IceCube-Gen2: Particle Physics
Perspectives and recent results

Mauricio Bustamante

Niels Bohr Institute, University of Copenhagen

UNIVERSITY OF COPENHAGEN

VILLUM FONDEN

IceCube Spring Collaboration Meeting
May 16, 2022

IceCube and Gen2 are astrophysics machines

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astrophysics *and* particle-physics machines

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What do we want?

To do both at the same time
To do each as well as possible

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Issues to keep in mind

Challenges at HE ≠ UHE
Strong trade-off of astro *vs.* particle?

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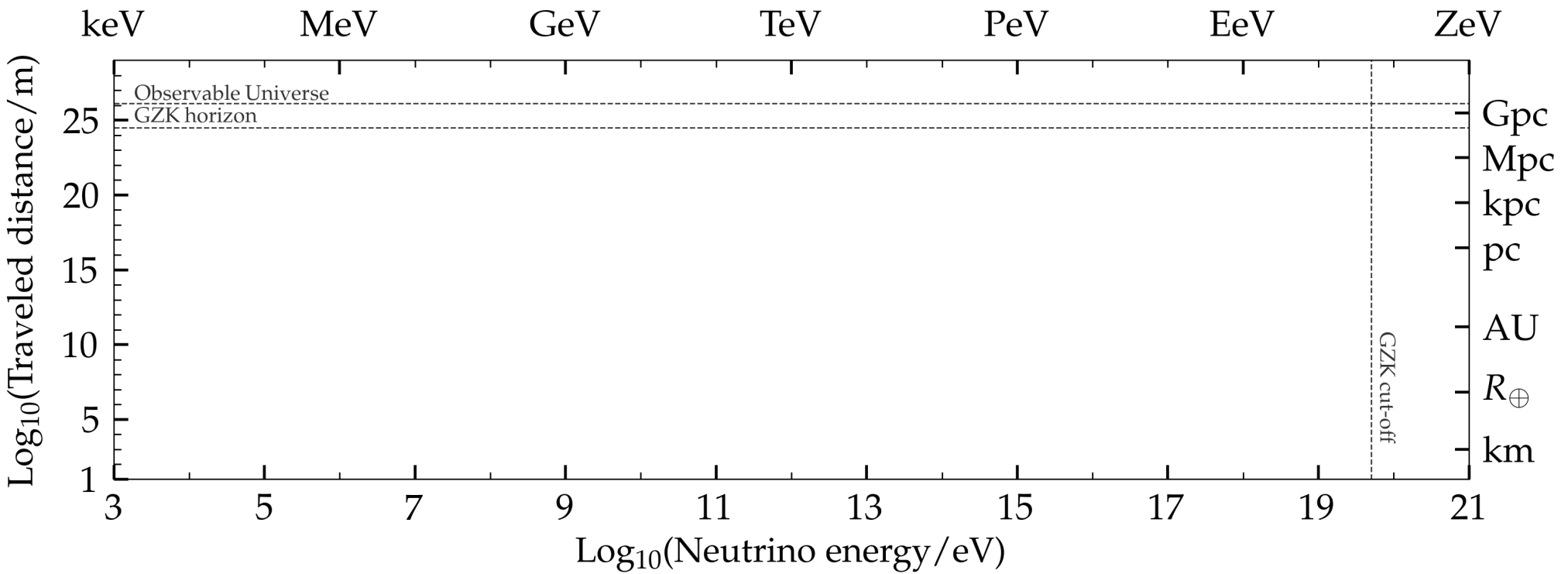
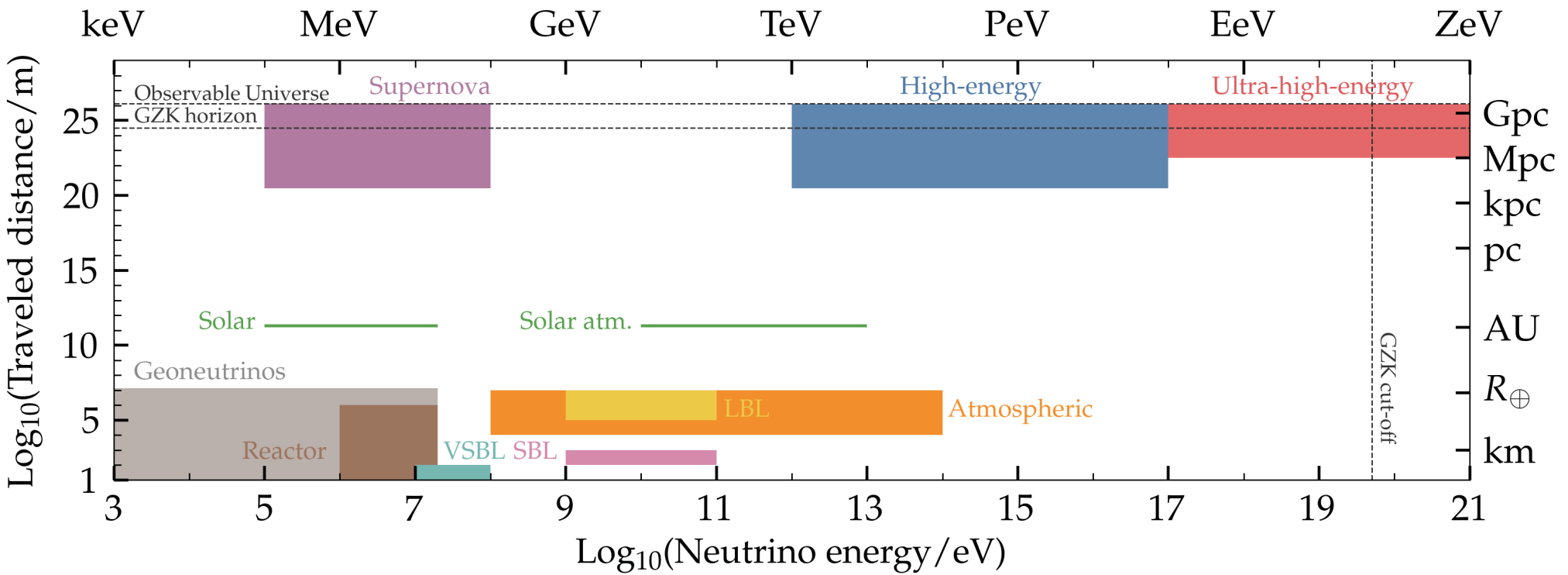
Spoiler: Maybe not!



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



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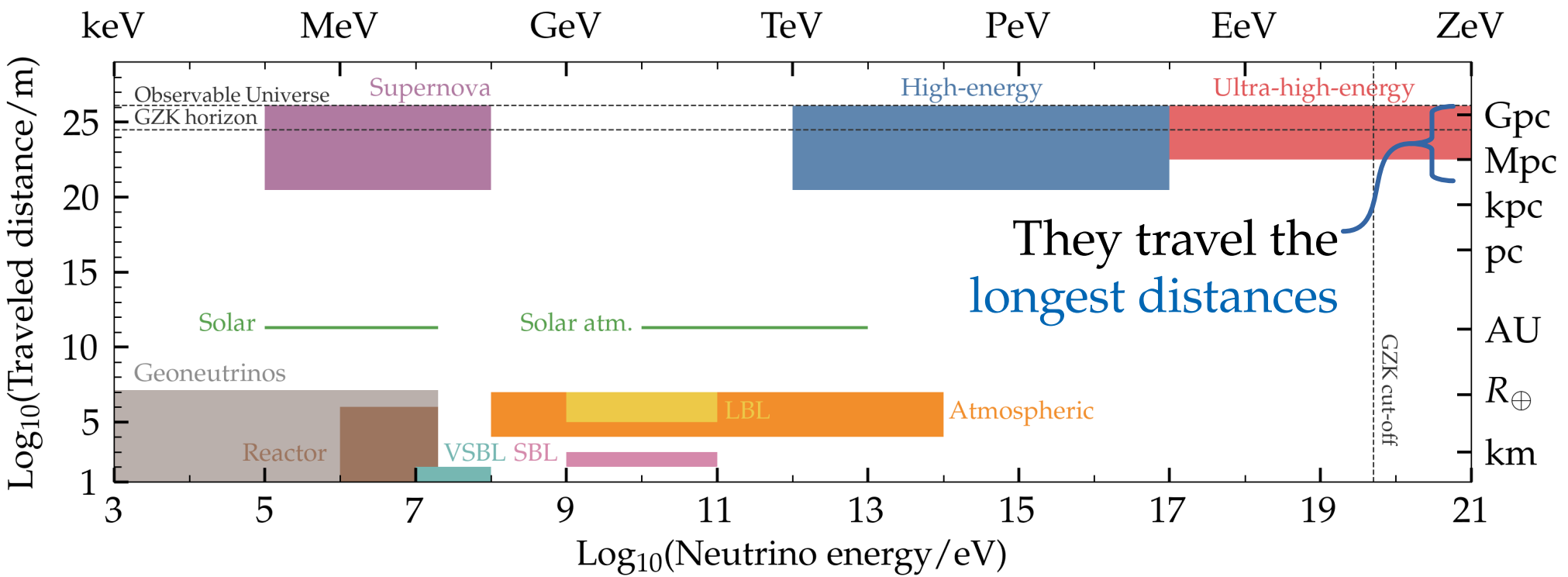
They have the highest energies



They travel the longest distances

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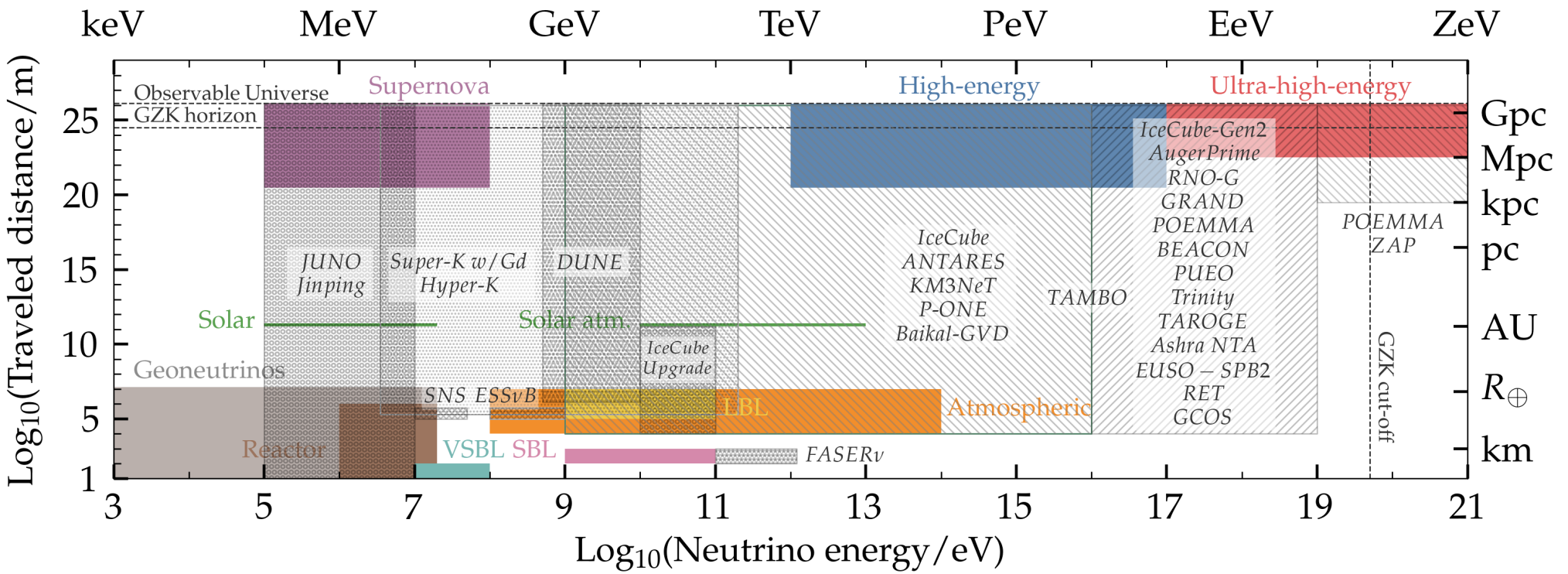

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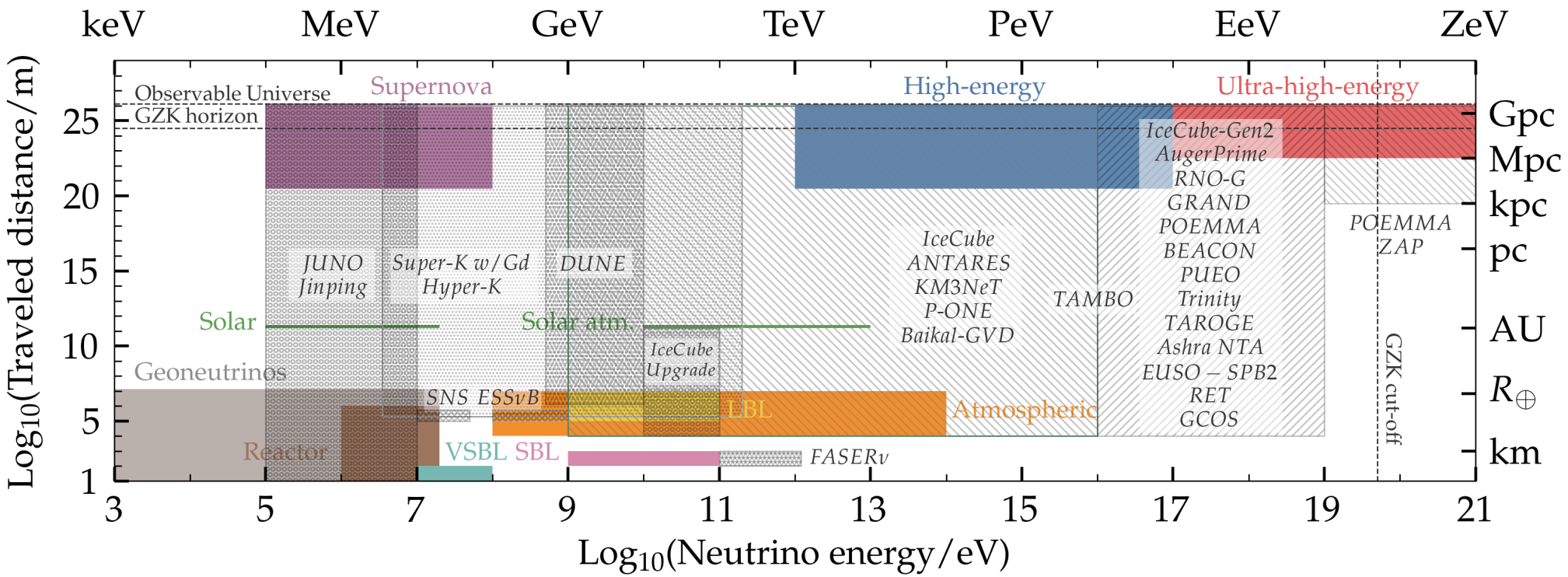

Synergies with lower energies

Increase TeV–PeV ν statistics

Discover > EeV ν

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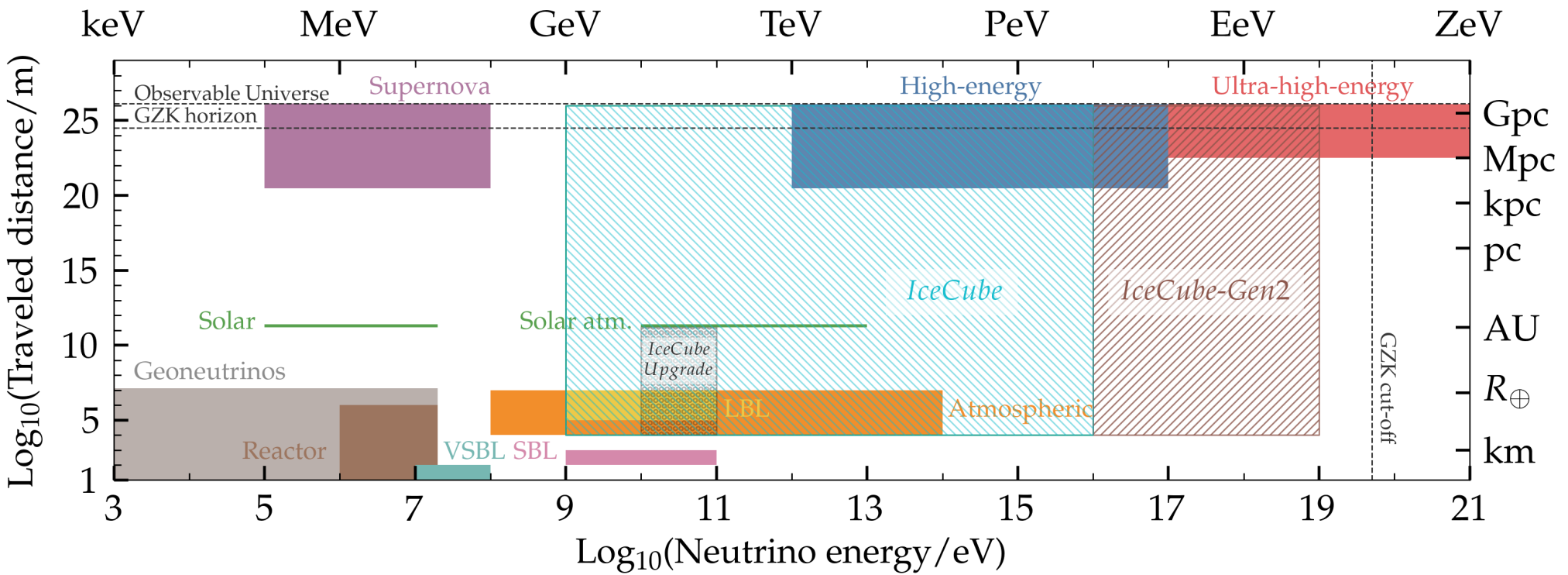
IceCube-Gen2:
~10 decades in energy for particle physics!



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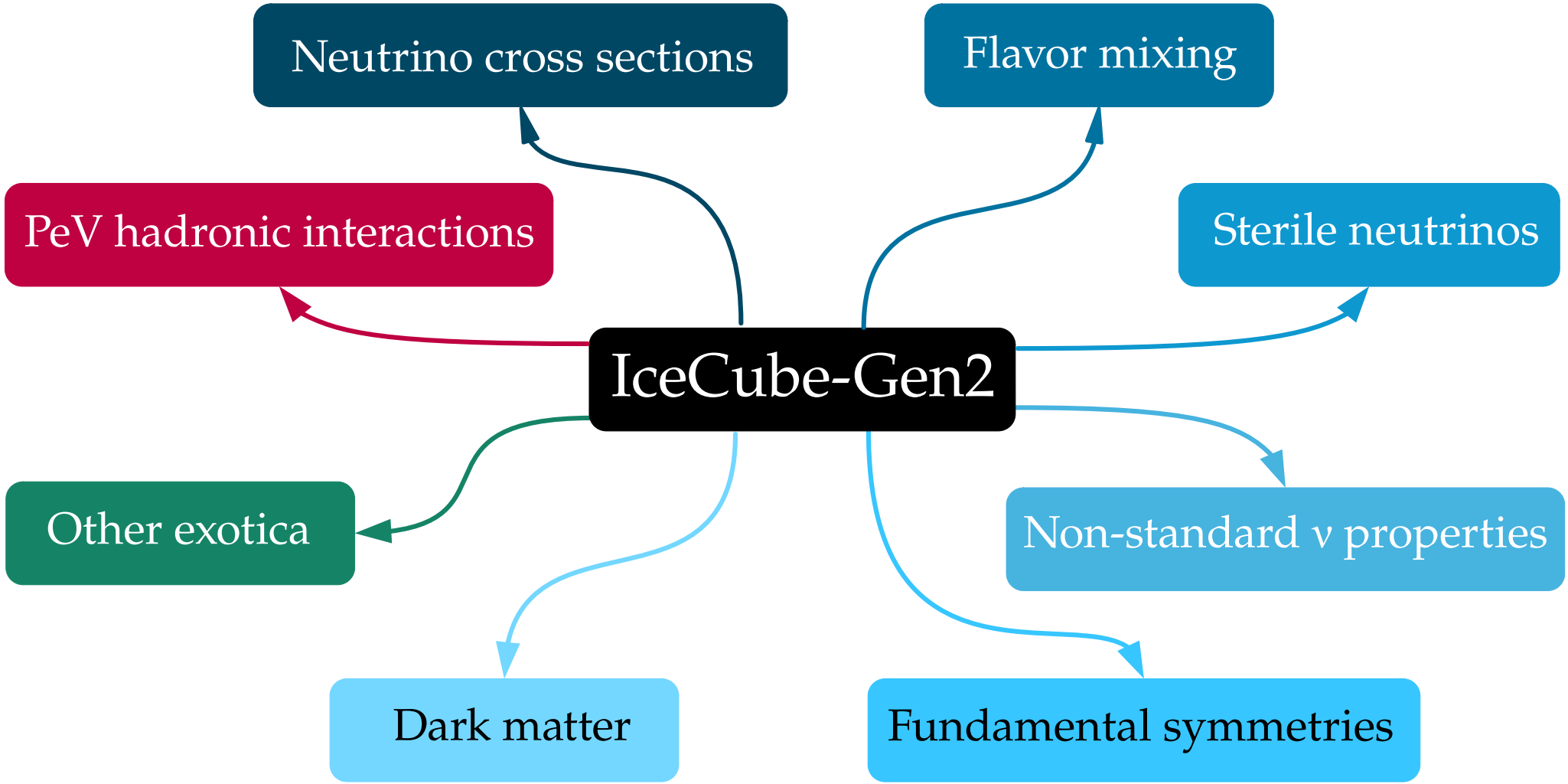
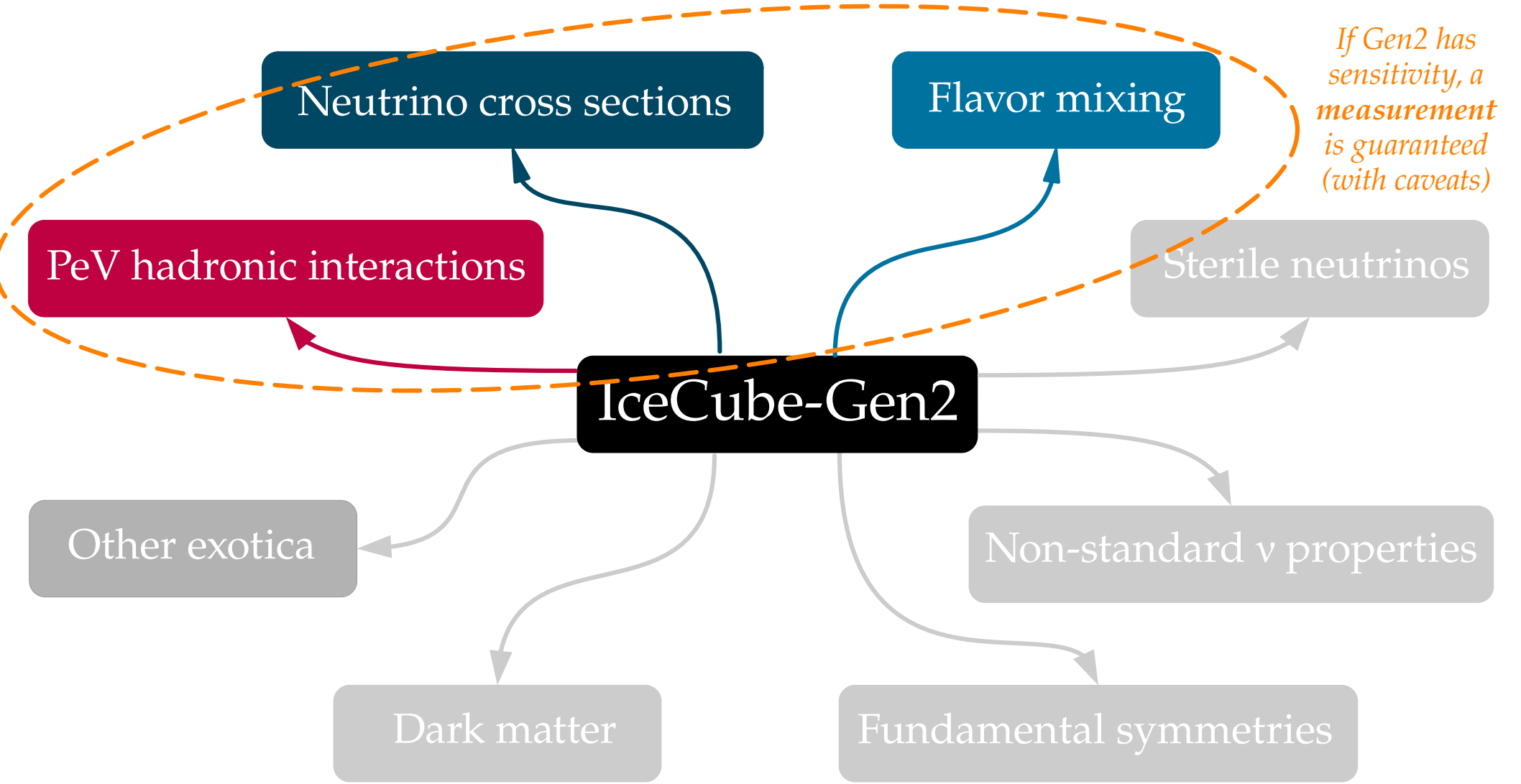

