The Flavor Composition of the High-Energy Astrophysical Neutrinos

Qinrui Liu

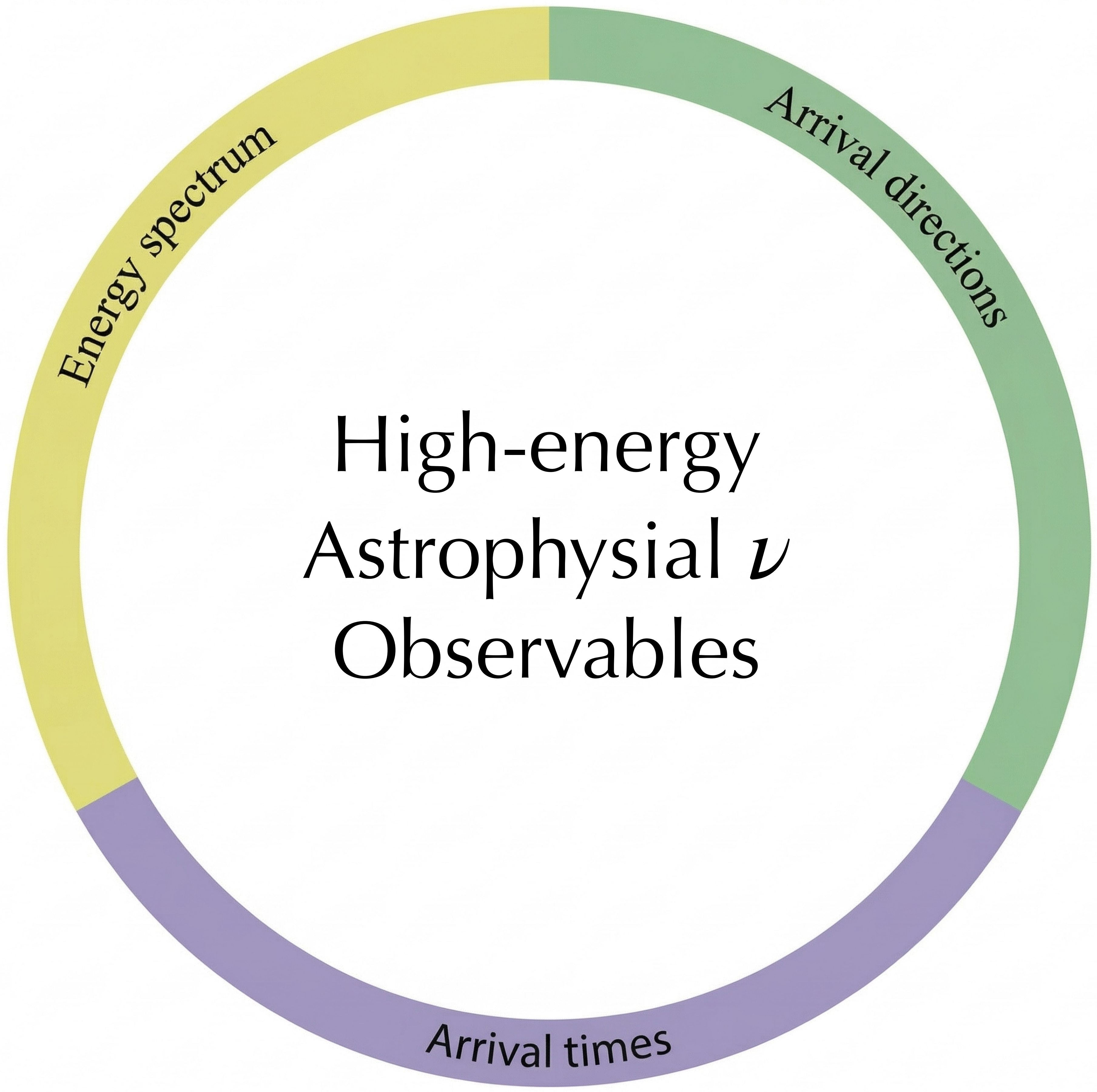
MACROS 2026 Workshop

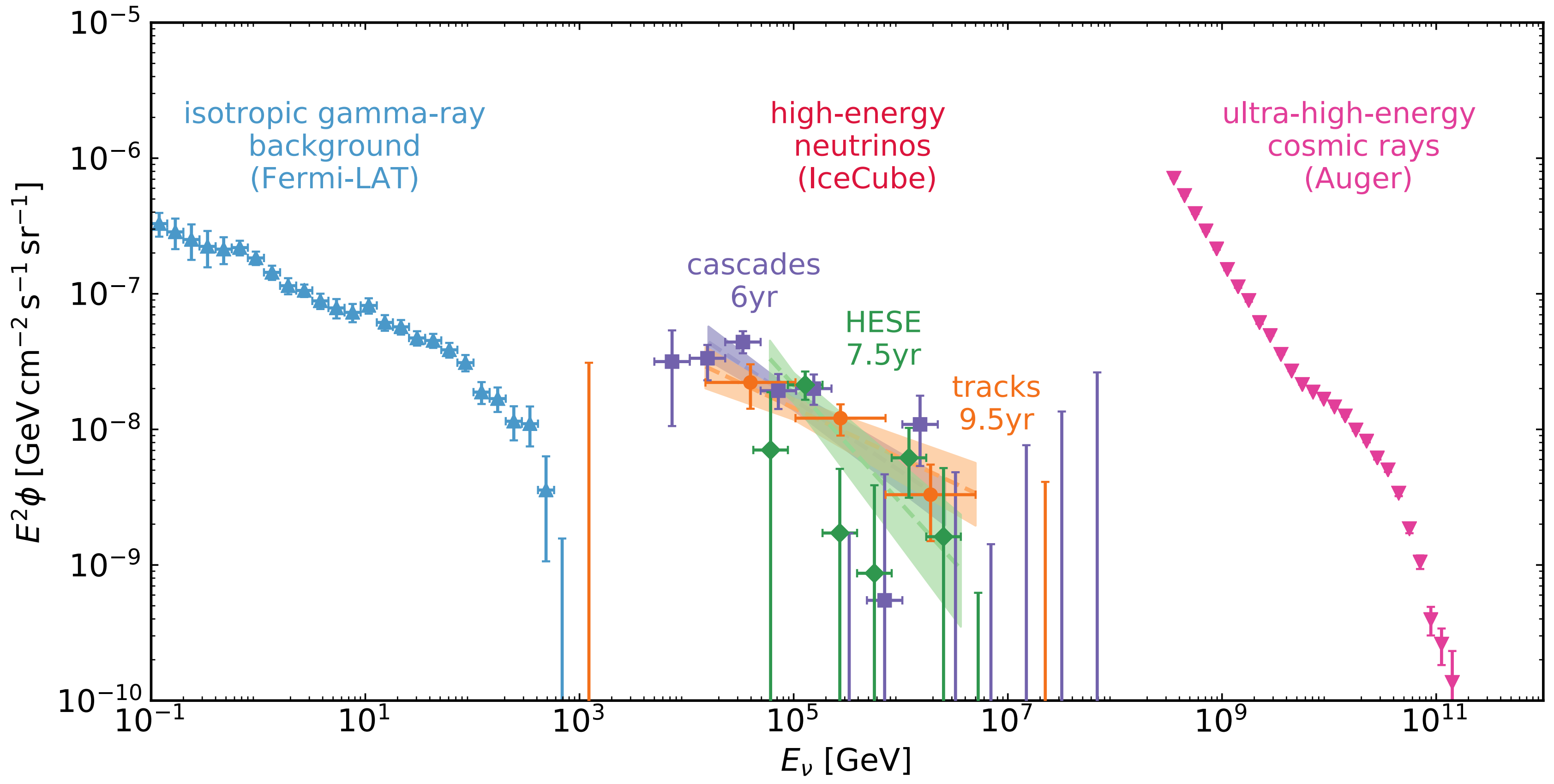
Penn State University

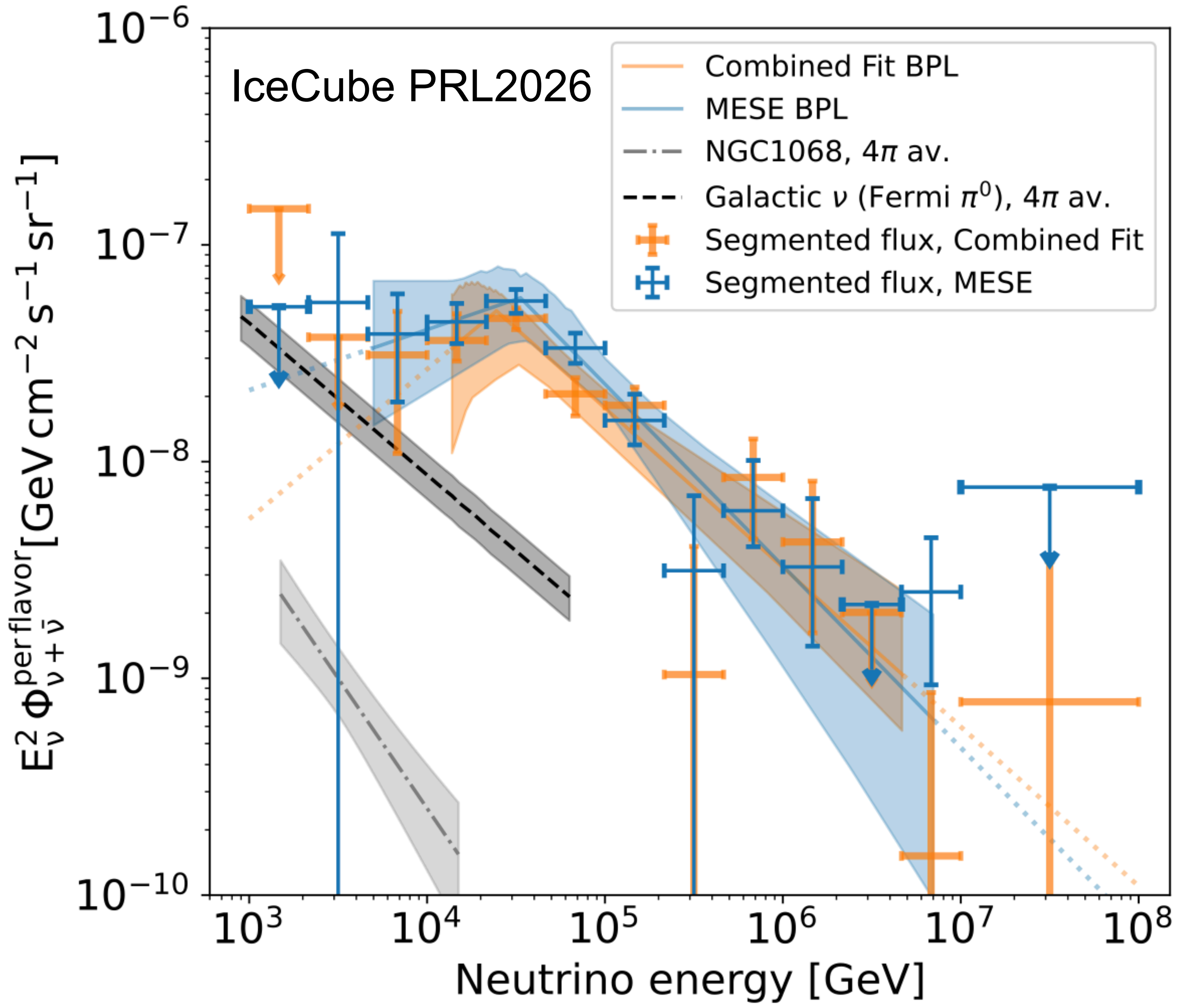
2026/04/24

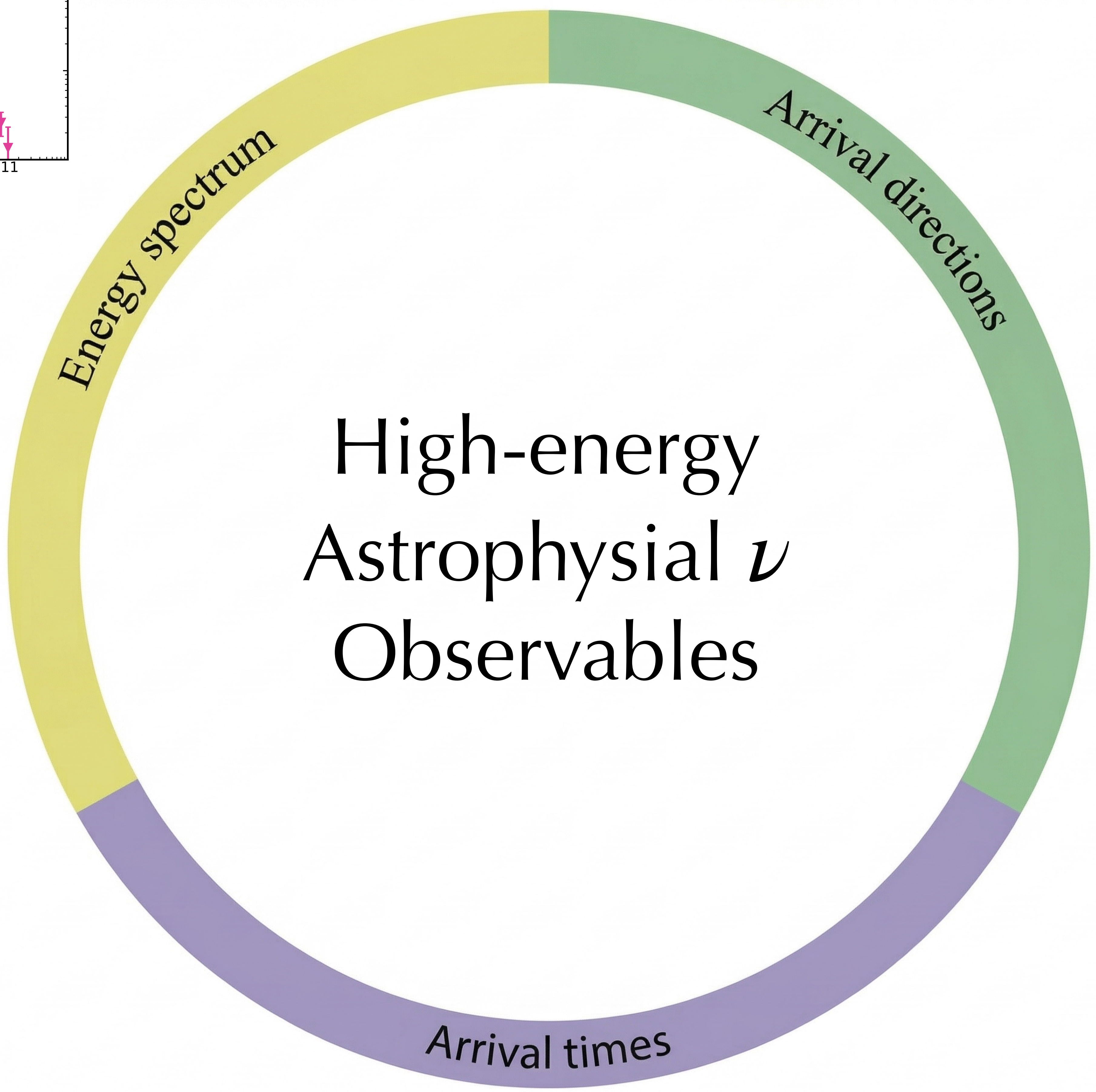
SIMON FRASER UNIVERSITY

Arthur B. McDonald
Canadian Astroparticle Physics Research Institute


Energy spectrum
Arrival directions
High-energy
Astrophysial ν
Observables
Arrival times


isotropic gamma-ray background (Fermi-LAT)
high-energy neutrinos (IceCube)
ultra-high-energy cosmic rays (Auger)
cascades 6yr
HESE 7.5yr
tracks 9.5yr
$E^2\phi$ [GeV cm^{-2} s^{-1} sr^{-1}]
E_ν [GeV]


IceCube PRL2026
Combined Fit BPL
MESE BPL
NGC1068, 4π av.
Galactic ν (Fermi π⁰), 4π av.
Segmented flux, Combined Fit
Segmented flux, MESE
$E_\nu^2 \Phi_{\nu+\bar\nu}^{\mathrm{per\,flavor}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy [GeV]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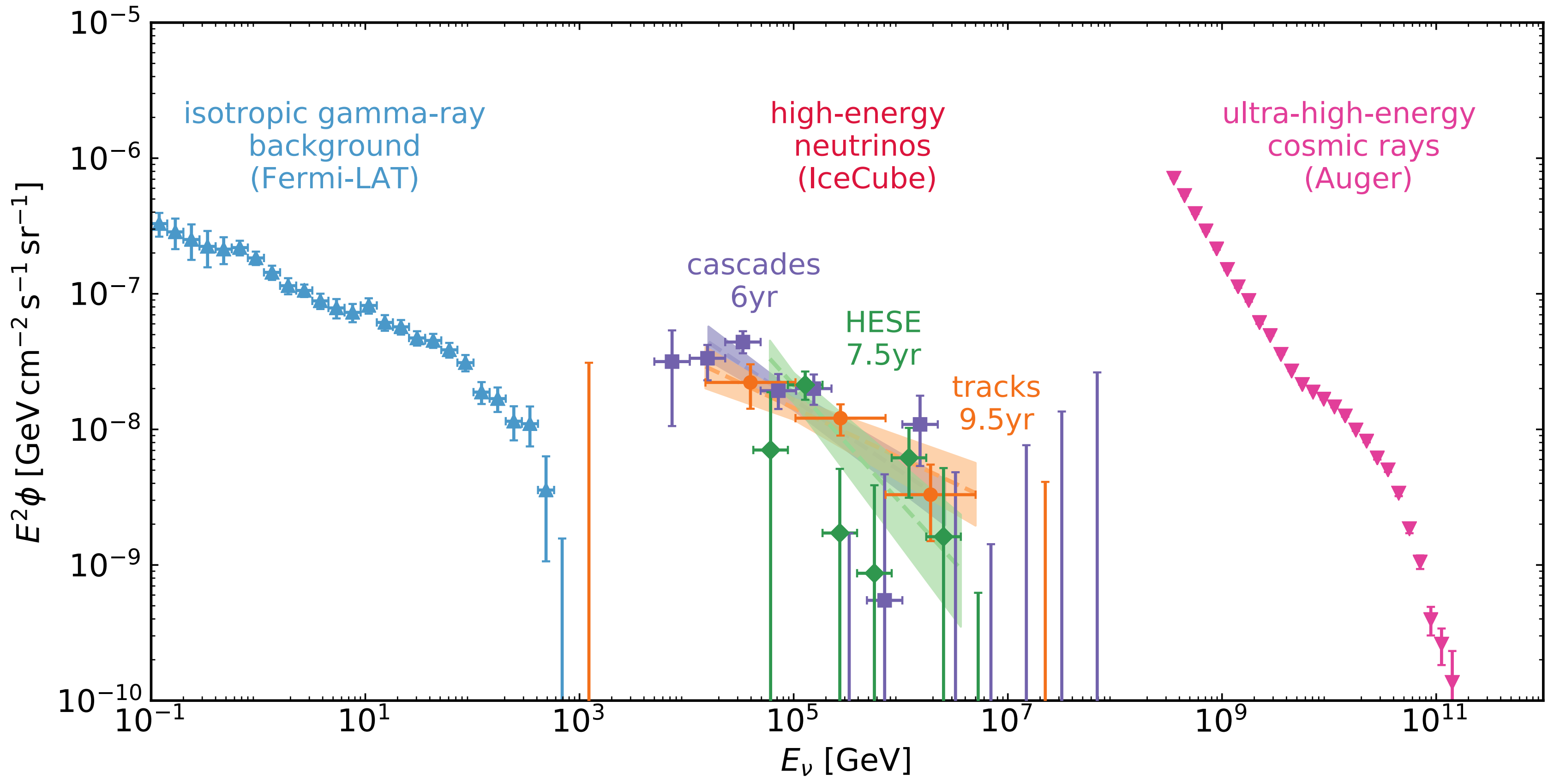
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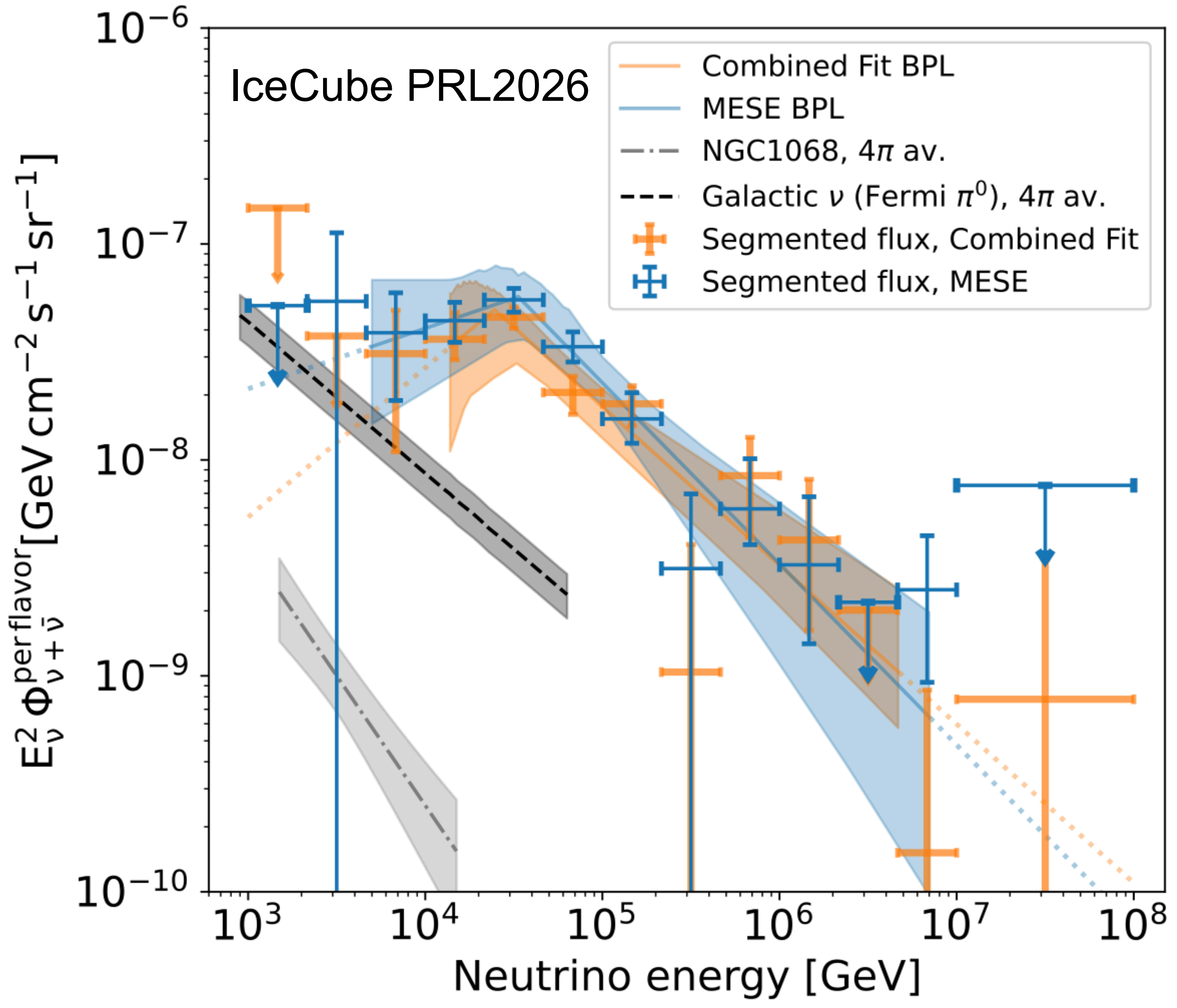
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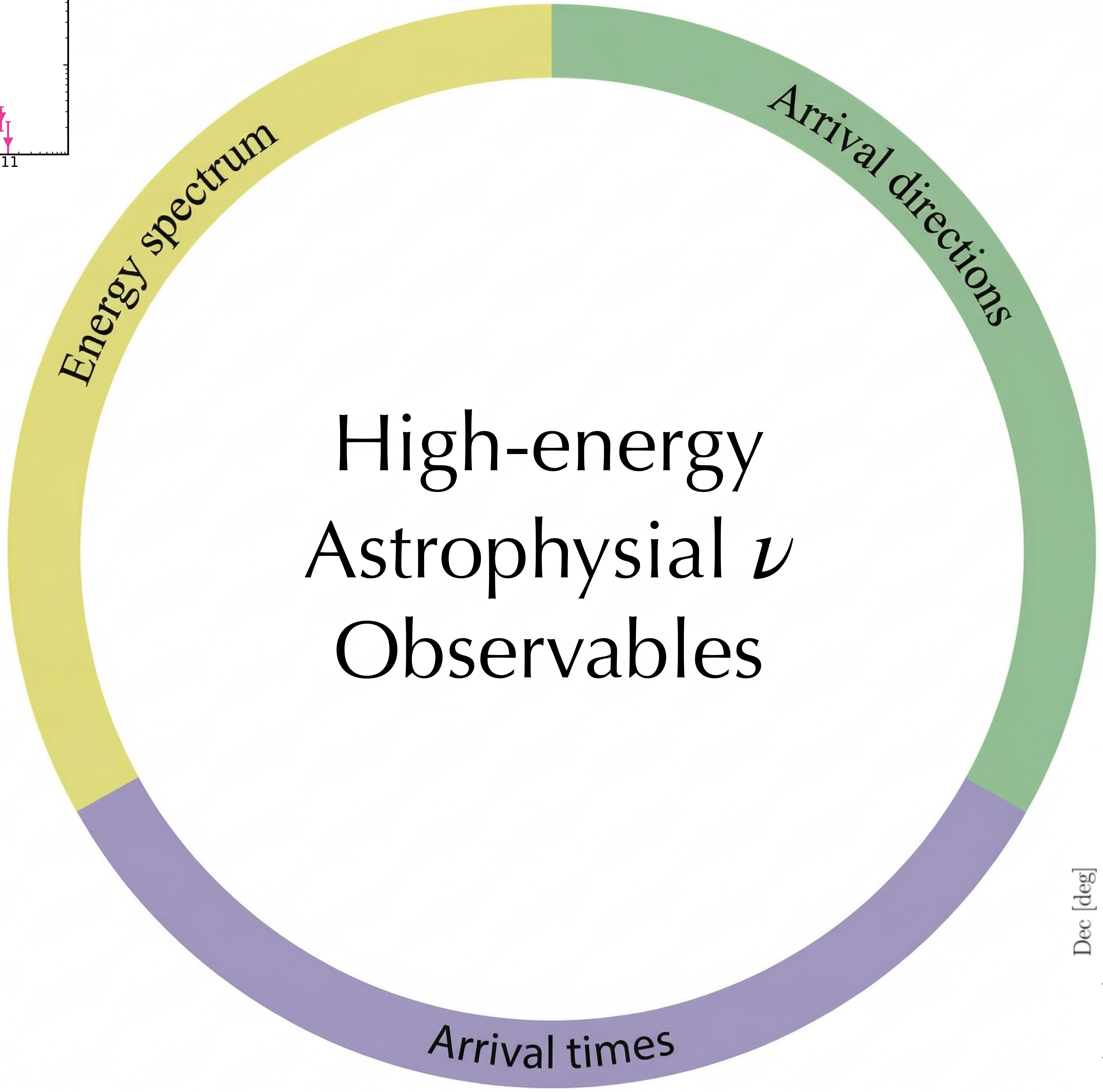
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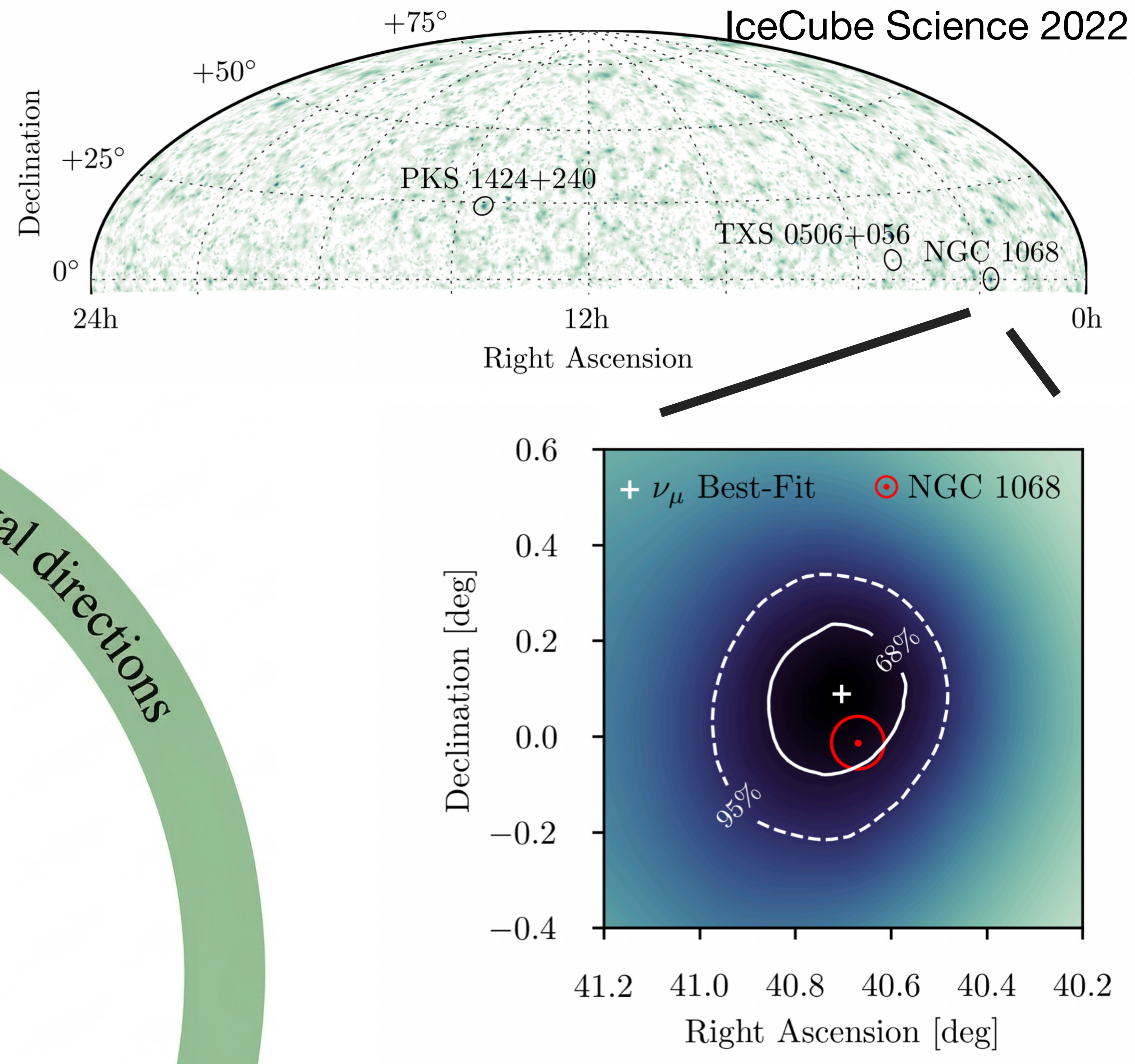
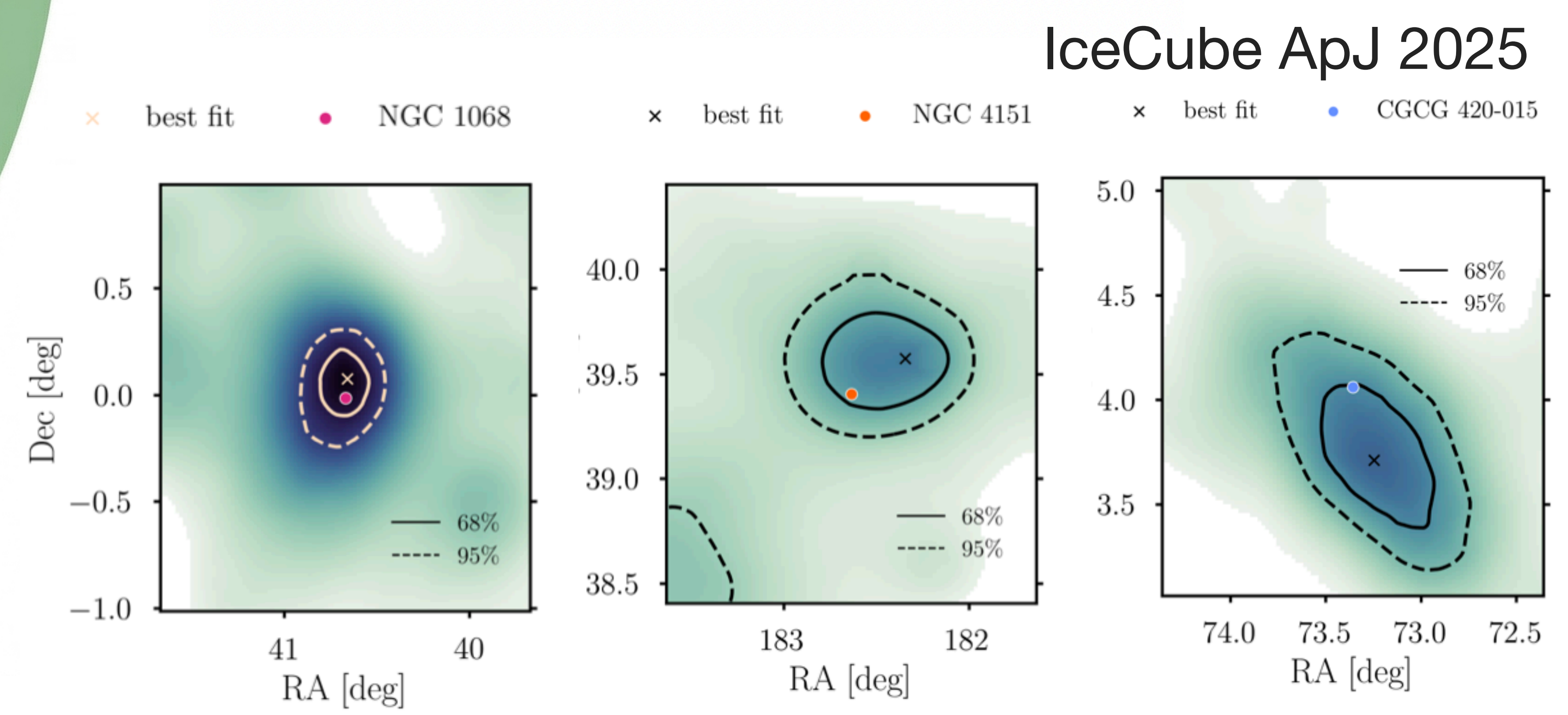
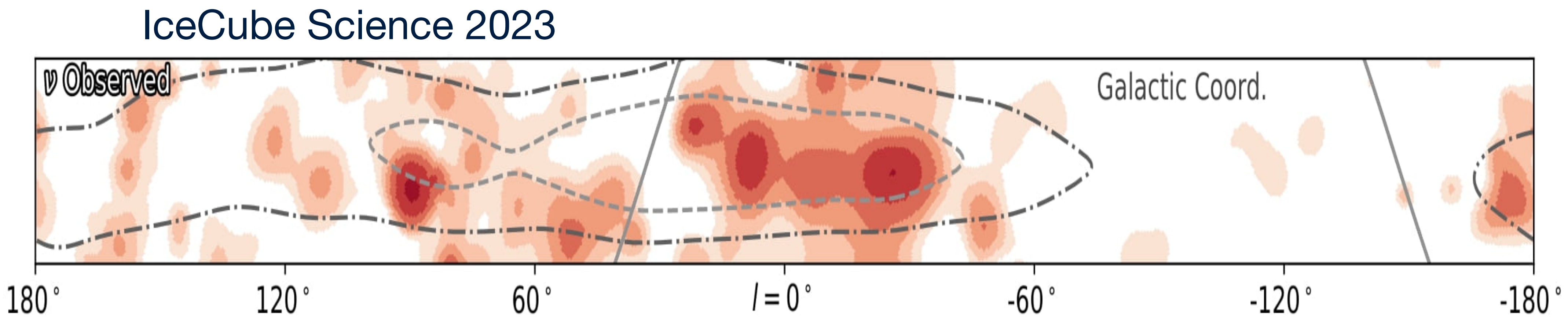
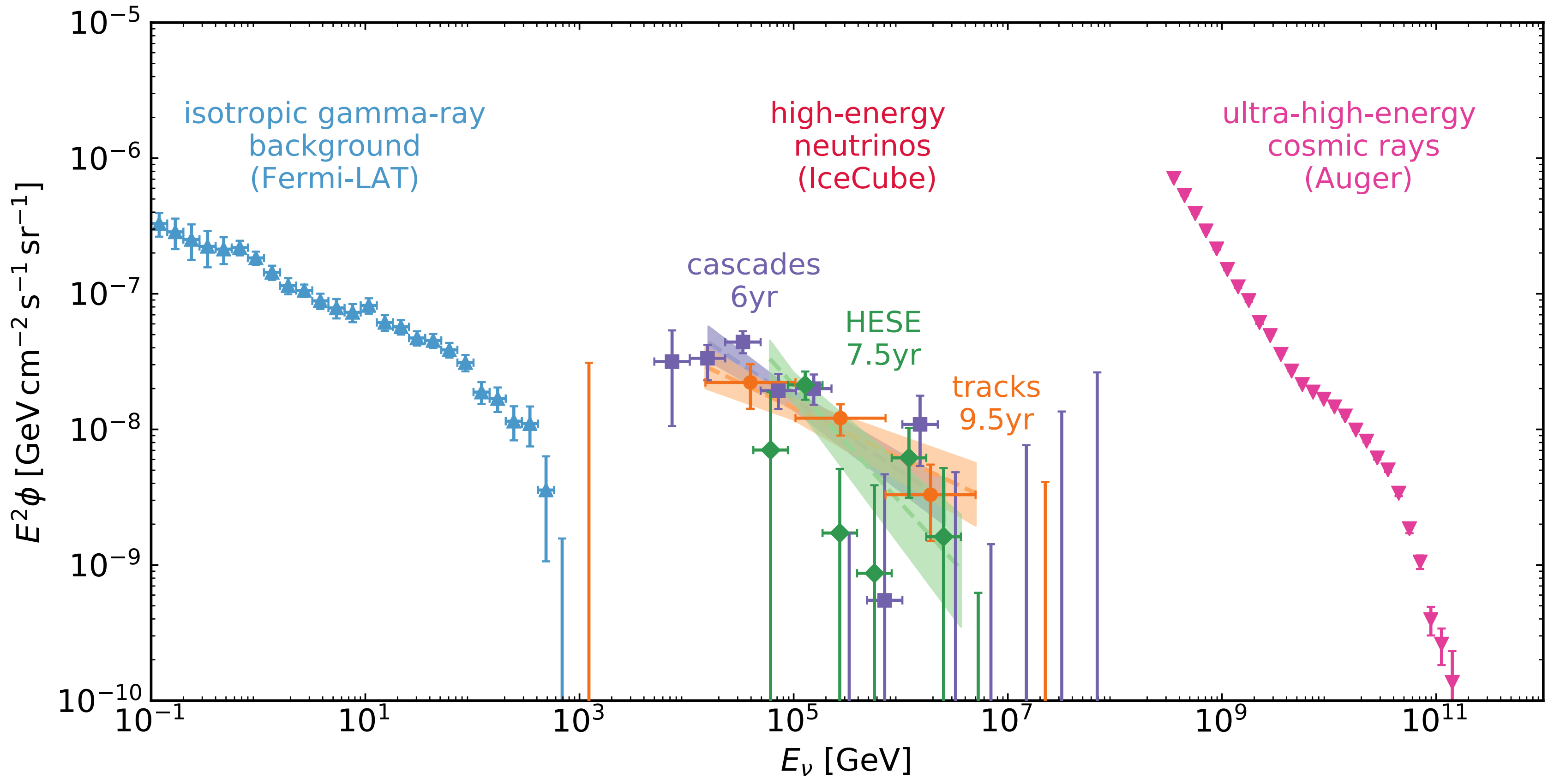

IceCube Science 2022
PKS 1424+240
TXS 0506+056
NGC 1068
Declination
Right Ascension
+ ν_μ Best-Fit
NGC 1068
68%
95%
Declination [deg]
Right Ascension [deg]


IceCube ApJ 2025
best fit
NGC 1068
NGC 4151
CGCG 420-015
68%
95%
Dec [deg]
RA [deg]


IceCube Science 2023
ν Observed
Galactic Coord.
180°
120°
60°
l = 0°
-60°
-120°
-180°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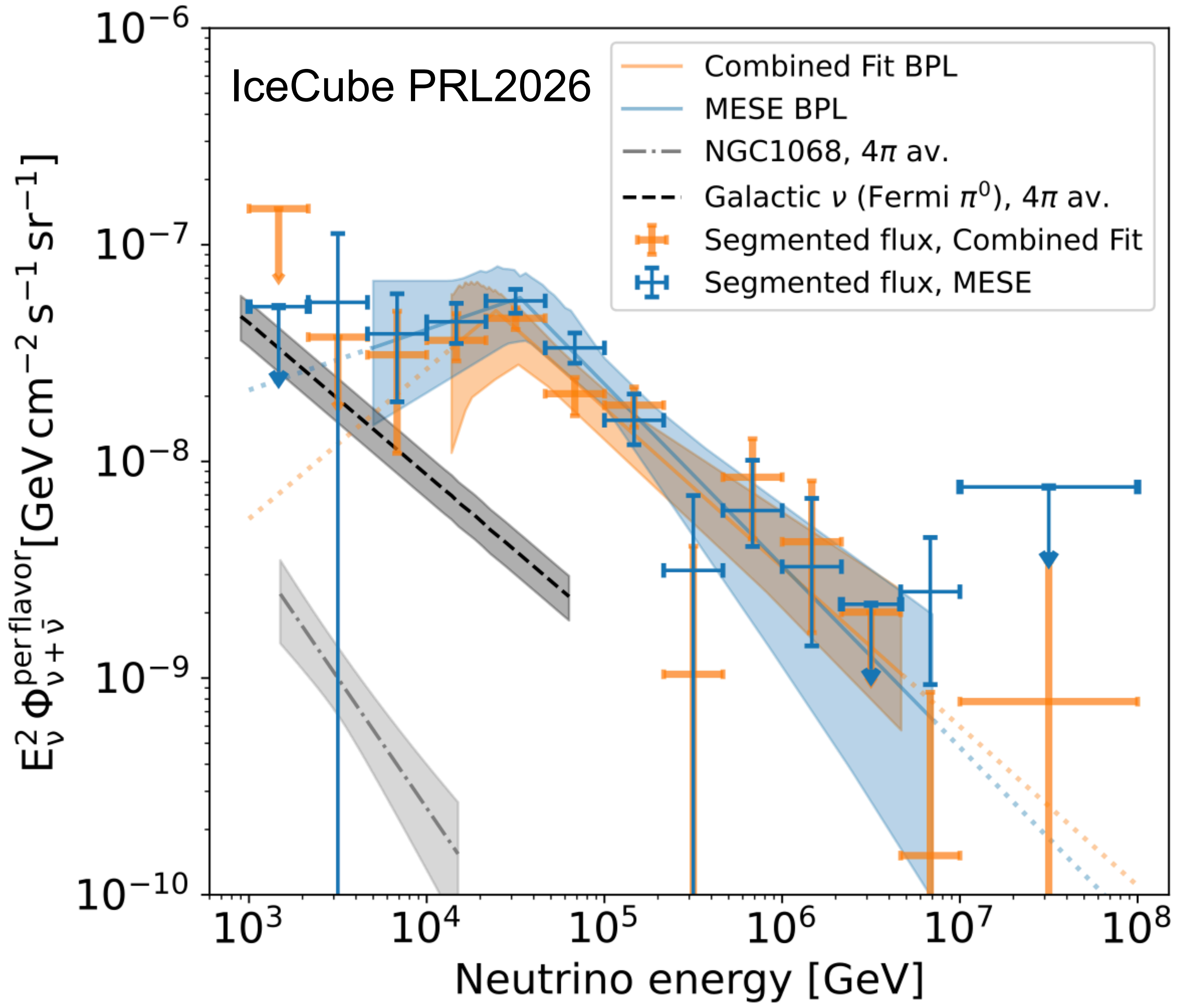
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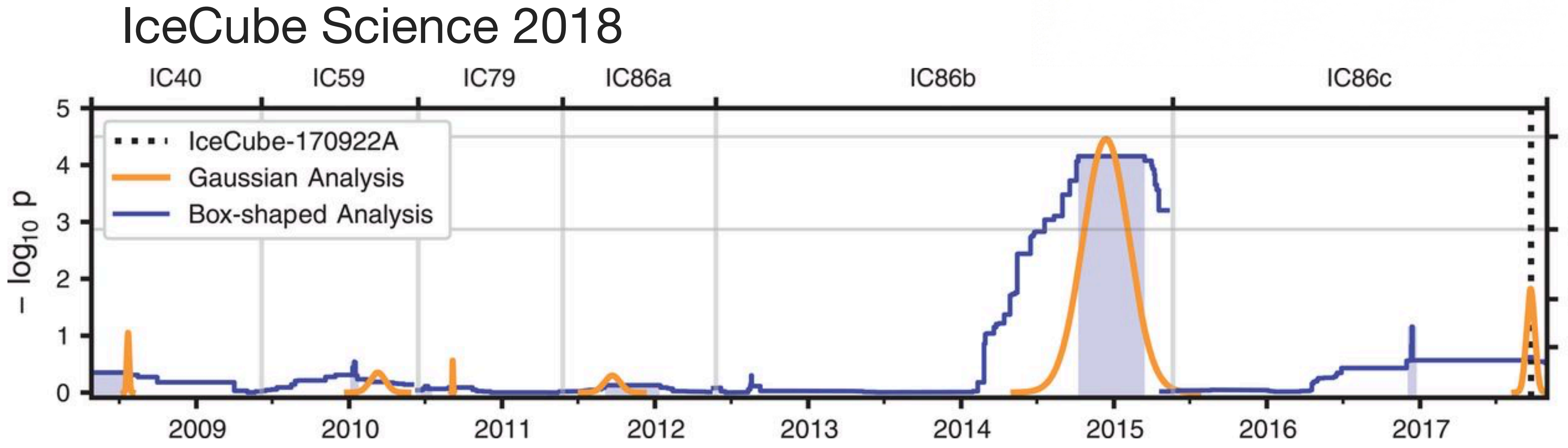
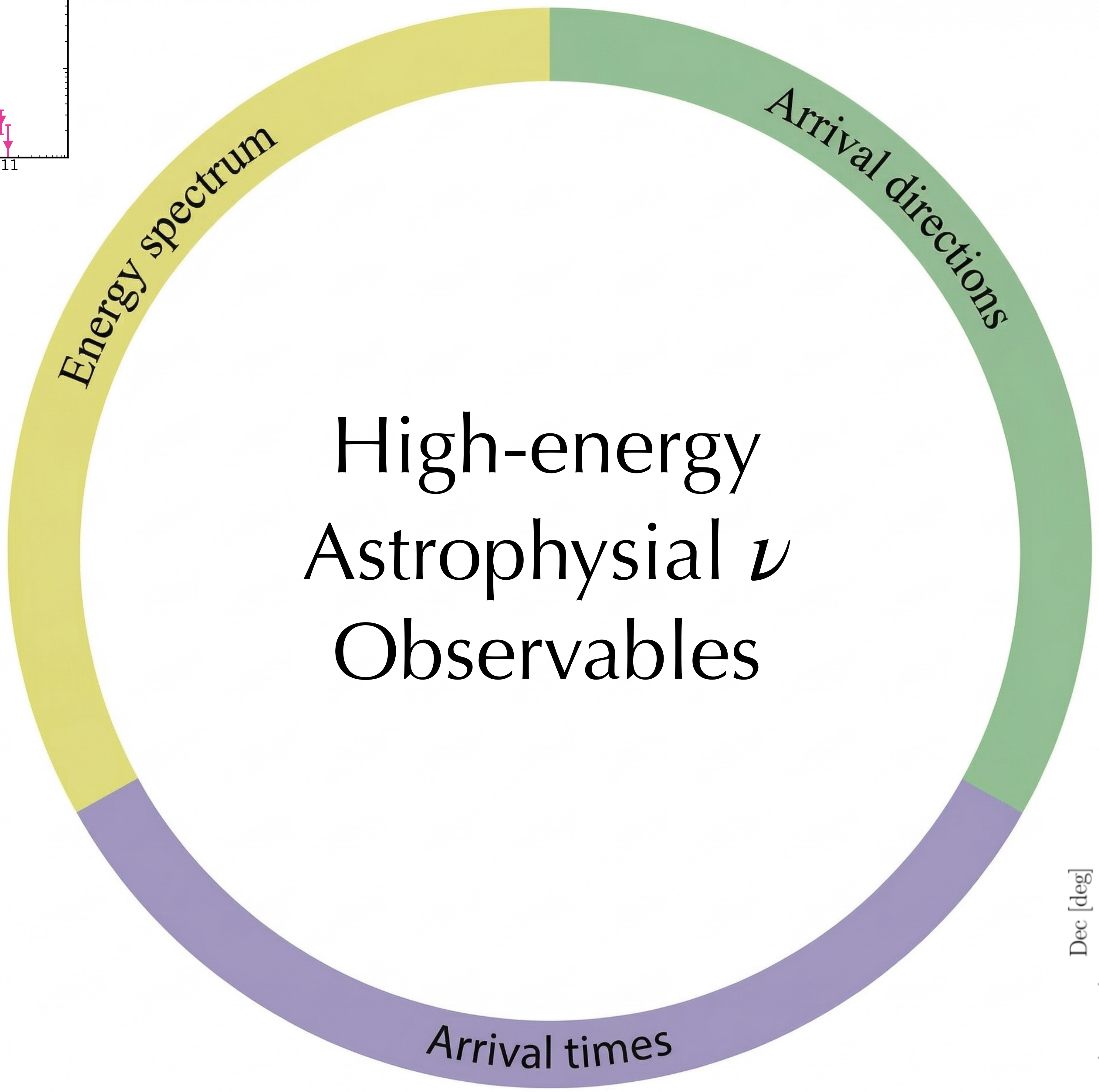

