OPEN PROBLEMS IN NEUTRINO ASTROPHYSICS

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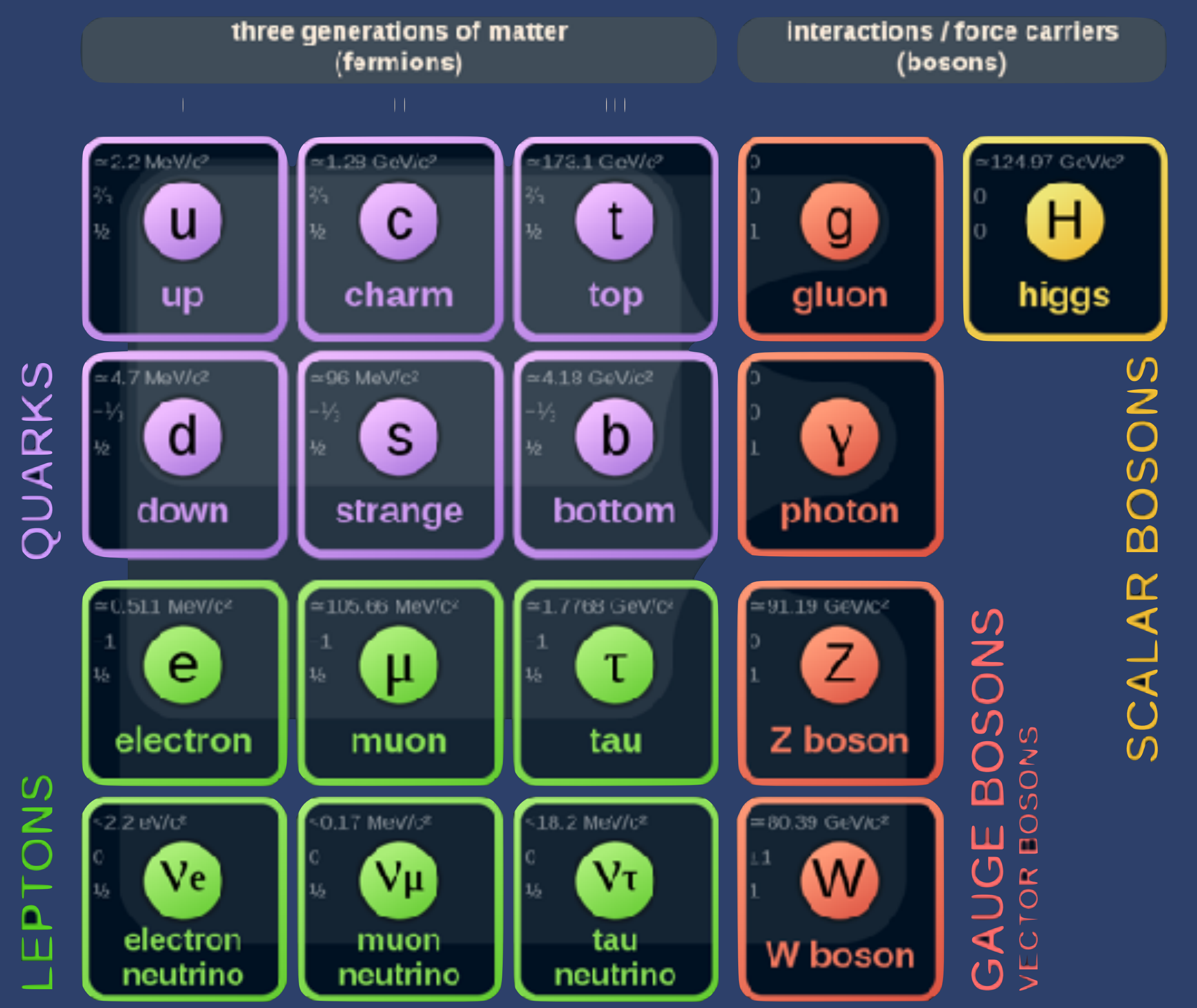
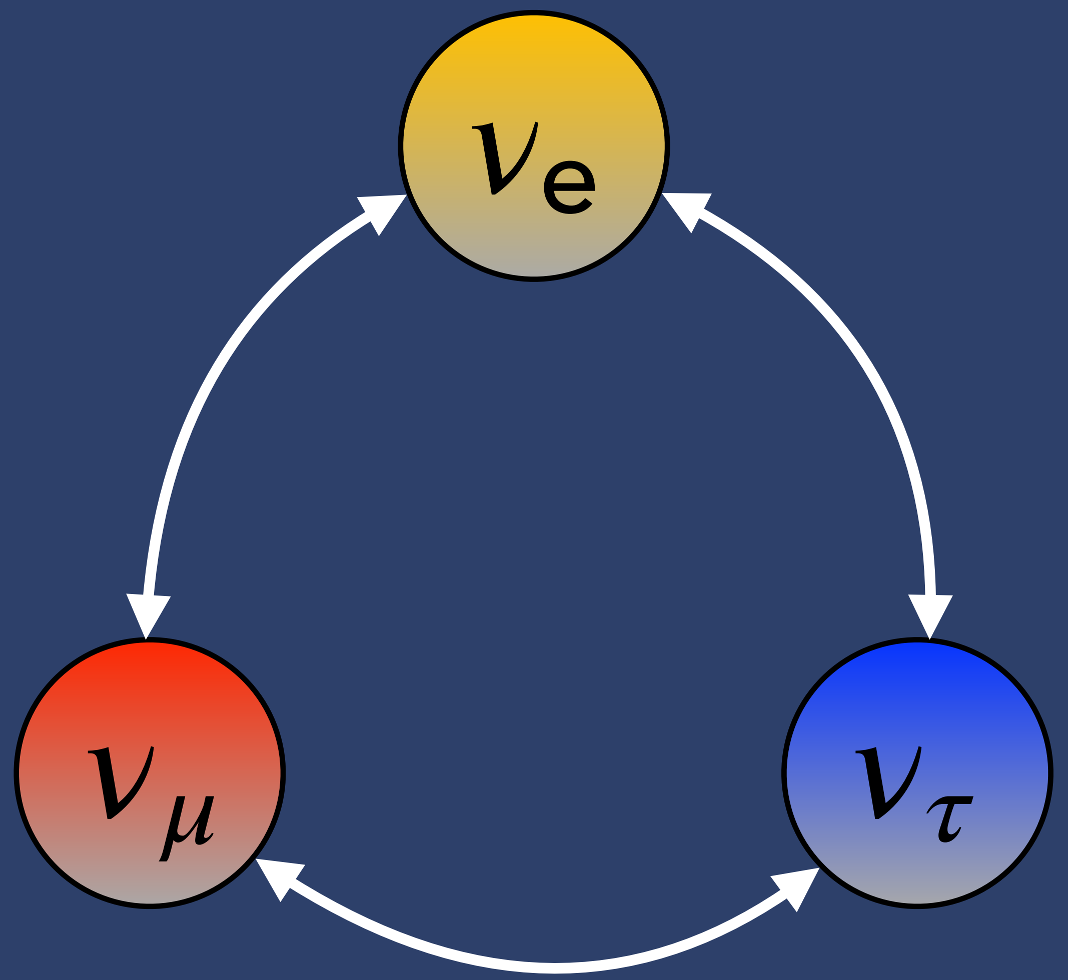
23/4/2020

OUTLINE

1. **Introduction**
2. Solar neutrinos
3. Atmospheric neutrinos
4. Cosmic neutrinos
5. Summary and outlook

Standard Model of Elementary Particles





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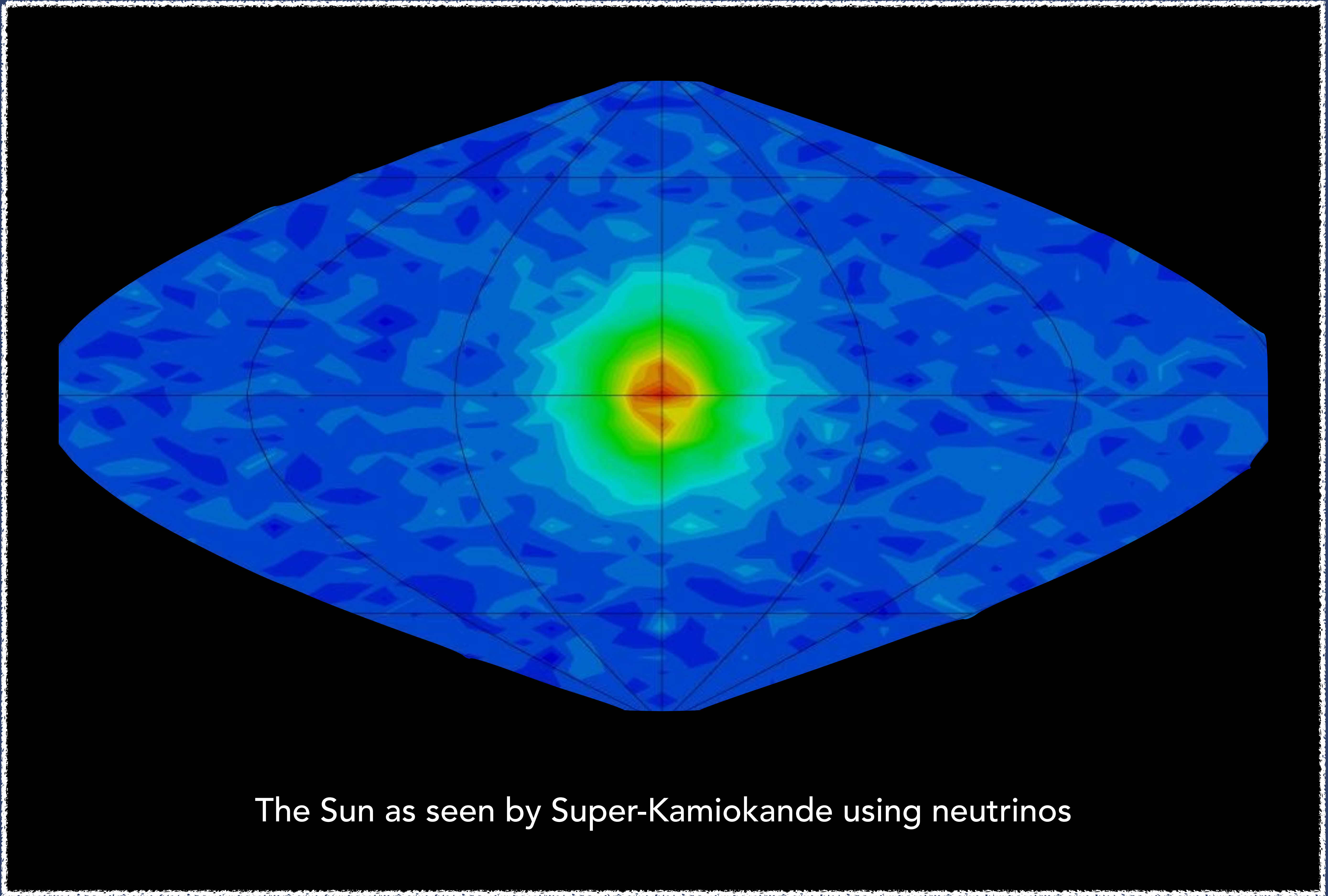

The Sun as seen by Super-Kamiokande using neutrinos

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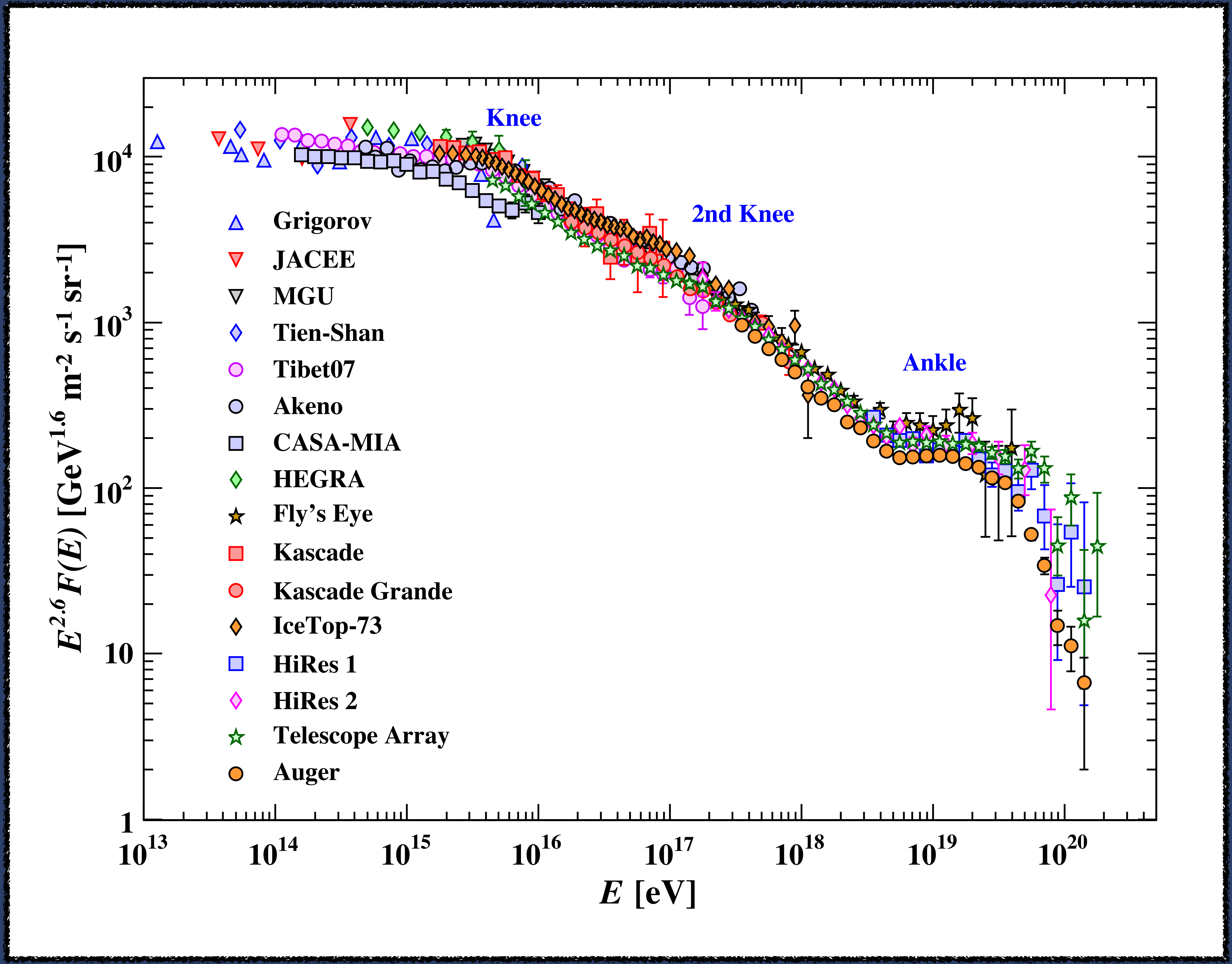

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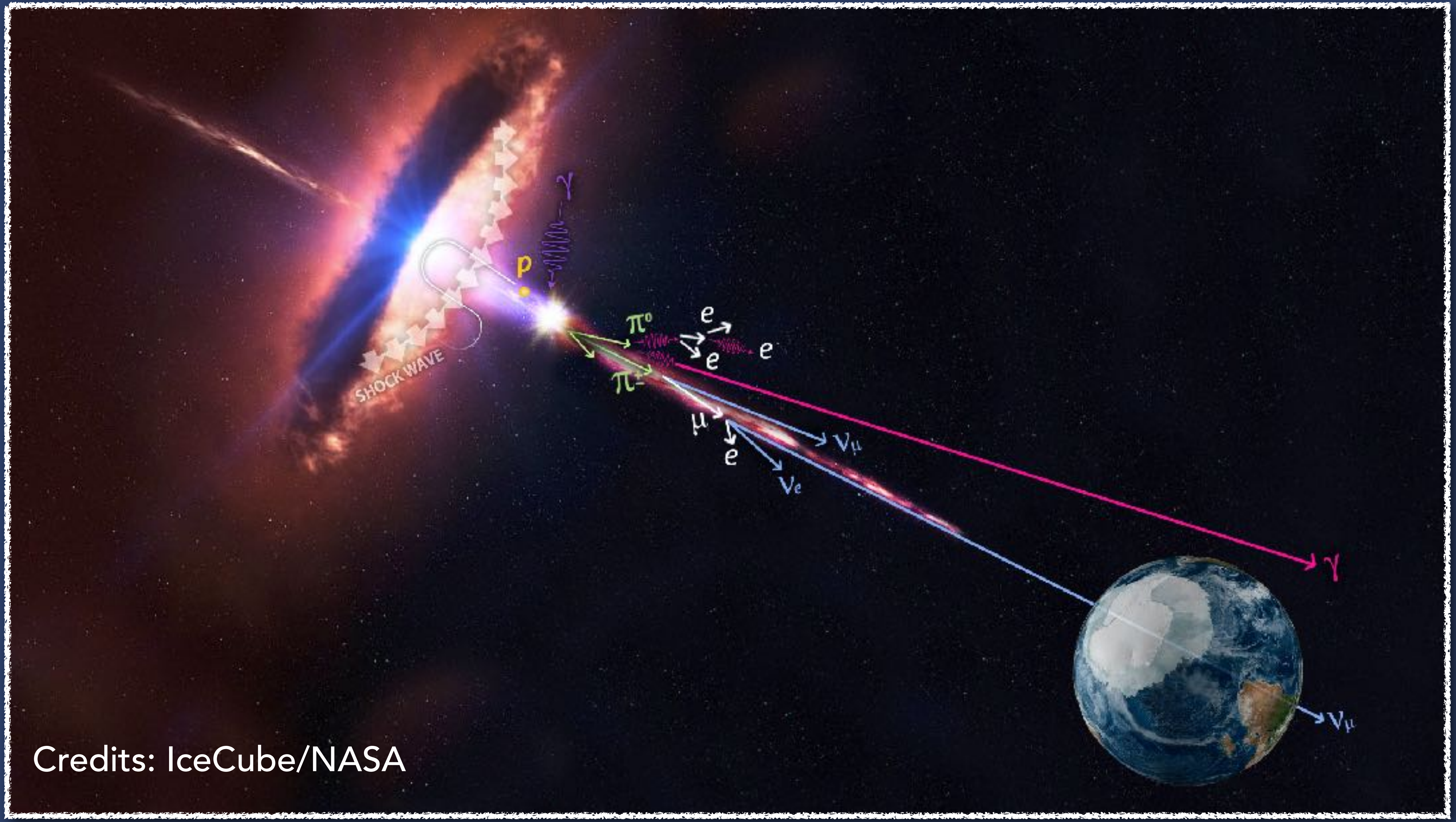

Credits: IceCube/NASA

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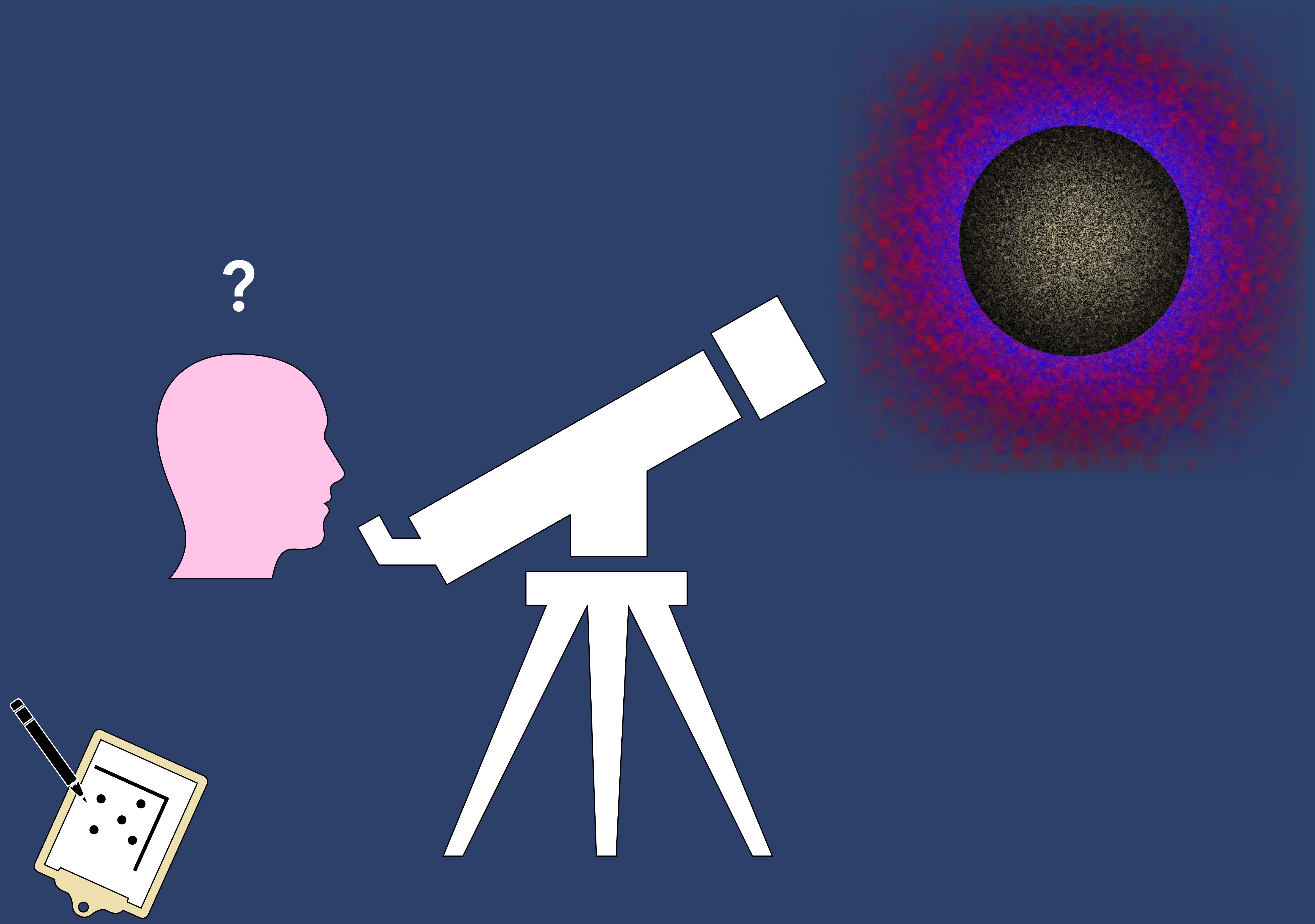
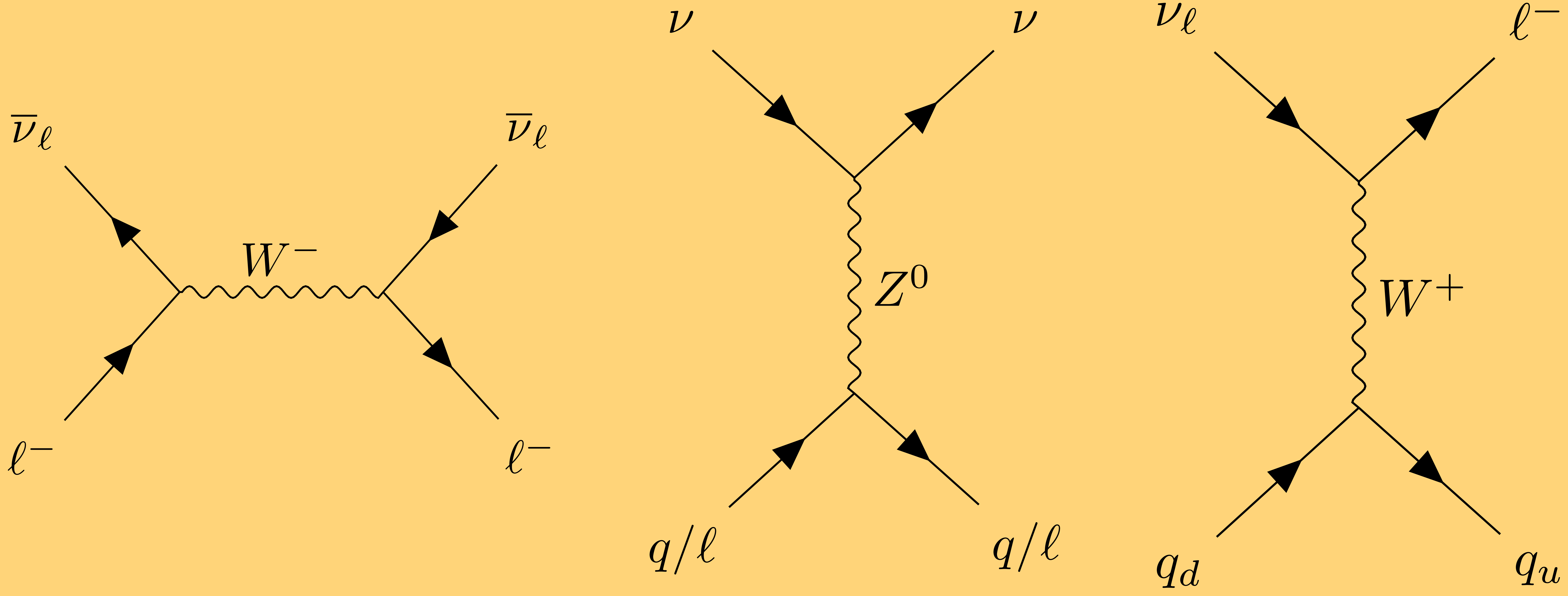


1. INTRODUCTION: NEUTRINO INTERACTIONS

Neutrinos in the Standard Model: neutral leptons associated to the charged ones ∈ SU(2) doublets



…and their crossing symmetrics

1. INTRODUCTION: NEUTRINO OSCILLATIONS (1/2)

Neutrinos transform into one another along their path

$$|\nu_\ell\rangle = \sum_k U^*_{\ell k} |\nu_k\rangle \qquad P_{\ell\ell'}(L,E) = \sum_{k,j} U^*_{\ell' j} U_{\ell j} U_{\ell' k} U^*_{\ell k} \exp\left(-i\frac{\Delta m^2_{kj} L}{2E}\right)$$

➡ they have mass

➡ clear indication of **B**eyond-**S**tandard-**M**odel (BSM) physics

1. INTRODUCTION: NEUTRINO OSCILLATIONS (2/2)

One parametrization of the mixing matrix, assuming three mass eigenstates:

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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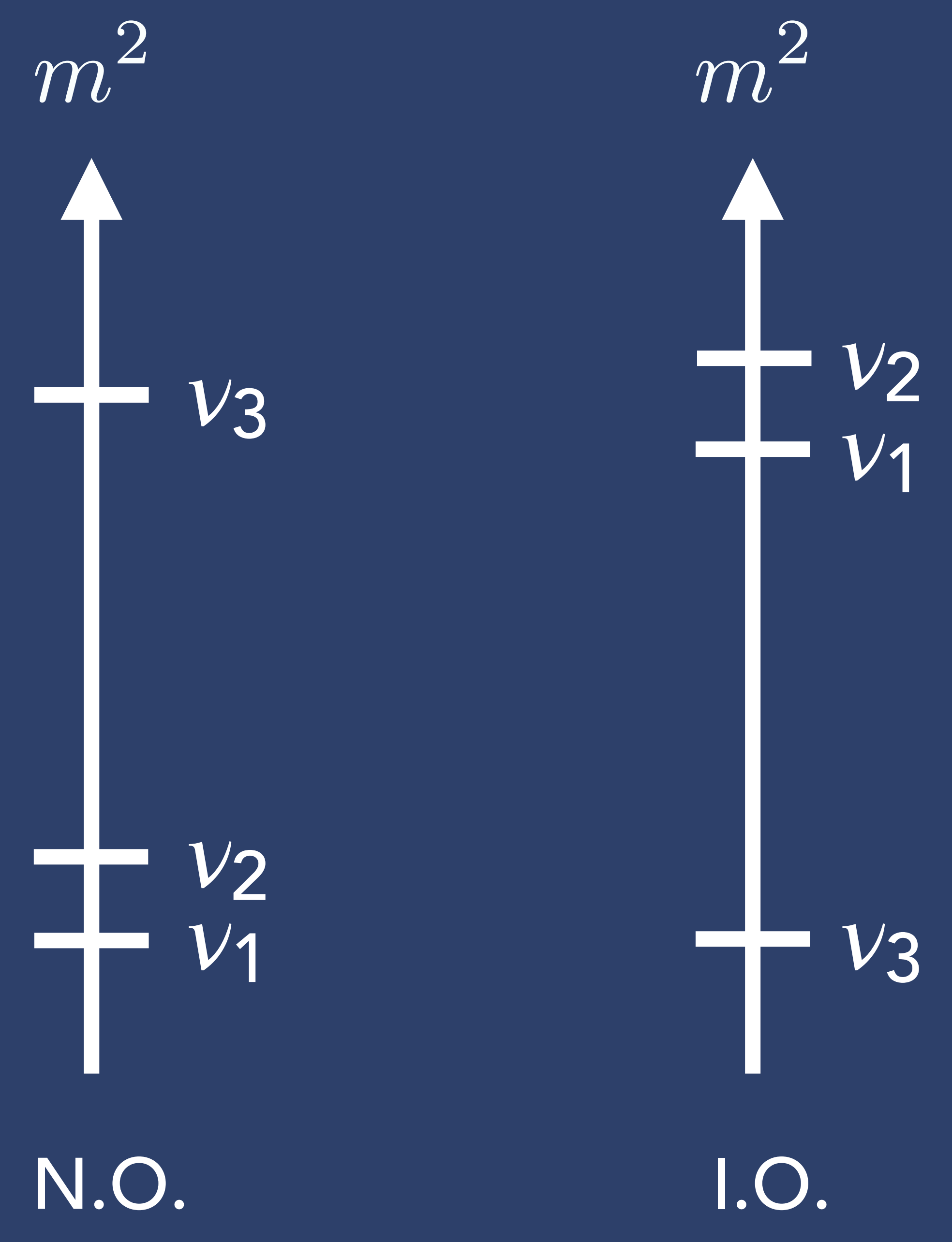
parameter	N.O.	I.O.
$\sin^2\theta_{12}$	$0.304^{+0.014}_{-0.013}$	$0.303^{+0.014}_{-0.013}$
$\sin^2\theta_{23}$	$0.551^{+0.019}_{-0.070}$	$0.557^{+0.017}_{-0.024}$
$\sin^2\theta_{13}$	$0.021^{+0.001}_{-0.001}$	$0.022^{+0.001}_{-0.001}$
δ/π	$1.32^{+0.23}_{-0.18}$	$1.52^{+0.14}_{-0.15}$
Δm^2	$2.455^{+0.045}_{-0.022} \times 10^{-3}\,\mathrm{eV}^2$	$-2.441^{+0.033}_{-0.035} \times 10^{-3}\,\mathrm{eV}^2$
δm^2	$7.34^{+0.17}_{-0.14} \times 10^{-5}\,\mathrm{eV}^2$	$7.34^{+0.17}_{-0.14} \times 10^{-5}\,\mathrm{eV}^2$

Capozzi et al. (2018)



1. INTRODUCTION: FUNDAMENTAL OPEN PROBLEMS

Neutrino oscillations probed from MeV to PeV, yet questions about their particle nature remain:

- **open problem:** what is the mass of the neutrino? ($m_\nu < 1$ eV)
- **open problem:** which is the correct ordering of the neutrino masses? (N.O. favoured at 3σ)
- **open problem**: nature of neutrinos, Dirac or Majorana?

1. UPDATE ON COSMIC NEUTRINO OSCILLATION PROBABILITIES

Based on the papers:

1. A. Palladino, C. Mascaretti, F. Vissani, EPJC **77** (2017) 684
2. A. Palladino, C. Mascaretti, F. Vissani, JCAP **2018** (2017) 08
3. C. Mascaretti & F. Vissani, JCAP **2019** (2019) 08

1. UPDATE ON COSMIC NEUTRINO OSCILLATION PROBABILITIES (1/3)

For cosmic distances $L \gg 2E/\Delta m^2$, so that:

$$P_{\ell\ell'}(L,E) = \sum_{k,j} U^*_{\ell' j} U_{\ell j} U_{\ell' k} U^*_{\ell k} \exp\left(-i\frac{\Delta m^2_{kj} L}{2E}\right) \approx \sum_k |U_{\ell k}|^2 |U_{\ell' k}|^2$$

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➡ $P_{\ell\ell'}$ is symmetric under $\ell \leftrightarrow \ell'$

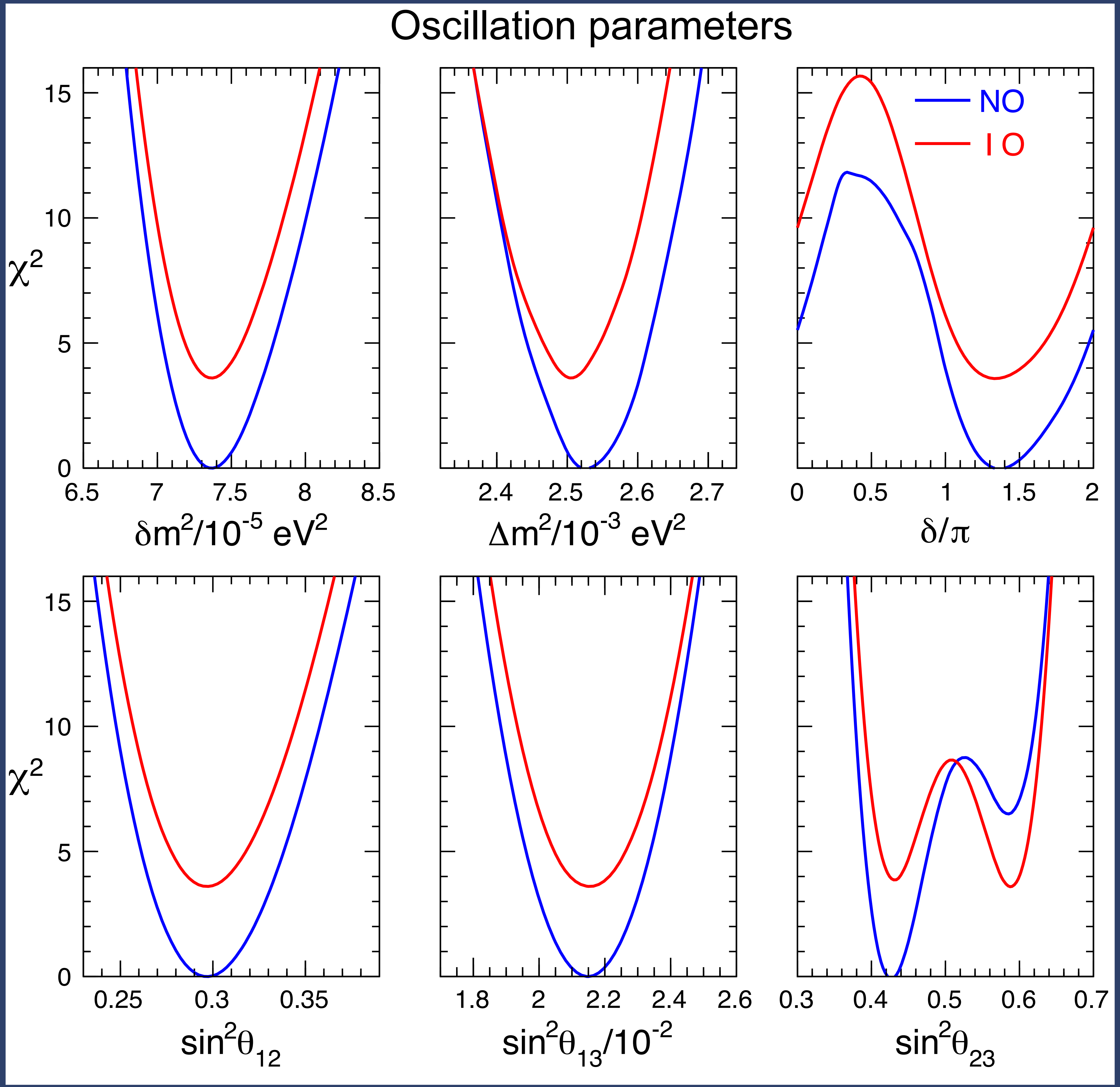
➡ only 3, "natural", parameters to describe it: P_0, P_1, P_2 (Palladino & Vissani, EPJC **75** (2015) 433)

➡ P_0, P_1, and P_2 are function of the oscillation parameters Δm^2, δm^2, $\sin^2\theta_{ij}$, δ

➡ we sampled the oscillation parameters according to their distributions to update $P_{\ell\ell'}$

1. UPDATE ON COSMIC NEUTRINO OSCILLATION PROBABILITIES (2/3)

Capozzi et al., PR **D95** (2017) 096014



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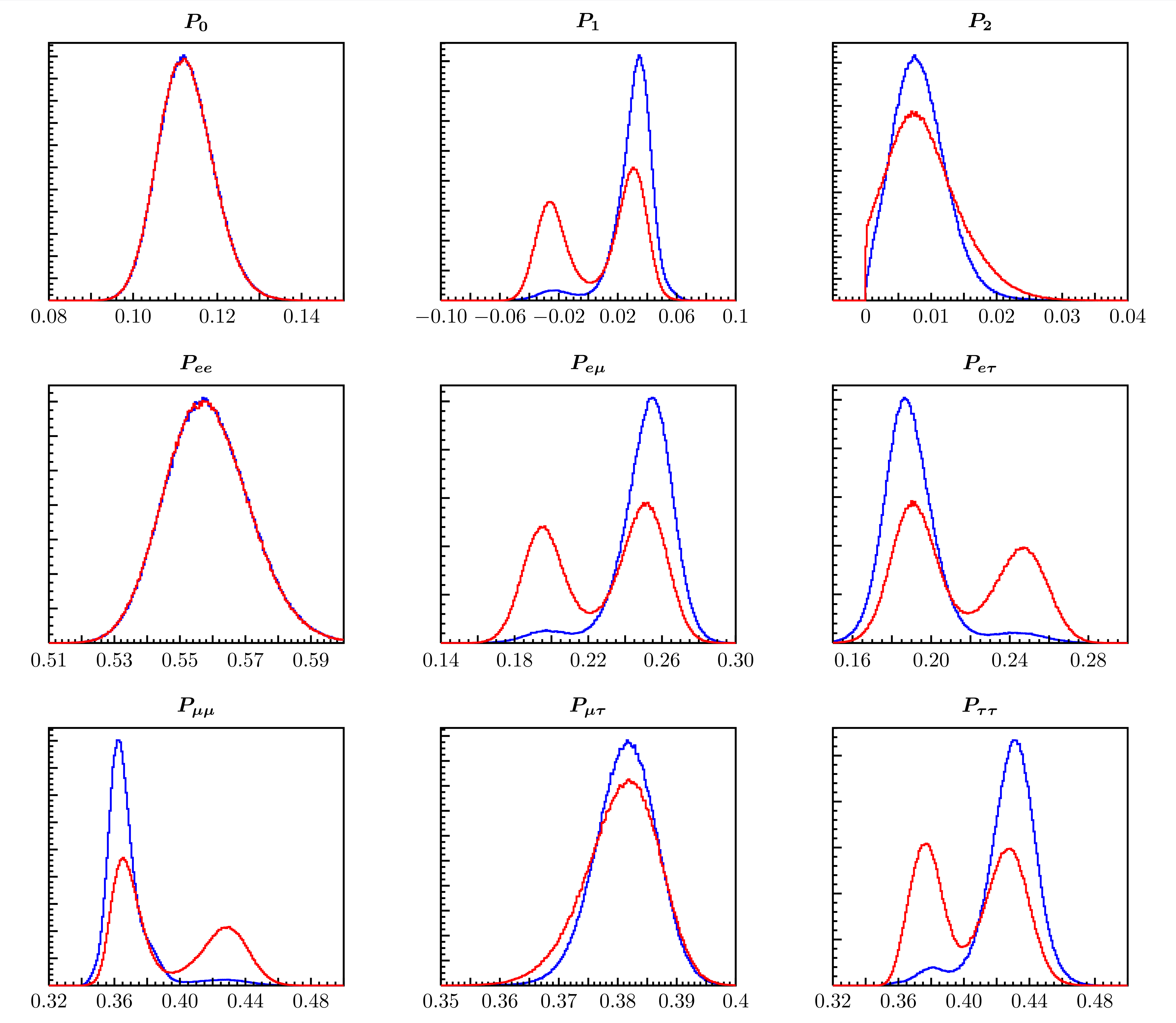

1. UPDATE ON COSMIC NEUTRINO OSCILLATION PROBABILITIES (3/3)

$$P_{\ell\ell'} = \frac{\mathbb{I}}{3} + \begin{pmatrix} 2P_0 & -P_0 + P_1 & -P_0 - P_1 \\ & P_0/2 - P_1 + P_2 & P_0/2 - P_2 \\ & & P_0/2 + P_1 + P_2 \end{pmatrix}$$

Oscillation parameters and their distributions from Capozzi et al., PR **D95** (2017) 096014.

ordering	P_{ee}	$P_{e\mu}$	$P_{e\tau}$	$P_{\mu\mu}$	$P_{\mu\tau}$	$P_{\tau\tau}$
NO	0.56 ± 0.01	$0.25^{+0.02}_{-0.01}$	$0.19^{+0.01}_{-0.02}$	$0.37^{+0.01}_{-0.02}$	0.381 ± 0.005	$0.43^{+0.02}_{-0.01}$
IO		$0.23^{+0.04}_{-0.03}$	$0.21^{+0.04}_{-0.04}$	$0.39^{+0.04}_{-0.04}$	0.381 ± 0.006	$0.40^{+0.03}_{-0.03}$

