

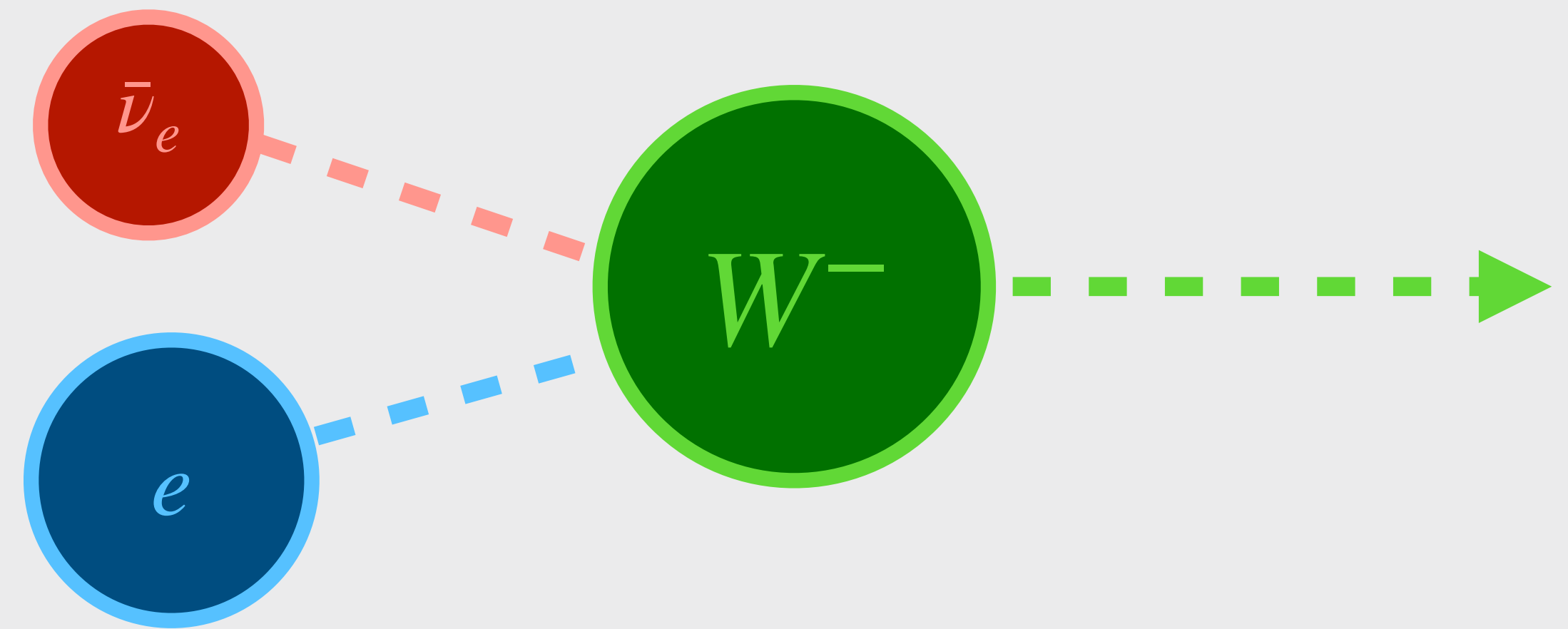
Probing Neutrino Production in High-energy Astrophysical Neutrino Sources with the Glashow Resonance

Qinrui Liu

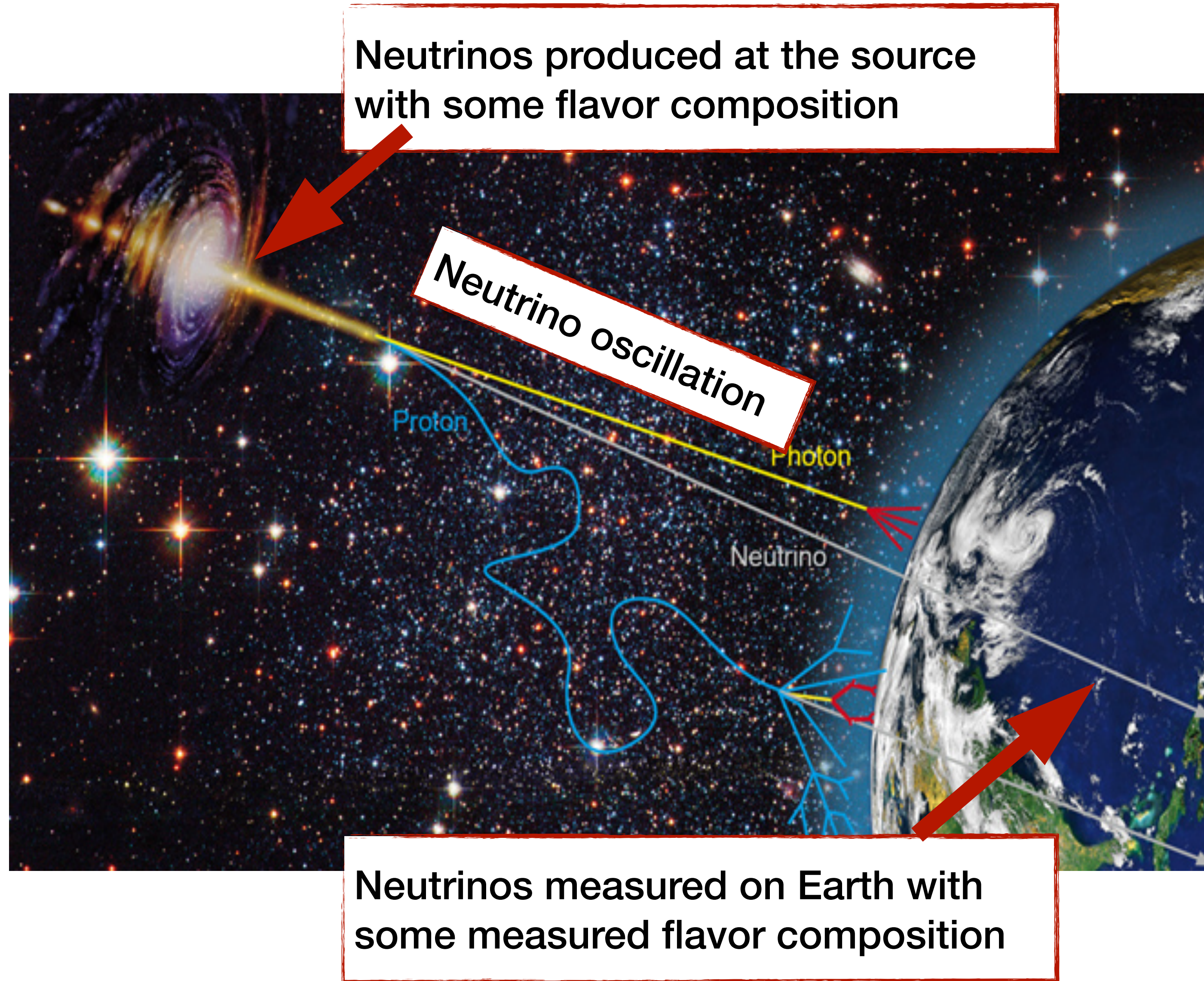
Queen's University

with N. Song and A. C. Vincent

based on PRD 108 (2023) 4, 043022 [2304.06068]



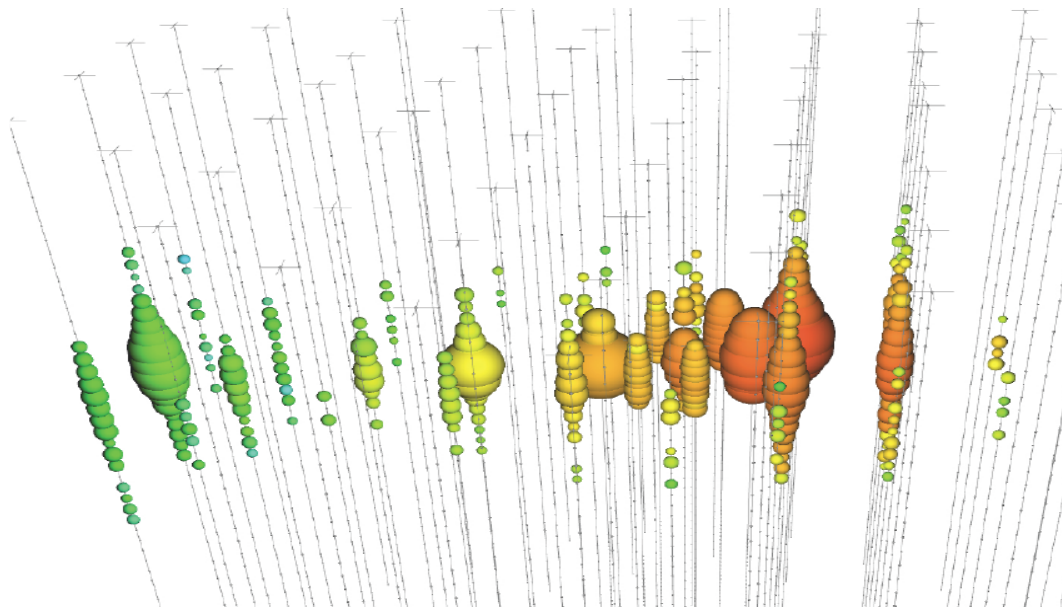
Flavor Composition of High-energy Astrophysical Neutrinos



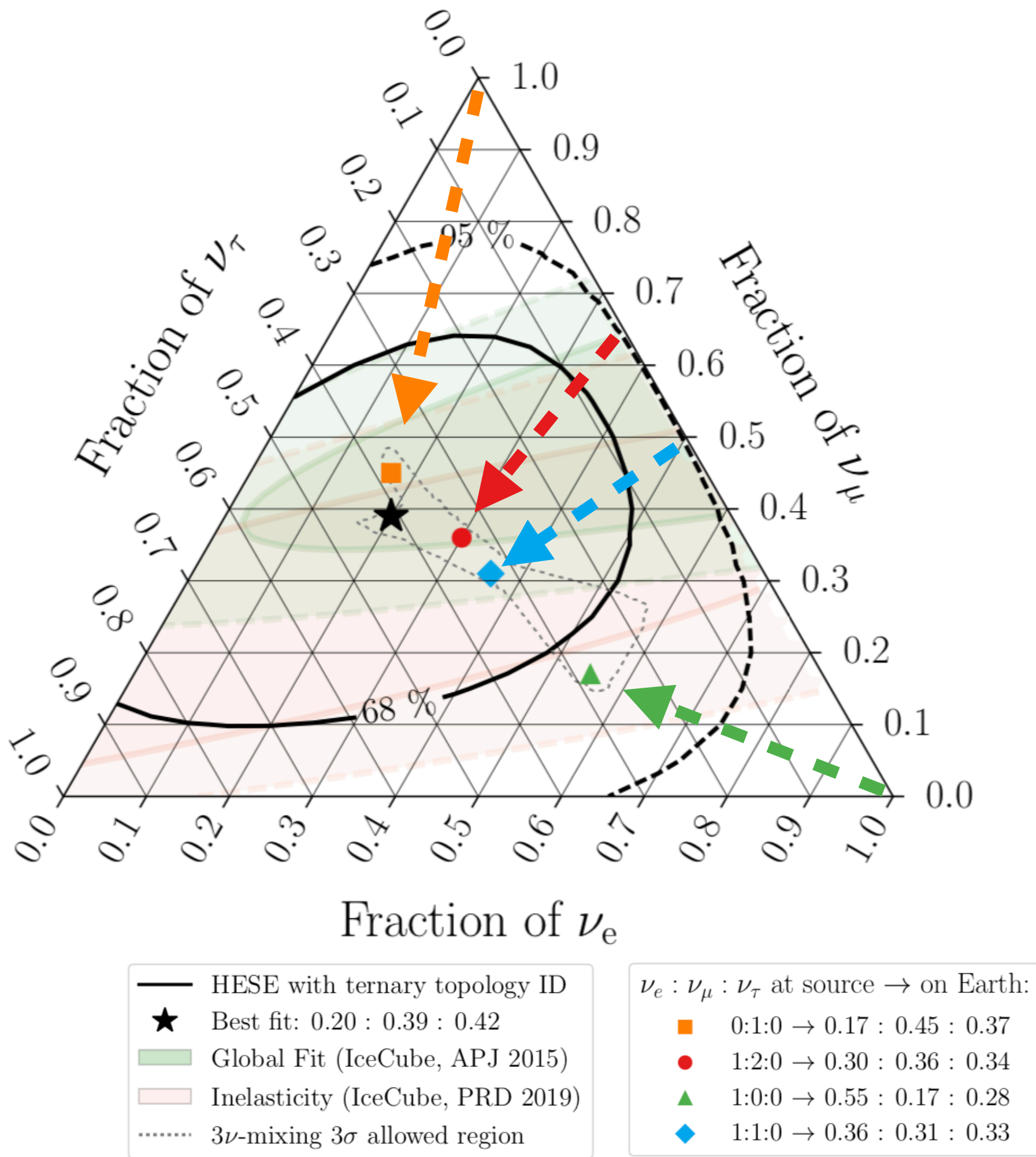
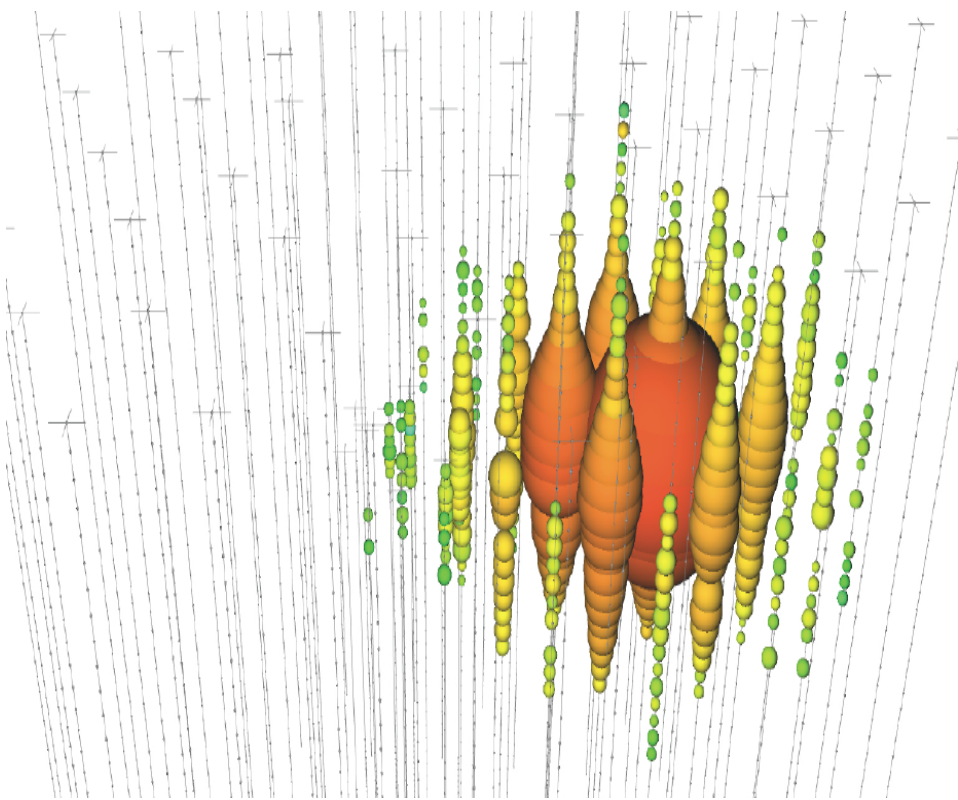
- High-energy astrophysical neutrinos arrive on Earth with a flavor composition.
- The production mechanisms and propagation effects affect the flavor composition.
- Measuring the flavor composition of high-energy astrophysical neutrinos on Earth is a window to examine the physics.

