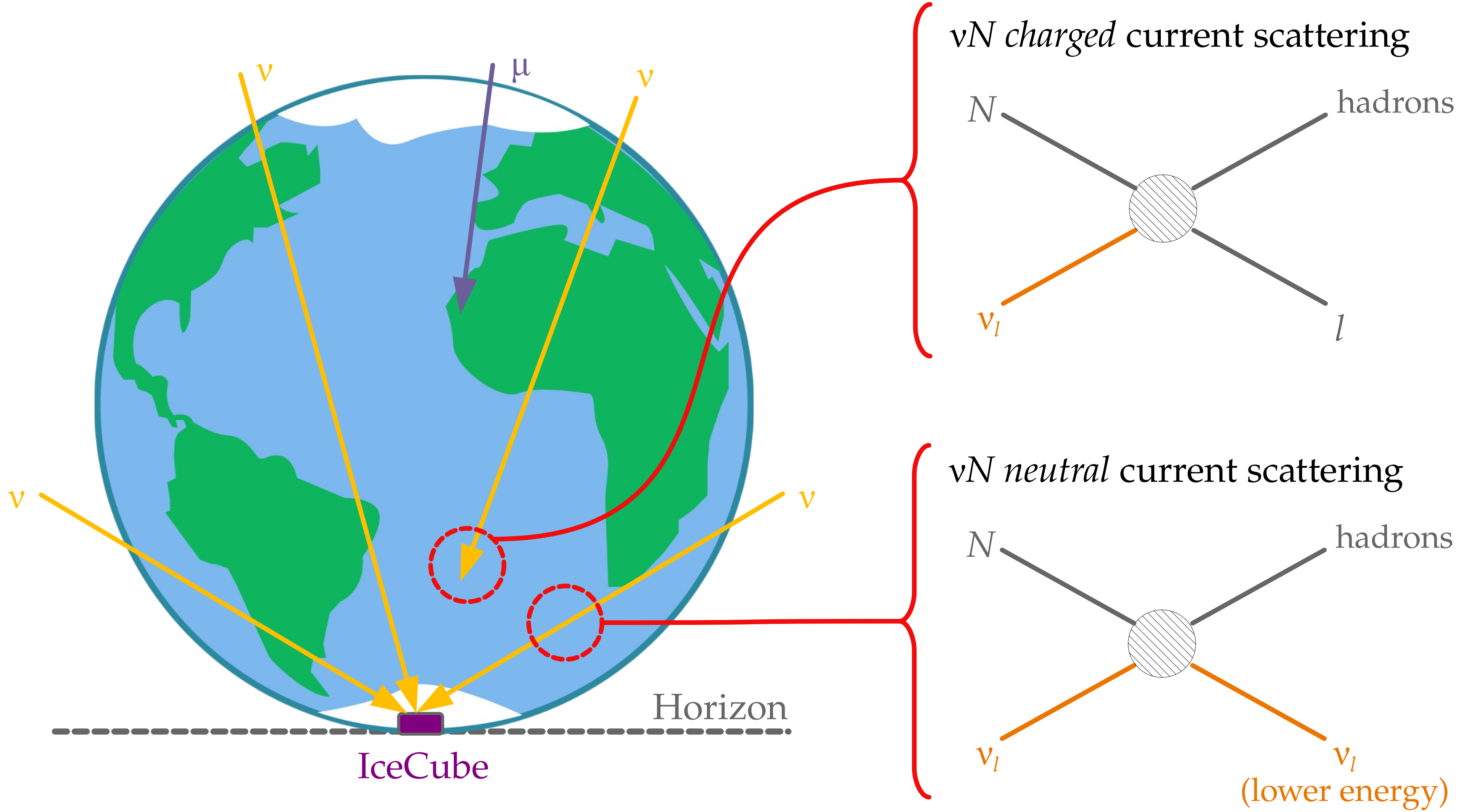
From colliders:
Parton distribution functions


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, $\sigma_{\nu N}^{\mathrm{CC}}$ [10^{-38} cm^2]
Neutrino energy, E_ν [GeV]

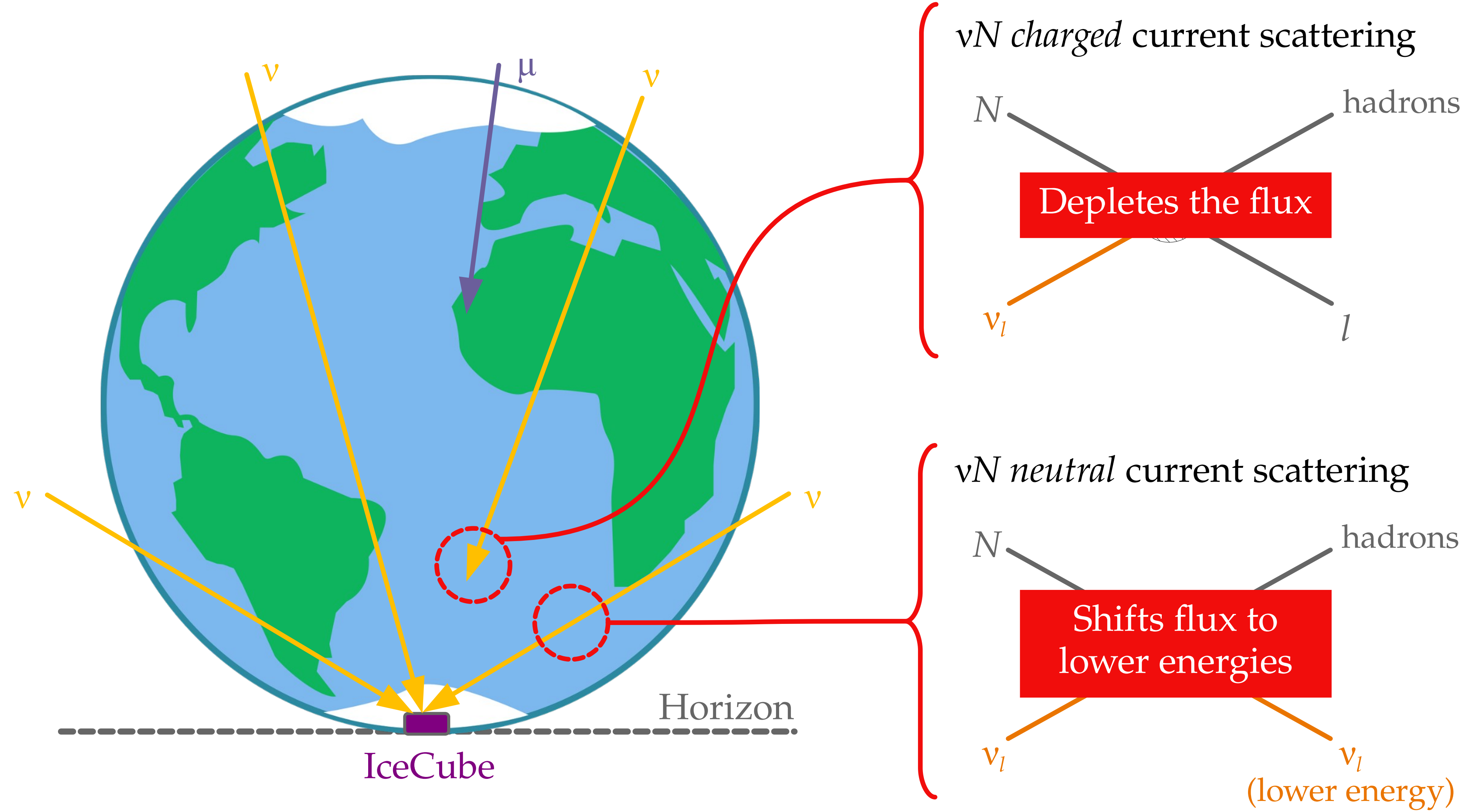

ν
μ
ν
ν
ν
Horizon
IceCube



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)

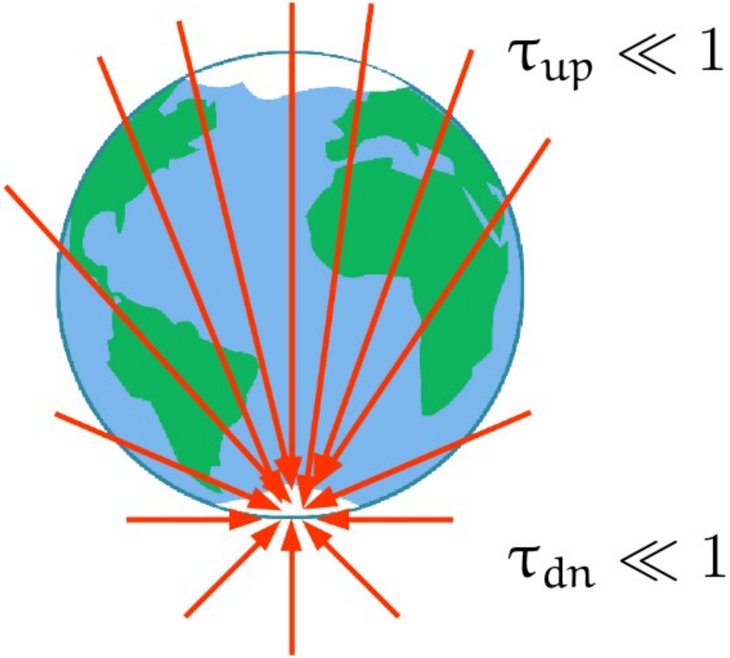


ν
μ
ν
ν
ν
Horizon
IceCube
νN charged current scattering
N
hadrons
Depletes the flux
ν_l
l
νN neutral current scattering
N
hadrons
Shifts flux to lower energies
ν_l
ν_l
(lower energy)

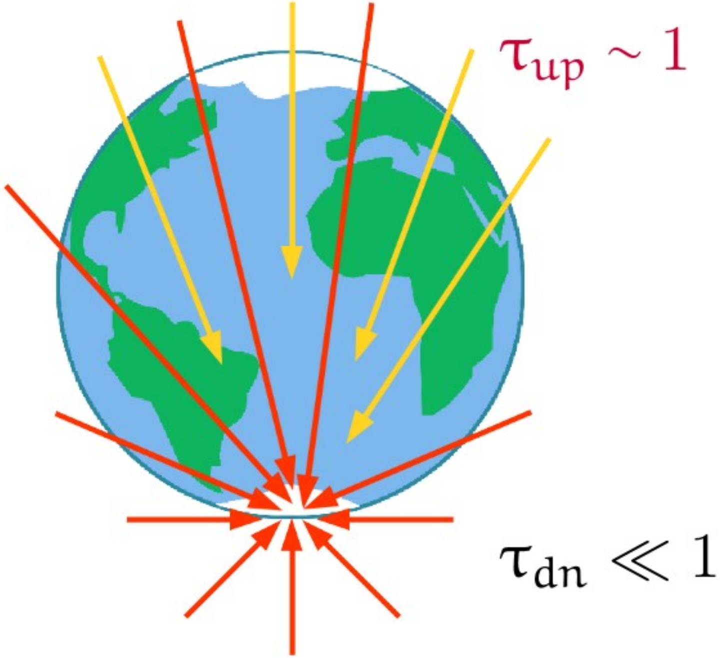
Measuring the high-energy *νN* cross section

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

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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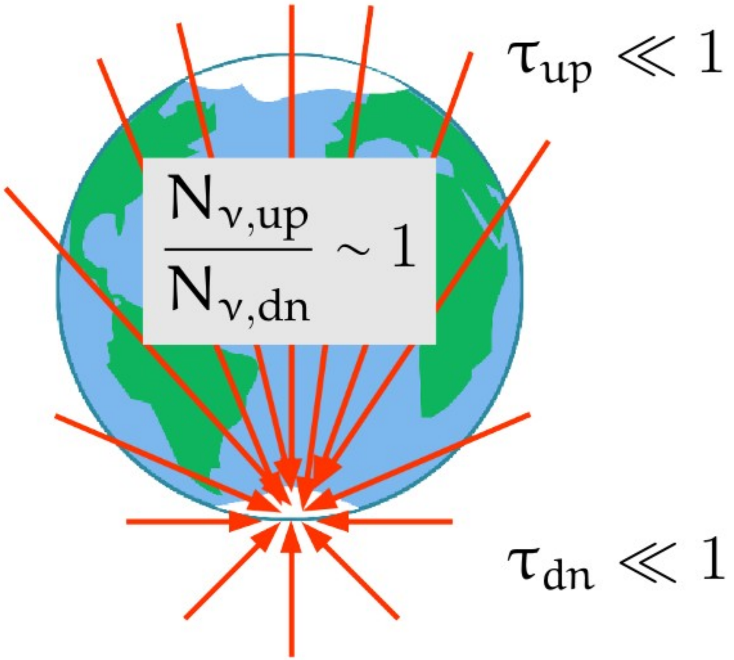

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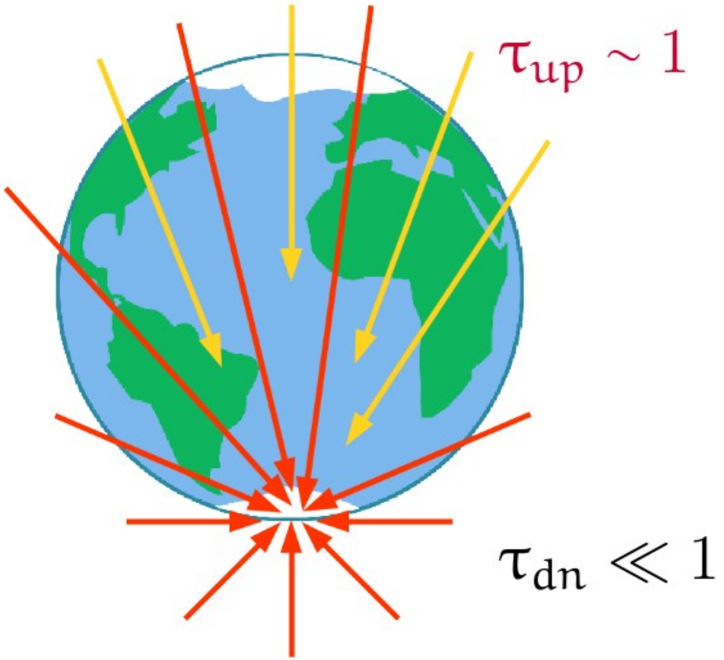

Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
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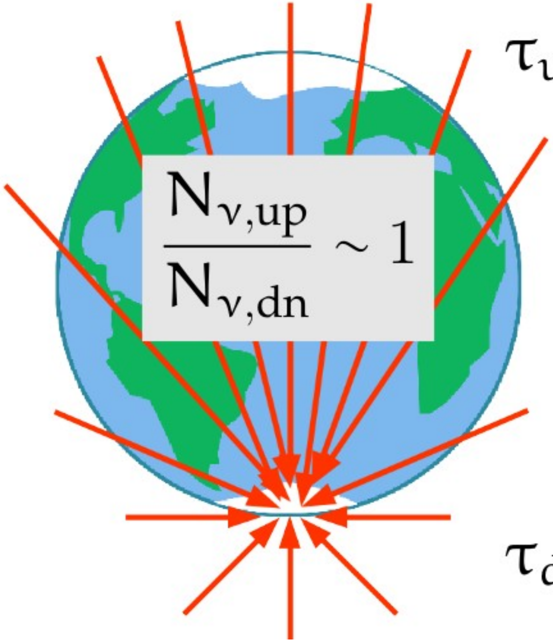
Below ~ 10 TeV: Earth is transparent

$\tau_{up} \ll 1$

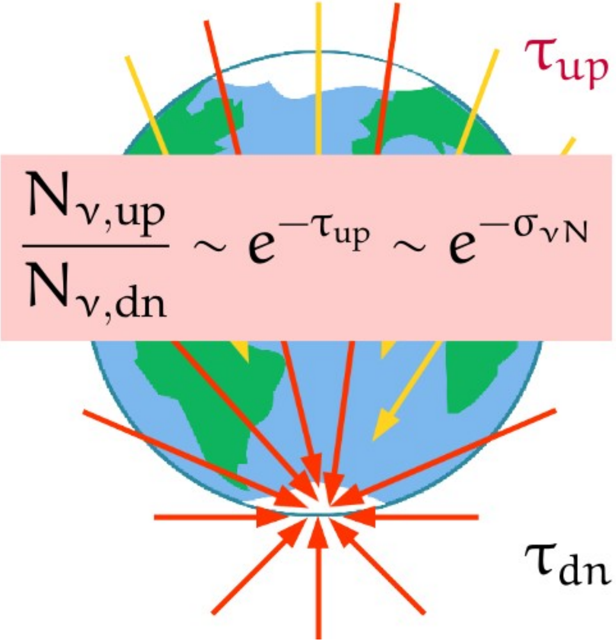


$$\frac{N_{\nu,up}}{N_{\nu,dn}} \sim 1$$

$\tau_{dn} \ll 1$

Above ~ 10 TeV: Earth is opaque

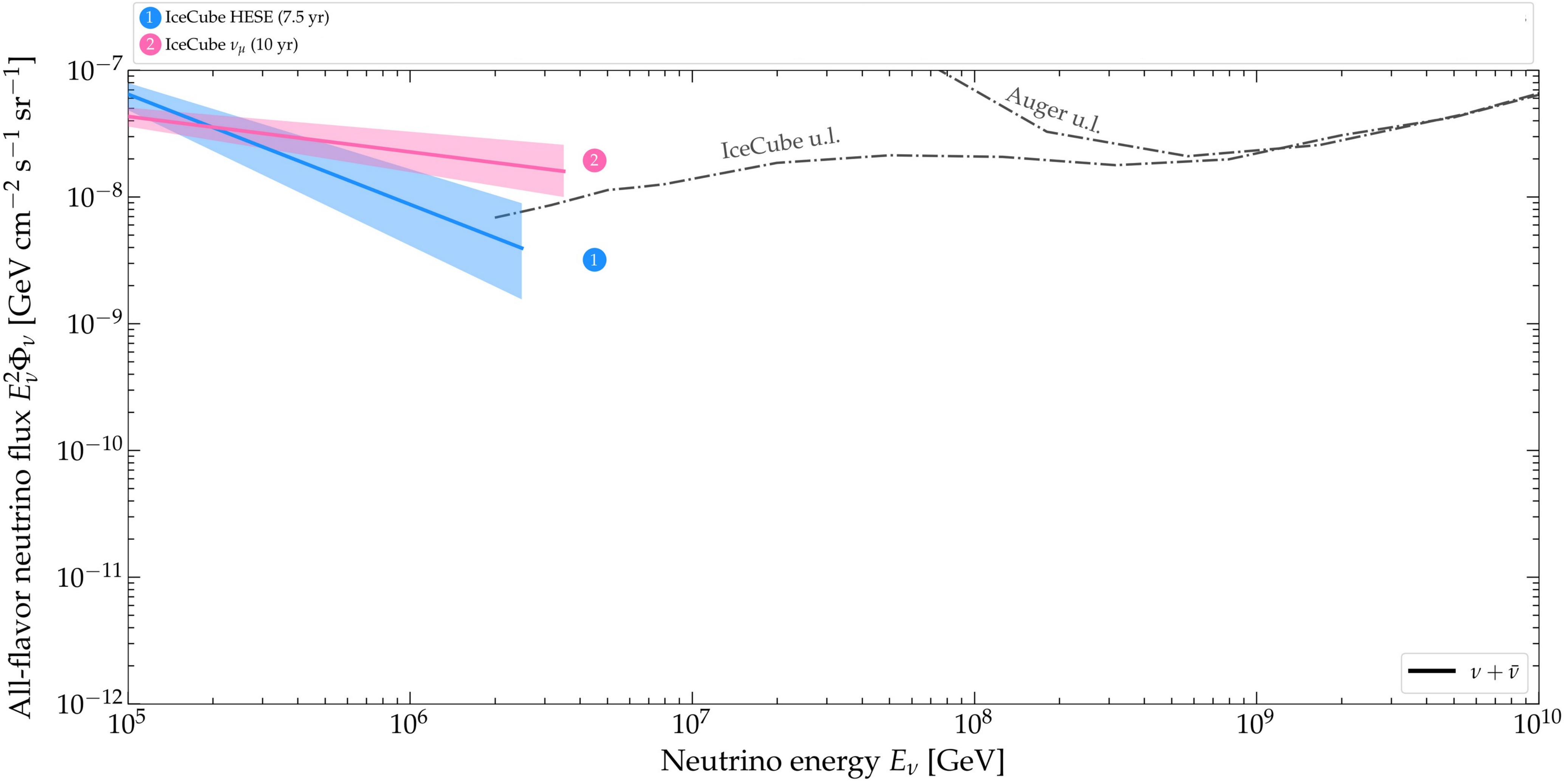
$\tau_{up} \sim 1$



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

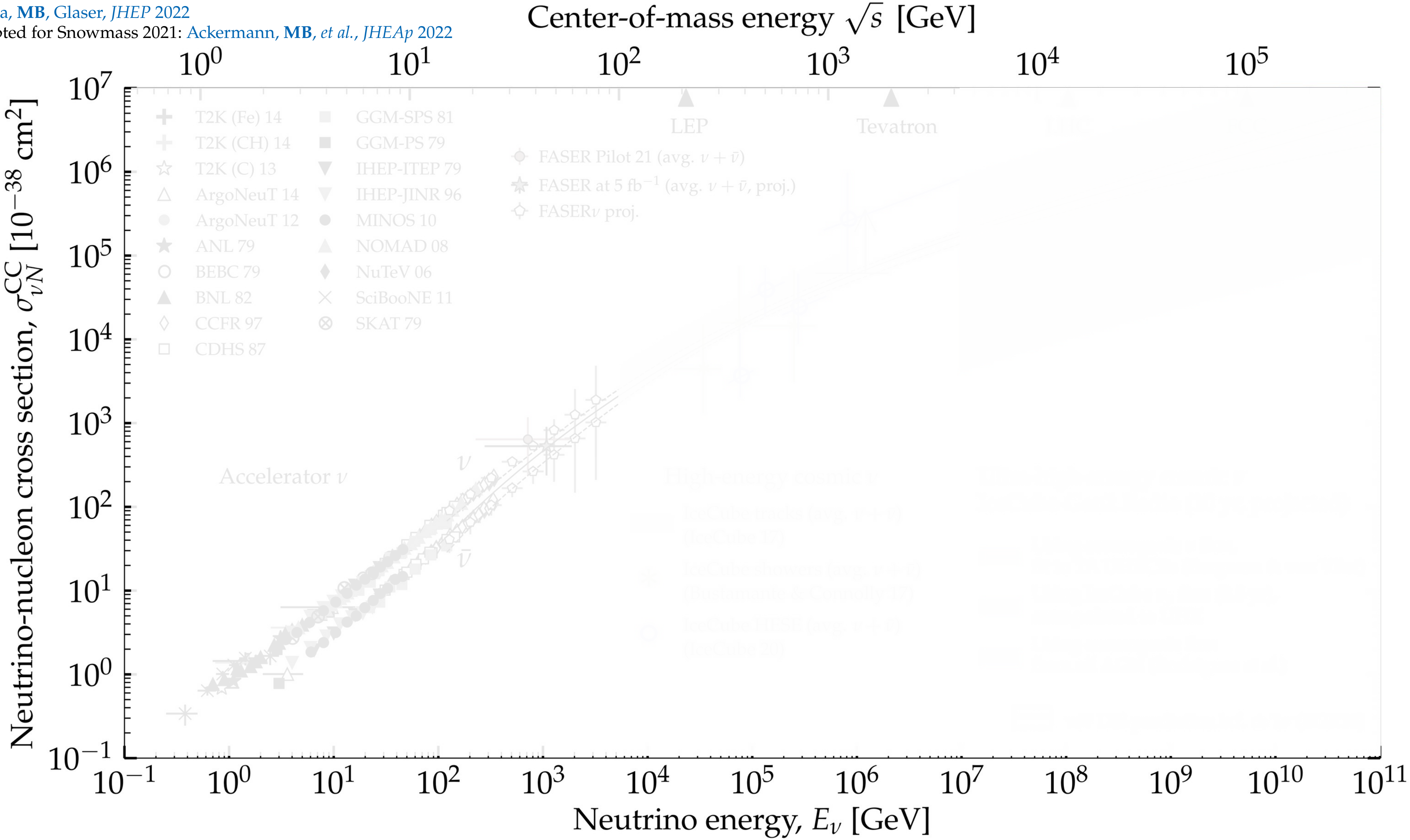
$\tau_{dn} \ll 1$

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 (10 yr)
Auger u.l.
IceCube u.l.
$\nu + \bar{\nu}$
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy E_ν [GeV]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^5
10^6
10^7
10^8
10^9
10^{10}

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



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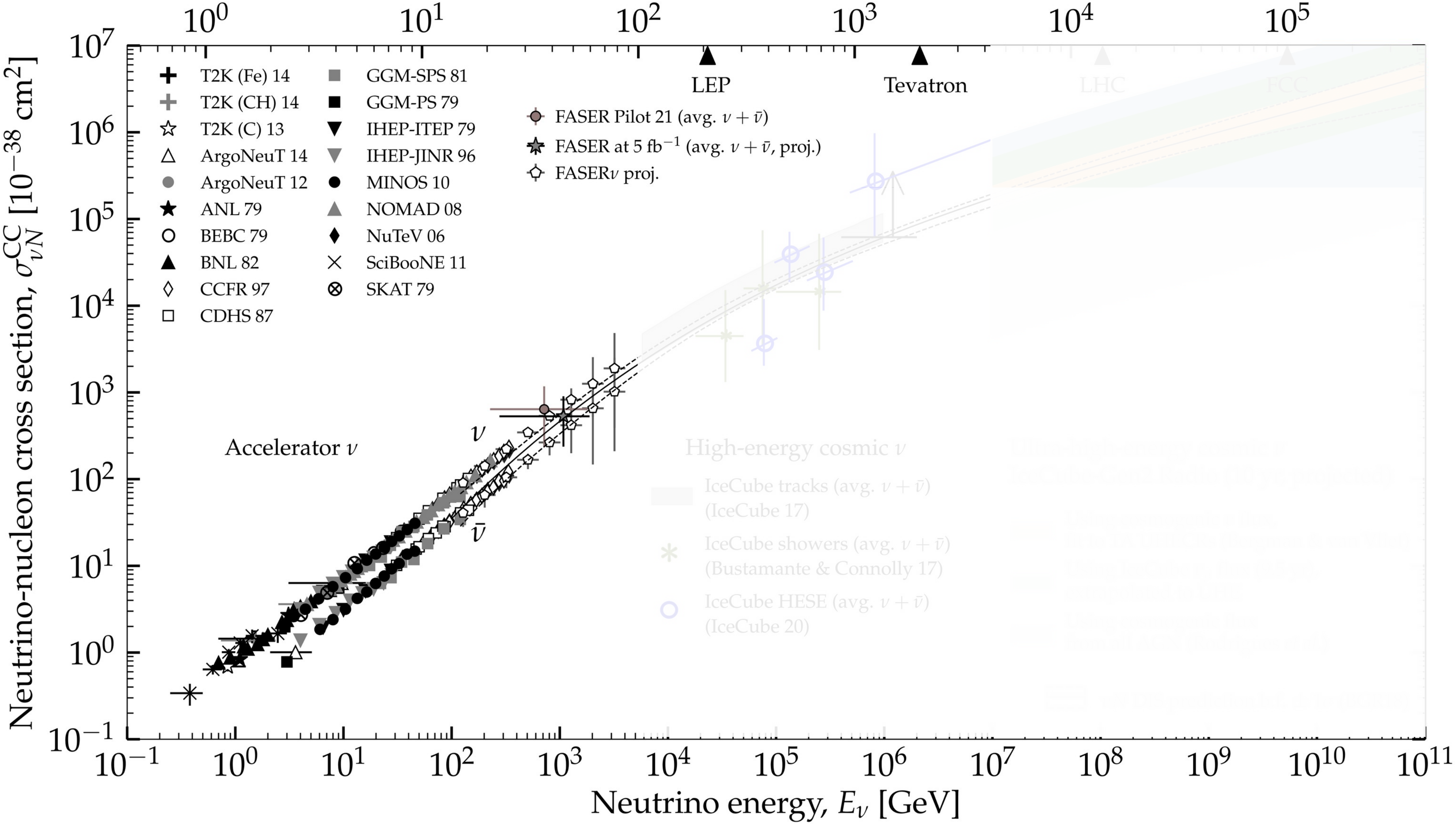
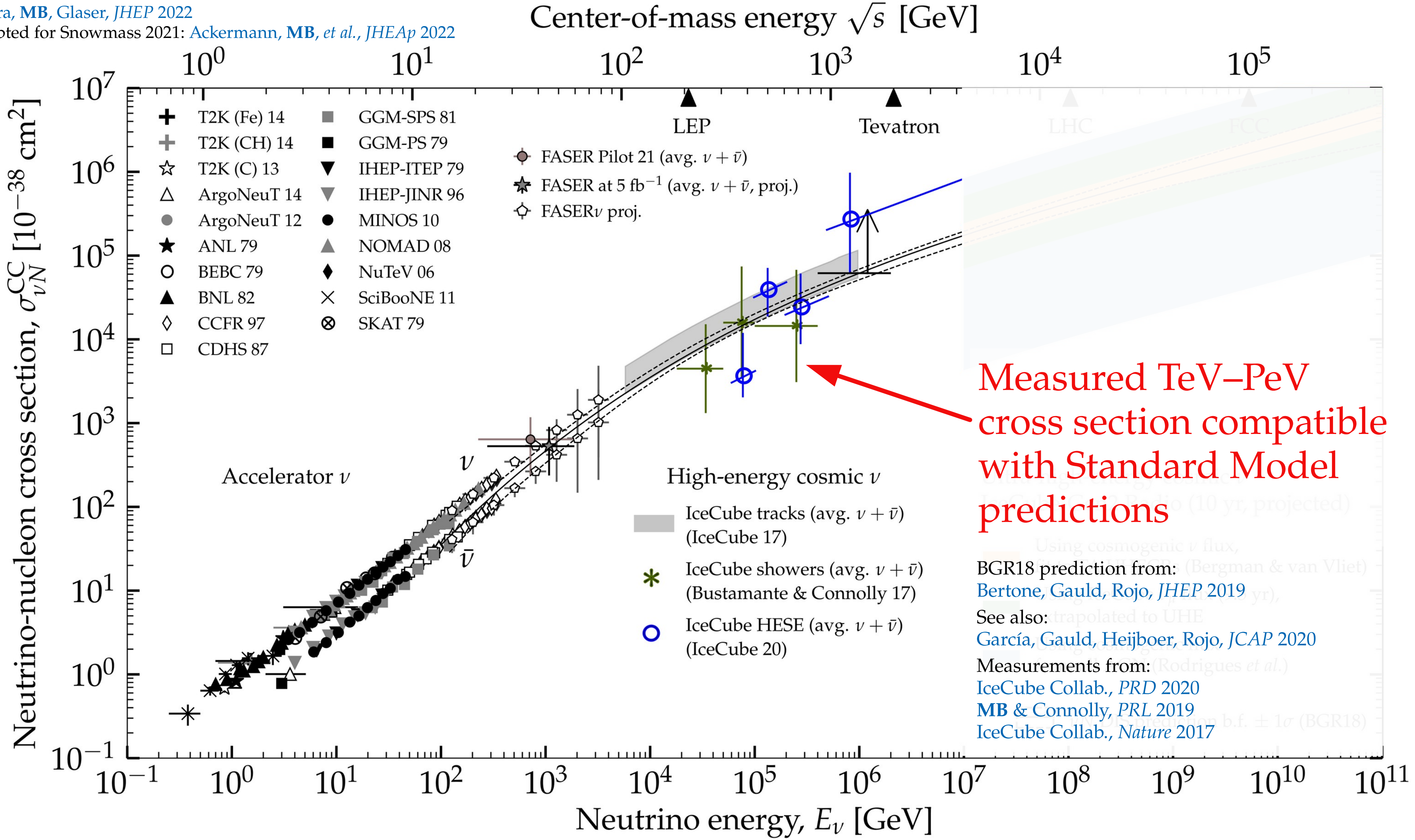
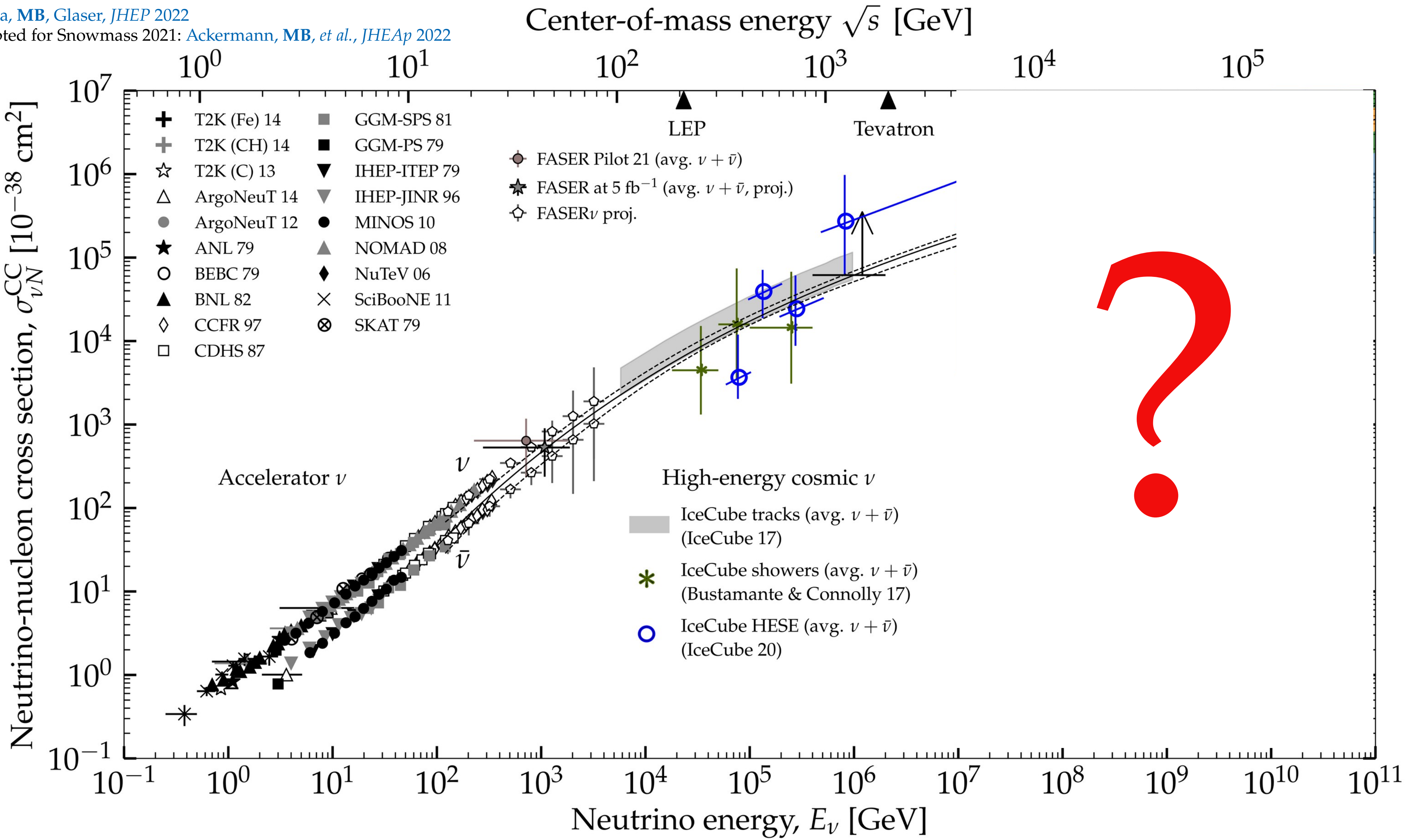


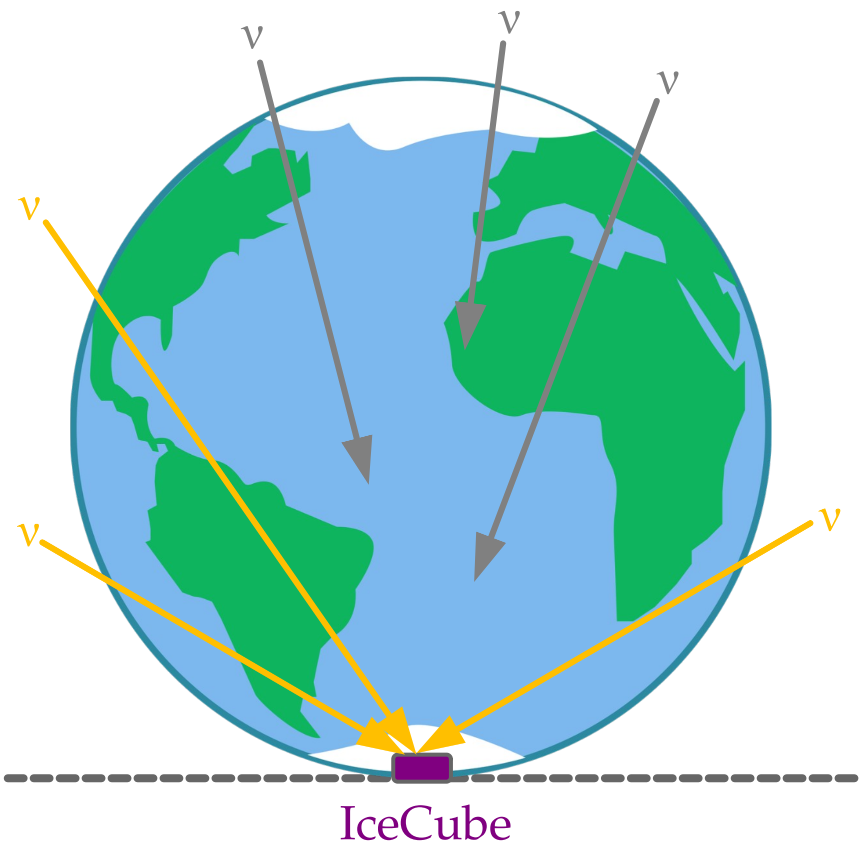
Valera, **MB**, Glaser, *JHEP* 2022
Adapted for Snowmass 2021: Ackermann, **MB**, *et al.*, *JHEAp* 2022



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

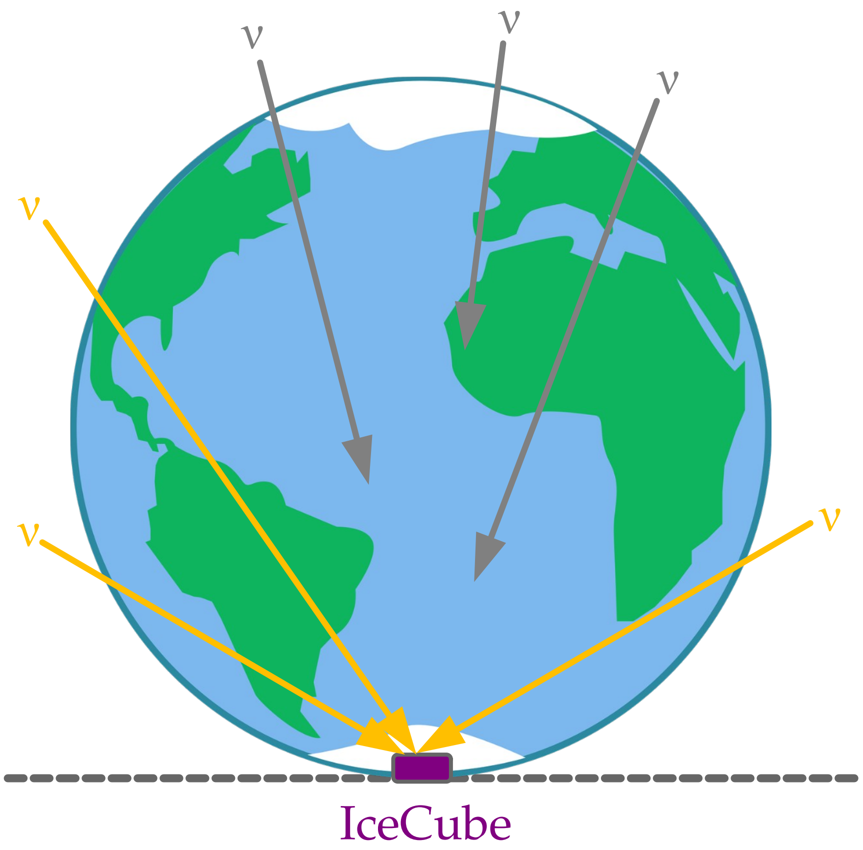


TeV–PeV:



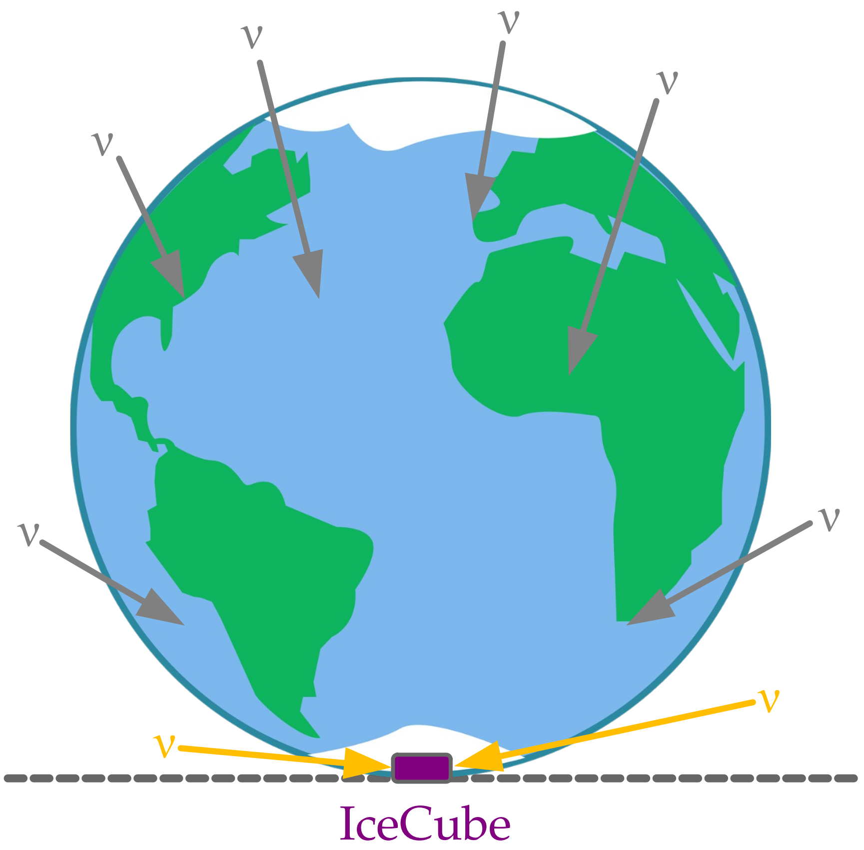
Earth is *almost fully* opaque,
some upgoing ν still make it through

TeV–PeV:

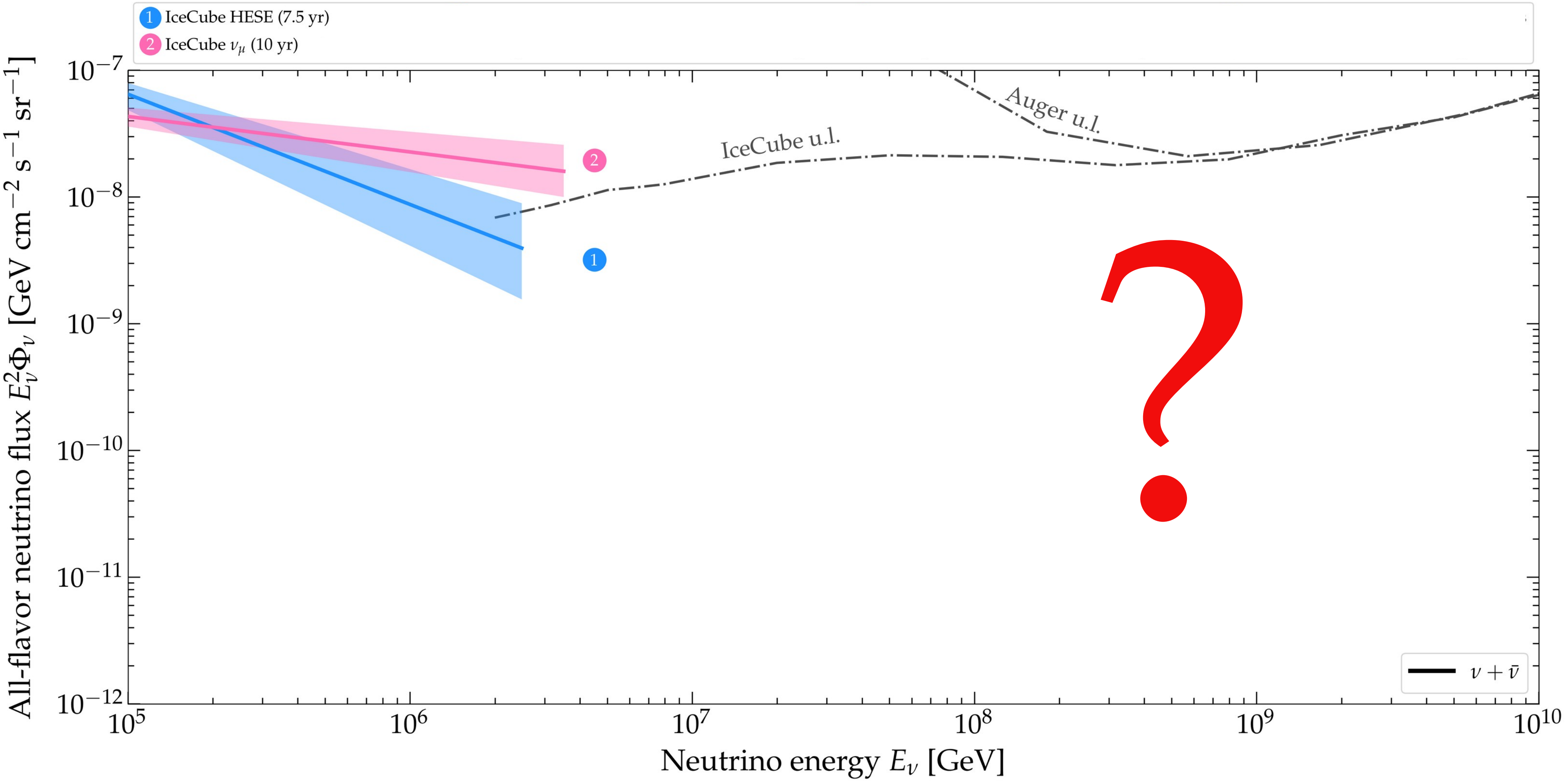


Earth is *almost fully* opaque,
some upgoing ν still make it through

> 100 PeV:



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



1 IceCube HESE (7.5 yr)
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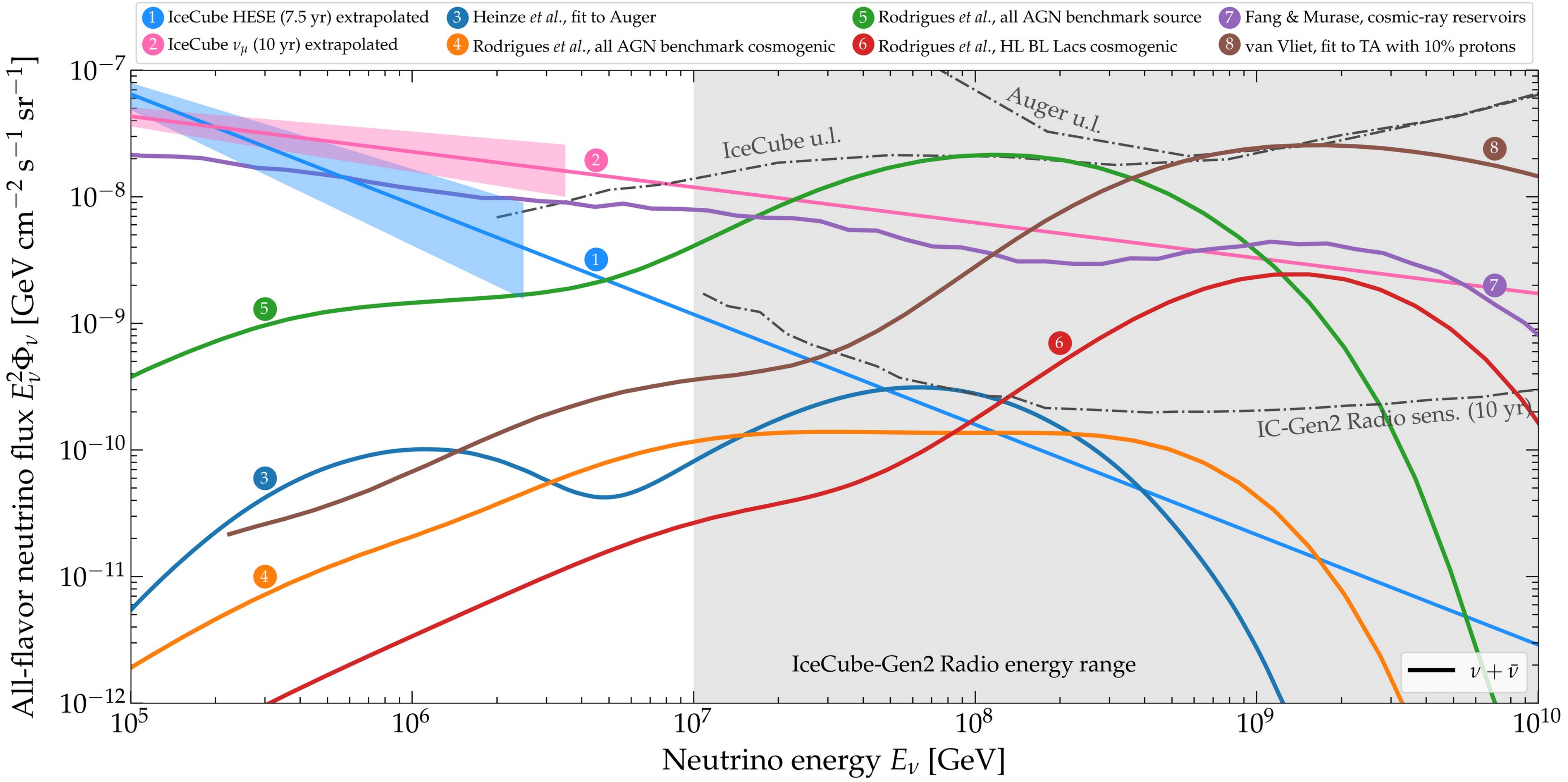
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy E_ν [GeV]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^5
10^6
10^7
10^8
10^9
10^{10}
Auger u.l.
IceCube u.l.
2
1
?
$\nu + \bar{\nu}$



1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (10 yr) extrapolated
3 Heinze et al., fit to Auger
4 Rodrigues et al., all AGN benchmark cosmogenic
5 Rodrigues et al., all AGN benchmark source
6 Rodrigues et al., HL BL Lacs cosmogenic
7 Fang & Murase, cosmic-ray reservoirs
8 van Vliet, fit to TA with 10% protons
Auger u.l.
IceCube u.l.
IC-Gen2 Radio sens. (10 yr)
IceCube-Gen2 Radio energy range
$\nu + \bar{\nu}$
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy E_ν [GeV]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
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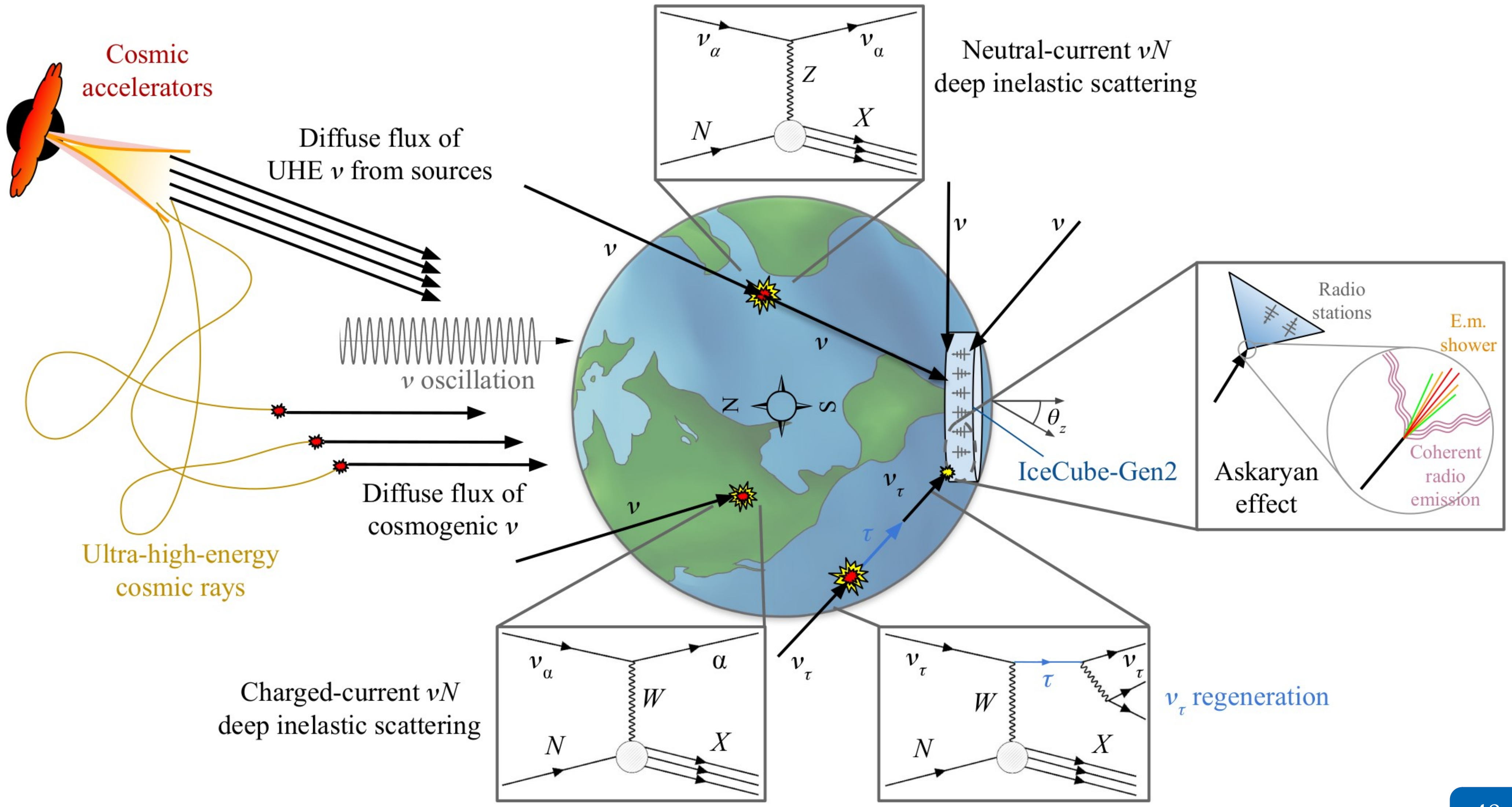
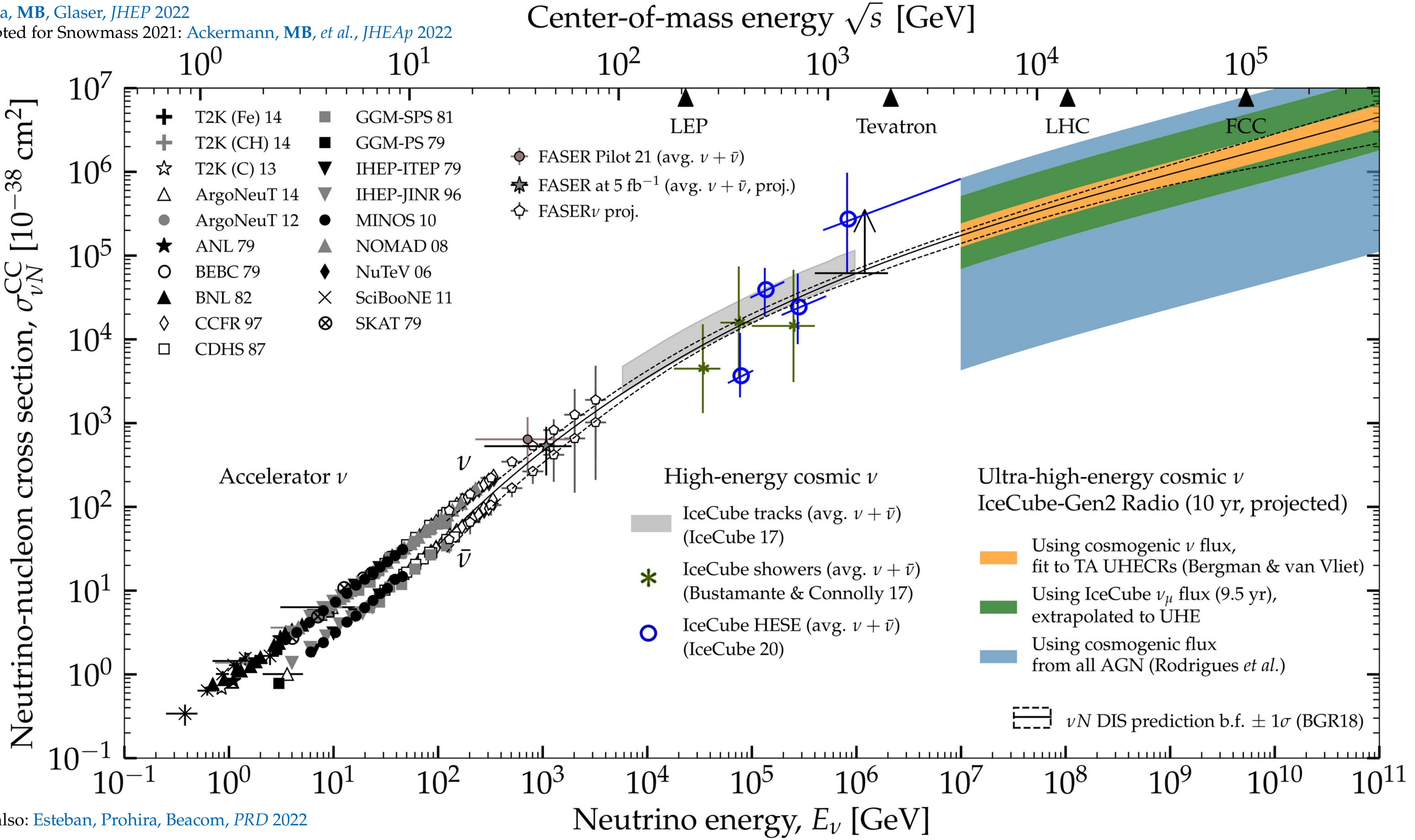
10^5
10^6
10^7
10^8
10^9
10^{10}



Cosmic accelerators
Diffuse flux of UHE ν from sources
ν oscillation
Ultra-high-energy cosmic rays
Diffuse flux of cosmogenic ν
Neutral-current νN deep inelastic scattering
Z
N
X
Charged-current νN deep inelastic scattering
W
α
τ
ν_τ regeneration
IceCube-Gen2
θ_z
Radio stations
E.m. shower
Askaryan effect
Coherent radio emission

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



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

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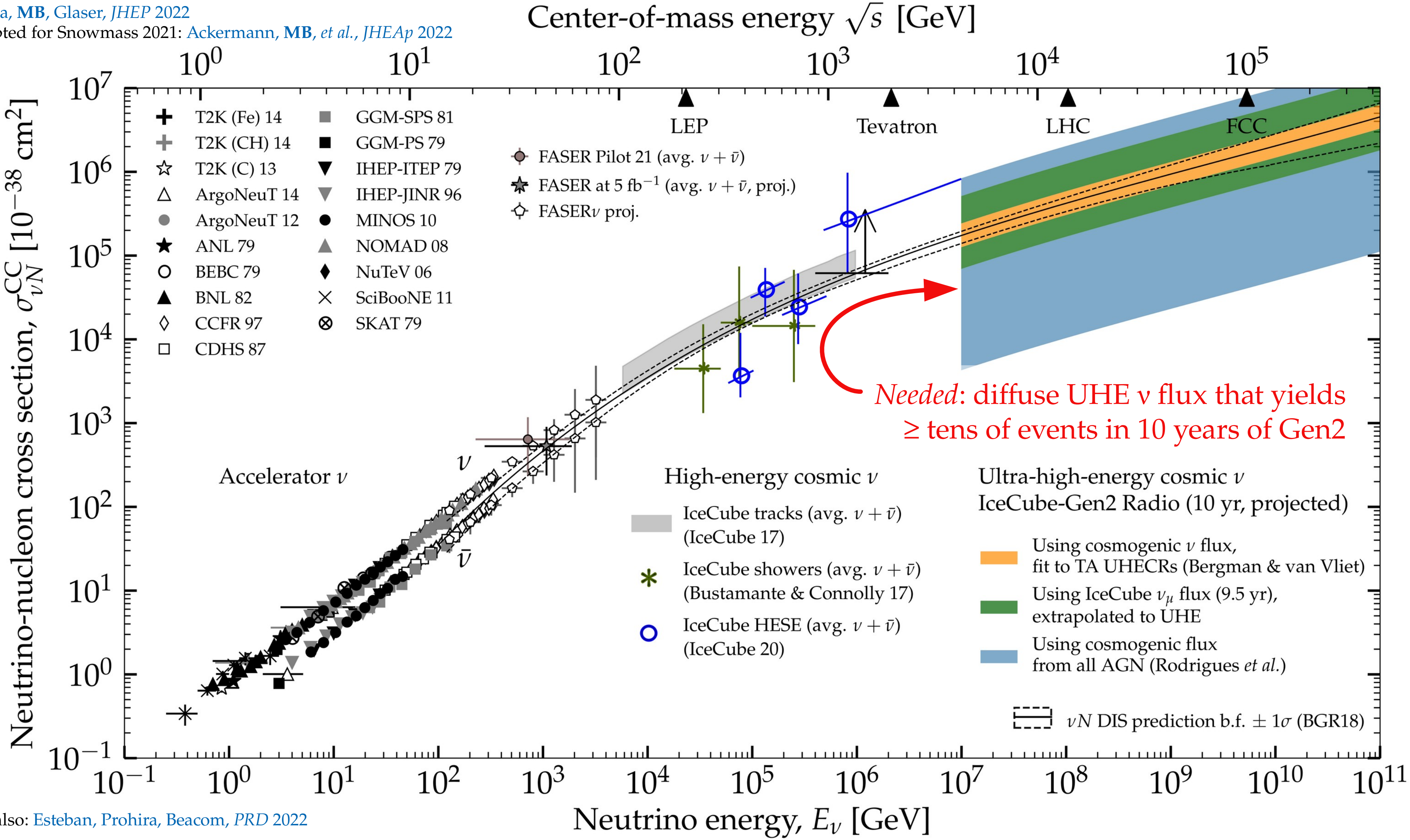

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Valera, **MB**, Glaser, *JHEP* 2022
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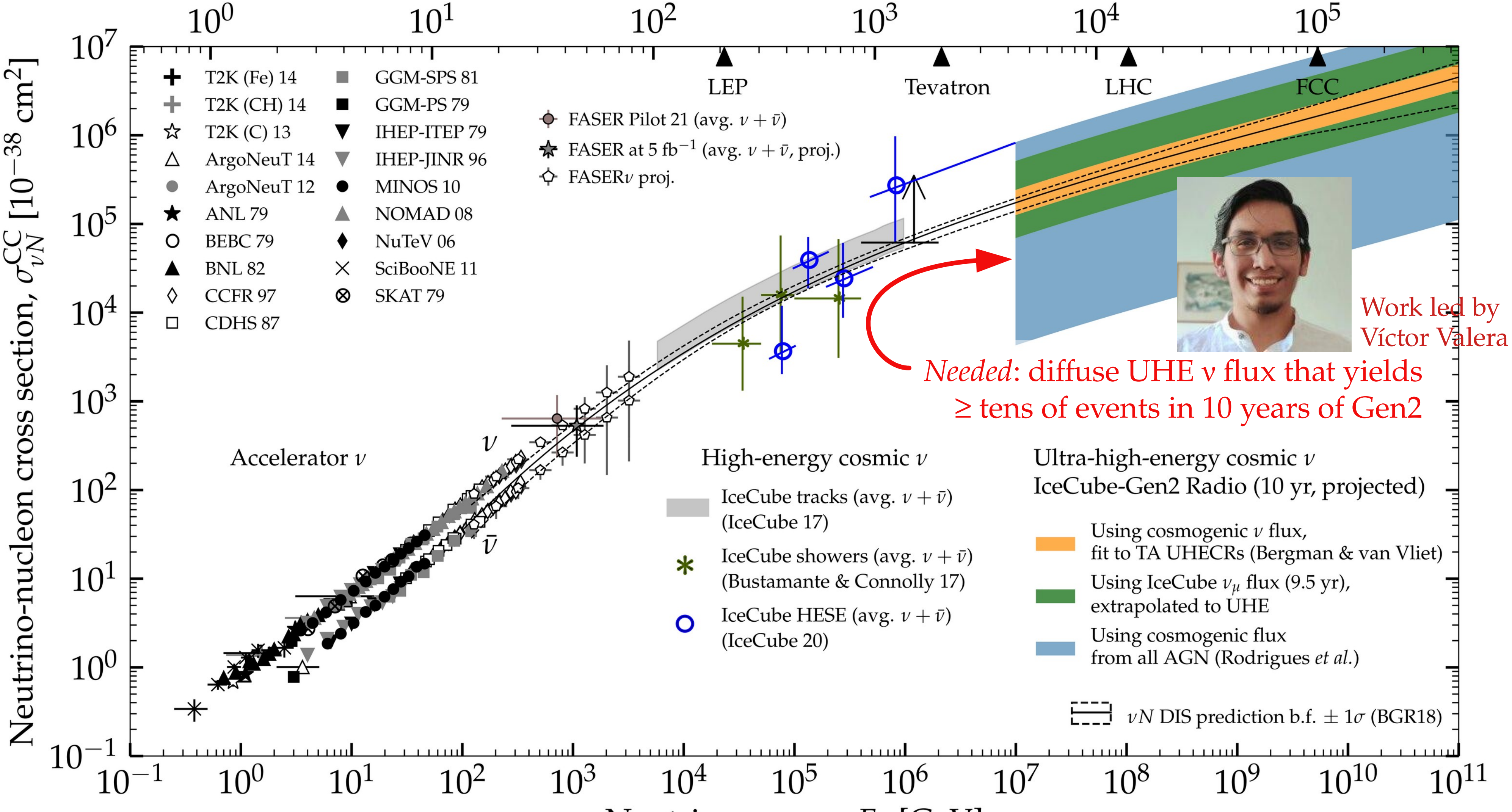
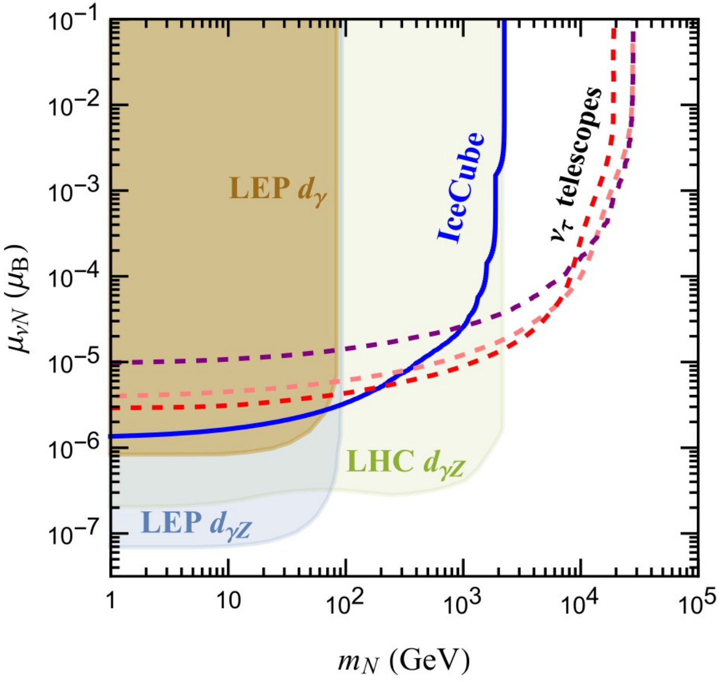


See also: Esteban, Prohira, Beacom, *PRD* 2022

New physics in UHE neutrinos

New physics in UHE neutrinos

Heavy sterile neutrinos
via the dipole portal



Huang, Jana, Lindner, Rodejohann, 2204.10347

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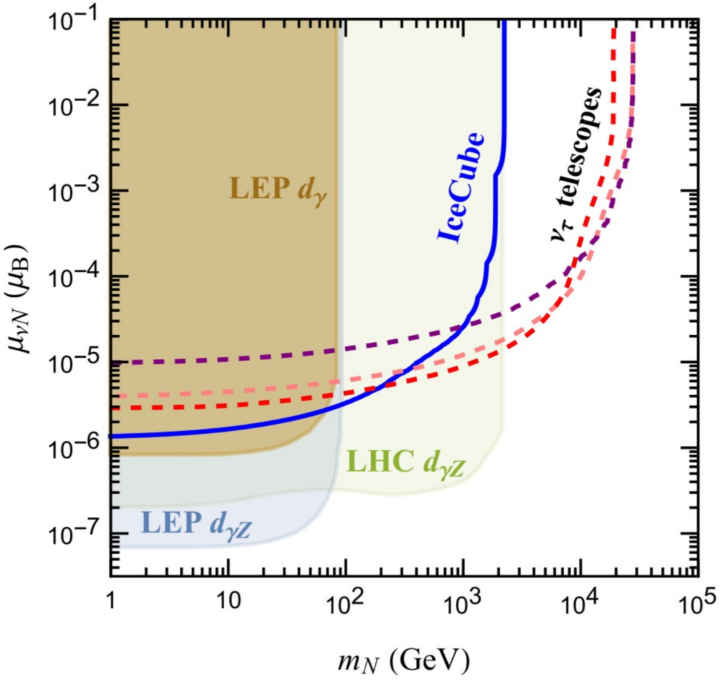
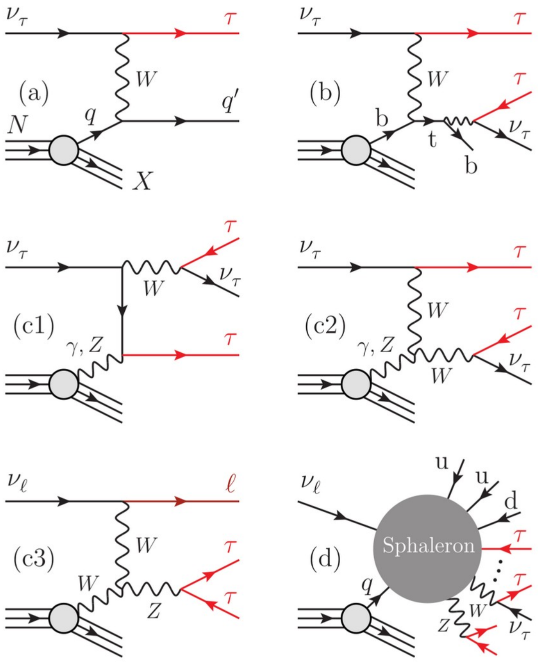


Huang, Jana, Lindner, Rodejohann, 2204.10347

Multiple ν_τ-induced
bangs



Huang, *EPJC* 2022 [2207.02222]

New physics in UHE neutrinos

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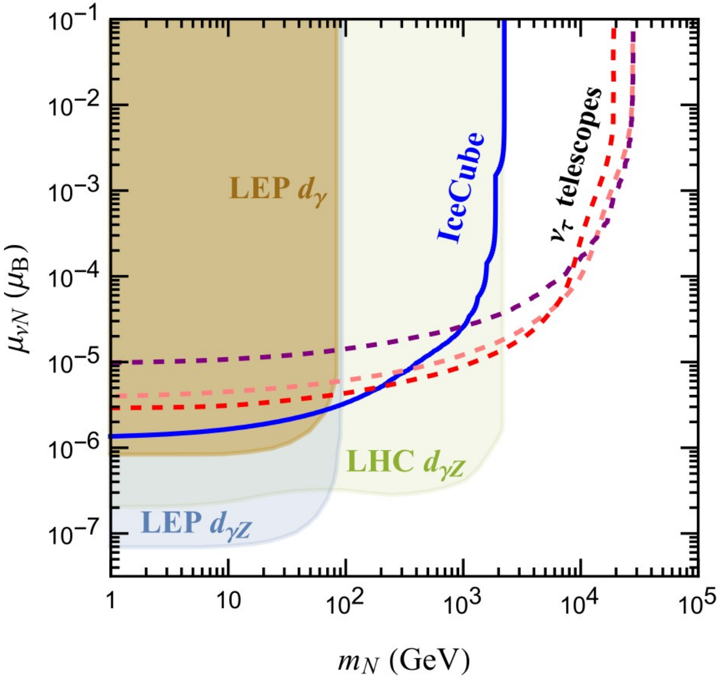
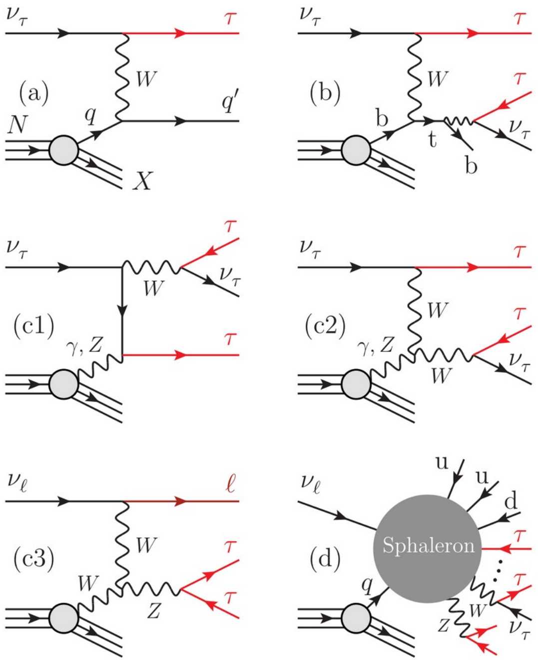


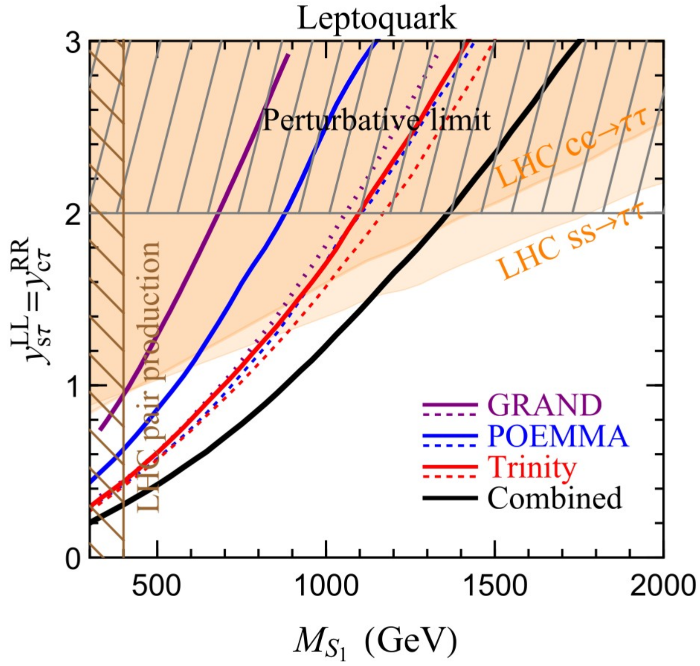
Huang, Jana, Lindner, Rodejohann, 2204.10347

Multiple ν_τ-induced bangs



Huang, *EPJC* 2022 [2207.02222]

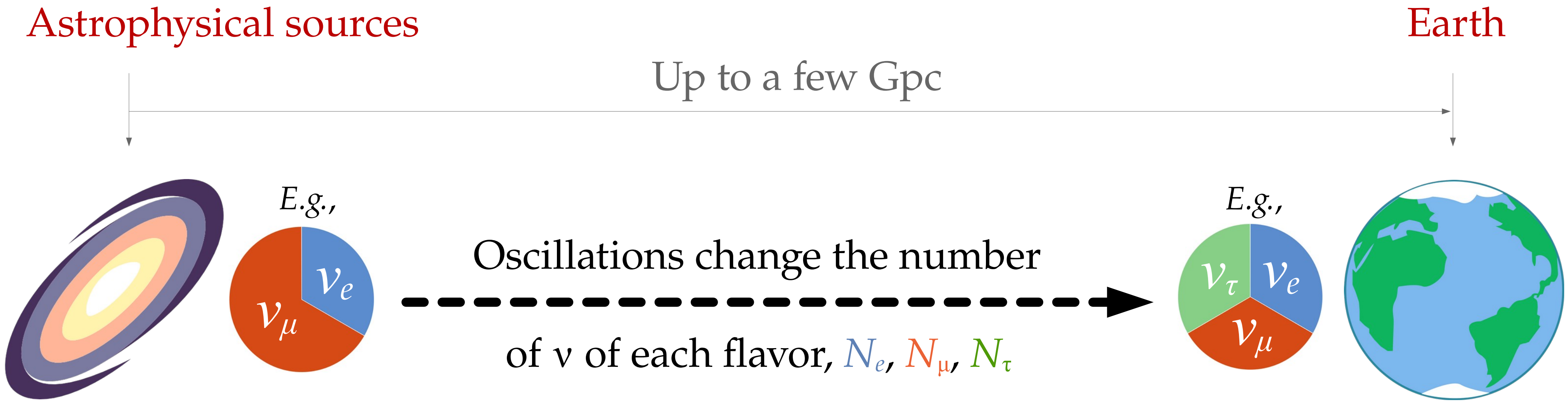
New physics affecting the neutrino cross section



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

3. Flavor:
Towards precision, finally

(with the help of lower-energy experiments)

