Neutrino physics at the highest energies *today and in the future*

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Niels Bohr Institute, University of Copenhagen

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UNIVERSITY OF COPENHAGEN

VILLUM FONDEN

Neutrinos are elementary particles,

electrically neutral,

very light,

and superbly antisocial

Neutrinos are elementary particles,

= *indivisible*

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Neutrinos are elementary particles,

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electrically neutral,

= *no electric charge*

very light,

= *so light that we don't know their mass!*

and superbly antisocial

= *barely interact with matter*

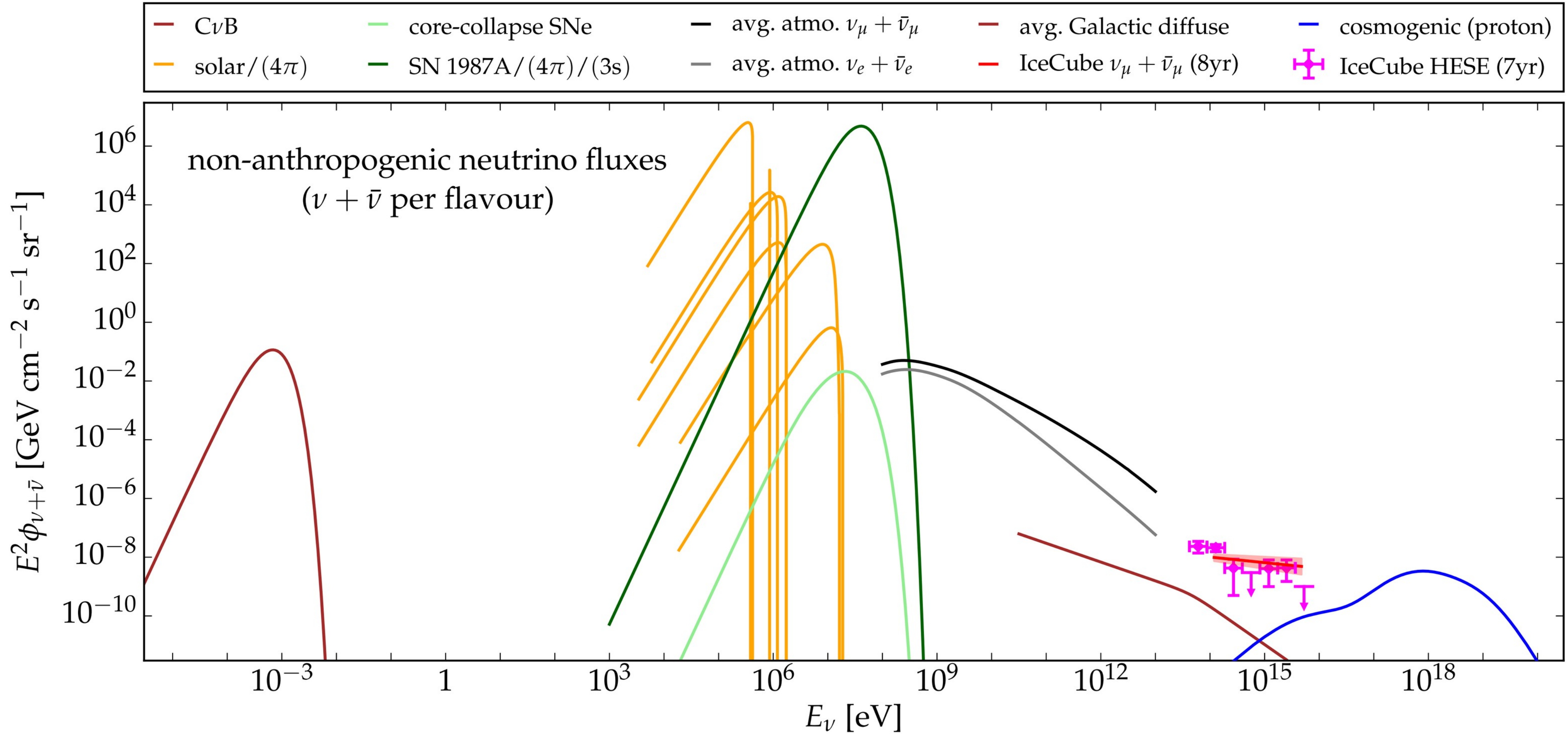
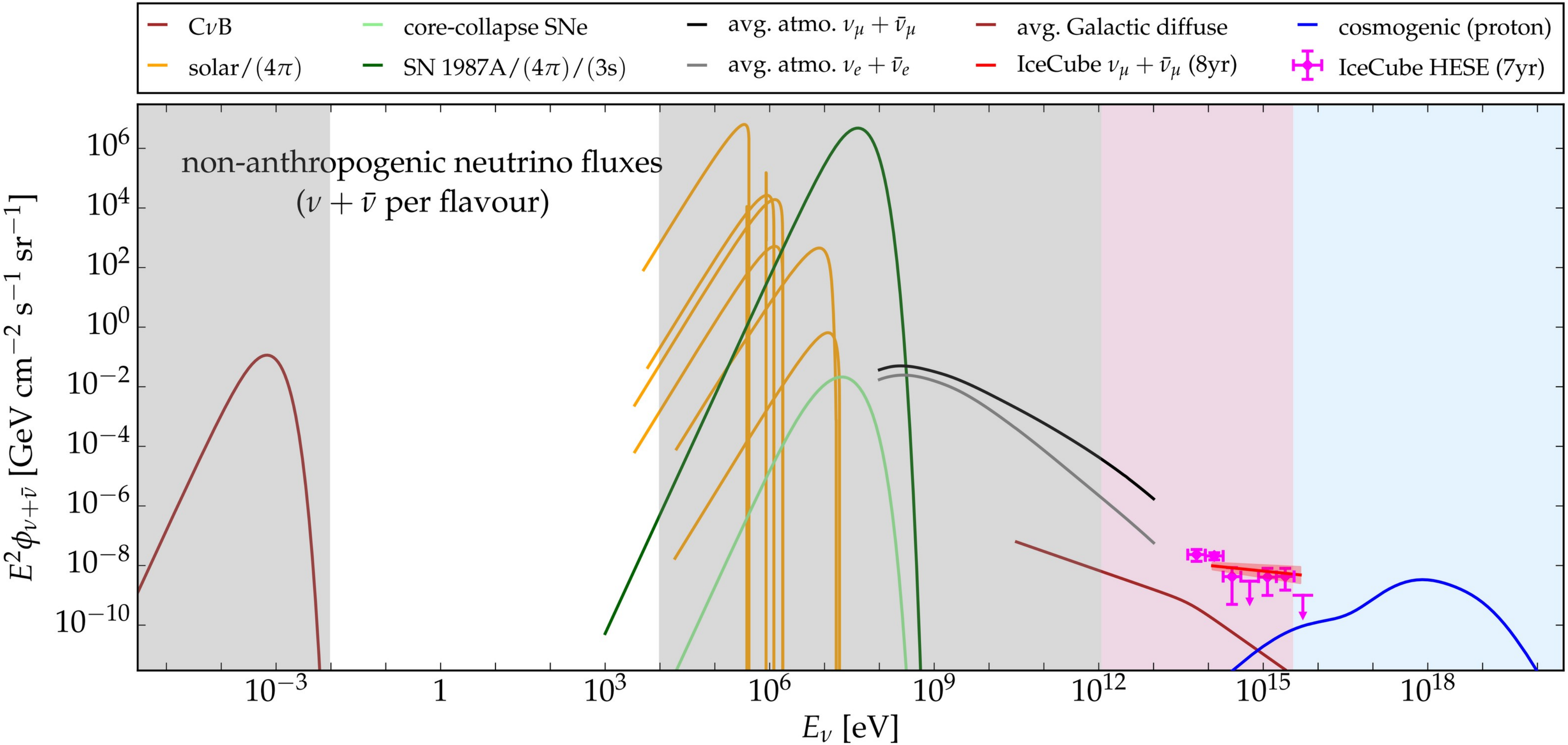


Figure courtesy of Markus Ahlers

Maoloud, De Wasseige, Ahlers, **MB**, Van Elewyck, PoS(ICRC2019), 1023



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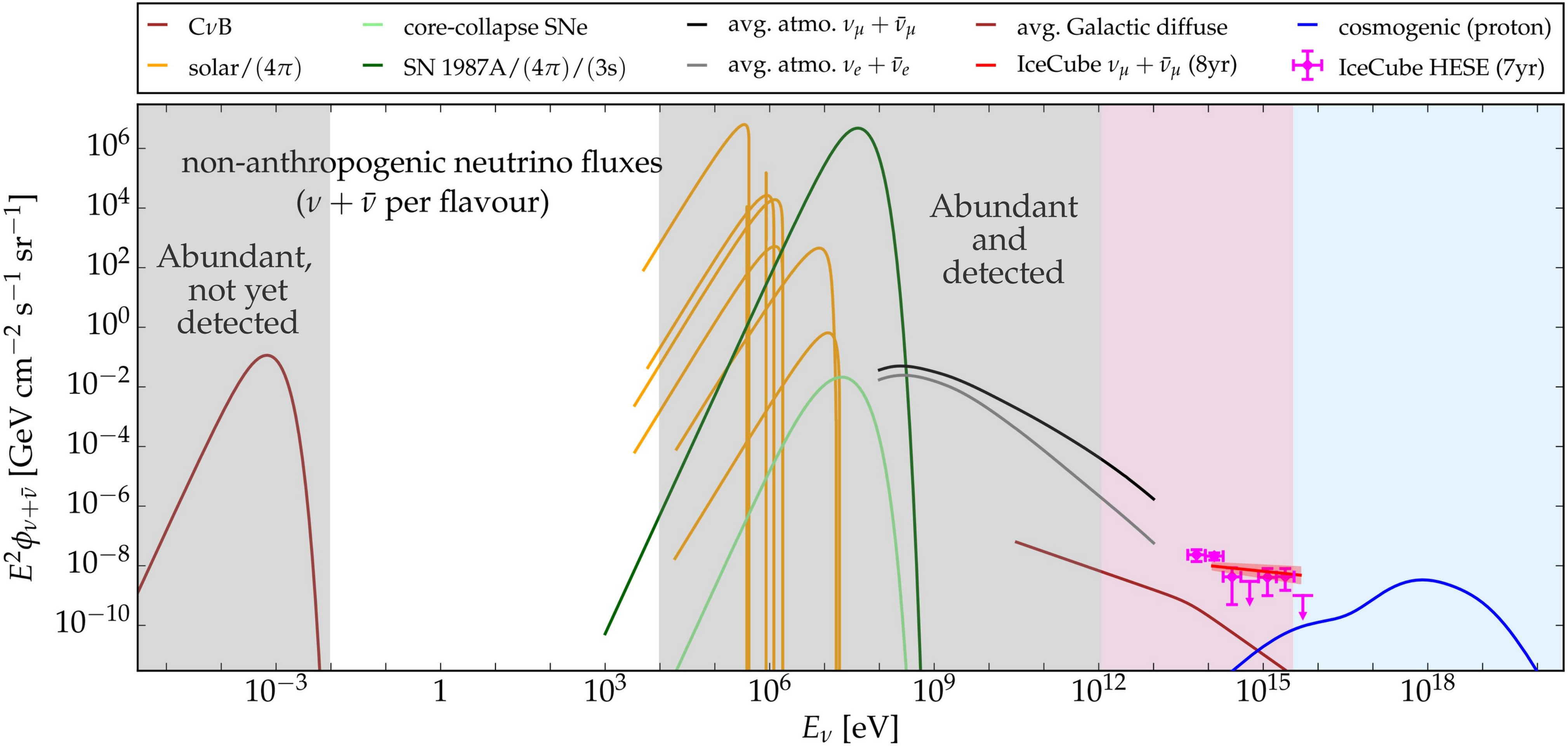

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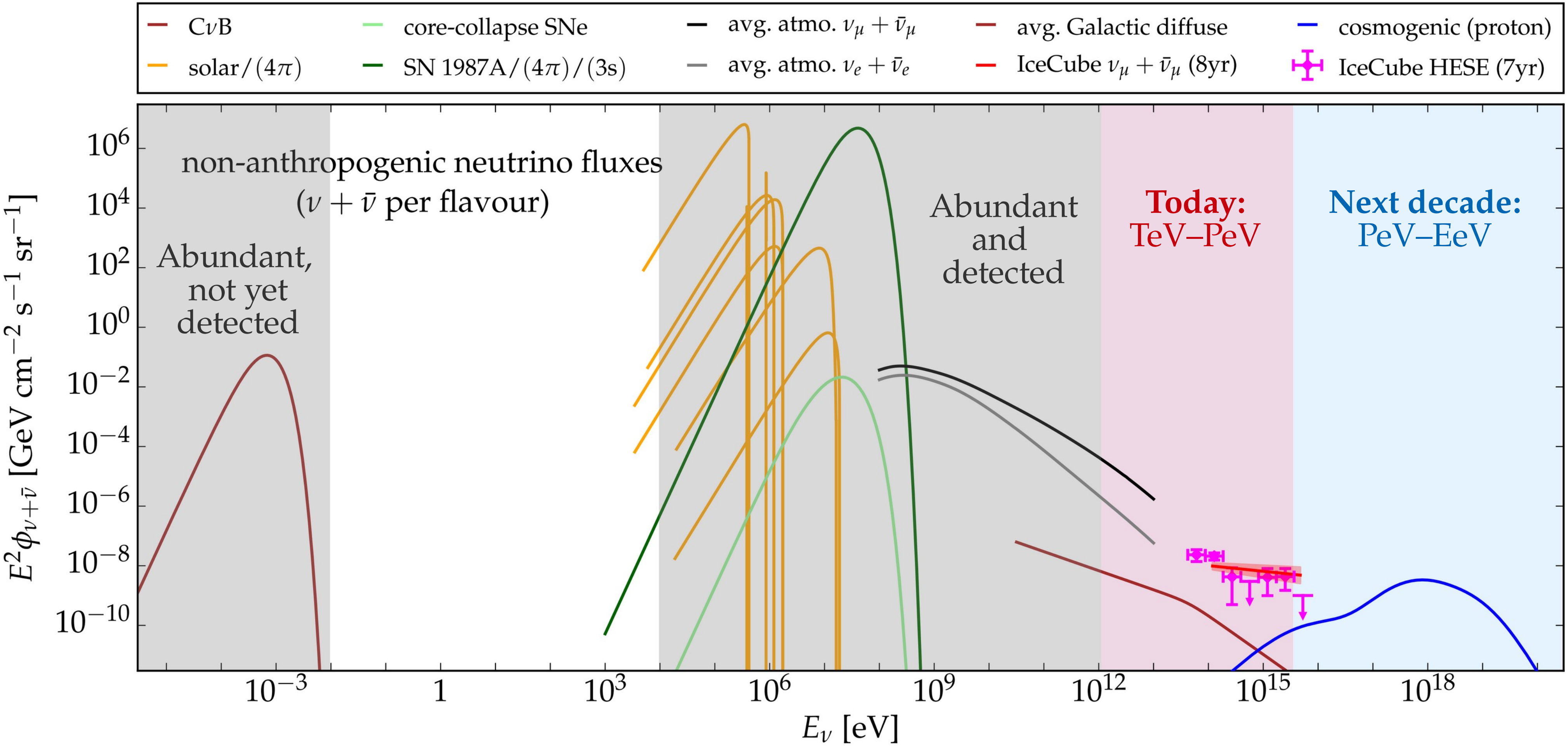

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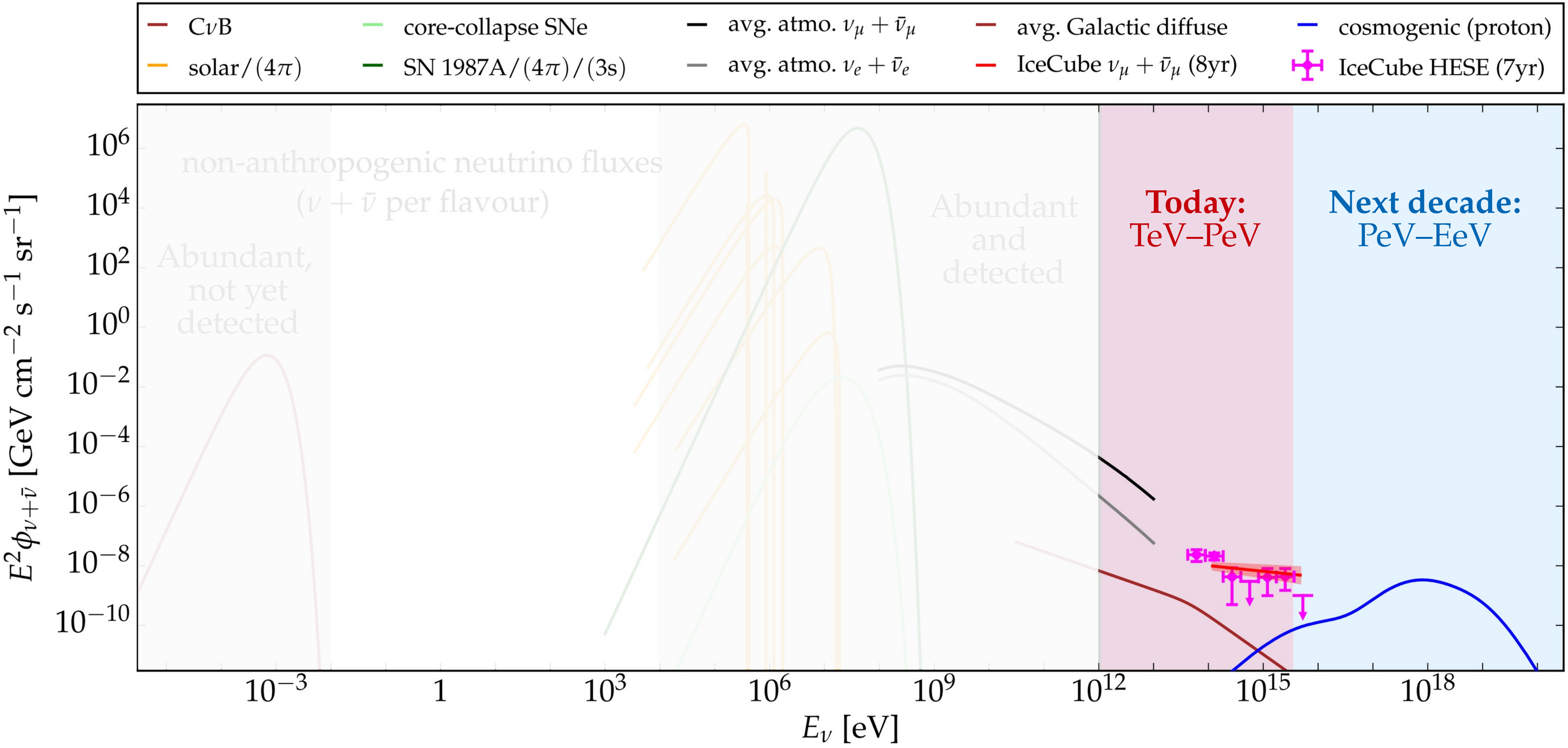

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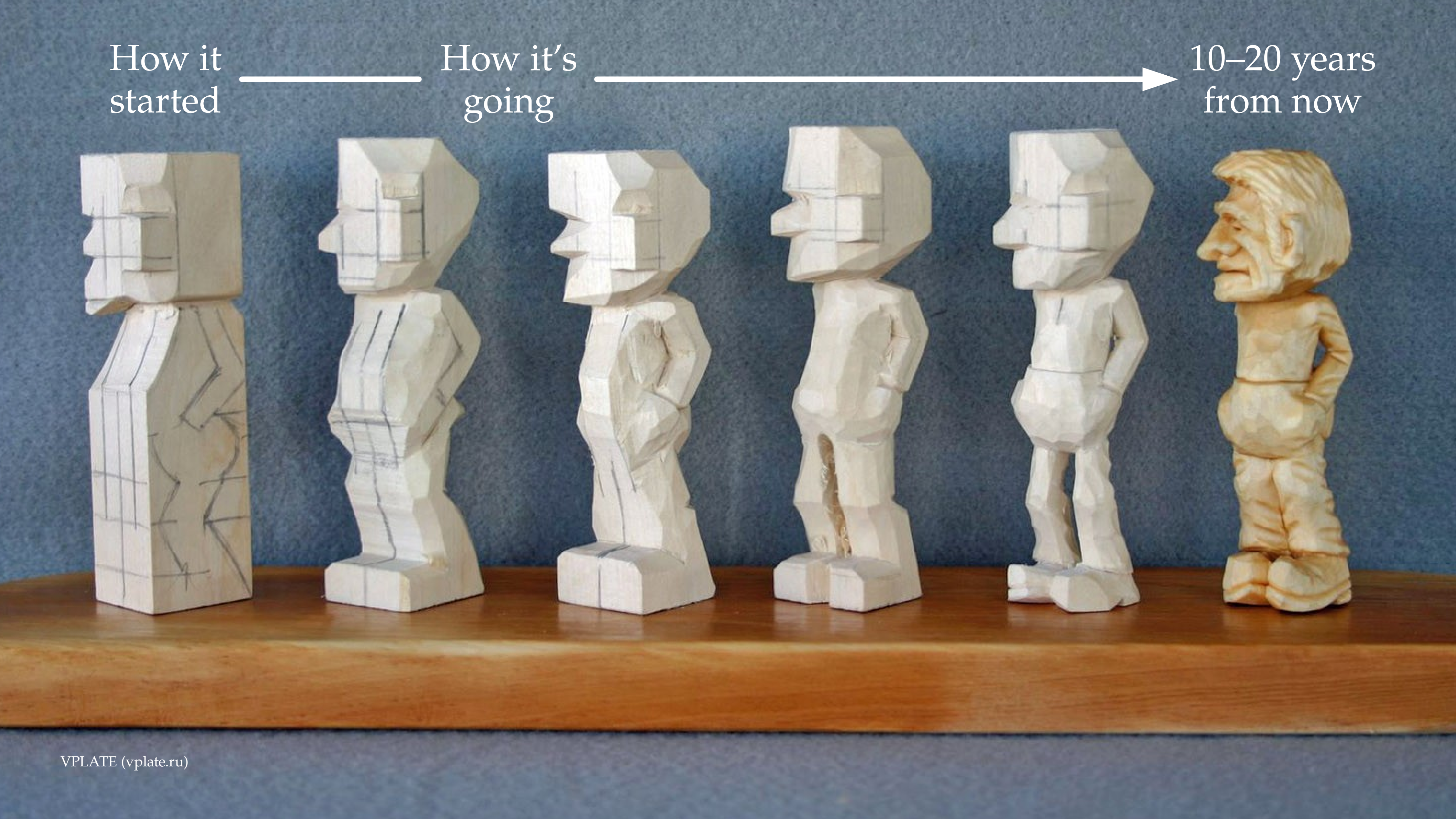
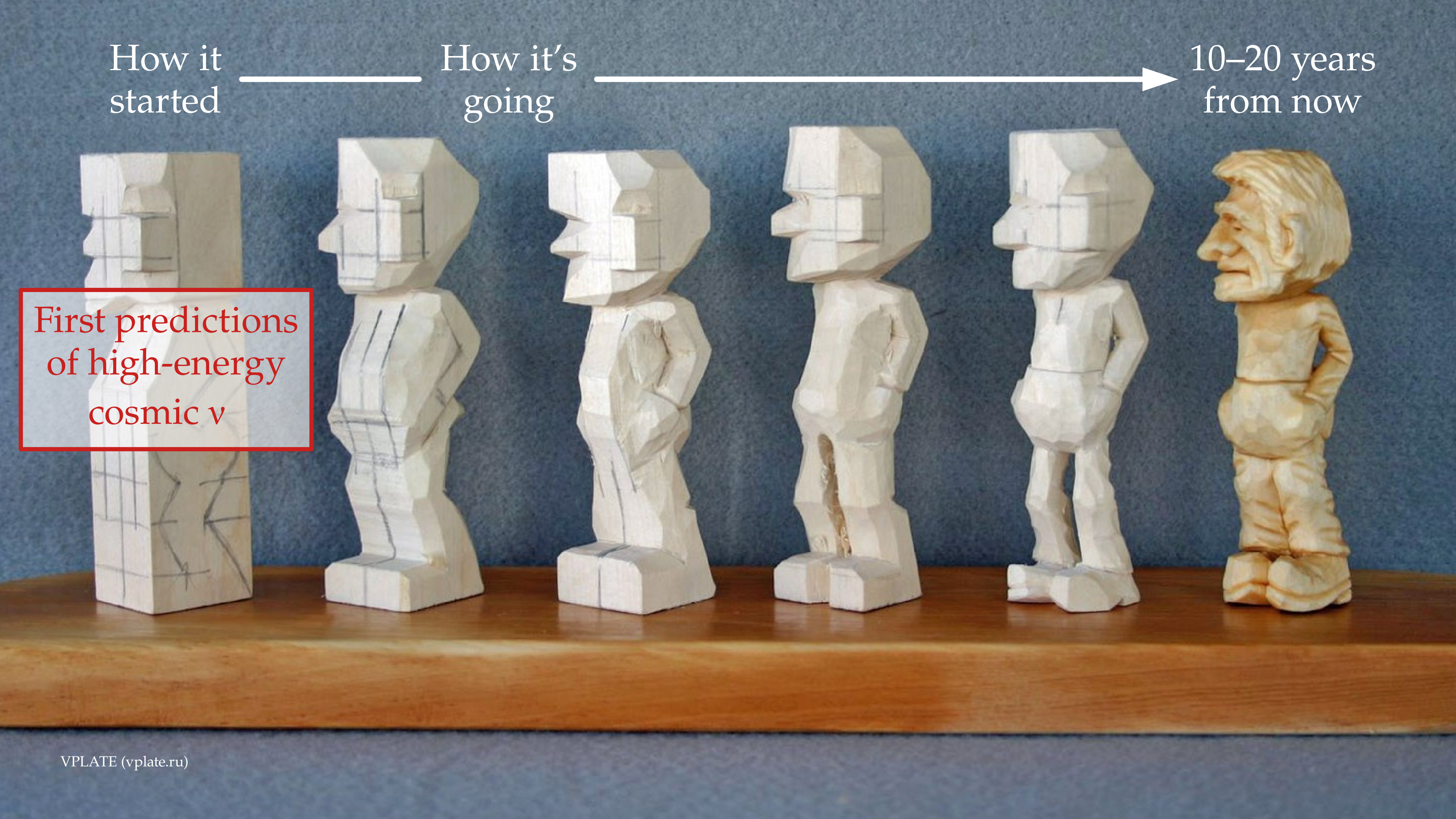


VPLATE (vplate.ru)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How it's going
10–20 years from now
First predictions of high-energy cosmic ν
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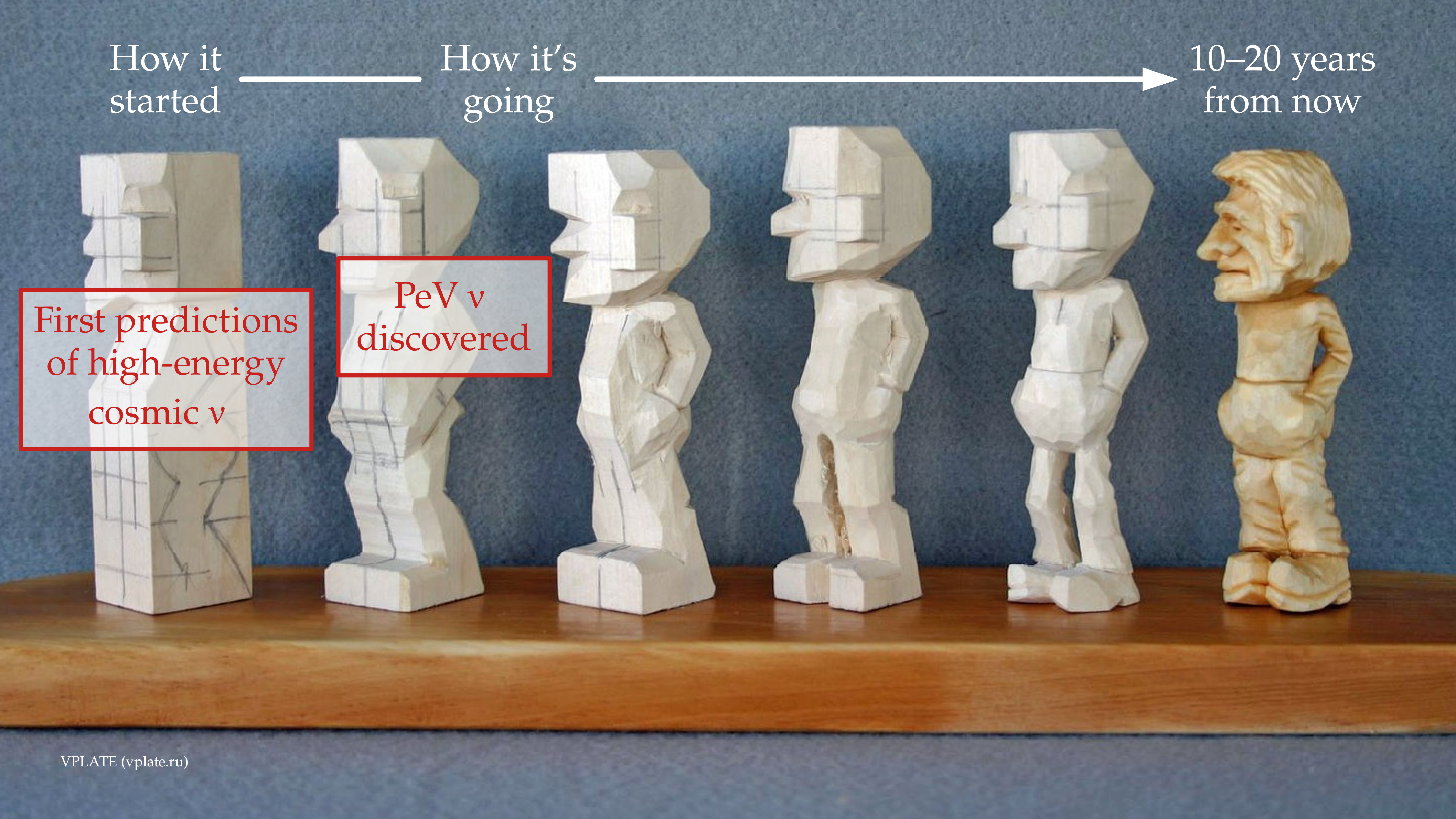

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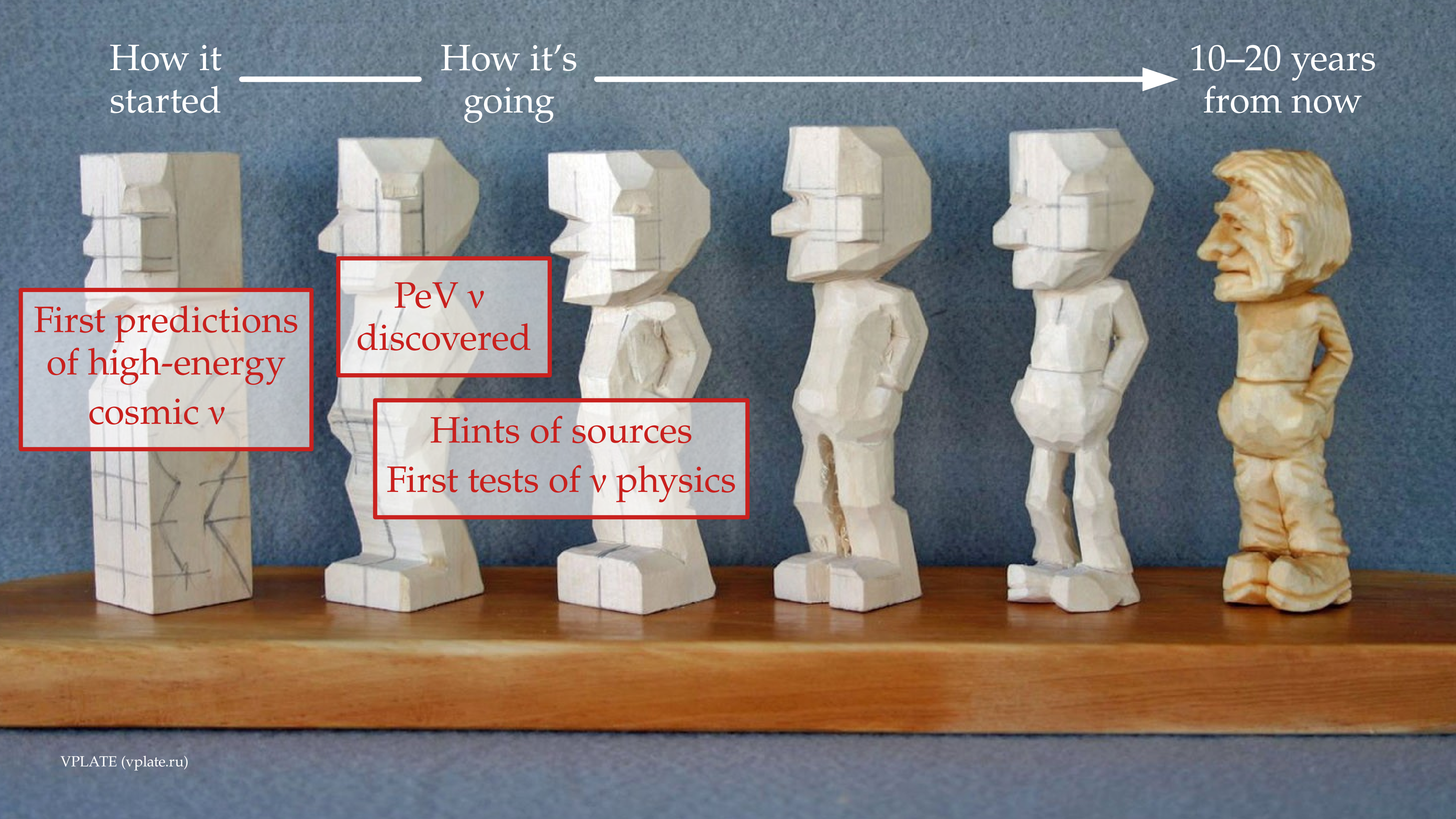
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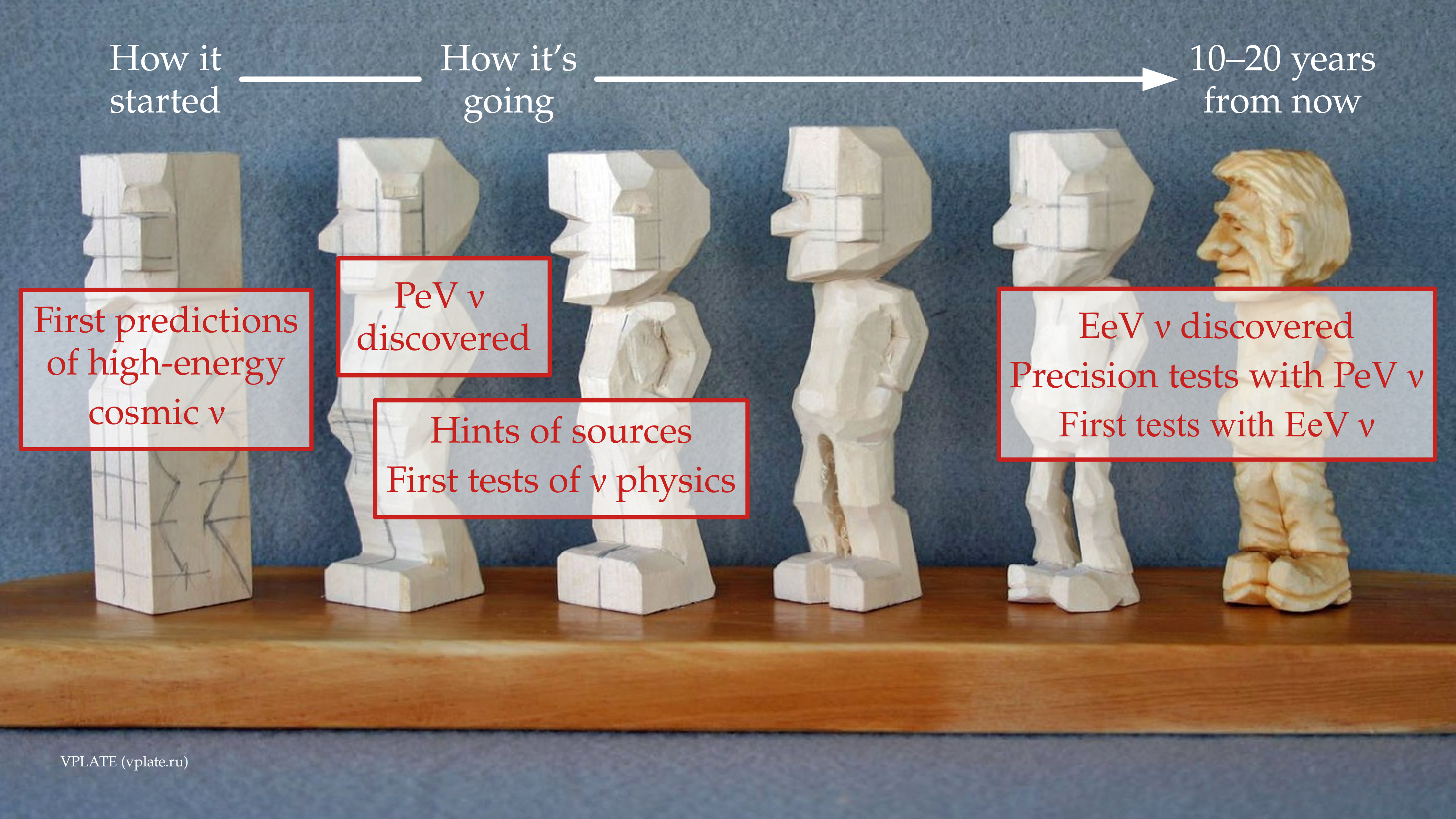
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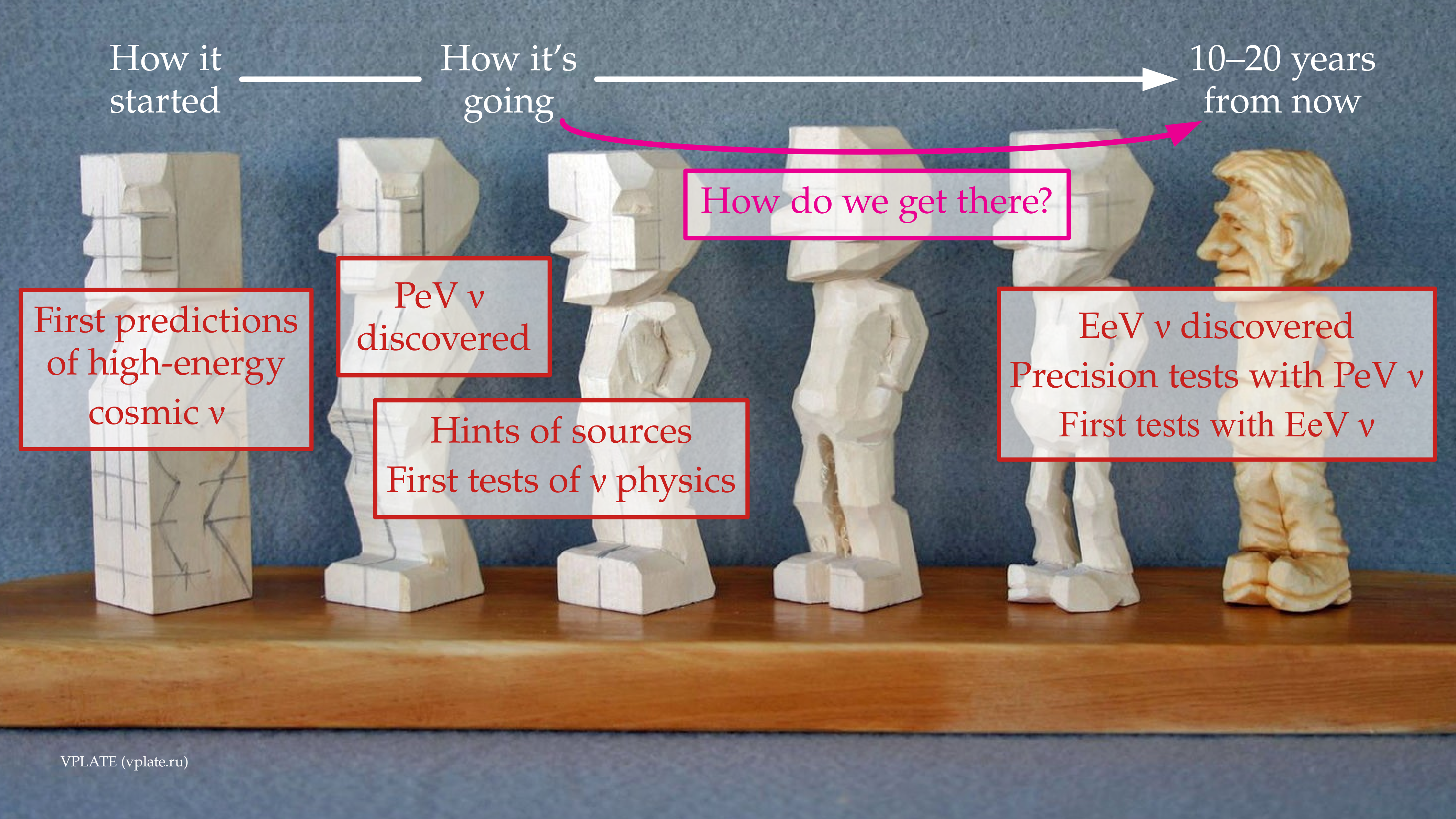

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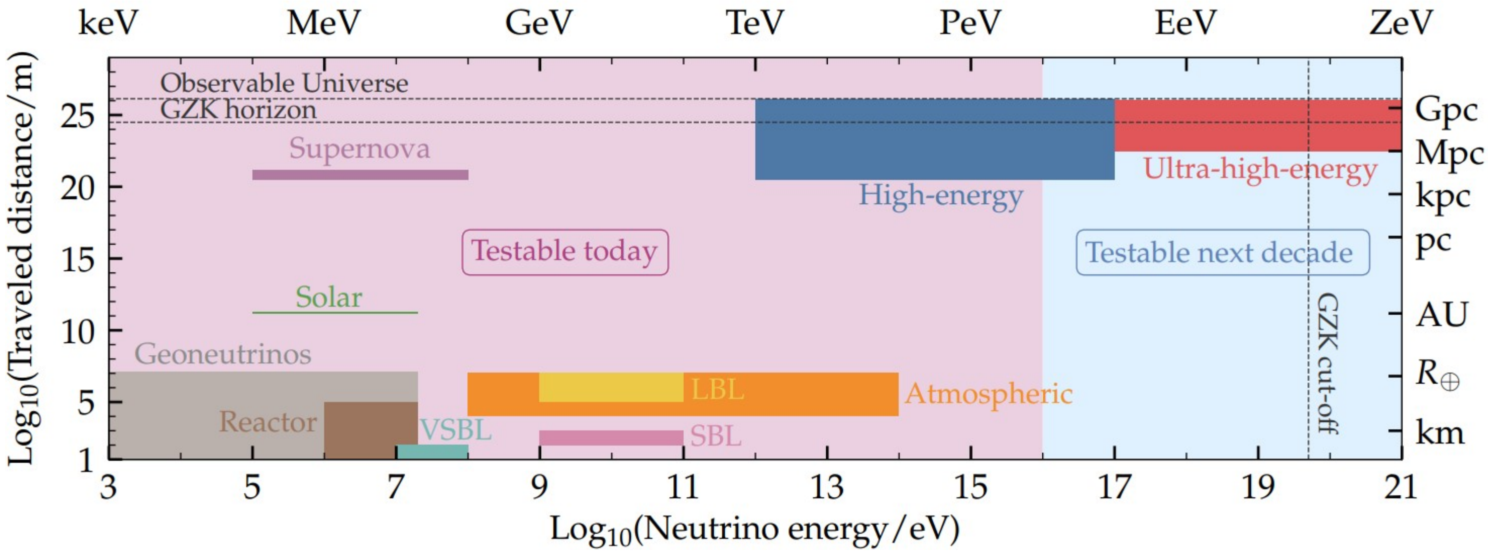
What makes high-energy cosmic ν exciting?



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

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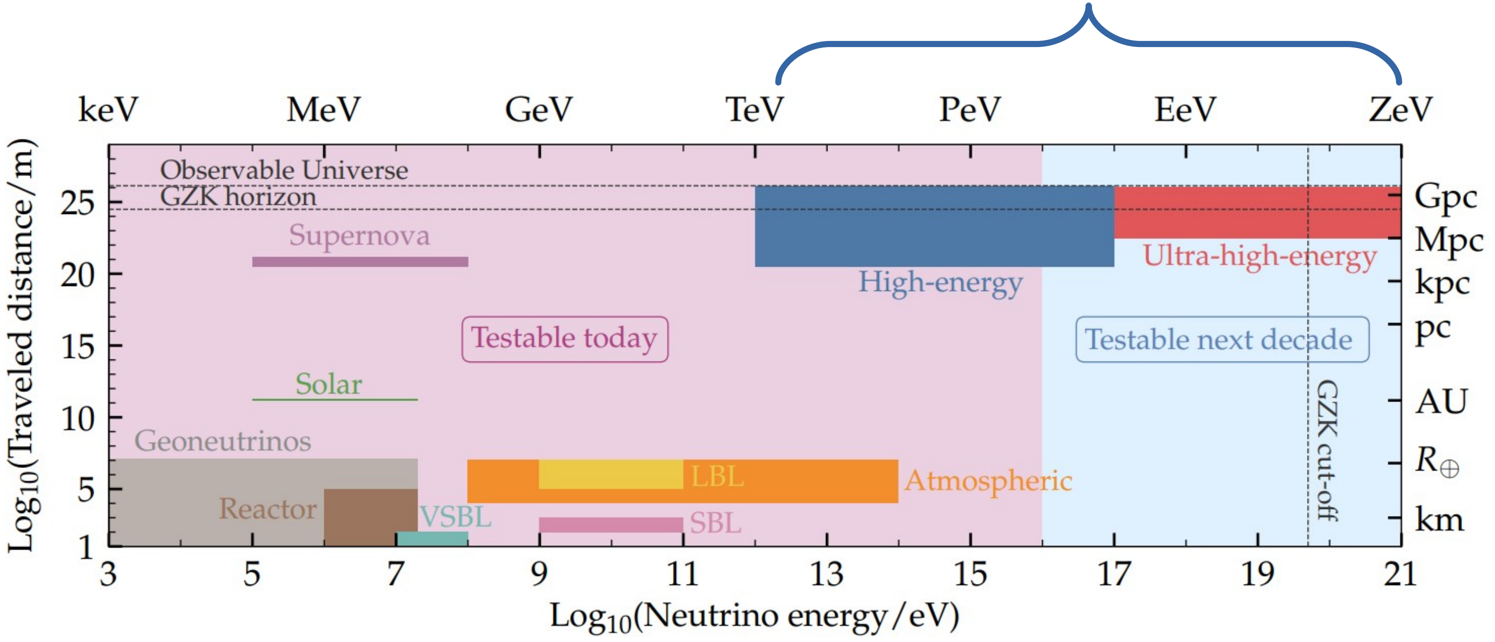
They have the highest energies



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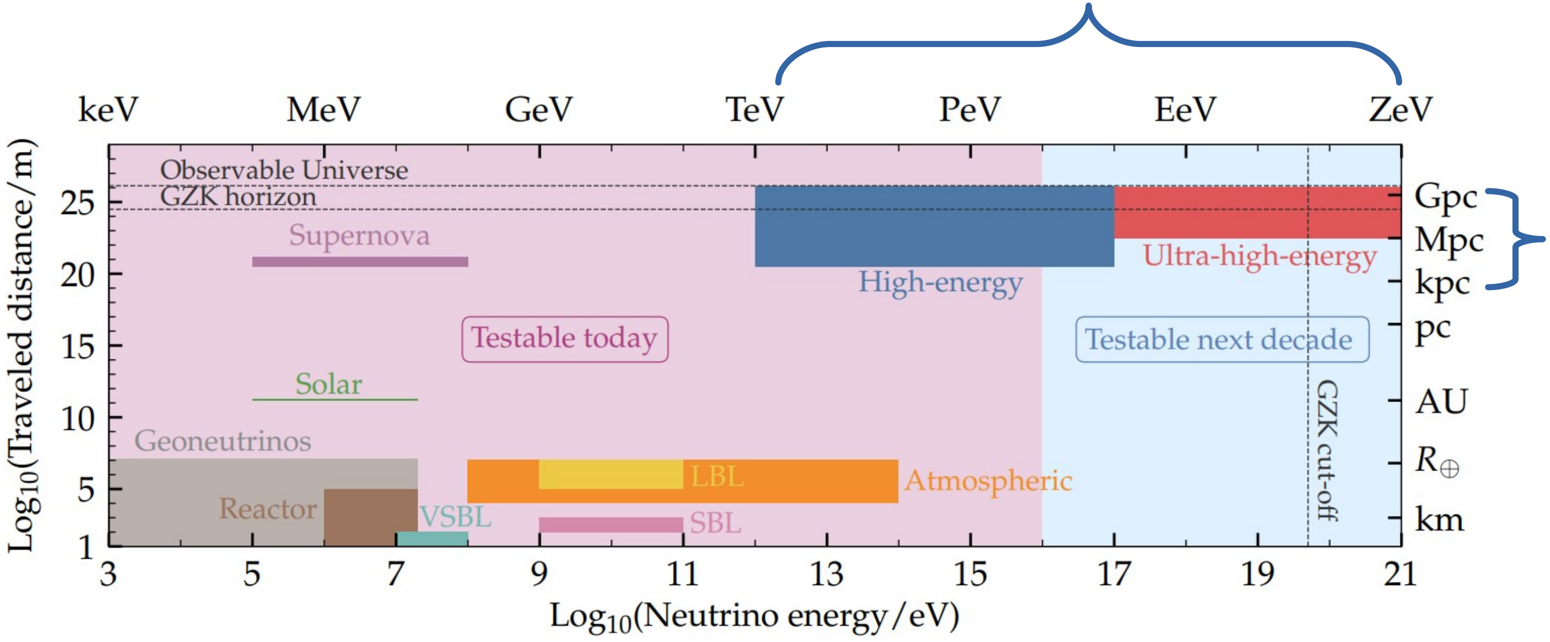
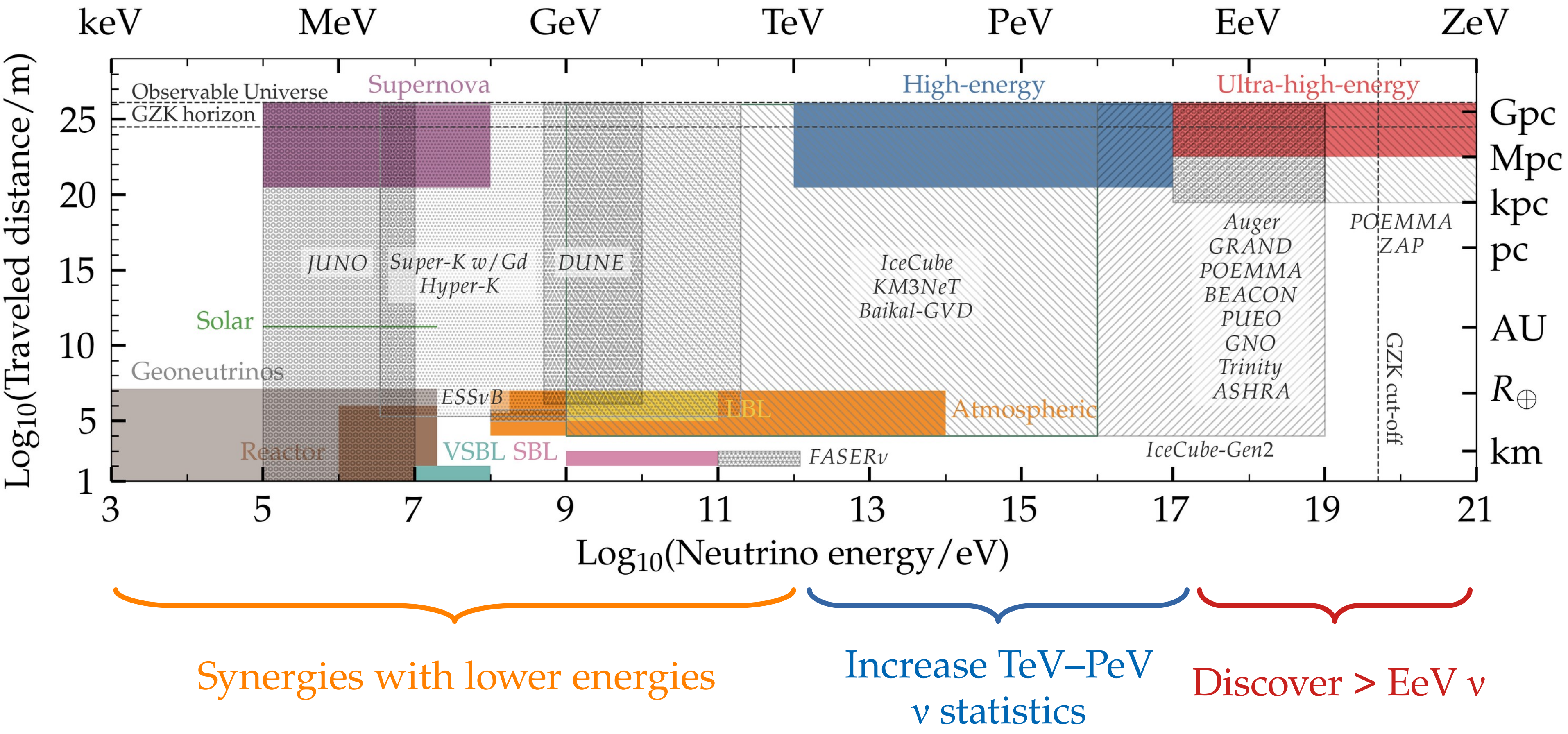


They travel the longest distances

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

Next decade: a host of planned neutrino detectors



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

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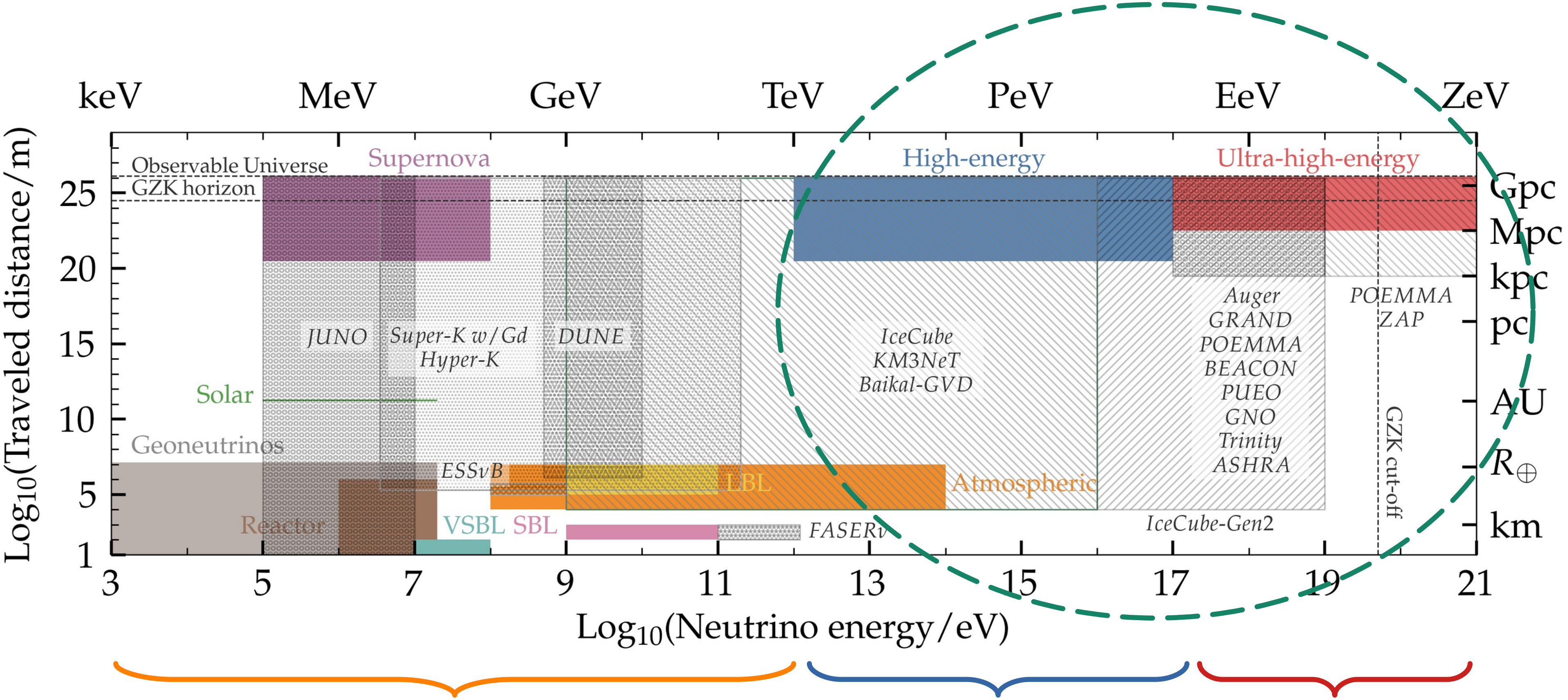

Synergies with lower energies

Increase TeV–PeV ν statistics

Discover > EeV ν

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

High-energy neutrinos: TeV–PeV

(*Discovered*)

Ultra-high-energy neutrinos: > 100 PeV

(*Predicted but undiscovered*)

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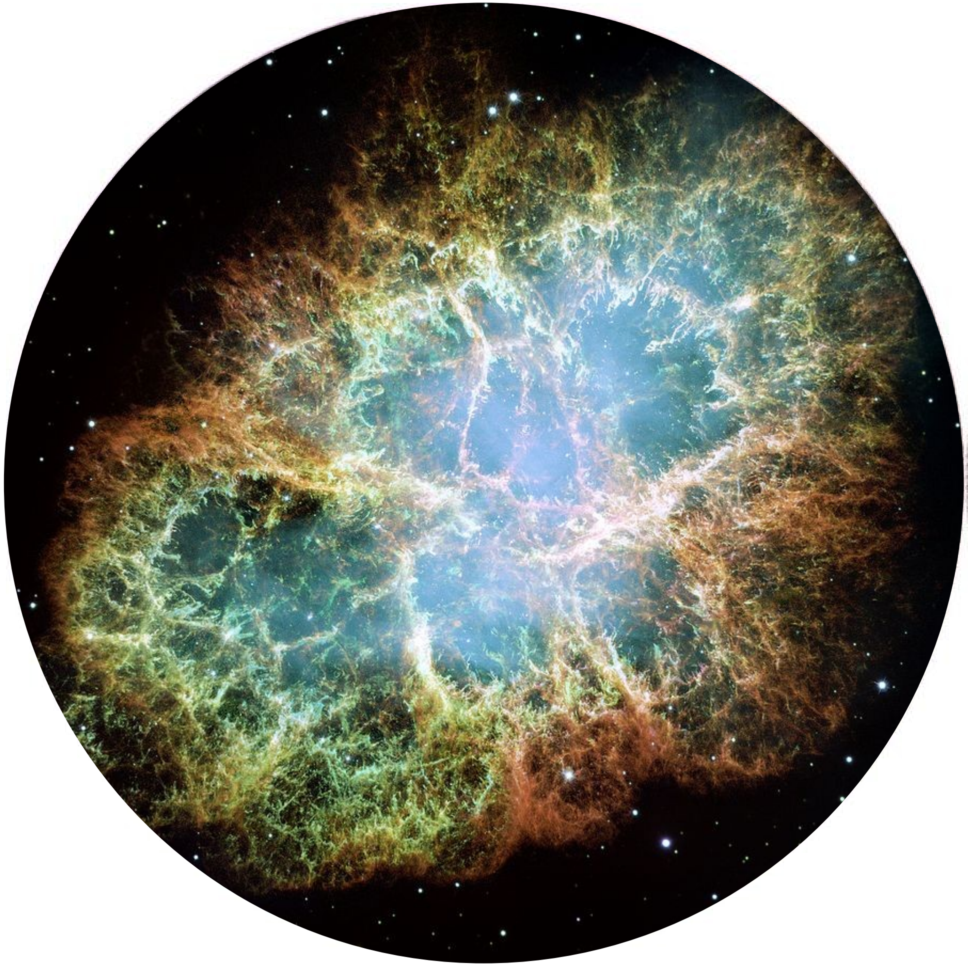

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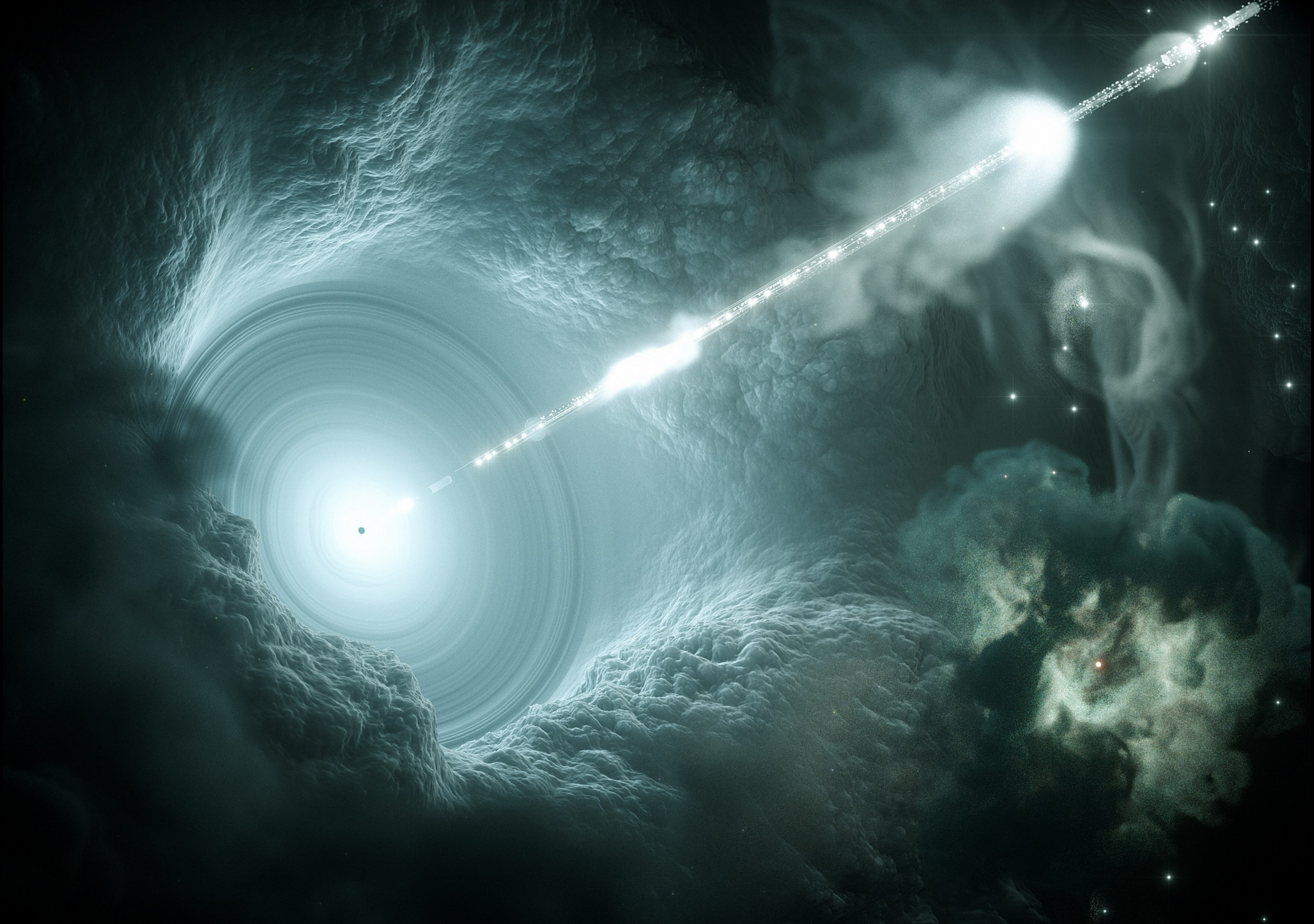

DESY

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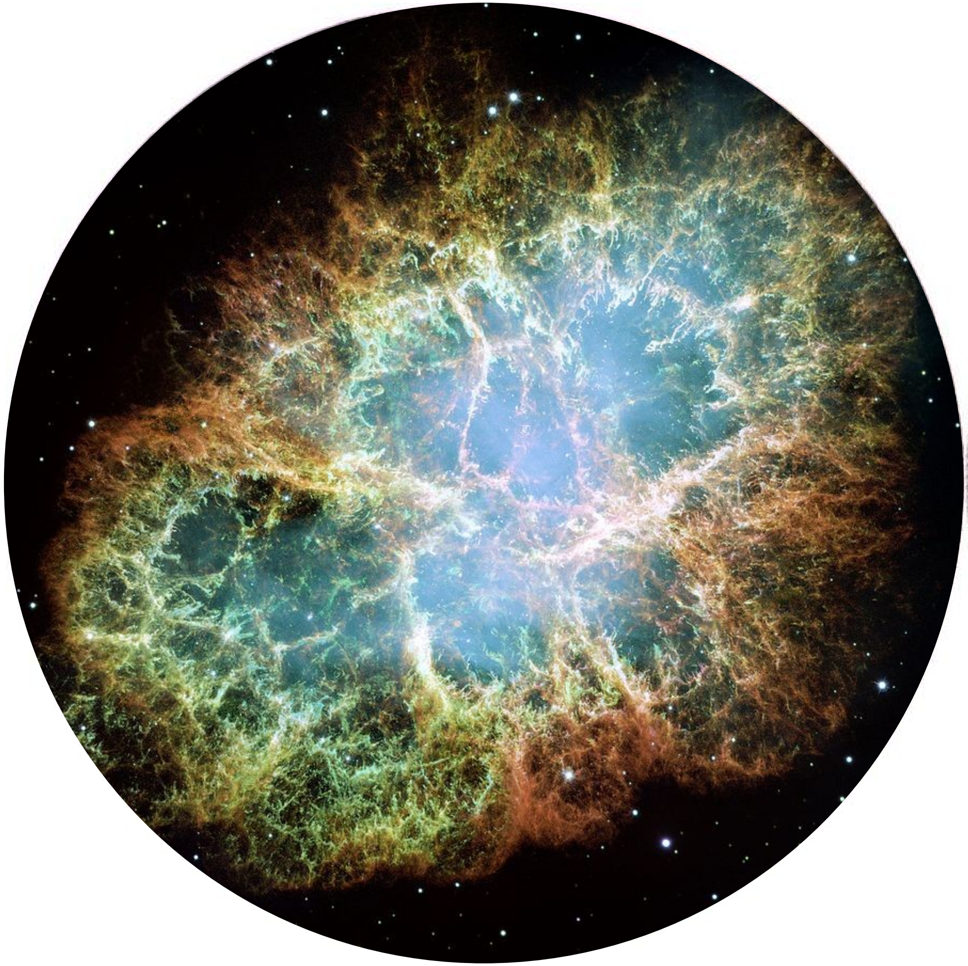

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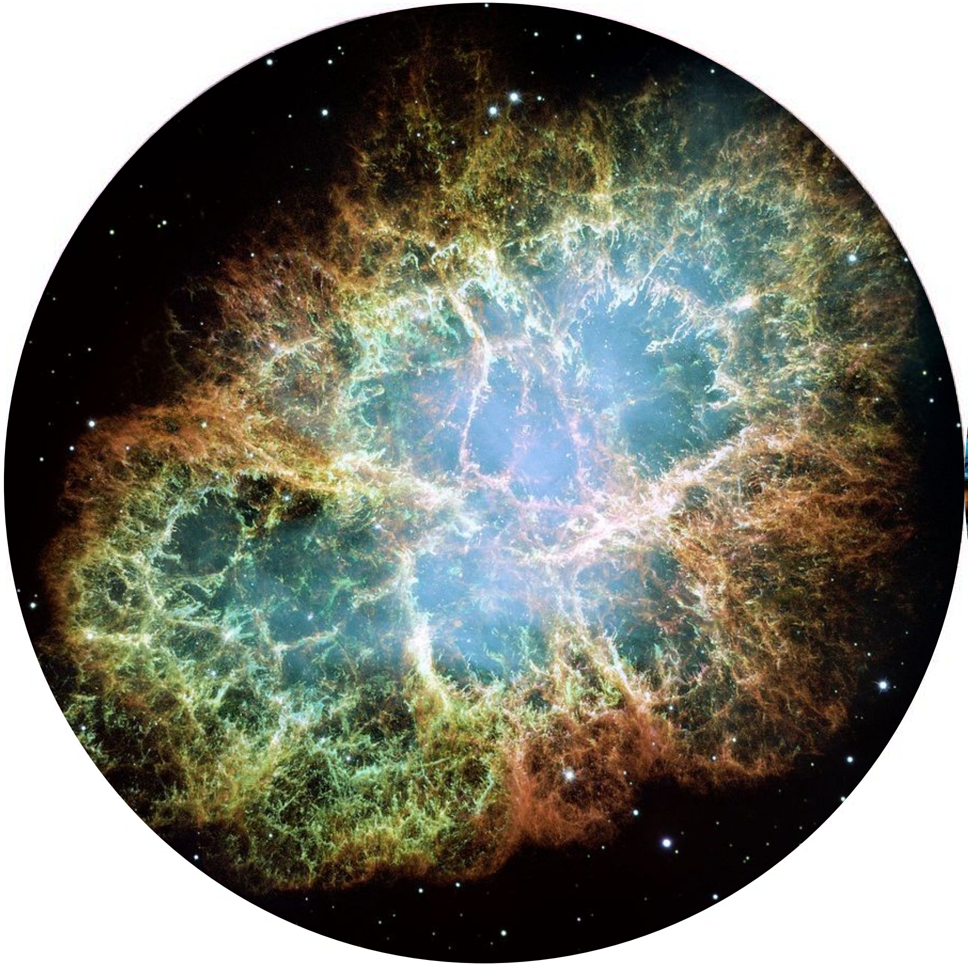

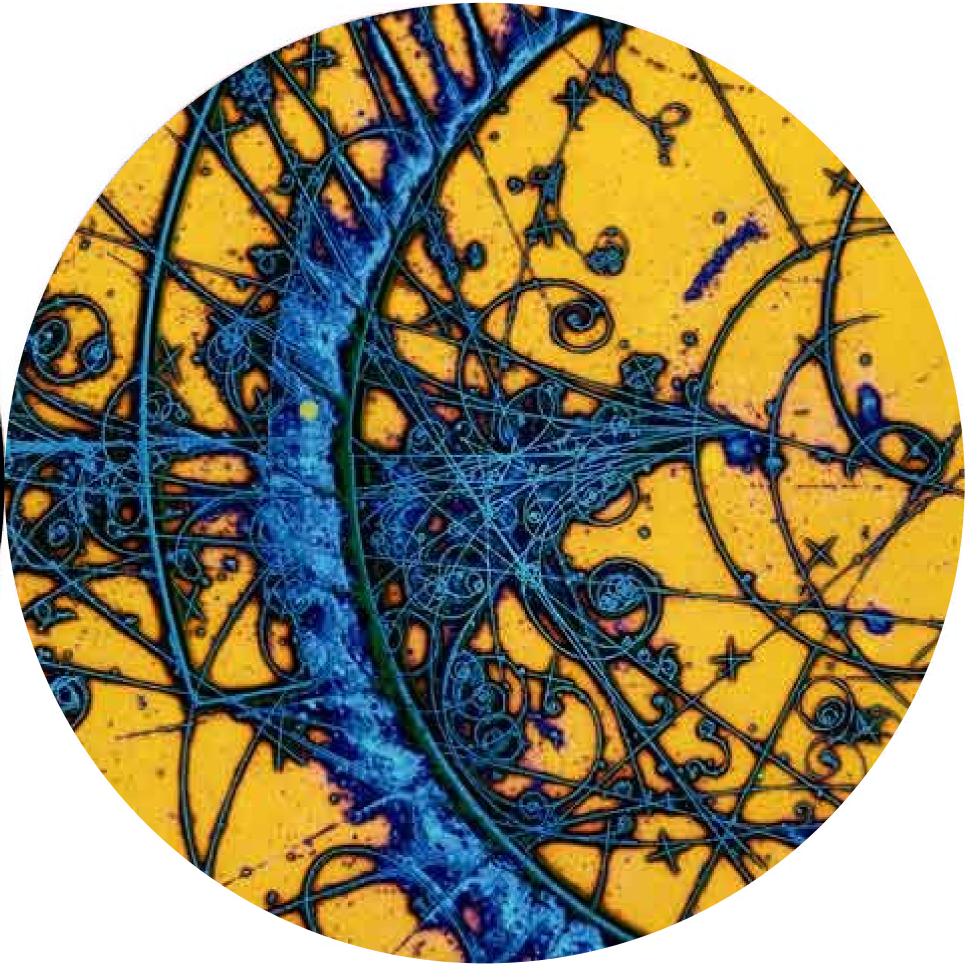

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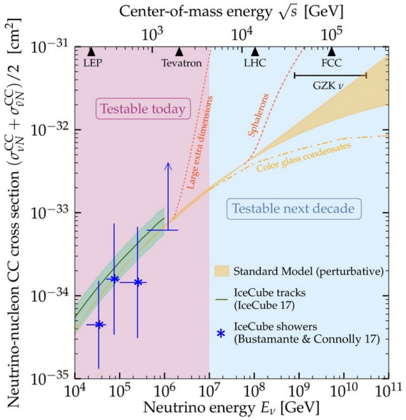
TeV–EeV ν cross sections



MB & Connolly, *PRL* 2019

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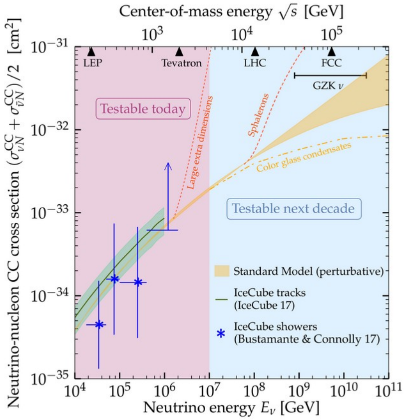
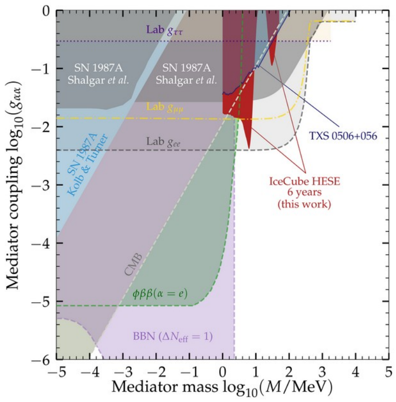


MB & Connolly, *PRL* 2019

ν self-interactions



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

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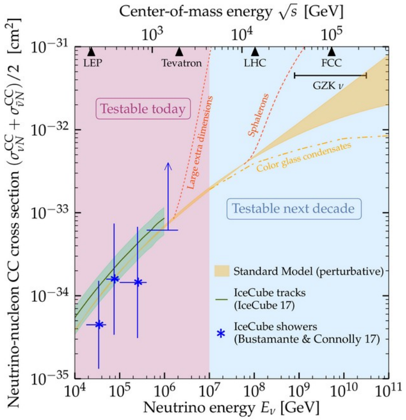

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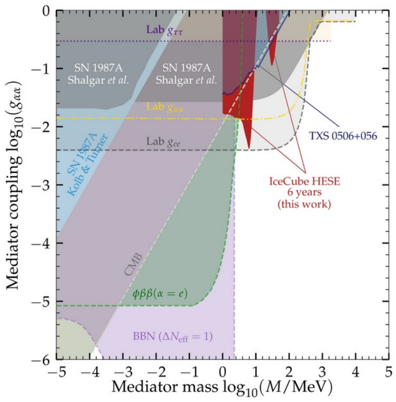
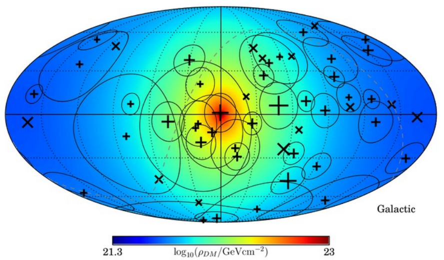


MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

ν scattering on Galactic DM



Argüelles, Kheirandish, Vincent, *PRL* 2017

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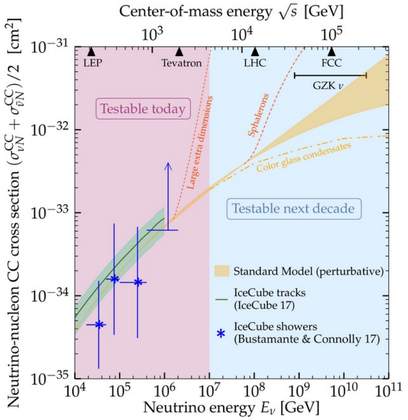

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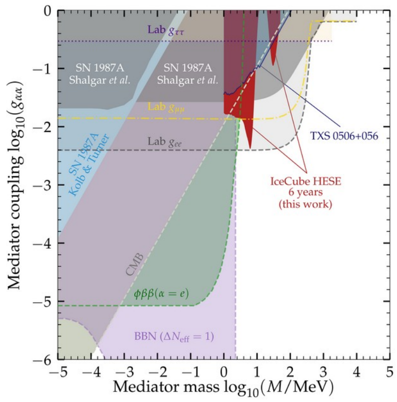

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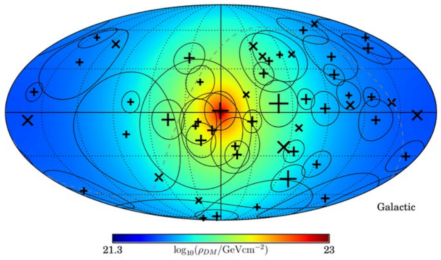

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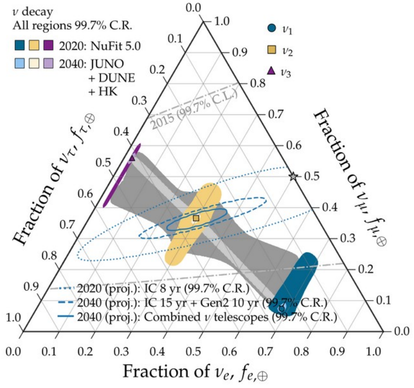

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

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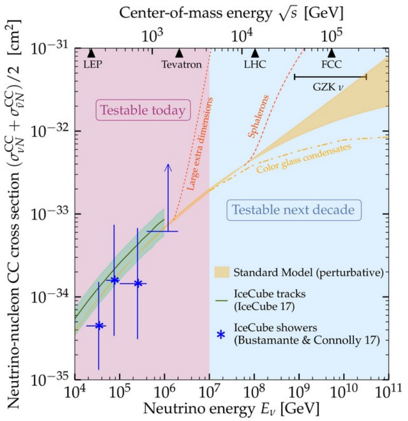

MB & Connolly, *PRL* 2019

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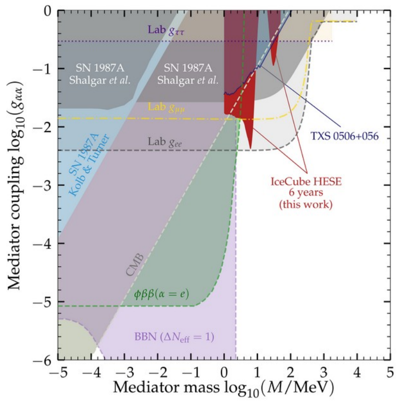

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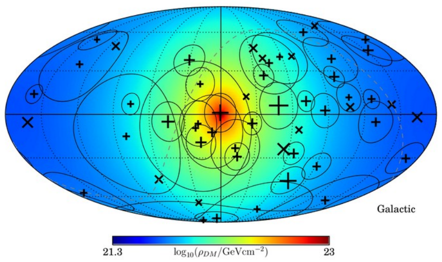

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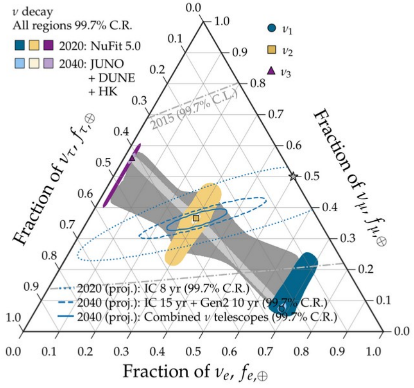
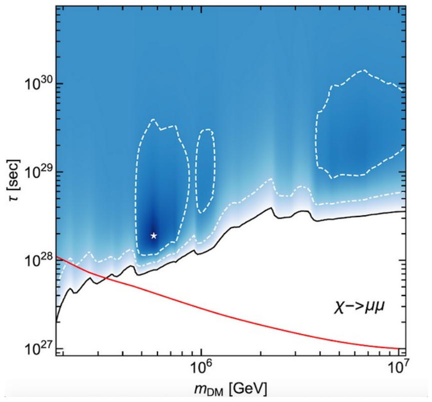


Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Dark matter decay



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

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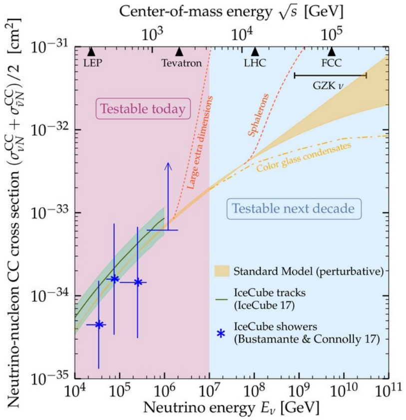

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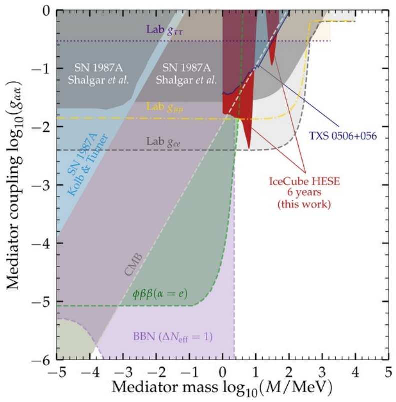

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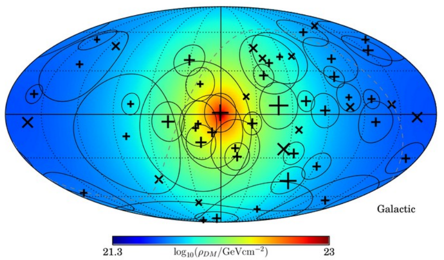

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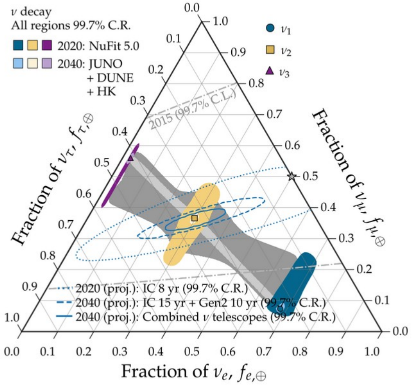

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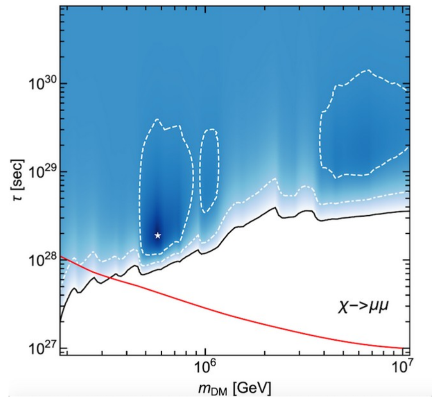
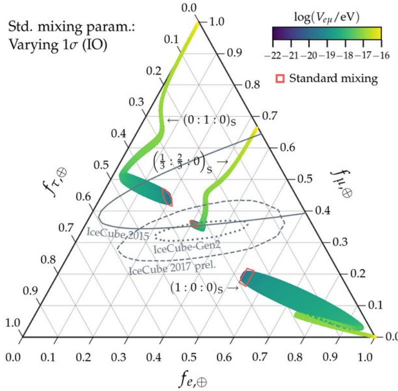


Chianese, Fiorillo, Miele, Morisi, Pisanti, *JCAP* 2019

ν-electron interaction



MB & Agarwalla, *PRL* 2019

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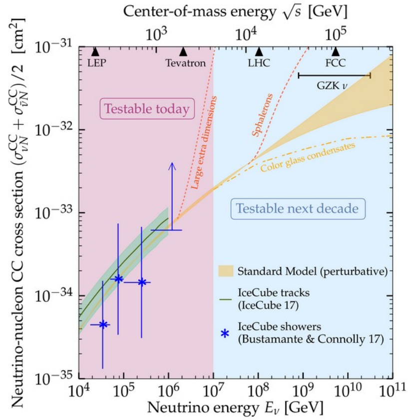

MB & Connolly, *PRL* 2019

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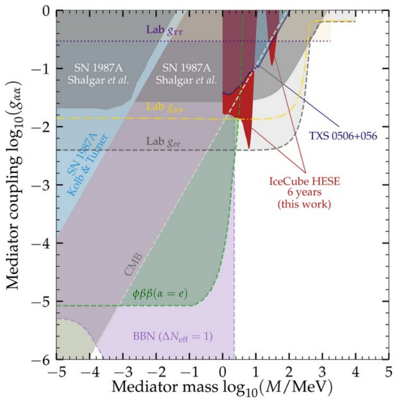

MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

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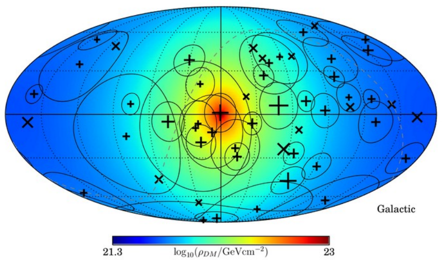

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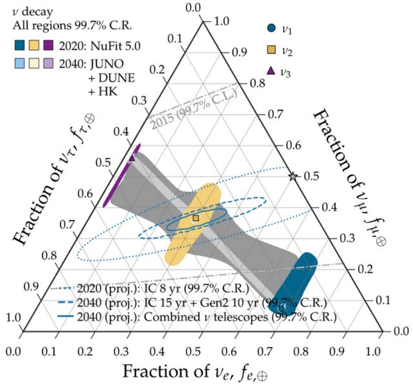

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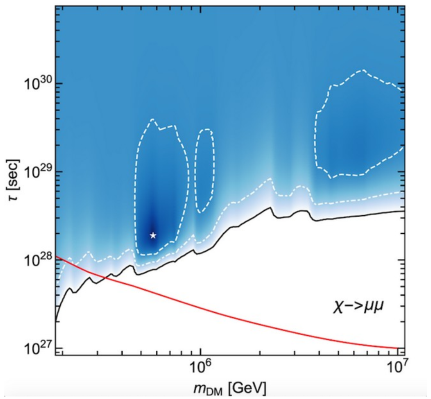

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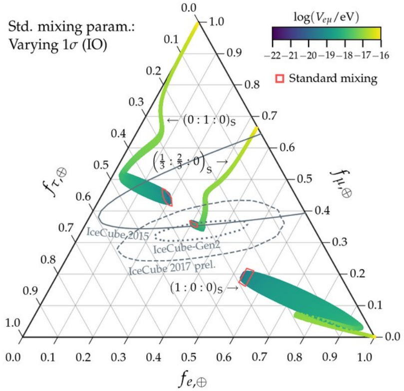
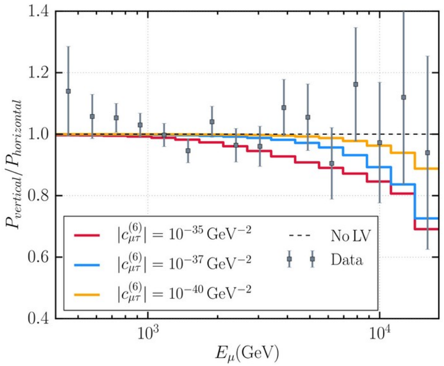


MB & Agarwalla, *PRL* 2019

Lorentz-invariance violation



IceCube, *Nature Phys.* 2018

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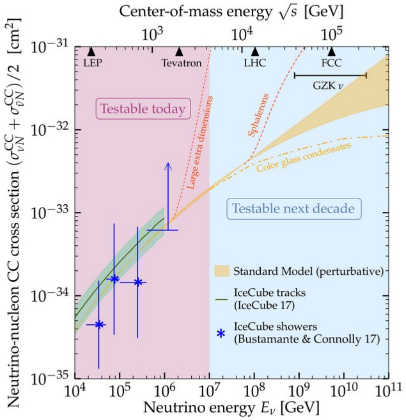

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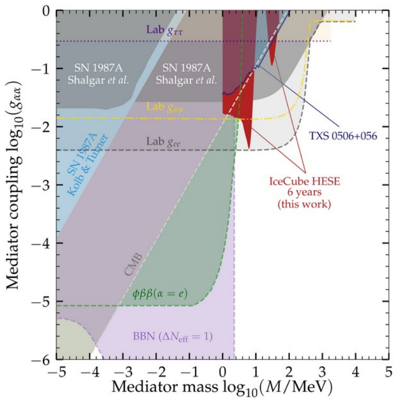

MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

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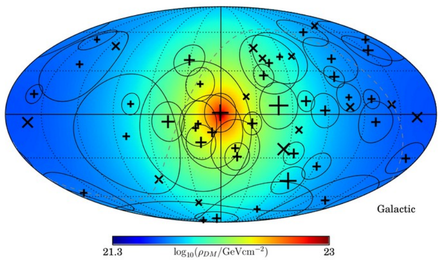

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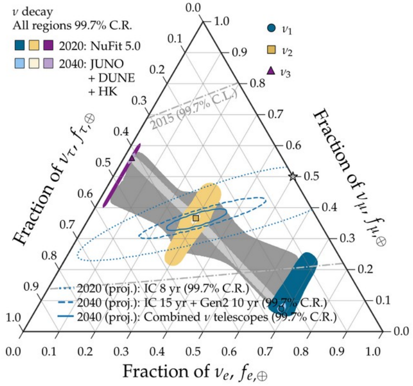

Song, Li, Argüelles, MB, Vincent, *JCAP* 2021

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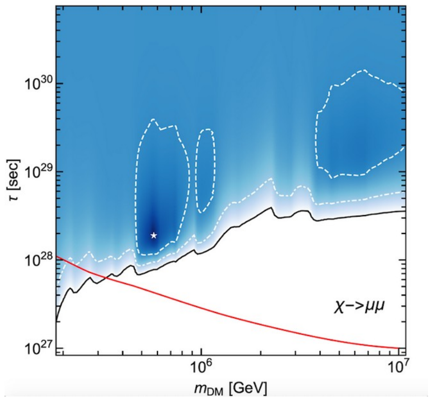

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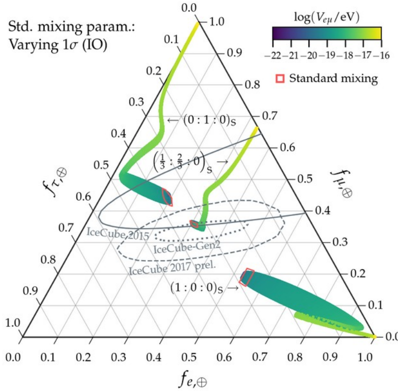

MB & Agarwalla, *PRL* 2019

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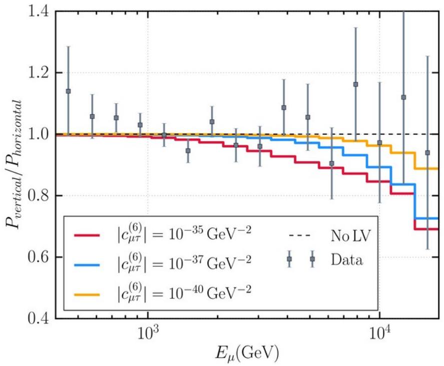
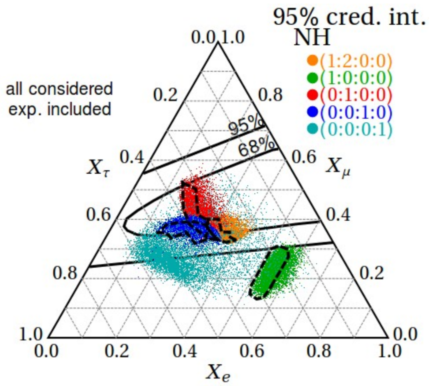


IceCube, *Nature Phys.* 2018

Sterile neutrinos



Brdar, Kopp, Wang, *JCAP* 2017

Fundamental physics with high-energy cosmic neutrinos

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

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

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

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

Fundamental physics with high-energy cosmic neutrinos

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

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

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

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

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  - Angular distribution
  - Flavor composition
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  - Flavor composition
  - Timing

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

Today

TeV–PeV ν

Turn predictions
into data-driven tests

Next decade

$>$ 100-PeV ν

Make predictions for
a new energy regime

I.
The story so far

Making high-energy astrophysical neutrinos

(or $p + p$)

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

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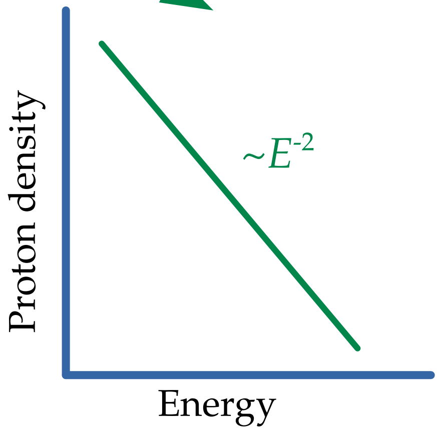

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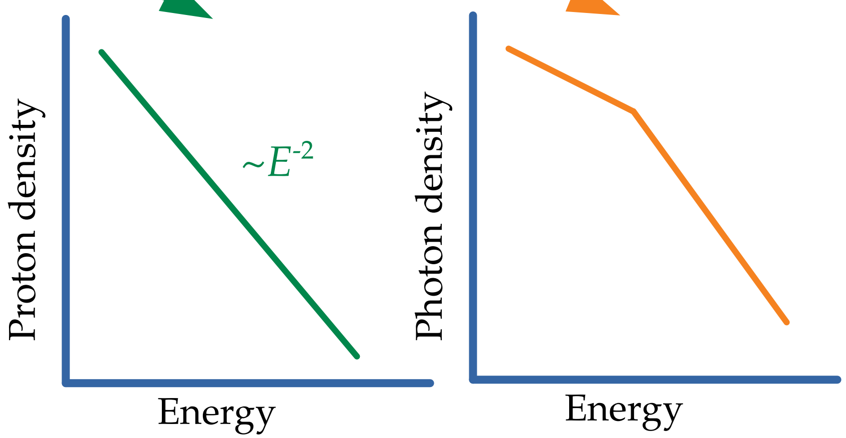

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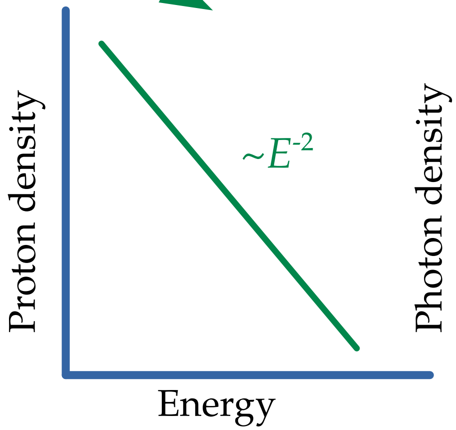
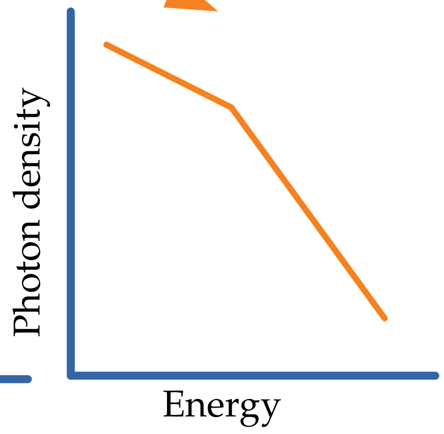
$$\pi^0 \longrightarrow \gamma + \gamma$$

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

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





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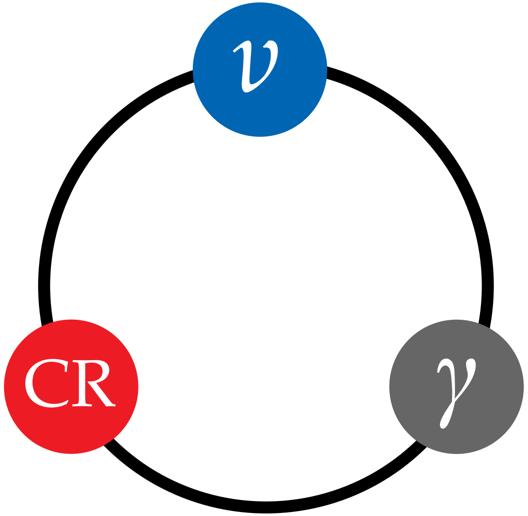
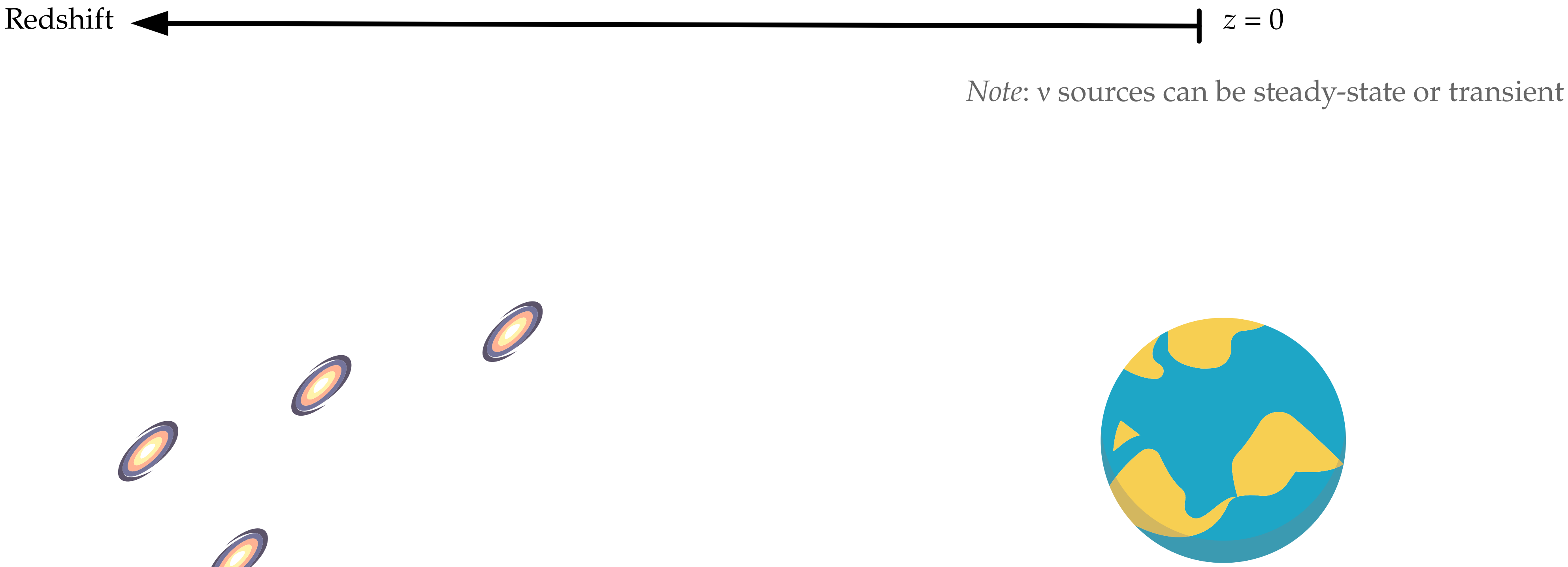
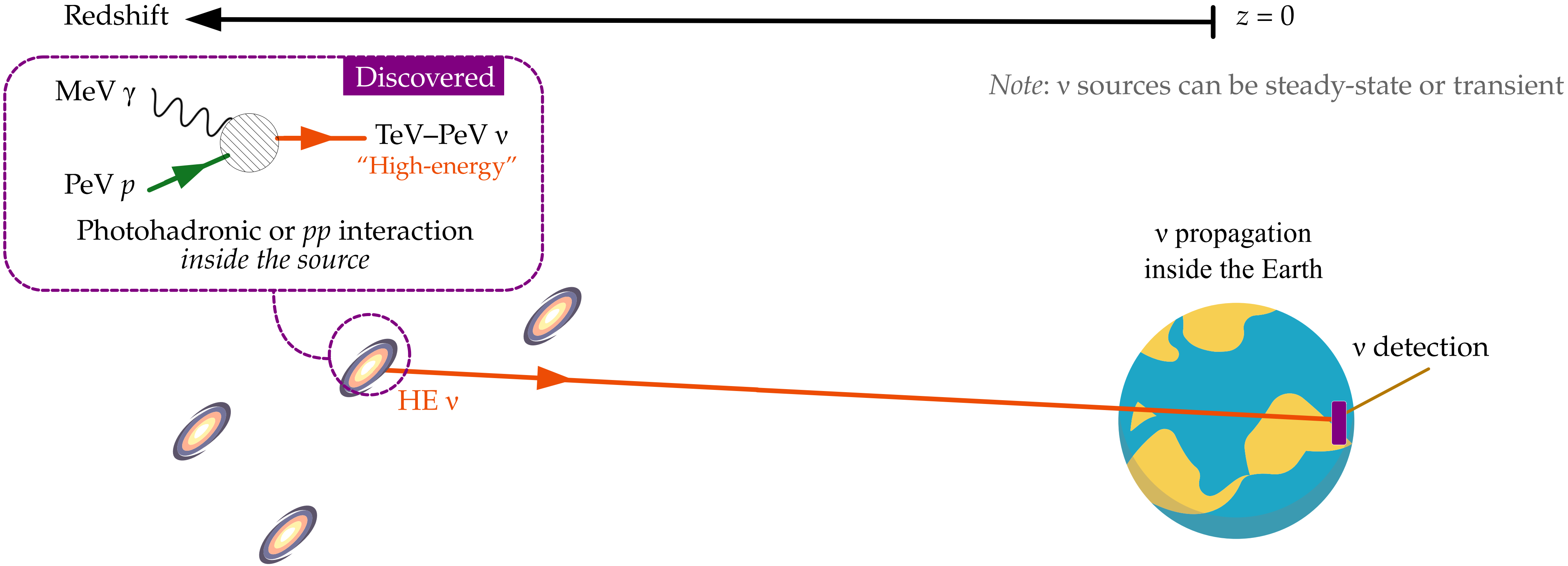


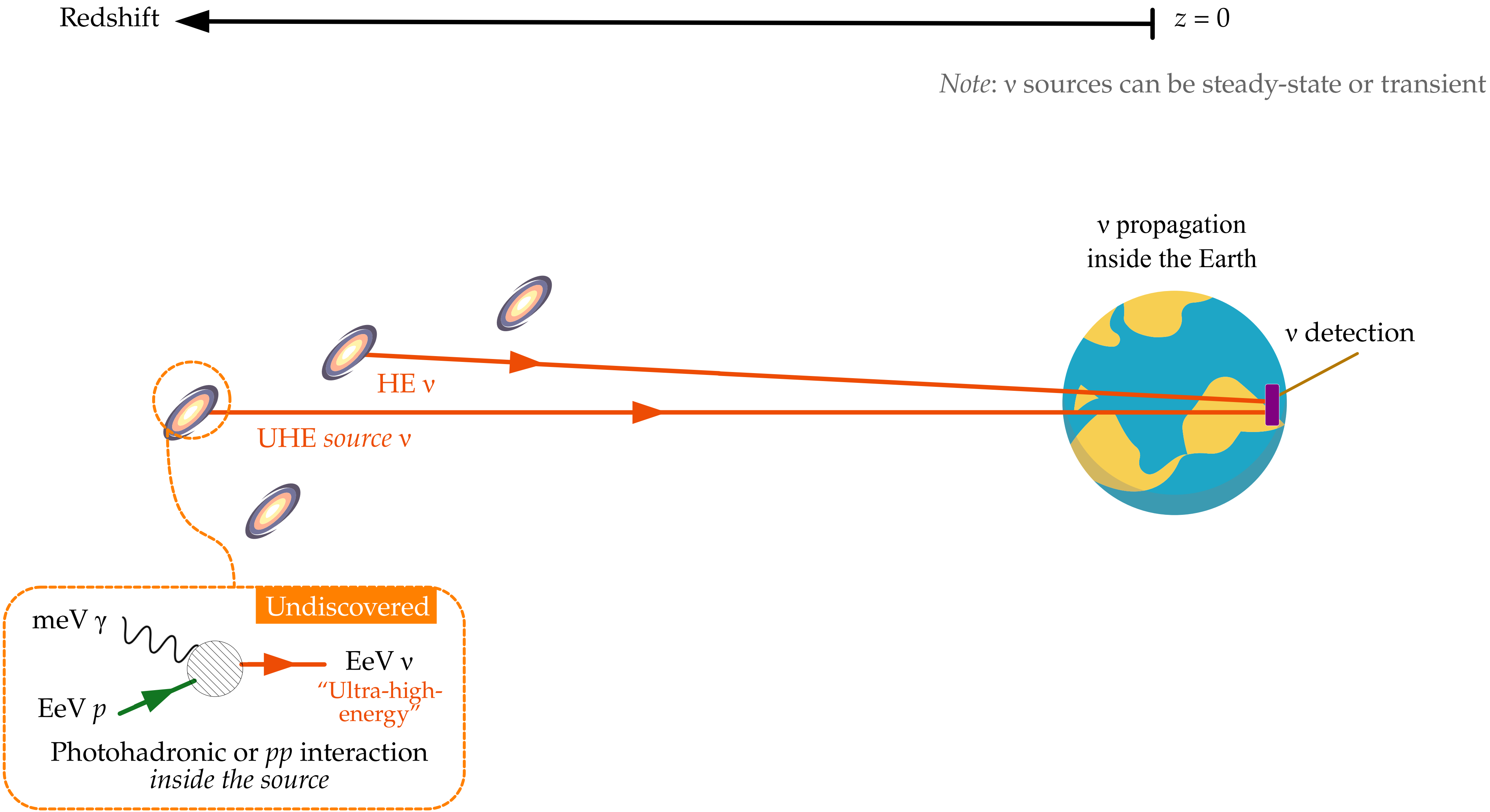
Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10


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



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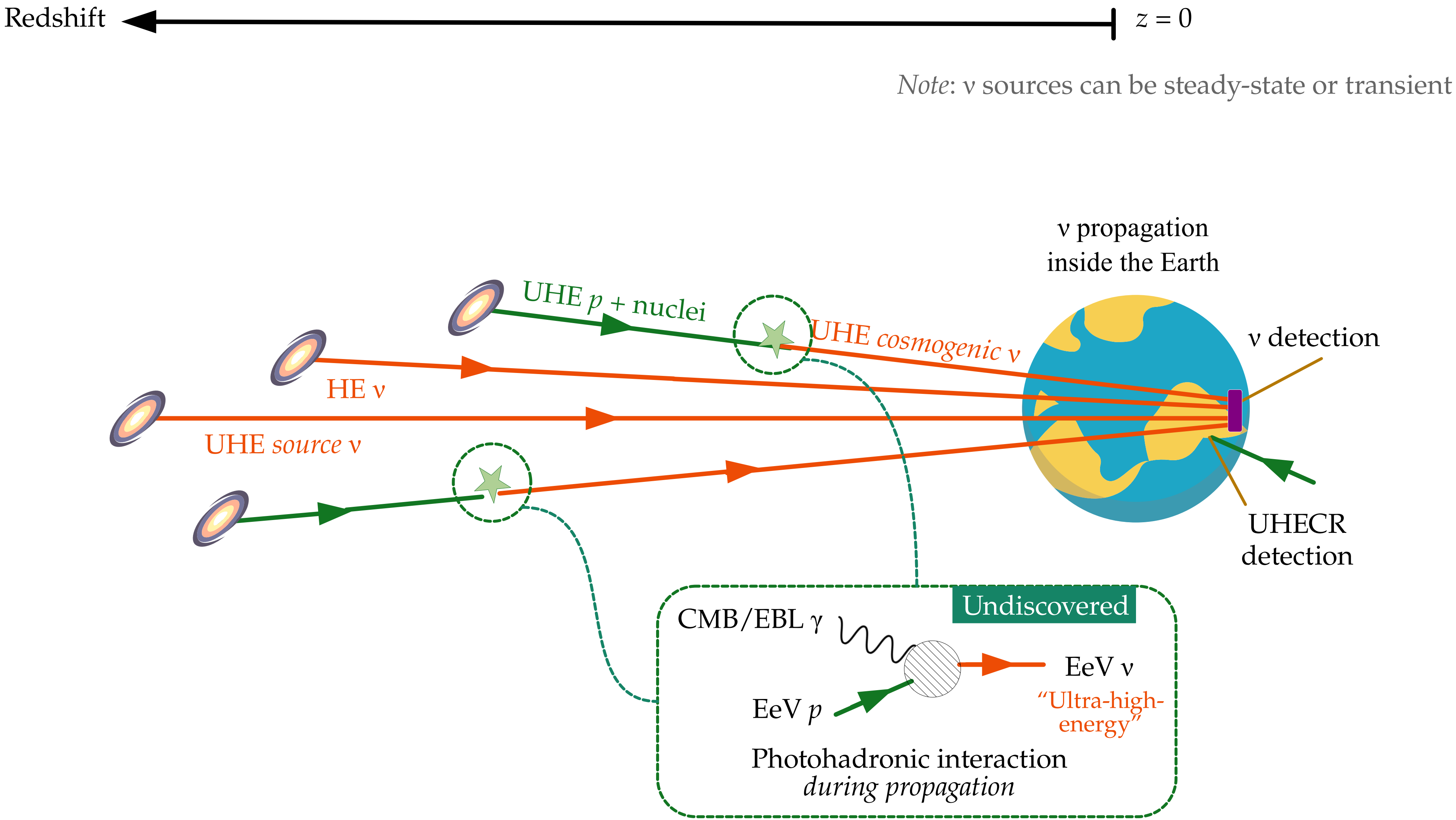
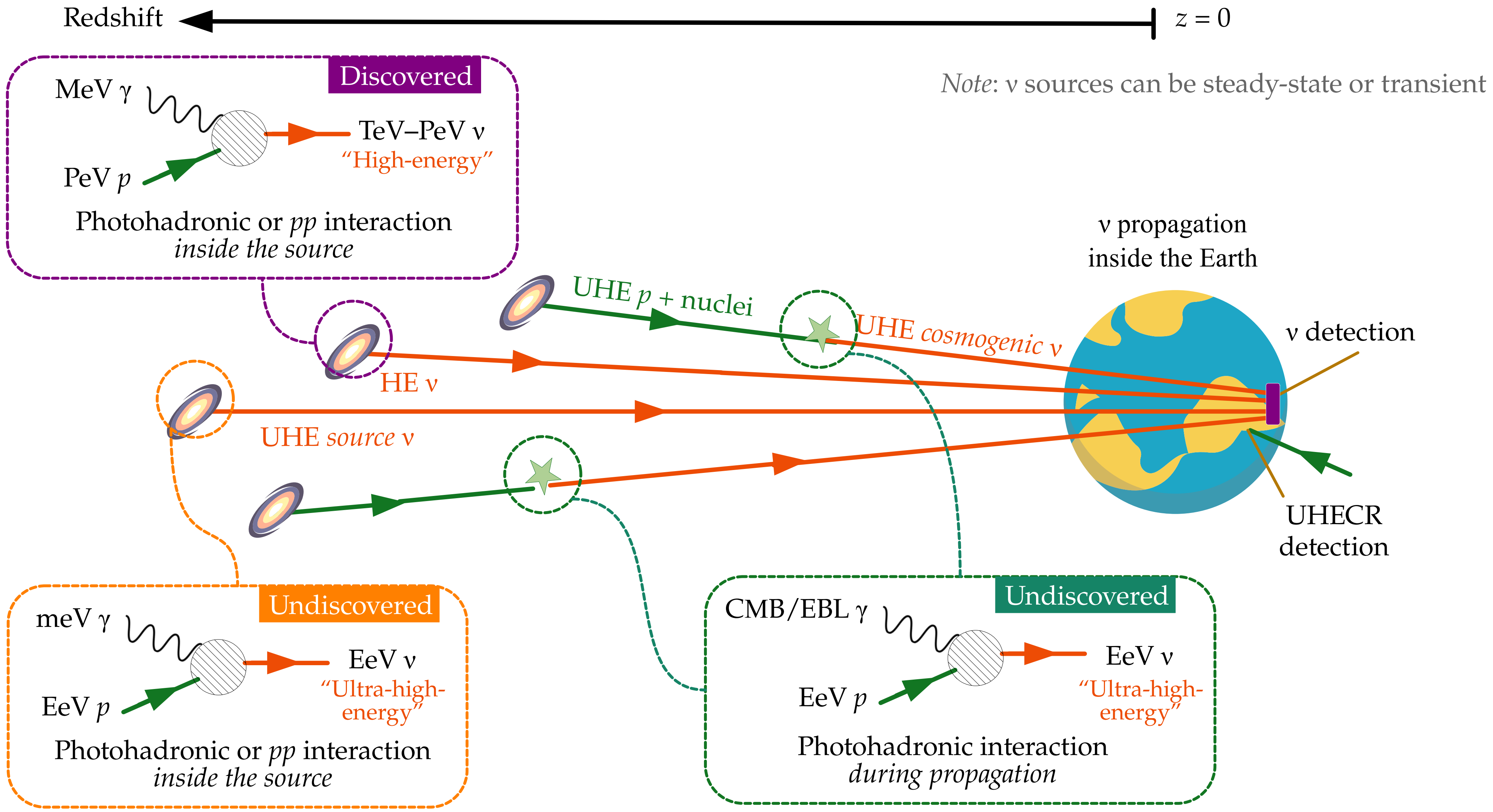
inside the Earth
ν detection
HE ν
UHE *source* ν
Undiscovered
meV γ
EeV ν
"Ultra-high-energy"
EeV *p*
Photohadronic or *pp* interaction
inside the source


Redshift
$z = 0$
Note: ν sources can be steady-state or transient
ν propagation inside the Earth
UHE p + nuclei
UHE *cosmogenic* ν
ν detection
HE ν
UHE *source* ν
UHECR detection
Undiscovered
CMB/EBL γ
EeV ν
EeV p
"Ultra-high-energy"
Photohadronic interaction
during propagation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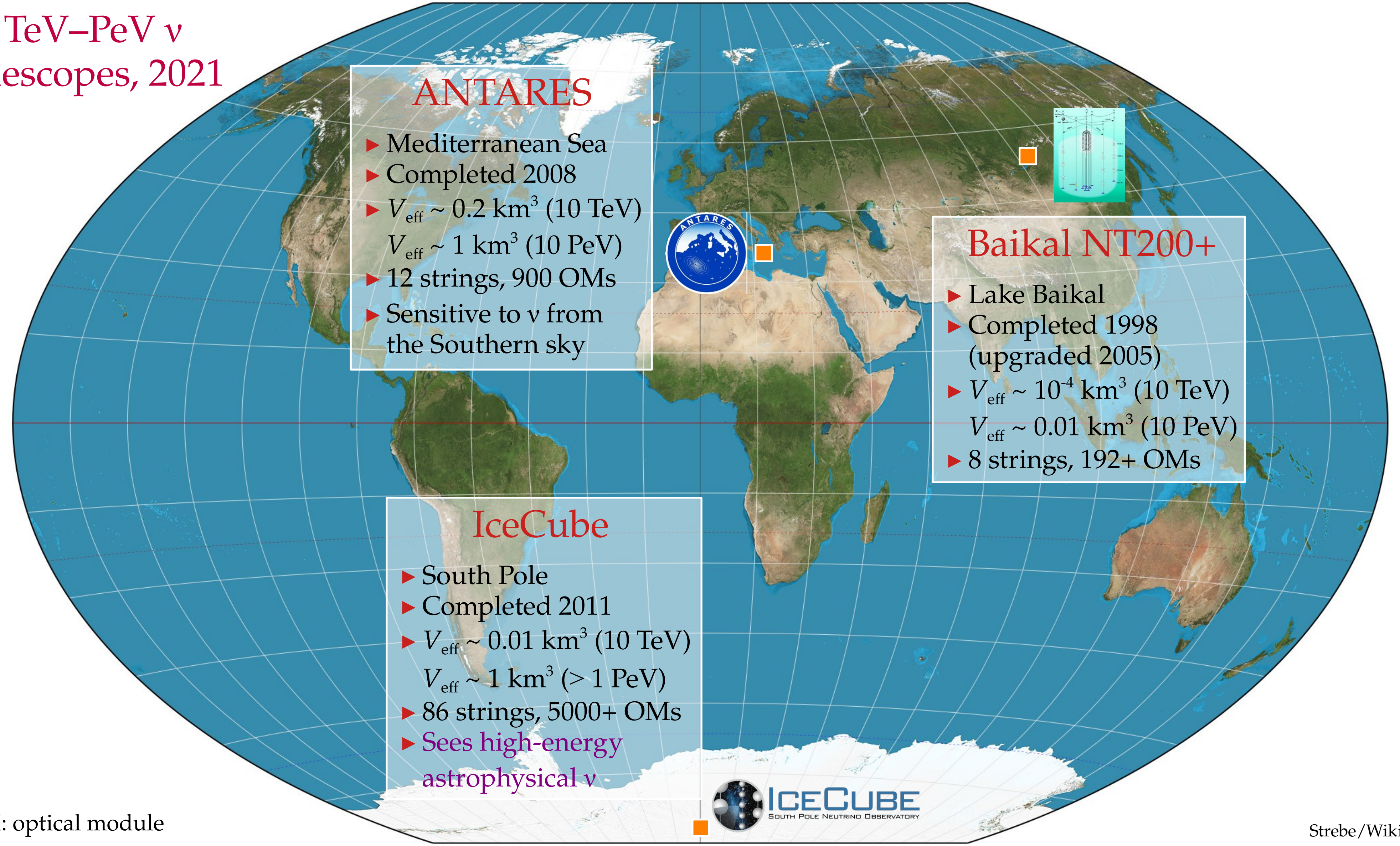
TeV–PeV ν telescopes, 2021



ANTARES

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

Baikal NT200+

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

IceCube

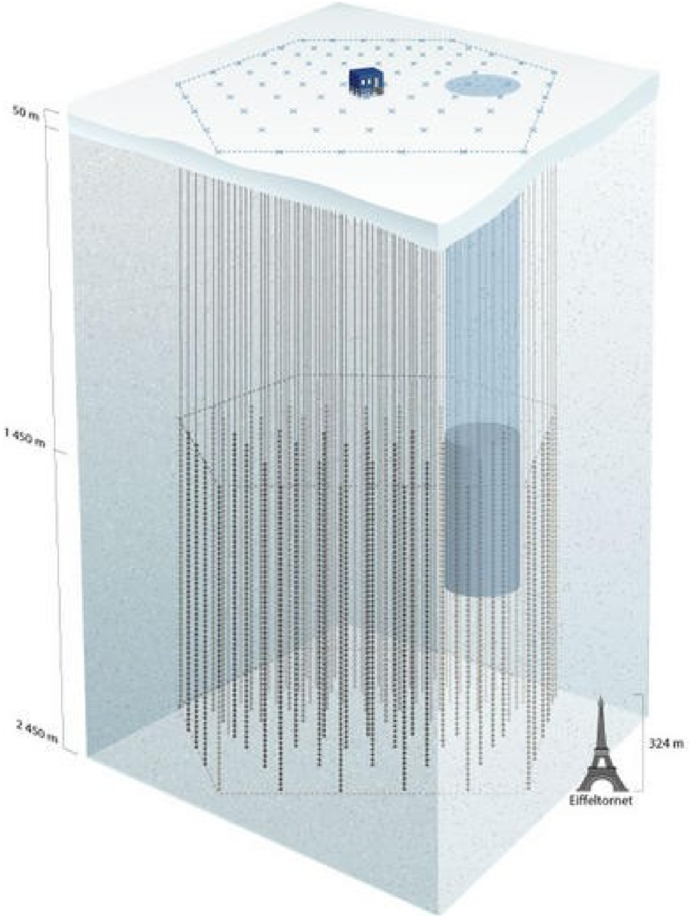
- South Pole
- Completed 2011
- V_{eff} ~ 0.01 km^3 (10 TeV)
  V_{eff} ~ 1 km^3 (> 1 PeV)
- 86 strings, 5000+ OMs
- Sees high-energy astrophysical ν

OM: optical module

Strebe/Wikipedia

Yuya Makino, IceCube/NSF

IceCube – What is it?



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

How does IceCube see TeV–PeV neutrinos?

Deep inelastic neutrino-nucleon scattering

Neutral current (NC)

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

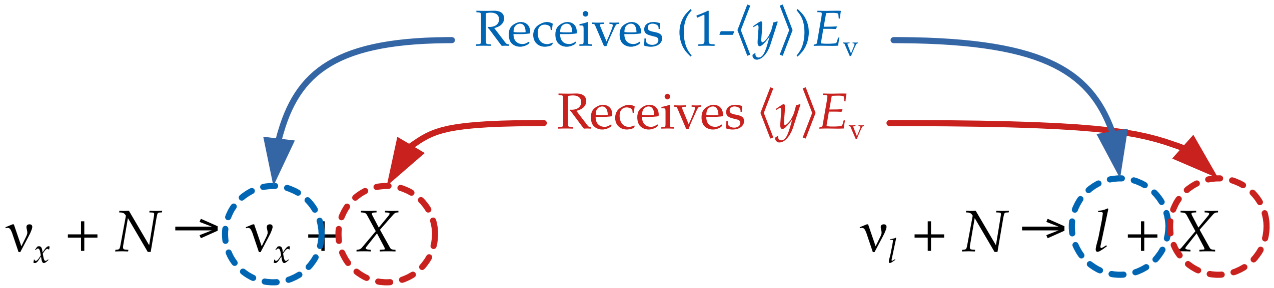
Charged current (CC)

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

How does IceCube see TeV–PeV neutrinos?

Deep inelastic neutrino-nucleon scattering

Neutral current (NC) Charged current (CC)



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

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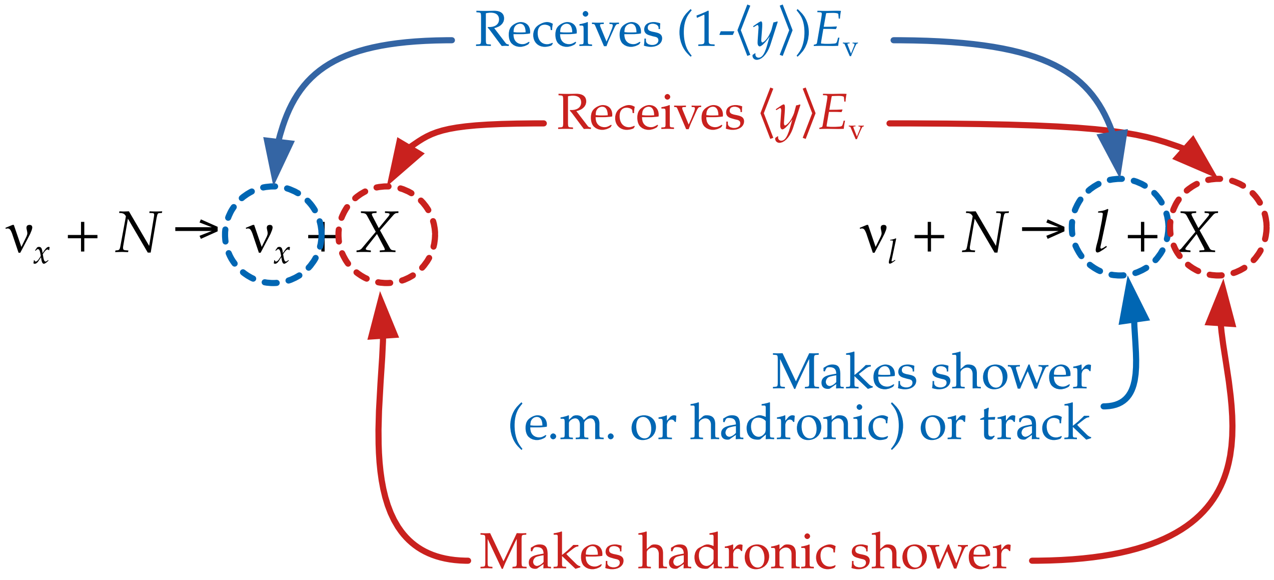

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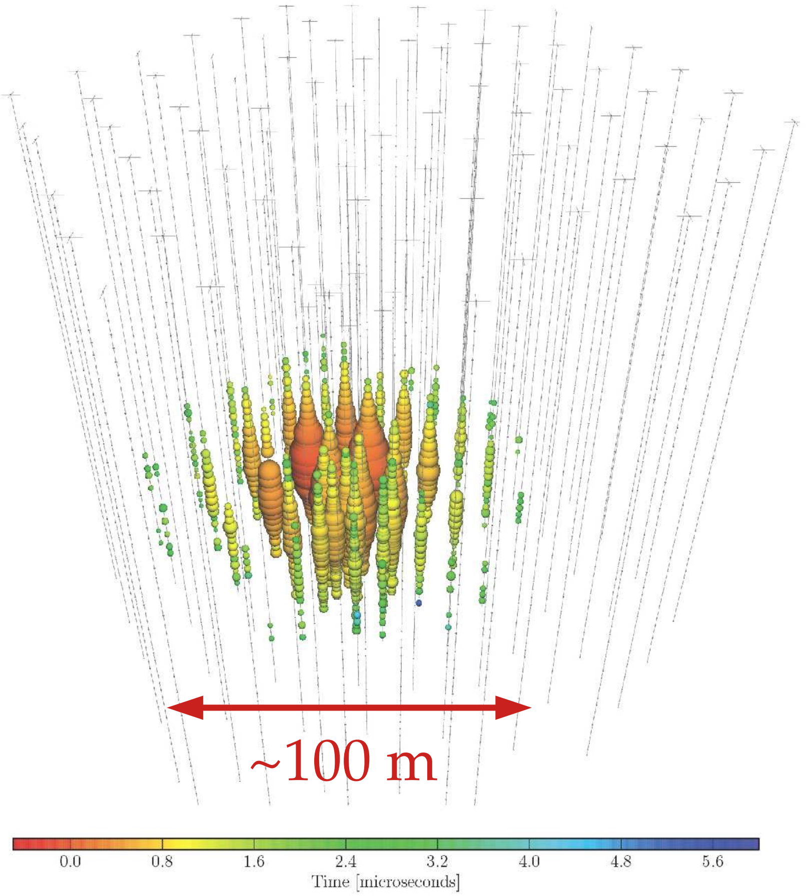
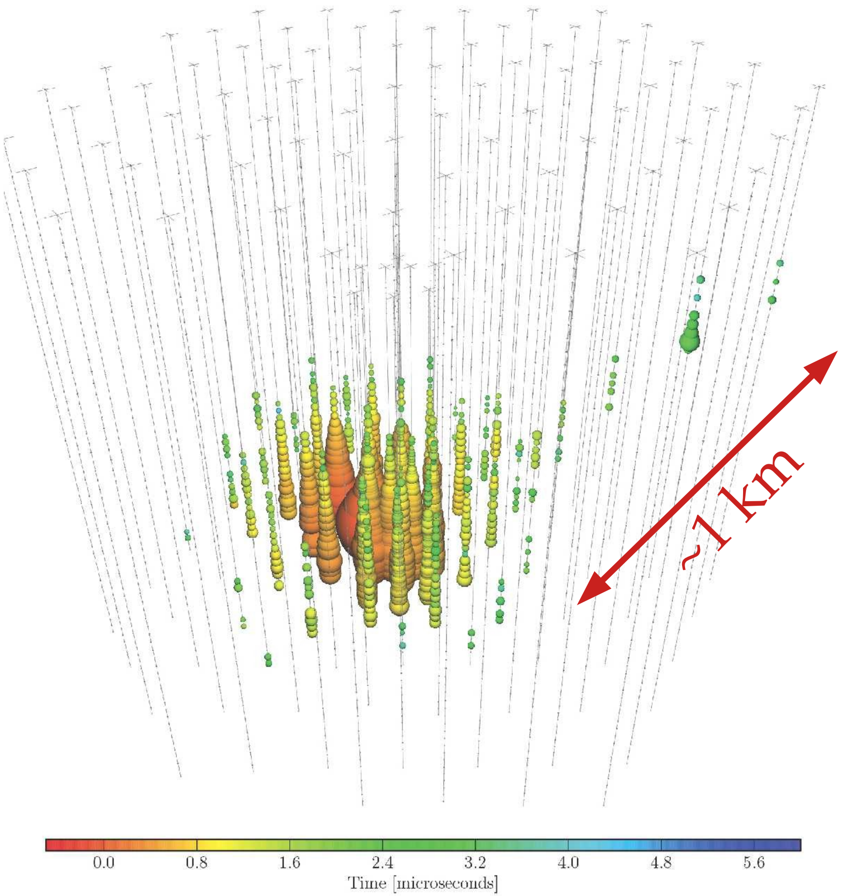
Shower
(mainly from ν_e and ν_τ)

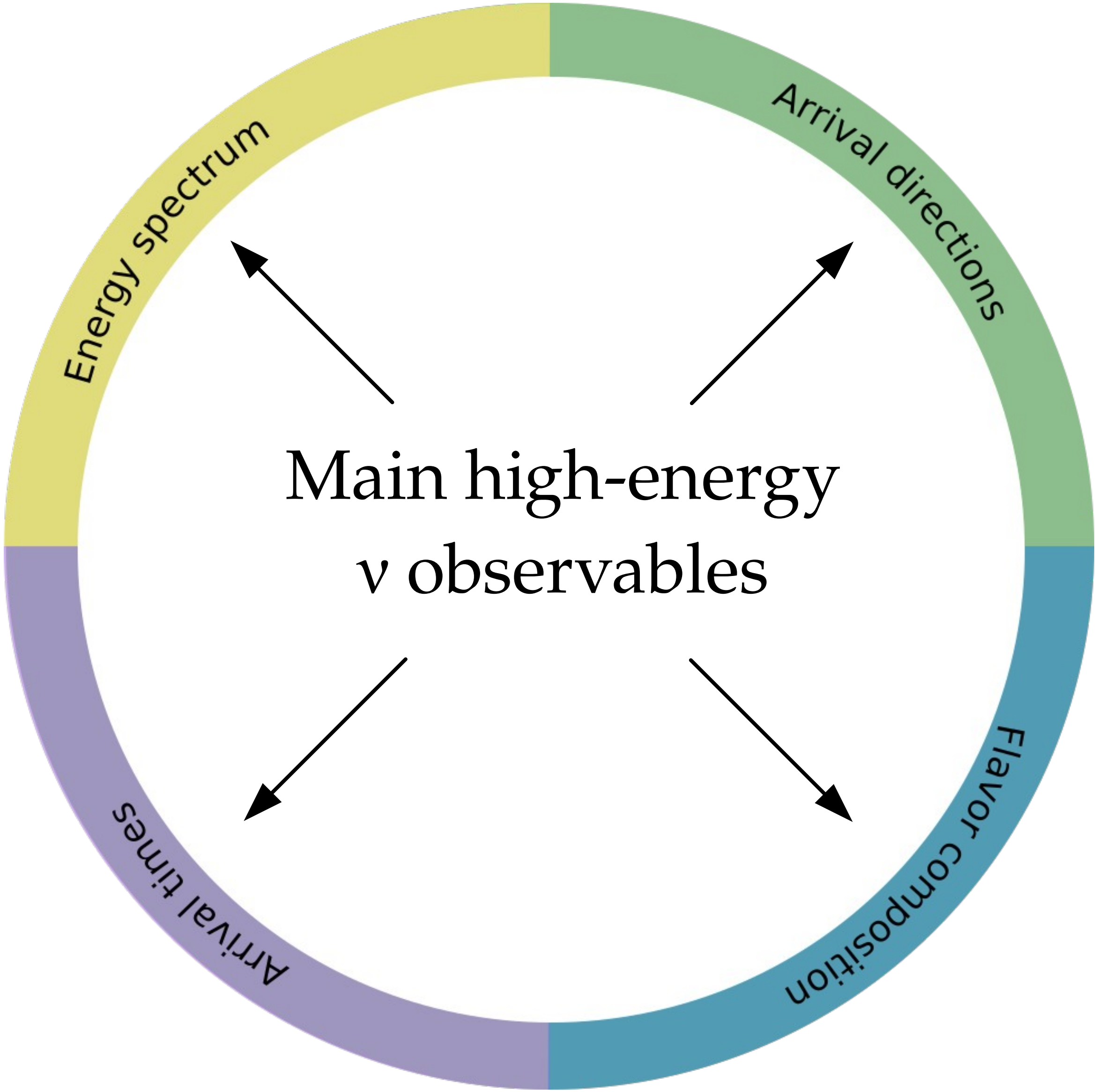


Poor angular resolution: ~10°

Track
(mainly from ν_μ)

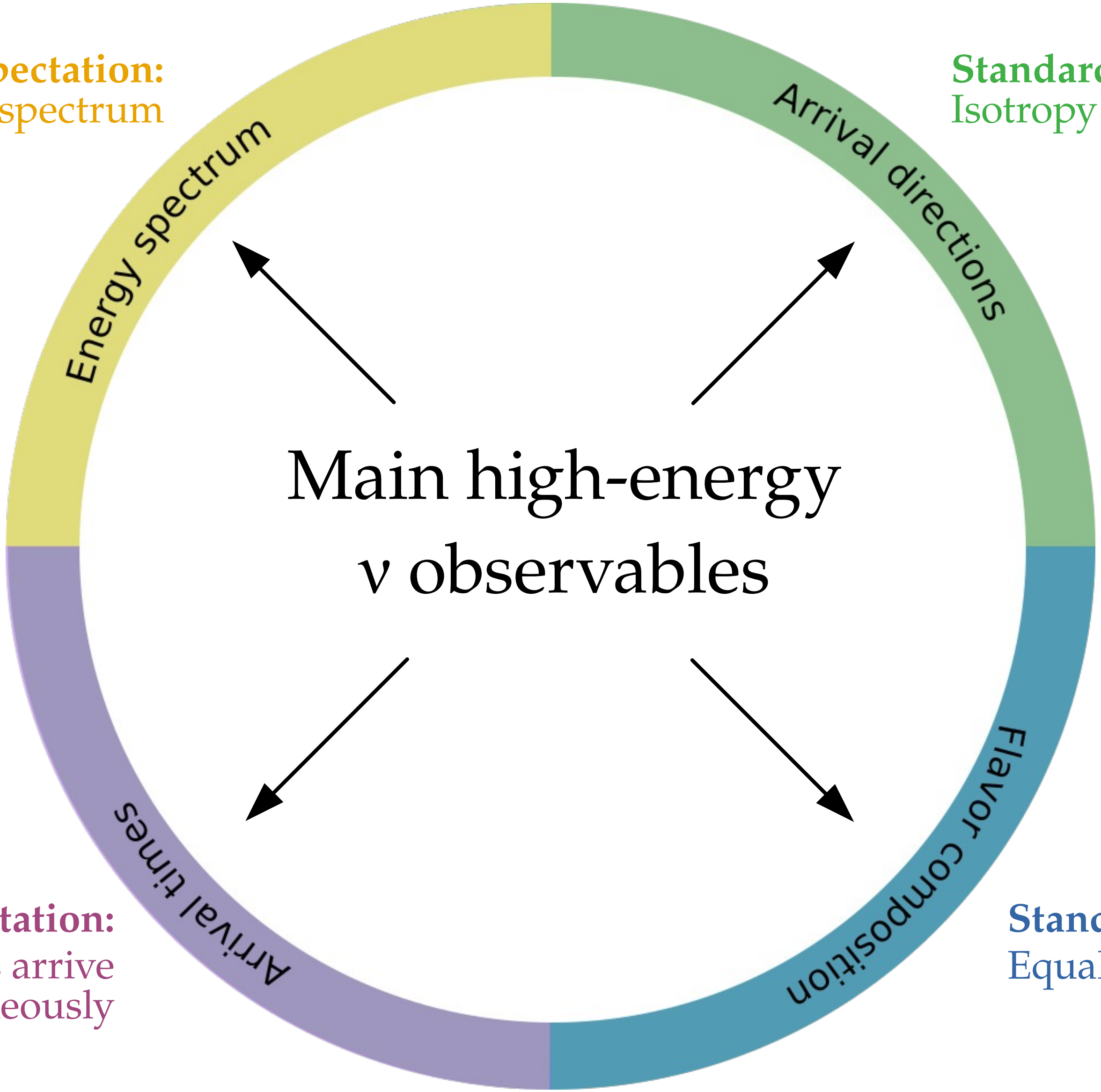


Angular resolution: < 1°


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

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)

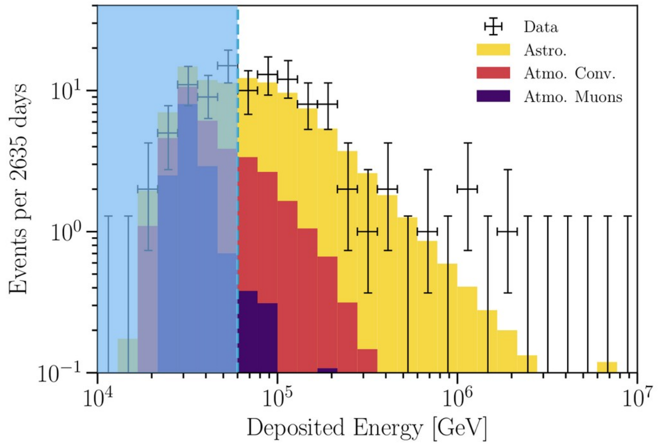


Standard expectation:
ν and γ from transients arrive simultaneously

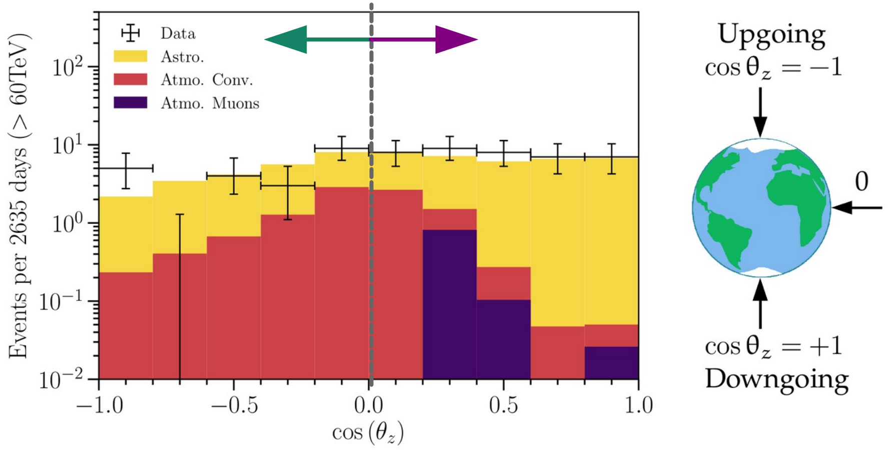
Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Energy spectrum (7.5 yr)

100+ contained events above 60 TeV:

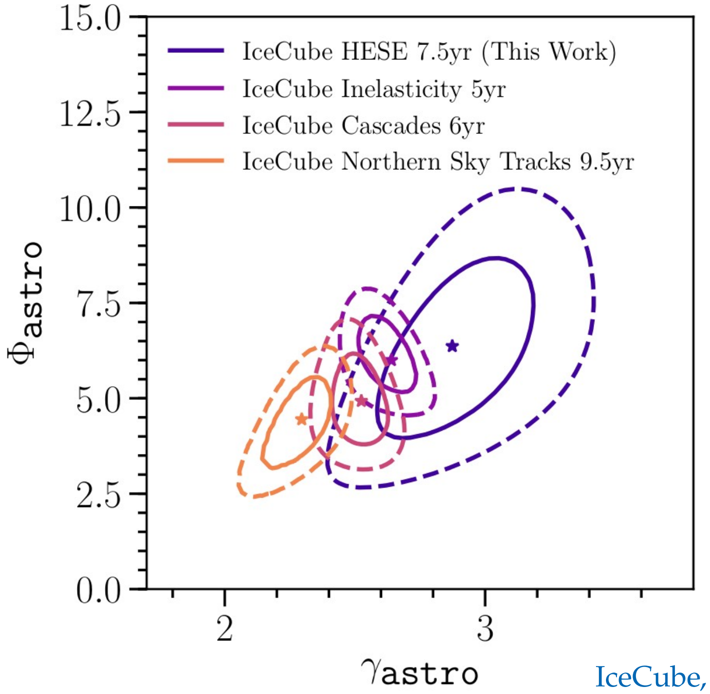


ν attenuated by Earth Atm. ν and μ vetoed



Data is fit well by a single power law:

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



IceCube, 2011.03545

Energy spectrum (7.5 yr)

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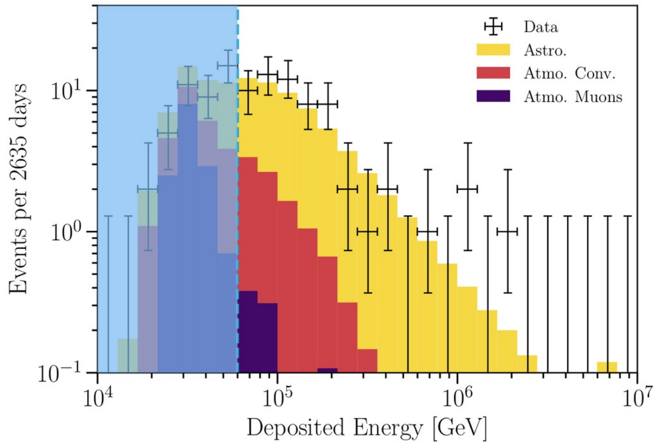
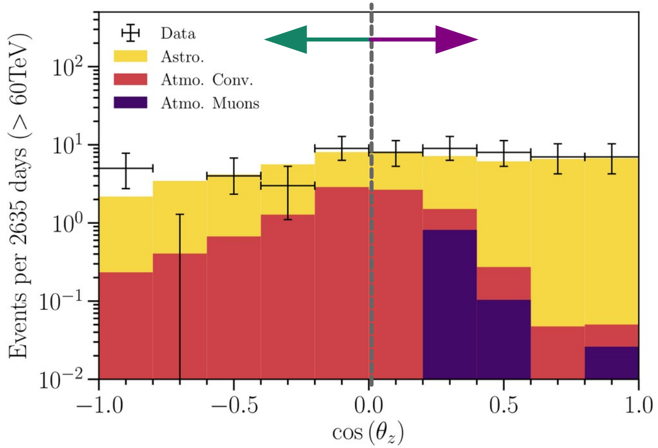
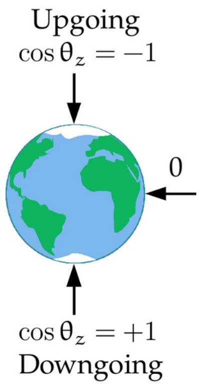