Neutrino cross sections
Flavor mixing
PeV hadronic interactions
Sterile neutrinos
IceCube-Gen2
Other exotica
Non-standard ν properties
Dark matter
Fundamental symmetries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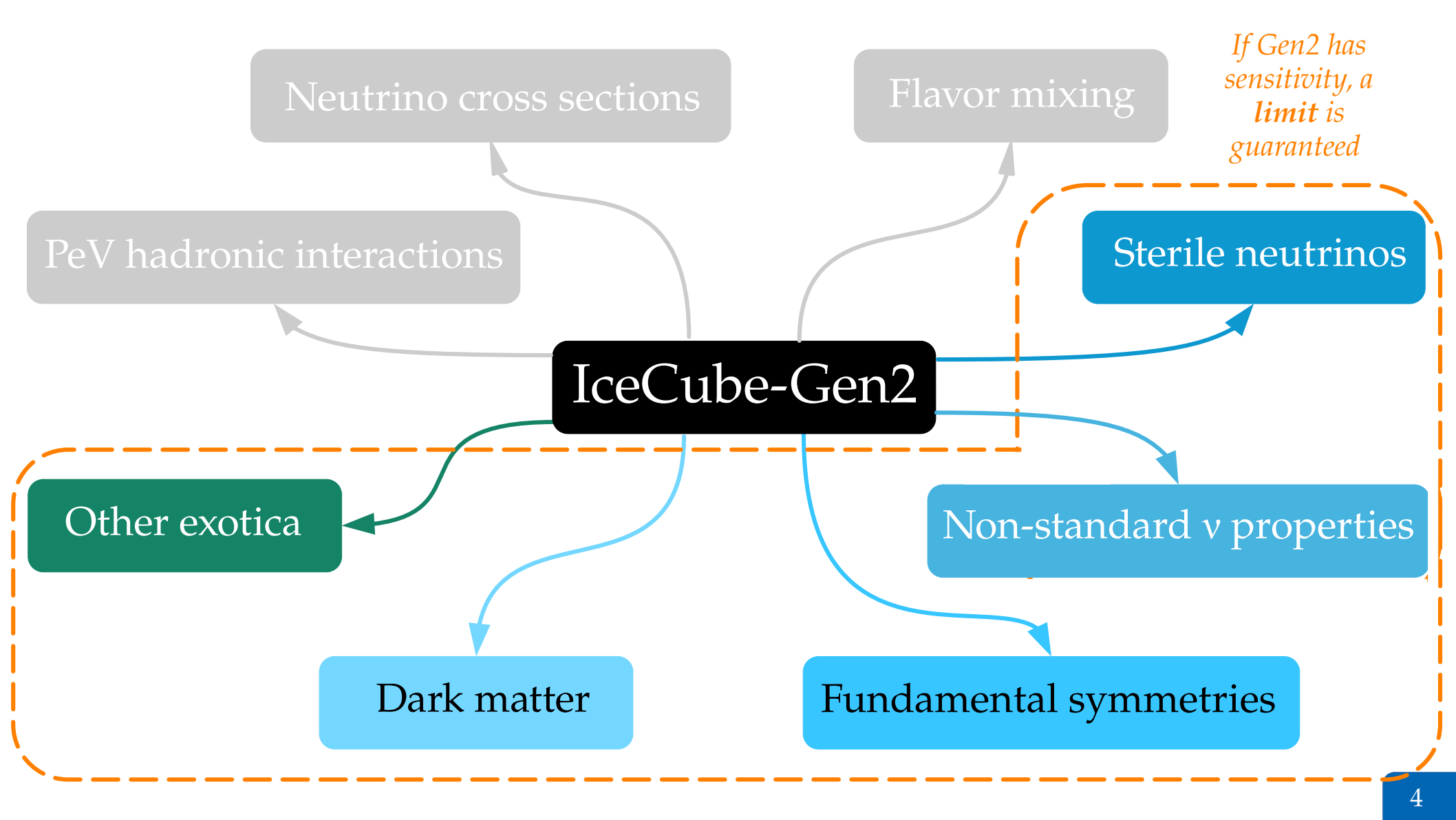
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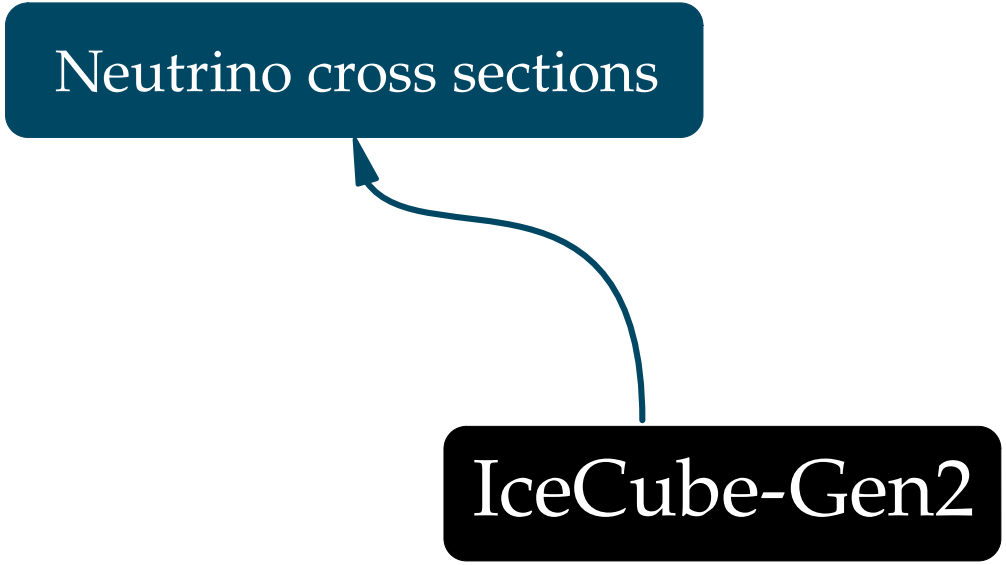
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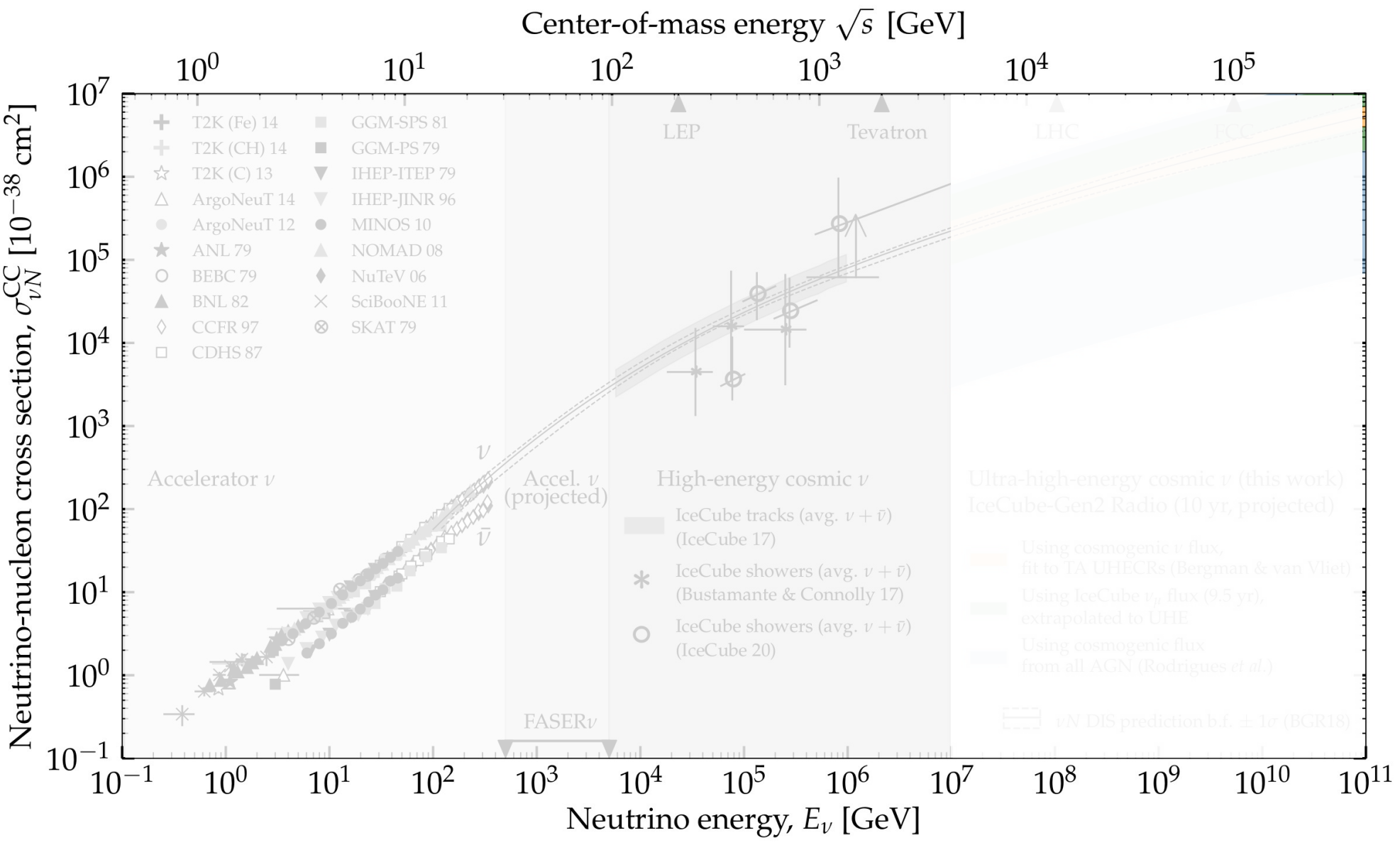
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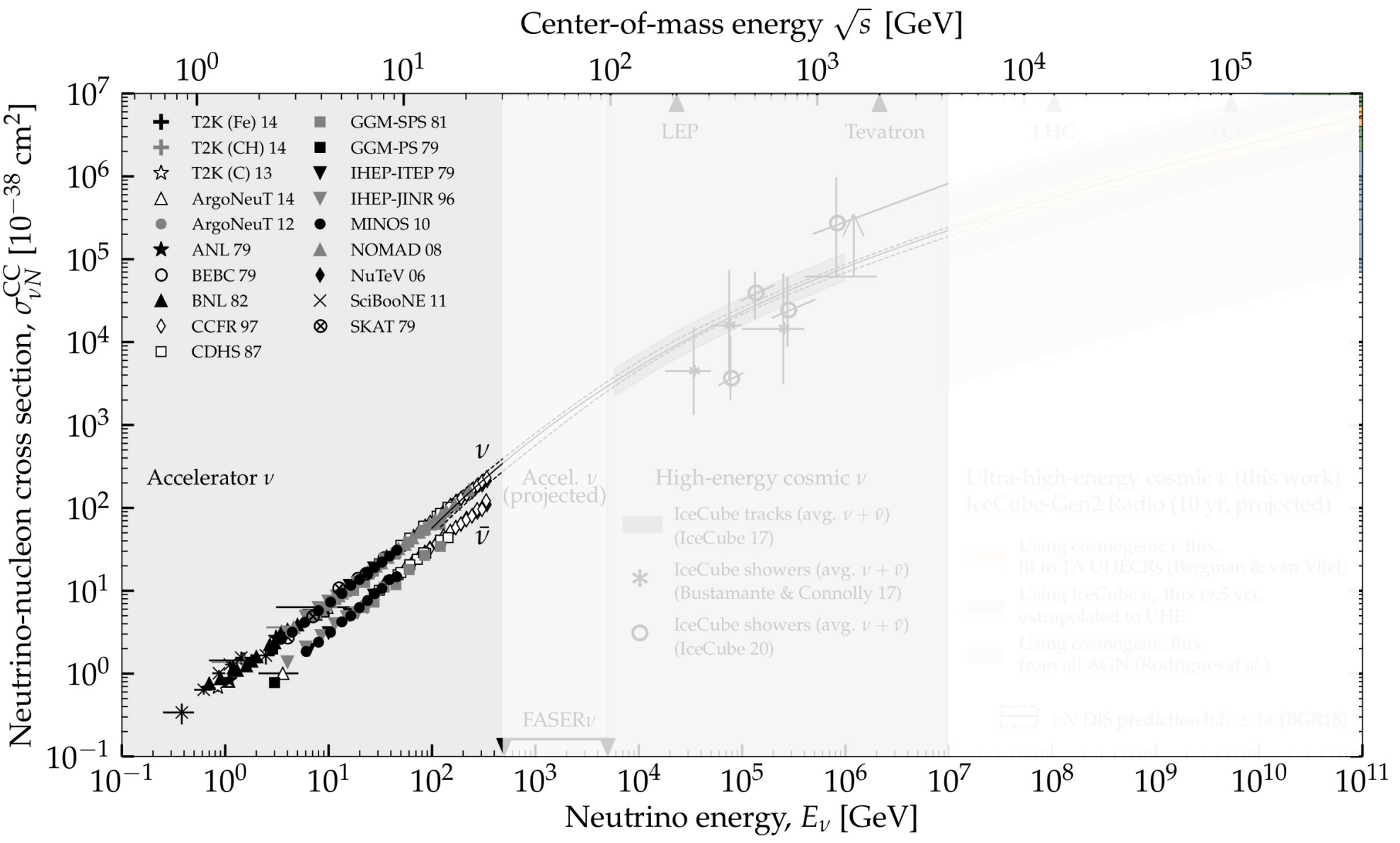
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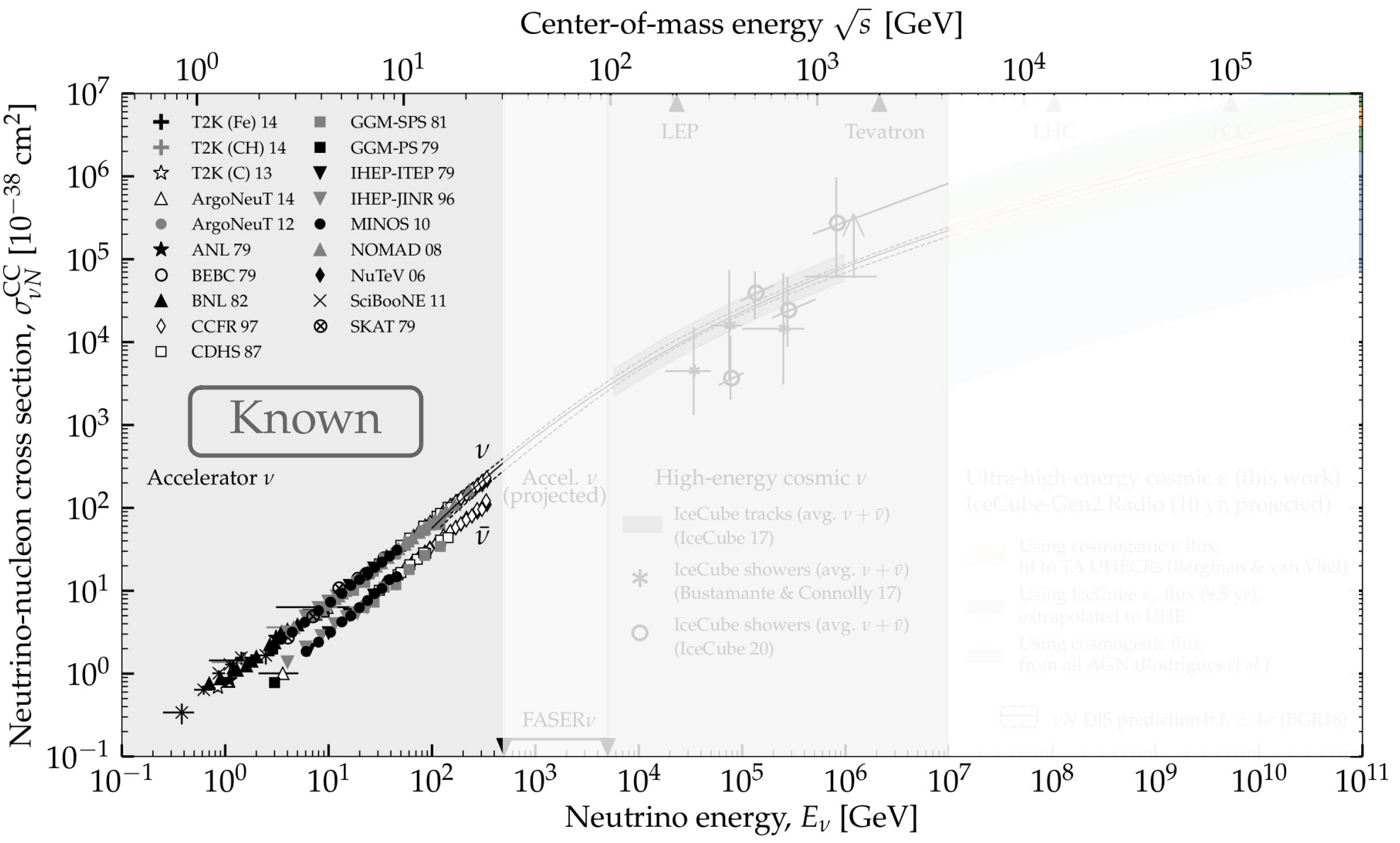
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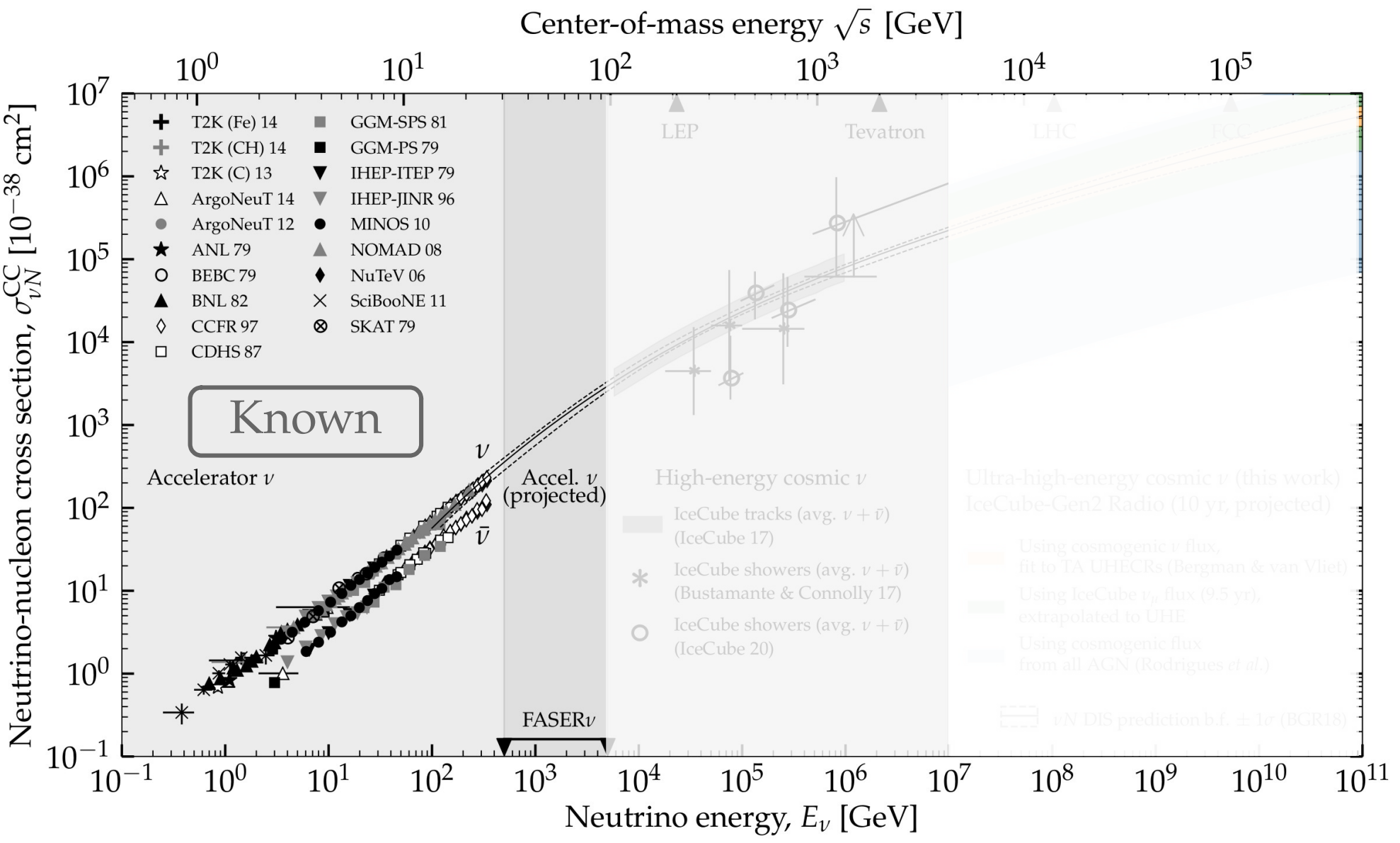
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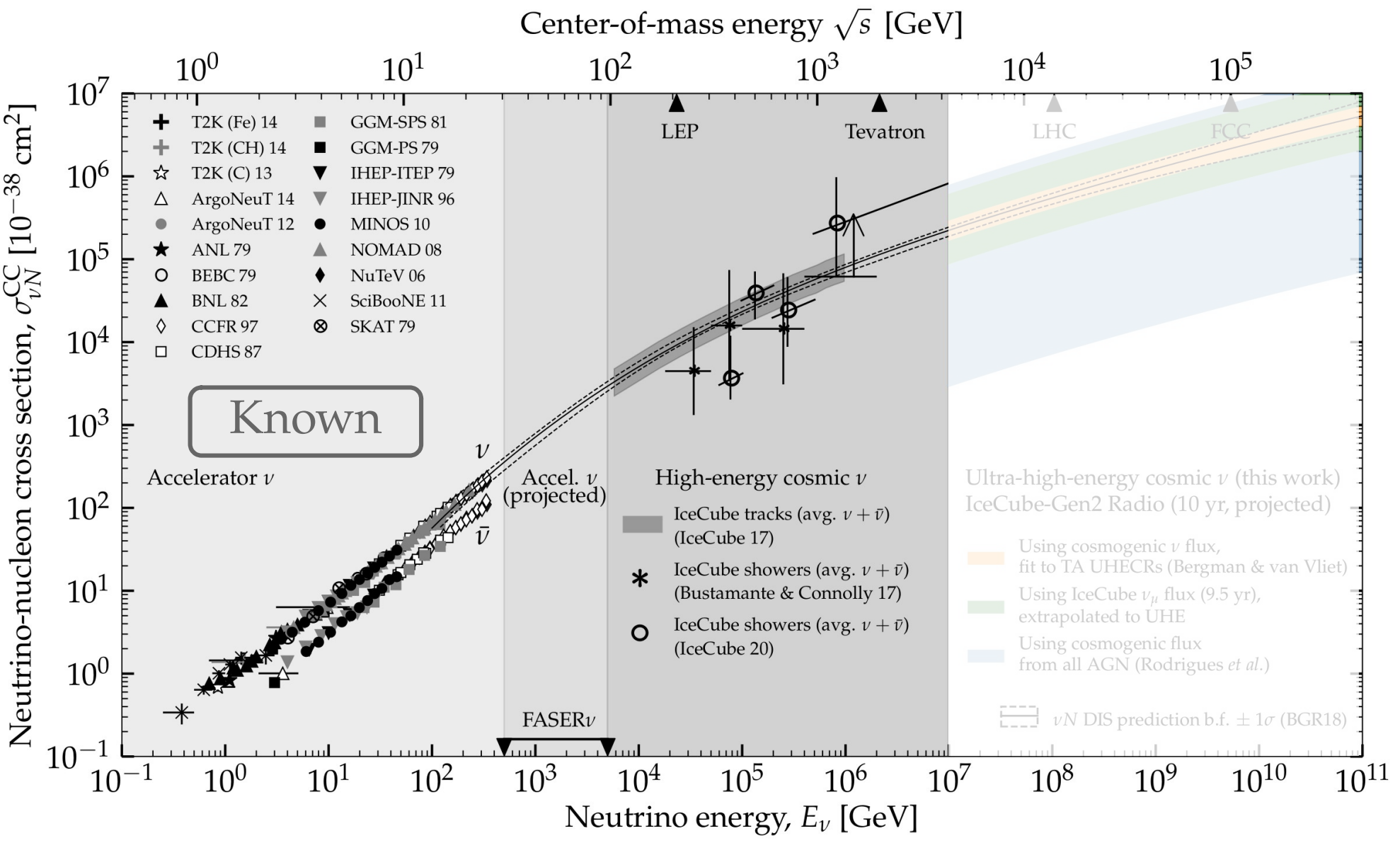
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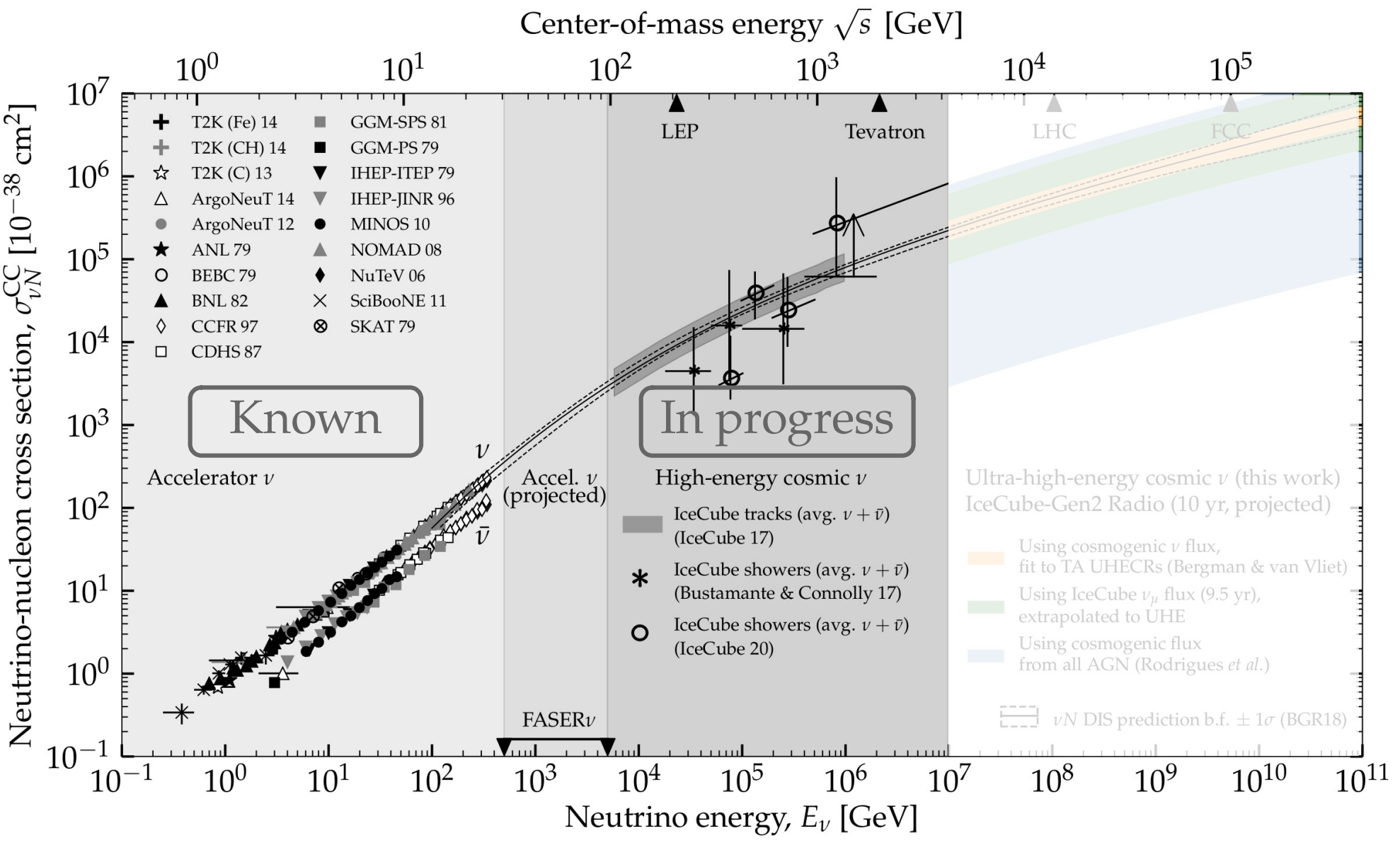
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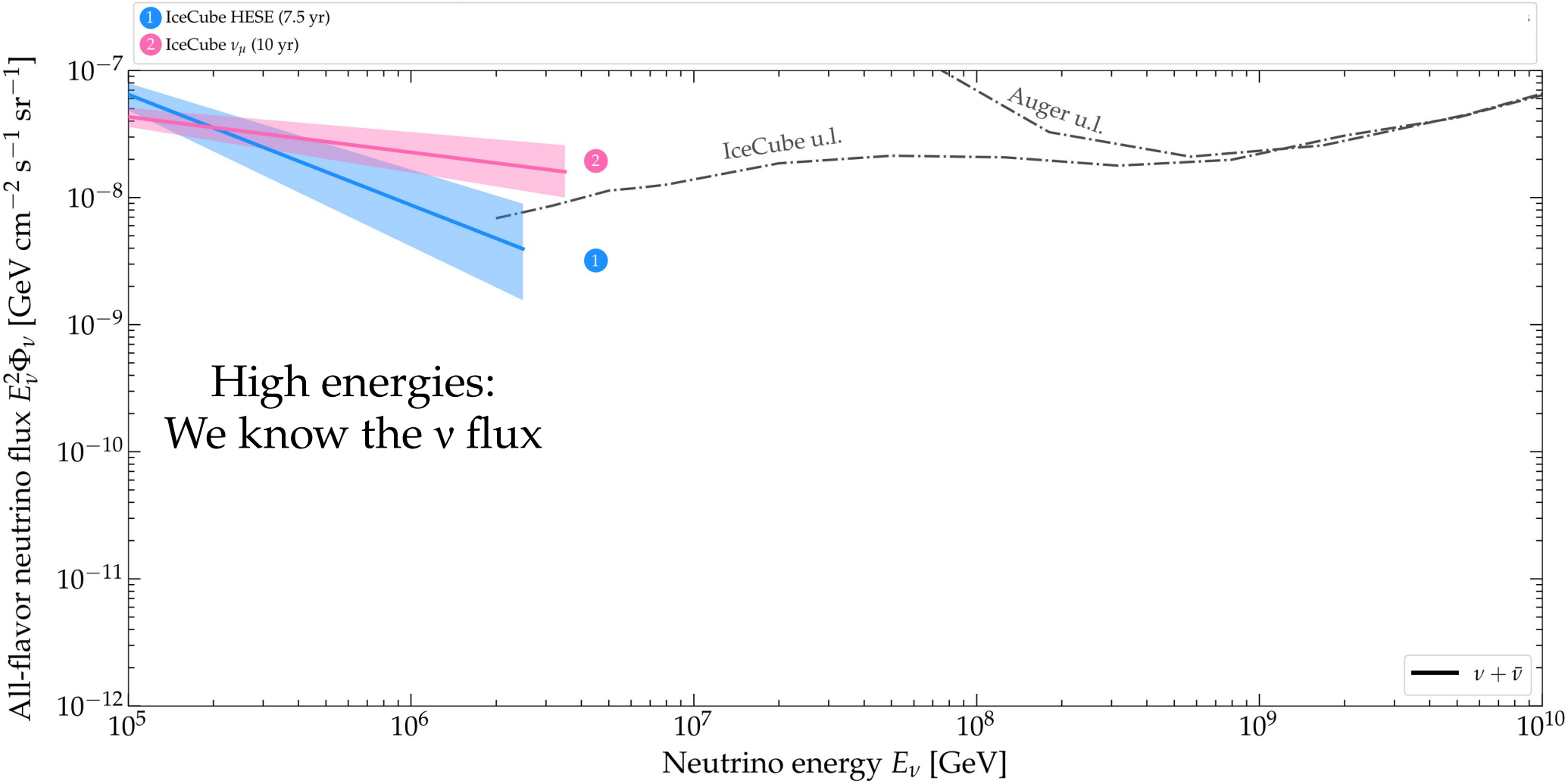
1 IceCube HESE (7.5 yr)
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IceCube u.l.
Auger u.l.
High energies:
We know the ν flux
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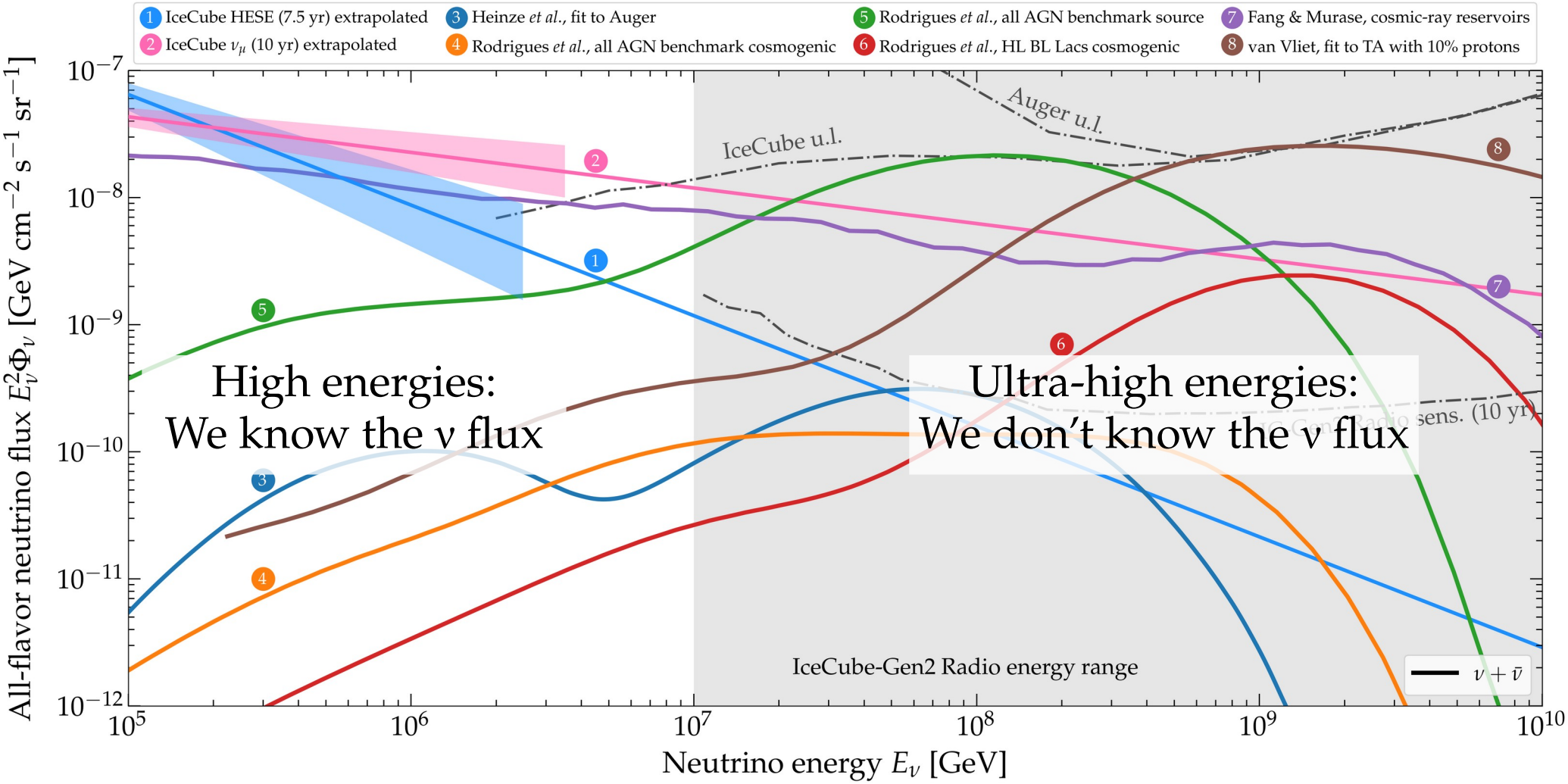
1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (10 yr) extrapolated
3 Heinze *et al.*, fit to Auger
4 Rodrigues *et al.*, all AGN benchmark cosmogenic
5 Rodrigues *et al.*, all AGN benchmark source
6 Rodrigues *et al.*, HL BL Lacs cosmogenic
7 Fang & Murase, cosmic-ray reservoirs
8 van Vliet, fit to TA with 10% protons
IceCube u.l.
Auger u.l.
High energies:
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IceCube-Gen2 Radio energy range
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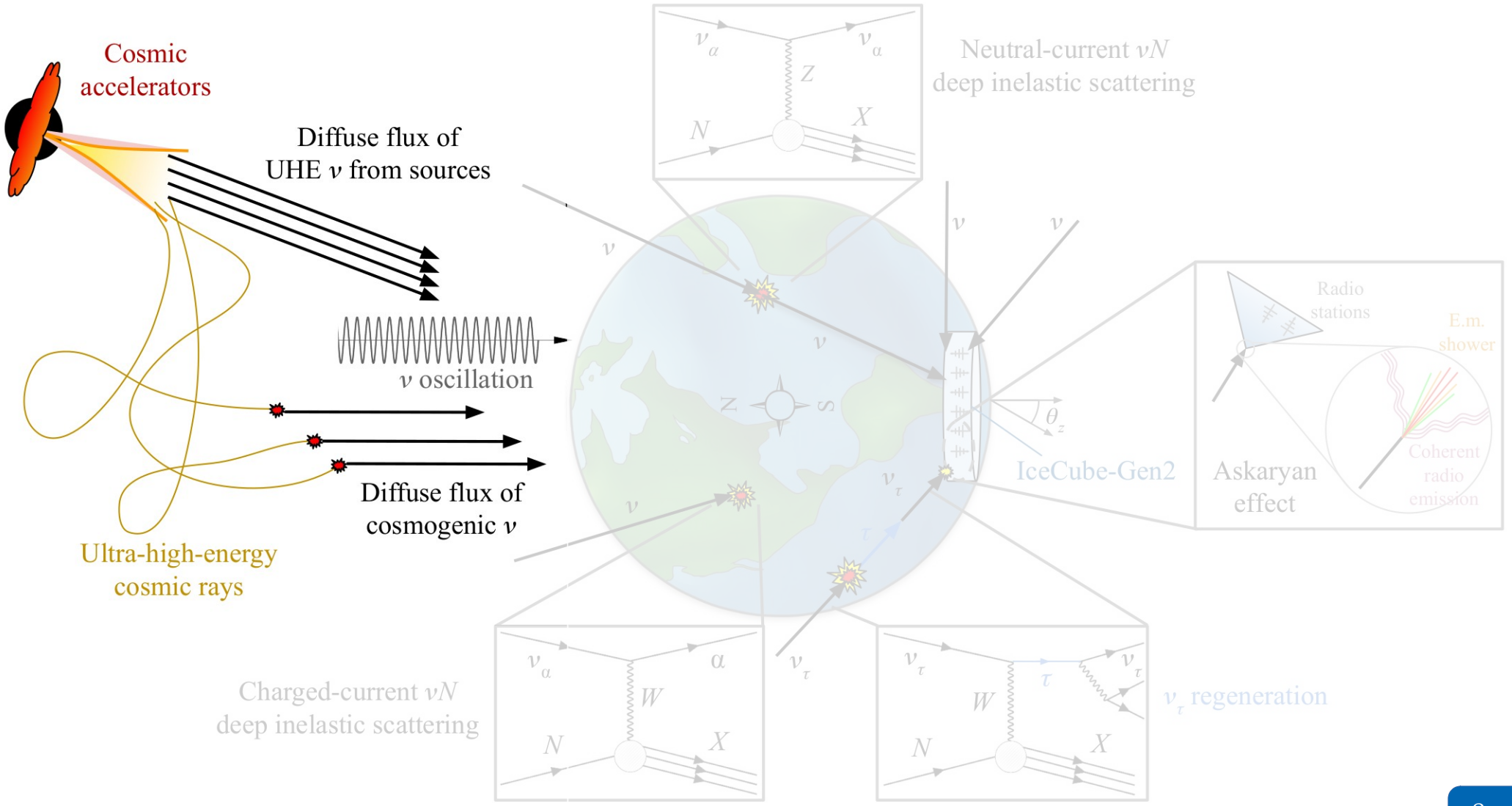
Cosmic accelerators
Diffuse flux of UHE ν from sources
ν oscillation
Diffuse flux of cosmogenic ν
Ultra-high-energy cosmic rays
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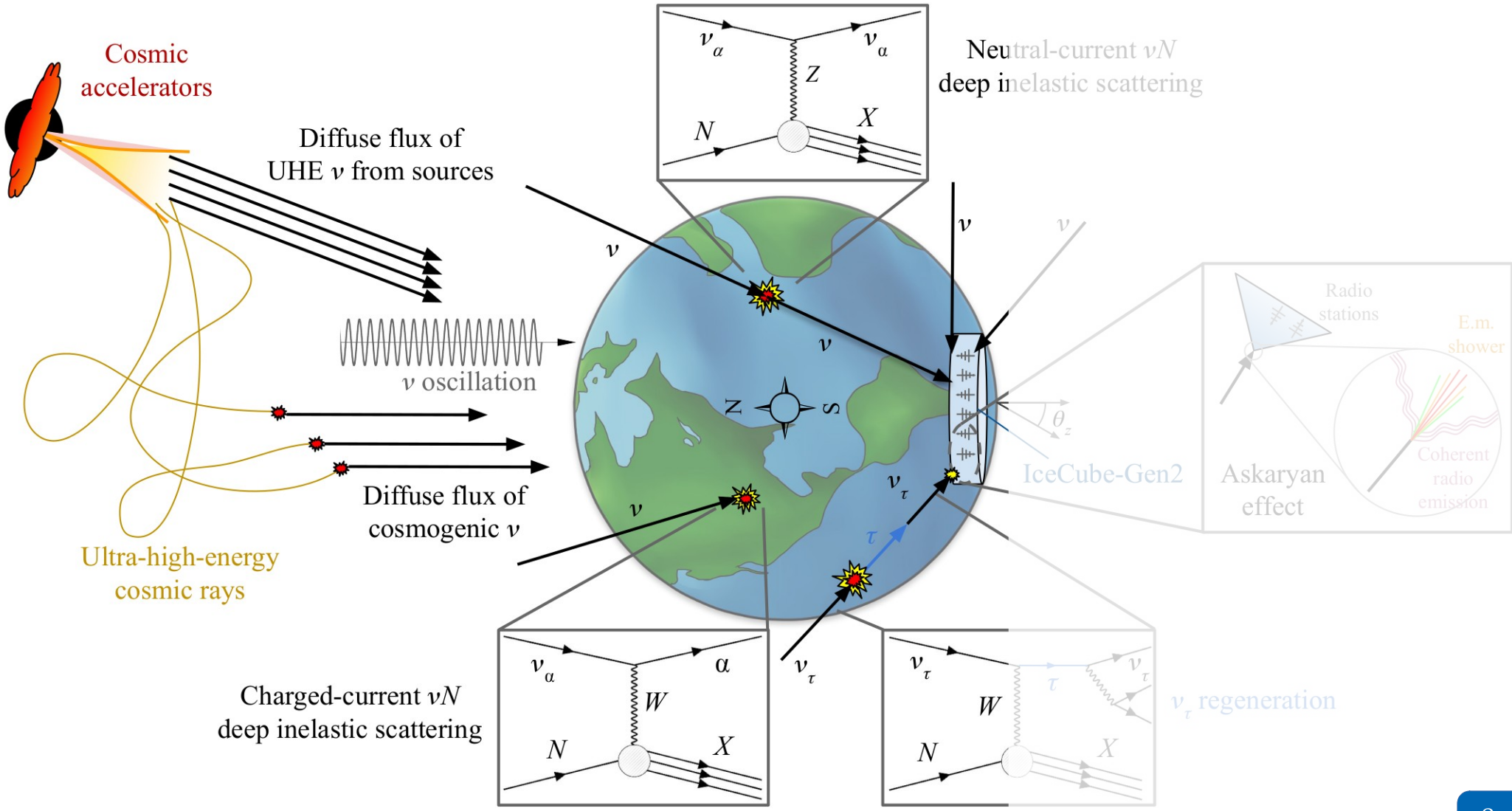
Charged-current νN deep inelastic scattering
IceCube-Gen2
Askaryan effect
Radio stations
E.m. shower
Coherent radio emission
ν regeneration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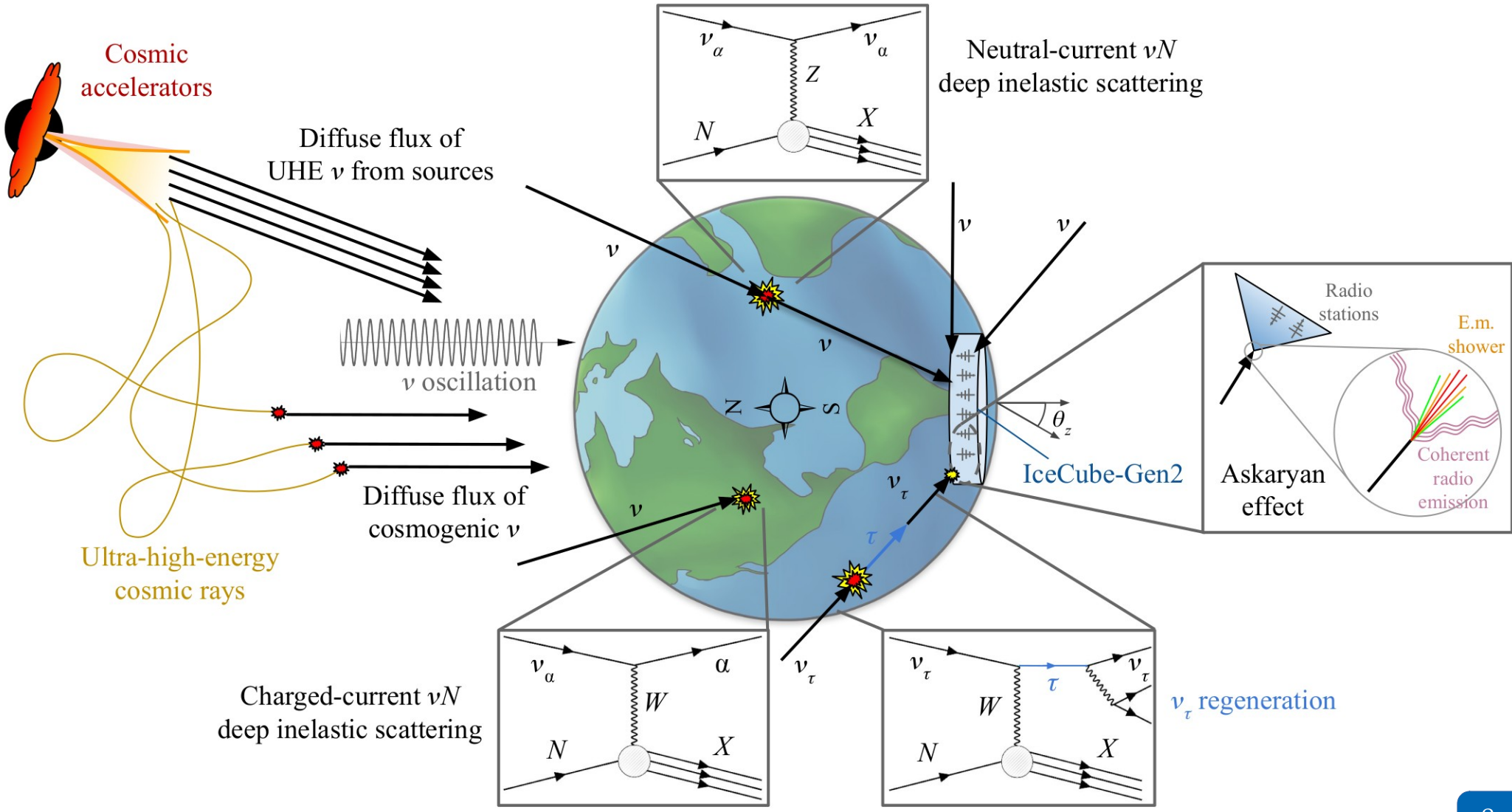
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Measuring neutrino-nucleon cross sections at UHE

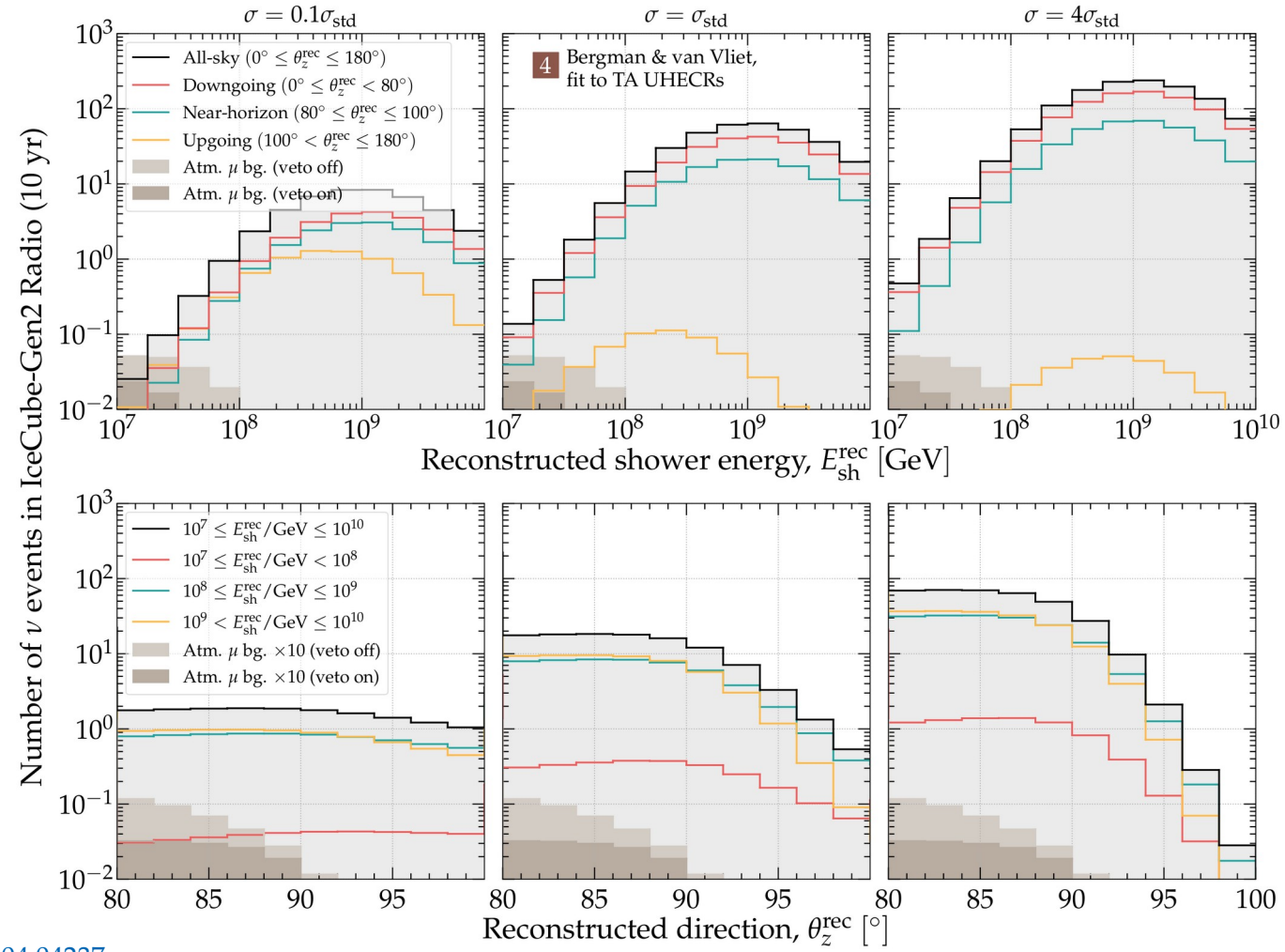
Baseline Gen2 radio array design:

- 169 hybrid stations (shallow + deep) + 144 deep stations
- Detector angular resolution (zenith angle): 2°
- Detector shower energy resolution: 10%

Ask about alternative choices

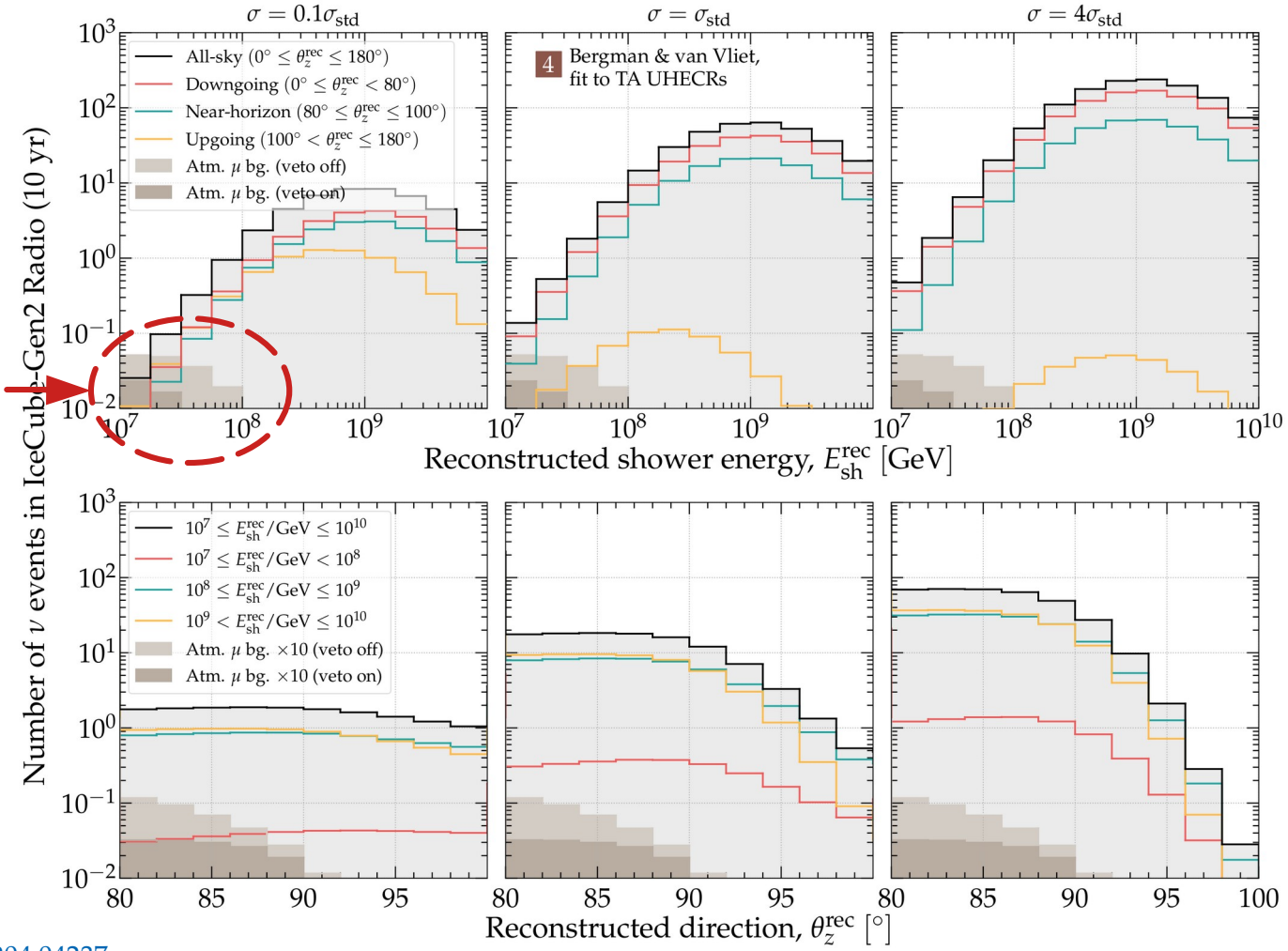
Detailed event-rate calculation scheme:

- V_{eff} *vs.* shower energy *vs.* angle, custom-generated in NuRadioMC
- In-Earth propagation, leading & sub-leading ν interactions in NuPropEarth
- Inelasticity distribution factored in
- Use recent cross-section predictions as baseline
- Background from atmospheric muons (< 0.1 event per year above 10^7 GeV)



Valera, **MB**, Glaser, 2204.04237

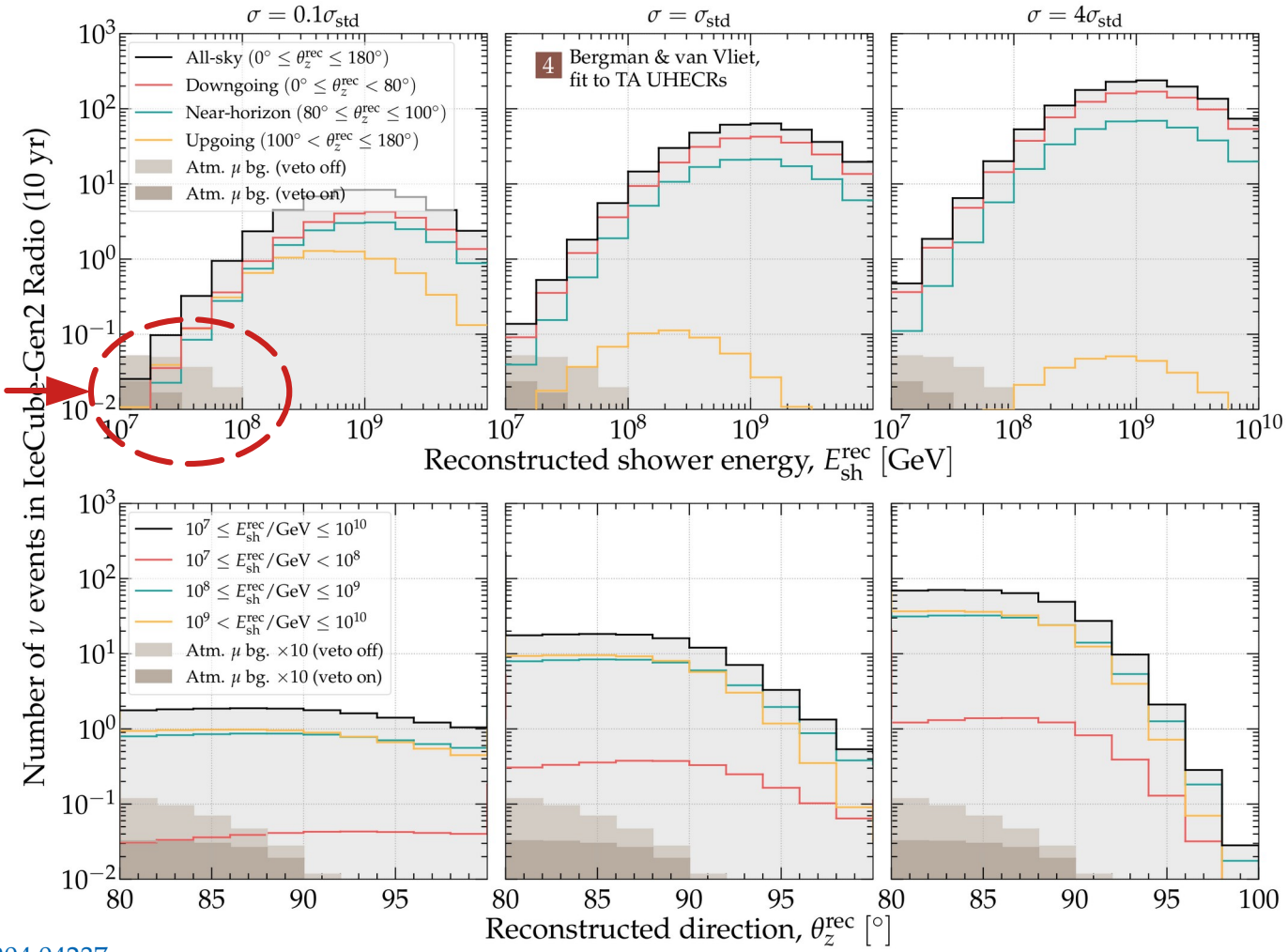
Atmospheric muon background



Valera, **MB**, Glaser, 2204.04237

Larger neutrino-nucleon cross section

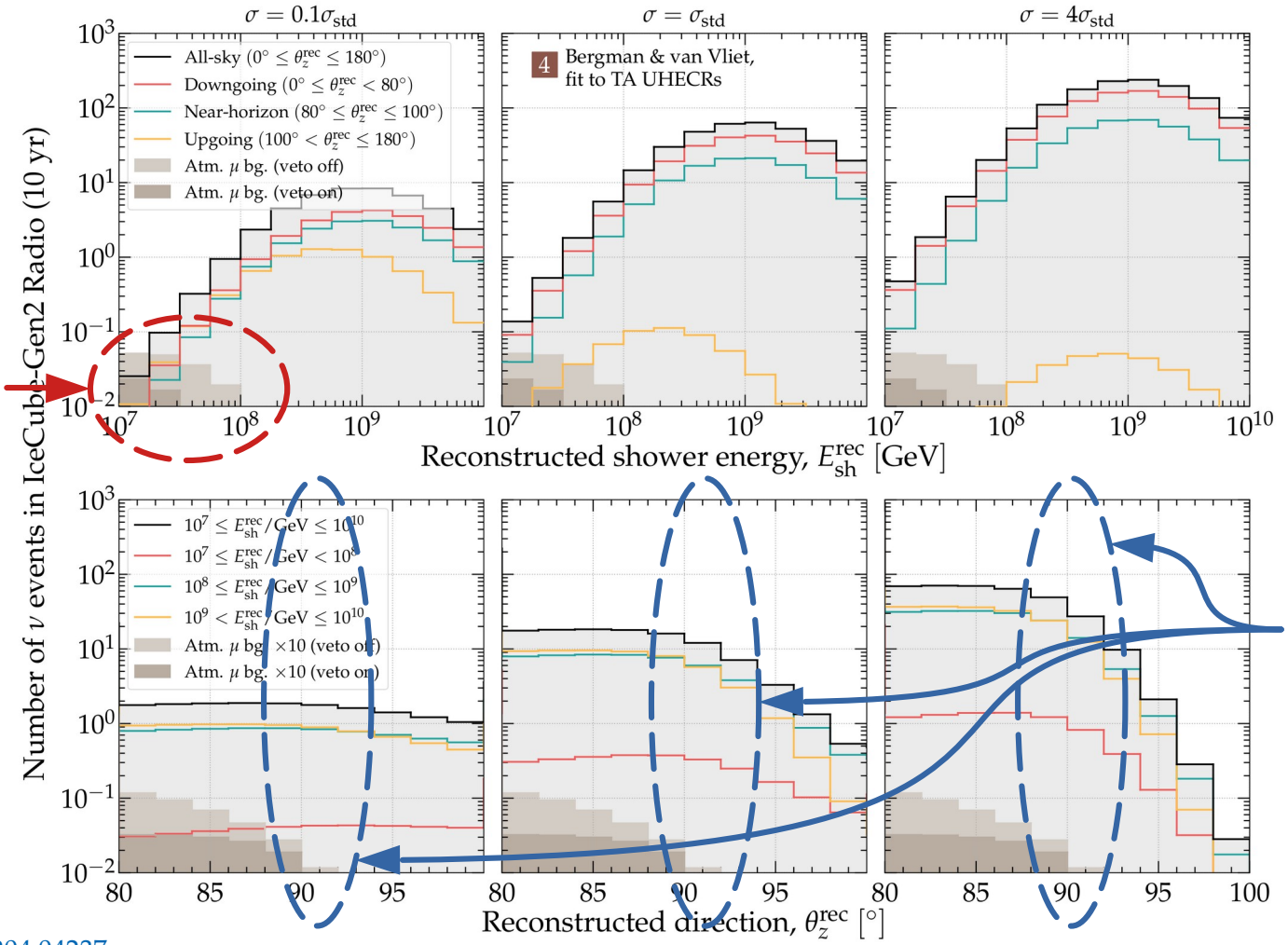
Atmospheric muon background



Valera, **MB**, Glaser, 2204.04237

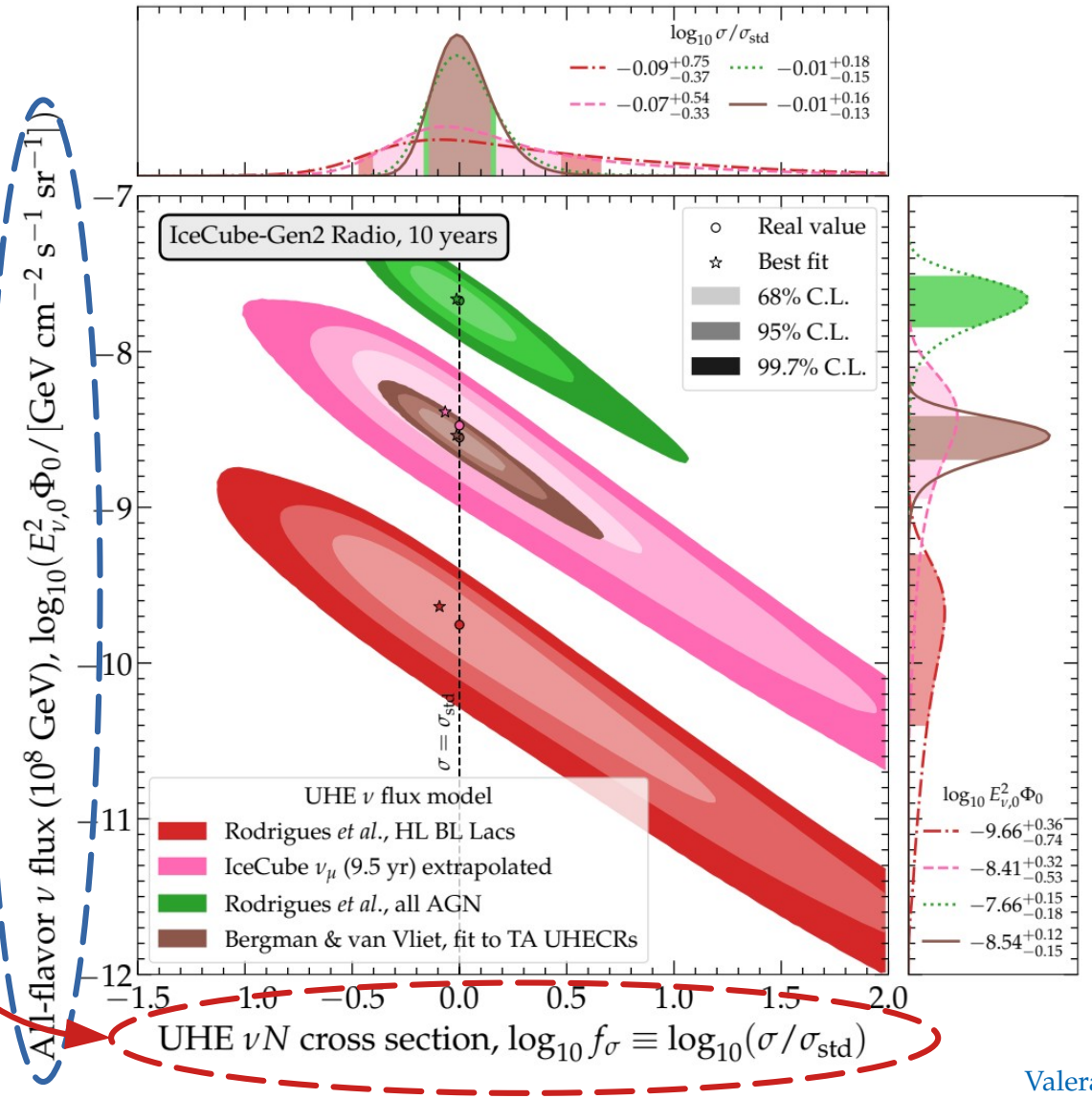
Larger neutrino-nucleon cross section

Atmospheric muon background



Sensitivity to cross section comes from horizontal neutrinos

Valera, **MB**, Glaser, 2204.04237



Flux normalization

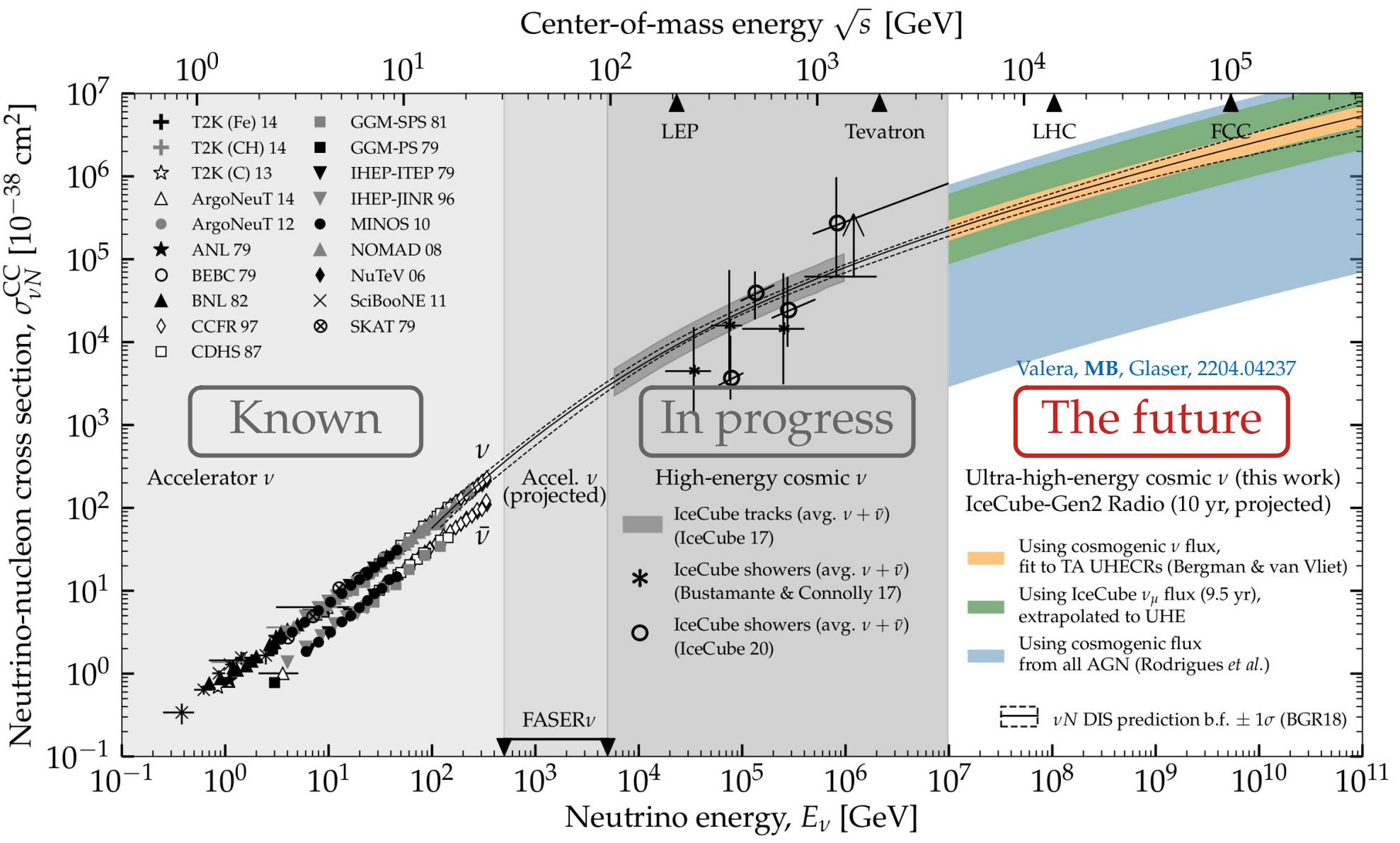
Cross section

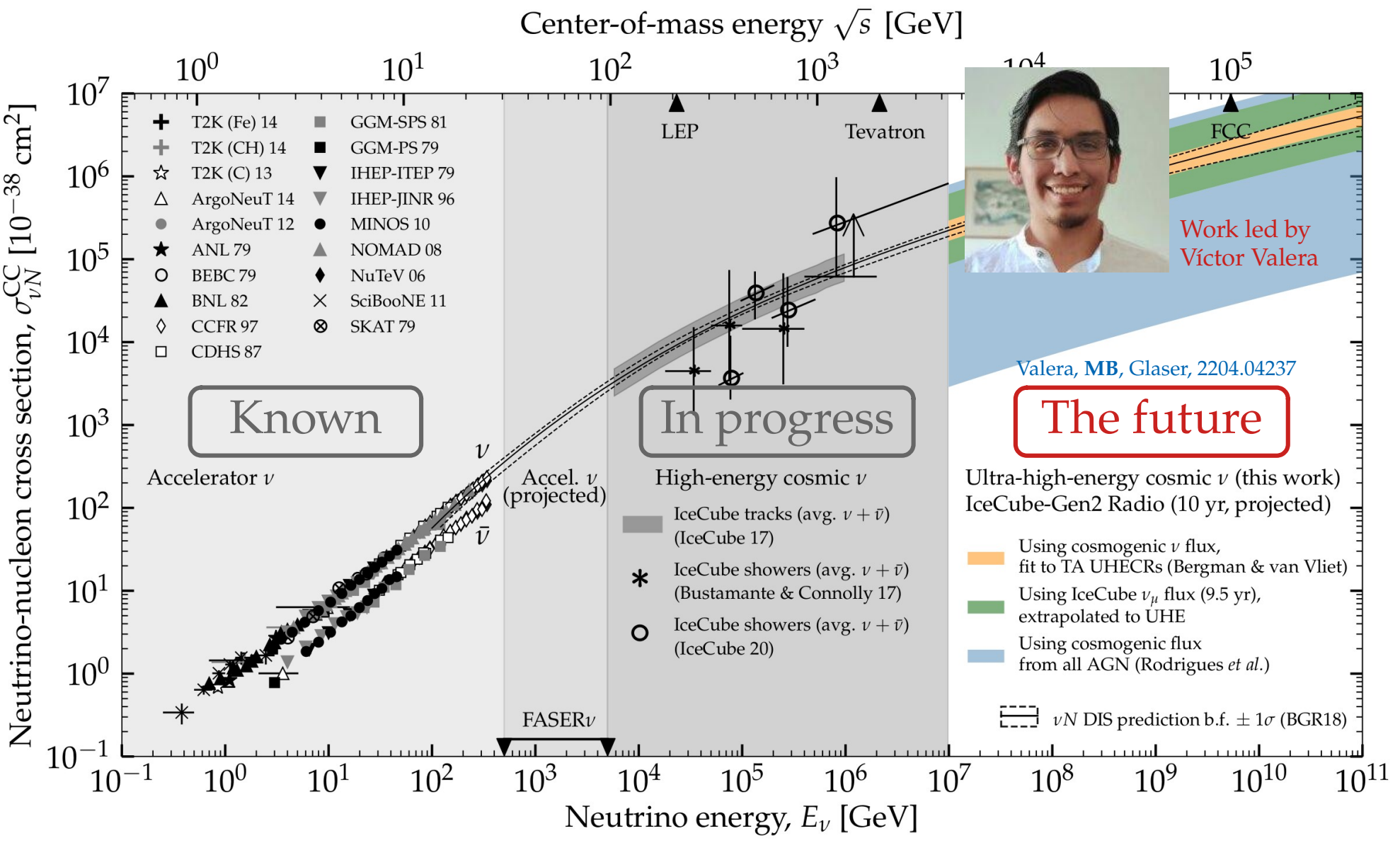
Note: We fix the spectral shape, but explore many alternatives

Needed to measure the cross section?