2. SOLAR NEUTRINOS

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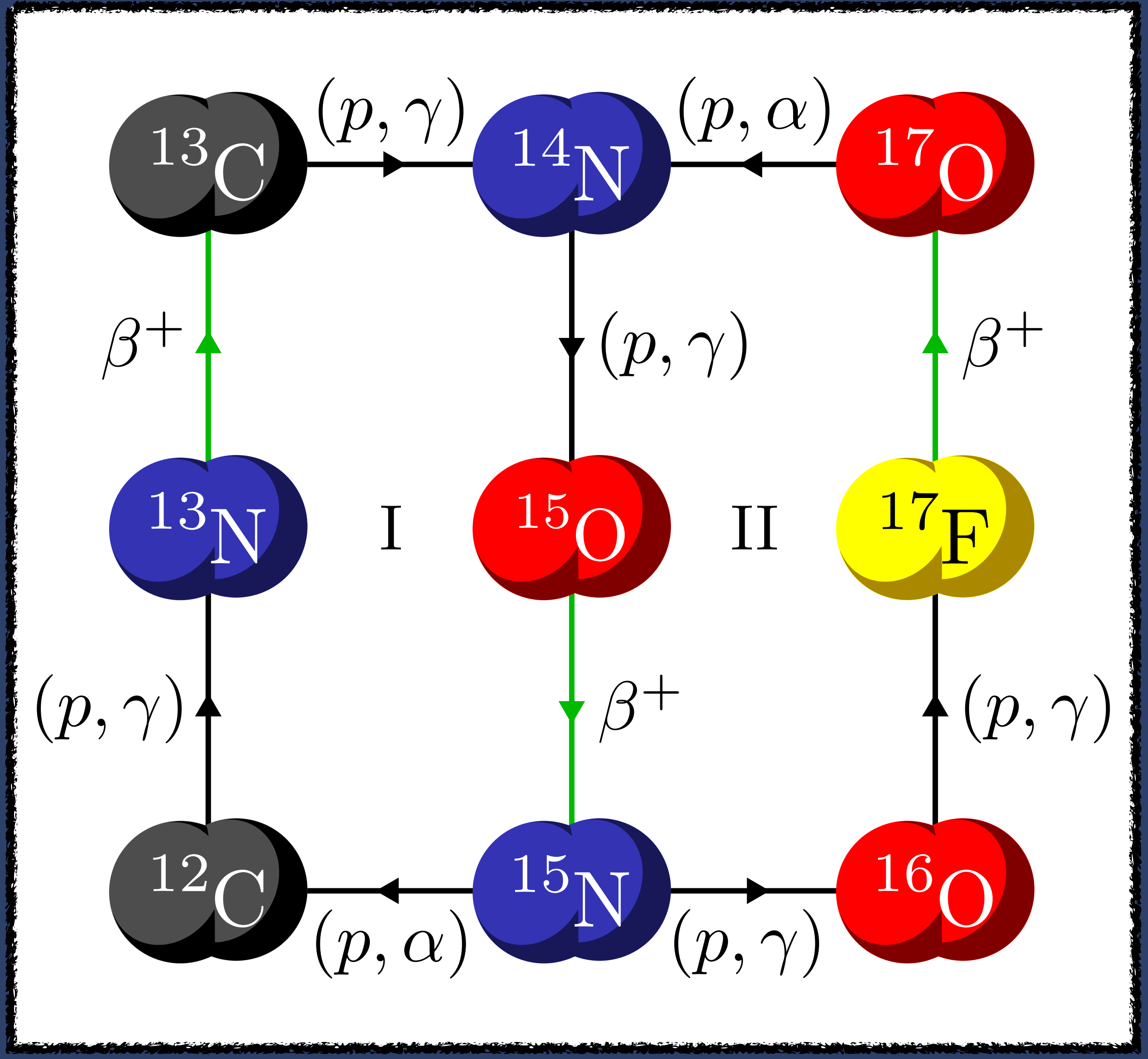
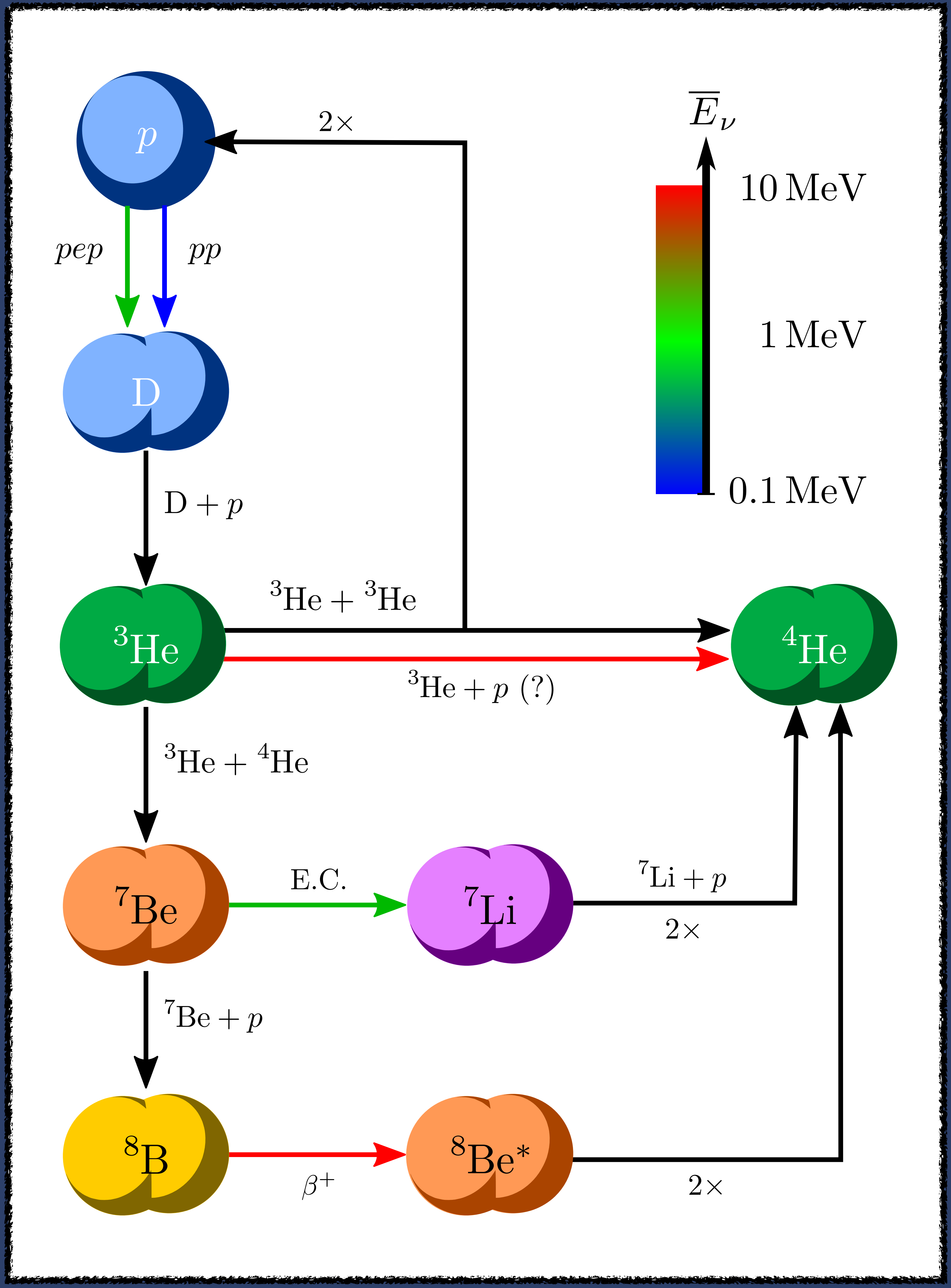
- Nuclear fusion processes fuel the Sun
- Two main sequences of reactions: the pp chain and the CNO cycles



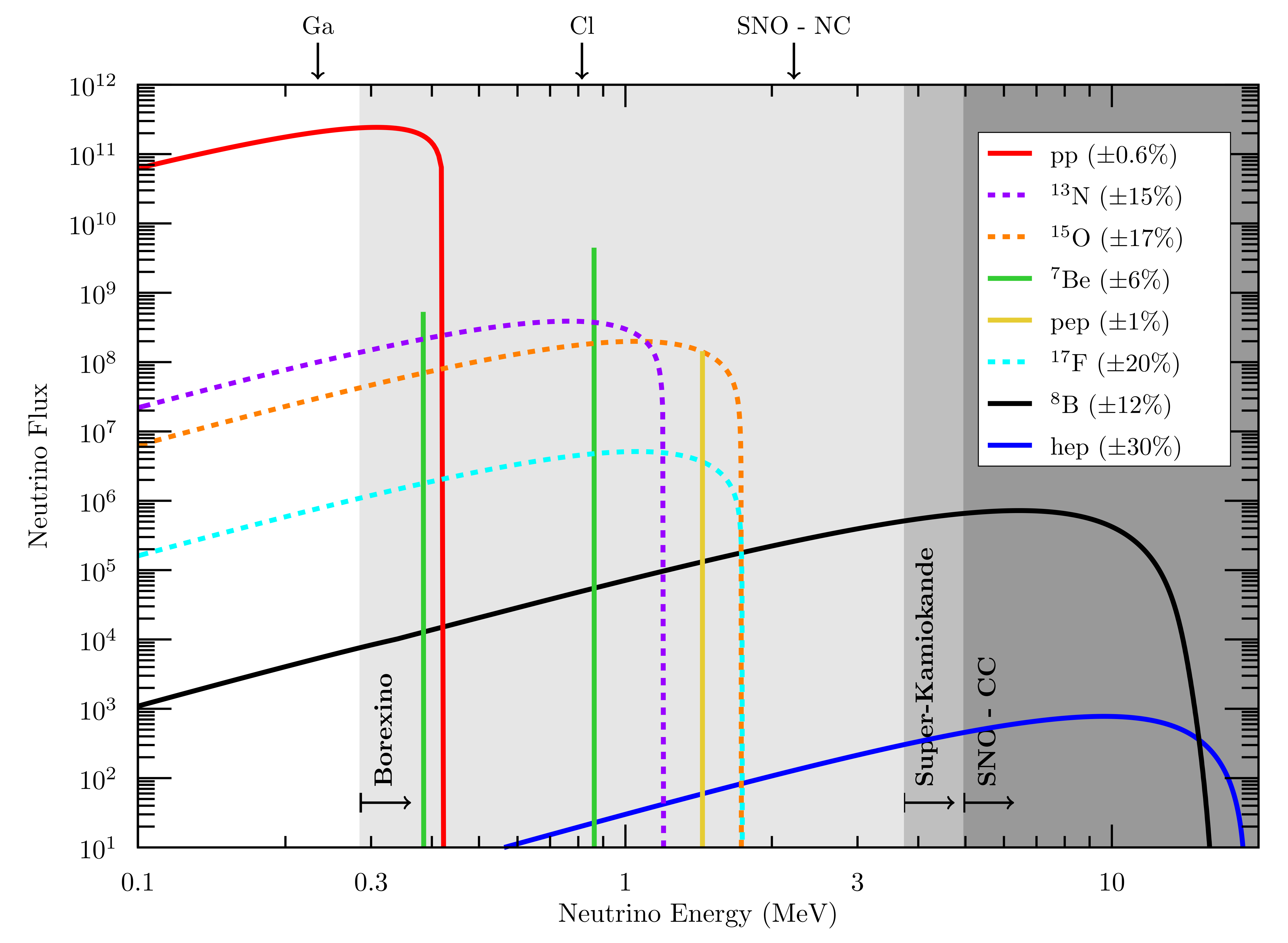


2. SOLAR NEUTRINOS: THE SSM

A Standard Solar Model (SSM) is a model

- constructed with best available physics and input data
- has to fit luminosity and radius of the Sun
- has to fit the observed heavy-element-to-hydrogen ratio at the surface of the Sun (*metallicity*)

Results: quantitative predictions (Vinyoles et al. 2016) on the neutrino fluxes at Earth



A. Gallo Rosso, C. Mascaretti, A. Palladino, F. Vissani, *Introduction to neutrino astronomy,* EPJ+ **133** (2018) 7

2. SOLAR NEUTRINOS: EXPERIMENTAL STATE OF THE ART

Very precise determination of the solar luminosity = 3.8275 (1 ± 0.04%) × 10^{33} erg s^{-1} (Mamajek et al. 2015)

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Solar neutrino fluxes are probed with high precision by Borexino (BX, Agostini et al., PR **D100** 082004) anc Super-Kamiokande (SK, Abe et al., arXiv: 1606.07538):

Flux	Theory	Experimental result	
$\Phi_{\rm pp}$	$5.98(1 \pm 0.006) \times 10^{10}$	$6.1(1 \pm 0.1) \times 10^{10}$	BX
$\Phi_{\rm pep}$	$1.44(1 \pm 0.01) \times 10^{8}$	$1.27(1 \pm 0.17) \times 10^{8}$	BX
$\Phi_{\rm Be}$	$4.93(1 \pm 0.06) \times 10^{9}$	$4.99(1 \pm 0.03) \times 10^{9}$	BX
$\Phi_{\rm B}$	$5.46(1 \pm 0.12) \times 10^{6}$	$5.41(1 \pm 0.016) \times 10^{6}$	SK
$\Phi_{\rm hep}$	$7.98(1 \pm 0.3) \times 10^{3}$	(b.f. value) 12.3×10^{3}	SK
$\Phi_{\rm CNO}$	$4.88(1 \pm 0.11) \times 10^{8}$	$< 7.9 \times 10^{8}$ (95% CL)	BX

(units are cm^{-2} s^{-1})

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It can constrain help addressing all the issues above!

2. SOLAR NEUTRINOS: THE "STANDARD" LUMINOSITY CONSTRAINT

The luminosity constraint is based on:

1. lepton number conservation
2. stationarity of the Sun
3. only ^{4}He accumulates

$$L_\odot + 4\pi d_\odot^2 \sum_i \langle E_i \rangle \, \Phi_i = Q_4 \frac{4\pi d_\odot^2 \sum_i \Phi_i}{2}$$

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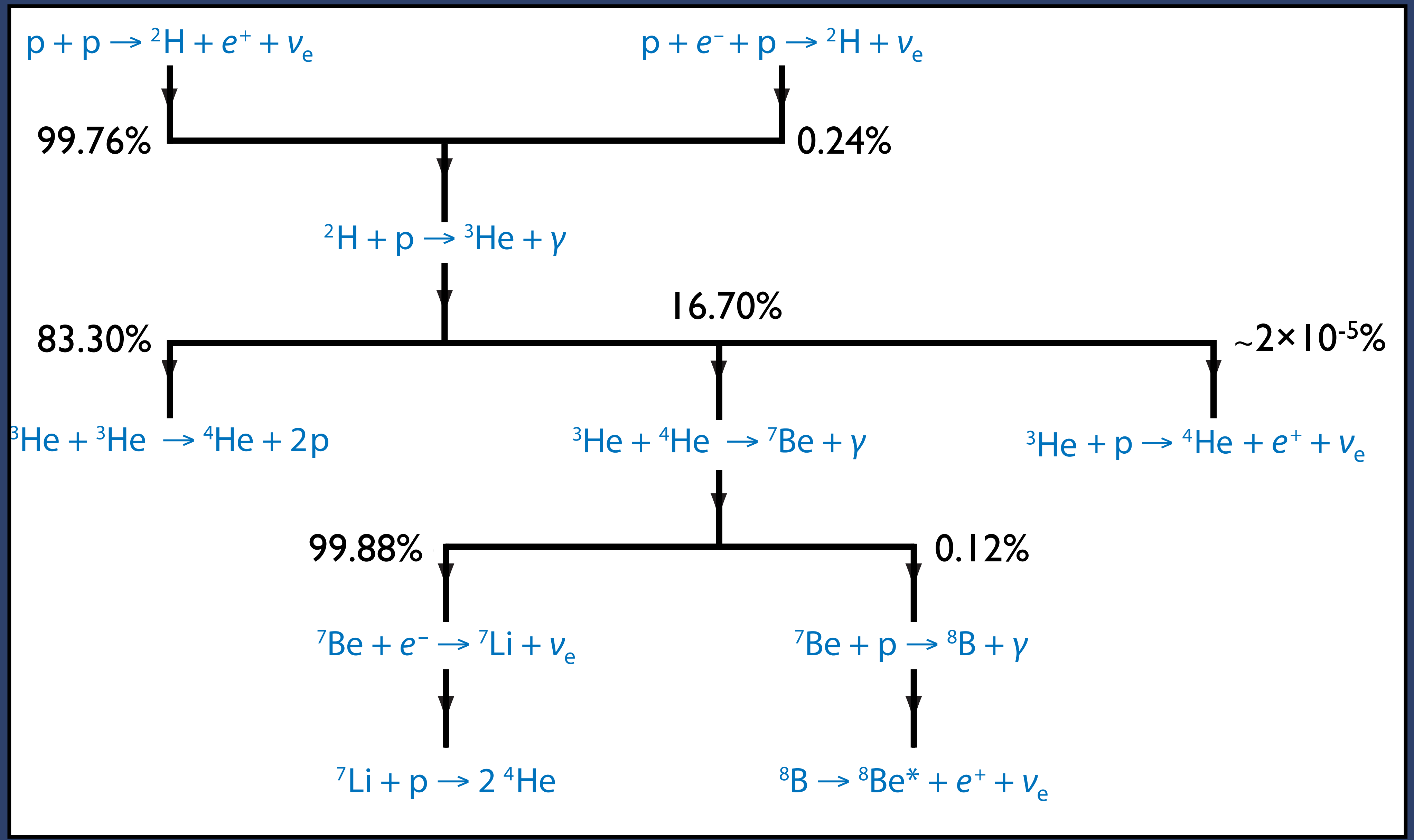

$p + p \to {}^2H + e^+ + \nu_e$

$p + e^- + p \to {}^2H + \nu_e$

99.76%

0.24%

${}^2H + p \to {}^3He + \gamma$

83.30%

16.70%

~2×10⁻⁵%

${}^3He + {}^3He \to {}^4He + 2p$

${}^3He + {}^4He \to {}^7Be + \gamma$

${}^3He + p \to {}^4He + e^+ + \nu_e$

99.88%

0.12%

${}^7Be + e^- \to {}^7Li + \nu_e$

${}^7Be + p \to {}^8B + \gamma$

${}^7Li + p \to 2\,{}^4He$

${}^8B \to {}^8Be^* + e^+ + \nu_e$

Adelberger et al., Rev. Mod. Phys. 83 195

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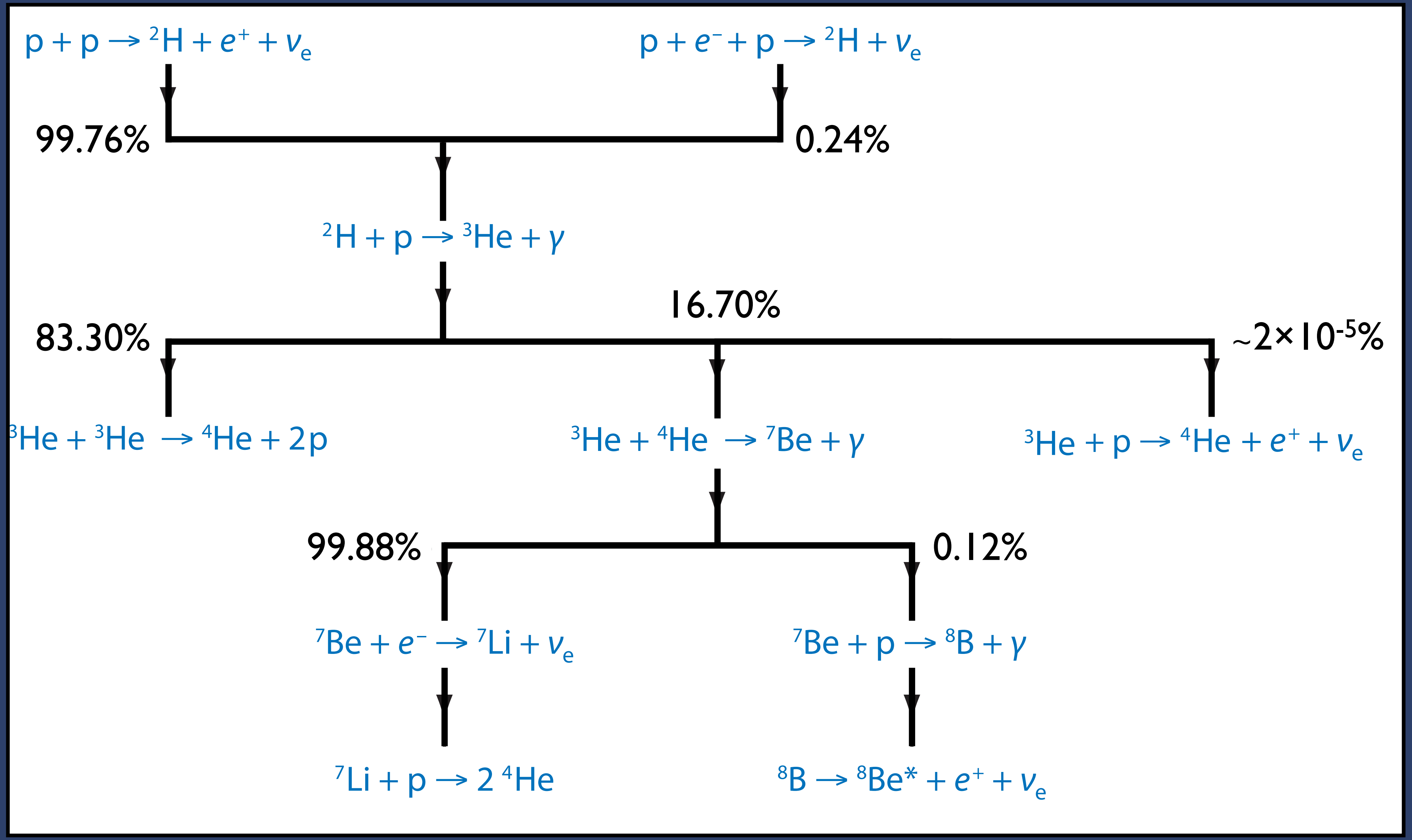

Adelberger et al., Rev. Mod. Phys. 83 195

Extremely precise determination of $L_\odot$ ➡ test for corrections to the “standard” form

2. SOLAR NEUTRINOS: THE “UPDATED” LUMINOSITY CONSTRAINT

Work in progress with F. Vissani, D. Vescovi, L. Piersanti, O. Straniero

More accurate assumptions:

1. not only ^{4}He accumulates: allow for other species to accumulate
2. stationarity of the Sun - power is emitted as the Sun expands = change in gravitational potential

$$L_\odot + L_\nu + L_{\rm g} = \sum_j Q_j \dot{N}(j)$$

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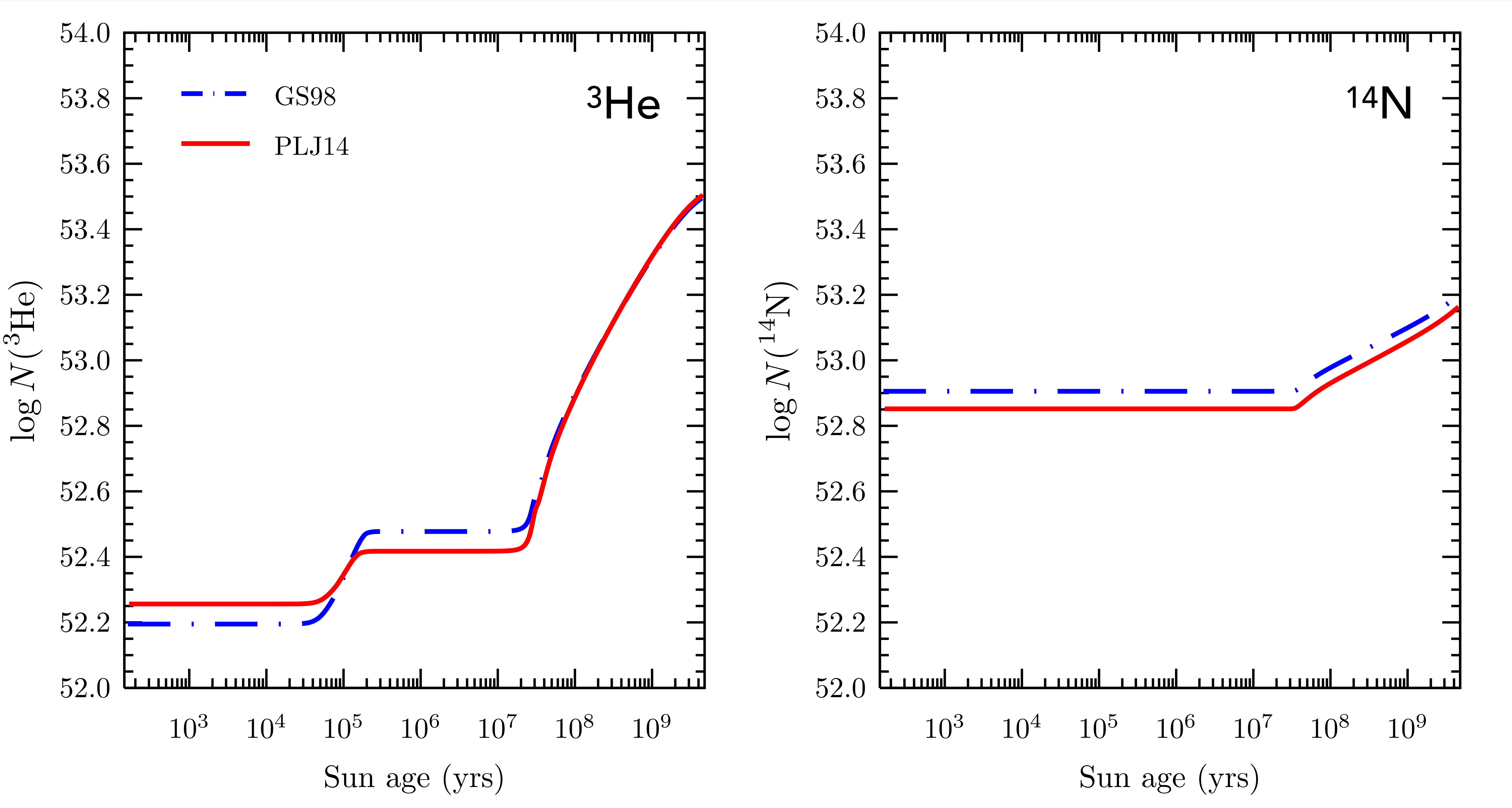
Relevance criterion for the corrections: they must of the order of $\delta L_\odot = 1.5 \times 10^{30}$ erg s^{-1}

Model	$L_{^3\mathrm{He}}[\mathrm{erg\ s^{-1}}]$	$L_{^{14}\mathrm{N}}[\mathrm{erg\ s^{-1}}]$	$L_\mathrm{g}\ [\mathrm{erg\ s^{-1}}]$
GS98	2.55×10^{30}	5.78×10^{29}	2.48×10^{30}
PLJ14	2.02×10^{30}	5.62×10^{29}	3.13×10^{30}

2. SOLAR NEUTRINOS: ACCUMULATING ELEMENTS

^{3}He and ^{14}N accumulate as the reactions that consume them are very slow



2. SOLAR NEUTRINOS: THE CONSTRAINT ON PP AND CNO

In order to obtain a precise constraint on the flux of pp and CNO neutrinos we can:

- neglect $\boldsymbol{\Phi}_{\mathrm{hep}}$ and $\boldsymbol{\Phi}_{\mathrm{F}}$ - they are very small
- fix $\boldsymbol{\Phi}_{\mathrm{Be}}$ and $\boldsymbol{\Phi}_{\mathrm{B}}$ to the experimental results - known better than theory
- fix the ratios $\boldsymbol{\Phi}_{\mathrm{pep}}/\boldsymbol{\Phi}_{\mathrm{pp}}$ and $\boldsymbol{\Phi}_{\mathrm{O}}/\boldsymbol{\Phi}_{\mathrm{N}}$

$$\frac{\Phi_{pep}}{\Phi_{pp}} = 2.37 \times 10^{-3} \qquad \frac{\Phi_{\mathrm{O}}}{\Phi_{\mathrm{N}}} = 0.72$$

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$$\frac{\Phi_{pep}}{\Phi_{pp}} = 2.37 \times 10^{-3} \qquad \frac{\Phi_{\mathrm{O}}}{\Phi_{\mathrm{N}}} = 0.72$$

The resulting constraint is: $\Phi_{pp} + 1.646\,\Phi_{\mathrm{N}} = \boxed{k}(1 \pm 0.2\%) \times 10^{10}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

	standard	^{3}He	^{3}He + ^{14}N	^{3}He + ^{14}N + L_{g}
GS98	6.007	6.011	6.012	6.016
PLJ14	6.007	6.010	6.011	6.017

3. ATMOSPHERIC NEUTRINOS

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Cosmic rays collide with the nuclei in the atmosphere, producing showers of particles.

Some of these decay into neutrinos:

- pions and kaons ($\tau_{\text{rest}} \sim 10^{-8}$ s) produce conventional neutrinos
- charmed mesons, baryons and tau leptons ($\tau_{\text{rest}} \sim 10^{-12}$ s) produce prompt neutrinos

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Conventional neutrinos:

- anisotropic, ~ $|\cos(\theta)|^{-1}$
- follow $E^{-3.7}$
- $(\nu_e : \nu_\mu : \nu_\tau) = (1/3 : 2/3 : 0)$ for $E_\mu \lesssim 2.5$ GeV
- measured between 1 GeV and few TeV

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In this work we will talk about both!

3. ATMOSPHERIC NEUTRINOS AND THE COSMIC-RAY KNEE

Atmospheric neutrinos may be used for cosmic-ray studies.

Rule of thumb: $E_{\nu\ \mathrm{atm.}} \sim E_{\mathrm{CR}}/20A$

➡ CR knee should be visible in the neutrino spectrum at $E_{\nu\ \mathrm{atm.}} \sim E_{\mathrm{knee}}/20$

➡ possibility to discriminate between the knee as measured by ARGO and KASCADE-Grande?

3. ATMOSPHERIC NEUTRINOS AND THE COSMIC-RAY KNEE

Atmospheric neutrinos may be used for cosmic-ray studies.

Rule of thumb: $E_{\nu\ \mathrm{atm.}} \sim E_{\mathrm{CR}}/20A$

➡ CR knee should be visible in the neutrino spectrum at $E_{\nu\ \mathrm{atm.}} \sim E_{\mathrm{knee}}/20$

➡ possibility to discriminate between the knee as measured by ARGO and KASCADE-Grande?

C. Mascaretti, P. Blasi, C. Evoli, *Atmospheric neutrinos and the knee of the Cosmic Ray spectrum,*
Astroparticle Physics **114** (2020) 22-29

Strategy of the work:

- define custom primary CR flux models
- compute atmospheric neutrino flux from them
- compare to available data to discriminate

3. ATMOSPHERIC NEUTRINOS AND THE COSMIC-RAY KNEE

PART 1: THE PRIMARY FLUX OF COSMIC RAYS (1/2)

Custom cosmic-ray flux:

- only protons and Helium nuclei

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$$\frac{d\Phi_{\mathrm{CR}}}{dE} = \sum_{i=\mathrm{p,He}} N_i \left(\frac{E}{10\ \mathrm{TeV}}\right)^{-\gamma_i}$$

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$$\frac{d\Phi_{\mathrm{CR}}}{dE} = \sum_{i=\mathrm{p,He}} N_i \left(\frac{E}{10\ \mathrm{TeV}}\right)^{-\gamma_i} f_{\mathrm{knee}}(E/Z_i)$$

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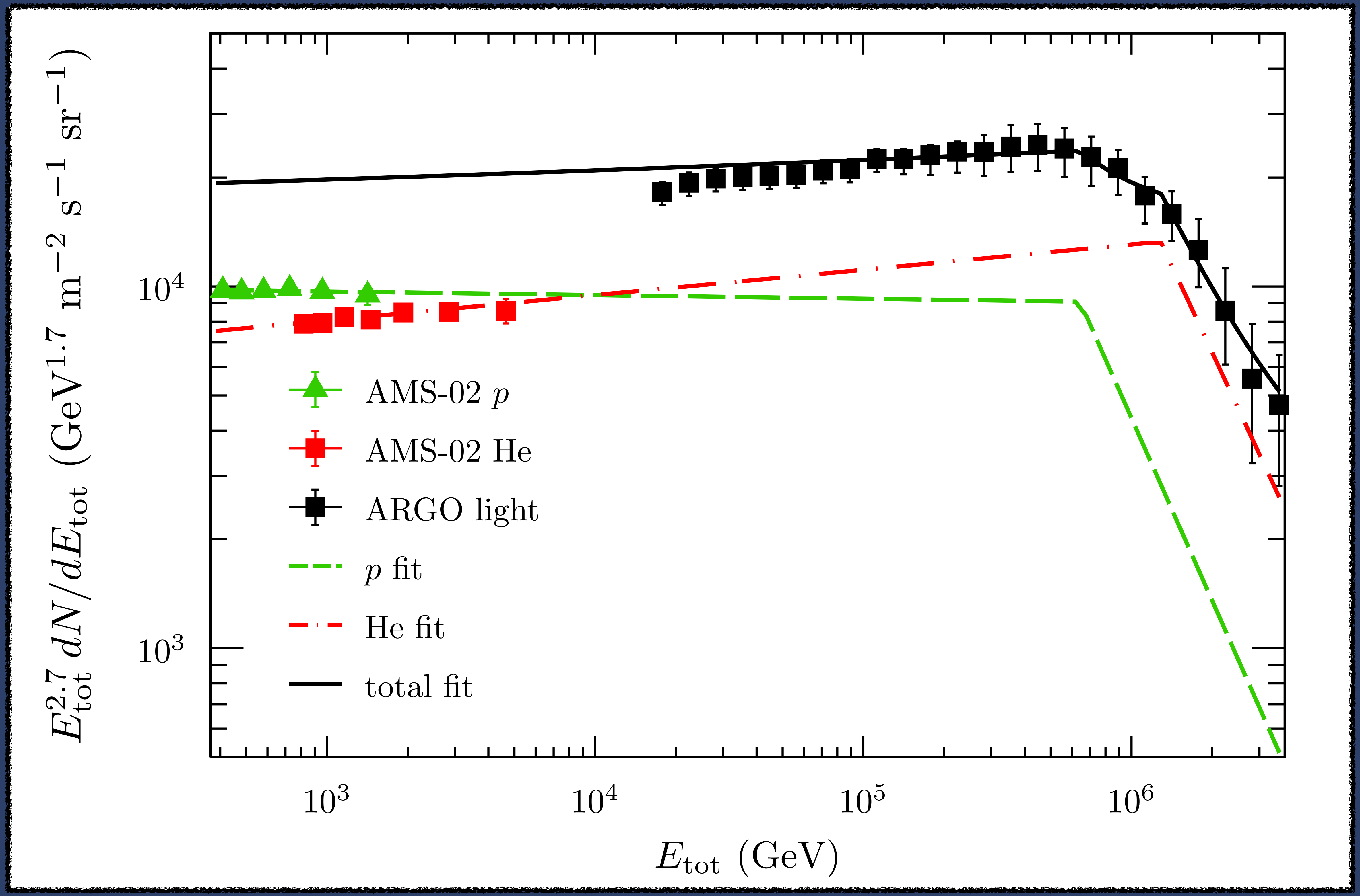
- additional extra-galactic component fitted to KASCADE-Grande: protons ~ $E^{-2.7}$

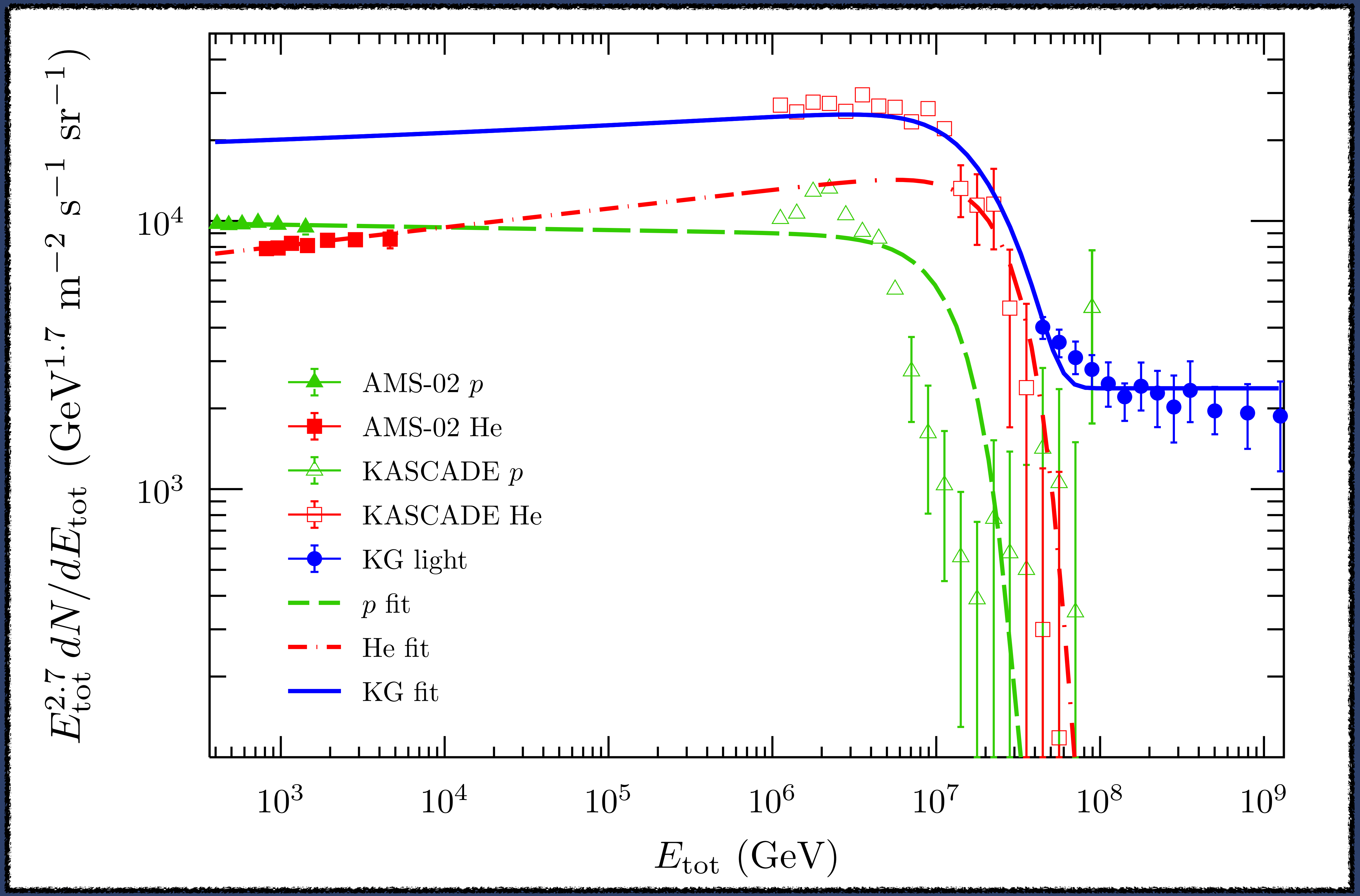
$$\frac{d\Phi_{\mathrm{CR}}}{dE} = \sum_{i=\mathrm{p,He}} N_i \left(\frac{E}{10\ \mathrm{TeV}}\right)^{-\gamma_i} f_{\mathrm{knee}}(E/Z_i) + \left.\frac{d\Phi_p}{dE}\right|_{\text{x-gal}}$$

3. ATMOSPHERIC NEUTRINOS AND THE COSMIC-RAY KNEE

PART 1: THE PRIMARY FLUX OF COSMIC RAYS (2/2)



“Delta-slope” knee at 640 TV, ARGO data



“Exp2-cut” knee at 15 PV, KG data

3. ATMOSPHERIC NEUTRINOS AND THE COSMIC-RAY KNEE

PART 2: COMPUTATIONAL TOOLS

We used “Matrix Cascade Equations” (MCEq) to compute $\Phi_{\nu \text{ atm.}}$:

- custom CR flux models
- many hadronic interaction models (SIBYLL-2.3c used otherwise noted)
- zenith dependence
- conditions of the atmosphere at the South Pole in January and July

3. ATMOSPHERIC NEUTRINOS AND THE COSMIC-RAY KNEE

PART 3: DEPENDENCE ON THE PRIMARY CR SPECTRUM

Check for dependence on primary CR spectrum: run the code with our models and with Hillas-Gaisser "H3a":

$$\frac{dN_i}{d\log E} = \sum_{j=1}^{3} \mathcal{N}_{i,j} E^{-\gamma_{i,j}} \exp\left(-\frac{E}{Z_i R_j}\right)$$

where i = p, He, CNO, Mg-Si, Fe.