ν attenuated by Earth   Atm. ν and μ vetoed





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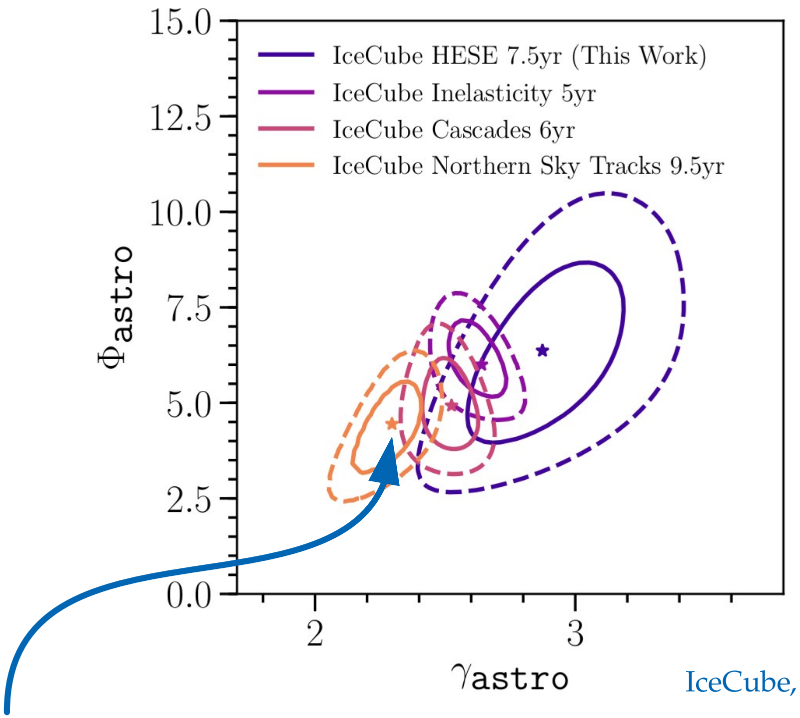
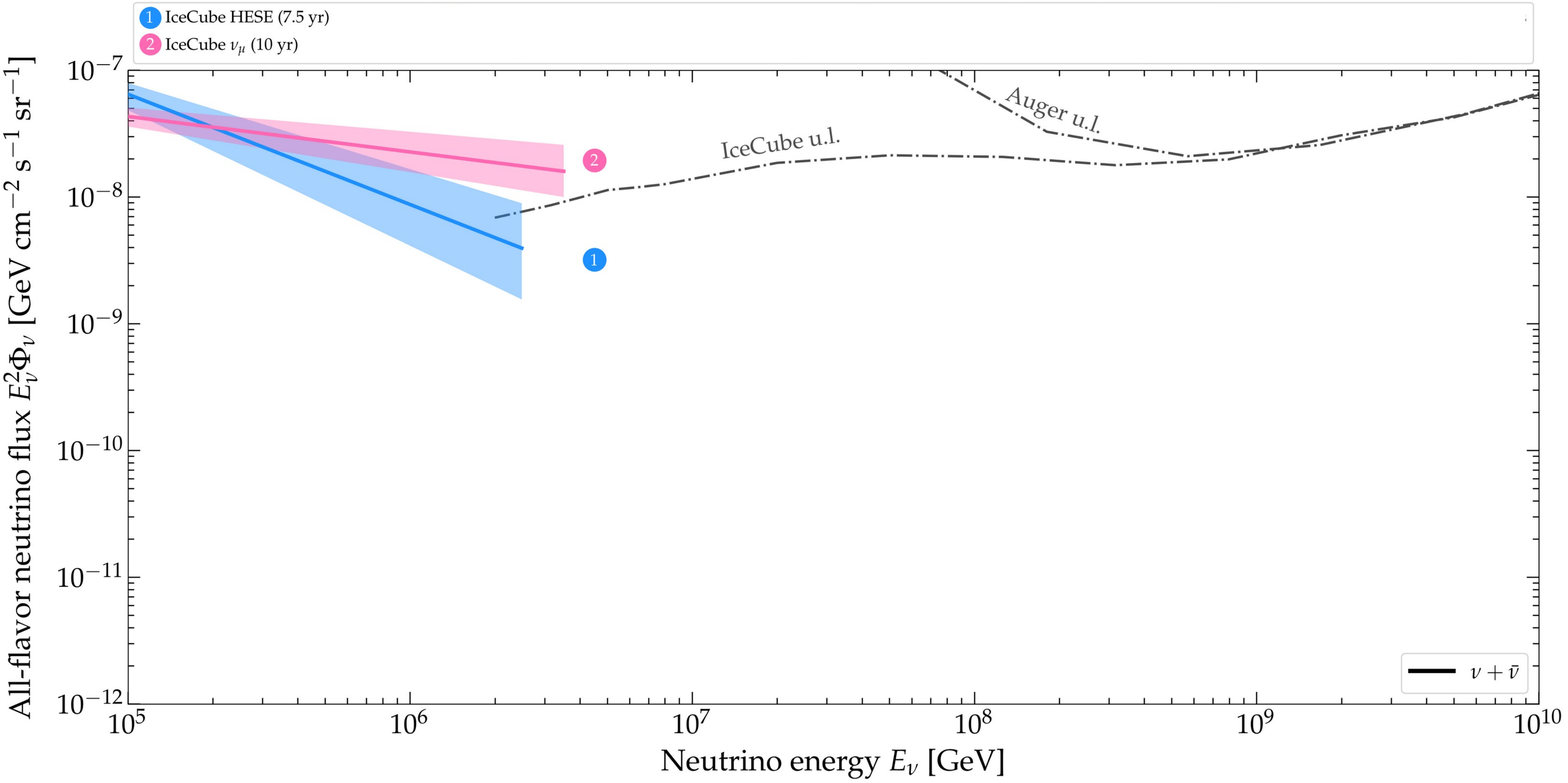


IceCube, 2011.03545

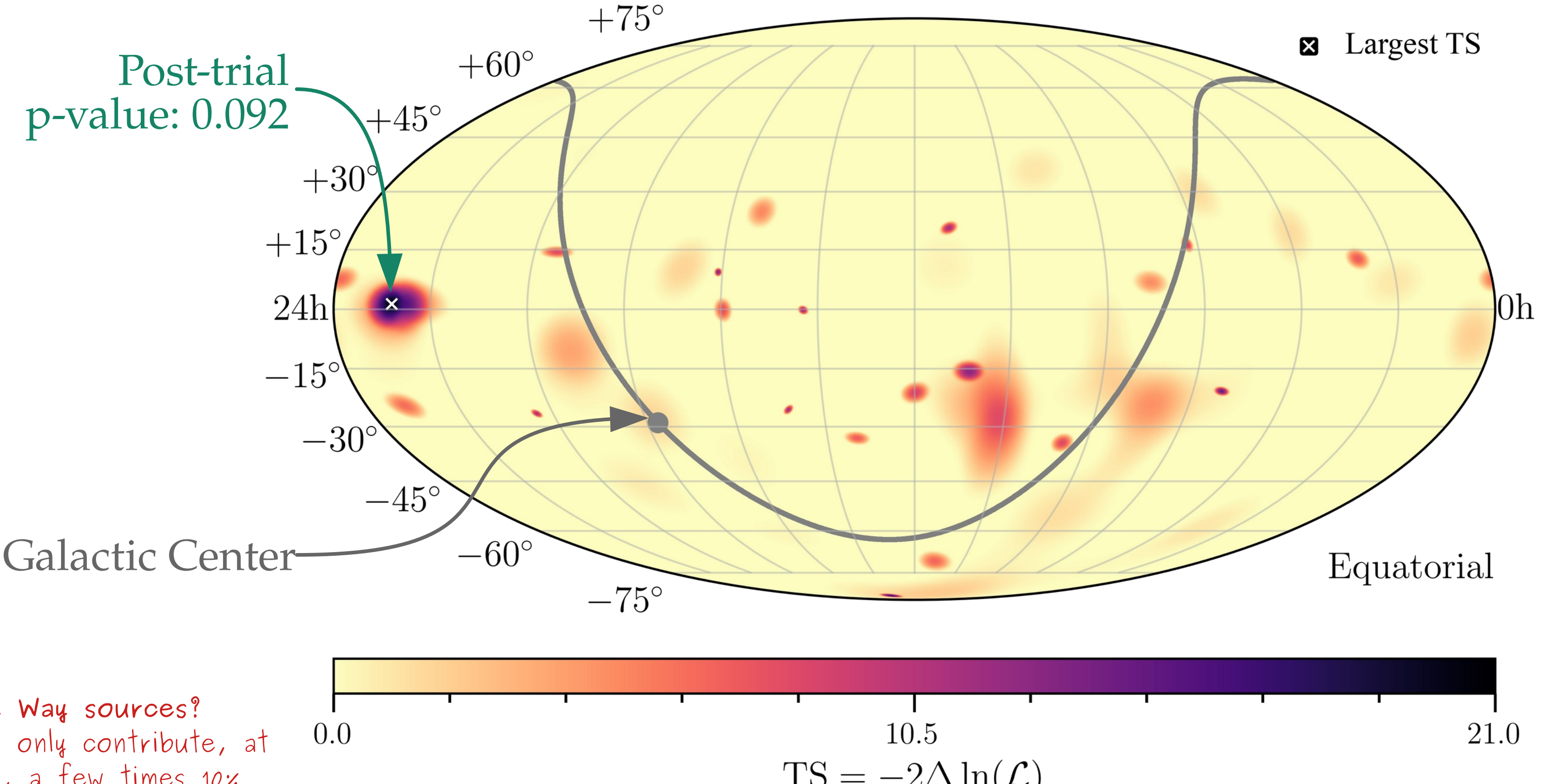
Spectrum looks harder for through-going ν_μ



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

Arrival directions (7.5 yr)

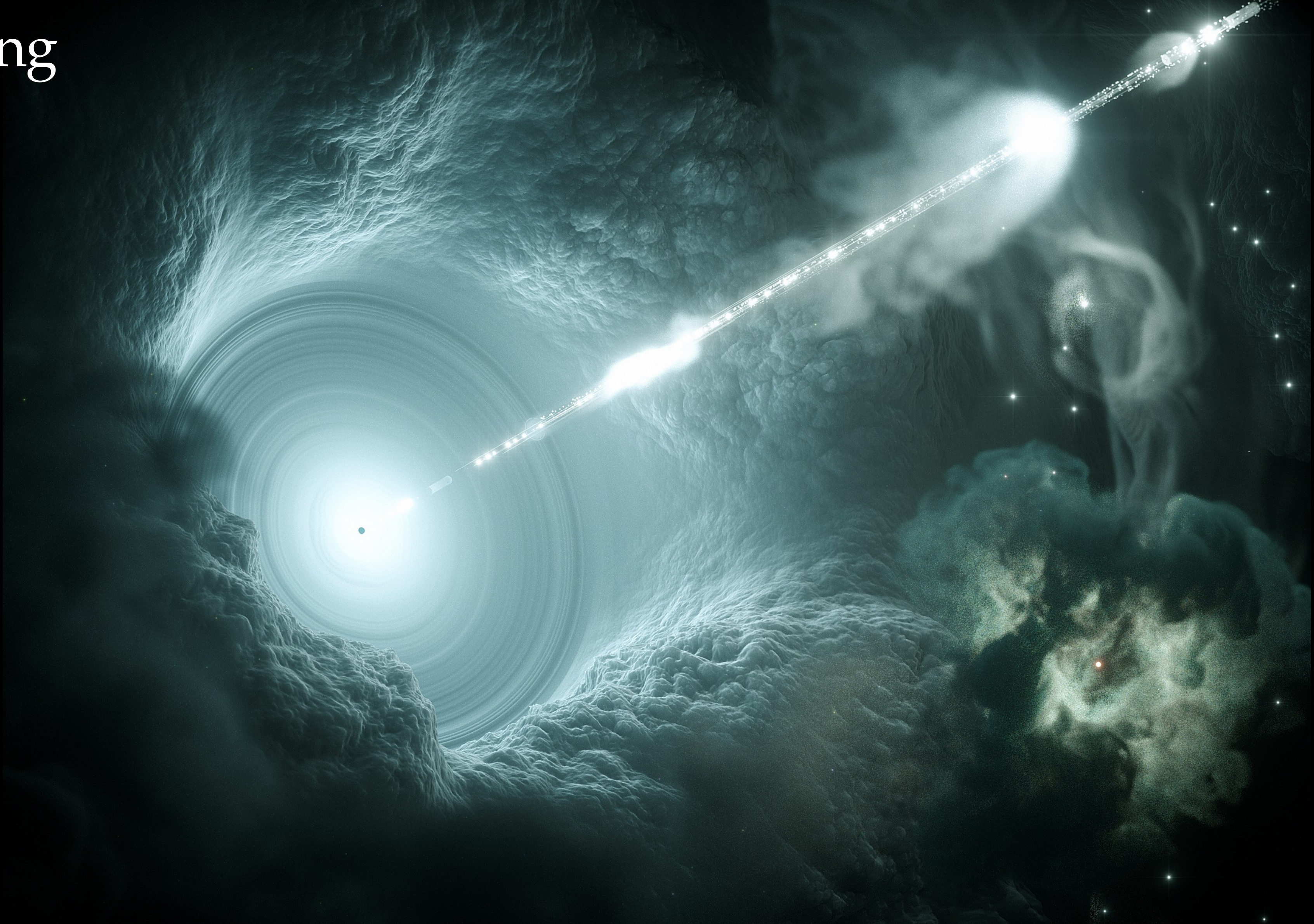
No significant excess in the neutrino sky map:



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

IceCube, 2011.03545

Timing

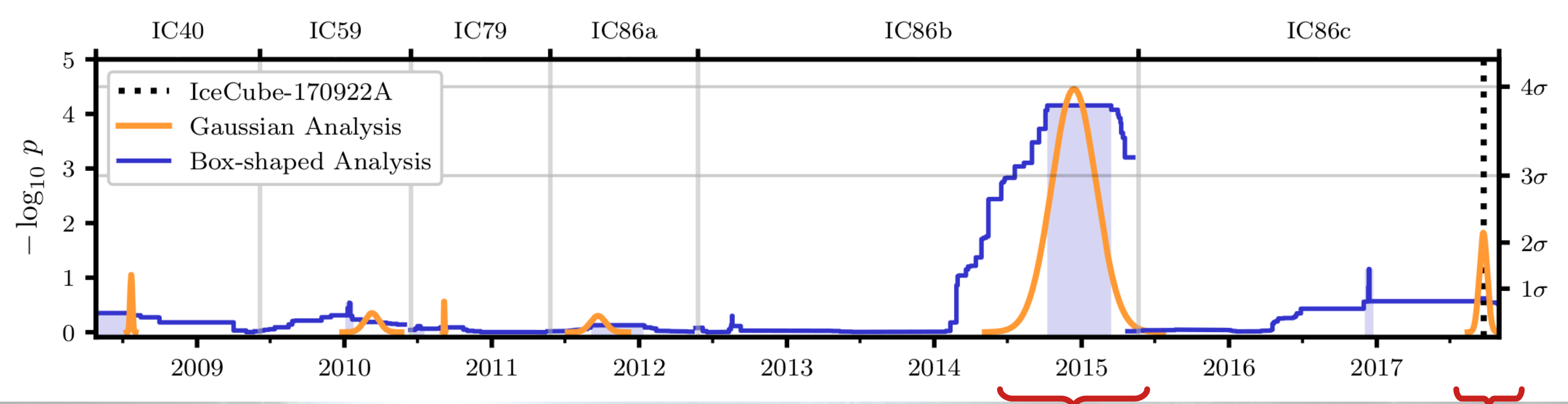


DESY

Timing

Blazar TXS 0506+056:

IceCube, *Science* 2018

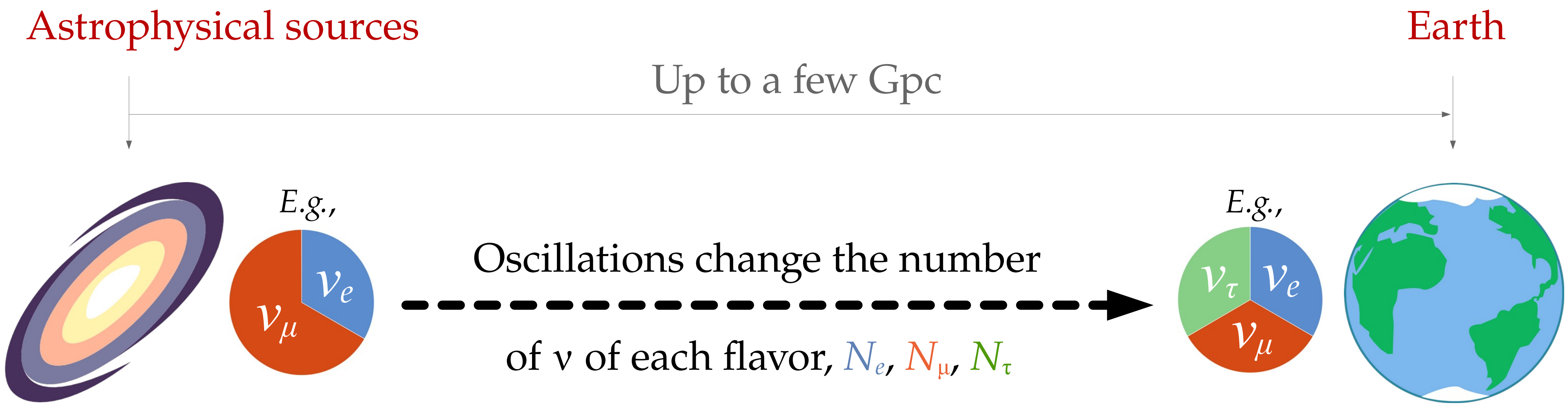


After re-analysis (2101.09836), significance dropped from $p=7\times10^{-5}$ to $p=8\times10^{-3}$

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

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

Combined (pre-trial): 4.1σ

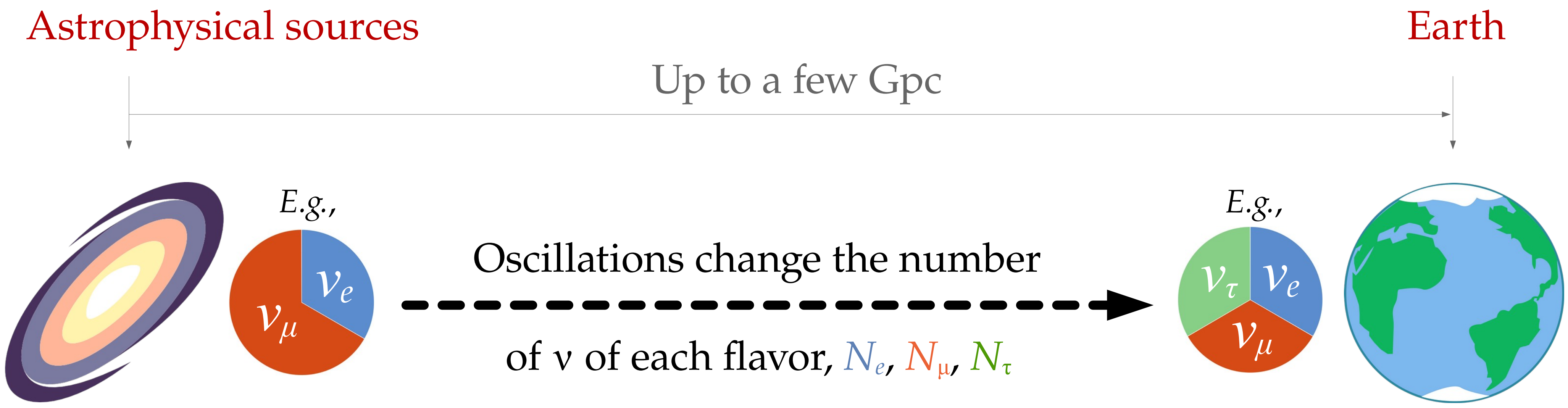


Different production mechanisms yield different flavor ratios:

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

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

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



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Standard oscillations
or
new physics

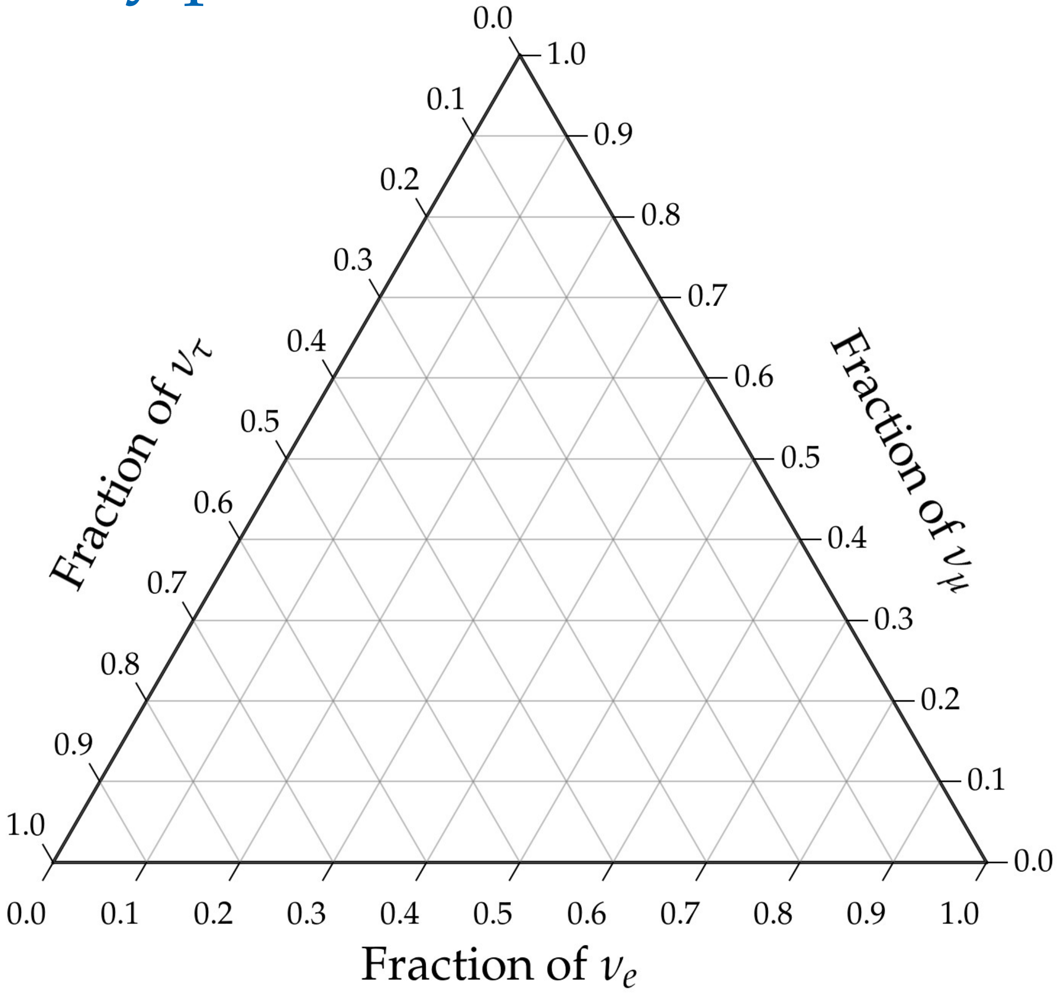
Quick aside: how to read a ternary plot

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

How to read it:

Follow the tilt of the tick marks

Always in this order: (f_e, f_μ, f_τ)



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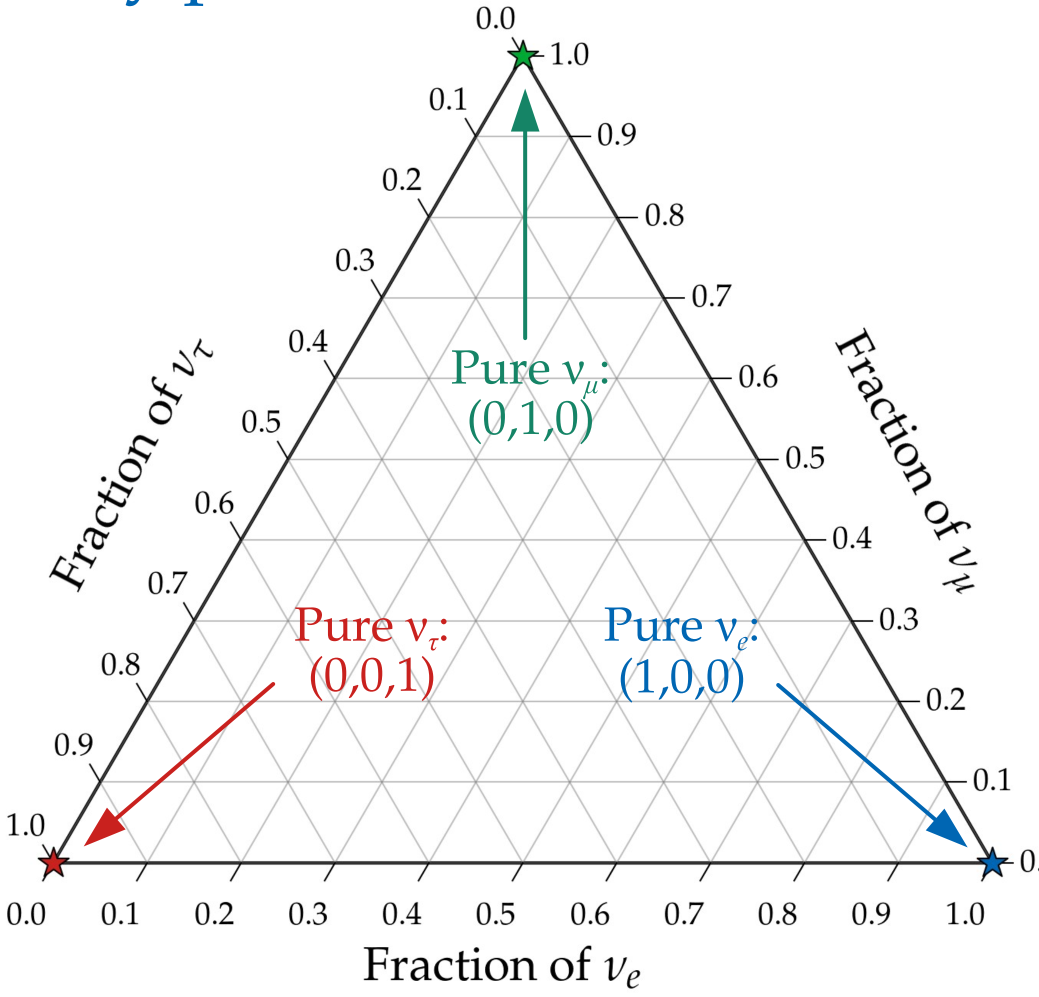

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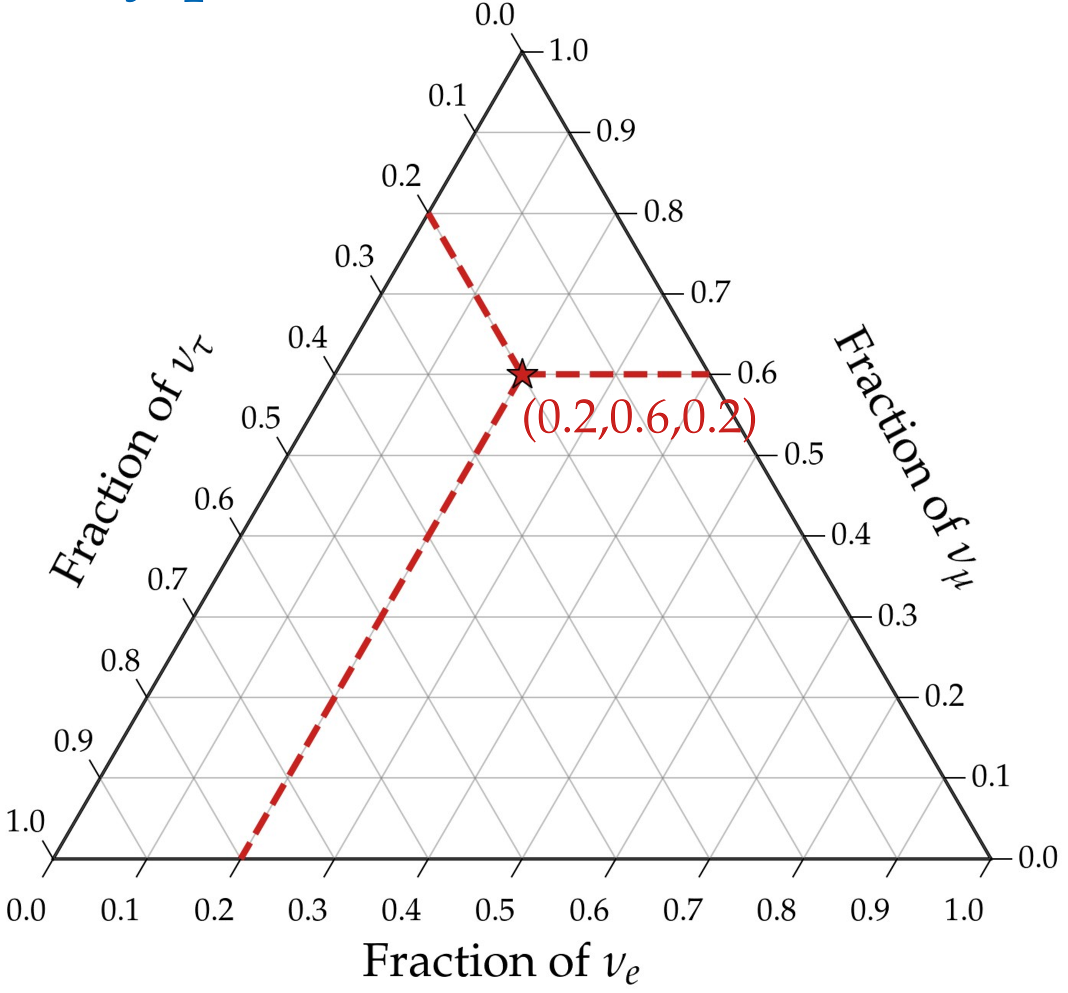

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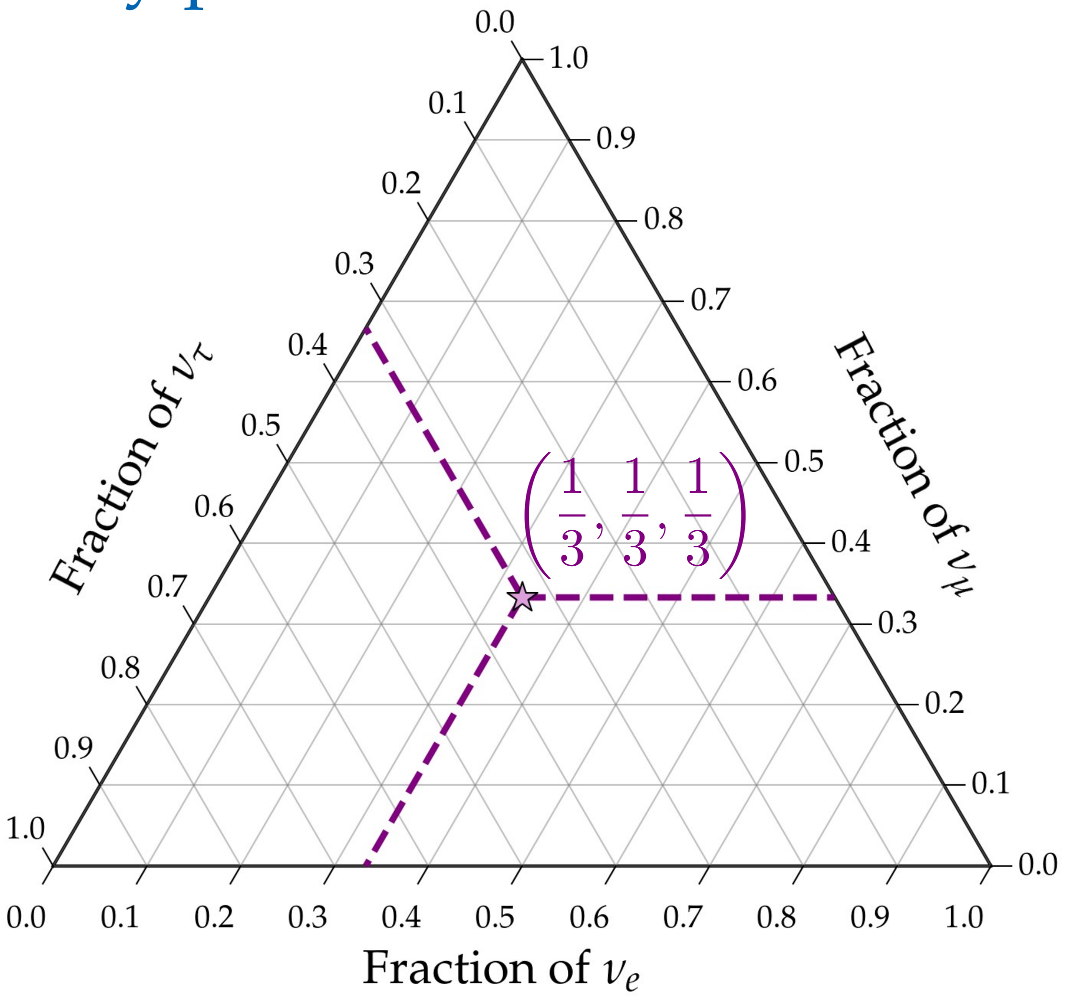

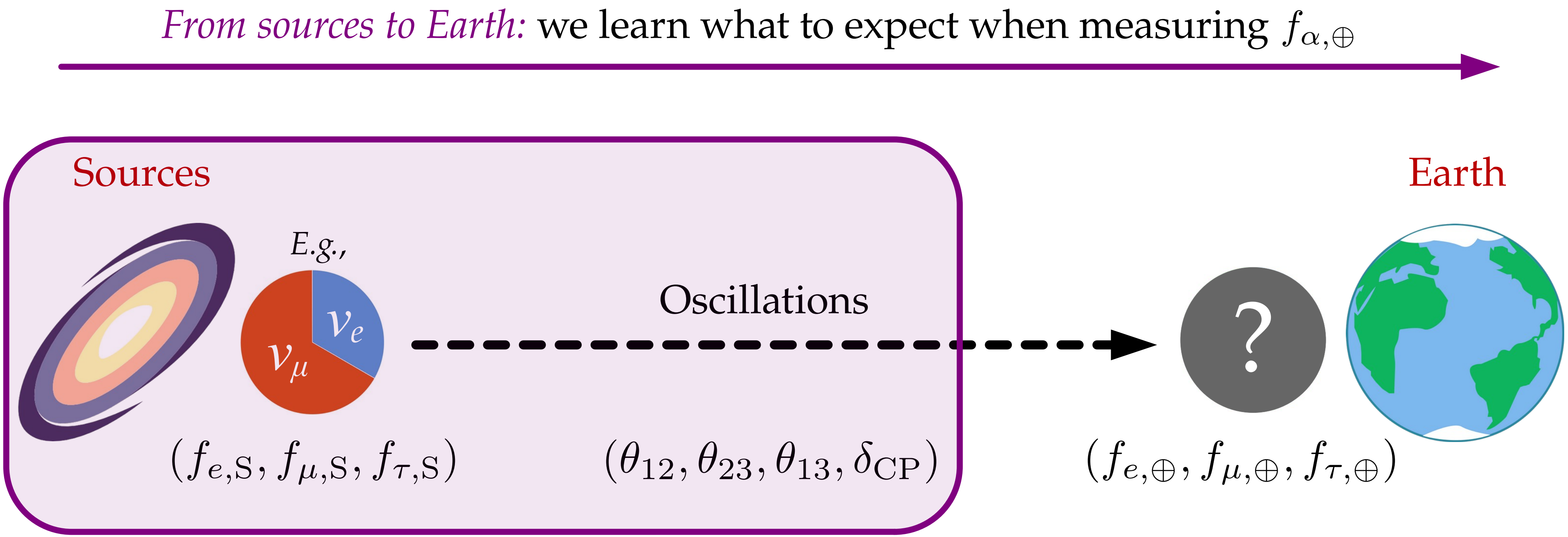

From sources to Earth: we learn what to expect when measuring $f_{\alpha,\oplus}$
Sources
Earth
E.g.,
ν_e
ν_μ
Oscillations
?
$(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}})$
$(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\mathrm{CP}})$
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$

One likely TeV–PeV ν production scenario:

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

Full π decay chain

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

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

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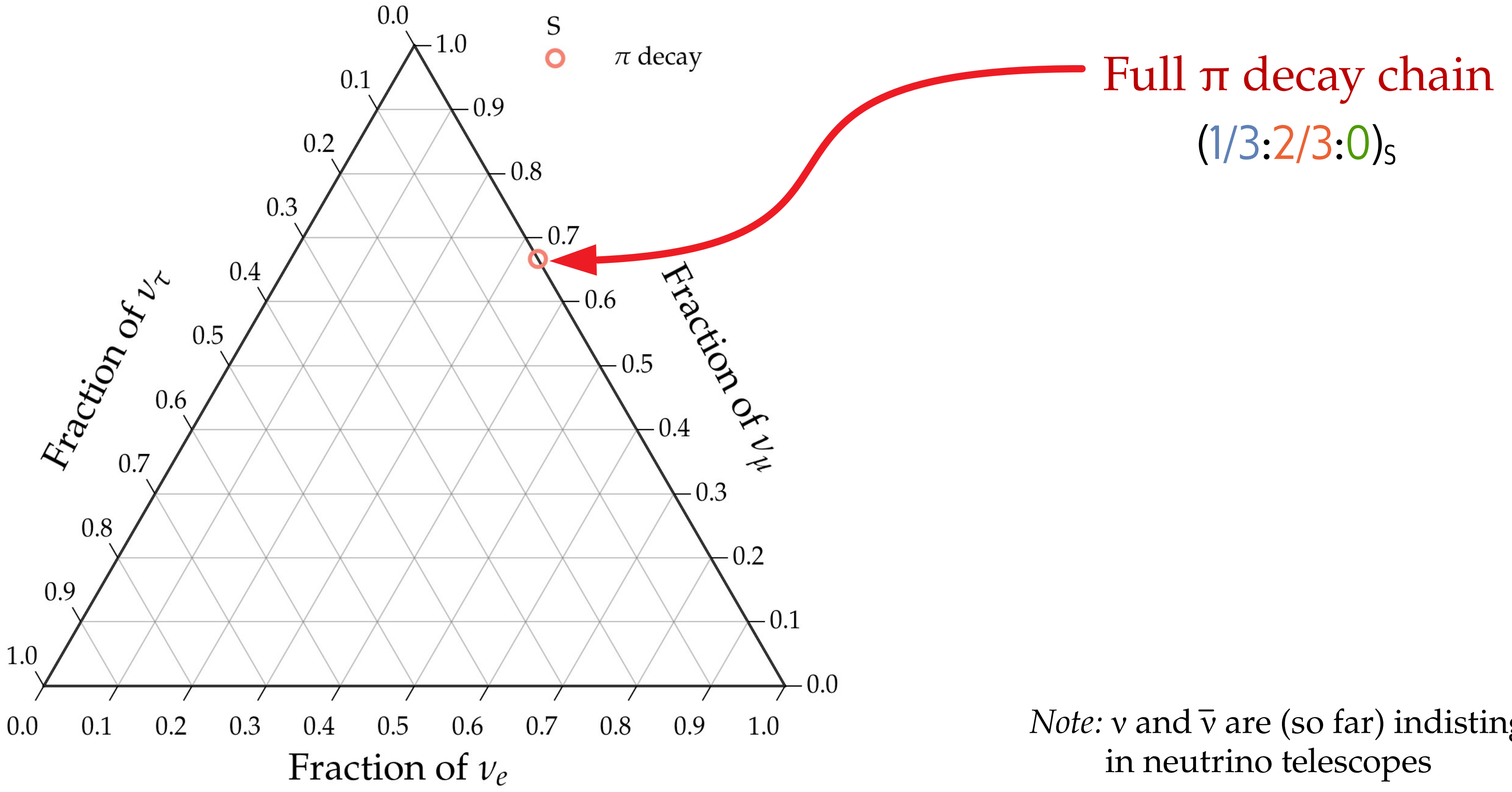

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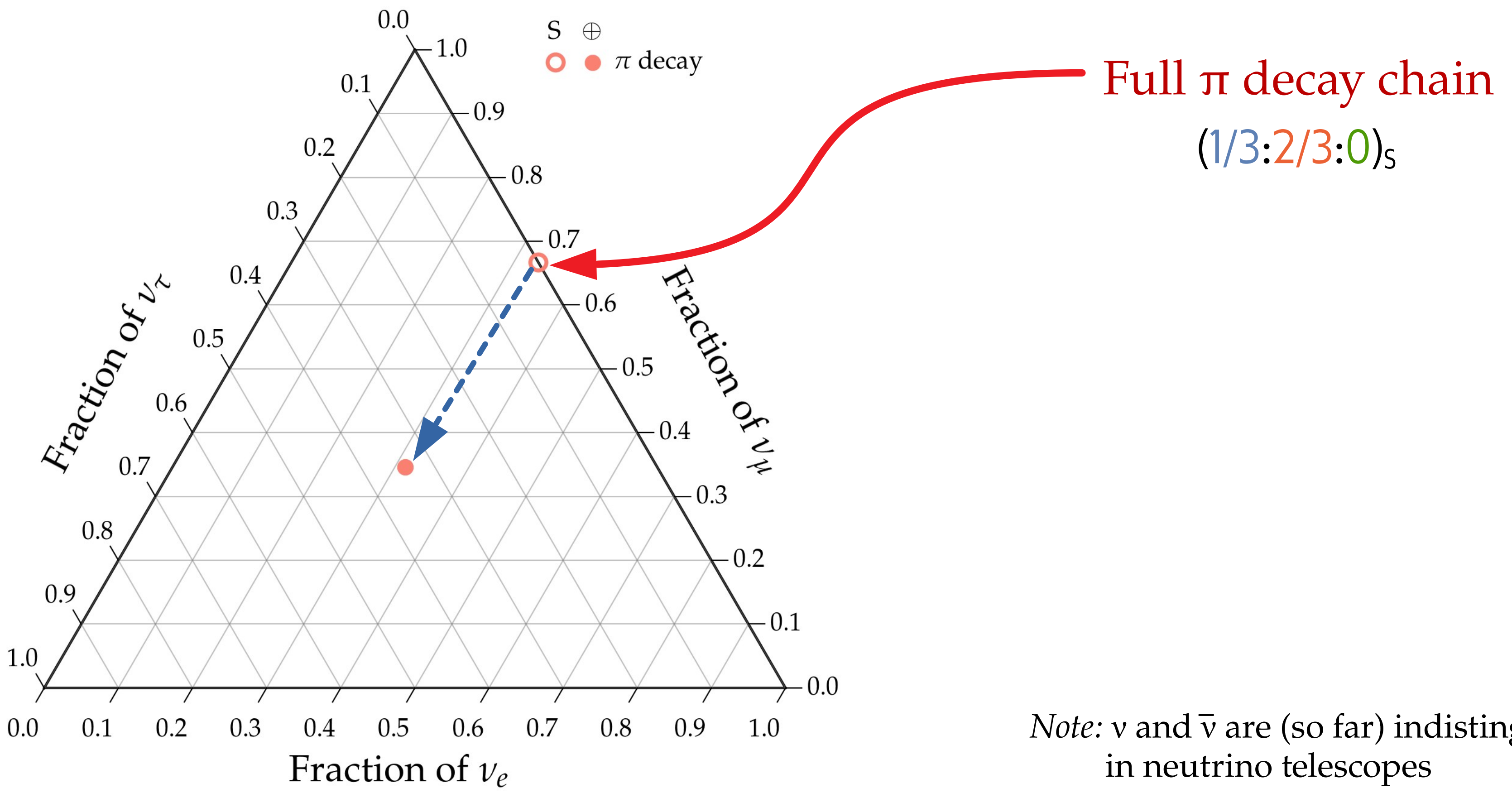

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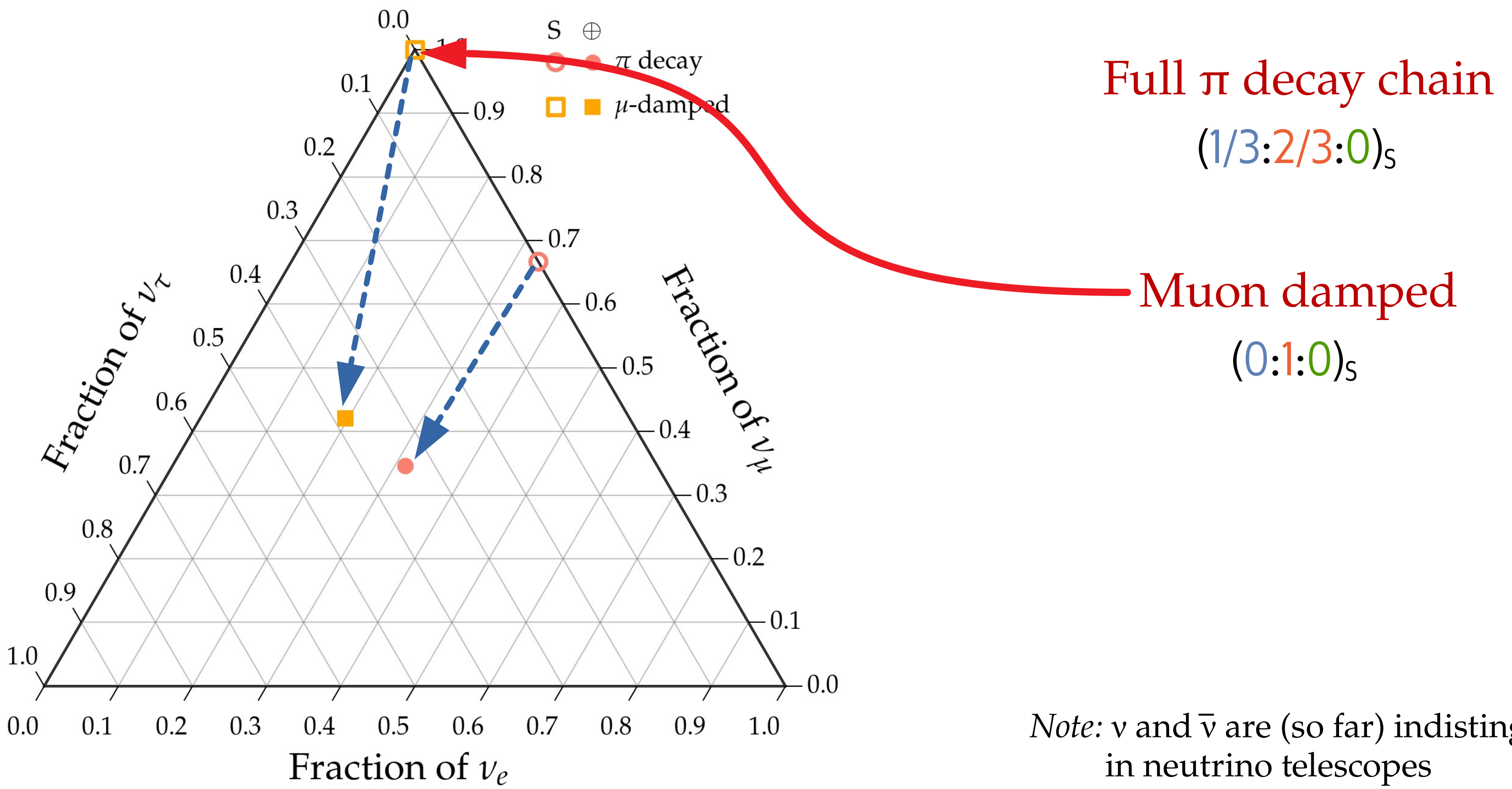

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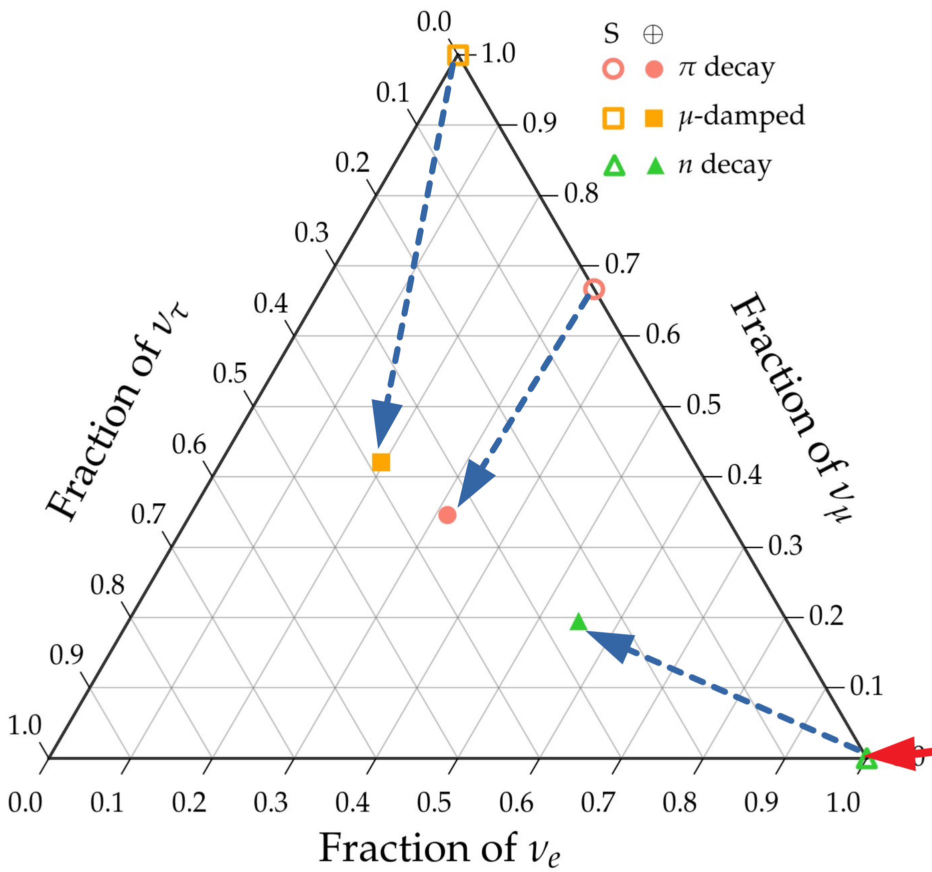

Full π decay chain

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

Muon damped

$(0:1:0)_S$

Neutron decay

$(1:0:0)_S$

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

II.
High-energy and ultra-high-energy neutrino physics

Note: Not an exhaustive list

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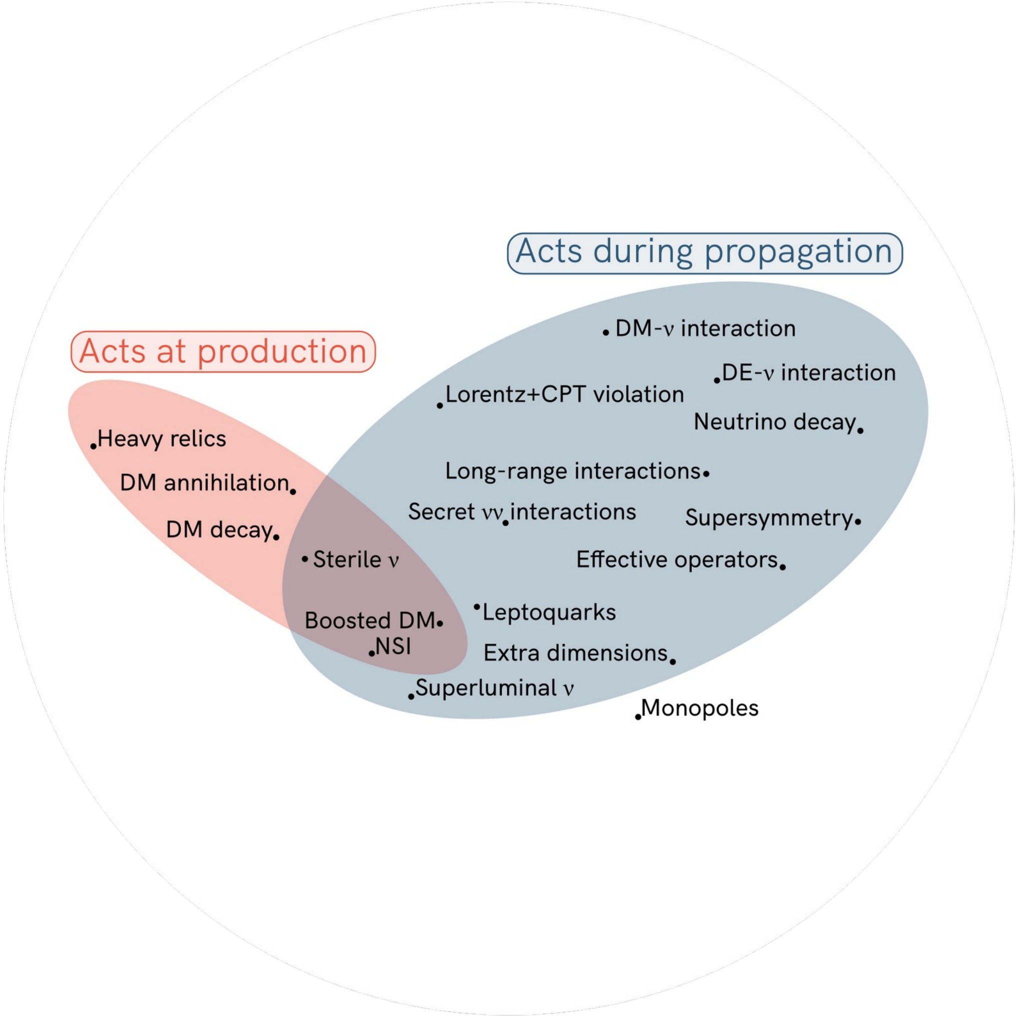

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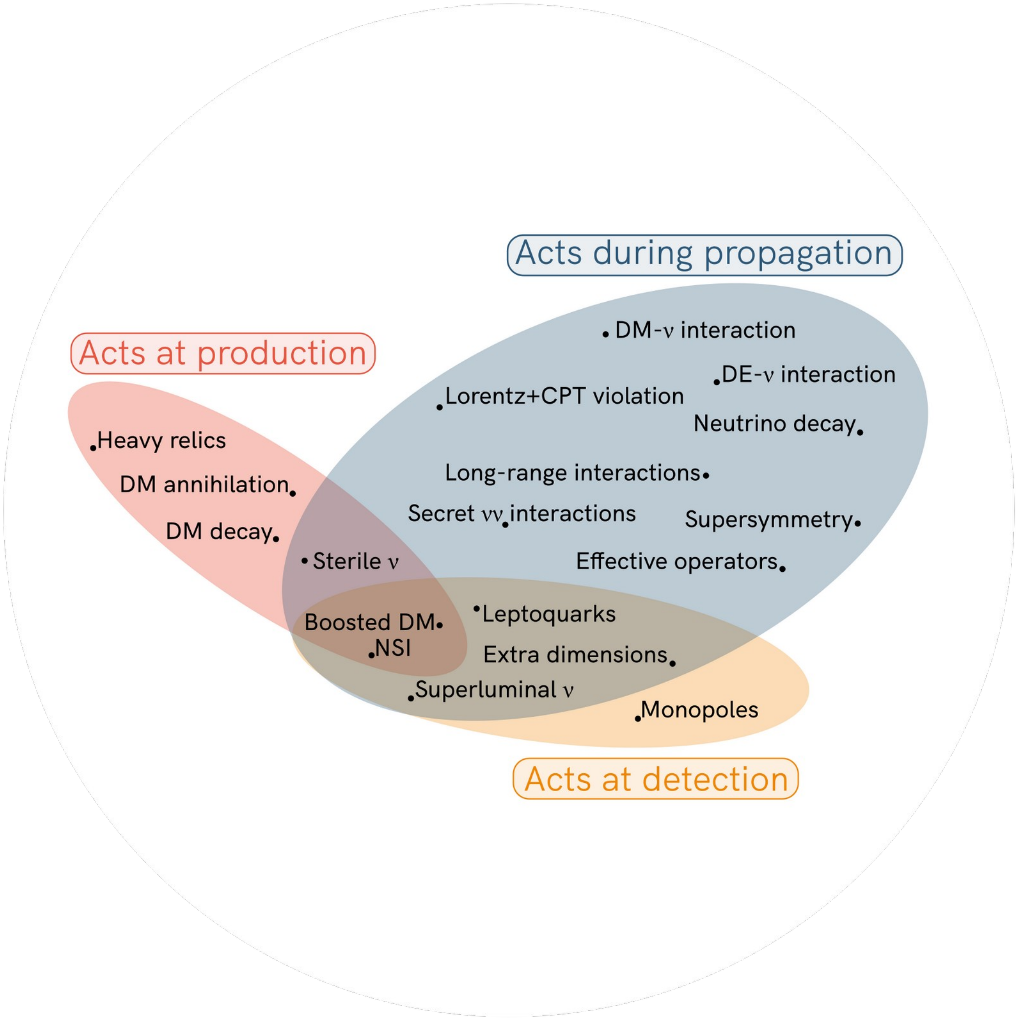

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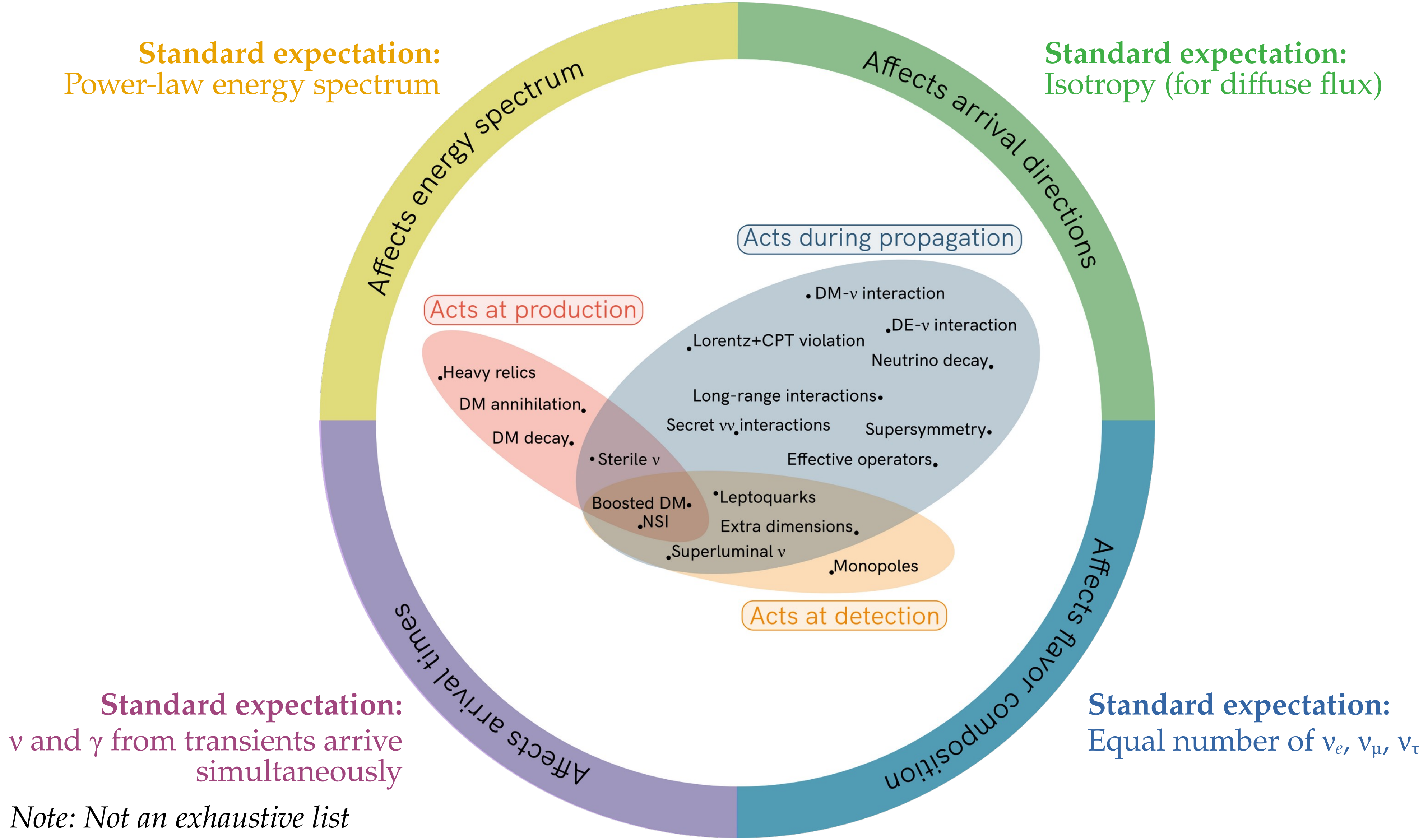
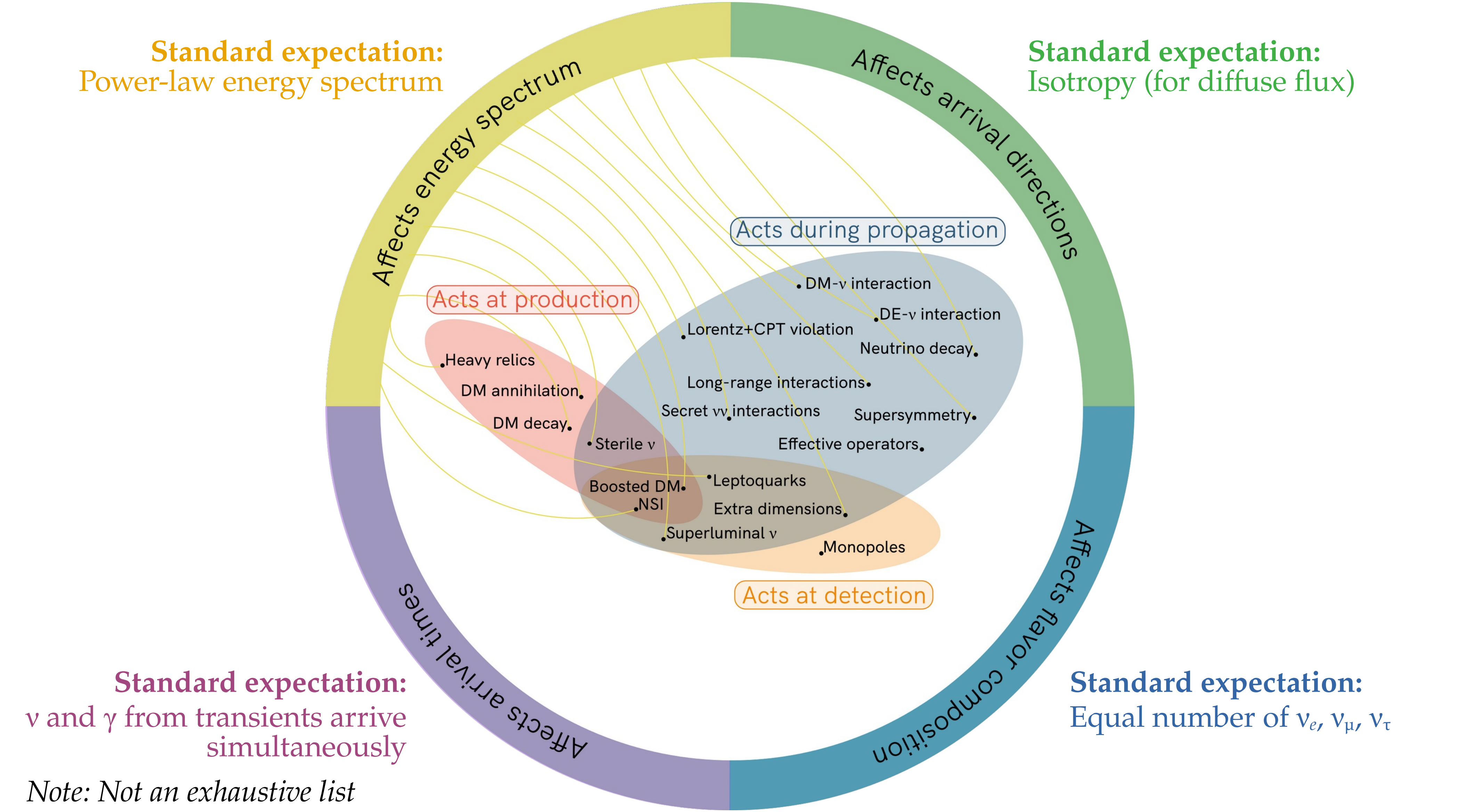

Standard expectation:
Power-law energy spectrum
Standard expectation:
Isotropy (for diffuse flux)
Affects energy spectrum
Affects arrival directions
Acts during propagation
Acts at production
DM-ν interaction
DE-ν interaction
Lorentz+CPT violation
Neutrino decay
Heavy relics
DM annihilation
DM decay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



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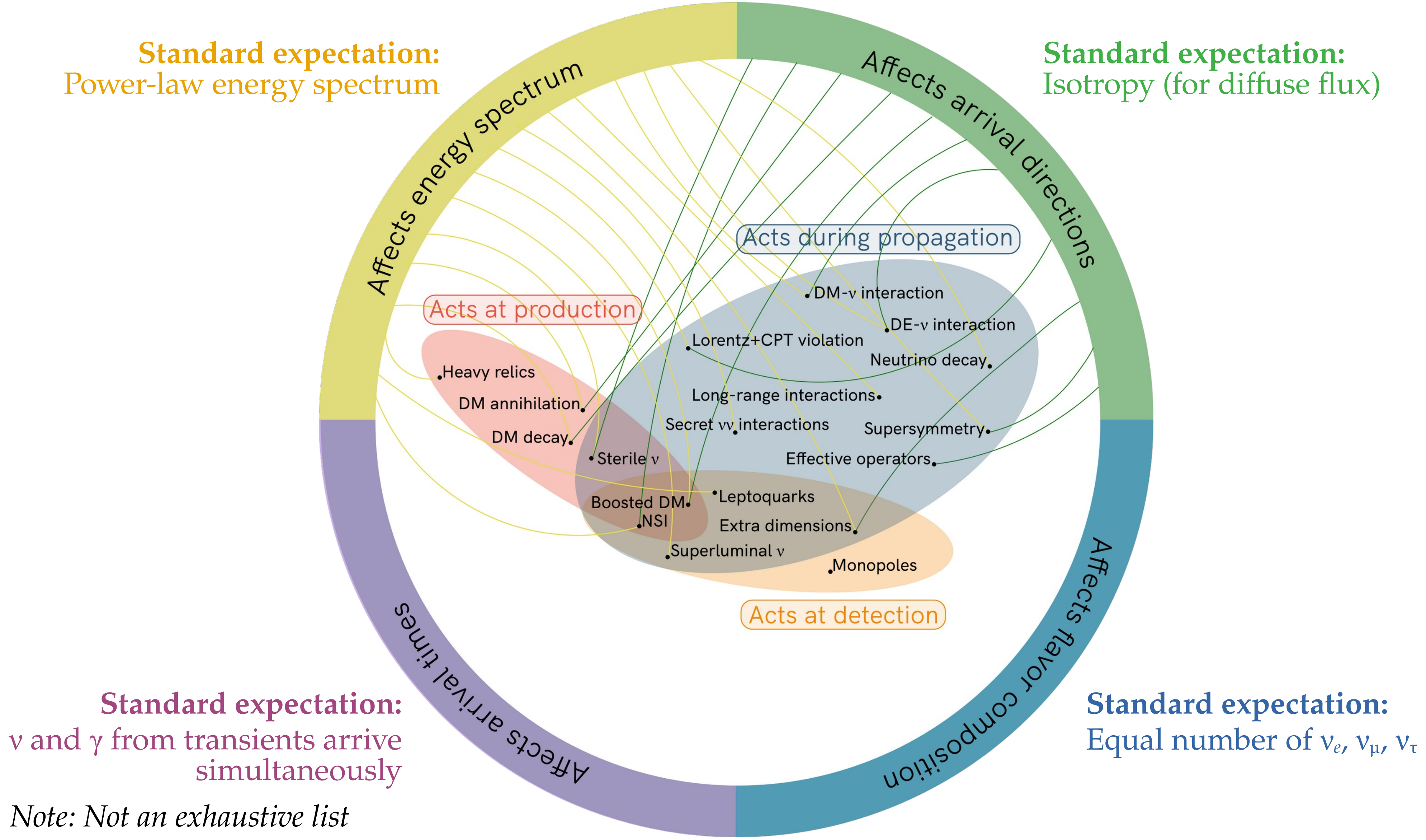

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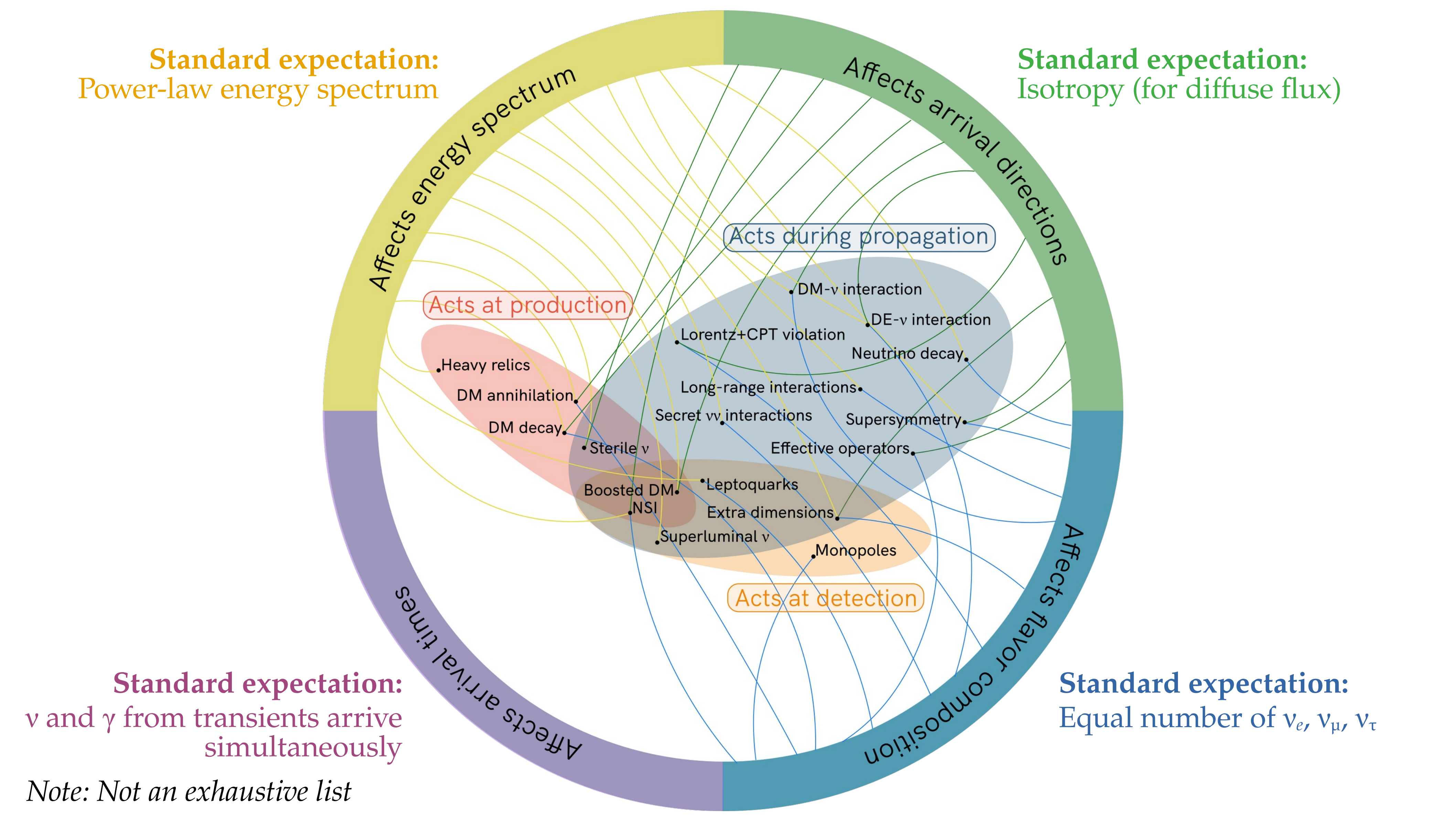

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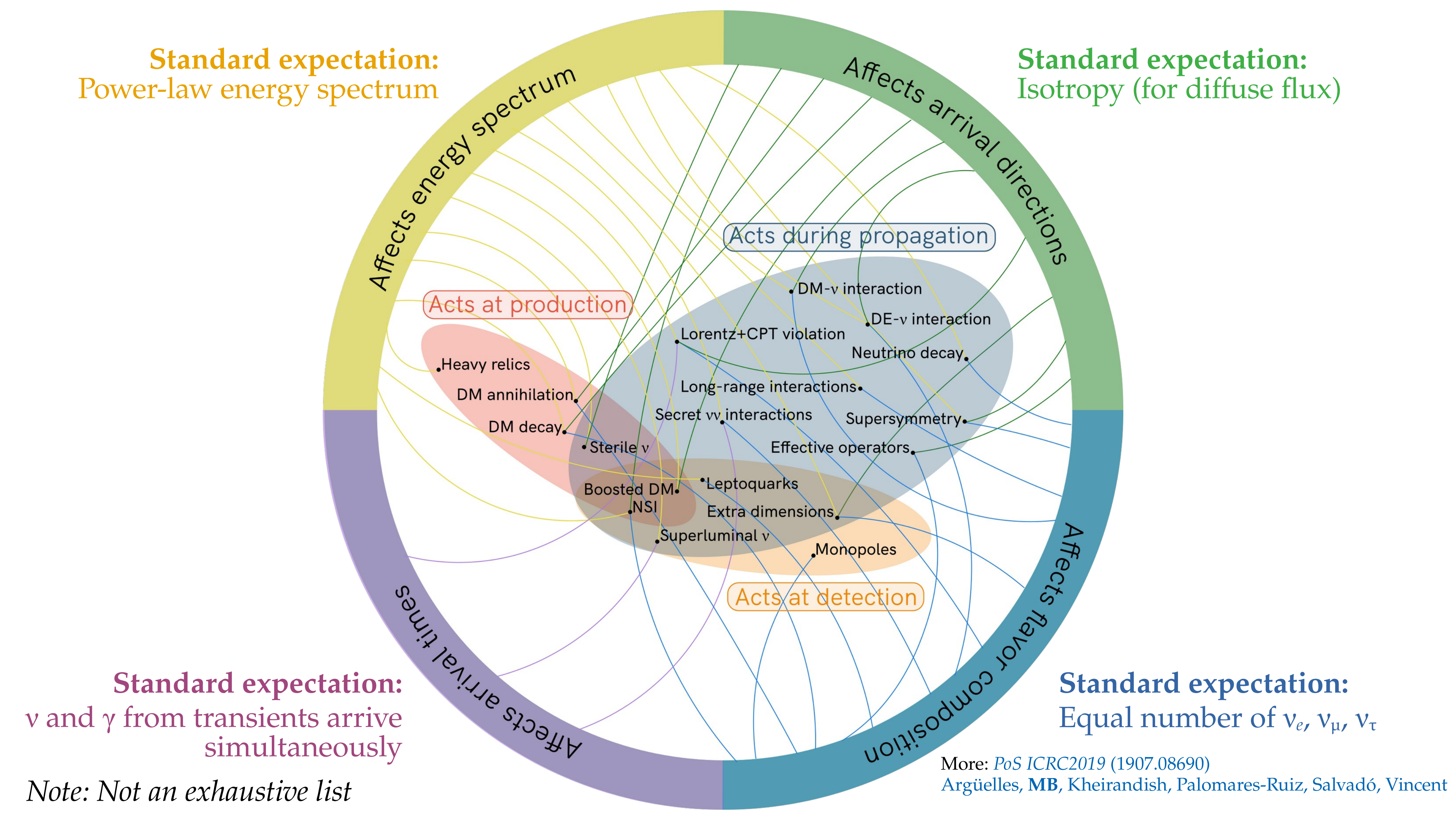

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More: PoS ICRC2019 (1907.08690)
Argüelles, MB, Kheirandish, Palomares-Ruiz, Salvadó, Vincent
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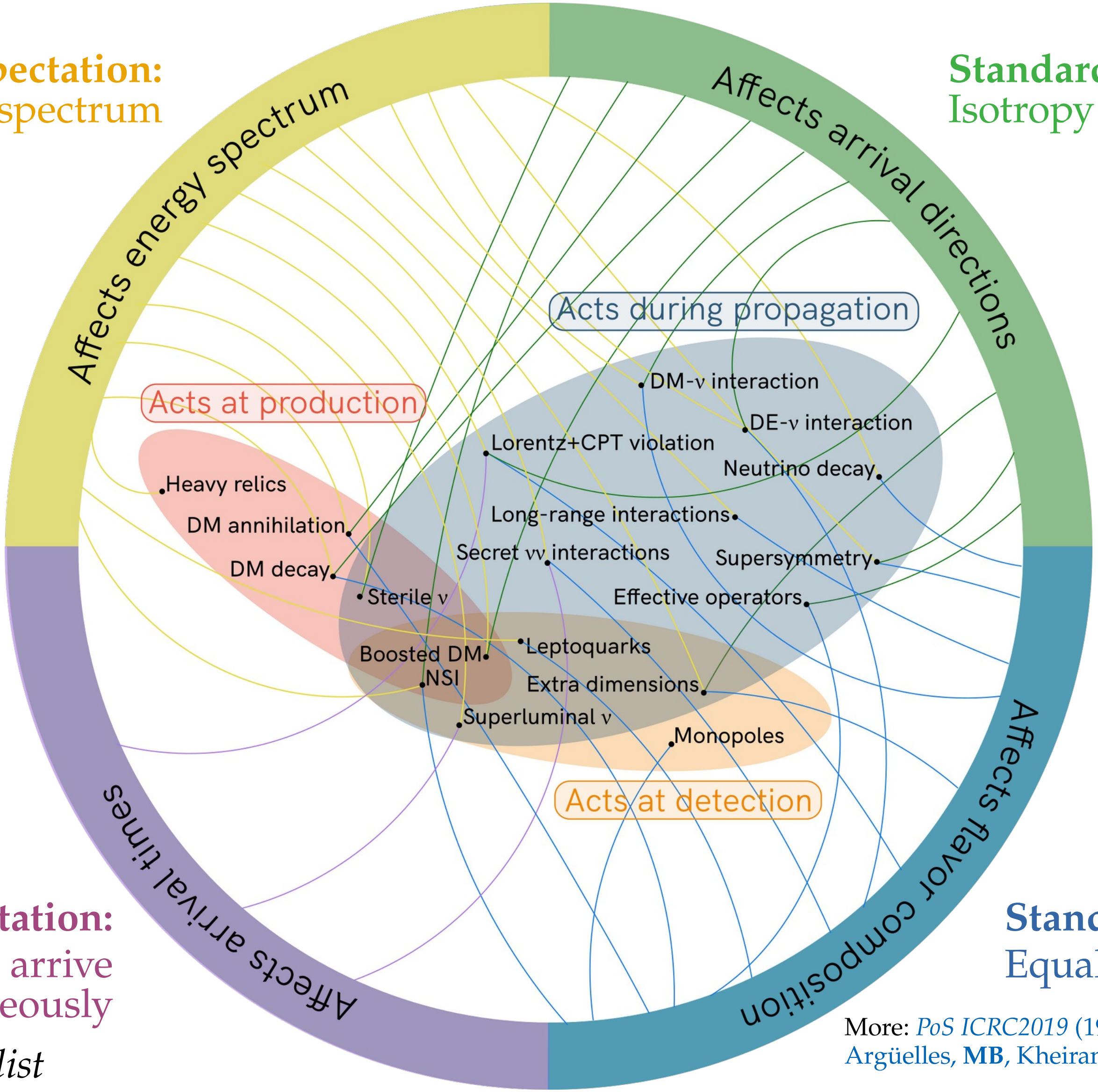

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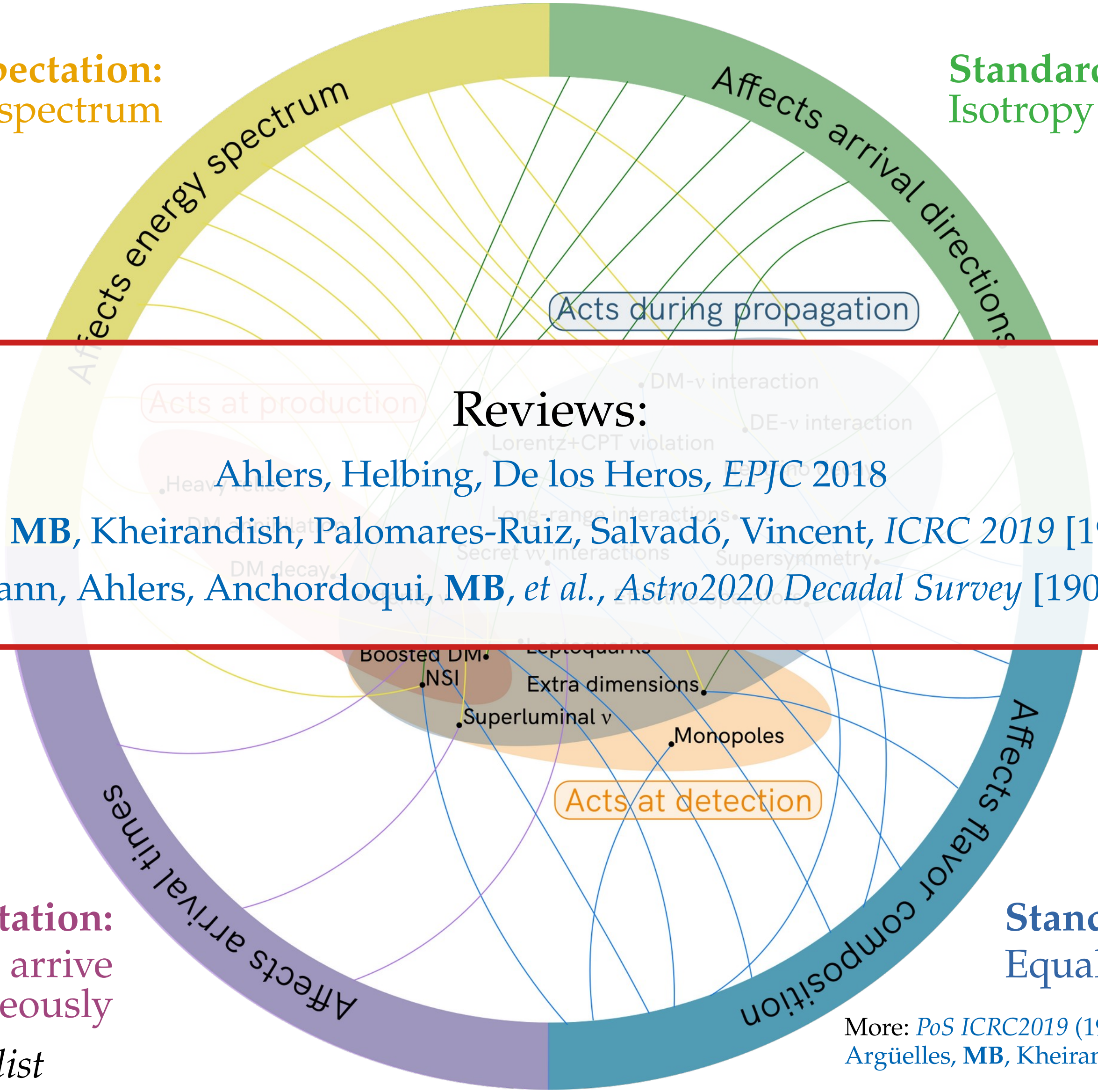

Reviews:

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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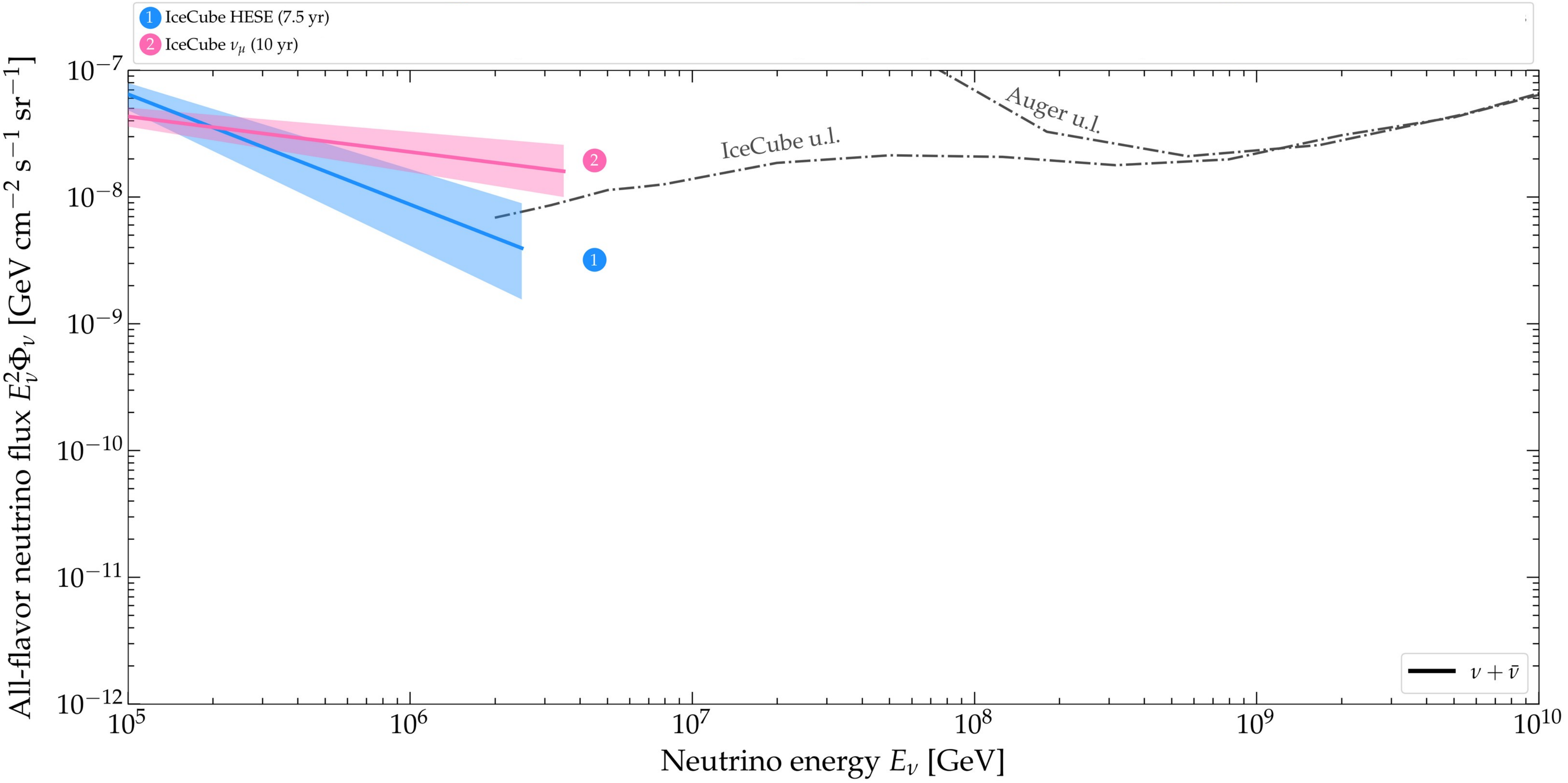

1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (10 yr)
Auger u.l.
IceCube u.l.
$\nu + \bar{\nu}$
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy E_ν [GeV]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
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10^5
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Today

TeV–PeV ν

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TeV–PeV ν

Turn predictions
into data-driven tests

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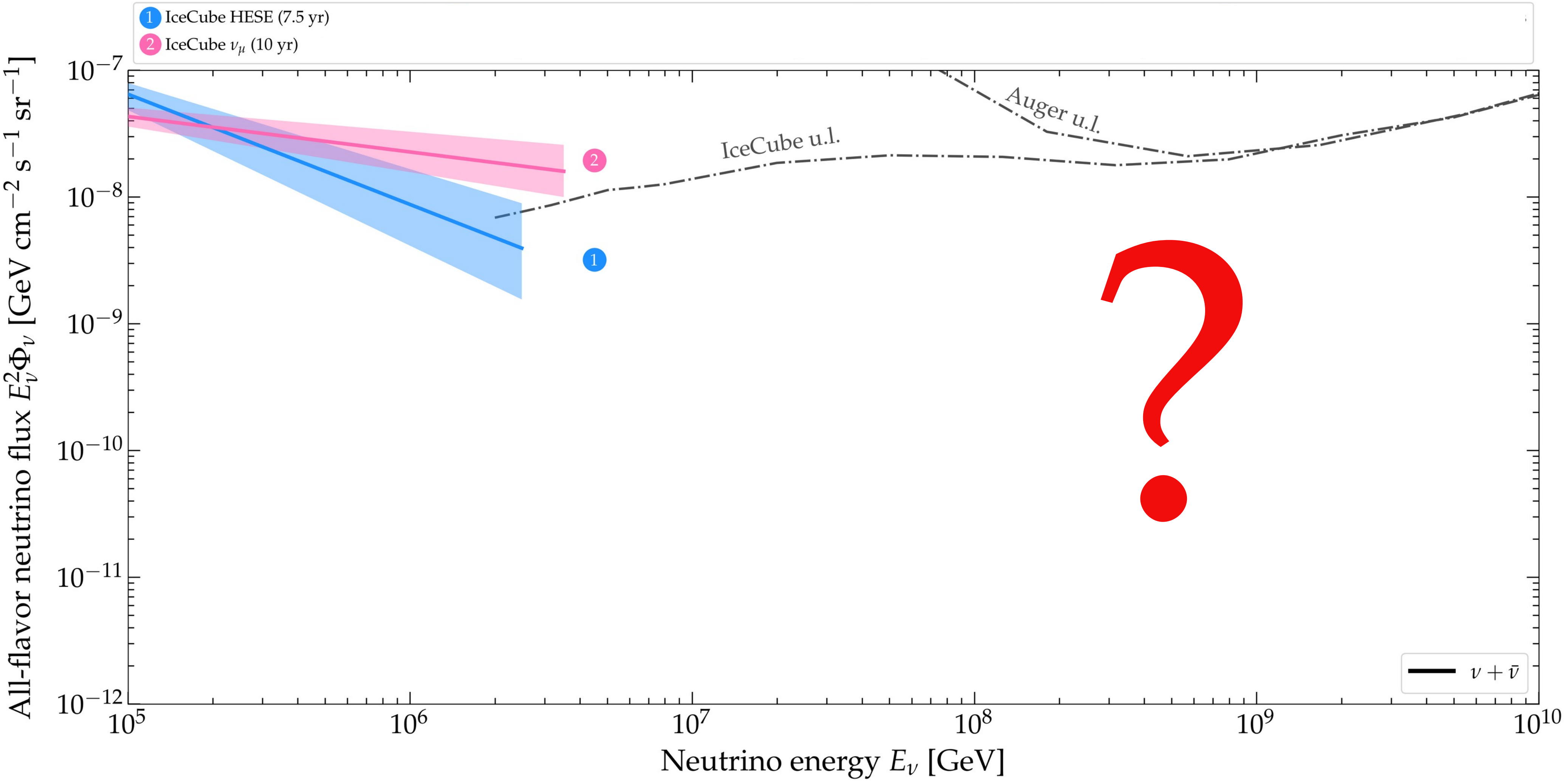
Key developments:
Bigger detectors → larger statistics
Better reconstruction
Smaller astrophysical uncertainties



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Auger u.l.
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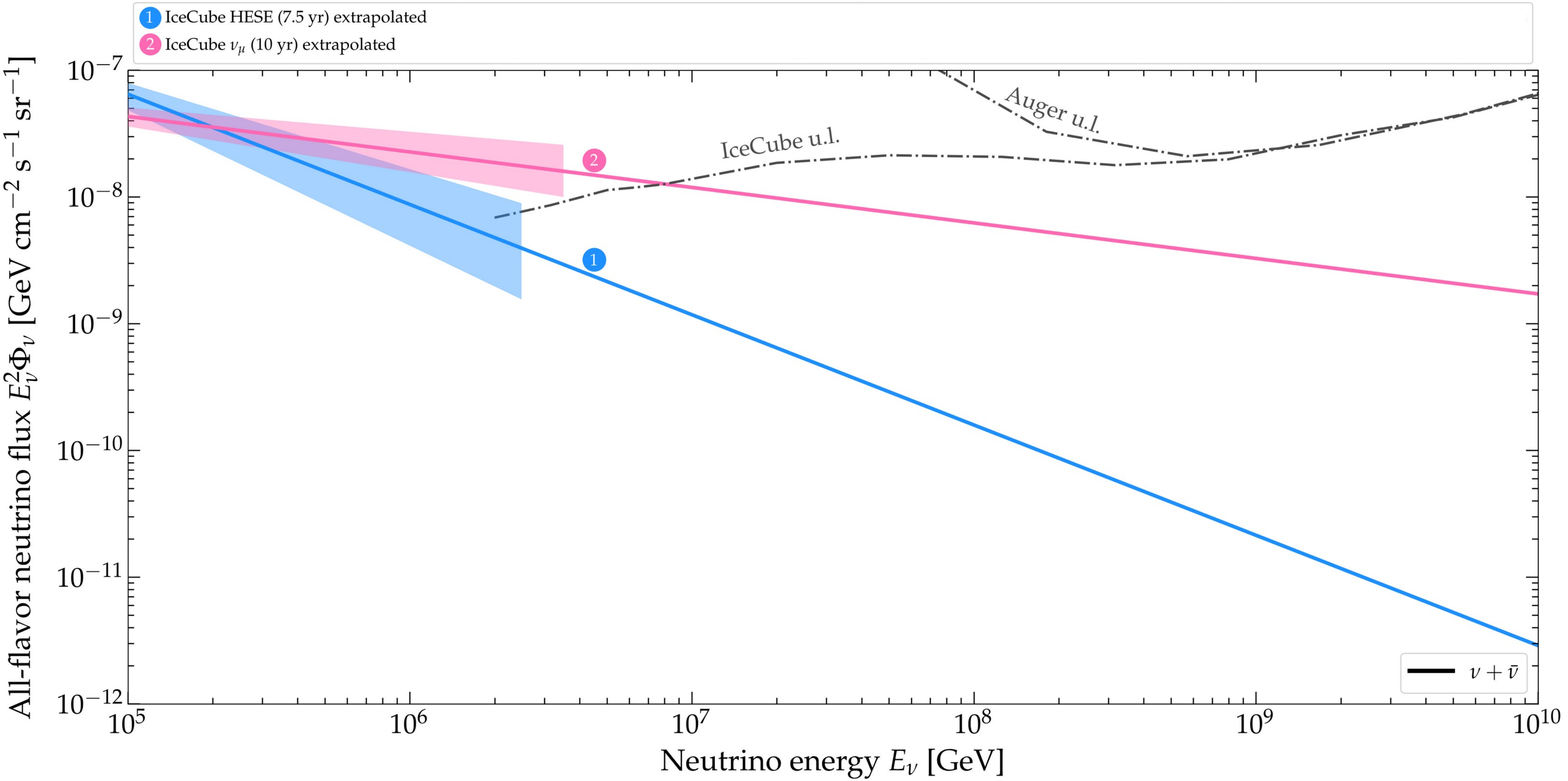

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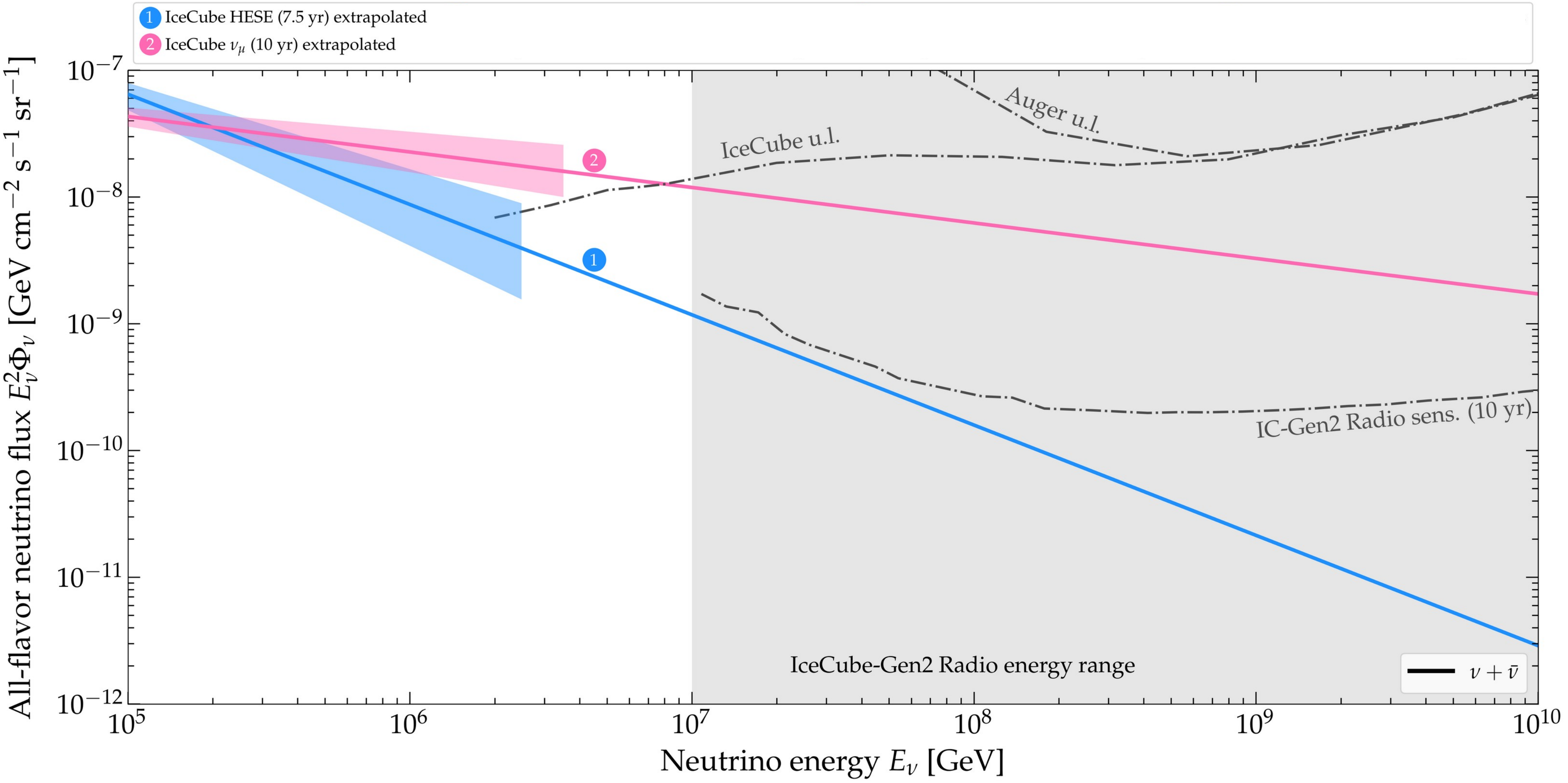

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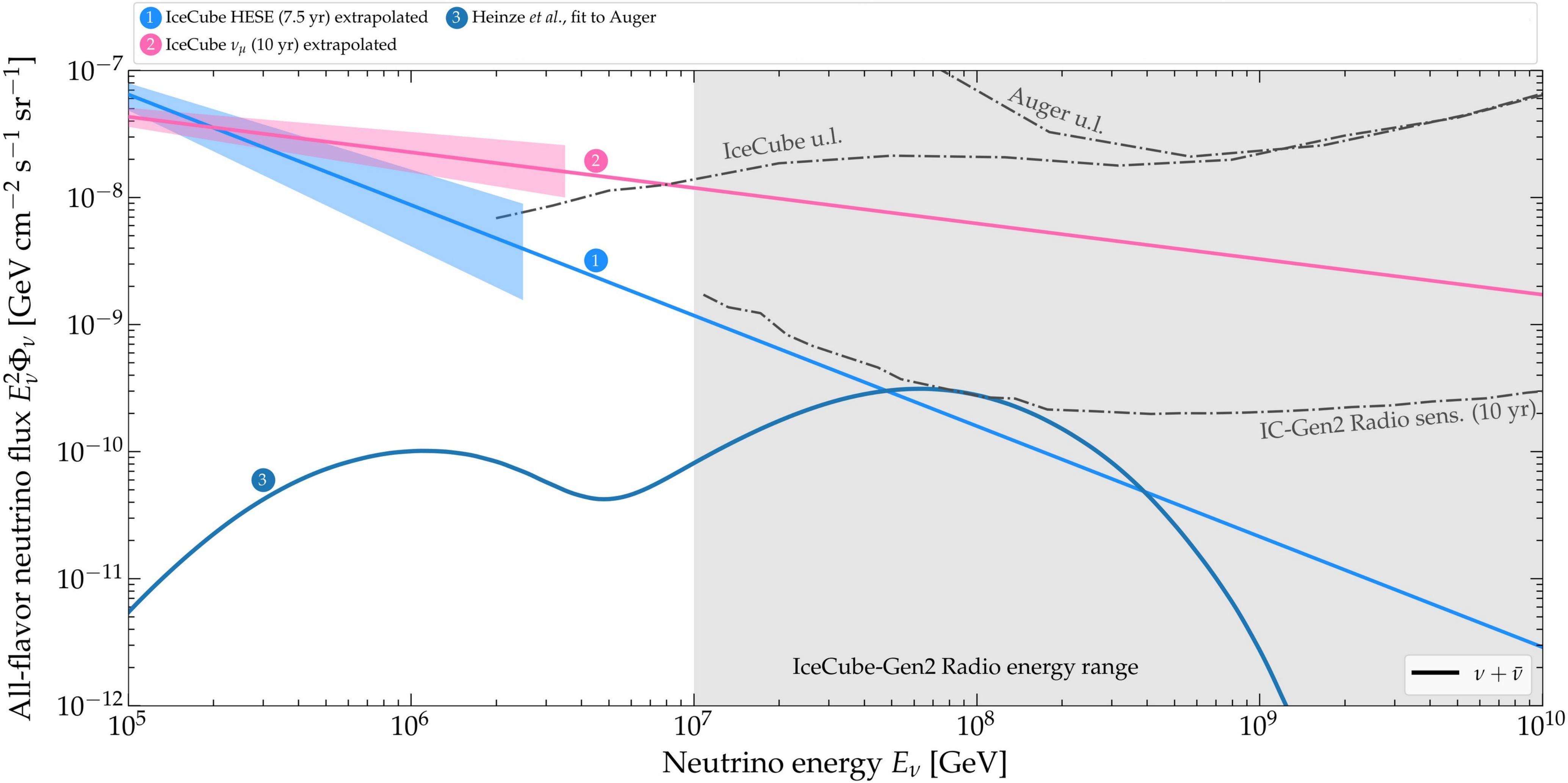

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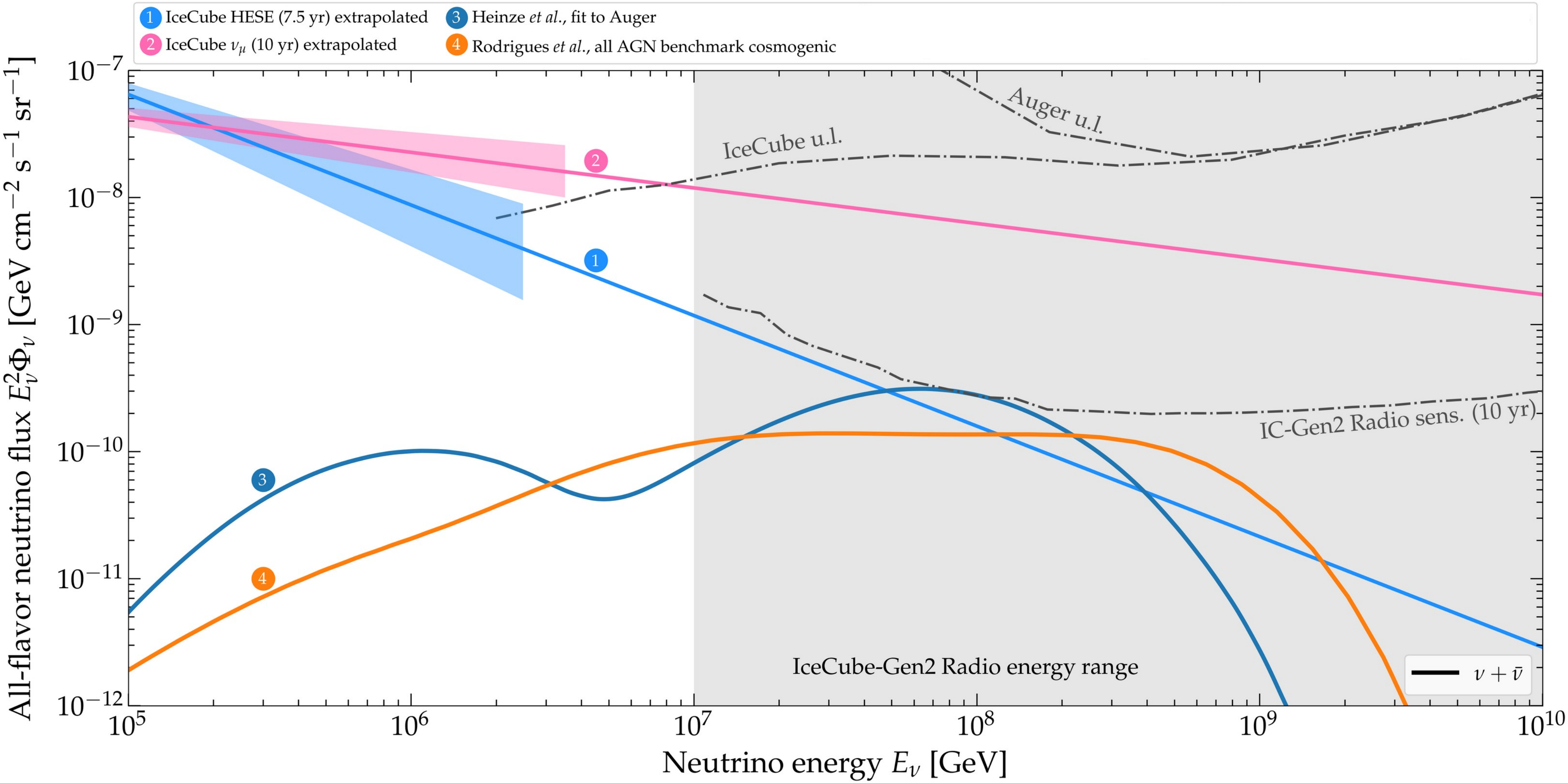

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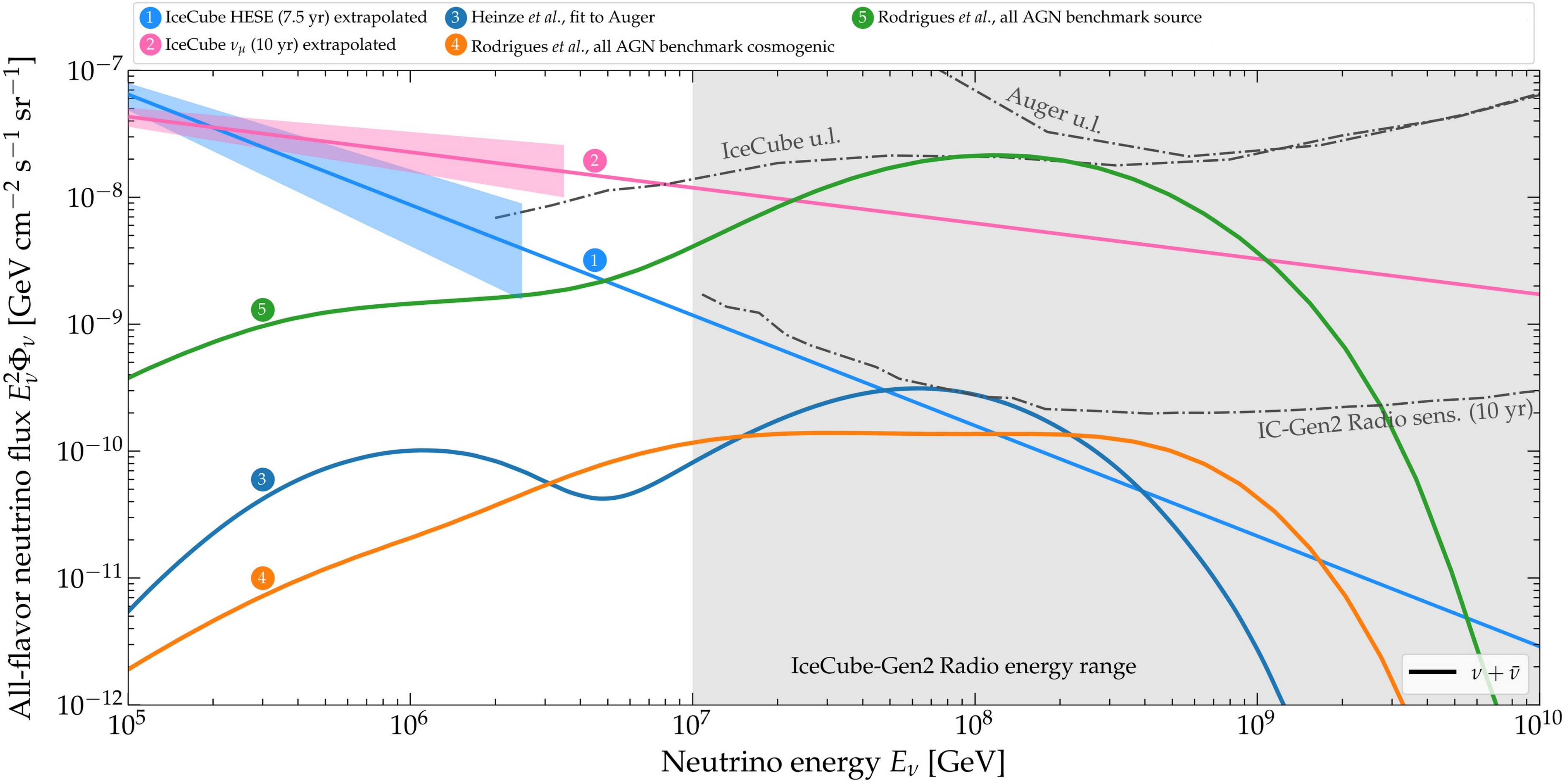
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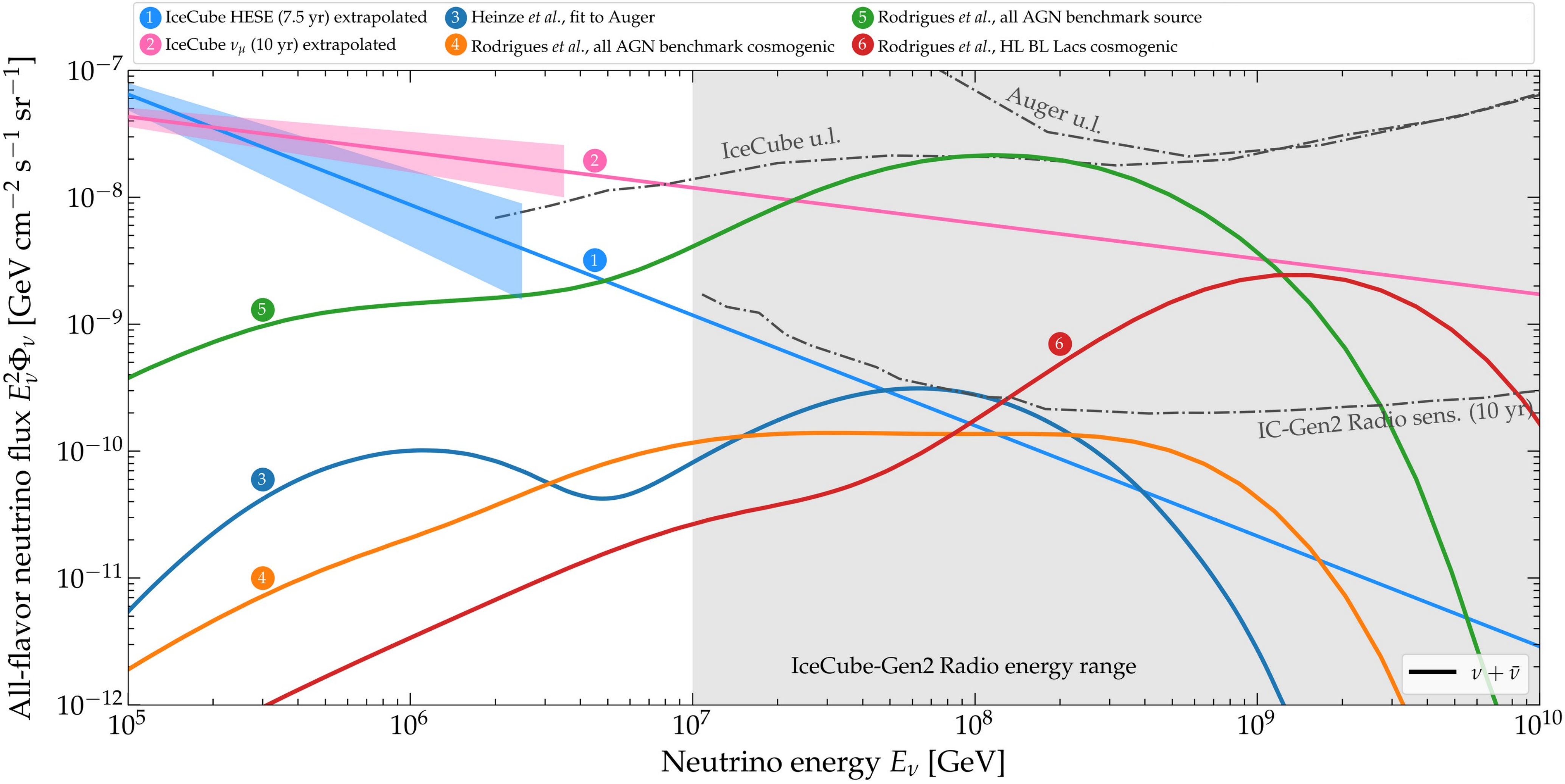

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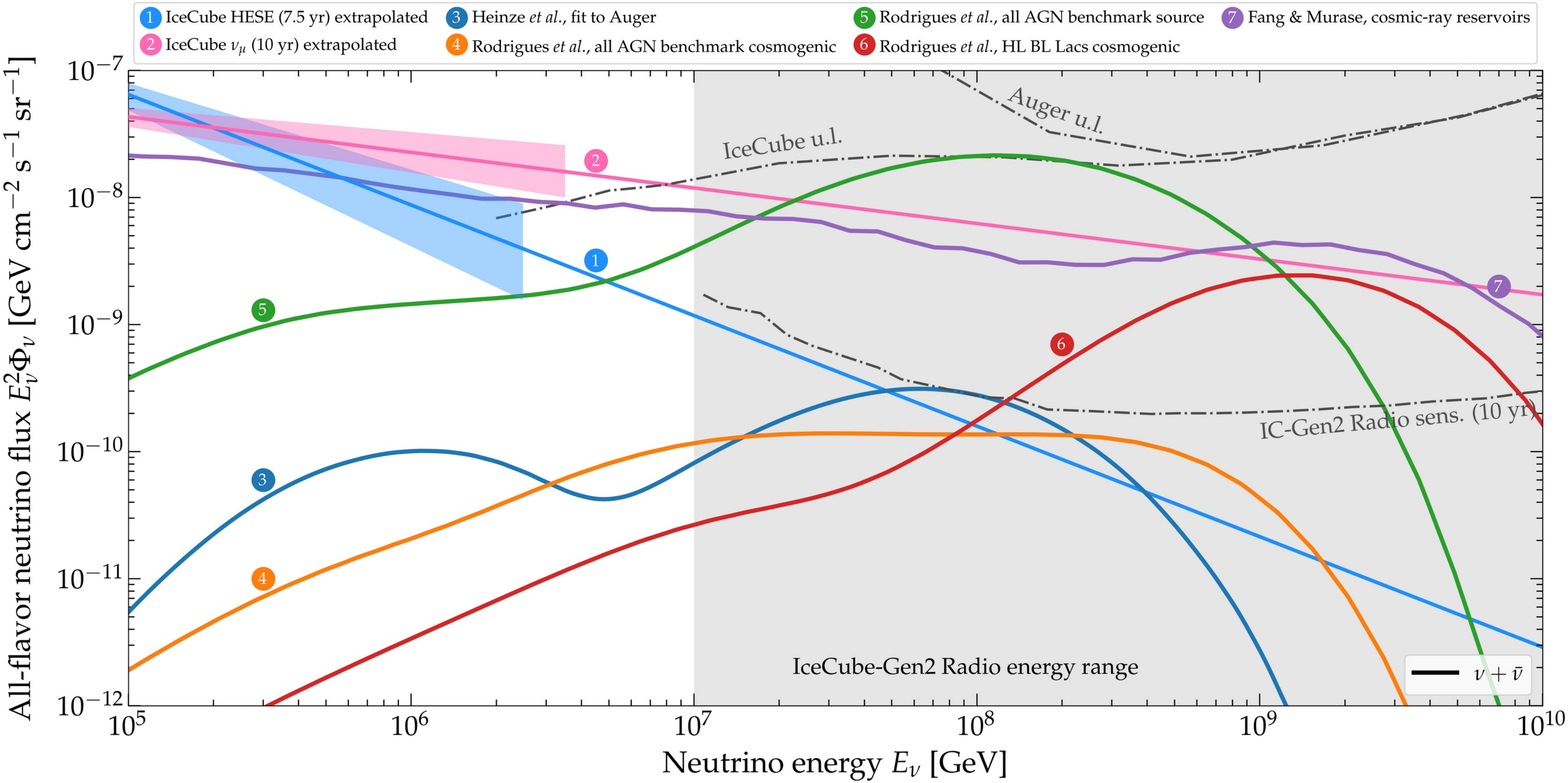

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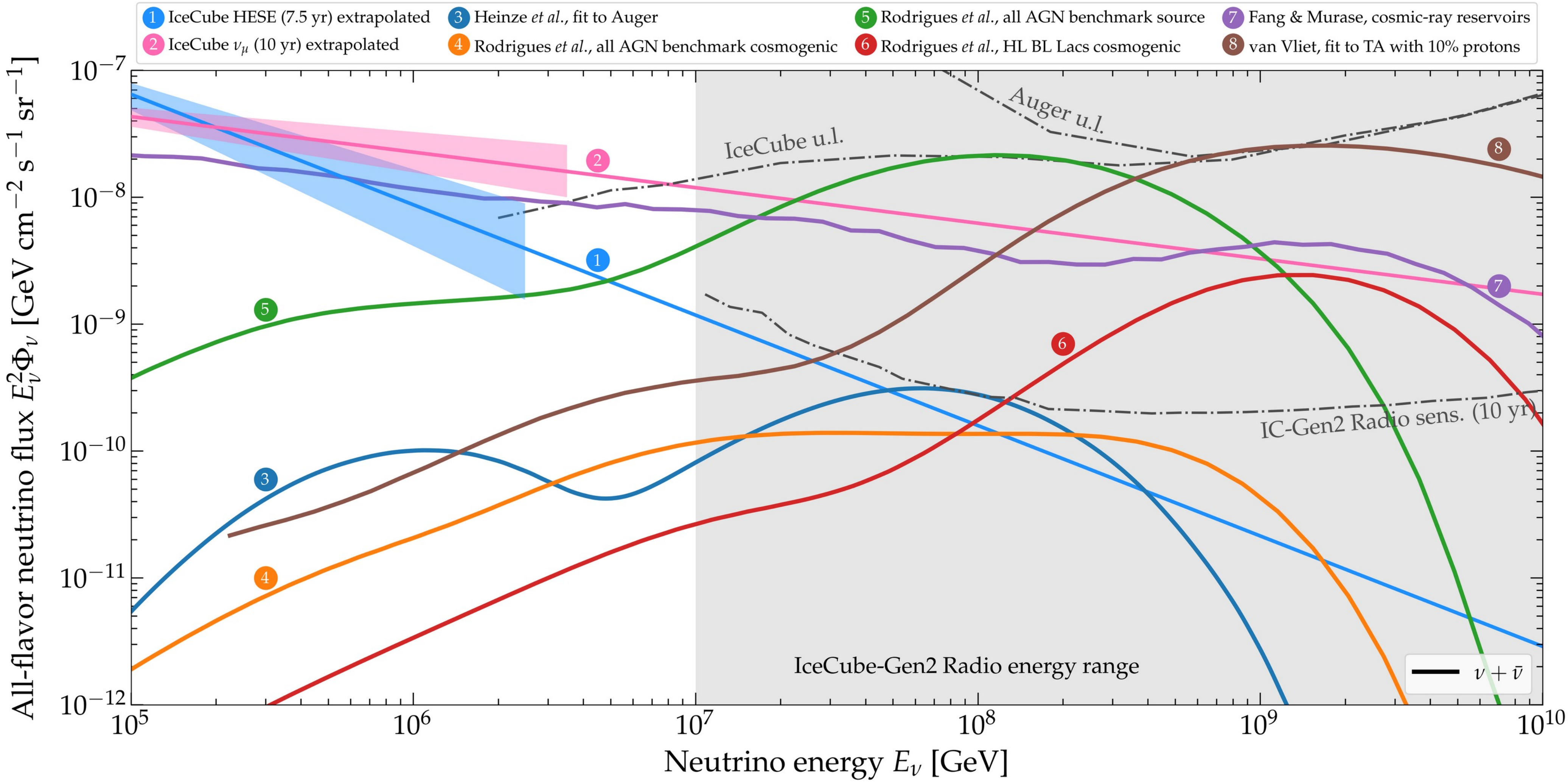

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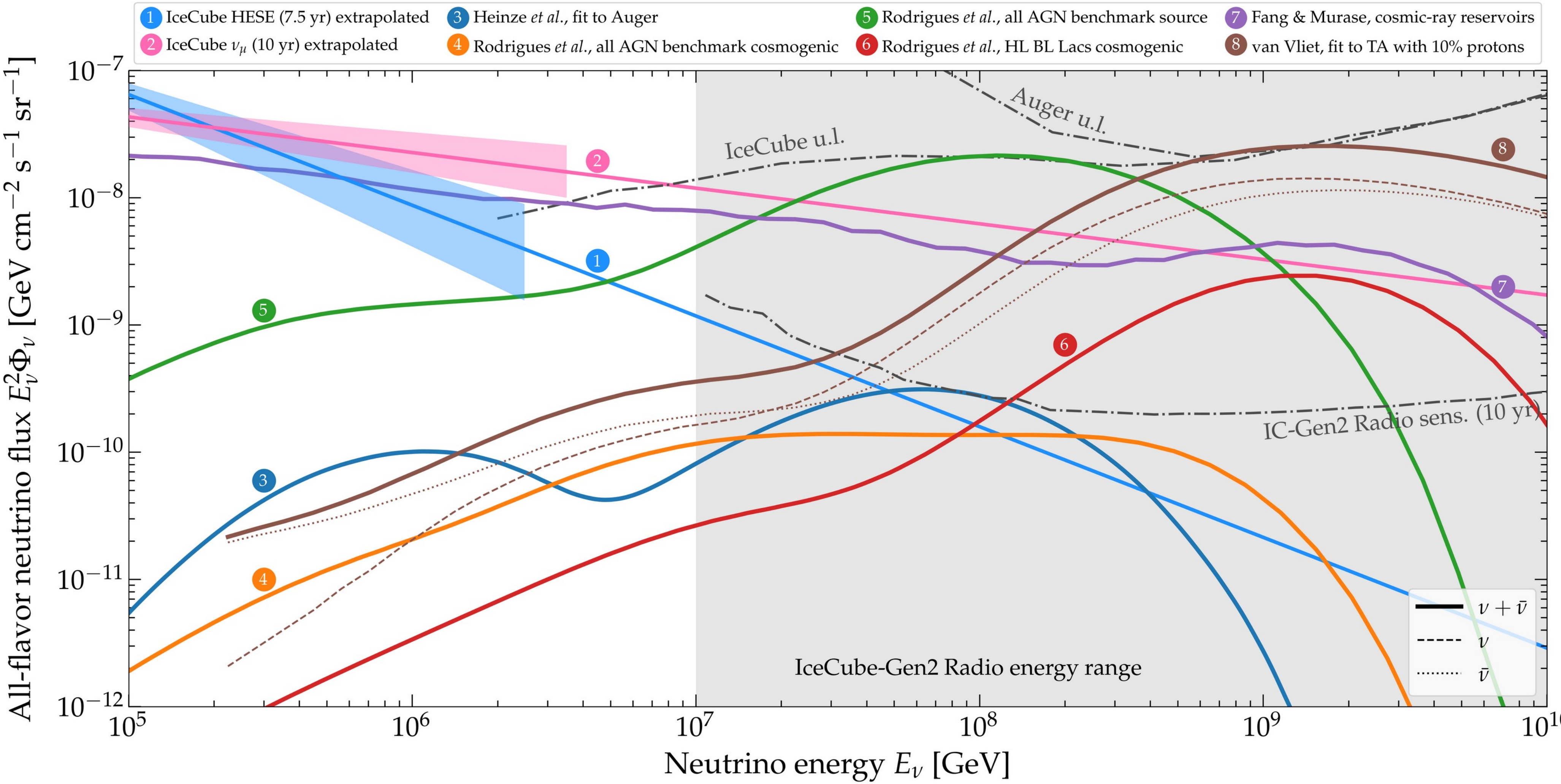

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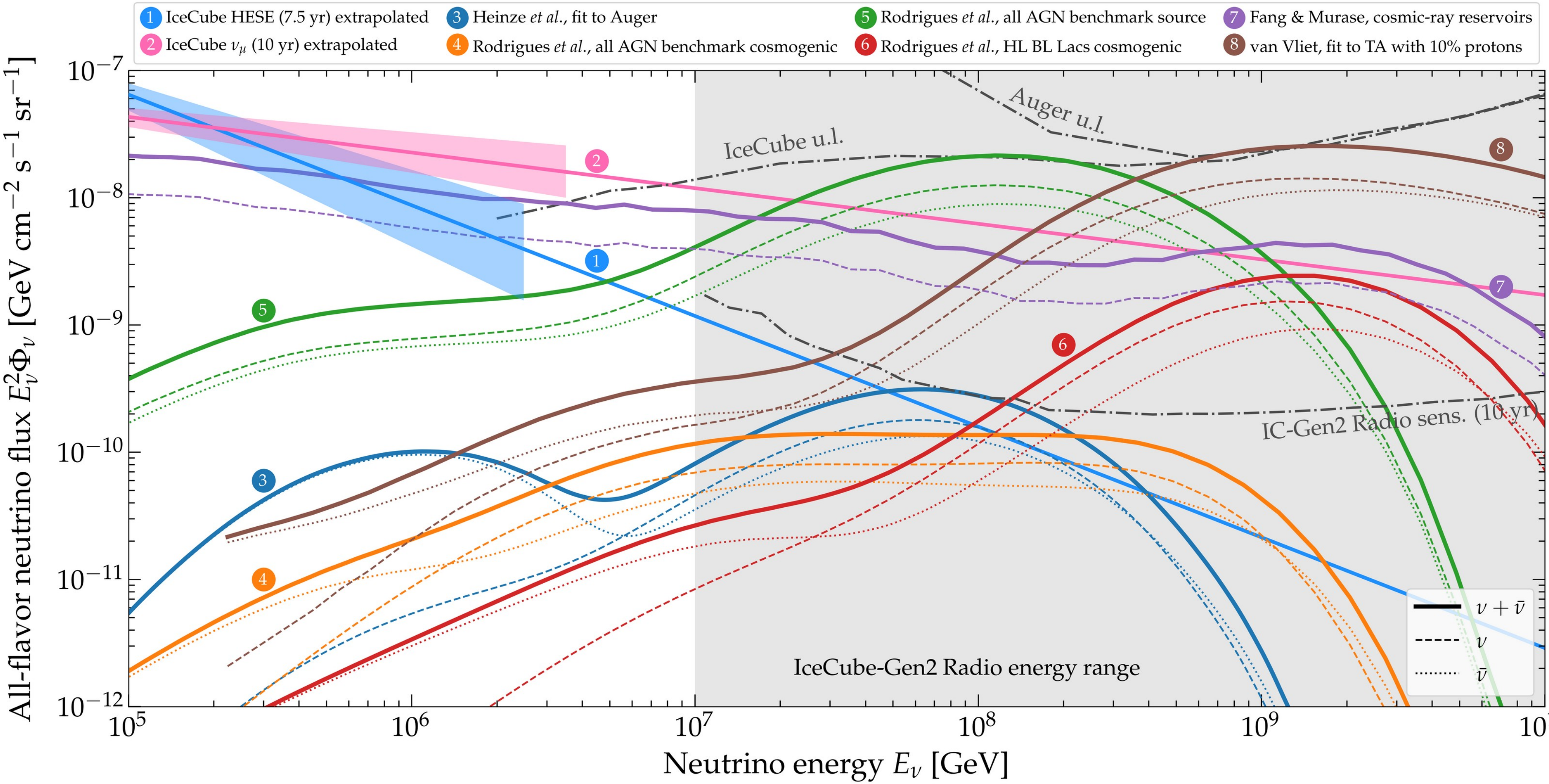

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TeV–PeV ν

Turn predictions
into data-driven tests

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

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Next decade

> 100-PeV ν

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

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Key developments:

Bigger detectors → larger statistics

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Next decade

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Make predictions for
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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

Two examples

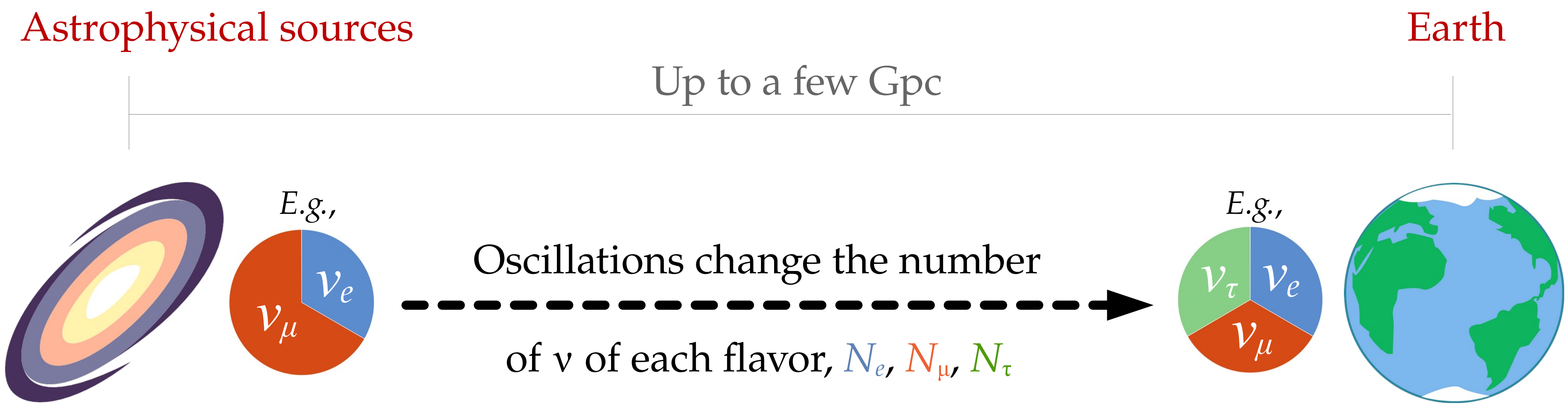
1. Flavor stuff
2. Cross-section stuff

Good chances of discovery or setting strong bounds

Keep ourselves grounded by accounting for all relevant particle and astrophysics unknowns

Flavor:
Towards precision, finally

(with the help of lower-energy experiments)

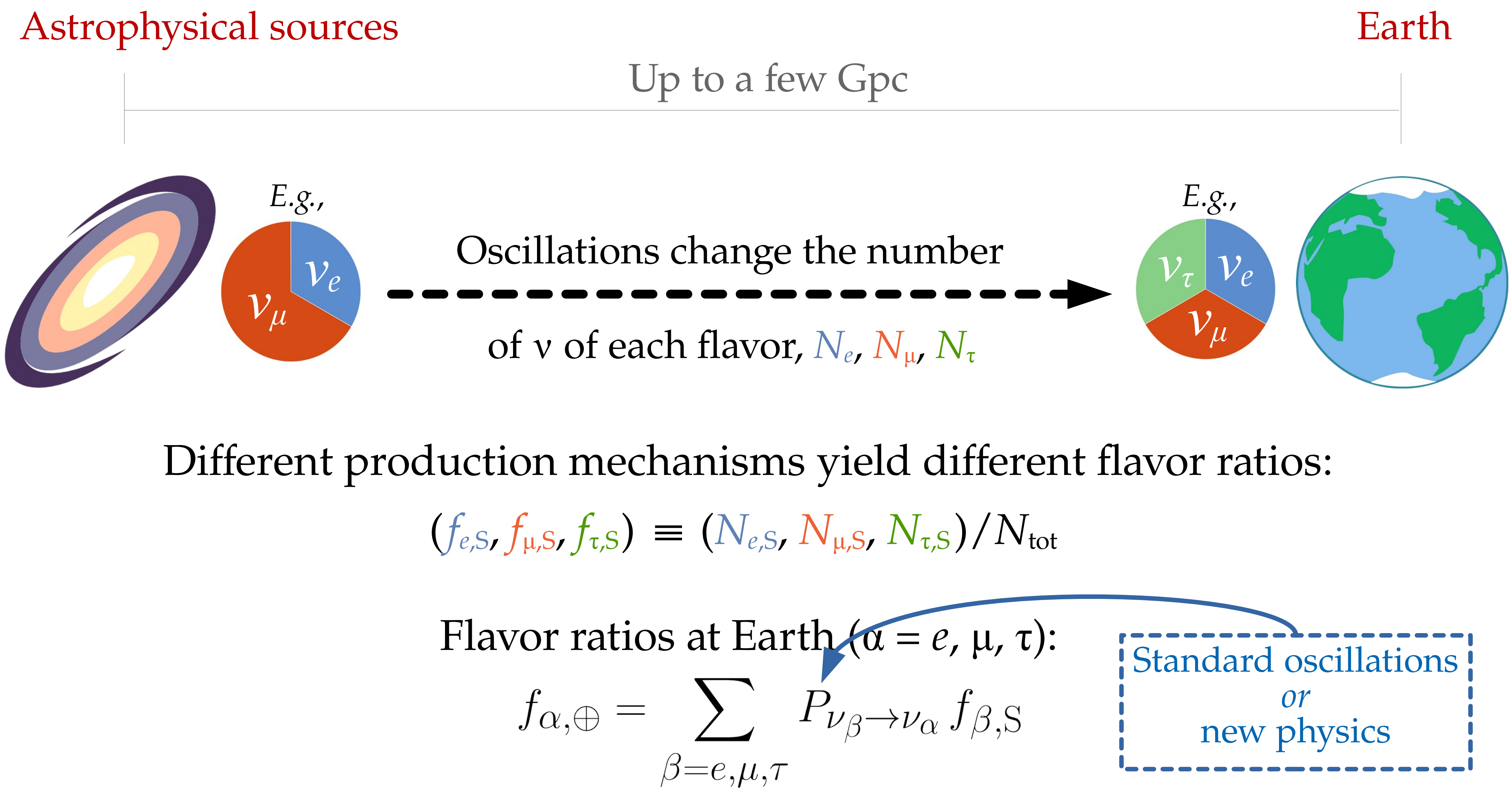


Different production mechanisms yield different flavor ratios:

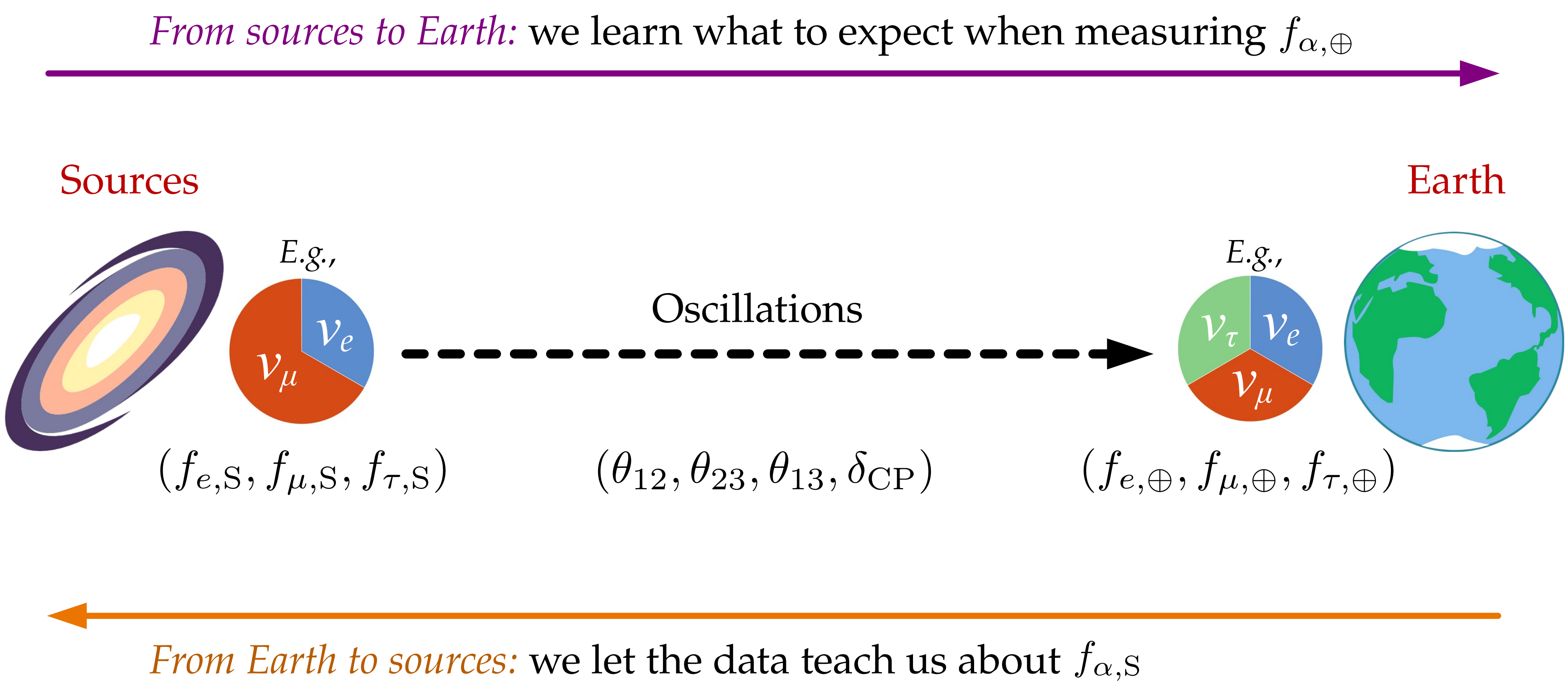
$$(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}}) \equiv (N_{e,\mathrm{S}}, N_{\mu,\mathrm{S}}, N_{\tau,\mathrm{S}})/N_{\mathrm{tot}}$$

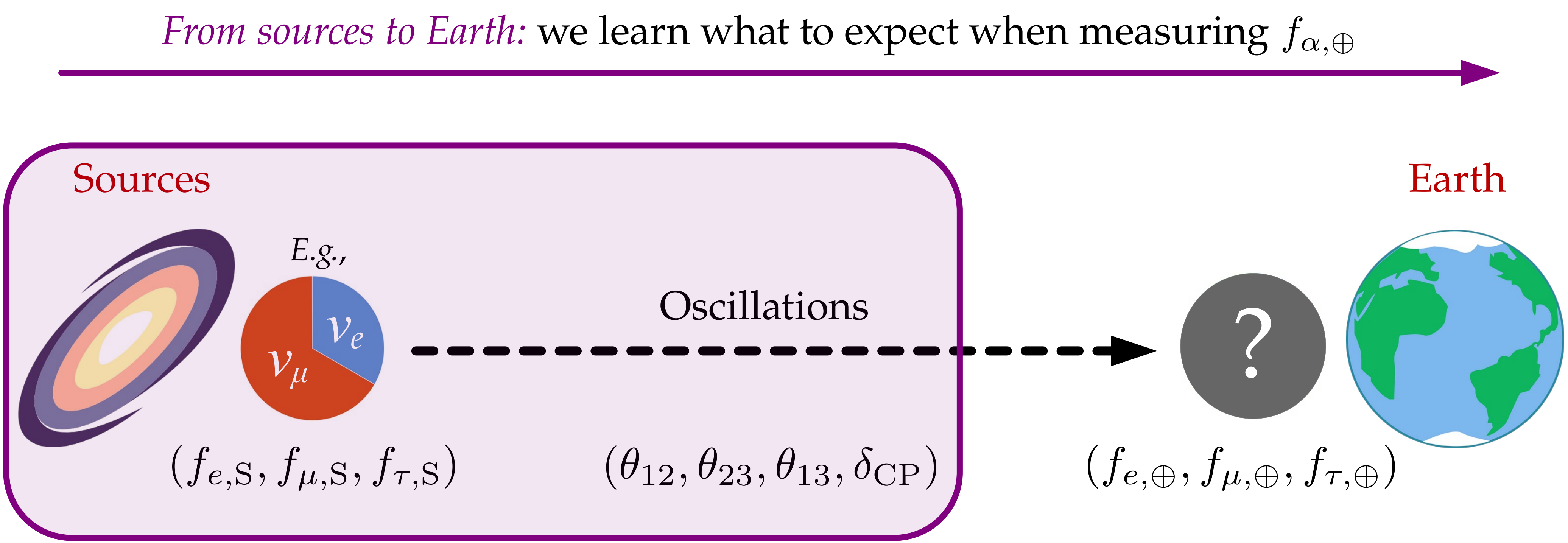
Flavor ratios at Earth ($\alpha = e, \mu, \tau$):

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



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

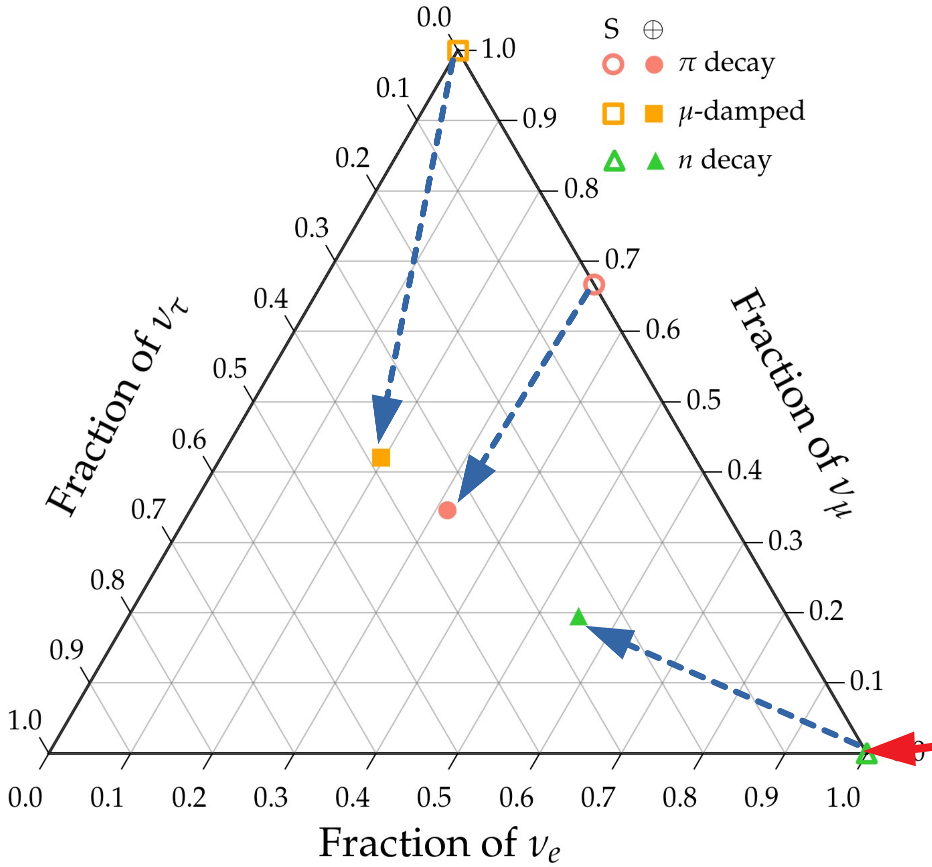

From sources to Earth: we learn what to expect when measuring $f_{\alpha,\oplus}$
Sources
Earth
E.g.,
ν_e
ν_μ
Oscillations
E.g.,
ν_τ
ν_e
ν_μ
$(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}})$
$(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\mathrm{CP}})$
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$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



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

One likely TeV–PeV ν production scenario:

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

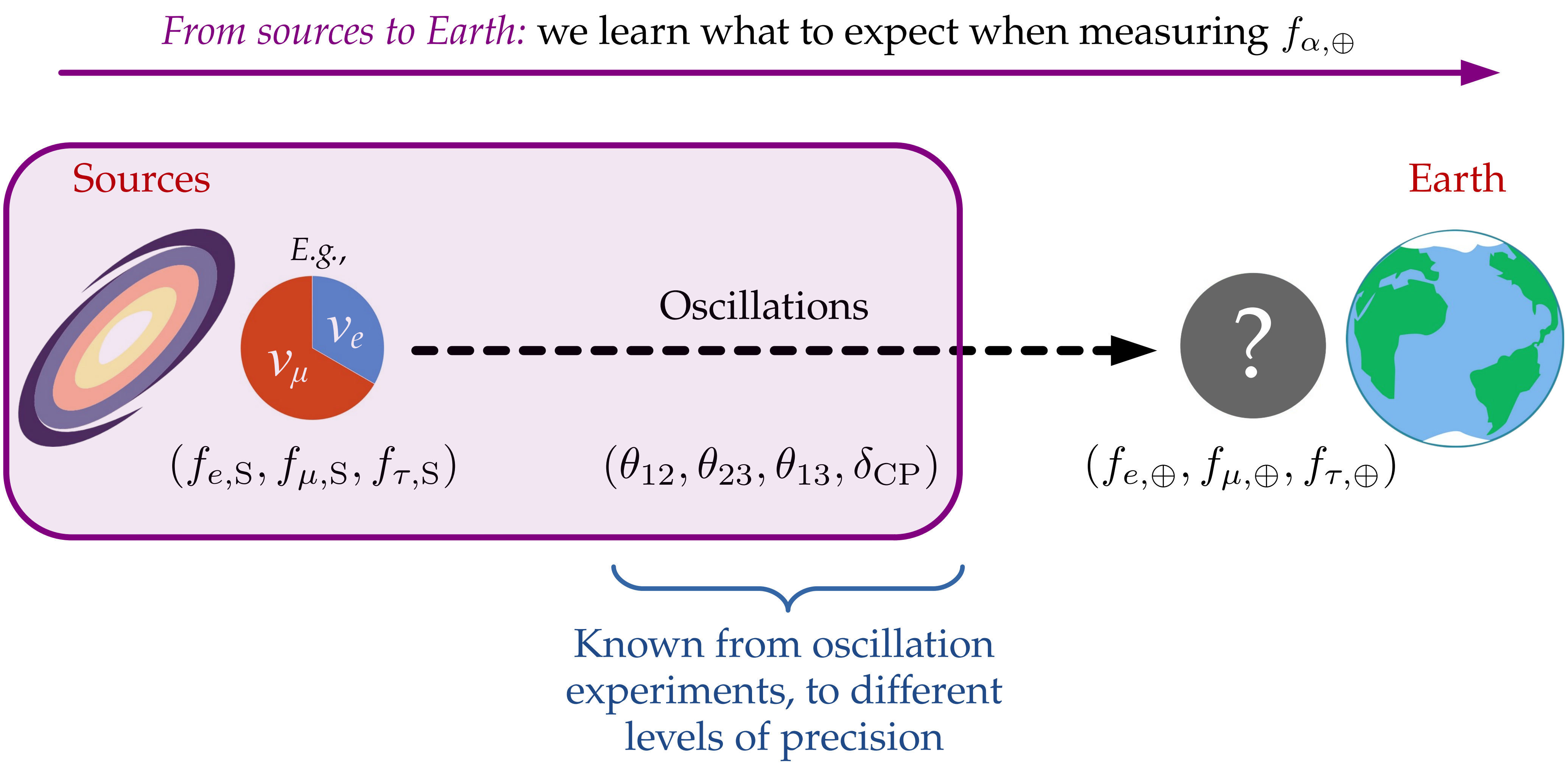


Full π decay chain
(1/3:2/3:0)$_S$

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

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

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



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

Flavor at the Earth: *theoretically palatable regions*

Theoretically palatable flavor regions

$\equiv$

MB, Beacom, Winter, *PRL* 2015

Allowed regions of flavor ratios at Earth derived from oscillations

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

Flavor at the Earth: *theoretically palatable regions*

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Allowed regions of flavor ratios at Earth derived from oscillations

Ingredient #1:

Flavor ratios at the source,

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

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

or

Explore all possible combinations

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

Flavor at the Earth: *theoretically palatable regions*

Theoretically palatable flavor regions

≡

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

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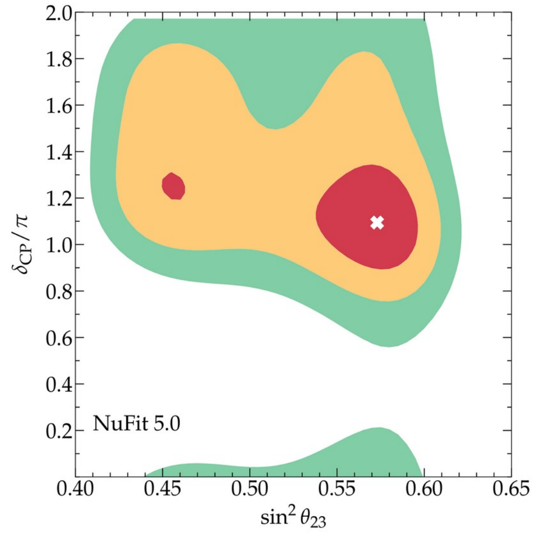
2020: Use χ^2 profiles from the NuFit 5.0 global fit (solar + atmospheric + reactor + accelerator)

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



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Esteban *et al.*, *JHEP* 2020
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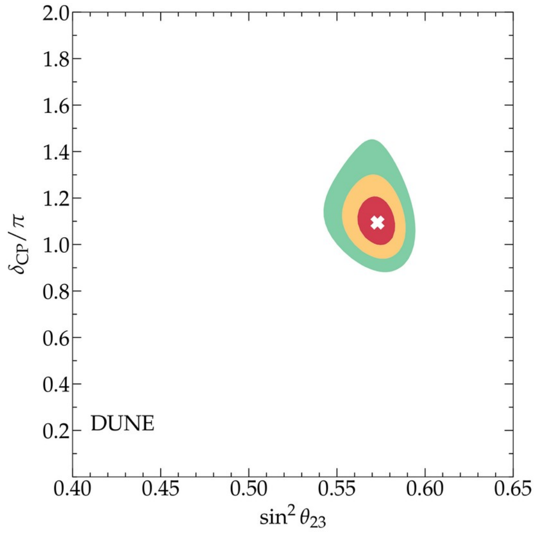
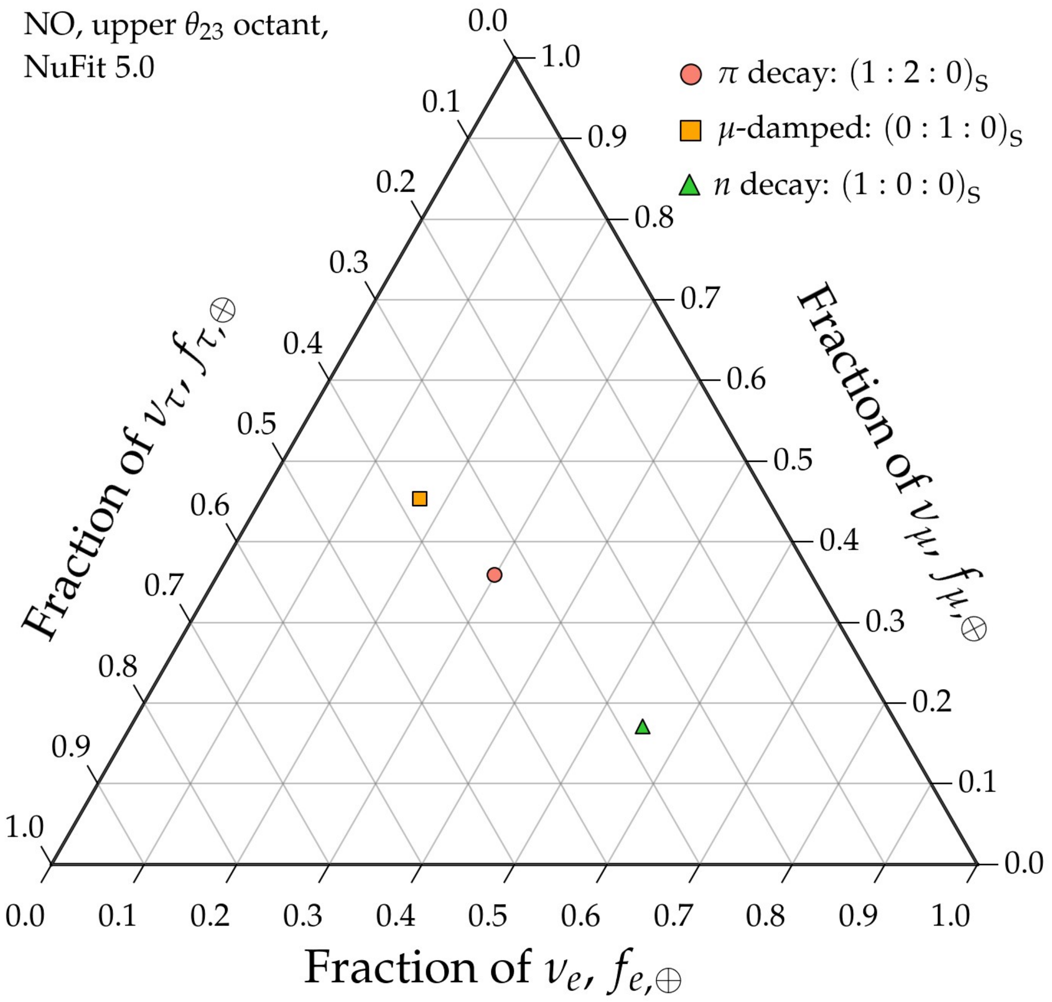
Post-2020: Build our own profiles using simulations of JUNO, DUNE, Hyper-K

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



Theoretically palatable regions: today (2021)



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

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

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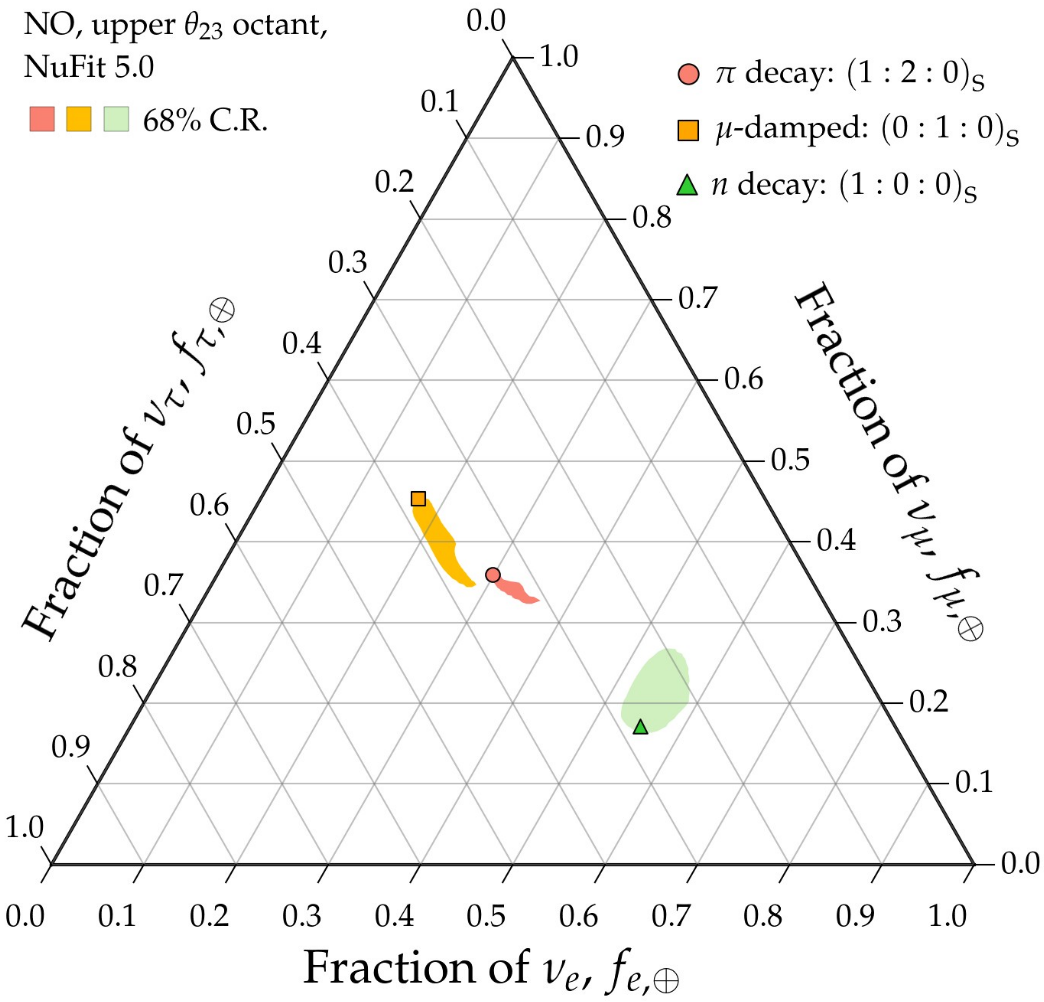

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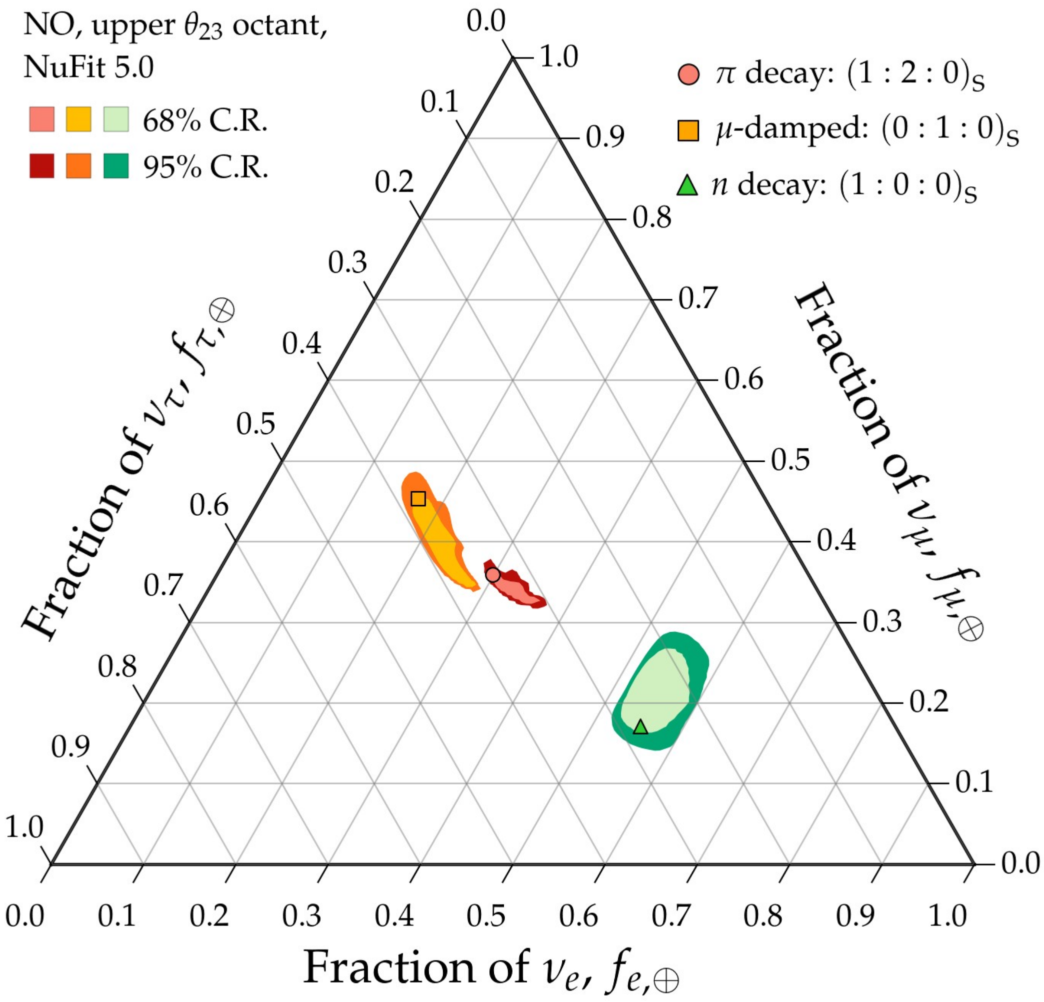

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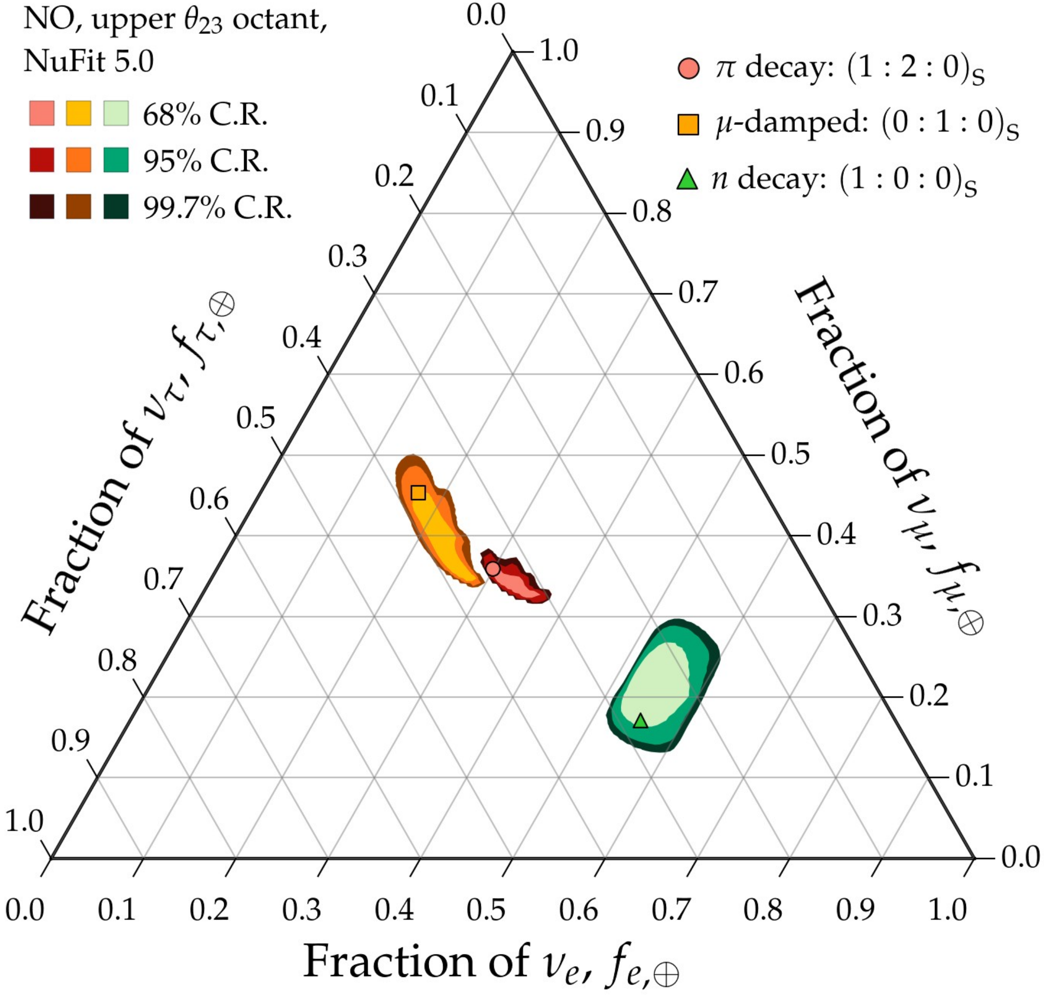

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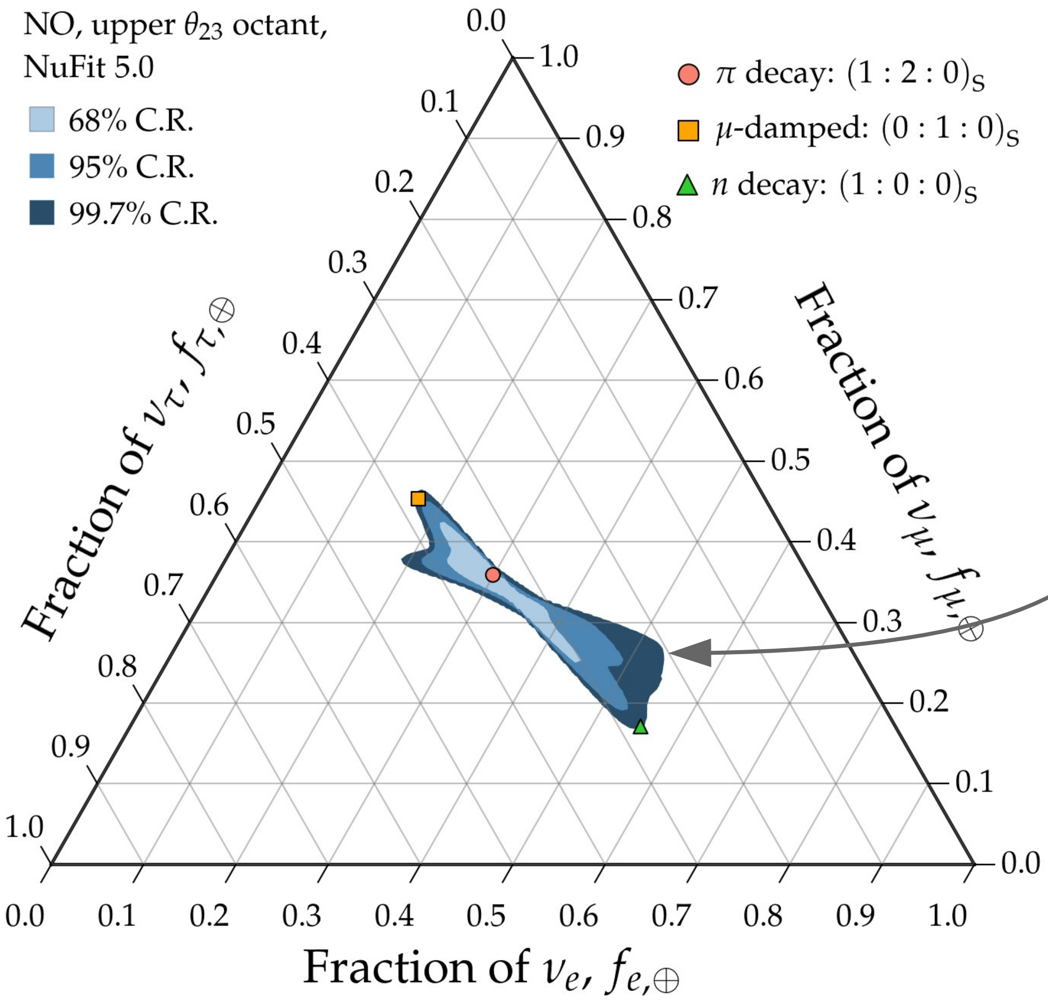

Varying over all possible flavor ratios at the source

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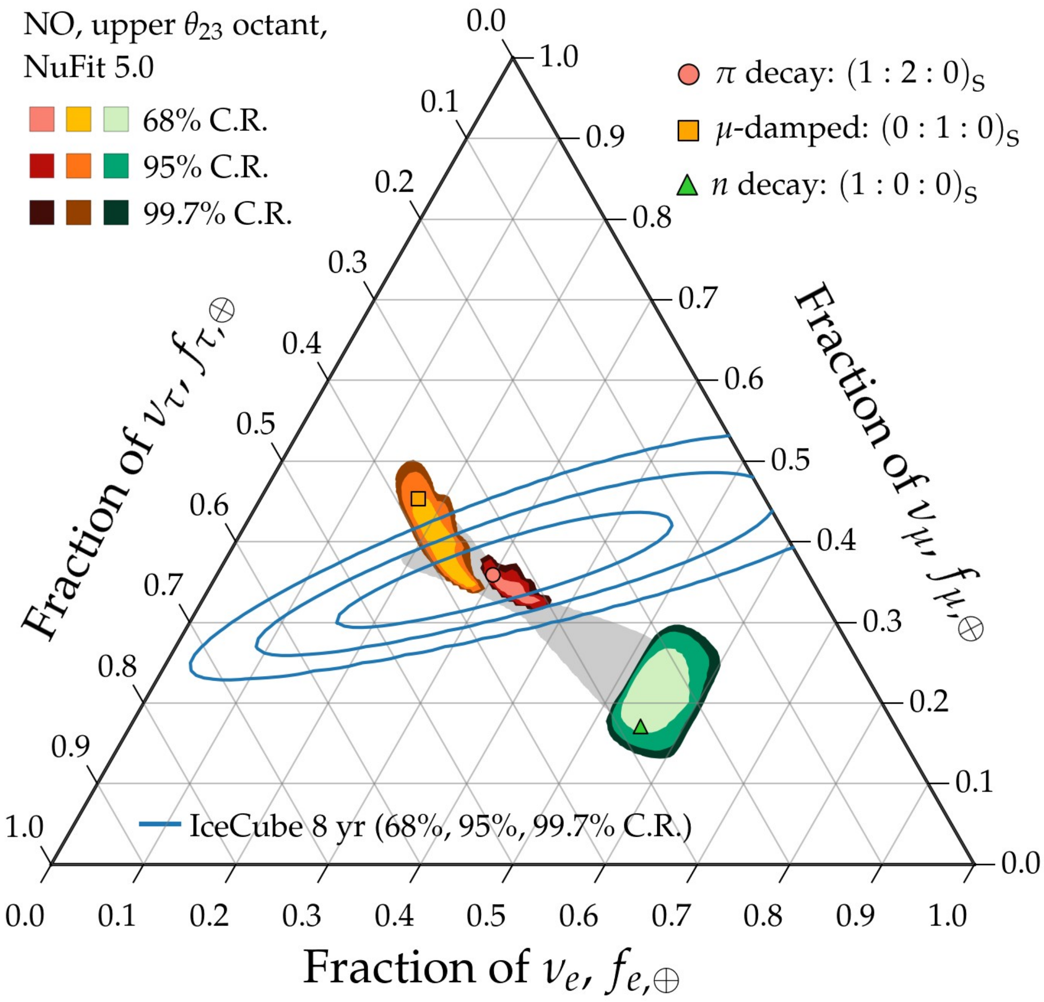
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Theoretically palatable regions: today (2021)



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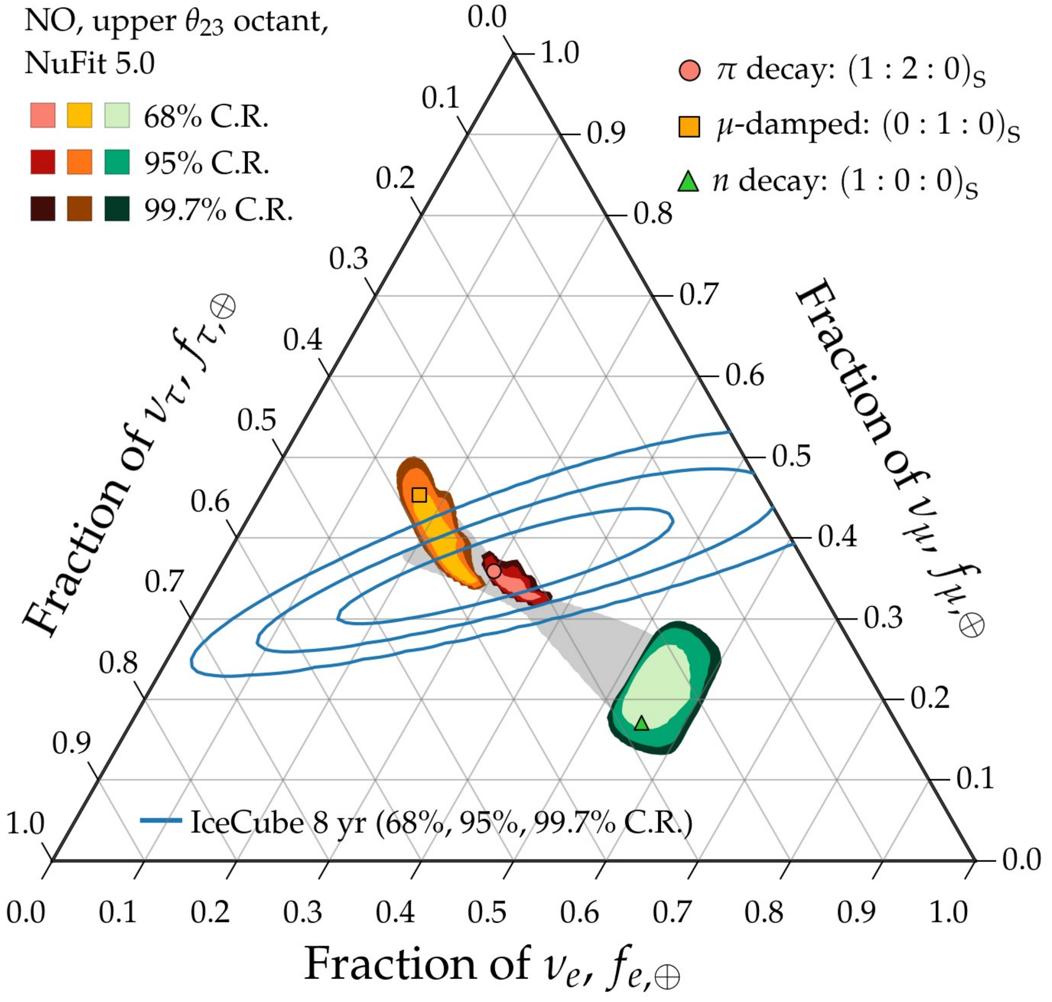
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Theoretically palatable regions: today (2021)



Two limitations:

Allowed flavor regions overlap –
Insufficient precision in the mixing parameters

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

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

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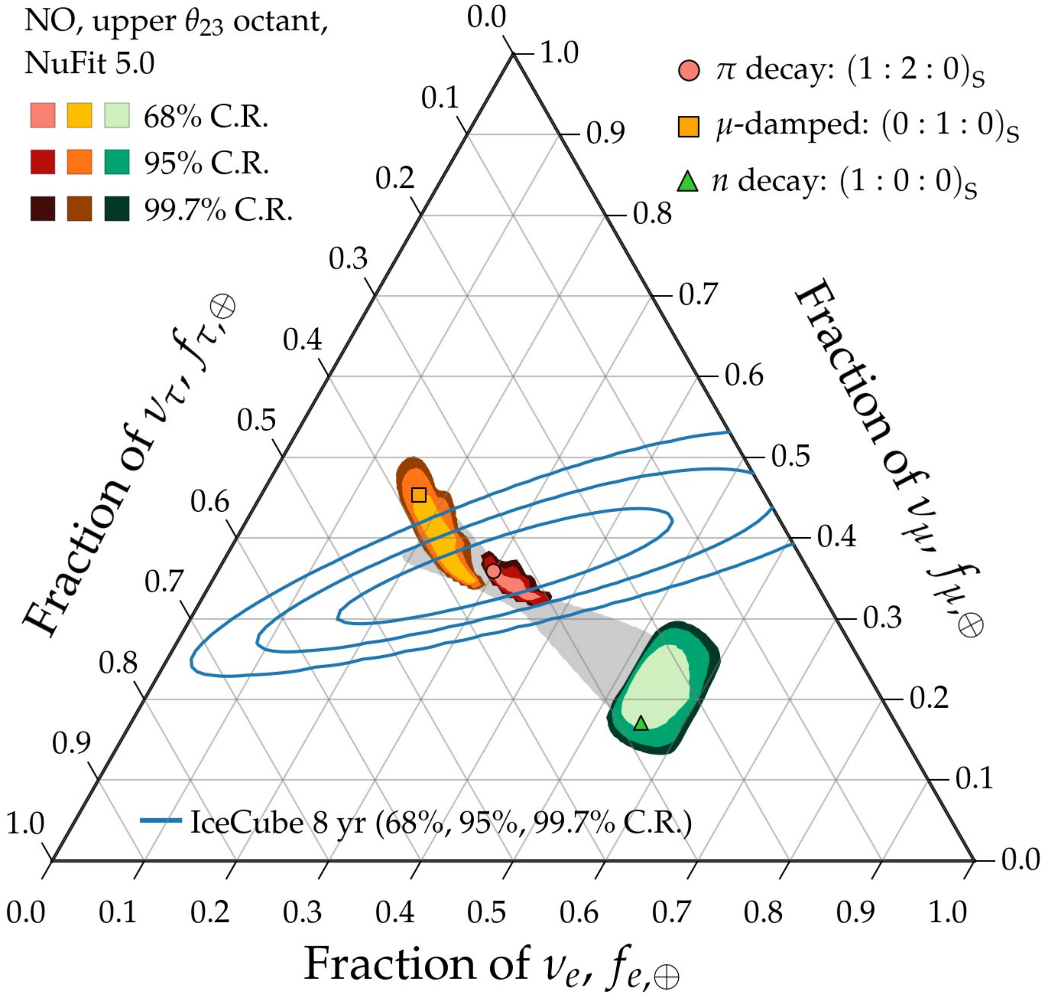

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Will be overcome by 2030

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

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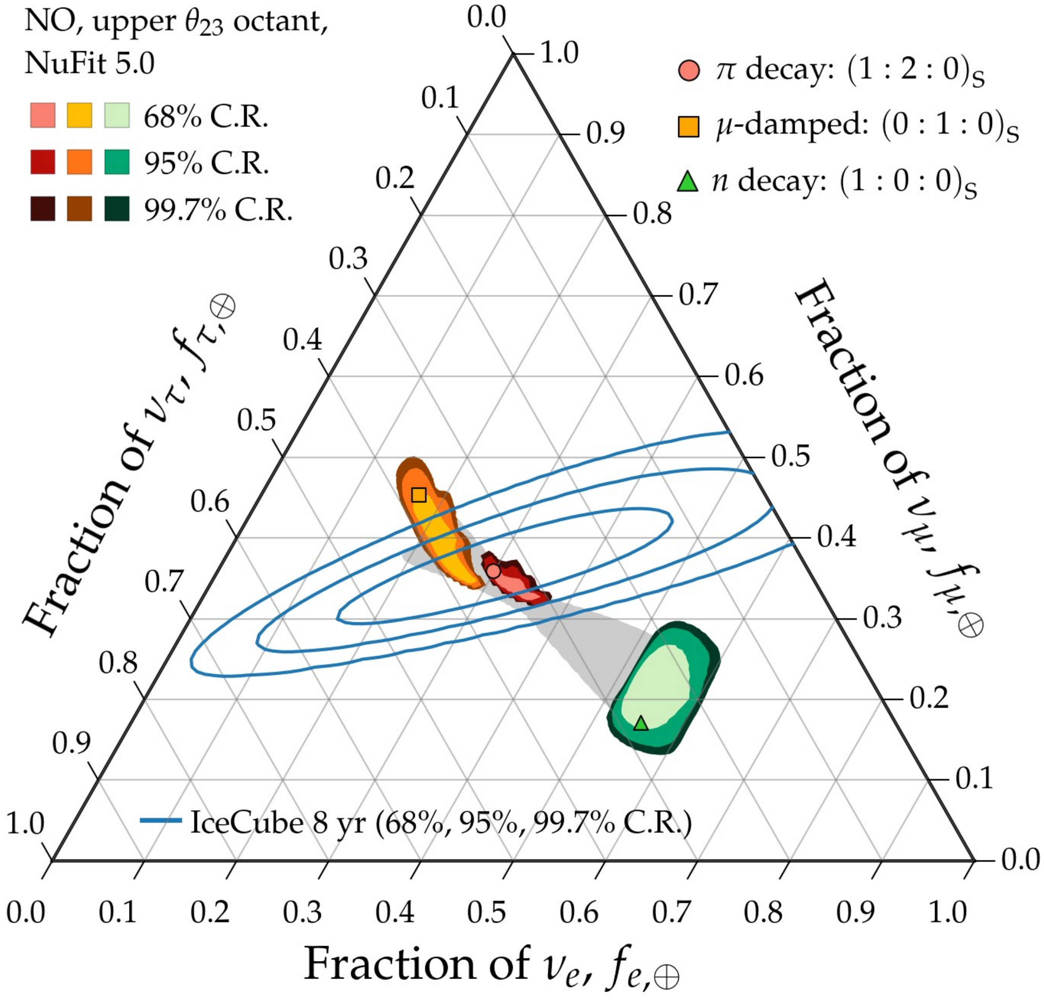

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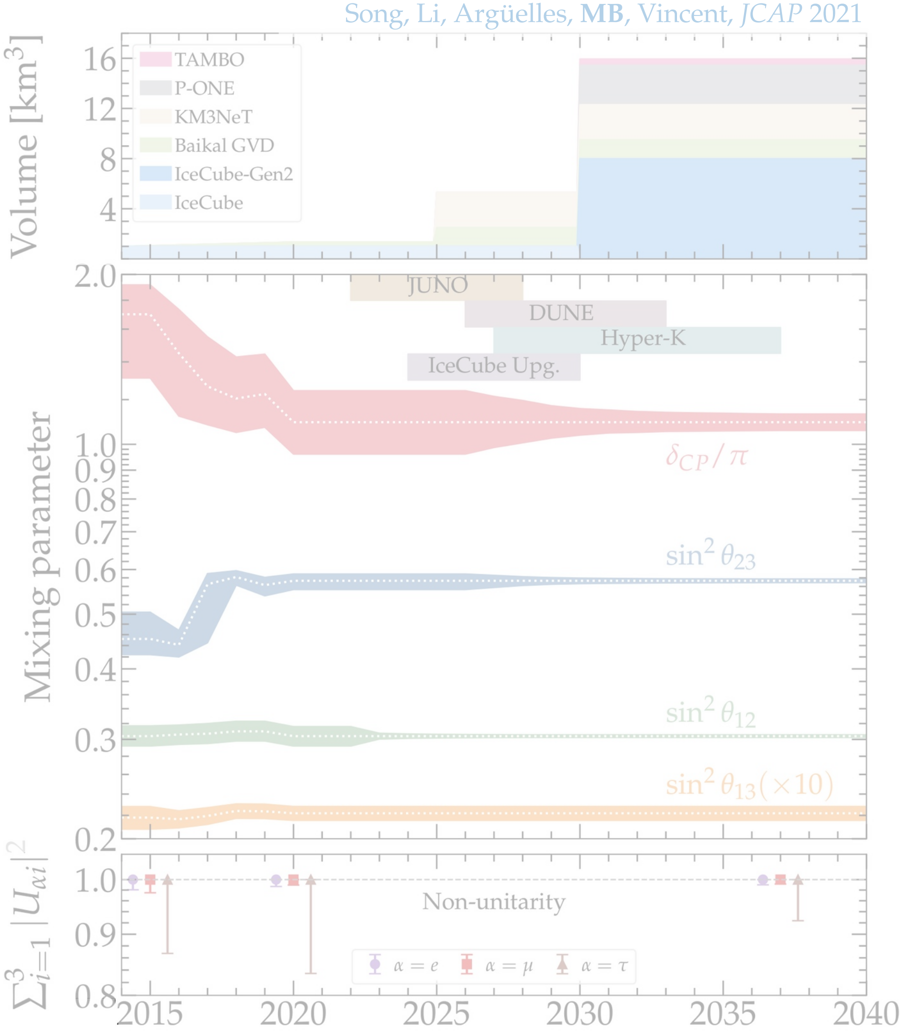
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Three reasons to be excited



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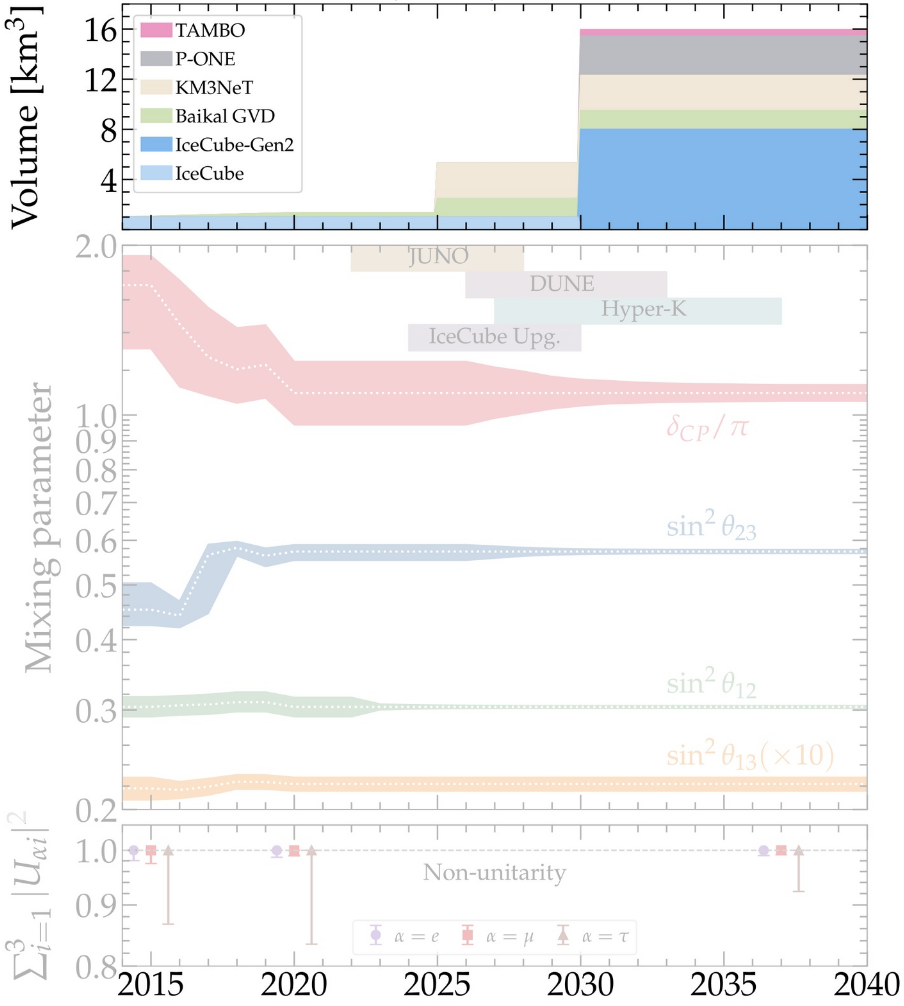
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



Flavor measurements:

New neutrino telescopes = more events, better flavor measurement

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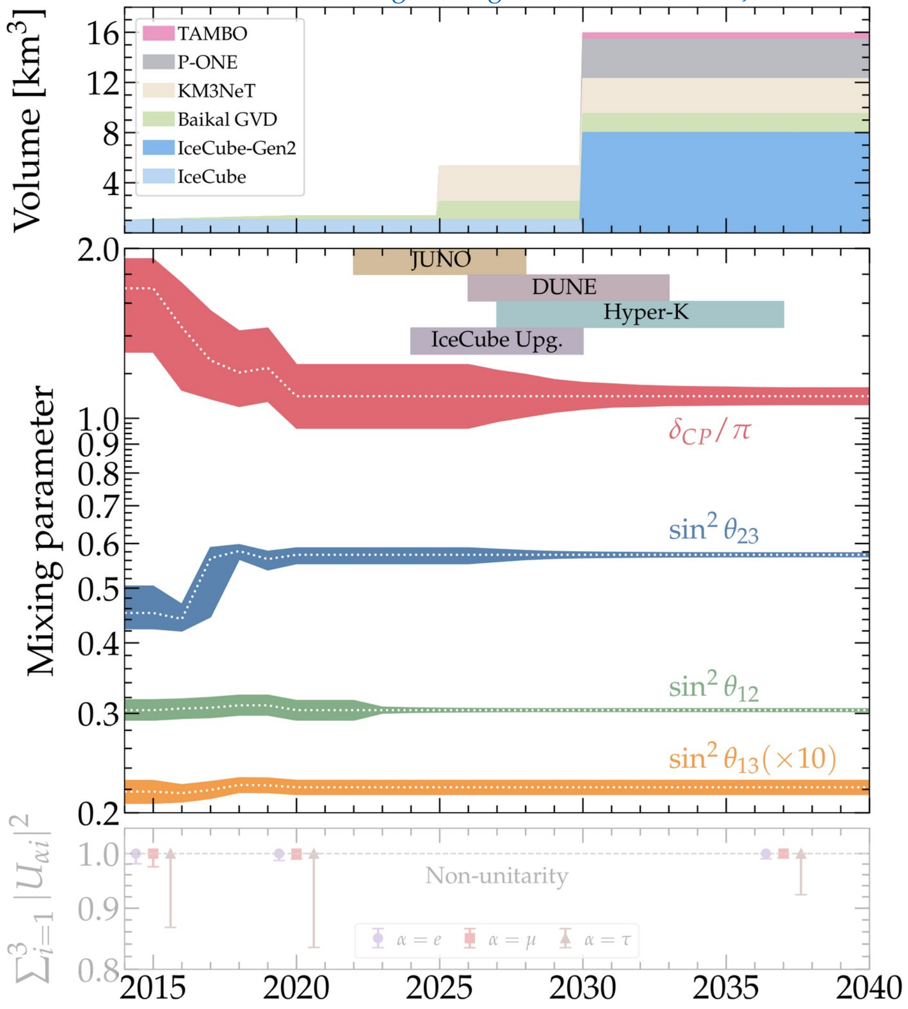
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



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We will know the mixing parameters better (JUNO, DUNE, Hyper-K, IceCube Upgrade)

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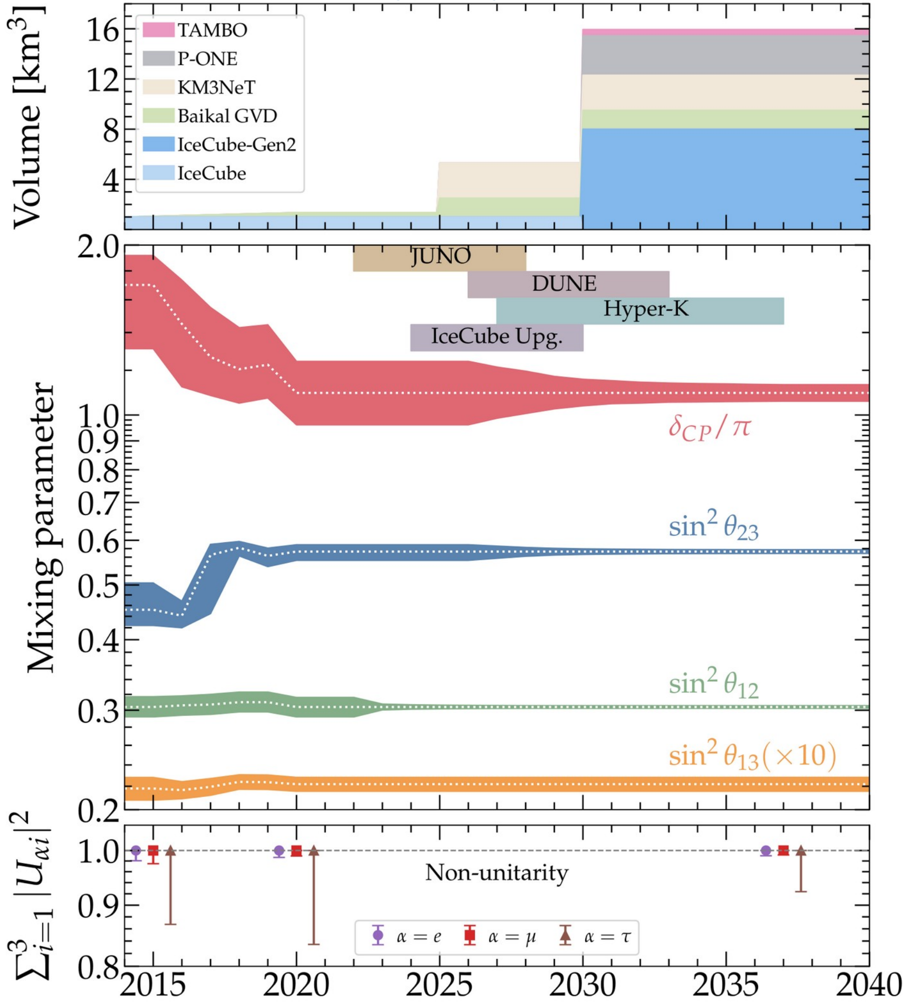

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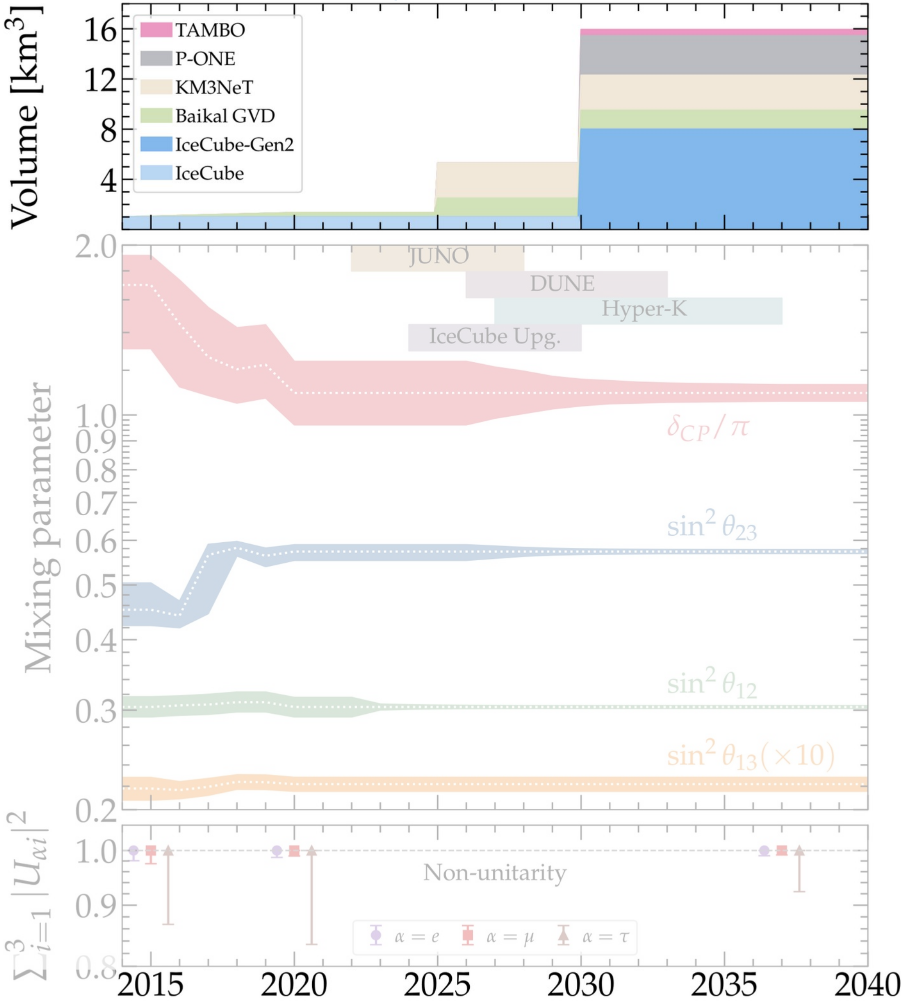
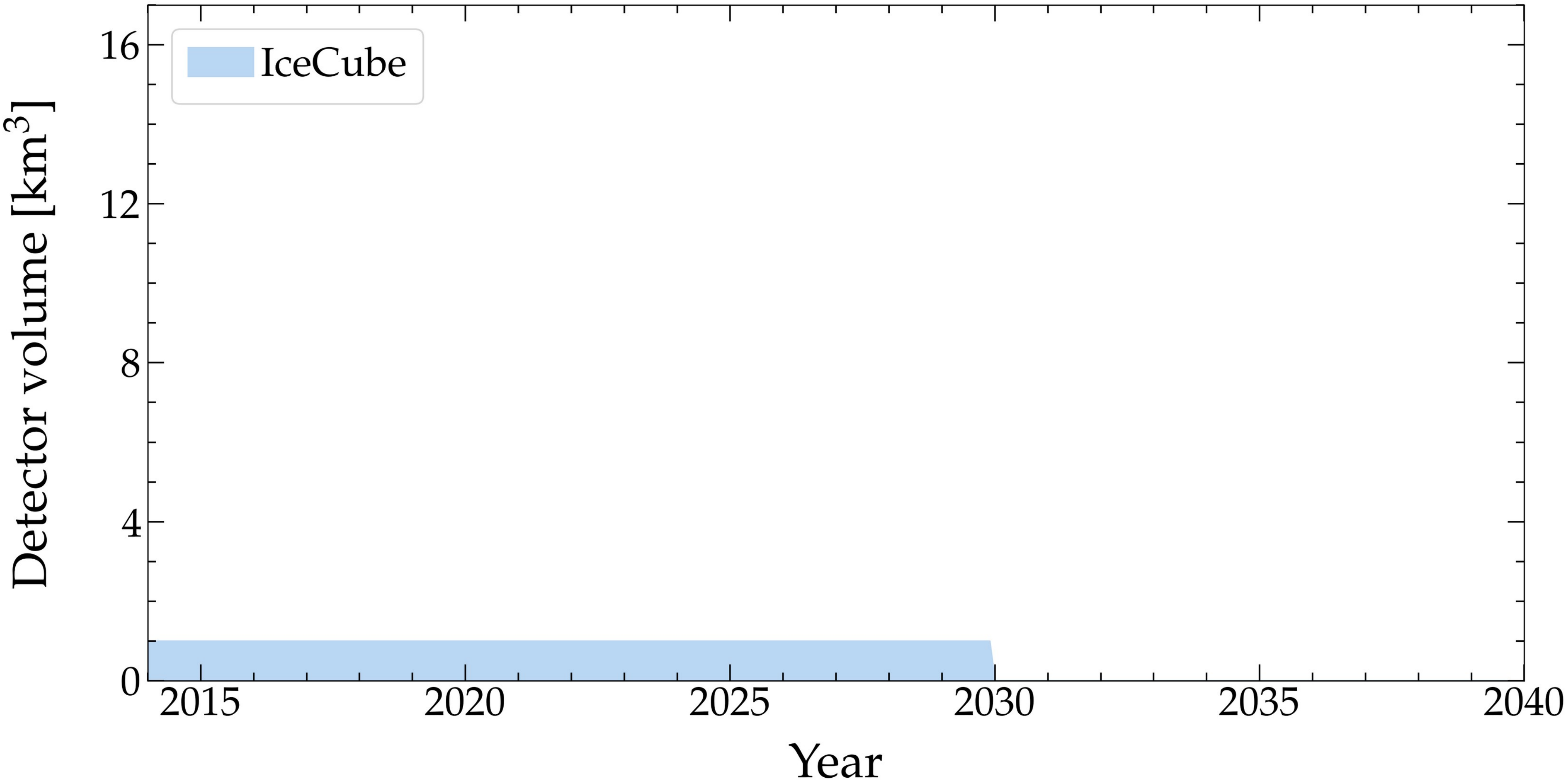
Oscillation physics:
We will know the mixing parameters better (JUNO, DUNE, Hyper-K, IceCube Upgrade)

Test of the oscillation framework:
We will be able to do what we want even if oscillations are non-unitary

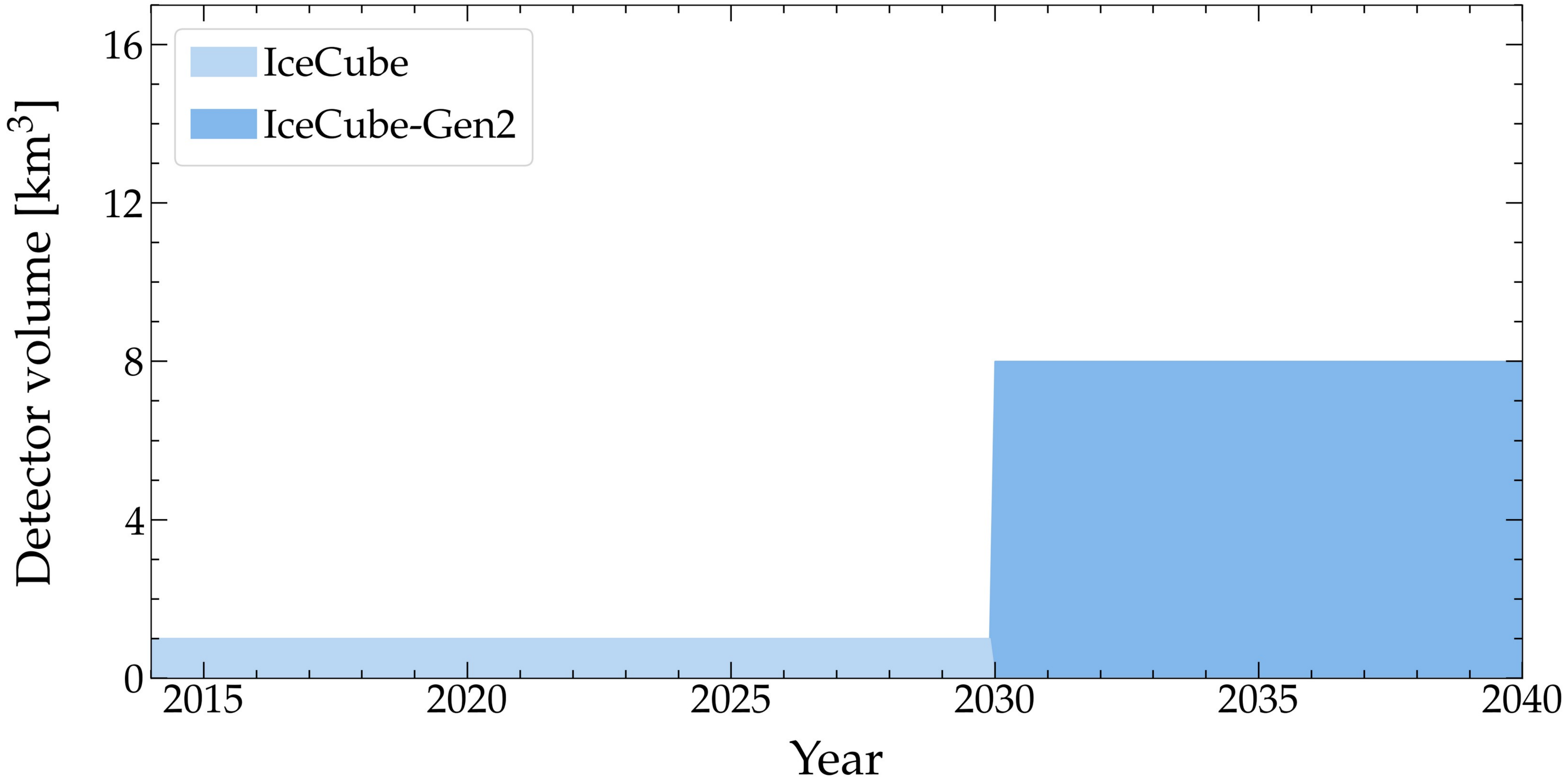
Measuring flavor composition: 2015–2040

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

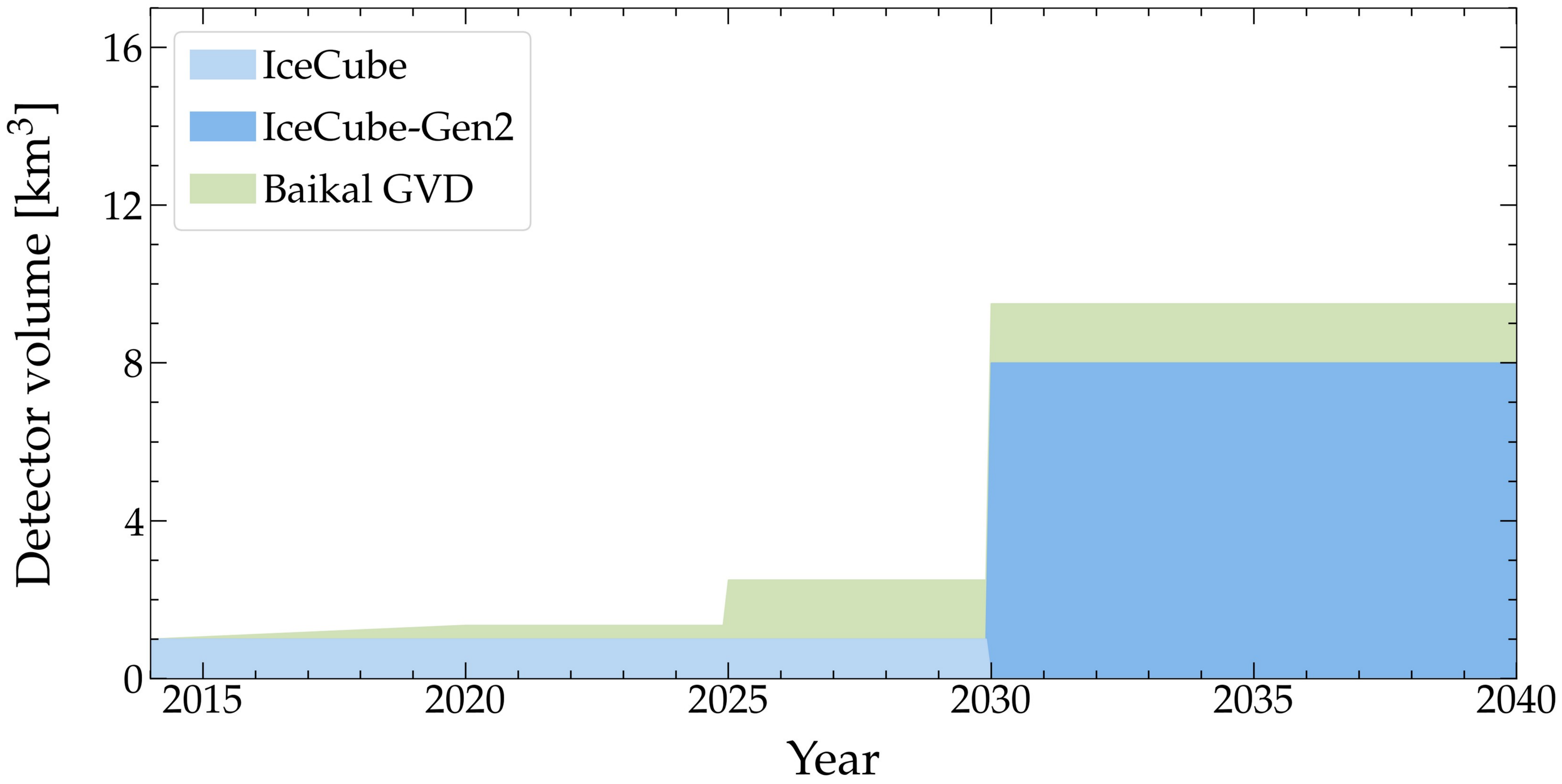




Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



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



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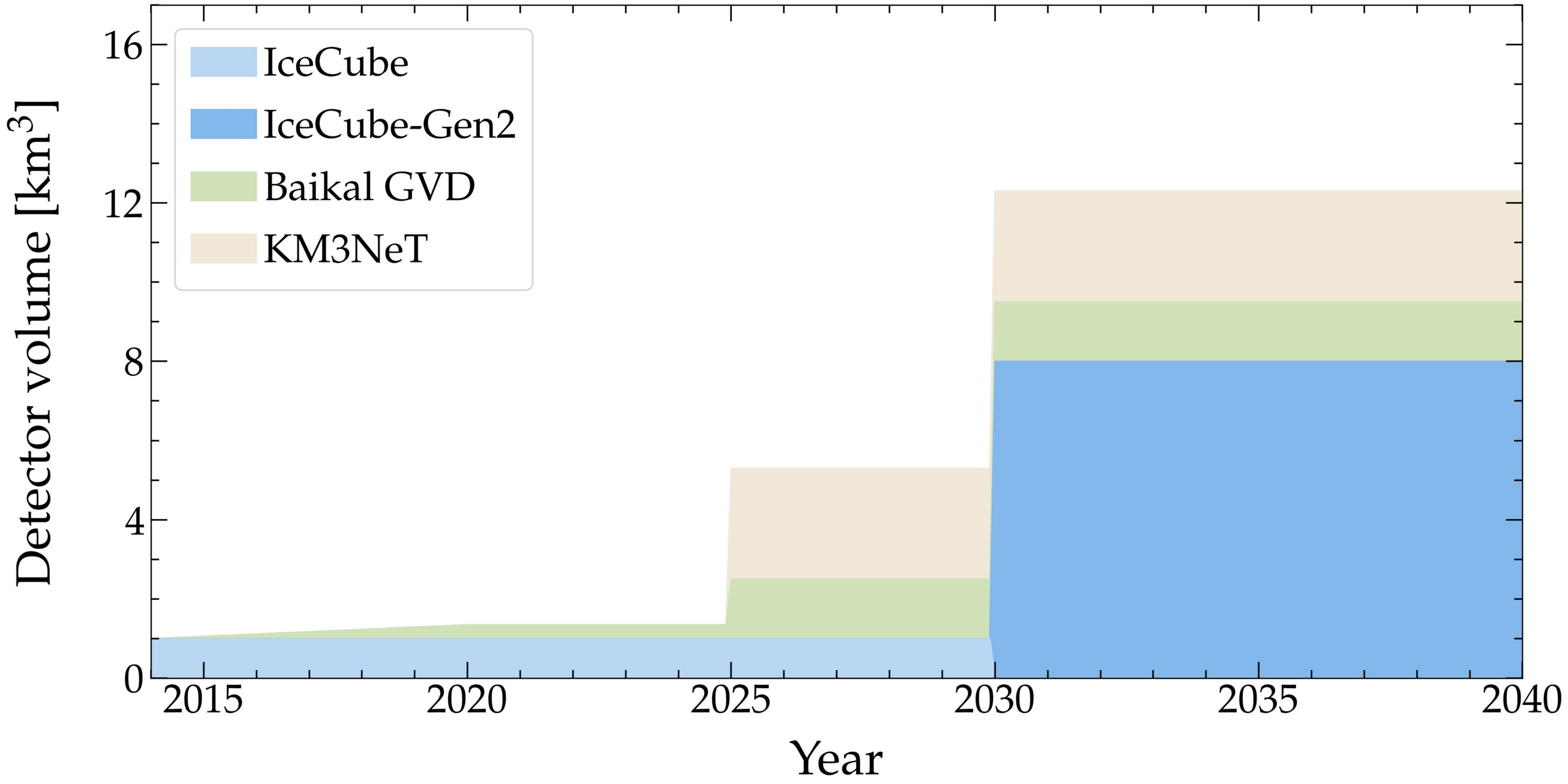

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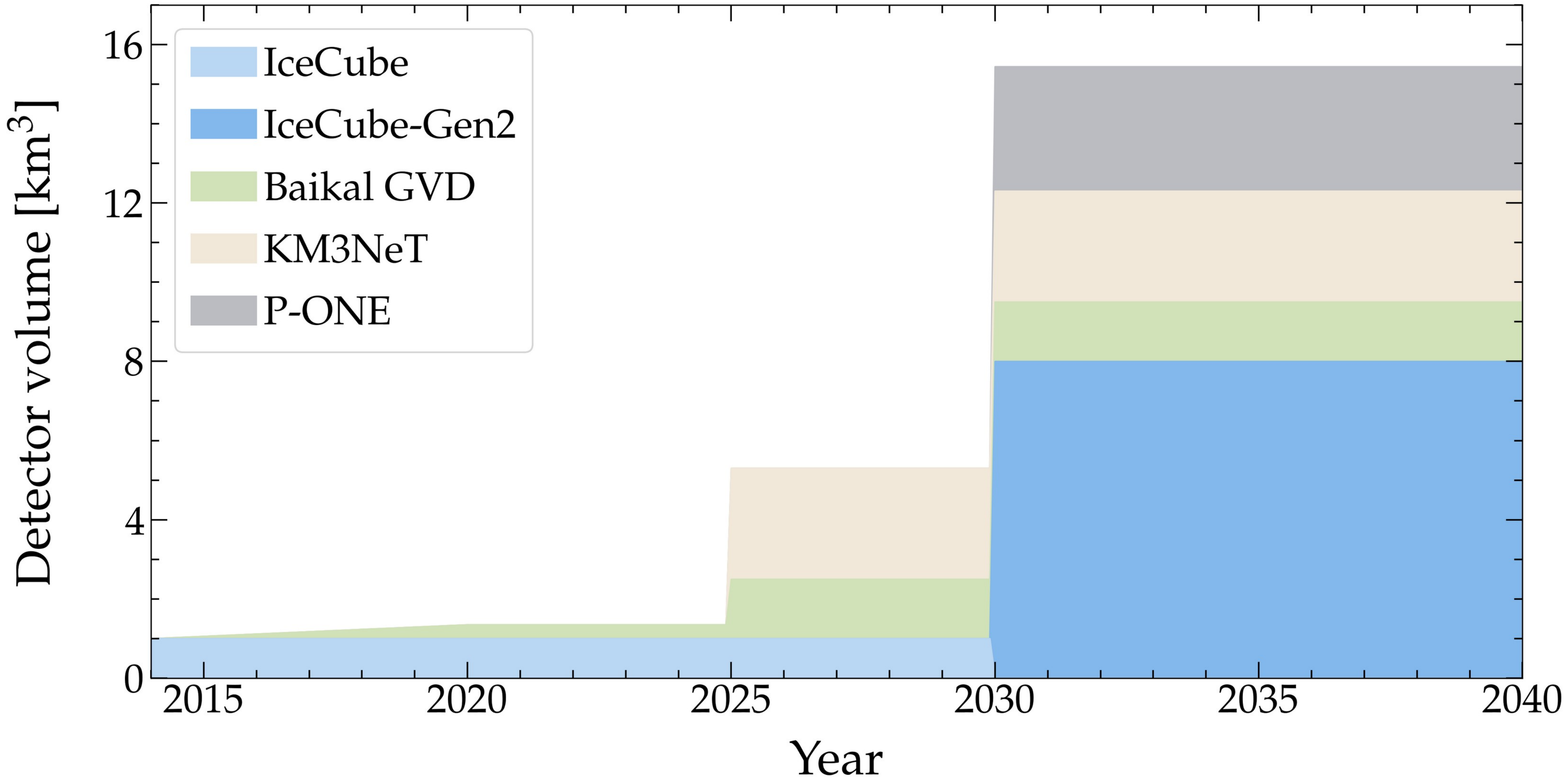
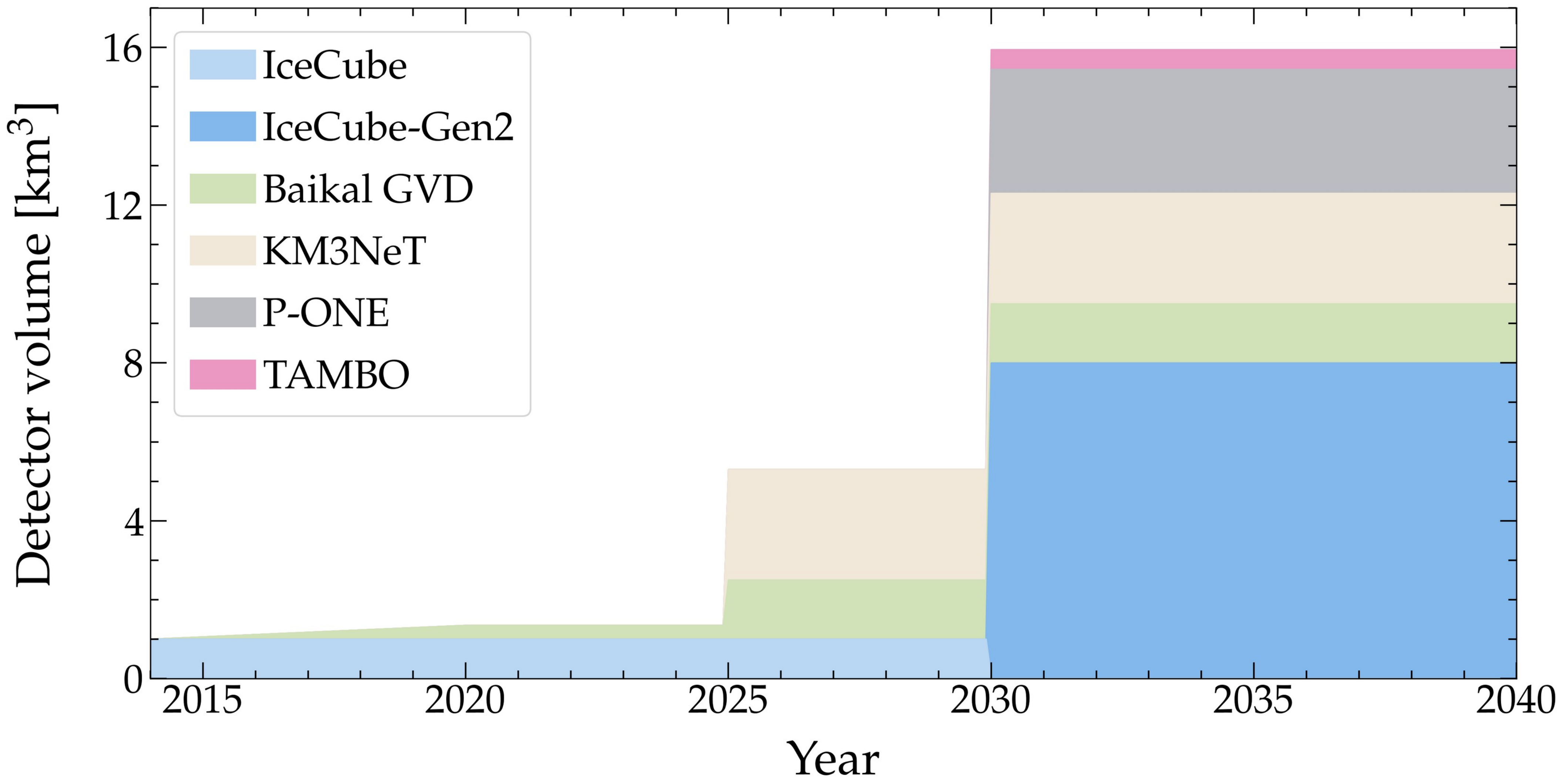


IceCube
IceCube-Gen2
Baikal GVD
KM3NeT
P-ONE
Detector volume [km^3]
0
4
8
12
16
2015
2020
2025
2030
2035
2040
Year



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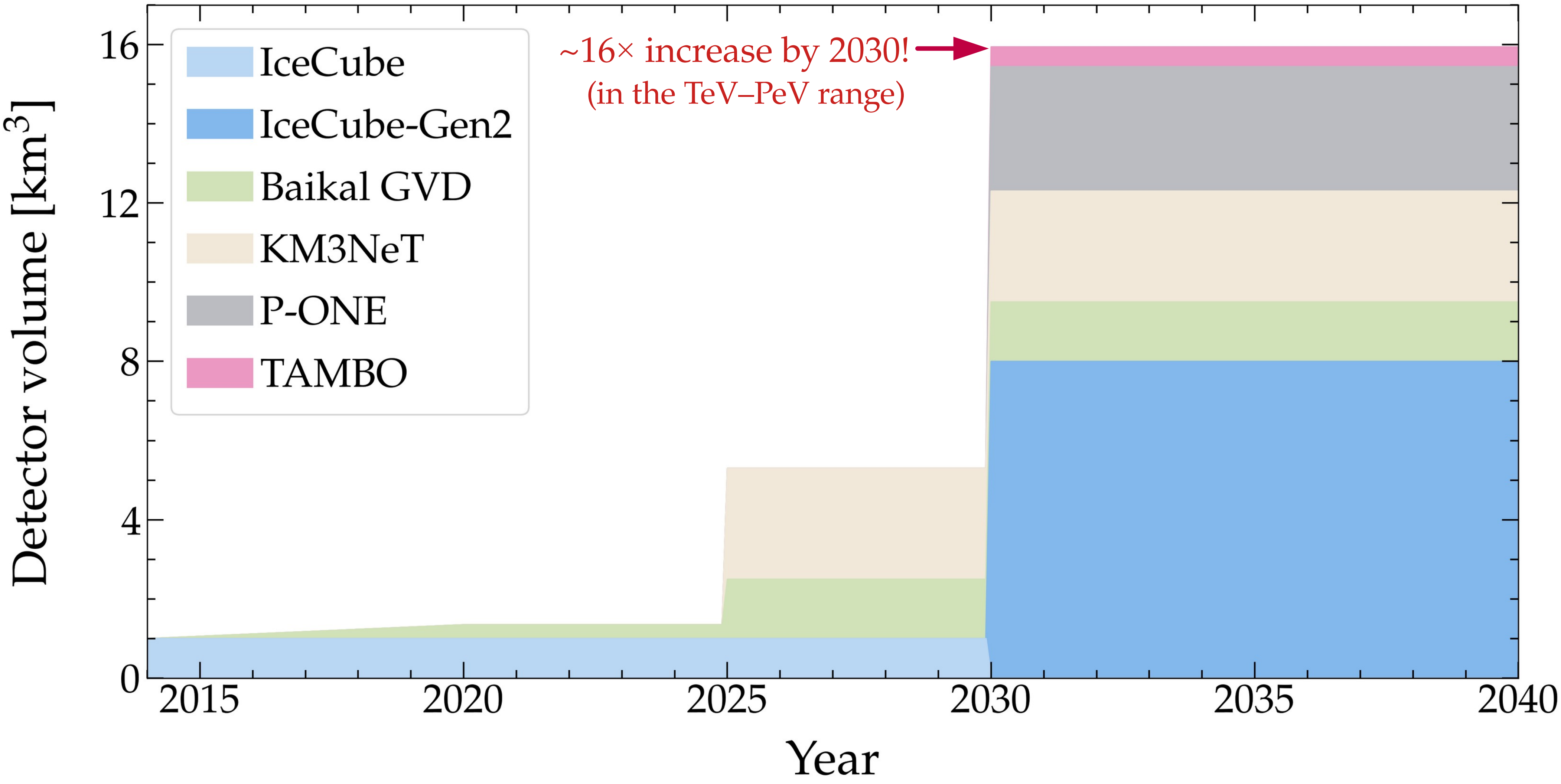
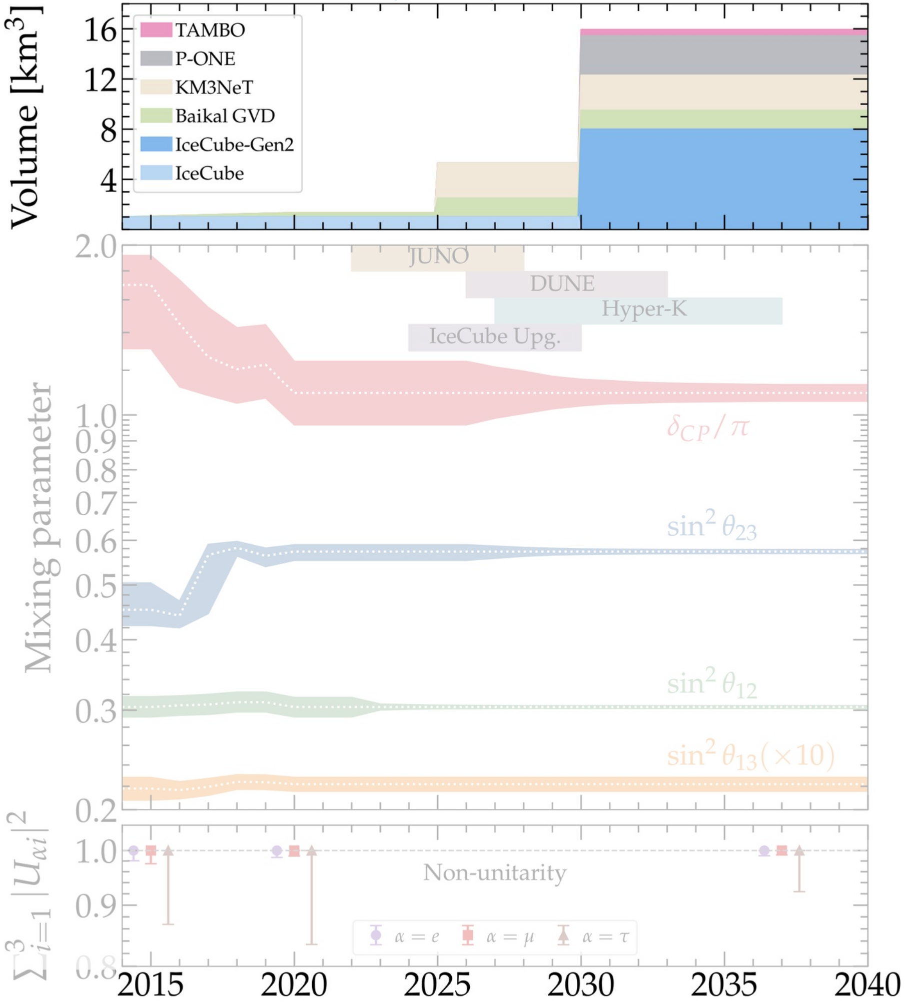


Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Measuring flavor composition: 2015–2040

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



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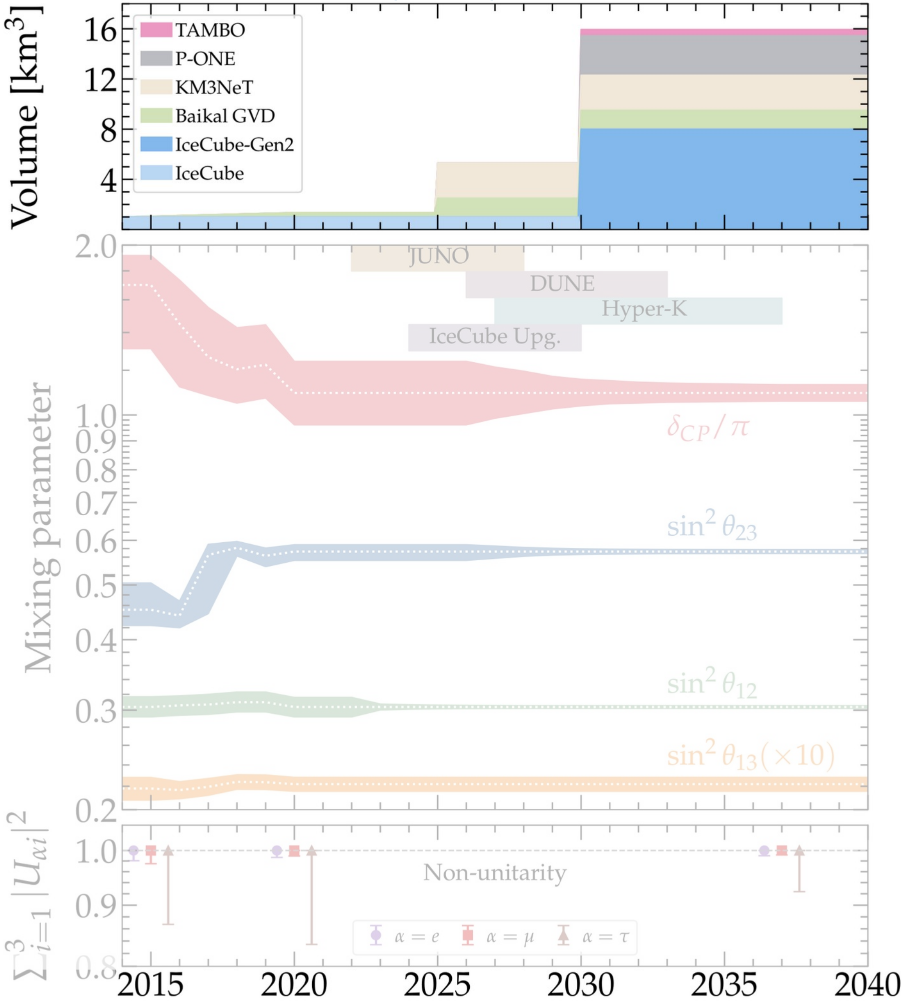

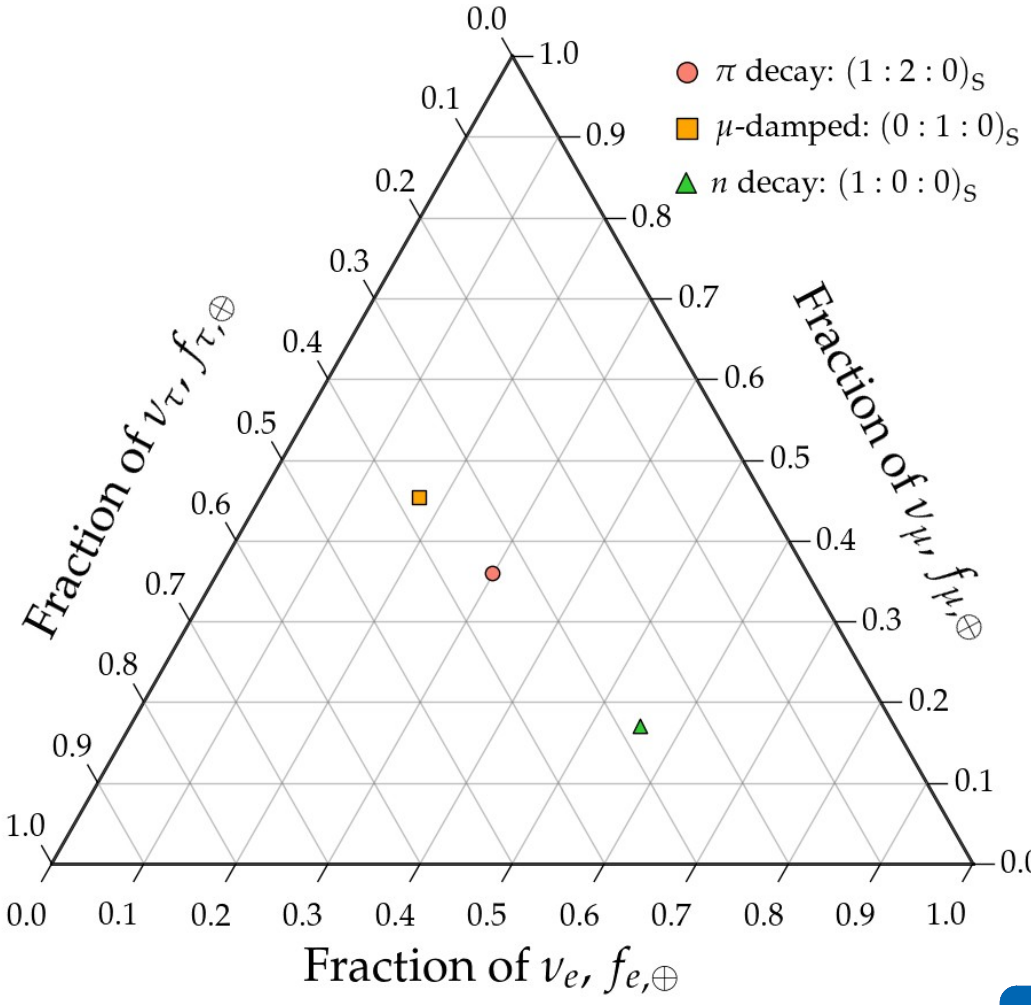

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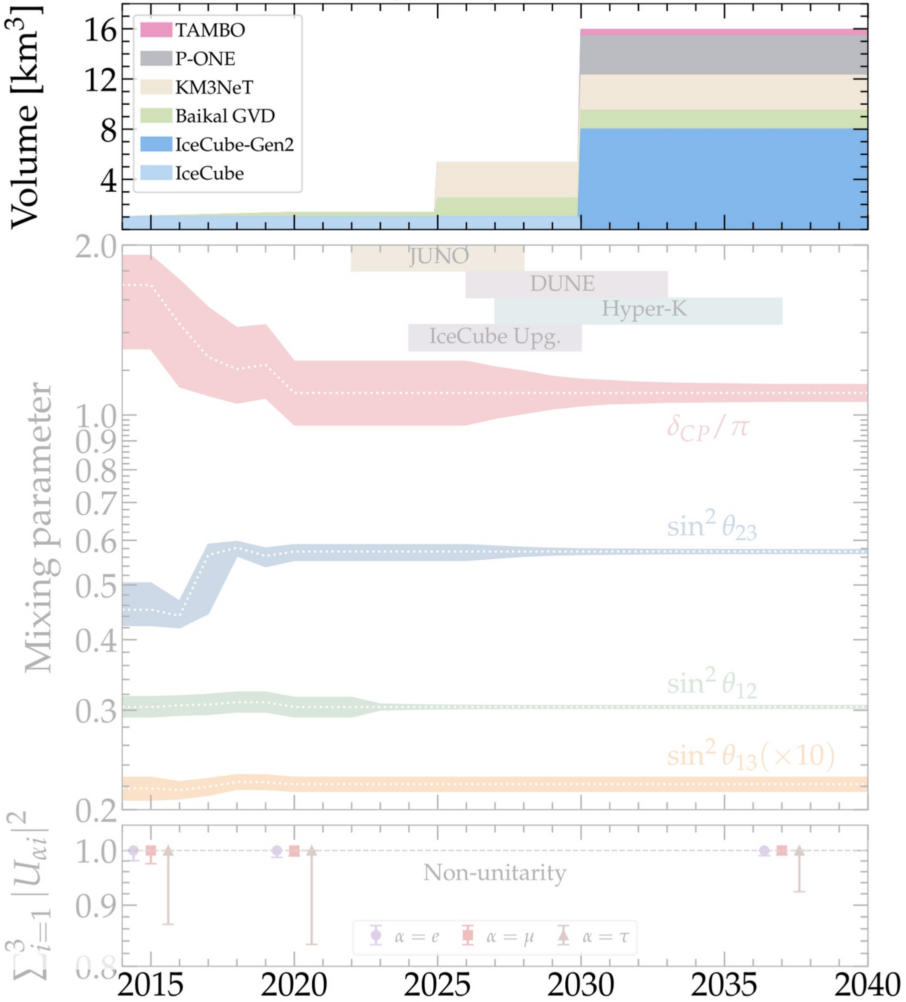

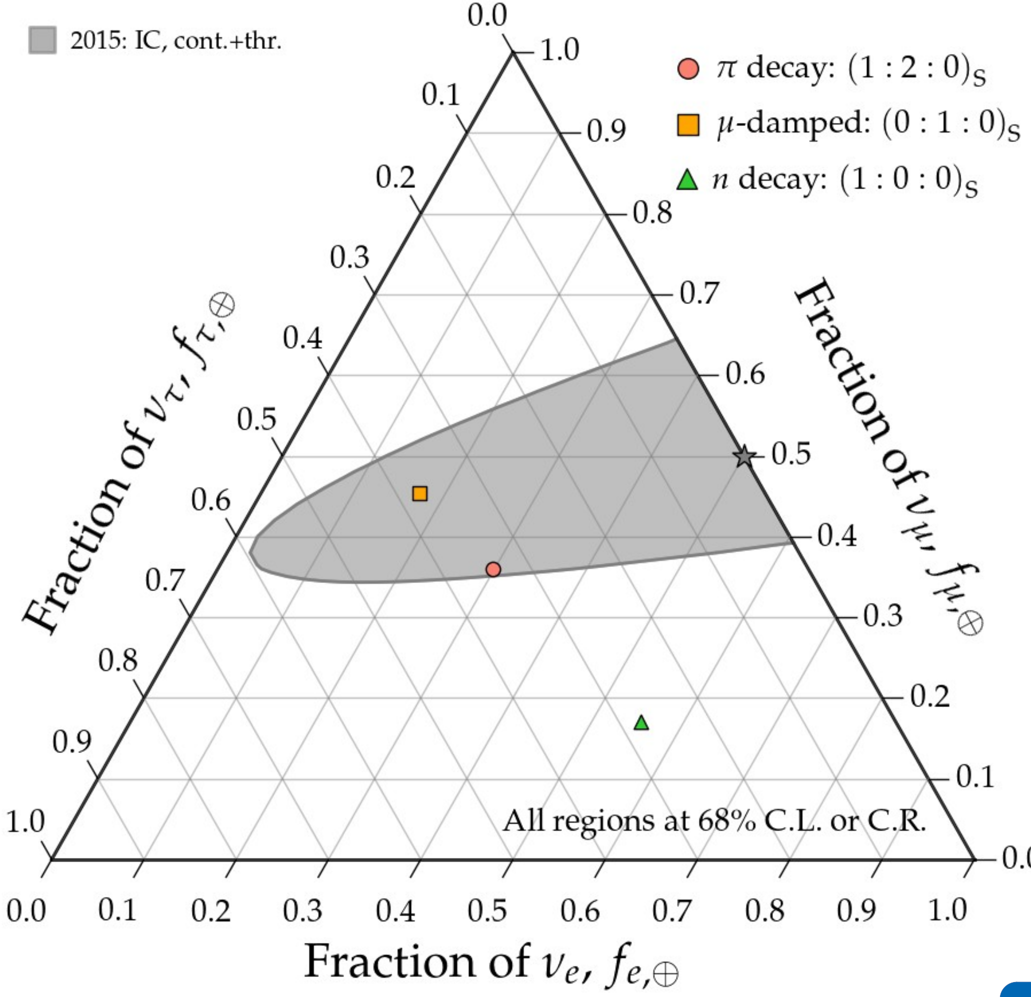

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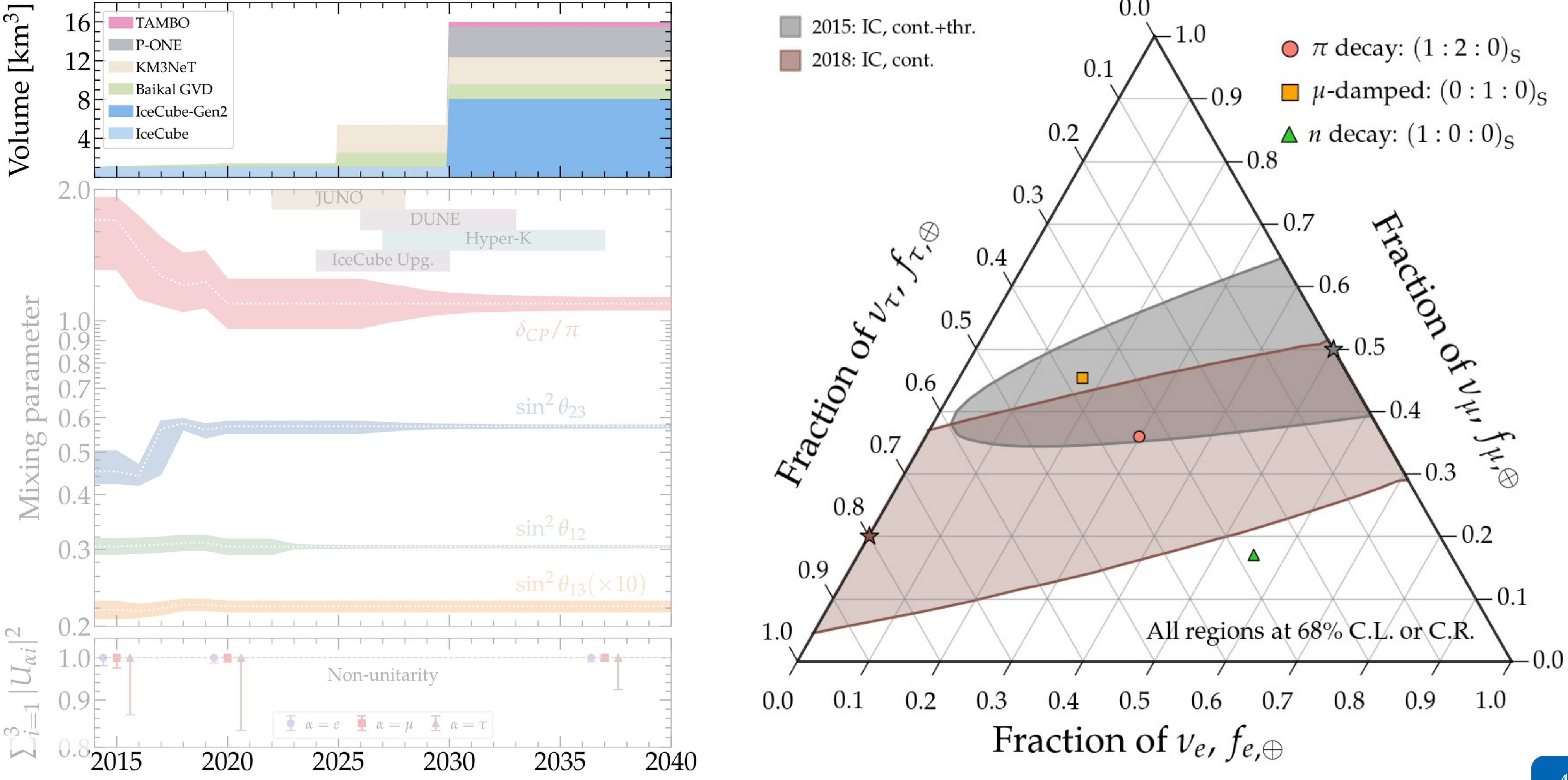

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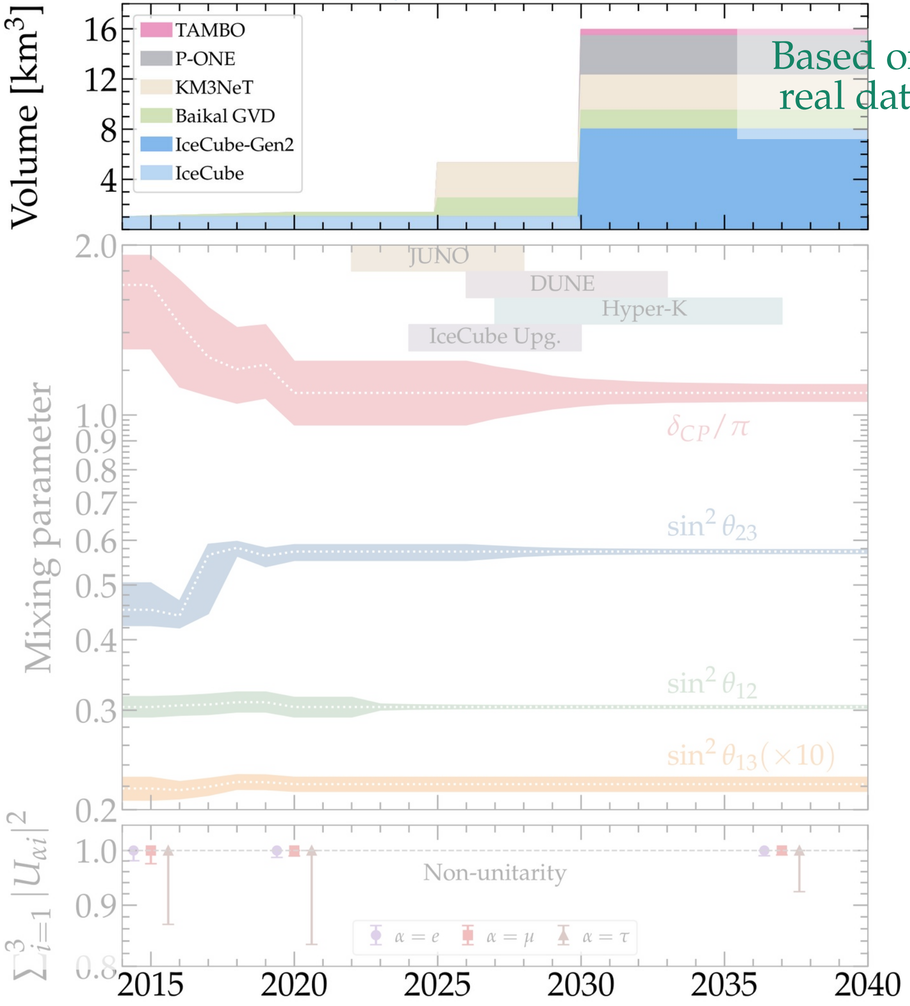
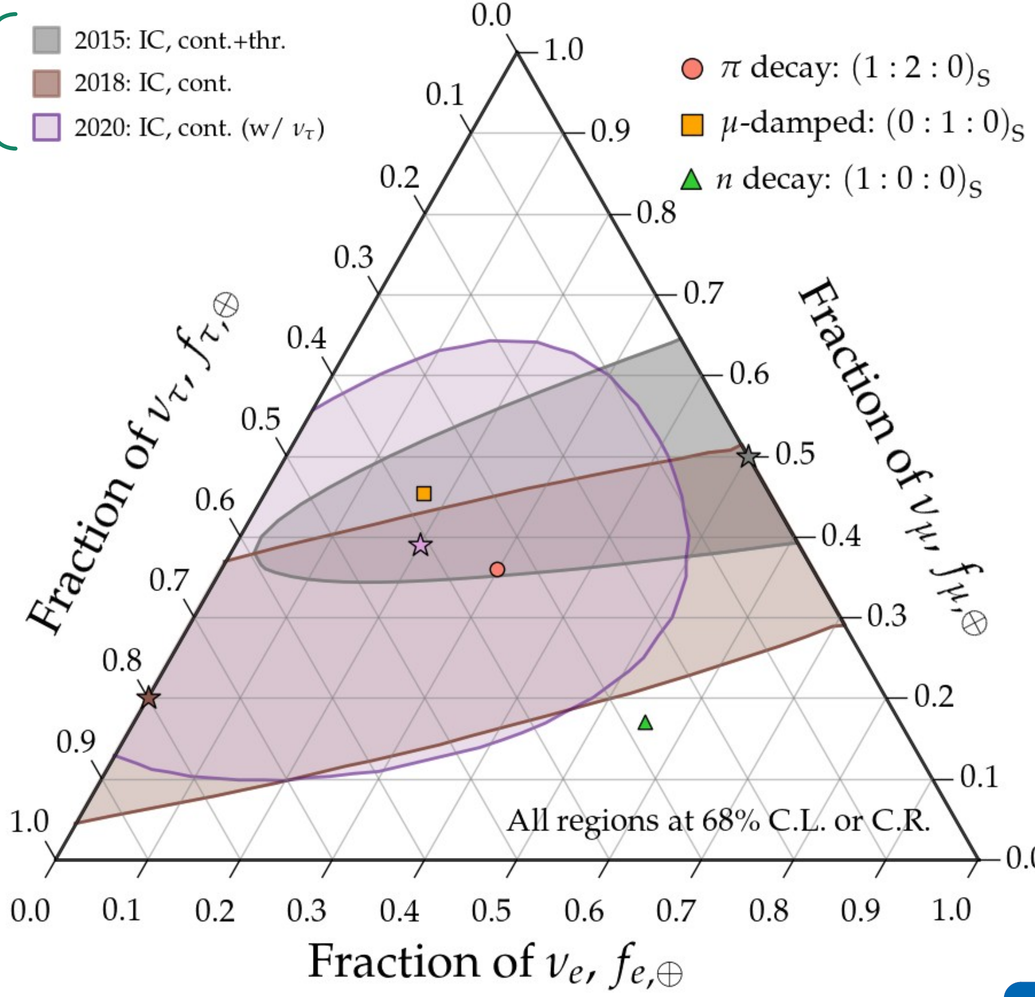


Based on real data



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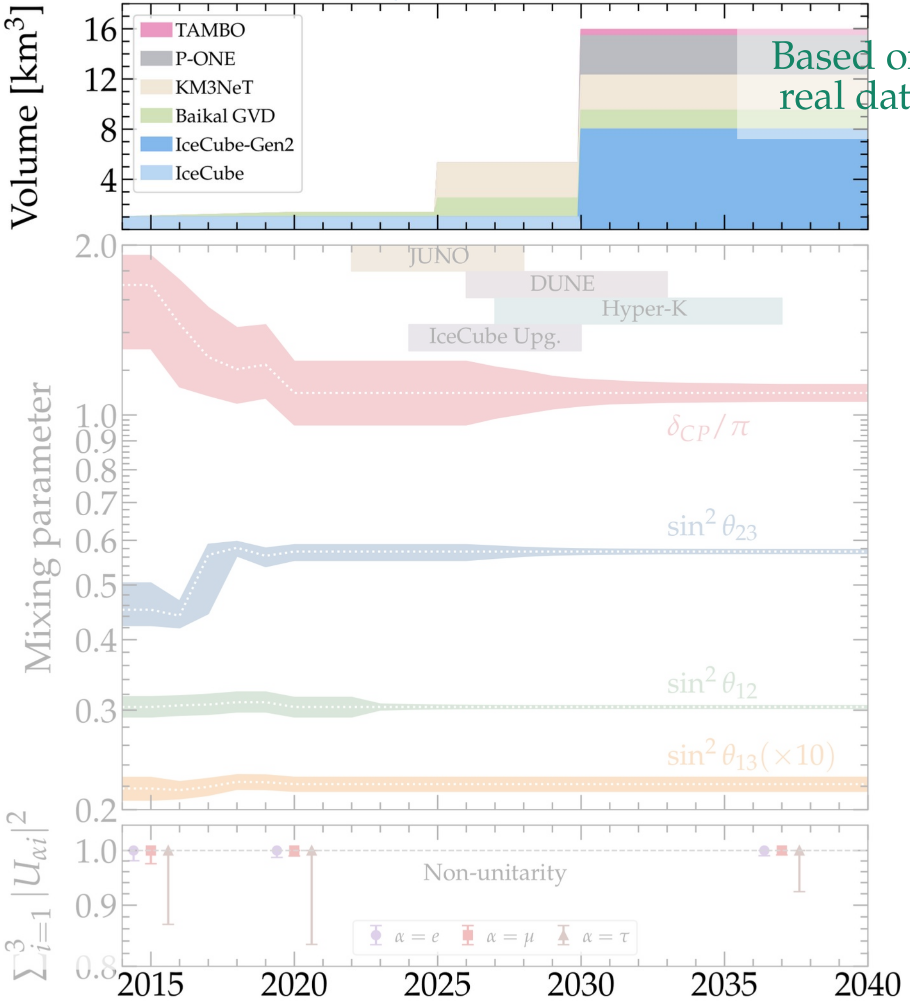

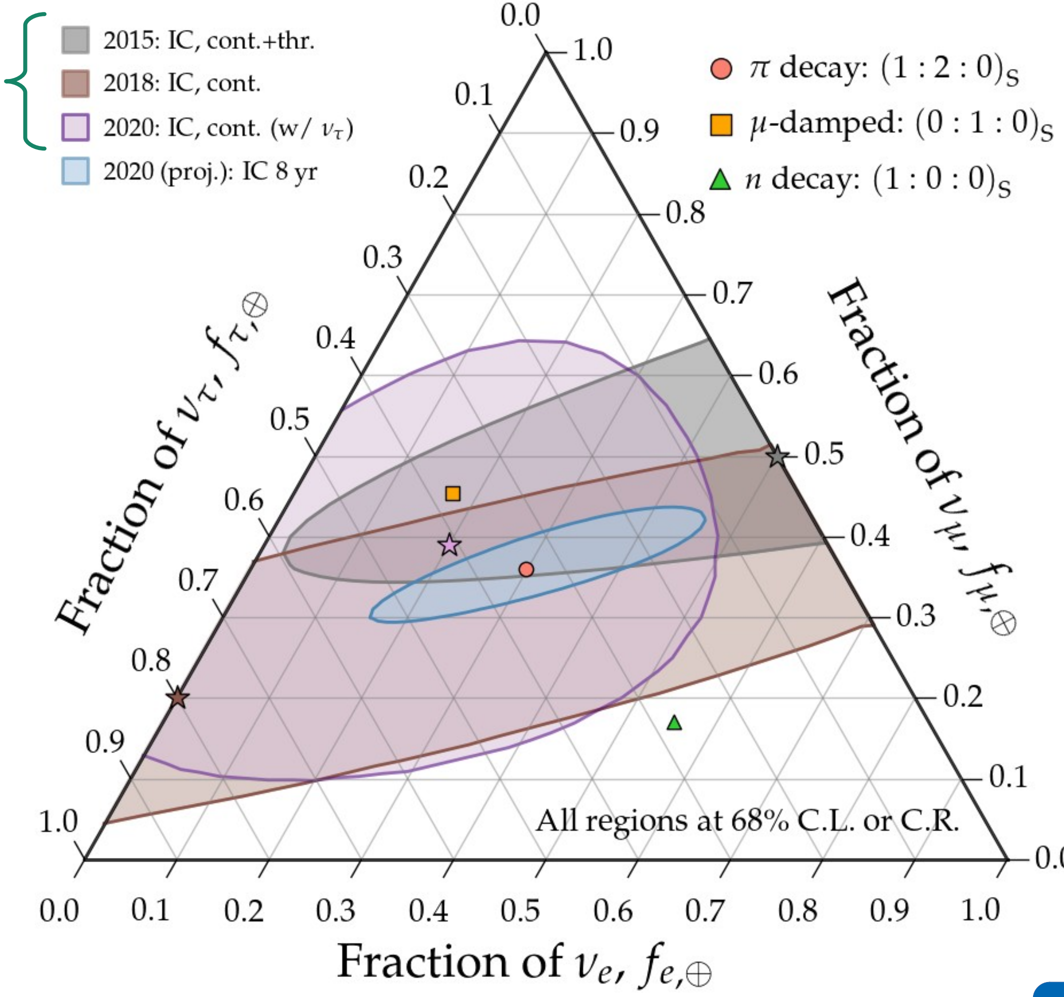

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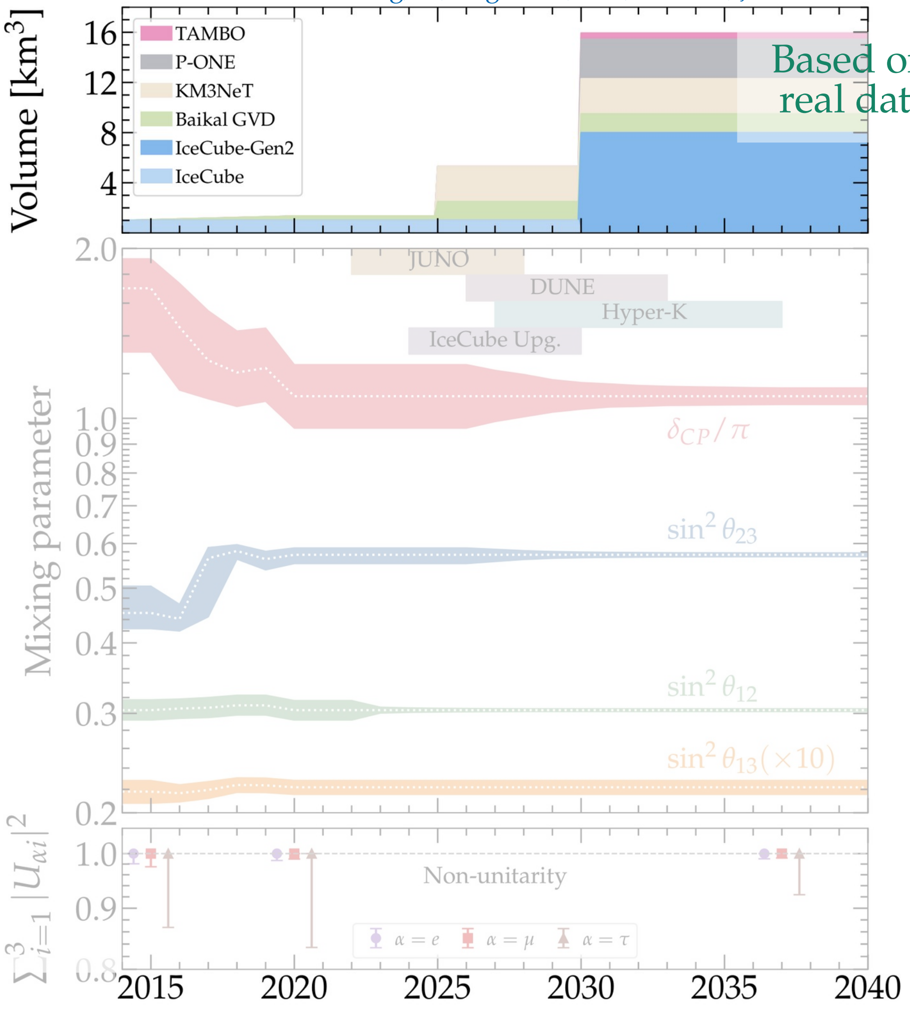
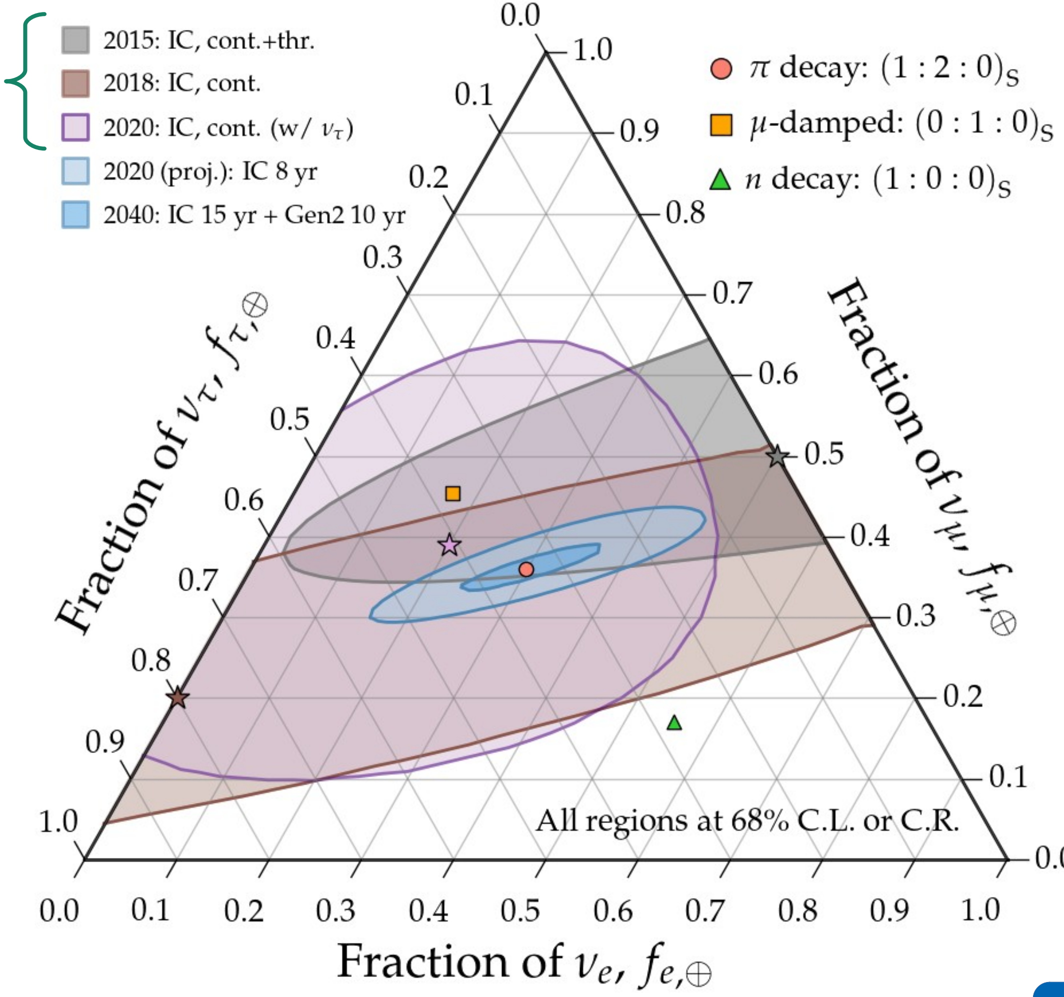
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021





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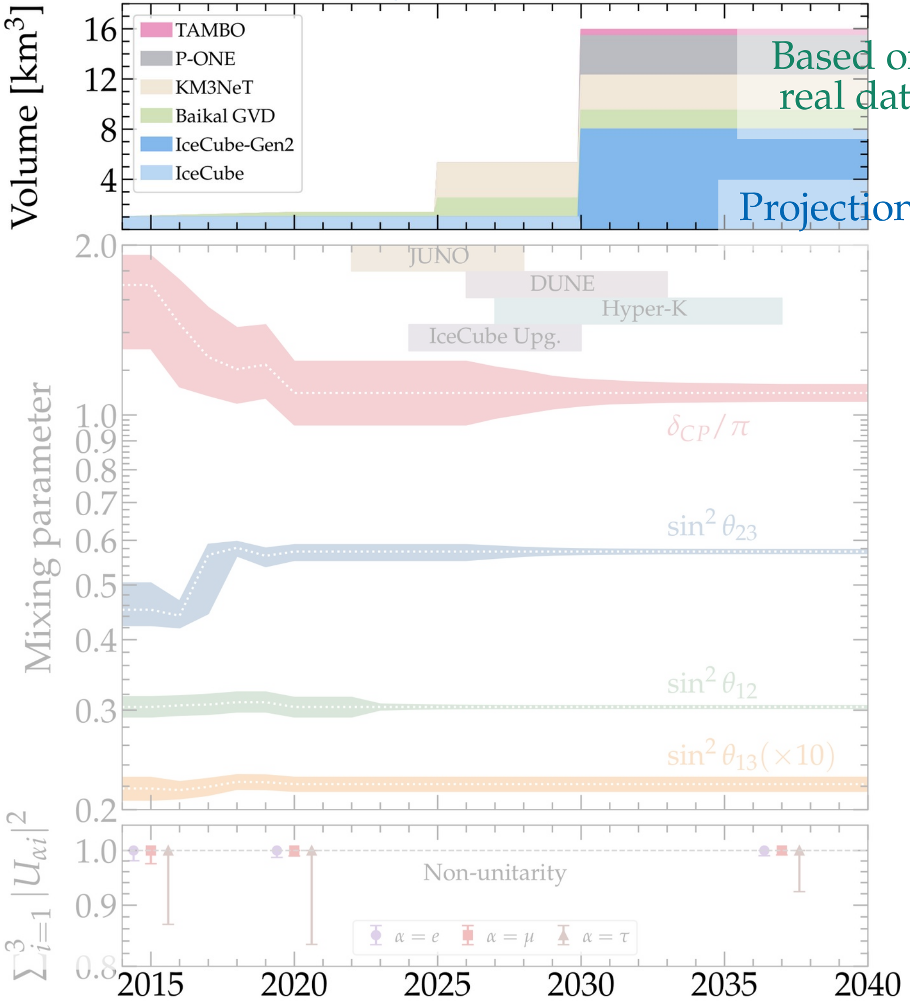
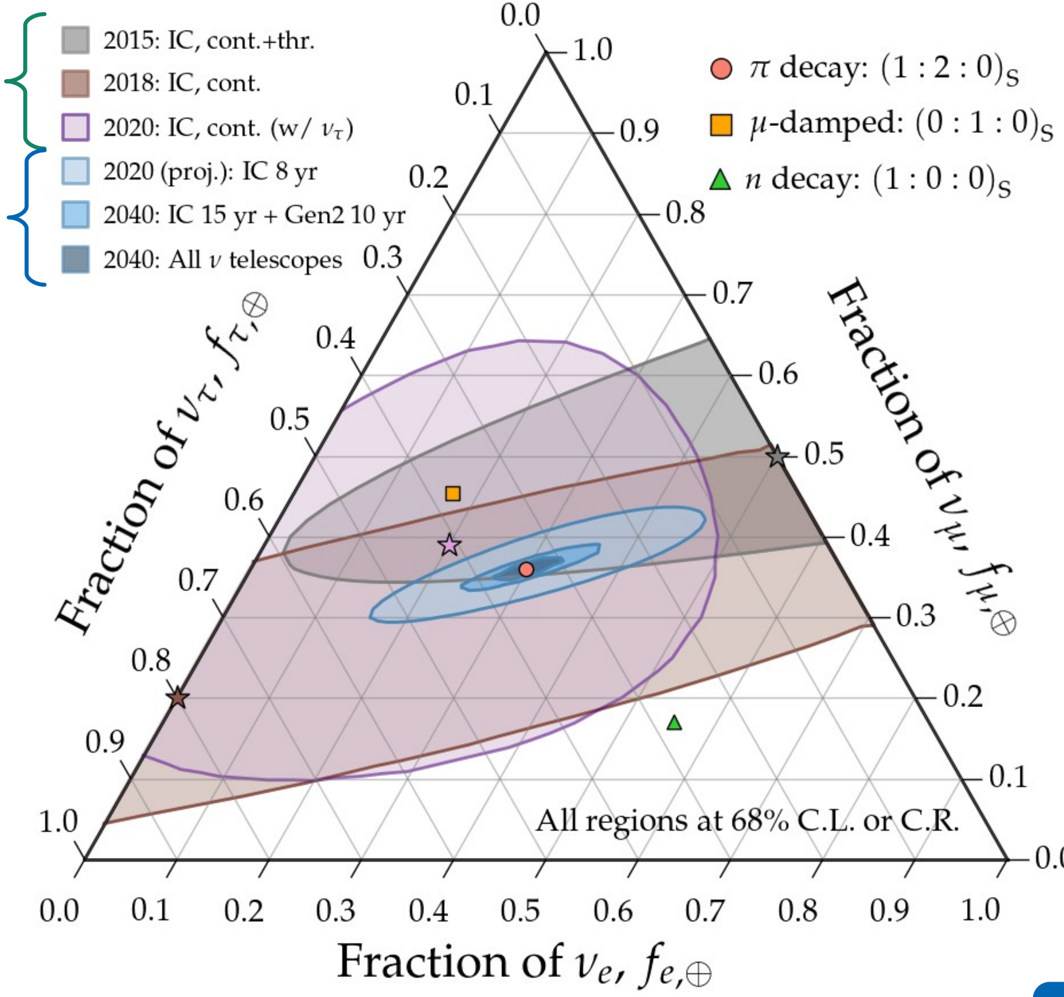
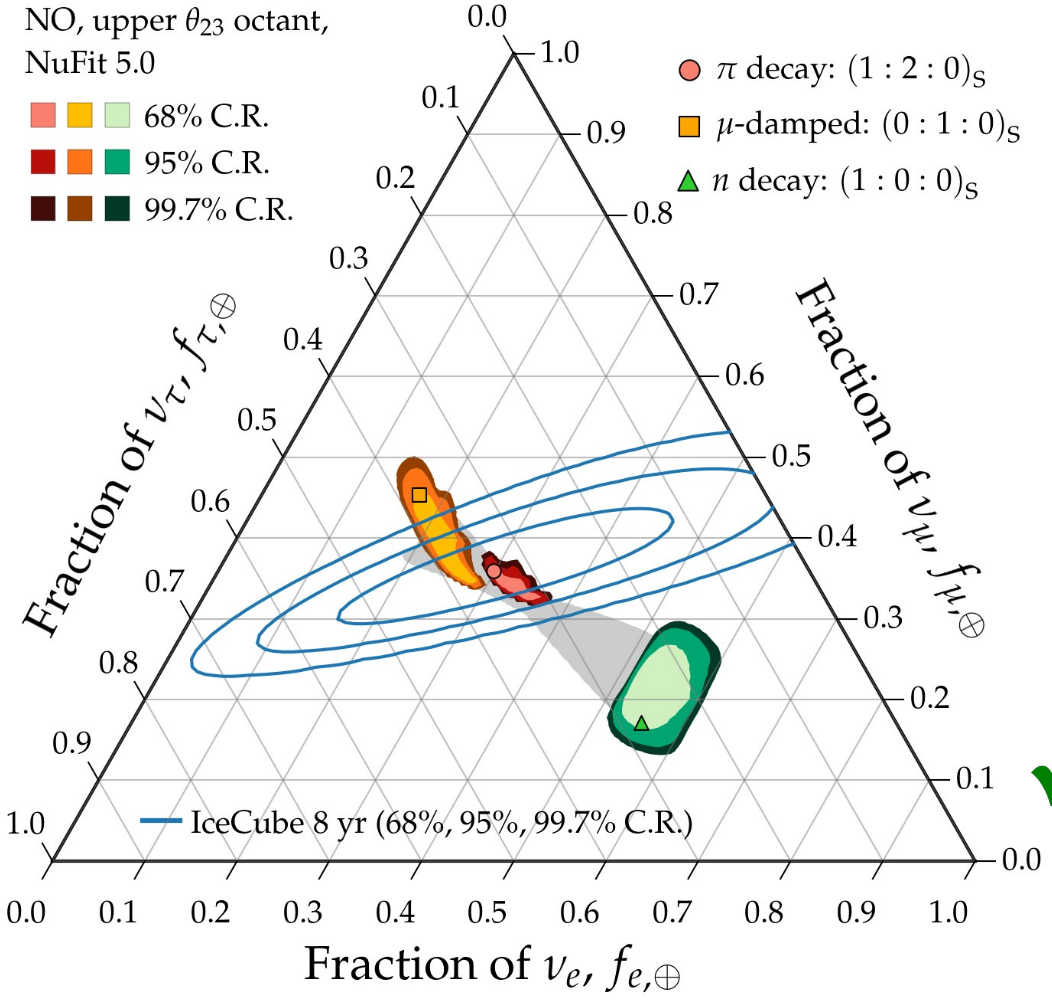




Theoretically palatable regions: today (2021)



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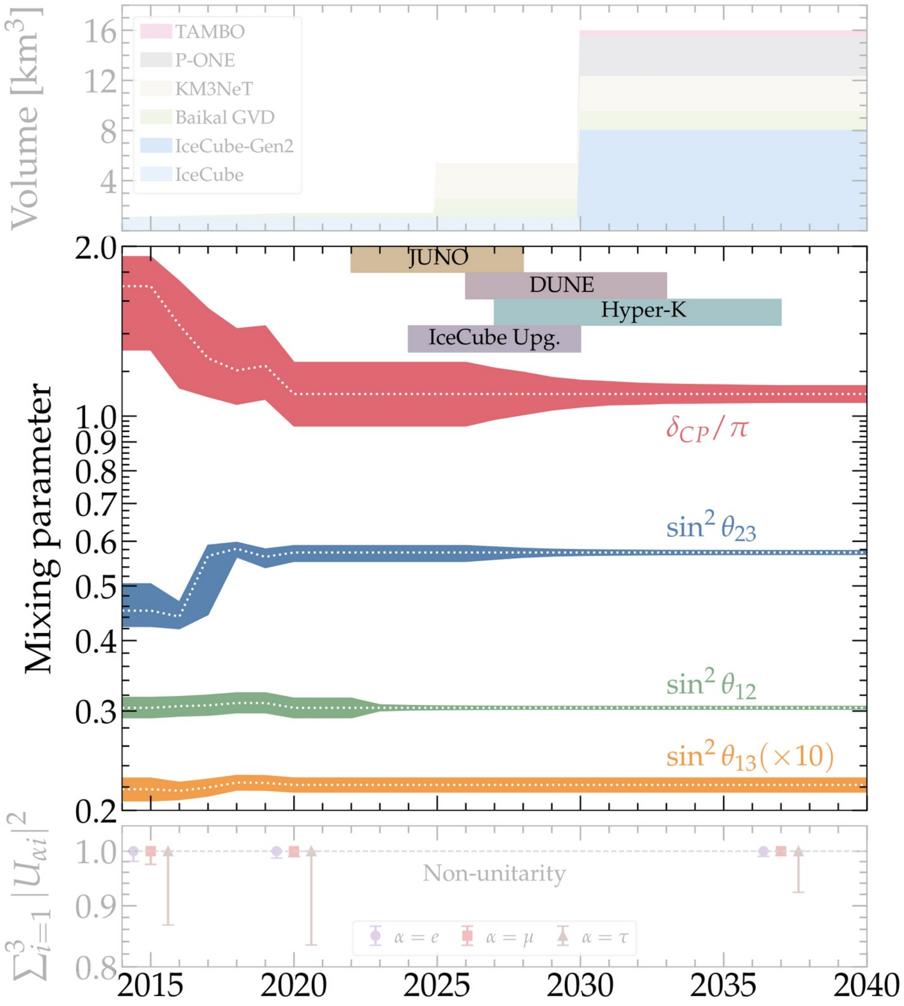
✓ *Will be overcome by 2040*

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

How knowing the mixing parameters better helps

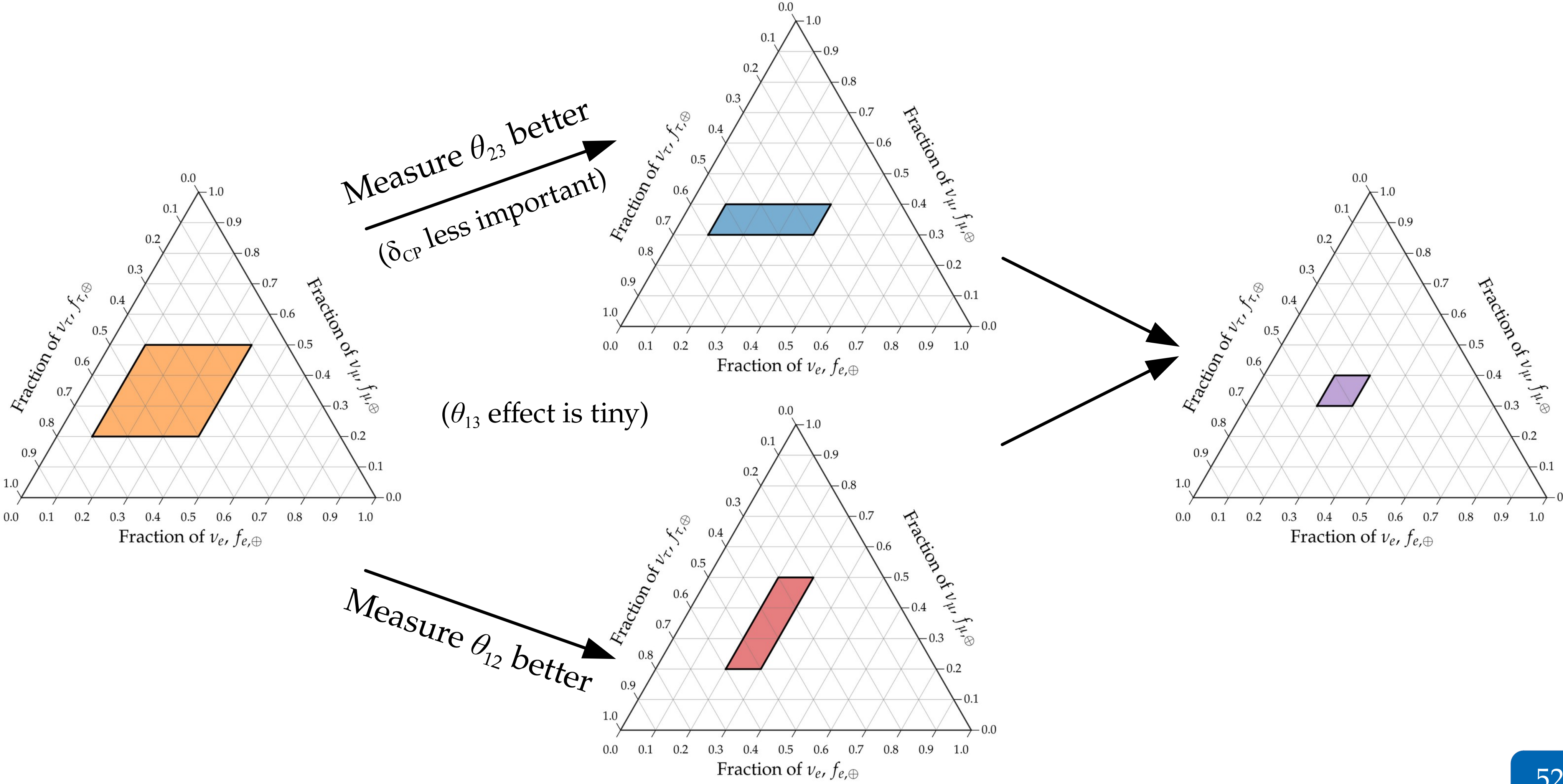


We can compute the oscillation probability more precisely:

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

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

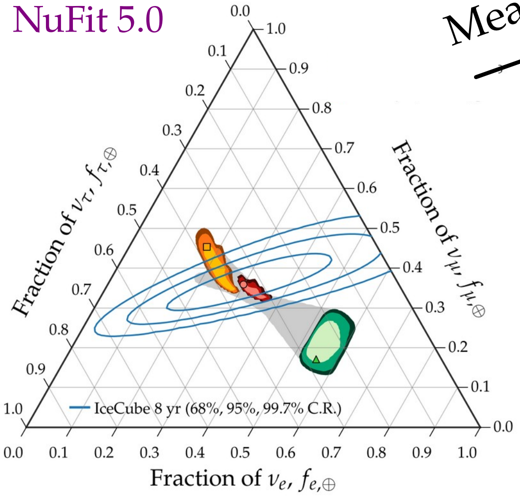
How knowing the mixing parameters better helps



How knowing the mixing parameters better helps

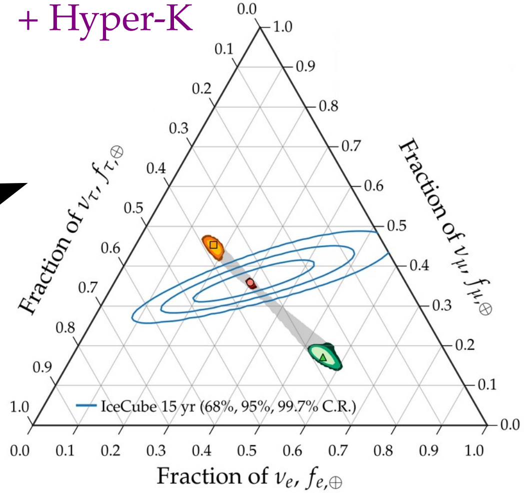
2020

NuFit 5.0



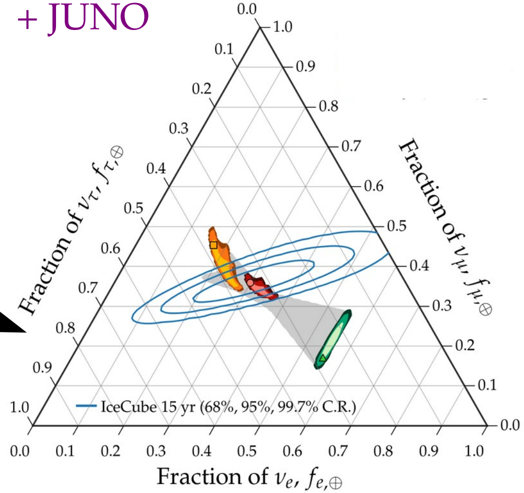
Measure θ_{23} better

+ Hyper-K



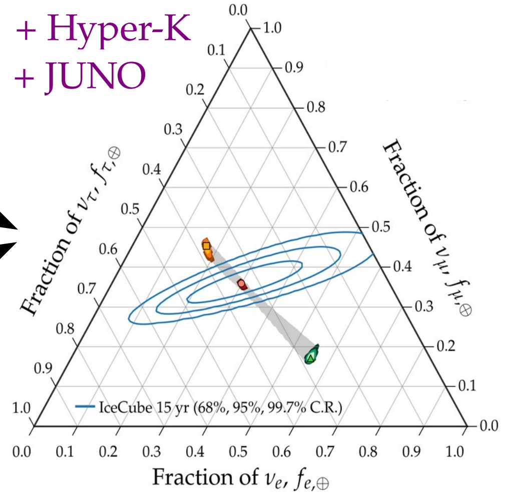
Measure θ_{12} better

+ JUNO



~2030

+ Hyper-K
+ JUNO



In our results:
JUNO + Hyper-K + DUNE

Marginal improvement til 2040

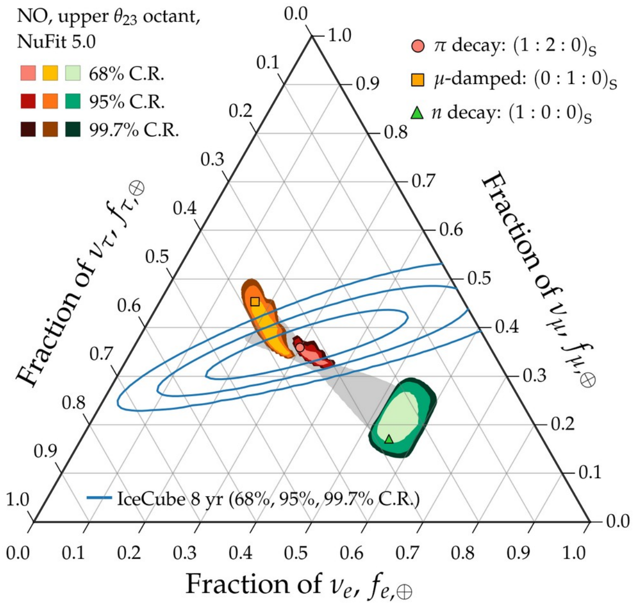
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Theoretically palatable regions: 2020 → 2030 → 2040

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

Theoretically palatable regions: 2020 → 2030 → 2040

2020



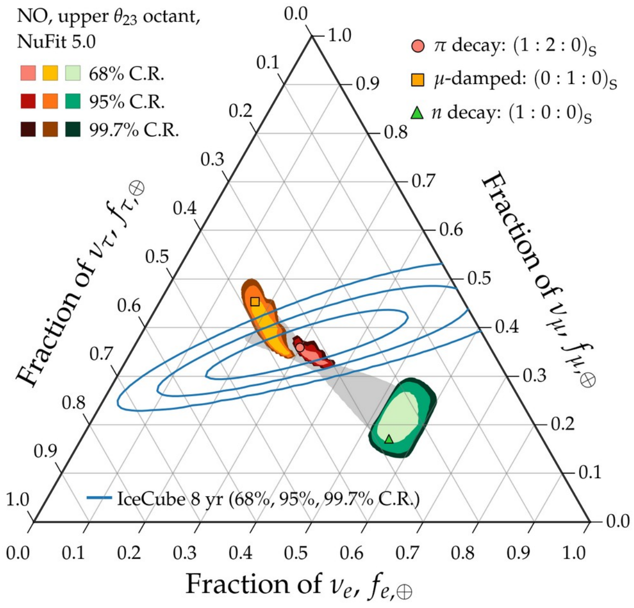
Allowed regions: overlapping

Measurement: imprecise

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

Theoretically palatable regions: 2020 → 2030 → 2040

2020



Allowed regions: overlapping

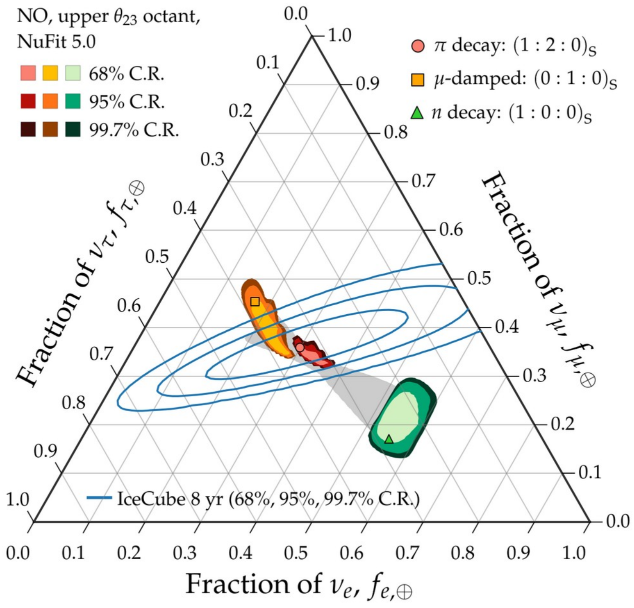
Measurement: imprecise

Not ideal

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

Theoretically palatable regions: 2020 → 2030 → 2040

2020



Allowed regions: overlapping

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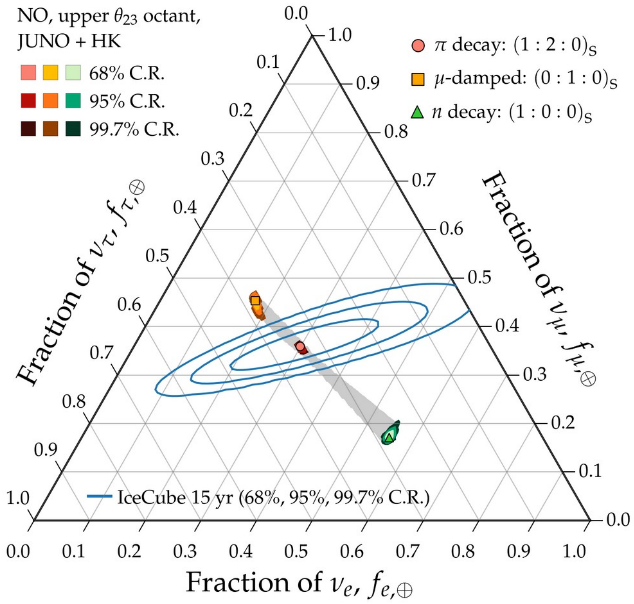
Not ideal

2030



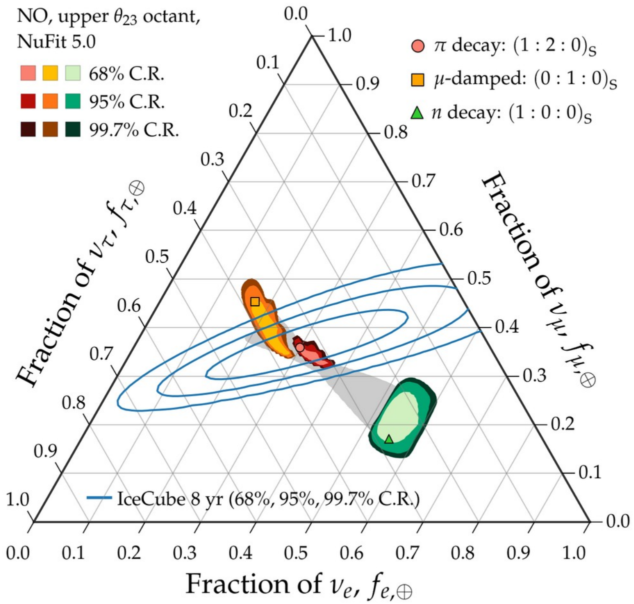
Allowed regions: well separated

Measurement: improving

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

Theoretically palatable regions: 2020 → 2030 → 2040

2020



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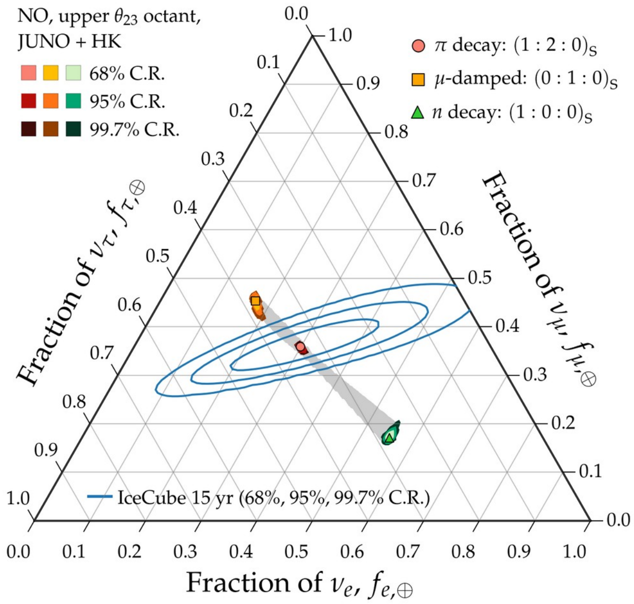
Measurement: imprecise