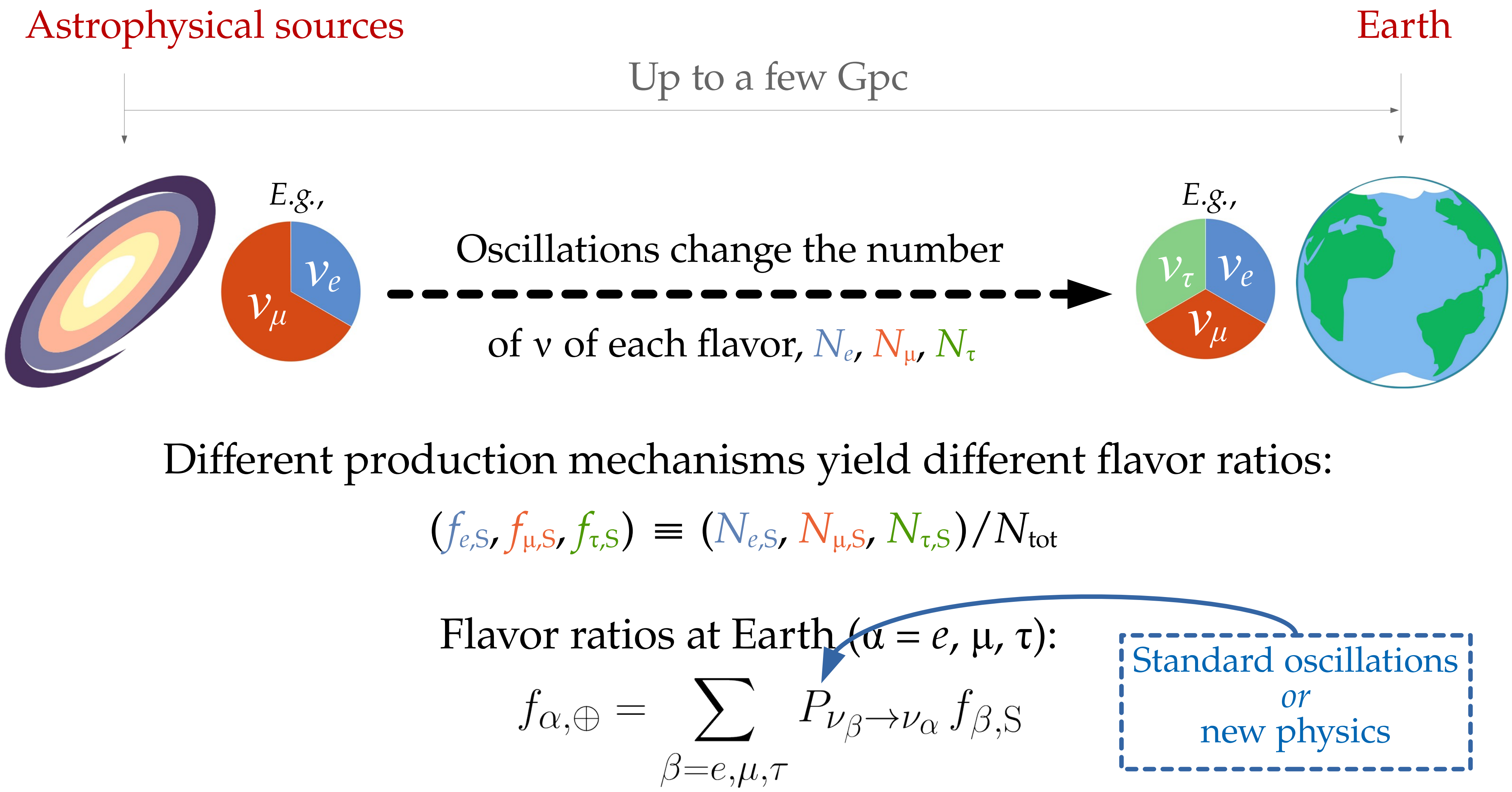


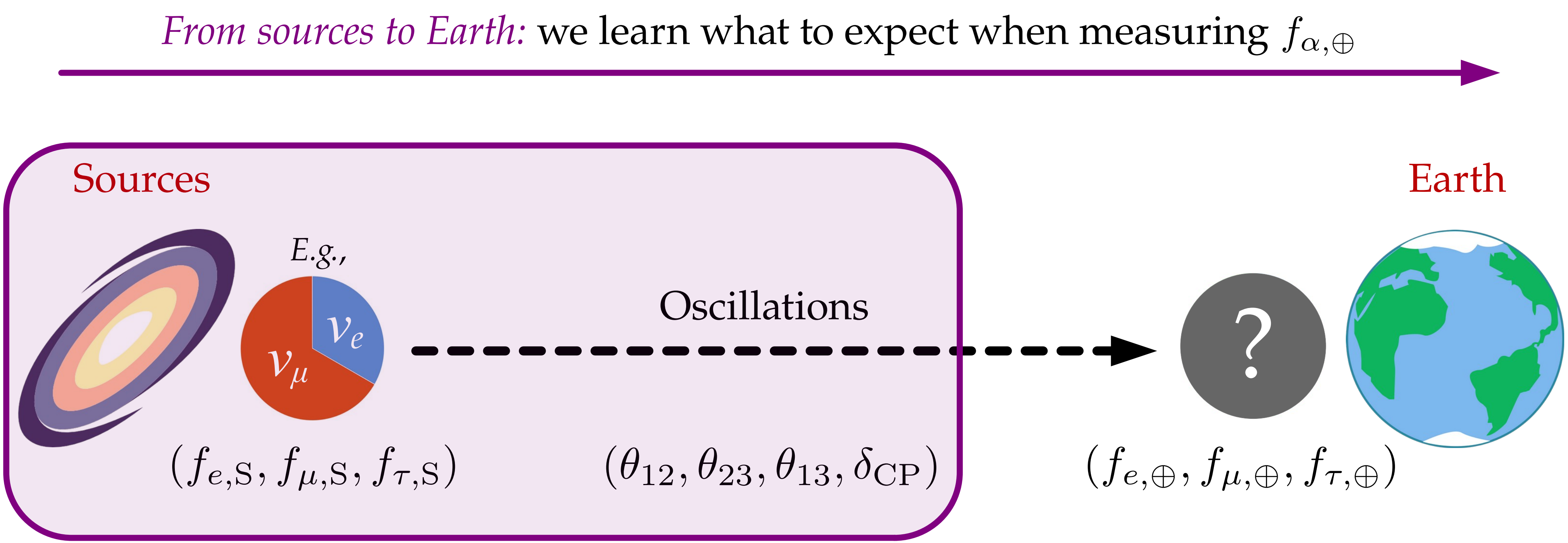
Different production mechanisms yield different flavor ratios:

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

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

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


Astrophysical sources
Earth
Up to a few Gpc
E.g.,
ν_e
ν_μ
Oscillations change the number
of ν of each flavor, N_e, N_μ, N_τ
E.g.,
ν_τ
ν_e
ν_μ
Different production mechanisms yield different flavor ratios:
$(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}}) \equiv (N_{e,\mathrm{S}}, N_{\mu,\mathrm{S}}, N_{\tau,\mathrm{S}})/N_{\mathrm{tot}}$
Flavor ratios at Earth ($\alpha = e, \mu, \tau$):
$f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} P_{\nu_\beta\to\nu_\alpha} f_{\beta,\mathrm{S}}$
Standard oscillations
or
new physics



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

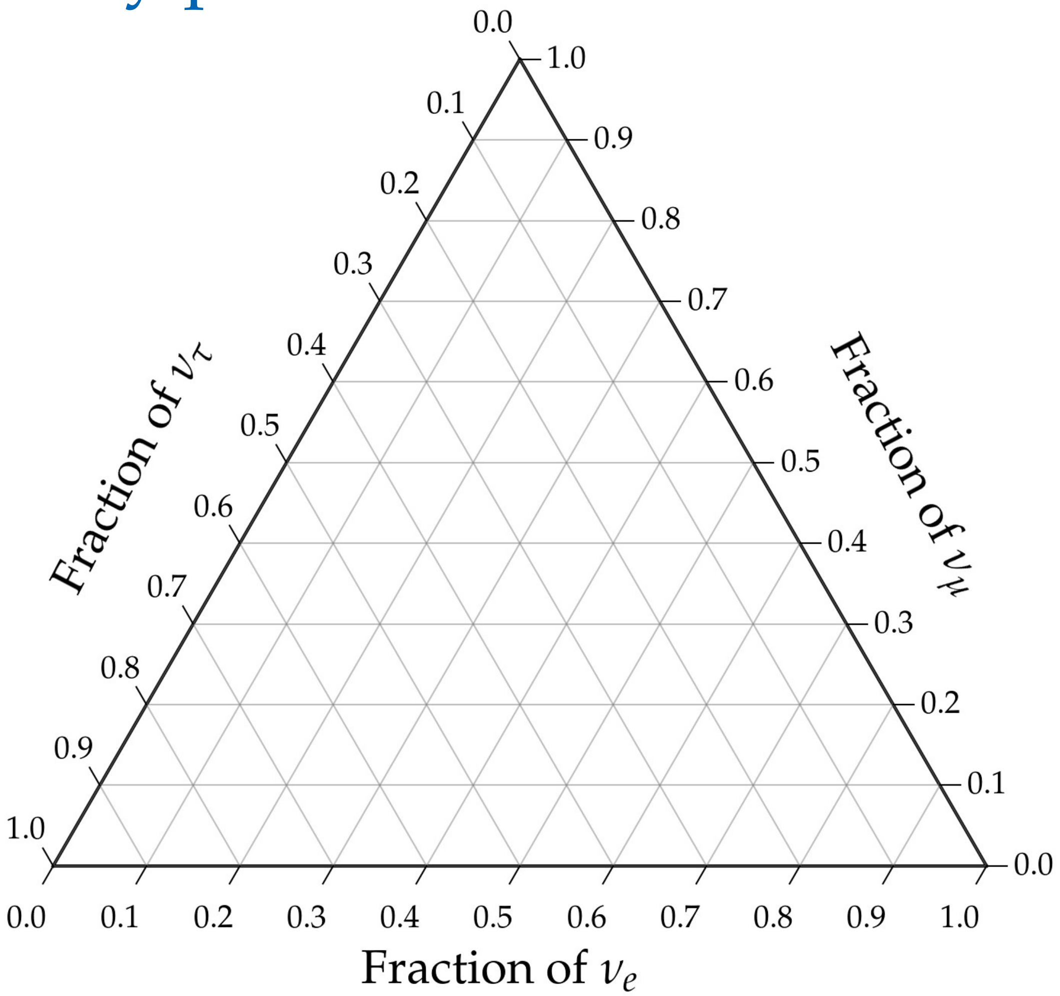
Quick aside: how to read a ternary plot

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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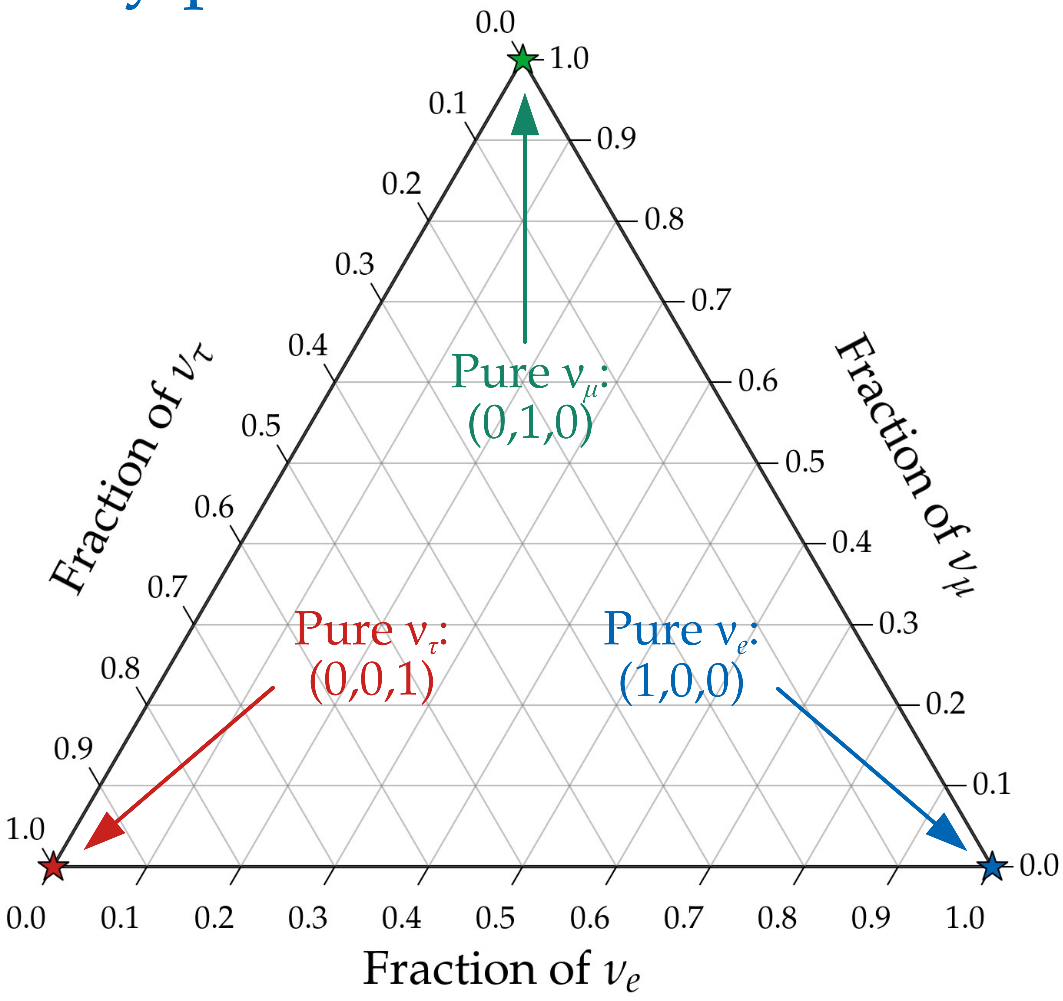

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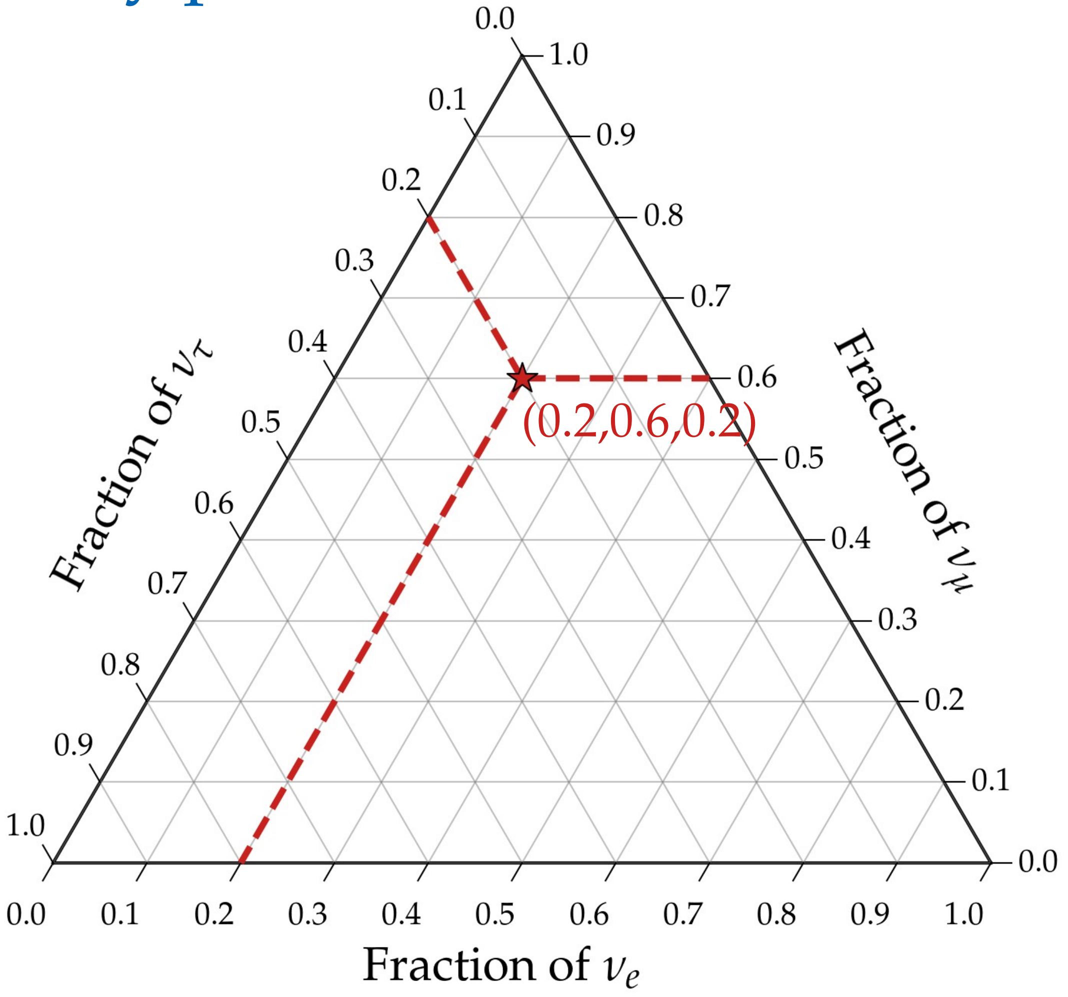

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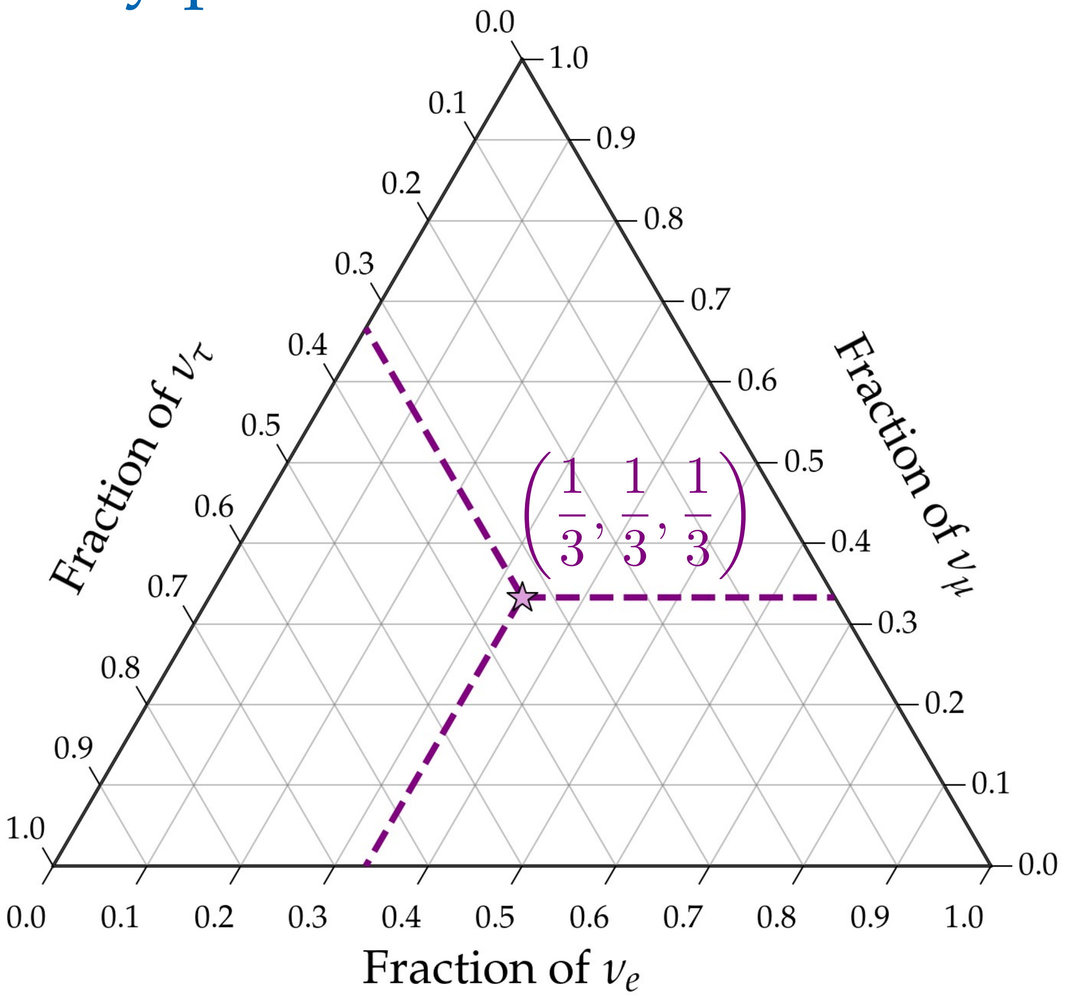

One likely TeV–PeV ν production scenario:

$p + \gamma \longrightarrow \pi^+ \rightarrow \mu^+ + \nu_\mu$ 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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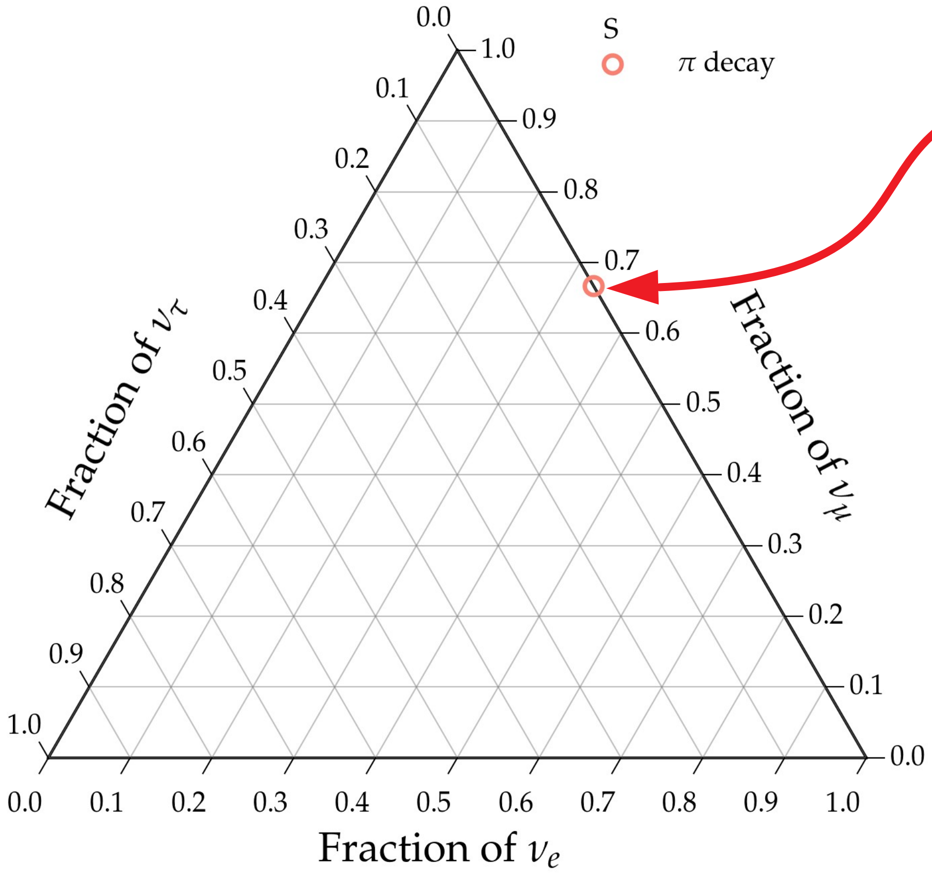

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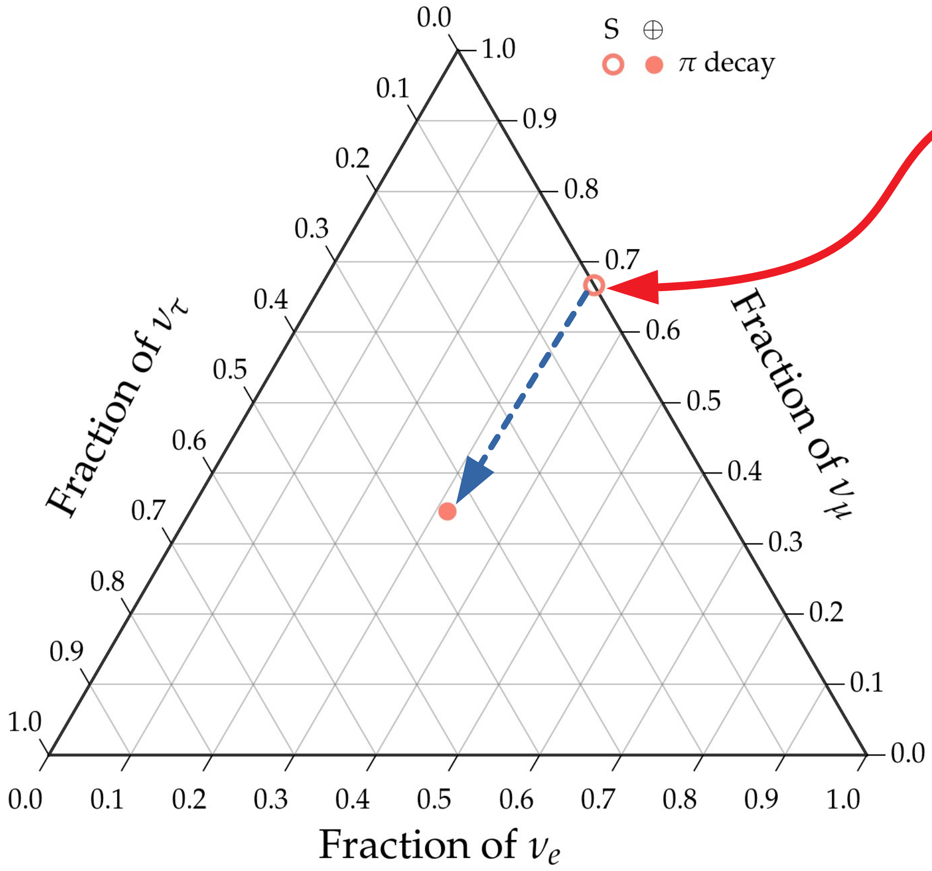

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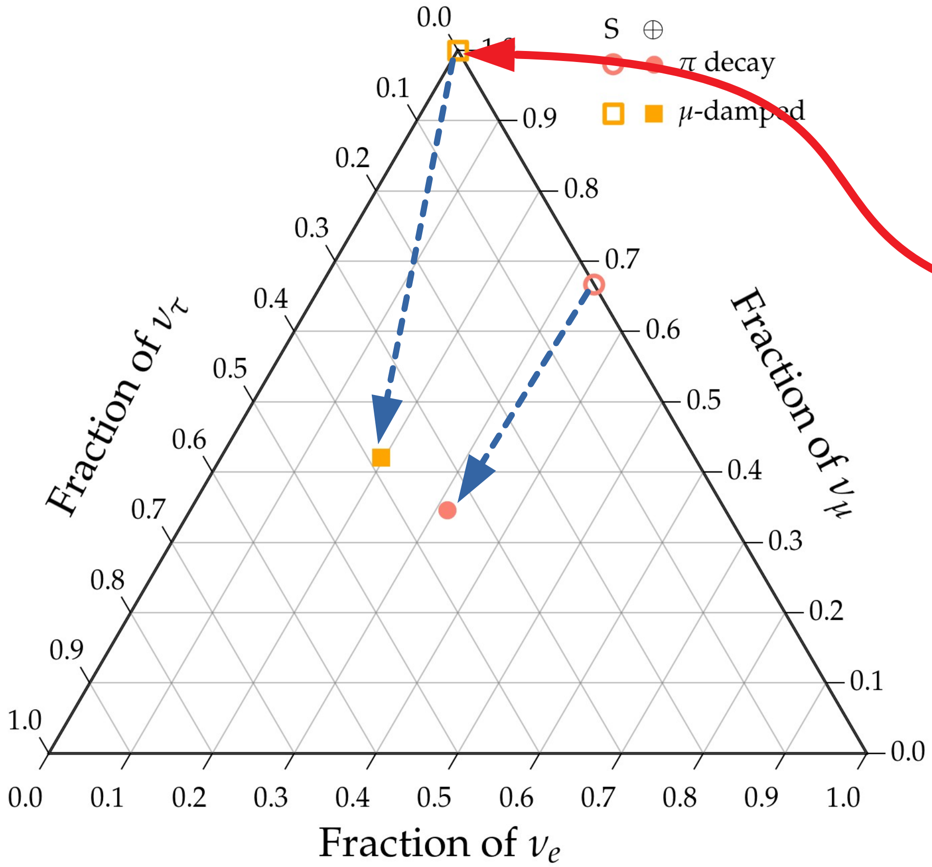

Full π decay chain

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

Muon damped

$(0:1:0)_S$

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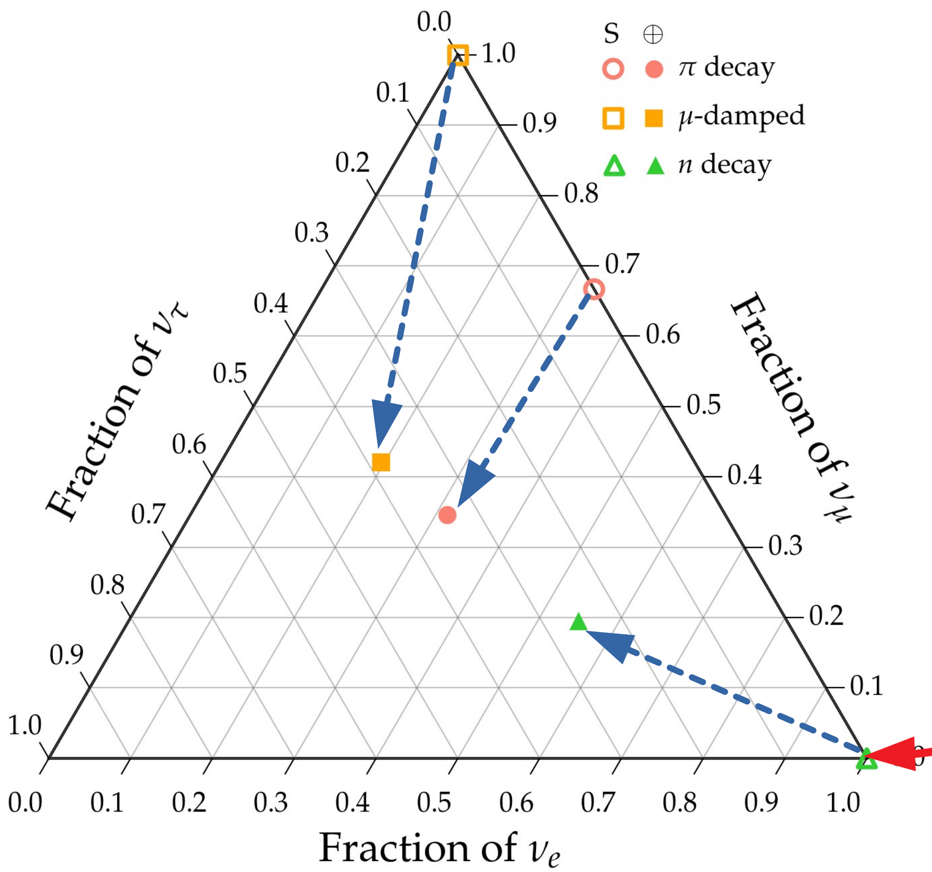


Full π decay chain

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

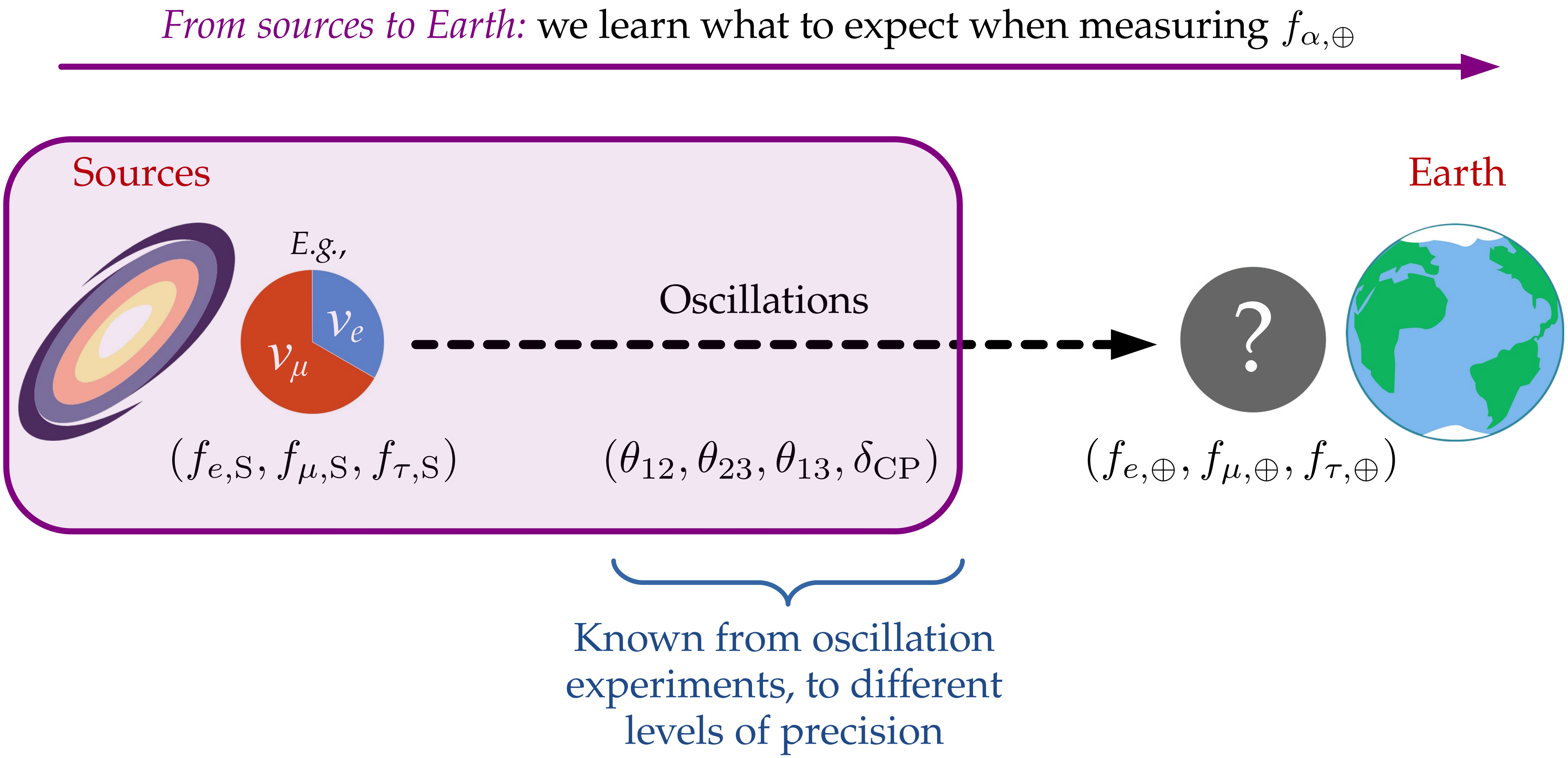
Muon damped

$(0:1:0)_S$

Neutron decay

$(1:0:0)_S$

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


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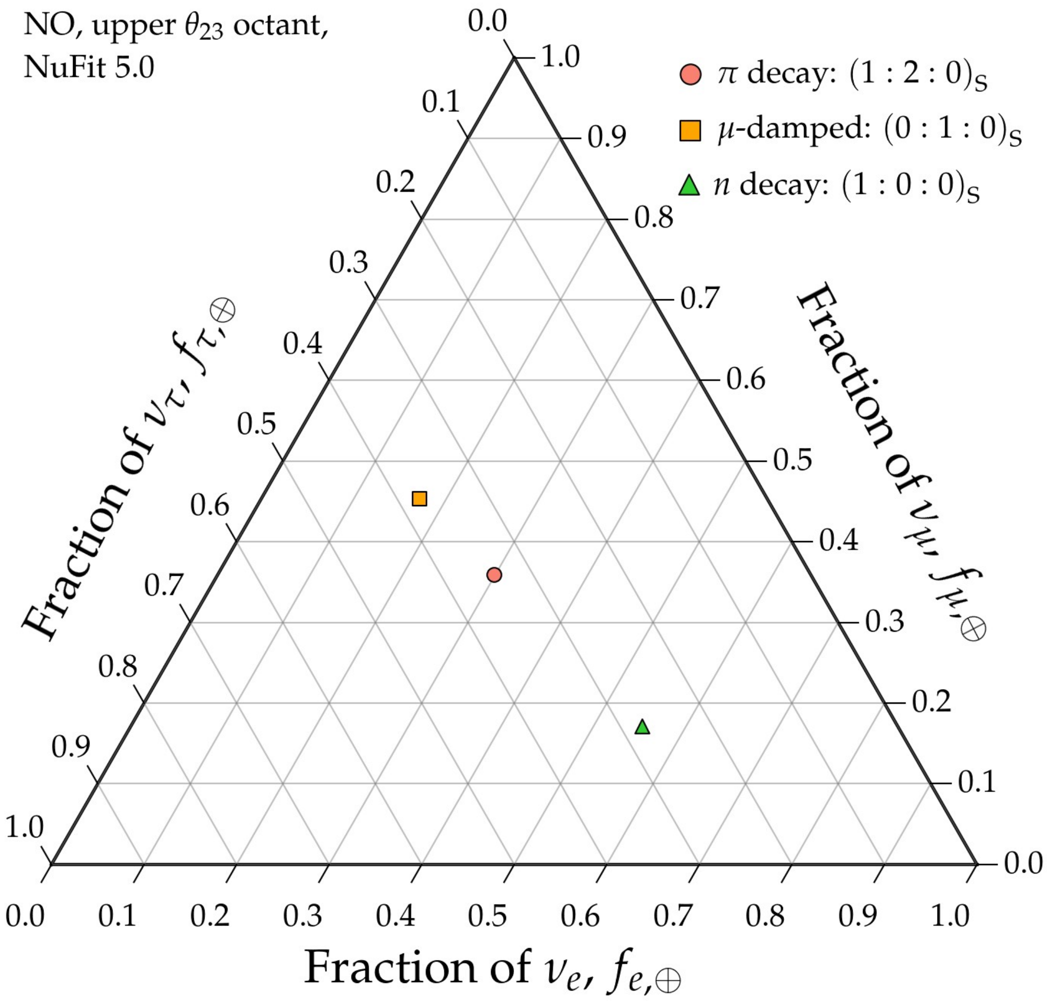
Oscillations
?
Earth
$(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}})$
$(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\mathrm{CP}})$
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$
Known from oscillation experiments, to different levels of precision

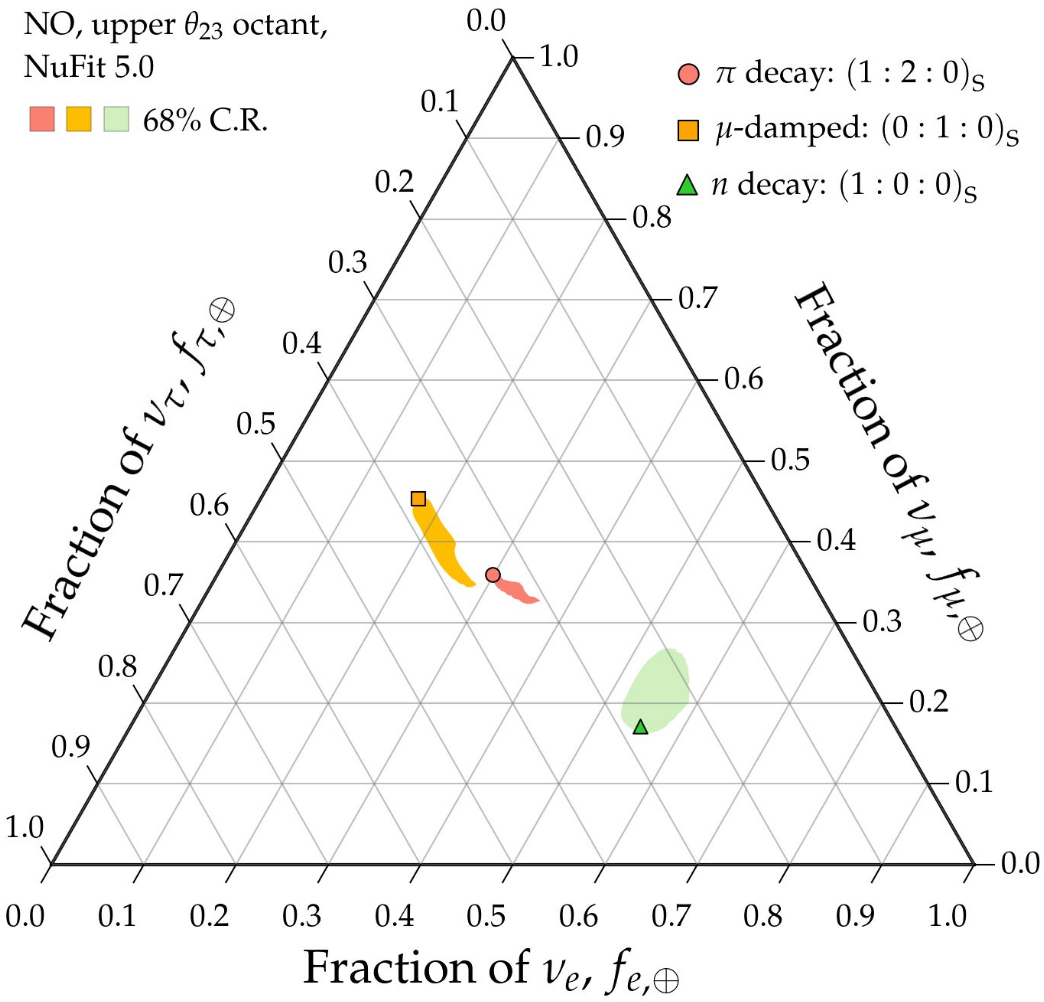
Theoretically palatable regions: today



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

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

Theoretically palatable regions: today



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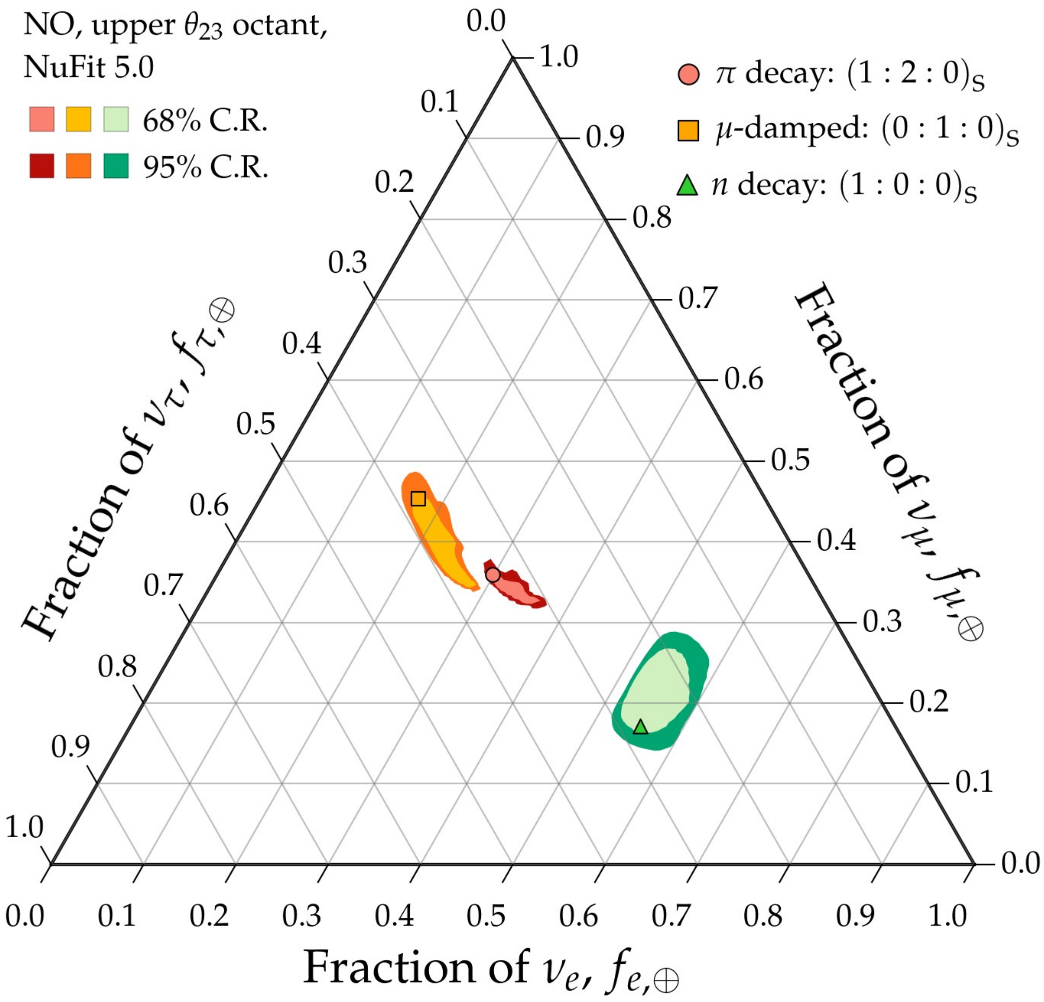

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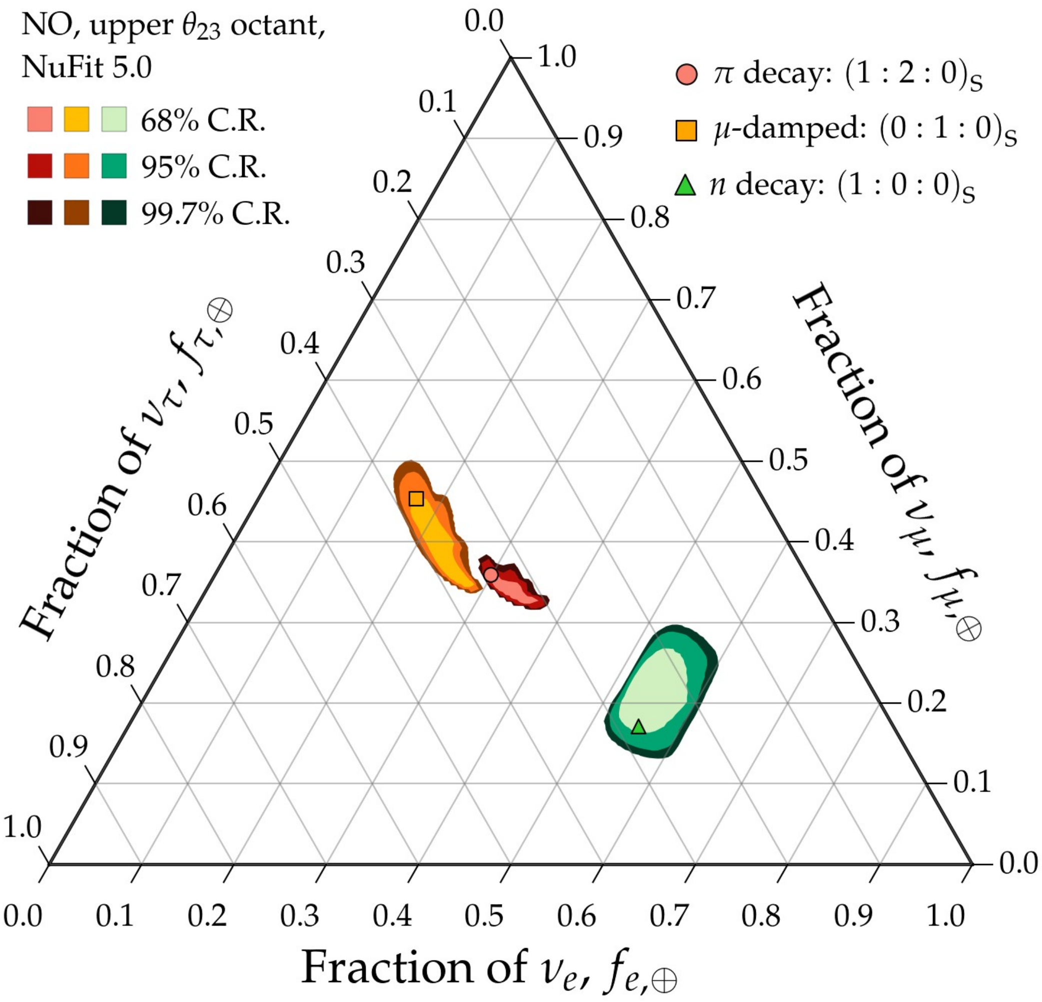

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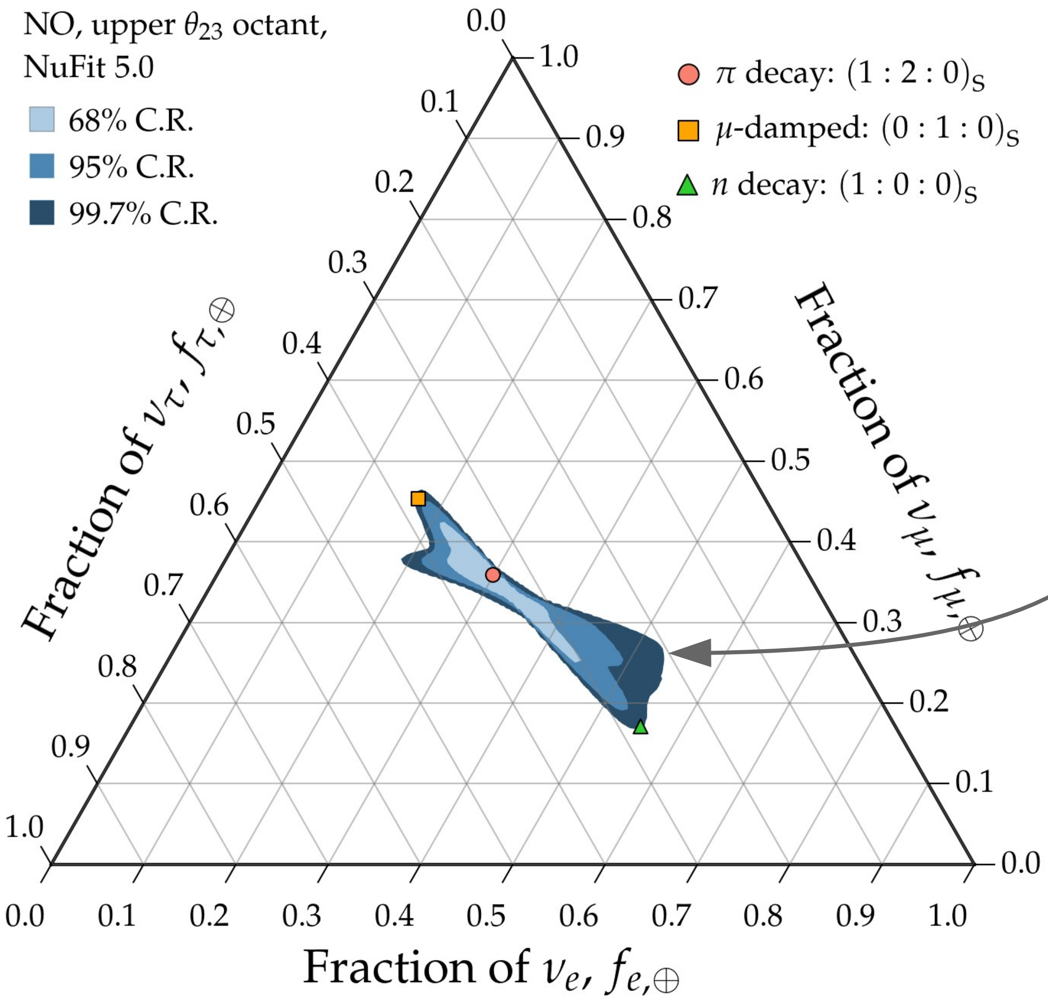

Varying over all possible flavor ratios at the source

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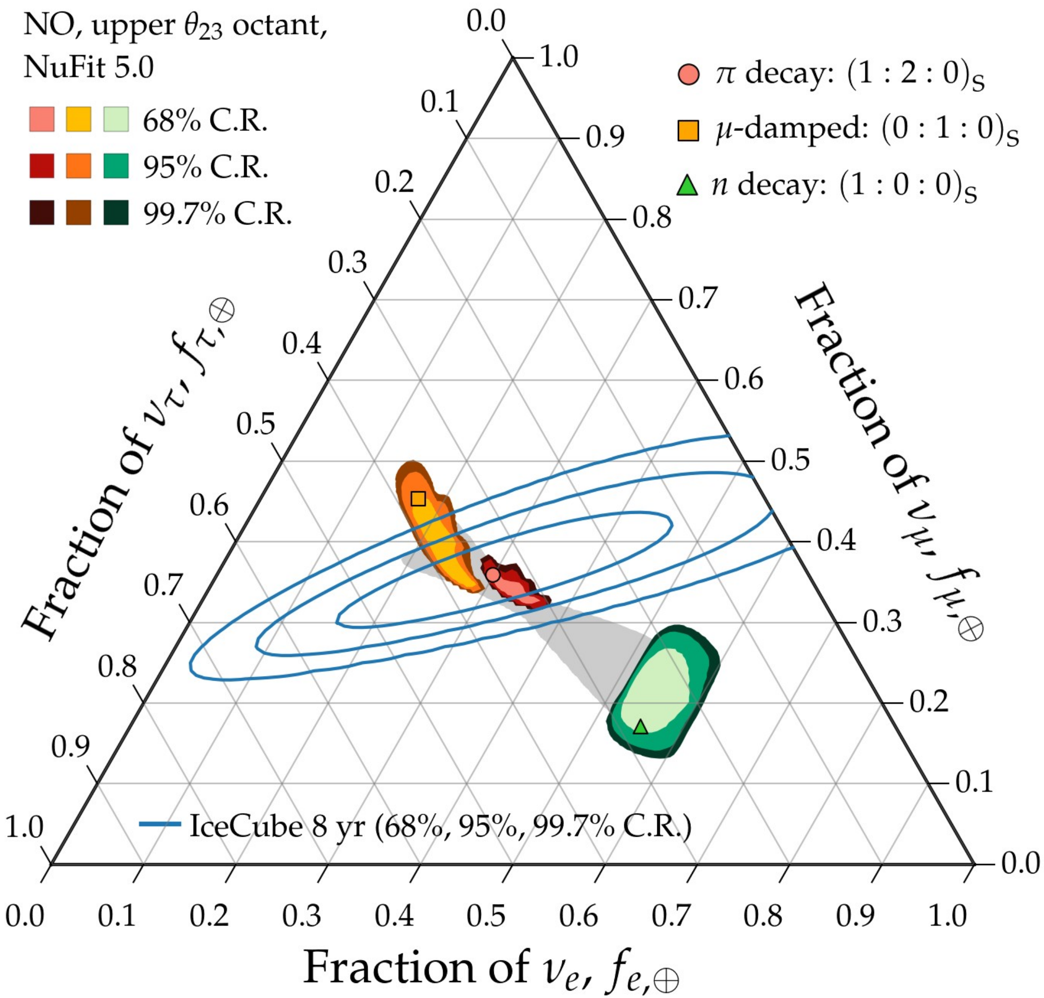
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Theoretically palatable regions: today



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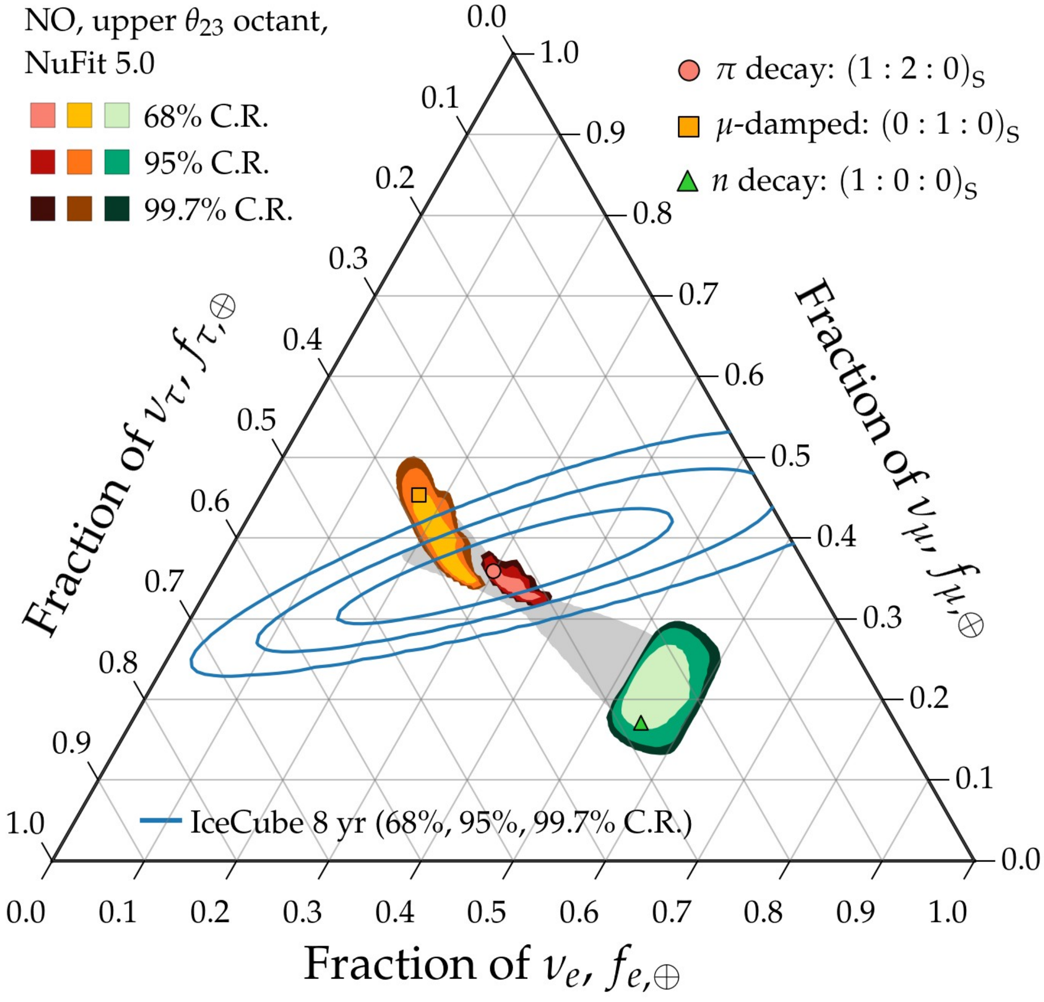
Theoretically palatable regions: today



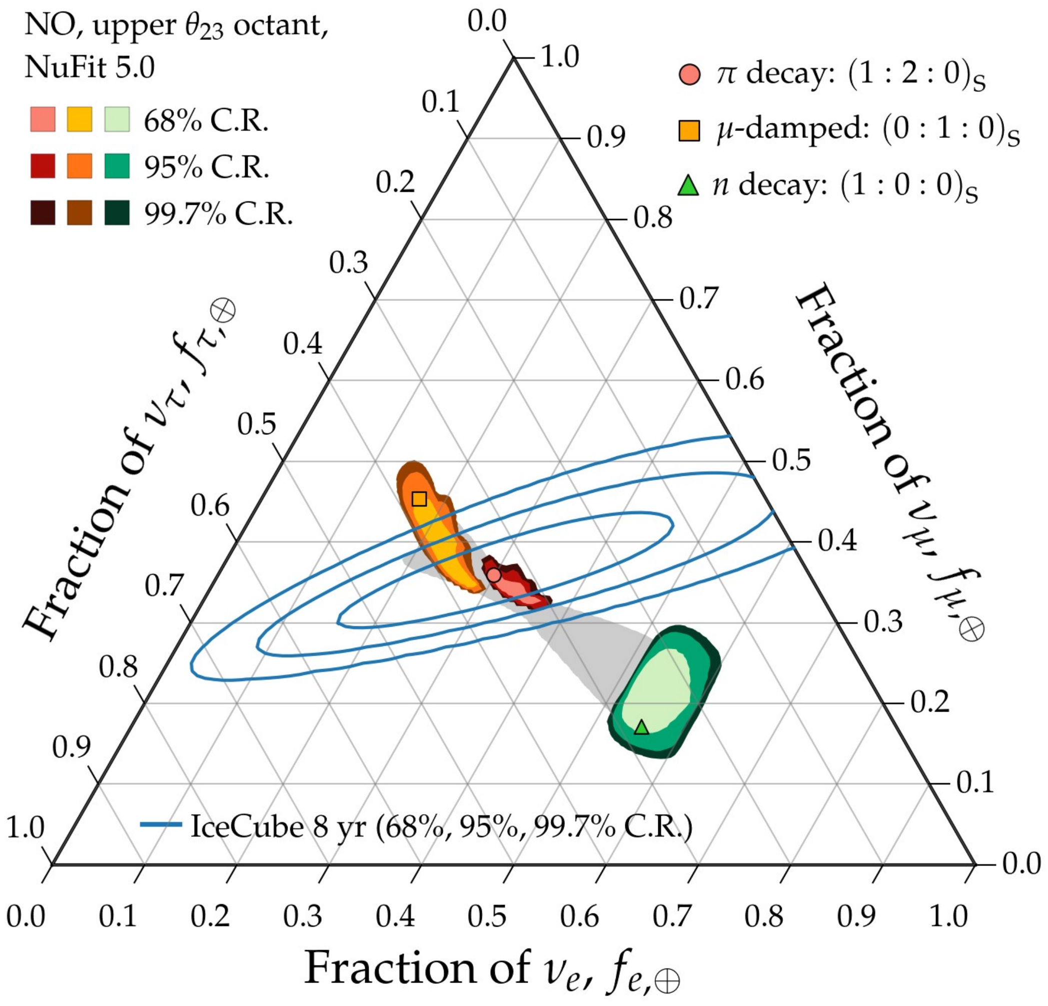
Two limitations:

Allowed flavor regions overlap – Insufficient precision in the mixing parameters

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

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

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)

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

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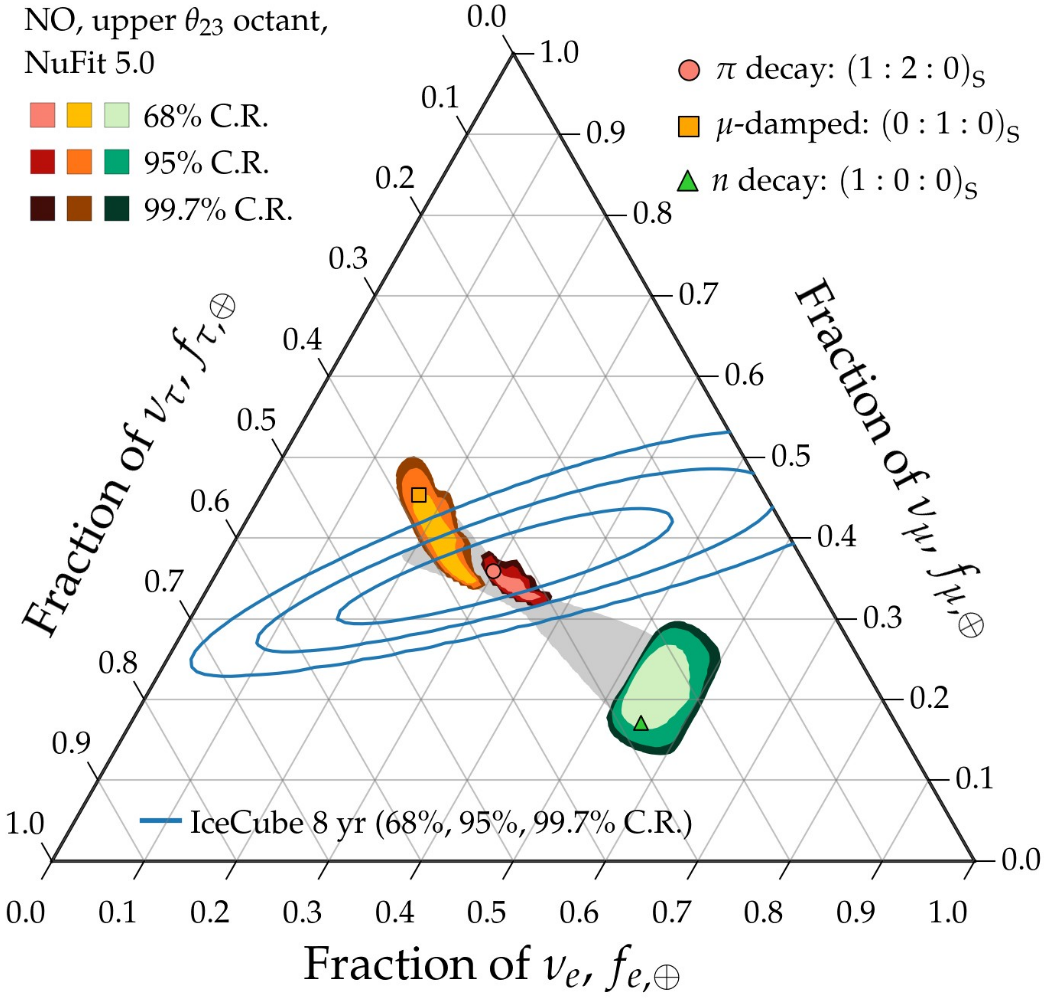

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Insufficient precision in the mixing parameters

Will be overcome by 2030

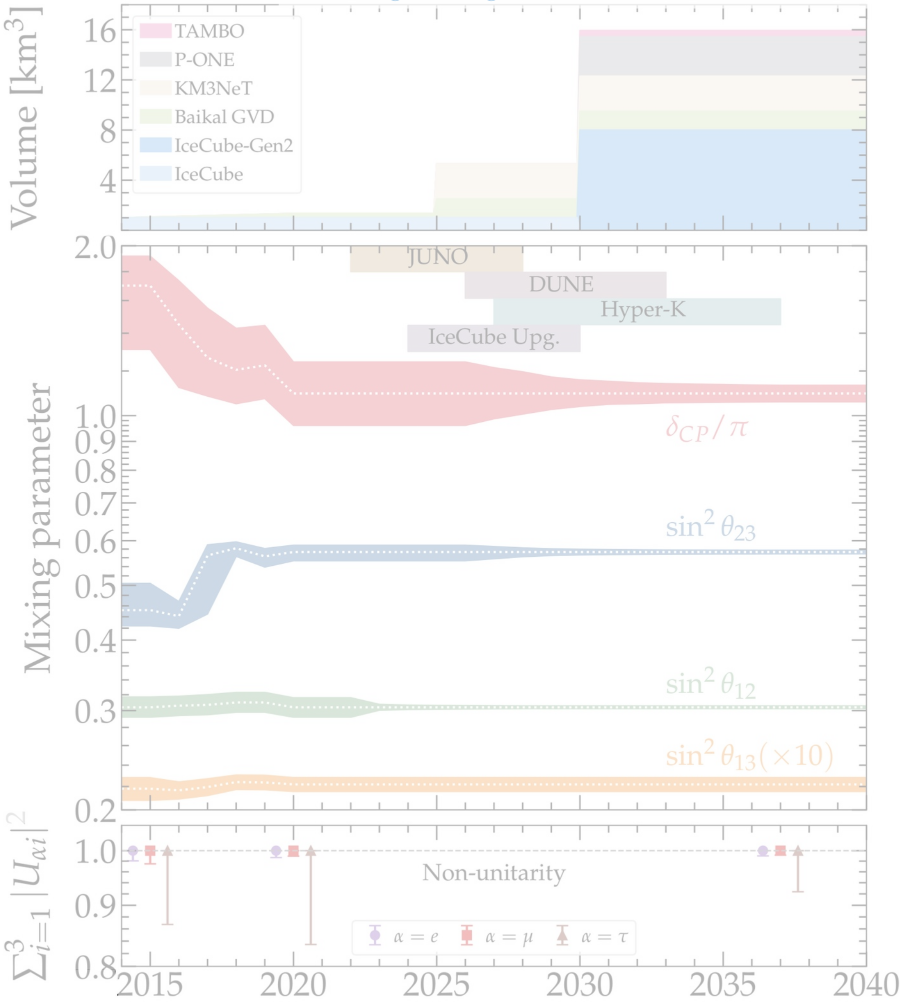
Measurement of flavor ratios –
Cannot distinguish between pion-decay and muon-damped benchmarks even at 68% C.R. (1σ)

Will be overcome by 2040

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

Three reasons to be excited

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



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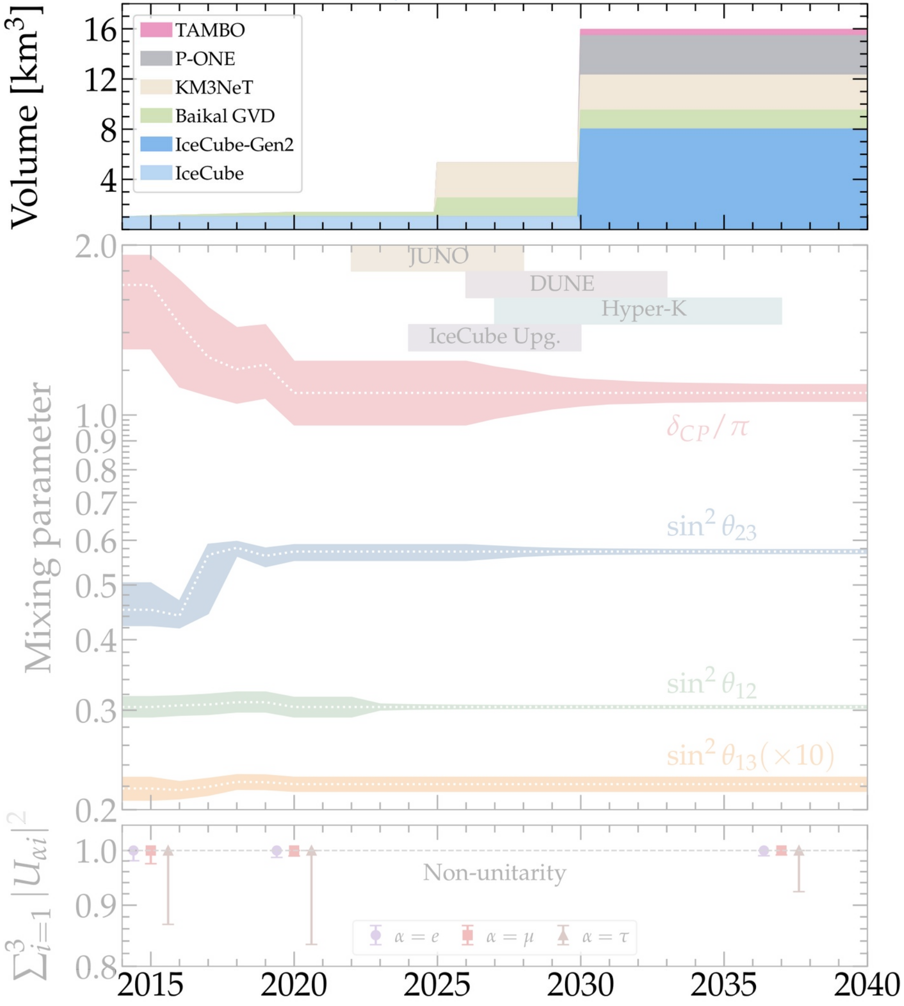
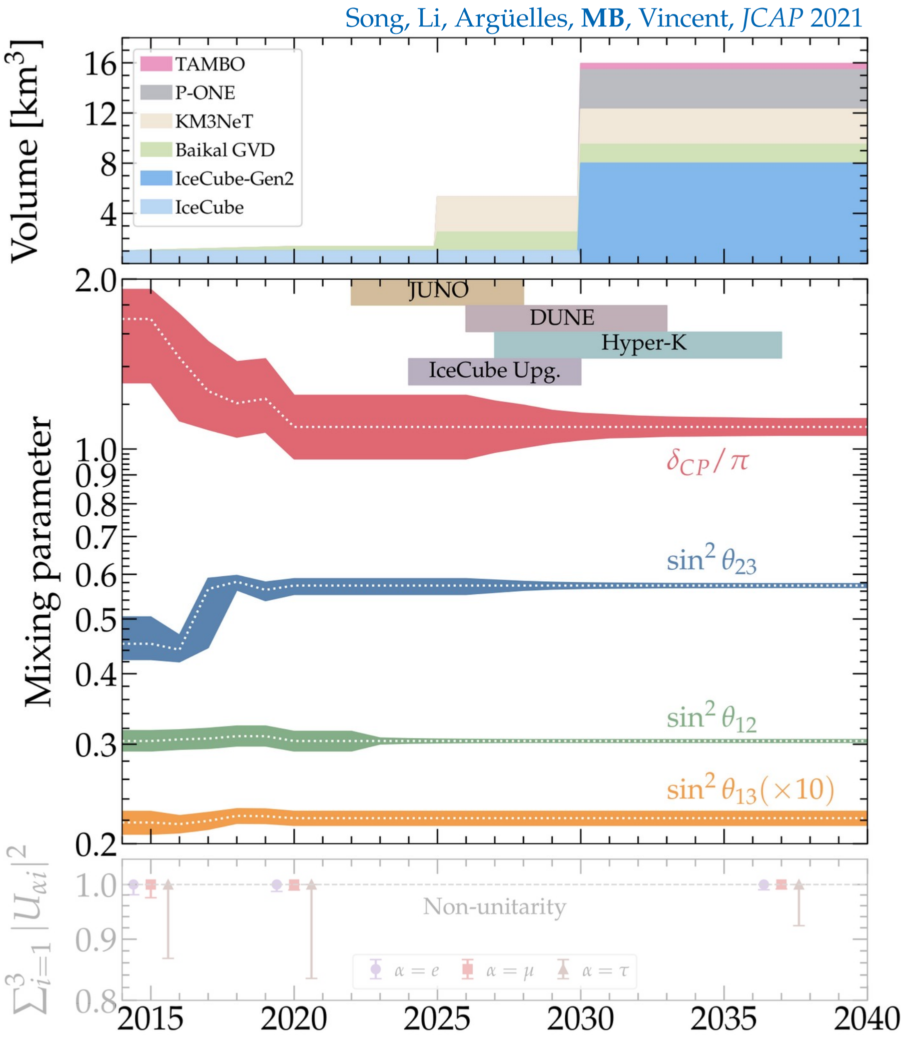


Flavor measurements:

New neutrino telescopes = more events, better flavor measurement

Three reasons to be excited



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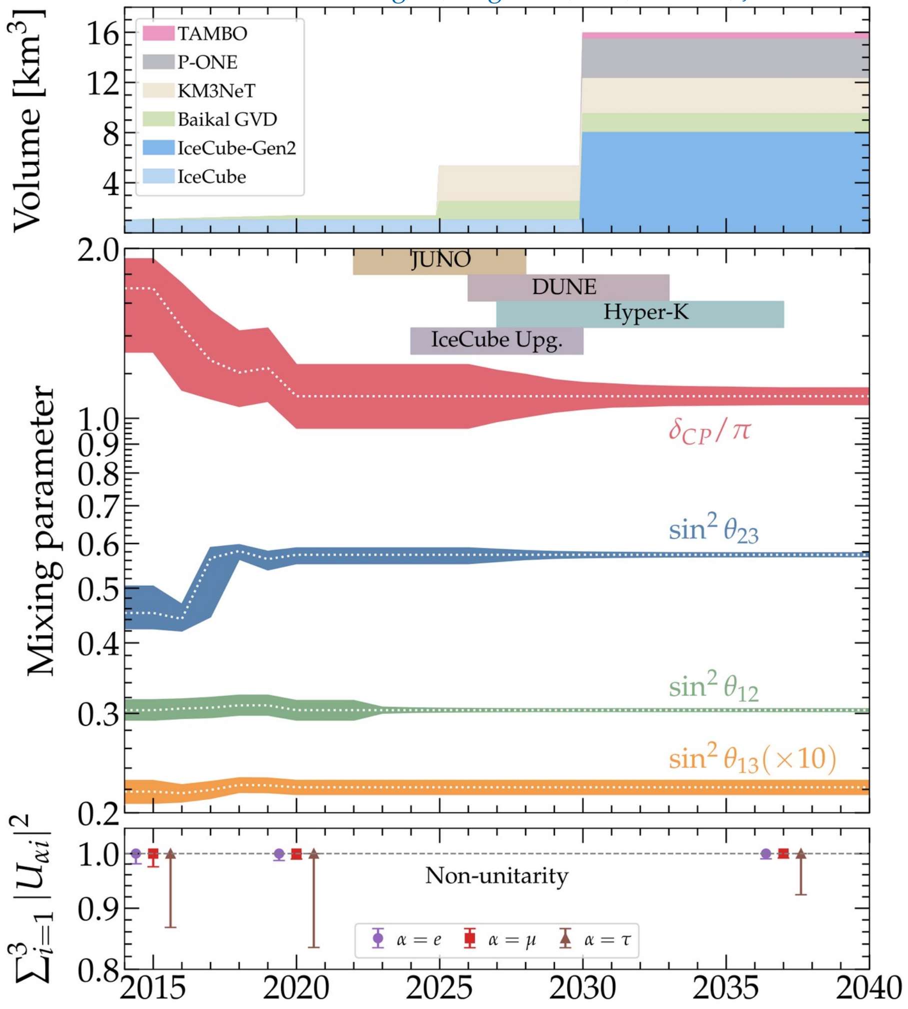
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



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Test of the oscillation framework:
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Measuring flavor composition: 2015–2040

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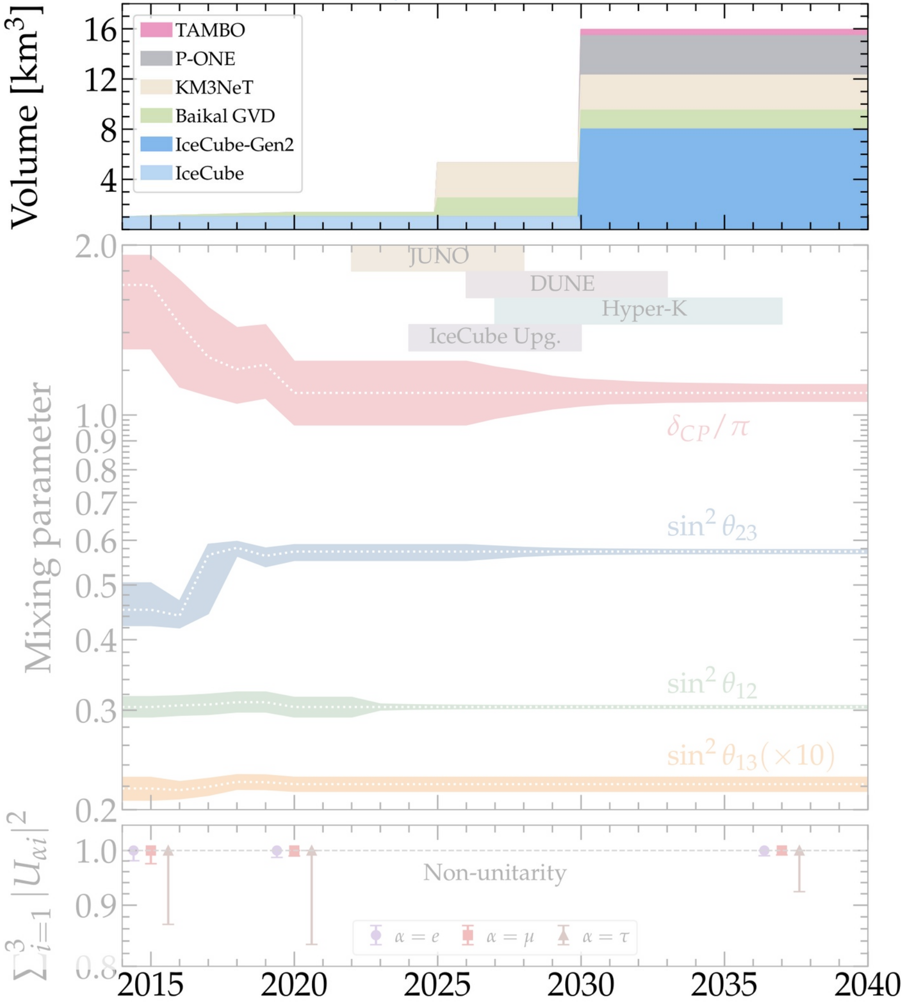
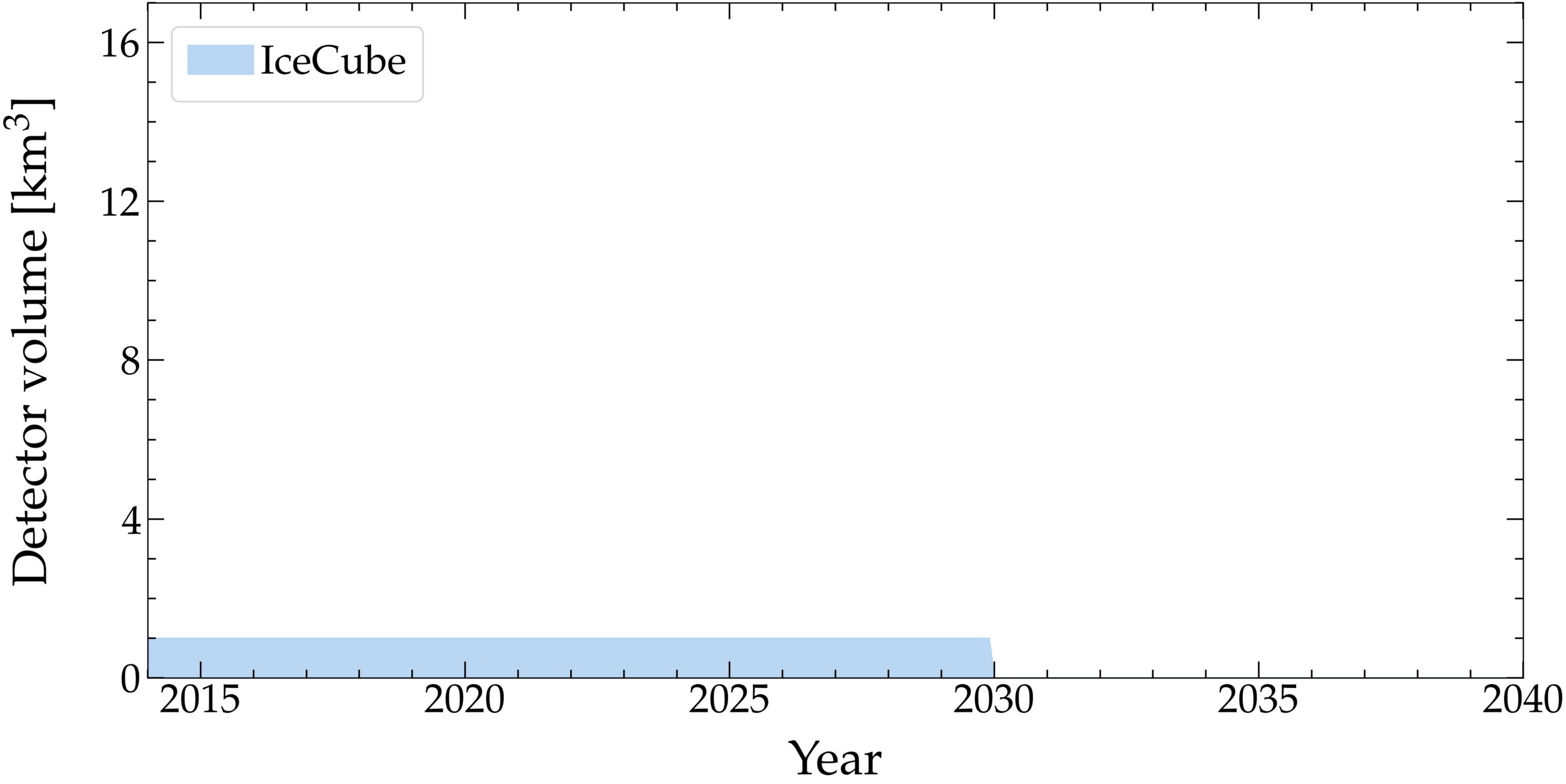
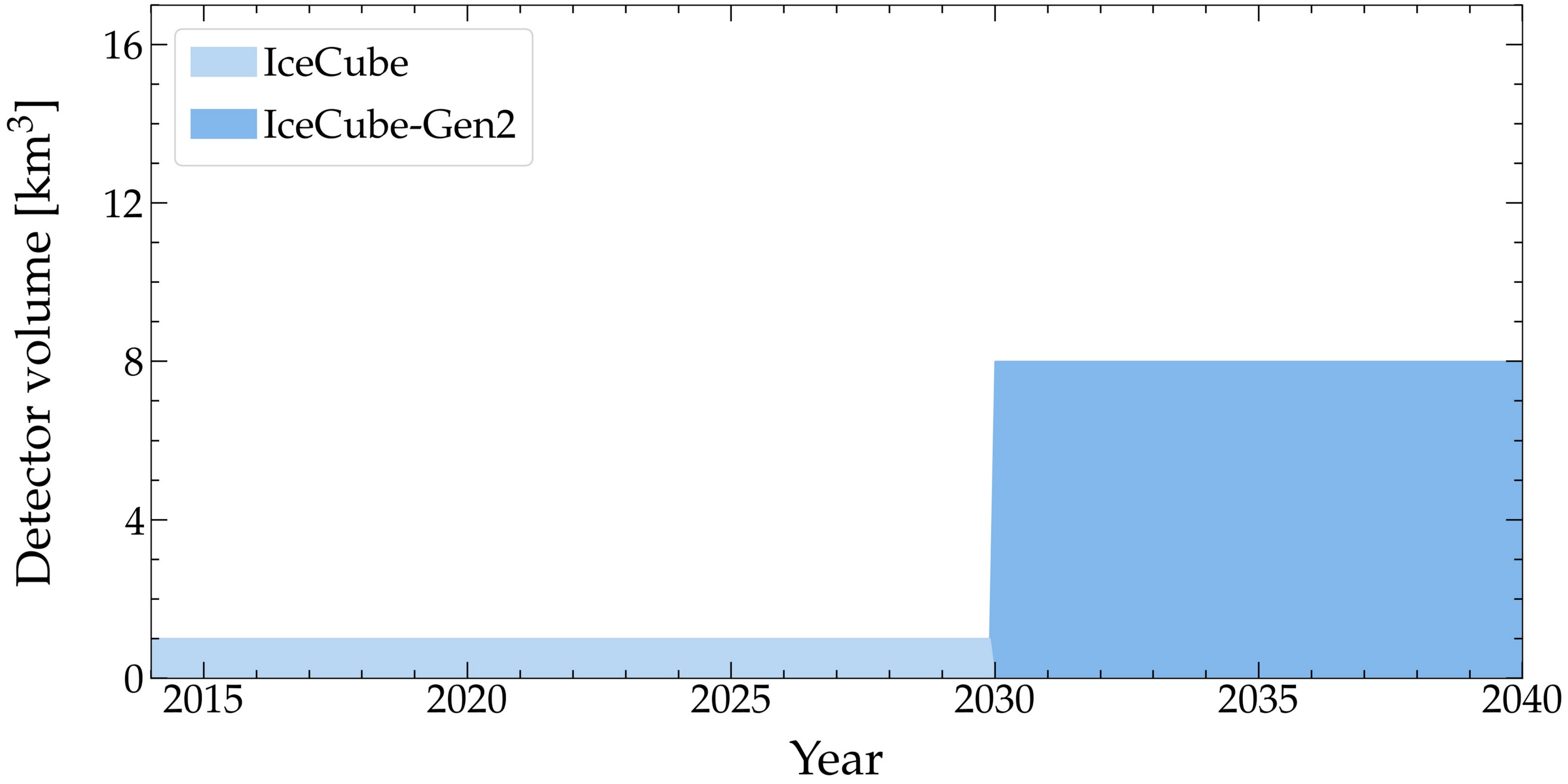



