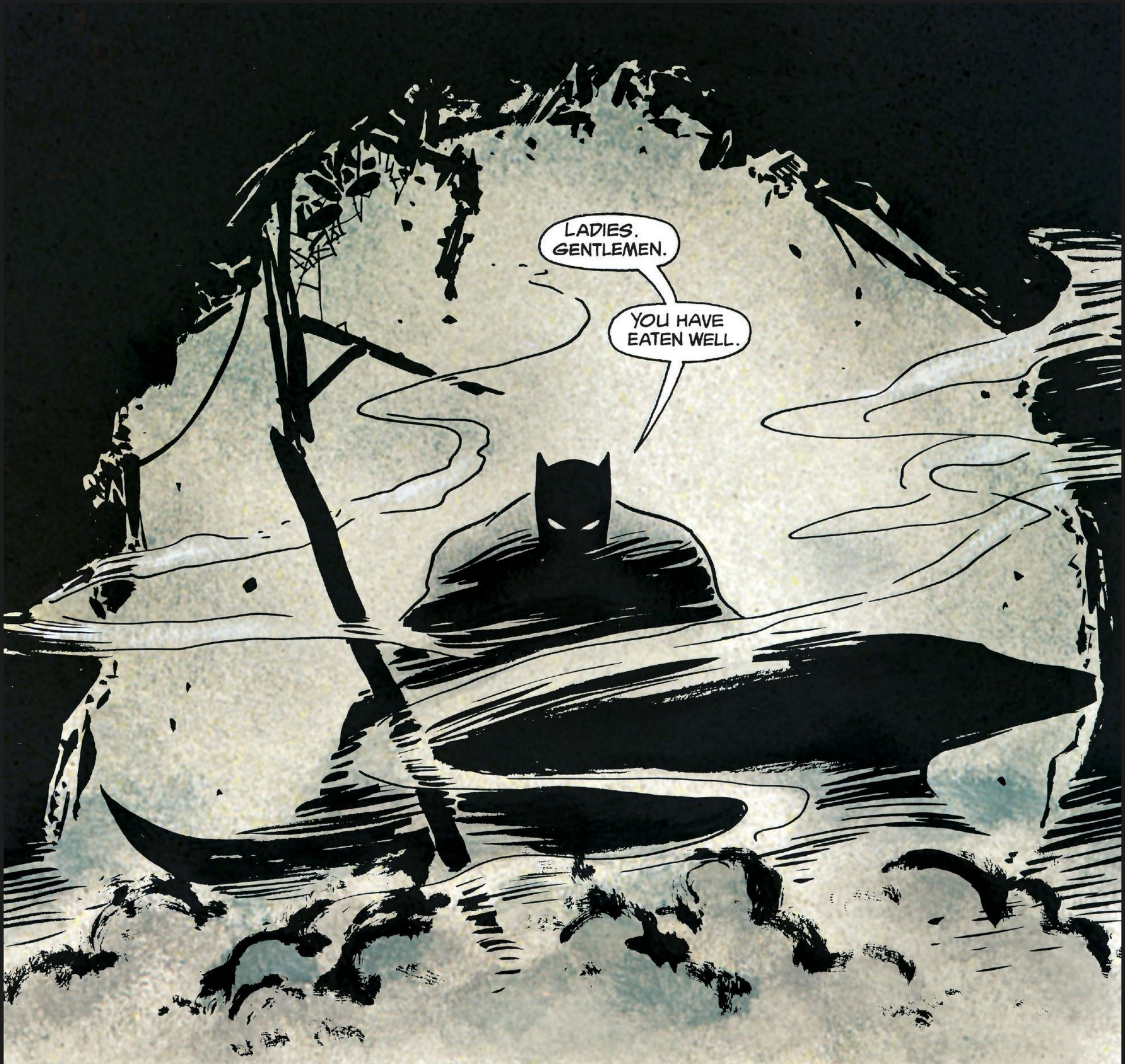

Batman: Year One,
Frank Miller, David Mazzuchelli,
Todd Klein & Richmond Lewis,
DC Comics (1987)

New physics with high-energy astrophysical neutrinos

Mauricio Bustamante
Niels Bohr Institute, University of Copenhagen

Neutrinos in the Multi-Messenger Era
UC Louvain, December 02, 2022

UNIVERSITY OF COPENHAGEN

VILLUM FONDEN

New physics with high-energy astrophysical neutrinos: Part 1/2

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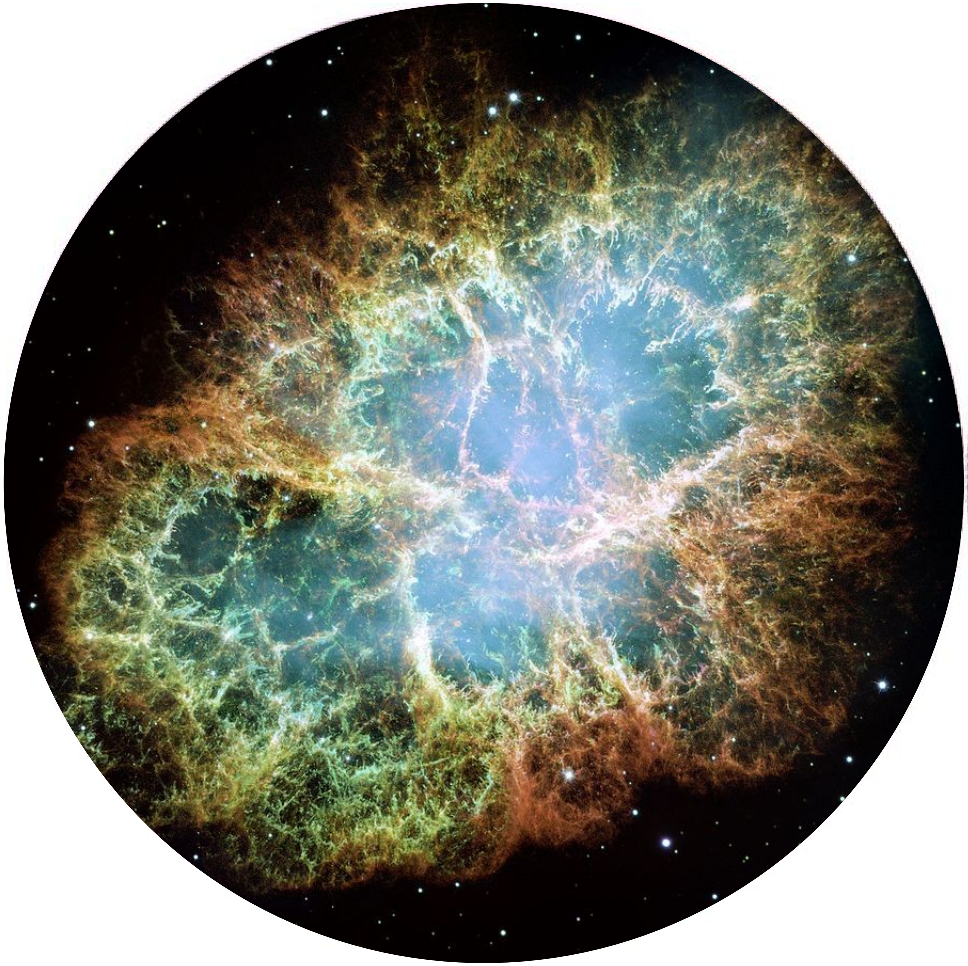
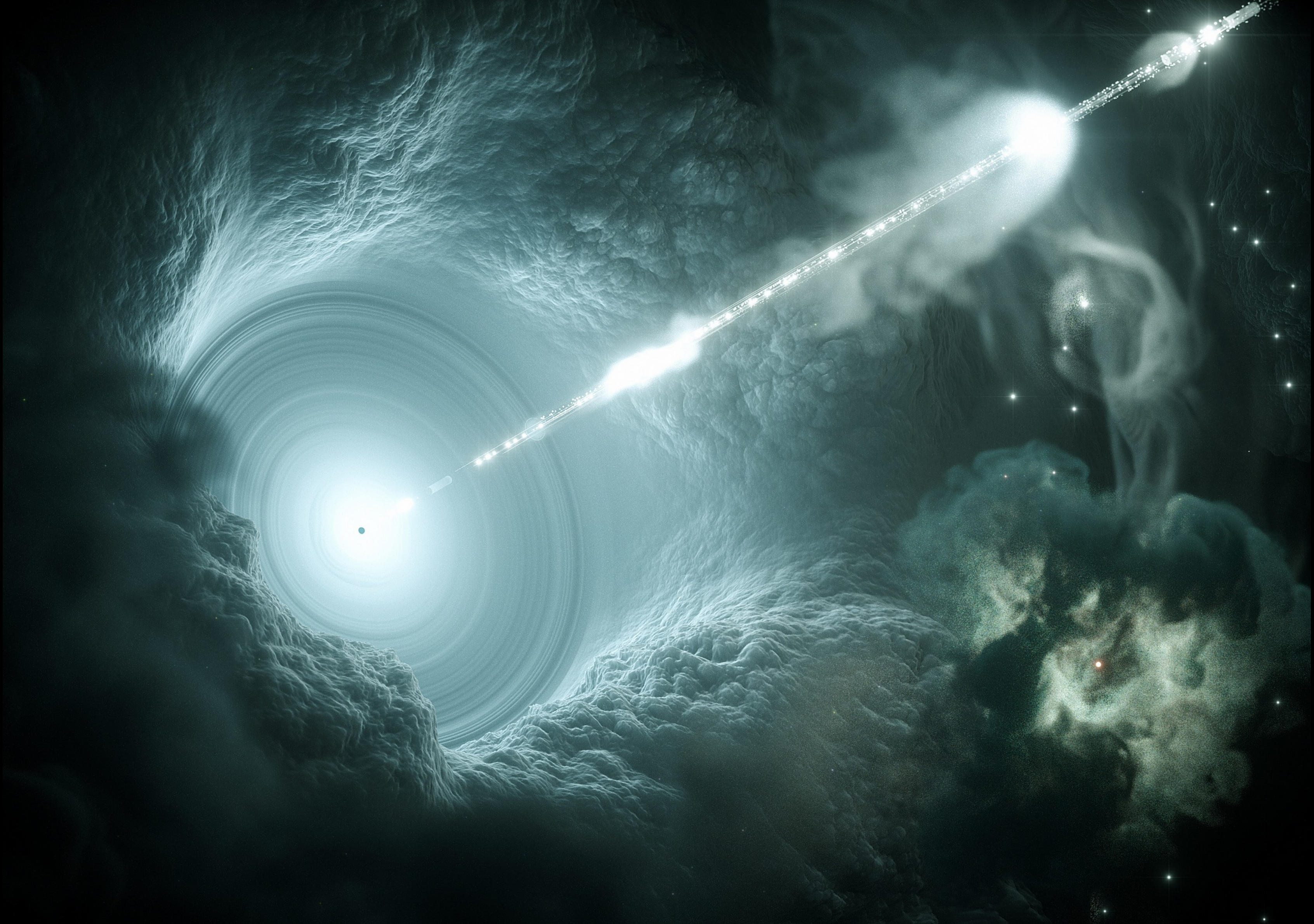
Banco Central de Reserva del Perú / NASA / ESA / CERN / Symmetry Magazine



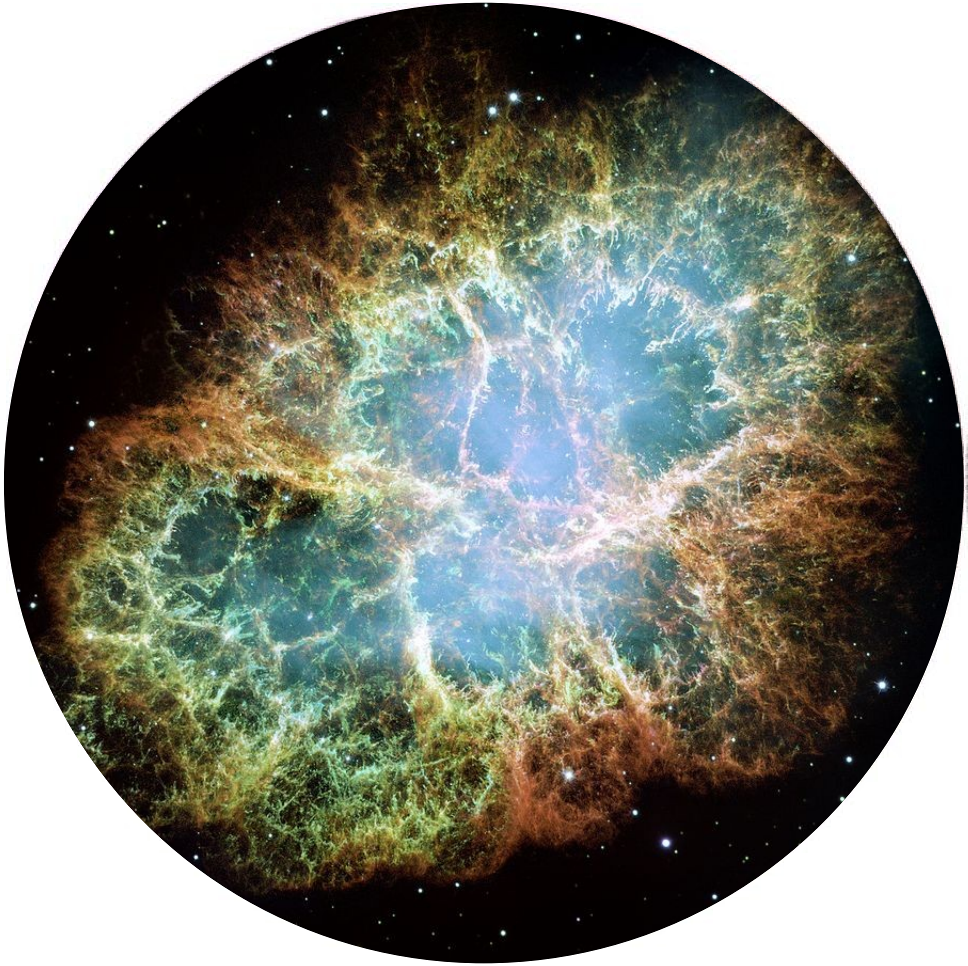
Banco Central de Reserva del Perú / NASA / ESA / CERN / Symmetry Magazine



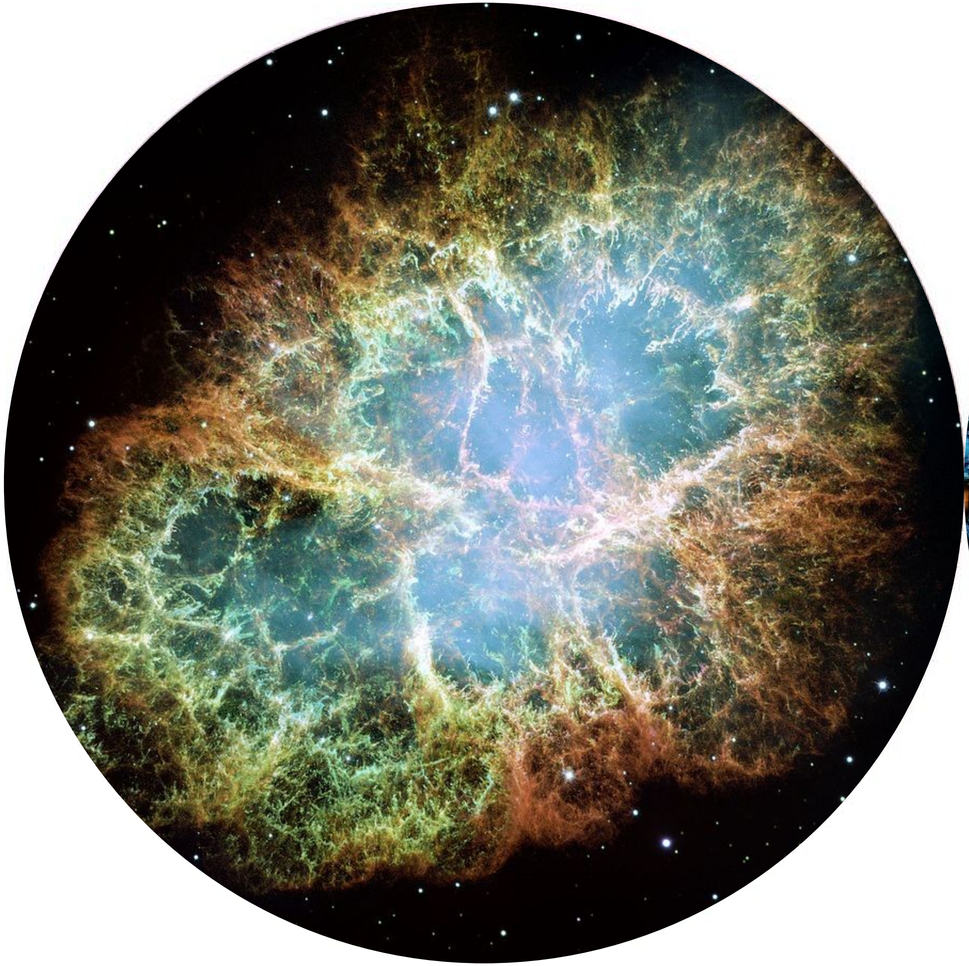
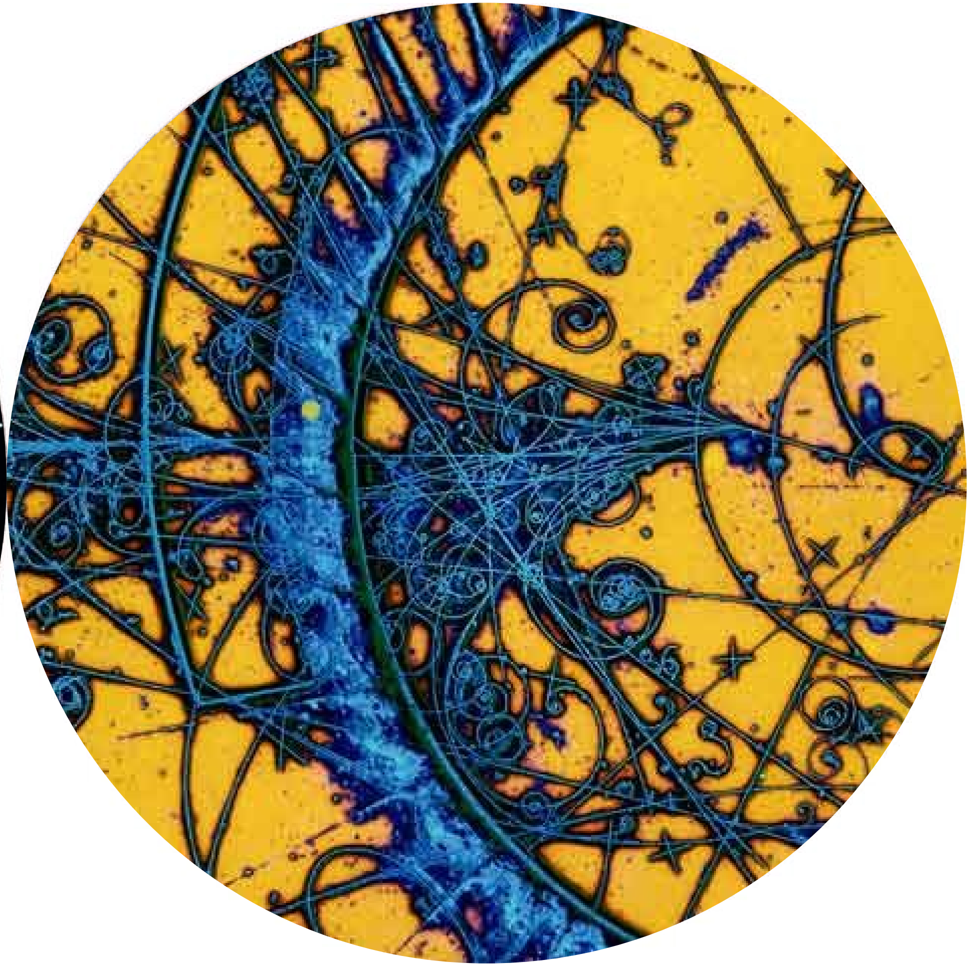
DESY

DESY

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

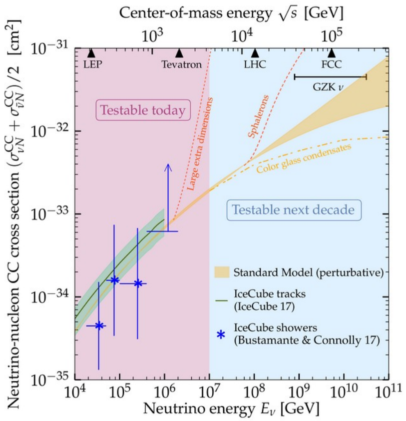


Banco Central de Reserva del Perú / NASA / ESA / CERN / Symmetry Magazine

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

TeV–EeV ν cross sections



MB & Connolly, *PRL* 2019

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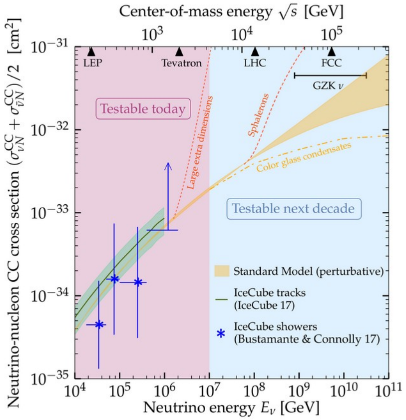
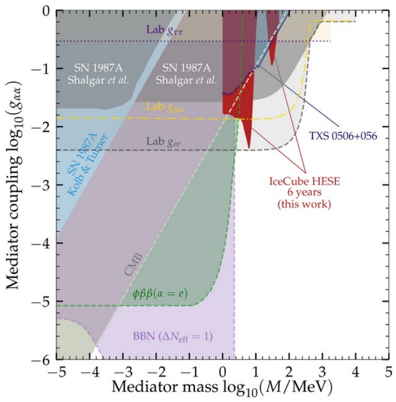


MB & Connolly, *PRL* 2019

ν self-interactions



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

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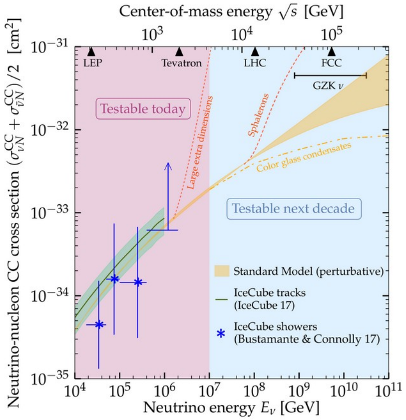

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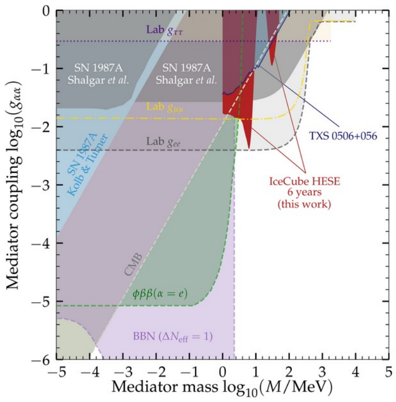
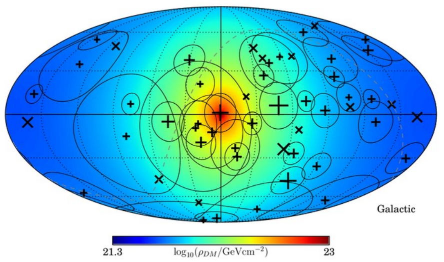


MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

ν scattering on Galactic DM



Argüelles, Kheirandish, Vincent, *PRL* 2017

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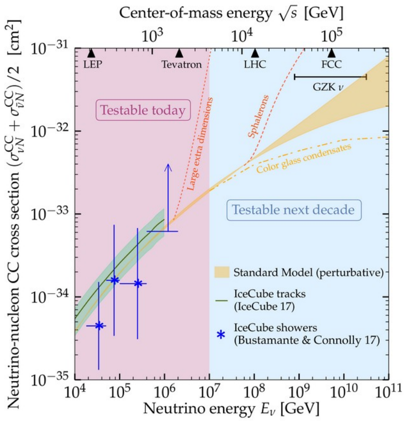

MB & Connolly, *PRL* 2019

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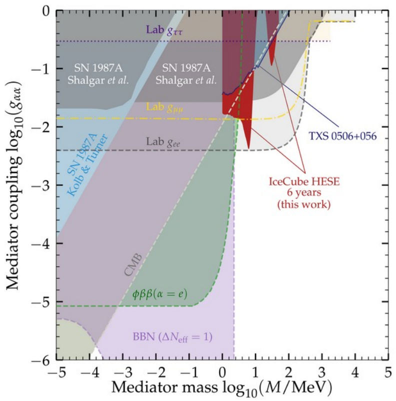

MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

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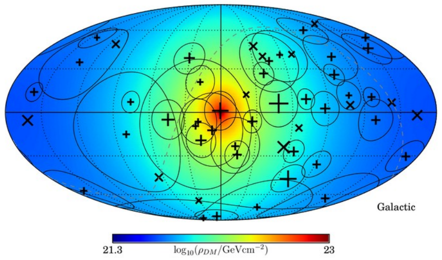
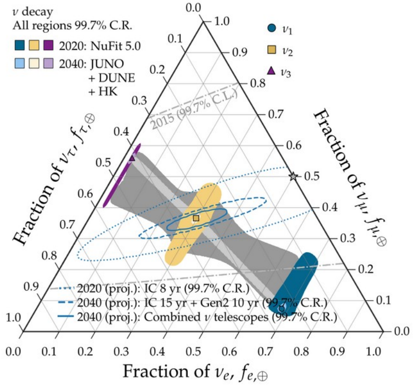


Argüelles, Kheirandish, Vincent, *PRL* 2017

ν decay



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

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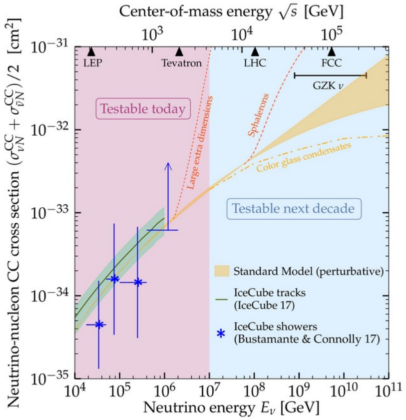

MB & Connolly, *PRL* 2019

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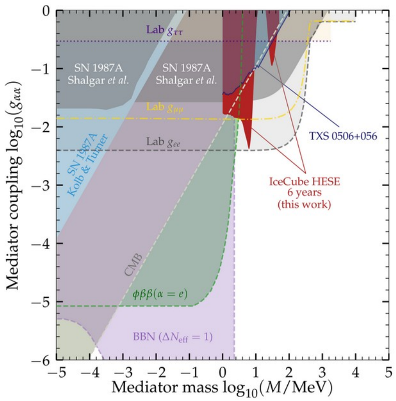

MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

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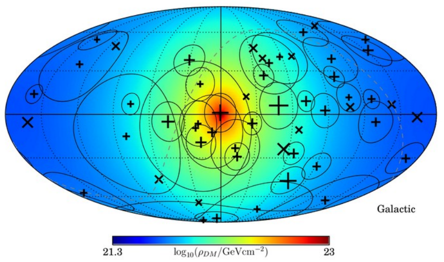

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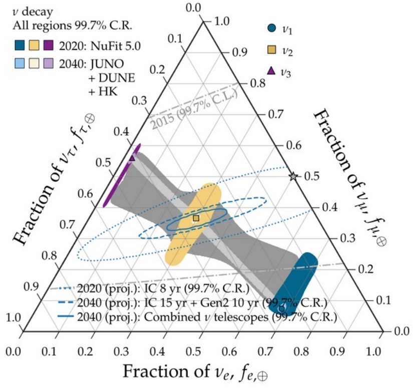
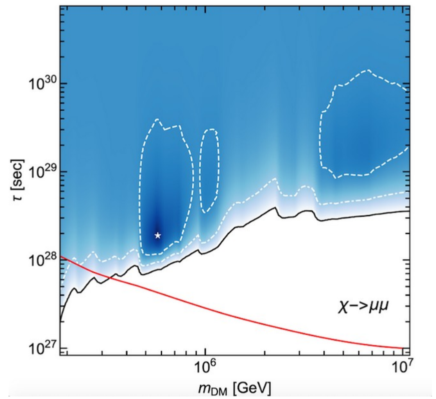


Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Dark matter decay



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

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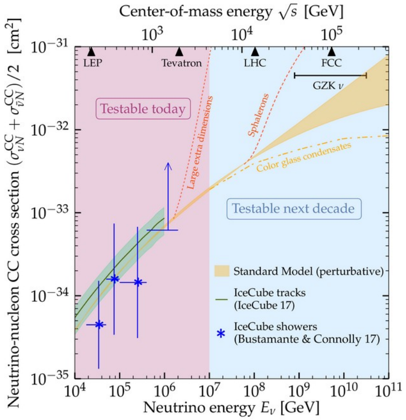

MB & Connolly, *PRL* 2019

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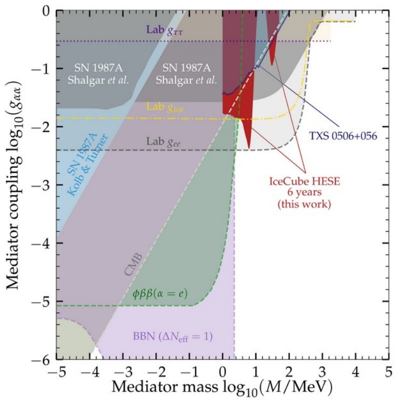

MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

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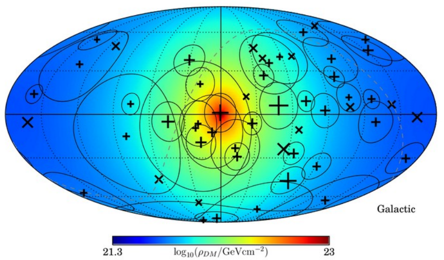

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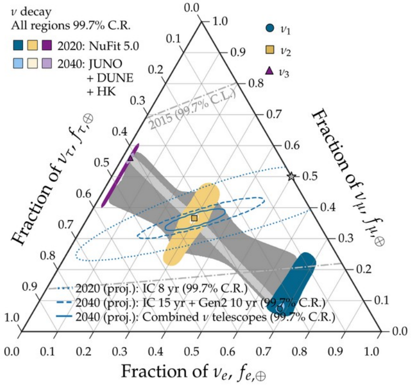

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

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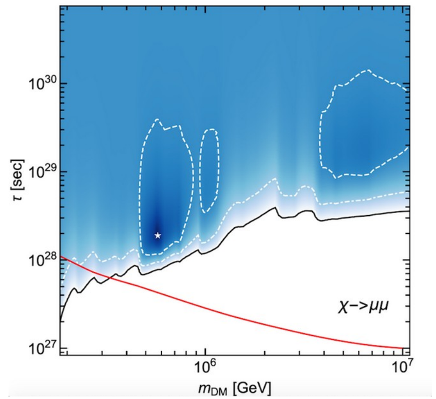
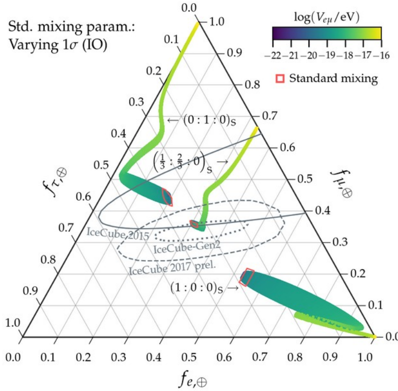


Chianese, Fiorillo, Miele, Morisi, Pisanti, *JCAP* 2019

ν-electron interaction



MB & Agarwalla, *PRL* 2019

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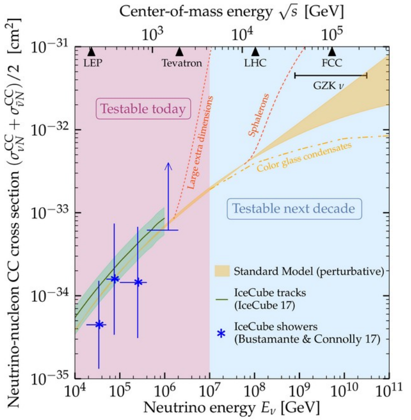

MB & Connolly, *PRL* 2019

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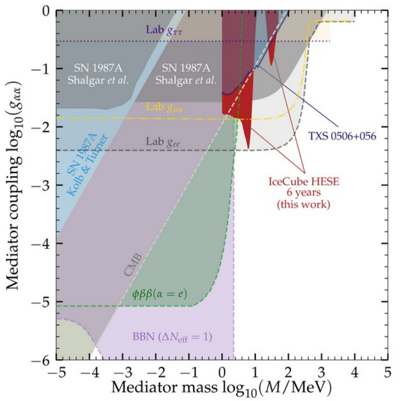
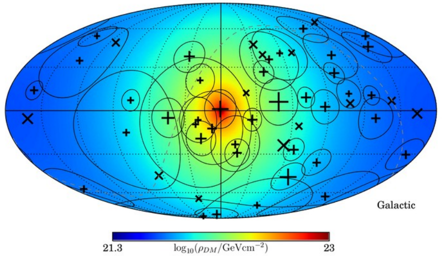


MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

ν scattering on Galactic DM



Argüelles, Kheirandish, Vincent, *PRL* 2017

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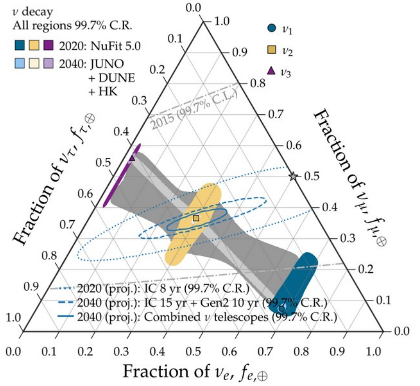
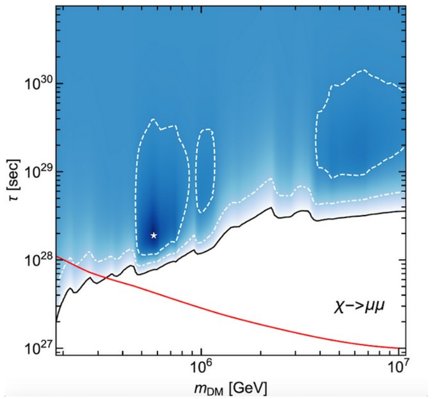


Song, Li, Argüelles, MB, Vincent, *JCAP* 2021

Dark matter decay



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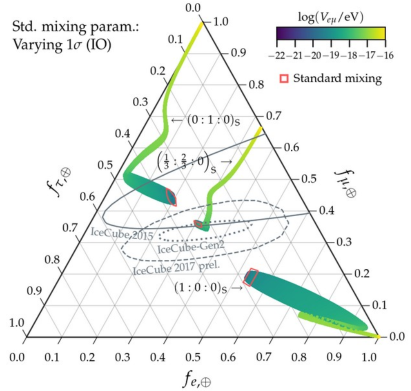
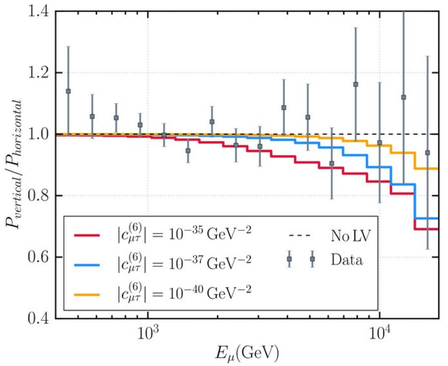


MB & Agarwalla, *PRL* 2019

Lorentz-invariance violation



IceCube, *Nature Phys.* 2018

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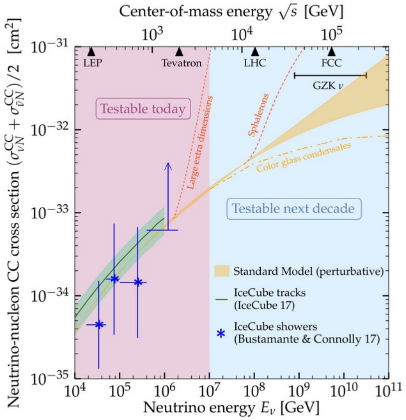

MB & Connolly, *PRL* 2019

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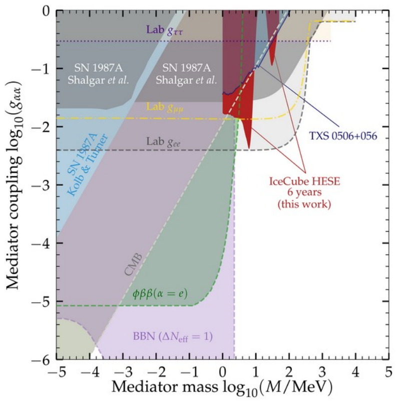
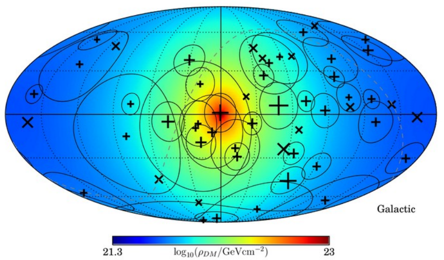


MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

ν scattering on Galactic DM



Argüelles, Kheirandish, Vincent, *PRL* 2017

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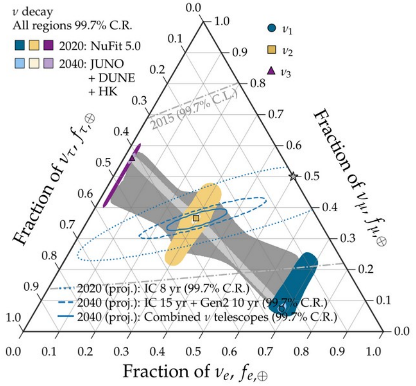

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

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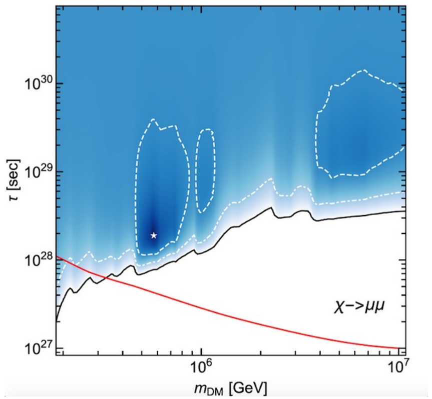

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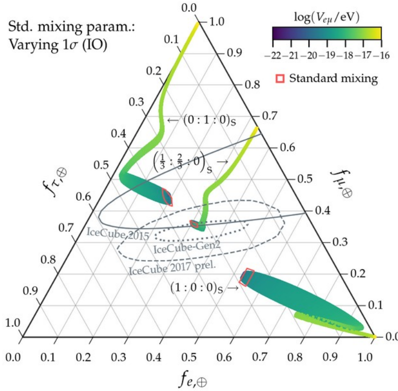

MB & Agarwalla, *PRL* 2019

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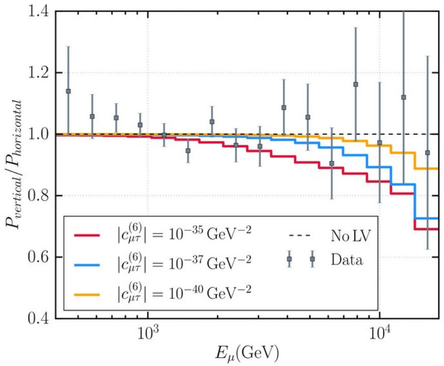
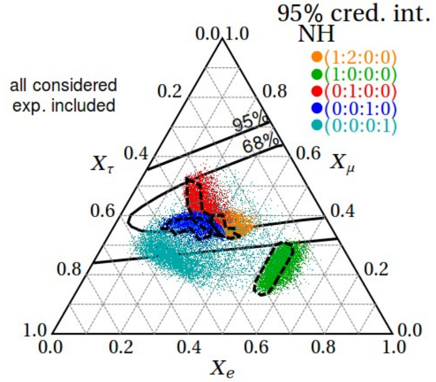
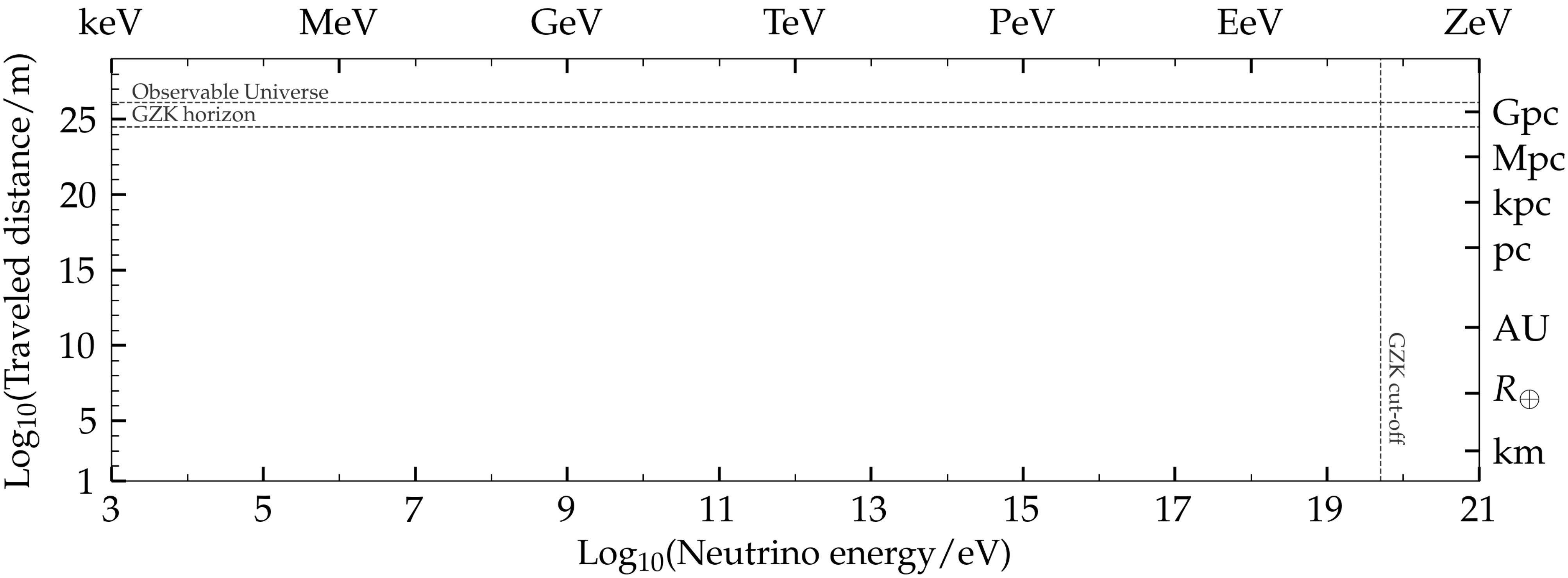


IceCube, *Nature Phys.* 2018

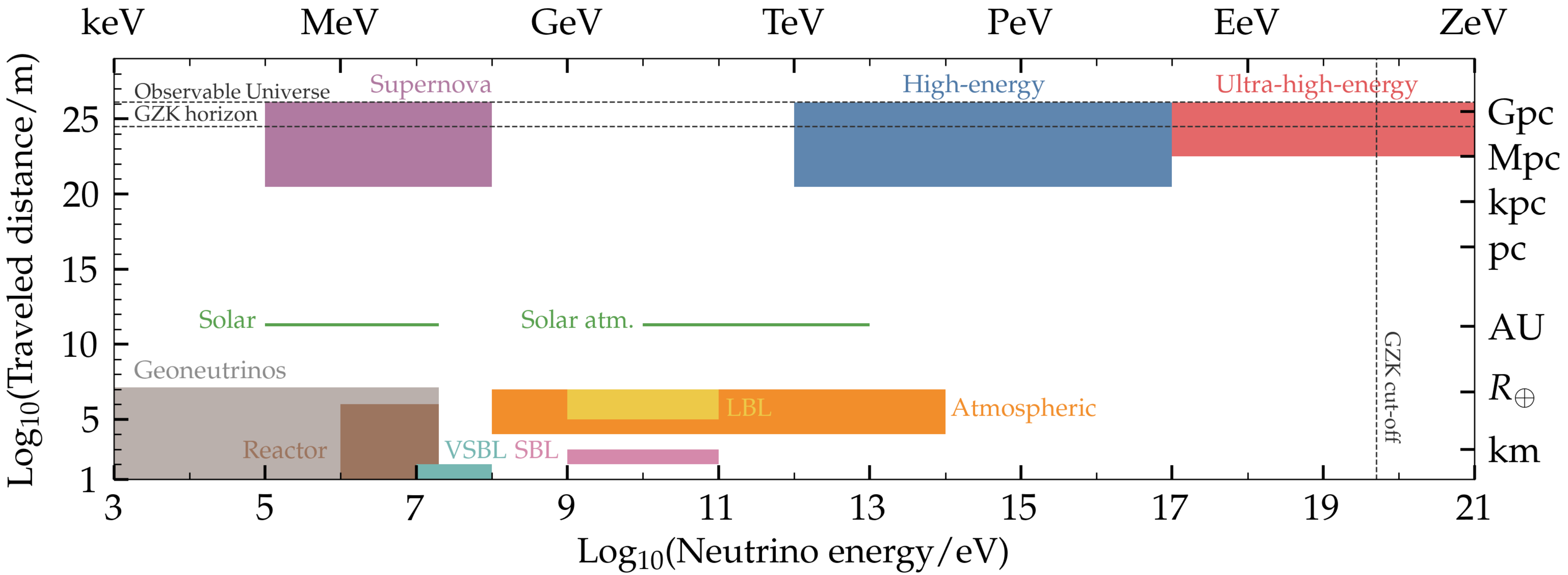
Sterile neutrinos



Brdar, Kopp, Wang, *JCAP* 2017

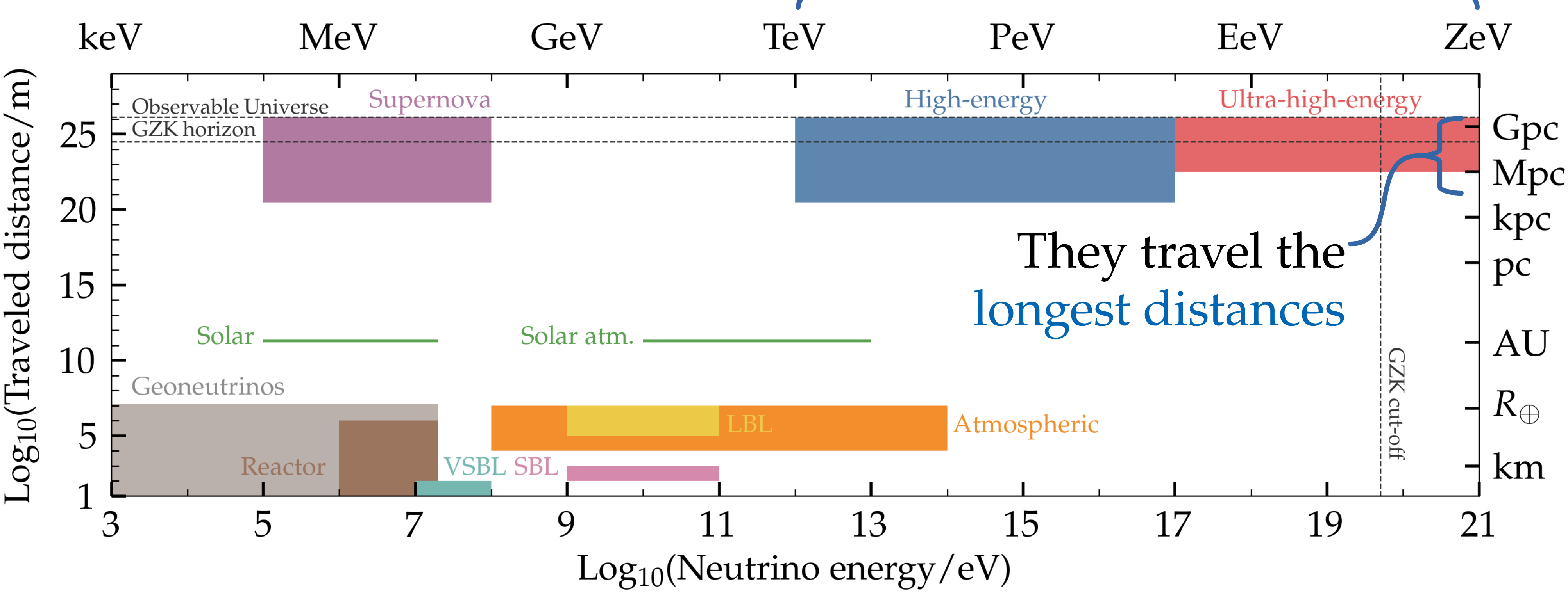


Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted



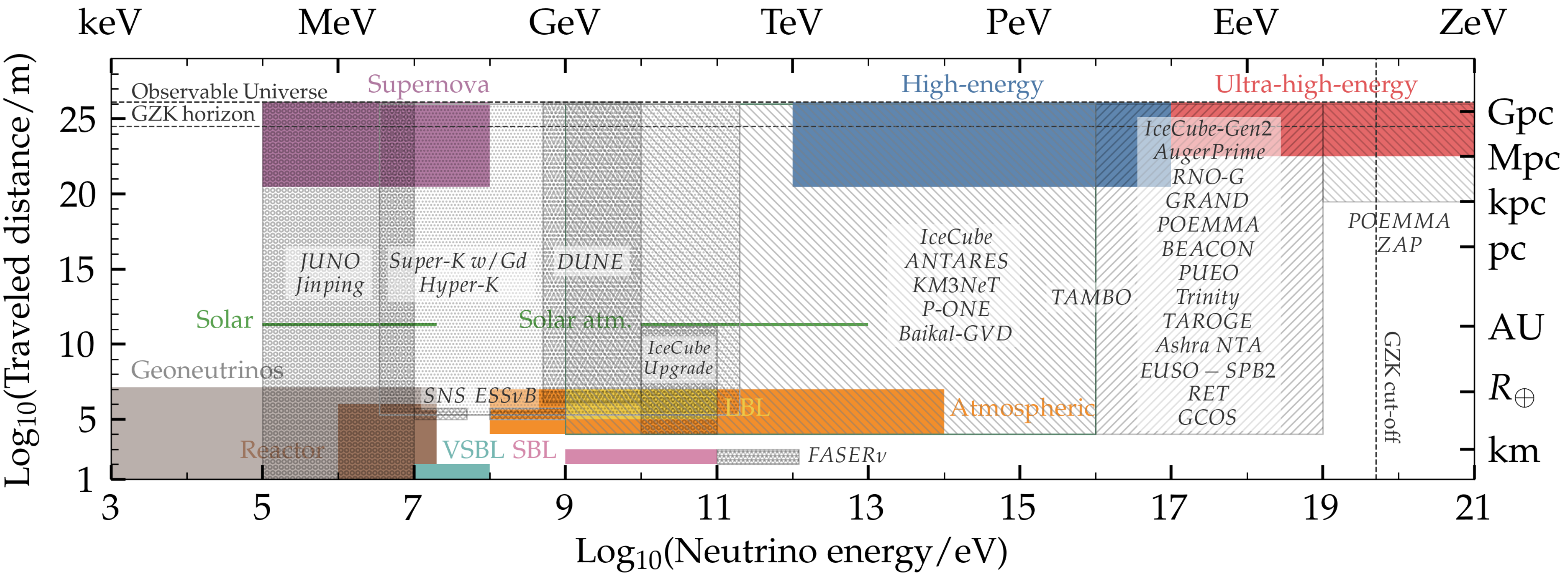
Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted

They have the highest energies



They travel the longest distances

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



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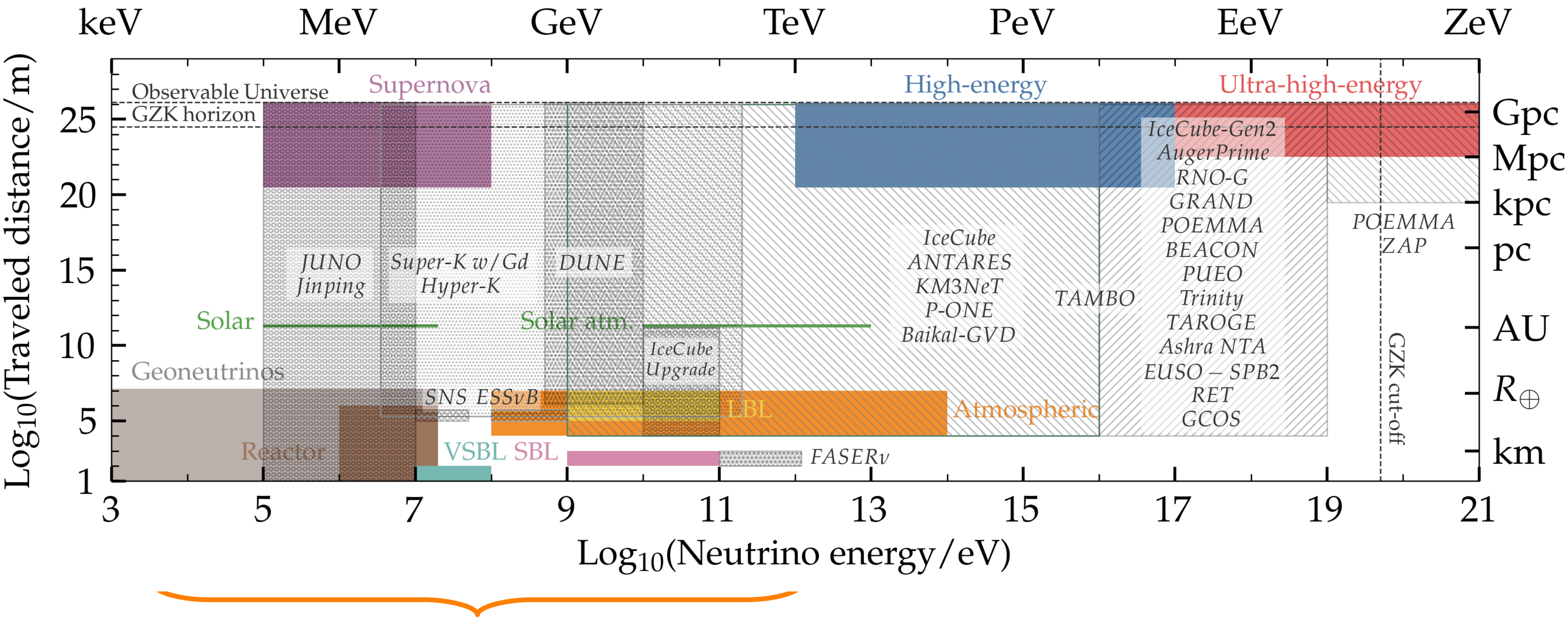
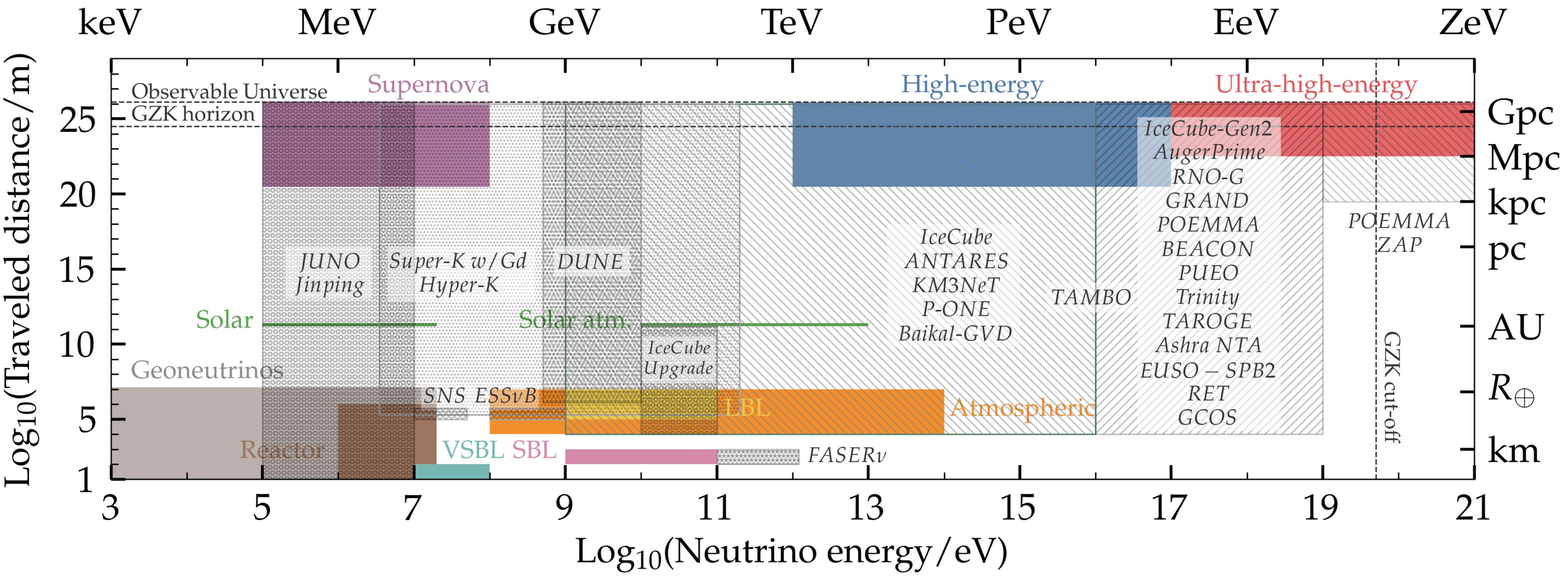


Synergies with lower energies

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

Discovered in 2013 by IceCube



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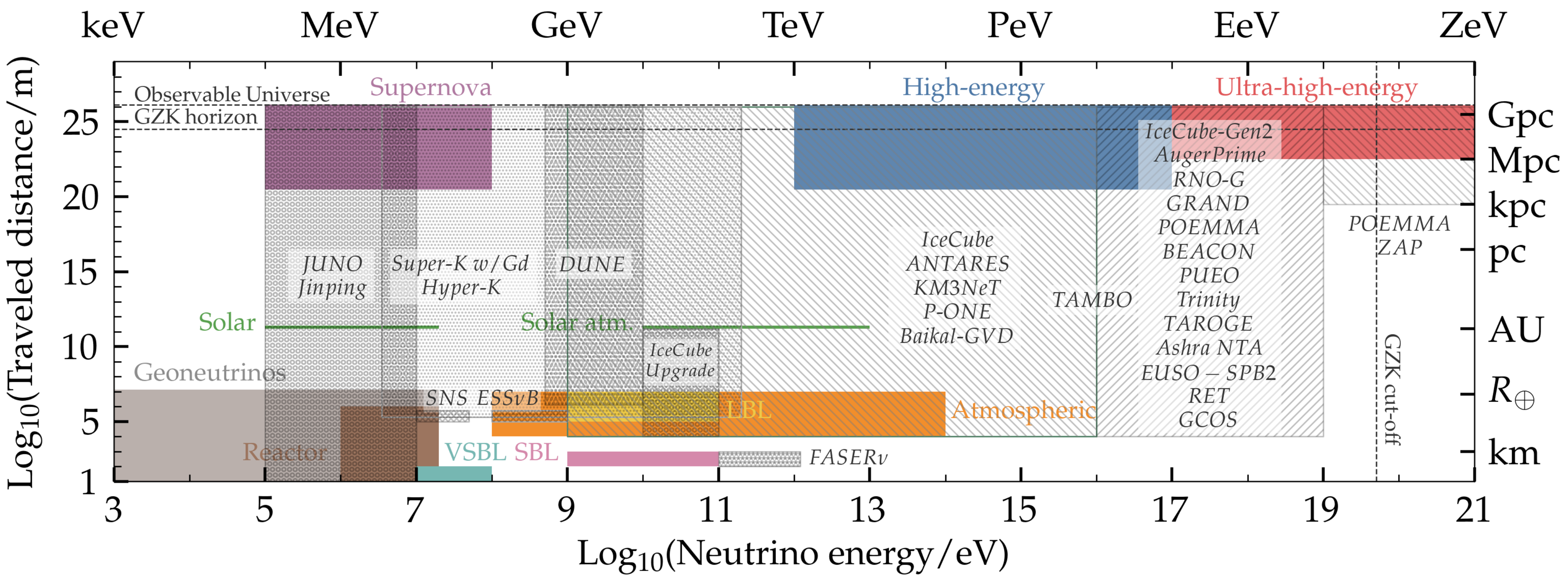
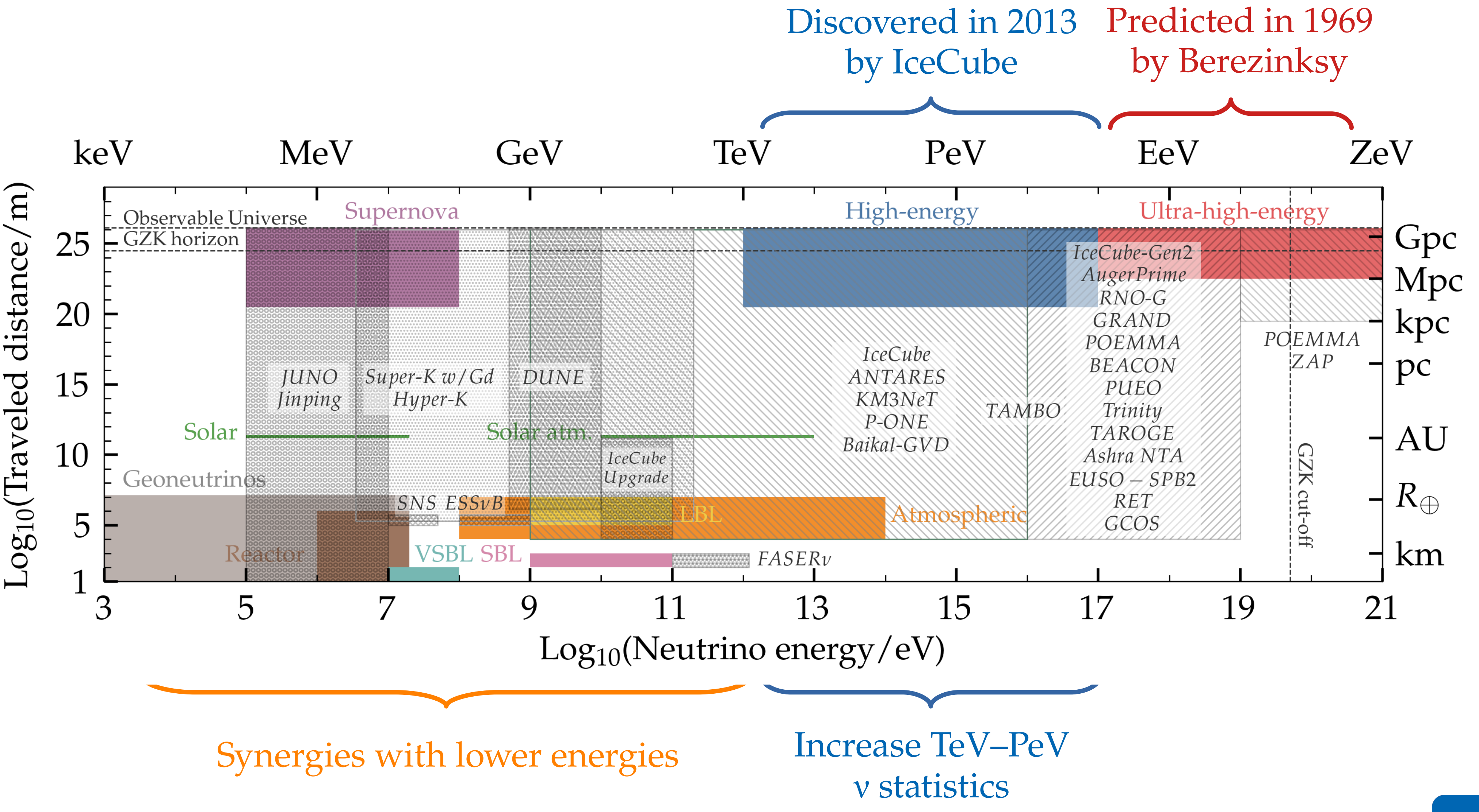


Synergies with lower energies

Increase TeV–PeV
ν statistics

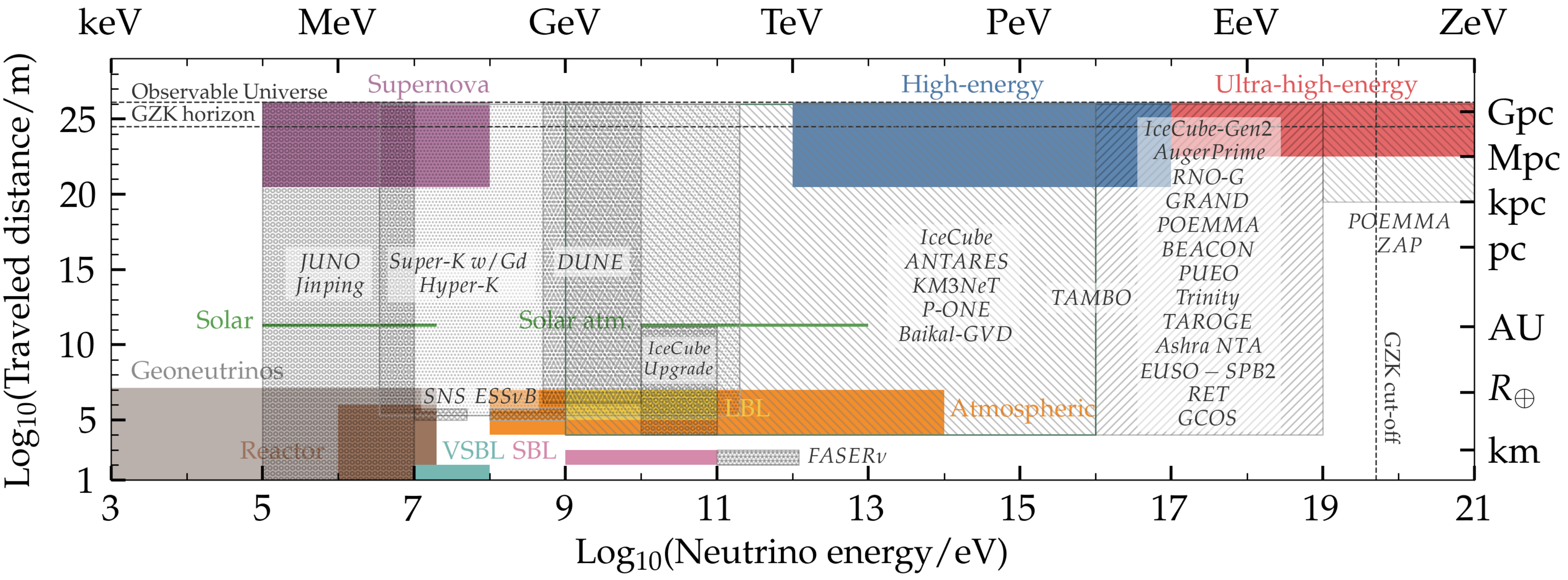
Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted



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

Discovered in 2013 by IceCube

Predicted in 1969 by Berezinksy



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, $\kappa_1 < 10^{-33}$

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  - Spectral shape
  - Angular distribution
  - Flavor composition
  - Timing

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  E.g.,
  n = -1: neutrino decay
  n = 0: CPT-odd Lorentz violation
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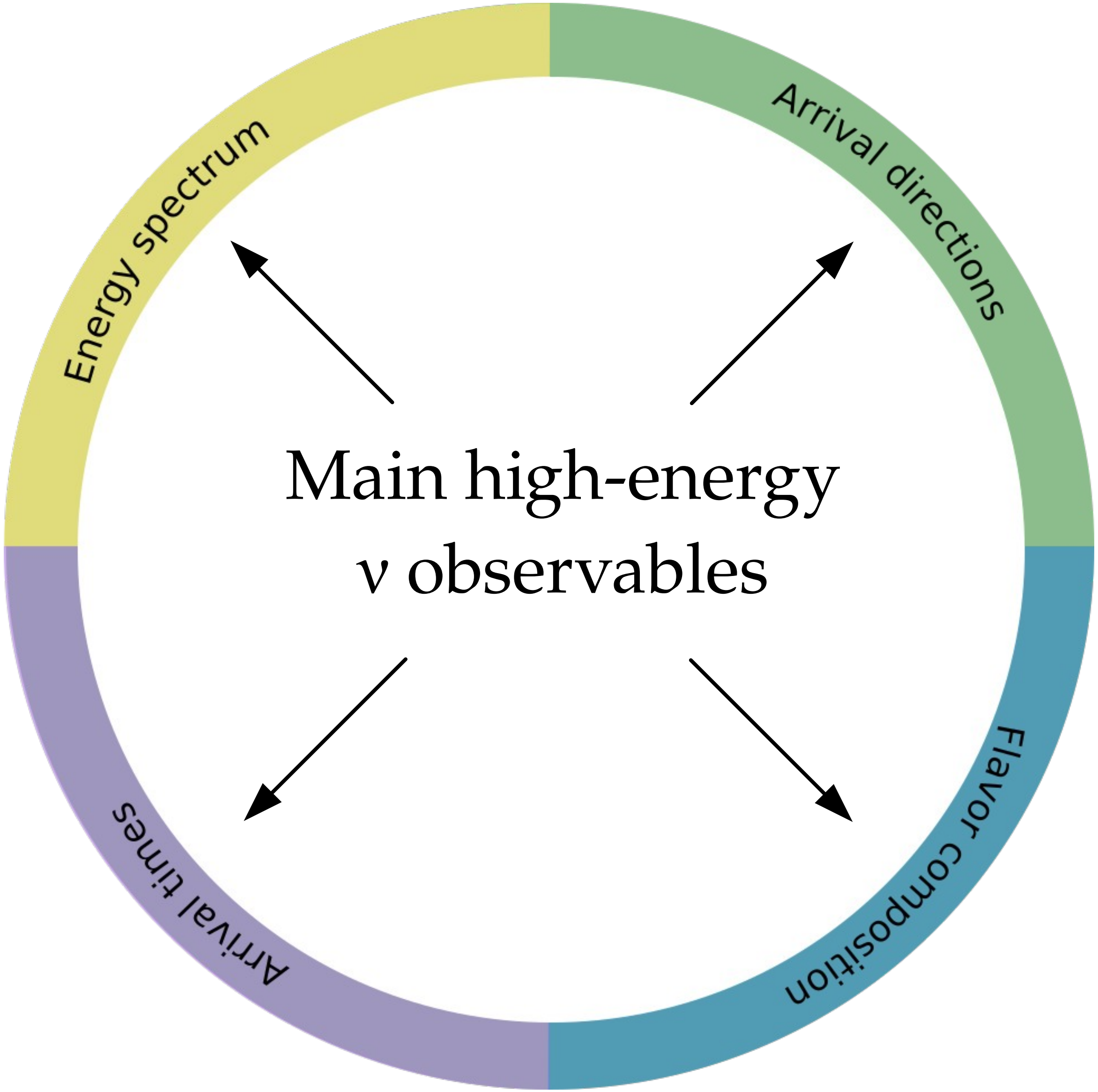
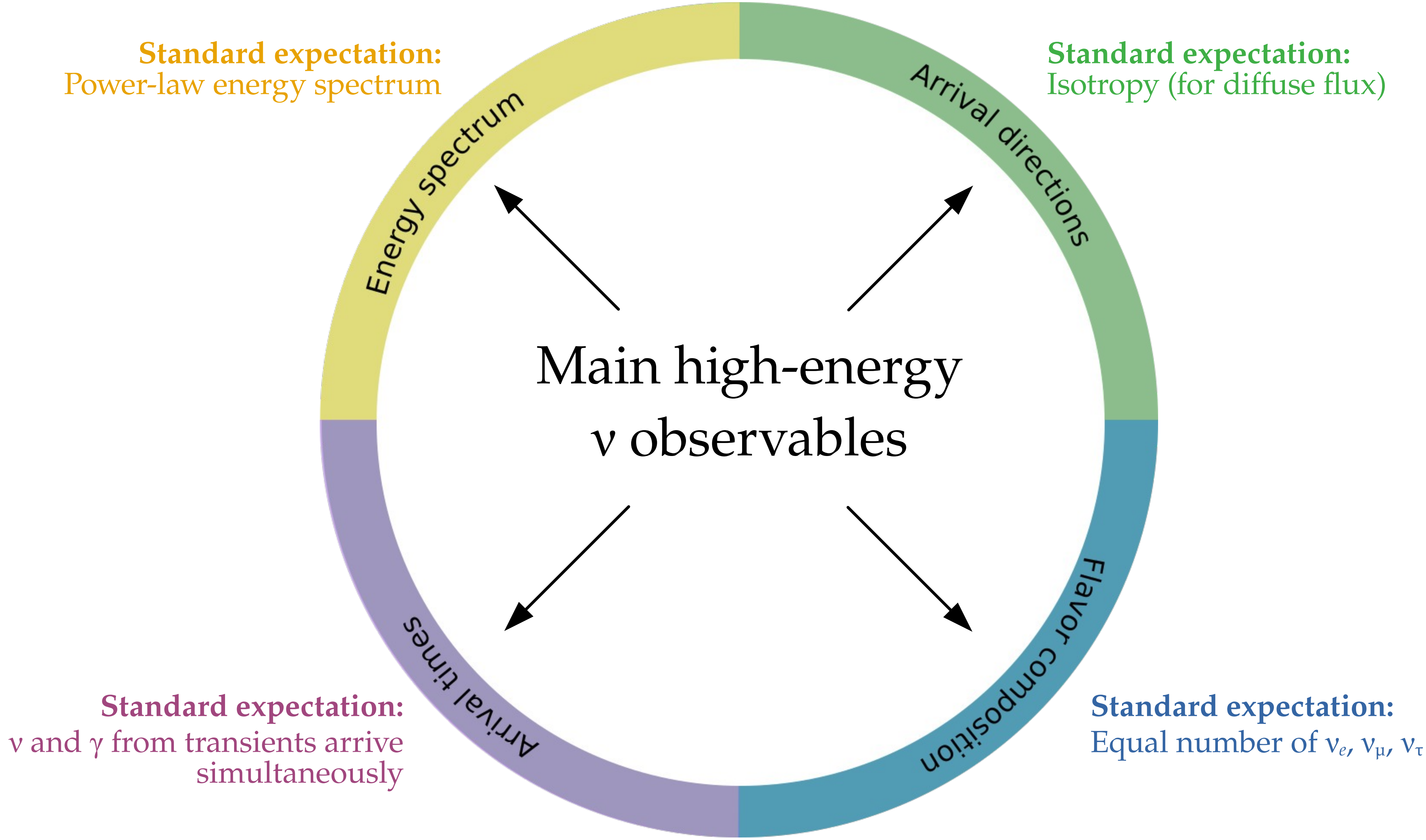
  In spite of
  poor energy, angular, flavor reconstruction
  & astrophysical unknowns


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


Standard expectation:
Power-law energy spectrum
Standard expectation:
Isotropy (for diffuse flux)
Energy spectrum
Arrival directions
Main high-energy
ν observables
Arrival times
Flavor composition
Standard expectation:
ν and γ from transients arrive simultaneously
Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Note: Not an exhaustive list

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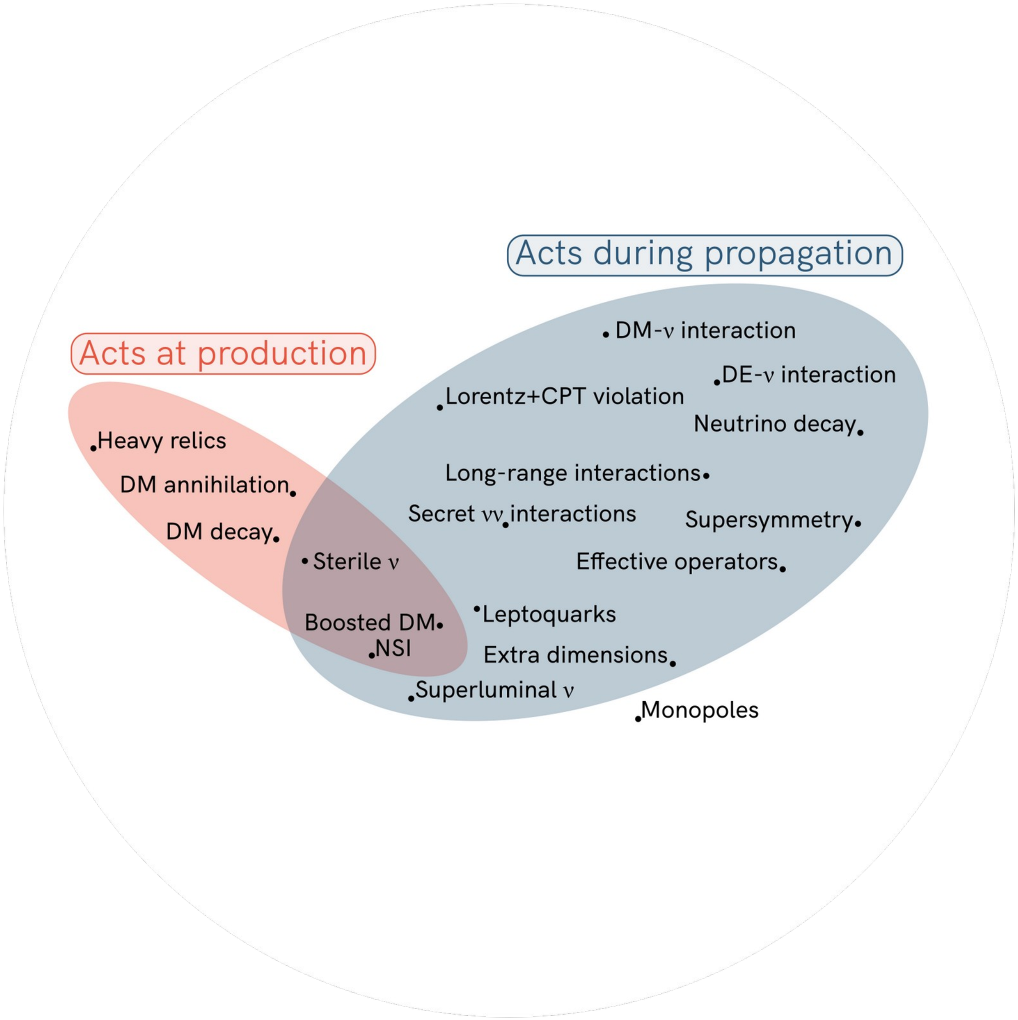