IceCube Science 2018
IC40
IC59
IC79
IC86a
IC86b
IC86c
IceCube-170922A
Gaussian Analysis
Box-shaped Analysis
$-\log_{10}$ p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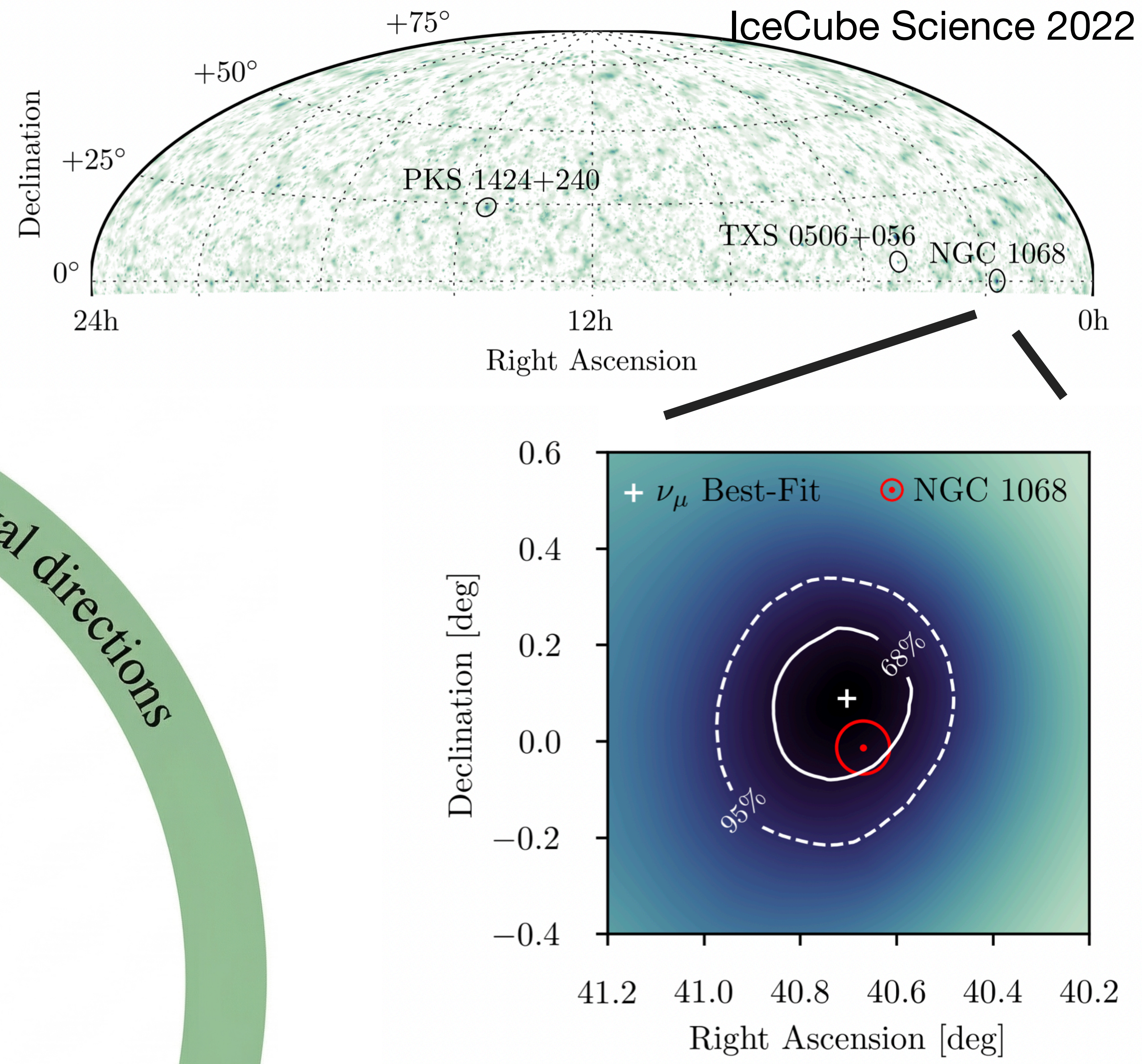
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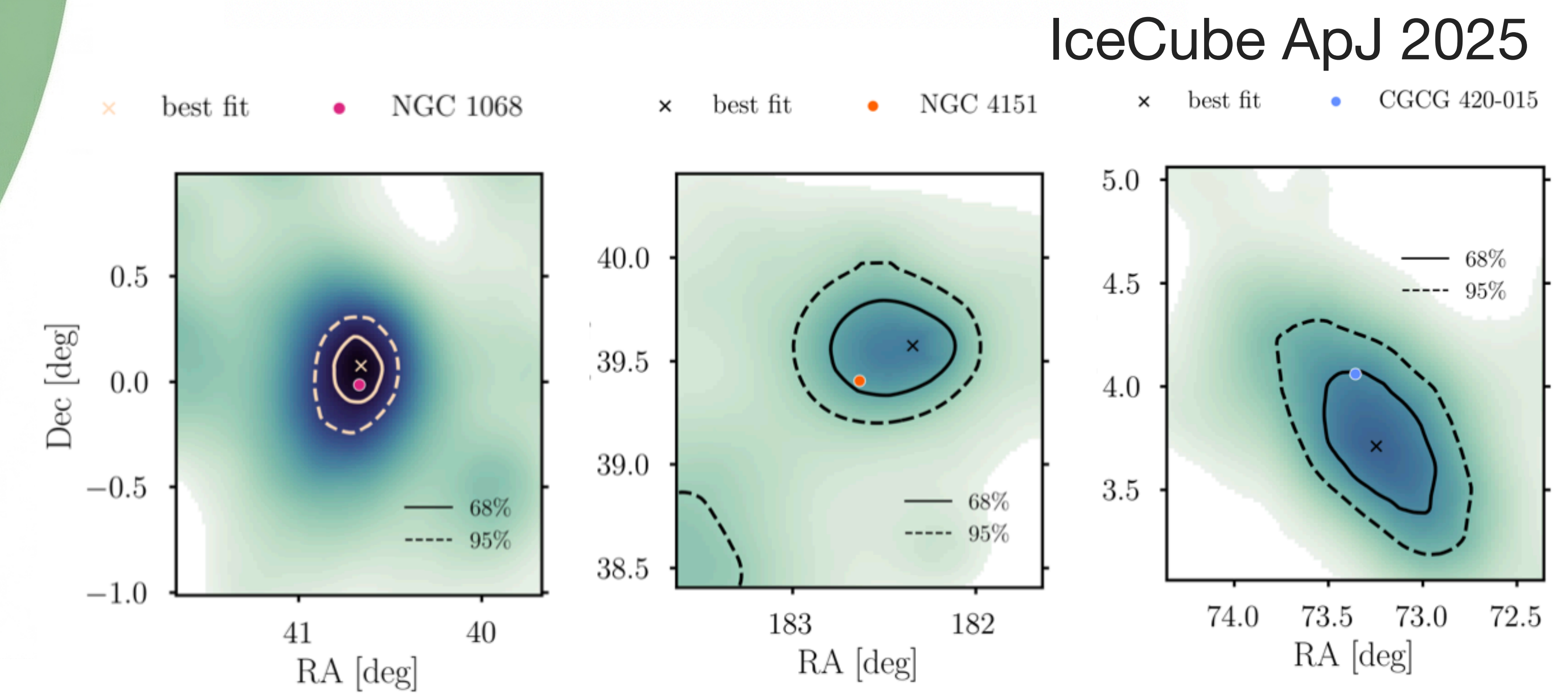
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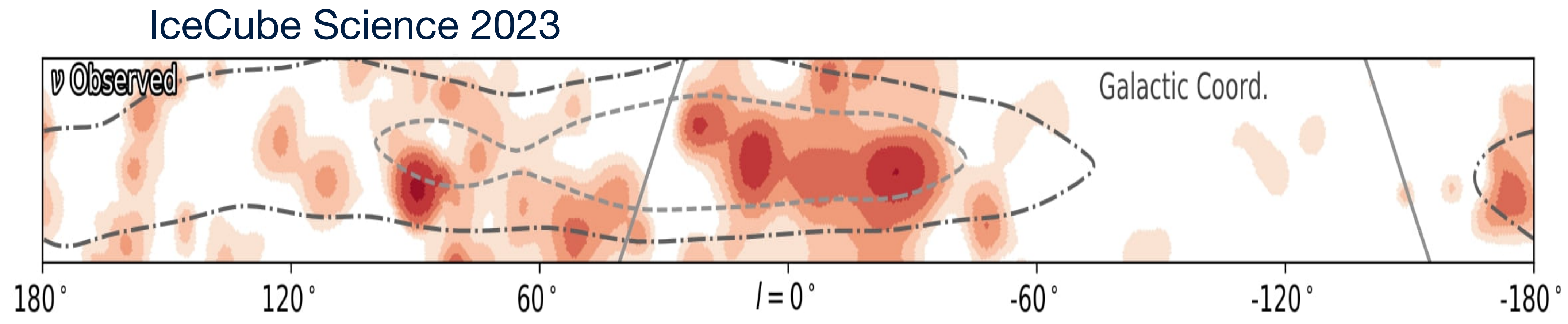
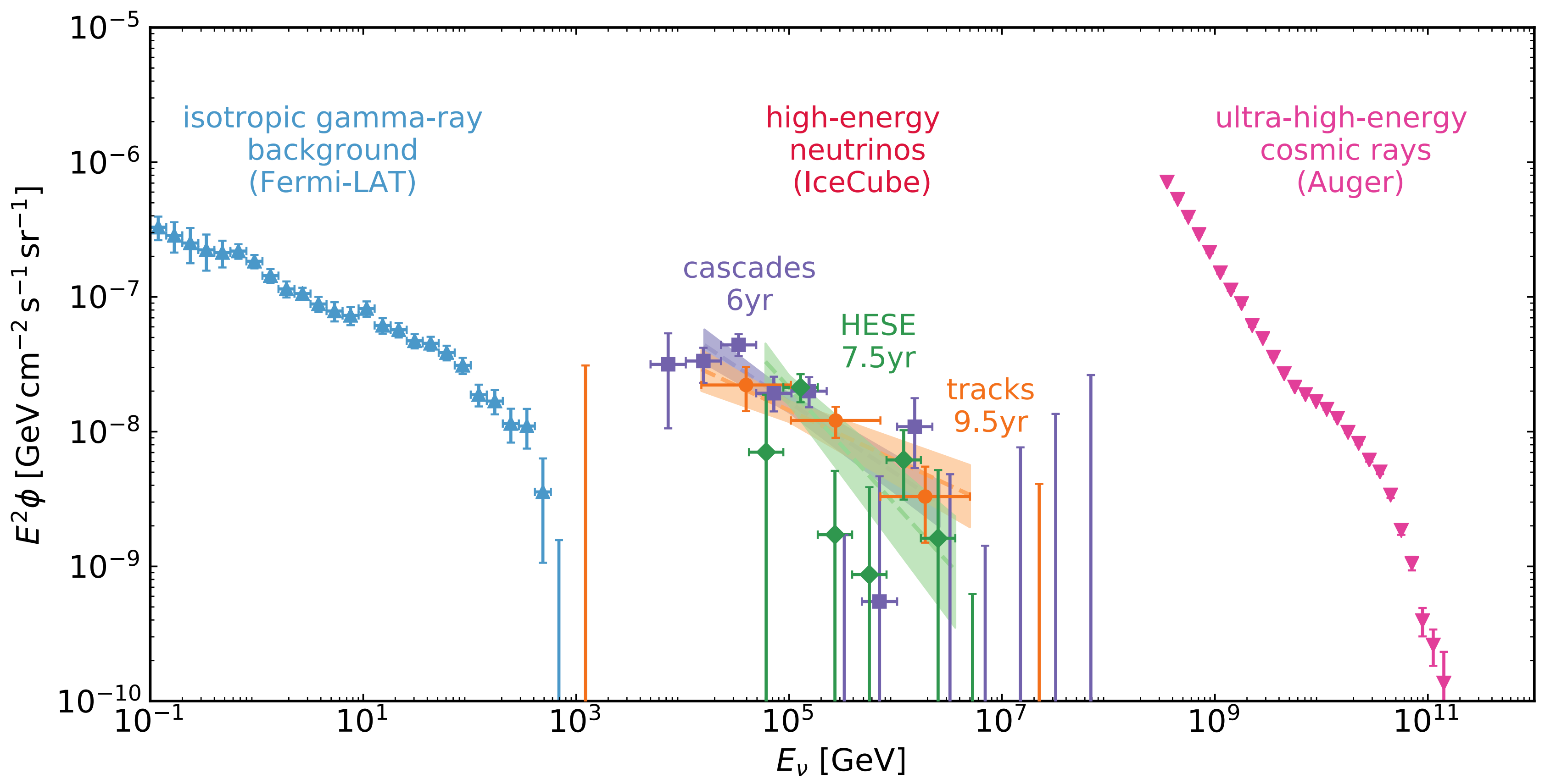
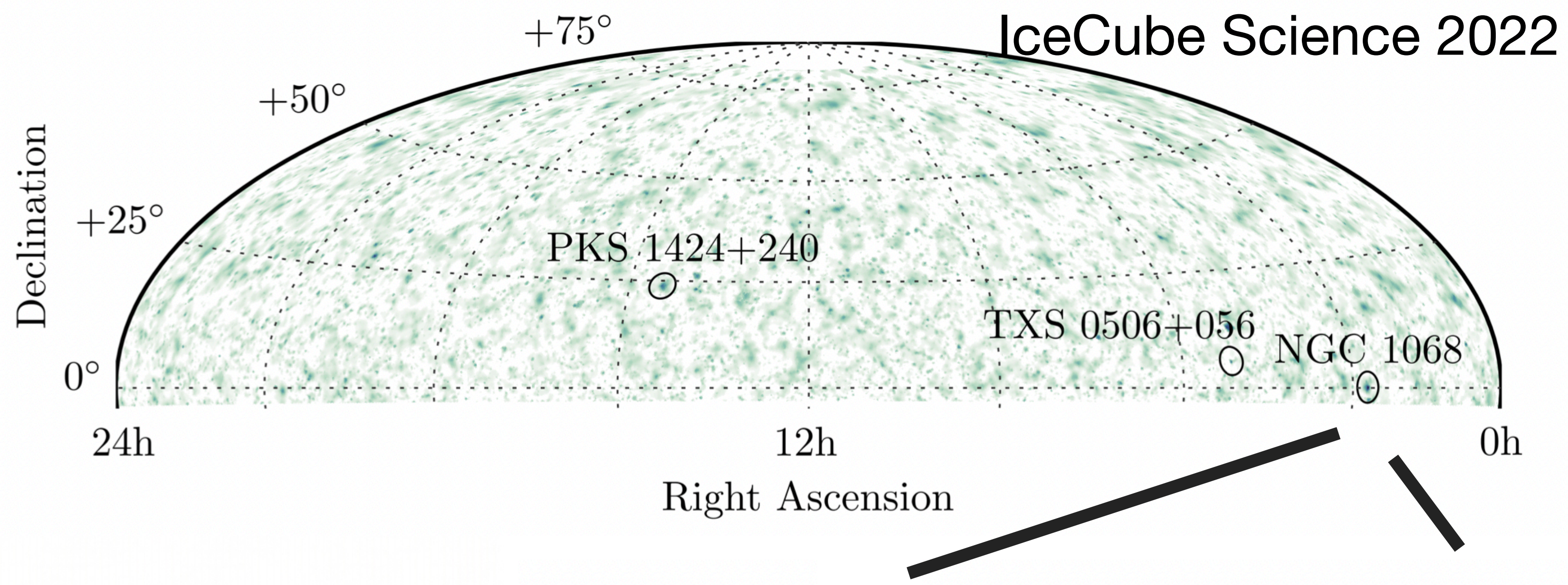
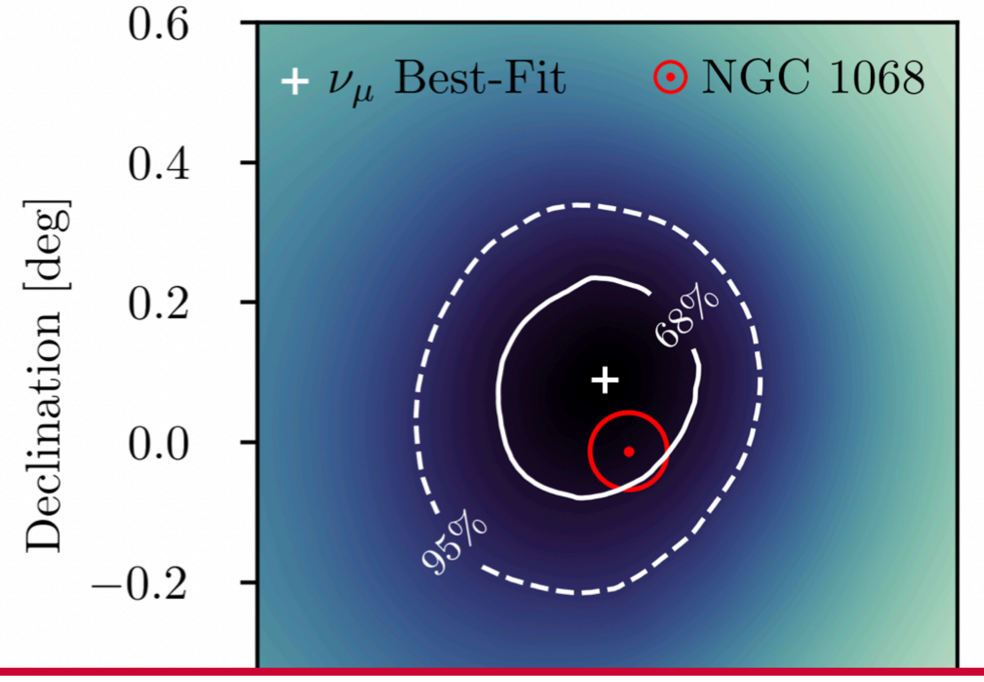

IceCube Science 2023
ν Observed
Galactic Coord.

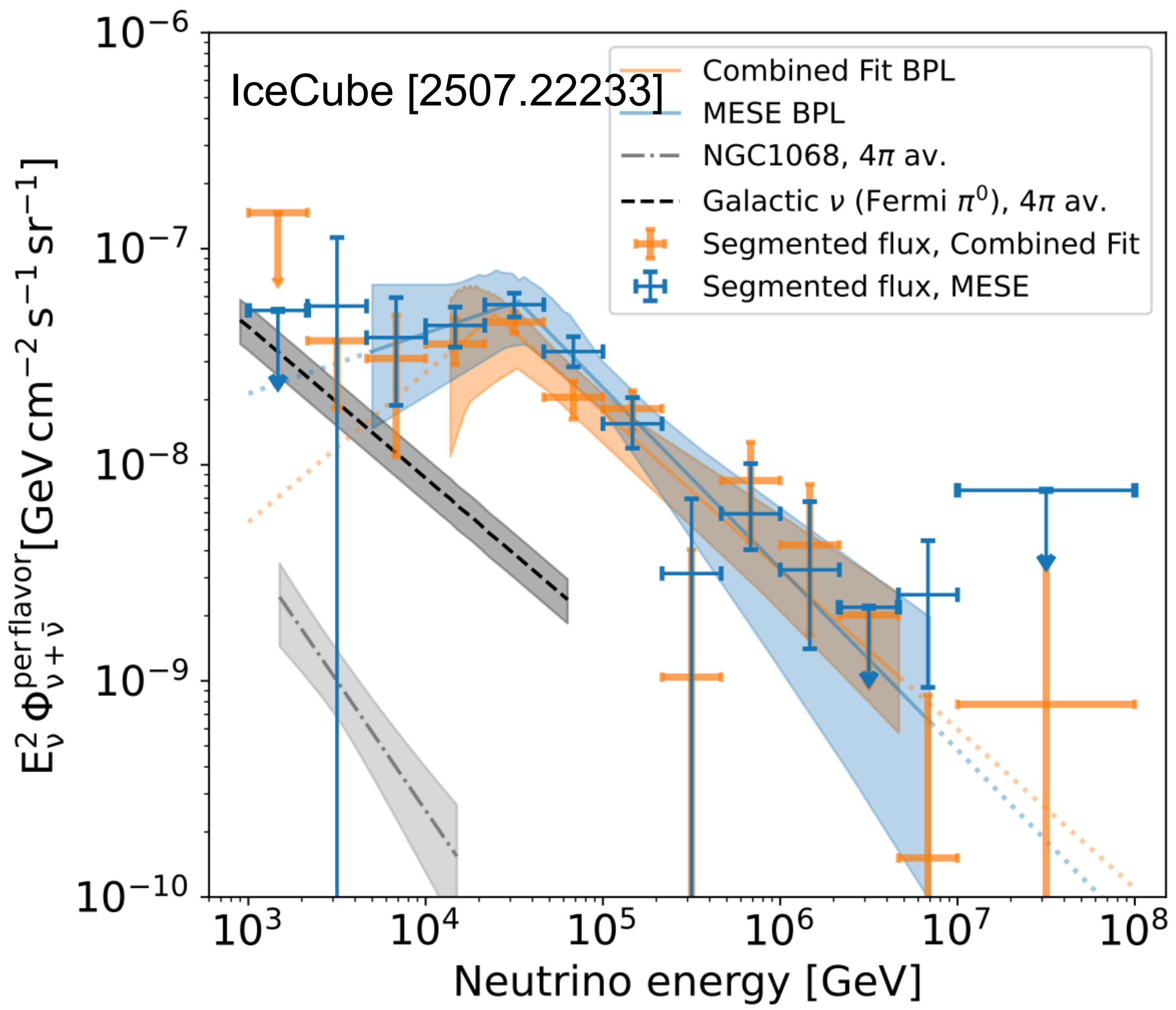
Neutrinos are the hardest to detect among all particle messengers.
Low statistics, but…

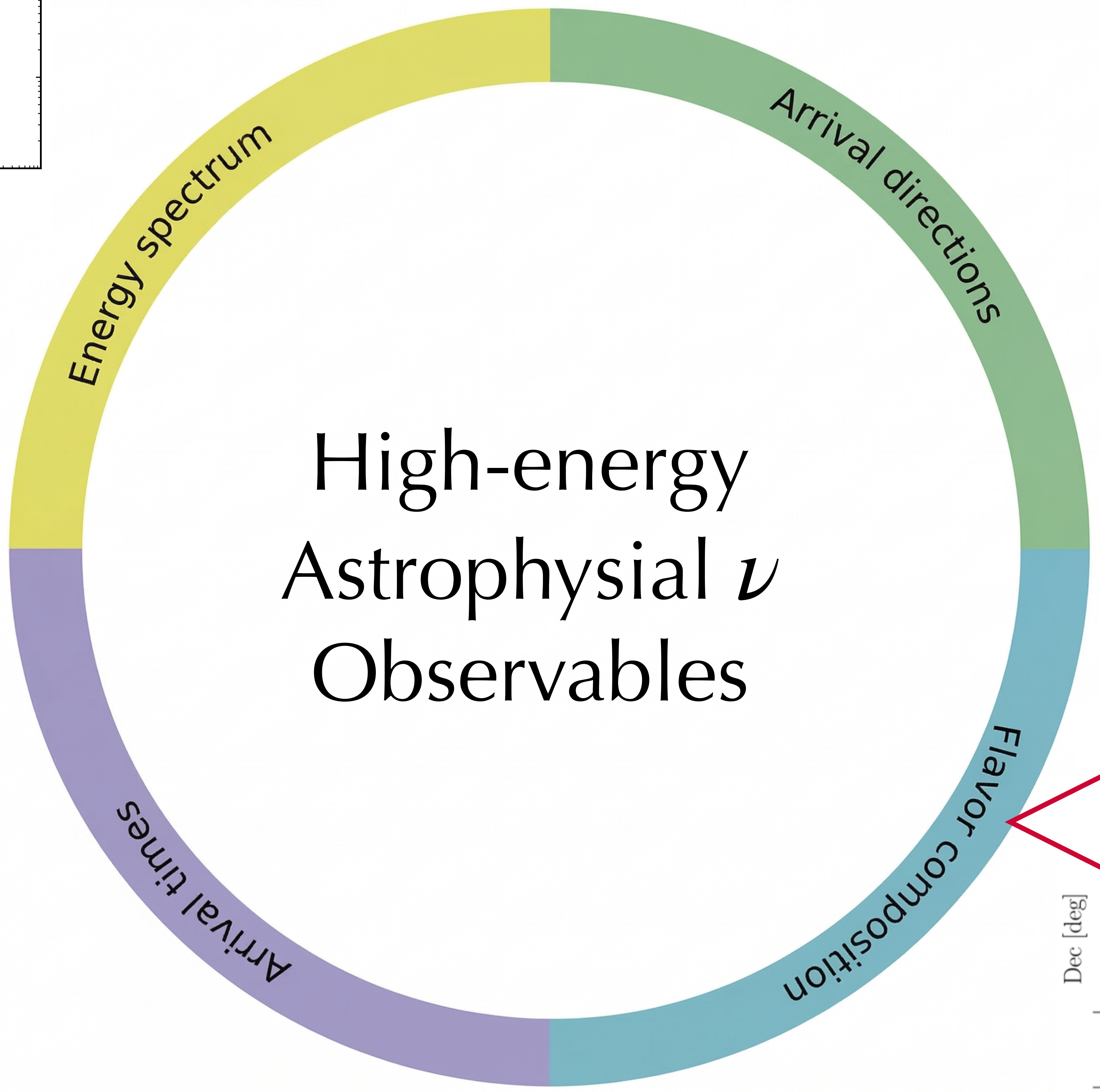
Neutrinos carry an extra piece of information:
flavor!





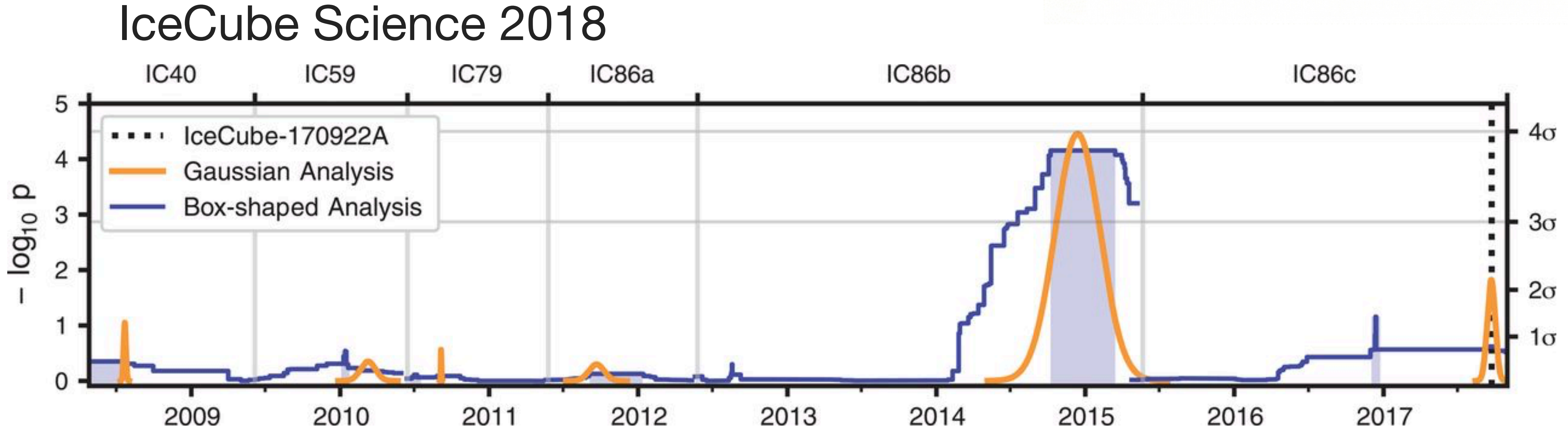


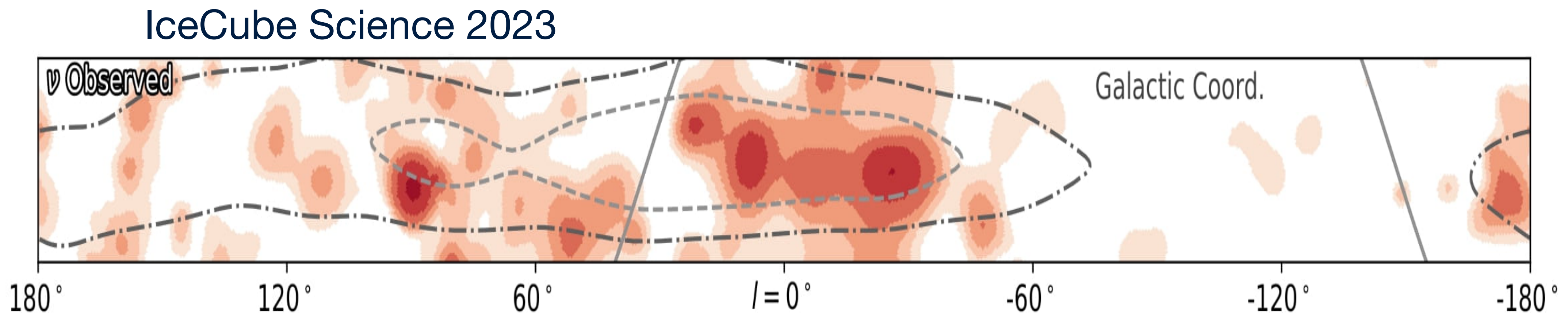


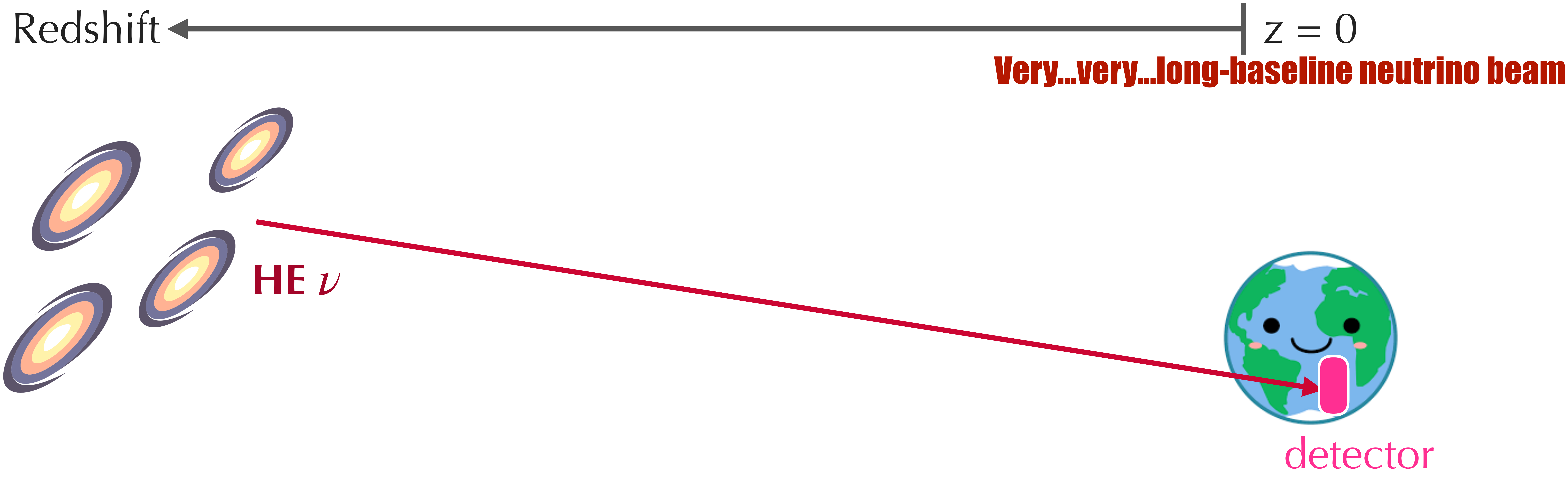


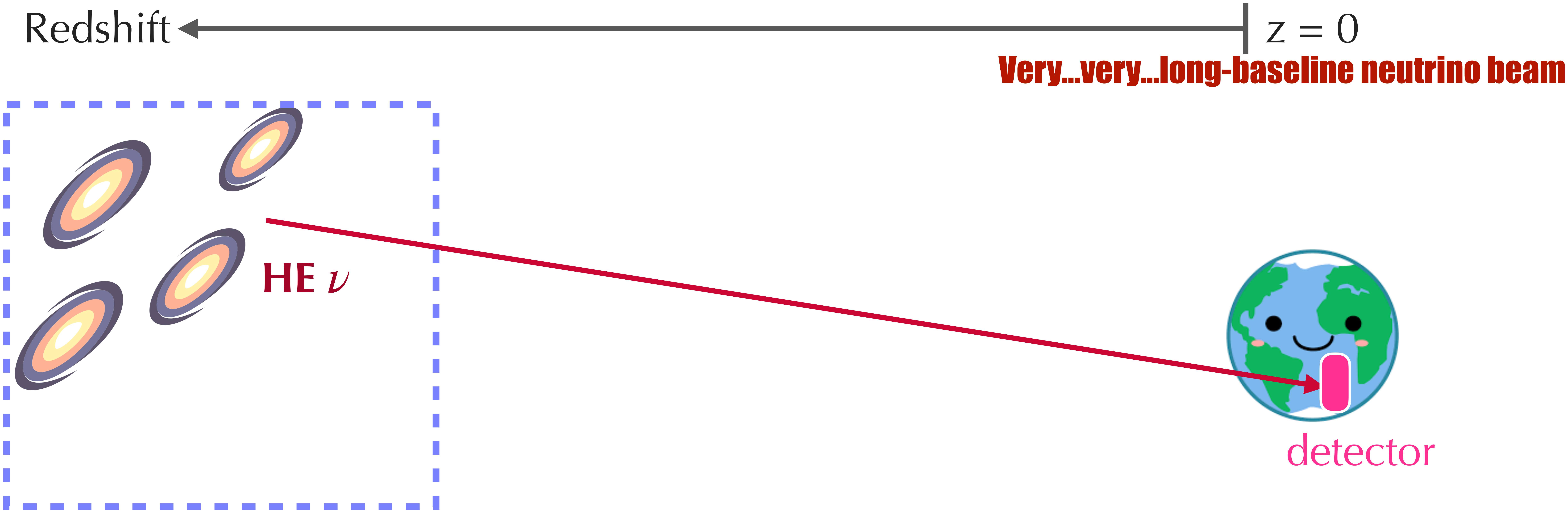
High-energy Astrophysial ν Observables

What to probe with the flavor composition & flavor composition + other information?

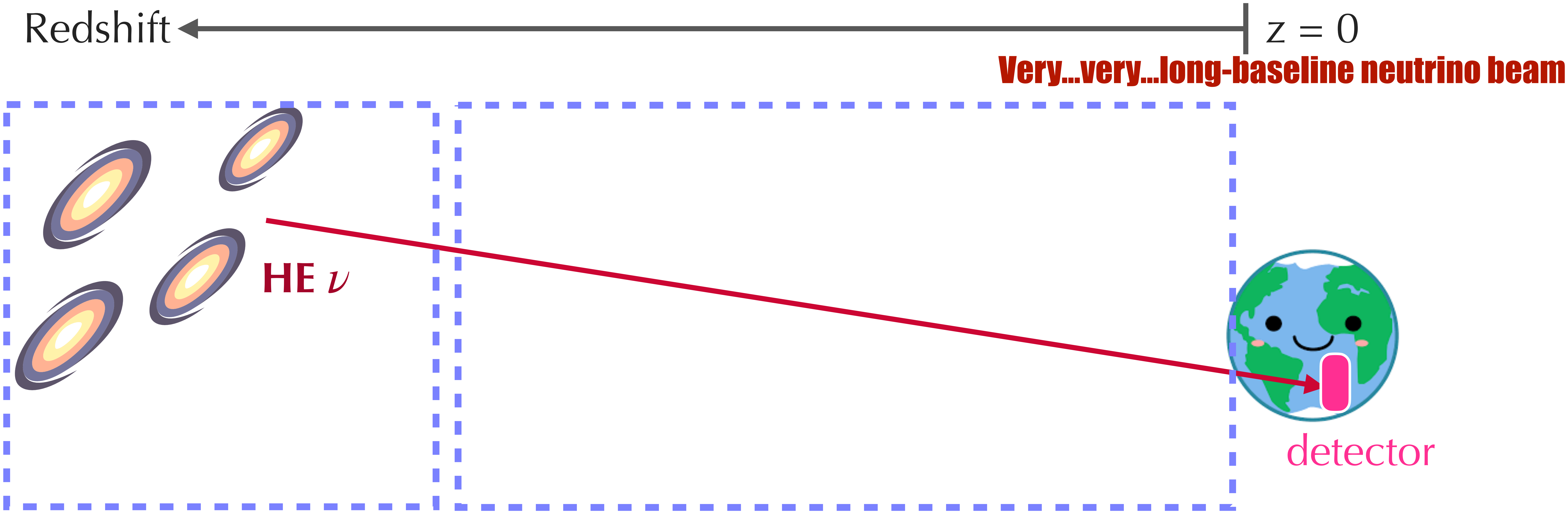





Redshift
z = 0
Very…very…long-baseline neutrino beam
HE ν
detector

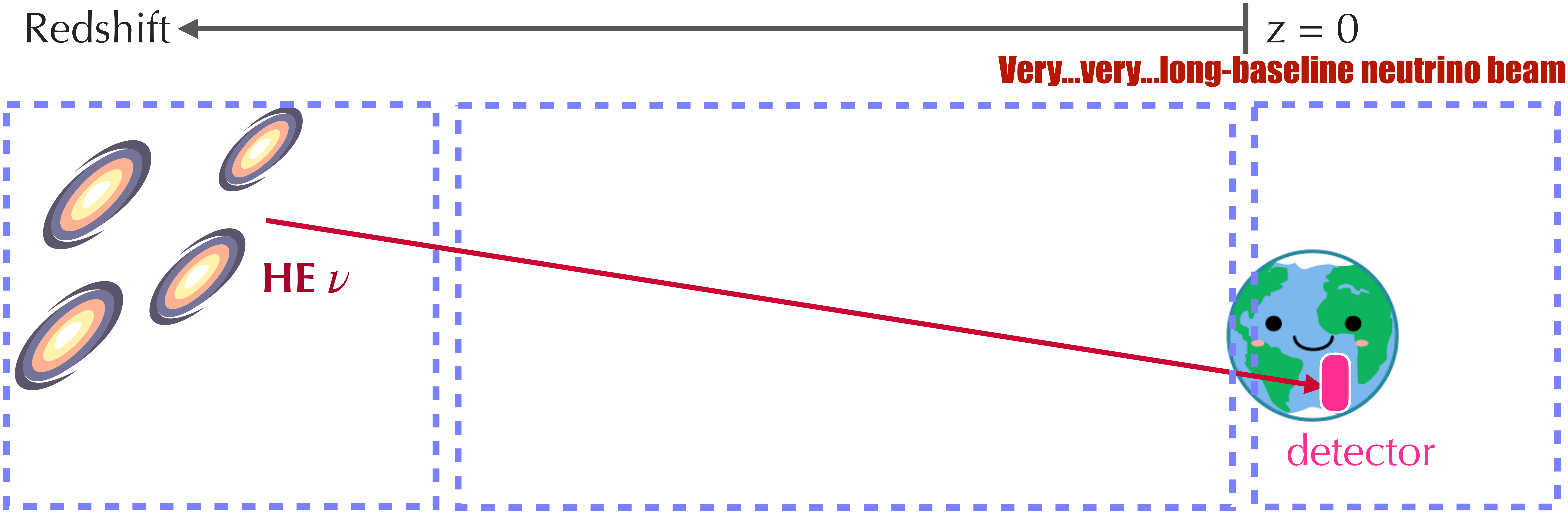


Neutrinos are produced at the sources with a flavor composition.



Neutrinos are produced at the sources with a flavor composition.

Neutrino oscillations change the flavor composition.



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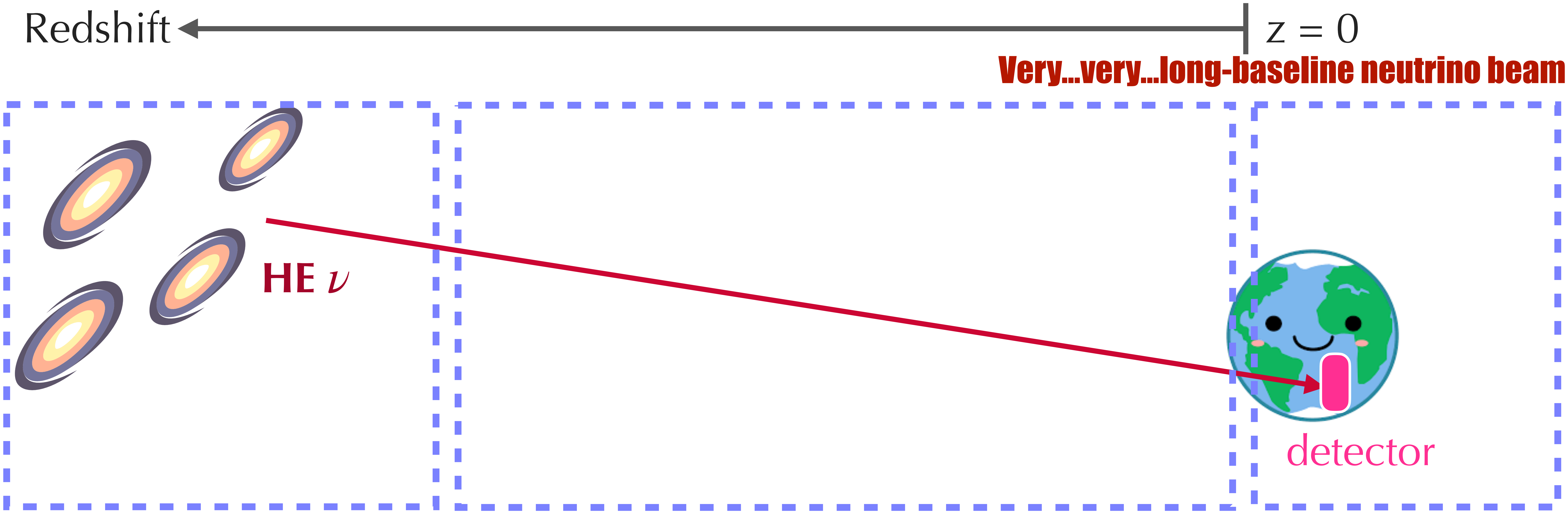
Neutrinos are measured on Earth with a flavor composition.