~30–300 events

Valera, **MB**, Glaser, 2204.04237


Center-of-mass energy $\sqrt{s}$ [GeV]
10^0
10^1
10^2
10^3
10^4
10^5
Neutrino-nucleon cross section, $\sigma_{\nu N}^{CC}$ [10^{-38} cm^2]
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
T2K (Fe) 14
T2K (CH) 14
T2K (C) 13
ArgoNeuT 14
ArgoNeuT 12
ANL 79
BEBC 79
BNL 82
CCFR 97
CDHS 87
GGM-SPS 81
GGM-PS 79
IHEP-ITEP 79
IHEP-JINR 96
MINOS 10
NOMAD 08
NuTeV 06
SciBooNE 11
SKAT 79
LEP
Tevatron
LHC
FCC
Known
In progress
The future
Valera, MB, Glaser, 2204.04237
Accelerator ν
ν
$\bar{\nu}$
Accel. ν (projected)
FASERν
High-energy cosmic ν
IceCube tracks (avg. $\nu + \bar{\nu}$) (IceCube 17)
IceCube showers (avg. $\nu + \bar{\nu}$) (Bustamante & Connolly 17)
IceCube showers (avg. $\nu + \bar{\nu}$) (IceCube 20)
Ultra-high-energy cosmic ν (this work)
IceCube-Gen2 Radio (10 yr, projected)
Using cosmogenic ν flux, fit to TA UHECRs (Bergman & van Vliet)
Using IceCube ν_μ flux (9.5 yr), extrapolated to UHE
Using cosmogenic flux from all AGN (Rodrigues *et al.*)
νN DIS prediction b.f. $\pm 1\sigma$ (BGR18)
10^{-1}
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
Neutrino energy, E_ν [GeV]


Center-of-mass energy $\sqrt{s}$ [GeV]
10^0
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The future
Work led by
Víctor Valera
Valera, MB, Glaser, 2204.04237
Accelerator ν
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10^5
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10^8
10^9
10^{10}
10^{11}
Neutrino energy, E_ν [GeV]

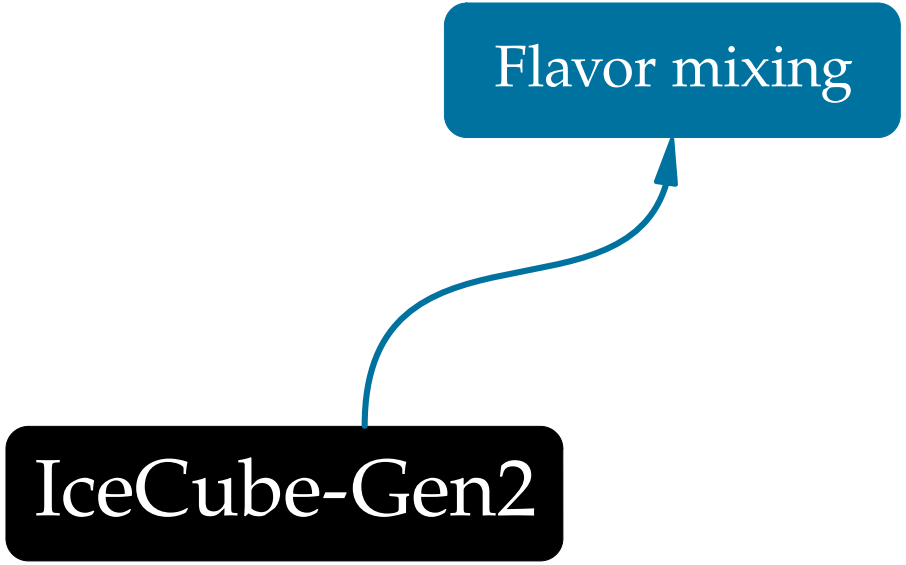
Neutrino cross sections: outlook for Gen2

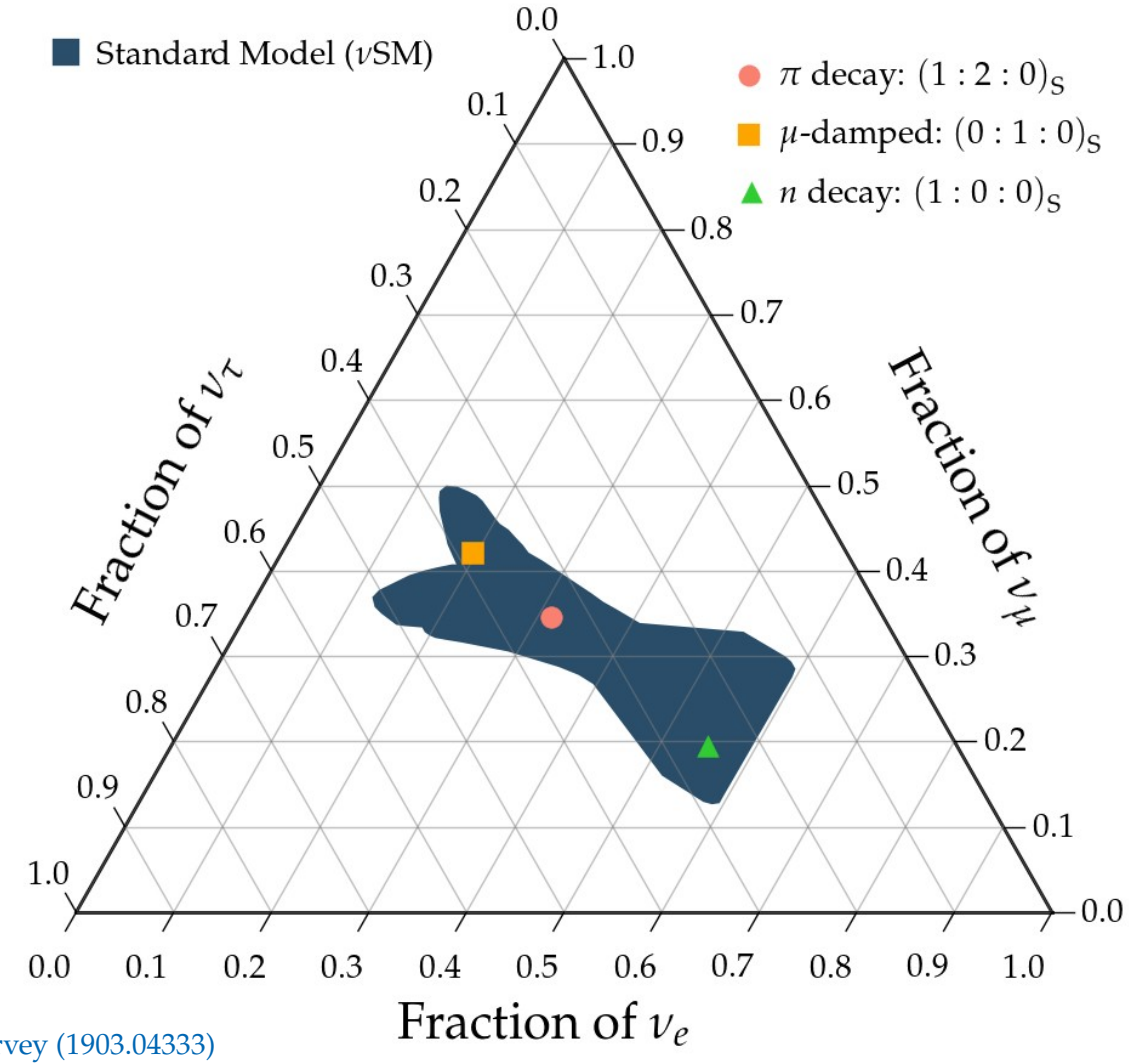
Limitations of our estimates / future work (see 2204.04237 for details):

- Extract cross section, flux normalization, *and* energy spectrum shape (*ongoing*)
- Use unbinned likelihood (*ongoing*)
- Adding secondary lepton interactions to effective volume
- Improving effect of LPM effect in relation between neutrino and shower energy

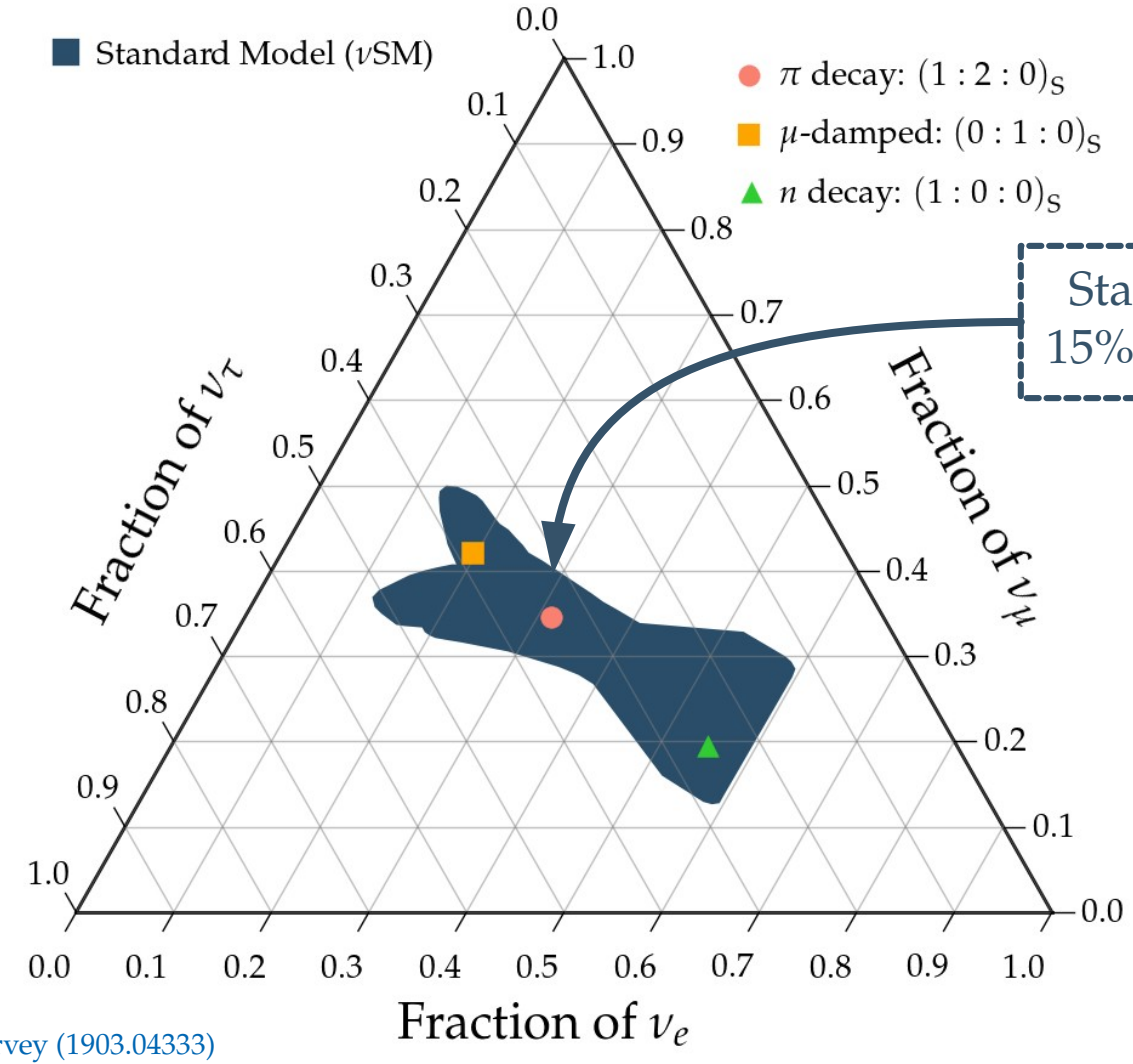
Needed:

- Forecast TeV–PeV cross section measurement in optical array
- Forecast UHE cross section for competing radio array designs (*ongoing*)
- Urgent: estimate background of reflect air-shower cores
  (could be as high as 10 events per year!)


Flavor mixing
IceCube-Gen2



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



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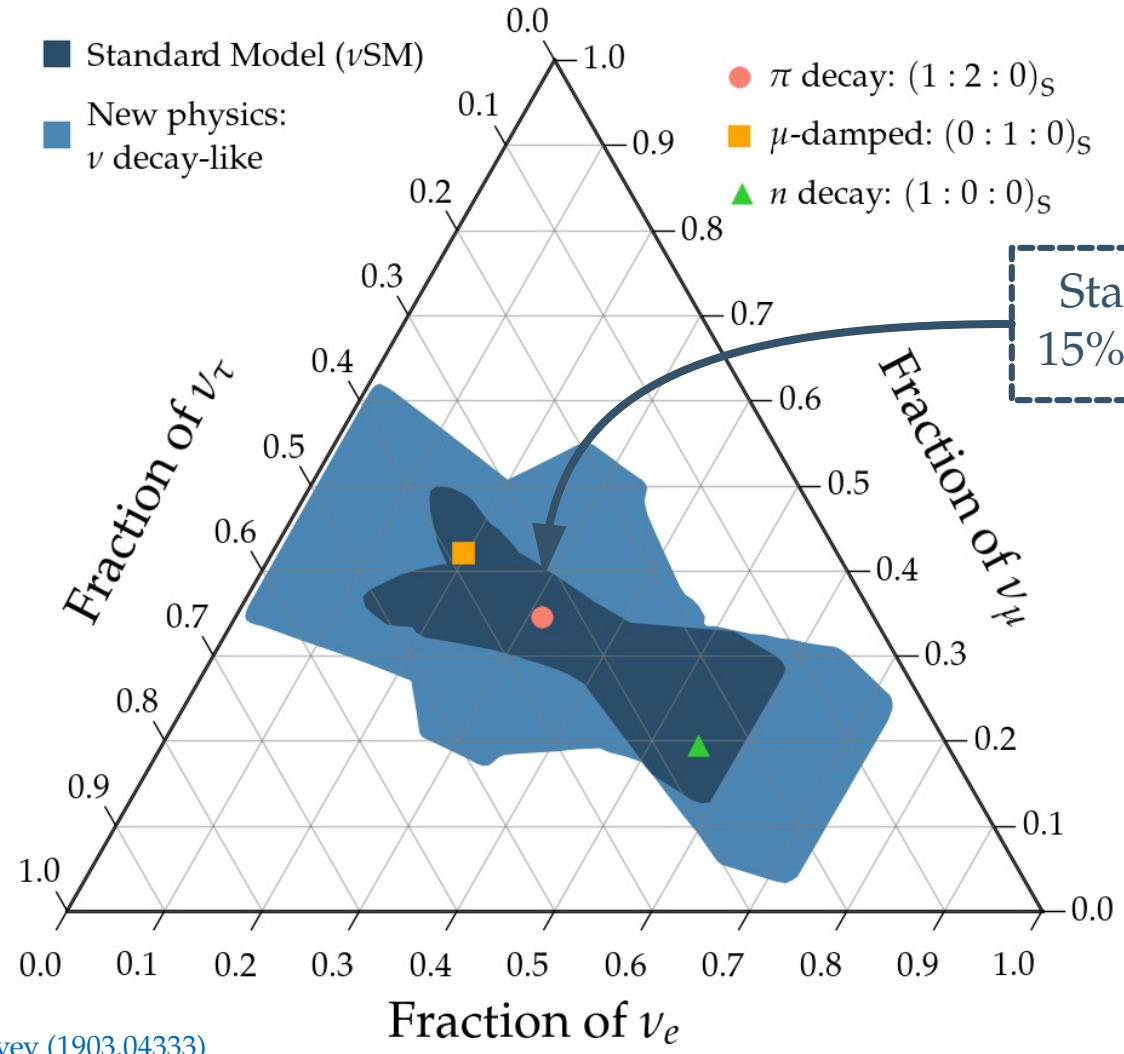

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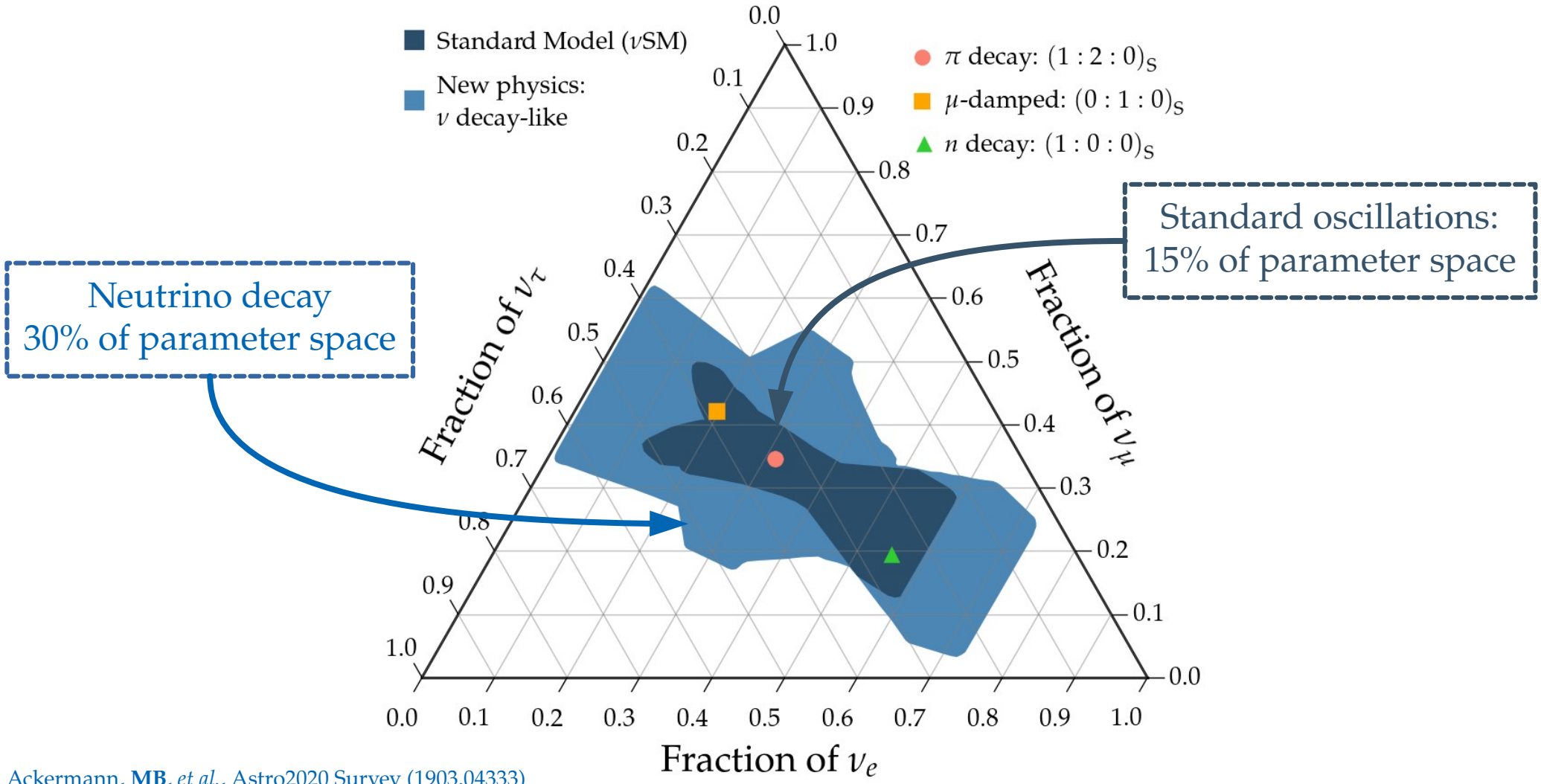

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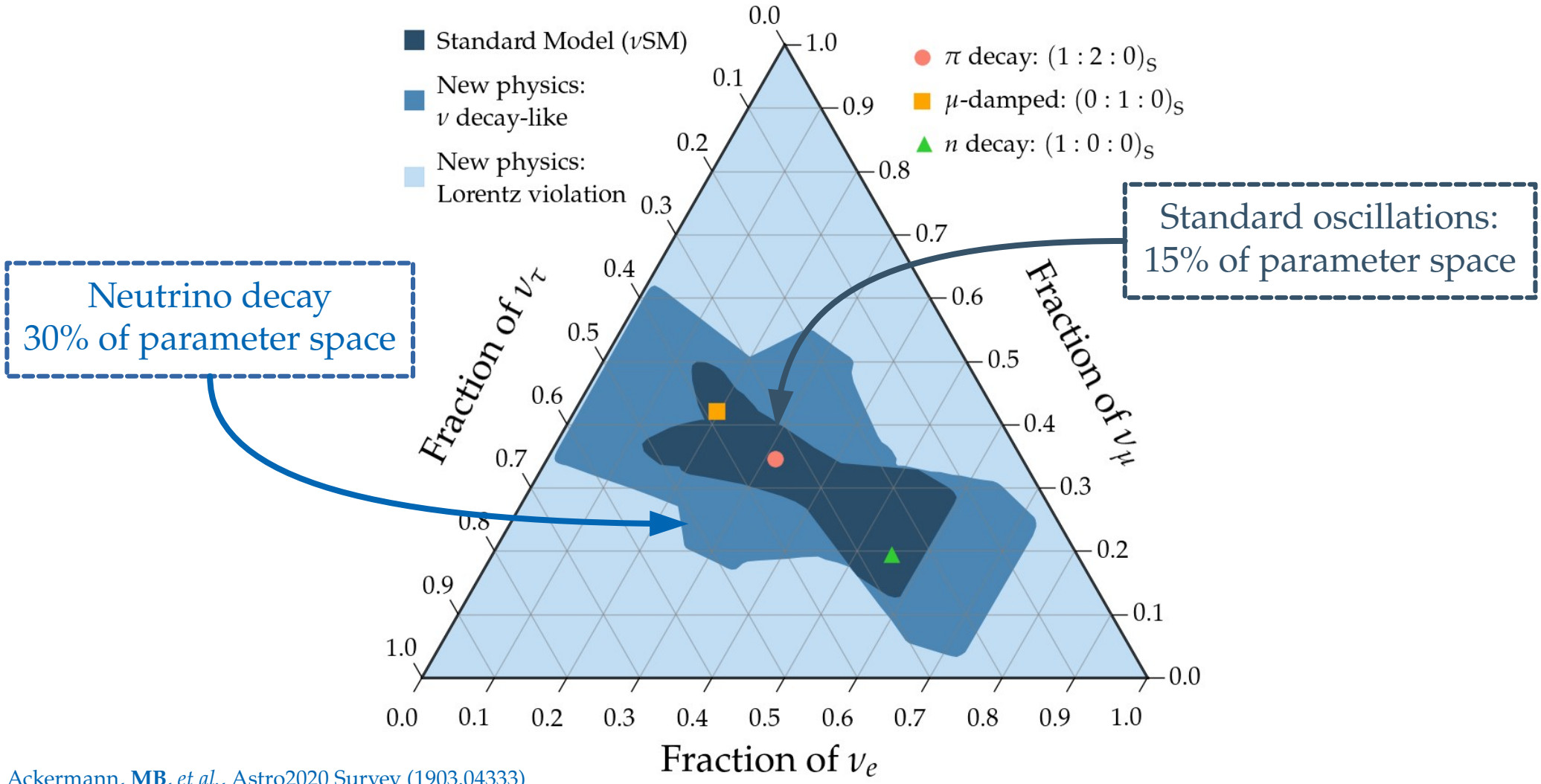

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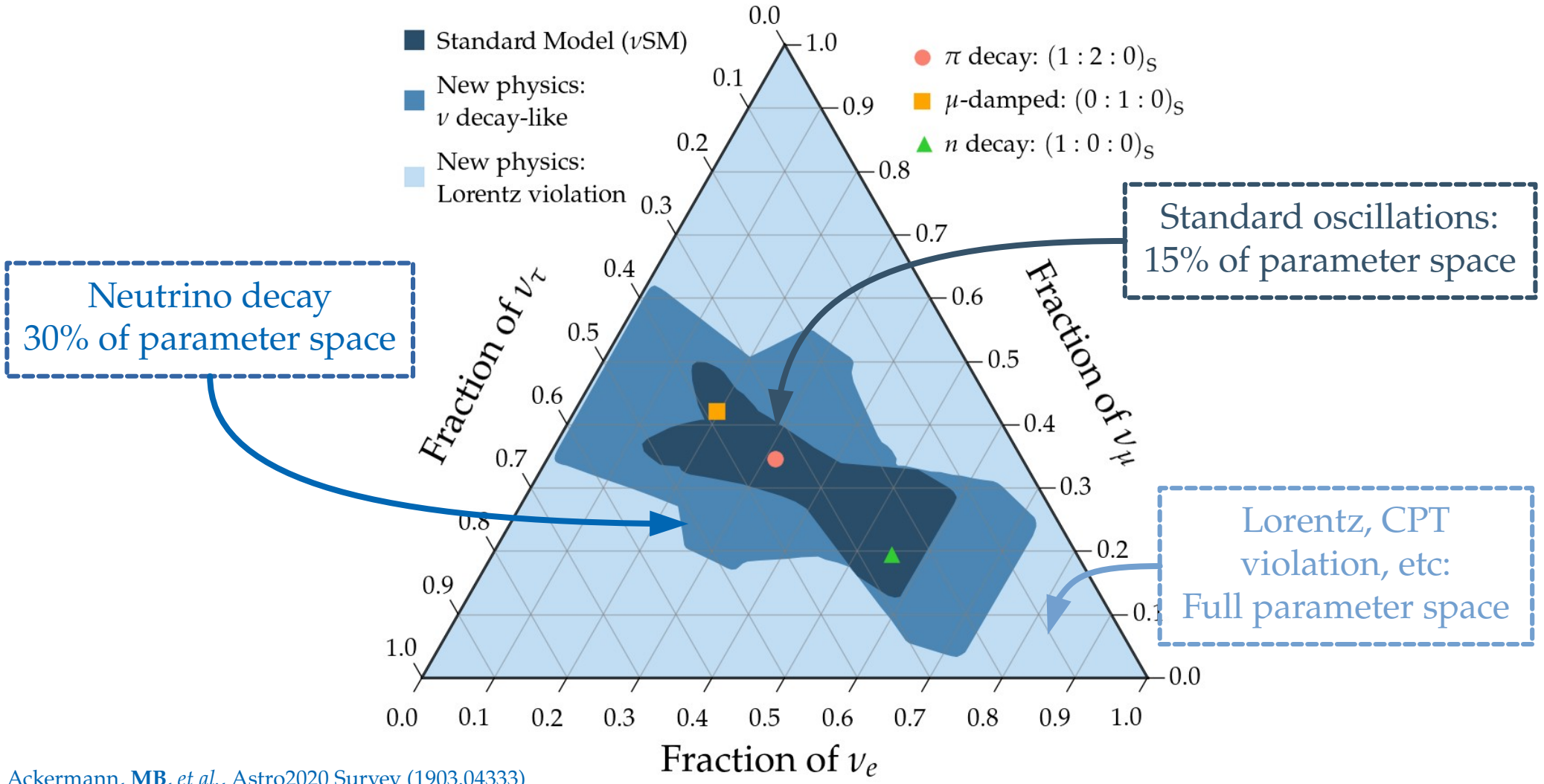

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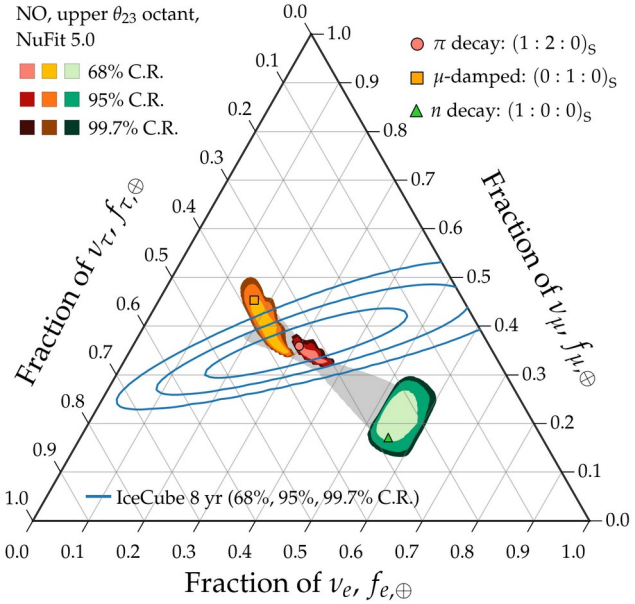
Theoretically palatable regions: 2020 → 2030 → 2040

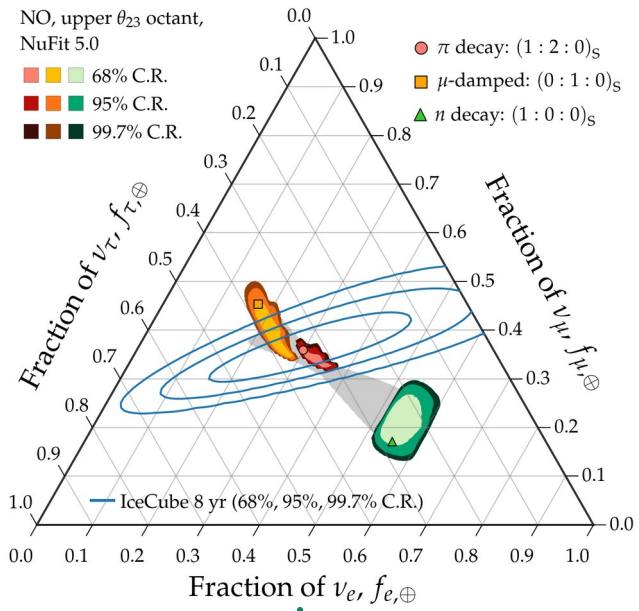
2020



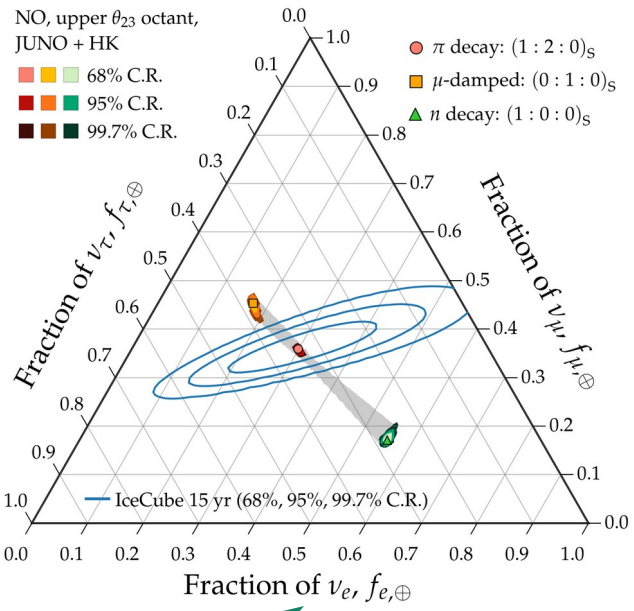
Song, Li, **MB**, Argüelles, Vincent, *JCAP* 2021

Theoretically palatable regions: 2020 → 2030 → 2040

2020



2030



Hyper-K improves θ_{23}

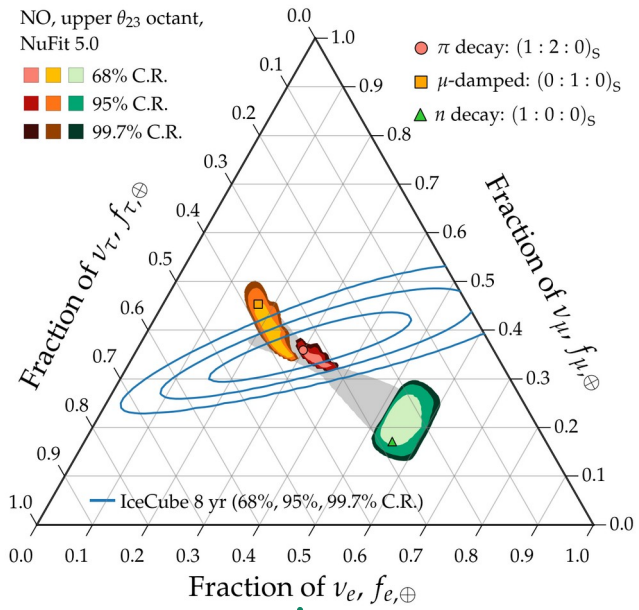
JUNO improves θ_{12}

15 yr of IceCube

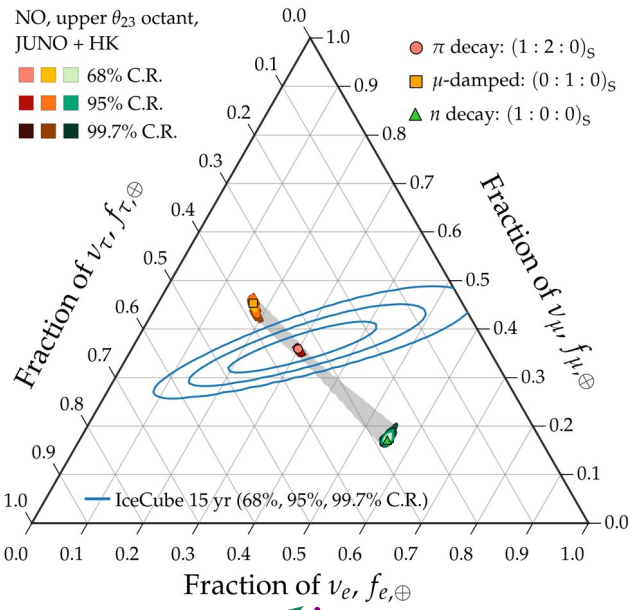
Song, Li, **MB**, Argüelles, Vincent, *JCAP* 2021

Theoretically palatable regions: 2020 → 2030 → 2040

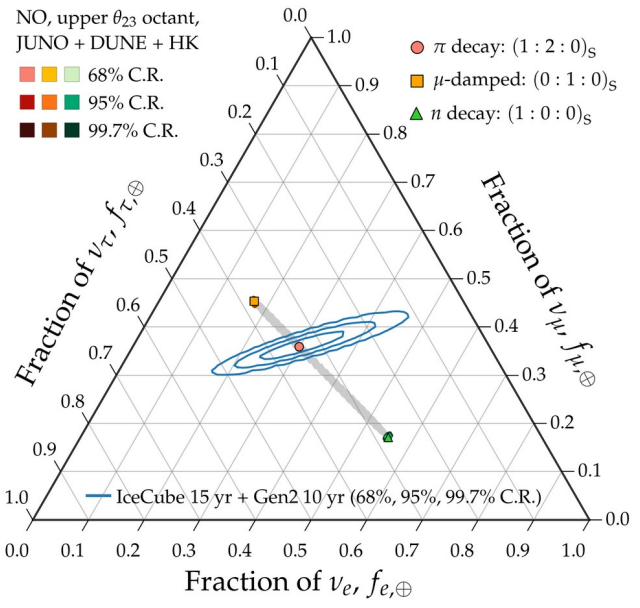
2020



2030



2040



Hyper-K improves θ_{23}

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15 yr of IceCube

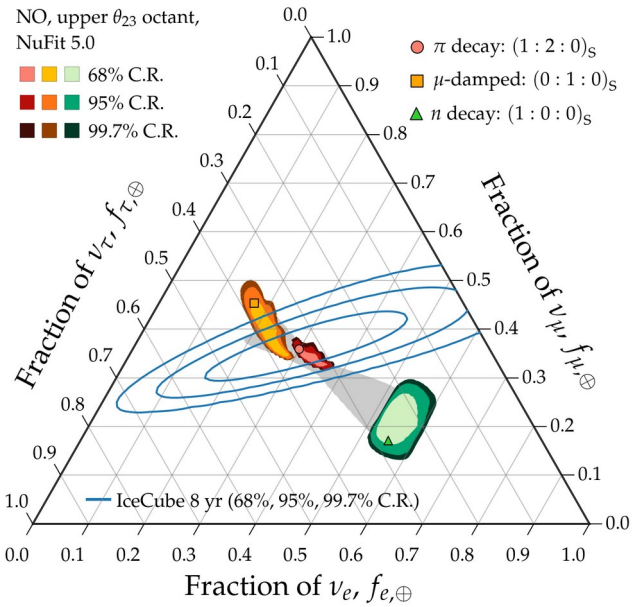
DUNE improves θ_{23}

15 yr of IceCube + 10 yr of Gen2

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

Theoretically palatable regions: 2020 → 2030 → 2040

2020



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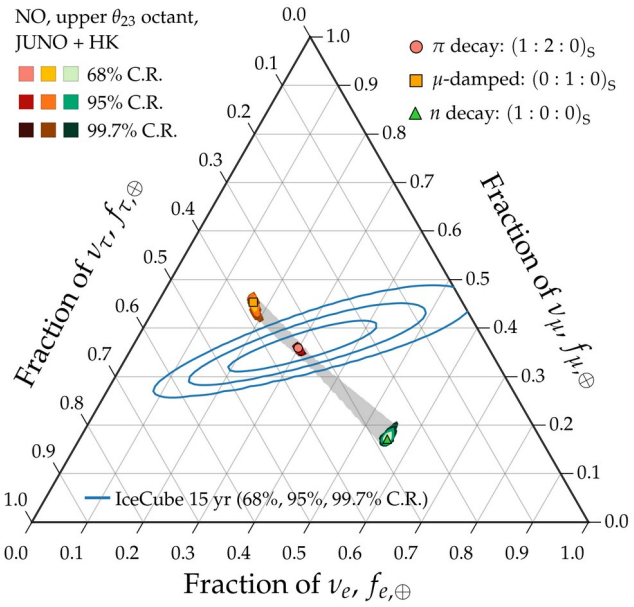

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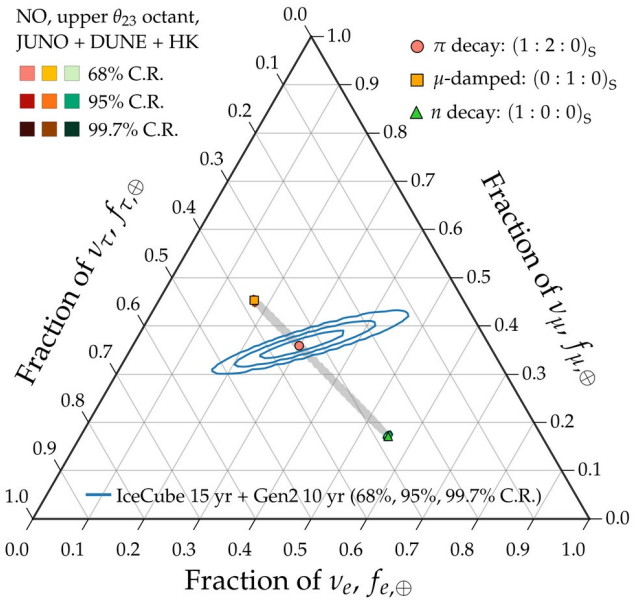

Song, Li, **MB**, Argüelles, Vincent, *JCAP* 2021

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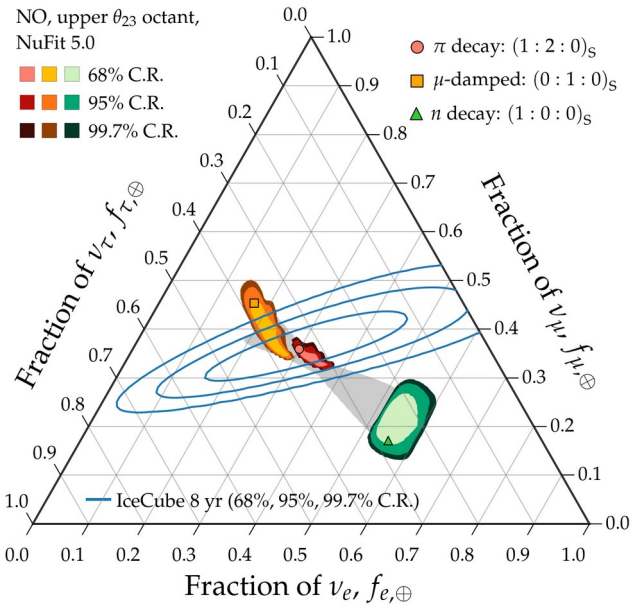

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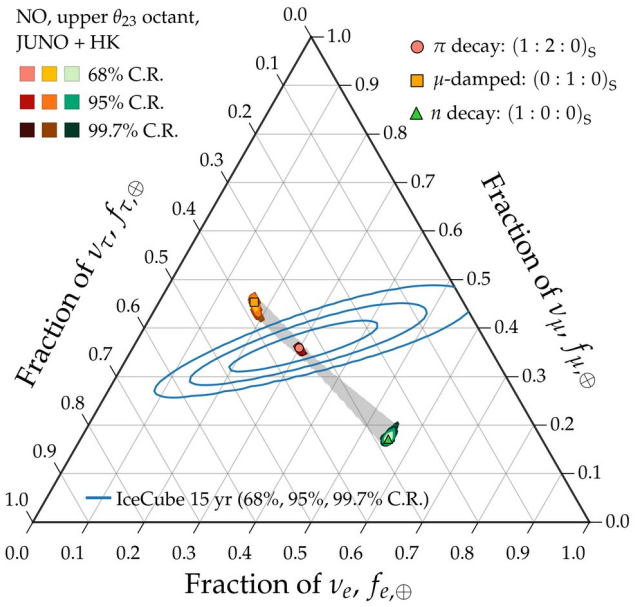
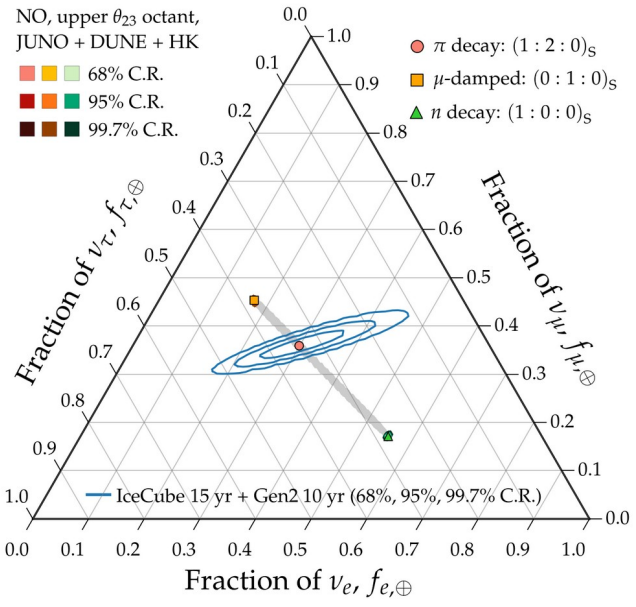


2040



Allowed regions: overlapping

Measurement: imprecise

Not ideal

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

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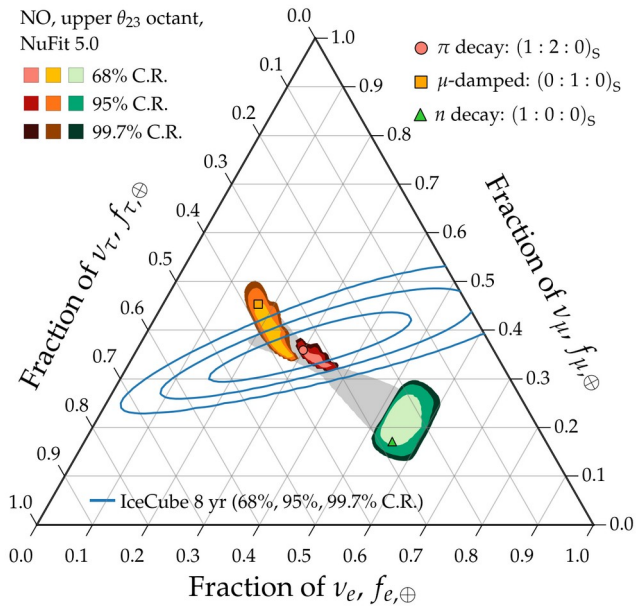
2020