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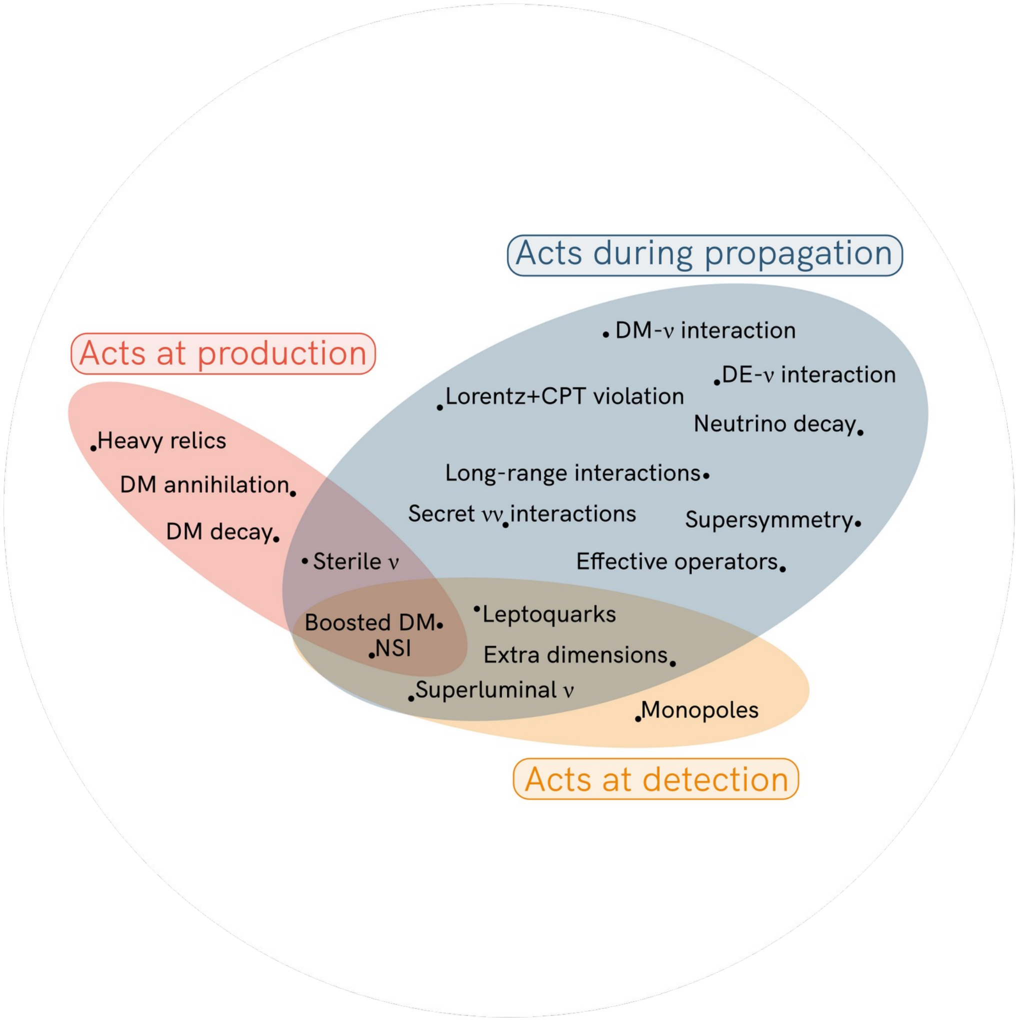

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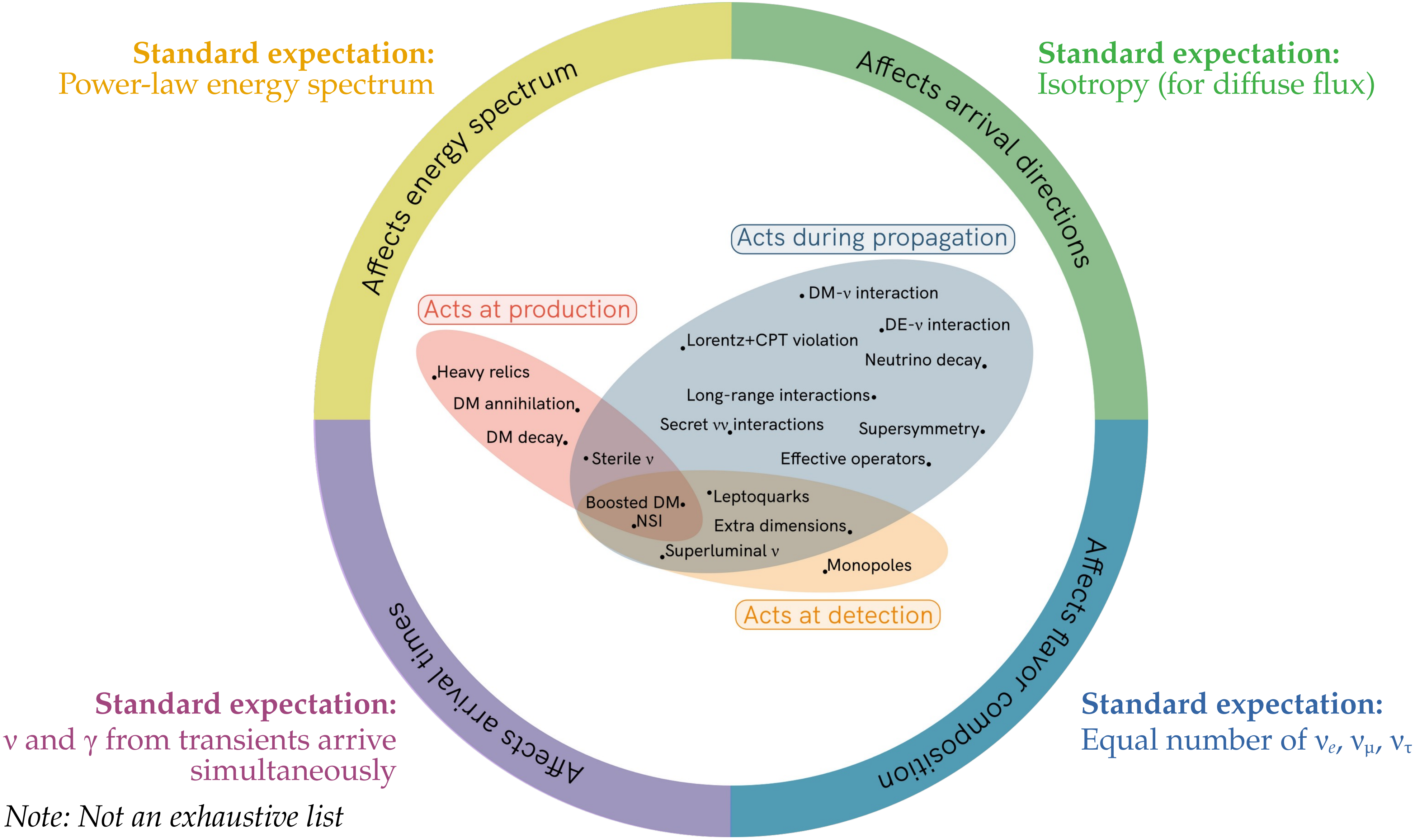

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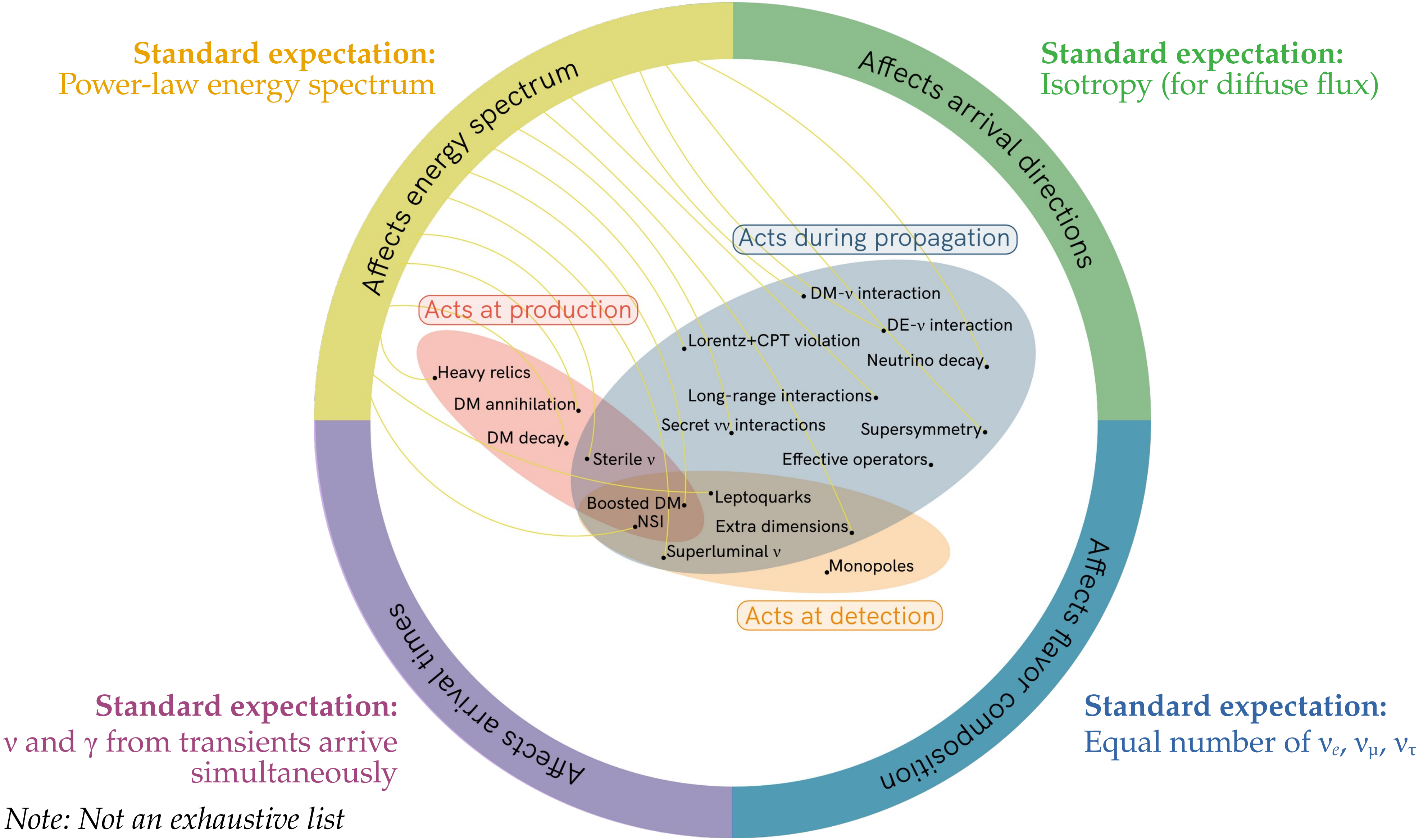
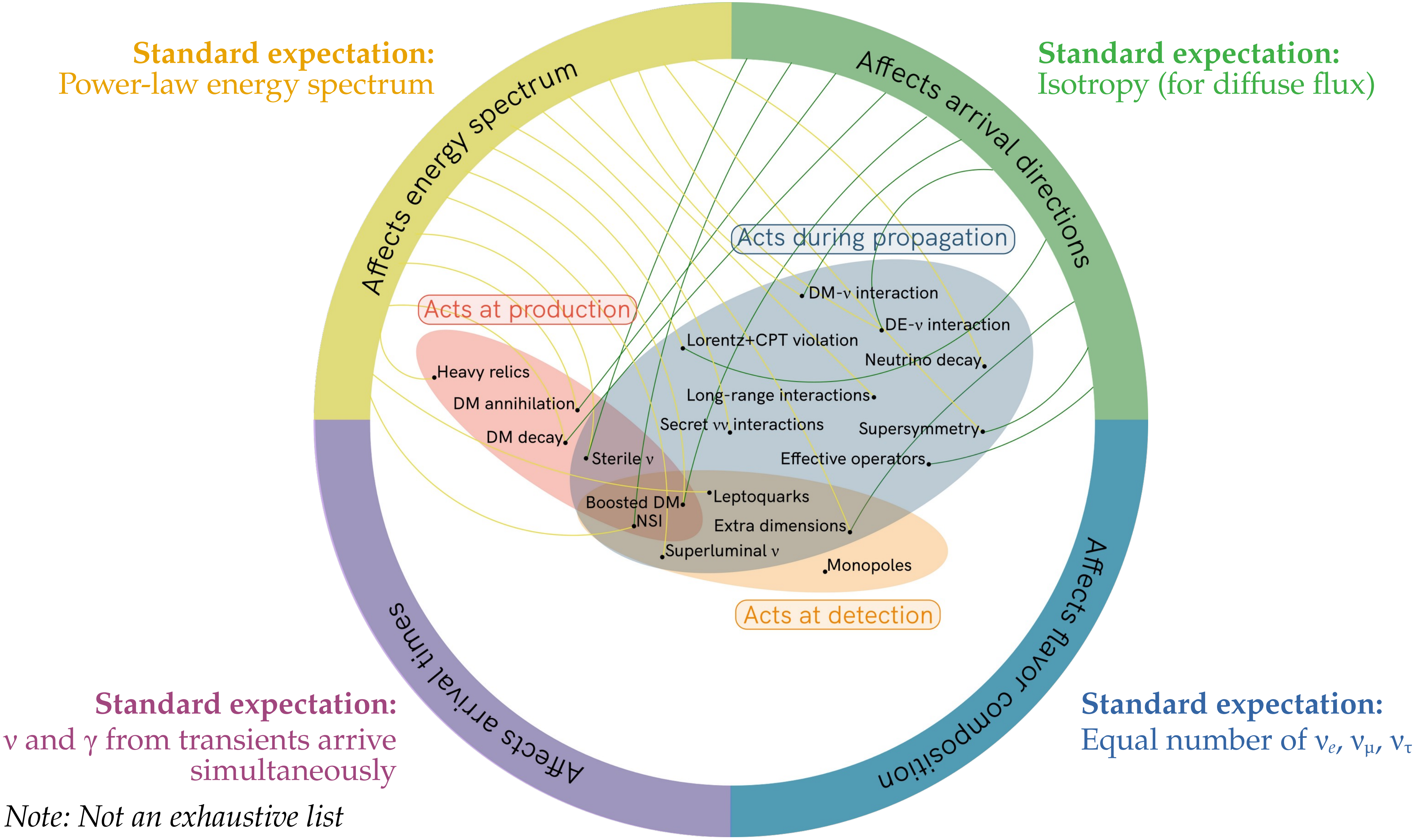


Standard expectation:
Power-law energy spectrum
Standard expectation:
Isotropy (for diffuse flux)
Affects energy spectrum
Affects arrival directions
Affects flavor composition
Affects arrival times
Acts during propagation
Acts at production
Acts at detection
DM-ν interaction
DE-ν interaction
Lorentz+CPT violation
Neutrino decay
Heavy relics
DM annihilation
DM decay
Long-range interactions
Secret νν interactions
Supersymmetry
Sterile ν
Effective operators
Leptoquarks
Boosted DM
NSI
Extra dimensions
Superluminal ν
Monopoles
Standard expectation:
ν and γ from transients arrive simultaneously
Standard expectation:
Equal number of ν_e, ν_μ, ν_τ
Note: Not an exhaustive list



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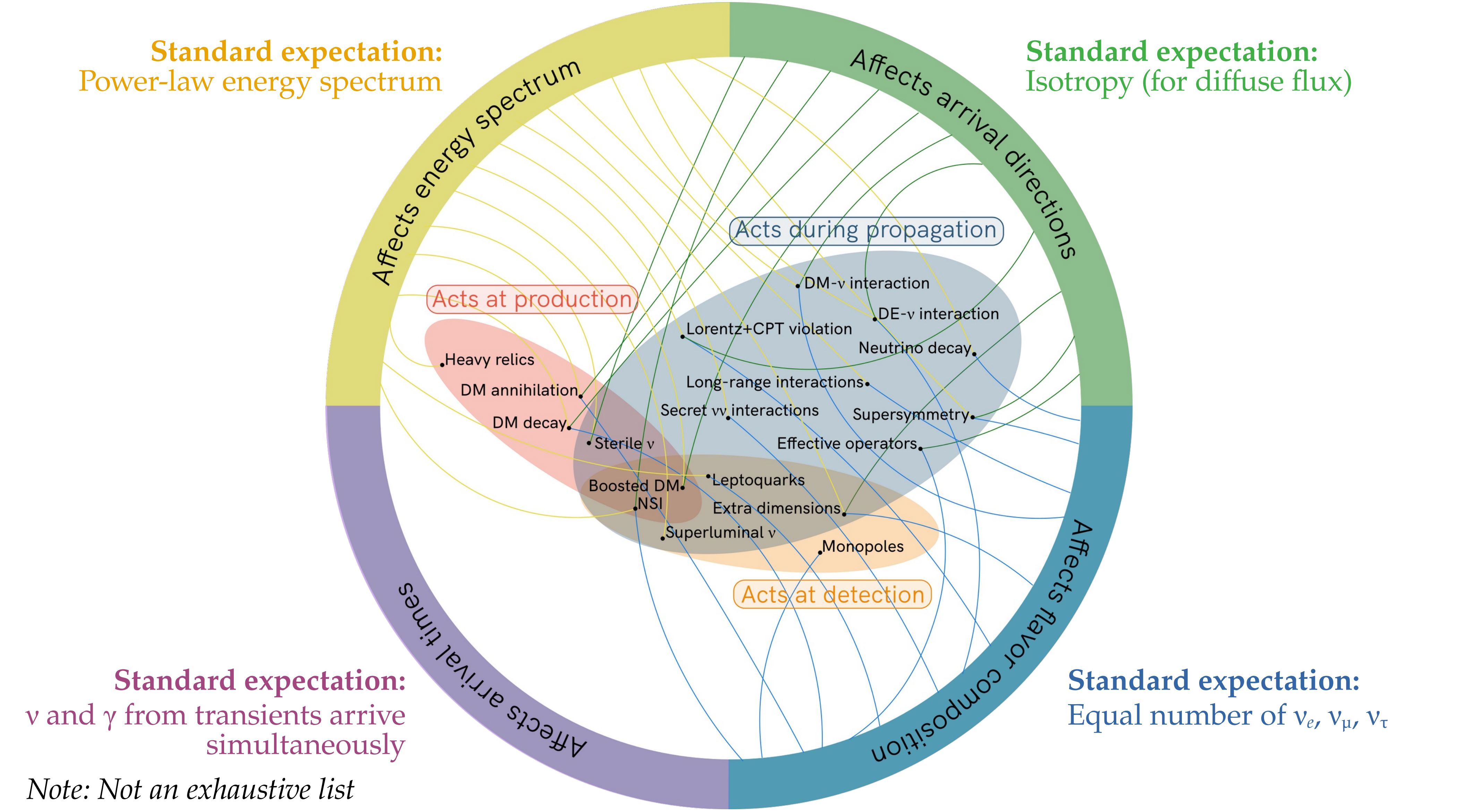

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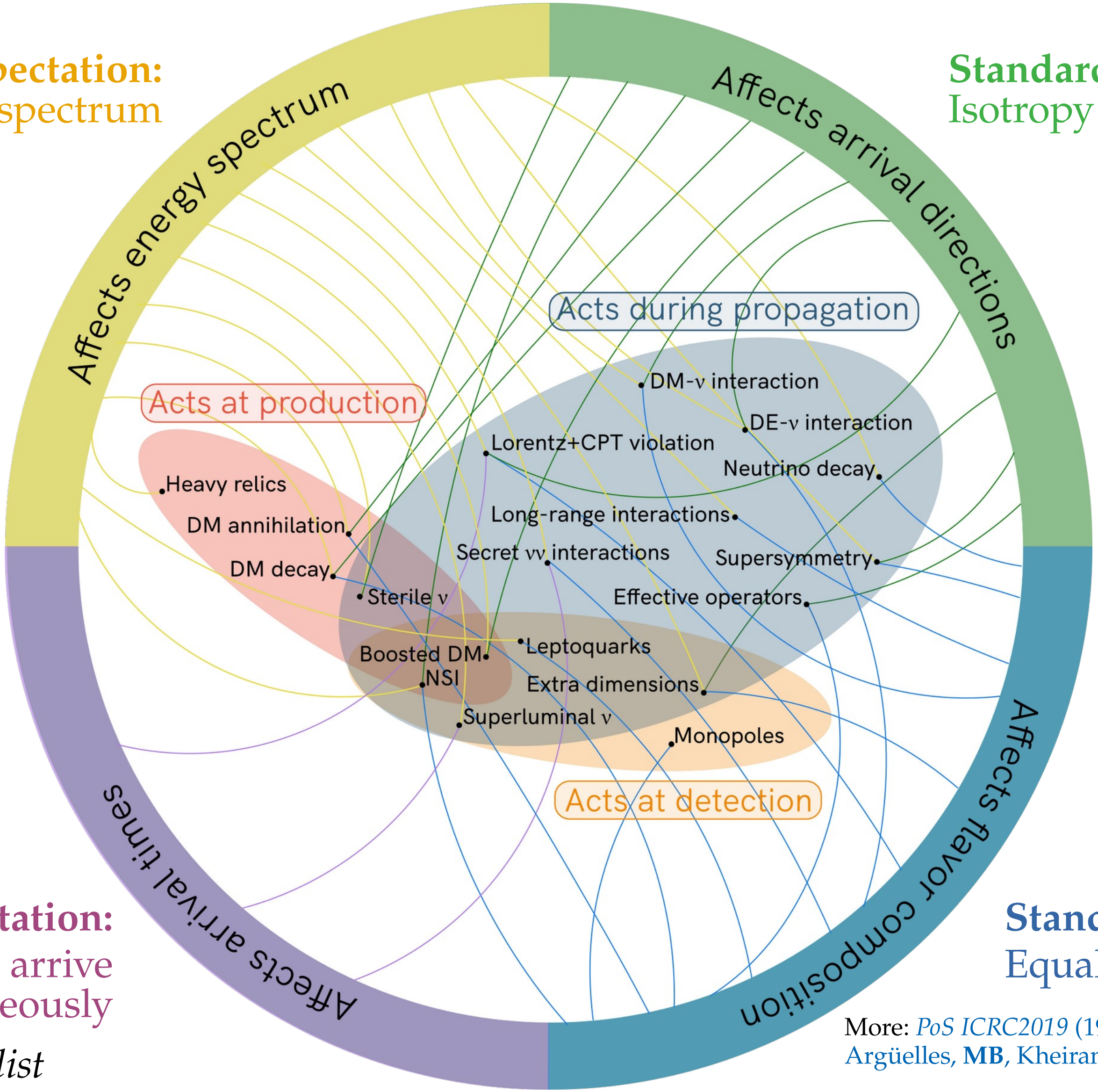

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More: *PoS ICRC2019* (1907.08690)
Argüelles, **MB**, Kheirandish, Palomares-Ruiz, Salvadó, Vincent

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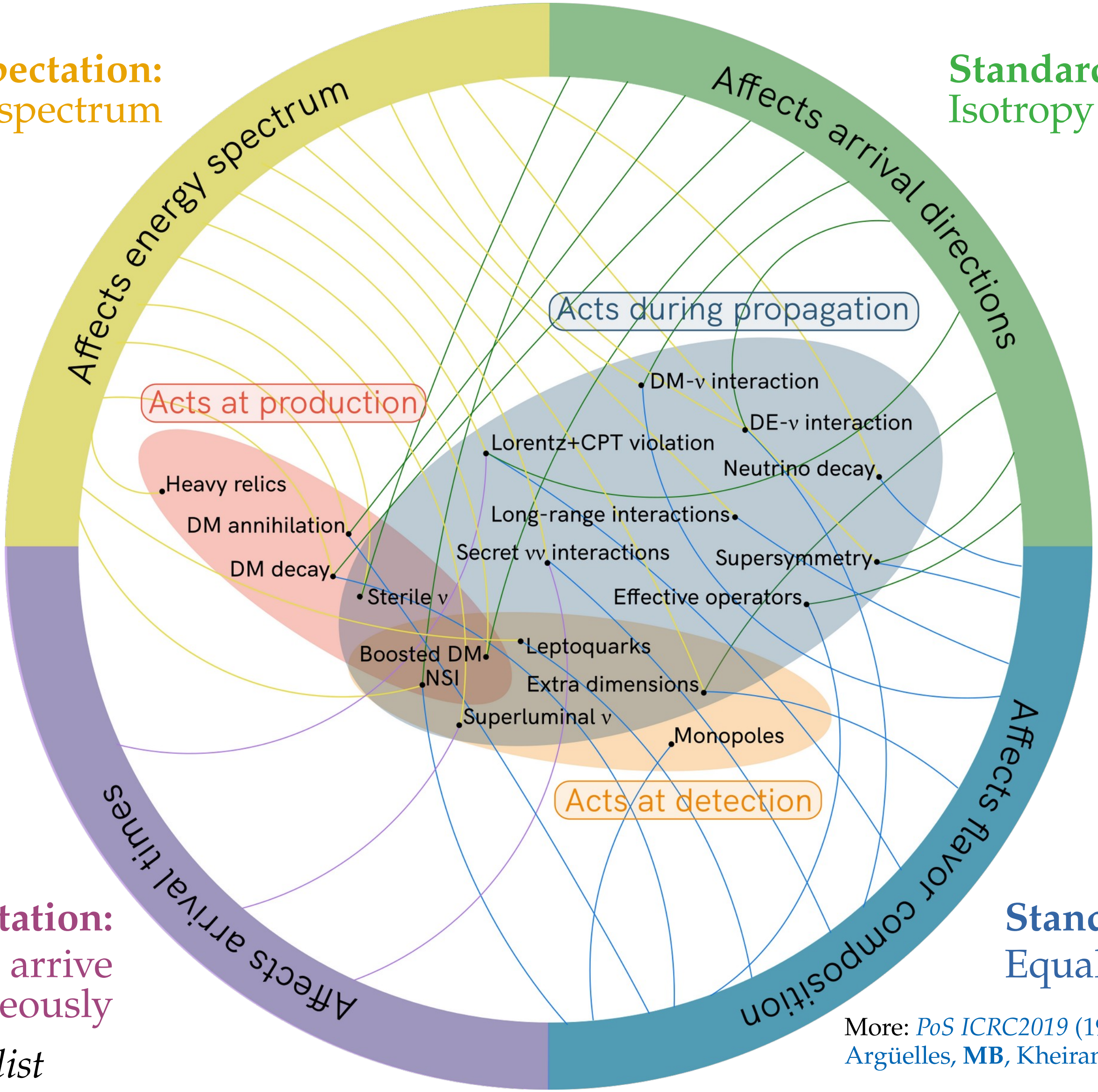

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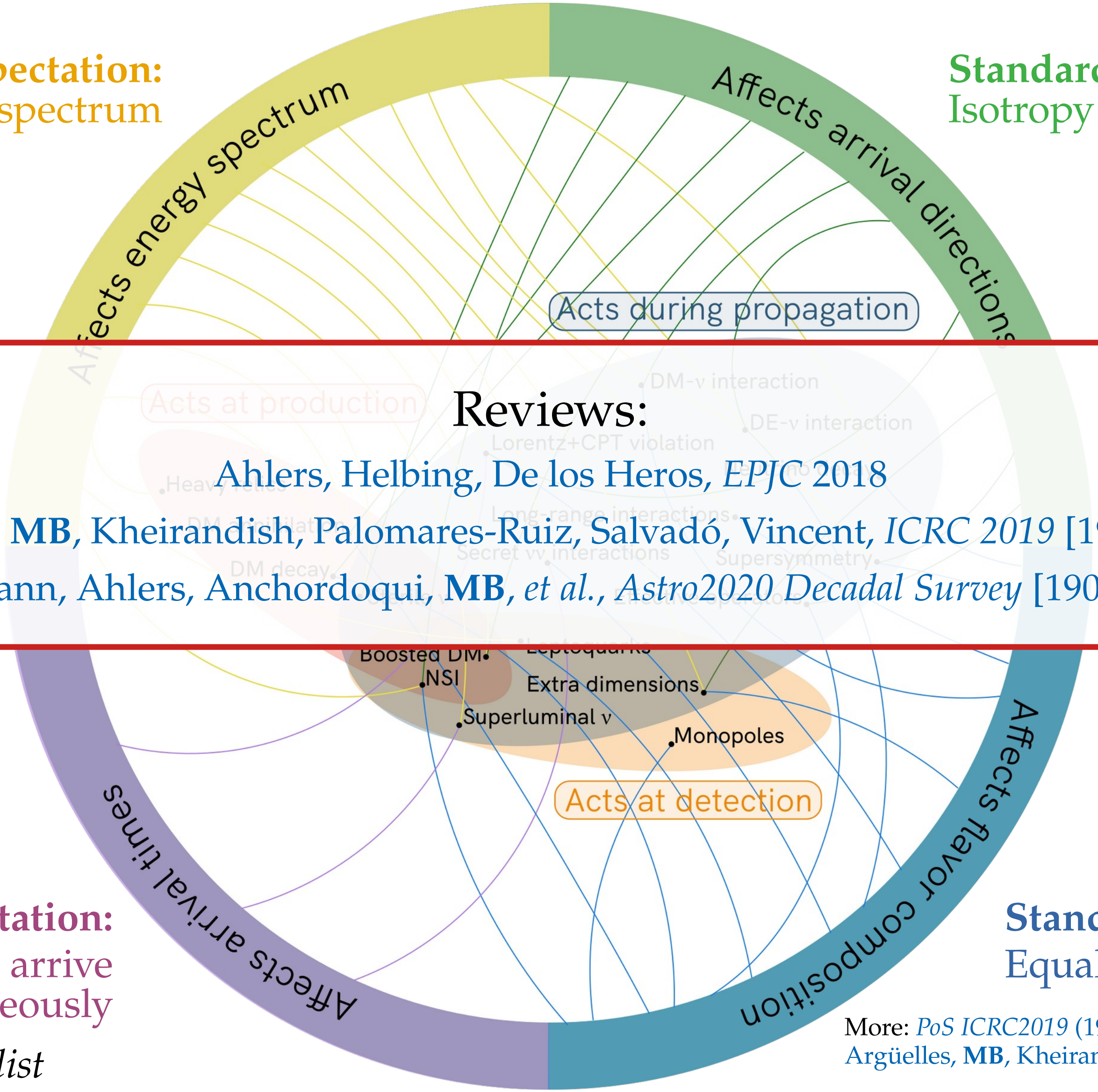

Reviews:

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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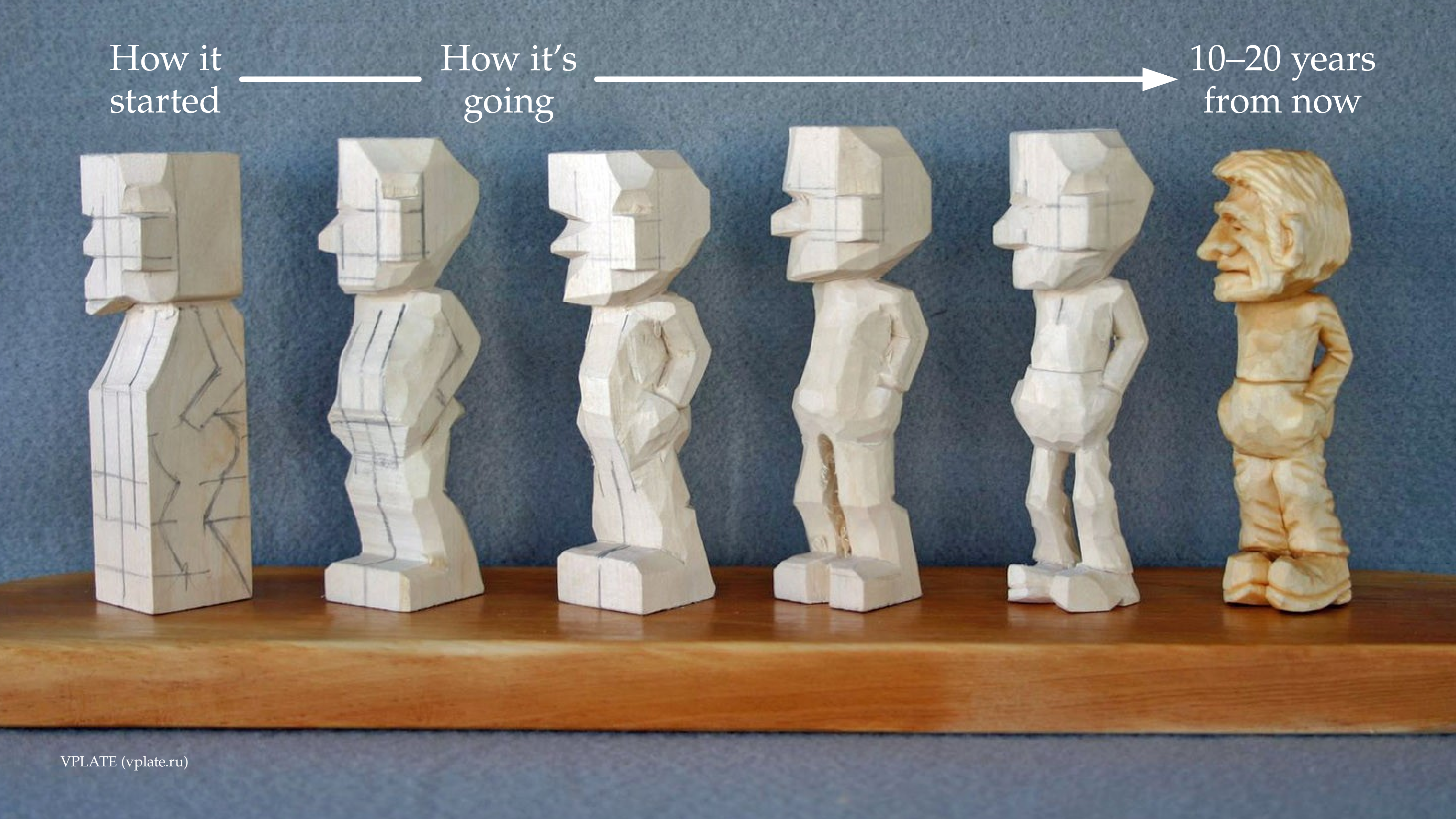
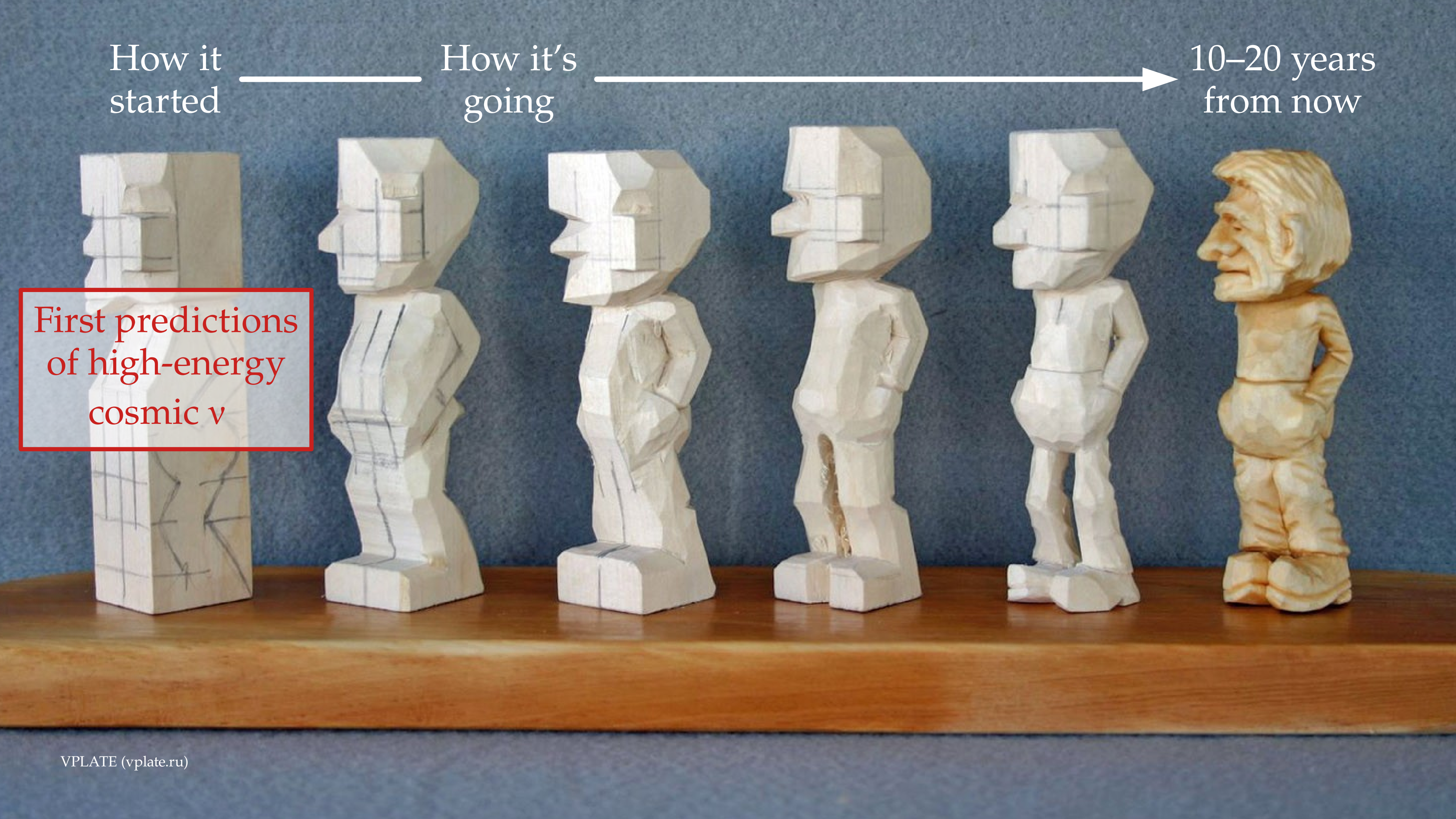
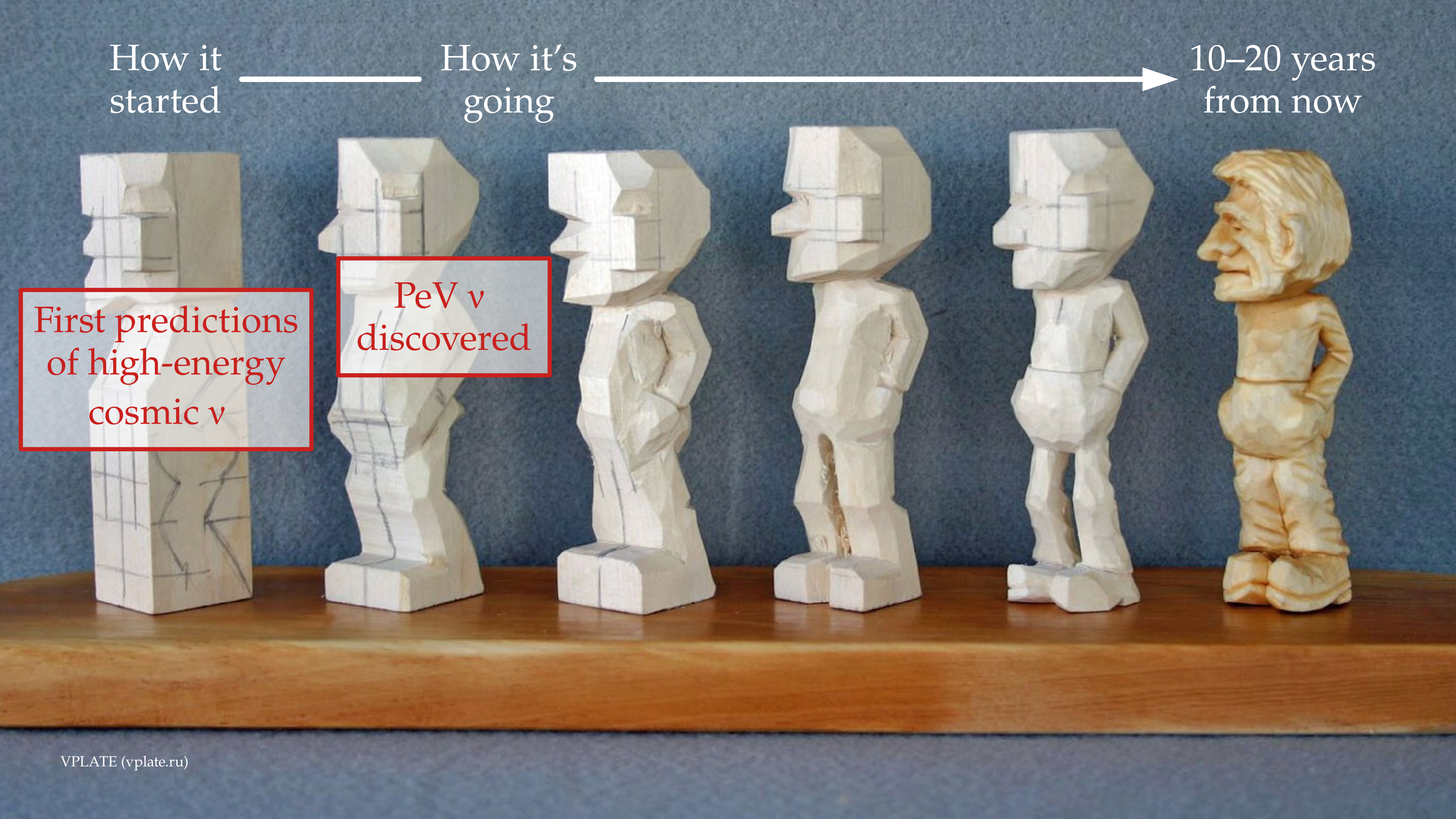

How it started
How it's going
10–20 years from now


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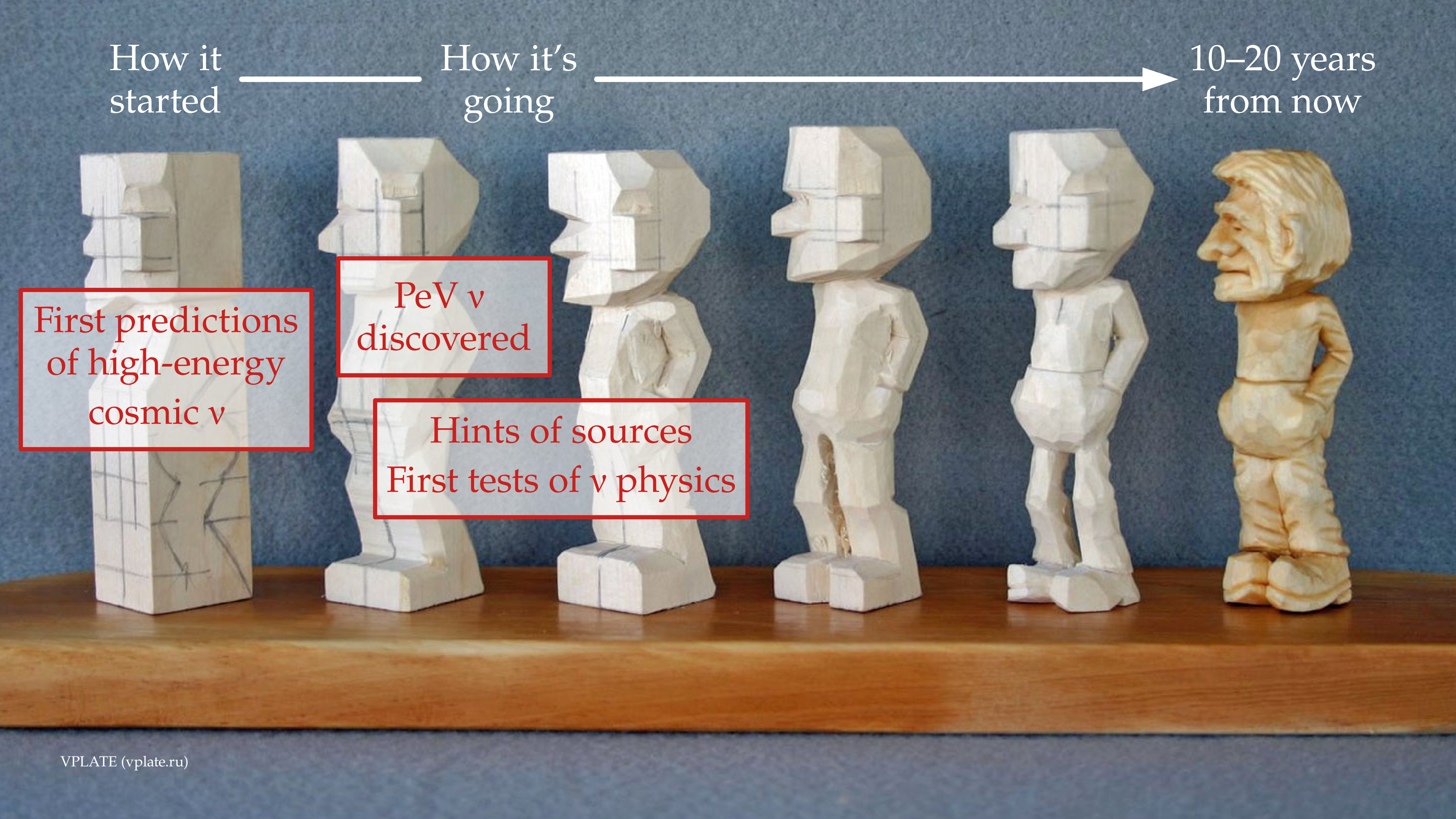
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Hints of sources
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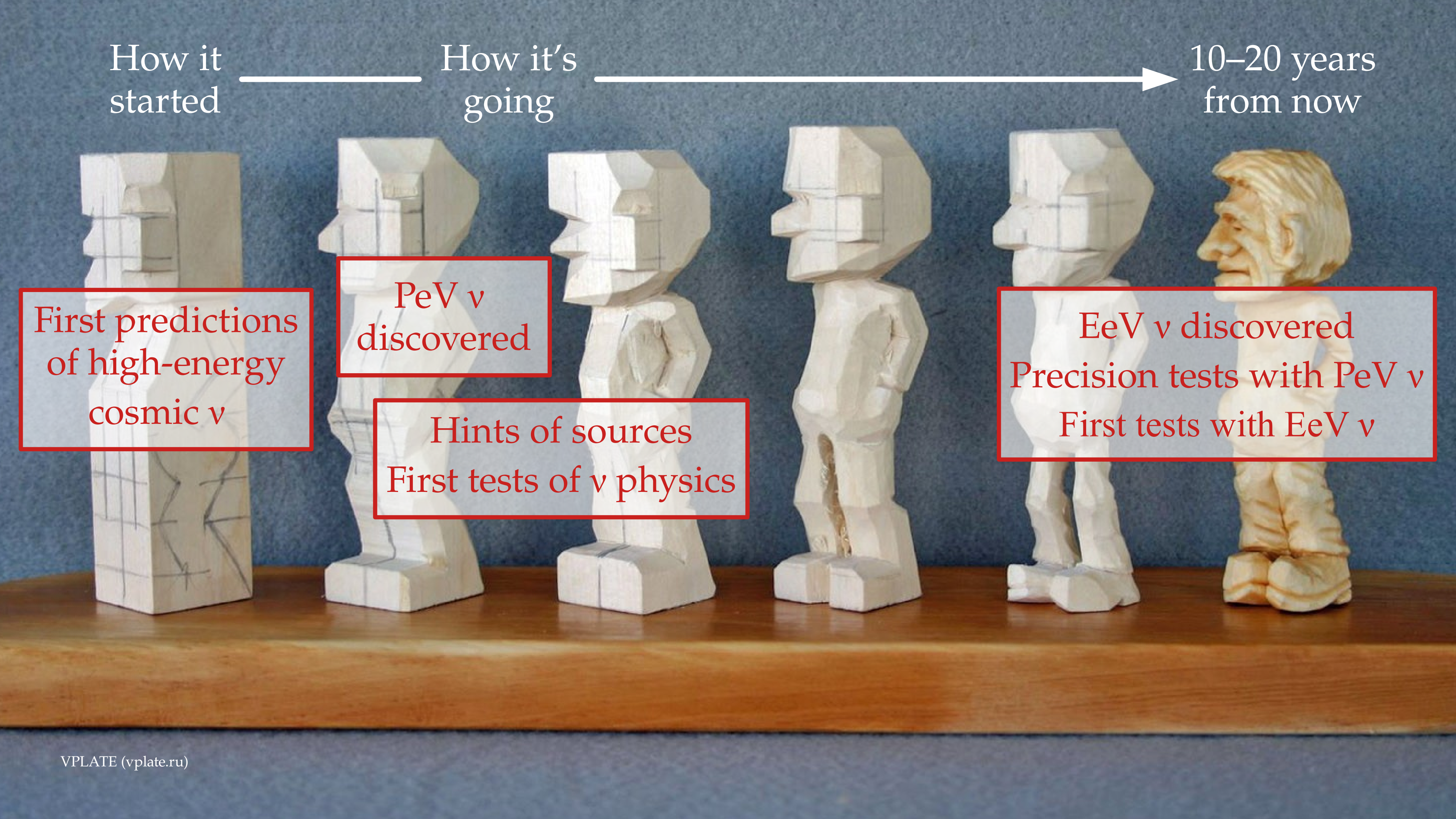
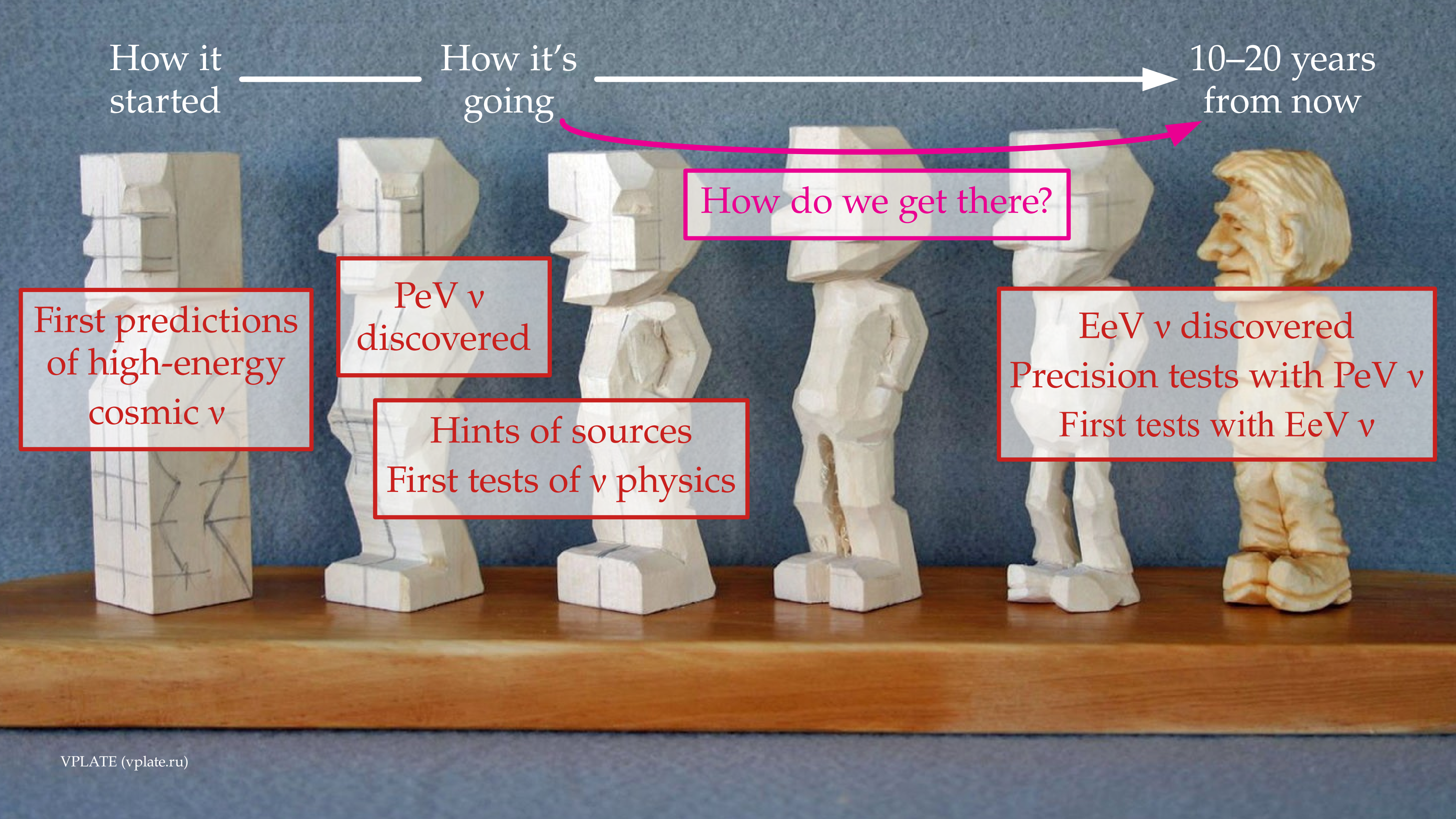

How it started
How it's going
10–20 years from now
First predictions of high-energy cosmic ν
PeV ν discovered
Hints of sources
First tests of ν physics
EeV ν discovered
Precision tests with PeV ν
First tests with EeV ν
VPLATE (vplate.ru)


How it started
How it's going
10–20 years from now
How do we get there?
First predictions of high-energy cosmic ν
PeV ν discovered
Hints of sources
First tests of ν physics
EeV ν discovered
Precision tests with PeV ν
First tests with EeV ν
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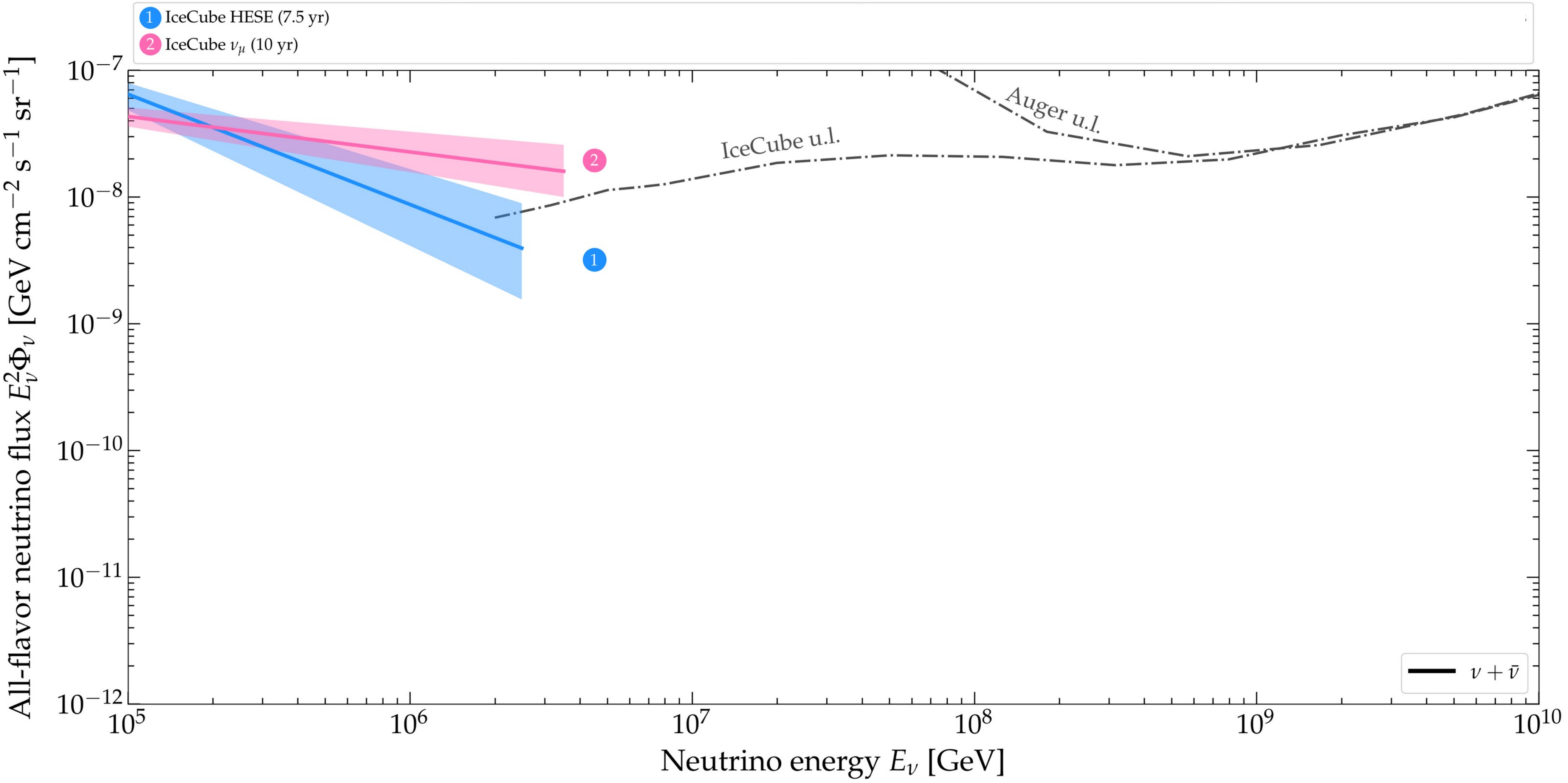


1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (10 yr)
Auger u.l.
IceCube u.l.
$\nu + \bar{\nu}$
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy E_ν [GeV]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^5
10^6
10^7
10^8
10^9
10^{10}

Today

TeV–PeV ν

Today

TeV–PeV ν

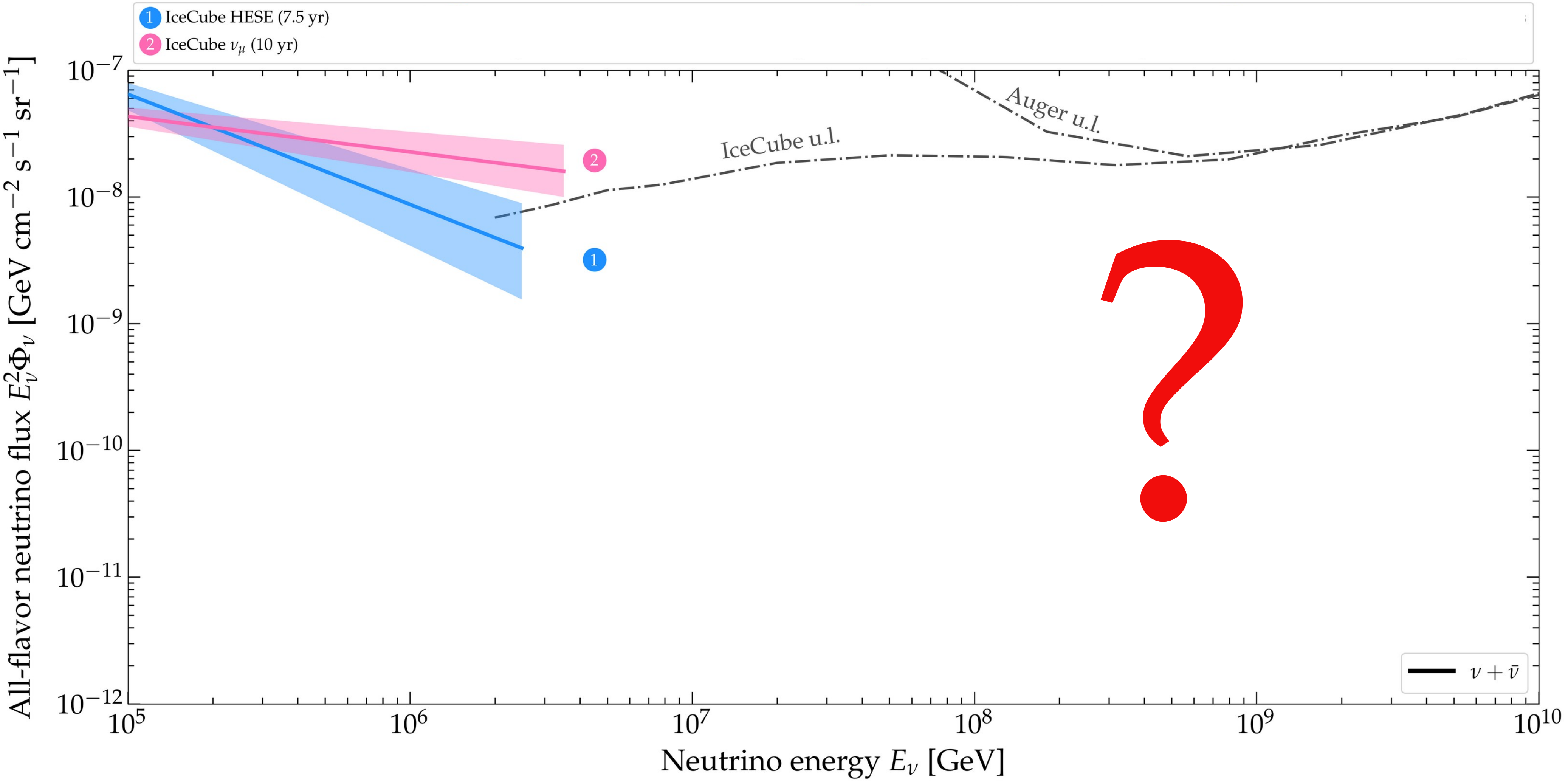
Turn predictions
into data-driven tests

Today

TeV–PeV ν

Turn predictions
into data-driven tests

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



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10^{-7}
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10^{-11}
10^{-12}
Auger u.l.
IceCube u.l.
2
1
?
$\nu + \bar{\nu}$
10^5
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy E_ν [GeV]

Today

TeV–PeV ν

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TeV–PeV ν

Turn predictions
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Next decade

> 100-PeV ν

Today

TeV–PeV ν

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Smaller astrophysical uncertainties

Next decade

> 100-PeV ν

Make predictions for
a new energy regime

Today

TeV–PeV ν

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<u>Key developments</u>:
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Better reconstruction
Smaller astrophysical uncertainties

Next decade

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Make predictions for
a new energy regime

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

Today

TeV–PeV ν

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Next decade

$>$ 100-PeV ν

Make predictions for
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Key developments:
Discovery
New detection techniques
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Made robust and meaningful by accounting
for all relevant particle and astrophysics uncertainties

Today

TeV–PeV ν

Turn predictions
into data-driven tests

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

Next decade

$>$ 100-PeV ν

Make predictions for
a new energy regime

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

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

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

New-physics menu

1. Neutrino-matter cross section
2. Unstable neutrinos
3. New neutrino interactions

(If time allows)

4. Neutrinos & dark matter
5. Flavor composition
6. Physics with individual sources
7. ANITA mystery events

New-physics menu

1. Neutrino-matter cross section
2. Unstable neutrinos
3. New neutrino interactions
   (If time allows)

} Mauricio (this talk)

4. Neutrinos & dark matter
5. Flavor composition
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New-physics menu

1. Neutrino-matter cross section
2. Unstable neutrinos
3. New neutrino interactions *(If time allows)*

Mauricio (this talk)

4. Neutrinos & dark matter
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Carlos (next talk)

New-physics menu

1. Neutrino-matter cross section
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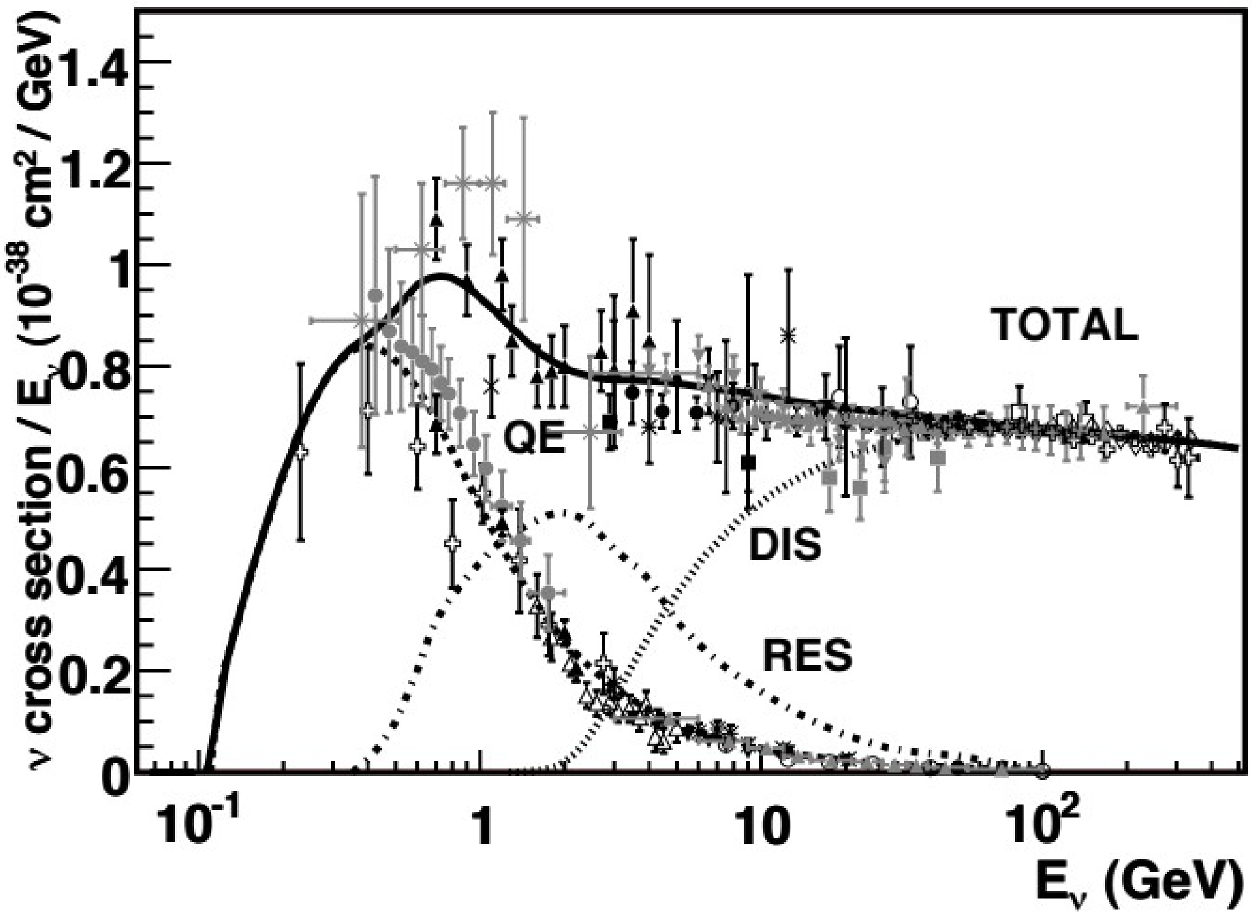
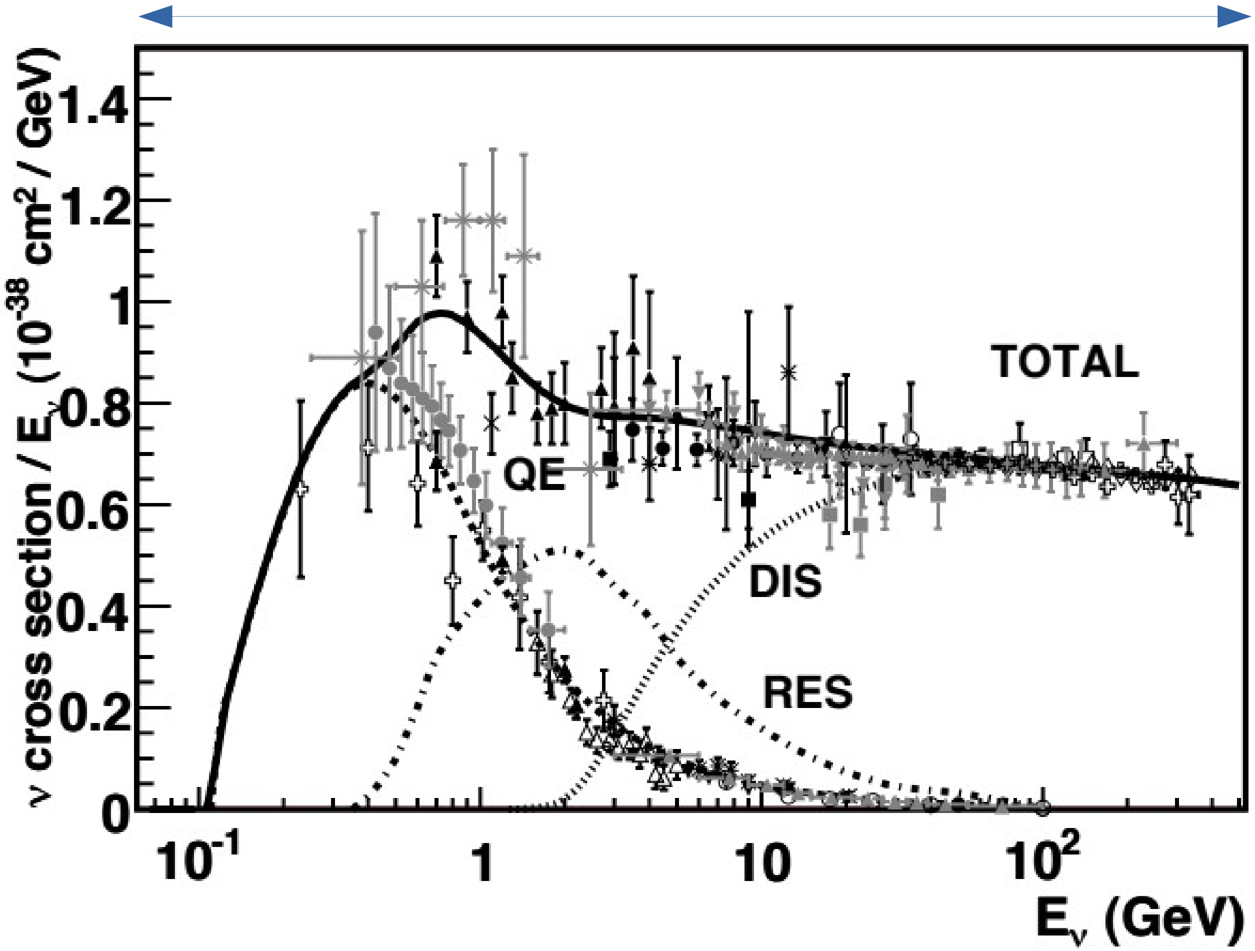


Particle Data Group

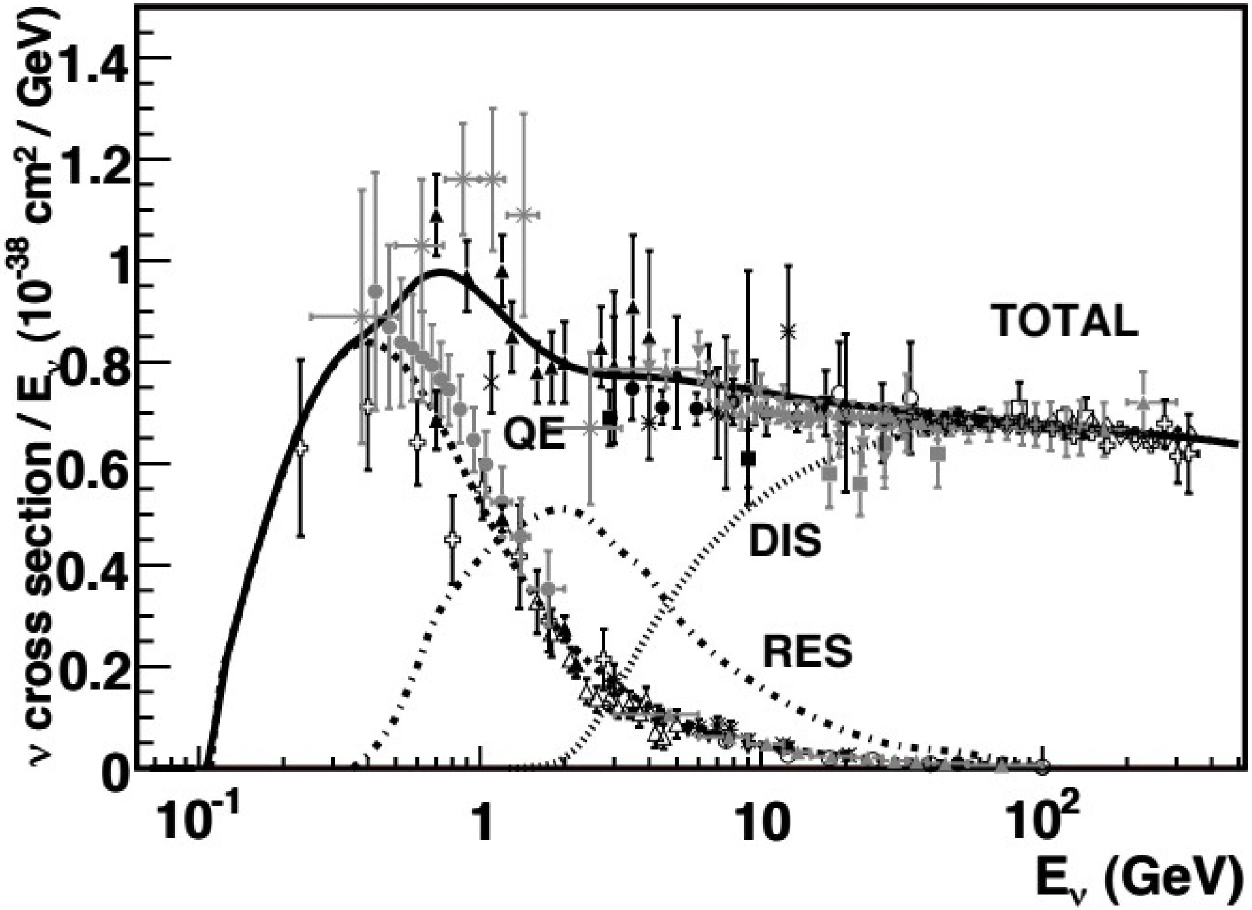
Accelerator experiments



Particle Data Group

Accelerator experiments

One recent measurement (COHERENT)



Particle Data Group

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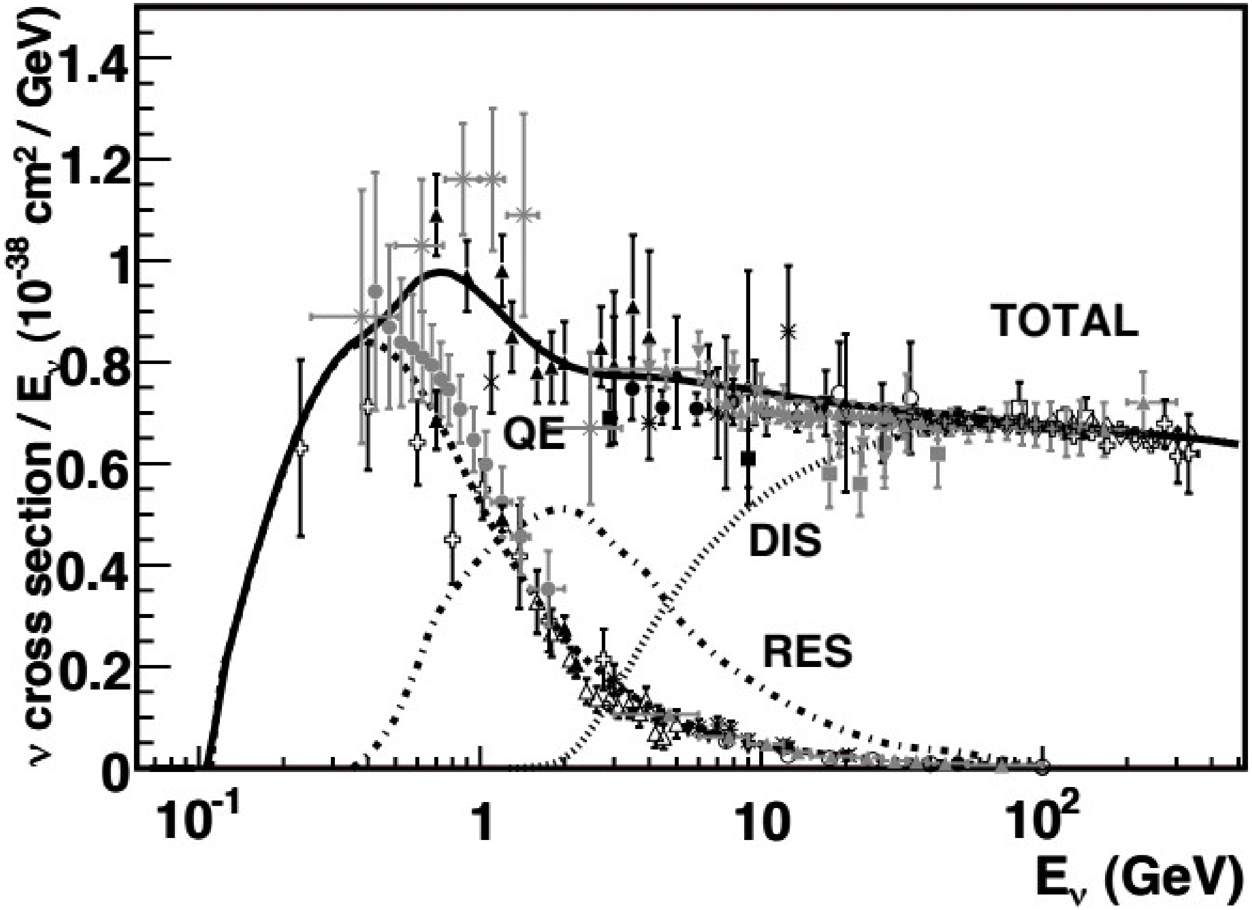
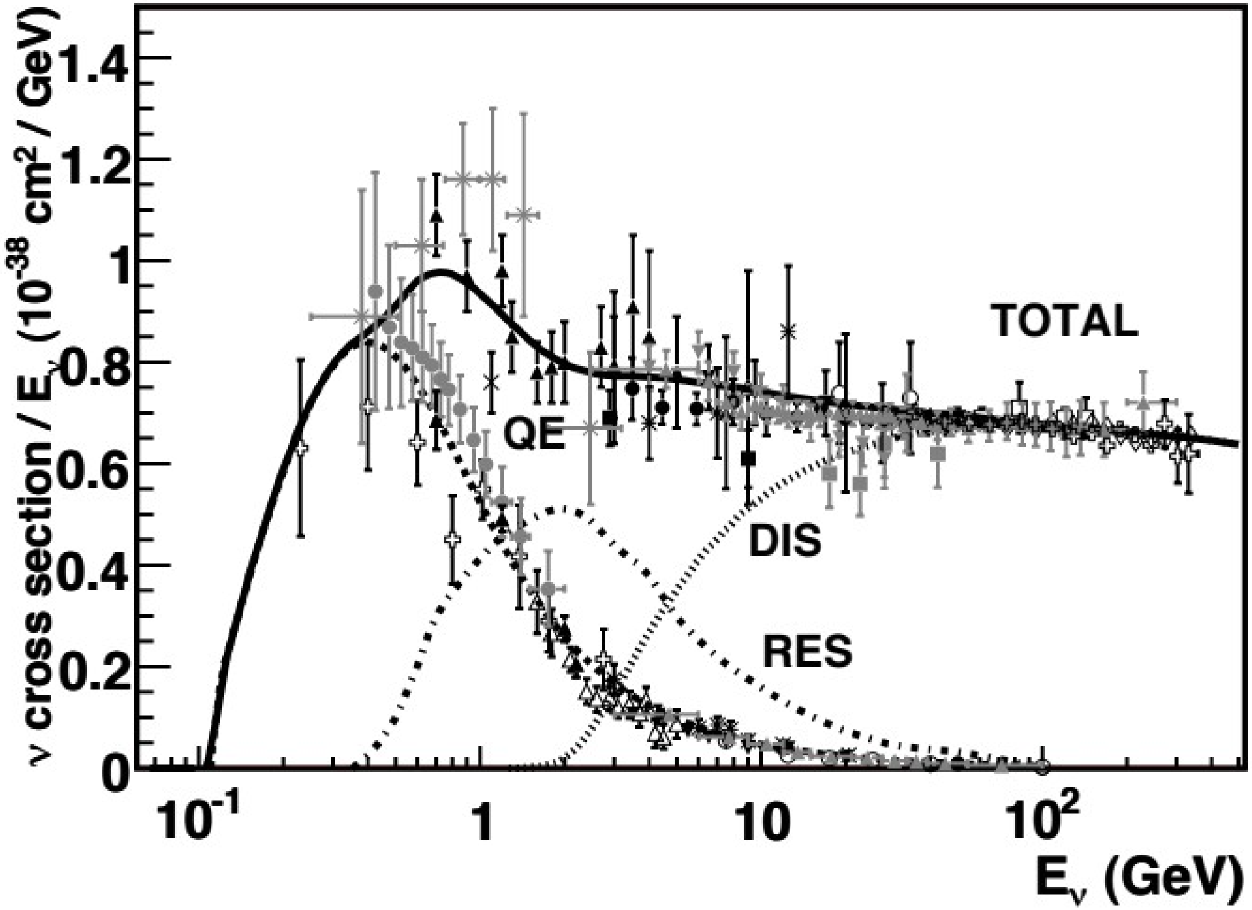


Particle Data Group

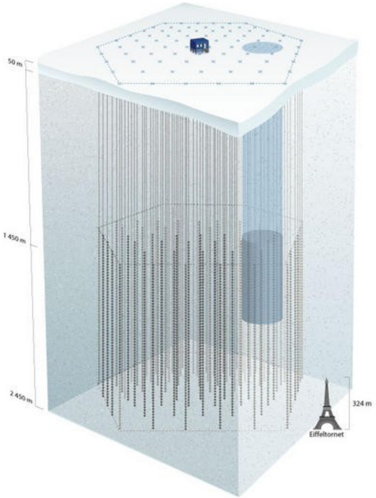
No measurements … until recently!