IceCube
Detector volume [km^3]
16
12
8
4
0
2015
2020
2025
2030
2035
2040
Year



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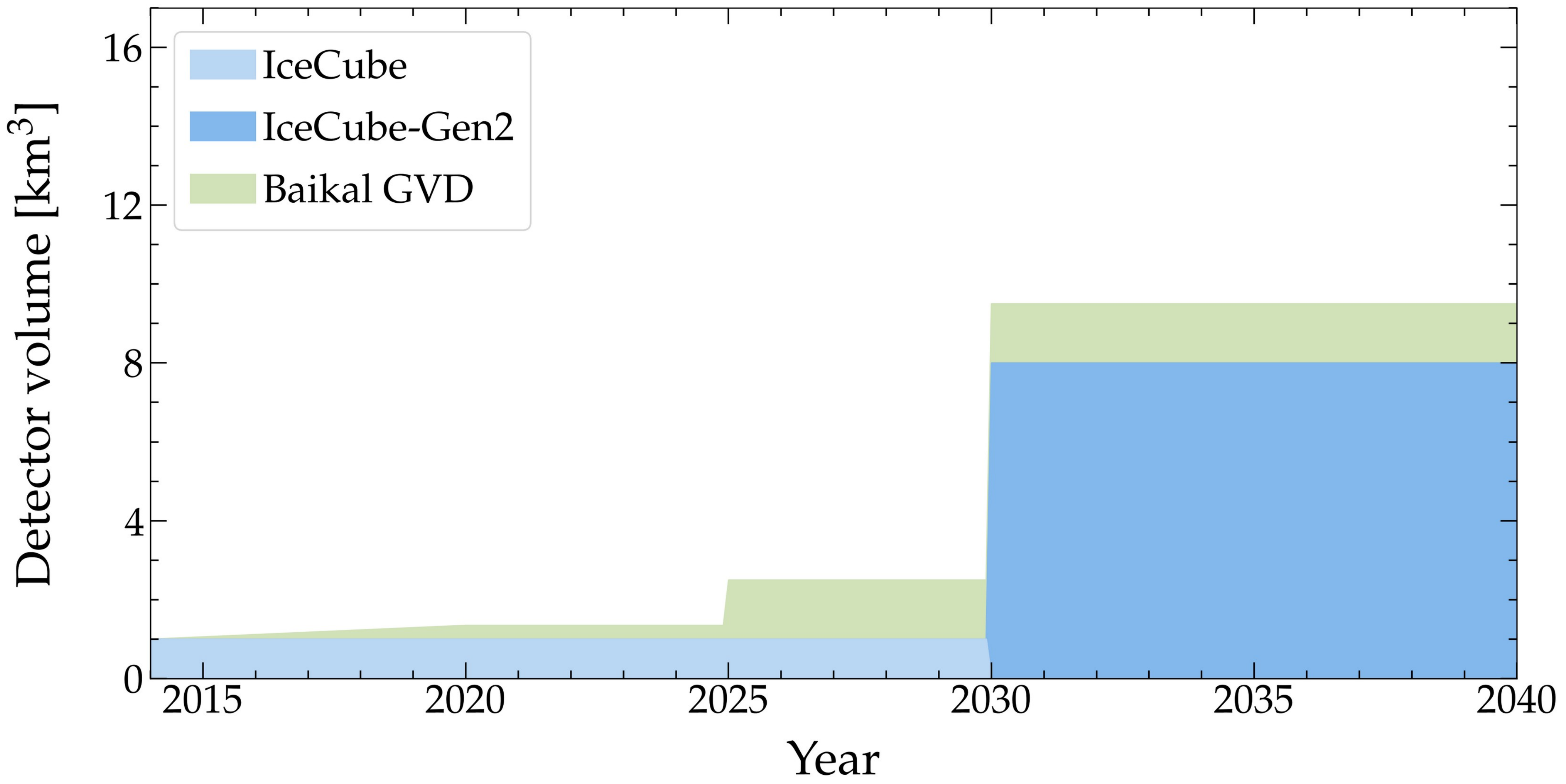

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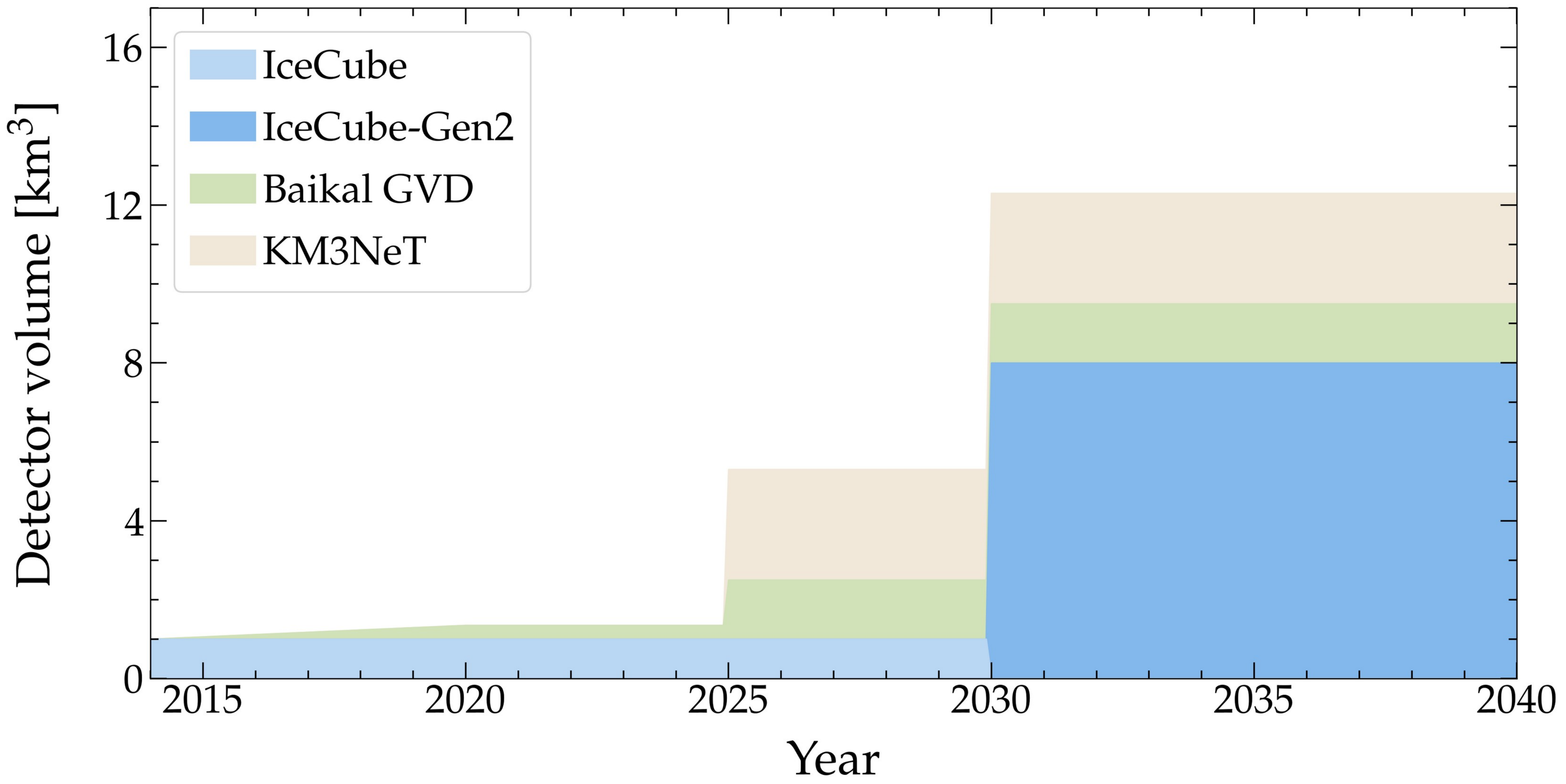

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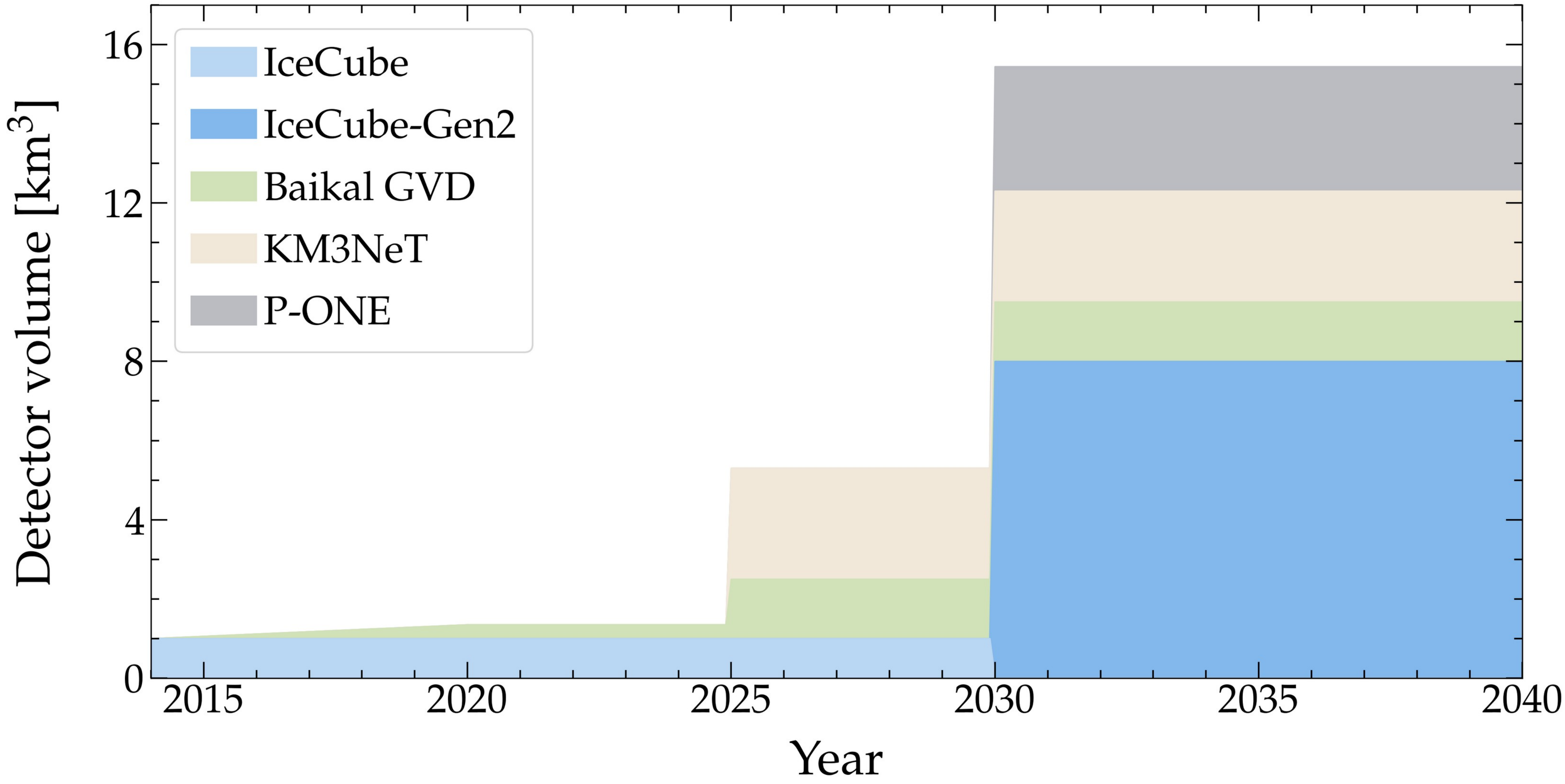

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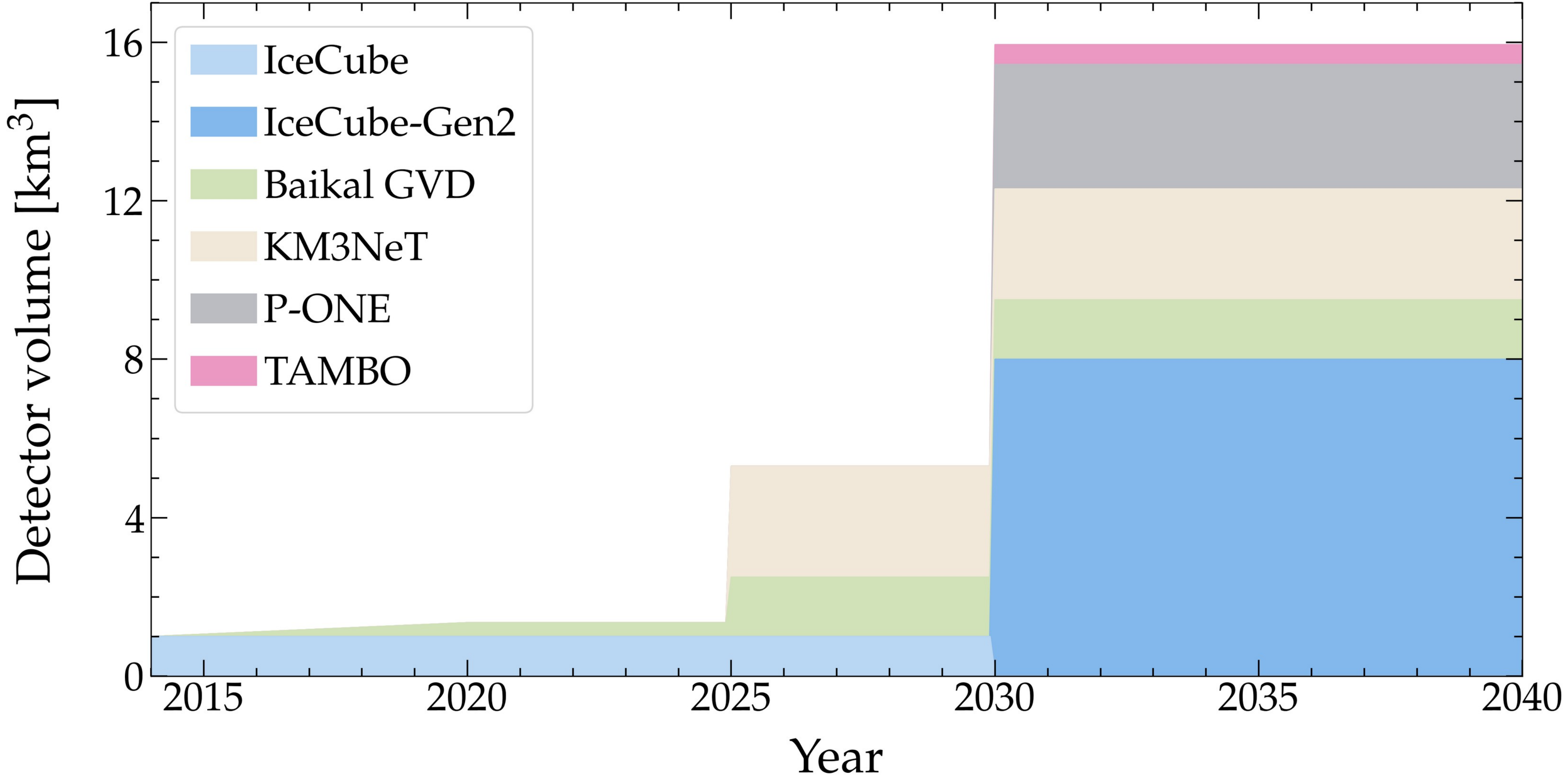

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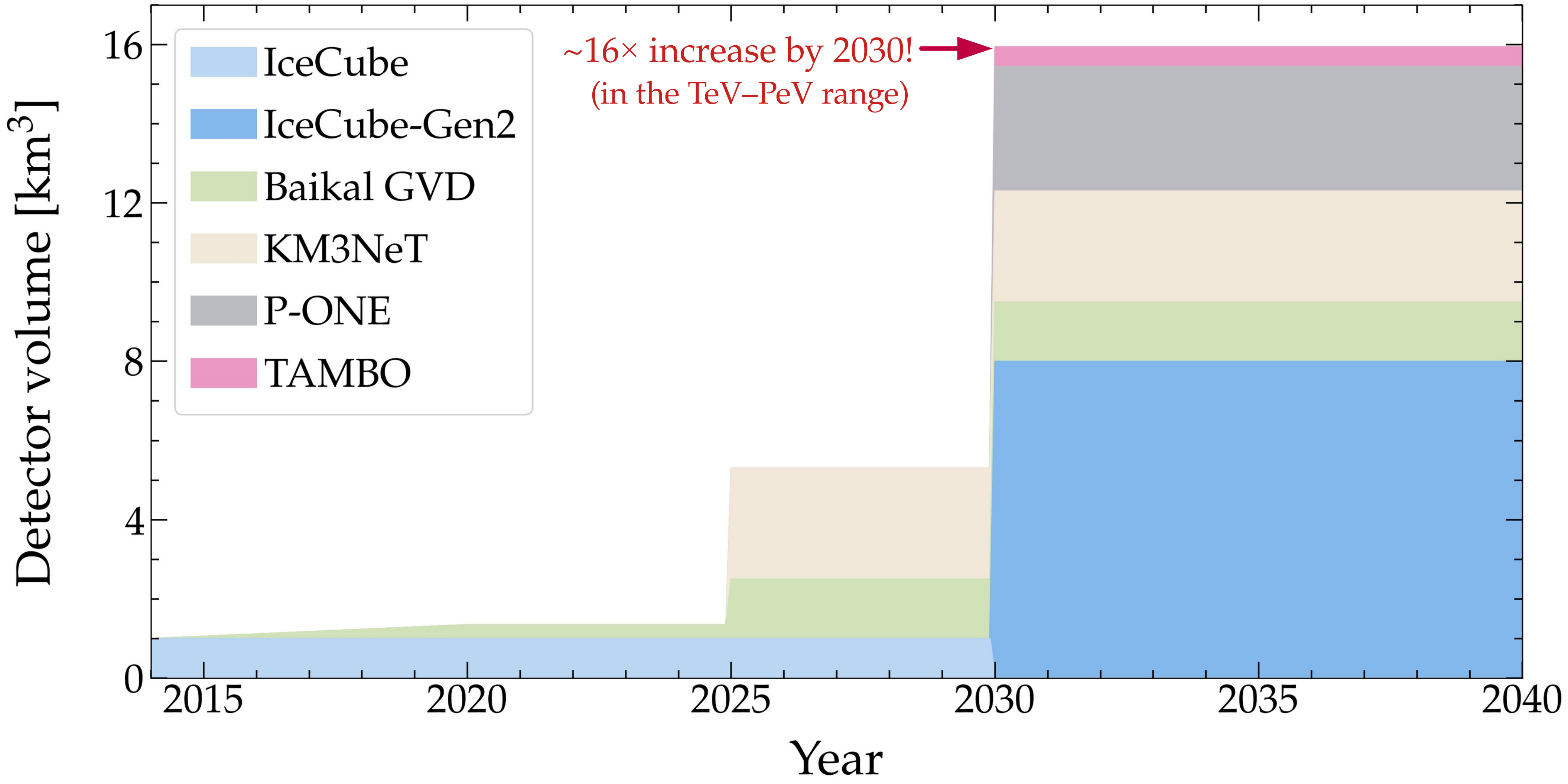

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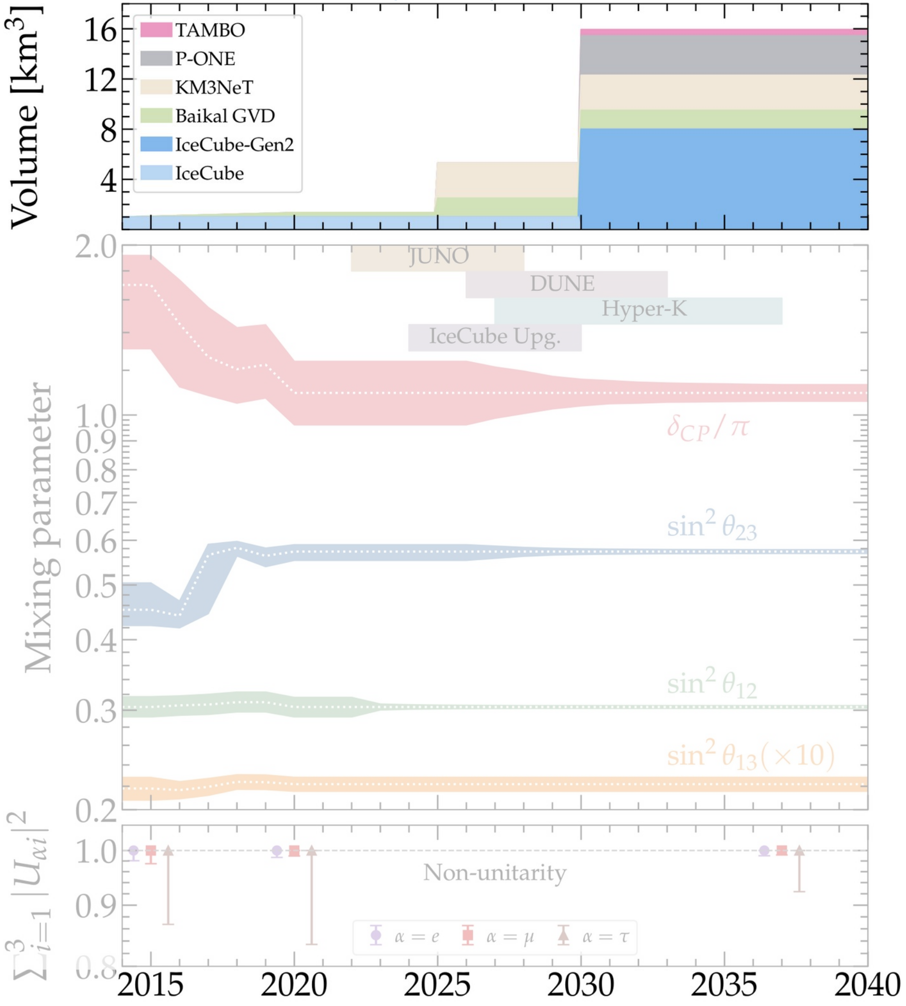

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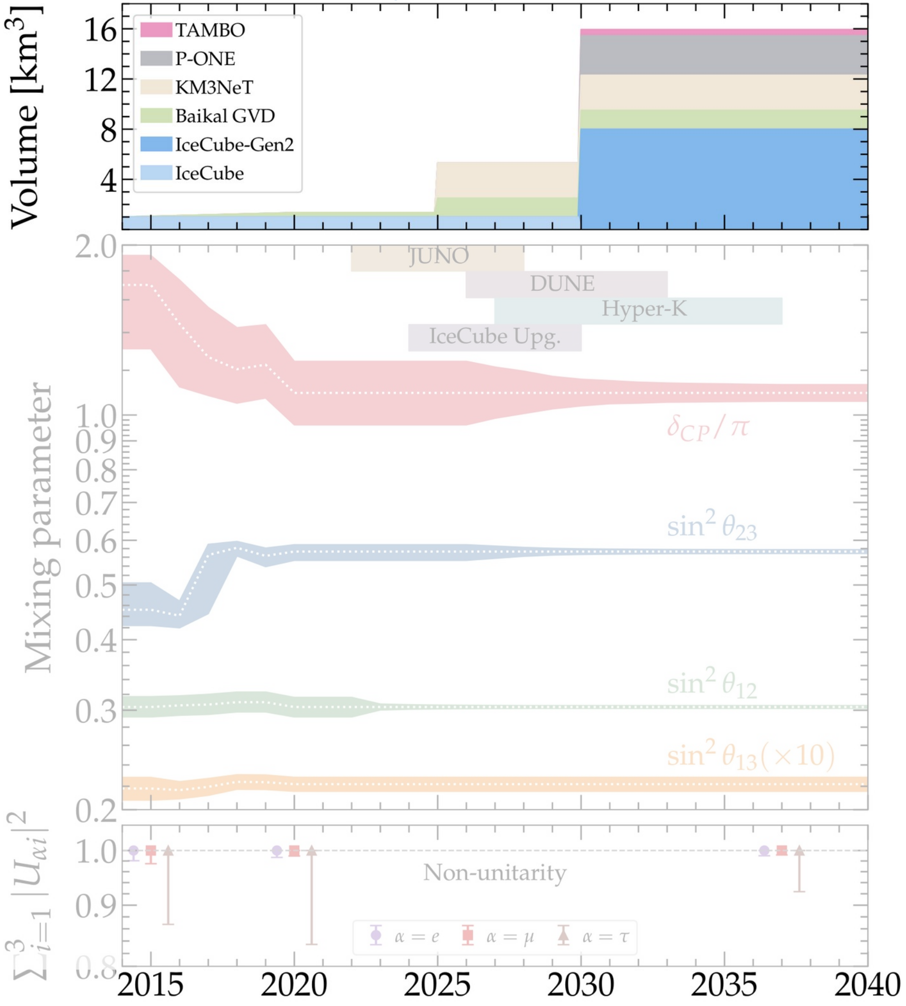

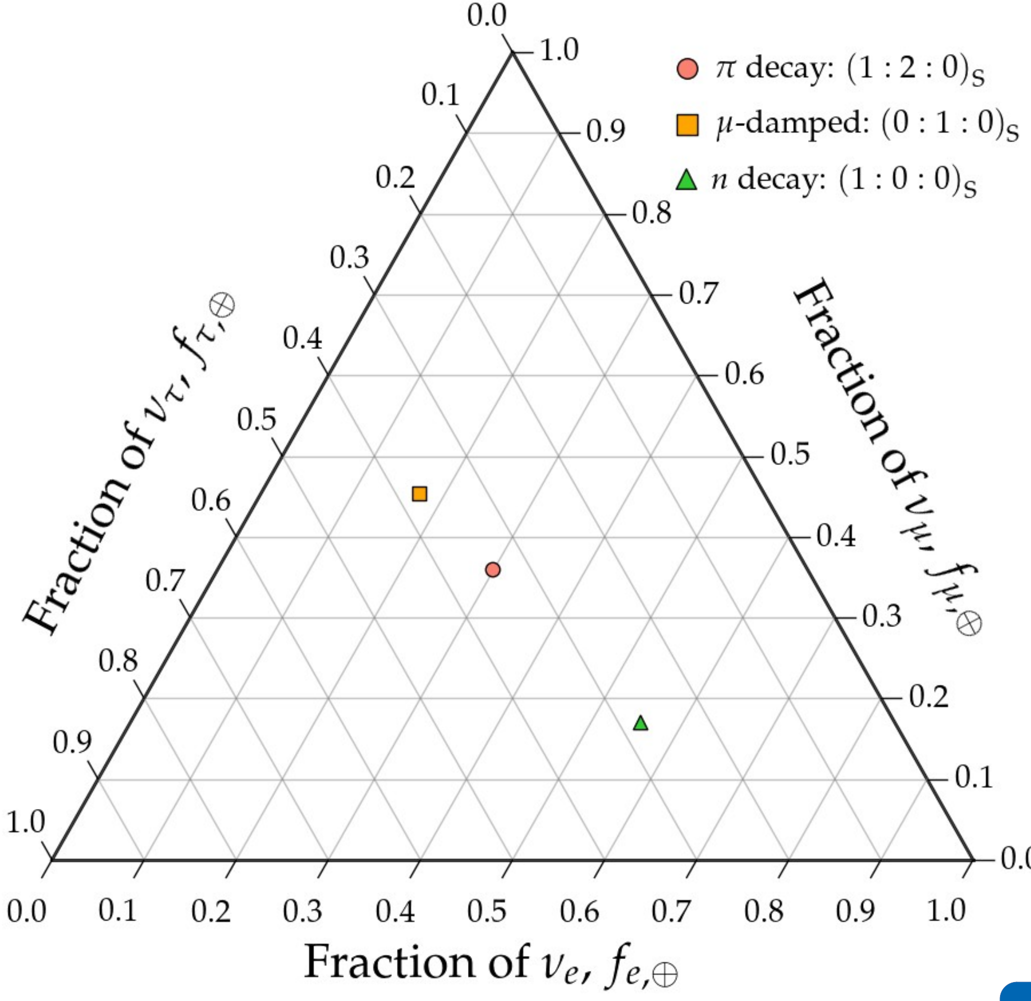

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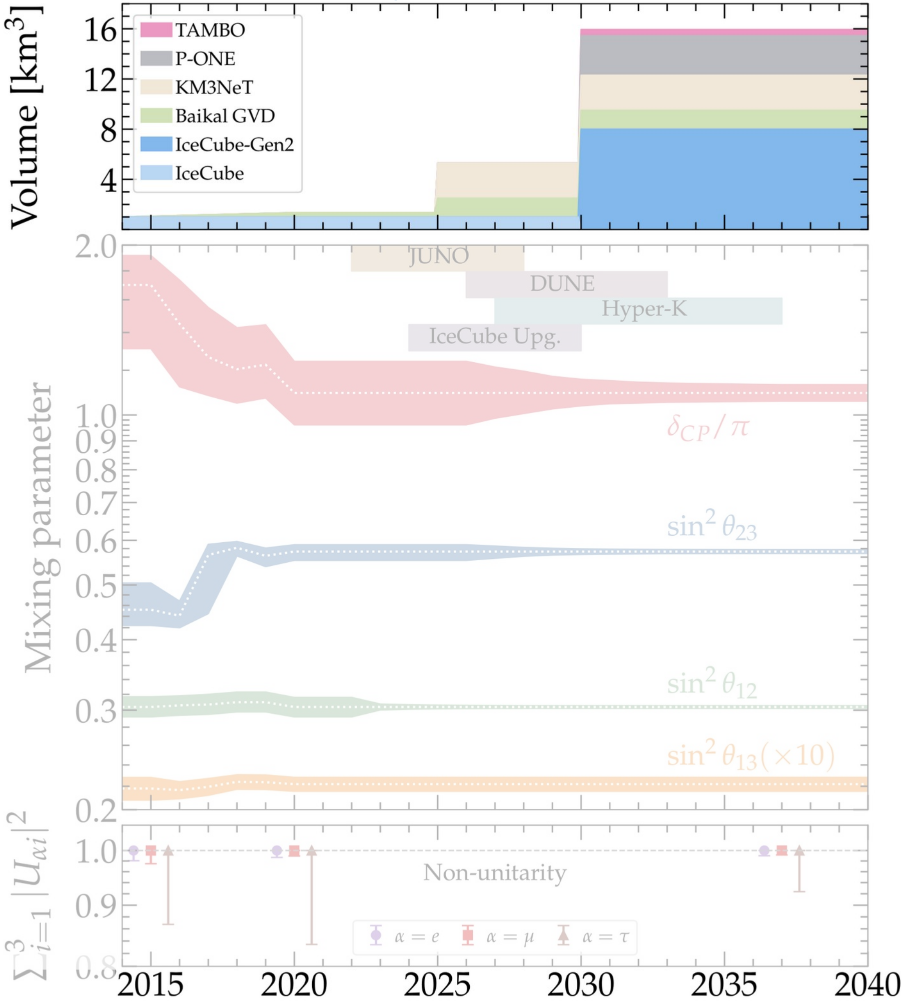

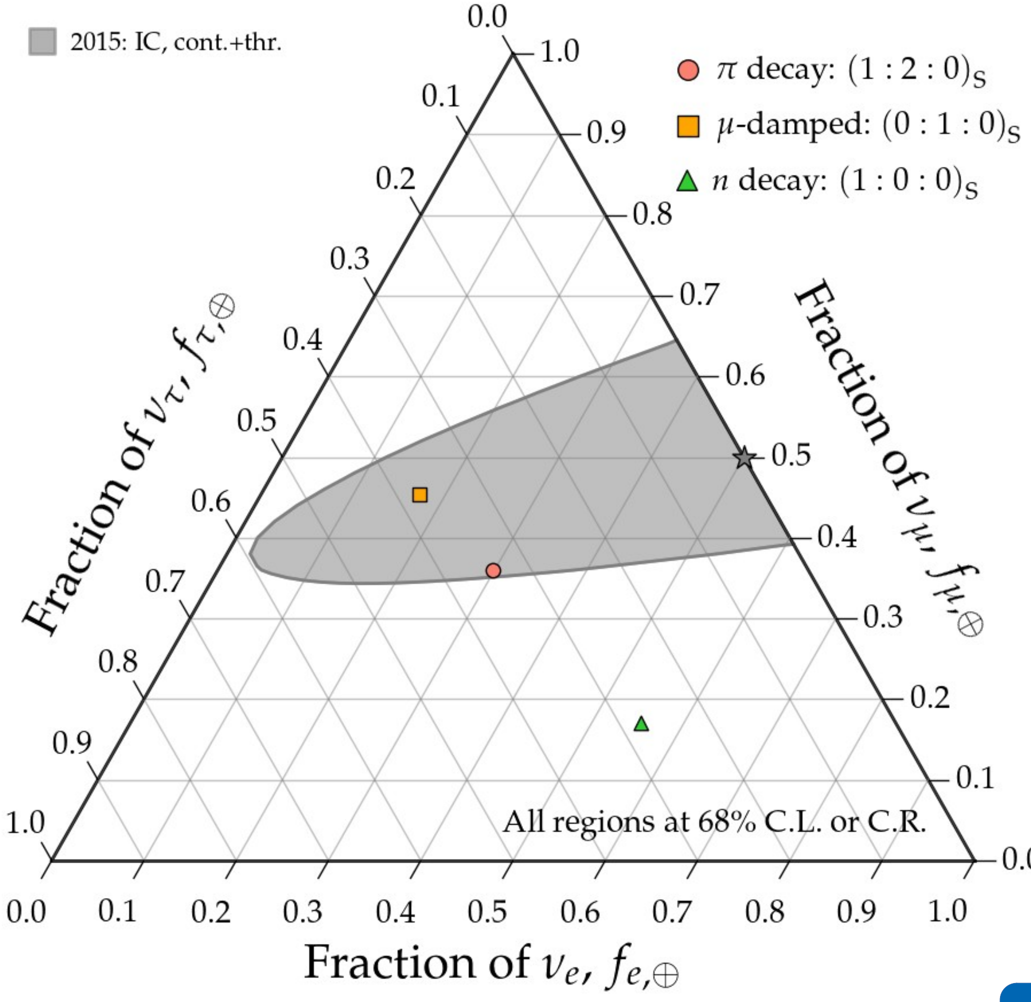

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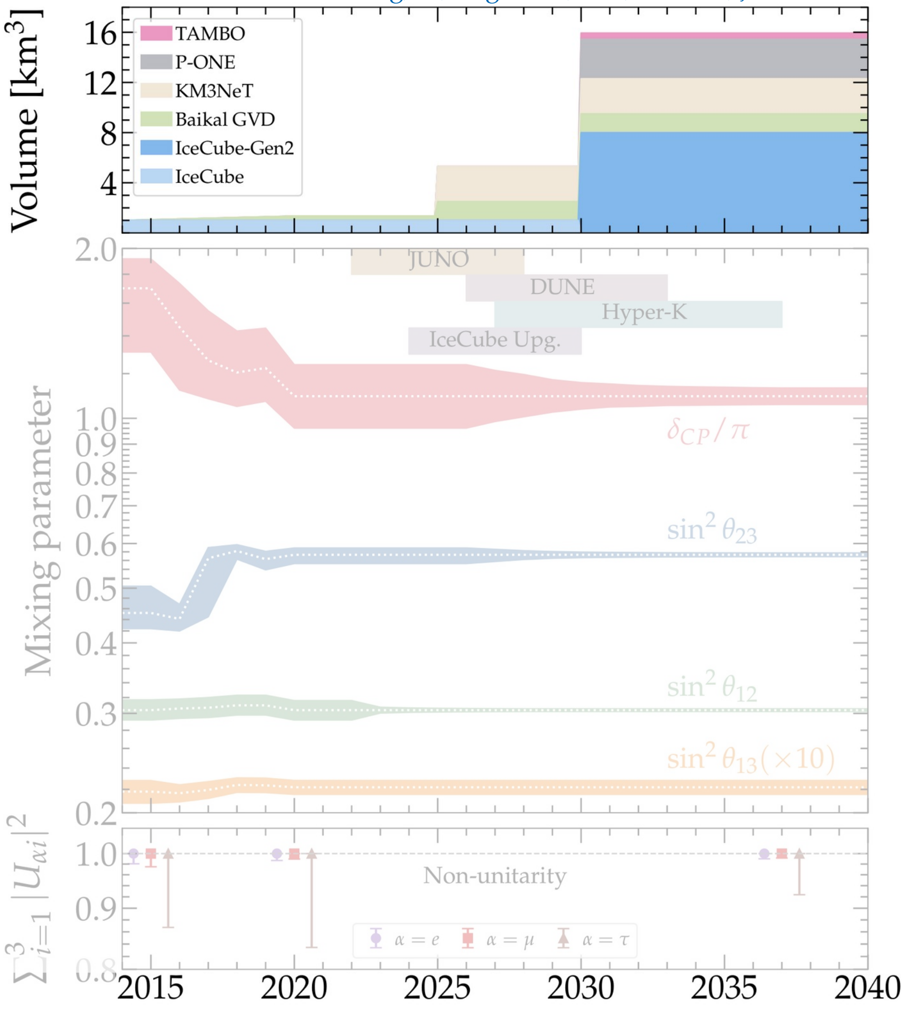

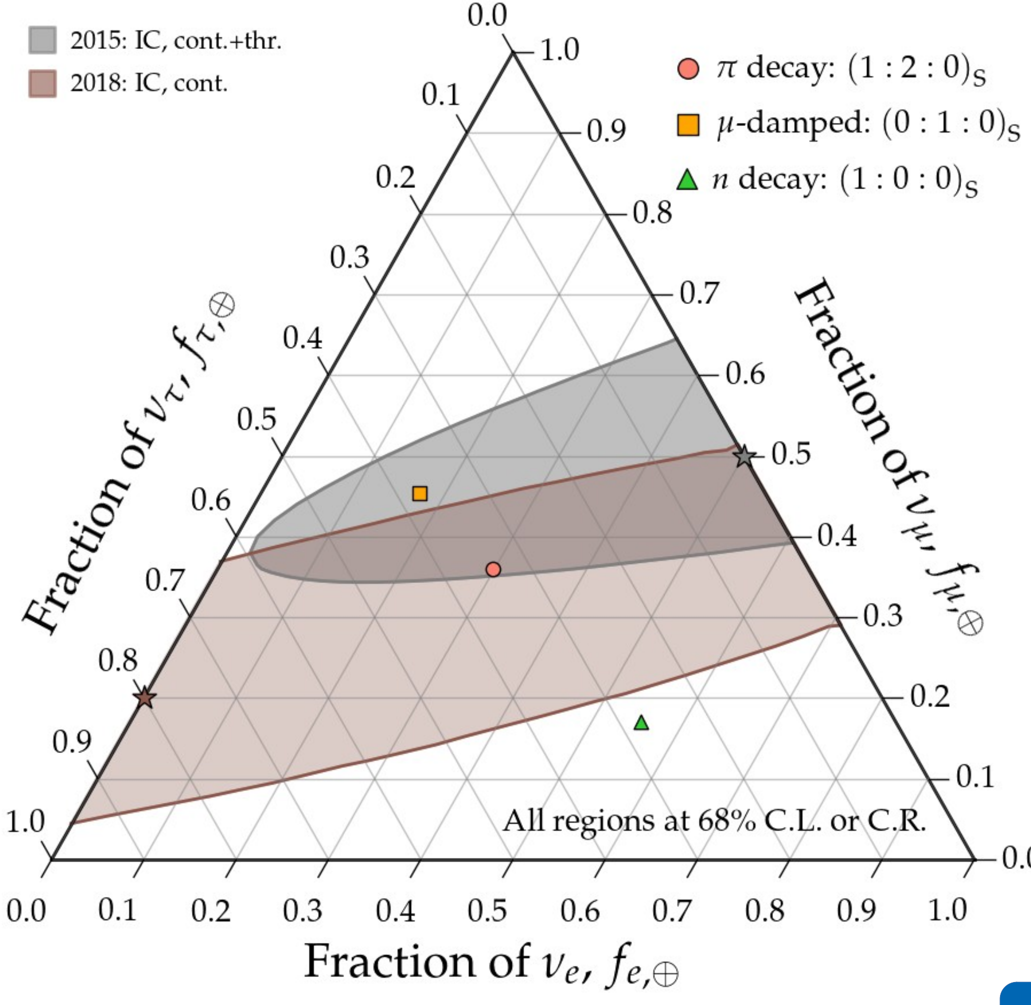

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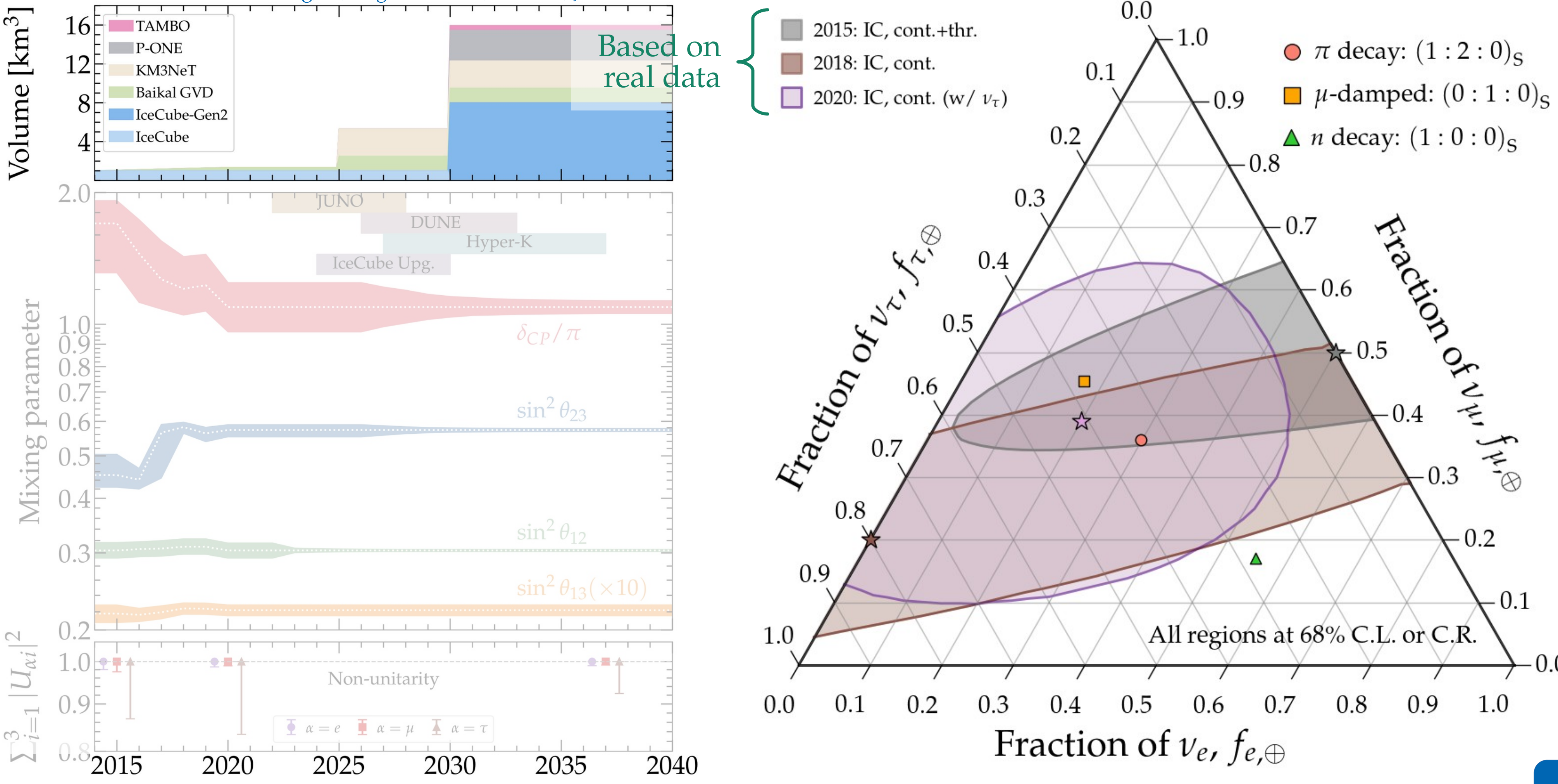

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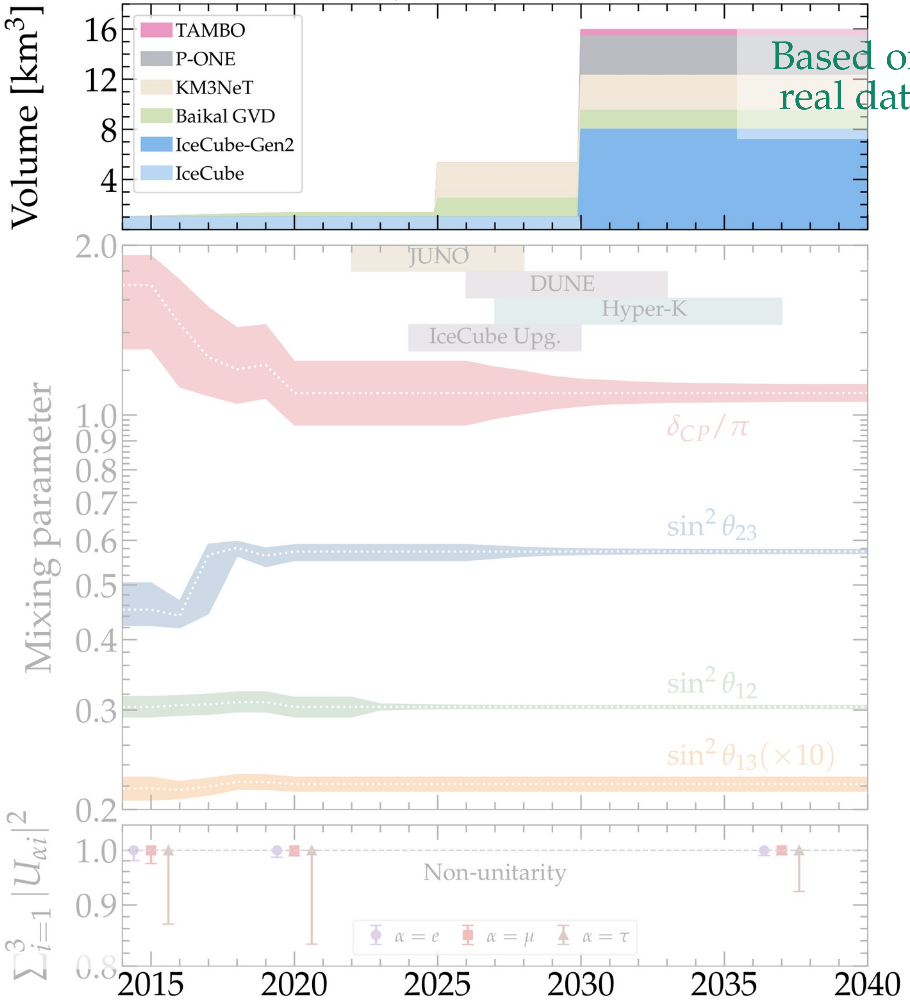
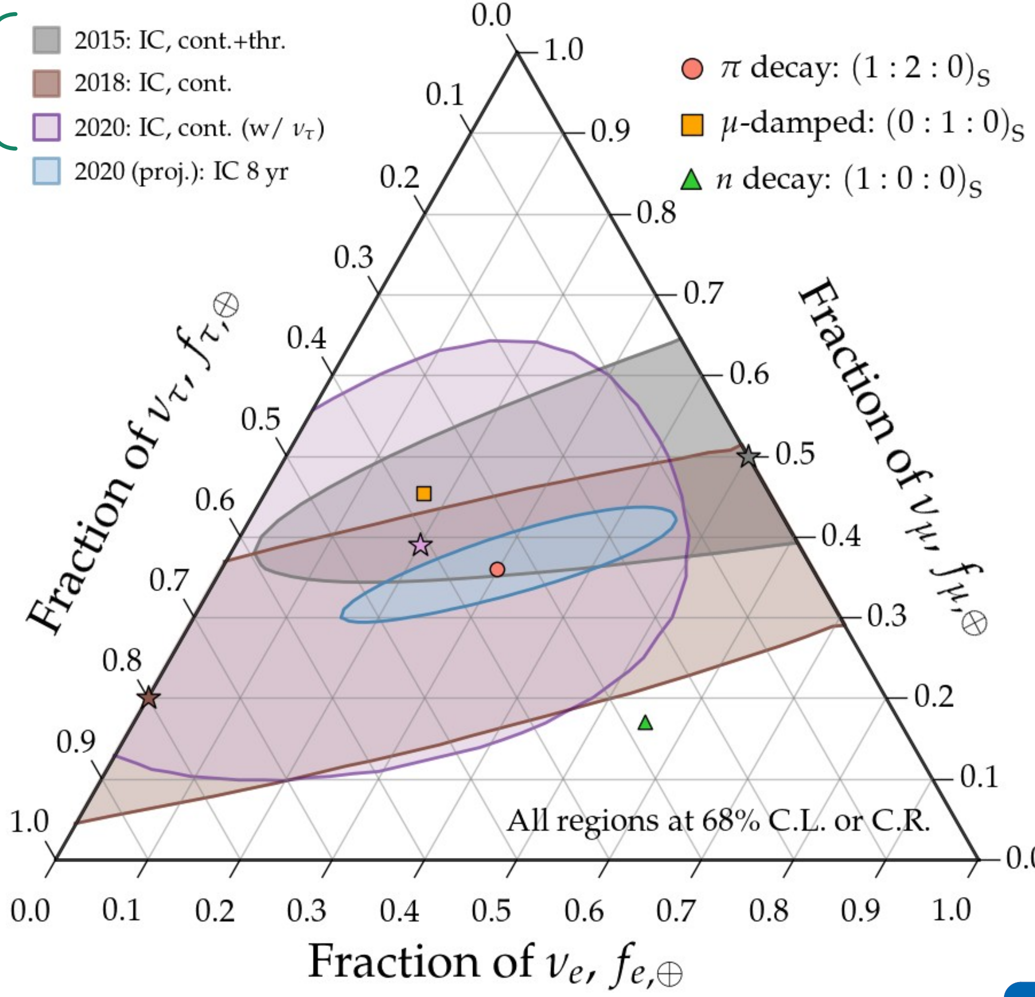


Based on real data



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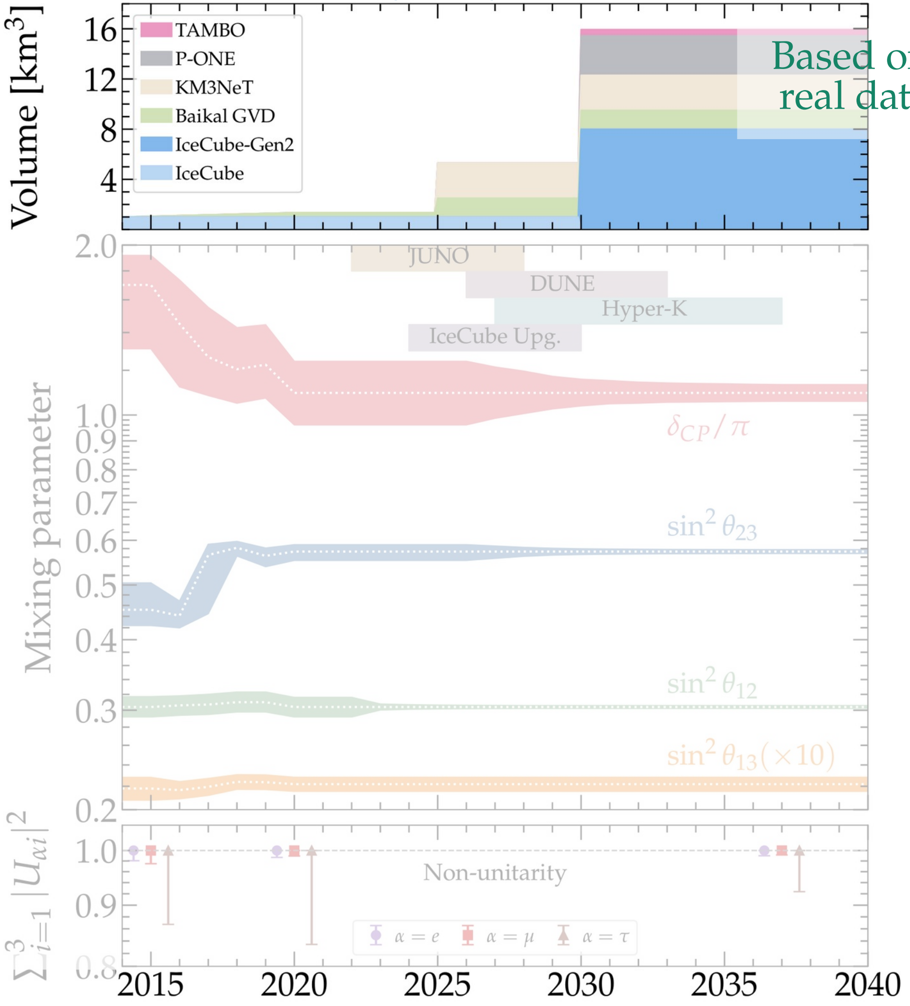

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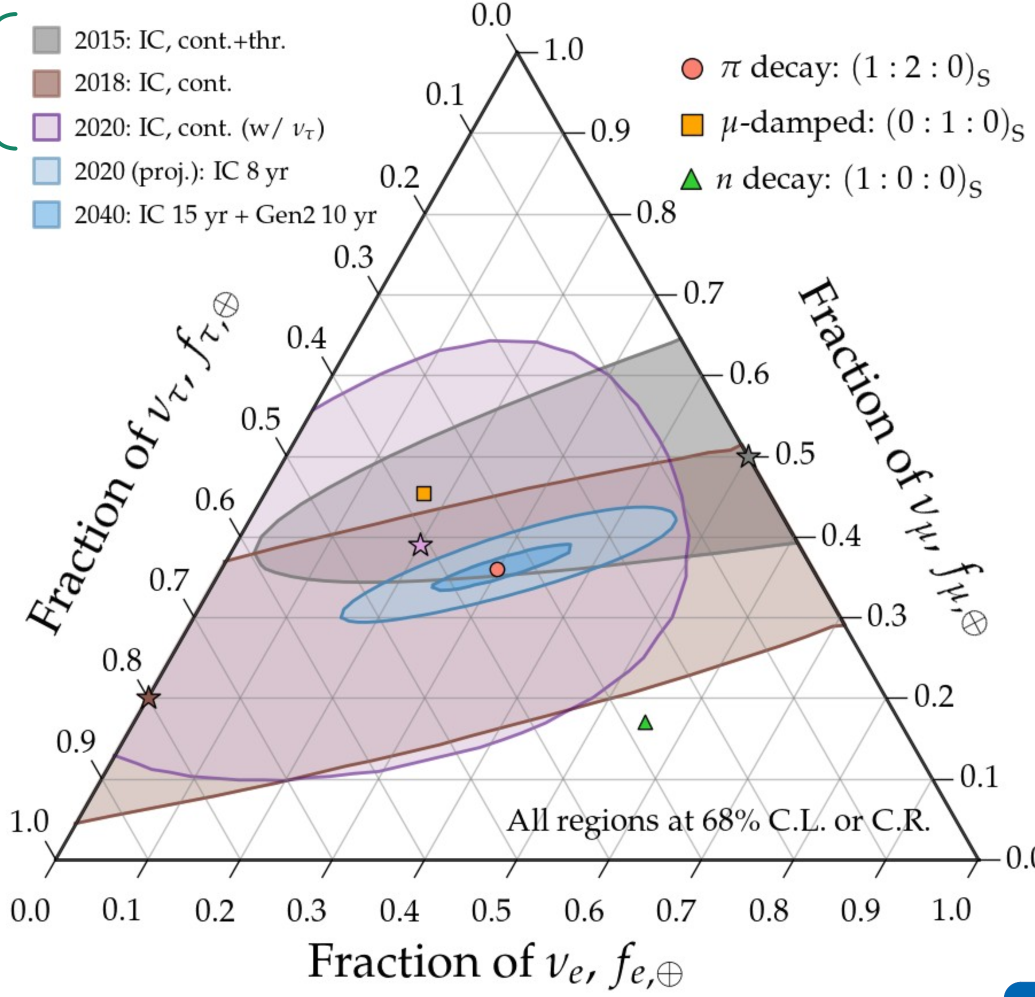

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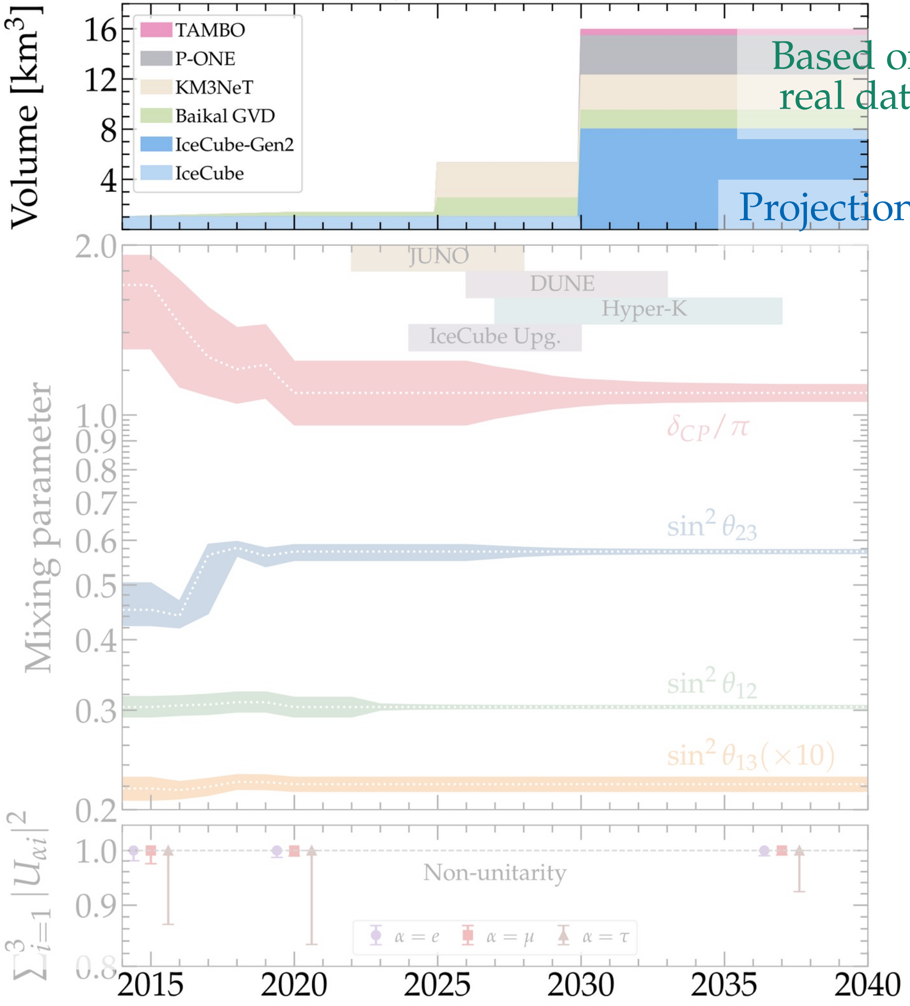
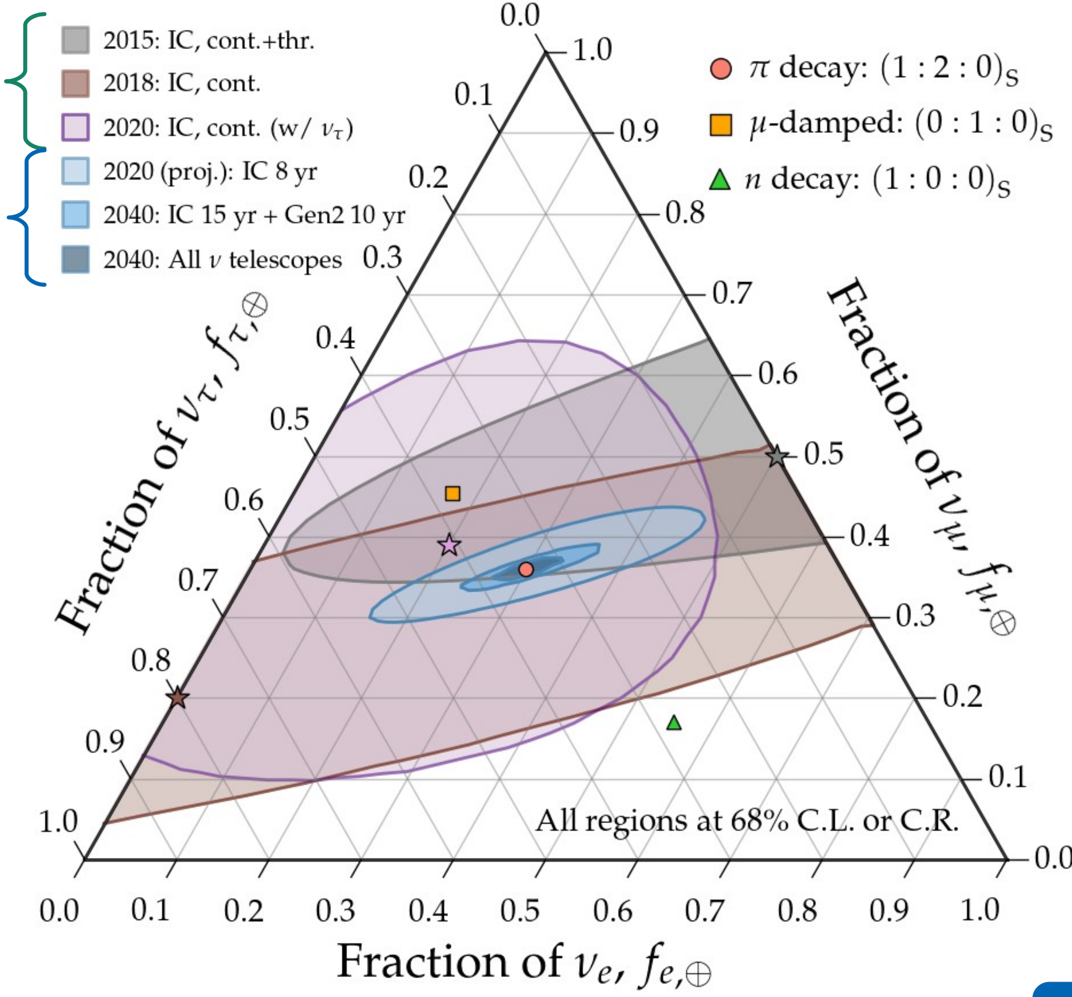
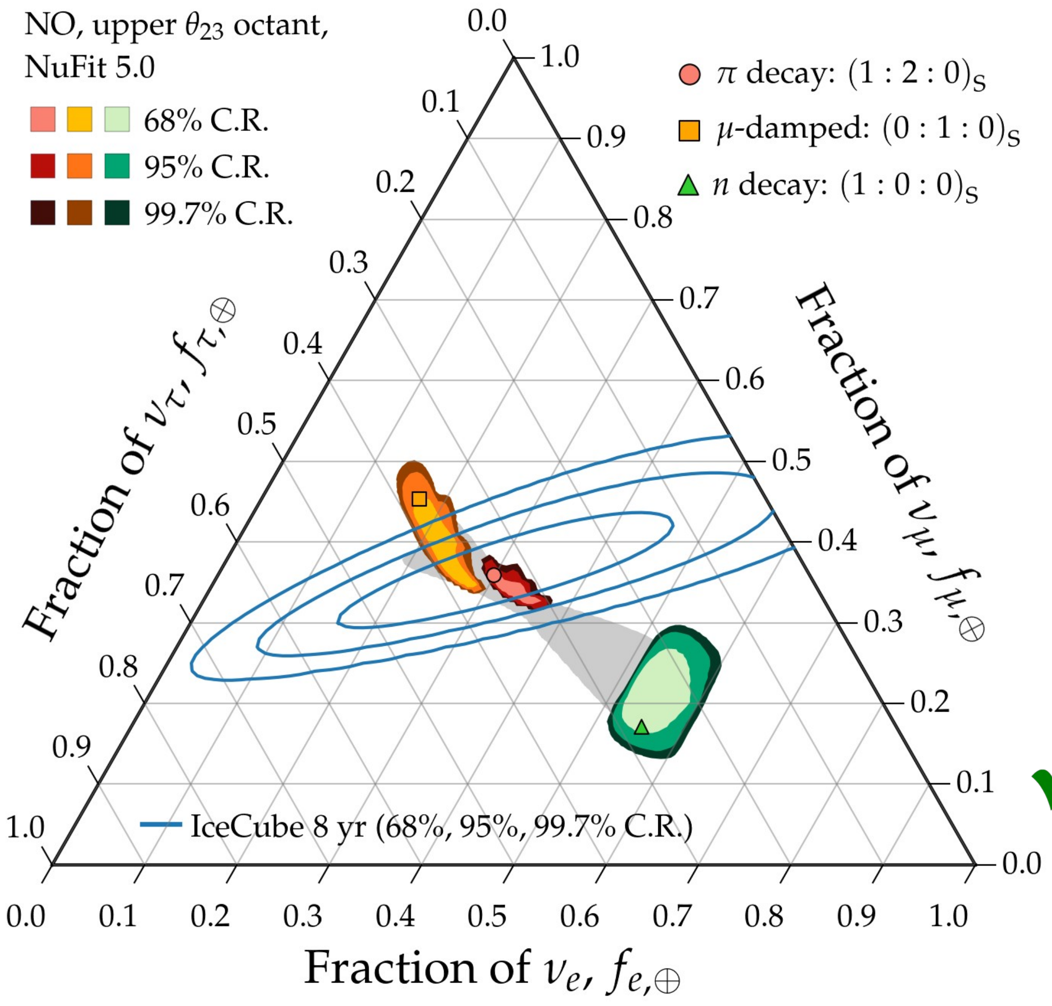




Theoretically palatable regions: today



Two limitations:

Allowed flavor regions overlap –
Insufficient precision in the mixing parameters

Will be overcome by 2030

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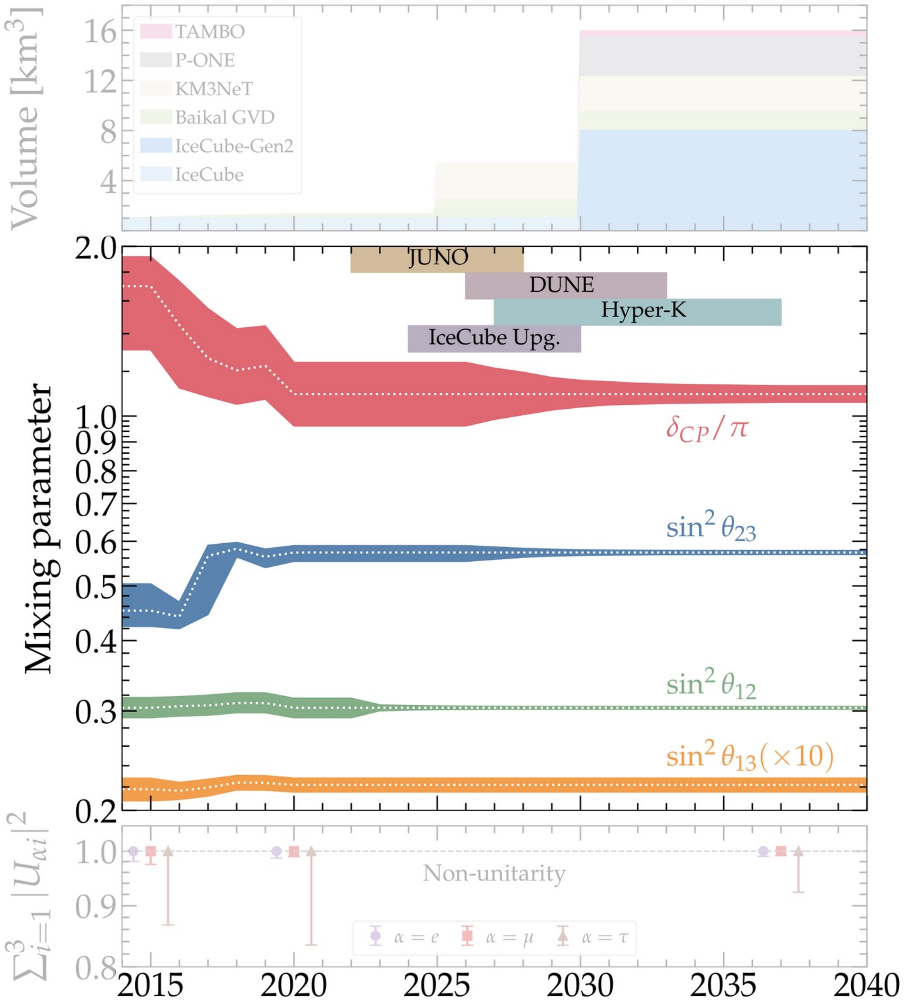
~~Cannot distinguish between pion-decay and muon-damped benchmarks even at 68% C.R. (1σ)~~

✓ *Will be overcome by 2040*

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

How knowing the mixing parameters better helps

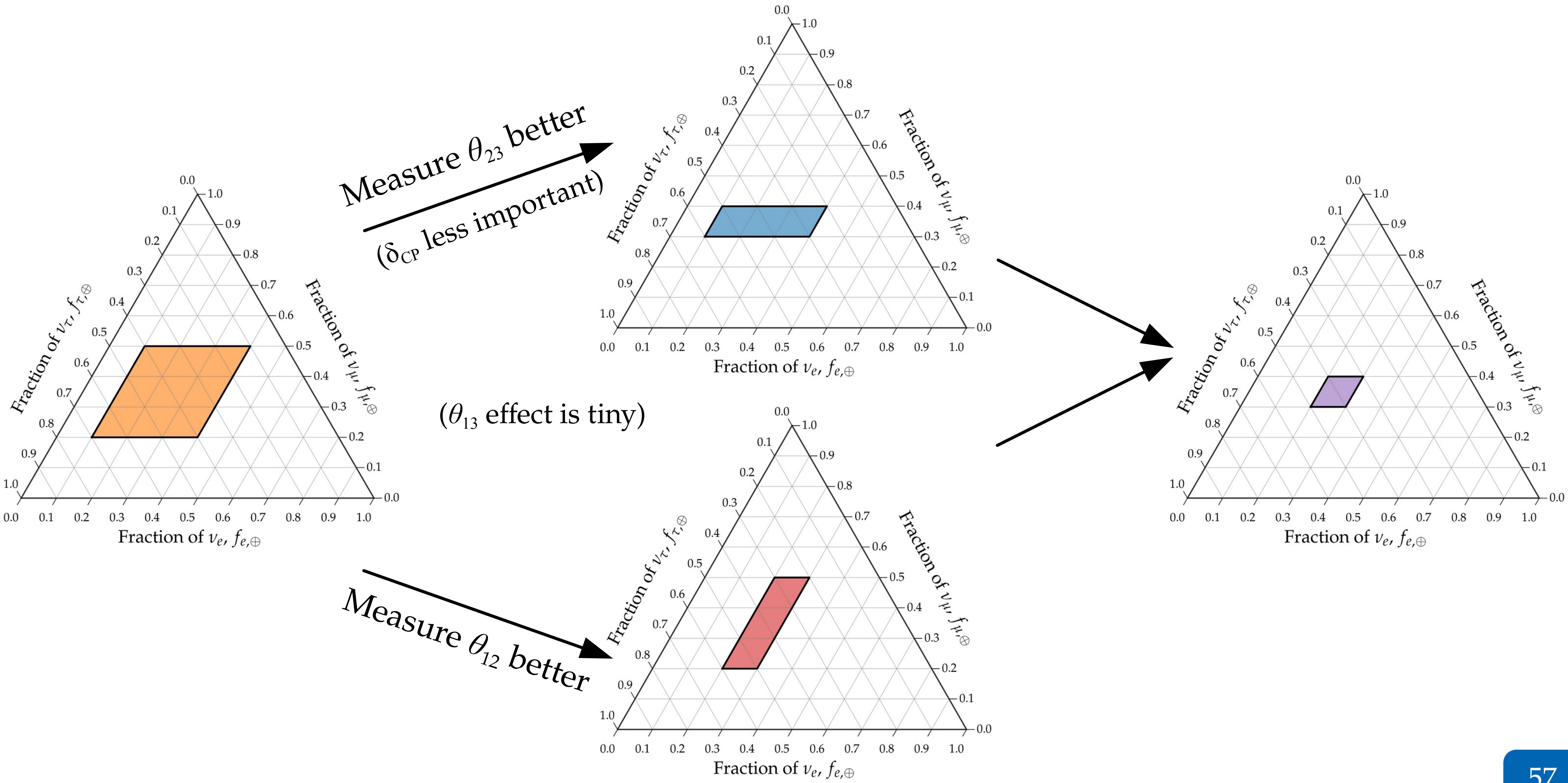


We can compute the oscillation probability more precisely:

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

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

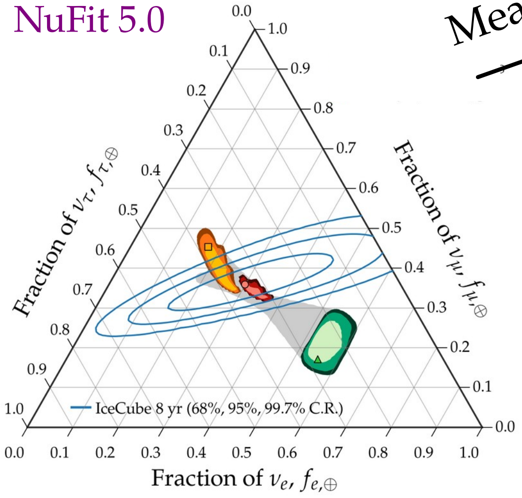
How knowing the mixing parameters better helps



How knowing the mixing parameters better helps

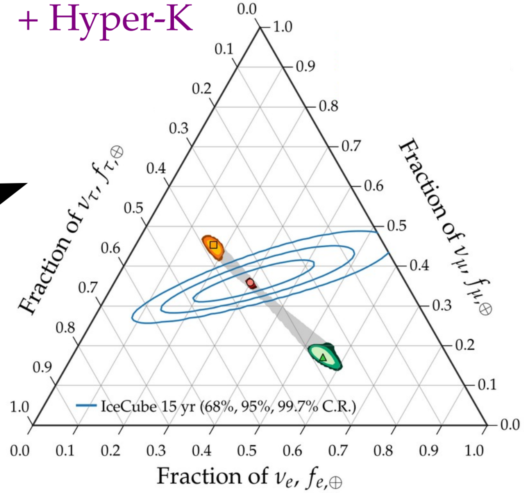
2020

NuFit 5.0



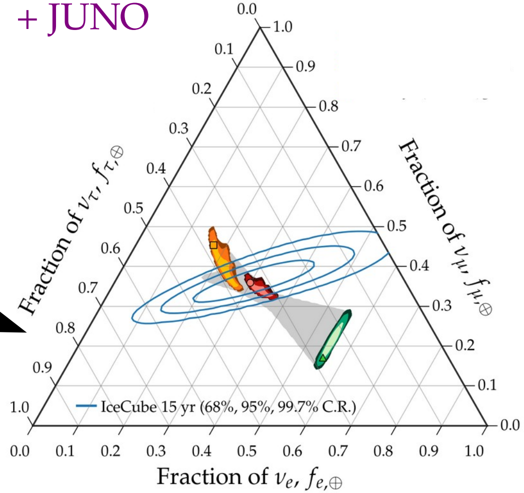
Measure θ_{23} better

+ Hyper-K



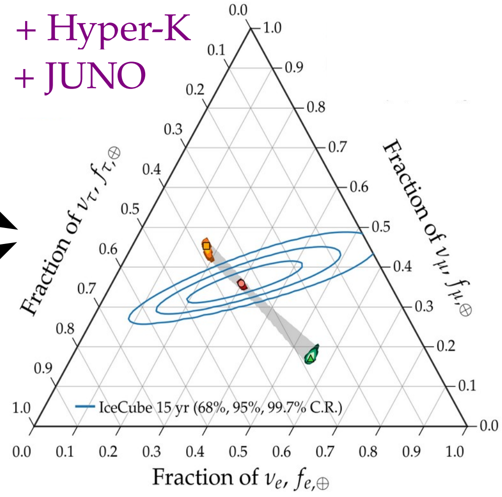
Measure θ_{12} better

+ 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

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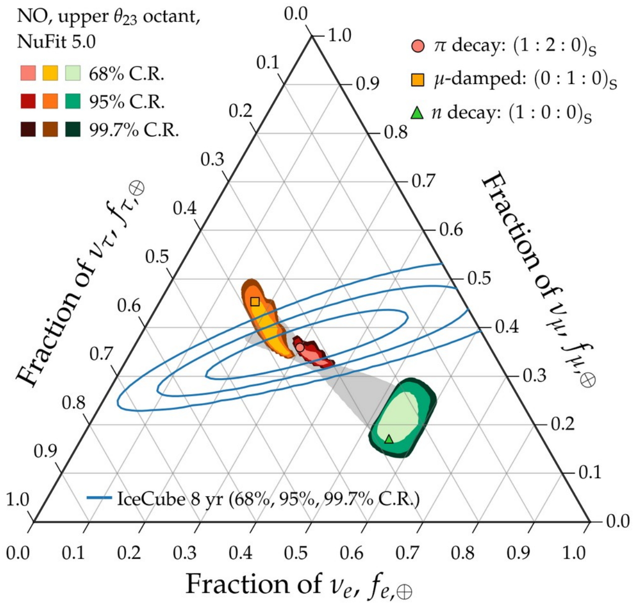