Not ideal

2030



Allowed regions: well separated

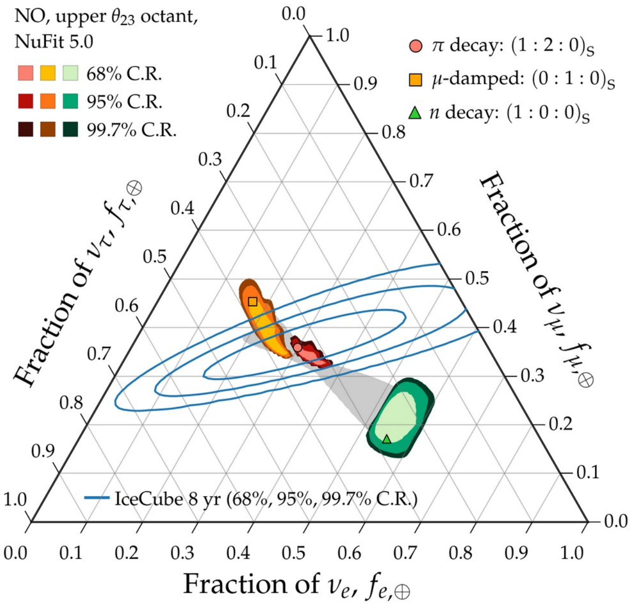
Measurement: improving

Nice

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

Theoretically palatable regions: 2020 → 2030 → 2040

2020

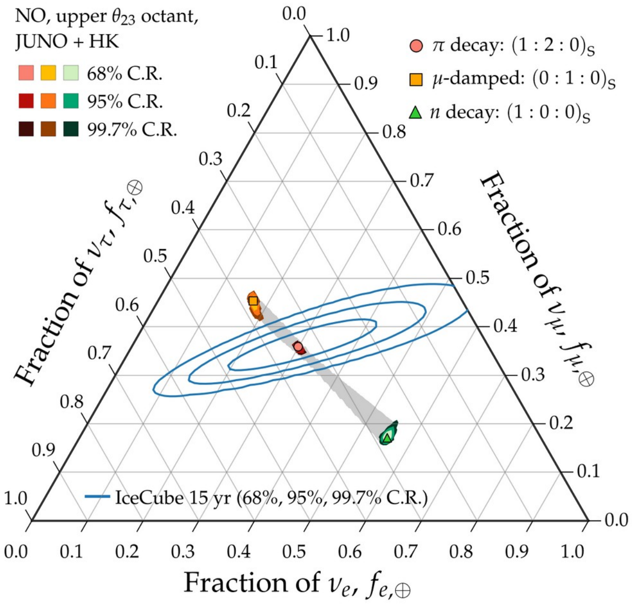


Allowed regions: overlapping

Measurement: imprecise

Not ideal

2030

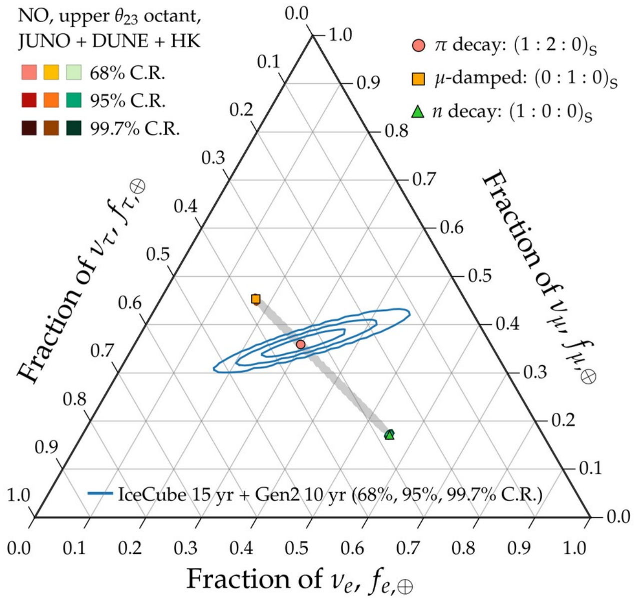


Allowed regions: well separated

Measurement: improving

Nice

2040



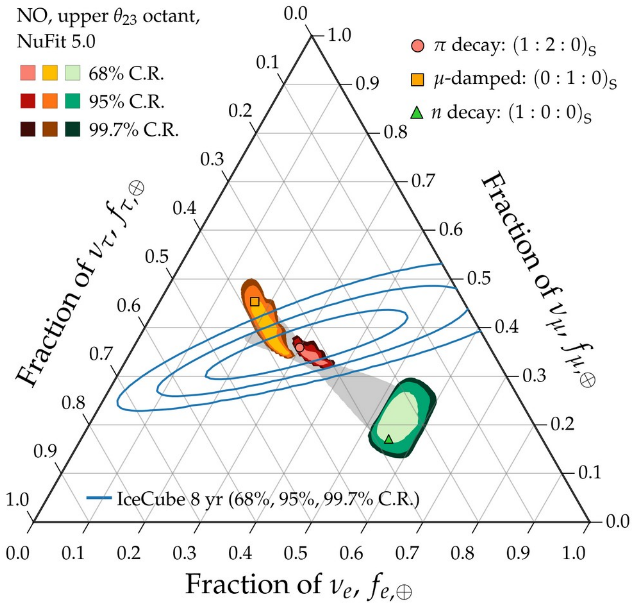
Allowed regions: well separated

Measurement: precise

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

Theoretically palatable regions: 2020 → 2030 → 2040

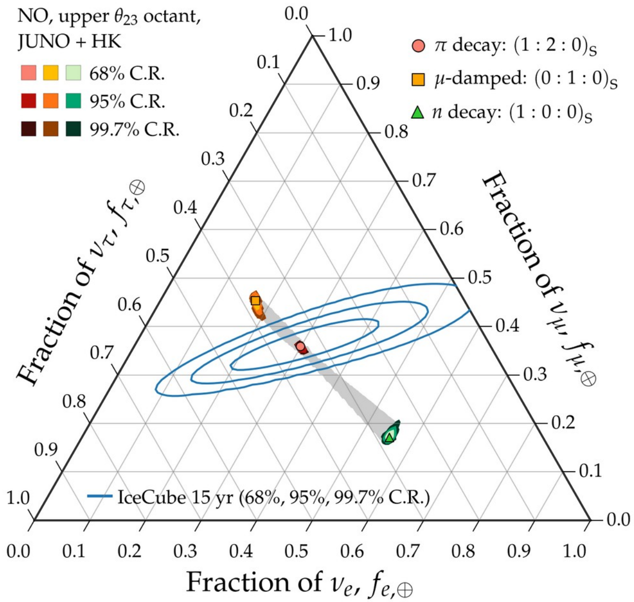
2020



Allowed regions: overlapping
Measurement: imprecise

Not ideal

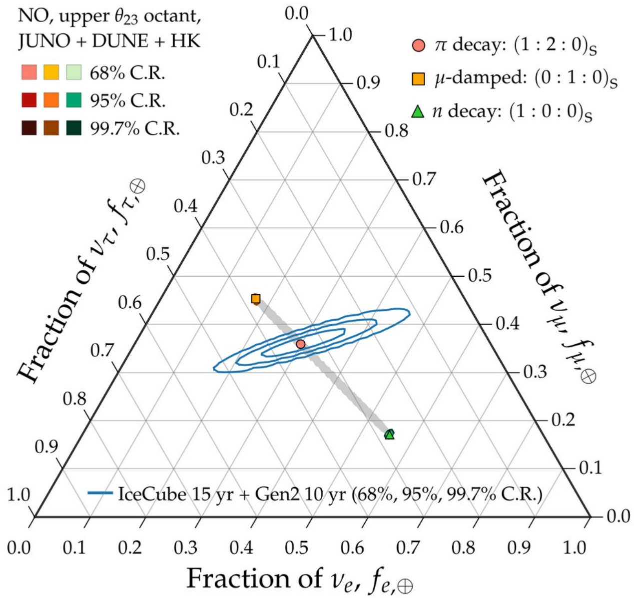
2030



Allowed regions: well separated
Measurement: improving

Nice

2040

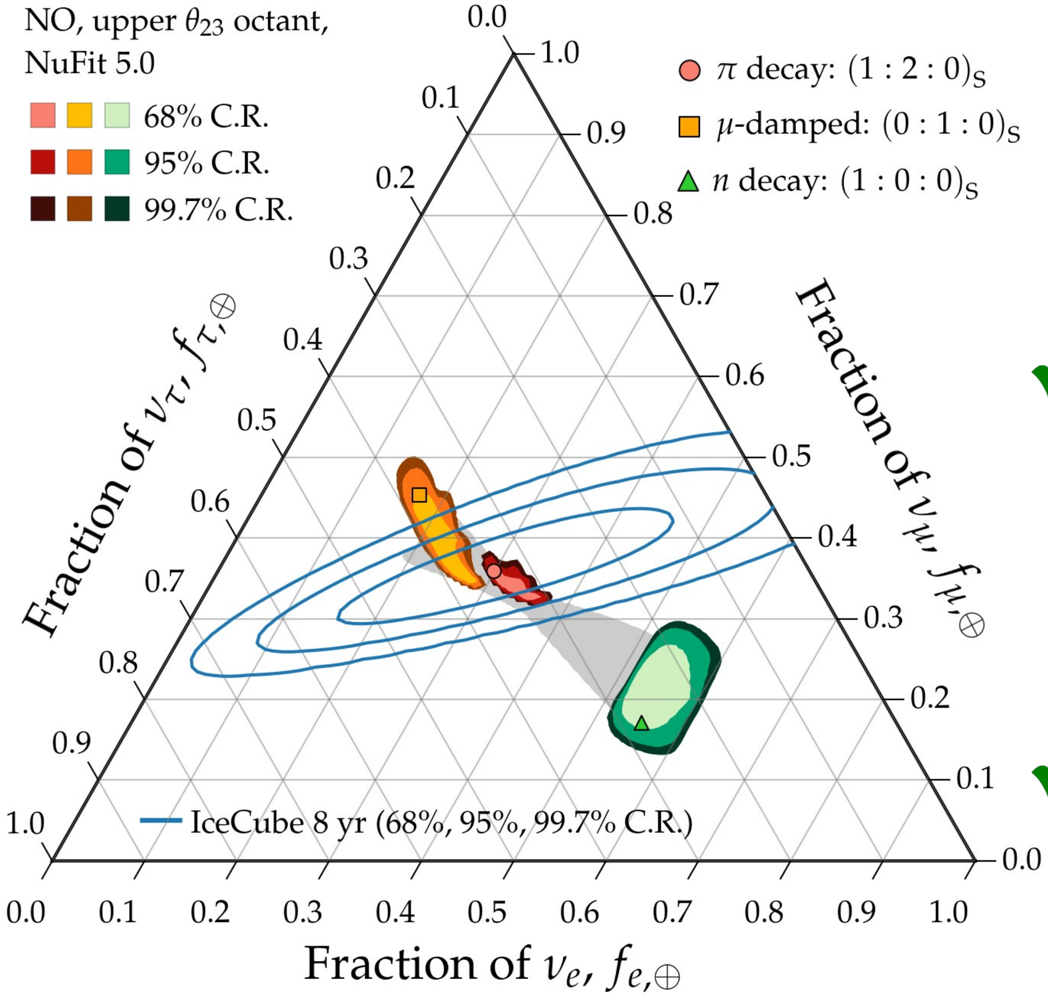


Allowed regions: well separated
Measurement: precise

Success

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

Theoretically palatable regions: today (2021)



Two limitations:

Allowed flavor regions overlap –
~~Insufficient precision in the mixing parameters~~

✓ *Will be overcome by 2030*

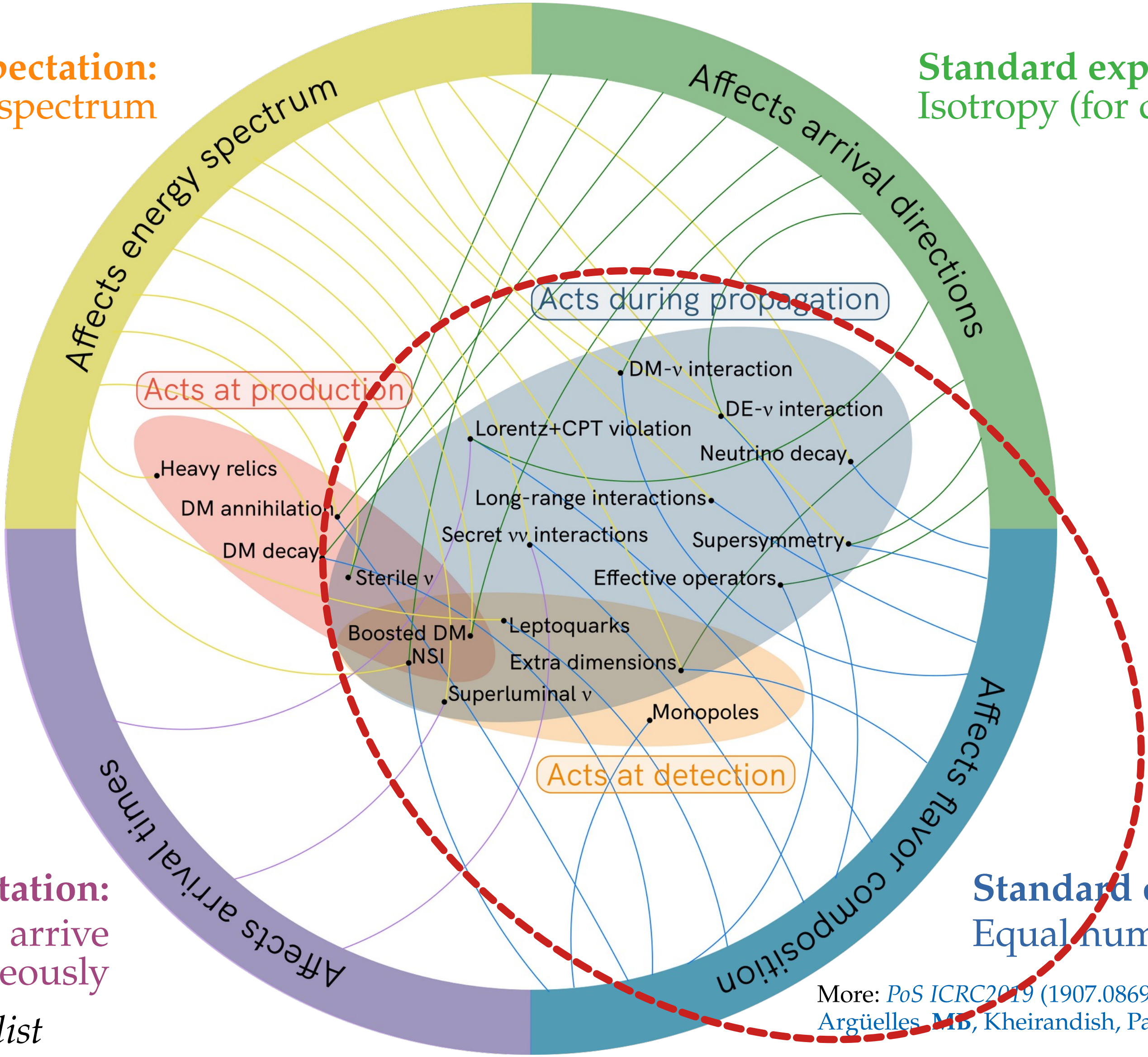
Measurement of flavor ratios –
~~Cannot distinguish between pion-decay and muon-damped benchmarks even at 68% C.R. (1σ)~~

✓ *Will be overcome by 2040*

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

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Note: Not an exhaustive list

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

New physics in flavor composition

Repurpose the flavor sensitivity to test new physics:

New physics in flavor composition

Repurpose the flavor sensitivity to test new physics:

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

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- Neutrino decay
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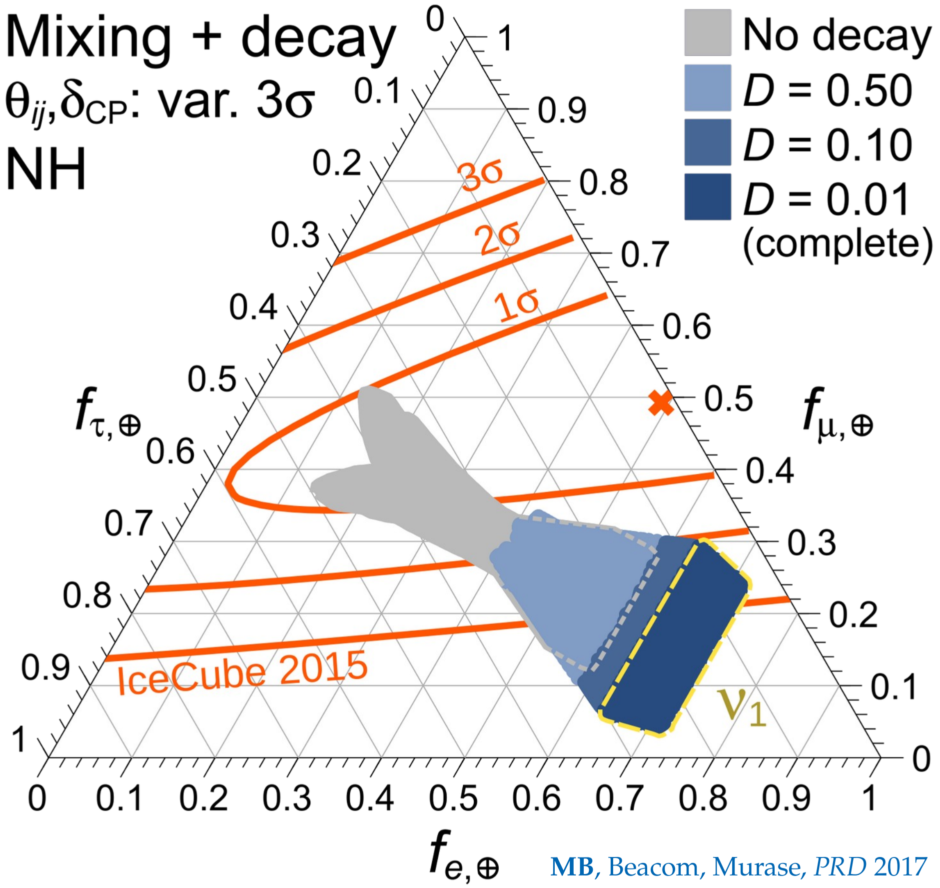

MB, Beacom, Murase, *PRD* 2017

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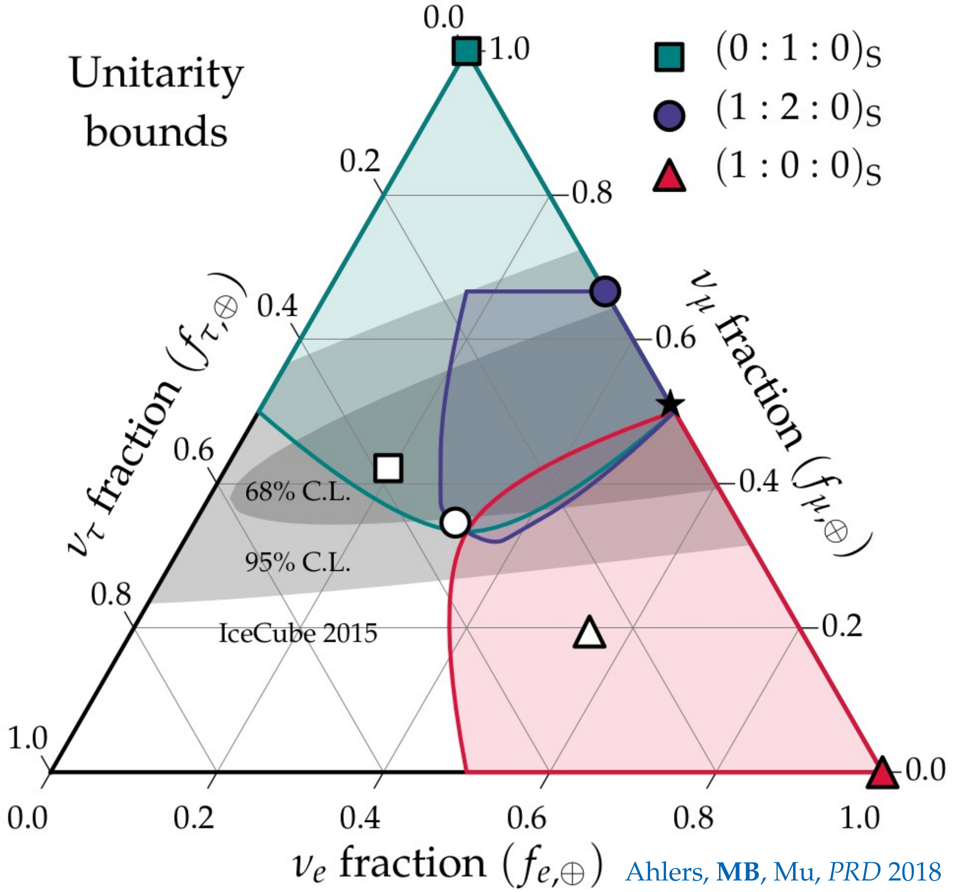

Ahlers, **MB**, Mu, *PRD* 2018

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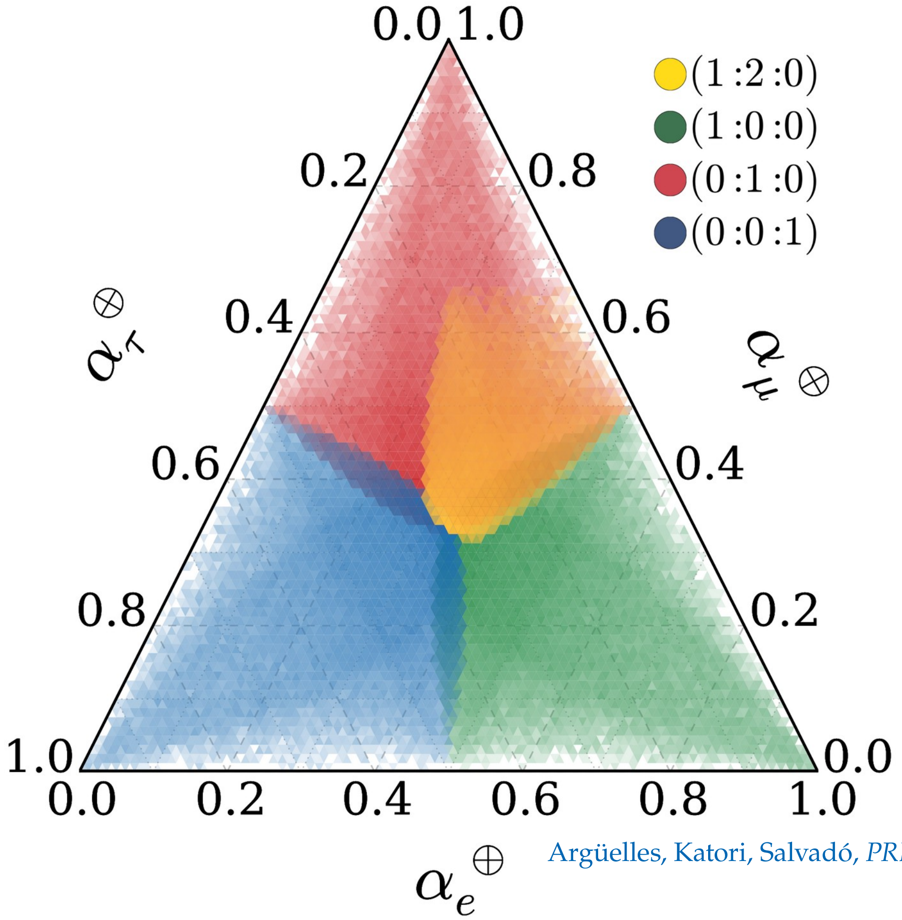

Argüelles, Katori, Salvadó, *PRL* 2015

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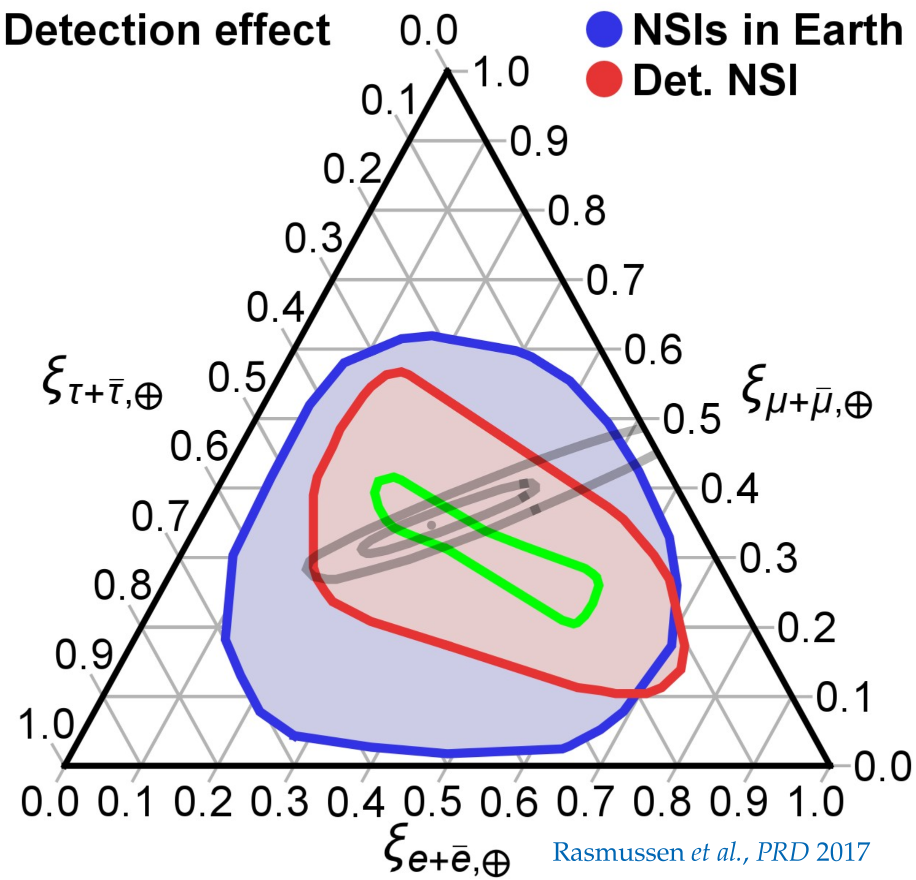

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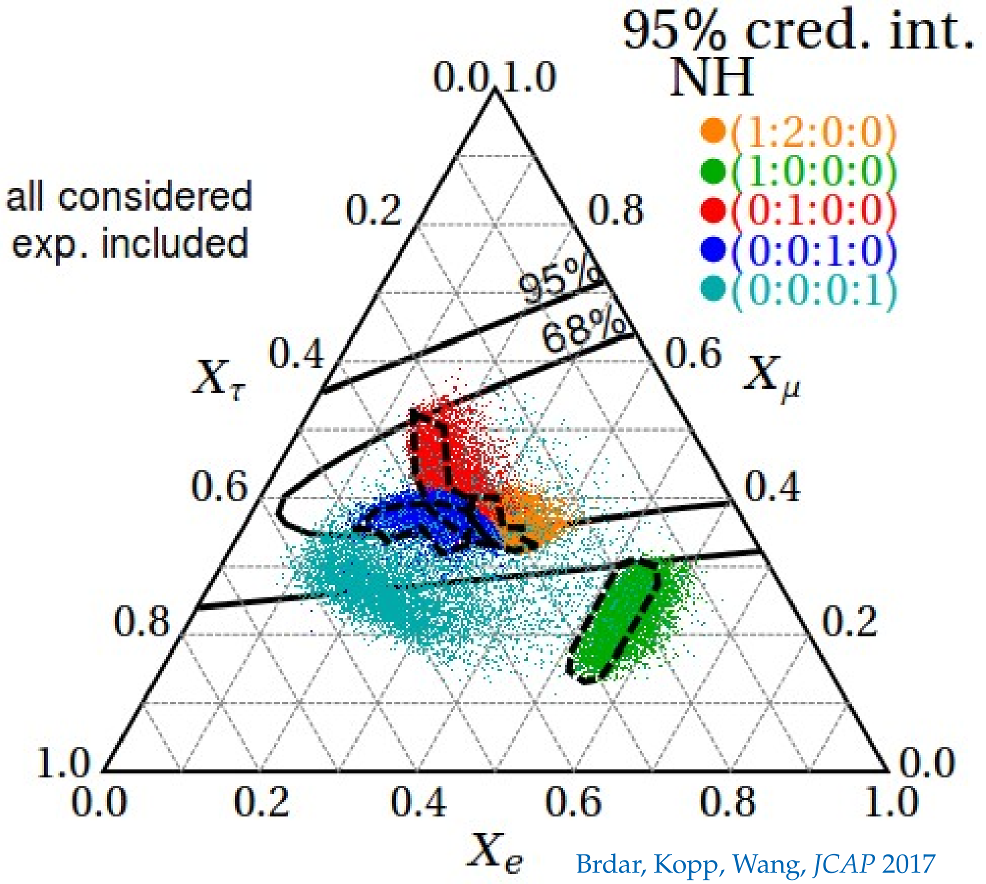

Brdar, Kopp, Wang, *JCAP* 2017

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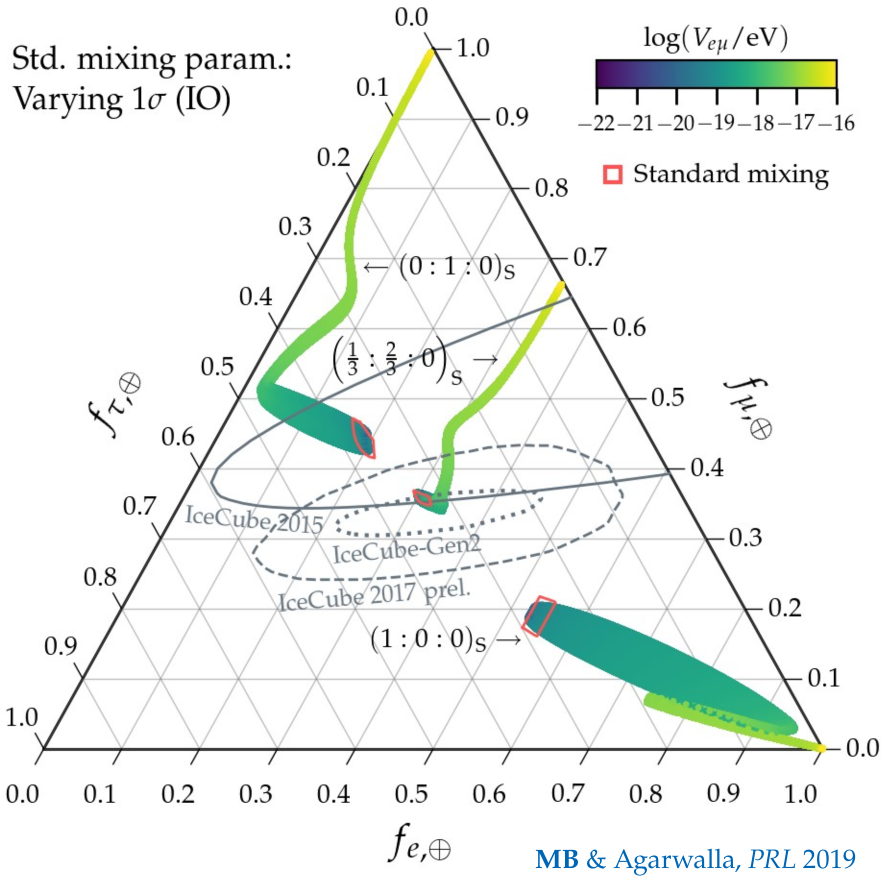
- Long-range *e*ν interactions
  [**MB** & Agarwalla, *PRL* 2019]

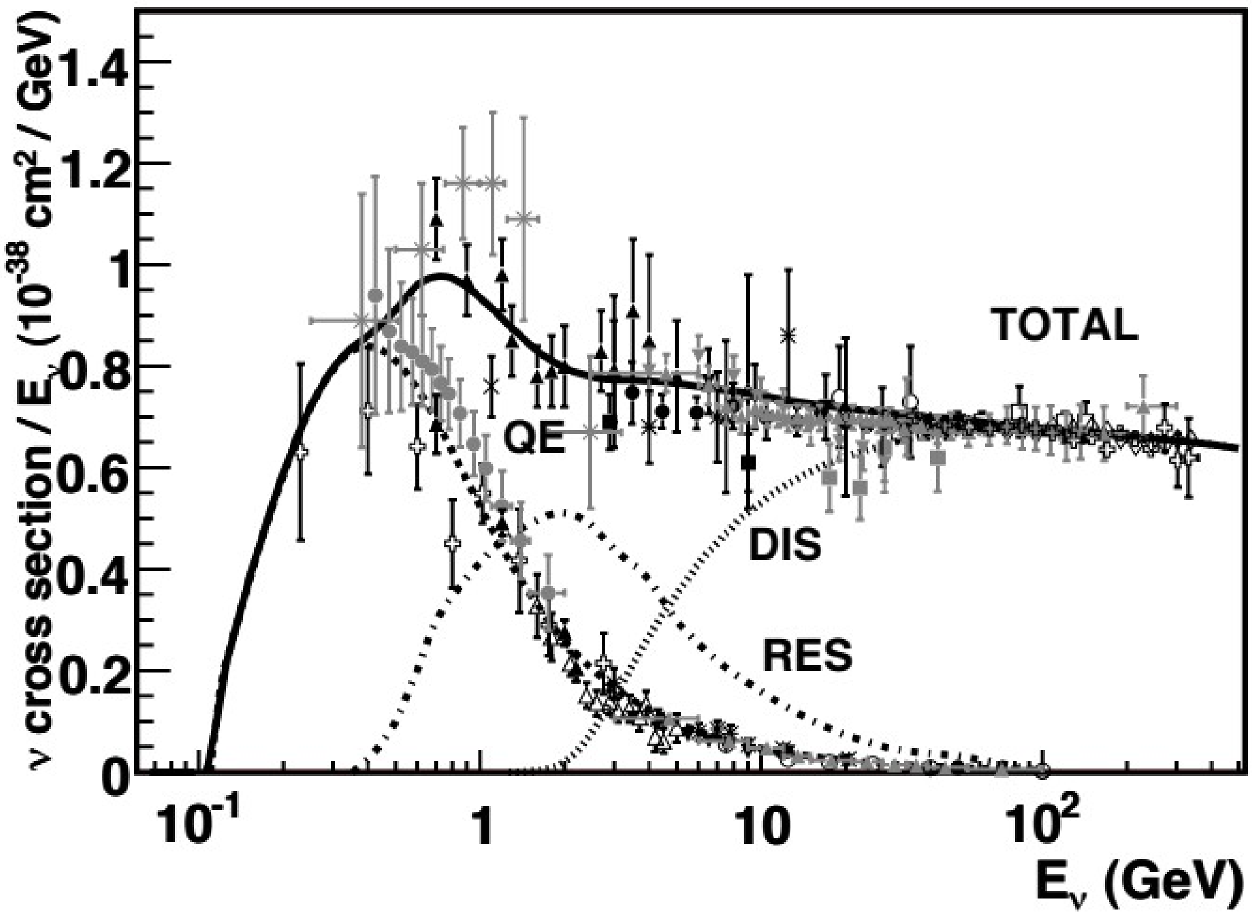
Reviews:
Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017



MB & Agarwalla, *PRL* 2019

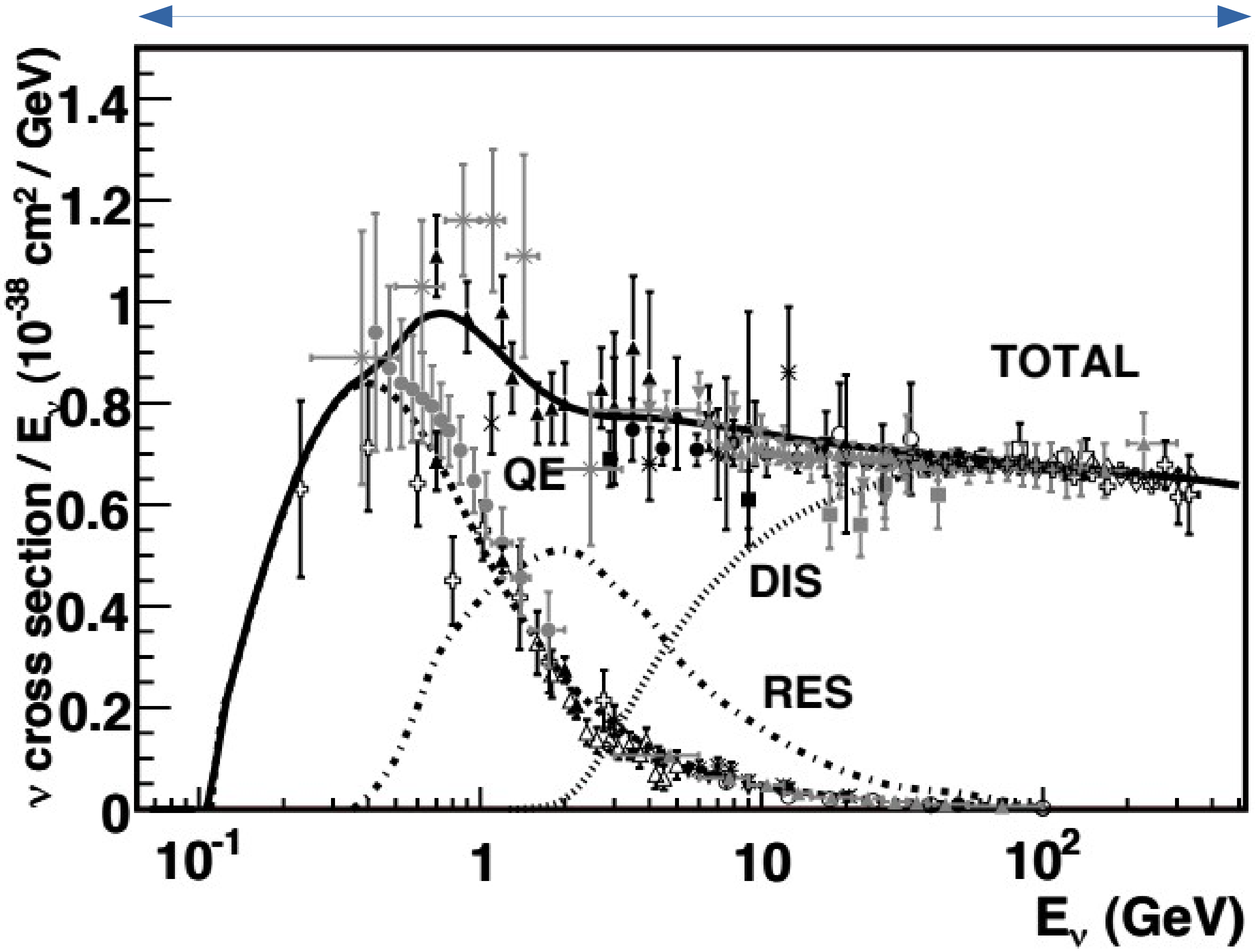
Neutrino-nucleon cross section:

From high to ultra-high energies



Particle Data Group

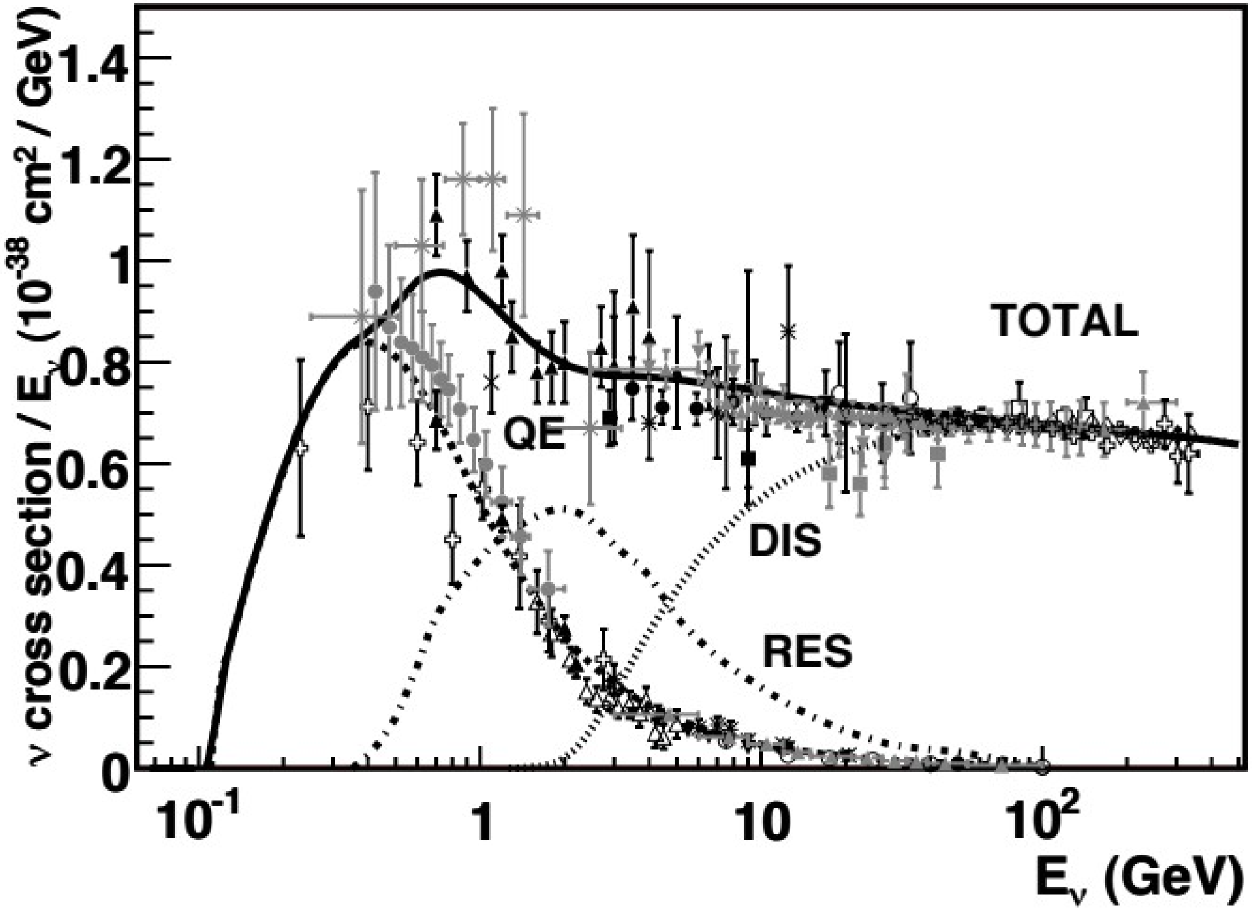
Accelerator experiments



Particle Data Group

Accelerator experiments

One recent measurement (COHERENT)



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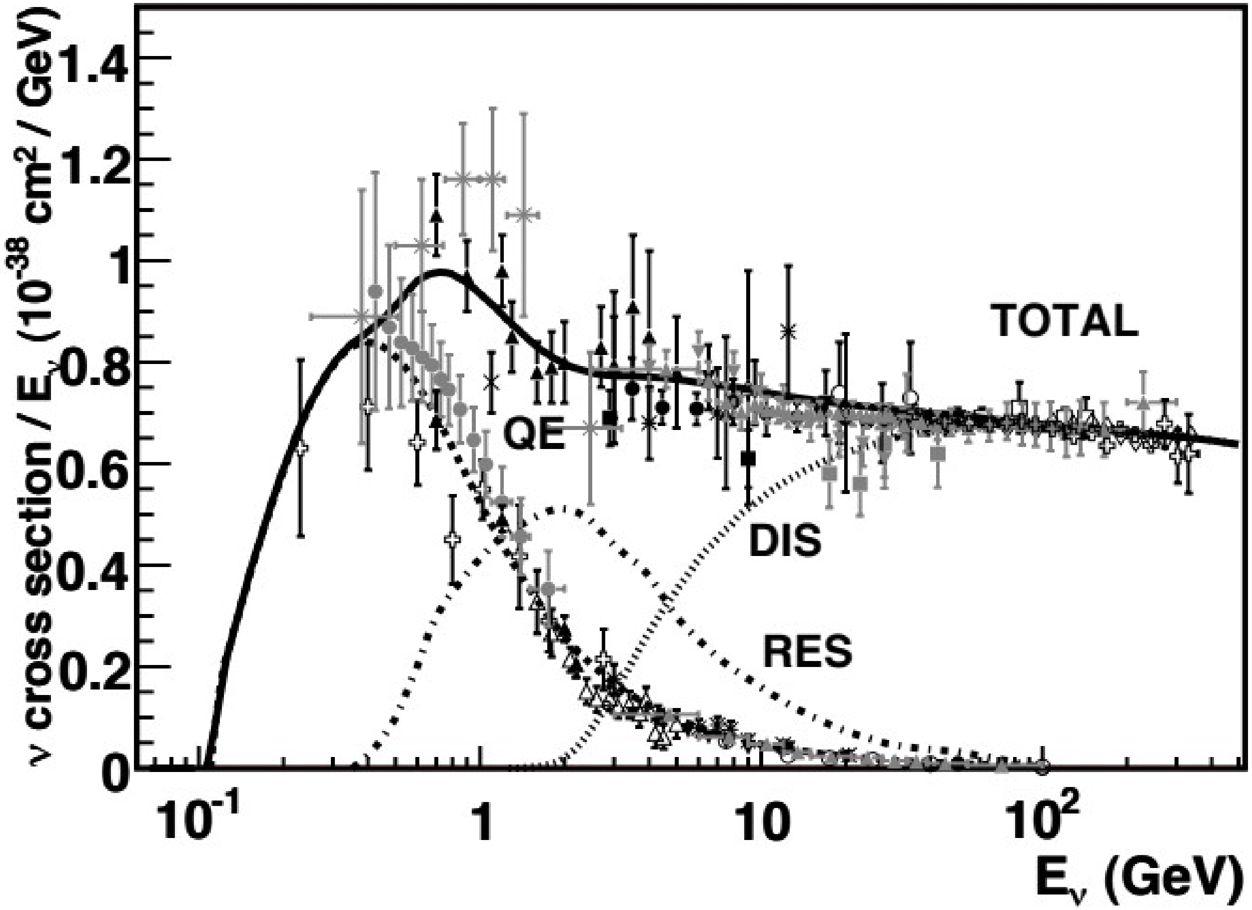
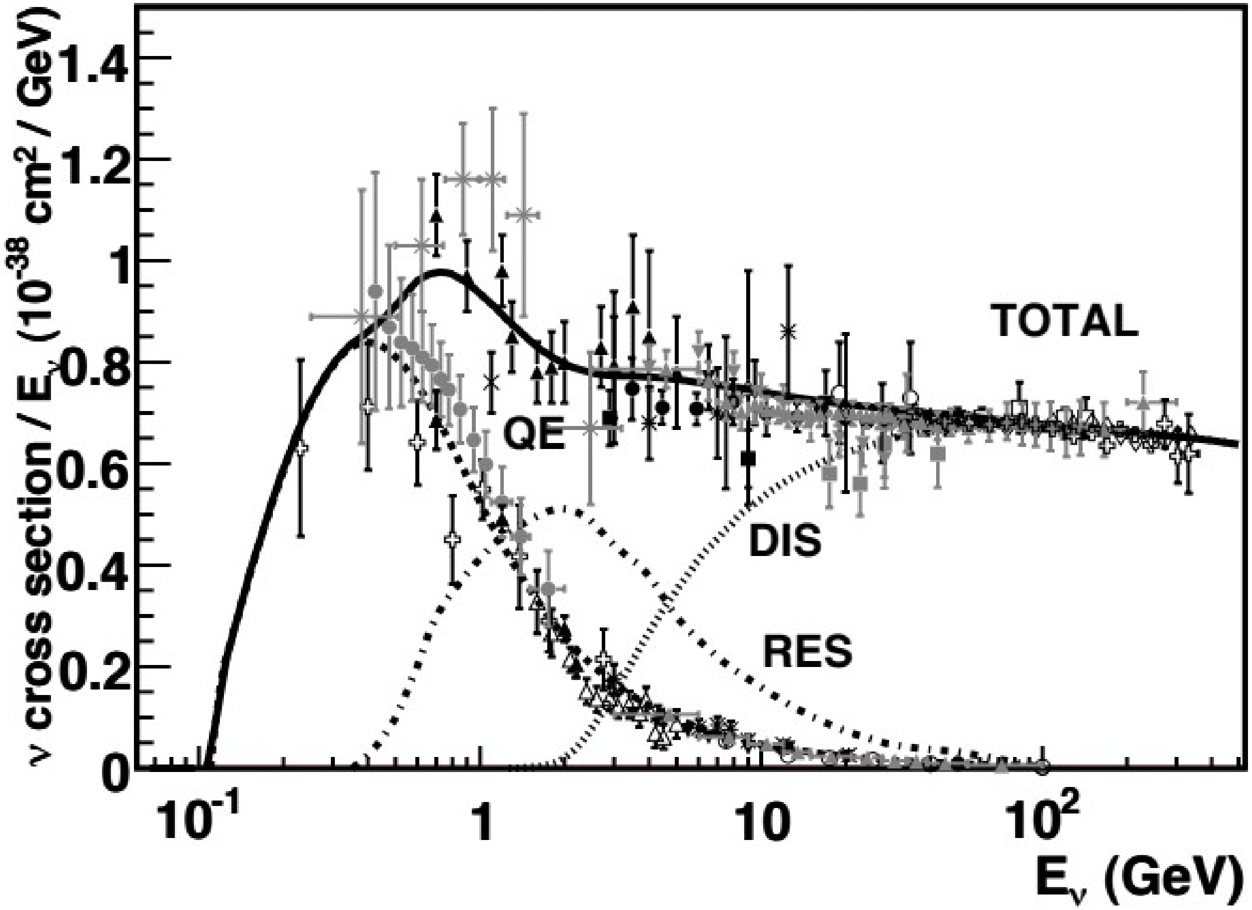


Particle Data Group

No measurements … until recently!

Accelerator experiments



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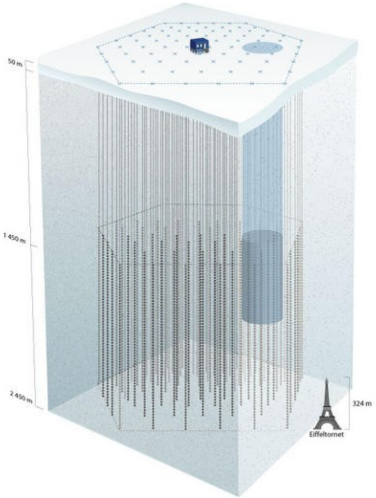
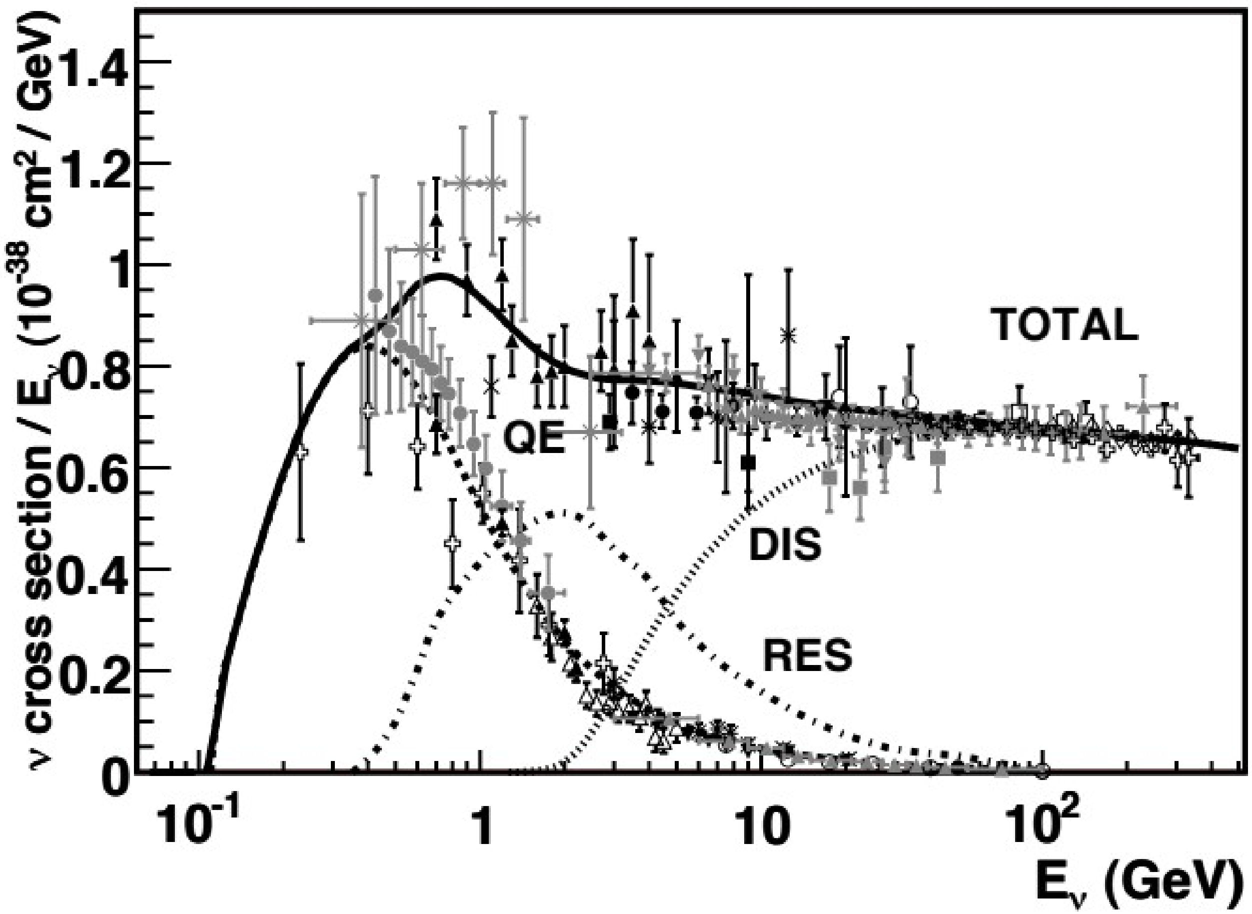


Particle Data Group

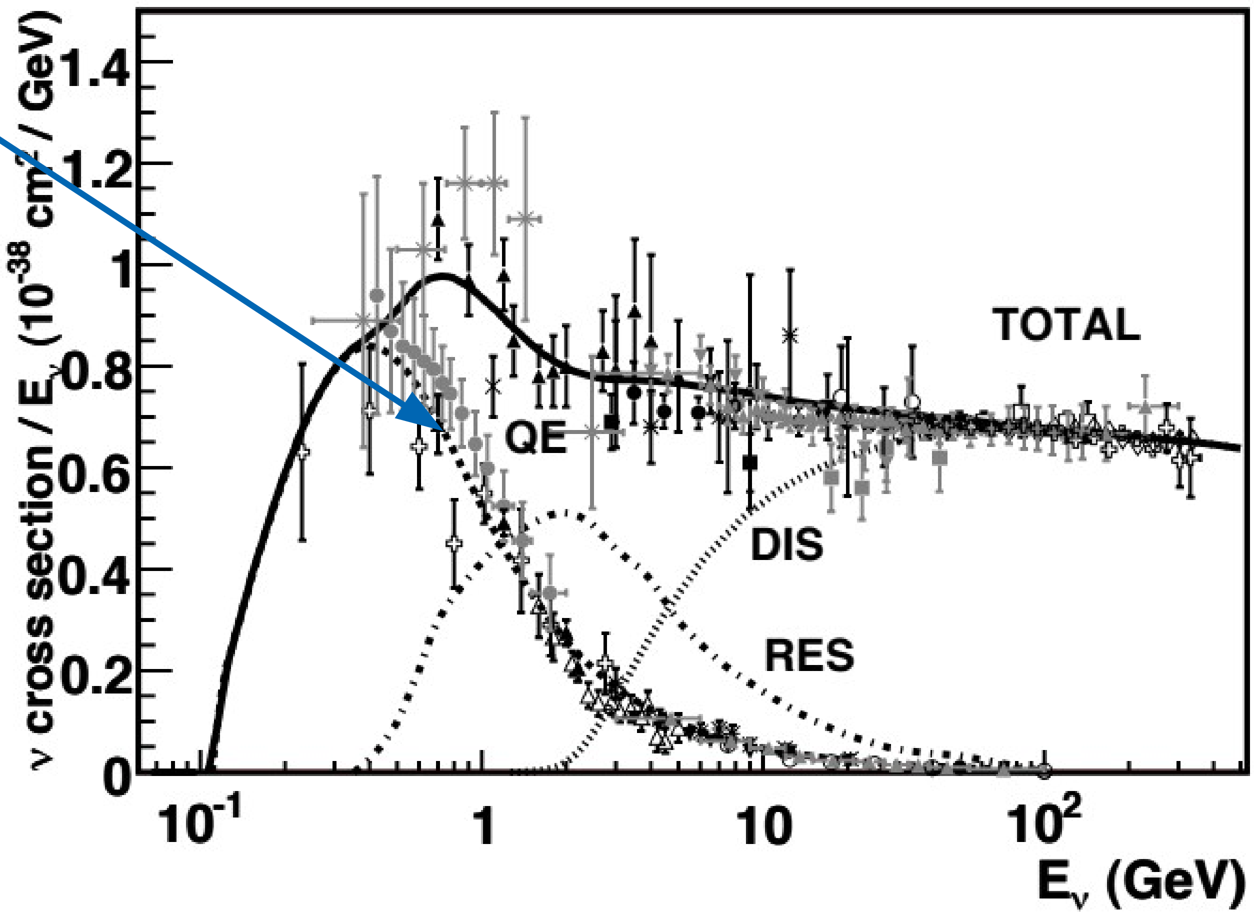


Particle Data Group

Quasi-elastic scattering:

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

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



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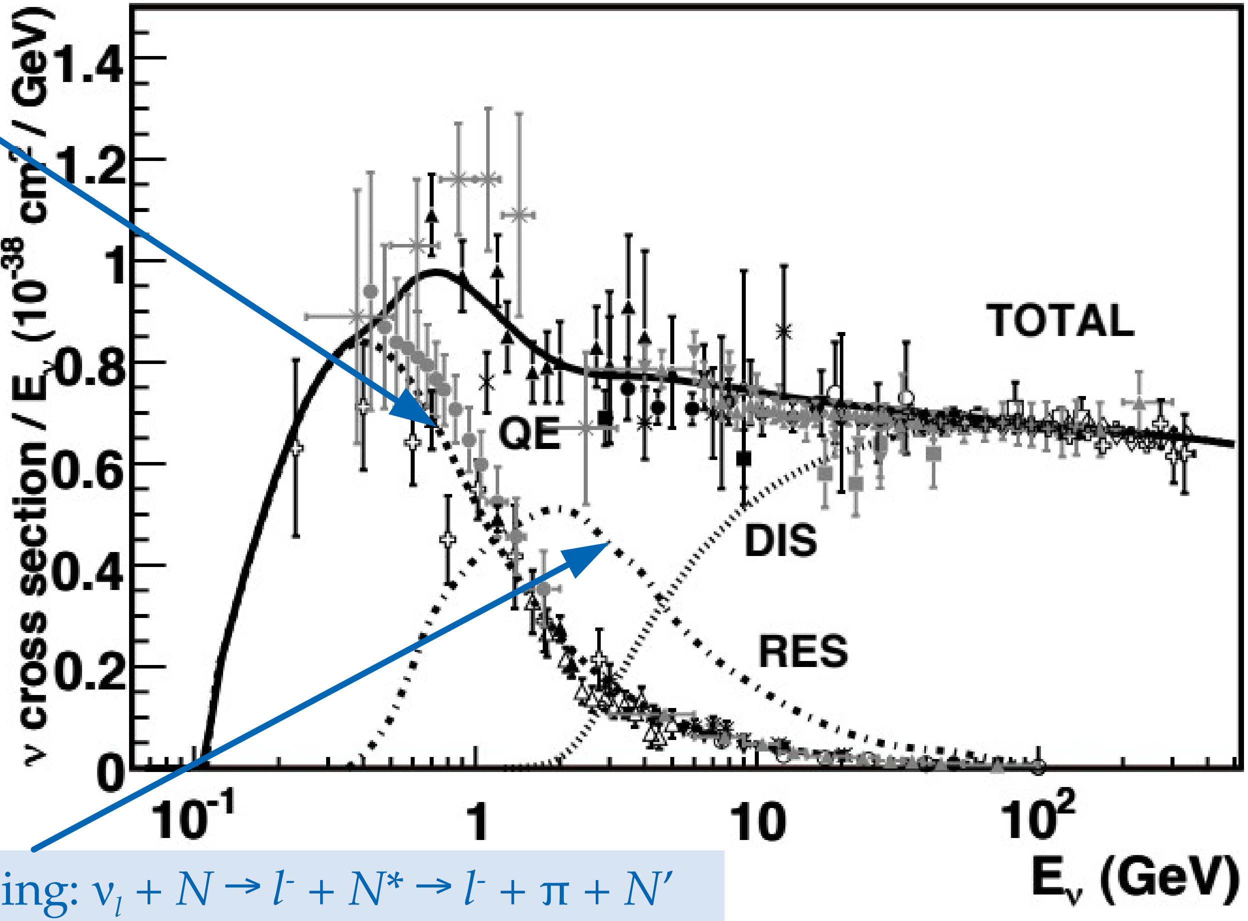

Resonant scattering: $\nu_l + N \rightarrow l^- + N^* \rightarrow l^- + \pi + N'$

Particle Data Group

Quasi-elastic scattering:

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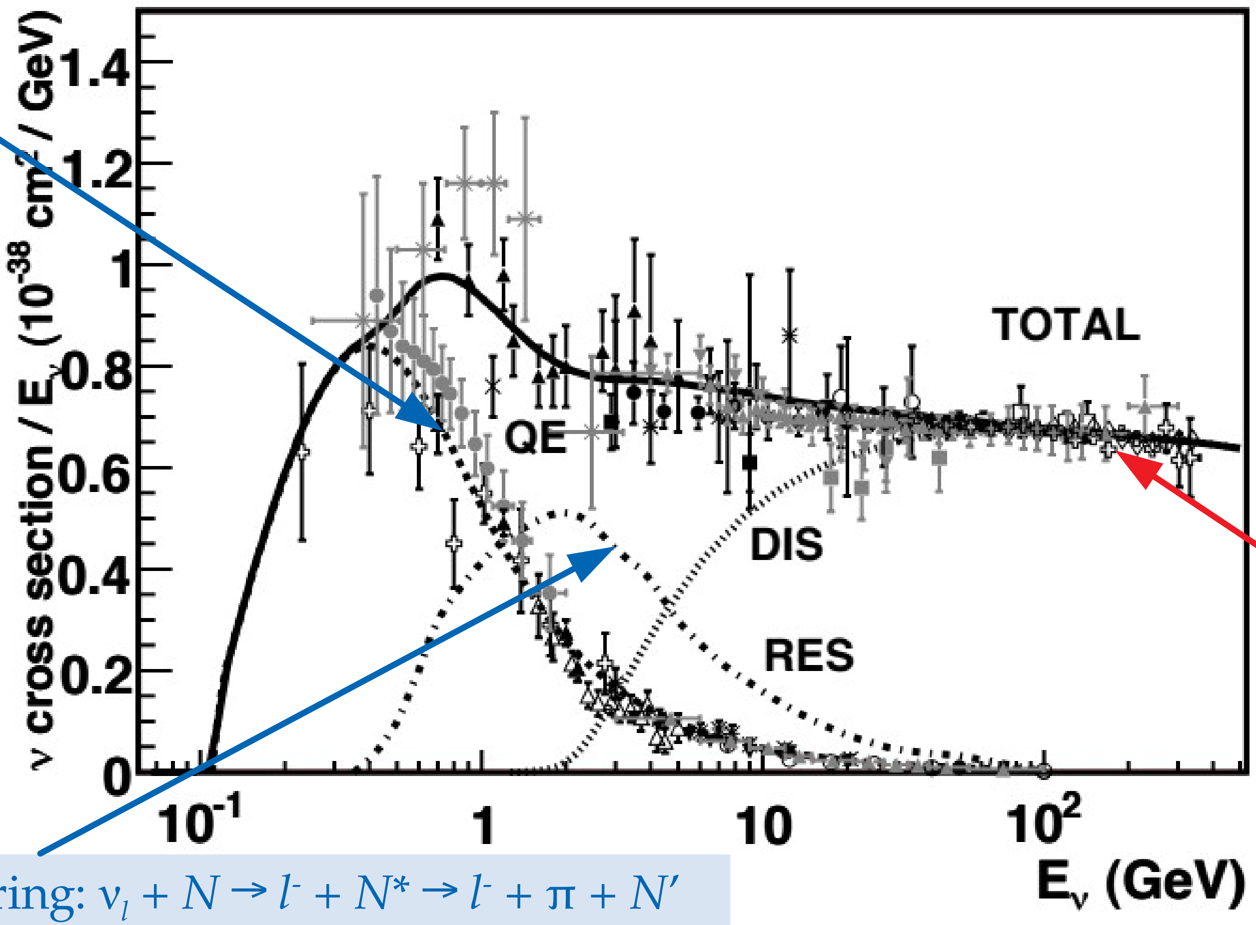


Deep inelastic scattering:

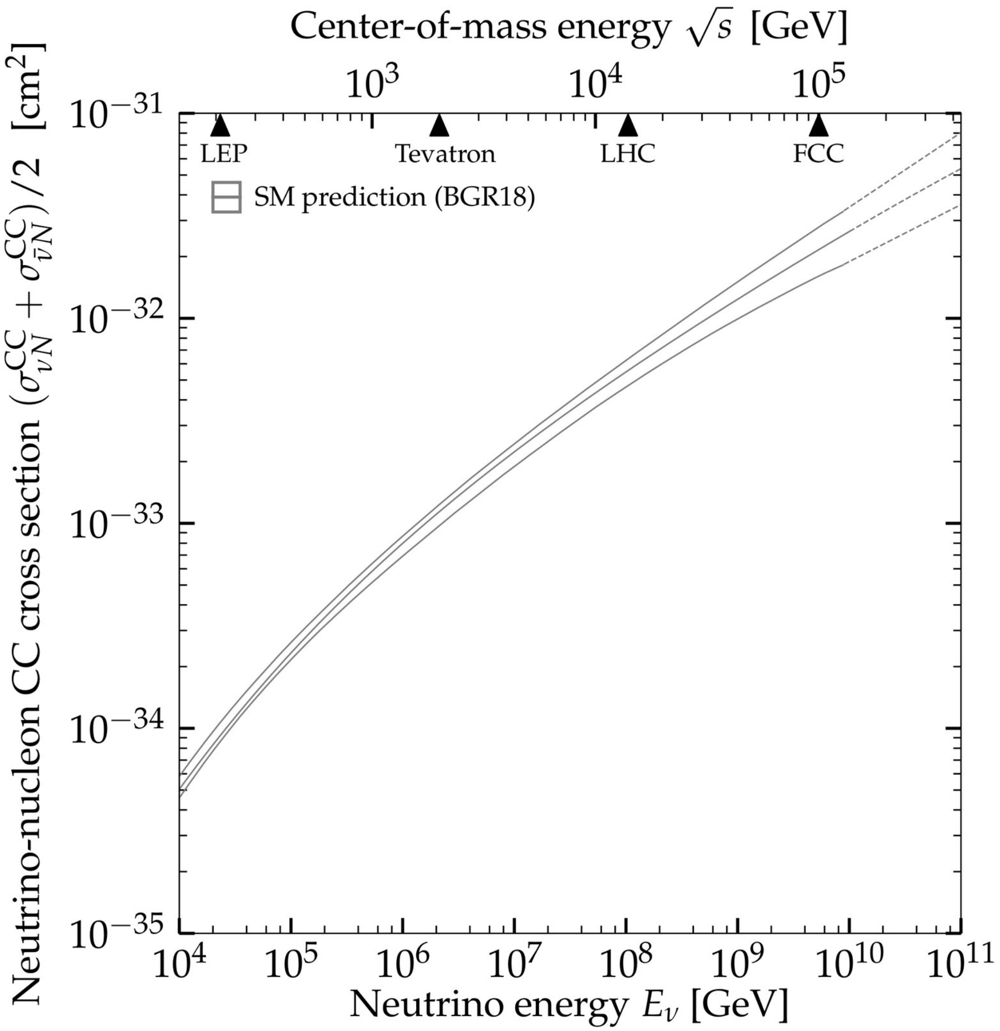
$\nu_l + N \rightarrow l^- + X$

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

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

Particle Data Group

High-energy νN cross section: *prediction*

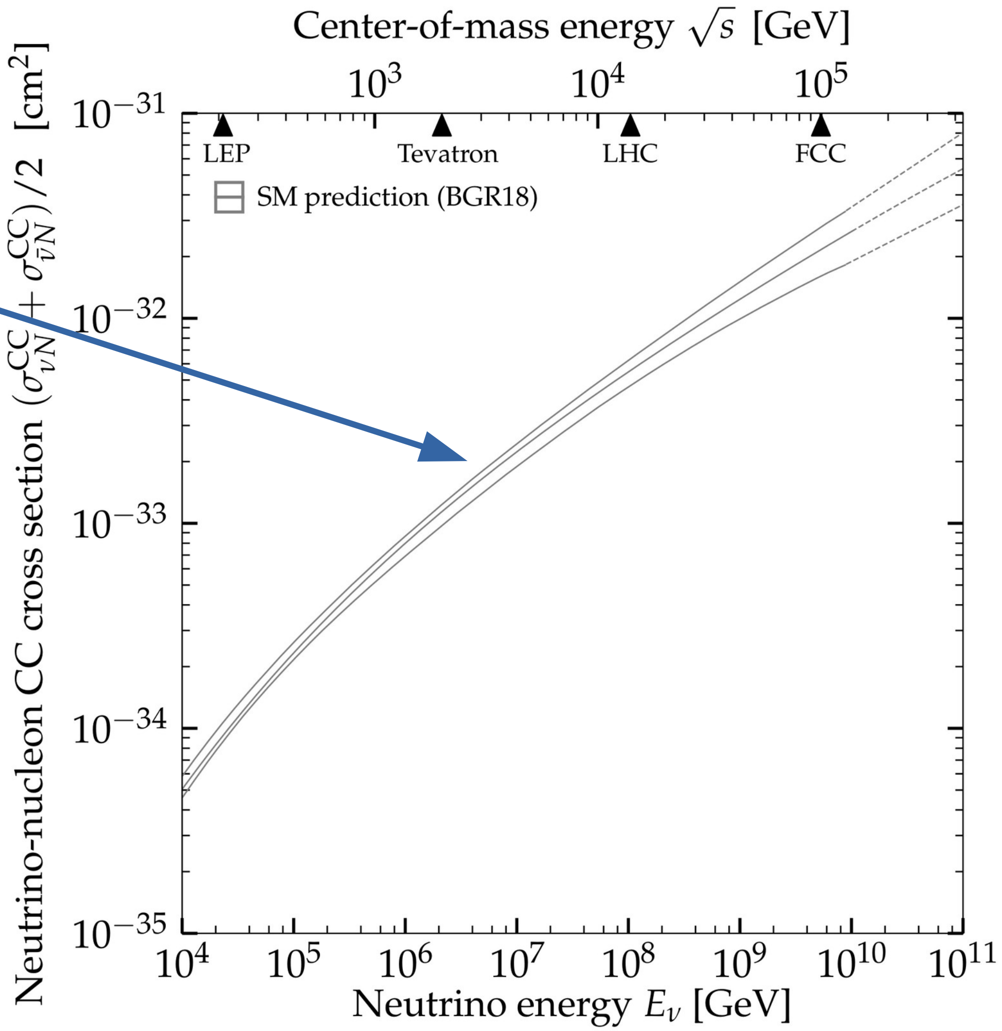


Bertone, Gauld, Rojo, *JHEP* 2019

High-energy νN cross section: *prediction*

Softer-than-linear dependence on E_ν due to the W pole

Uncertainty from extrapolating parton distribution functions (PDFs) to Bjorken $x \sim m_W/E_\nu \sim 10^{-6}$



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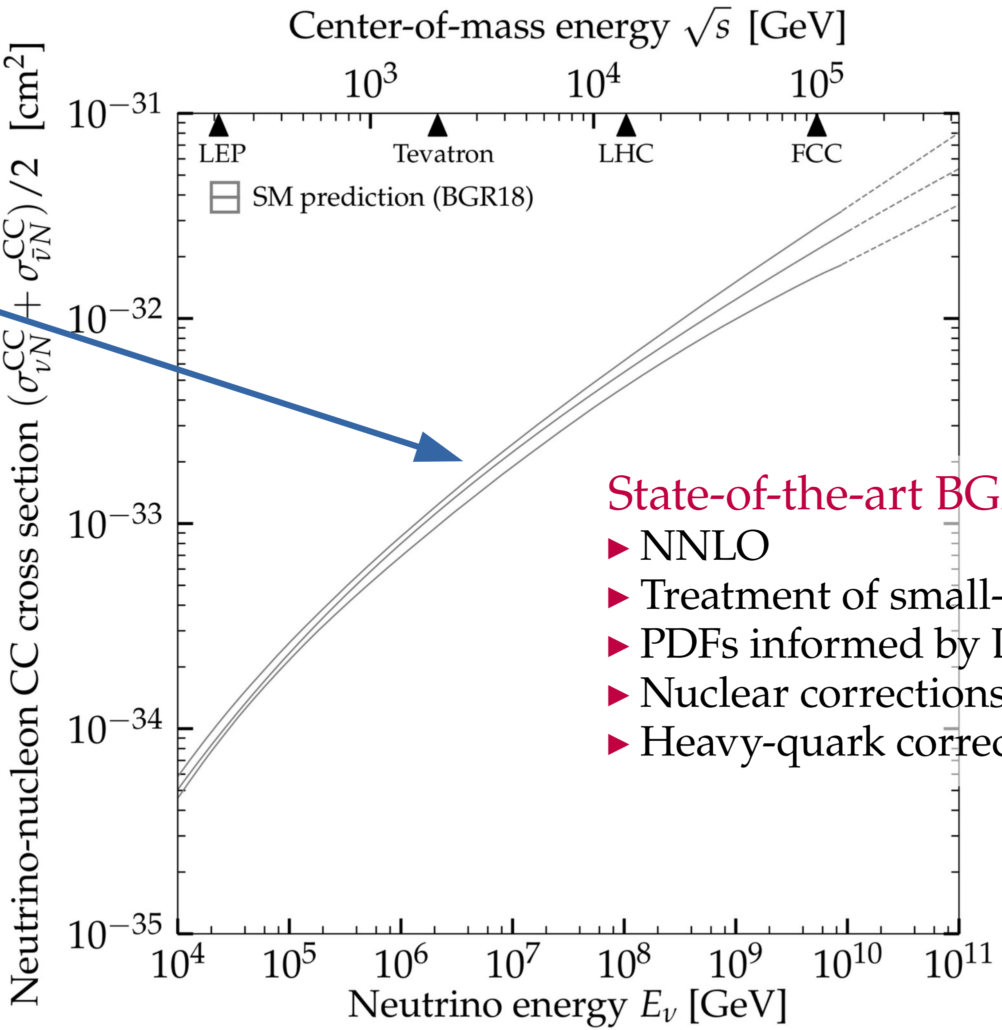
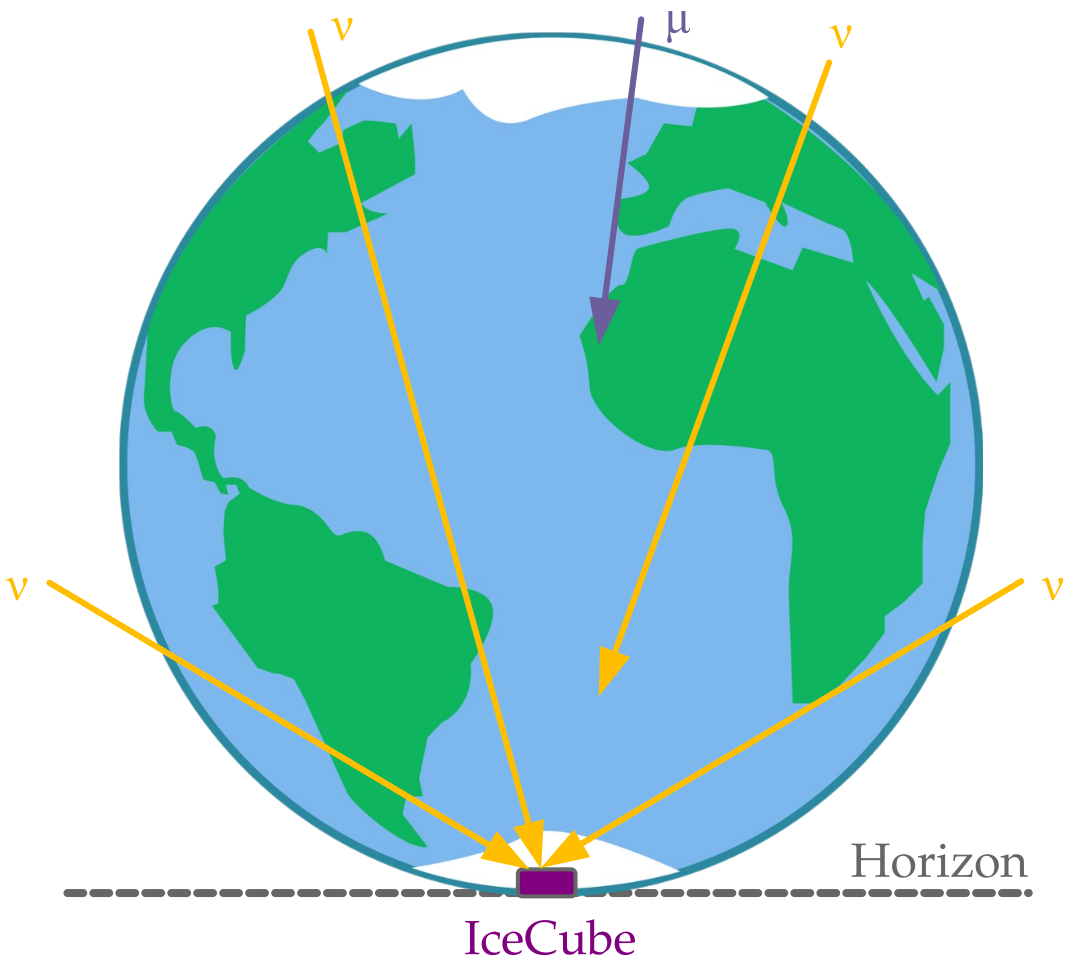


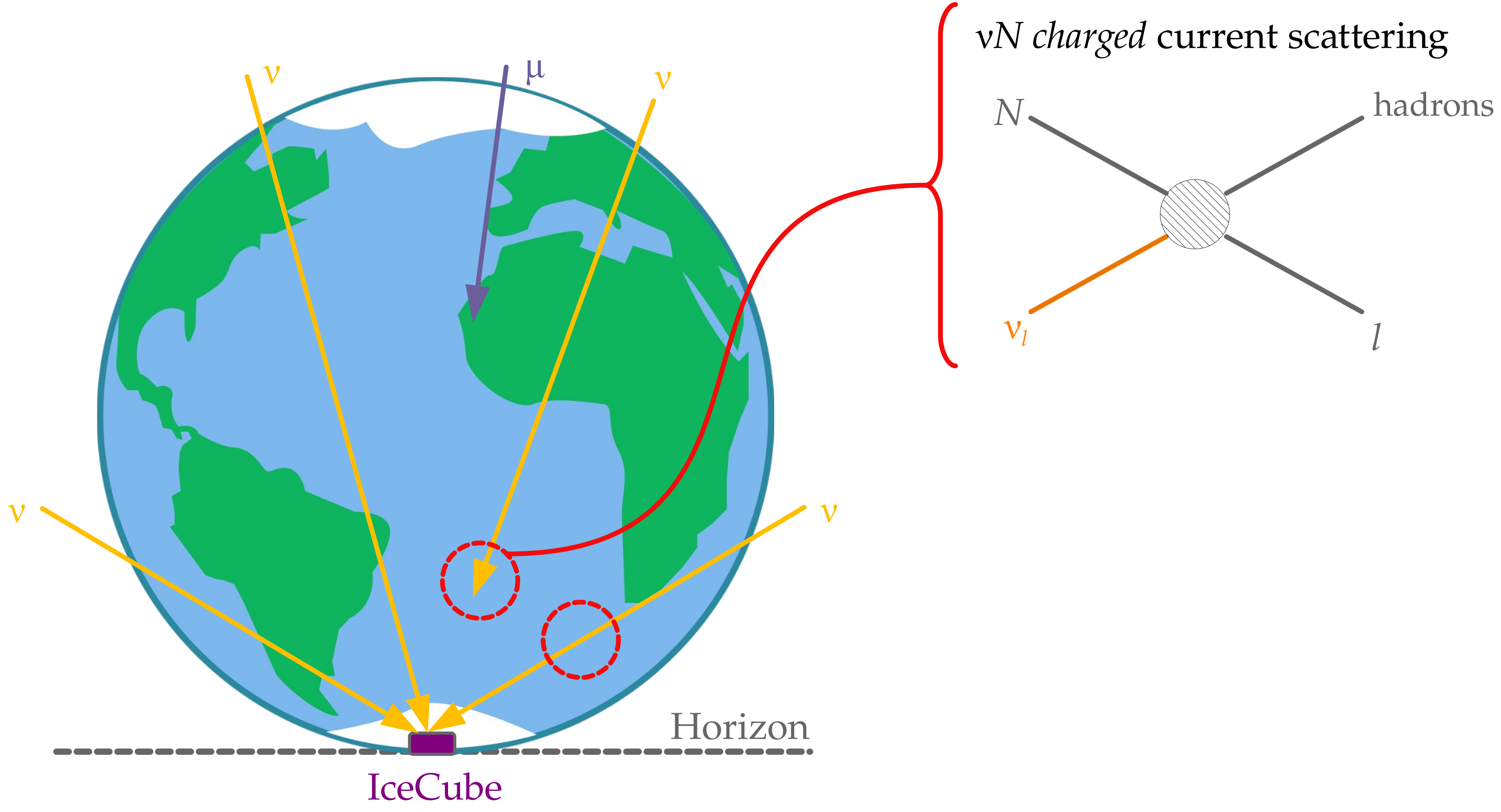
State-of-the-art BGR18 prediction:

- NNLO
- Treatment of small-x effects
- PDFs informed by LHCb D-meson data
- Nuclear corrections
- Heavy-quark corrections

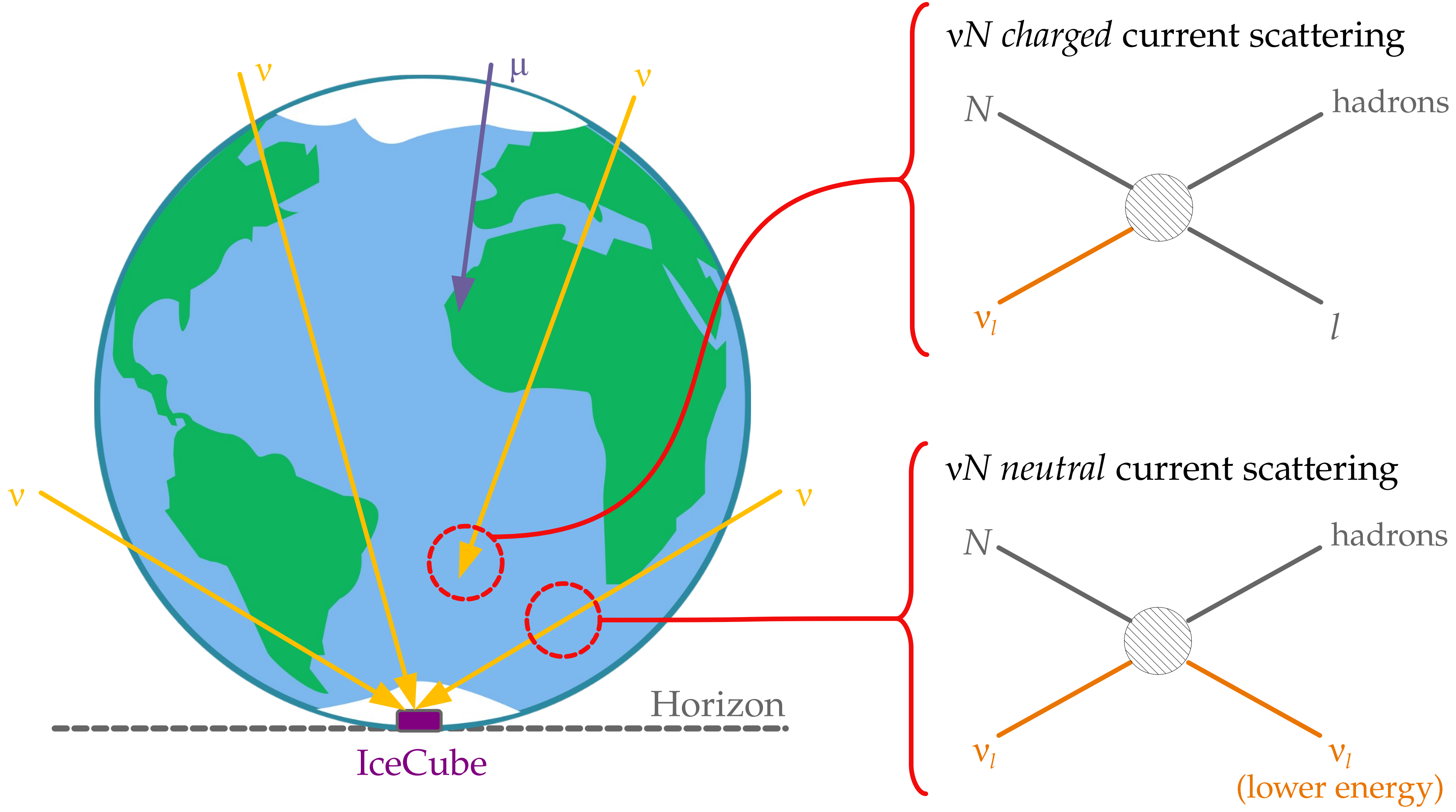
Bertone, Gauld, Rojo, *JHEP* 2019

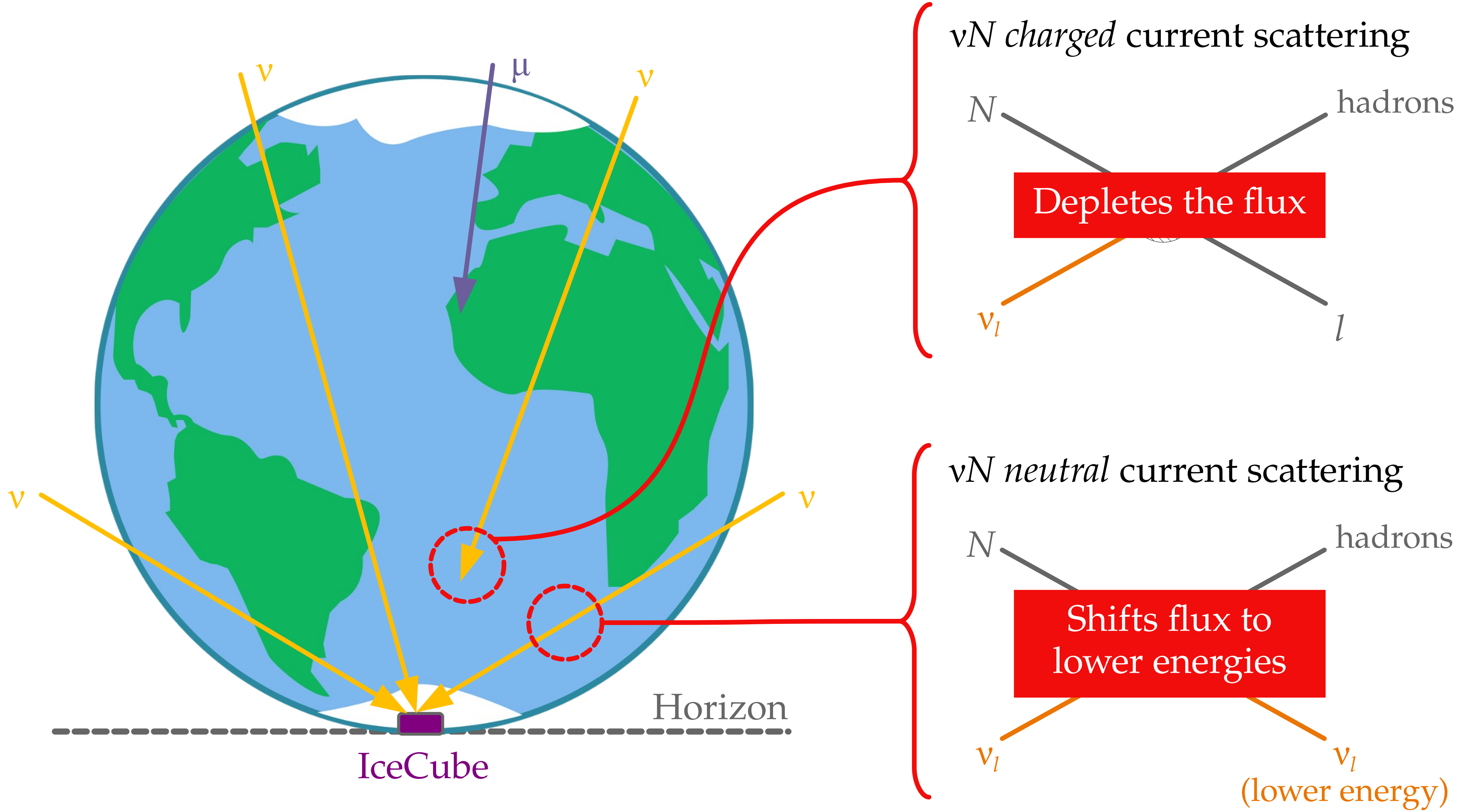


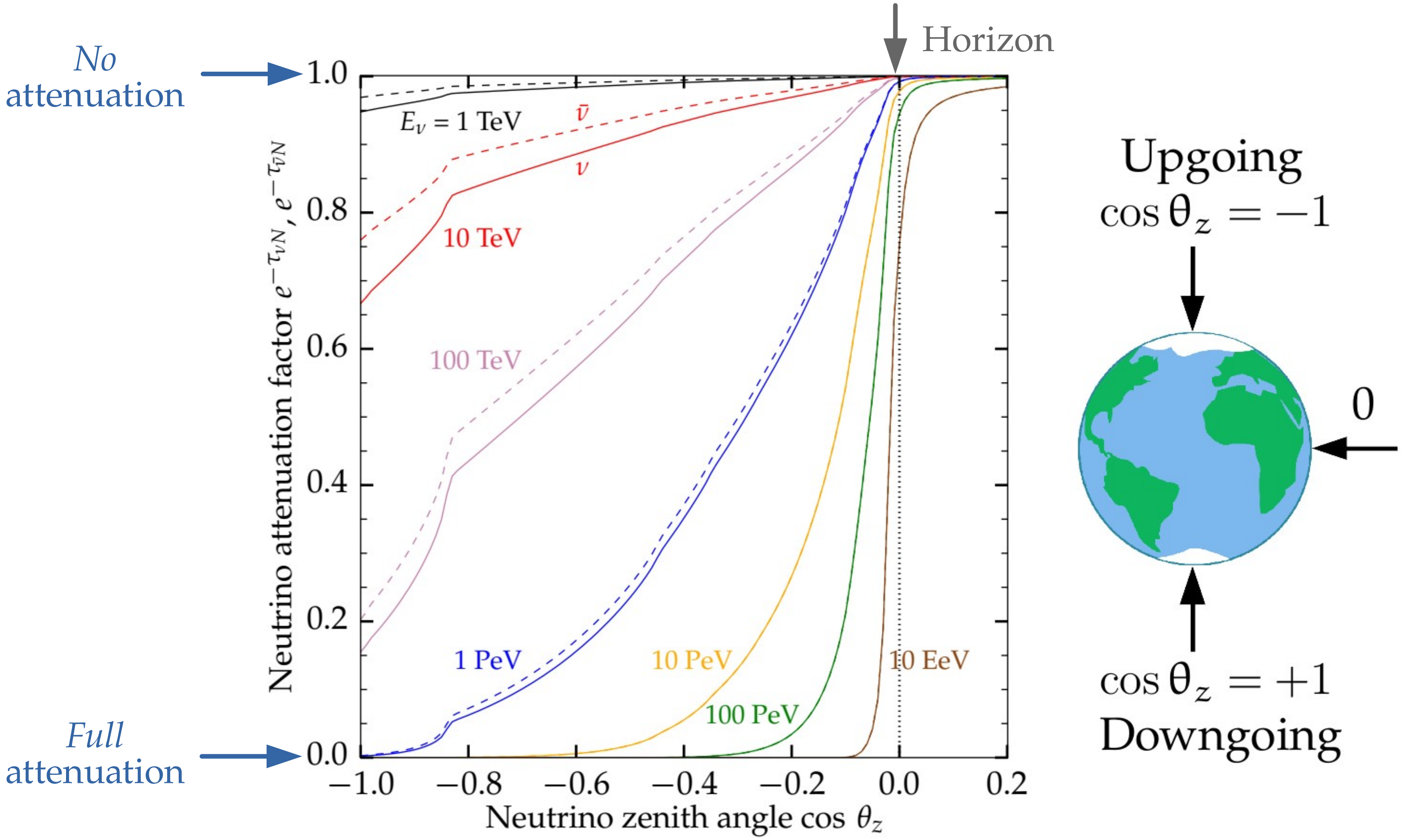
ν
μ
ν
ν
ν
Horizon
IceCube



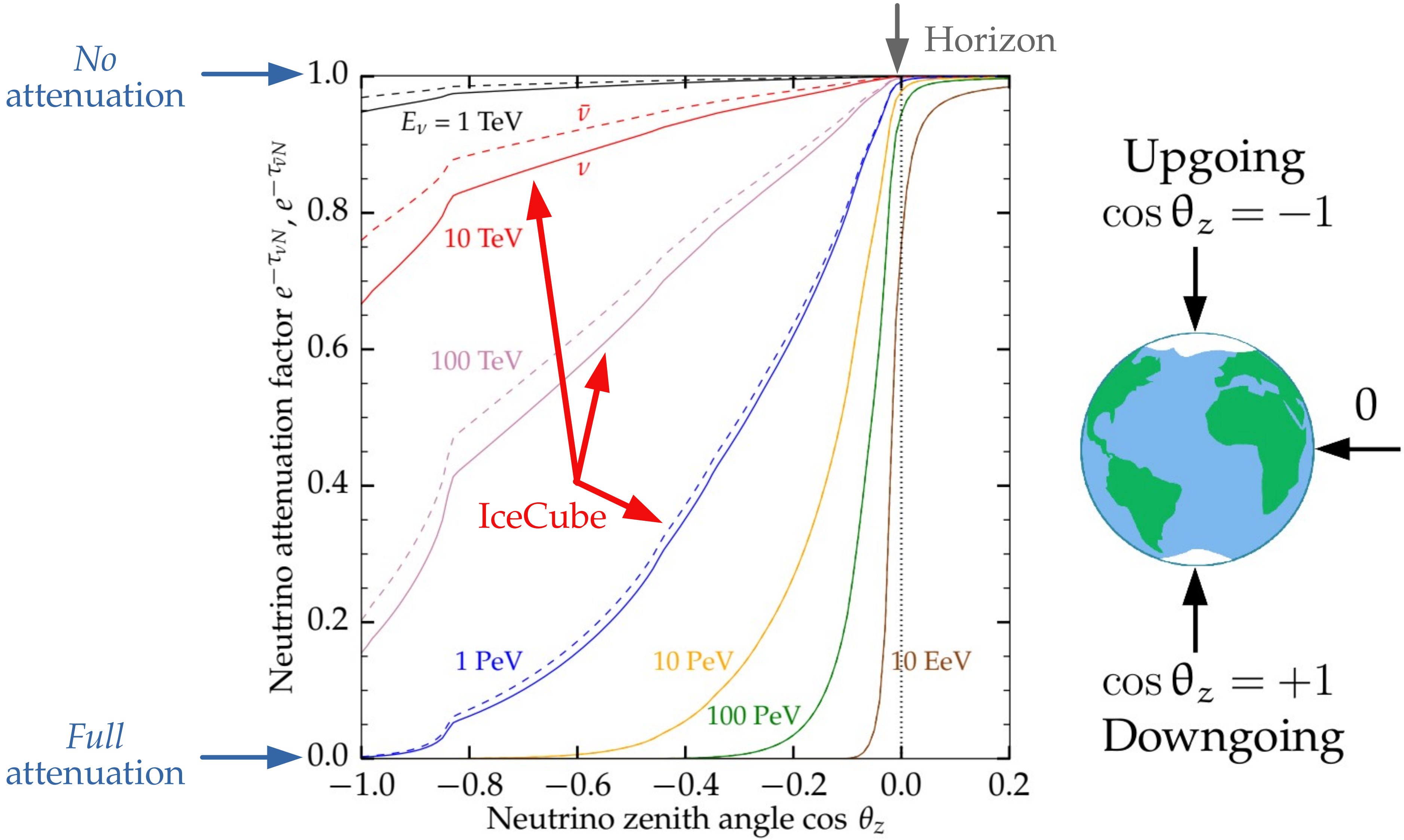
ν
μ
ν
νN *charged* current scattering
N
hadrons
ν_l
l
ν
ν
Horizon
IceCube


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


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



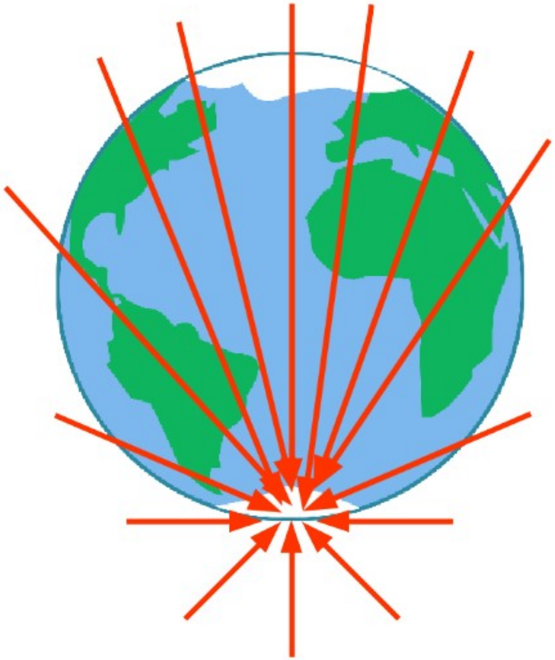
MB & Connolly, *PRL* 2019



MB & Connolly, *PRL* 2019

Measuring the high-energy νN cross section

Below ~ 10 TeV: Earth is transparent



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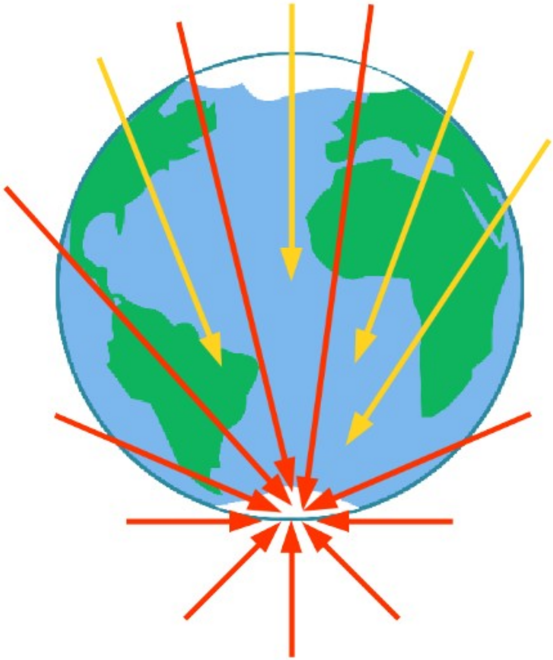

Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
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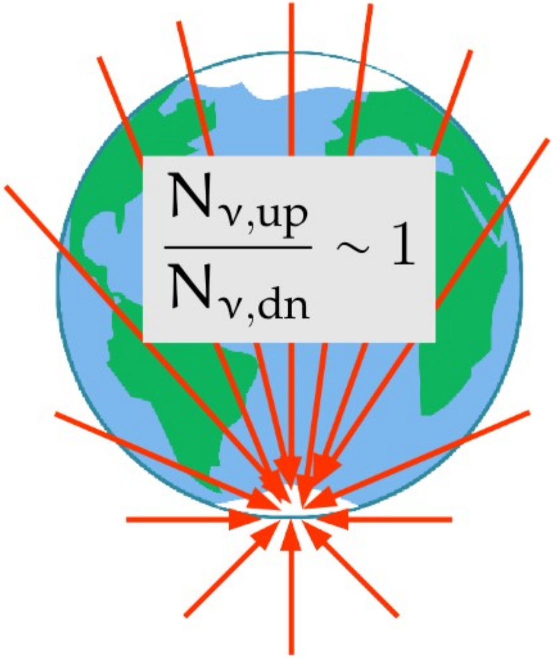

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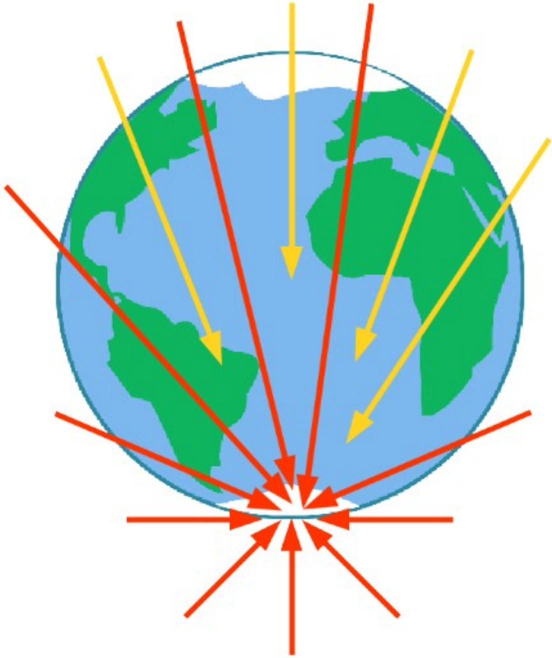

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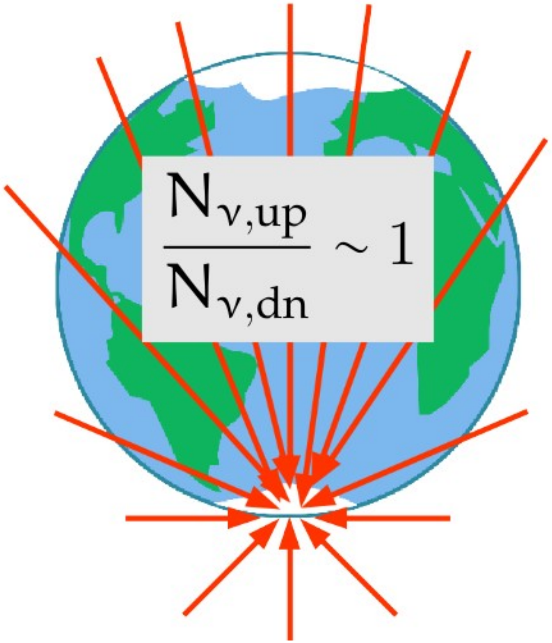

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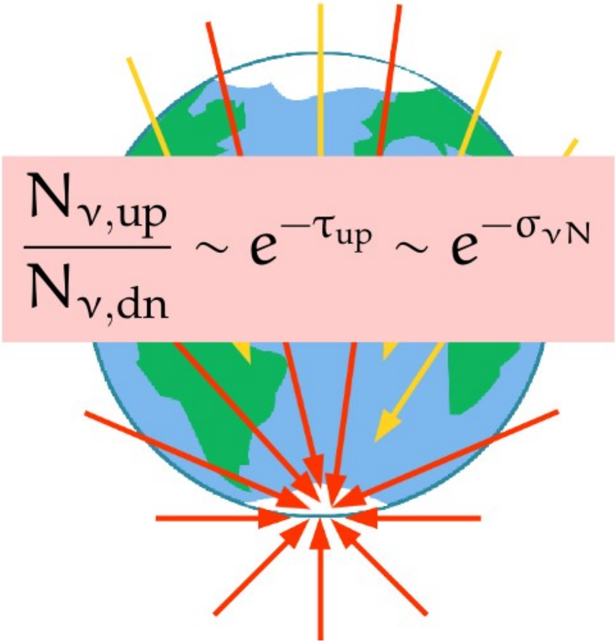

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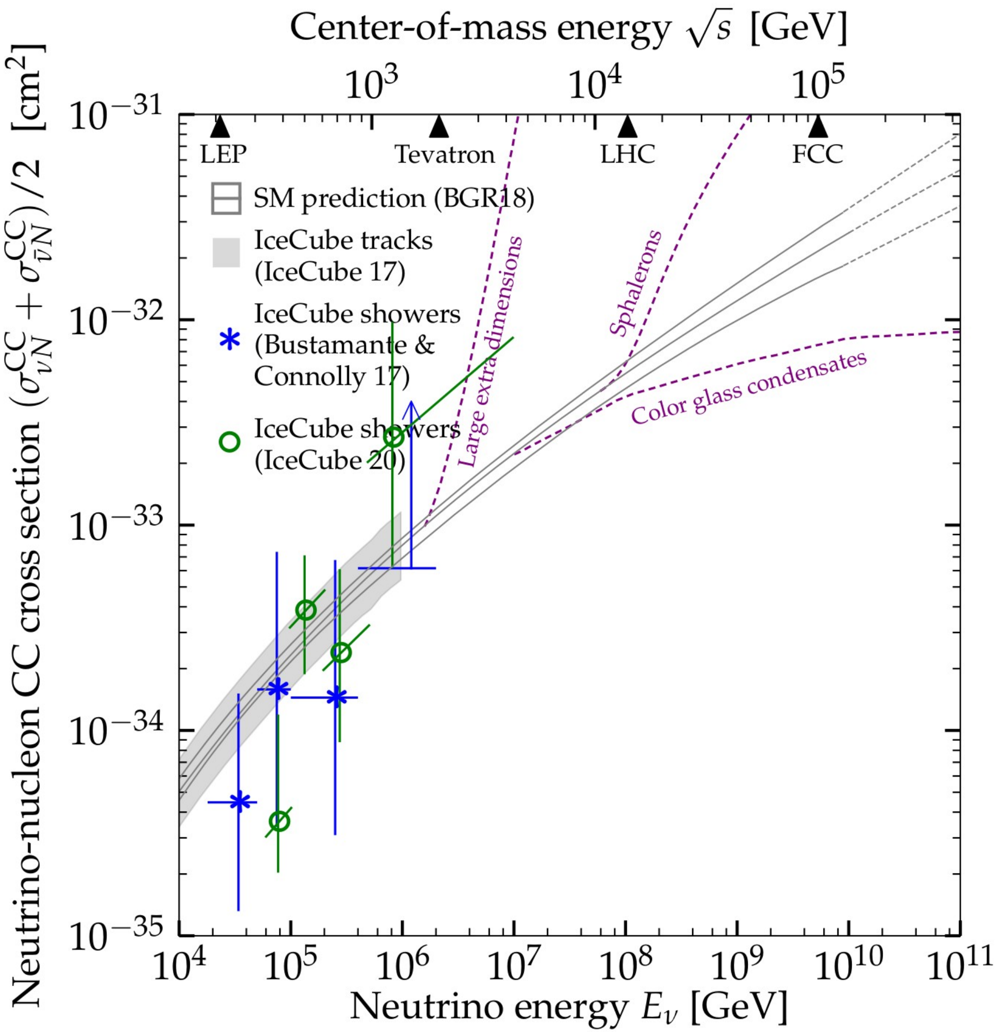
High-energy *νN* cross section: *today*



BGR18 prediction from:
Bertone, Gauld, Rojo, *JHEP* 2019

See also:
García, Gauld, Heijboer, Rojo, *JCAP* 2020

Measurements from:
IceCube, 2011.03560
MB & Connolly, *PRL* 2019
IceCube, *Nature* 2017

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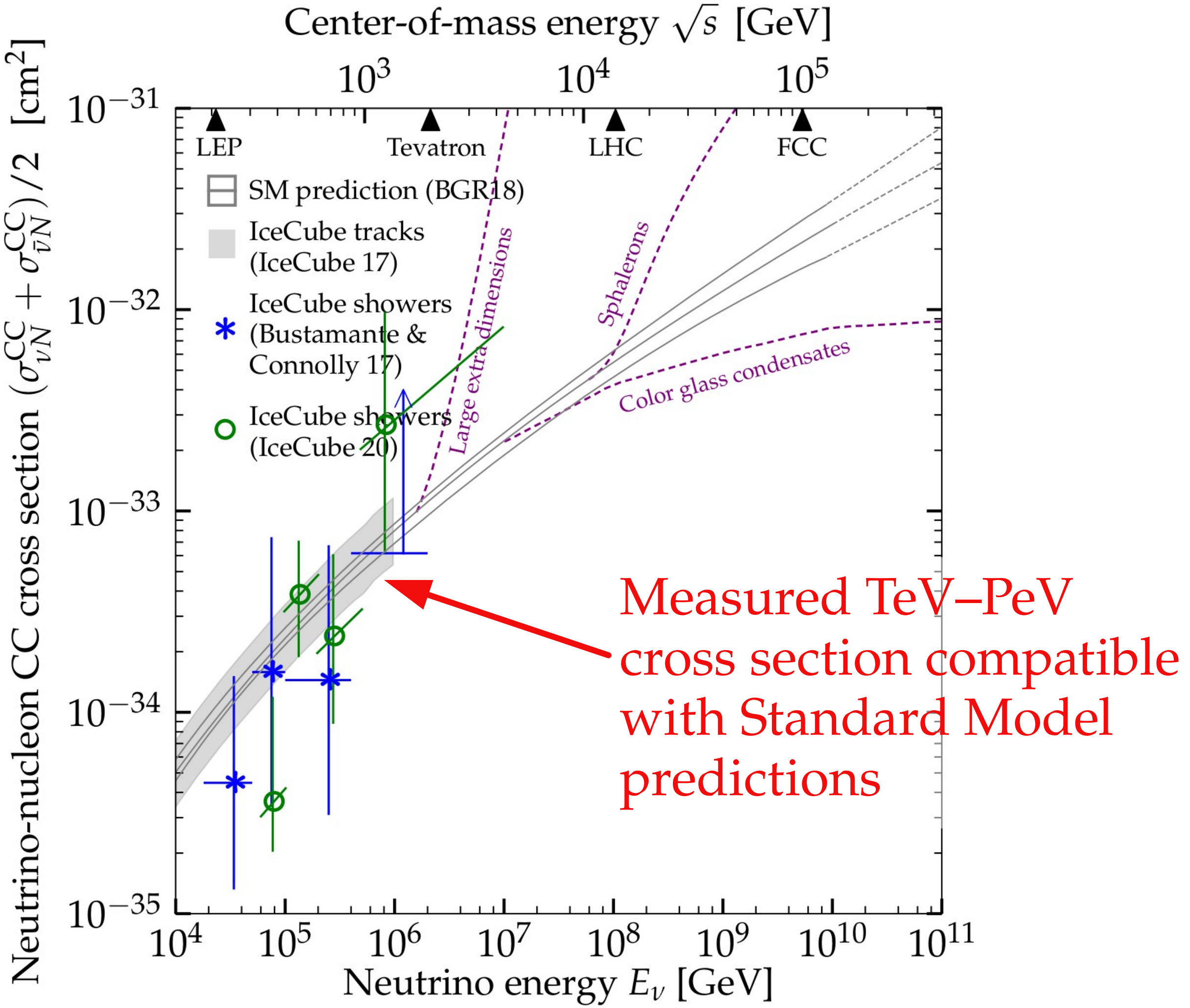

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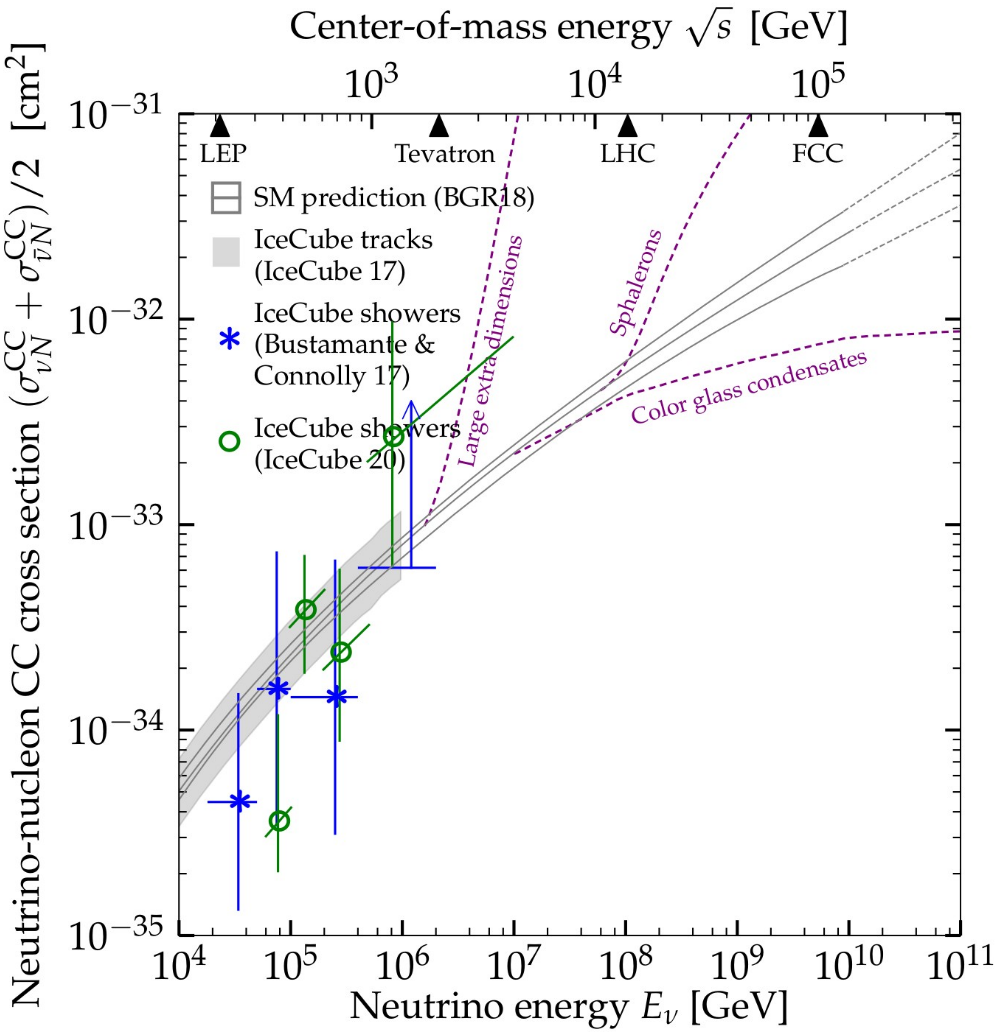

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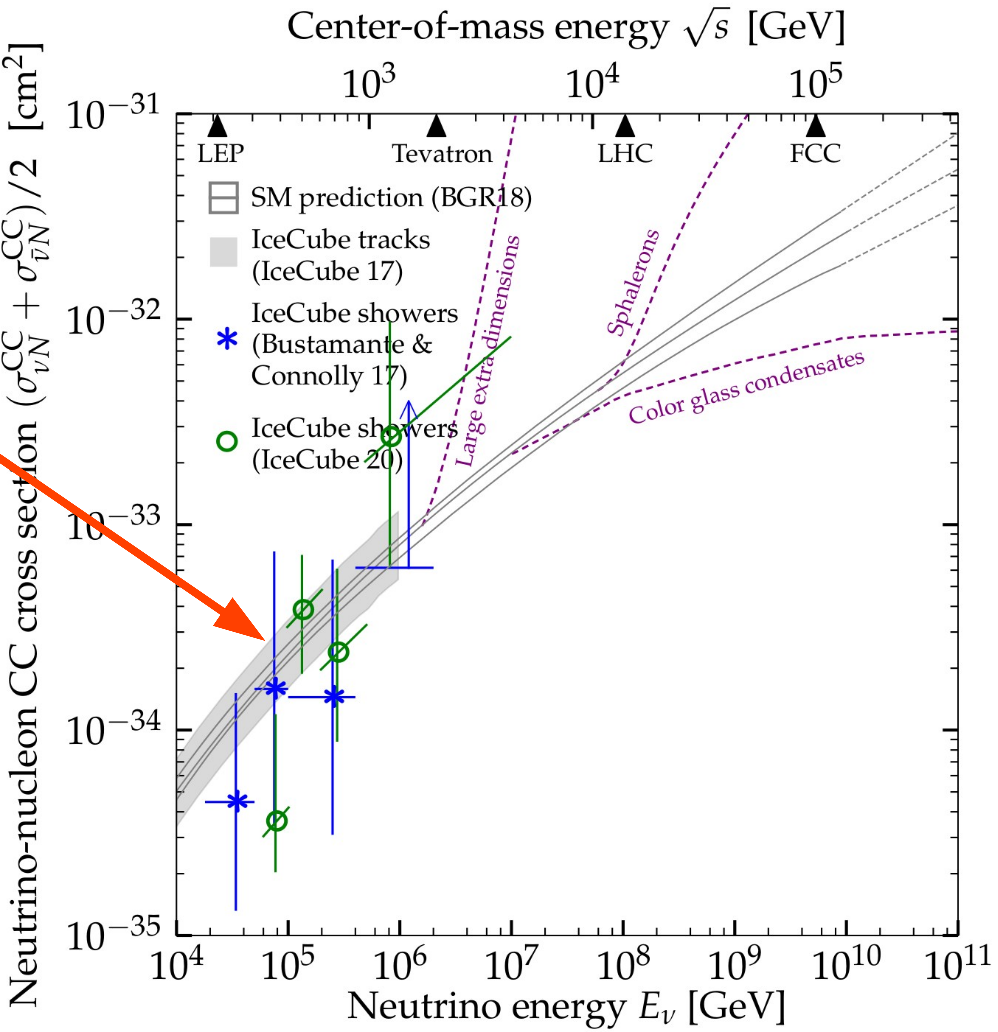
IceCube, 2011.03560
MB & Connolly, *PRL* 2019
IceCube, *Nature* 2017

High-energy νN cross section: *today*

Measured:
TeV – PeV
cross section



BGR18 prediction from:
Bertone, Gauld, Rojo, *JHEP* 2019

See also:
García, Gauld, Heijboer, Rojo, *JCAP* 2020

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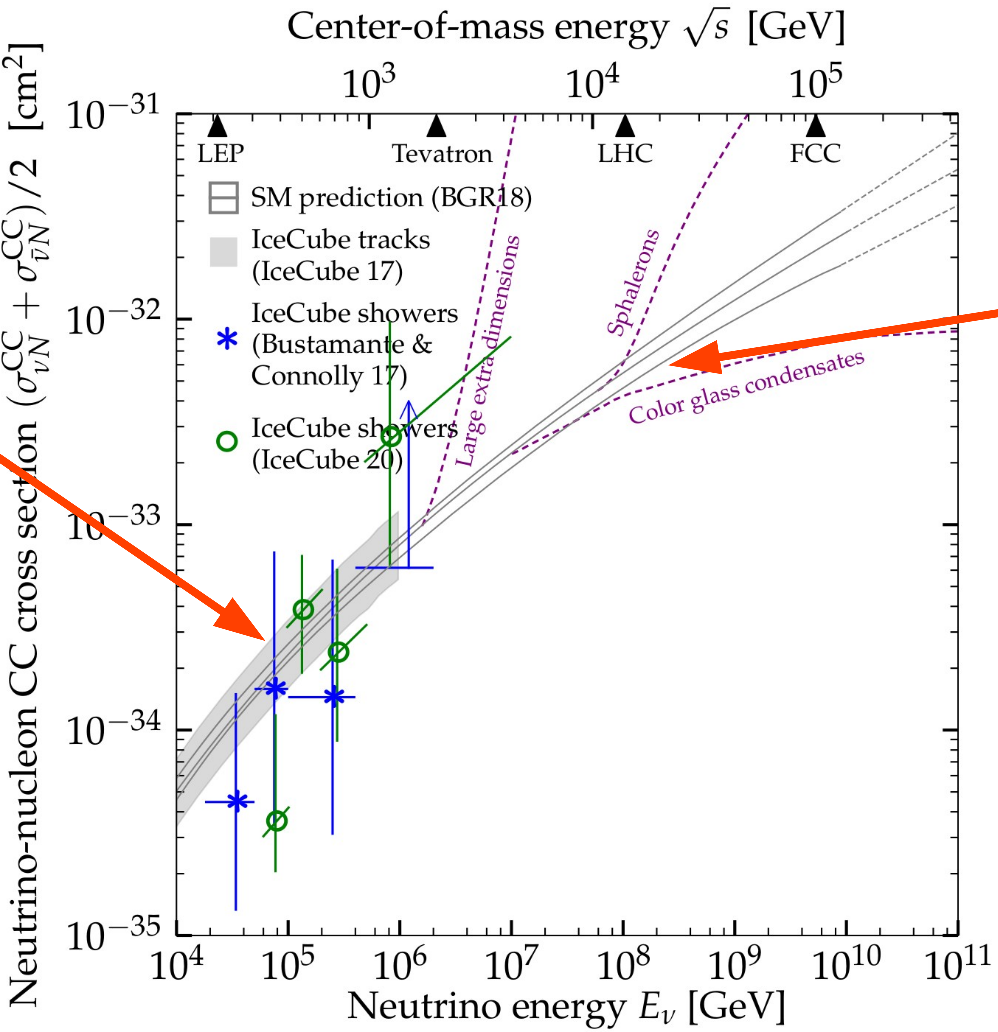

Measured:
TeV – PeV cross section

Not measured:
> 10-PeV cross section

BGR18 prediction from:
Bertone, Gauld, Rojo, *JHEP* 2019

See also:
García, Gauld, Heijboer, Rojo, *JCAP* 2020

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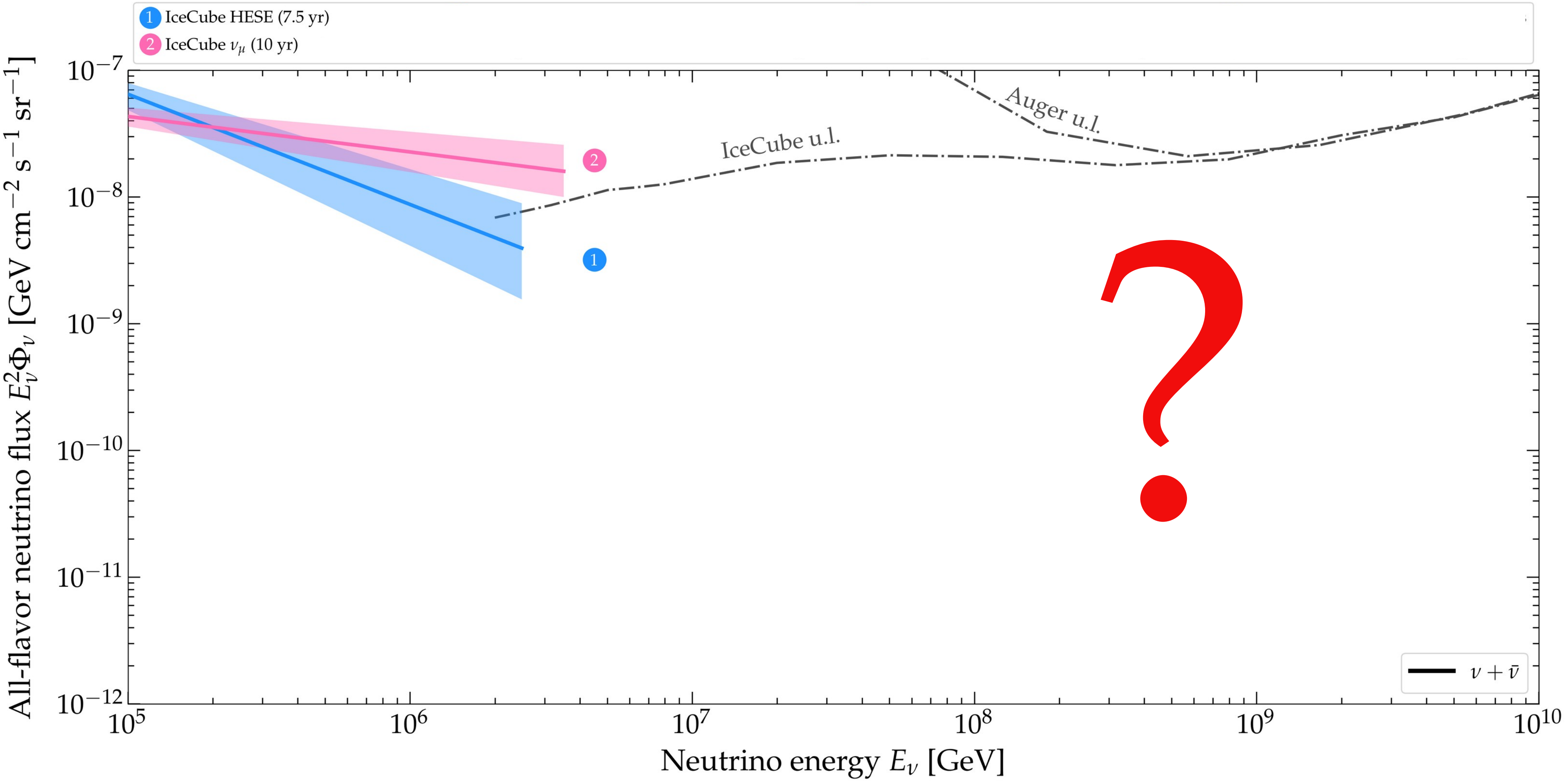
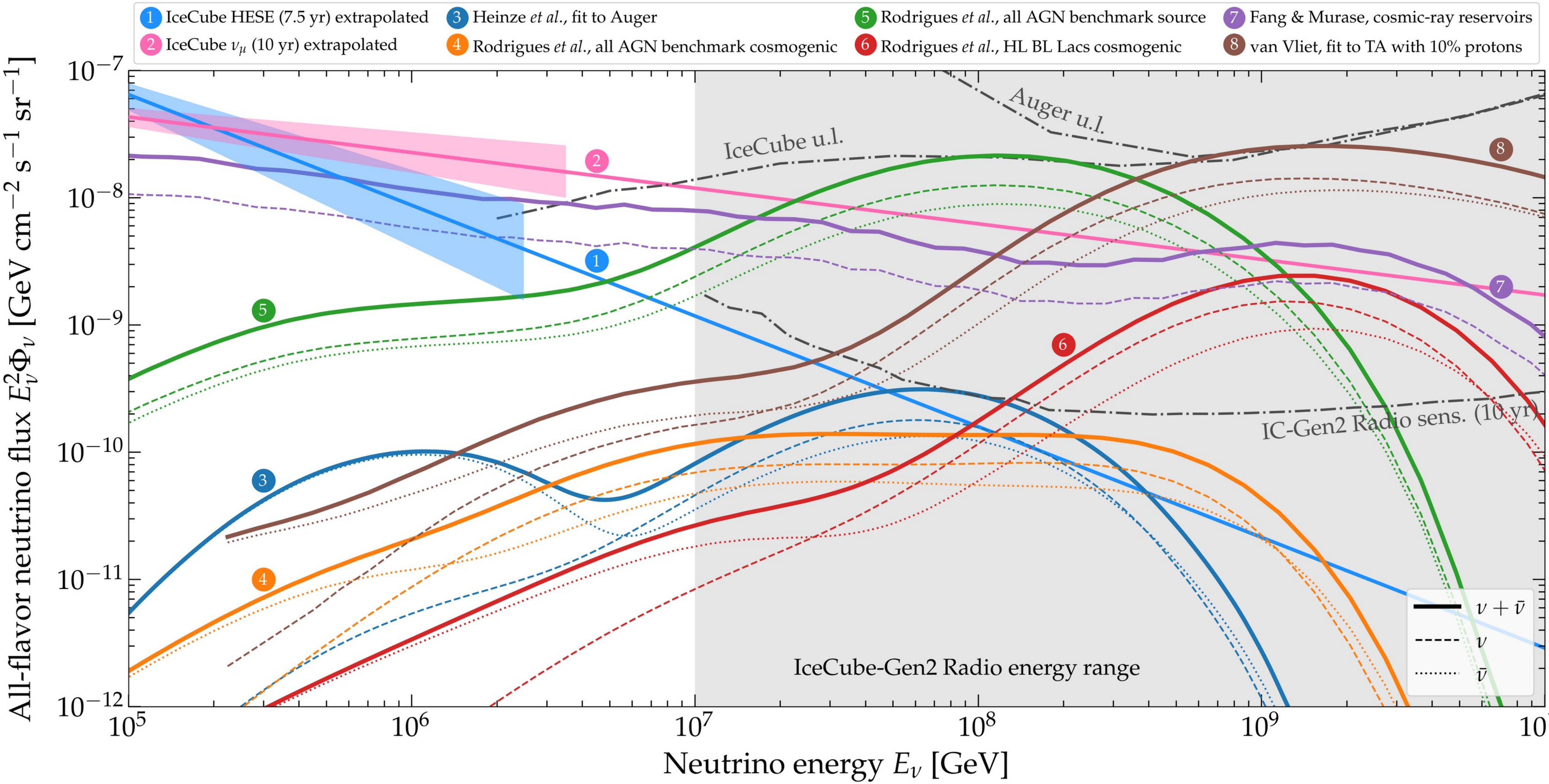
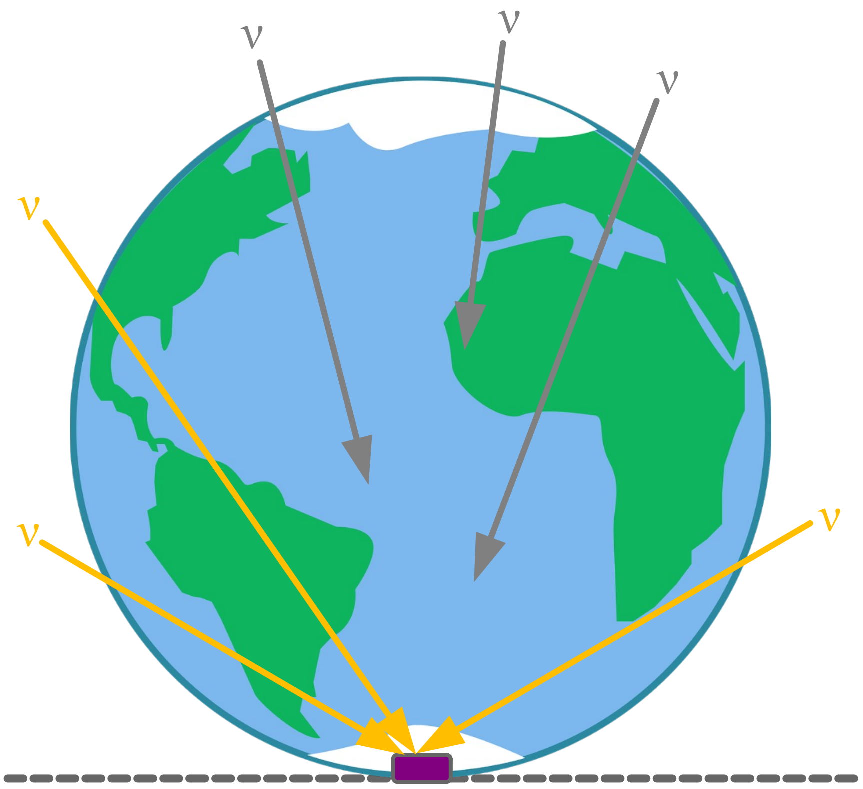


1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (10 yr)
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
All-flavor neutrino flux $E_\nu^2\Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
Auger u.l.
IceCube u.l.
2
1
?
$\nu + \bar{\nu}$
10^5
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy E_ν [GeV]



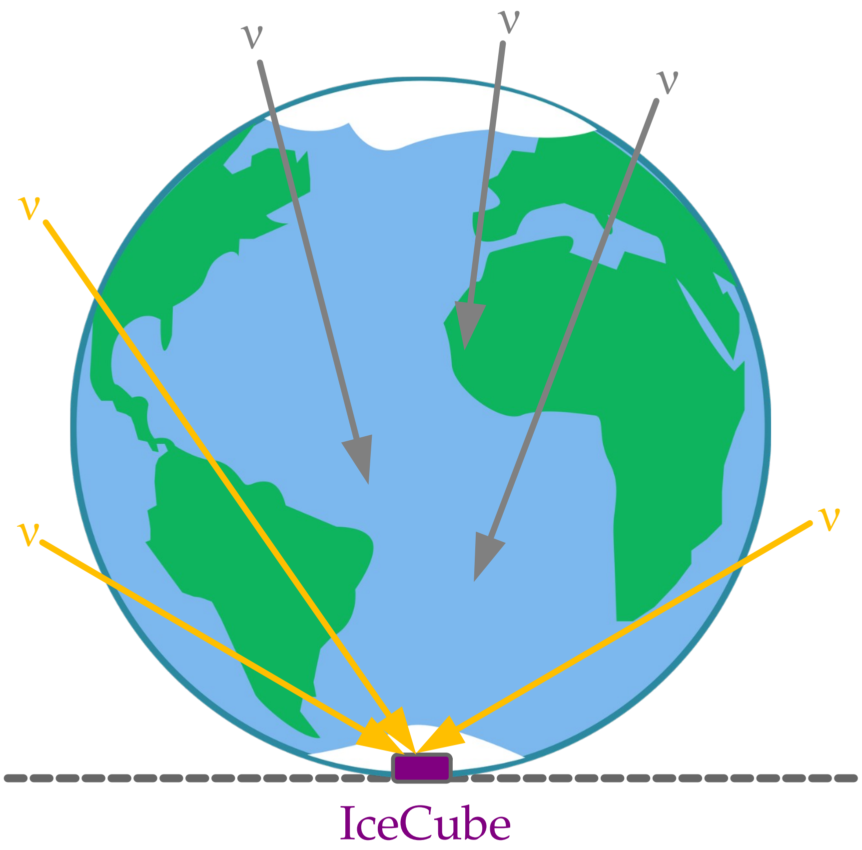
1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (10 yr) extrapolated
3 Heinze et al., fit to Auger
4 Rodrigues et al., all AGN benchmark cosmogenic
5 Rodrigues et al., all AGN benchmark source
6 Rodrigues et al., HL BL Lacs cosmogenic
7 Fang & Murase, cosmic-ray reservoirs
8 van Vliet, fit to TA with 10% protons
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
$\nu + \bar{\nu}$
ν
$\bar{\nu}$

TeV–PeV:



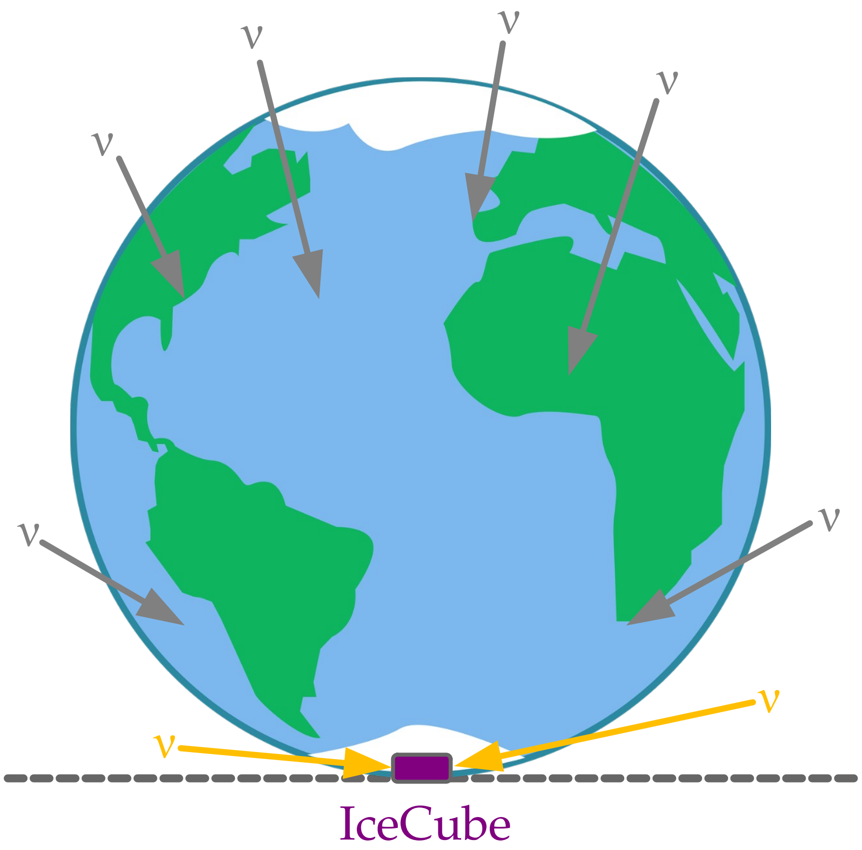
Earth is *almost fully* opaque,
some upgoing ν still make it through

TeV–PeV:



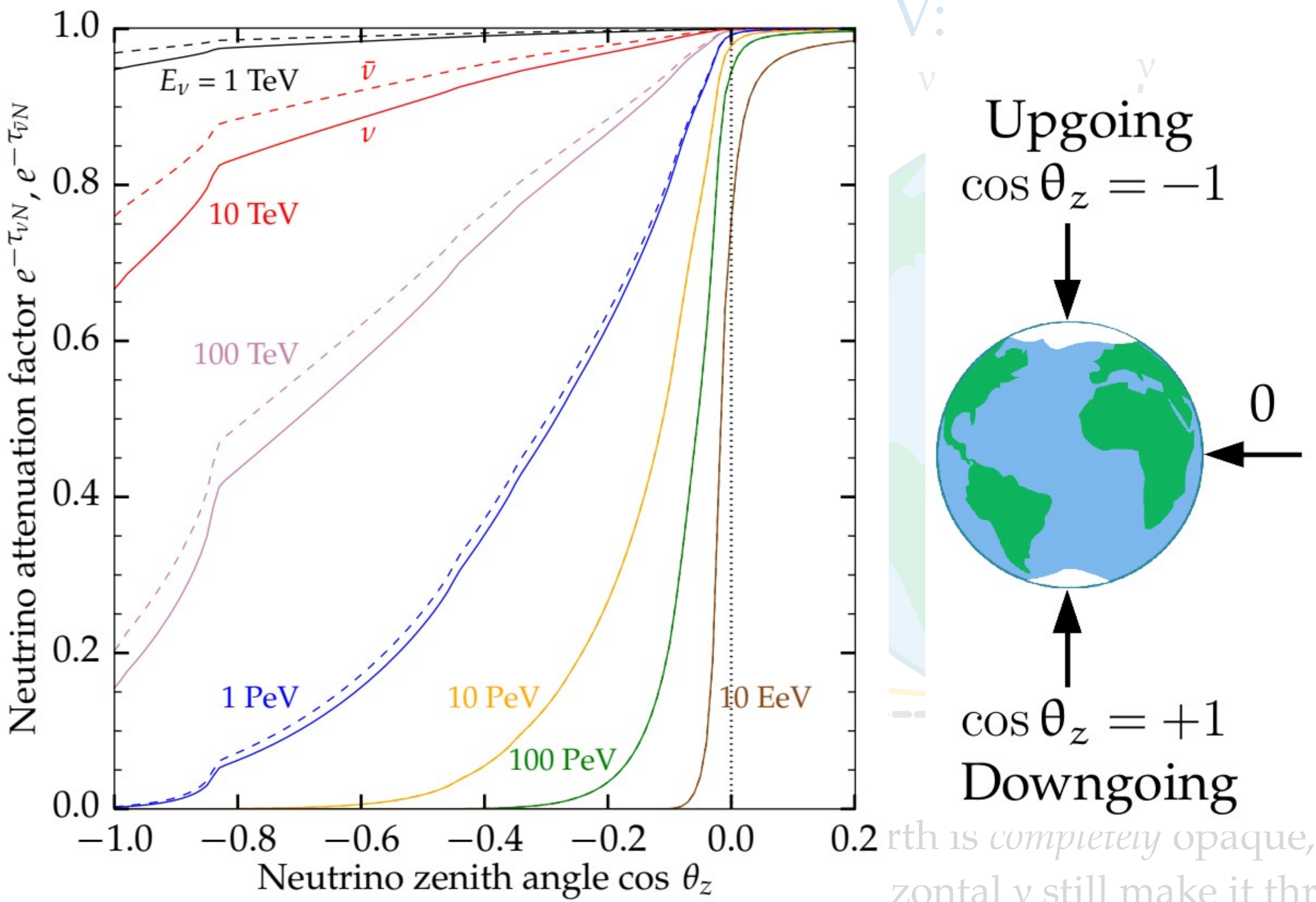
Earth is *almost fully* opaque,
some upgoing ν still make it through

> 100 PeV:



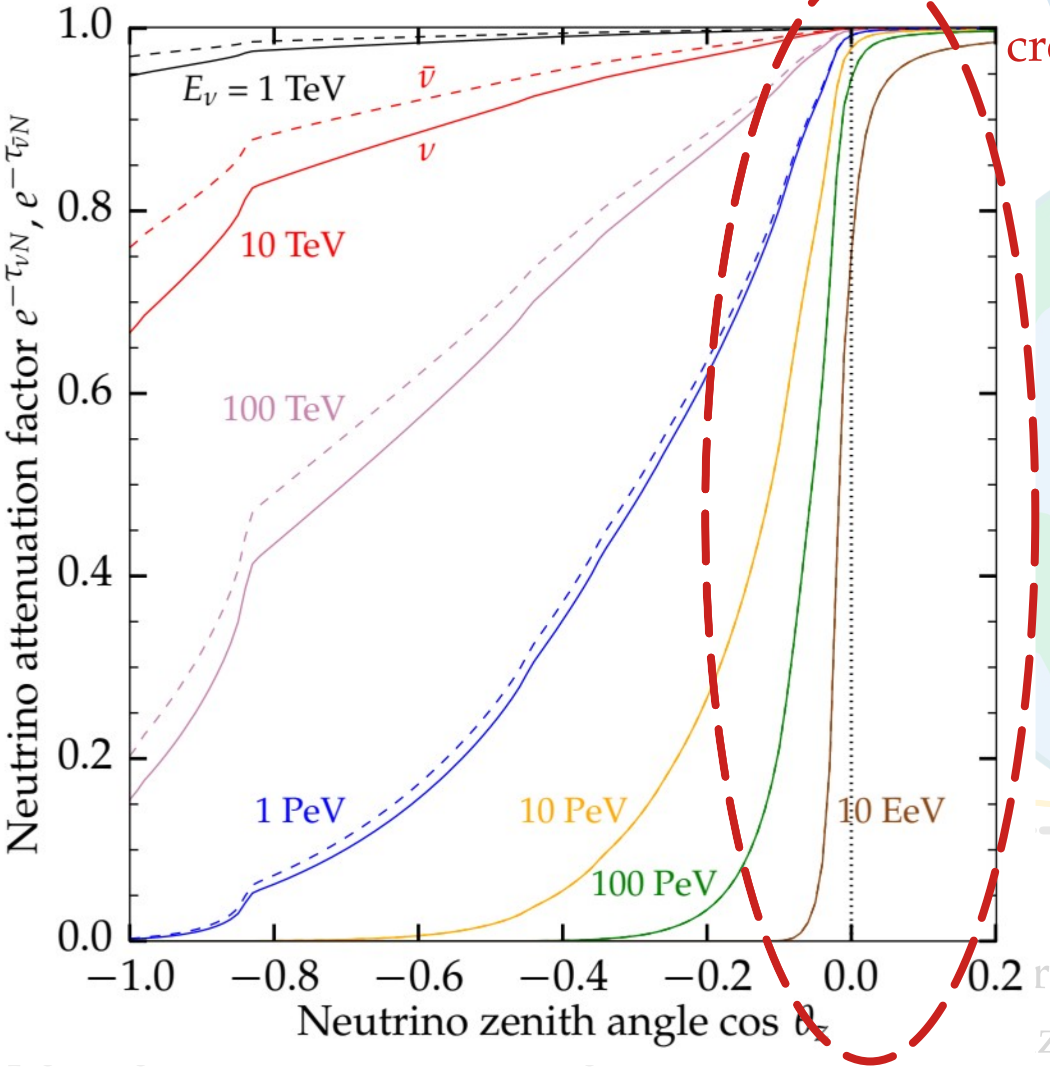
Earth is *completely* opaque,
but horizontal ν still make it through