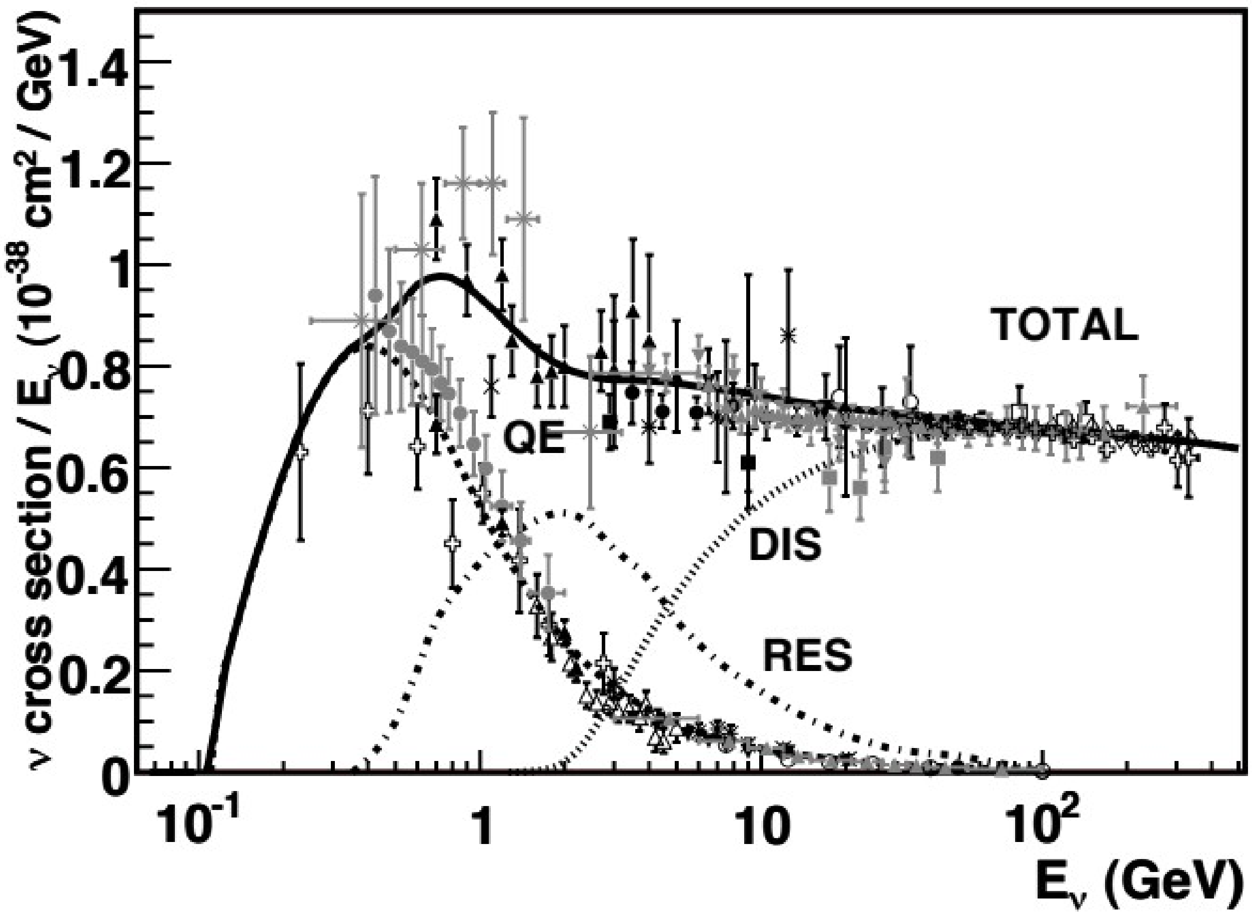
Accelerator experiments

One recent measurement (COHERENT)



Particle Data Group



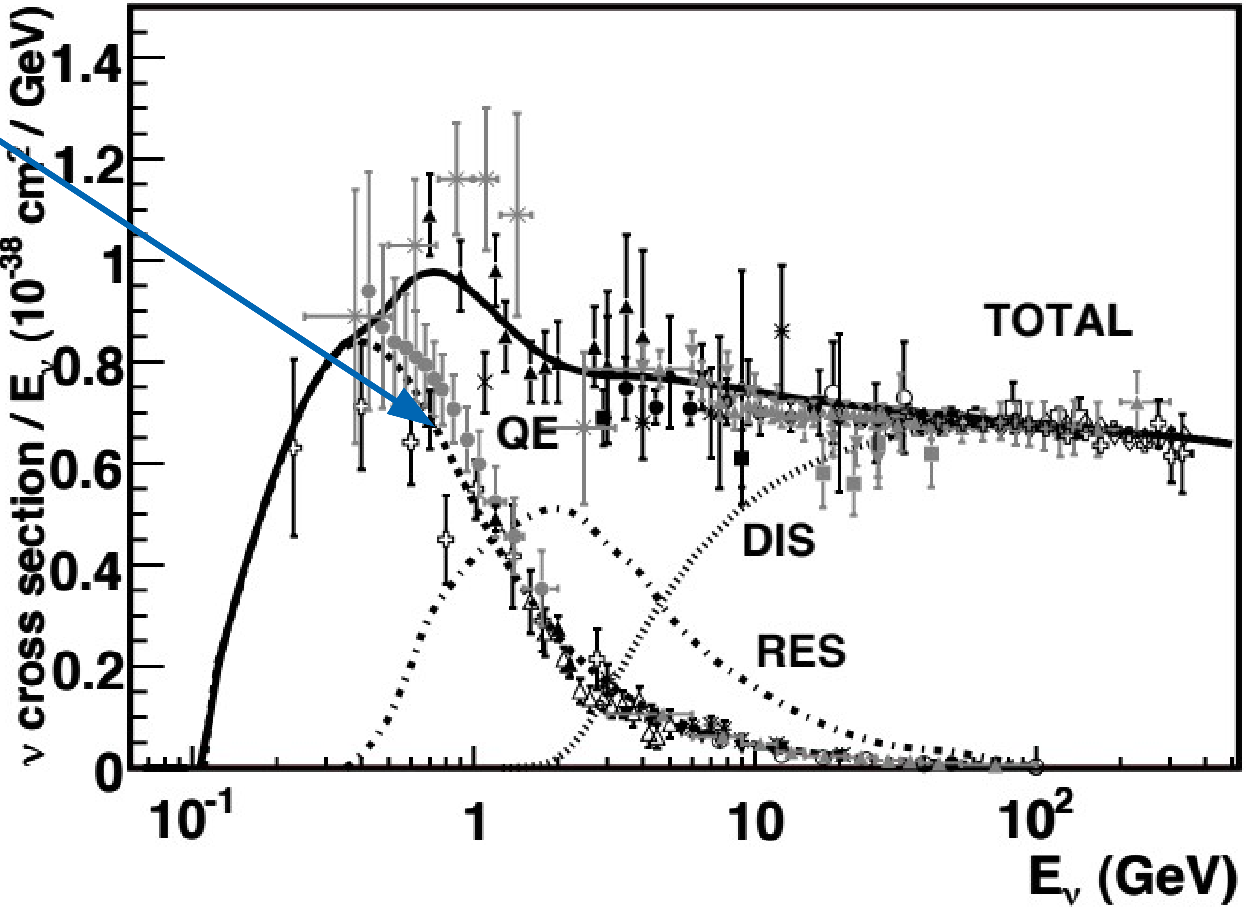


Particle Data Group

Quasi-elastic scattering:

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

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



Particle Data Group

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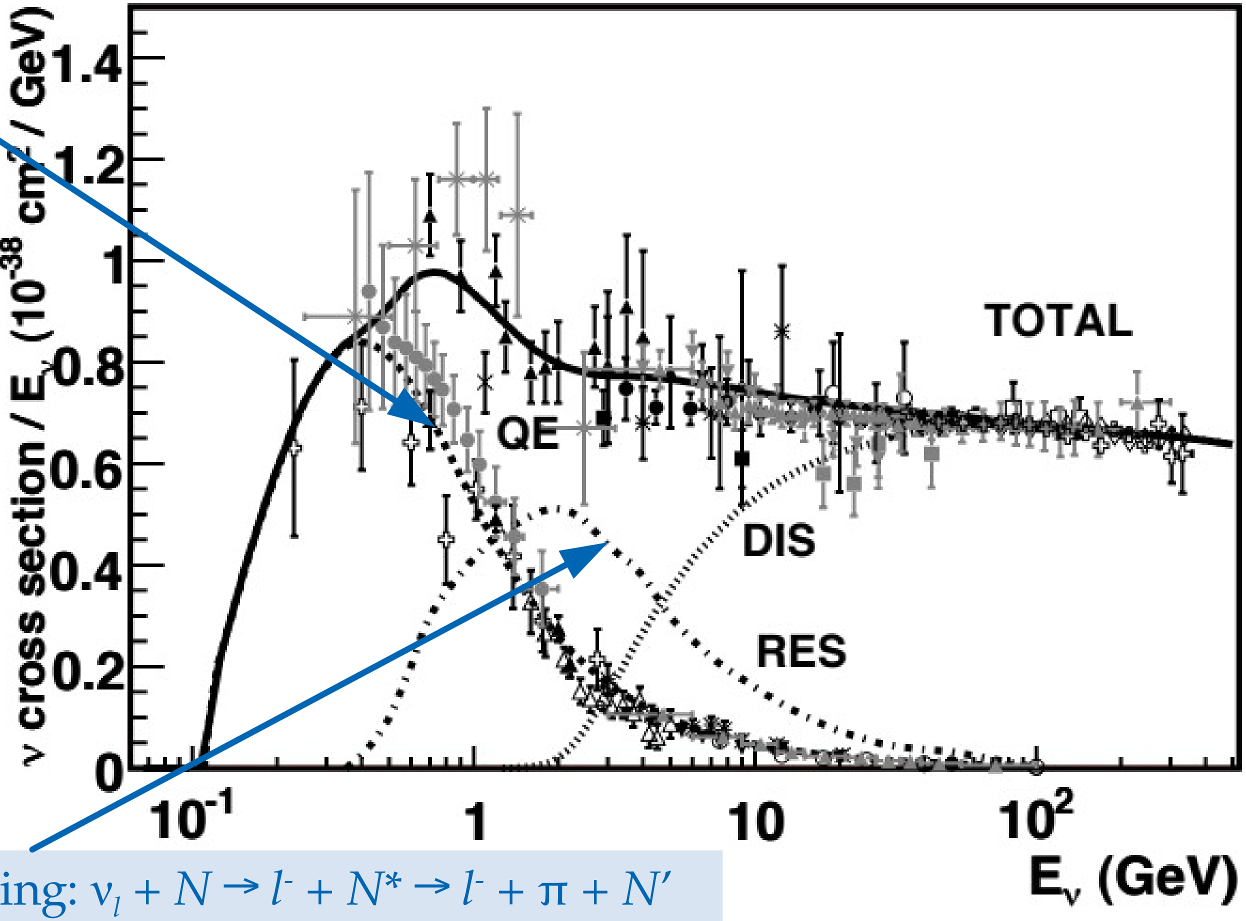


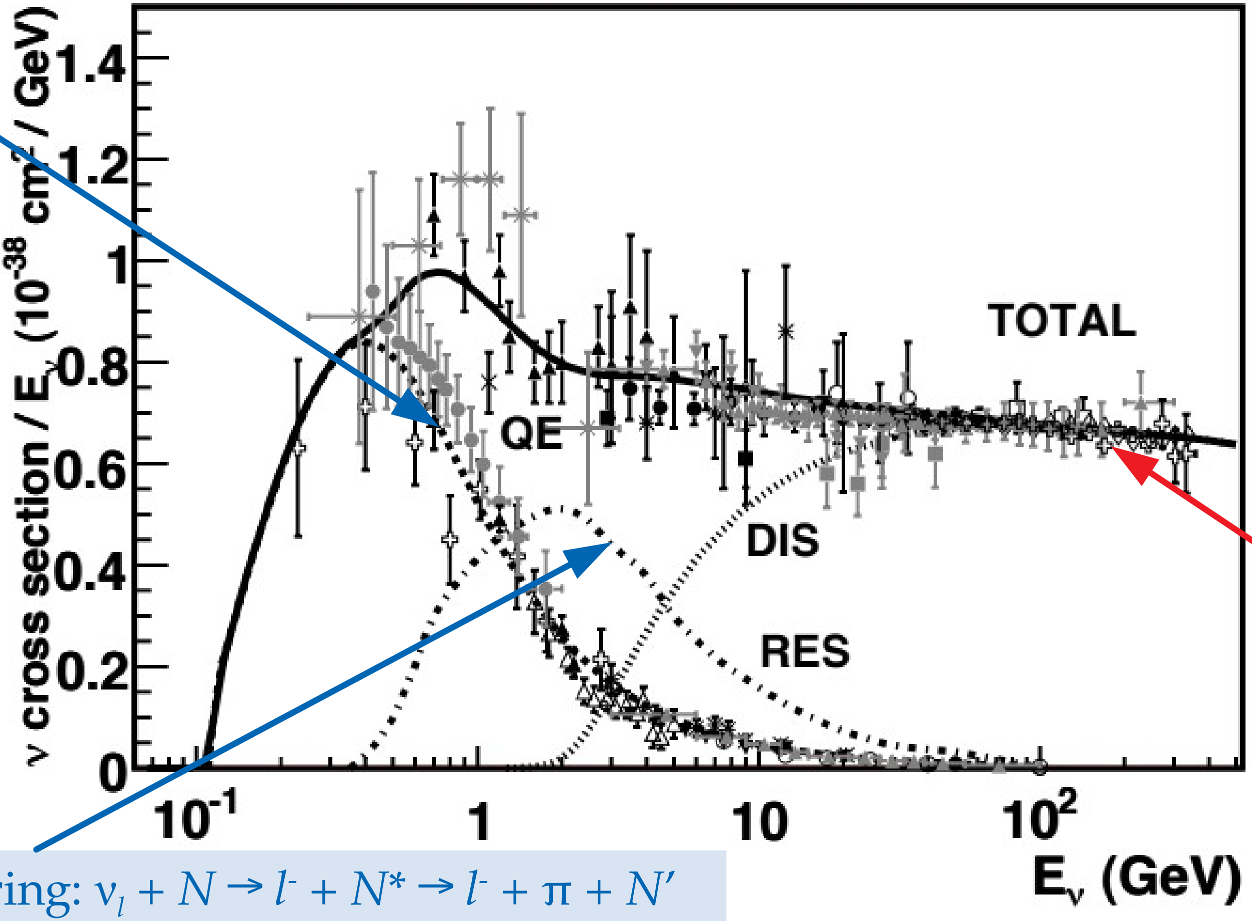
Resonant scattering: $\nu_l + N \rightarrow l^- + N^* \rightarrow l^- + \pi + N'$

Particle Data Group

Quasi-elastic scattering:

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

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



Deep inelastic scattering:

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

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

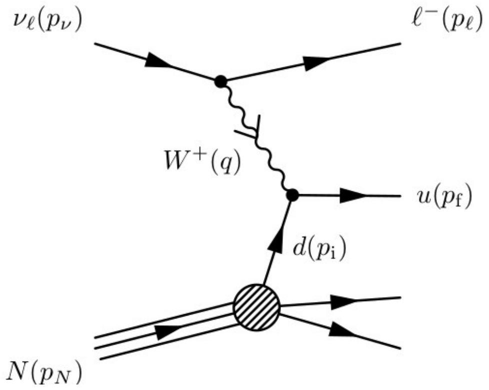
Resonant scattering: $\nu_l + N \rightarrow l^- + N^* \rightarrow l^- + \pi + N'$

Particle Data Group

Extrapolating the cross section to high energies

Extrapolating the cross section to high energies

From theory:
Standard Model
neutrino-quark
cross section



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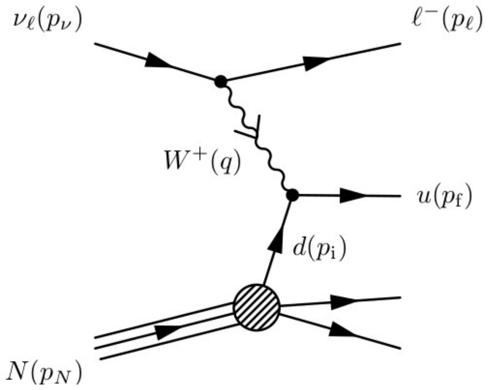
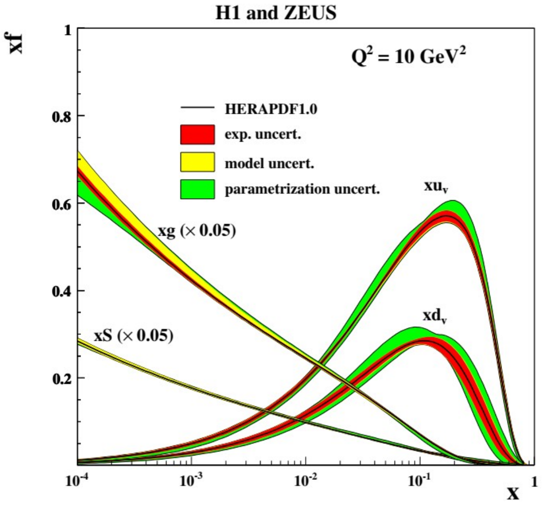


+

From colliders:
parton
distribution
functions



Extrapolating the cross section to high energies

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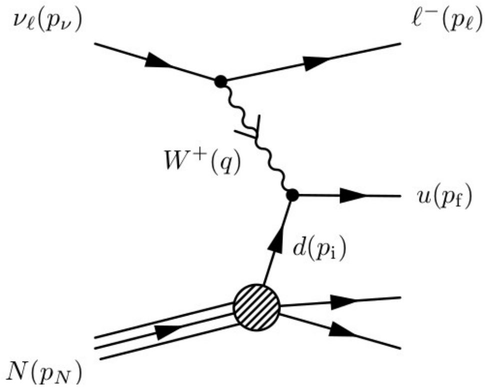

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From colliders:
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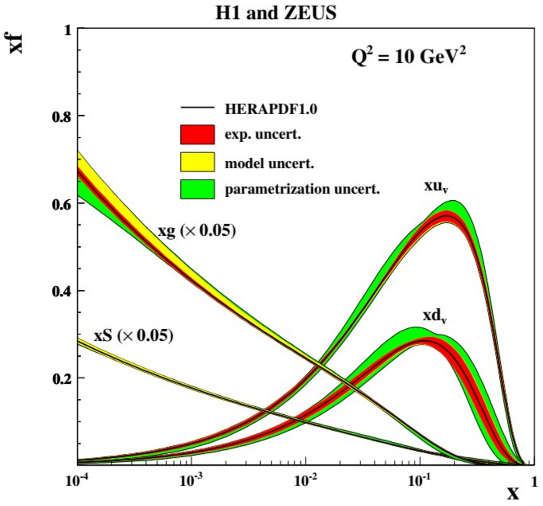

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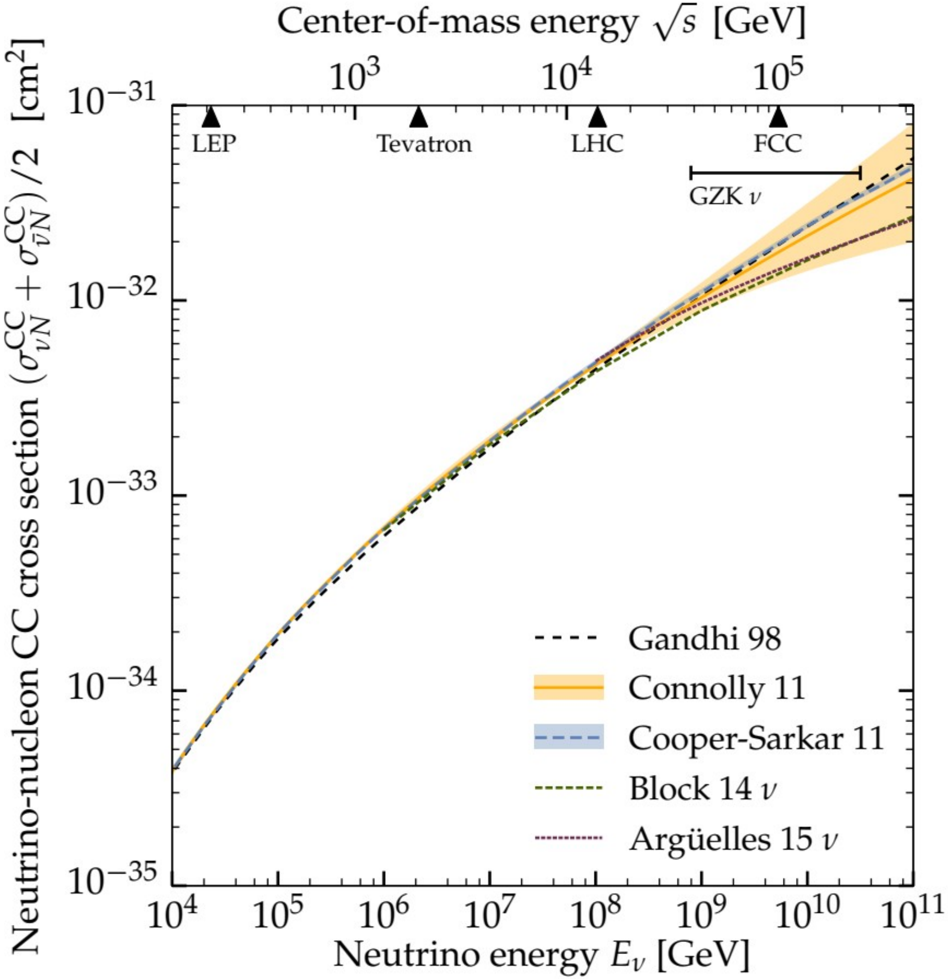

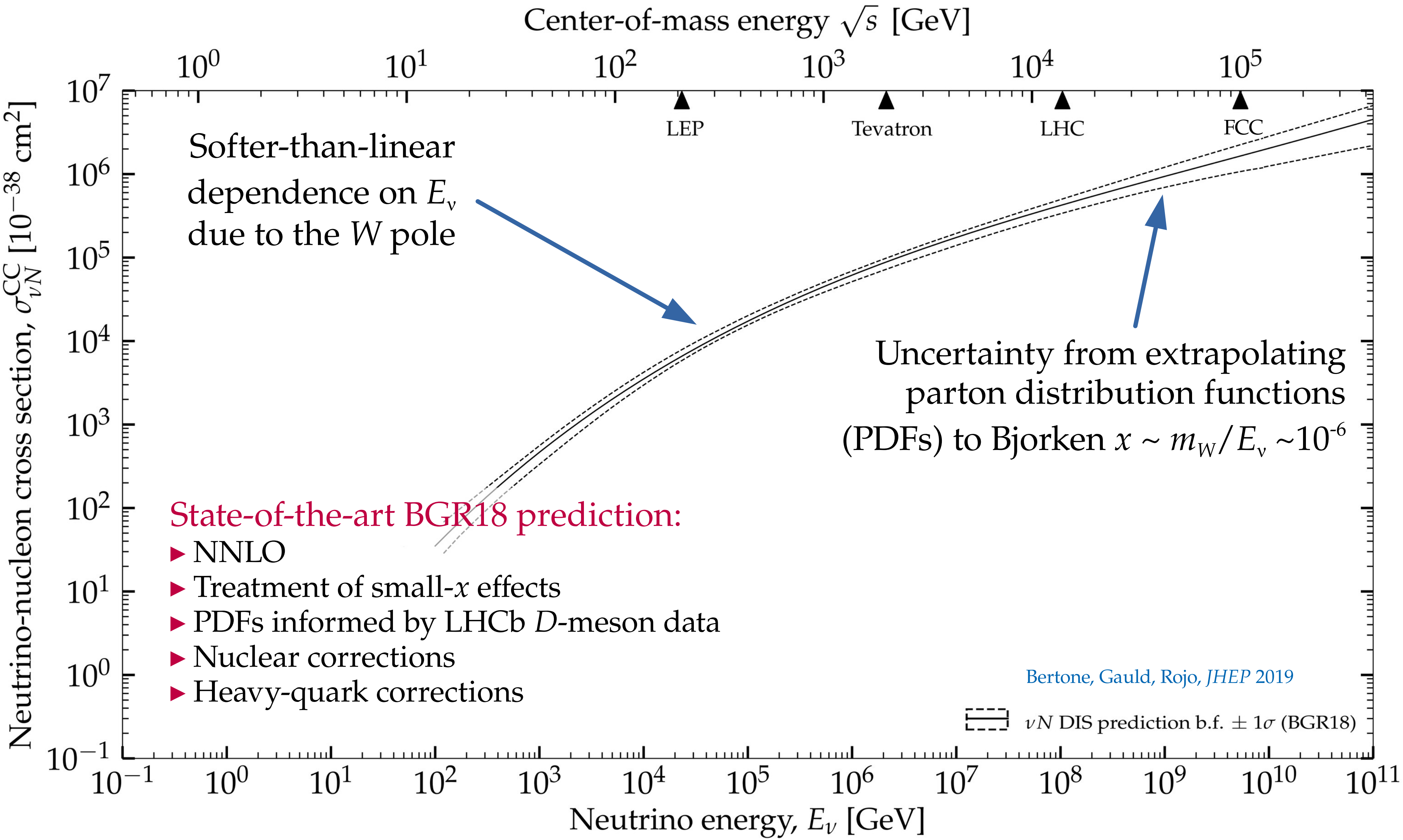

Center-of-mass energy $\sqrt{s}$ [GeV]
10^0 10^1 10^2 10^3 10^4 10^5
LEP
Tevatron
LHC
FCC
Softer-than-linear dependence on E_ν due to the W pole
Uncertainty from extrapolating parton distribution functions (PDFs) to Bjorken $x \sim m_W/E_\nu \sim 10^{-6}$
State-of-the-art BGR18 prediction:
▸ NNLO
▸ Treatment 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, $\sigma^{\rm CC}_{\nu N}$ [10^{-38} cm^2]
10^{-1} 10^0 10^1 10^2 10^3 10^4 10^5 10^6 10^7
Neutrino energy, E_ν [GeV]
10^{-1} 10^0 10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^{10} 10^{11}

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

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How? Use high-energy & ultra-high-energy cosmic neutrinos
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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

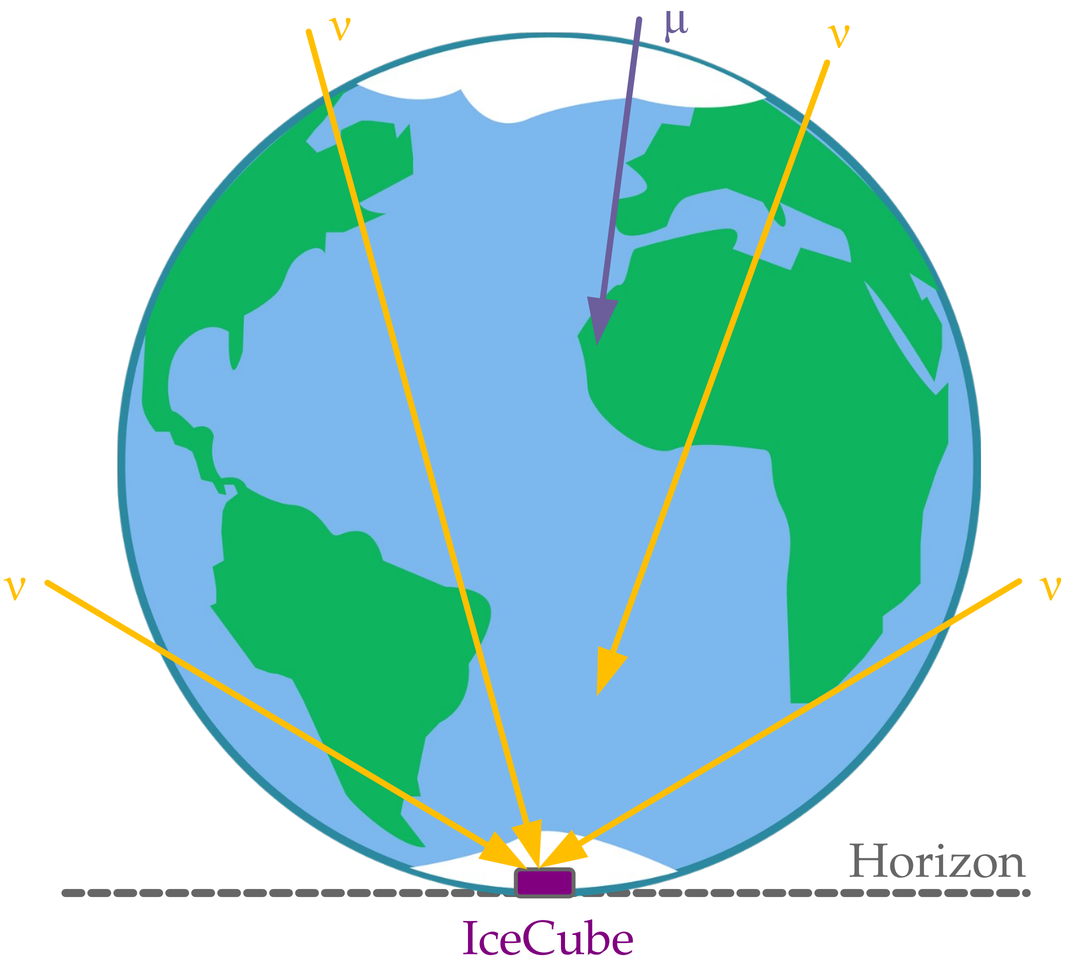
Why? Probe nucleons deeper than ever
Search for new high-energy physics

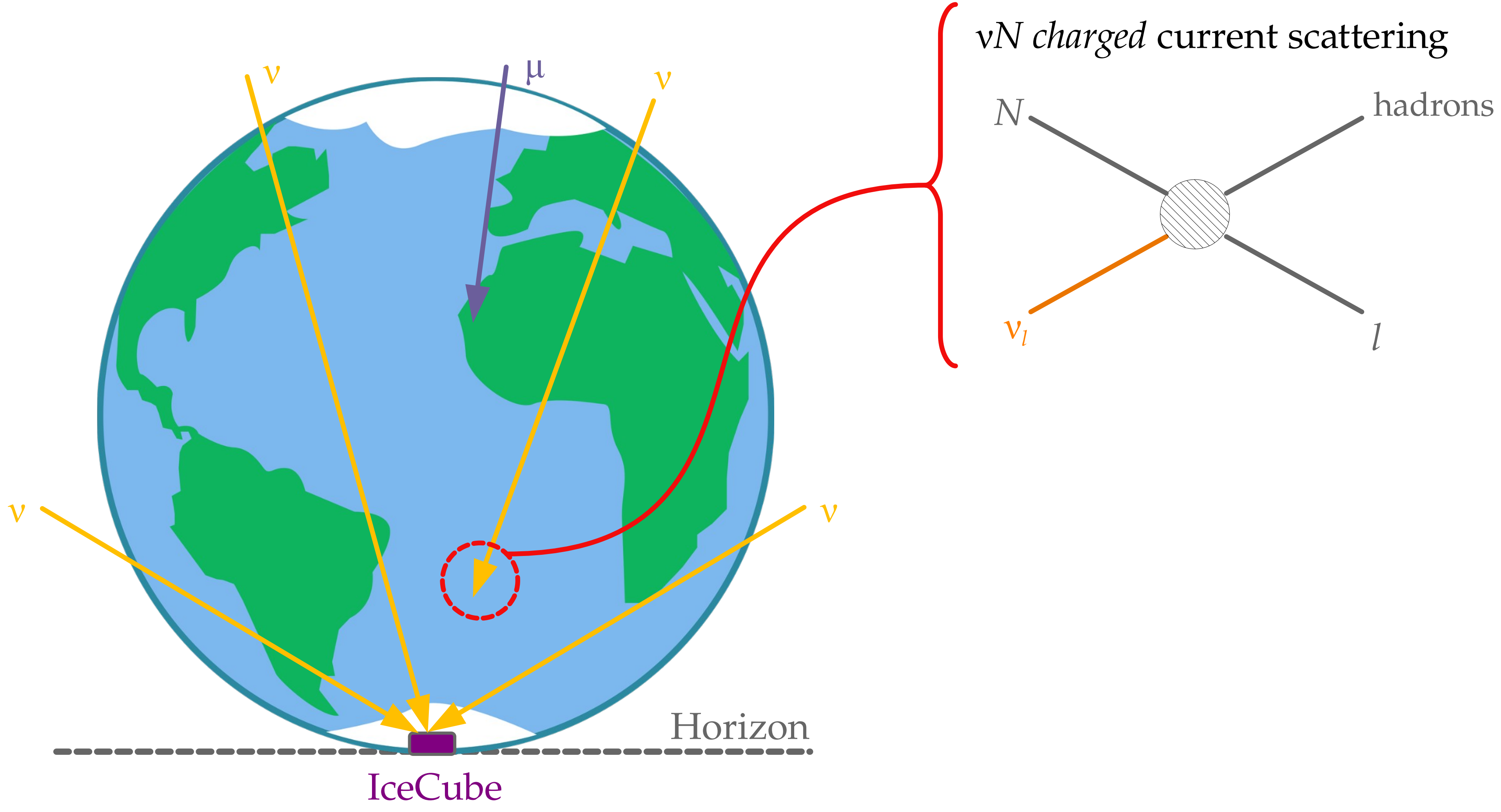
How? Use high-energy & ultra-high-energy cosmic neutrinos
Use the Earth as target

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

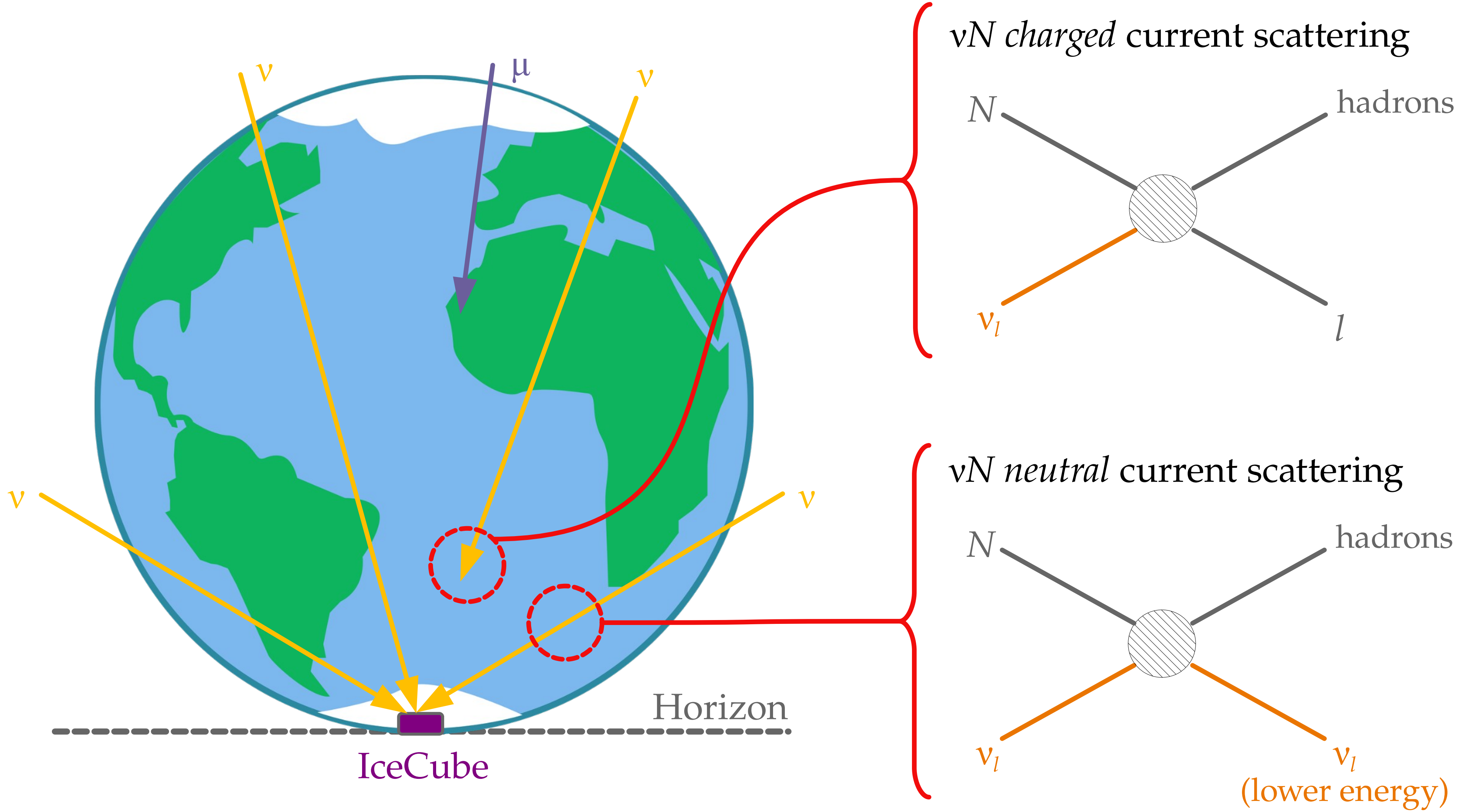
Why hard? Limited event statistics
At UHE, need to have decent angular resolution (~2°)

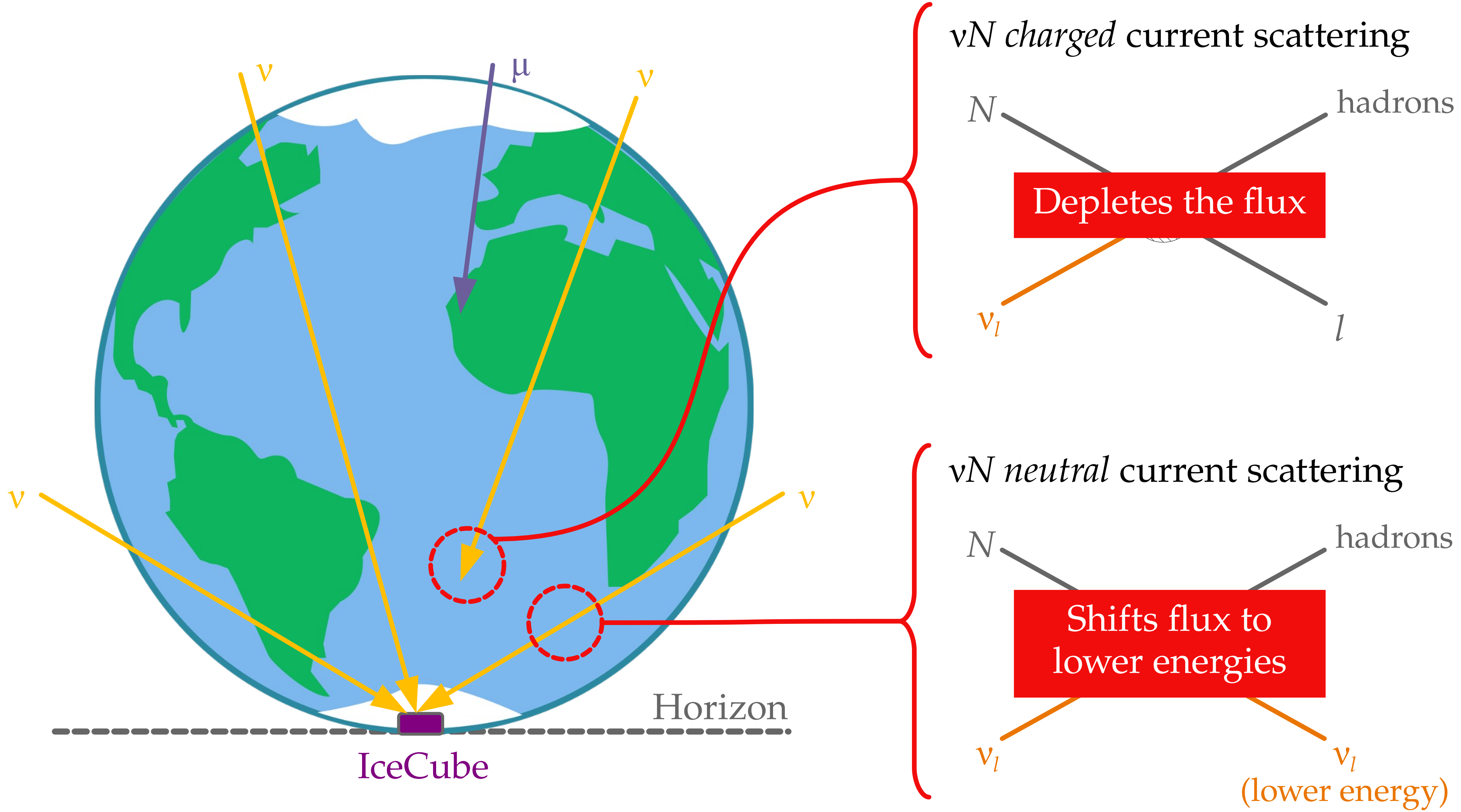
† Fingers crossed


ν
μ
ν
ν
ν
Horizon
IceCube



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


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


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

Number of detected neutrinos (simplified for presentation):

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

Neutrino flux   Cross section

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

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Downgoing neutrinos
(L short → no matter)

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

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

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Downgoing neutrinos
(L short $\rightarrow$ no matter)

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

Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
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Measuring the high-energy νN cross section

Number of detected neutrinos (simplified for presentation):

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Downgoing neutrinos
(L short → no matter)

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

Upgoing neutrinos
(L long → lots of matter)

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

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

Measuring the high-energy νN cross section

Number of detected neutrinos (simplified for presentation):

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

Downgoing neutrinos
(L short → no matter)

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

Upgoing neutrinos
(L long → lots of matter)

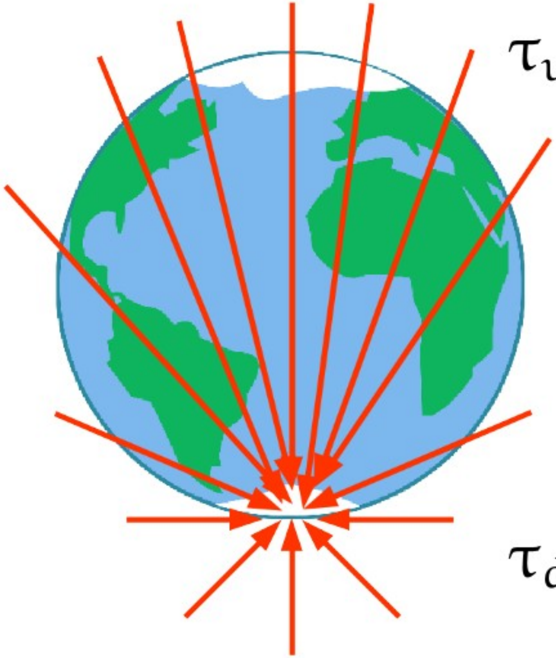
$$N \propto \Phi_\nu \sigma_{\nu N} \underbrace{e^{-L \sigma_{\nu N} n_N}}_{\text{Breaks the degeneracy}}$$

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

Measuring the high-energy νN cross section

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

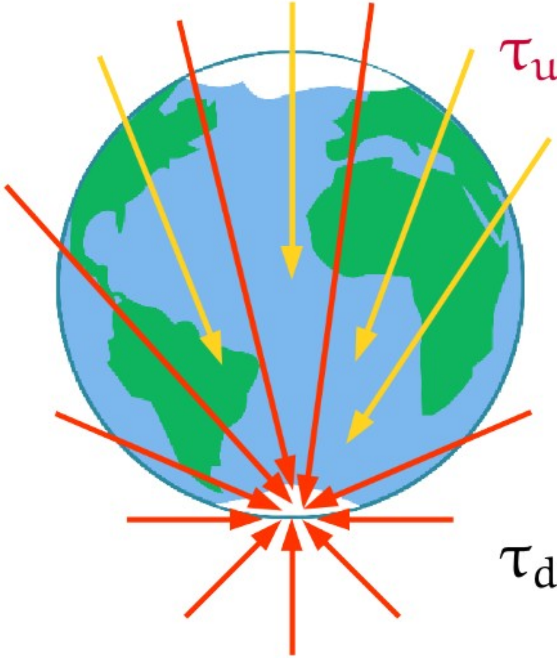
Below ~ 10 TeV: Earth is transparent



$\tau_{up} \ll 1$

$\tau_{dn} \ll 1$

Above ~ 10 TeV: Earth is opaque



$\tau_{up} \sim 1$

$\tau_{dn} \ll 1$

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

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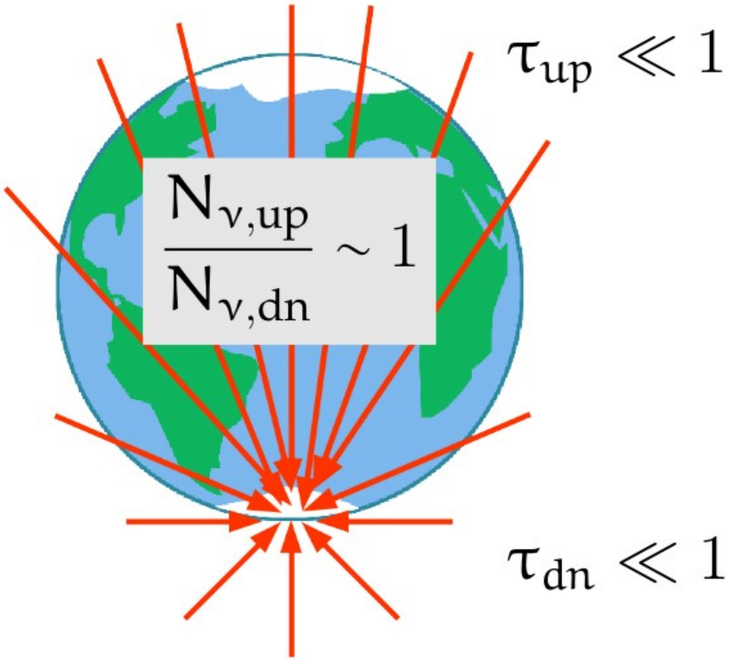

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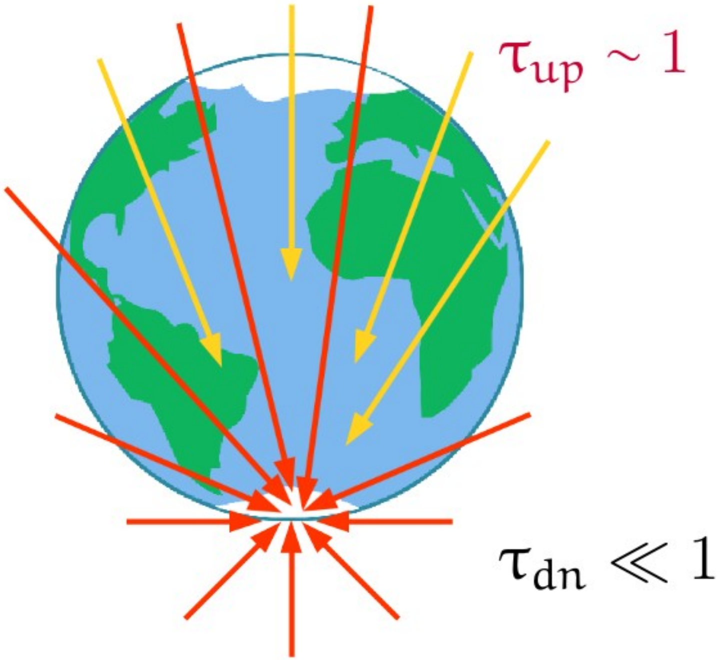

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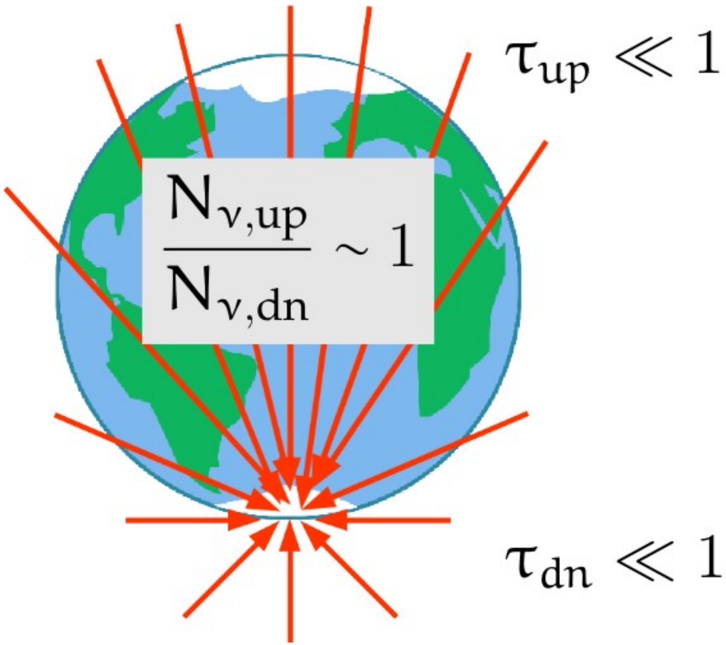

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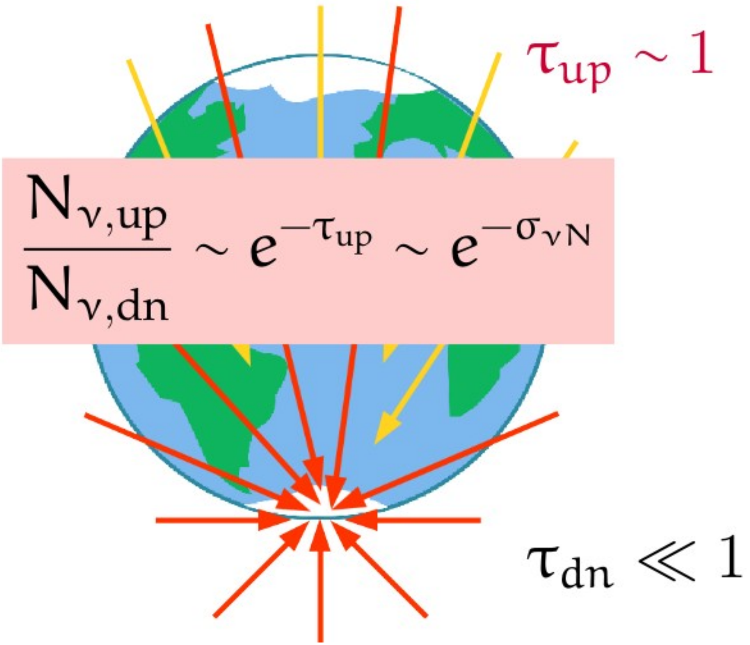

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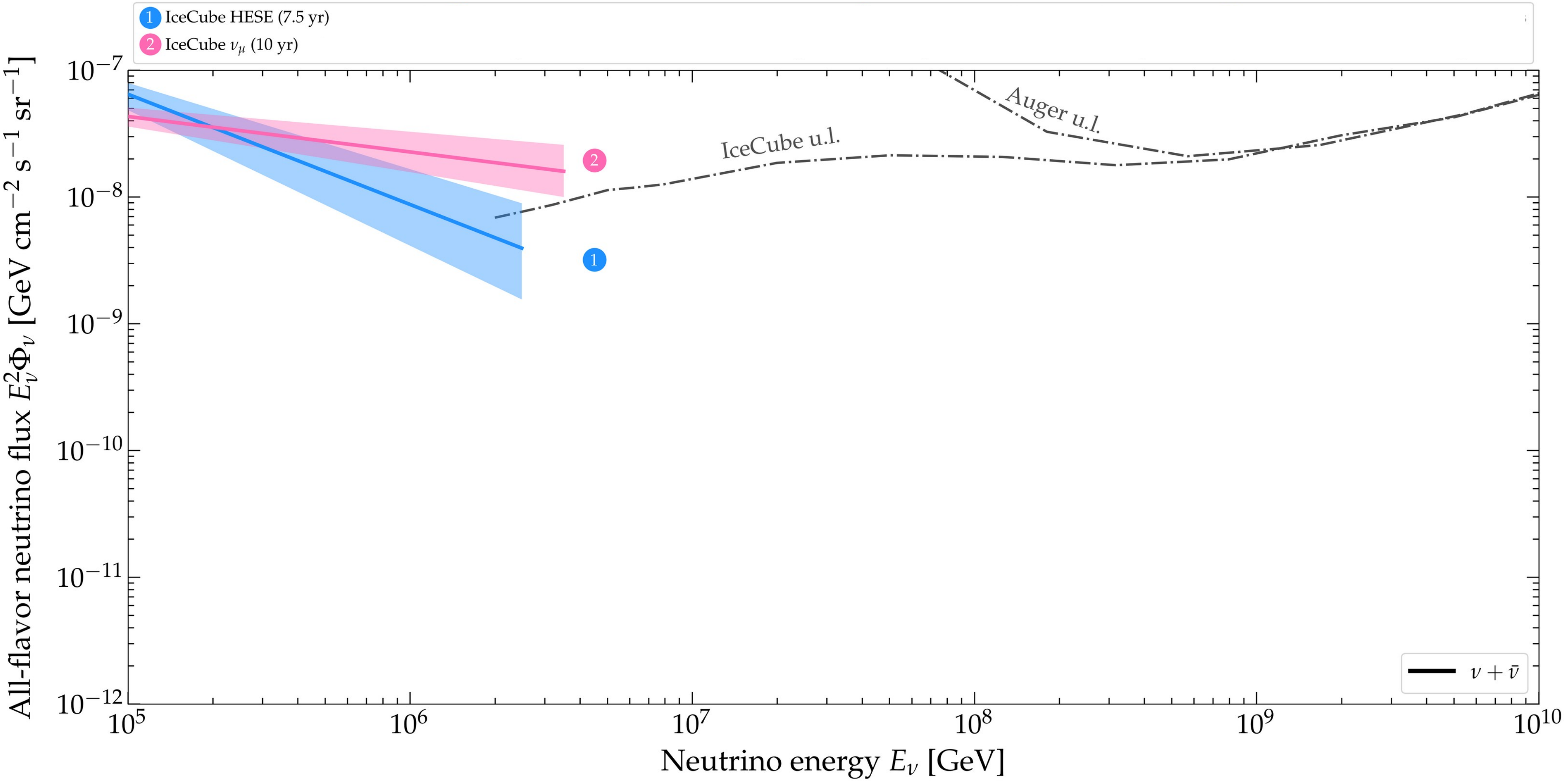
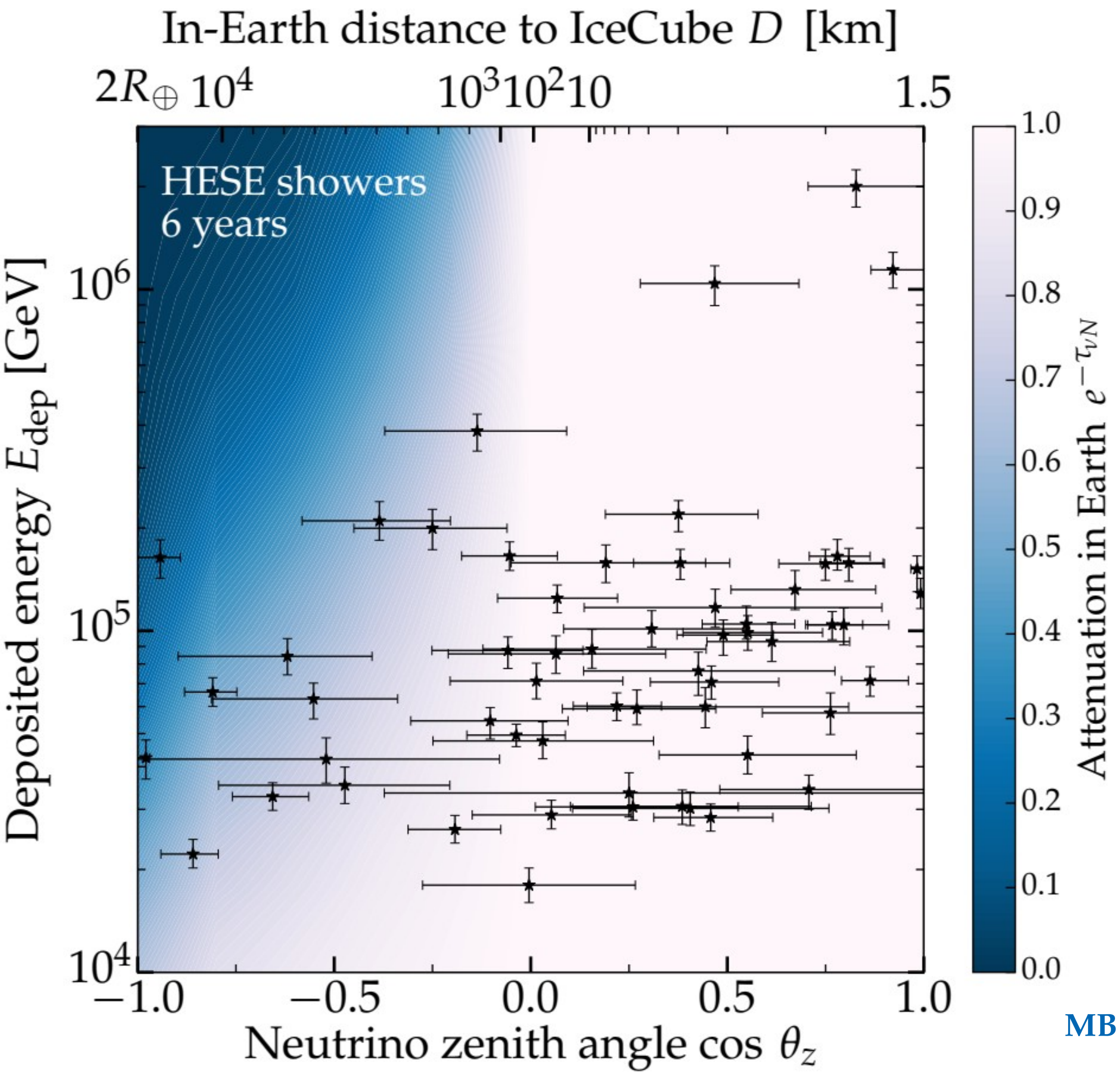
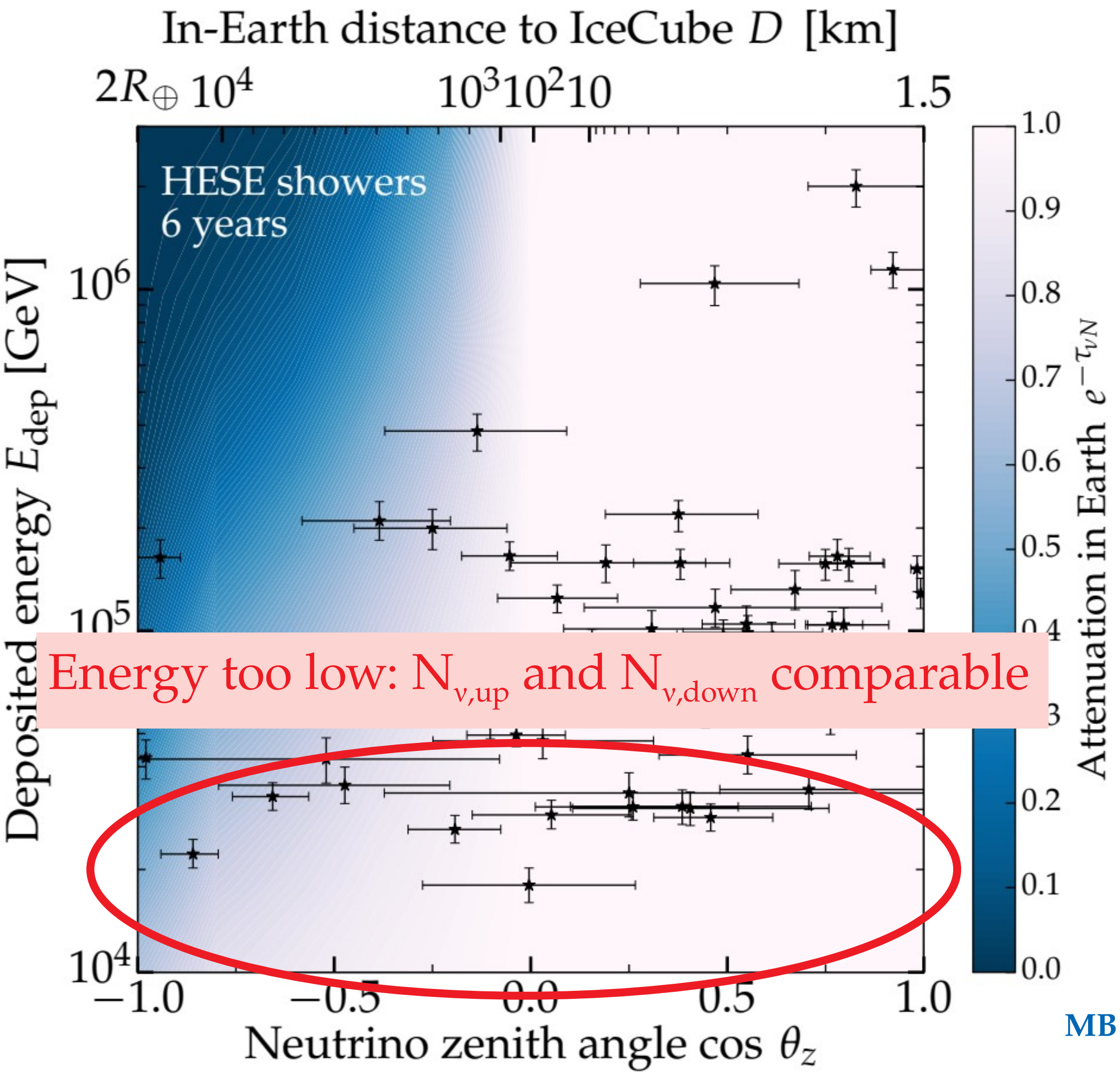


1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (10 yr)
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
Auger u.l.
IceCube u.l.
2
1
$\nu + \bar{\nu}$
10^5
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy E_ν [GeV]



MB & Connolly, *PRL* 2019



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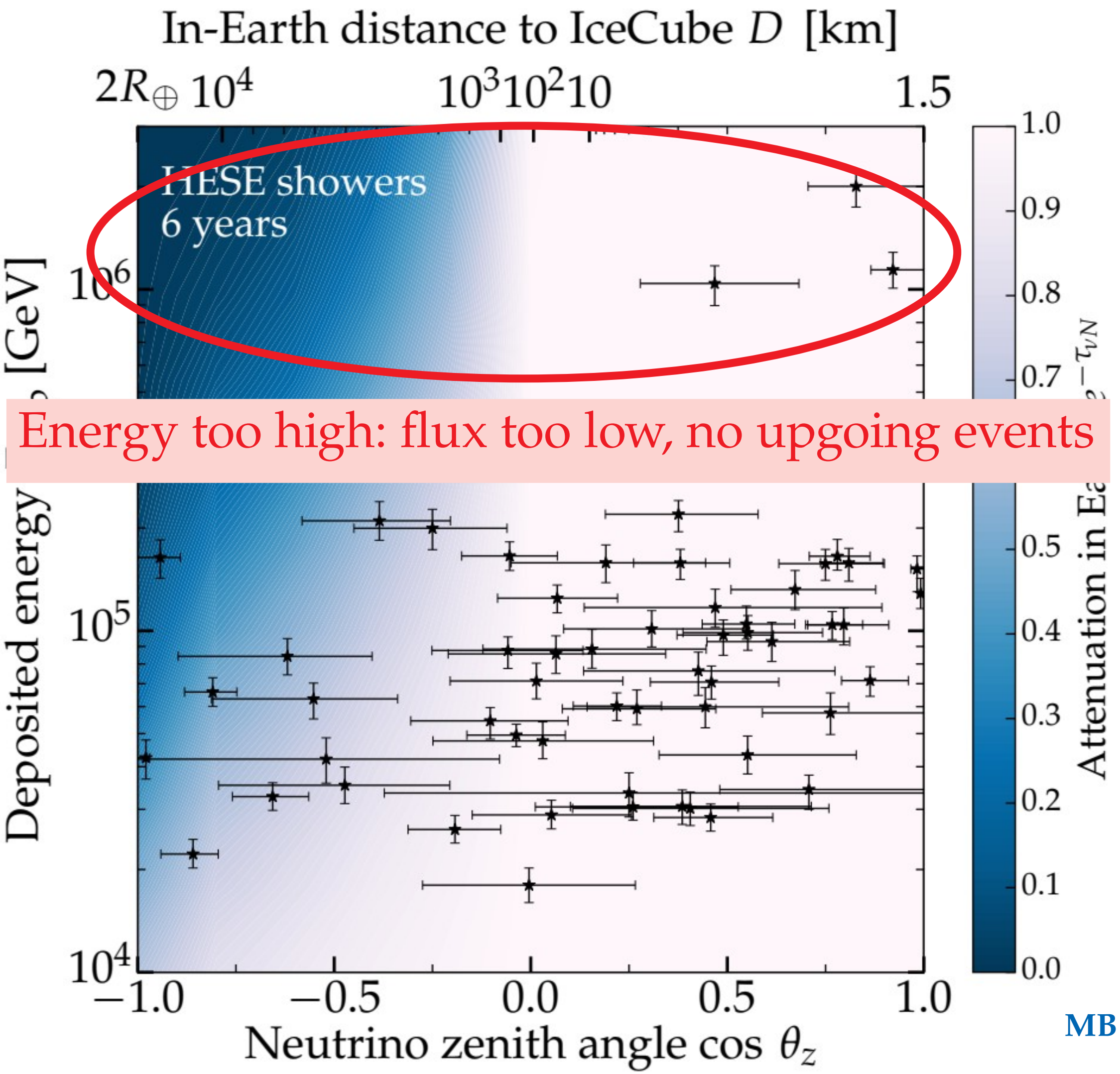

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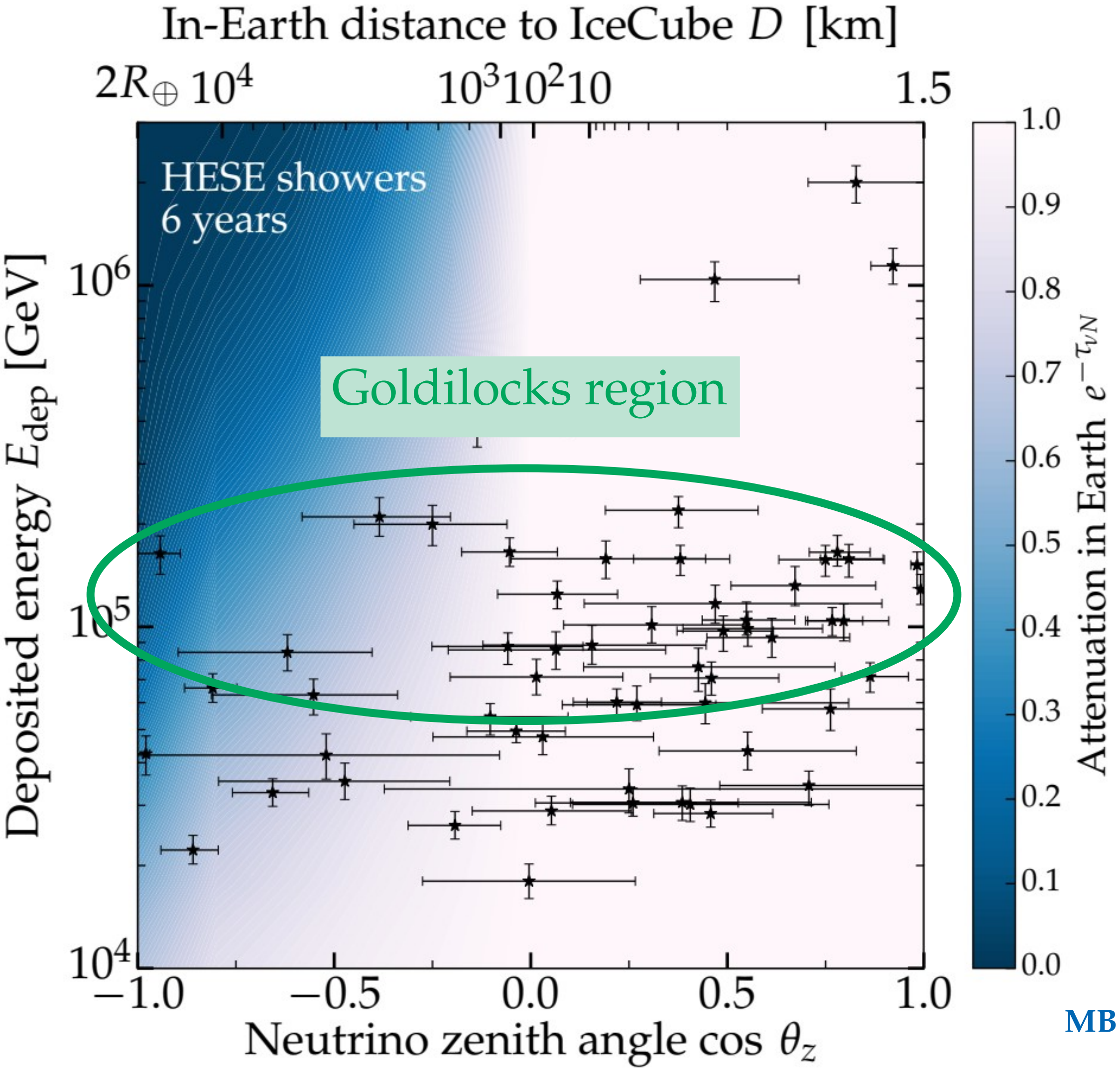
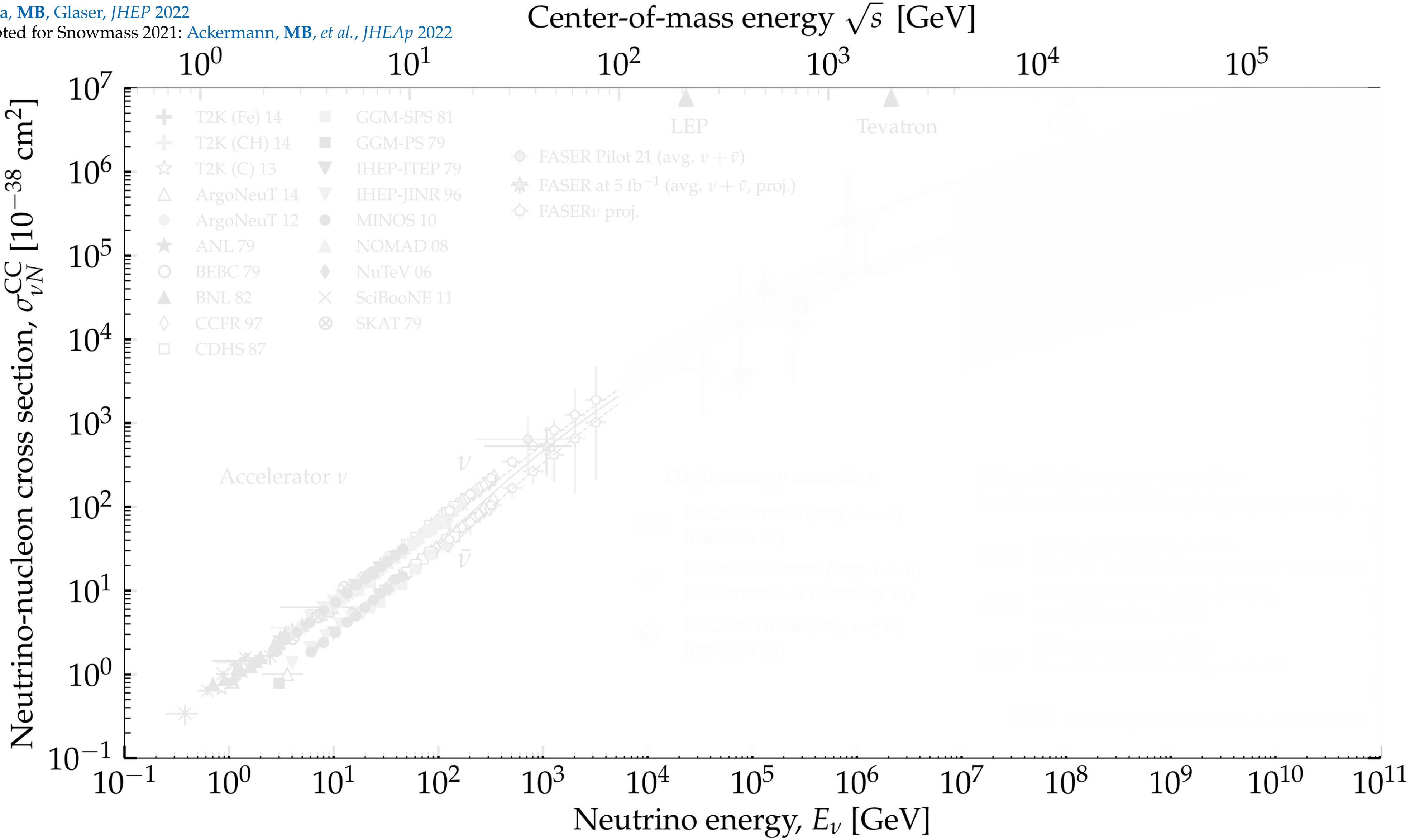
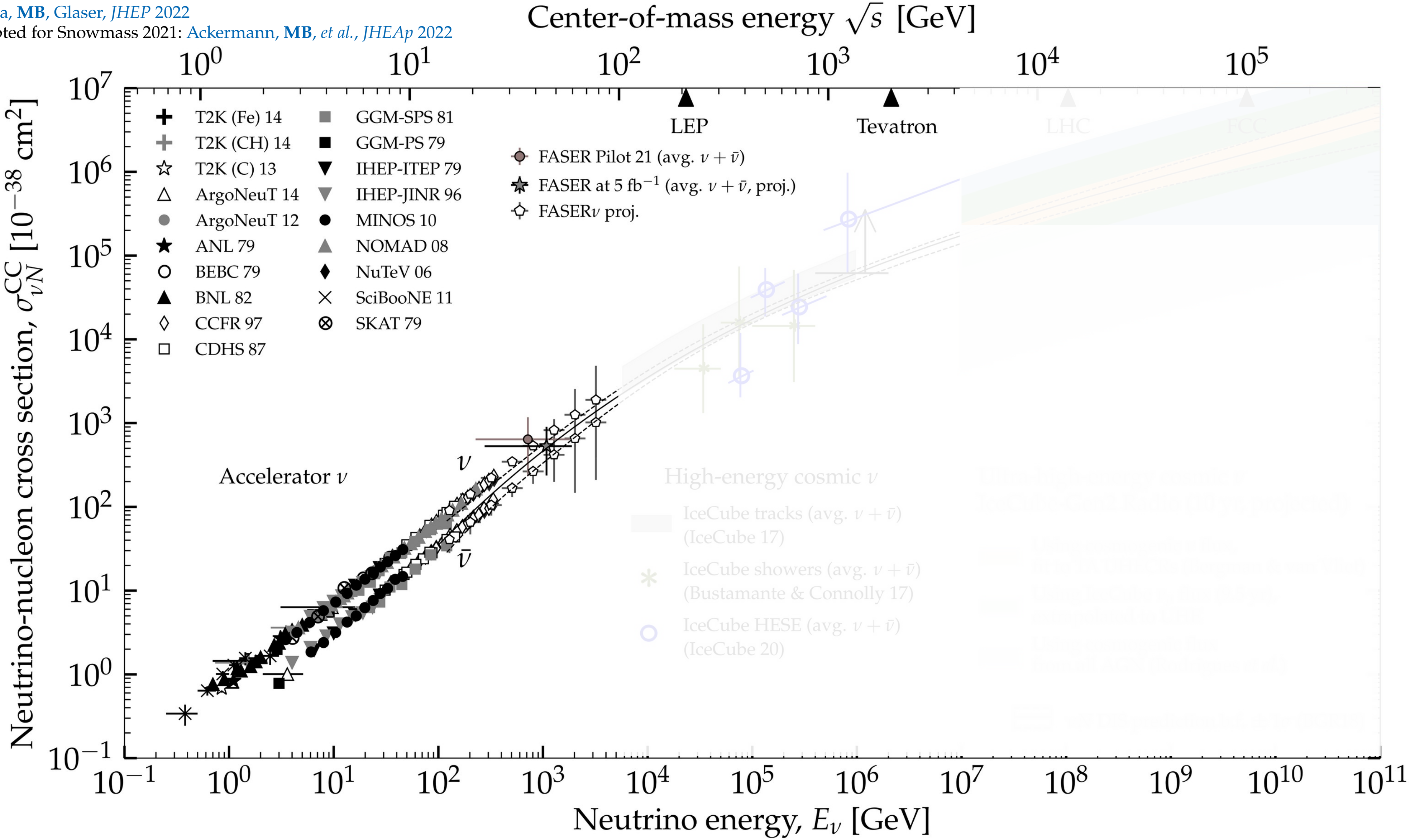