High-energy Neutrino Flavor Identification

Track ~ CC ν_μ

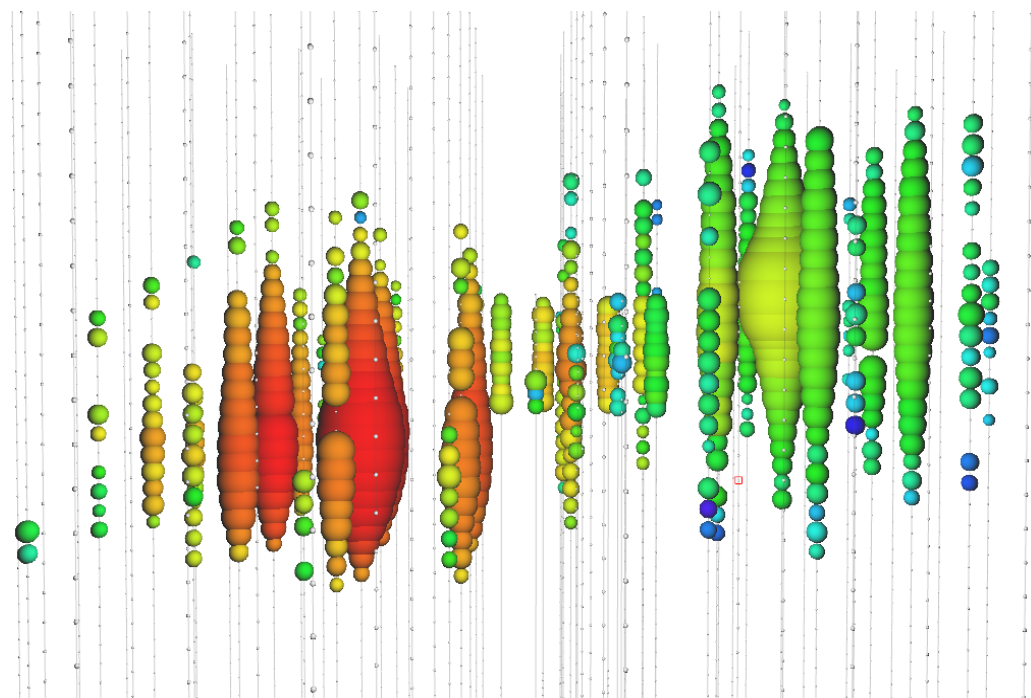


Cascade ~ NC all flavor / CC ν_e



IceCube EPJC 82 (2022) 11, 1031

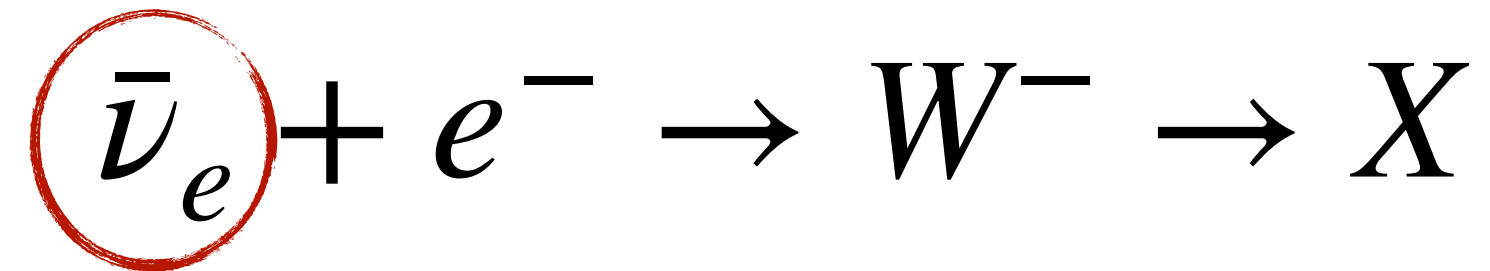
“Double-Bang” ~ CC ν_τ



- Challenging to distinguish flavors.
- Detection is blind to neutrinos and anti-neutrinos.
- flavor analyses have been focusing on the 3-flavor composition.

Glashow Resonance

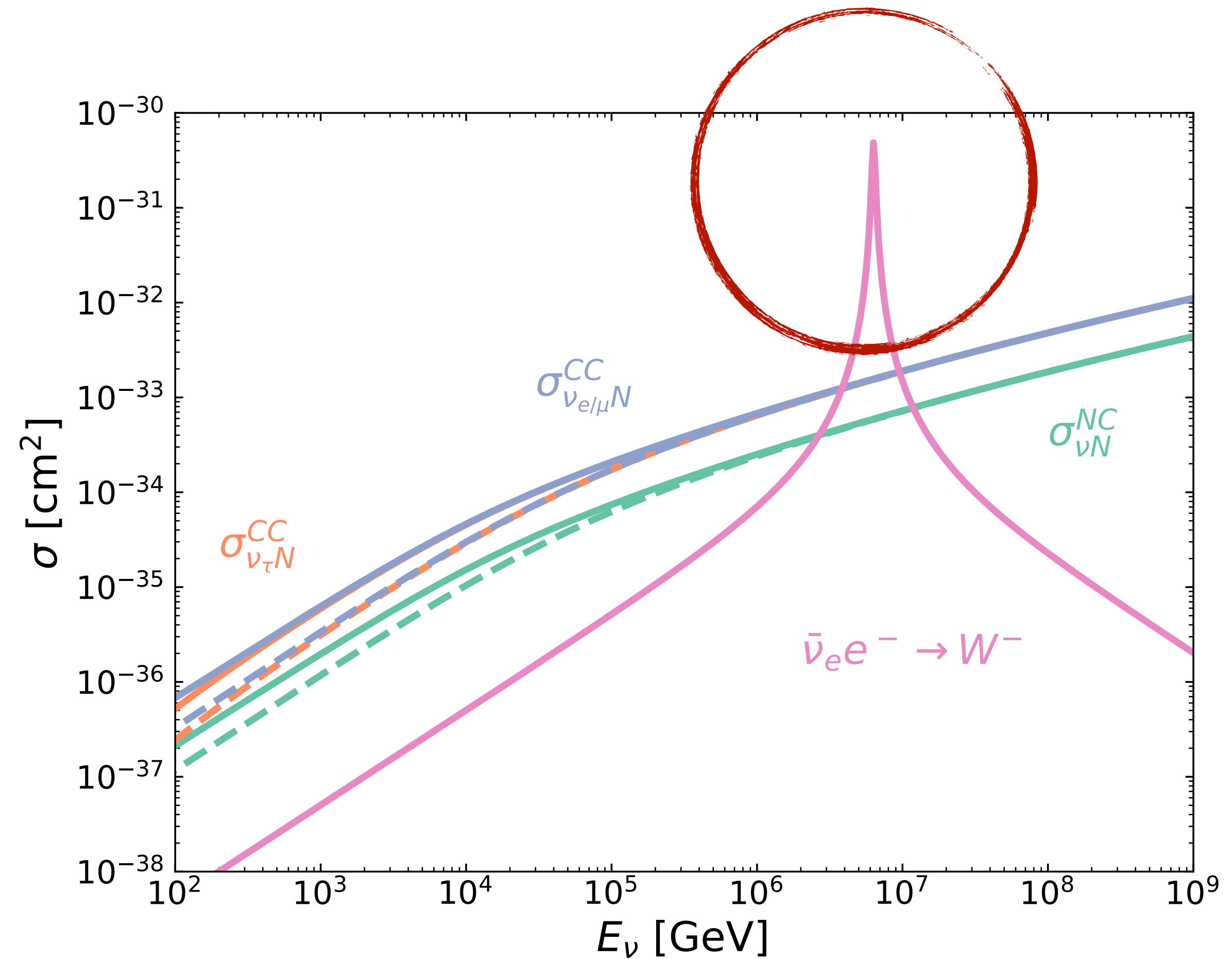
$\bar{\nu}_e$ can be disentangled with resonant interactions



6.3 PeV 511 KeV 80.38 GeV

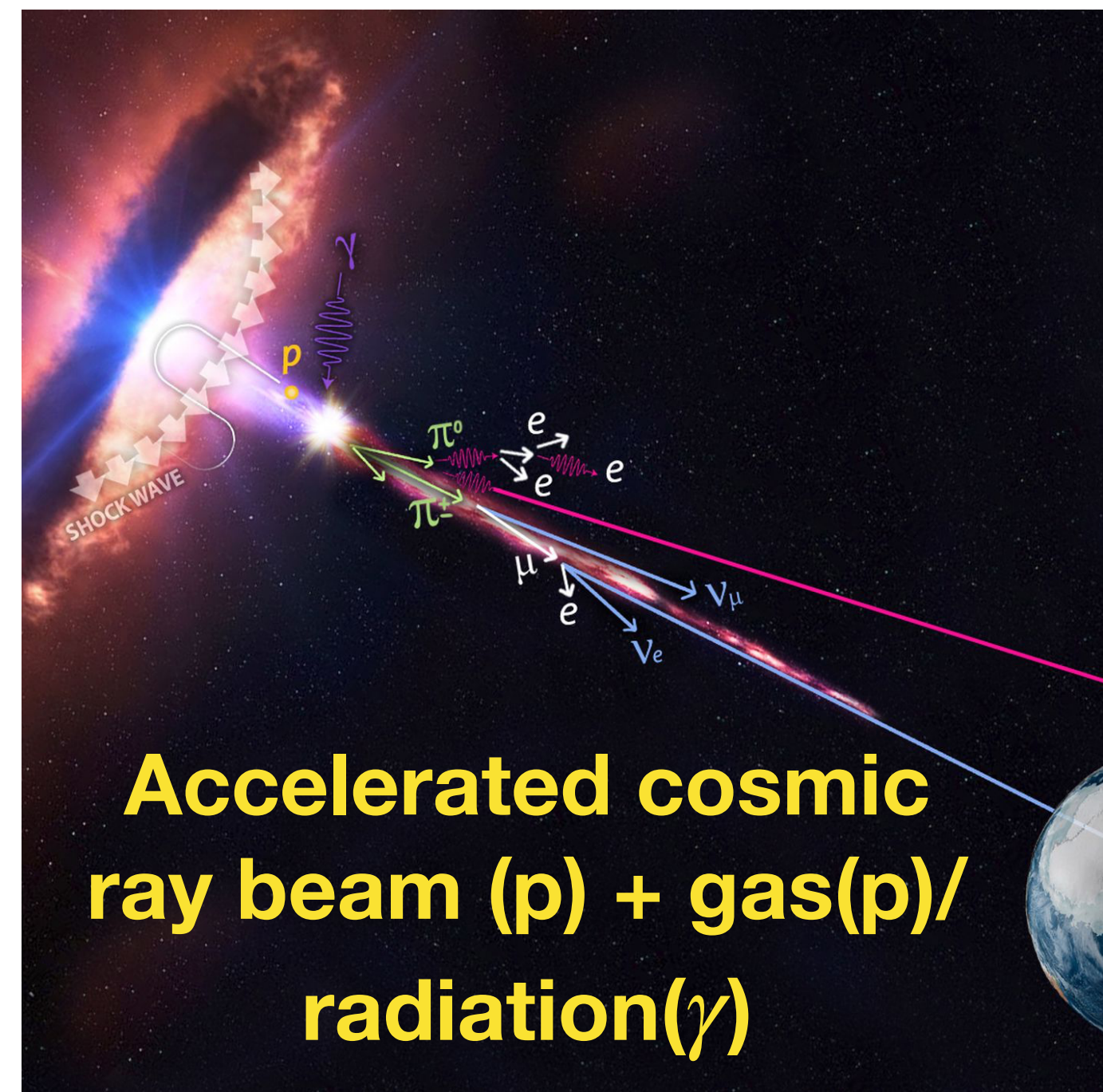
S. Glashow *Phys.Rev.* 118 (1960) 316-317

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



High-energy Cosmic Neutrino Production & Flavors

Typical Neutrino Production Mechanisms at Sources



Hadronuclear $p + p \rightarrow n_{\pi} [\pi^0 + \pi^+ + \pi^-]$

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

$$\left\{ \begin{array}{l} \pi^+ \rightarrow \nu_{\mu} + \mu^+ \rightarrow \nu_{\mu} + (e^+ + \nu_e + \bar{\nu}_{\mu}) \\ \pi^- \rightarrow \bar{\nu}_{\mu} + \mu^- \rightarrow \bar{\nu}_{\mu} + (e^- + \bar{\nu}_e + \nu_{\mu}) \\ \pi^0 \rightarrow \gamma + \gamma \end{array} \right.$$

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

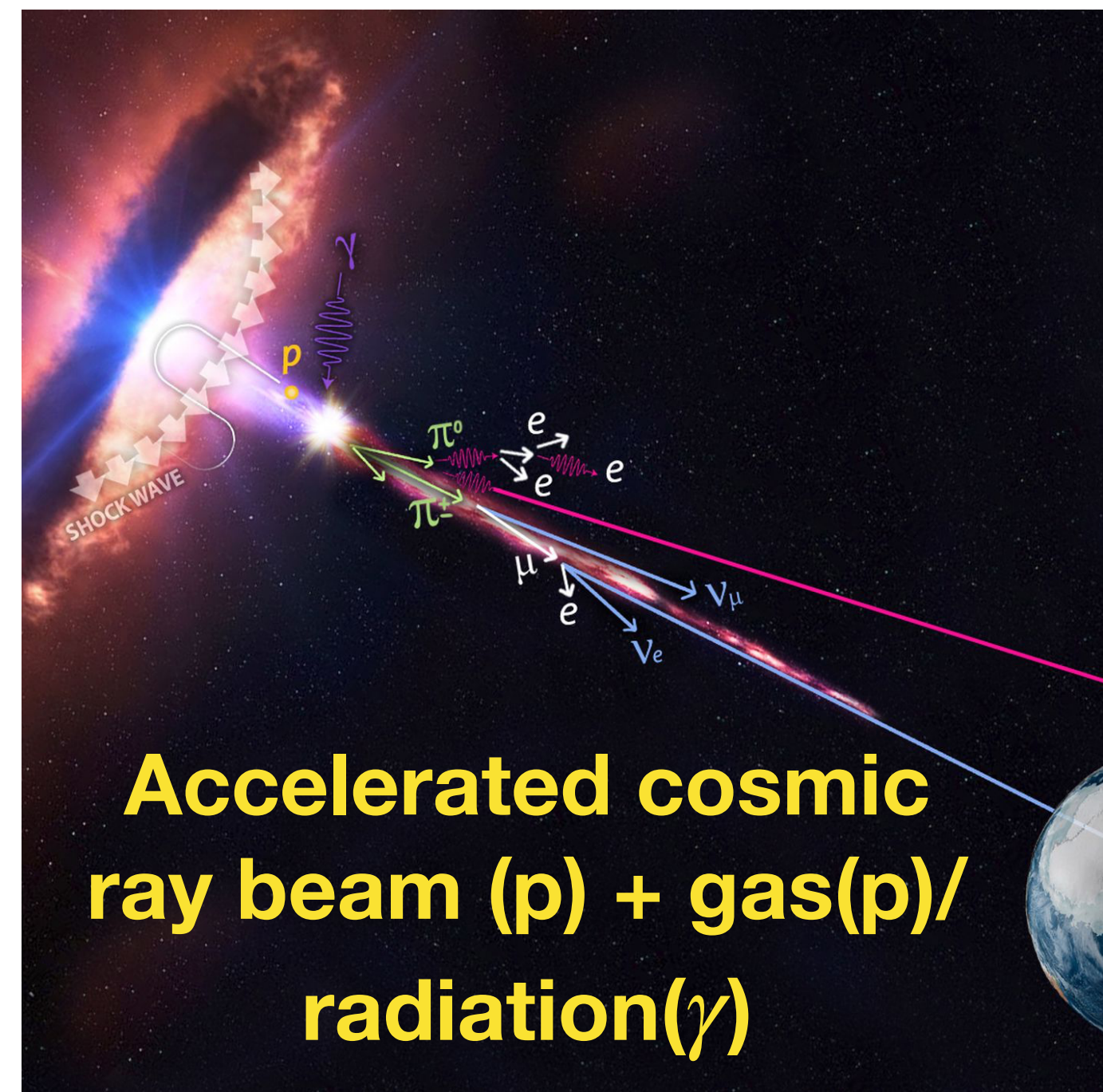
$pp/p\gamma$
 $pp/p\gamma$ μ damped

	standard mixing	
$f_{e,s} : f_{\mu,s} : f_{\tau,s}$	\longrightarrow	$f_{e,\oplus} : f_{\mu,\oplus} : f_{\tau,\oplus}$
$\{1 : 2 : 0\}$		$\{0.33 : 0.34 : 0.33\}$
$\{0 : 1 : 0\}$		$\{0.23 : 0.39 : 0.38\}$