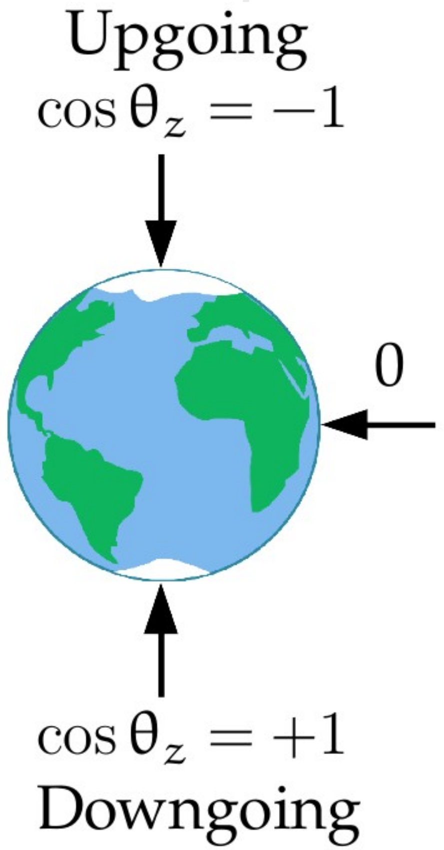
TeV–PeV

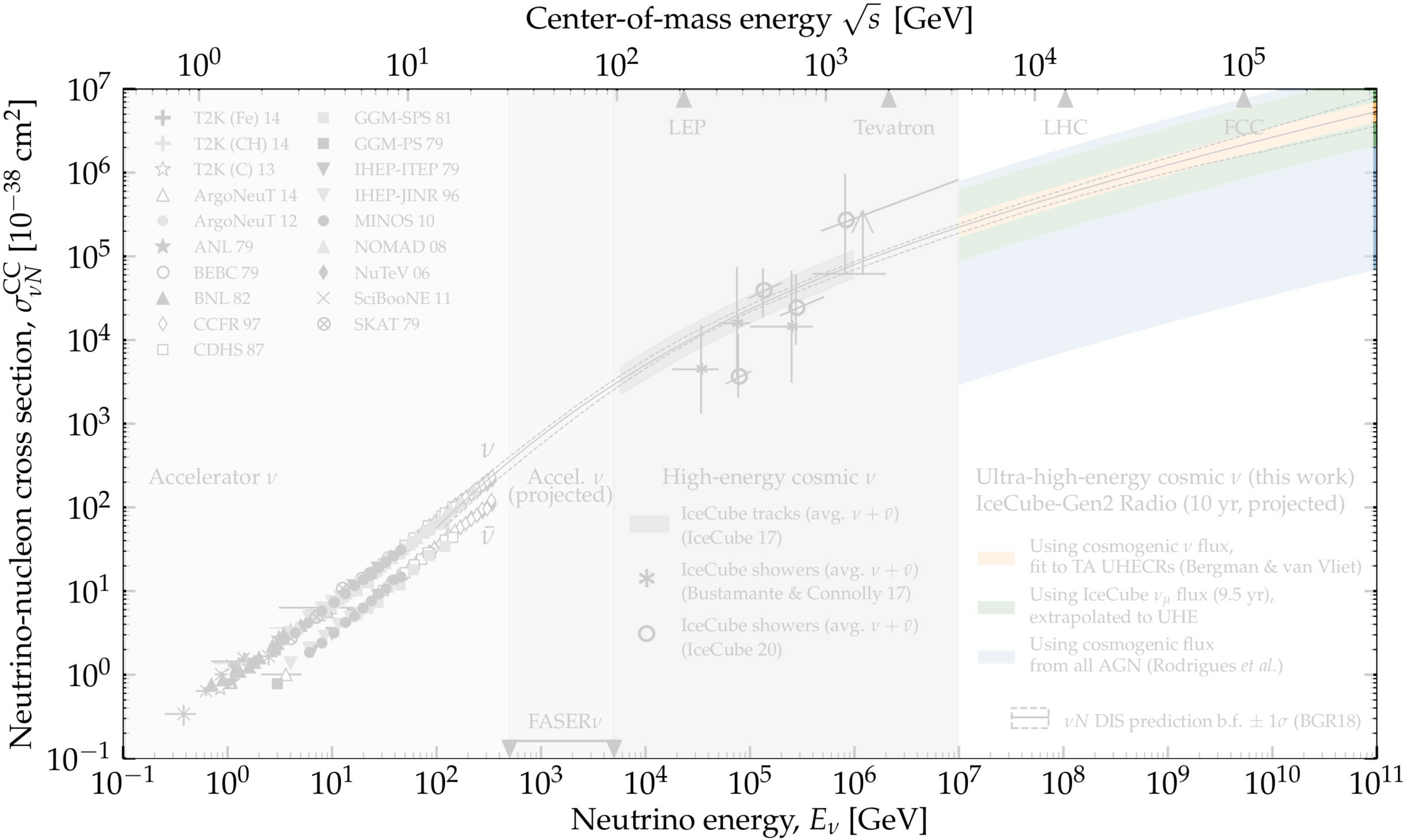


Ea… rth is *completely* opaque,
some … zontal ν still make it through

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







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T2K (CH) 14
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SKAT 79
LEP
Tevatron
LHC
FCC
Accelerator ν
Accel. ν (projected)
High-energy cosmic ν
Ultra-high-energy cosmic ν (this work)
IceCube-Gen2 Radio (10 yr, projected)
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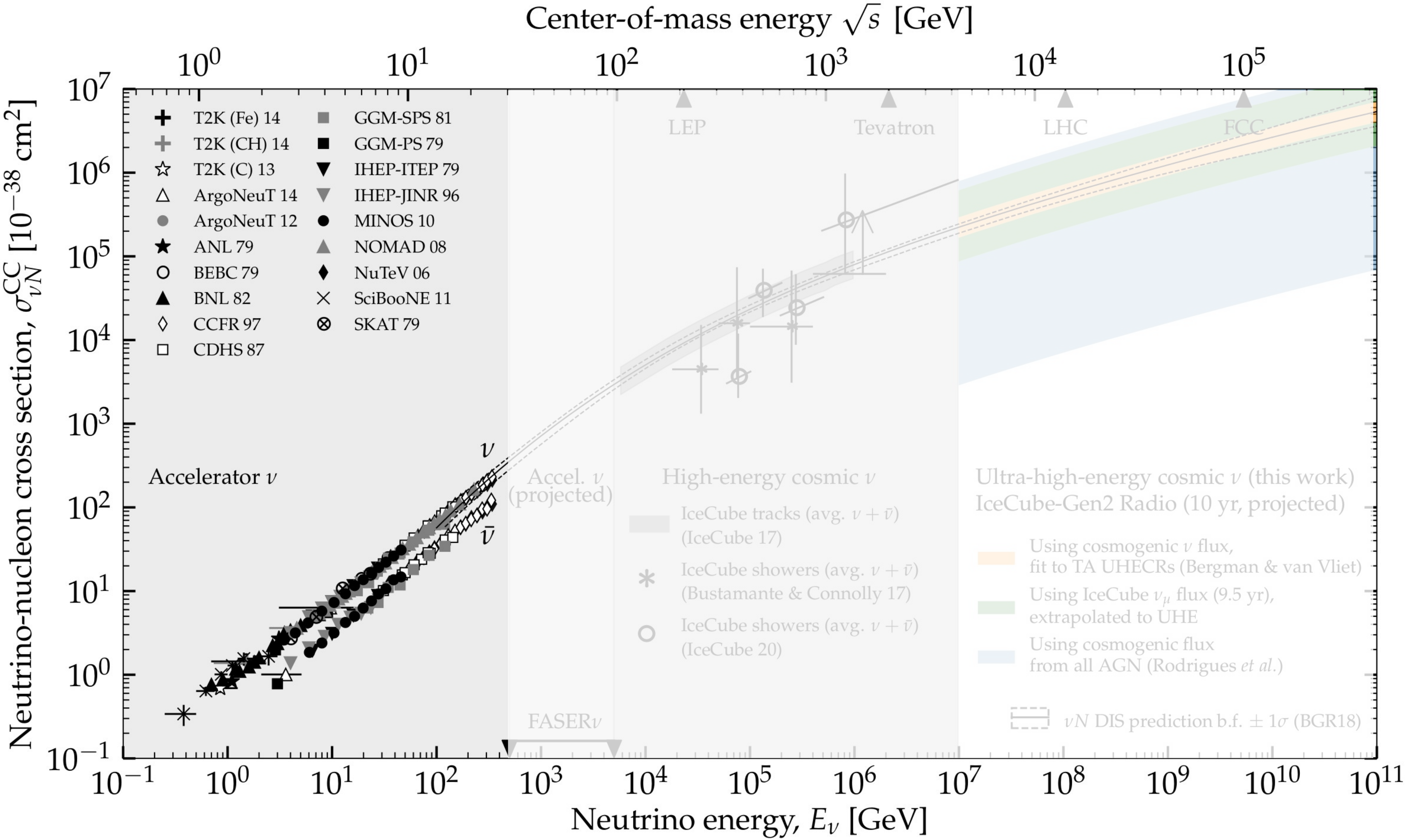
FASERν
ν
$\bar{\nu}$



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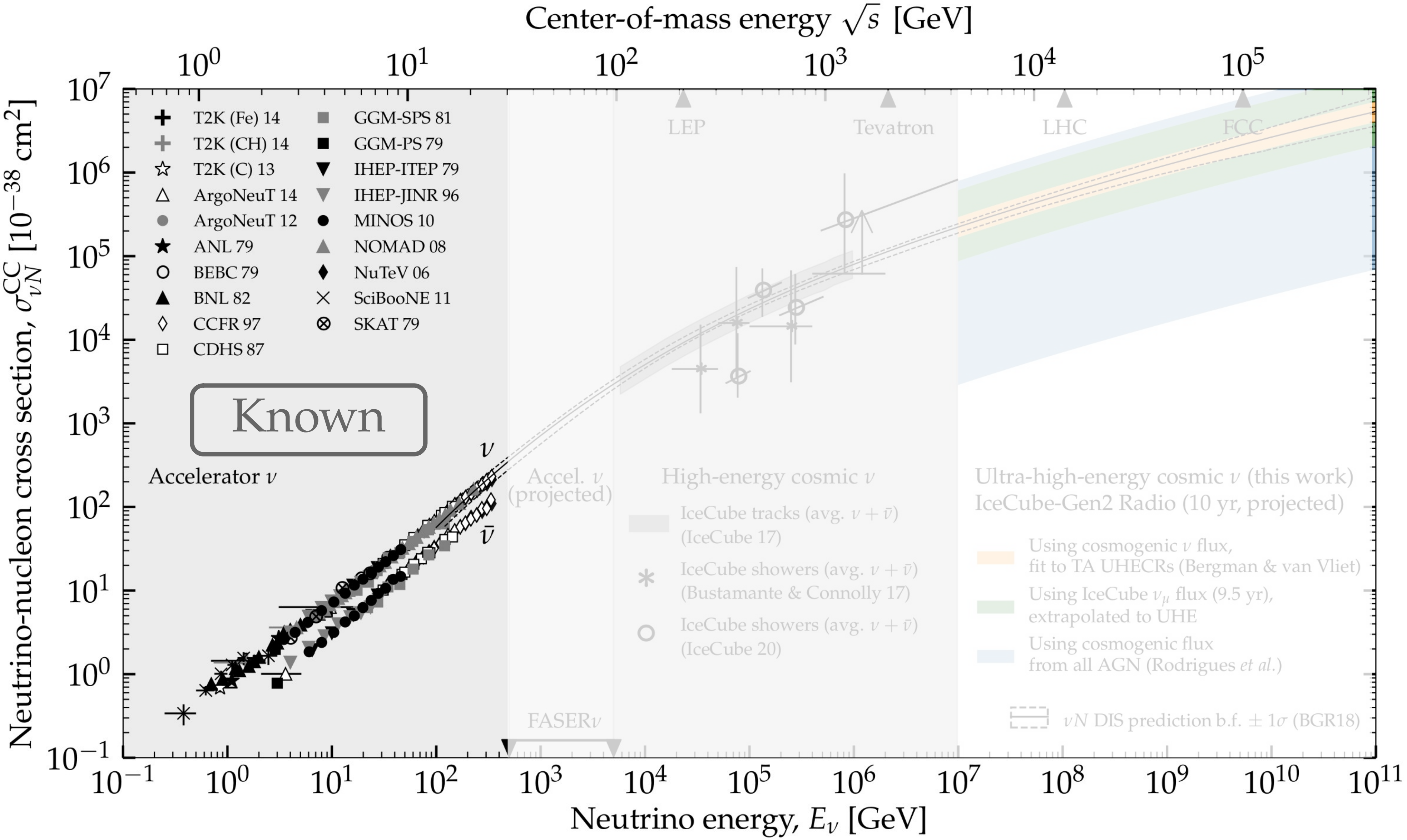

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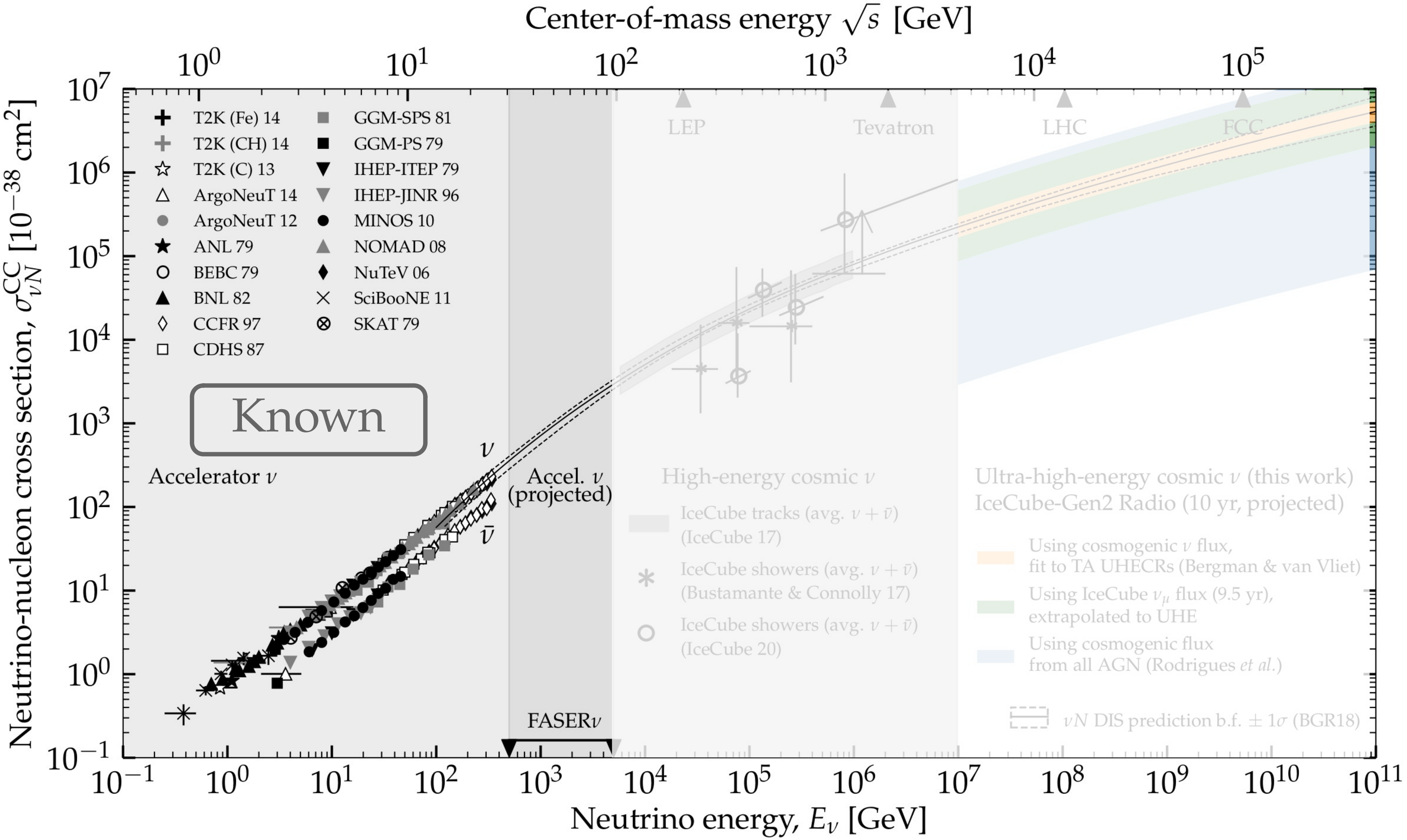

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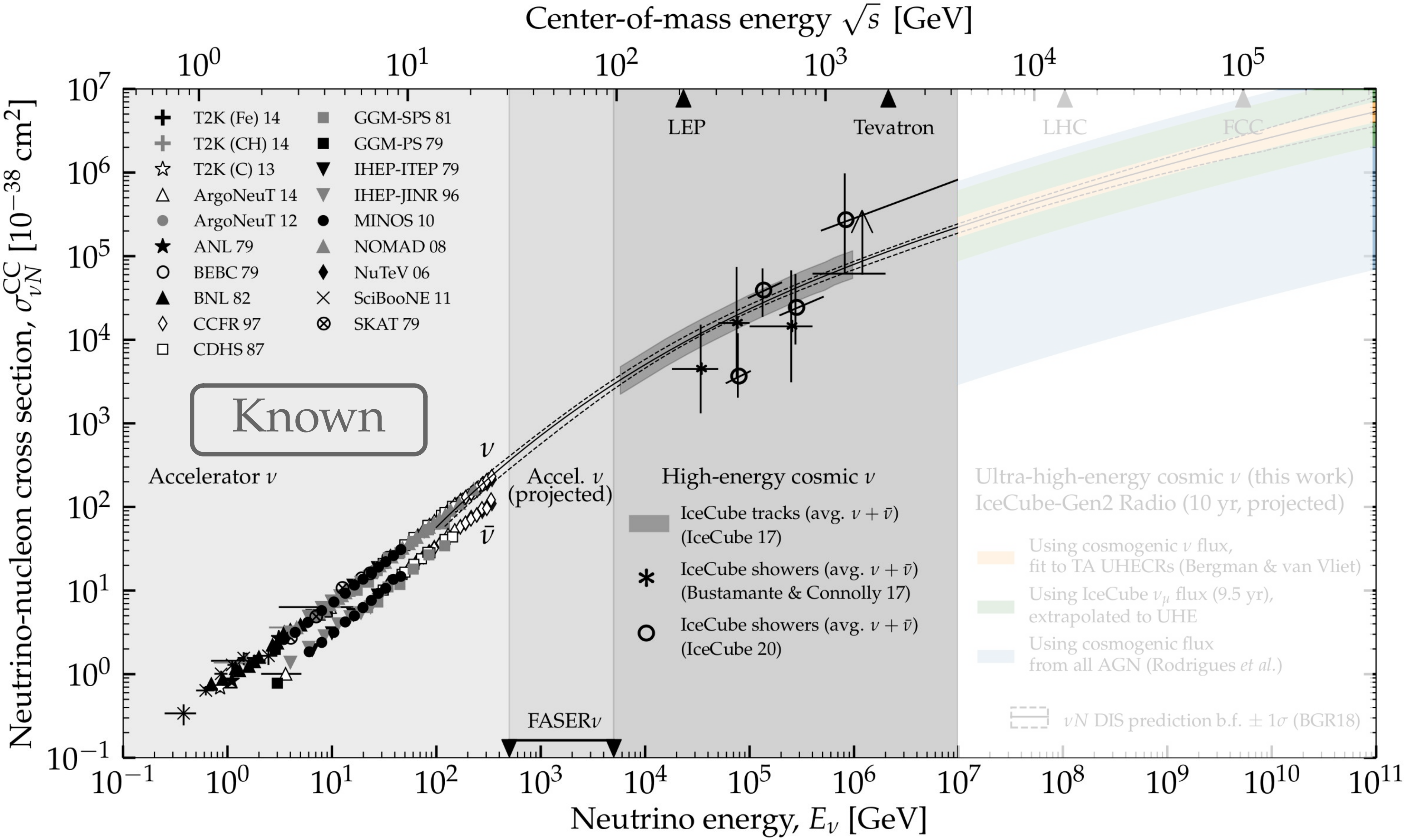

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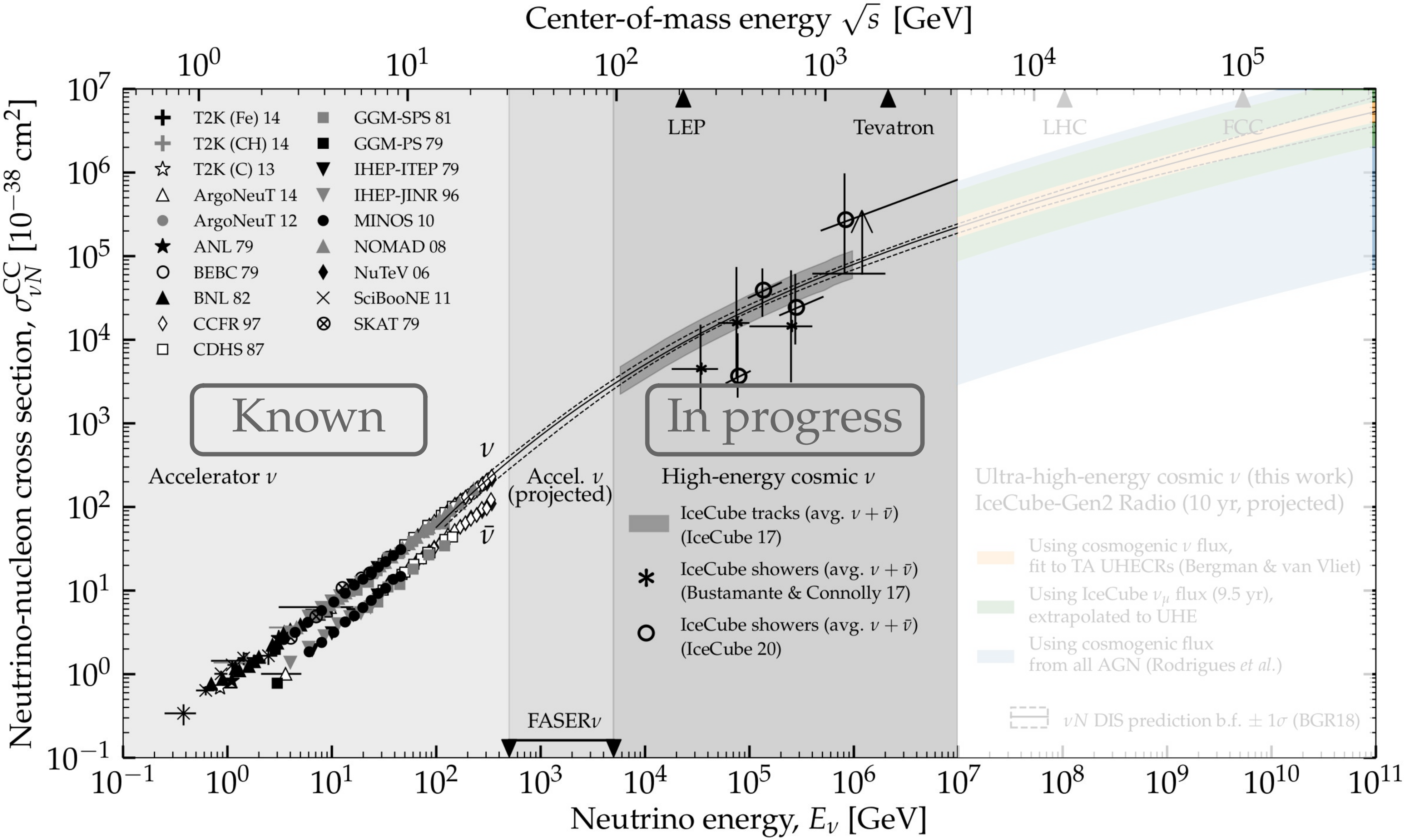

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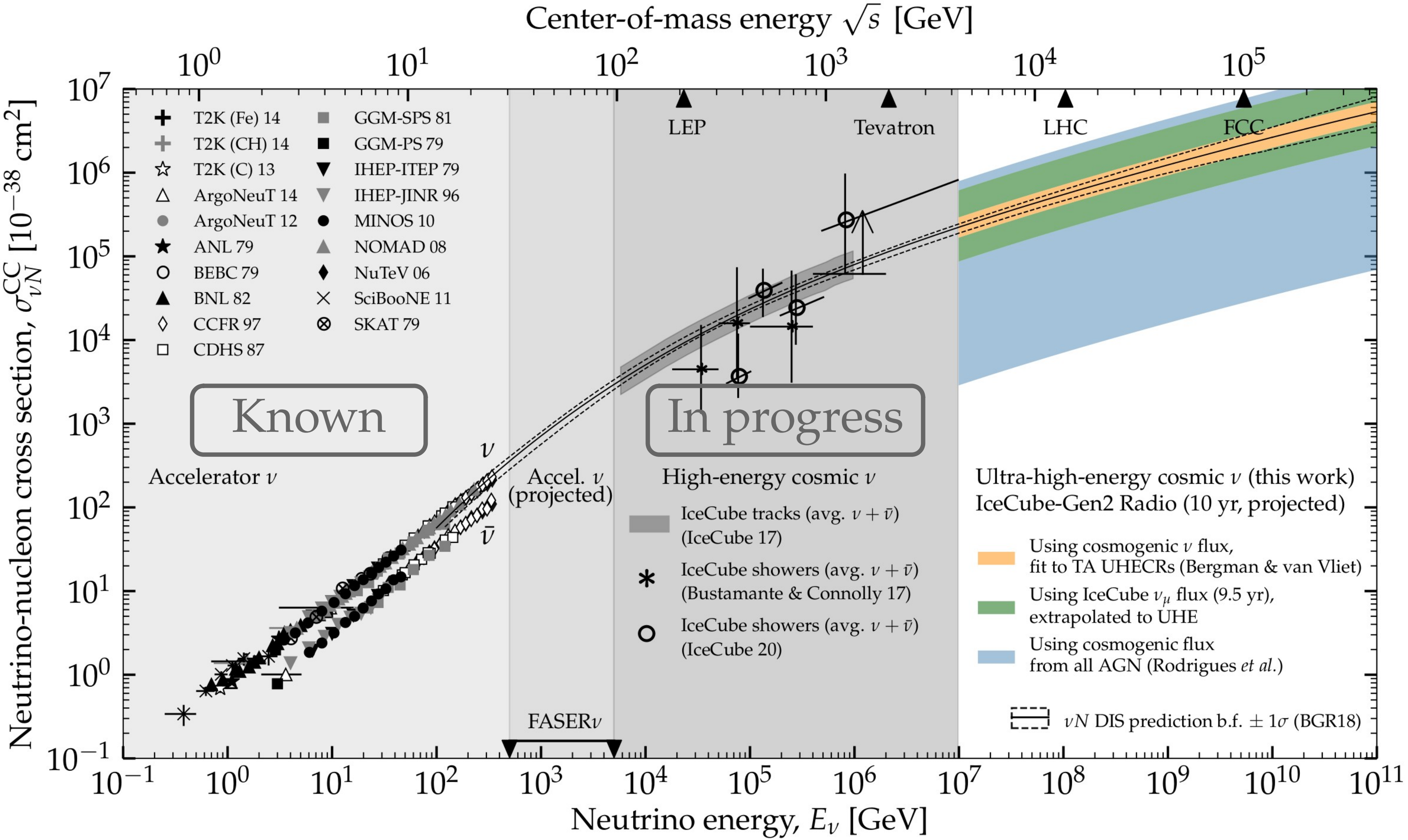

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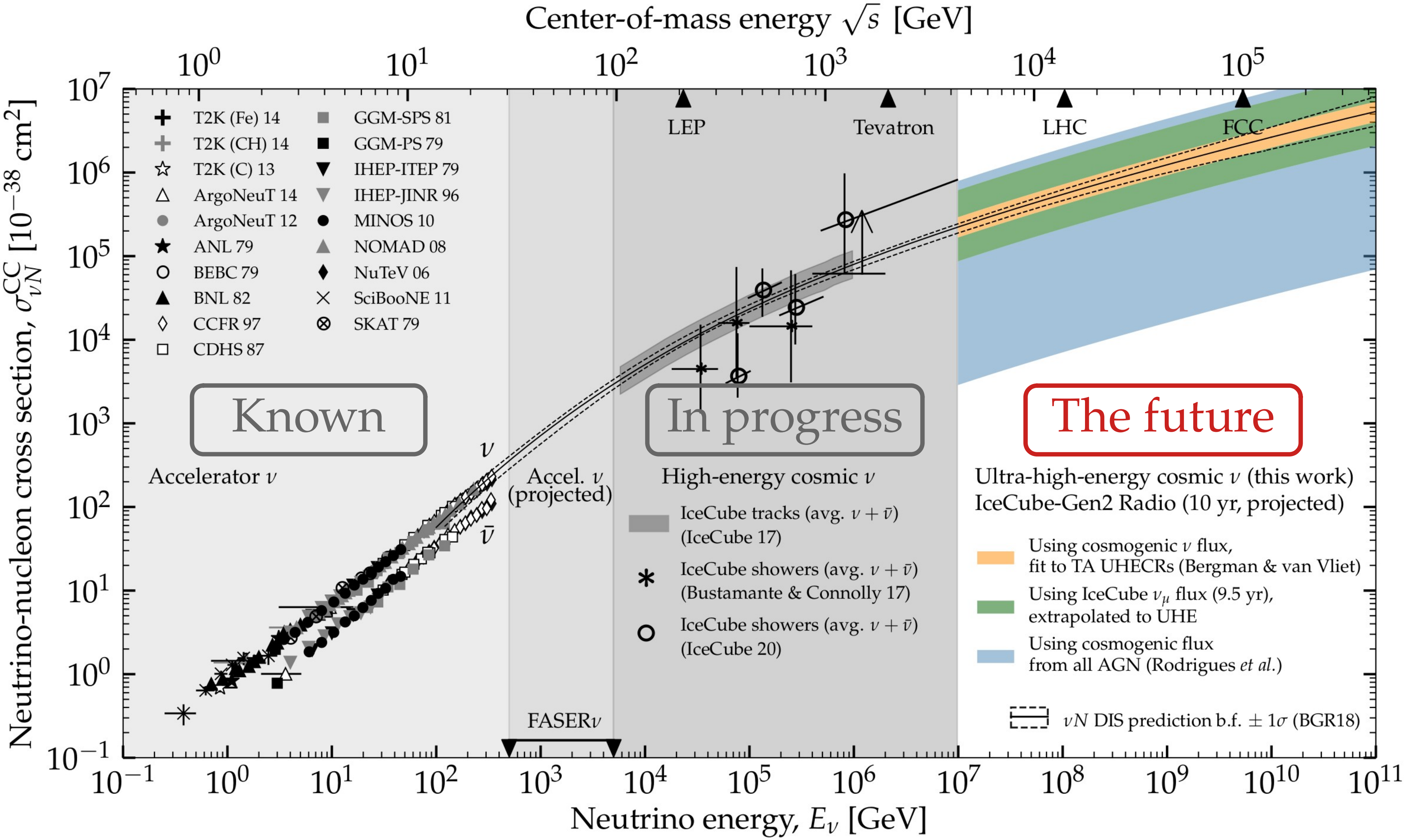

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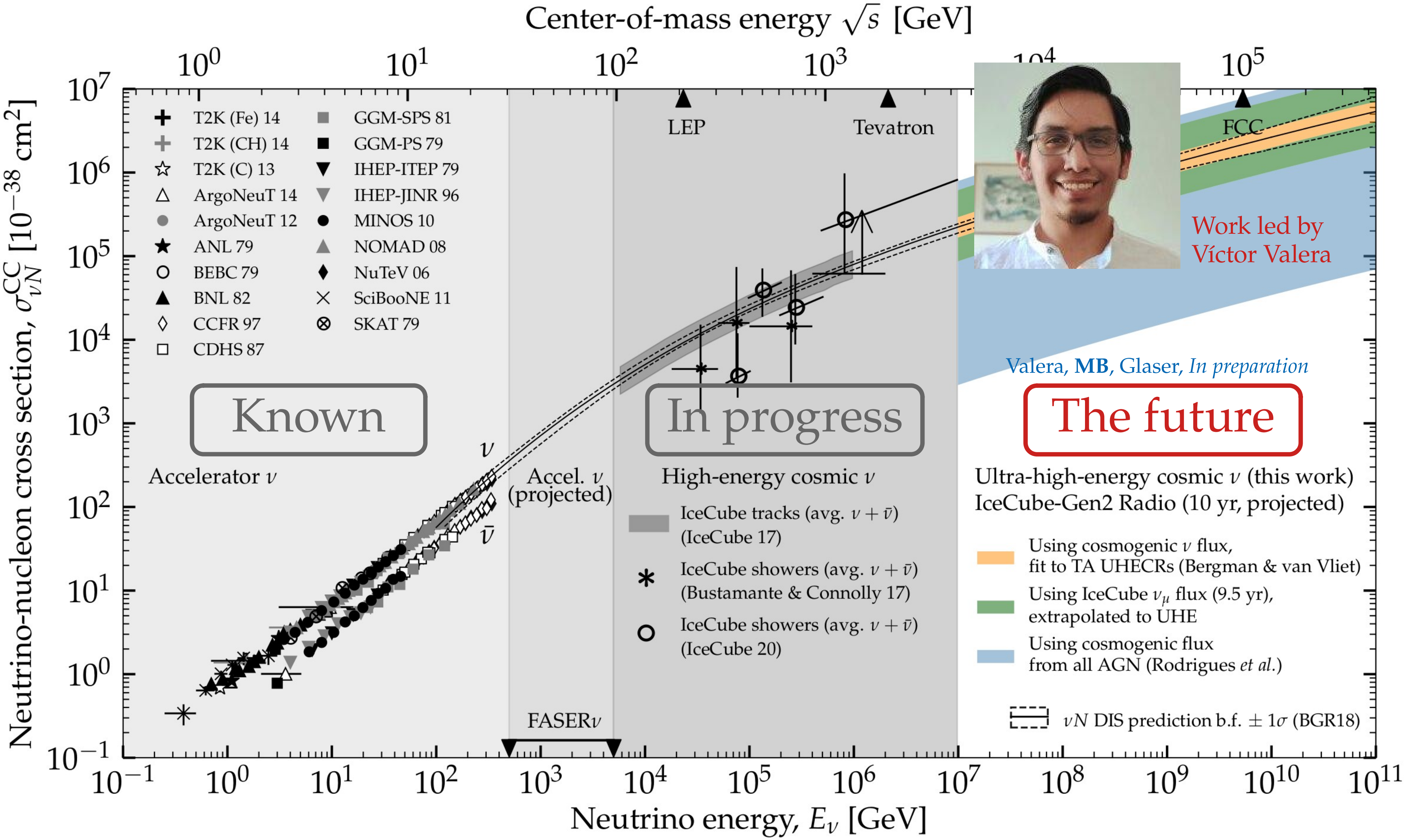

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Work led by Víctor Valera
Valera, **MB**, Glaser, *In preparation*
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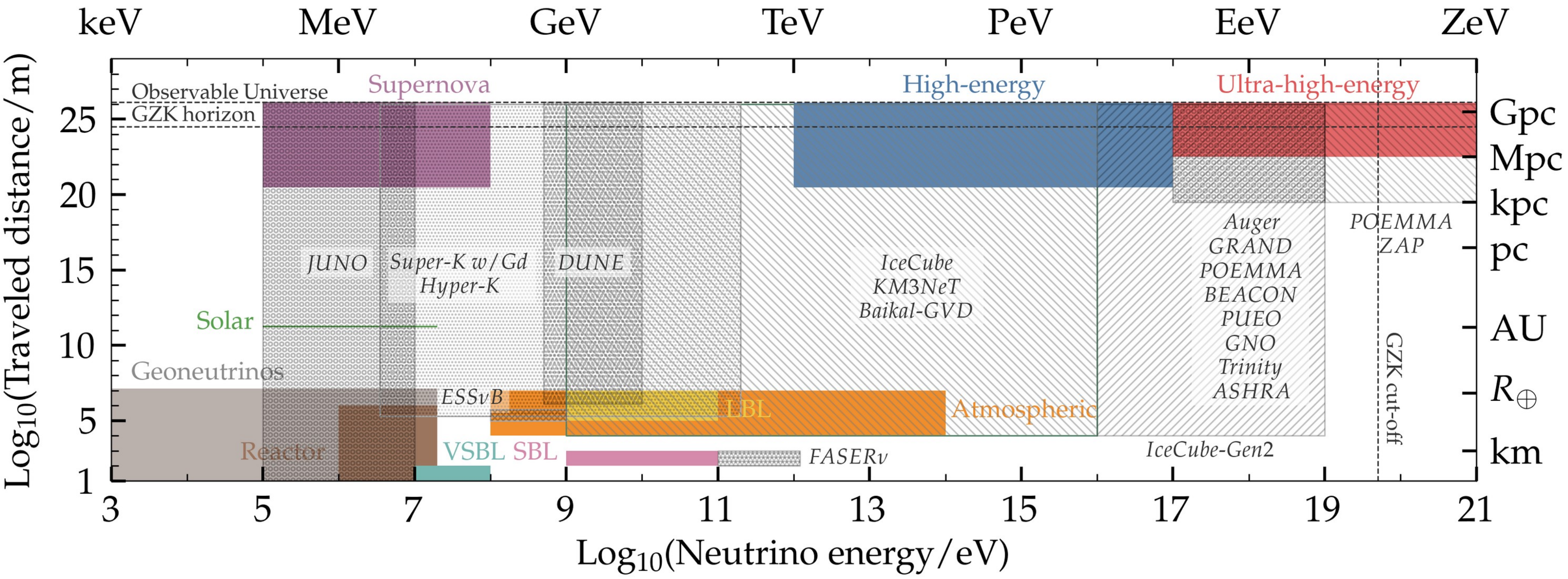
FASERν

III.
The future

Next decade: a host of planned neutrino detectors



Synergies with lower energies

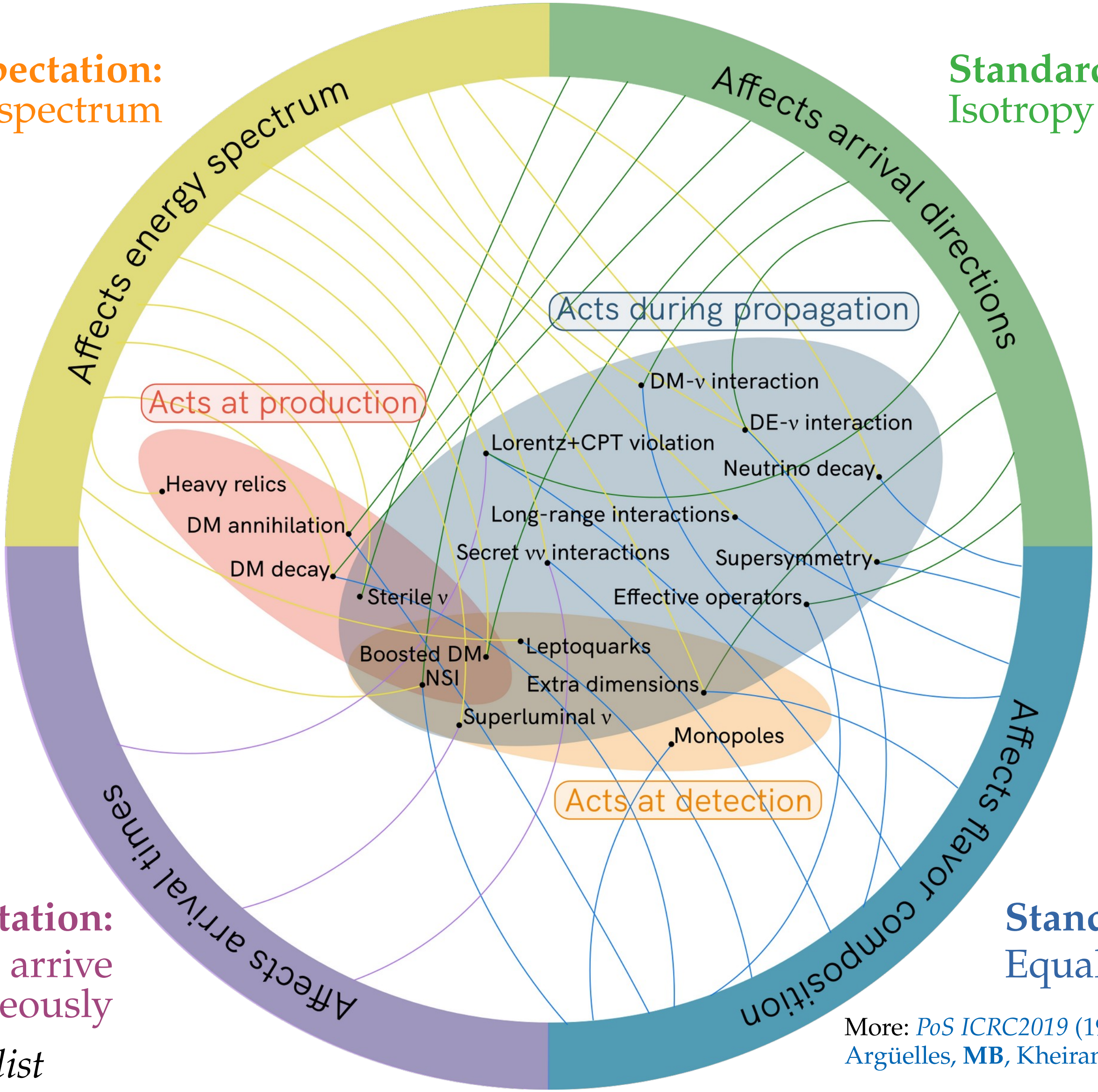
Increase TeV–PeV ν statistics

Discover > EeV ν

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

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



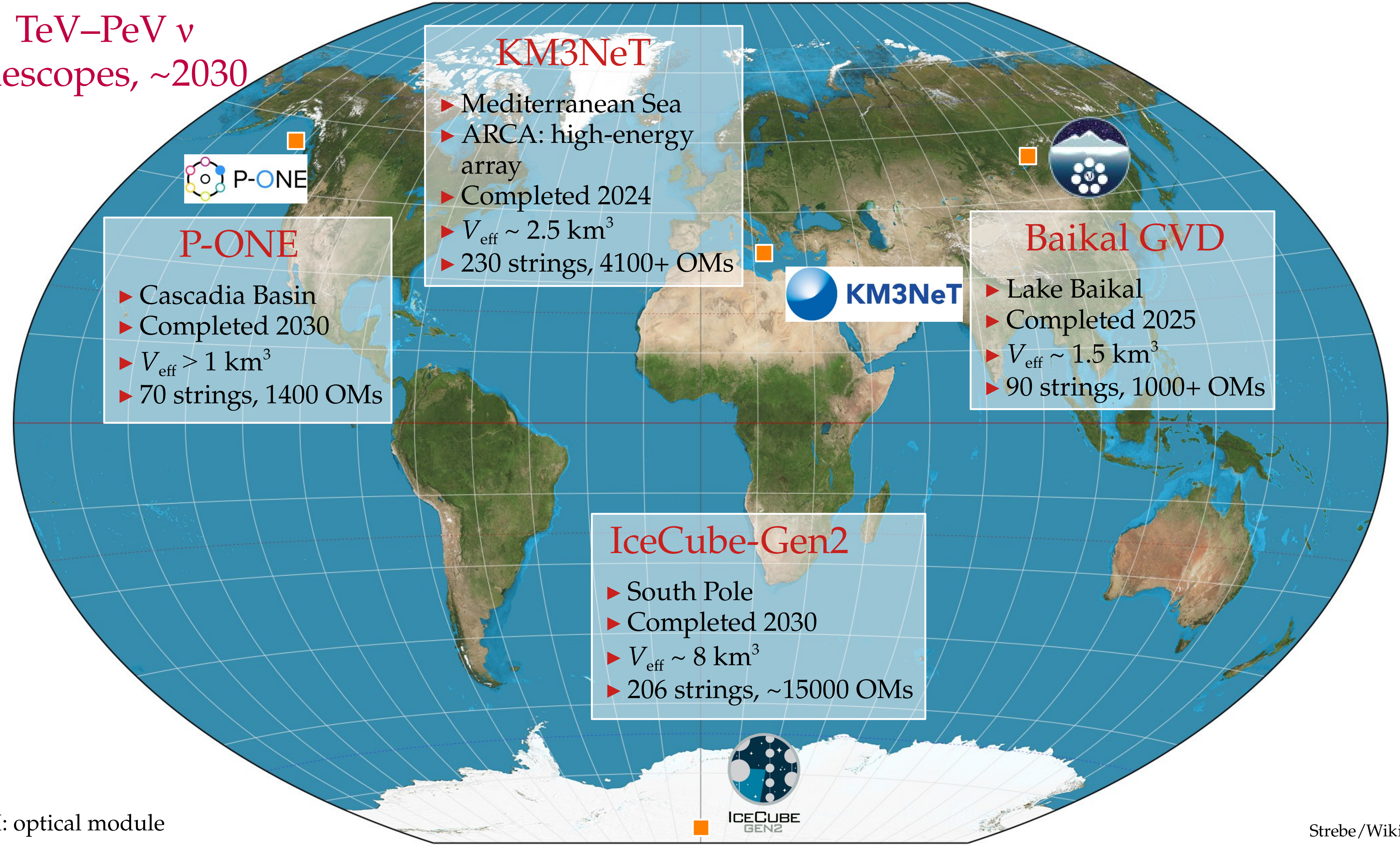
Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Note: Not an exhaustive list

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

TeV–PeV ν telescopes, ~2030



OM: optical module

Strebe/Wikipedia

Detection of UHE ν in ice and water

Optical detection in ice or water

IceCube → IceCube-Gen2
ANTARES → KM3NeT
NT200+ → Baikal GVD
P-ONE

Radio detection in ice

ARA
ARIANNA
RNO-G
IceCube-Gen2

Radio detection from the air or space

✓ANITA → PUEO
NuMoon✓

Detection of air showers from UHE ν_τ

Surface particle detection

Auger → AugerPrime
TA → TA×4
HAWC
TAMBO

Radio detection in the atmosphere

✓ANITA → PUEO
BEACON
GRAND
TAROGE & TAROGE-M

Air-shower imaging from the ground

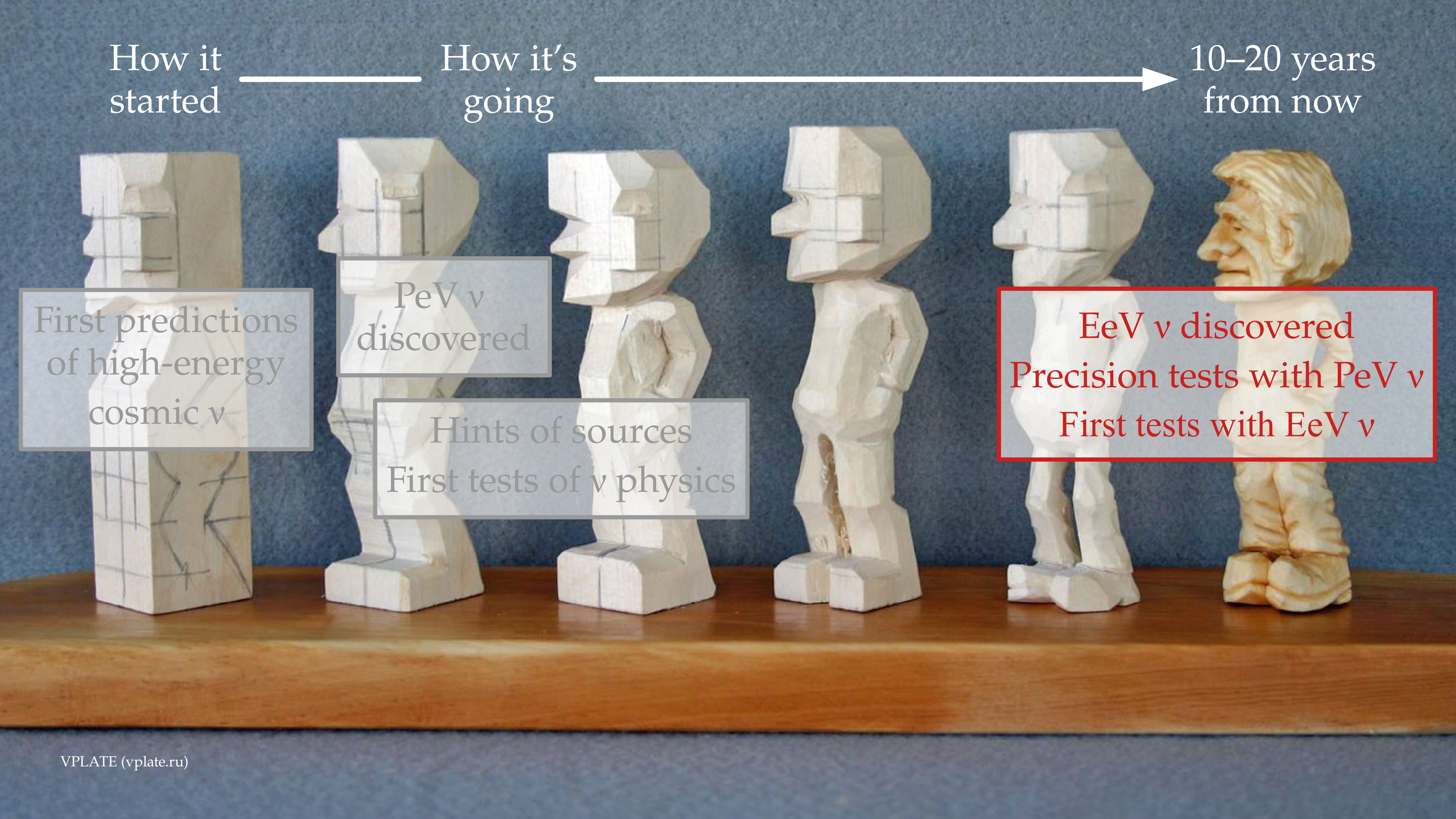
Trinity
MAGIC
CTA
ASHRA NTA

Cherenkov/fluorescence from air or space

EUSO-SPB2
POEMMA

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

Operating   Proposed or under construction   ✓ Completed


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)

International Journal of Modern Physics A
Vol. 24, No. 31 (2009) 5819–5829

World Scientific
www.worldscientific.com

HIGH ENERGY ASTROPHYSICAL NEUTRINO FLUX AND MODIFIED DISPERSION RELATIONS

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‡*agago@pucp.edu.pe*

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omr@fis.cinvestav.mx

Received 2 March 2009
Revised 28 June 2009

- Predominantly in-person school …
- … but we will likely offer remote participation, too
- No participation fee
  (+ free coffee breaks & lunch & social program)
- Neutrino theory & phenomenology
  Neutrino cosmology
  Neutrino astrophysics & astronomy
- Problem sessions & discussion sessions

nbia.dk/neutrino2022

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- Problem sessions & discussion sessions

Deadline to register: March 31 (*register early!*)

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End

Backup slides

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PHYSICS

Searching for the Universe's Most Energetic Particles, Astronomers Turn on the Radio

New radio-based observatories could soon detect ultrahigh-energy neutrinos, opening a new window on extreme cosmic physics

By Katrina Miller on April 27, 2021

Artist's composite of the IceCube Neutrino Observatory in Antarctica, accompanied by a distant astrophysical source emitting neutrinos that are detected in IceCube's subsurface sensors. Credit: IceCube and NSF

Ever since their discovery in the 1960s, ultrahigh-energy cosmic rays have

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Katrina Miller for *Scientific American*, April 27, 2021 [link]

Basics

Status quo of high-energy cosmic neutrinos

What we know

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

What we don't know

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

Status quo of high-energy cosmic neutrinos

But we have solid theory expectations
+ fast experimental progress

What we know

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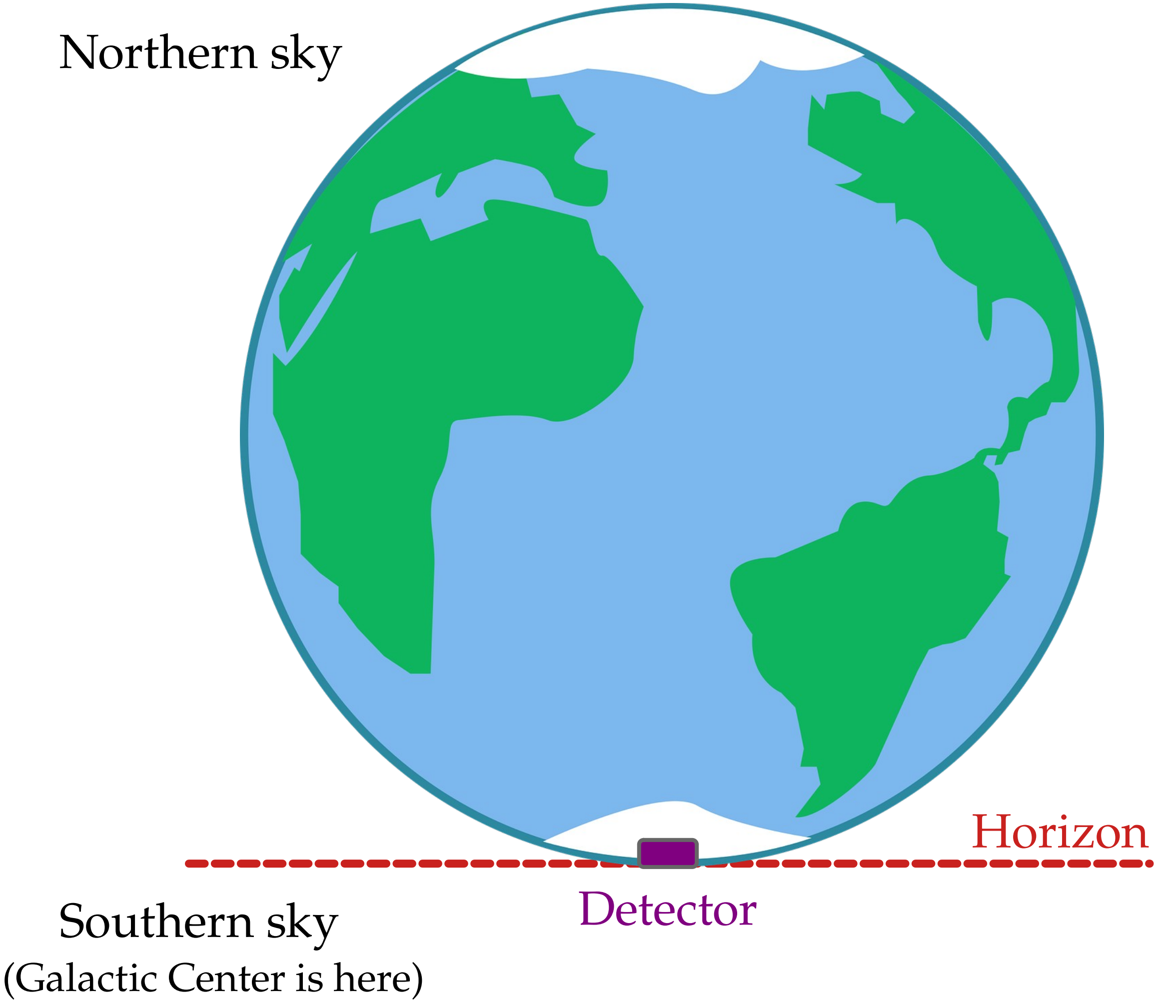
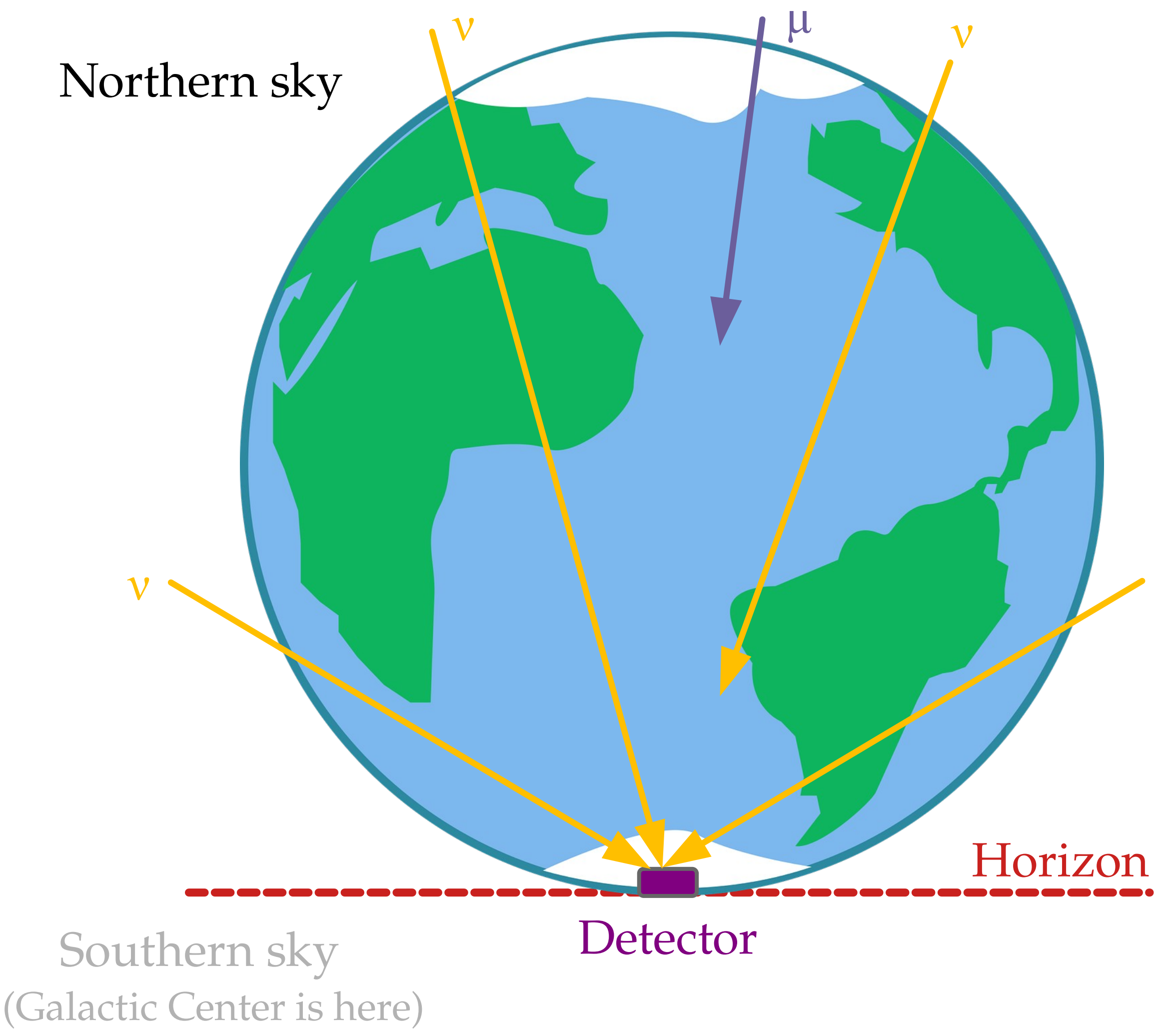
Upgoing *vs.* downgoing neutrinos



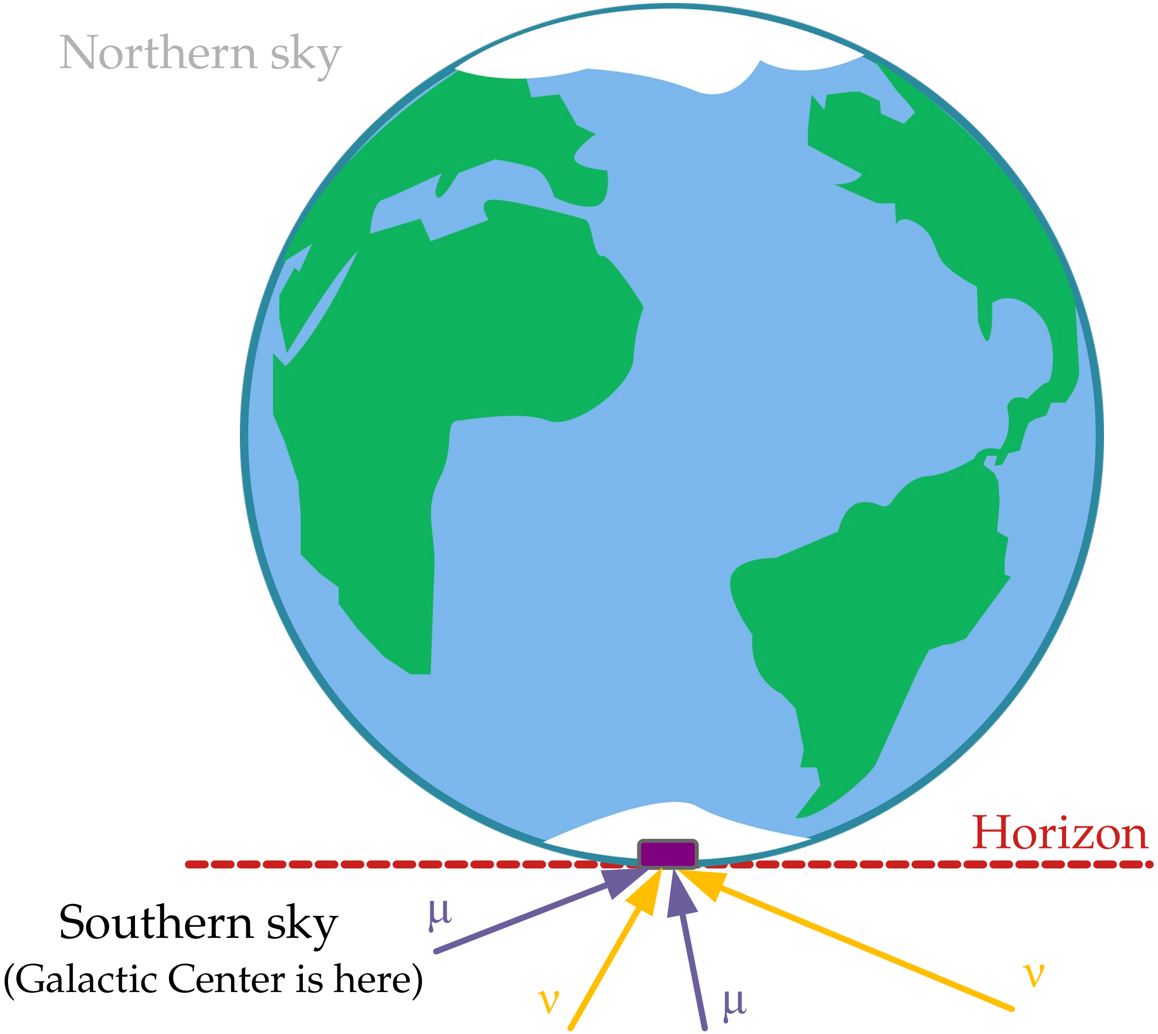
Upgoing *vs.* downgoing neutrinos



Neutrinos from the Northern sky
≡
Upgoing neutrinos

- Atmospheric muons stopped
- Dominated by atmospheric ν
- High-energy ν flux attenuated
- High statistics
- Good for finding sources with through-going muon tracks

Downgoing *vs.* upgoing neutrinos



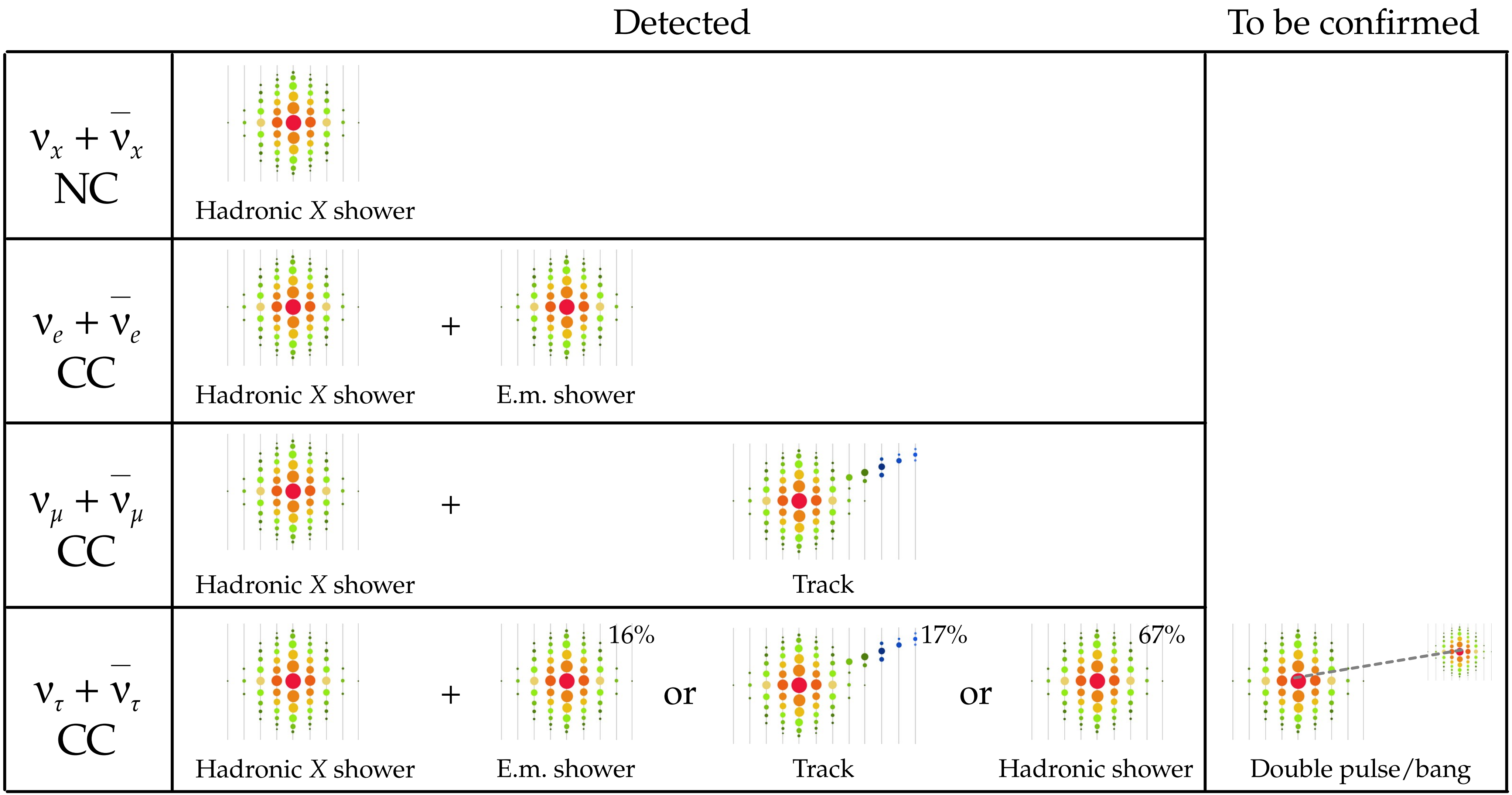
Neutrinos from the Southern sky

≡

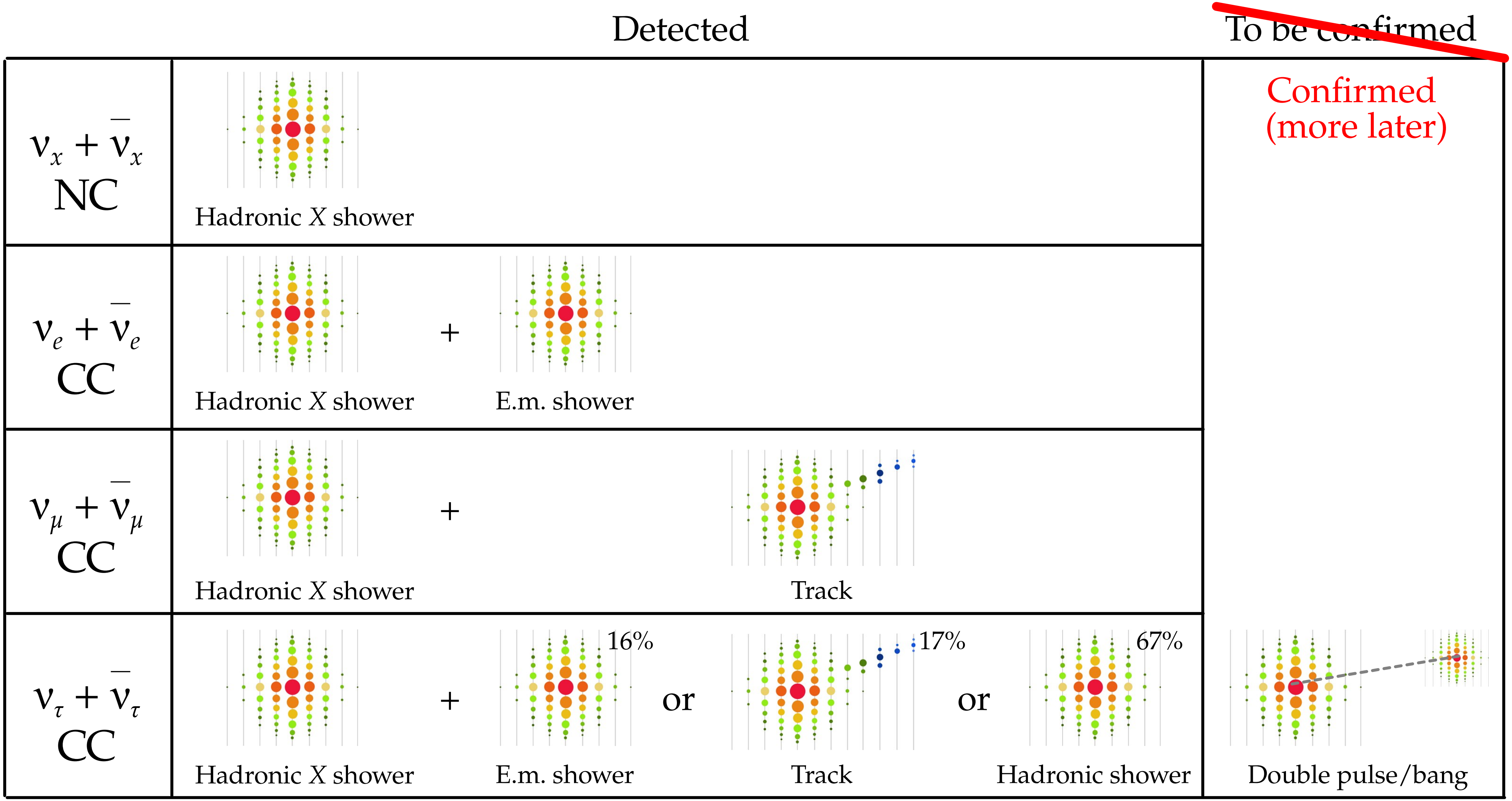
Downgoing neutrinos

- Need to mitigate atmospheric muons and ν:
  - Use higher-energy events
  - Use starting a self-veto
- Dominated by astrophysical ν (*after* event selection)
- Low statistics
- Good for measuring the diffuse flux of astrophysical ν

IceCube



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



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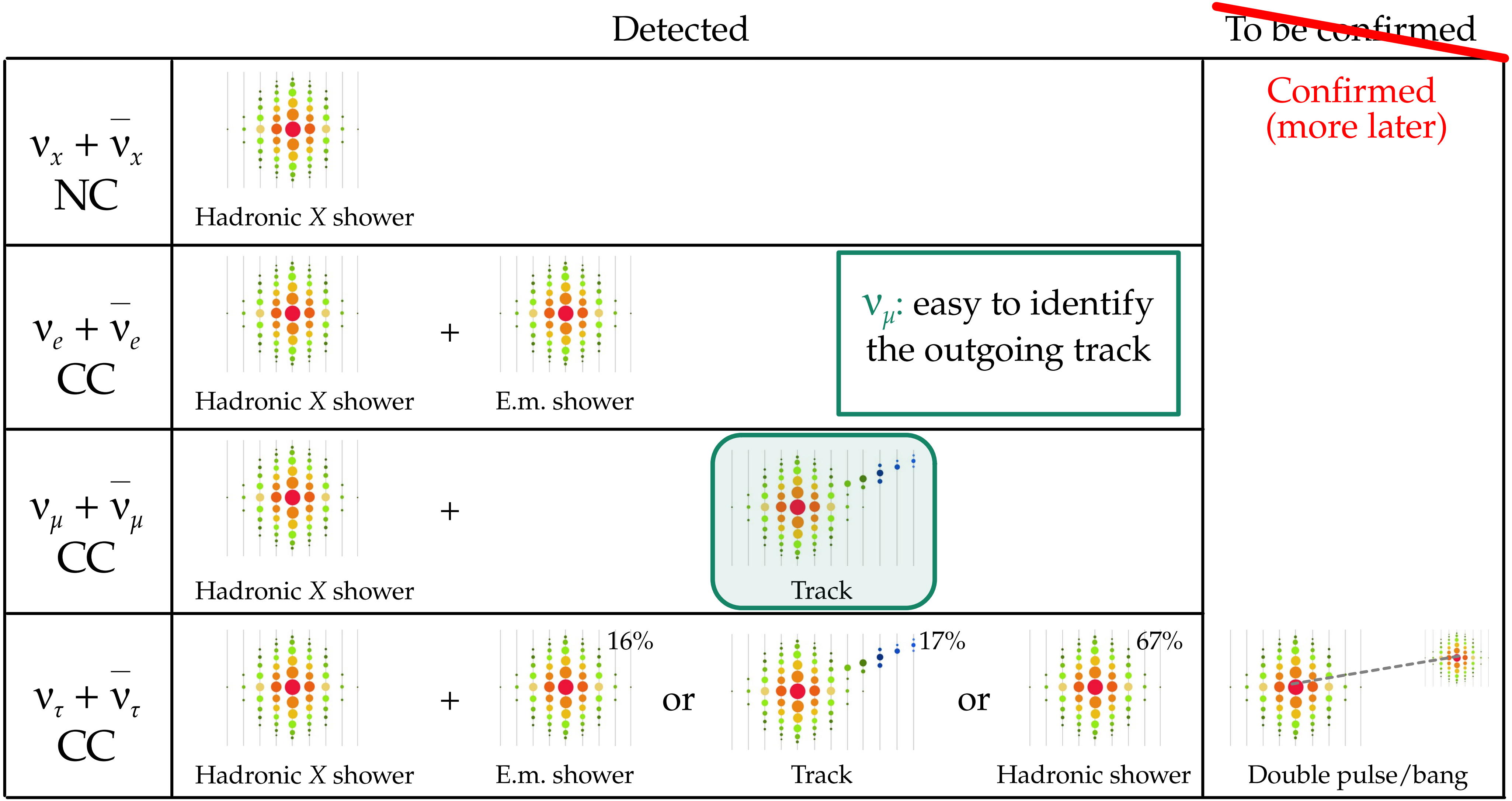
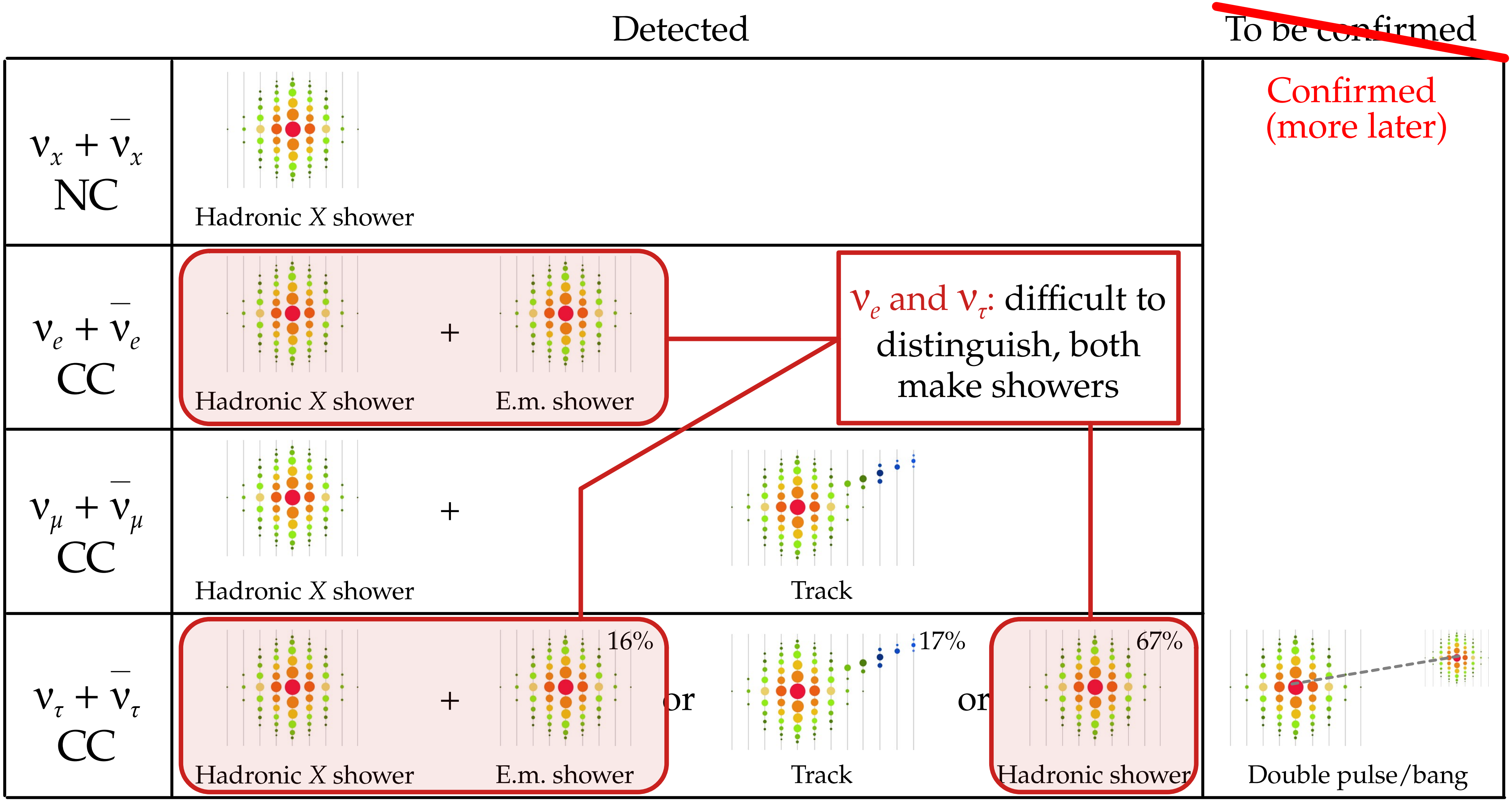
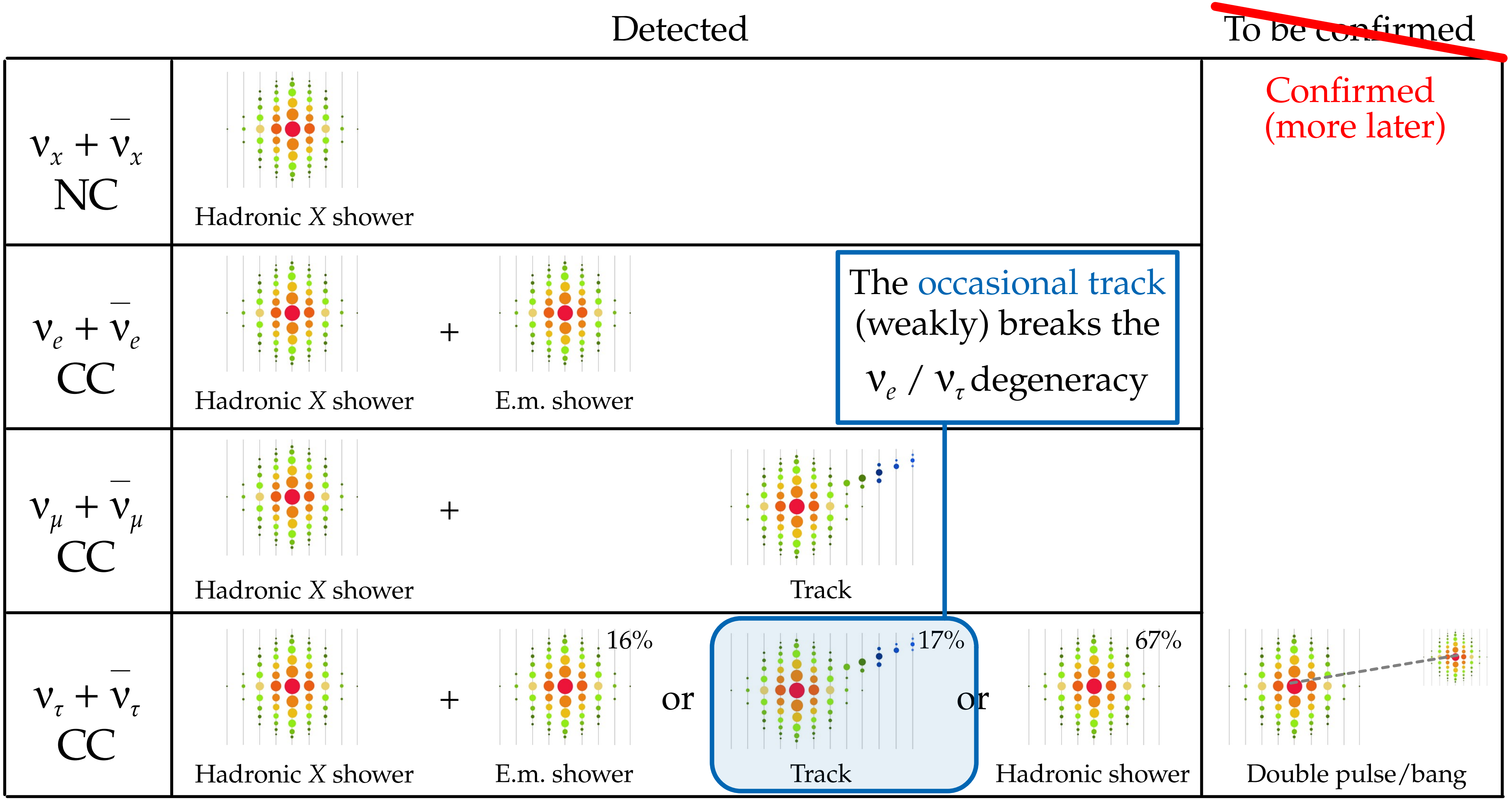
Hadronic shower
Double pulse/bang

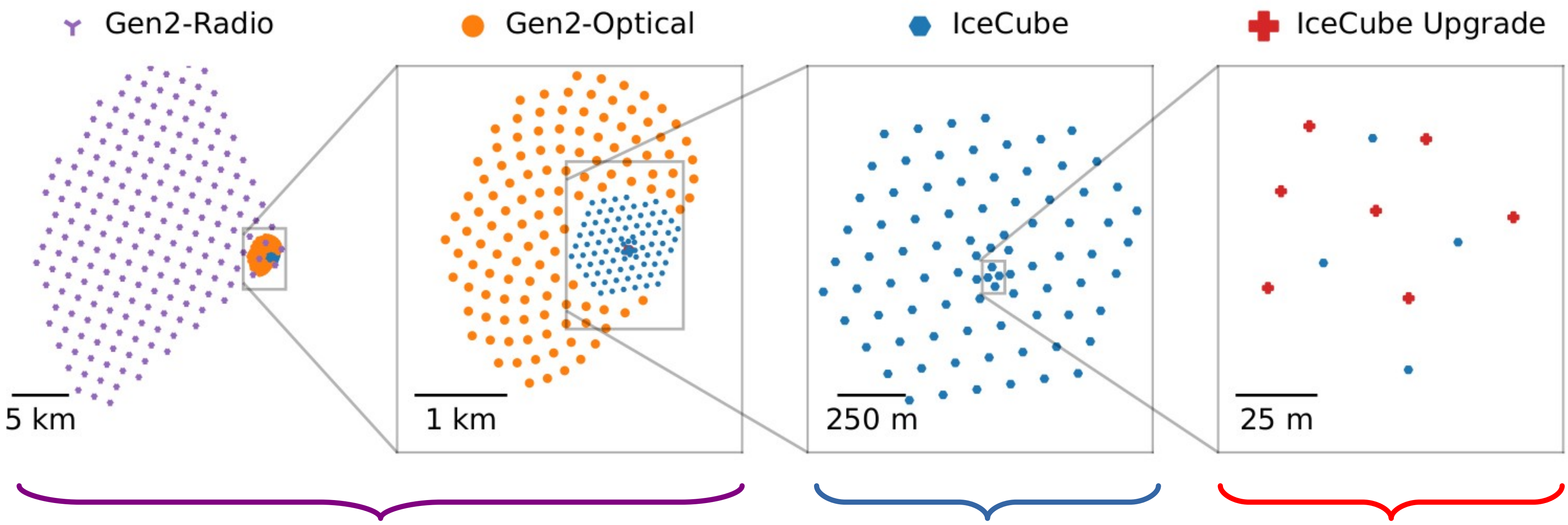


Detected
To be confirmed
Confirmed
(more later)
$\nu_x + \bar{\nu}_x$ NC
Hadronic X shower
$\nu_e + \bar{\nu}_e$ CC
Hadronic X shower
+
E.m. shower
ν_μ: easy to identify the outgoing track
$\nu_\mu + \bar{\nu}_\mu$ CC
Hadronic X shower
+
Track
$\nu_\tau + \bar{\nu}_\tau$ CC
Hadronic X shower
+
16%
E.m.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


Detected
To be confirmed
Confirmed
(more later)
$\nu_x + \bar{\nu}_x$ NC
Hadronic X shower
$\nu_e + \bar{\nu}_e$ CC
Hadronic X shower
+
E.m. shower
ν_e and ν_τ: difficult to distinguish, both make showers
$\nu_\mu + \bar{\nu}_\mu$ CC
Hadronic X shower
+
Track
$\nu_\tau + \bar{\nu}_\tau$ CC
Hadronic X shower
+
E.m. shower
16%
or
Track
17%
or
Hadronic shower
67%
Double pulse/bang


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

IceCube-Gen2



~2040

Today

2023

10s km^3

> 100 PeV ν

~8 km^3

TeV–10 PeV ν

1 km^3

TeV–few PeV ν

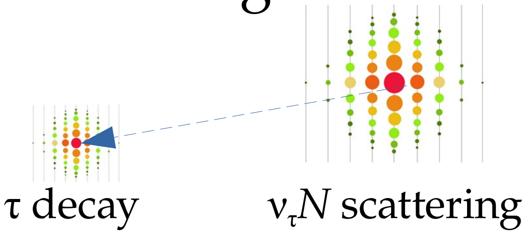
7 new strings

GeV–TeV ν

IceCube-Gen2, 2008.04323

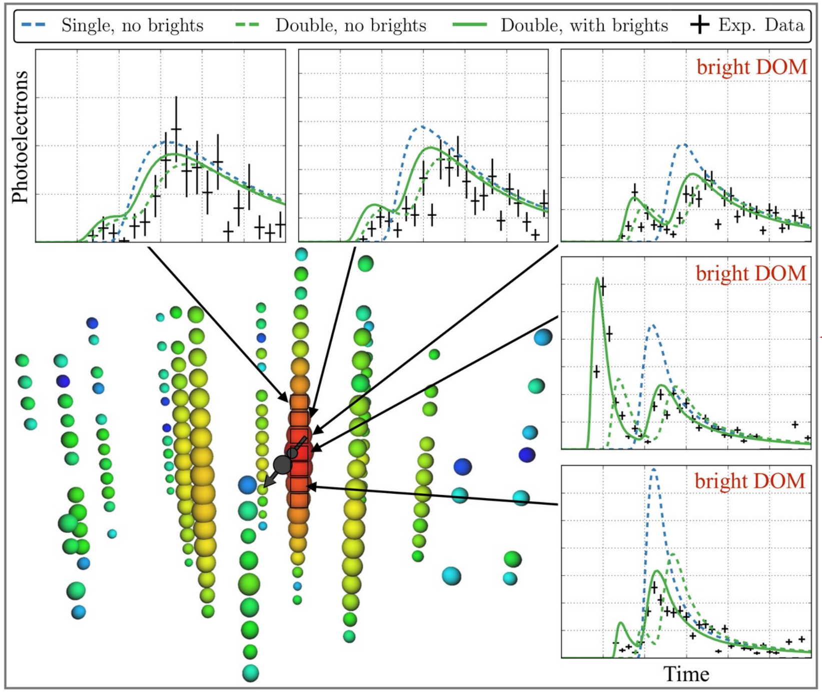
First identified high-energy astrophysical ν_τ

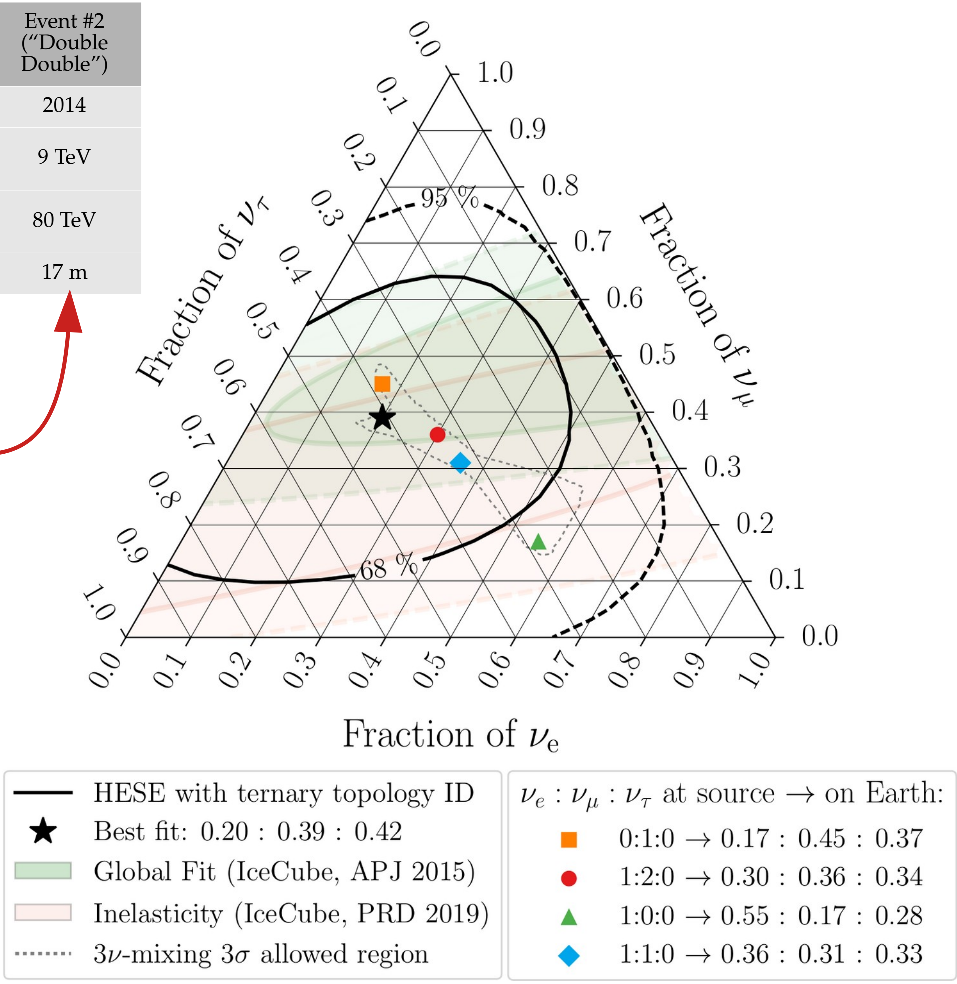
Double bang:



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

Most likely to be a ν_τ

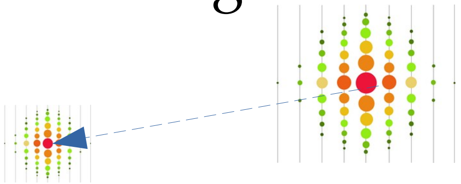




IceCube, 2011.03561

First identified high-energy astrophysical ν_τ

Double bang:



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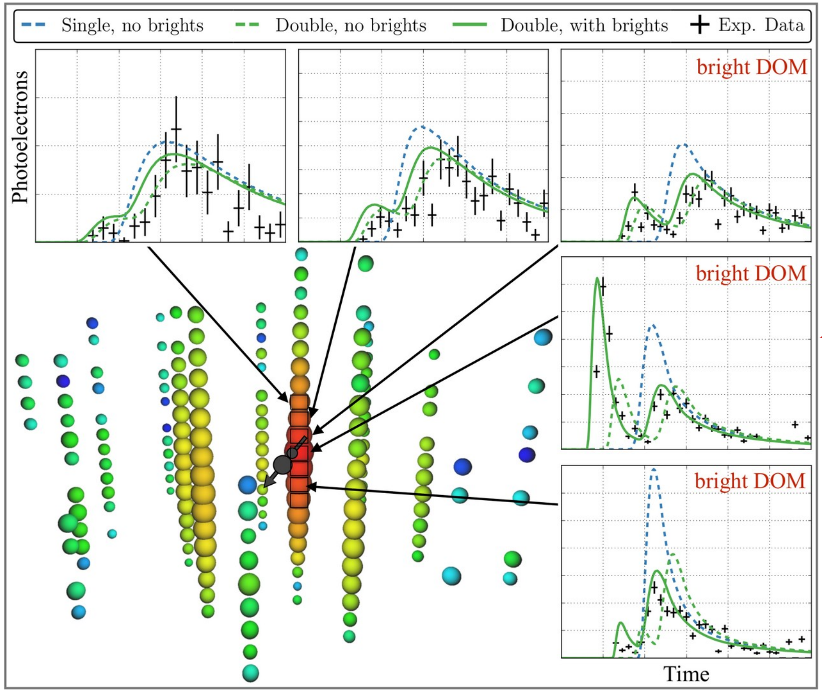
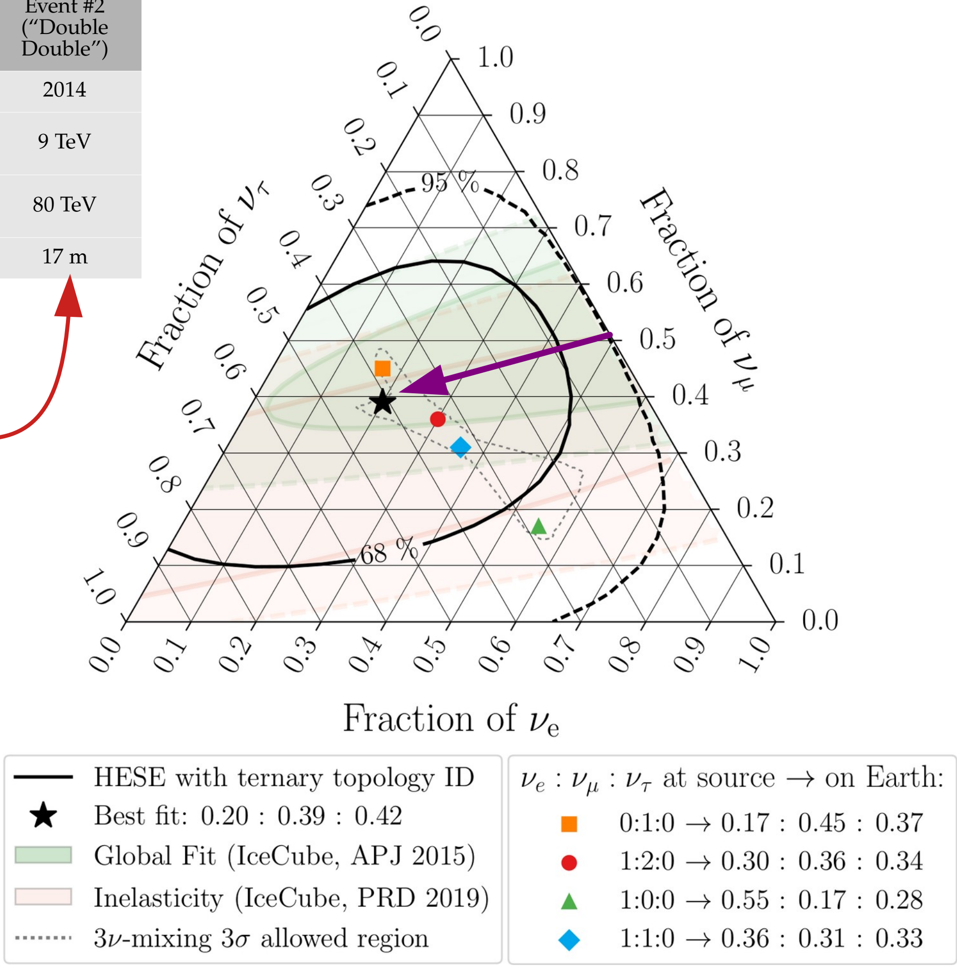
Most likely to be a ν_τ





IceCube, 2011.03561

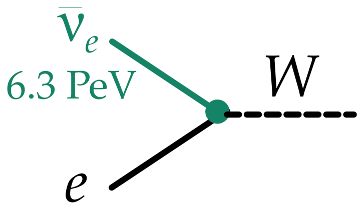
First observation of a Glashow resonance

Predicted in 1960:

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

First observation of a Glashow resonance

Predicted in 1960:



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

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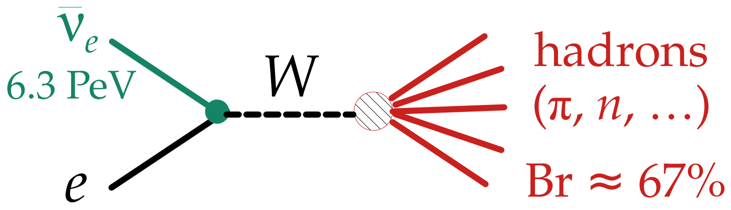
Predicted in 1960:



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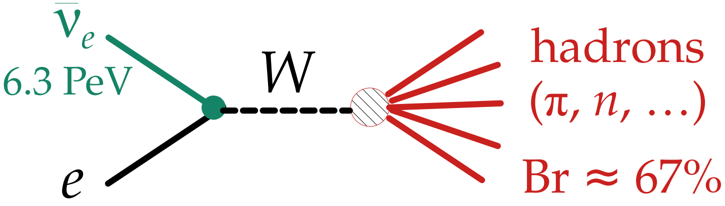

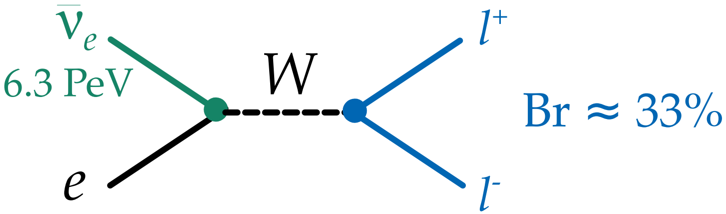

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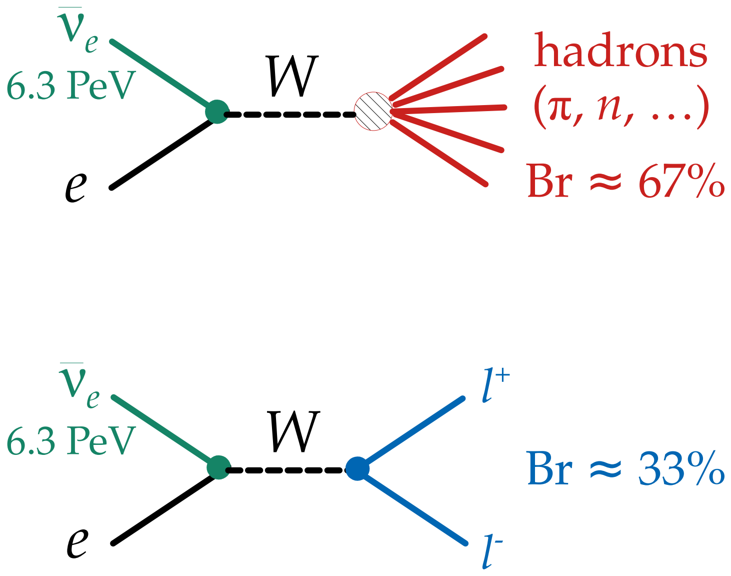
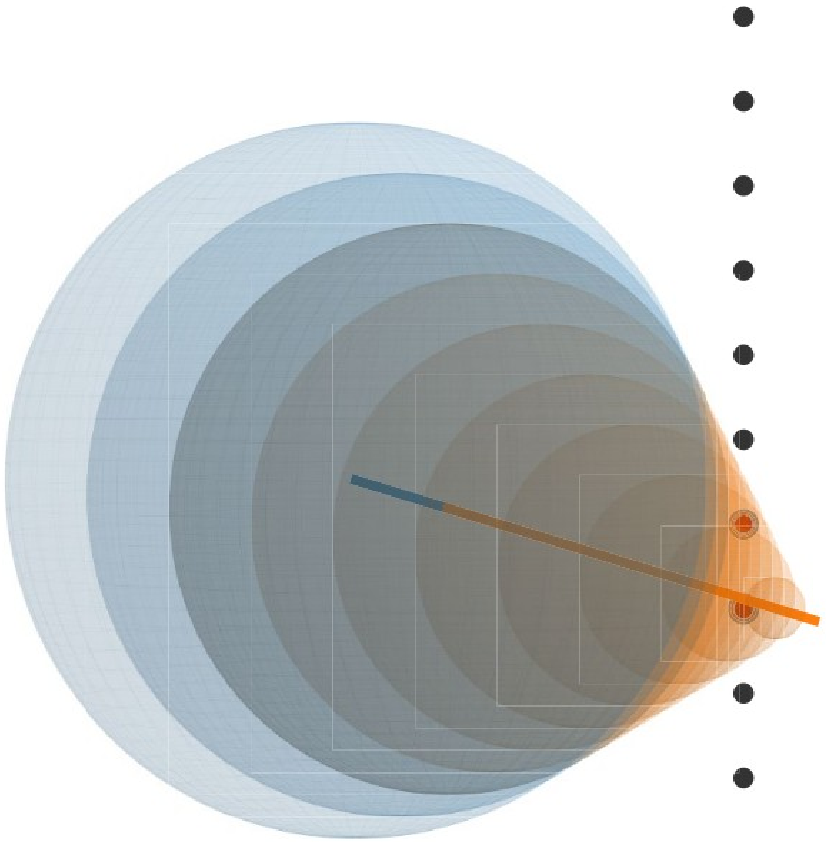


First reported by IceCube in 2021:



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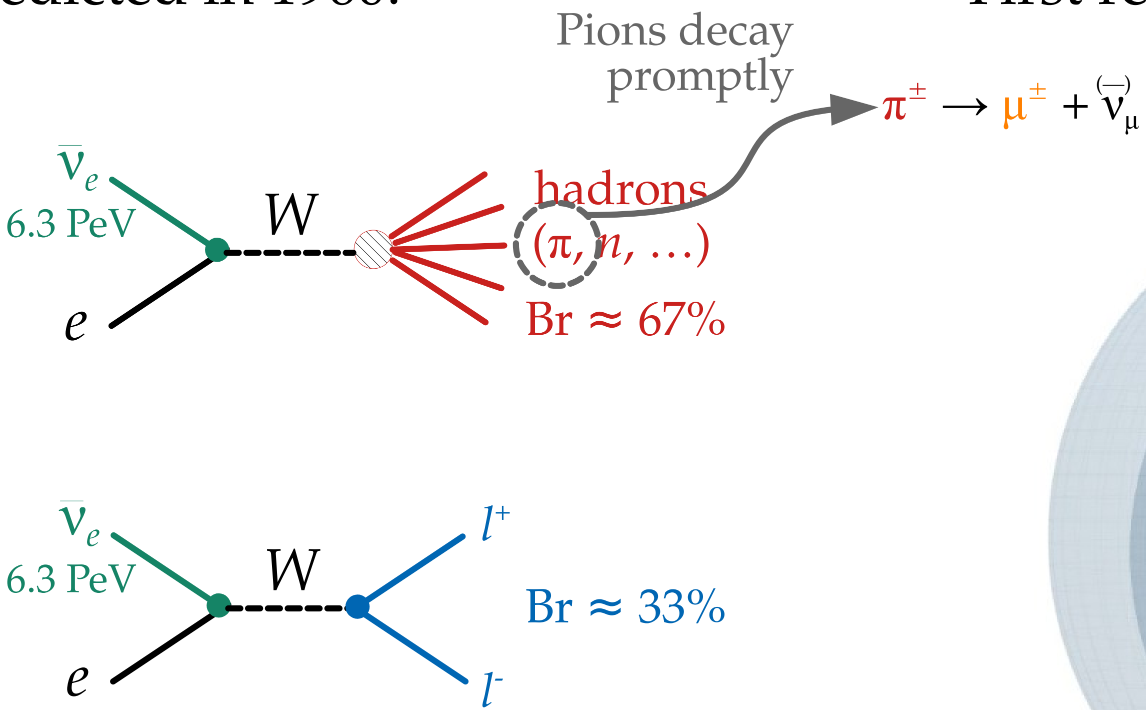

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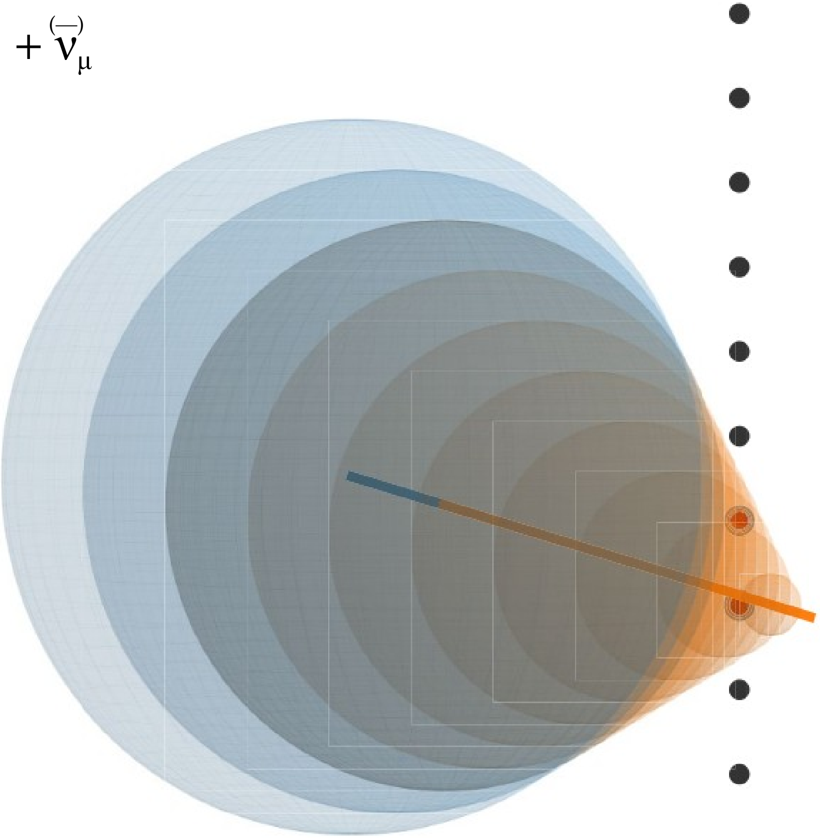

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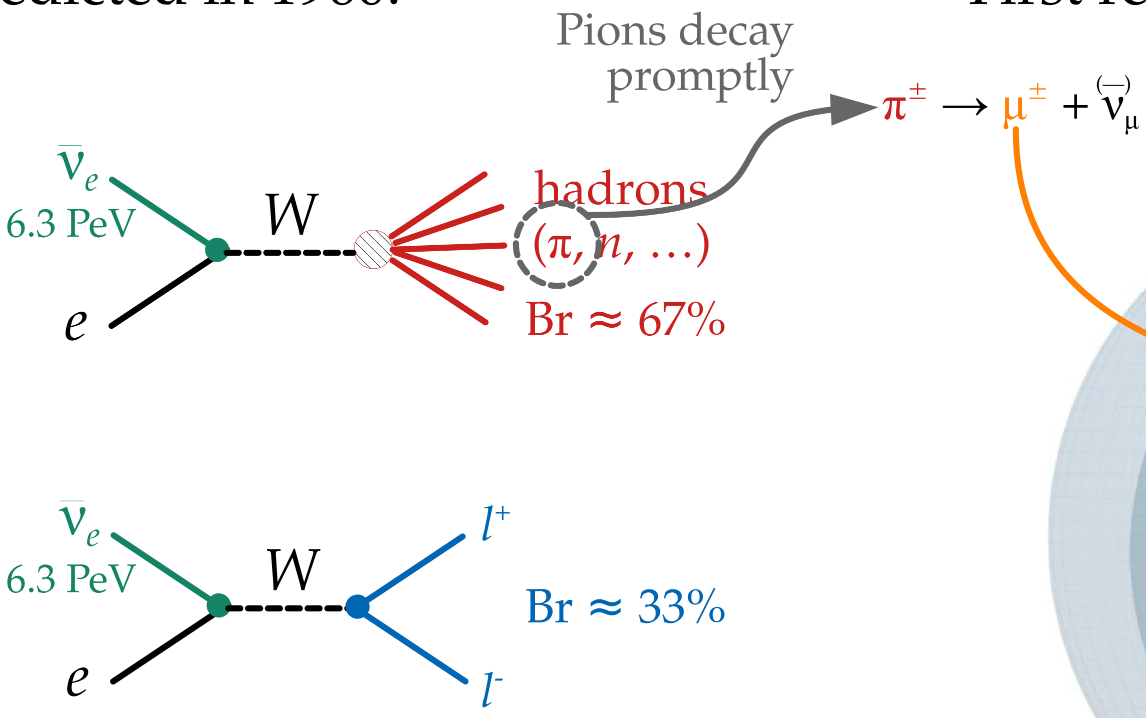

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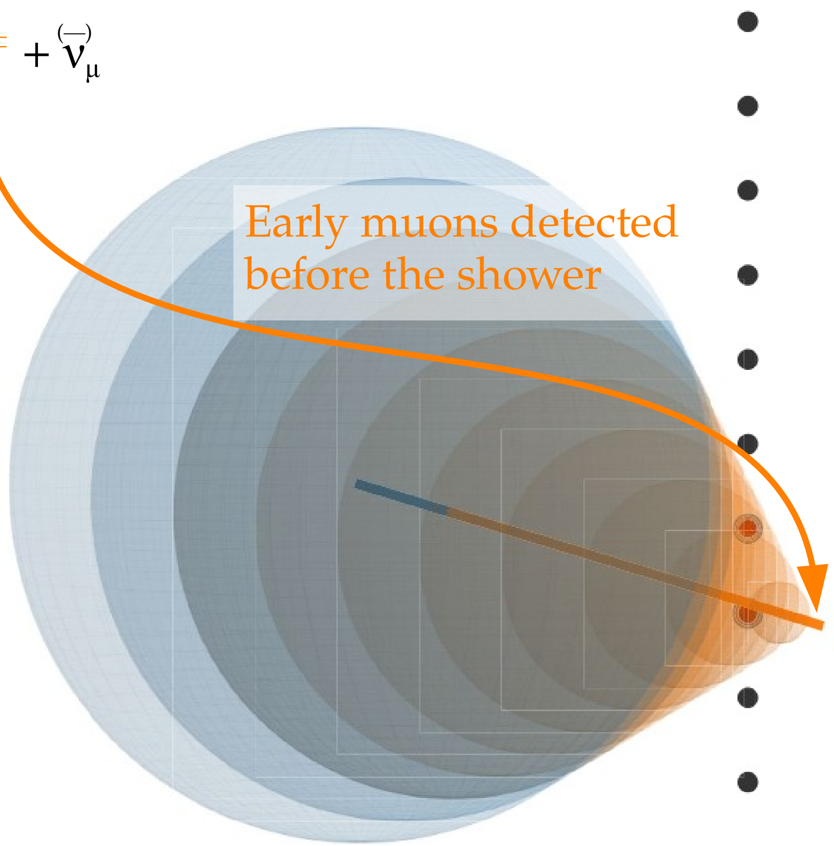

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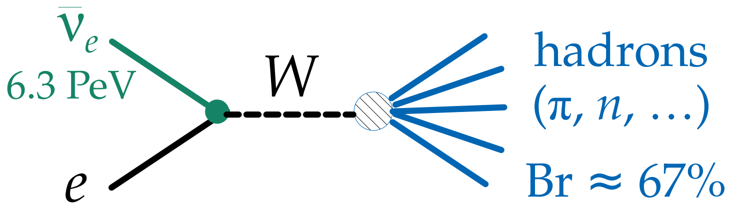

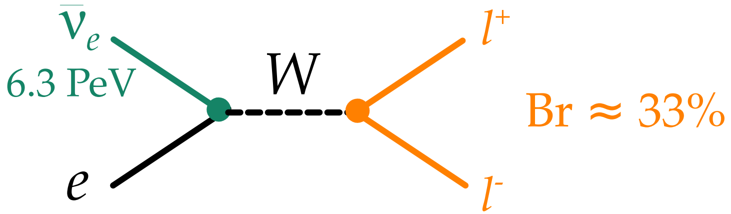

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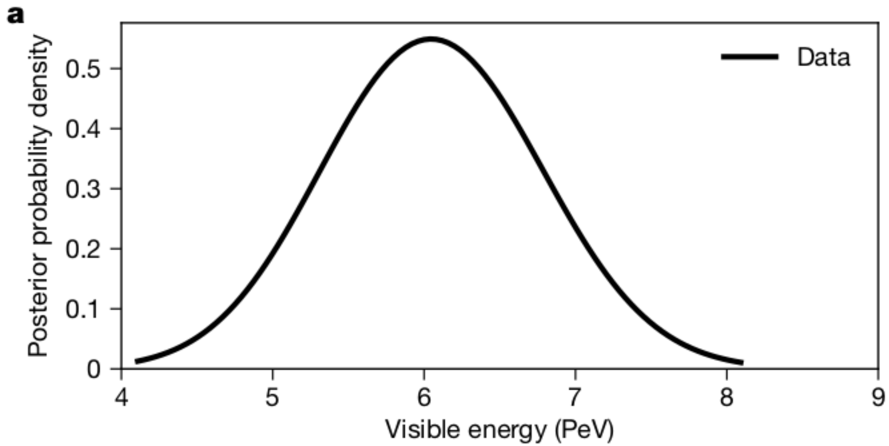

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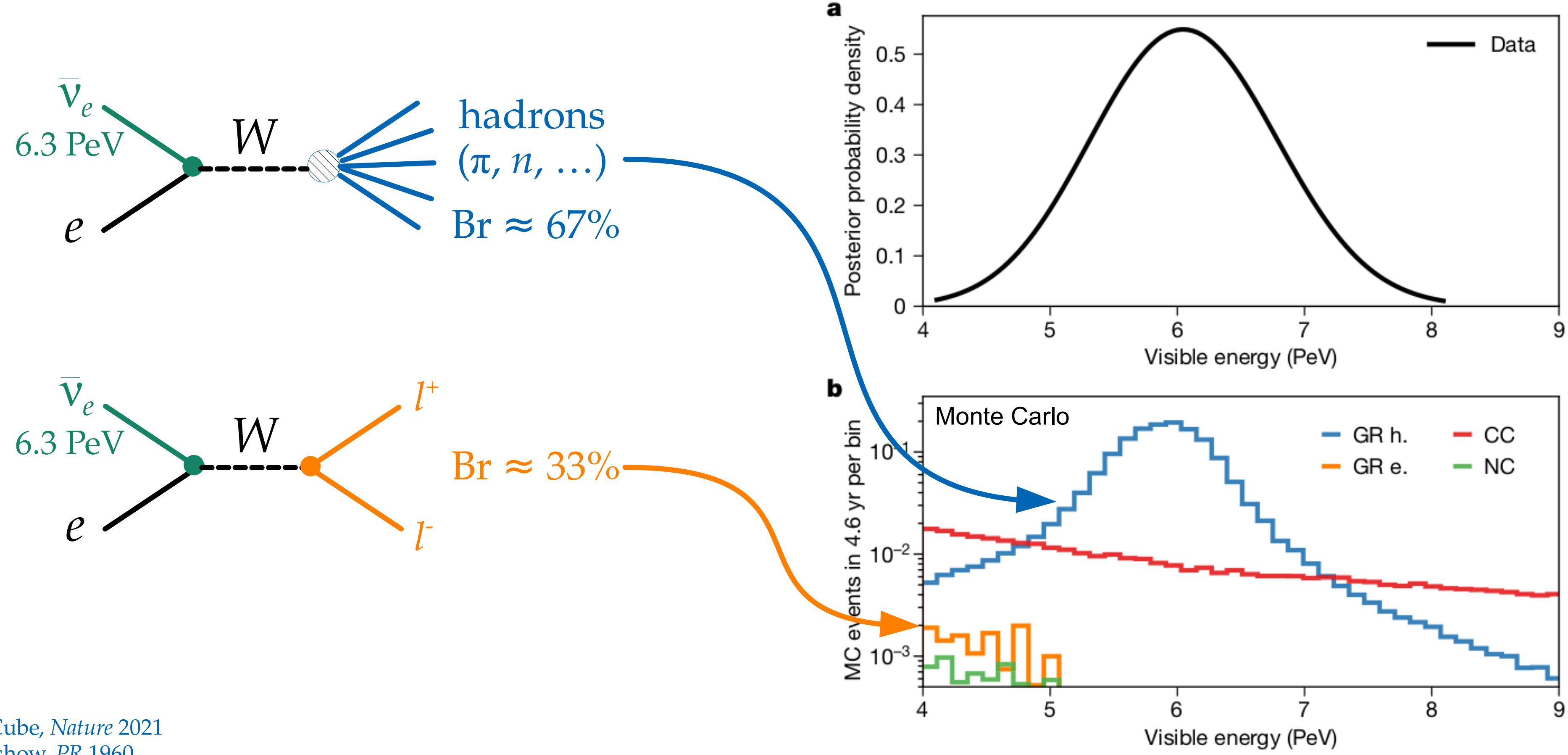

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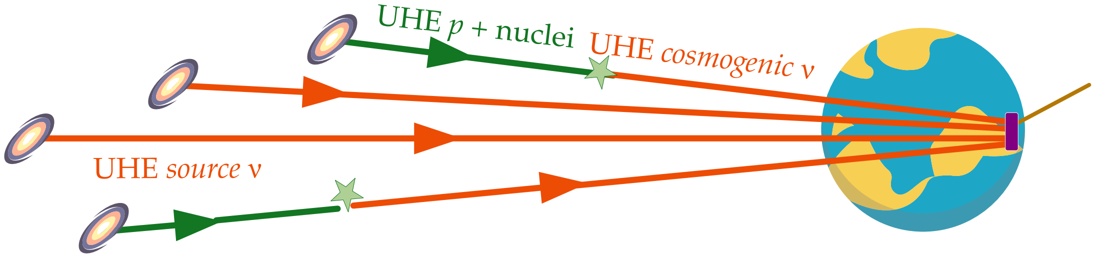
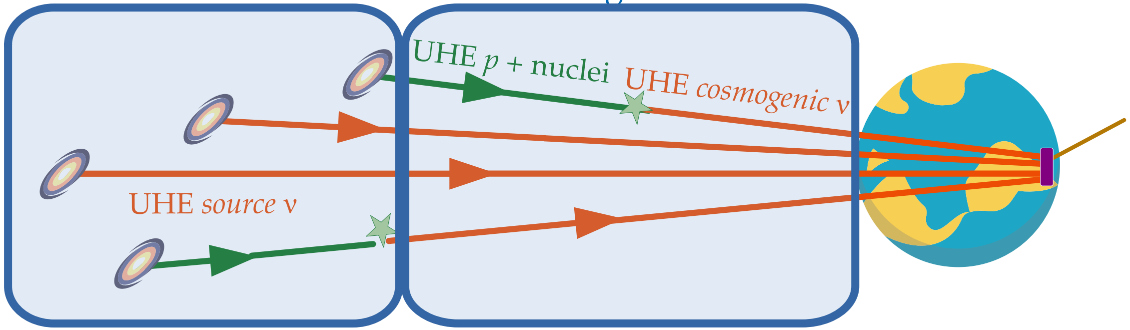
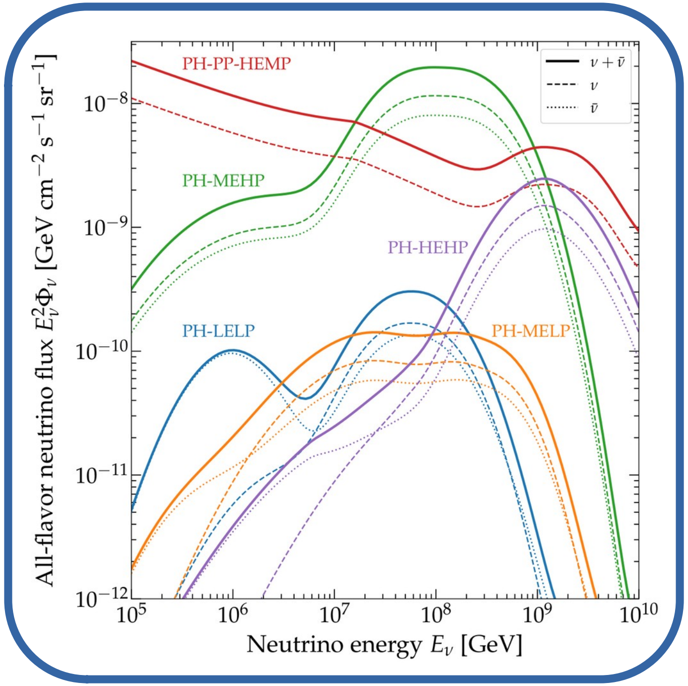
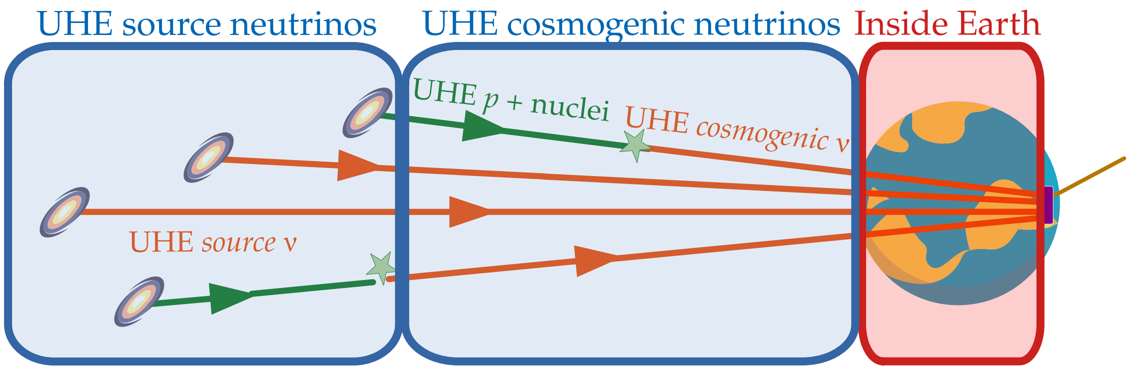
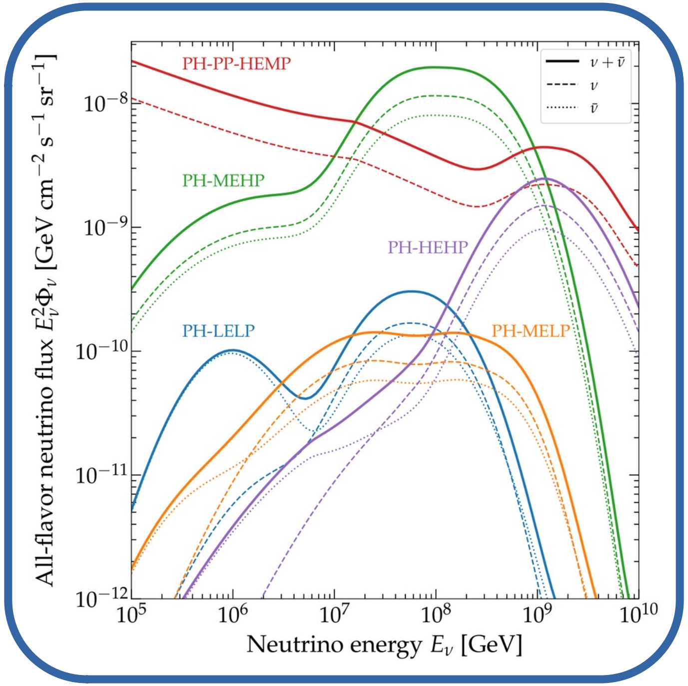

UHE p + nuclei
UHE *cosmogenic* ν
UHE *source* ν





UHE ν from *pp* and *pγ* interactions, account for cosmic-ray spectrum & mass composition, source properties





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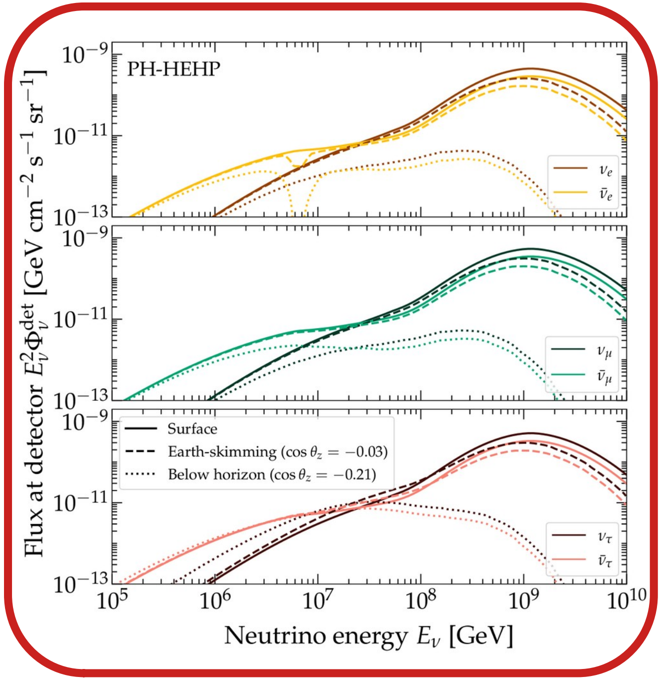
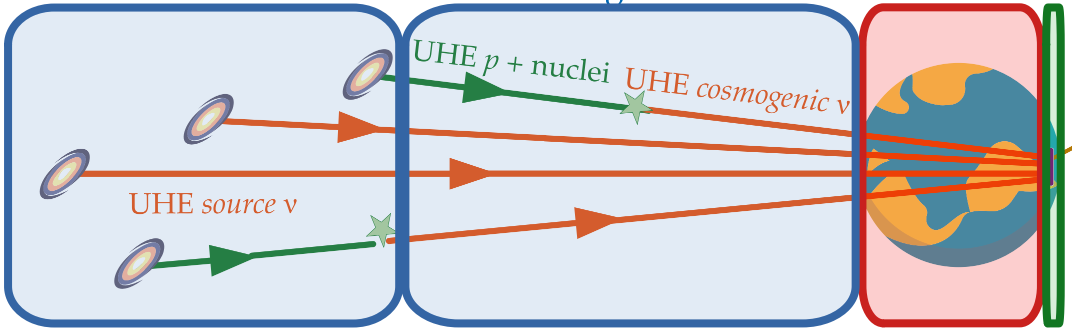
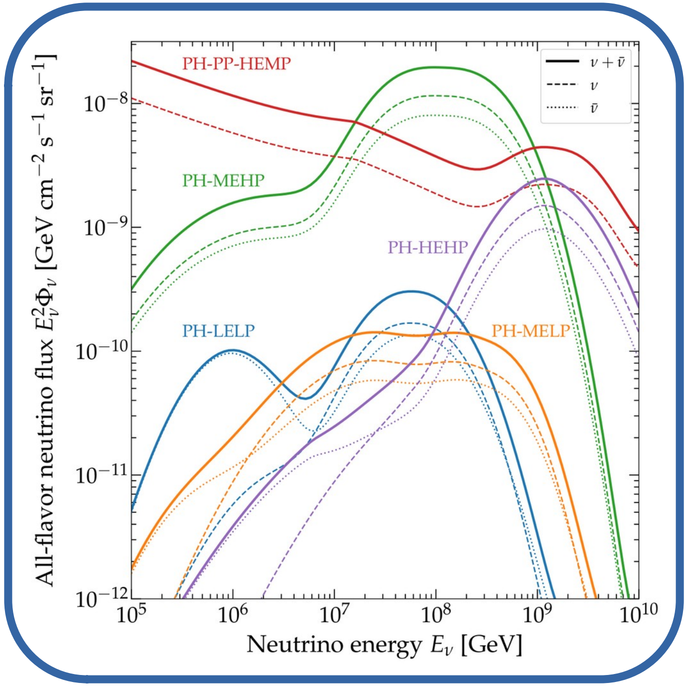


Propagate each flavor of ν and $\bar{\nu}$ separately: deep inelastic scattering, diffractive scattering, ν_τ regeneration





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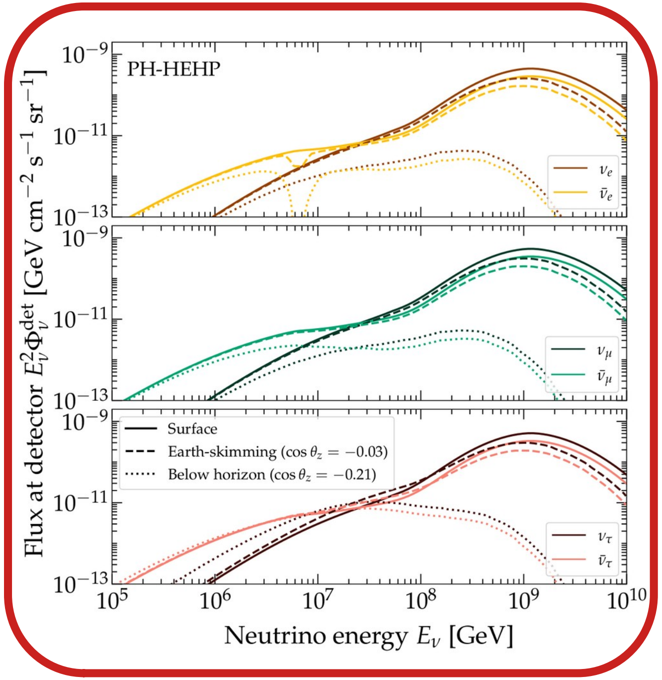

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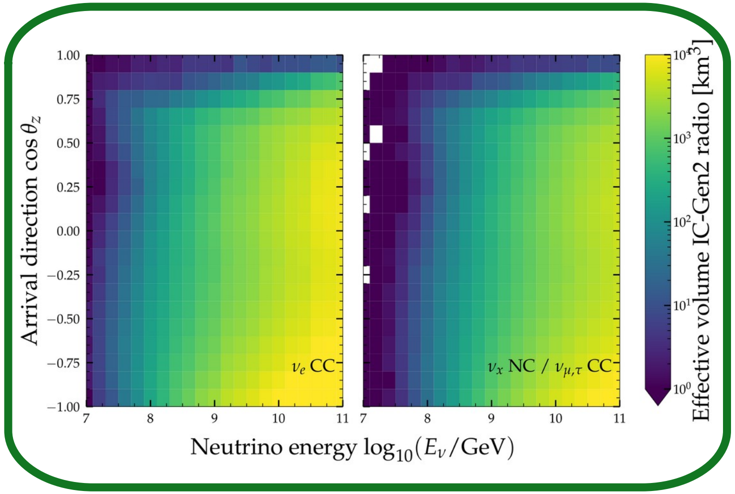

Model radio propagation in ice, antenna response, angular and energy resolution, inelasticity distribution

Fundamental physics

Fundamental physics with HE cosmic neutrinos

- Numerous new-physics effects grow as $\sim \kappa_n \cdot E^n \cdot L$
- So we can probe $\kappa_n \sim 4 \cdot 10^{-47}\,(E/\mathrm{PeV})^{-n}\,(L/\mathrm{Gpc})^{-1}\,\mathrm{PeV}^{1-n}$
- Improvement over limits using atmospheric ν: $\kappa_0 < 10^{-29}$ PeV, $\kappa_1 < 10^{-33}$
- Fundamental physics can be extracted from four neutrino observables:
  - Spectral shape
  - Angular distribution
  - Flavor composition
  - Timing

Fundamental physics with HE cosmic neutrinos

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

  - n = -1: neutrino decay
  - n = 0: CPT-odd Lorentz violation
  - n = +1: CPT-even Lorentz violation

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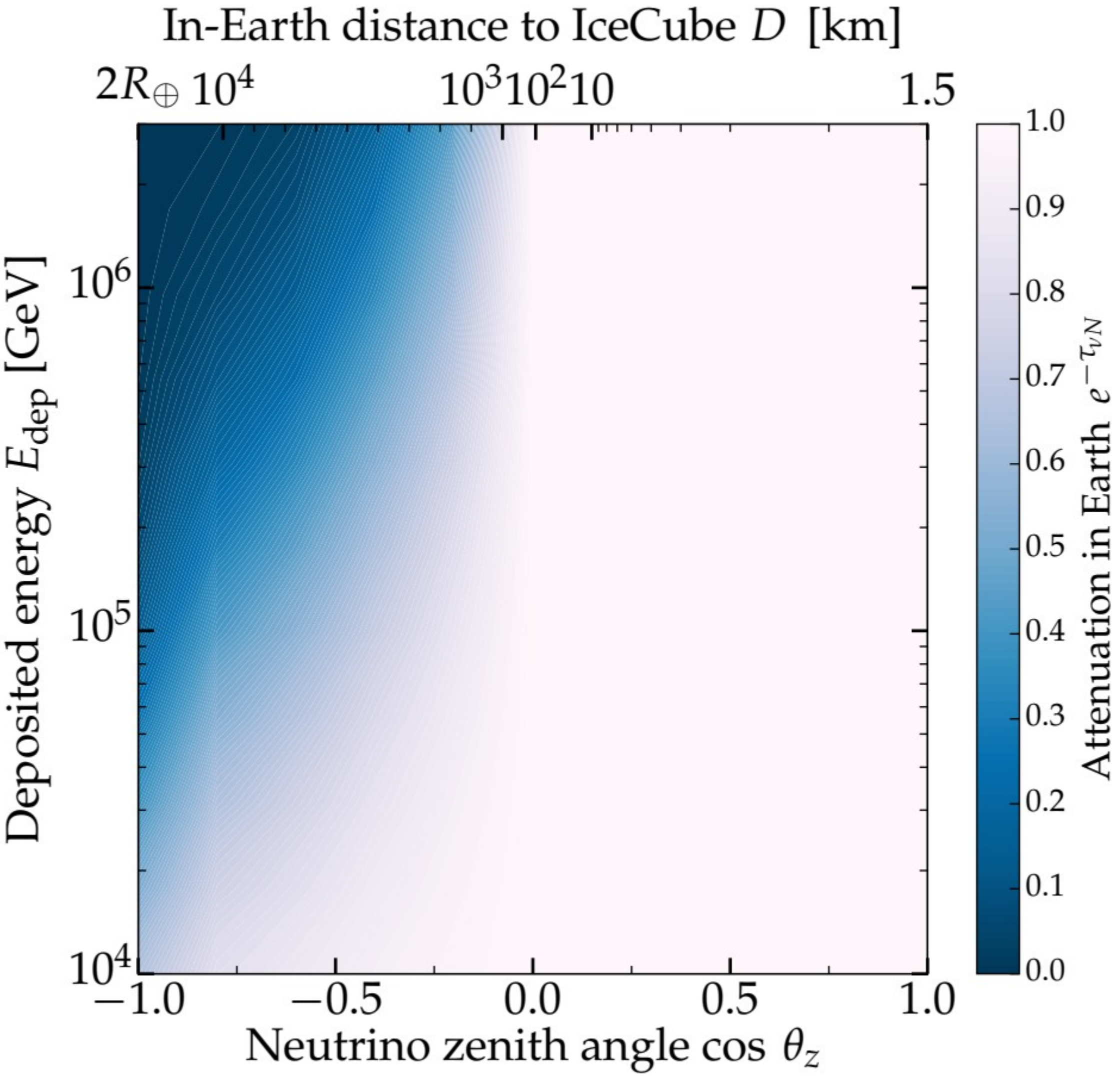
- Fundamental physics can be extracted from four neutrino observables:
  - Spectral shape
  - Angular distribution
  - Flavor composition
  - Timing

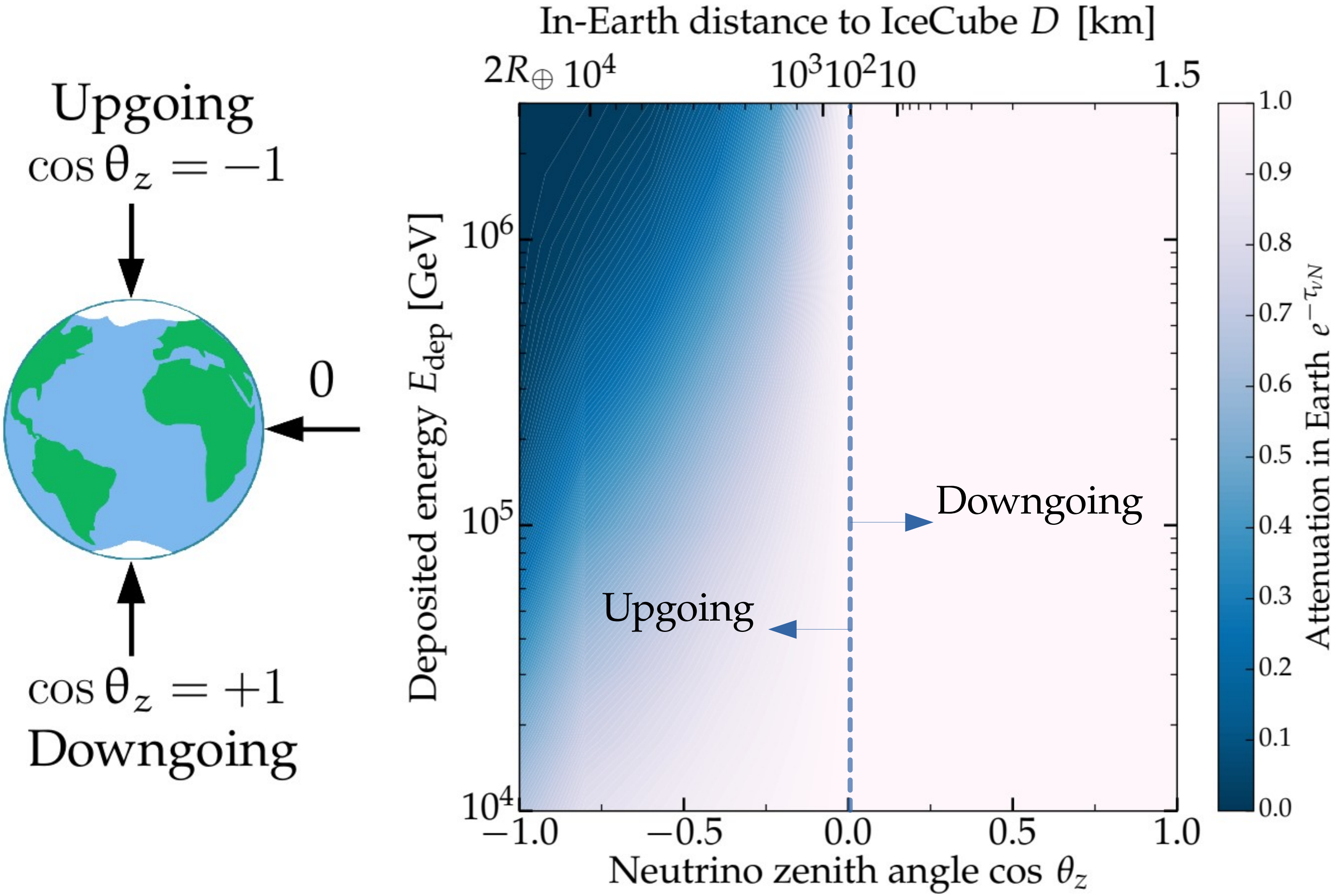
In spite of
poor energy, angular, flavor reconstruction
& astrophysical unknowns

Example 1:

Measuring TeV–PeV ν cross sections



In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4 10^3 10^2 10 1.5
Deposited energy $E_{\rm dep}$ [GeV]
10^6
10^5
10^4
−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



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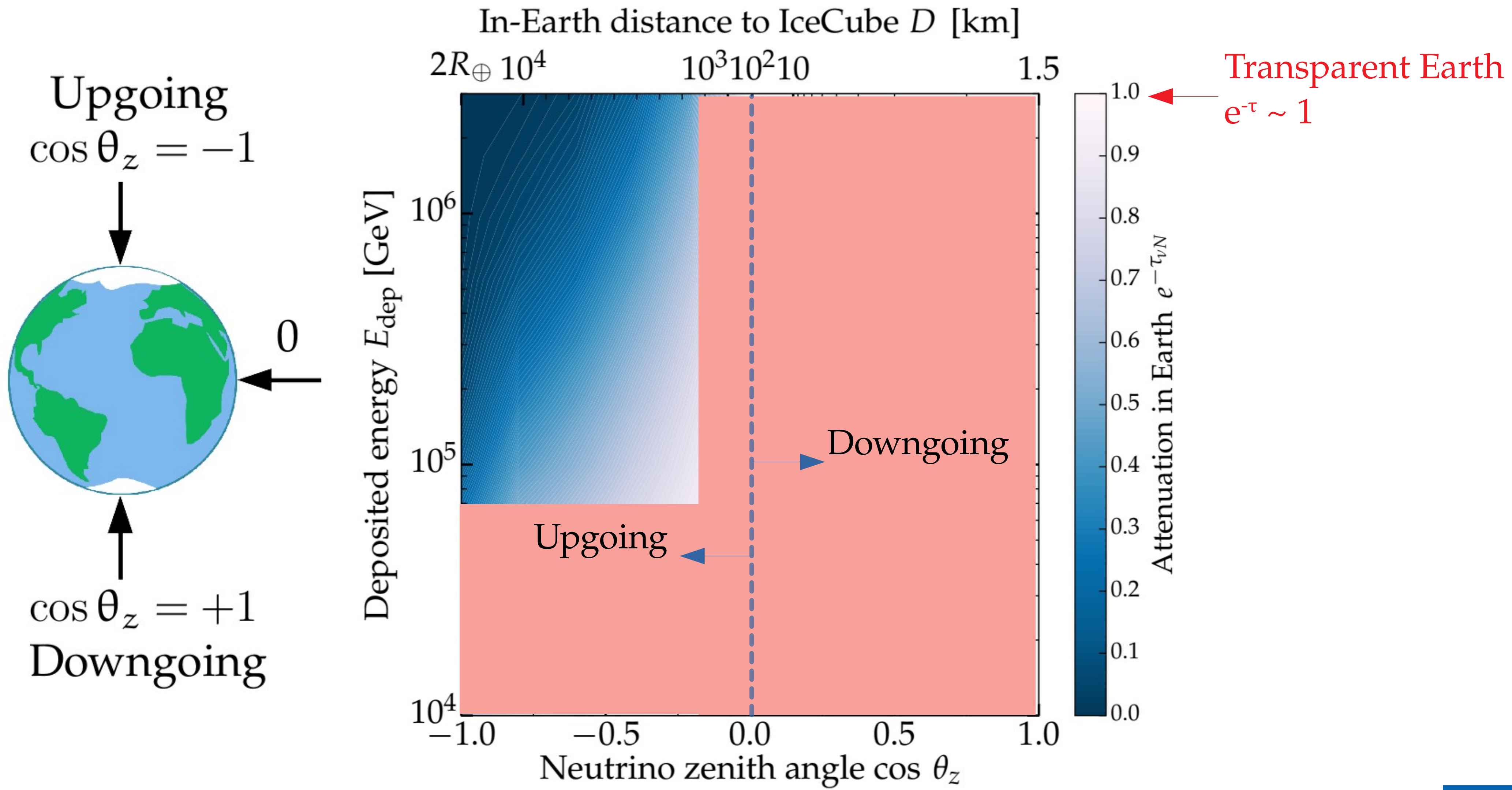
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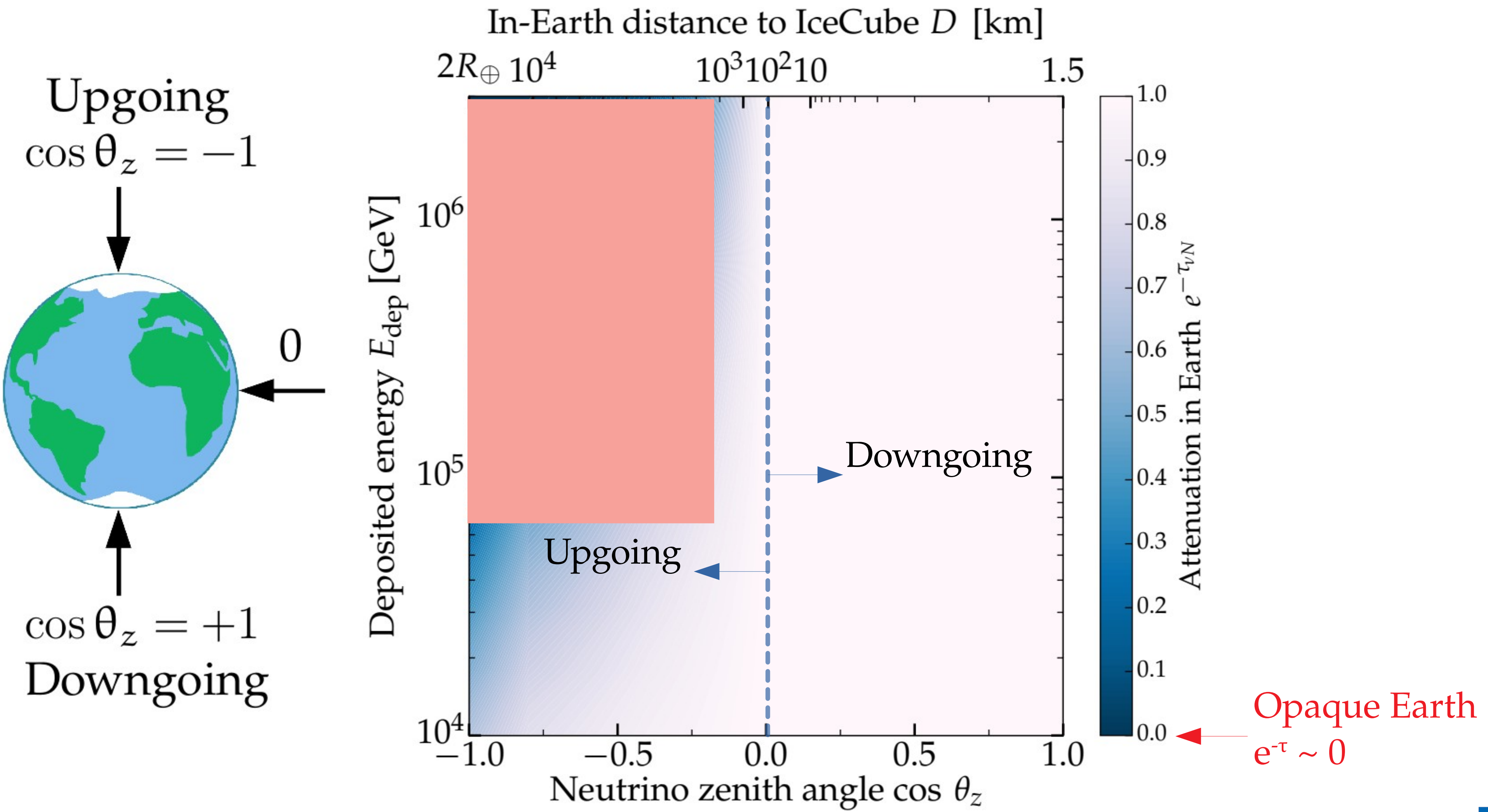
Deposited energy E_{dep} [GeV]
10^6
10^5
10^4
Downgoing
Upgoing
−1.0 −0.5 0.0 0.5 1.0
Neutrino zenith angle cos θ_z
Attenuation in Earth $e^{-\tau_{\nu N}}$
1.0 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.0
Transparent Earth
$e^{-\tau} \sim 1$