MB & Connolly, *PRL* 2019

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



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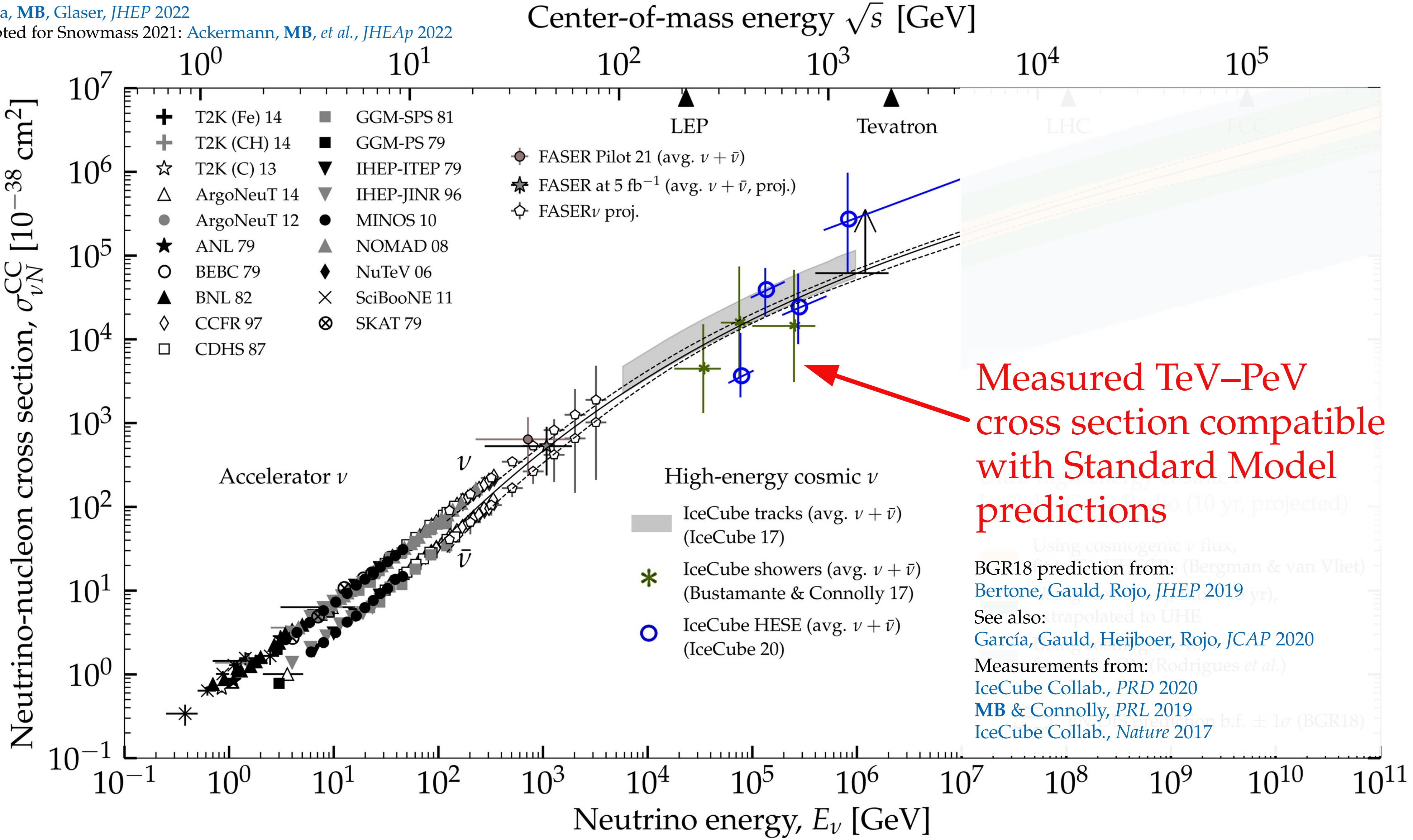


Bonus: Measuring the inelasticity $\langle y \rangle$

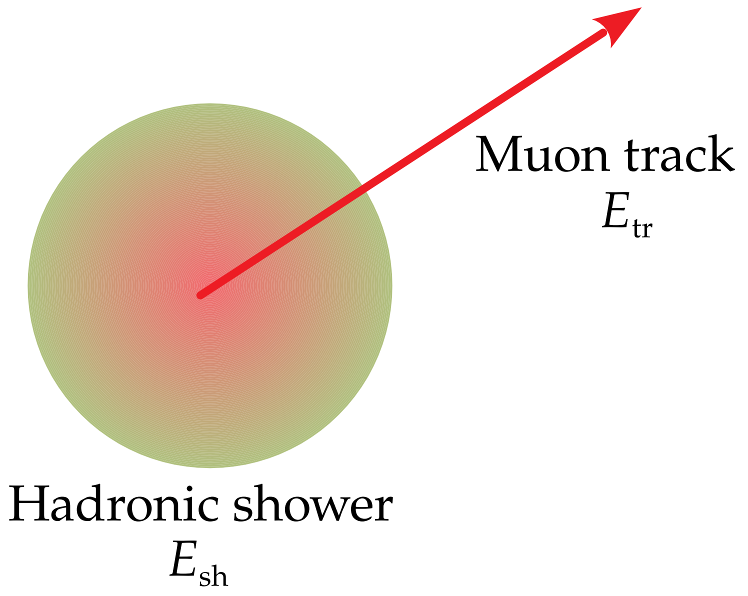
- Inelasticity in CC ν_μ interaction $\nu_\mu + N \rightarrow \mu + X$:

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

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

- In a HESE starting track:

  $E_X = E_{sh}$ (energy of shower)
  $E_\mu = E_{tr}$ (energy of track)
  $\Big\}\; y = (1 + E_{tr}/E_{sh})^{-1}$



IceCube Collab., *PRD* 2019

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

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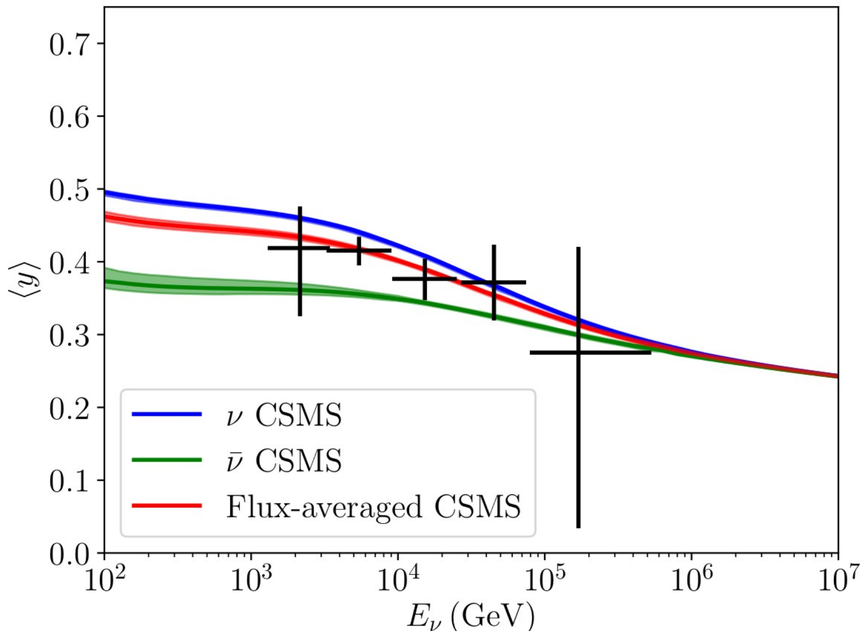

IceCube Collab., *PRD* 2019

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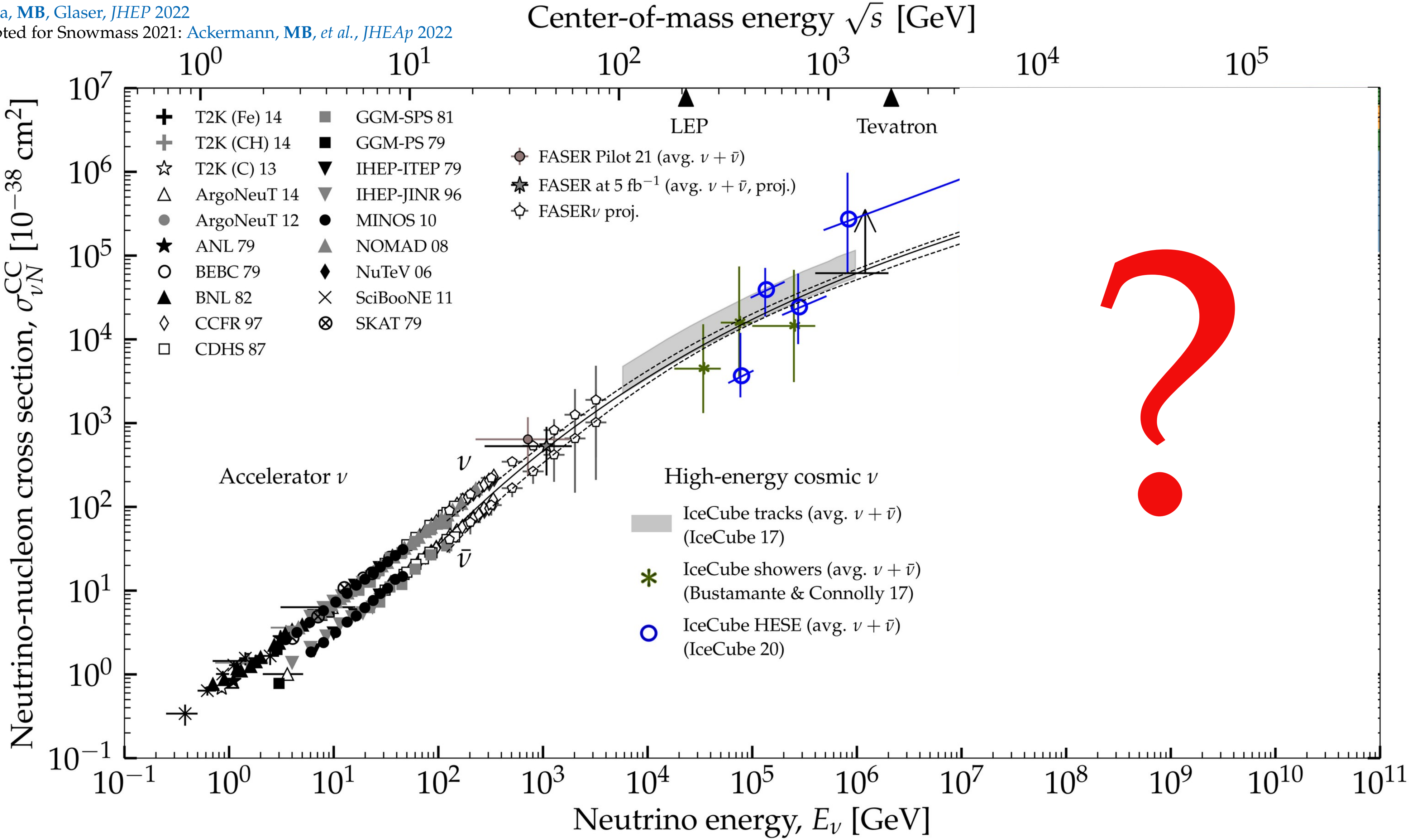
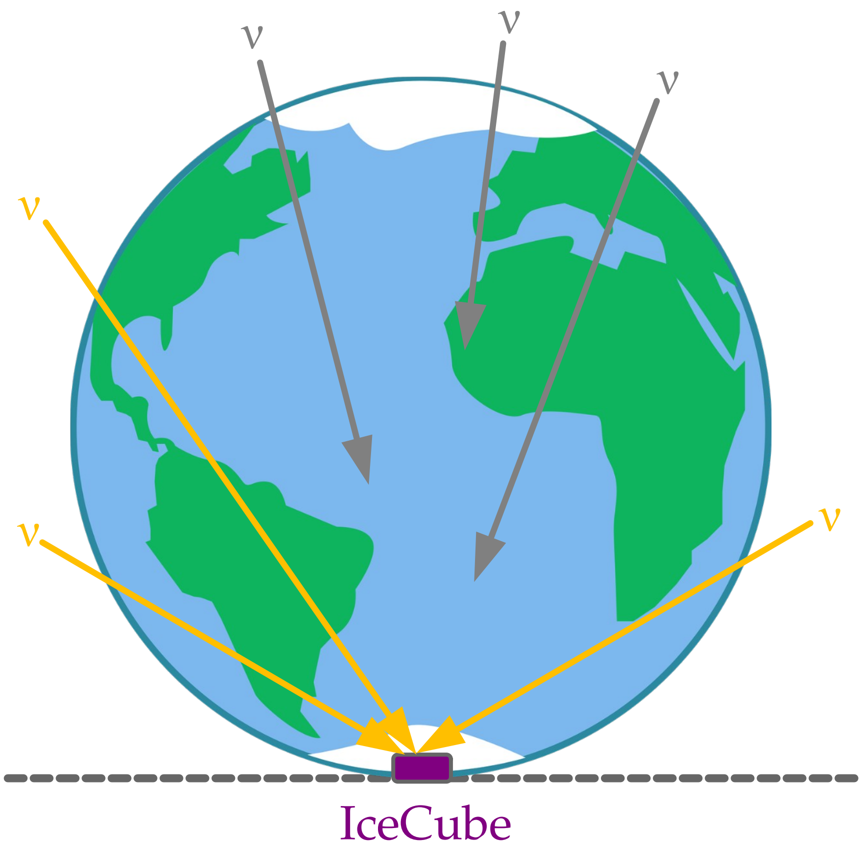
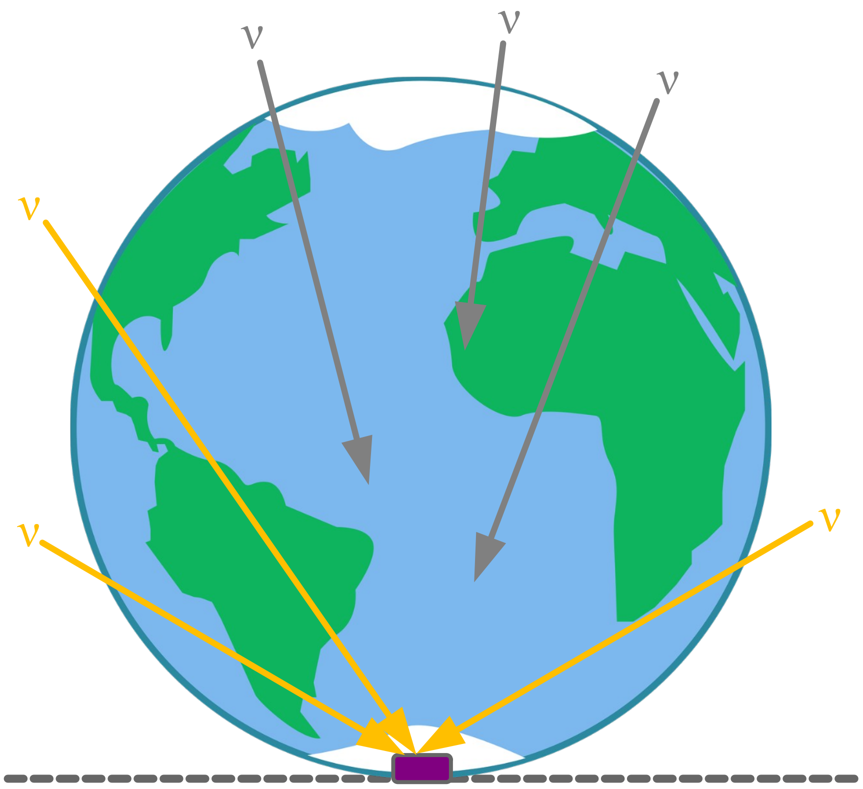


TeV–PeV:



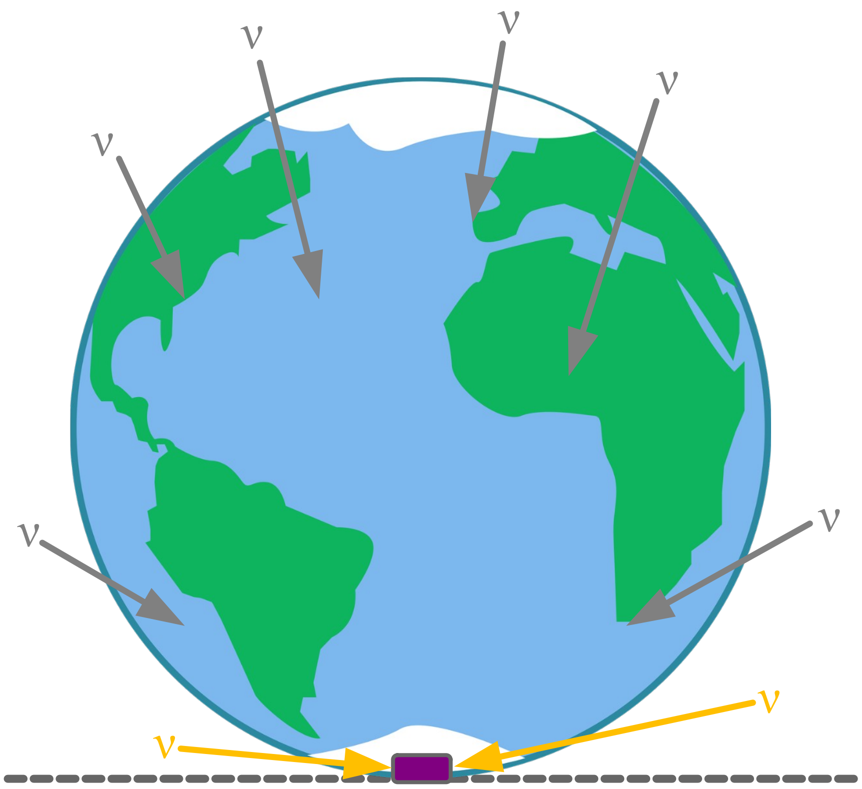
Earth is *almost fully* opaque,
some upgoing ν still make it through

TeV–PeV:



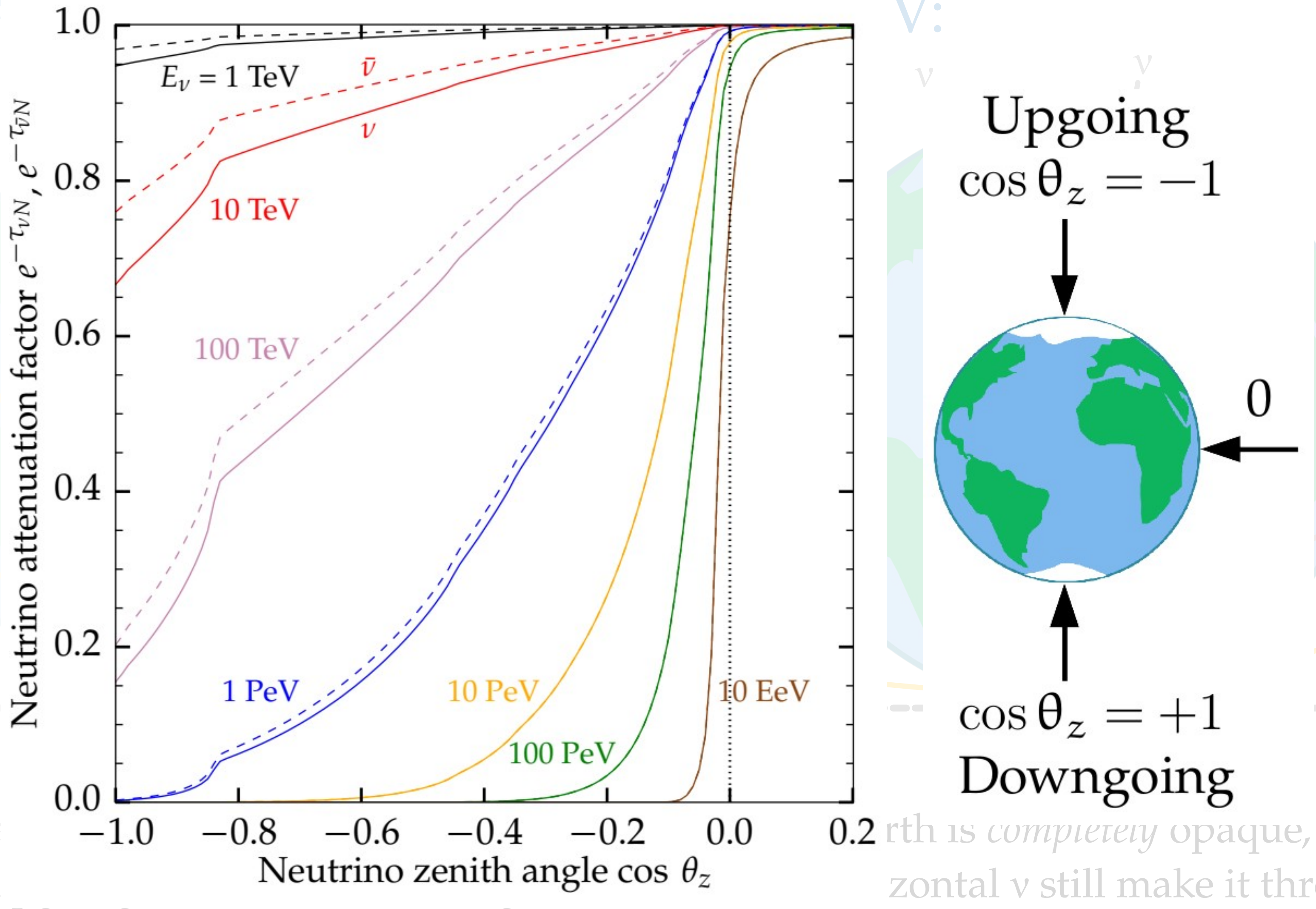
Earth is *almost fully* opaque,
some upgoing ν still make it through

$>$ 100 PeV:



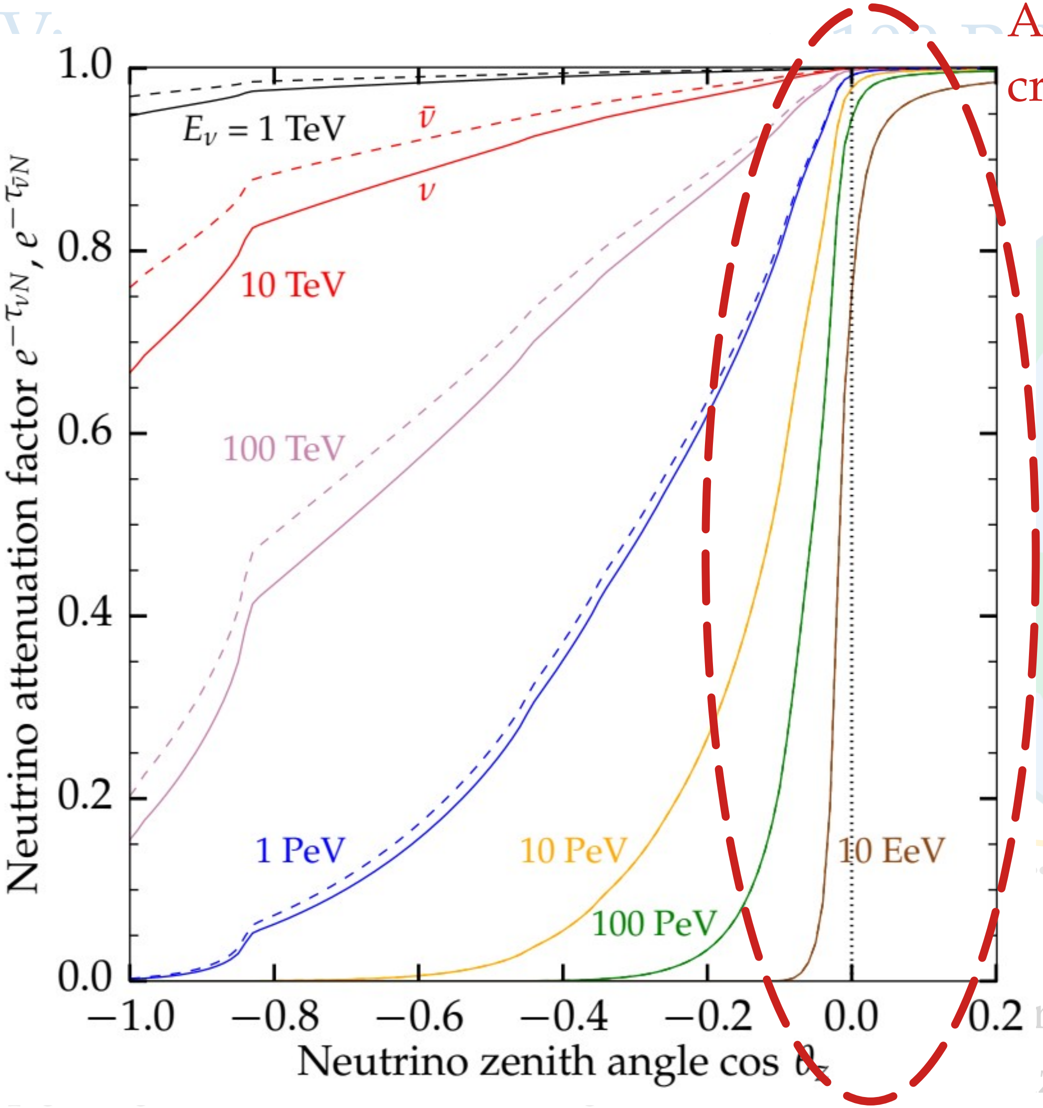
Earth is *completely* opaque,
but horizontal ν still make it through

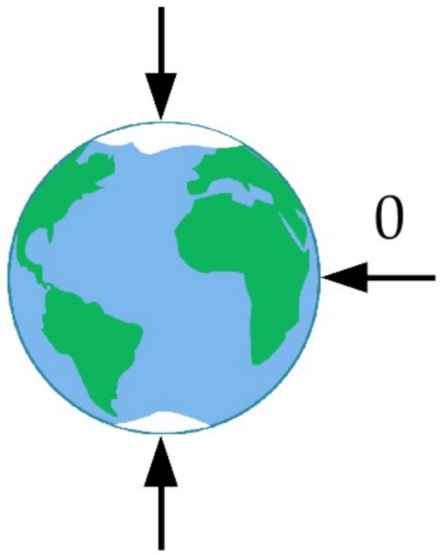
TeV–PeV ... V:

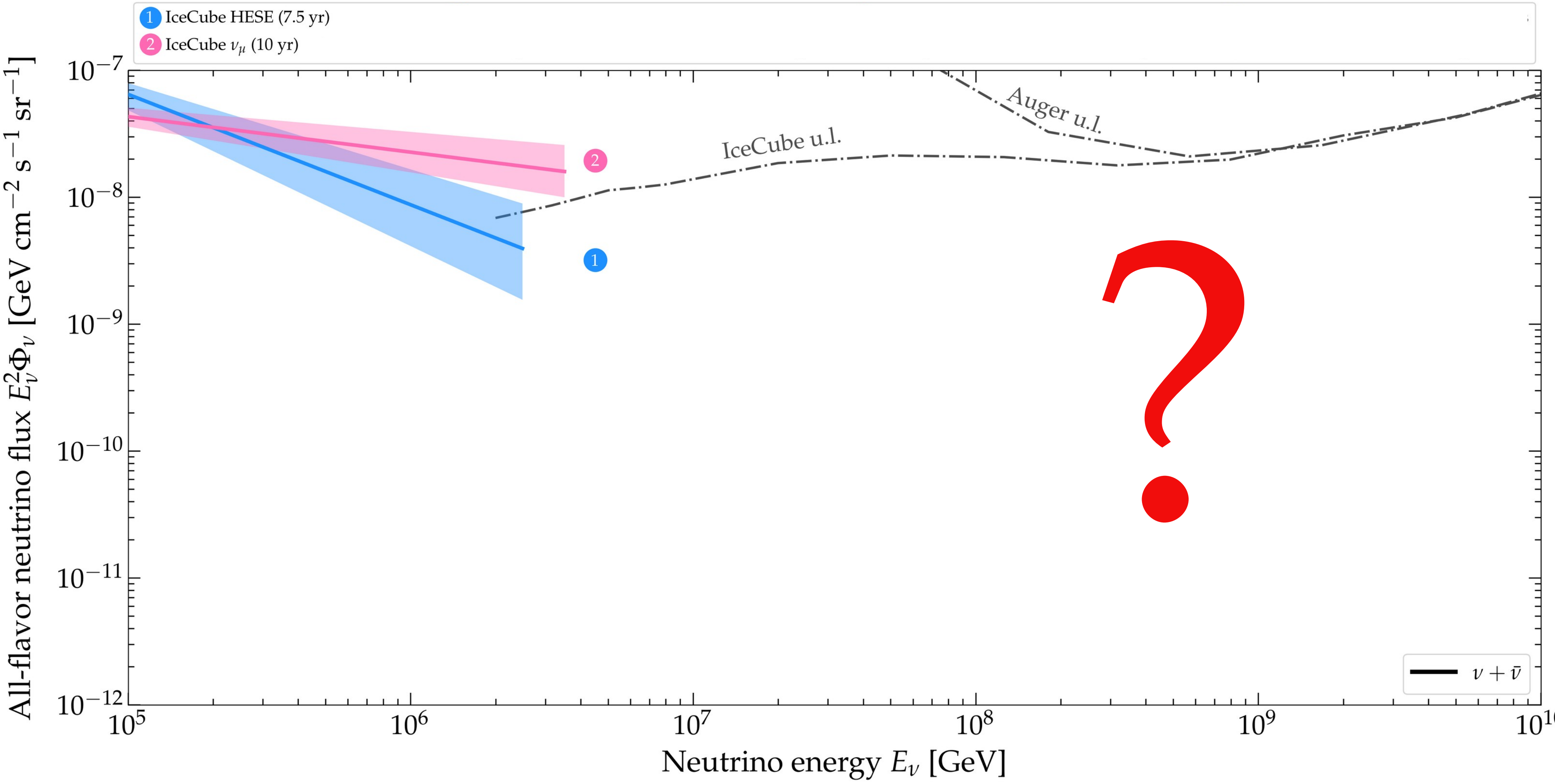


Ea ... rth is *completely* opaque,
some ... zontal ν still make it through

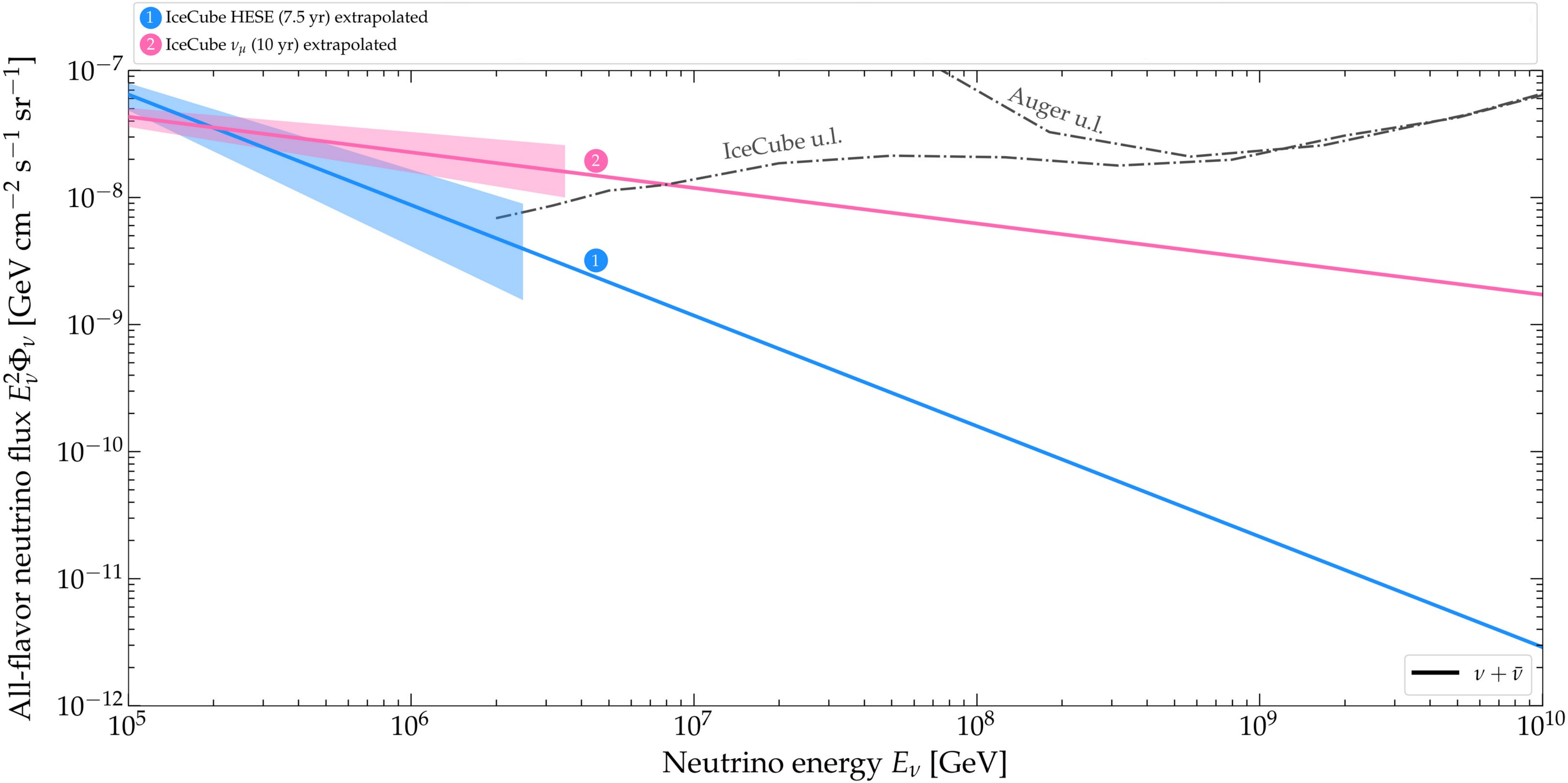
At UHE, we can only extract the cross section using horizontal ν



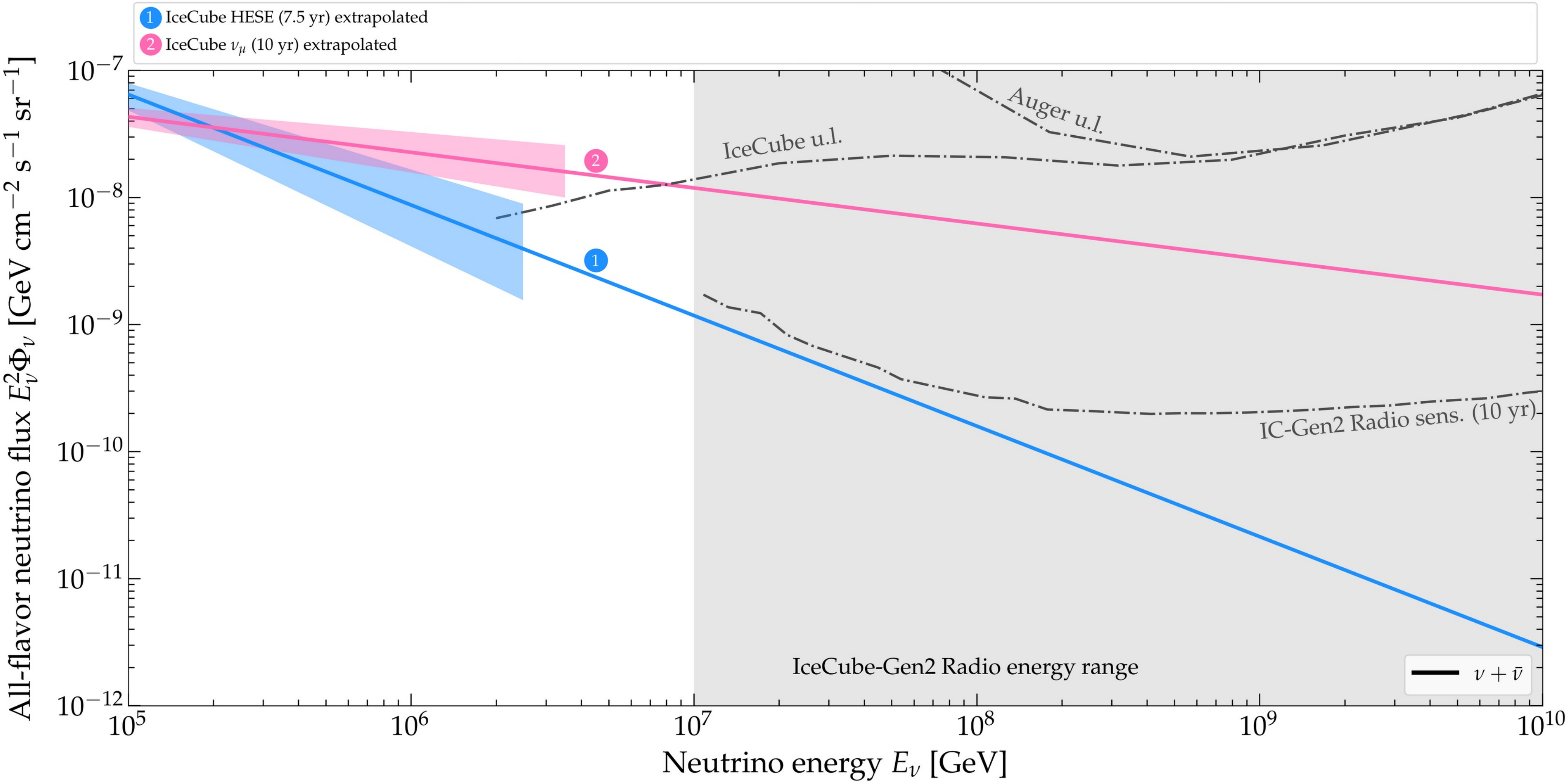




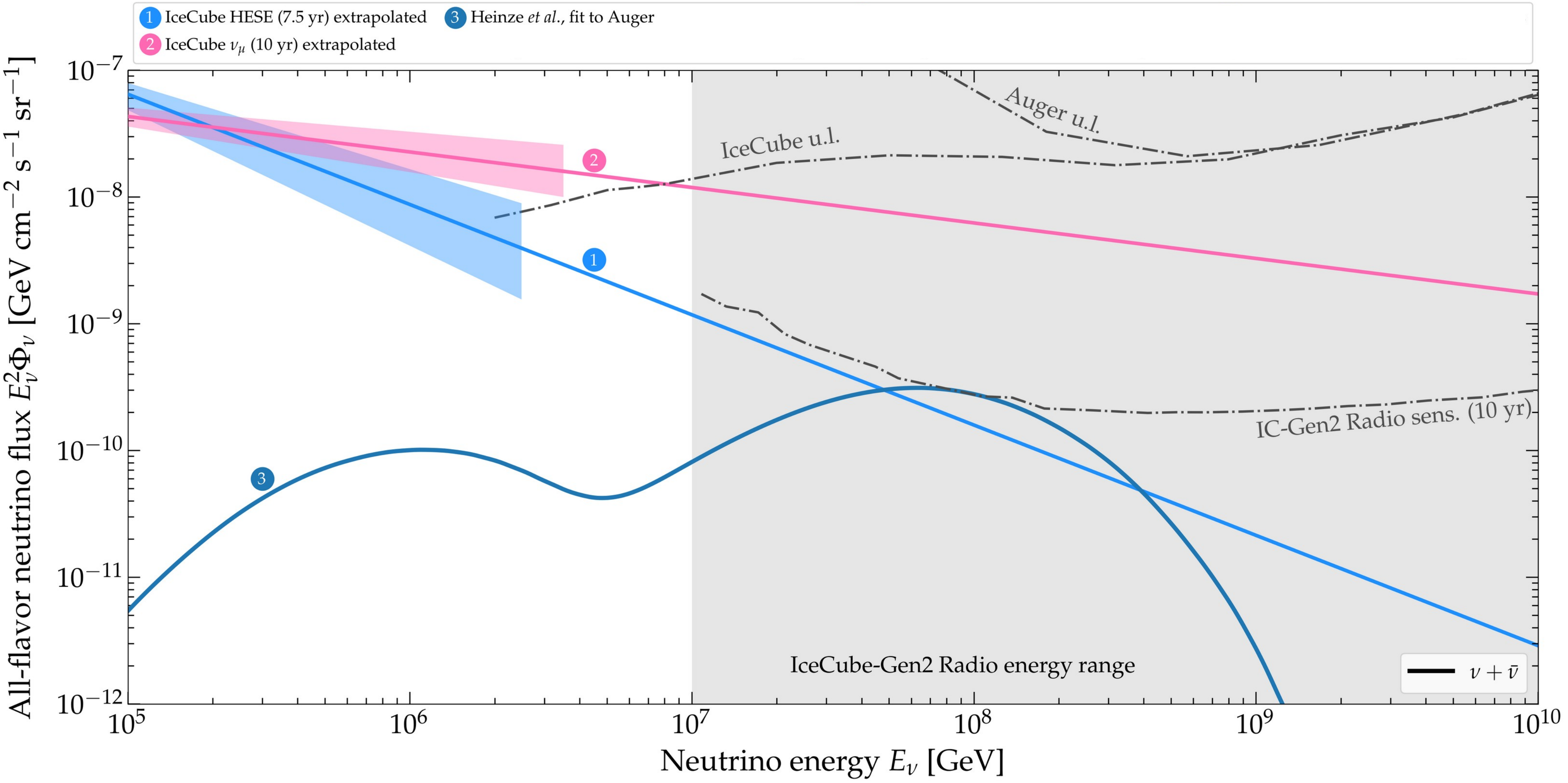
1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (10 yr)
Auger u.l.
IceCube u.l.
?
$\nu + \bar{\nu}$
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy E_ν [GeV]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^5
10^6
10^7
10^8
10^9
10^{10}



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.
$\nu + \bar{\nu}$
10^5
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy E_ν [GeV]



1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (10 yr) extrapolated
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}]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
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}]
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Auger u.l.
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10^8
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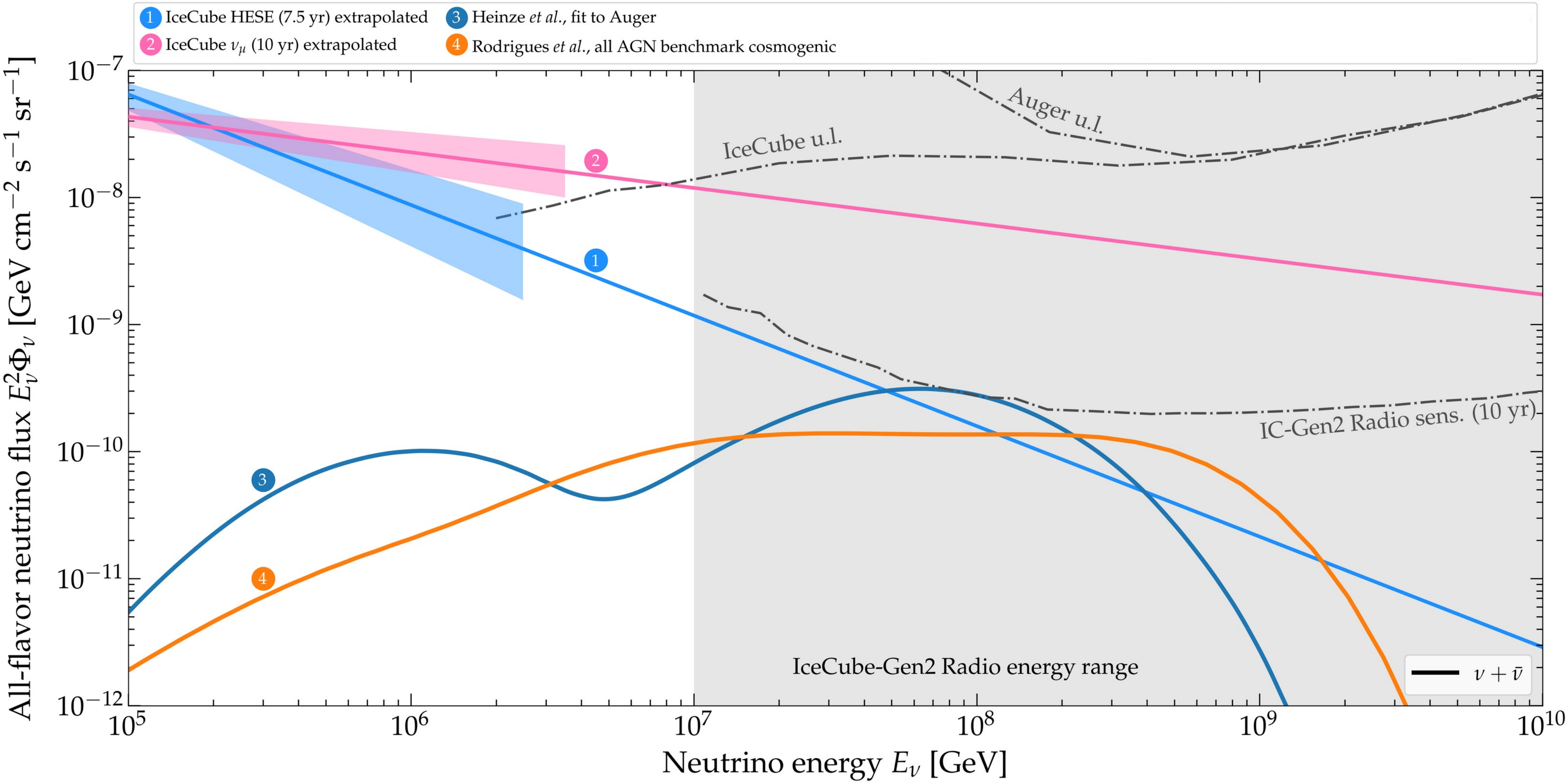
Neutrino energy E_ν [GeV]



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Auger u.l.
IceCube u.l.
IC-Gen2 Radio sens. (10 yr)
IceCube-Gen2 Radio energy range
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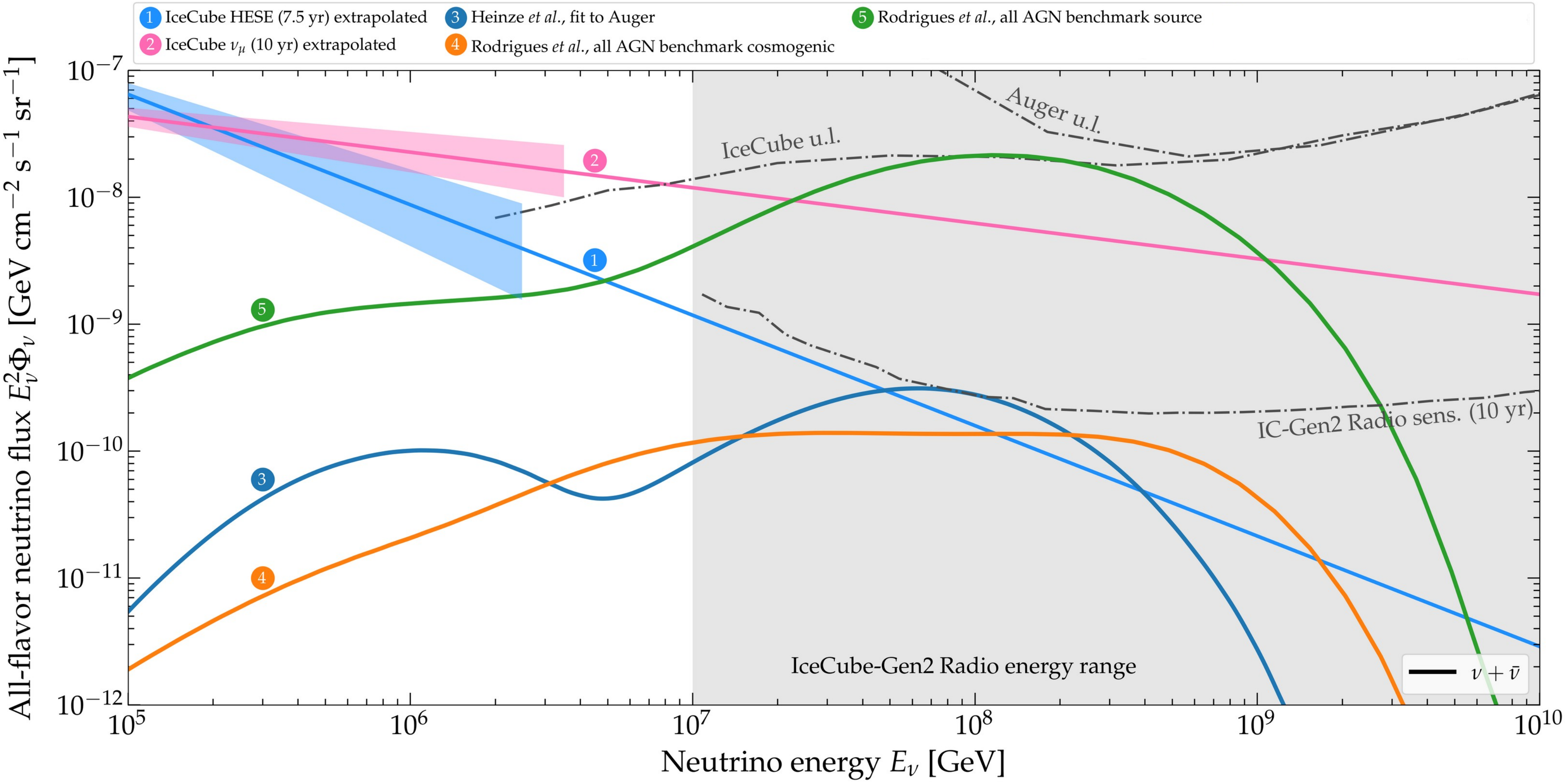

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5 Rodrigues et al., all AGN benchmark source
Auger u.l.
IceCube u.l.
IC-Gen2 Radio sens. (10 yr)
IceCube-Gen2 Radio energy range
$\nu + \bar{\nu}$
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy E_ν [GeV]
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10^8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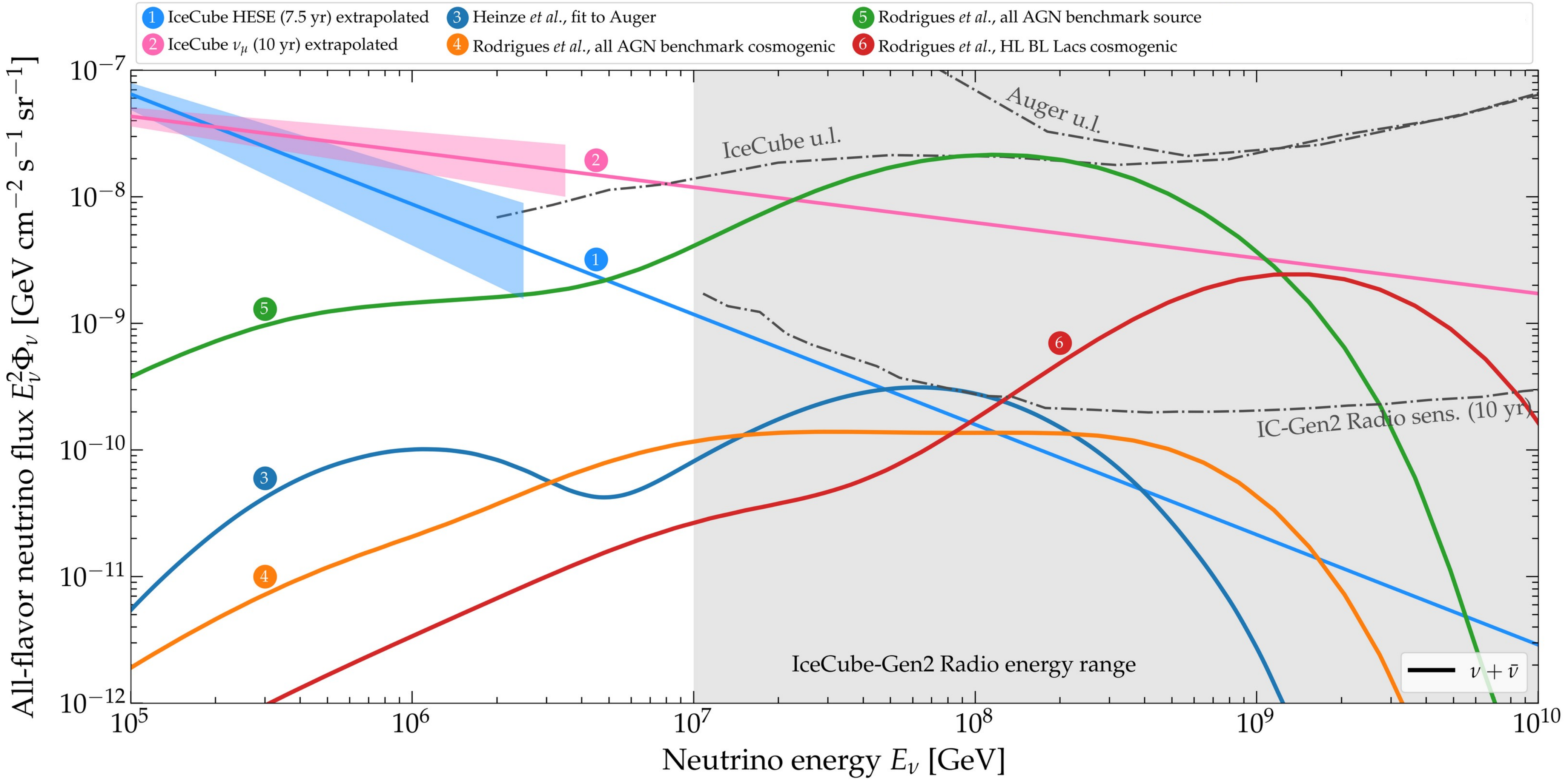

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3 Heinze *et al.*, fit to Auger
4 Rodrigues *et al.*, all AGN benchmark cosmogenic
5 Rodrigues *et al.*, all AGN benchmark source
6 Rodrigues *et al.*, HL BL Lacs cosmogenic
Auger u.l.
IceCube u.l.
IC-Gen2 Radio sens. (10 yr)
IceCube-Gen2 Radio energy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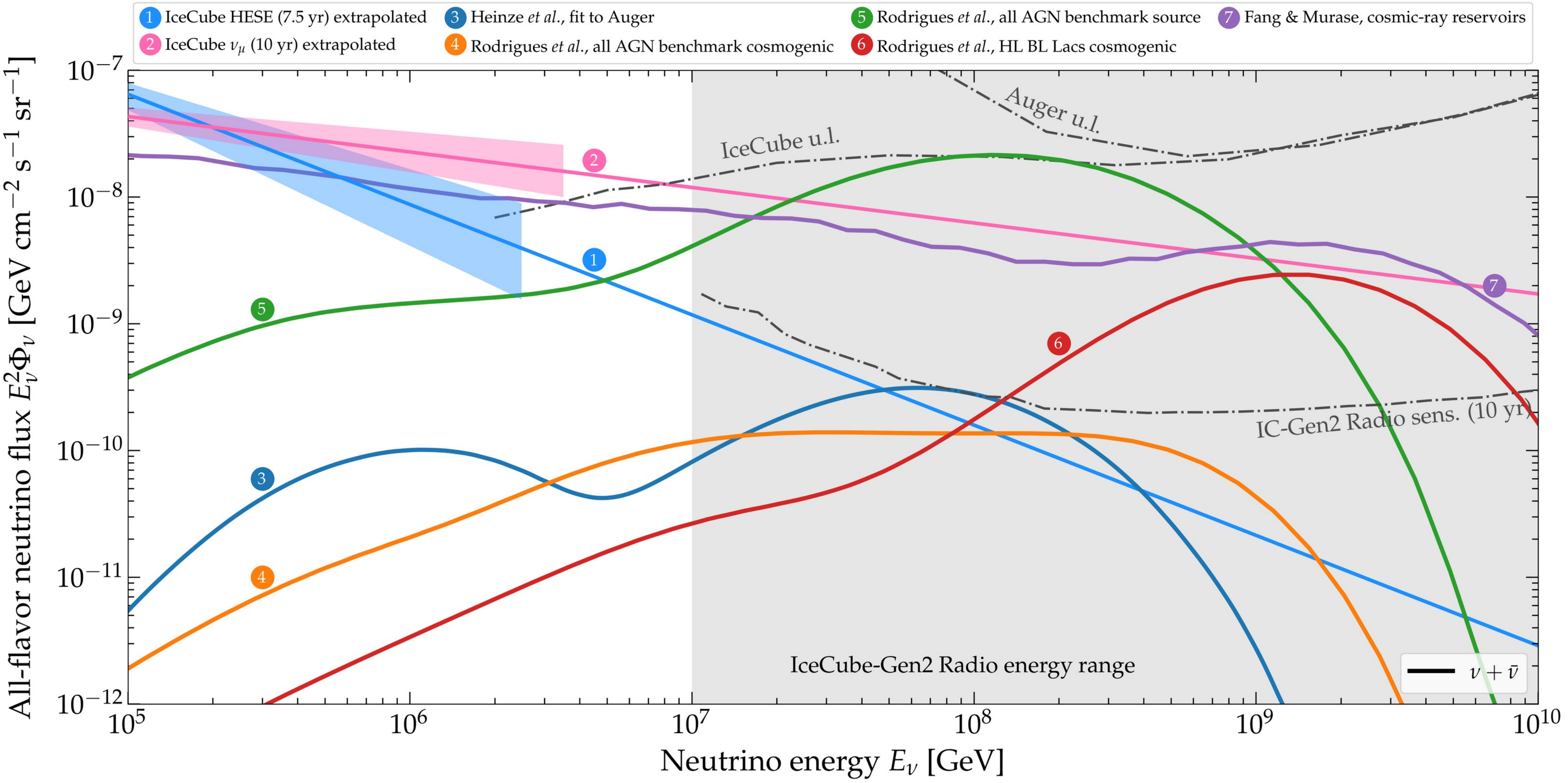
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6 Rodrigues et al., HL BL Lacs cosmogenic
7 Fang & Murase, cosmic-ray reservoirs
Auger u.l.
IceCube u.l.
IC-Gen2 Radio sens. (10 yr)
IceCube-Gen2 Radio energy range
$\nu + \bar{\nu}$
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]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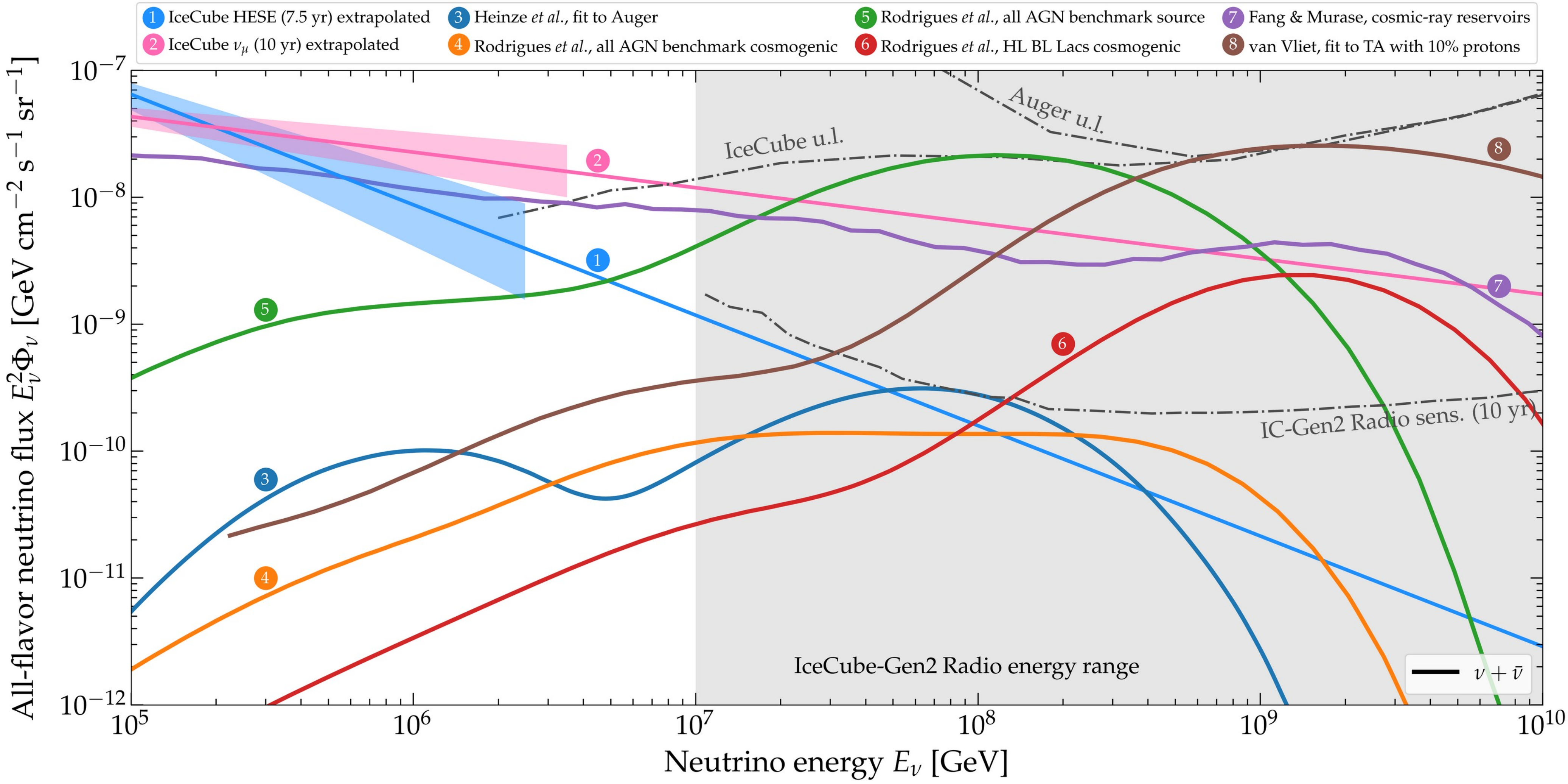

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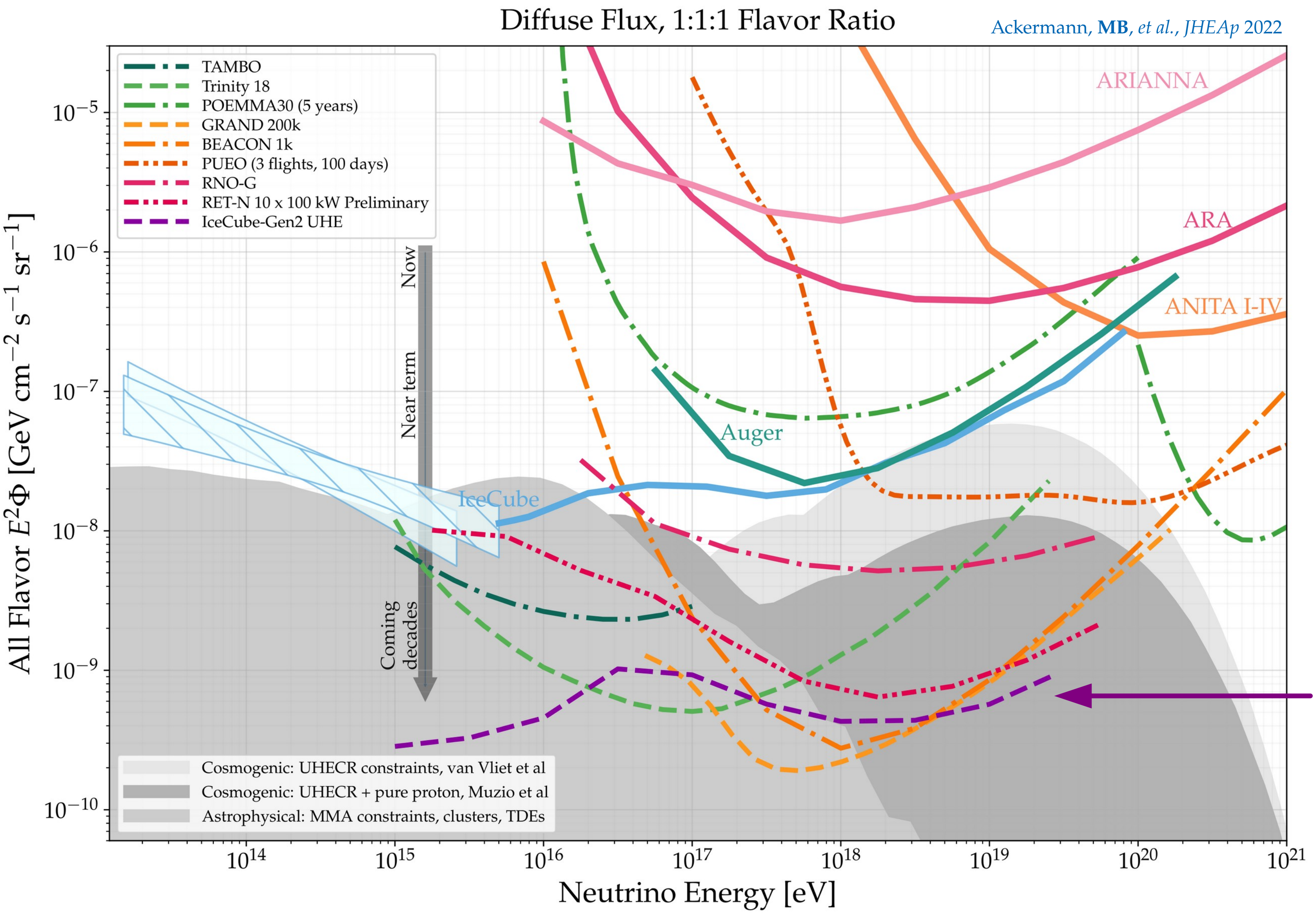
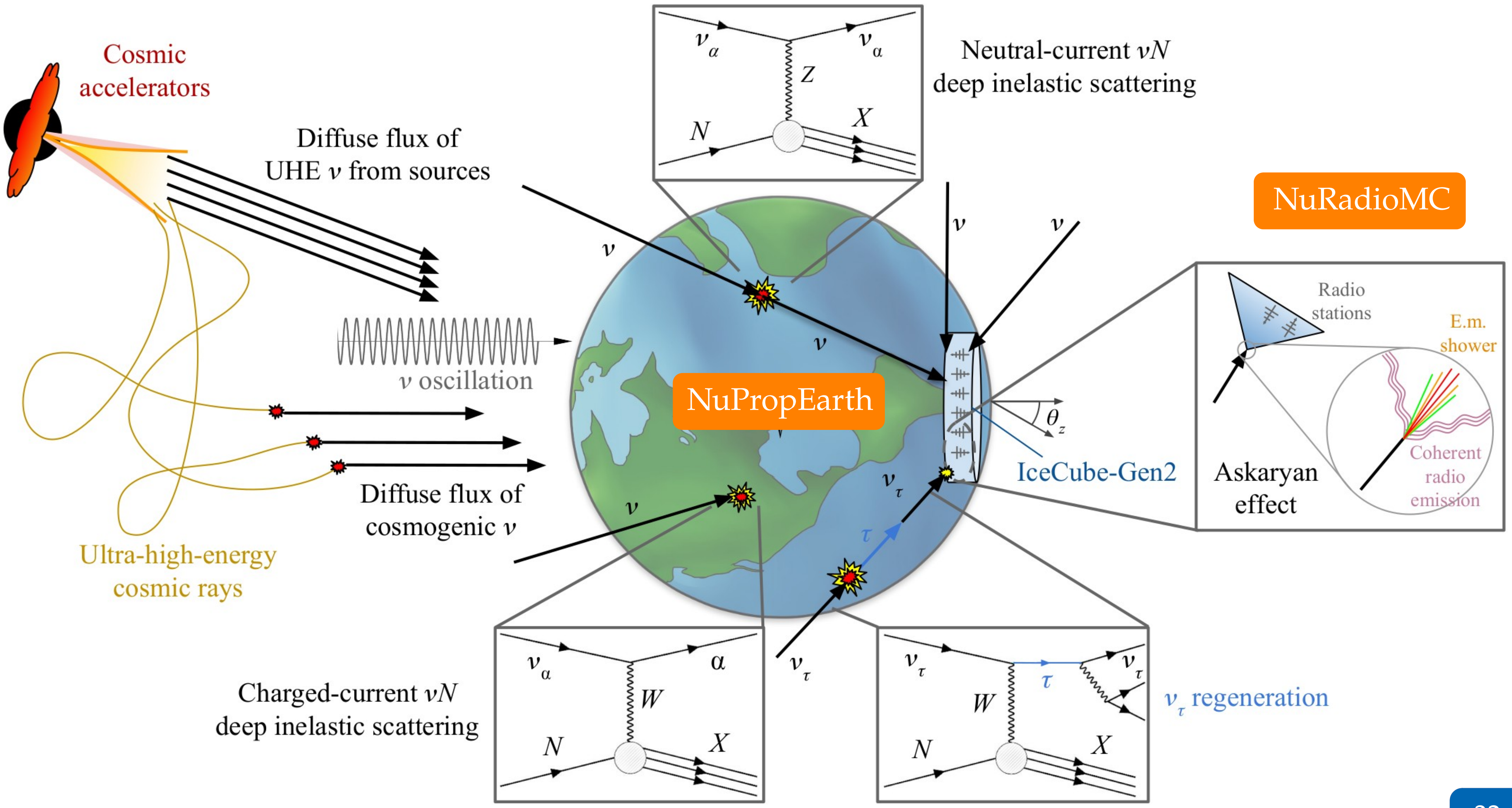
3 Heinze et al., fit to Auger
4 Rodrigues et al., all AGN benchmark cosmogenic
5 Rodrigues et al., all AGN benchmark source
6 Rodrigues et al., HL BL Lacs cosmogenic
7 Fang & Murase, cosmic-ray reservoirs
8 van Vliet, fit to TA with 10% protons
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2}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

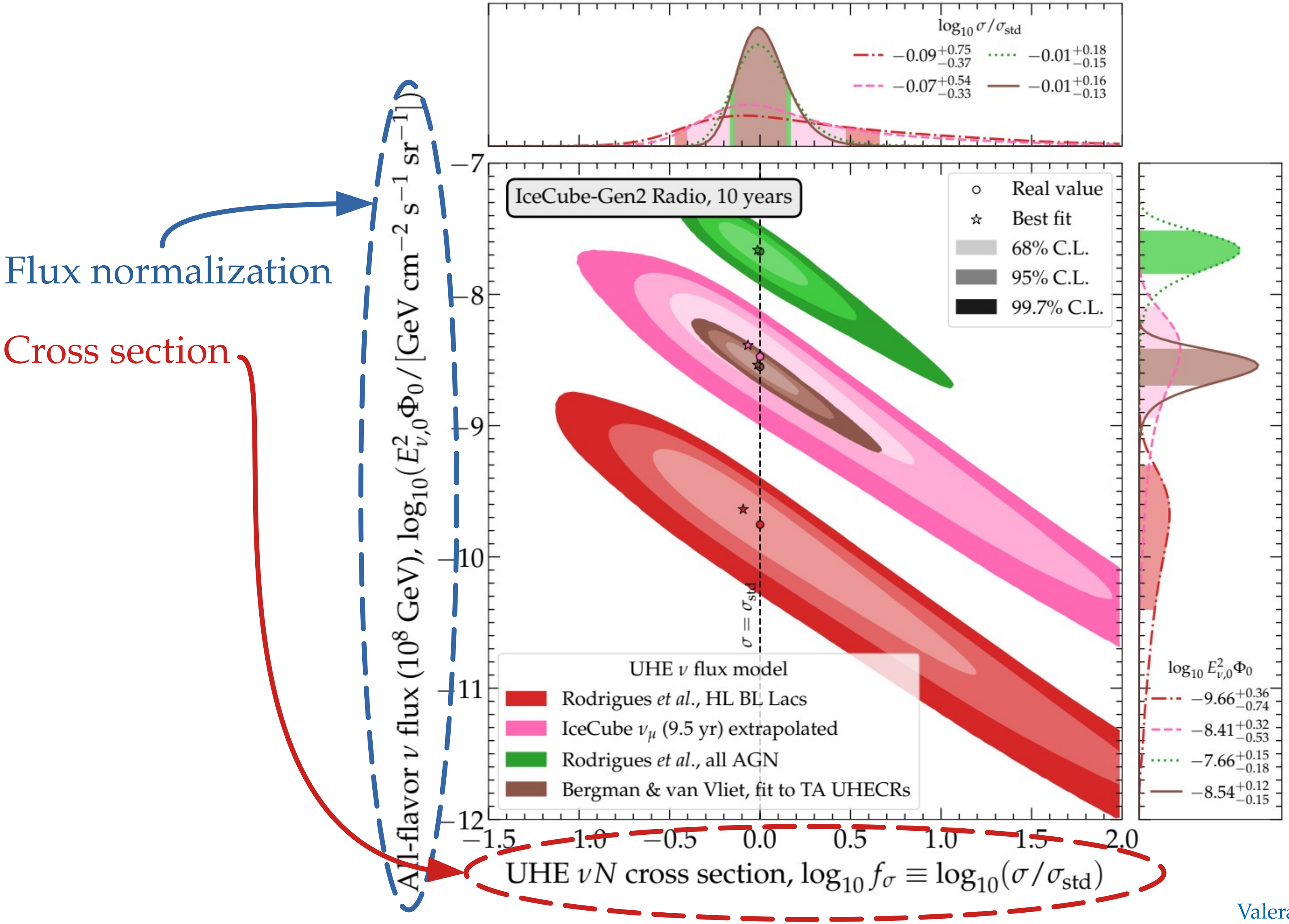
Ackermann, **MB**, *et al.*, *JHEAp* 2022



UHE radio-detection at Gen2 in our forecasts



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



Needed to measure the cross section?