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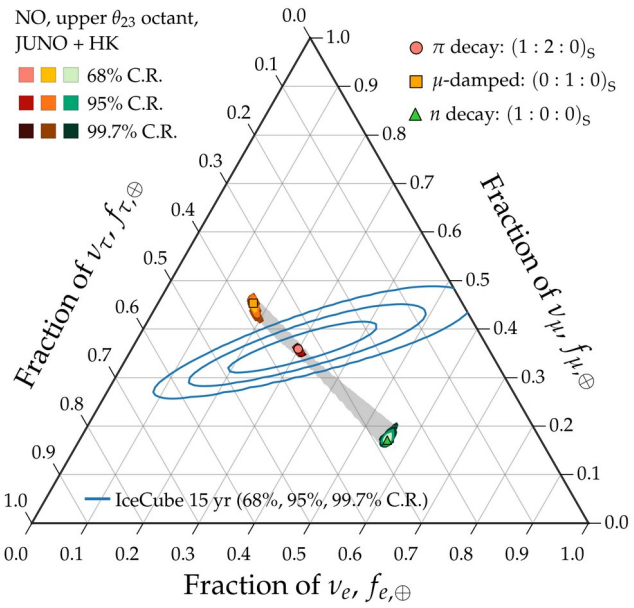
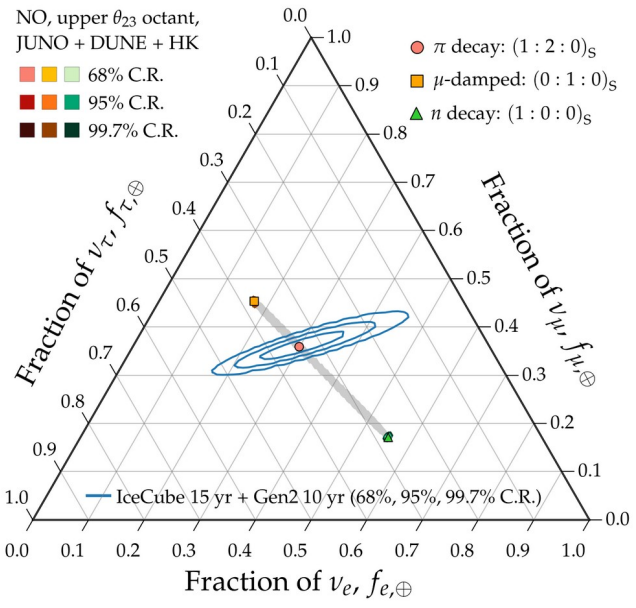


Allowed regions: well separated

Measurement: improving

Nice

2040



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

Theoretically palatable regions: 2020 → 2030 → 2040

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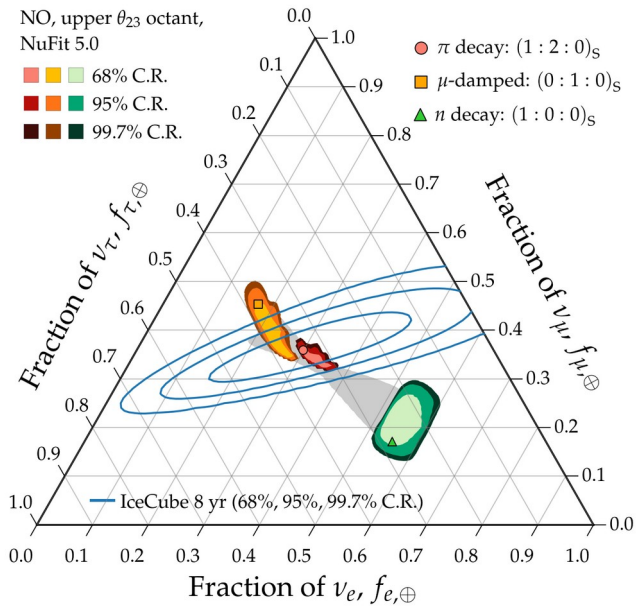

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Measurement: imprecise

Not ideal

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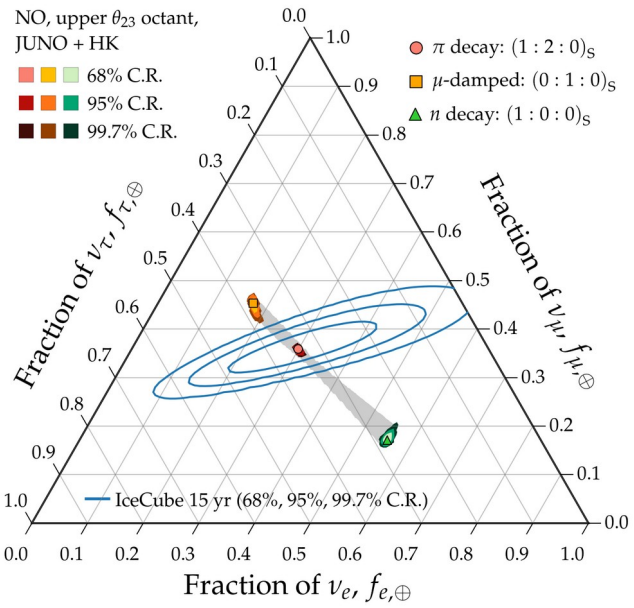

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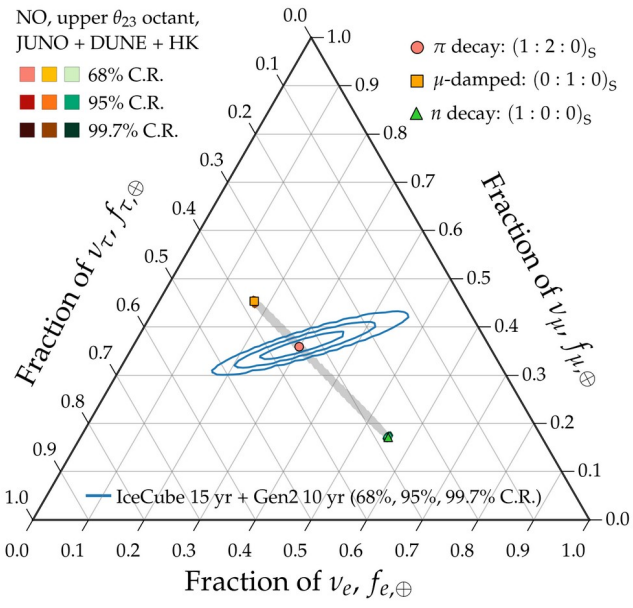
Measurement: improving

Nice

2040



Allowed regions: well separated

Measurement: precise

Success

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

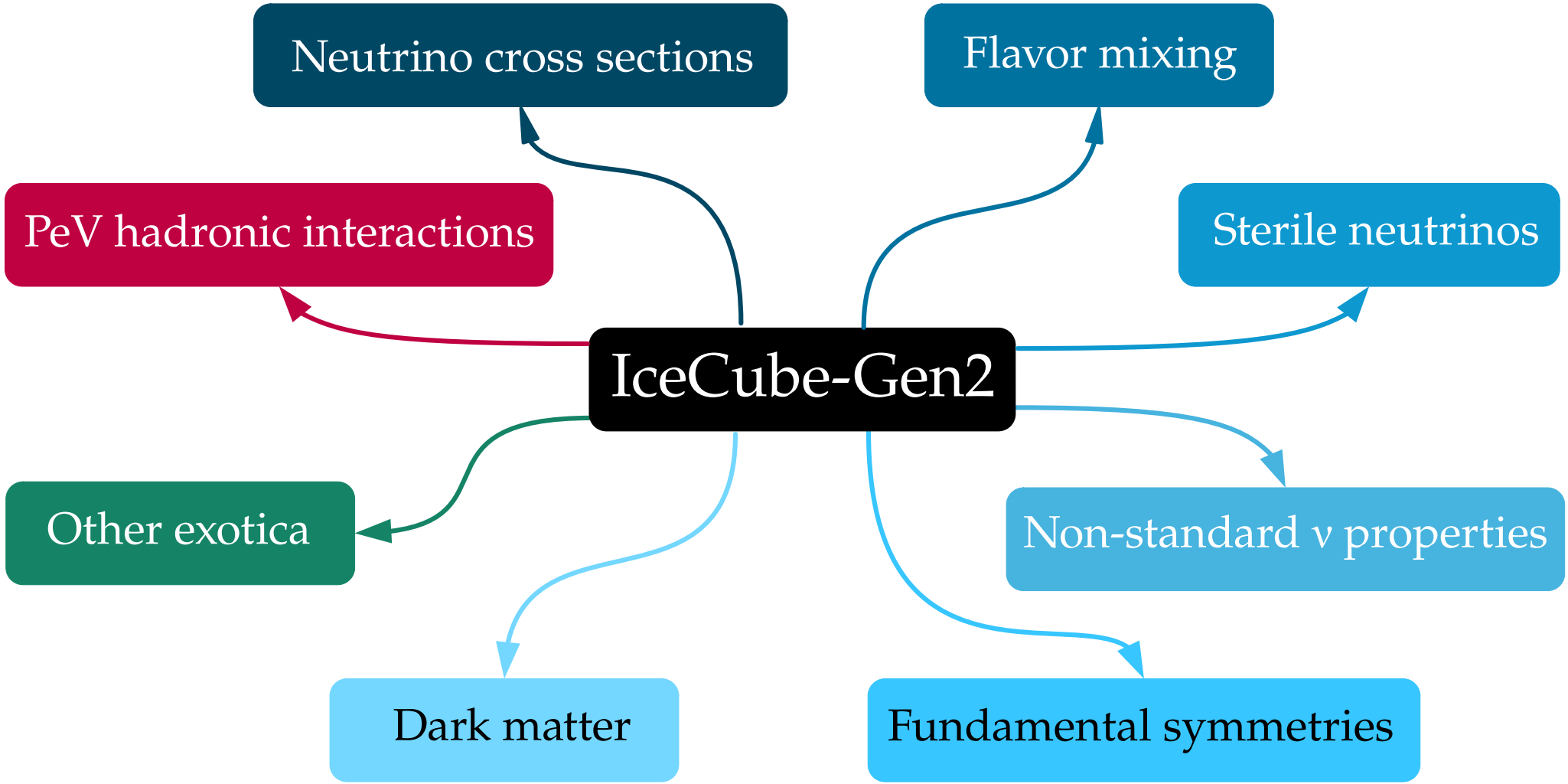
Flavor mixing: outlook

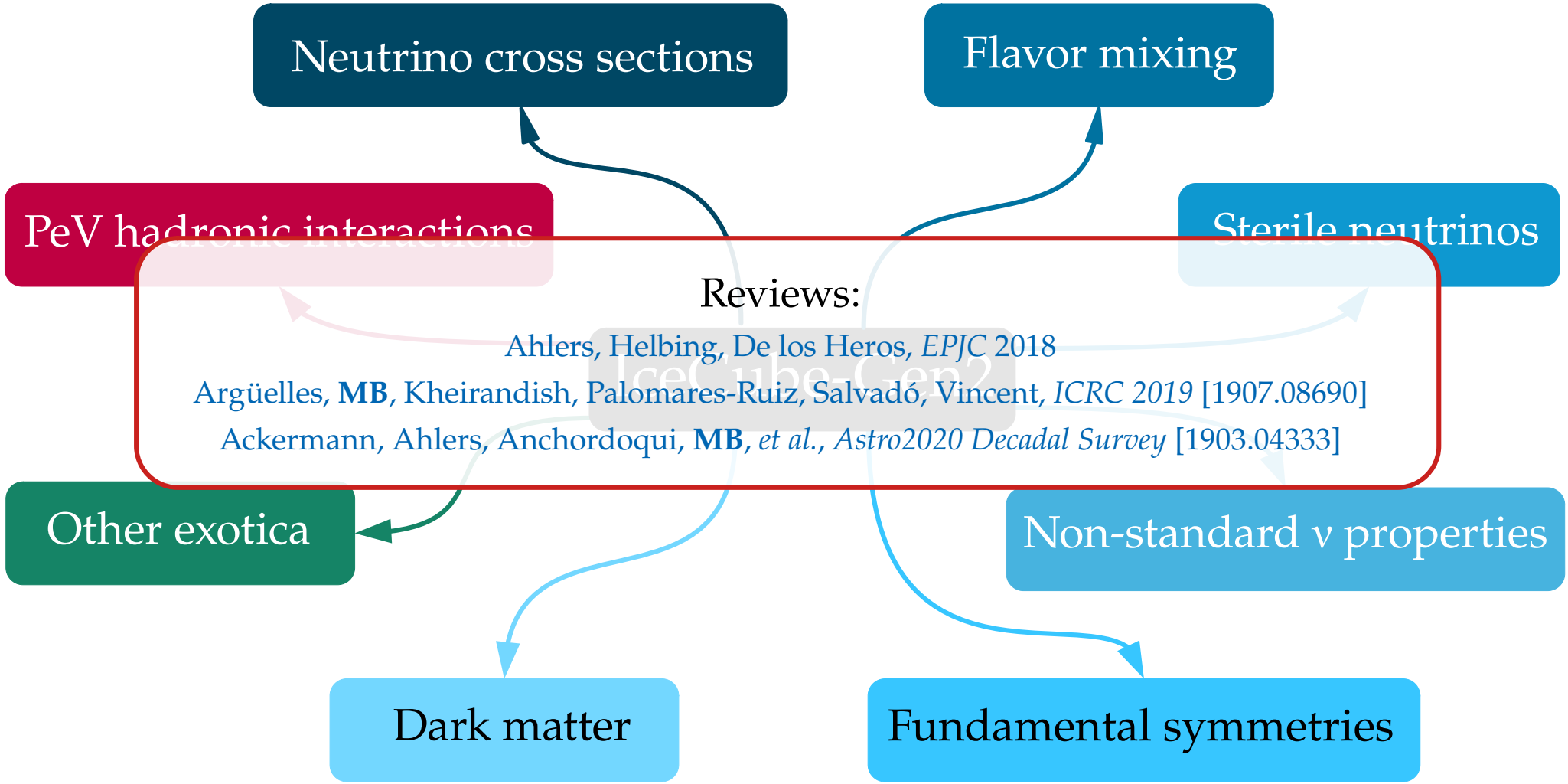
Limitations of our estimates so far:

- Our flavor sensitivity projections are based on early Gen2 estimates
  → Need to be updated for latest Gen2 design
- Not transparent what went into those early Gen2 estimates

Ongoing work:

- Sensitivity to the energy dependence of flavor ratios?
  → Stay tuned [Fiorillo, Liu, Argüelles, MB, Song, Vincent]
- Flavor sensitivity at UHE with radio?
  → Early, but promising [García-Fernández, Nelles, Glaser, *PRD* 2020; Stjärnholm, Ericsson, Glaser, ICRC 2021]


Neutrino cross sections
Flavor mixing
PeV hadronic interactions
Sterile neutrinos
IceCube-Gen2
Other exotica
Non-standard ν properties
Dark matter
Fundamental symmetries


Neutrino cross sections
Flavor mixing
PeV hadronic interactions
Sterile neutrinos
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]
Other exotica
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High energy
TeV–PeV ν

Gen2 offers improved statistics

We know the diffuse flux already!

Maintain roughly the same energy and angular resolution of IceCube

Gen2 optical array can still be optimized for diffuse and point-source searches

"Guaranteed" sensitivity to more subtle particle-physics effects

Ultra-high energy
> 100-PeV ν

Gen2 offers a chance of discovery

Particle physics possible only if we discover UHE neutrinos

Naively, three competing thrusts:

Diffuse flux discovery

vs. Point-source discovery

vs. Particle-physics studies

Find a three-way compromise for the Gen2 radio array design

High energy
TeV–PeV ν

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Particle physics possible only if we discover UHE neutrinos

Naively, three competing thrusts:

Diffuse flux discovery

vs. Point-source discovery

vs. Particle-physics studies

(Ongoing work is promising!)

Find a three-way compromise for the Gen2 radio array design

End

Backup slides

Fundamental physics with HE cosmic neutrinos

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

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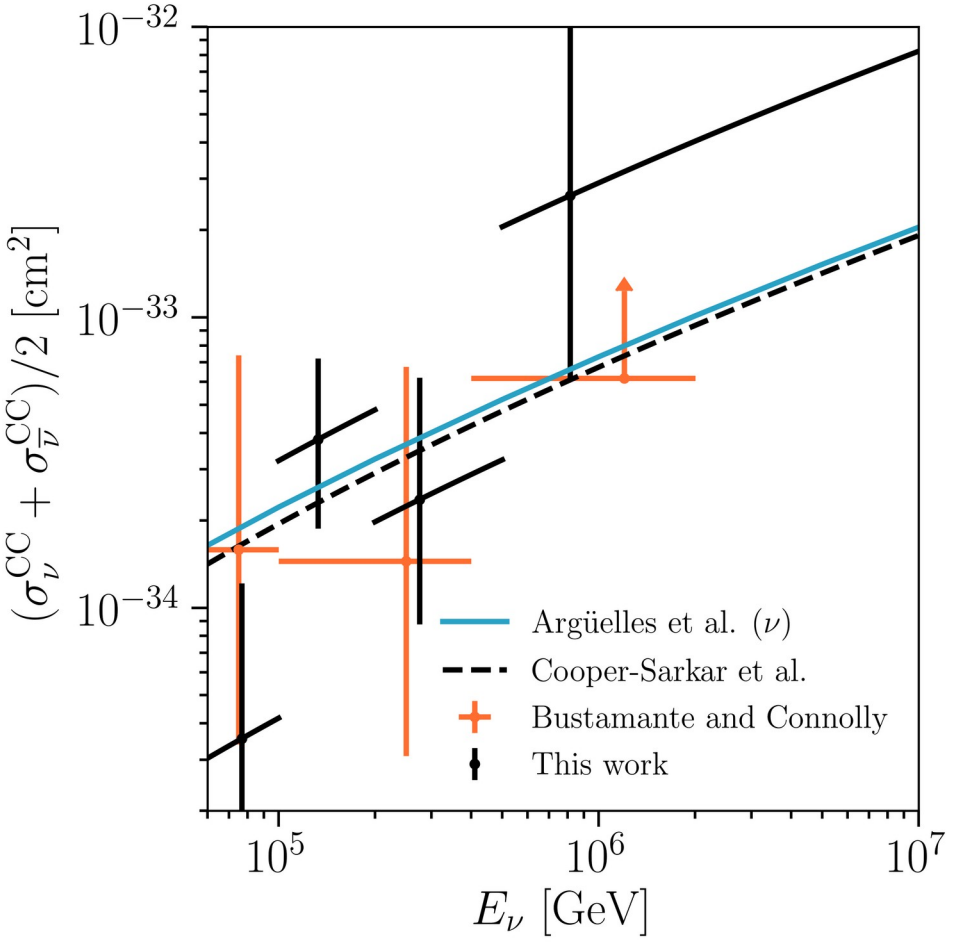
- Fundamental physics can be extracted from four neutrino observables:
  - Spectral shape
  - Angular distribution
  - Flavor composition
  - Timing

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

Updated cross section measurement

- Uses 7.5 years of IceCube data
- Uses starting showers + tracks
  - *Vs.* starting showers only in Bustamante & Connolly 2017
  - *Vs.* throughoing 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

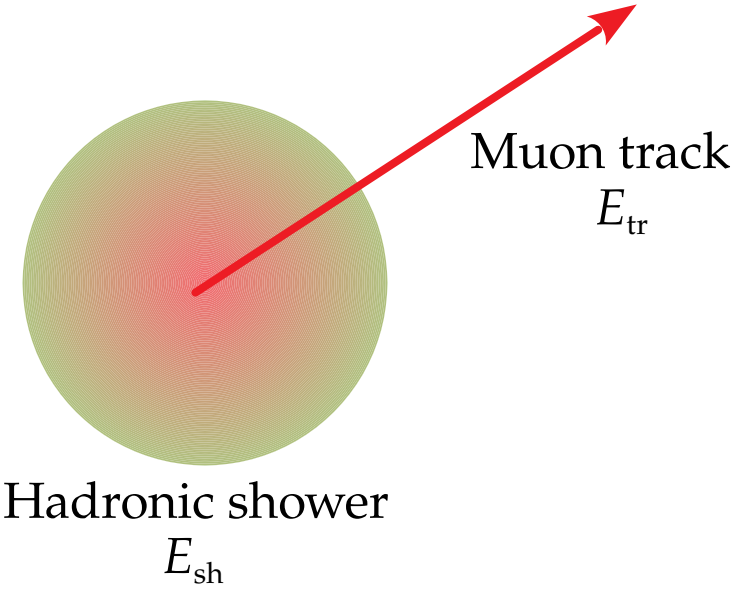
Bonus: Measuring the inelasticity $\langle y \rangle$

- Inelasticity in CC ν_μ interaction $\nu_\mu + N \rightarrow \mu + X$:
  $E_X = y\,E_\nu$ and $E_\mu = (1\text{-}y)\,E_\nu \Rightarrow y = (1 + E_\mu/E_X)^{-1}$

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

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

- 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

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

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

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

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

- In a HESE starting track:

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

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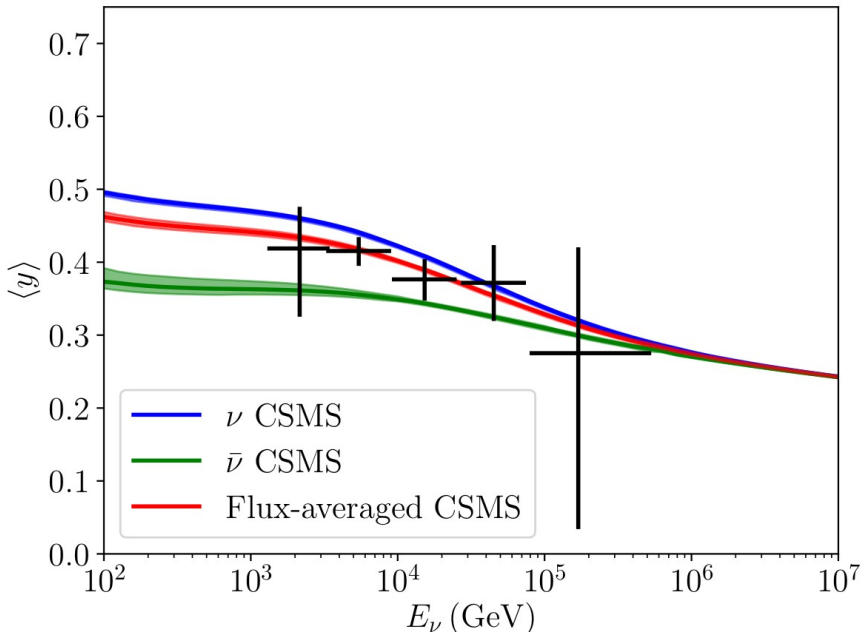


IceCube, *PRD* 2019

νSI with the UHE diffuse flux

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

Coupling matrix:

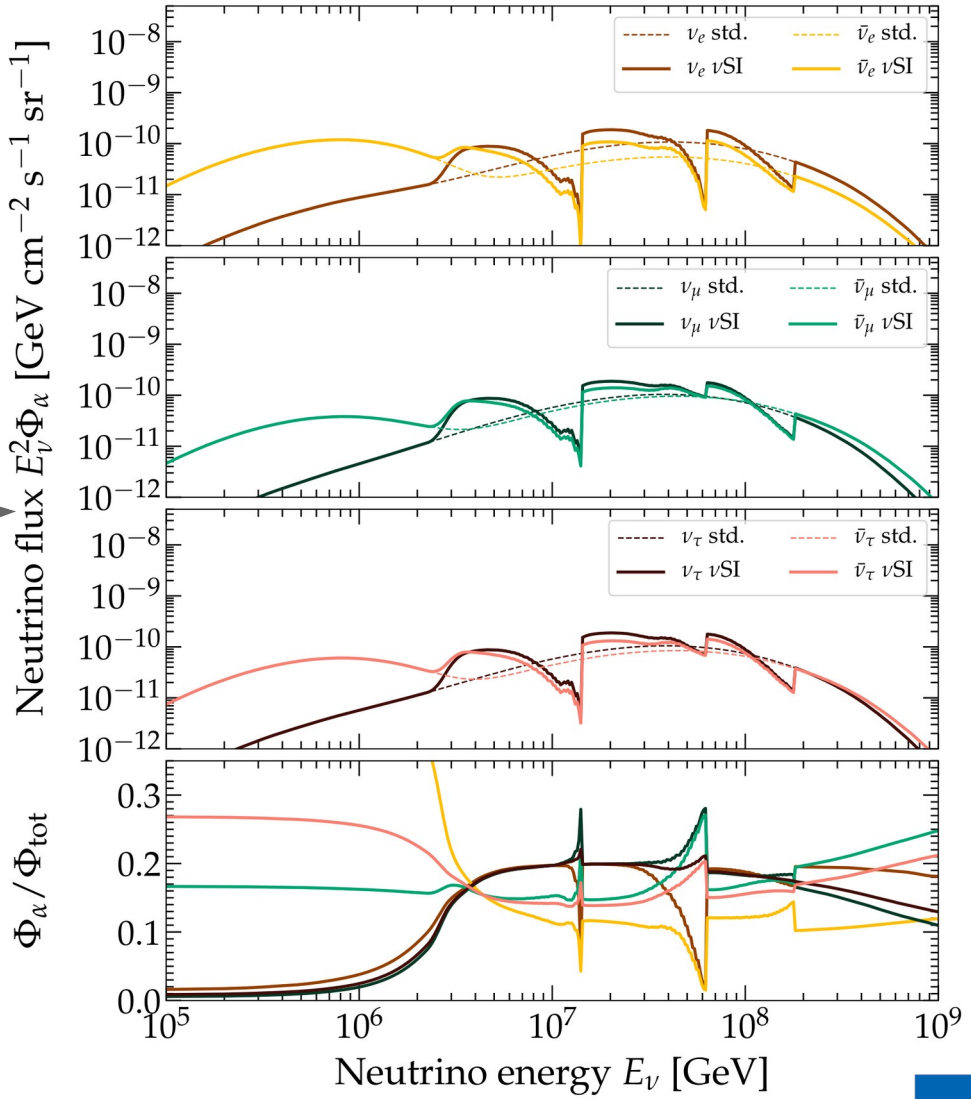
$$\mathbf{G} \equiv \begin{pmatrix} g_{ee} & g_{e\mu} & g_{e\tau} \\ g_{e\mu} & g_{\mu\mu} & g_{\mu\tau} \\ g_{e\tau} & g_{\mu\tau} & g_{\tau\tau} \end{pmatrix}$$

Different flavors can have different couplings

νSI dips and bumps in the diffuse UHE ν flux:

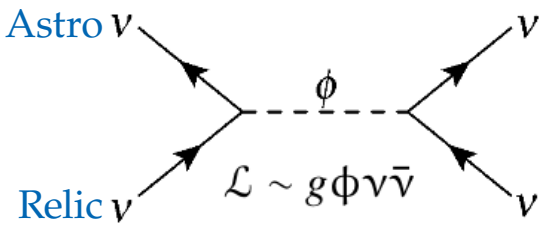
- In the cosmogenic flux
- In the flux from sources

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: $l_{\rm int}(E) = [n_{\rm C\nu B}\sigma_{\nu\nu}(E)]^{-1}$

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

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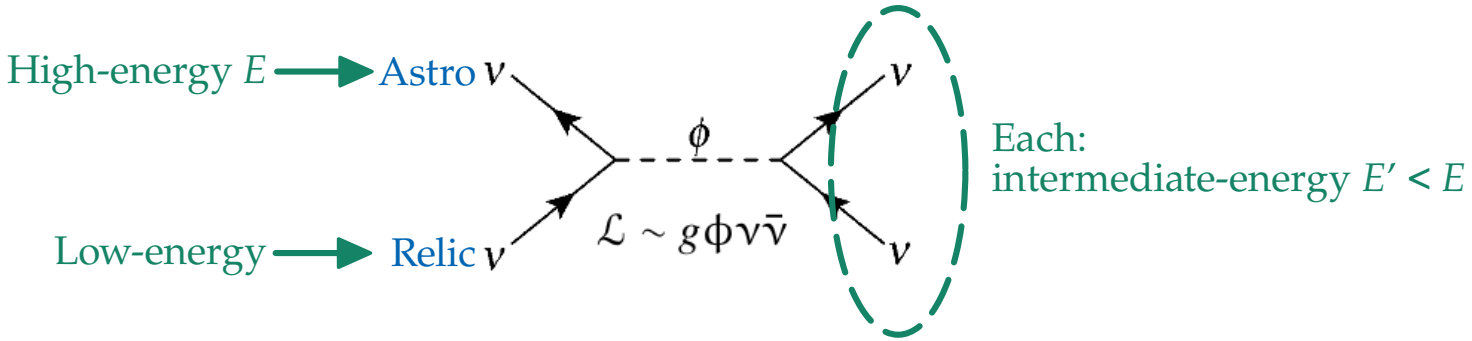

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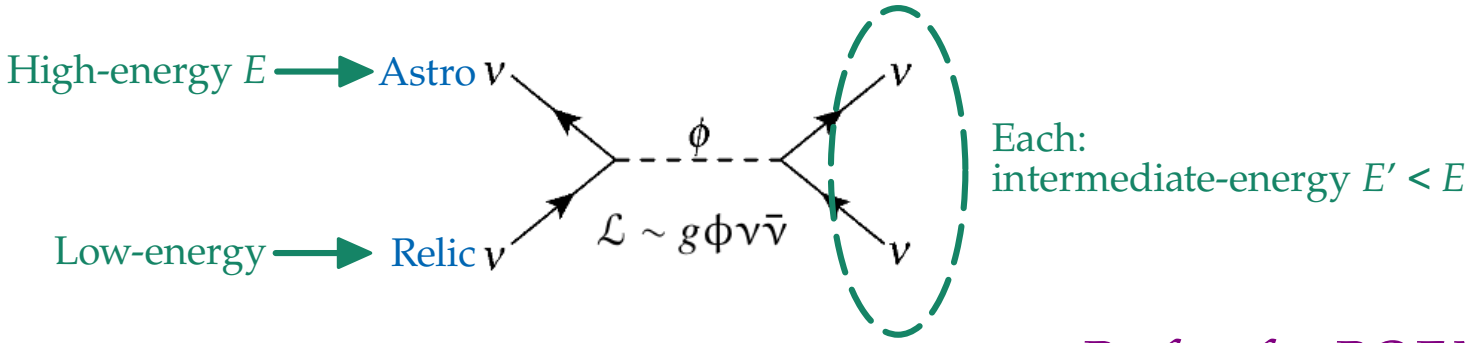

Perfect for POEMMA!

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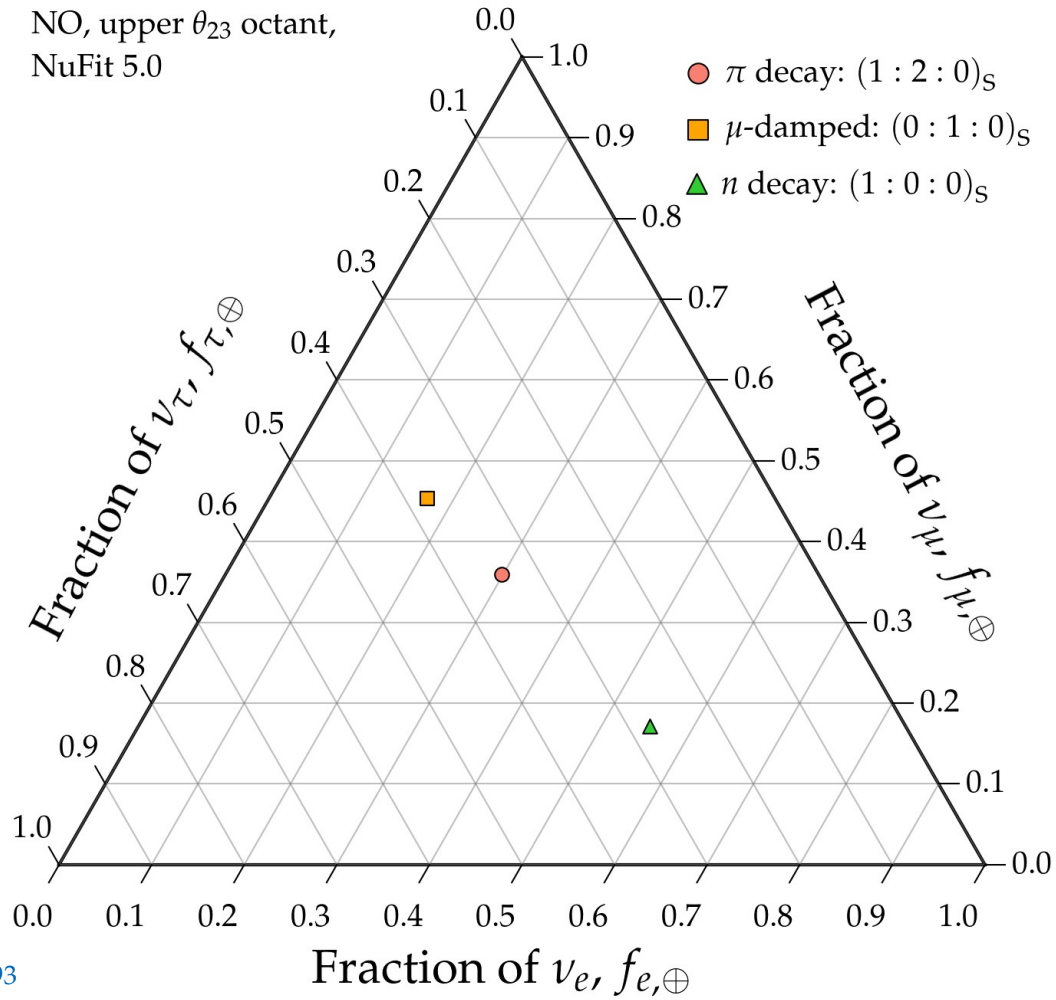
Theoretically palatable regions: today (2020)



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

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

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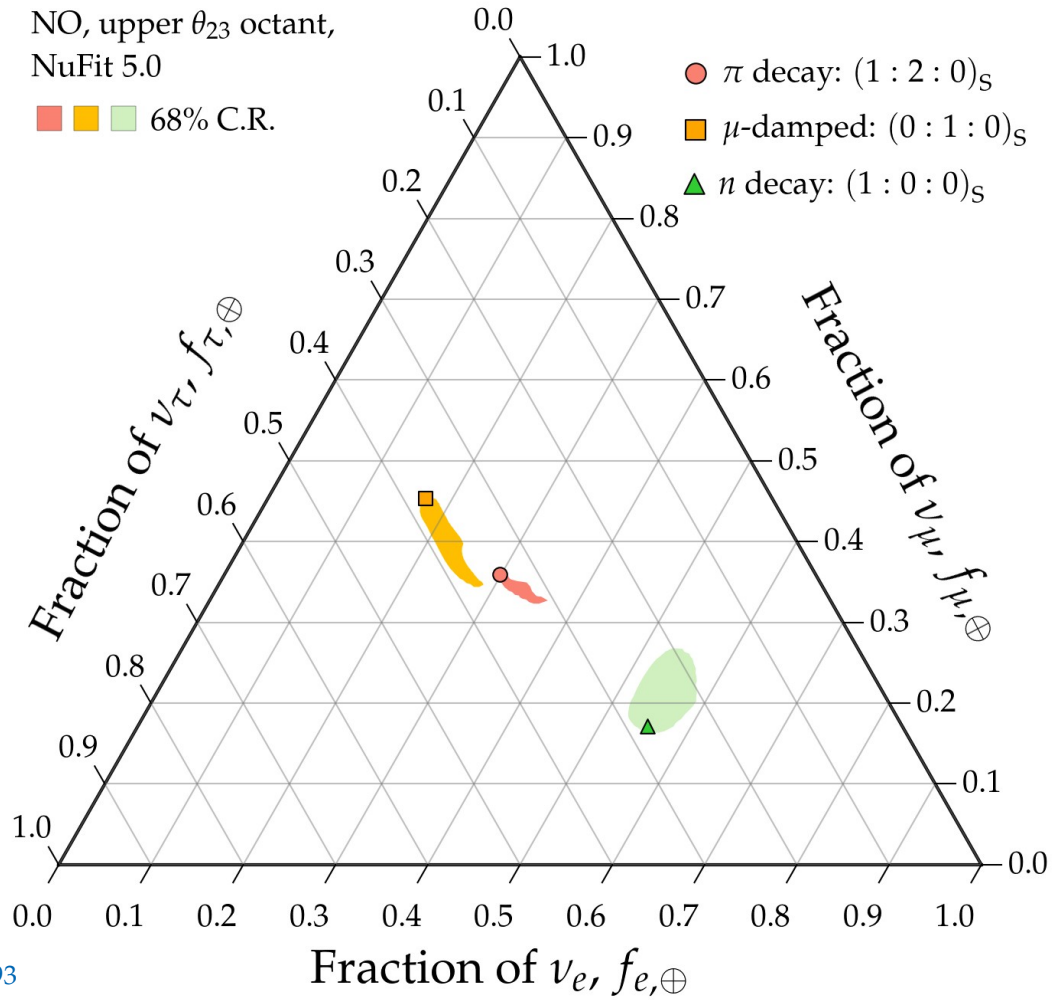

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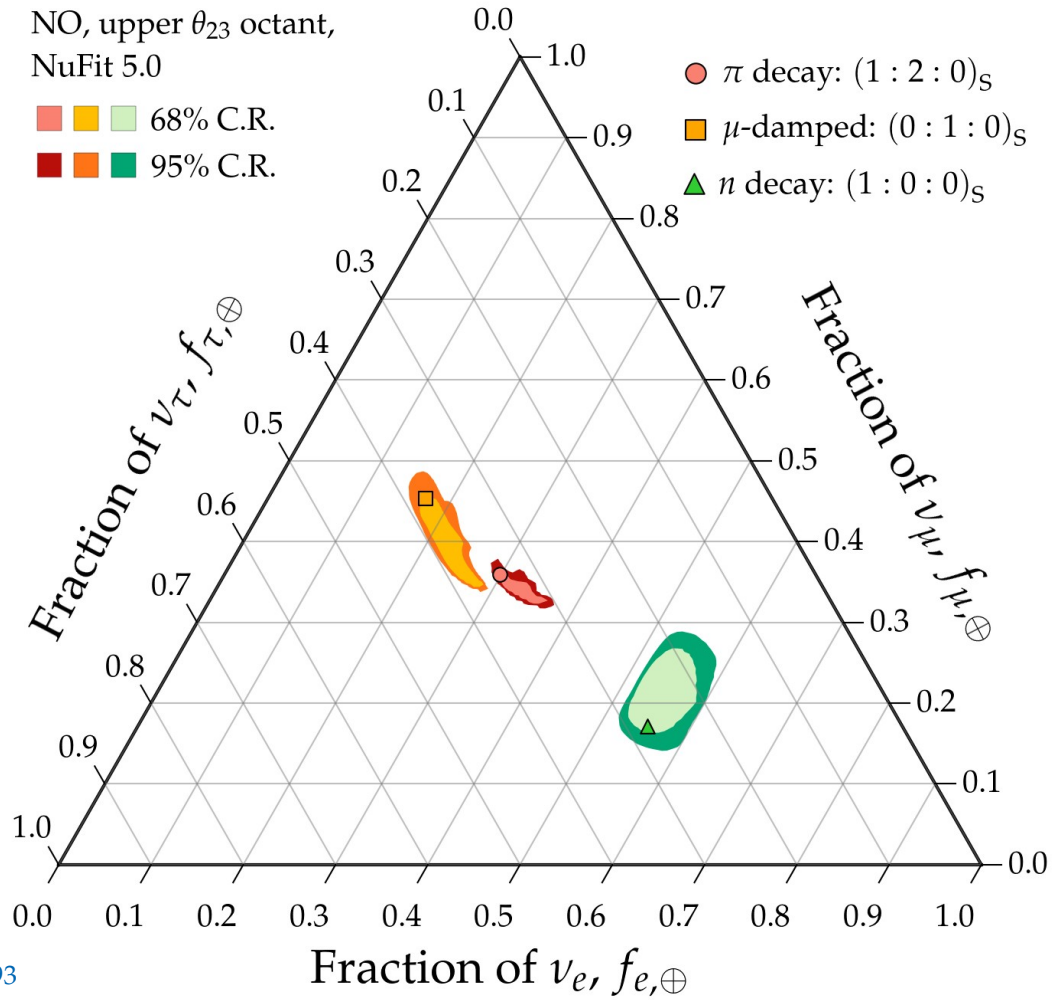

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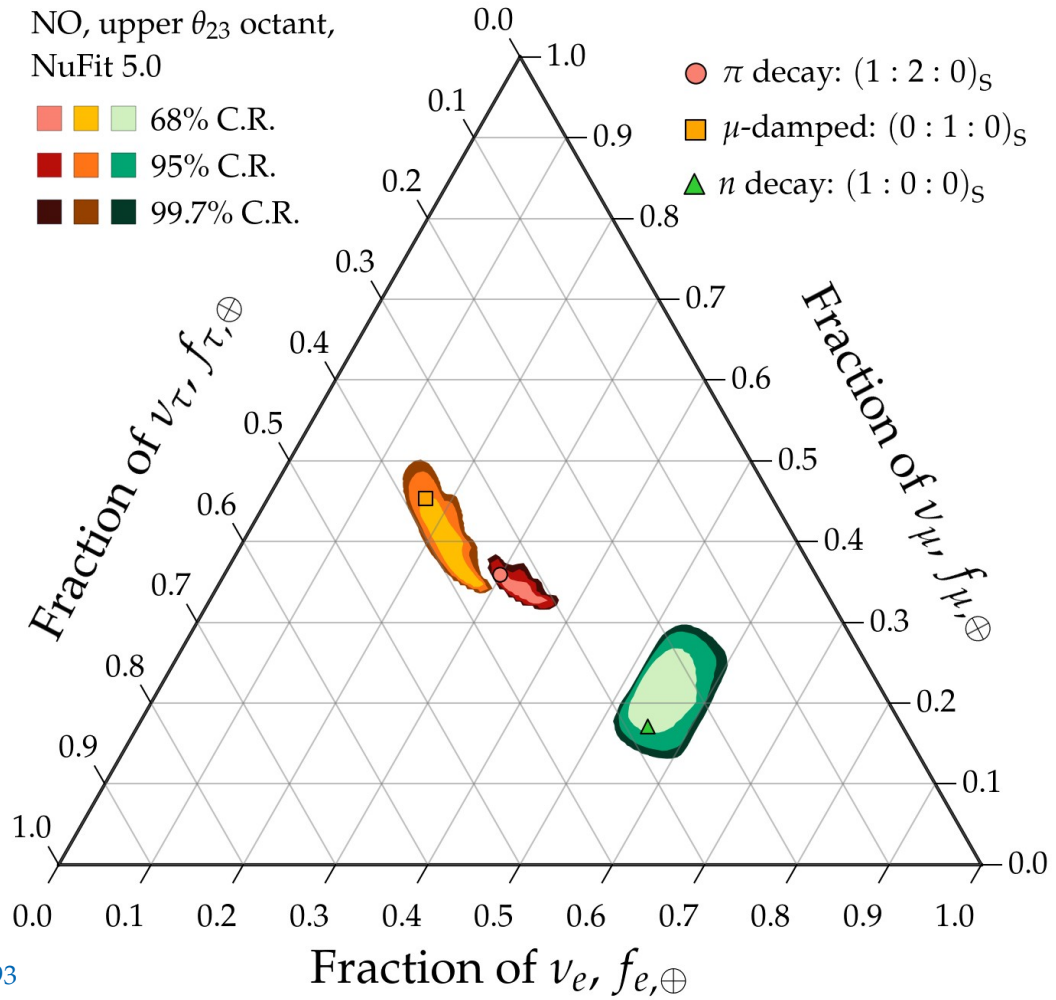

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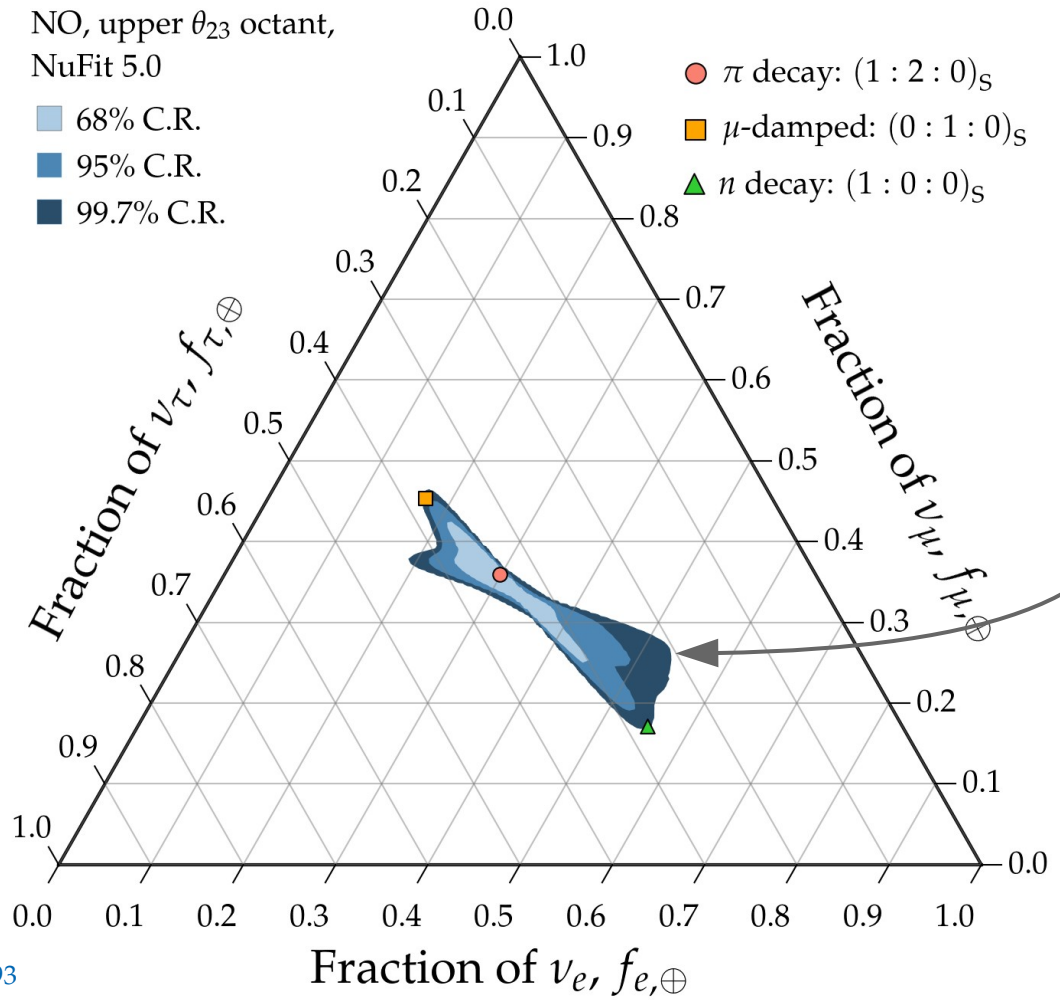