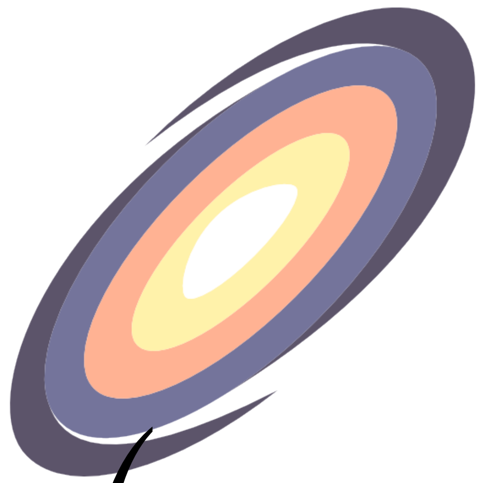
Neutrinos are produced at the sources with a flavor composition.

Neutrino oscillations change the flavor composition.

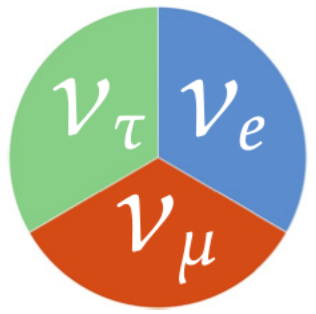
Neutrinos are measured on Earth with a flavor composition.

A venue to infer neutrino production, propagation, and detection.

Flavor Composition of High-energy Astrophysical Neutrinos



Oscillations



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

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

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

3ν oscillation probability:

$$P_{\nu_\alpha\to\nu_\beta}(E,L) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}\left(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\right)\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right)$$

$$+2\sum_{i>j} \mathrm{Im}\left(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\right)\sin\left(\frac{\Delta m^2_{ij}L}{2E}\right)$$

Flavor Composition of High-energy Astrophysical Neutrinos

Oscillations

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

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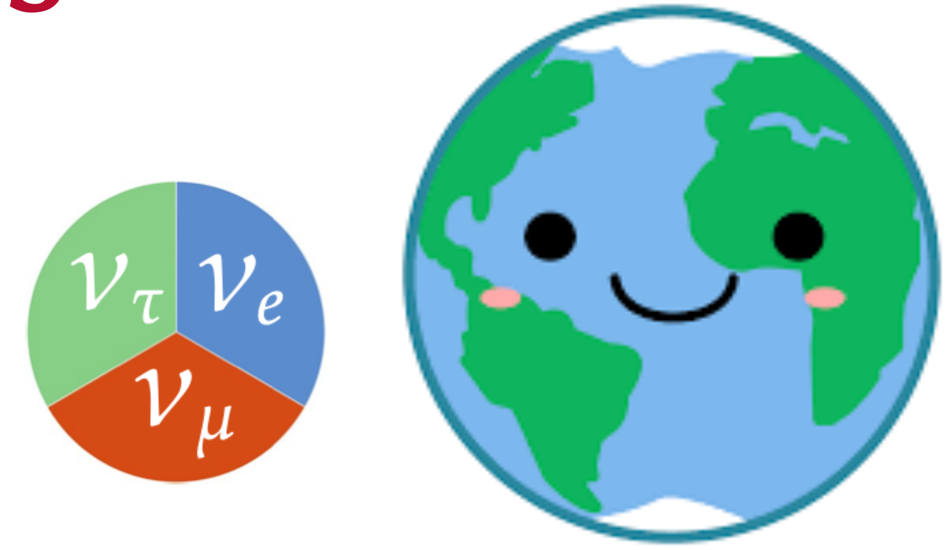
- Oscillation length for TeV-PeV neutrinos: $\lesssim$ pc. Sources are much further away (Mpc~Gpc).
- Locations of sources and neutrino production sites vary.

Flavor Composition of High-energy Astrophysical Neutrinos

Oscillations



$$f_{\beta,\oplus} = \sum P_{\nu_\alpha \to \nu_\beta} f_{\beta,S}$$

$\left(f_{e,S}, f_{\mu,S}, f_{\tau,}\right.$

$\left(f\right. \quad {}_{\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus}\left.\right)$

3ν oscillation p

Oscillation patterns cannot be resolved

Averaged probability

$$P_{\nu_\alpha \to \nu_\beta} = \sum_i^3 |U_{\beta i}|^2 |U_{\alpha i}|^2$$

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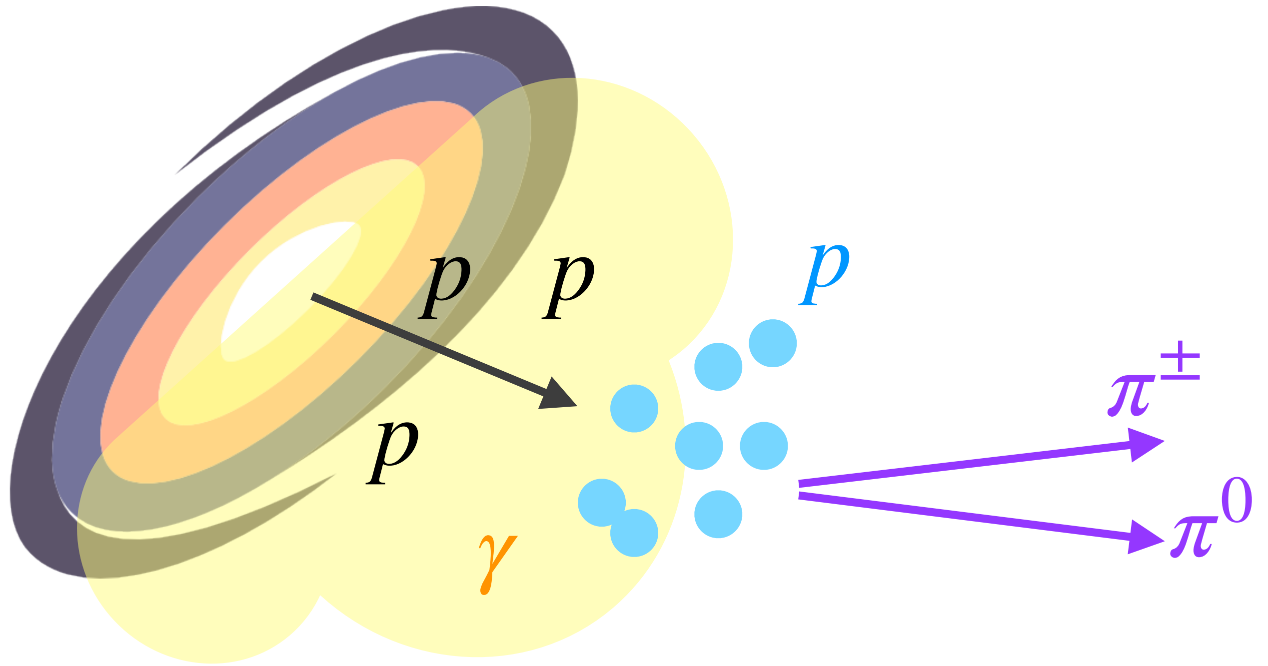
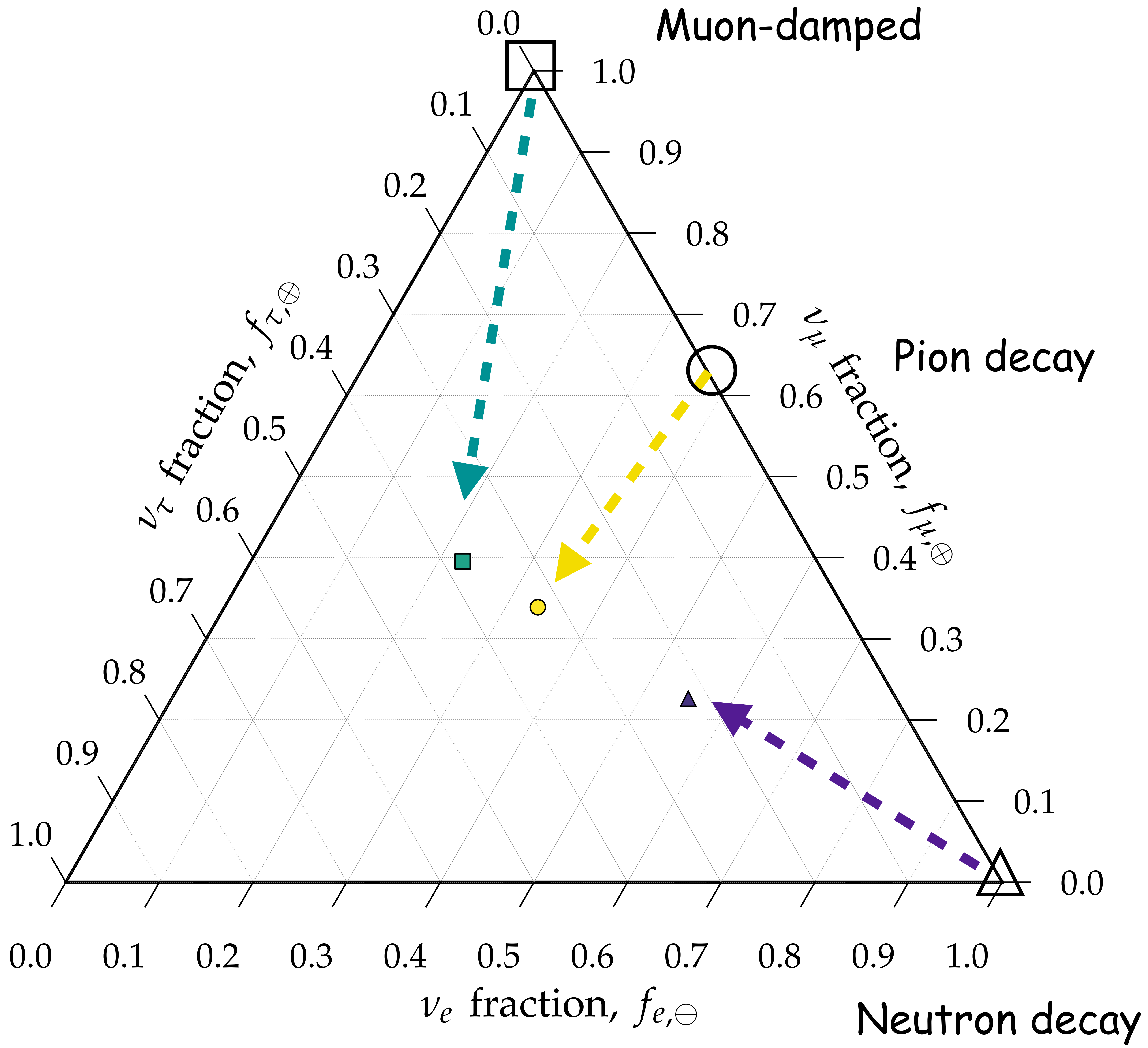
Flavor Composition of High-energy Astrophysical Neutrinos



		$f_{e,s} : f_{\mu,s} : f_{\tau,s}$	$f_{e,\oplus} : f_{\mu,\oplus} : f_{\tau,\oplus}$
• Pion decay	$\pi^+ \to \nu_\mu + \mu^+$, $\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$	$\{1 : 2 : 0\}$	$\{0.34 : 0.33 : 0.33\}$
• Muon-damped	$\pi^+ \to \nu_\mu + \not{\mu}^+$	$\{0 : 1 : 0\}$	$\{0.24 : 0.37 : 0.39\}$
• Neutron decay	$n \to p + e^- + \bar{\nu}_e$	$\{1 : 0 : 0\}$	$\{0.55 : 0.23 : 0.22\}$

→ nufit6.1
(global analysis of neutrino oscillation measurements)

Flavor Composition of High-energy Astrophysical Neutrinos



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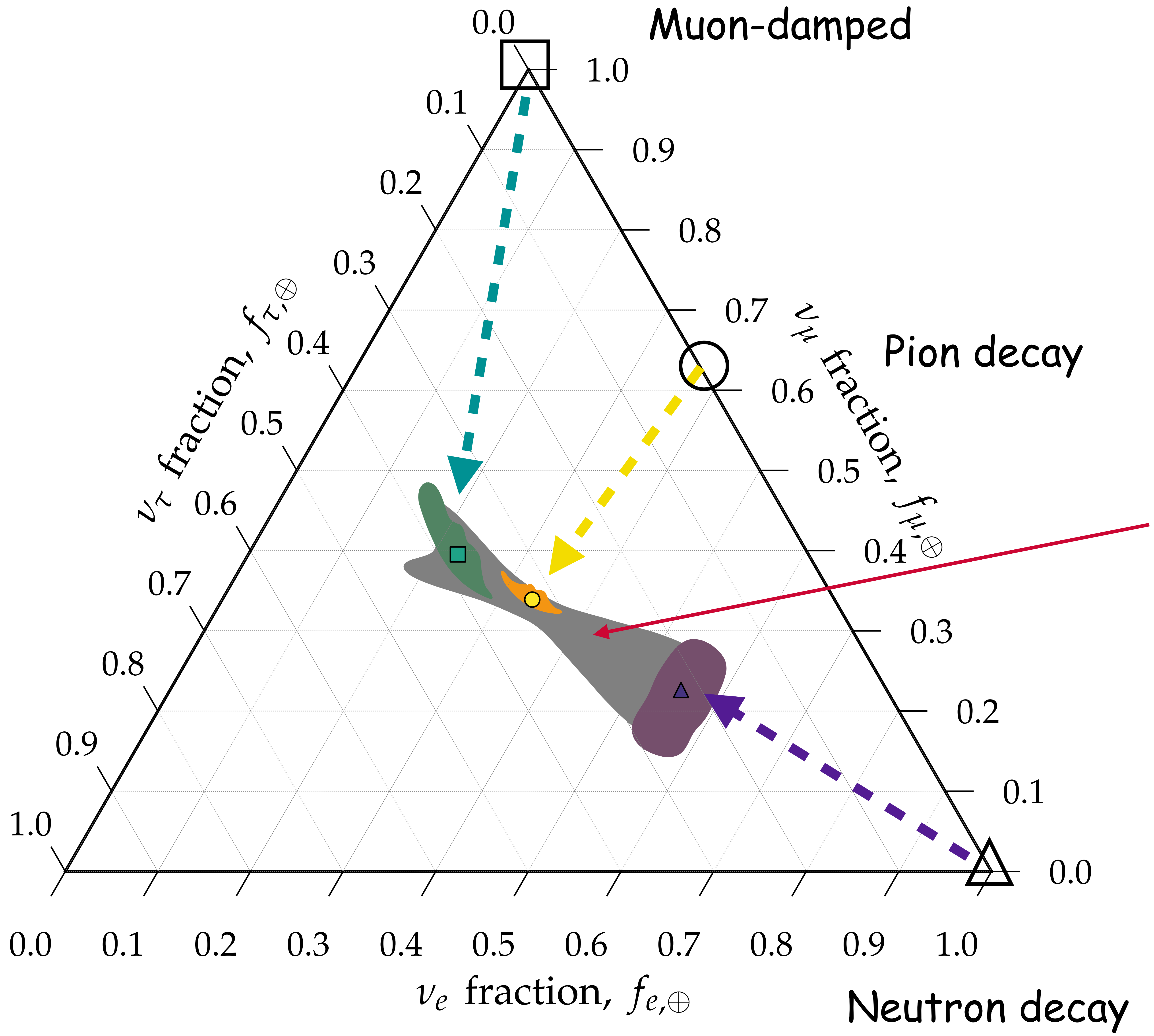
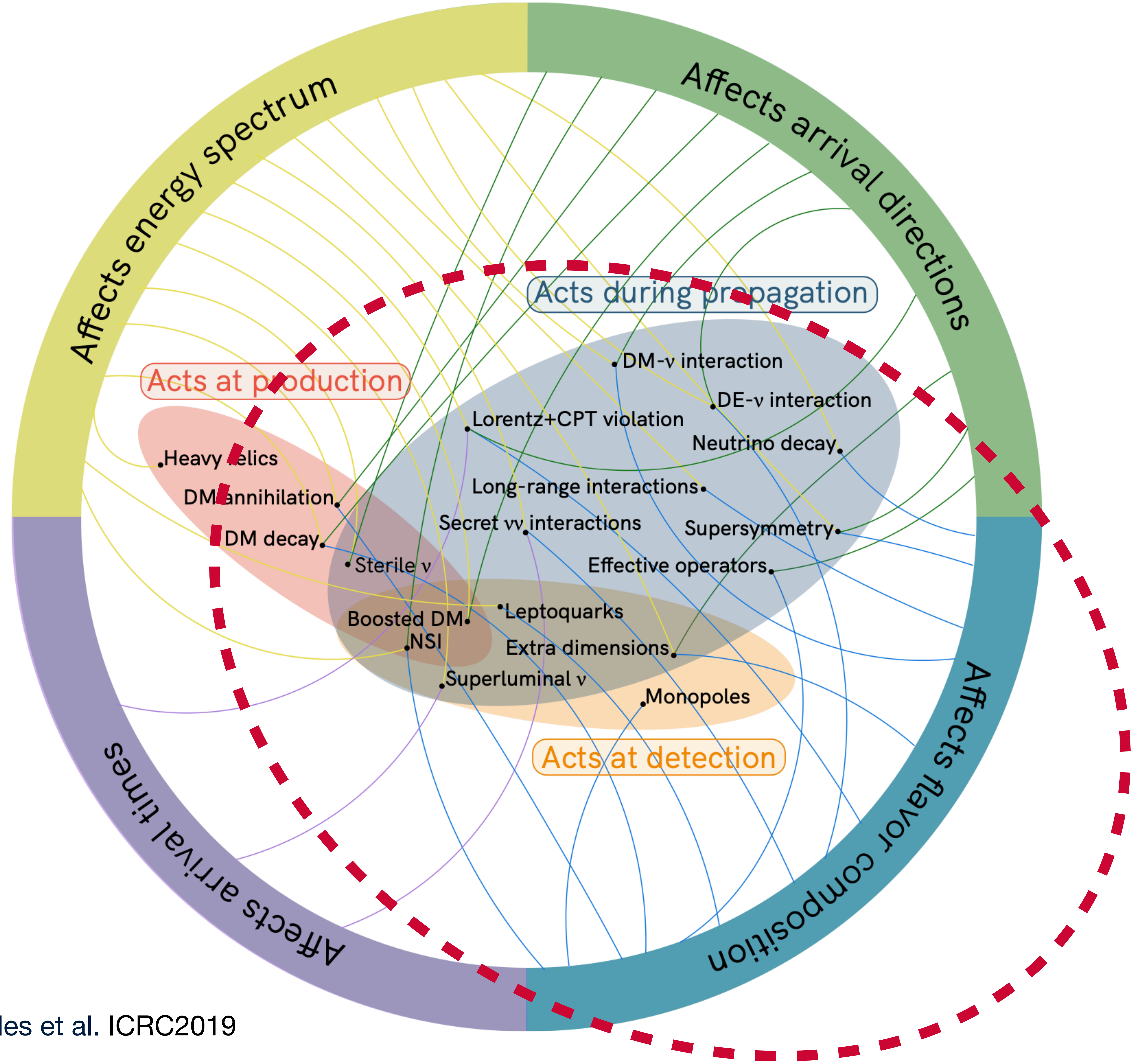


Standard neutrino oscillation (nufit) allowed region.
A flavour composition outside of this region: new physics
(or you messed up!)

New Physics & Flavor Composition



Argüelles et al. ICRC2019

How is the Flavor Determined Experimentally?

There is no event-wise particle identification …

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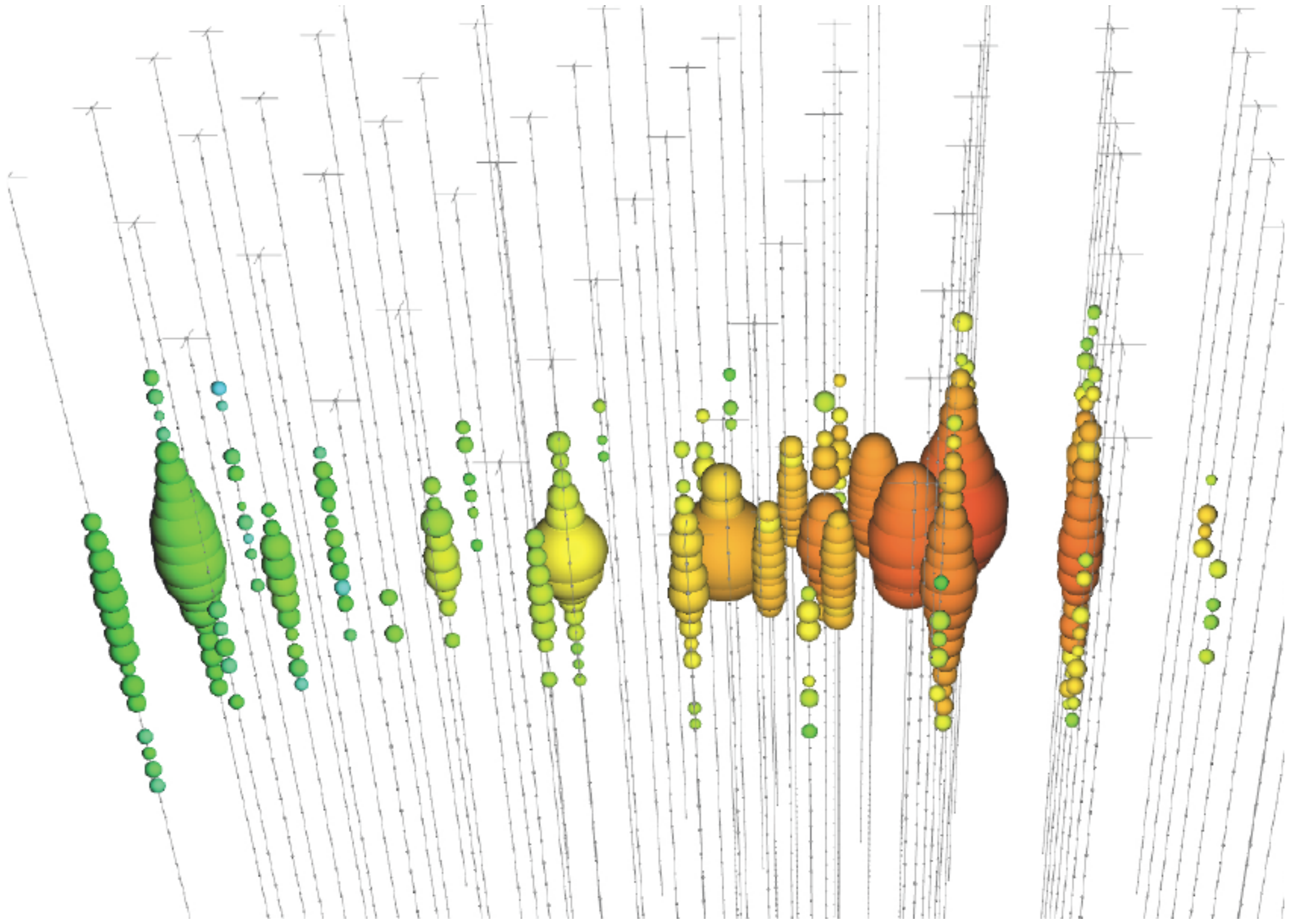
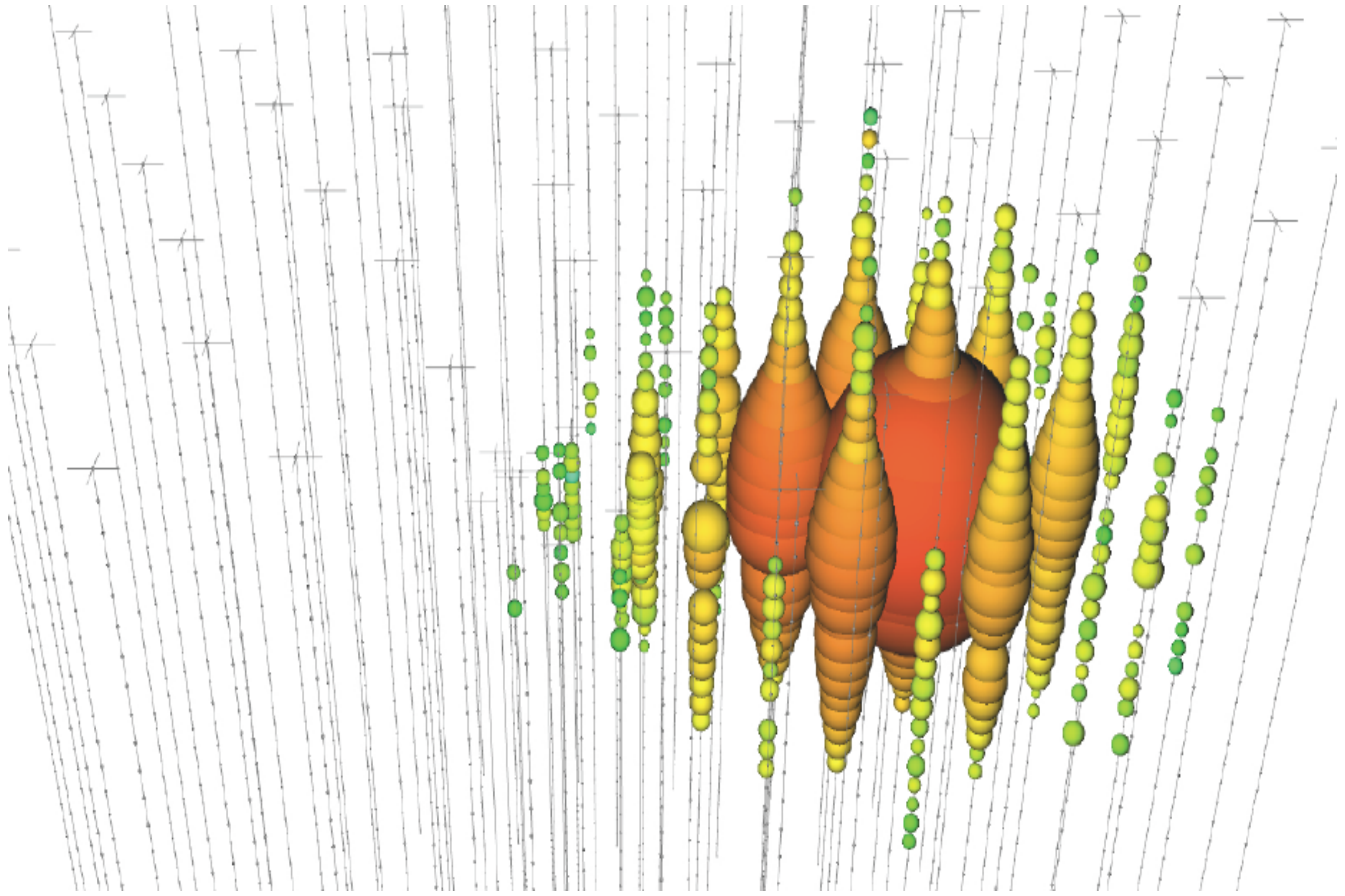
Tracks



$$\nu_\mu + N \rightarrow \mu + X$$

Cascades

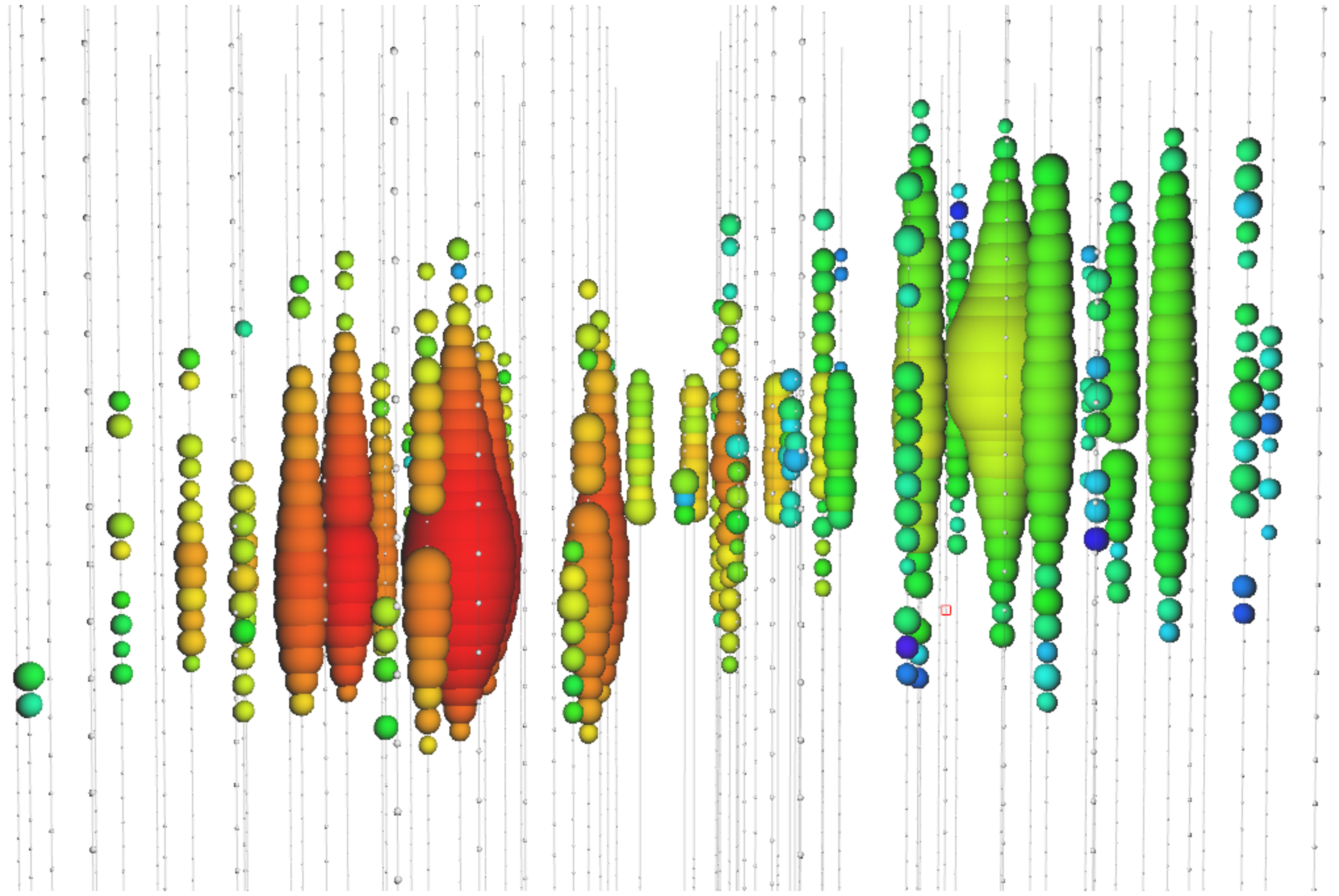


$$\nu_e + N \rightarrow e + X$$

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

main contribution

Double Cascades

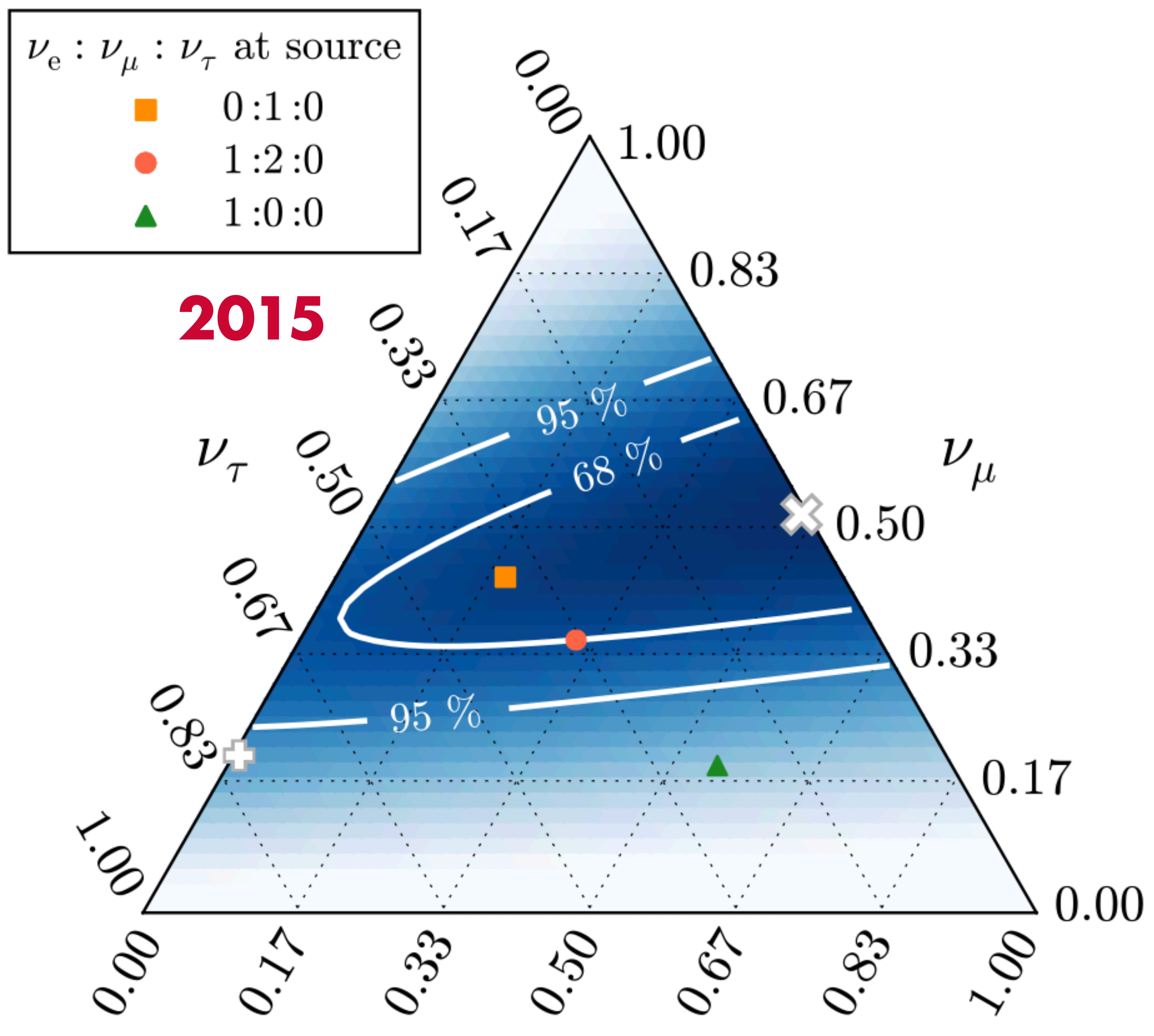


$$\nu_\tau + N \rightarrow \tau + X$$

$\nu_\tau \gtrsim \text{PeV}$

IceCube Flavor Composition Measurements

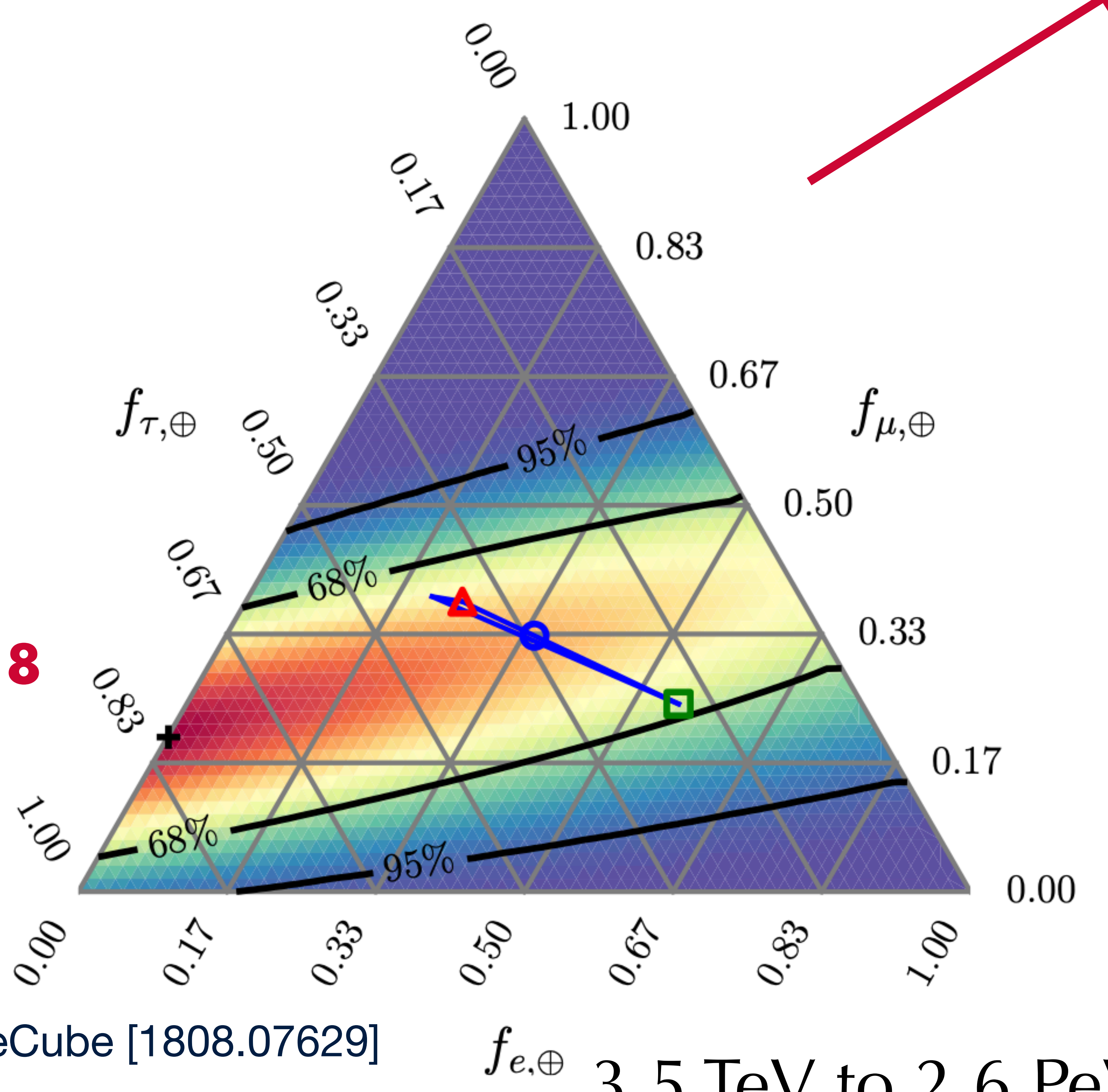
2015



IceCube [1507.03991]

25 TeV and 2.8 PeV

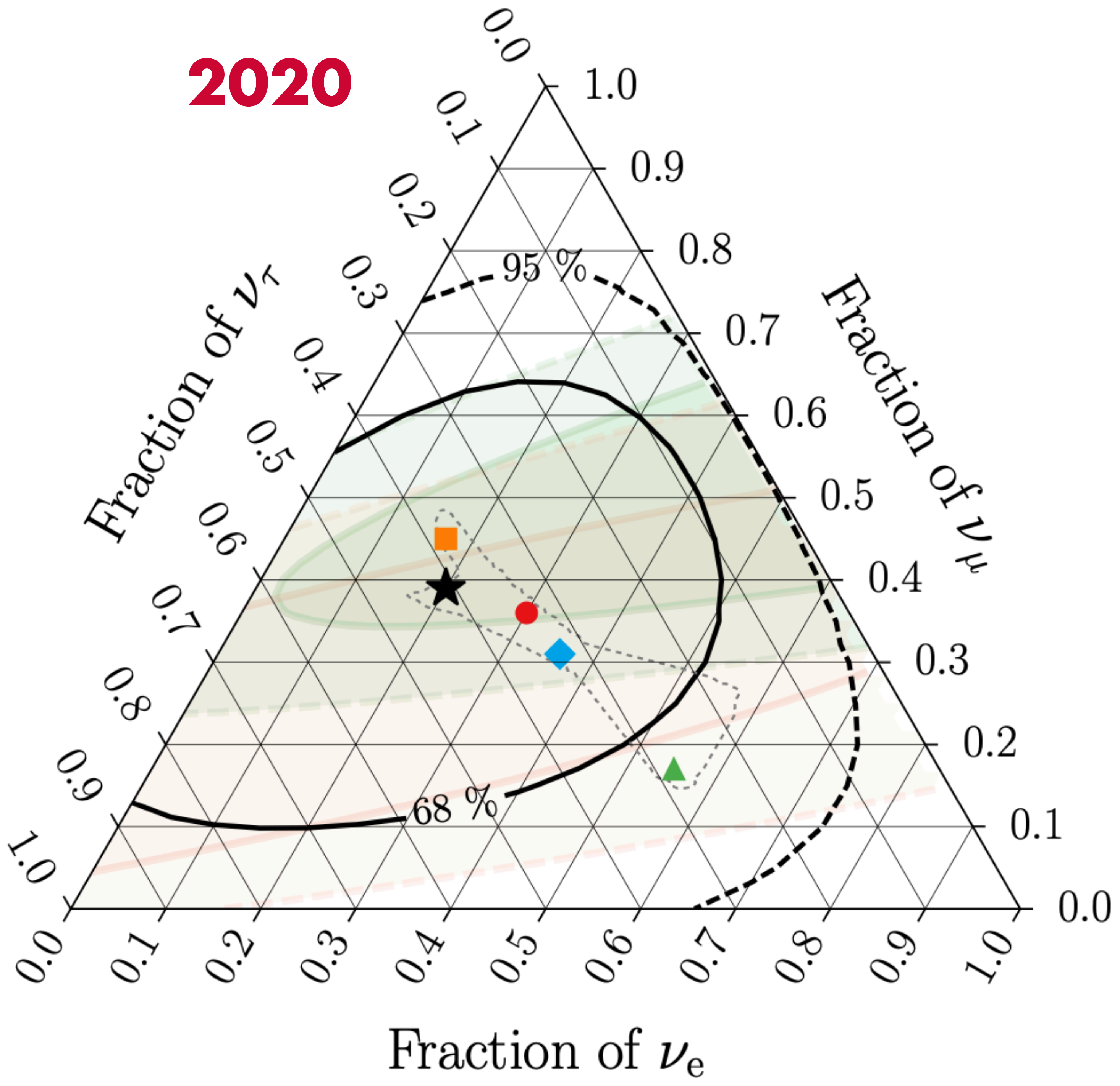
2018



IceCube [1808.07629]

3.5 TeV to 2.6 PeV

2020

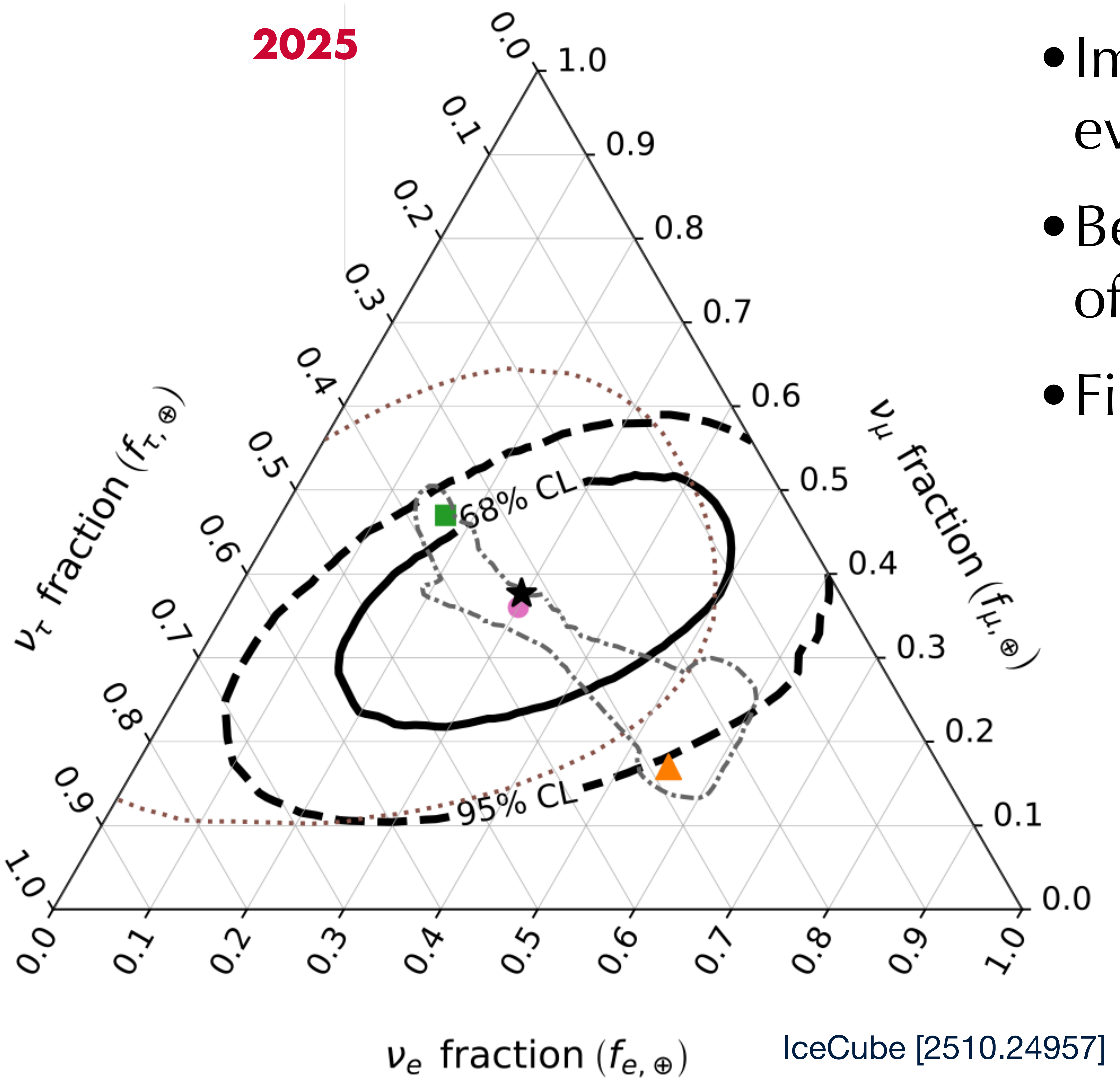


IceCube [2011.03561]

> 60 TeV

First identification of tau double cascades

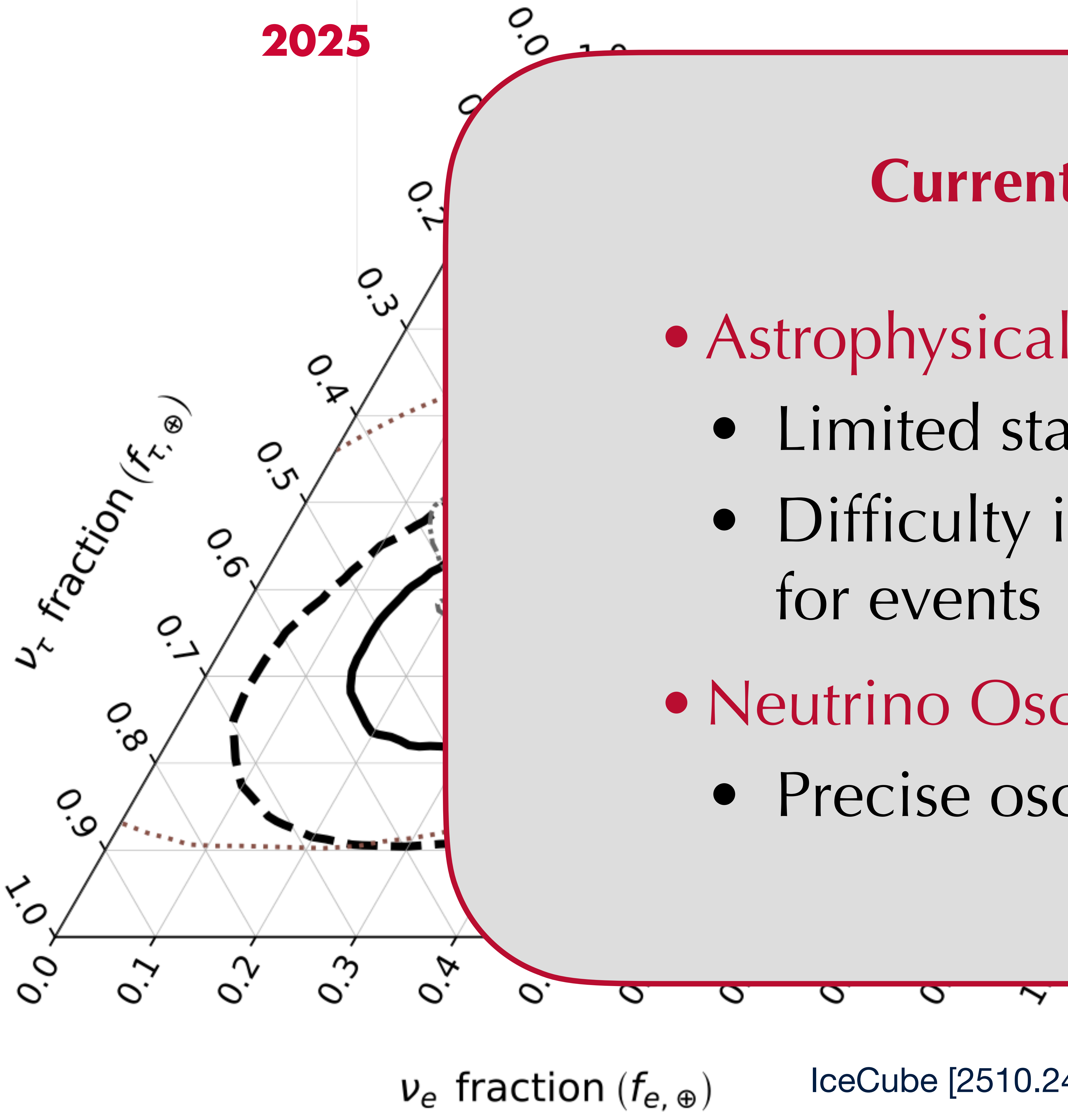
Where Are We Now?