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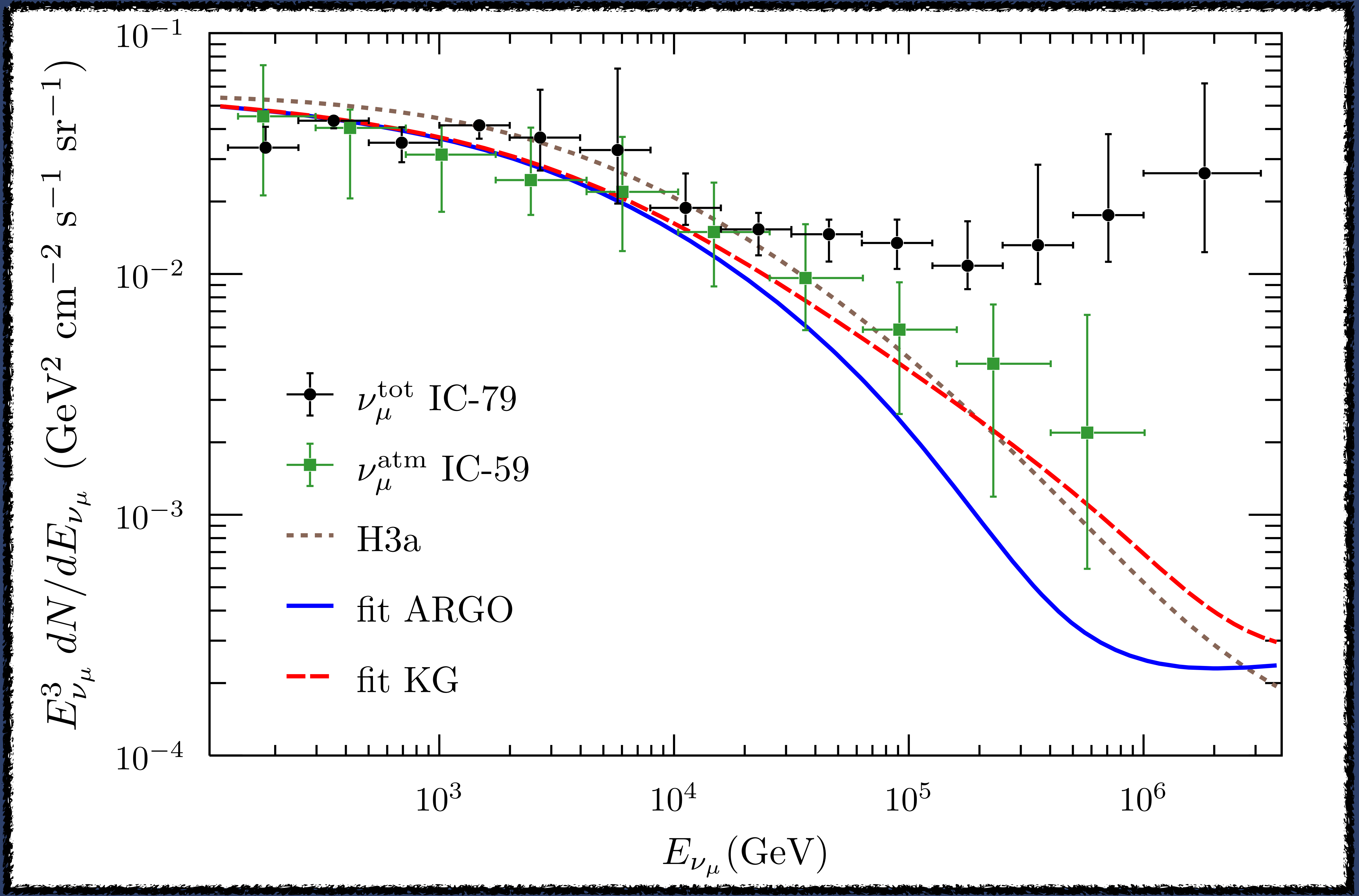

$E^3\, dN\nu_\mu/dE\nu_\mu$ vs $E\nu_\mu$

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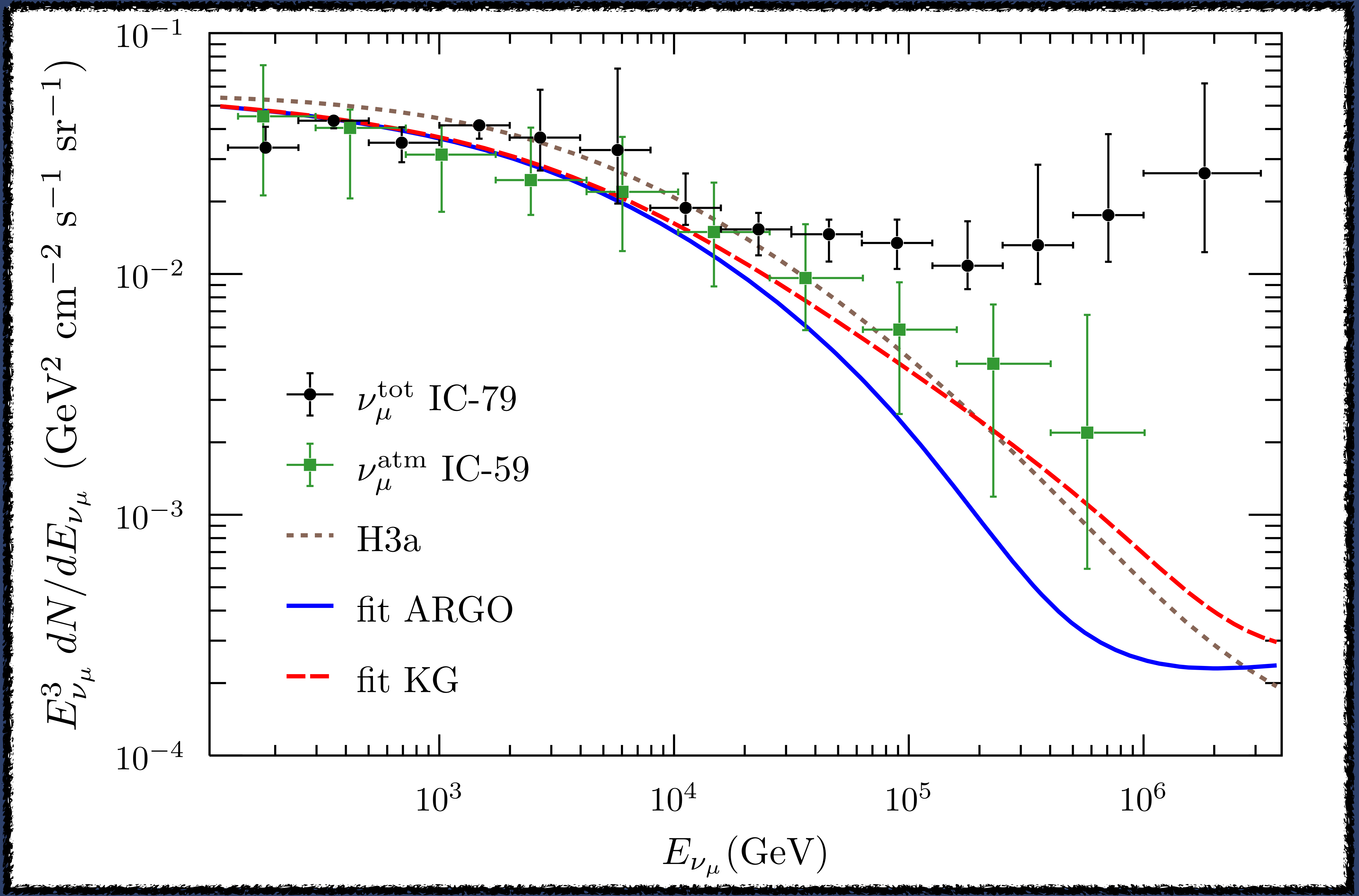
➡ Light elements dominate



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Assessment of theoretical uncertainties due to:

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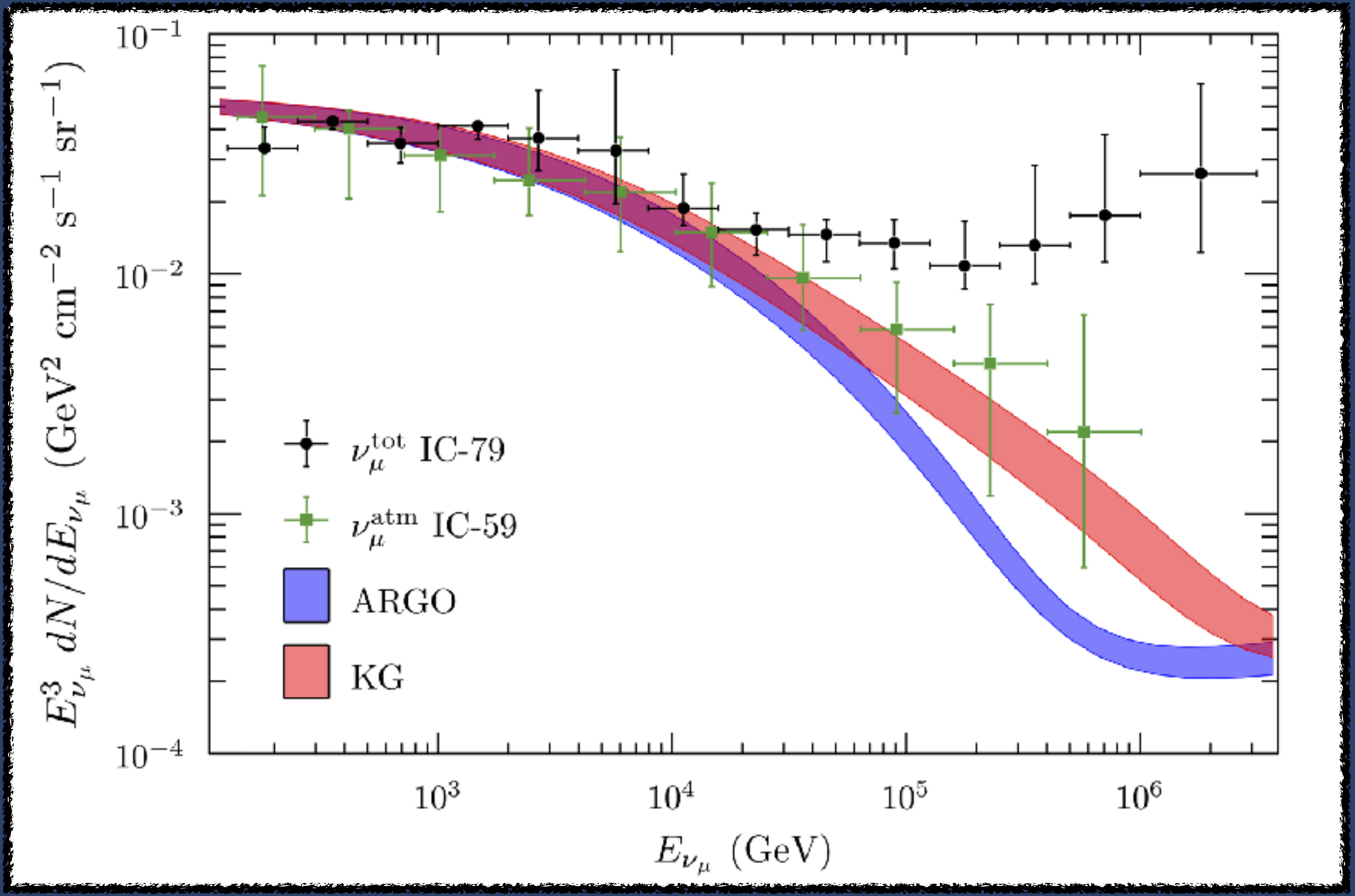

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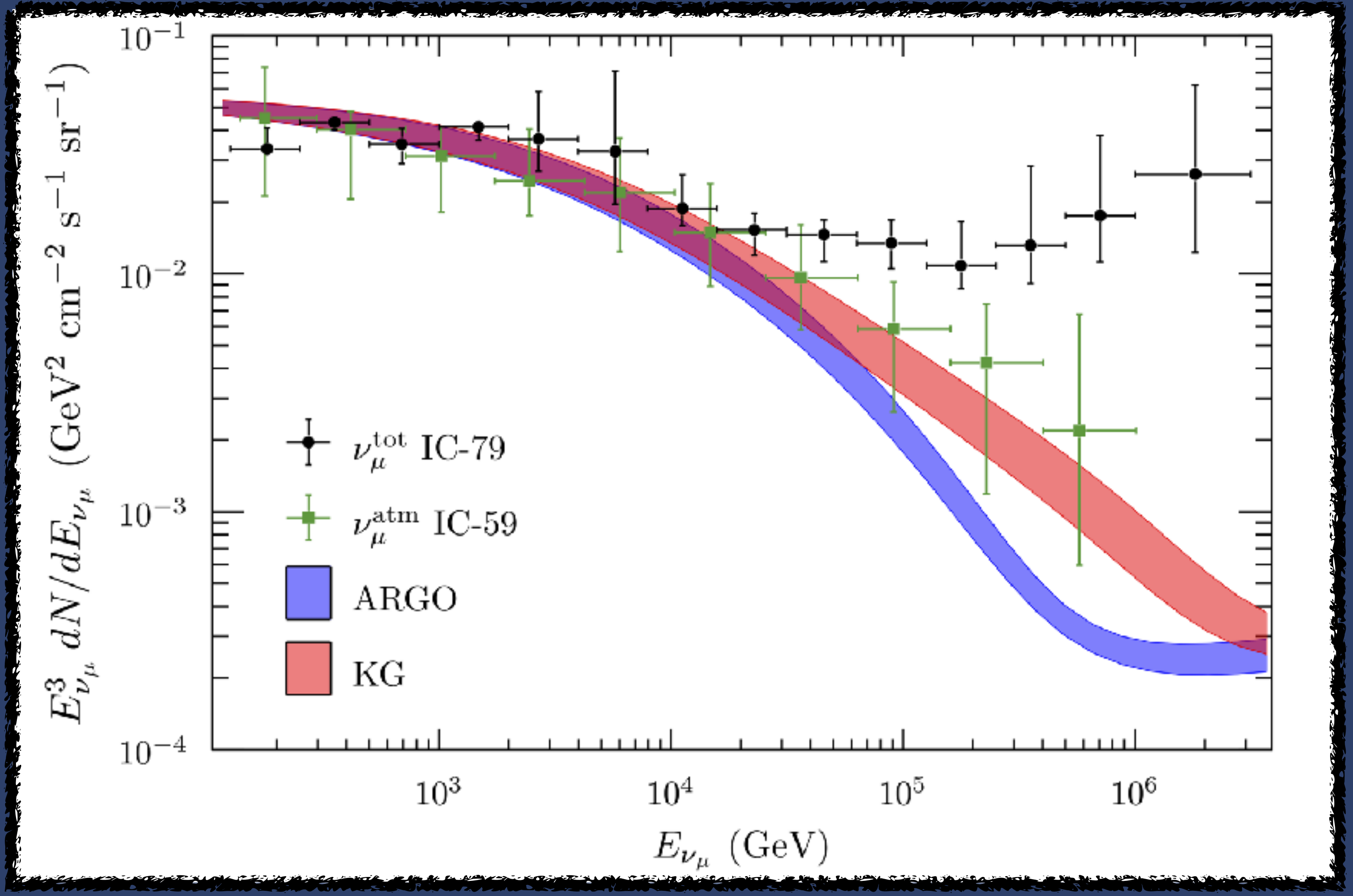

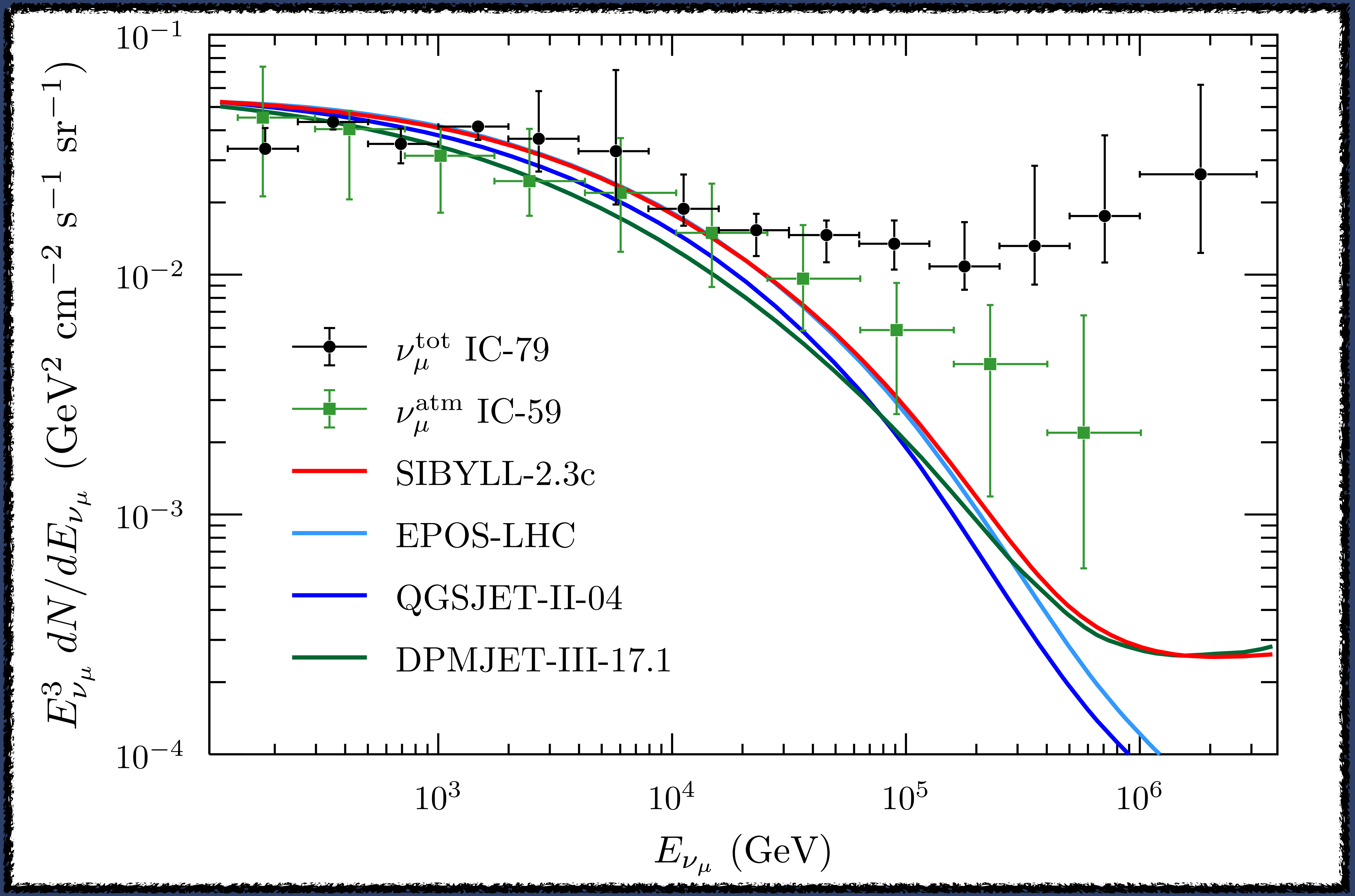

Largest flux from ARGO within 1σ

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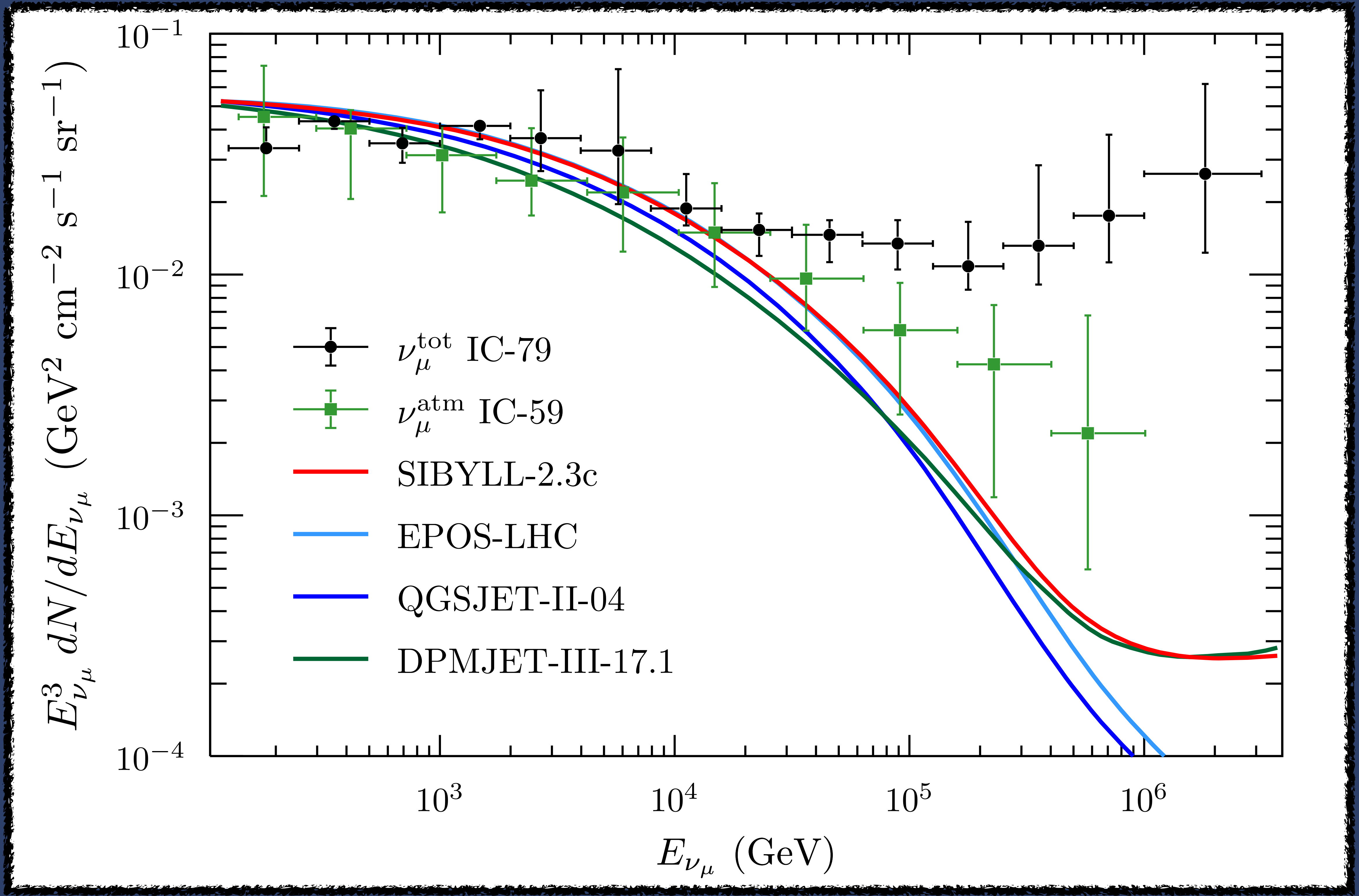
➡ *Tentative* preference for KG-knee



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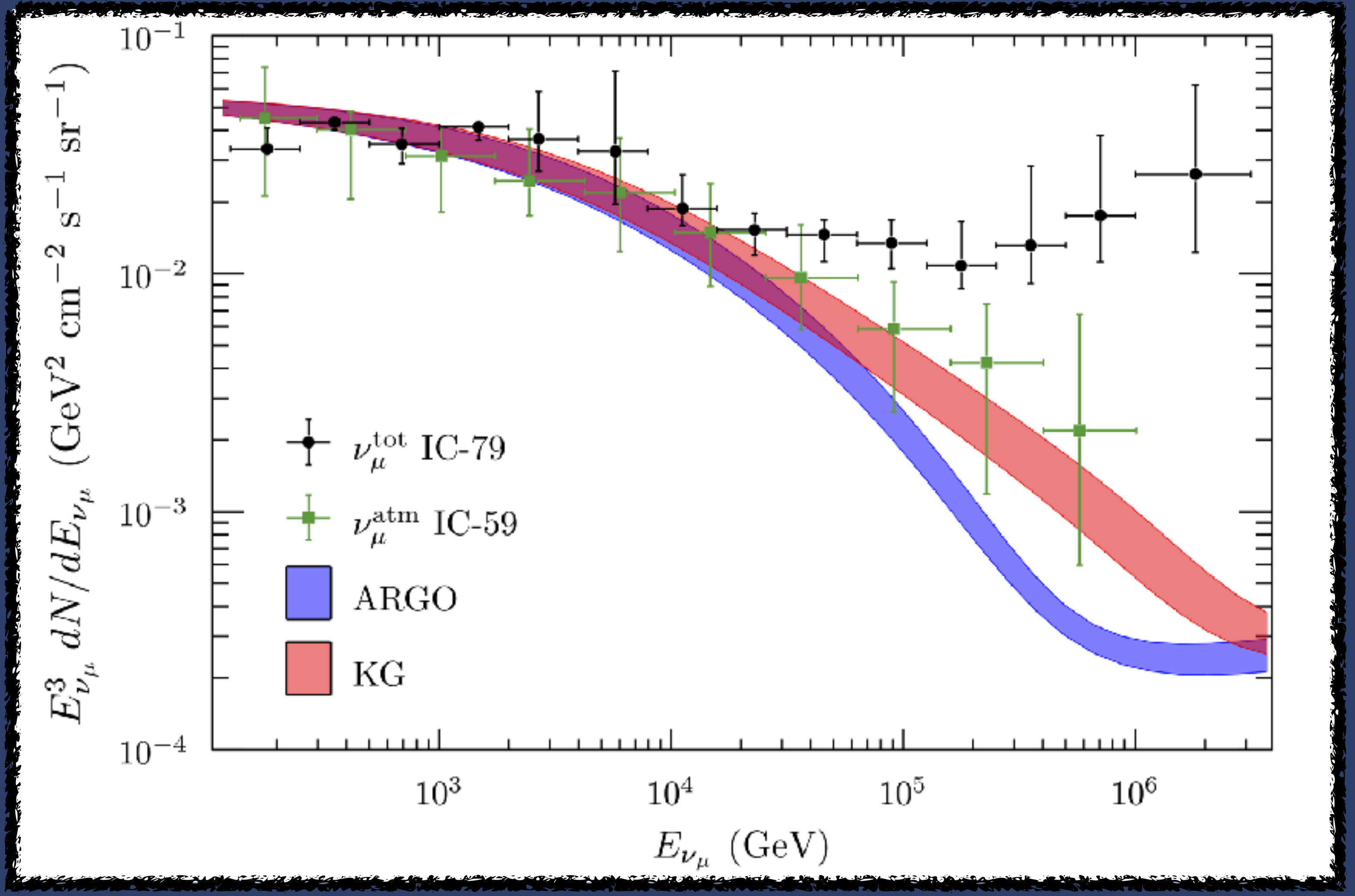

3. ATMOSPHERIC NEUTRINOS AND THE COSMIC-RAY KNEE

PART 3: ANGULAR DISCRIMINATION?

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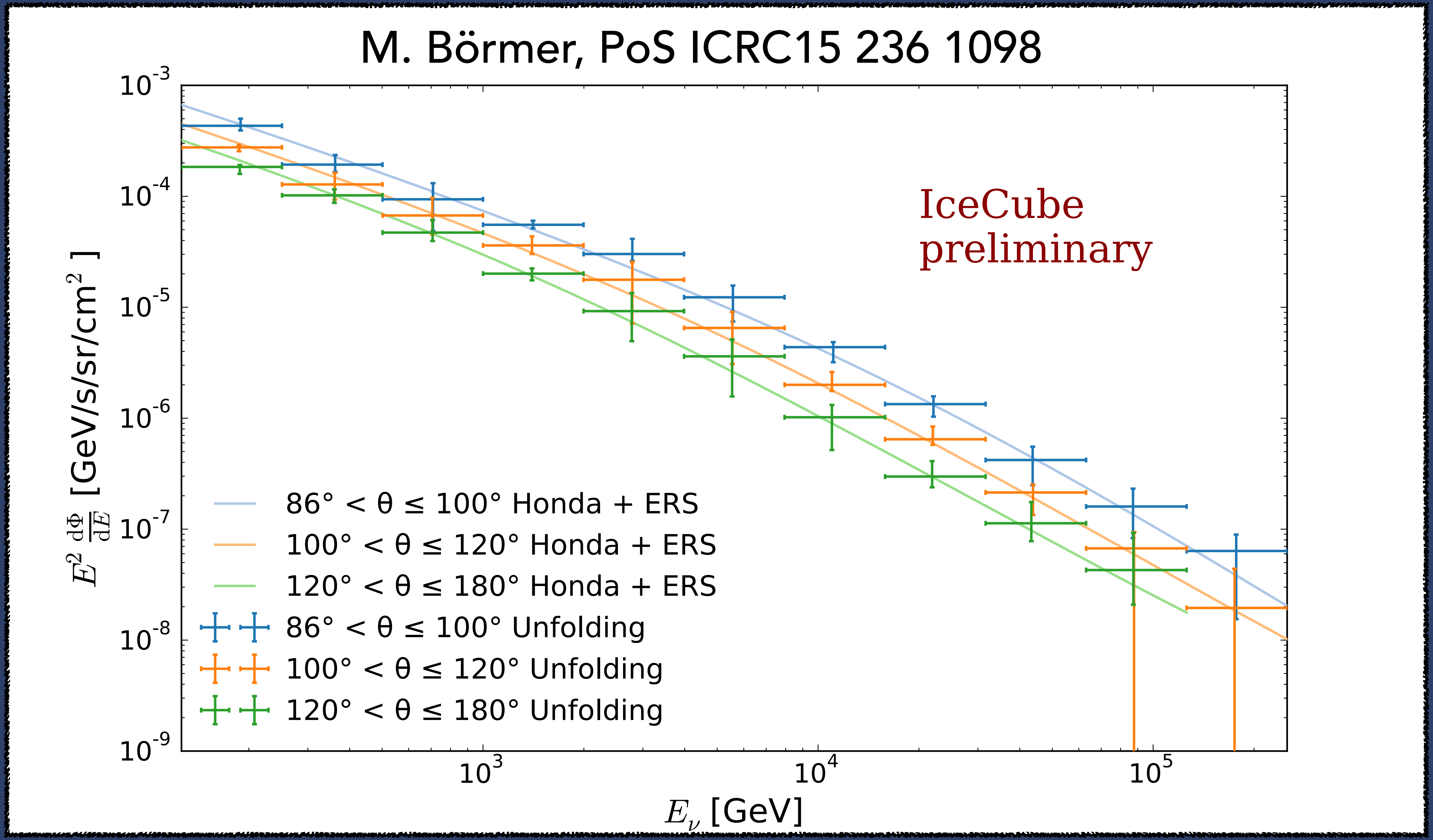

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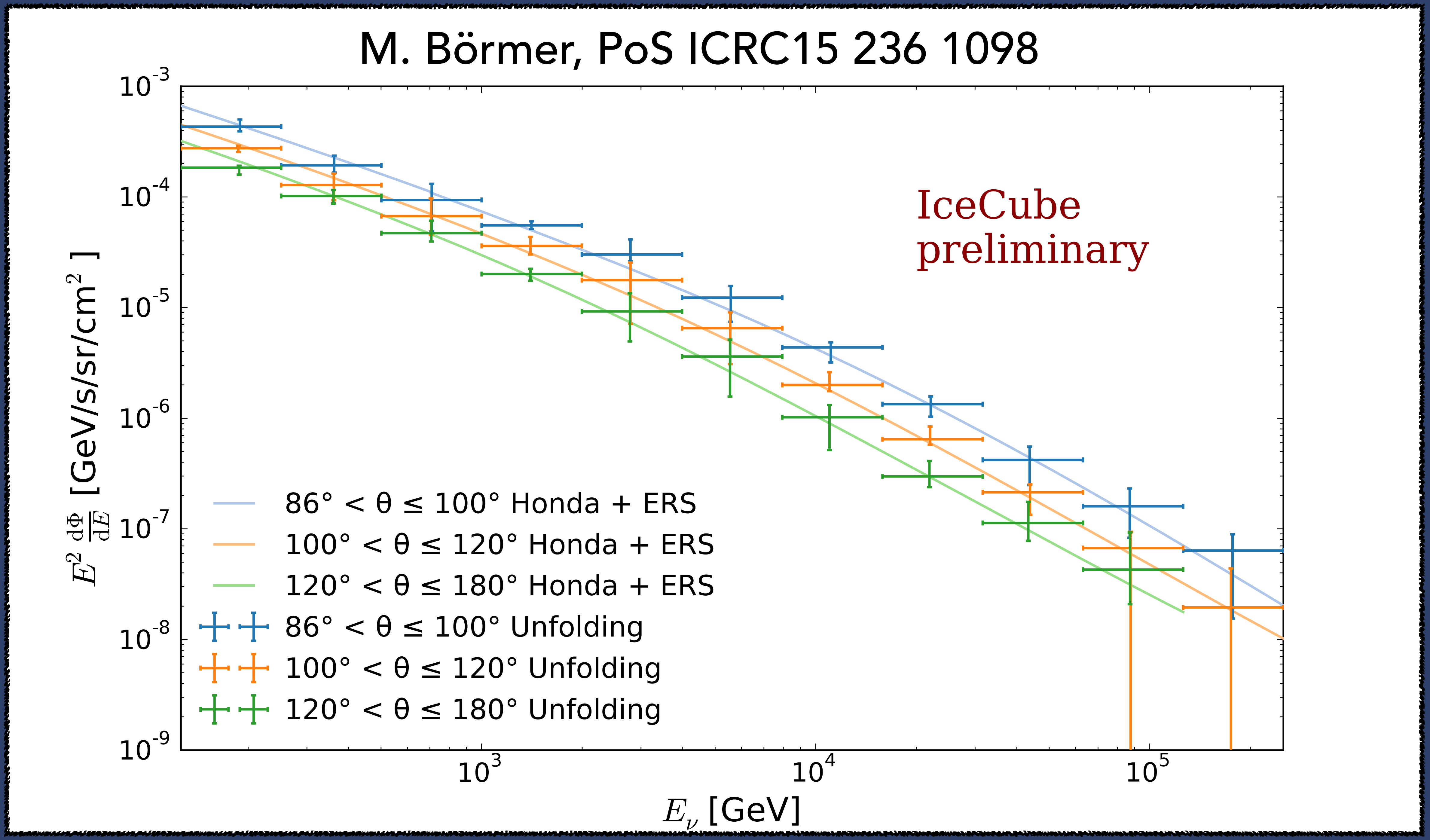

M. Börmer, PoS ICRC15 236 1098

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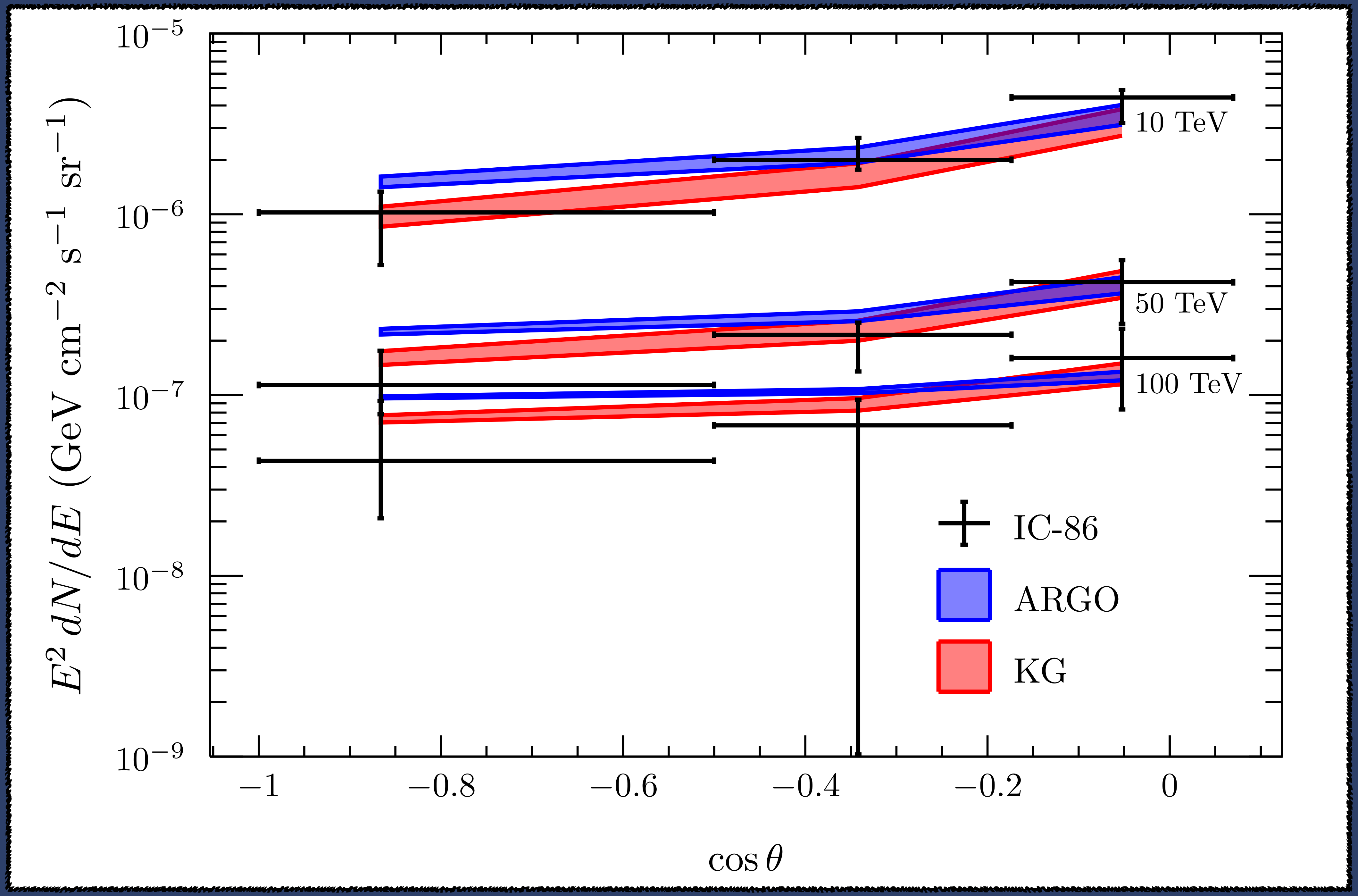

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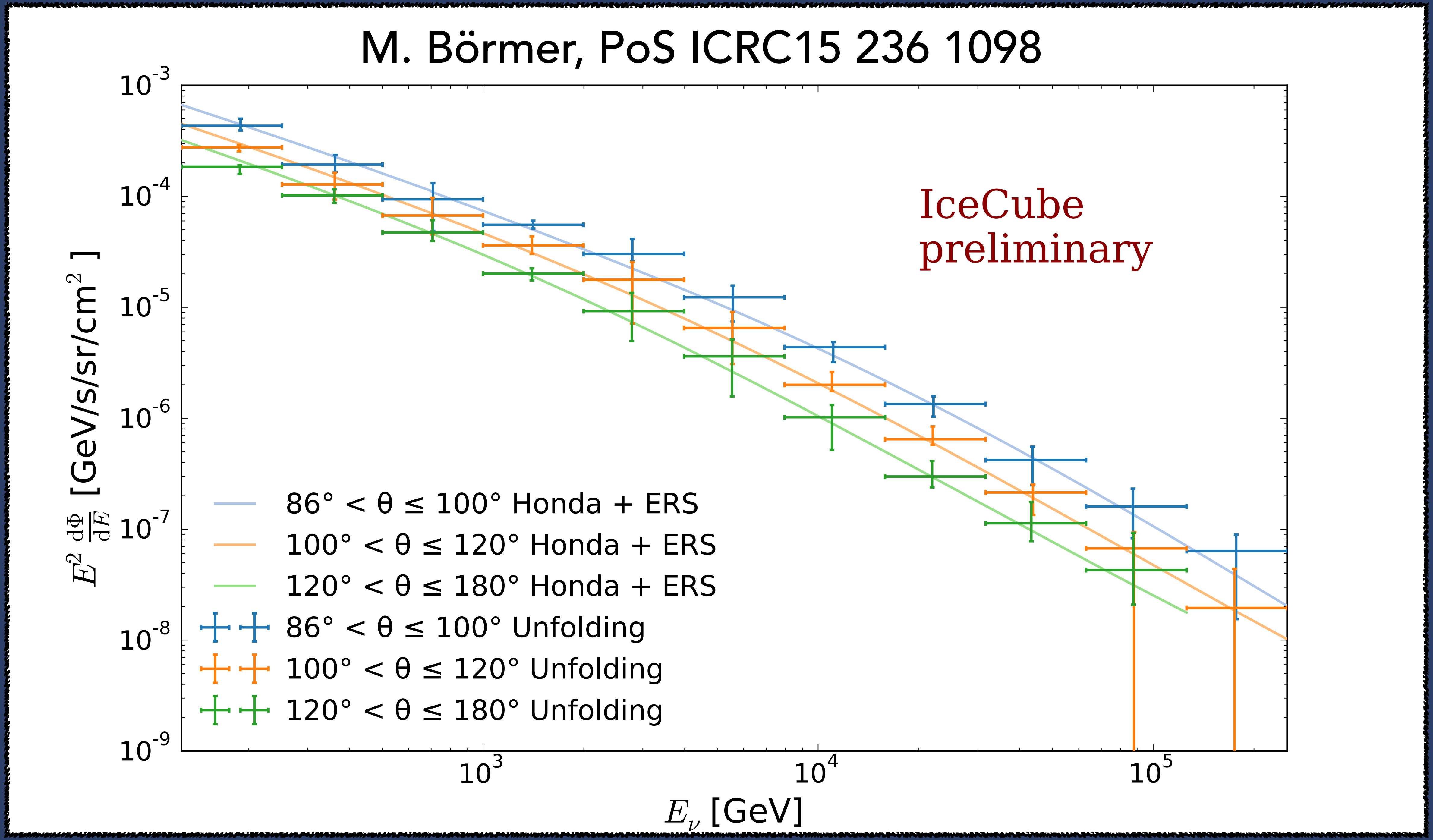