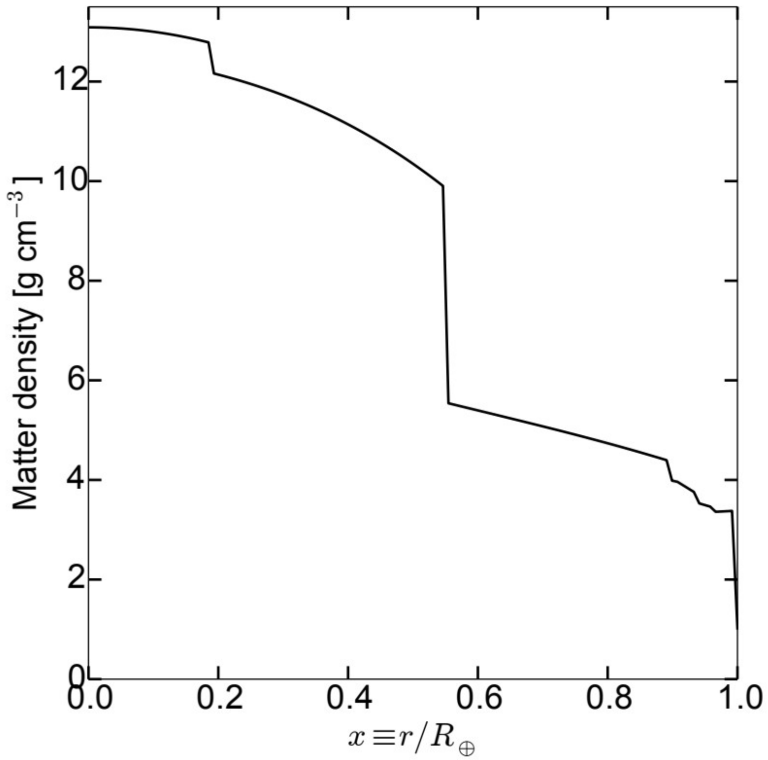


Upgoing
$\cos\theta_z = -1$
0
$\cos\theta_z = +1$
Downgoing
In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4 10^3 10^2 10 1.5
Deposited energy E_{dep} [GeV]
10^4
10^5
10^6
Downgoing
Upgoing
−1.0 −0.5 0.0 0.5 1.0
Neutrino zenith angle $\cos\theta_z$
Attenuation in Earth $e^{-\tau_{\nu N}}$
0.0 0.1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

A feel for the in-Earth attenuation

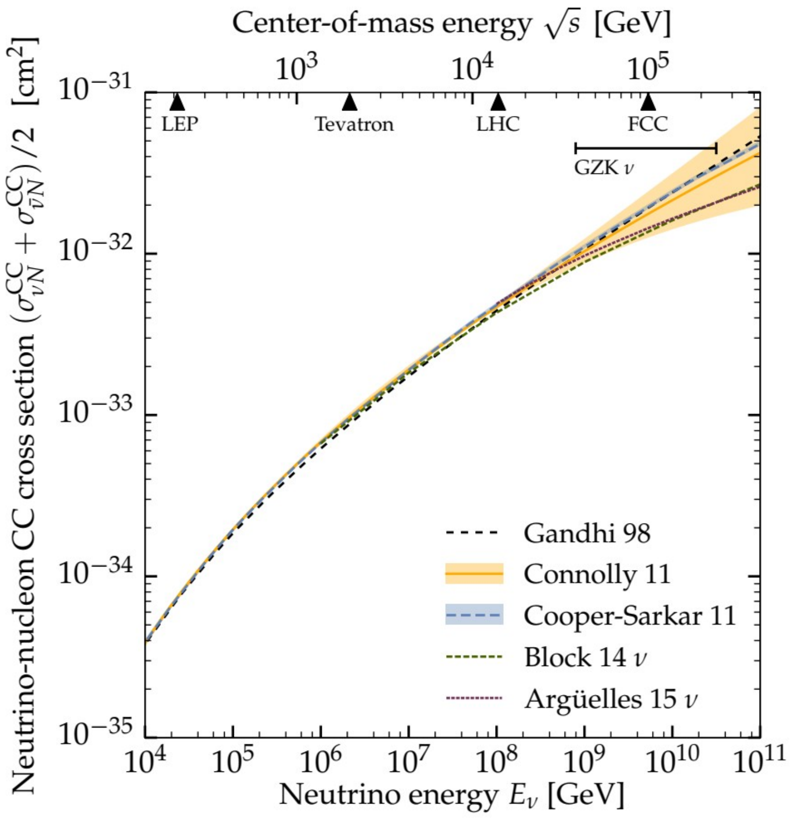
Earth matter density

(Preliminary Reference Earth Model)



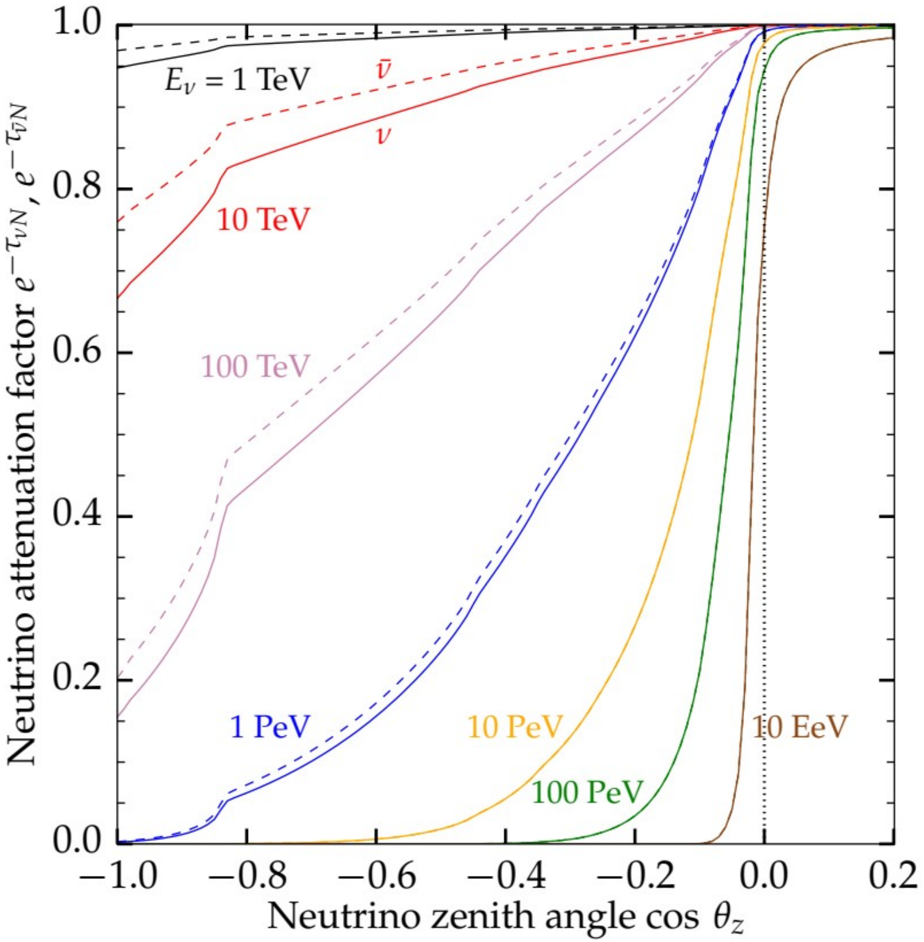
+

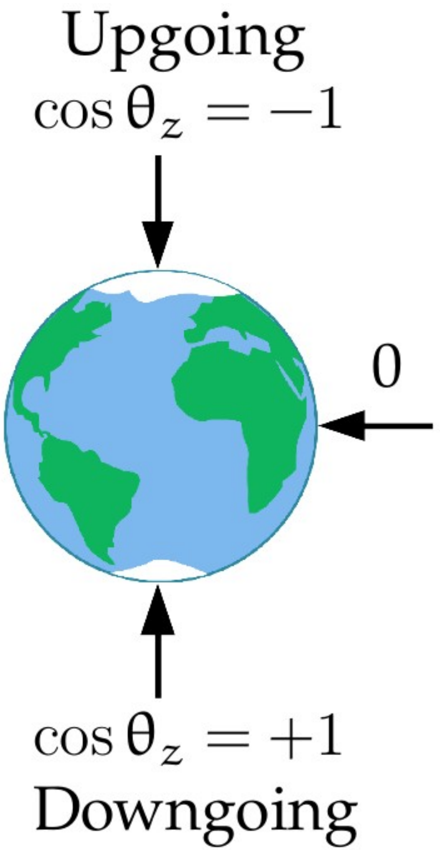
Neutrino-nucleon cross section



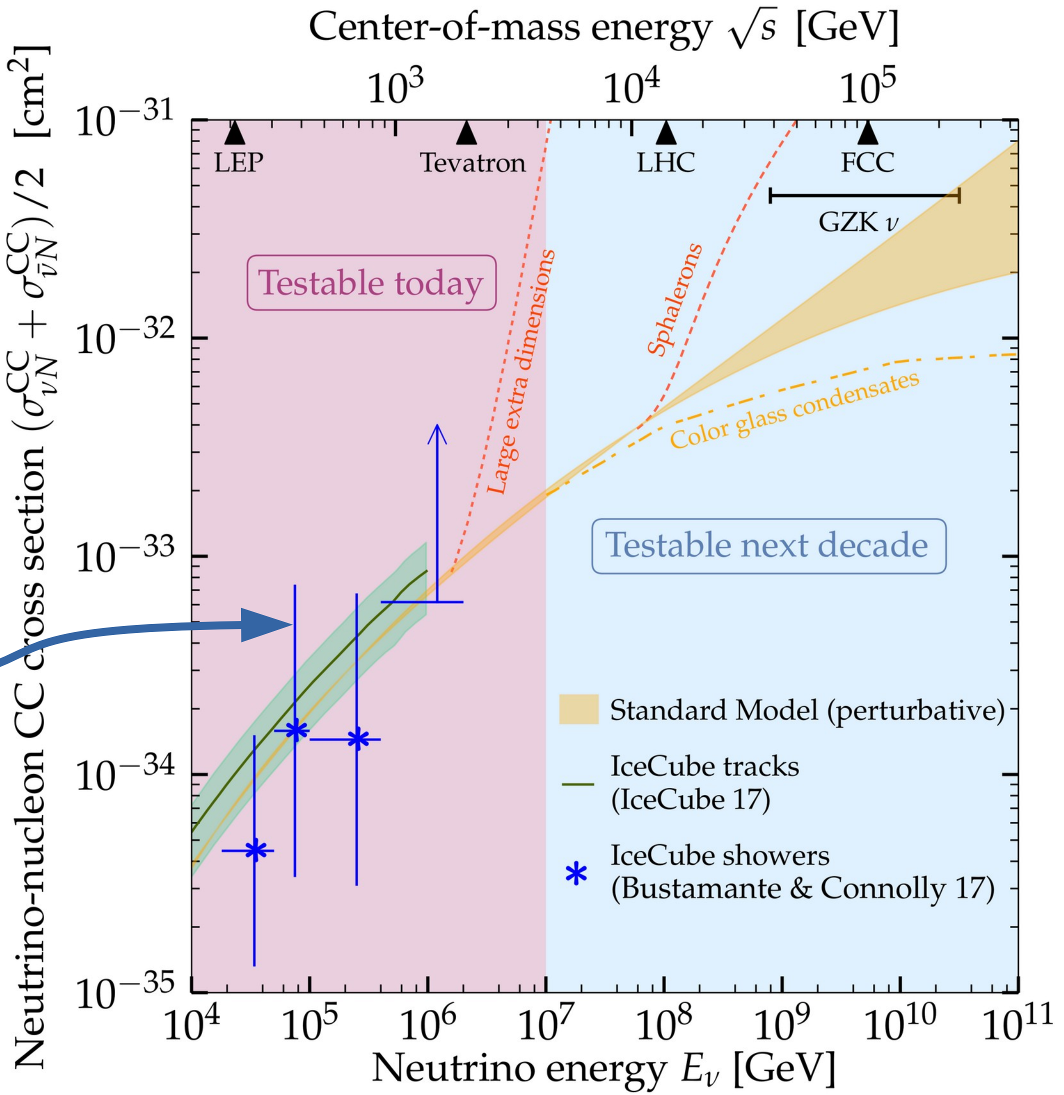
A feel for the in-Earth attenuation

=





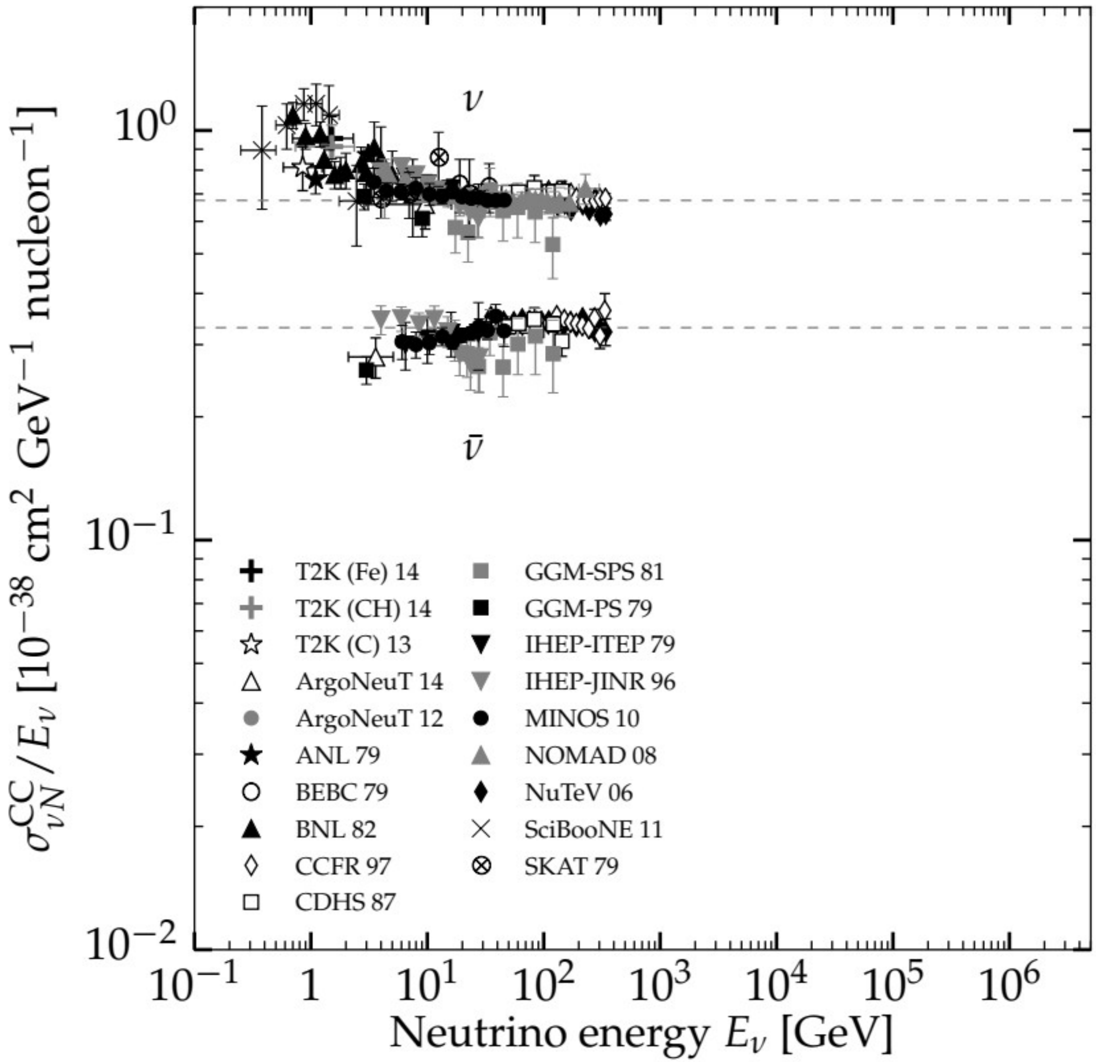
- Fold in astrophysical unknowns (spectral index, normalization)
- Compatible with SM predictions
- Still room for new physics
- Today, using IceCube:
  - Extracted from ~60 showers in 6 yr
  - Limited by statistics
- Future, using IceCube-Gen2:
  - × 5 volume ⇒ 300 showers in 6 yr
  - Reduce statistical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



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

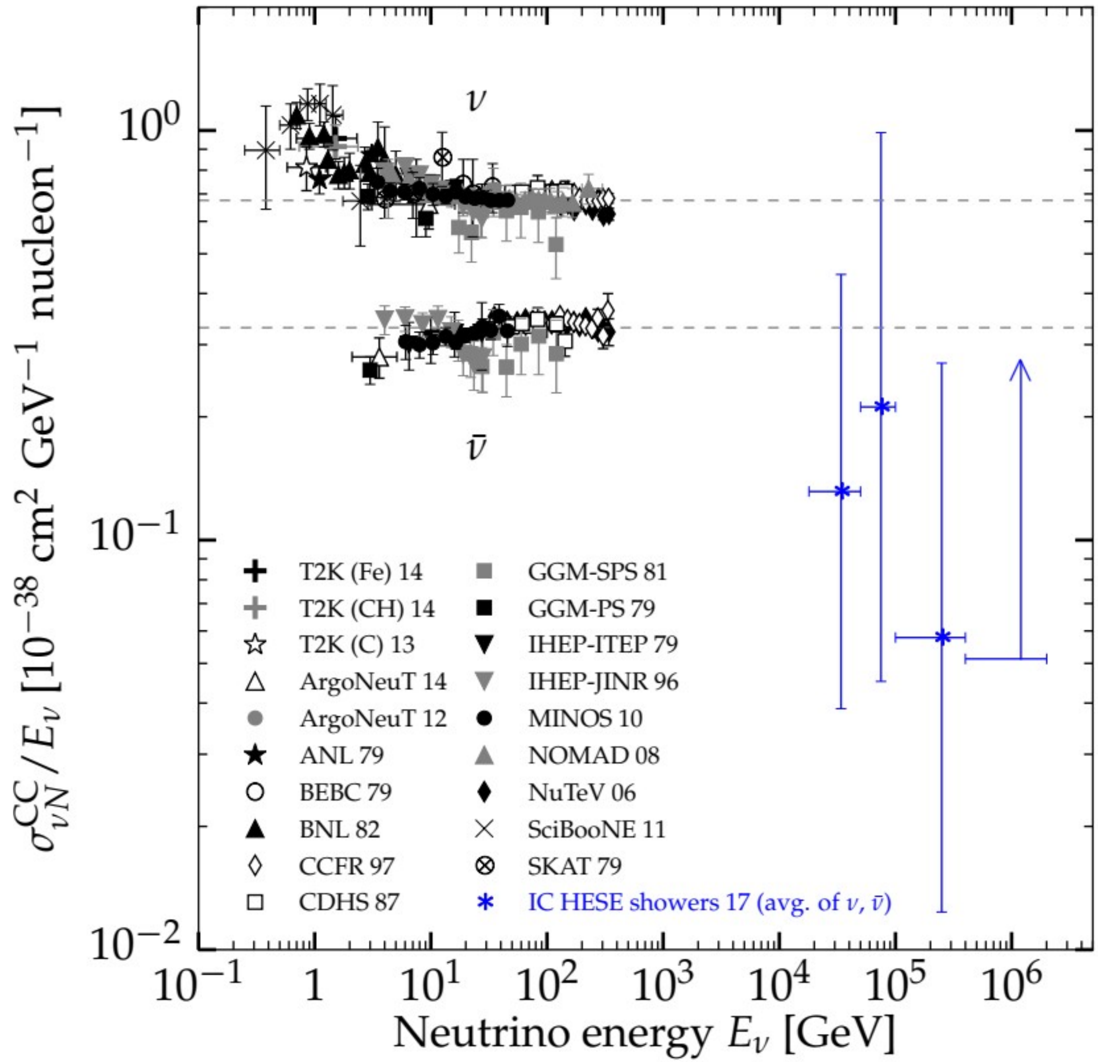
Cross sections from:
MB & Connolly, *PRL* 2019
IceCube, *Nature* 2017

Recent update:
IceCube, 2011.03560

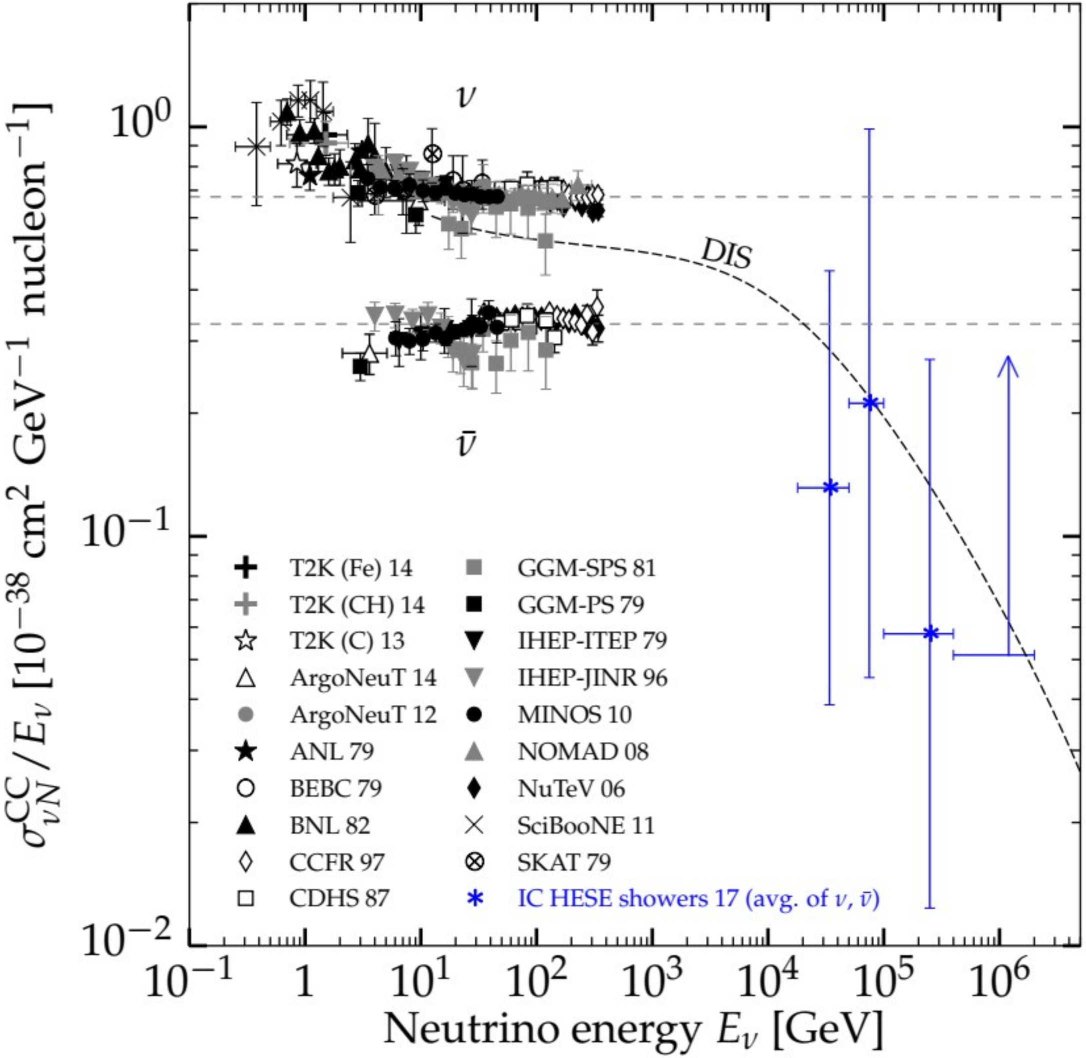


MB & Connolly *PRL* 2019
See also: IceCube, *Nature* 2017

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

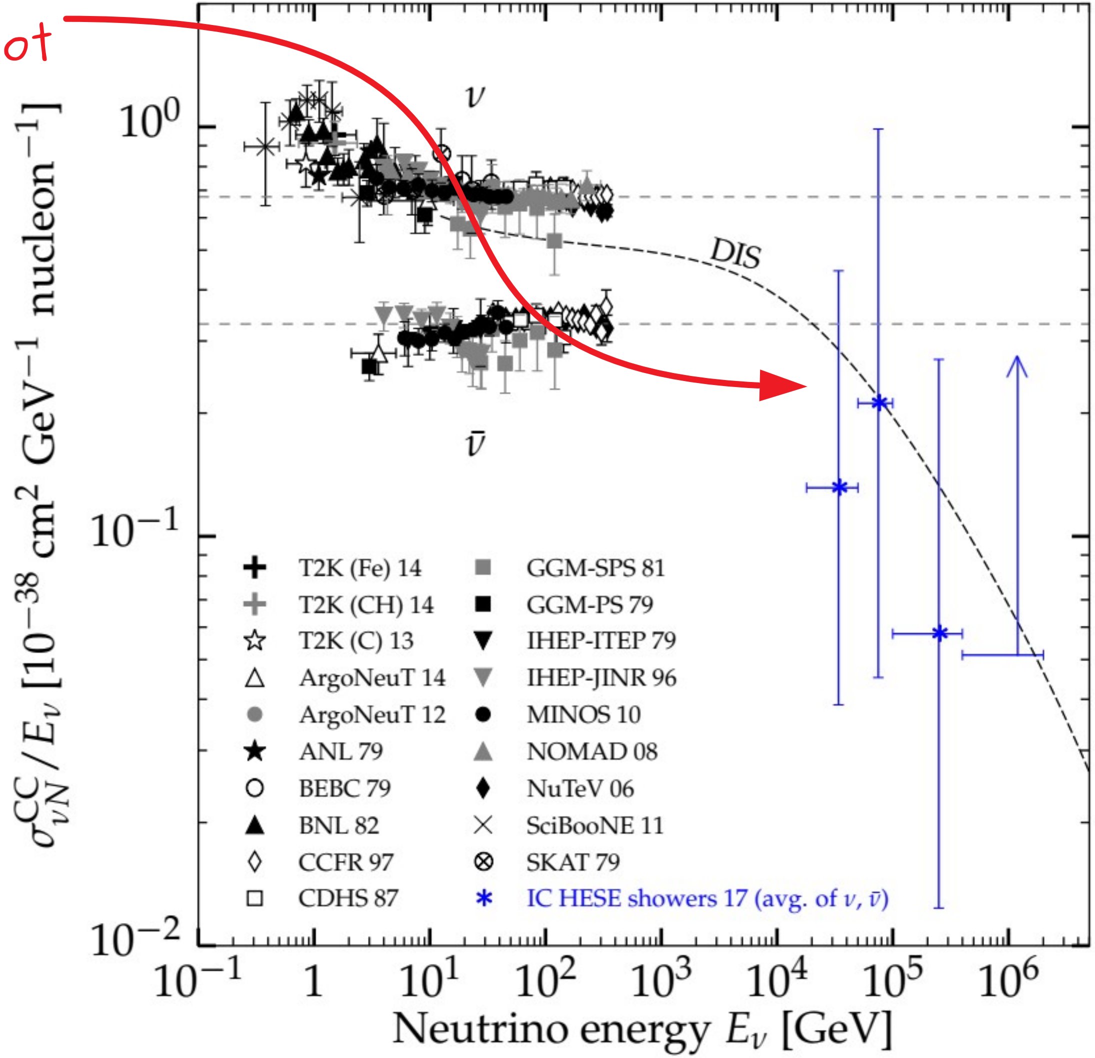


MB & Connolly *PRL* 2019
See also: IceCube, *Nature* 2017



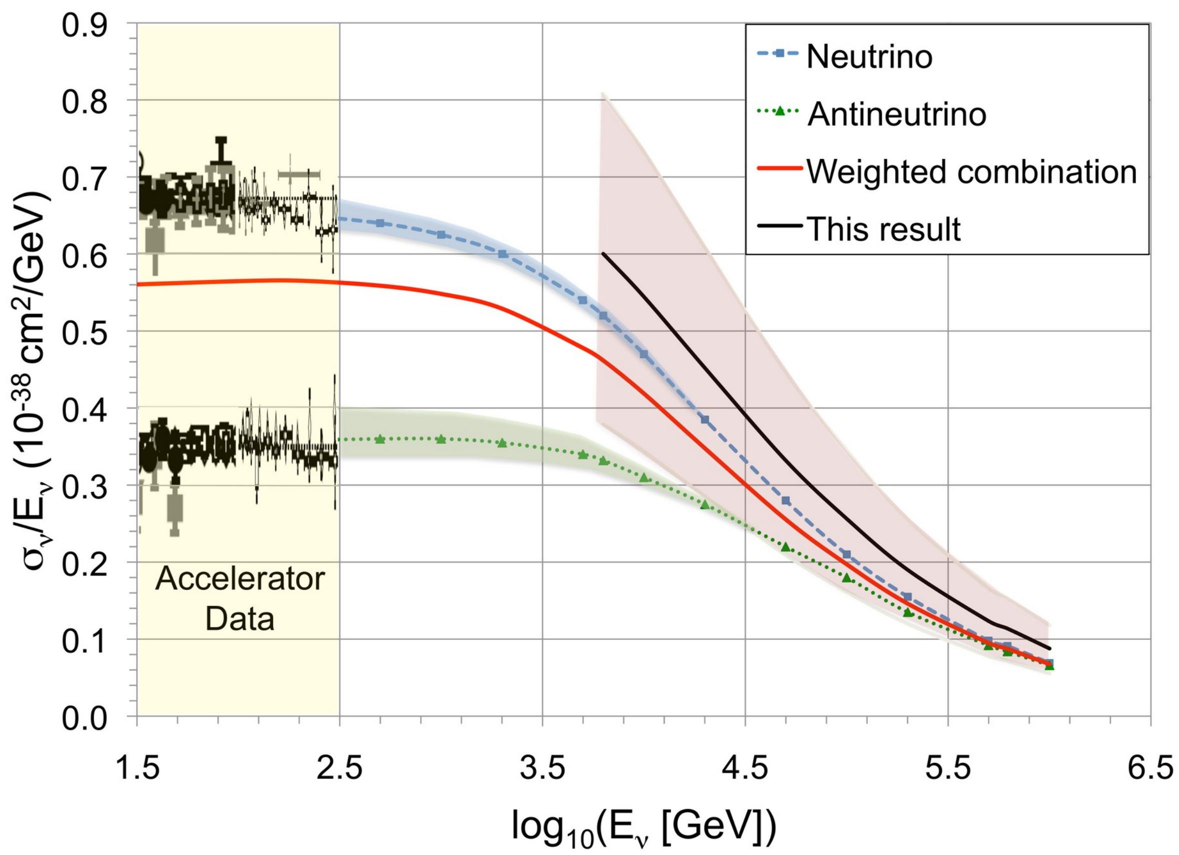
Extending the PDG cross-section plot

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



Using through-going muons instead

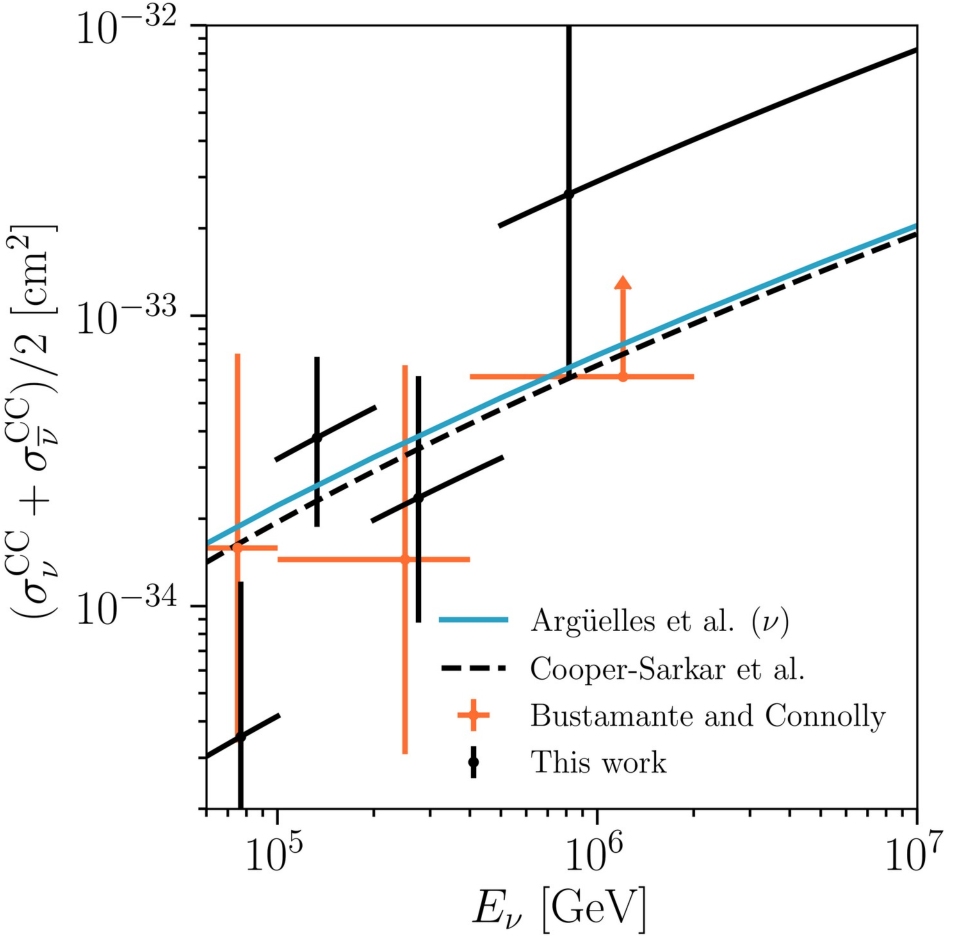
- Use ~10^4 through-going muons
- Measured: dE_μ/dx
- Inferred: $E_\mu \approx dE_\mu/dx$
- From simulations (uncertain): most likely E_ν given E_μ
- Fit the ratio σ_{obs}/σ_{SM}
  $1.30\,^{+0.21}_{-0.19}\,(\text{stat.})\,^{+0.39}_{-0.43}\,(\text{syst.})$
- All events grouped in a single energy bin 6–980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



IceCube, *Nature* 2017

Updated cross section measurement

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



IceCube, 2011.03560

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

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

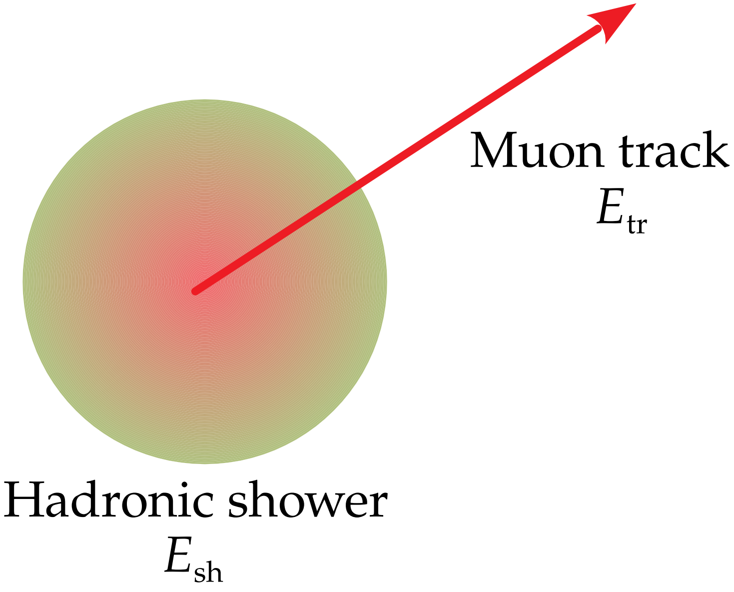
  $E_X = y\, E_\nu$ and $E_\mu = (1-y)\, E_\nu \;\Rightarrow\; y = (1 + E_\mu/E_X)^{-1}$

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

- In a HESE starting track:

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

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



IceCube, *PRD* 2019

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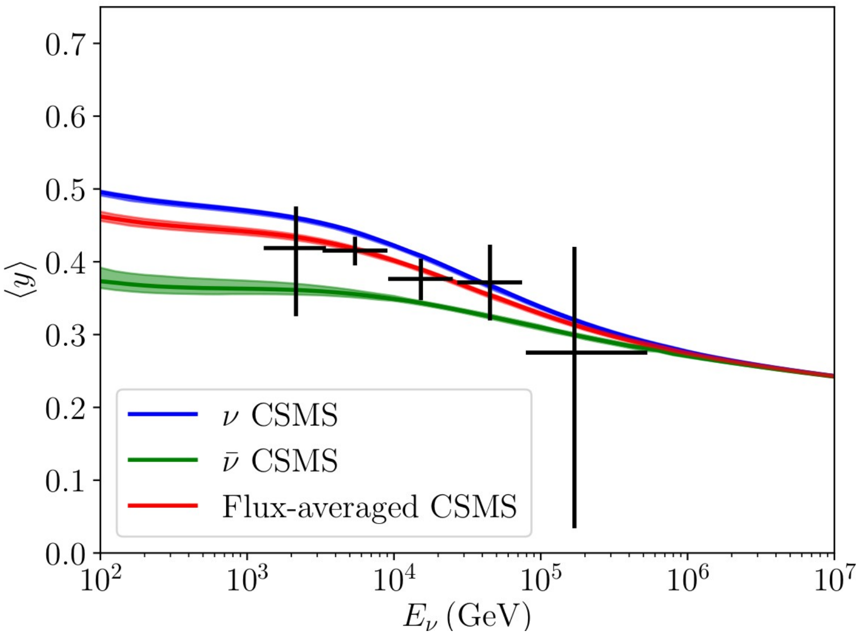
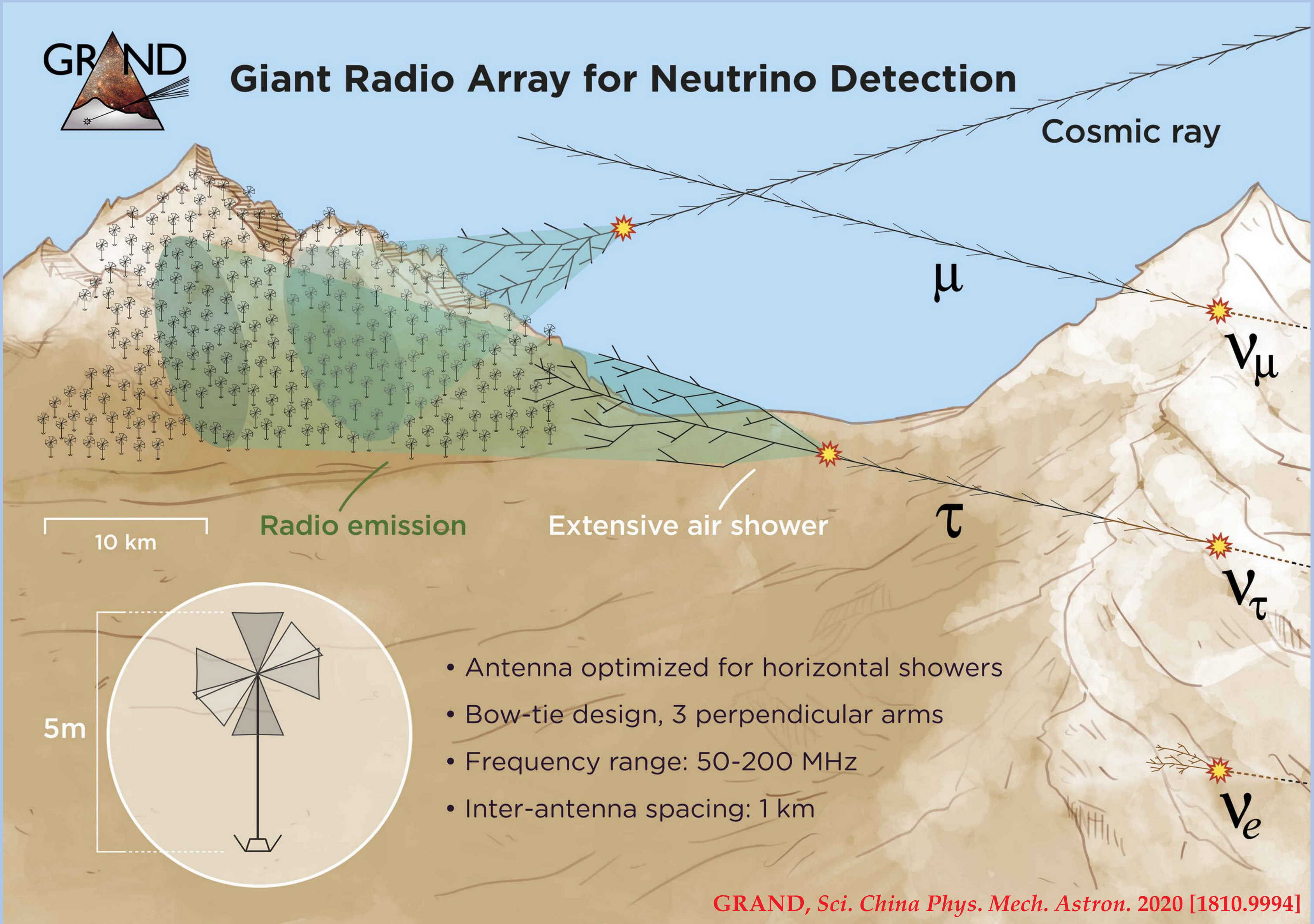


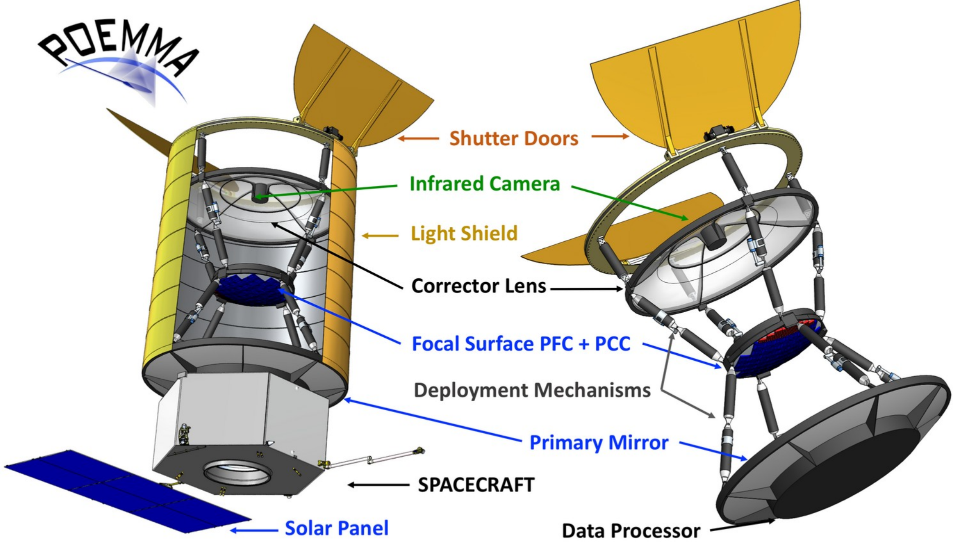
IceCube, *PRD* 2019



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

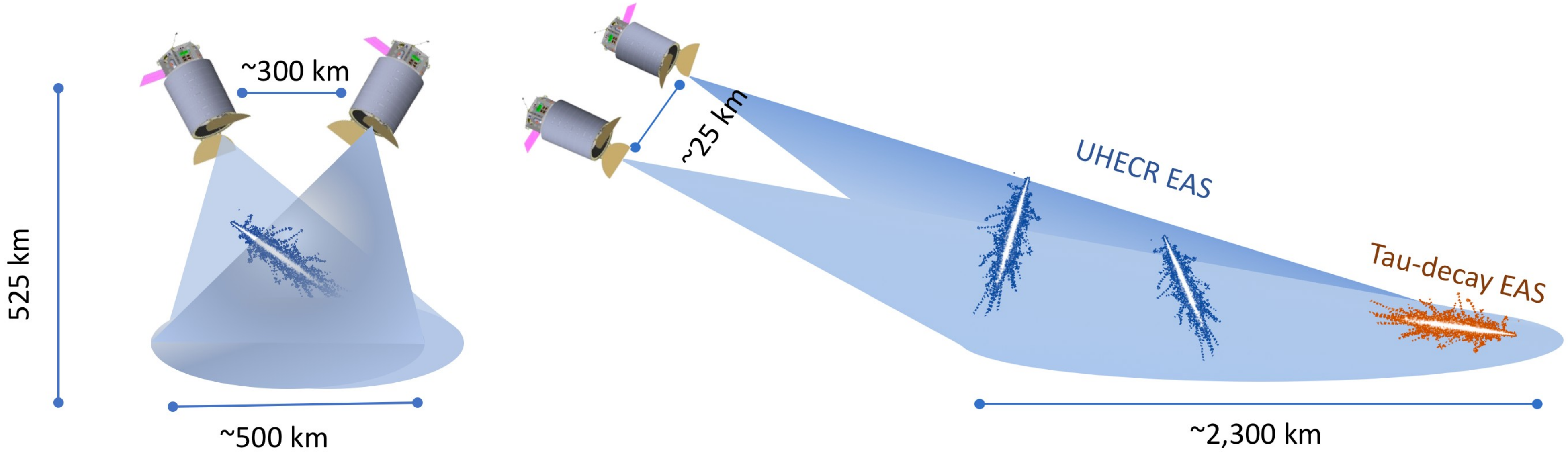
POEMMA:
Probe of Extreme Multi-Messenger Astrophysics

POEMMA, *JCAP* 2021 (2012.07945)



POEMMA-Stereo

POEMMA-Limb



POEMMA:
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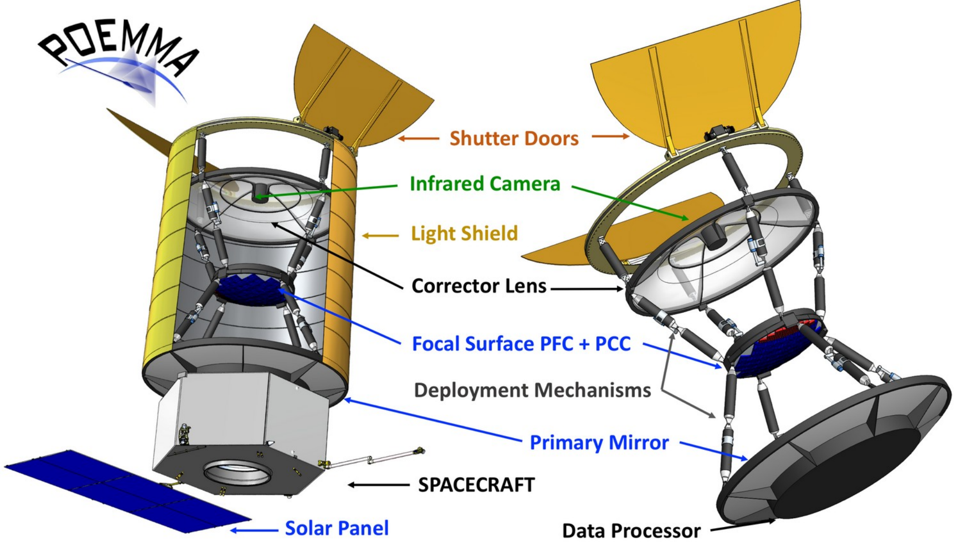
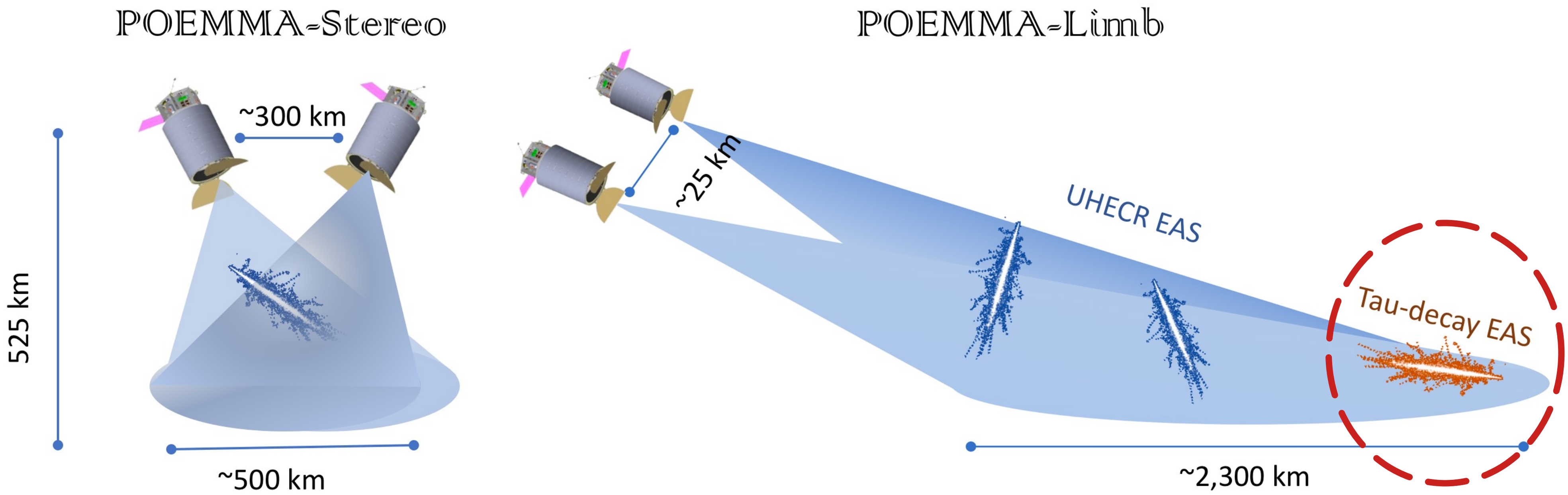
POEMMA, *JCAP* 2021 (2012.07945)

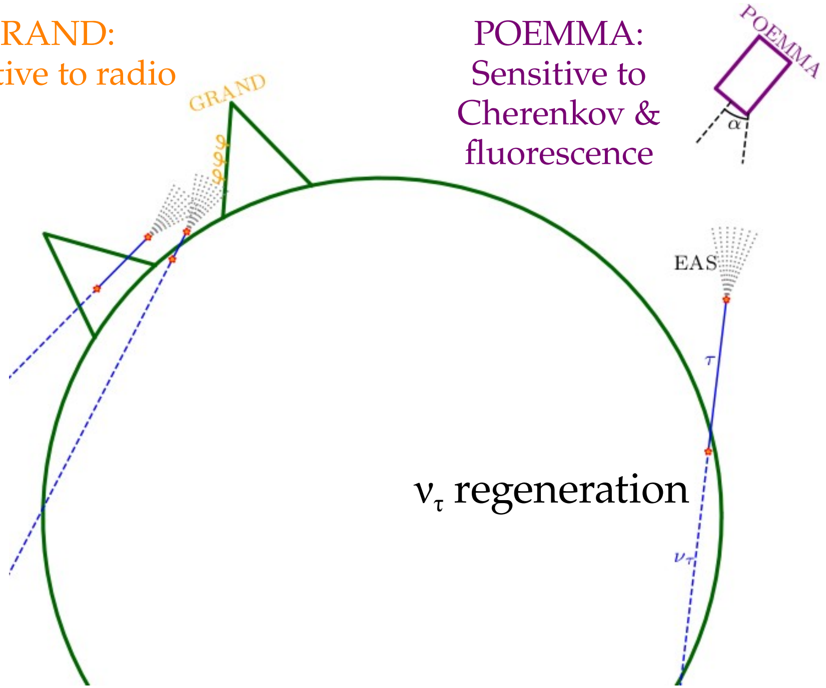




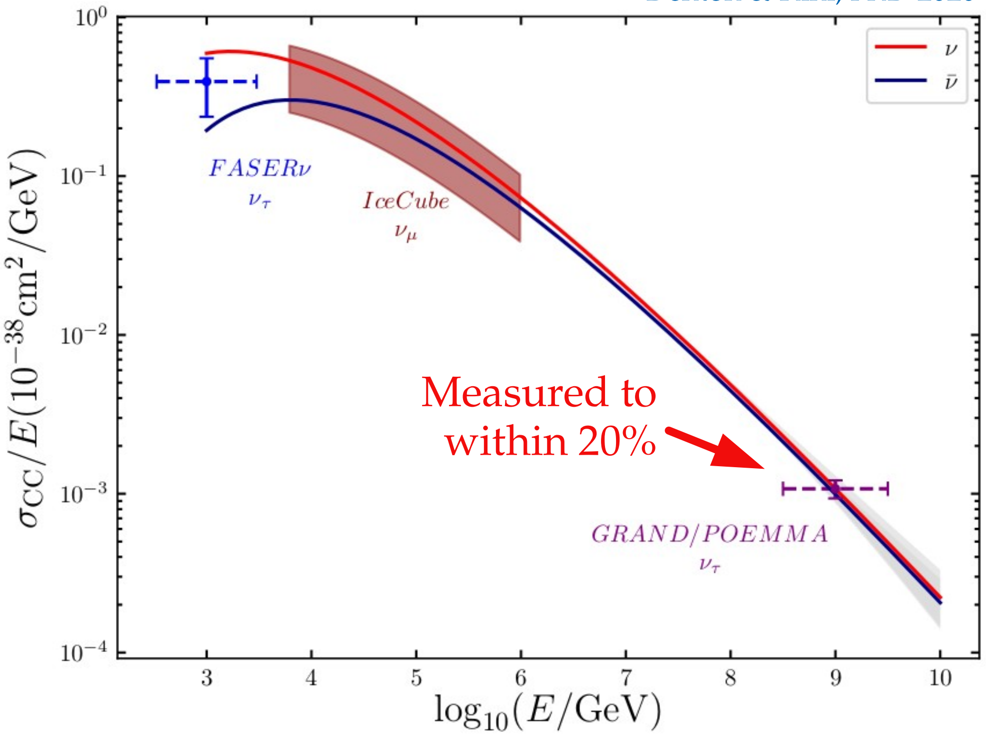
GRAND & POEMMA

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

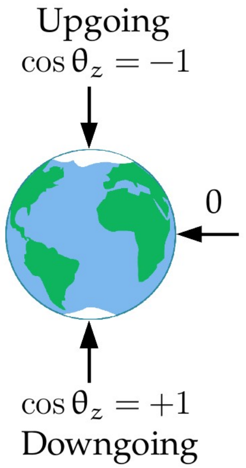
If they see 100 events from ν_τ with initial energy of 10^9 GeV (pre-attenuation):

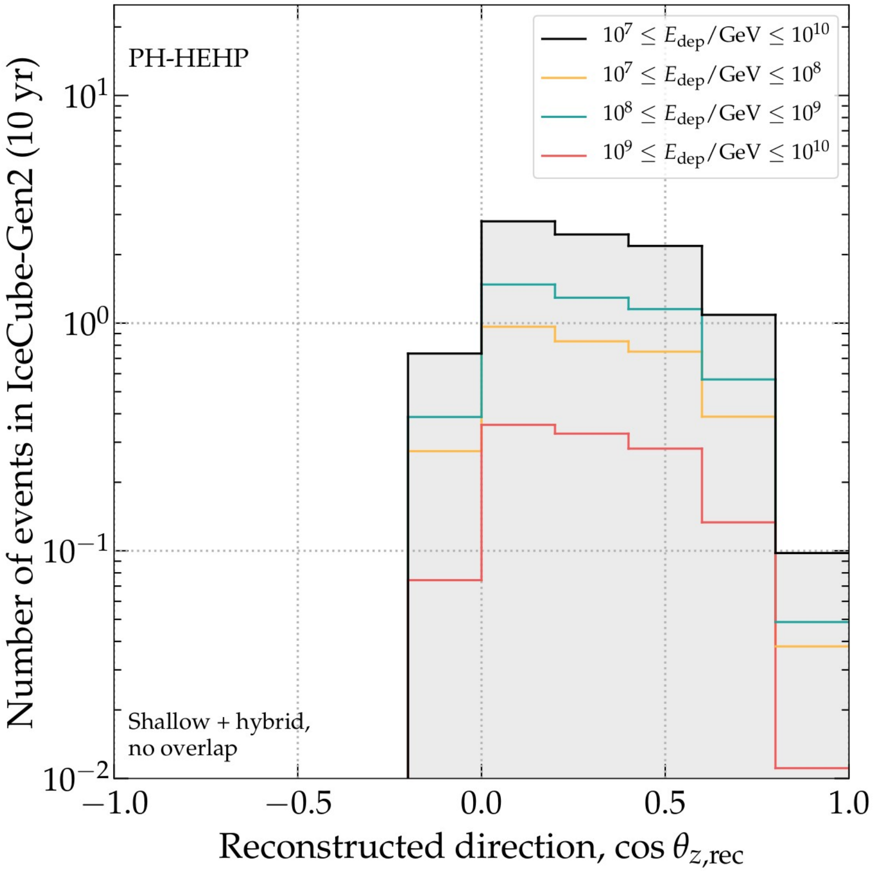


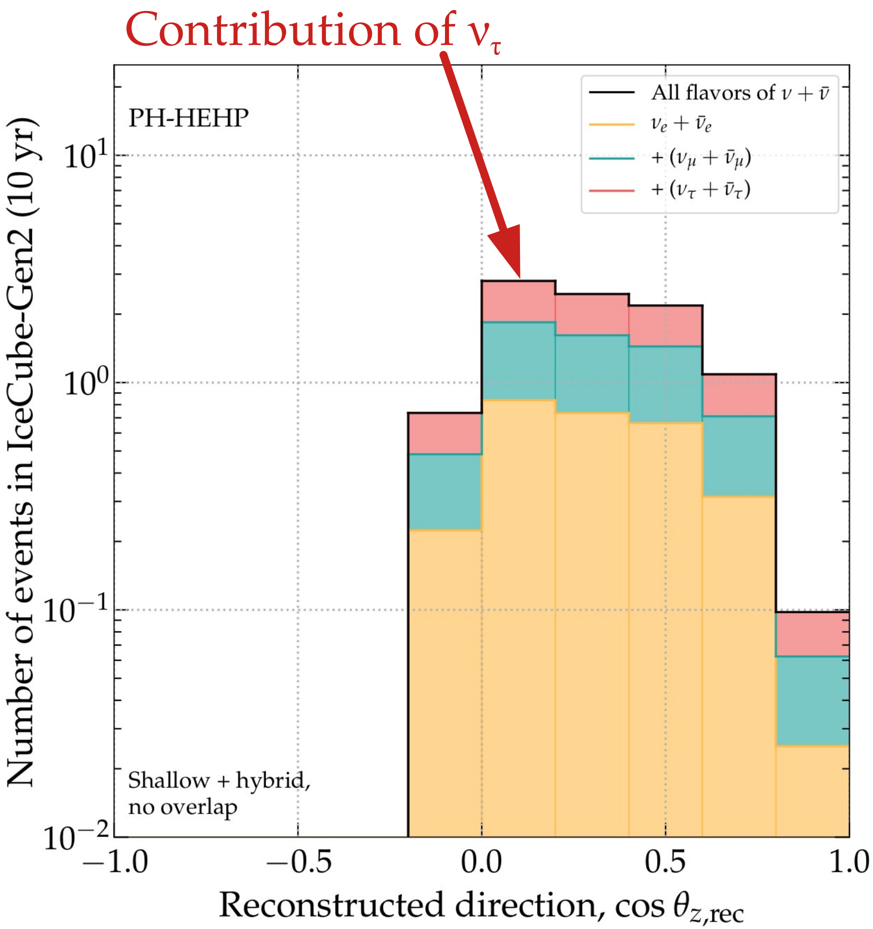
Denton & Kini, *PRD* 2020



IceCube-Gen2 Radio



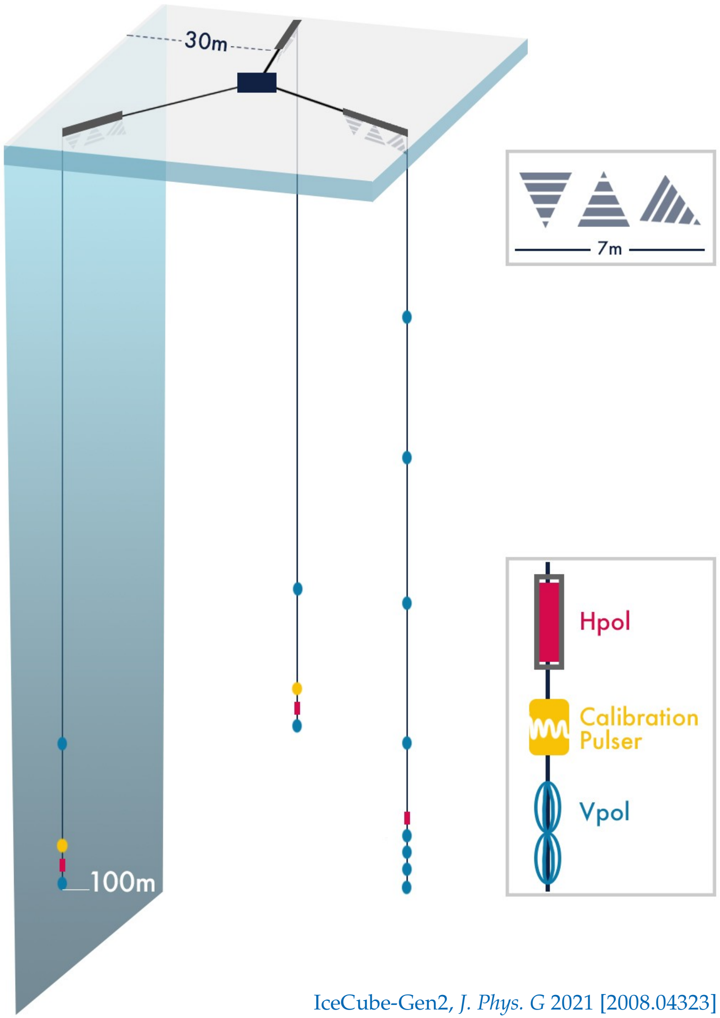




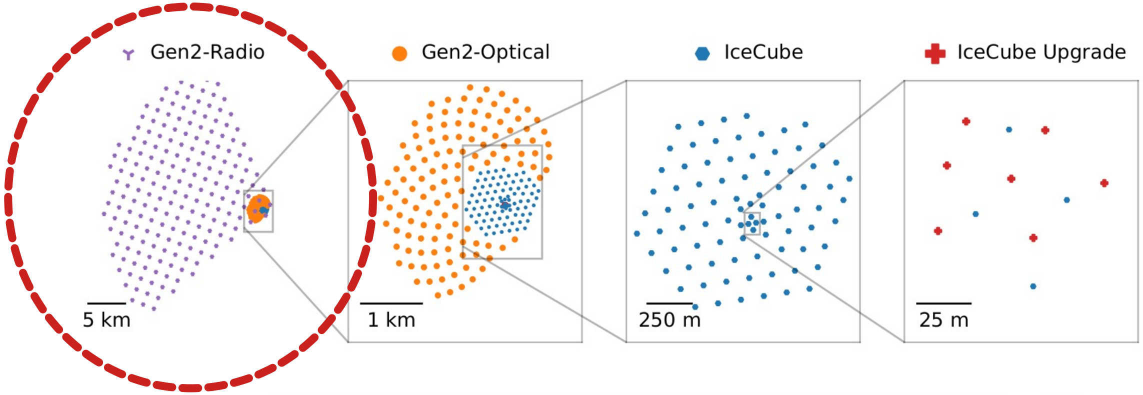
(Angular resolution in $\theta_{z,\mathrm{rec}}$: 2°
Energy resolution in $\log_{10}(E_{dep}/\mathrm{GeV})$: 0.1)

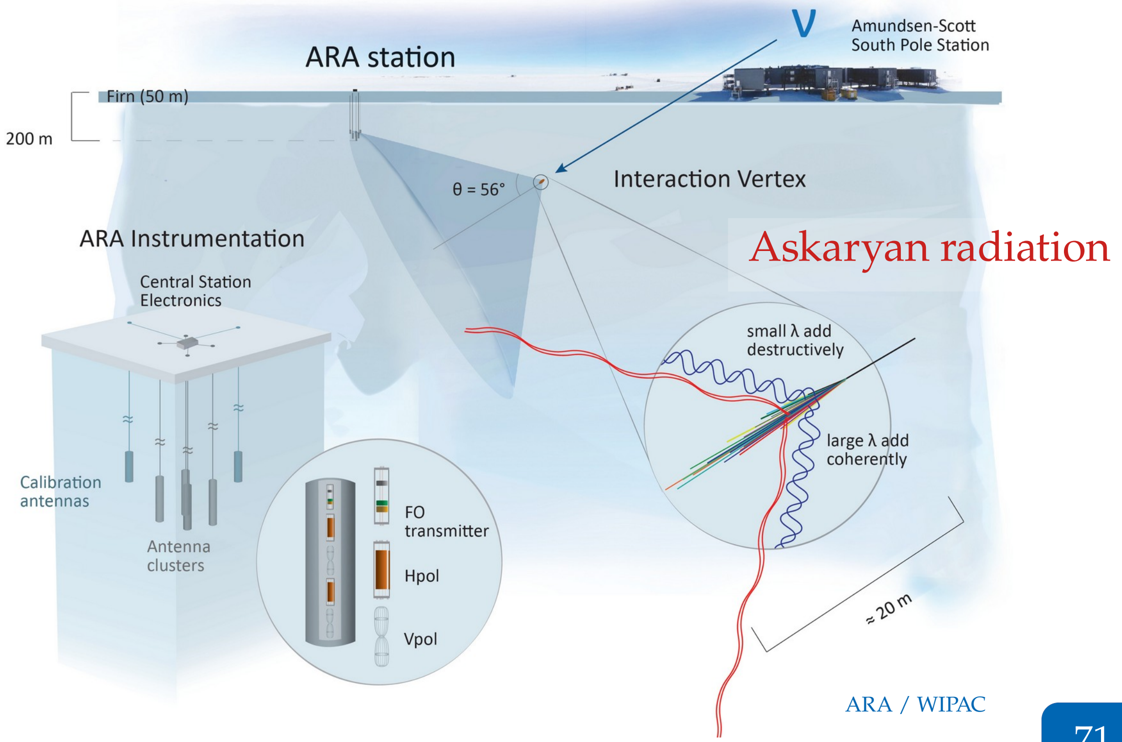
Valera, **MB**, Glaser, *In preparation*

IceCube-Gen2 Radio



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





ARA / WIPAC

Example 2:
Secret neutrino interactions

νSI with the UHE diffuse flux

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

Coupling matrix:

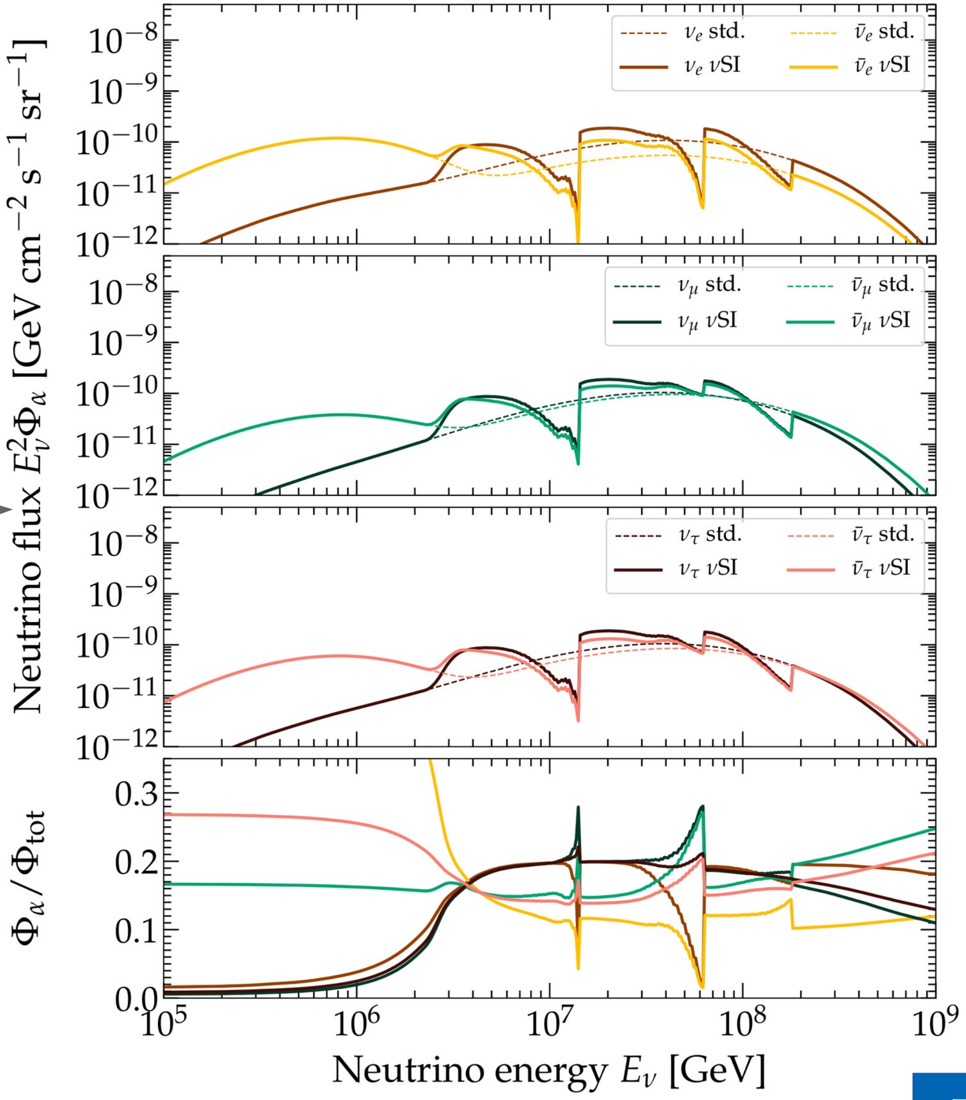
$$\mathbf{G} \equiv \begin{pmatrix} g_{ee} & g_{e\mu} & g_{e\tau} \\ g_{e\mu} & g_{\mu\mu} & g_{\mu\tau} \\ g_{e\tau} & g_{\mu\tau} & g_{\tau\tau} \end{pmatrix}$$

Different flavors can have different couplings

νSI dips and bumps in the diffuse UHE ν flux:

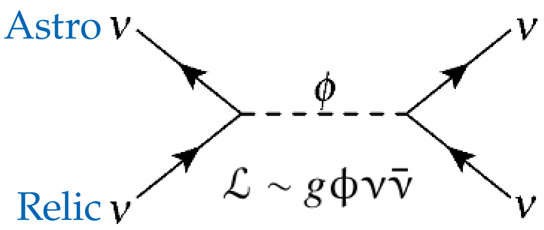
- In the cosmogenic flux
- In the flux from sources

But we need enough events to detect the spectral features – we need POEMMA-360!



MB, Másson, Valera, In prep.

νSI with the UHE transient flux



If this happens repeatedly, high-energy neutrinos disappear

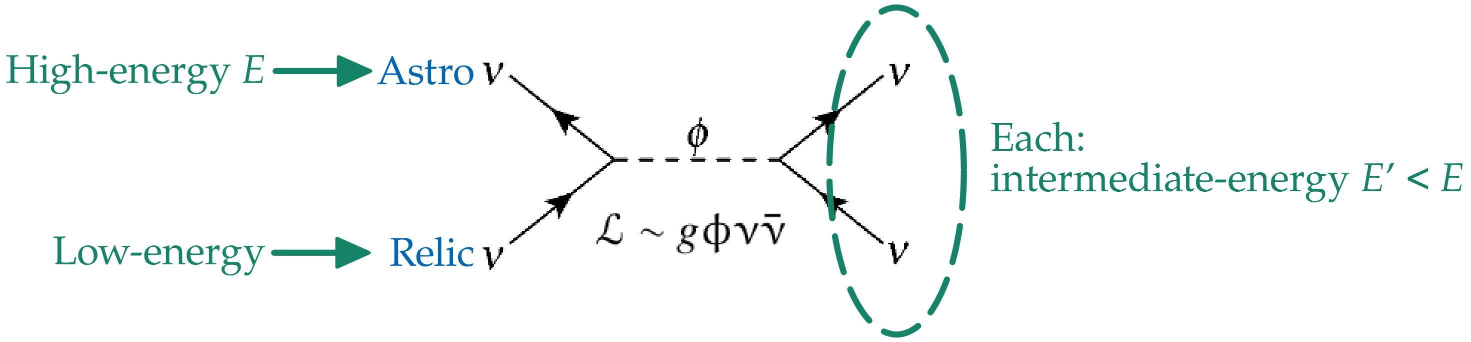
So, if we see high-energy neutrinos, we can set an upper limit on the νSI strength

Original idea by Kolb & Turner, using SN1987A (*PRD* 1987)

Mean free path of a ν of energy E: $l_{\rm int}(E) = [n_{{\rm C}\nu{\rm B}} \sigma_{\nu\nu}(E)]^{-1}$

Estimated optical depth if emitted by a source at a distance L: $\tau(E) = \dfrac{l_{\rm int}(E)}{L}$

νSI with the UHE transient flux



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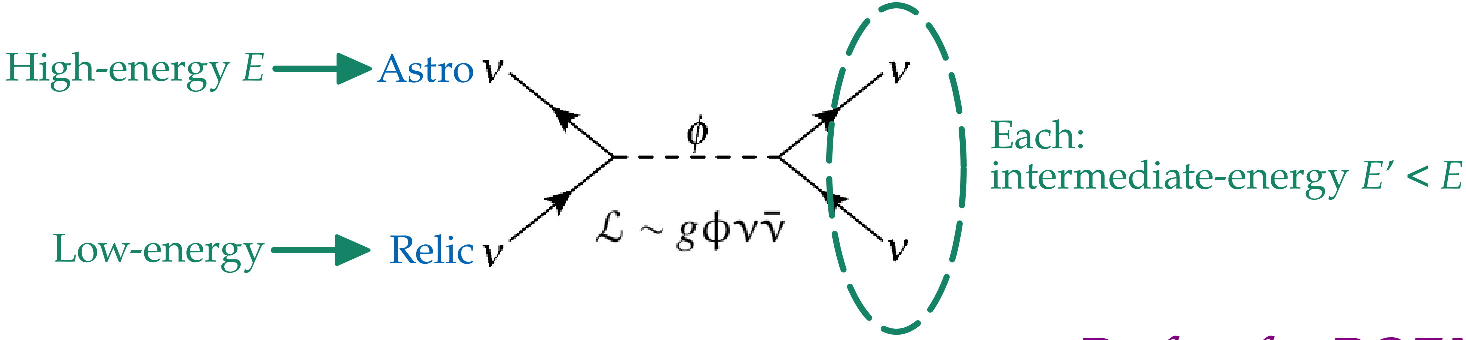
νSI with the UHE transient flux



Perfect for POEMMA!

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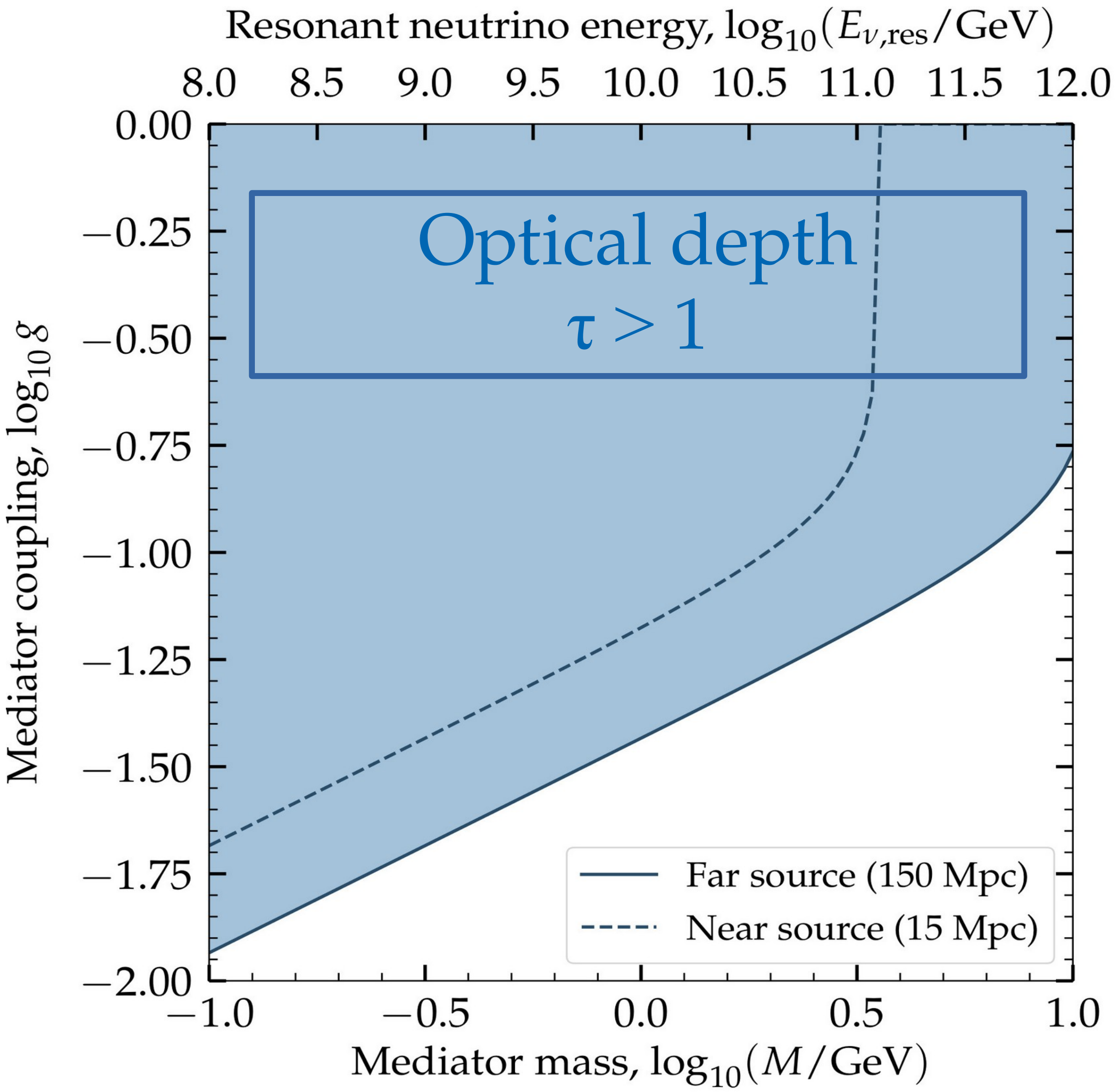
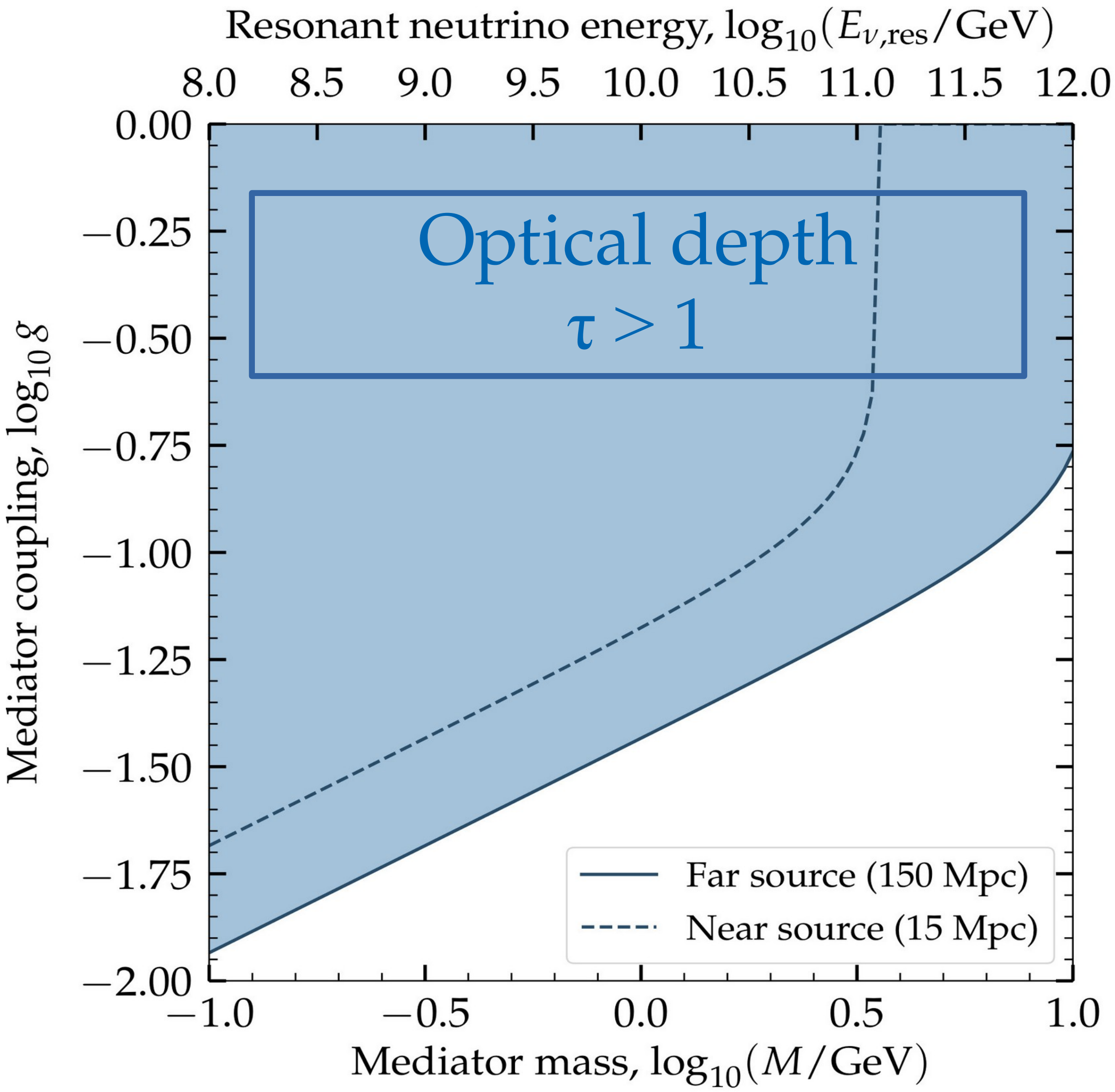


POEMMA Collab., *JCAP* 2021



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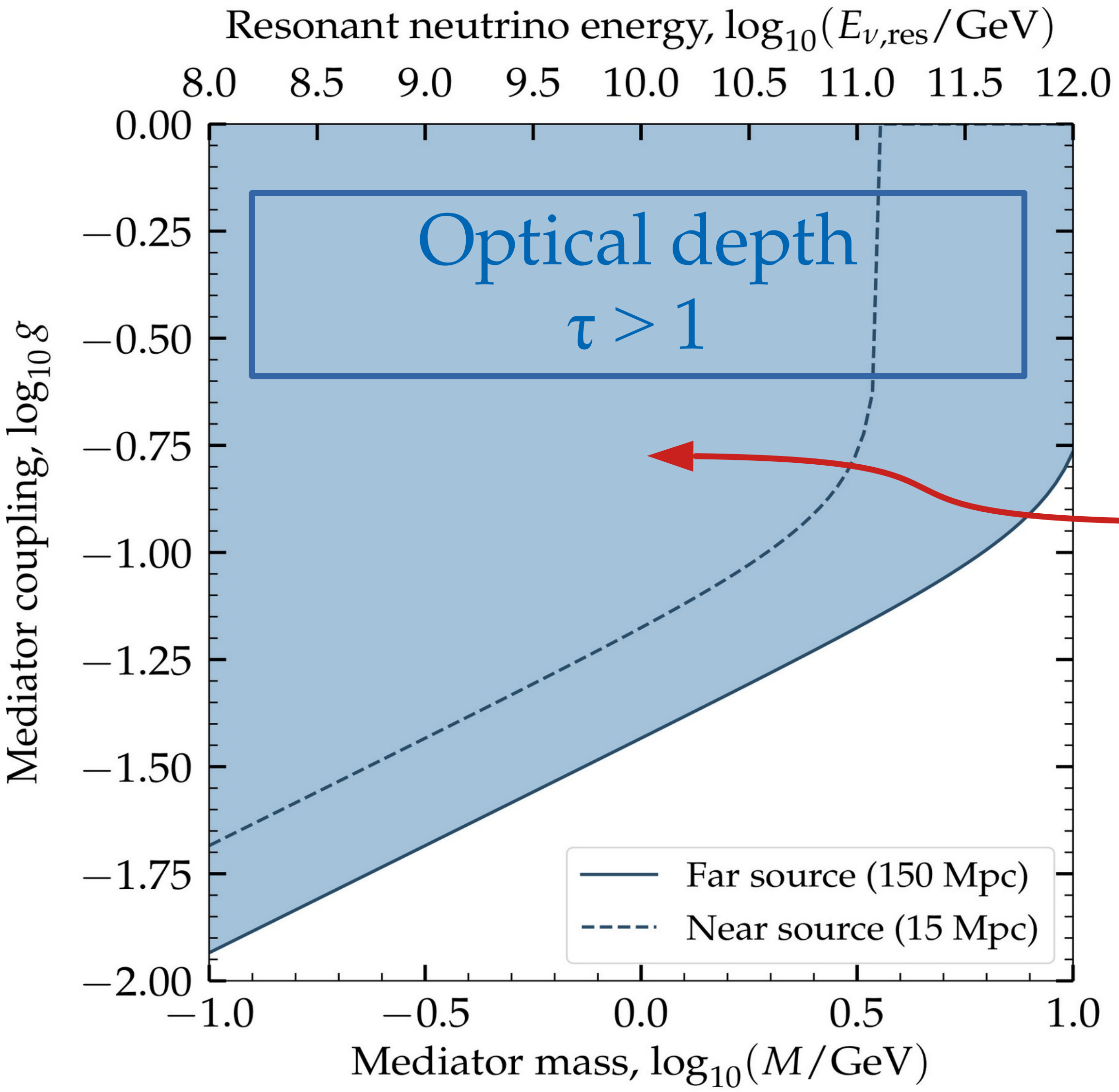


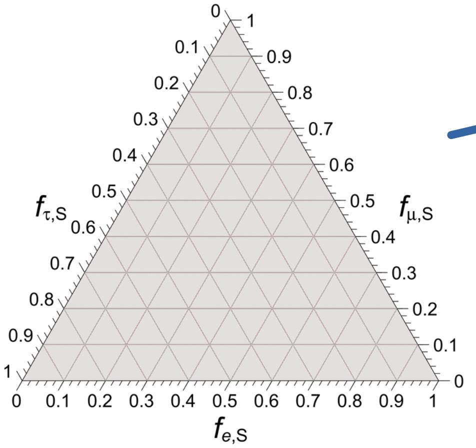
If POEMMA sees UHE ν from a flare, we can kill part of this parameter space

POEMMA Collab., *JCAP* 2021

Example 4: Neutrino decay

Measuring the neutrino lifetime

Sources



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

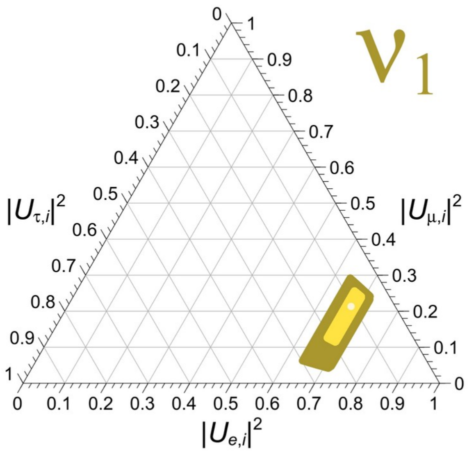
ν_1 lightest and stable
(normal mass ordering)

If all unstable
neutrinos decay

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

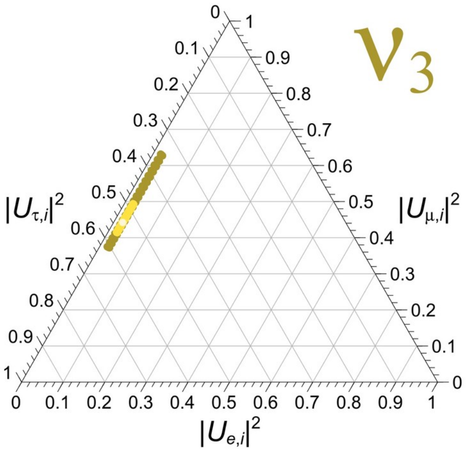
ν_3 lightest and stable
(inverted mass ordering)

Earth



ν_1

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



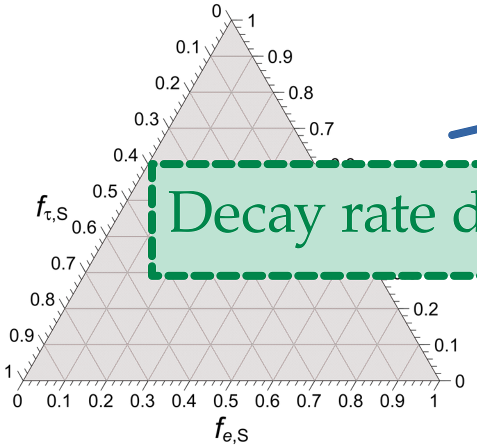
ν_3

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

Measuring the neutrino lifetime

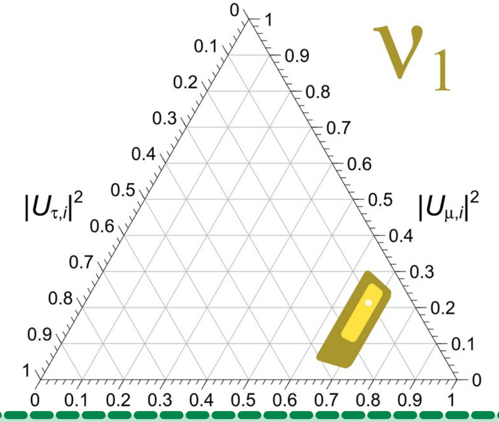
Earth

Sources



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

ν_1 lightest and stable (normal mass ordering)



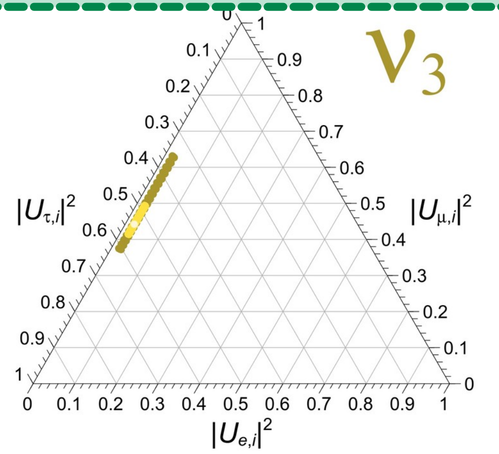
ν_1

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

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

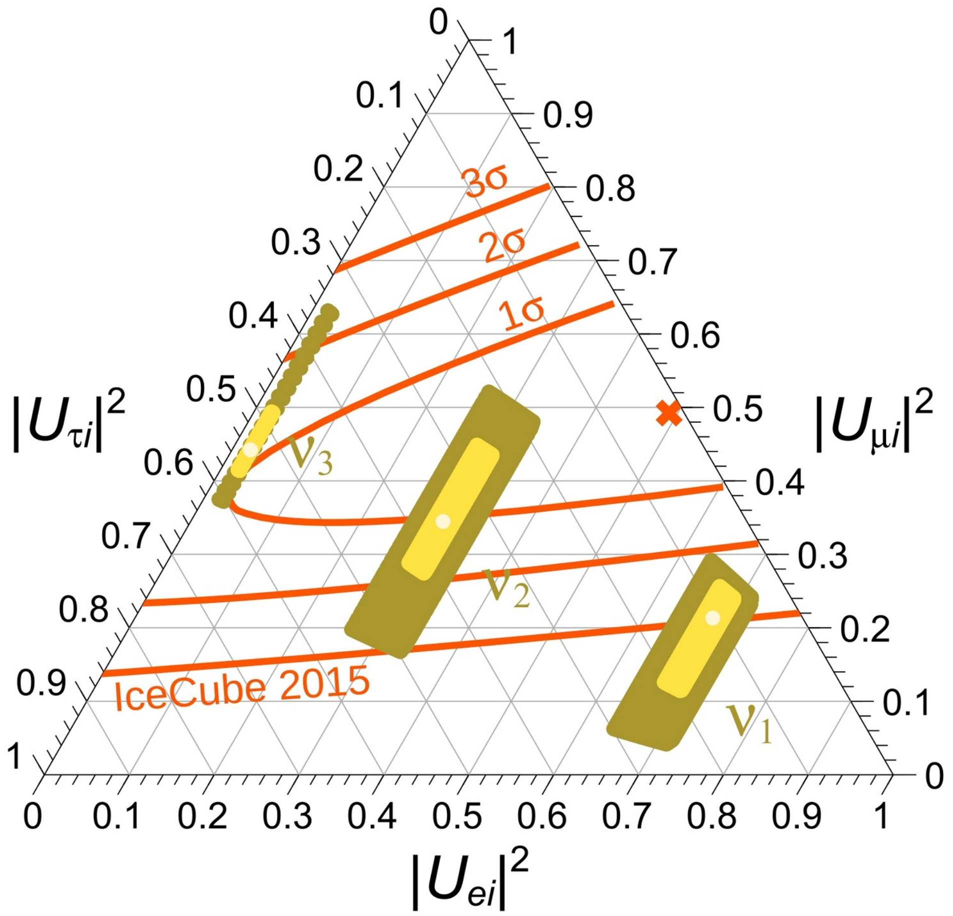
$\underbrace{\nu_1, \nu_2 \to \nu_3}$

ν_3 lightest and stable (inverted mass ordering)



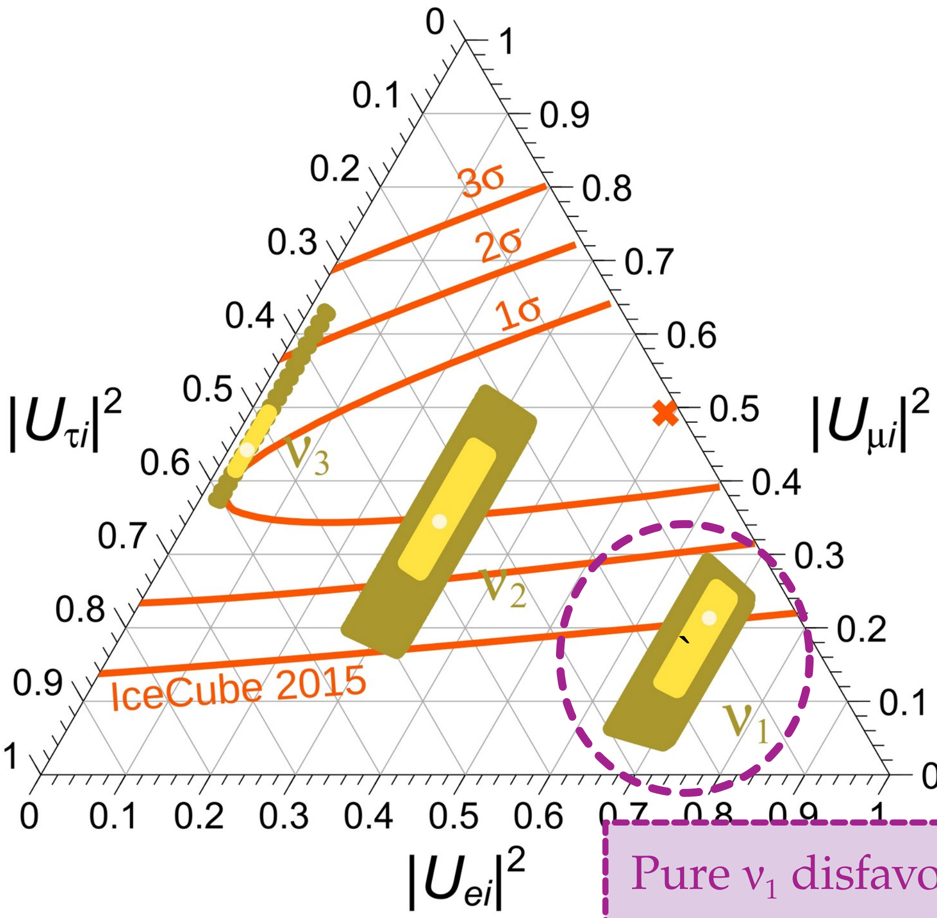
ν_3

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



MB, Beacom, Murase, *PRD* 2017

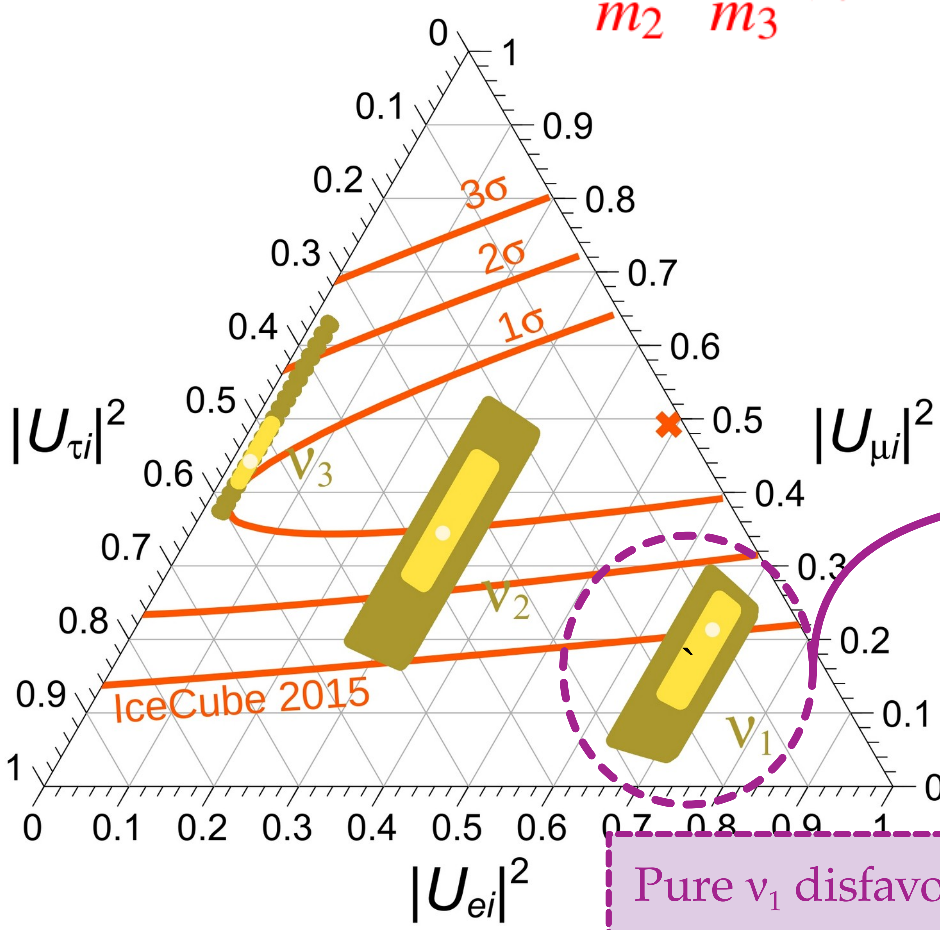
Baerwald, **MB**, Winter, *JCAP* 2012

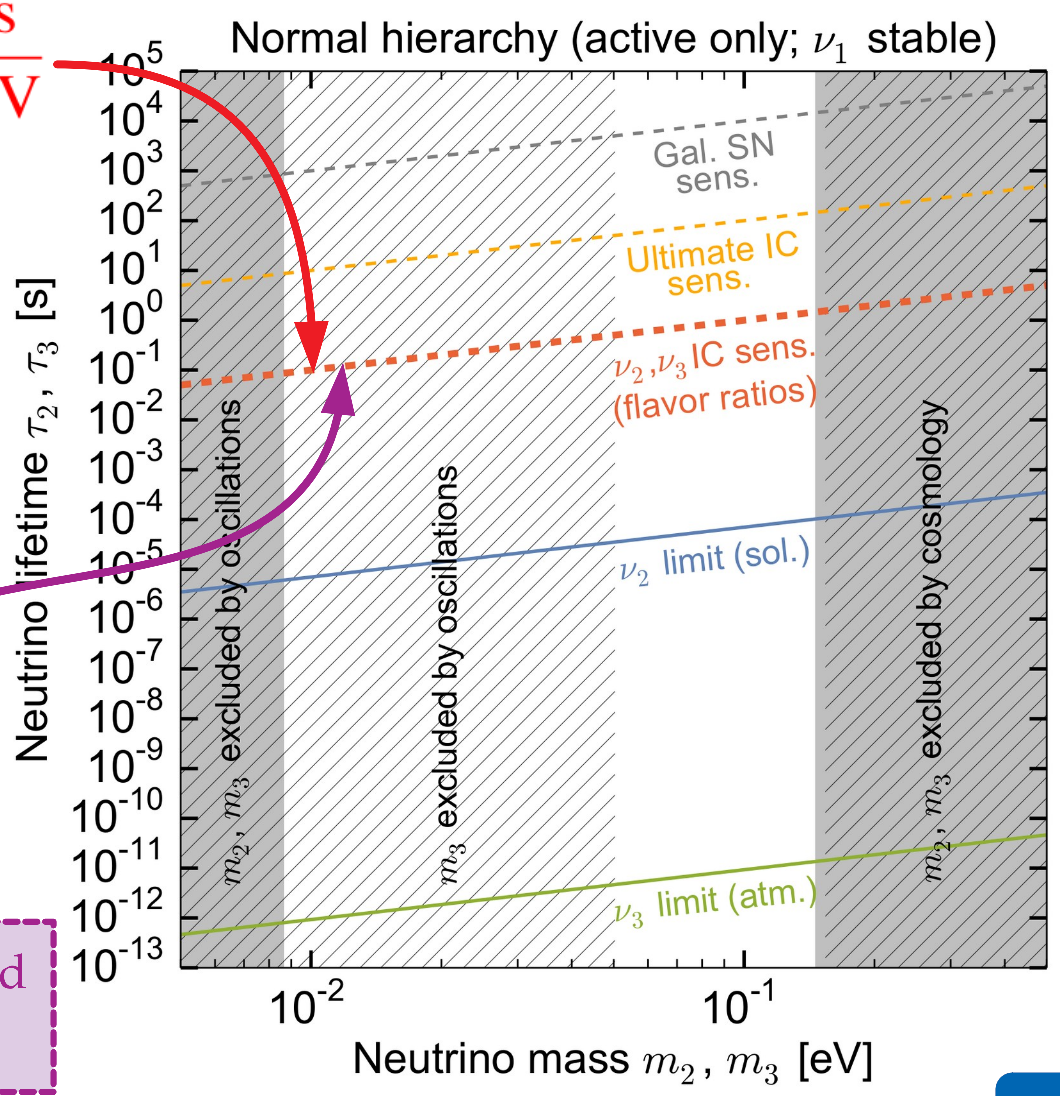


Pure ν_1 disfavored at > 2σ

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

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





Pure ν_1 disfavored at > 2σ

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

Are neutrinos forever?

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

  » Age of Universe (~ 14.5 Gyr)

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

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

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

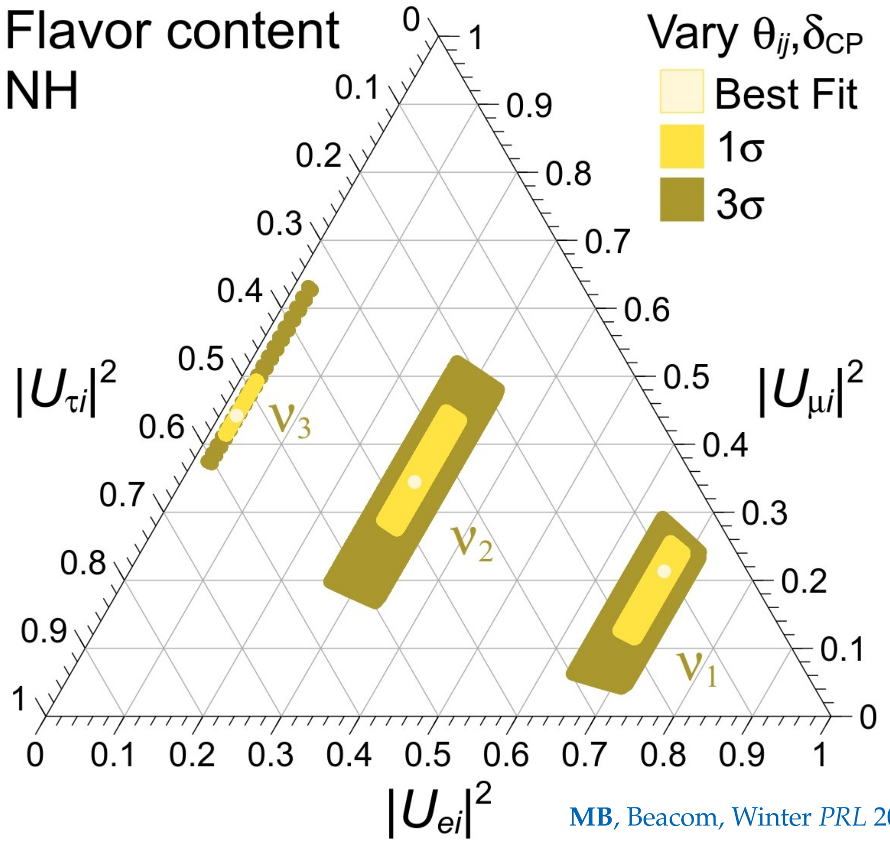
Flavor content of neutrino mass eigenstates

Known to within 2%

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

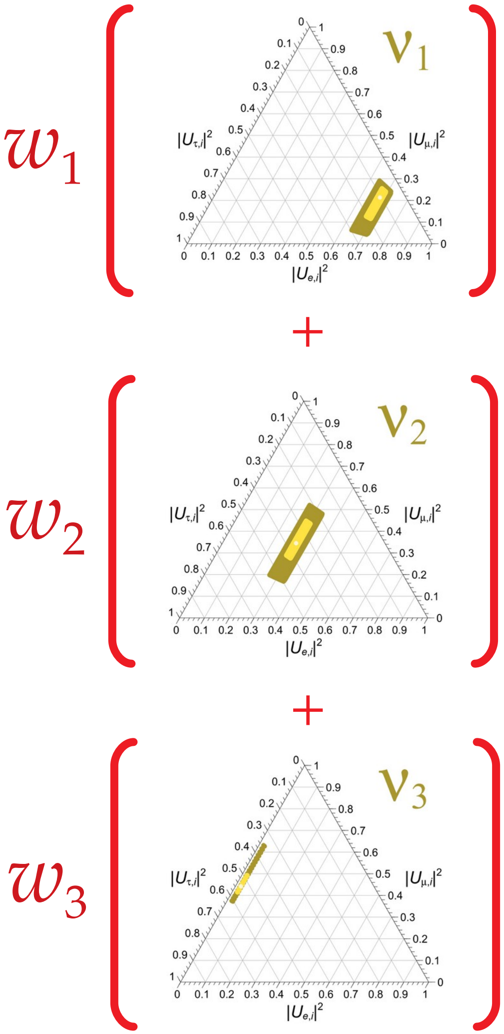
Known to within 8%

Known to within 20% (or worse)

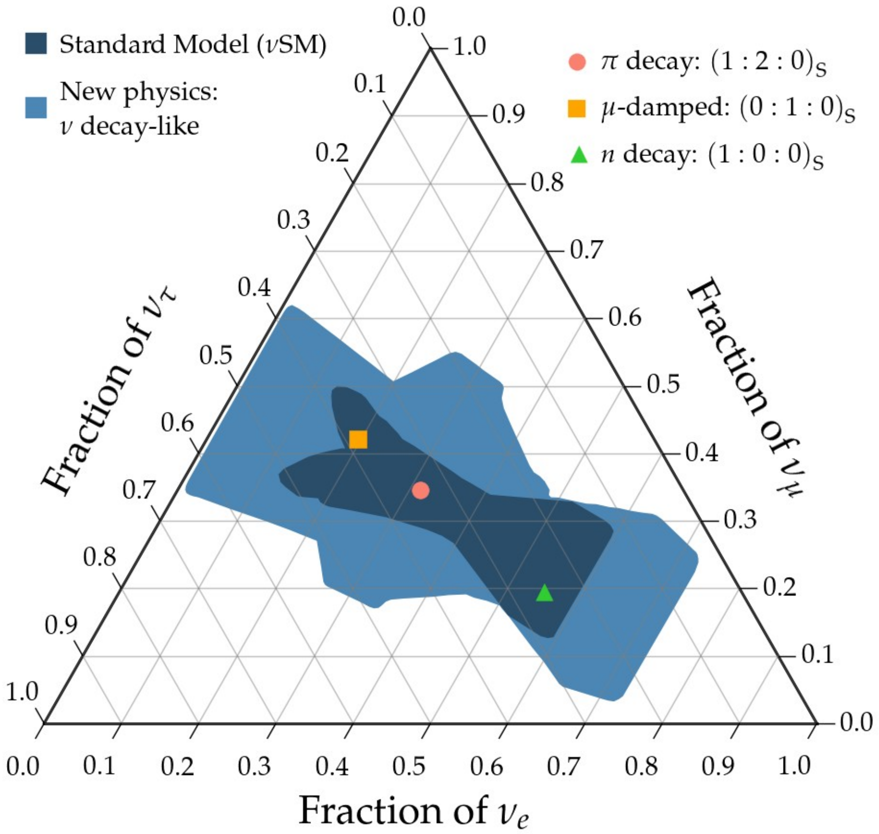


MB, Beacom, Winter *PRL* 2015

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



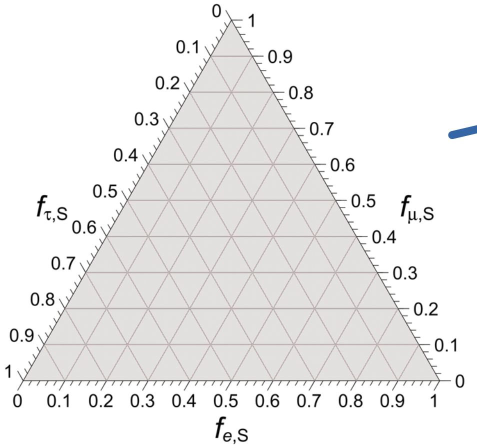
Varying all possible combinations of weights w_i and mixing parameters



Complete decay selects particular weights ▸
with striking consequences for flavor

Measuring the neutrino lifetime

Sources



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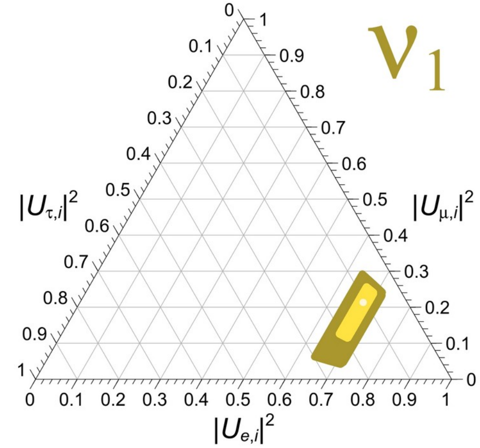
(inverted mass ordering)

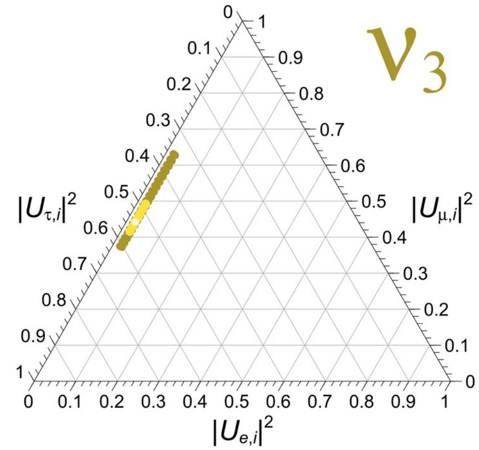
Earth



ν_1

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

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



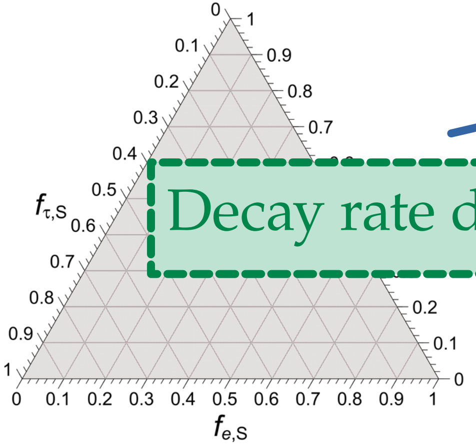
ν_3

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

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

Measuring the neutrino lifetime

Sources



$\nu_2, \nu_3 \to \nu_1$

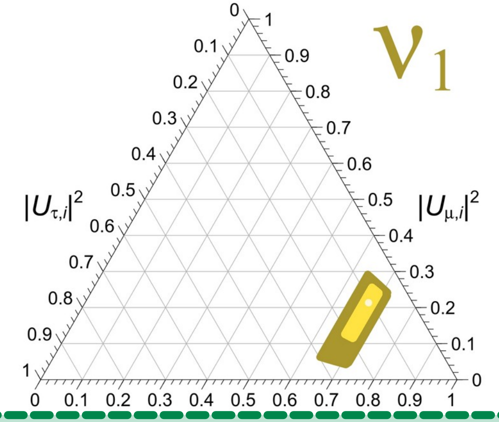
ν_1 lightest and stable
(normal mass ordering)

$\nu_1, \nu_2 \to \nu_3$

ν_3 lightest and stable
(inverted mass ordering)

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

Earth



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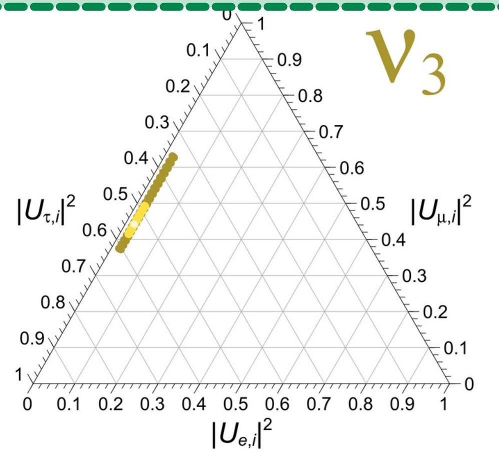

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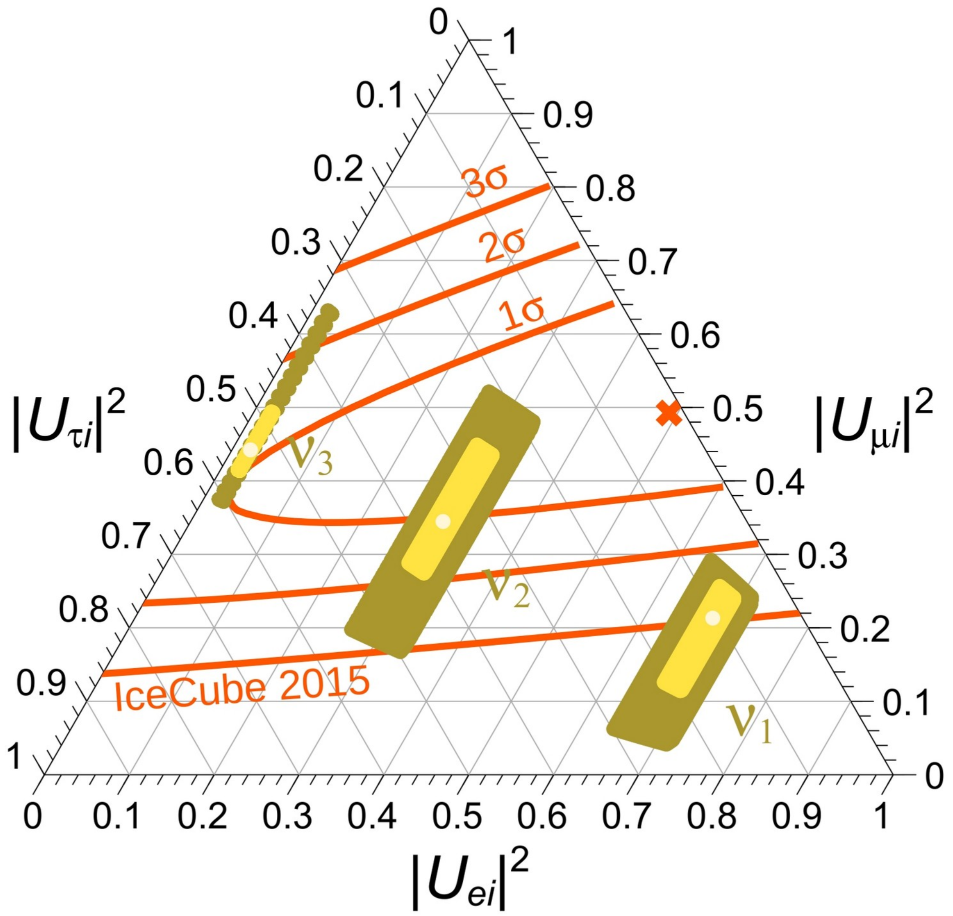
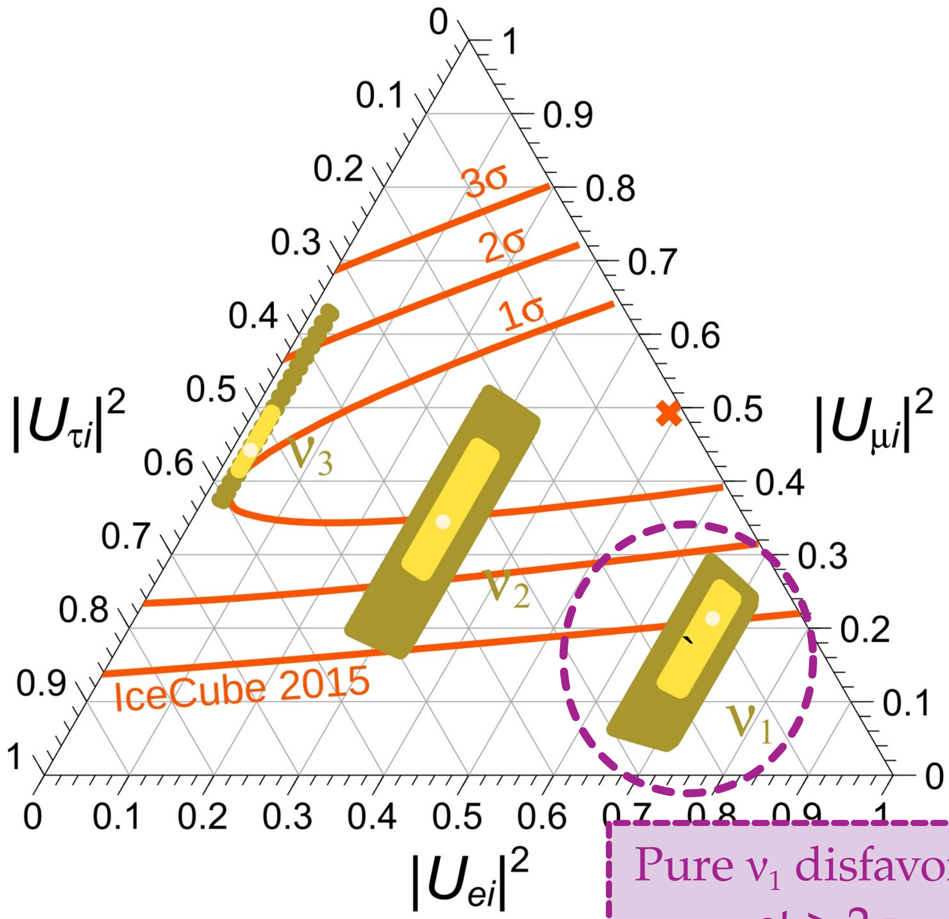


MB, Beacom, Murase, *PRD* 2017

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

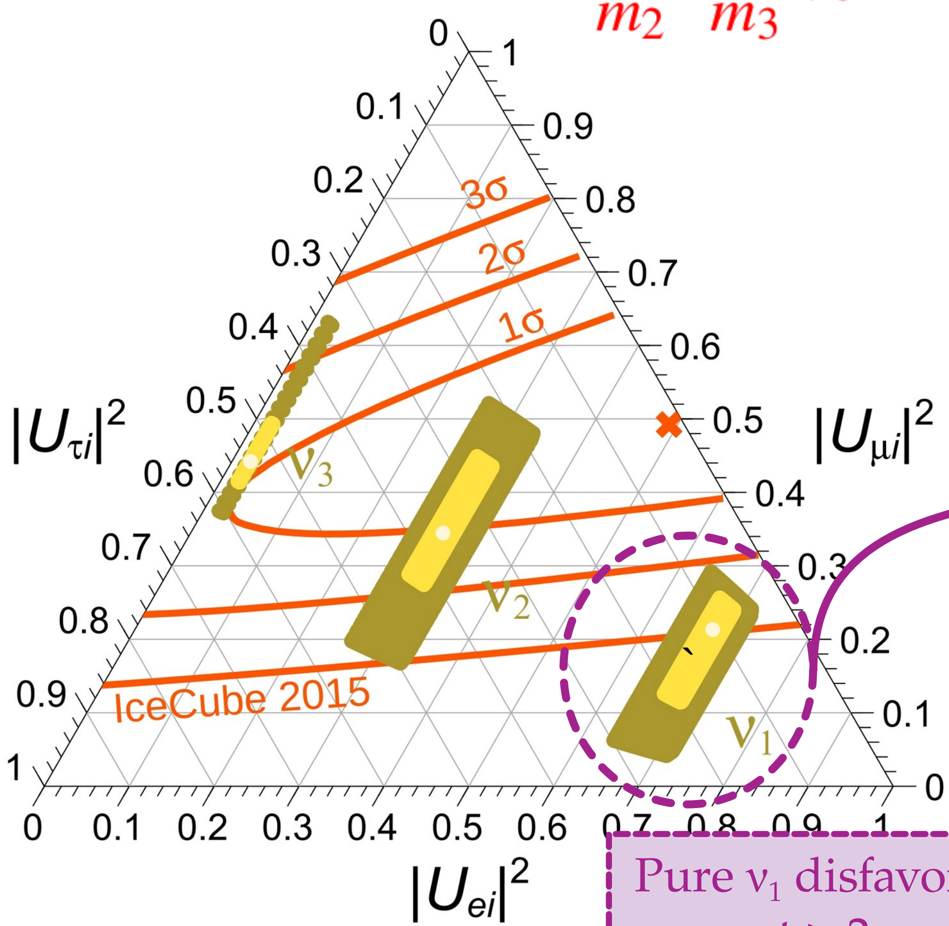


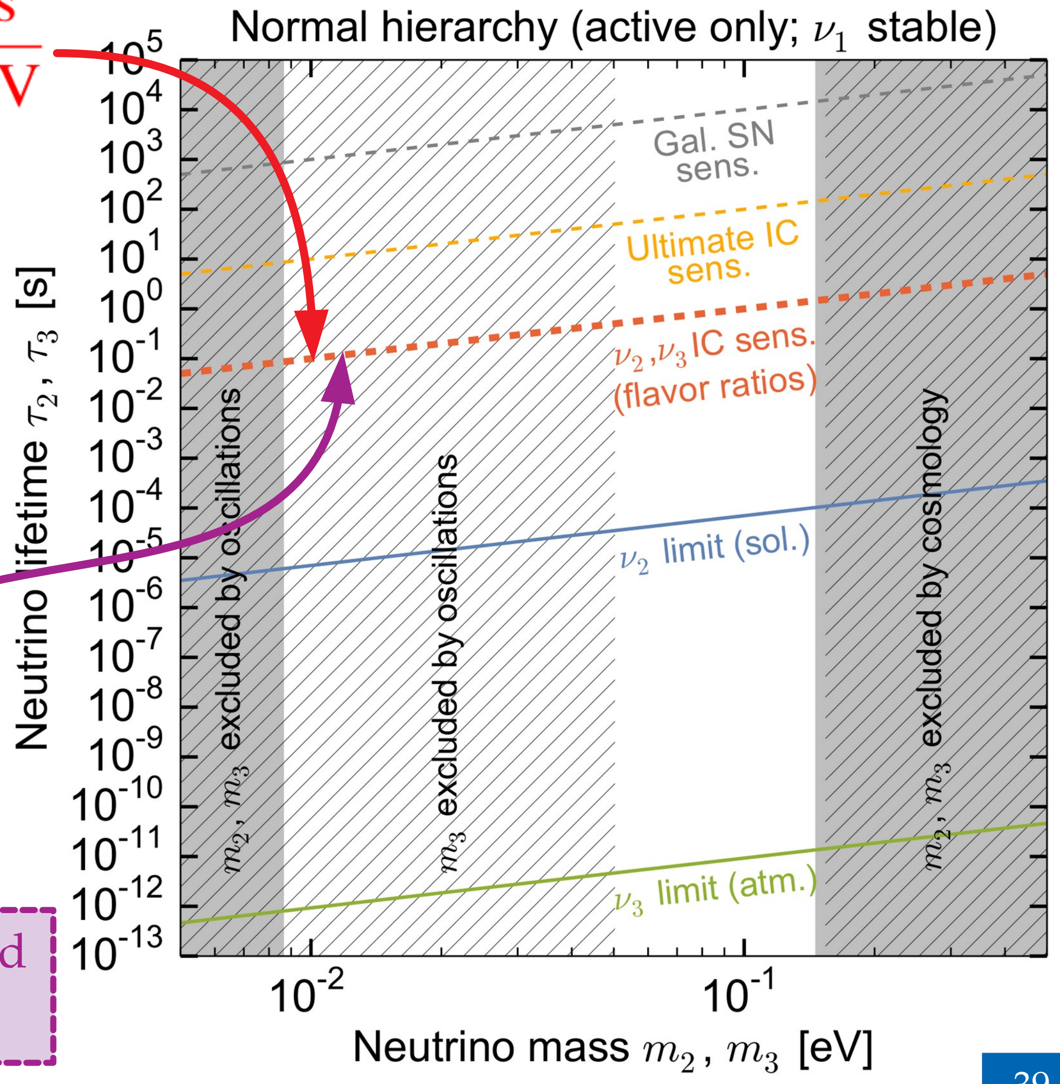
Pure ν_1 disfavored at > 2σ

MB, Beacom, Murase, *PRD* 2017

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

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





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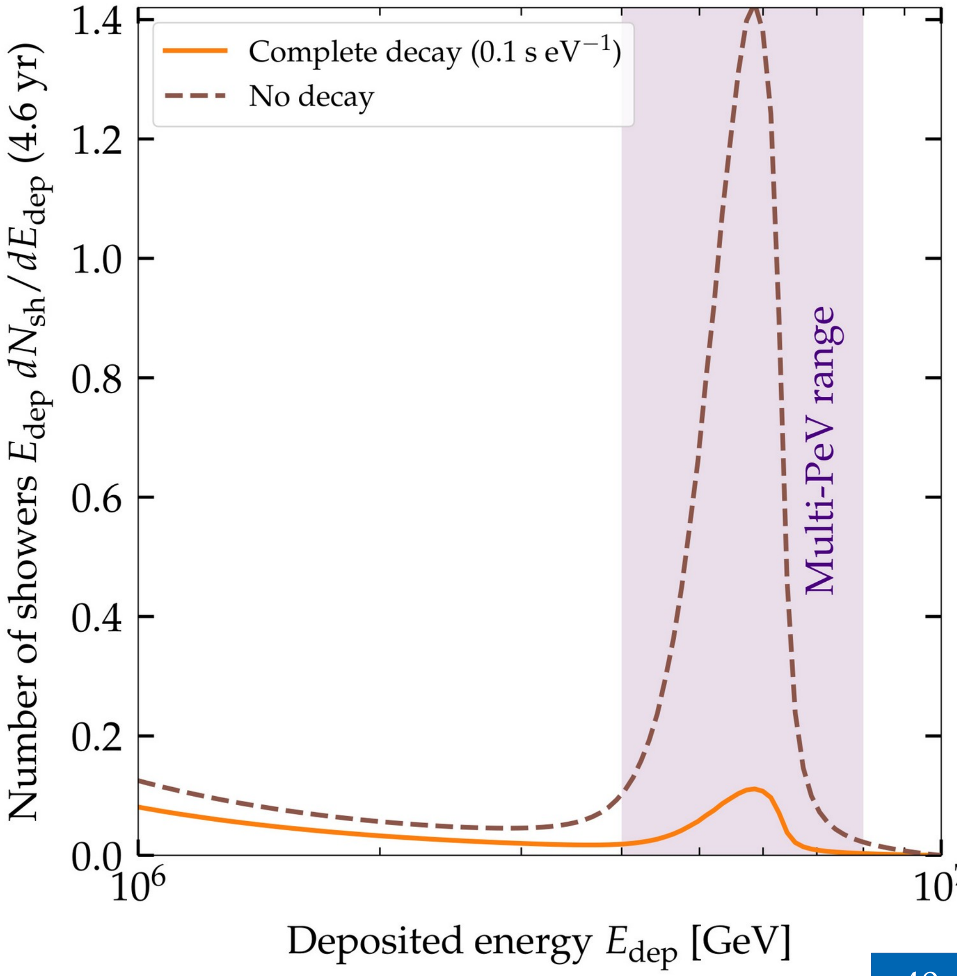
Using the Glashow resonance to test decay

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



MB, 2004.06844
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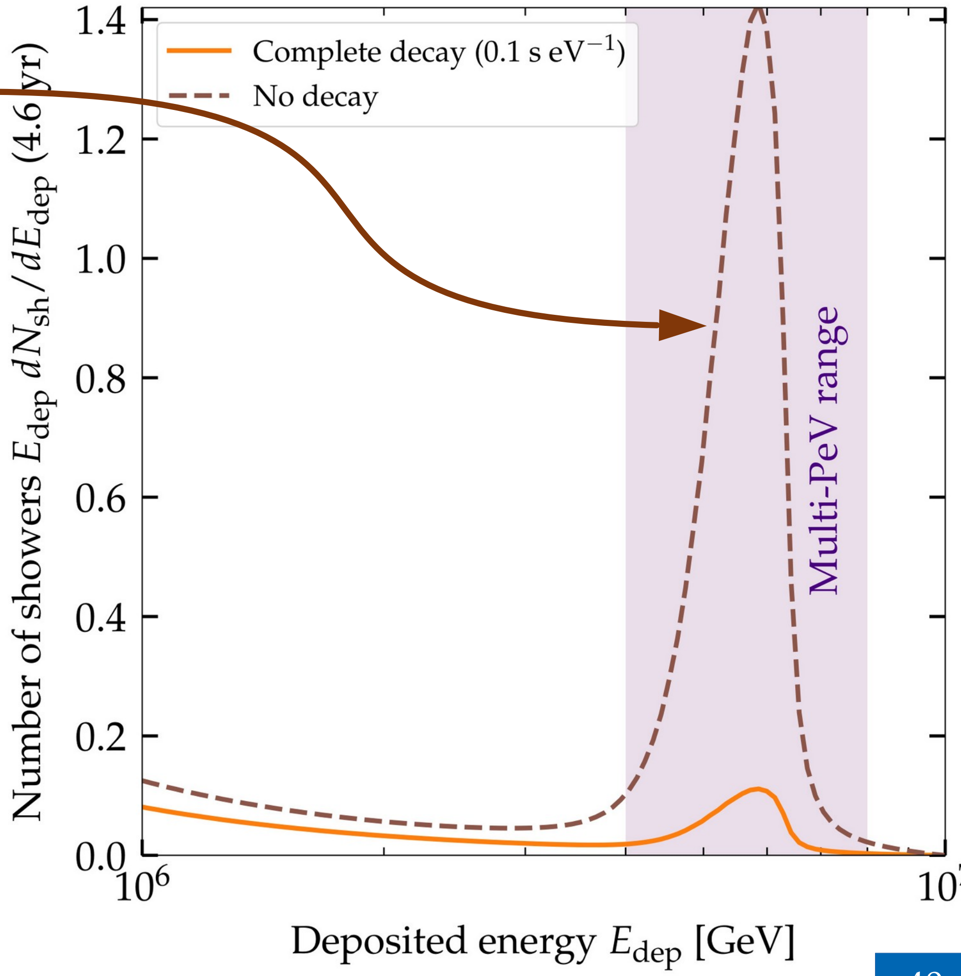

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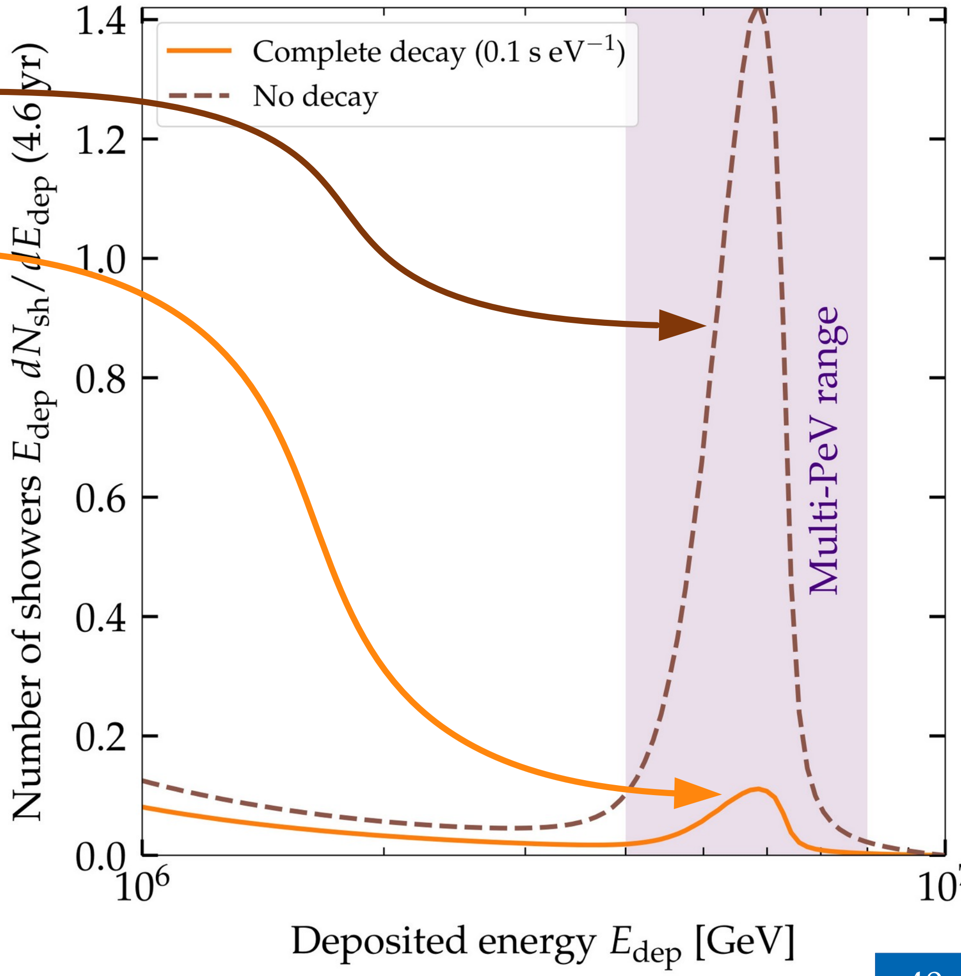

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Using the Glashow resonance to test decay

$\tau_1/m_1 > 2.91 \times 10^{-3}$ s eV^{-1} (90% C.L.)
$\tau_2/m_2 > 1.26 \times 10^{-3}$ s eV^{-1} (90% C.L.)