- Improved double cascades identification. 9 events above 30 TeV.
- Best fit very close to the nominal expectation of ~(1:1:1) from pion decay.
- First time all flavors are nonzero at 68% C.L.

11.4 yr Medium Energy Starting Events (MESE), 5TeV-10PeV

Where Are We Now?



IceCube [2510.24957]

• Improved double cascades identification. 9

...inal expectation

...ero at 68% C.L.

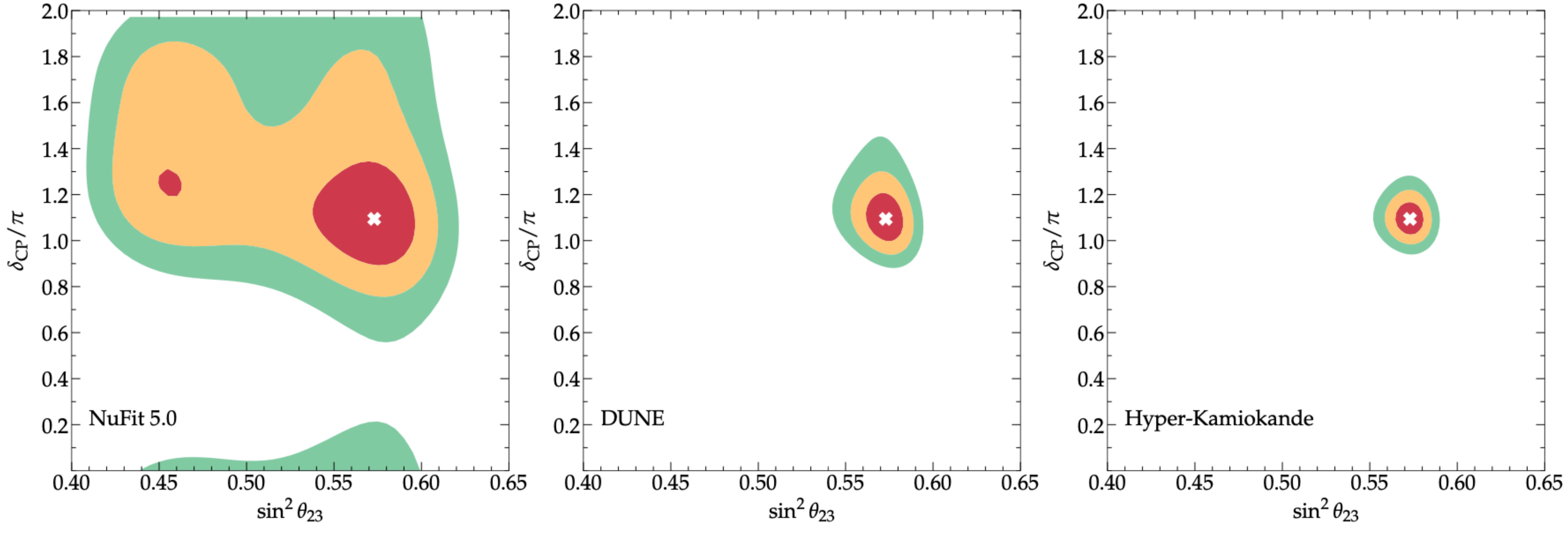
Current Limitations

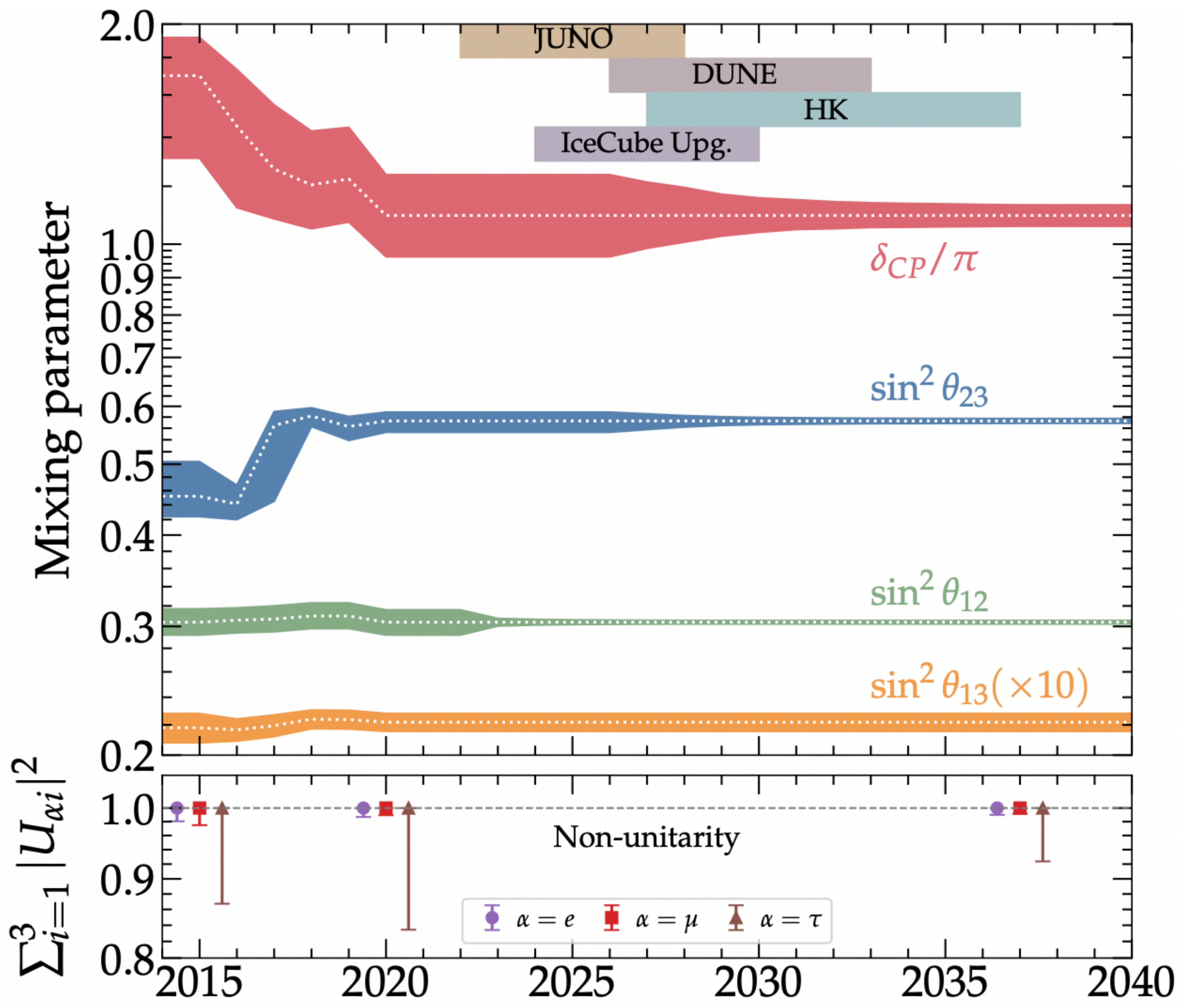
- Astrophysical Flux Measurements
  - Limited statistics
  - Difficulty in flavor identification for events
- Neutrino Oscillation Measurements
  - Precise oscillation parameters

11.4 yr Medium Energy Starting Events (MESE), 5TeV-10PeV

Precise Neutrino Oscillation Measurements

- JUNO: 20kt liquid scintillator reactor measurement θ_{12}
- DUNE: 40kt liquid argon long baseline experiment θ_{23} & δ_{CP}
- Hyper-Kamiokande: 187kt water Cherenkov θ_{23} & δ_{CP}
- IceCube Upgrade: dense instrumentation, θ_{23} & unitarity

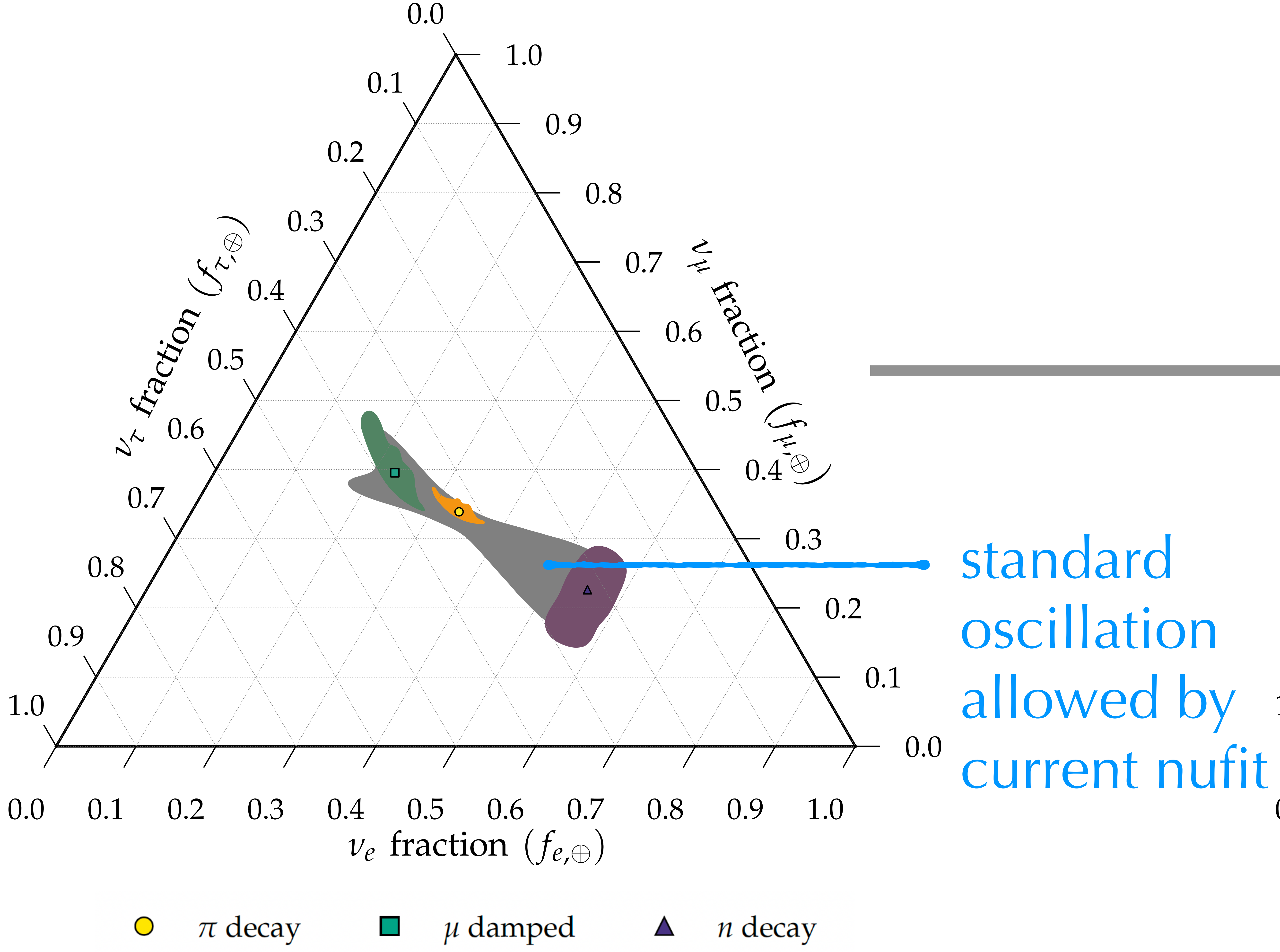


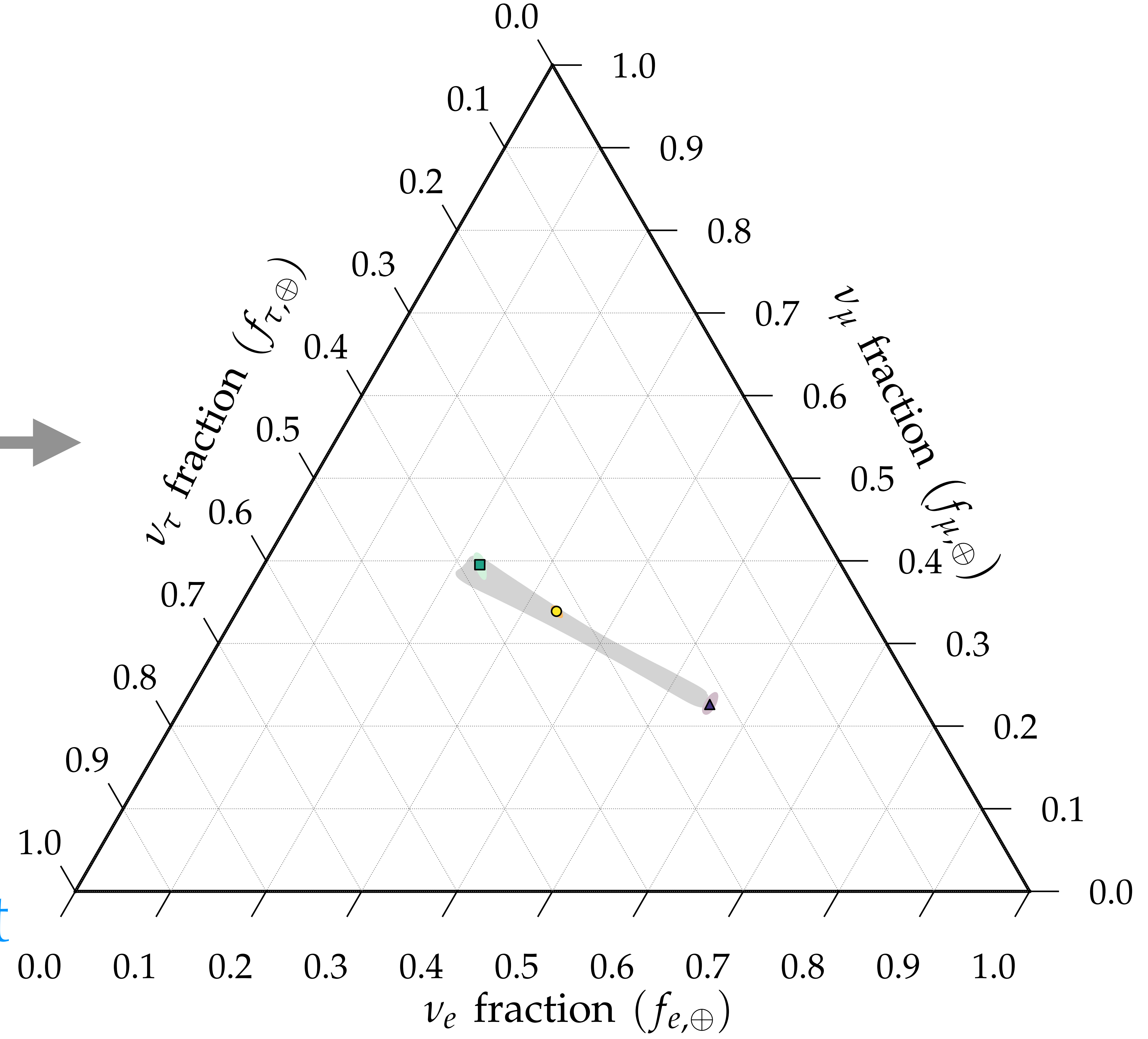


Song et al [2012.12893]

Improved Allowed Regions

Future combined oscillation measurements





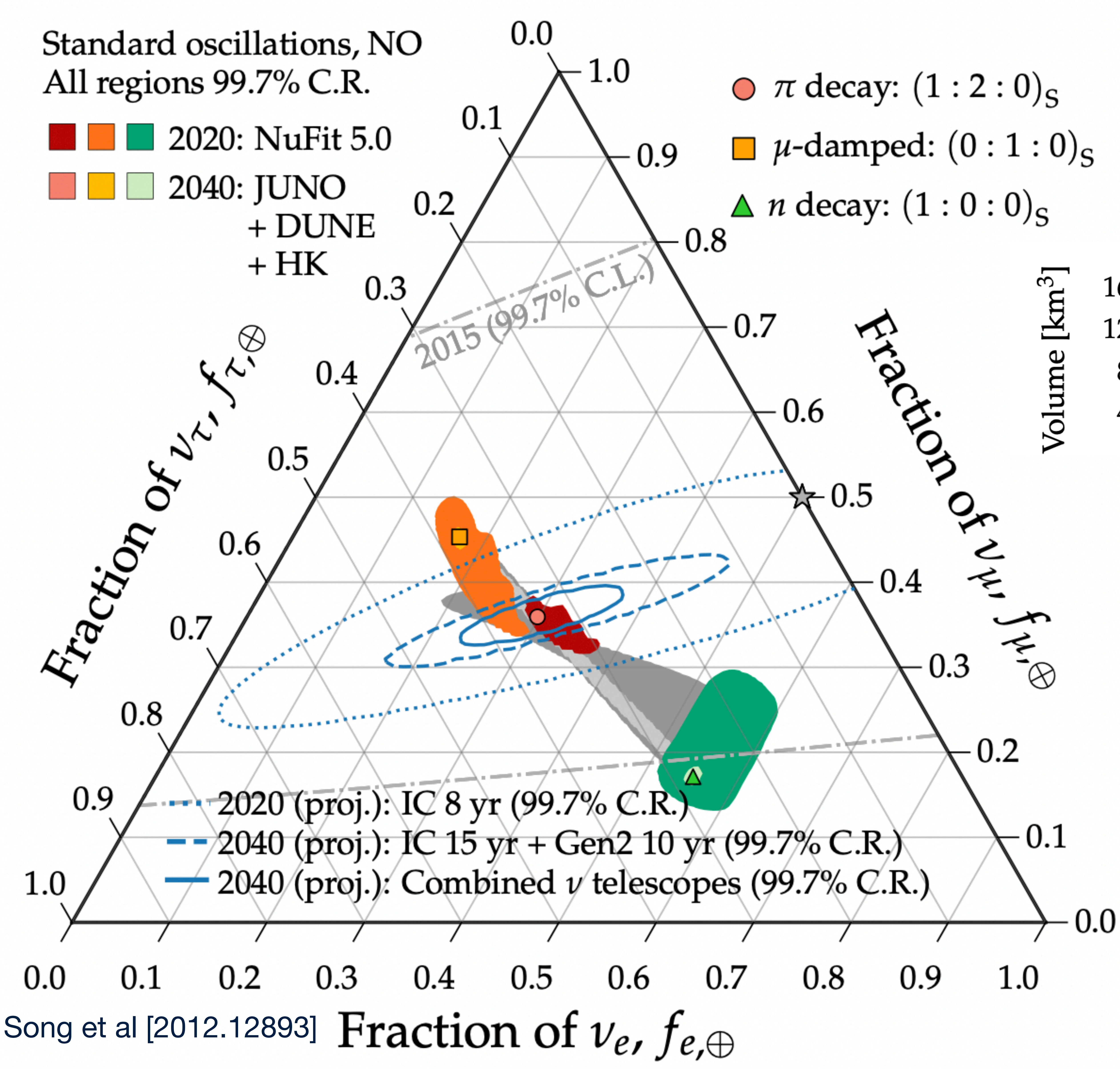
Precise oscillation parameter measurements are crucial for the interpretation of the astrophysical neutrino flavor measurements.

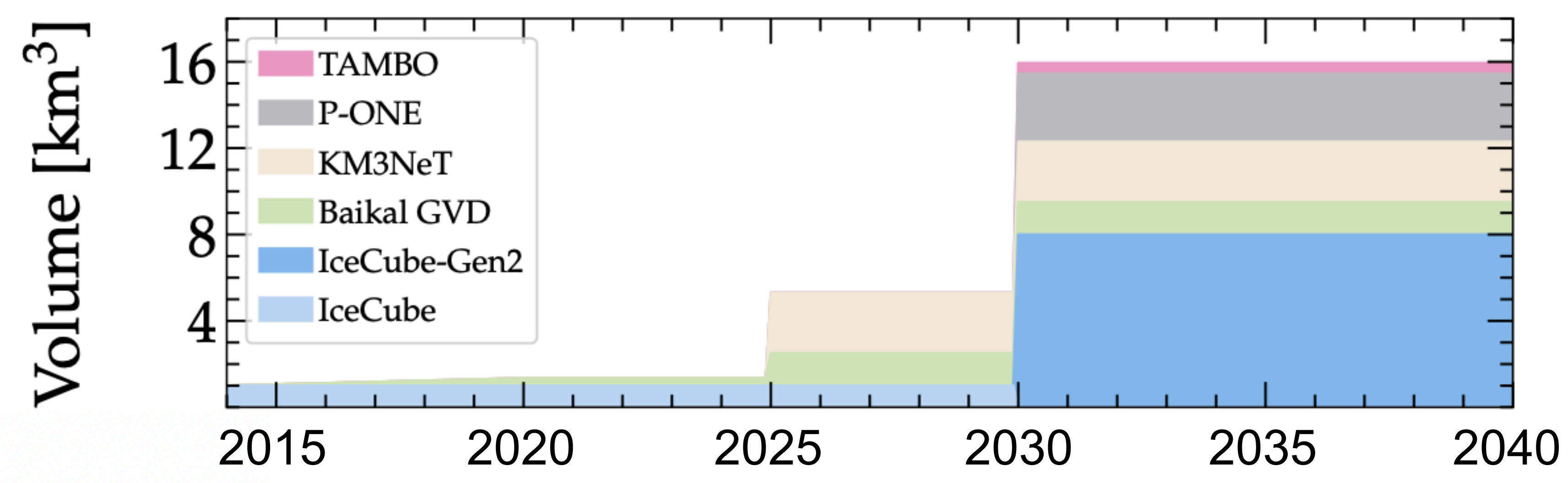
Next-generation HE and VHE neutrino telescopes

(UHE neutrino telescopes are not shown)

Next-generation HE and V
neutrino telescopes
(UHE neutrino telescopes are not shown)

Future of the Flavor Measurements on Inferring Neutrino Sources





Song et al [2012.12893]

Infering Neutrino Oscillation Parameters

- Neutrino oscillation measurements have achieved great precision, but exclusively at sub-TeV energies.
- Above TeV, the mixing paradigm remains largely unexplored.
- High-energy astrophysical neutrinos provide the only probe of standard and non-standard mixing above TeV.

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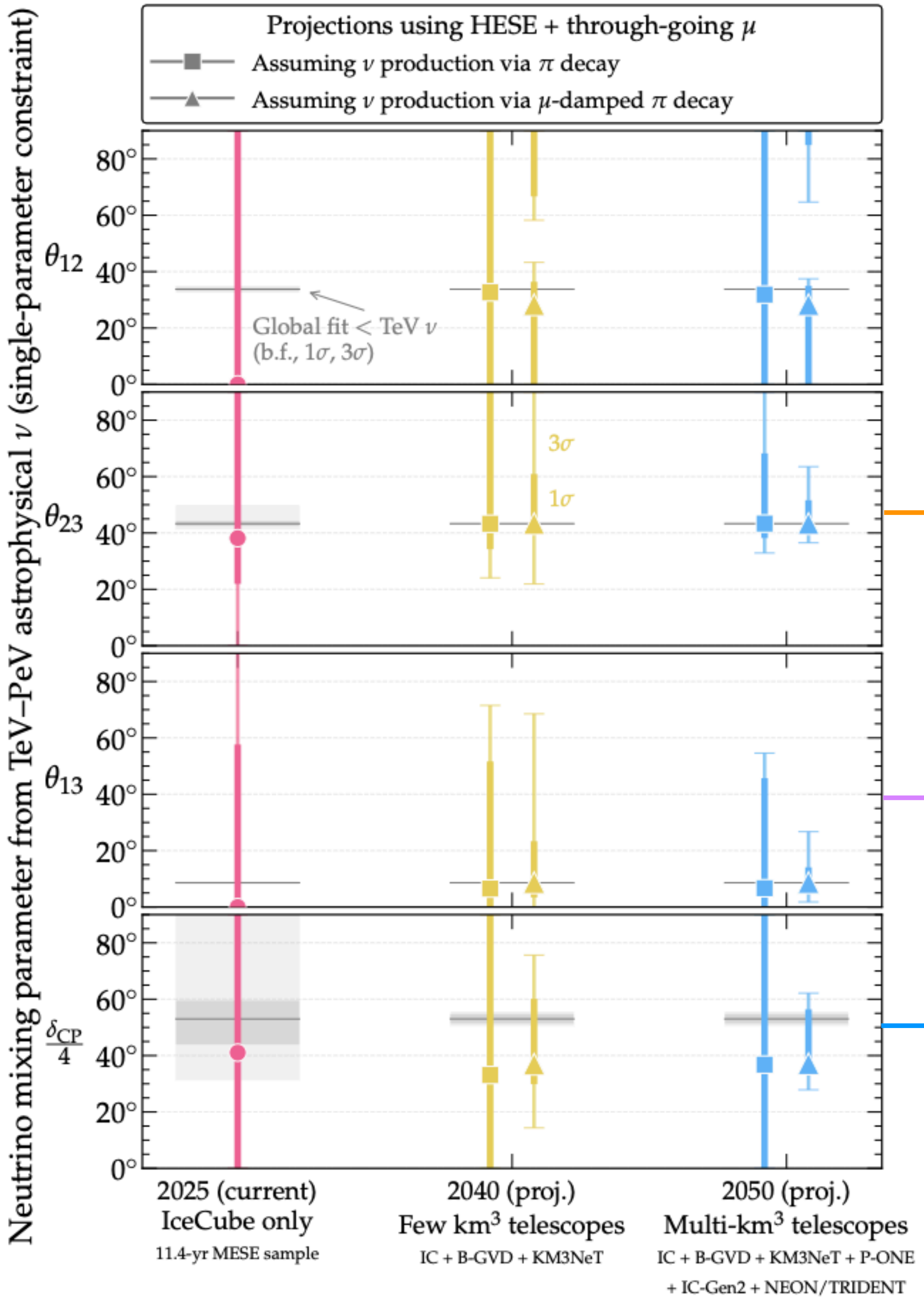


Optimistic projection

50% (π decay)
17% (μ damped)

~6 (π decay)
53% (μ damped)

~51% (μ damped)

- Future experiments improve the constraints, while results depend on the neutrino production. θ_{23} and θ_{13} can always be constrained.
- Large deviations from sub-TeV parameter values caused by BSM can be constrained.

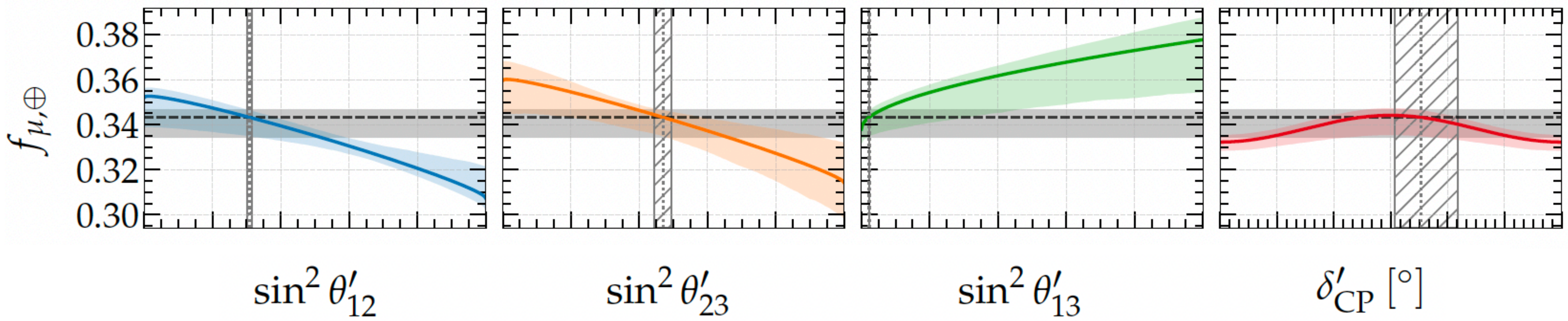
Bustamante, **QL**, Barenboim [2602.14308]

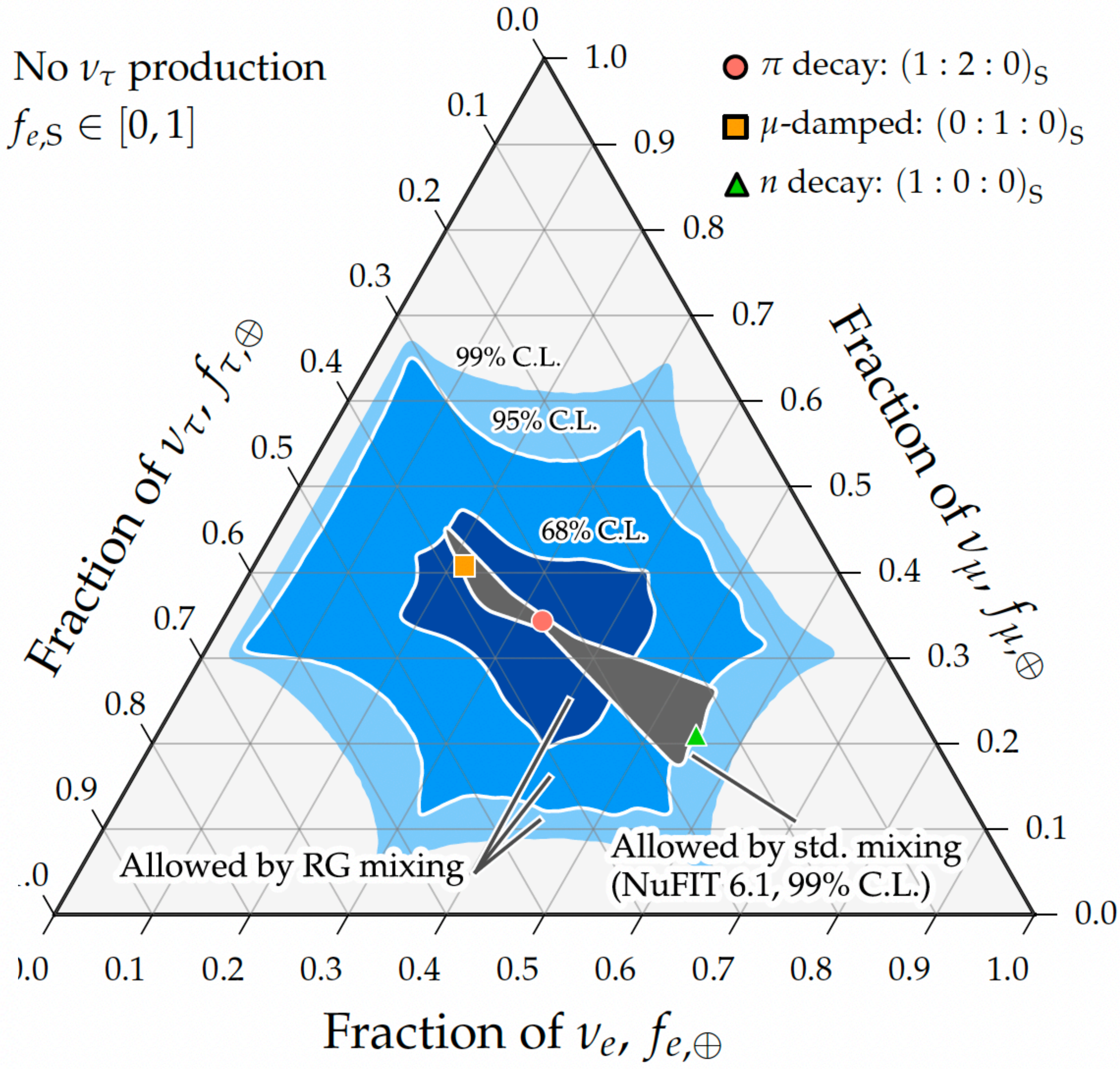
Parameter Running with the Transferred Momentum

Neutrino Production, pion decay, low Q (MeV), Standard parameters are well measured.

$$P_{\nu_\alpha \to \nu_\beta} = \sum_{i}^{3} |U_{\beta i}|^2 |U'_{\alpha i}|^2$$

Neutrino detection, high-energy neutrino deep inelastic scattering, > GeV Q. Parameter running may happen due to renormalization-group effects.





Future experiments improve the constraints, while results depend on the neutrino production. θ'_{23} can be measured at 33% for 1σ, assuming muon-damped.

Bustamante, **QL**, Barenboim [2604.14409]

Babu, Leung, Pantaleone, PLB 1993; Casas, Espinosa, Ibarra, Navarro, Nucl. Phys. B 2000; Antusch, Kersten, Lindner, Ratz, Nucl. Phys. B 2003

Energy-Dependence of the Flavor Composition

- Flavor composition measurements have been focusing on the power-law spectrum + 1 set flavor composition.
- The flavor composition is expected to be energy-dependent, due to energy-dependent neutrino production mechanisms and new physics effects.

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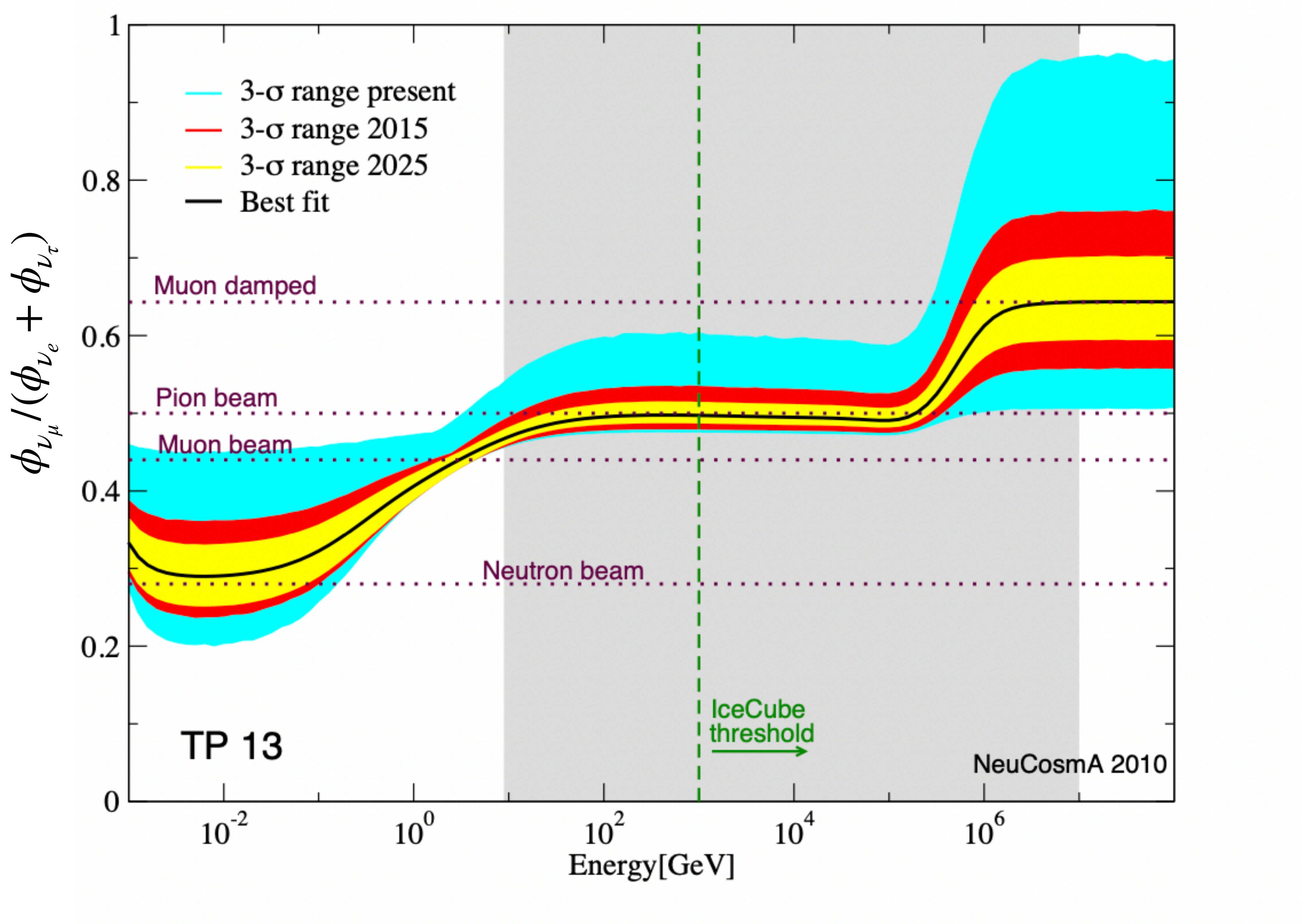

neutrino source

Hümmer et al 2010

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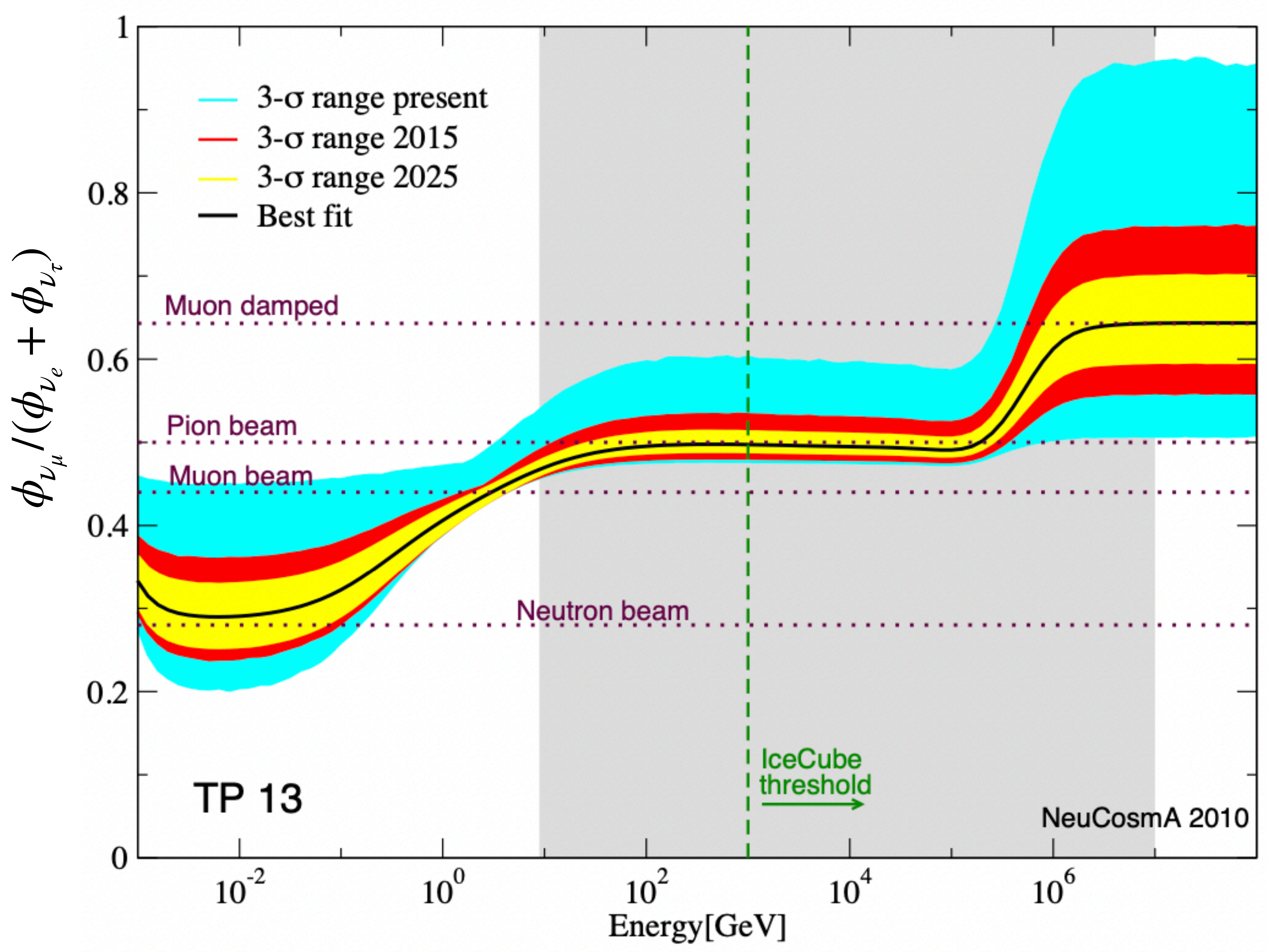
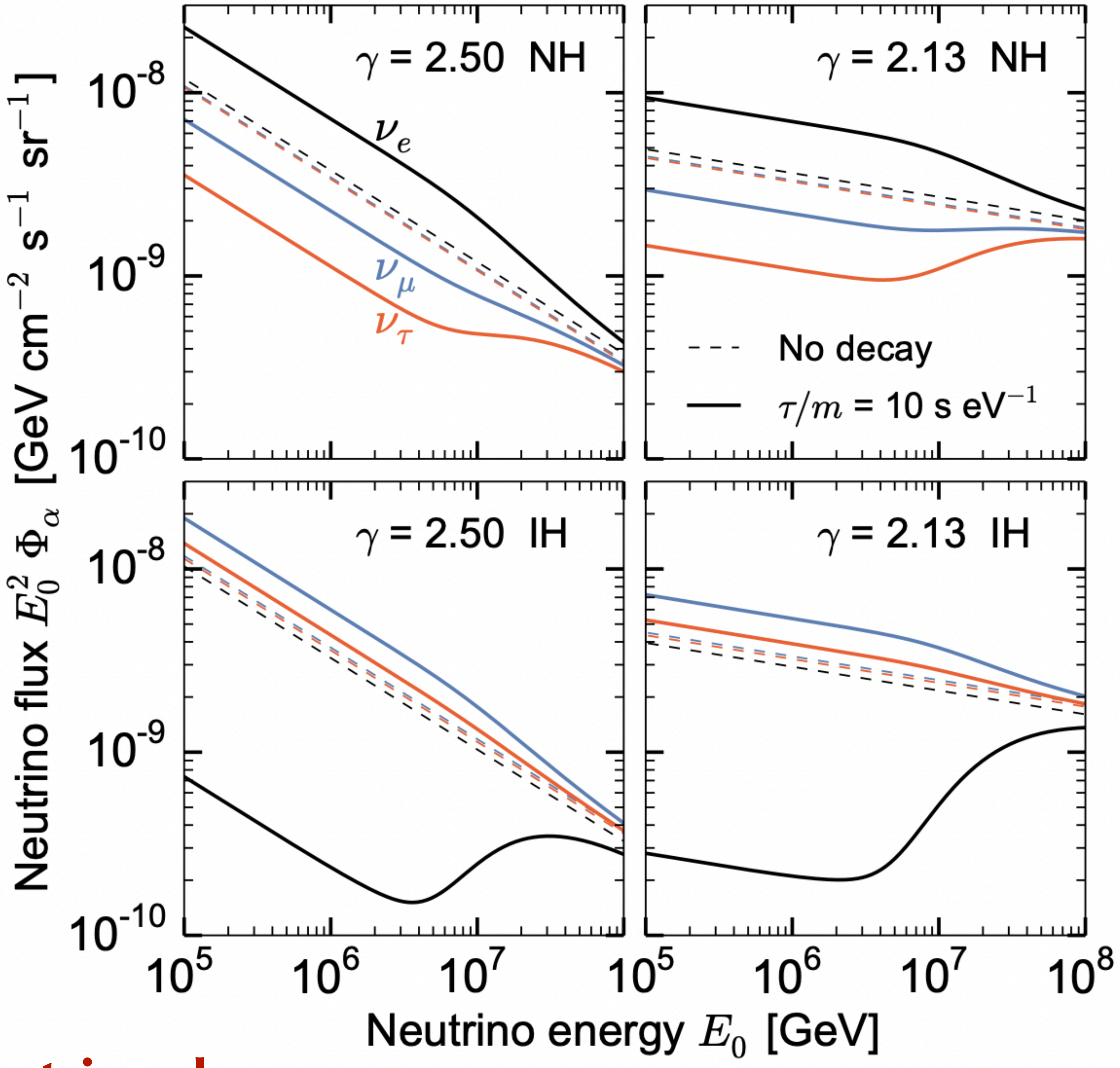