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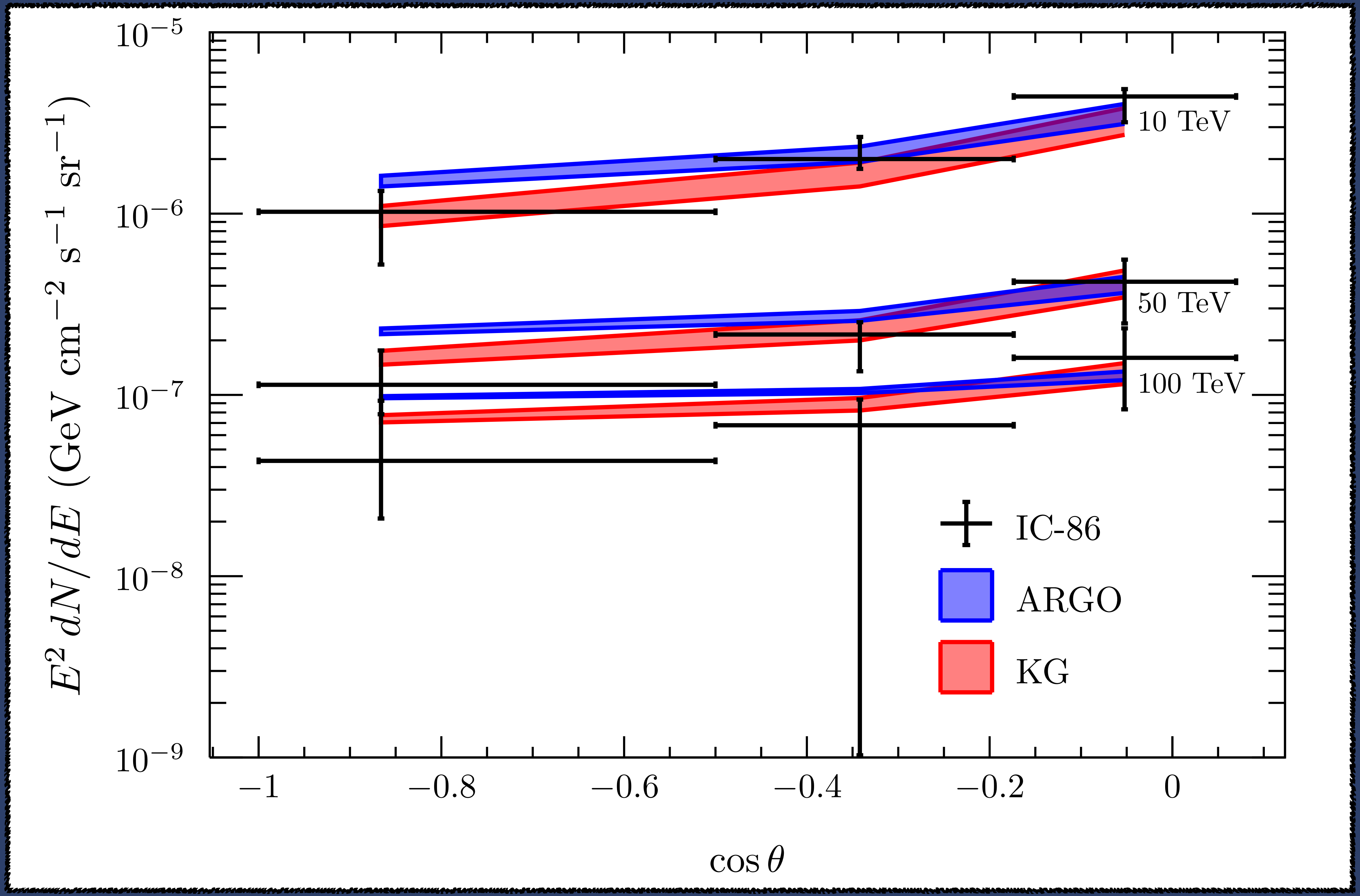

➡ No discrimination power

4. COSMIC NEUTRINOS

4. COSMIC NEUTRINOS: THEORETICAL EXPECTATIONS

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“Cosmic”: originating out of the Solar System

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Firmest assumptions:

- need for a powerful accelerator, $E_\nu \sim E_{\mathrm{CR}}/20A$ (hadronic collisions) and $E_{\nu\ \mathrm{max\ obs}}$ = few PeV
- need for targets: either gas ("pp mechanism") or photons ("pγ mechanism")
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We will focus on extragalactic, high-energy ($E_\nu \geq 10$ TeV) neutrinos

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Flavour ratio at the source: distribution in flavour of (anti-)neutrinos ≡ $(\nu_\mathrm{e} : \nu_\mu : \nu_\tau)_0$

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Popular scenarios:

- pion decay ➡ $(1/3 : 2/3 : 0)_0$

$$p_{\rm CR} + p_{\rm gas} \to X + \pi^+ + \pi^- + \pi^0$$

$$p_{\rm CR} + \gamma_{\rm bckgr} \to X + \pi^+ + \pi^0$$

➡

$$\pi^- \to \mu^- + \overline{\nu}_\mu$$ ➡ $$\mu^- \to \nu_\mu + e^- + \overline{\nu}_e$$

$$\pi^0 \to \gamma + \gamma$$

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- damped muons ➡ $(0 : 1 : 0)_0$

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$$R_{e\mu} = \frac{P_{ee}(1-x) + P_{e\mu}x}{P_{e\mu}(1-x) + P_{\mu\mu}x}$$

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Production mechanism	$R_{e\mu}$	$R_{\tau\mu}$
generic ($x \in [0,1]$)	$0.78^{+0.57}_{-0.07}$	$1.00^{+0.05}_{-0.15}$
pion decay ($x = 2/3$)	$1.09^{+0.03}_{-0.04}$	$0.97^{+0.03}_{-0.04}$
neutron decay ($x = 0$)	$2.18^{+0.13}_{-0.11}$	0.74 ± 0.07
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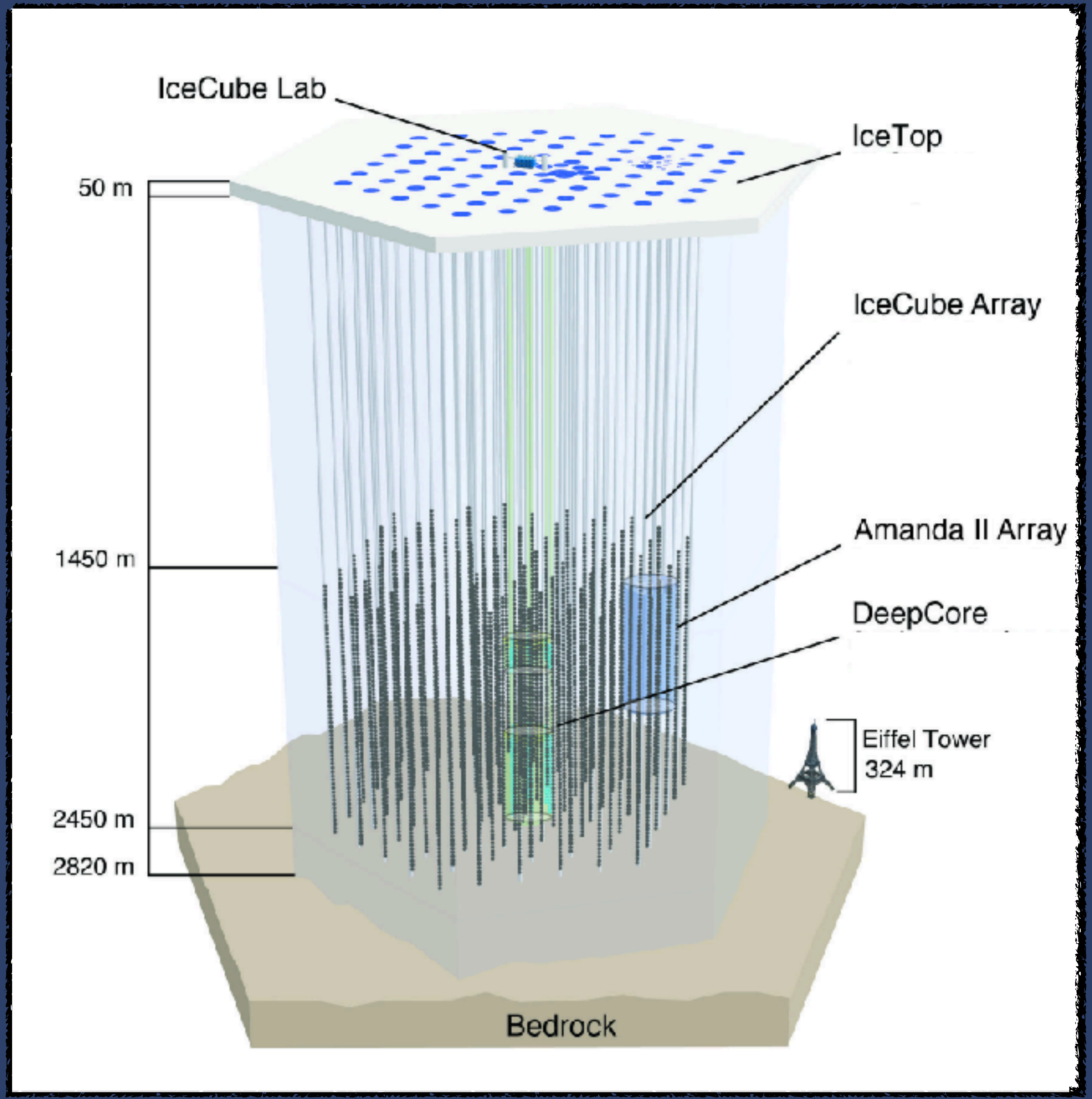
Generic and pion decay cases compatible with uniform distribution of neutrino flavour at Earth

4. THE ICECUBE DETECTOR

Detection principle: collect Cherenkov light produced by neutrino-induced charged particles

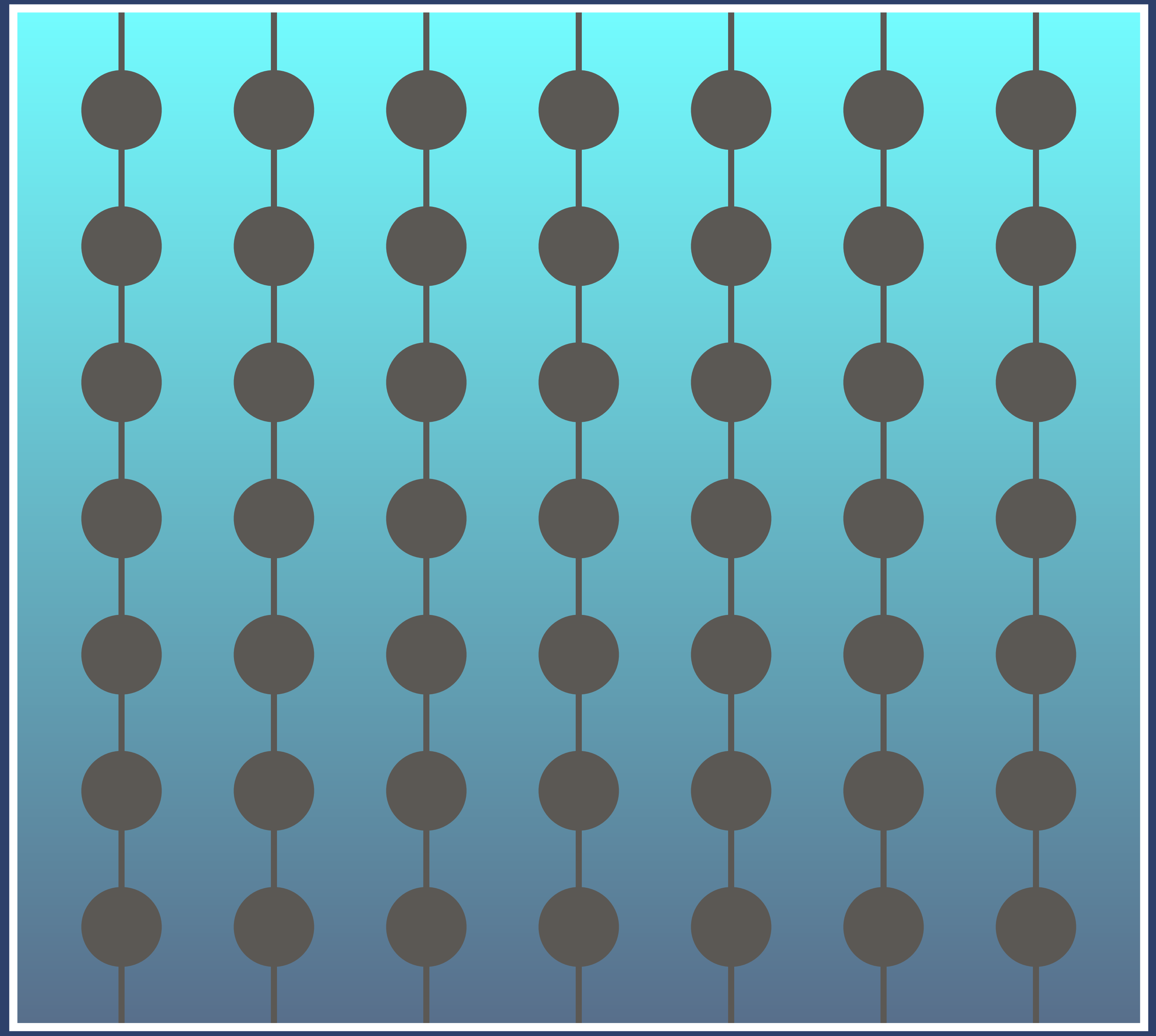
- Embedded in the Antarctic ice
- km^3-scale detector
- 86 vertical strings, 60 DOMs each
- vertical DOM separation: 17 m
- string separation: 120 m
- IceTop: km^2-scale air shower array
- operational since 2010
- discovery of astrophysical neutrinos in 2013



4. THE ICECUBE DATASETS

IceCube is the most important cosmic ν detector

Southern Sky



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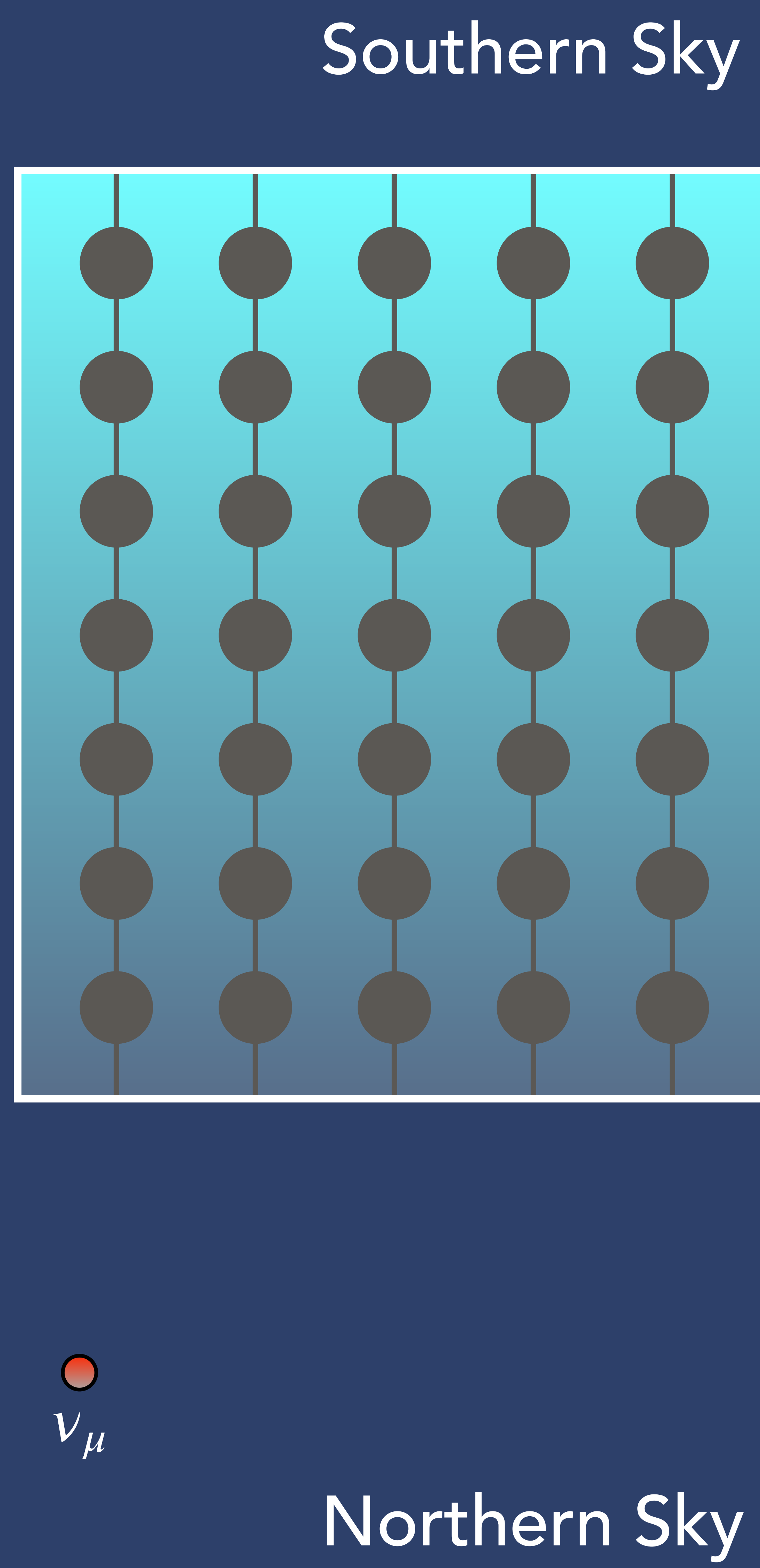

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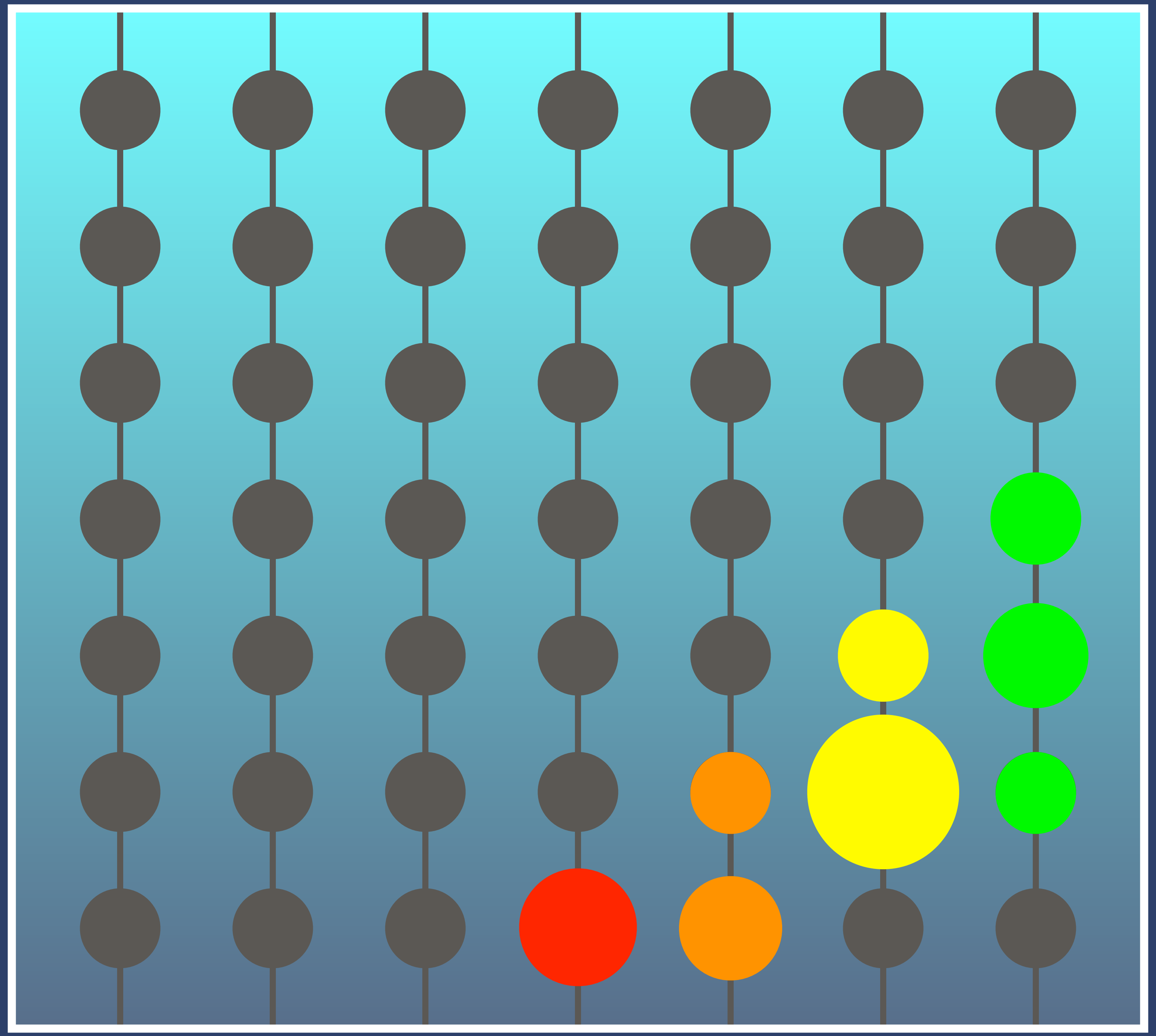

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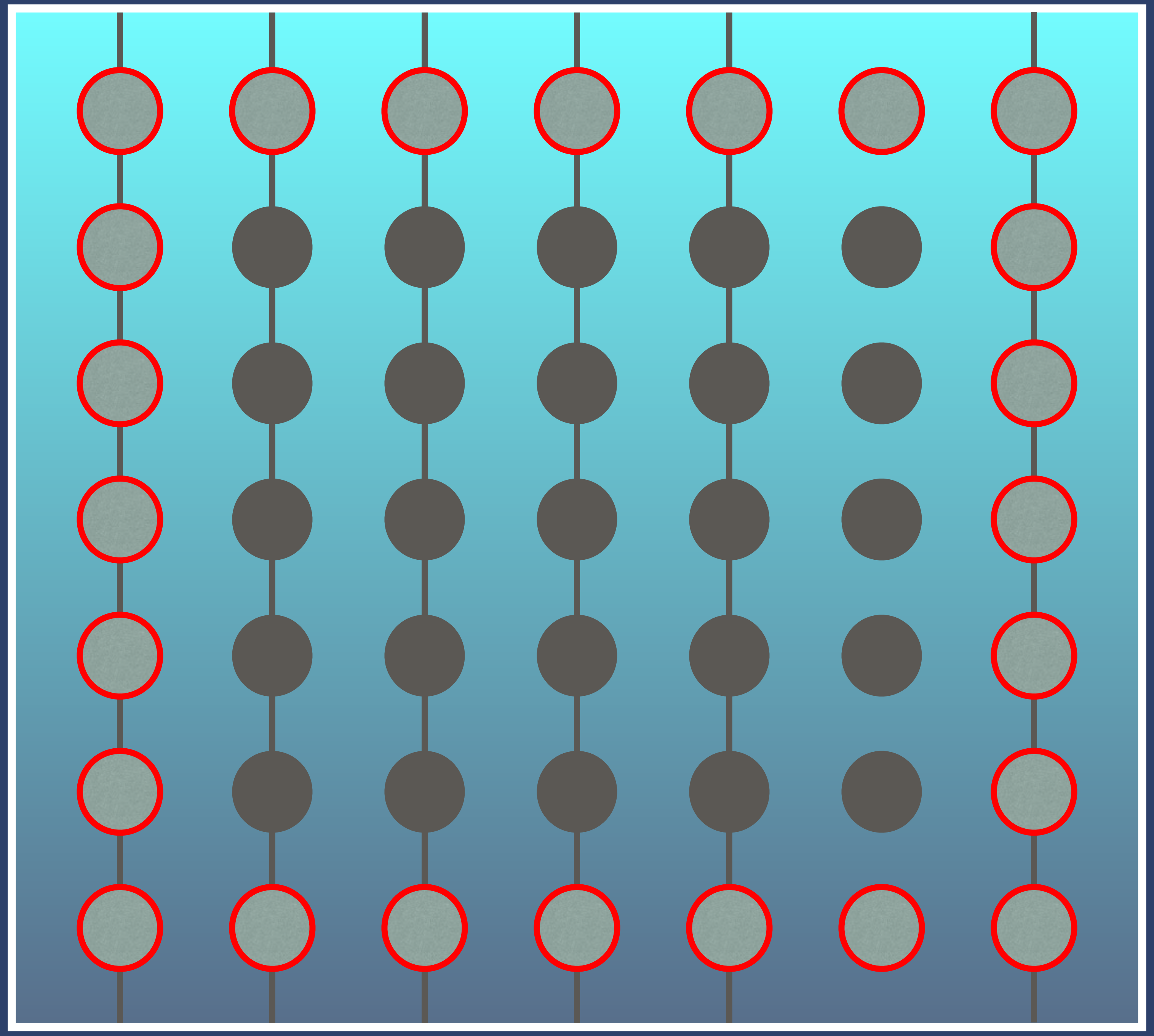

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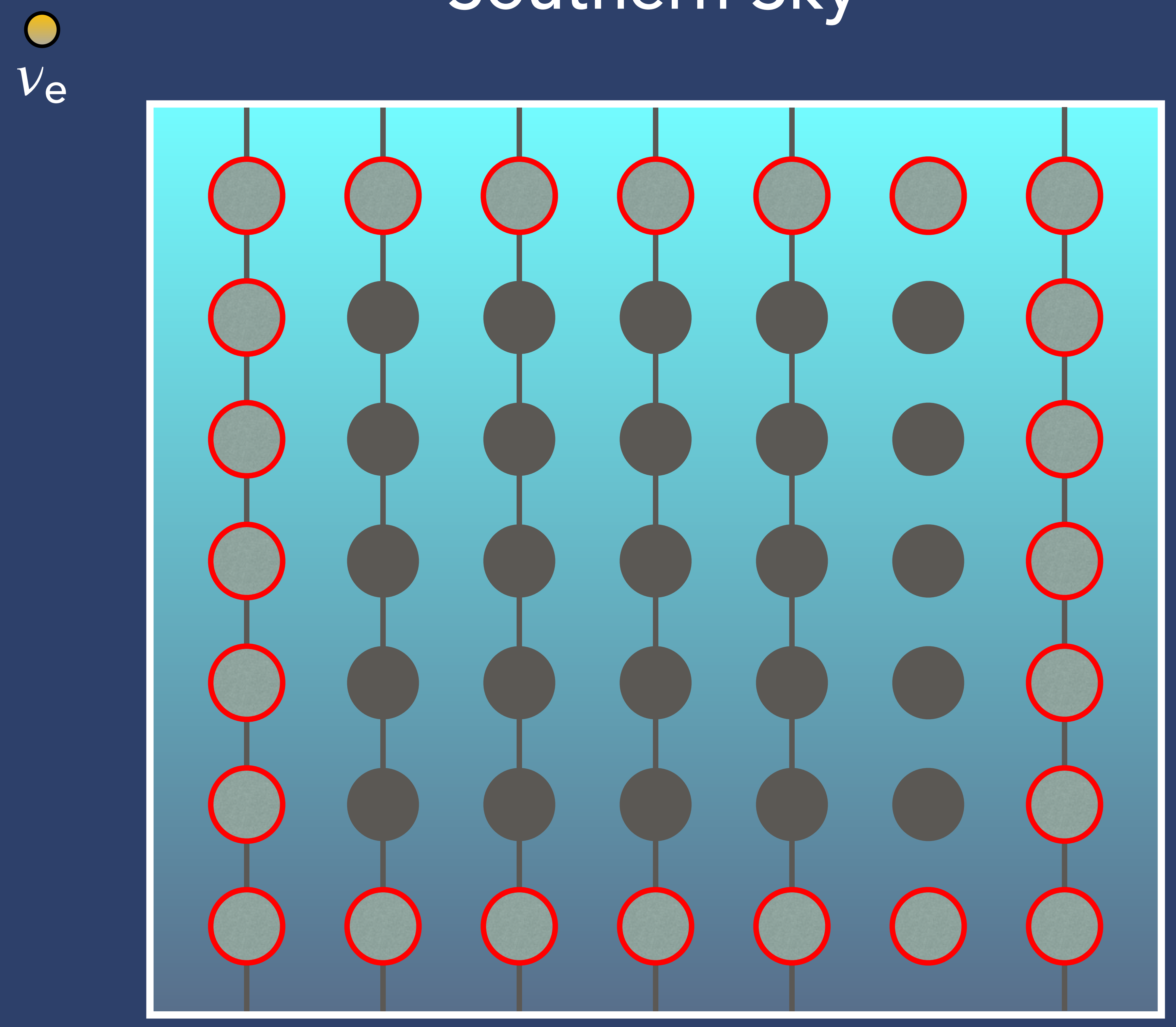

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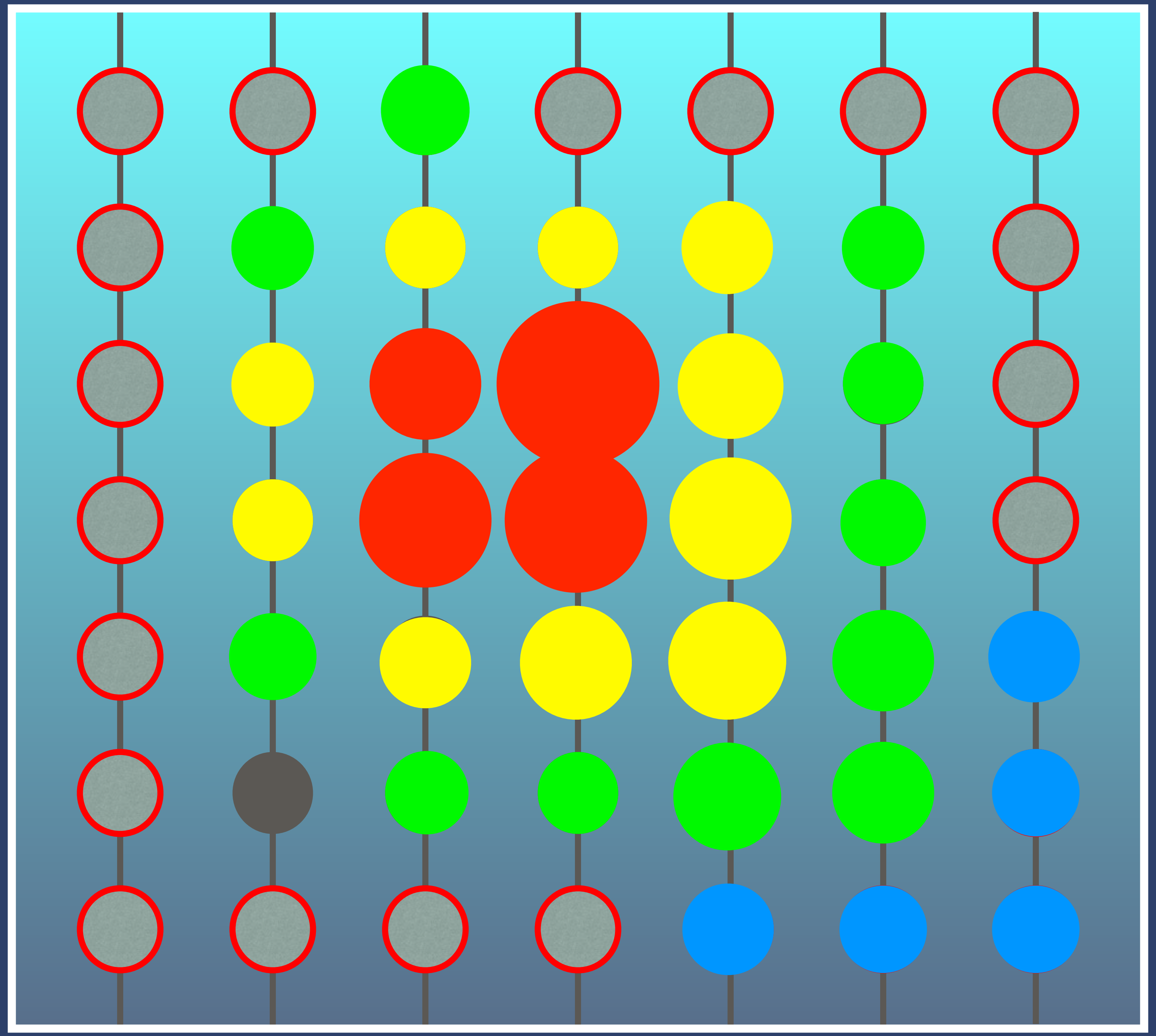

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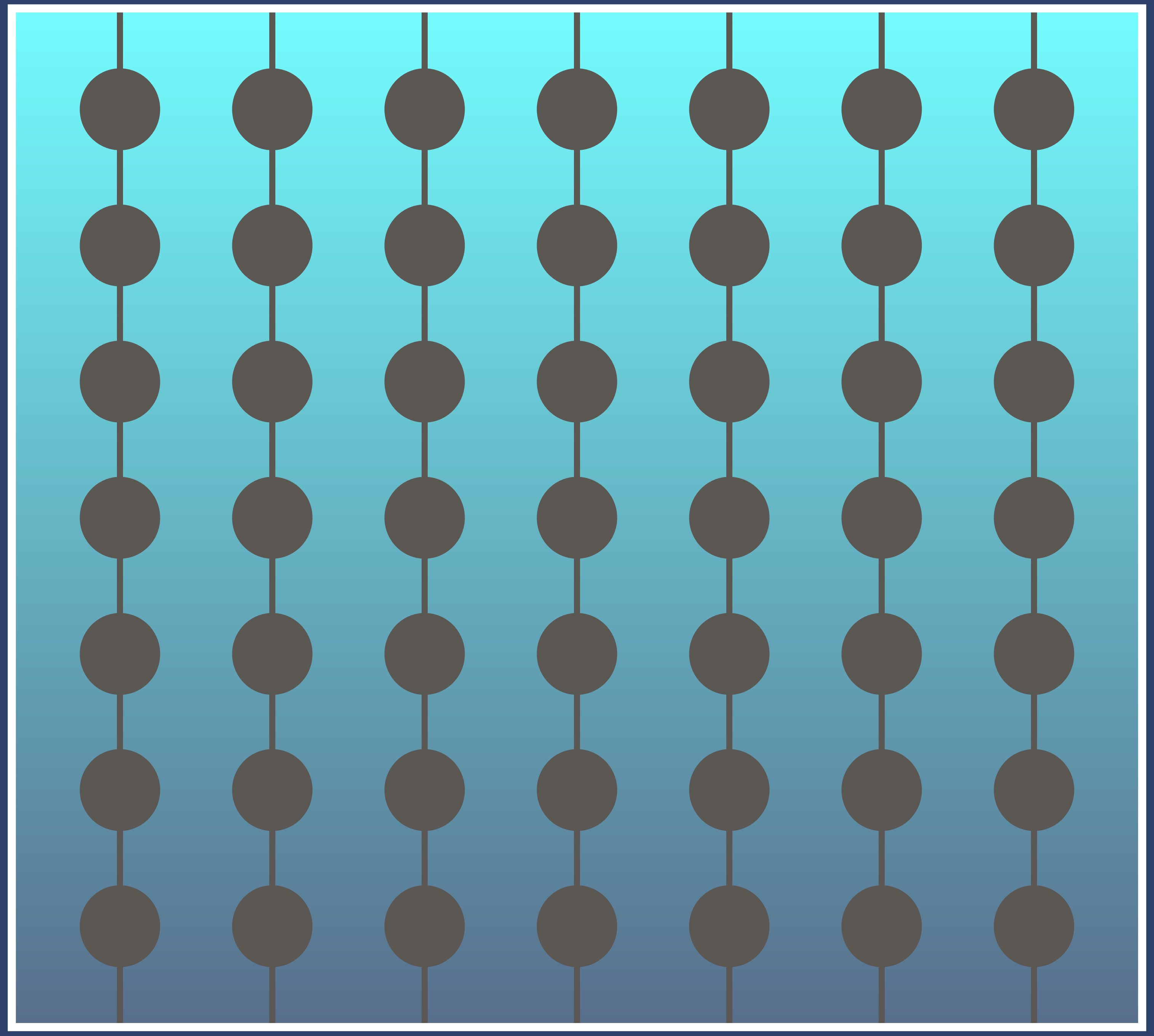
4. COSMIC NEUTRINO DETECTORS: "SPECIAL" EVENTS

Glashow resonances: $\overline{\nu}_e + e^- \rightarrow W^-$

- only electron antineutrinos
- antineutrino energy of at least 6.32 PeV



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Double cascades:

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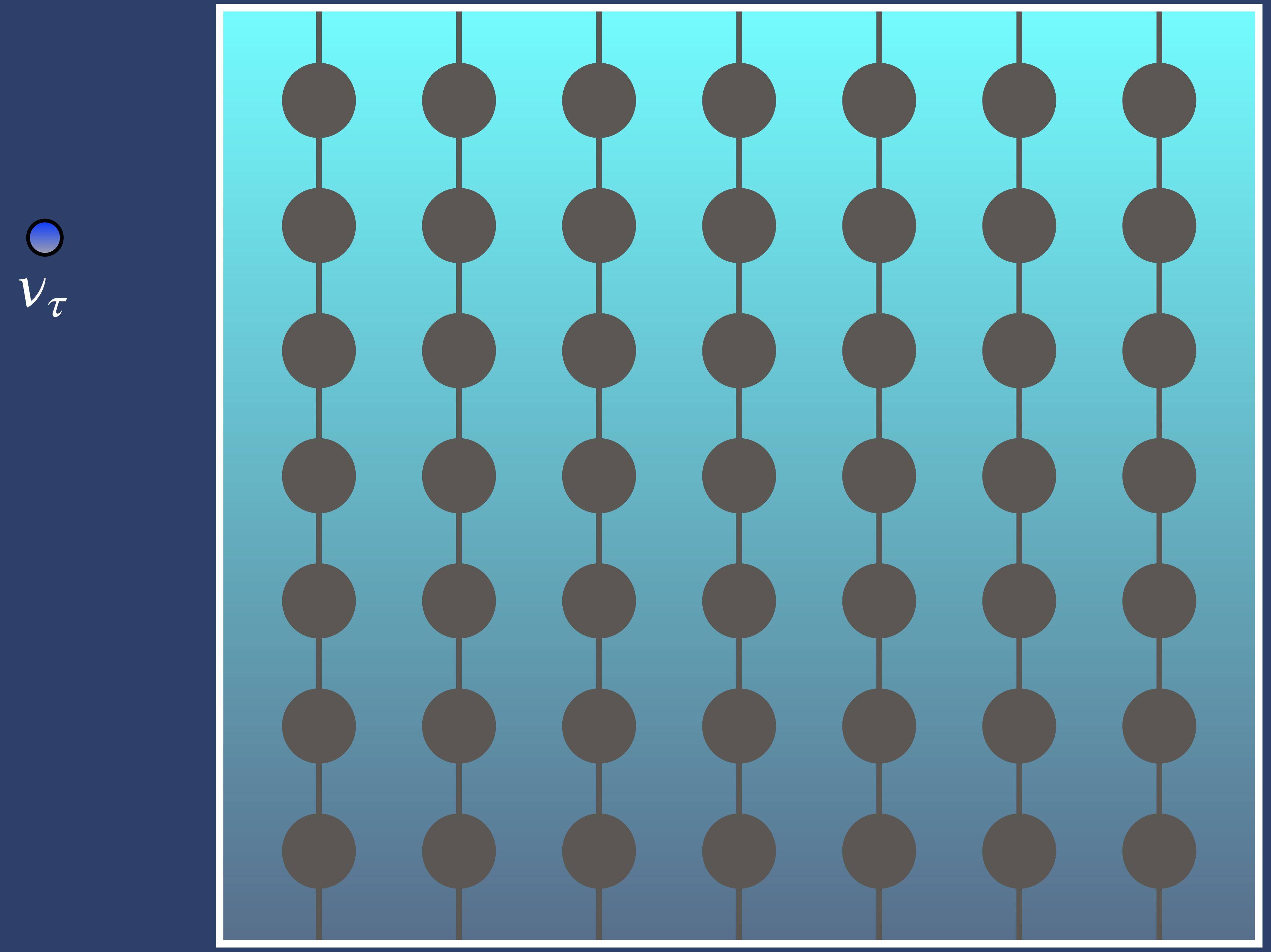
- first cascade ➡ ν_τ CC interaction
- second cascade ➡ τ lepton hadronic decay
- granularity is important: d_τ ~ 50 m (E/1 PeV)