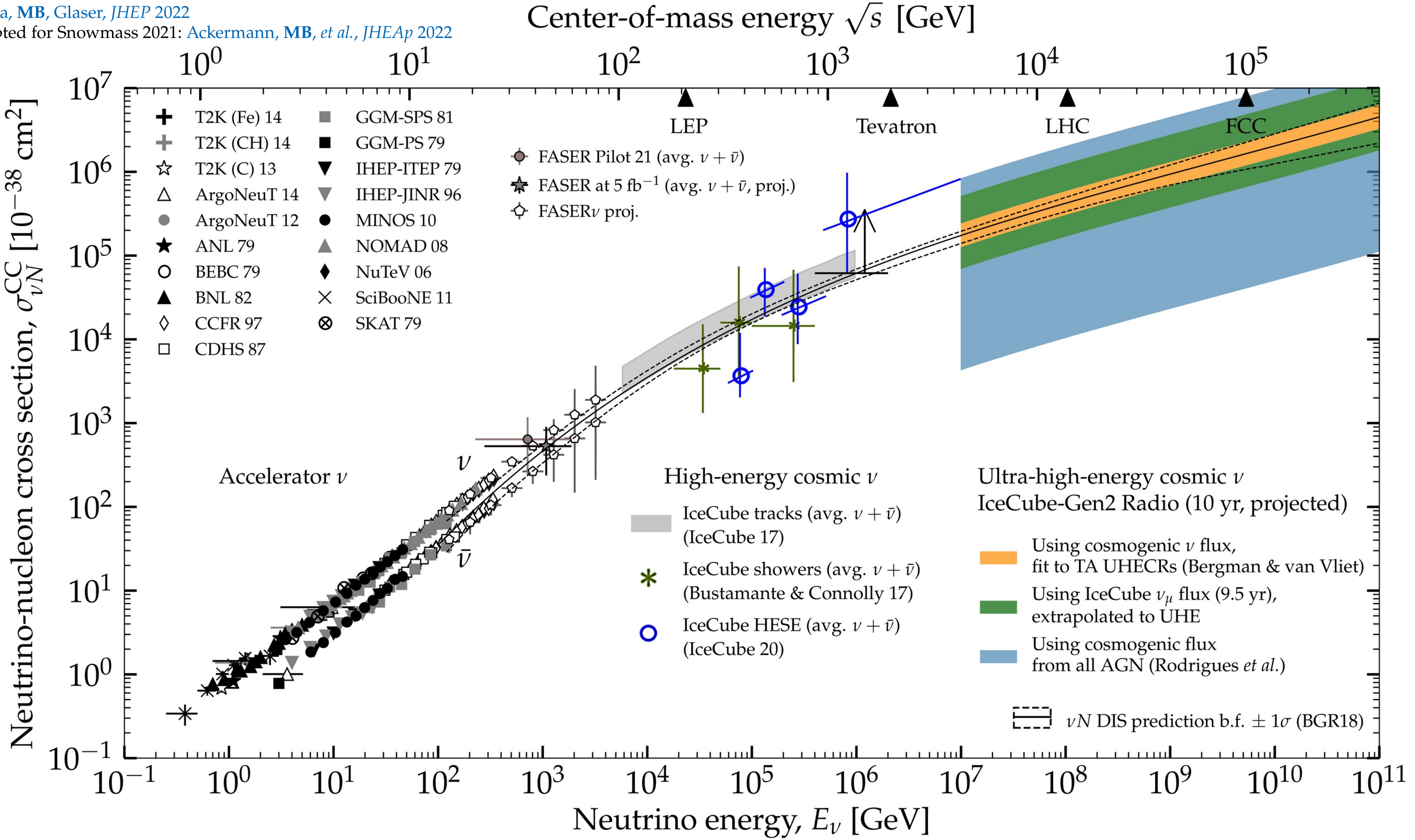
~30–300 events

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

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



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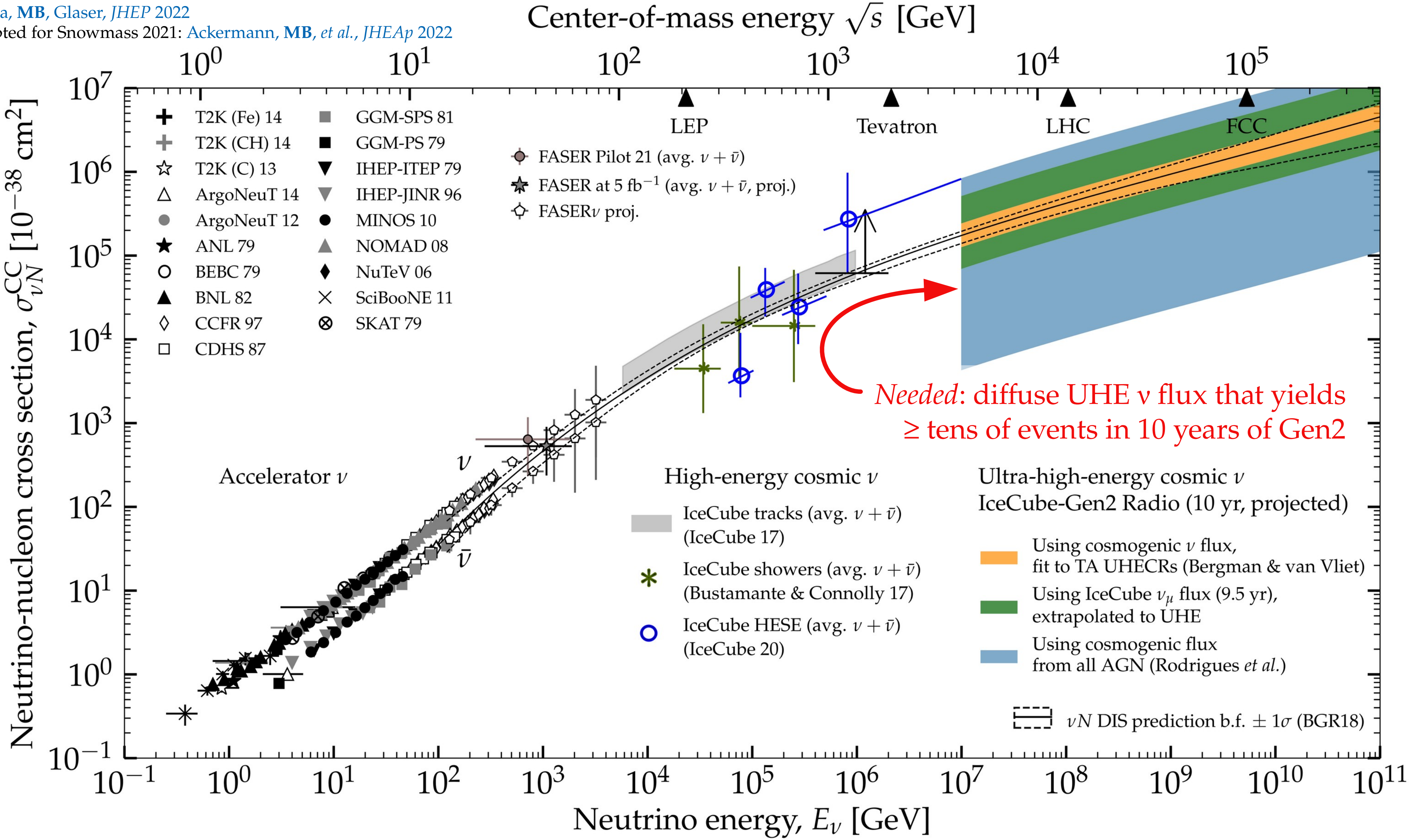

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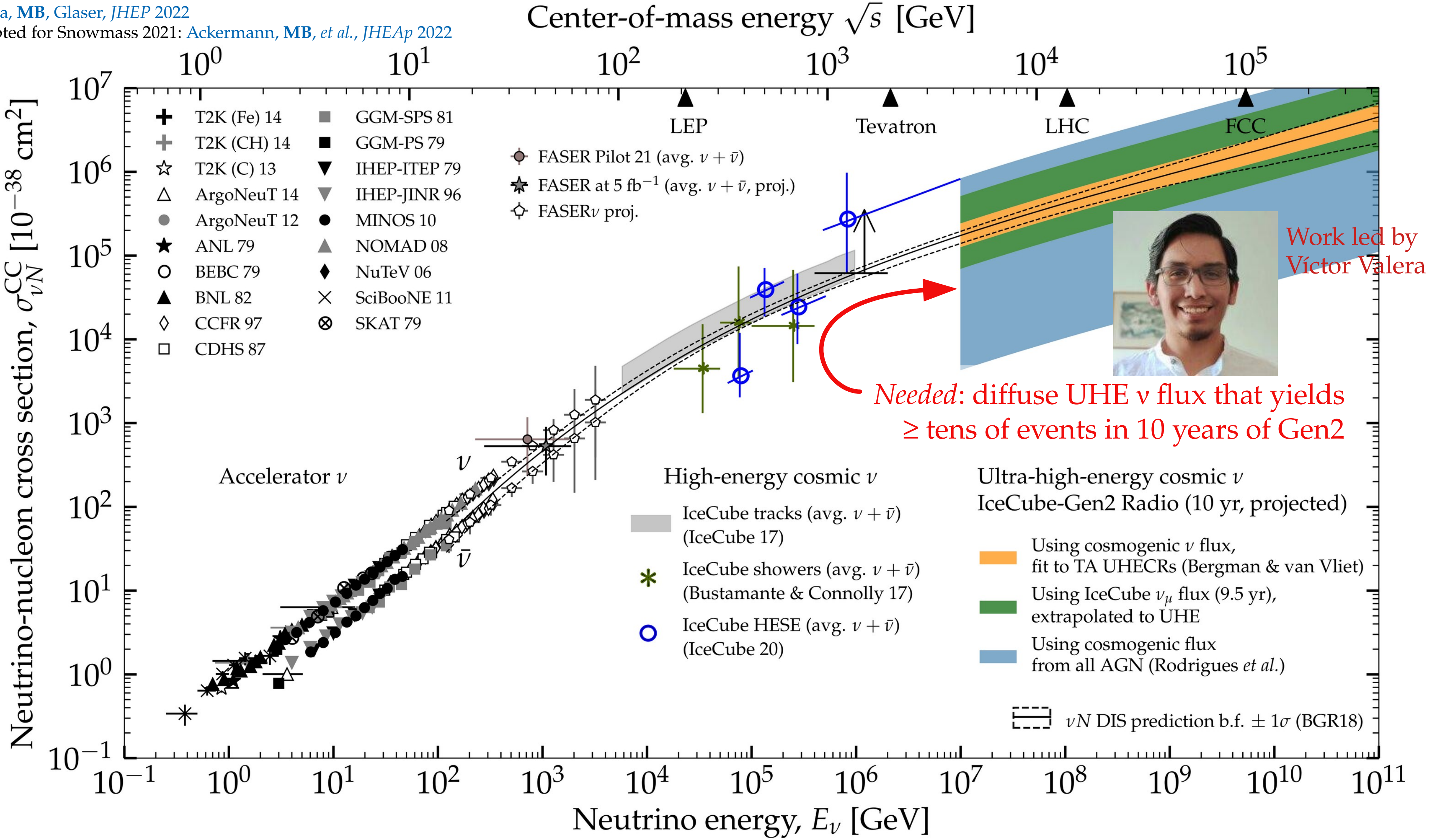
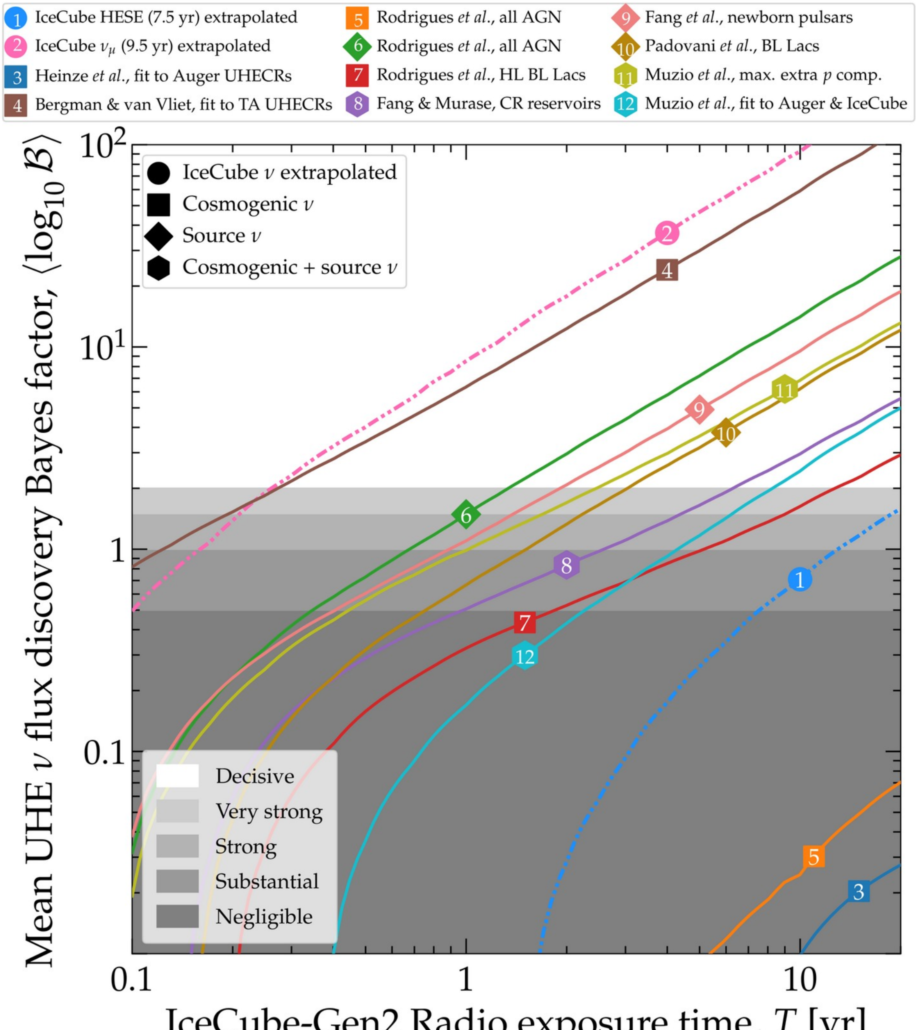


Side note: Discovering the diffuse flux of UHE neutrinos

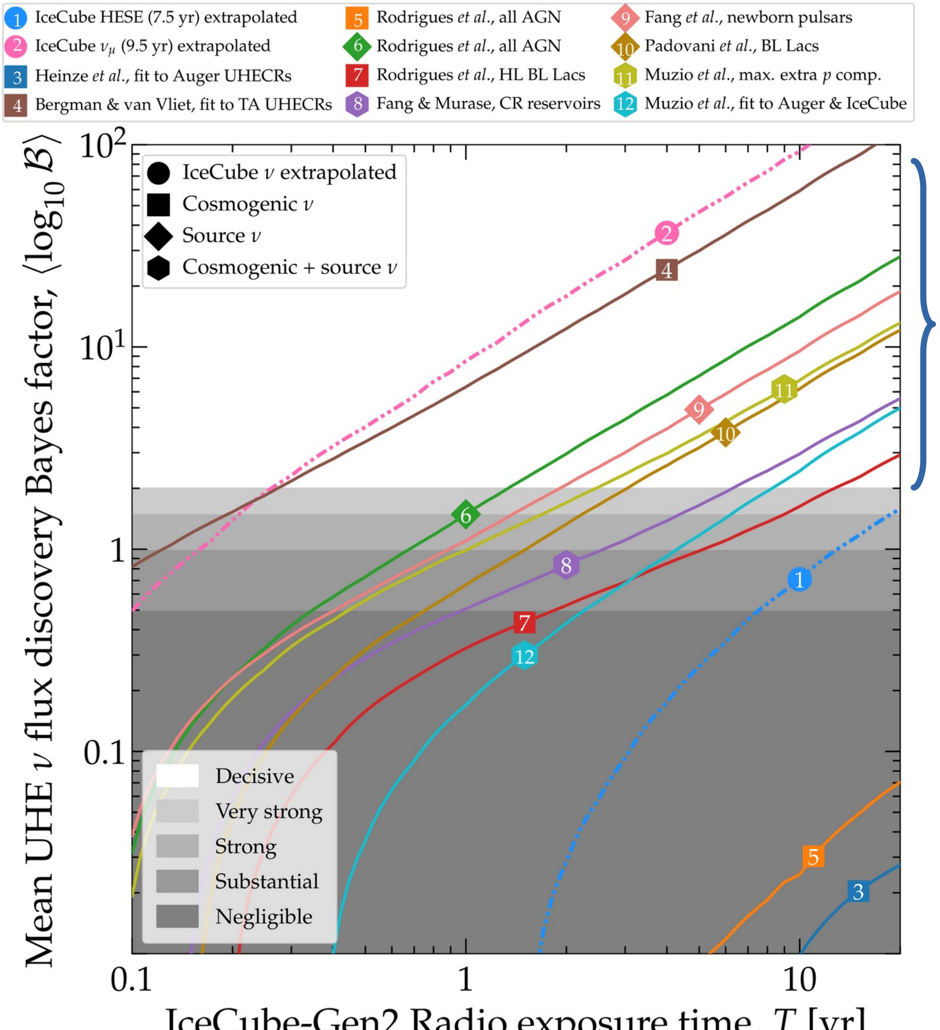


Work led by
Víctor Valera

Valera, **MB**, Glaser, 2210.03756

Side note: Discovering the diffuse flux of UHE neutrinos

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



Large Bayes factor = decisive flux discover

Work led by Víctor Valera

Valera, **MB**, Glaser, 2210.03756

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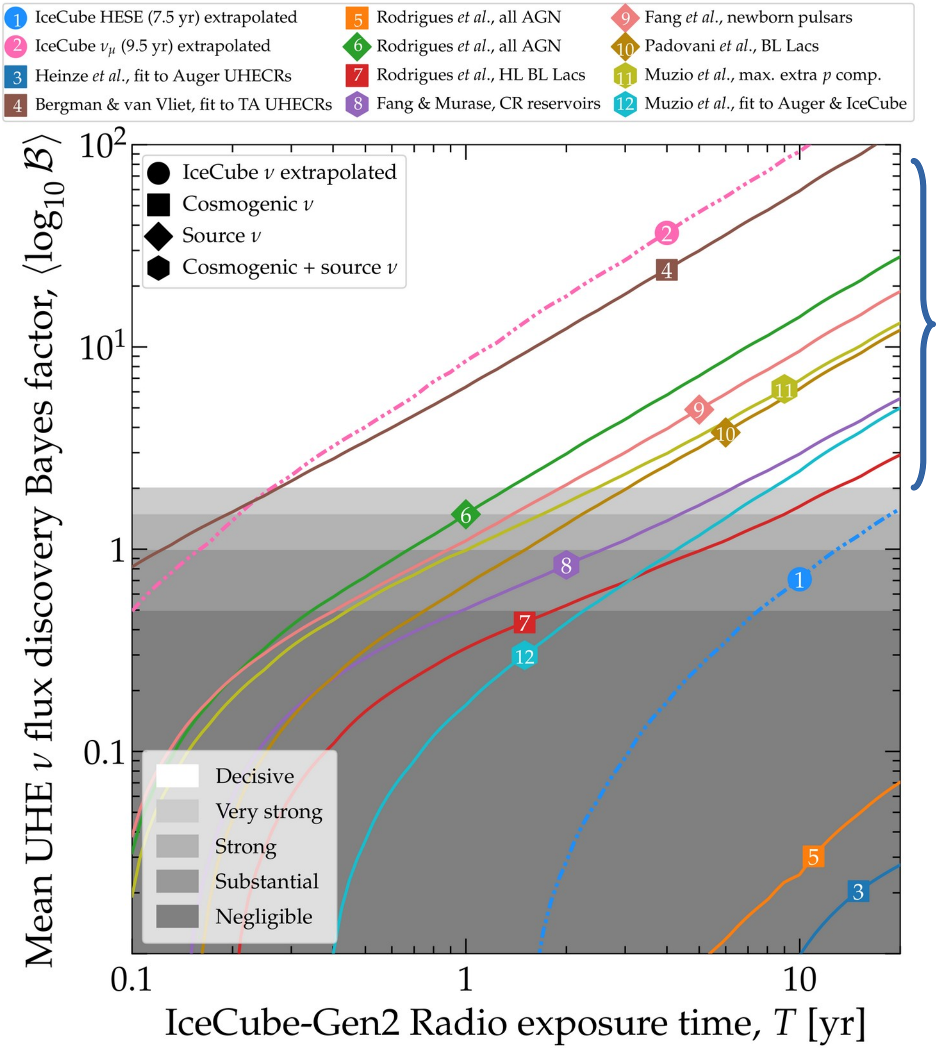

Work led by Víctor Valera

Large Bayes factor = decisive flux discover

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

Valera, **MB**, Glaser, 2210.03756

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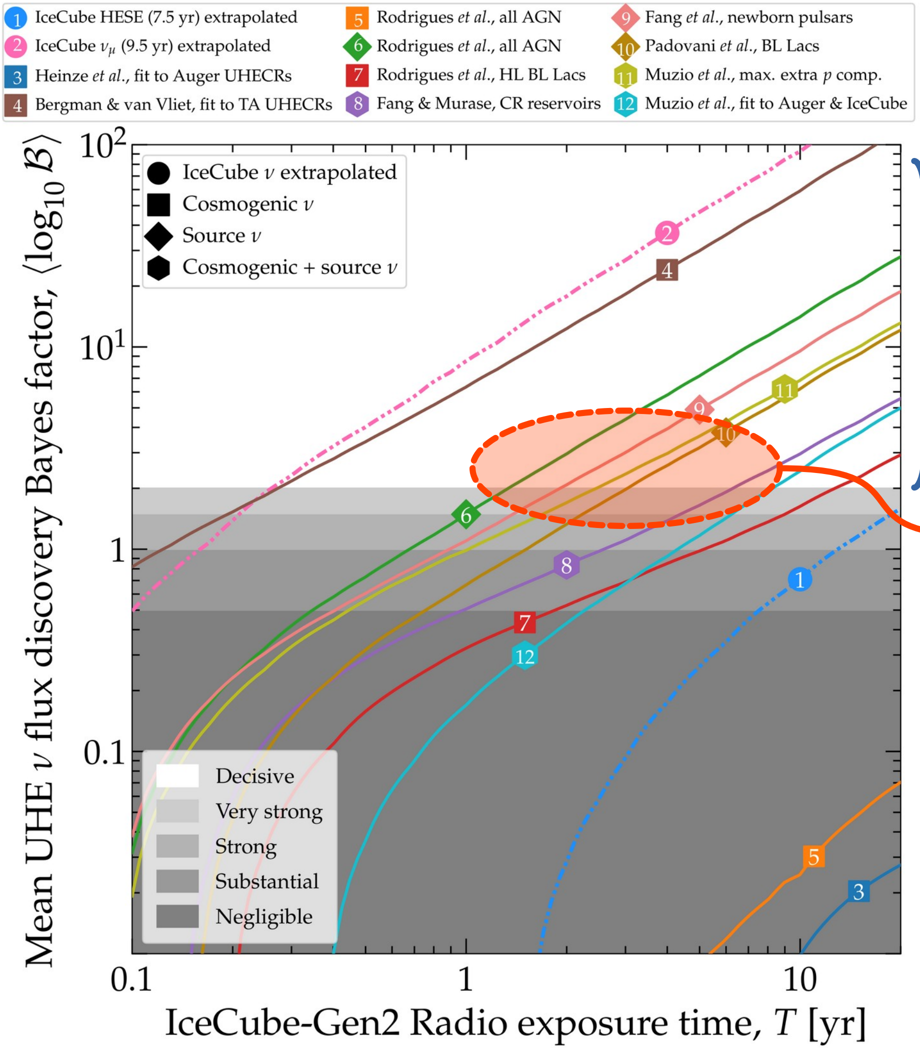


Work led by Víctor Valera

Large Bayes factor = decisive flux discover

Most flux models are discoverable with a few years

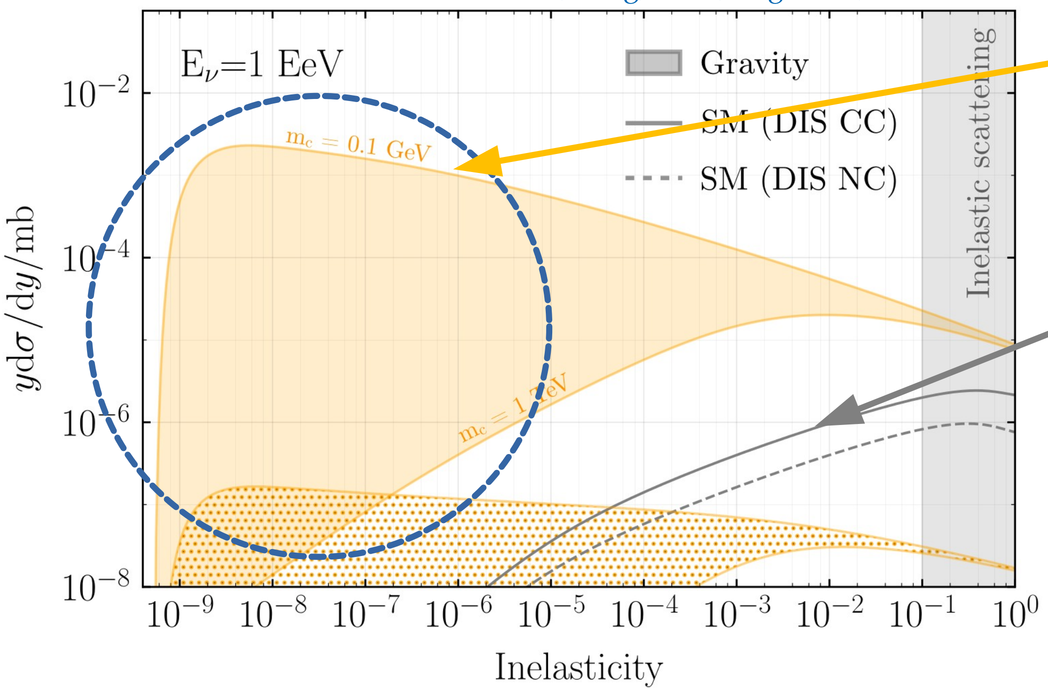
Forecasts are state-of-the-art:
- Neutrino propagation inside Earth
- Detailed simulation of radio in ice
- Detailed antenna response
- Detector energy & angular resolution
- Statistical fluctuations

Valera, **MB**, Glaser, 2210.03756

Warning: UHE BSM that changes inelasticity needs care

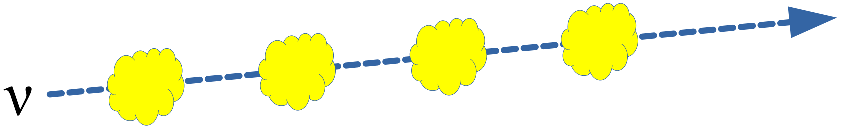
TeV-scale gravity may induce EeV-scale *elastic* neutrino interactions, *i.e.*, with low *y*:

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

New-physics menu

1. Neutrino-matter cross section
2. Unstable neutrinos
3. New neutrino interactions

4. Neutrinos & dark matter
5. Flavor composition
6. Physics with individual sources
7. ANITA mystery events

Are neutrinos forever?

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

  » Age of Universe (~ 14.5 Gyr)

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

- 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

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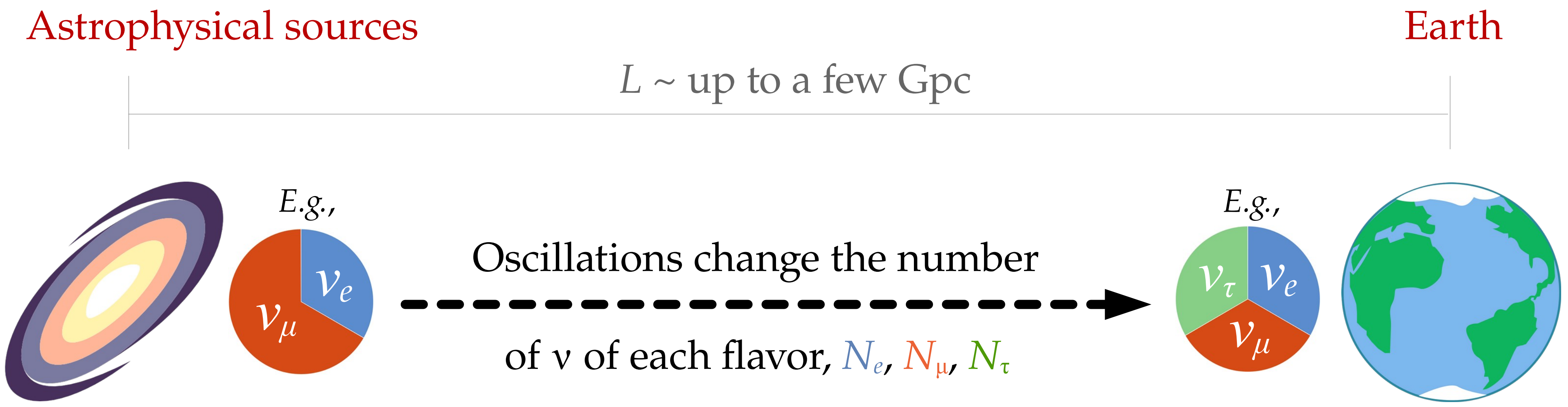
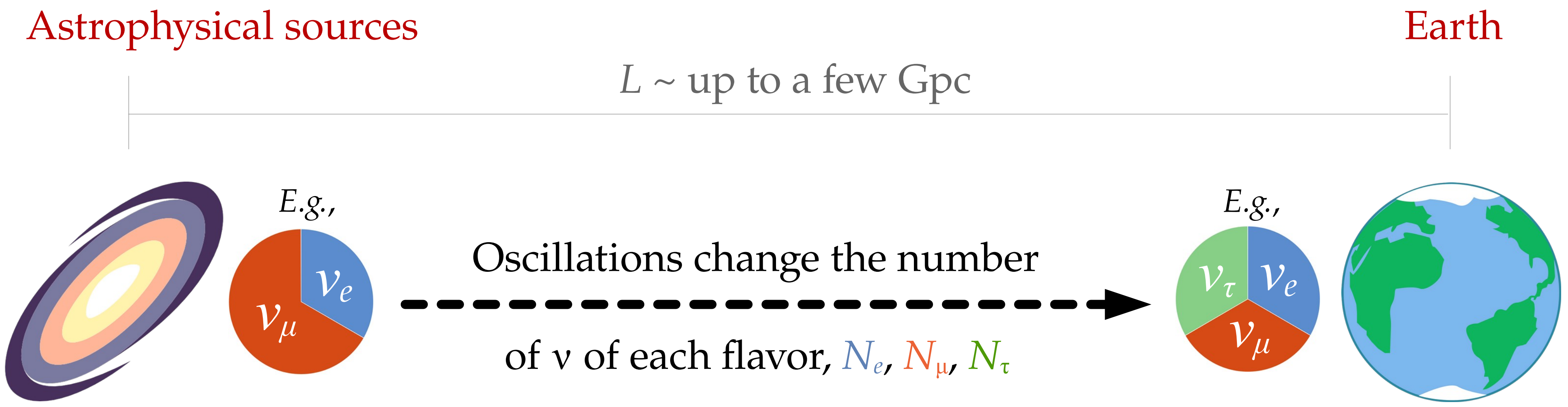


Different production mechanisms yield different flavor ratios:

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

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

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



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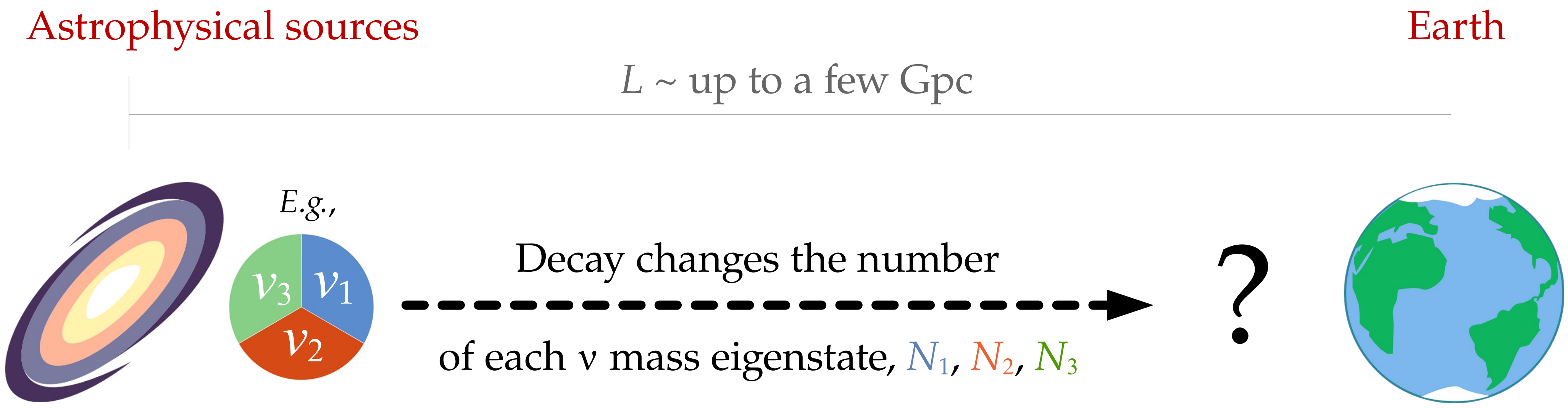
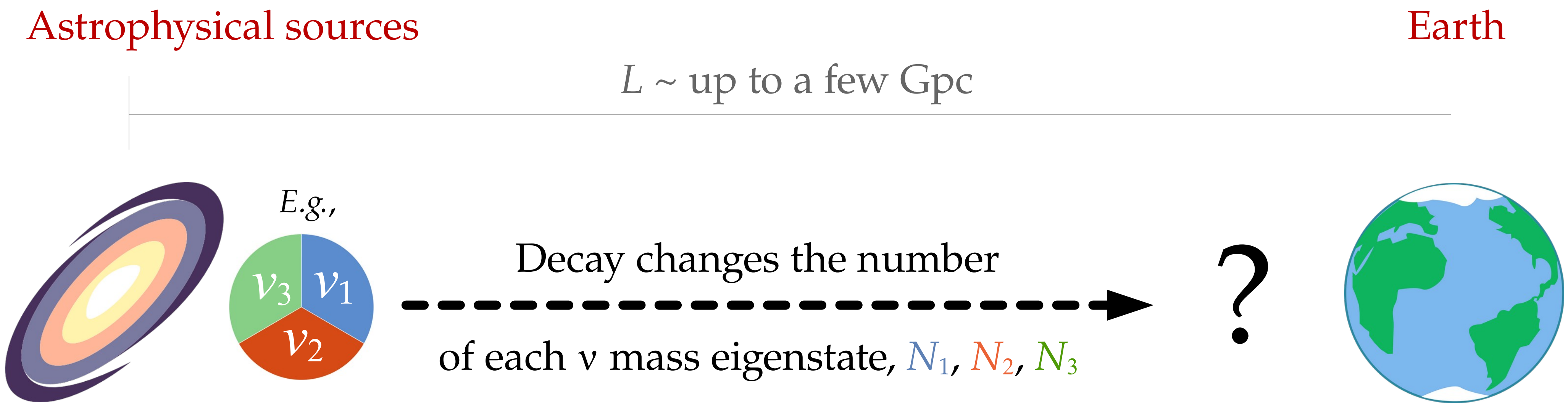
Standard oscillations
or
new physics



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

Mass of ν_i — Lifetime of ν_i



Only sensitive to their ratio

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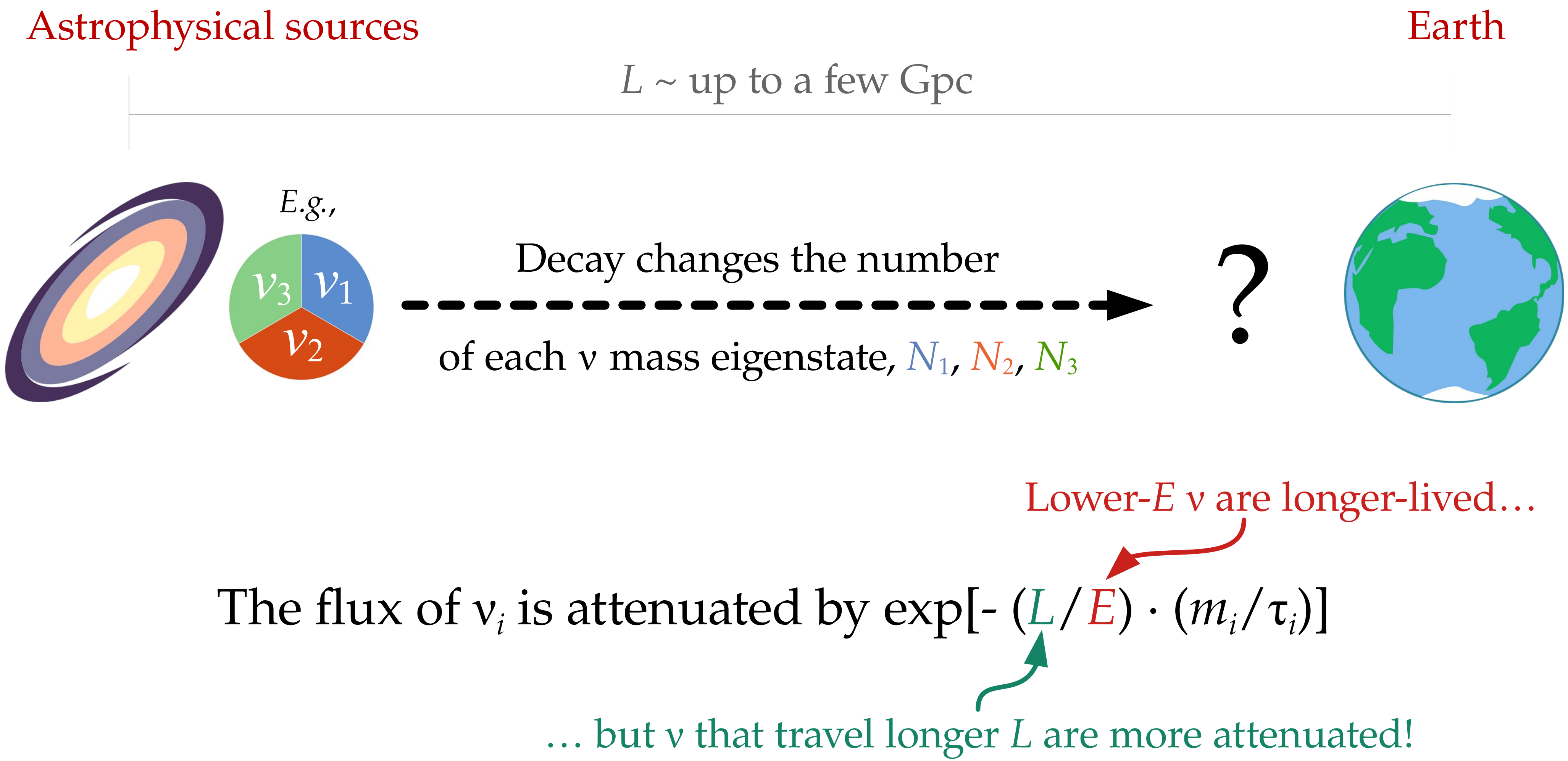
Mass of ν_i Lifetime of ν_i

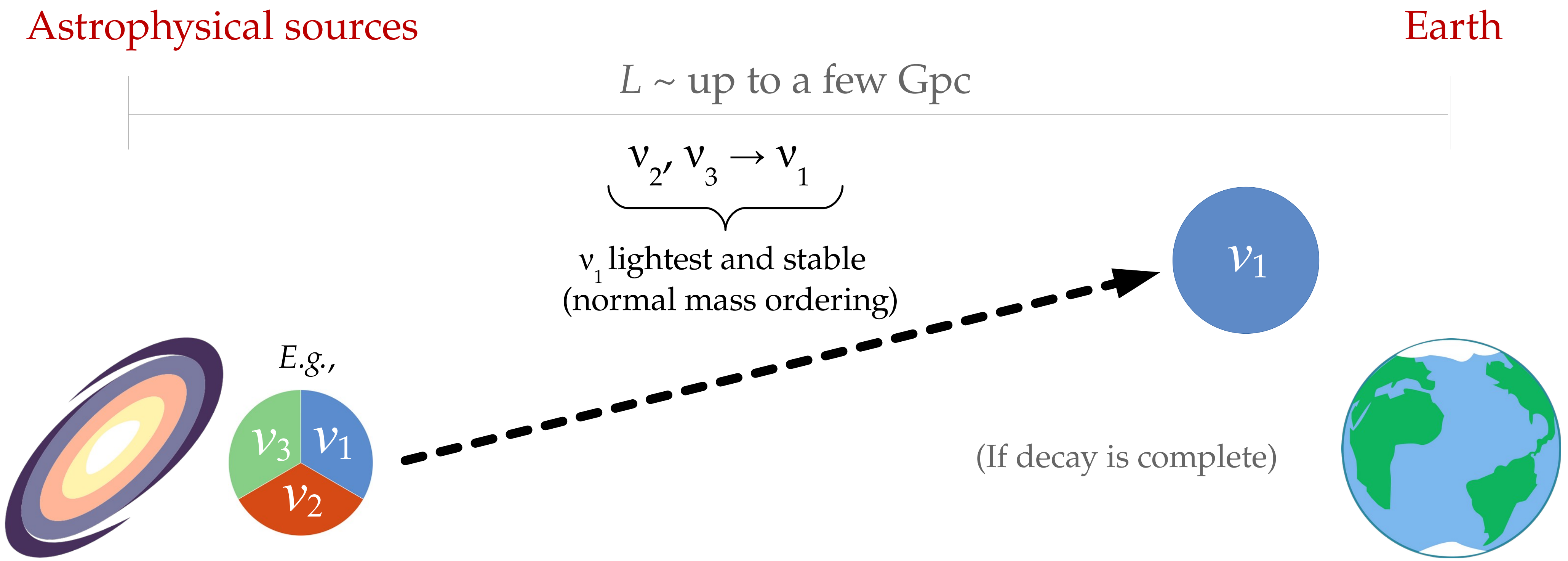

Astrophysical sources
Earth
L ~ up to a few Gpc
E.g.,
ν3 ν1
ν2
Decay changes the number
of each ν mass eigenstate, N1, N2, N3
?
Lower-E ν are longer-lived…
The flux of νi is attenuated by exp[- (L/E) · (mi/τi)]
… but ν that travel longer L are more attenuated!

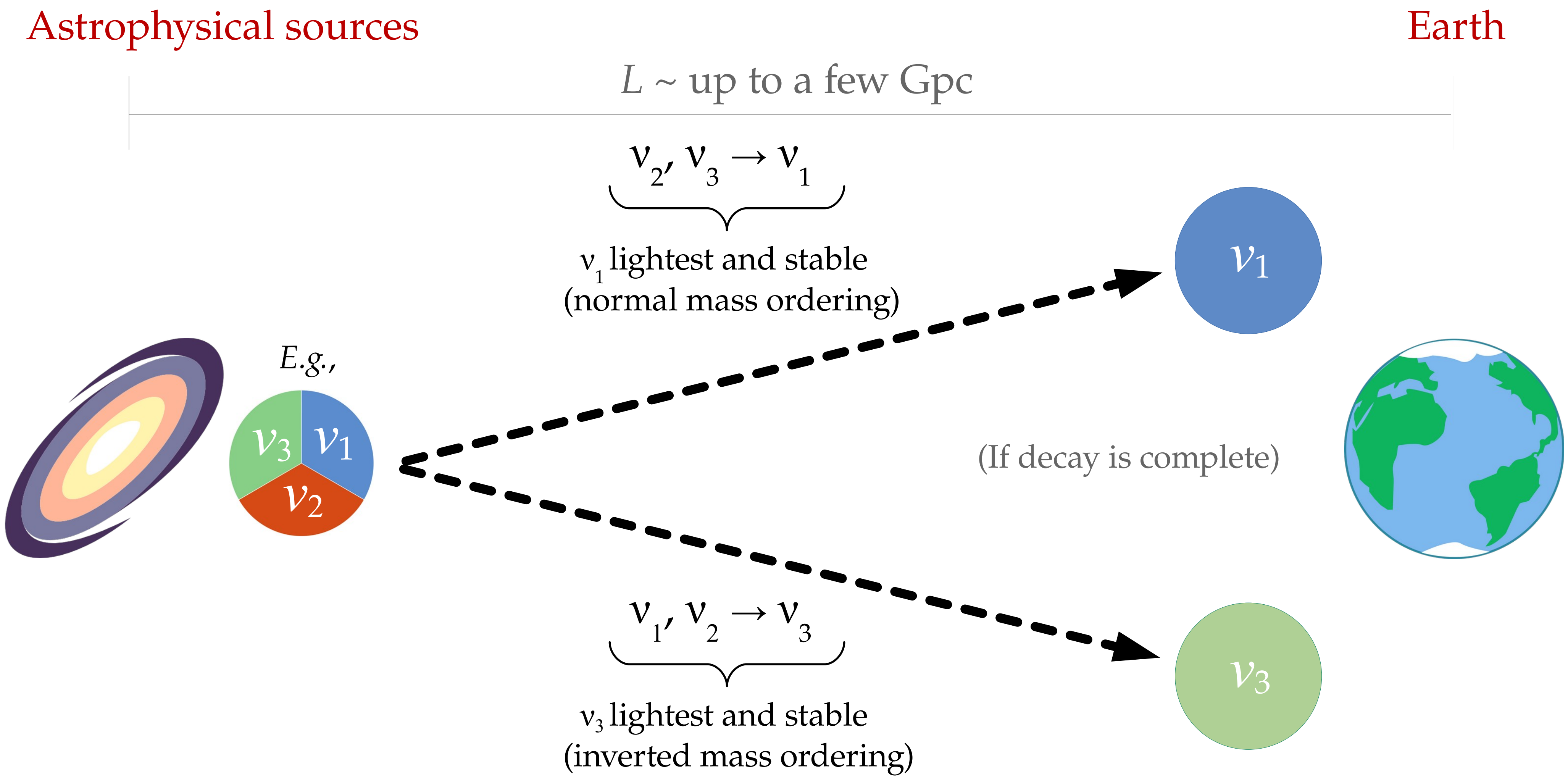
Astrophysical sources

Earth

$L \sim$ up to a few Gpc

E.g.,


Astrophysical sources
Earth
L ~ up to a few Gpc
ν2, ν3 → ν1
ν1 lightest and stable
(normal mass ordering)
E.g.,
ν3
ν1
ν2
ν1
(If decay is complete)



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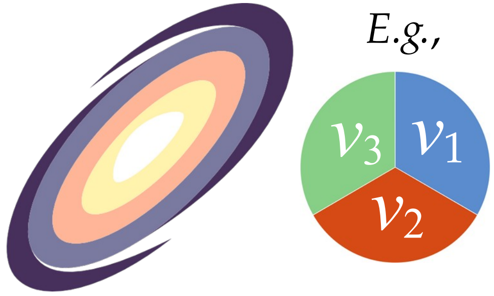
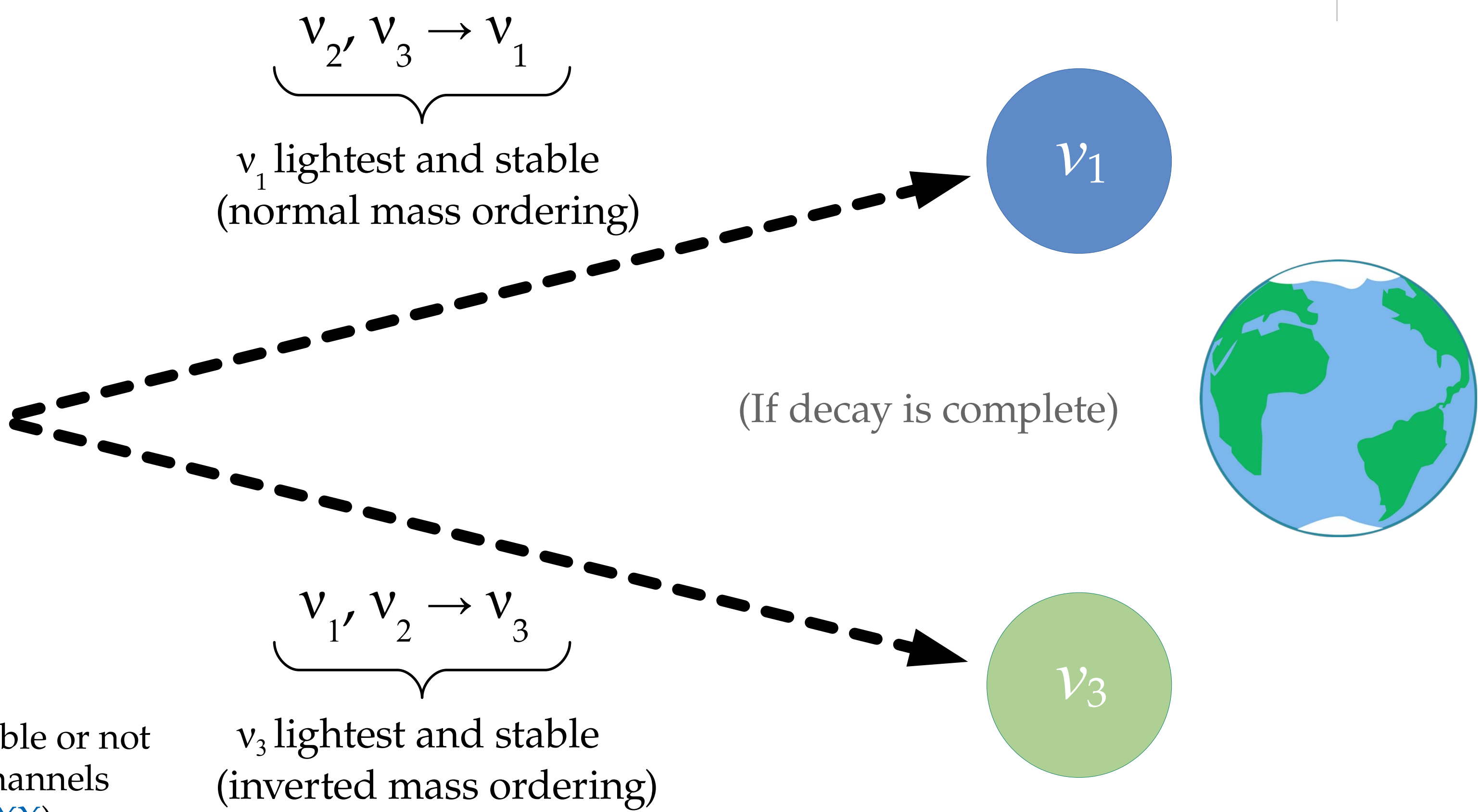
ν_1 lightest and stable
(normal mass ordering)
E.g.,
ν_3
ν_1
ν_2
ν_1
(If decay is complete)
$\nu_1, \nu_2 \rightarrow \nu_3$
ν_3 lightest and stable
(inverted mass ordering)
ν_3

Astrophysical sources — Earth

$L \sim$ up to a few Gpc

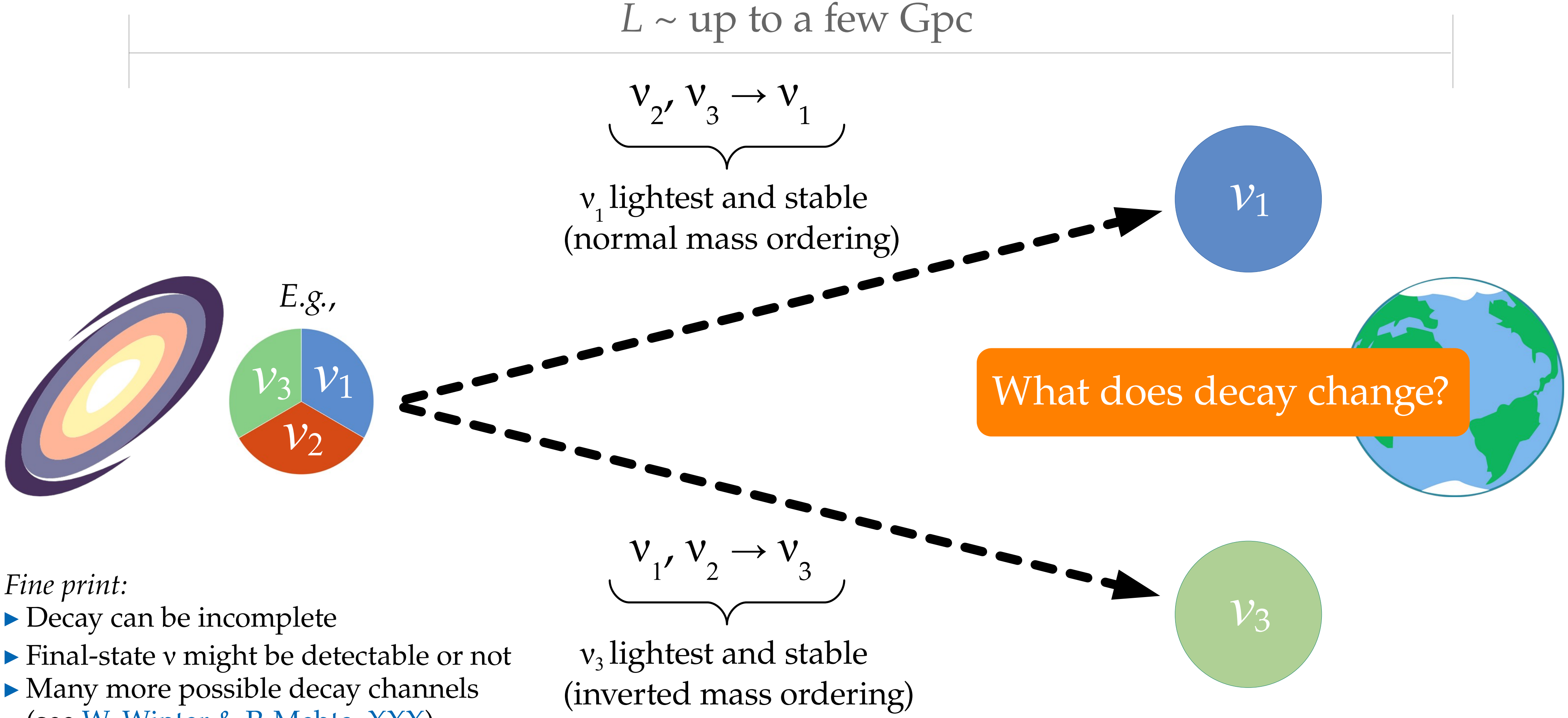




Fine print:

- Decay can be incomplete
- Final-state ν might be detectable or not
- Many more possible decay channels (see W. Winter & P. Mehta, XXX)

Astrophysical sources — Earth



Fine print:

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What does neutrino decay change?

Flavor composition ⟺ Spectrum shape ⟺ Event rate

What does neutrino decay change?

Flavor composition ⟺ Spectrum shape ⟺ Event rate

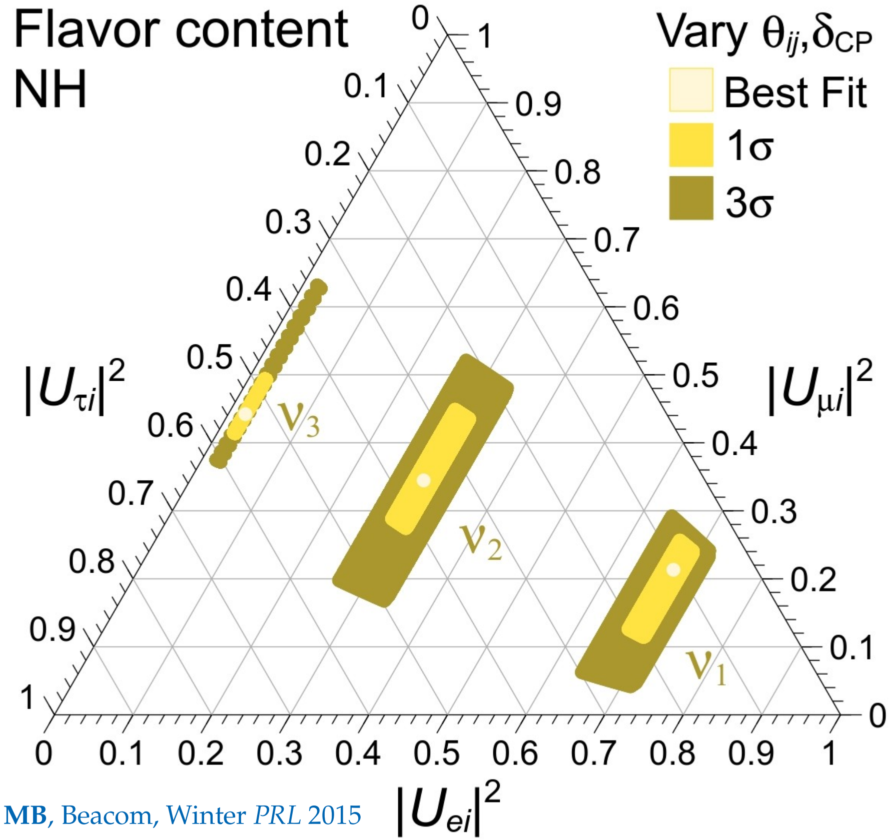
Flavor content of mass eigenstates:

Known to within 2%

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

Known to within 8%

Known to within 20% (or worse)

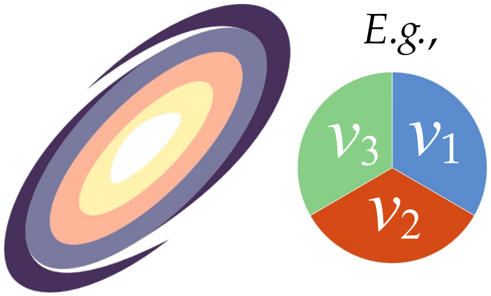


MB, Beacom, Winter *PRL* 2015

What does neutrino decay change?

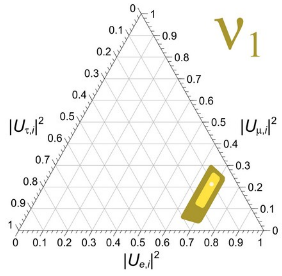
Flavor composition ⟺ Spectrum shape ⟺ Event rate

E.g.,



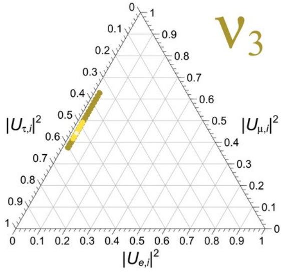
$\underbrace{\nu_2, \nu_3 \rightarrow \nu_1}$

ν_1 lightest and stable
(normal mass ordering)



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

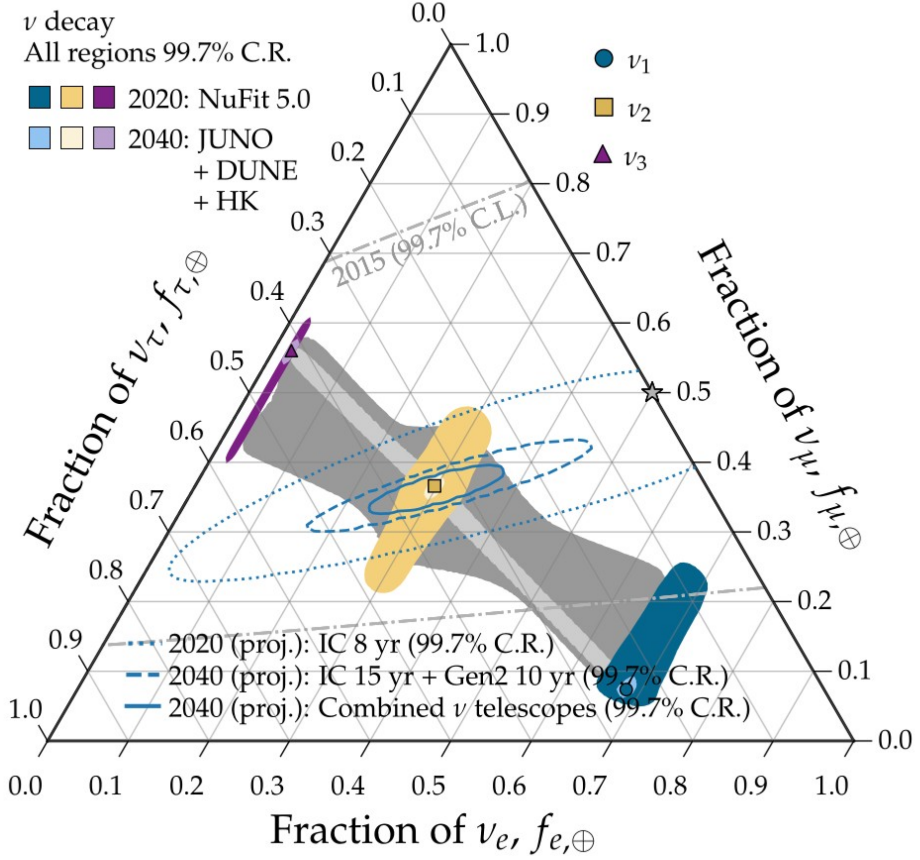
ν_3 lightest and stable
(inverted mass ordering)



What does neutrino decay change?

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

Flavor composition ⇔ Spectrum shape ⇔ Event rate



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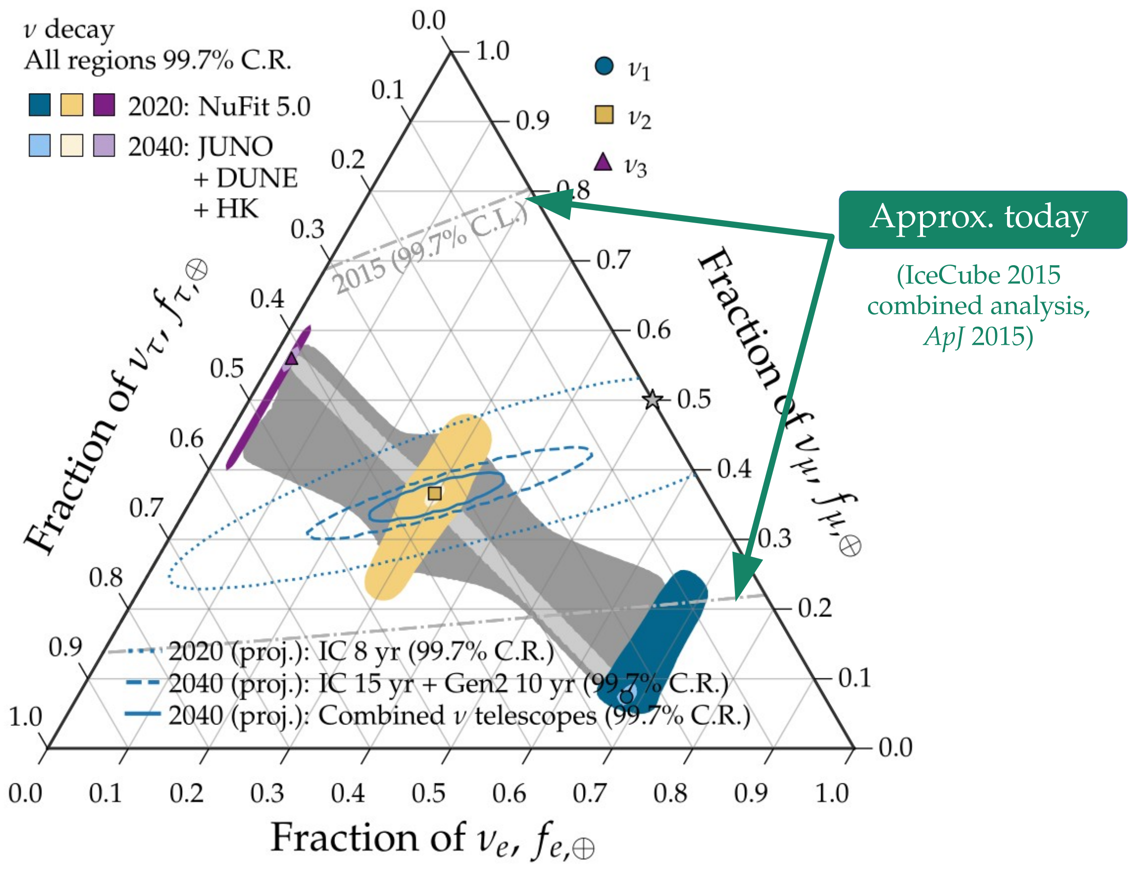

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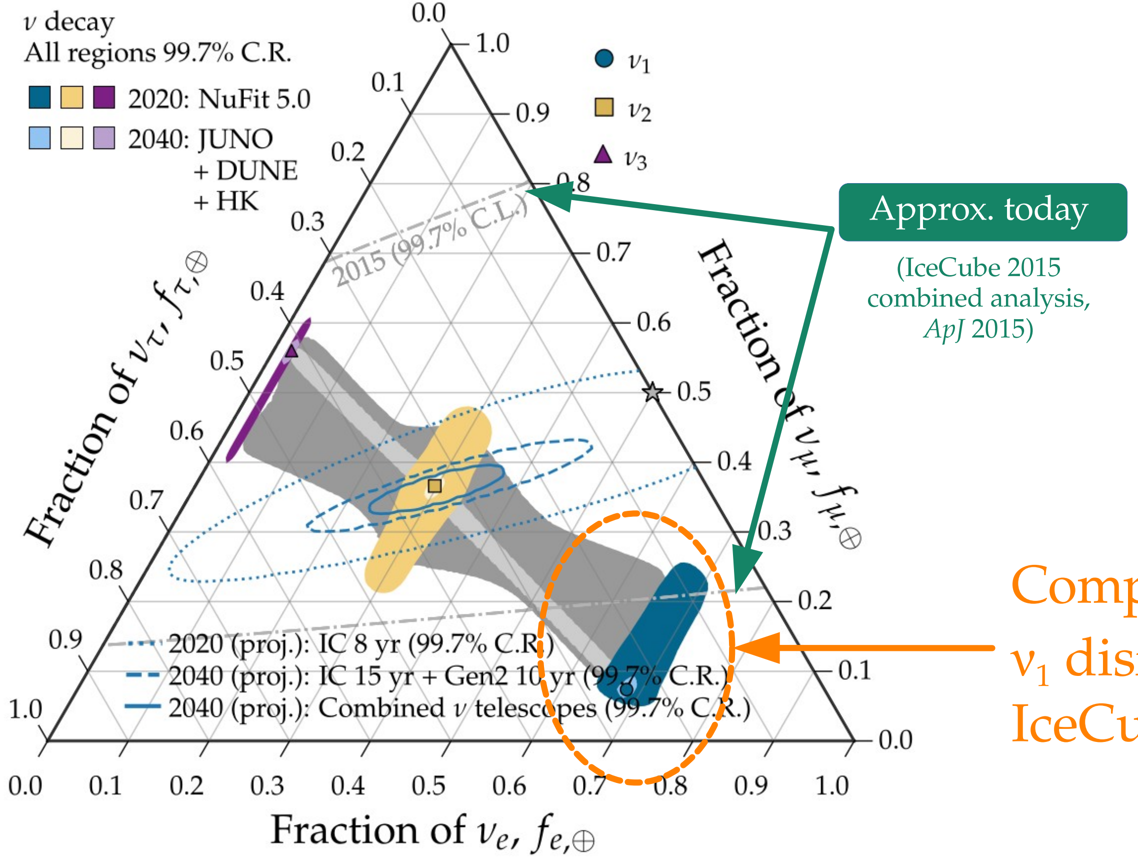

Complete decay into ν_1 disfavored by 2015 IceCube flavor measurement

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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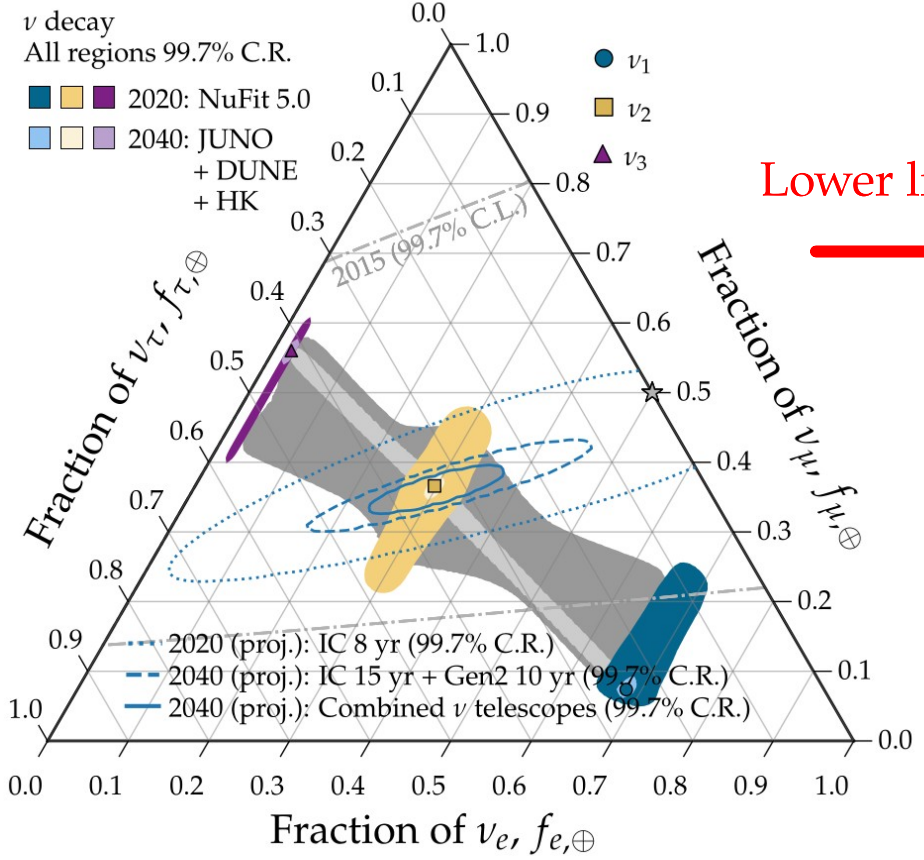

Lower limit on τ/m →

What does neutrino decay change?

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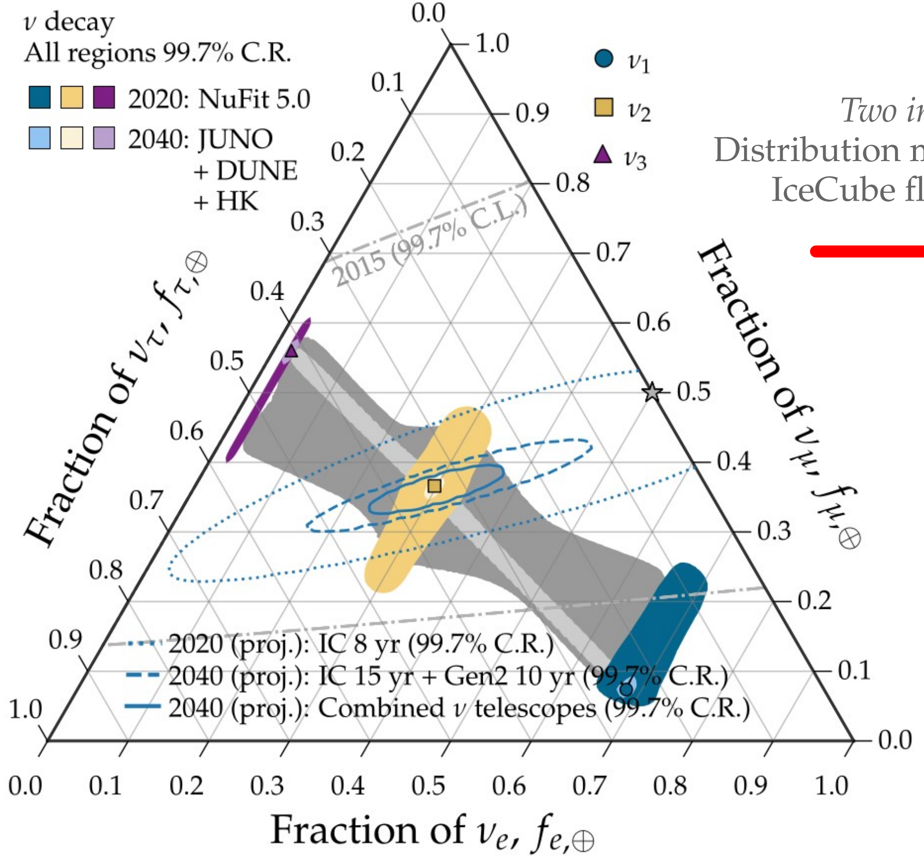

Two ingredients:
Distribution mixing parameters
IceCube flavor posterior

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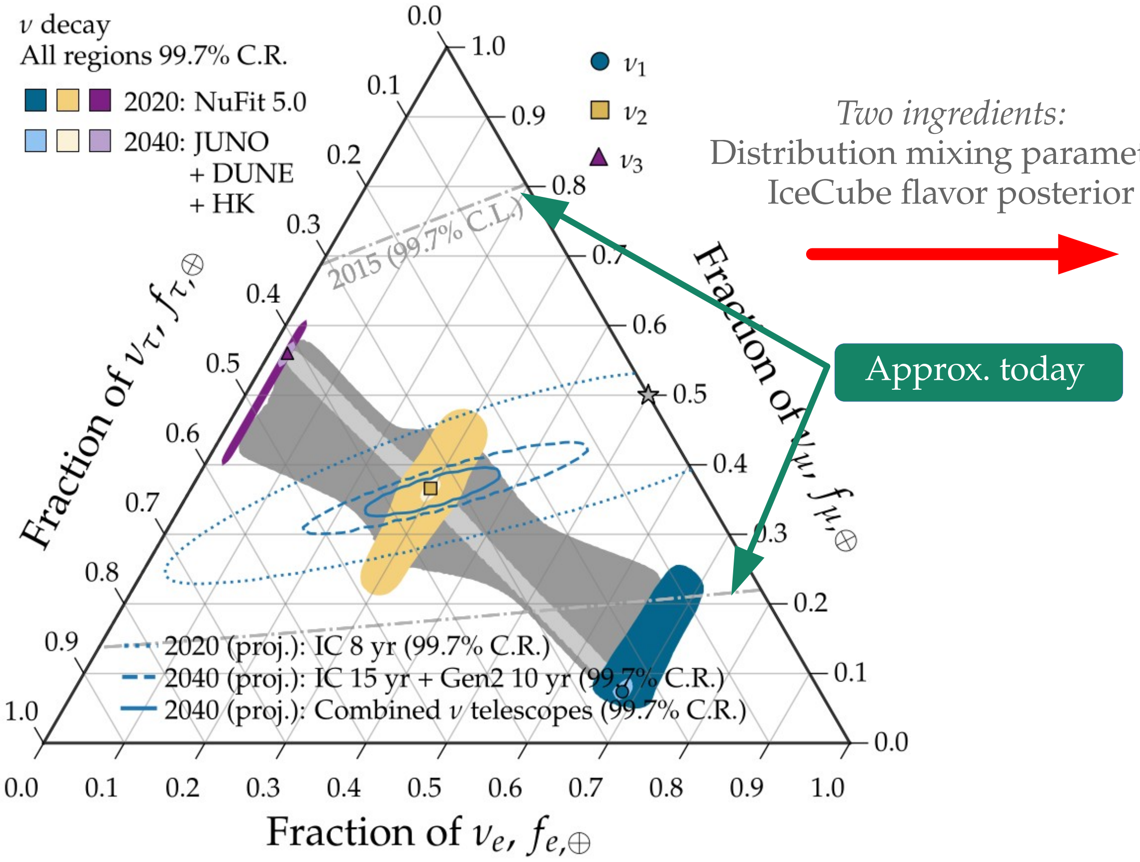

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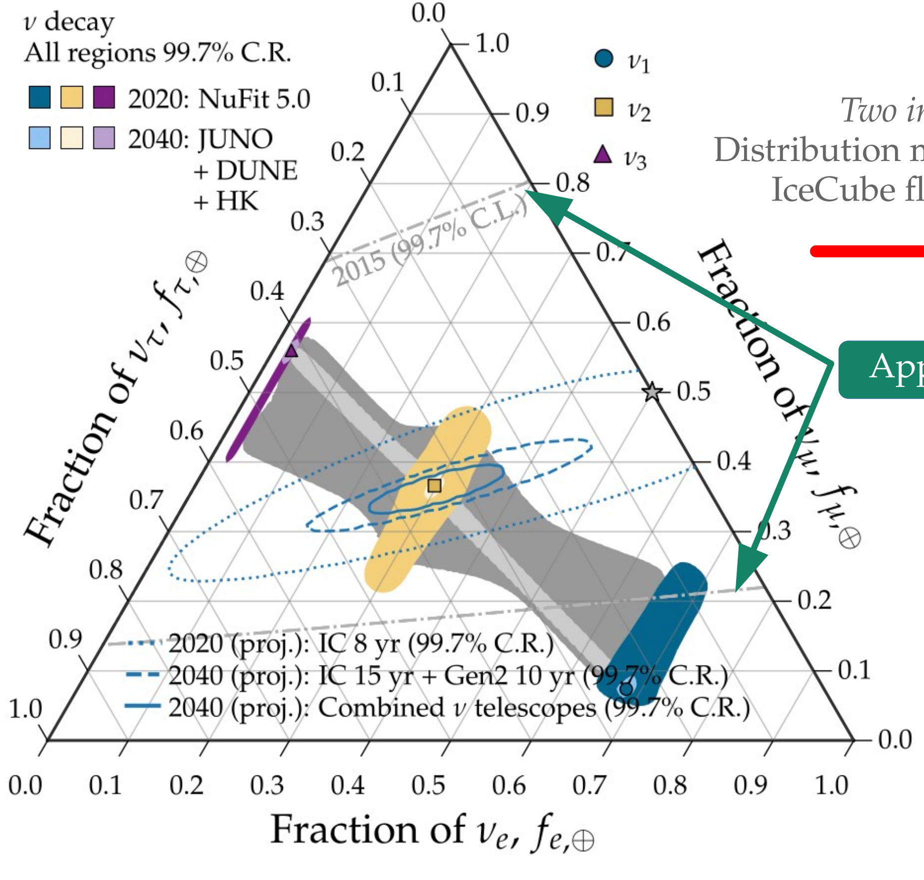

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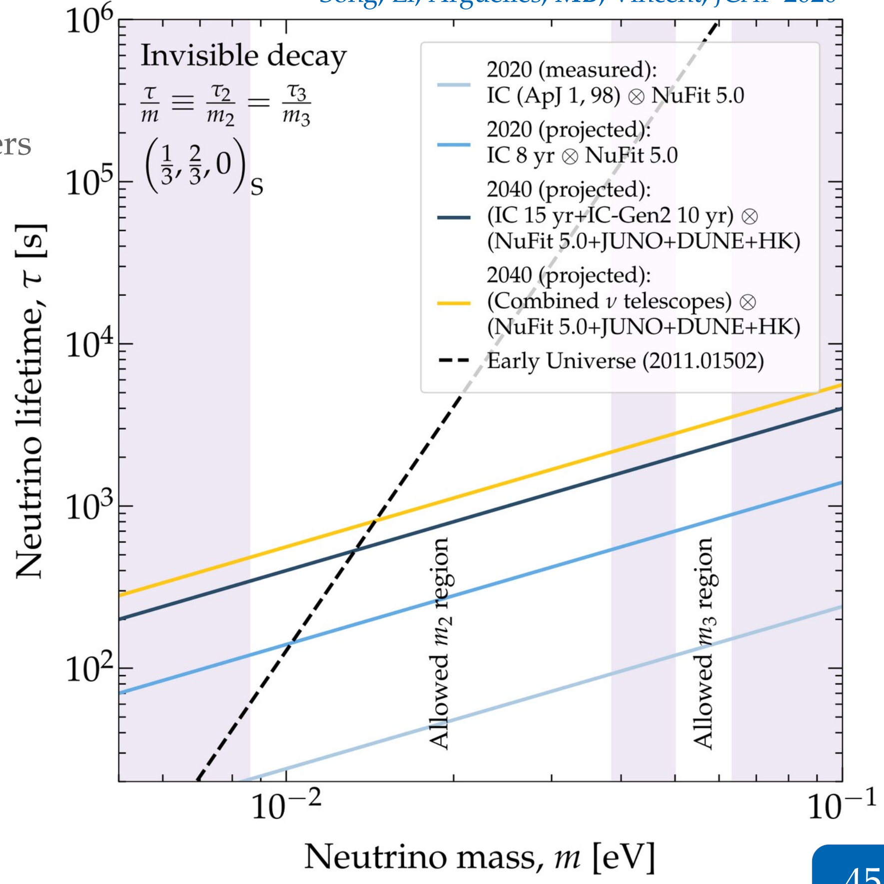
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2020



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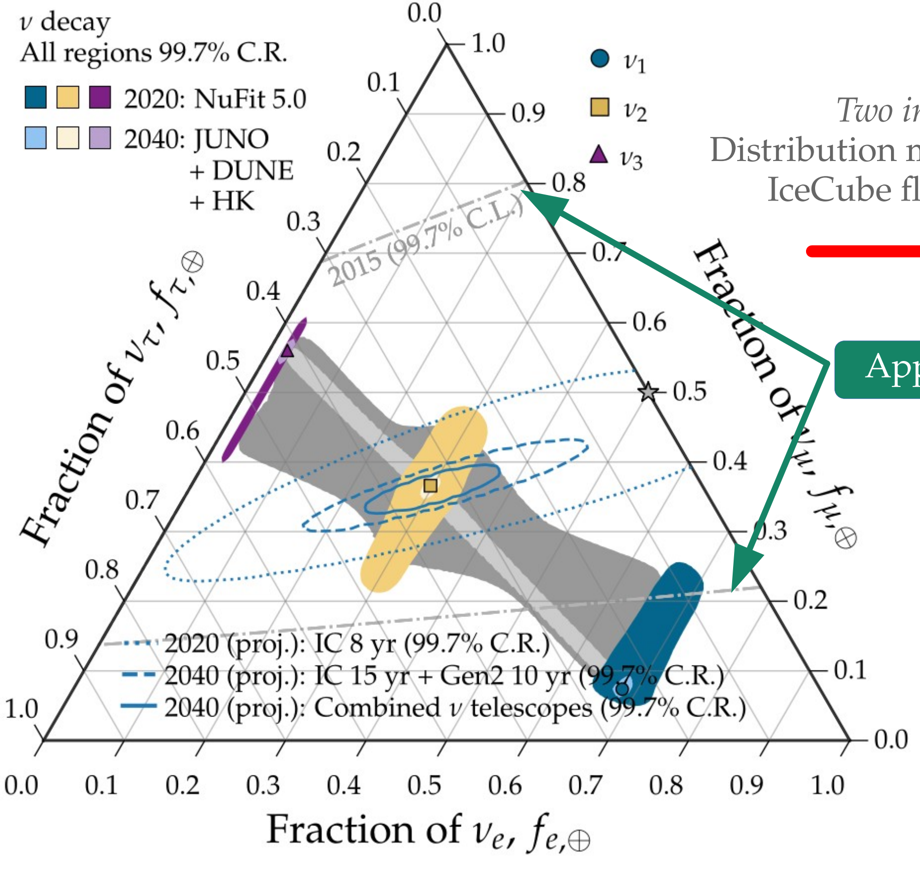

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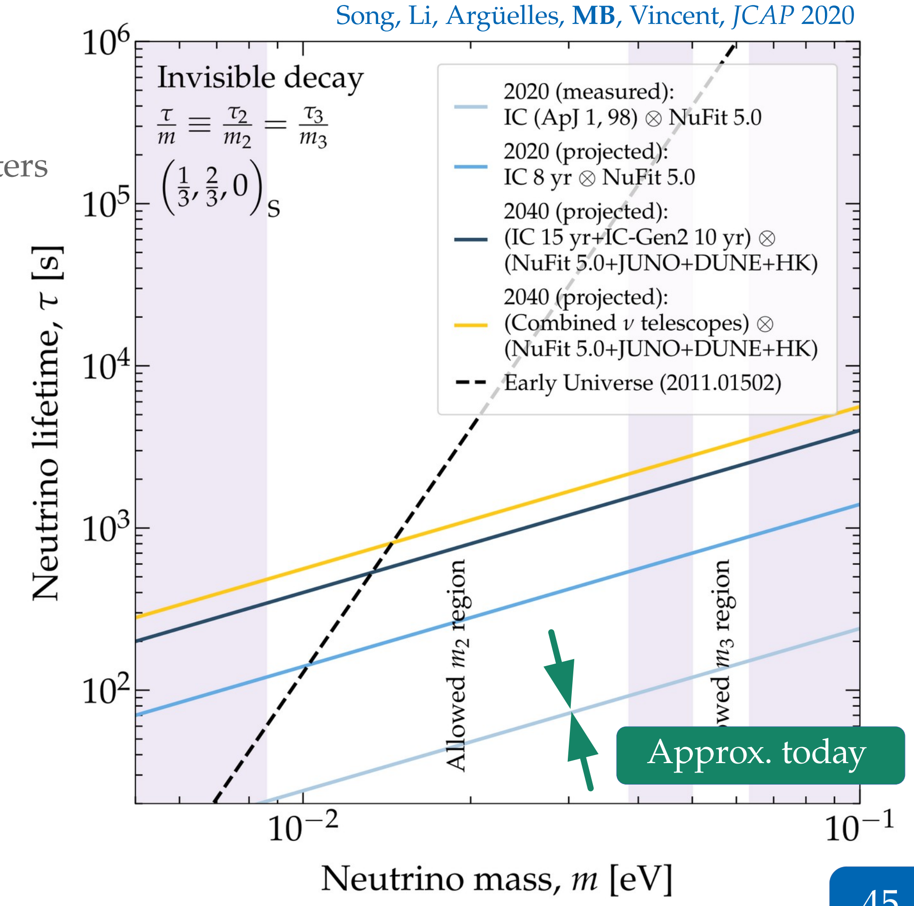

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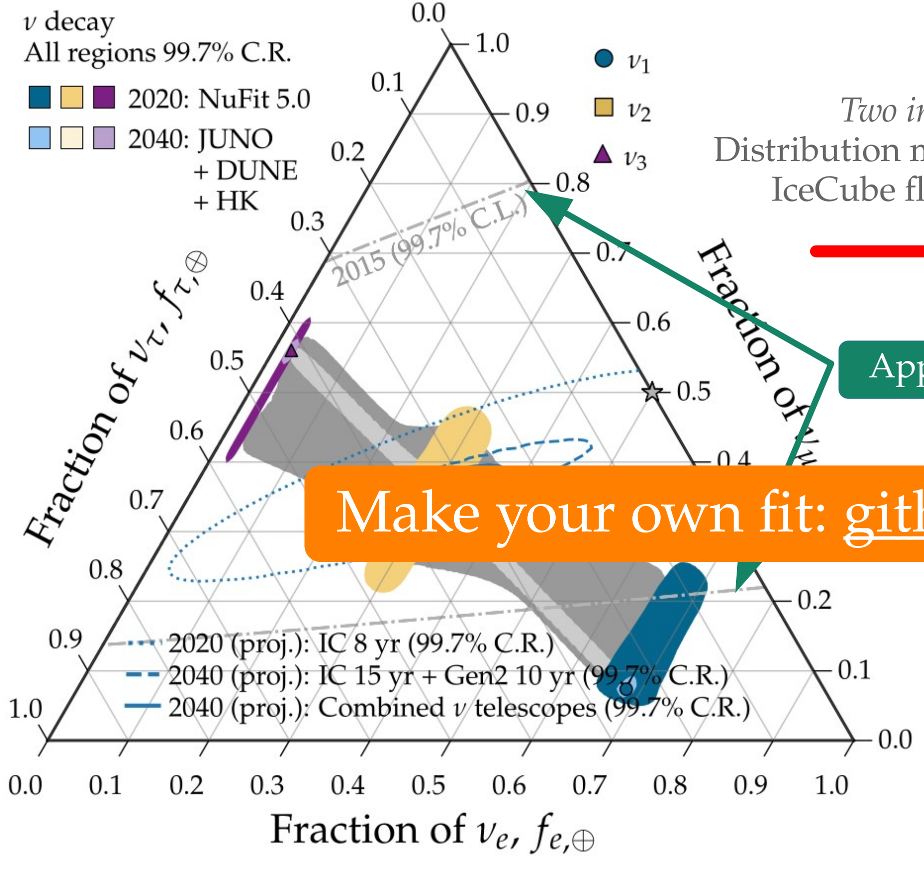

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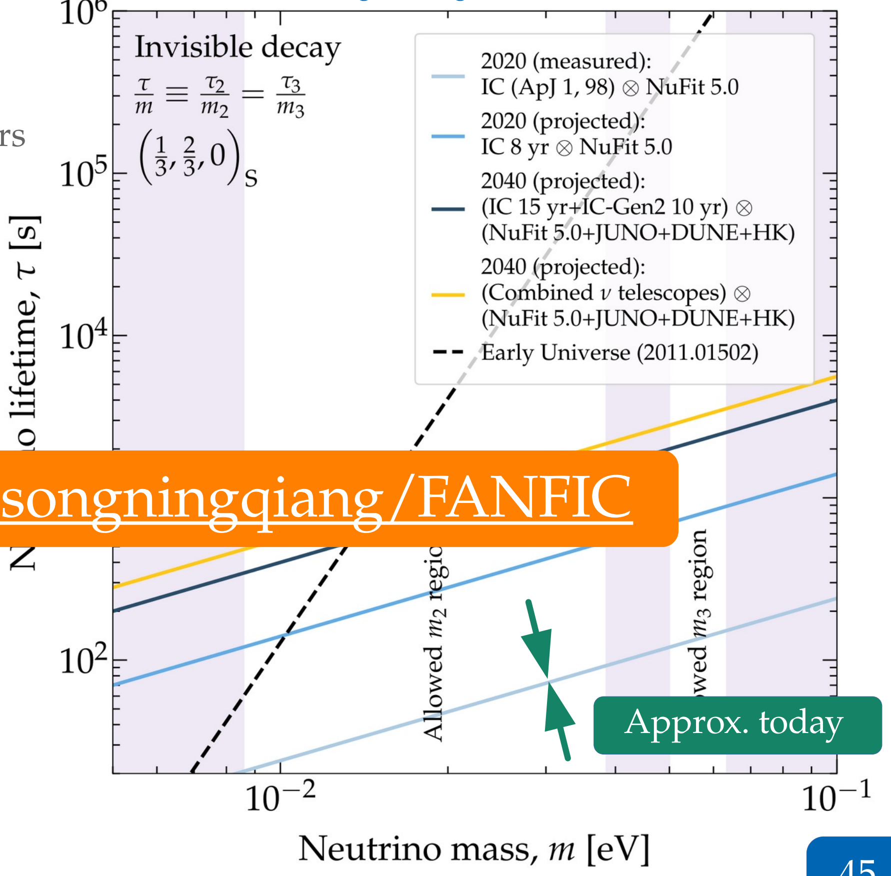
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2020

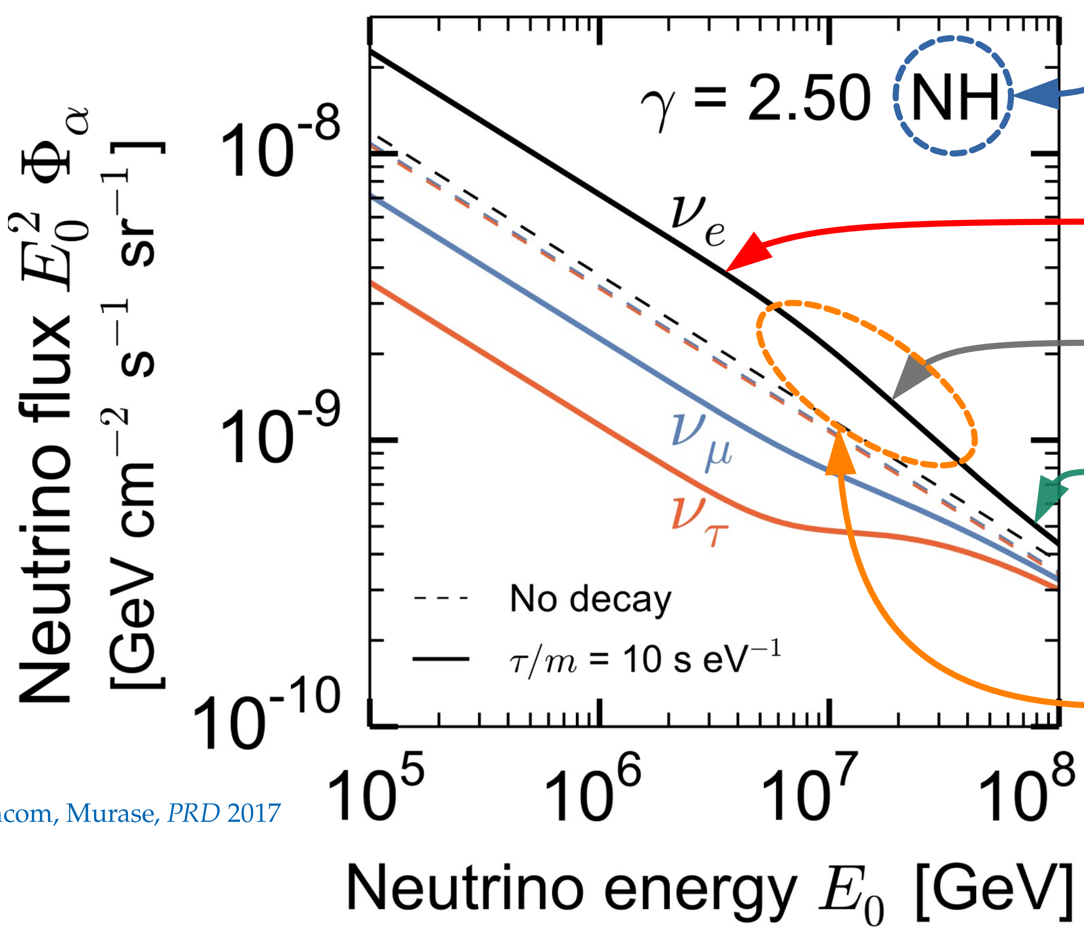


Make your own fit: github.com/songningqiang/FANFIC

What does neutrino decay change?