Allowed regions: overlapping

Measurement: imprecise

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

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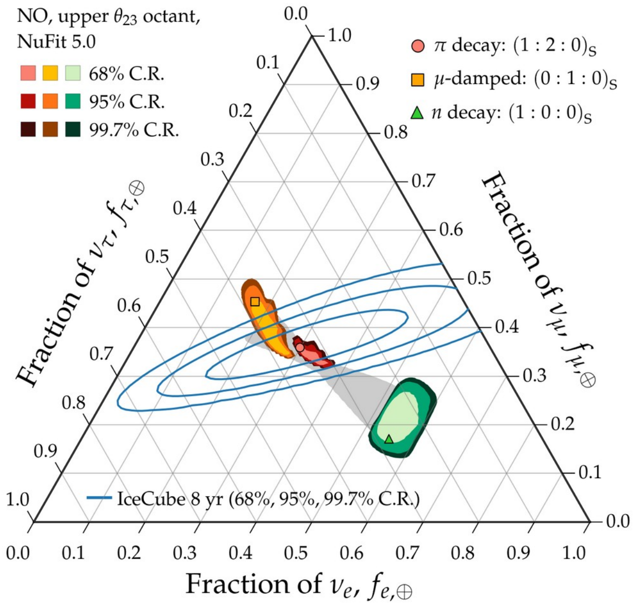

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Not ideal

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

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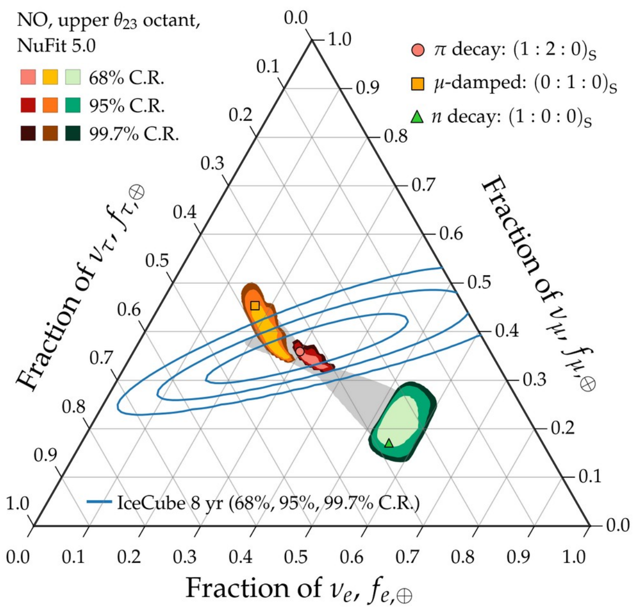
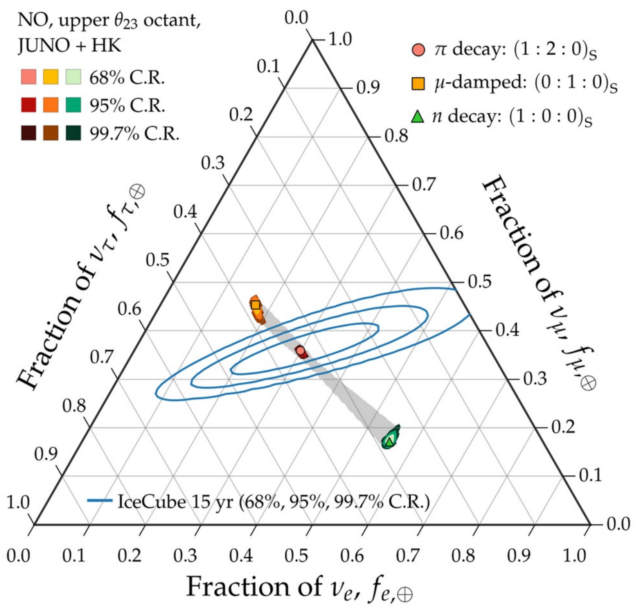


2030



Allowed regions: overlapping
Measurement: imprecise

Not ideal

Allowed regions: well separated
Measurement: improving

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

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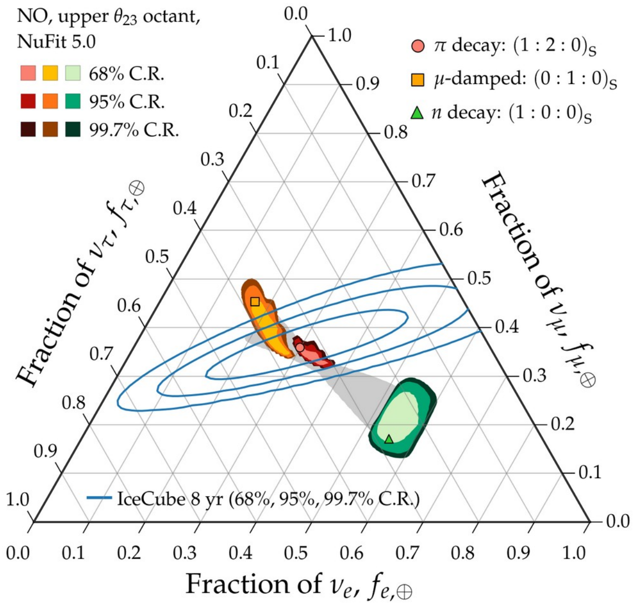

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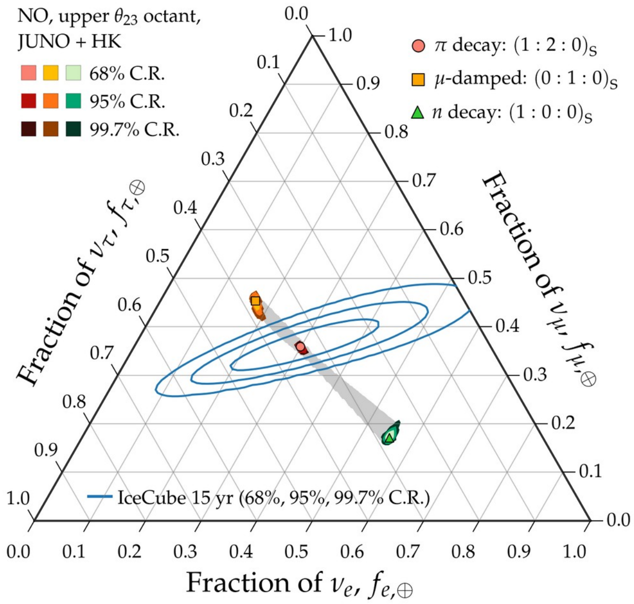
2030



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Nice

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

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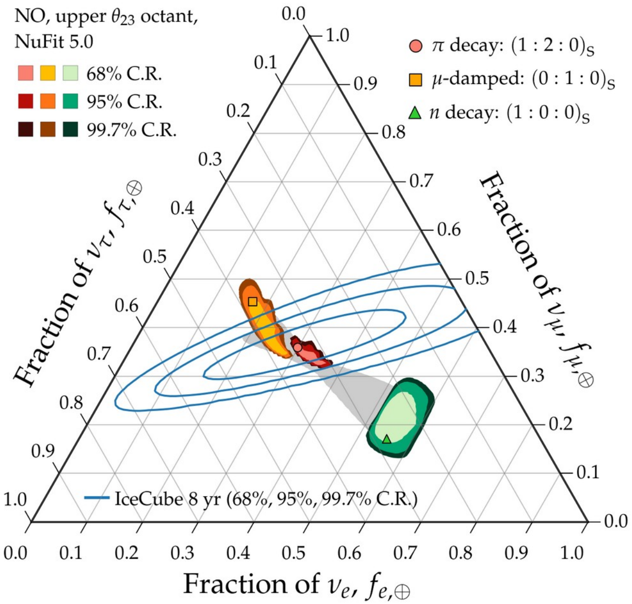

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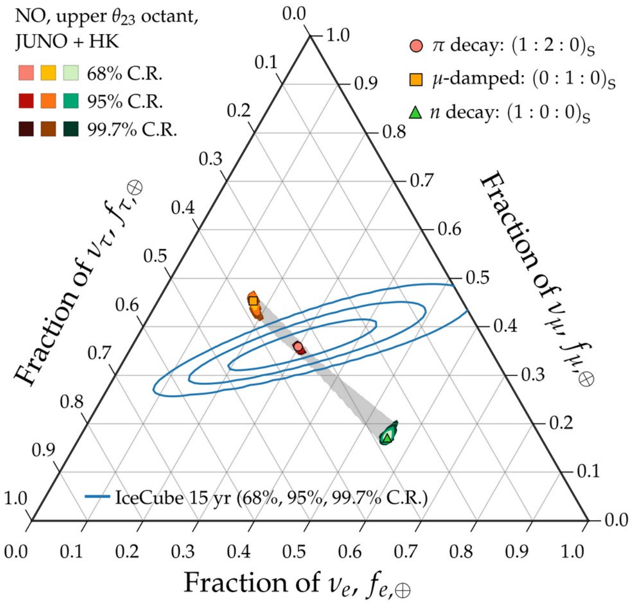

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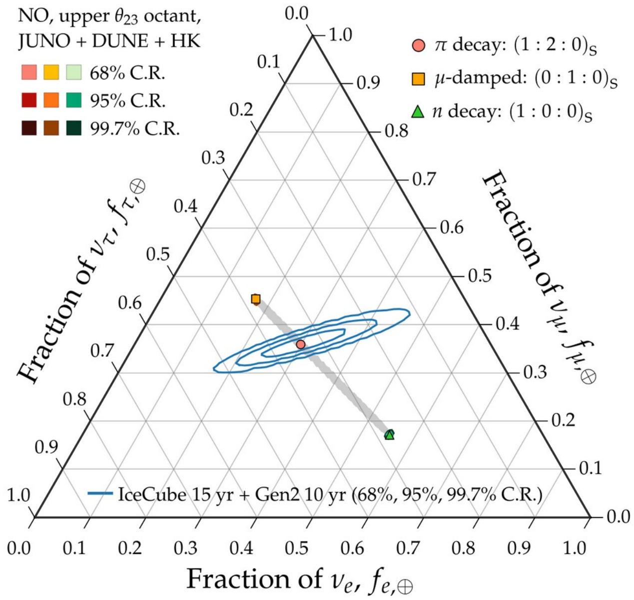
2040



Allowed regions: well separated

Measurement: precise

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

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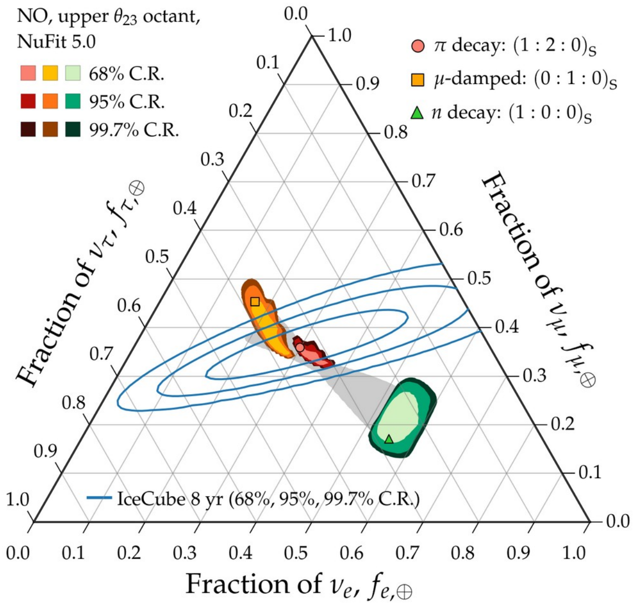
2020



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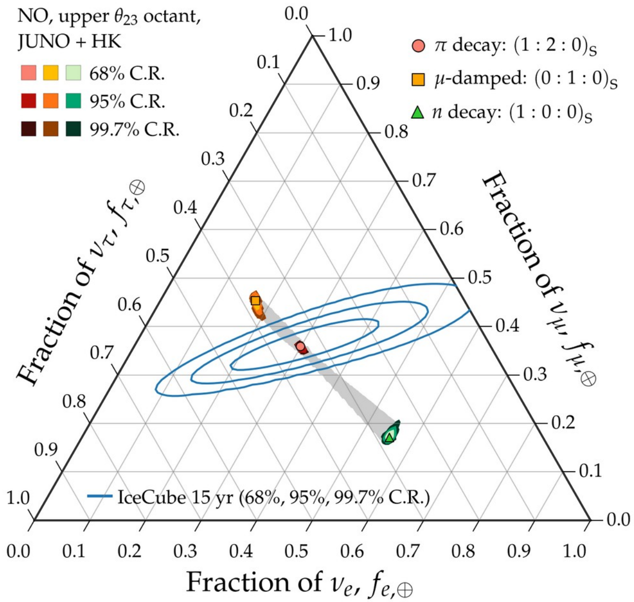
2030



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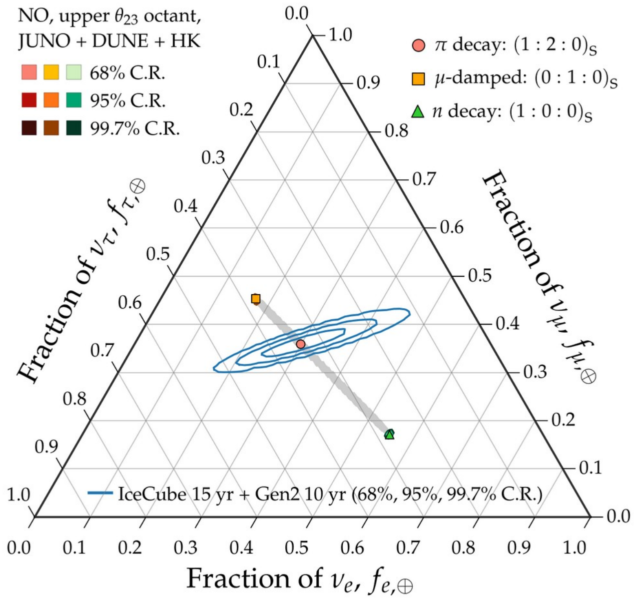
Measurement: improving

Nice

2040



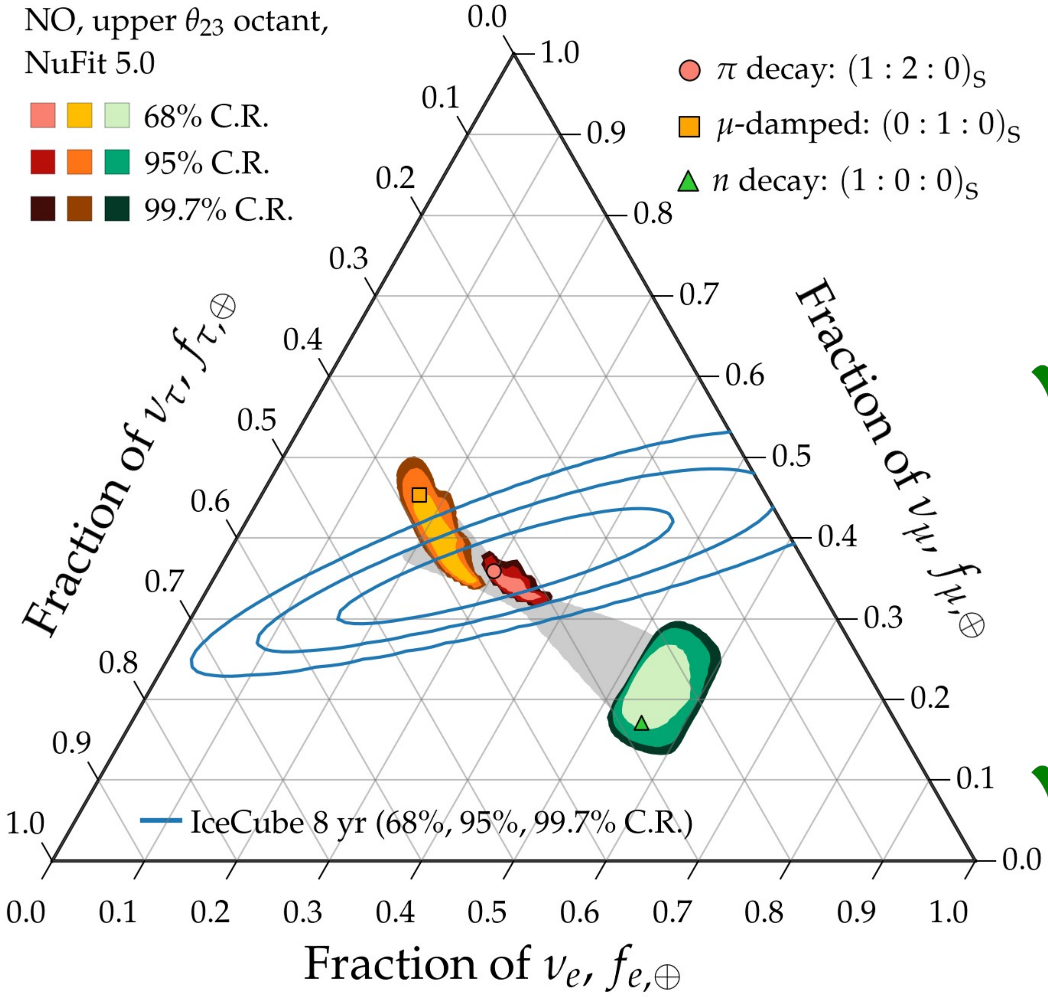
Allowed regions: well separated

Measurement: precise

Success

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

Theoretically palatable regions: today



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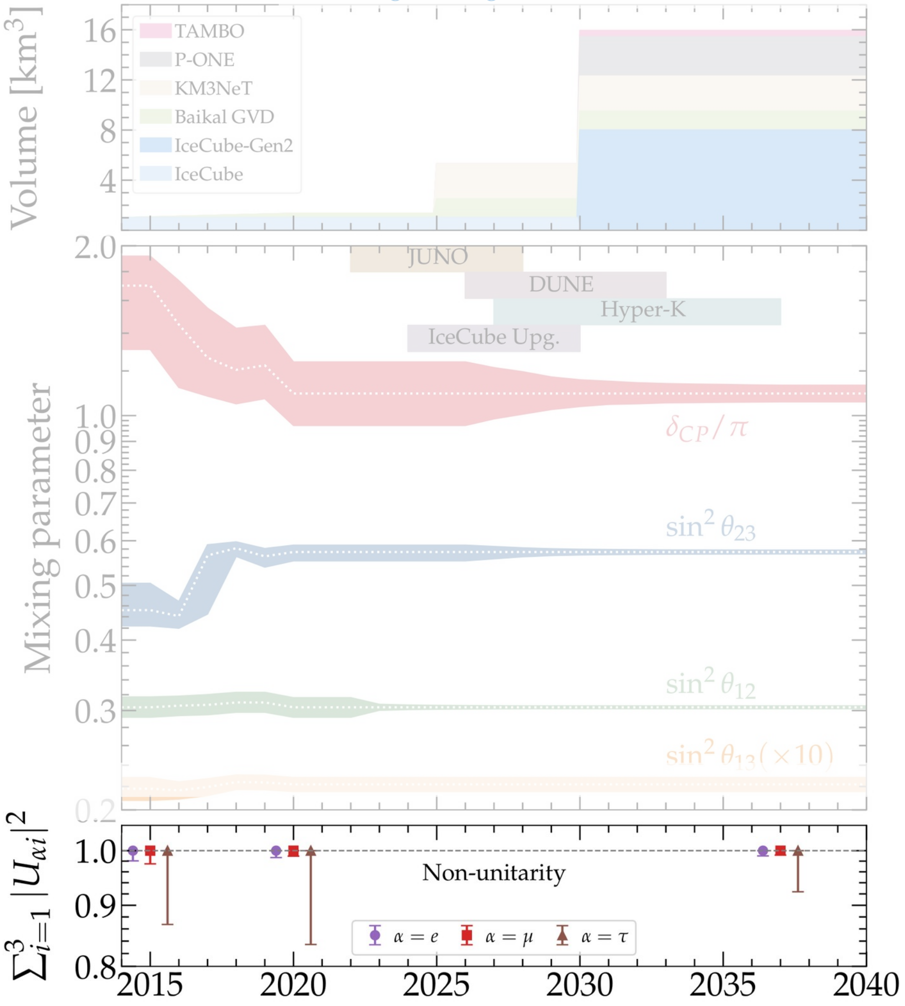

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Test of the oscillation framework:
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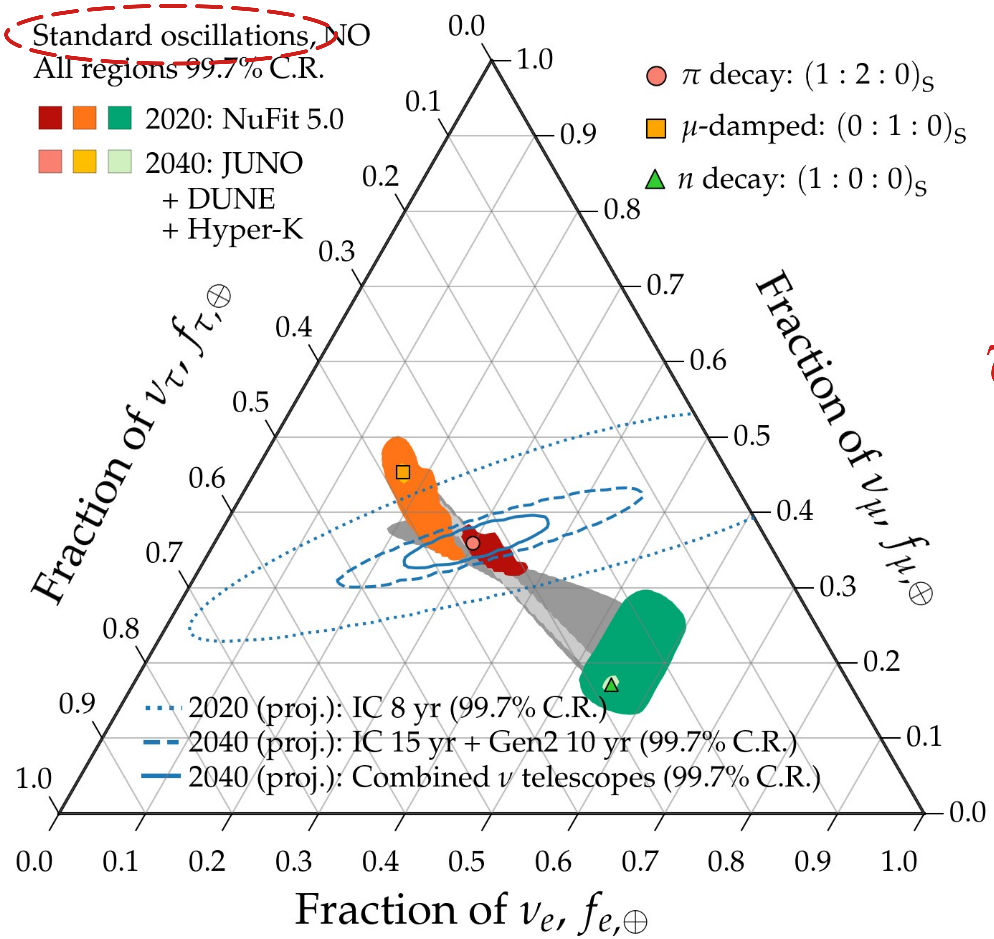
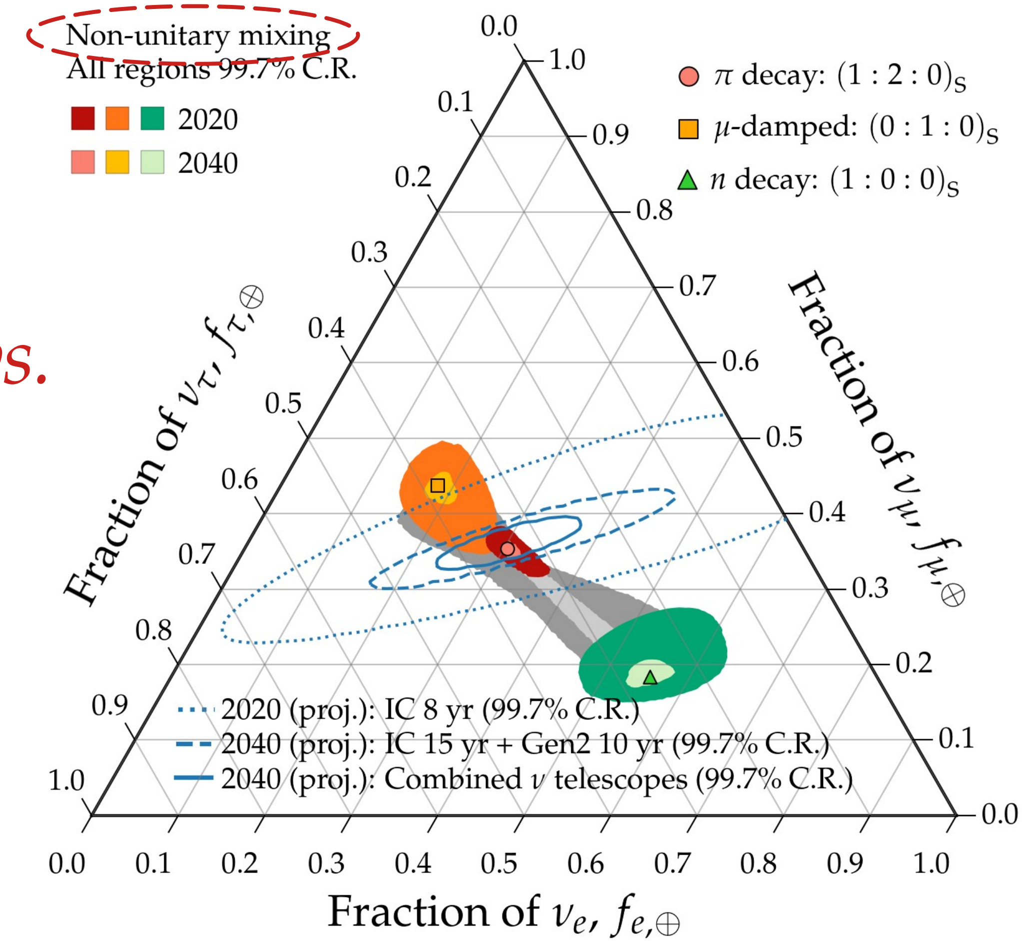
No unitarity? *No problem*



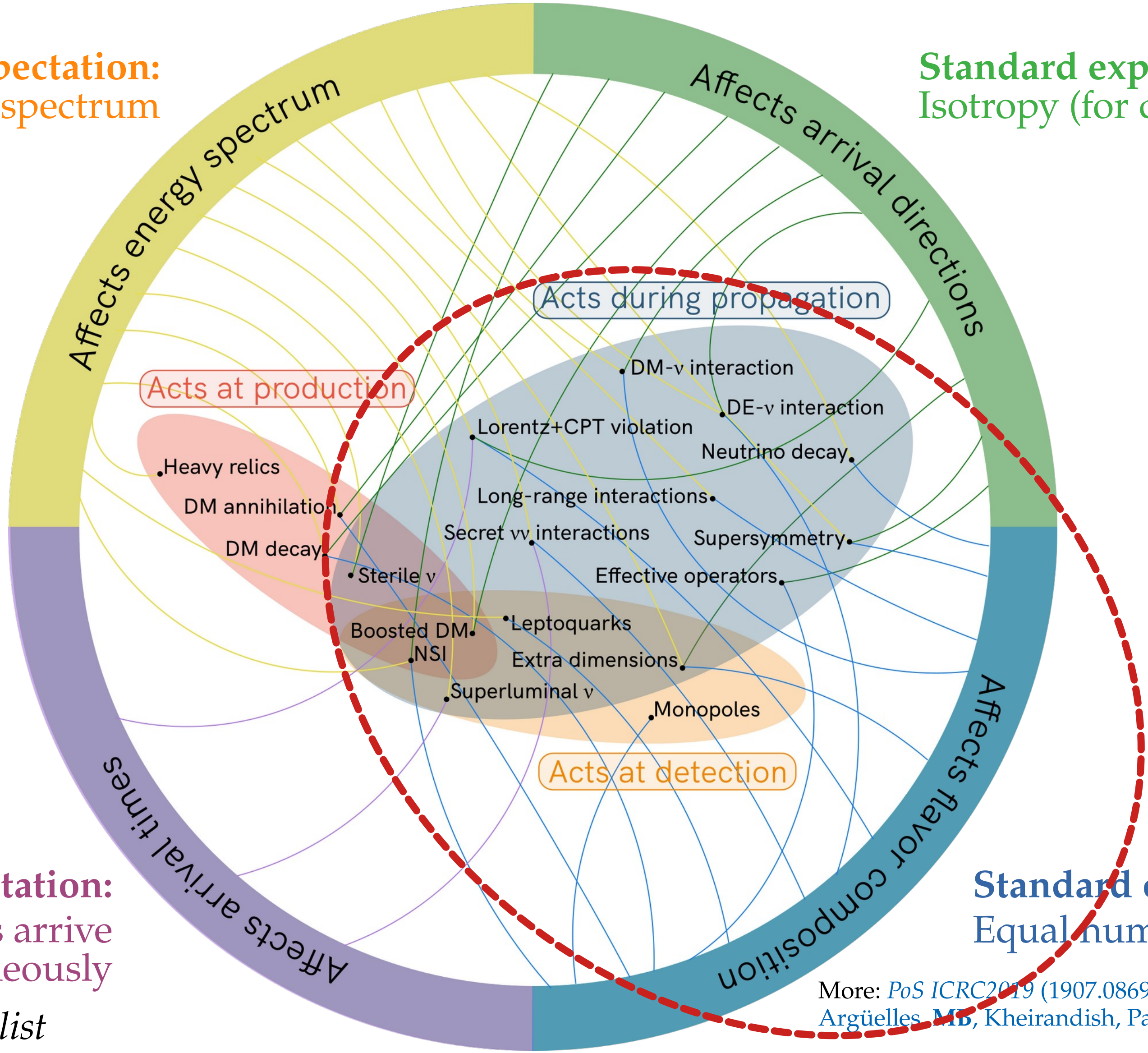
vs.



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

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Note: Not an exhaustive list

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

New physics in flavor composition

Repurpose the flavor sensitivity to test new physics:

New physics in flavor composition

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

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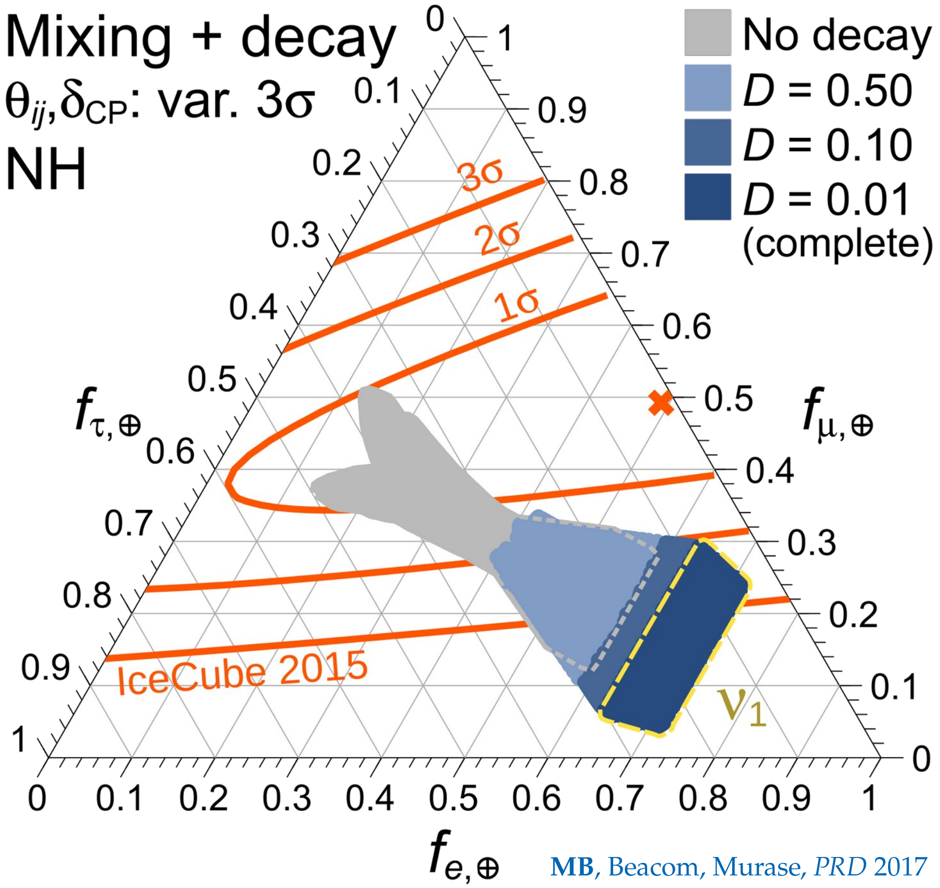
- Neutrino decay
  [Beacom *et al.*, *PRL* 2003; Baerwald, **MB**, Winter, JCAP 2010; **MB**, Beacom, Winter, *PRL* 2015; **MB**, Beacom, Murase, *PRD* 2017]



MB, Beacom, Murase, *PRD* 2017

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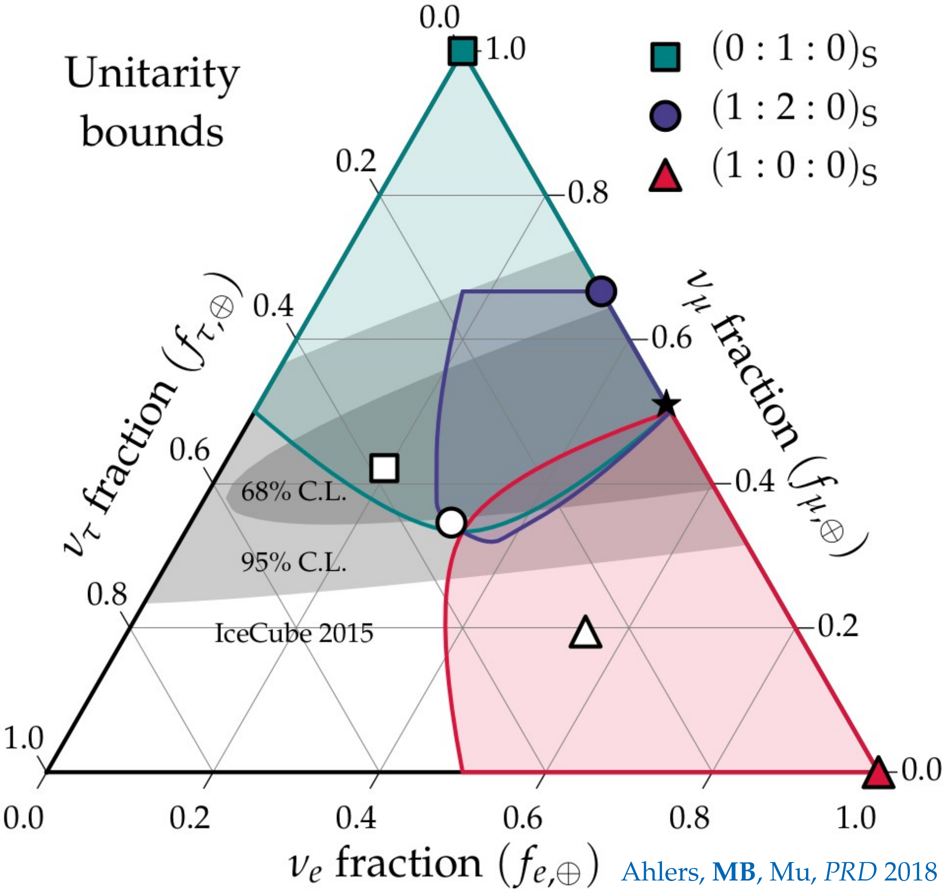

Ahlers, **MB**, Mu, *PRD* 2018

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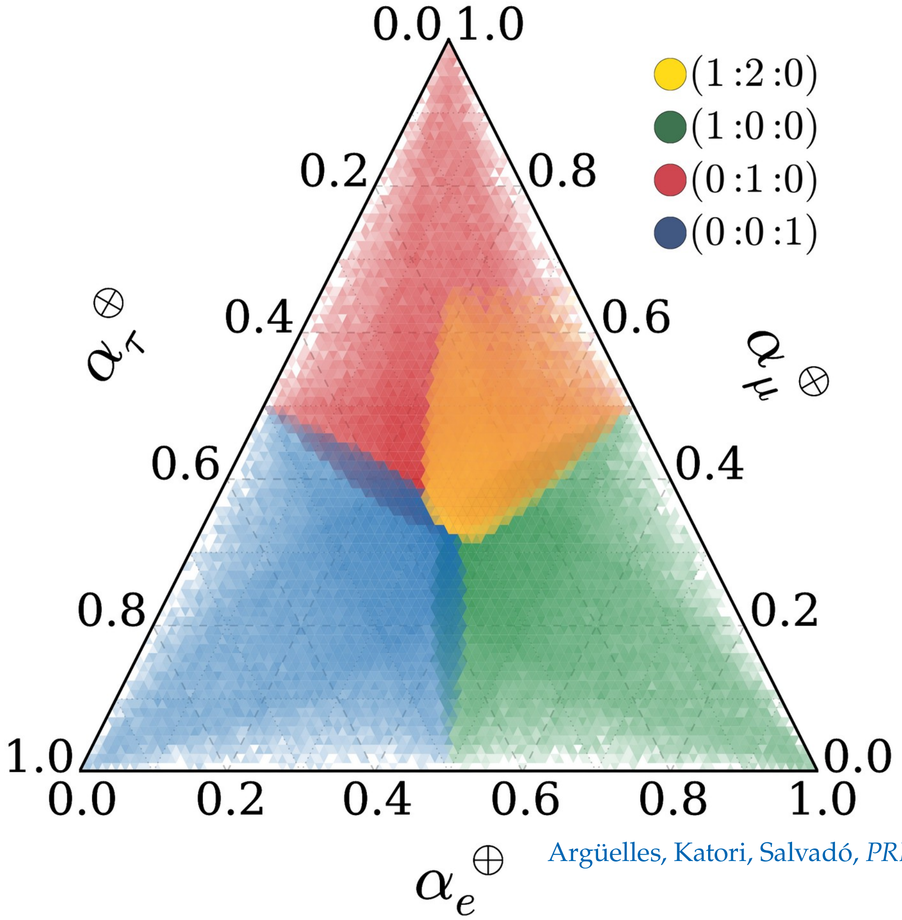

Argüelles, Katori, Salvadó, *PRL* 2015

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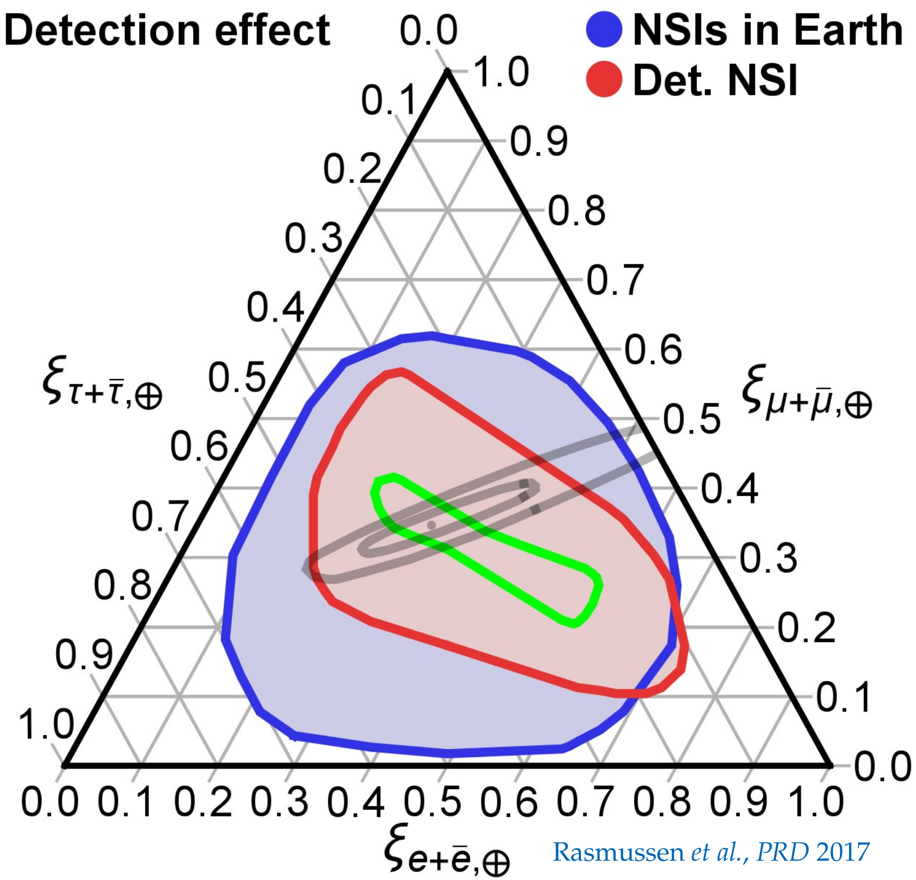
- Non-standard interactions
  [González-García *et al.*, *Astropart. Phys.* 2016; Rasmussen *et al.*, *PRD* 2017]



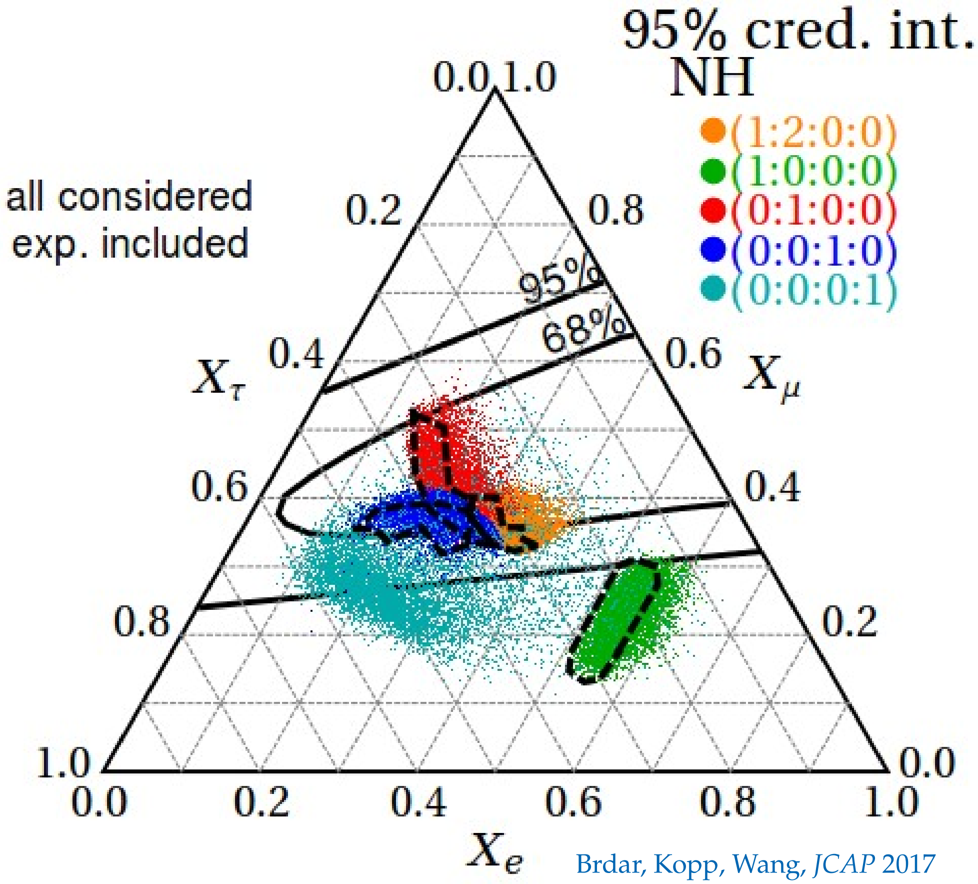
Rasmussen *et al.*, *PRD* 2017

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

New physics in flavor composition

Repurpose the flavor sensitivity to test new physics:

- Neutrino decay
  [Beacom *et al.*, *PRL* 2003; Baerwald, **MB**, Winter, JCAP 2010; **MB**, Beacom, Winter, *PRL* 2015; **MB**, Beacom, Murase, *PRD* 2017]
- Tests of unitarity at high energy
  [Xu, He, Rodejohann, *JCAP* 2014; Ahlers, **MB**, Mu, *PRD* 2018; Ahlers, **MB**, Nortvig, *JCAP* 2021]
- Lorentz- and CPT-invariance violation
  [Barenboim & Quigg, *PRD* 2003; **MB**, Gago, Peña-Garay, *JHEP* 2010; Kostelecky & Mewes 2004; Argüelles, Katori, Salvadó, *PRL* 2015]
- Non-standard interactions
  [González-García *et al.*, *Astropart. Phys.* 2016; Rasmussen *et al.*, *PRD* 2017]
- Active-sterile ν mixing
  [Aeikens *et al.*, *JCAP* 2015; Brdar, Kopp, Wang, *JCAP* 2017; Argüelles *et al.*, *JCAP* 2020; Ahlers, **MB**, *JCAP* 2021]



Brdar, Kopp, Wang, *JCAP* 2017

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

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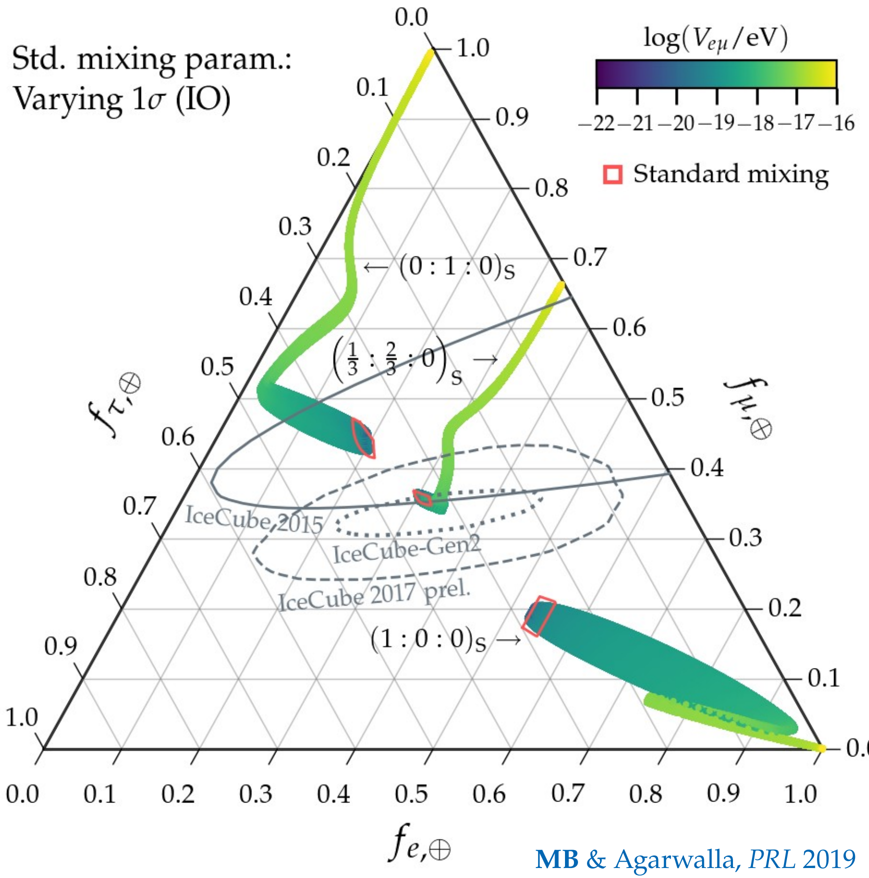
- **Long-range *e*ν interactions**
  [**MB** & Agarwalla, *PRL* 2019]

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



MB & Agarwalla, *PRL* 2019

4. Unstable neutrinos:
Are neutrinos for ever?

Are neutrinos forever?

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

  » Age of Universe (~ 14.5 Gyr)

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

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

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  Nambu-Goldstone boson of a broken symmetry

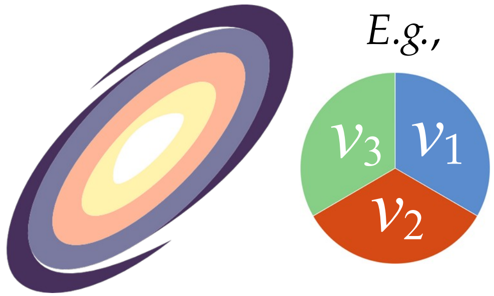
- We work in a model-independent way:
  the nature of φ is unimportant if it is invisible to neutrino detectors

Astrophysical sources

Earth

L ~ up to a few Gpc

E.g.,



Decay changes the number

of each ν mass eigenstate, N_1, N_2, N_3

?

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

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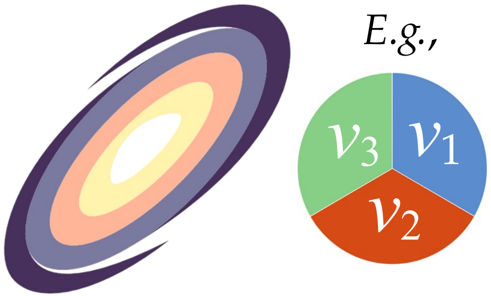

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The flux of ν_i is attenuated by $\exp[-\,(L/E)\cdot\overbrace{(\underbrace{m_i}_{\text{Mass of } \nu_i}/\underbrace{\tau_i}_{\text{Lifetime of } \nu_i})}^{\text{Only sensitive to their ratio}}]$

Astrophysical sources

Earth

L ~ up to a few Gpc

E.g.,

Decay changes the number

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?

Lower-E ν are longer-lived…

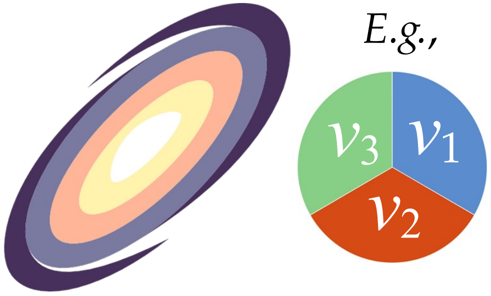
The flux of ν_i is attenuated by exp[- $(L/E) \cdot (m_i/\tau_i)$]

… but ν that travel longer L are more attenuated!

Astrophysical sources

Earth

$L \sim$ up to a few Gpc



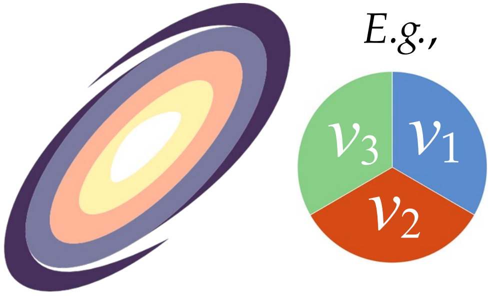
Astrophysical sources Earth

$L \sim$ up to a few Gpc

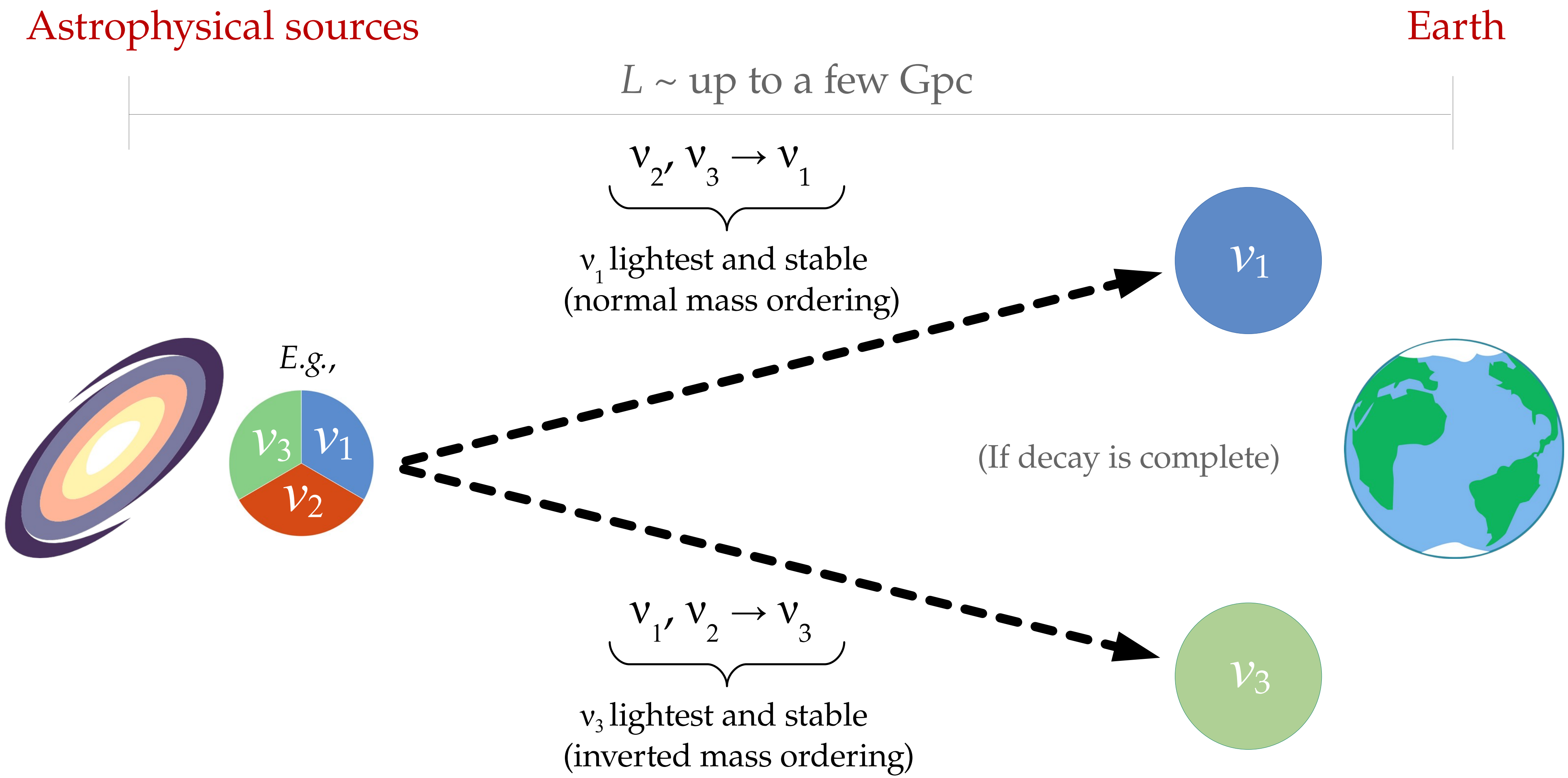
$$\underbrace{\nu_2, \nu_3 \to \nu_1}$$

ν_1 lightest and stable
(normal mass ordering)

E.g.,



(If decay is complete)


Astrophysical sources
Earth
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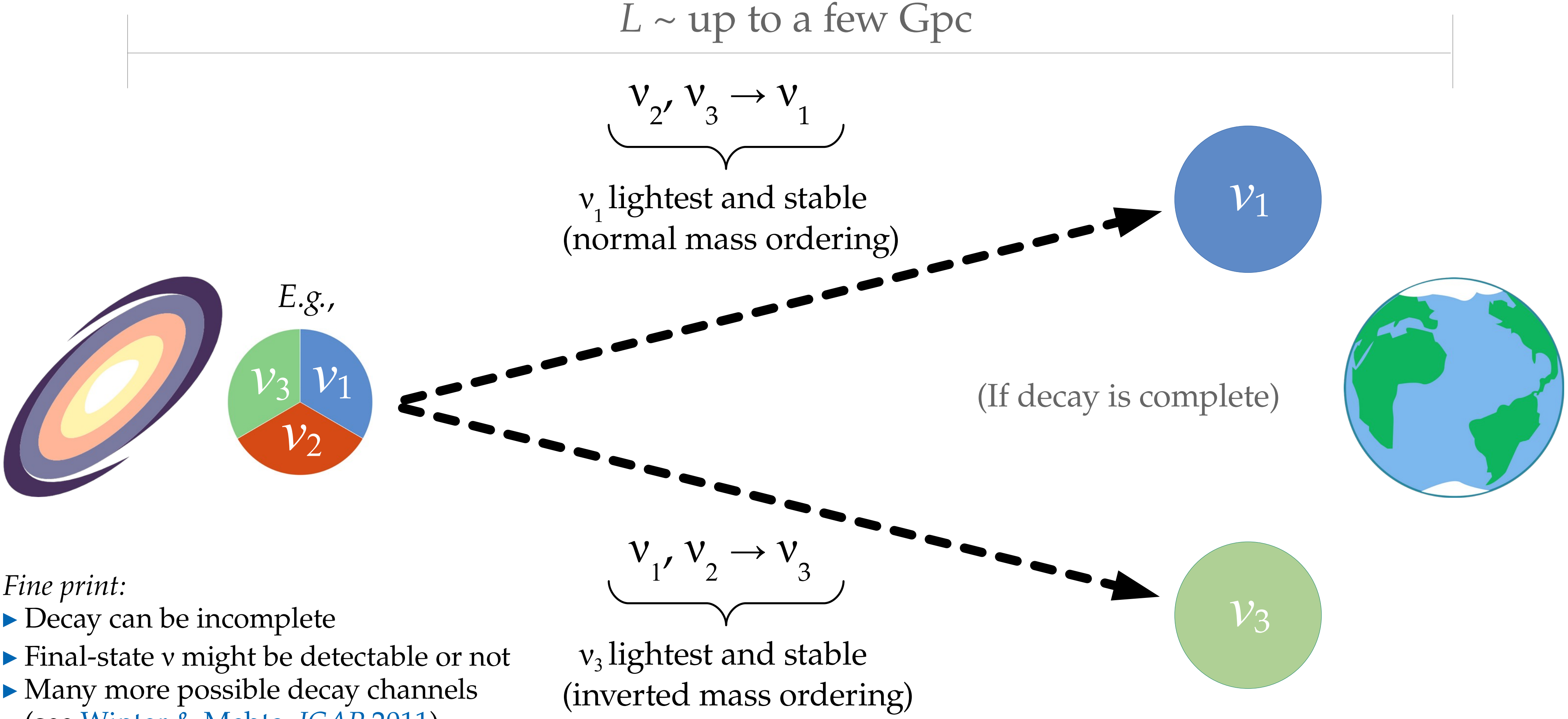
E.g.,
ν_3 ν_1 ν_2
ν_1
(If decay is complete)
$\underbrace{\nu_1, \nu_2 \to \nu_3}$
ν_3 lightest and stable
(inverted mass ordering)
ν_3

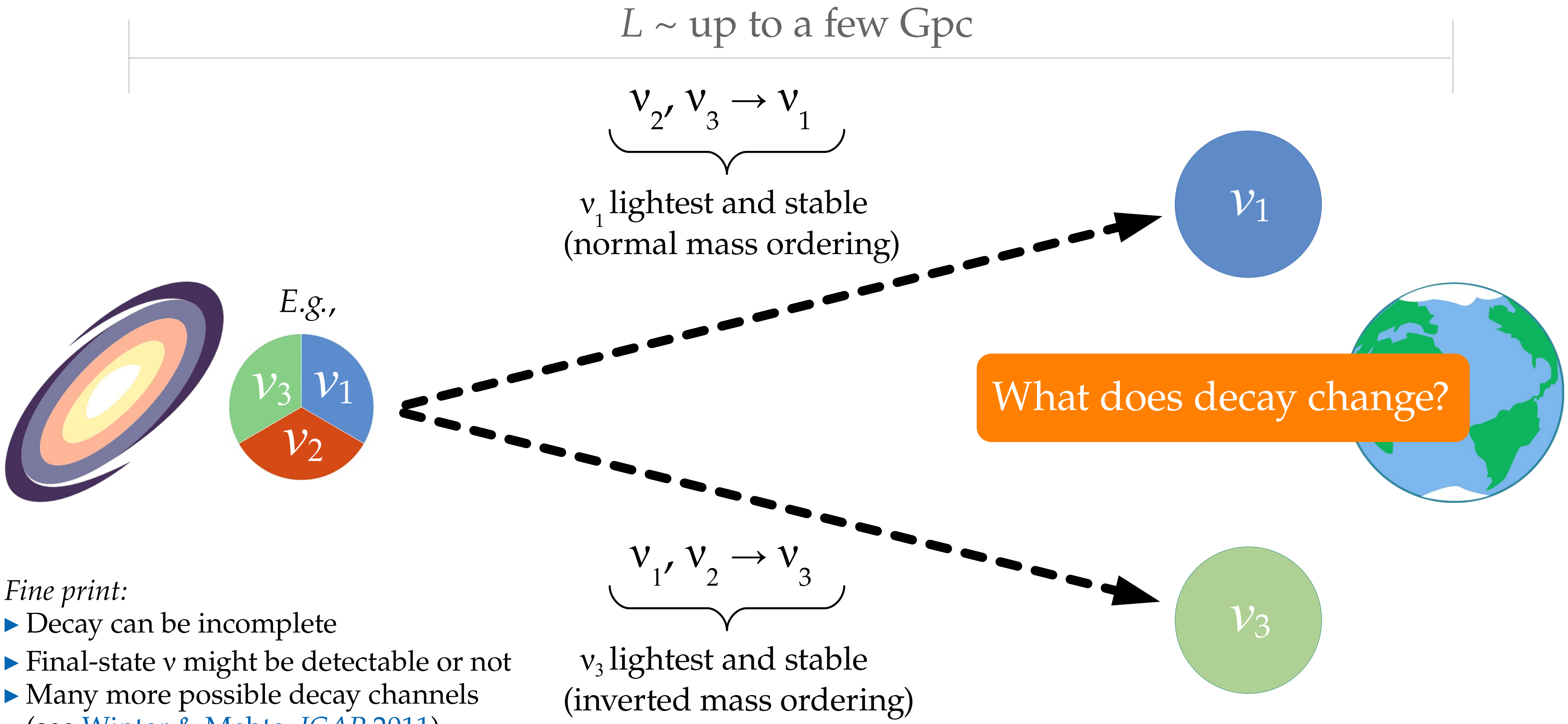
Astrophysical sources Earth



Fine print:

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

Astrophysical sources — Earth



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What does neutrino decay change?

Flavor composition ⟺ Spectrum shape ⟺ Event rate

What does neutrino decay change?

Flavor composition ⟺ Spectrum shape ⟺ Event rate

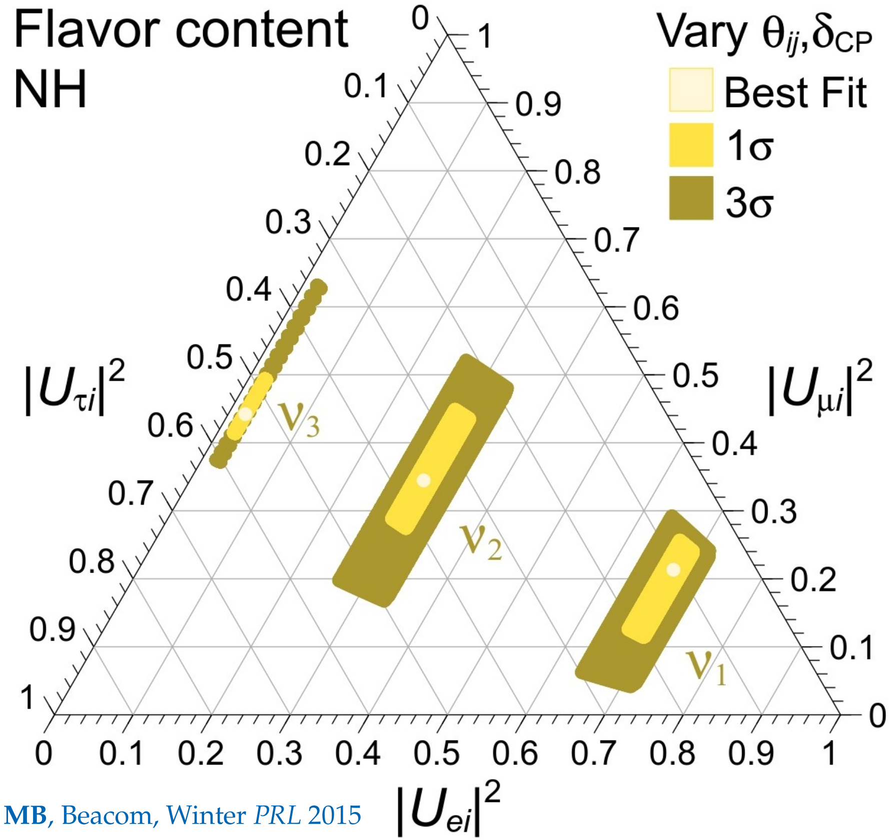
Flavor content of mass eigenstates:

Known to within 2%

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

Known to within 8%

Known to within 20%
(or worse)



MB, Beacom, Winter *PRL* 2015

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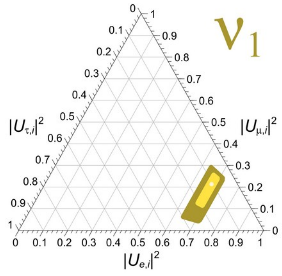

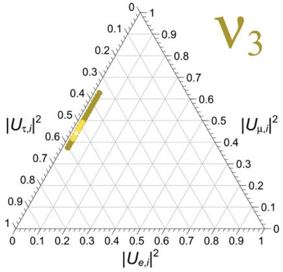

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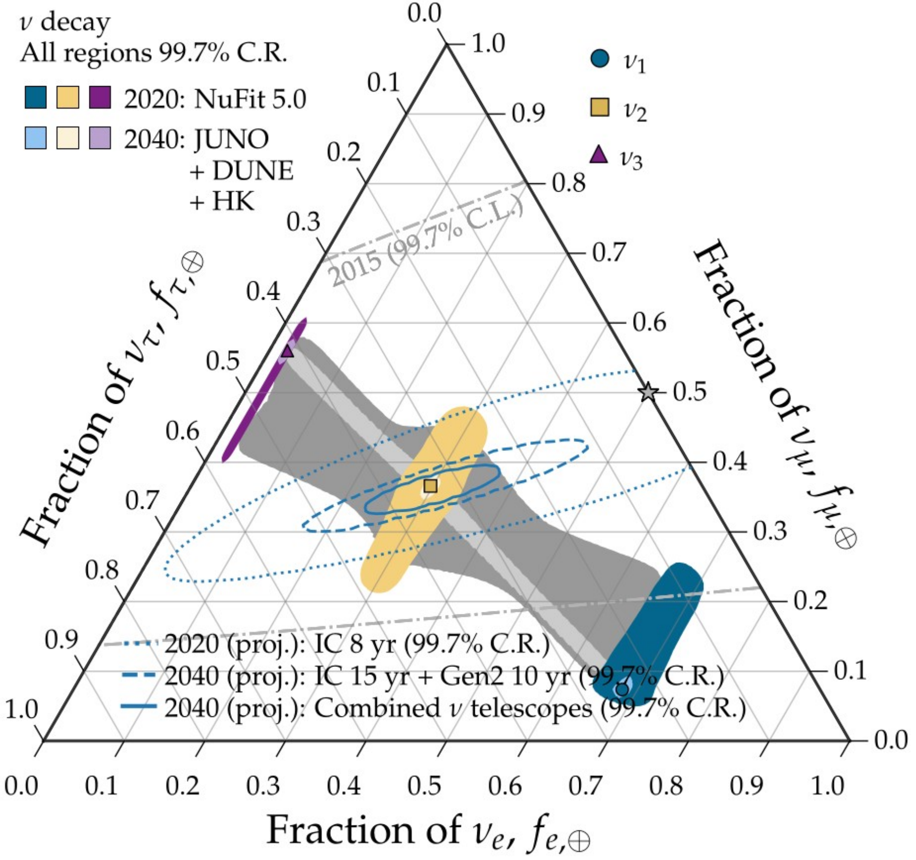
Flavor composition ⟺ Spectrum shape ⟺ Event rate



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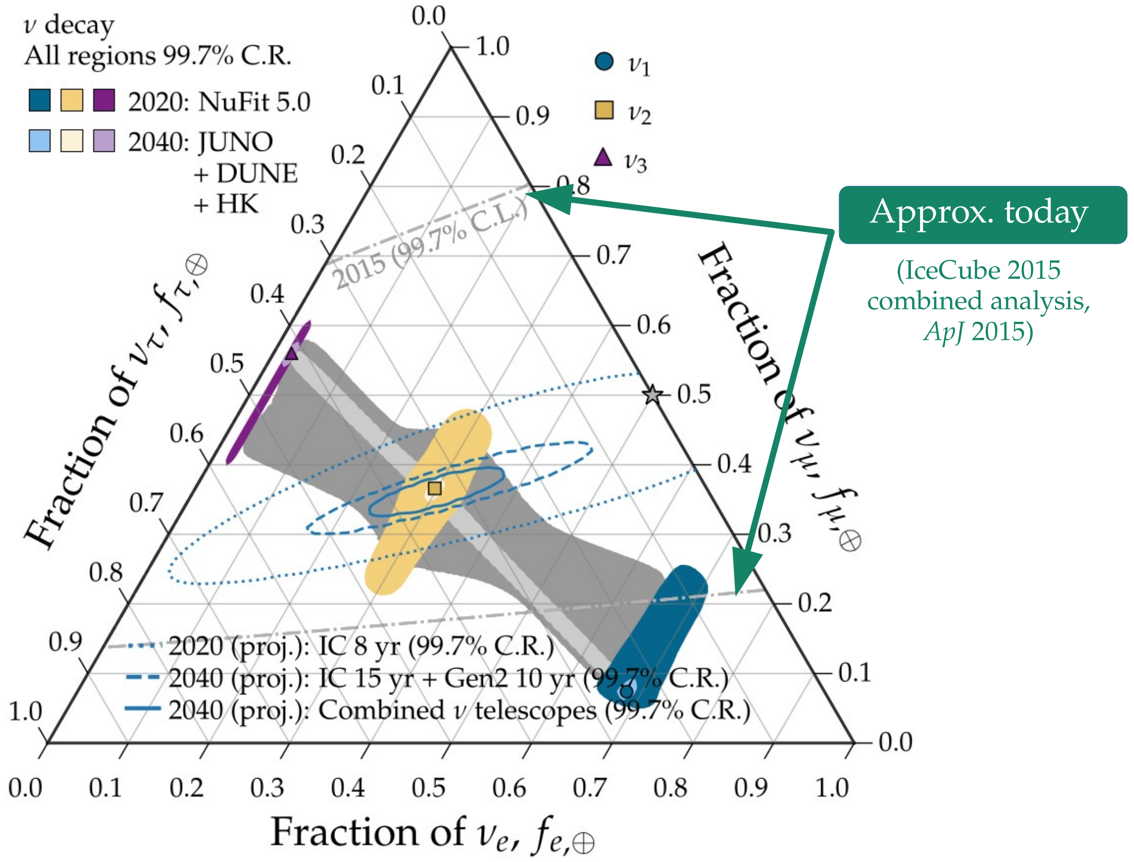

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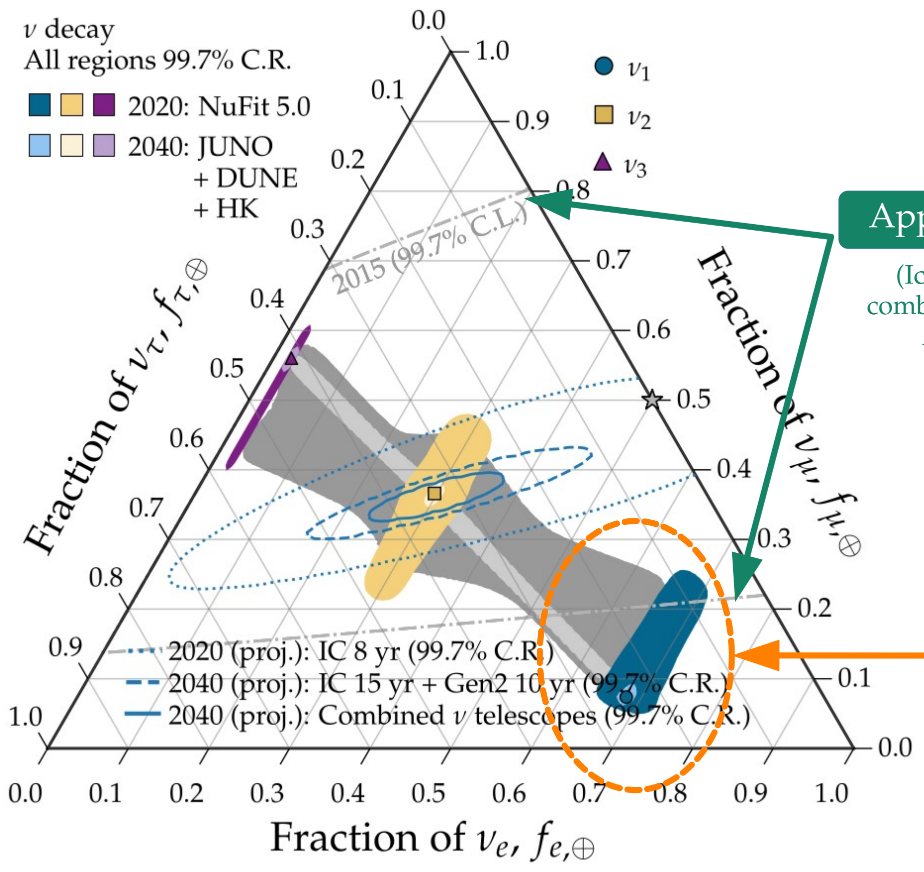

Approx. today

(IceCube 2015 combined analysis, *ApJ* 2015)

Complete decay into ν_1 disfavored by 2015 IceCube flavor measurement

What does neutrino decay change?