Varying over all possible flavor ratios at the source

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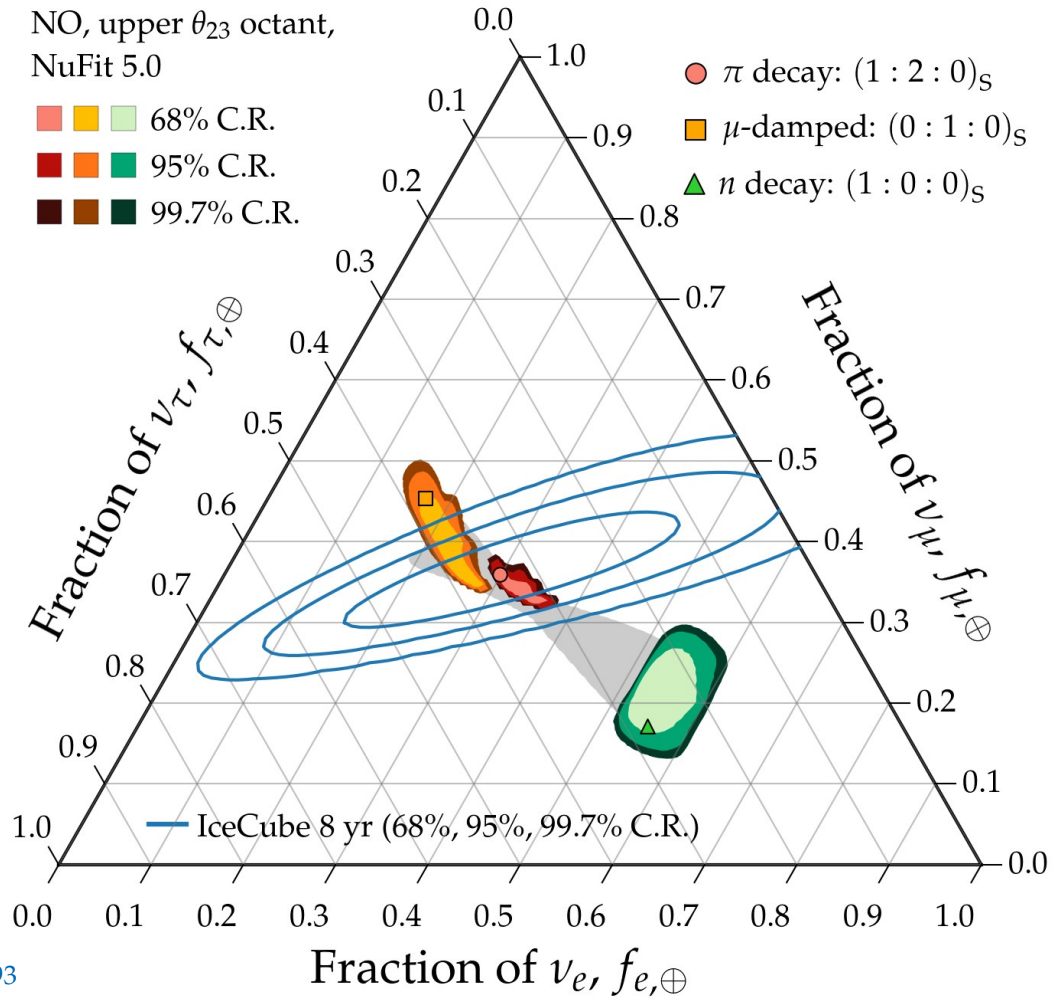

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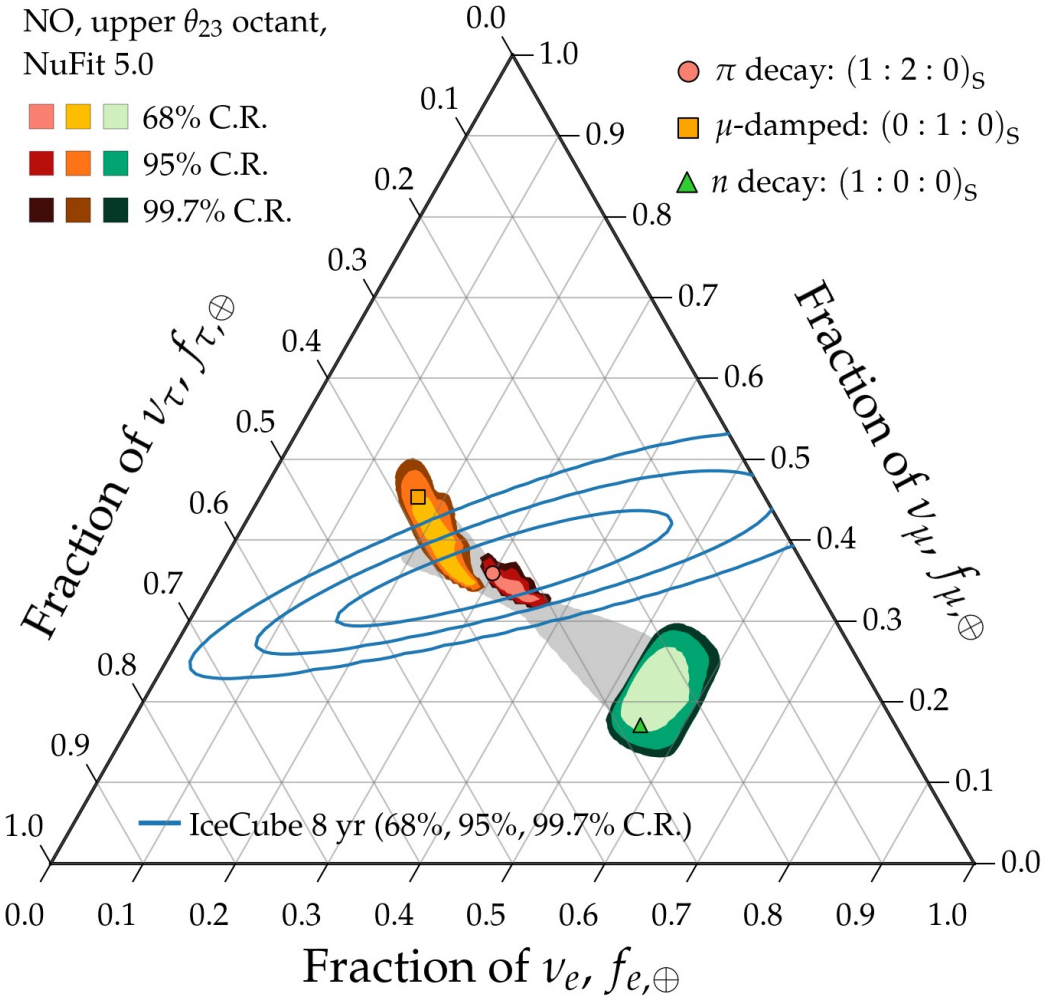

Two limitations:

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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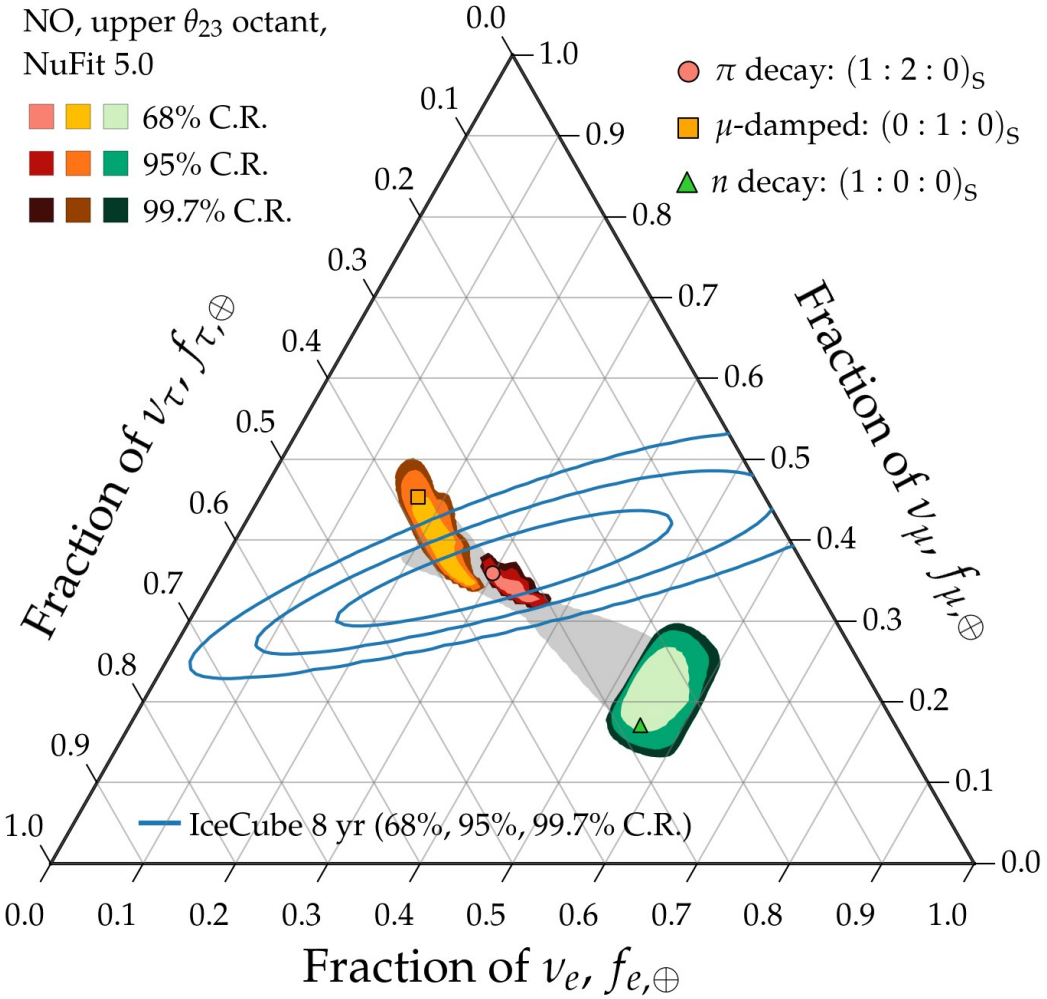

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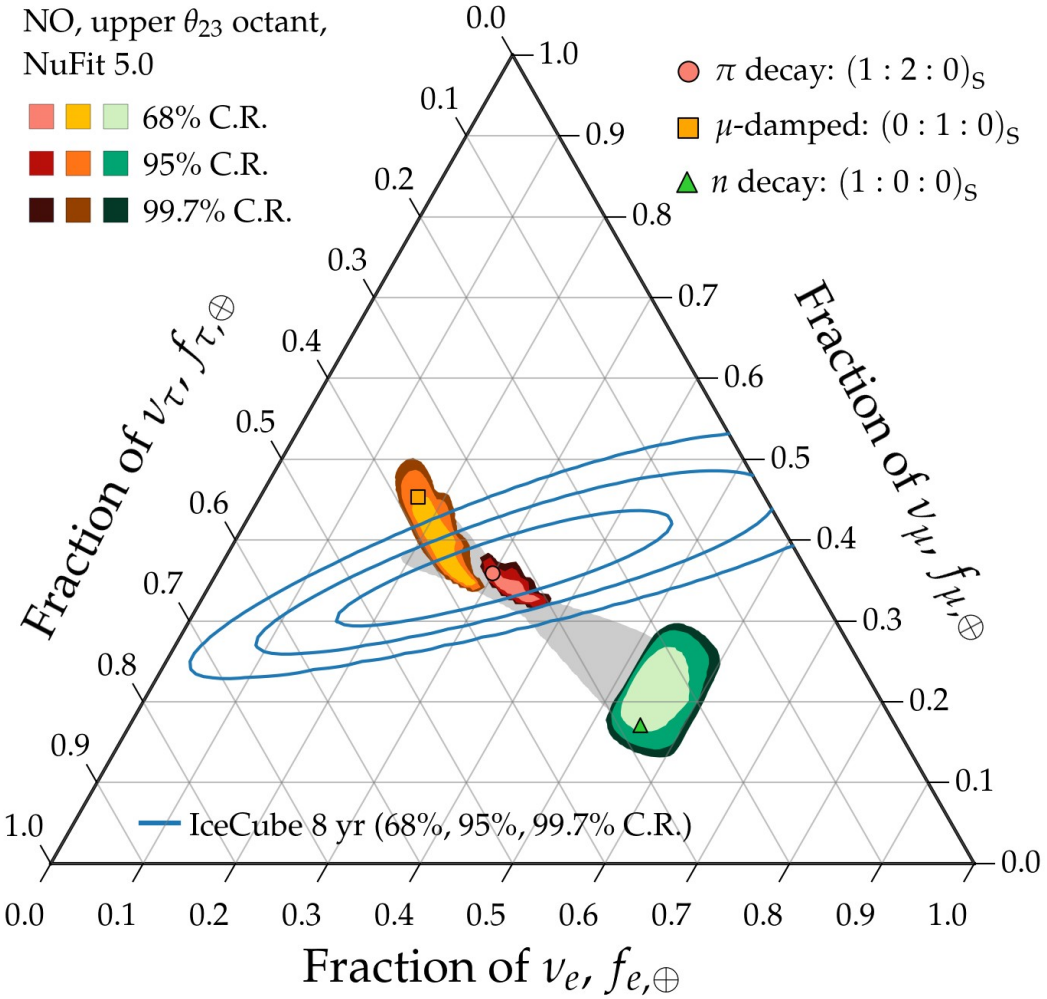

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Flavor at the Earth: *theoretically palatable regions*

Theoretically palatable flavor regions

≡

Allowed regions of flavor ratios at Earth derived from oscillations

MB, Beacom, Winter, *PRL* 2015

Note:
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Ingredient #1:

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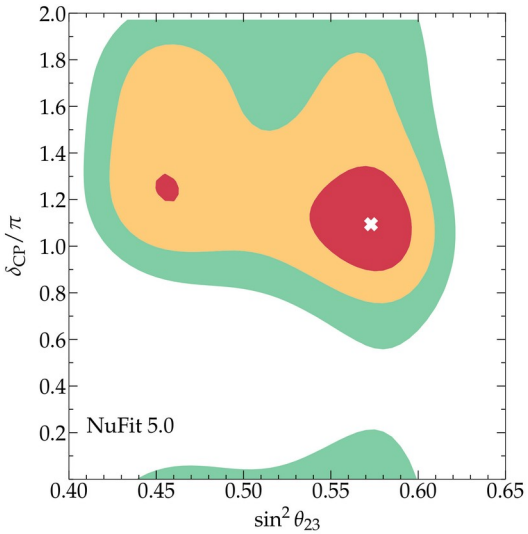
Esteban *et al.*, *JHEP* 2020
www.nu-fit.org



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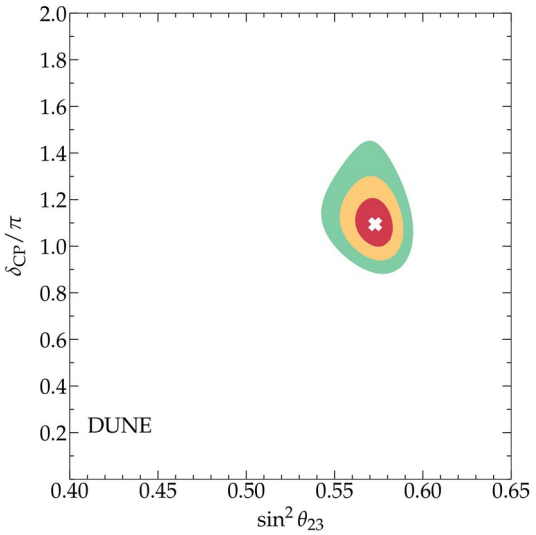
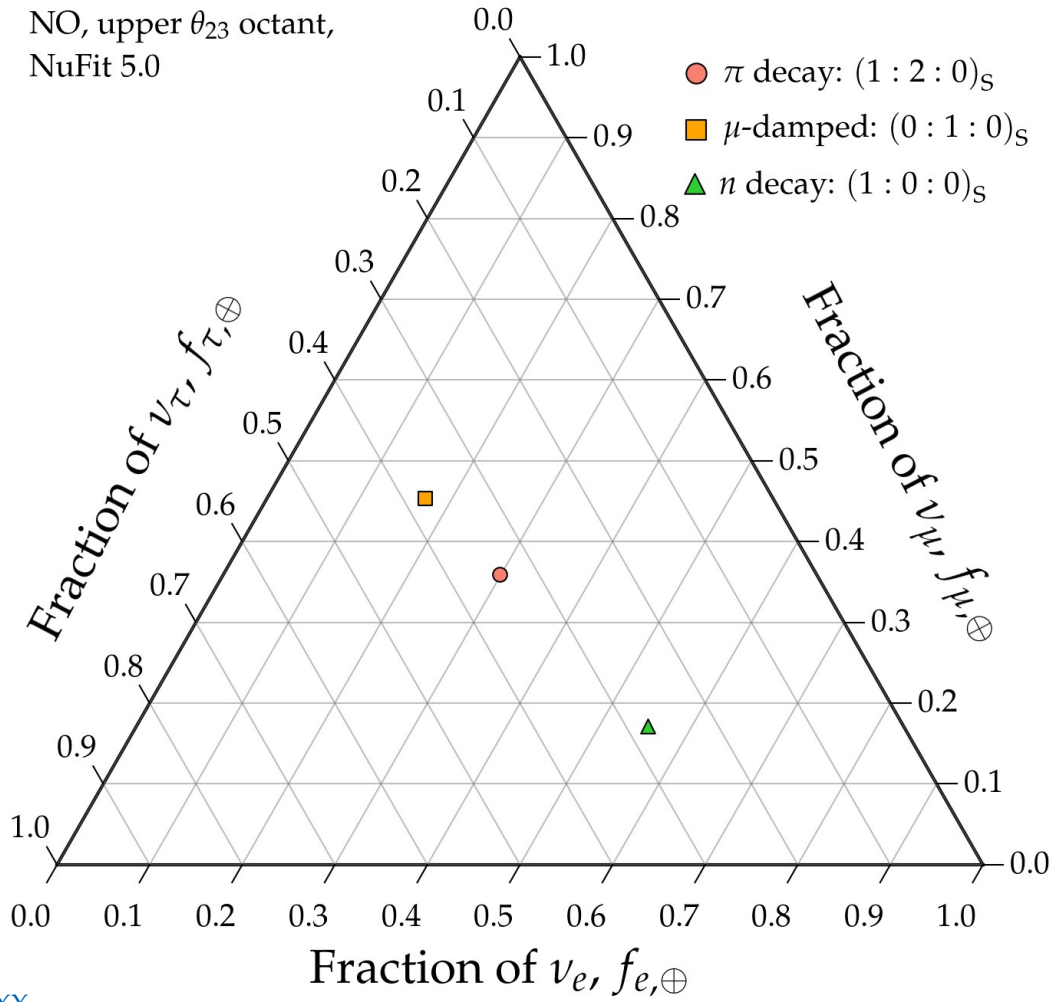
Esteban *et al.*, *JHEP* 2020
www.nu-fit.org

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

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



Theoretically palatable regions: today (2020)



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

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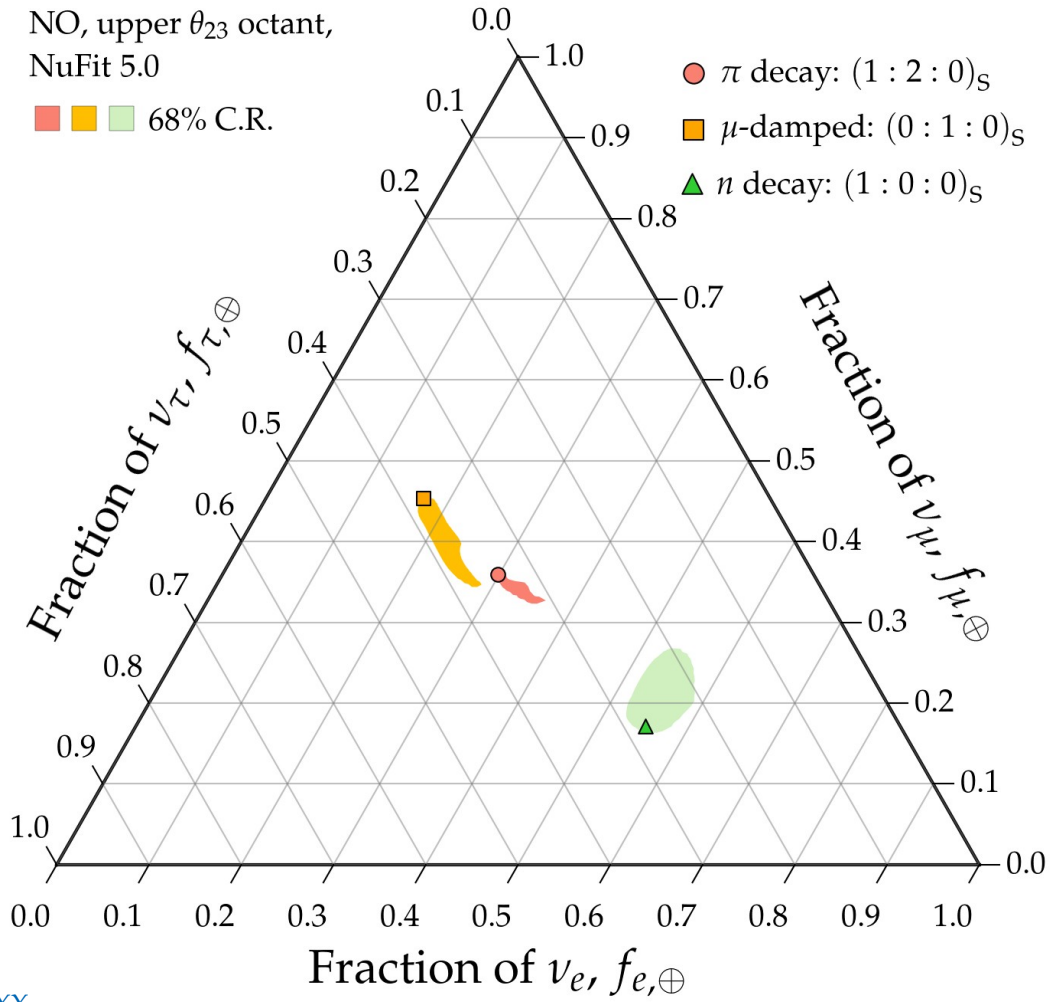

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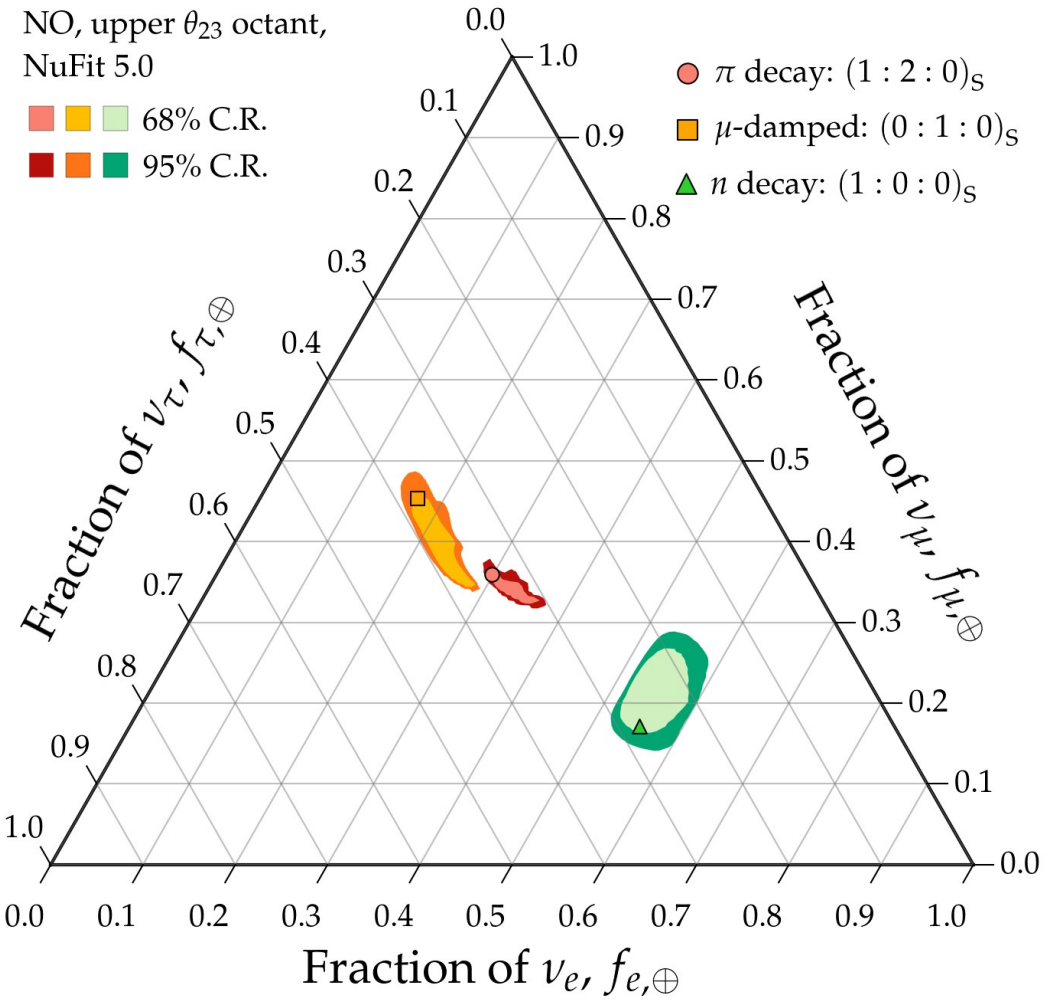

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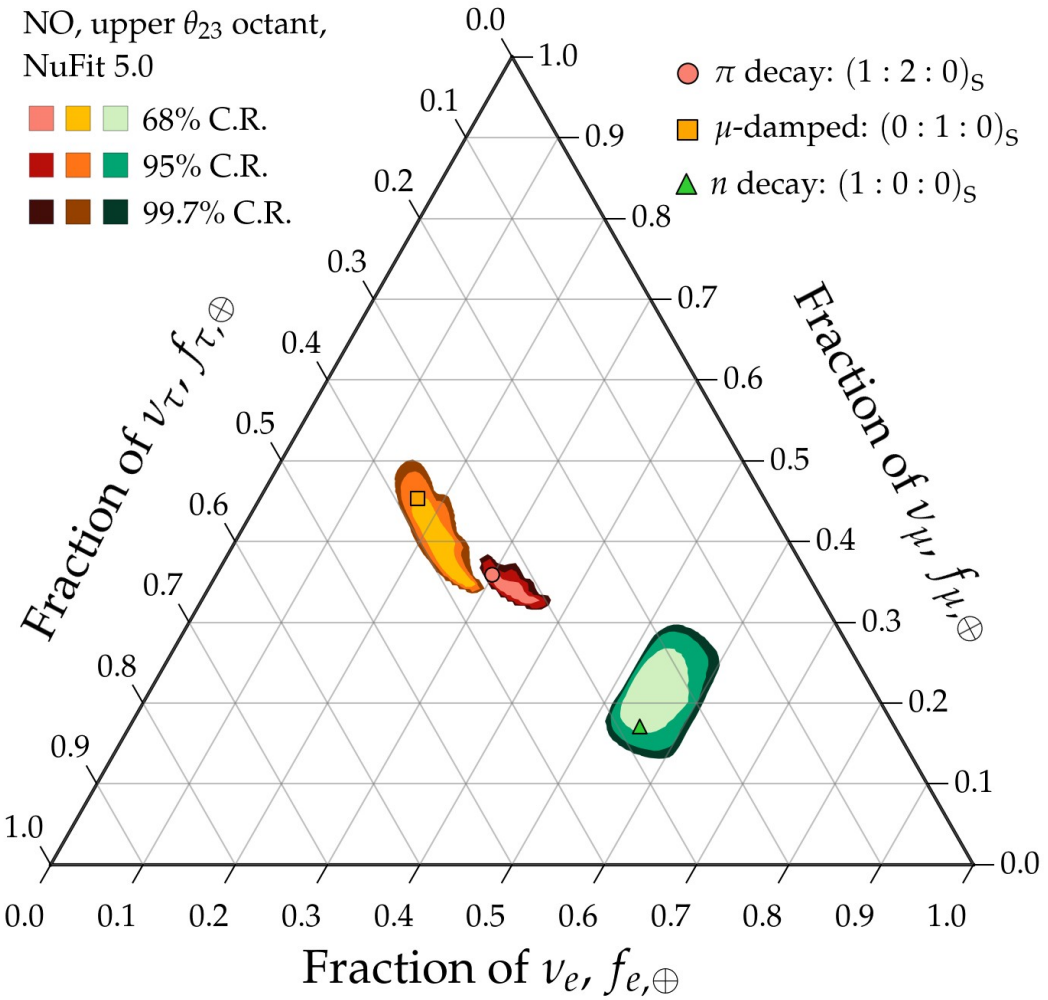

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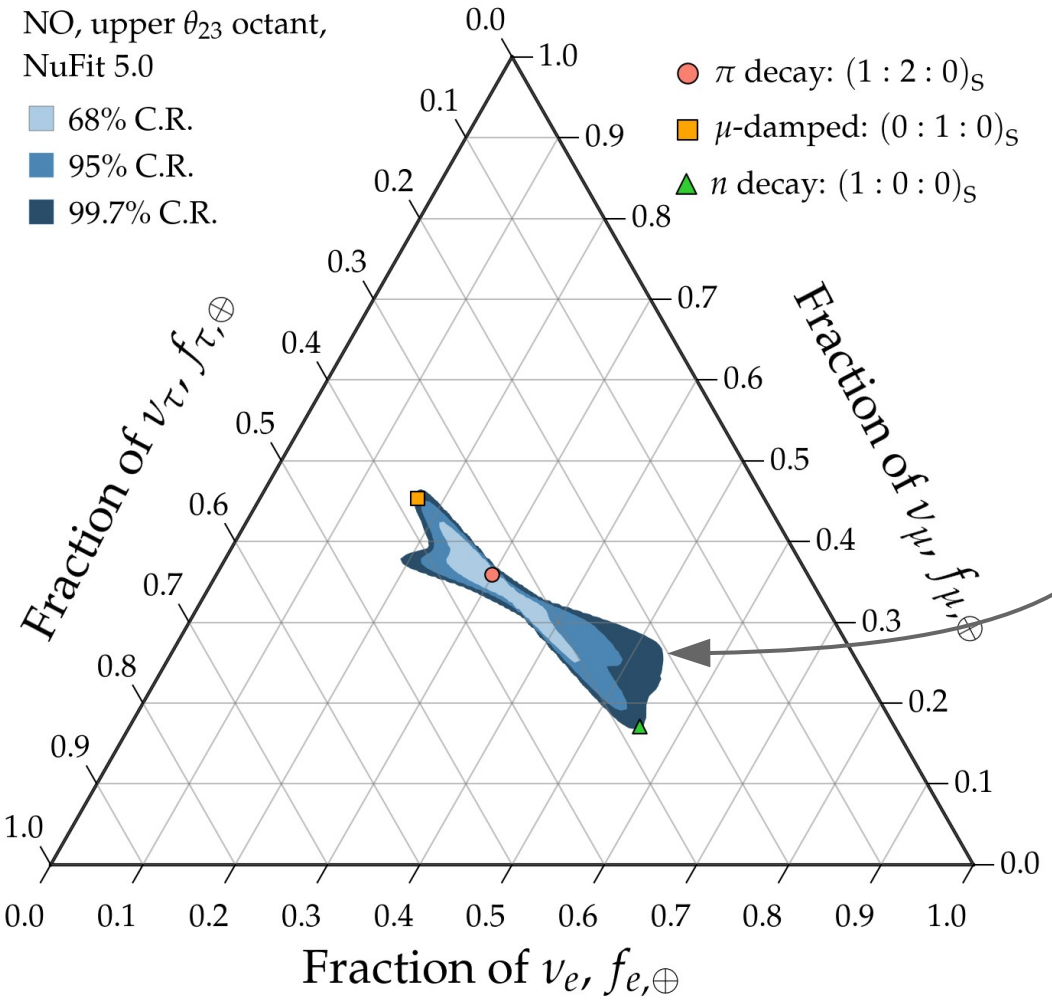

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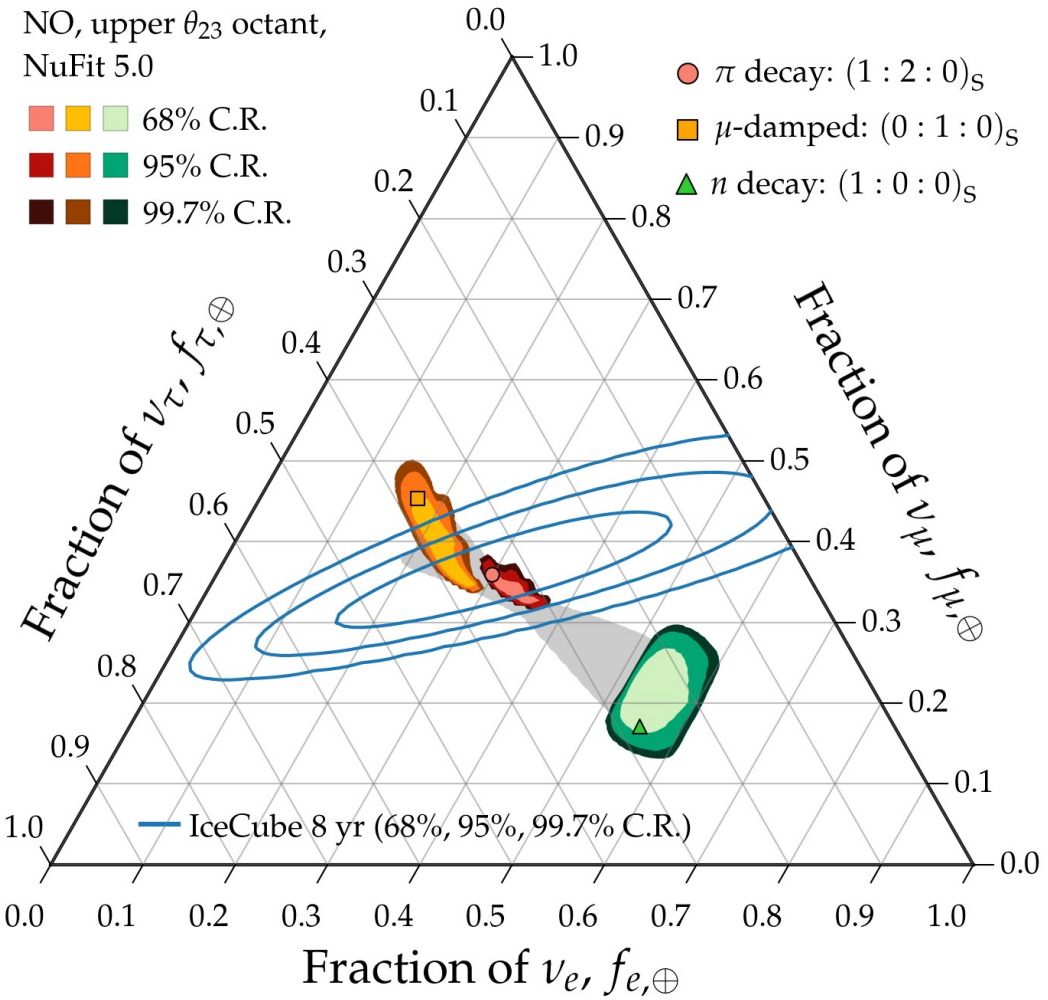

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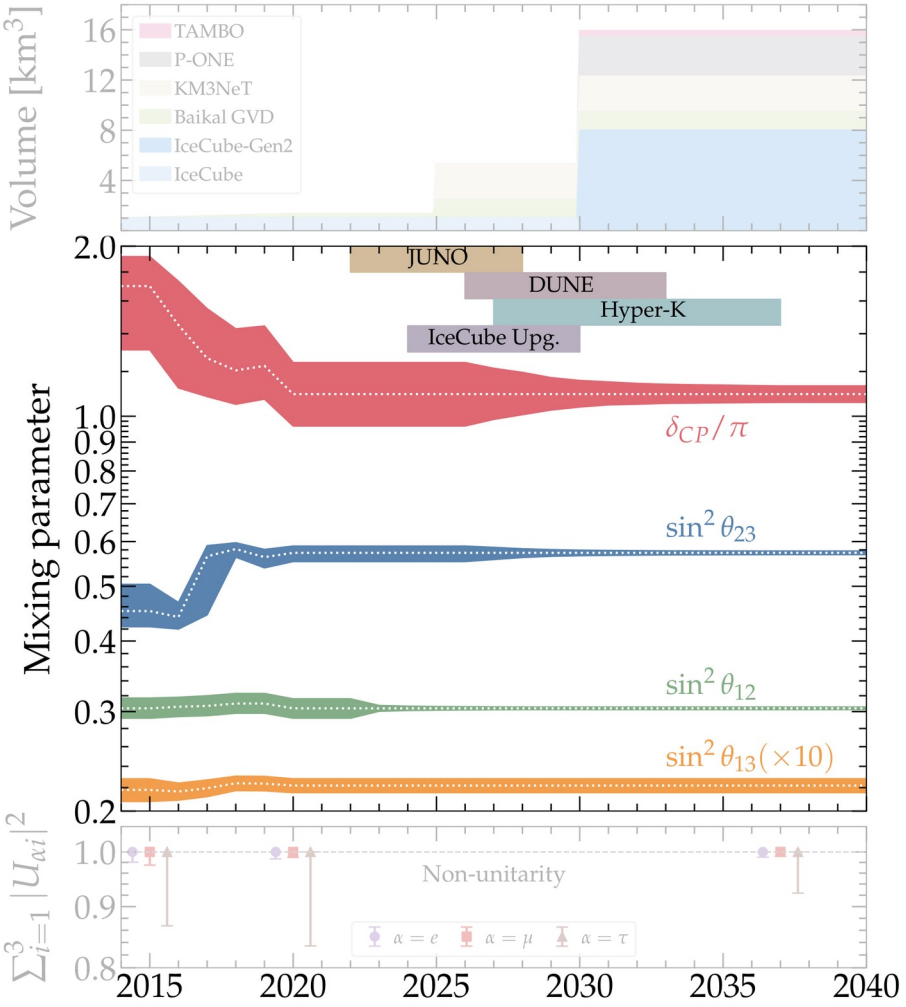
How knowing the mixing parameters better helps

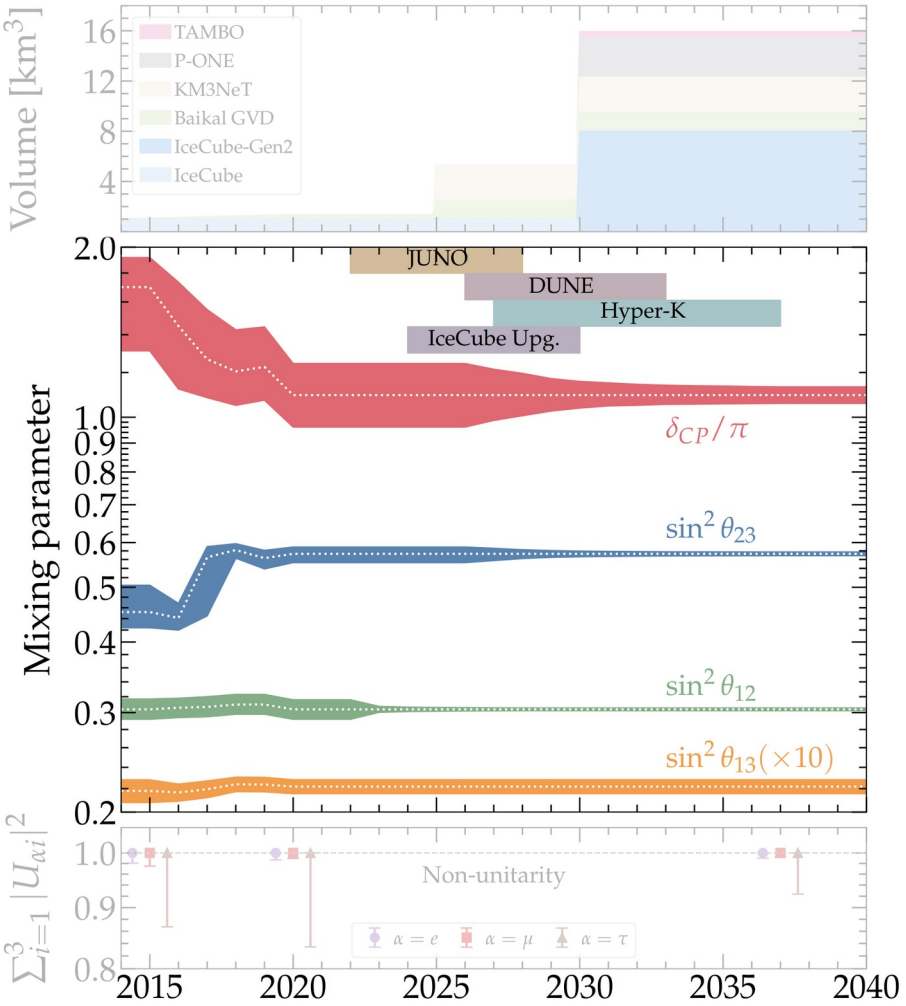


We can compute the oscillation probability more precisely:

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

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

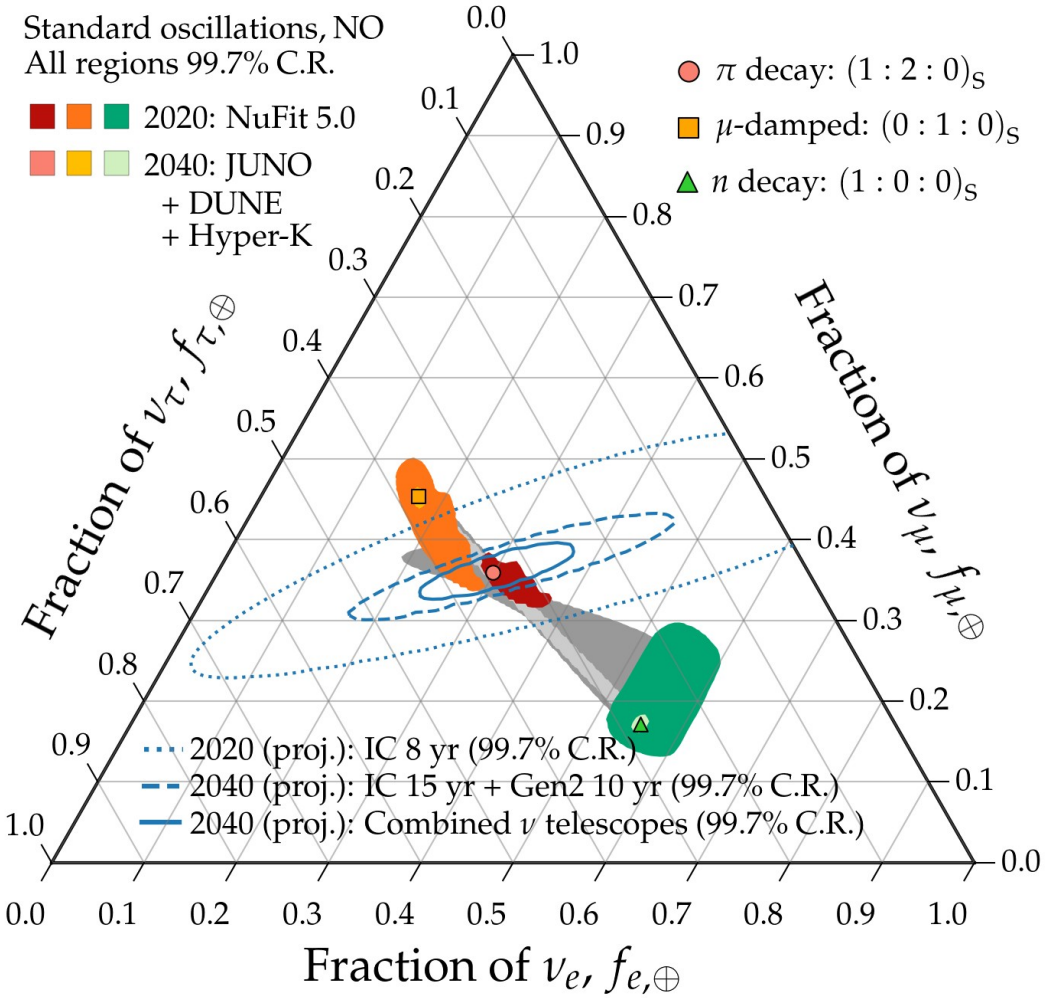
$$\chi^2_\varepsilon(\boldsymbol{\vartheta}) = \sum_i \frac{(\vartheta_i - \bar{\vartheta}_i)^2}{\sigma^2_{i,\varepsilon}}$$

From our simulations

We combine experiments in a likelihood:

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

Theoretically palatable regions: 2020 *vs.* 2040



By 2040:

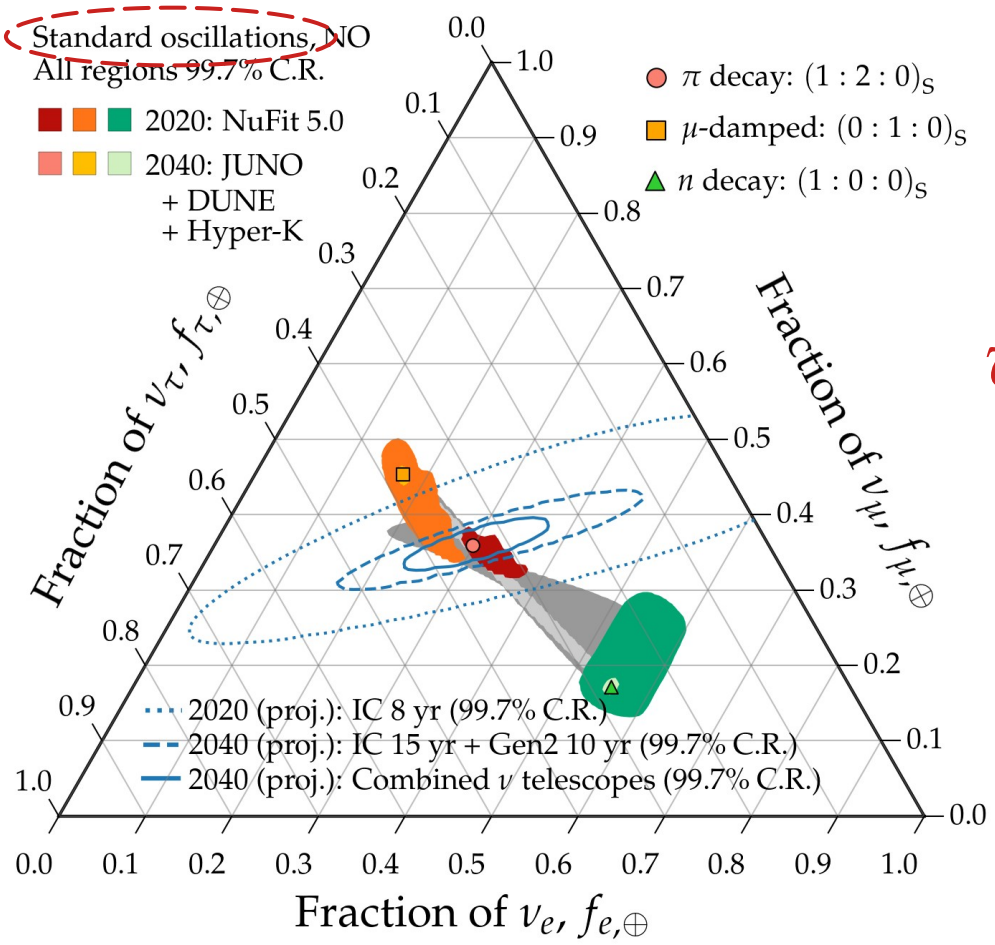
Theory –
Mixing parameters known precisely: allowed flavor regions are *almost* points (already by 2030)

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

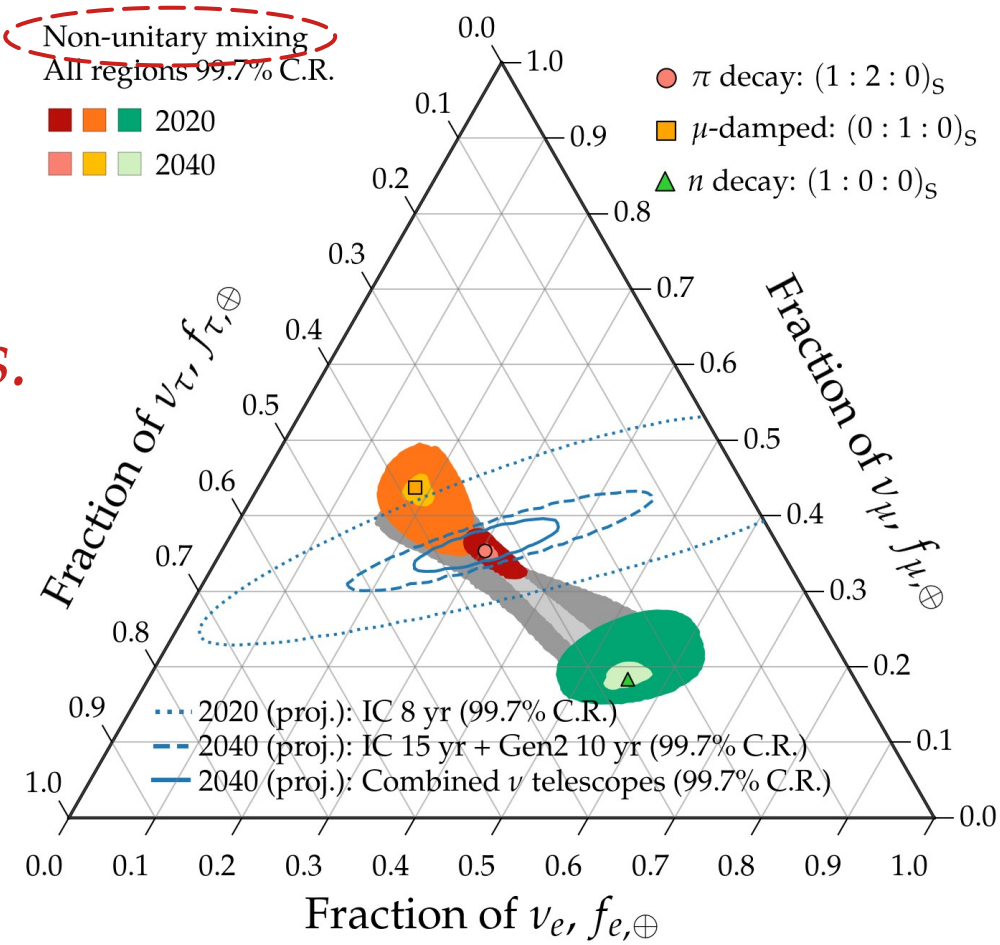
Can finally use the full power of flavor composition for astrophysics and neutrino physics

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

No unitarity? *No problem*



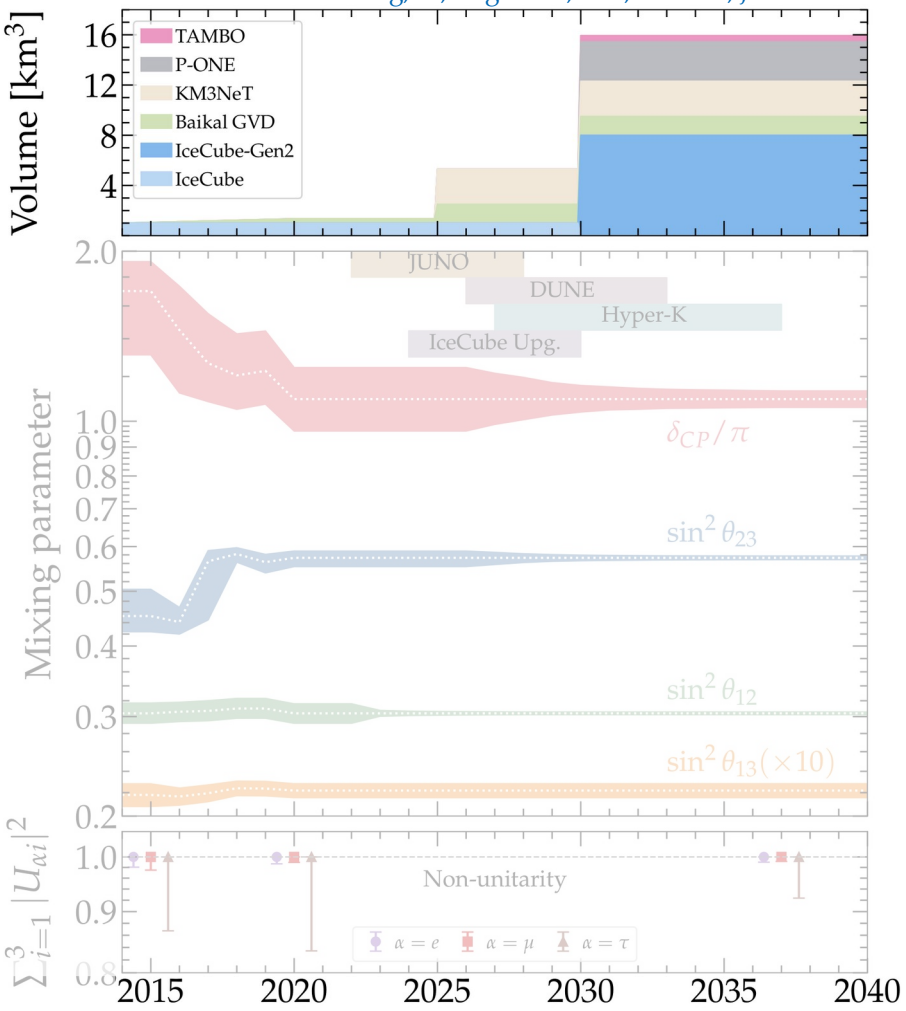
vs.