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

High-energy Cosmic Neutrino Production & Flavors

Typical Neutrino Production Mechanisms at Sources



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Uniform distribution of all charges

Dominating π^+

Asymmetry of pion charges can be seen in the ν vs $\bar{\nu}$ ratio

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

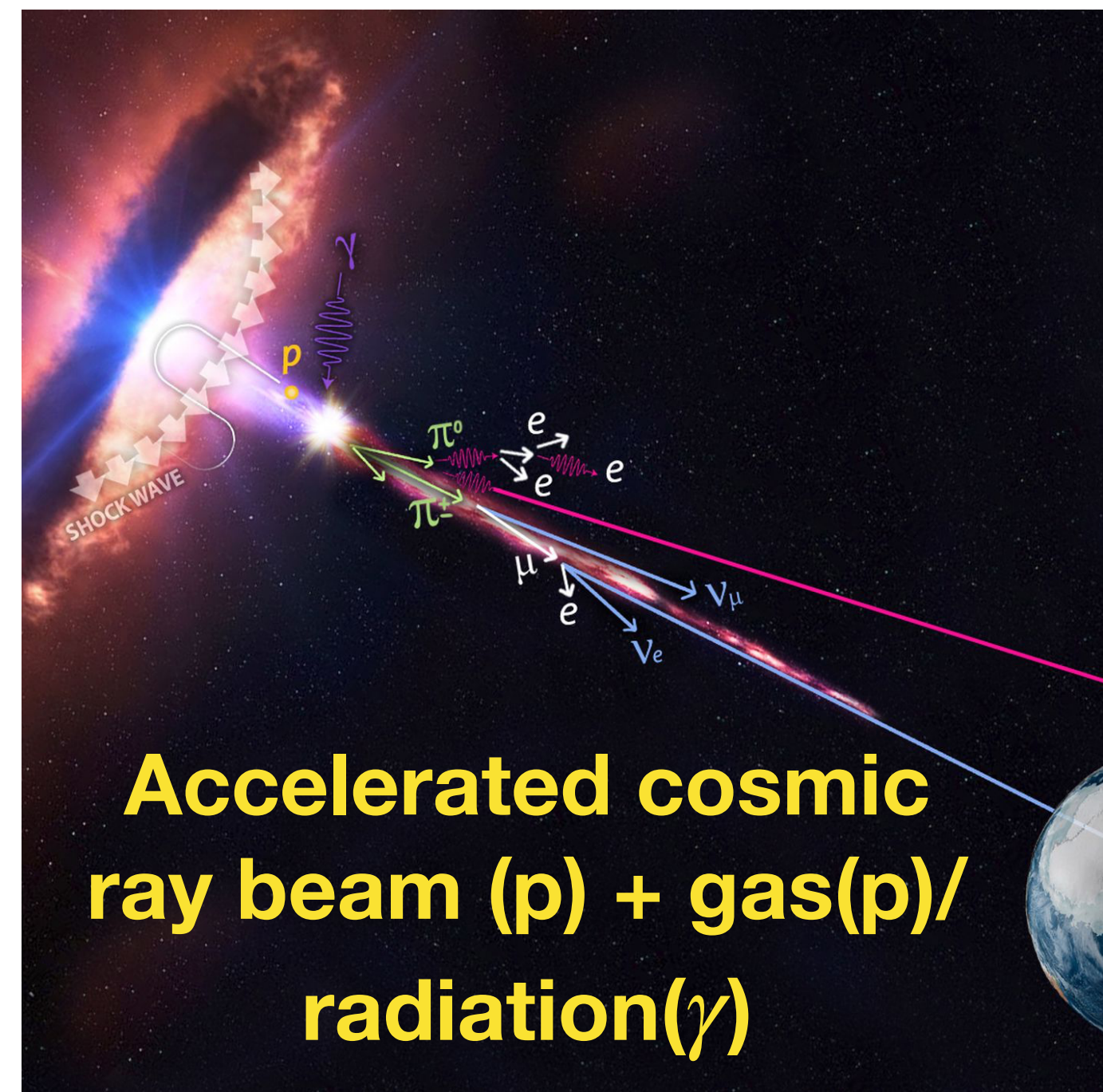
Differentiating ν and $\bar{\nu}$

pp
 $p\gamma$
 pp μ damped
 $p\gamma$ μ damped

pp and $p\gamma$ can be distinguished

High-energy Cosmic Neutrino Production & Flavors

Typical Neutrino Production Mechanisms at Sources



Hadronuclear $p + p \rightarrow n_{\pi} [\pi^0 + \pi^+ + \pi^-]$

Uniform distribution
of all charges

Dominating π^+

$\bar{\nu}_e$ fraction can be used to differentiate the production mechanisms at sources.
It is the only way to resolve 3-flavor degenerated scenarios.

Asymmetry of pion charges can be seen in the ν vs $\bar{\nu}$ ratio

$\pi^0 \rightarrow \gamma + \gamma$

standard mixing

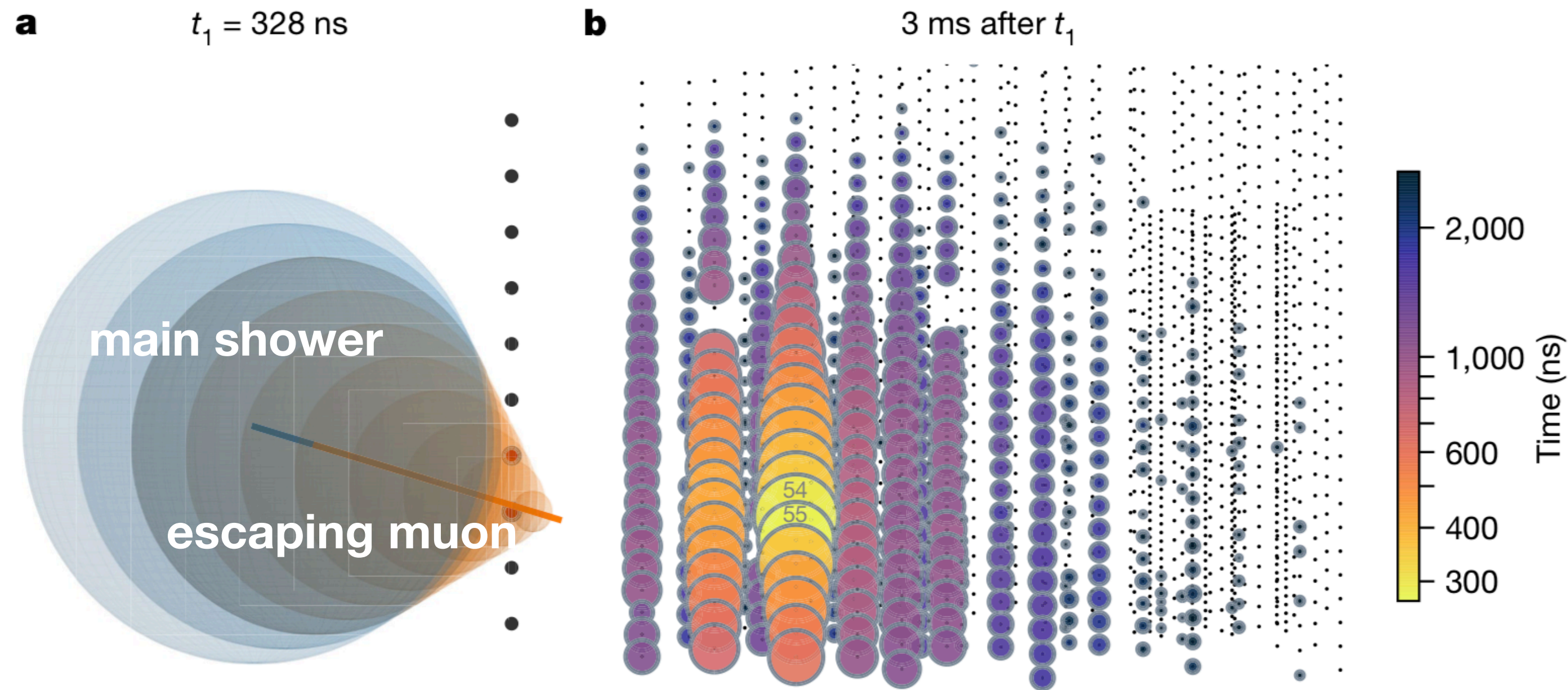
$\{f_{\nu_e,s}, f_{\bar{\nu}_e,s}\} : \{f_{\nu_\mu,s}, f_{\bar{\nu}_\mu,s}\} : \{f_{\nu_\tau,s}, f_{\bar{\nu}_\tau,s}\}$	\longrightarrow	$\{f_{\nu_e,\oplus}, f_{\bar{\nu}_e,\oplus}\} : \{f_{\nu_\mu,\oplus}, f_{\bar{\nu}_\mu,\oplus}\} : \{f_{\nu_\tau,\oplus}, f_{\bar{\nu}_\tau,\oplus}\}$
$\{1,1\} : \{2,2\} : \{0,0\}$		$\{0.17, 0.17\} : \{0.17, 0.17\} : \{0.16, 0.16\}$
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$\{0,0\} : \{1,0\} : \{0,0\}$		$\{0.23, 0.00\} : \{0.39, 0.00\} : \{0.38, 0.00\}$