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

Flavor composition ⟺ Spectrum shape ⟺ Event rate



MB, Beacom, Murase, *PRD* 2017

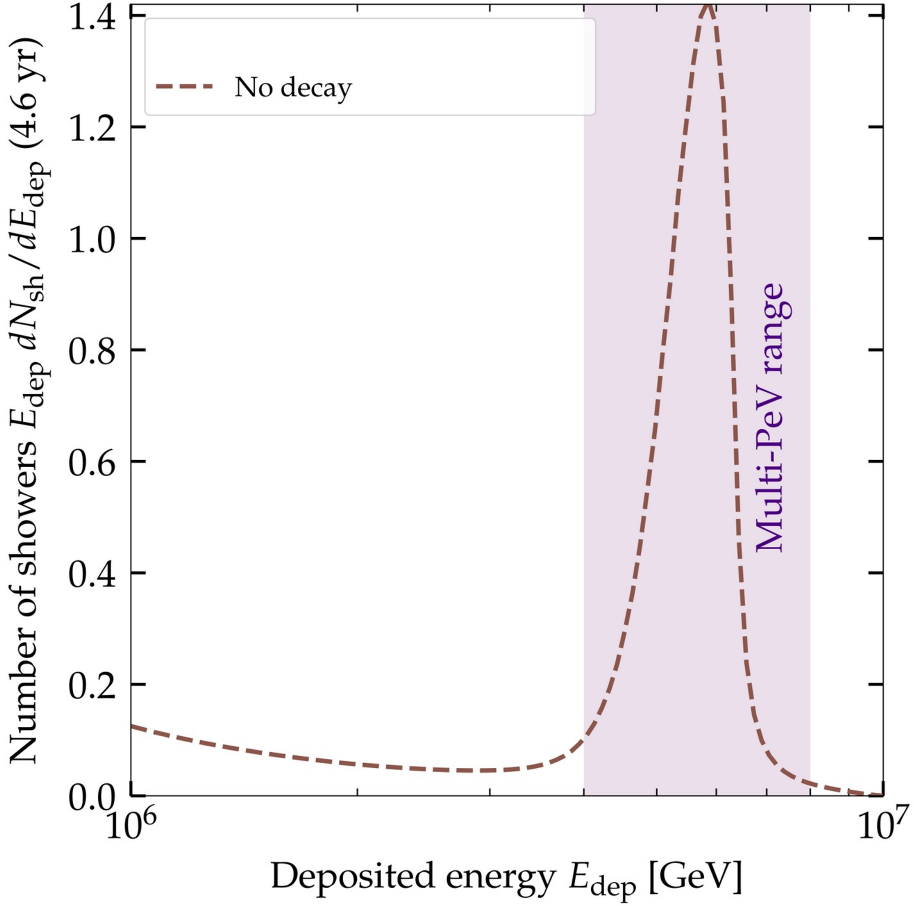
Look for sigmoid-like transition in spectrum: *challenging, but possible with more statistics*!

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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Flavor composition ⟺ Spectrum shape ⟺ Event rate

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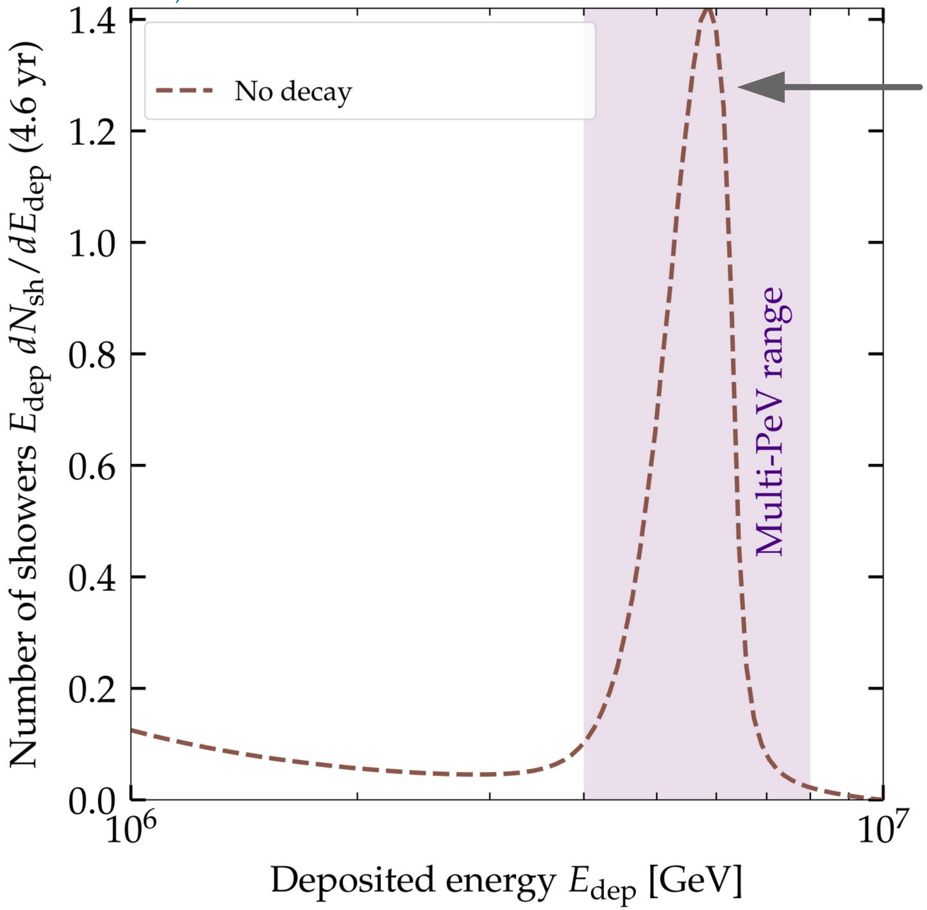

Glashow resonance (GR):
$\bar{\nu}_e + e \rightarrow W \rightarrow$ hadrons $\rightarrow$ shower

What does neutrino decay change?

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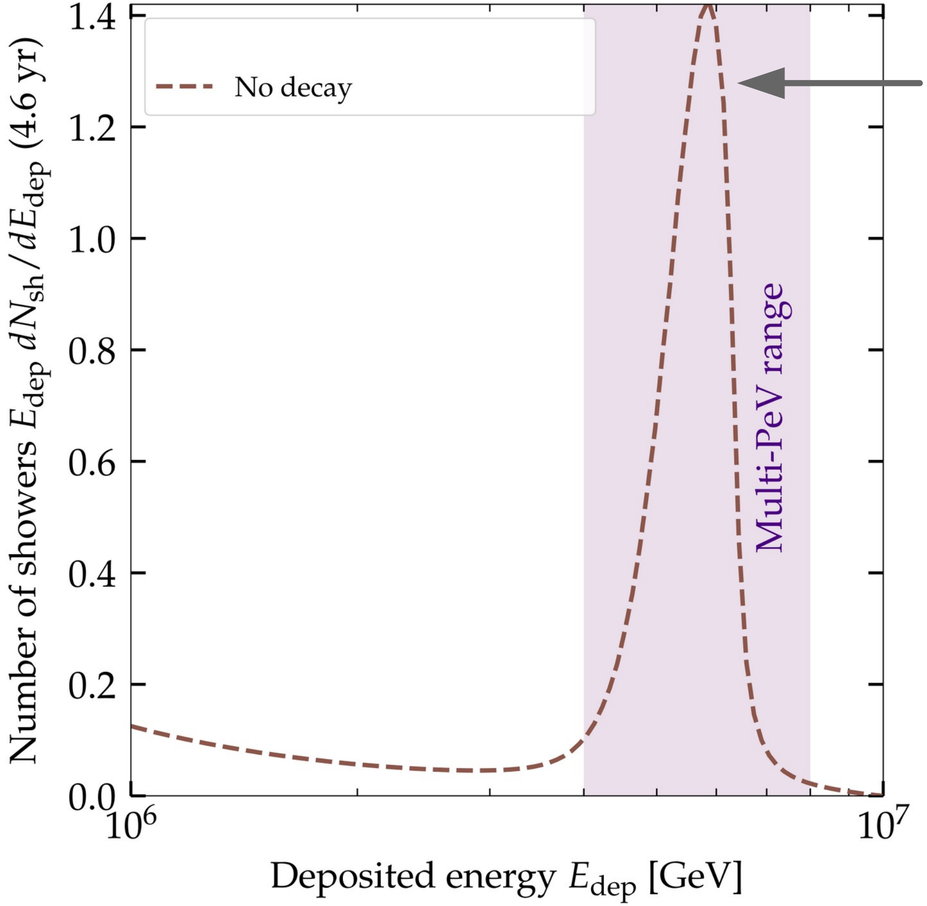
Flavor composition ⟺ Spectrum shape ⟺ **Event rate**

MB, 2004.06844



Glashow resonance (GR):
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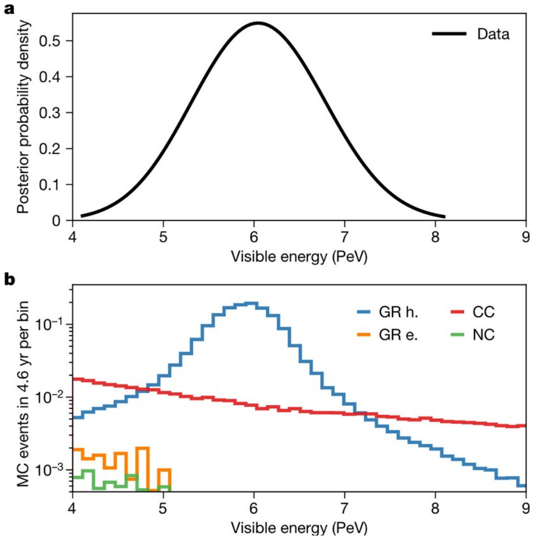
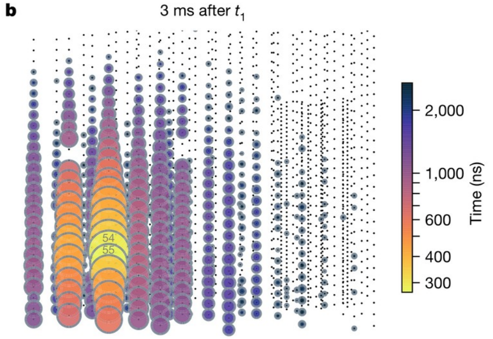
IceCube has seen one GR candidate in 4.6 years:





IceCube Collab., *Nature* 2021

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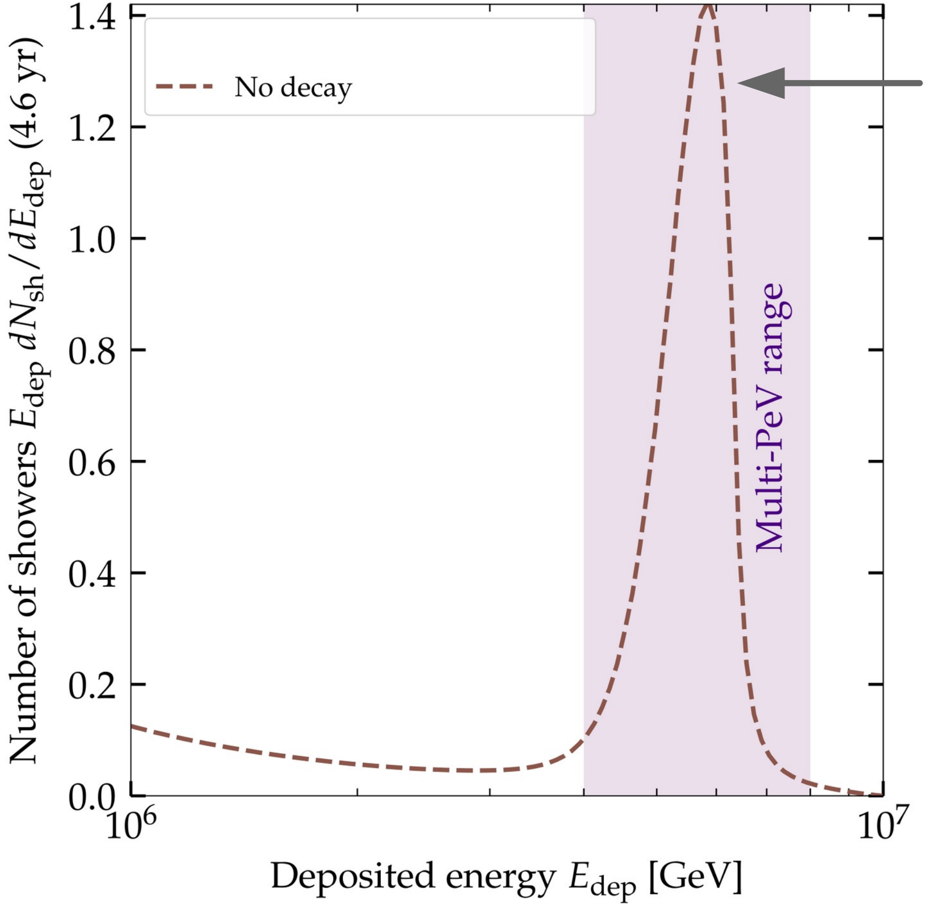
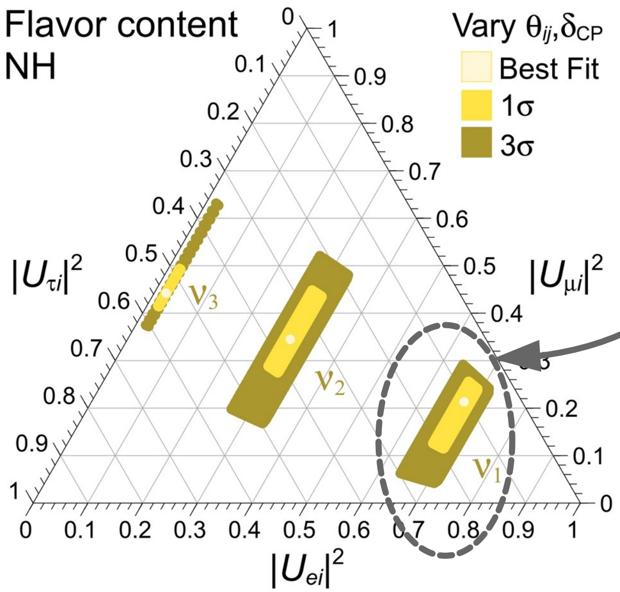
Flavor composition ⟺ Spectrum shape ⟺ **Event rate**

MB, 2004.06844



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

ν_1 is the mass eigenstate with the most e flavor



What does neutrino decay change?

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

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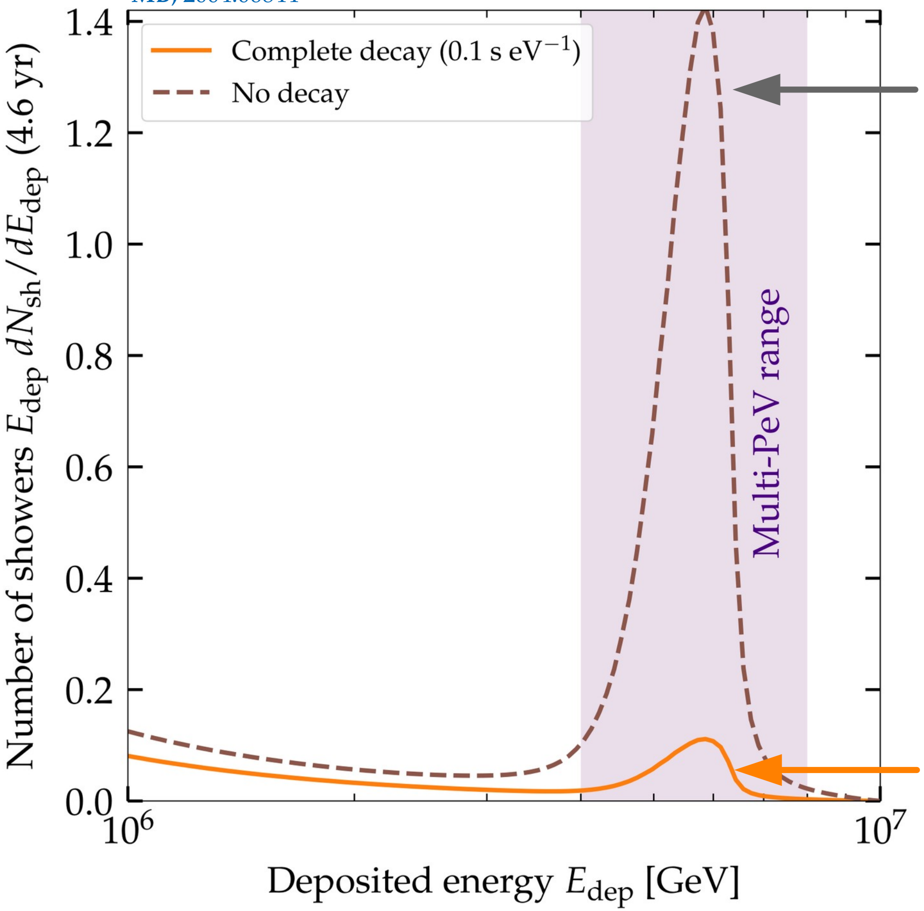

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If $\bar{\nu}_1$ had decayed en route to Earth, there would not have been $\bar{\nu}_e$ left to trigger a GR

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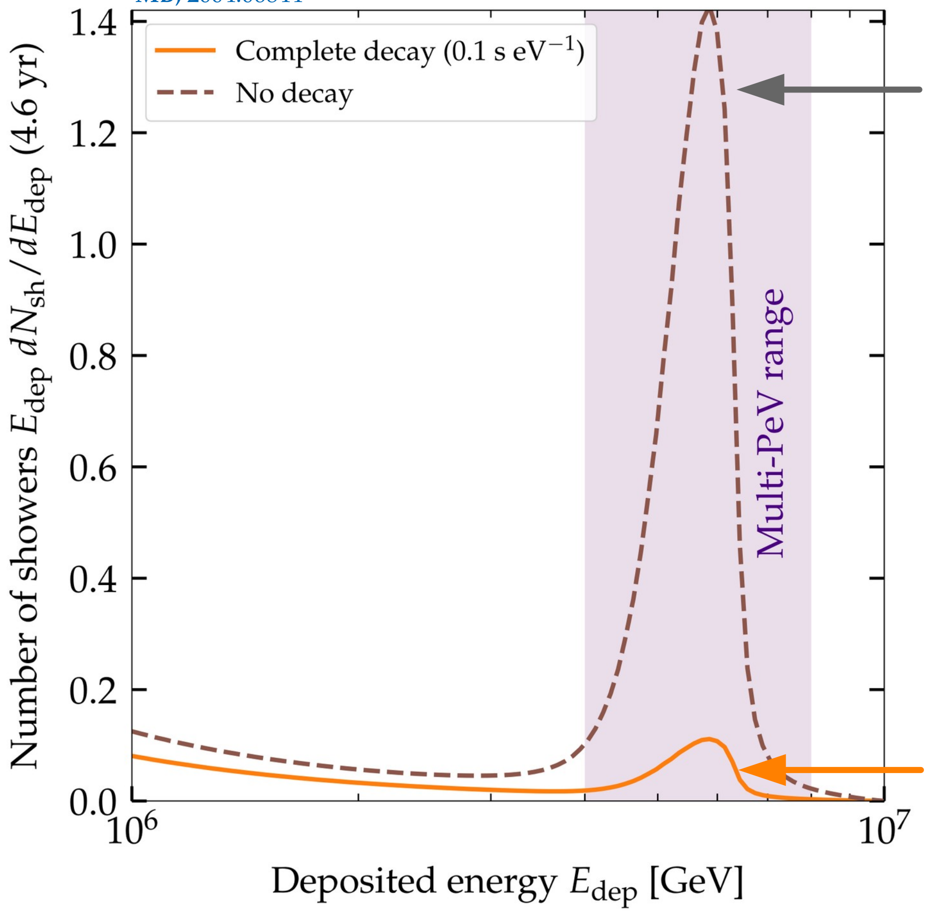

Glashow resonance (GR):
$\bar{\nu}_e + e \rightarrow W \rightarrow$ hadrons $\rightarrow$ shower

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

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

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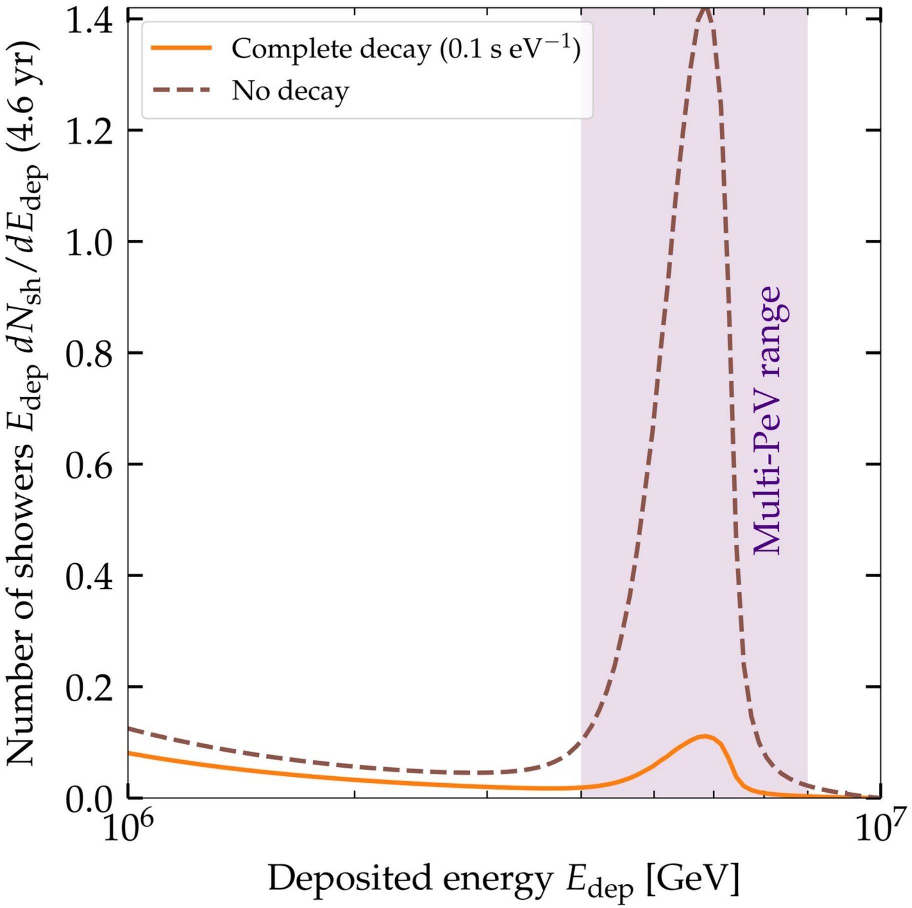

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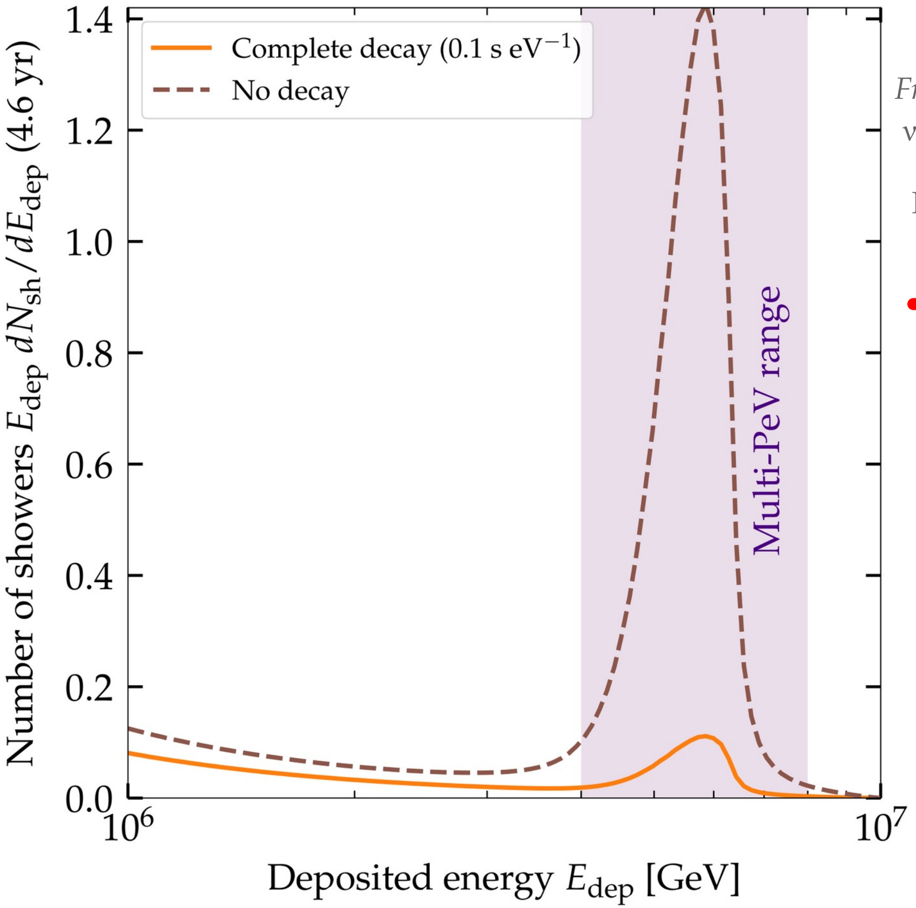

Free parameters:
ν_1, ν_2 lifetimes
Mix. par.
Flavor ratios
$\bar{\nu}/\nu$ ratio

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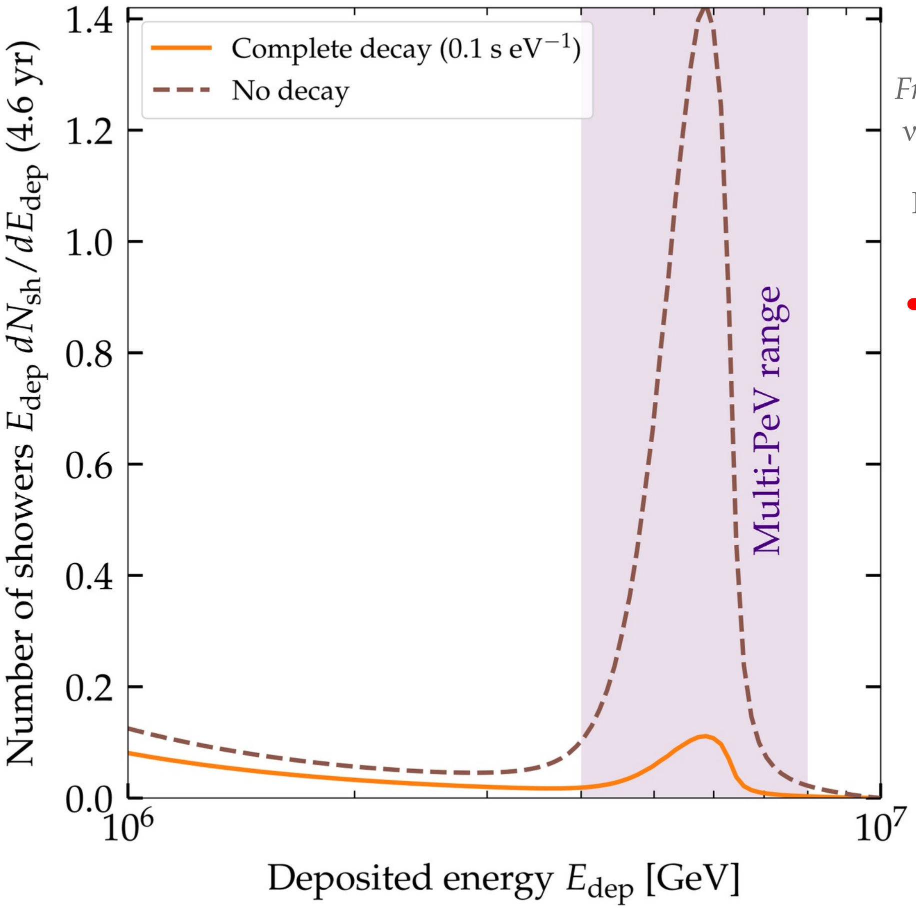

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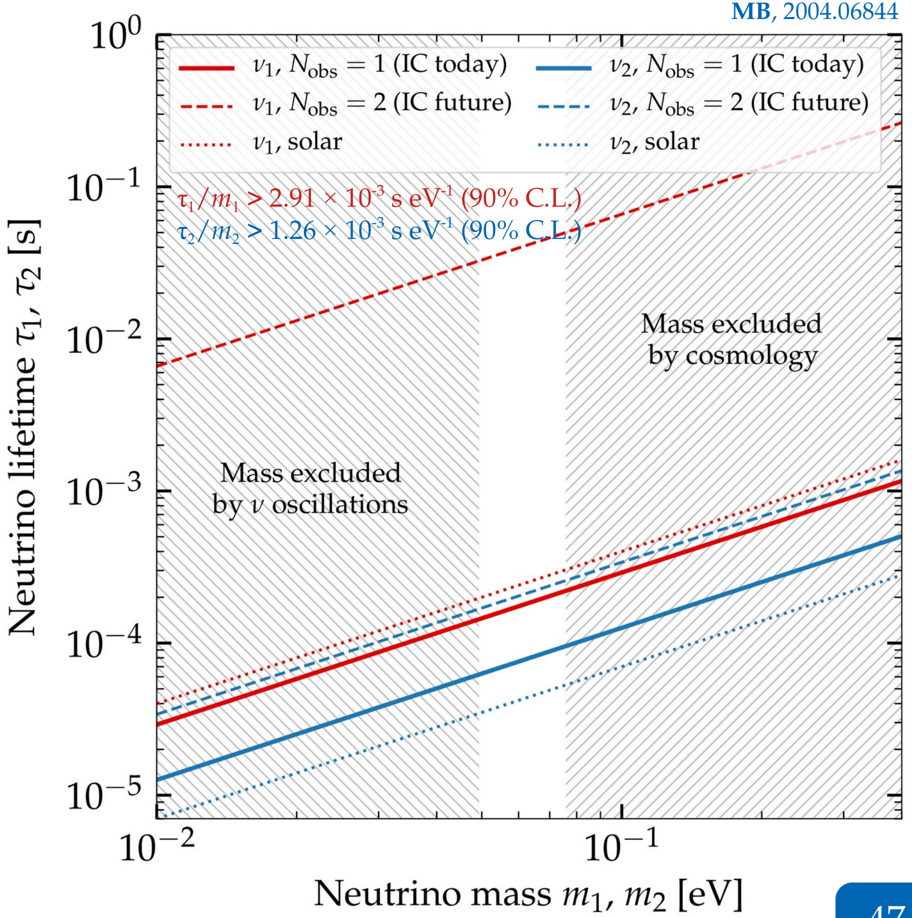

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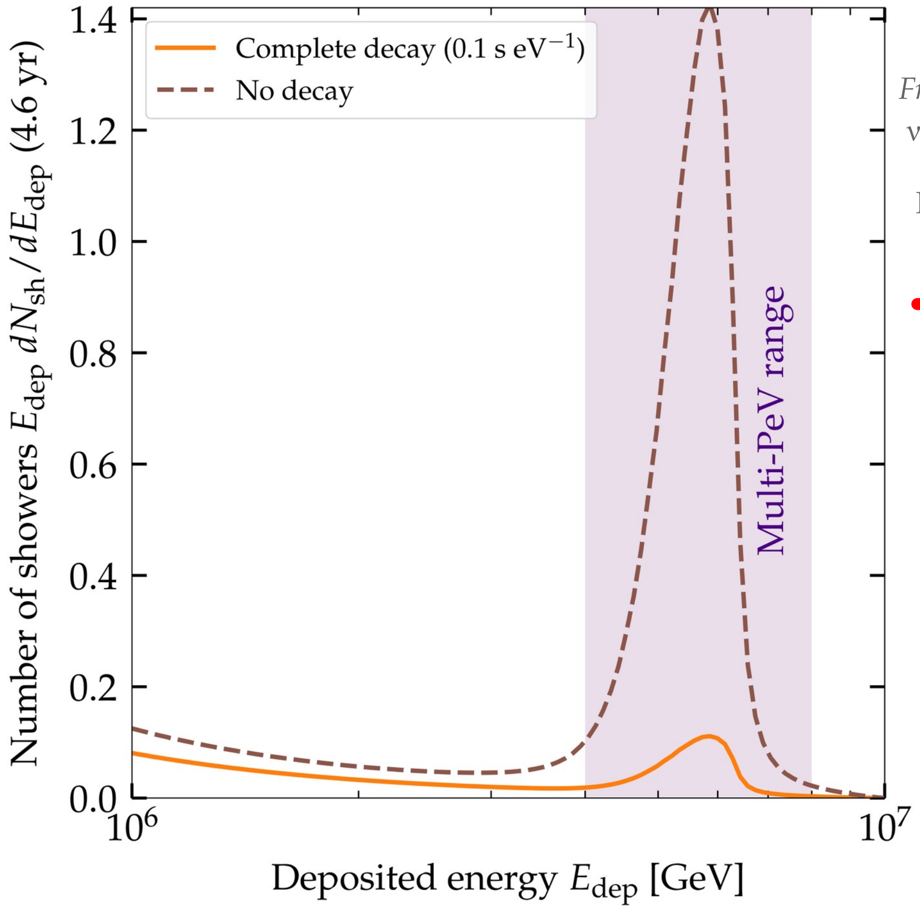

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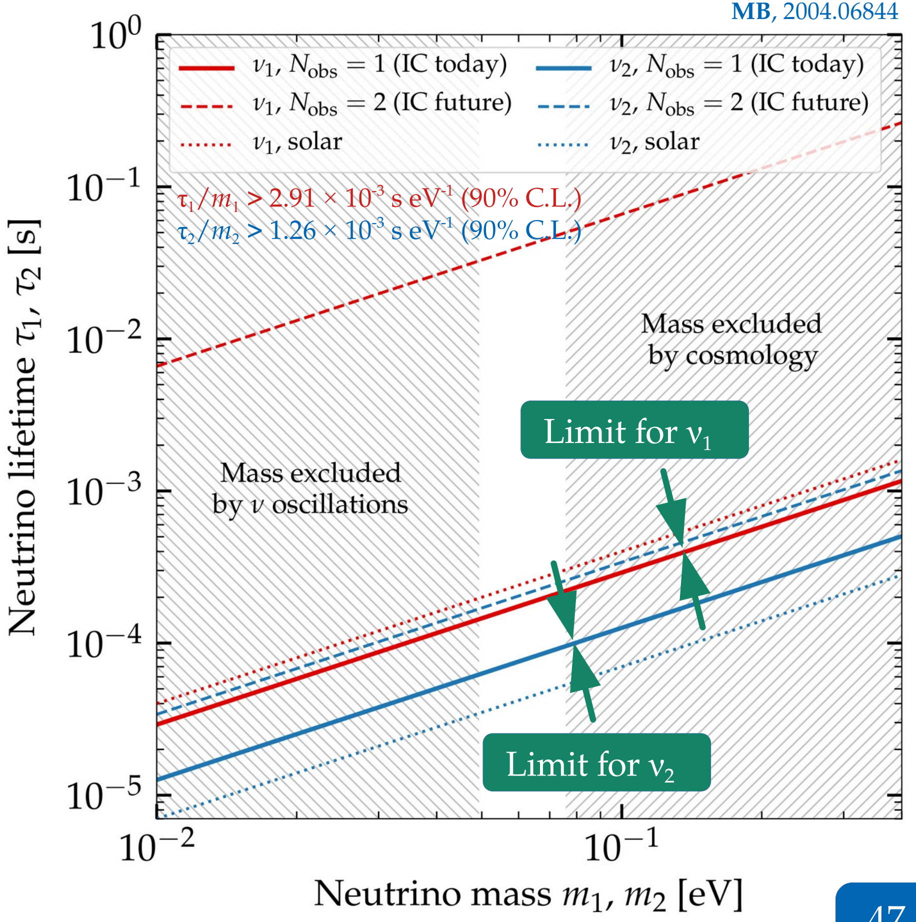

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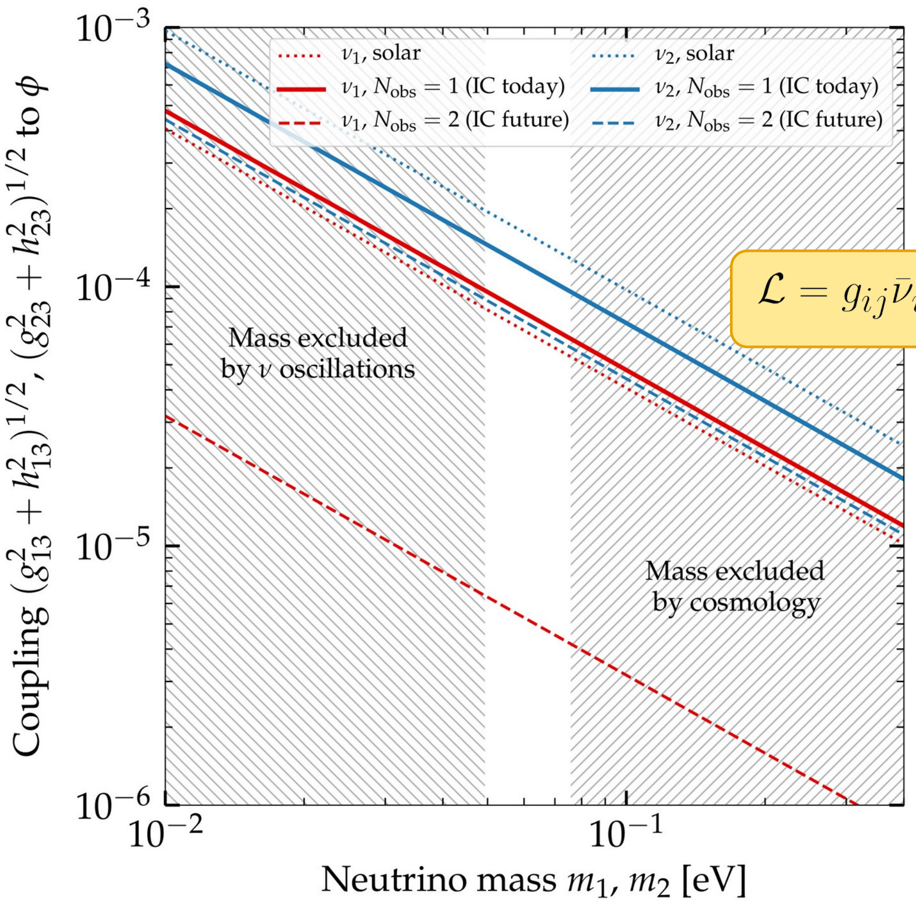

$$\mathcal{L} = g_{ij}\bar{\nu}_i\nu_j\phi + h_{ij}\bar{\nu}_i\gamma_5\nu_j\phi + \text{h.c.}$$

Lower limits on couplings

What does neutrino decay change?

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Flavor composition ⟺ Spectrum shape ⟺ Event rate

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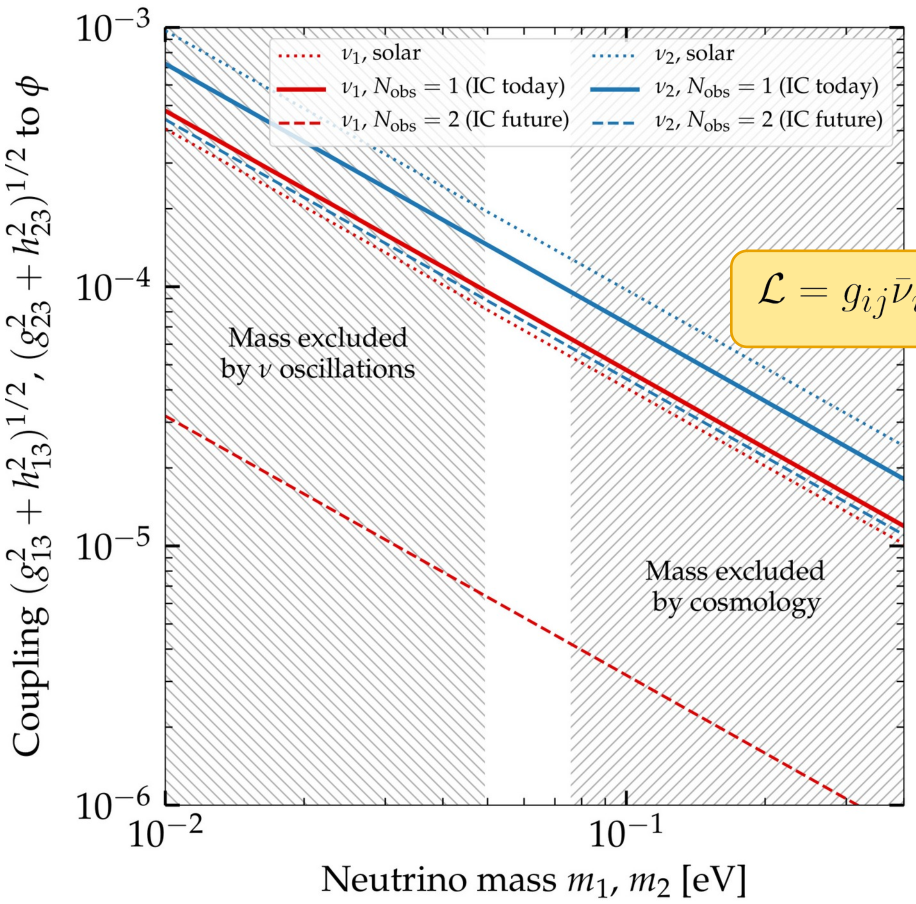

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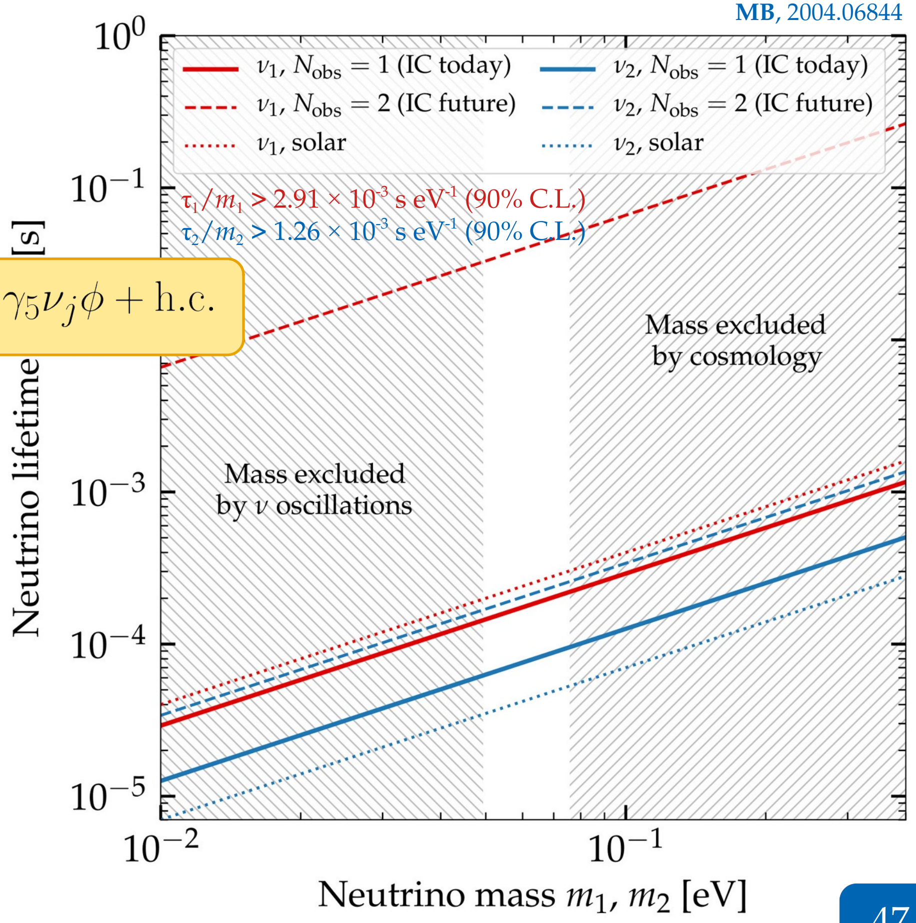

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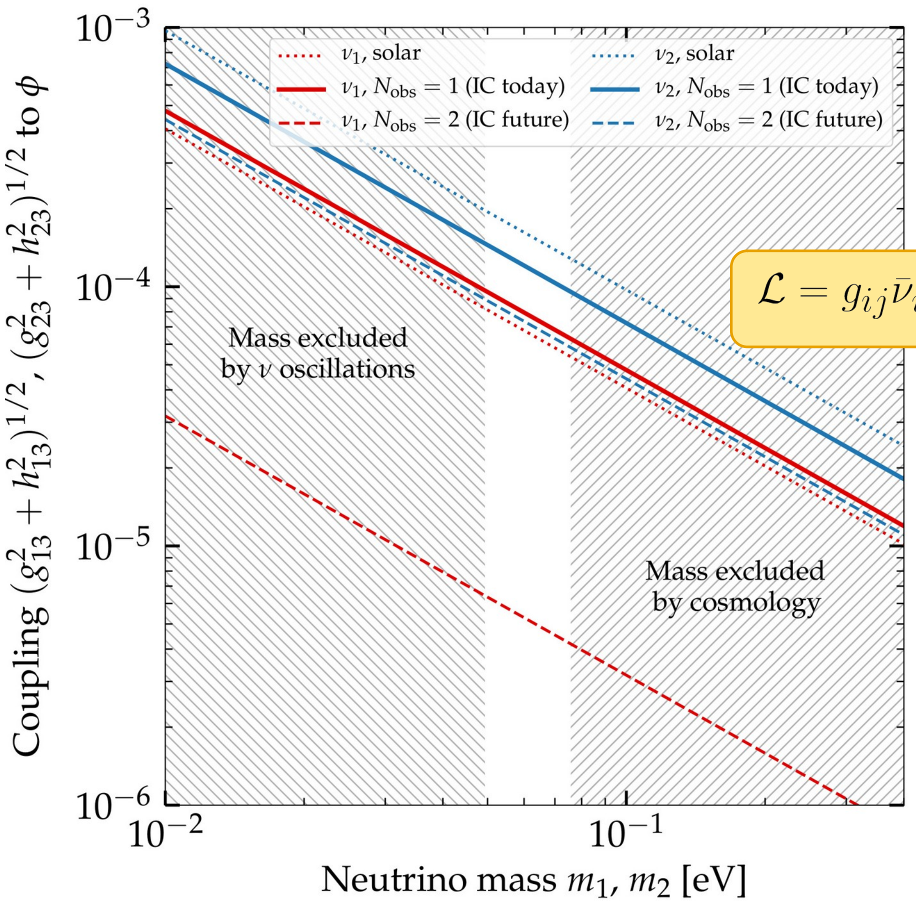
Flavor composition ⟺ Spectrum shape ⟺ **Event rate**

MB, 2004.06844



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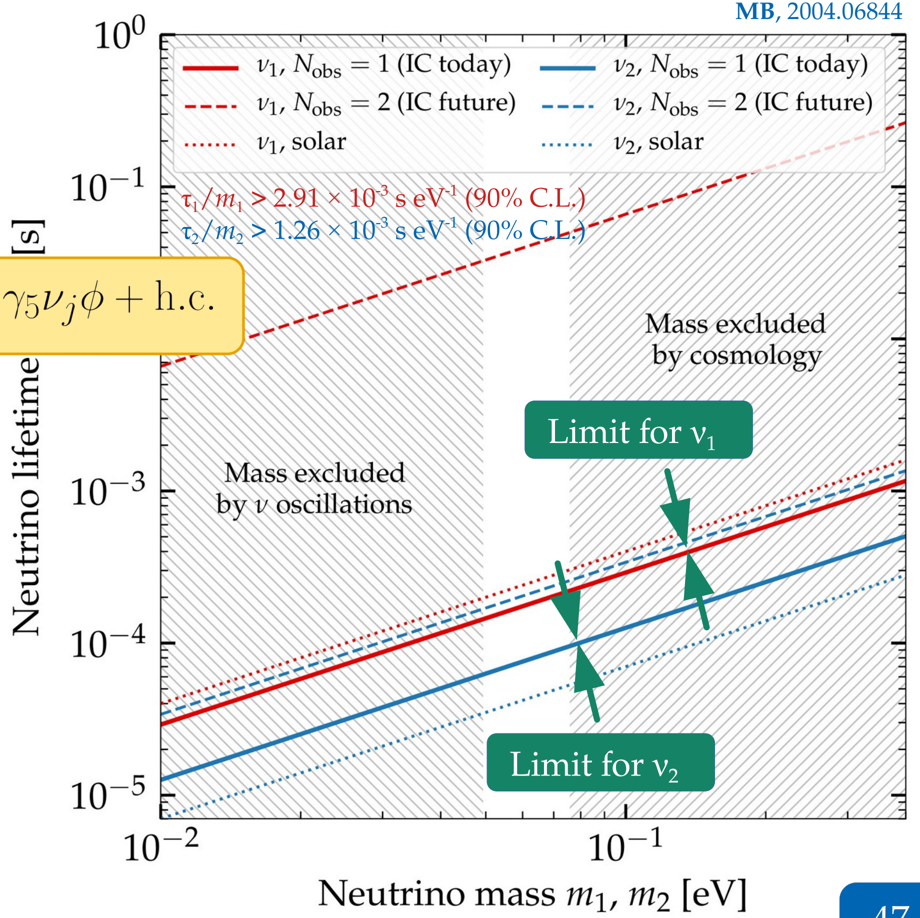


What does neutrino decay change?

Flavor composition ⟺ Spectrum shape ⟺ Event rate

What does neutrino decay change?

Flavor composition + Spectrum shape + Event rate

Joint analysis: pending, worth trying now
(*work in progress*)

Side note:
We need only larger statistics, not higher energies
(because higher energies = longer-lived neutrinos)

New-physics menu

1. Neutrino-matter cross section
2. Unstable neutrinos
3. **New neutrino interactions**
4. Neutrinos & dark matter
5. Flavor composition
6. Physics with individual sources
7. ANITA mystery events

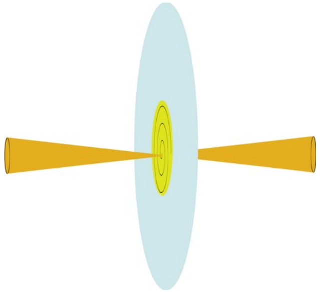
Astrophysical neutrino sources

Earth

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

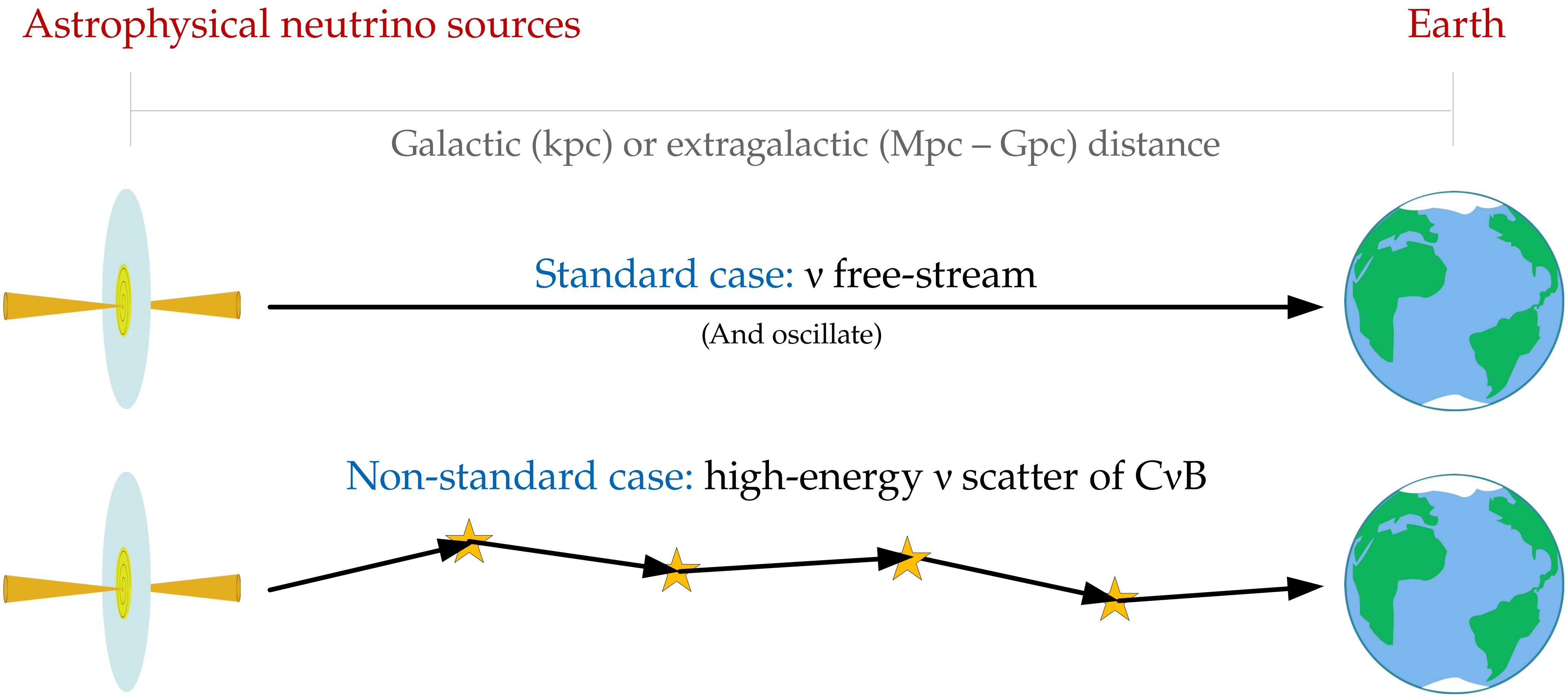
Astrophysical neutrino sources — Earth

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



Standard case: ν free-stream

(And oscillate)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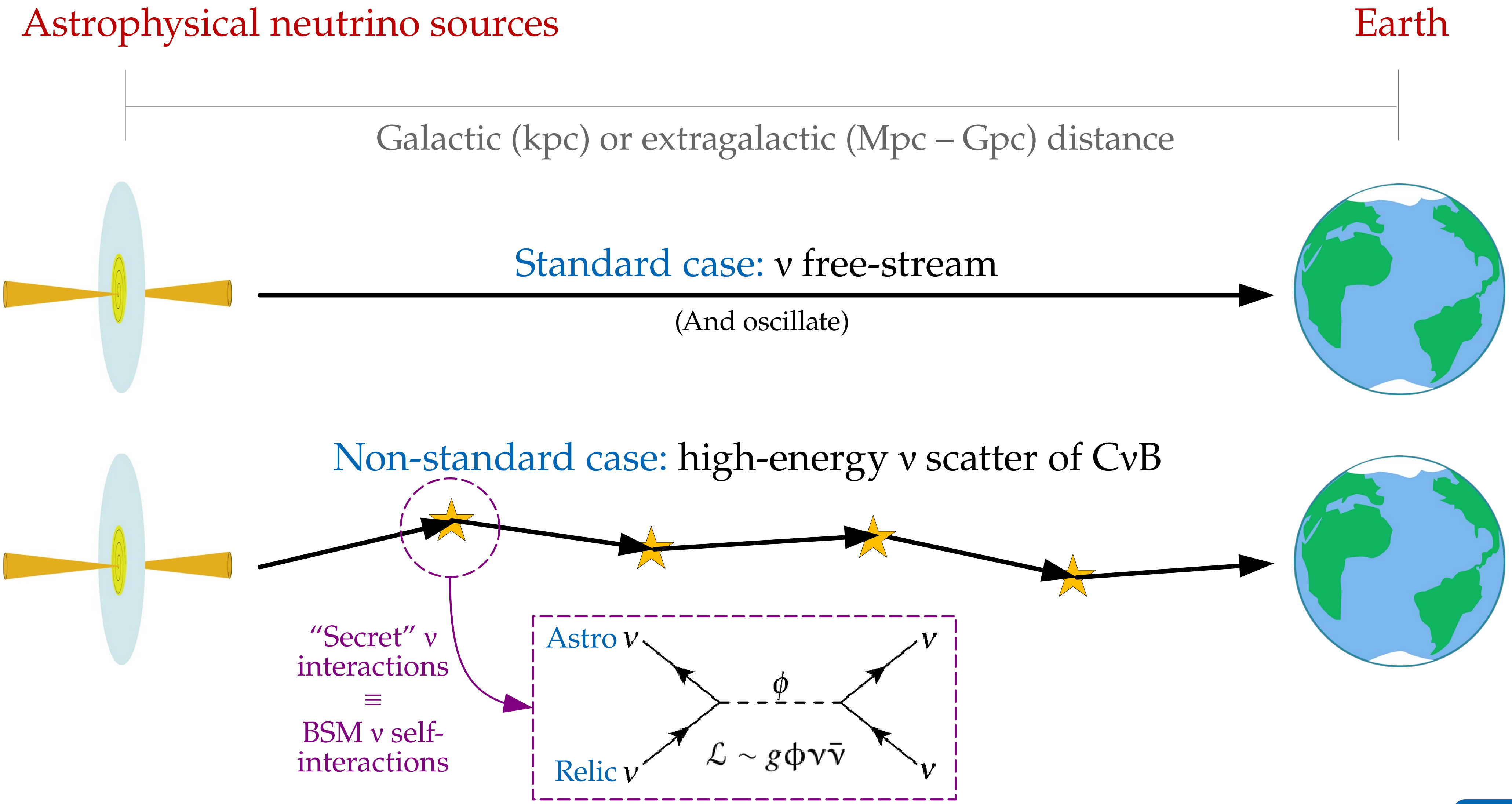
Non-standard case: high-energy ν scatter of CνB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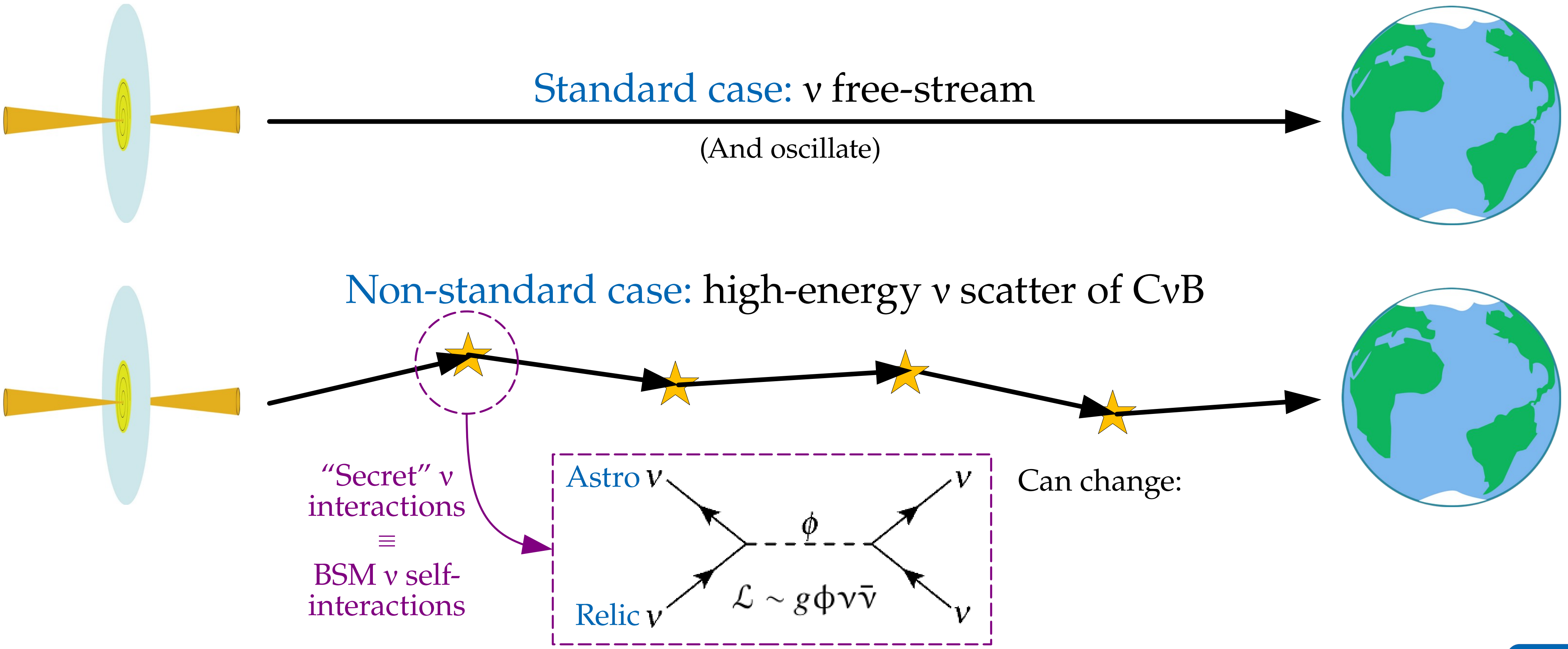
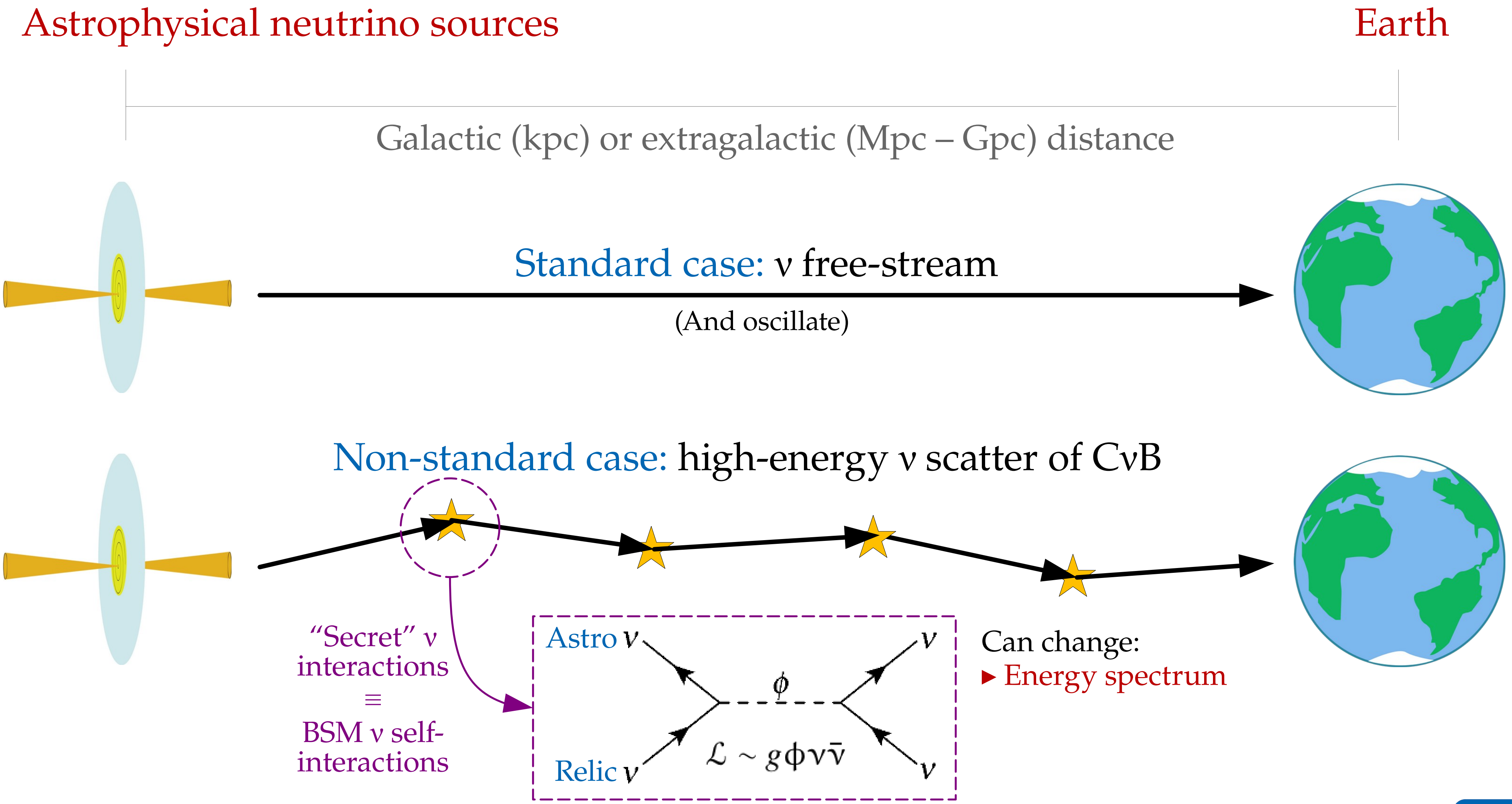
"Secret" ν interactions ≡ BSM ν self-interactions
Astro ν
Relic ν
ν
ν
ϕ
$\mathcal{L} \sim g\phi\nu\bar{\nu}$