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

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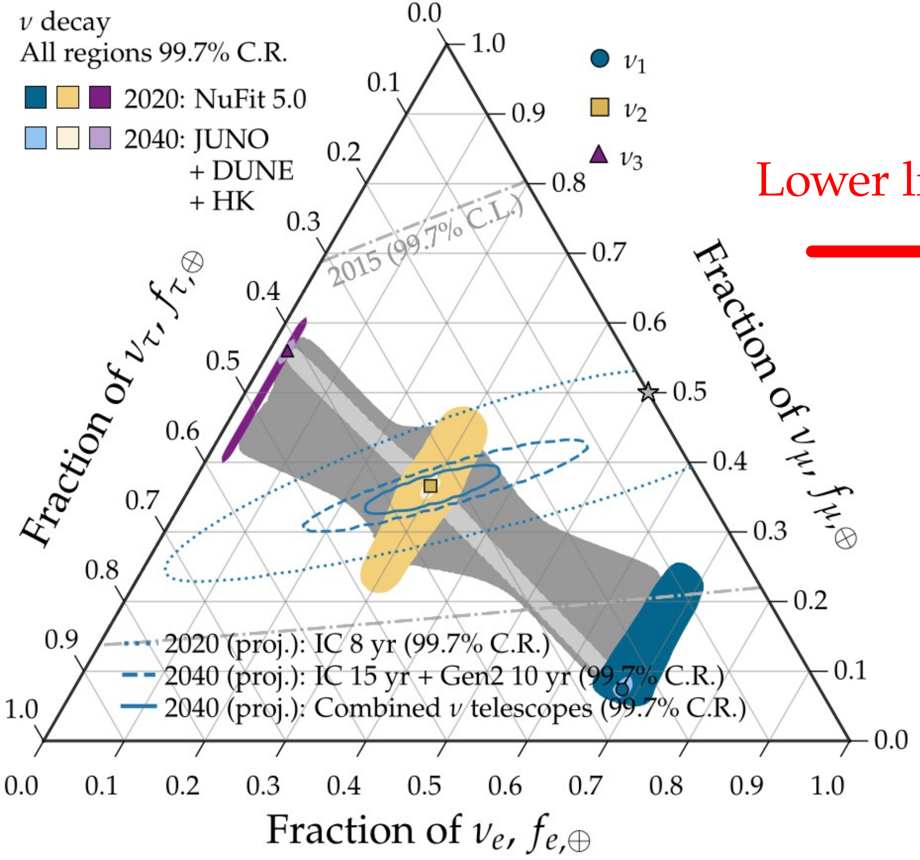

Lower limit on τ/m →

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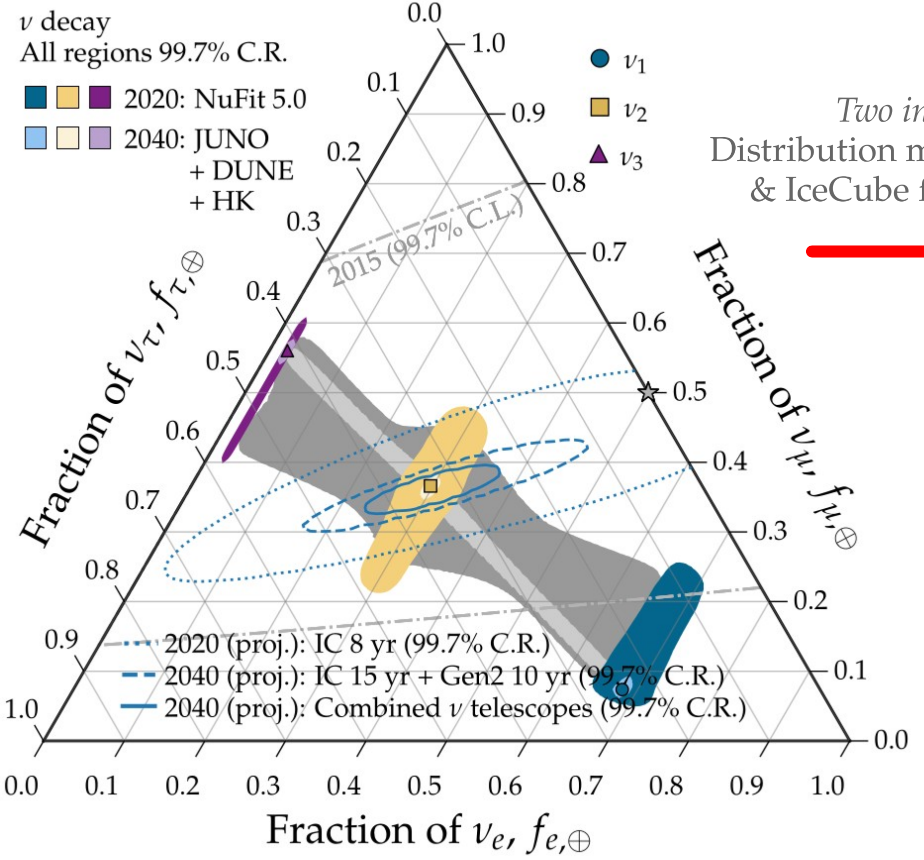

Two ingredients:
Distribution mixing parameters
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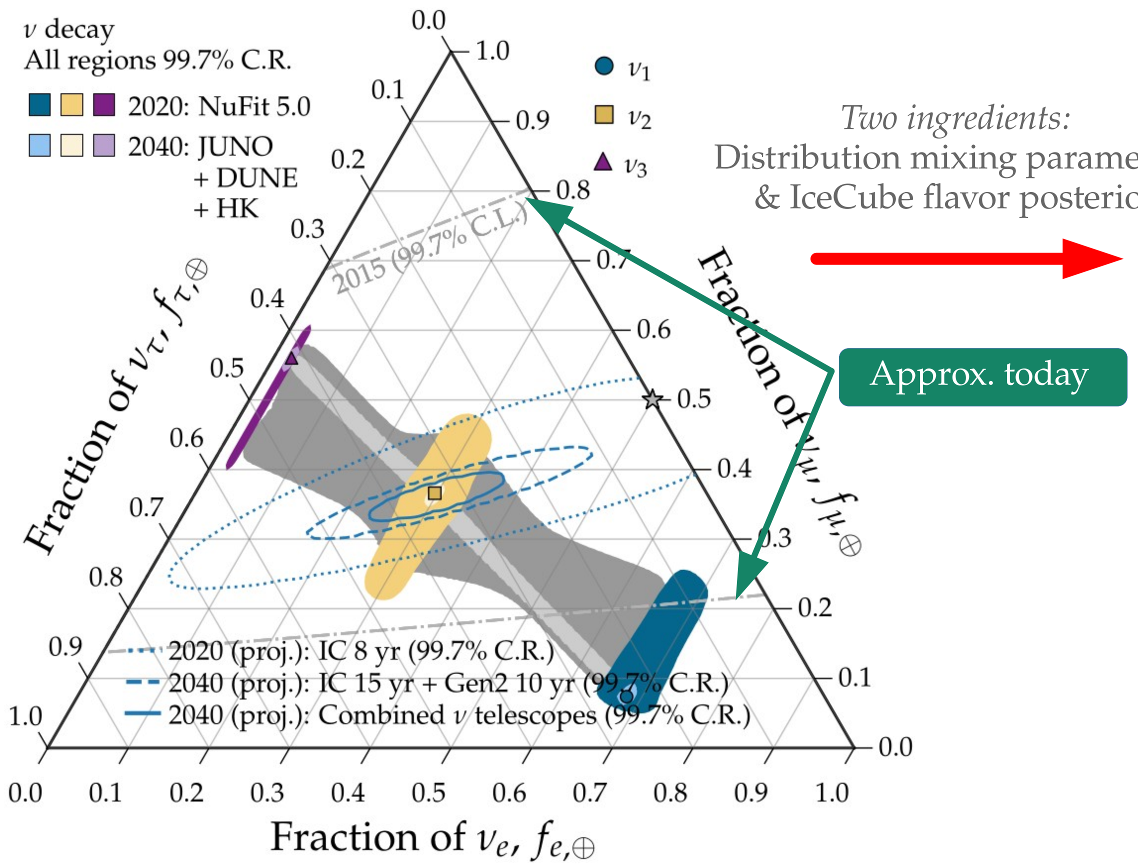

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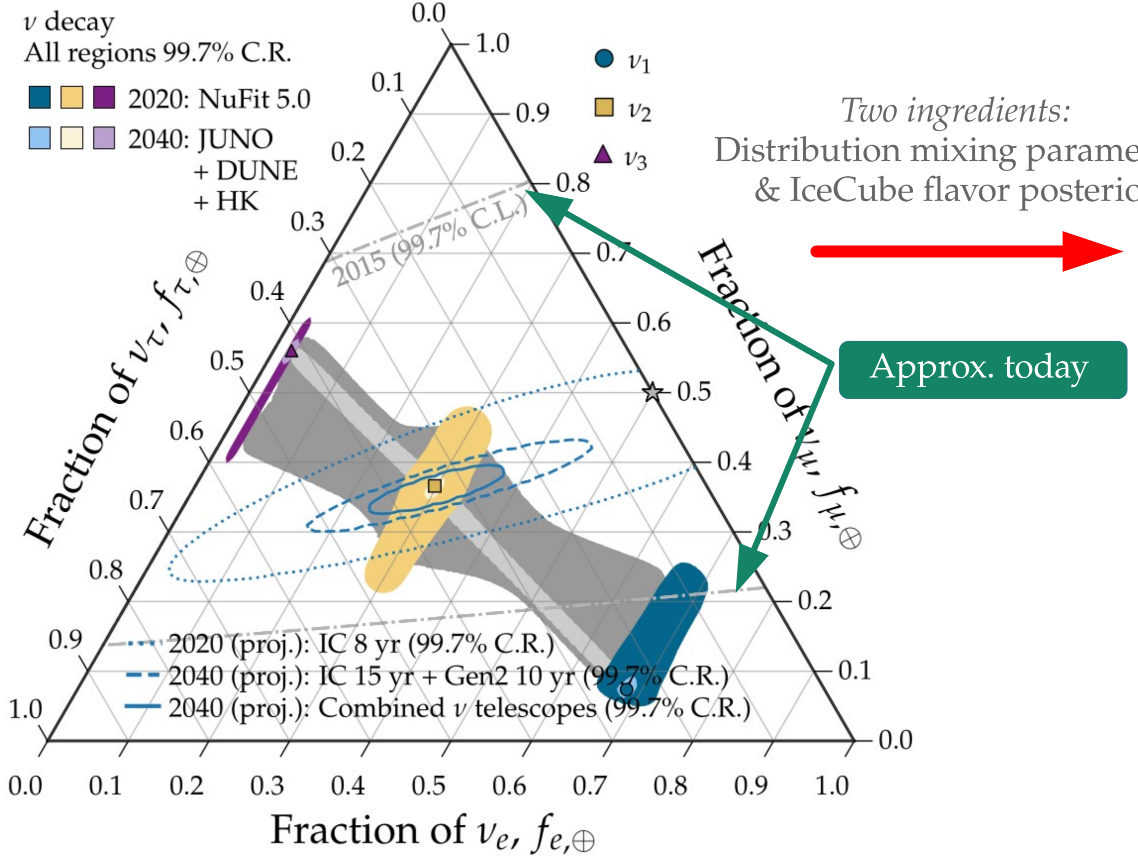

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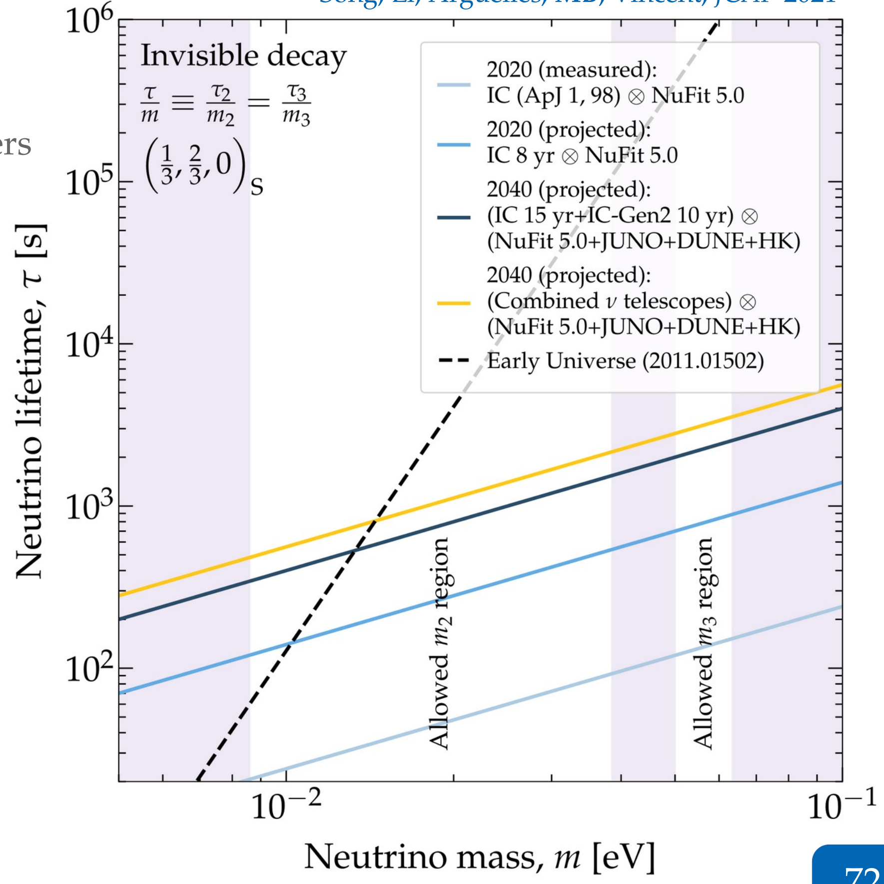
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



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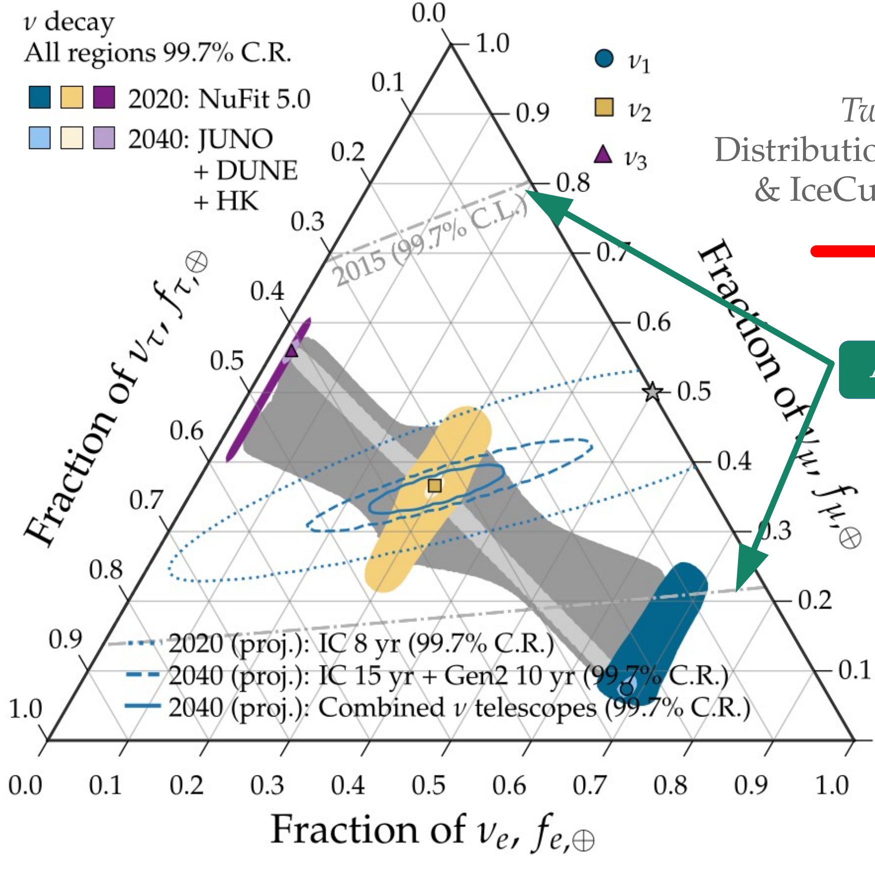

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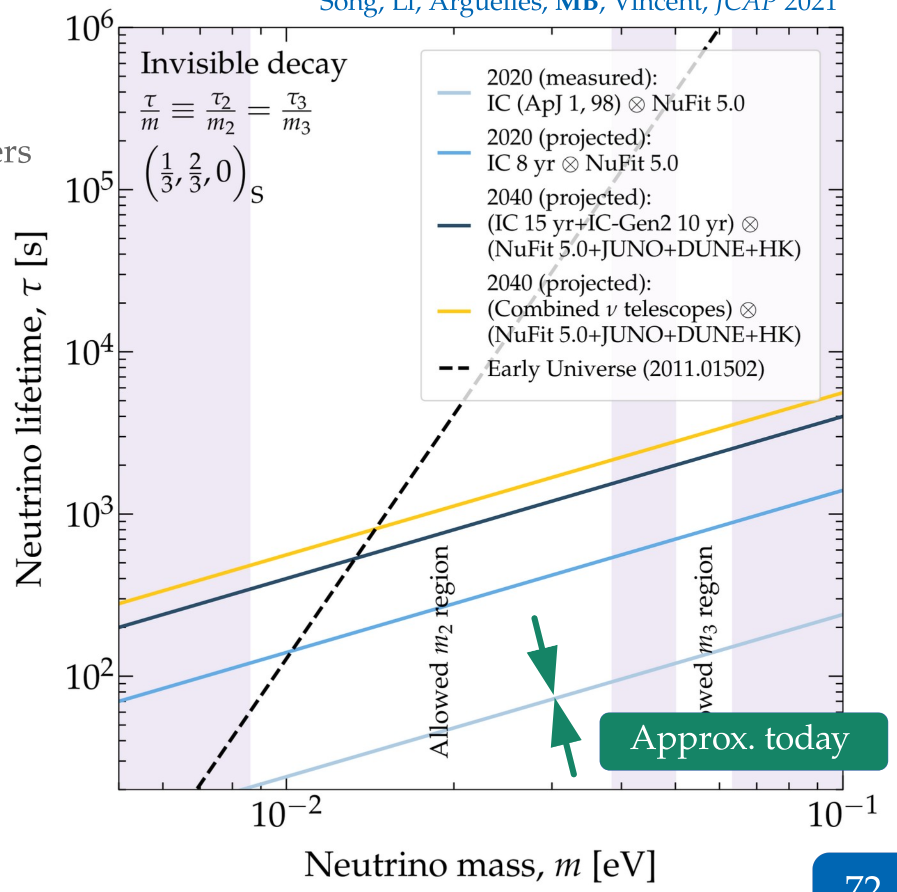

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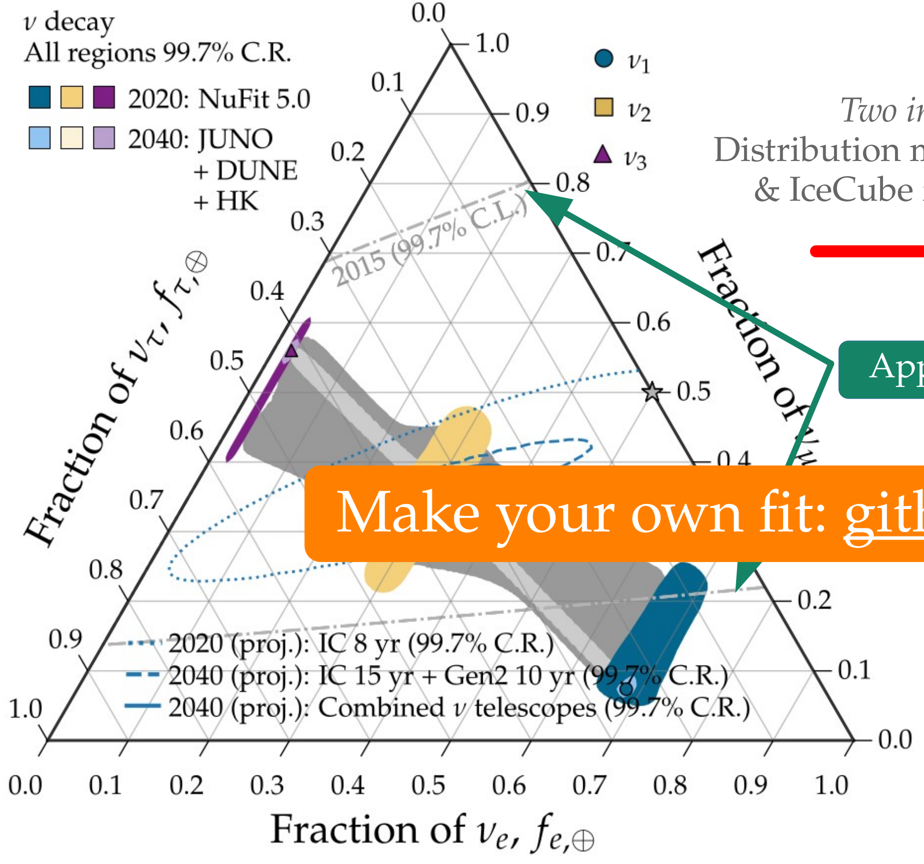

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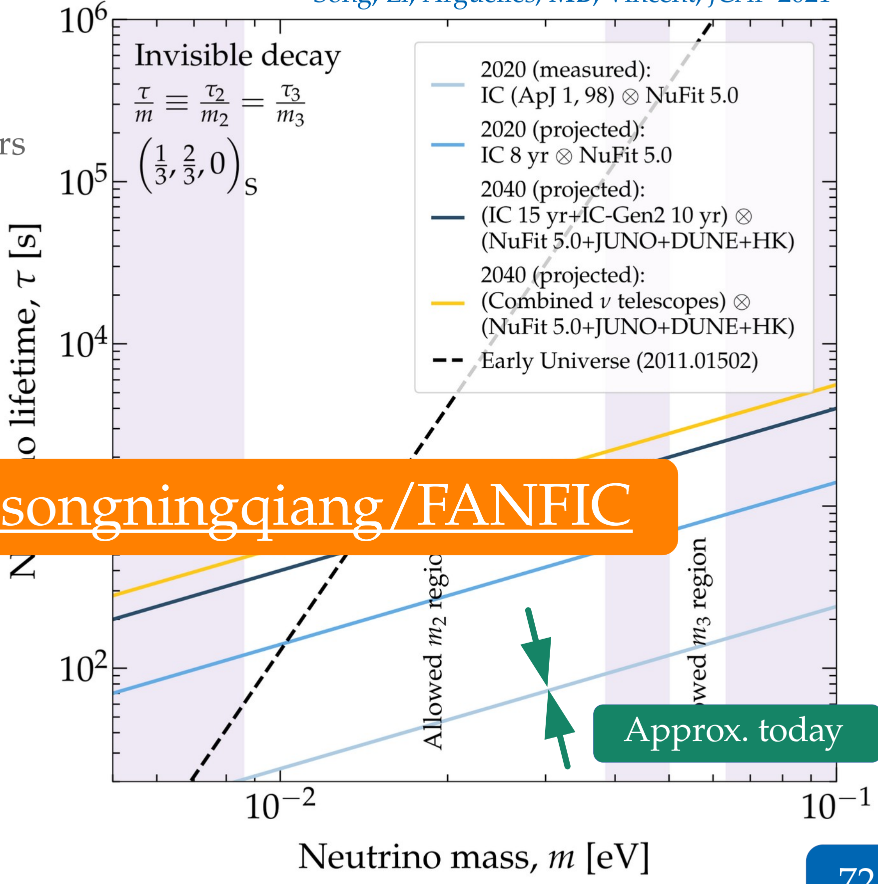

Make your own fit: github.com/songningqiang/FANFIC

What does neutrino decay change?

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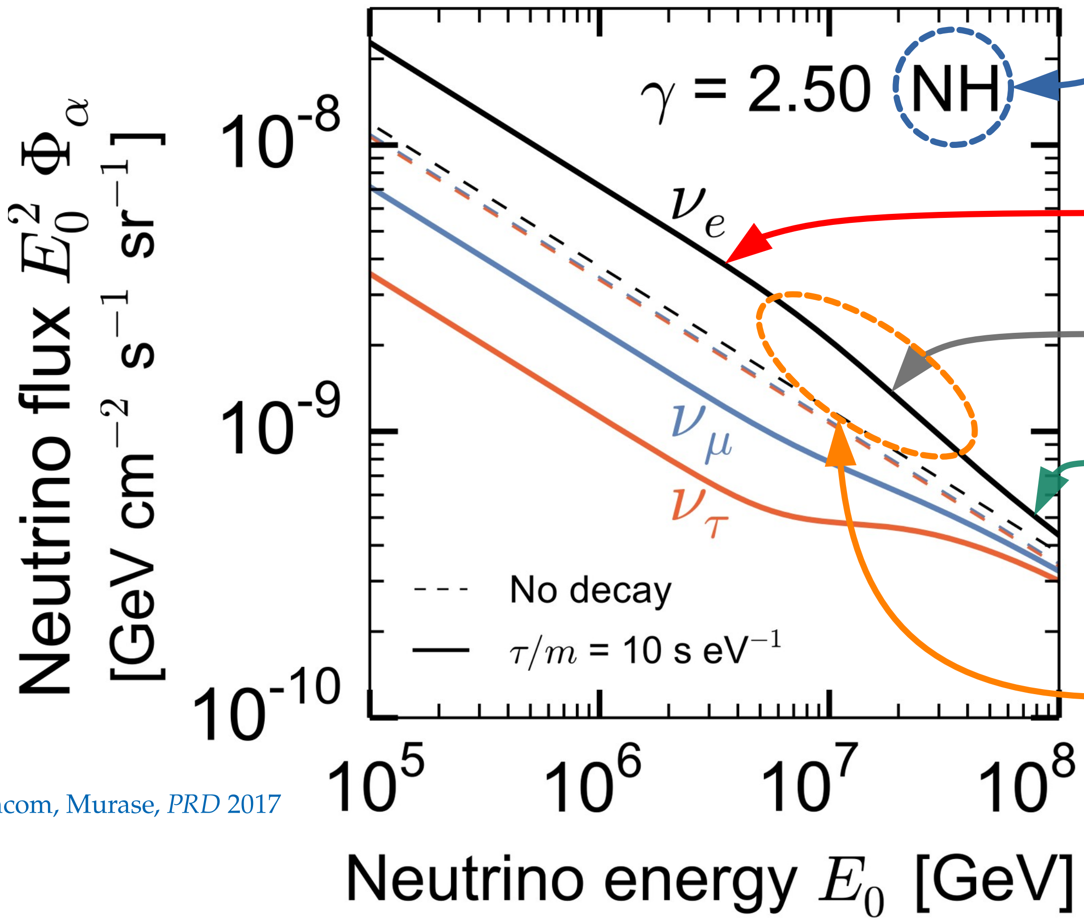
Flavor composition ⟺ Spectrum shape ⟺ Event rate



MB, Beacom, Murase, *PRD* 2017

$\nu_2, \nu_3 \to \nu_1$

Low energy: decay evident

Transition region

High energy: no decay

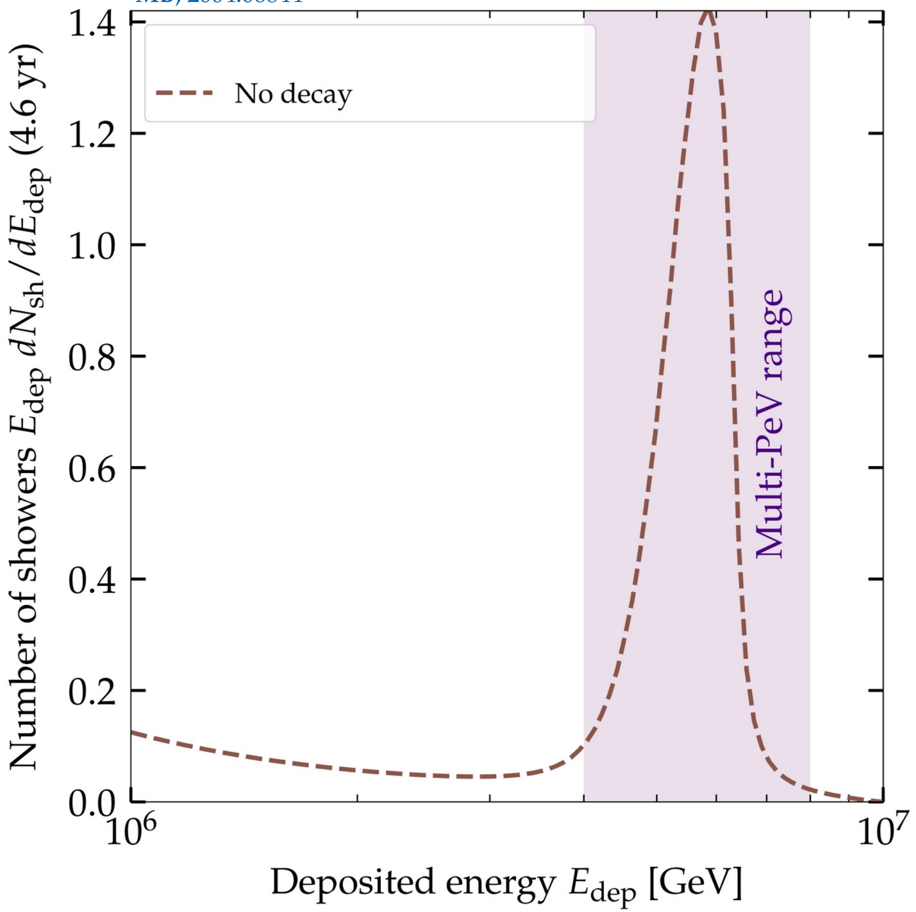
Look for sigmoid-like transition in spectrum: *challenging, but possible with more statistics*!

What does neutrino decay change?

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

Flavor composition ⟺ Spectrum shape ⟺ Event rate

MB, 2004.06844



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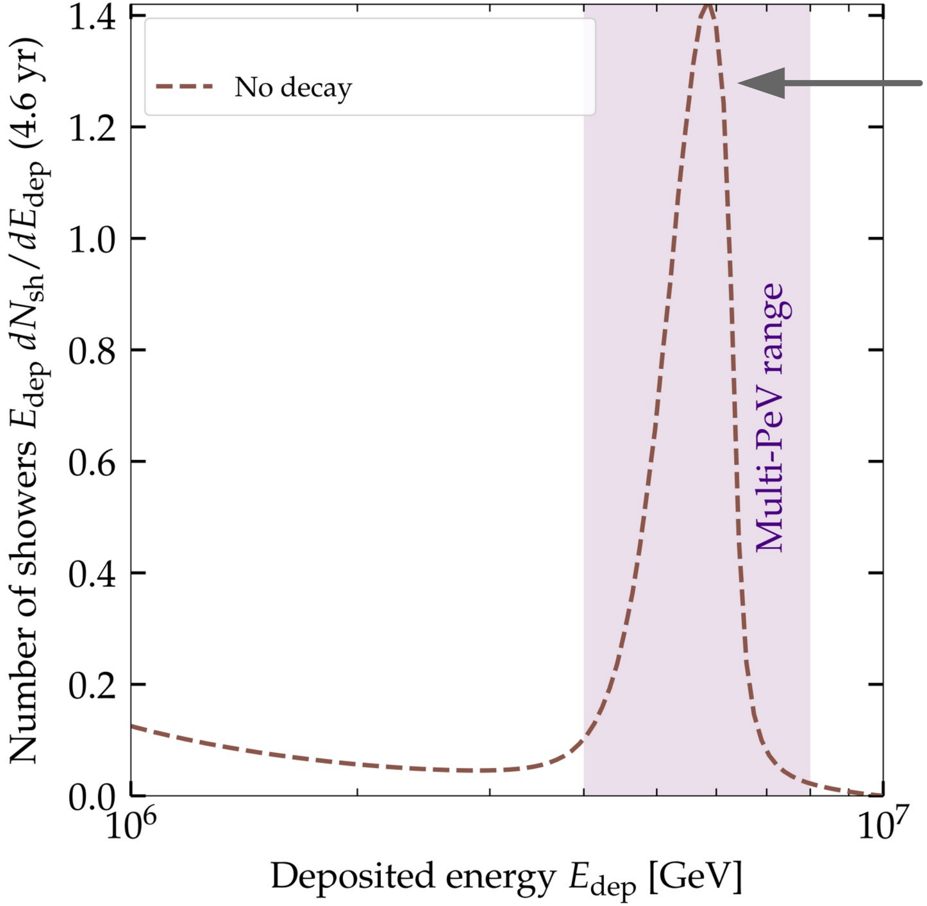

Glashow resonance (GR):
$\bar{\nu}_e + e \rightarrow W \rightarrow$ hadrons $\rightarrow$ shower

What does neutrino decay change?

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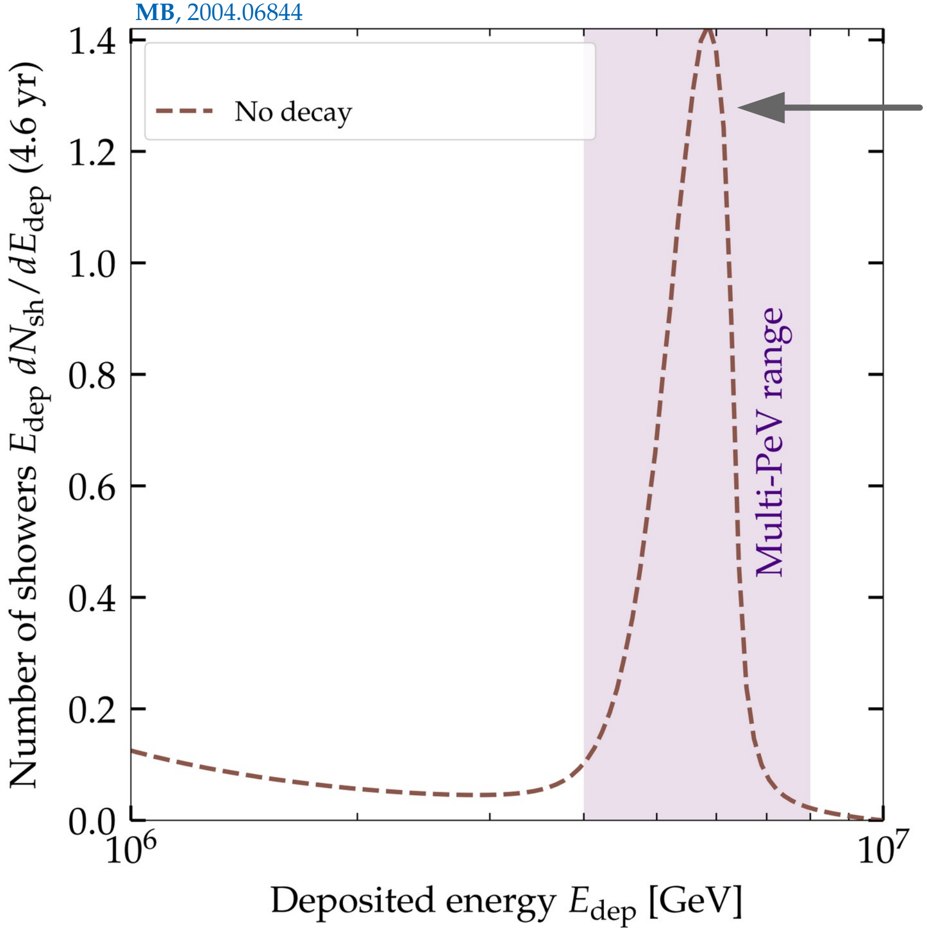
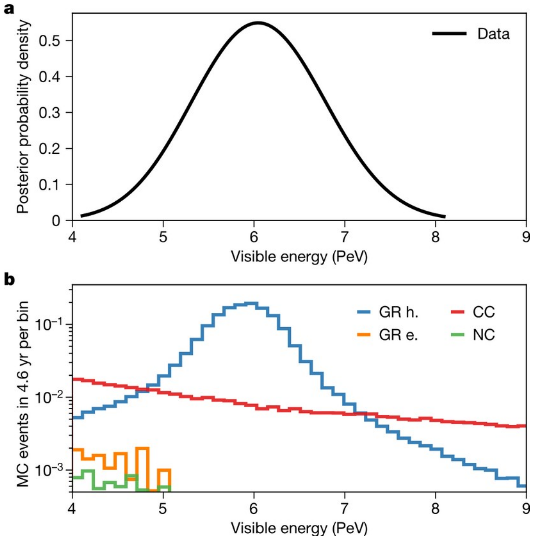
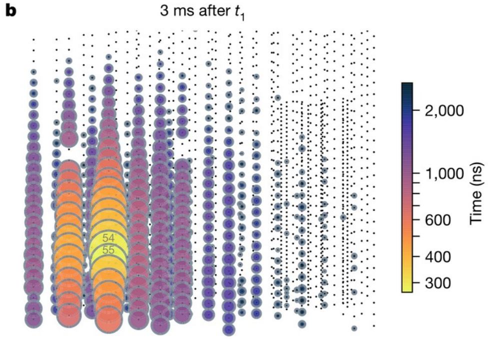


Glashow resonance (GR):
$\bar{\nu}_e + e \to W \to$ hadrons $\to$ shower

IceCube has seen one GR candidate in 4.6 years:





IceCube Collab., *Nature* 2021

What does neutrino decay change?

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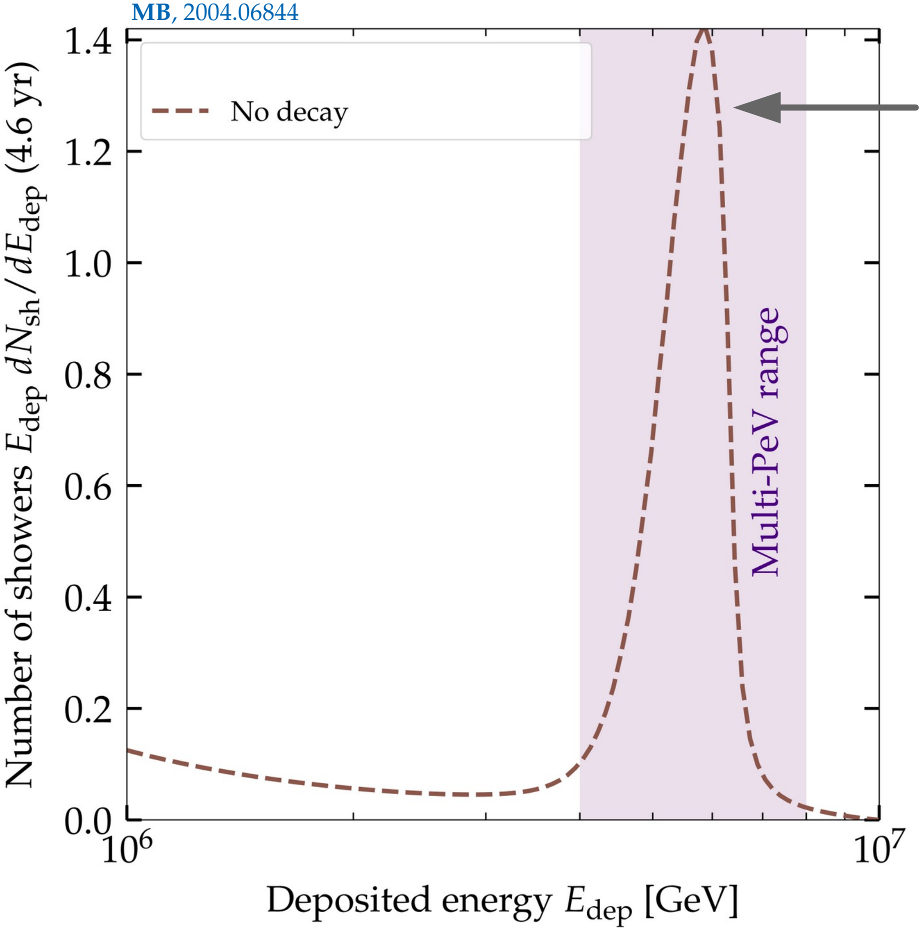
Flavor composition ⟺ Spectrum shape ⟺ **Event rate**

MB, 2004.06844



Glashow resonance (GR):
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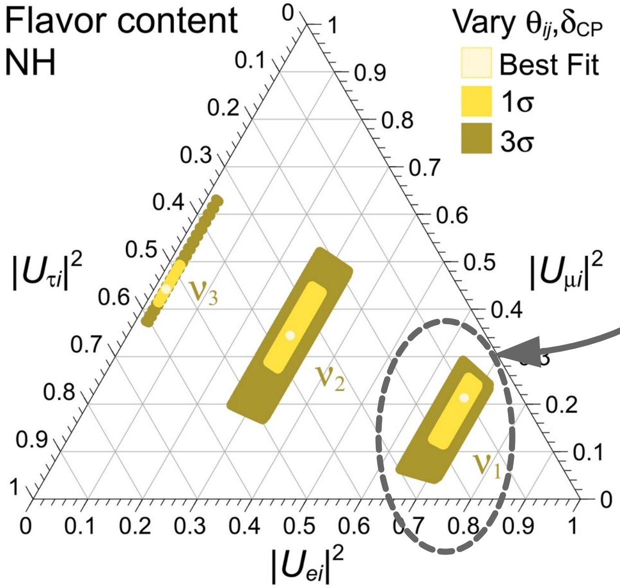
ν_1 is the mass eigenstate with the most e flavor



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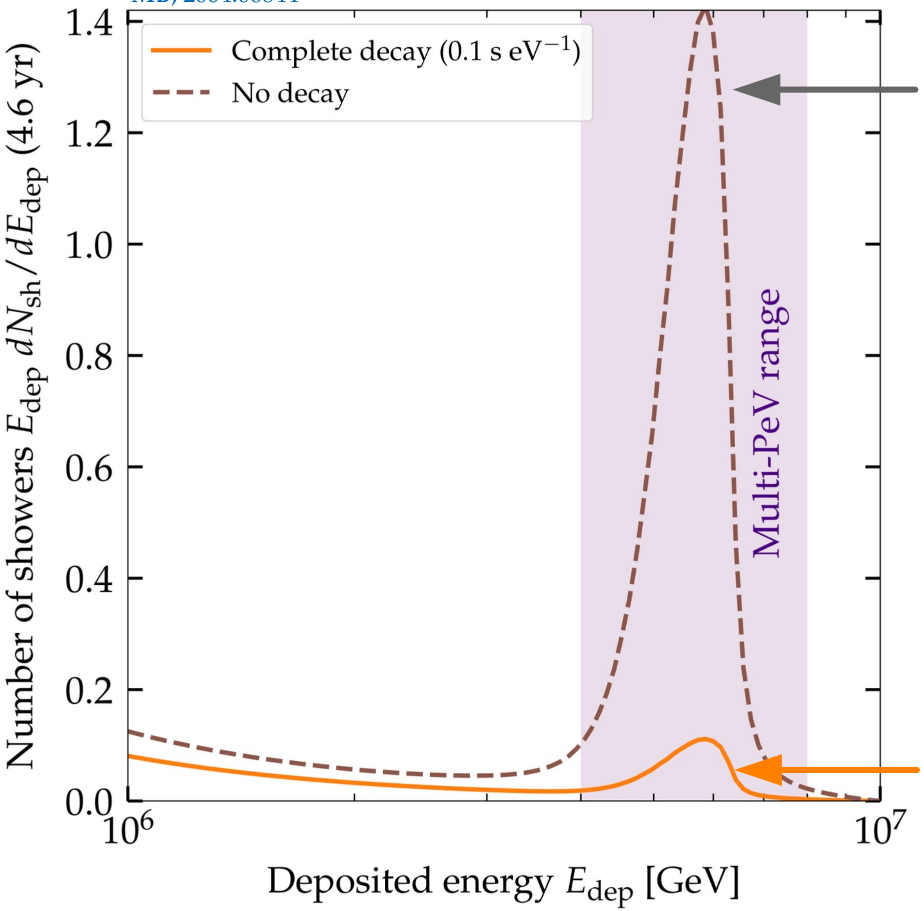

Glashow resonance (GR):
$\bar{\nu}_e + e \rightarrow W \rightarrow$ hadrons $\rightarrow$ shower

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

What does neutrino decay change?

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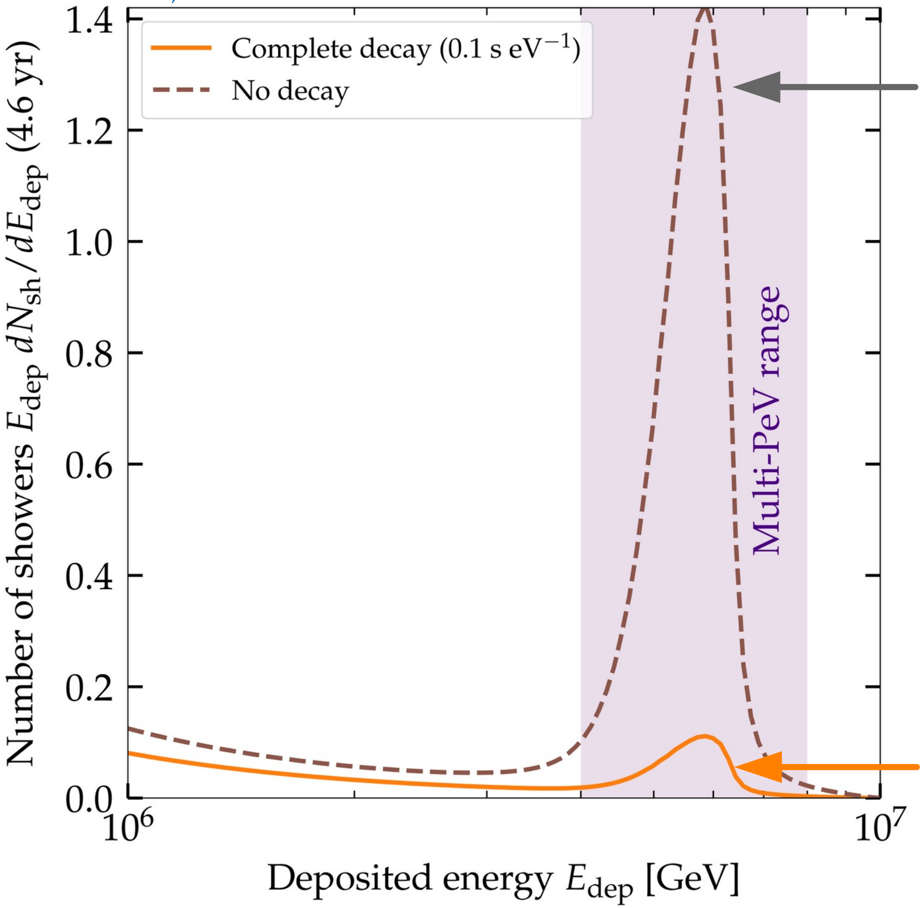
Flavor composition ⟺ Spectrum shape ⟺ **Event rate**

MB, 2004.06844



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

So by having observed 1 GR event we can place a *lower* limit on the lifetime of $\bar{\nu}_1$ (= ν_1)

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

What does neutrino decay change?

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

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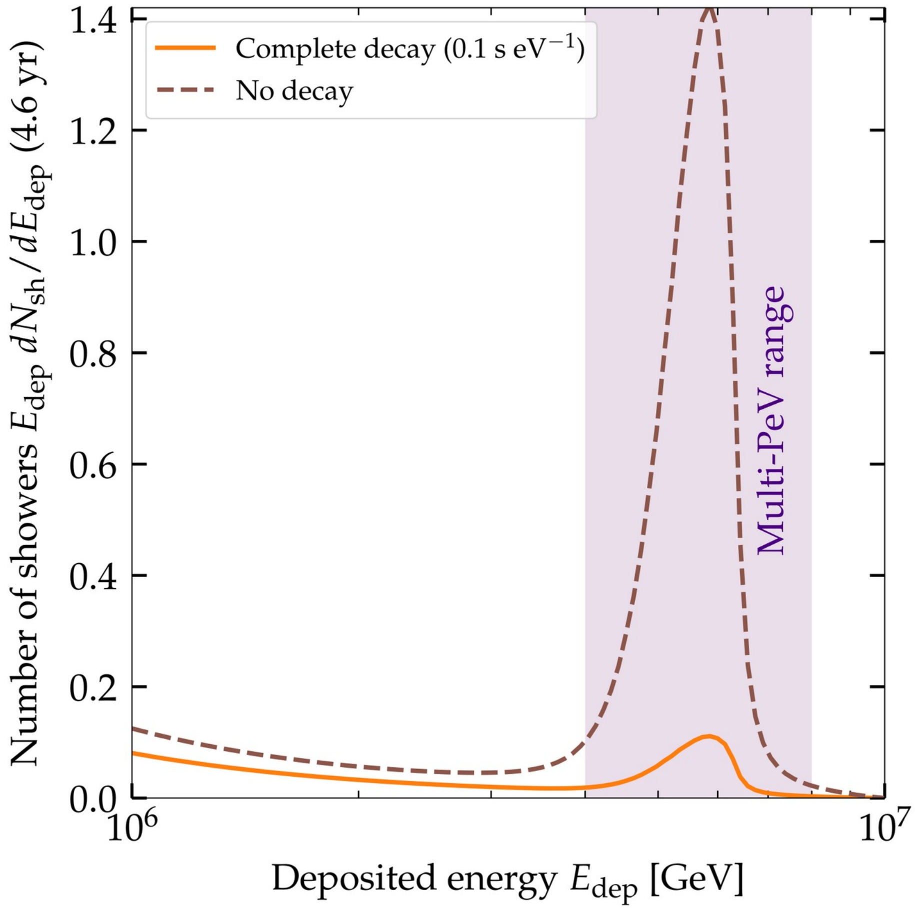

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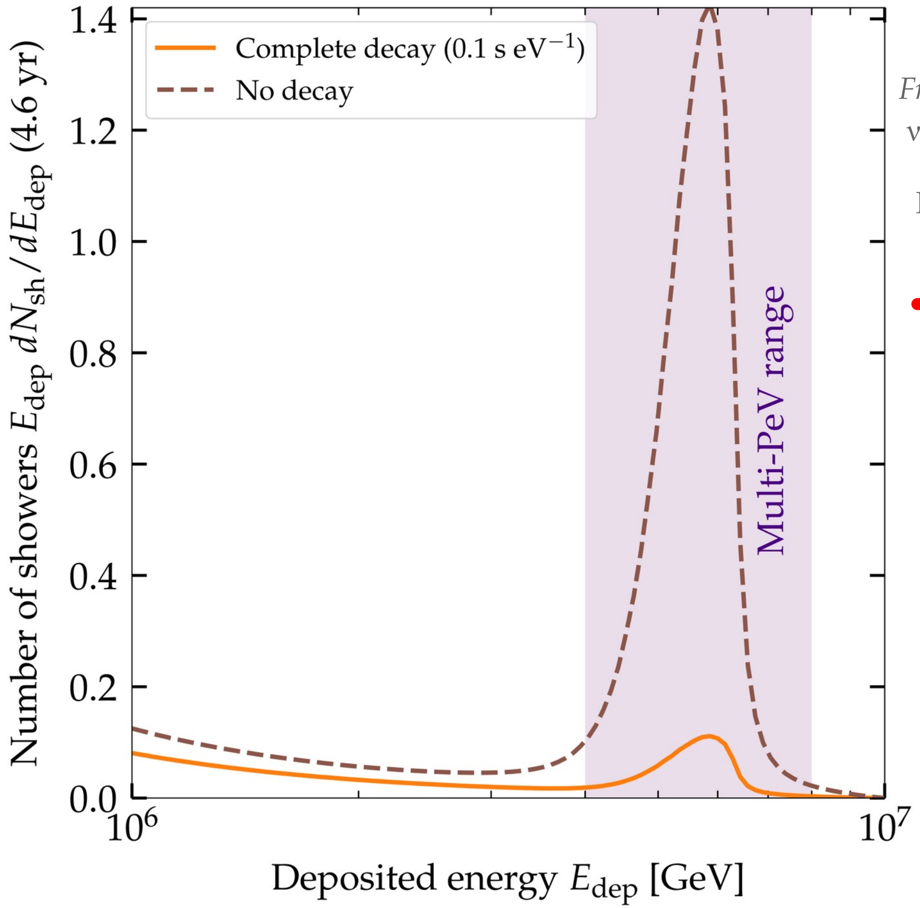

Free parameters:
ν_1, ν_2 lifetimes
Mix. par.
Flavor ratios
$\bar{\nu}/\nu$ ratio

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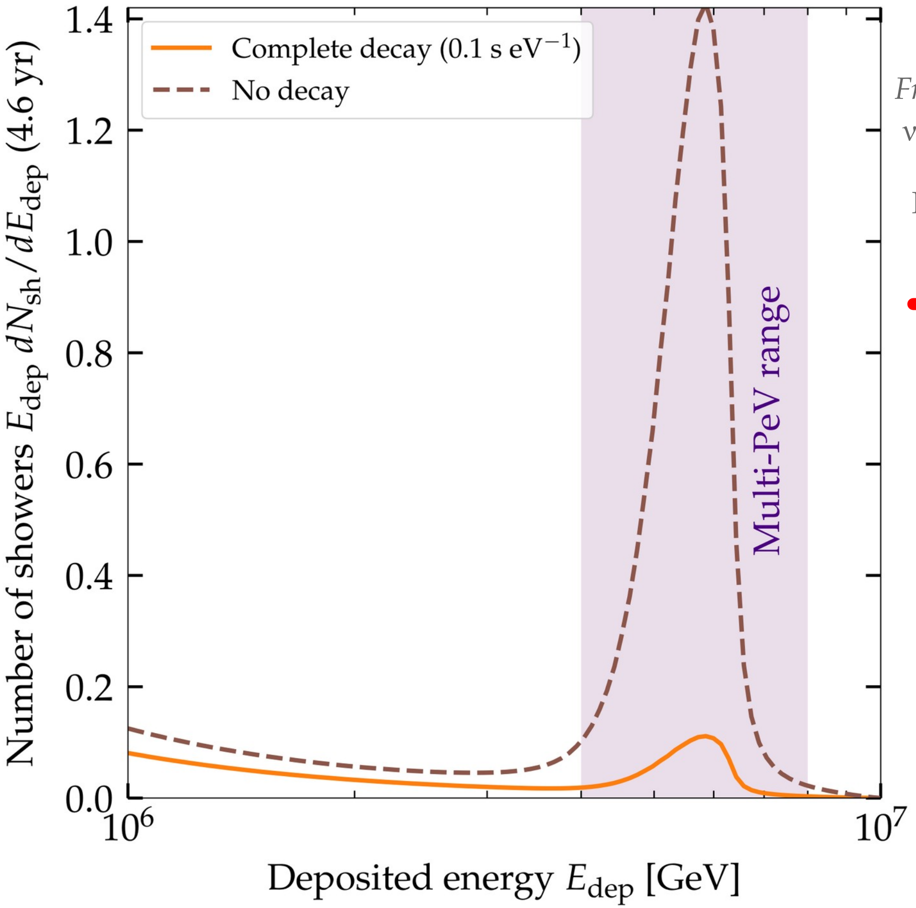

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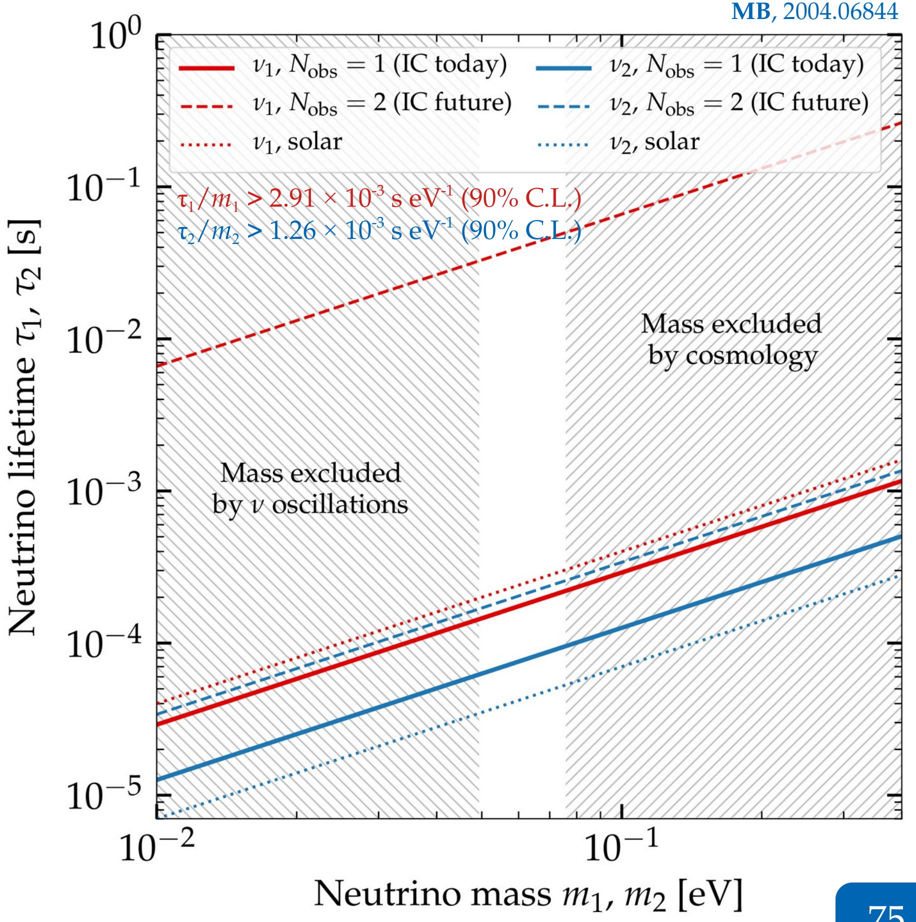

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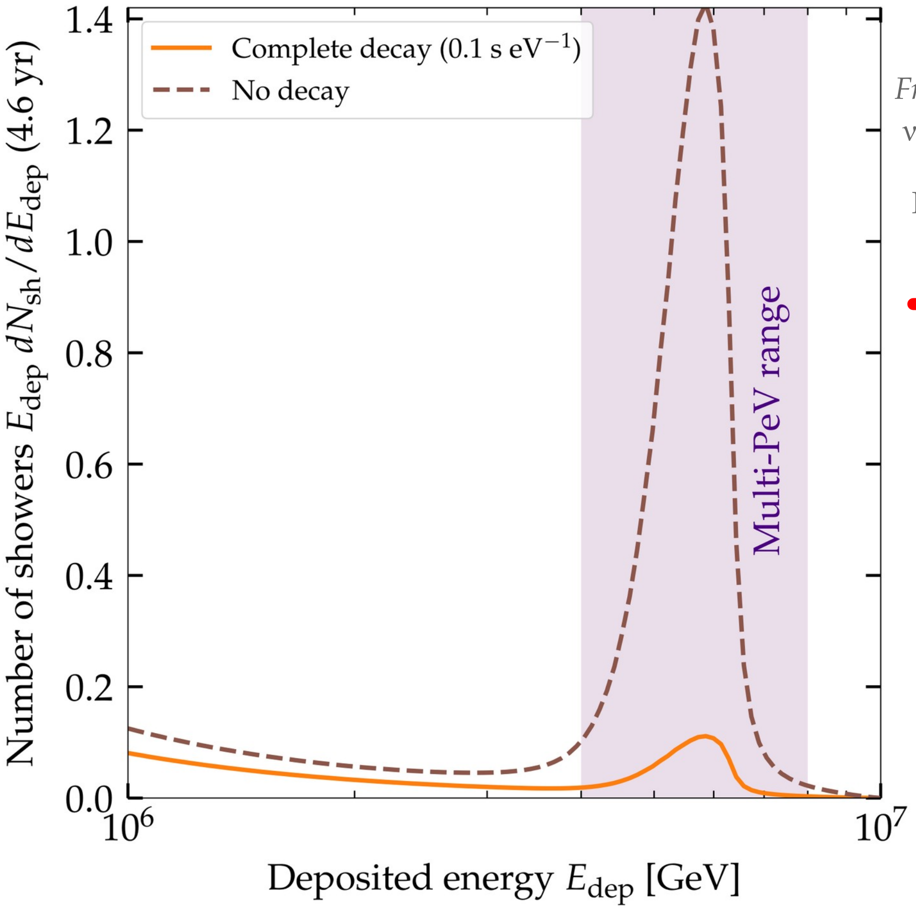

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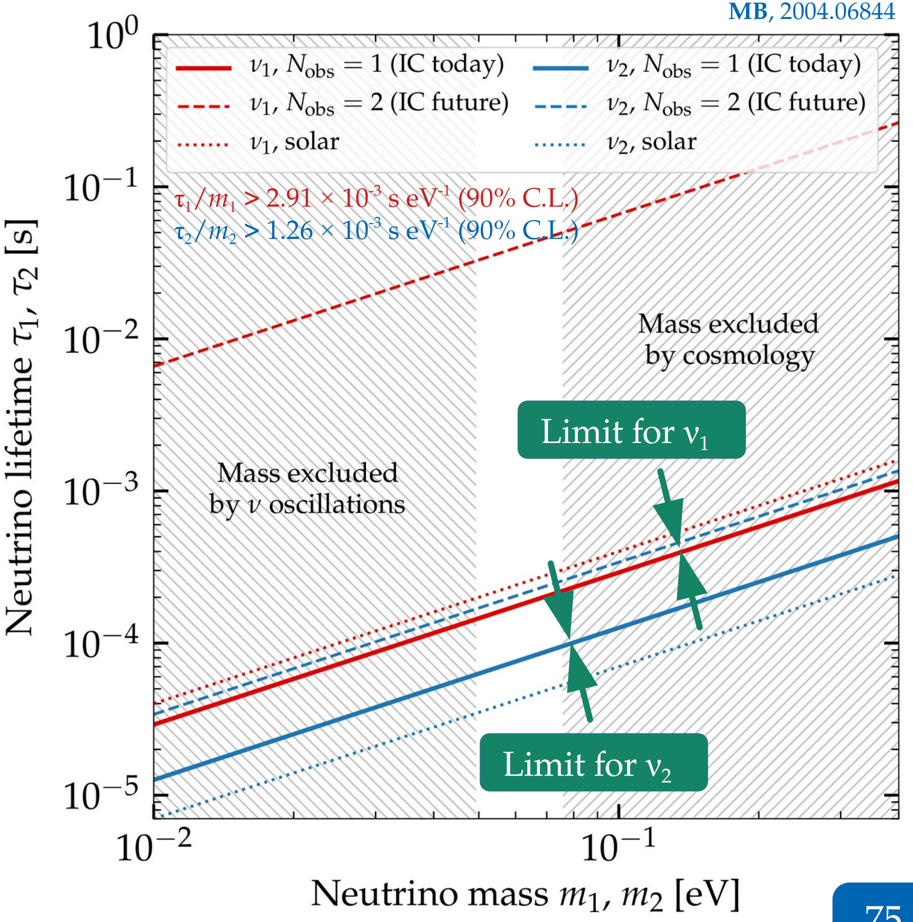

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Flavor composition ⟺ Spectrum shape ⟺ Event rate

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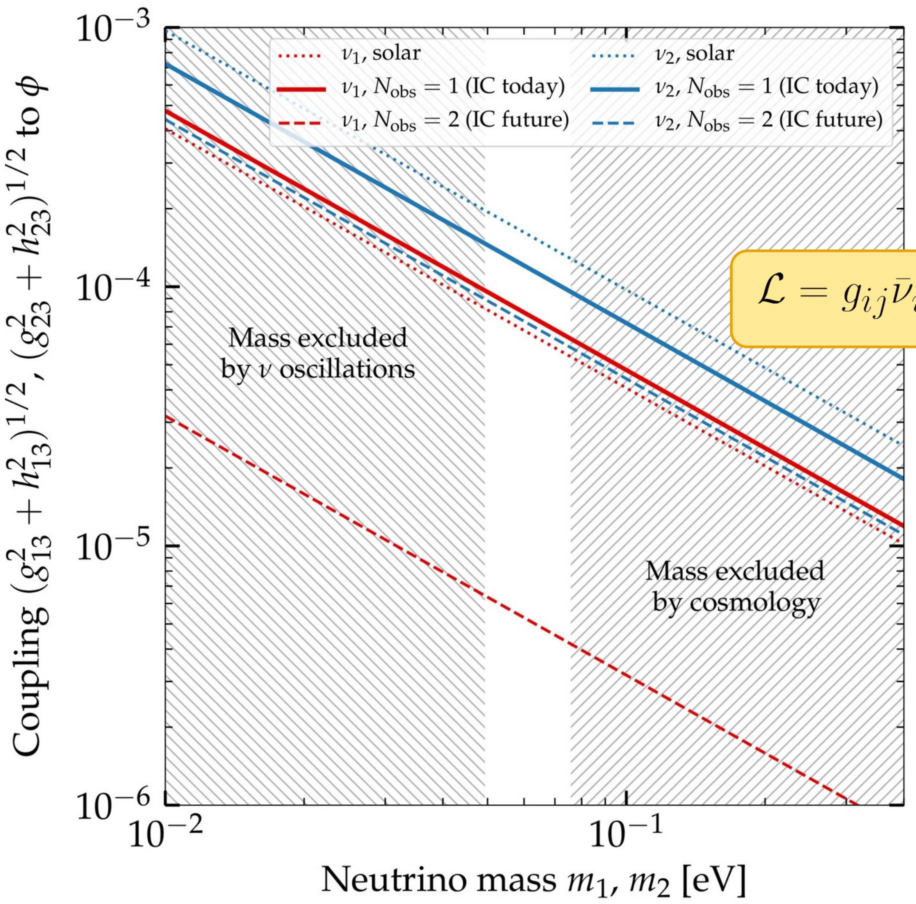

$$\mathcal{L} = g_{ij}\bar{\nu}_i\nu_j\phi + h_{ij}\bar{\nu}_i\gamma_5\nu_j\phi + \text{h.c.}$$

Lower limits on couplings

What does neutrino decay change?

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

Flavor composition ⇔ Spectrum shape ⇔ **Event rate**

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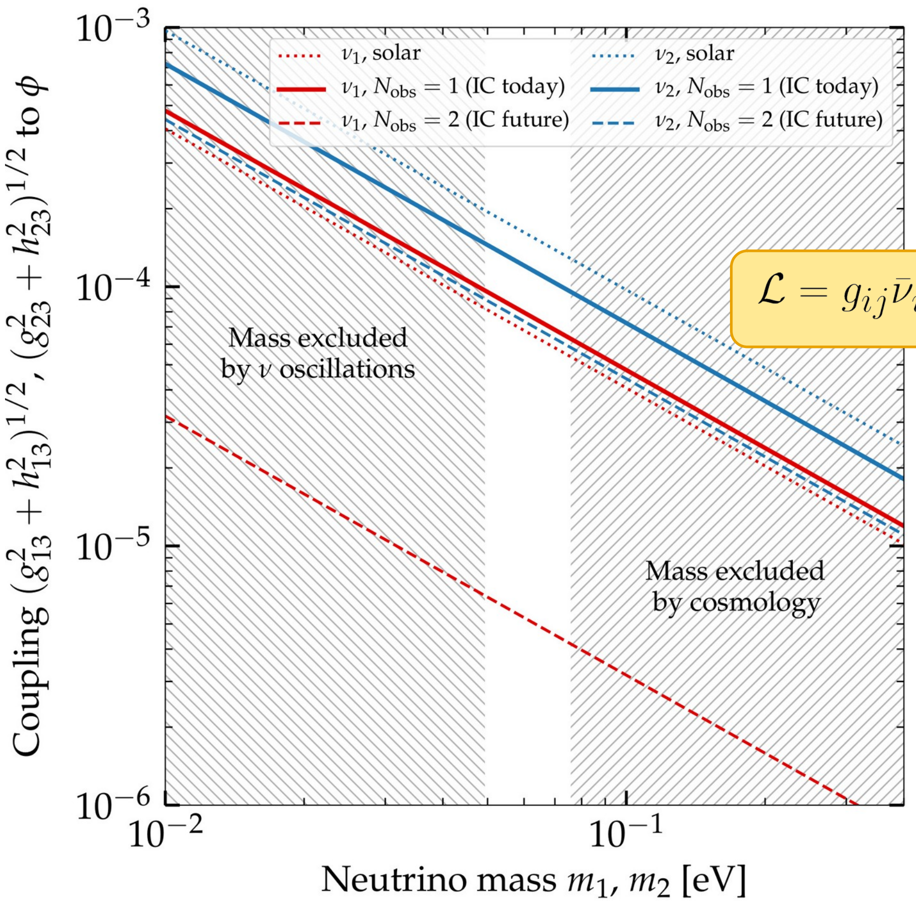

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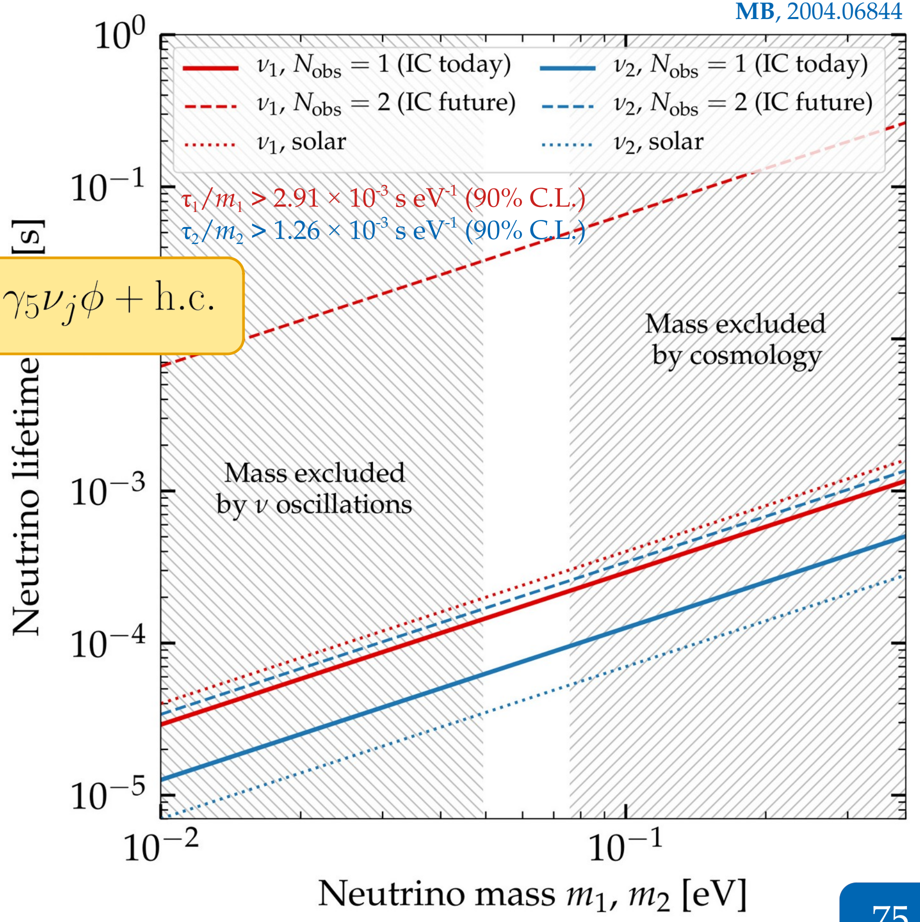

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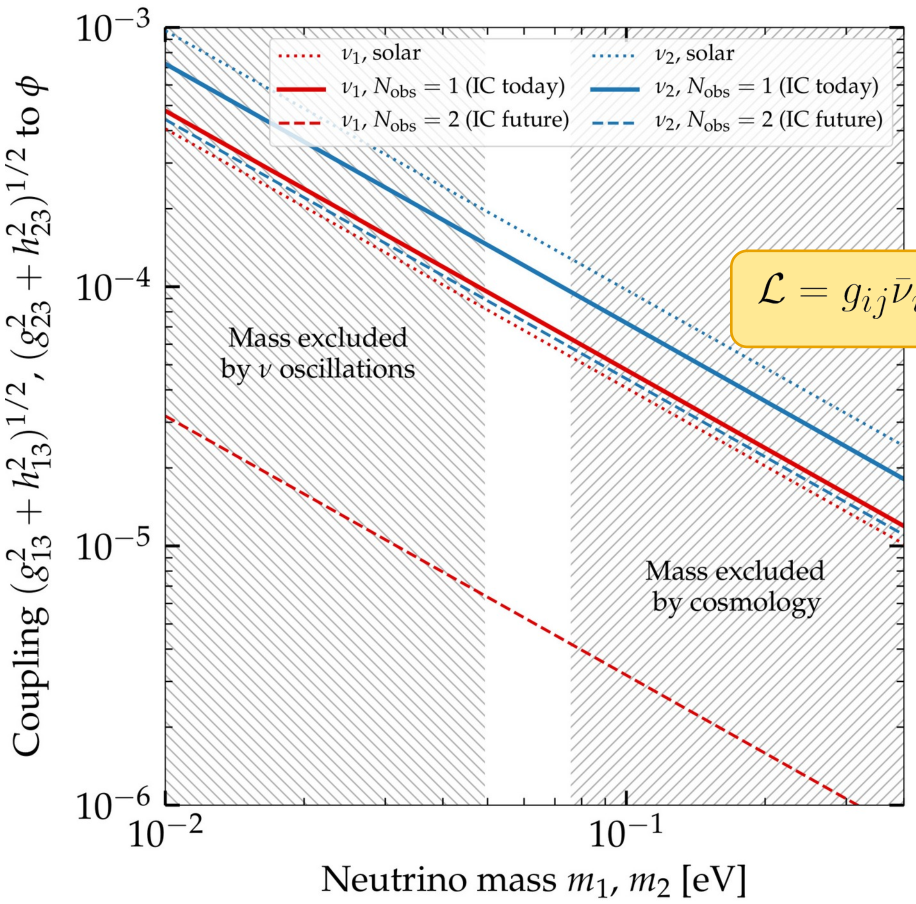

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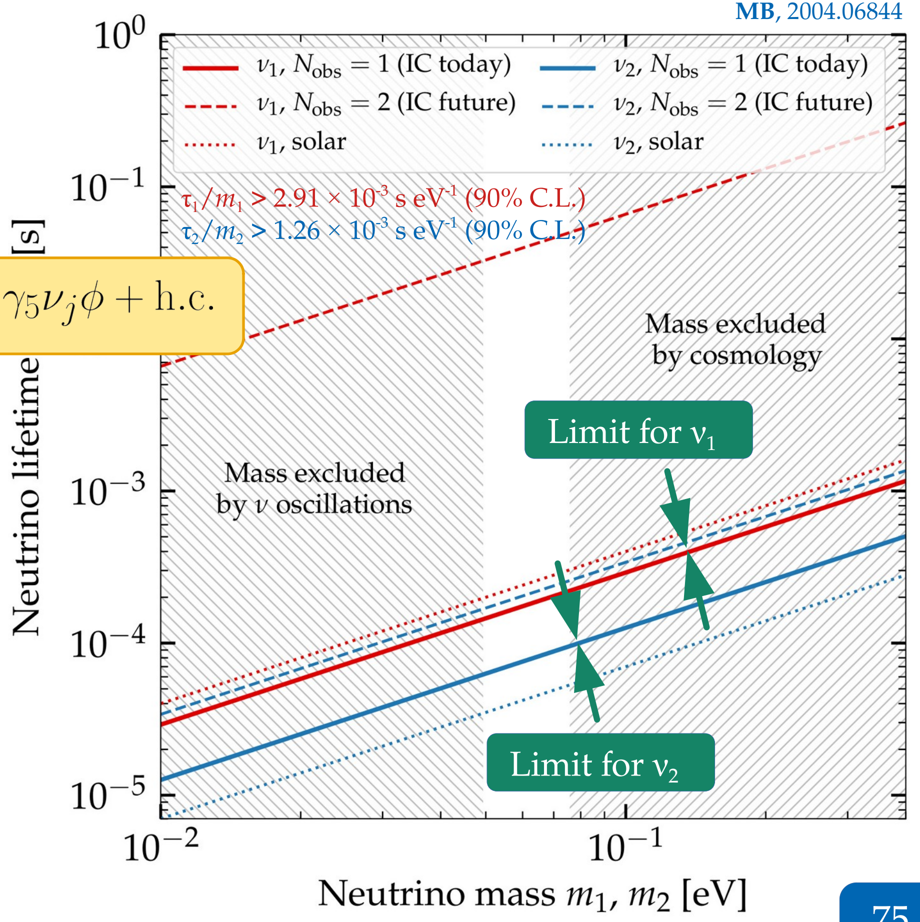


5. New neutrino interactions:

Are there secret $\nu\nu$ interactions?