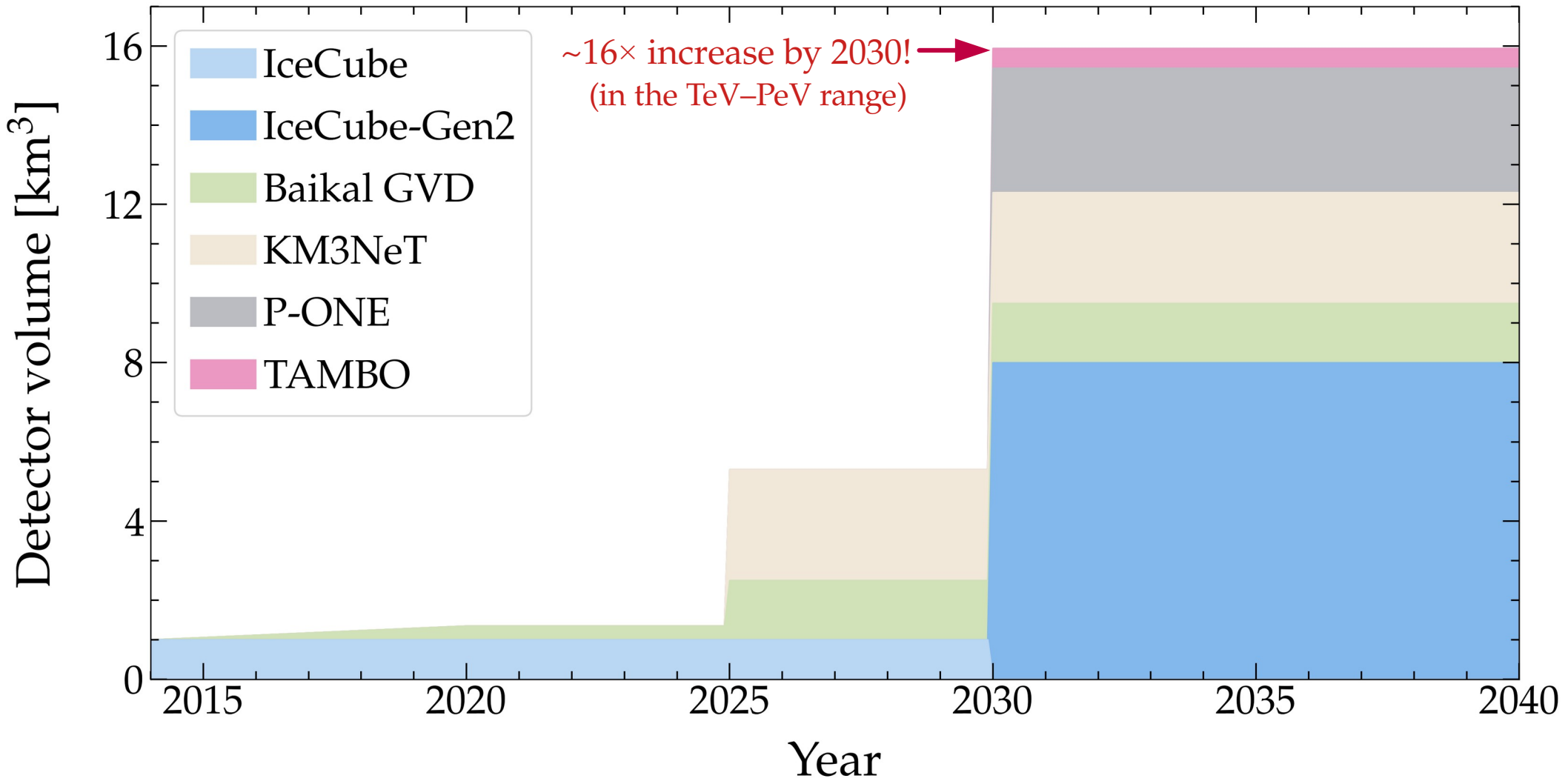


Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Measuring flavor composition: 2015–2040

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





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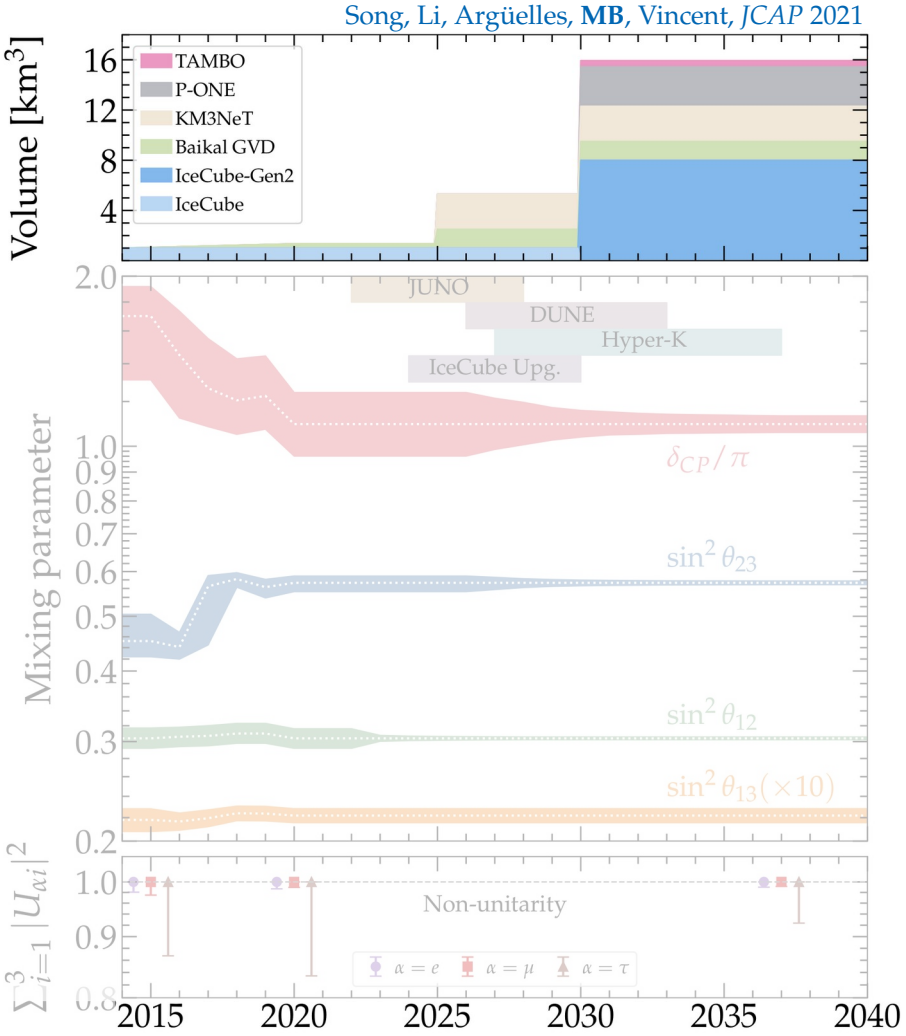

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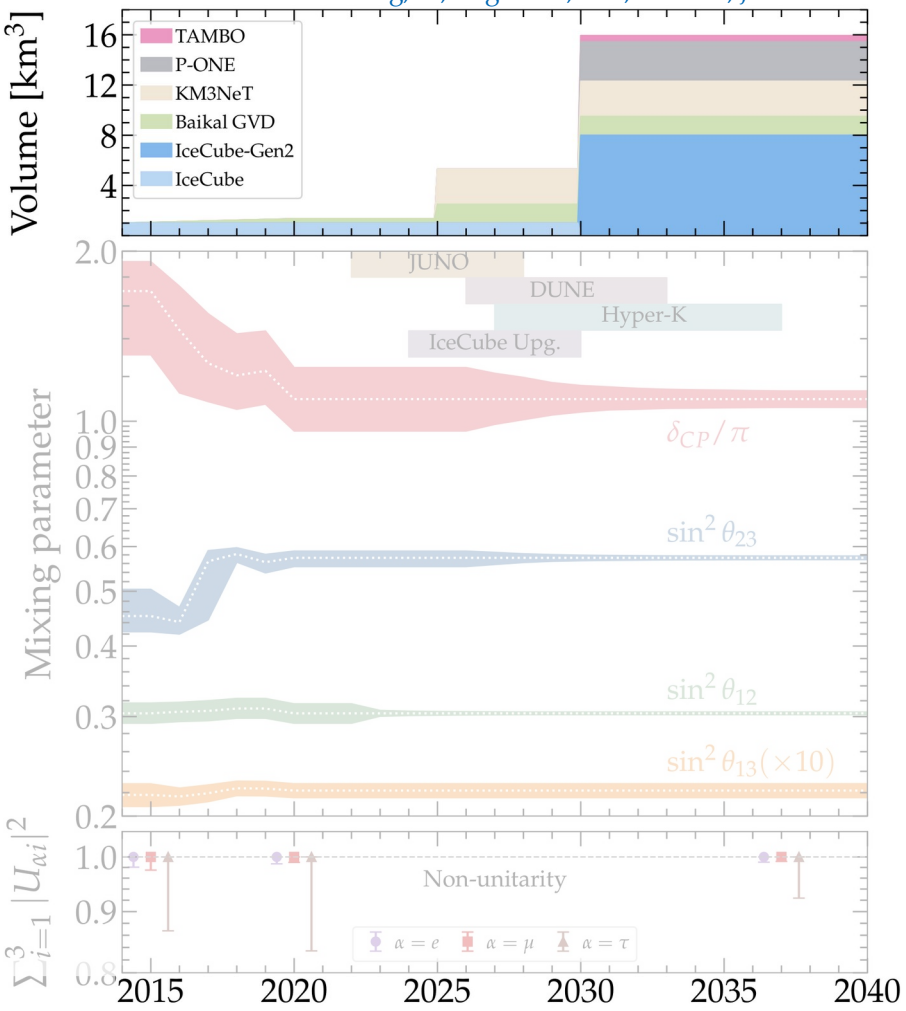

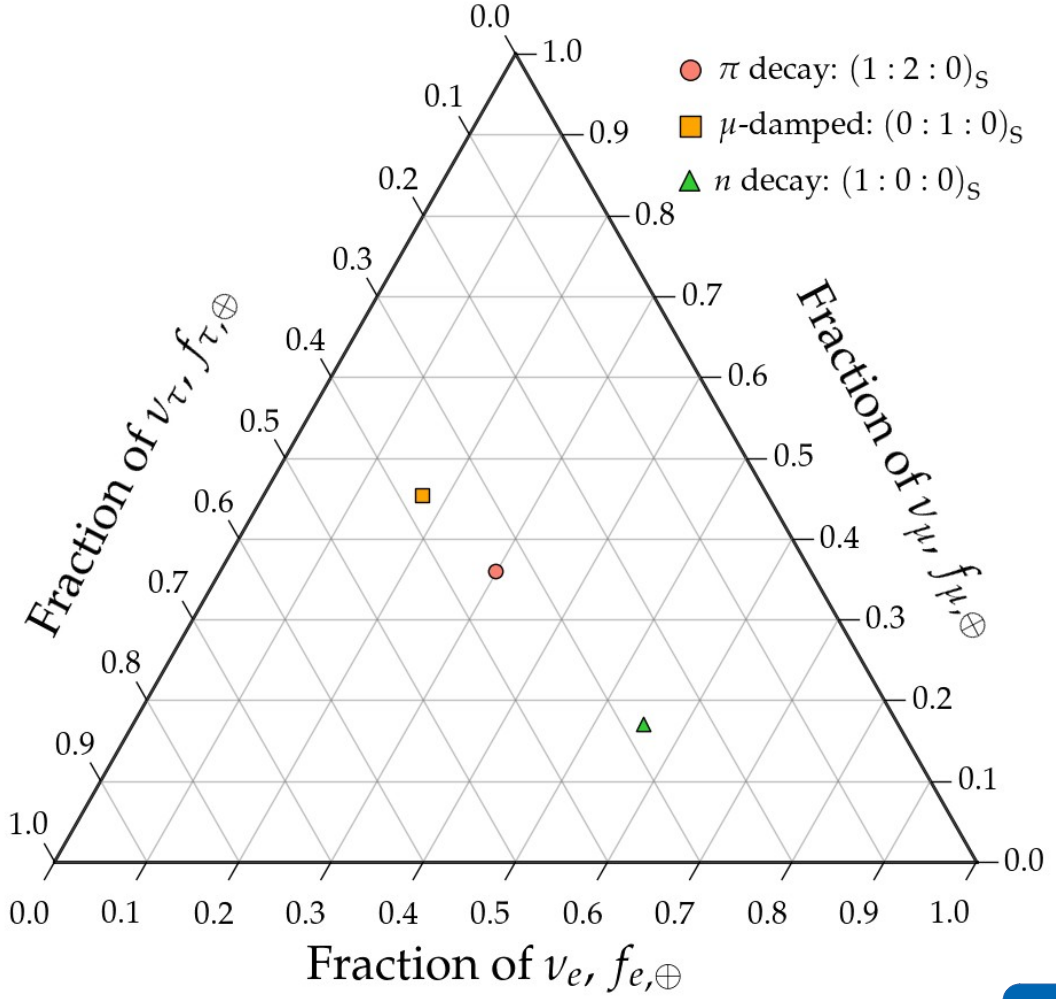

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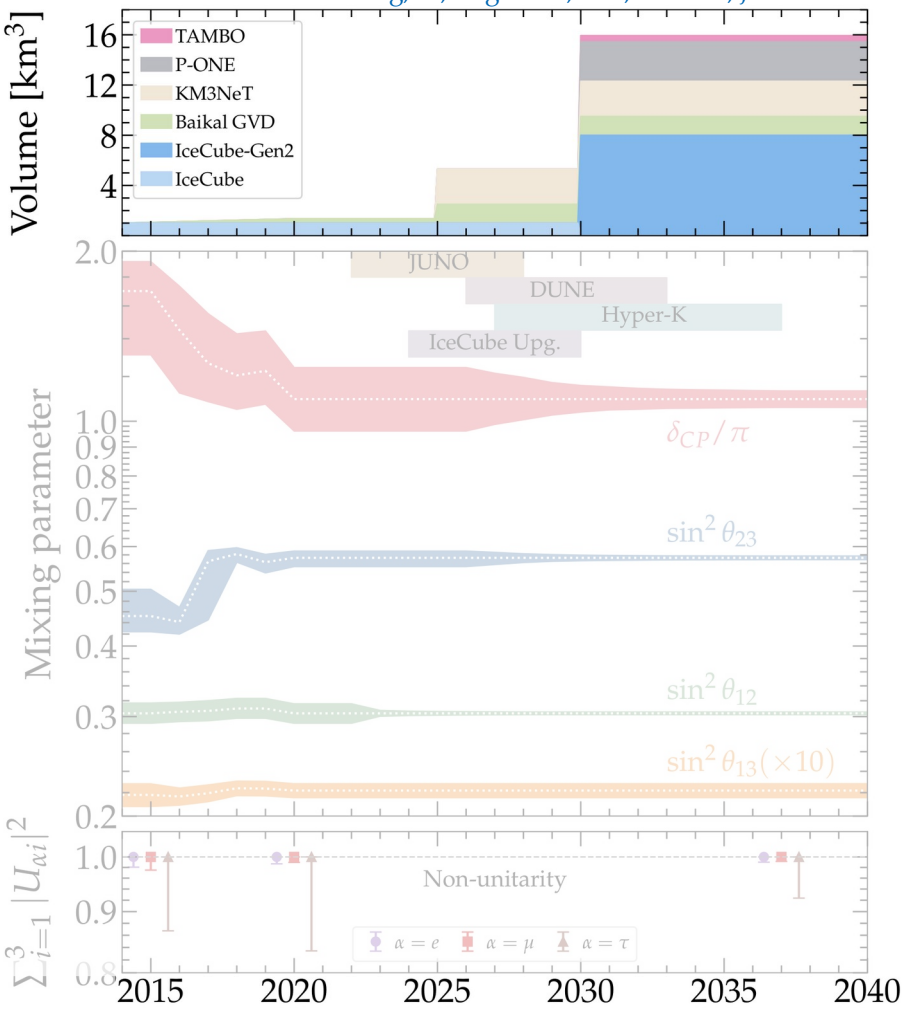
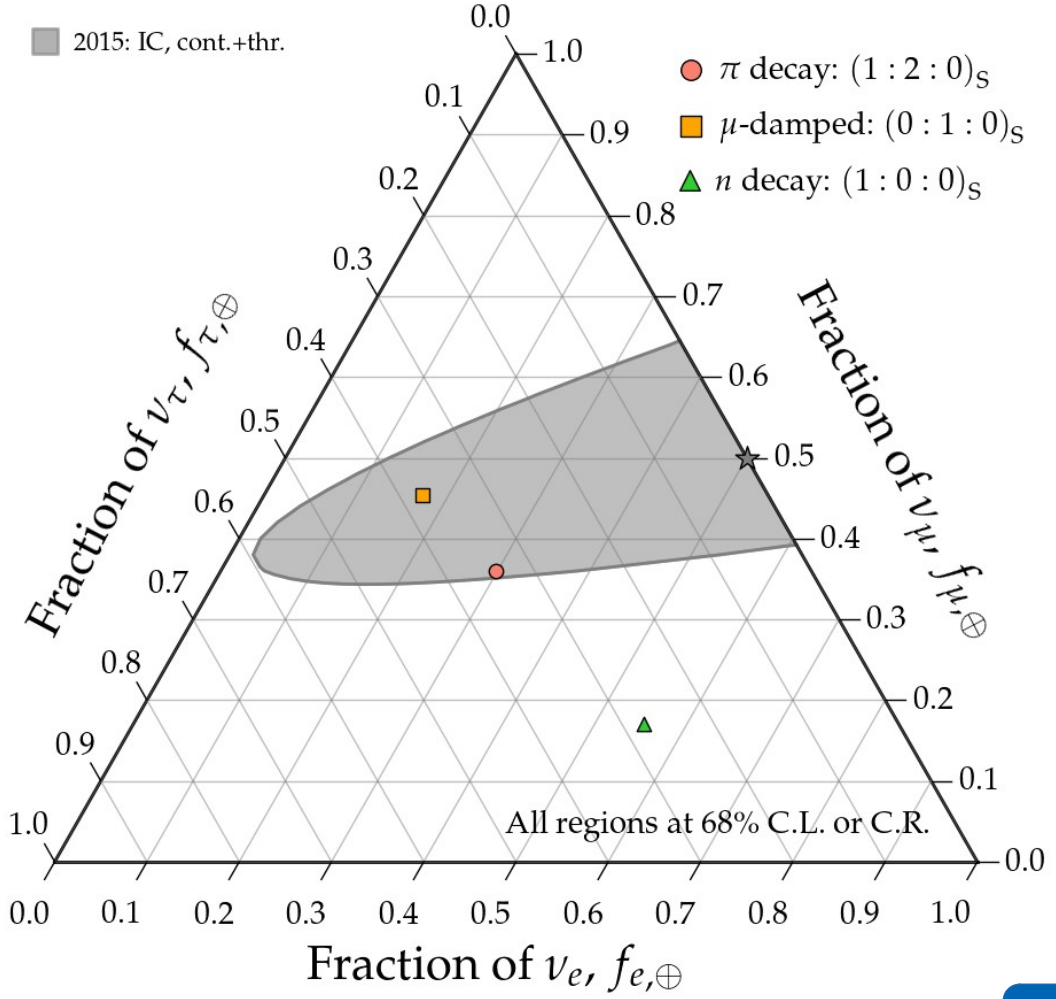
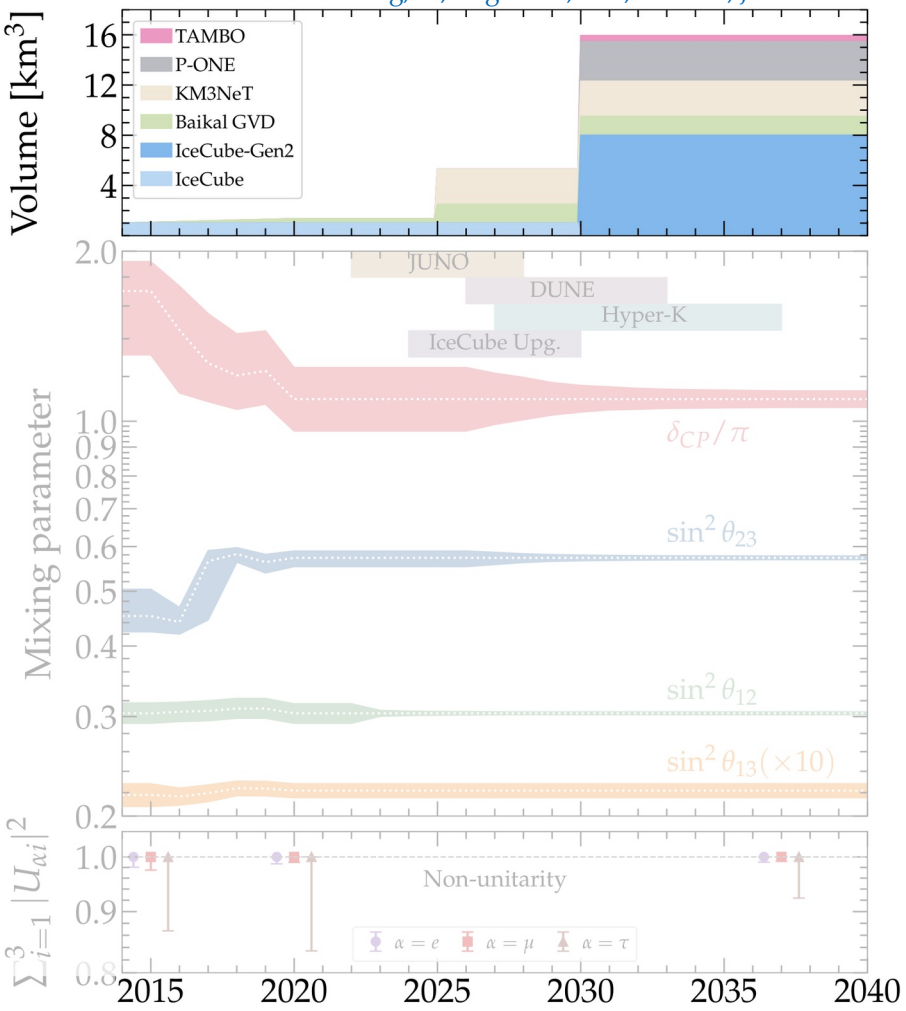
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

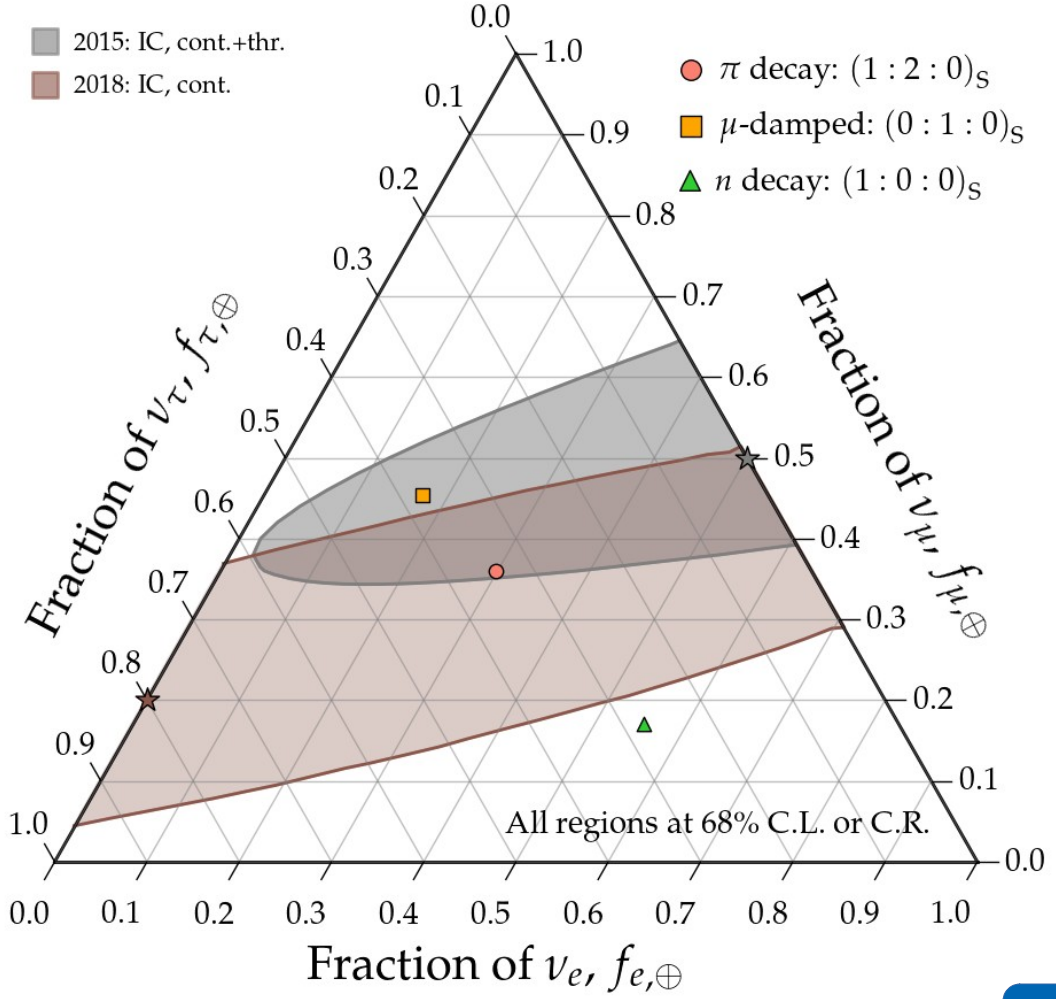




Measuring flavor composition: 2015–2040

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





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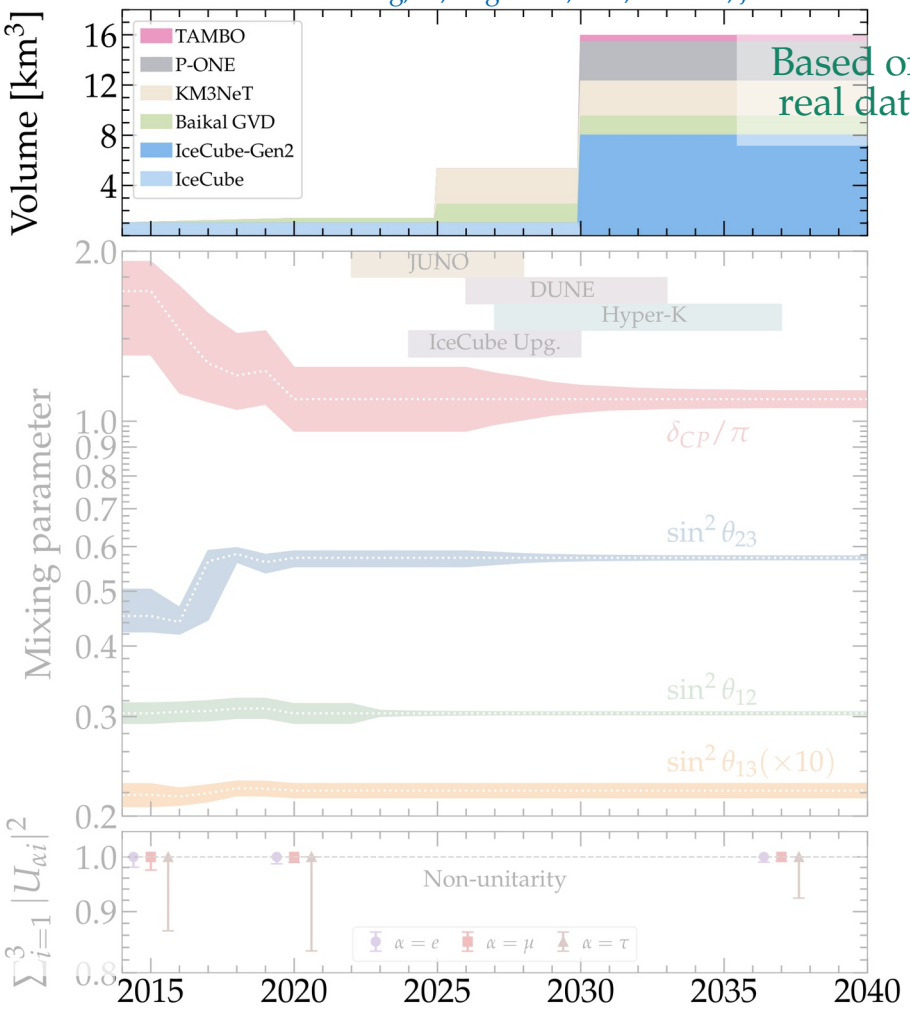

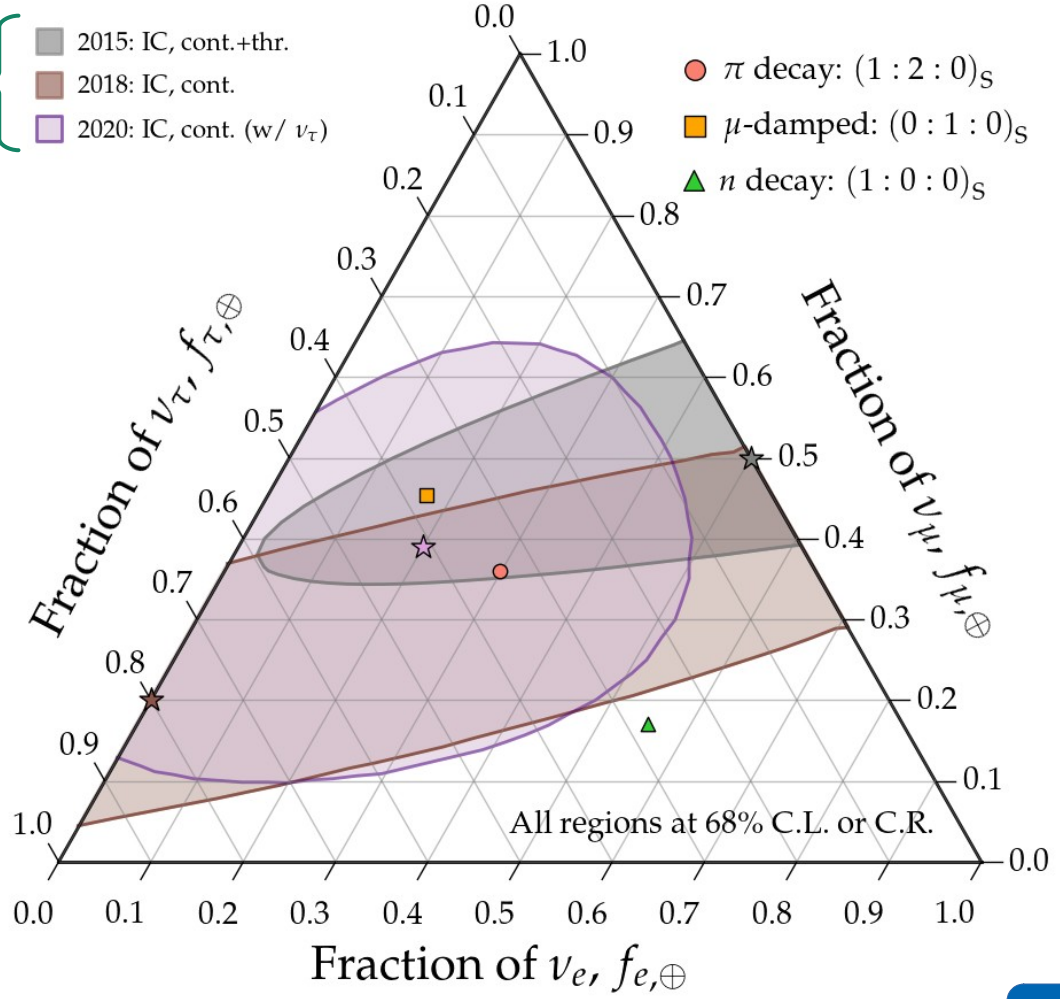

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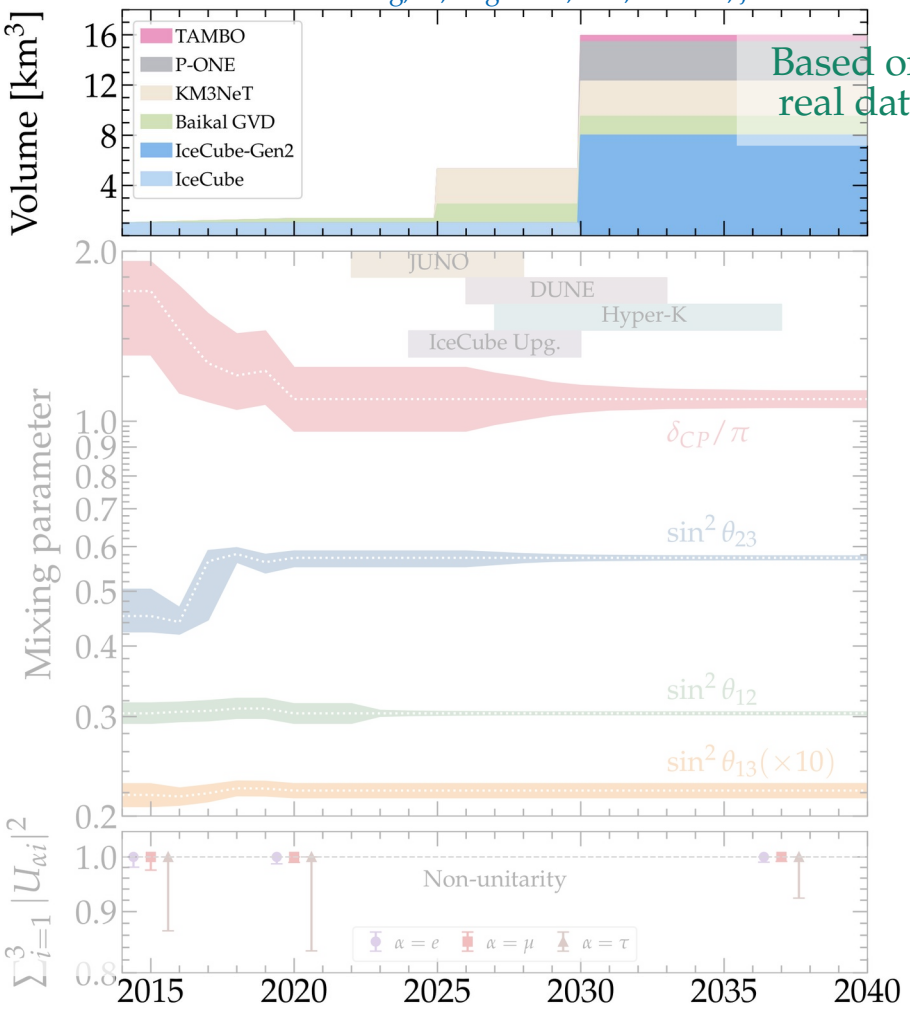

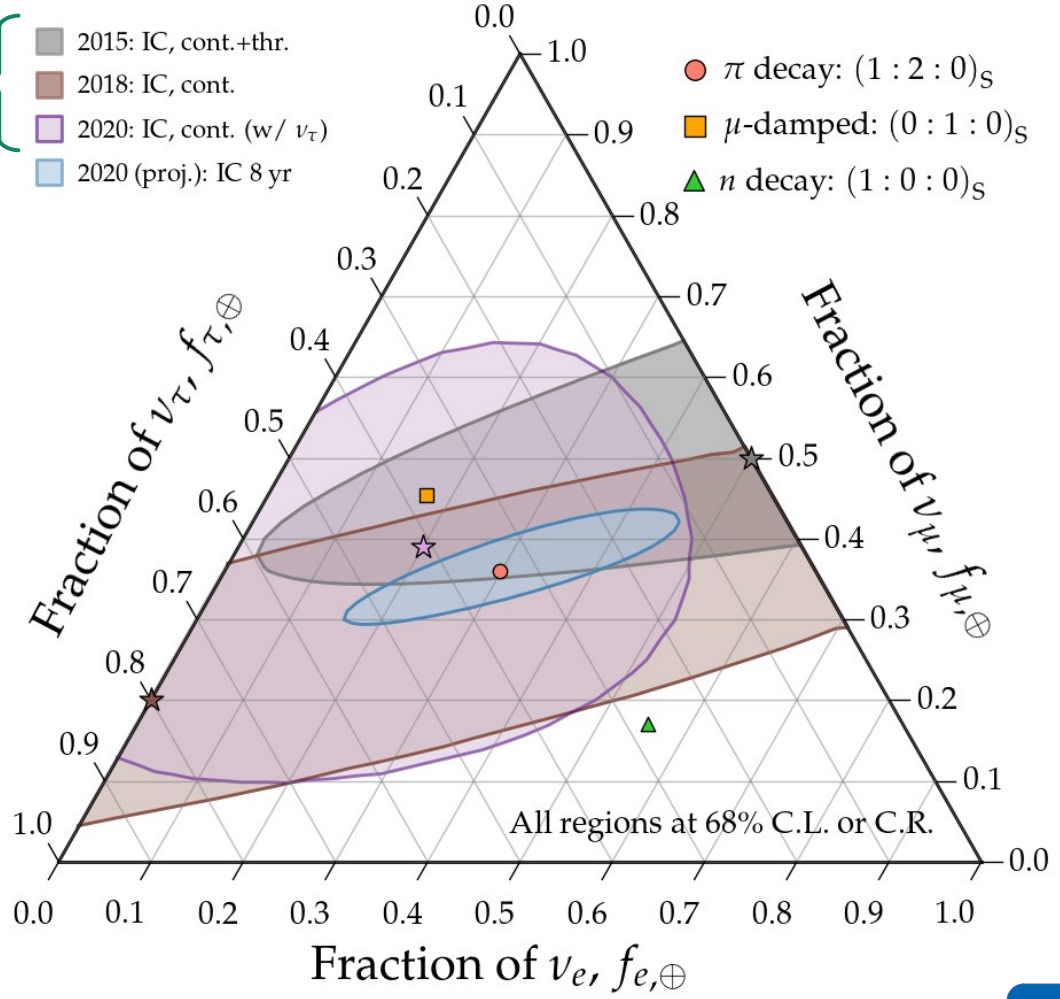

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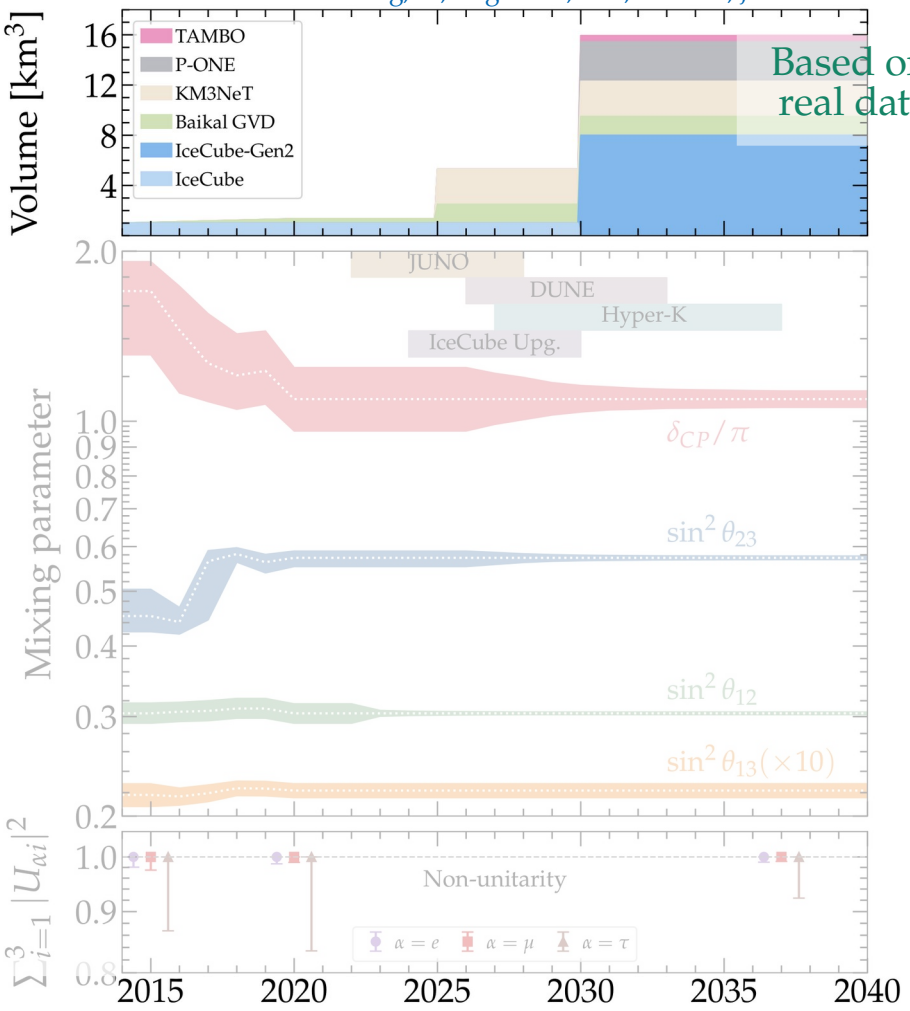