Differentiating
 ν and $\bar{\nu}$

pp
 $p\gamma$
 $pp \mu$ damped
 $p\gamma \mu$ damped

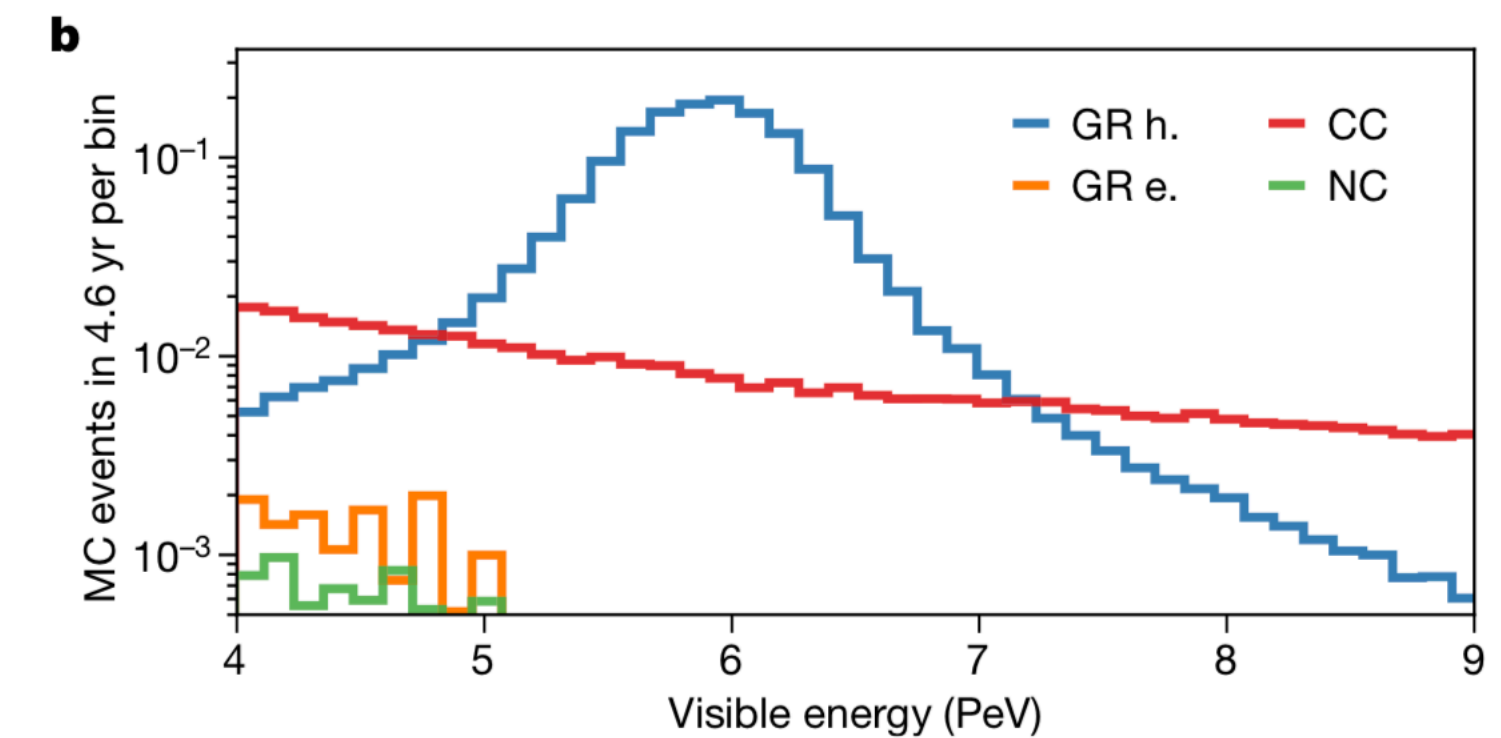
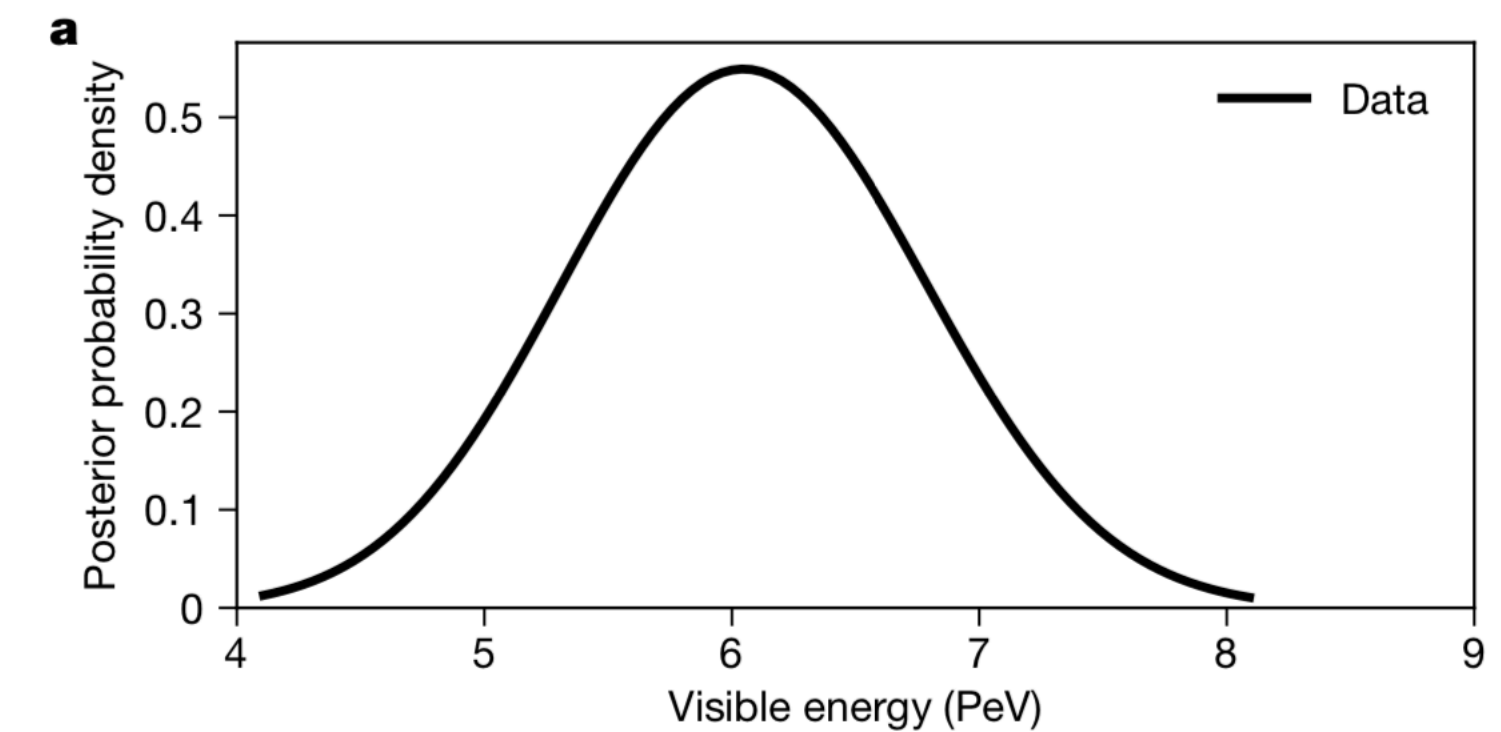
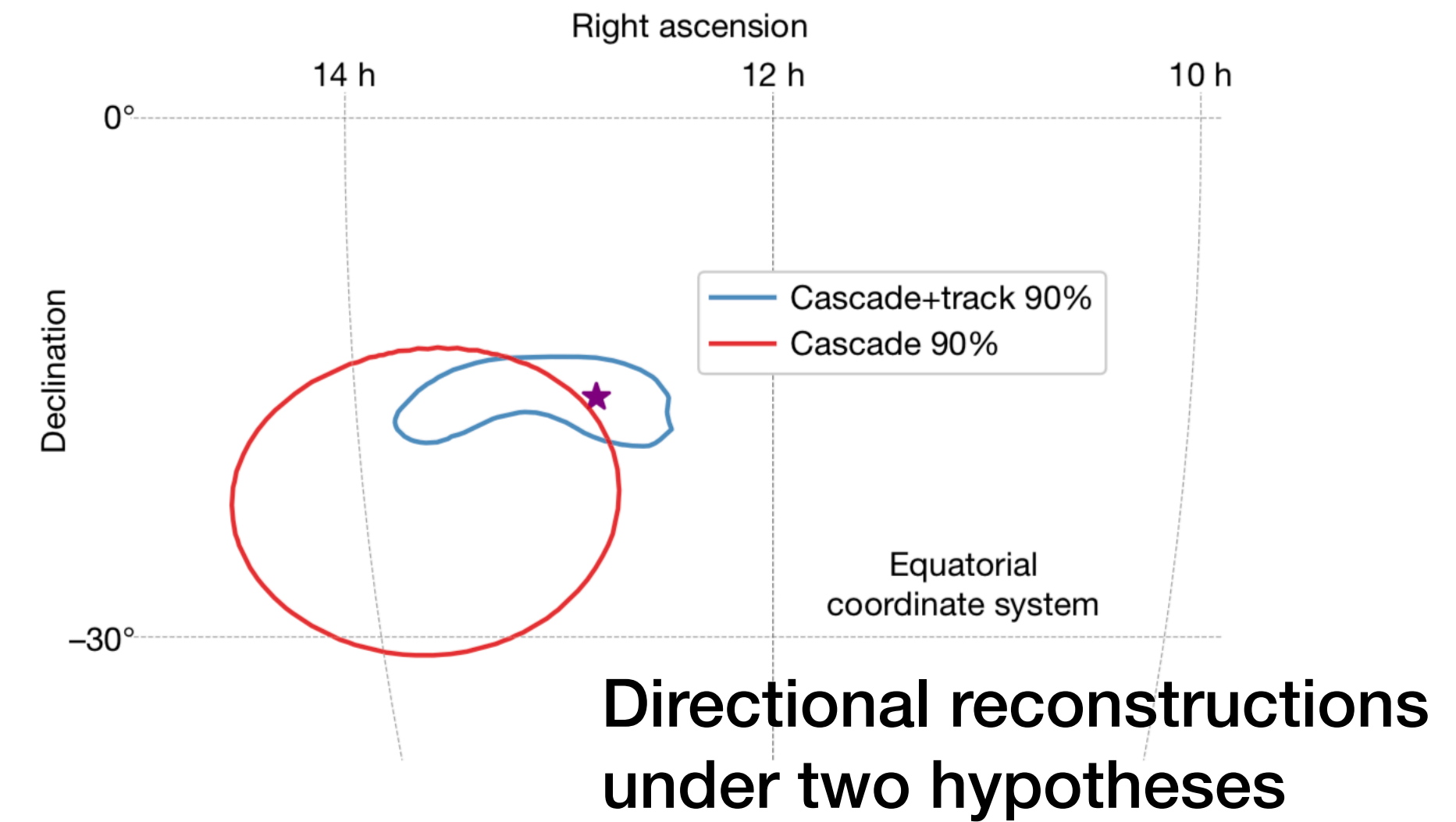
pp and $p\gamma$ can be distinguished

First Detection of Glashow Resonance



PeV energy partially-contained event (PEPE) selection

- The detectable escaping muon suggests it's a hadronic shower
- visible energy of $6.05 \pm 0.72 \text{ PeV}$, 2.3σ assuming a $E^{-2.5}$ spectrum



Current 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

- The observed event in the PEPE selection is from $W^- \rightarrow$ hadrons
- The non-observation in the high-energy starting event (HESE) selection

→
90 % C.L.

Hard spectrum $E^{-2.37}$: $2 \% \leq f_{\bar{\nu}_e} \leq 51 \%$
Soft spectrum $E^{-2.87}$: $f_{\bar{\nu}_e} \geq 10 \%$

A factor of 2
difference
between PEPE
and HESE in
the effective
area in the
energy window

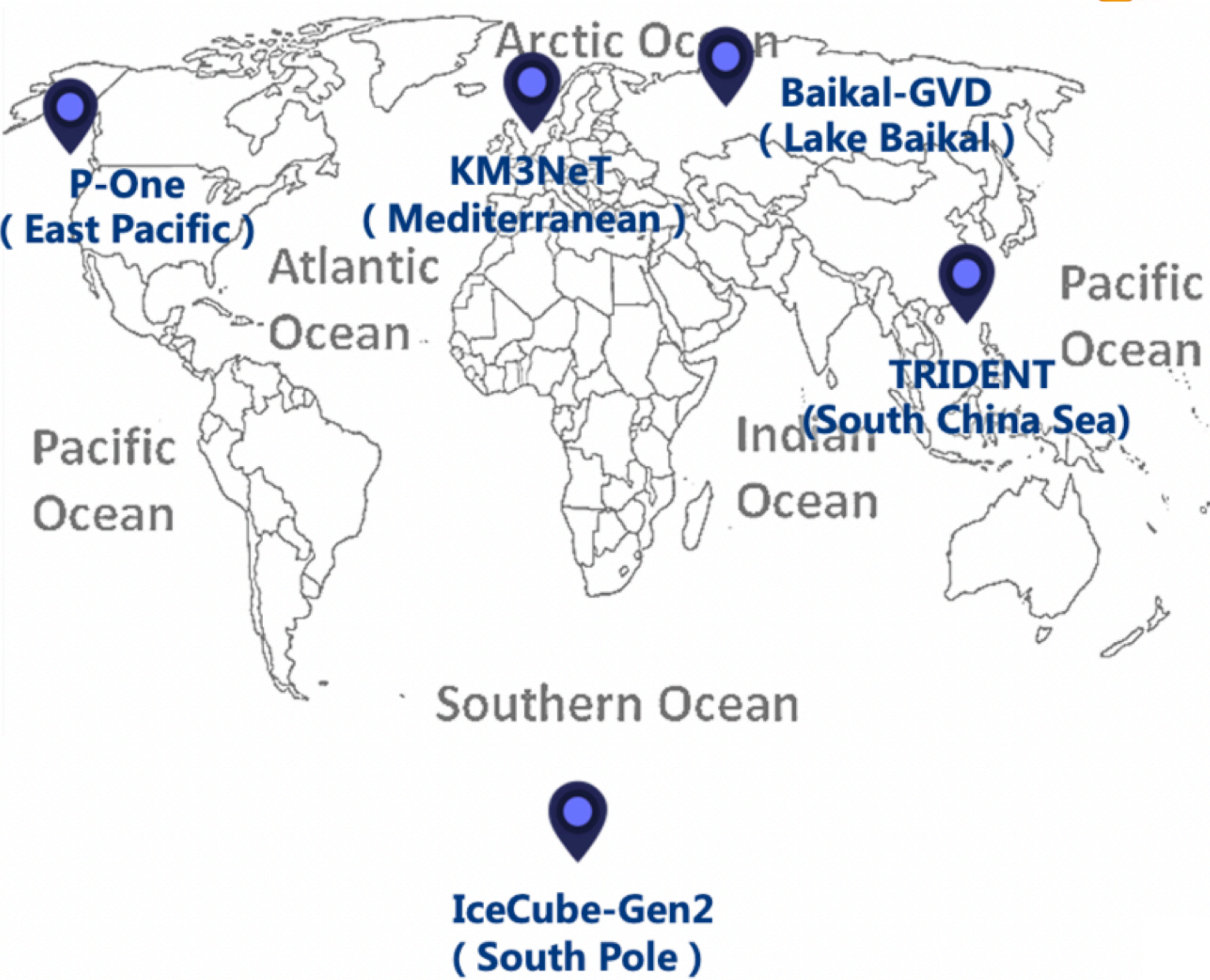
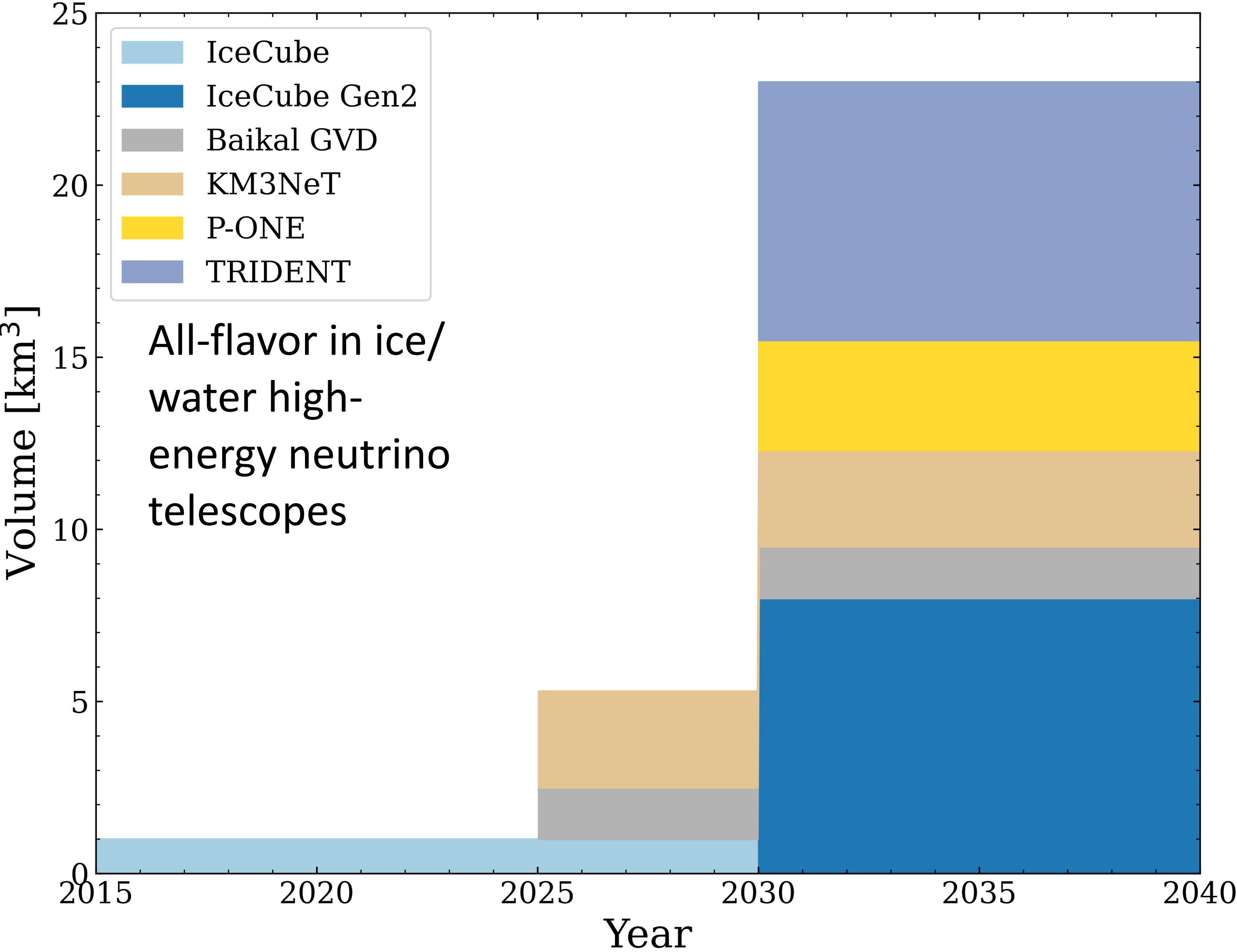
- The current data disfavors the $p\gamma\mu$ damped scenario which has no antineutrinos.
- The allowed fraction range is still large.