neutrino source

Hümmer et al 2010

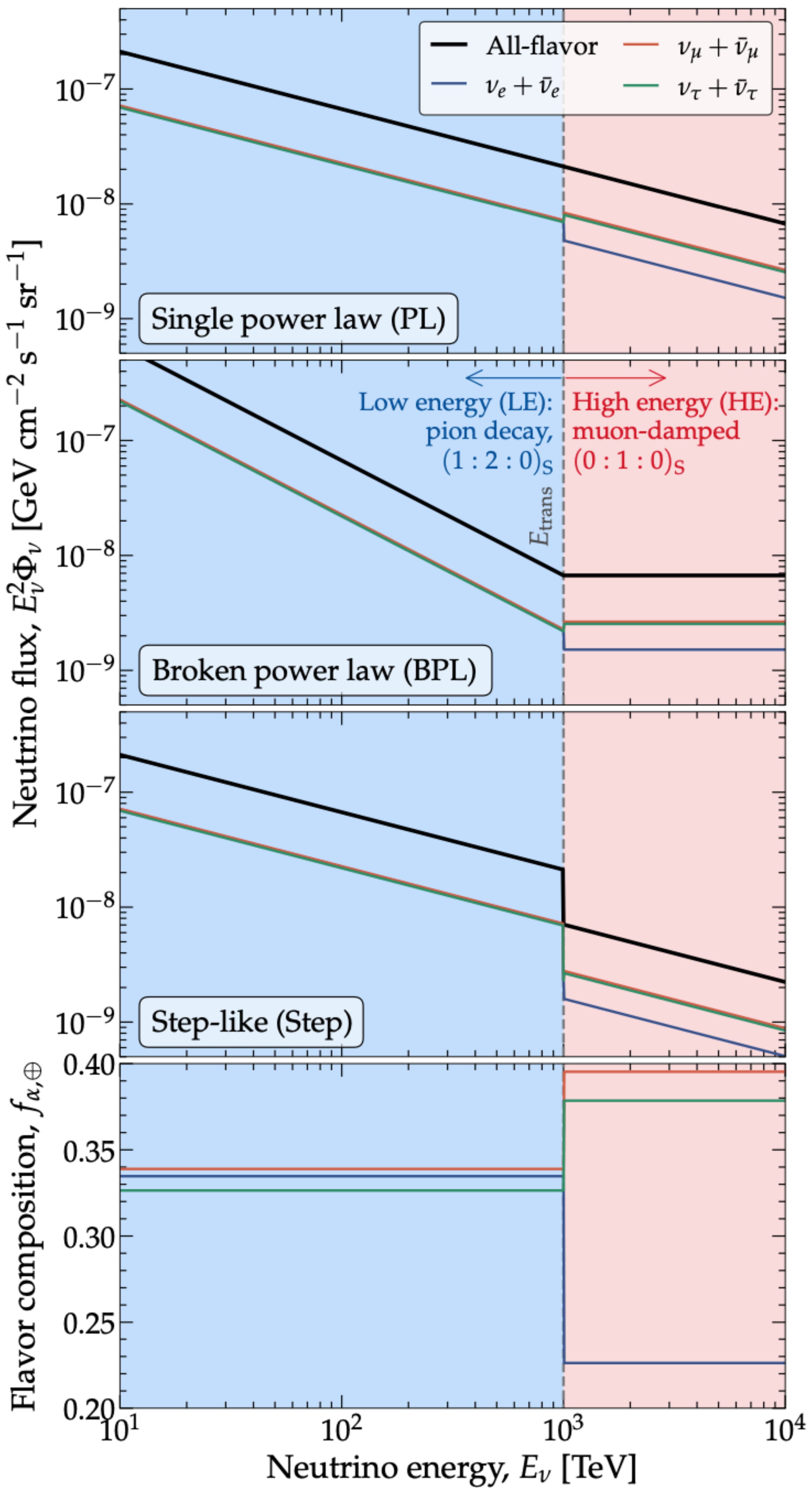


neutrino decay

Bustamante, Beacom, Murase 2017

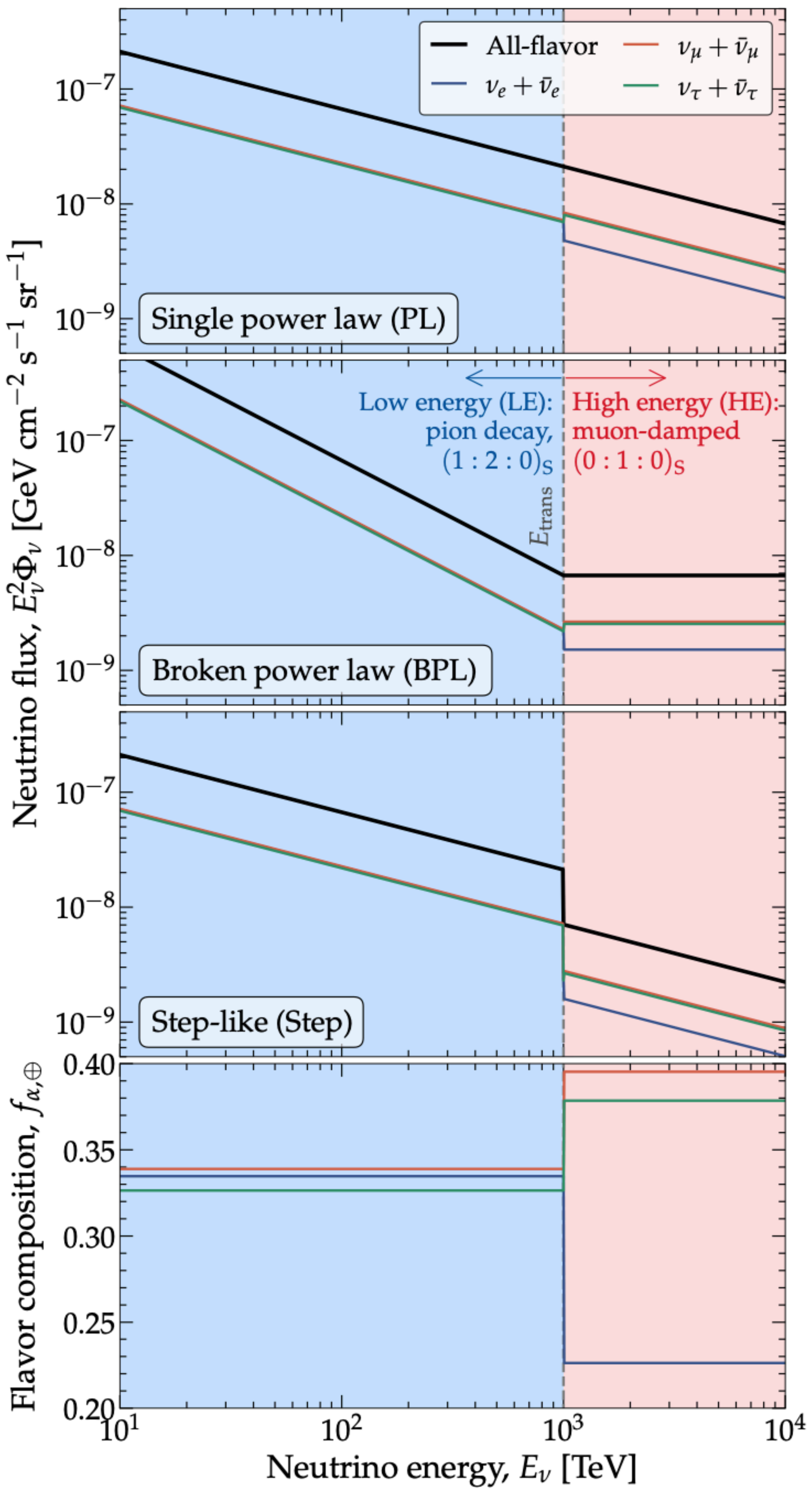
Other BSM examples: Lorentz-invariance violation, dark matter interactions, non-standard neutrino interactions, sterile neutrinos…

Energy-Dependent Flavor Composition



- Introduce a transition energy $E_{trans} \Longrightarrow$ 2 sets of flavor compositions
- Test 3 general scenarios independent of specific models to cover possible flavor transition from either neutrino production at sources or BSM effects.

Energy-Dependent Flavor Composition



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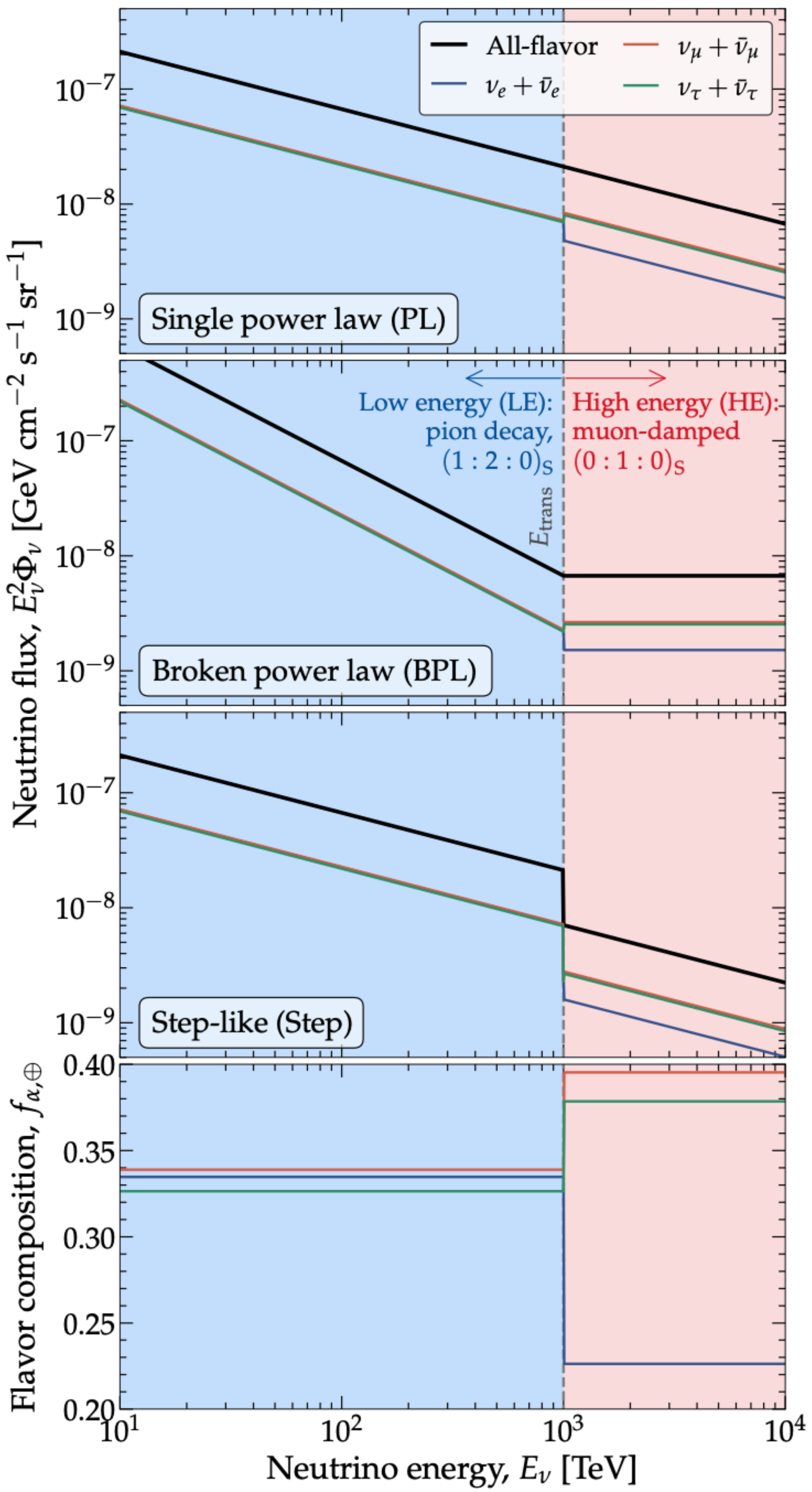

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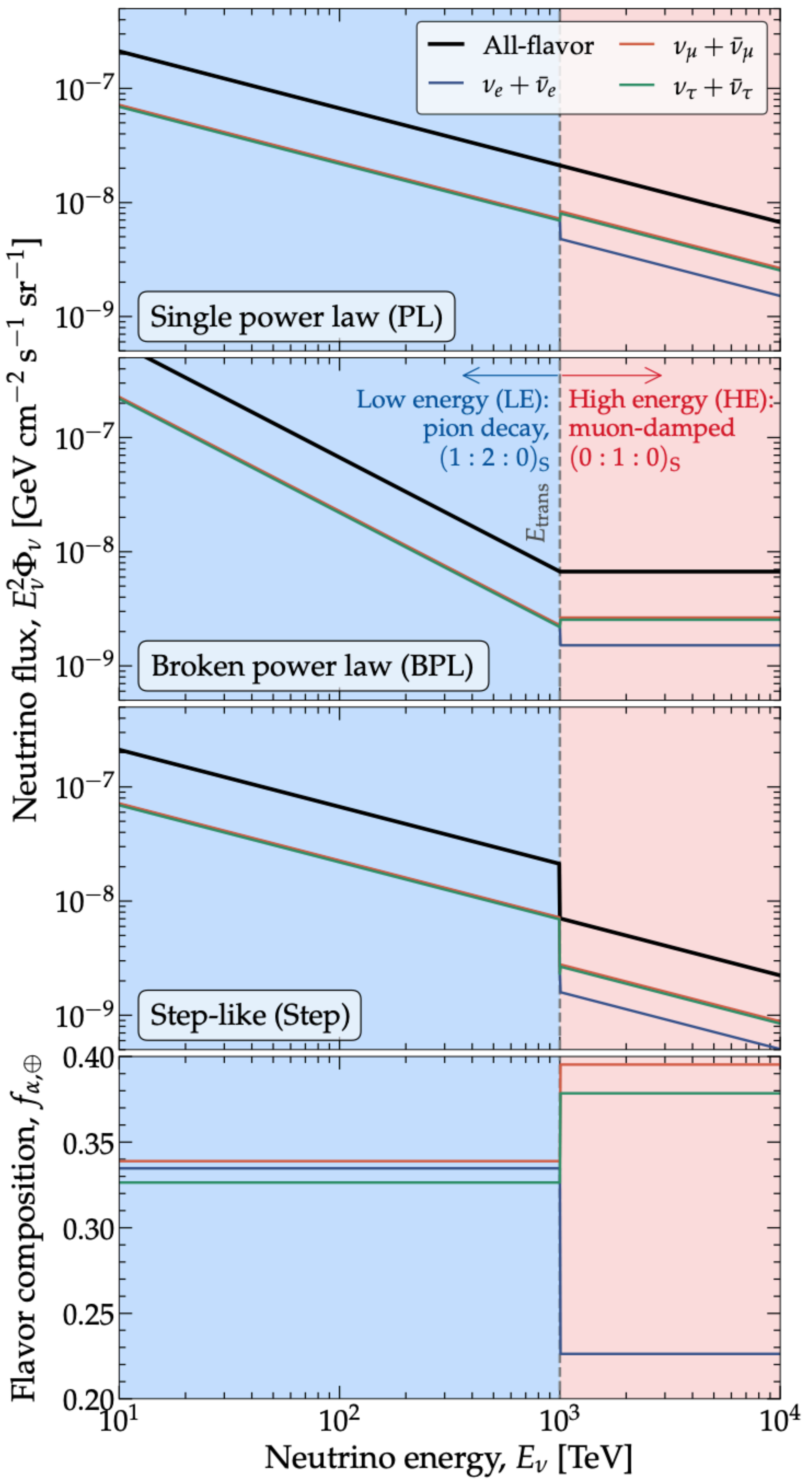
Energy-Dependent Flavor Composition



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  - Broken power-law spectrum: the spectral index changes at the transition energy; e.g. source classes with different mechanisms dominating different energy ranges.

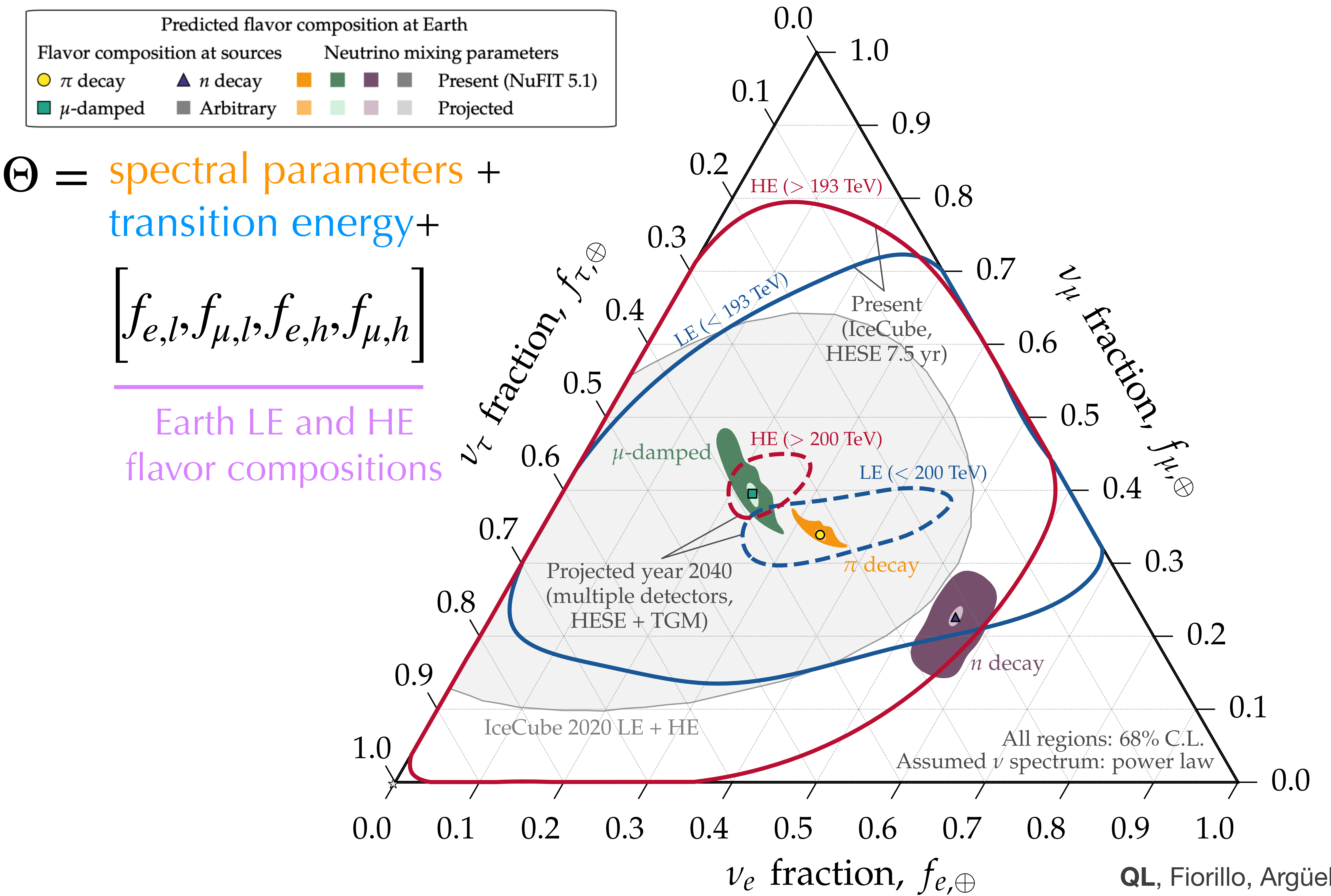
  - Step spectrum: flux normalization changes at the transition energy; e.g. a transition from pion decay to muon-damped for the same sources, oscillation to sterile neutrinos…

Energy-Dependent Flavor Composition

Future projections with combined exposure: IceCube/IceCube-Gen2+KM3NeT+Baikal-GVD+P-ONE+TAMBO+TRIDENT

Θ = spectral parameters + transition energy+ $\left[f_{e,l}, f_{\mu,l}, f_{e,h}, f_{\mu,h}\right]$

Earth LE and HE flavor compositions



QL, Fiorillo, Argüelles, Bustamante, Song, Vincent PRD25

Energy-Dependent Flavor Composition

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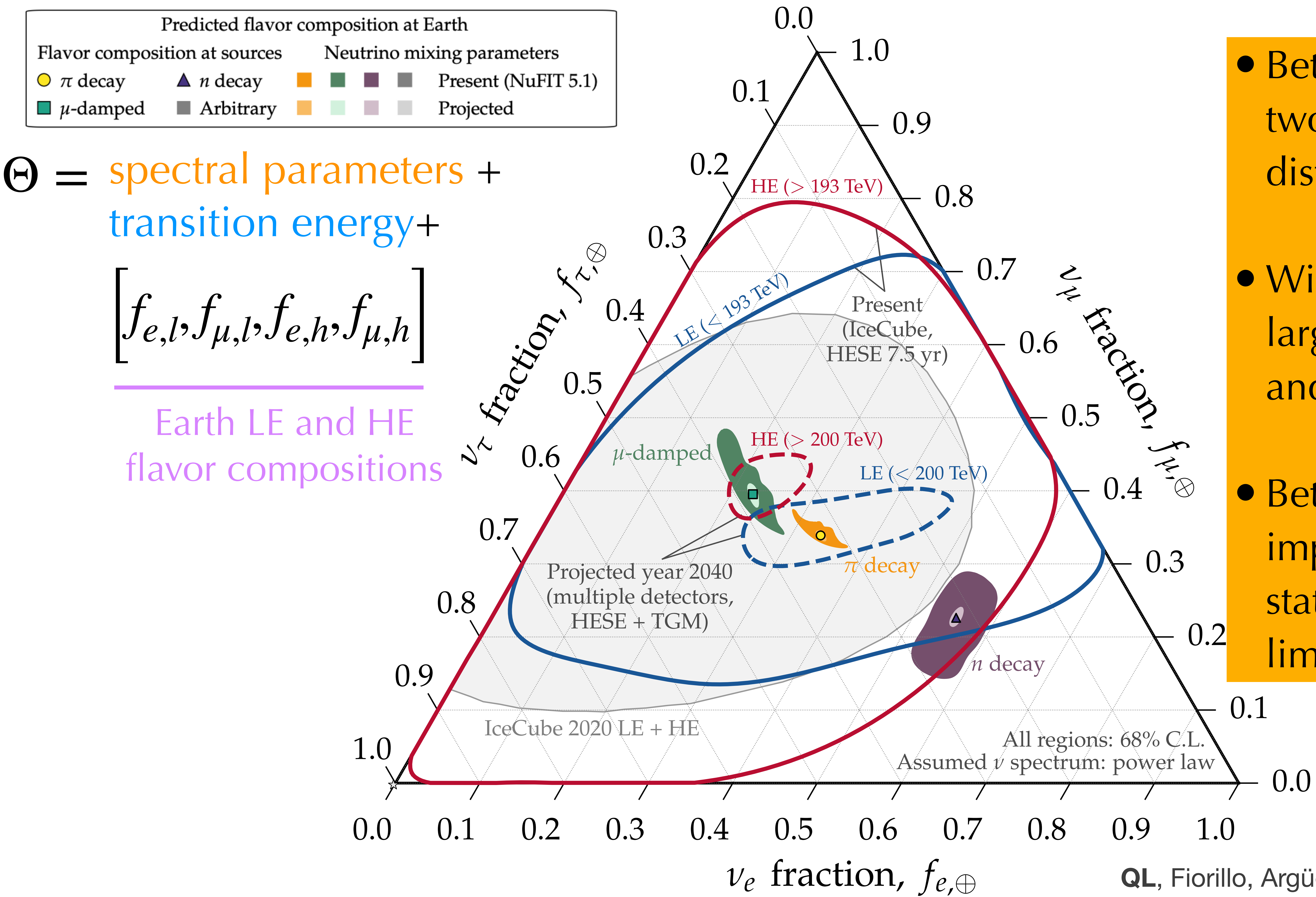


- Better sensitivity is expected if the two flavor compositions are more distant in the ternary plot.
- Wider energy coverage will largely improve the measurement and expand the parameter space.
- Better reconstruction will largely improve the measurement when statistics is no longer the limitation.

QL, Fiorillo, Argüelles, Bustamante, Song, Vincent PRD25

From Measurements to the Flavor Compositions at Sources

From measurement back to the source

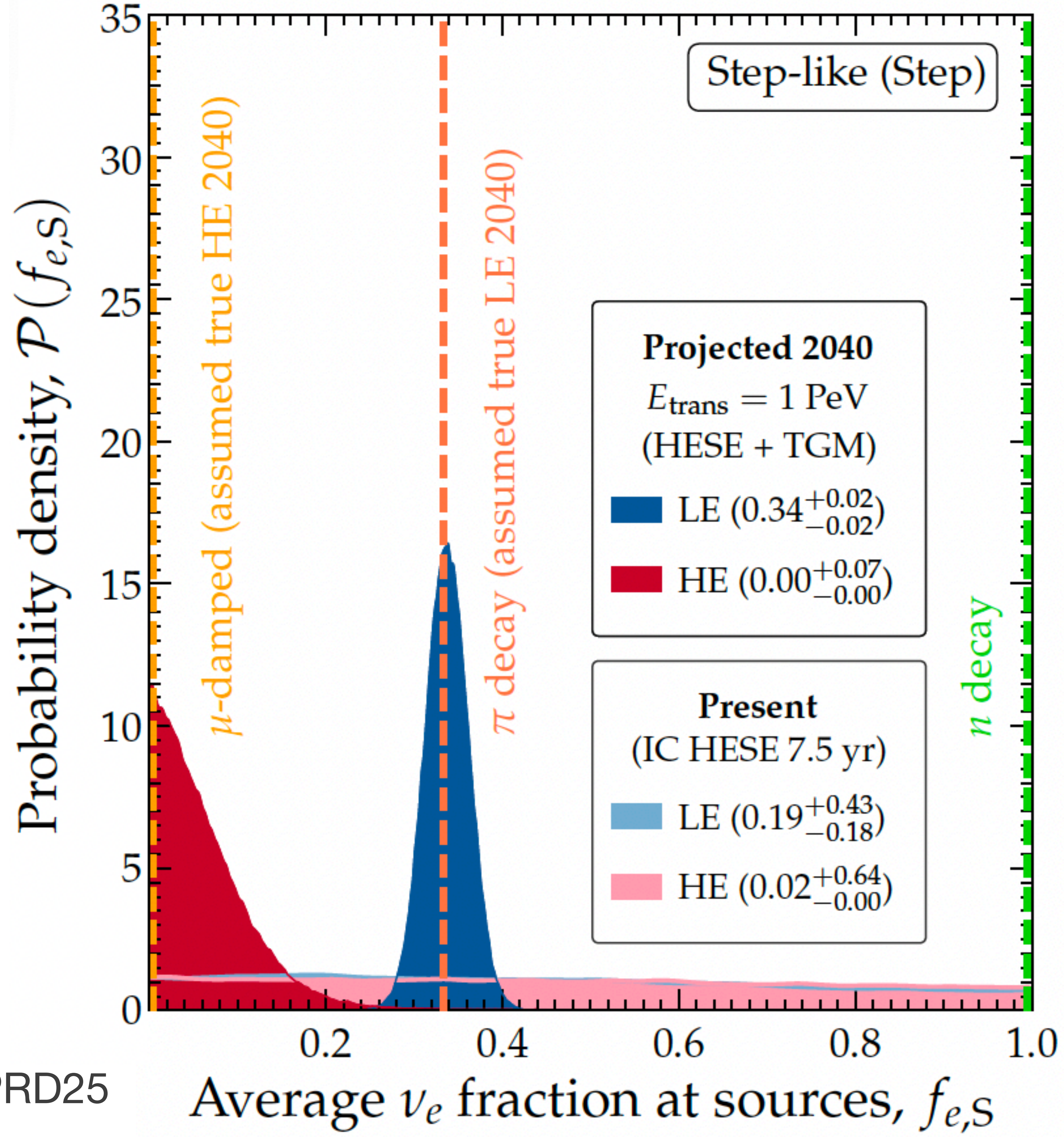
spectrum + transition energy + $\left[f_{e,l}, f_{\mu,l}, f_{e,h}, f_{\mu,h}\right] \rightarrow \left[f_{e,S;l}, f_{e,S;h}\right] + \left[s_{12}, s_{23}, s_{13}, \delta_{cp}\right]$

Earth LE and HE flavor compositions (measurement)

source LE and HE flavor compositions (sources)

Standard oscillation (propagation)

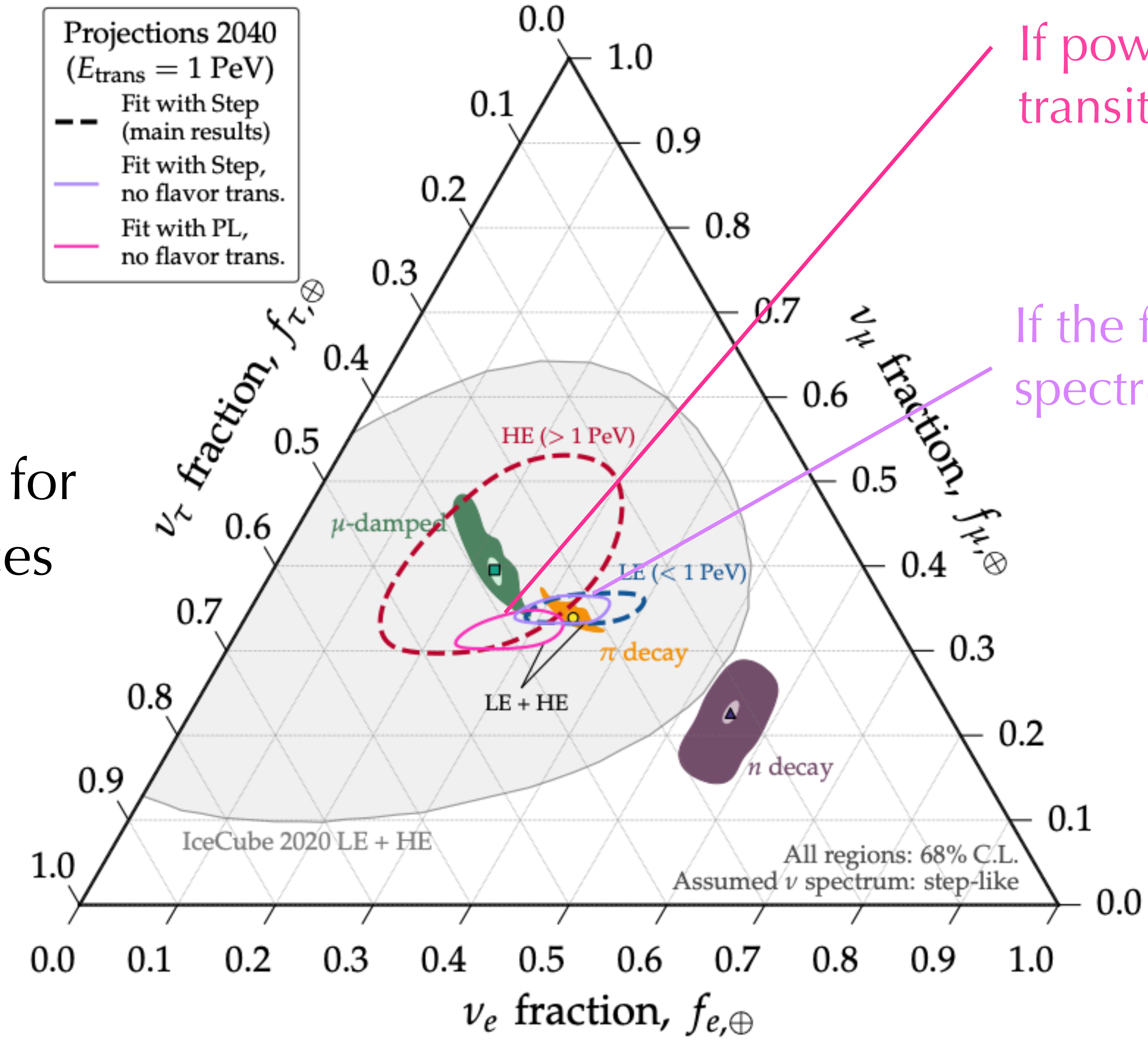
pion decay -> muon damped for the same sources



The low-energy and high-energy flavor compositions at the sources can be determined <10% by 2040

QL, Fiorillo, Argüelles, Bustamante, Song, Vincent PRD25

Comparison with the General Approach



If power law spectrum+ no flavor transition is fitted

If the fitting assumption assumes the correct spectrum but without the flavor transition

pion decay -> muon damped for the same sources

- Mismodeling of the flavor composition can lead to unexpected interpolation!
- Flavor measurements must use flexible descriptions to avoid reporting inaccurate flavor composition measurements.

QL, Fiorillo, Argüelles, Bustamante, Song, Vincent PRD25

A Step Further on the Energy Dependence

Can We Do Better?

- Finding the transition energy is very difficult without prior knowledge.
- We can try to infer the piece-wise spectrum of each flavor separately.

A Step Further on the Energy Dependence

QL, Bustamante, Vincent, in prep

Can We Do Better?

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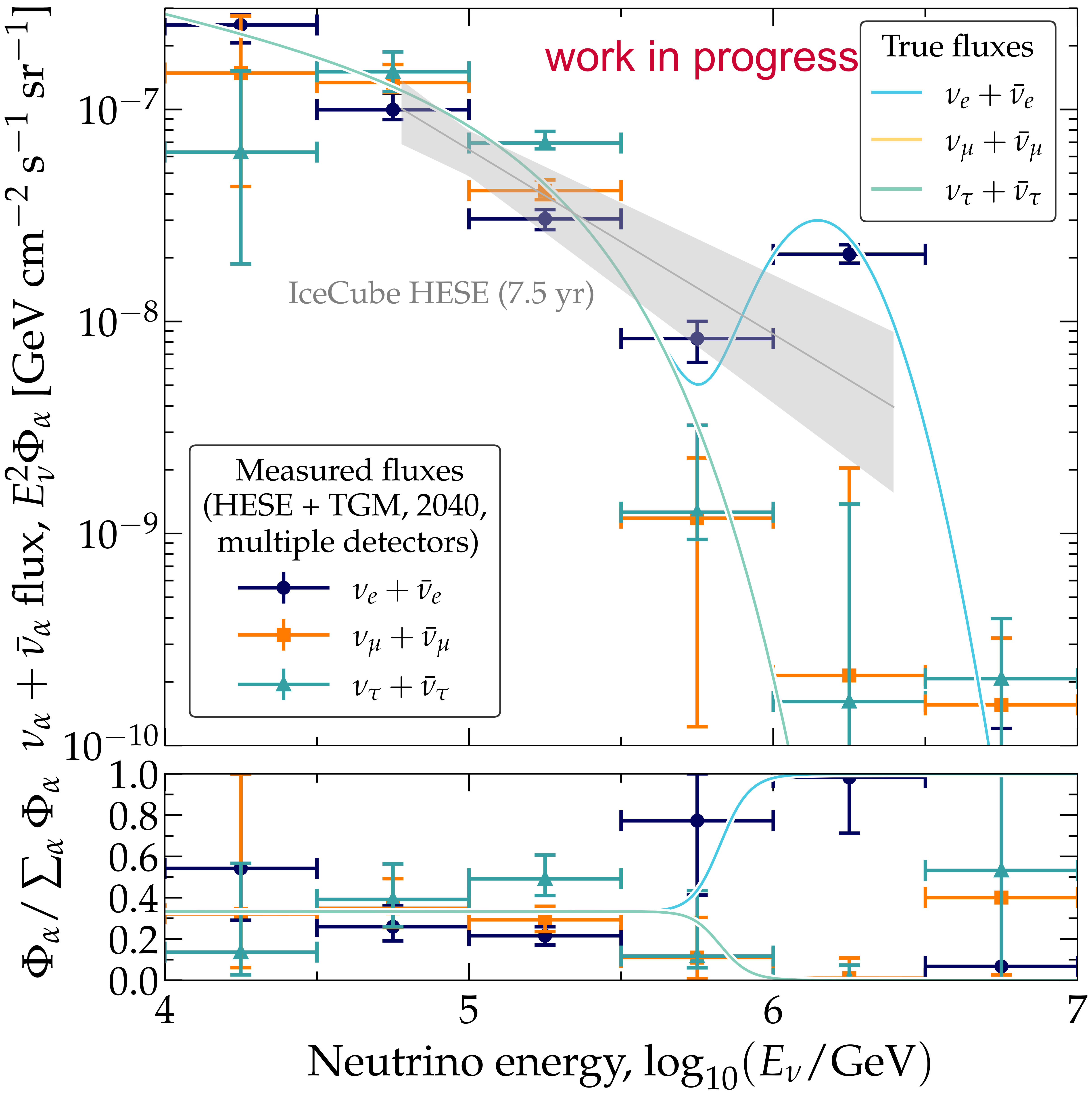
- We can try to infer the piece-wise spectrum of each flavor separately.

~~$\Theta =$ spectral params + transition energy + $[f_{e,l}, f_{\mu,l}, f_{e,h}, f_{\mu,h}]$~~ → $\Theta = [f_e, f_\mu, \phi] \times n_{\text{bins}}$



Beyond the Ternary?

$\nu - \bar{\nu}$?

Neutrino telescopes are blind to neutrinos and antineutrinos.
Is there a way to differentiate?