Astrophysical neutrino sources — Earth

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

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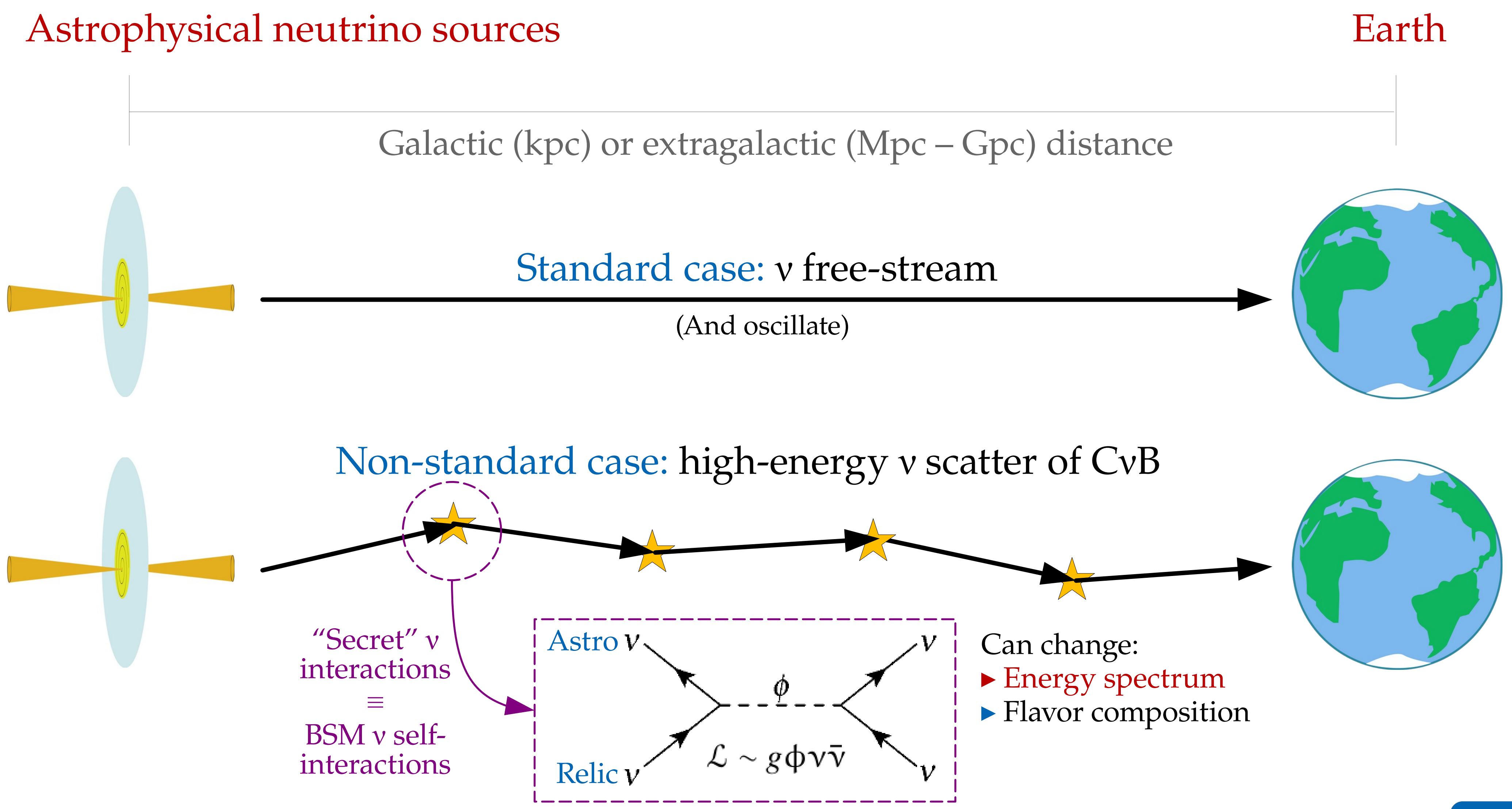
Can change:
▸ Energy spectrum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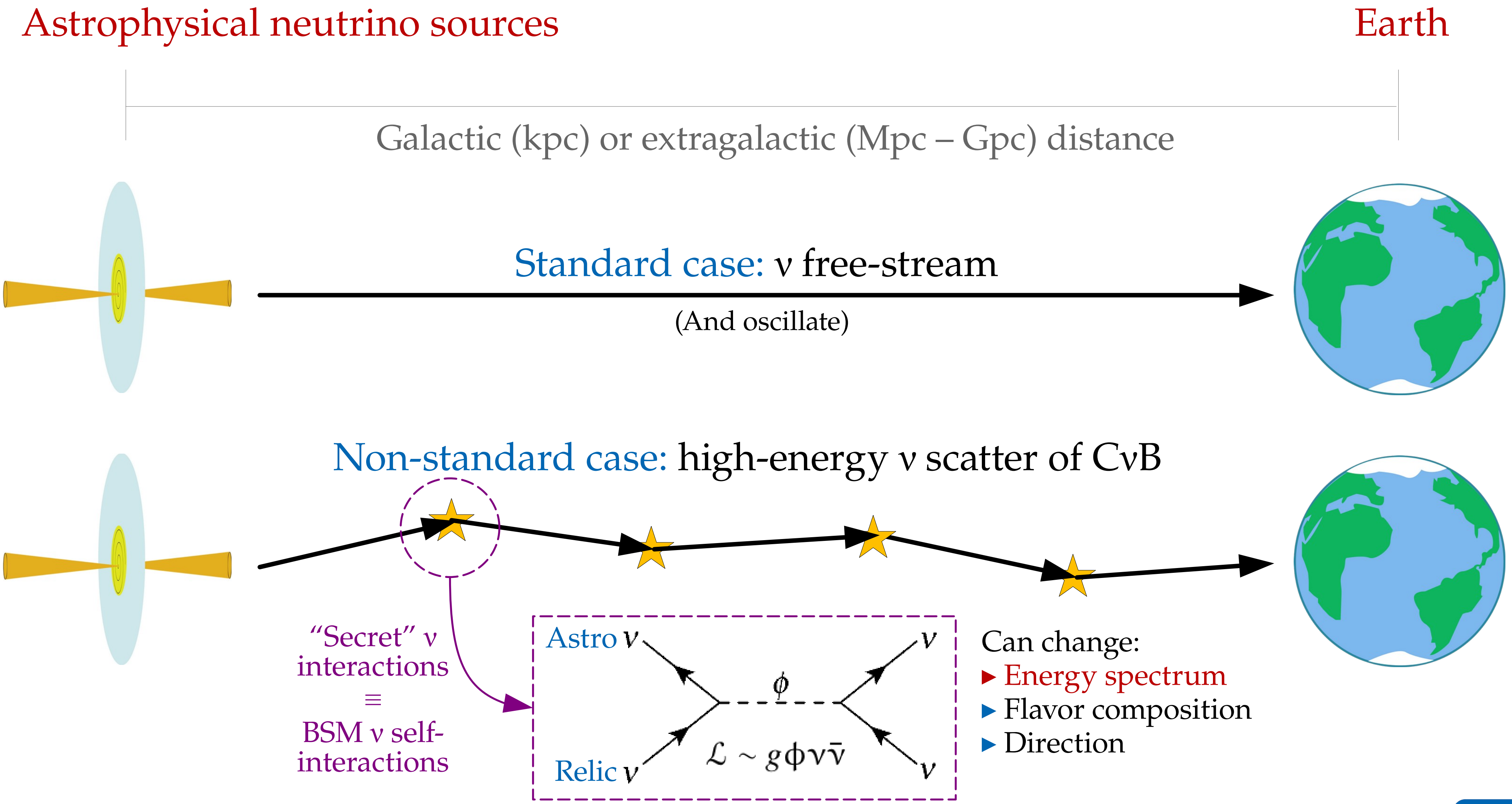
Can change:
▸ Energy spectrum
▸ Flavor composition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Can change:
Energy spectrum
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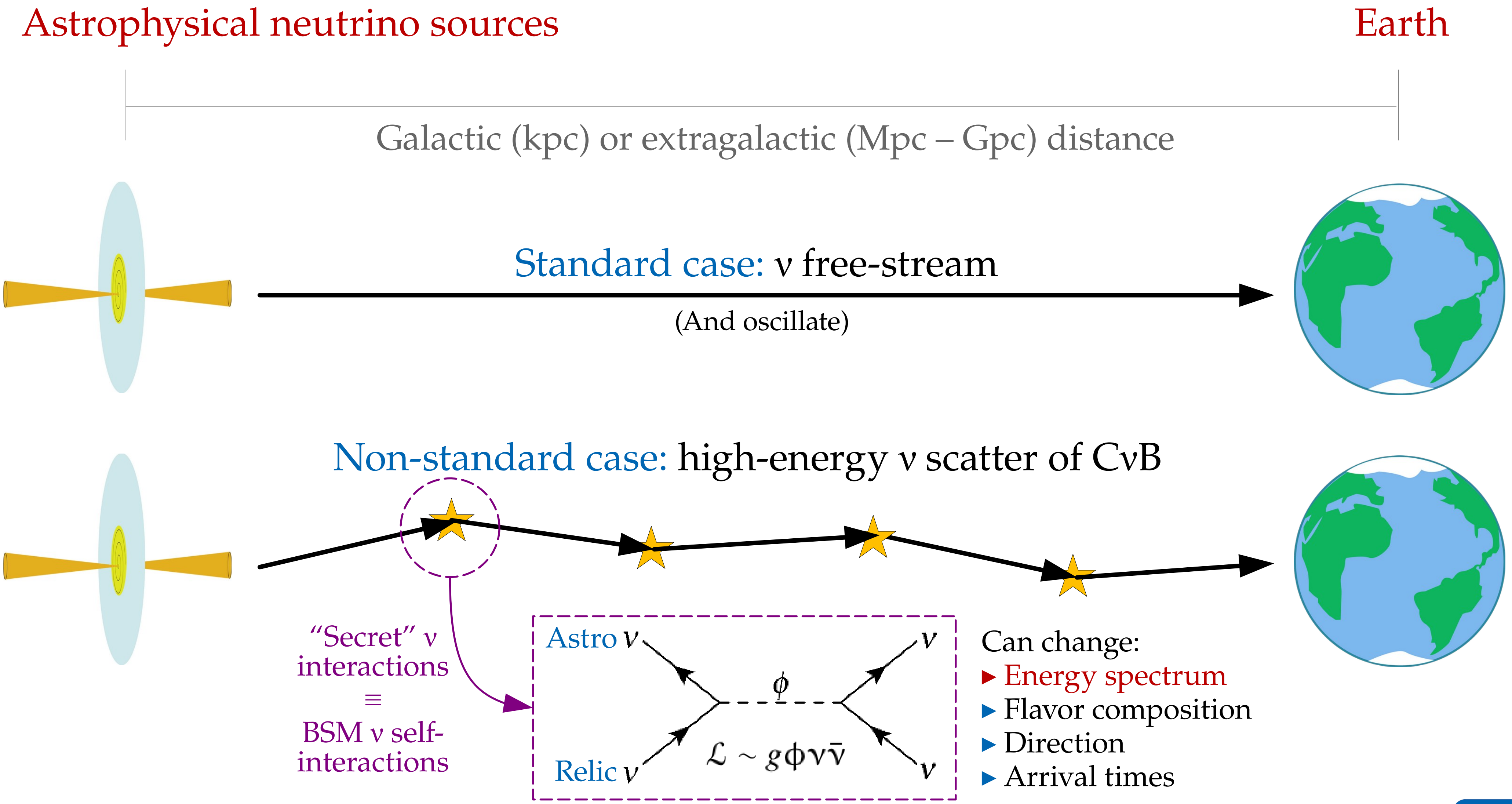
Direction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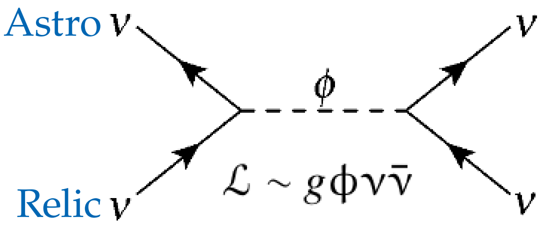
Can change:
▸ Energy spectrum
▸ Flavor composition
▸ Direction
▸ Arrival times

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

MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020

See also: Esteban, Pandey, Brdar, Beacom, *PRD* 2021
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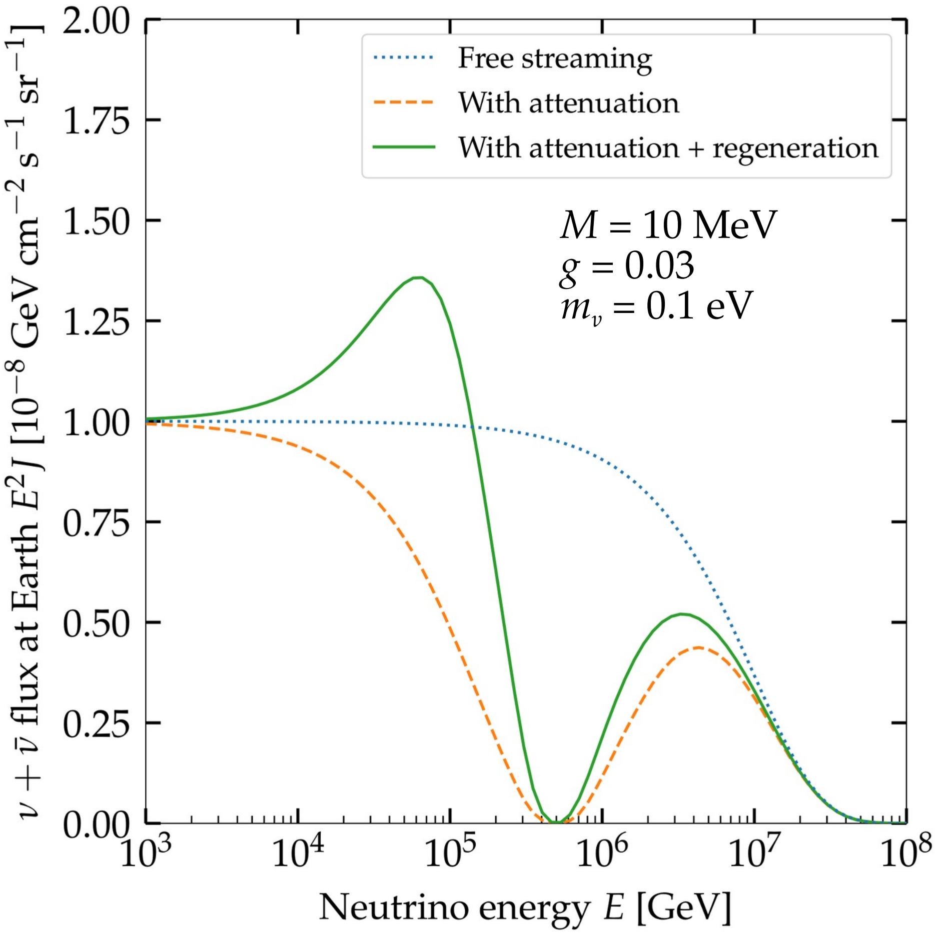
Ng & Beacom, *PRD* 2014
Cherry, Friedland, Shoemaker, 1411.1071
Blum, Hook, Murase, 1408.3799



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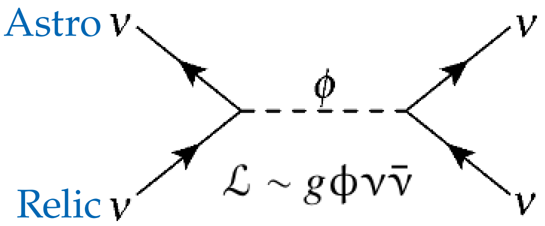

New coupling

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

Mediator mass

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

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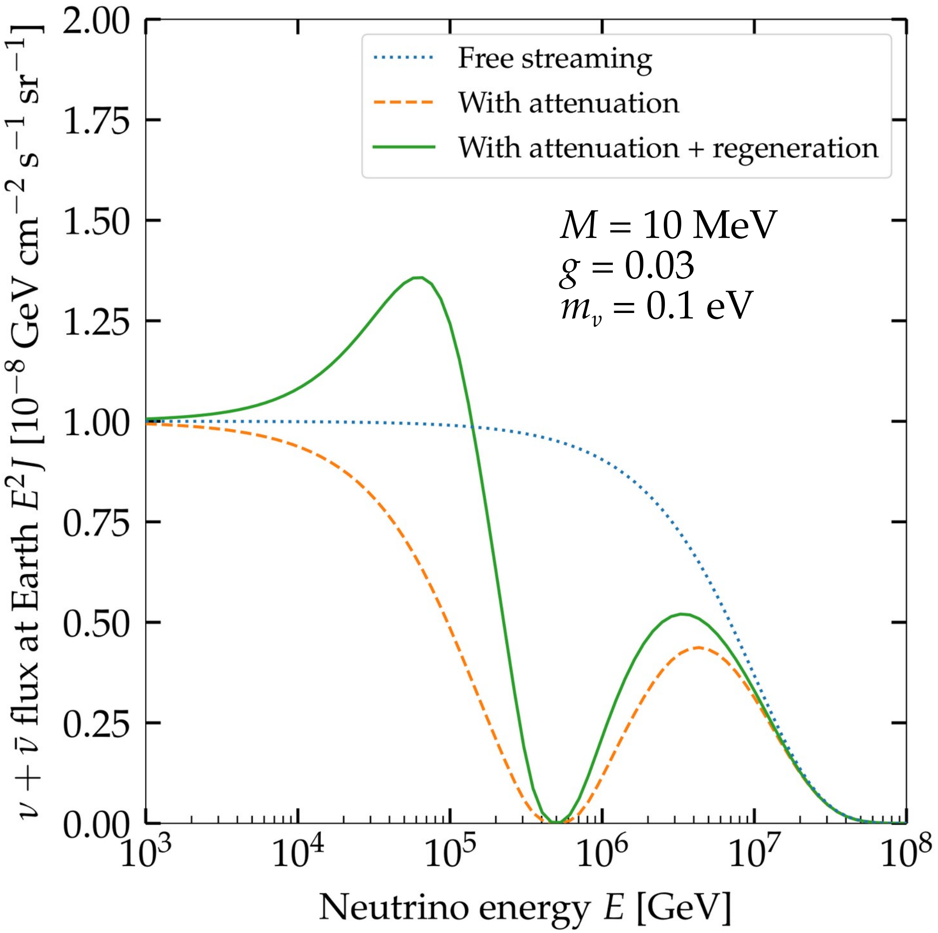

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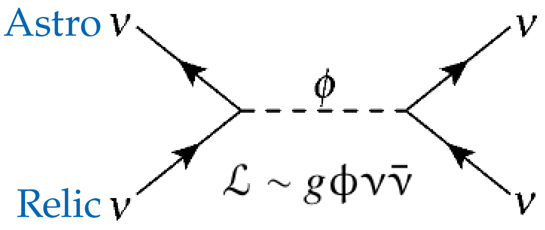

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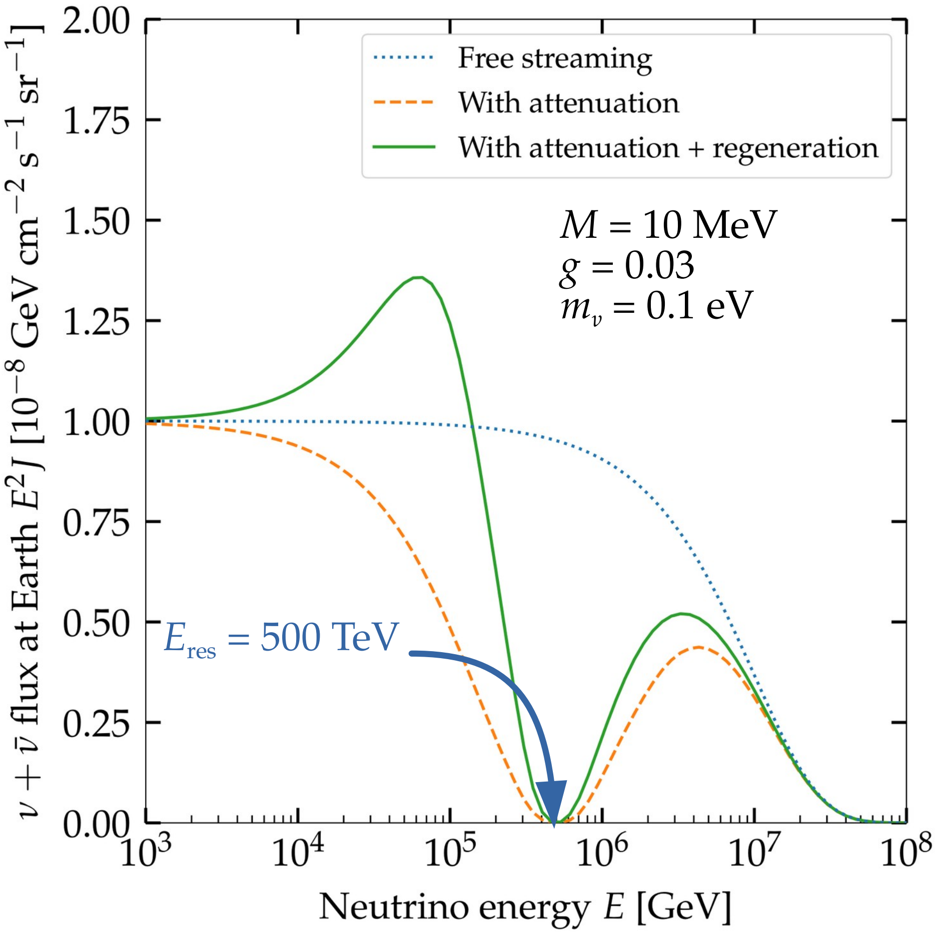

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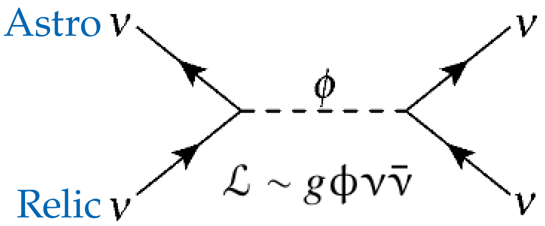

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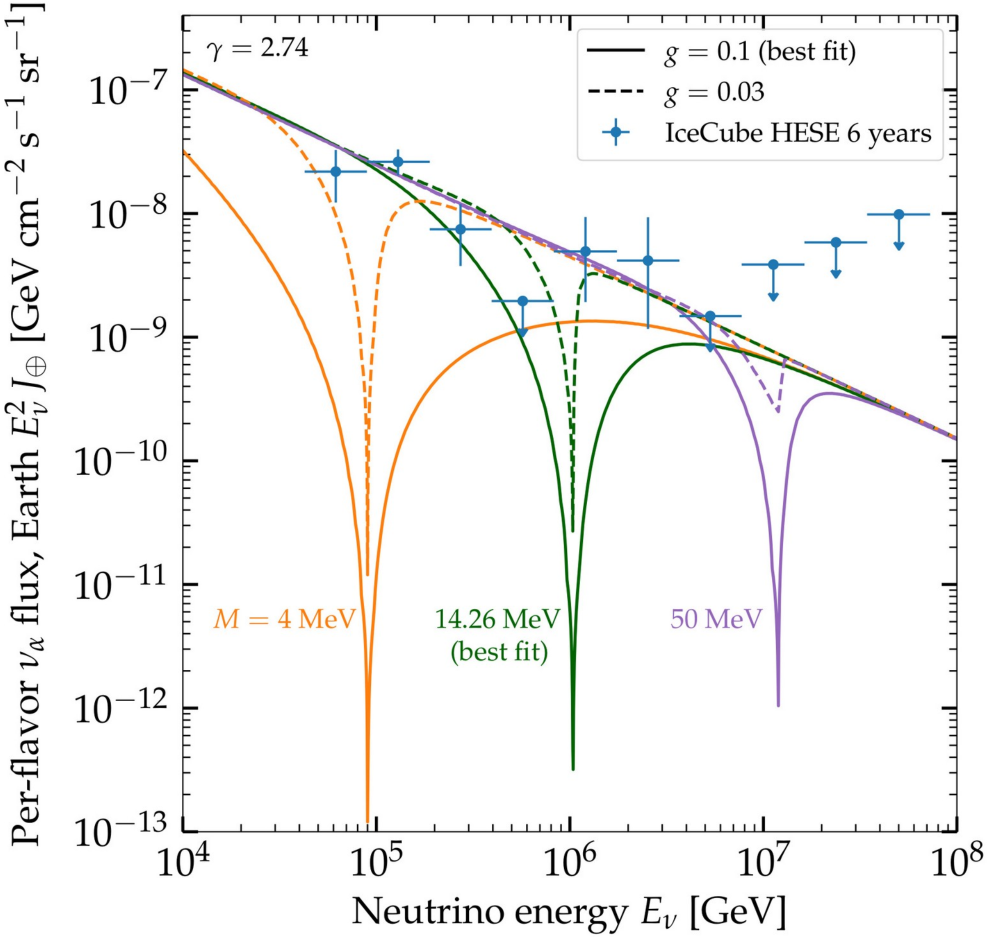

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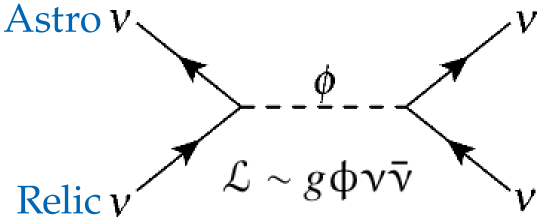

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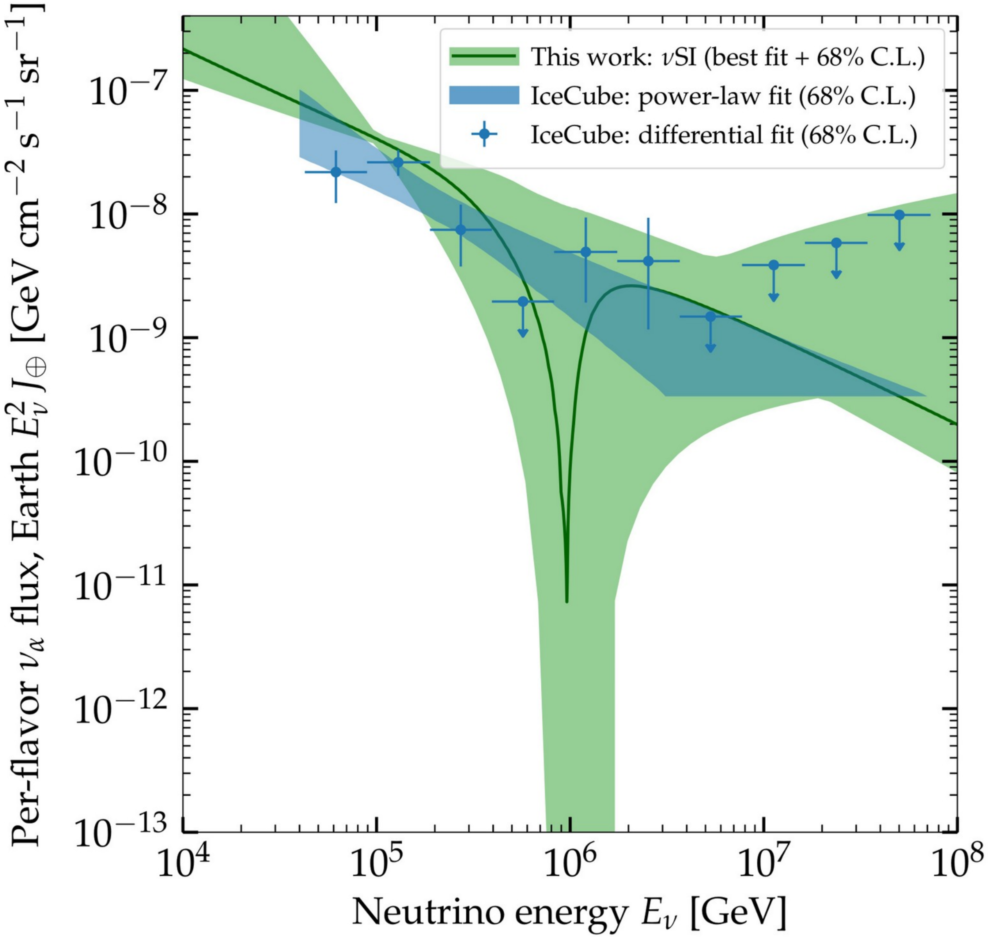
Looking for evidence of νSI

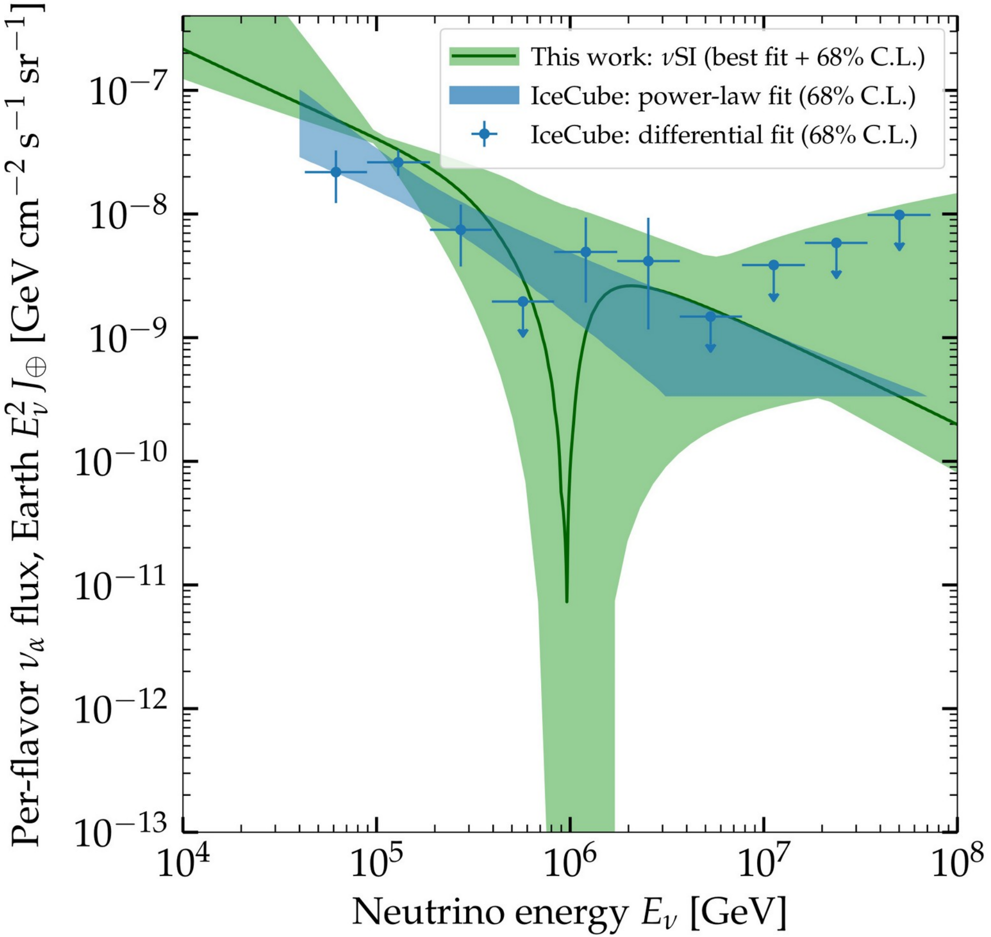
- Look for dips in 6 years of public IceCube data (HESE)
- 80 events, 18 TeV–2 PeV
- Assume flavor-diagonal and universal: $g_{\alpha\alpha} = g\,\delta_{\alpha\alpha}$
- Bayesian analysis varying *M*, *g*, shape of emitted flux (γ)
- Account for atmospheric ν, in-Earth propagation, detector uncertainties

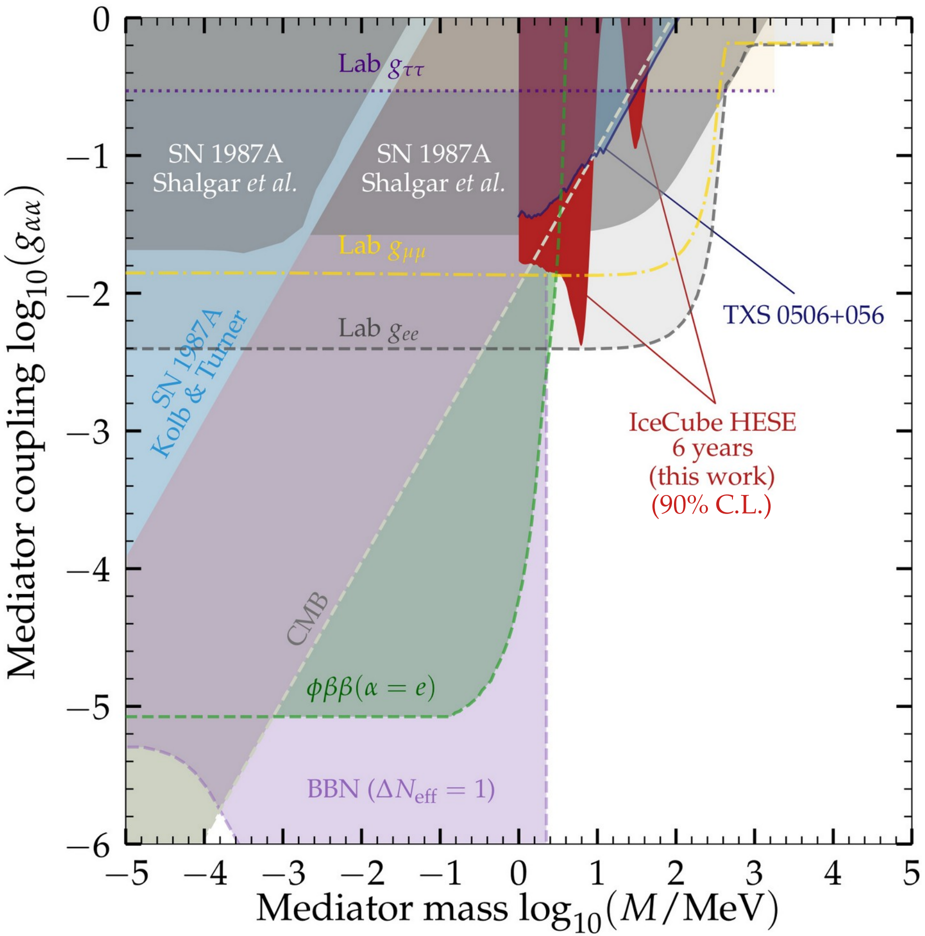
No significant (> 3σ) evidence for a spectral dip …



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

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





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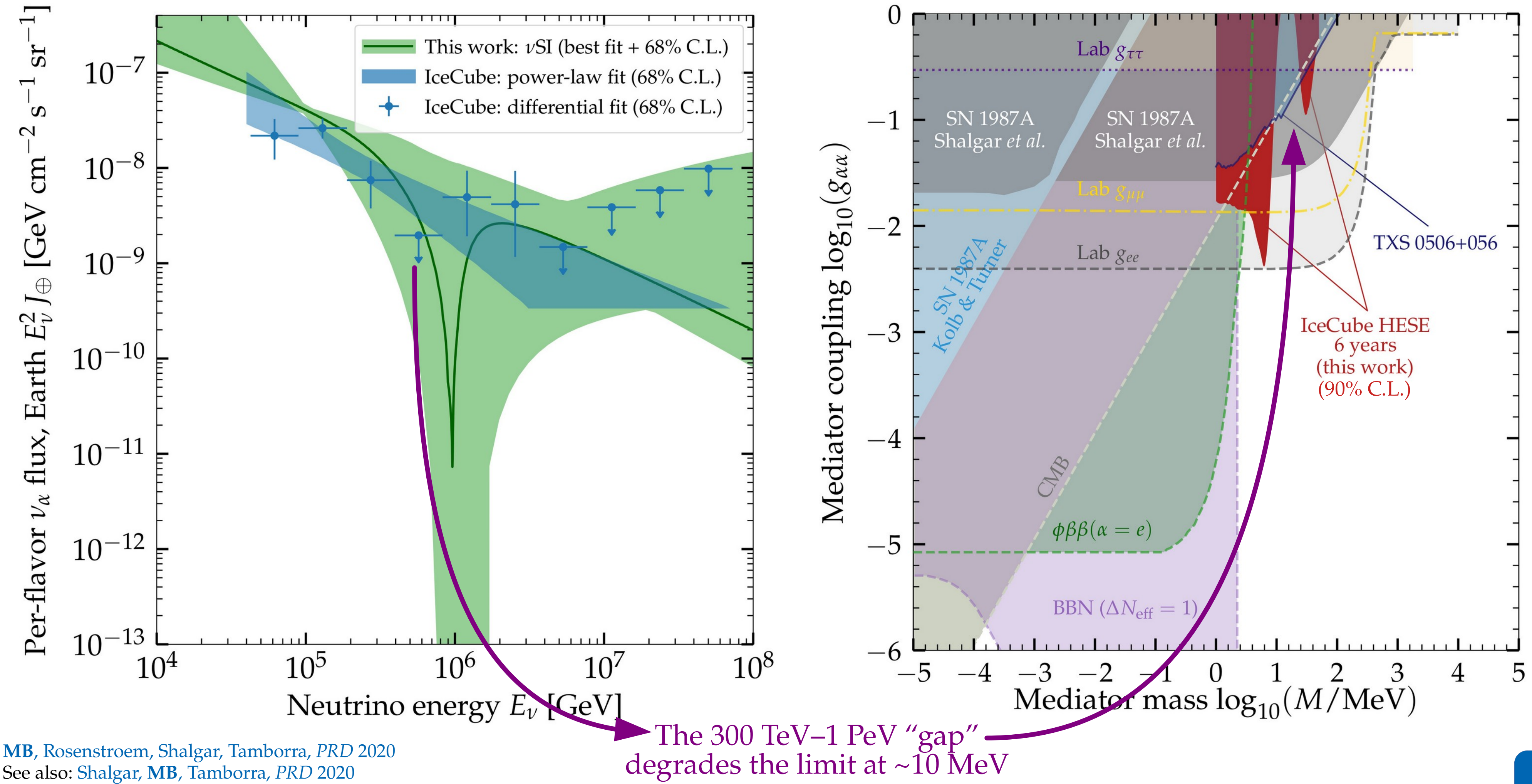


MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020
See also: Shalgar, MB, Tamborra, *PRD* 2020

Thanks!

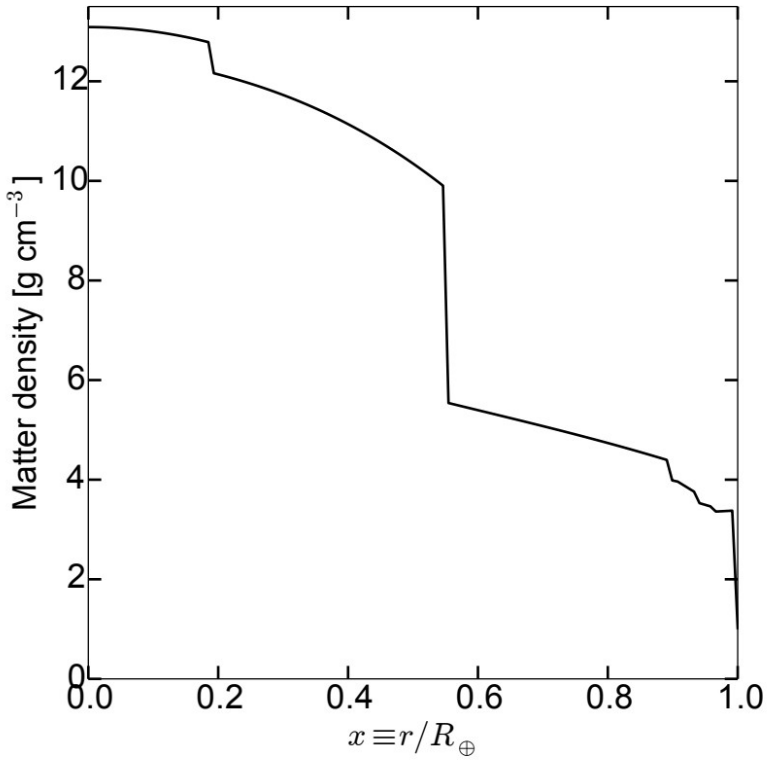
And now for Part 2—

Backup slides

A feel for the in-Earth attenuation

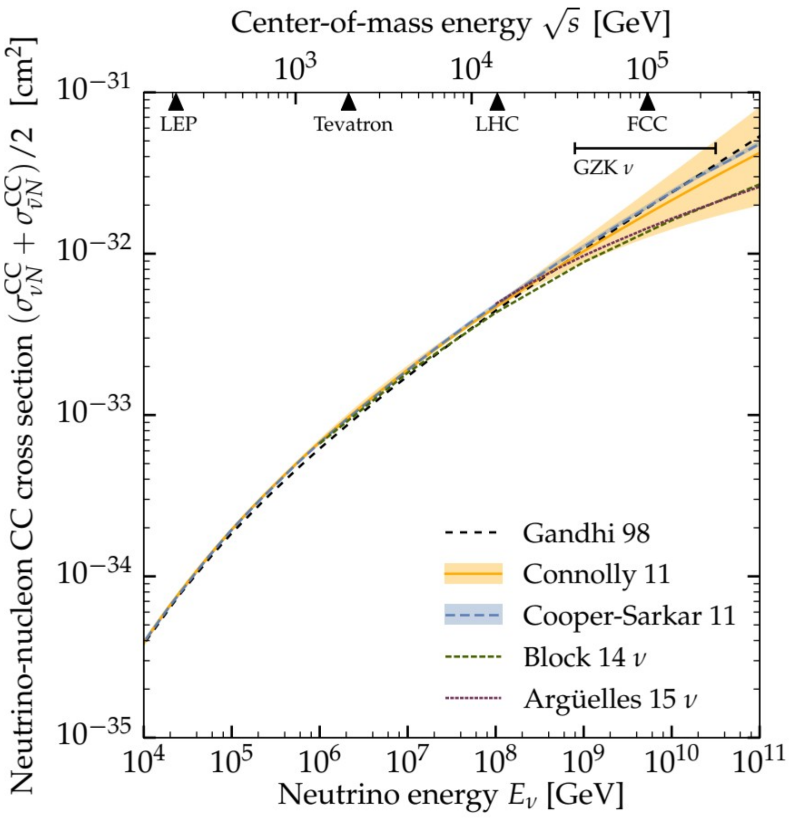
Earth matter density

(Preliminary Reference Earth Model)



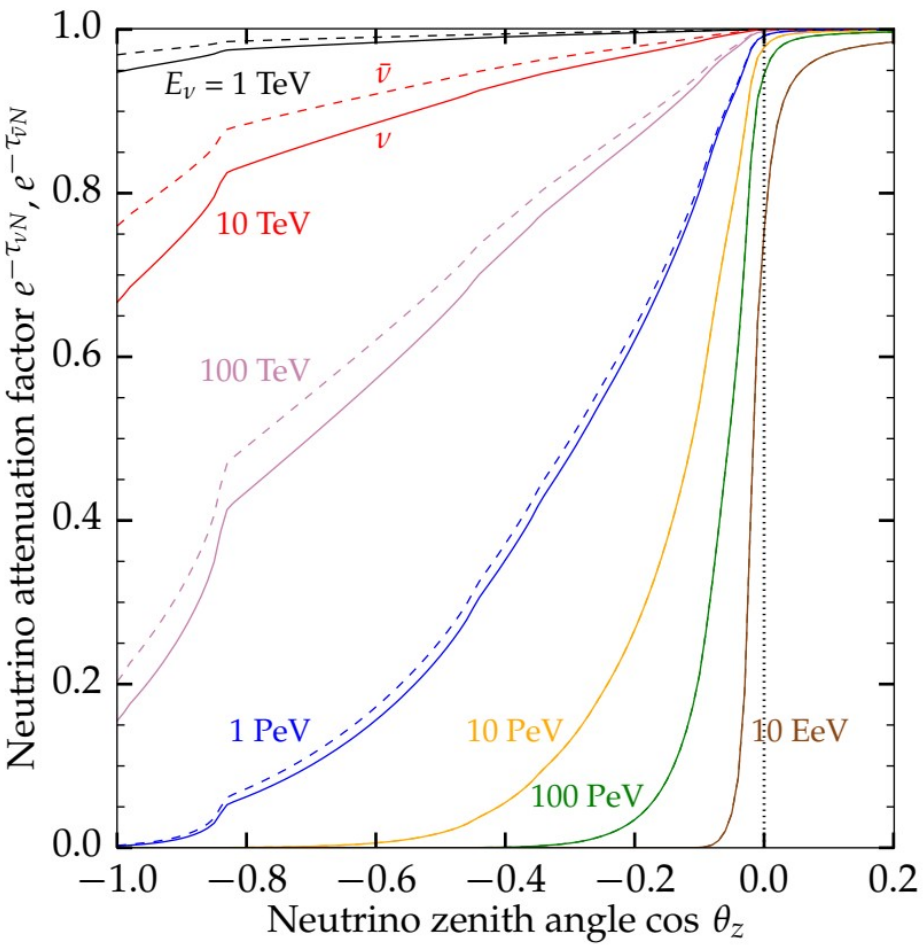
+

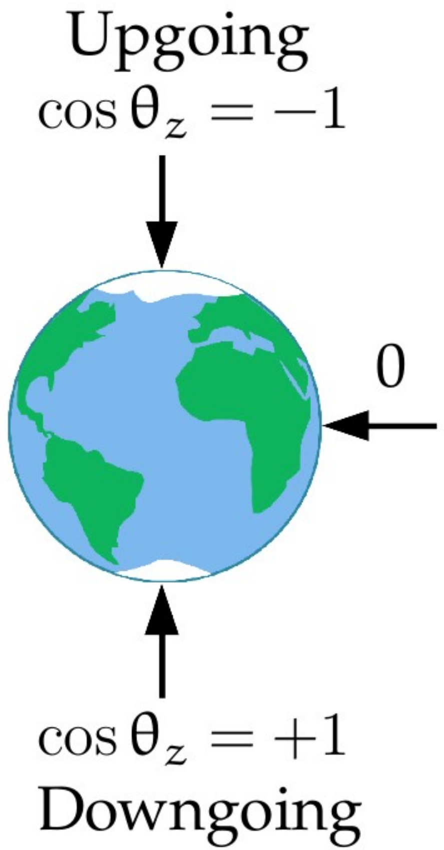
Neutrino-nucleon cross section

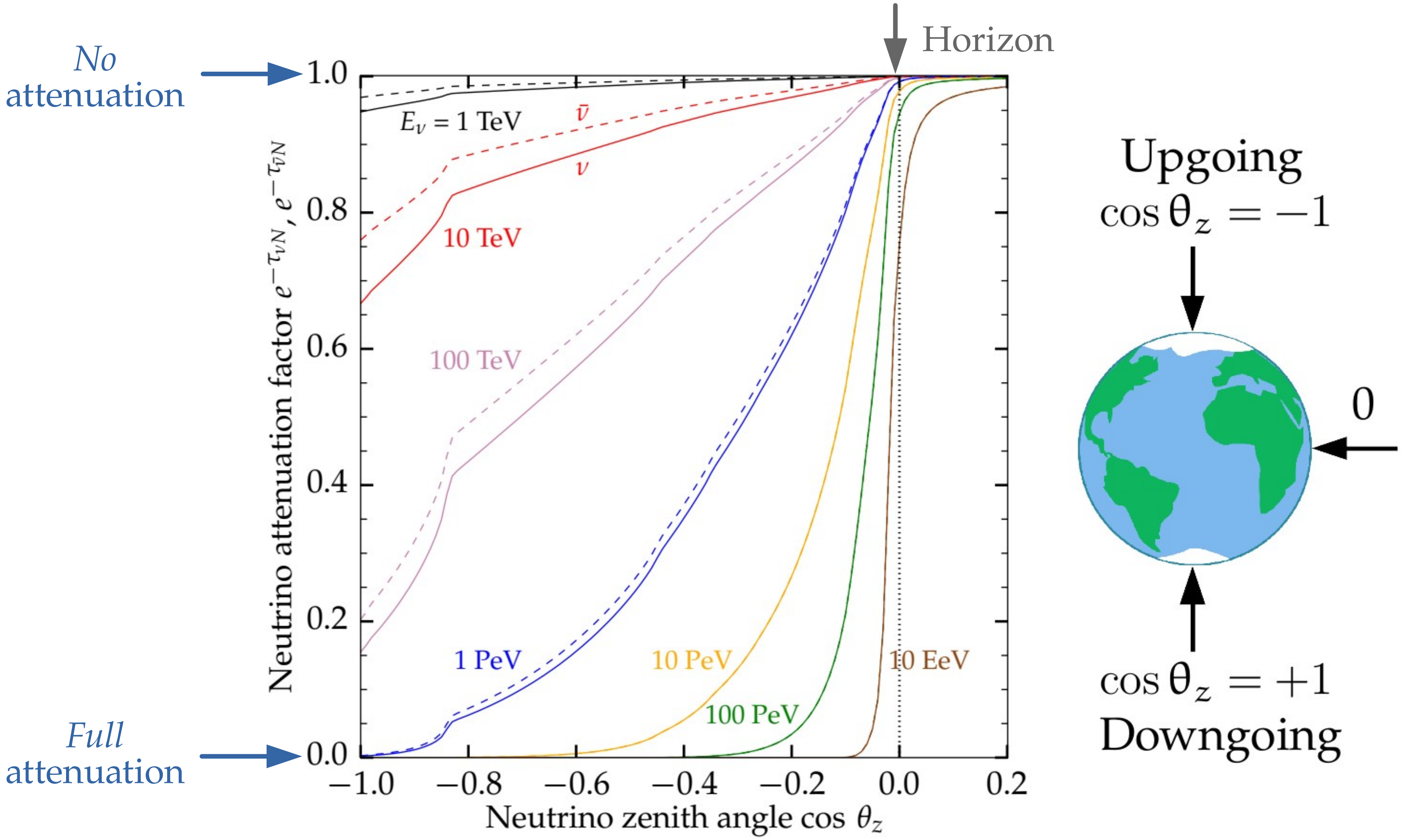


A feel for the in-Earth attenuation

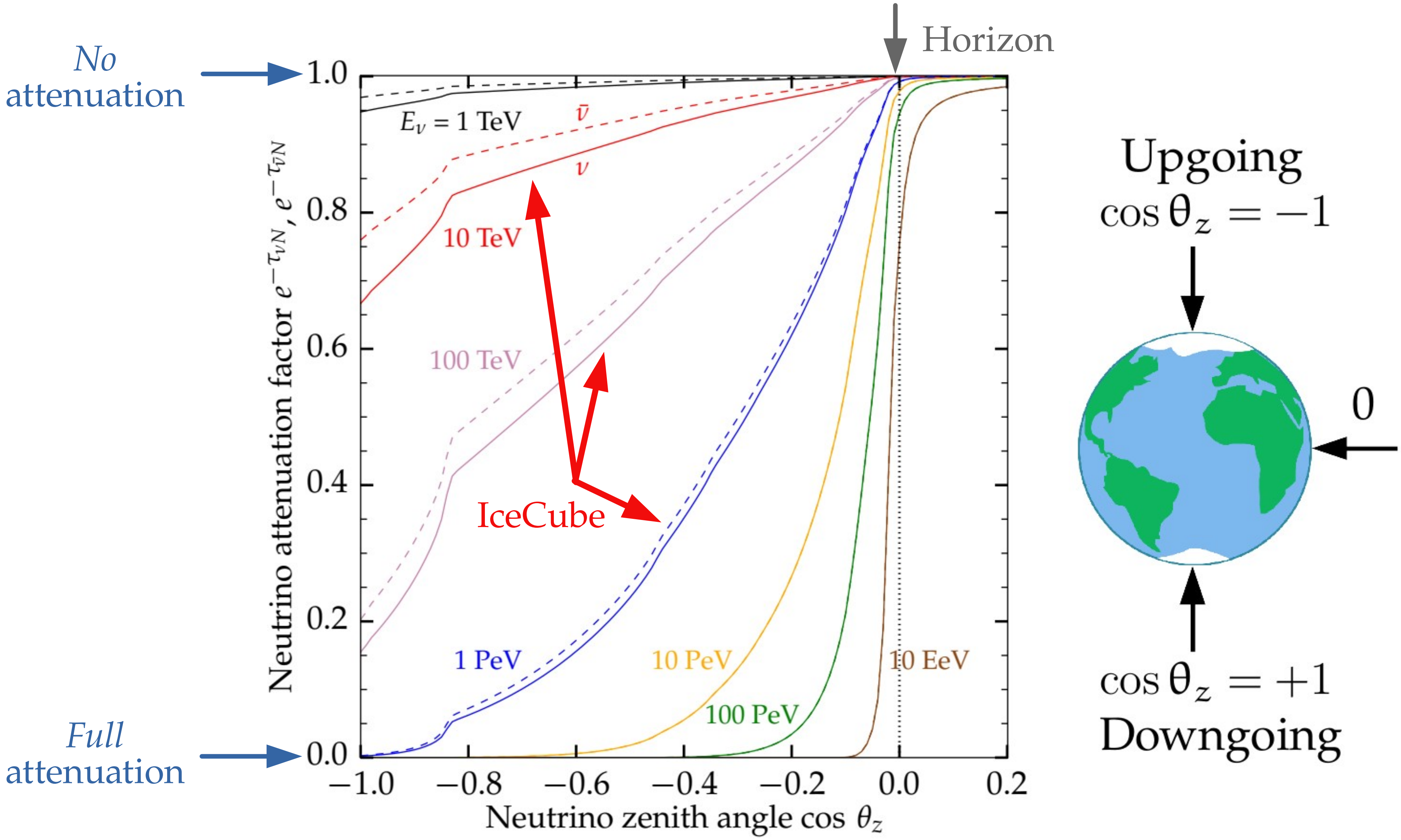
=



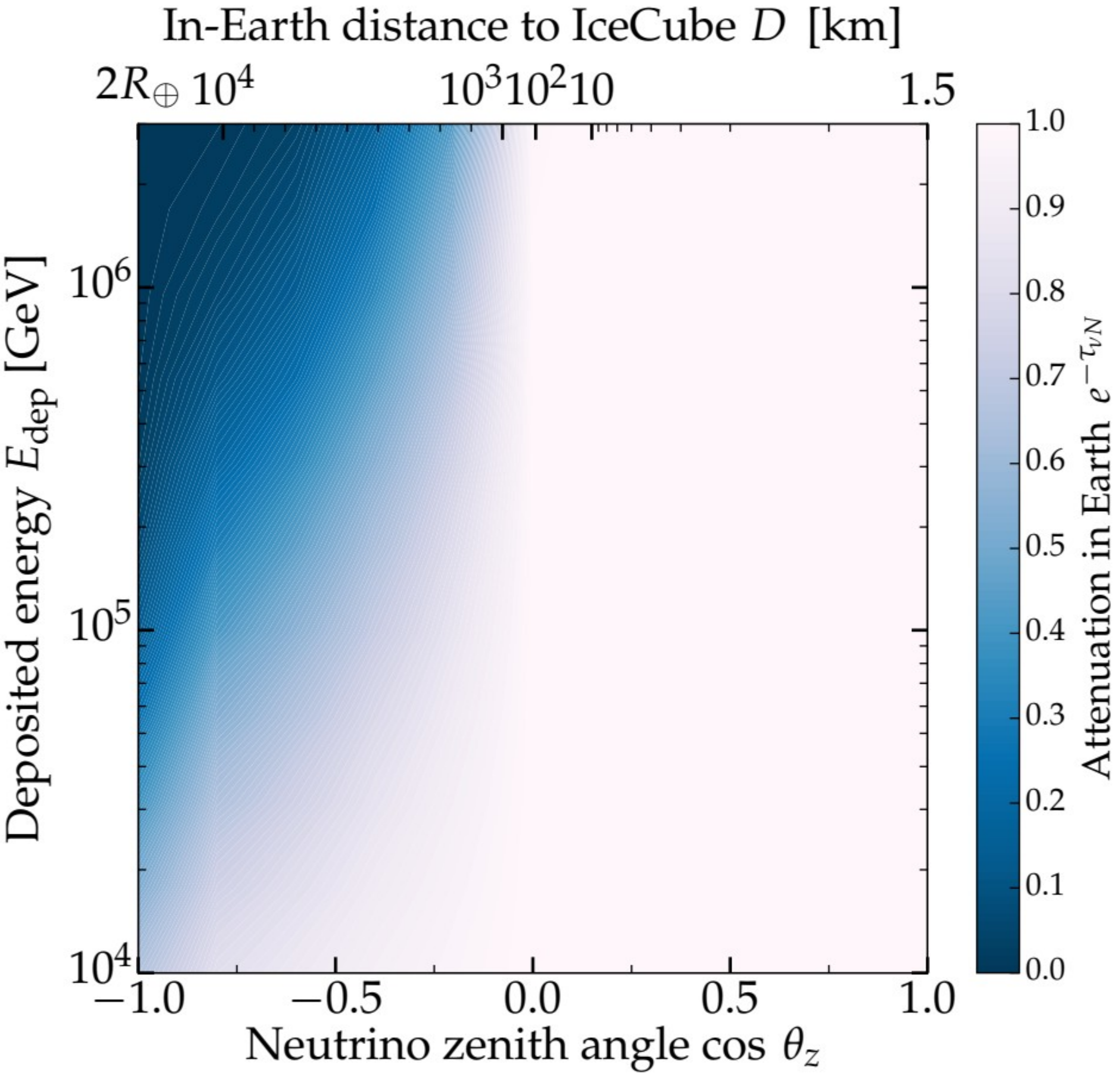




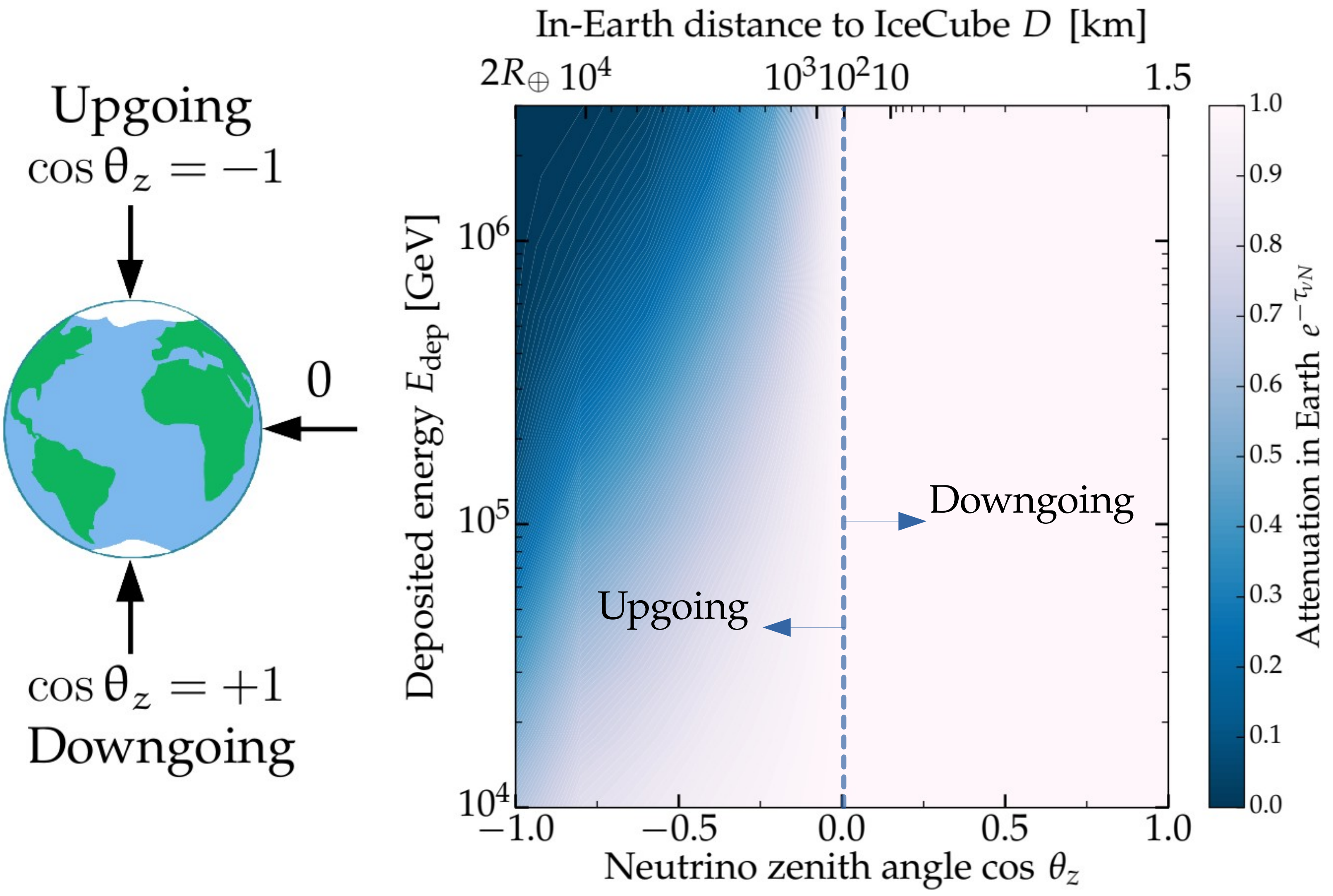
MB & Connolly, *PRL* 2019



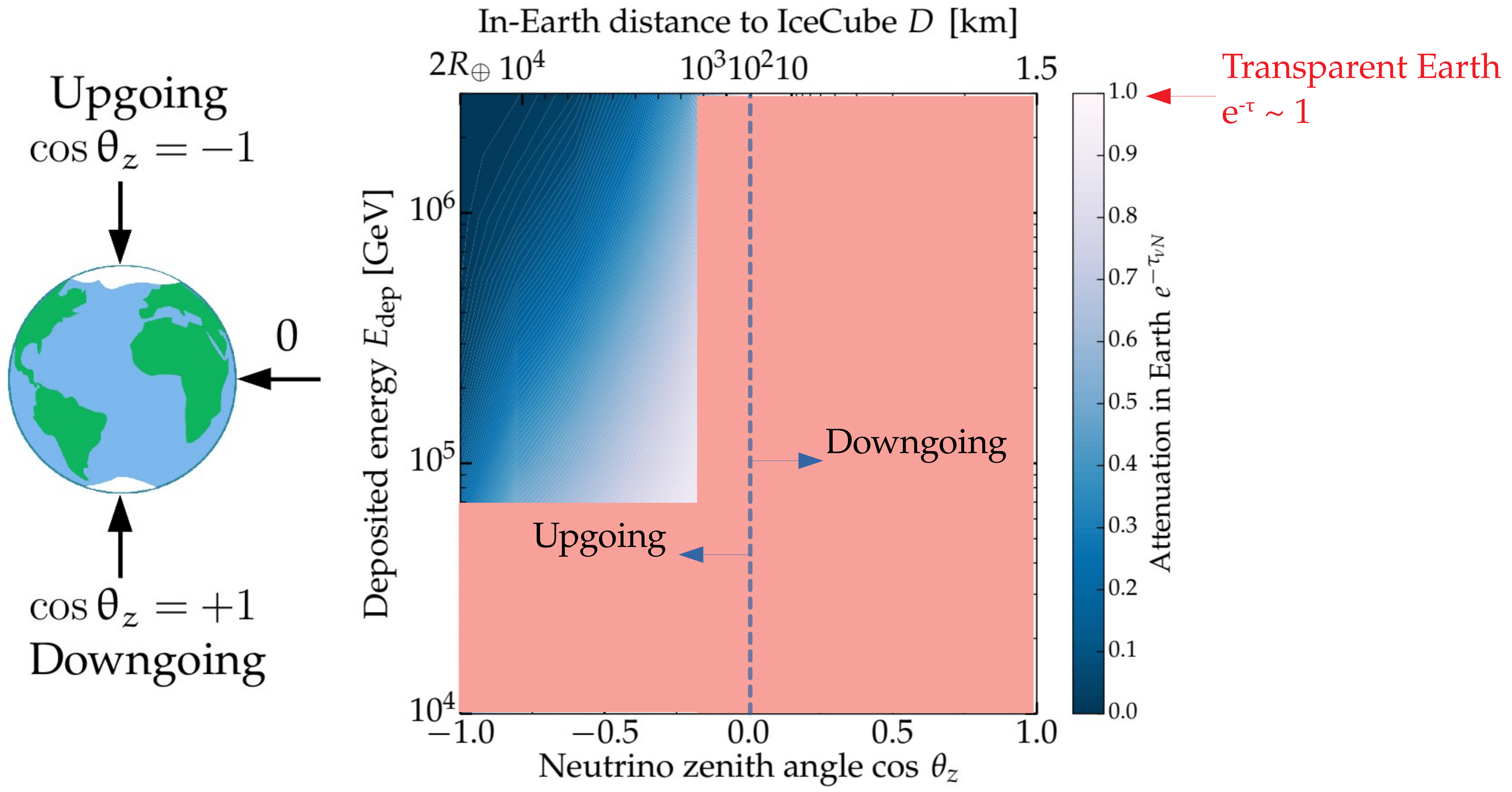
MB & Connolly, *PRL* 2019



In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4
10^3 10^2 10
1.5
10^6
10^5
10^4
Deposited energy $E_{\rm dep}$ [GeV]
−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]
10^4
10^5
10^6
−1.0 −0.5 0.0 0.5 1.0
Neutrino zenith angle cos θ_z
Downgoing
Upgoing
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



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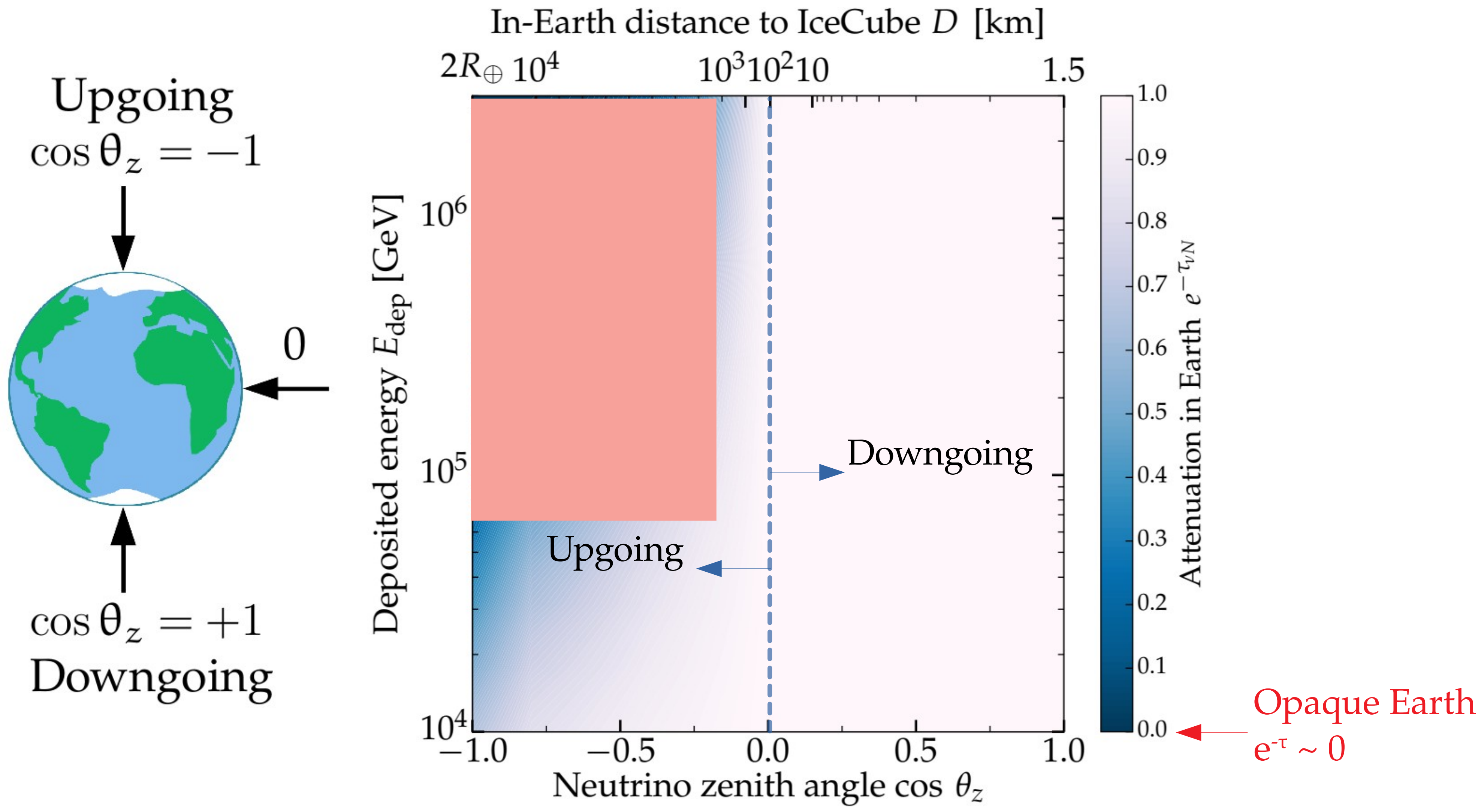
Deposited energy $E_{\rm dep}$ [GeV]
10^4 10^5 10^6
Neutrino zenith angle $\cos\theta_z$
−1.0 −0.5 0.0 0.5 1.0
Downgoing
Upgoing
Attenuation in Earth $e^{-\tau_{\nu N}}$
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
Transparent Earth
$e^{-\tau} \sim 1$



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_{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
$e^{-\tau} \sim 0$

Use NuPropEarth for in-Earth propagation
[github.com/pochoarus/NuPropEarth]

Interactions:
- BGR18 νN deep inelastic scattering (DIS) on partons (dominant)
- DIS on photon field of nucleons
- Coherent νA scattering
- Elastic & diffractive νN scattering
- ν scattering on atomic electrons

Sub-dominant: increase attenuation by ~10%

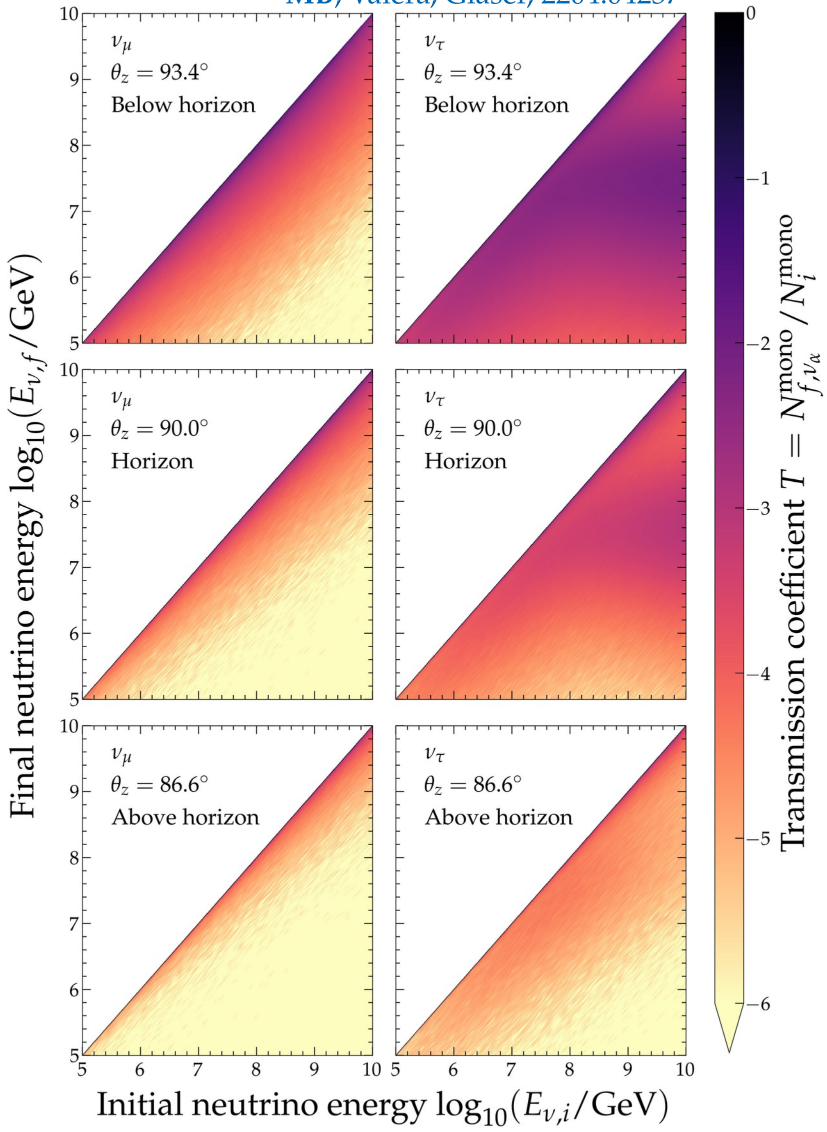
Includes ν_τ regeneration:
- TAUSIC: Energy losses of intermediate τ
- TAUOLA: Distribution of τ decay products

Matter inside Earth:
- Density: Preliminary Reference Earth Model
- Top layer of ice
- Varying element composition (non-isoscalar)

We propagate ν_e, $\bar{\nu}_e$, ν_μ, $\bar{\nu}_\mu$, ν_τ, $\bar{\nu}_\tau$ separately

García, Gauld, Heijboer, Rojo, *JCAP* 2020

MB, Valera, Glaser, 2204.04237



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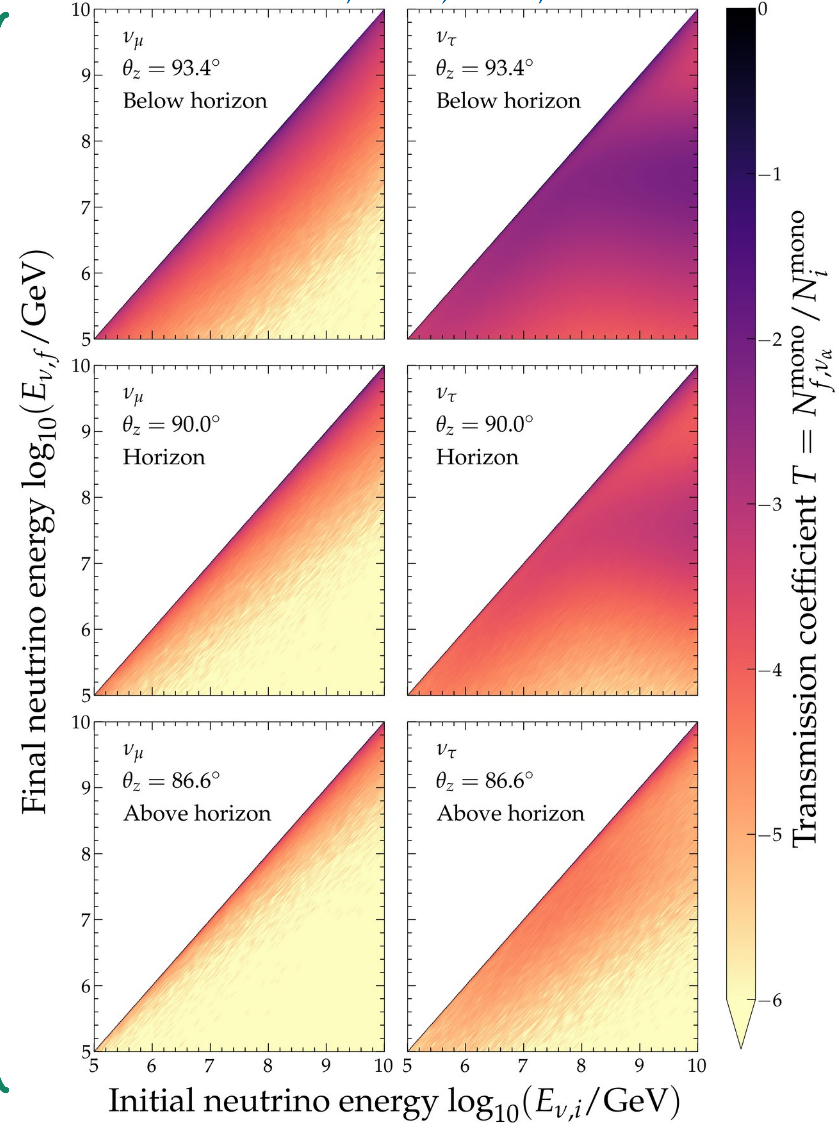
Save look-up tables of propagated ν spectra

MB, Valera, Glaser, 2204.04237



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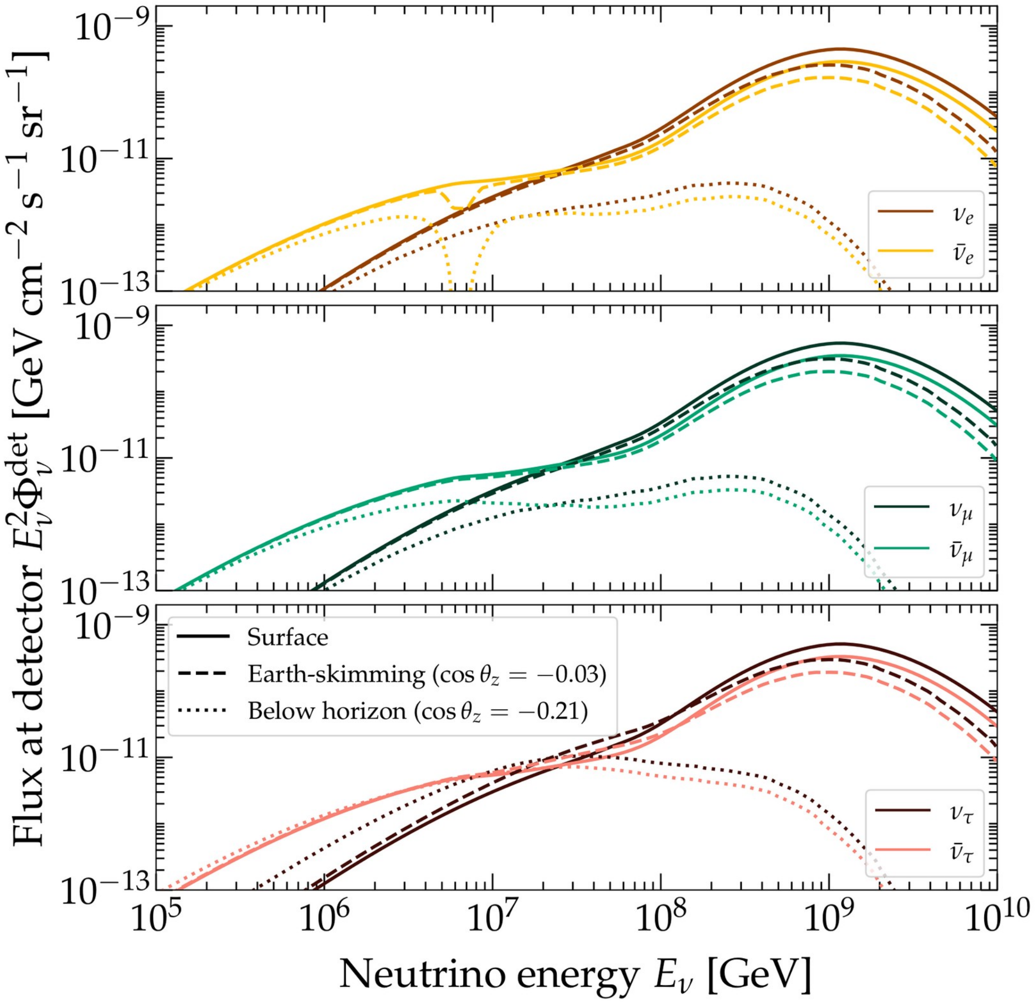


García, Gauld, Heijboer, Rojo, *JCAP* 2020

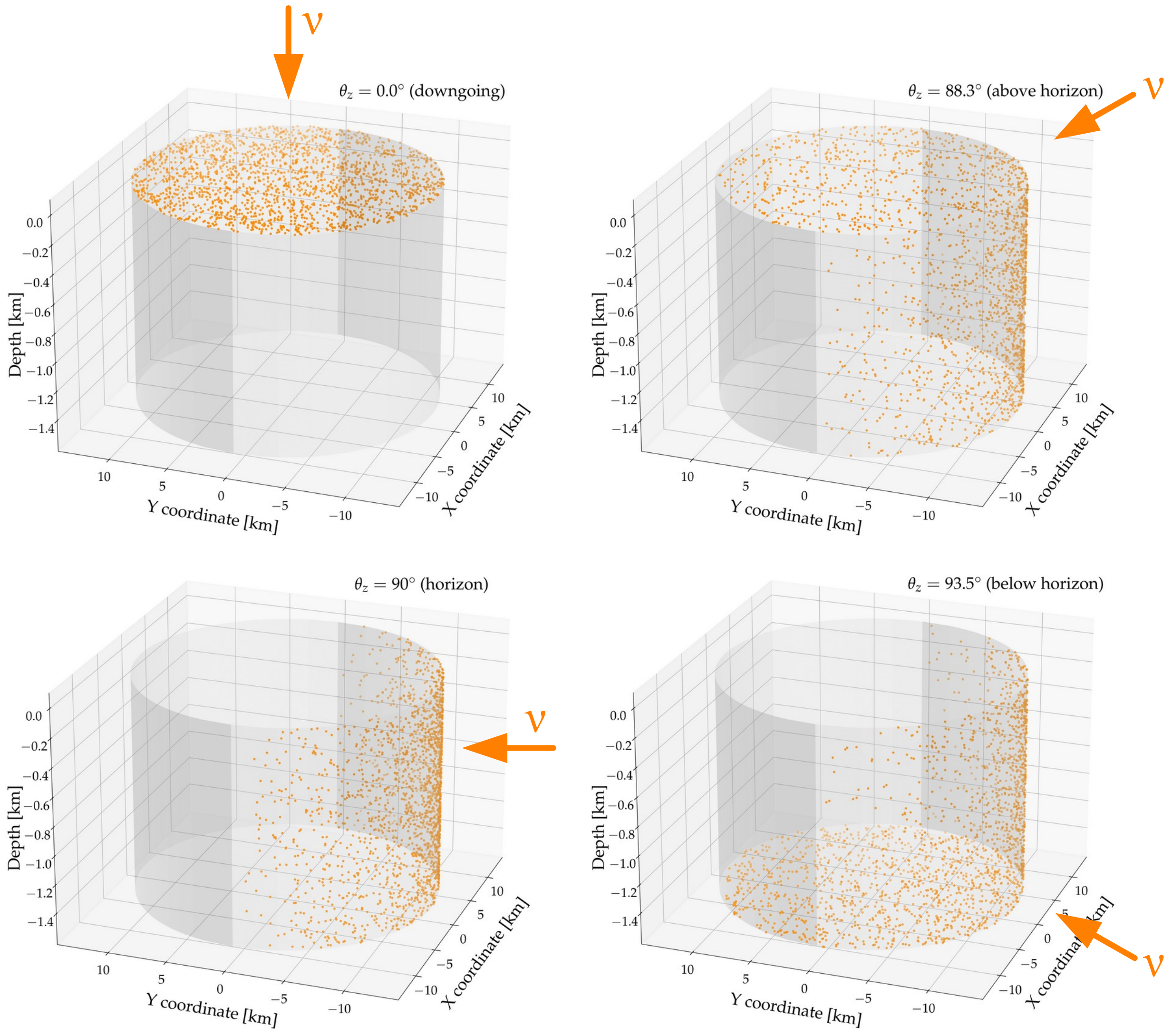
Detector geometry

Underground cylinder

Area of lid: 500 km^2

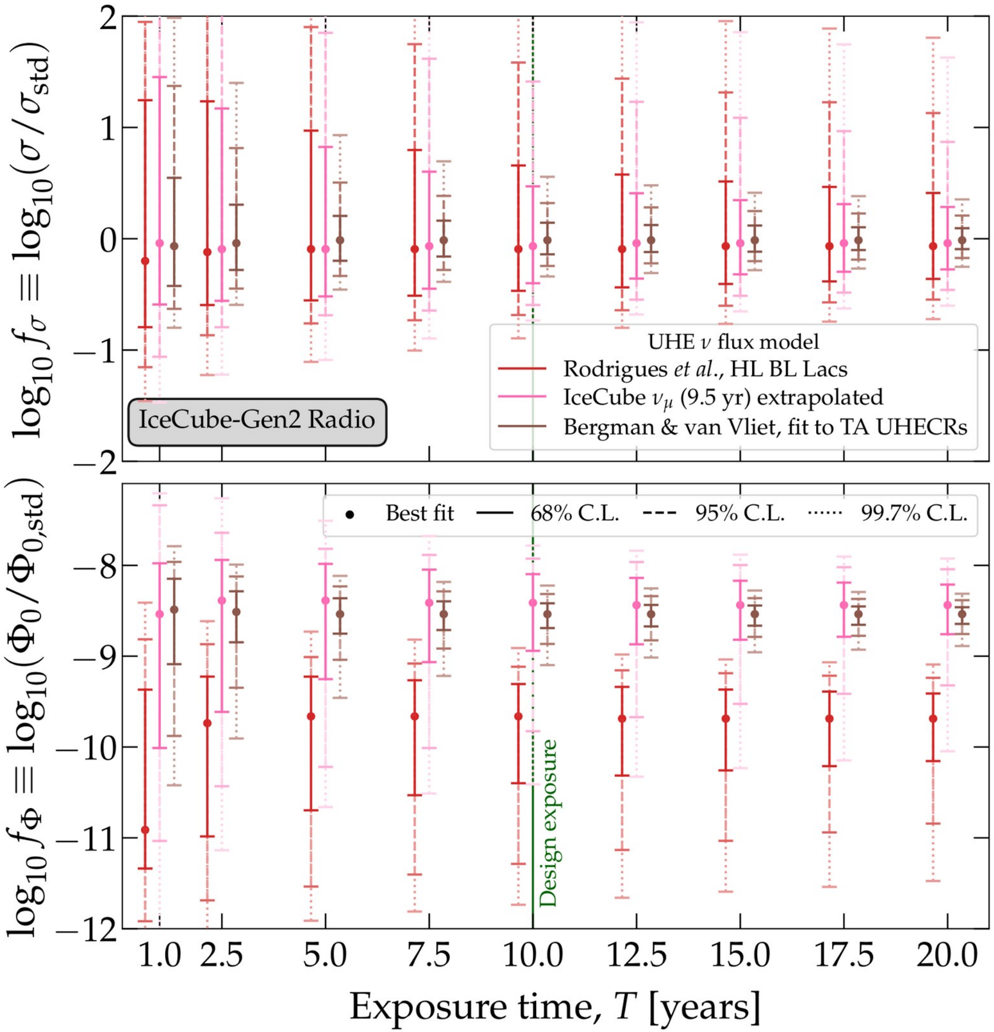
Height: 1.5 km

Detector geometry now available in NuPropEarth
[github.com/pochoarus/NuPropEarth]