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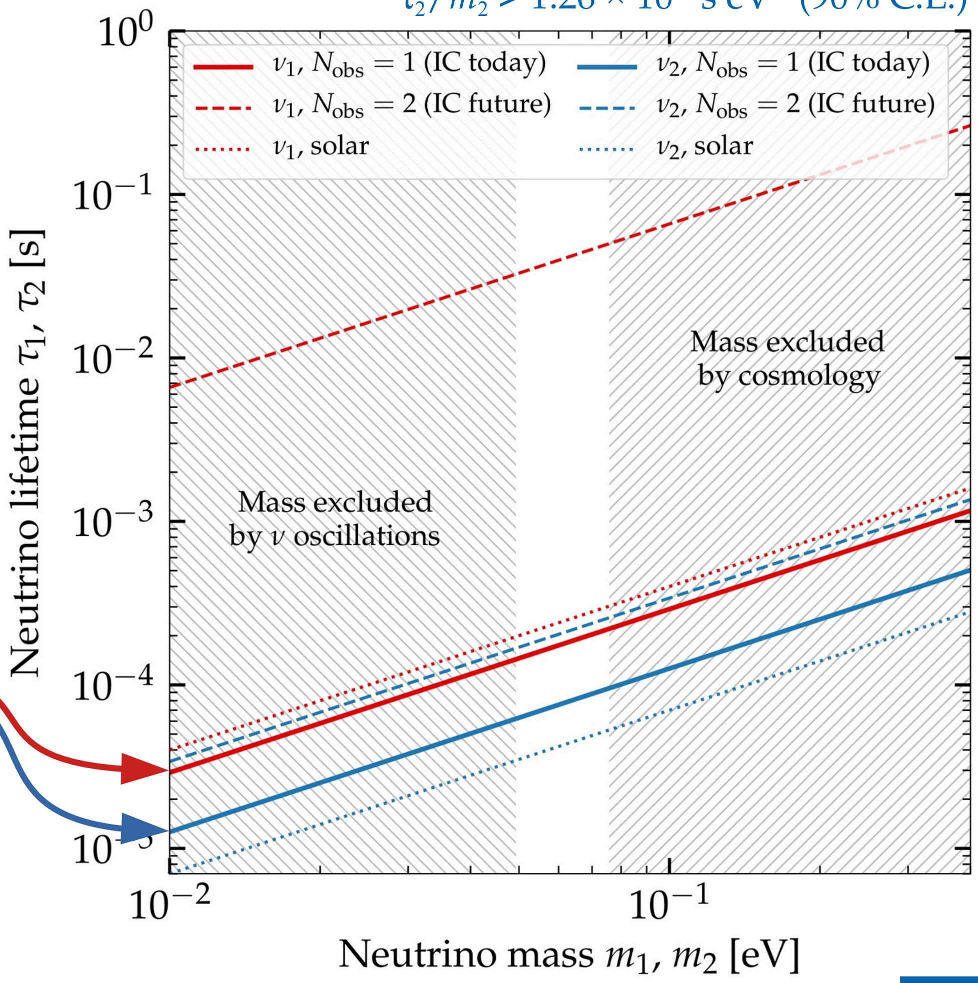

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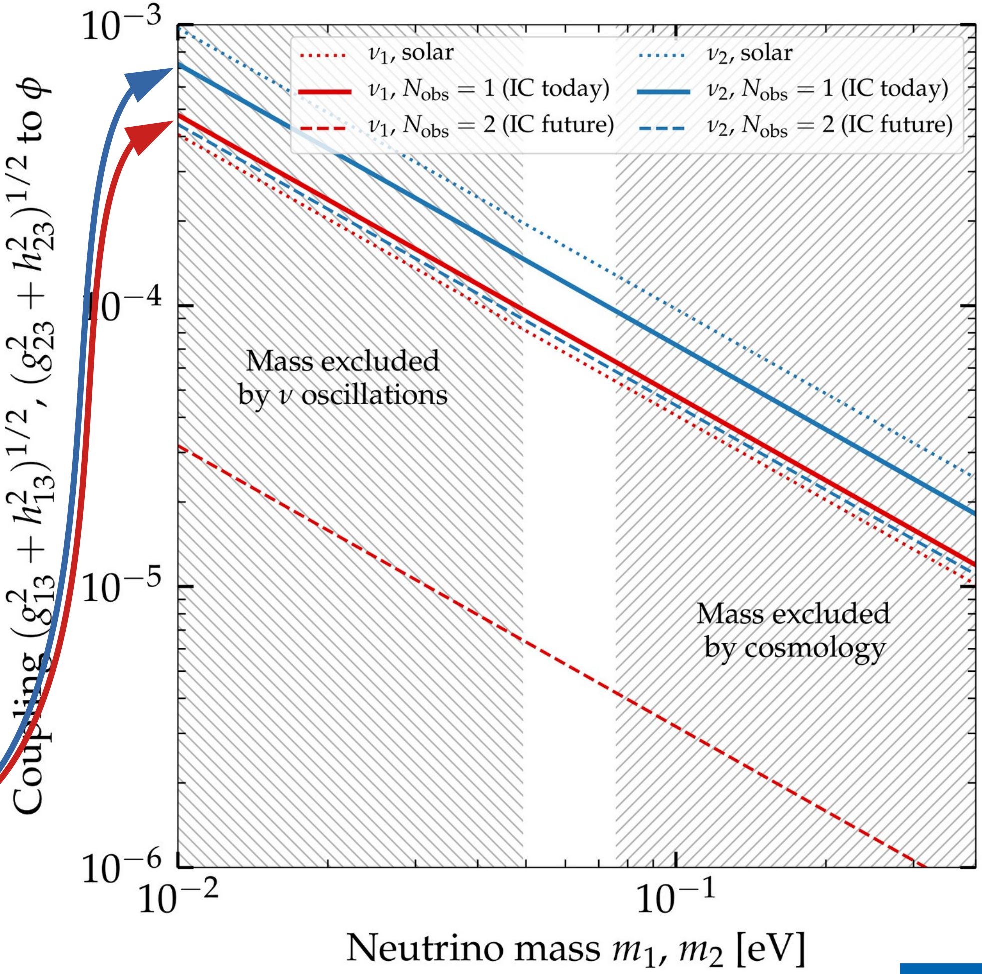
$$\mathcal{L} = g_{ij}\bar{\nu}_i\nu_j\phi + h_{ij}\bar{\nu}_i\gamma_5\nu_j\phi + \text{h.c.}$$



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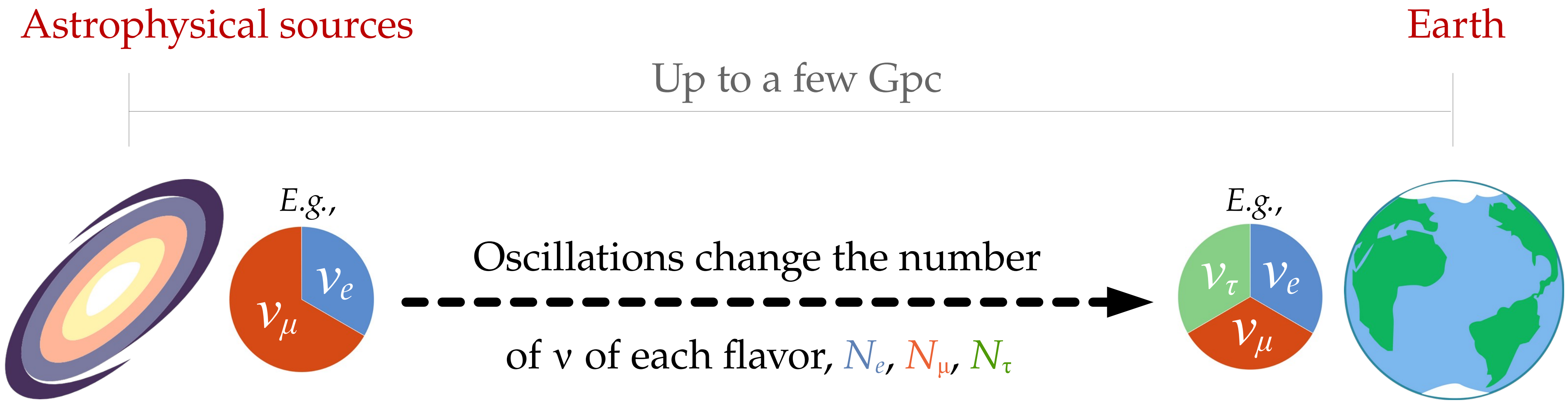
Flavor composition

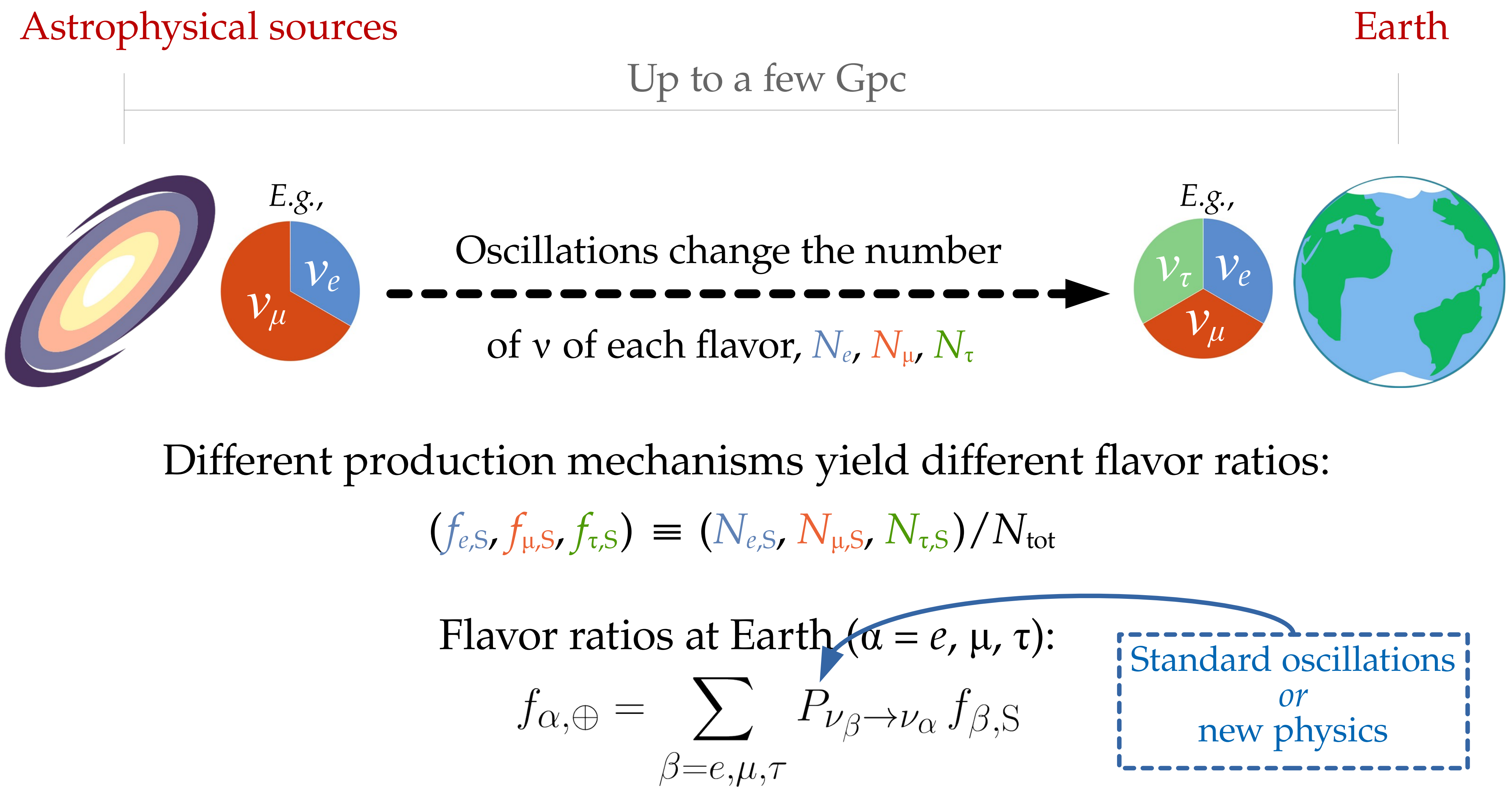


Different production mechanisms yield different flavor ratios:

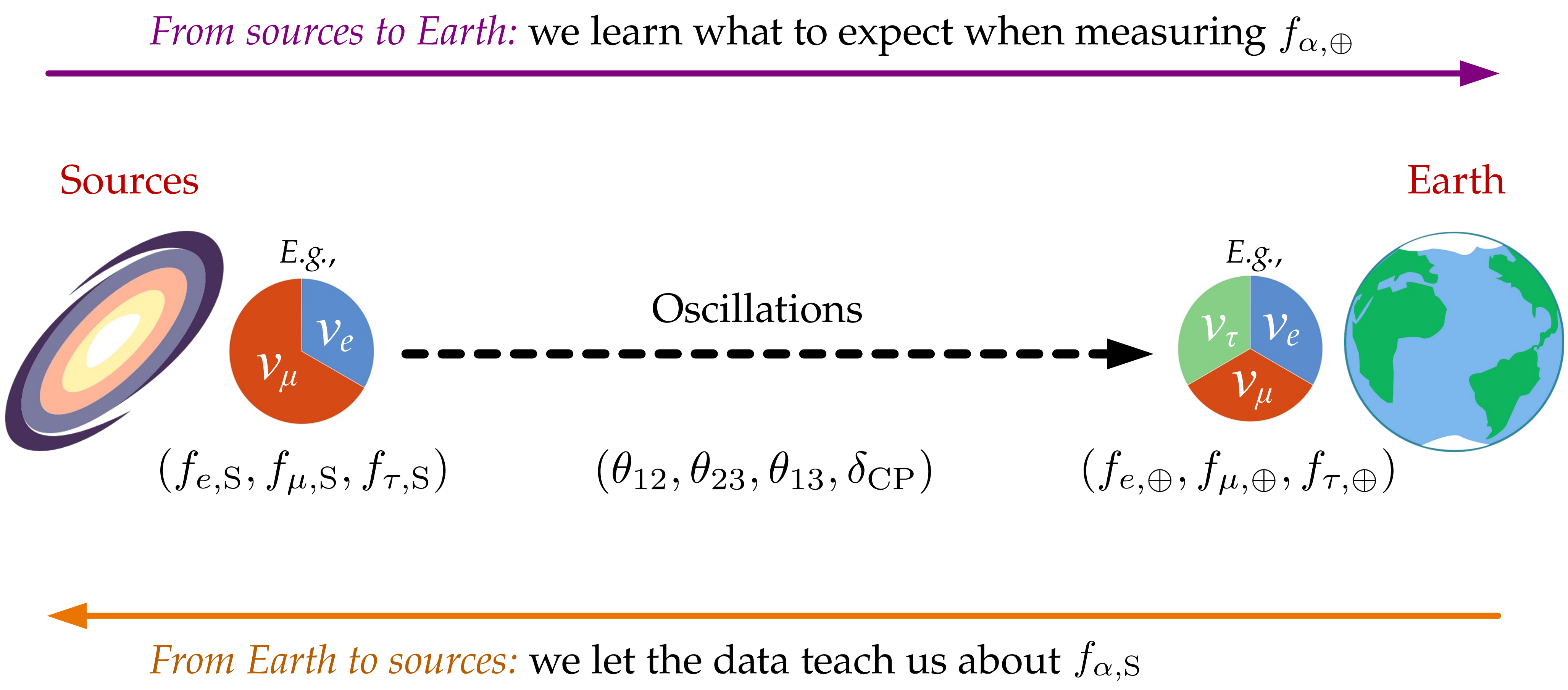
$$(f_{e,\rm S}, f_{\mu,\rm S}, f_{\tau,\rm S}) \equiv (N_{e,\rm S}, N_{\mu,\rm S}, N_{\tau,\rm S})/N_{\rm tot}$$

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

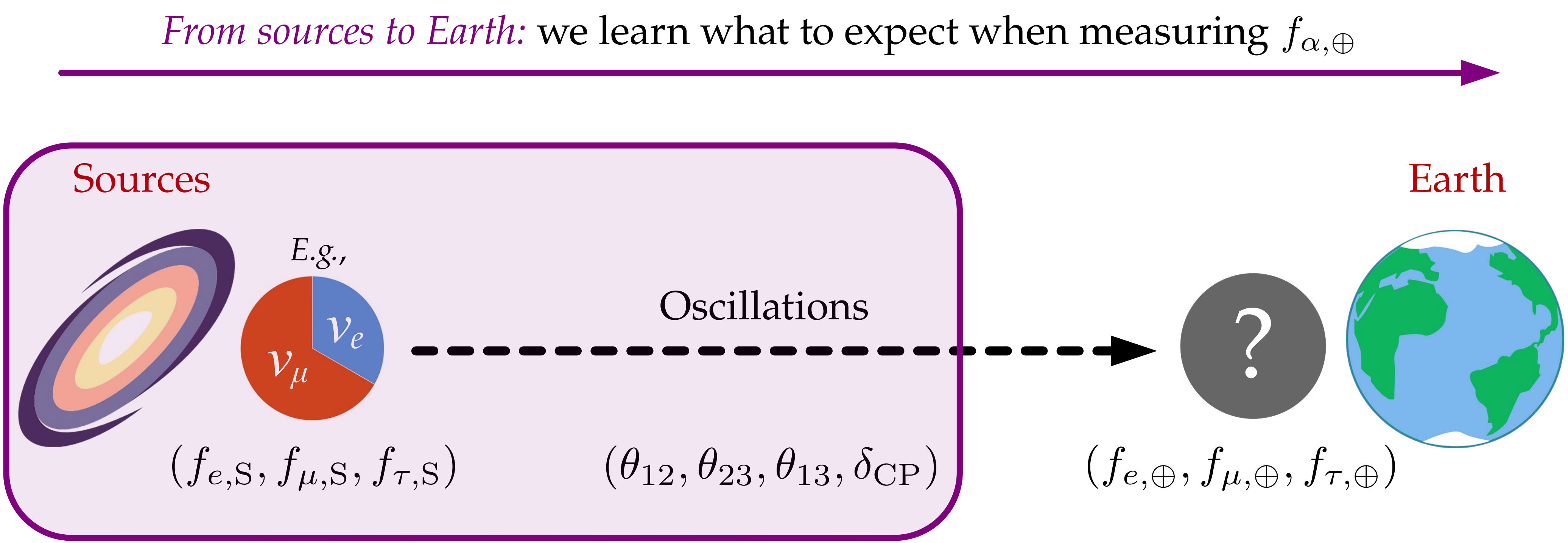
$$f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} P_{\nu_\beta \to \nu_\alpha} f_{\beta,\rm S}$$



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



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


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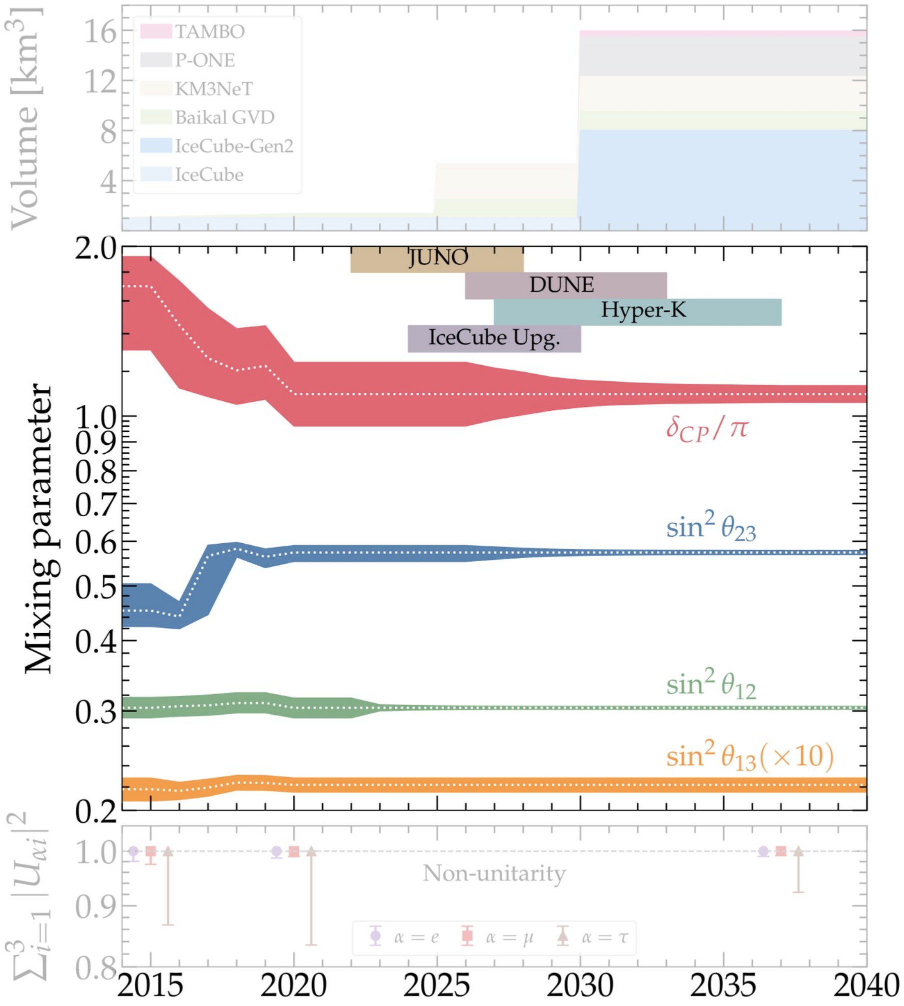
$(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\mathrm{CP}})$
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$

How knowing the mixing parameters better helps



For a future experiment
ε = JUNO, DUNE, Hyper-K:

Best fit from NuFit 5.0

$$\chi^2_\varepsilon(\boldsymbol{\vartheta}) = \sum_i \frac{(\vartheta_i - \bar{\vartheta}_i)^2}{\sigma^2_{i,\varepsilon}}$$

From our simulations

We combine experiments in a likelihood:

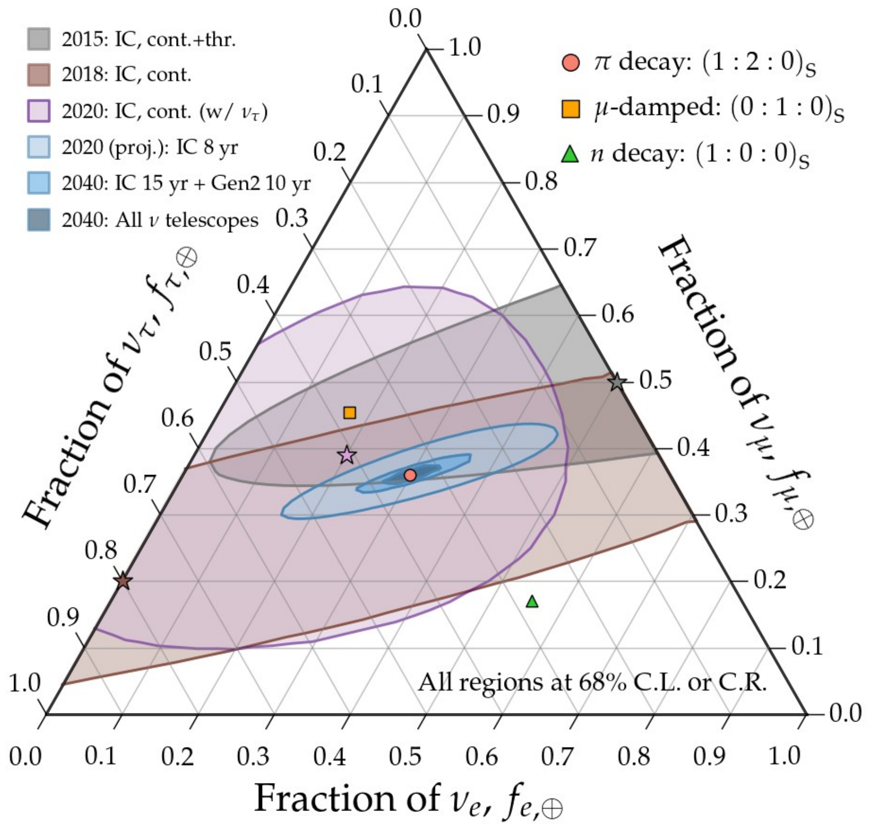
$$-2\log\mathcal{L}(\boldsymbol{\theta}) = \sum_\varepsilon \chi^2_\varepsilon(\boldsymbol{\vartheta})$$

Inferring the flavor composition at the sources

Ingredient #1:

Flavor ratios measured at Earth,

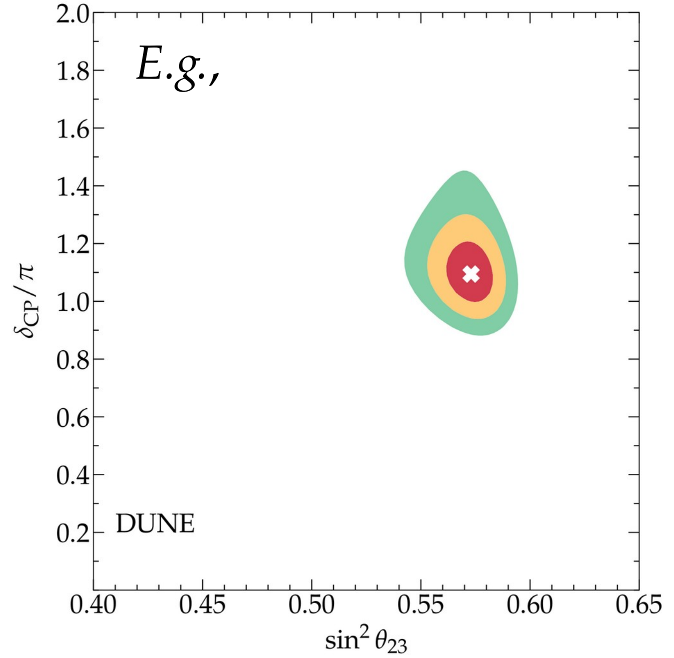
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$



Ingredient #2:

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

$\mathcal{L}(\boldsymbol{\vartheta})$



Song, Li, Argüelles, **MB**, Vincent, 2012.12893
MB & Ahlers, *PRL* 2019

Inferring the flavor composition at the sources

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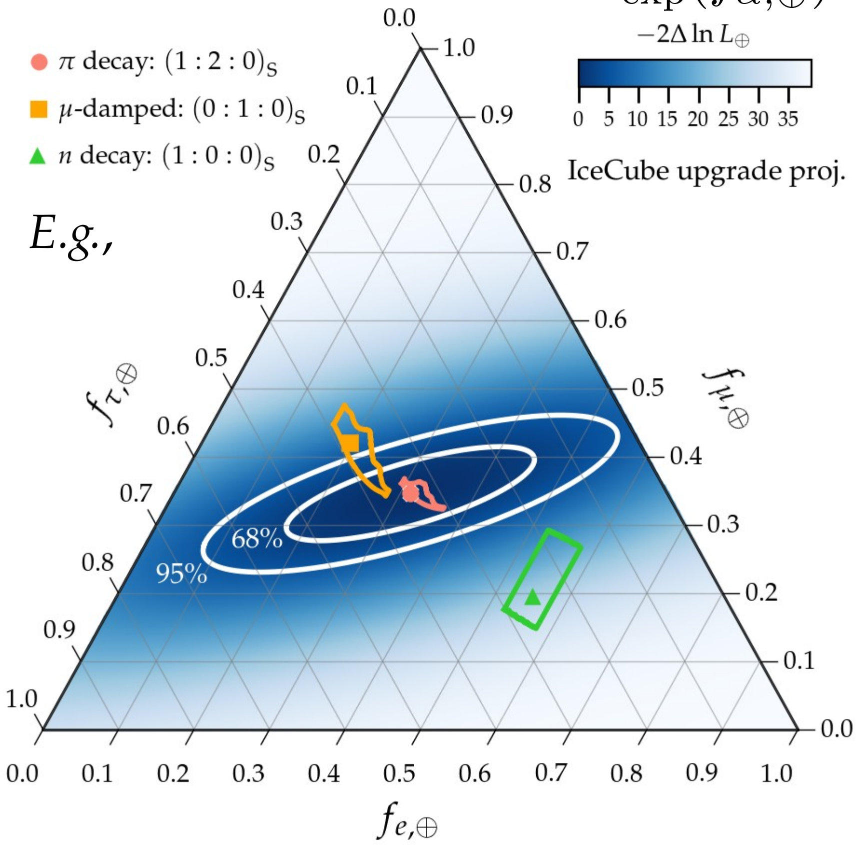
$\mathcal{P}_{\rm exp}(f_{\alpha,\oplus})$



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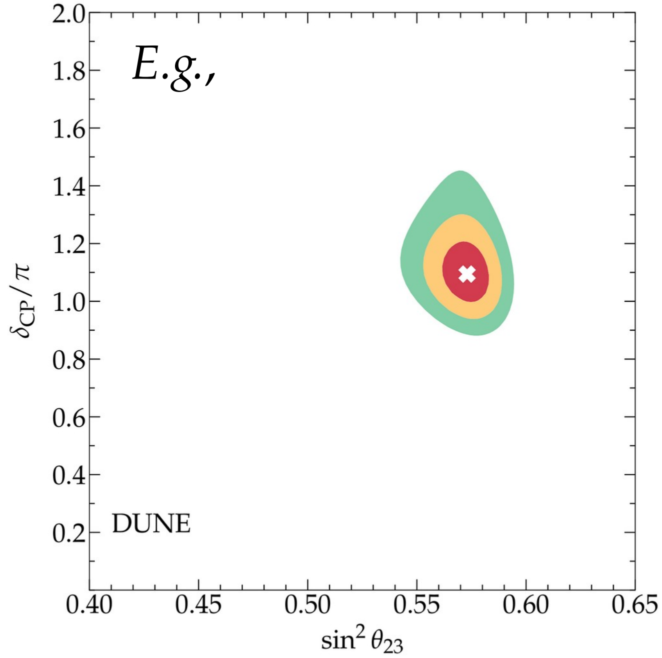

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Posterior probability of $f_{\alpha,\rm S}$ [**MB** & Ahlers, *PRL* 2019]:

$$\mathcal{P}(\boldsymbol{f}_s) = \int d\boldsymbol{\vartheta} \mathcal{L}(\boldsymbol{\vartheta}) \mathcal{P}_{\rm exp}(\boldsymbol{f}_\oplus(\boldsymbol{f}_{\rm S}, \boldsymbol{\vartheta}))$$

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Oscillation experiments Neutrino telescopes

Song, Li, Argüelles, **MB**, Vincent, 2012.12893
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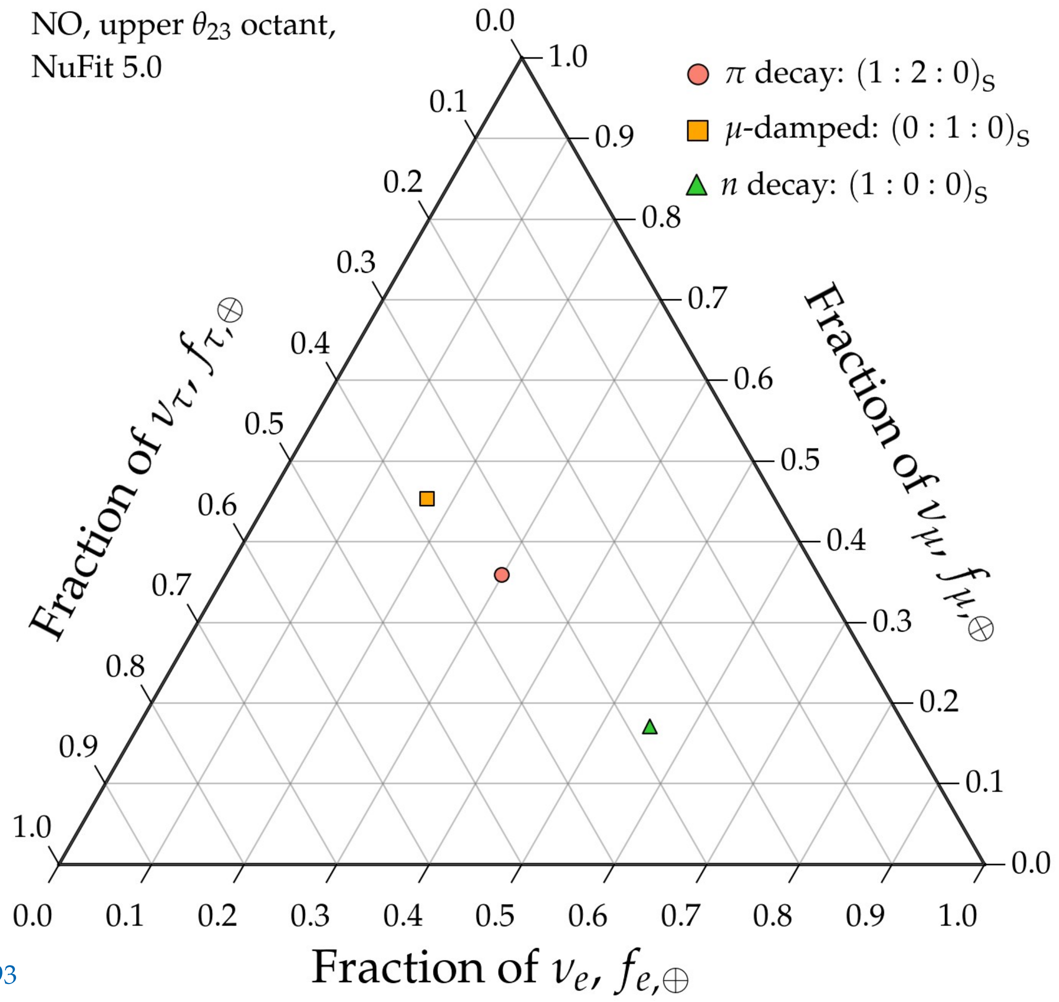
Theoretically palatable regions: today (2020)



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

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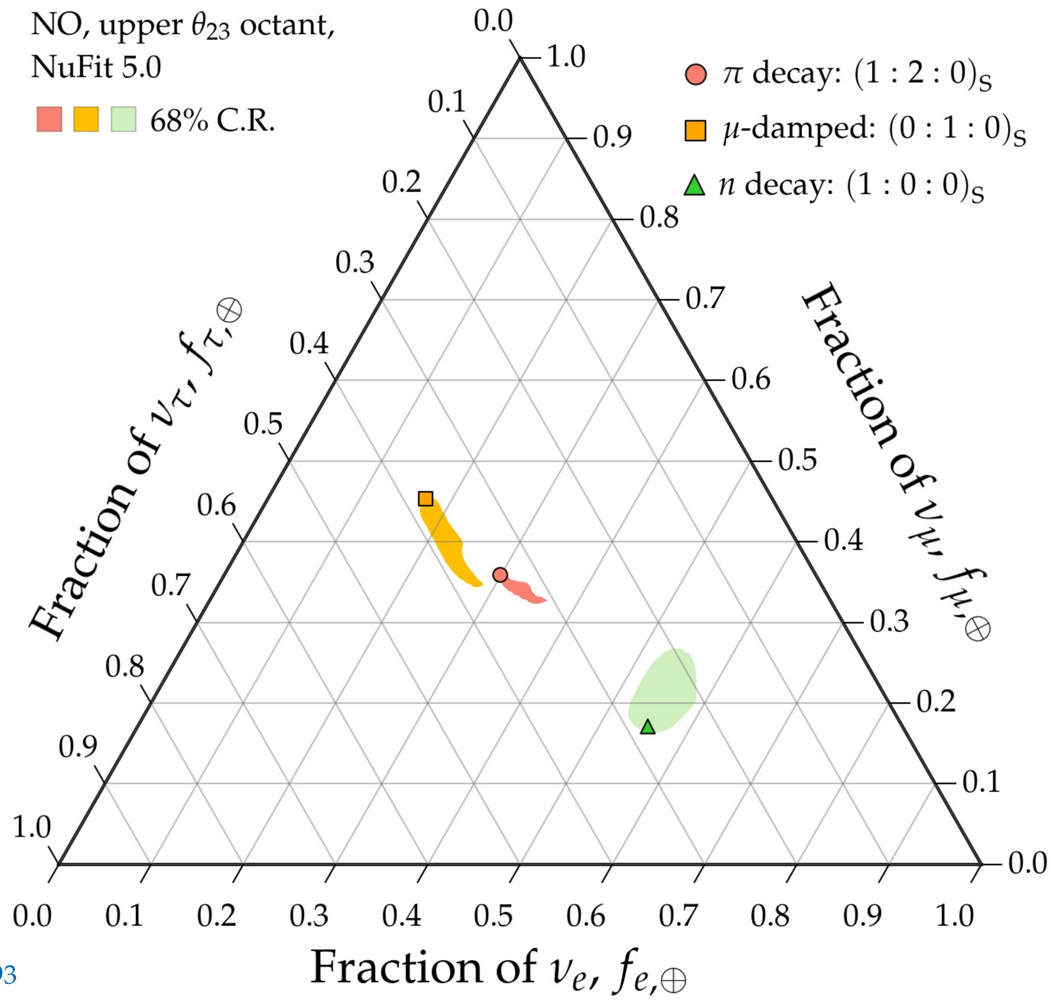

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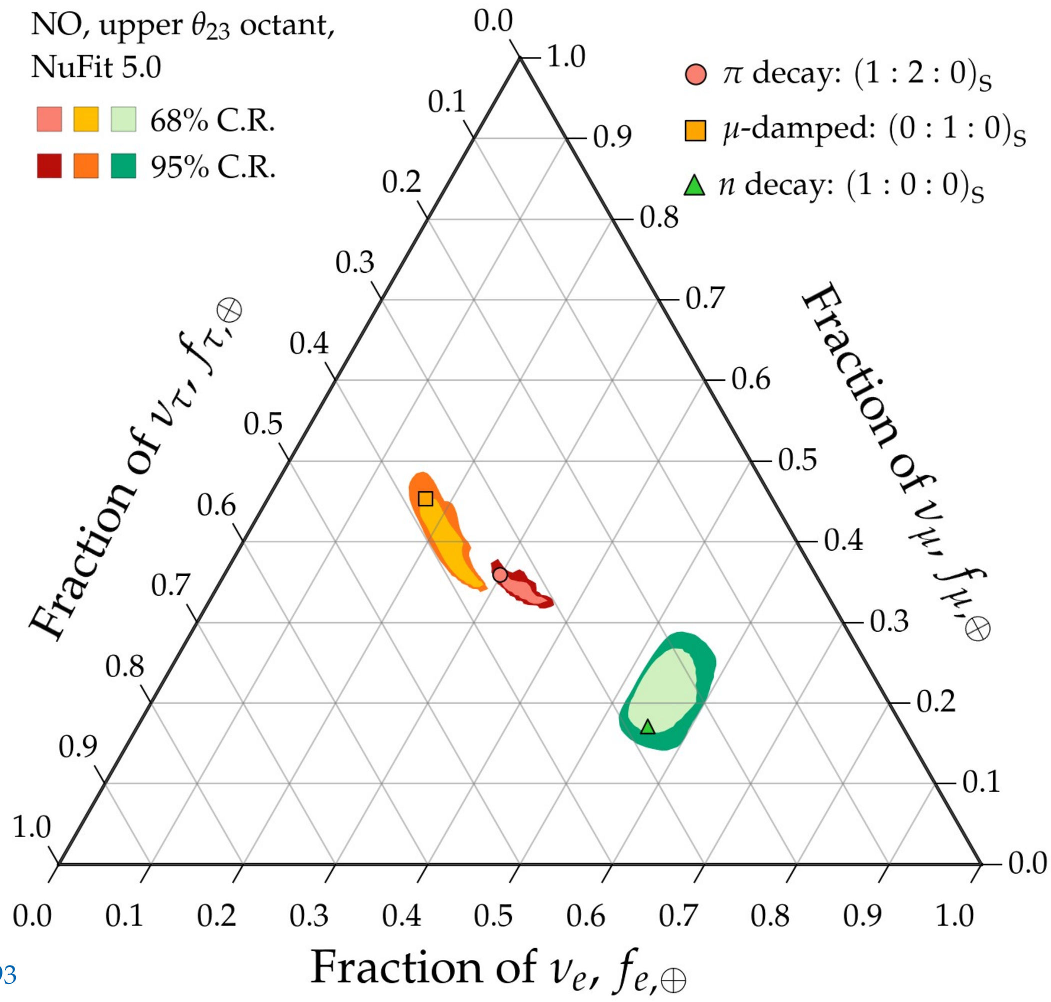

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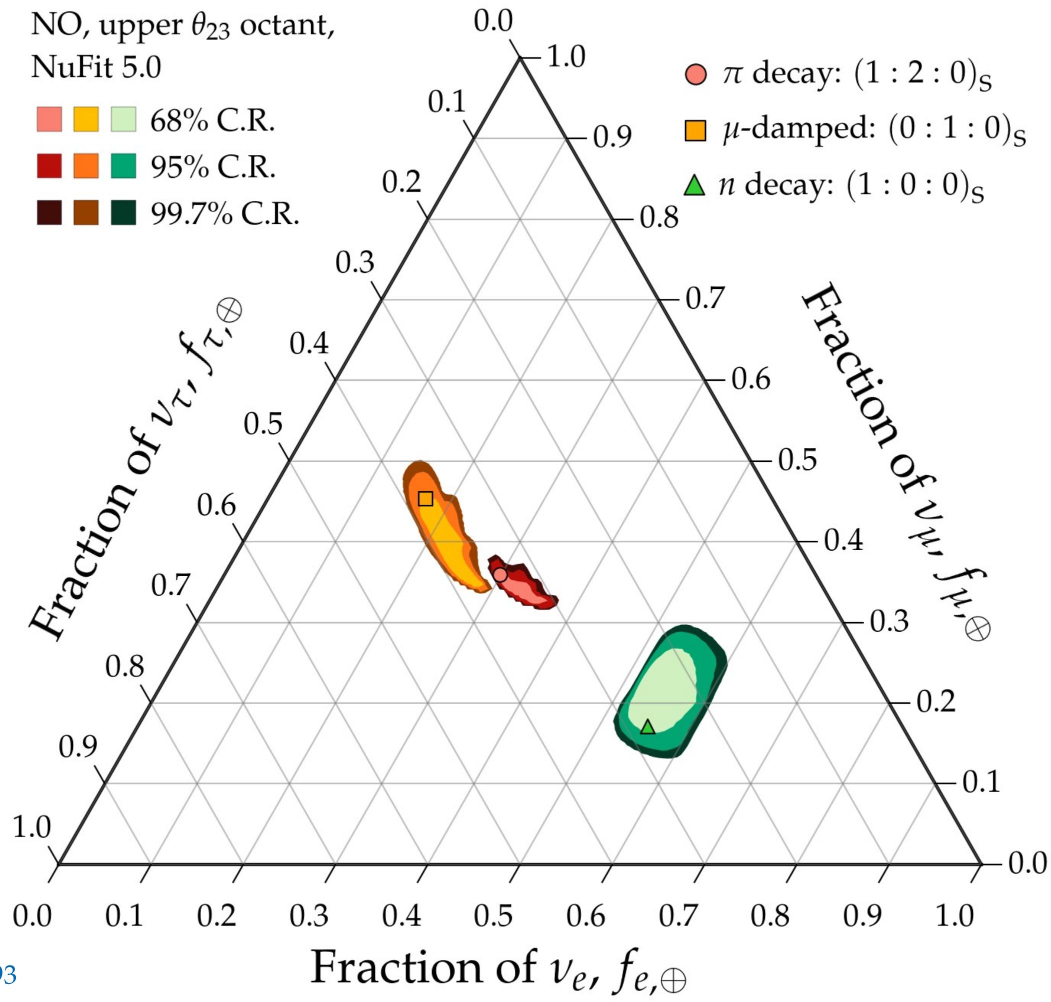

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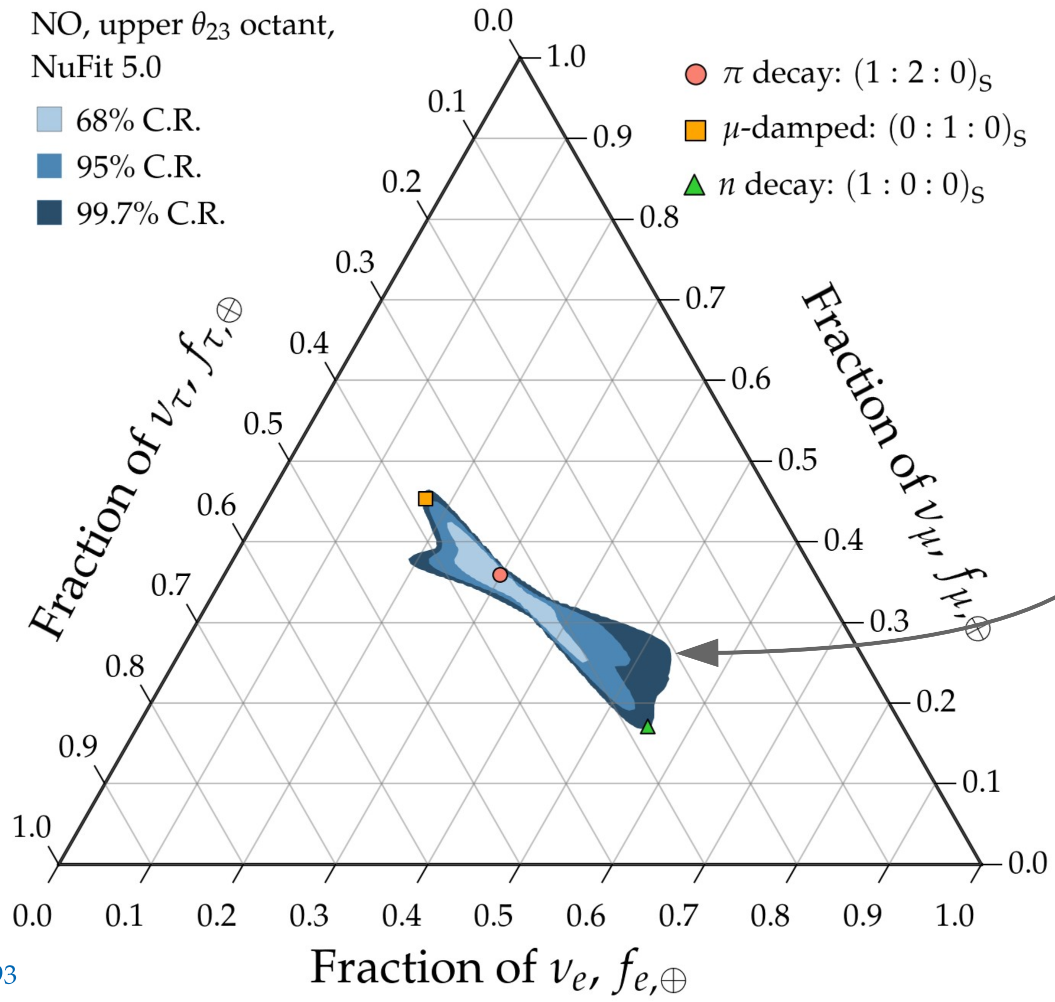

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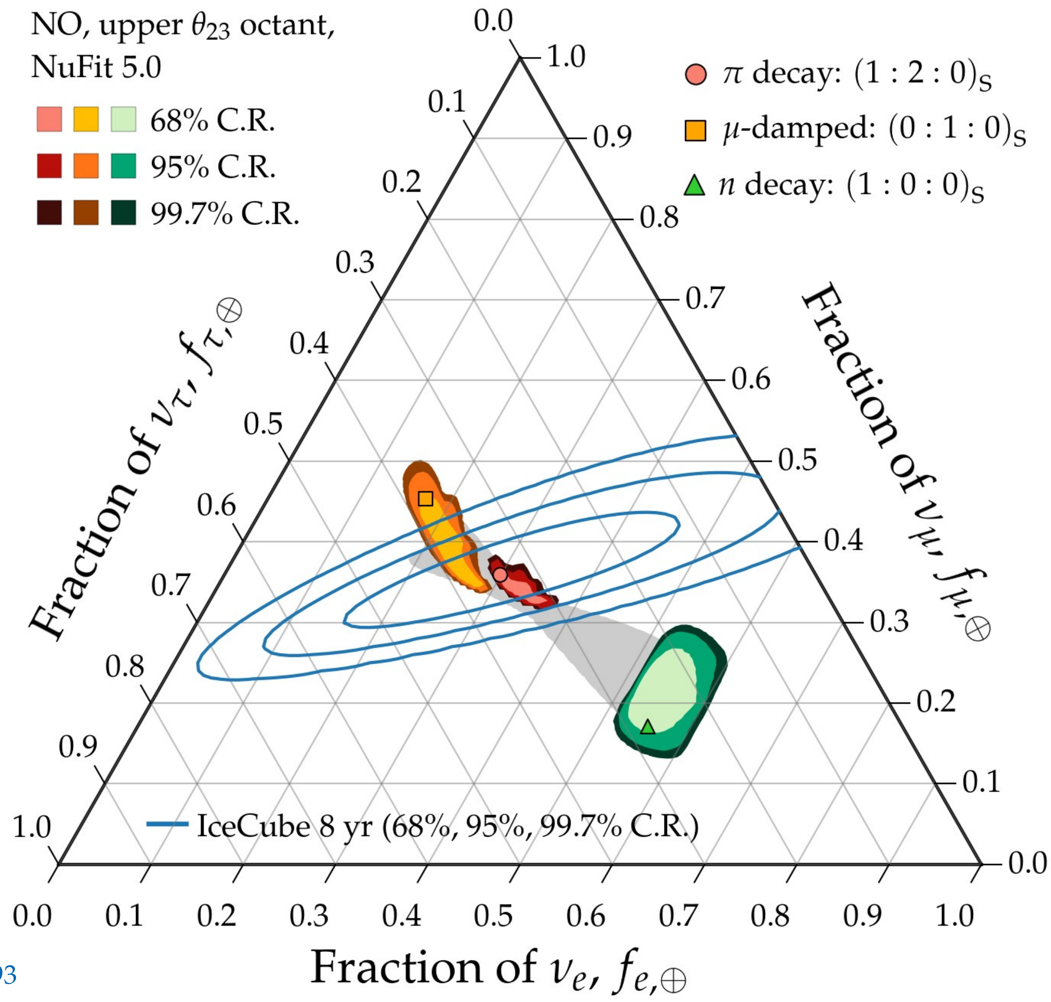

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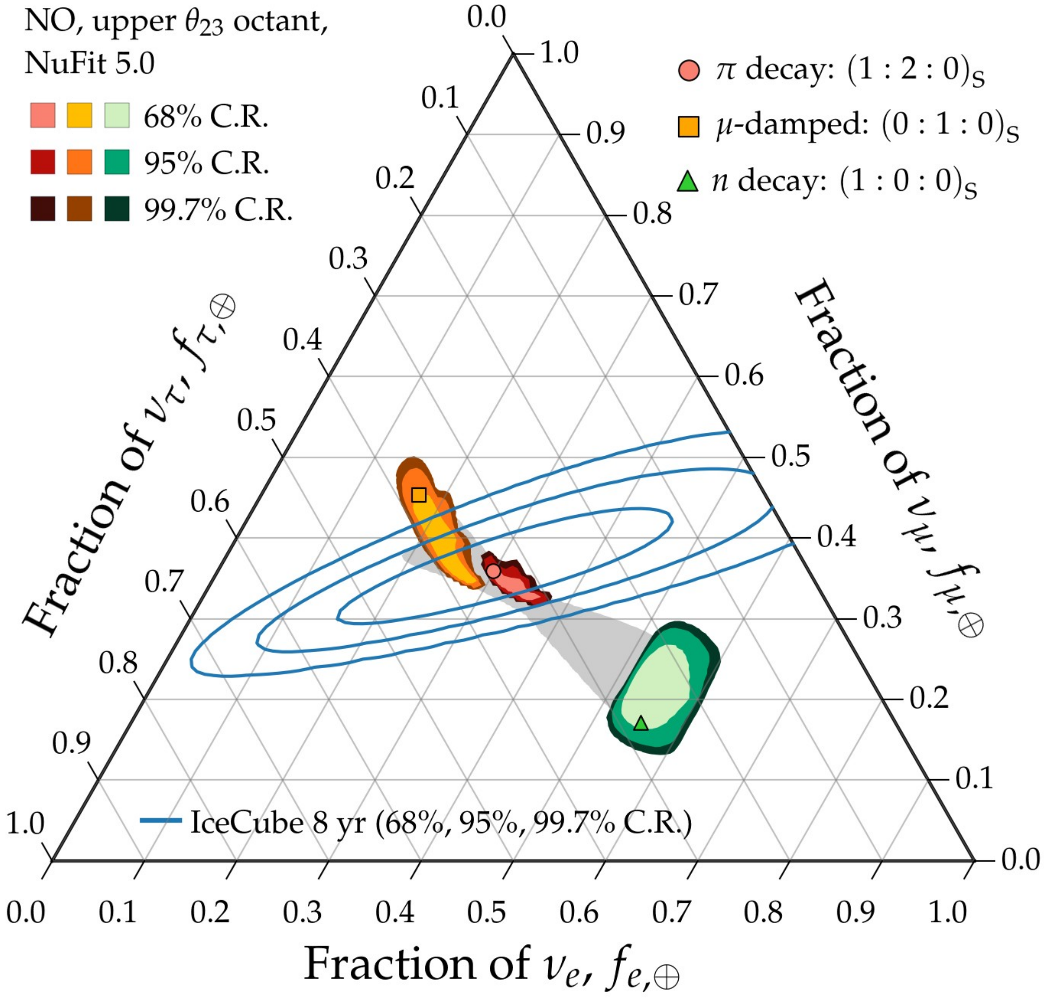

Two limitations:

Allowed flavor regions overlap –
Insufficient precision in the mixing parameters

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

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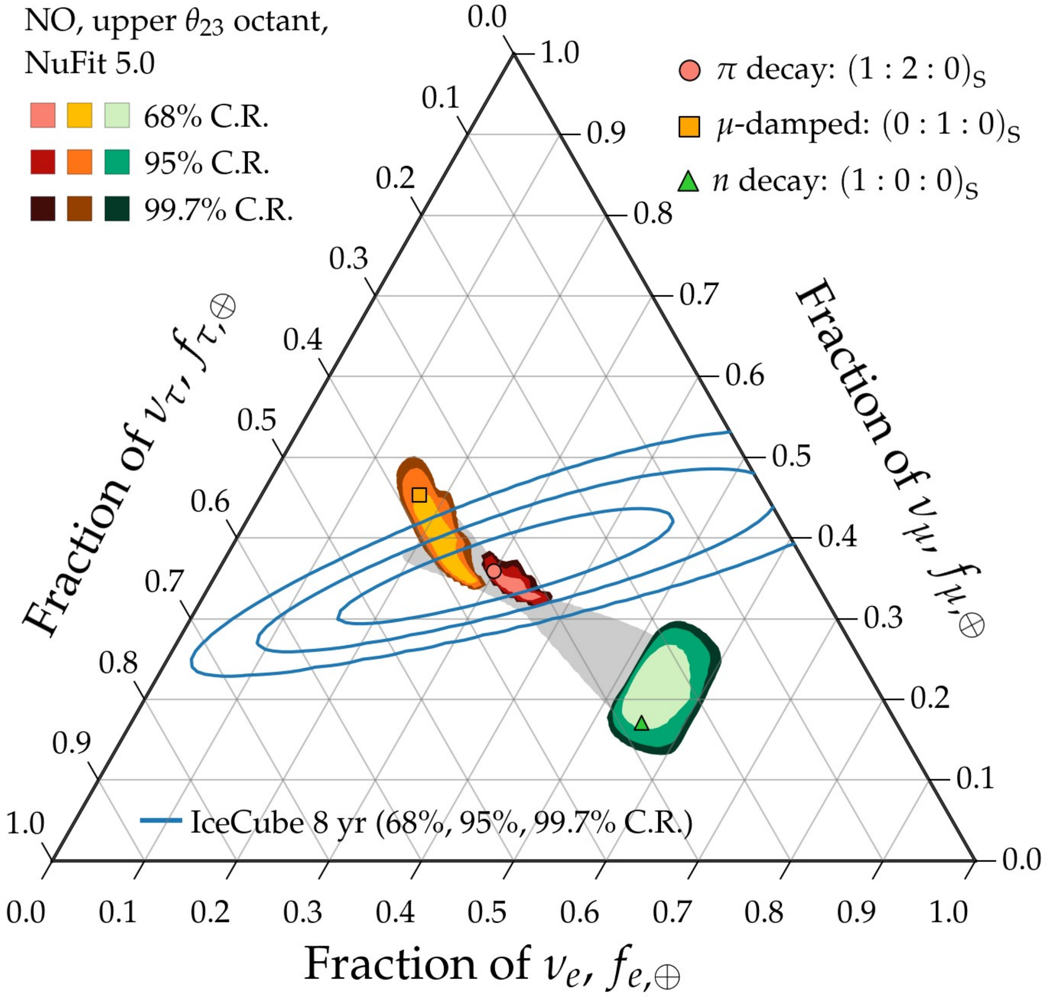

Two limitations:

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Will be overcome by 2030

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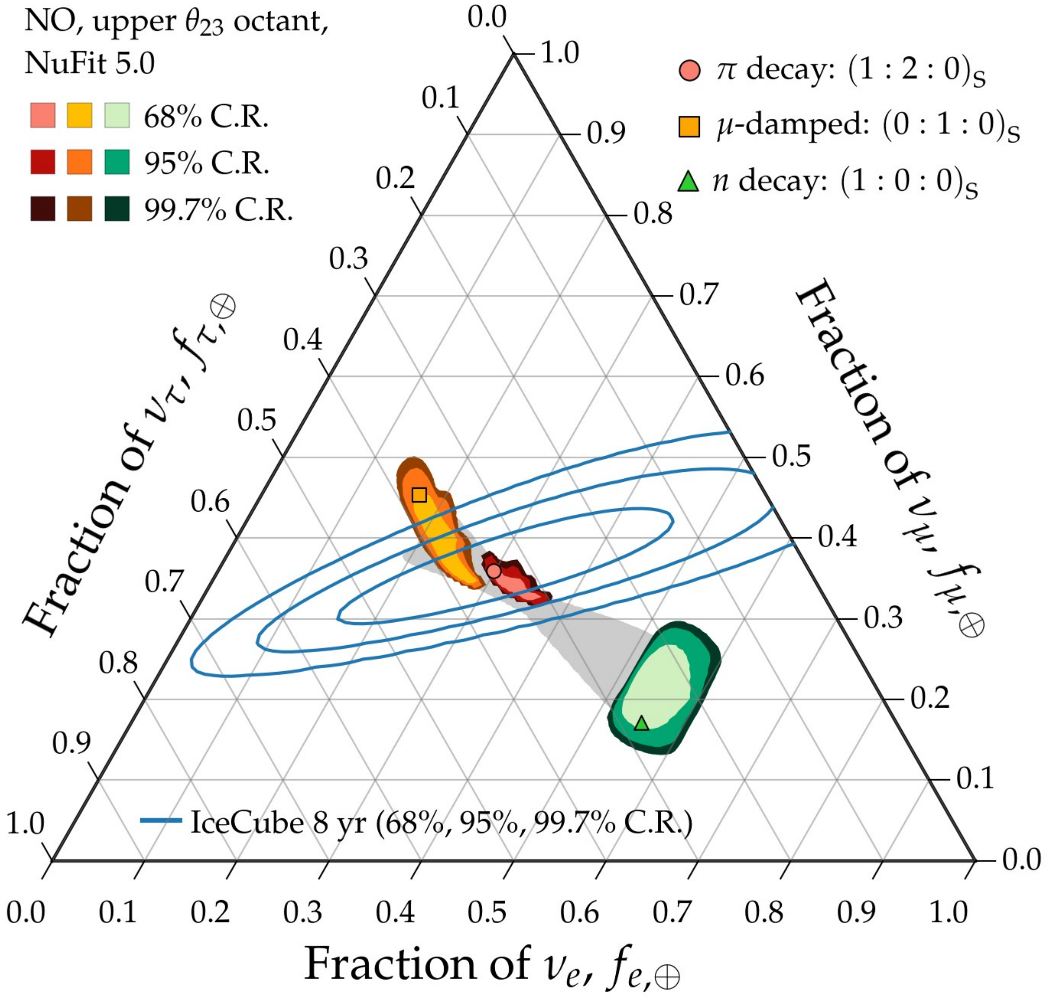

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Will be overcome by 2040

Song, Li, Argüelles, **MB**, Vincent, 2012.12893
See also: **MB**, Beacom, Winter, *PRL* 2015

Flavor at the Earth: *theoretically palatable regions*

Theoretically palatable flavor regions

$\equiv$

MB, Beacom, Winter, *PRL* 2015

Allowed regions of flavor ratios at Earth derived from oscillations

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

Flavor at the Earth: *theoretically palatable regions*

Theoretically palatable flavor regions

≡

MB, Beacom, Winter, *PRL* 2015

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Flavor ratios at the source,

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

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

or

Explore all possible combinations

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$\equiv$

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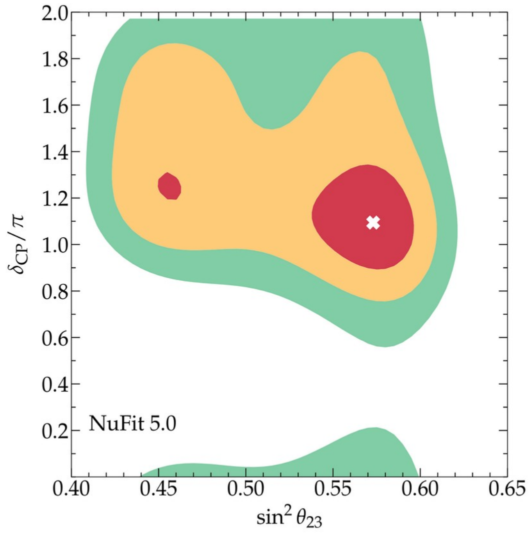
2020: Use χ^2 profiles from the NuFit 5.0 global fit (solar + atmospheric + reactor + accelerator)

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



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

Flavor at the Earth: *theoretically palatable regions*

Theoretically palatable flavor regions

≡

MB, Beacom, Winter, *PRL* 2015

Allowed regions of flavor ratios at Earth derived from oscillations

Ingredient #1:

Flavor ratios at the source,

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

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

or

Explore all possible combinations

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

Ingredient #2:

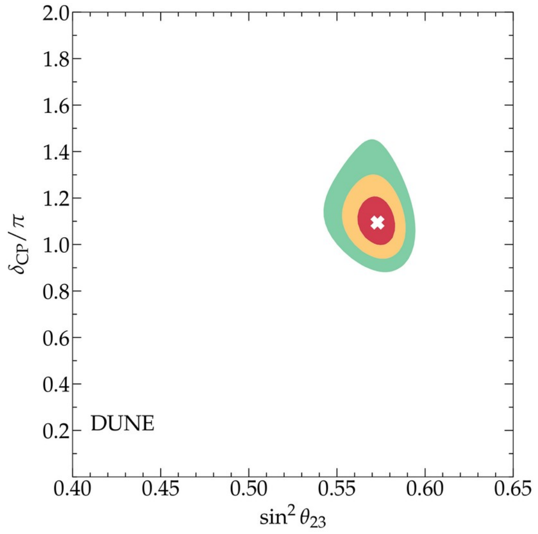
Probability density of mixing parameters $(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\mathrm{CP}})$

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

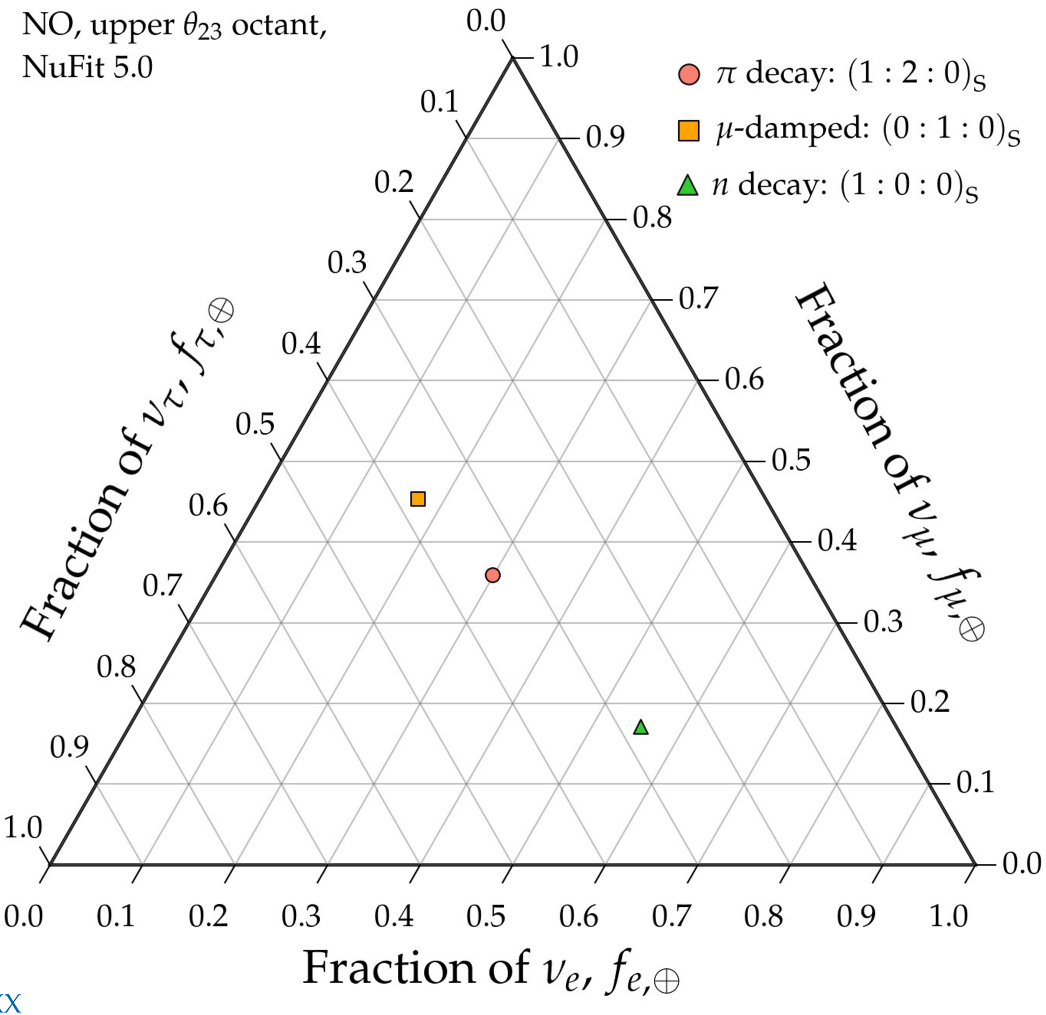
Esteban *et al.*, *JHEP* 2020
www.nu-fit.org

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

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



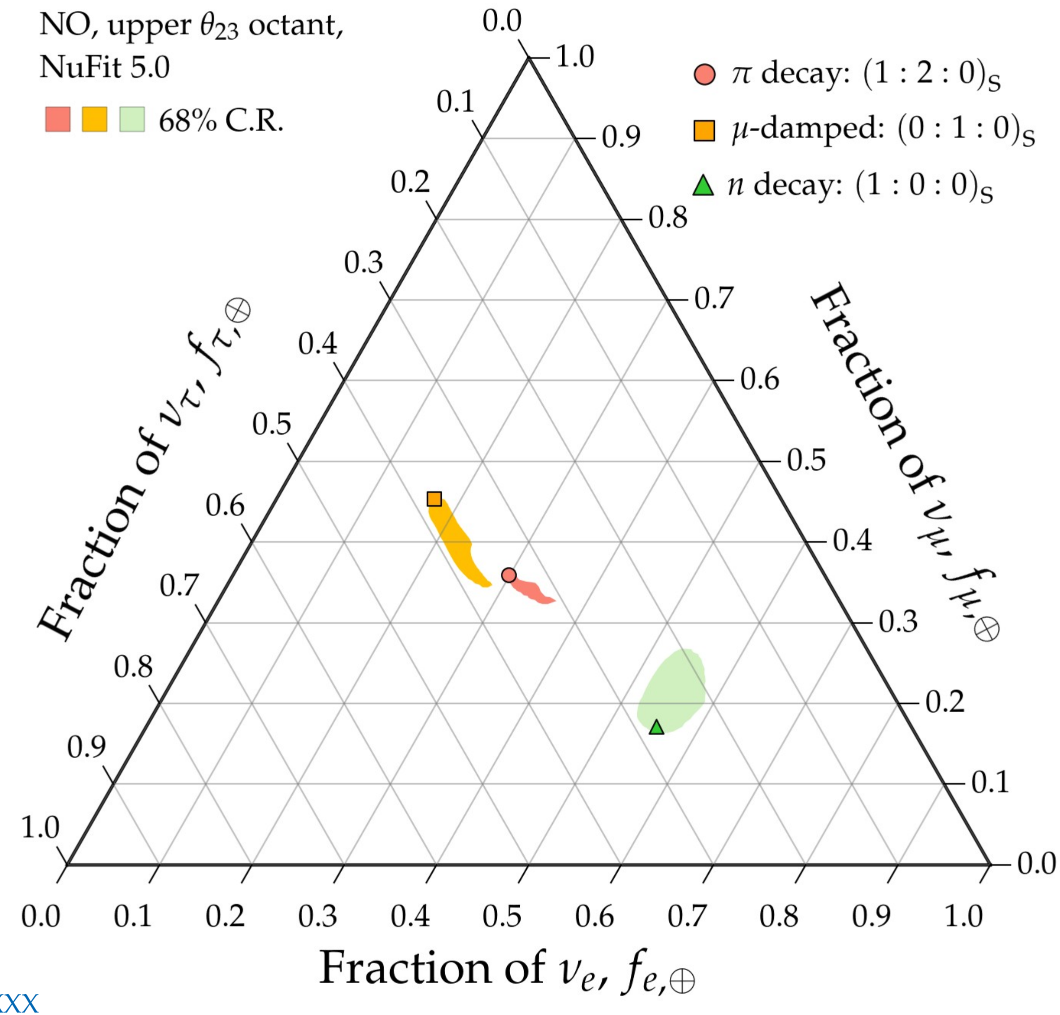
Theoretically palatable regions: today (2020)



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

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: today (2020)



Note:
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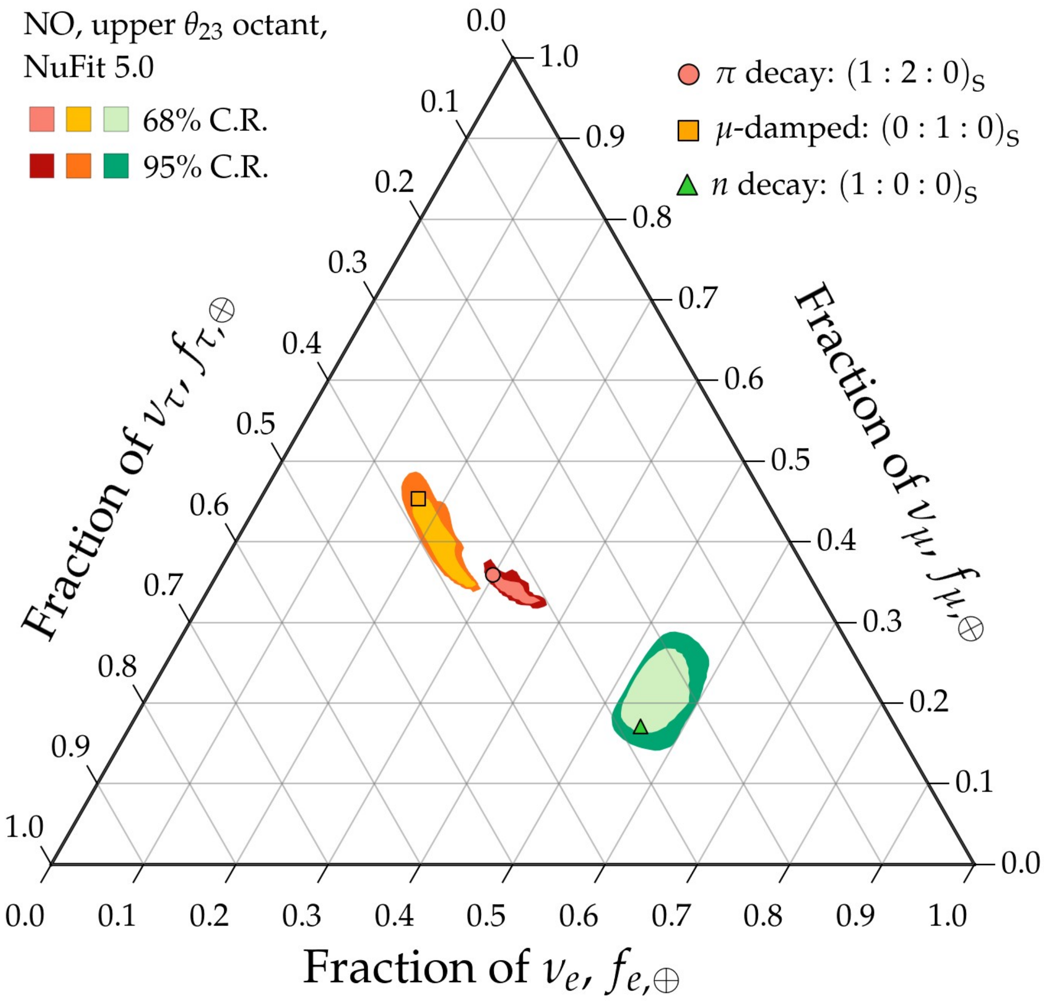
Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: today (2020)



Note:
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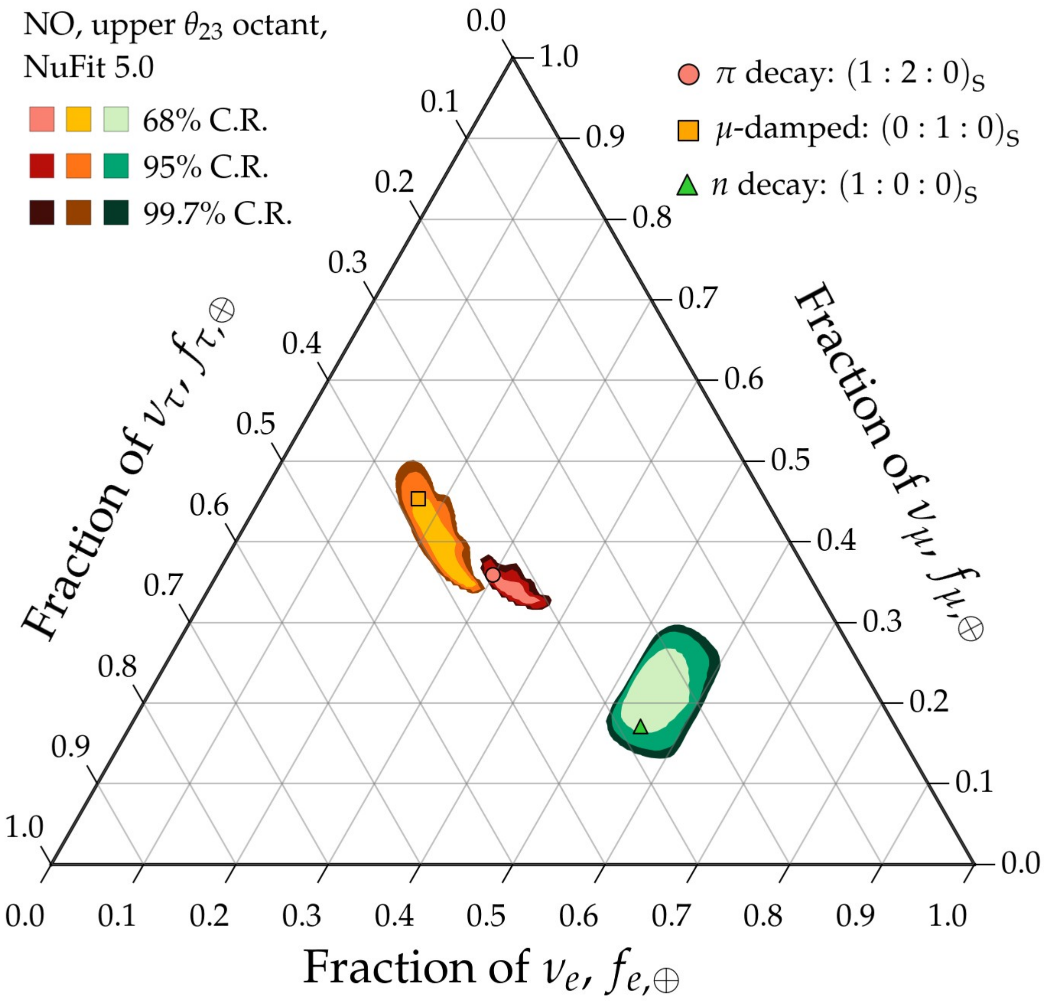
Song, Li, **MB**, Argüelles, Vincent, 2012.X

Theoretically palatable regions: today (2020)



Note:
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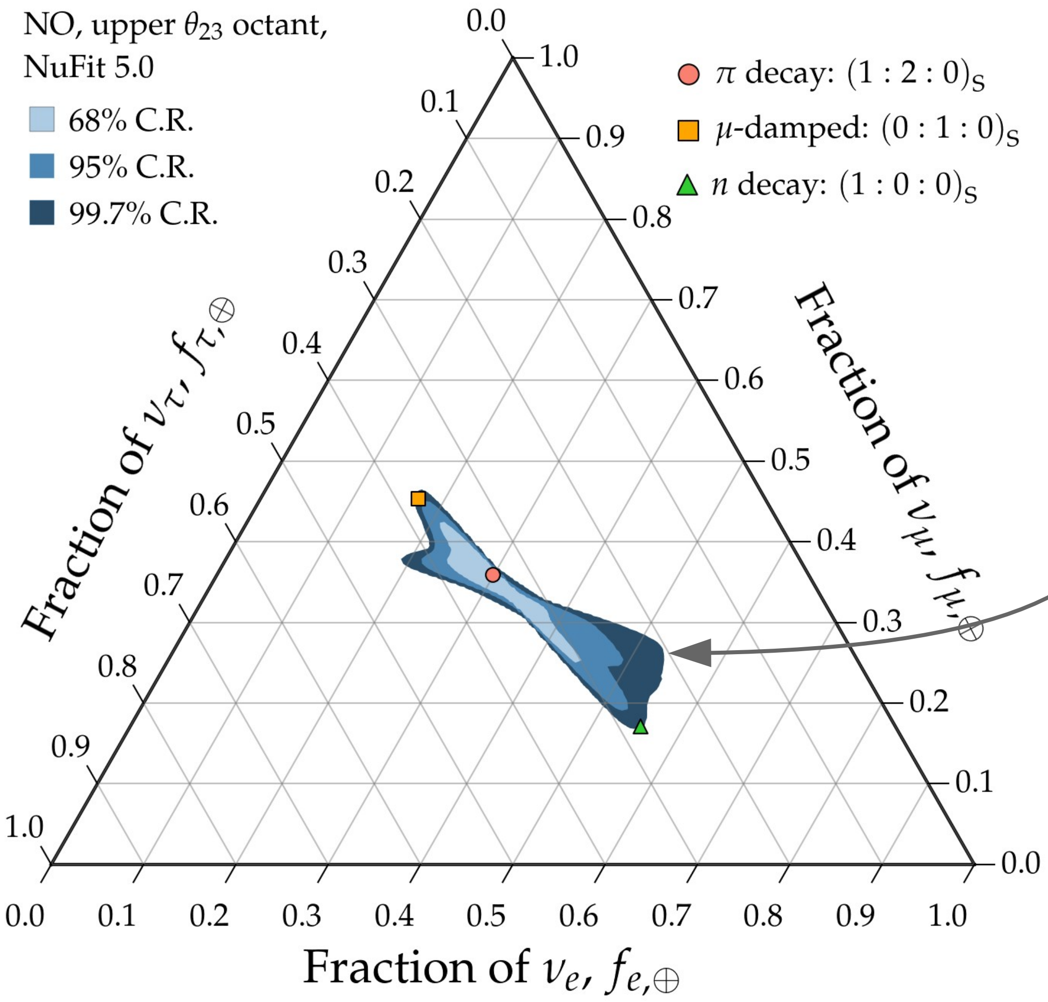
Song, Li, **MB**, Argüelles, Vincent, 2012.X

Theoretically palatable regions: today (2020)

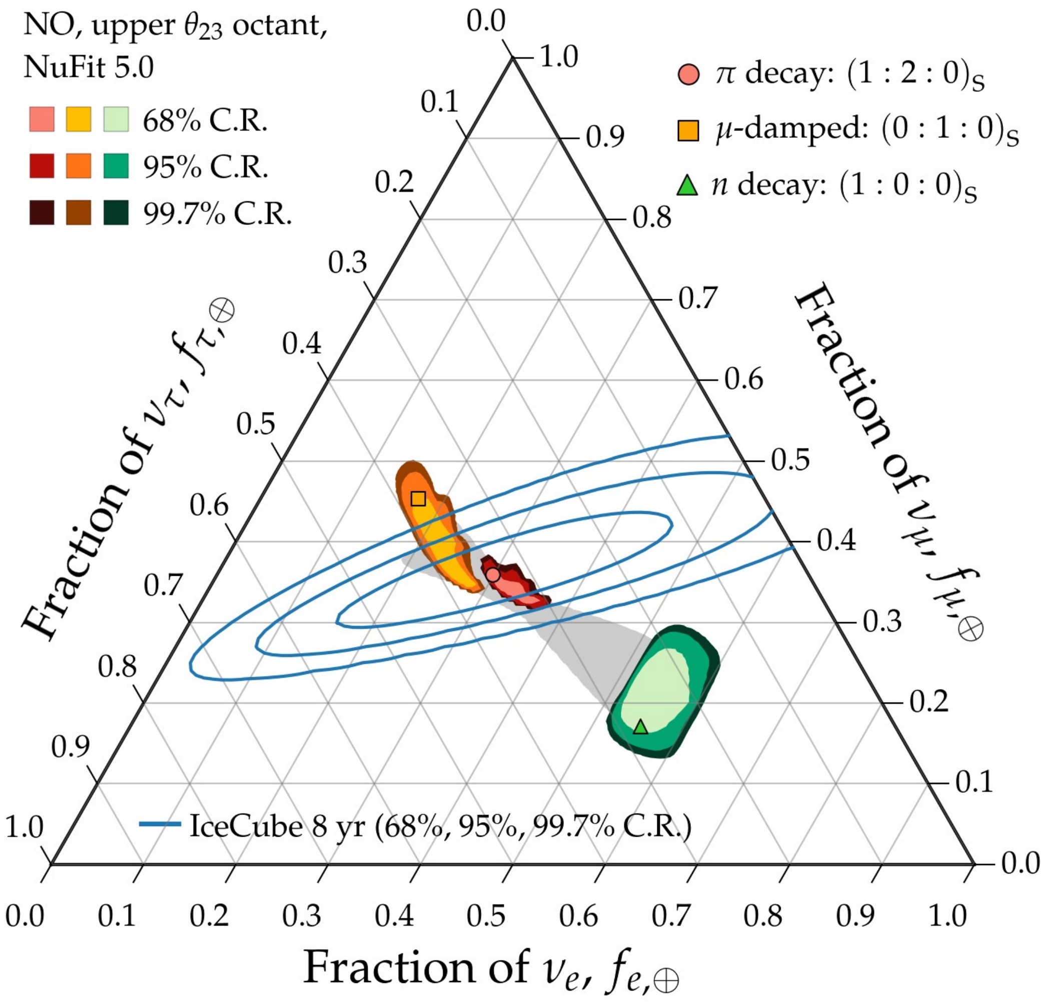


Varying over all possible flavor ratios at the source

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

Song, Li, **MB**, Argüelles, Vincent, 2012.X

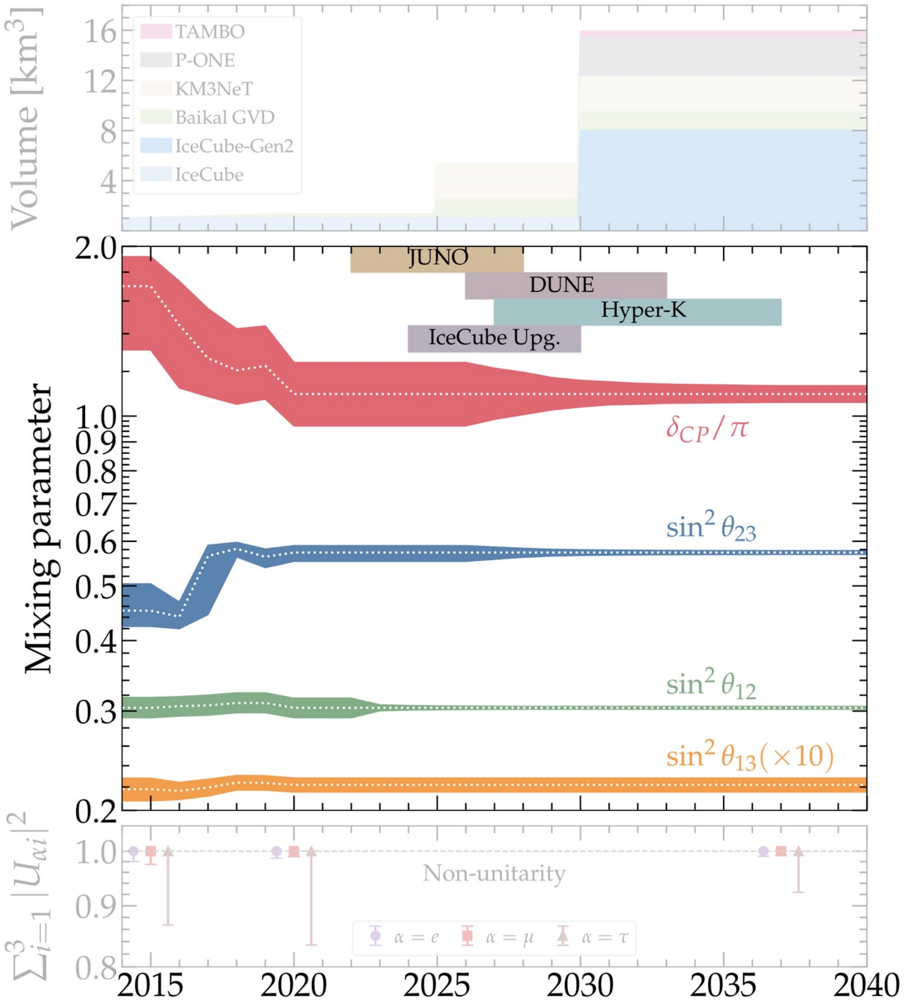
Theoretically palatable regions: today (2020)



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

Song, Li, **MB**, Argüelles, Vincent, 2012.X

How knowing the mixing parameters better helps

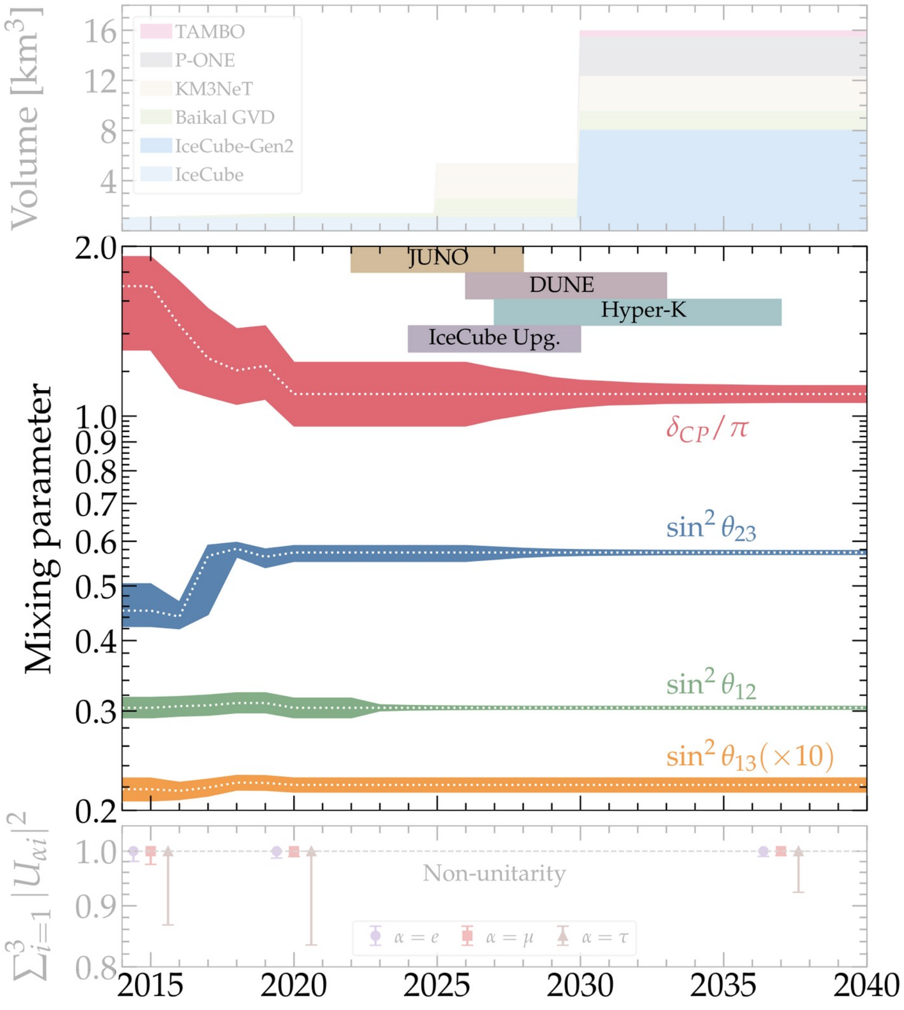


We can compute the oscillation probability more precisely:

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

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

How knowing the mixing parameters better helps



For a future experiment ε = JUNO, DUNE, Hyper-K:

Best fit from NuFit 5.0

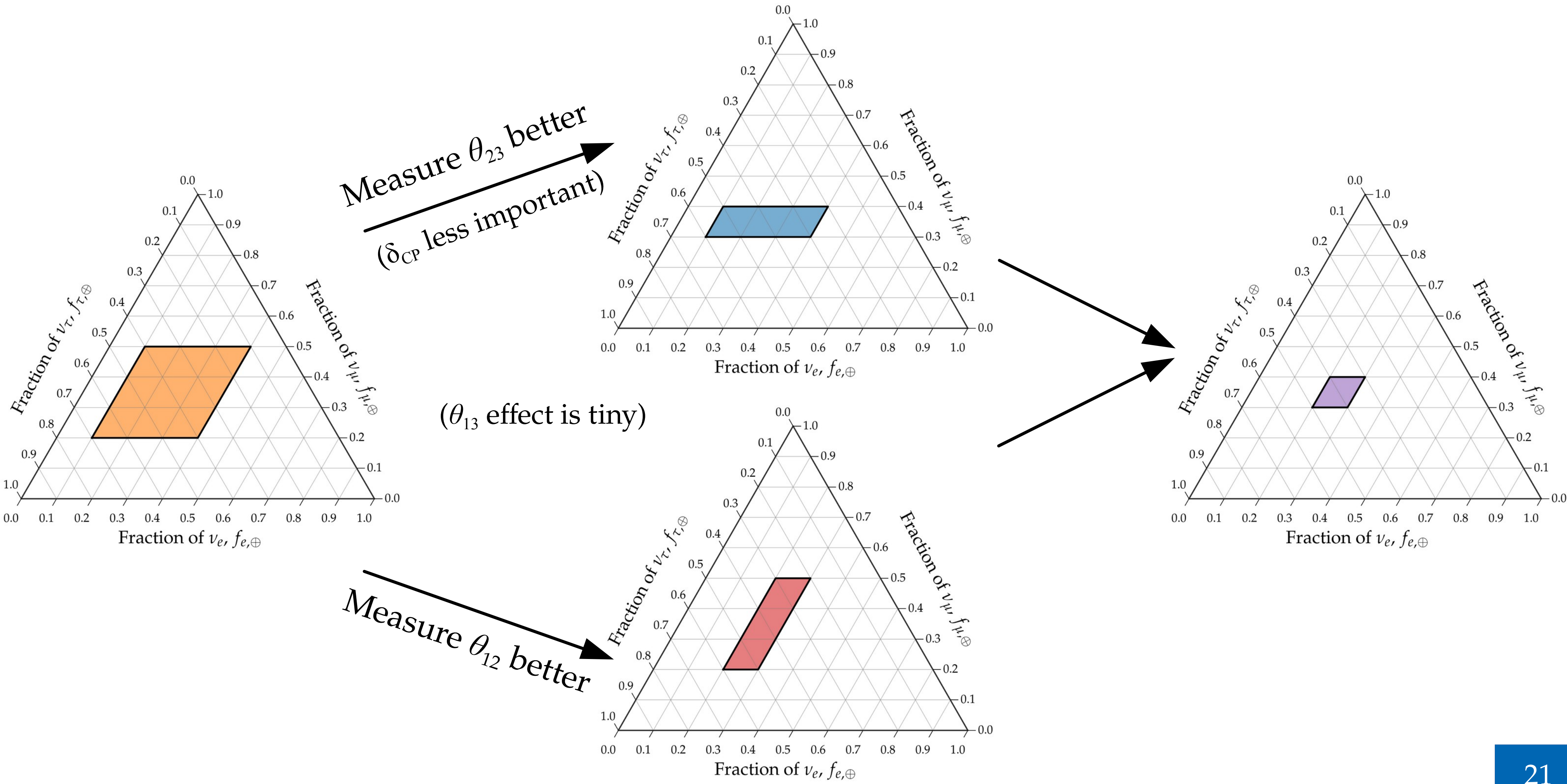
$$\chi^2_\varepsilon(\boldsymbol{\vartheta}) = \sum_i \frac{(\vartheta_i - \bar{\vartheta}_i)^2}{\sigma^2_{i,\varepsilon}}$$

From our simulations

We combine experiments in a likelihood:

$$-2\log\mathcal{L}(\boldsymbol{\theta}) = \sum_\varepsilon \chi^2_\varepsilon(\boldsymbol{\vartheta})$$

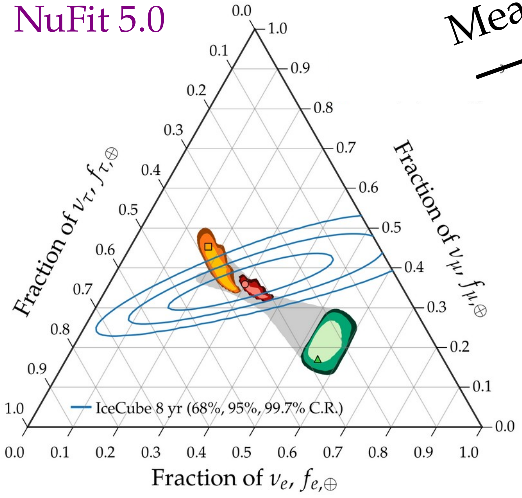
How knowing the mixing parameters better helps



How knowing the mixing parameters better helps

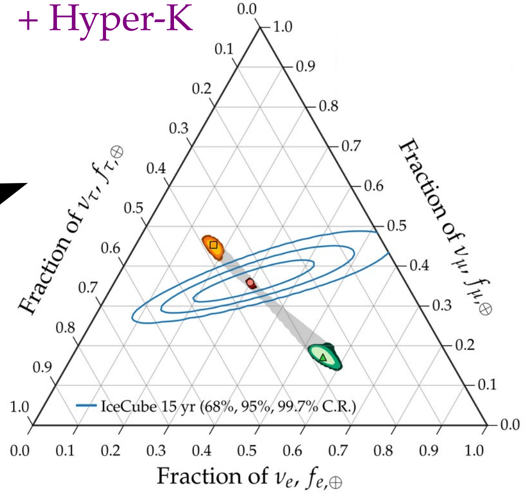
2020

NuFit 5.0



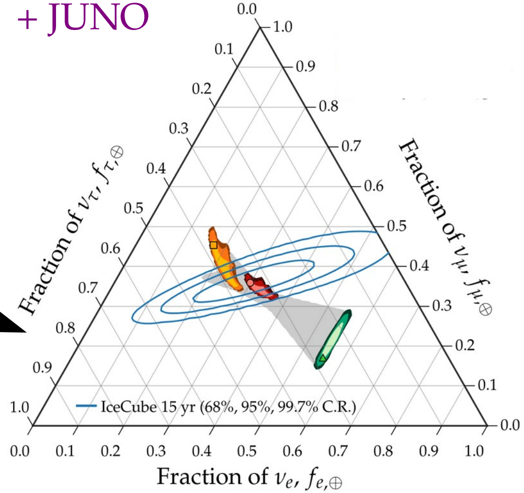
Measure θ_{23} better

+ Hyper-K



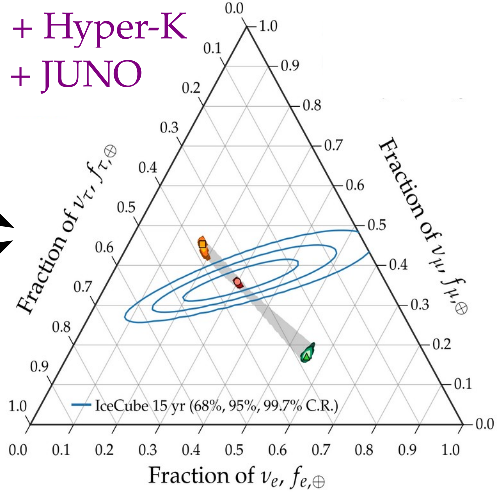
Measure θ_{12} better

+ JUNO



~2030

+ Hyper-K
+ JUNO



In our results:
JUNO + Hyper-K + DUNE

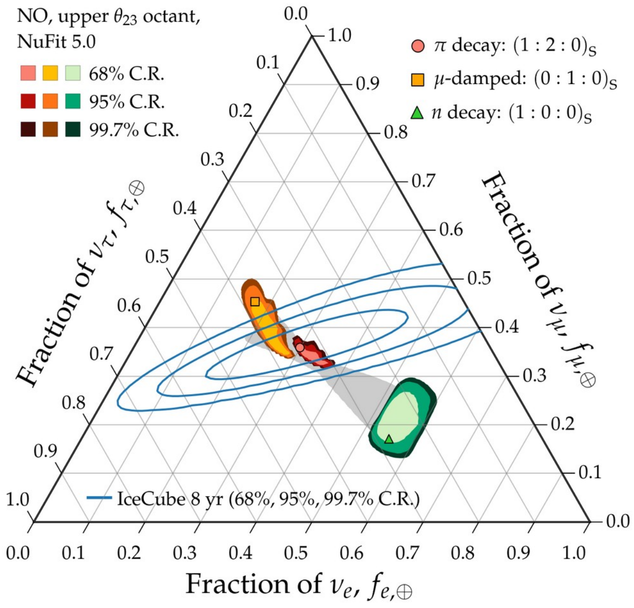
Marginal improvement til 2040

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: 2020 $\to$ 2030 $\to$ 2040

Theoretically palatable regions: 2020 → 2030 → 2040

2020



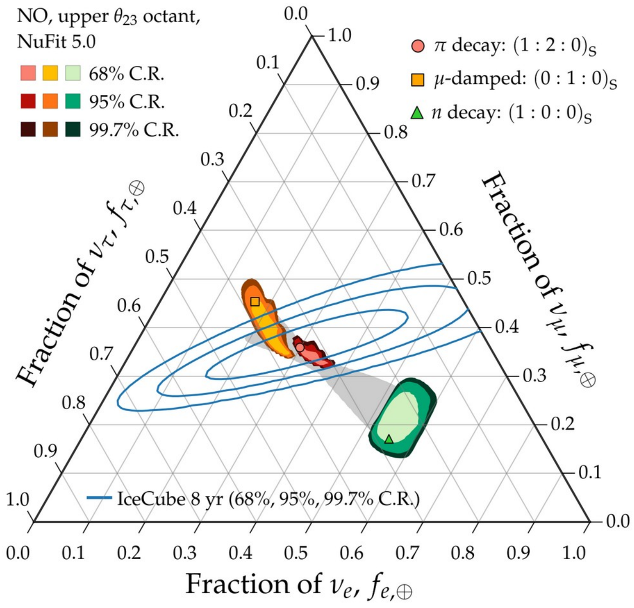
Allowed regions: overlapping

Measurement: imprecise

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: 2020 → 2030 → 2040

2020



Allowed regions: overlapping

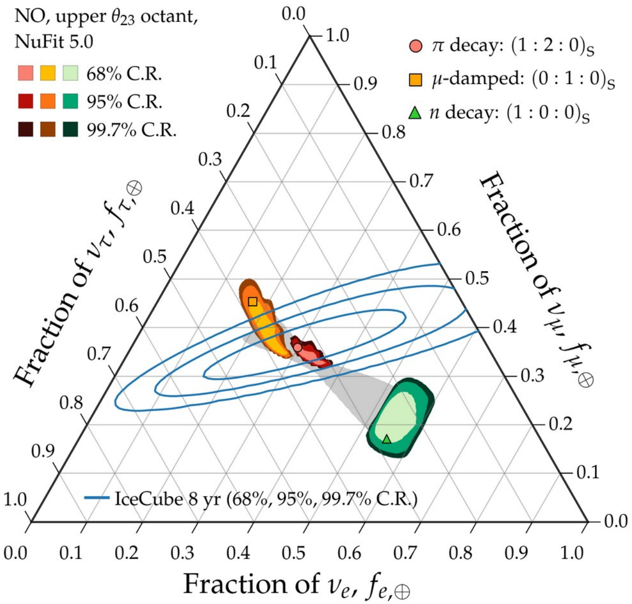
Measurement: imprecise

Not ideal

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: 2020 → 2030 → 2040

2020

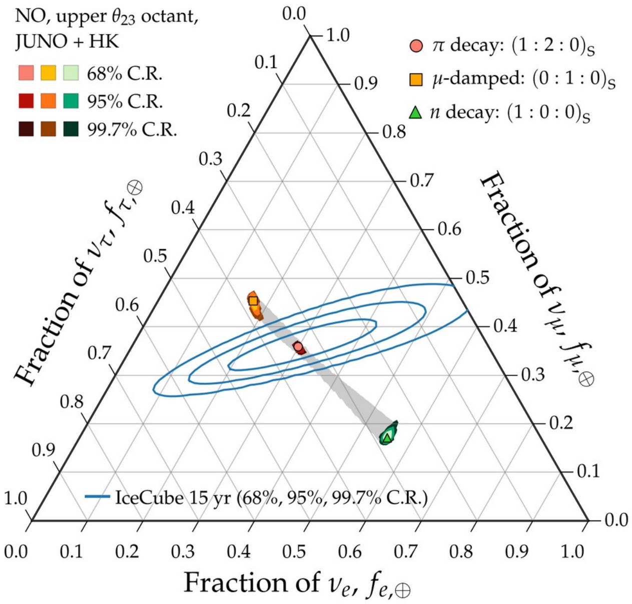


Allowed regions: overlapping

Measurement: imprecise

Not ideal

2030



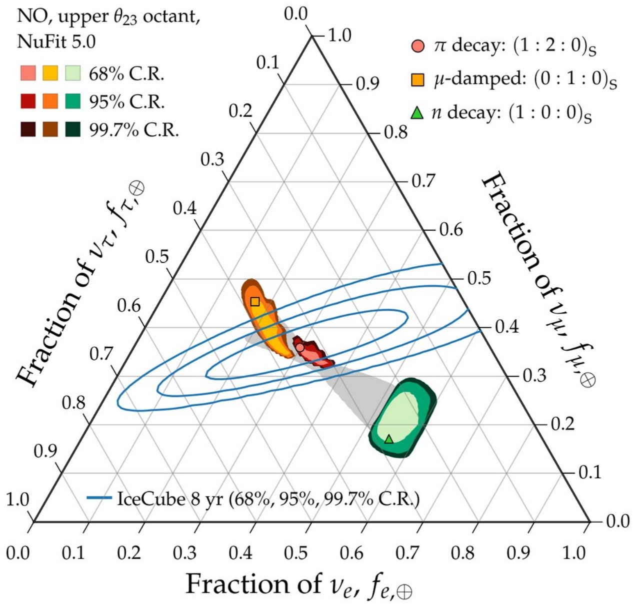
Allowed regions: well separated

Measurement: improving

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: 2020 → 2030 → 2040

2020

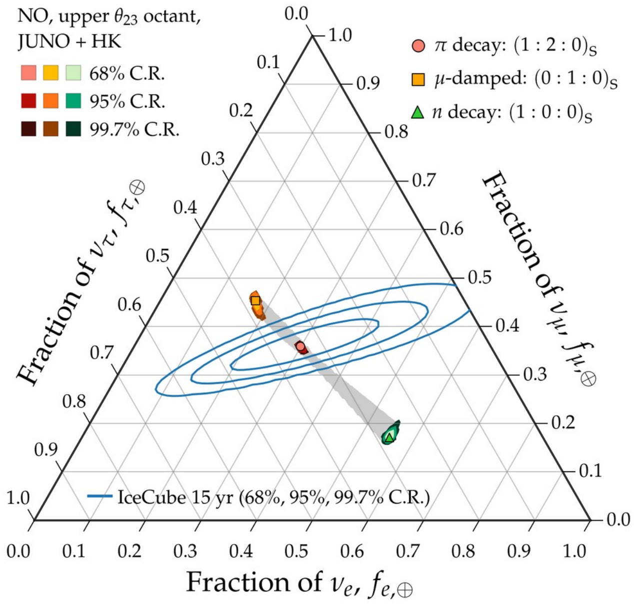


Allowed regions: overlapping

Measurement: imprecise

Not ideal

2030



Allowed regions: well separated

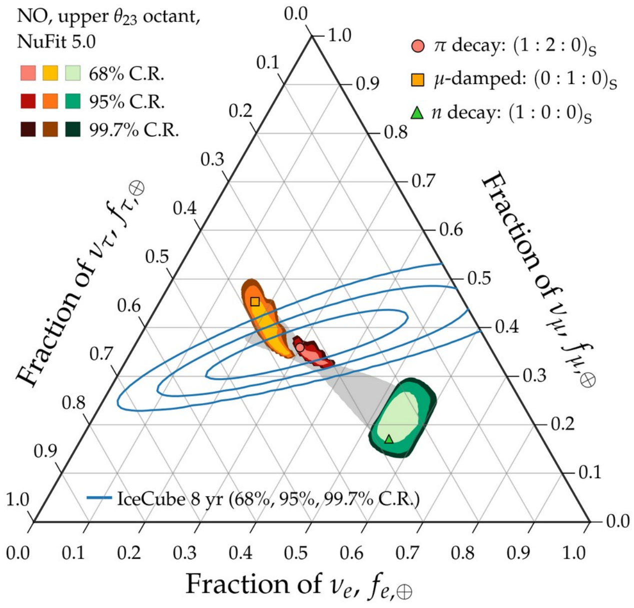
Measurement: improving

Nice

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: 2020 → 2030 → 2040

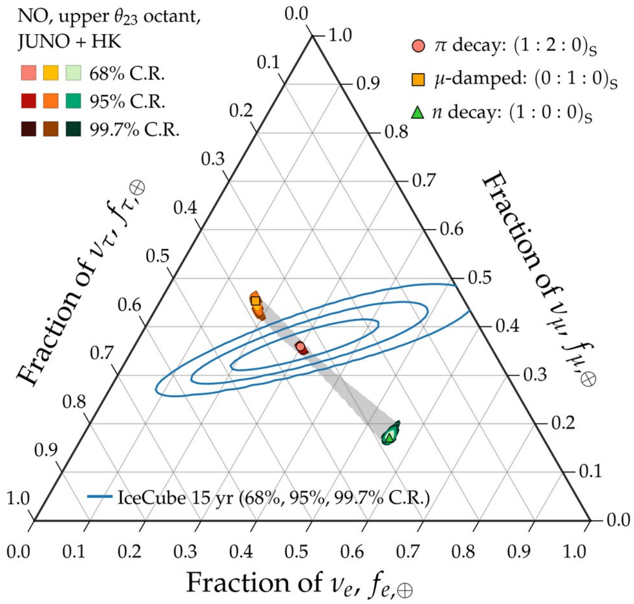
2020



Allowed regions: overlapping
Measurement: imprecise

Not ideal

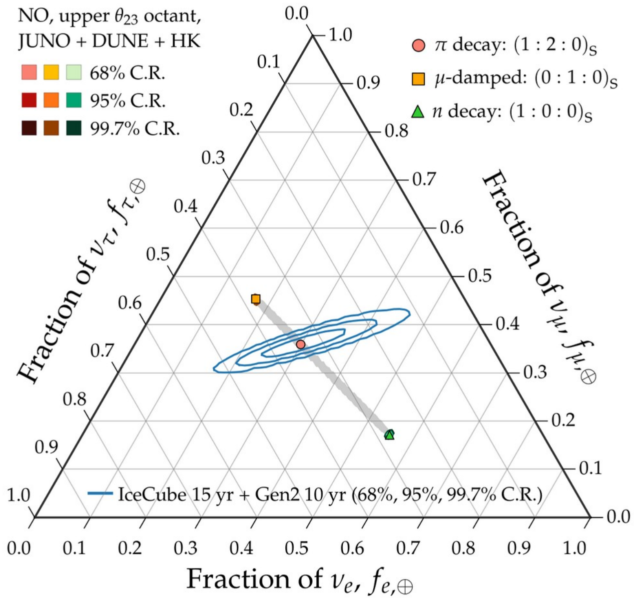
2030



Allowed regions: well separated
Measurement: improving

Nice

2040

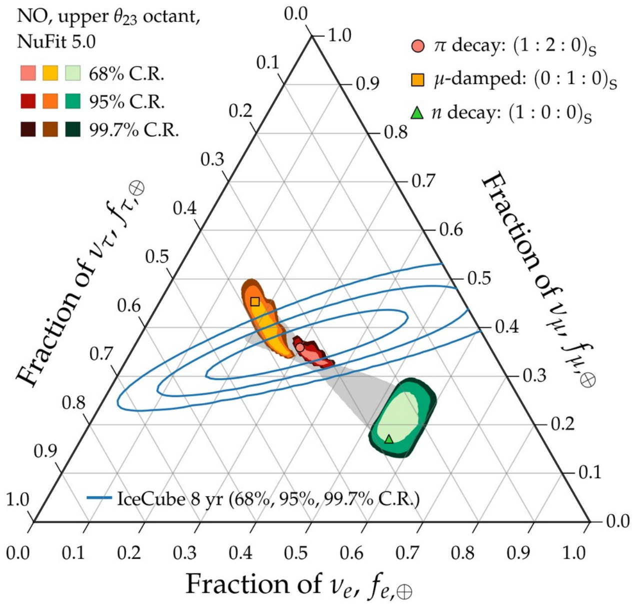


Allowed regions: well separated
Measurement: precise

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: 2020 → 2030 → 2040

2020

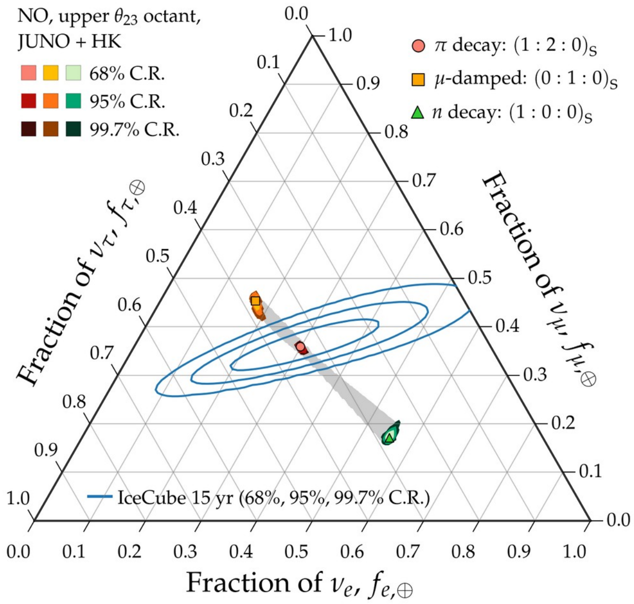


Allowed regions: overlapping

Measurement: imprecise

Not ideal

2030

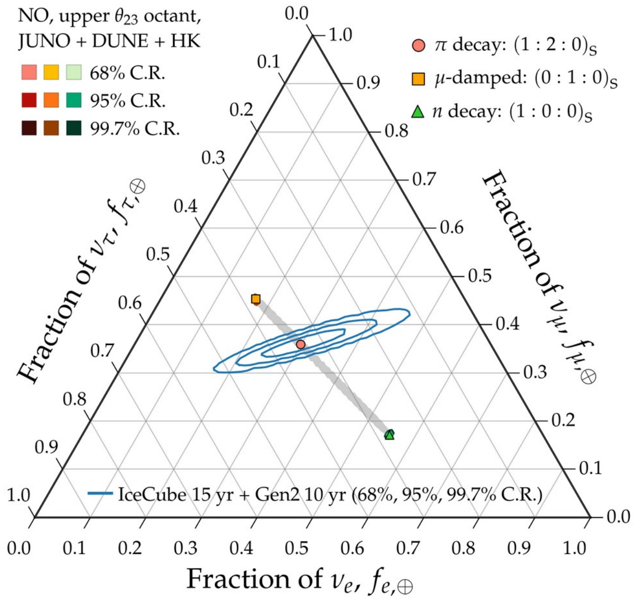


Allowed regions: well separated

Measurement: improving

Nice

2040



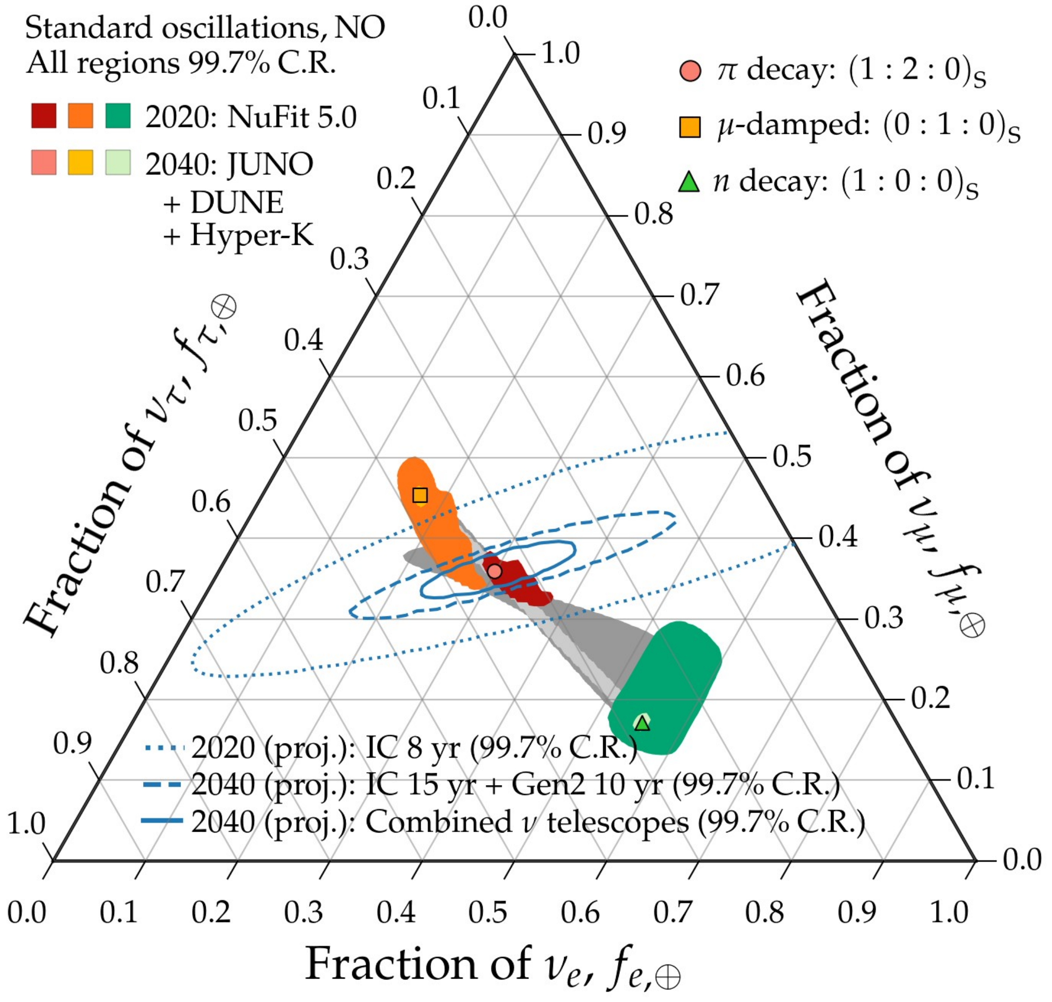
Allowed regions: well separated

Measurement: precise

Success

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: 2020 *vs.* 2040



By 2040:

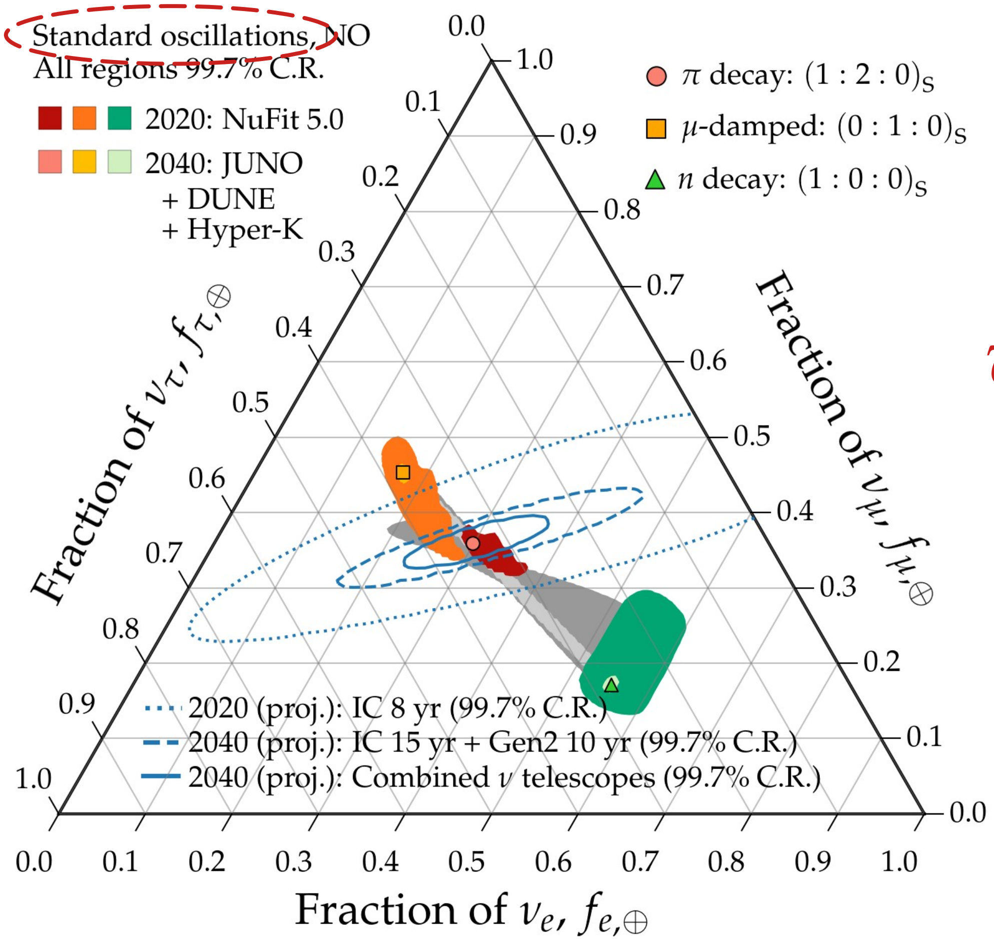
Theory –
Mixing parameters known precisely: allowed flavor regions are *almost* points (already by 2030)

Measurement of flavor ratios –
Can distinguish between similar predictions at 99.7% C.R. (3σ)

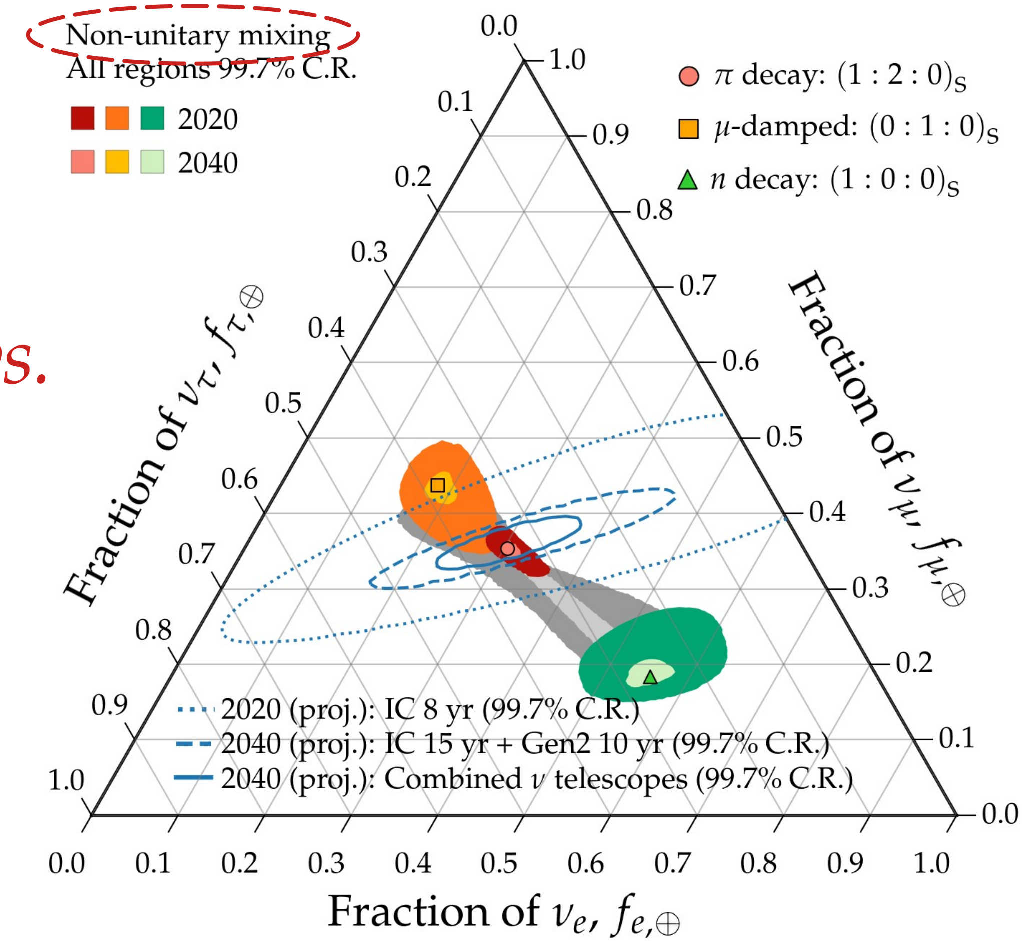
Can finally use the full power of flavor composition for astrophysics and neutrino physics

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

No unitarity? *No problem*



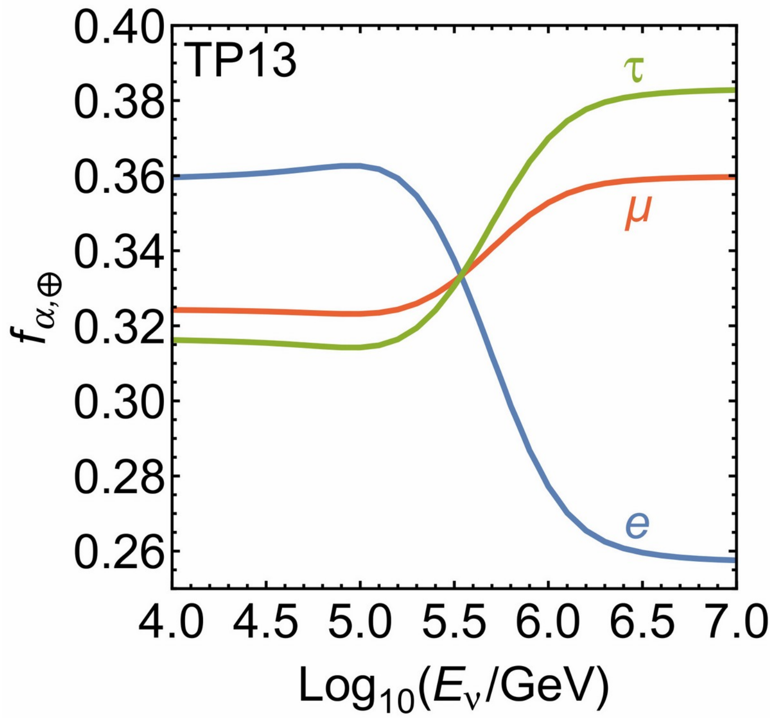
vs.

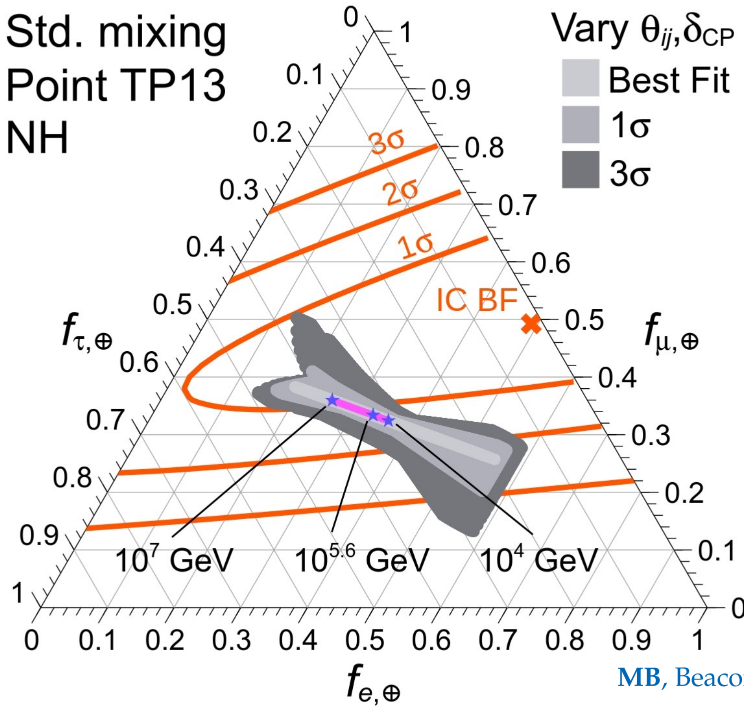


Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Energy dependence of the flavor composition?

Different neutrino production channels accessible at different energies –



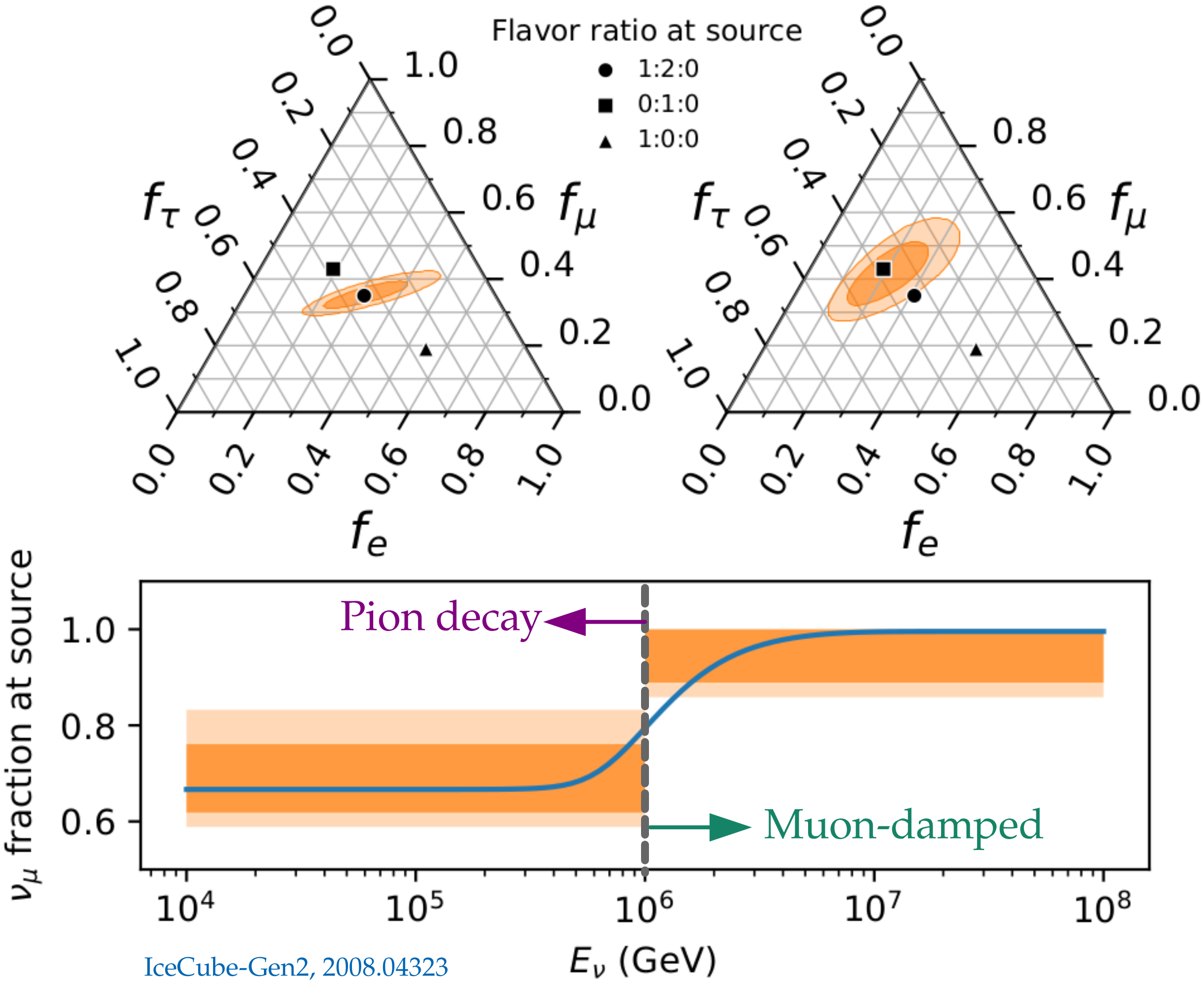


MB, Beacom, Winter, *PRL* 2015

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

Energy dependence of flavor ratios – in IceCube-Gen2

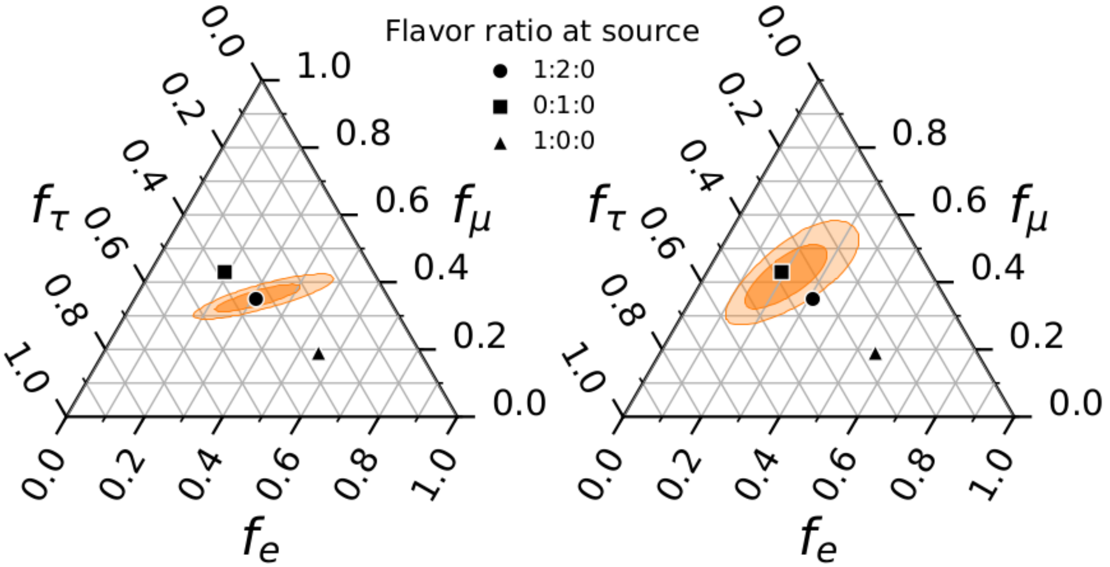
Measured:

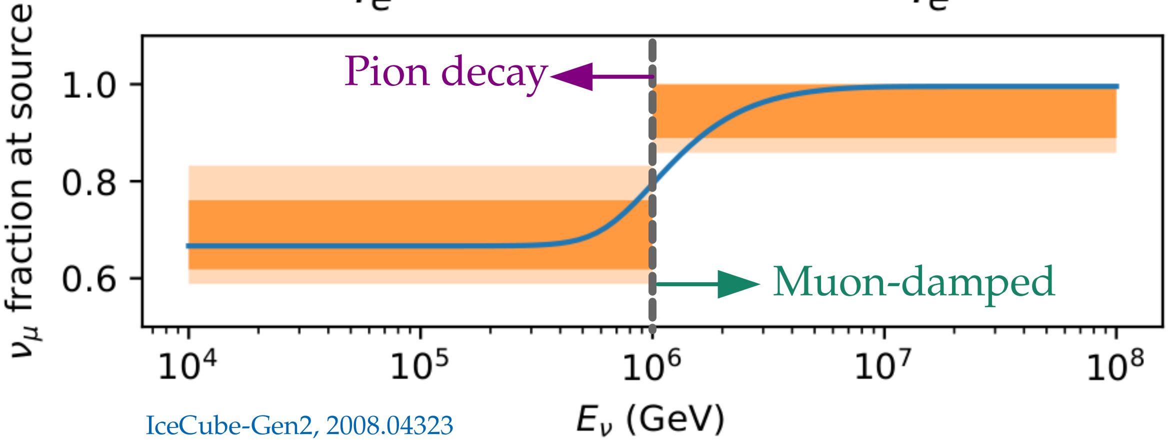


IceCube-Gen2, 2008.04323

Energy dependence of flavor ratios – in IceCube-Gen2

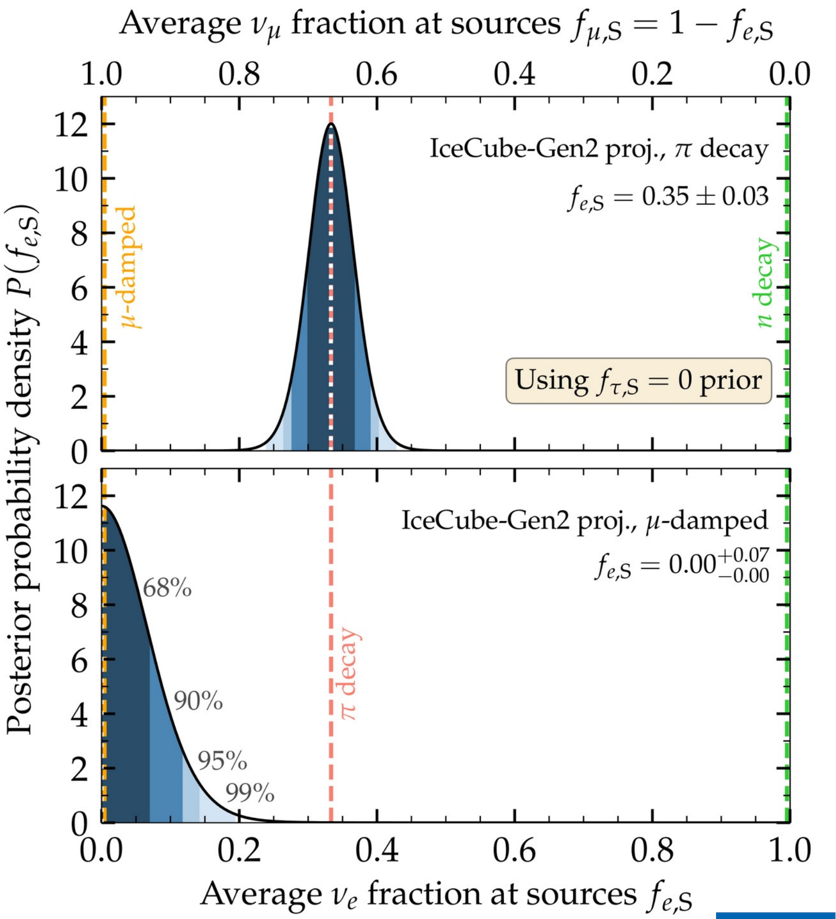
Measured:





IceCube-Gen2, 2008.04323

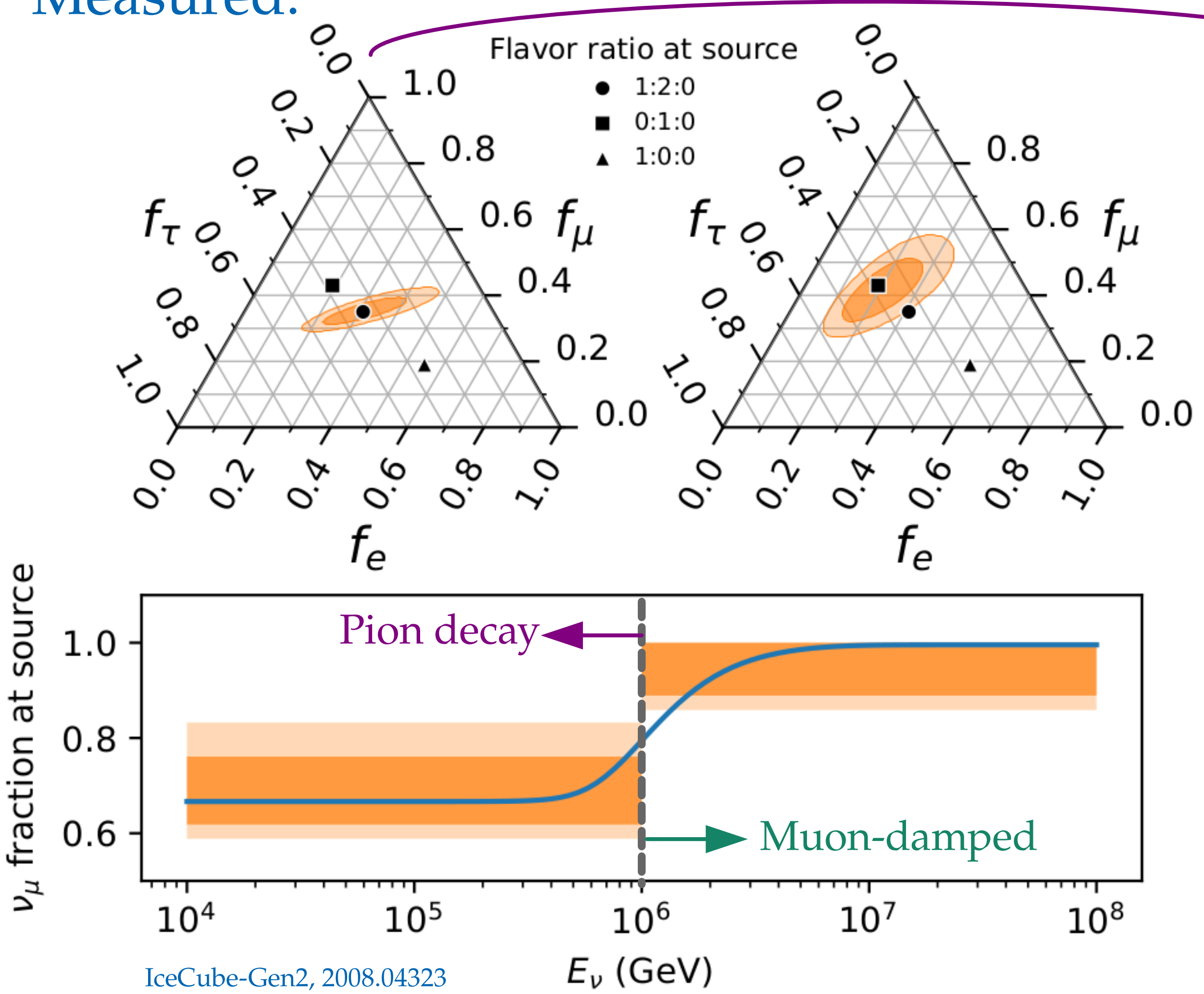
Inferred (at sources):



MB & Ahlers, *PRL* 2019

Energy dependence of flavor ratios – in IceCube-Gen2

Measured:



IceCube-Gen2, 2008.04323

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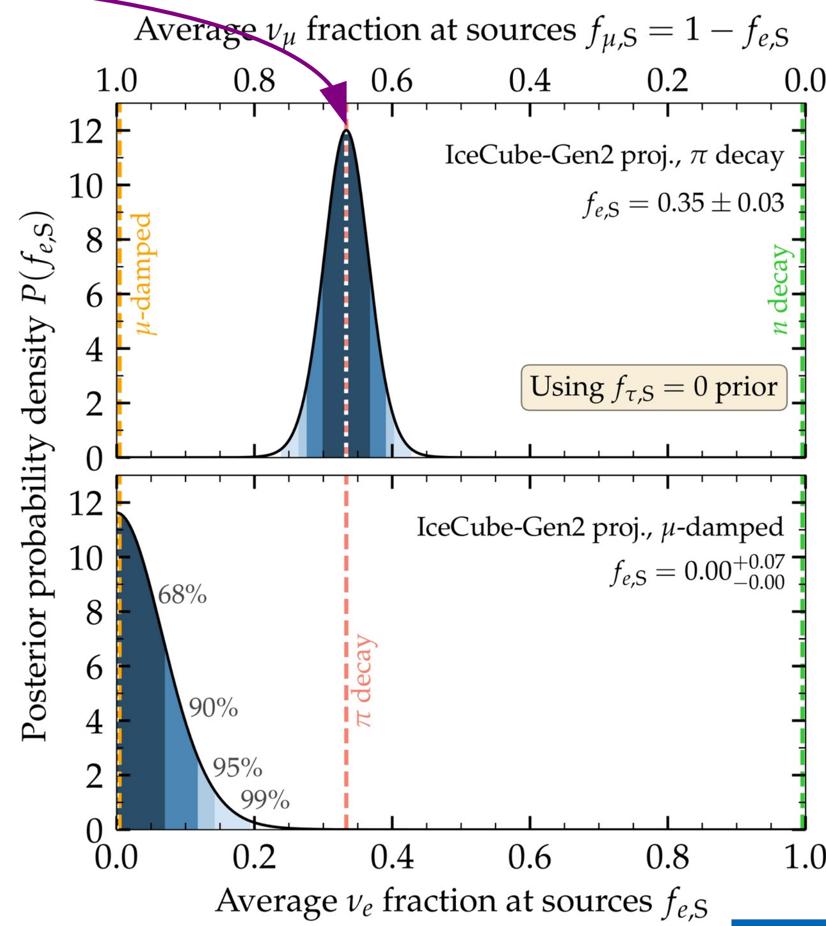
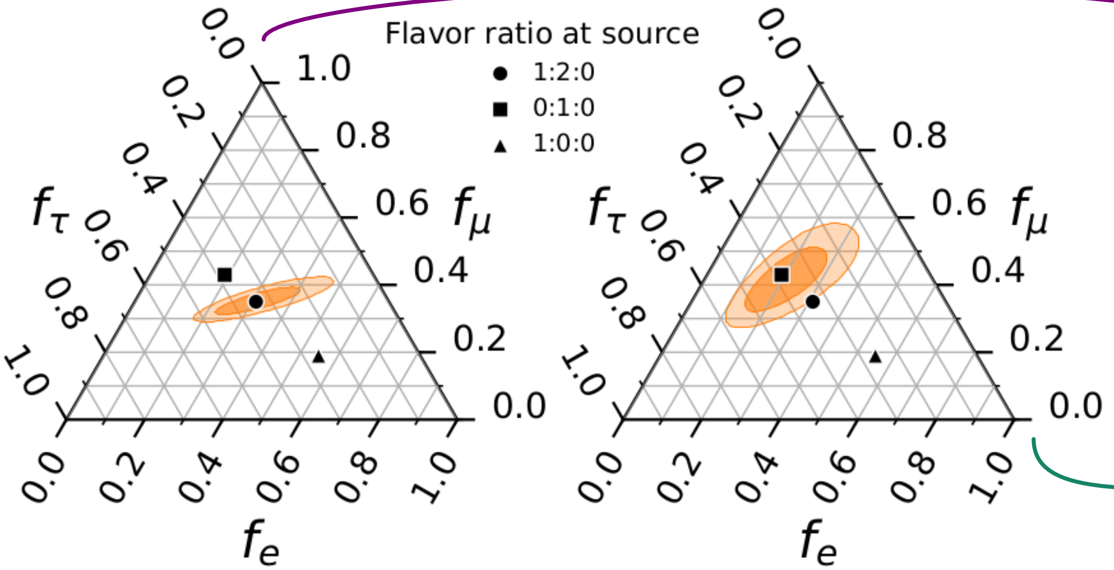
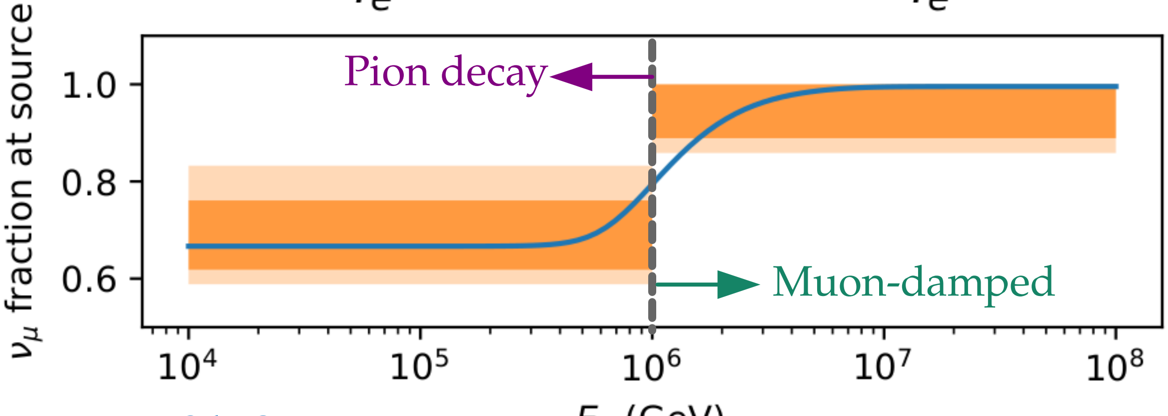


MB & Ahlers, *PRL* 2019

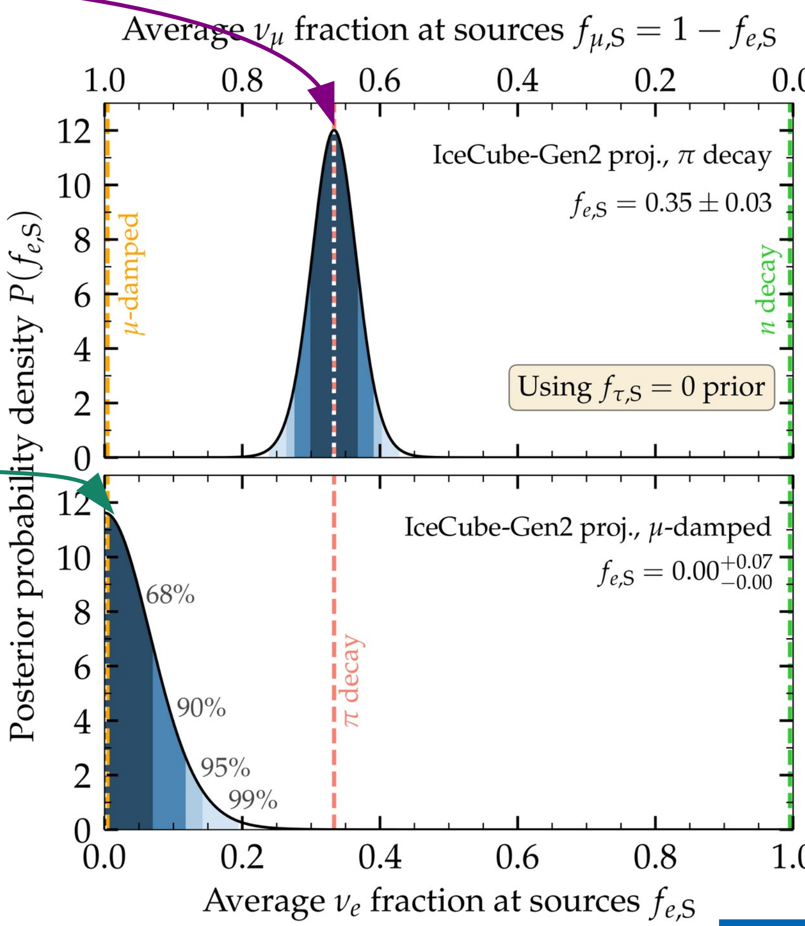
Energy dependence of flavor ratios – in IceCube-Gen2

Measured:





Inferred (at sources):