Glashow Resonance

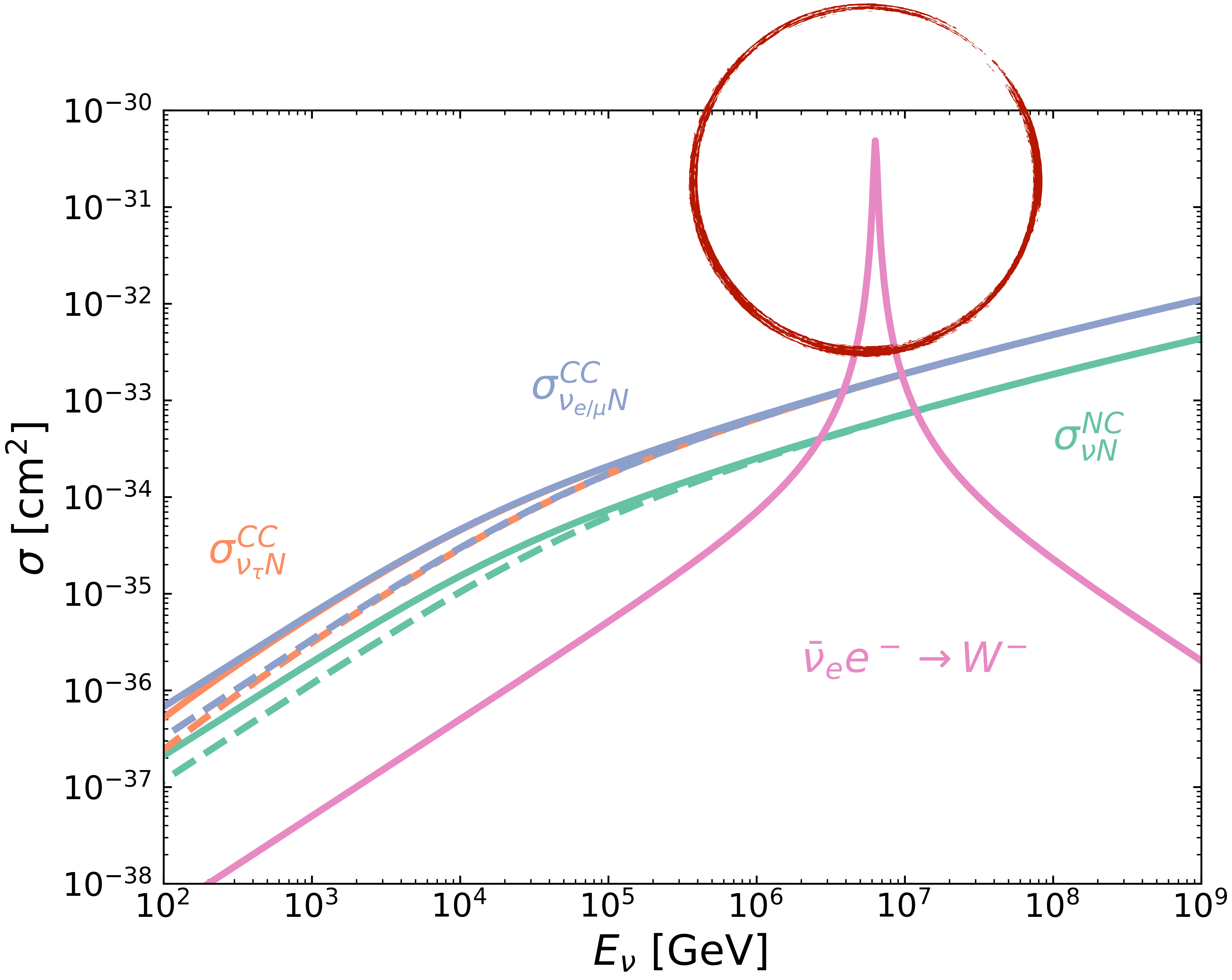
$\bar{\nu}_e$ can be disentangled with resonant interactions

$$\bar{\nu}_e + e^- \rightarrow W^- \rightarrow X$$

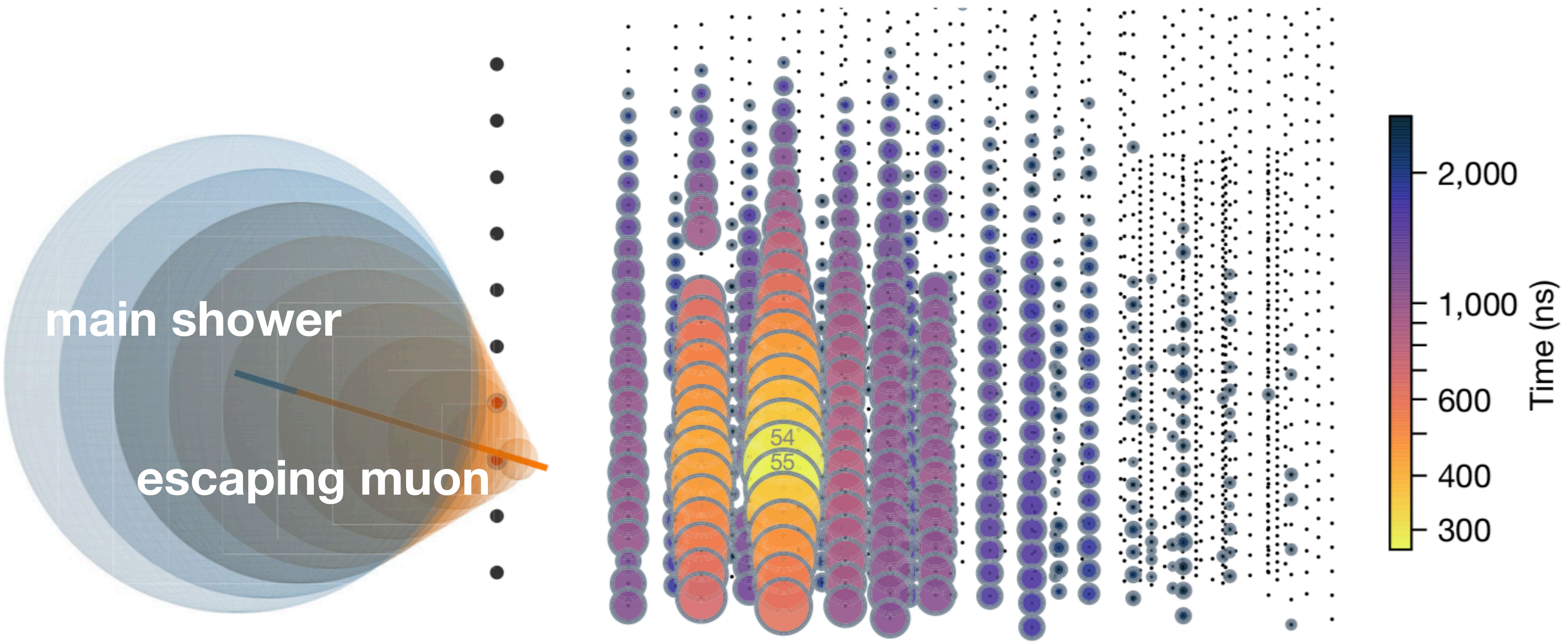
6.3 PeV   511 KeV   80.38 GeV

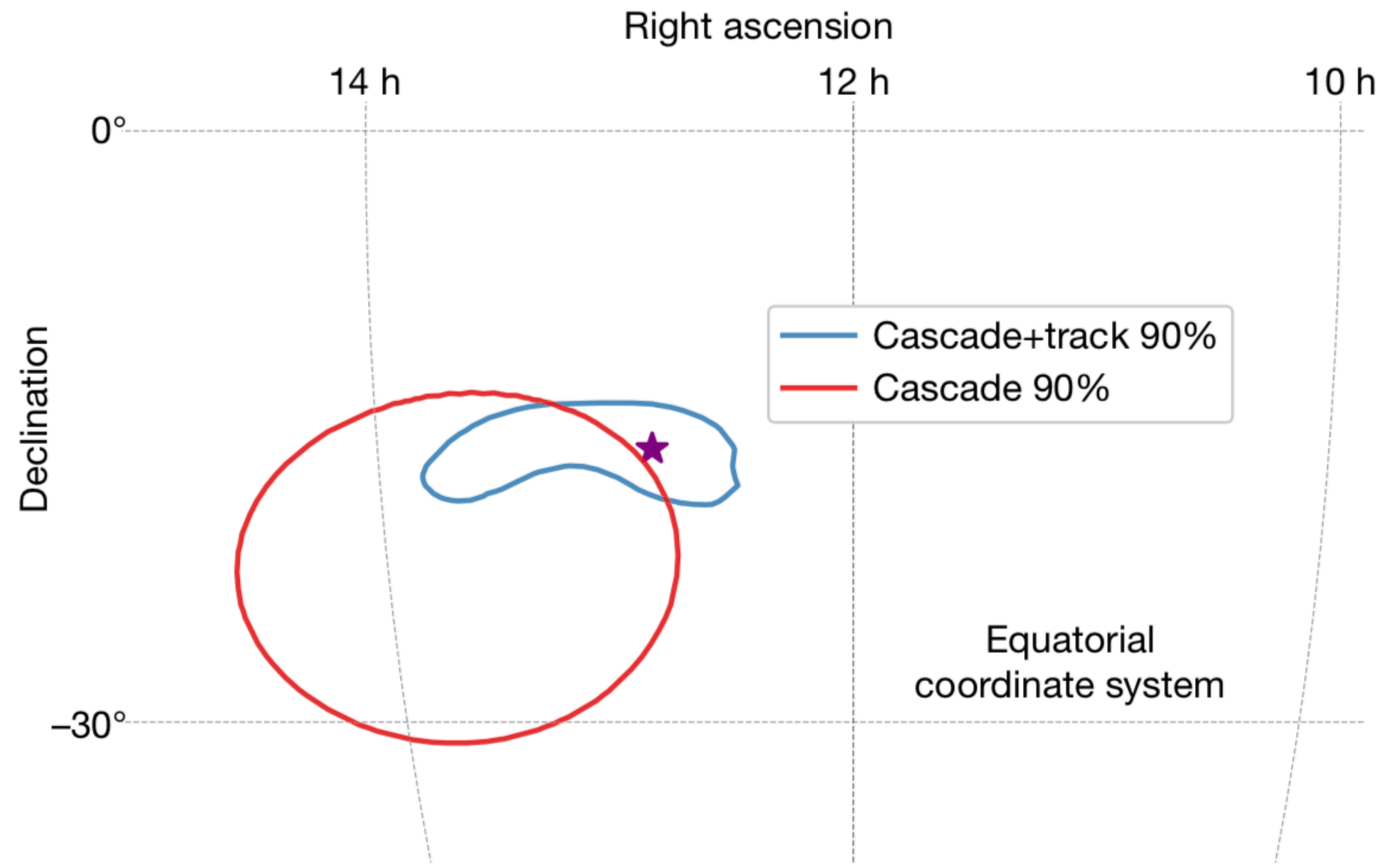
S. Glashow *Phys.Rev.* 1960

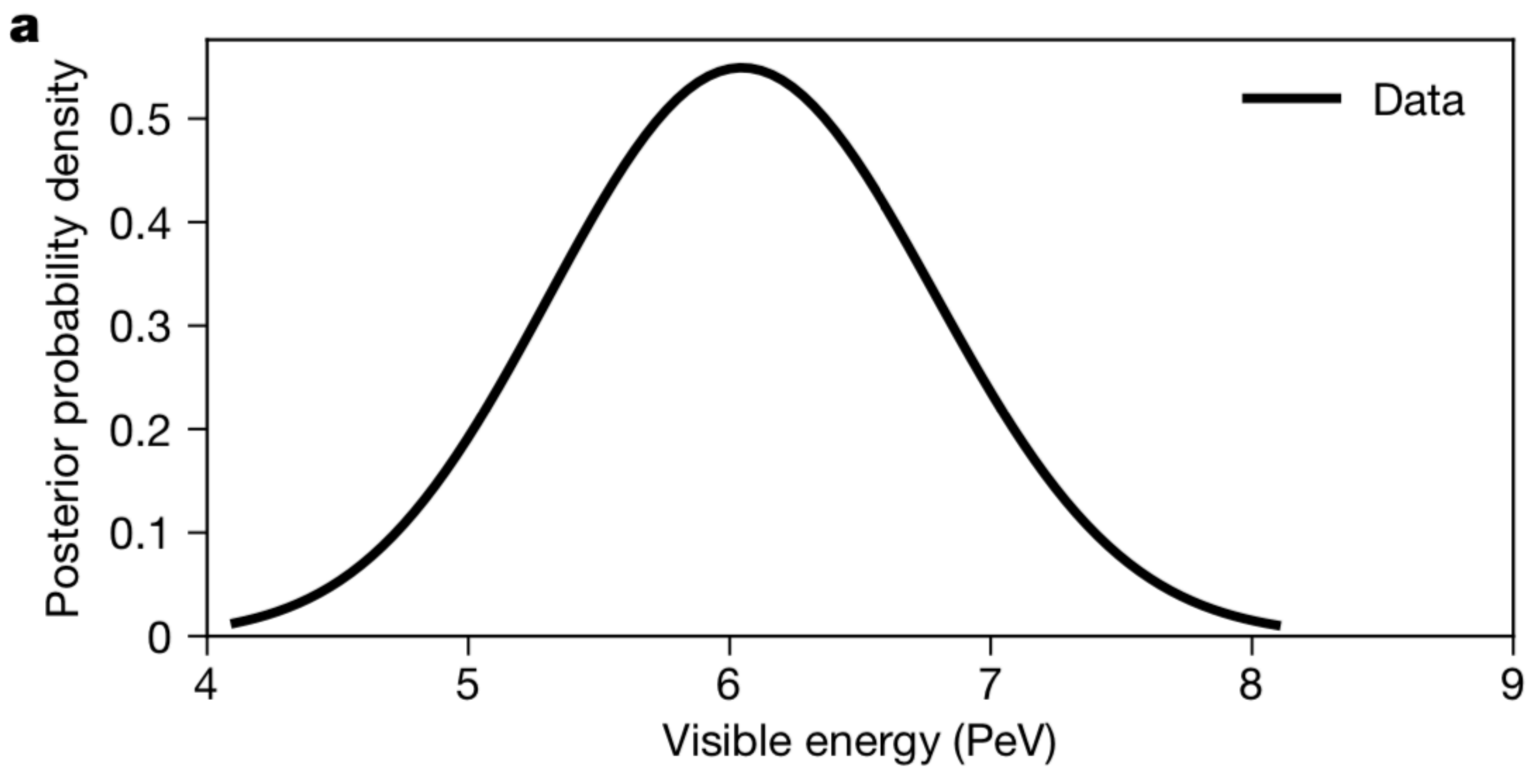
The only way to differentiate the anti-neutrino flux from the total flux at high energies.

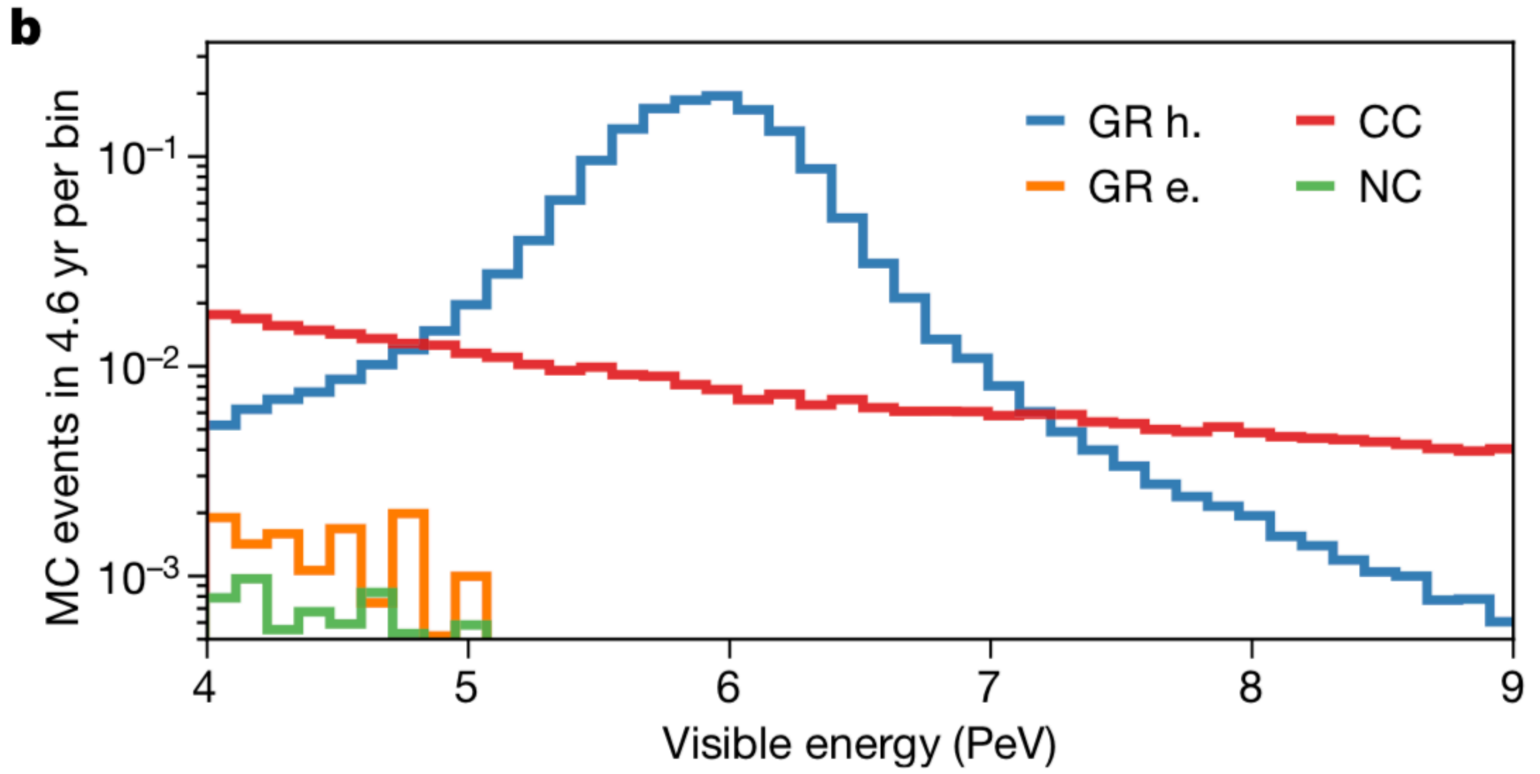


First Detection of Glashow Resonance









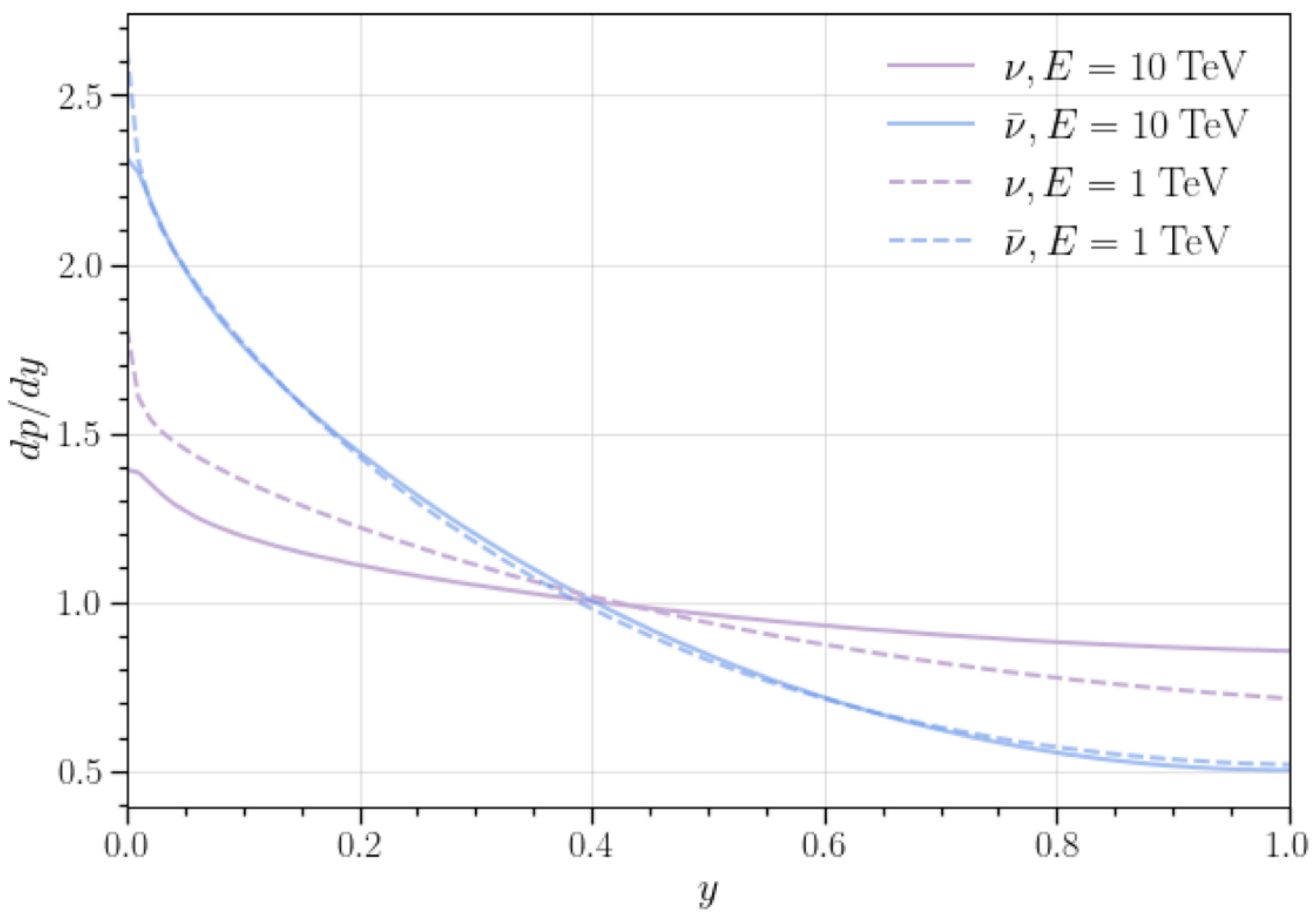
PeV energy partially-contained event selection

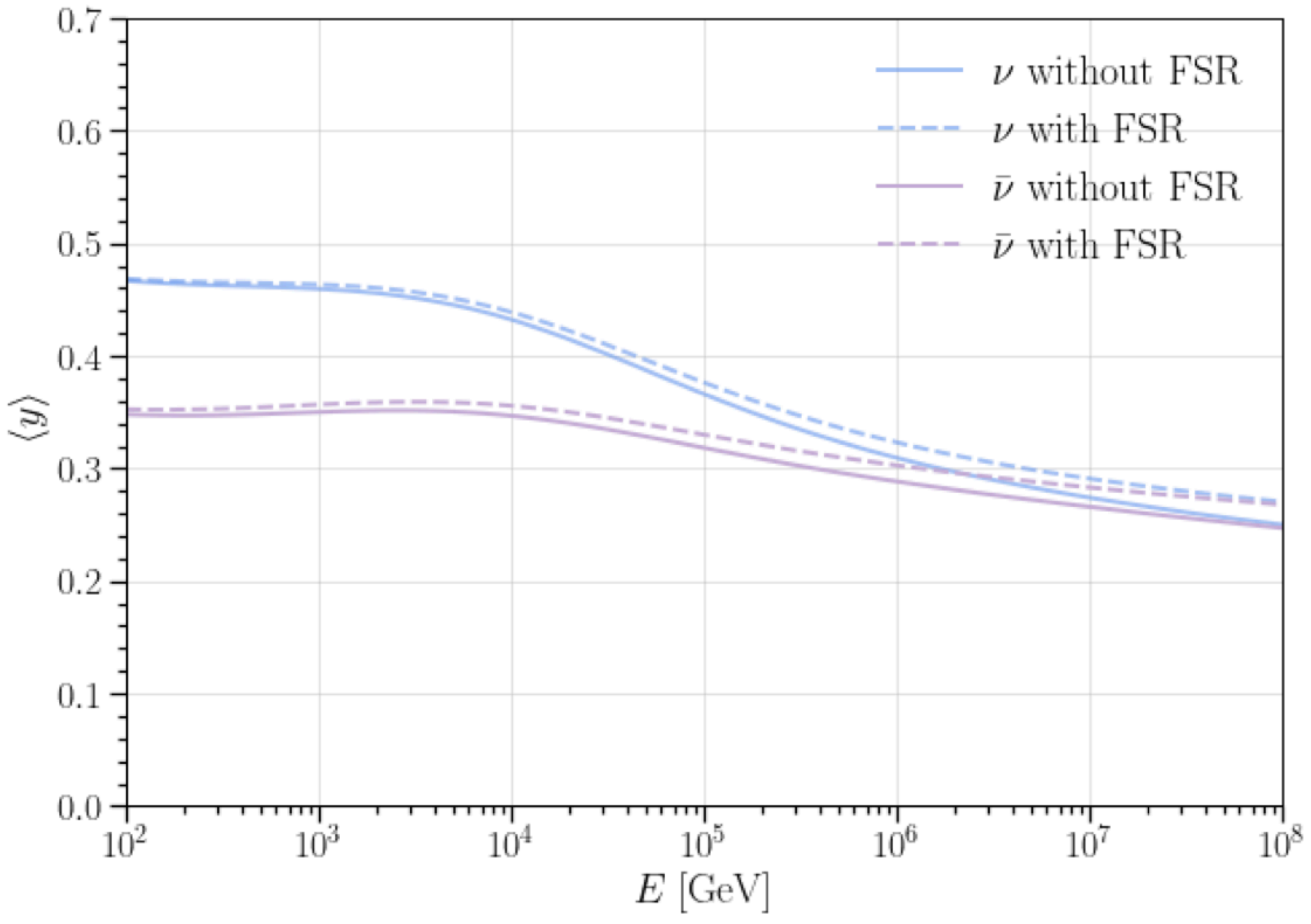
- The detectable escaping muons suggest it's a hadronic shower
- visible energy of 6.05 ± 0.72 PeV, 2.3σ assuming a $E^{-2.5}$ spectrum.

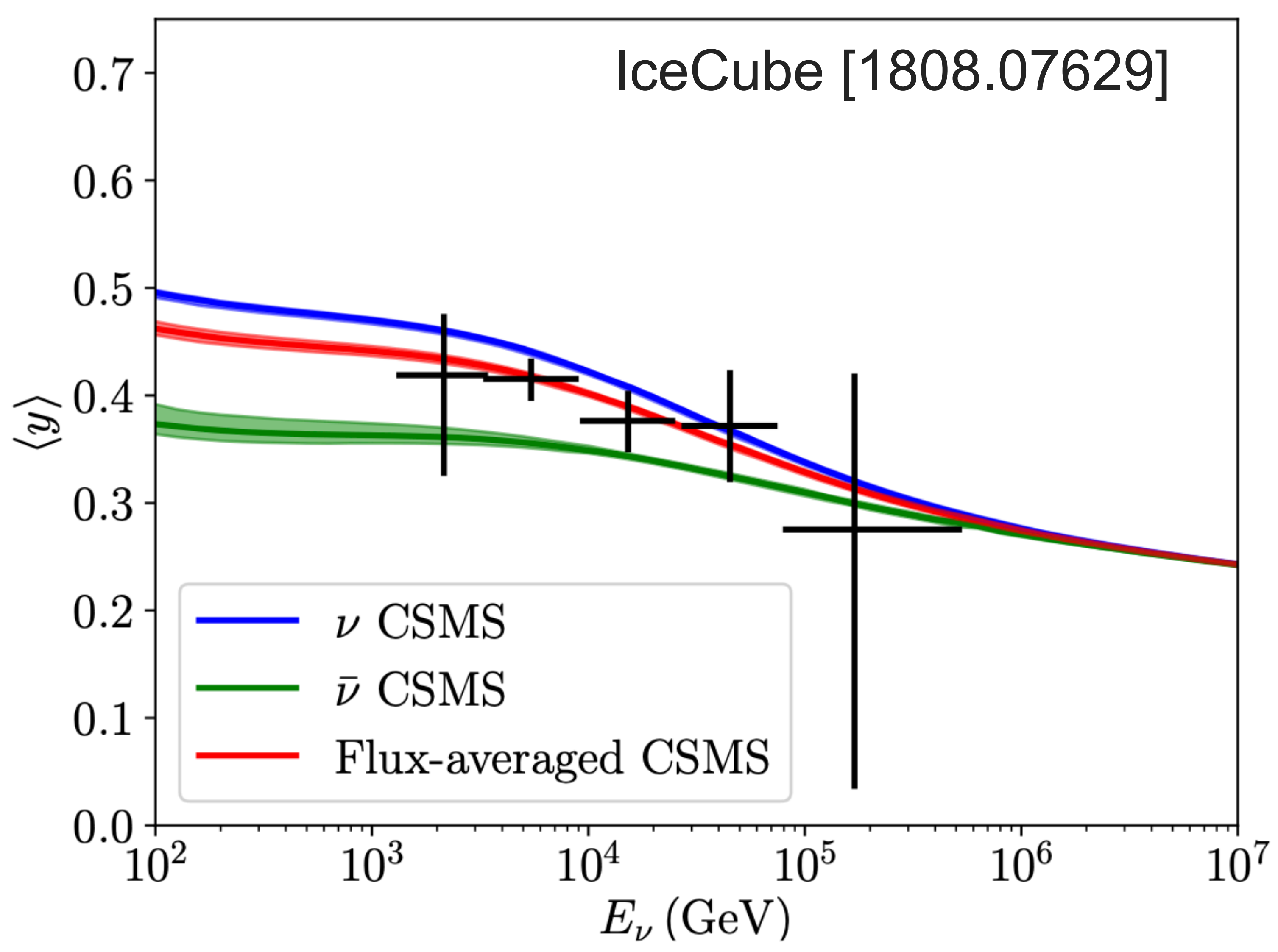
IceCube Nature 2021

Probing $\bar{\nu} : \nu$ with the Inelasiticity Measurement

For below 100 TeV, $\bar{\nu} : \nu$ may be probed by measuring the inelasticity of deep inelastic scattering using starting tracks.

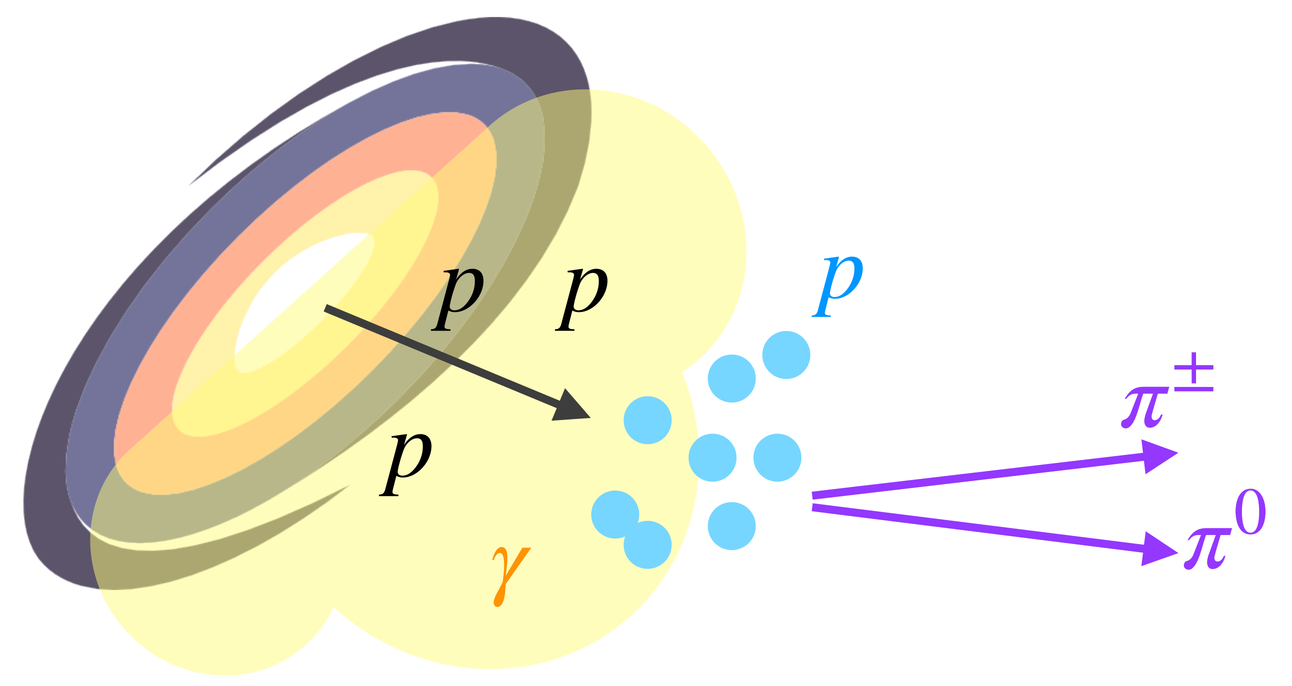






Skrzypek & Klein ICRC2025

Limitation of the 3-Flavor Measurements



Accelerated cosmic ray beam (p) + gas(p)/ radiation(γ)

Hadronuclear $p + p \to n_\pi \left[\pi^0 + \pi^+ + \pi^-\right]$

Photohadronic $p + \gamma \to \Delta^+ \to \pi^+ + n$

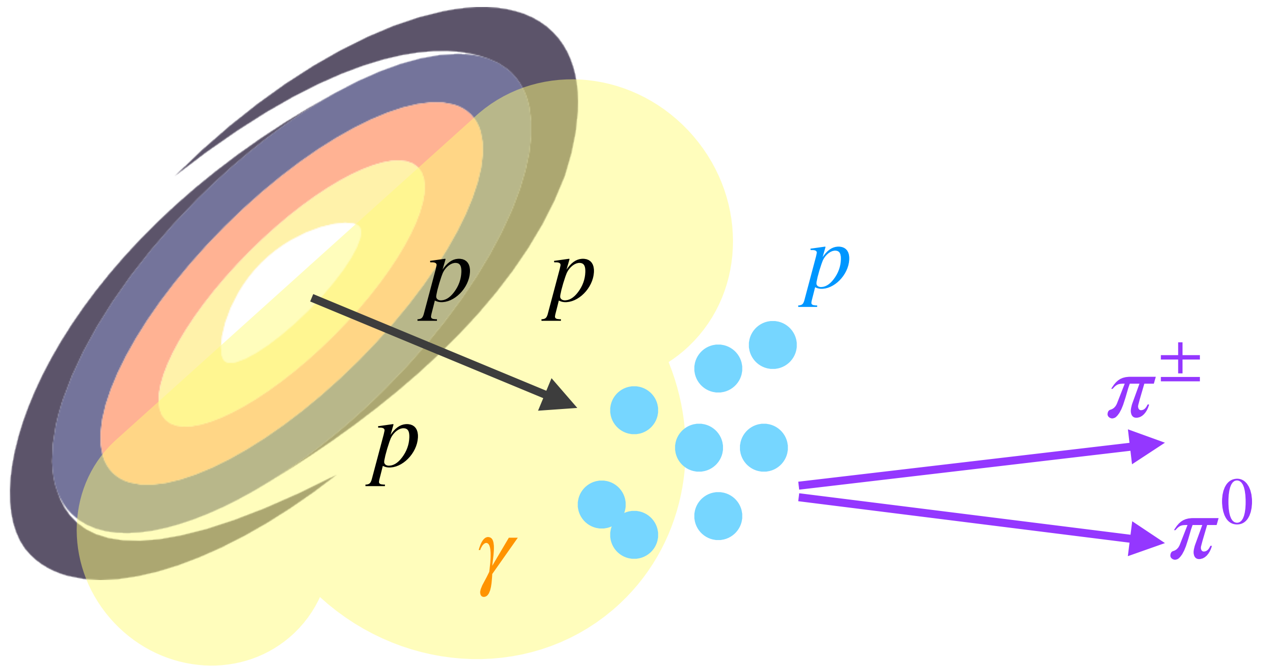
$$\begin{cases} \pi^+ \to \nu_\mu + \mu^+ \to \nu_\mu + \left(e^+ + \nu_e + \bar{\nu}_\mu\right) \\ \pi^- \to \bar{\nu}_\mu + \mu^- \to \bar{\nu}_\mu + \left(e^- + \bar{\nu}_e + \nu_\mu\right) \end{cases}$$

Considering $\nu + \bar{\nu}$ together

	$f_{e,s} : f_{\mu,s} : f_{\tau,s}$	standard mixing $\longrightarrow$	$f_{e,\oplus} : f_{\mu,\oplus} : f_{\tau,\oplus}$
$pp/p\gamma$	$\{1 : 2 : 0\}$		$\{0.33 : 0.34 : 0.33\}$
$pp/p\gamma$ μ damped	$\{0 : 1 : 0\}$		$\{0.23 : 0.39 : 0.38\}$

The presence of suppressed μ decay can be distinguished but not pp and $p\gamma$

Breaking the Limitation of the 3-Flavor Measurements



Accelerated cosmic ray beam (p) + gas(p)/ radiation(γ)

Hadronuclear $p + p \to n_\pi \left[\pi^0 + \pi^+ + \pi^-\right]$

Uniform distribution of all charges

Photohadronic $p + \gamma \to \Delta^+ \to \pi^+ + n$

Dominating π^+

$$\begin{cases} \pi^+ \to \nu_\mu + \mu^+ \to \nu_\mu + \left(e^+ + \nu_e + \bar{\nu}_\mu\right) \\ \pi^- \to \bar{\nu}_\mu + \mu^- \to \bar{\nu}_\mu + \left(e^- + \bar{\nu}_e + \nu_\mu\right) \end{cases}$$

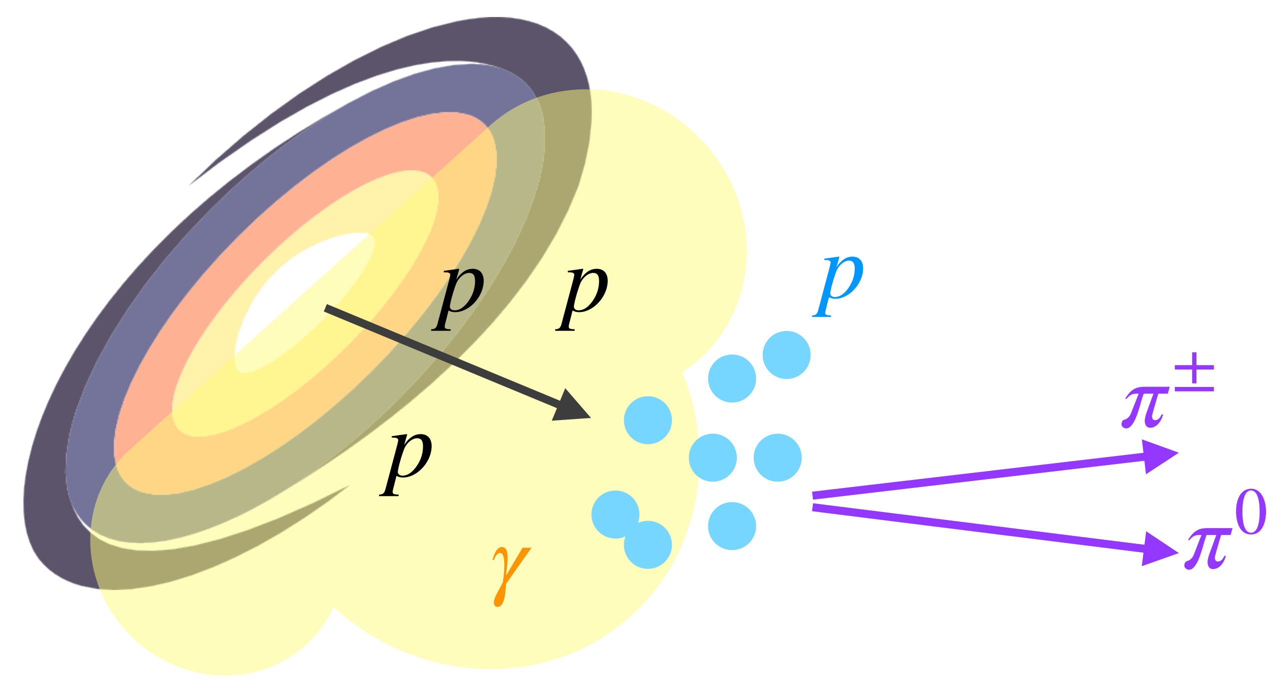
standard mixing

	$\{f_{\nu_e,s}, f_{\bar{\nu}_e,s}\} : \{f_{\nu_\mu,s}, f_{\bar{\nu}_\mu,s}\} : \{f_{\nu_\tau,s}, f_{\bar{\nu}_\tau,s}\}$	$\longrightarrow$	$\{f_{\nu_e,\oplus}, f_{\bar{\nu}_e,\oplus}\} : \{f_{\nu_\mu,\oplus}, f_{\bar{\nu}_\mu,\oplus}\} : \{f_{\nu_\tau,\oplus}, f_{\bar{\nu}_\tau,\oplus}\}$
pp	$\{1,1\} : \{2,2\} : \{0,0\}$		$\{0.17, 0.17\} : \{0.17, 0.17\} : \{0.16, 0.16\}$
$p\gamma$	$\{1,0\} : \{1,1\} : \{0,0\}$		$\{0.26, 0.08\} : \{0.21, 0.13\} : \{0.20, 0.13\}$
pp μ damped	$\{0,0\} : \{1,1\} : \{0,0\}$		$\{0.11, 0.11\} : \{0.20, 0.20\} : \{0.19, 0.19\}$
$p\gamma$ μ damped	$\{0,0\} : \{1,0\} : \{0,0\}$		$\{0.23, 0.00\} : \{0.39, 0.00\} : \{0.38, 0.00\}$

Differentiating ν and $\bar{\nu}$

pp and $p\gamma$ can be distinguished

Breaking the Limitation of the 3-Flavor Measurements



Accelerated cosmic ray beam (p) + gas(p)/ radiation(γ)

Hadronuclear	$p + p \rightarrow n_\pi \left[\pi^0 + \pi^+ + \pi^-\right]$	Uniform distribution of all charges
Photohadronic	$p + \gamma \rightarrow \Delta^+ \rightarrow \pi^+ + n$	Dominating π^+

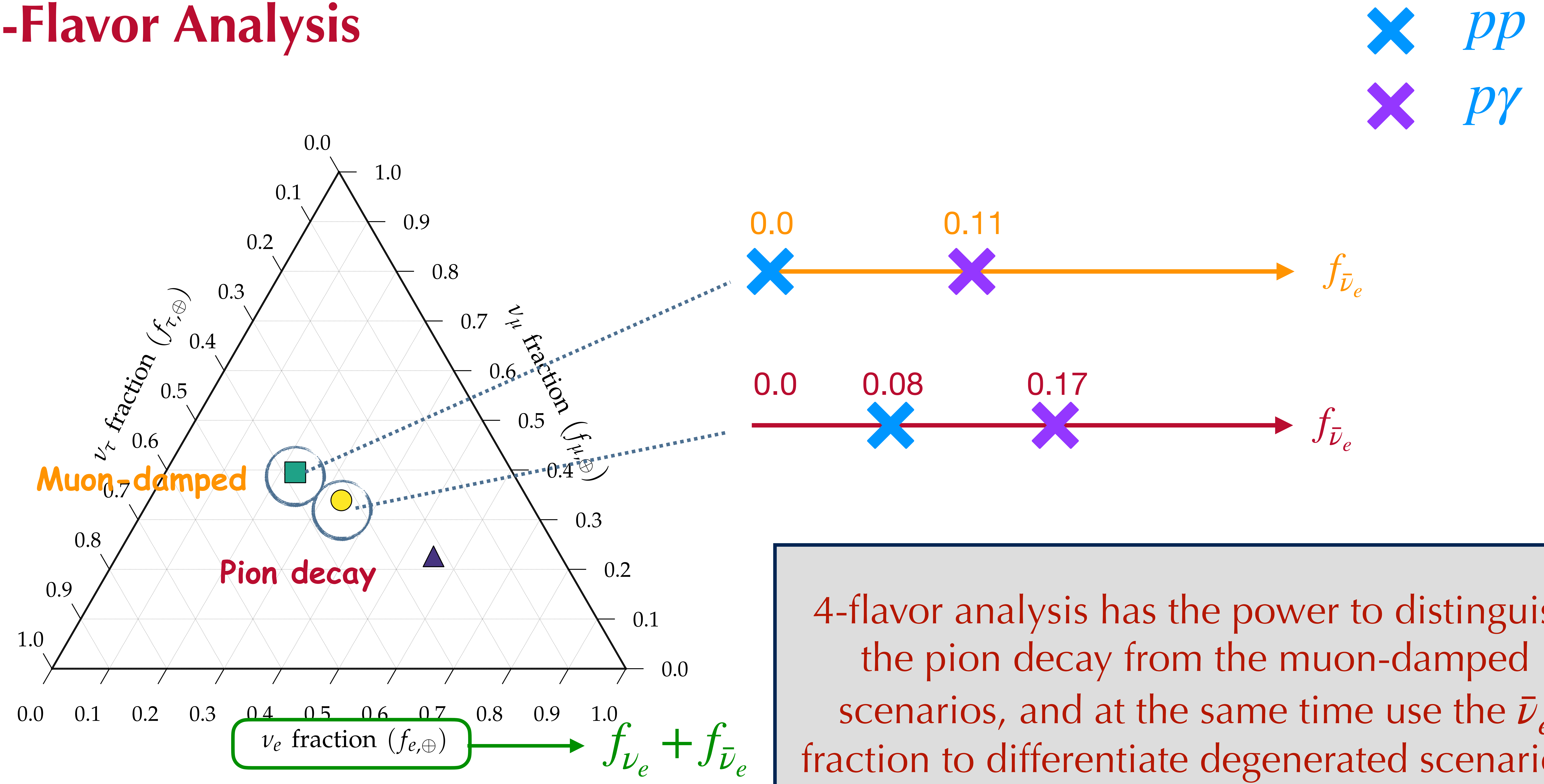
$\bar{\nu}_e$ fraction can be used to differentiate the production mechanisms at sources.

		$, f_{\bar{\nu}_\mu,\oplus}\} : \{f_{\nu_\tau,\oplus}, f_{\bar{\nu}_\tau,\oplus}\}$
pp	$\{1,1\} : \{2,2\} : \{0,0\}$	$\{0.17,0.17\} : \{0.17,0.17\} : \{0.16,0.16\}$
$p\gamma$	$\{1,0\} : \{1,1\} : \{0,0\}$	$\{0.26,0.08\} : \{0.21,0.13\} : \{0.20,0.13\}$
pp μ damped	$\{0,0\} : \{1,1\} : \{0,0\}$	$\{0.11,0.11\} : \{0.20,0.20\} : \{0.19,0.19\}$
$p\gamma$ μ damped	$\{0,0\} : \{1,0\} : \{0,0\}$	$\{0.23,0.00\} : \{0.39,0.00\} : \{0.38,0.00\}$

Differentiating ν and $\bar{\nu}$

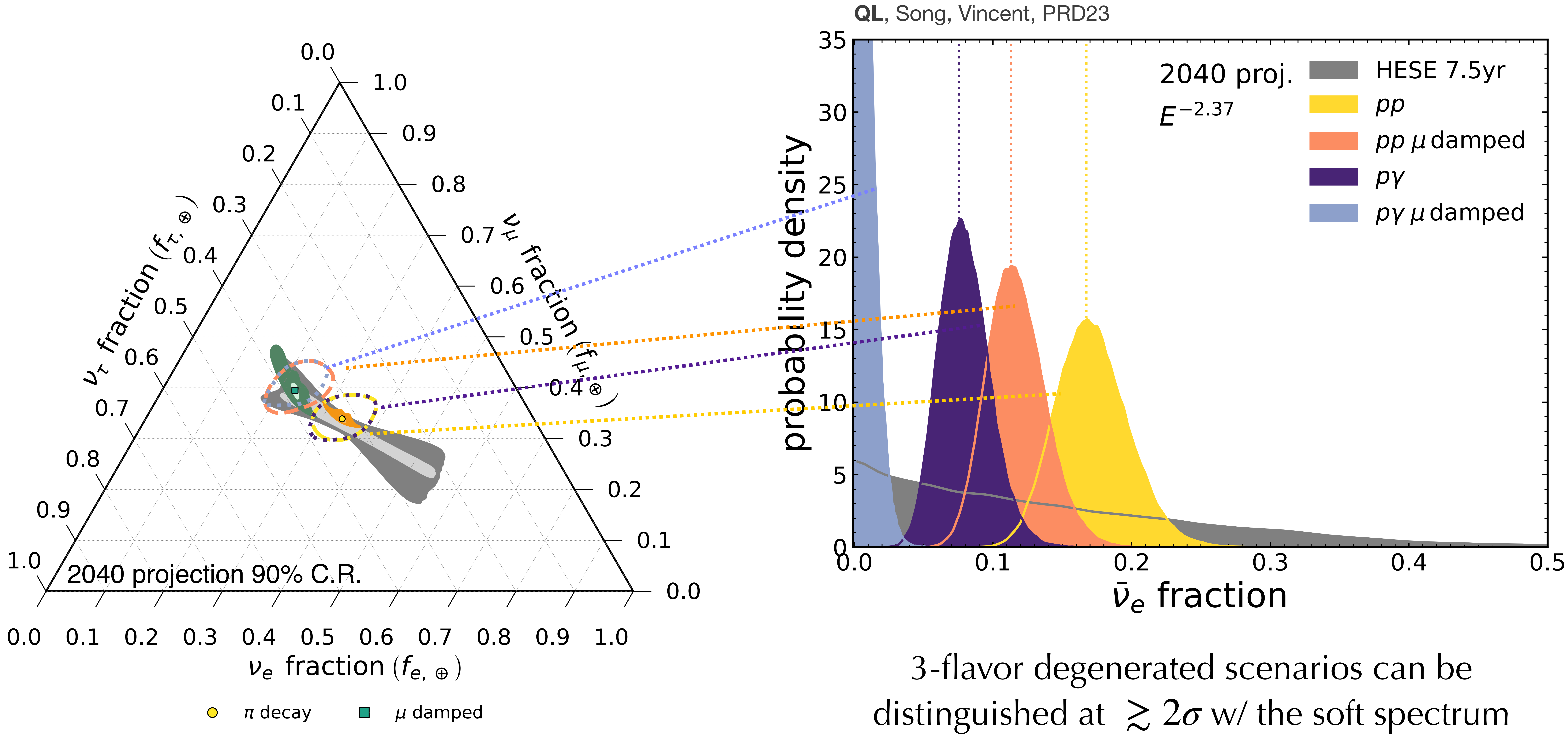
pp and $p\gamma$ can be distinguished

4-Flavor Analysis



4-flavor analysis has the power to distinguish the pion decay from the muon-damped scenarios, and at the same time use the $\bar{\nu}_e$ fraction to differentiate degenerated scenarios.