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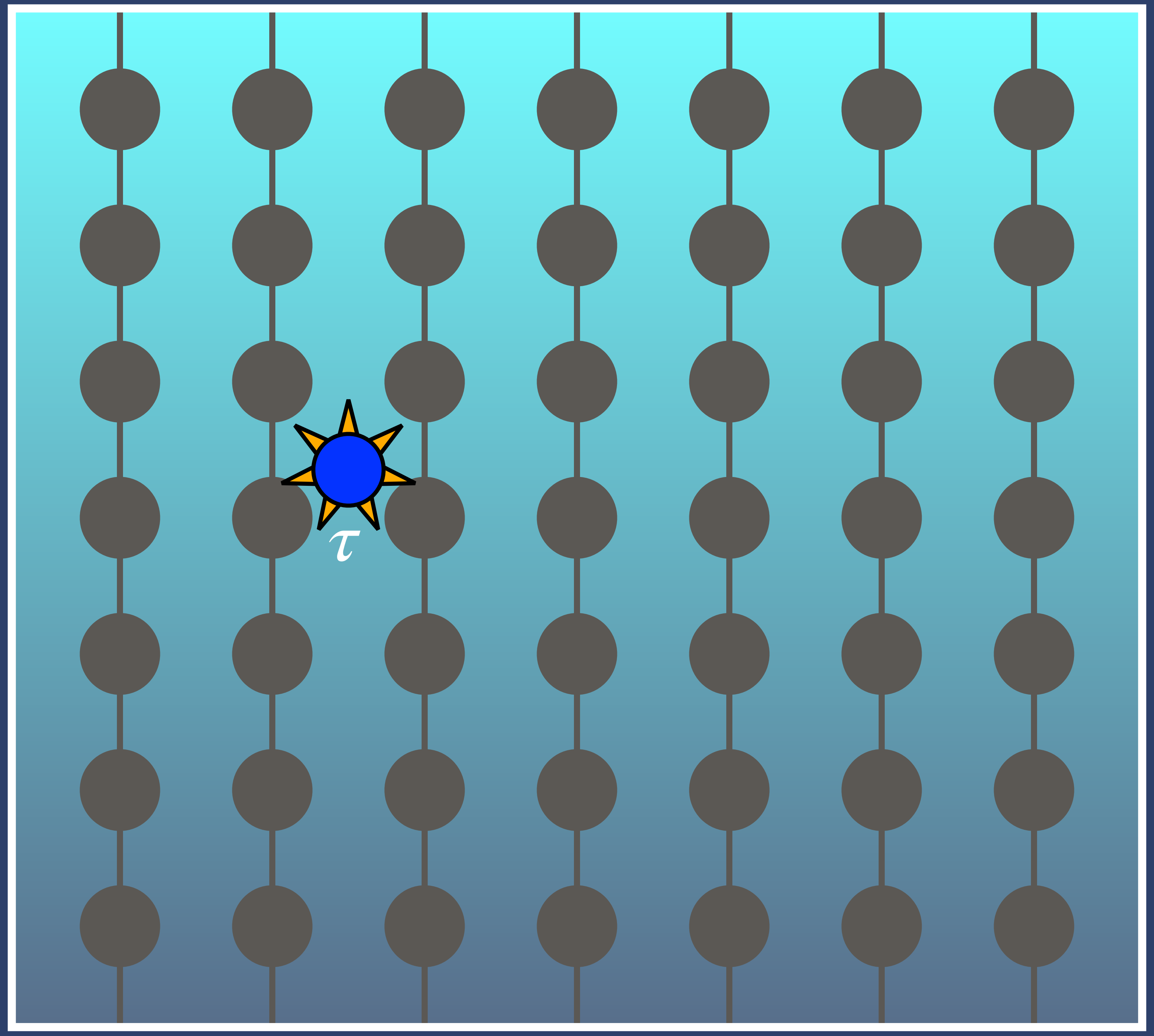

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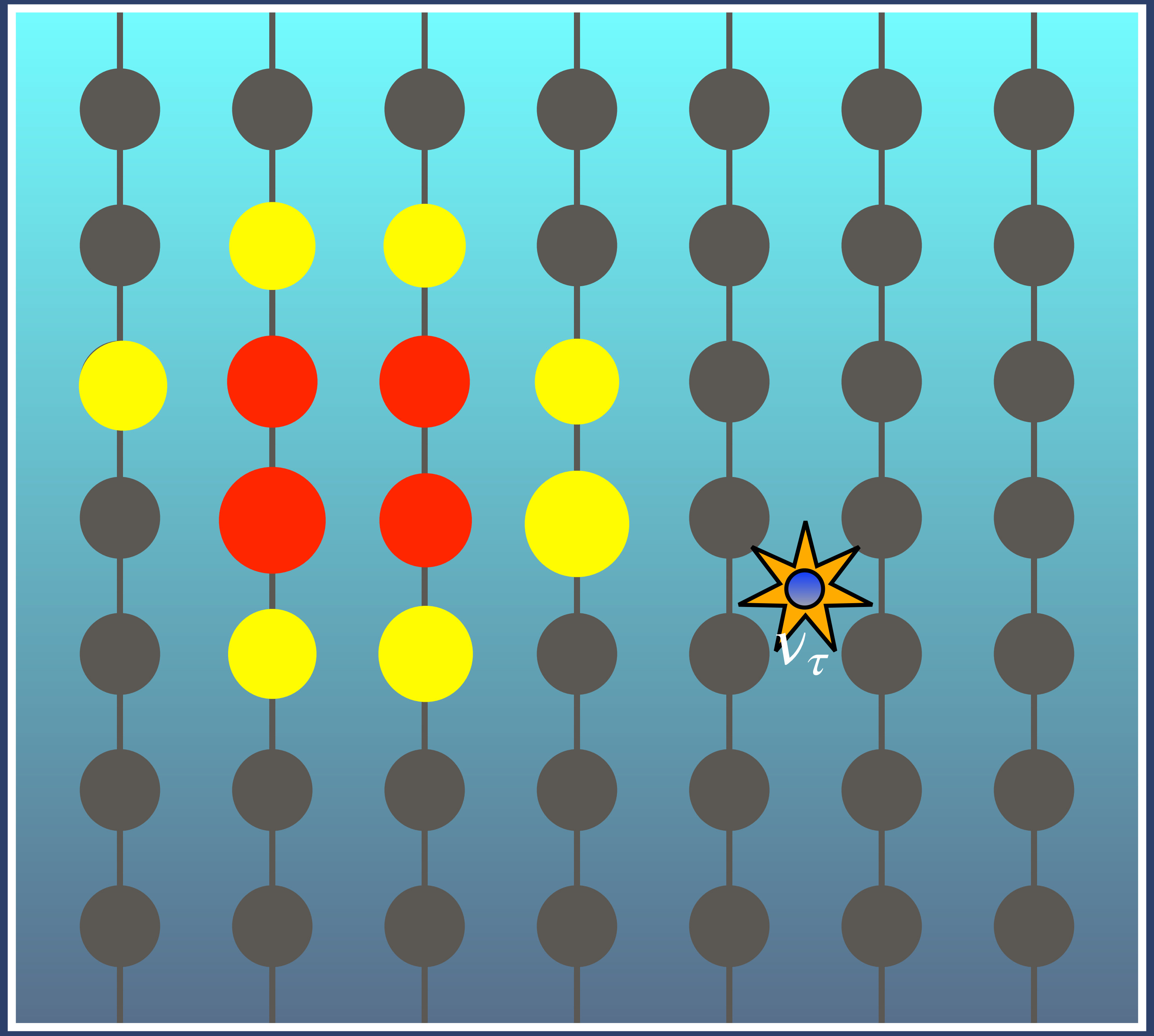

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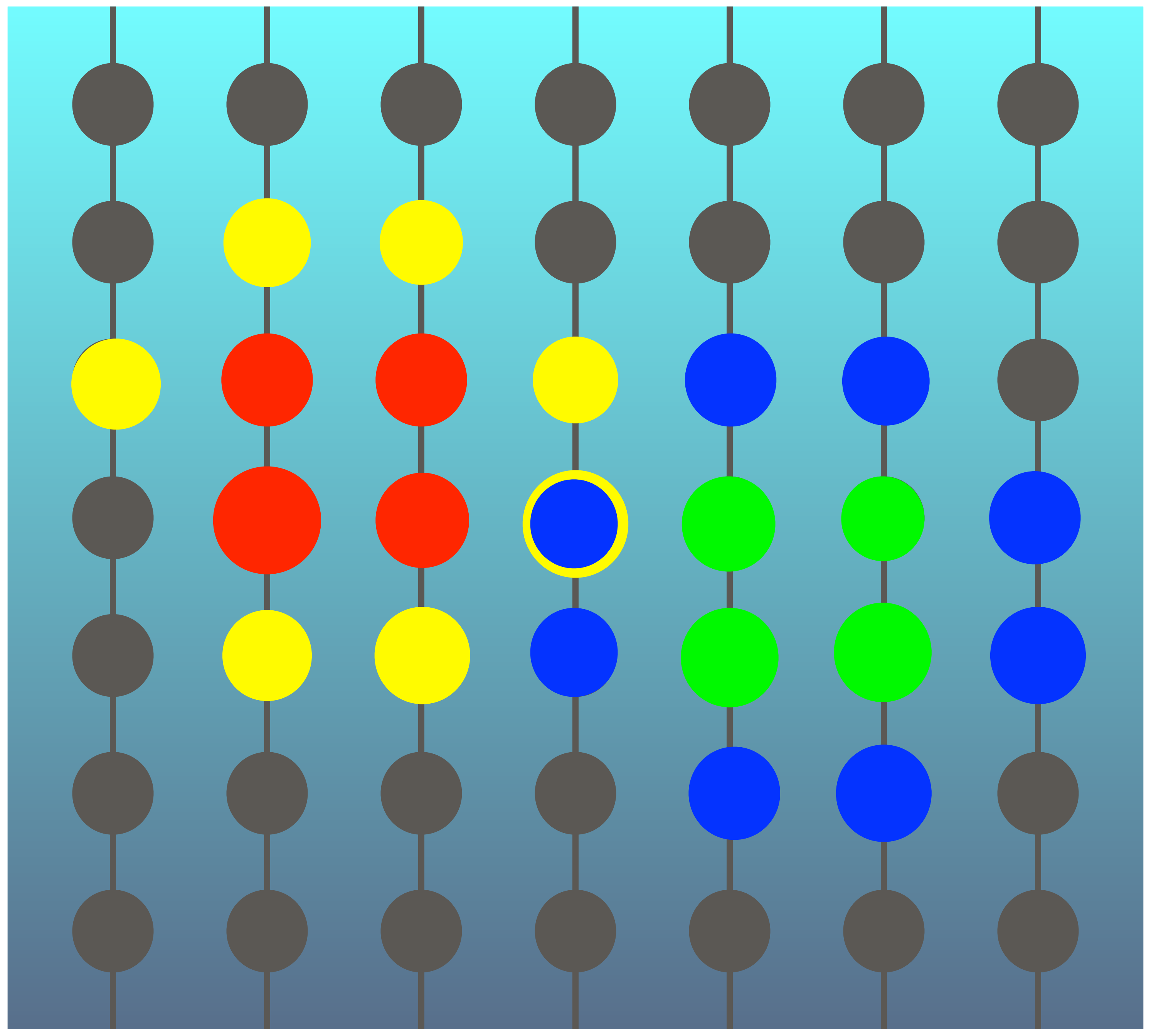
4. COSMIC NEUTRINO DETECTORS: "SPECIAL" EVENTS



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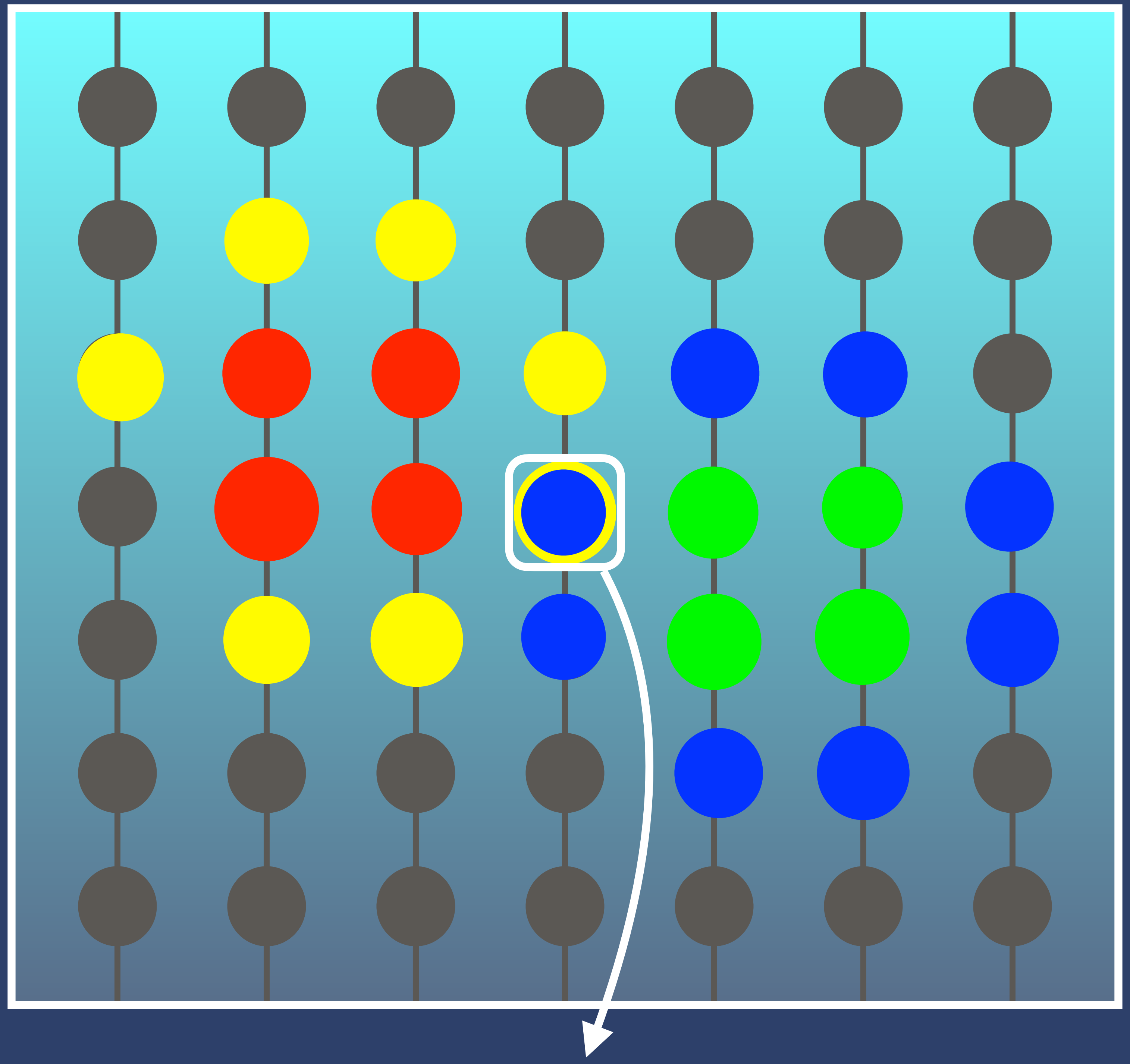
“Double pulse”

4. ICECUBE: EFFECTIVE AREAS

Effective area of detector to compute event number in ΔT:

$$N = \Delta T \int d\Omega \int_{E_{\min}}^{E_{\max}} dE\, A_{\mathrm{eff}}(E, \theta, \varphi) \frac{d\Phi}{dE d\Omega}$$

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X-sec of detection
process

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physical and
veto effects

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response
efficiency

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Fits to the datasets ➡ cosmic ν spectrum

- unbroken power-law
- isotropic signal
- standard 3ν oscillations

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$$\frac{d\Phi}{dE} = \Phi_{100}\left(\frac{E}{100\,\mathrm{TeV}}\right)^{-\gamma} \times 10^{-18}\,\mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$$

Dataset	main flavour	year	min E_ν	Φ_{100}	γ
HESE†	all	2019	60 TeV	$2.15^{+0.49}_{-0.15}$	$2.89^{+0.20}_{-0.19}$
through-going μ	ν_μ	2016	194 TeV	$0.90^{+0.30}_{-0.27}$	2.13 ± 0.13

† = preliminary

4. A TWO-COMPONENT MODEL (1/2)

A. Palladino, C. Mascaretti, F. Vissani, *On the compatibility of the IceCube results with a universal neutrino spectrum*, EPJC **77** (2017) 684

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Experimental results on the cosmic ν spectrum are in tension with isotropy + single power law
➡ introduced a two-component neutrino spectrum

$$\frac{d\Phi_\ell}{dE} = \frac{N_\ell}{2}\left[\left(\frac{E}{200\ \mathrm{TeV}}\right)^{-\alpha} + \left(\frac{E}{200\ \mathrm{TeV}}\right)^{-\beta}\right]$$

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➡ used standard oscillations and available data to constrain it:

- observed HESE events
- observed double cascades
- observed Glashow resonances

4. A TWO-COMPONENT MODEL (2/2)

Predictions on:

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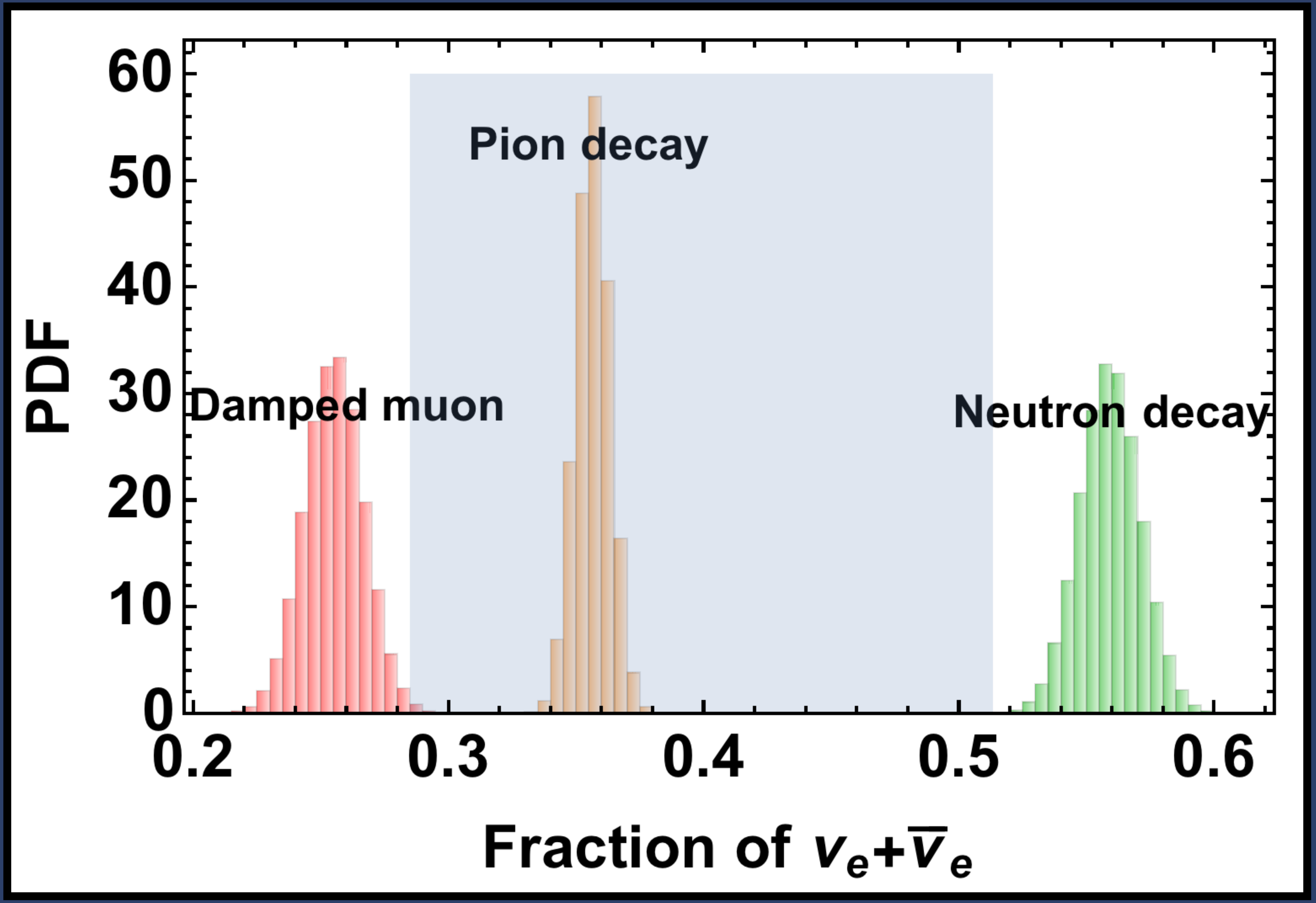
Predictions on:

- flavour composition



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Predictions on:

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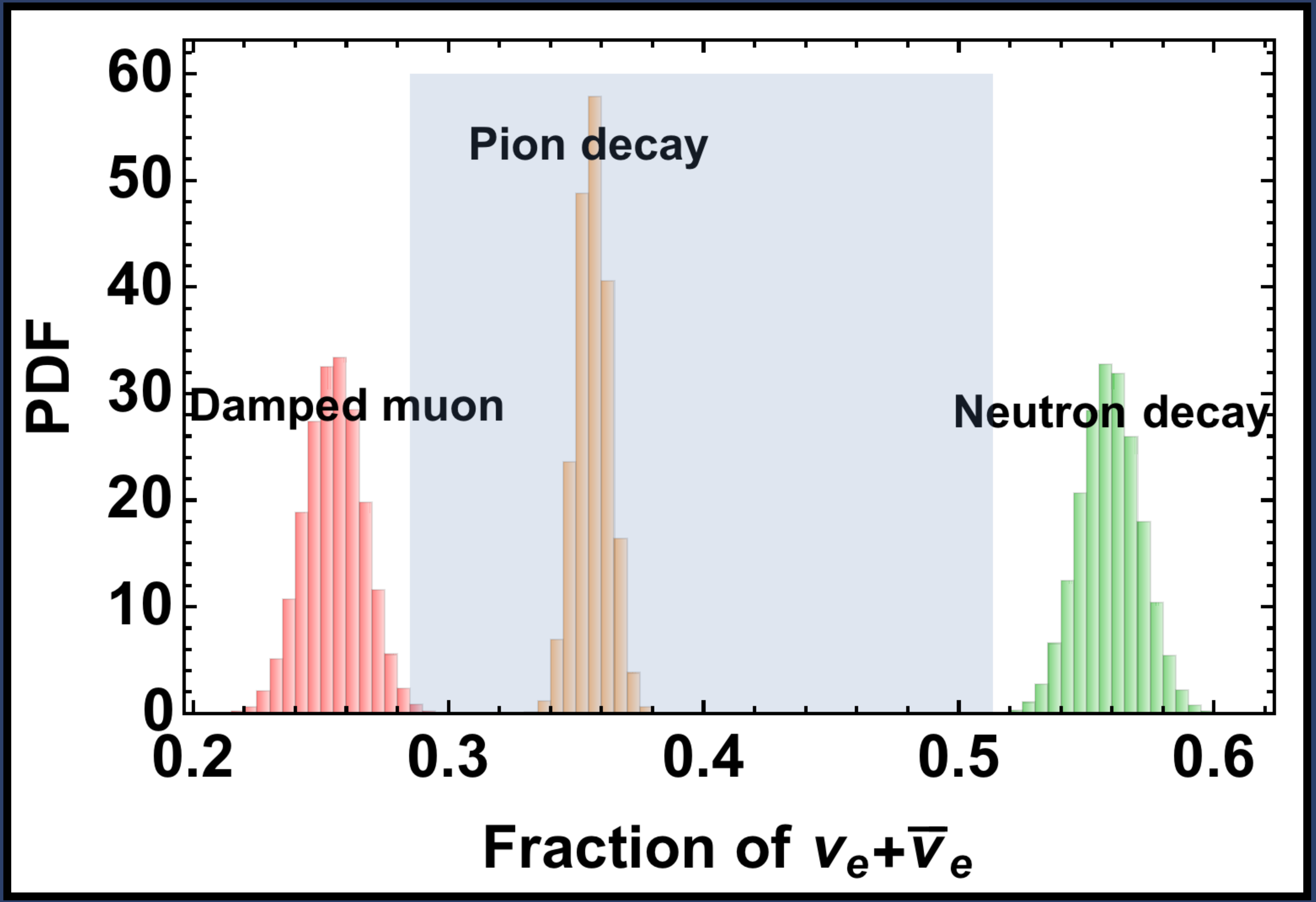
- double pulse (2p) rates

$$R_{\mathrm{2p}} = 0.65 \pm 0.24$$



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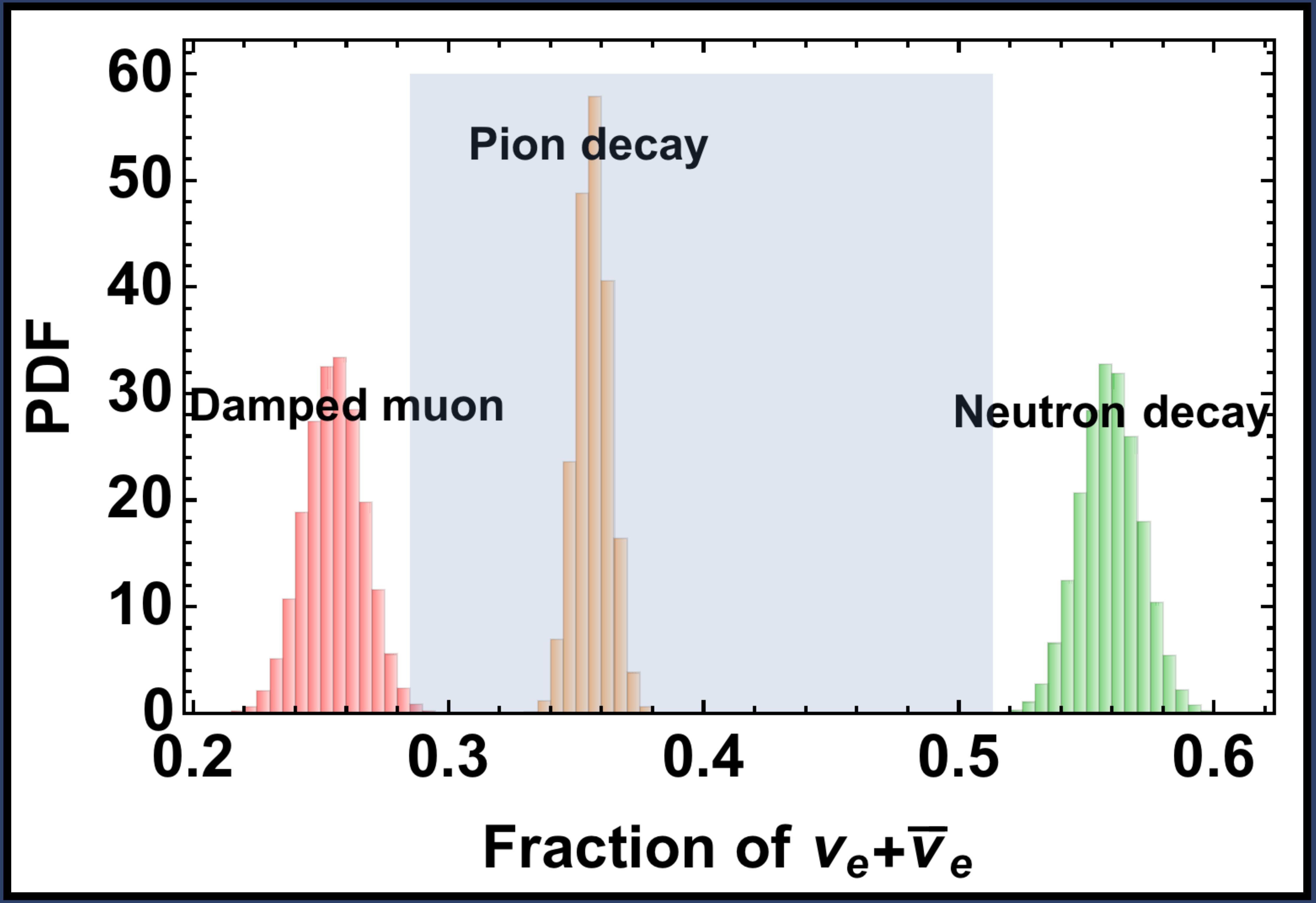
- Glashow resonances at high energy

$$R_{\rm 2p} = 0.65 \pm 0.24 \qquad R_{\rm G} = \begin{cases} 2.28 \pm 0.52 & pp \\ 1.14 \pm 0.26 & p\gamma \end{cases}$$



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Predictions on:

- flavour composition
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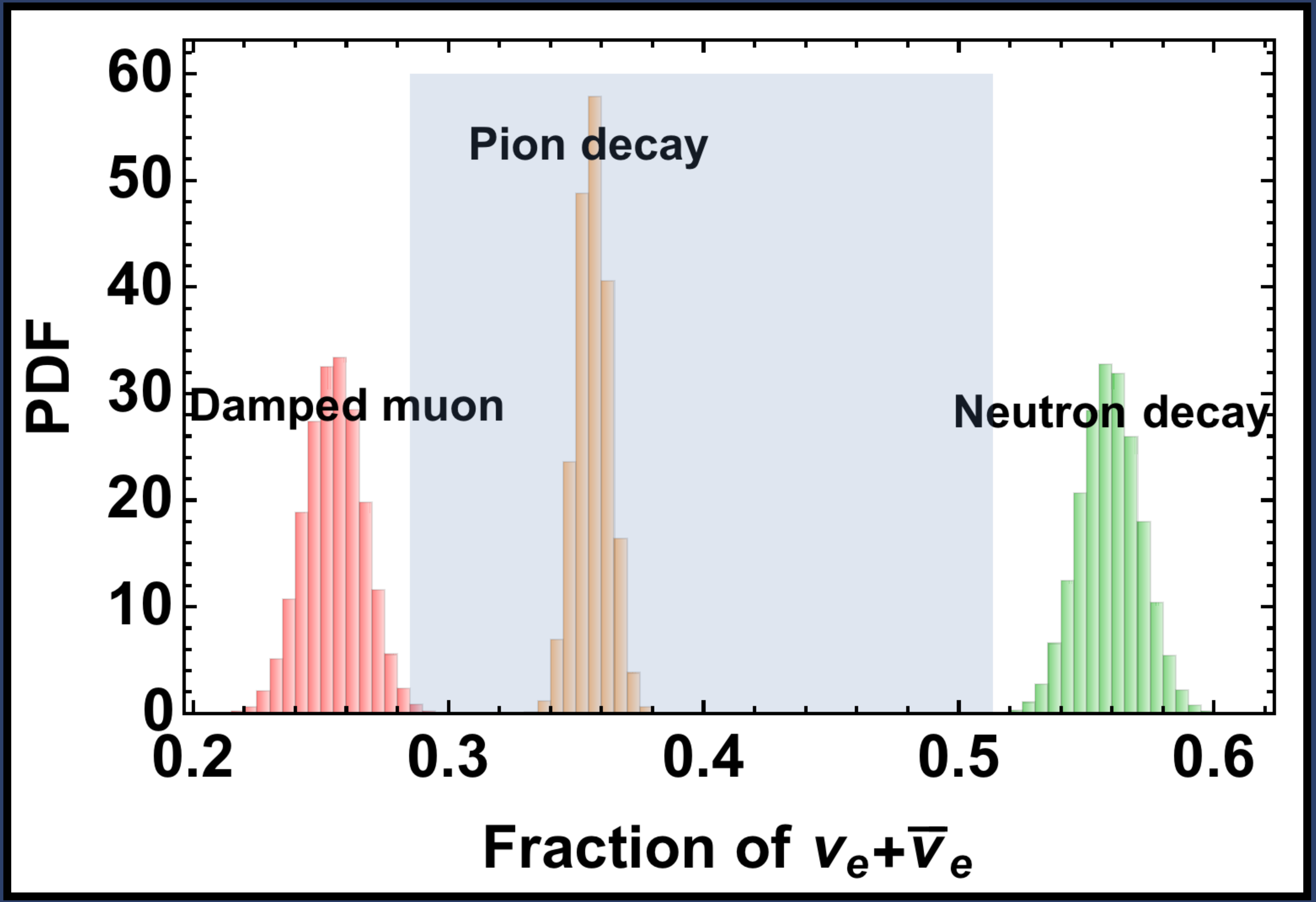
$$\boxed{R_{2\mathrm{p}} = 0.65 \pm 0.24}$$

↓

expected soon,
maybe seen

$$R_{\mathrm{G}} = \begin{cases} 2.28 \pm 0.52 & pp \\ 1.14 \pm 0.26 & p\gamma \end{cases}$$



4. THE IMPORTANCE OF OBSERVING COSMIC TAU NEUTRINOS

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- predictions of double cascade rates in IceCube, IceCube-gen2, KM3NeT

4. THE IMPORTANCE OF OBSERVING COSMIC TAU NEUTRINOS

PART 1: THE TAU NEUTRINO FLUX IS SIZEABLE

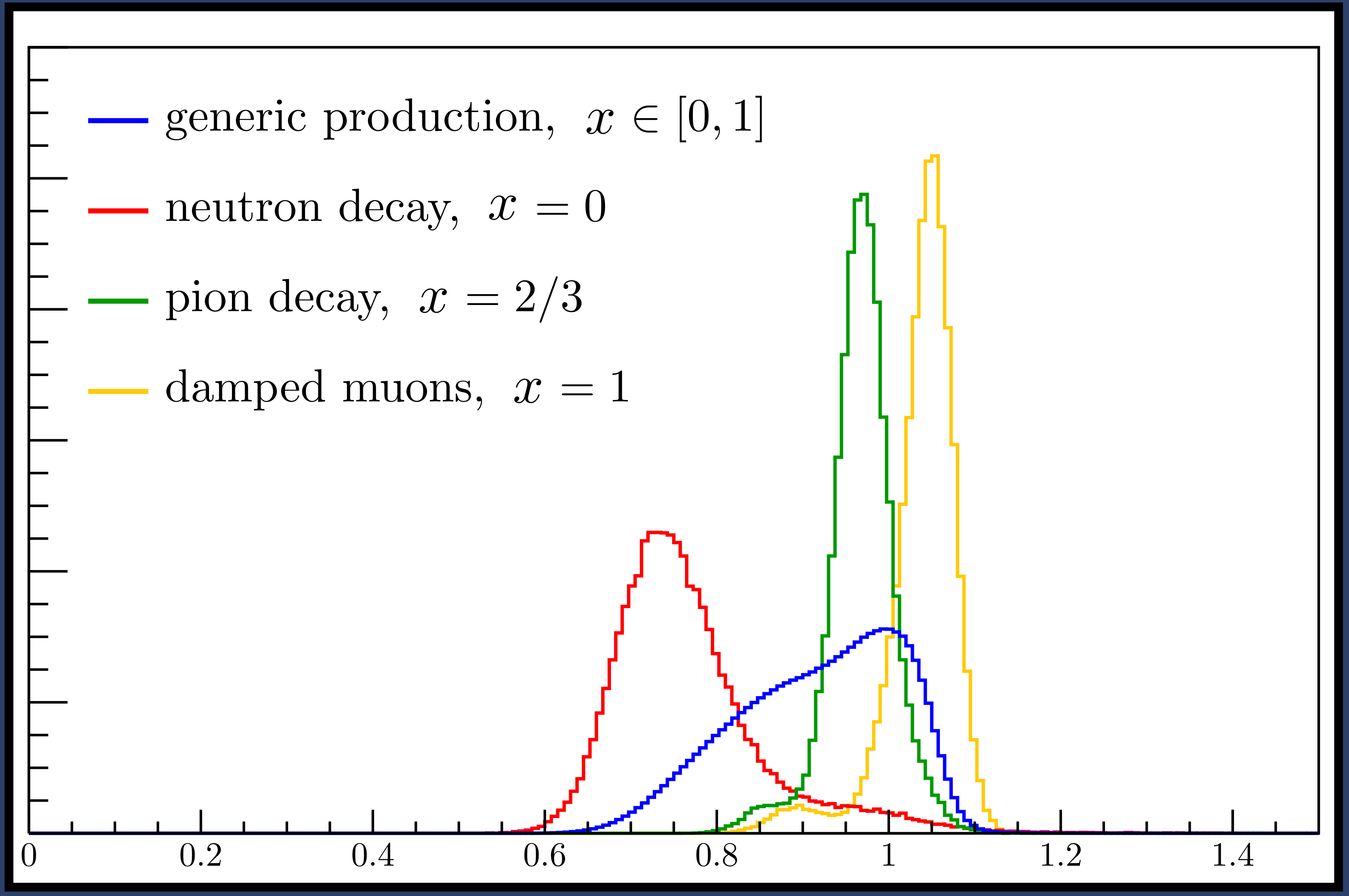
The $R_{\tau\mu}$ factor constrains the cosmic tau neutrino flux at Earth:

$$R_{\tau\mu} = \frac{P_{e\tau}(1-x) + P_{\mu\tau}x}{P_{e\mu}(1-x) + P_{\mu\mu}x}$$

$$N_\tau = R_{\tau\mu} N_\mu$$

where $(\nu_e : \nu_\mu : \nu_\tau)_0 = (1\text{-}x : x : 0)_0$

PDF of $R_{\tau\mu}$:



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Assumptions: - standard three flavour oscillations
- no tau neutrino at production

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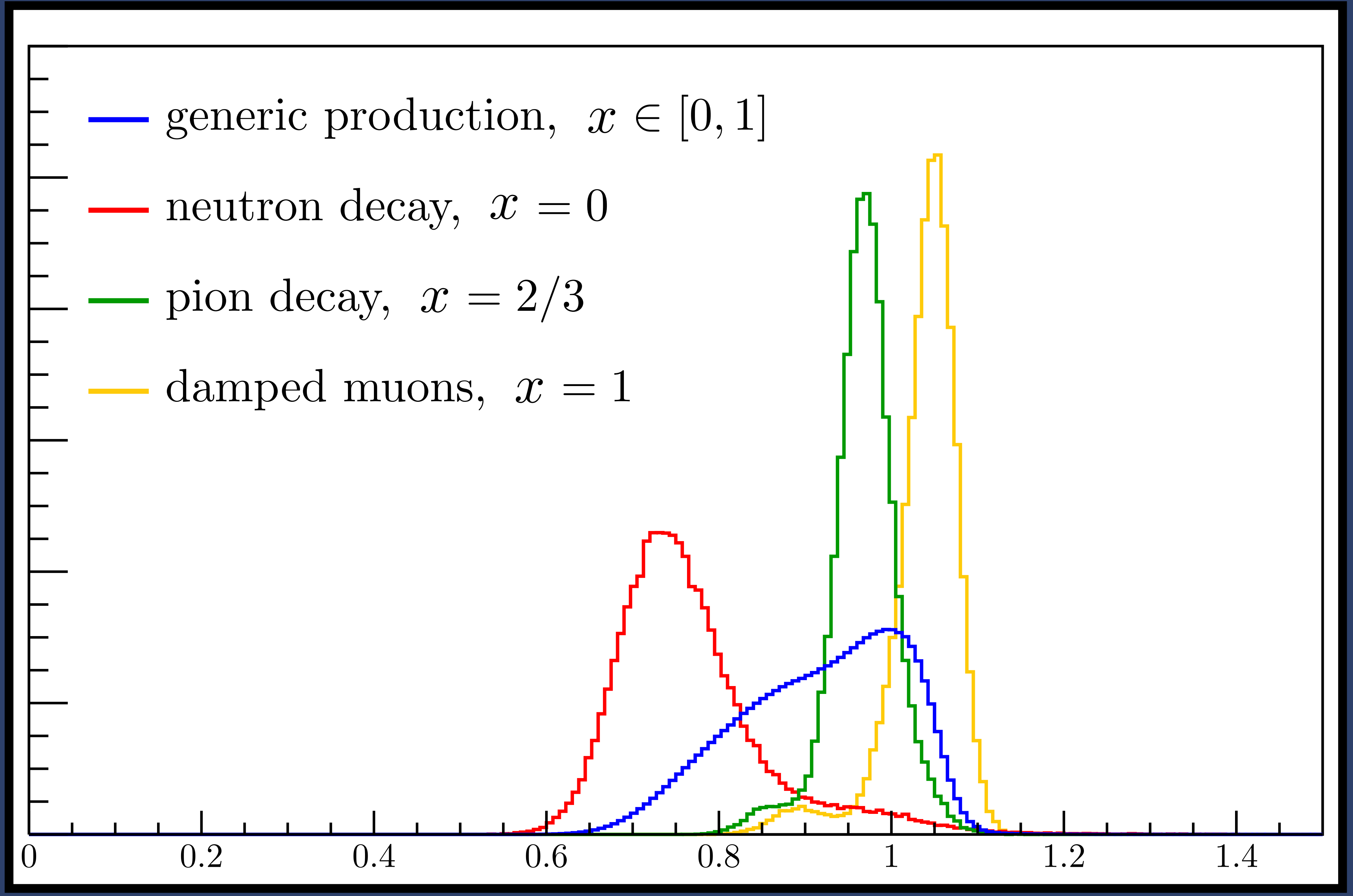

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Clear events due to ν_τ

- double bang = double cascade seen by different DOMs
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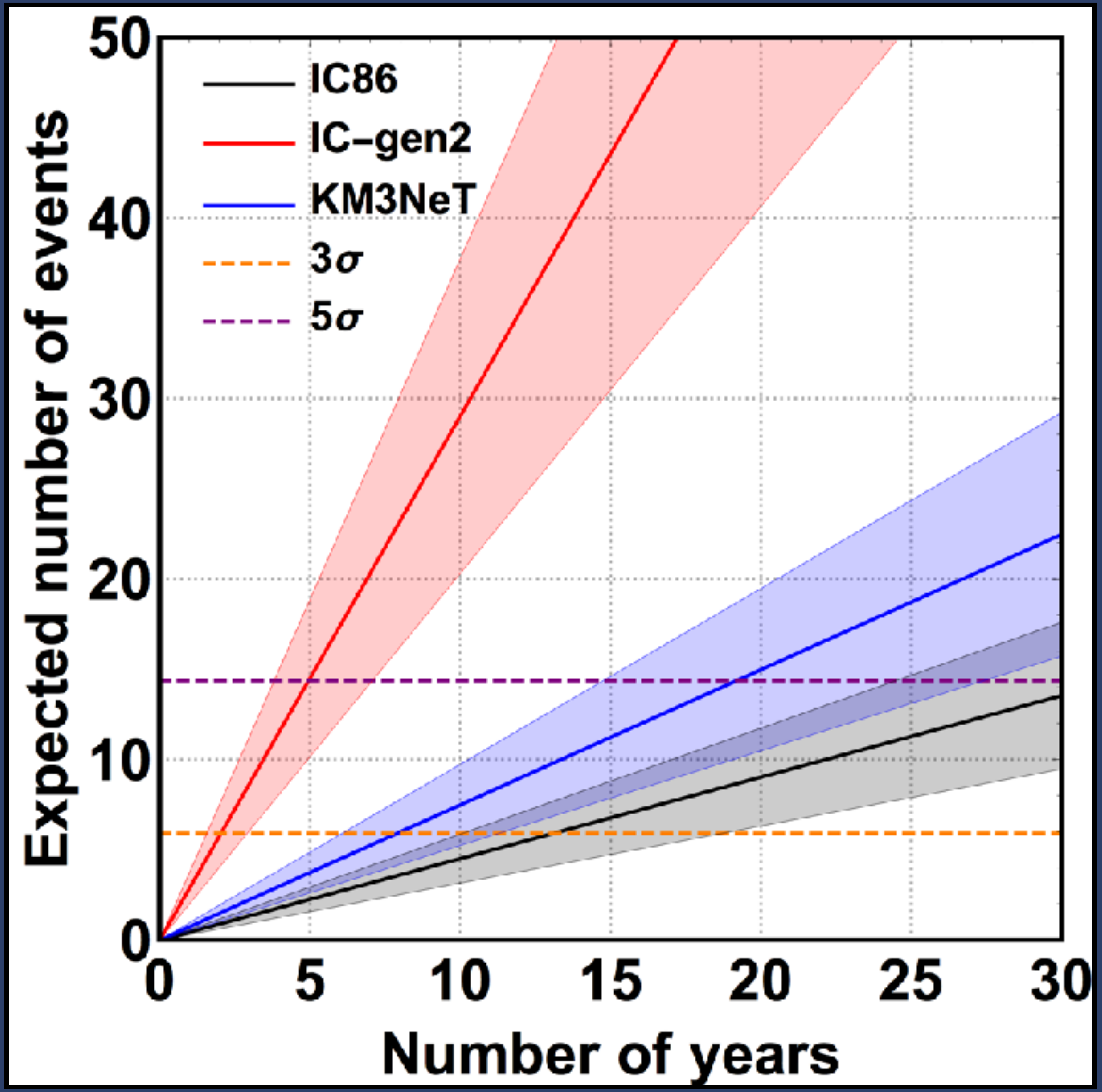
to see 2 int
vertices