Astrophysical neutrino sources

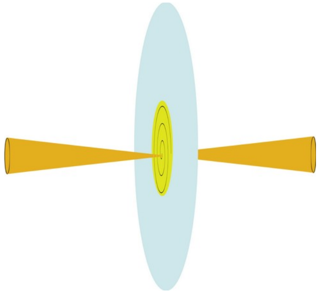
Earth

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

Astrophysical neutrino sources

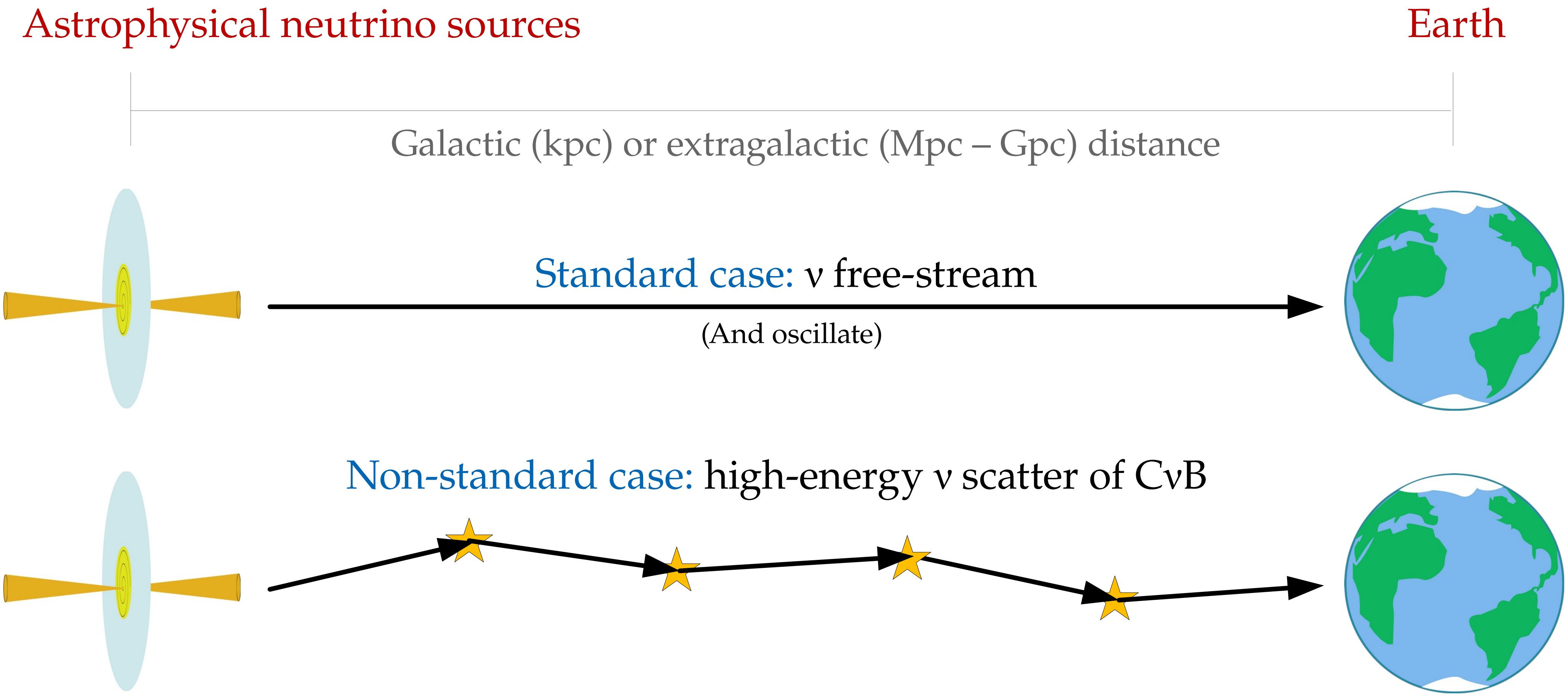
Earth

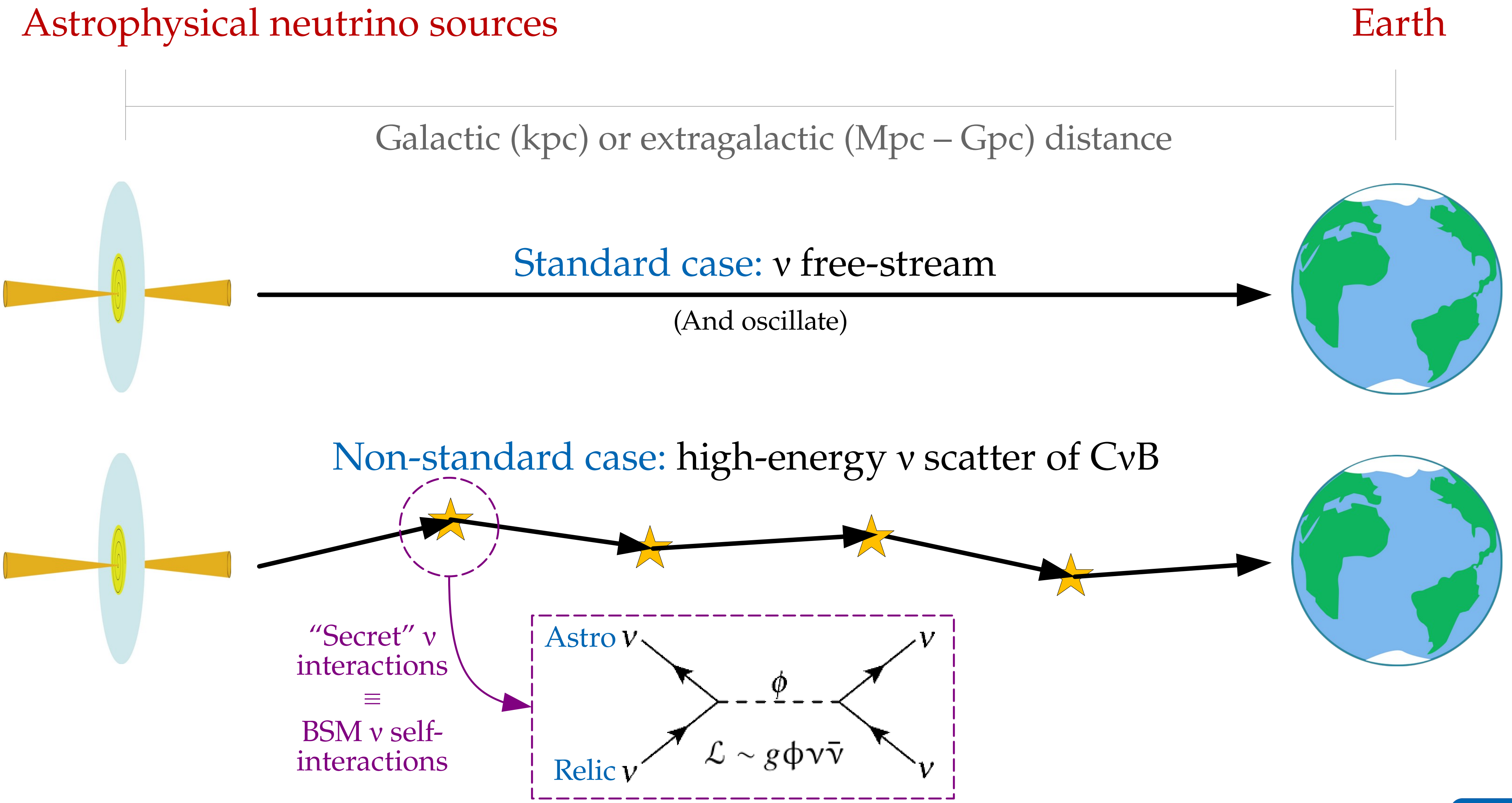
Galactic (kpc) or extragalactic (Mpc – Gpc) distance



Standard case: ν free-stream

(And oscillate)


Astrophysical neutrino sources
Earth
Galactic (kpc) or extragalactic (Mpc – Gpc) distance
Standard case: ν free-stream
(And oscillate)
Non-standard case: high-energy ν scatter of CνB


Astrophysical neutrino sources
Earth
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Standard case: ν free-stream
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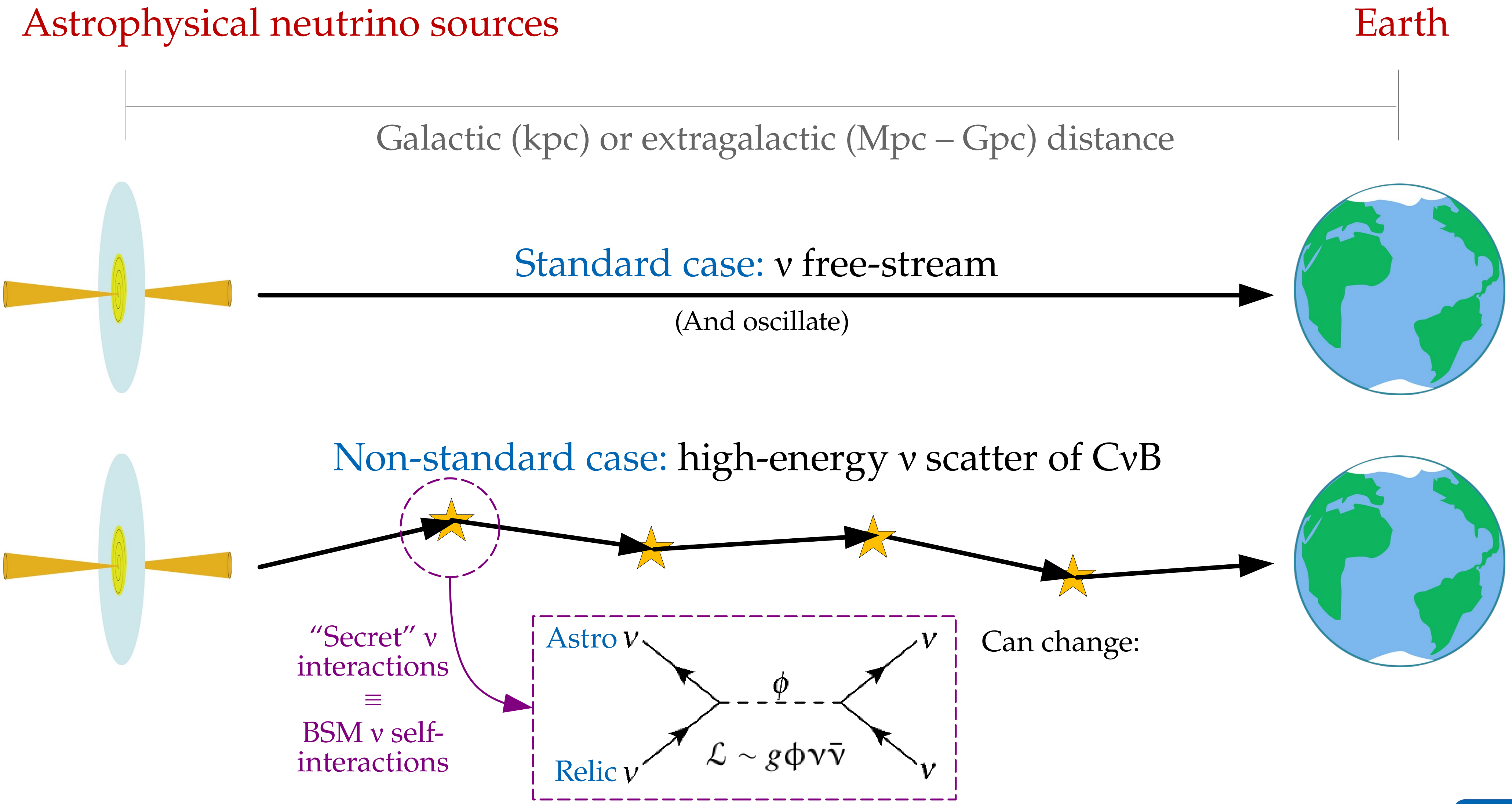
"Secret" ν interactions ≡ BSM ν self-interactions
Astro ν
Relic ν
ν
ν
ϕ
$\mathcal{L} \sim g\phi\nu\bar{\nu}$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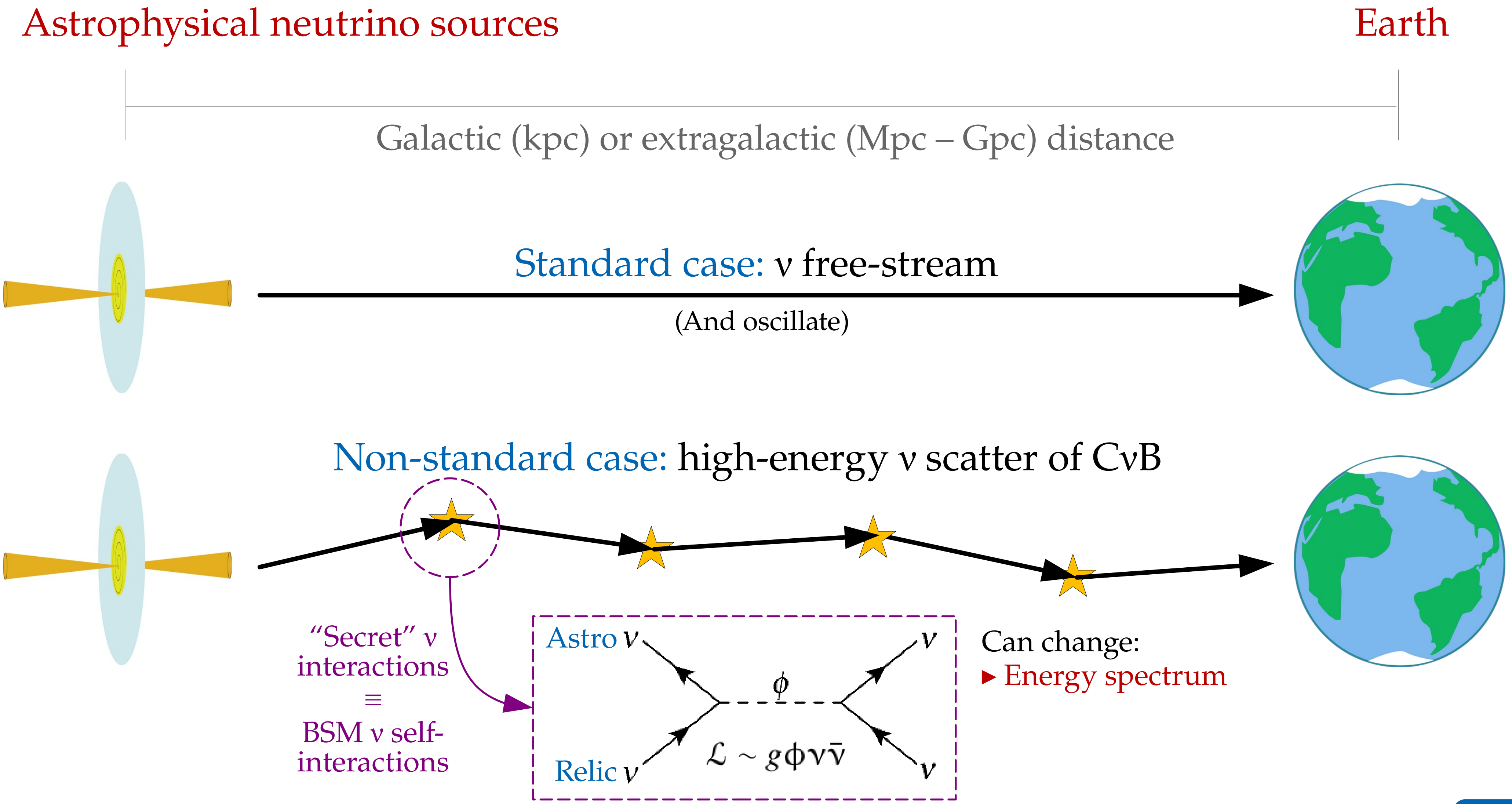
Astro ν
Relic ν
ν
ν
ϕ
$\mathcal{L} \sim g\phi\nu\bar{\nu}$
Can change: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ν
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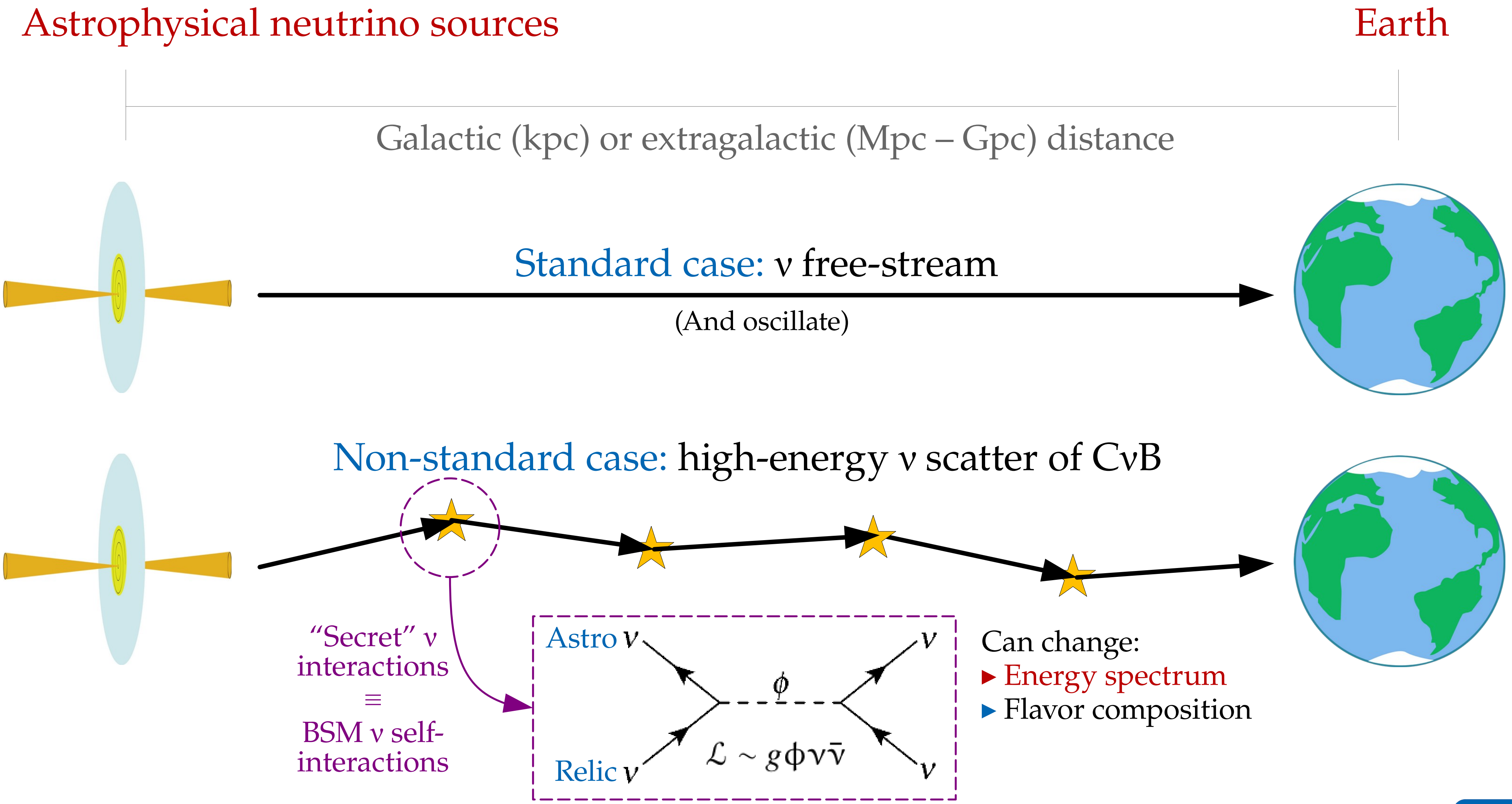
$\mathcal{L} \sim g\phi\nu\bar{\nu}$
Can change:
▸ Energy spectrum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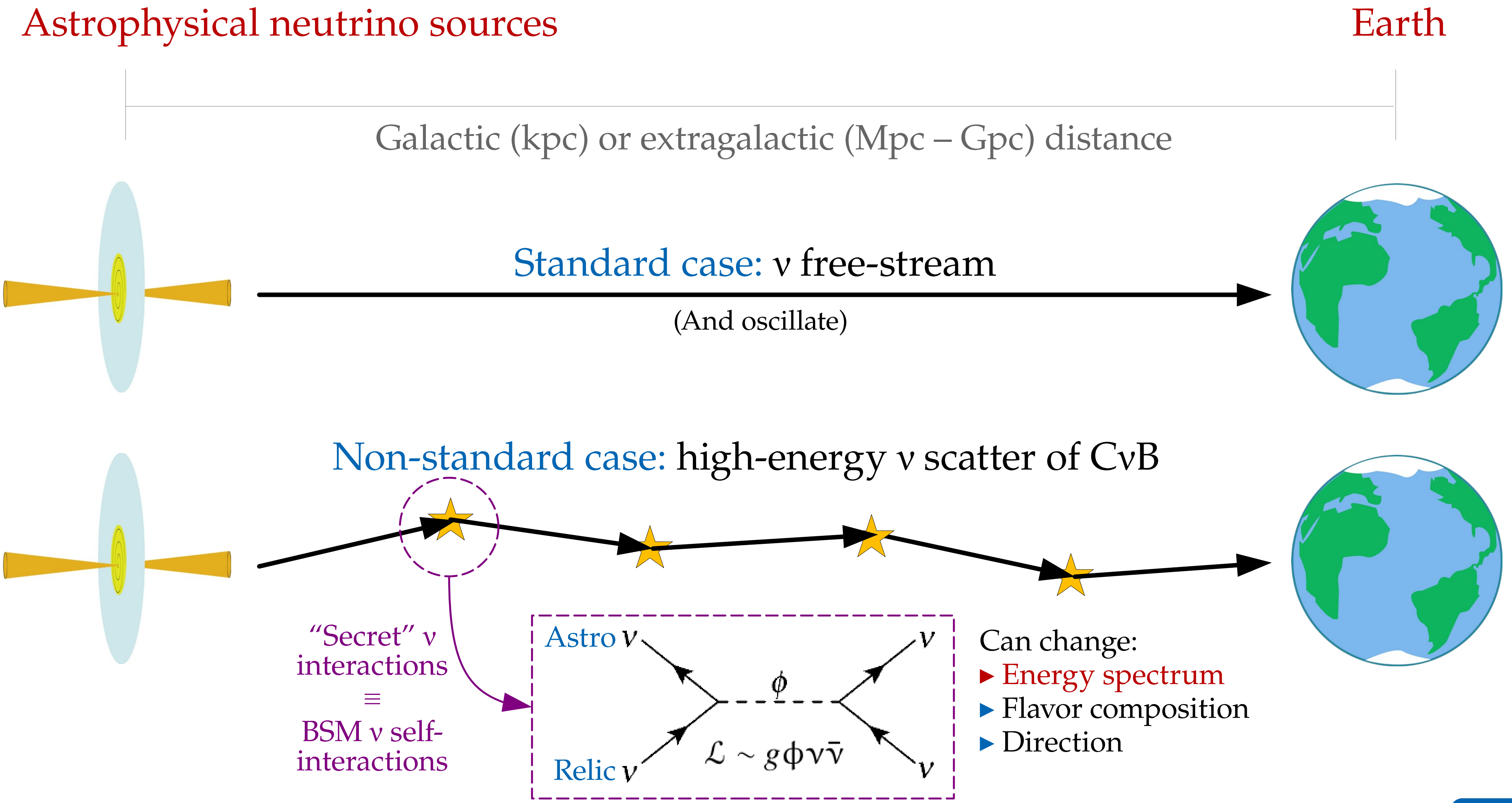
Can change:
▸ Energy spectrum
▸ Flavor composition



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Relic ν
ν
ν
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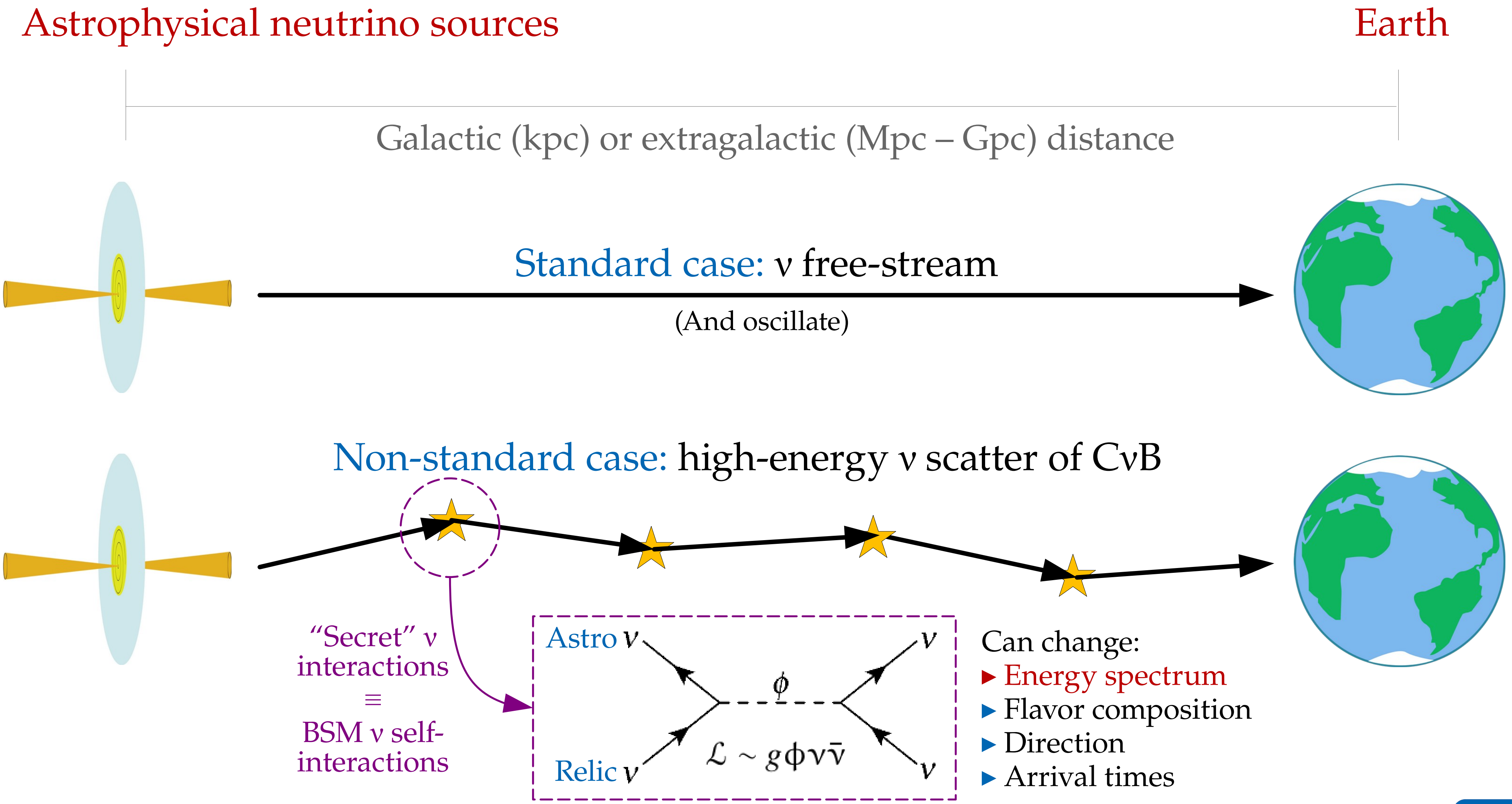
Can change:
▸ Energy spectrum
▸ Flavor composition
▸ Direction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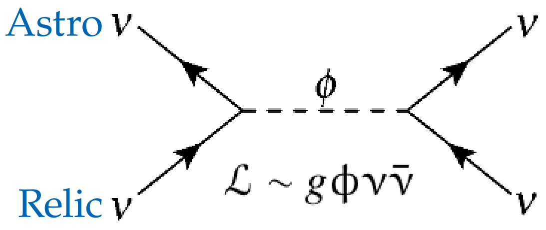
≡
BSM ν self-interactions
Astro ν
Relic ν
ν
ν
ϕ
$\mathcal{L} \sim g\phi\nu\bar{\nu}$
Can change:
Energy spectrum
Flavor composition
Direction
Arrival times

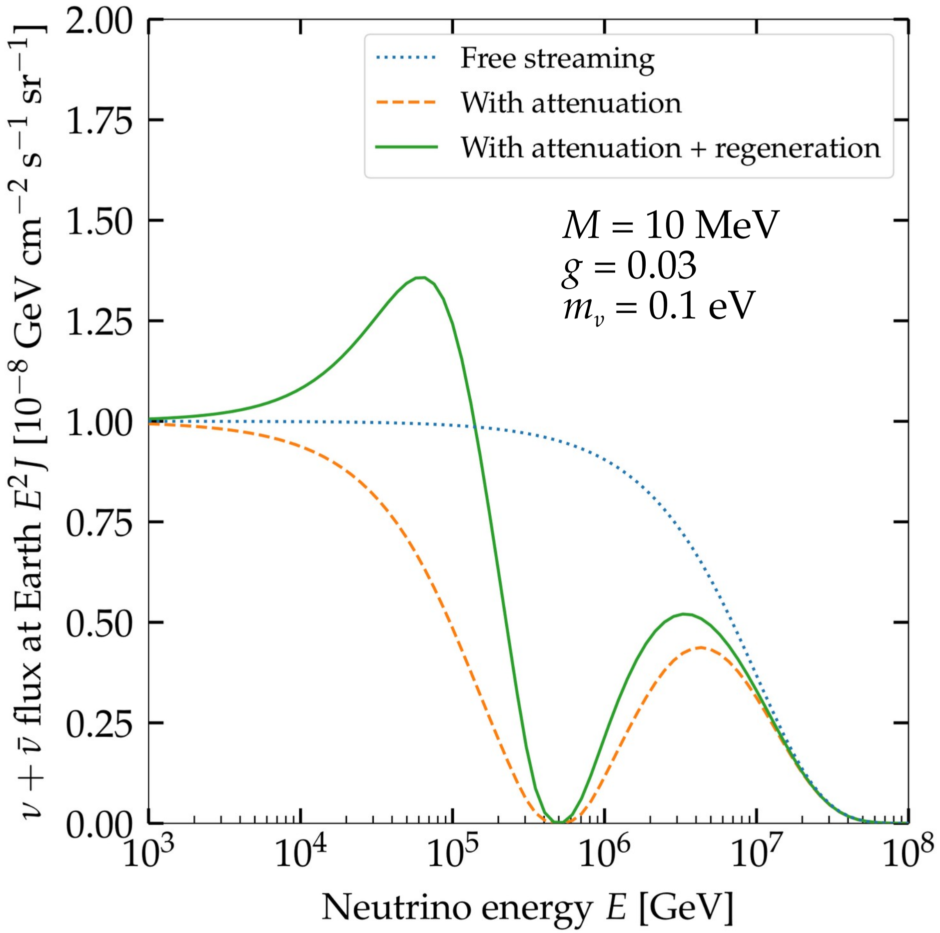
Secret interactions of high-energy astrophysical neutrinos

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



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

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



MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020
See also: Esteban, Pandey, Brdar, Beacom, *PRD* 2021
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Ng & Beacom, *PRD* 2014
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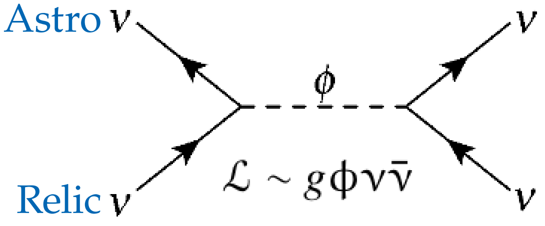
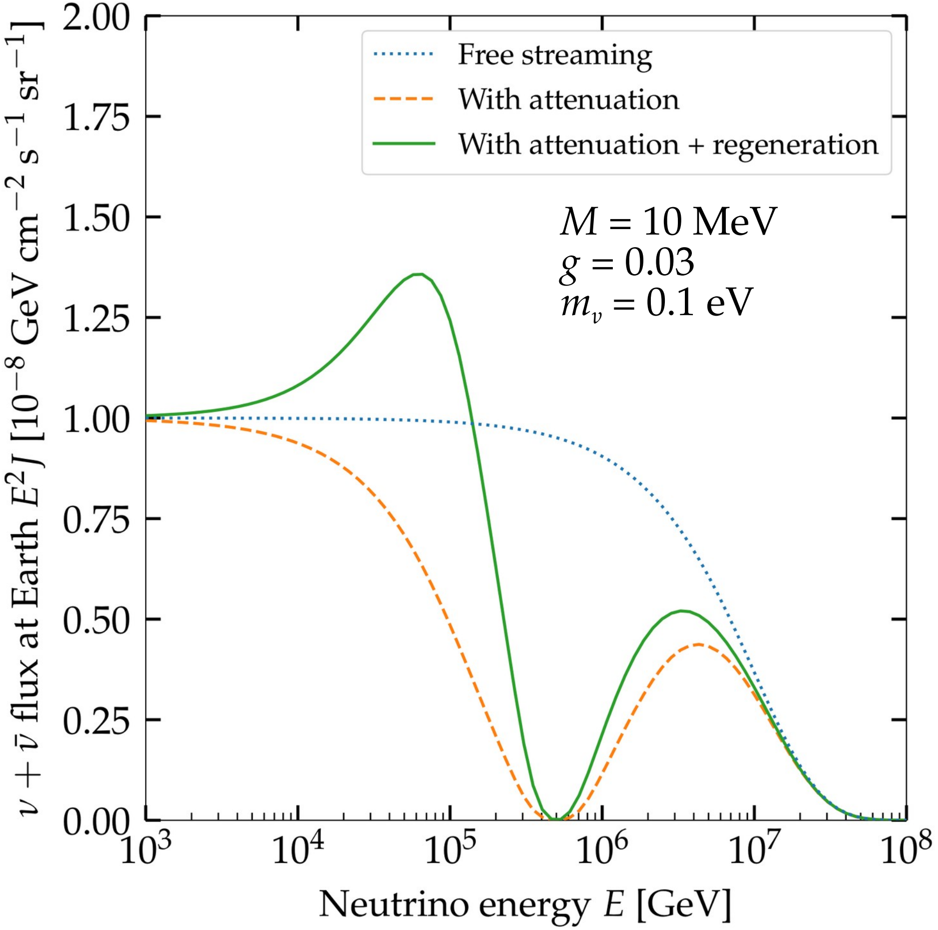


New coupling

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

Mediator mass

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



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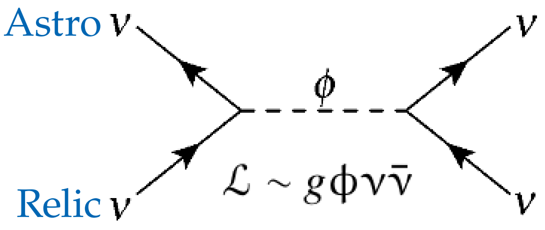

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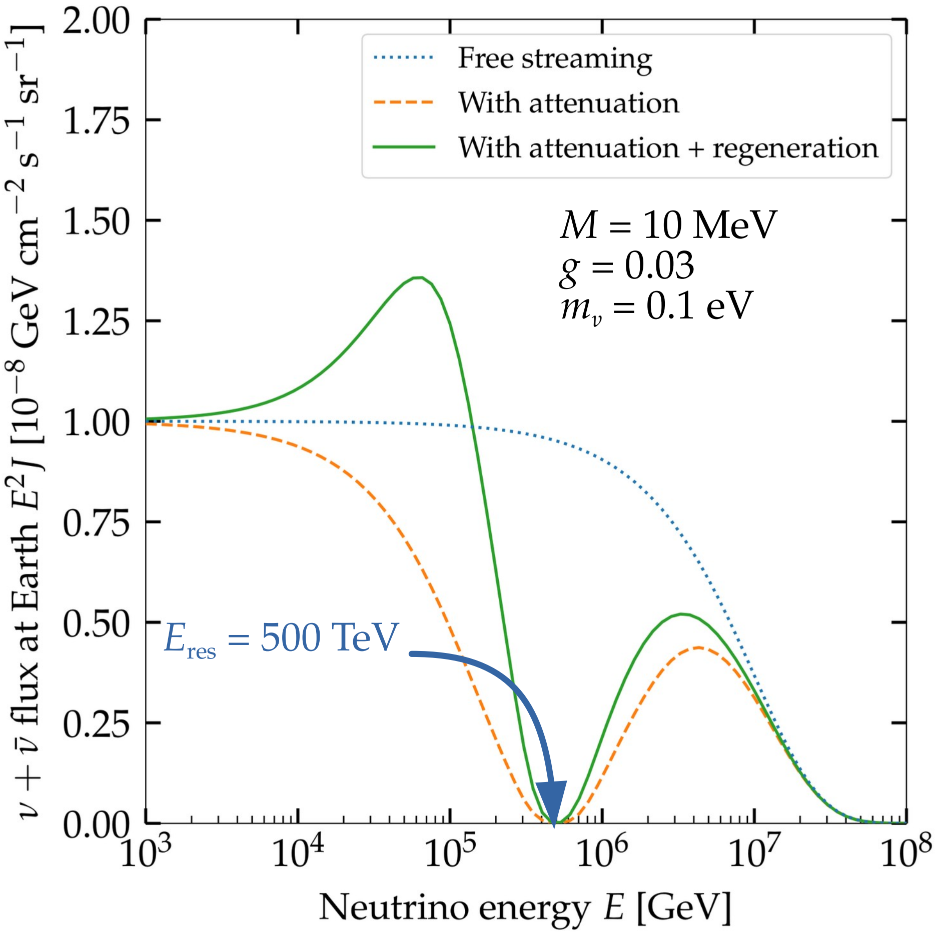

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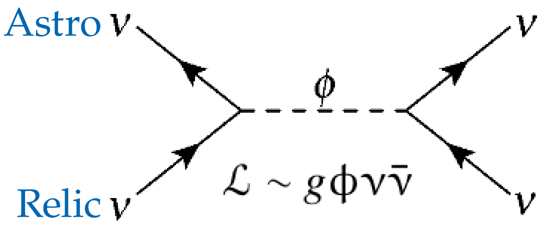

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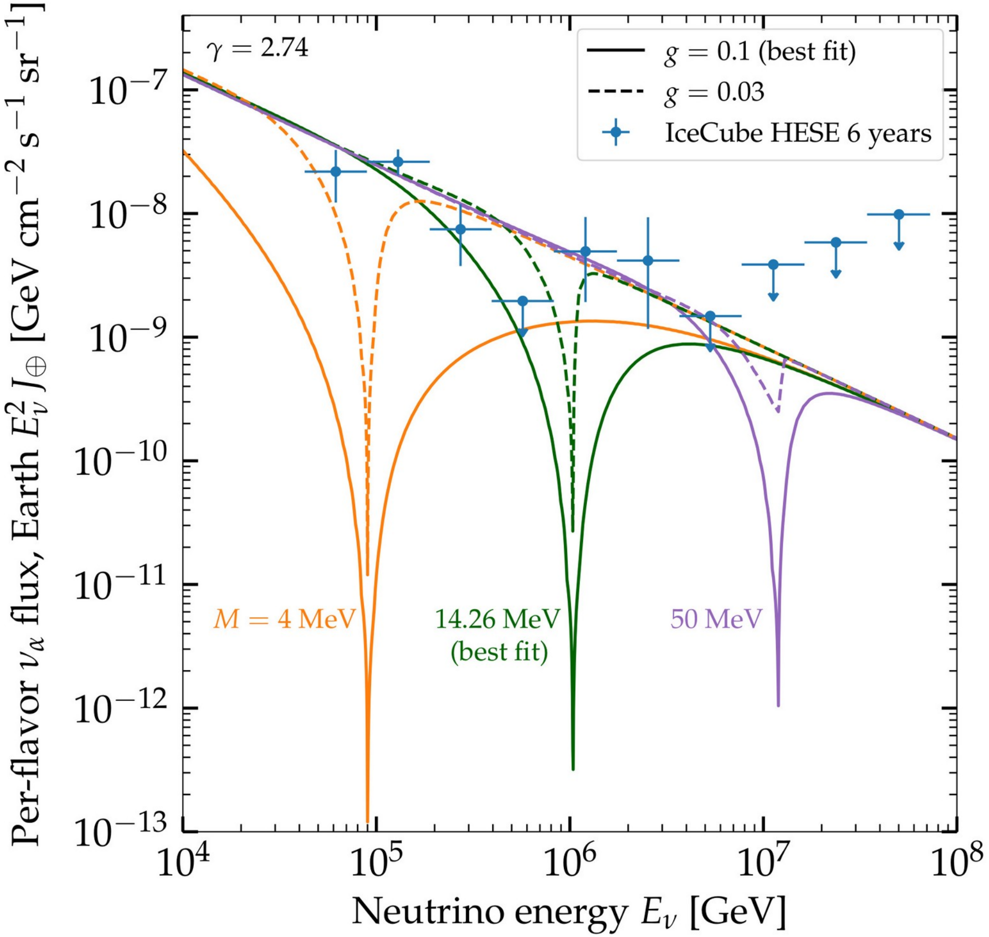

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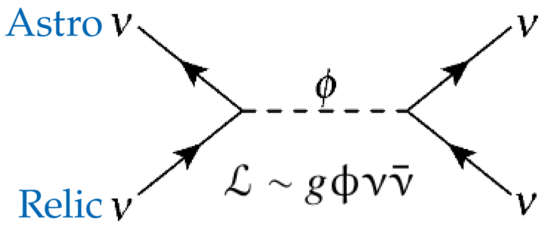

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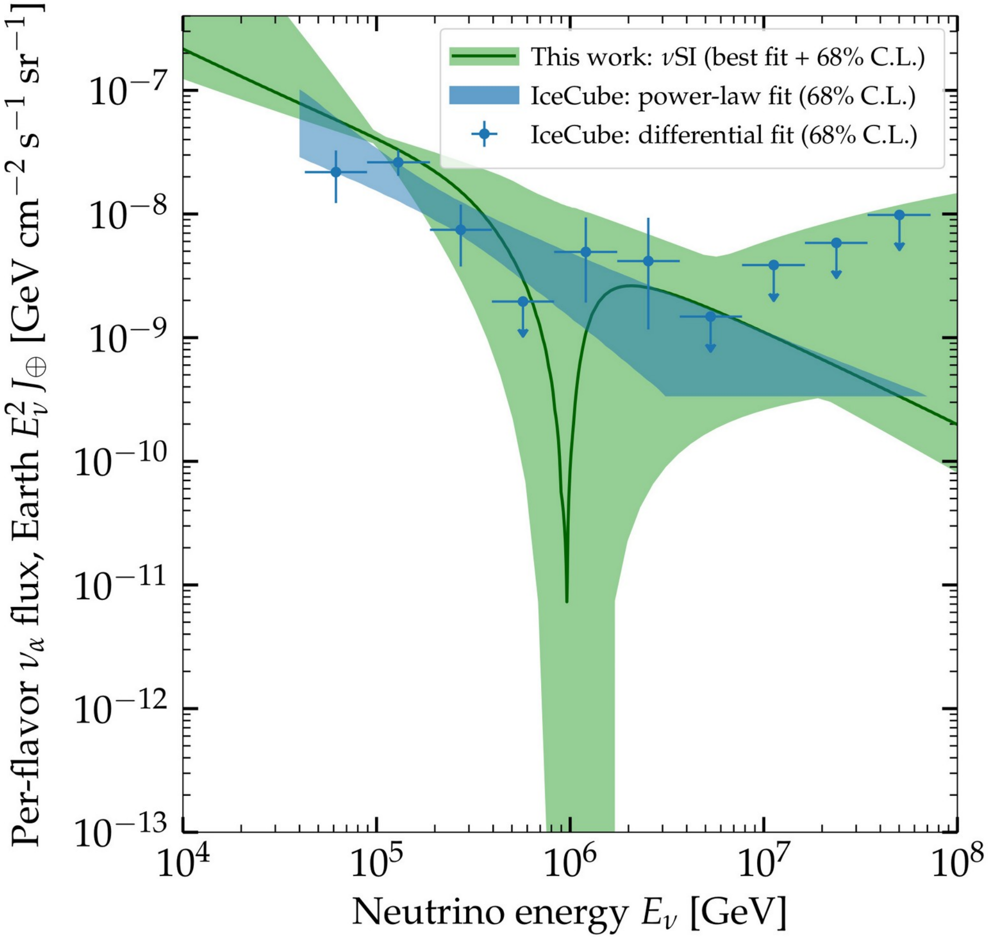
Looking for evidence of νSI

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

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



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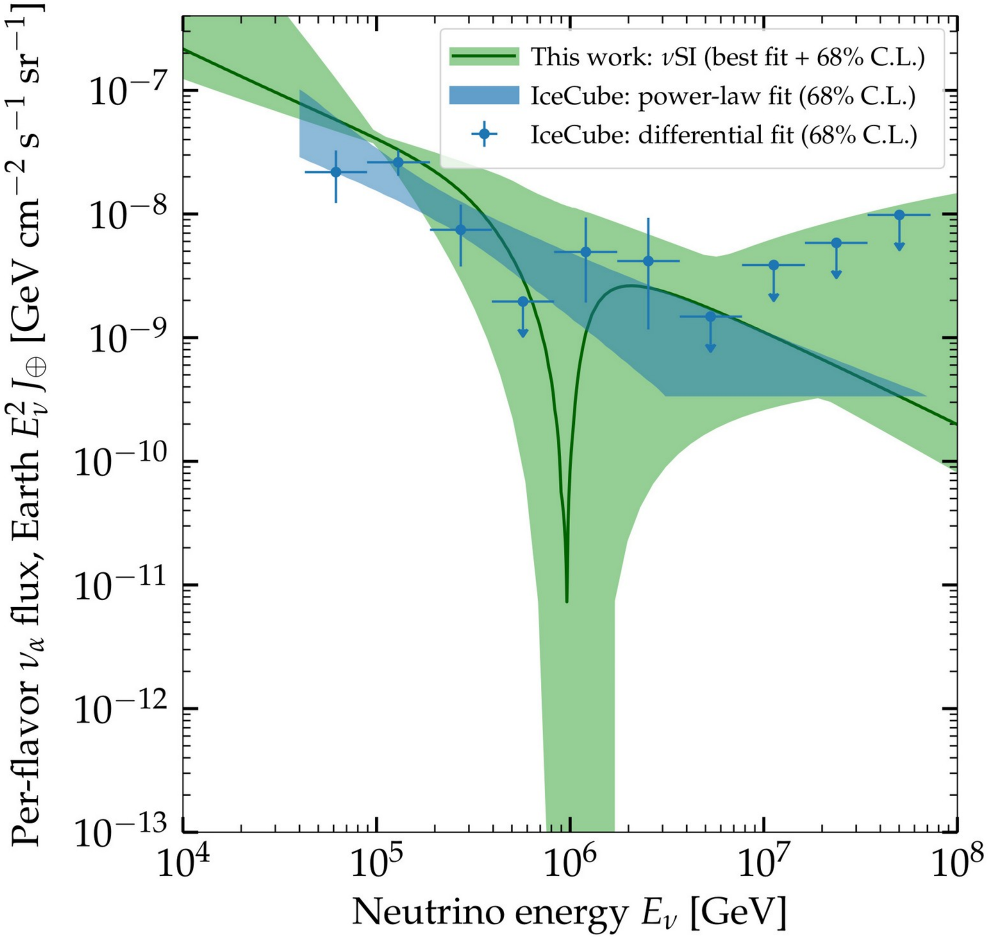
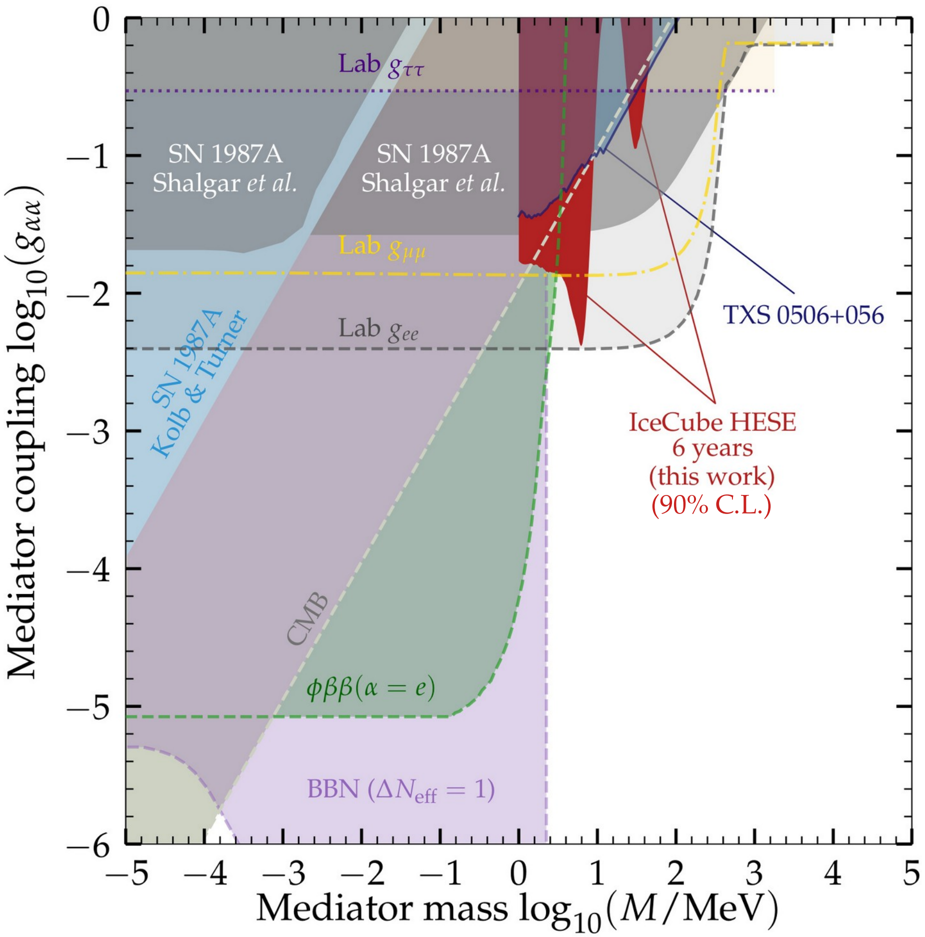
No significant (> 3σ) evidence for a spectral dip … … so we set upper limits on the coupling g





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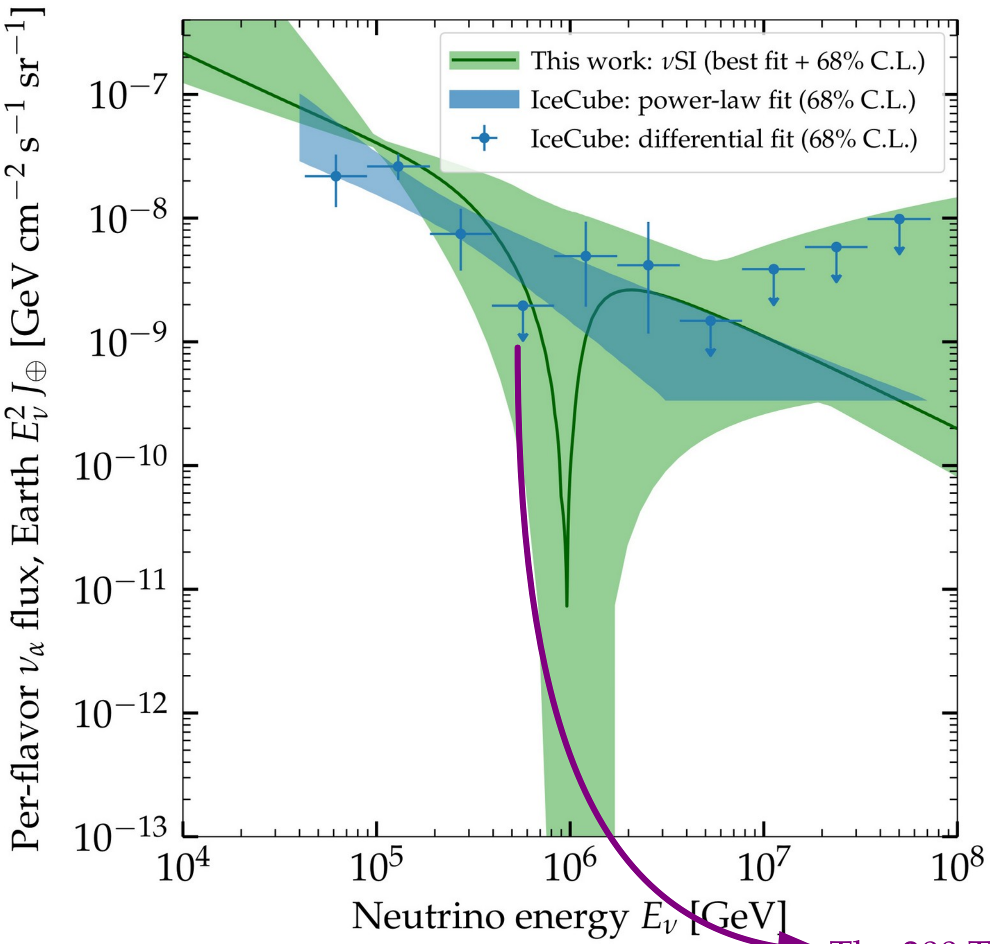
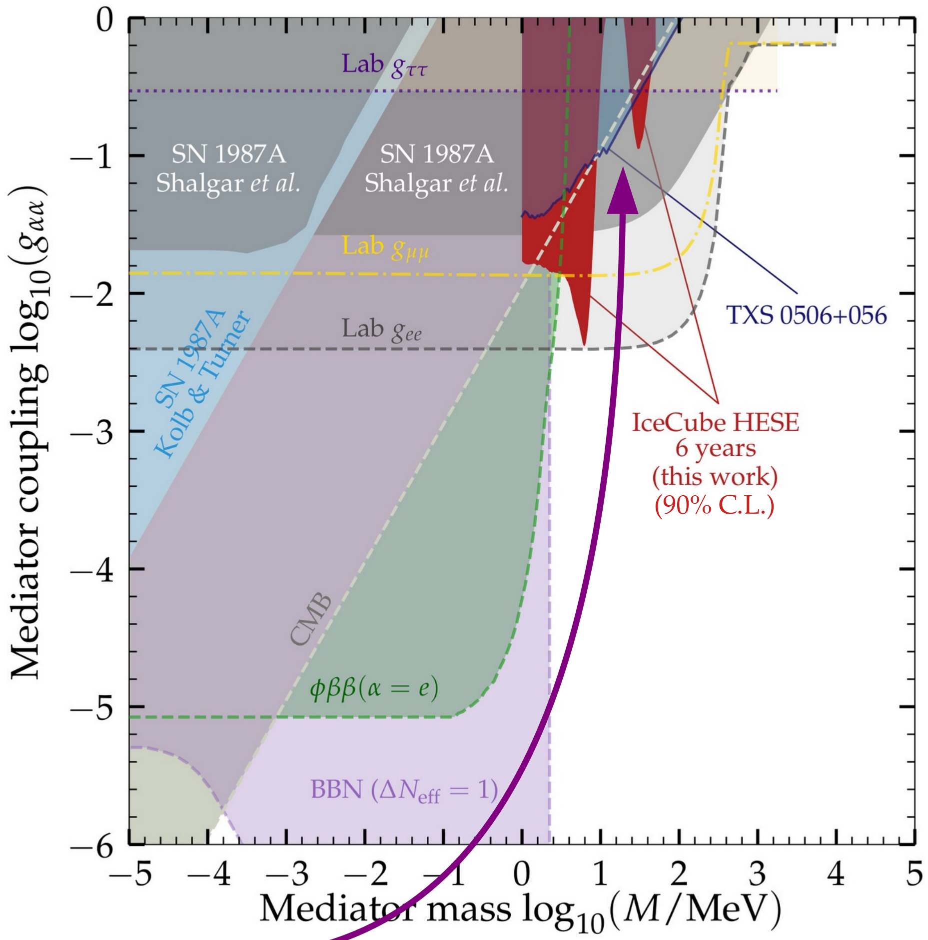


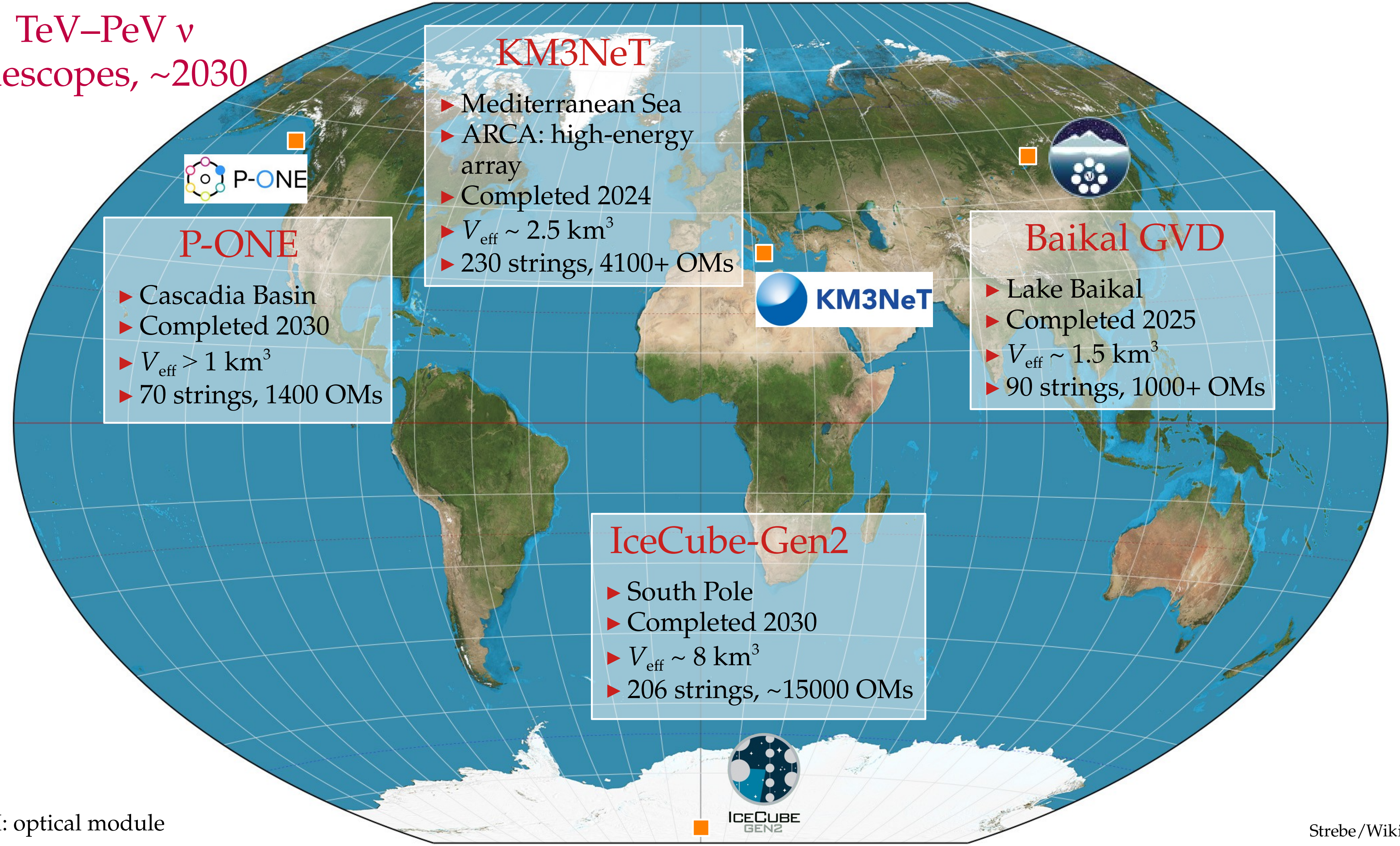


The 300 TeV–1 PeV "gap" degrades the limit at ~10 MeV

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

What's next?

TeV–PeV ν telescopes, ~2030



P-ONE

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

KM3NeT

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

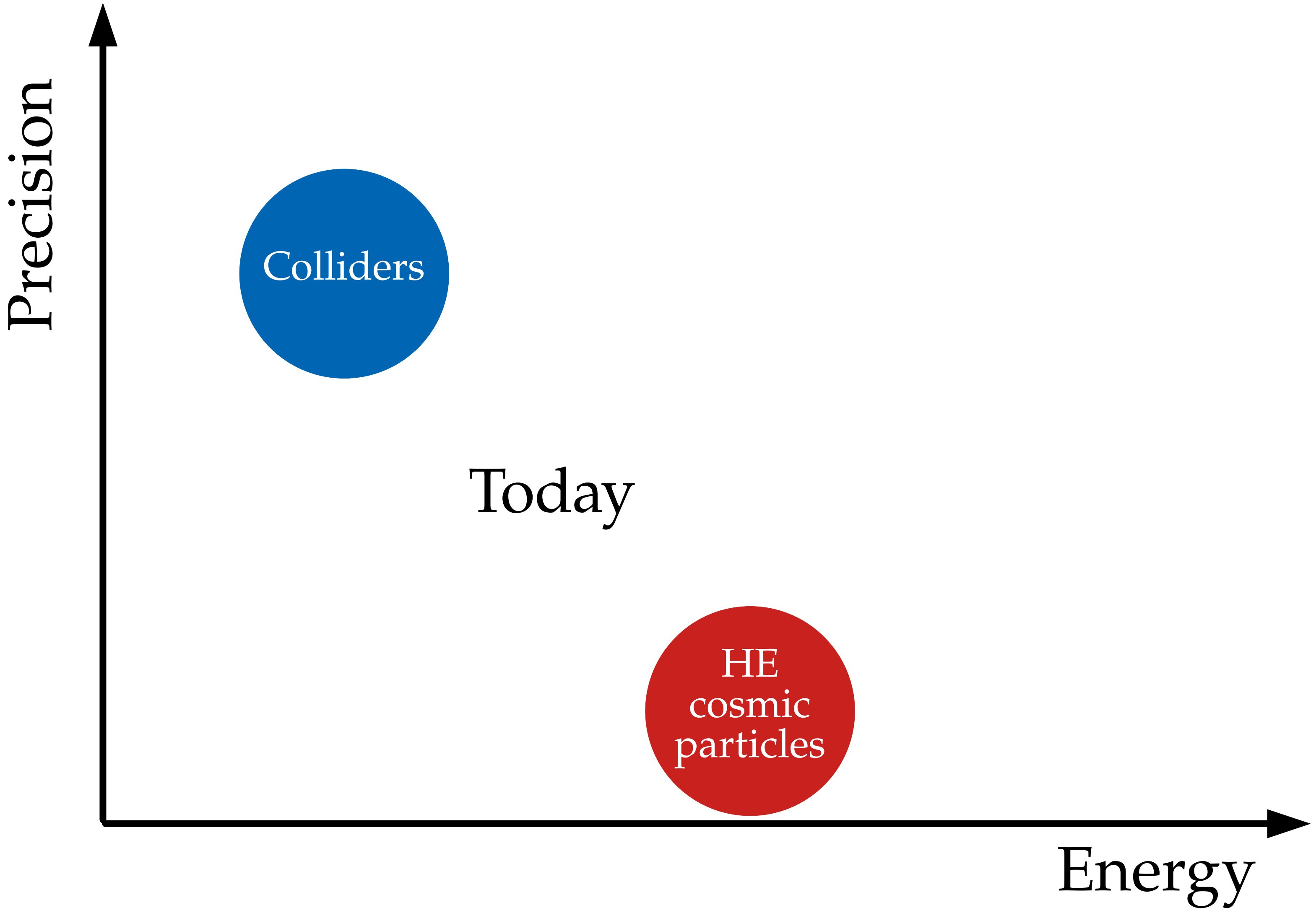
Strebe/Wikipedia

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

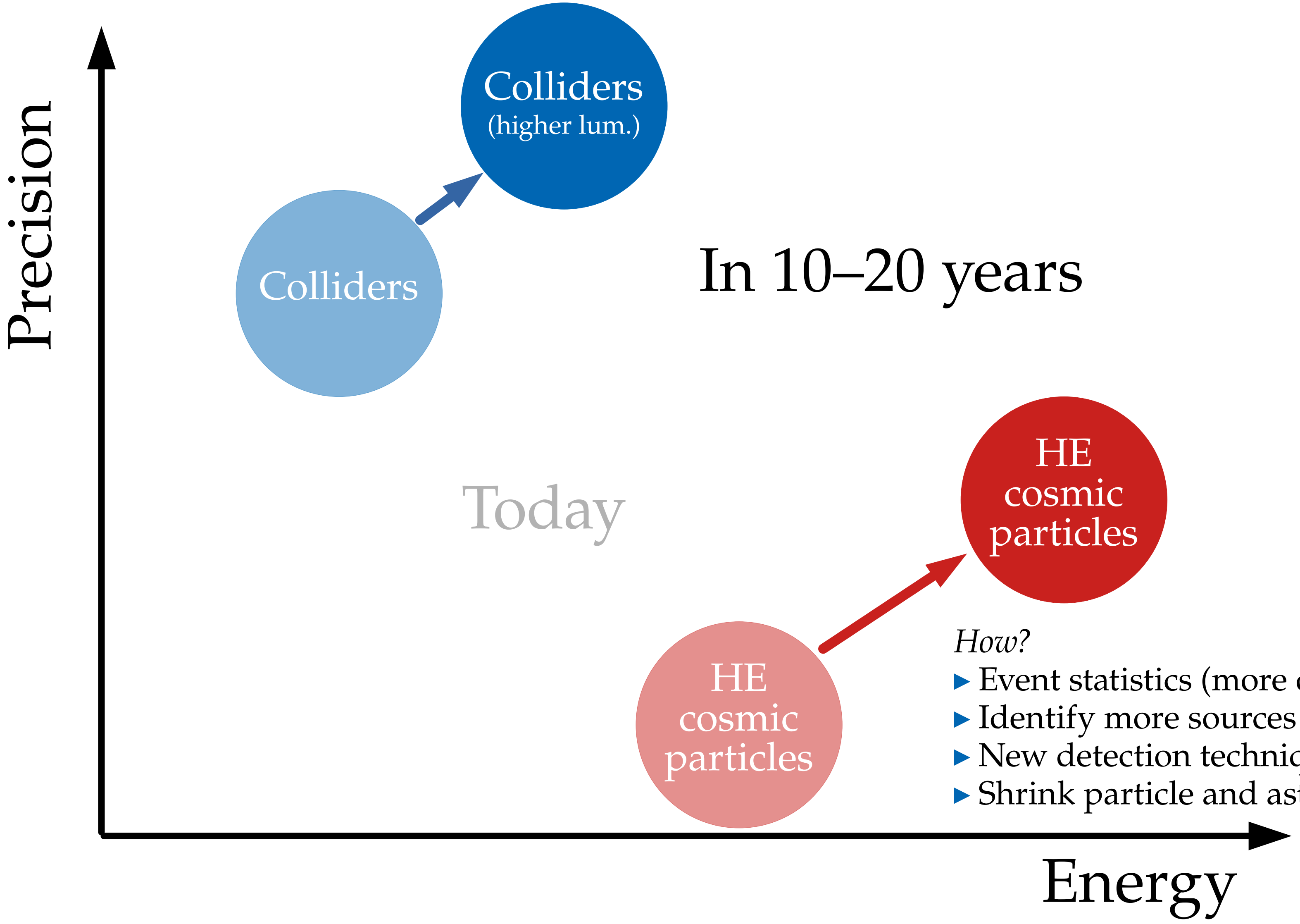
				Flavor		Technique			Neutrino Target					Geometry					
Experiments	Phase & Online Date	Energy Range	Site	Tau	All Flavor	Optical / UV	Radio	Showers	H_2O	Atmosphere	Earth's limb	Topography	Lunar Regolith	Embedded	Planar Arrays	Valley	Mountains	Balloon	Satellite
IceCube	2010	TeV-EeV	South Pole		✓	✓			✓					✓					
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]

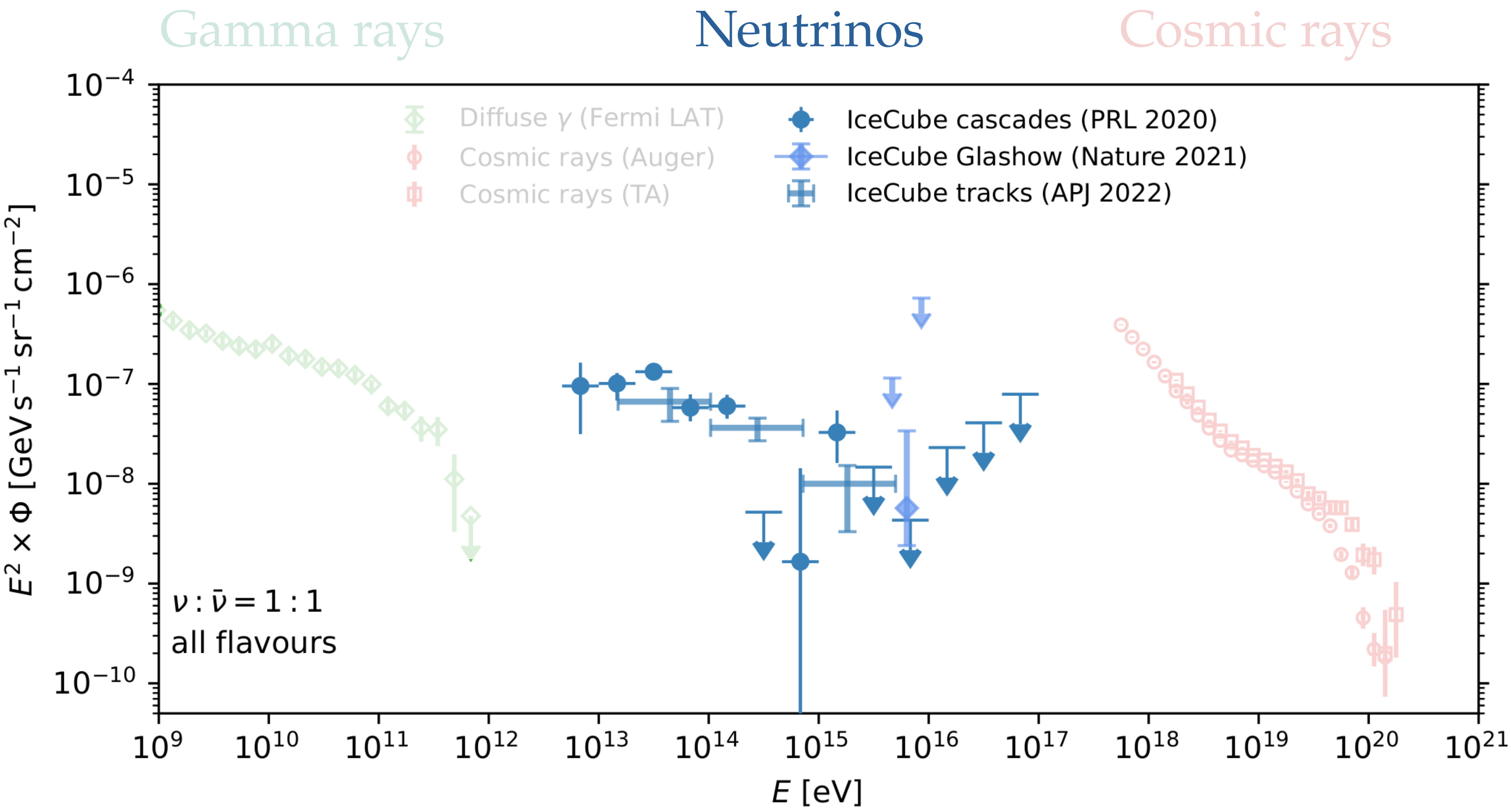

Precision
Colliders
Today
HE
cosmic
particles
Energy

In 10–20 years



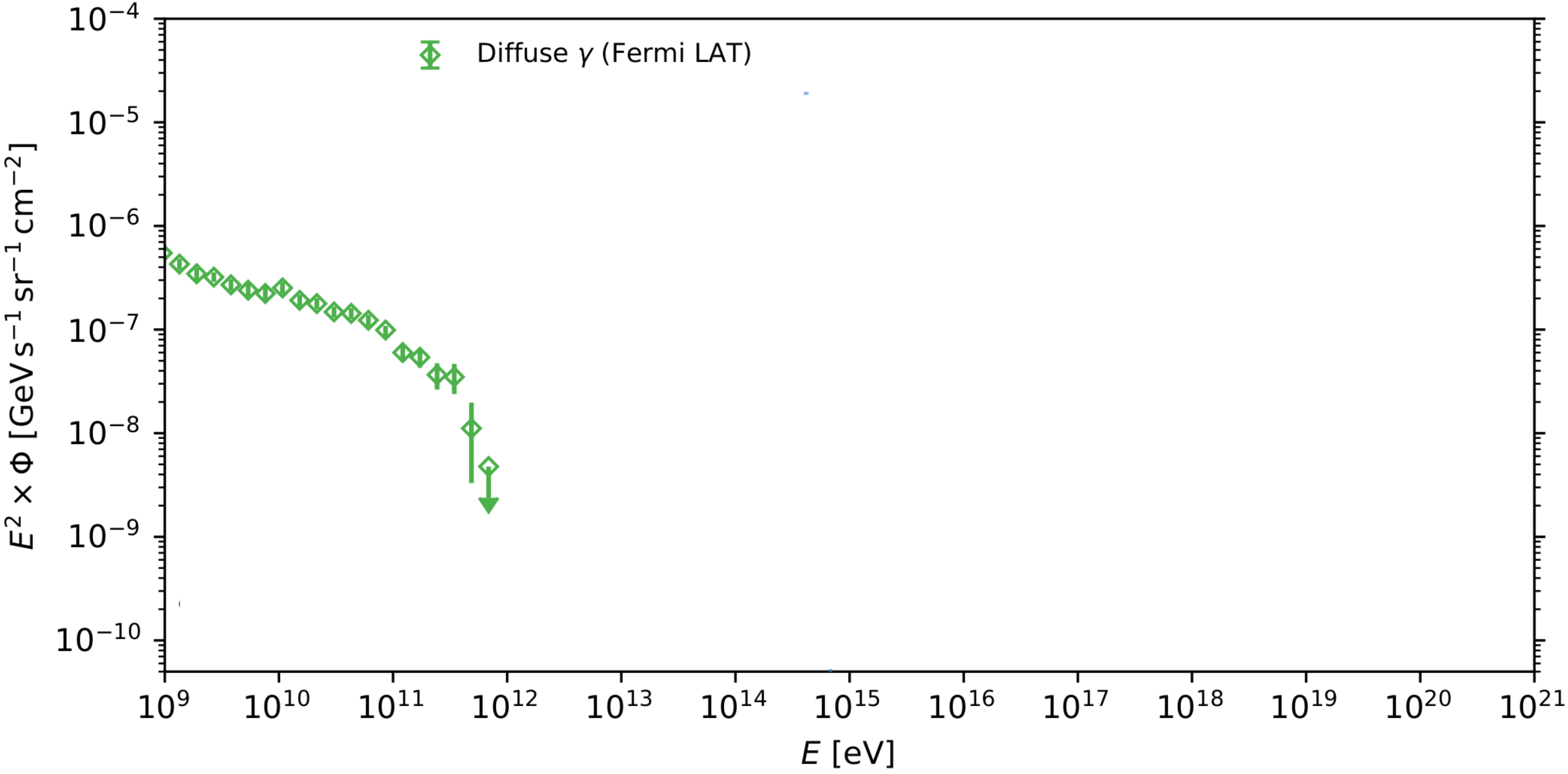
How?

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



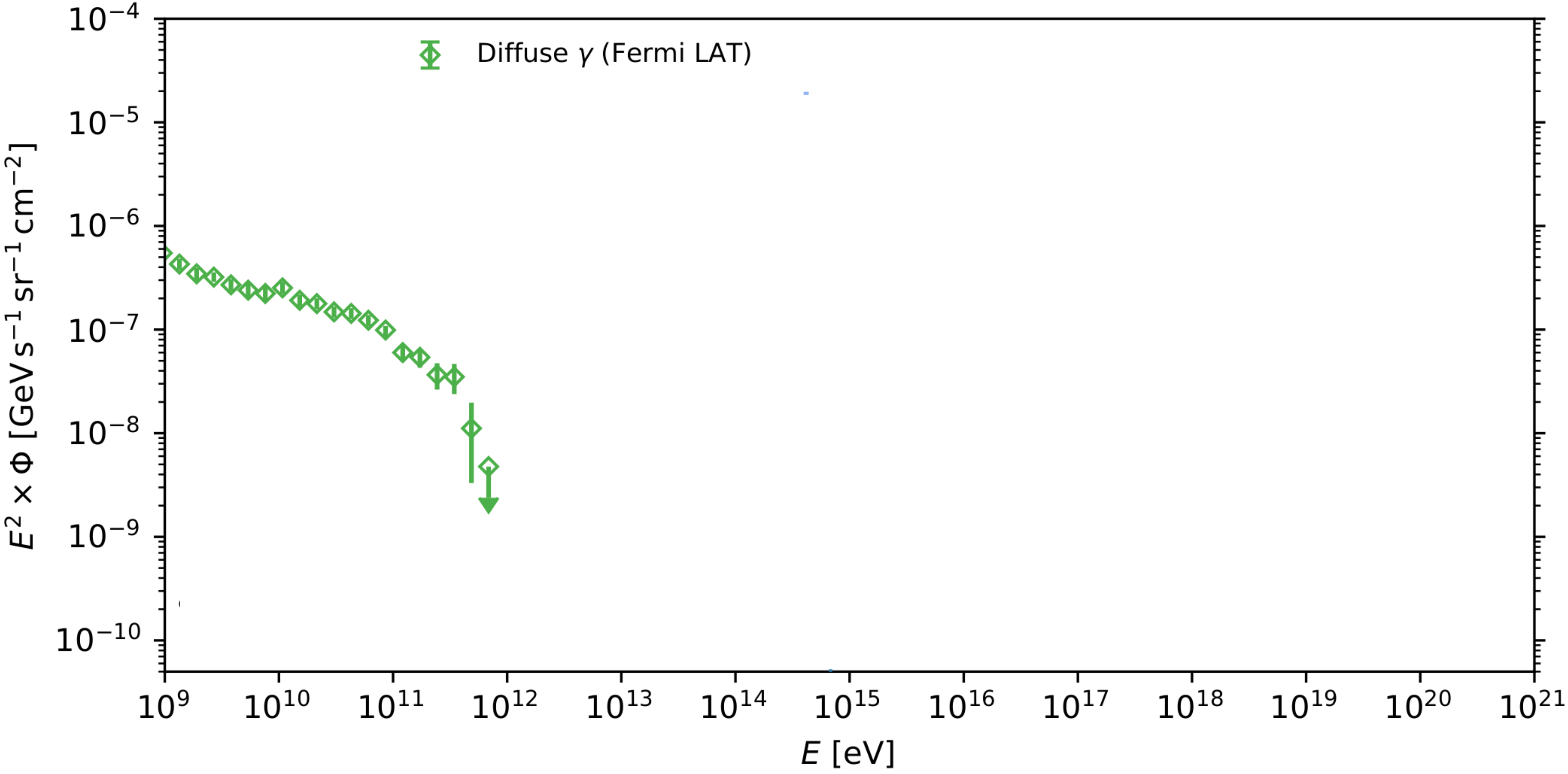
M. Ackermann, **MB**, *et al.*, *JHEAp* 35, 55 (2022) [2203.08096]

Gamma rays Neutrinos Cosmic rays



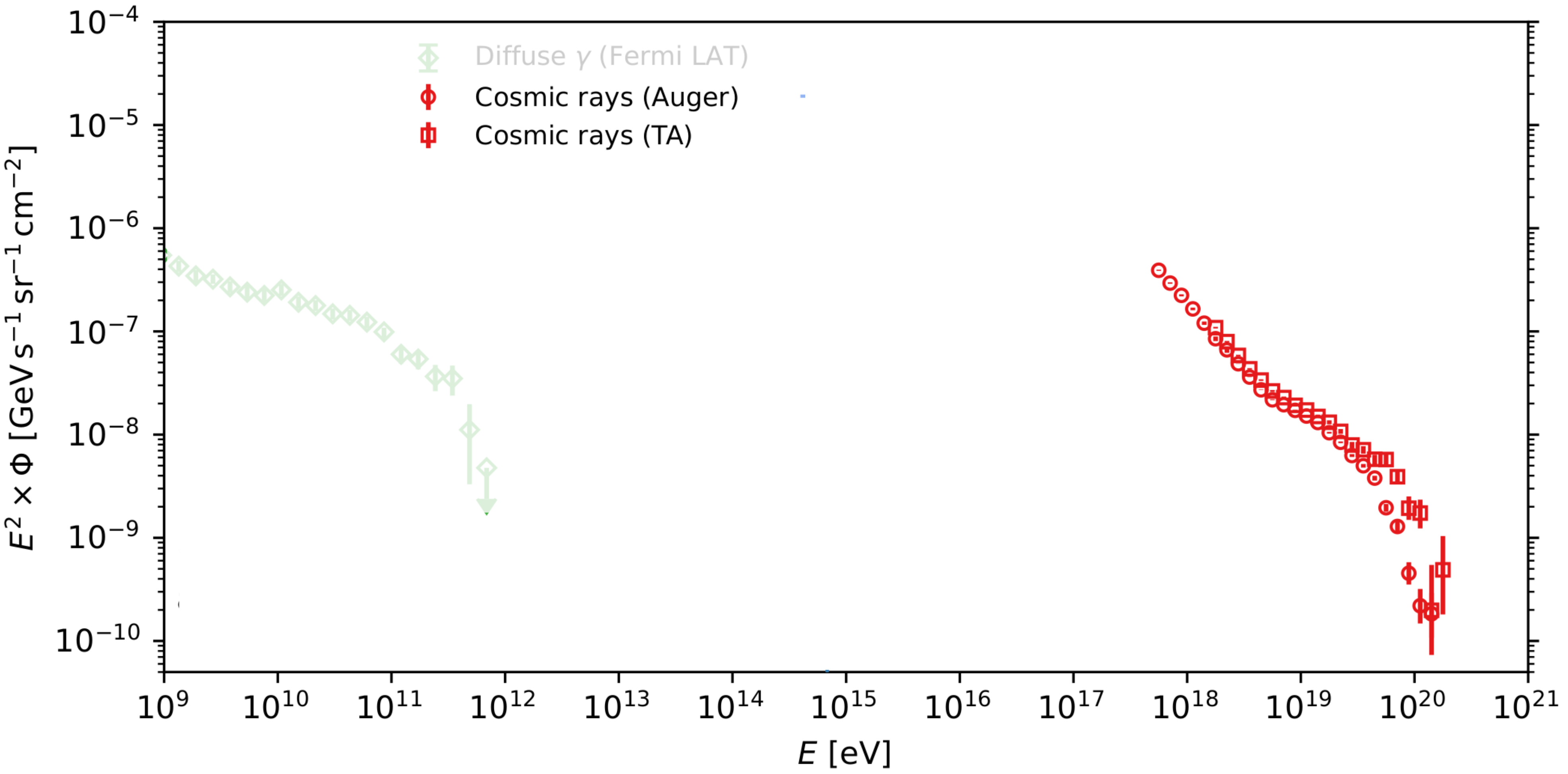
M. Ackermann, **MB**, *et al.*, *JHEAp* 35, 55 (2022) [2203.08096]

Gamma rays Neutrinos Cosmic rays

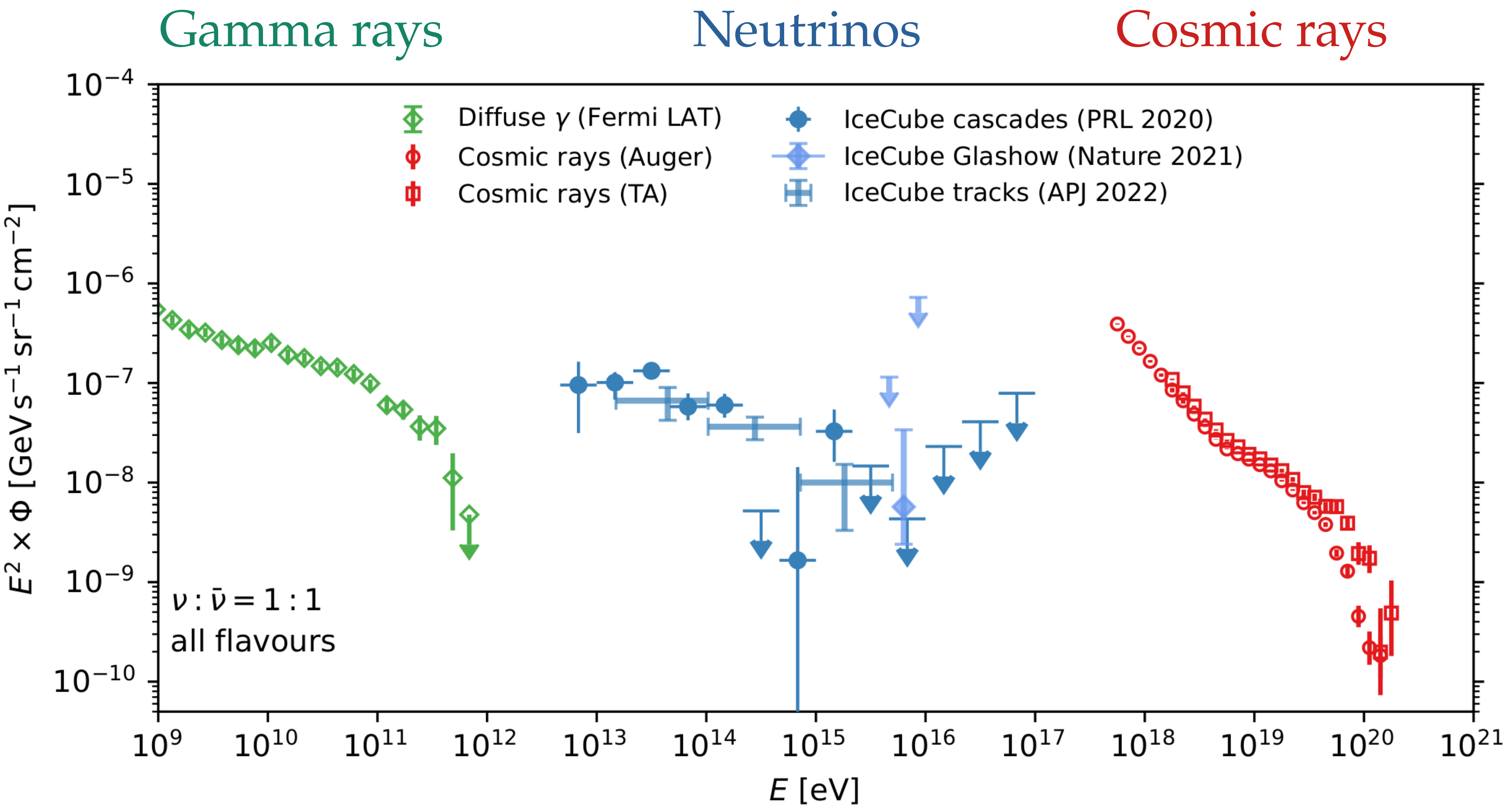


M. Ackermann, **MB**, *et al.*, *JHEAp* 35, 55 (2022) [2203.08096]

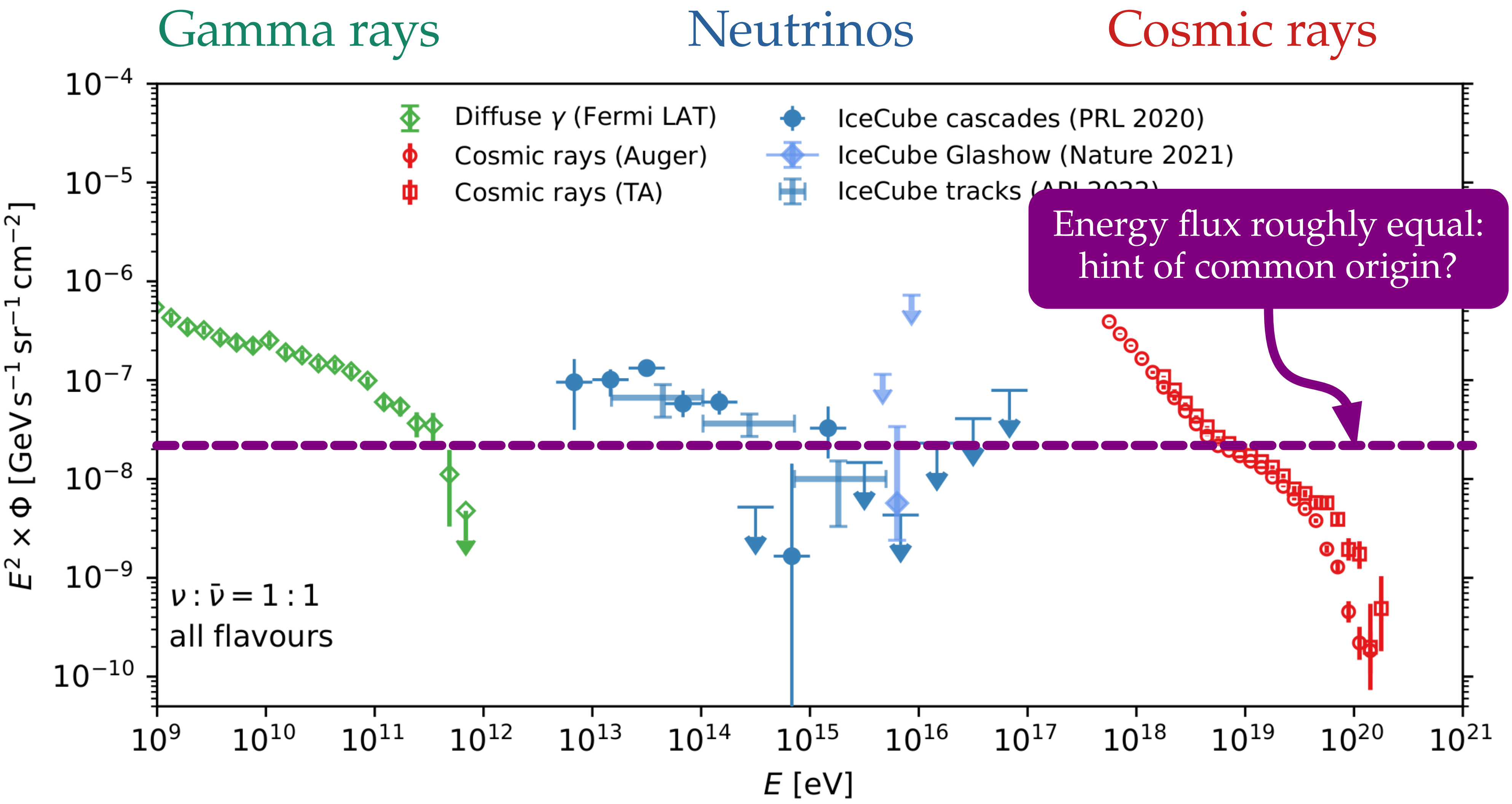
Gamma rays Neutrinos Cosmic rays



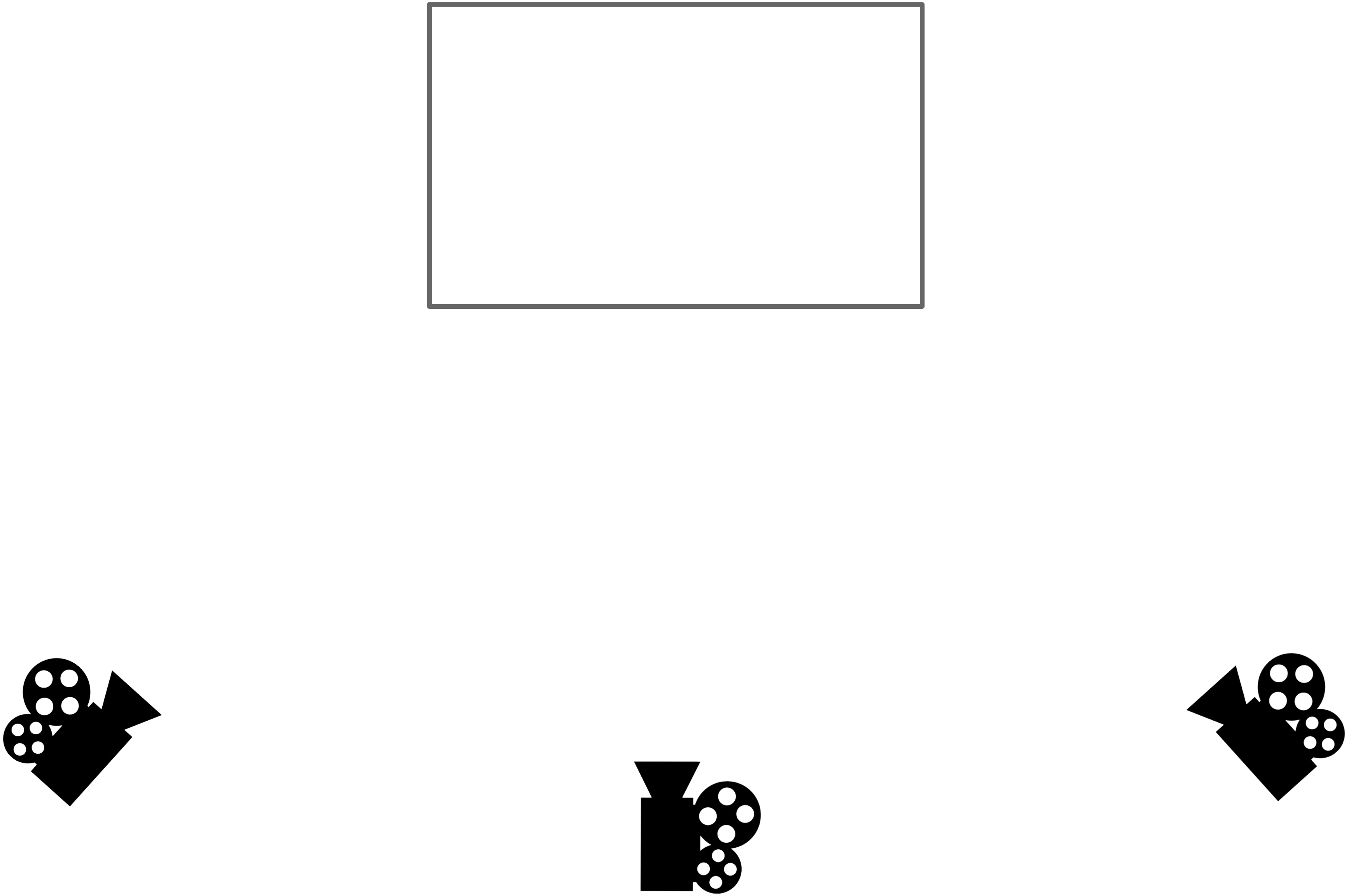
M. Ackermann, **MB**, *et al.*, *JHEAp* 35, 55 (2022) [2203.08096]