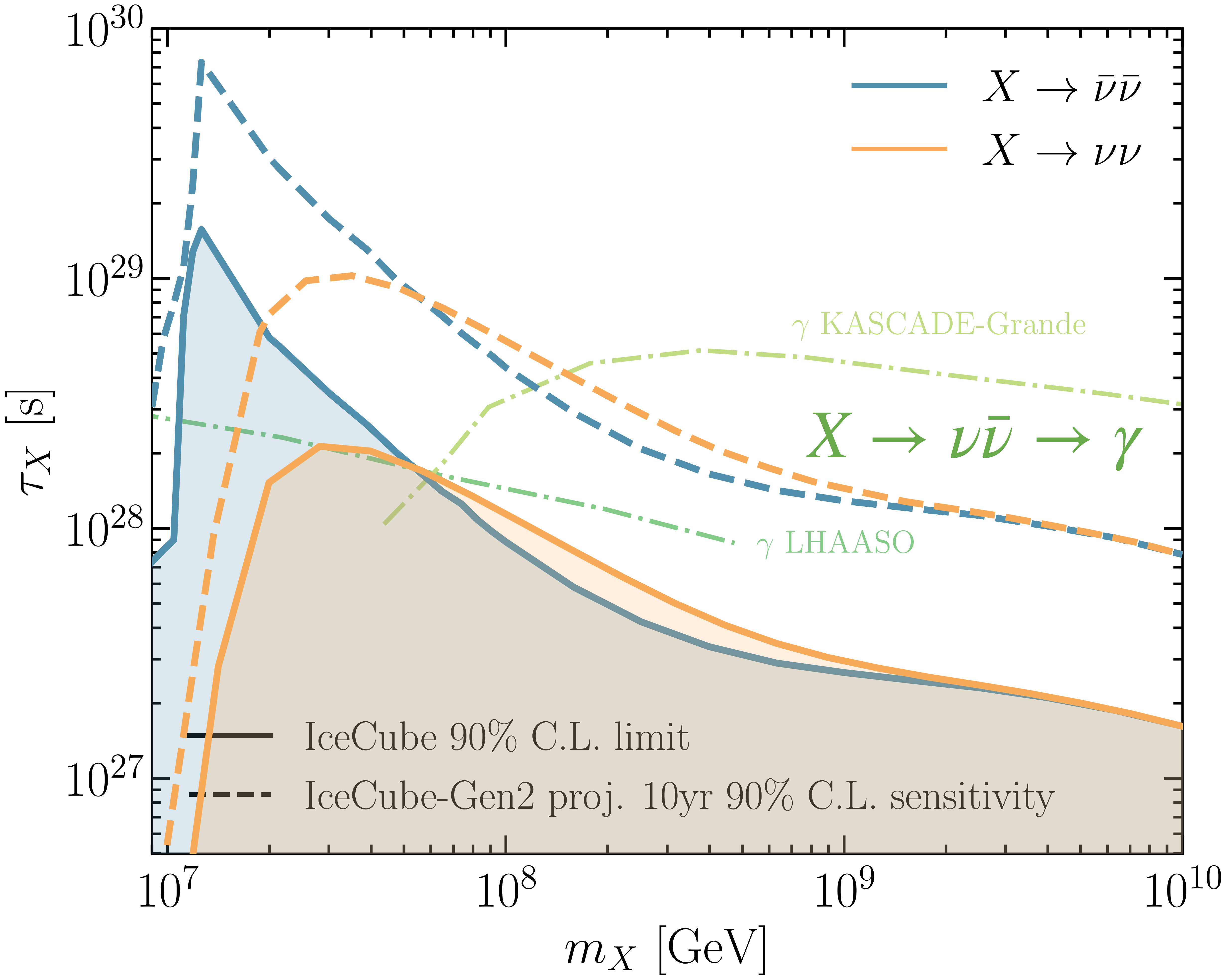
4-Flavor Analysis



3-flavor degenerated scenarios can be distinguished at $\gtrsim 2\sigma$ w/ the soft spectrum assumption and $\gtrsim 4\sigma$ w/ the hard spectrum assumption.

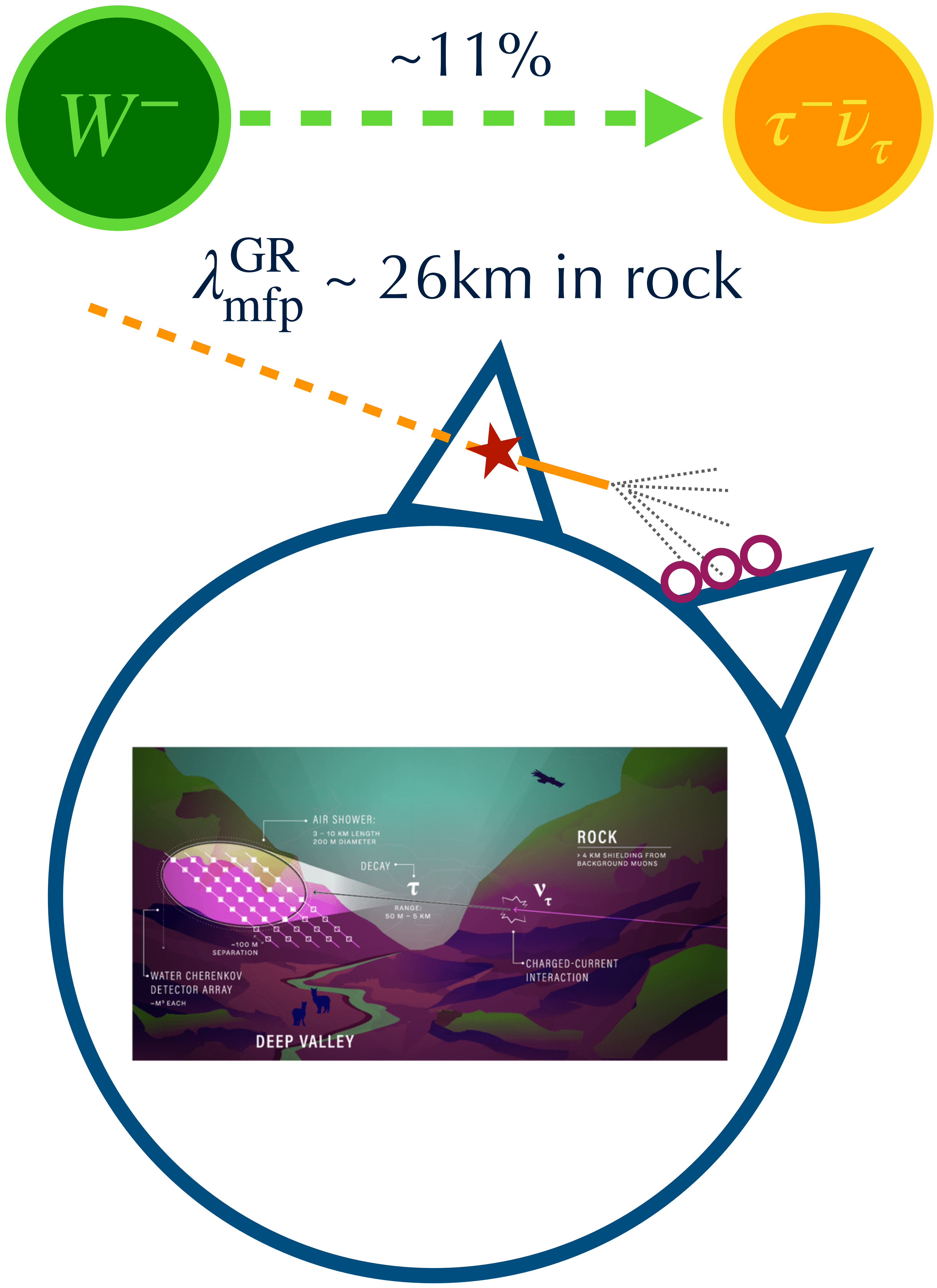
New Physics? Dark Matter Decays to Neutrinos

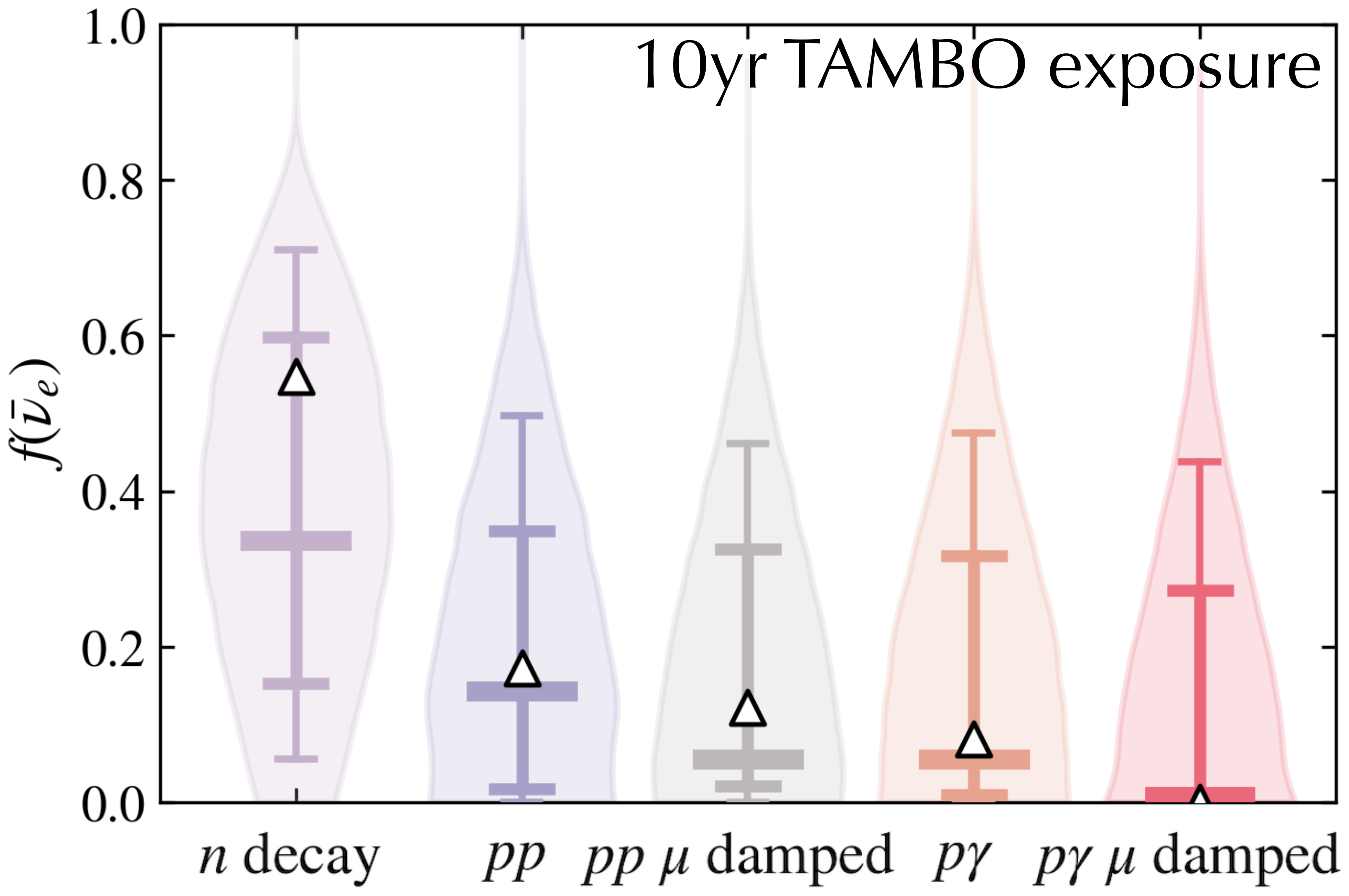
- Heavy dark matter (>PeV) decay to neutrinos produces an additional flux from electroweak showering.
- The ν or $\bar{\nu}$ flux in the Glashow resonance window is different from asymmetric decay to $\nu\nu$ vs $\bar{\nu}\bar{\nu}$.

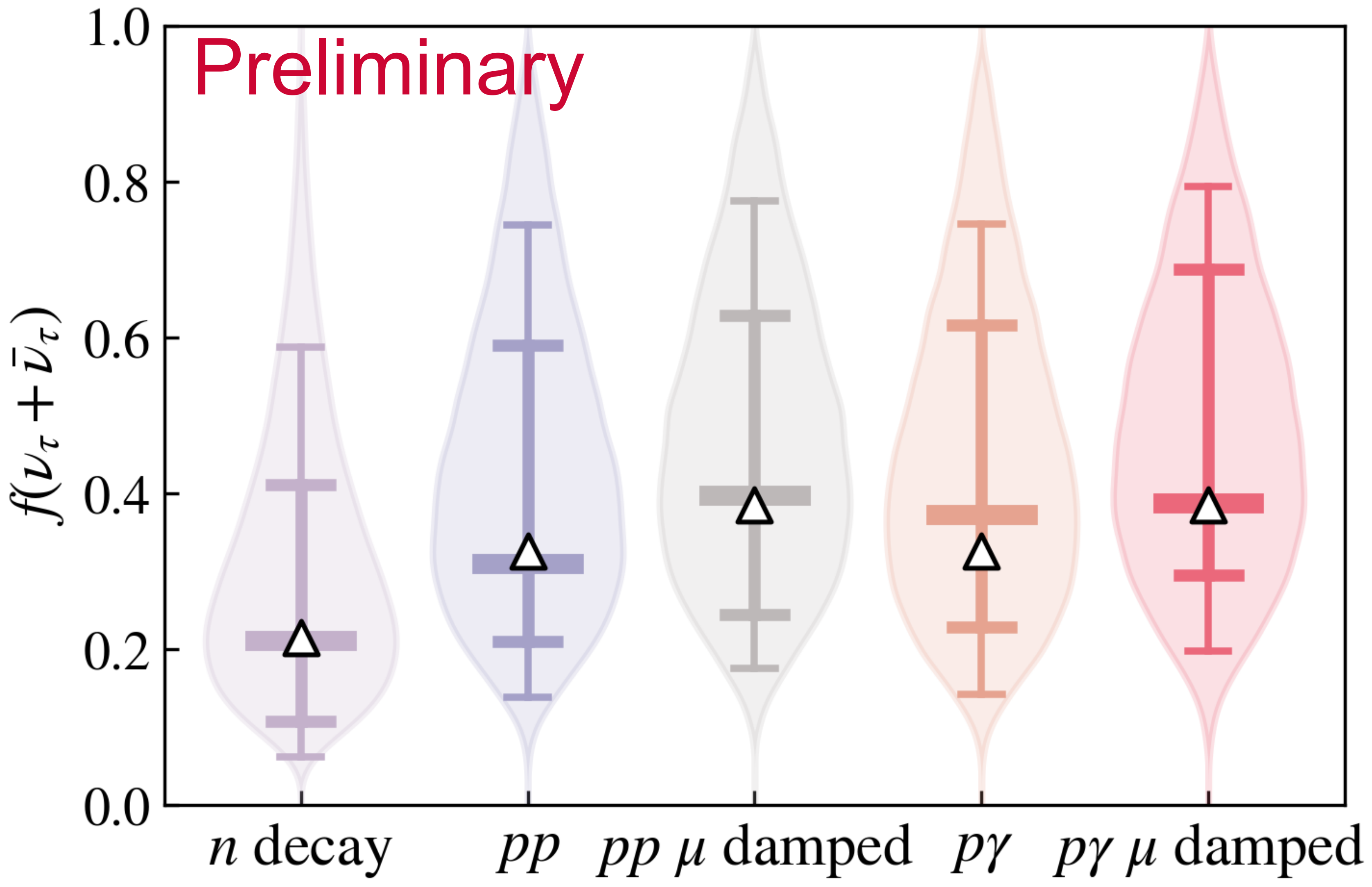


QL, Song, Vincent PRD25

Glashow Resonance in Tau Air Shower Neutrino Telescopes







- Flavor composition can be determined at ~20% for 1σ. A large $\bar{\nu}_e$ fraction can be excluded.
- May be combined with ice/water Cherenkov telescope flavor measurements for a complementary improvement.

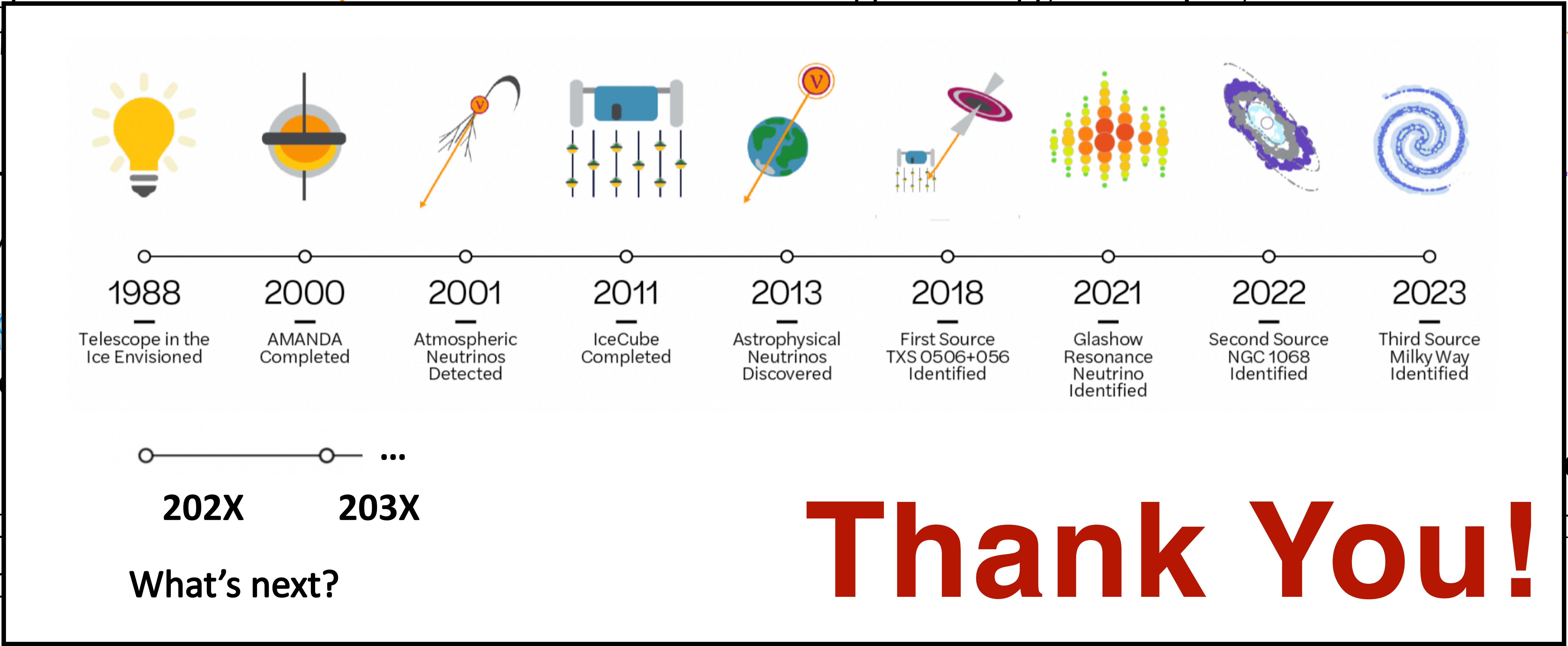
Huang & **QL** JCAP20
Ding, **QL**, in prep

Summary

- There are Fruitful results of the high-energy astrophysical neutrino observation in recent years.
- Measuring the flavor composition of the diffuse high-energy astrophysical neutrino flux reveals information about neutrino production mechanisms at the sources, propagation of neutrinos along cosmological distances, and interactions at detection.
- The flavor composition provides the only probe of standard and non-standard neutrino mixing above TeV.
- Energy dependence is expected to be present in the flavor composition due to both astrophysical processes and new physics.
- The observation of Glashow Resonant events provides the possibility of breaking the degeneracy of neutrinos and antineutrinos in flavor measurements, which helps further examine different models.
- The next-generation neutrino telescopes with larger exposure and better reconstruction techniques will significantly improve the sensitivities of flavor measurements in the future.

Summary

- There are Fruitful results of the high-energy astrophysical neutrino observation in recent years.
- Measuring the flavor composition of the diffuse high-energy astrophysical neutrino flux reveals int tion of neutrinos
- The flavor ino mixing above TeV
- Energy de astrophysi
- The obser e degenerac ther examine c



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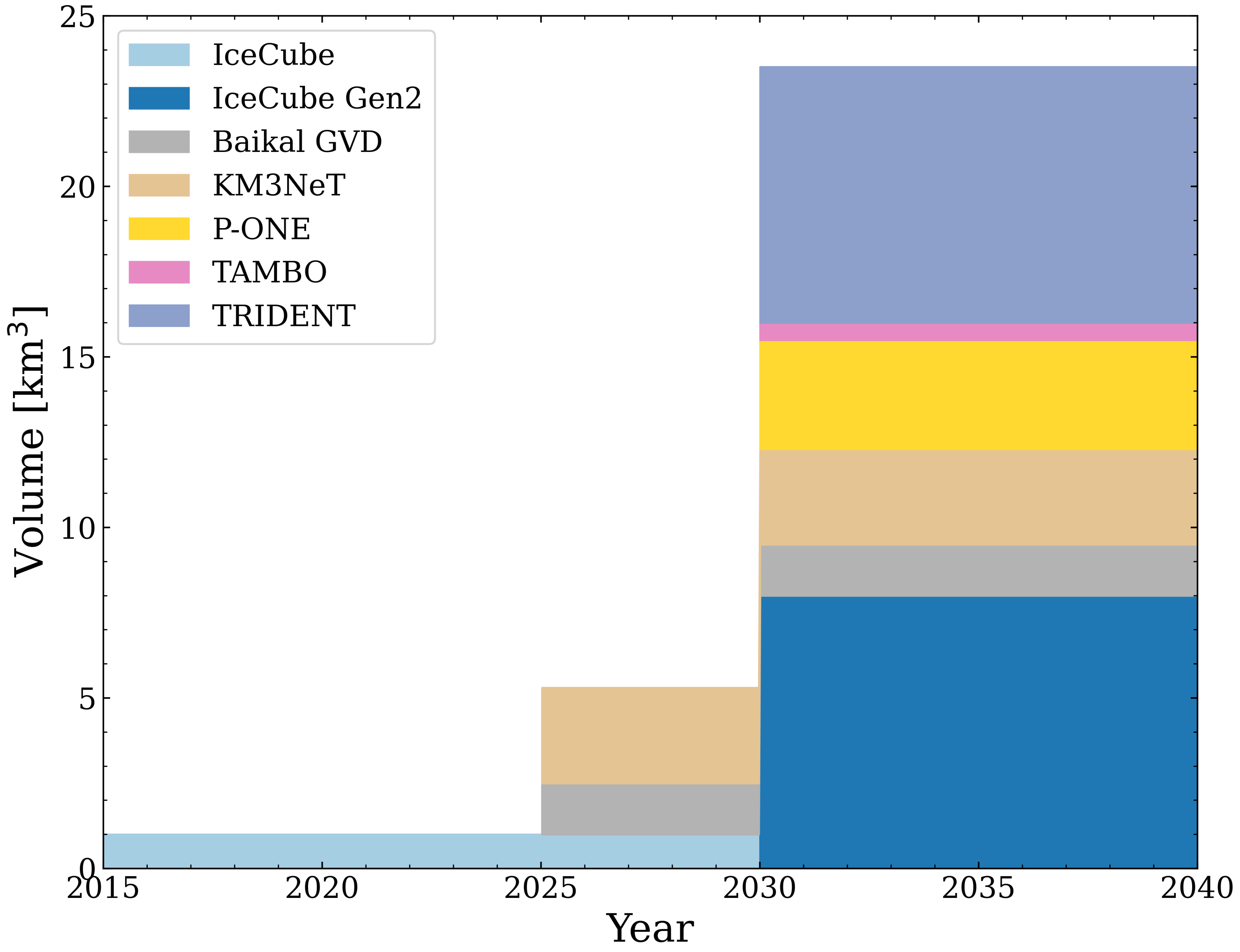
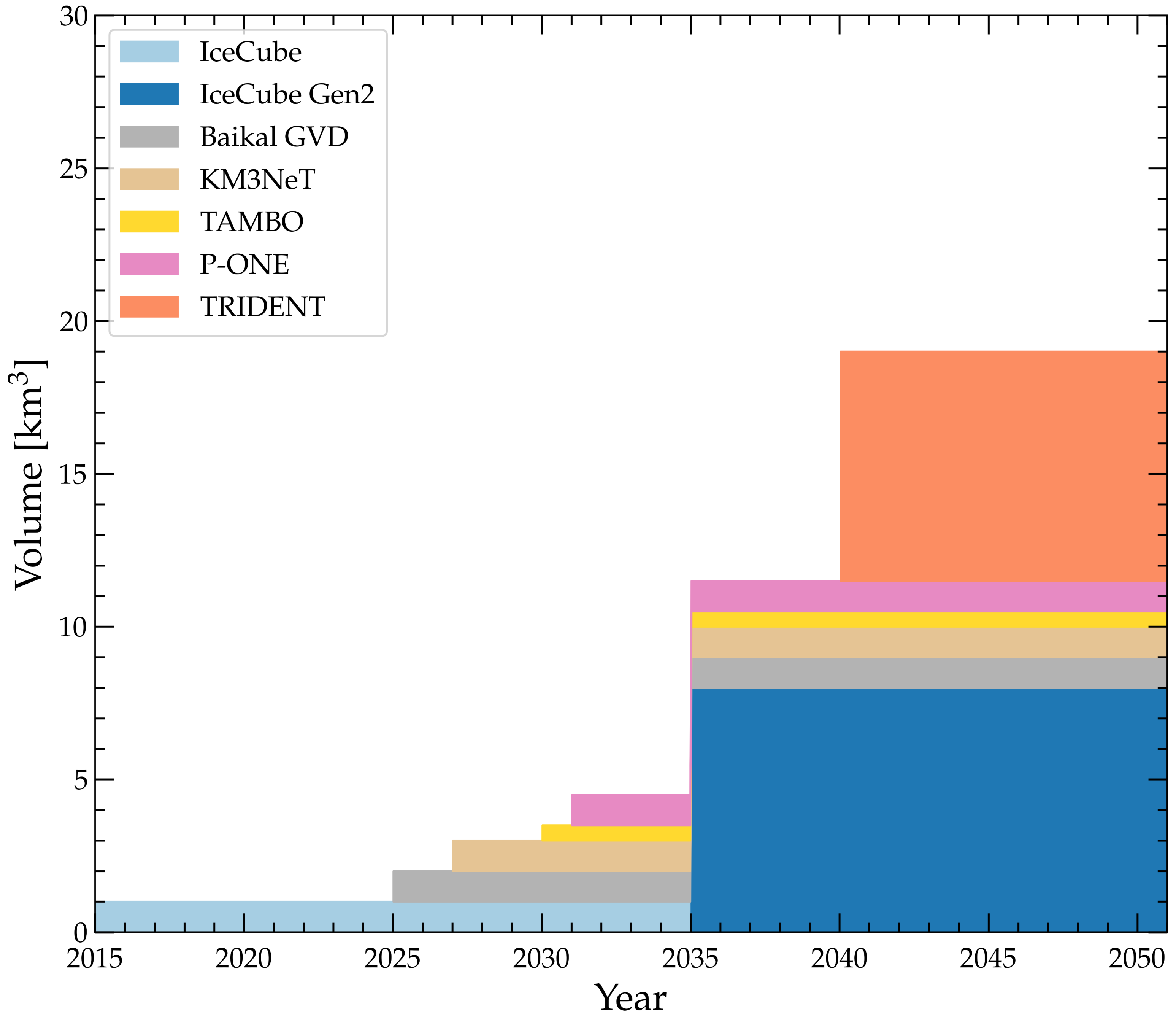
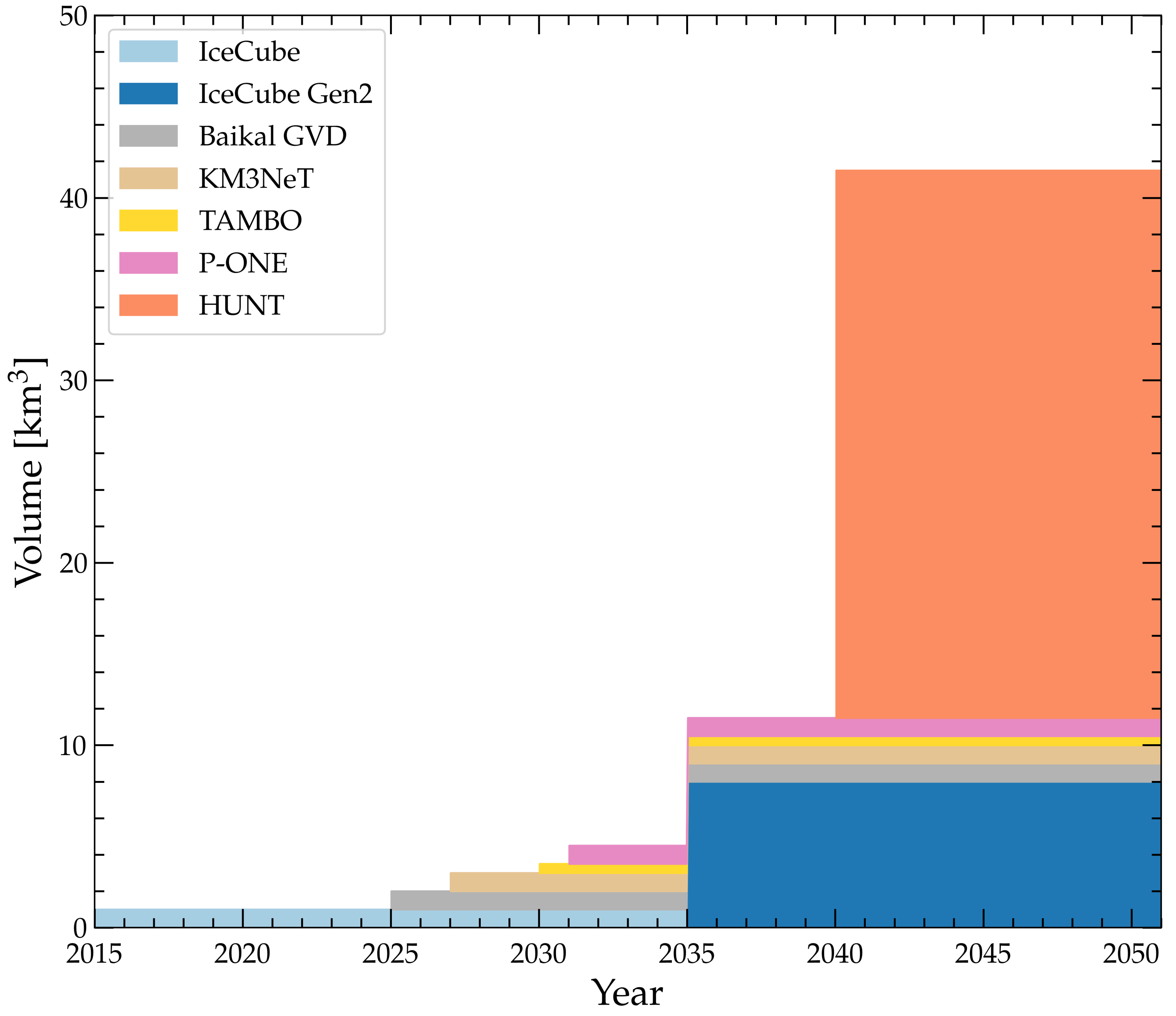
Bonus Slides

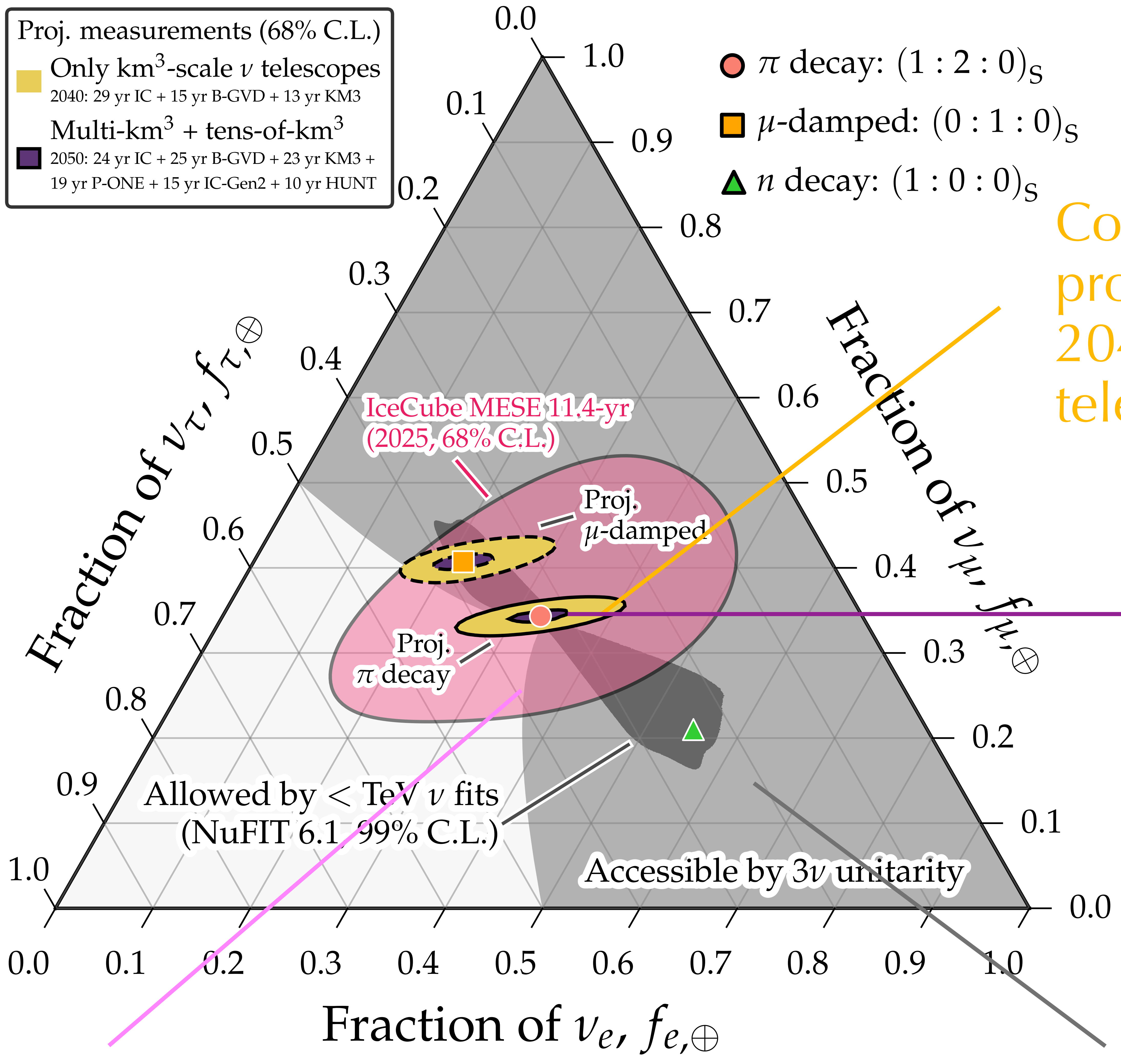
Timeline vs Telescope Volume







Current and Future Measurements



Conservative projection to 2040: running telescopes only.

Aggressive projection to 2050: proposed telescopes will be built with the largest exposure.

Reconstruction capability limits further improvement.

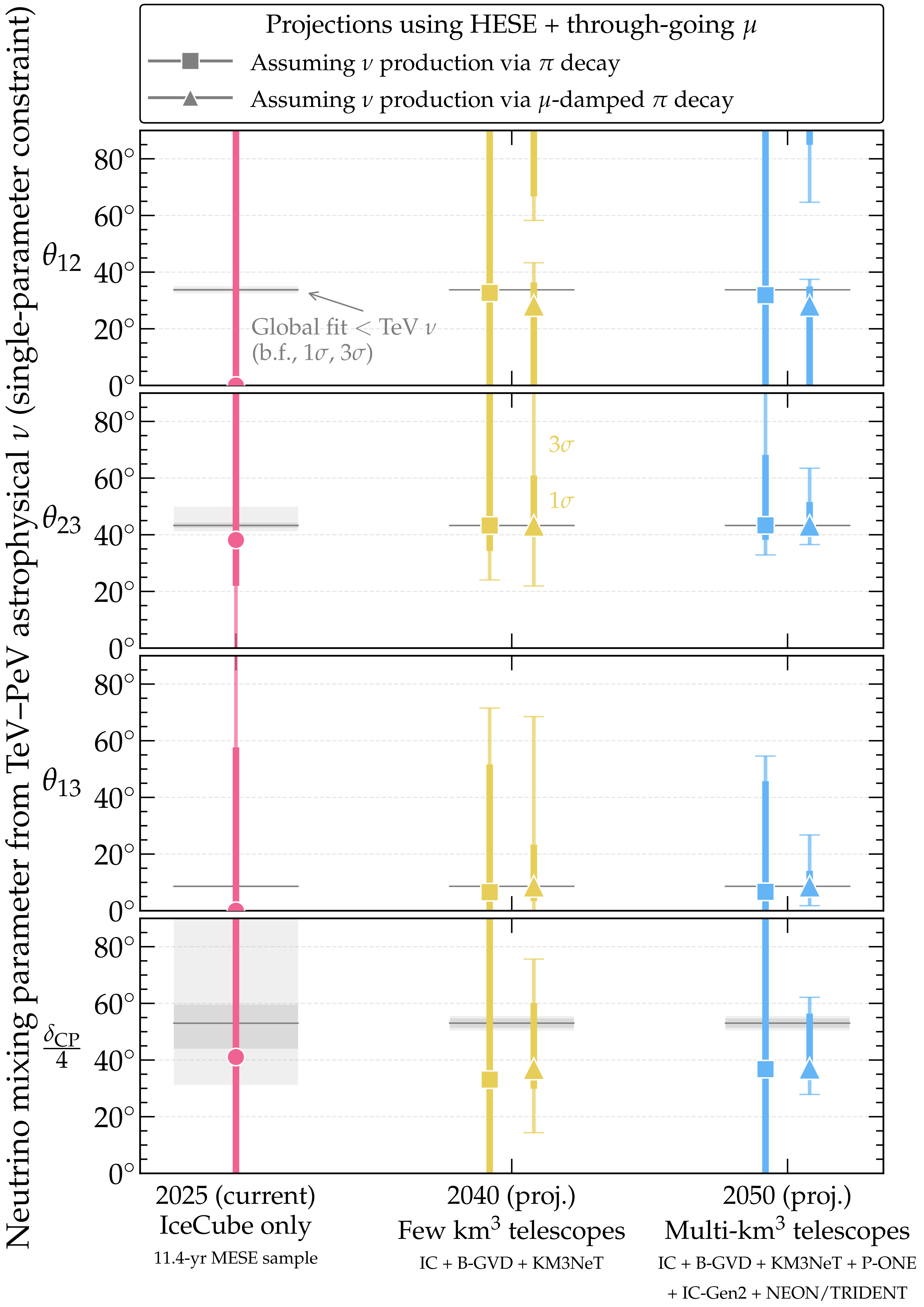
Most recent measurement

Spans the entire physically allowed range of the parameters while preserving the unitarity of flavor transitions.

- Projection based on MC simulations with current reconstruction capability included.
- Two event selections are combined to optimize the sensitivity:

high-energy starting events (HESE) (all-flavor all-sky high-energy starting events) & through-going muon tracks (TGM) (upgoing ν_μ events with vertices outside the detector).

Implication of the Future Flavor Measurement

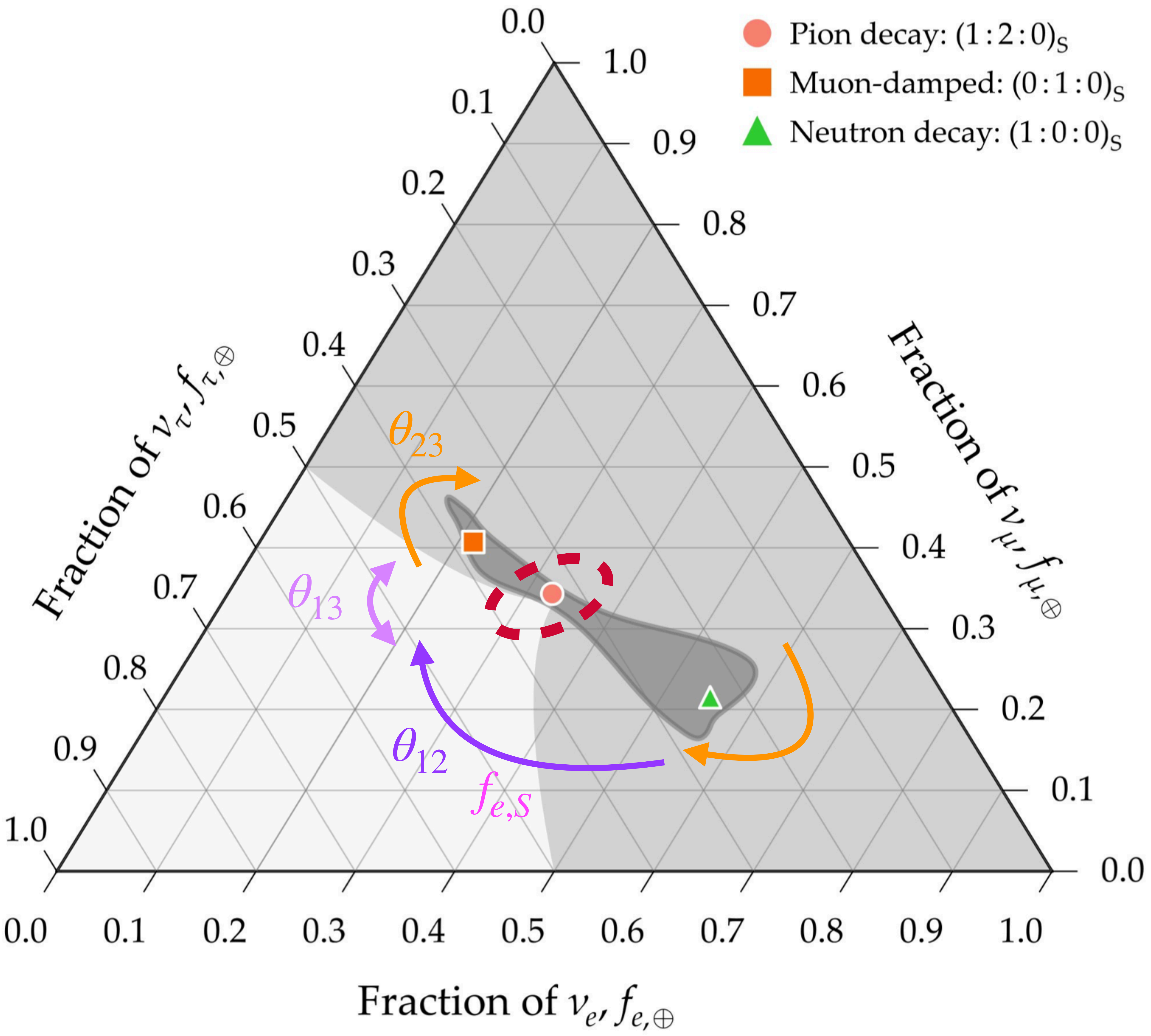


Future flavor identification improvement ~ mixing parameters

- ν_μ and ν_τ: better θ_{23} , θ_{13} (and δ_{CP} assuming the muon-damped case)
- ν_e: θ_{12}, but a free source composition can mimic the θ_{12} effect when measuring on Earth.

This level of sensitivity will be enough to constrain certain BSM scenarios that posit modifications to neutrino mixing and flavor ratios at Earth.
e.g., Lorentz-invariance violation, sterile neutrino mixings, and non-standard neutrino interactions.

Flavor Composition vs Sensitivity to Different Parameters



Bayes Factors

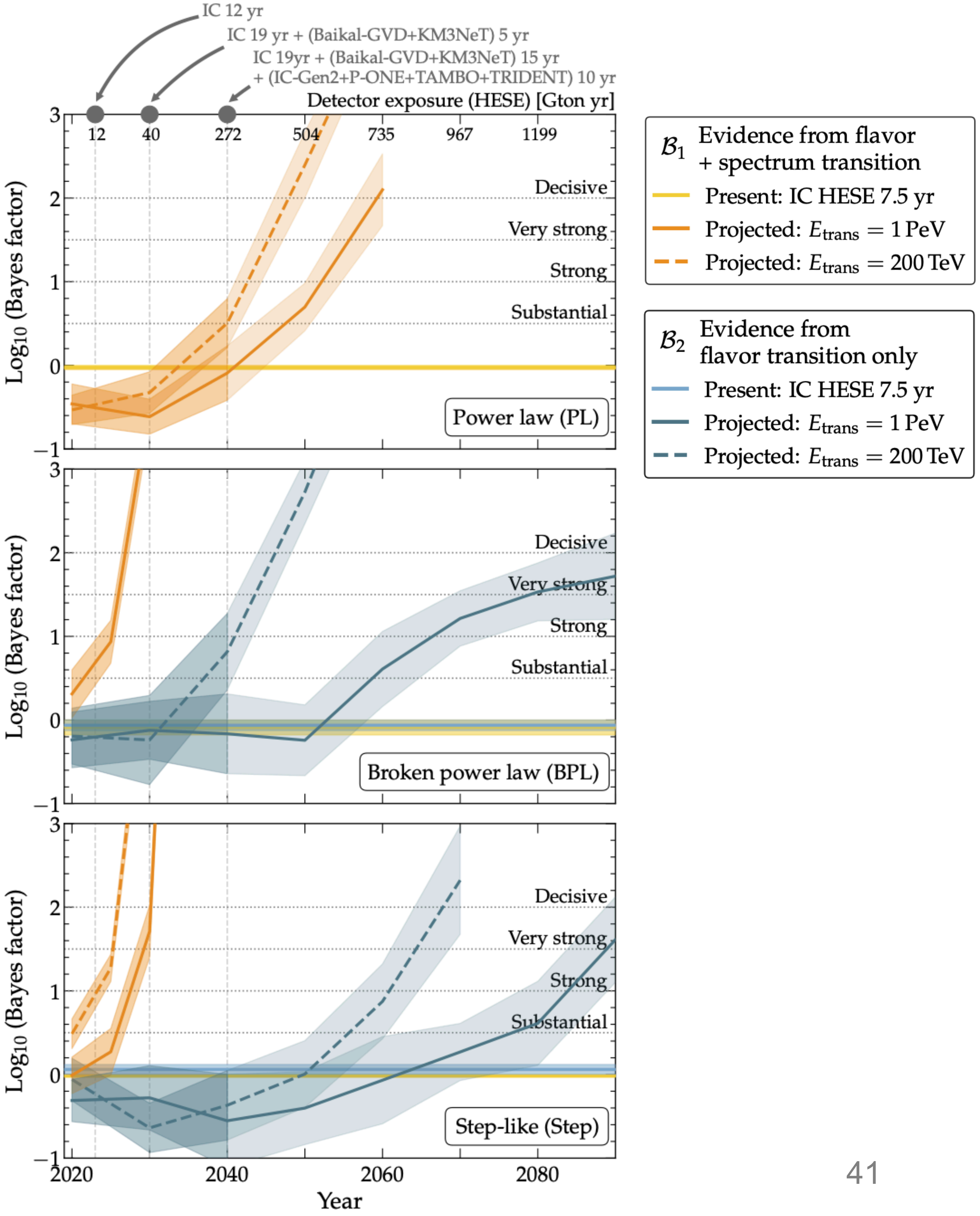
Evidence: $$\mathscr{Z} = \int \mathscr{L}(N_{obs}|\Theta) \times \pi(\Theta) d\Theta$$

Bayes factor: $$\mathscr{B} = \mathscr{Z}_1 / \mathscr{Z}_2$$

Current data indicate no preference.