What can we expect in the future?



Global Neutrino Telescopes

What can we expect in the future? 🤔



more telescopes, boosted exposure
combining global neutrino telescopes to reach the optimal detection!
for HESE, exposure $\propto A_{eff,IC} \cdot (V/1 \text{ km}^3)$

Event-wise Identification

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

$W^- \rightarrow \text{hadrons}$ **BR ~67 %**

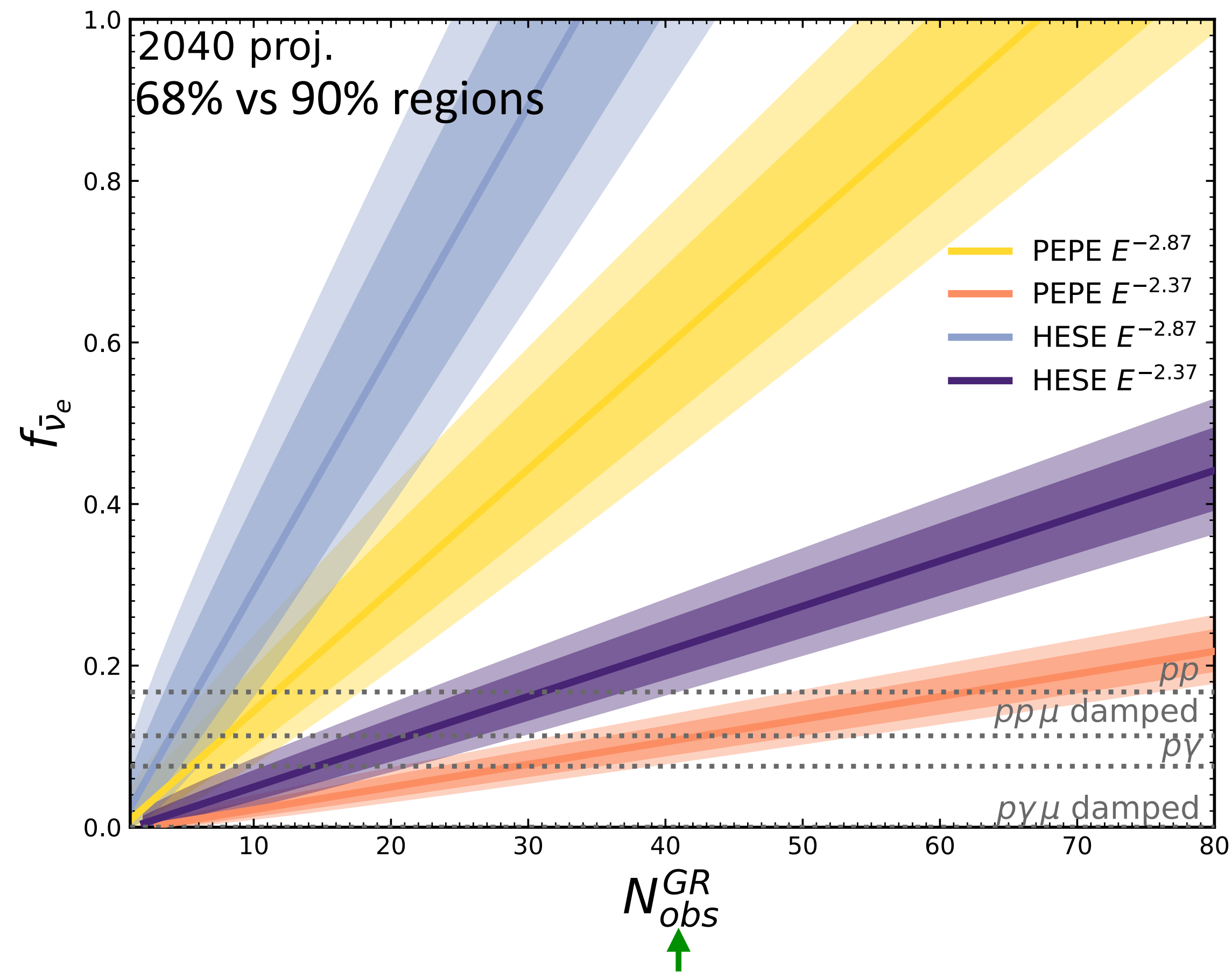
✓ escaping muons, the only irreducible background is from NCDIS events

$W^- \rightarrow e^- \bar{\nu}_e / \tau^- \bar{\nu}_\tau$ **BR ~11 %**

✗ Undistinguishable to a DIS cascade

$W^- \rightarrow \mu^- \bar{\nu}_\mu$ **BR ~11 %**

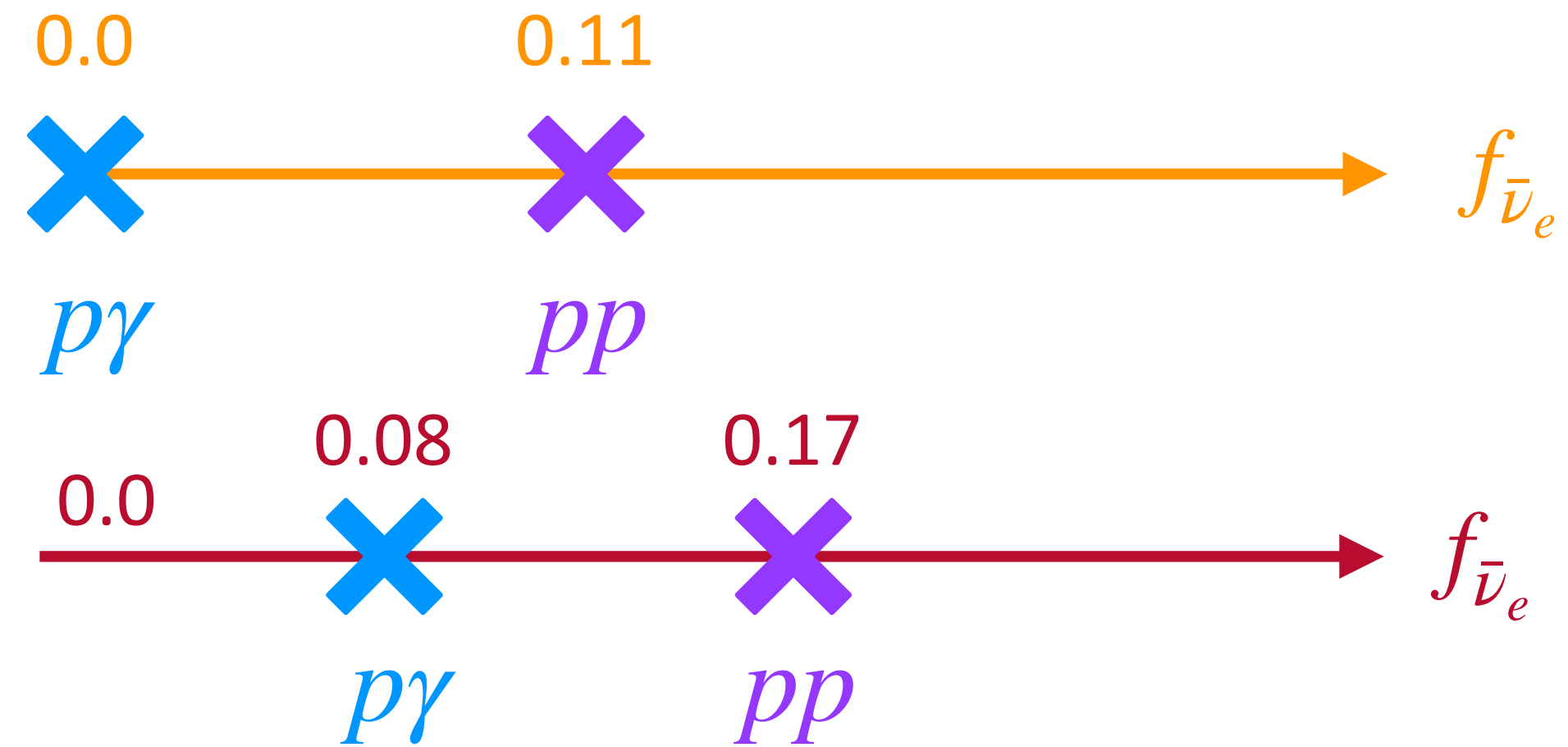
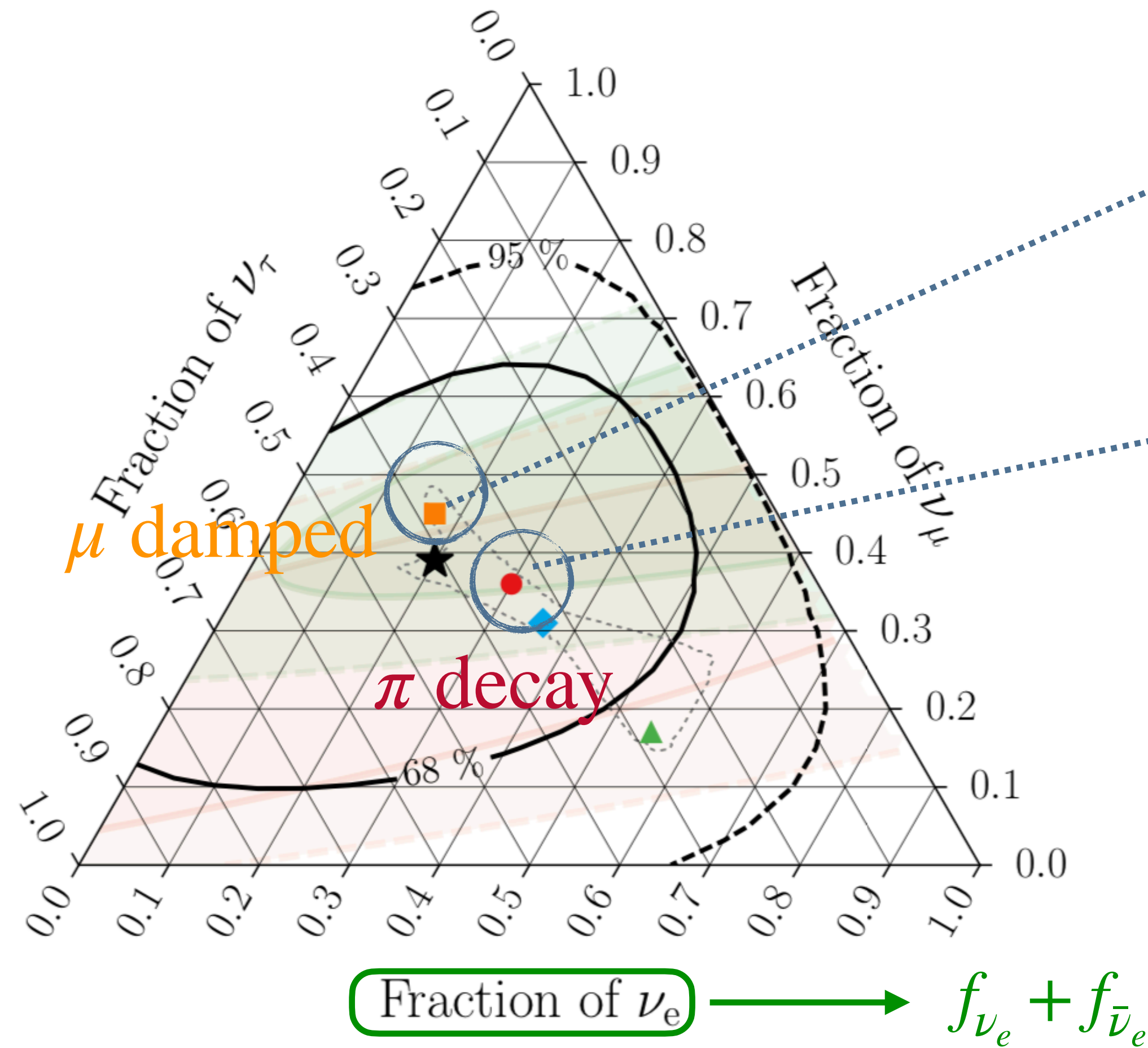
✓ track without the initial cascade comparing to ν_μ CCDIS



Number of Glashow resonant-like events observed

Analysis	Spectrum	pp from $p\gamma$	$p\gamma$ from pp	pp from $p\gamma$	$p\gamma$ from pp
		π decay	π decay	μ damped	μ damped
HESE event-wise	soft	1.6σ	1.4σ	$> 5\sigma$	0.7σ
	hard	3.8σ	3.3σ	$> 5\sigma$	6.0σ
PEPE event-wise	soft	2.3σ	2.0σ	$> 5\sigma$	1.4σ
	hard	5.3σ	4.7σ	$> 5\sigma$	6.9σ