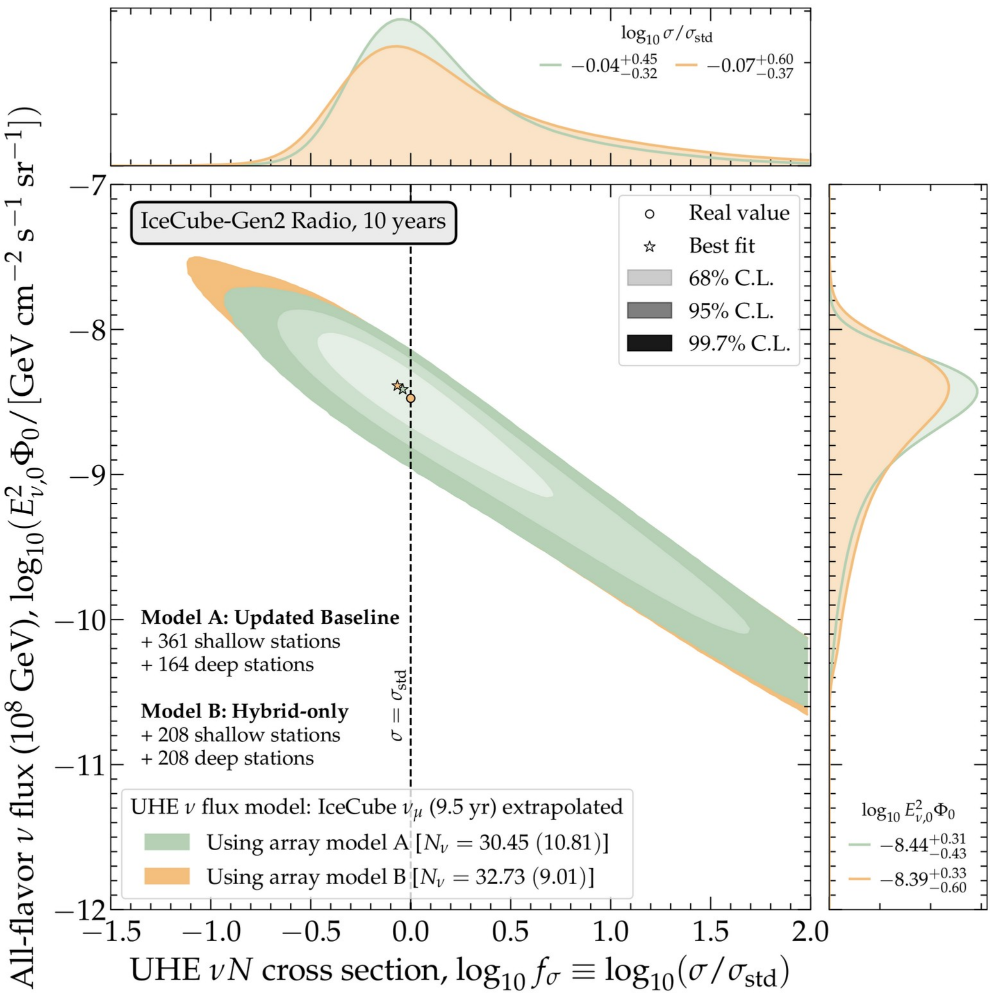
Valera, **MB**, Glaser, *JHEP* 2022

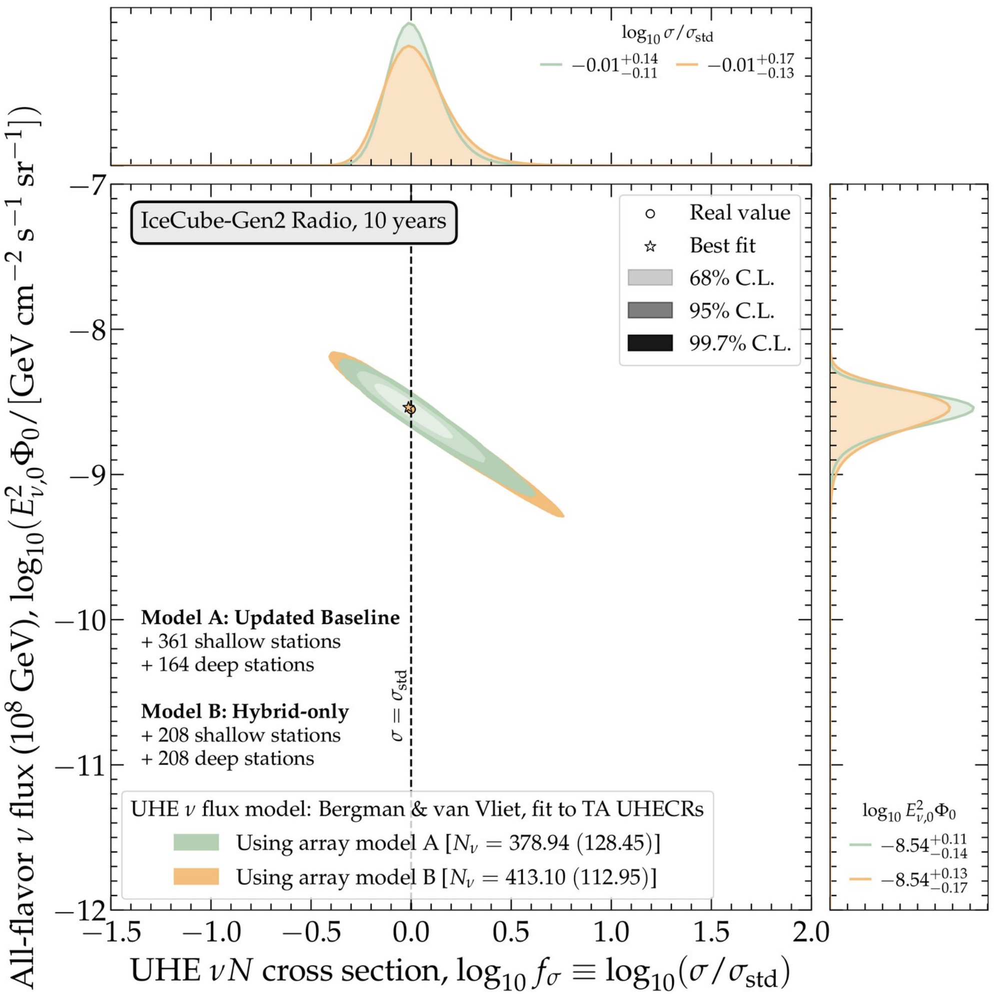
Precision *vs.* exposure time



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

Results for alternative radio array designs





Figures courtesy of Víctor Valera

Event rate at IC-Gen2 Radio

Event rate at IC-Gen2 Radio

Real event rate

$$\frac{d^3 N_{\nu_\alpha}^{\mathrm{CC}}}{dE_\nu \, dy \, d\cos\theta_z}$$

E_ν: Neutrino energy

y: Inelasticity

$\cos\theta_z$: Neutrino direction

Includes:

- Flux
- In-Earth propagation
- Effective volume
- Inelasticity distribution

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Detector effects →

Each ν species computed separately

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Detected event rate

$$\frac{d^2 N_{\nu_\alpha}^{\rm CC}}{dE_{\rm sh}^{\rm rec} d\theta_z^{\rm rec}}$$

$E_{\rm sh}^{\rm rec}$: Reconstructed *shower* energy

$\cos\theta_z^{\rm rec}$: Reconstructed direction

Includes, in addition:

- Connection between ν energy and shower energy
- Energy resolution
- Angular resolution

Event rate at IC-Gen2 Radio

Note: Calculations are similar for CC and NC

Real event rate

$$\frac{d^3 N_{\nu_\alpha}^{\mathrm{CC}}}{dE_\nu \, dy \, d\cos\theta_z}$$

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Detector effective volume

IC-Gen2 has stations containing:

- Shallow antennas
- Deep antennas

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Valera, **MB**, Glaser, 2204.04237

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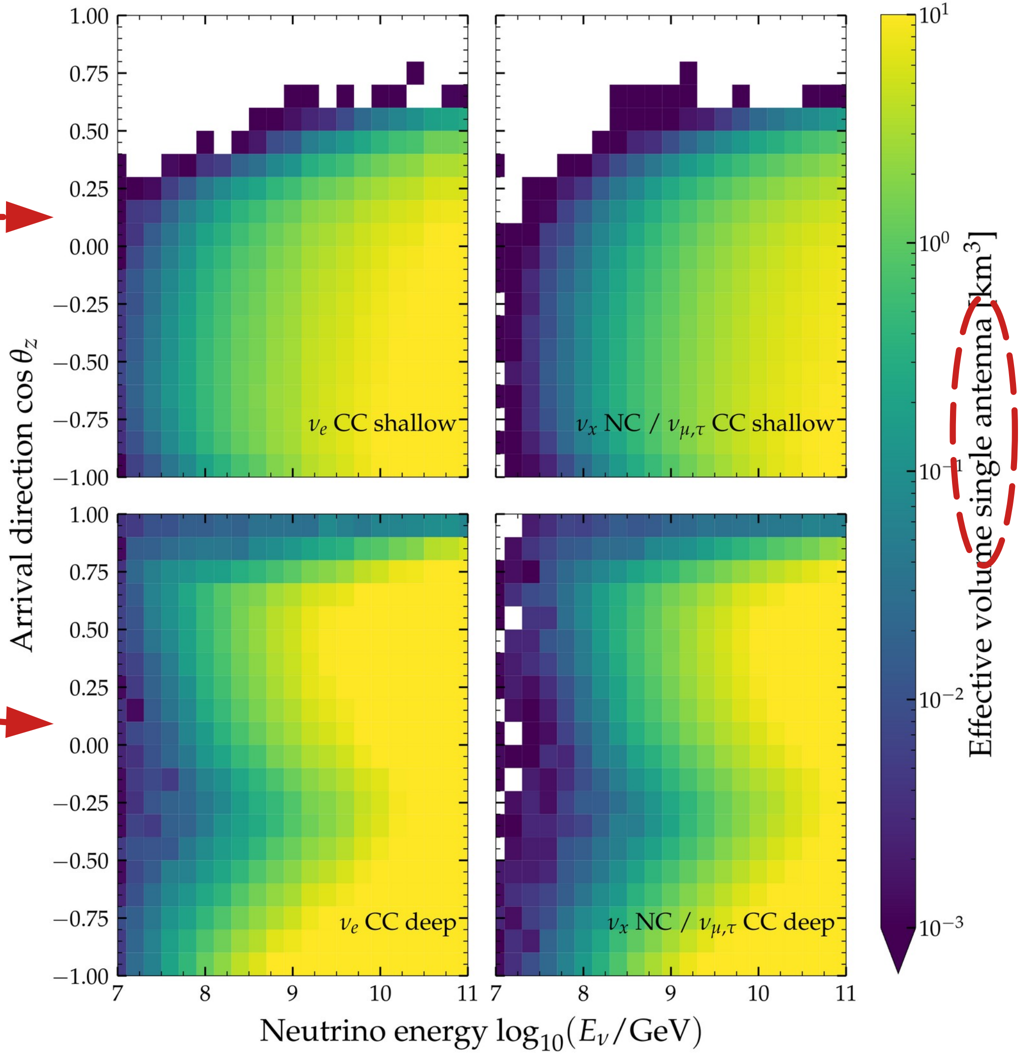

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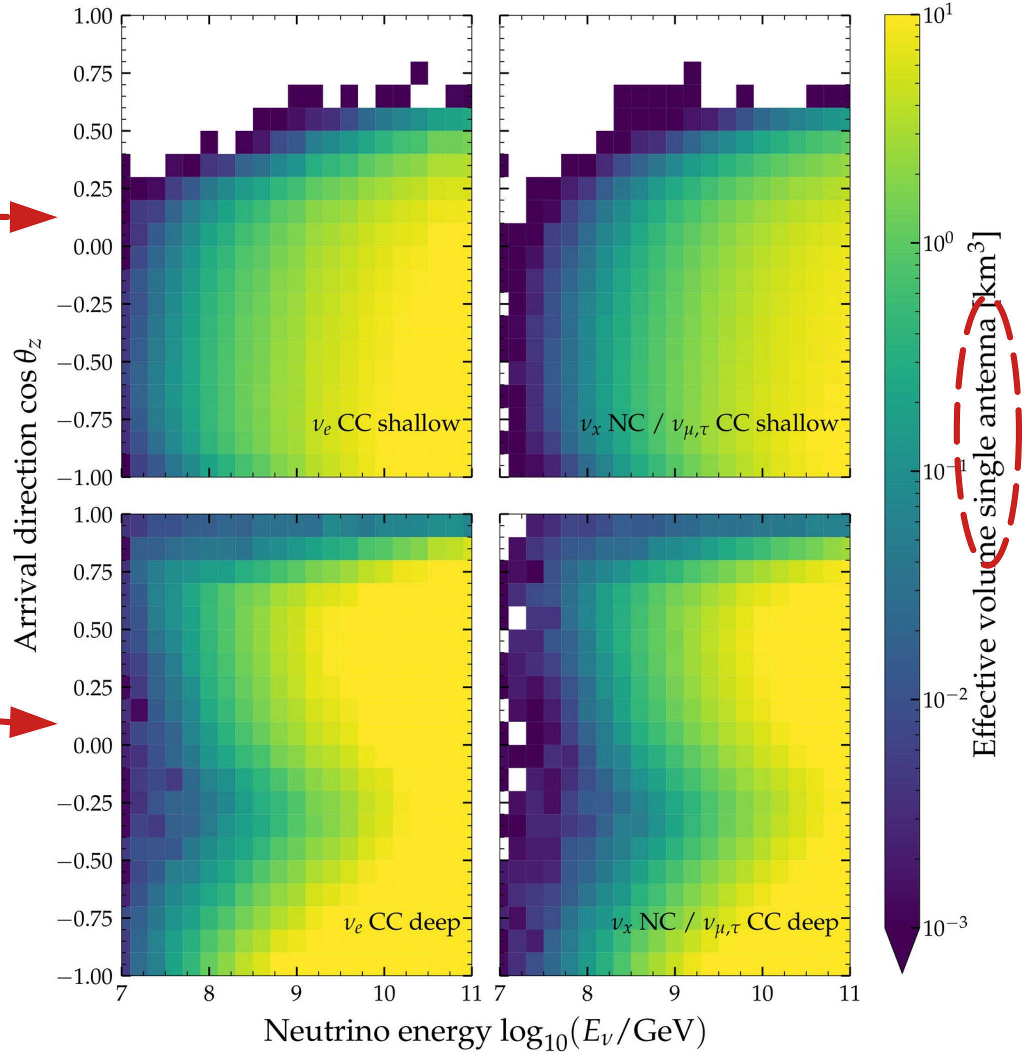
For ν_e CC: Use the CC $V_{\rm eff}$

For ν_μ CC, ν_τ CC, ν_l NC: Use the NC $V_{\rm eff}$



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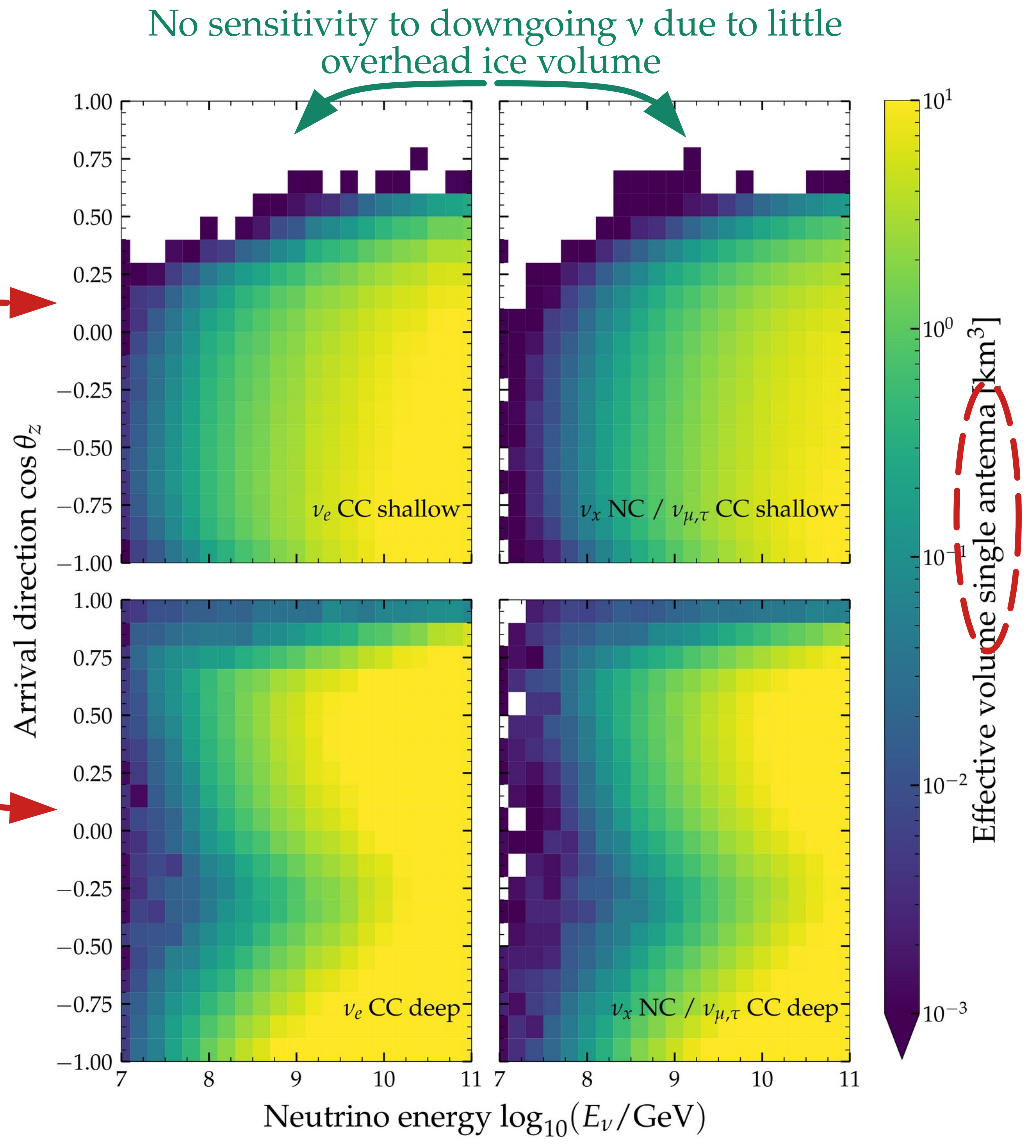
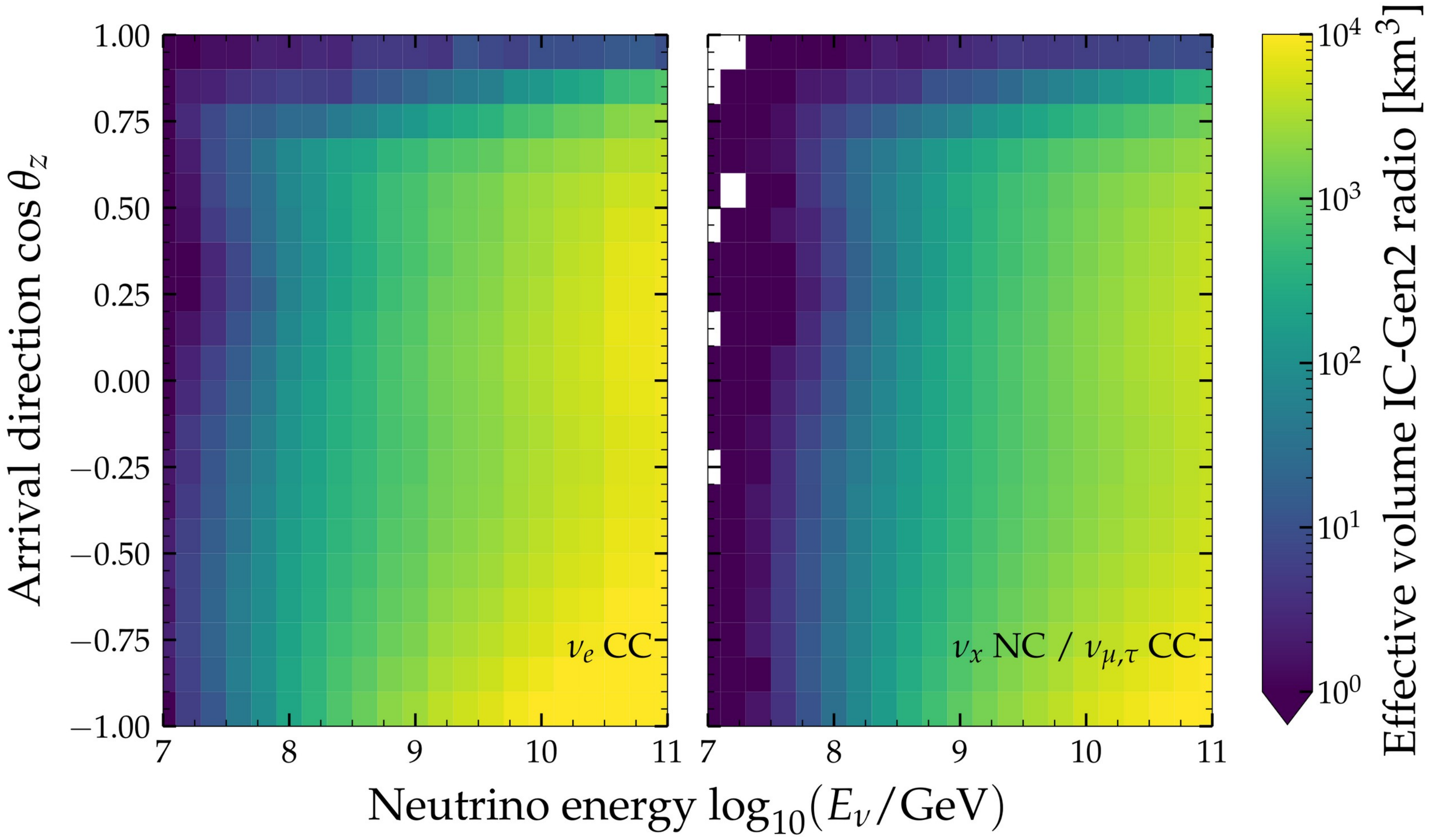


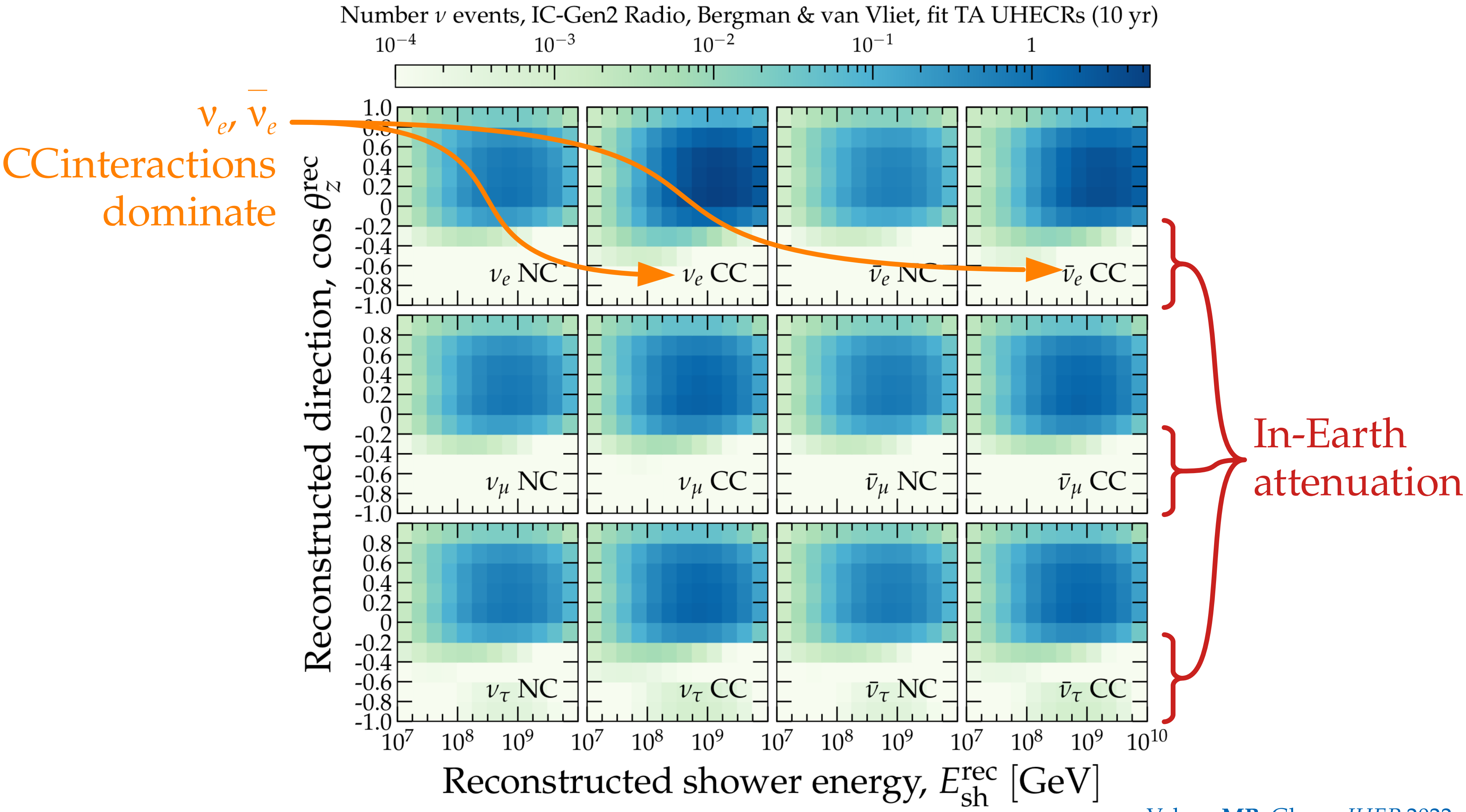
Valera, **MB**, Glaser, 2204.04237

Total volume = 169 shallow-only stations + 144 hybrid (shallow+deep) stations

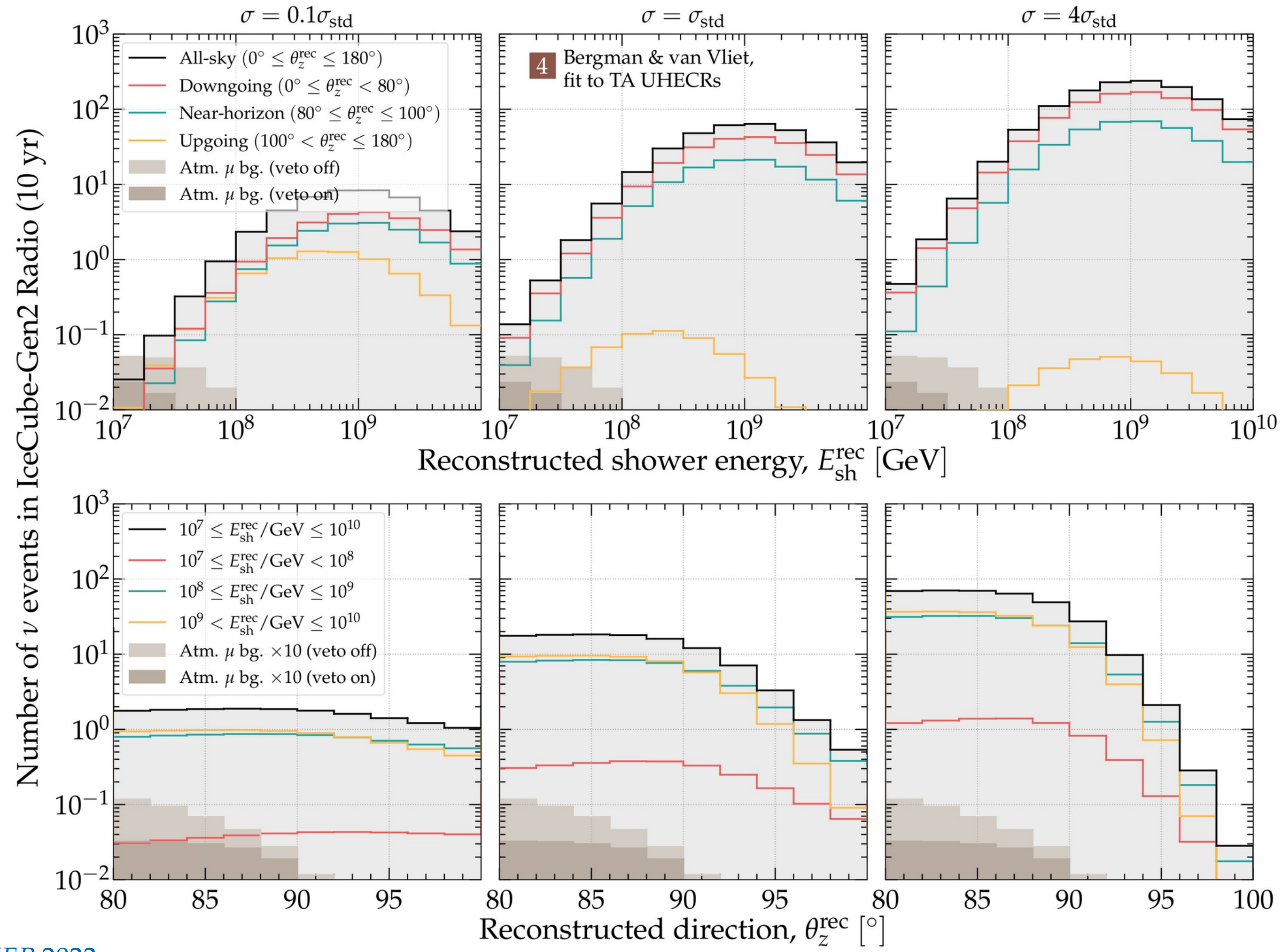


Valera, **MB**, Glaser, 2204.04237

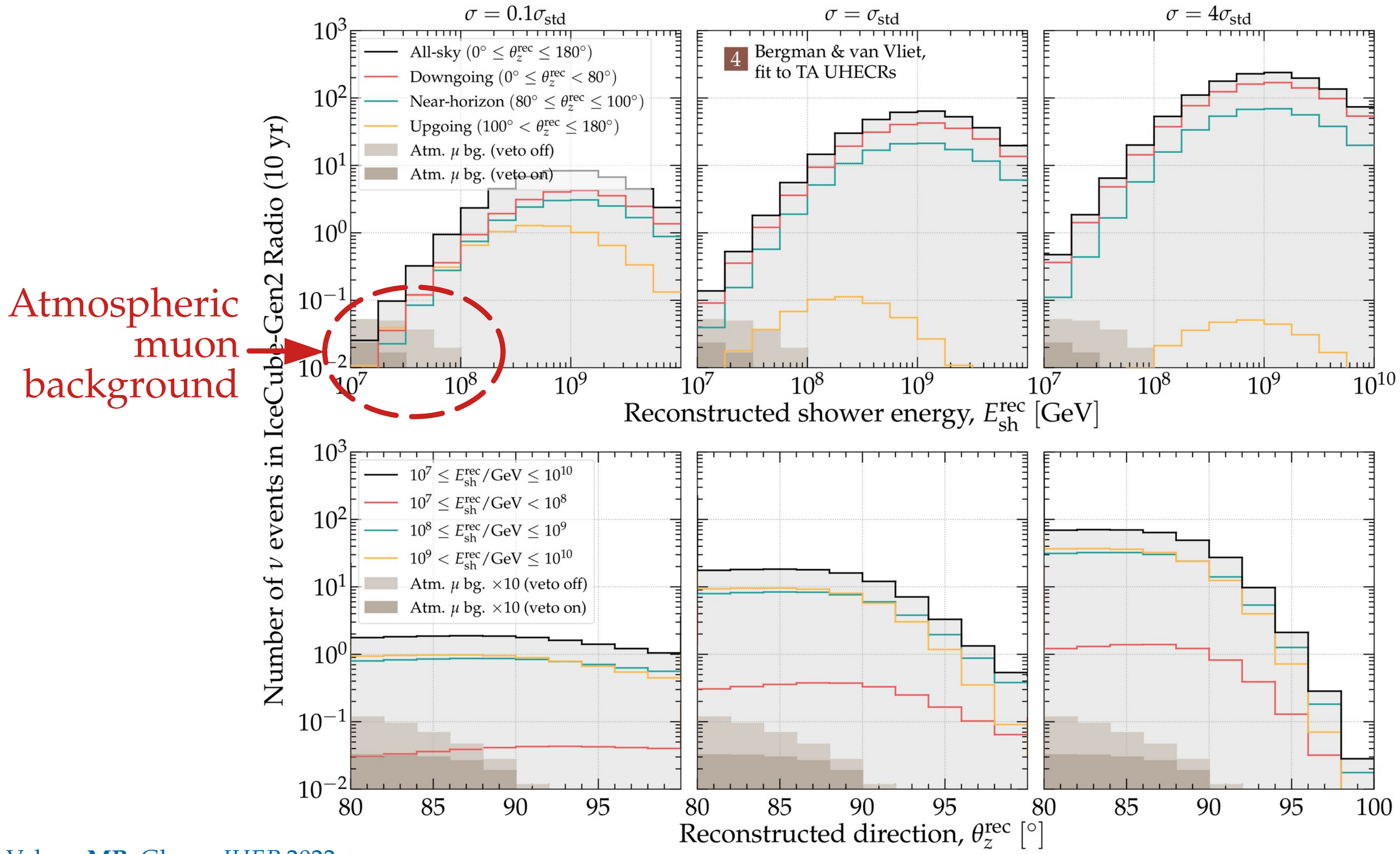
Event rates per channel



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



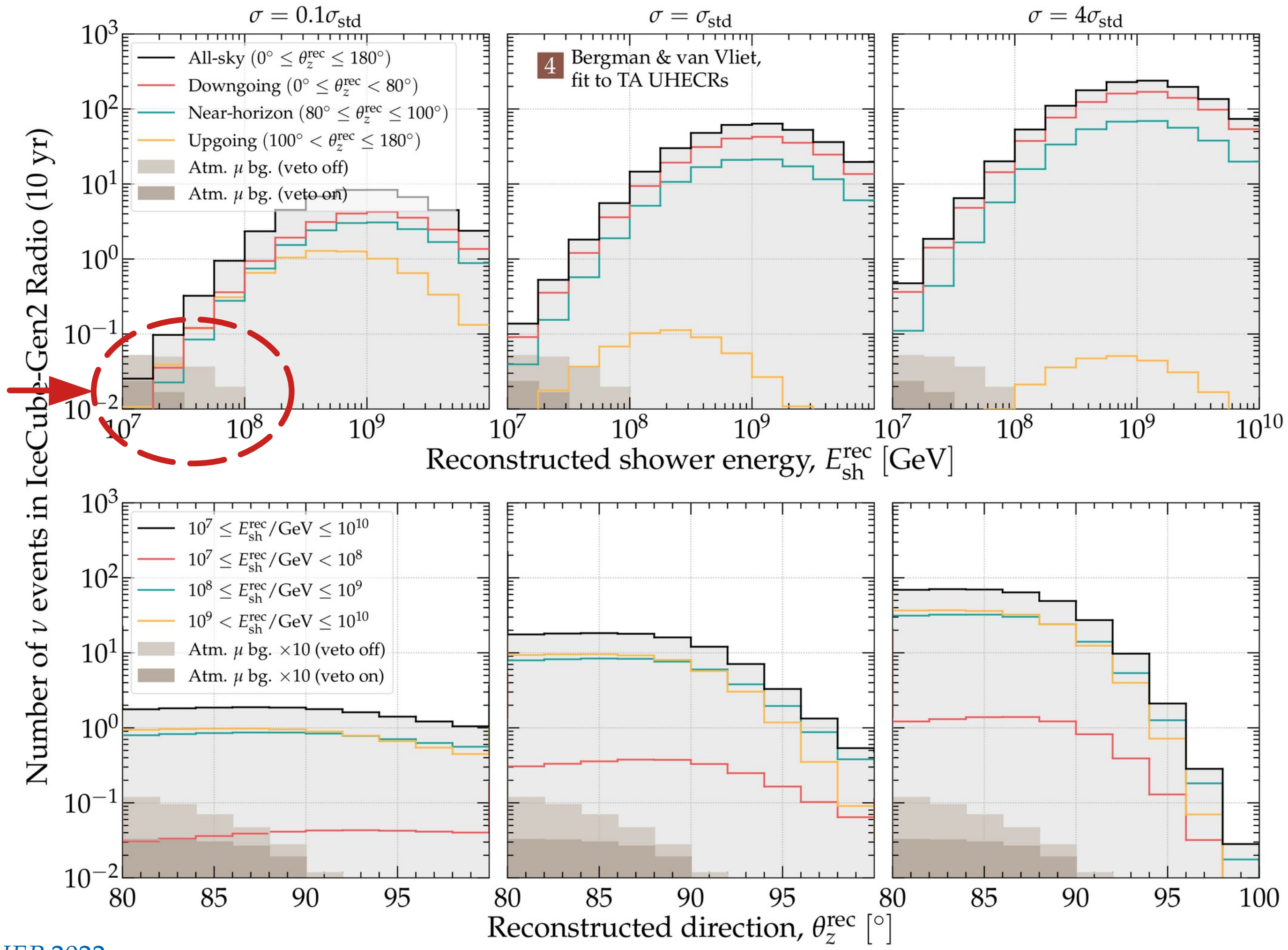
Valera, **MB**, Glaser, *JHEP* 2022



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

Larger neutrino-nucleon cross section

Atmospheric muon background



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

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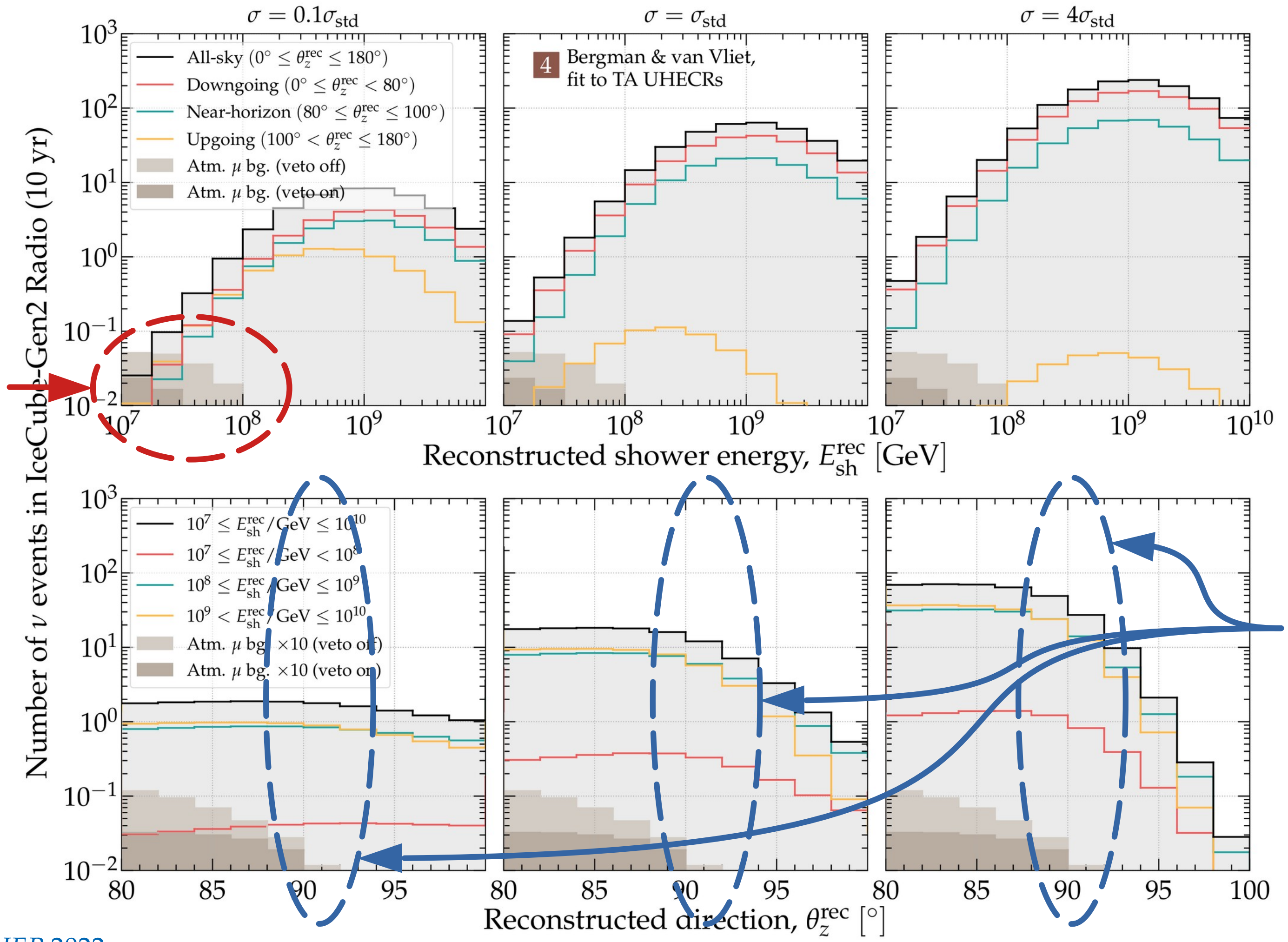


Sensitivity to cross section comes from horizontal neutrinos

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

Measuring cross section *and* flux normalization

Two physical parameters:

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

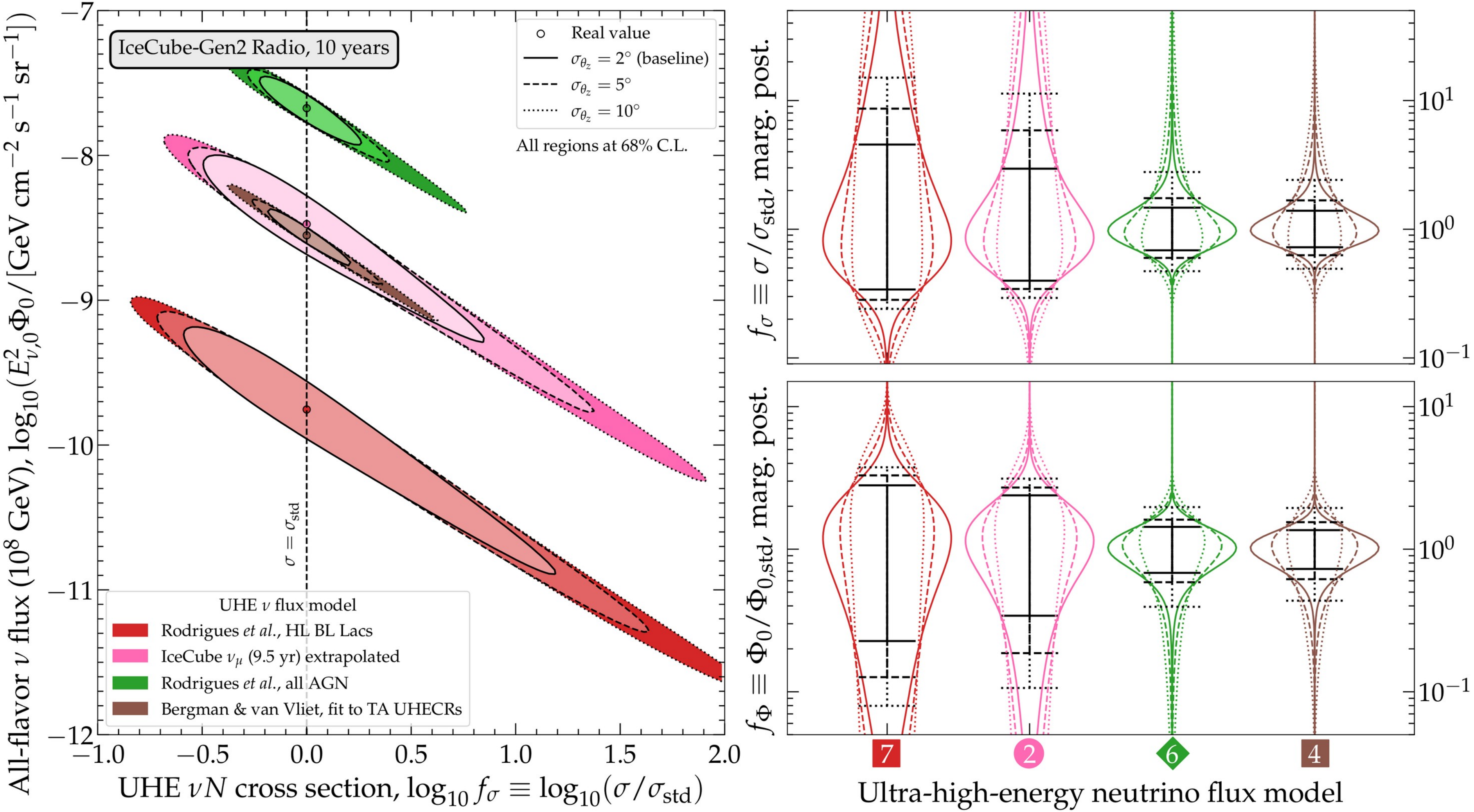
Neutrino flux normalization:
(Keep the spectral shape fixed for now)

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

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

Effect of angular resolution

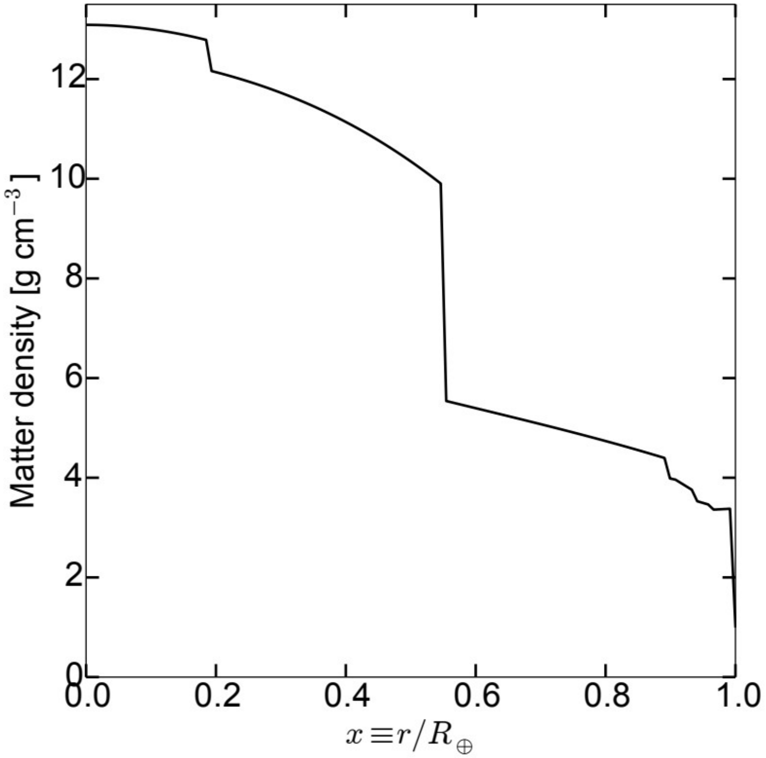
Valera, **MB**, Glaser, 2204.04237



A feel for the in-Earth attenuation

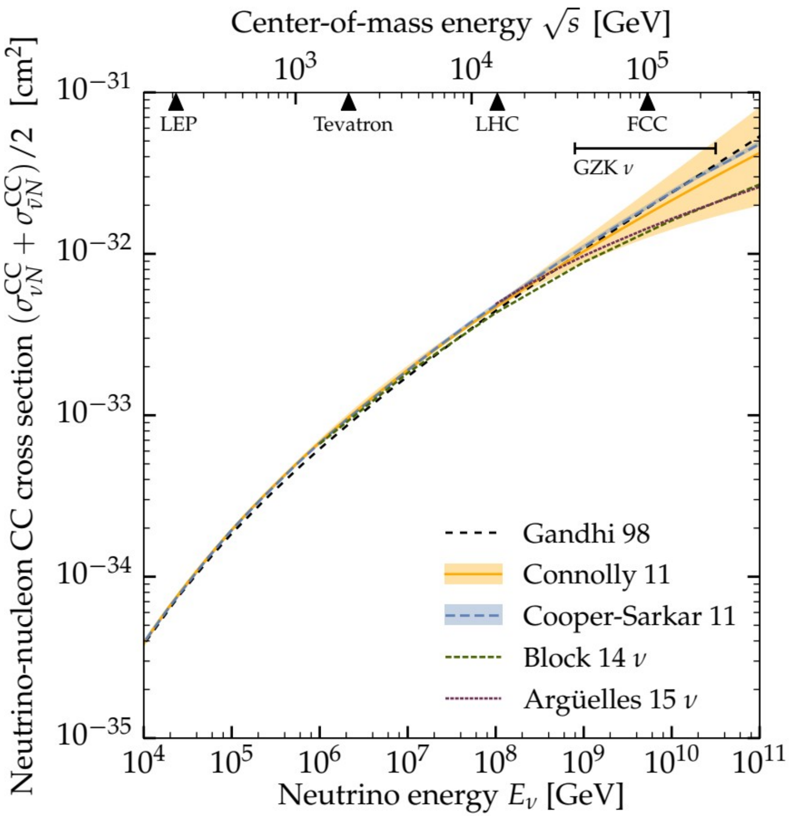
Earth matter density

(Preliminary Reference Earth Model)



+

Neutrino-nucleon cross section



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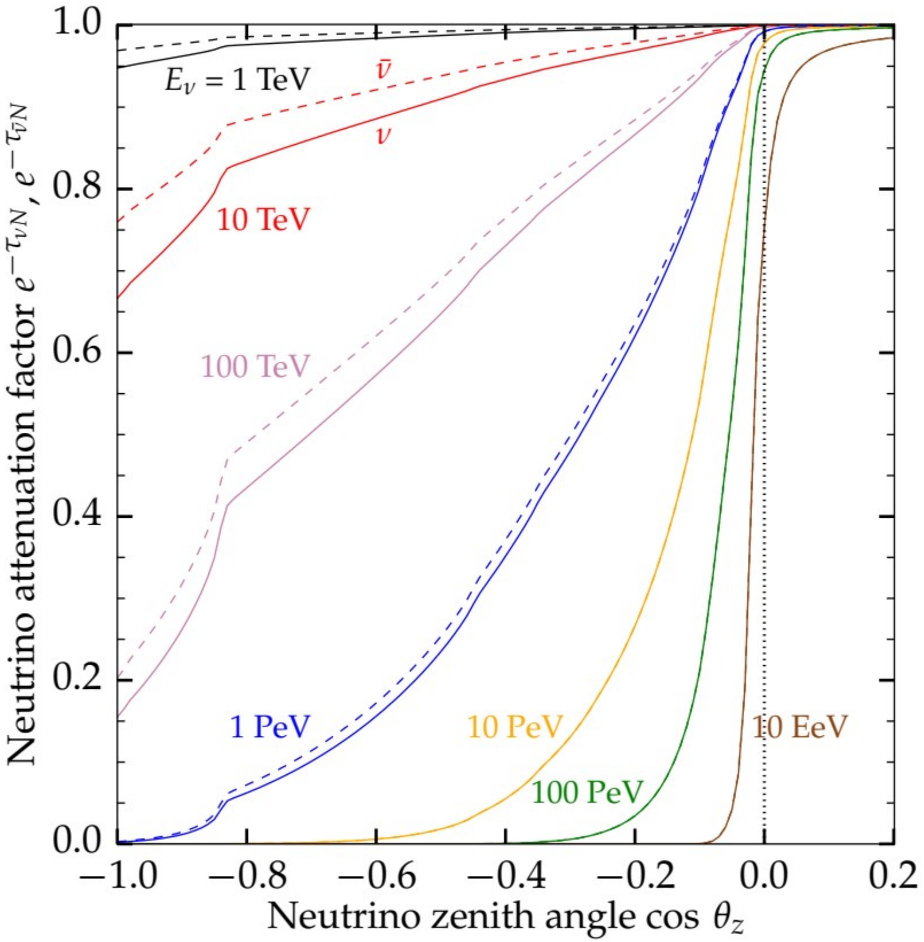
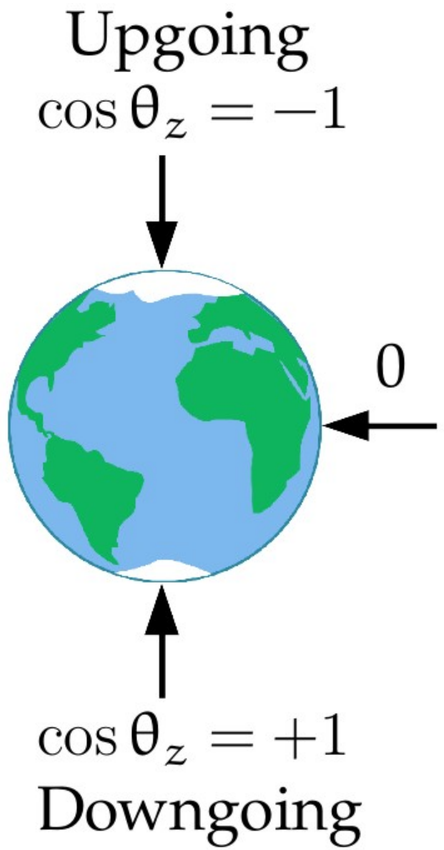
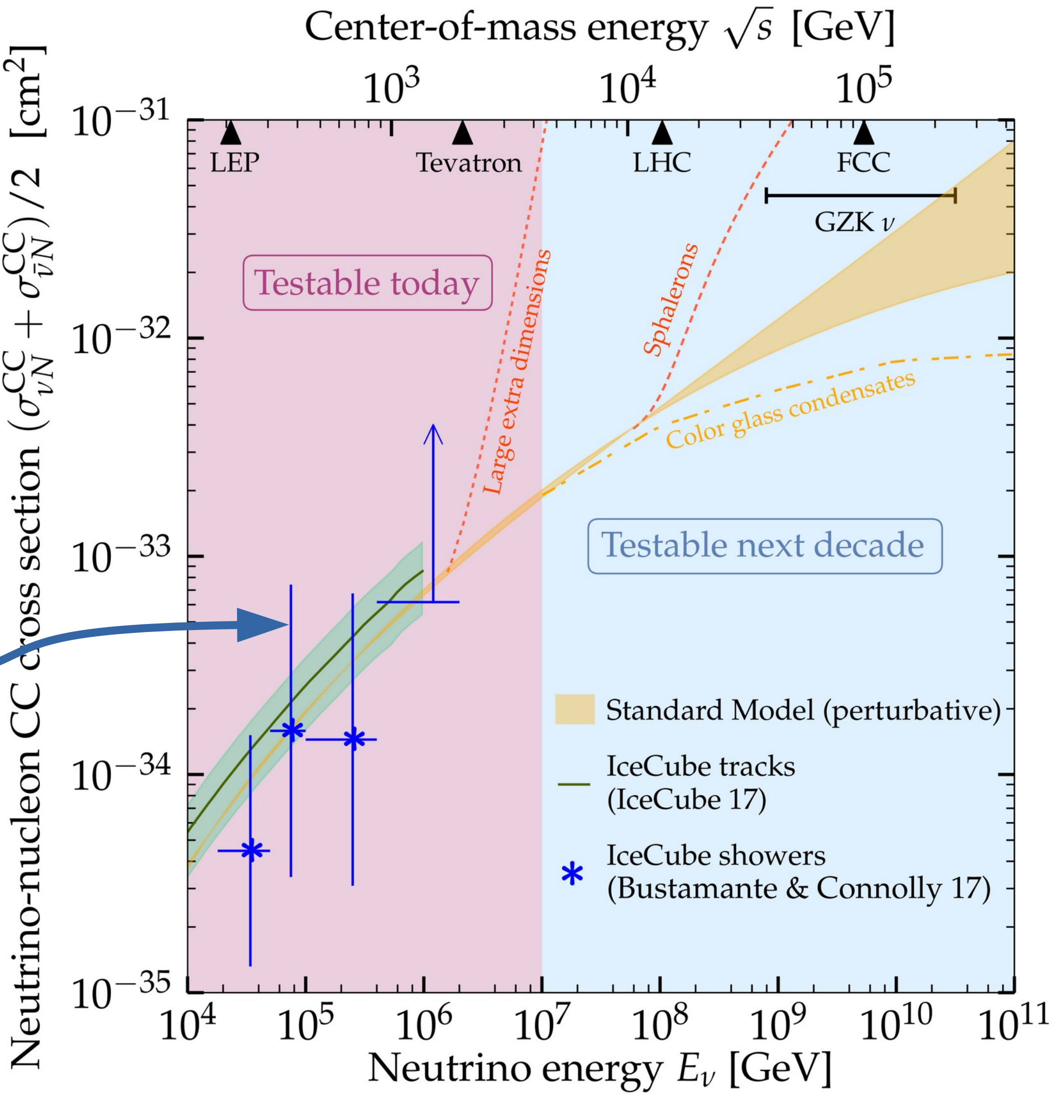




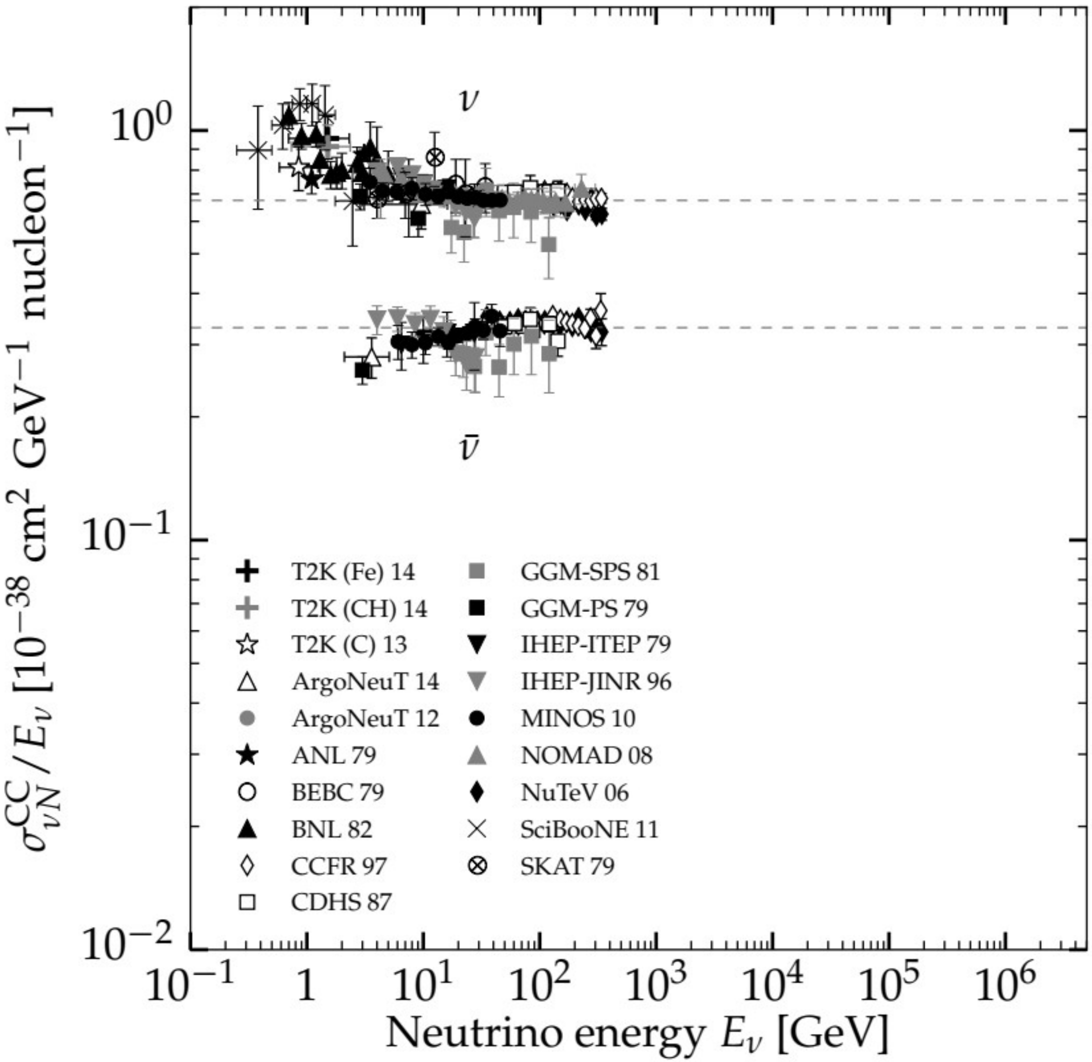
- Fold in astrophysical unknowns (spectral index, normalization)
- Compatible with SM predictions
- Still room for new physics
- Today, using IceCube:
  - Extracted from ~60 showers in 6 yr
  - Limited by statistics
- Future, using IceCube-Gen2:
  - × 5 volume ⇒ 300 showers in 6 yr
  - Reduce statistical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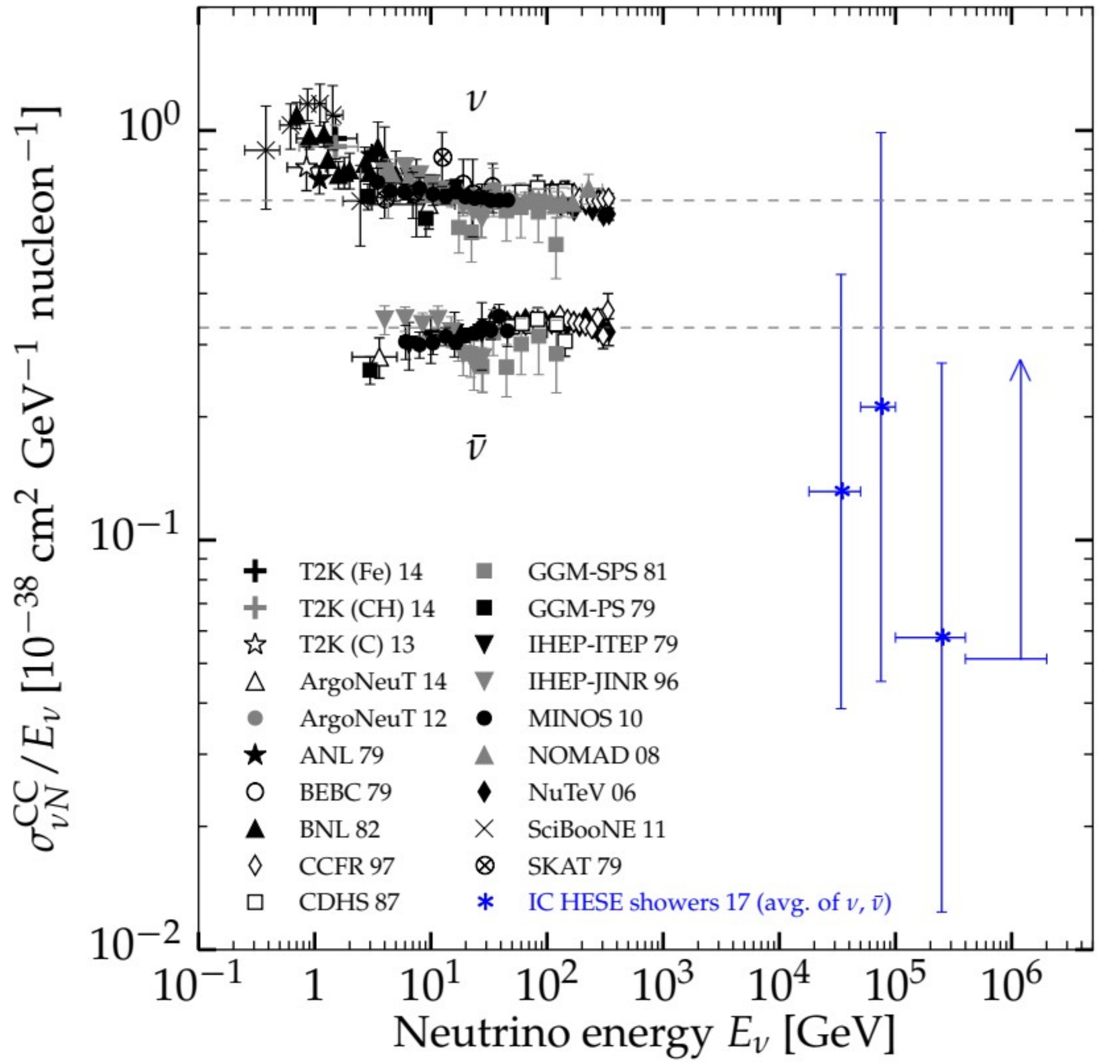

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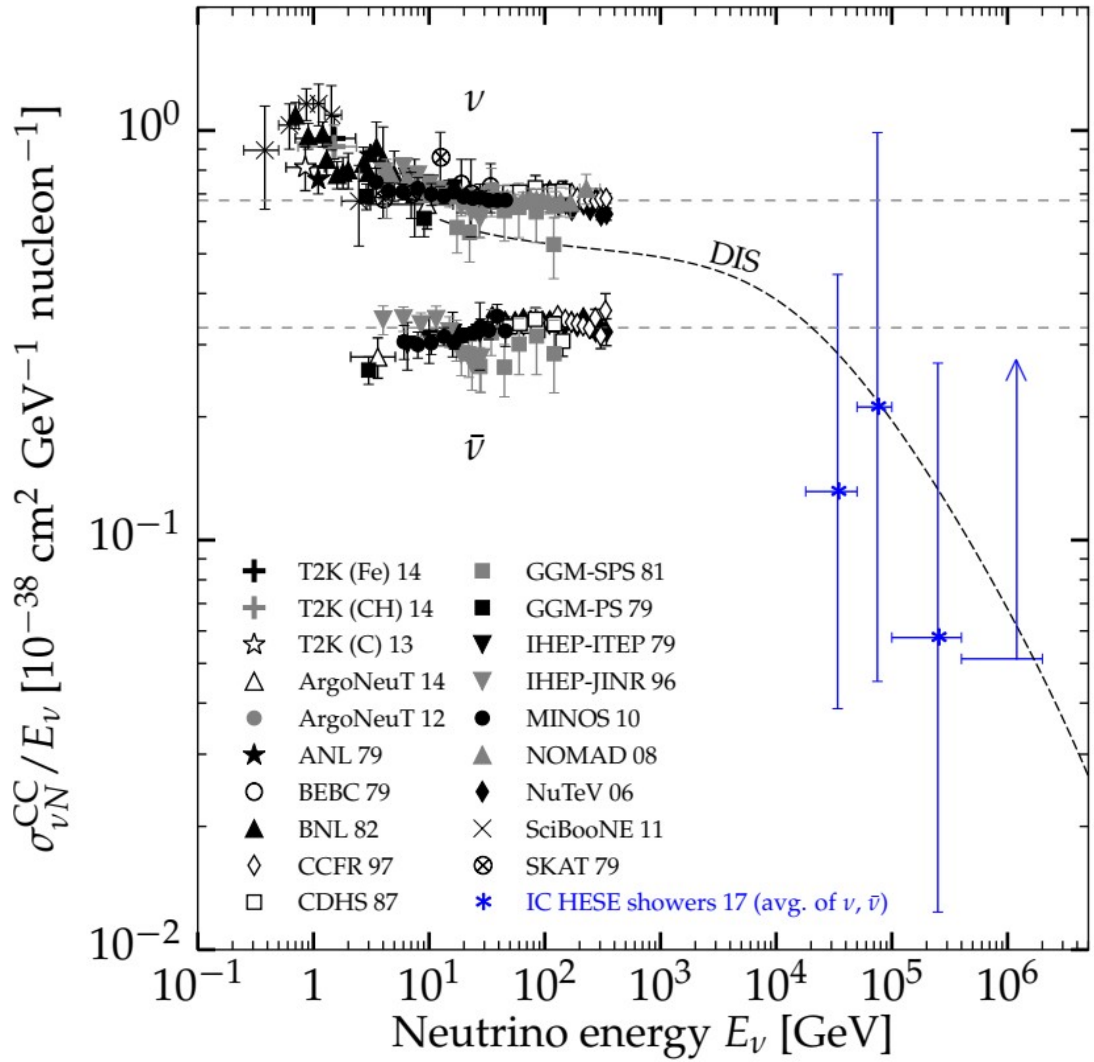
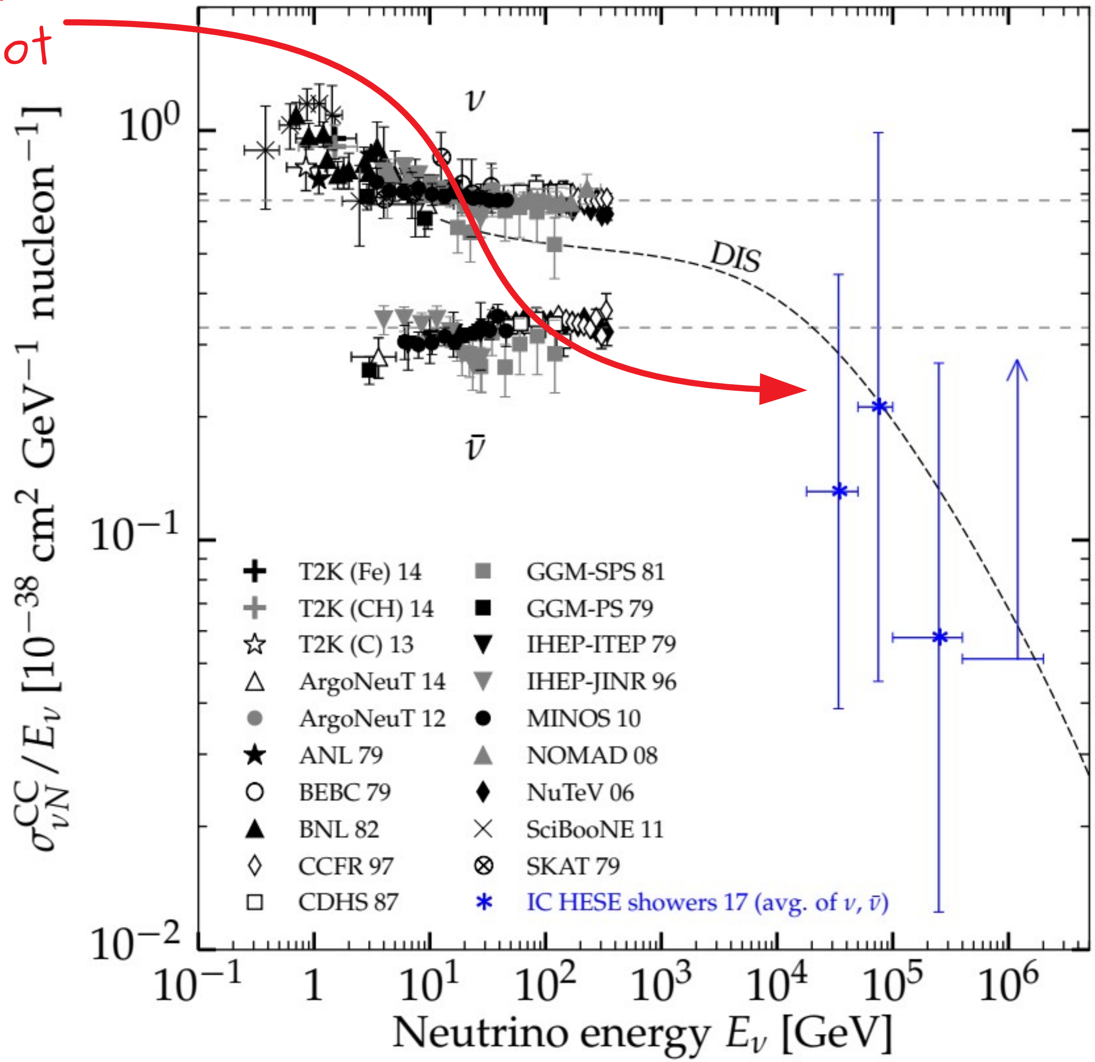


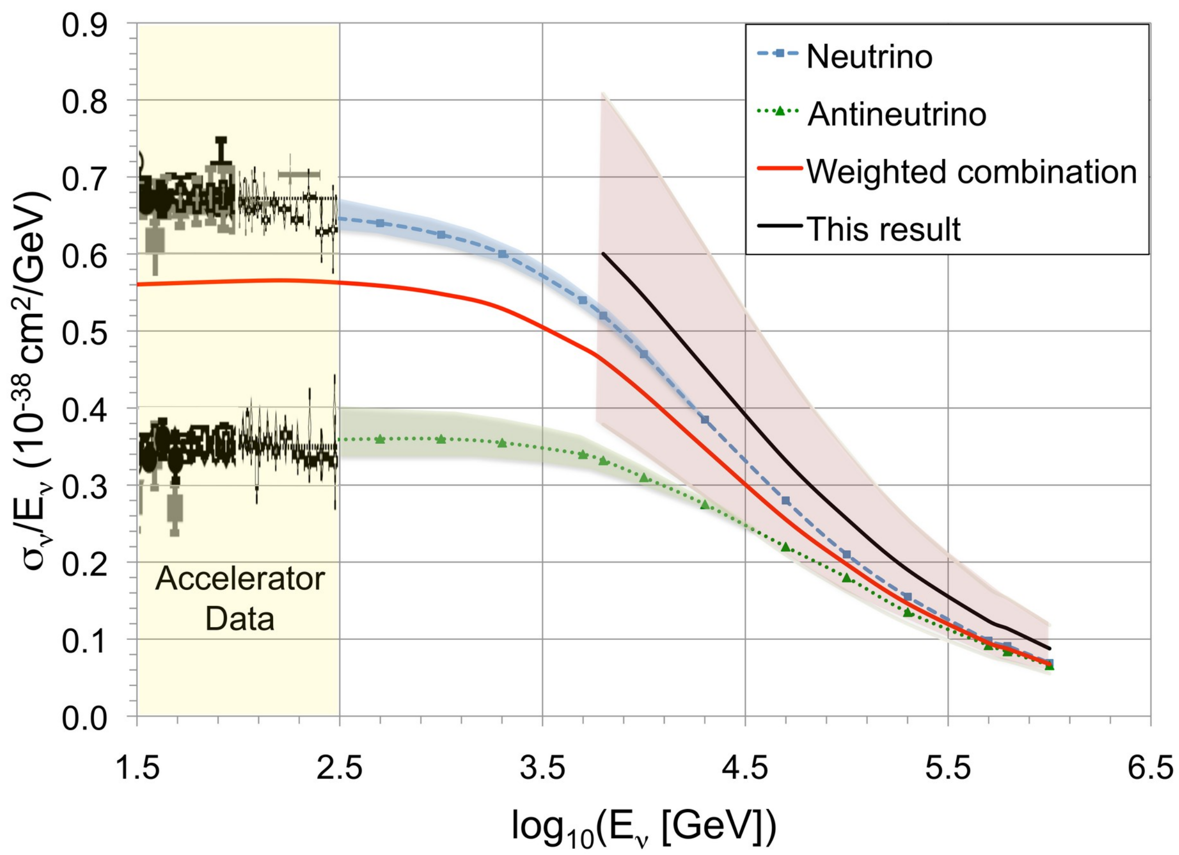
Extending the PDG cross-section plot

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



Using through-going muons instead

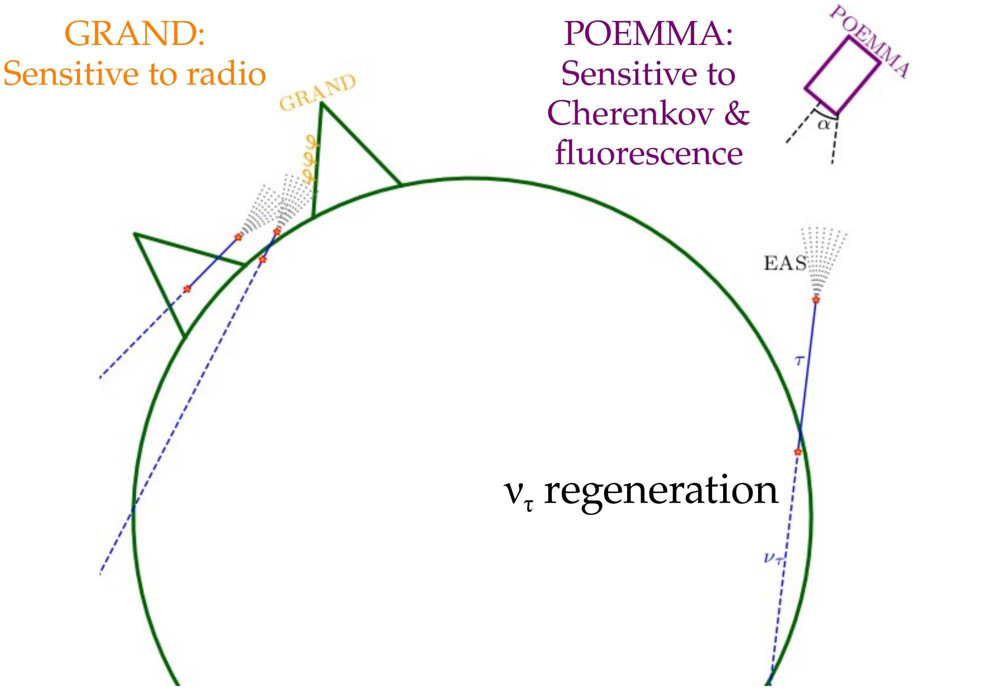
- Use ~10^4 through-going muons
- Measured: $\mathrm{d}E_\mu/\mathrm{d}x$
- Inferred: $E_\mu \approx \mathrm{d}E_\mu/\mathrm{d}x$
- From simulations (uncertain): most likely E_ν given E_μ
- Fit the ratio σ_{obs}/σ_{SM}
  $1.30\,^{+0.21}_{-0.19}(\text{stat.})\,^{+0.39}_{-0.43}(\text{syst.})$
- All events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



IceCube, *Nature* 2017

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