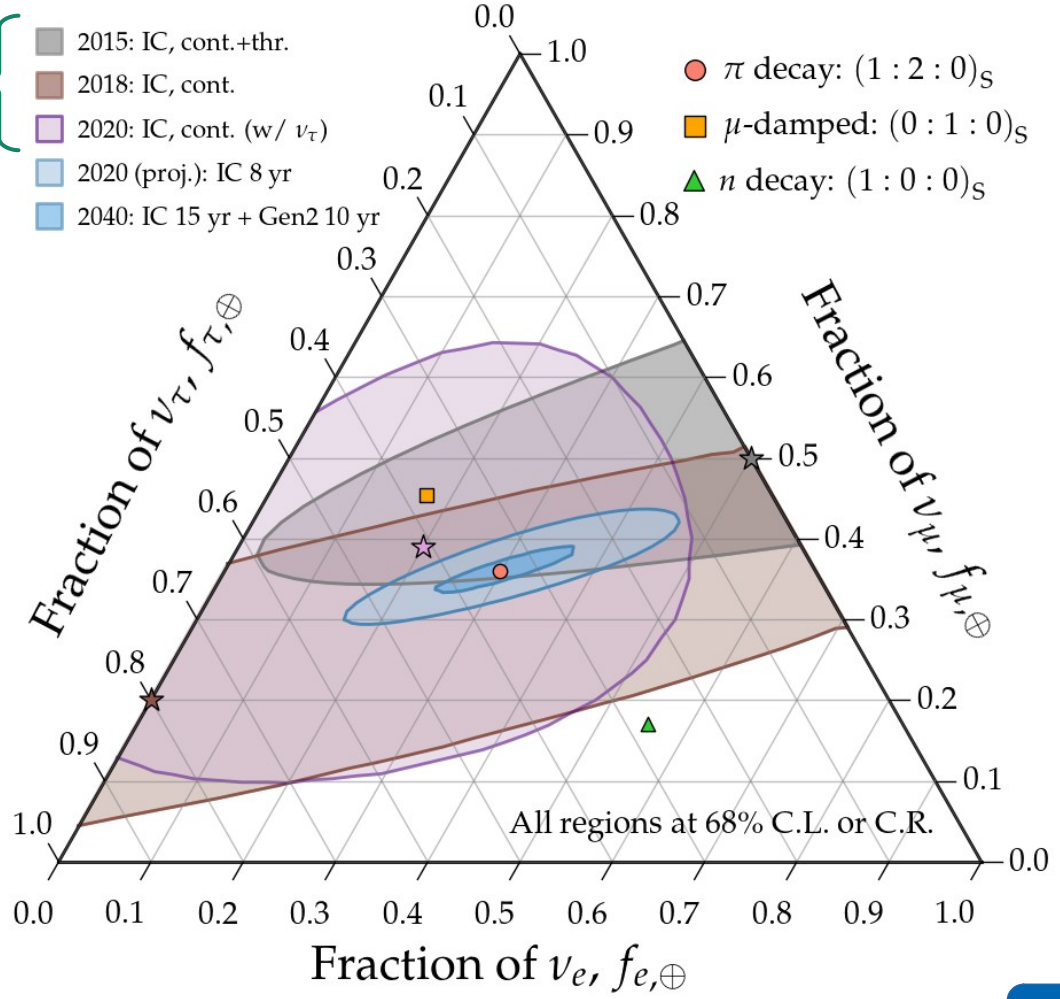

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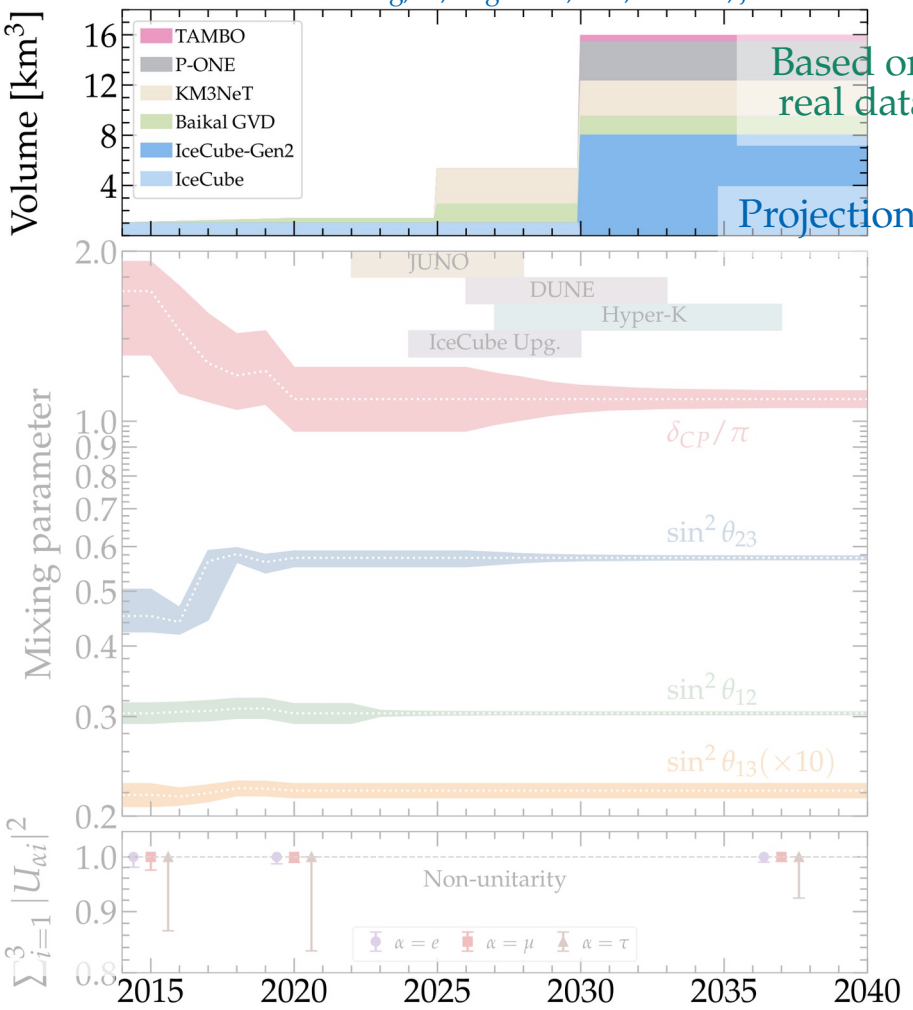
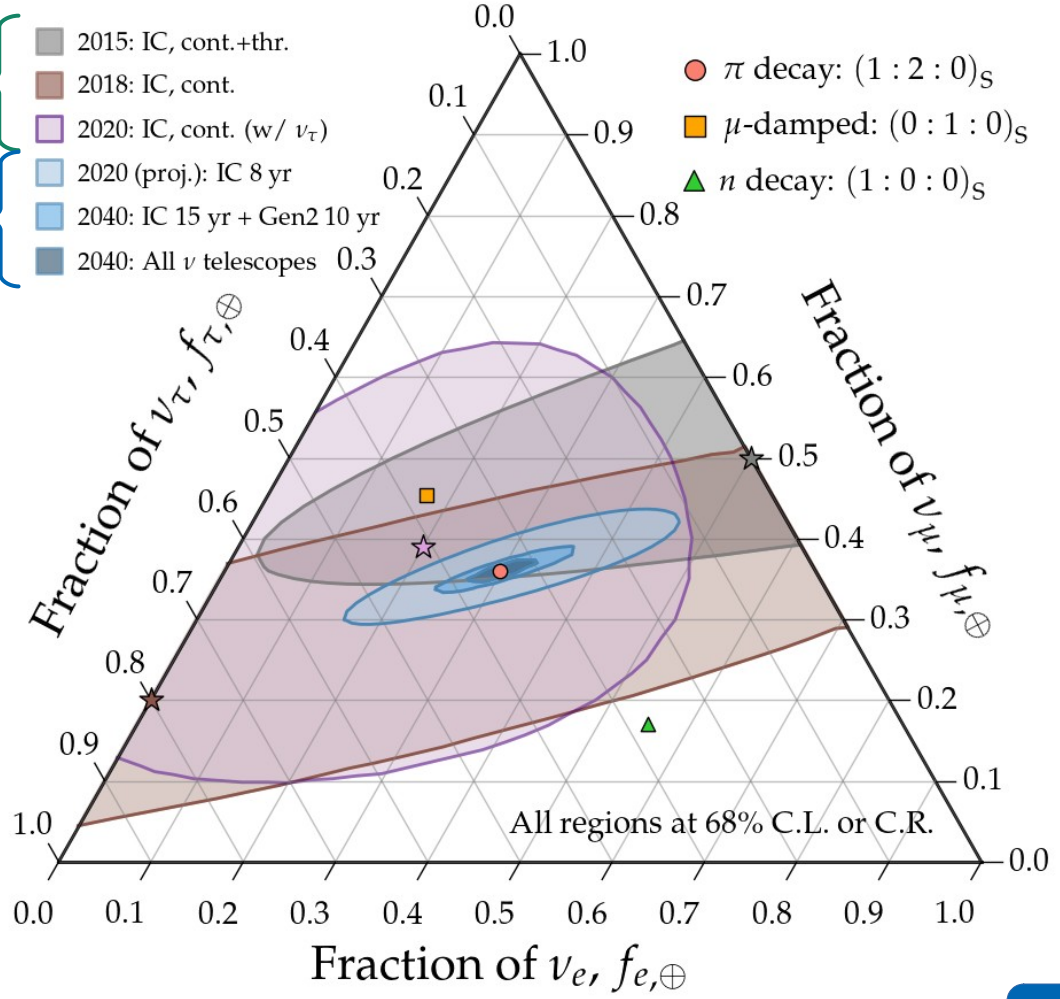
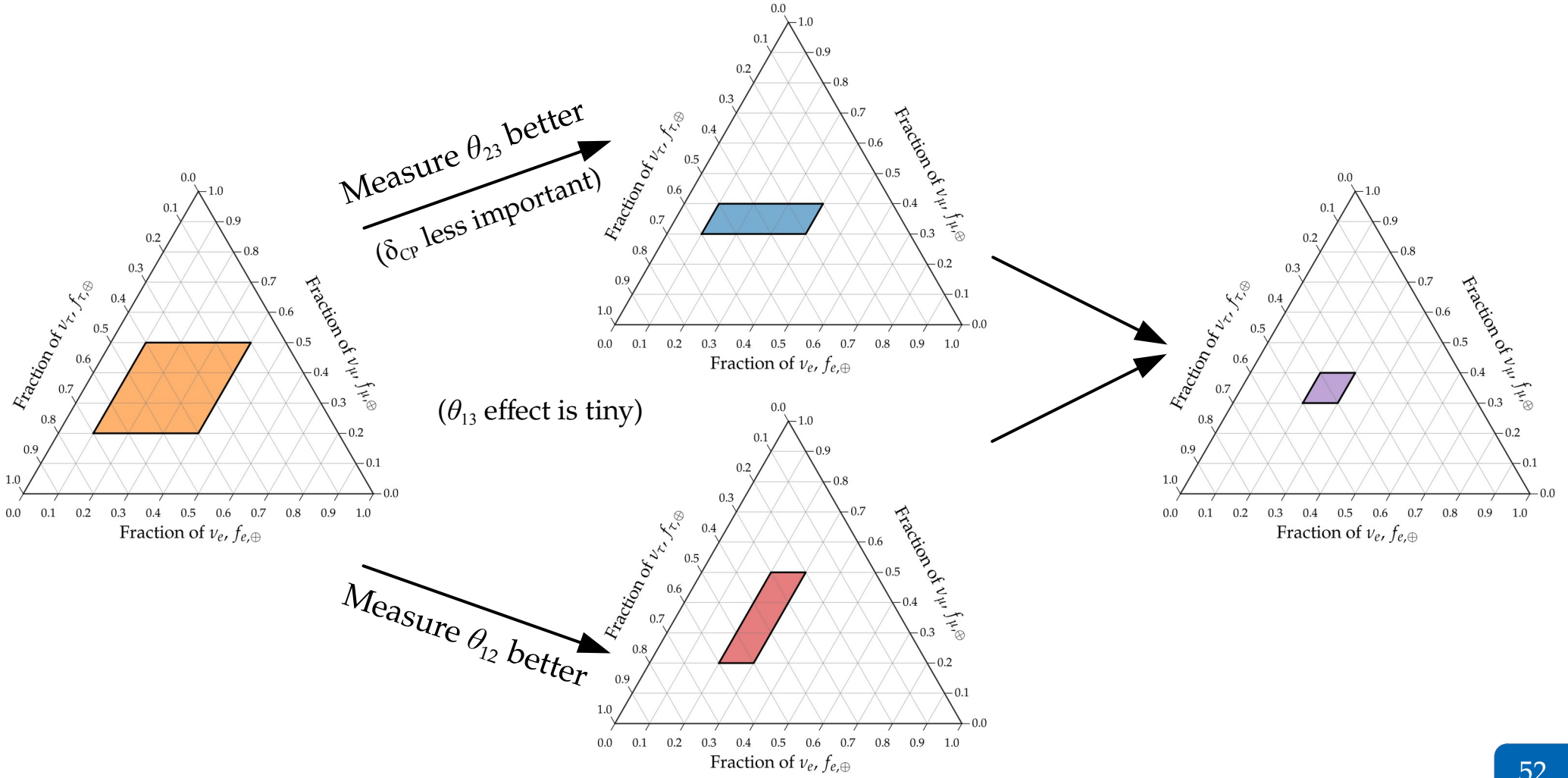




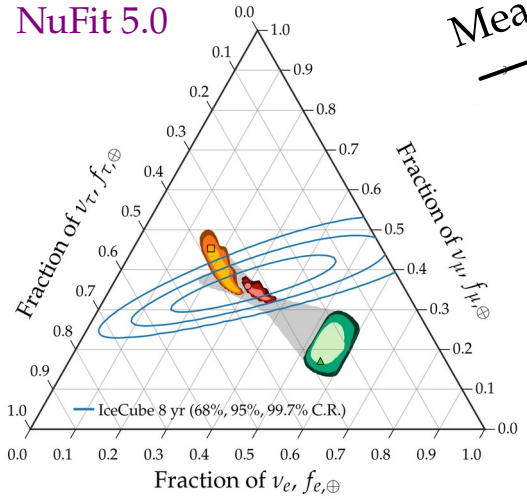
How knowing the mixing parameters better helps



How knowing the mixing parameters better helps

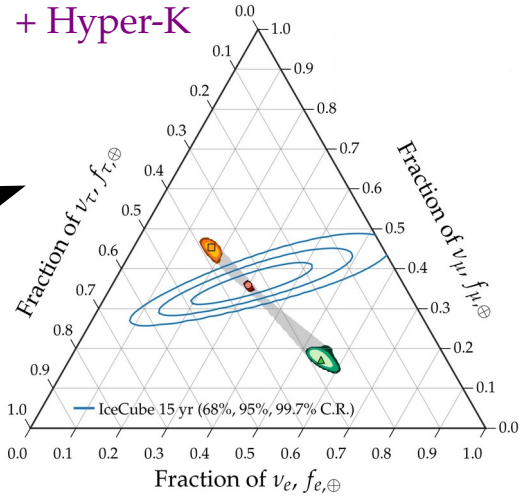
2020

NuFit 5.0

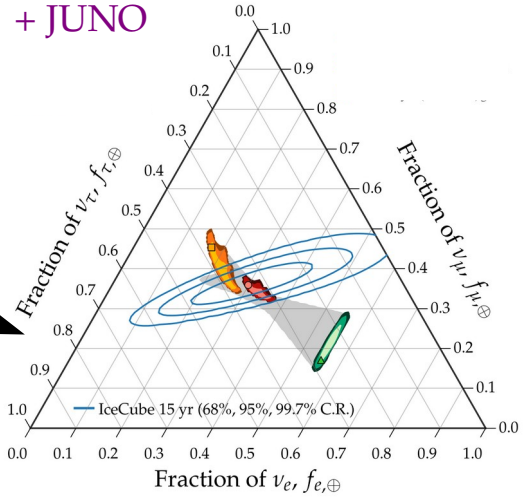


Measure θ_{23} better

+ Hyper-K



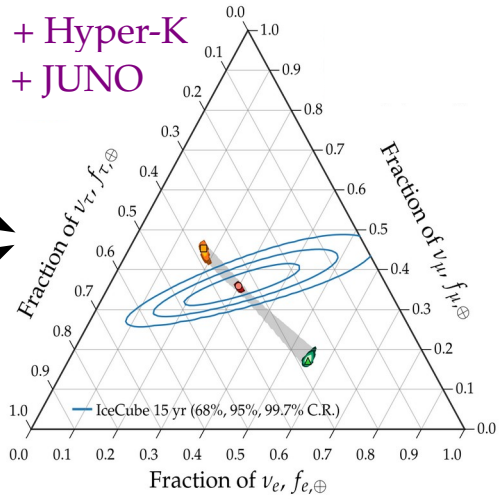
+ JUNO



Measure θ_{12} better

~2030

+ Hyper-K
+ JUNO



In our results:
JUNO + Hyper-K + DUNE

Marginal improvement til 2040

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

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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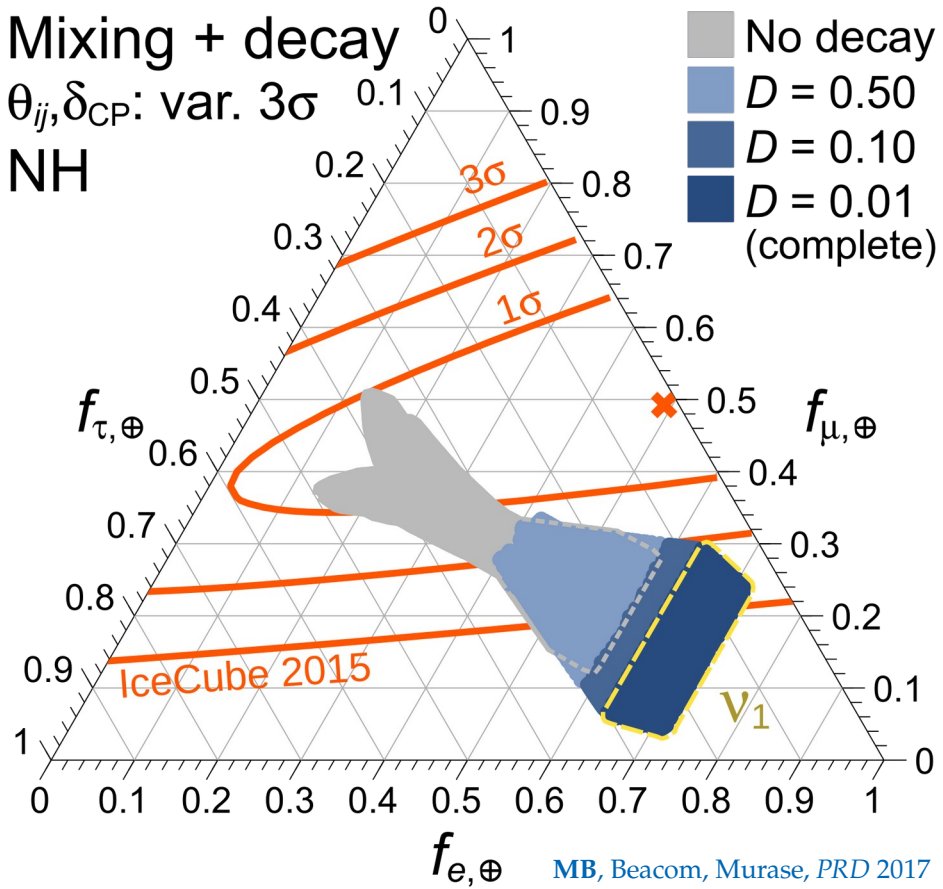

MB, Beacom, Murase, *PRD* 2017

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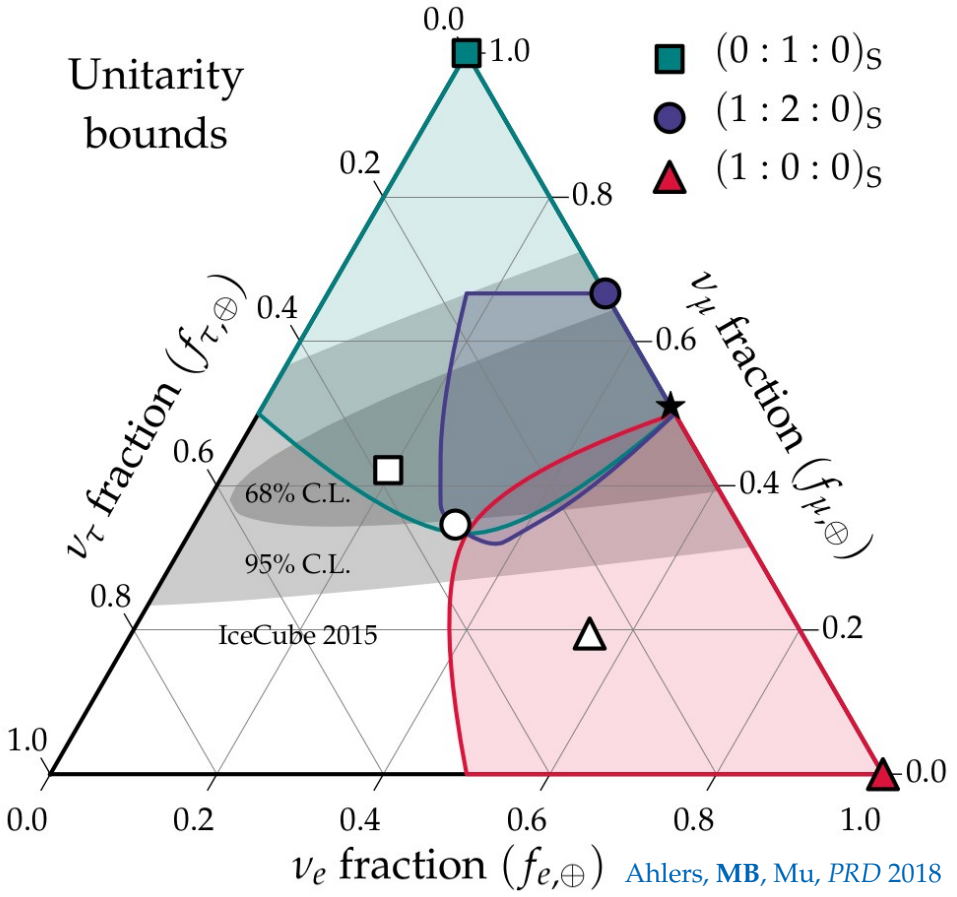

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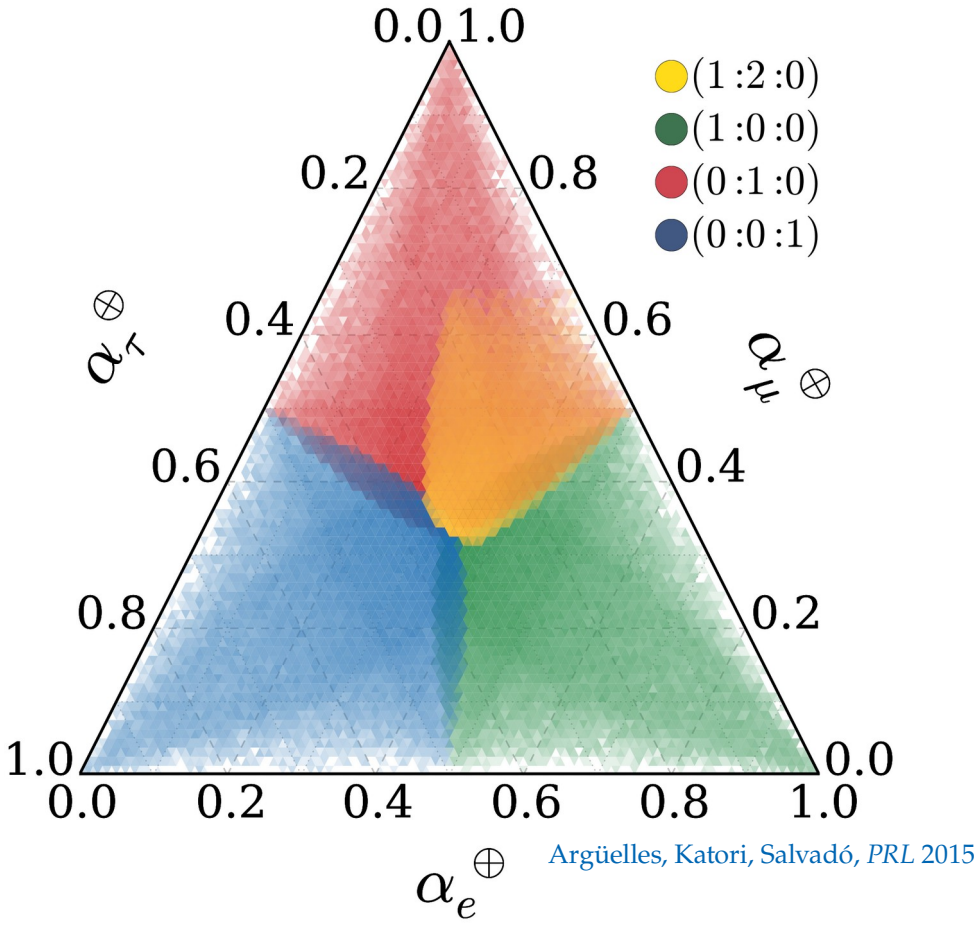

Argüelles, Katori, Salvadó, *PRL* 2015

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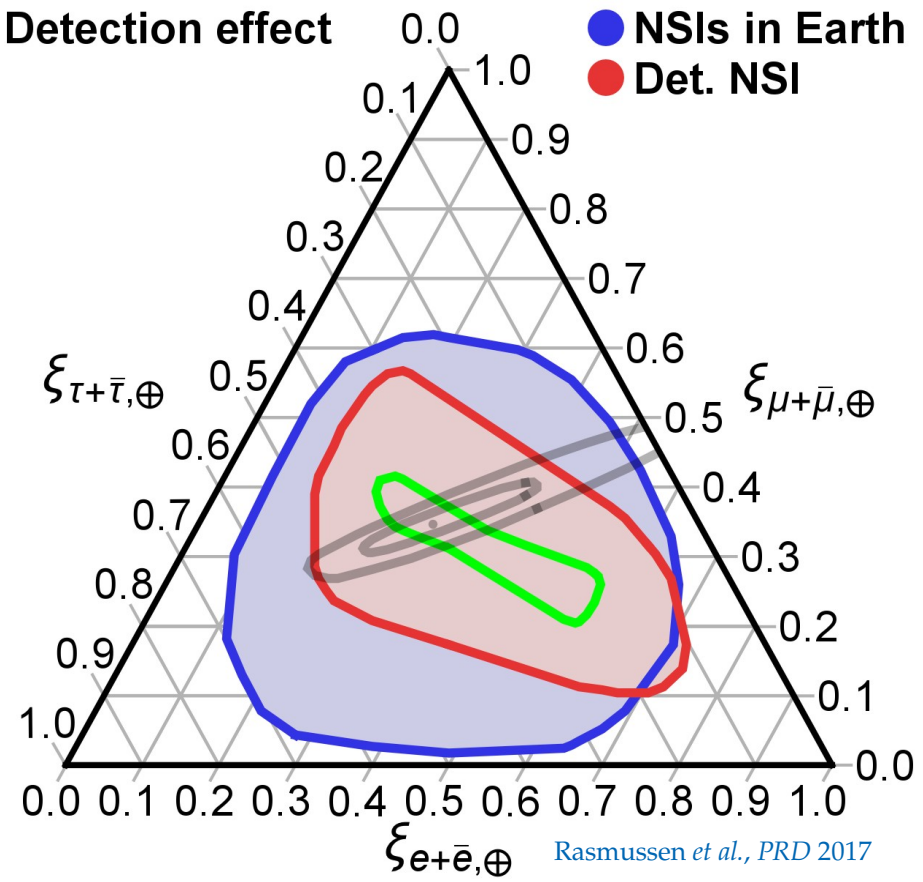

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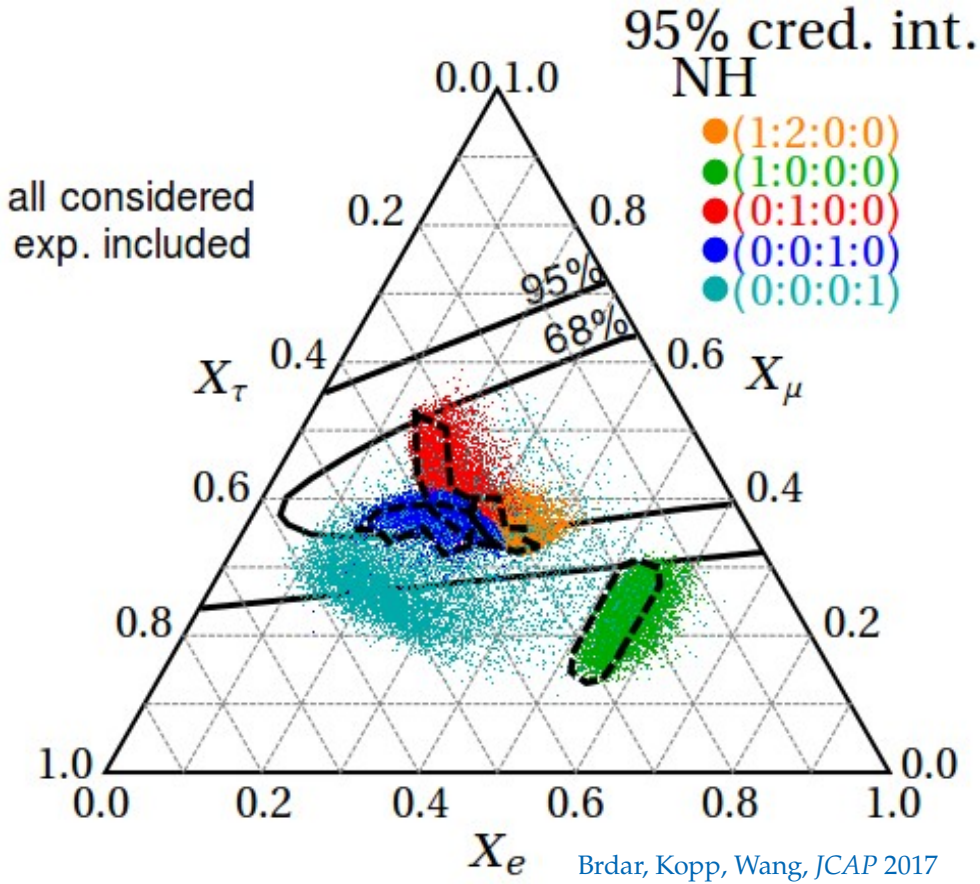

Brdar, Kopp, Wang, *JCAP* 2017

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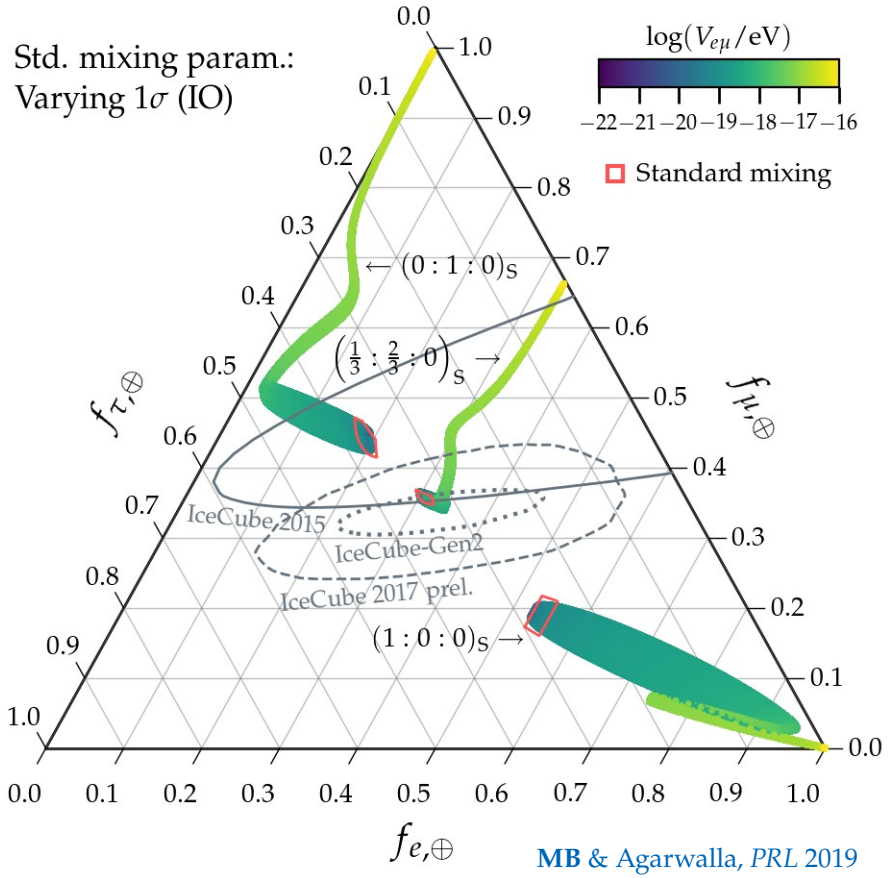
- Long-range *eν* interactions
  [**MB** & Agarwalla, *PRL* 2019]

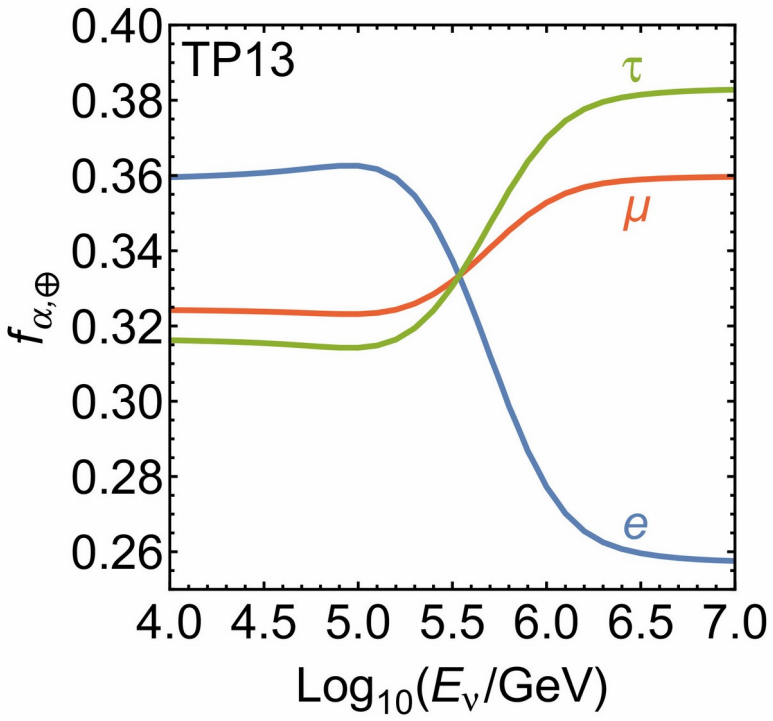
Reviews:
Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017

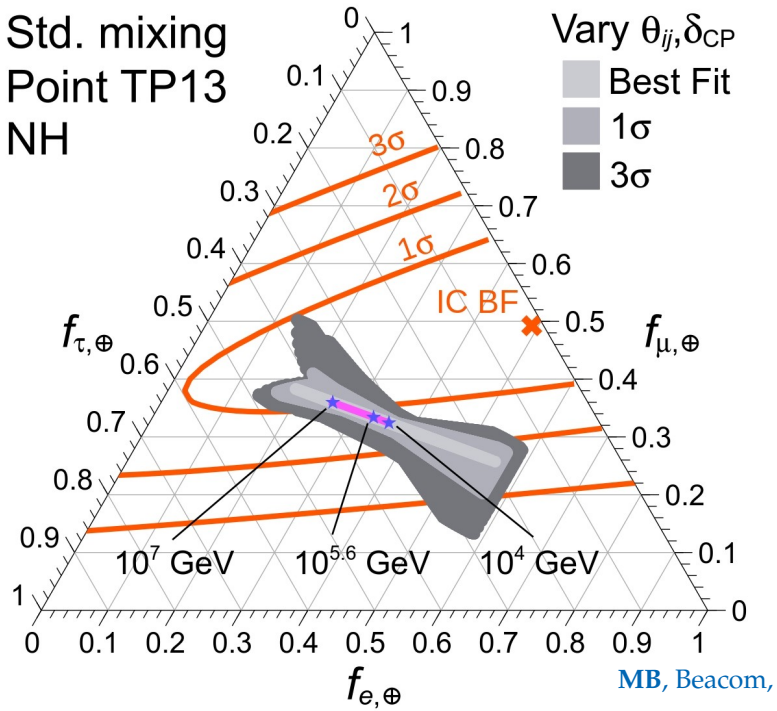


MB & Agarwalla, *PRL* 2019

Energy dependence of the flavor composition?

Different neutrino production channels accessible at different energies –



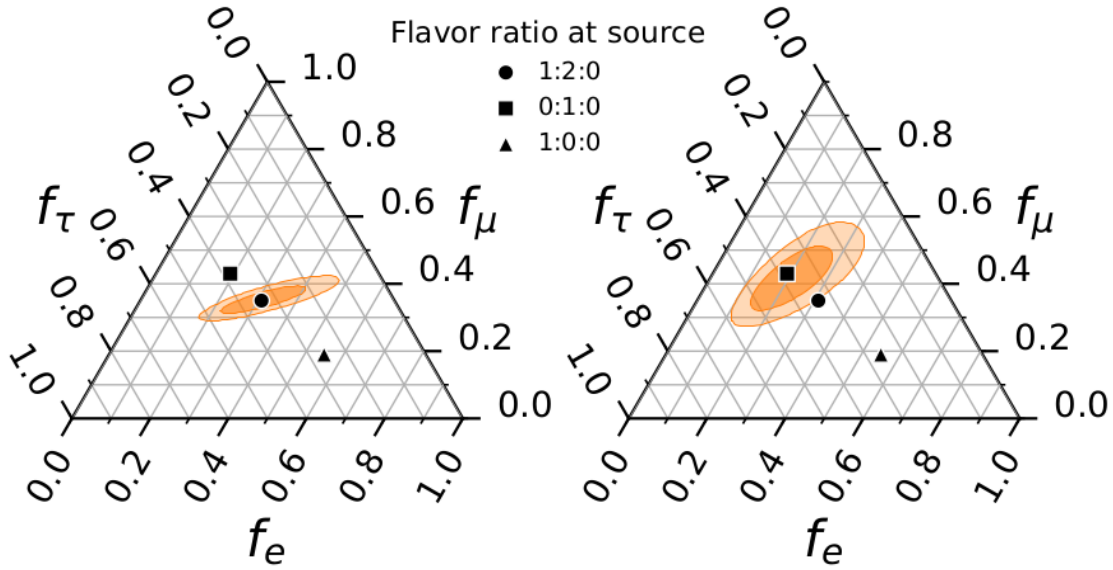


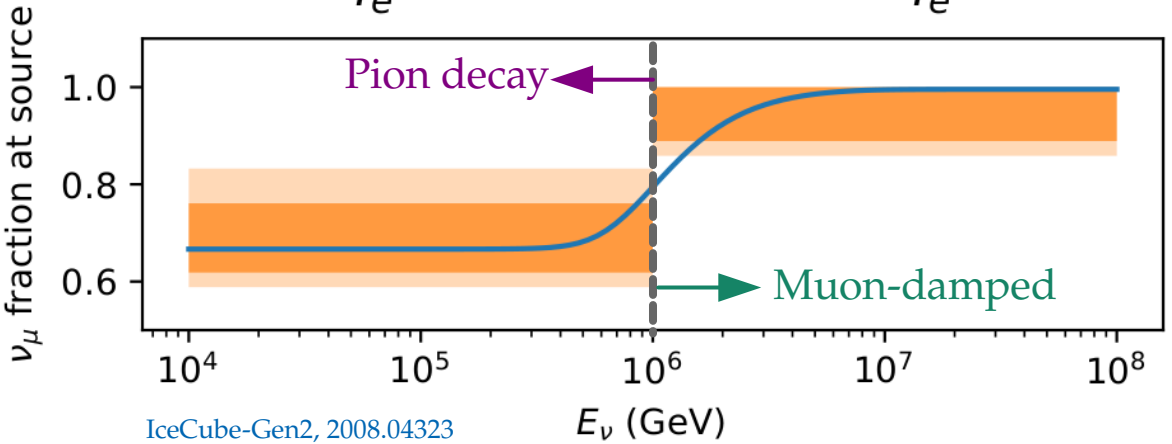
MB, Beacom, Winter, *PRL* 2015

- TP13: $p\gamma$ model, target photons from 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

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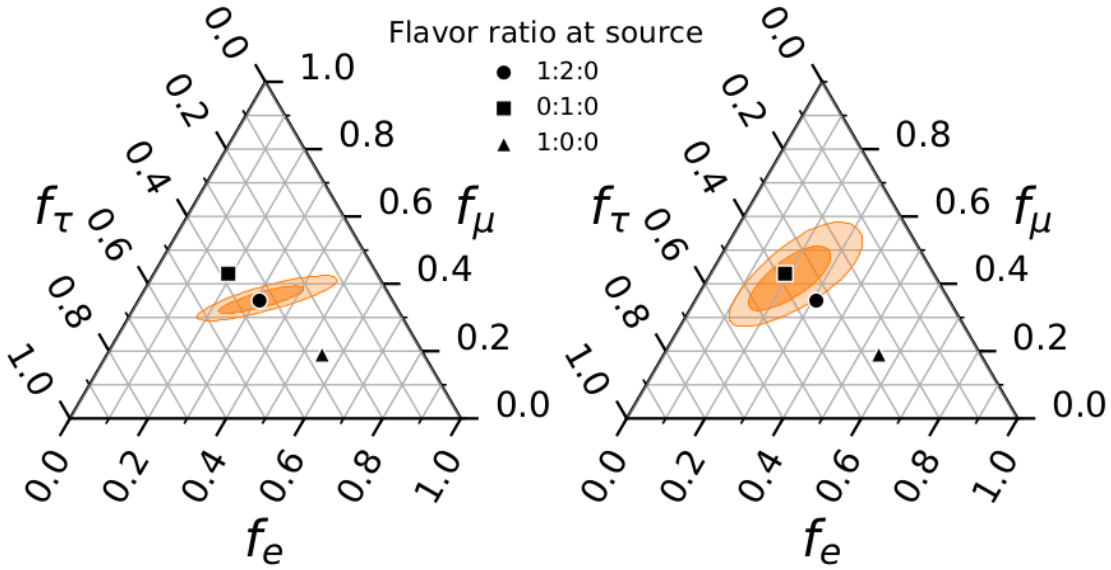

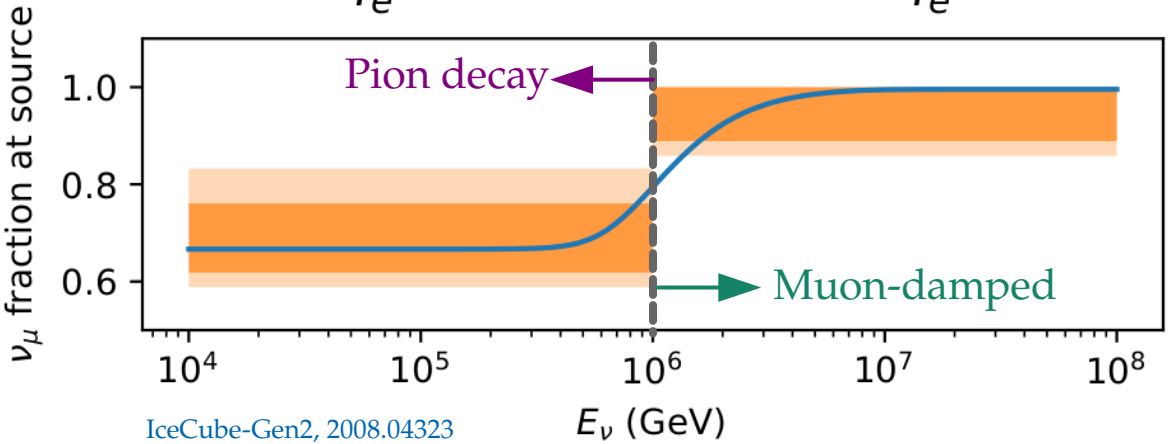

IceCube-Gen2, 2008.04323

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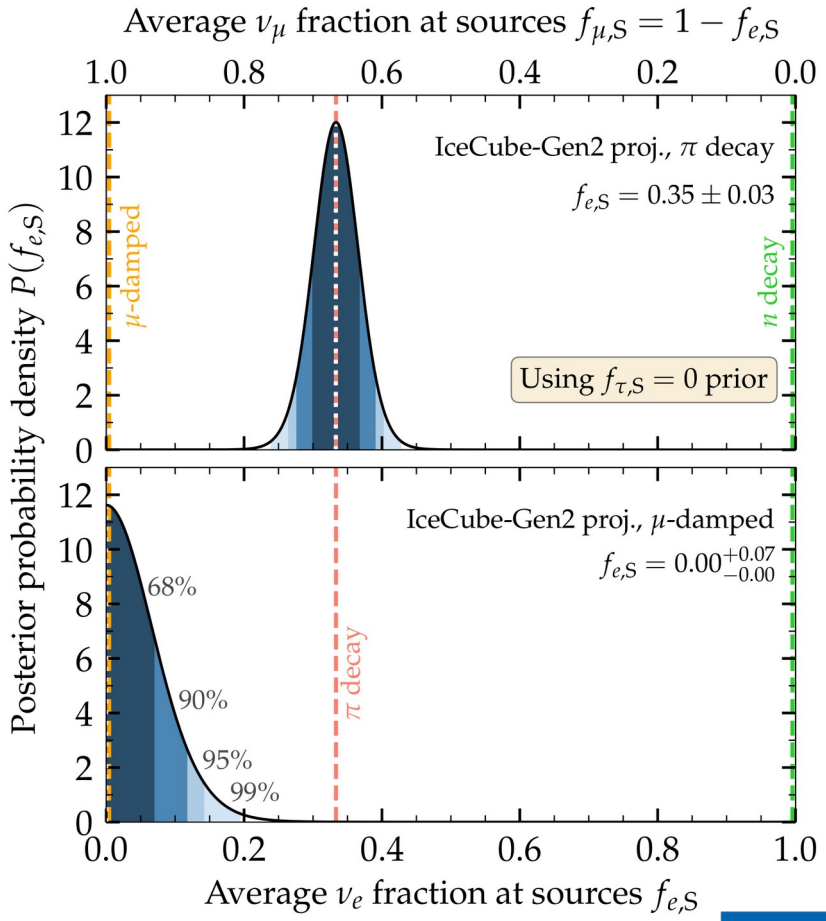

MB & Ahlers, *PRL* 2019

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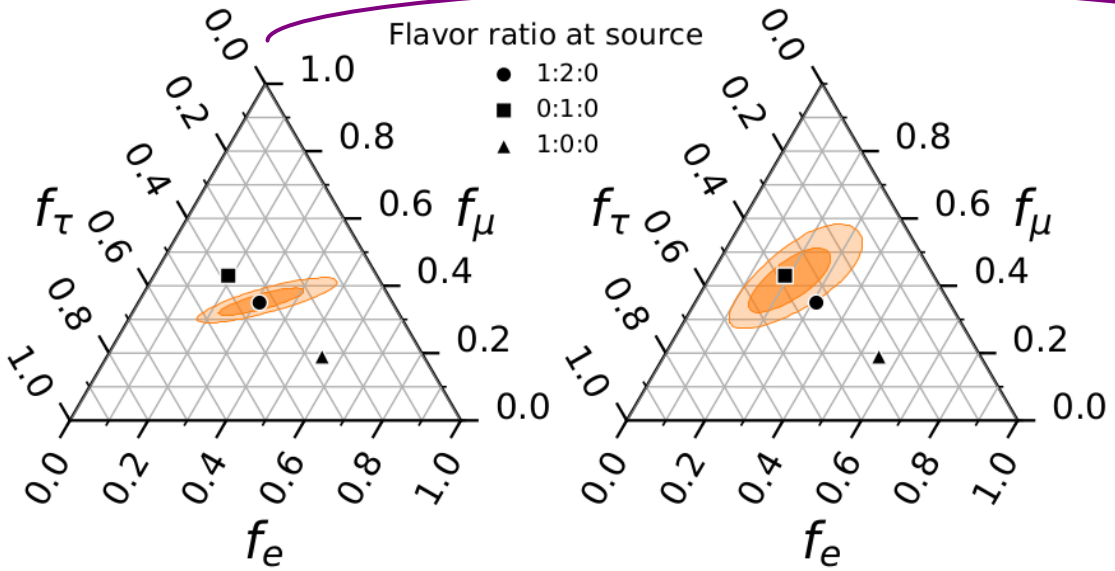