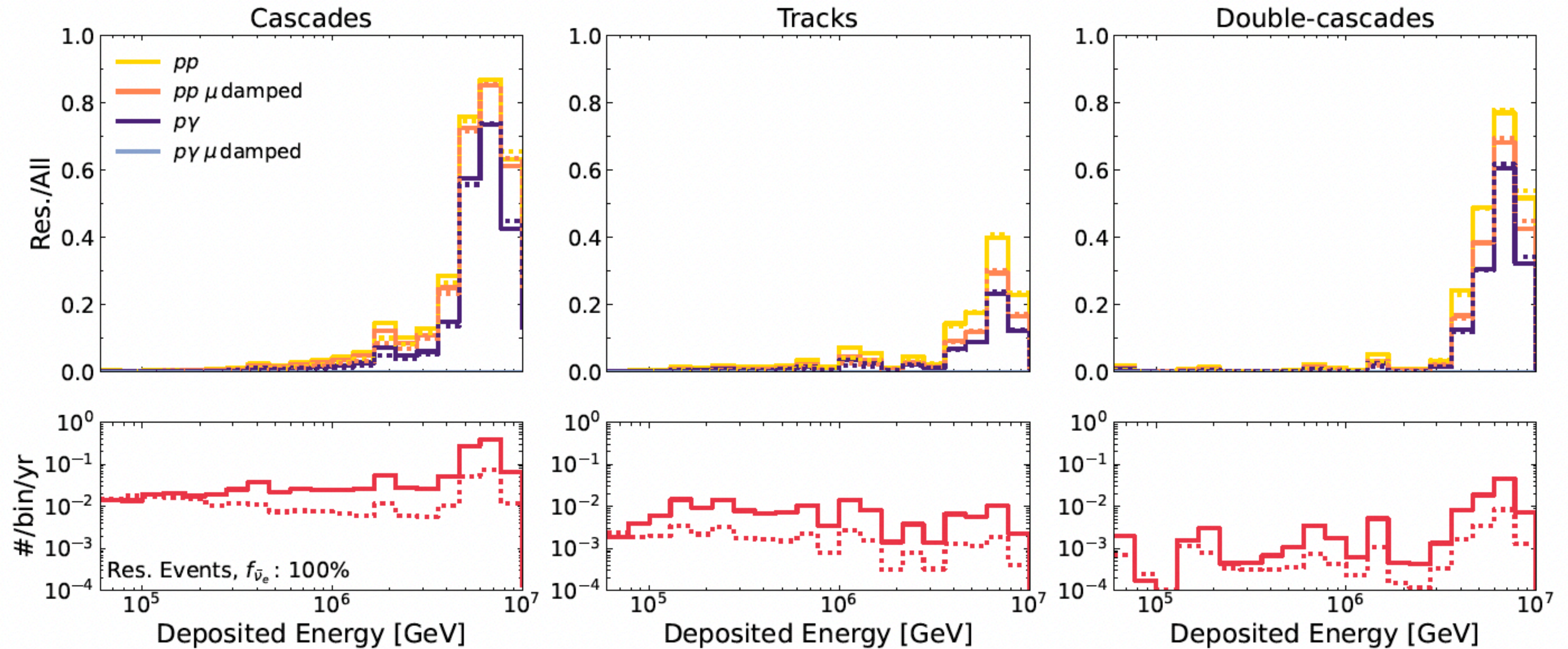
4-Flavor Analysis



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

4-Flavor Analysis

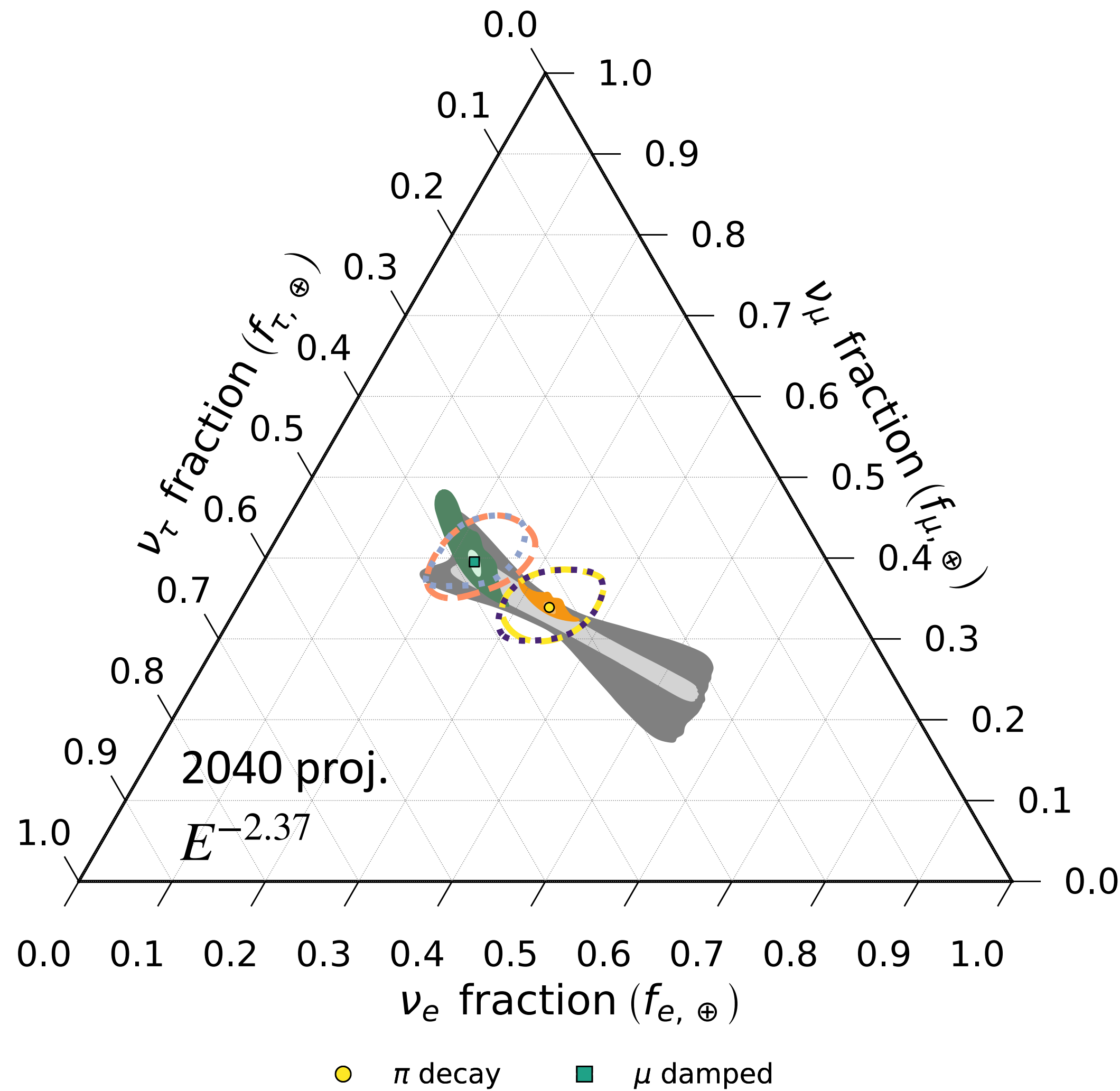
A Bayesian analysis based on public HESE events and MC.*



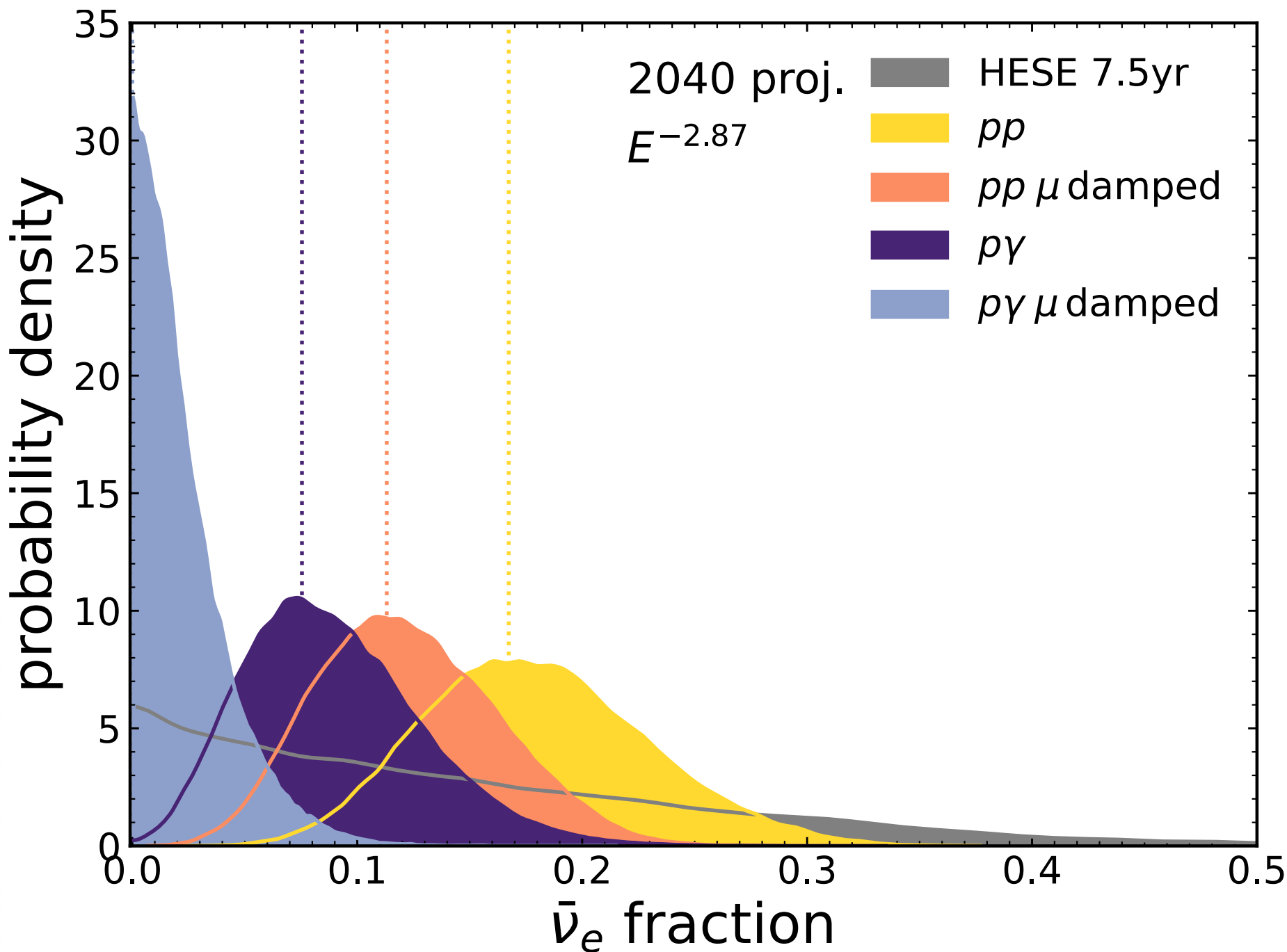
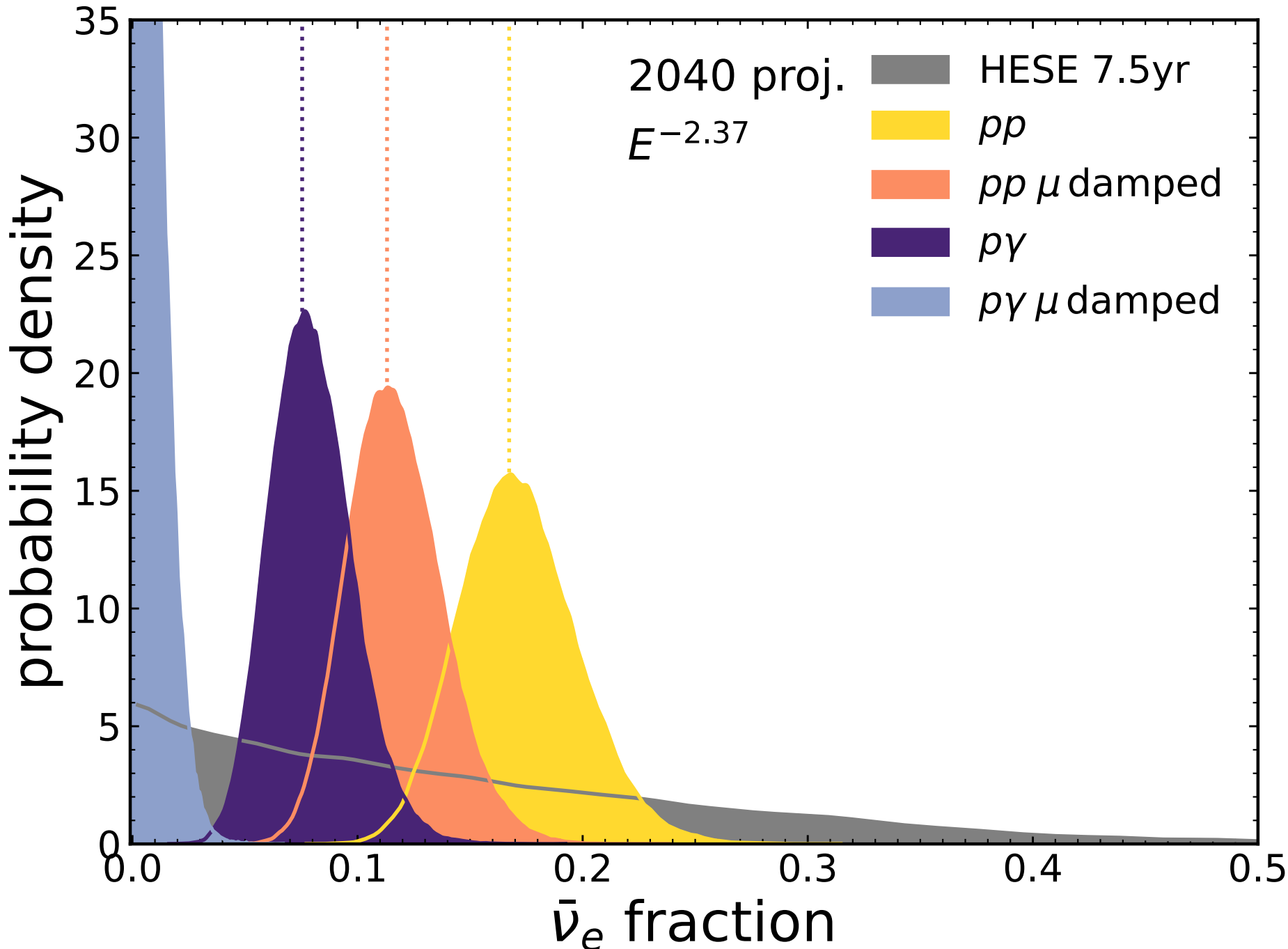
- Misidentification of events and reconstruction effects are taken into account.
- A wider energy range is considered.
- Fit for the **spectrum** (power-law spectrum normalization + spectral index) and the **4-flavor composition** (3-flavor composition $f_e : f_\mu : f_\tau + \bar{\nu}_e$ fraction in f_e).

* [HESE release](#)

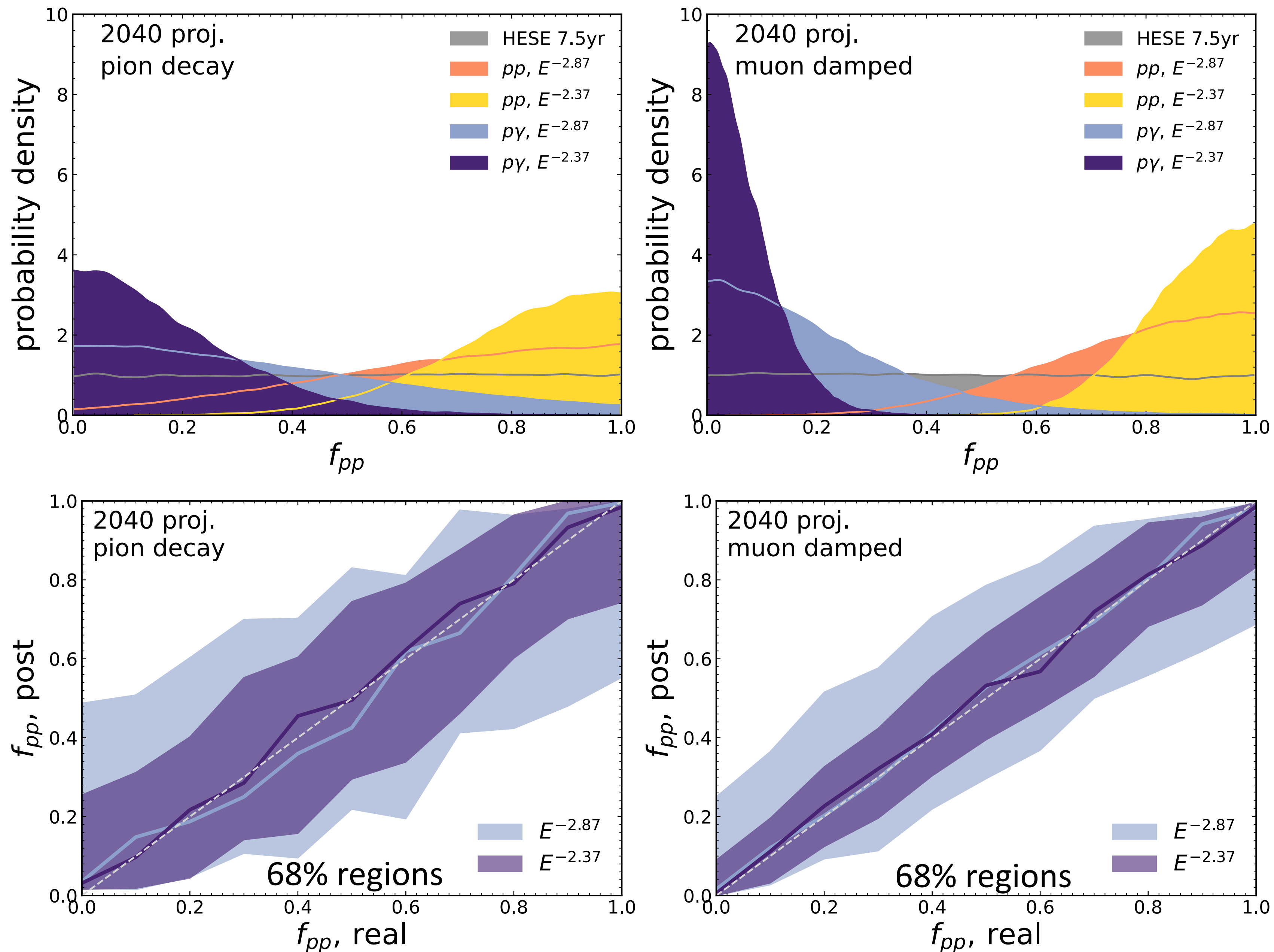
4-Flavor Analysis



Analysis	Spectrum	pp from $p\gamma$ π decay	$p\gamma$ from pp π decay	pp from $p\gamma$ μ damped	$p\gamma$ from pp μ damped
HESE Bayesian	soft	2.6σ	2.1σ	3.5σ	3.1σ
	hard	4.4σ	3.9σ	6.3σ	6.5σ