4. THE IMPORTANCE OF OBSERVING COSMIC TAU NEUTRINOS

PART 3: YEARLY RATES OF DOUBLE CASCADE EVENTS

Experiment	$T_{\text{year}}^{\text{P}>90\%}$	$T_{\text{year}}^{\text{P}>99\%}$	$T_{\text{year}}^{\text{P}>5\sigma}$
IC86	5.1	10.1	31.7
IC-gen2	0.8	1.6	5.0
KM3NeT	3.1	6.1	19.1

Background ~ 40% = misidentified double cascades (M. Usner, PoS ICRC17 **301** 974)



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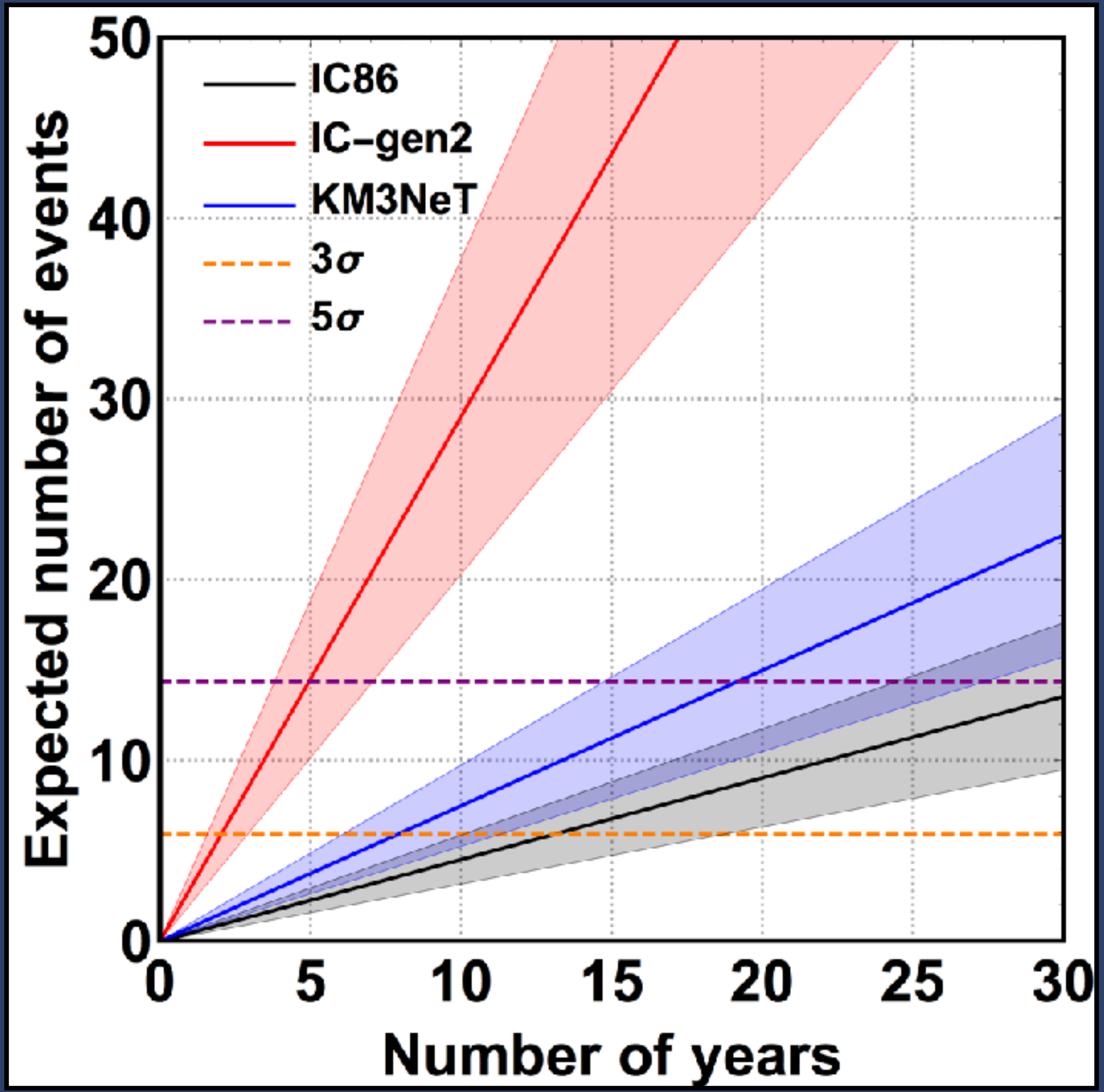
The hypothetical non-observation of double cascades in the next 10-20 years would mean:

- the observed events are not of cosmic origin
- standard three-flavour oscillations do not hold for cosmic neutrinos
- new physics



4. THE ROLE OF PROMPT NEUTRINOS IN THE ICECUBE ANALYSES

C. Mascaretti, F. Vissani, *On the relevance of prompt neutrinos for the interpretation of the IceCube signals*, JCAP **08** (2019) 004

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Strategy of the work:

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- cosmic ν analyses discrepancy due to prompt neutrinos?

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➡ Loeb-Waxman flux: theoretical expectation

$$\frac{d\Phi_{\mathrm{LW}}}{dE} = 2 \times 10^{\pm 0.5} \left(\frac{E}{100\,\mathrm{TeV}} \right)^{-2.15 \pm 0.10} \times 10^{-18}\,\mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$$

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➡ through-going muon spectrum: experimental result

$$\frac{d\Phi_{\mathrm{TM}}}{dE} = 0.90^{+0.30}_{-0.27} \left(\frac{E}{100\,\mathrm{TeV}} \right)^{-2.13\pm 0.13} \times 10^{-18}\,\mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$$

4. THE ROLE OF PROMPT NEUTRINOS IN THE ICECUBE ANALYSES

PART 1: THE OTHER COSMIC NEUTRINO FLUXES

Hadronic mechanism ➡ γ-ray and ν power-law fluxes are related at the source (F. Vissani and F. L. Villante, PR **D78** (2008) 103007):

$$\frac{d\Phi_{\nu_\ell}(E_\nu)}{dE_\nu} = \int_0^1 \frac{dx}{x} \left[\tilde{K}_{\nu_\ell}(x) + \tilde{K}_{\overline{\nu}_\ell}(x)\right] \frac{d\Phi_\gamma(x/E_\nu)}{dE}$$

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The cosmic neutrino spectra are proportional to each other via $C_{\ell\ell'}$ (~ no dependence on slope):

$$C_{\ell\ell'} = \frac{\zeta_{\nu_\ell}(\gamma)}{\zeta_{\nu_{\ell'}}(\gamma)} \qquad \zeta_{\nu_\ell}(\gamma) = \int_0^1 dx\, x^{\gamma-1} \left[\tilde{K}_{\nu_\ell}(x) + \tilde{K}_{\overline{\nu}_\ell}(x)\right]$$

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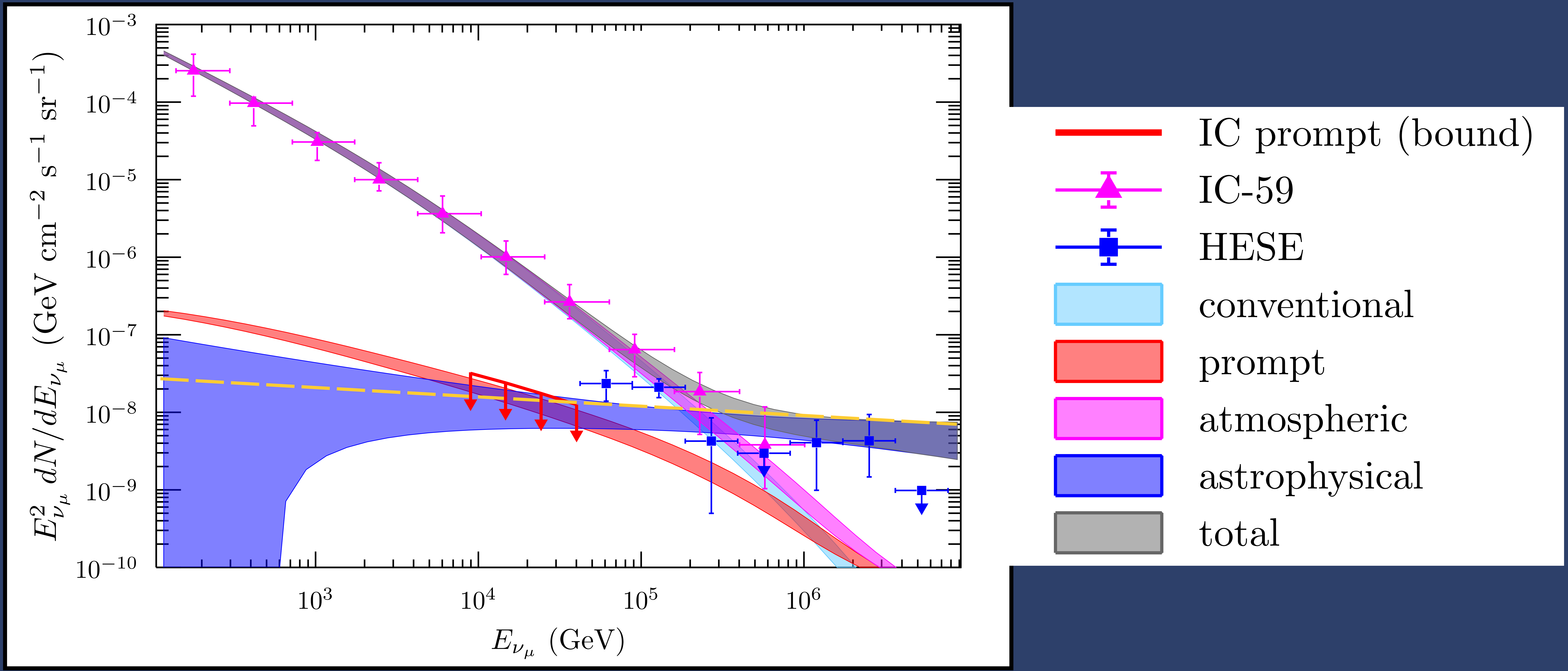
Other less physical, approach: “2:1” approximation: $C_{\ell\ell'} = R_{\ell\ell'}$

4. THE ROLE OF PROMPT NEUTRINOS IN THE ICECUBE ANALYSES

PART 1: THE COMPONENTS OF THE MUON NEUTRINO SPECTRUM



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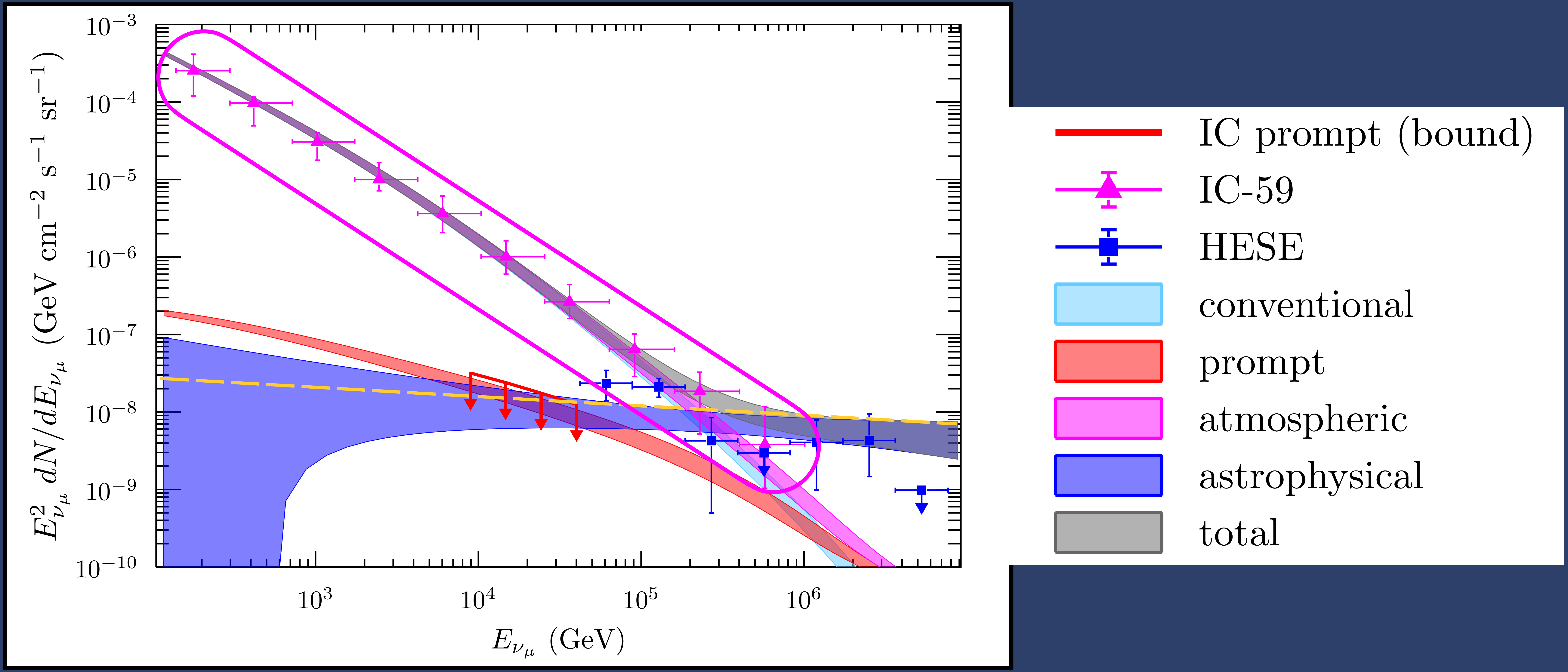

Good agreement between expectations and data for atmospheric neutrinos

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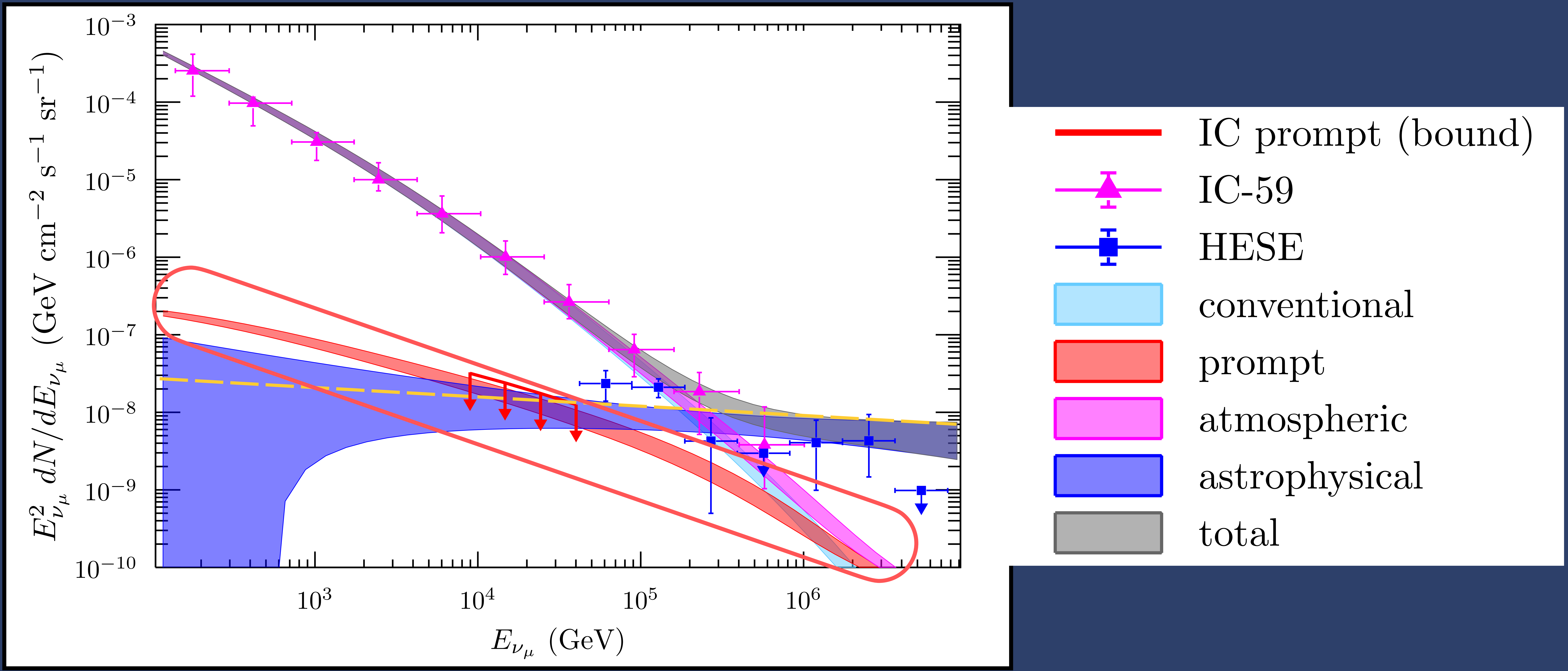
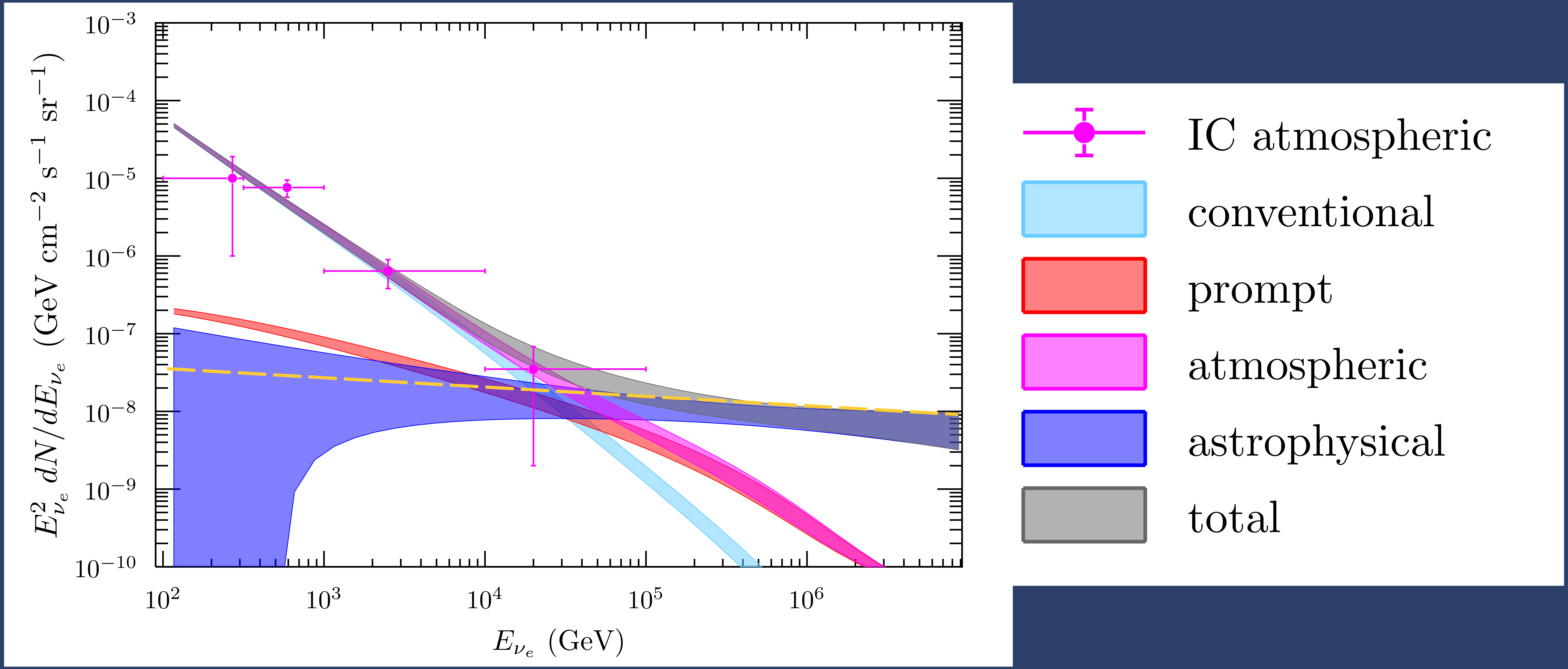


Prompt component always subdominant: very hard to see prompts in ν_μ

4. THE ROLE OF PROMPT NEUTRINOS IN THE ICECUBE ANALYSES

PART 1: THE COMPONENTS OF THE ELECTRON NEUTRINO SPECTRUM



$$C_{e\mu} = 1.30 \pm 0.05 \qquad (R^{\pi}_{e\mu} = 1.09^{+0.03}_{-0.04})$$

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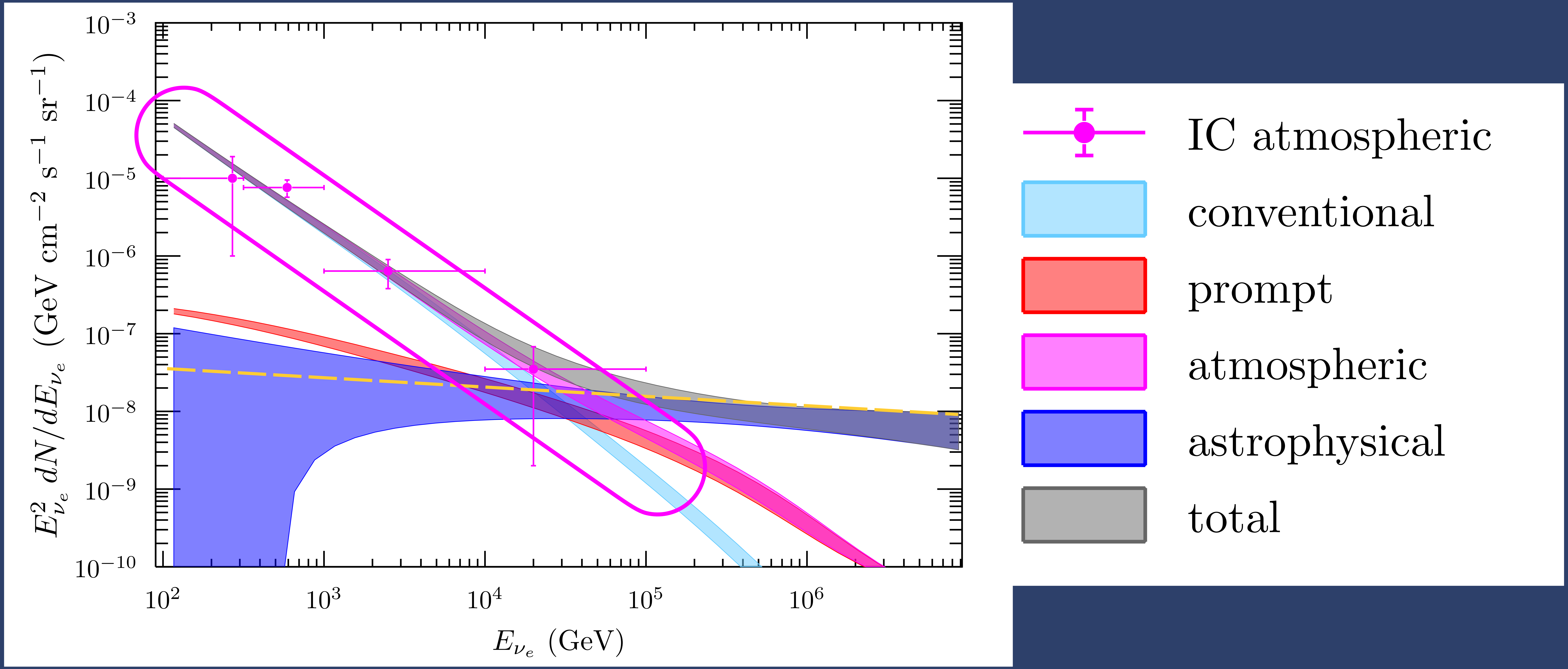

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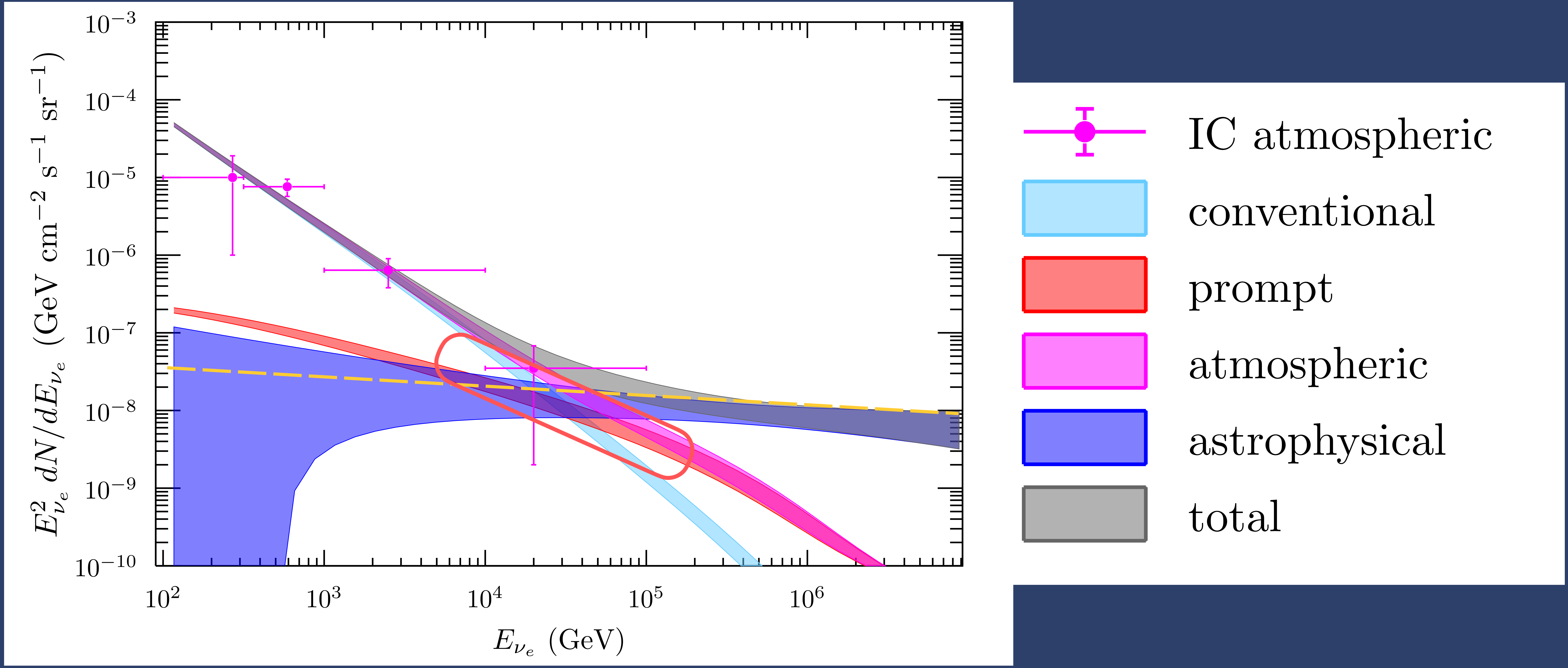

Prompt component relevant for 10 TeV ≤ *E* ≤ 100 TeV

4. THE ROLE OF PROMPT NEUTRINOS IN THE ICECUBE ANALYSES

PART 2: IS IT POSSIBLE TO EXTRACT THE PROMPT SIGNAL? (1/2)

Ideal search: ν_{e} events. Best dataset: cascades, smallest contribution of ν_μ.

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Estimate shower rate in one year due to all components:

- effective area

$$N_{\nu_\ell} = 2\pi \times 1\ \mathrm{year} \times \int_{1\,\mathrm{TeV}}^{10\,\mathrm{PeV}} dE\, \mathcal{A}_{\nu_\ell}(E)$$

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- neutrino flux

$$N_{\nu_\ell} = 2\pi \times 1\ \text{year} \times \int_{1\,\text{TeV}}^{10\,\text{PeV}} dE\, \mathcal{A}_{\nu_\ell}(E) \int_{-1}^{1} d\cos\theta\, \frac{d\Phi_\nu}{dE\, d\cos\theta}(E, \cos\theta)$$

4. THE ROLE OF PROMPT NEUTRINOS IN THE ICECUBE ANALYSES

PART 2: IS IT POSSIBLE TO EXTRACT THE PROMPT SIGNAL? (1/2)

Ideal search: ν_e events. Best dataset: cascades, smallest contribution of ν_μ.

Estimate shower rate in one year due to all components:

- effective area
- neutrino flux
- veto presence: passing fraction functions $P_\nu(E,\cos\theta)$ (C. A. Argüelles et al., JCAP **07** (2018) 047)

$$N_{\nu_\ell} = 2\pi\times 1\ \text{year}\times\int_{1\ \mathrm{TeV}}^{10\ \mathrm{PeV}} dE\,\mathcal{A}_{\nu_\ell}(E)\int_{-1}^{1} d\cos\theta\,\frac{d\Phi_\nu}{dE\,d\cos\theta}(E,\cos\theta)\,P_\nu(E,\cos\theta)$$

4. THE ROLE OF PROMPT NEUTRINOS IN THE ICECUBE ANALYSES

PART 2: IS IT POSSIBLE TO EXTRACT THE PROMPT SIGNAL? (2/2)

component	N_{ν_e}	N_{ν_μ}	N_{ν_τ}
conventional	140 – 180	385 – 485	0
prompt	9 – 12	1.4 – 1.8	0.77 – 1.02
cosmic	10 – 40	2 – 6	5 – 20

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It does not look easy…

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…but with angular selection

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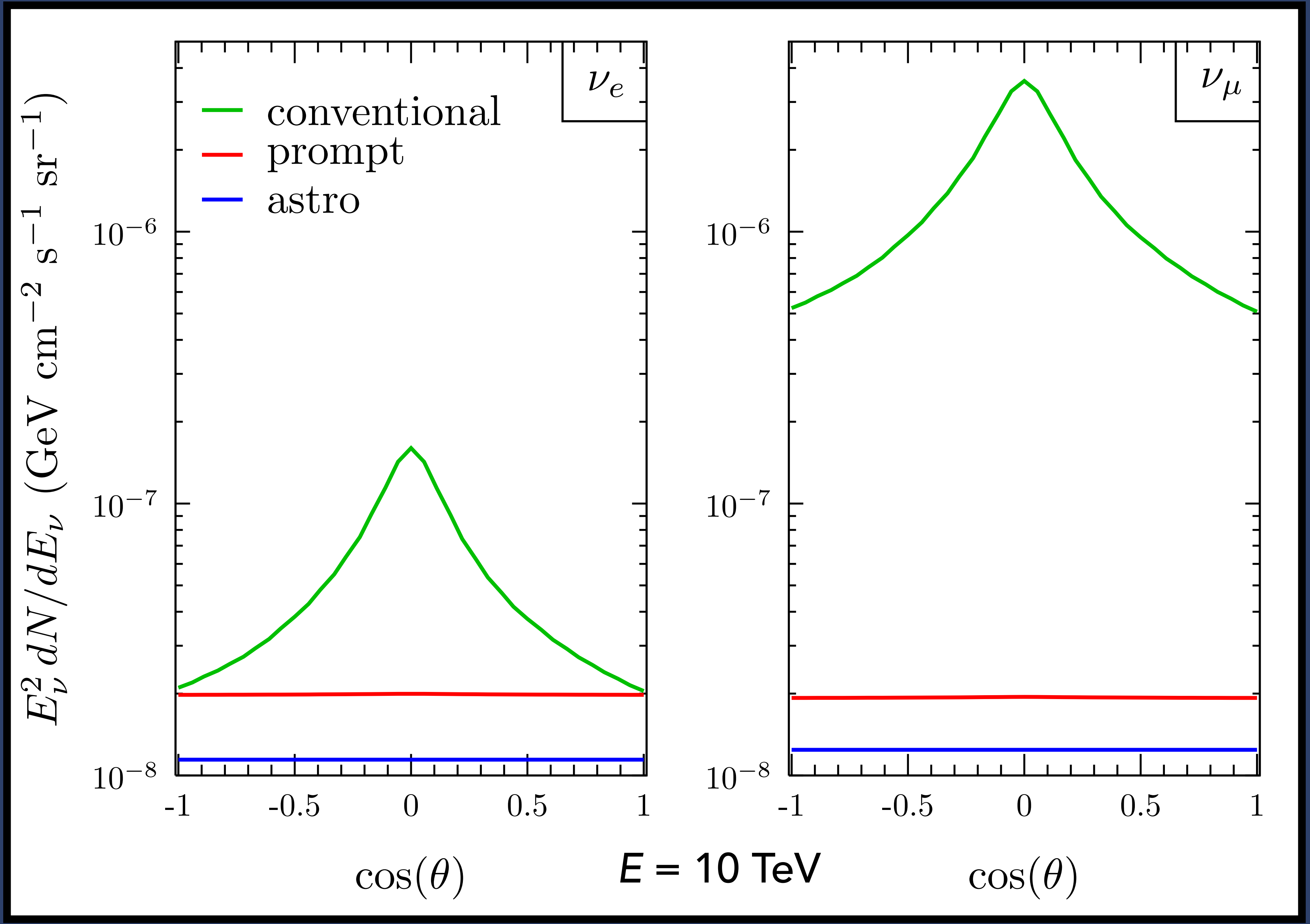

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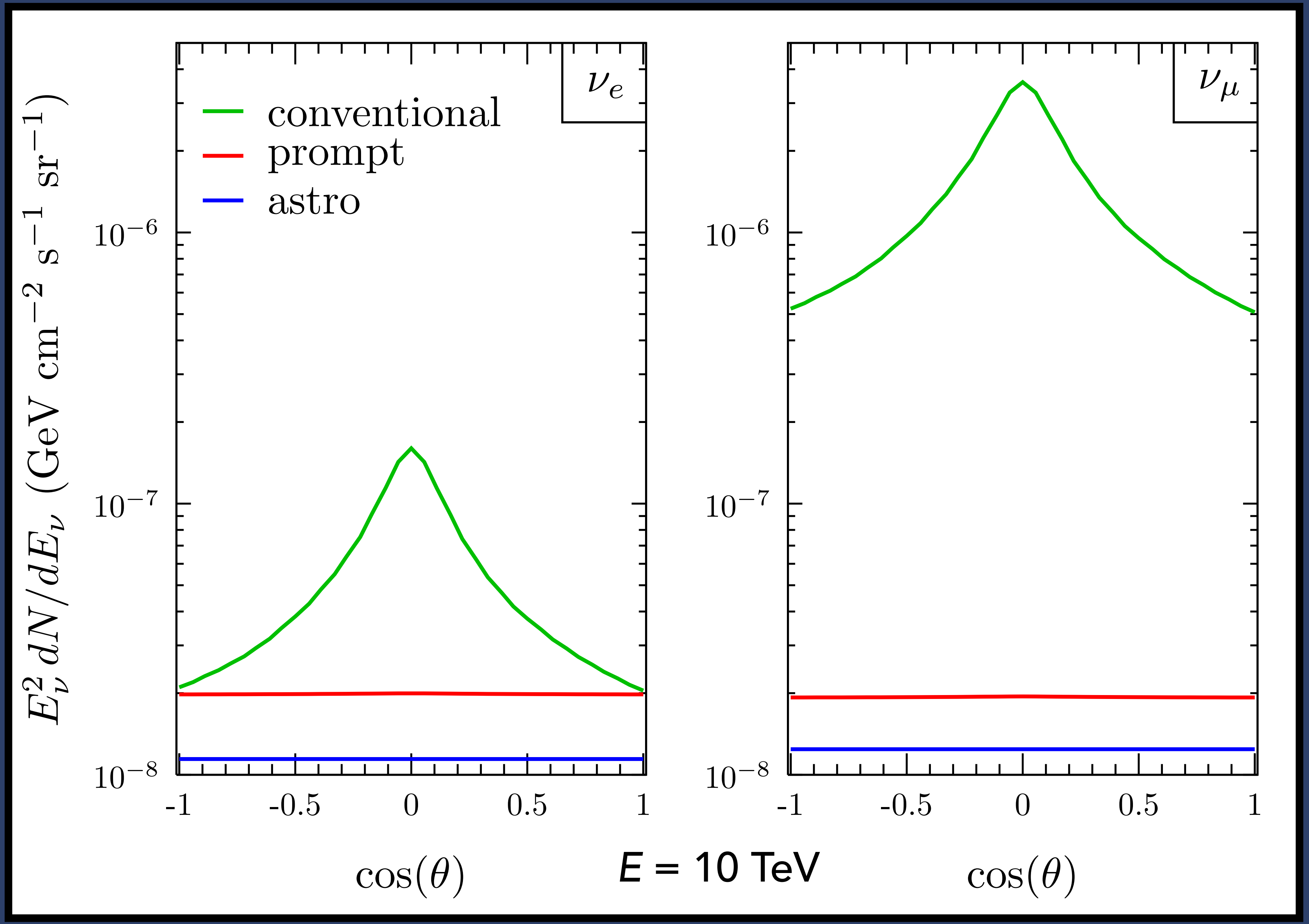