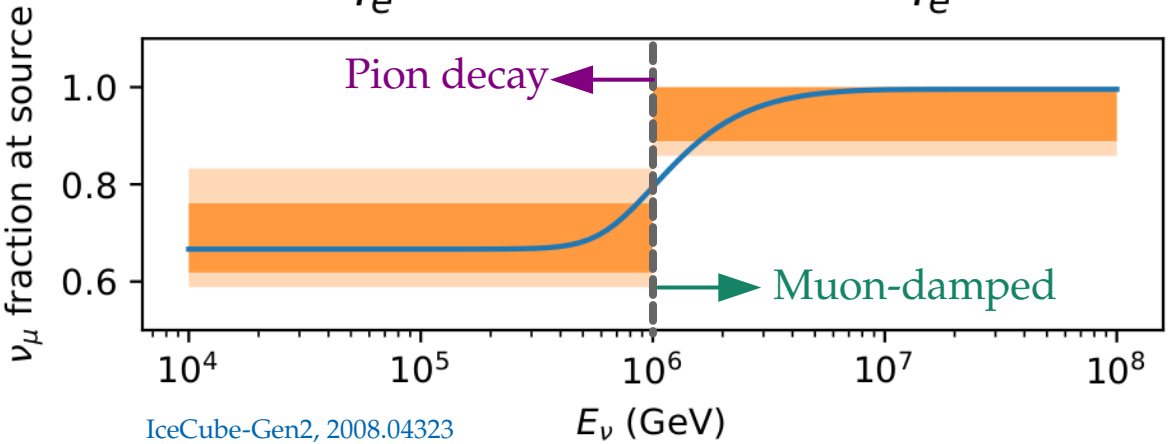

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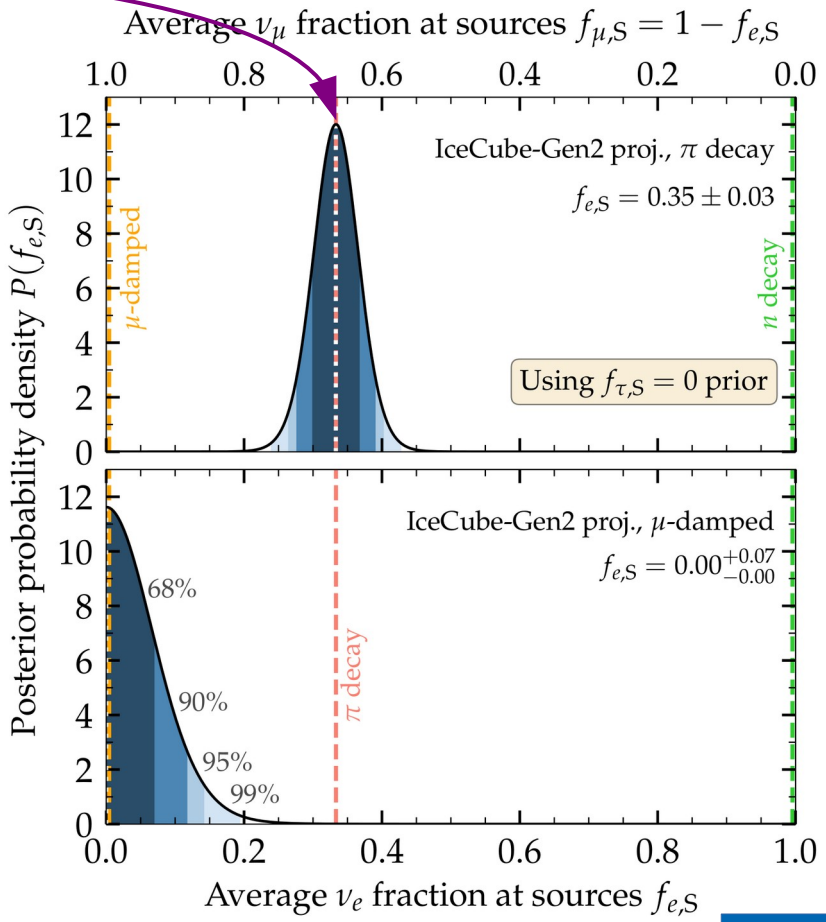

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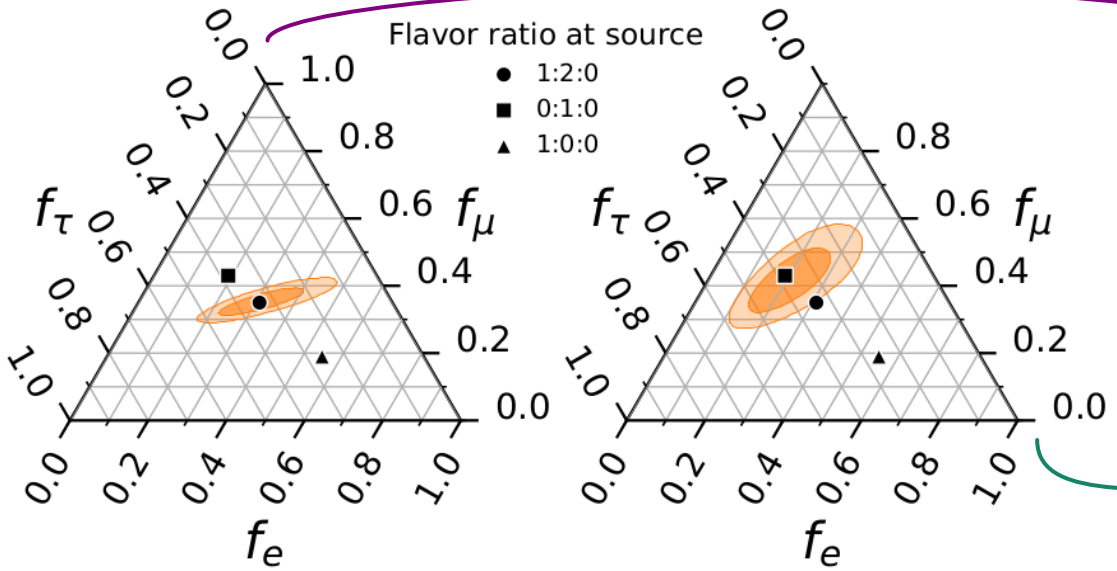

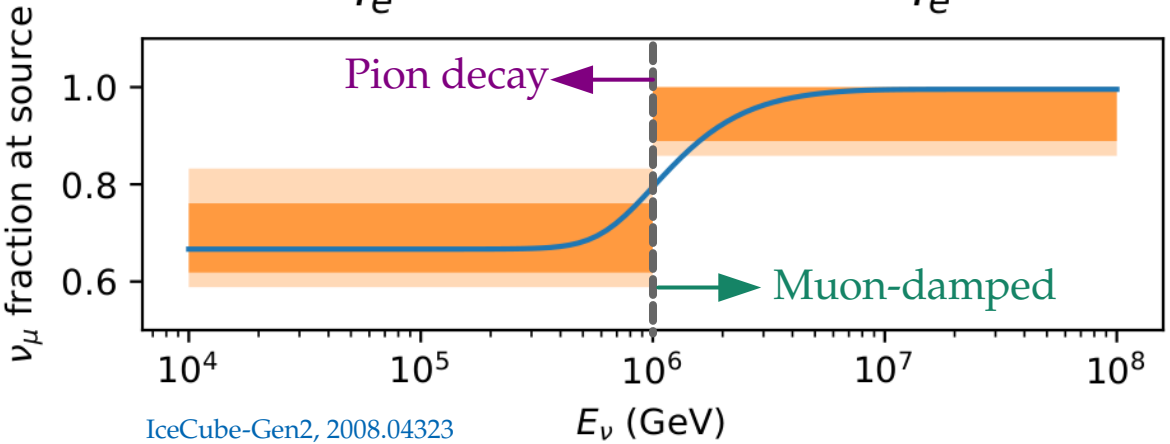

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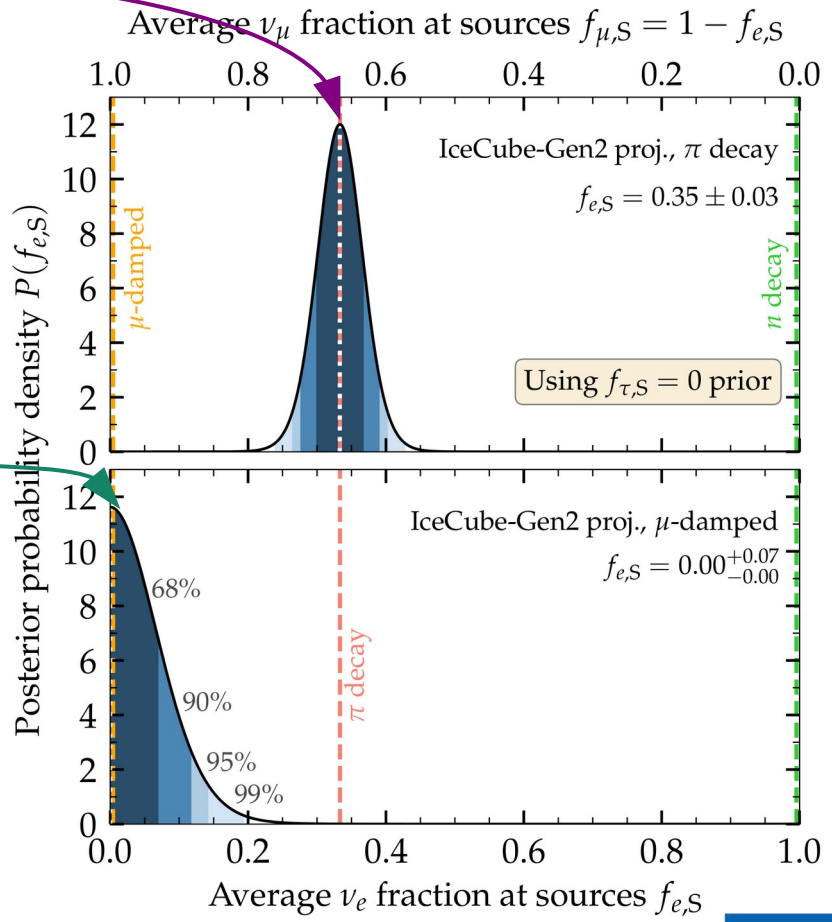
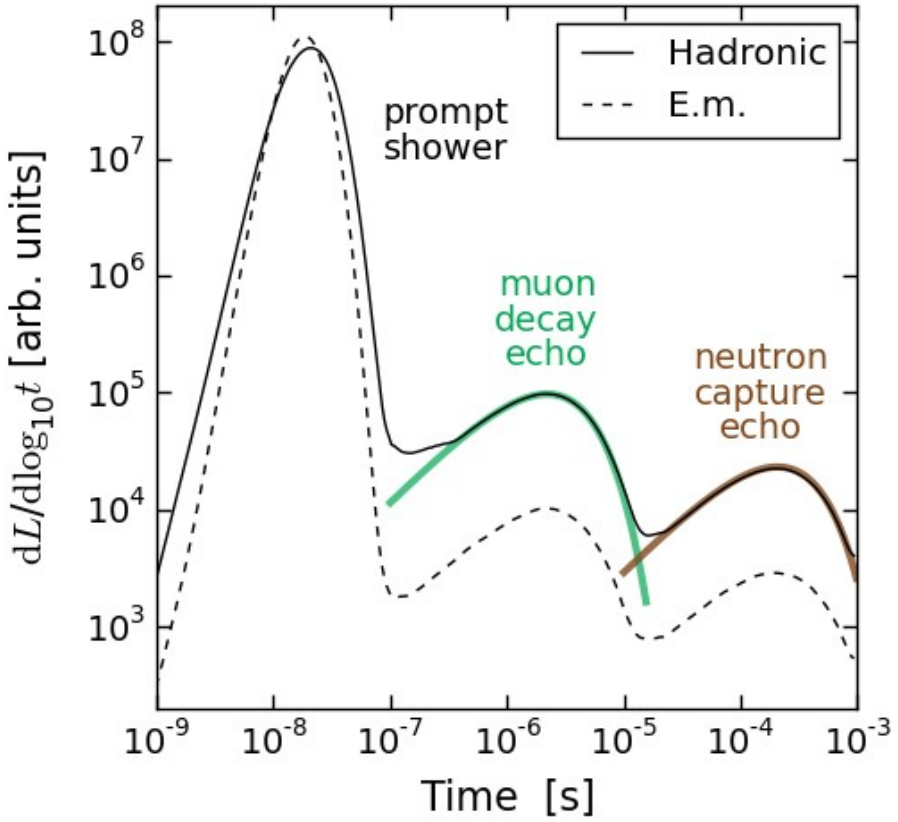
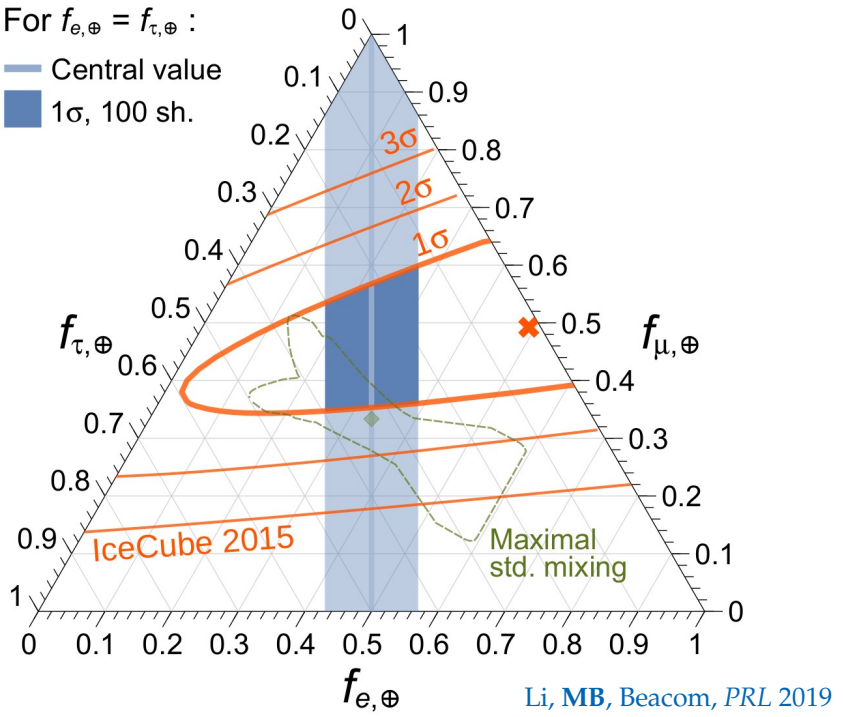


MB & Ahlers, *PRL* 2019

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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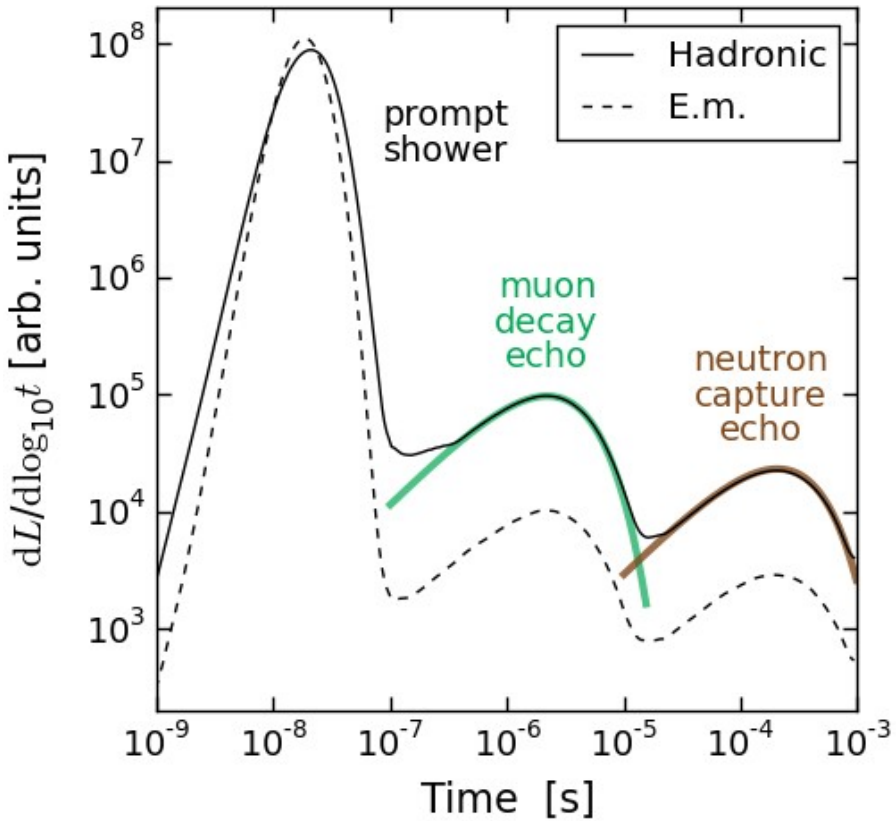
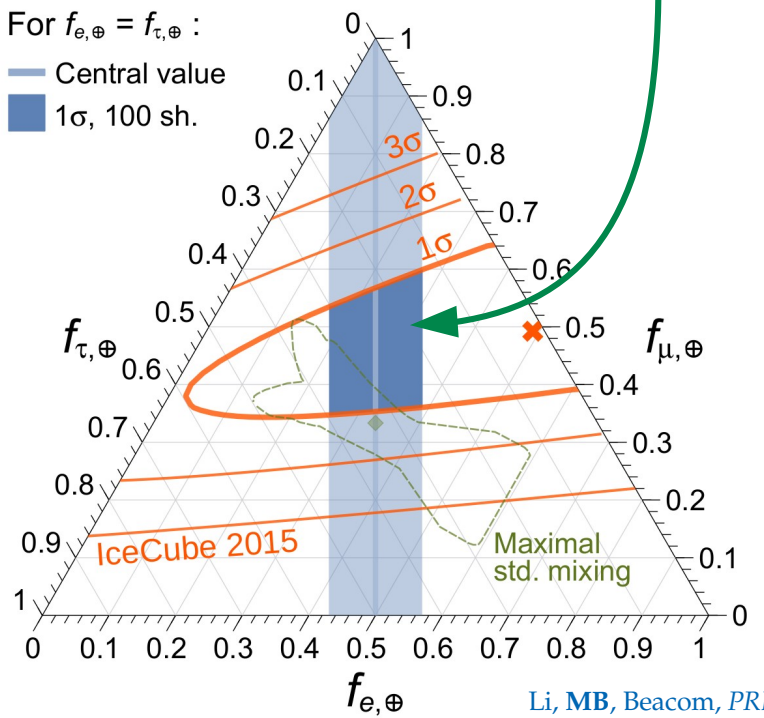


~10 × improvement over current measurement



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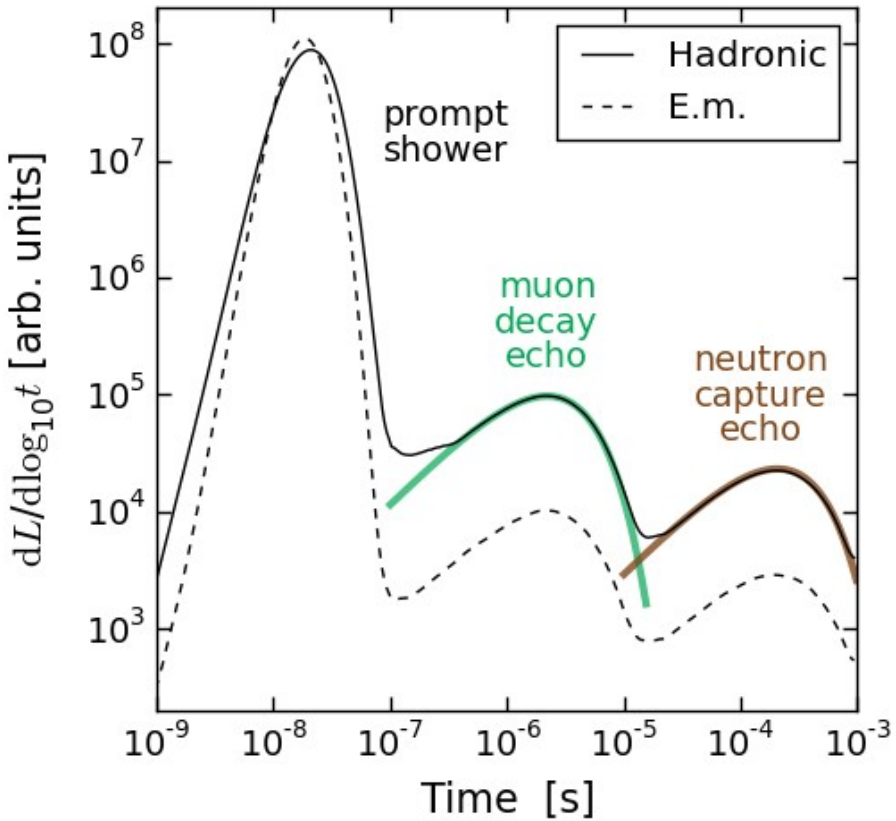

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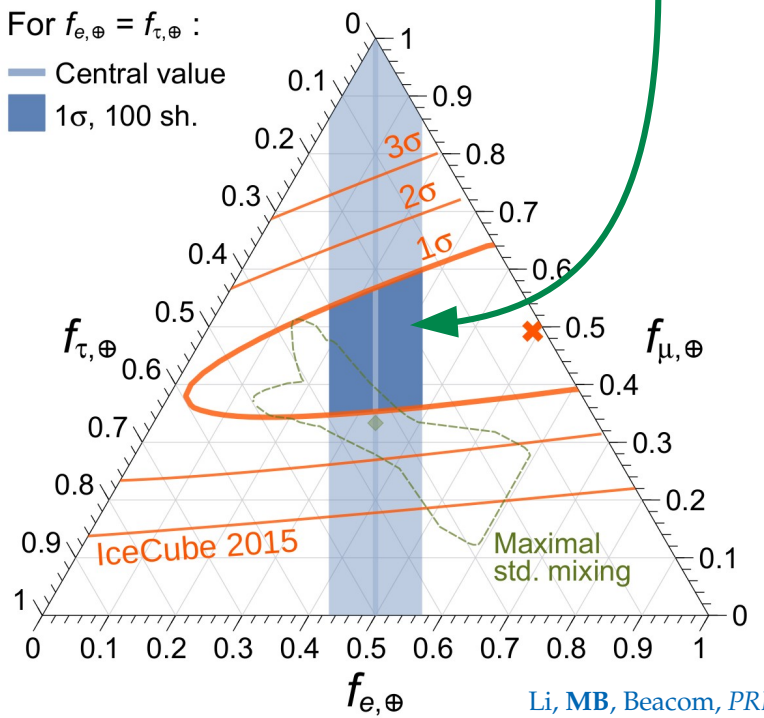
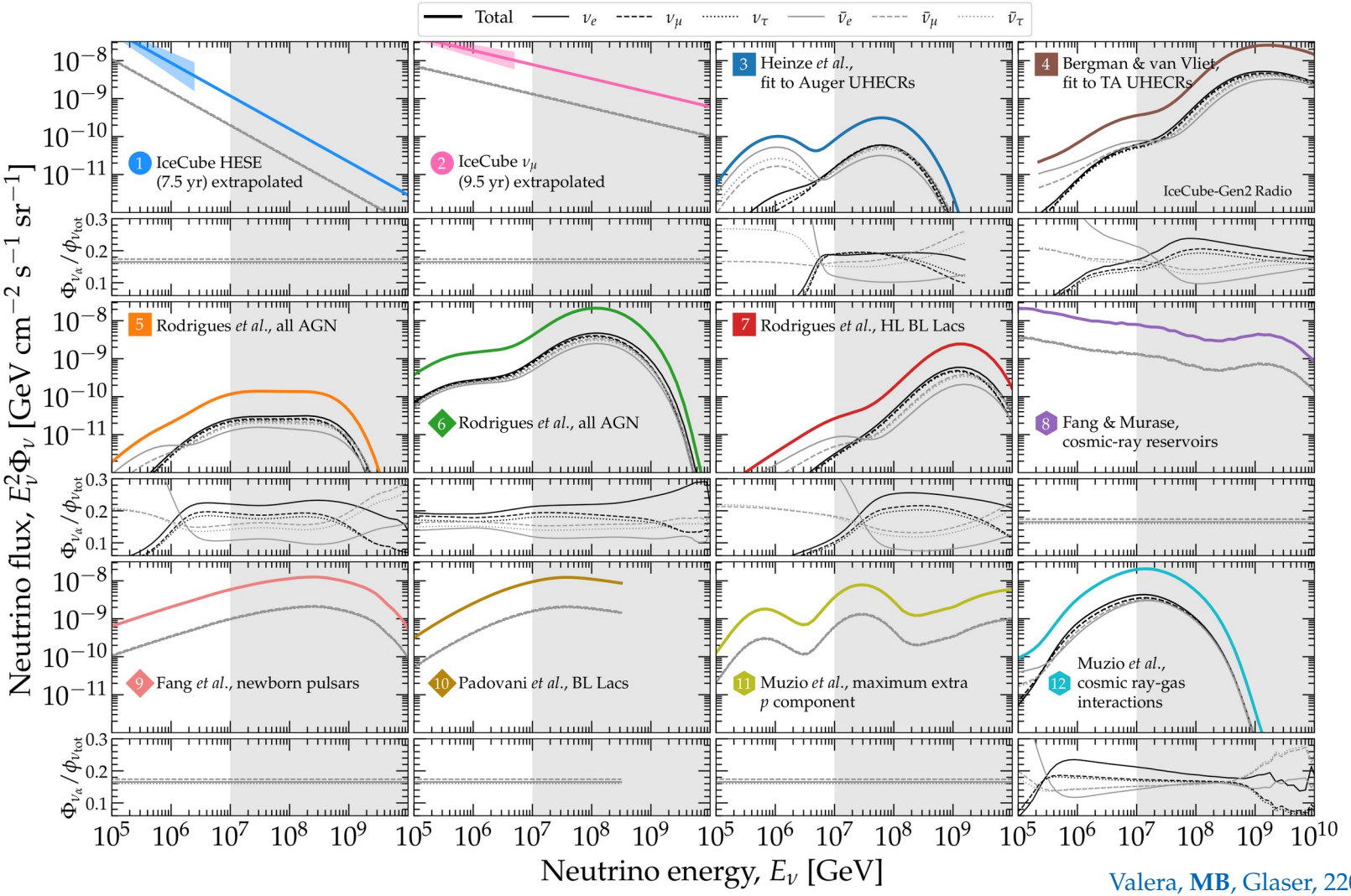


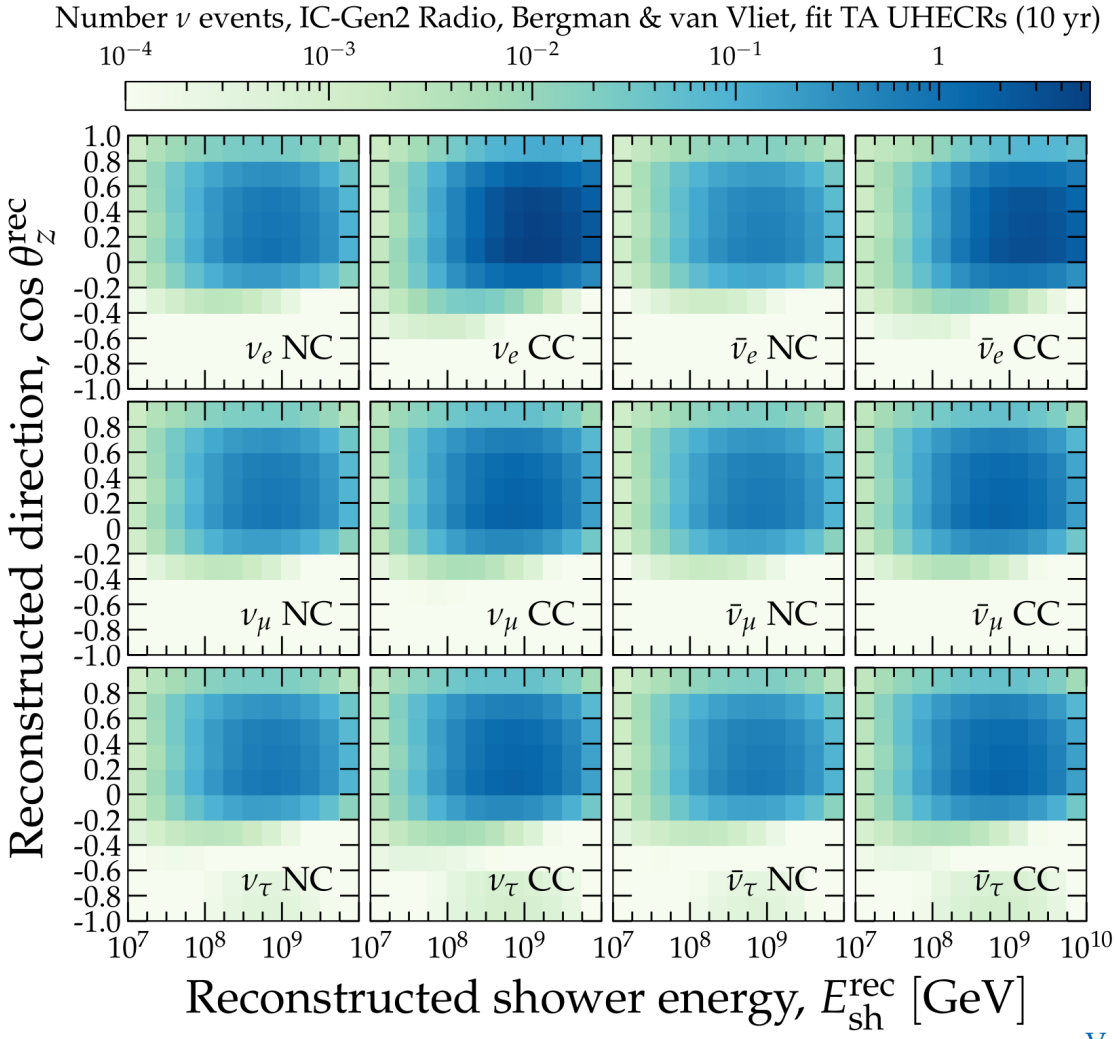
Li, **MB**, Beacom, *PRL* 2019

All UHE neutrino flux models



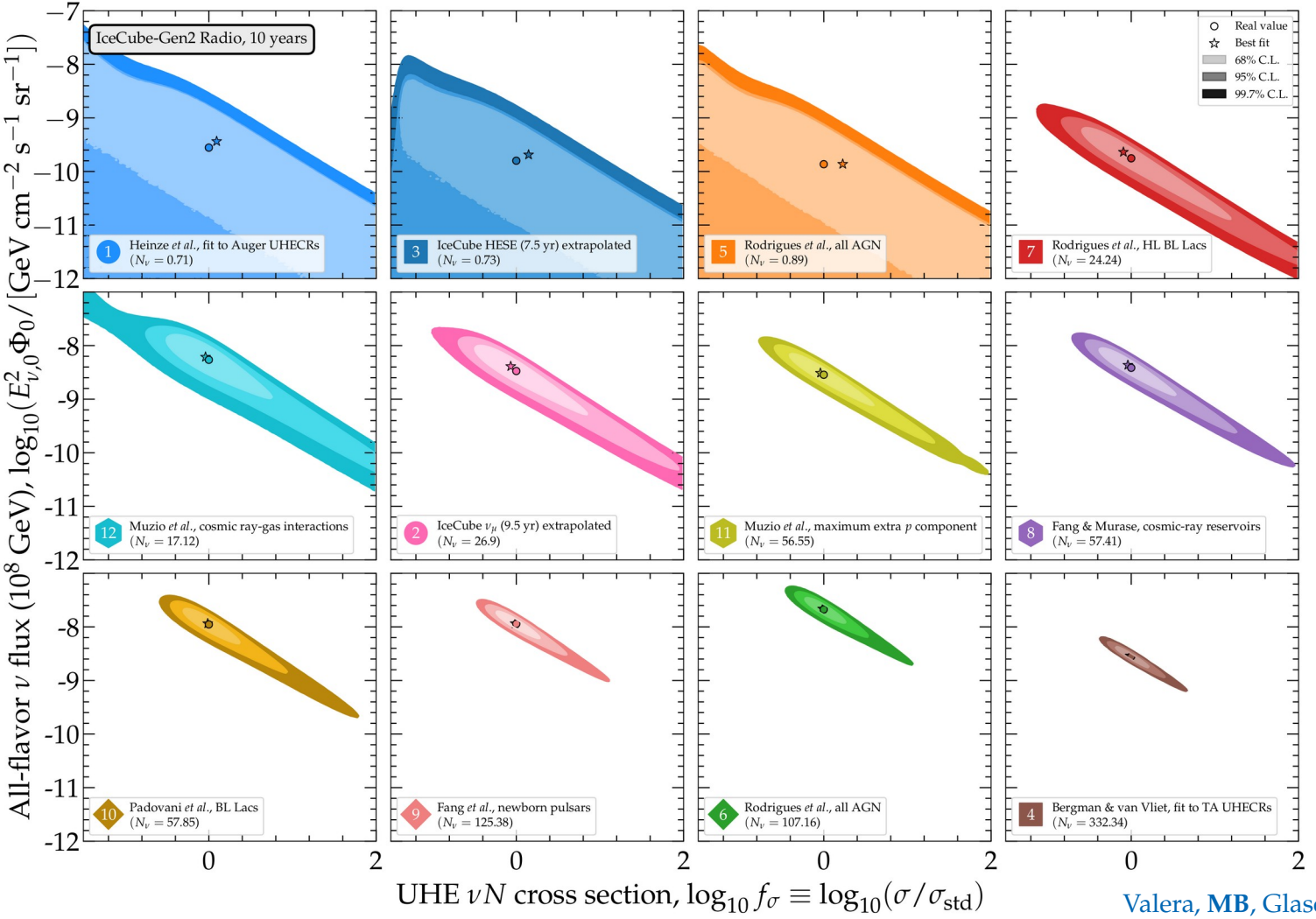
Valera, **MB**, Glaser, 2204.04237

Event rates per channel



Valera, **MB**, Glaser, 2204.04237

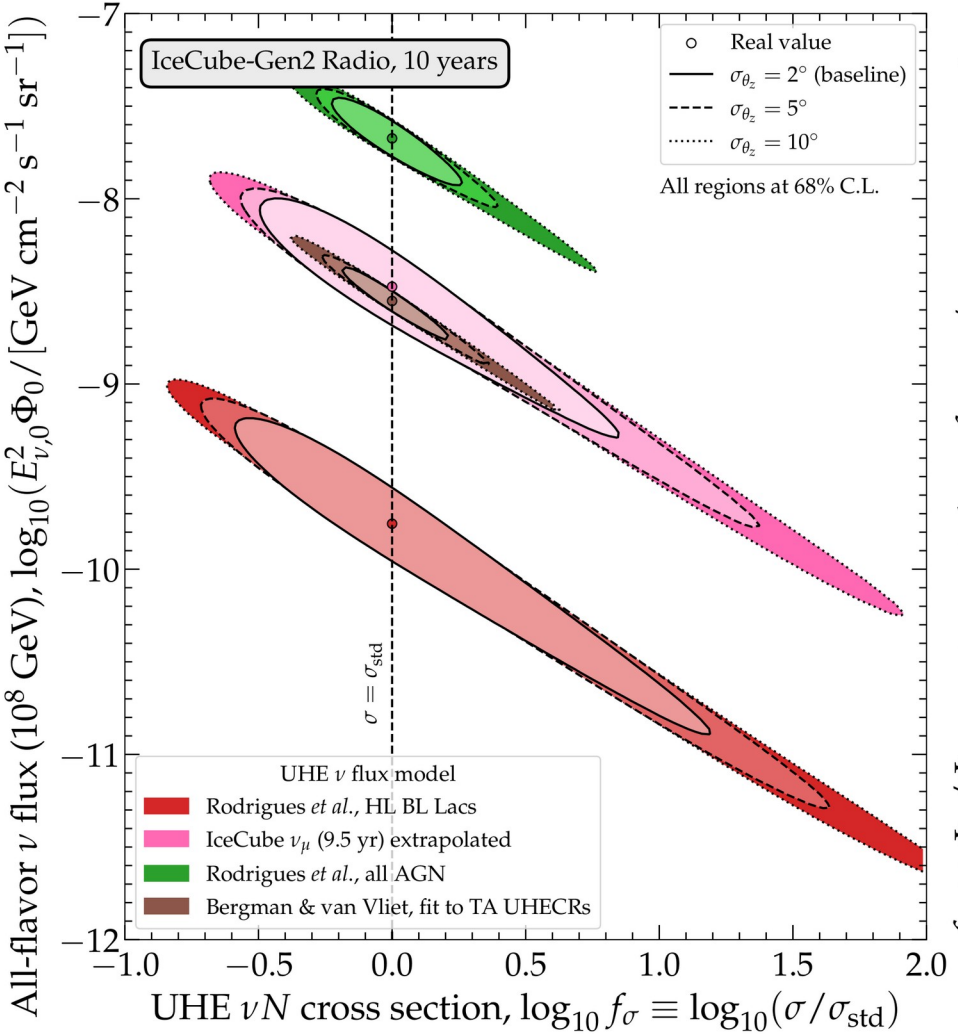
Posteriors for all UHE neutrino flux models

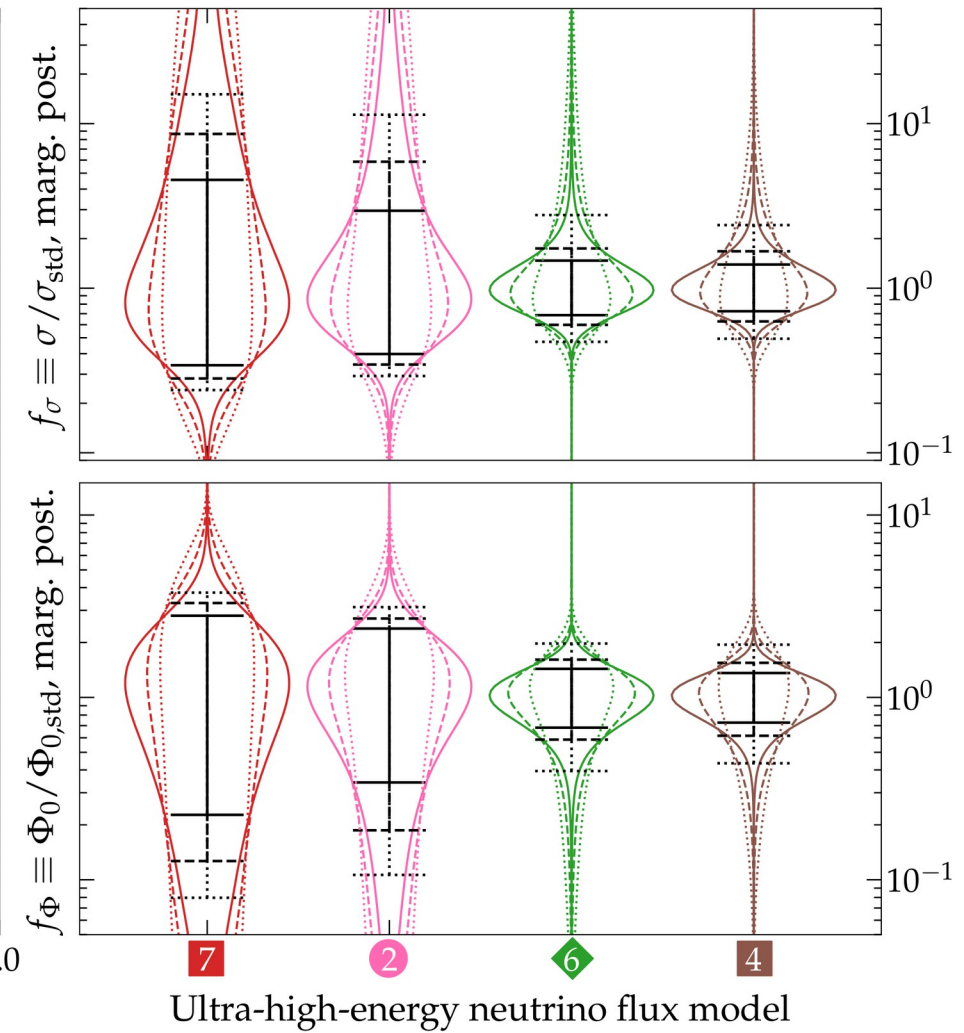


Valera, **MB**, Glaser, 2204.04237

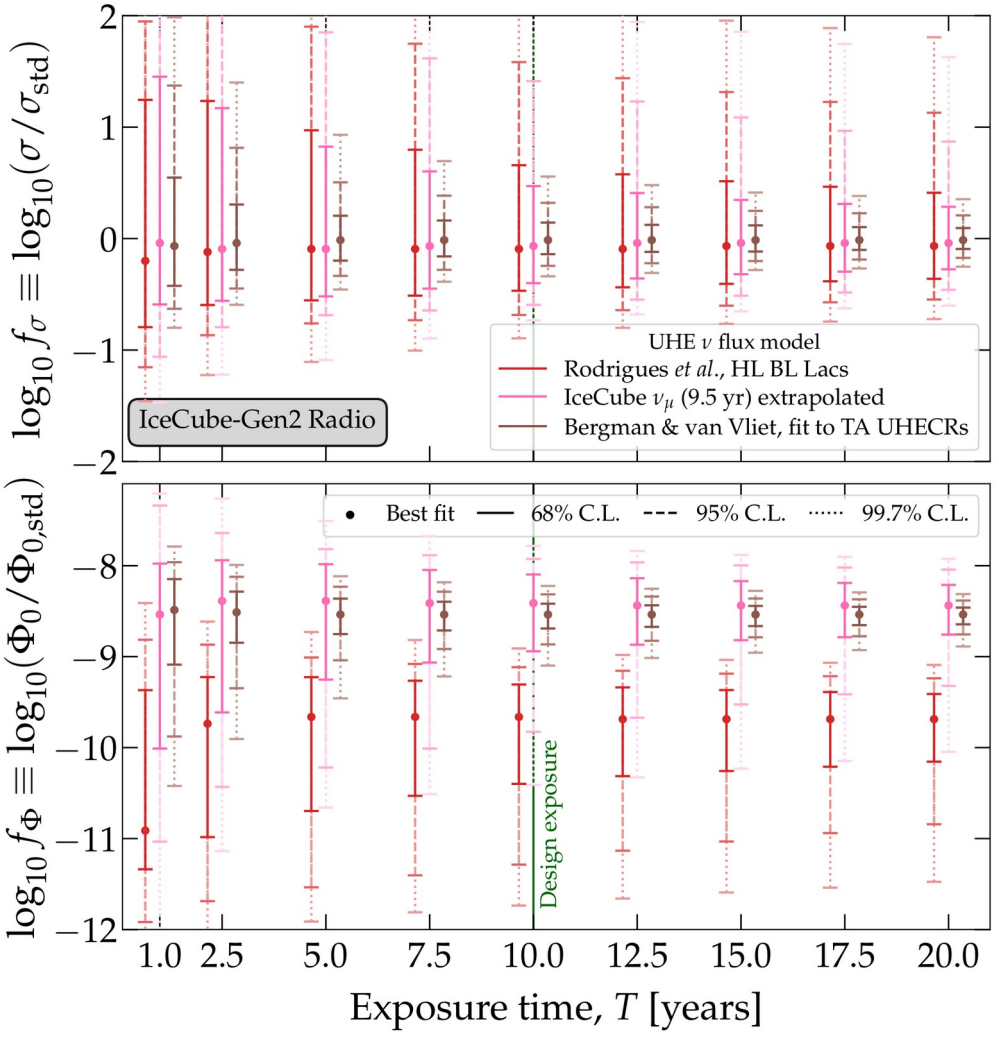
Effect of angular resolution

Valera, **MB**, Glaser, 2204.04237



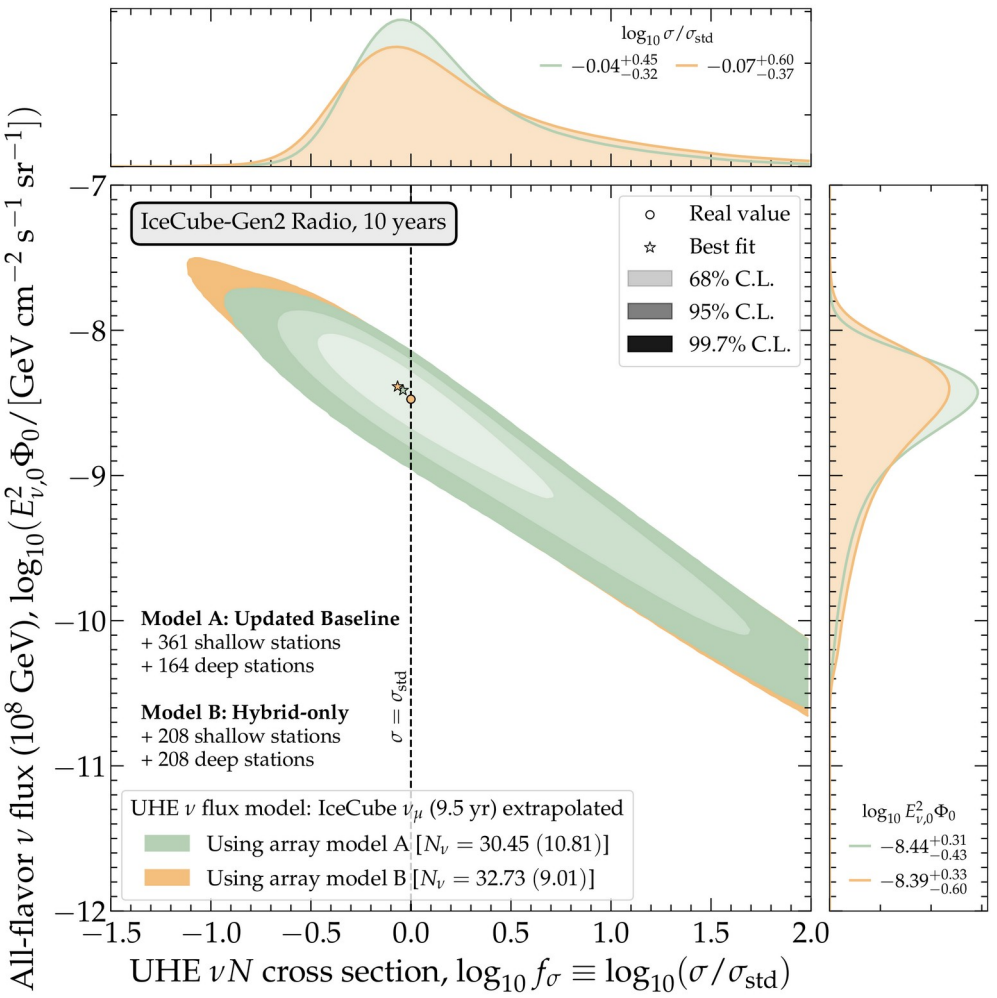


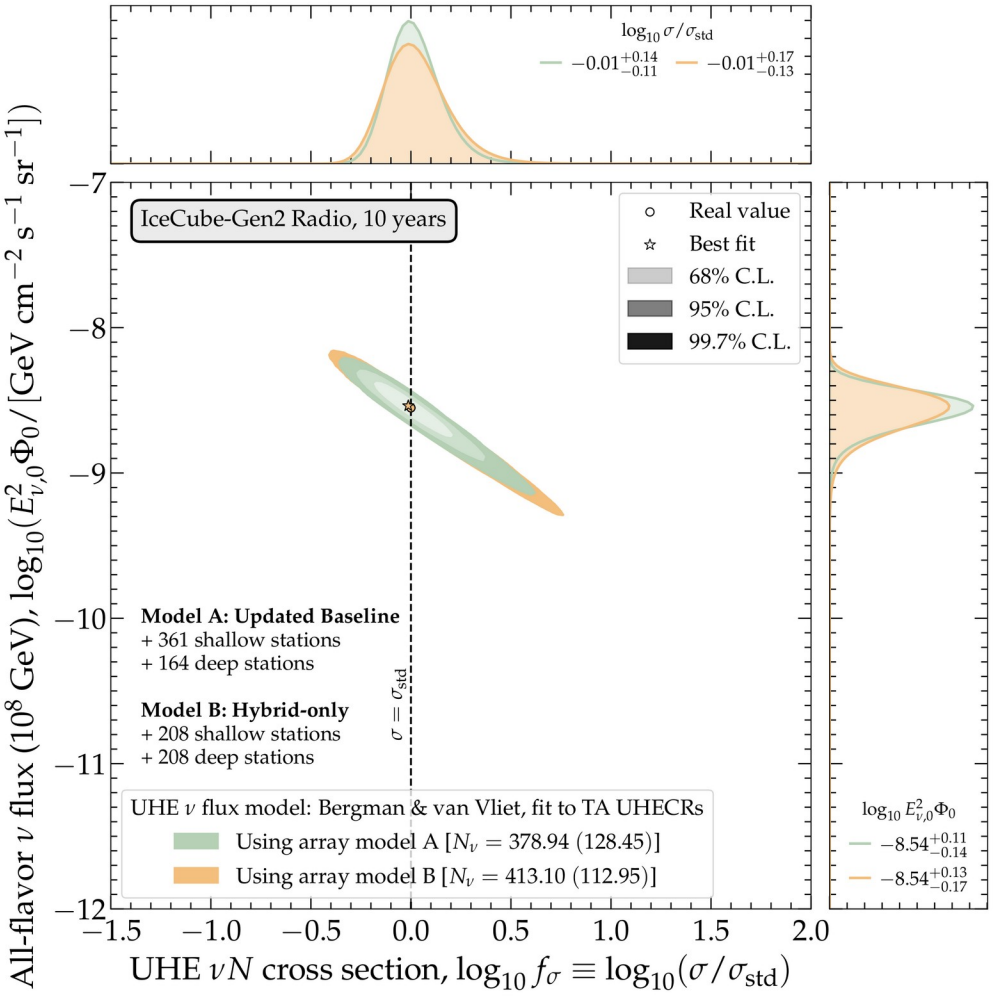
Precision *vs*. exposure time



Valera, **MB**, Glaser, 2204.04237

Results for alternative radio array designs





Figures courtesy of Víctor Valera