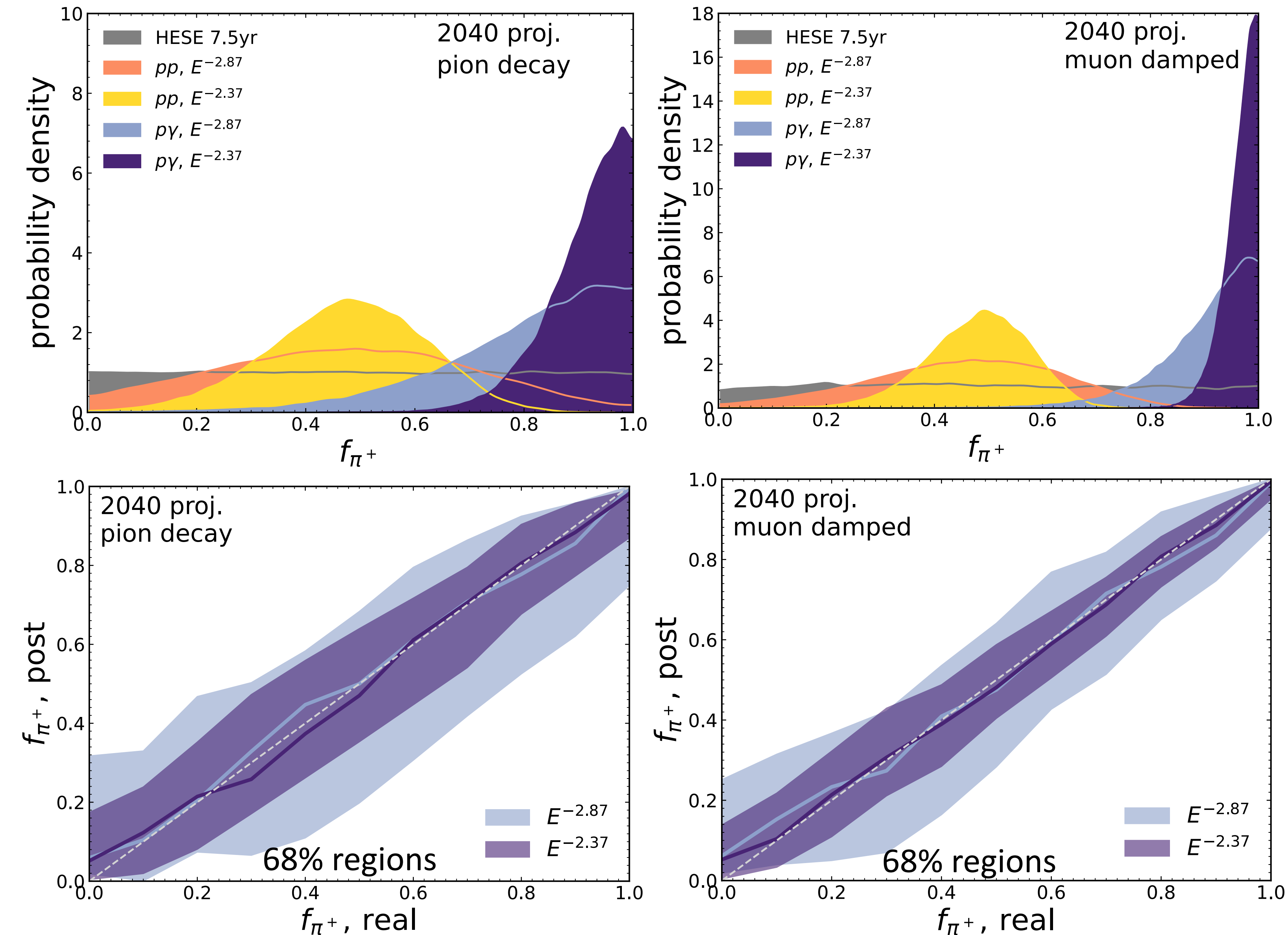
Mixture of pp and $p\gamma$



- 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?

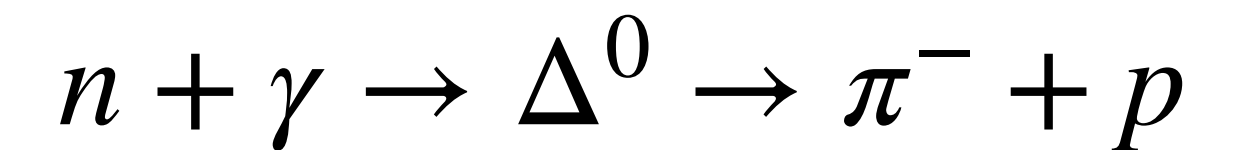
What's more can be inferred after breaking the degeneracy?

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. subdominant interactions depending on the injecting CRs and targets, the chemical composition of CRs, and other processes such as



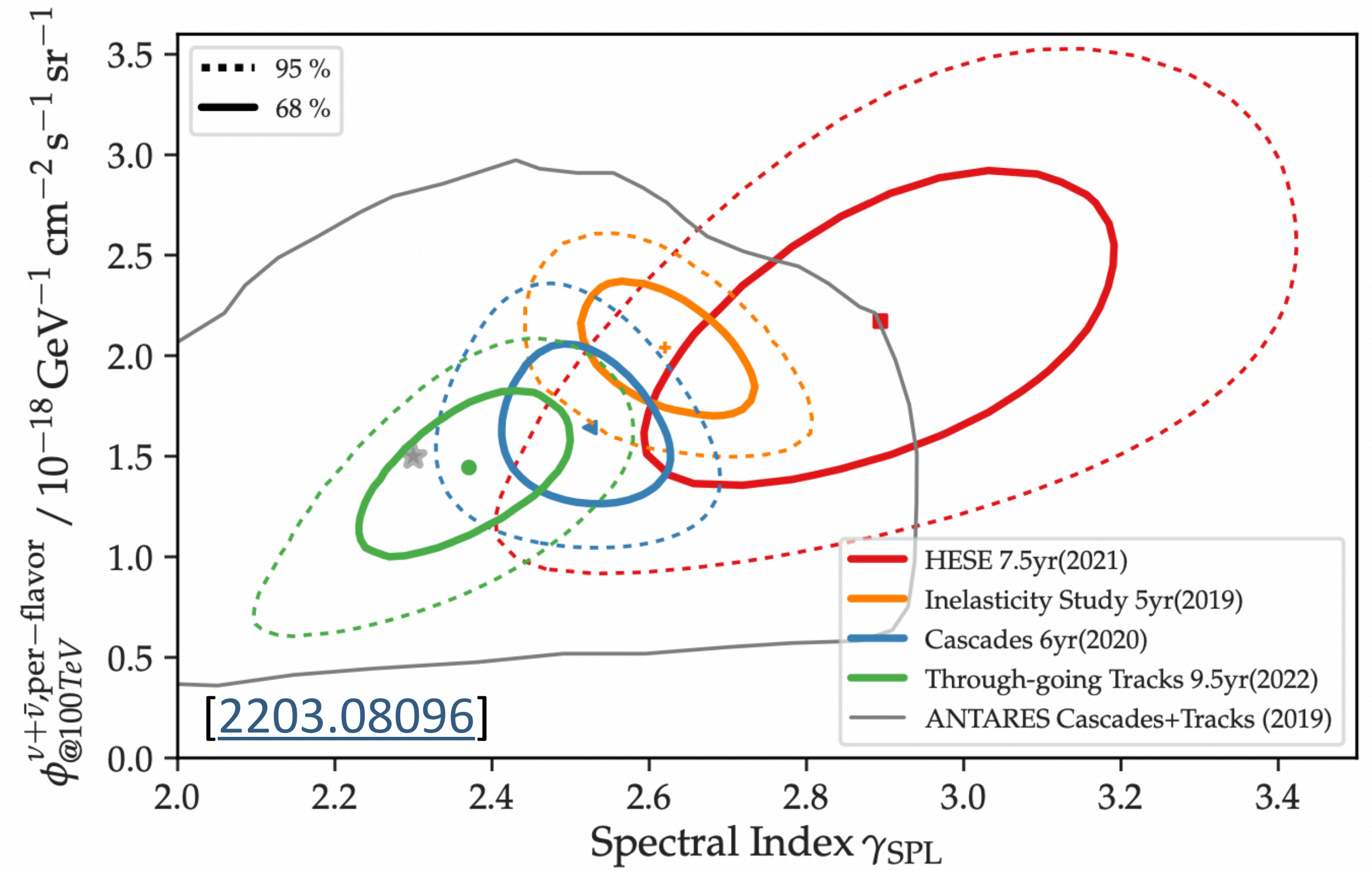
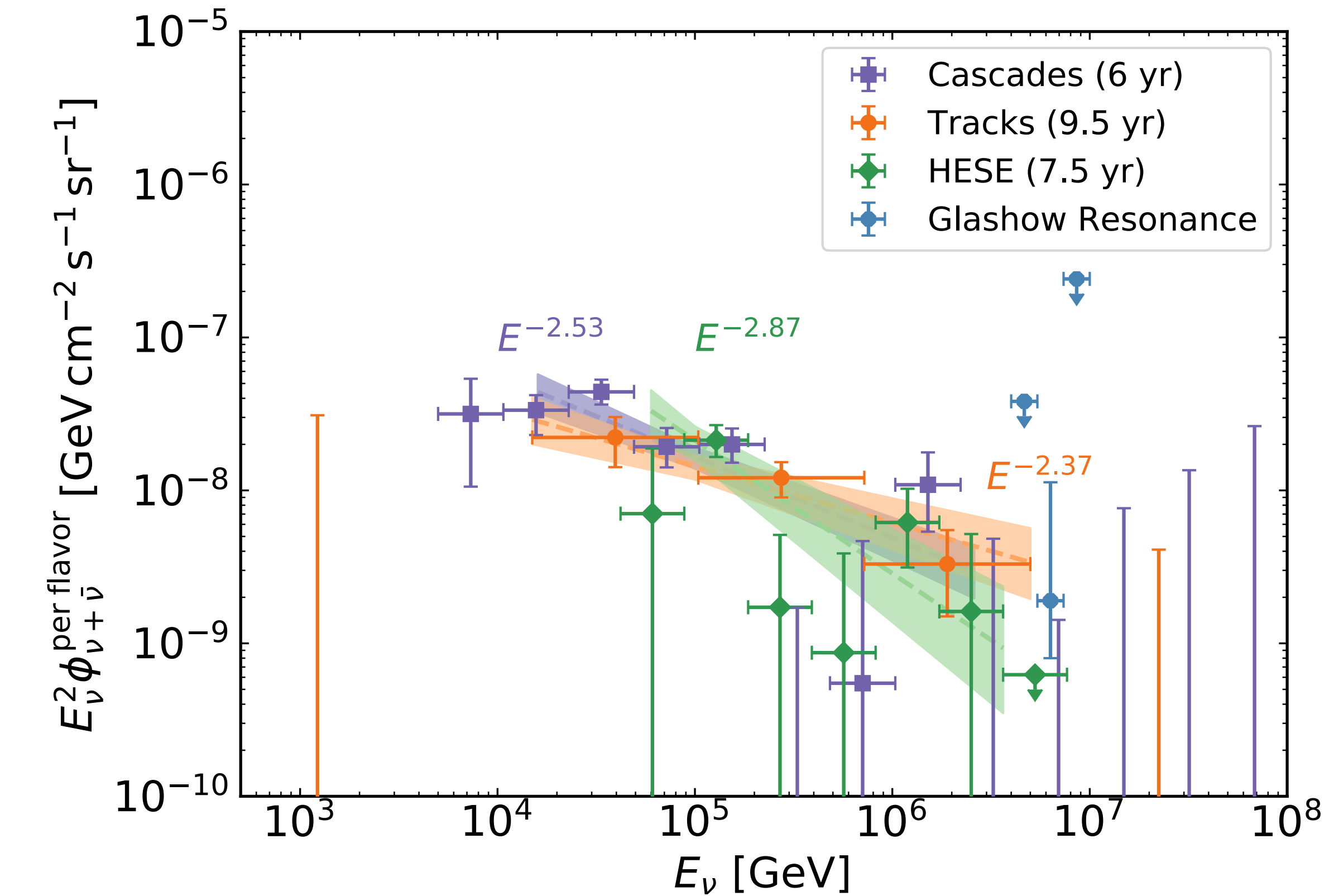
What's more can be inferred after breaking the degeneracy?