From flavor + spectrum transition 😀

From flavor transition only 🤔

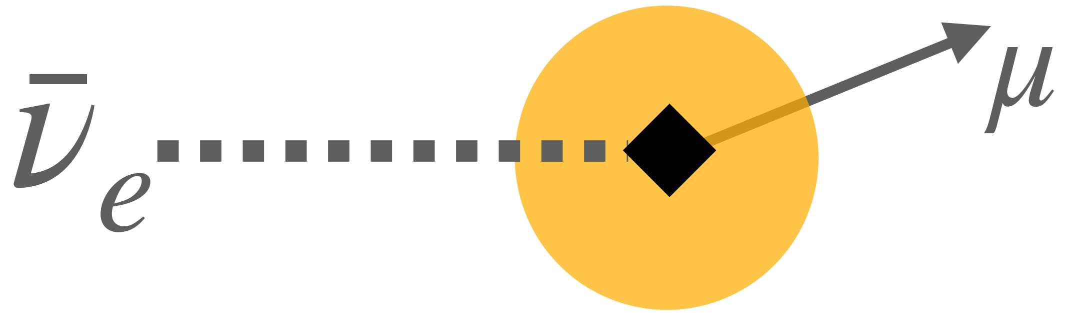


Event Level Identification in a Cherenkov Detector

$$W^- \rightarrow \text{hadrons}$$

BR ~67 %

✔ escaping muons, the only irreducible background is from NCDIS events which are suppressed

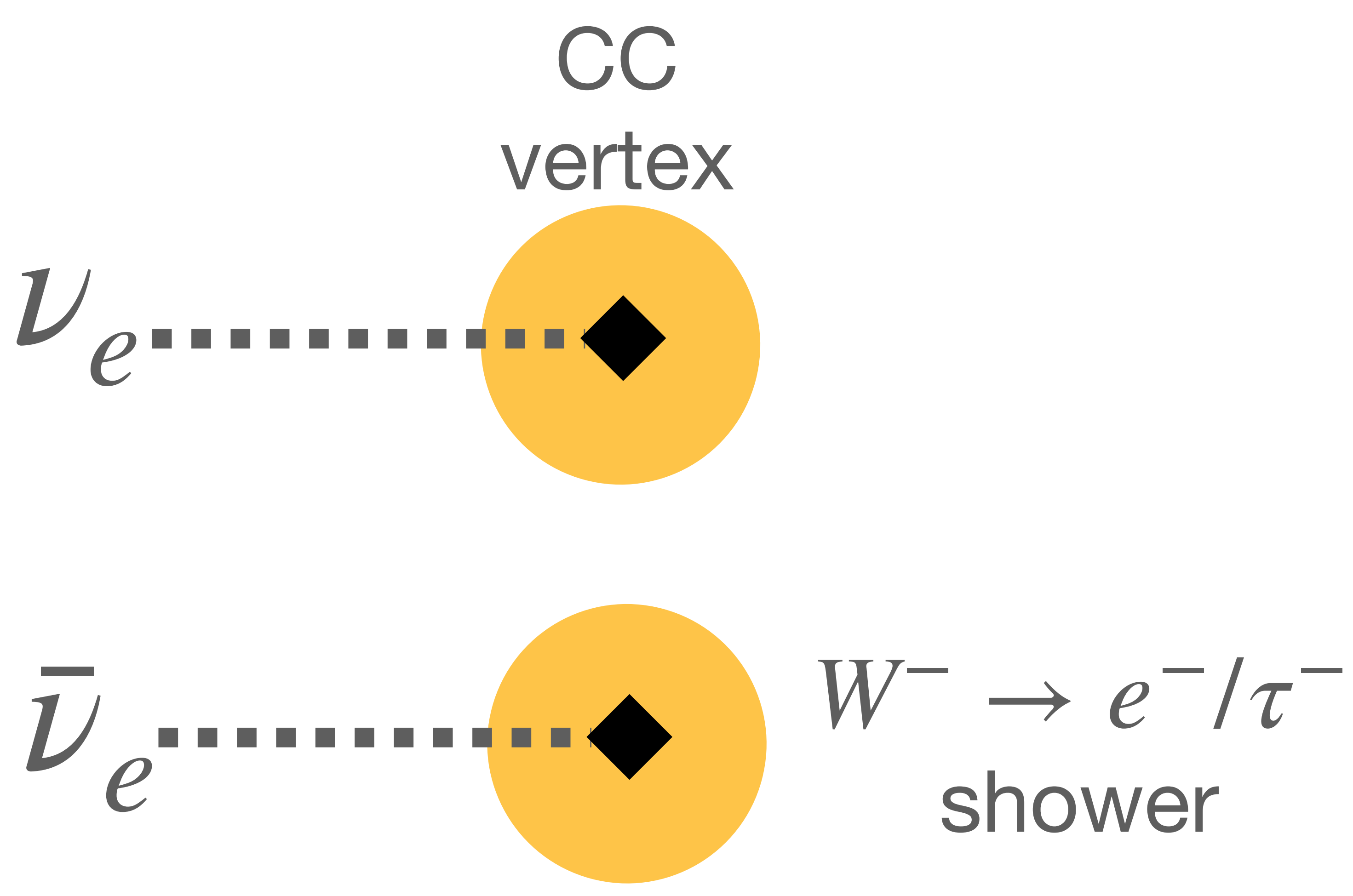


Main cascade + escaping muons

$$W^- \rightarrow e^-\bar{\nu}_e/\tau^-\bar{\nu}_\tau$$

BR ~11 %

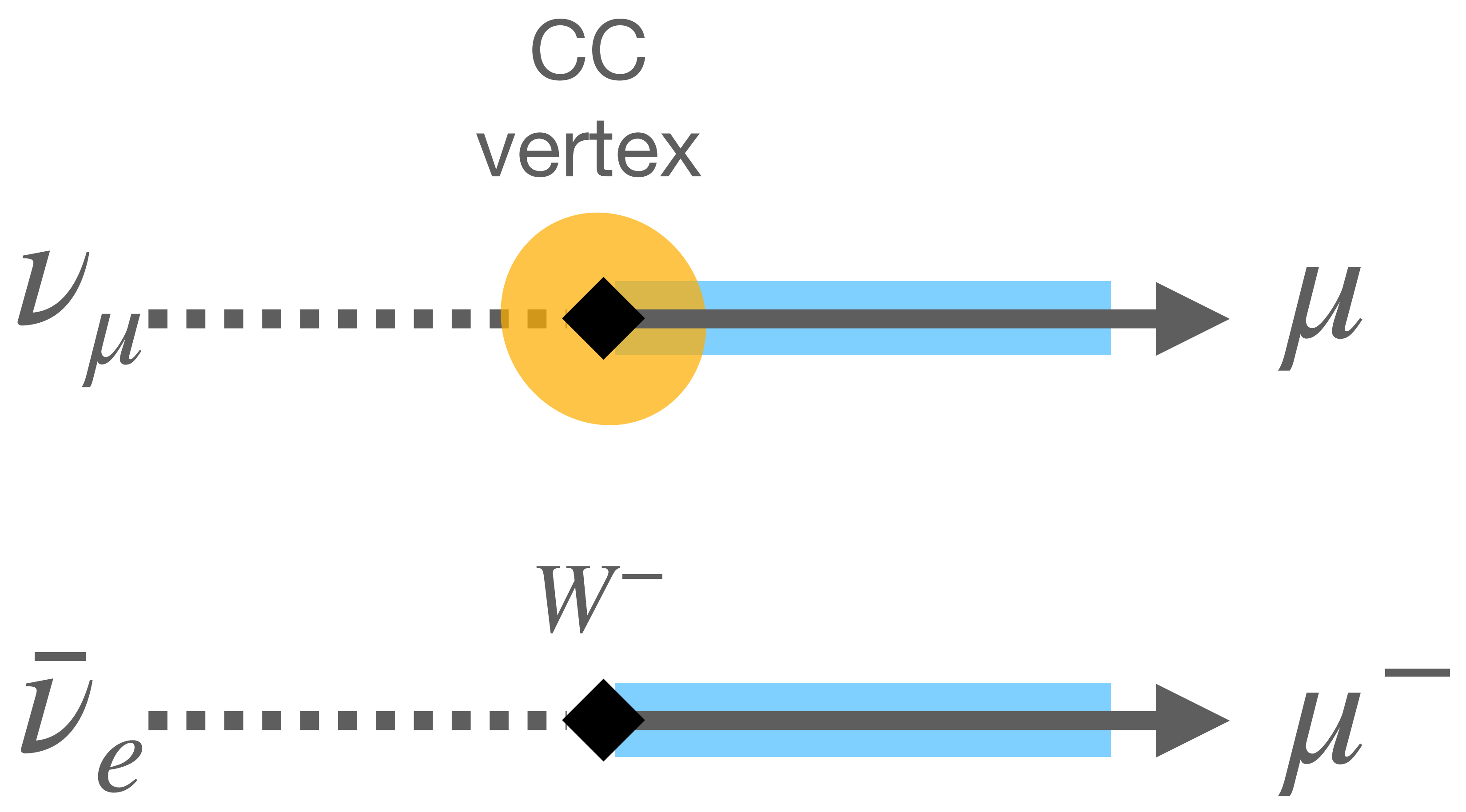
✖ Difficult to distinguish from a ν_e DIS cascade



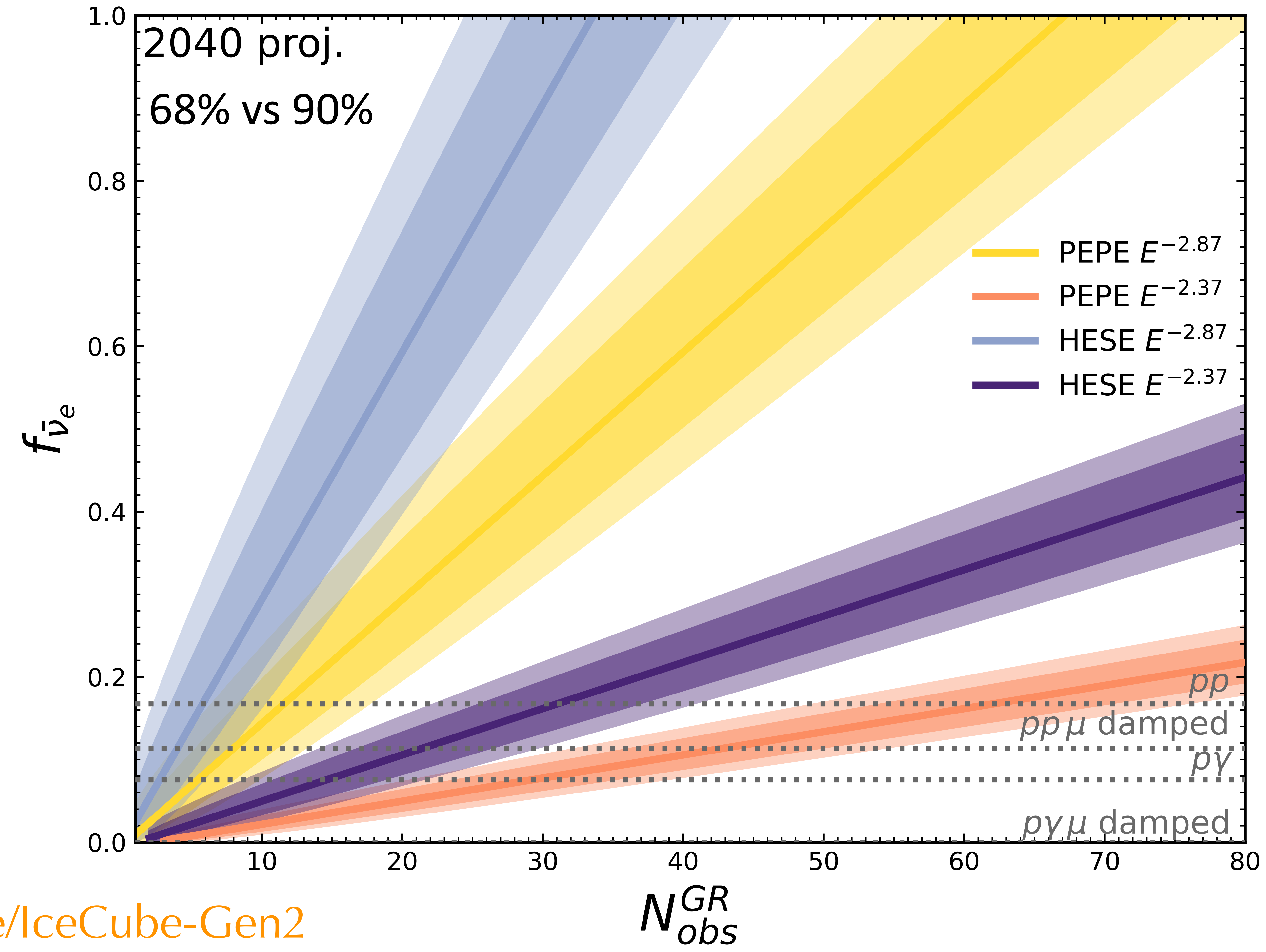
$$W^- \rightarrow \mu^-\bar{\nu}_\mu$$

BR ~11 %

✔ a track without the initial cascade compared to ν_μ CCDIS tracks



Event Level Identification & Constraints



The case where Glashow resonant events can be identified on an event-by-event basis in the [4,10] PeV deposited energy window. Only consider $\bar{\nu}_e$ fraction.

90% CL constraints on current observation:

Hard spectrum $E^{-2.37}$: $2\,\% \leq f_{\bar{\nu}_e} \leq 51\,\%$

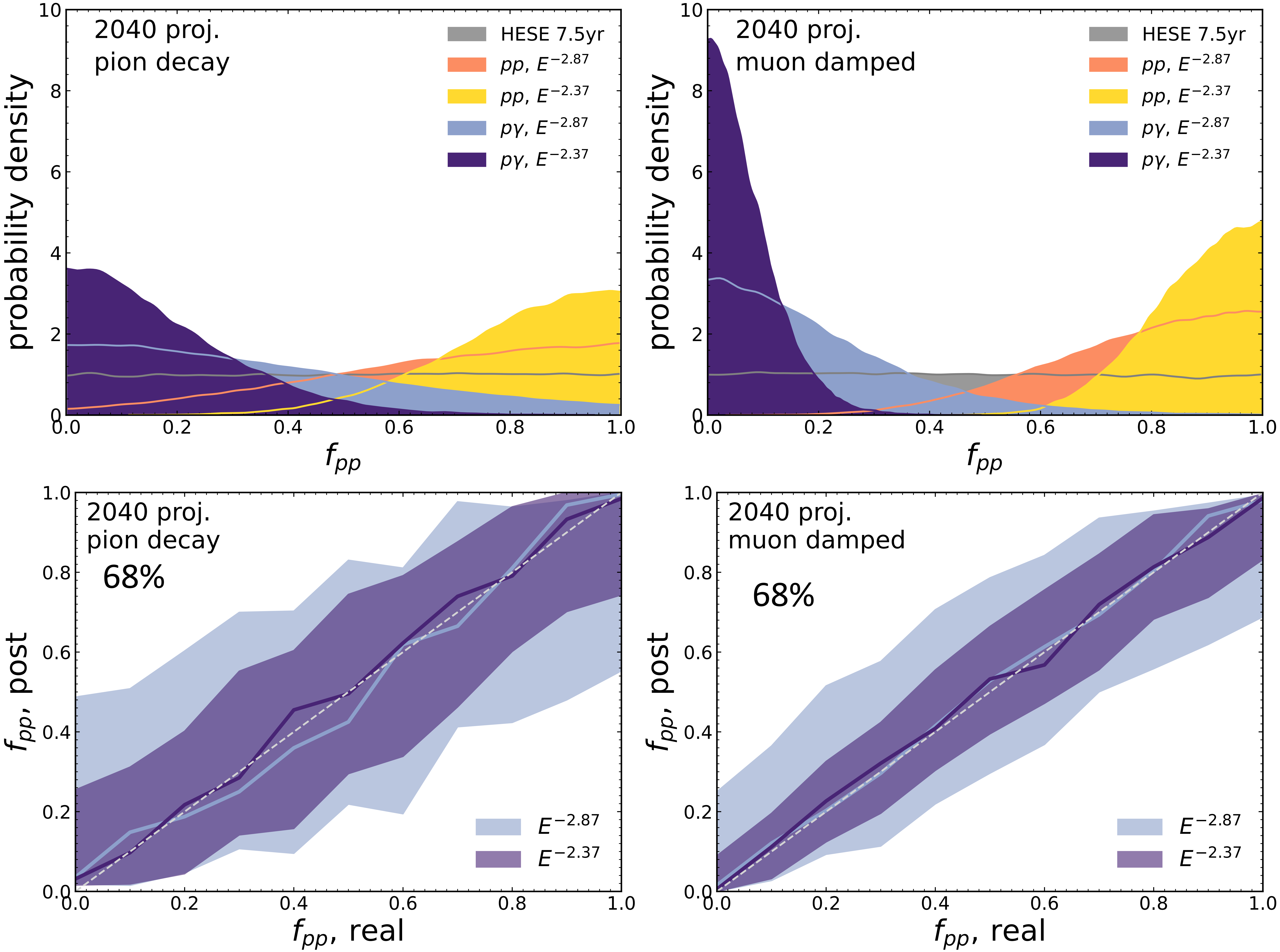
Soft spectrum $E^{-2.87}$: $f_{\bar{\nu}_e} \geq 10\,\%$

IceCube/IceCube-Gen2
+ KM3NeT
+ Baikal-GVD
+ P-ONE
+ TRIDENT

Number of Glashow resonant-like events observed

3-flavor degenerated scenarios can be distinguished at $\gtrsim 2\sigma$ w/ the soft spectrum assumption and $\sim 5\sigma$ w/ the hard spectrum assumption by 2040

Mixture of pp and $p\gamma$

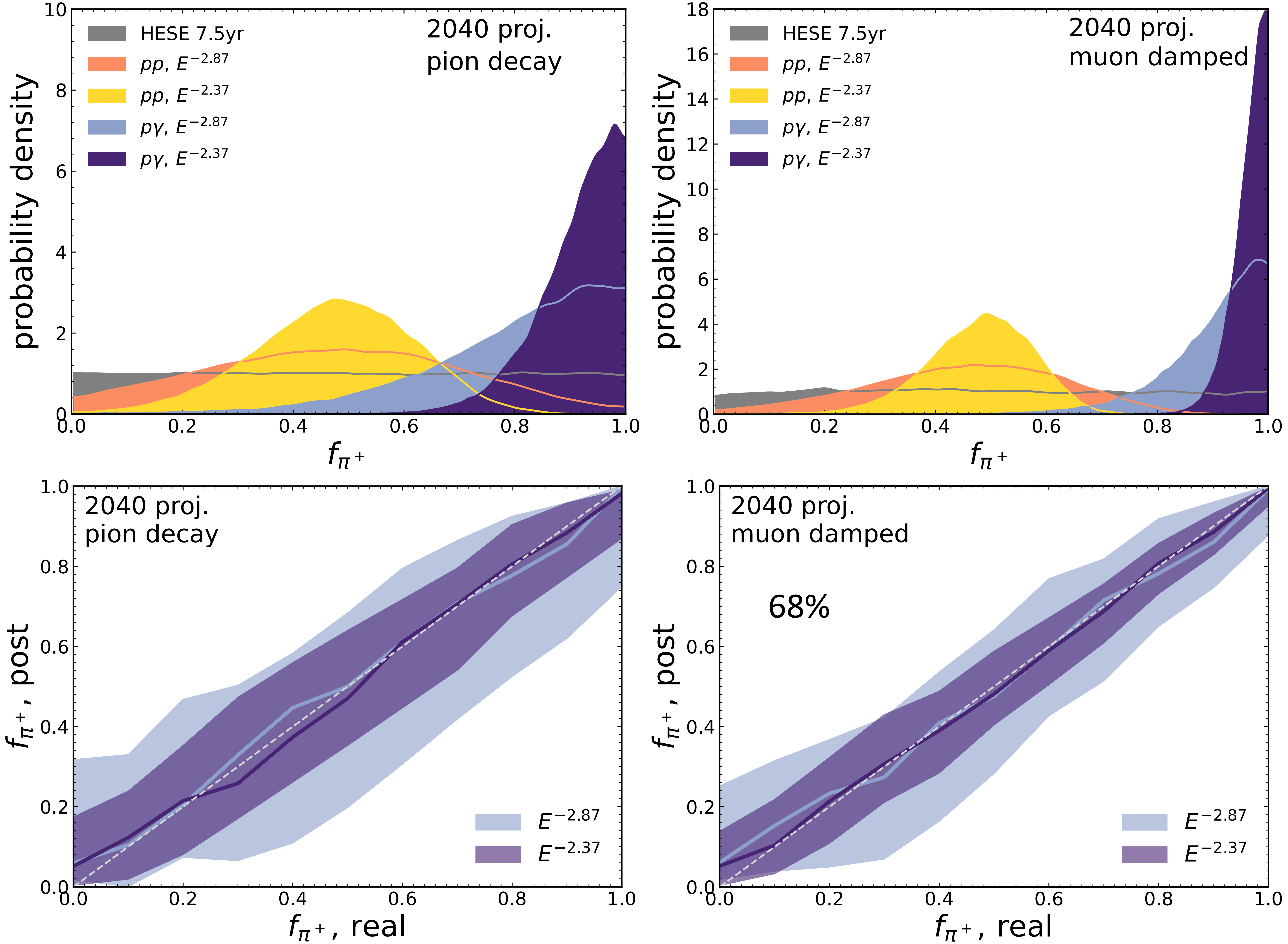


- It is possible that the observed diffuse astrophysical neutrino flux is from a mixed contribution from pp and $p\gamma$.
- If we can determine that the dominating production mechanism is pion decay or muon damped pion decay, how well can we tell a mixed contribution?

What's more can be inferred after breaking the degeneracy?

QL, Song, Vincent, PRD23

Mixture of π^+ and π^-

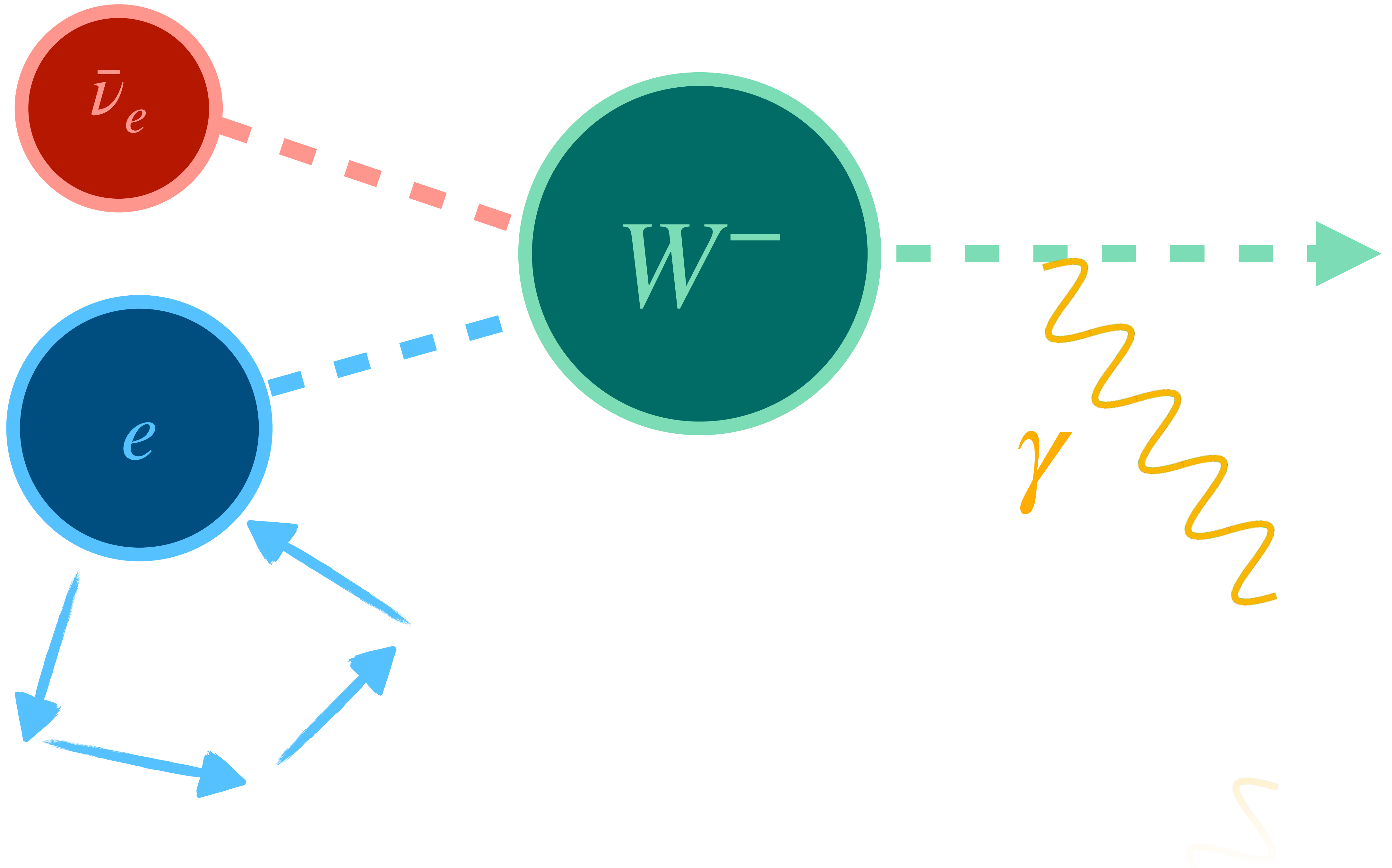


- The charged pion ratios for pp and $p\gamma$ discussed correspond to an ideal case.
- More realistically, the ratio can be affected by e.g. interactions depending on the injecting CRs and targets, the chemical composition of CRs, and other processes such as multi-pion production of $p\gamma$ and $n + \gamma \rightarrow \Delta^0 \rightarrow \pi^- + p$

What's more can be inferred after breaking the degeneracy?

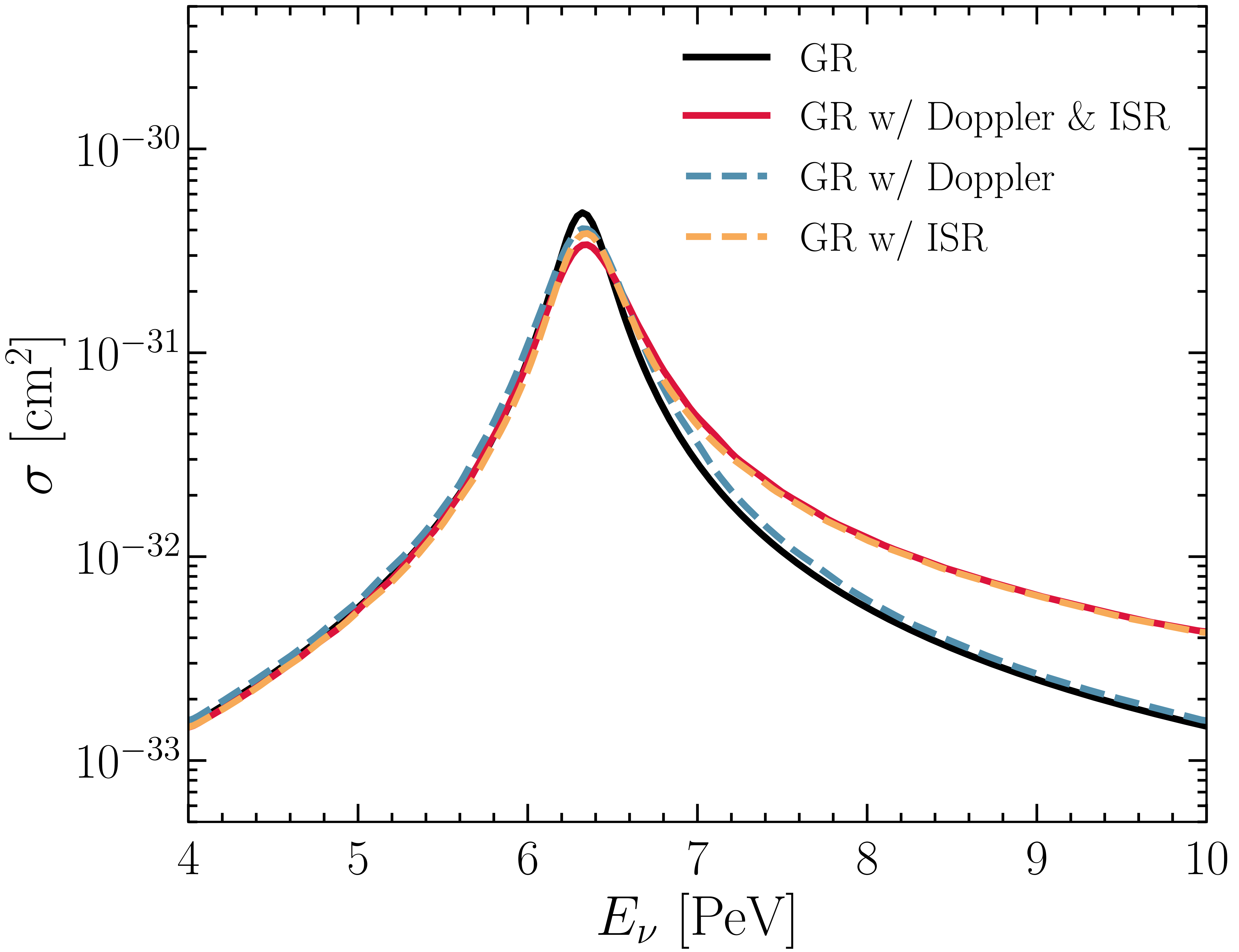
QL, Song, Vincent, PRD23

Updated Cross Section

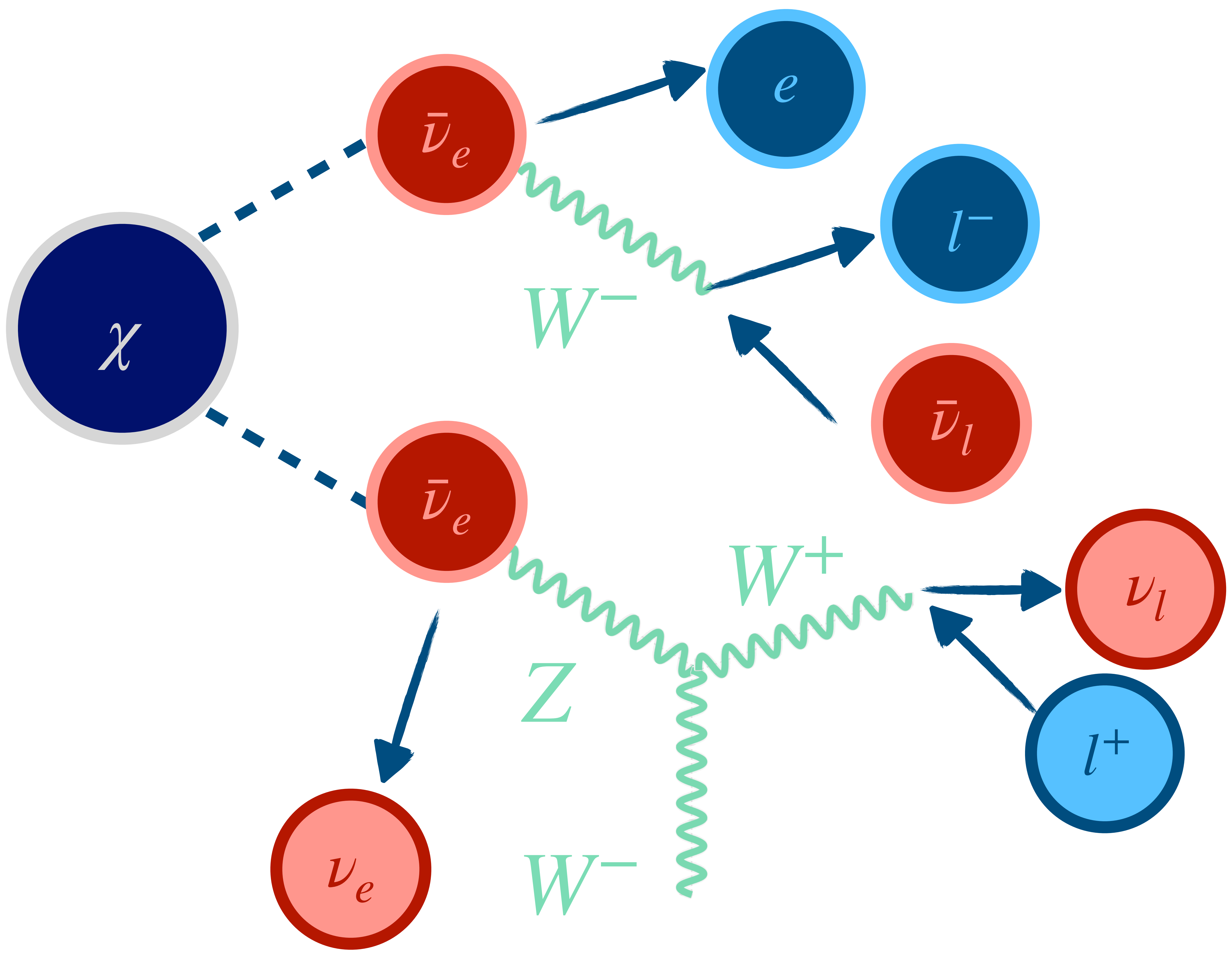


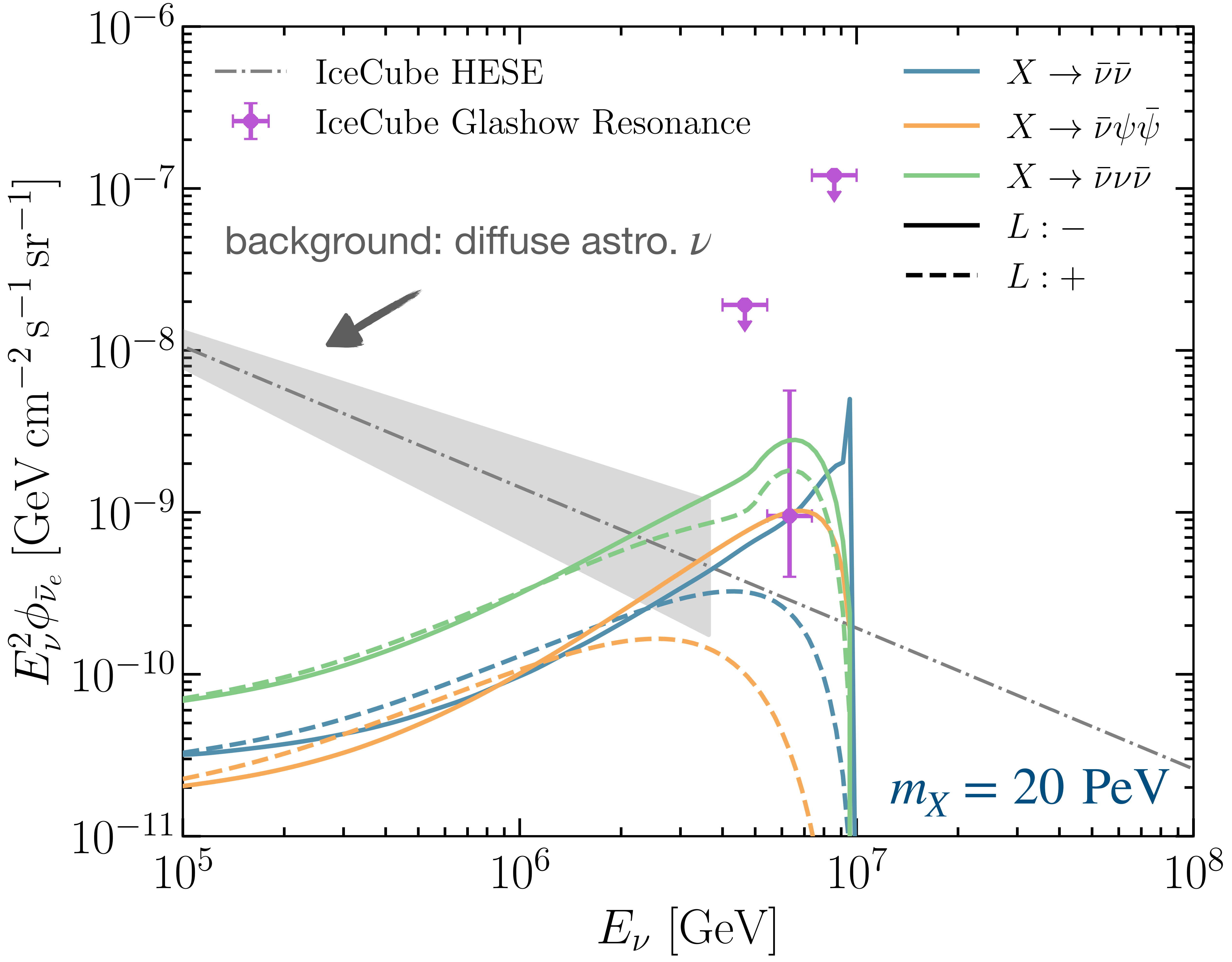
Atomic e motion:
Doppler Broadening

Initial State Radiation

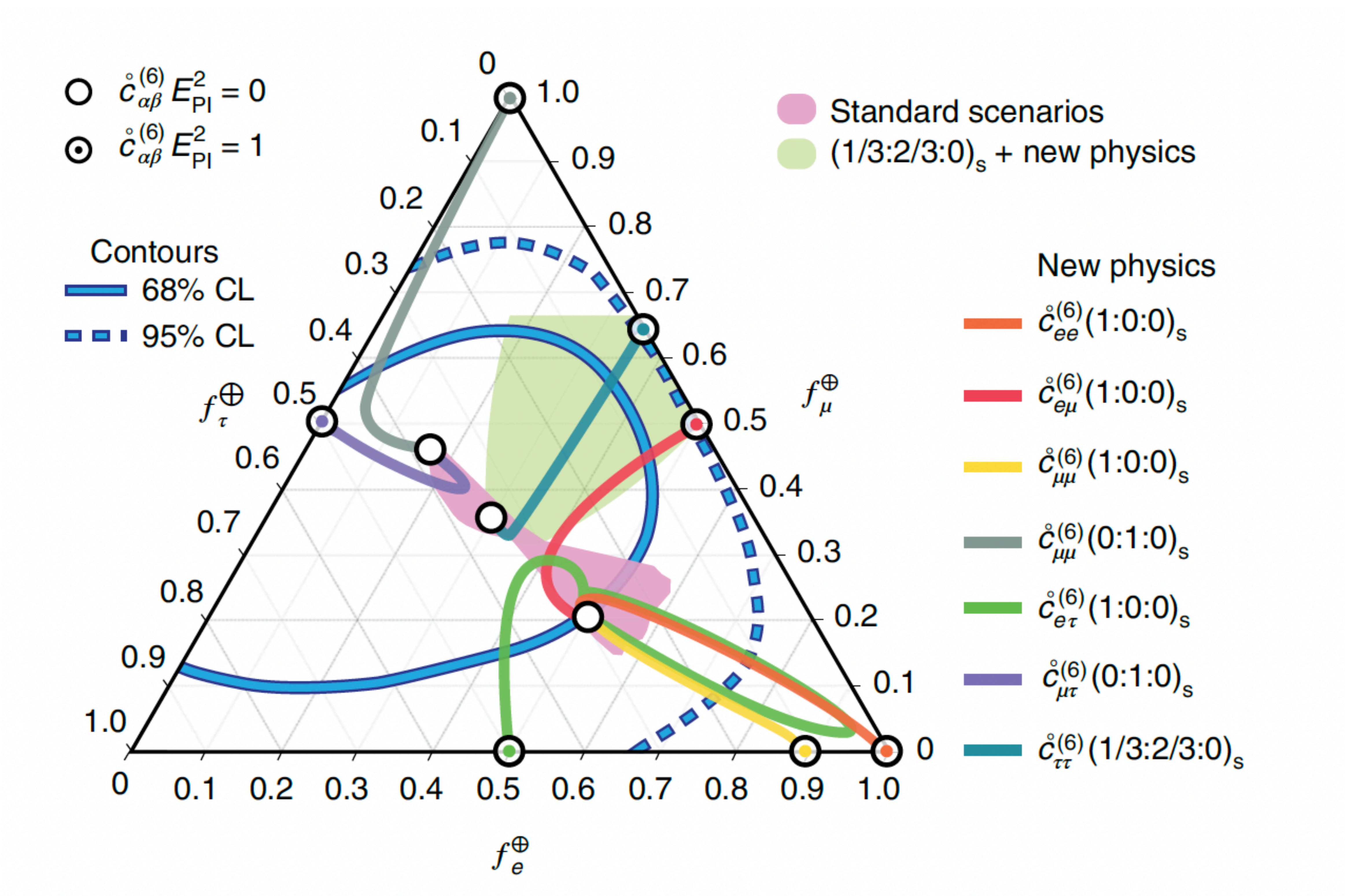


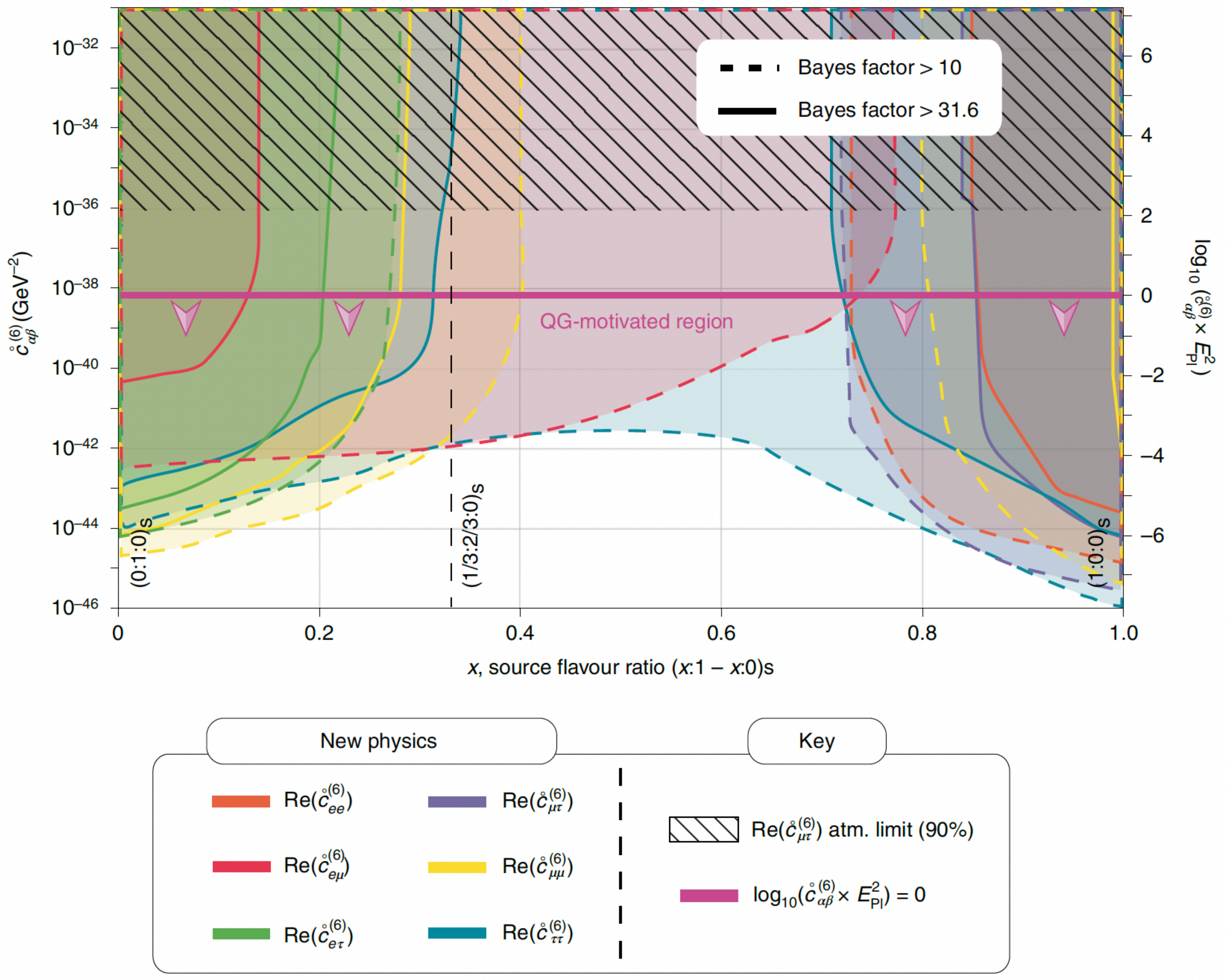
Spectrum Generation with Electroweak Corrections





IceCube Search for Quantum Gravity with the Flavor Composition





IceCube Nature Phys 2022