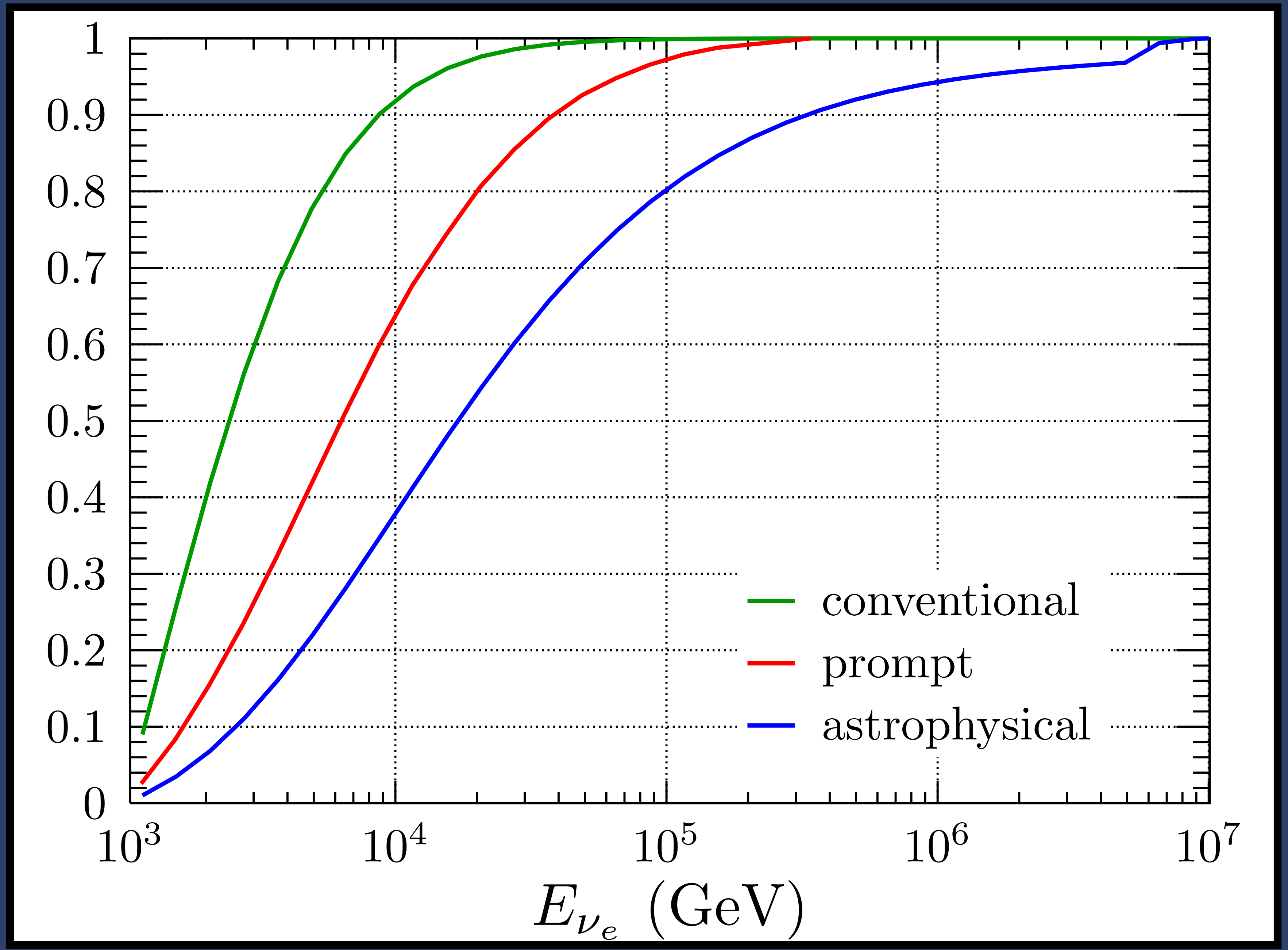

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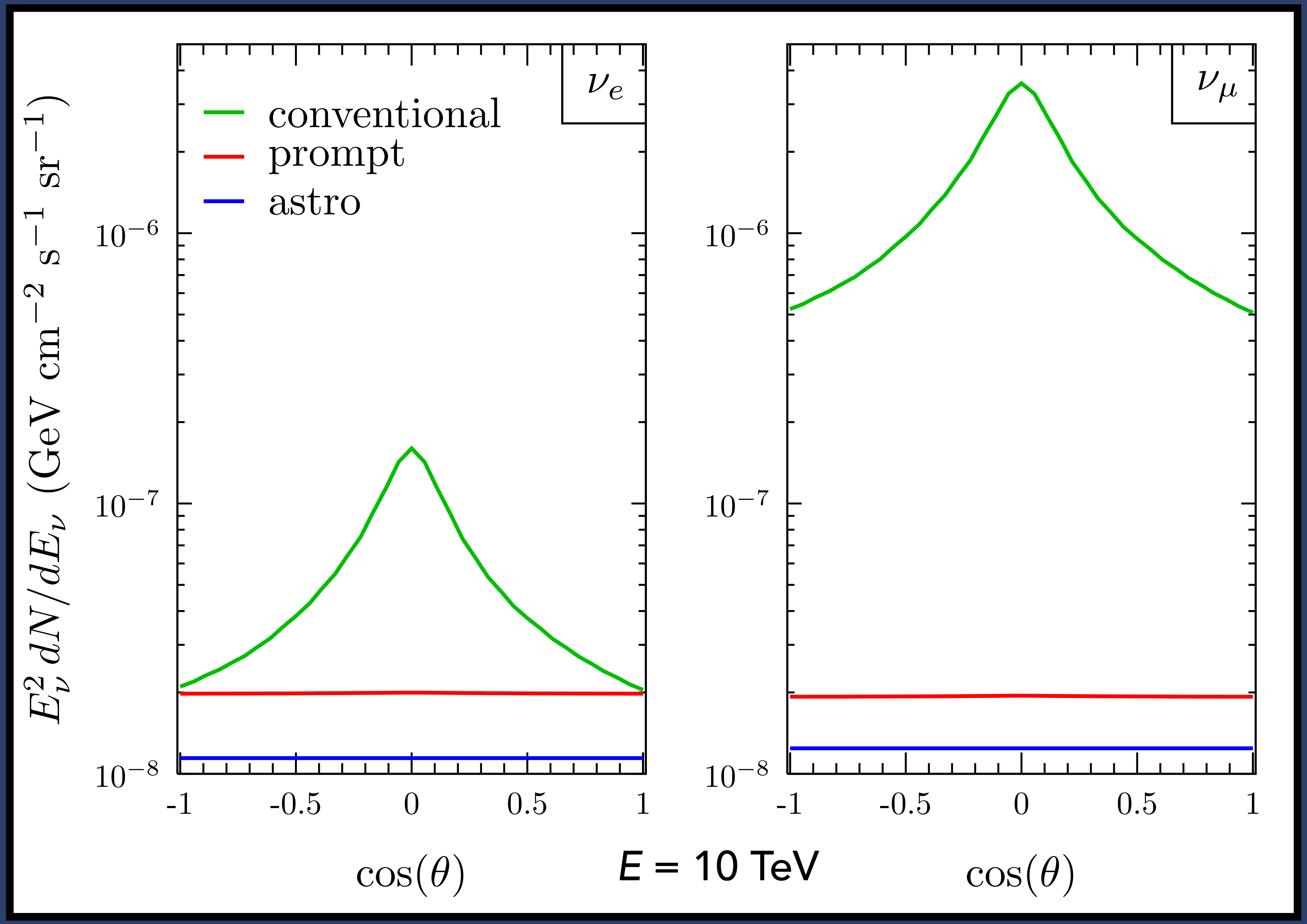
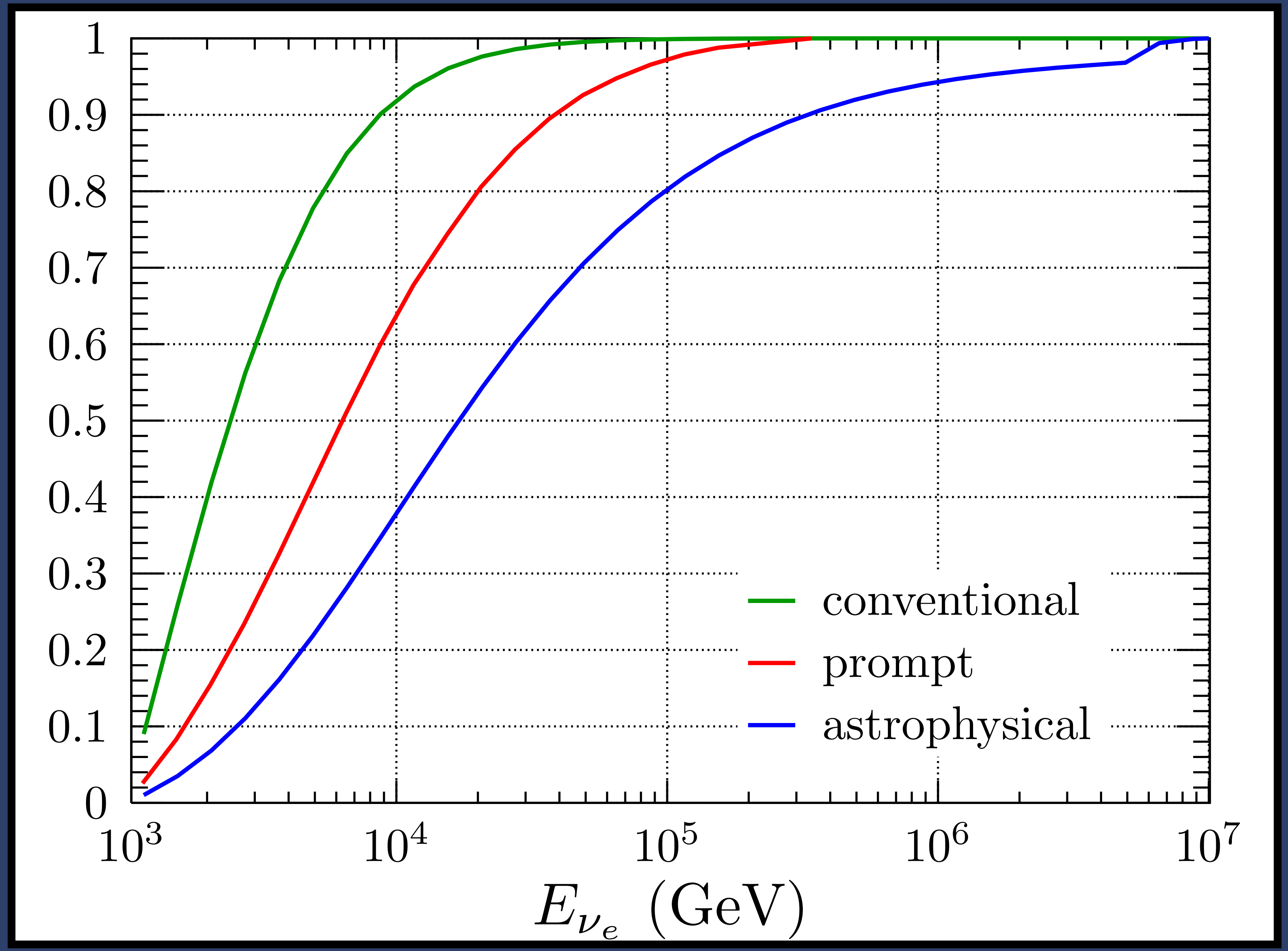


…it may be possible



4. THE ROLE OF PROMPT NEUTRINOS IN THE ICECUBE ANALYSES

PART 3: SPECTRAL TENSION DUE TO PROMPT NEUTRINOS? (1/2)

Possible issue: the veto may not work exactly as supposed to

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Possible issue: the veto may not work exactly as supposed to

Extreme case: veto does not work at all, so that

Component	N_{ν_e}	N_{ν_μ}	N_{ν_τ}	N_{tot}
Prompt	$18 - 24$	$3 - 4$	$1 - 2$	$22 - 30$
Cosmic	$10 - 40$	$2 - 6$	$5 - 20$	$15 - 65$

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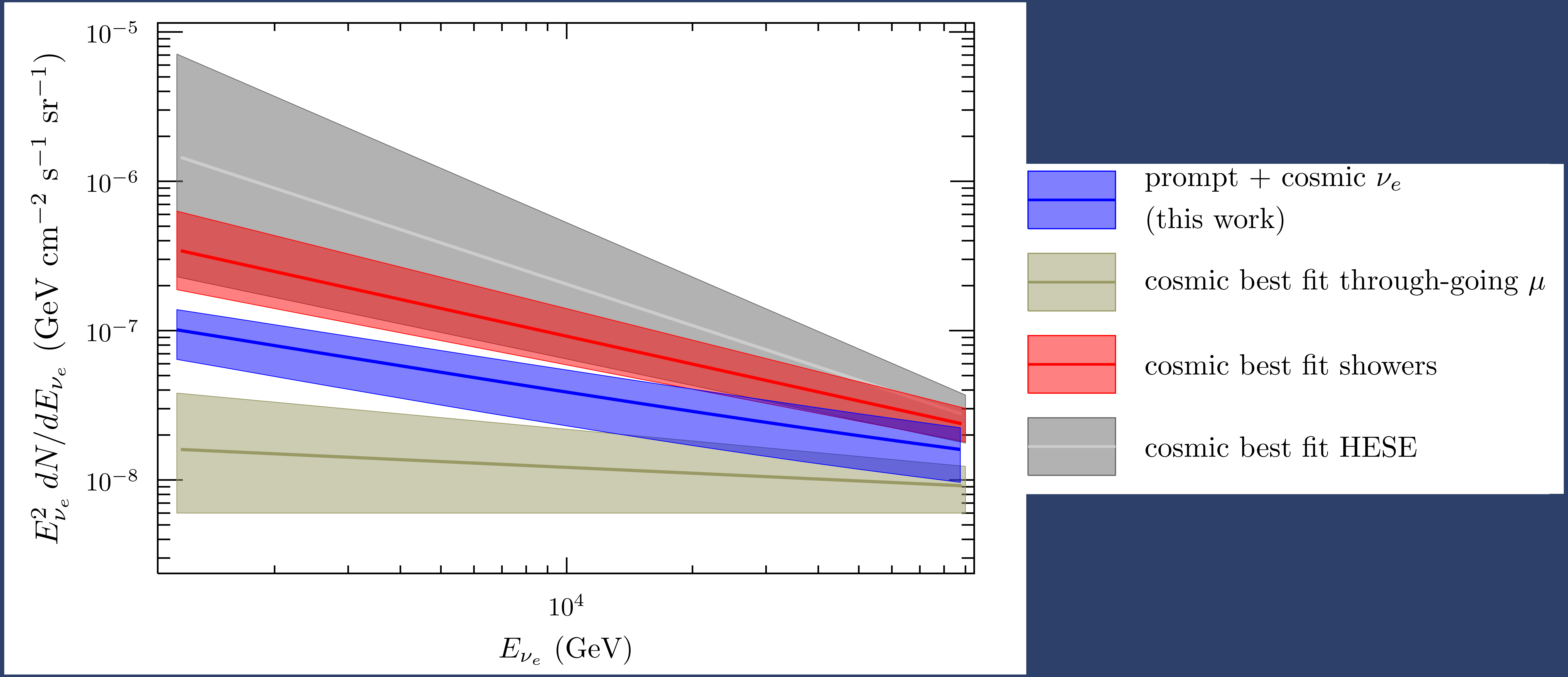
Component	N_{ν_e}	N_{ν_μ}	N_{ν_τ}	N_{tot}
Prompt	$18 - 24$	$3 - 4$	$1 - 2$	$22 - 30$
Cosmic	$10 - 40$	$2 - 6$	$5 - 20$	$15 - 65$

Similar number of events + same distribution
➡ difficult to distinguish
➡ can cause spectral tension?

4. THE ROLE OF PROMPT NEUTRINOS IN THE ICECUBE ANALYSES

PART 3: SPECTRAL TENSION DUE TO PROMPT NEUTRINOS? (2/2)



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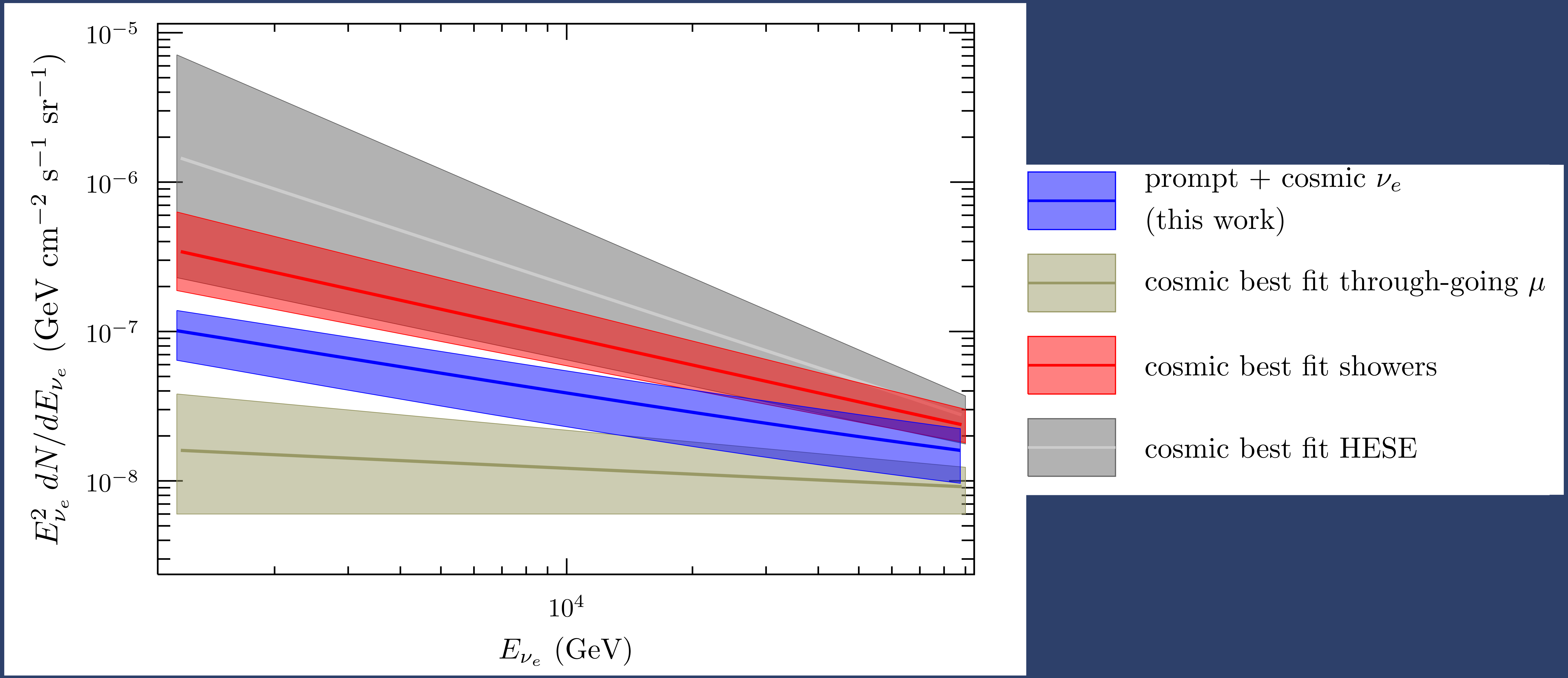

Prompt + cosmic spectrum closer to HESE/showers spectrum

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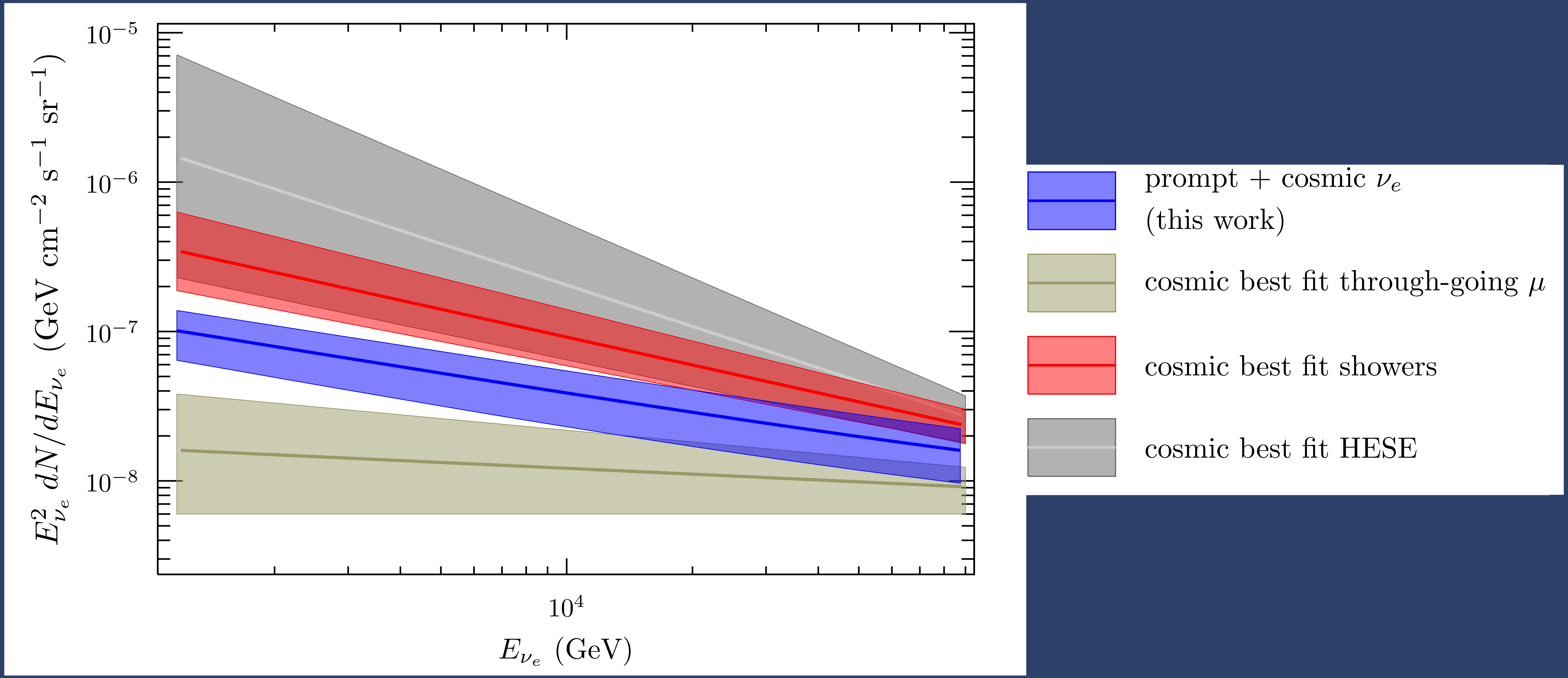
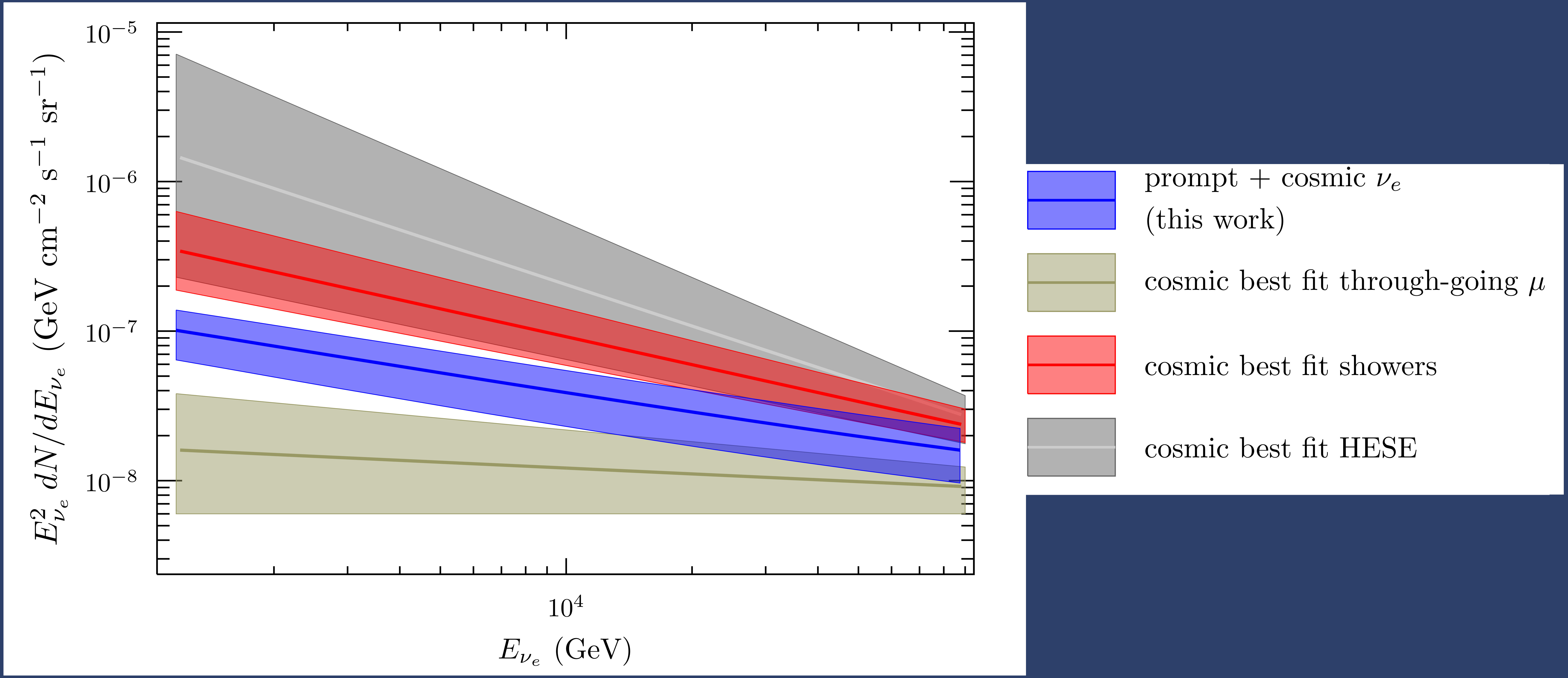
PART 3: SPECTRAL TENSION DUE TO PROMPT NEUTRINOS? (2/2)



Anomaly attributable to: prompts in cascades, background tracks in HESE.
This in the “minimal” proposal = no other hypothetical physical ingredients

4. THE ROLE OF PROMPT NEUTRINOS IN THE ICECUBE ANALYSES

PART 3: SPECTRAL TENSION DUE TO PROMPT NEUTRINOS? (2/2)



Other contributions to the low-energy HESE spectrum are not ruled out
e.g. Galactic neutrinos (see G. Pagliaroli, F. L. Villante JCAP 2018 08 035)

5. SUMMARY AND OUTLOOK

5. SUMMARY AND OUTLOOK

SOLAR NEUTRINOS

Contributions in the context of the luminosity constraint:

- clarification, test, corrections and improvement
- impact on the search of CNO neutrinos
- impact on the Solar chemical composition

5. SUMMARY AND OUTLOOK

ATMOSPHERIC NEUTRINOS

Simple primary CR flux ➡ numerical computation of atmospheric neutrino fluxes

- assessed possibility to probe the knee position with neutrinos
- slight preference for knee as measured by KASCADE-Grande
- better atmospheric neutrino measurements ➡ proxy for cosmic-ray studies

5. SUMMARY AND OUTLOOK

COSMIC NEUTRINOS AND THE PROMPT COMPONENT

Used previous results on atmospheric neutrinos:

- not surprising that prompt neutrinos have not been observed yet
- search for them seems possible in the inclined showers dataset with $E_{\mathrm{th}} \sim 10$s TeV
- possible impact of prompt neutrinos on the spectral tension in the IceCube analyses

5. SUMMARY AND OUTLOOK

COSMIC NEUTRINOS

Critical discussion of the experimental results:

- expanded on the isotropy + single power law assumption
- combination of theory and observations
- estimation of effective areas of neutrino detectors
- predictions of Glashow resonances and ν_τ induced events

5. SUMMARY AND OUTLOOK

OUTLOOK

Many scientific opportunities in neutrino astrophysics:

- solar neutrino detectors will measure and characterise CNO neutrinos
- more statistics ➡ better characterisation of the neutrino fluxes
- evidence for prompt neutrinos
- clear detection of double cascades and Glashow resonances
- …with neutrinos, better expect to the unexpected!

THANK YOU FOR YOUR ATTENTION!

BACKUP SLIDES

BACKUP SLIDES: UPDATE ON COSMIC NEUTRINO OSCILLATION PROBABILITIES (1/2)

$$P_{\ell\ell'} = \frac{\mathbb{I}}{3} + \begin{pmatrix} 2P_0 & -P_0 + P_1 & -P_0 - P_1 \\ & P_0/2 - P_1 + P_2 & P_0/2 - P_2 \\ & & P_0/2 + P_1 + P_2 \end{pmatrix}$$

$$P_0 = \frac{1}{2}\left[(1-\epsilon)^2\left(1 - \frac{\sin^2(2\theta_{12})}{2}\right) + \epsilon^2 - \frac{1}{3}\right]$$

$$P_1 = \frac{1-\epsilon}{2}\left(\gamma\cos 2\theta_{12} + \beta\frac{1-3\epsilon}{2}\right)$$

$$P_2 = \frac{1}{2}\left[\gamma^2 + \frac{3}{4}\beta^2(1-\epsilon)^2\right]$$

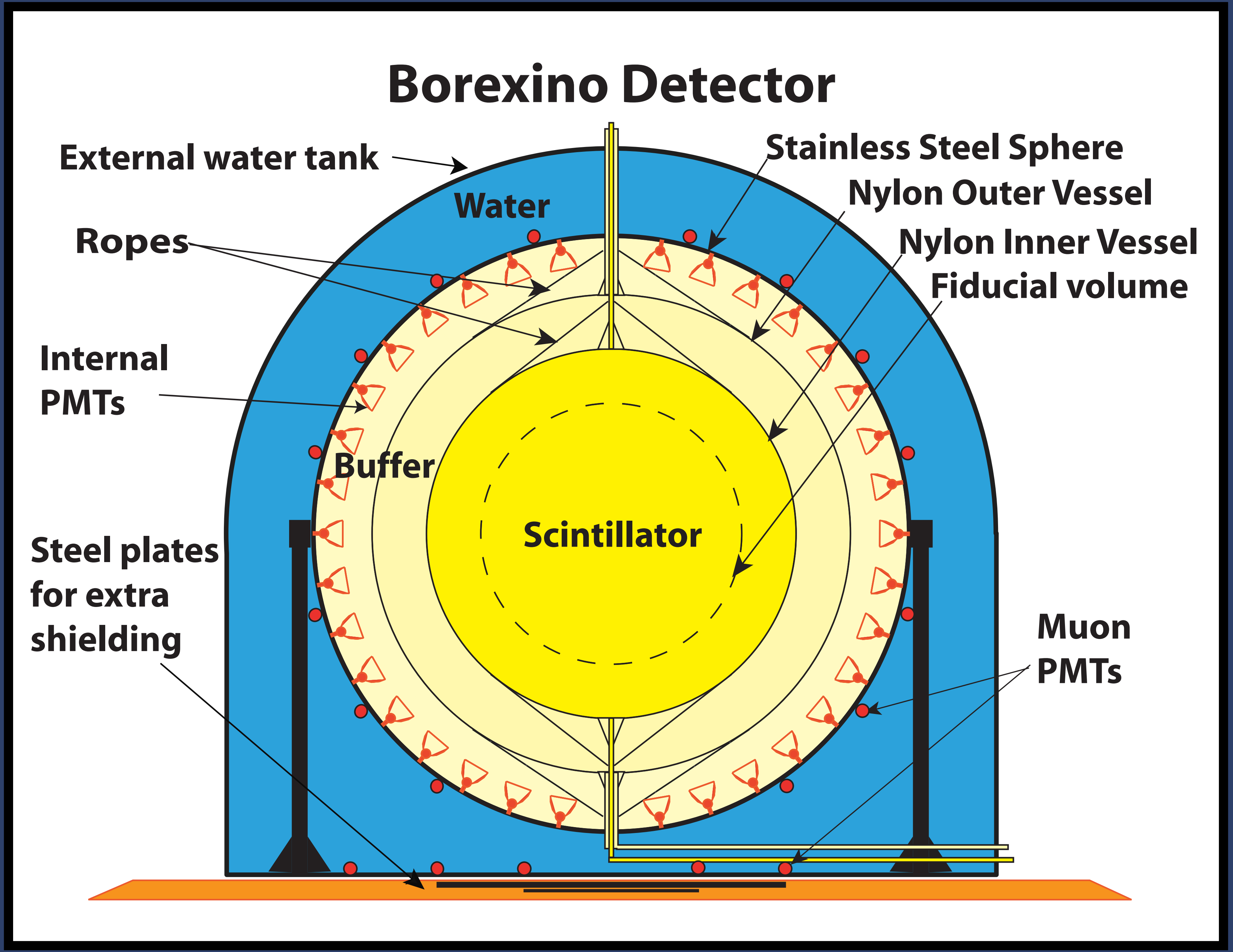
$$\epsilon = \sin^2\theta_{13}$$

$$\alpha = \sin\theta_{13}\cos\delta\sin 2\theta_{12}\sin 2\theta_{23}$$

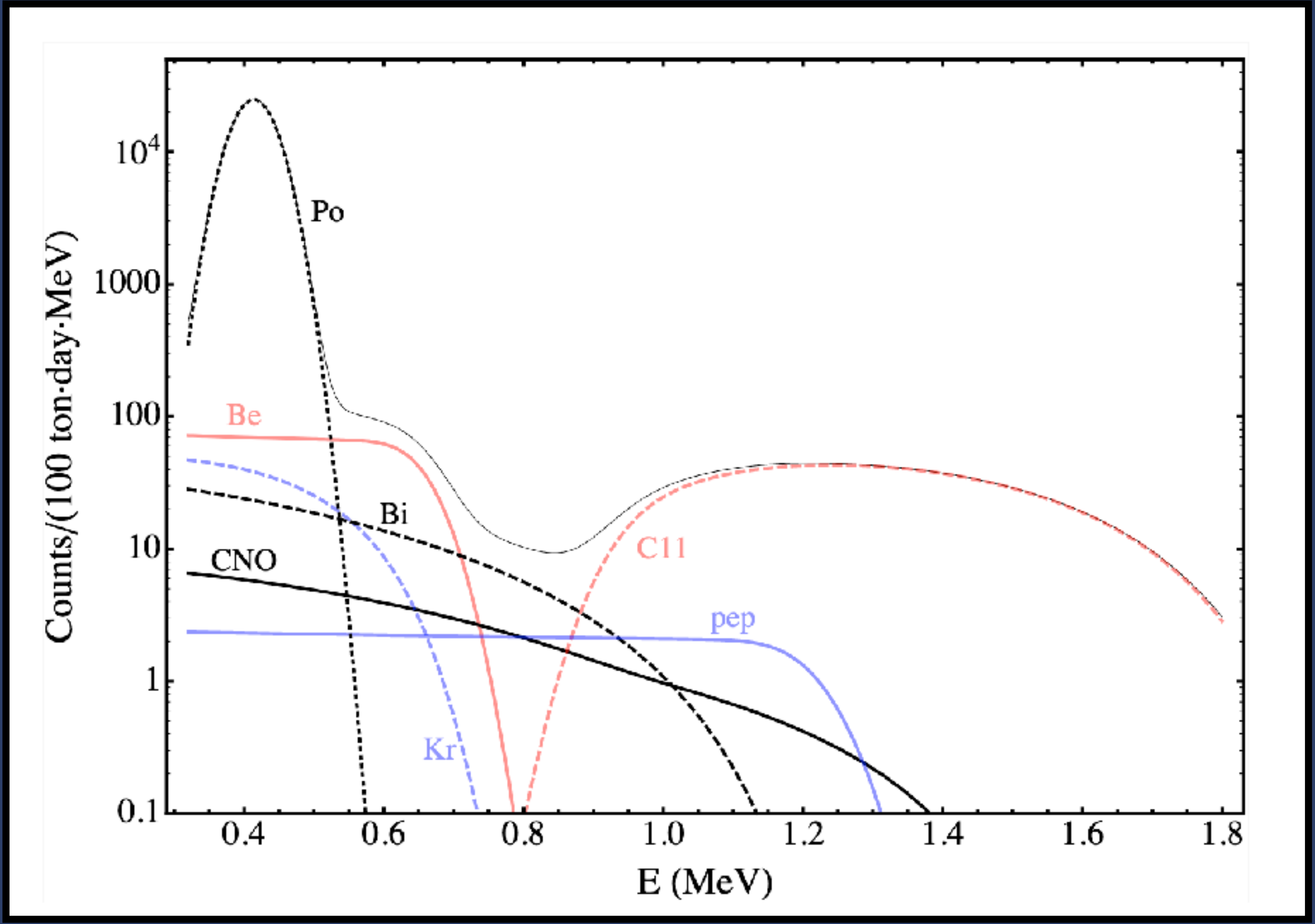
$$\beta = \cos 2\theta_{23}$$

$$\gamma = \alpha - \frac{\beta}{2}\cos 2\theta_{12}(1+\epsilon)$$

BACKUP SLIDES: BOREXINO AND THE CNO MEASUREMENT

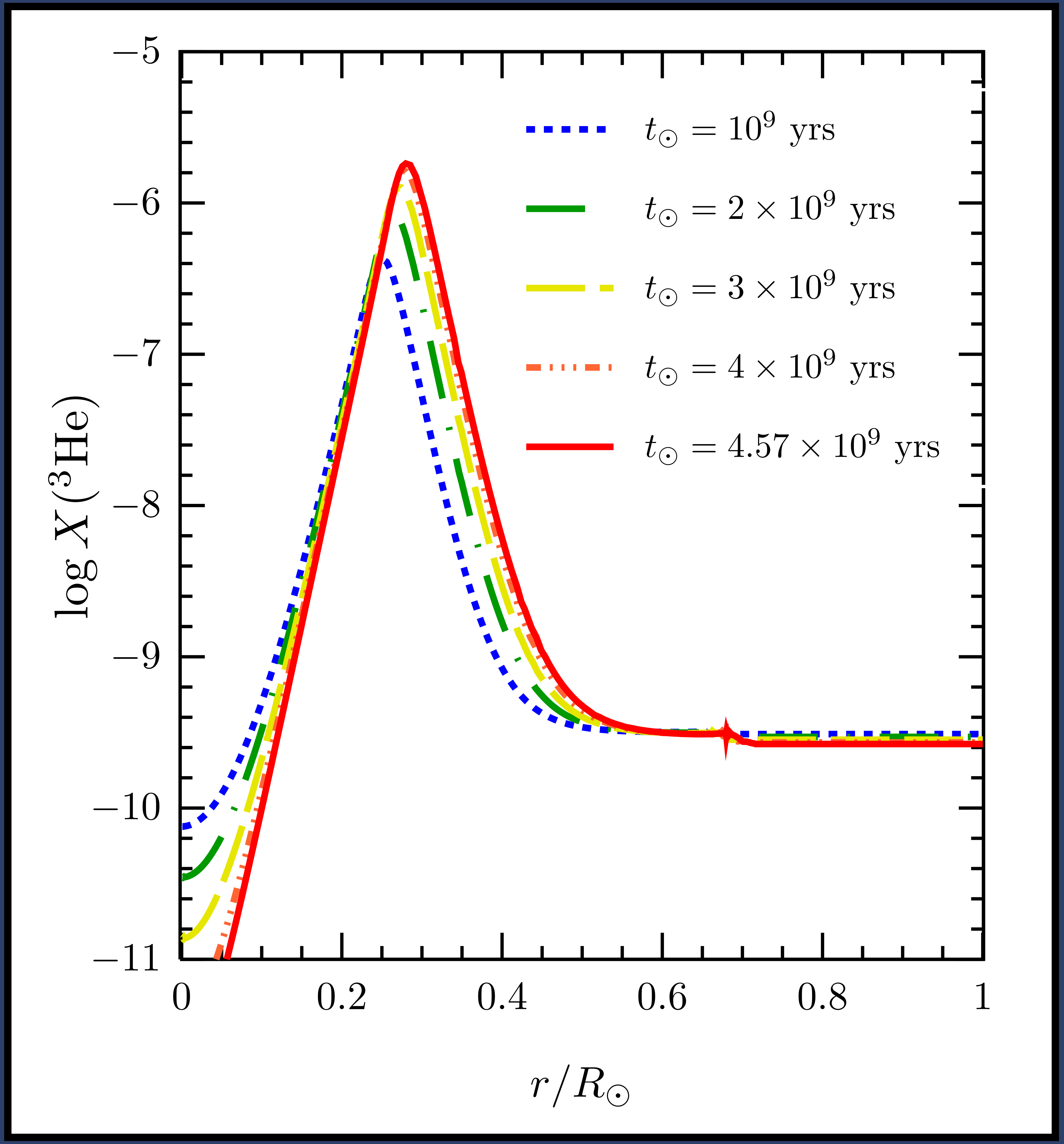


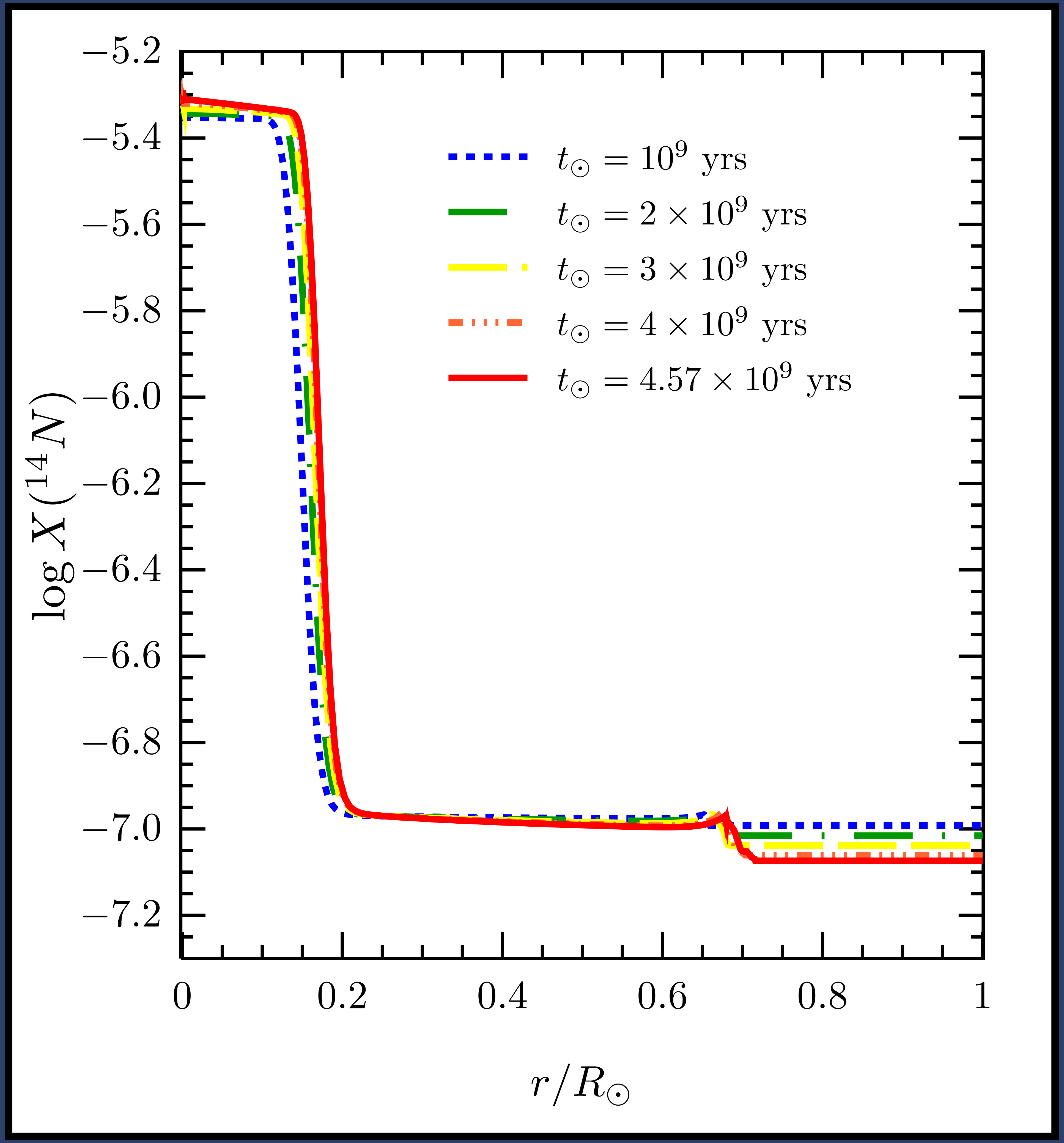
G. Alimonti et al., Nuc. Instr. & Meth. in Phys. Res. A 600 (2009) 3



F. L. Villante et al., Phys. Lett. B 701 (2011) 336-341

BACKUP SLIDES: ACCUMULATING ^{3}HE AND ^{14}N IN THE SUN





BACKUP SLIDES: SPECTROSCOPY VS HELIOSEISMOLOGY

Around 2000s: helioseismic results and SSMs agreed very well, supporting stellar evolution and neutrino flux calculations

2000-now: 3D hydrodynamical models of Sun + improved knowledge of atomic properties led to reviewing the solar abundances towards lower metallicity - debate is still ongoing

“Solar abundance problem”: the low-metallicity abundances fail to reproduce all helioseismic probes

Possibility: a radius-dependent increase of the radiative opacities could lead to low-metallicity SSMs which both satisfy helioseismic probes and older, higher-metallicity SSMs

See Vinyoles et al., “A New Generation of Standard Solar Models”, Astr. Journ., 835 2

BACKUP SLIDES: CUSTOM CR MODEL FITS

$$\frac{d\Phi_{\rm CR}}{dE} = \sum_{i=\rm p,He} N_i \left(\frac{E}{10\,\rm TeV}\right)^{-\gamma_i} f_{\rm knee}(E/Z_i) + \boxed{\left.\frac{d\Phi_p}{dE}\right|_{\rm x\text{-}gal}} \longrightarrow \propto E^{-2.7}$$

$$f_{\rm knee}(R) = \begin{cases} \exp\left[-\left(\dfrac{R}{\overline{R}}\right)^2\right] & \texttt{exp2-cut} \\ \theta(\overline{R}-R) + \theta(R-\overline{R})\left(\dfrac{Z_i R}{10\,\rm TeV}\right)^{-2+\delta} & \texttt{delta-slope} \end{cases}$$

Data	N_p	γ_p	$N_{\rm He}$	$\gamma_{\rm He}$	Knee model	$\overline{R}$	$N_{\rm eg}$
ARGO	1.5 ± 0.2	2.71 ± 0.04	1.5 ± 0.1	2.64 ± 0.03	`exp2-cut` `delta-slope`	1.3 ± 0.1 PV 640 ± 50 TV	6.0 ± 0.2 5.0 ± 0.5
KG	1.5 ± 0.2	2.71 ± 0.04	1.5 ± 0.1	2.64 ± 0.03	`exp2-cut` `delta-slope`	15.1 ± 0.7 PV 5.8 ± 0.6 PV	6.0 ± 0.2 5.0 ± 0.5

× 10^{-7} GeV^{-1} m^{-2} s^{-1} sr^{-1} @ 10 TeV

× 10^{-19} GeV^{-1} m^{-2} s^{-1} sr^{-1} @ 100 PeV

BACKUP SLIDES: THE H3A PRIMARY CR MODEL

$$\overset{\text{m}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}}{\overset{\uparrow}{\boxed{\frac{dN_i}{d\log E}}}} = \sum_{j=1}^{3} \mathcal{N}_{i,j} E^{-\gamma_{i,j}} \exp\left(-\frac{E}{Z_i R_j}\right)$$

	R_j	p	He	CNO	Mg-Si	Fe
$\mathcal{N}_{i,1}$	4 PV	7860	3550	2200	1430	2120
$\gamma_{i,1}$		1.66	1.58	1.63	1.67	1.63
$\mathcal{N}_{i,2}$	30 PV	20	20	13.4	13.4	13.4
$\gamma_{i,2}$		1.4	1.4	1.4	1.4	1.4
$\mathcal{N}_{i,3}$	2 EV	1.7	1.7	1.14	1.14	1.14
$\gamma_{i,3}$		1.4	1.4	1.4	1.4	1.4

BACKUP SLIDES: EXTRACTION OF ASTROPHYSICAL SIGNAL

FROM MASCARETTI, EVOLI, BLASI, AP 114 (2020) 22-29

- Sum a power-law to our atmospheric neutrino fluxes

$$\frac{d\Phi_{\mathrm{astro}}}{dE} = N\left(\frac{E}{100\,\mathrm{TeV}}\right)^{-\gamma} \times 10^{-18}\,\mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$$

BACKUP SLIDES: EXTRACTION OF ASTROPHYSICAL SIGNAL

FROM MASCARETTI, EVOLI, BLASI, AP 114 (2020) 22-29

- Sum a power-law to our atmospheric neutrino fluxes
- Fit the IC-79 ν_μ data and compare it to cosmic neutrino analyses

$$\frac{d\Phi_{\rm astro}}{dE} = N \left(\frac{E}{100\,{\rm TeV}} \right)^{-\gamma} \times 10^{-18}\,{\rm GeV}^{-1}\,{\rm cm}^{-2}\,{\rm s}^{-1}\,{\rm sr}^{-1}$$

	ARGO	KG	HESE	THR. MU
N	10 ± 3	7 ± 3	2.46 ± 0.8	$0.9^{+0.30}_{-0.27}$
γ	2.9 ± 0.2	2.6 ± 0.2	$2.92^{+0.33}_{-0.29}$	2.13 ± 0.13

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Flux of IC-79 is anomalously large for $E_{\text{rec.}\,\mu} \geq 100$ TeV - compatible with statistical fluctuation.