Summary

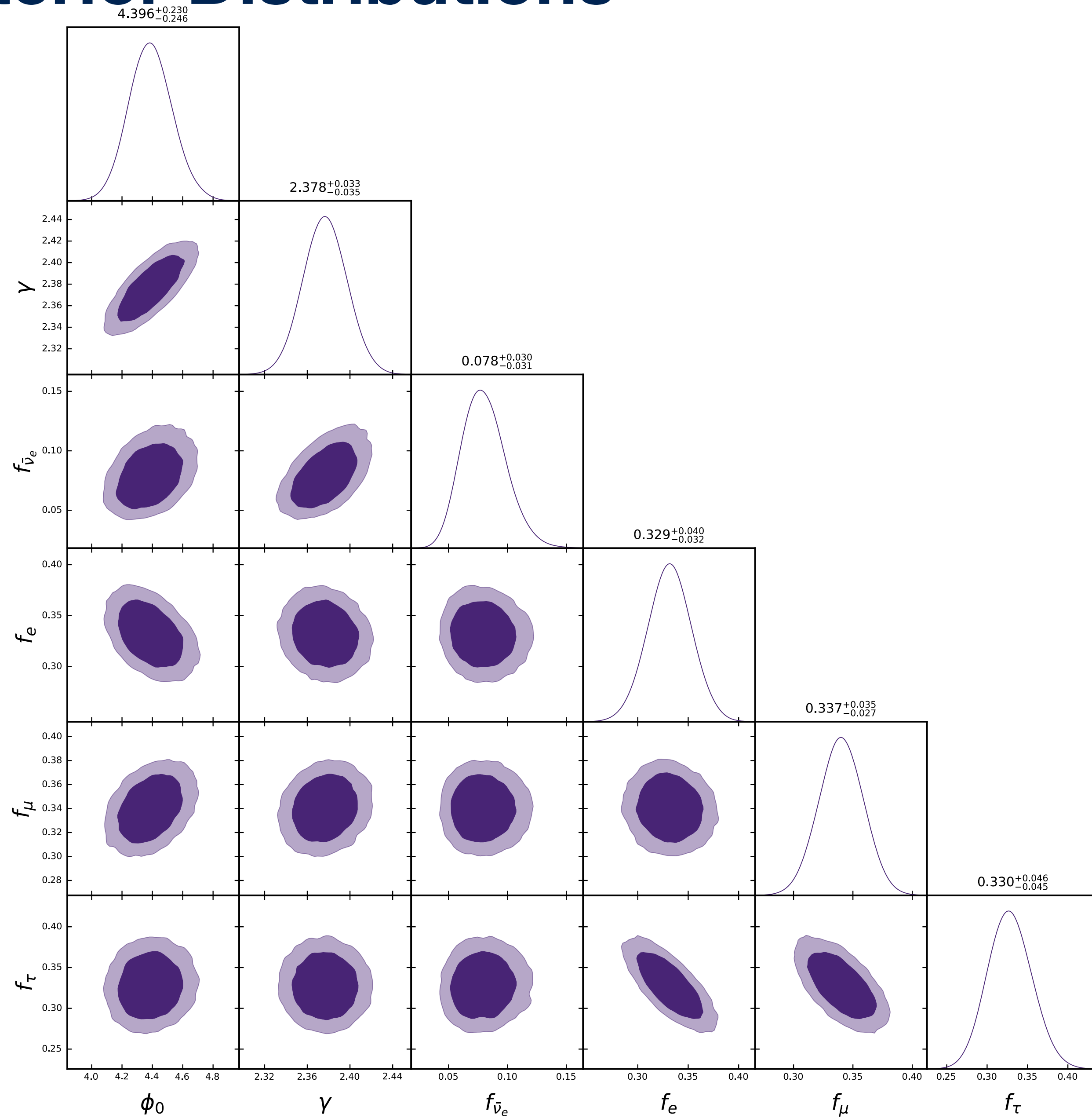
- Measuring the **flavor composition** of the diffuse high-energy astrophysical neutrino flux is crucial in the study of **neutrino production mechanisms** at the sources and **propagation of neutrinos** along the cosmological distances.
- The observation of **Glashow Resonant events** shines light on the possibility of breaking the degeneracy of neutrino and antineutrinos in flavor measurements, which helps further examine the models.
- The **next-generation neutrino telescopes** can boost the power of flavor measurements with the detection of Glashow Resonant events in the future.

Bonus Slides

Diffuse High-energy Astrophysical Neutrino Flux



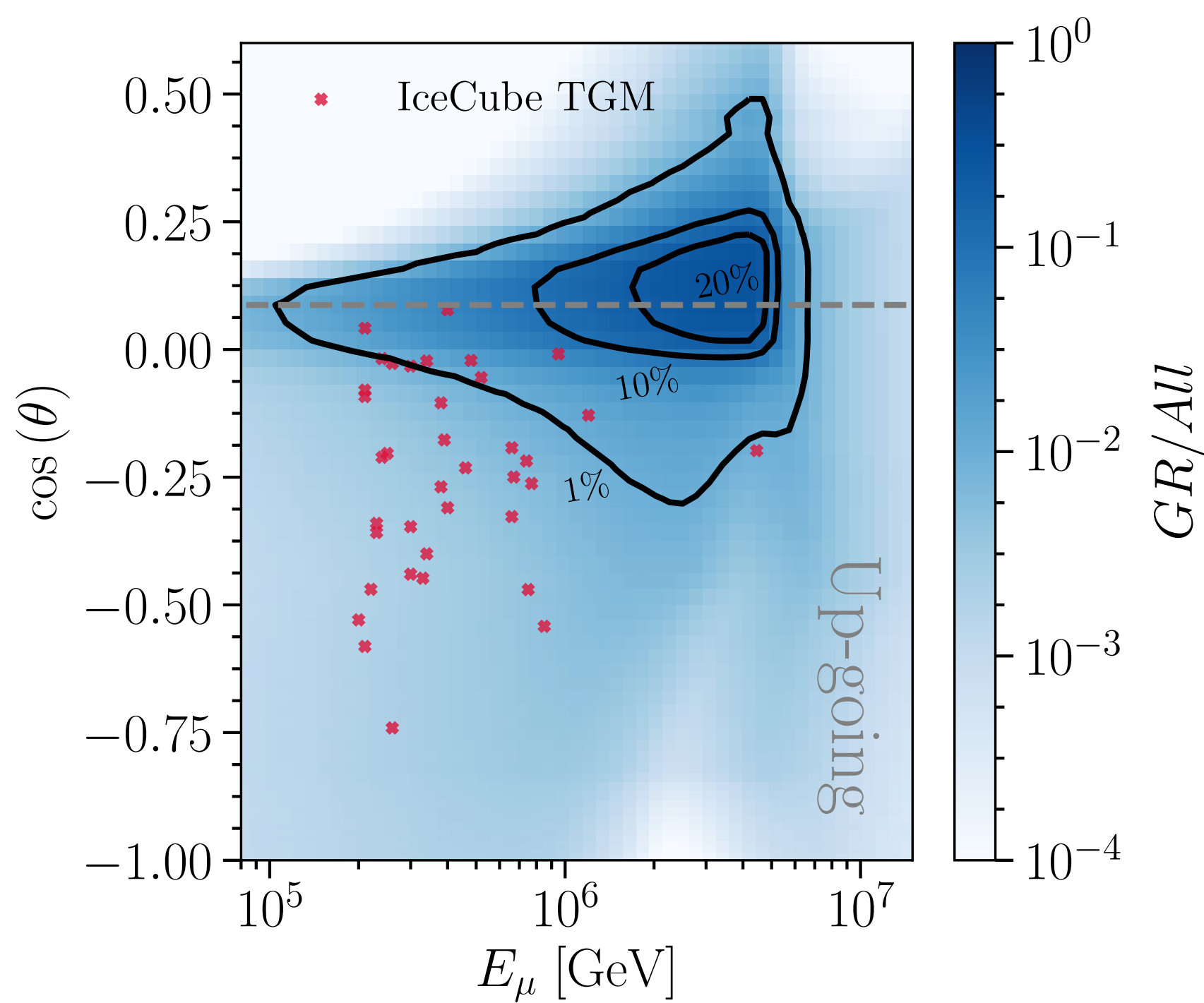
Posterior Distributions



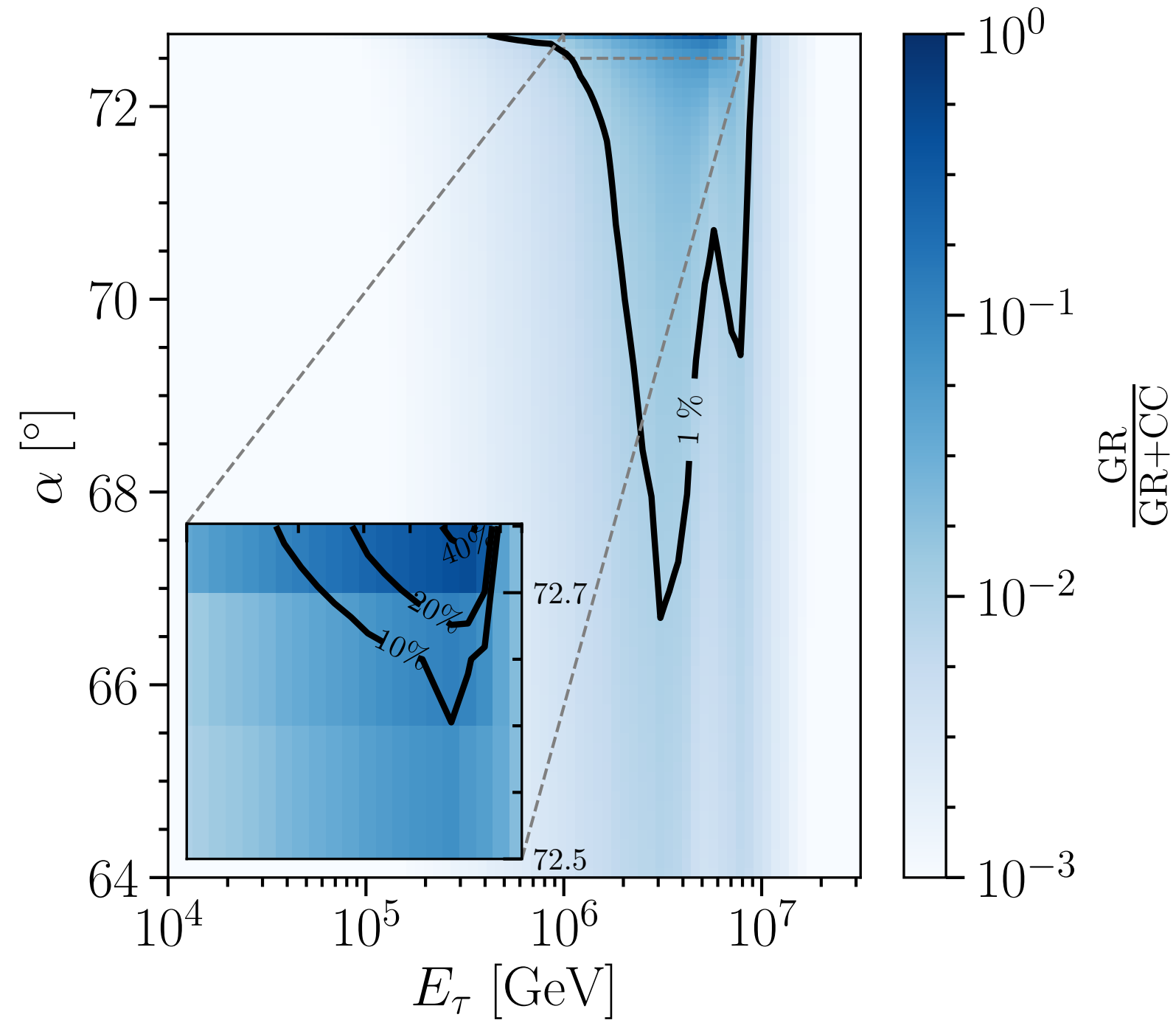
Joint posterior distributions for the astrophysical flux parameters in the 4-favor analysis for the combined exposure to 2040.

Other Observation Prospects of Glashow Resonance

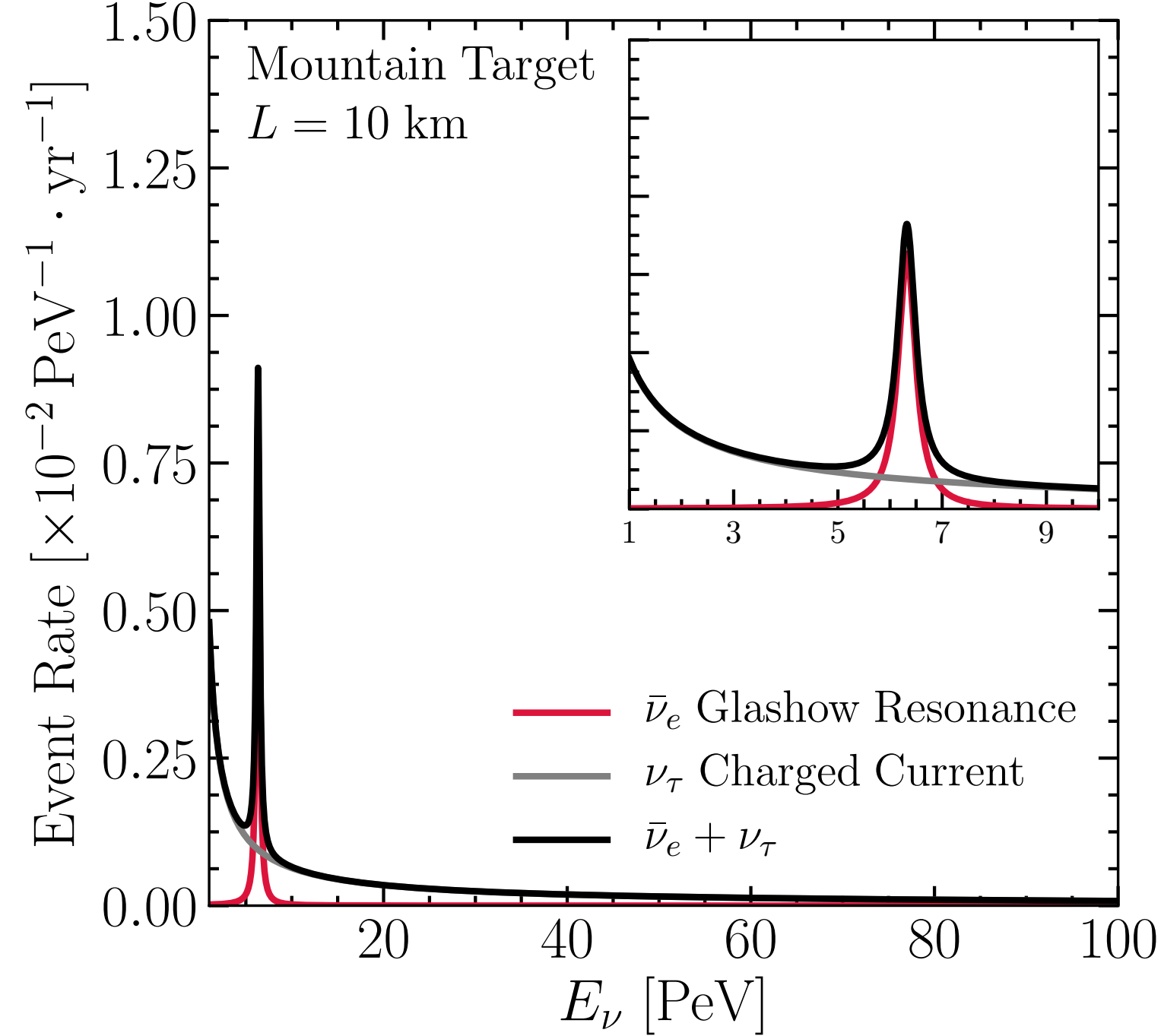
Possibility of observing Glashow resonance events as IceCube **through-going muon tracks**, in future **Earth-skimming** and **mountain-penetrating** detectors.



Fraction of through-going events induced by GR in IceCube



Fraction of air-shower tau events induced by GR in a space-based earth-skimming neutrino detector



Event rate in a mountain-penetrating neutrino detector