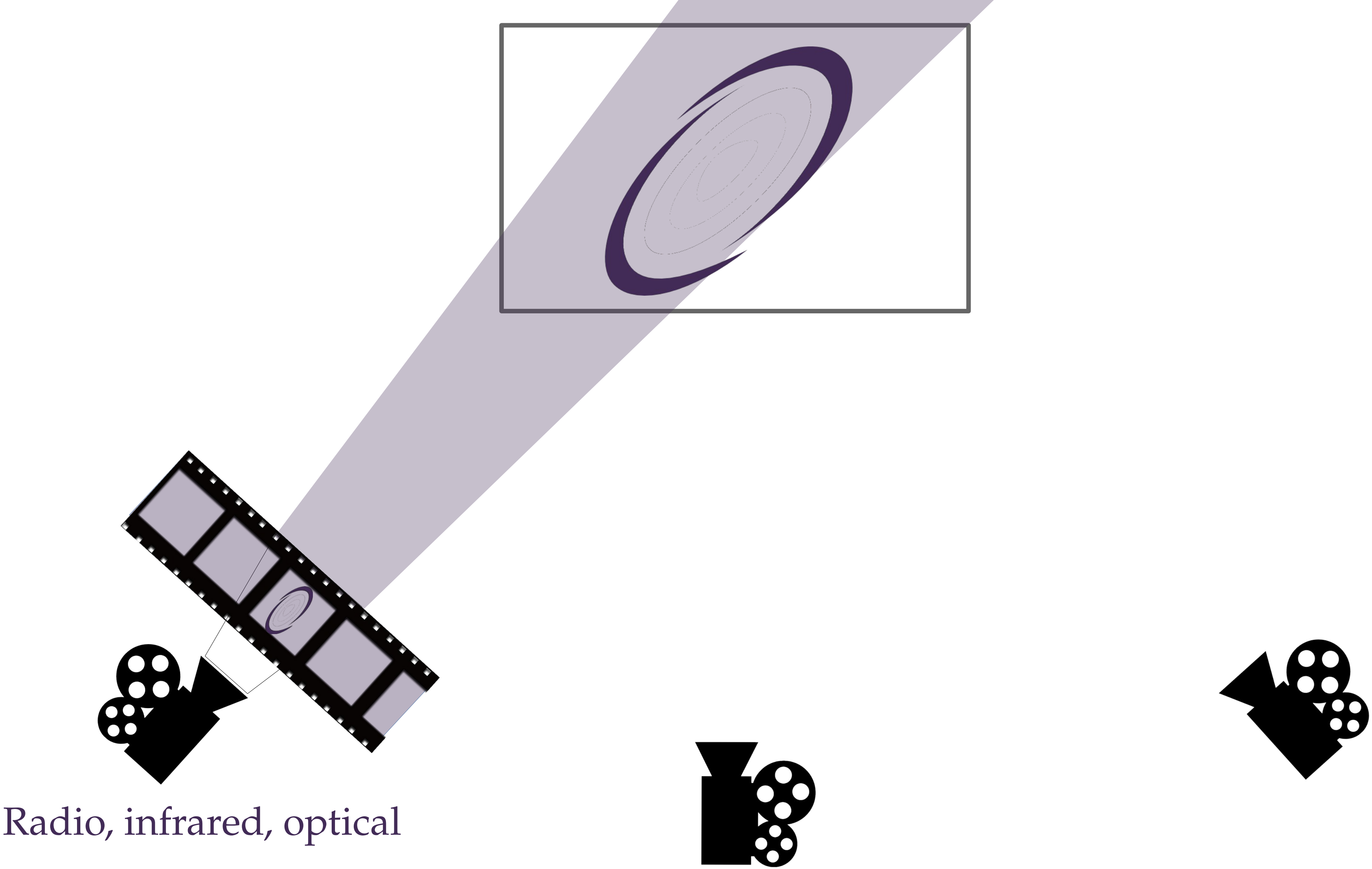


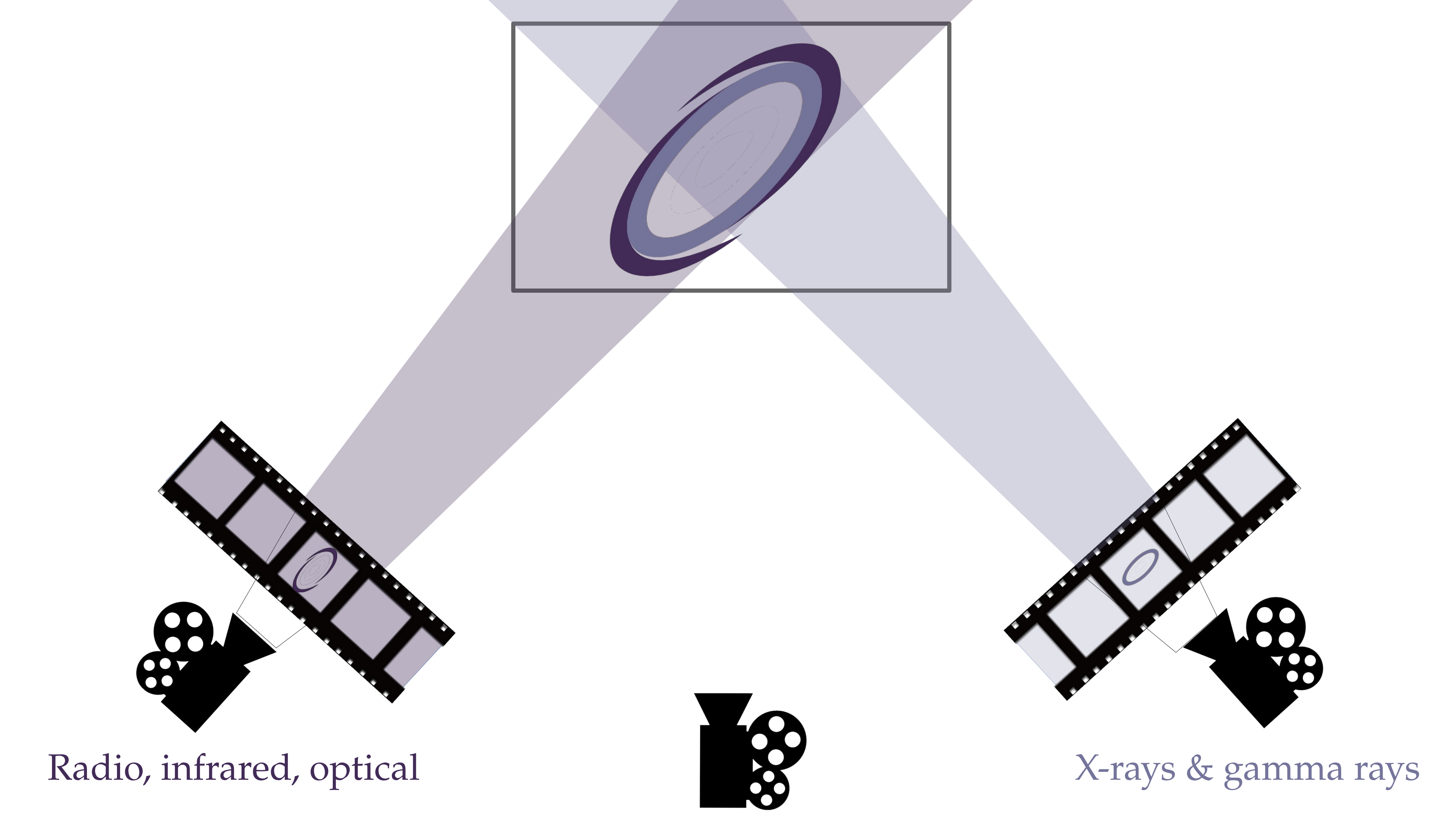
M. Ackermann, **MB**, *et al.*, *JHEAp* 35, 55 (2022) [2203.08096]



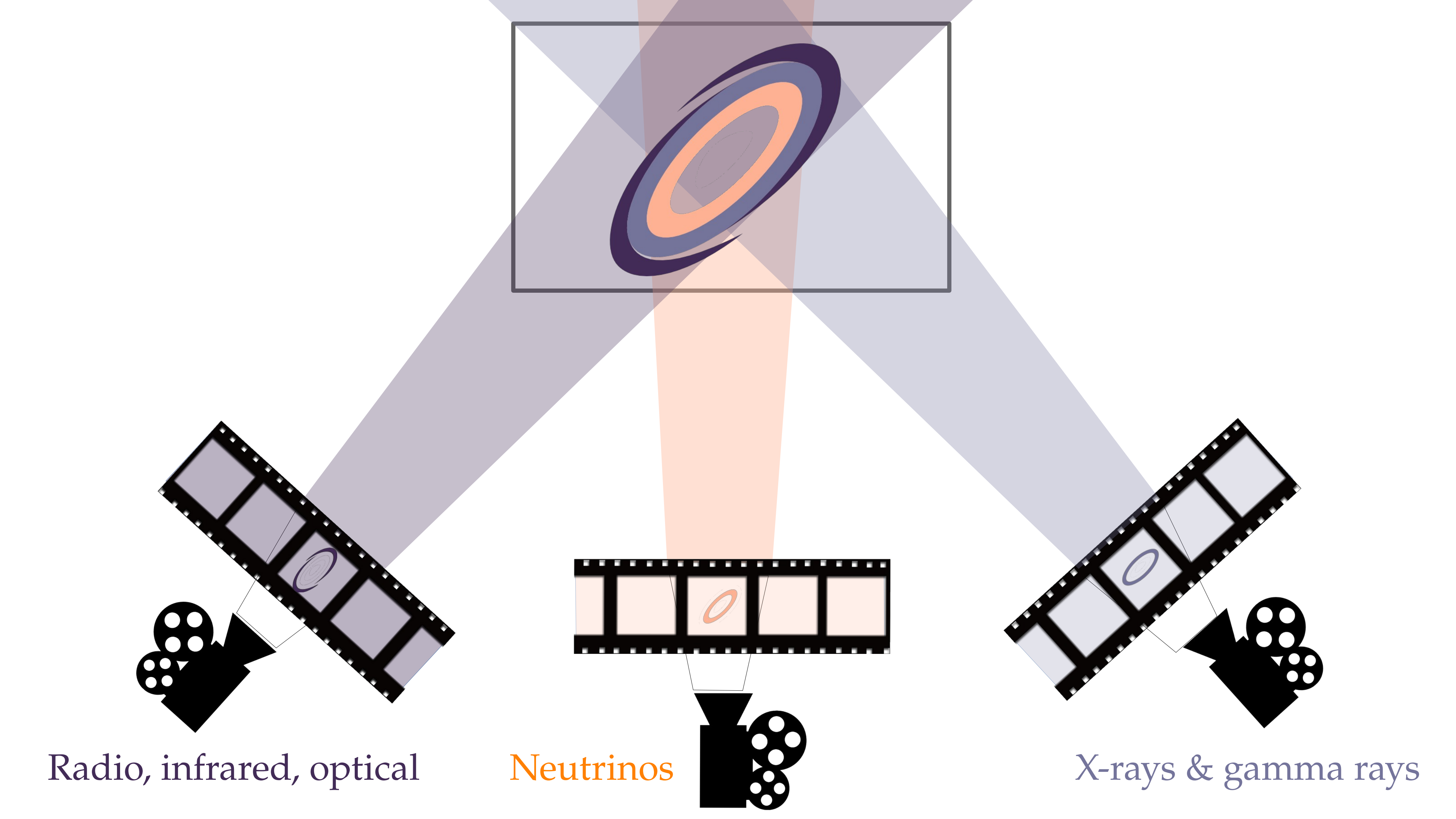
M. Ackermann, **MB**, *et al.*, *JHEAp* 35, 55 (2022) [2203.08096]

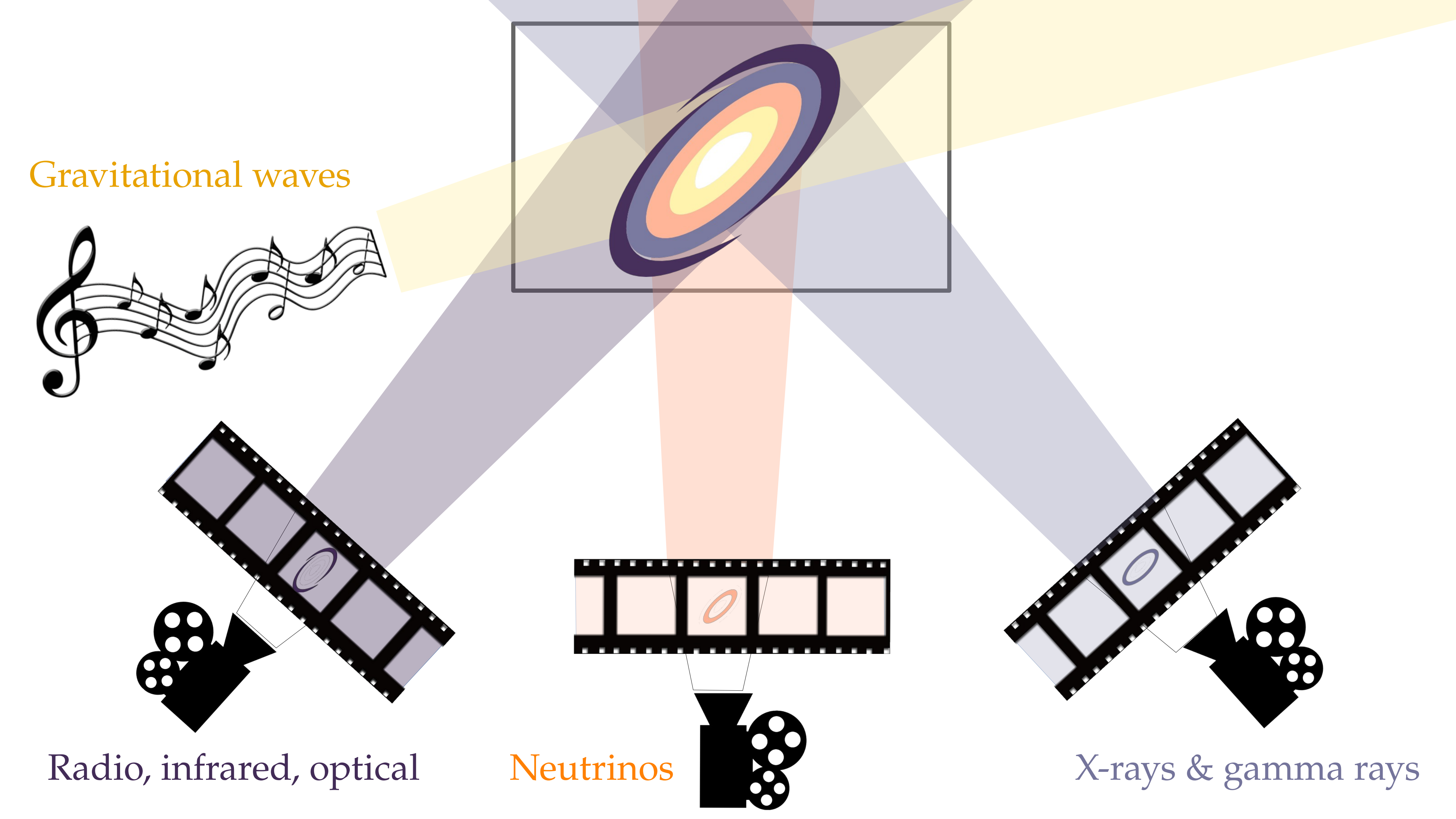



Radio, infrared, optical



Radio, infrared, optical
X-rays & gamma rays


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


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

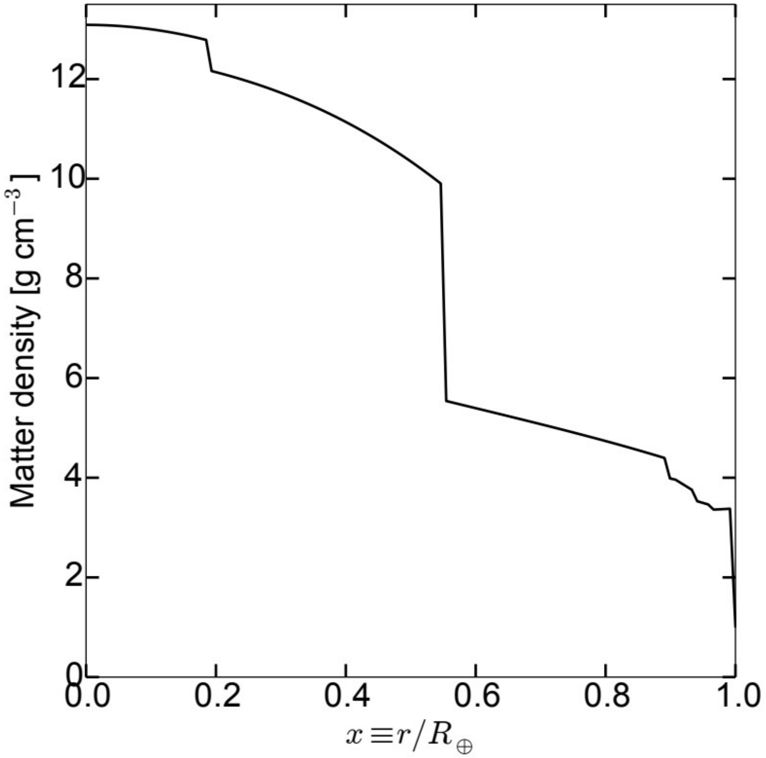
Thanks!

Backup slides

A feel for the in-Earth attenuation

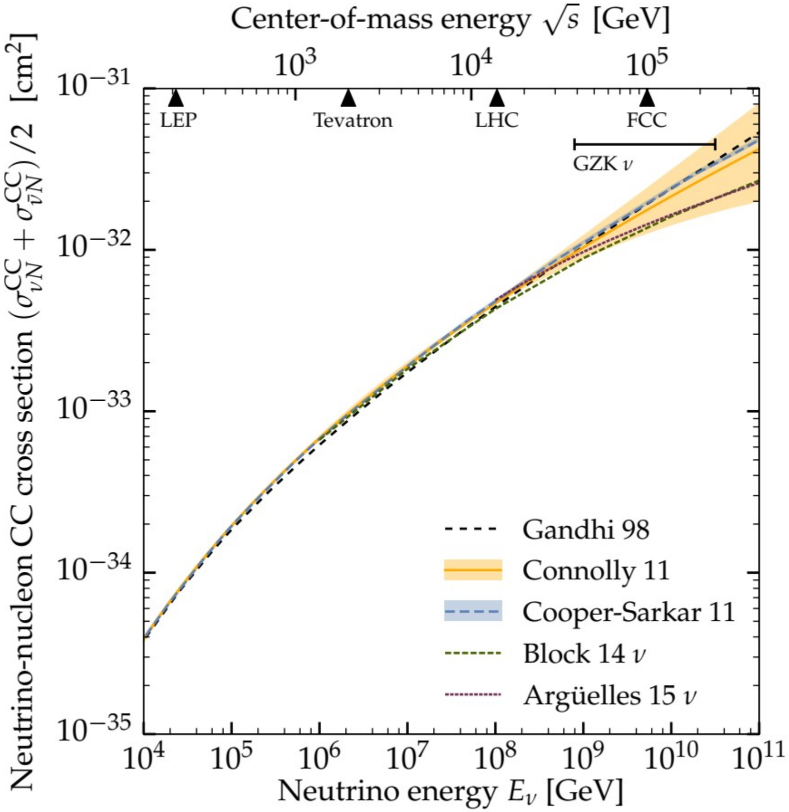
Earth matter density

(Preliminary Reference Earth Model)



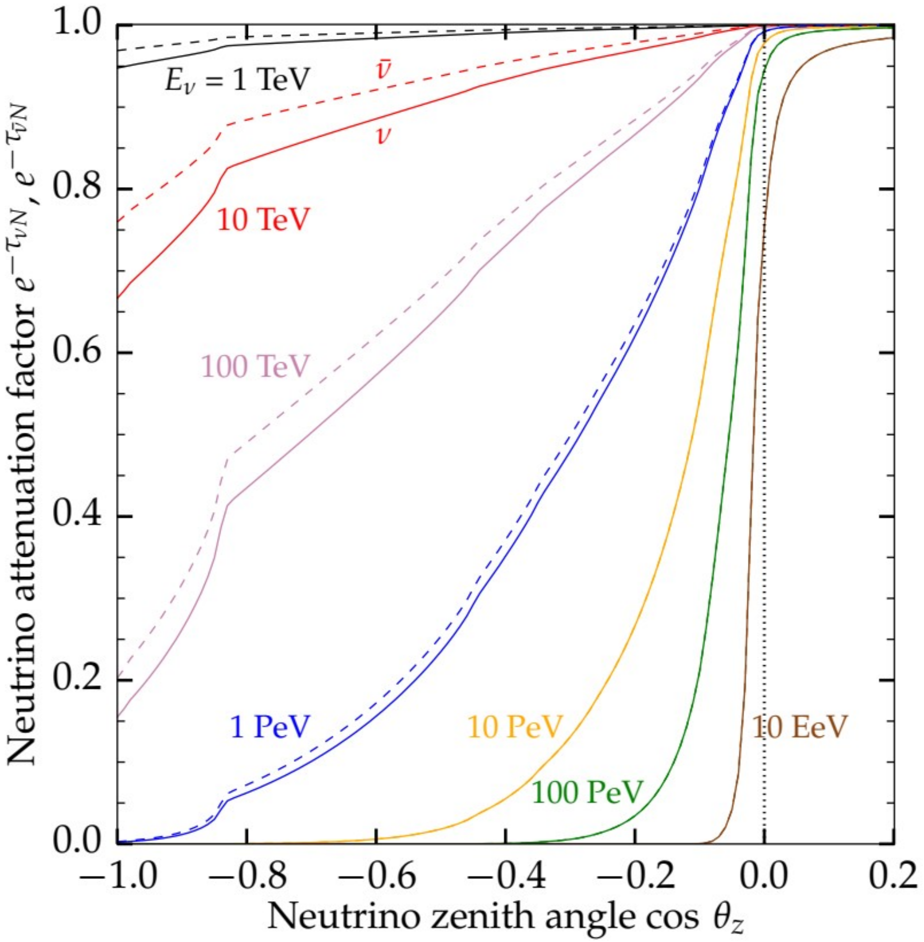
+

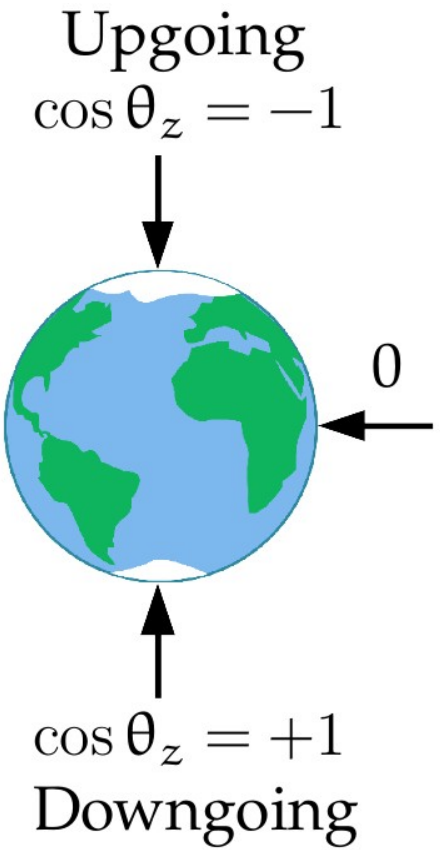
Neutrino-nucleon cross section

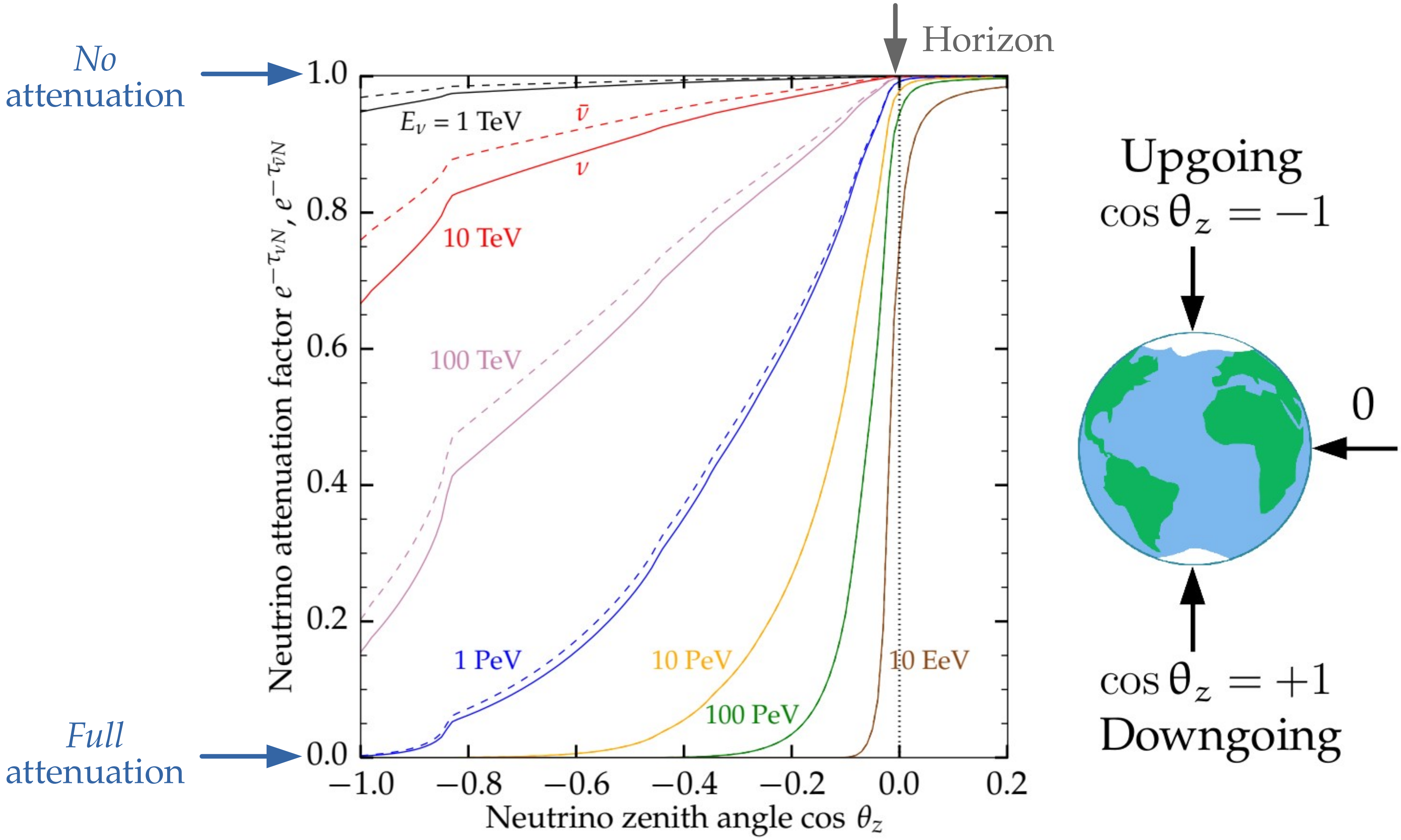


A feel for the in-Earth attenuation

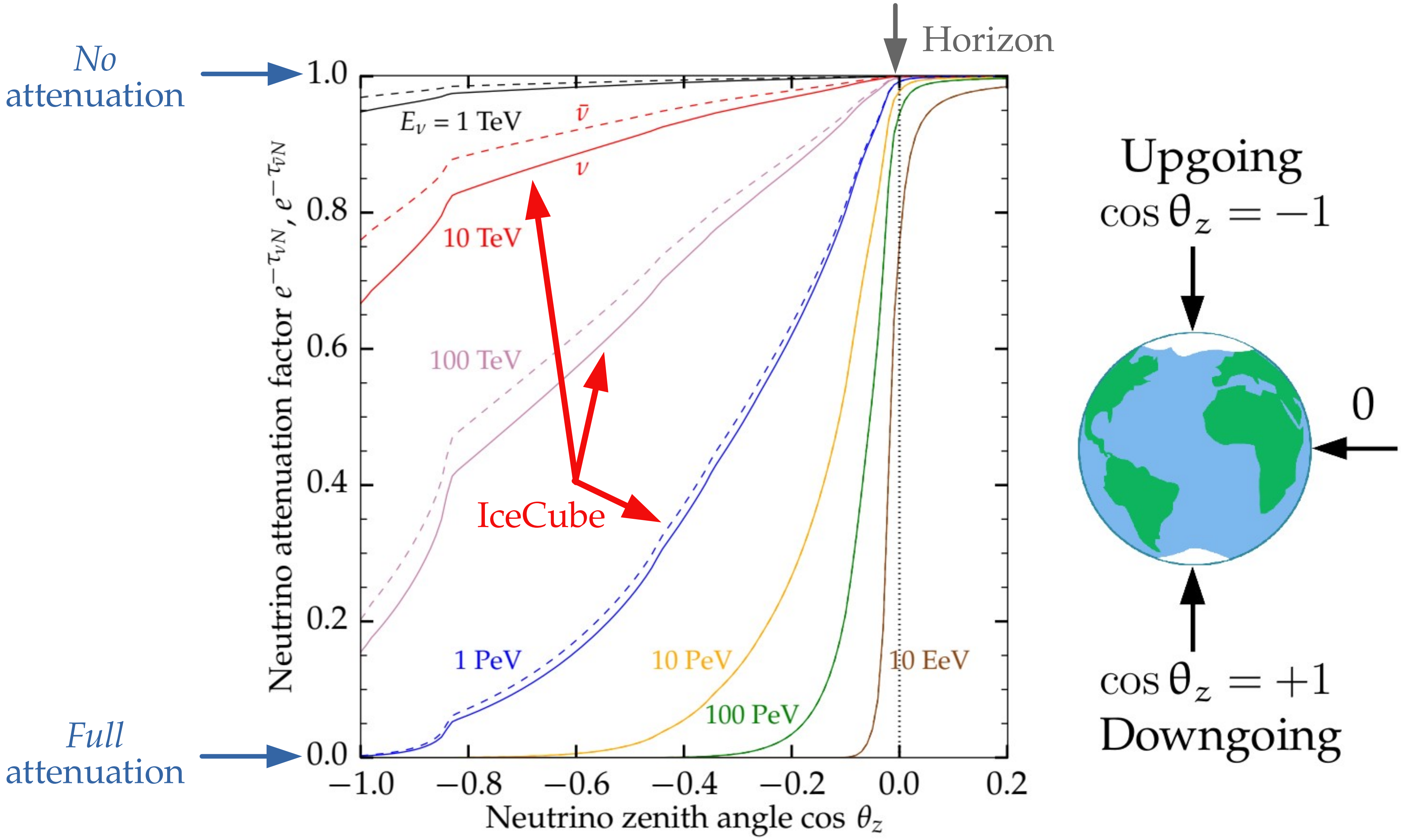
=



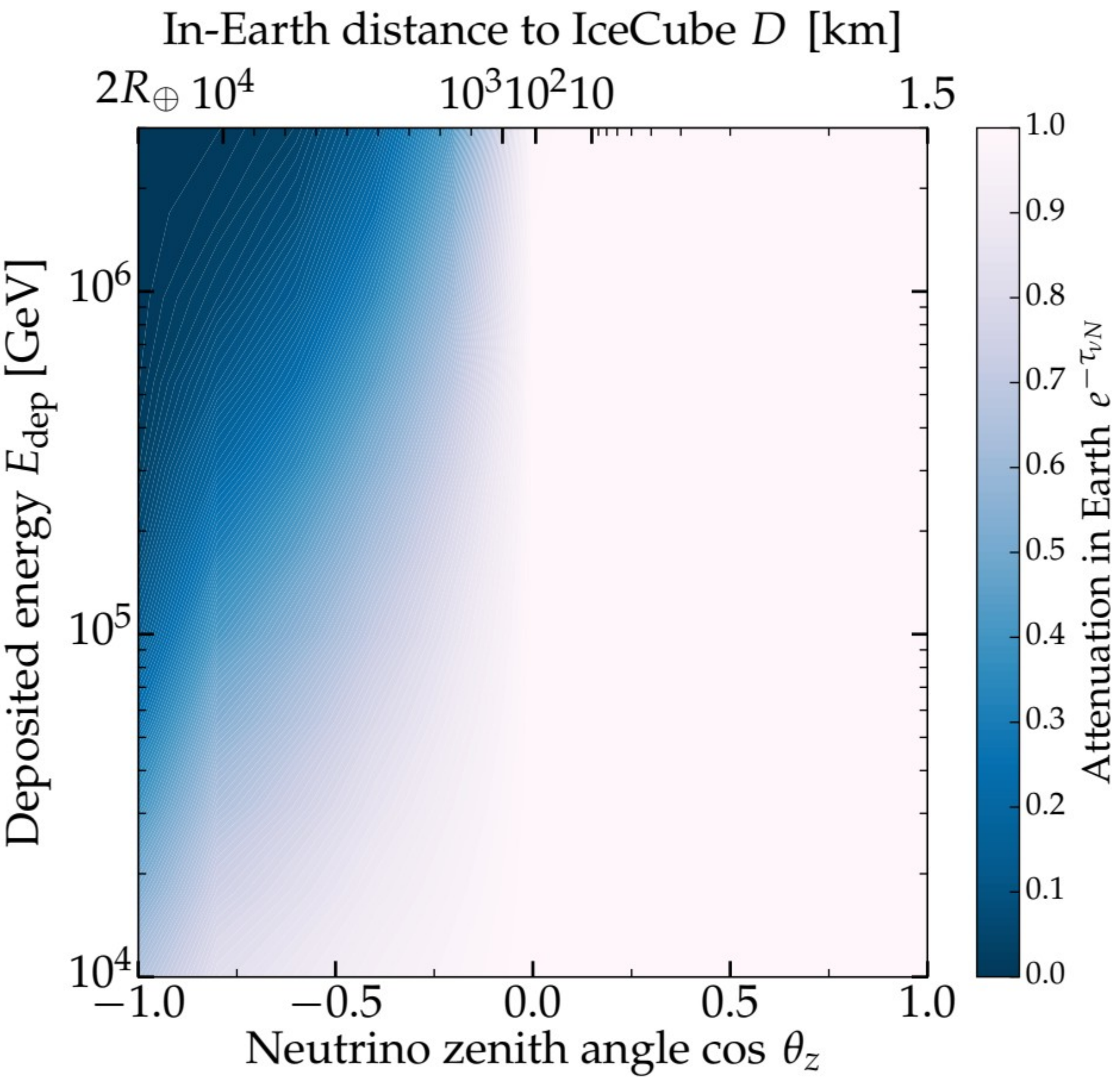


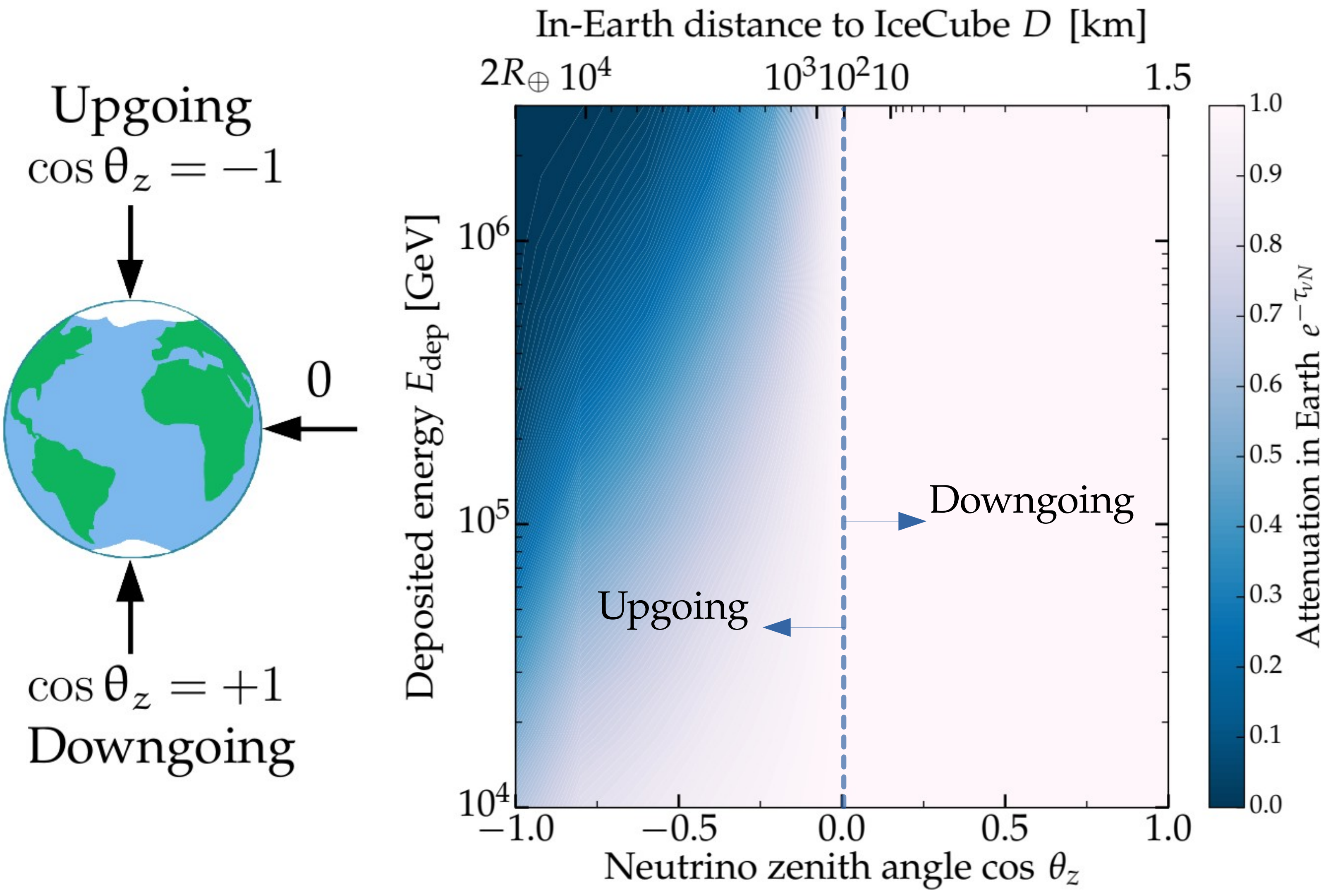


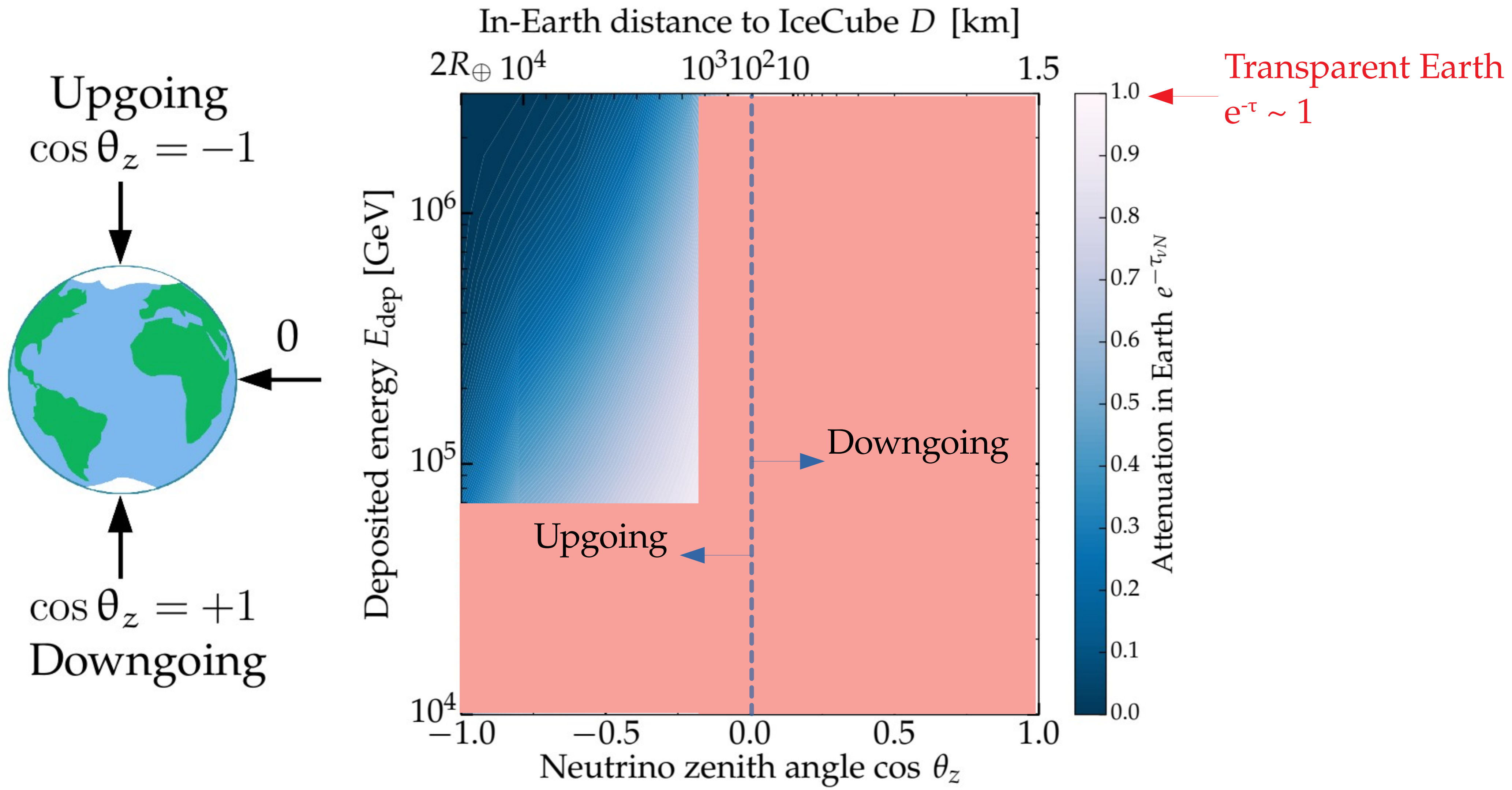
MB & Connolly, *PRL* 2019

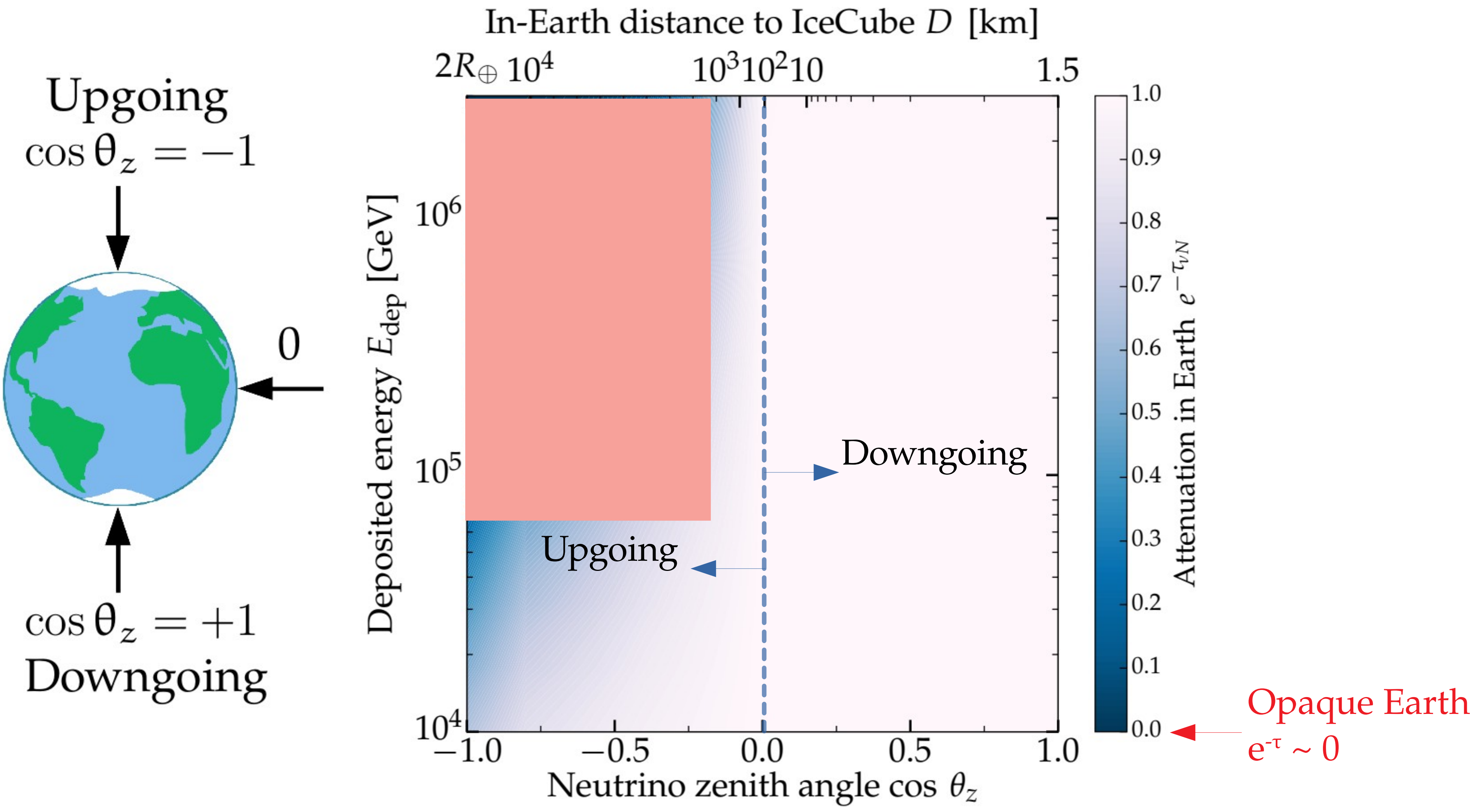


MB & Connolly, *PRL* 2019


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


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

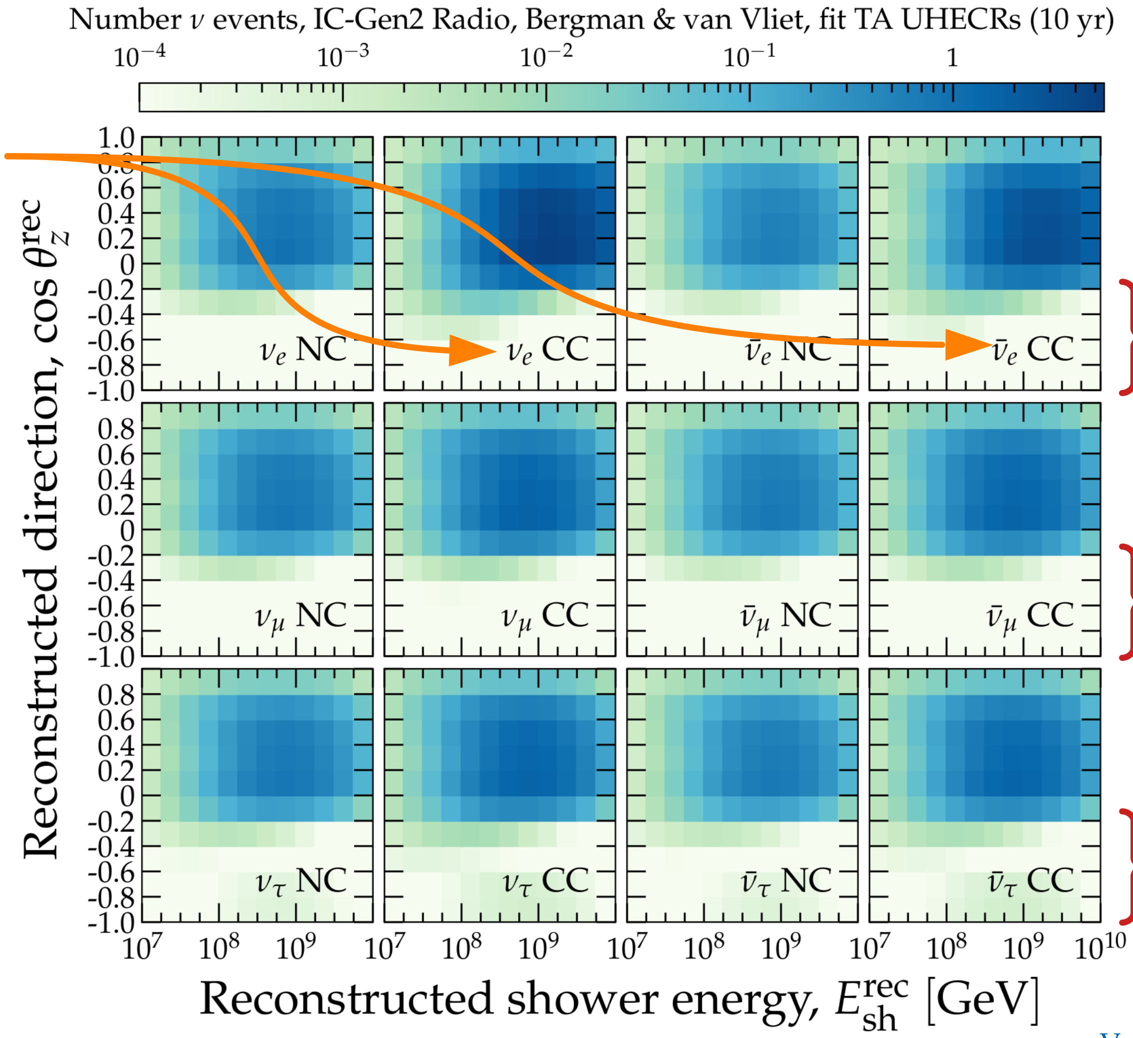

Upgoing
$\cos\theta_z = -1$
0
$\cos\theta_z = +1$
Downgoing
In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4 10^3 10^2 10 1.5
Deposited energy E_{dep} [GeV]
10^6
10^5
10^4
Downgoing
Upgoing
−1.0 −0.5 0.0 0.5 1.0
Neutrino zenith angle $\cos\theta_z$
1.0 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.0
Attenuation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



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

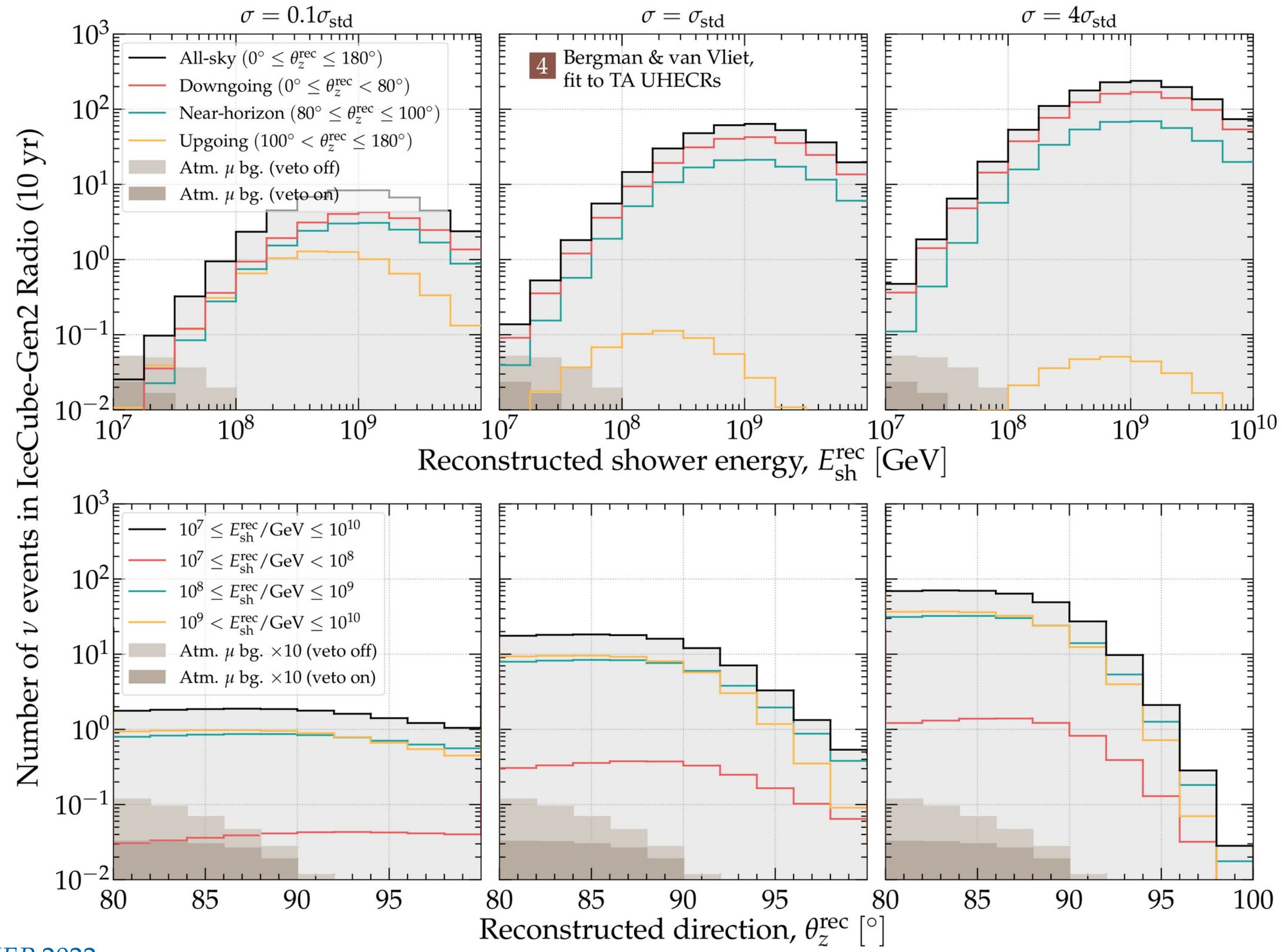
Event rates per channel

$\nu_e, \bar{\nu}_e$
CCinteractions
dominate

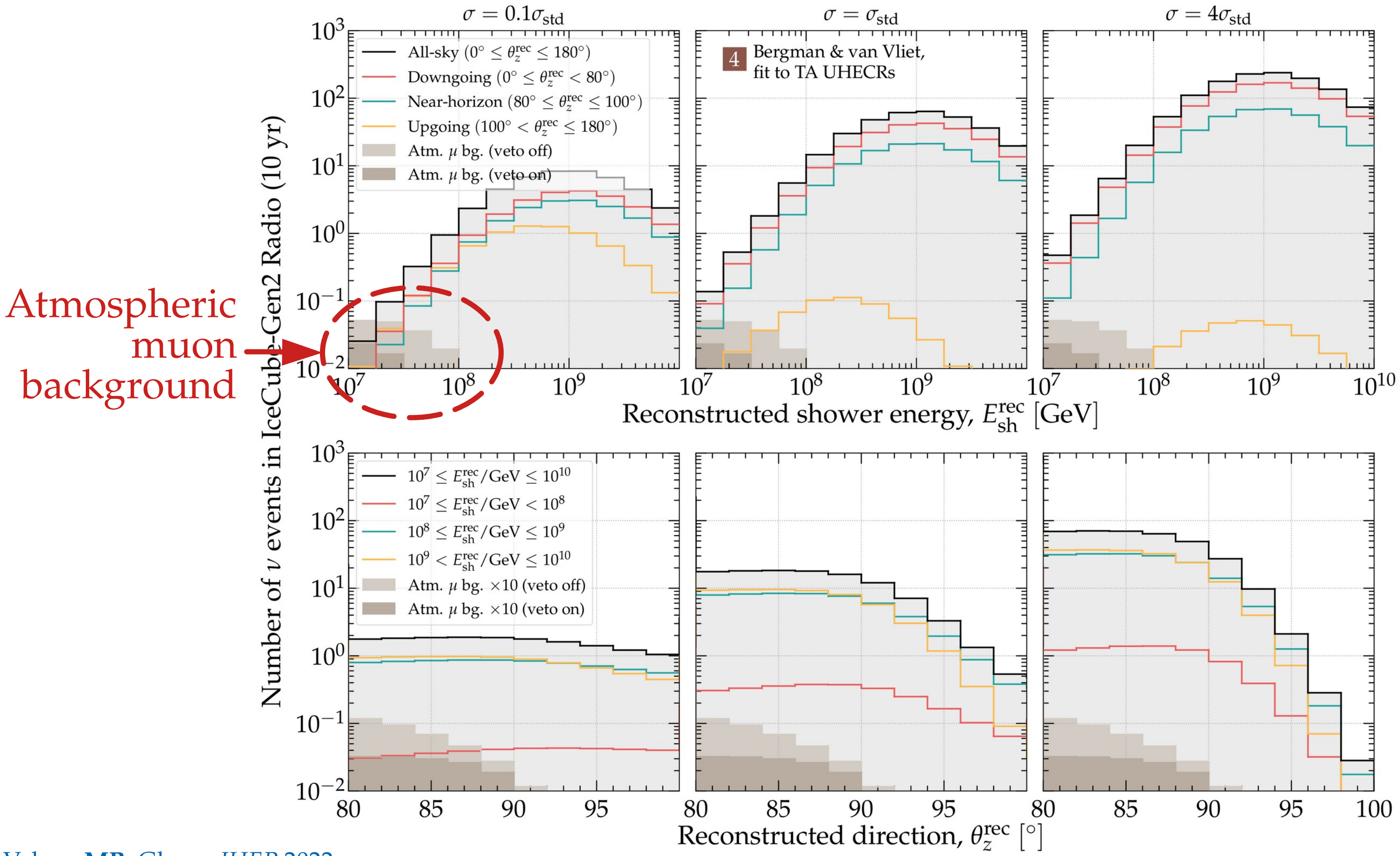


In-Earth
attenuation

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

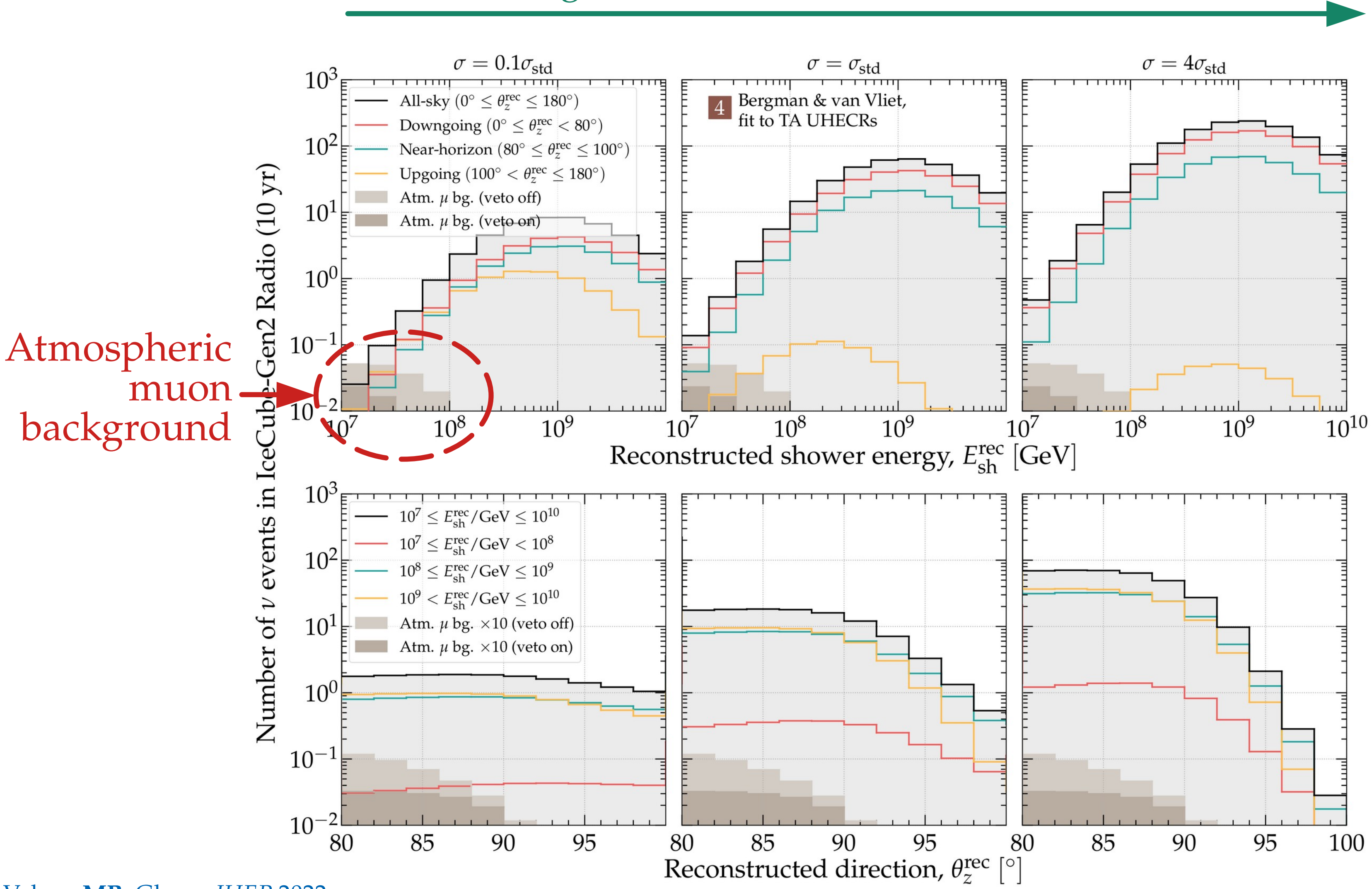


Valera, **MB**, Glaser, *JHEP* 2022

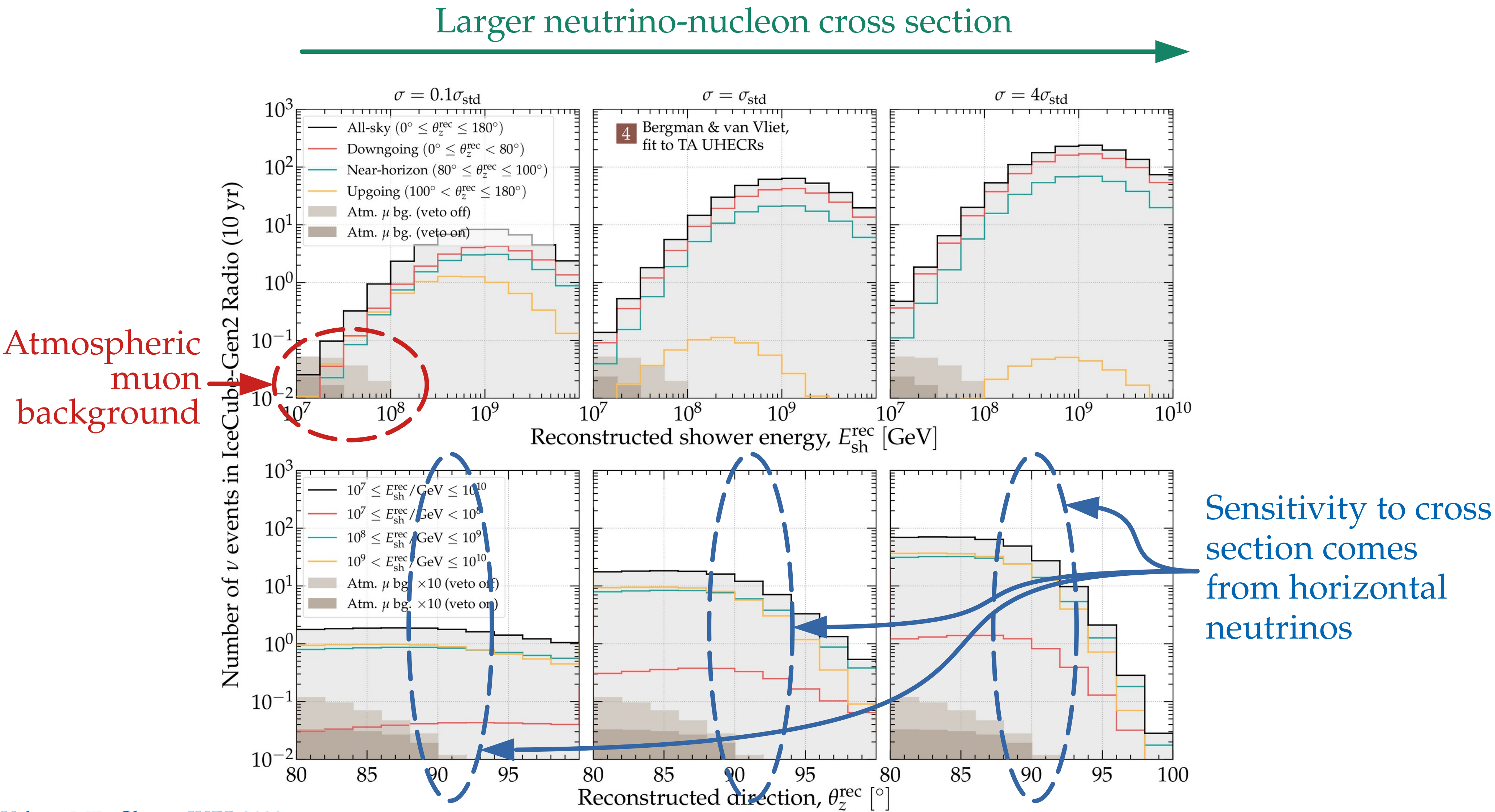


Valera, **MB**, Glaser, *JHEP* 2022

Larger neutrino-nucleon cross section



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



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

Measuring cross section *and* flux normalization

Two physical parameters:

Neutrino-nucleon cross section: $$f_\sigma = \frac{\sigma}{\sigma_{\rm std}}$$

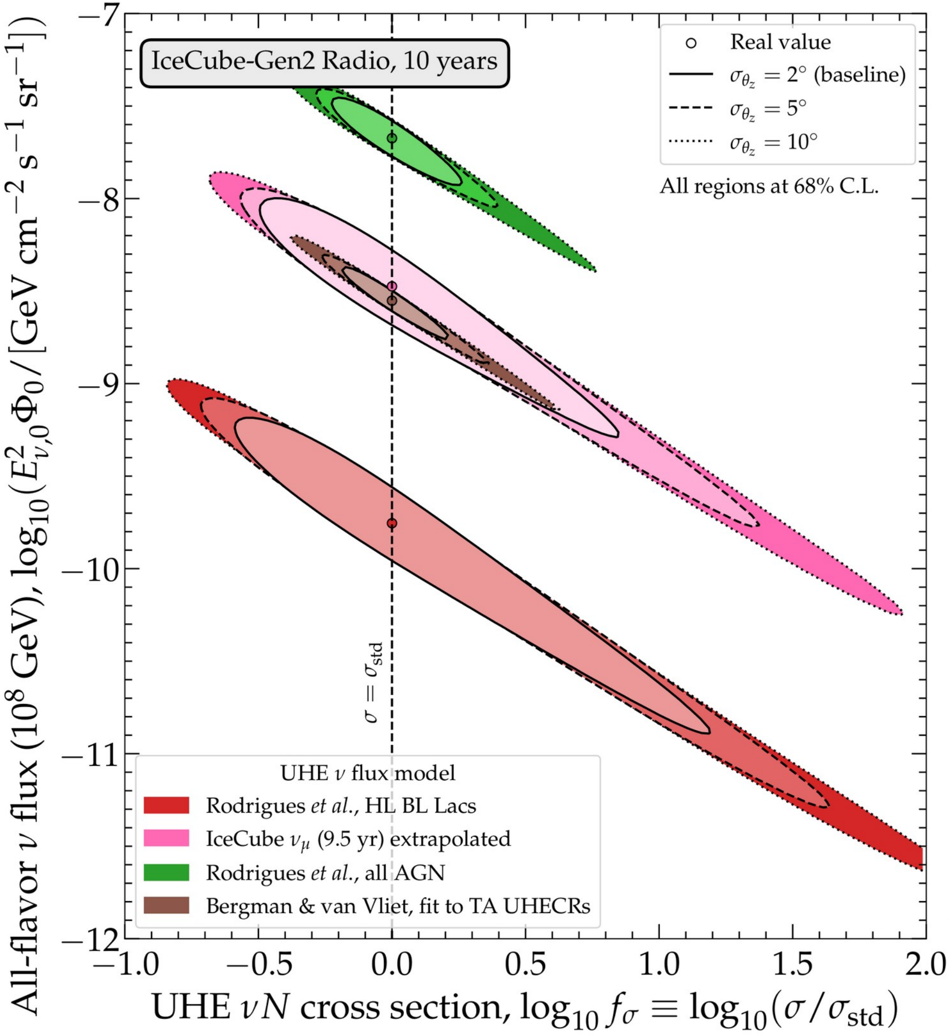
Neutrino flux normalization:
(Keep the spectral shape fixed for now)

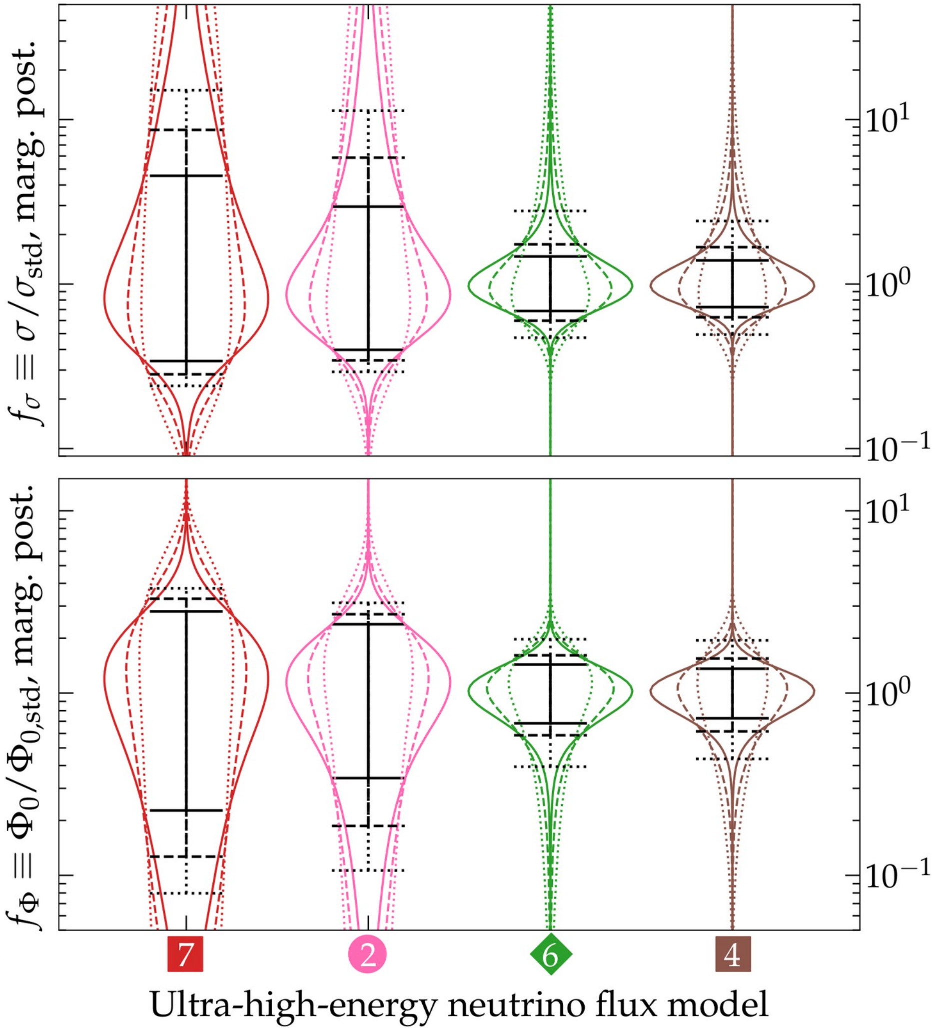
$$f_{=}\frac{\Phi_\nu(10^8\ \mathrm{GeV})}{\Phi_{\nu,\rm std}(10^8\ \mathrm{GeV})}$$

We vary and extract both simultaneously *always*,
and marginalize over each at a time

Effect of angular resolution

Valera, **MB**, Glaser, 2204.04237

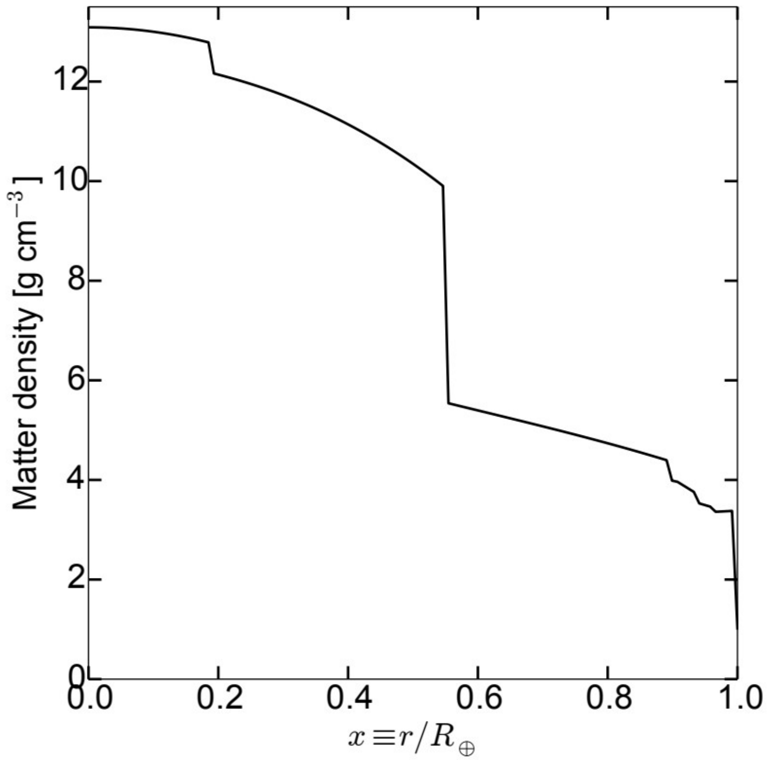




A feel for the in-Earth attenuation

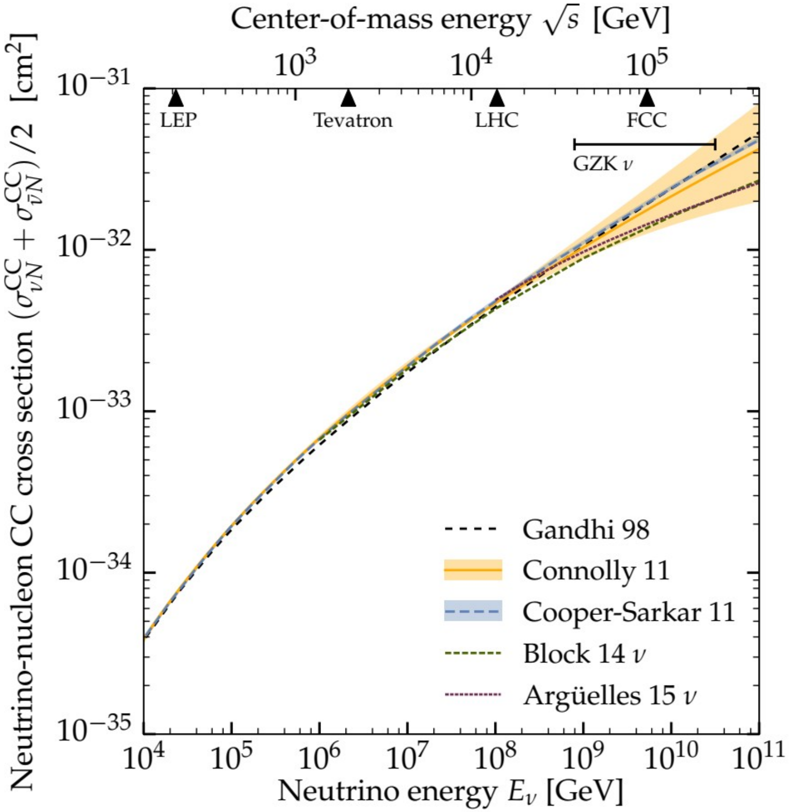
Earth matter density

(Preliminary Reference Earth Model)