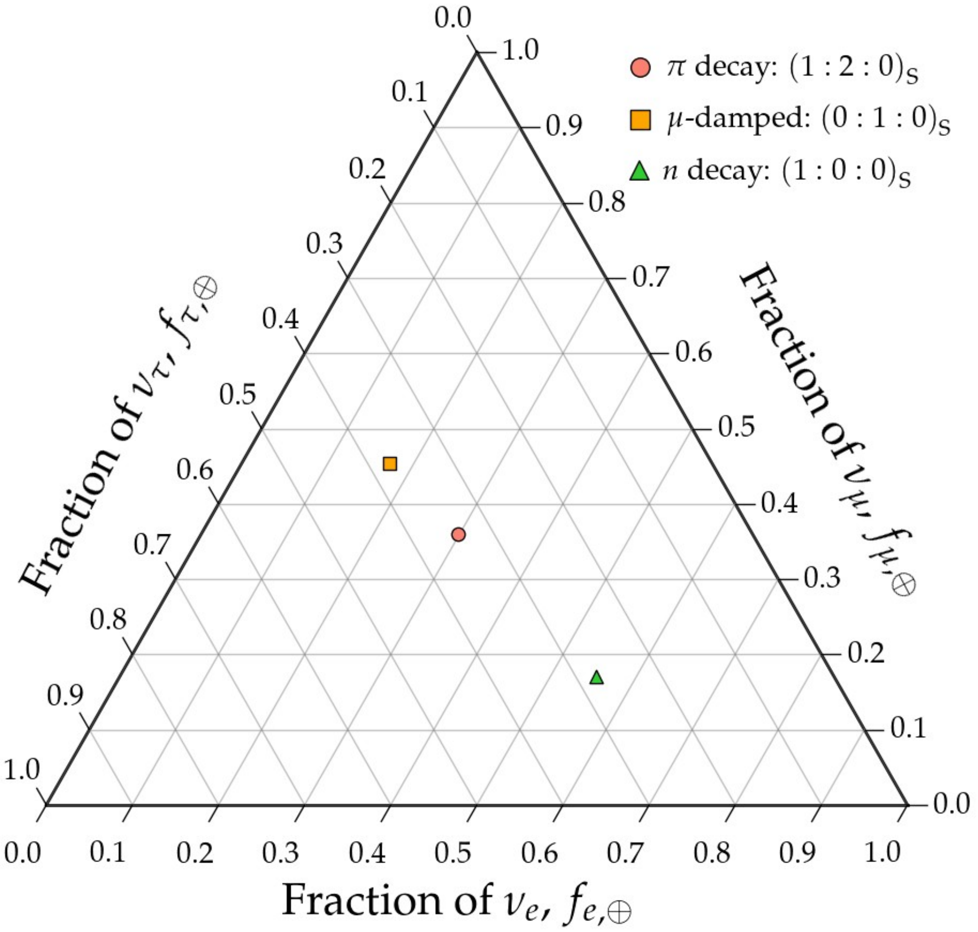
IceCube-Gen2, 2008.04323

MB & Ahlers, *PRL* 2019

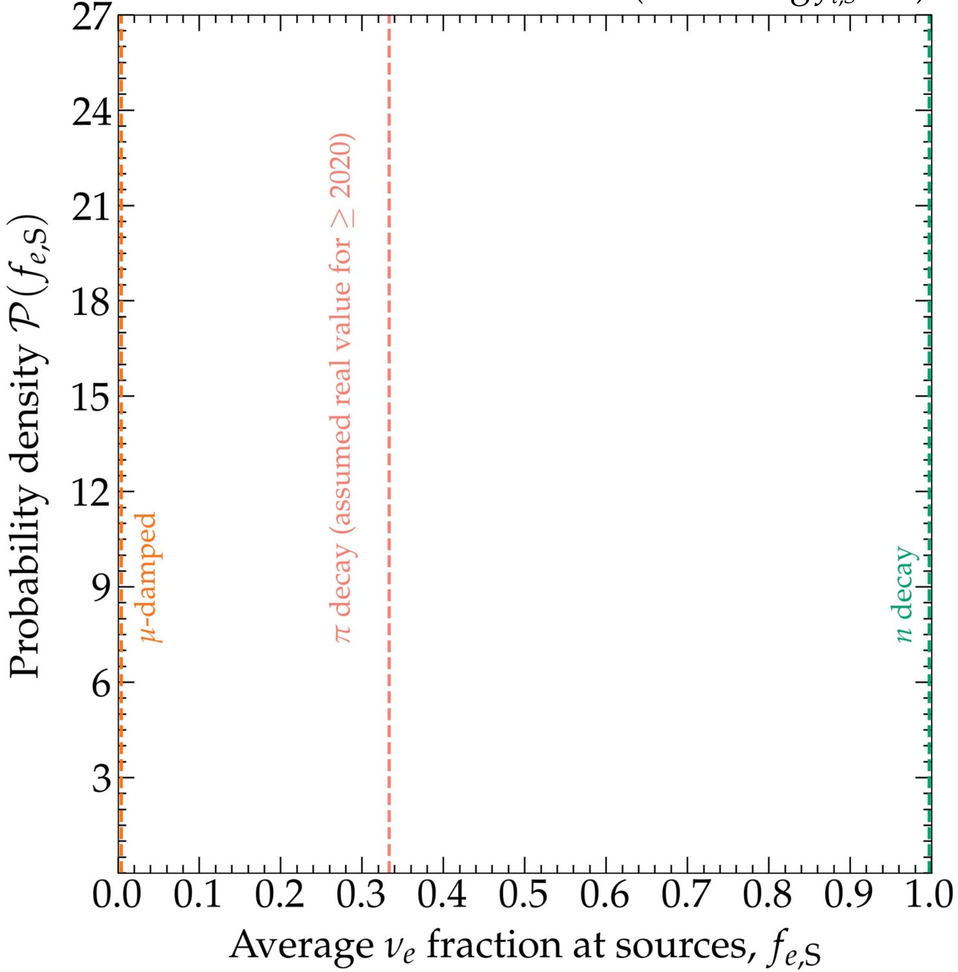
Inferring the flavor composition at the sources

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
MB & Ahlers, *PRL* 2019

Inferring the flavor composition at the sources

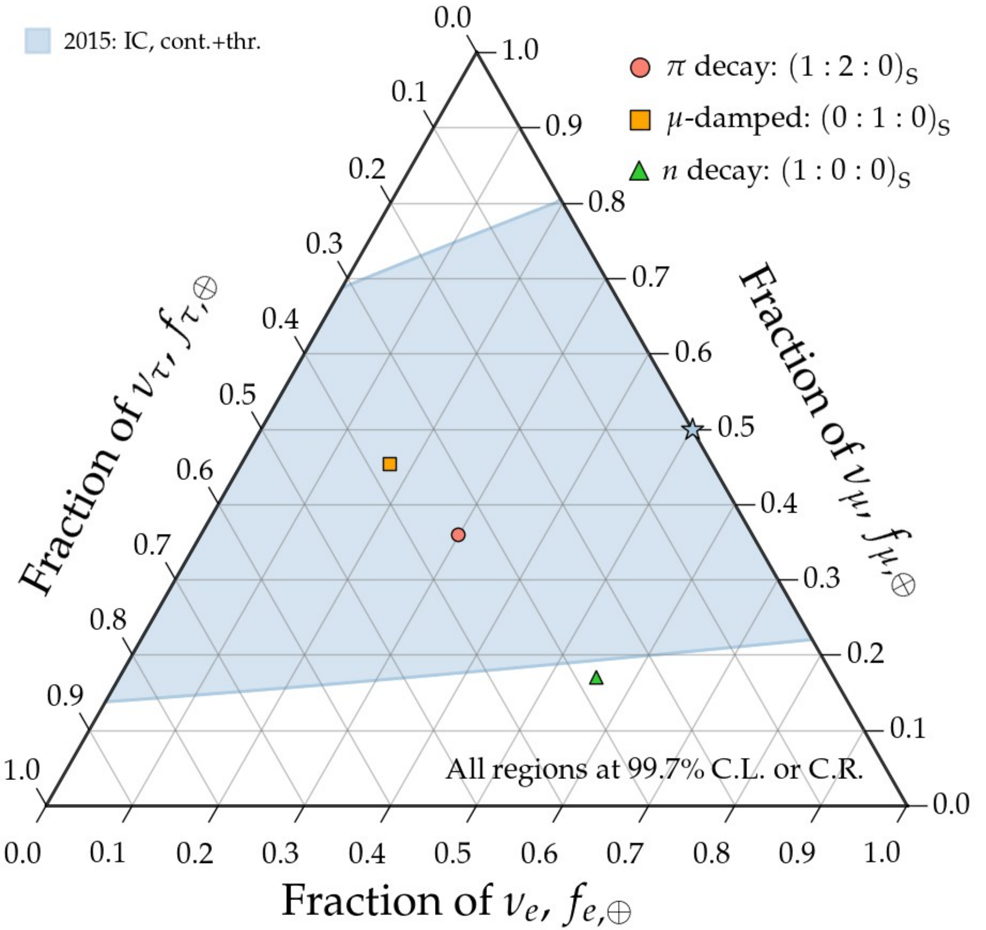


(Assuming $f_{\tau,S} = 0$)

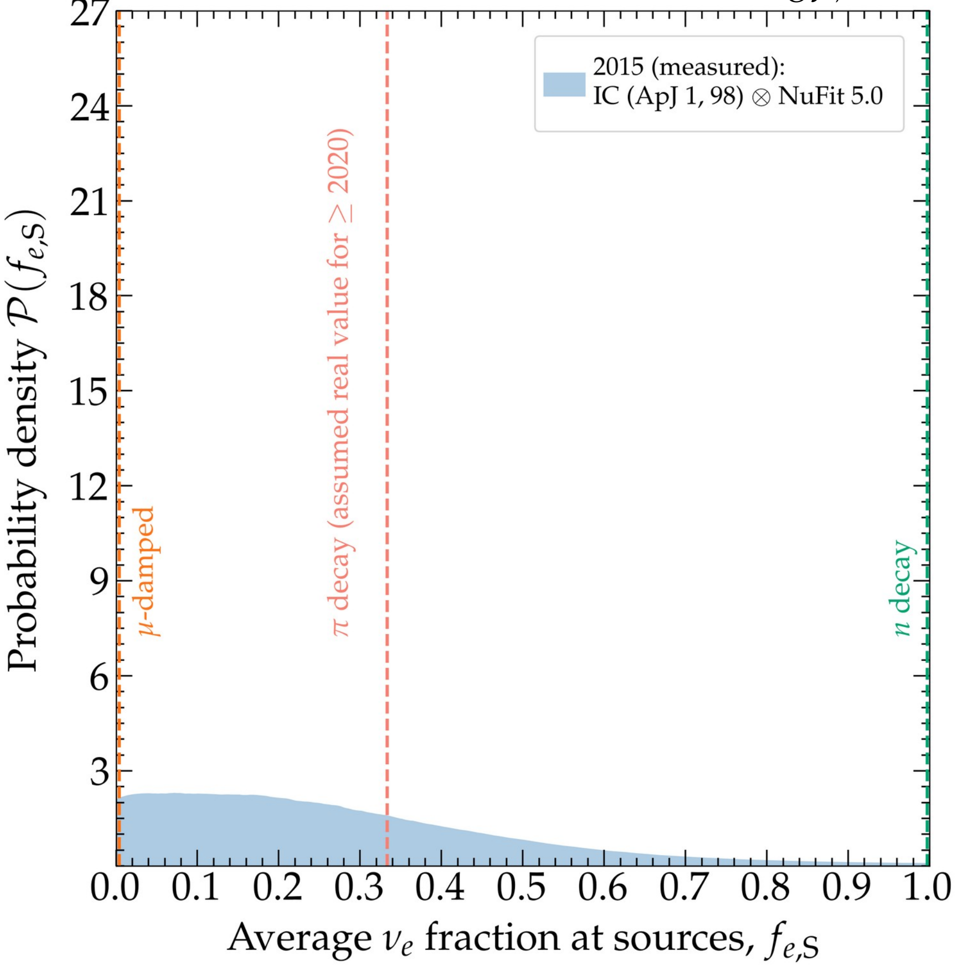


Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
MB & Ahlers, *PRL* 2019

Inferring the flavor composition at the sources

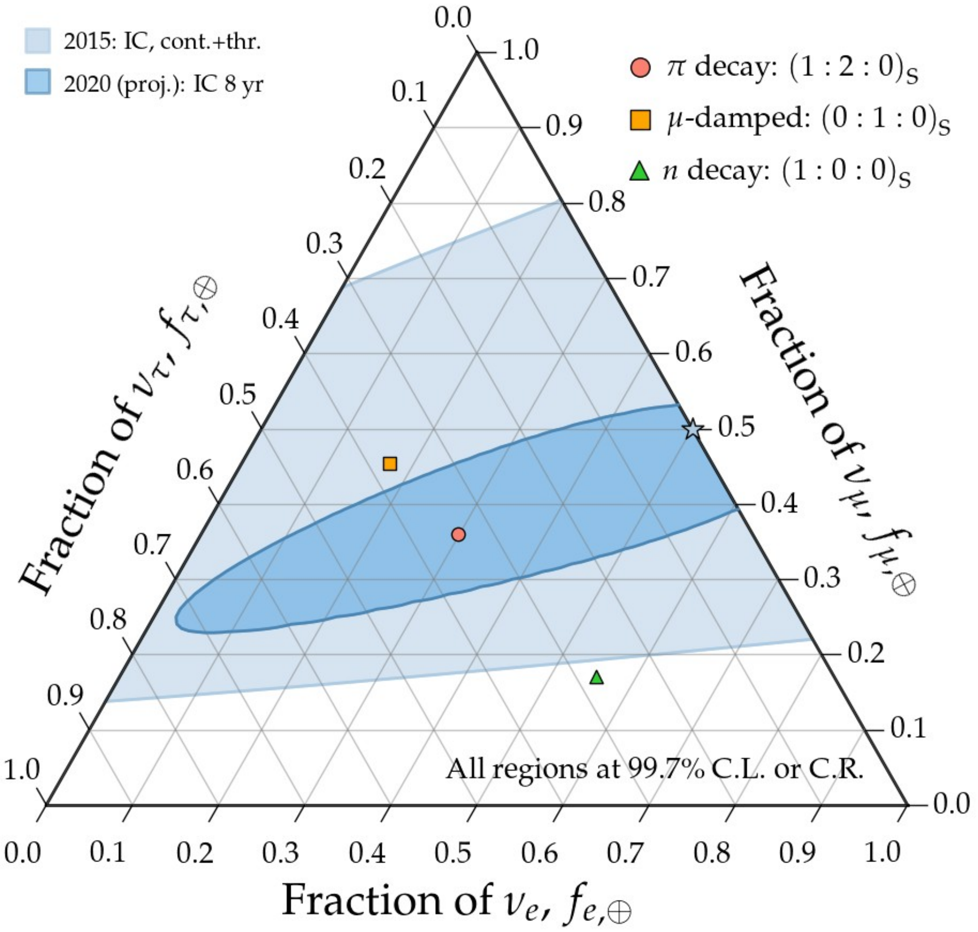


(Assuming $f_{\tau,S} = 0$)

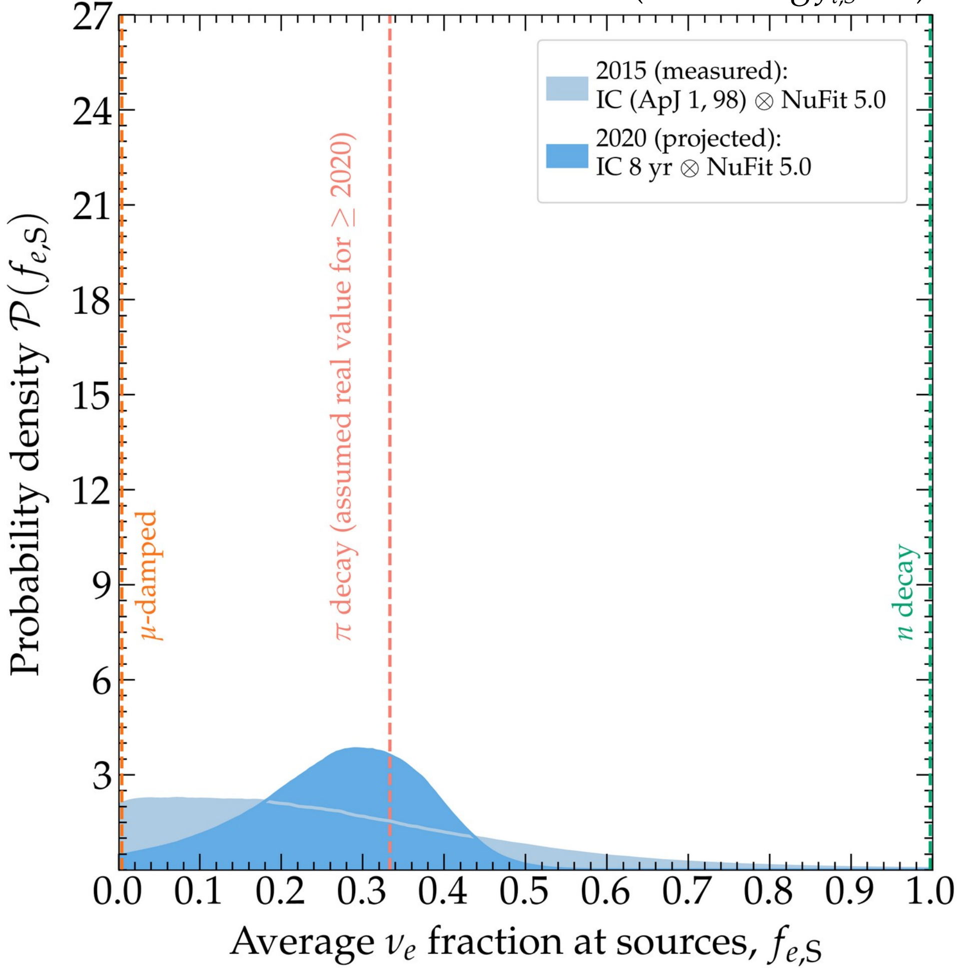


Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
MB & Ahlers, *PRL* 2019

Inferring the flavor composition at the sources

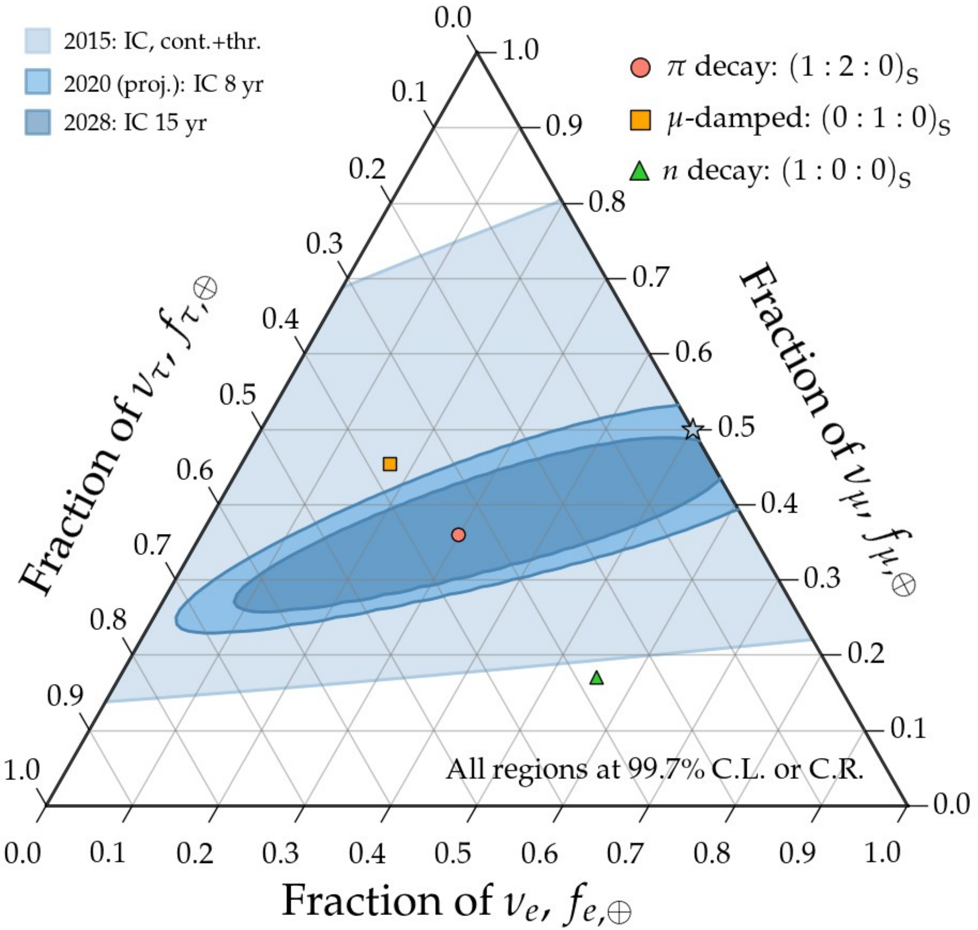


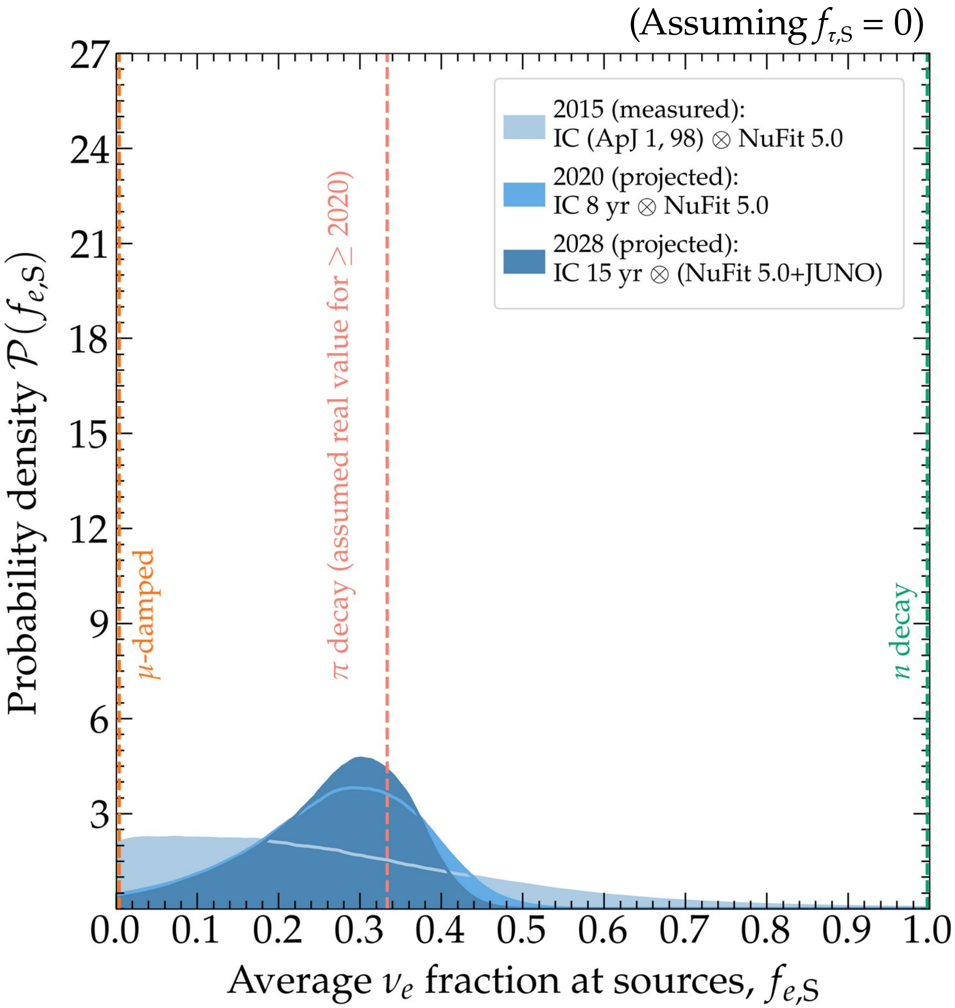
(Assuming $f_{\tau,S} = 0$)



Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
MB & Ahlers, *PRL* 2019

Inferring the flavor composition at the sources





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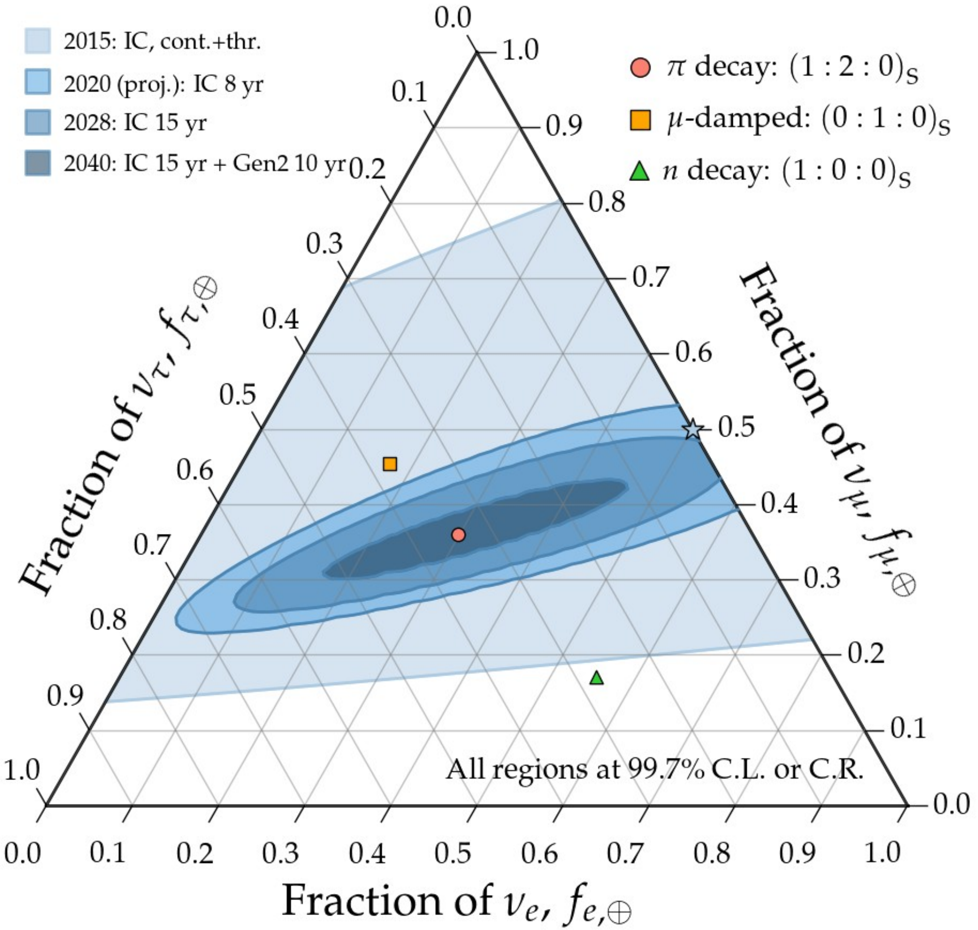
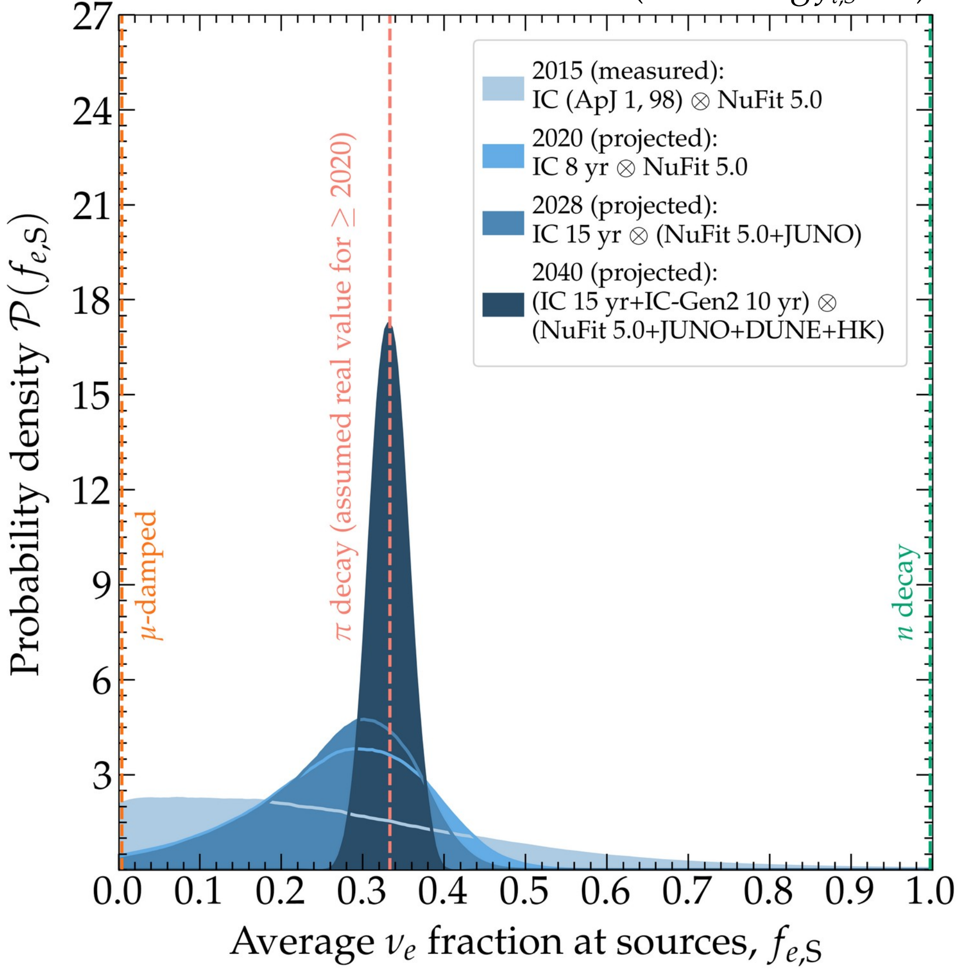
MB & Ahlers, *PRL* 2019

Inferring the flavor composition at the sources

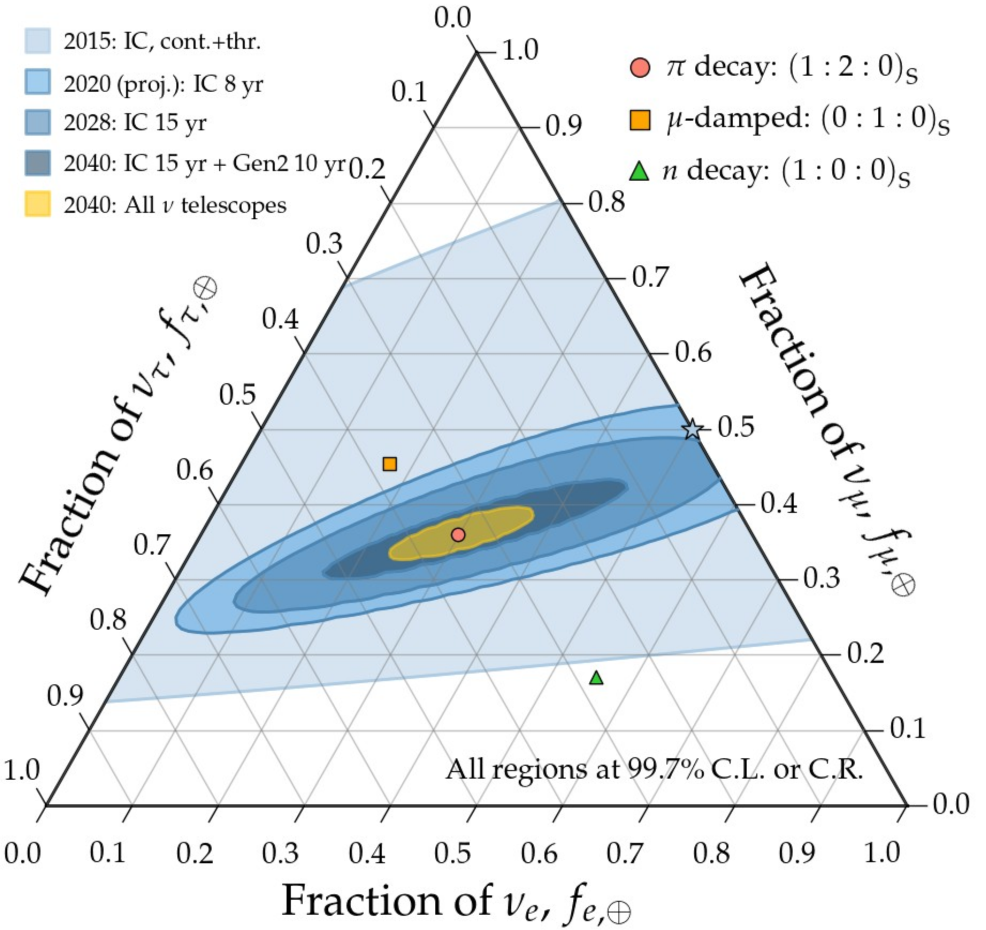


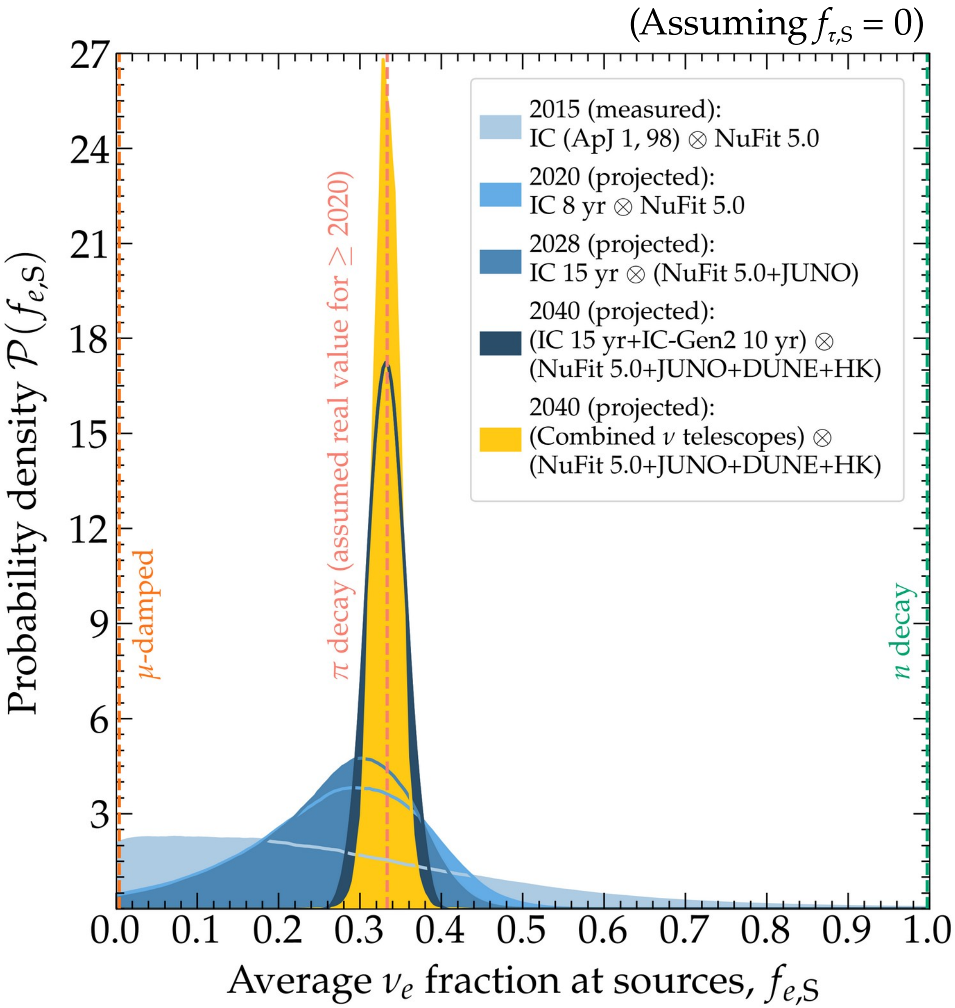
(Assuming $f_{\tau,S} = 0$)



Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
MB & Ahlers, *PRL* 2019

Inferring the flavor composition at the sources





Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
MB & Ahlers, *PRL* 2019

More than one production mechanism?

Can we detect the contribution of multiple ν production mechanisms?

$$\boldsymbol{f}_{\rm S} = \underbrace{k_\pi \boldsymbol{f}_{\rm S}^{\pi}}_{\pi \text{ decay: } (1/3,\, 2/3,\, 0)} + \underbrace{k_\mu \boldsymbol{f}_{\rm S}^{\mu}}_{\mu \text{ damped: } (0,\, 1,\, 0)} + \underbrace{k_n \boldsymbol{f}_{\rm S}^{n}}_{n \text{ decay: } (1,\, 0,\, 0)}$$

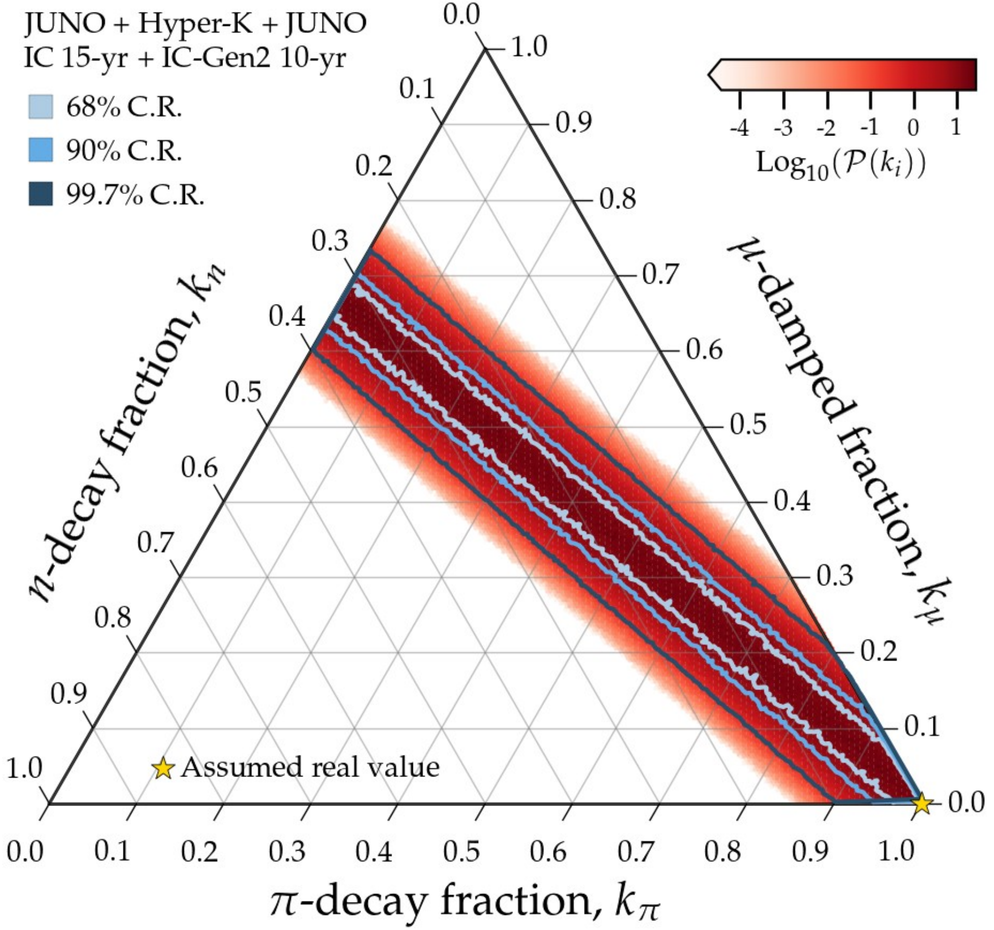
Propagate to Earth ↓

$$\boldsymbol{f}_\oplus$$

Assume real value $k_\pi = 1$ ($k_\mu = k_n = 0$)

By 2040, how well will we recover the real value?

[Adding spectrum information (not shown) will likely help]



More than one production mechanism?

Can we detect the contribution of multiple ν production mechanisms?

$$\boldsymbol{f}_{\rm S} = \underbrace{k_\pi \boldsymbol{f}_{\rm S}^{\pi}}_{} + \underbrace{k_\mu \boldsymbol{f}_{\rm S}^{\mu}}_{} + \underbrace{k_n \boldsymbol{f}_{\rm S}^{n}}_{}$$

π decay: (1/3, 2/3, 0) μ damped: (0, 1, 0) *n* decay: (1, 0, 0)

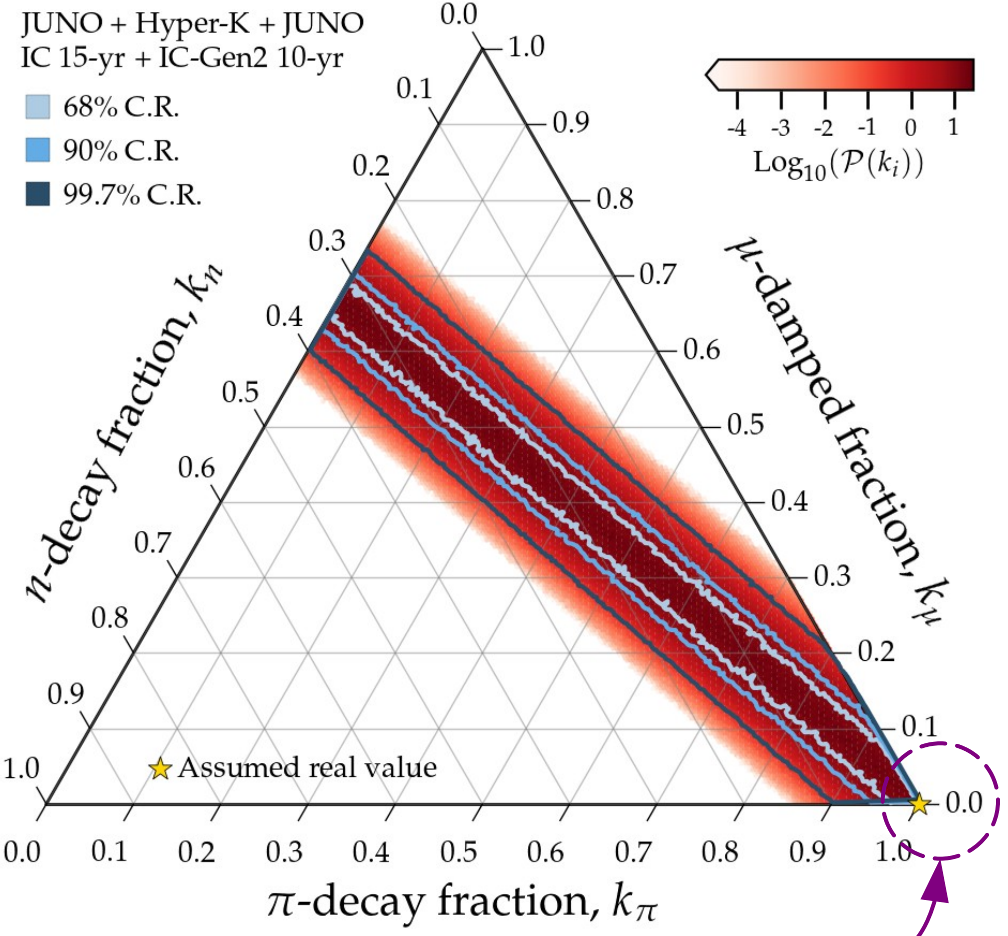
Propagate to Earth

$\boldsymbol{f}_\oplus$

Assume real value $k_\pi = 1$ ($k_\mu = k_n = 0$)

By 2040, how well will we recover the real value?

[Adding spectrum information (not shown) will likely help]



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Song, Li, Argüelles, **MB**, Vincent, 2012.12893

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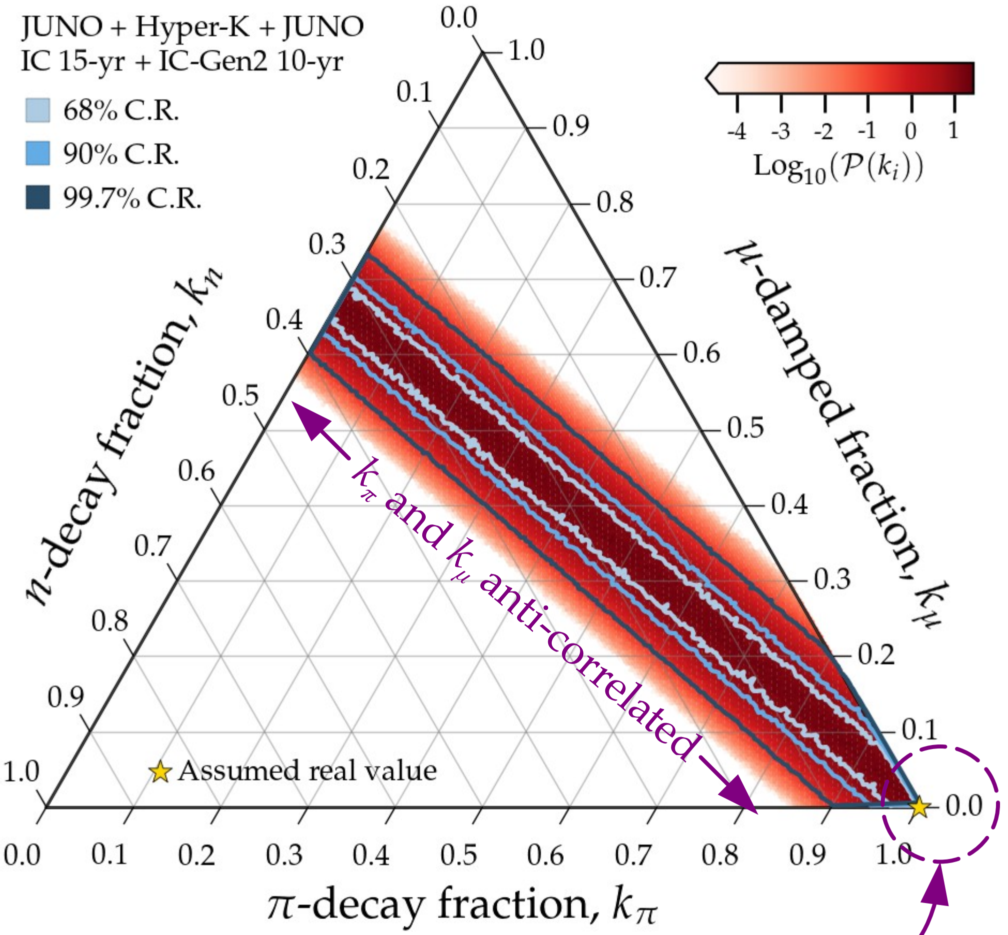

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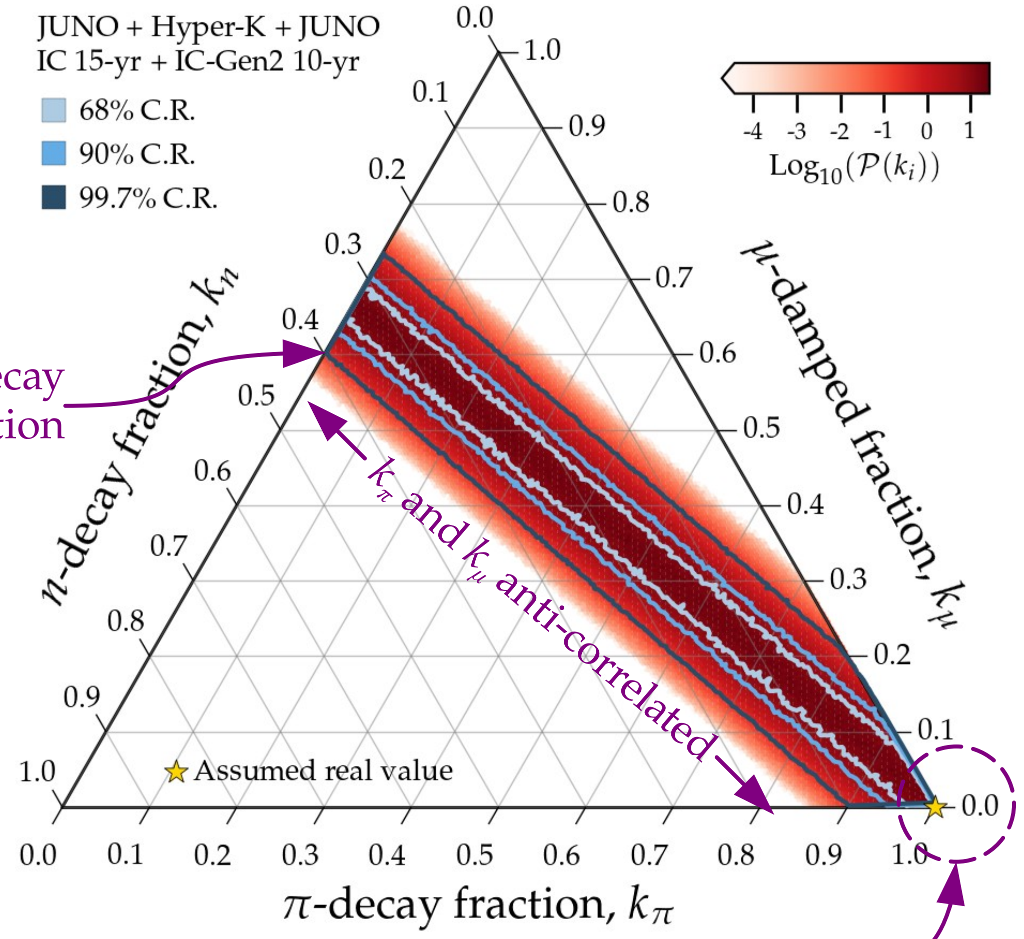

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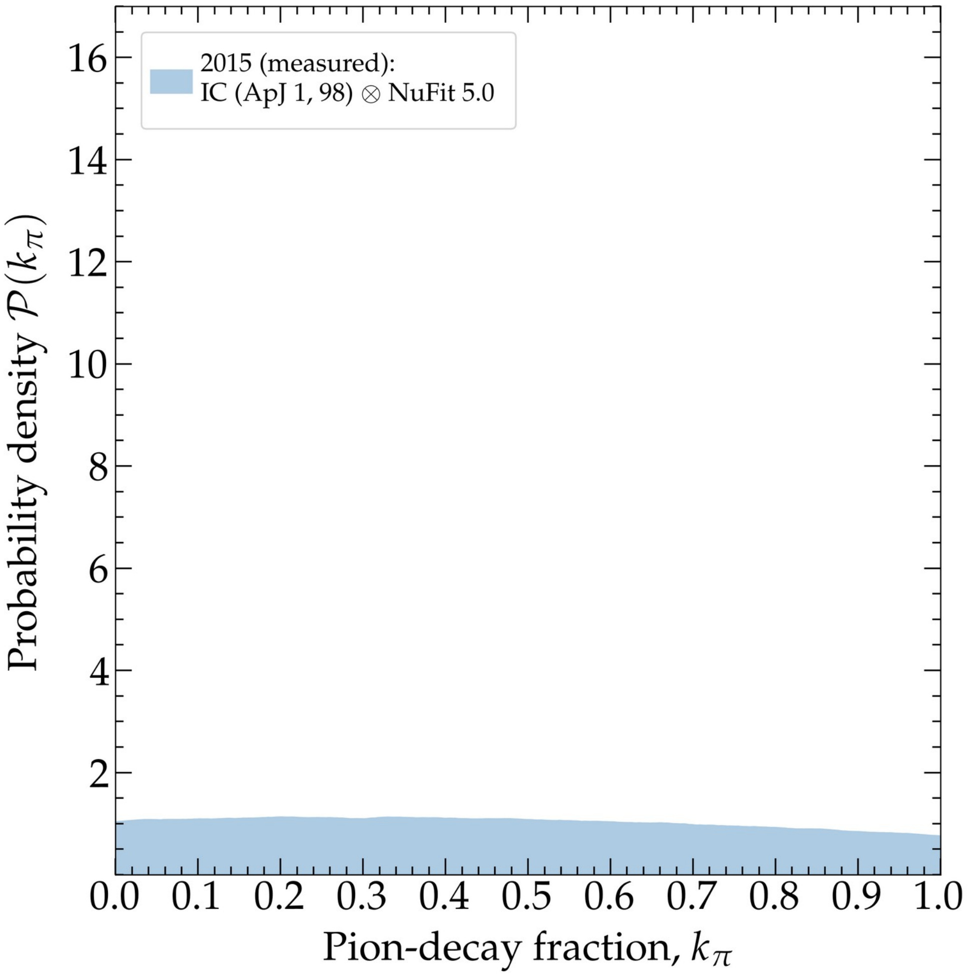

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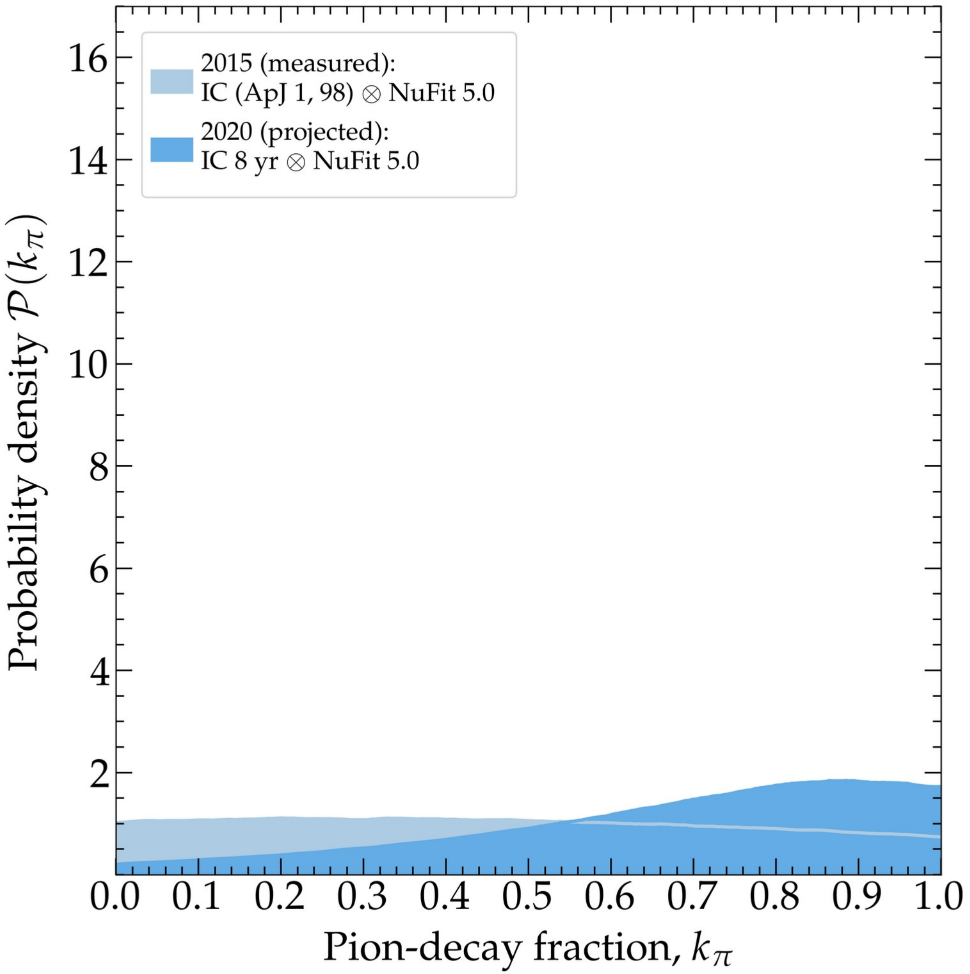

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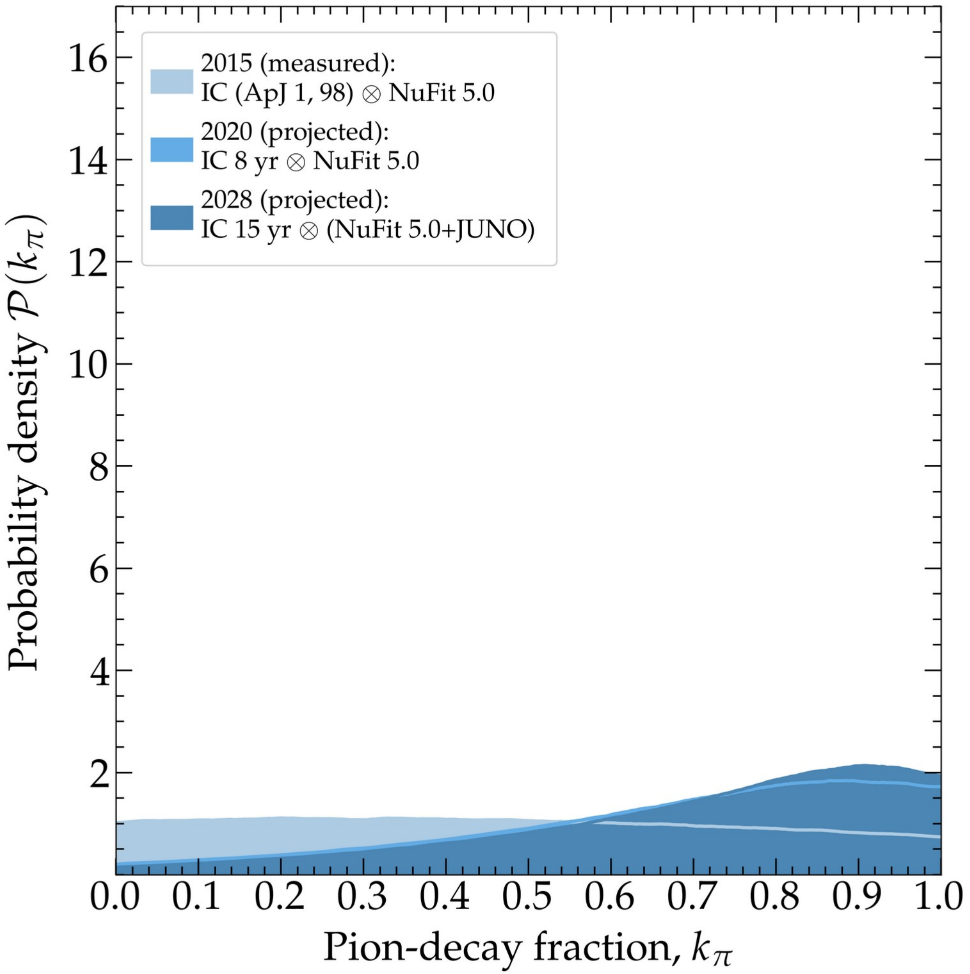

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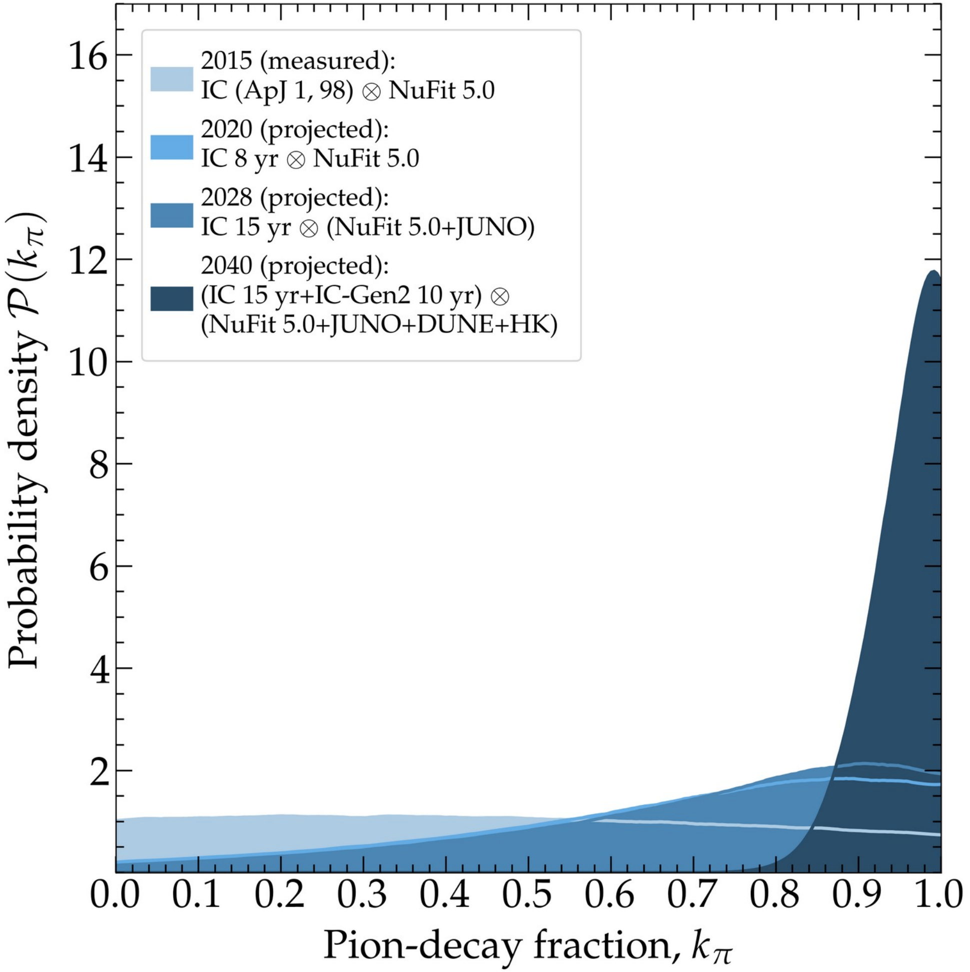

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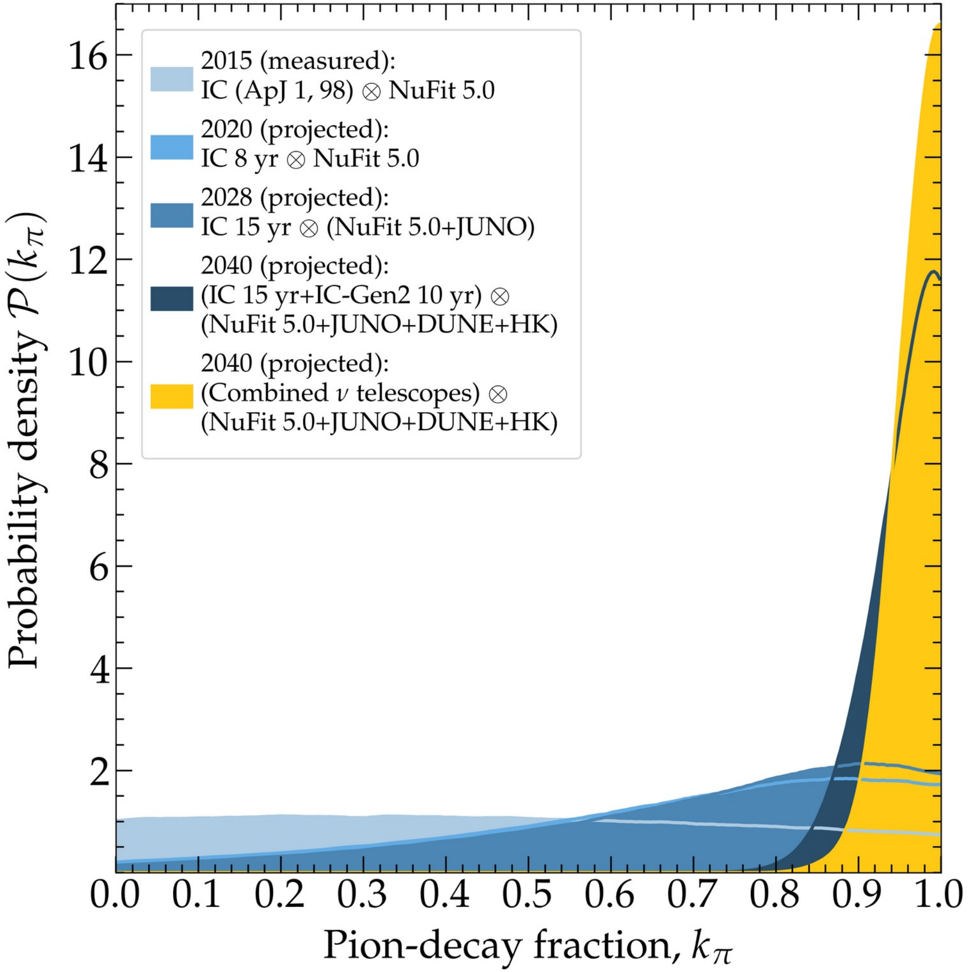

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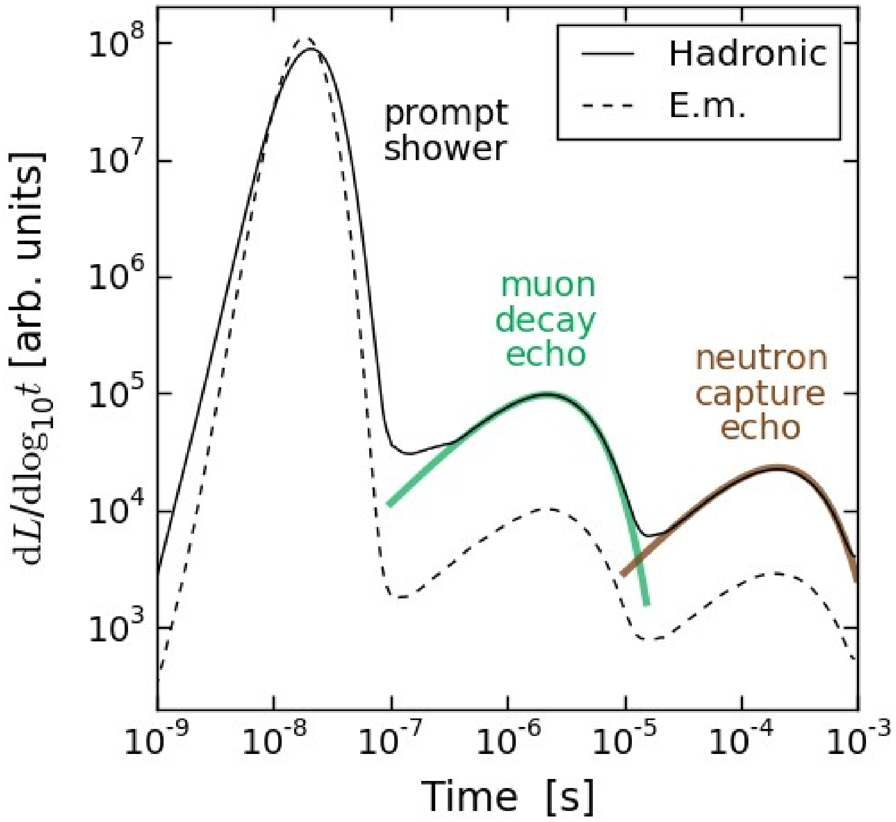
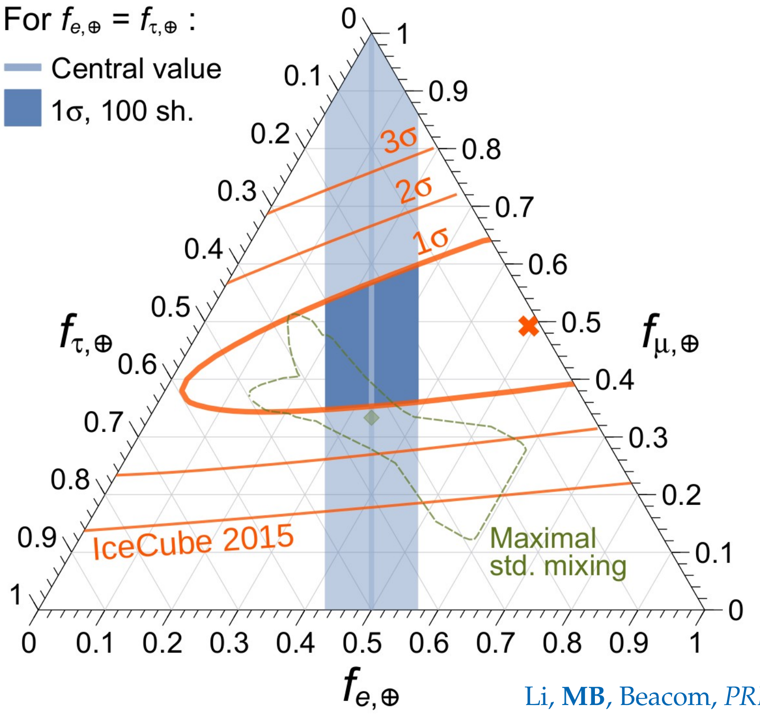
Side note: Improving flavor-tagging using *echoes*

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





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

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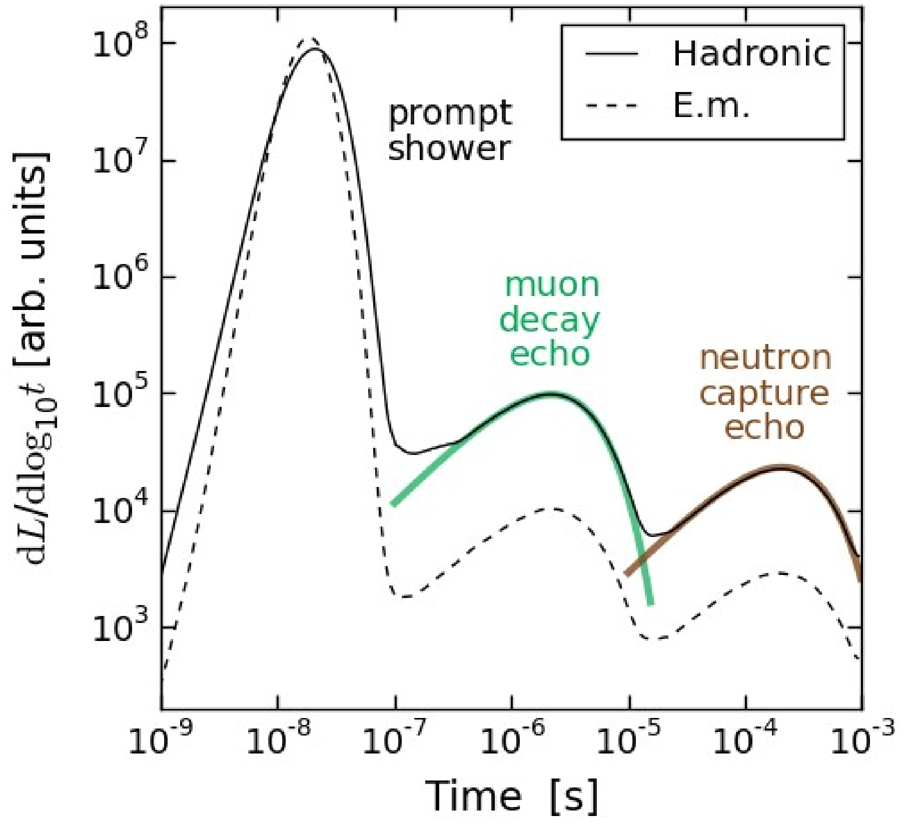
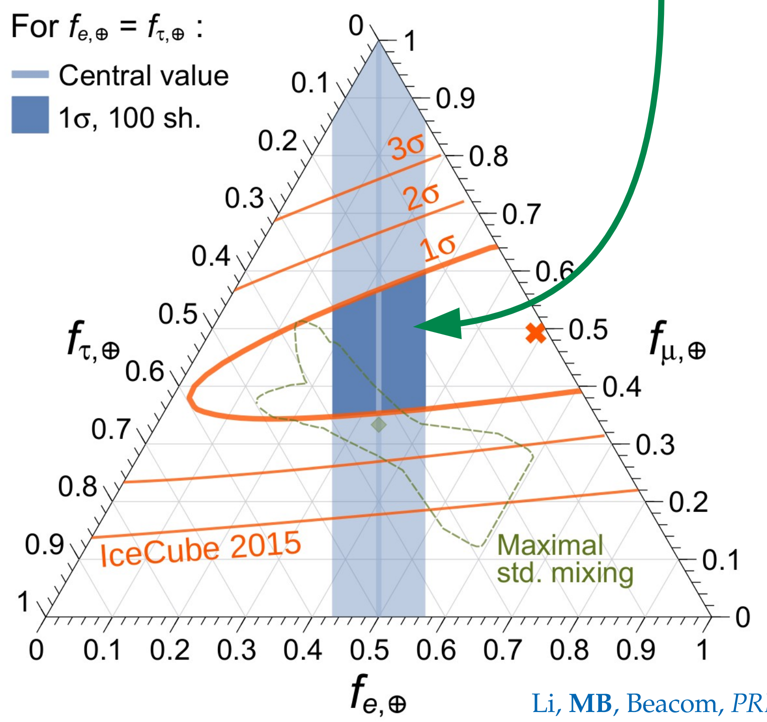


~10 × improvement over current measurement



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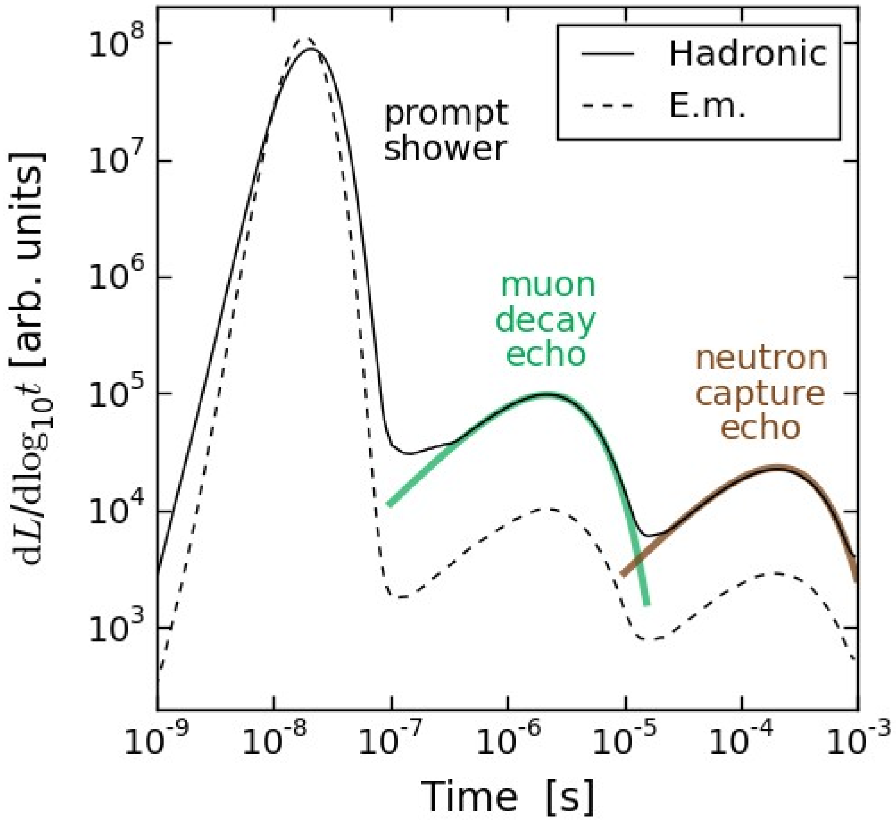

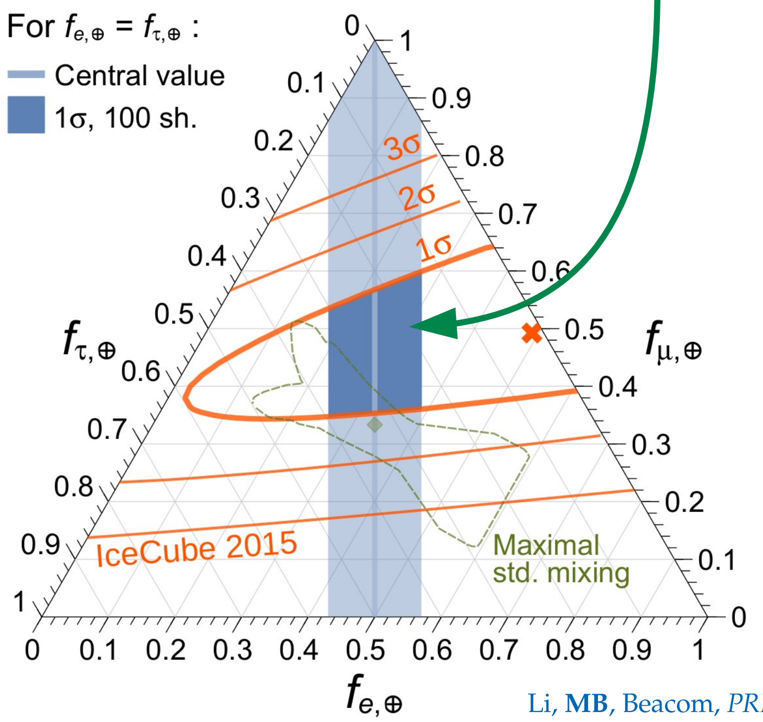

Li, **MB**, Beacom, *PRL* 2019

Detectors

TeV–PeV ν telescopes, ~2030

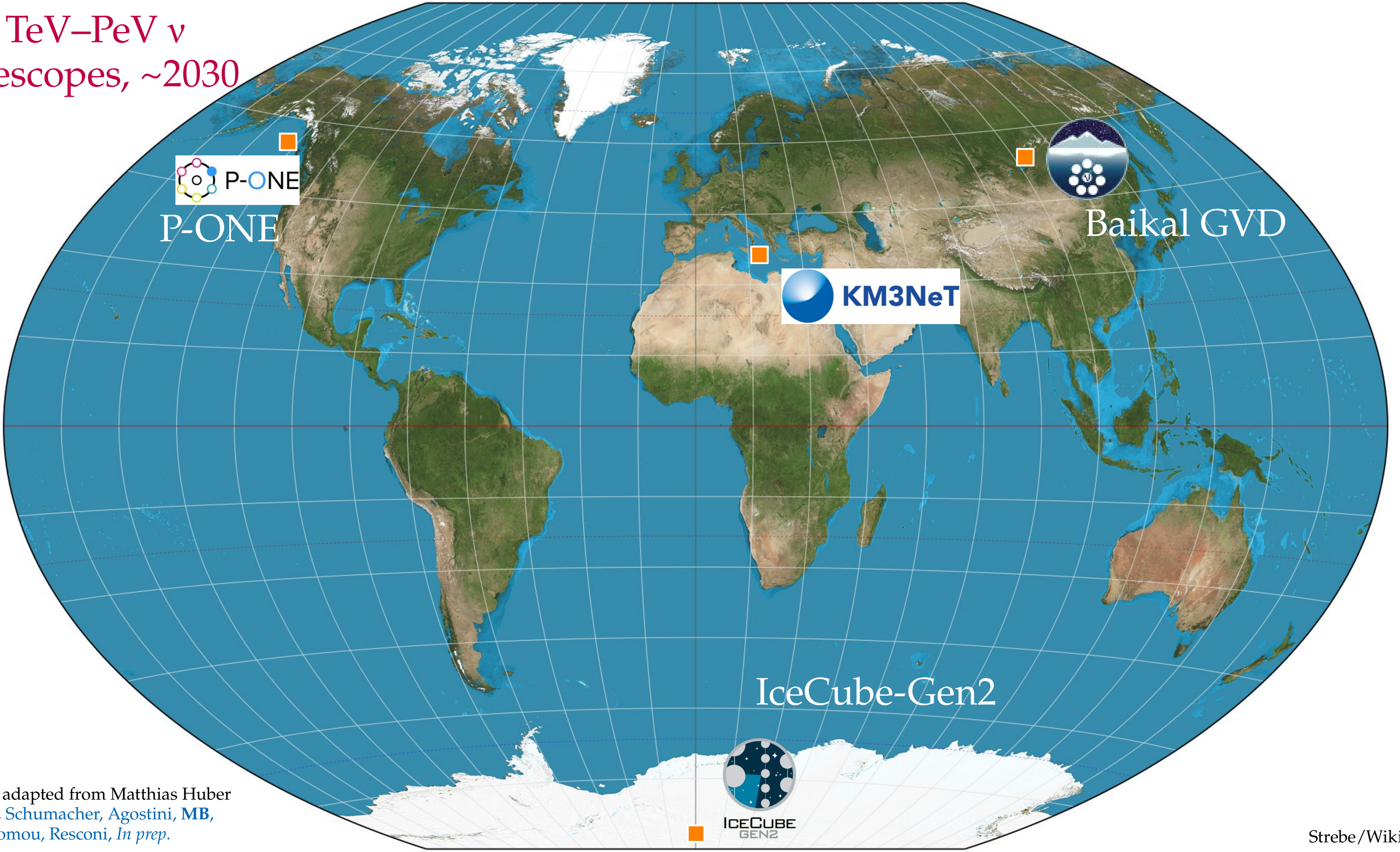

Figure adapted from Matthias Huber
Huber, Schumacher, Agostini, **MB**,
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Strebe/Wikipedia

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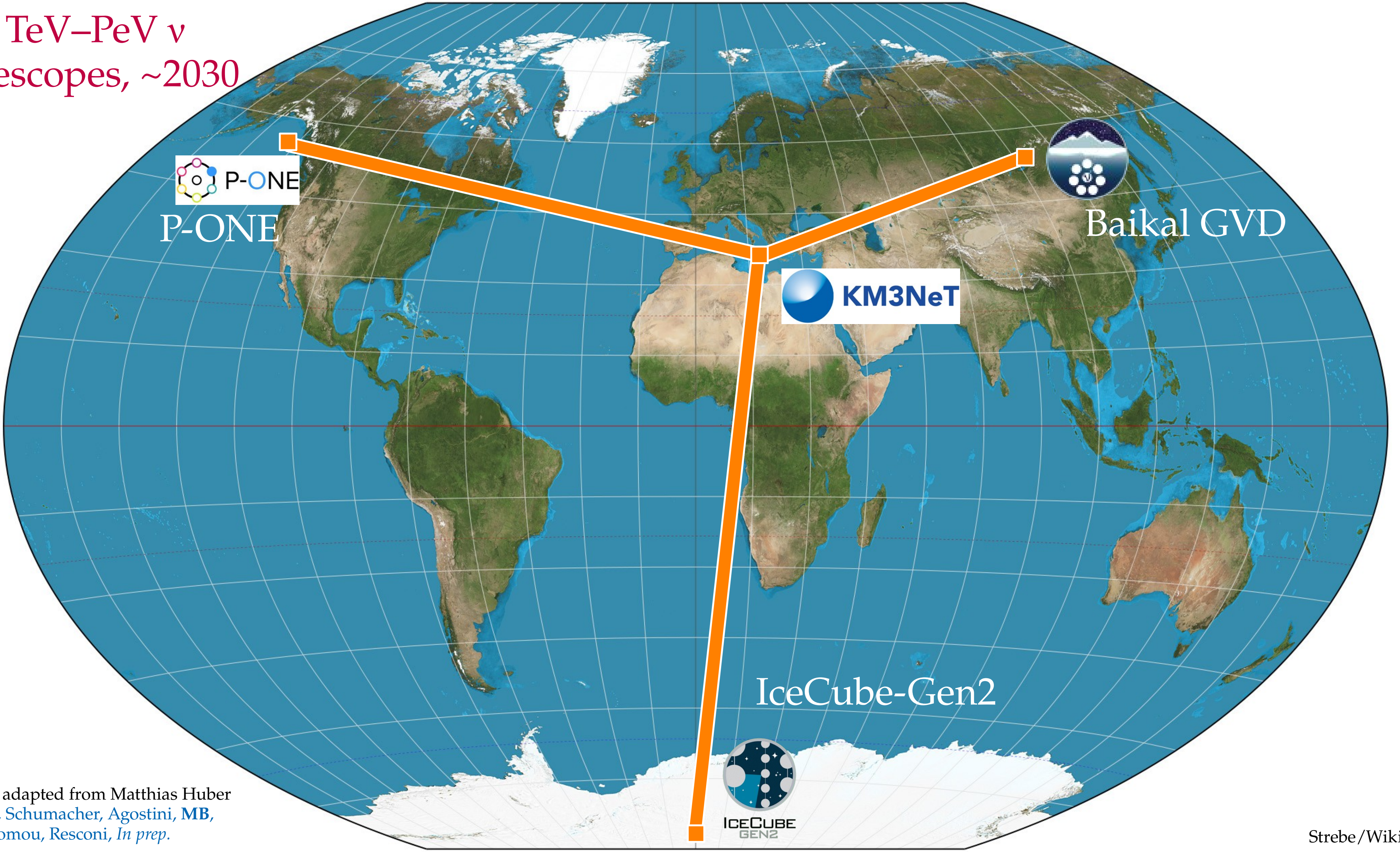

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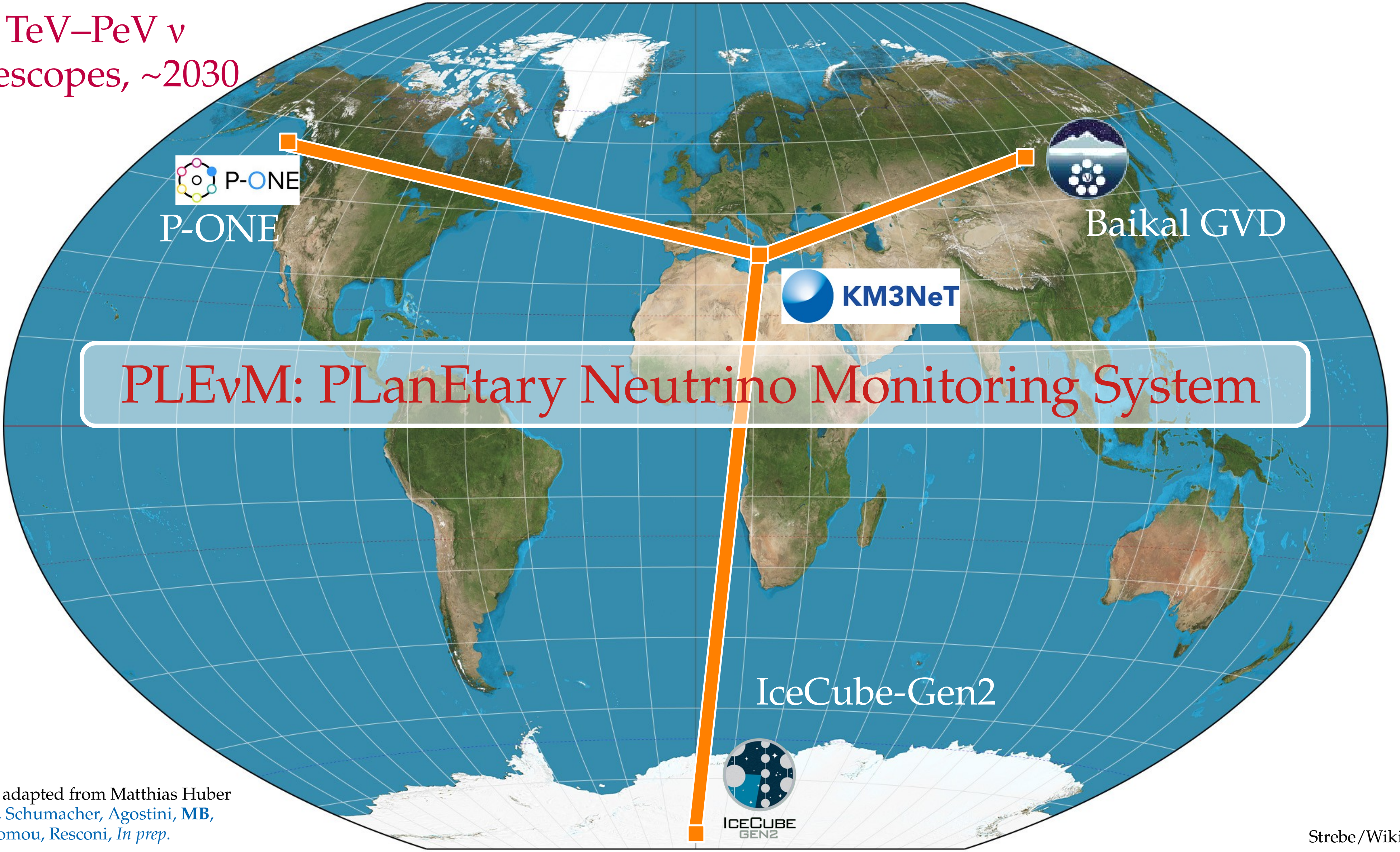

Figure adapted from Matthias Huber
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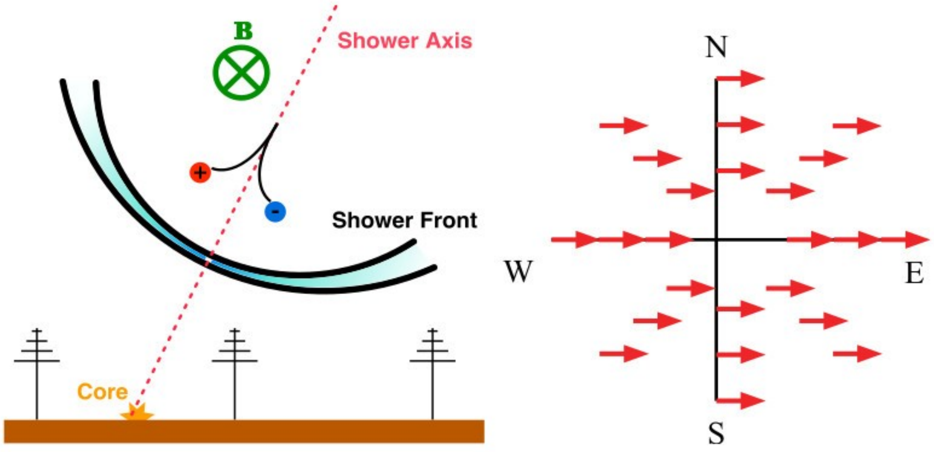
Strebe/Wikipedia

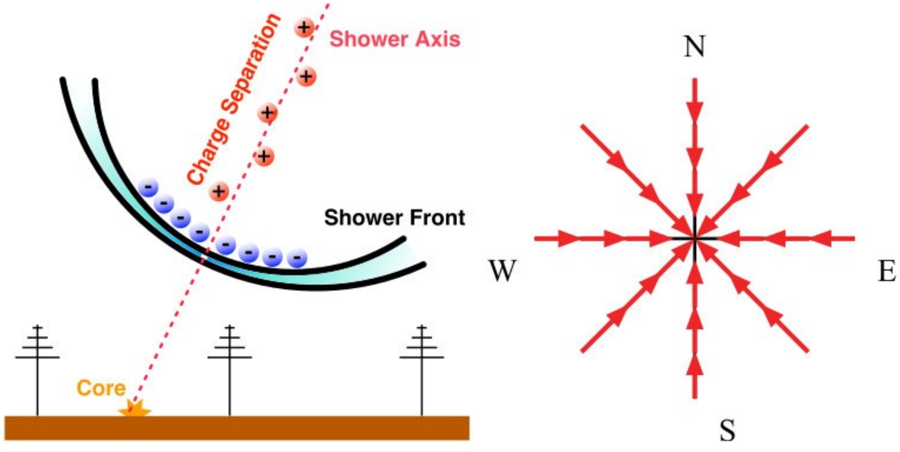
Radio emission: geomagnetic and Askaryan

Geomagnetic



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

Askaryan



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

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

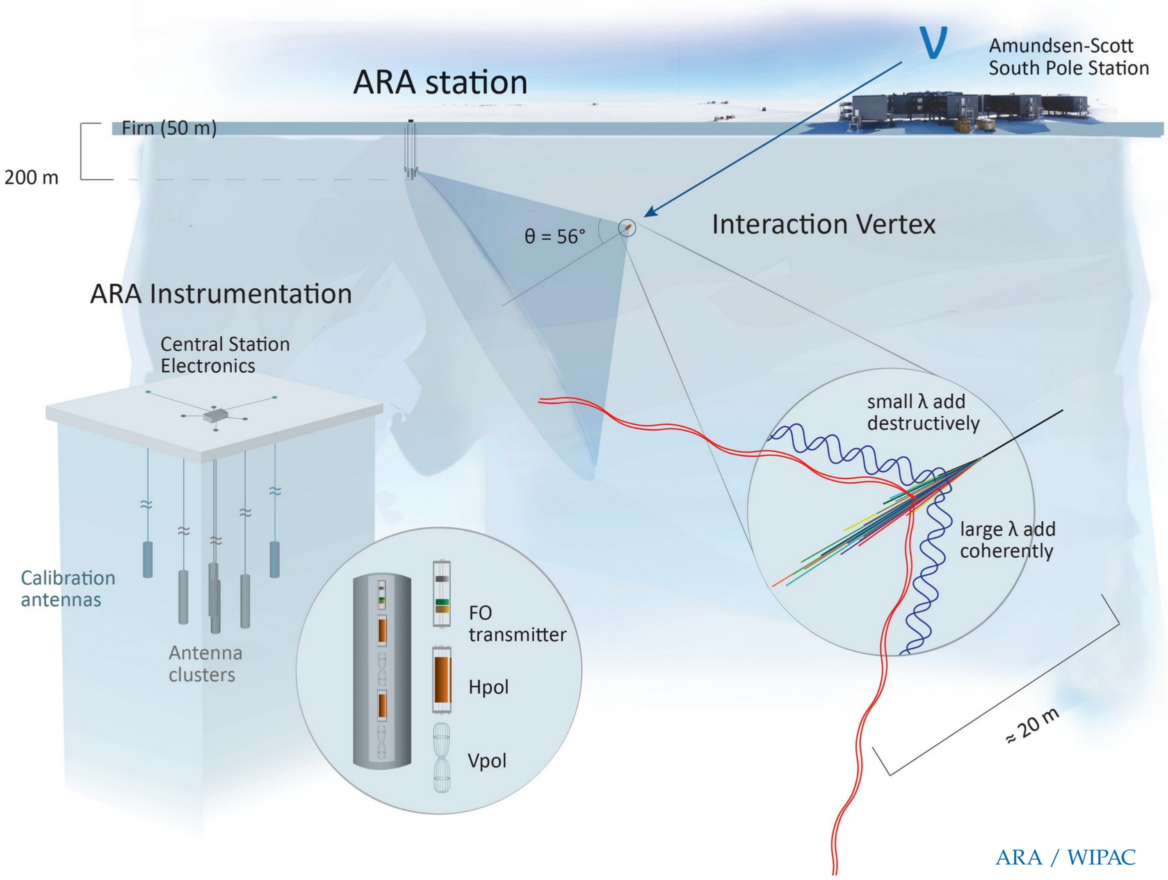
Radio emission: geomagnetic and Askaryan

Radio-detection of UHE neutrinos in ice

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

No ν detected yet

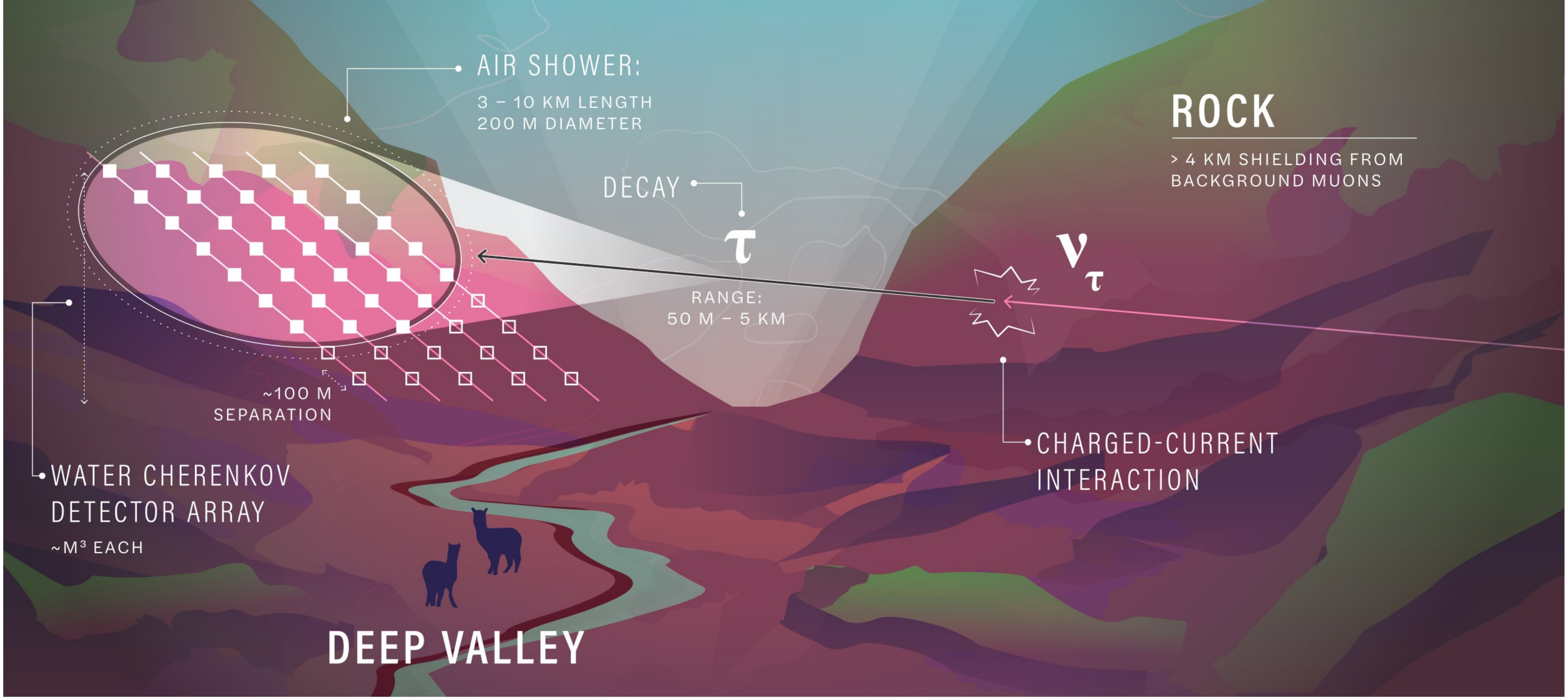
(But UHECRs detected regularly!)



ARA / WIPAC

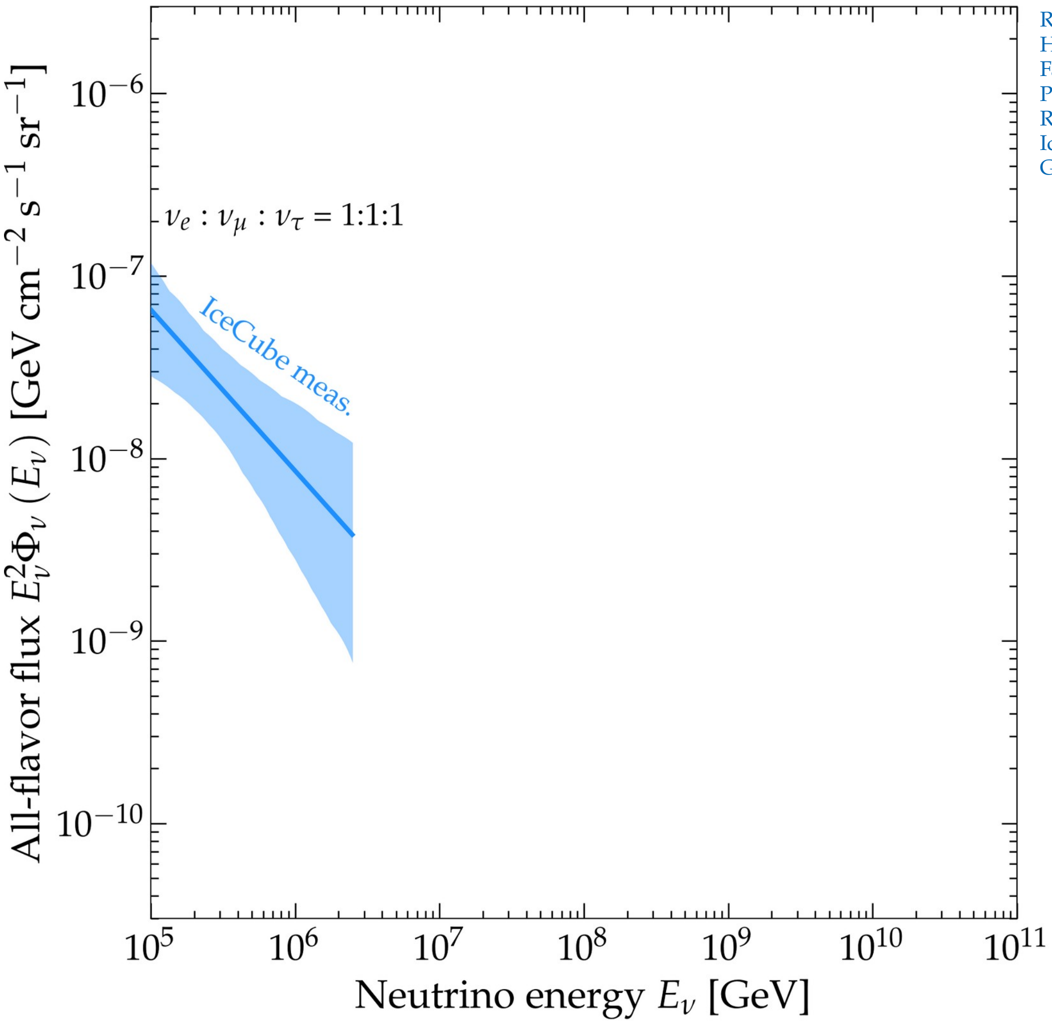
TAMBO

arXiv:2002.06475



TAU AIR-SHOWER MOUNTAIN-BASED OBSERVATORY (TAMBO) · COLCA VALLEY, PERU

UHE neutrinos: *steady-state sources*



Rodrigues, Heinze, Palladino, van Vliet, Winter, 2003.08392
Heinze, Fedynitch, Boncioli, Winter *ApJ* 2019
Fang & Murase, *Nature Phys.* 2018
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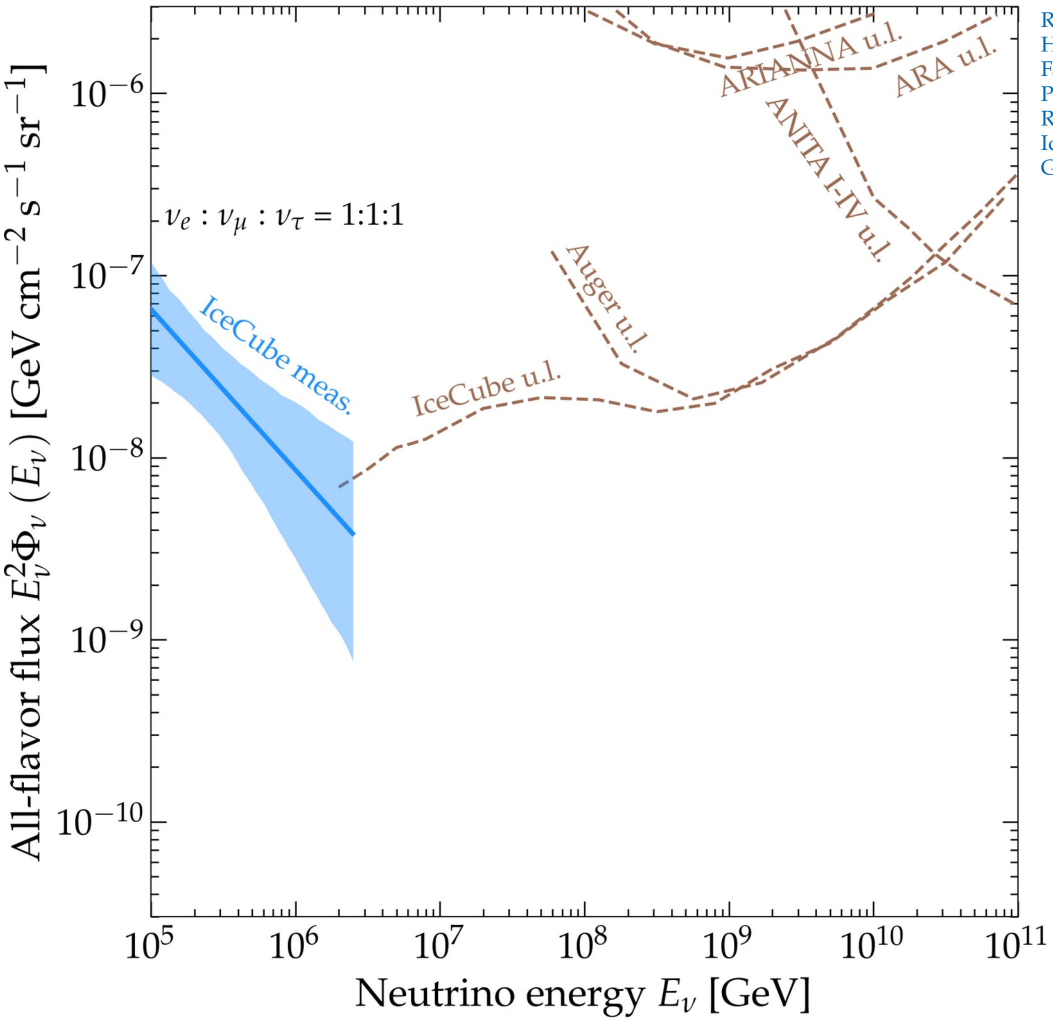

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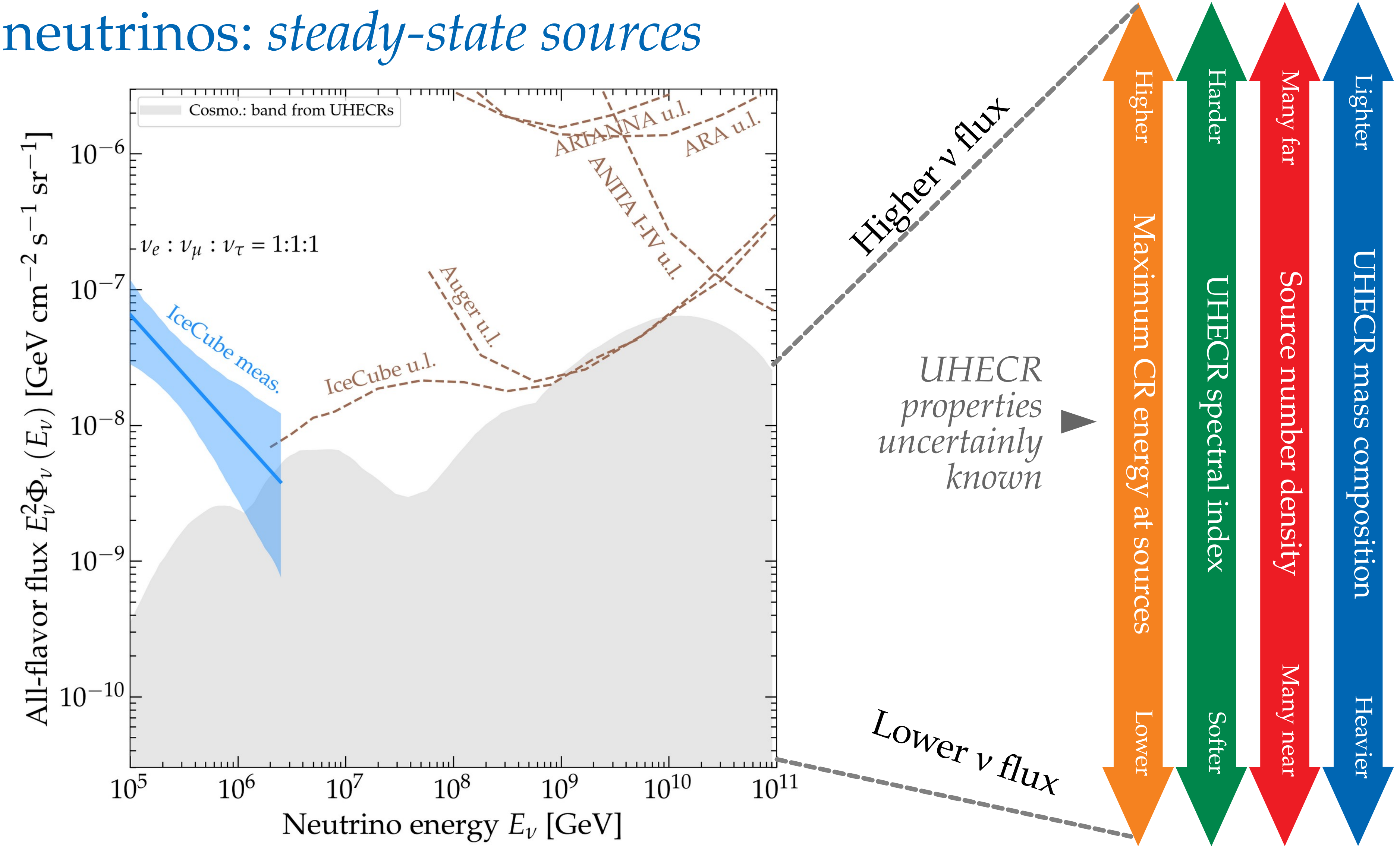

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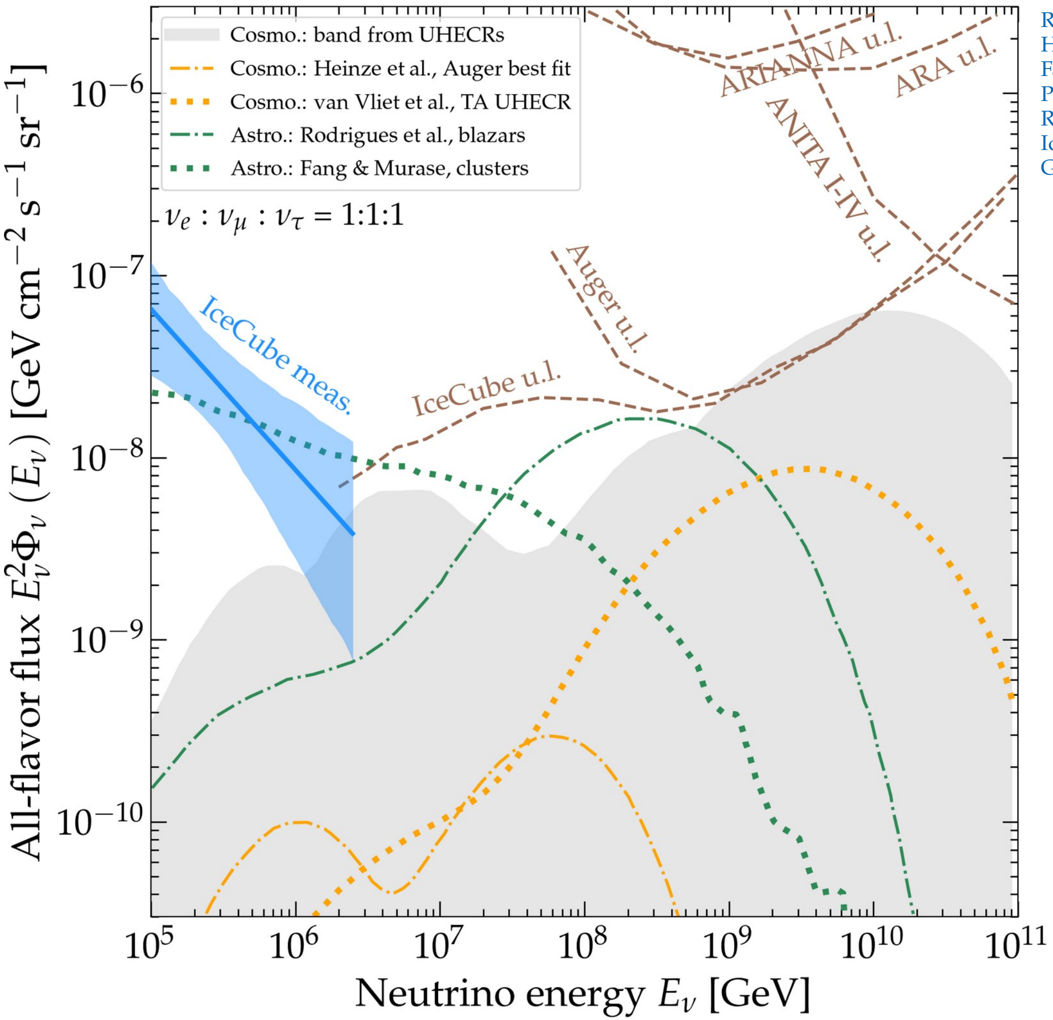

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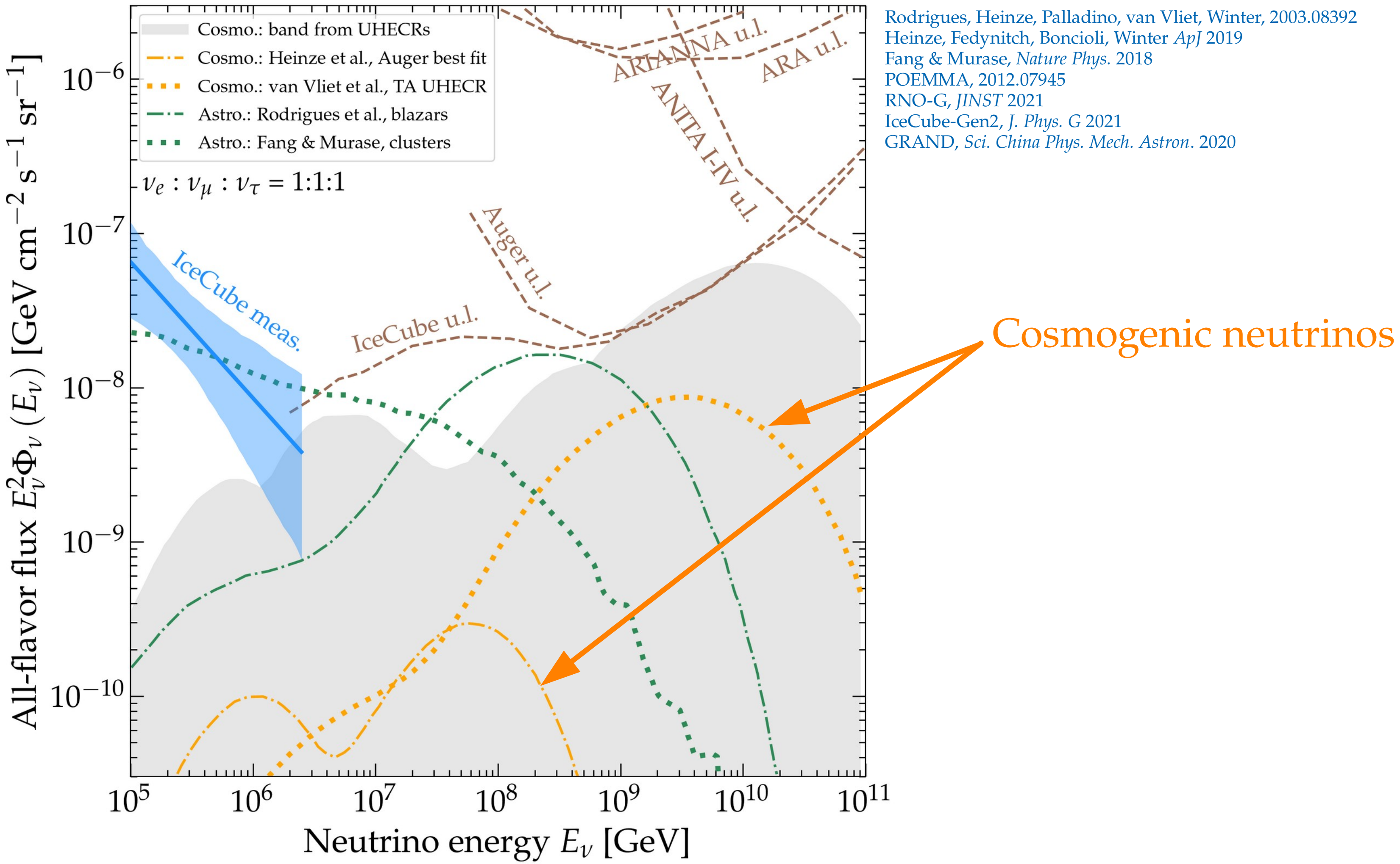

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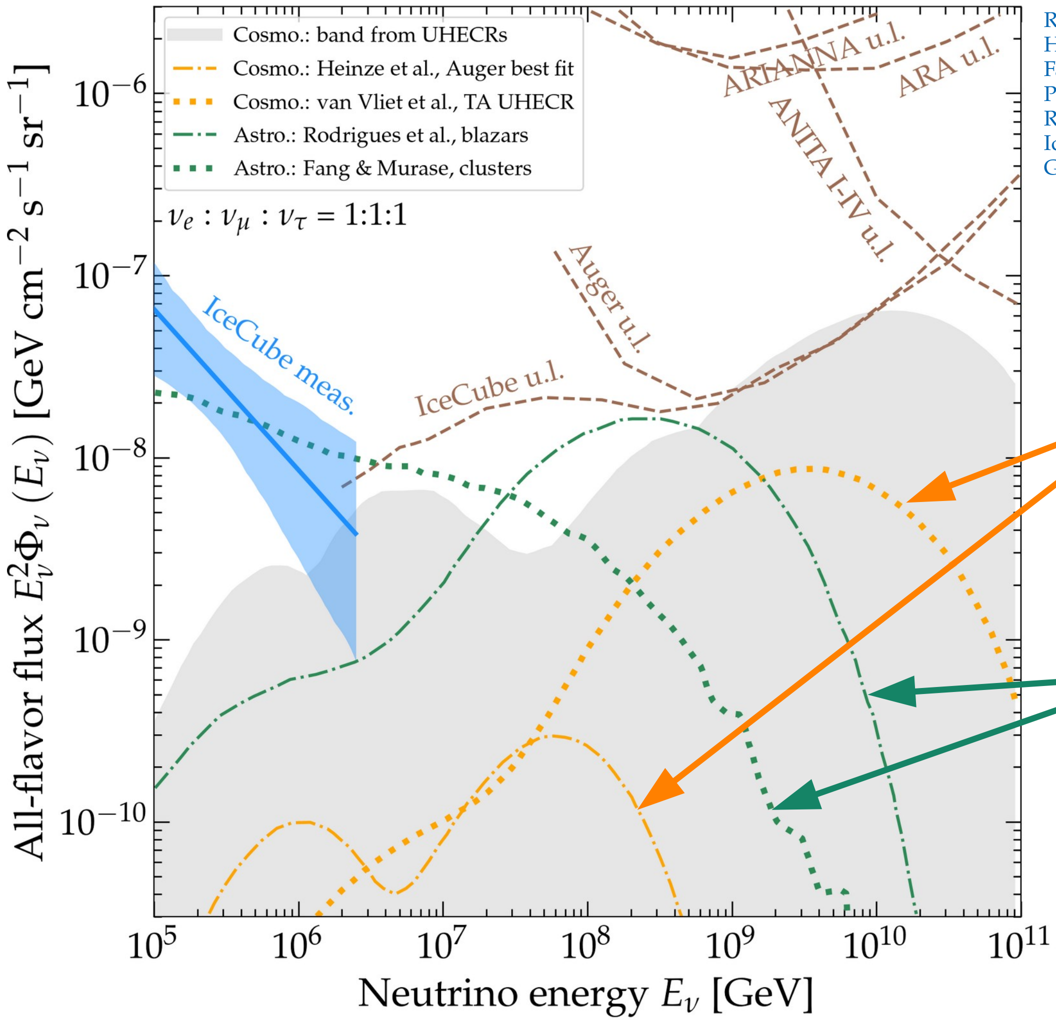

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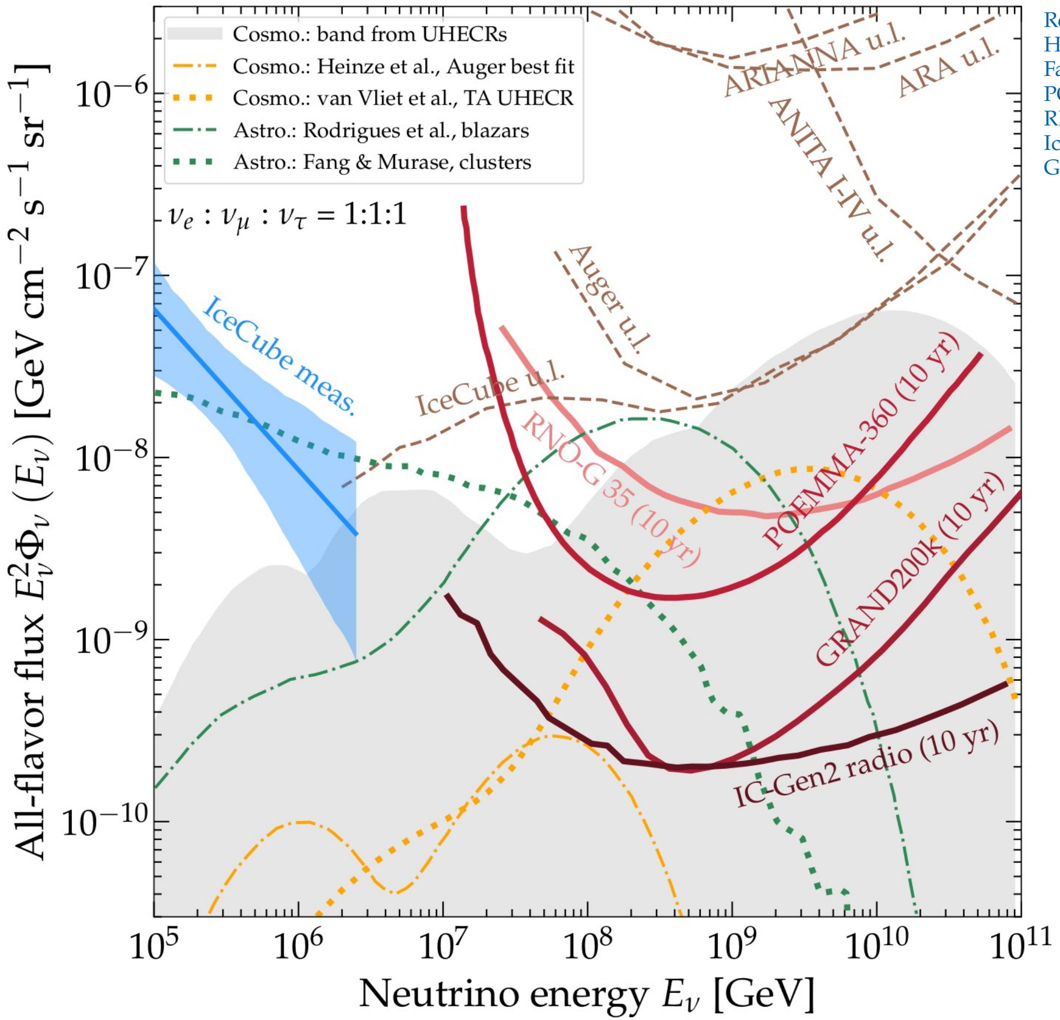
Cosmogenic neutrinos

Neutrinos from the sources
(possibly dominant flux!)

UHE neutrinos: *steady-state sources*



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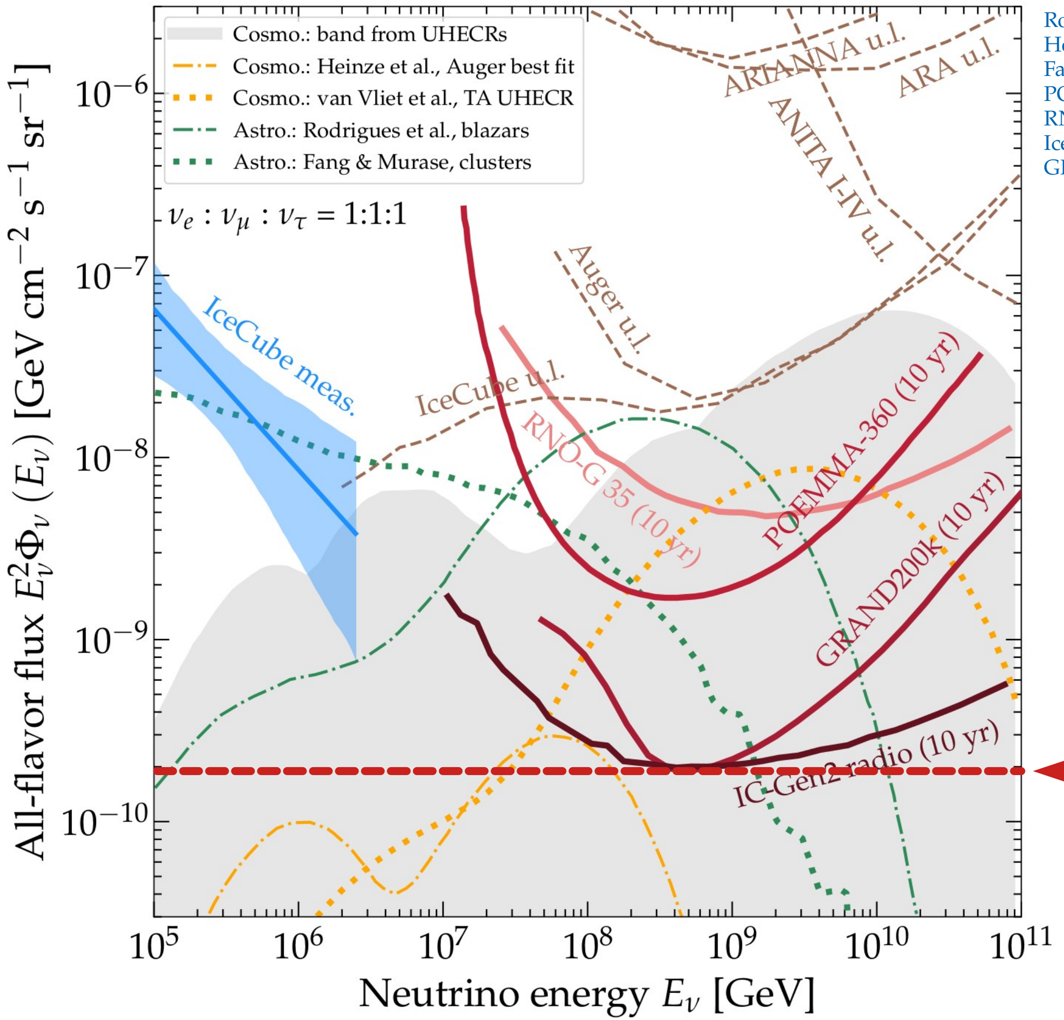

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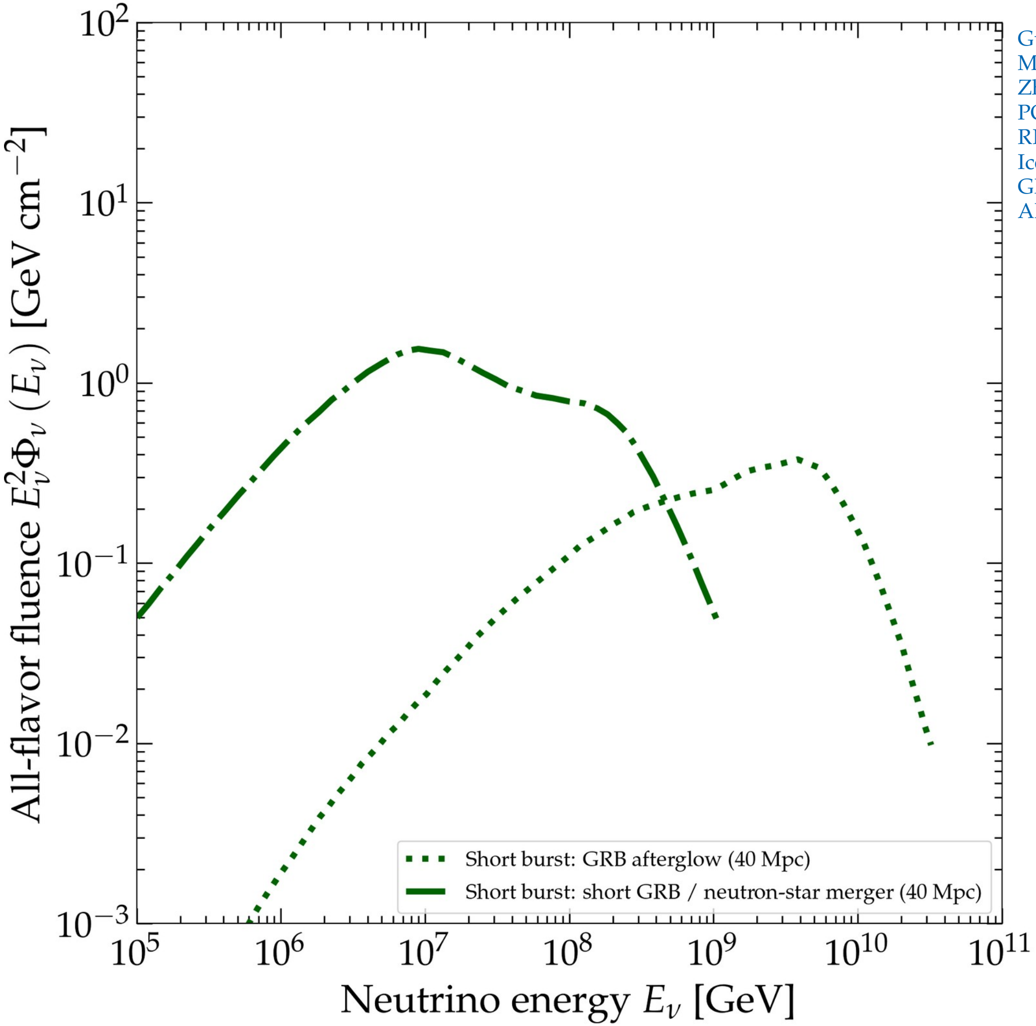
RNO-G, *JINST* 2021
IceCube-Gen2, *J. Phys. G* 2021
GRAND, *Sci. China Phys. Mech. Astron*. 2020

Ultimate target sensitivity for next-gen detectors

(if protons are ~10% of the highest-energy UHECRs)

UHE neutrinos: *transient sources*



Guépin, Kotera, Barausse, Fang, Murase, *A&A* 2018
Murase, *PRD* 2017
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RNO-G, *JINST* 2021
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ANTARES, IceCube, Auger, LIGO, Virgo, *ApJ* 2017

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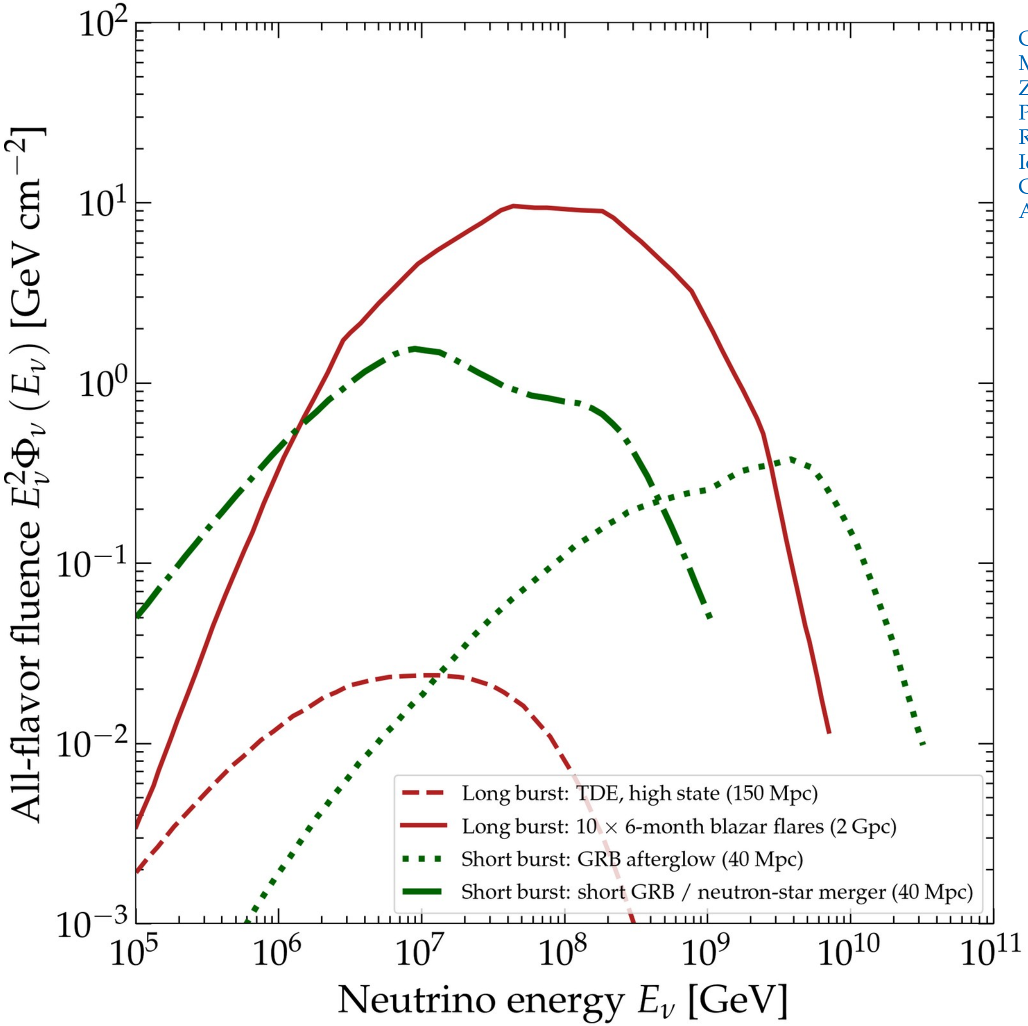

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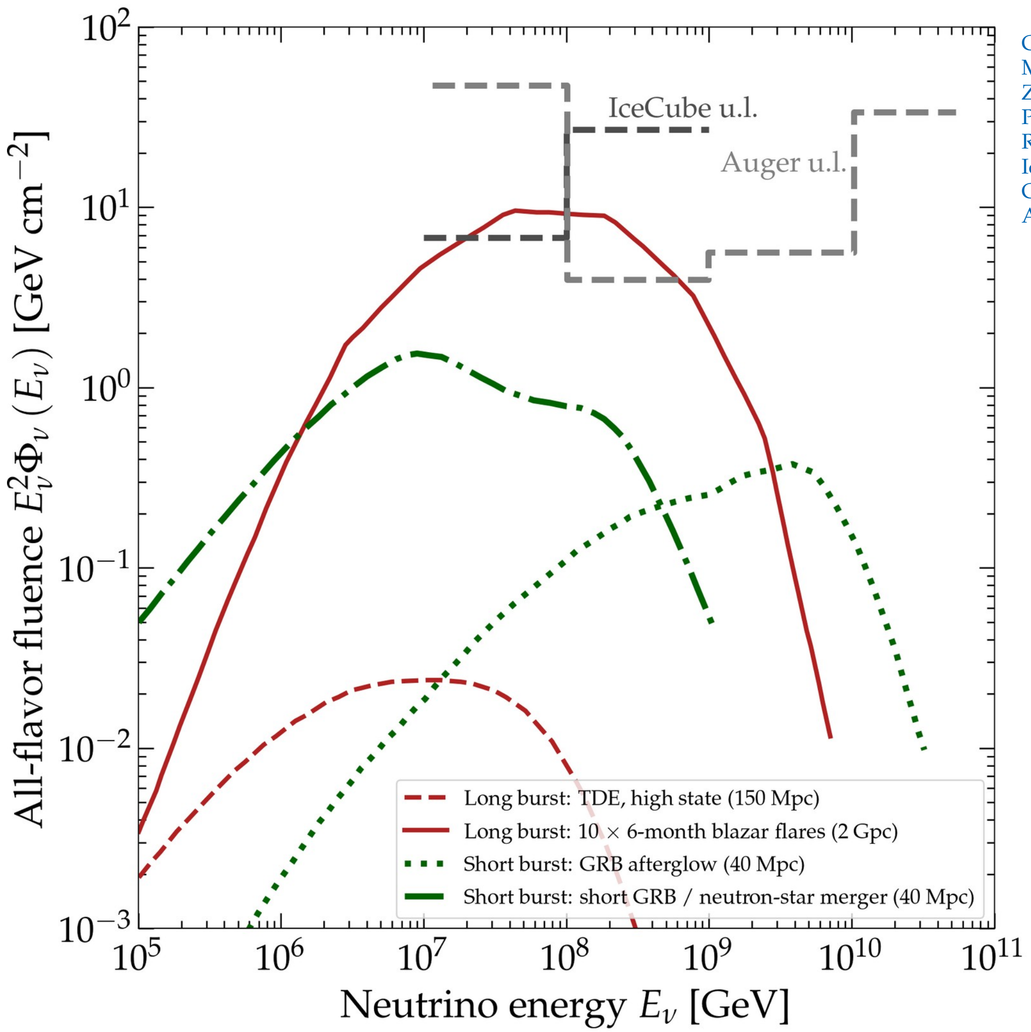

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PLEnuM

Characterizing the diffuse power-law flux in PLEνM

$$E^2\phi = \phi_{100\mathrm{TeV}} \left(\frac{E}{100\ \mathrm{TeV}}\right)^{2-\gamma}$$

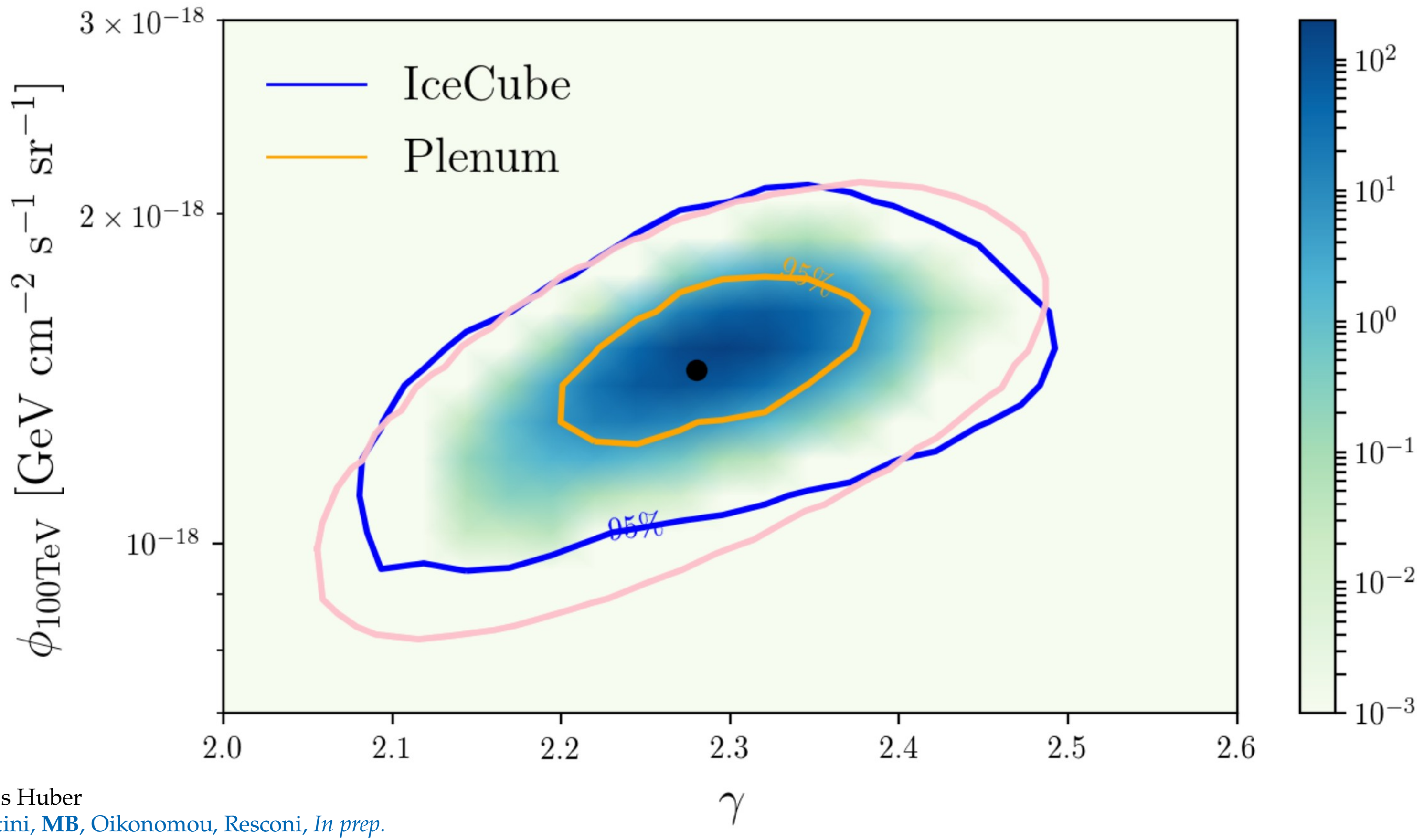
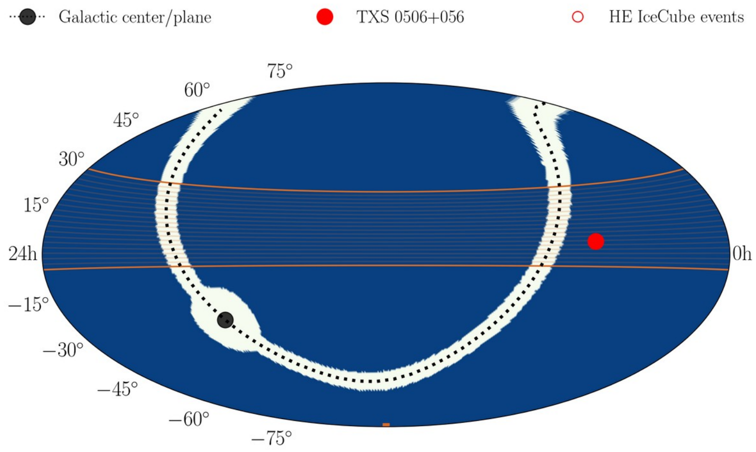


Figure courtesy of Matthias Huber
Huber, Schumacher, Agostini, **MB**, Oikonomou, Resconi, *In prep.*

Discovering a Galactic ν flux in PLEνM

Galactic emission template:



Flux uniformly distributed:

$$E^2\phi = \phi_{100\mathrm{TeV}} \left(\frac{E}{100\ \mathrm{TeV}}\right)^{2-\gamma}$$

5σ discovery potential (GC only)

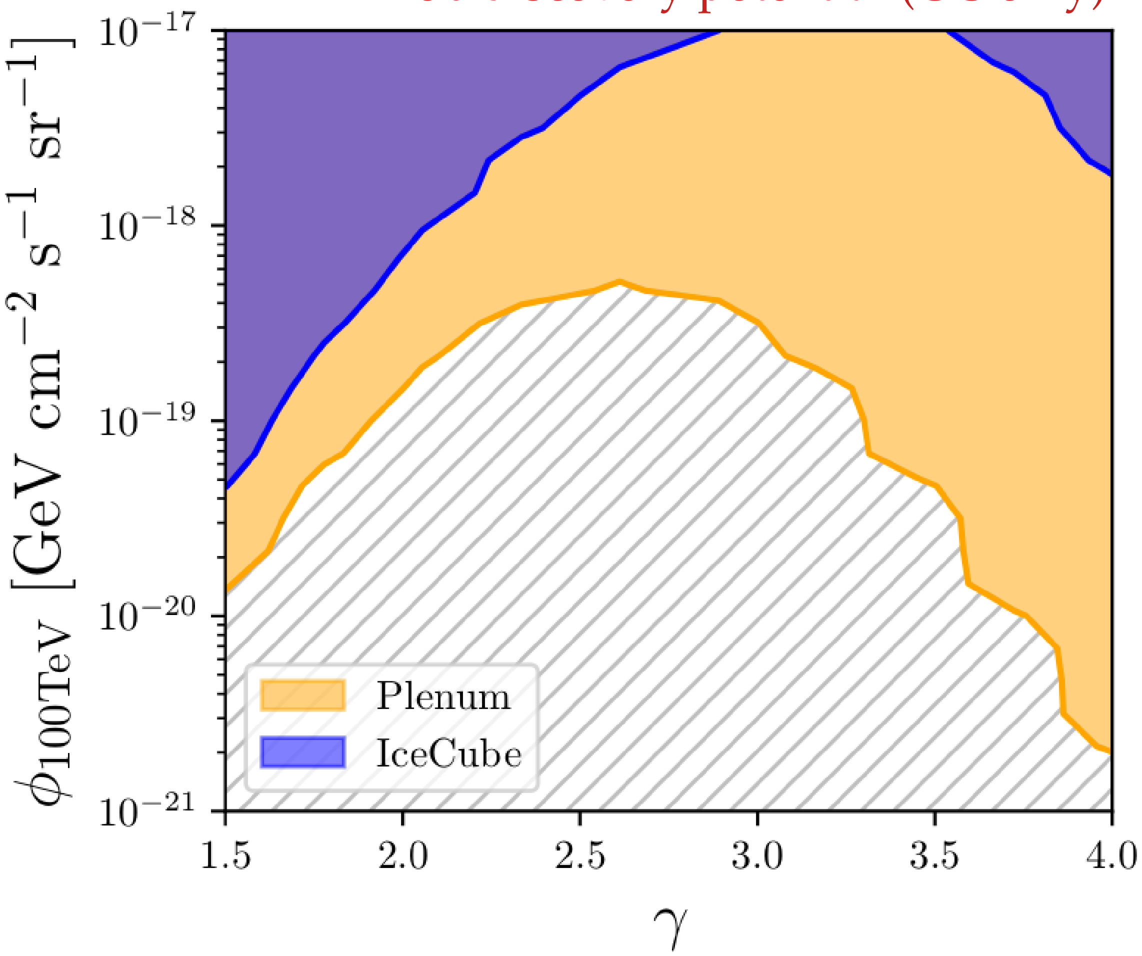


Figure courtesy of Matthias Huber

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