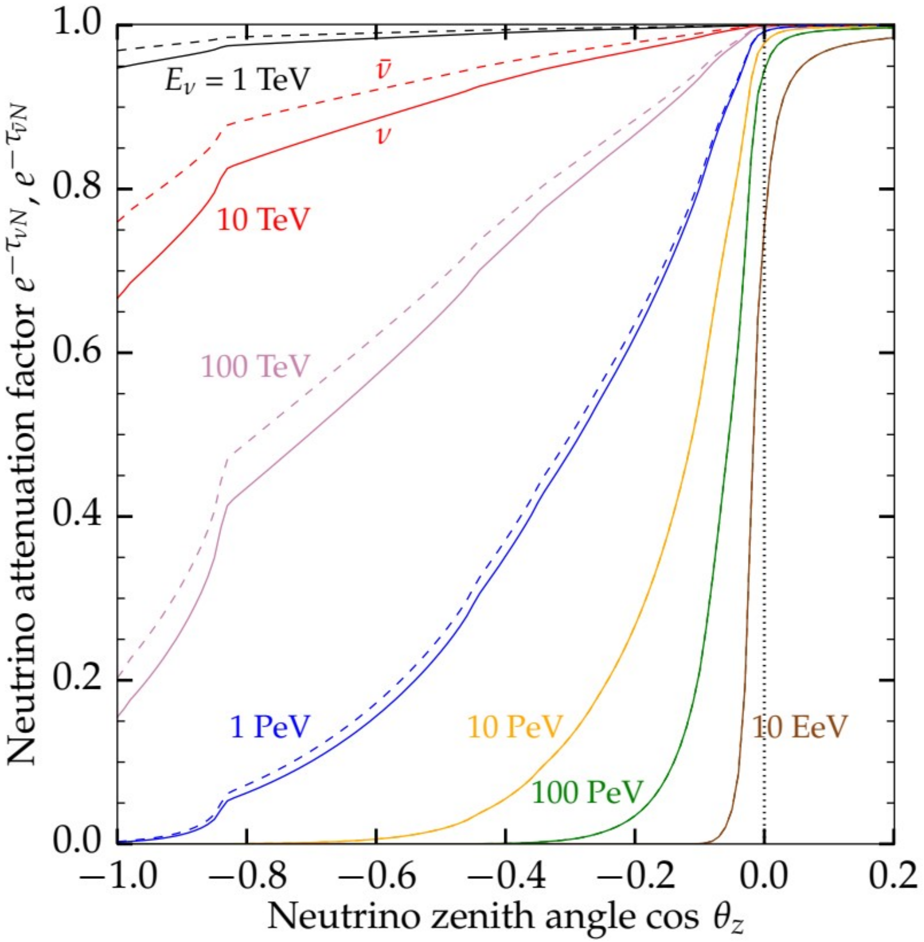
+

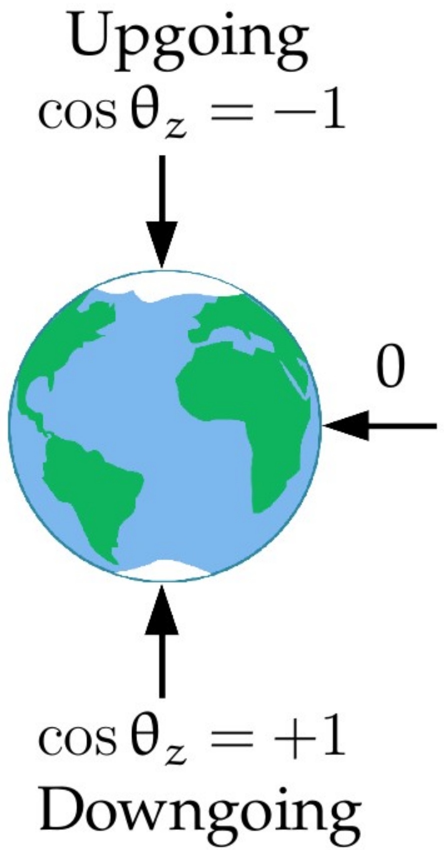
Neutrino-nucleon cross section



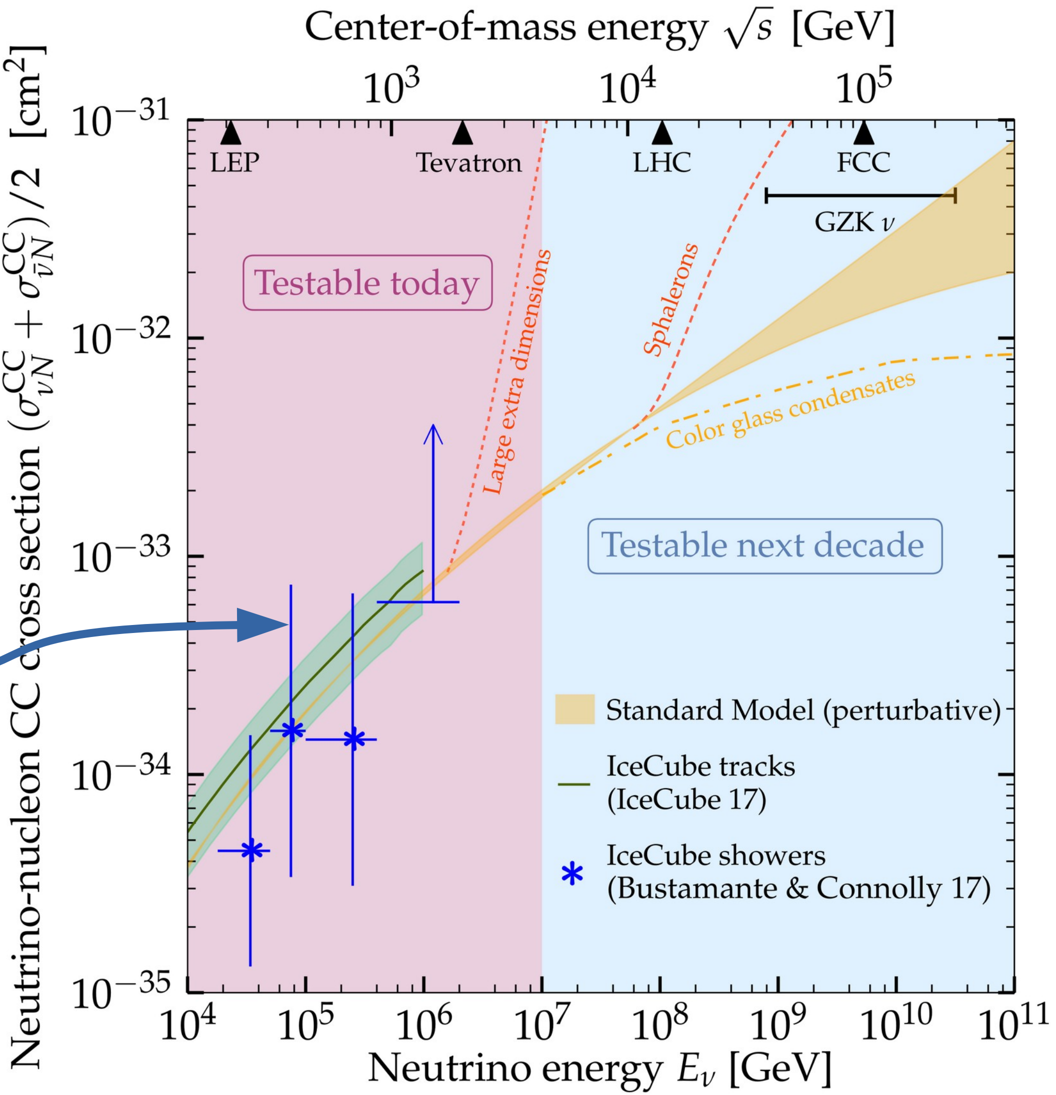
A feel for the in-Earth attenuation

=





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

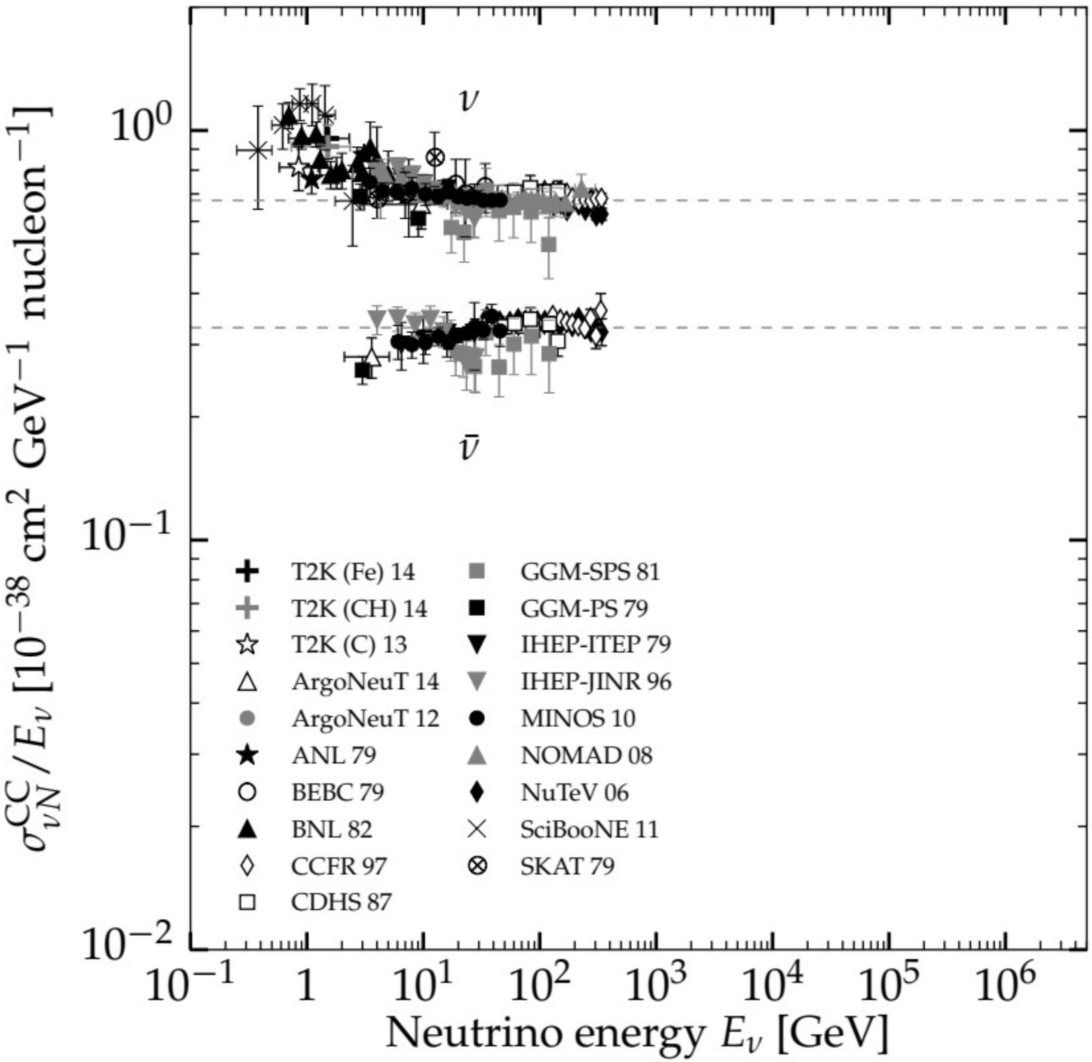


Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333)

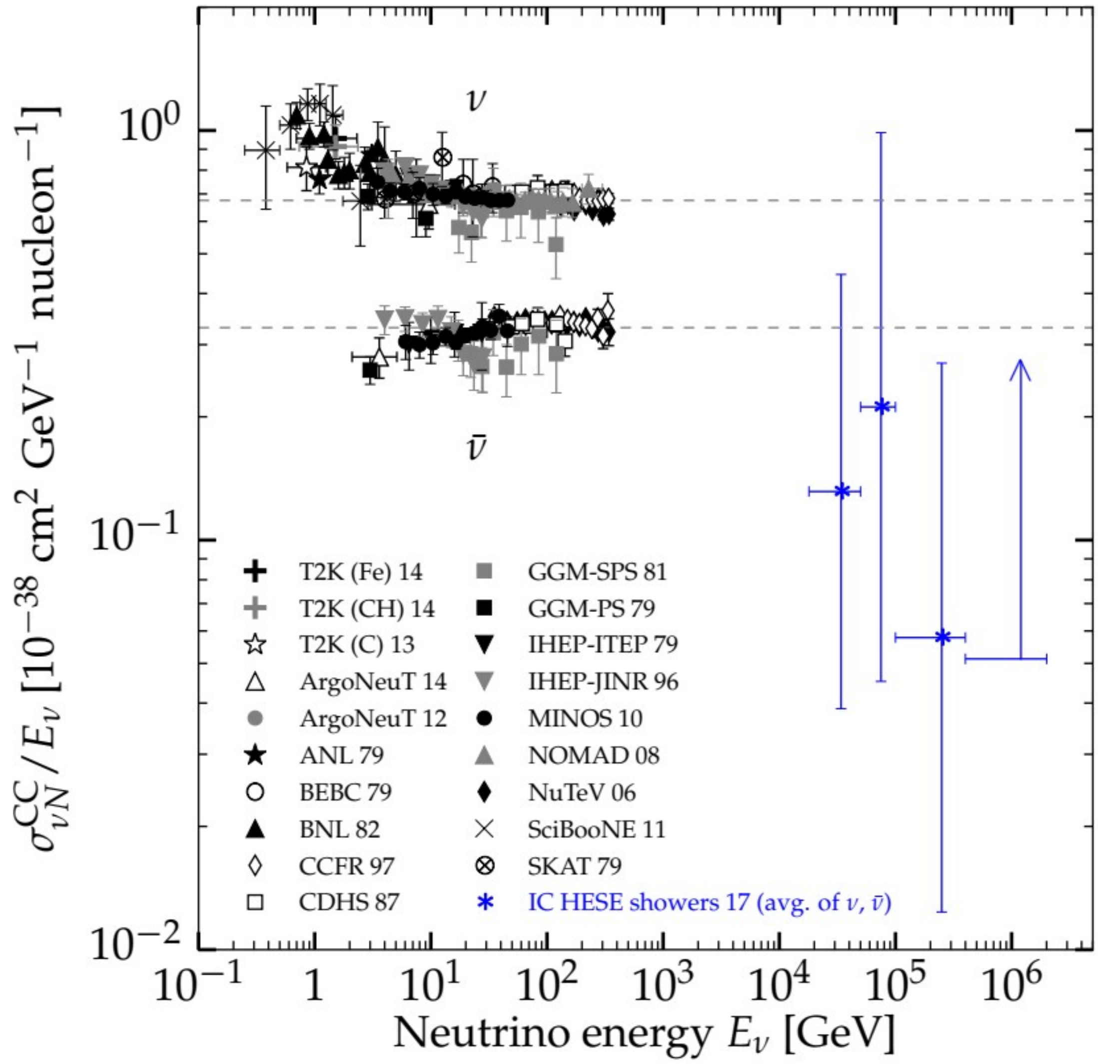
Cross sections from:
MB & Connolly, *PRL* 2019
IceCube, *Nature* 2017

Recent update:
IceCube, 2011.03560

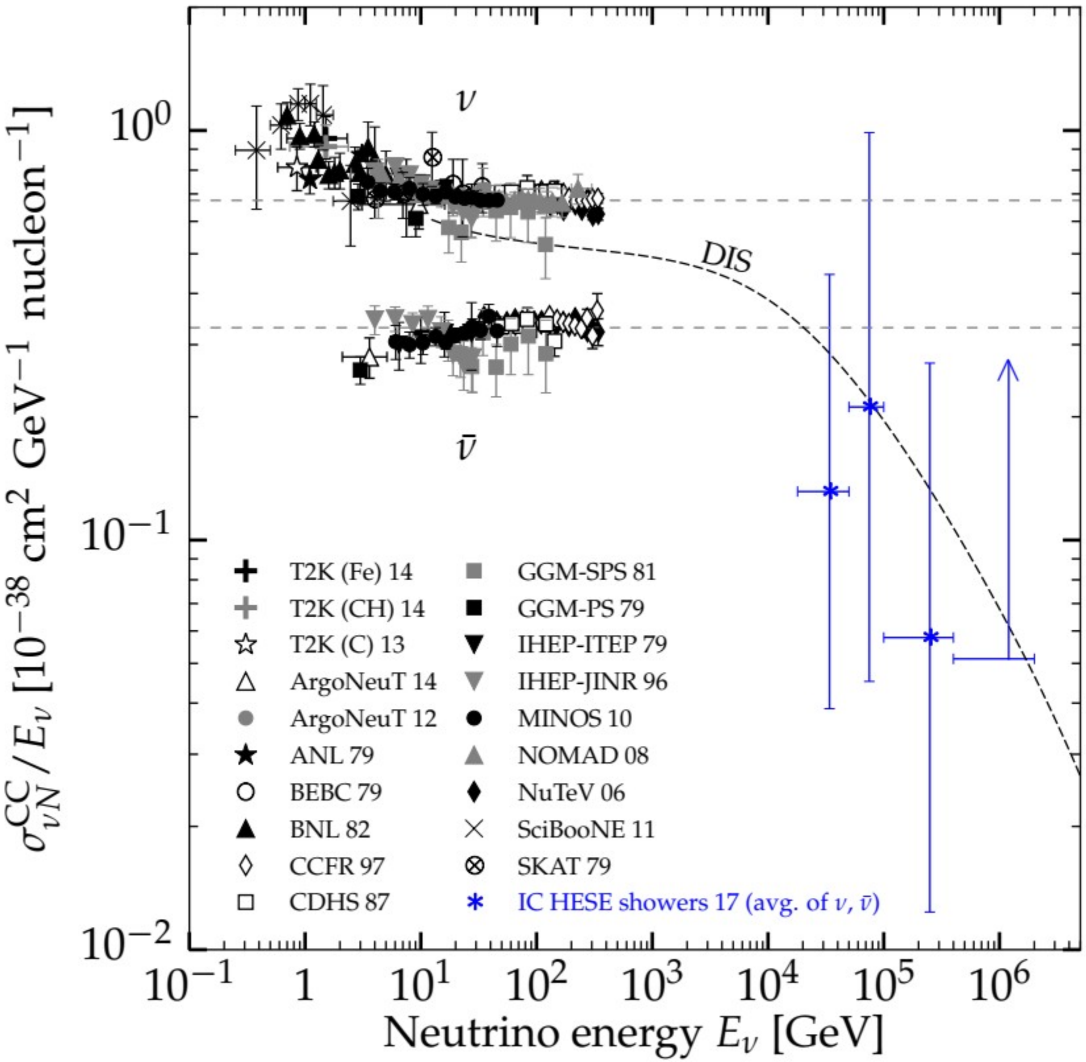
MB & Connolly *PRL* 2019
See also: IceCube, *Nature* 2017



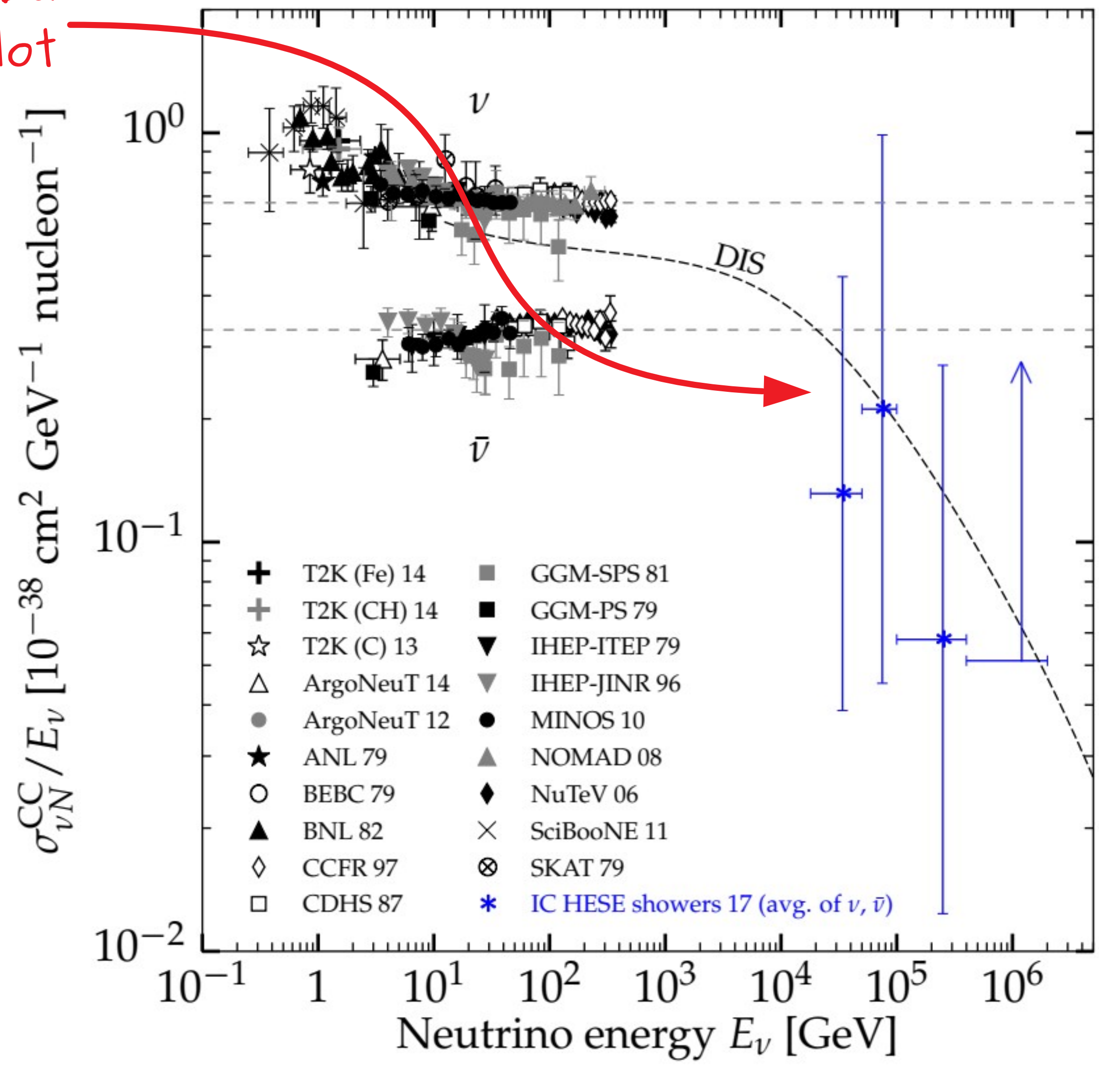
MB & Connolly *PRL* 2019
See also: IceCube, *Nature* 2017



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



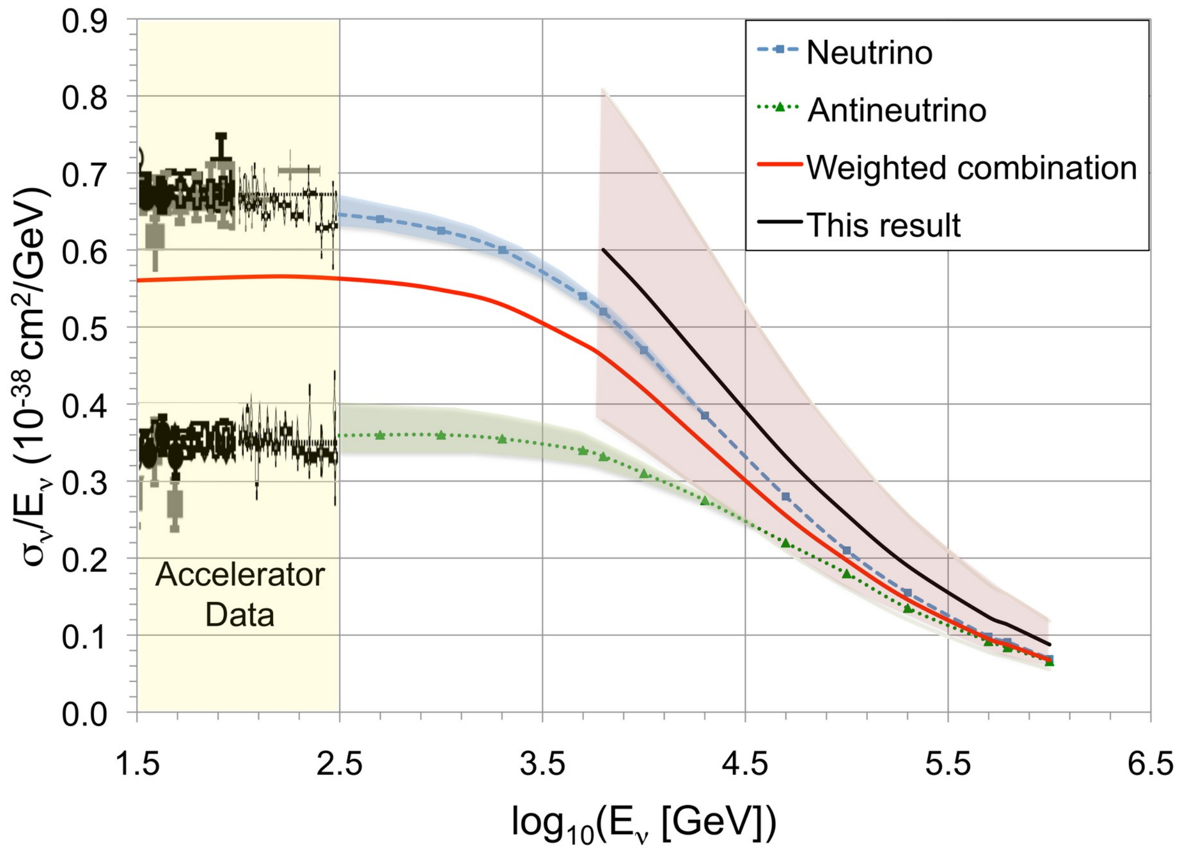
Extending the PDG cross-section plot



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

Using through-going muons instead

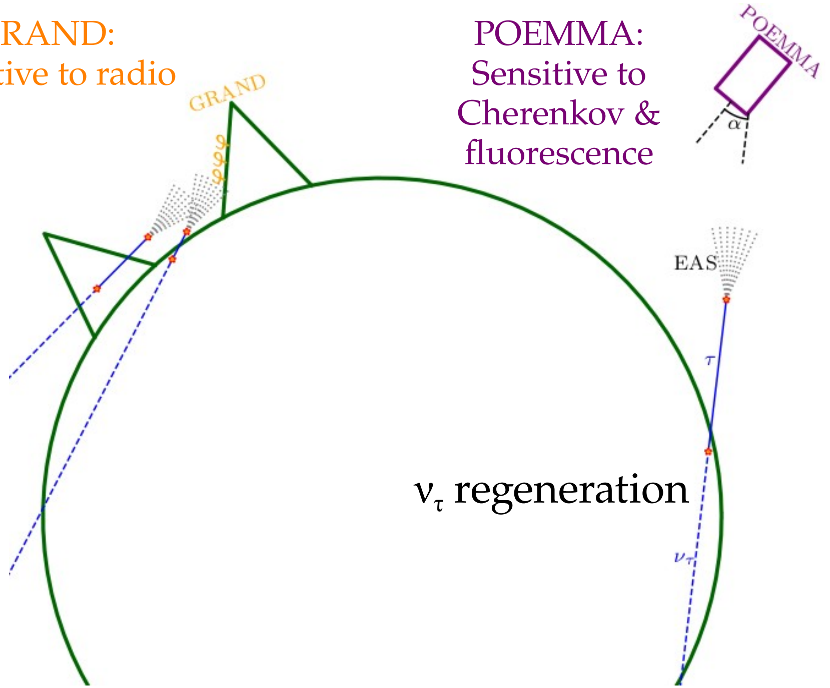
- Use ~10^4 through-going muons
- Measured: $\mathrm{d}E_\mu/\mathrm{d}x$
- Inferred: $E_\mu \approx \mathrm{d}E_\mu/\mathrm{d}x$
- From simulations (uncertain): most likely E_ν given E_μ
- Fit the ratio σ_{obs}/σ_{SM}
  $1.30^{+0.21}_{-0.19}$(stat.) $^{+0.39}_{-0.43}$(syst.)
- All events grouped in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



IceCube, *Nature* 2017

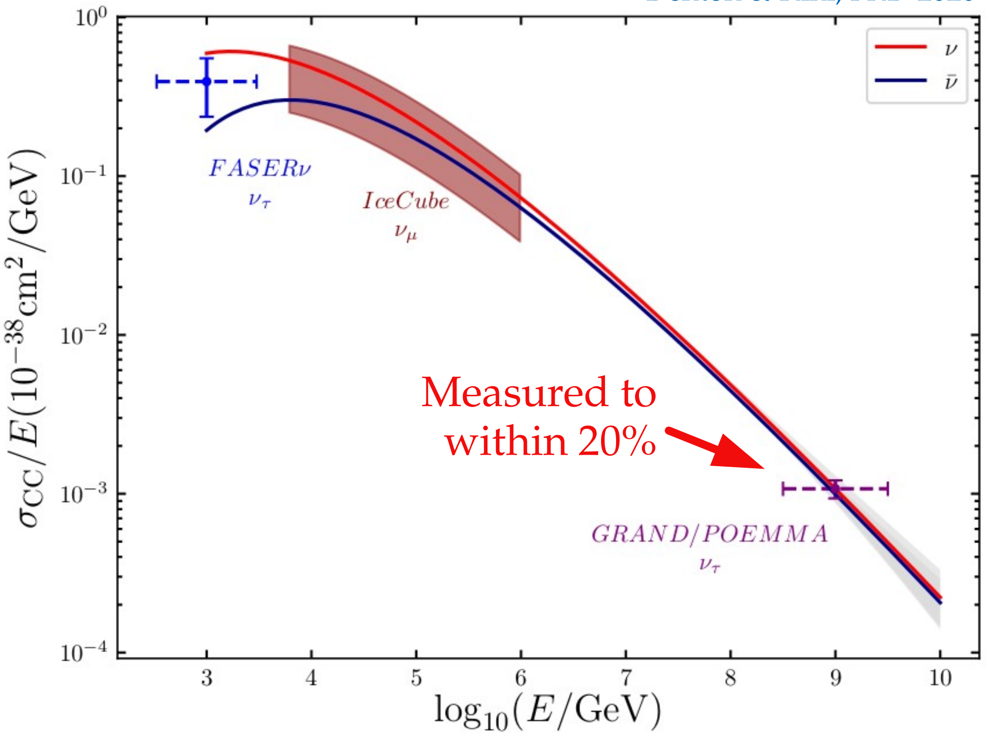
GRAND & POEMMA

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



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

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

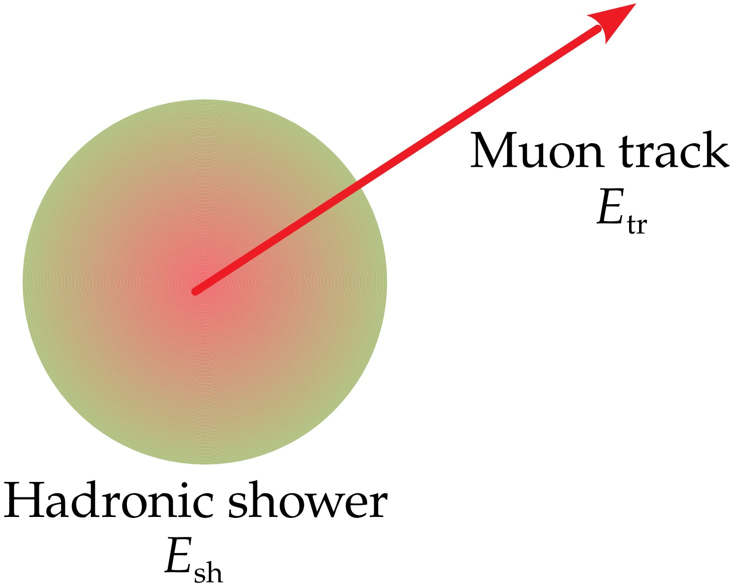
  $E_X = y\, E_\nu$ and $E_\mu = (1\text{-}y)\, E_\nu \;\Rightarrow\; y = (1 + E_\mu / E_X)^{-1}$

- The value of y follows a distribution $\mathrm{d}\sigma / \mathrm{d}y$

- In a HESE starting track:

  $$\left.\begin{aligned} E_X &= E_{sh} \text{ (energy of shower)} \\ E_\mu &= E_{tr} \text{ (energy of track)} \end{aligned}\right\} \; y = (1 + E_{tr} / E_{sh})^{-1}$$

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



IceCube Collab., *PRD* 2019

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

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

- In a HESE starting track:

  $$\left.\begin{array}{l} E_X = E_{sh} \text{ (energy of shower)} \\ E_\mu = E_{tr} \text{ (energy of track)} \end{array}\right\} \; y = (1 + E_{tr}/E_{sh})^{-1}$$

- New IceCube analysis:
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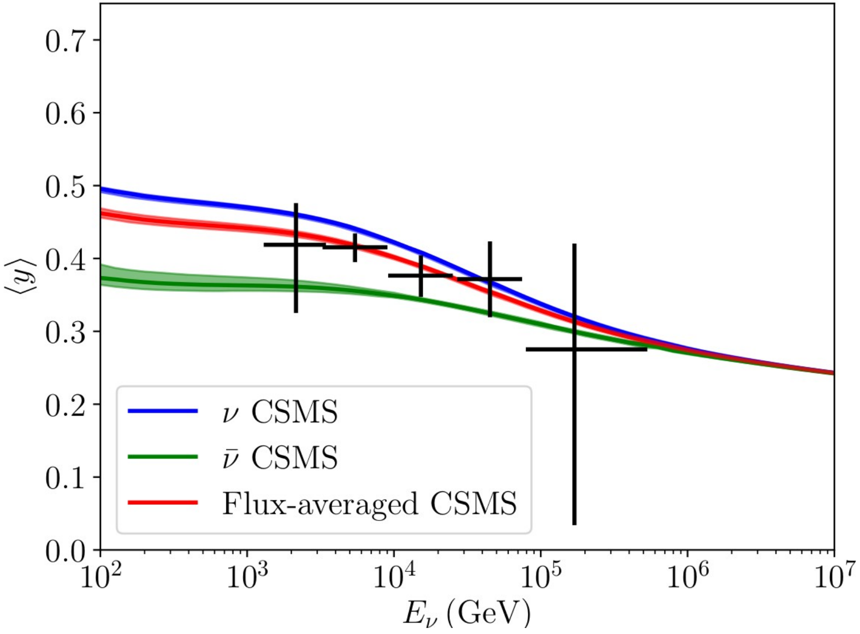
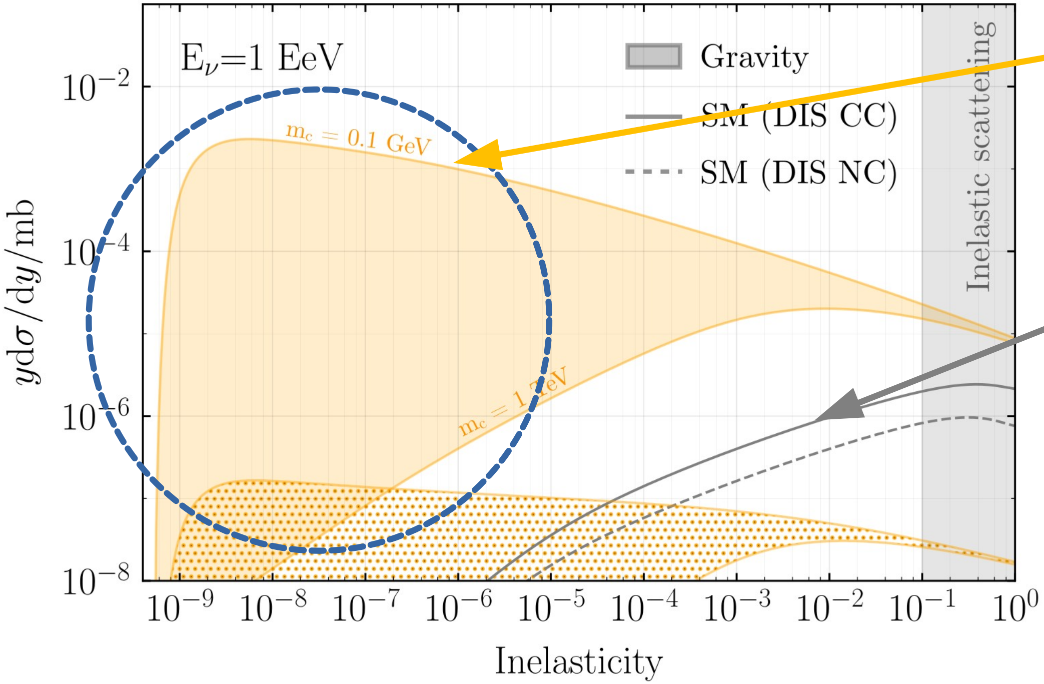


IceCube Collab., *PRD* 2019

Warning: UHE BSM that changes inelasticity needs care

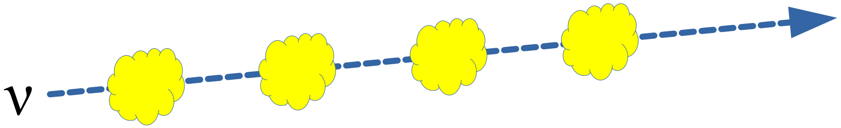
TeV-scale gravity may induce EeV-scale *elastic* neutrino interactions, *i.e.*, with low y:

Garcia Soto, Garg, Reno, Argüelles, 2209.06282



Gravity-mediated σ ⋙ SM σ

But neutrinos lose little energy in each gravity-mediated interaction



New event topology: multiple showers along the way

Inelasticity-changing BSM needs dedicated analysis

Measuring high-energy neutrino-matter interactions

Why? Probe nucleons deeper than ever
Search for new high-energy physics

Measuring high-energy neutrino-matter interactions

Why? Probe nucleons deeper than ever
Search for new high-energy physics

How? Use high-energy & ultra-high-energy cosmic neutrinos
Use the Earth as target

Measuring high-energy neutrino-matter interactions

Why? Probe nucleons deeper than ever
Search for new high-energy physics

How? Use high-energy & ultra-high-energy cosmic neutrinos
Use the Earth as target

When? With TeV–PeV ν: already now (IceCube)
With EeV ν: in 10–20 yr (IceCube-Gen2)†

†Fingers crossed

Measuring high-energy neutrino-matter interactions

Why? Probe nucleons deeper than ever
Search for new high-energy physics

How? Use high-energy & ultra-high-energy cosmic neutrinos
Use the Earth as target

When? With TeV–PeV ν: already now (IceCube)
With EeV ν: in 10–20 yr (IceCube-Gen2)[†]

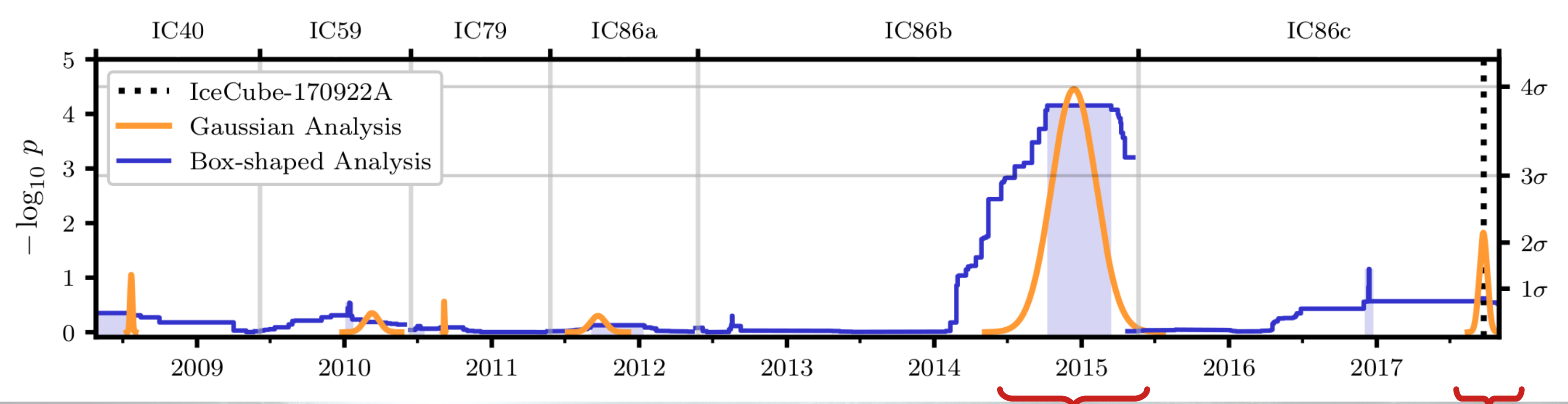
Why hard? Limited event statistics
At UHE, need to have decent angular resolution (~2°)

[†] Fingers crossed

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

Blazar TXS 0506+056:

IceCube, *Science* 2018



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

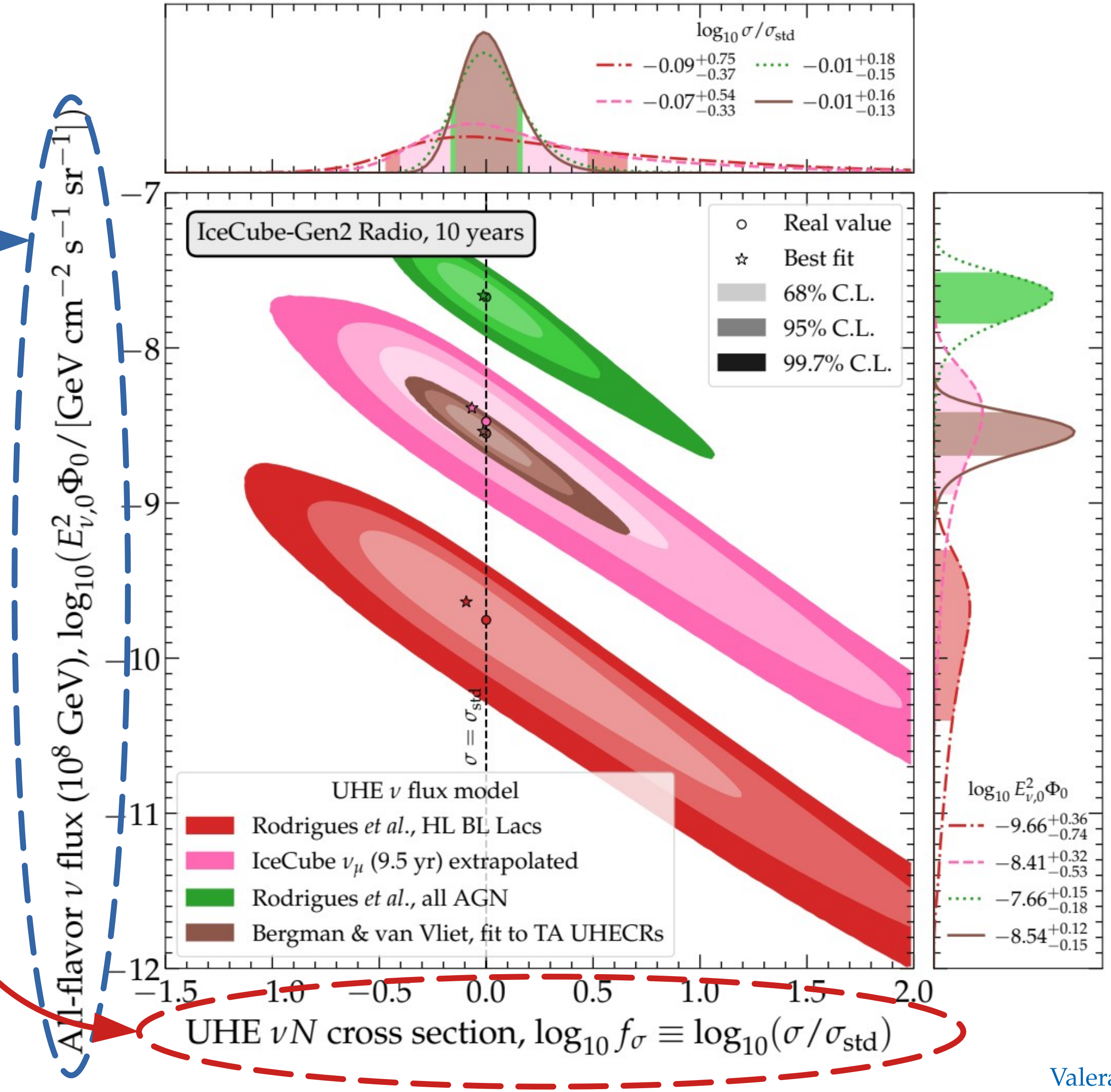
2014–2015: 13±5 ν flare, no X-ray flare
3.5σ significance of correlation (post-trial)

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

Combined (pre-trial): 4.1σ

Flux normalization

Cross section



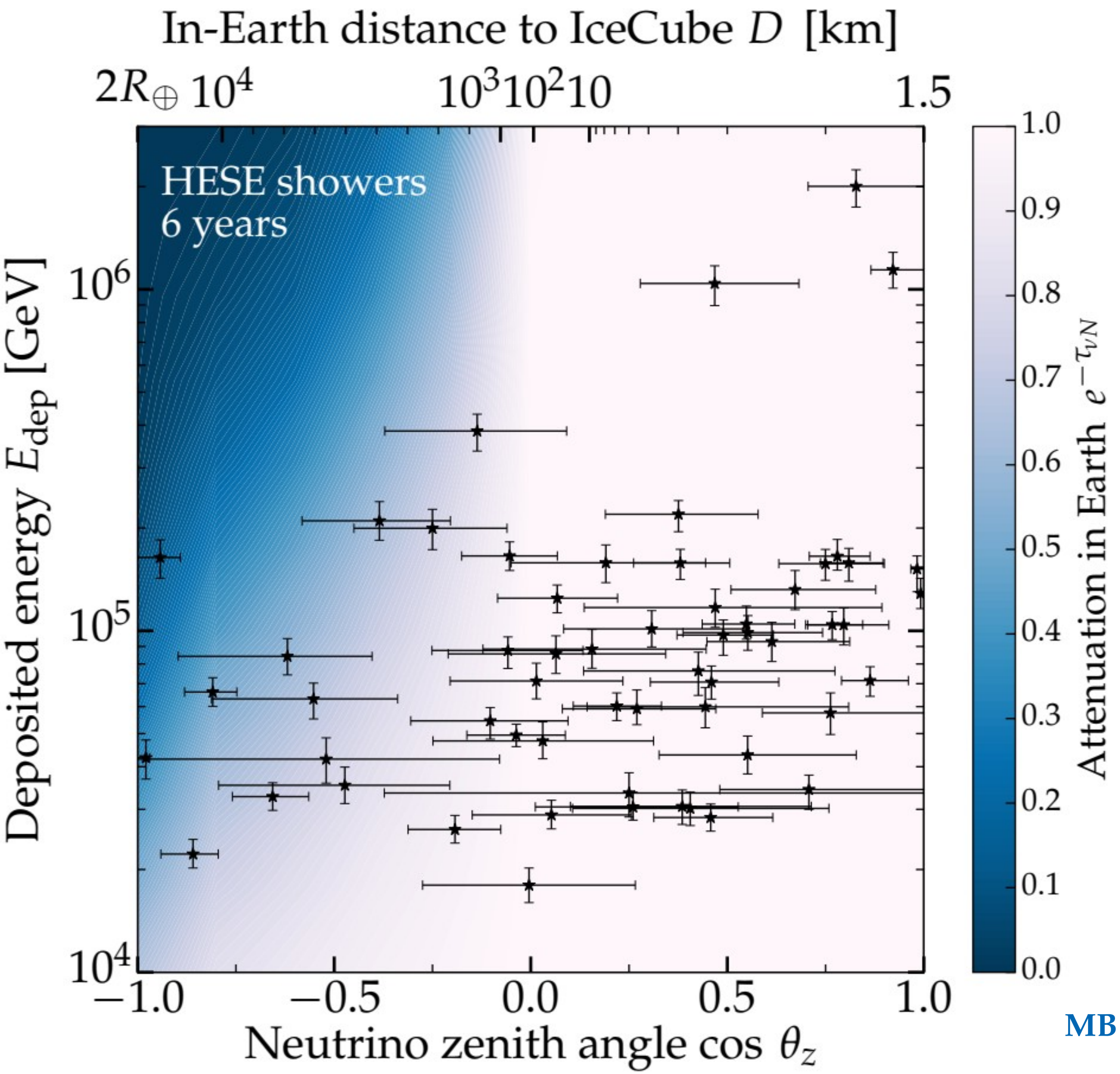
Needed to measure the cross section?

~30–300 events

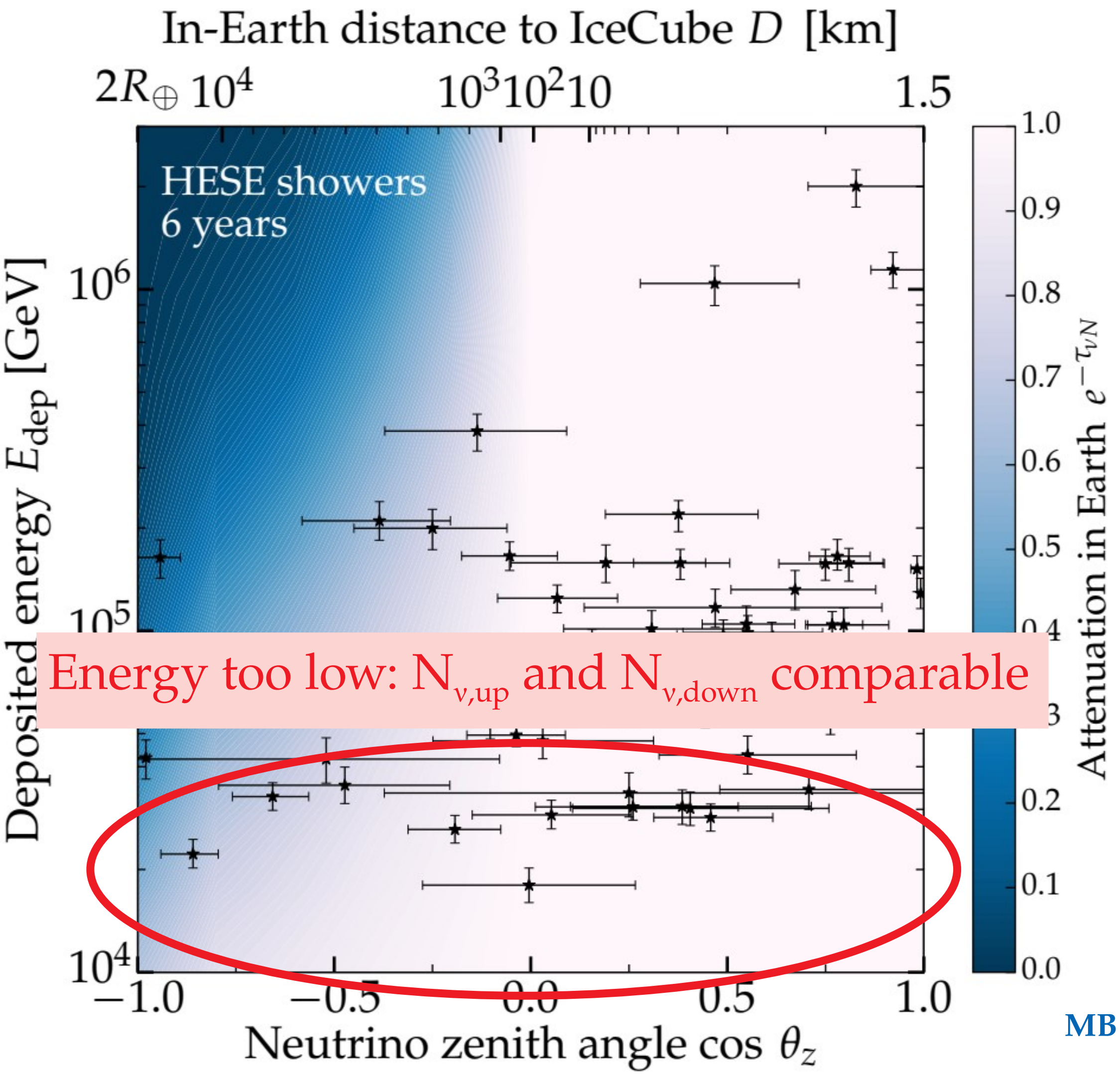
In this work:
We fix the energy dependence of flux and cross section (but explore many alternatives)

Soon to come:
Measure the energy dependence of the flux and cross section

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



MB & Connolly, *PRL* 2019



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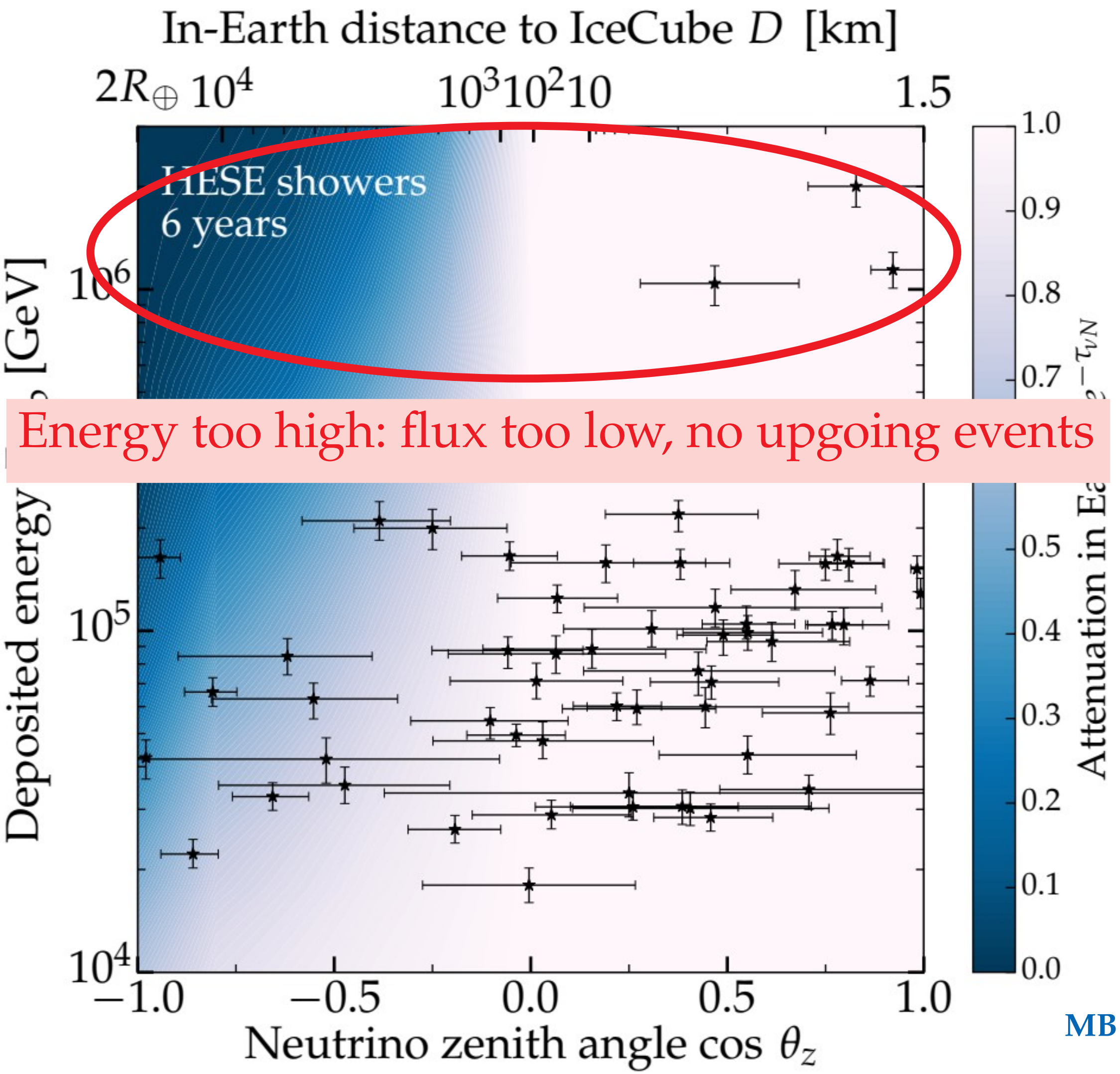

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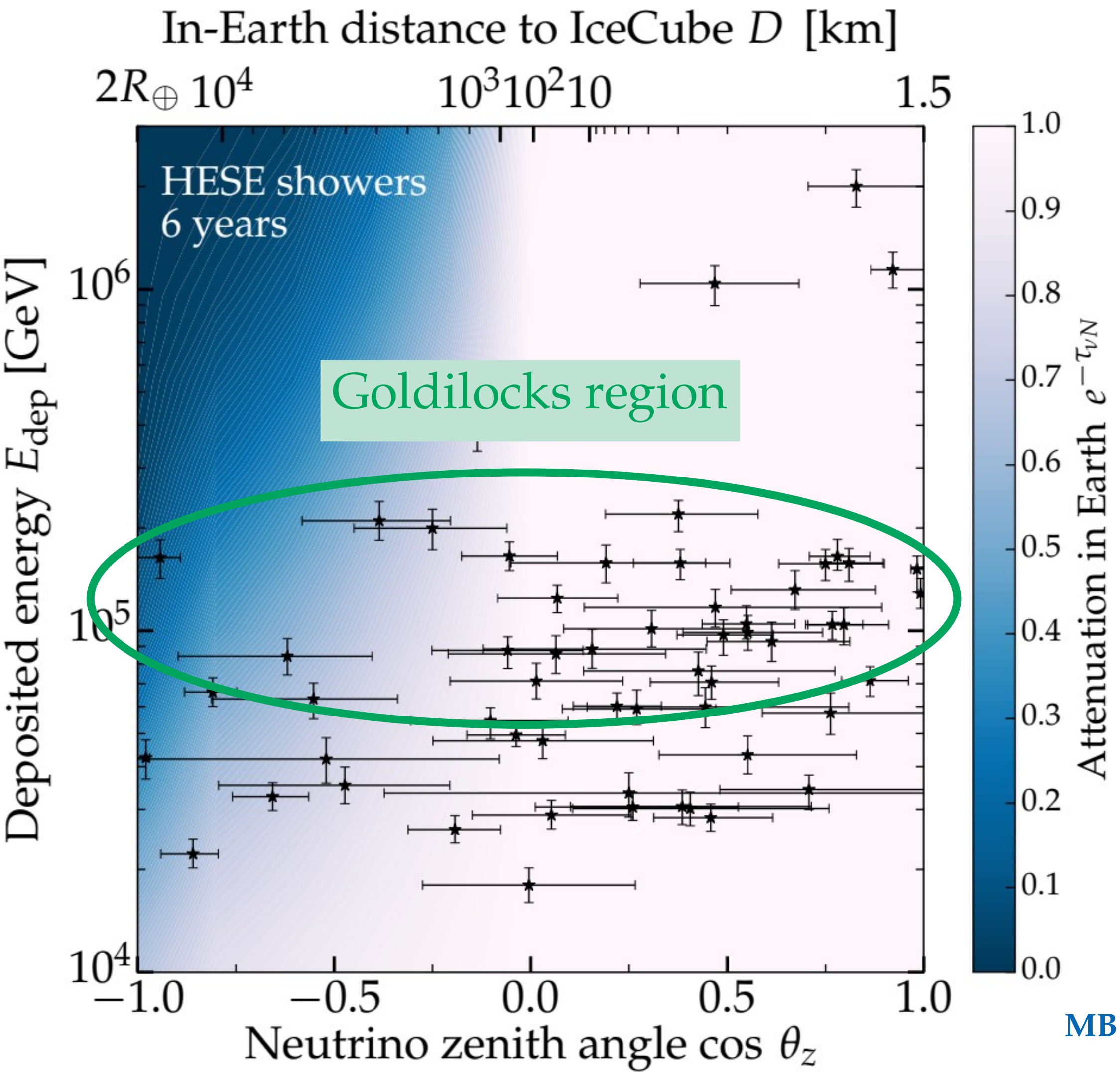

MB & Connolly, *PRL* 2019

Flavor at the Earth: *theoretically palatable regions*

Theoretically palatable flavor regions

$\equiv$

Allowed regions of flavor ratios at Earth derived from oscillations

MB, Beacom, Winter, *PRL* 2015

Note:
The original palatable regions were frequentist [**MB**, Beacom, Winter, *PRL* 2015]; the new ones are Bayesian

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Flavor ratios at the source,

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

Fix at one of the benchmarks
(pion decay, muon-damped, neutron decay)

or

Explore all possible combinations

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Probability density of mixing parameters $(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\mathrm{CP}})$

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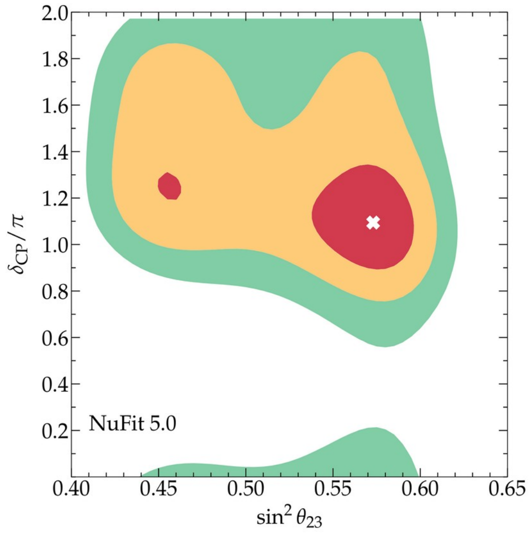
2020: Use χ^2 profiles from the NuFit 5.0 global fit (solar + atmospheric + reactor + accelerator)

Esteban *et al.*, *JHEP* 2020
www.nu-fit.org



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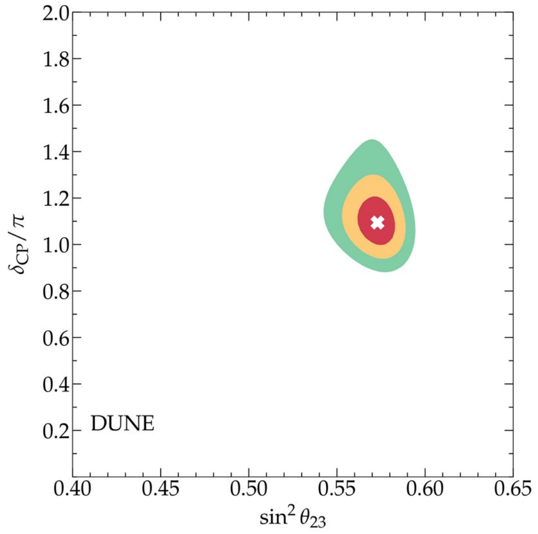
Esteban *et al.*, *JHEP* 2020
www.nu-fit.org

Post-2020: Build our own profiles using simulations of JUNO, DUNE, Hyper-K

An *et al.*, *J. Phys. G* 2016
DUNE, 2002.03005
Huber, Lindner, Winter, *Nucl. Phys. B* 2002



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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(L short → no matter)

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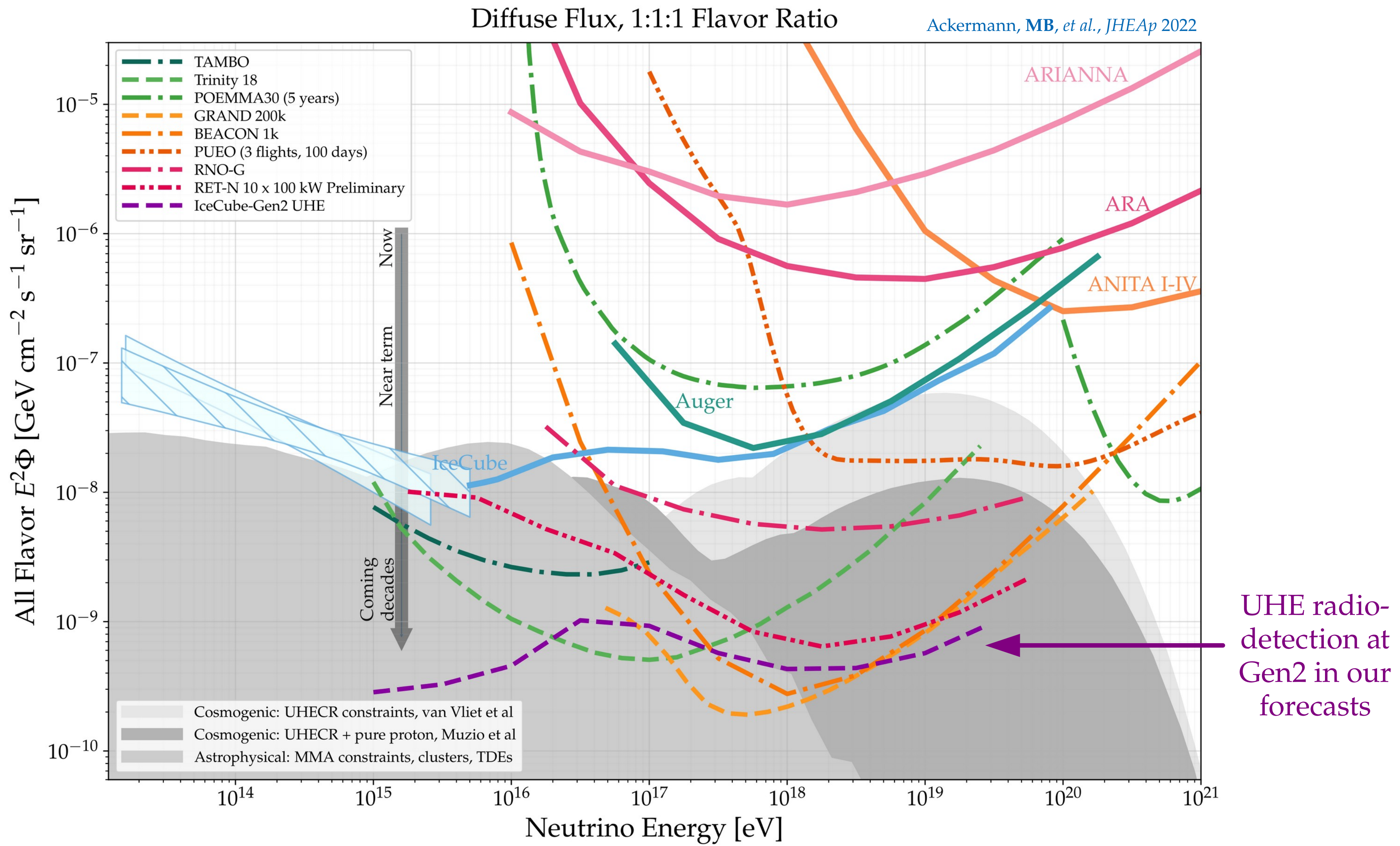
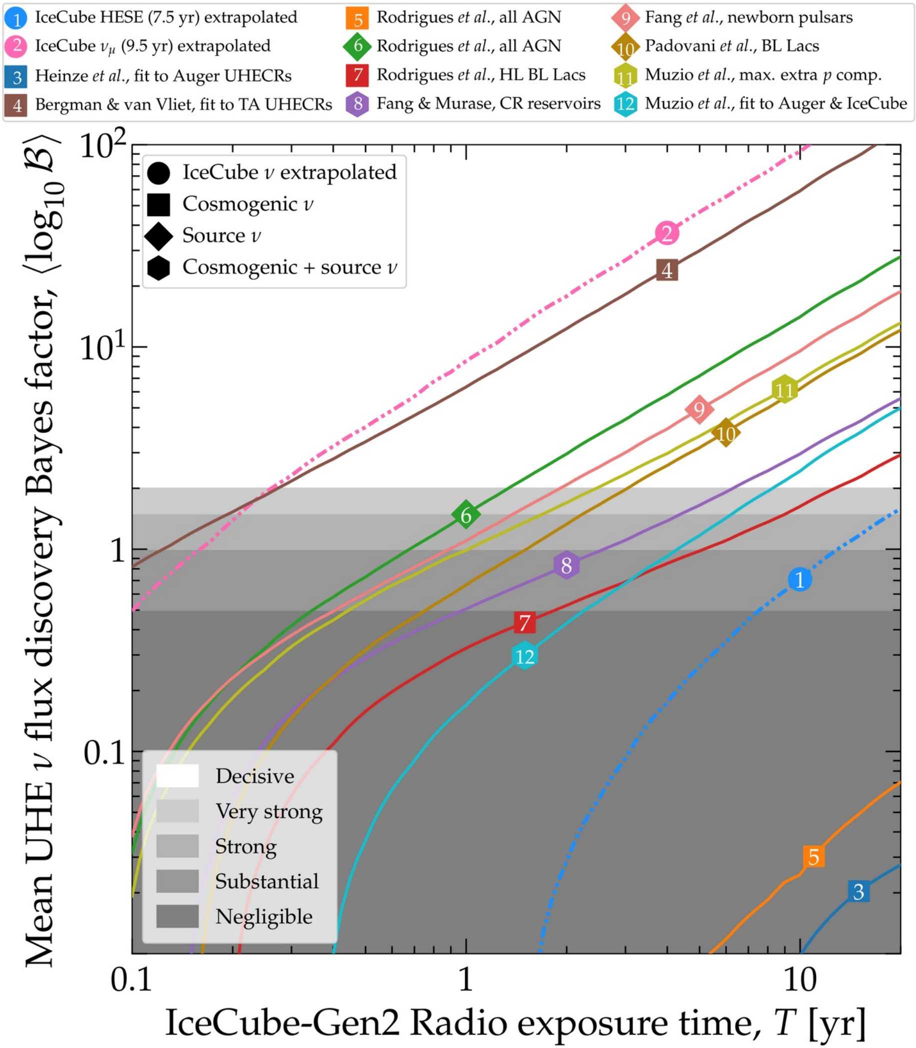
$$N \propto \Phi_\nu \sigma_{\nu N} \underbrace{e^{-L \sigma_{\nu N} n_N}}_{\text{Breaks the degeneracy}}$$

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


Diffuse Flux, 1:1:1 Flavor Ratio
Ackermann, MB, et al., JHEAp 2022
TAMBO
Trinity 18
POEMMA30 (5 years)
GRAND 200k
BEACON 1k
PUEO (3 flights, 100 days)
RNO-G
RET-N 10 x 100 kW Preliminary
IceCube-Gen2 UHE
ARIANNA
ARA
ANITA I-IV
Auger
IceCube
Now
Near term
Coming decades
Cosmogenic: UHECR constraints, van Vliet et al
Cosmogenic: UHECR + pure proton, Muzio et al
Astrophysical: MMA constraints, clusters, TDEs
All Flavor $E^2\Phi$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino Energy [eV]
UHE radio-detection at Gen2 in our forecasts

Side note: Discovering the diffuse flux of UHE neutrinos



Work led by Víctor Valera

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

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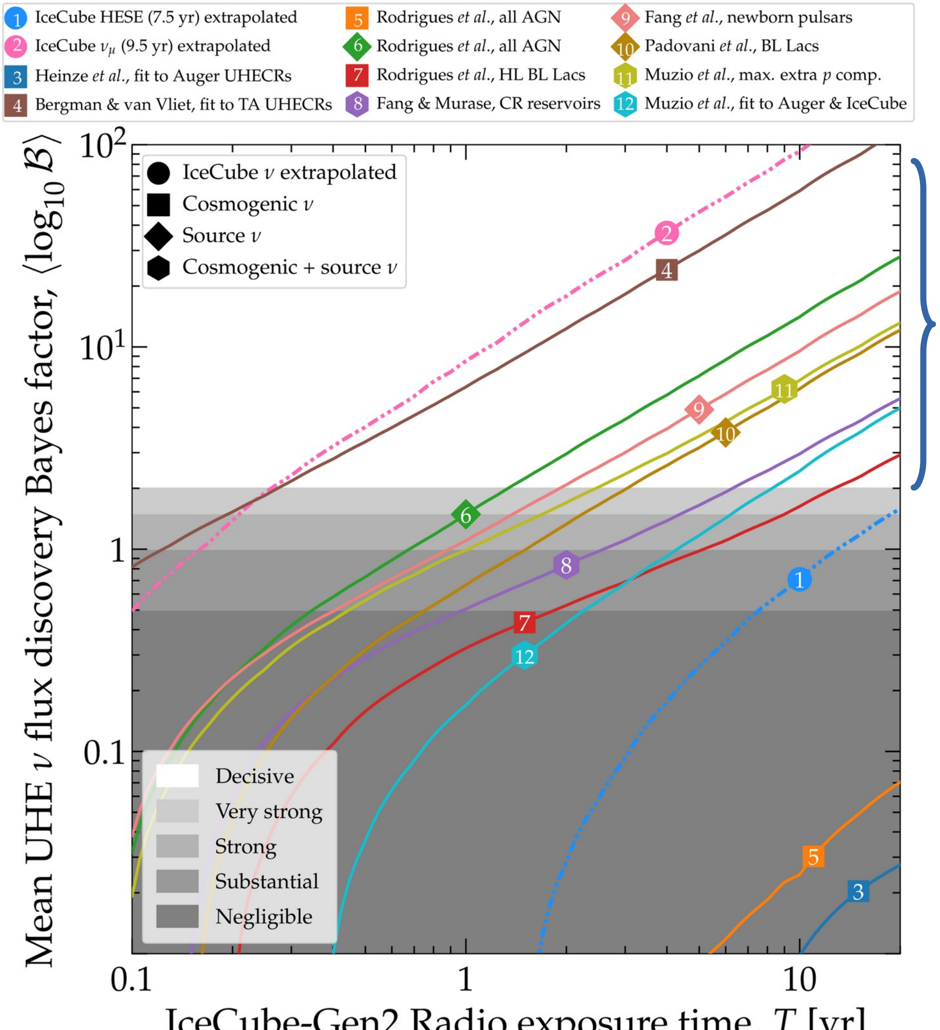

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Bayes factor compares signal+bkg. *vs.* bkg.-only

Large Bayes factor = decisive flux discover

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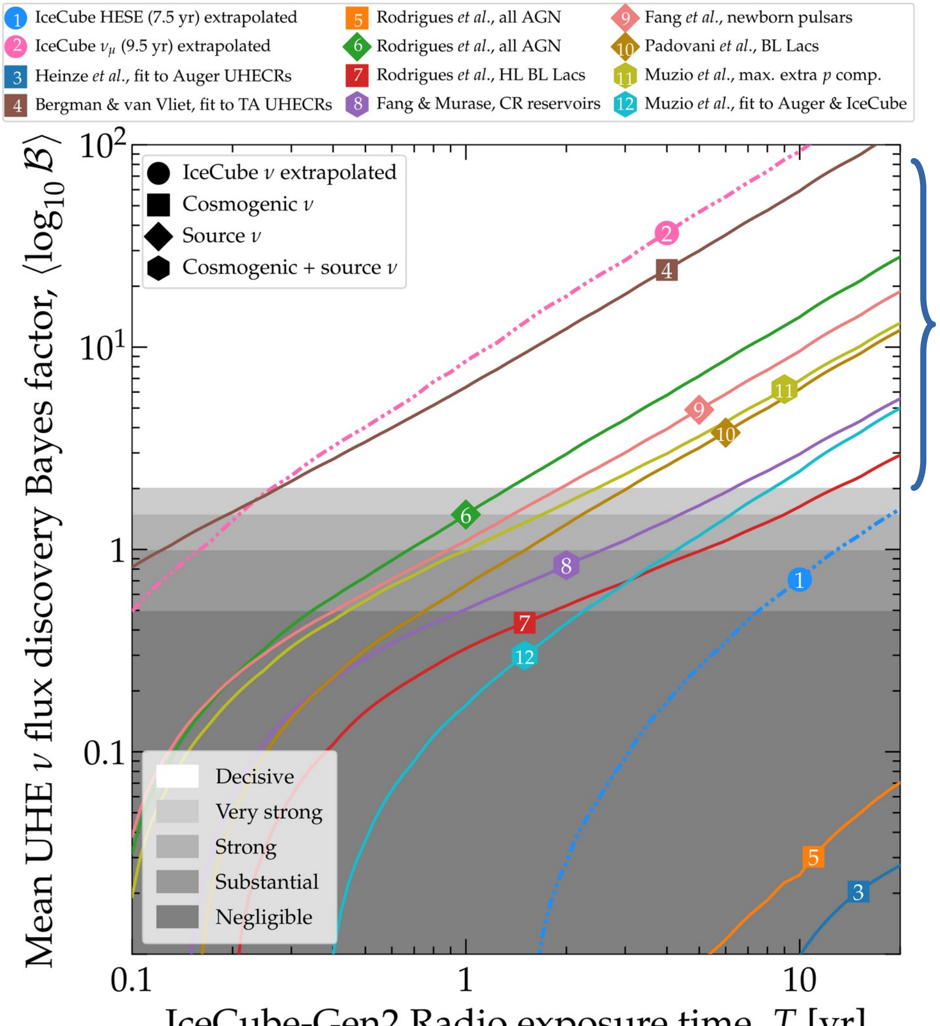

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Forecasts are state-of-the-art:

- Neutrino propagation inside Earth
- Detailed simulation of radio in ice
- Detailed antenna response
- Detector energy & angular resolution
- Statistical fluctuations

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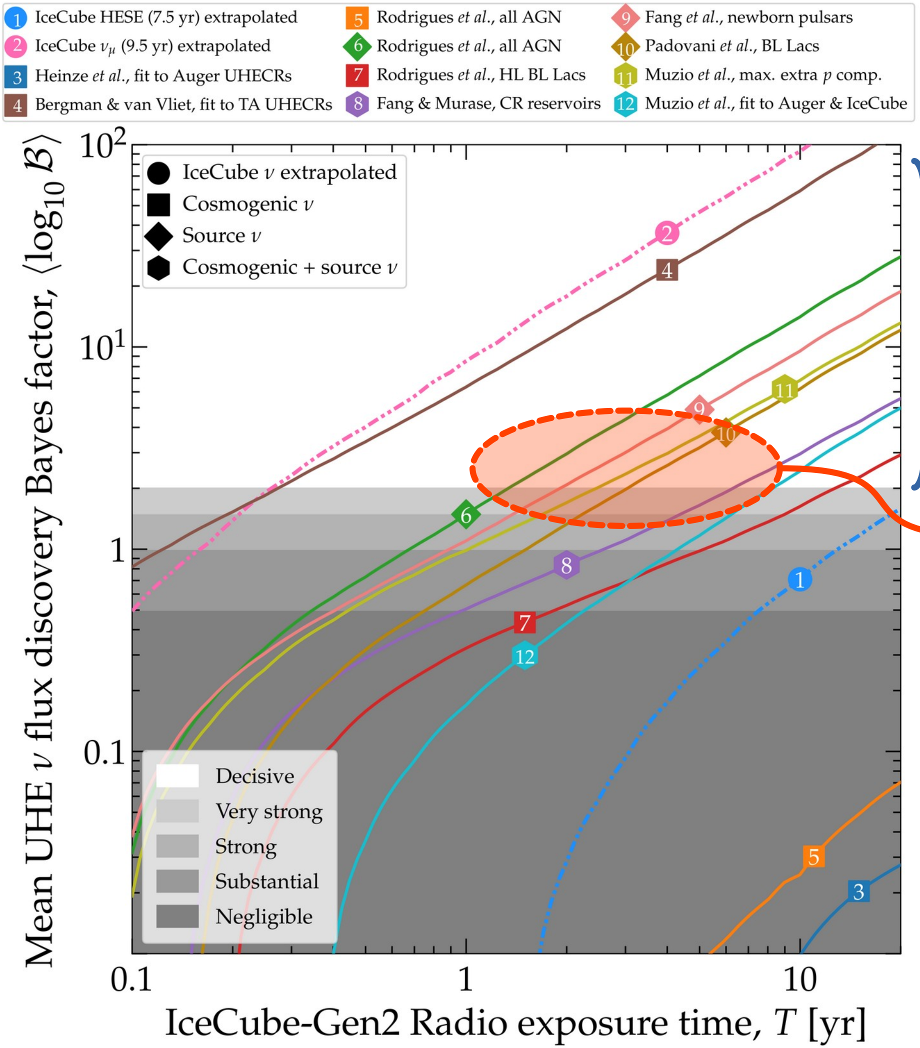

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Most flux models are discoverable with a few years

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