BACKUP SLIDES: DETECTOR SIZE FOR COSMIC NEUTRINOS

Very optimistic yearly rate of cosmic neutrino events:

- σ ~ 10^{-34} cm^2 = deep inelastic x-section at E_ν = 100 TeV
- flux = Waxman-Bahcall limit
- perfect, uniform response of detector above 100 TeV

$$R = \Delta T \, \sigma \, \frac{\rho V}{m_N} \int\limits_{100\,\mathrm{TeV}}^{\infty} dE \, 4\pi \, \frac{d\Phi_{\mathrm{WB}}}{dE} \approx 10\,\mathrm{yr}^{-1} \left(\frac{V}{1\,\mathrm{km}^3} \right)$$

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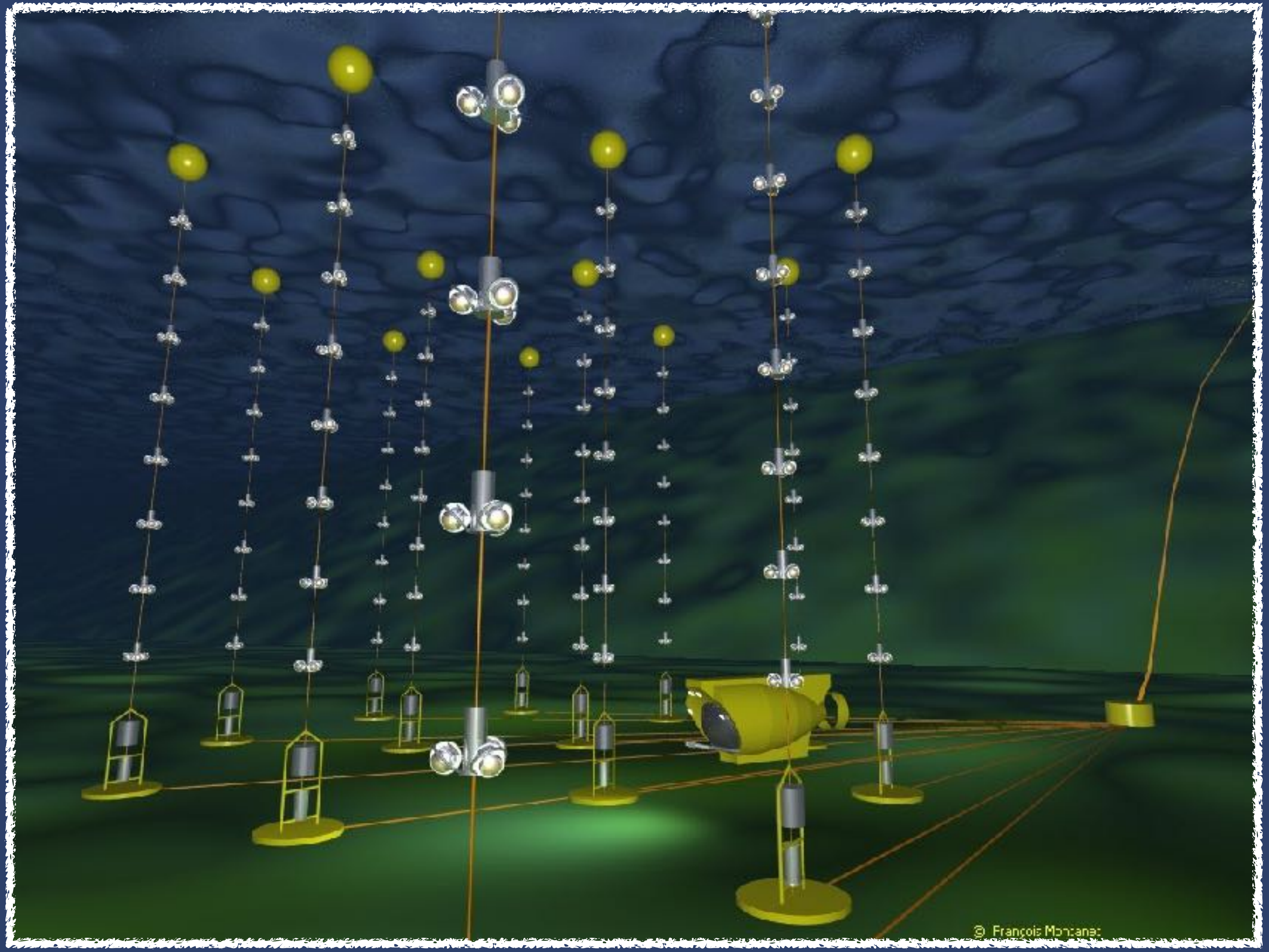
➡ need for km^3-scale detectors to detect cosmic neutrinos over atmospheric background

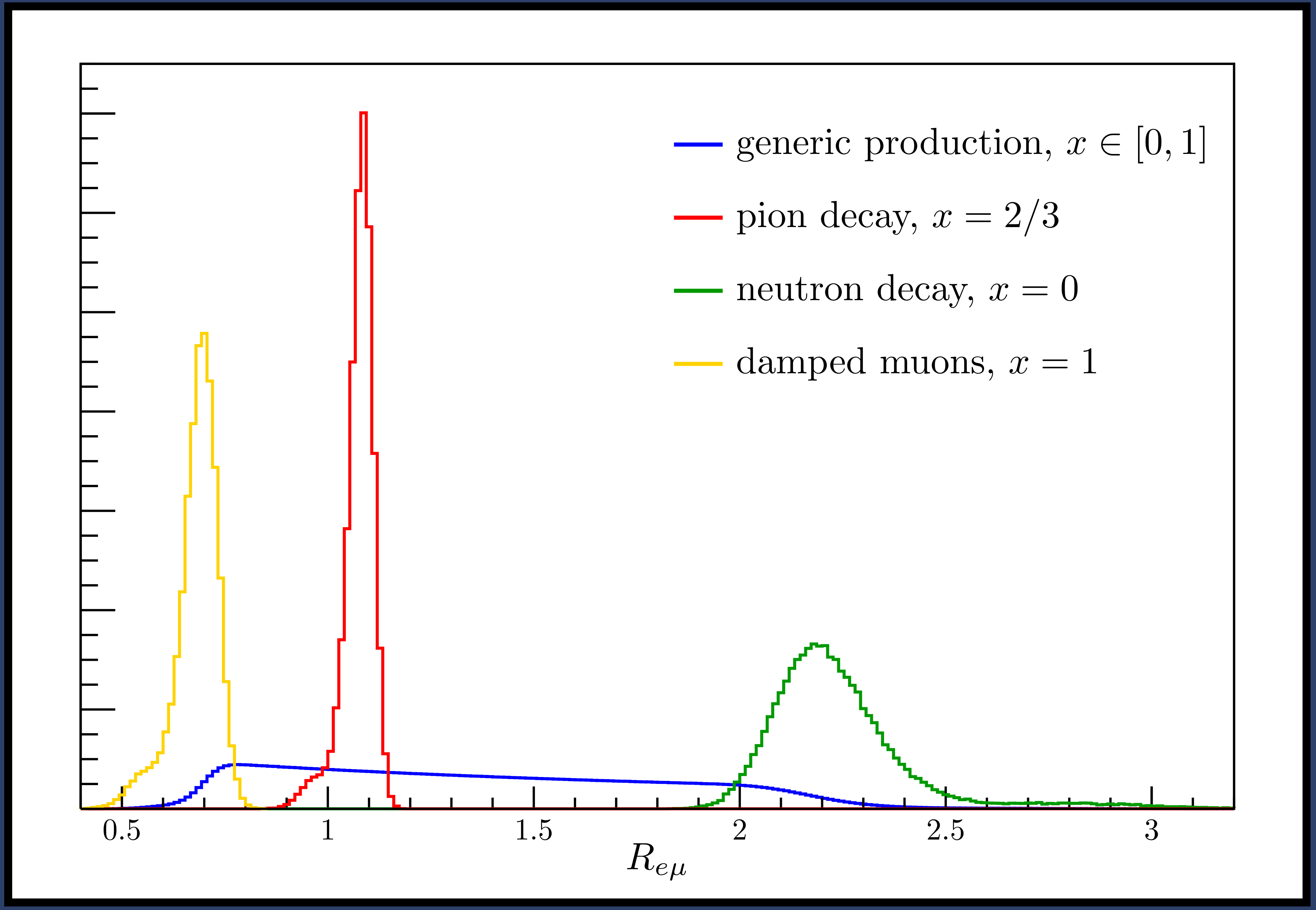
BACKUP SLIDES: ANTARES

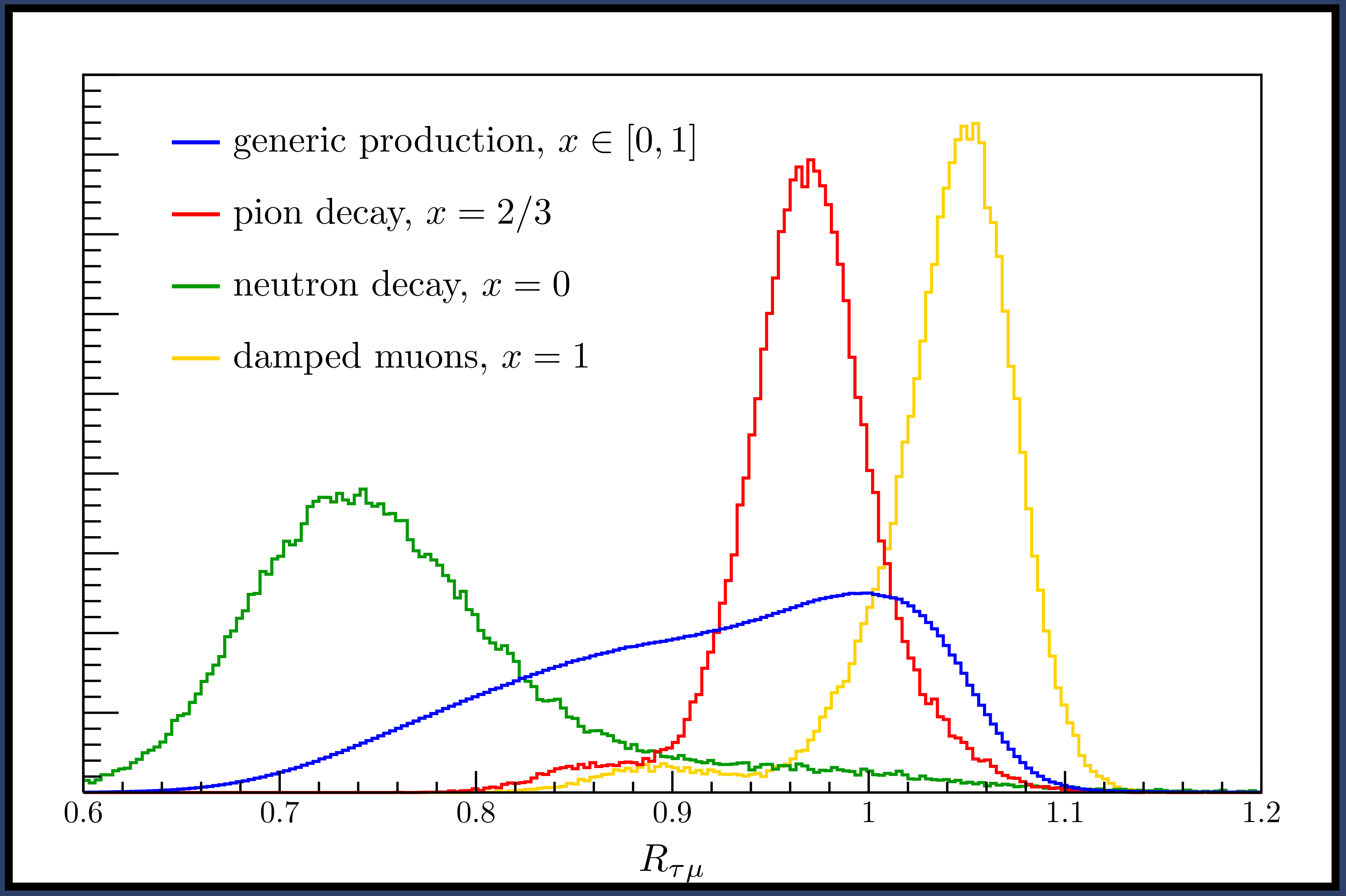
- 2475 m mooring depth in Mediterranean Sea
- $V \sim 0.025\ \mathrm{km}^3$
- 12 vertical strings, 25×3 OMs each
- vertical OM separation: 14.5 m
- string separation: 60 m
- operational since 2008
- recent evidence of astrophysical neutrinos



https://antares.in2p3.fr/Gallery/

BACKUP SLIDES: FLAVOUR AT EARTH

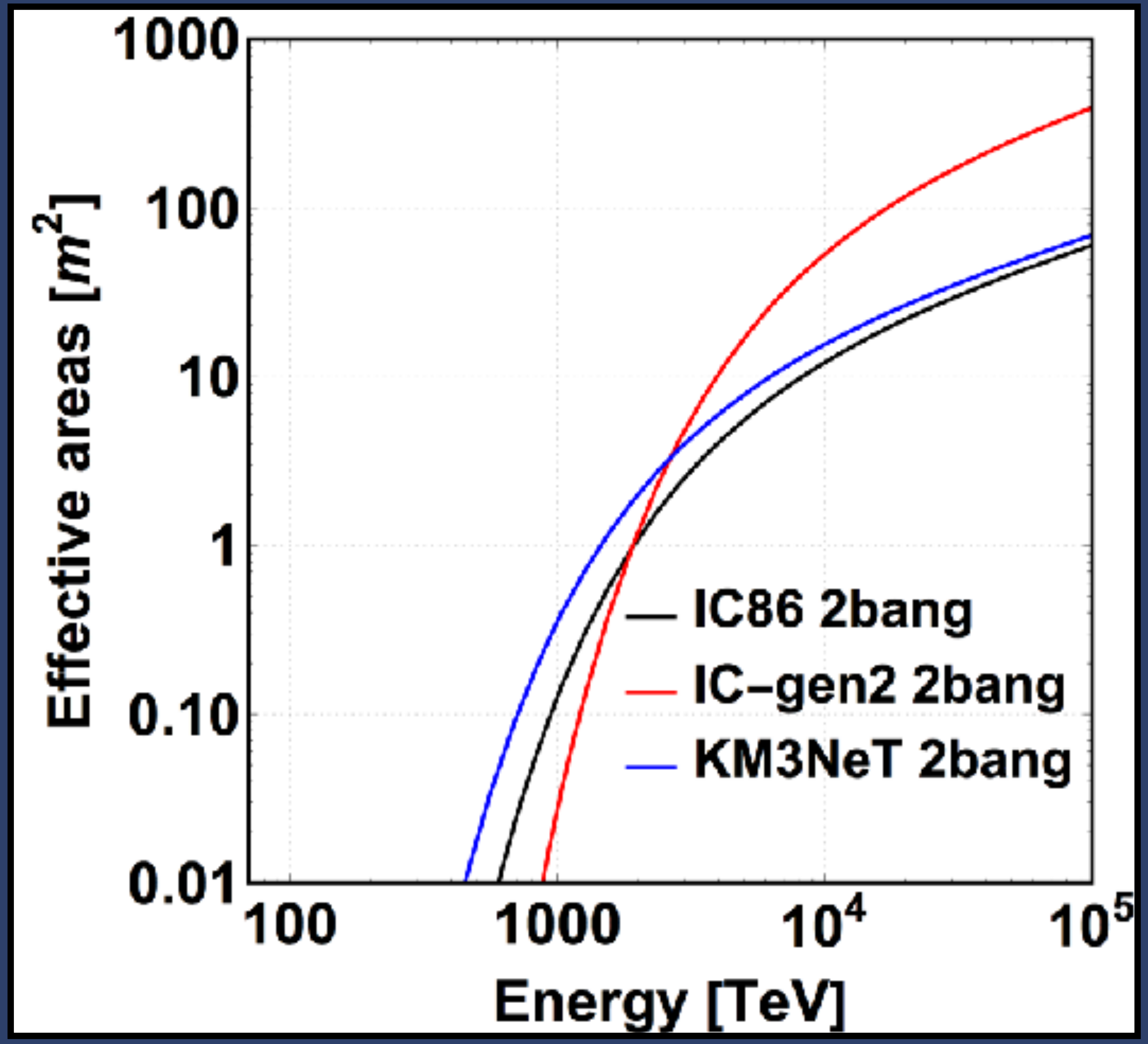


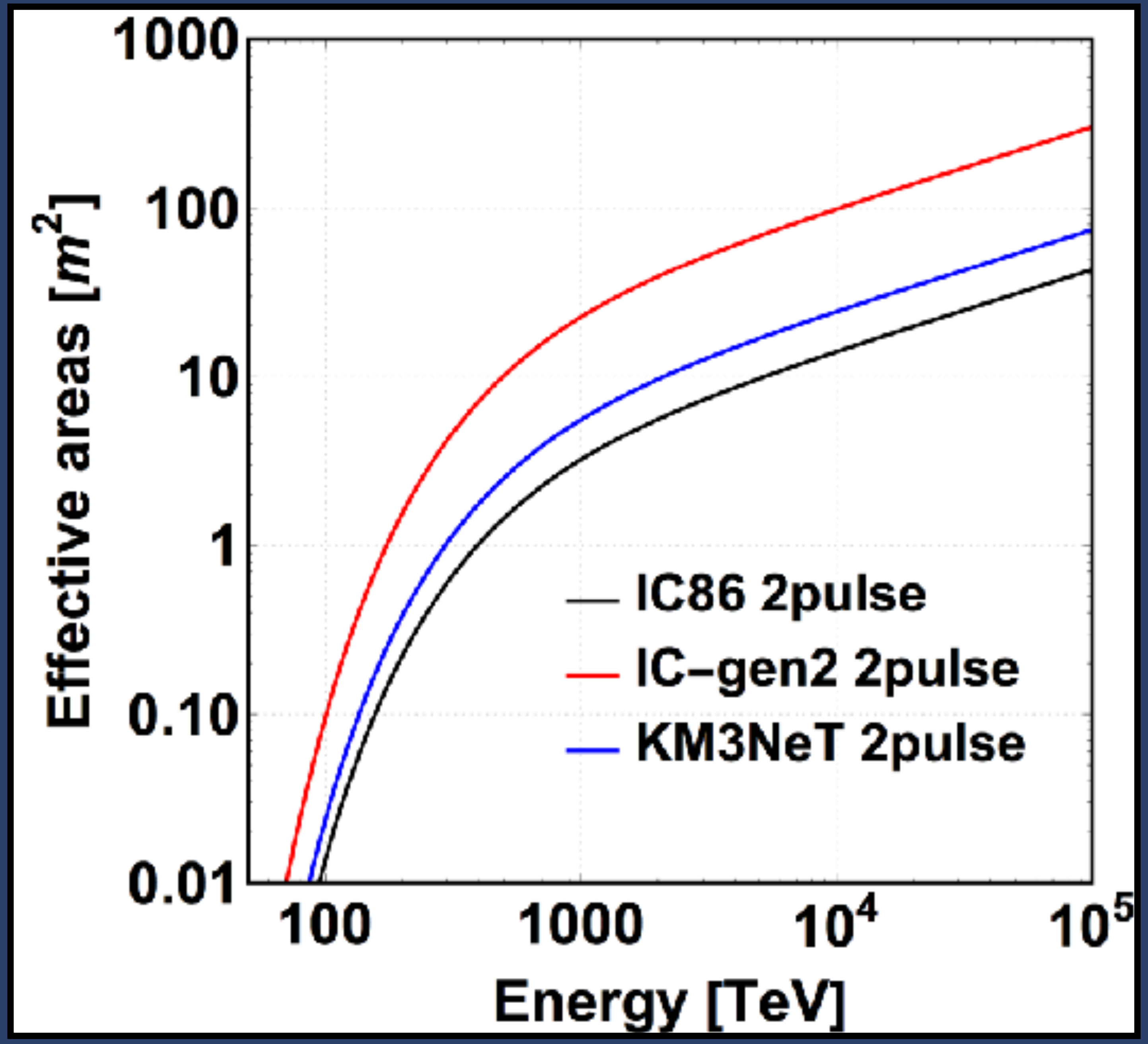


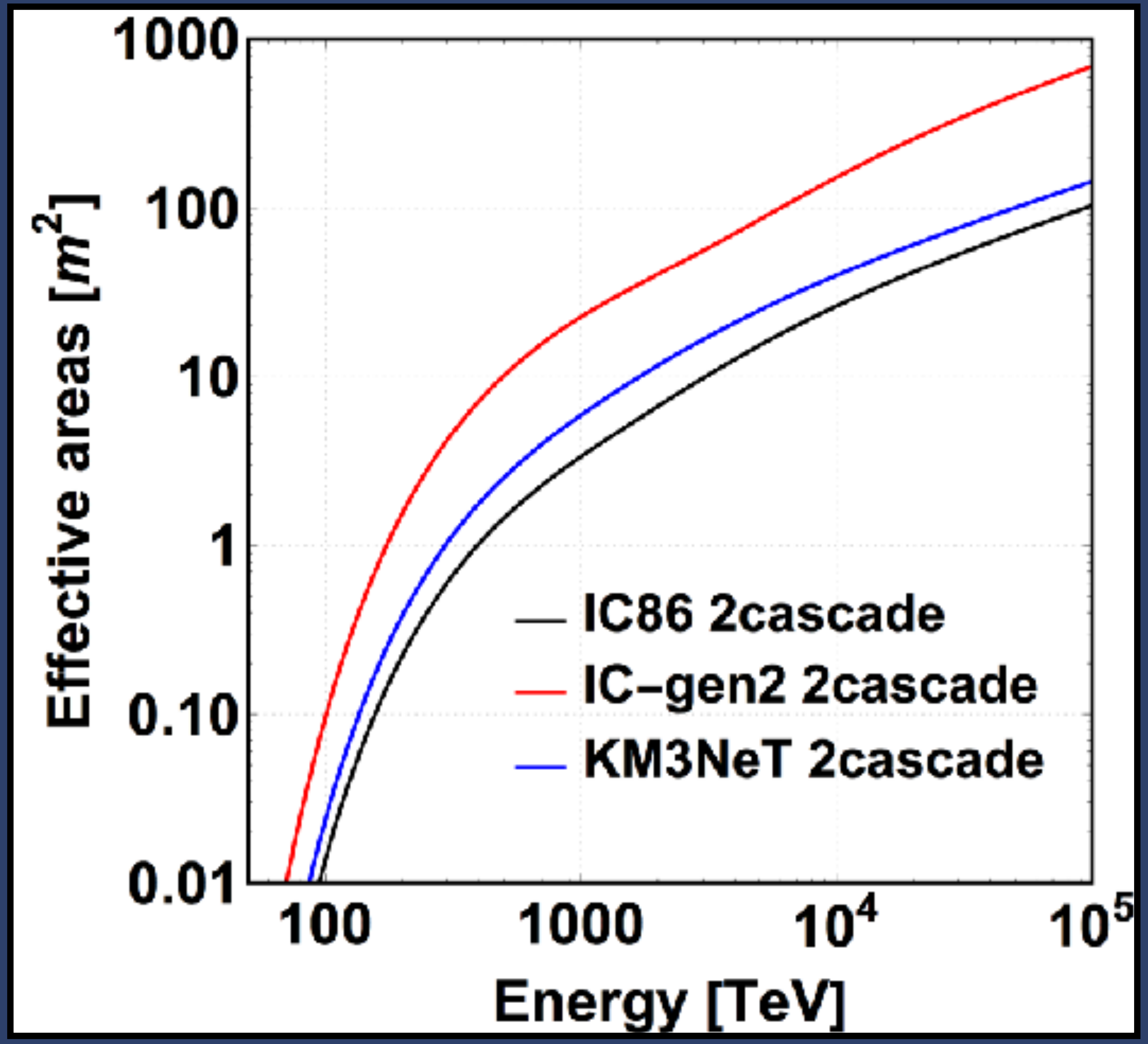
$$R_{e\mu} = \frac{P_{ee}(1-x) + P_{e\mu}x}{P_{e\mu}(1-x) + P_{\mu\mu}x}$$

$$R_{\tau\mu} = \frac{P_{e\tau}(1-x) + P_{\mu\tau}x}{P_{e\mu}(1-x) + P_{\mu\mu}x}$$

BACKUP SLIDES: THE EFFECTIVE AREAS FOR DOUBLE CASCADES







➡ The next-generation detectors will outperform IC-86 in all cases

BACKUP SLIDES: PARAMETRISATION OF IC EFF. AREAS

Efficient parametrisation nu, antinu avg:

$$A_{\rm eff}(E) \simeq \mathcal{N} \left(\frac{E}{1\,\rm TeV} \right)^{\alpha} \exp\left[-\beta \left(\frac{E}{1\,\rm TeV} \right)^{-\gamma} \right] \,{\rm m}^2$$

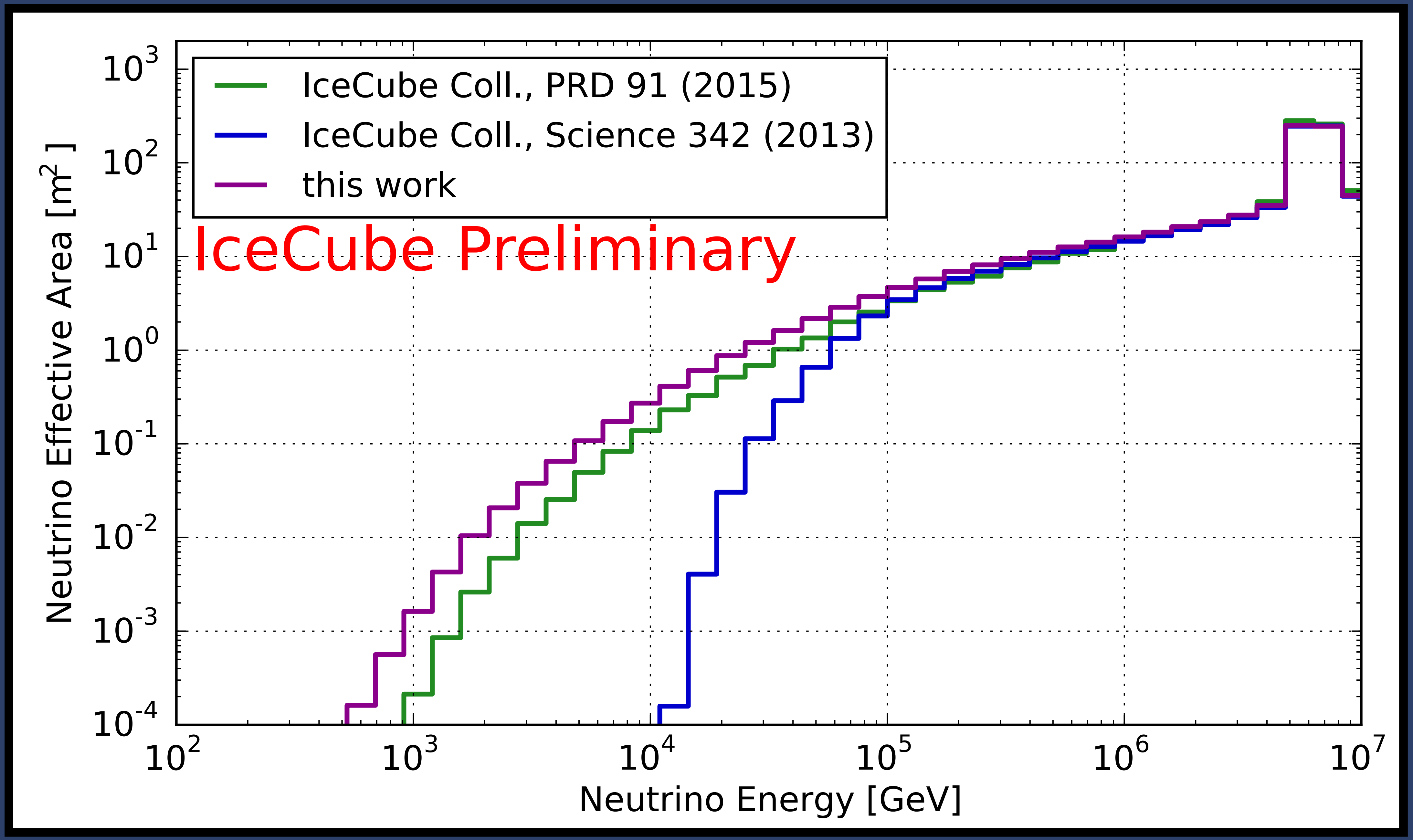
Glashow resonances:
(Γ =1/100)

$$A_{{\rm eff},\nu_e}(E) \simeq A_{\rm eff}(E) + \theta(E - 1\,{\rm PeV}) \left\{ 75\,{\rm m}^2 \frac{\Gamma^2}{\pi\Gamma[\log_{10}^2(E/6.32\,{\rm PeV}) + \Gamma^2]} \right\}$$

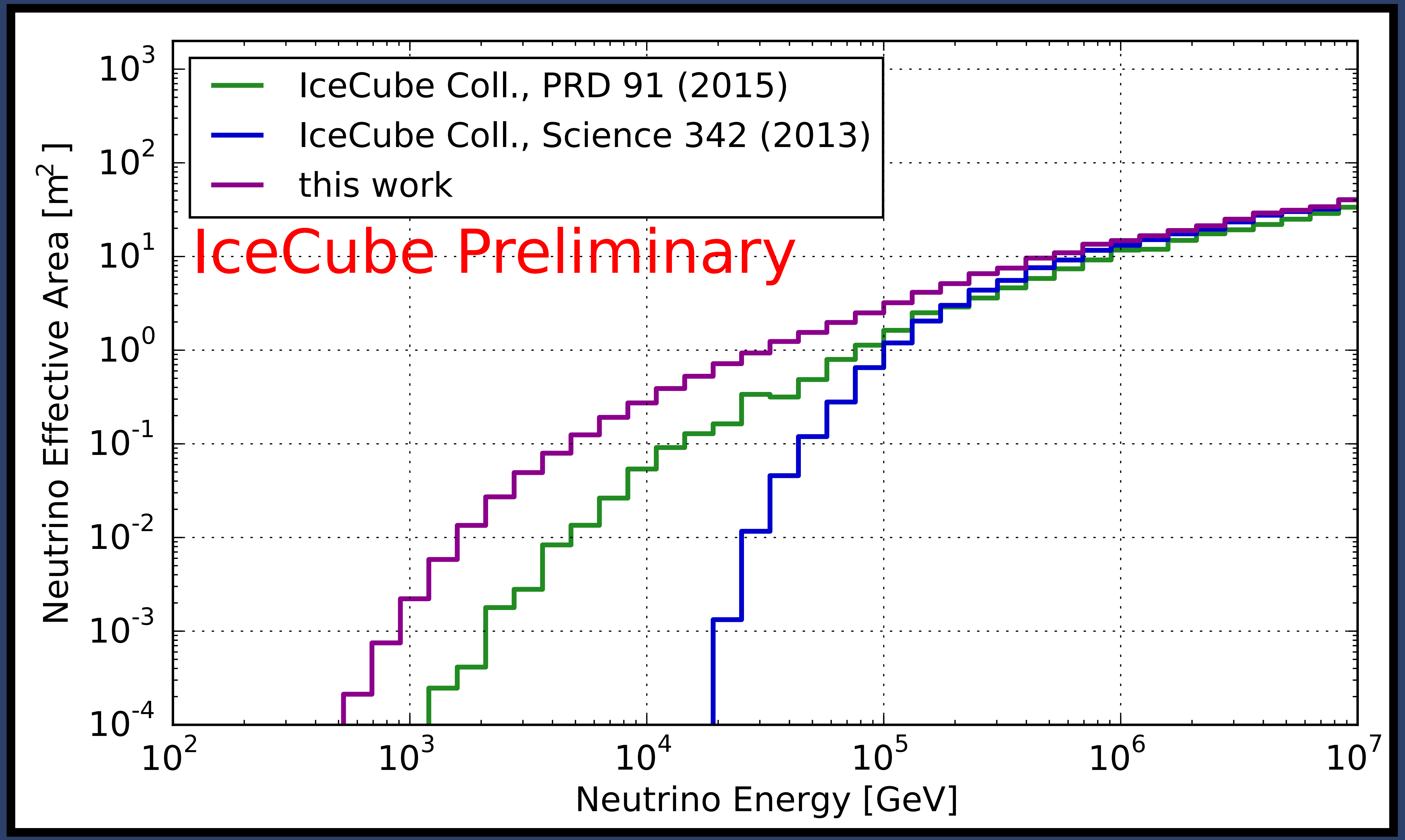
Event type	$\mathcal{N}$	α	β	γ	E range
ν_e-cascade	5	0.25	6	2/5	10^3-10^7 GeV
ν_μ-cascade	1.072	0.34	6.929	2/5	10^3-10^7 GeV
ν_τ-cascade	32.87	0.045	8.387	3/10	10^3-10^7 GeV
through-going μ	561.8	0.14	7.2	0.265	10^2-10^8 GeV

BACKUP SLIDES: ICECUBE EFFECTIVE AREAS (1/2)

Effective areas for **starting events**, averaged over solid angle



Electron neutrinos and tau neutrinos

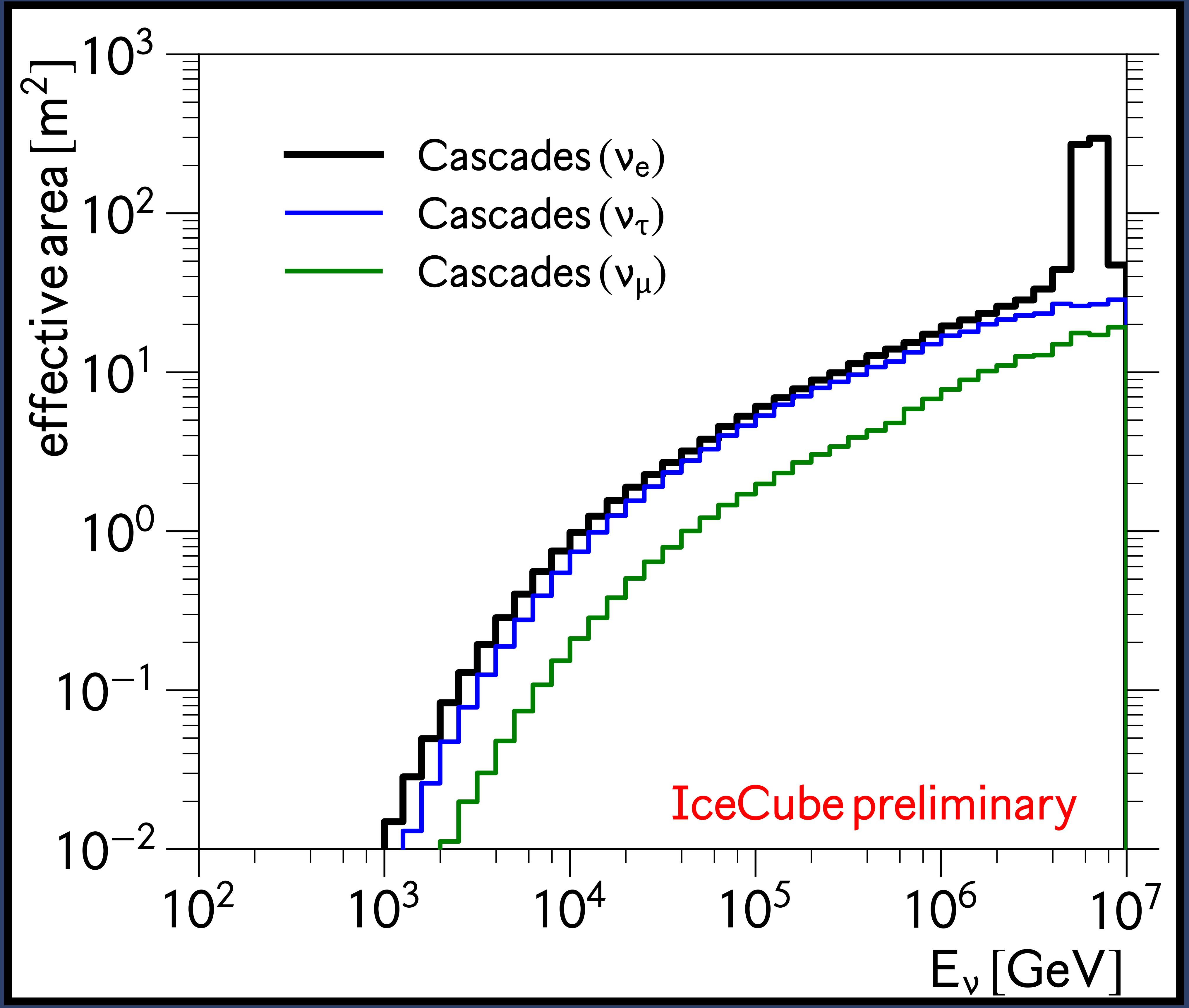


Muon neutrinos

C. Weaver, PoS ICRC17 **301** p. 976

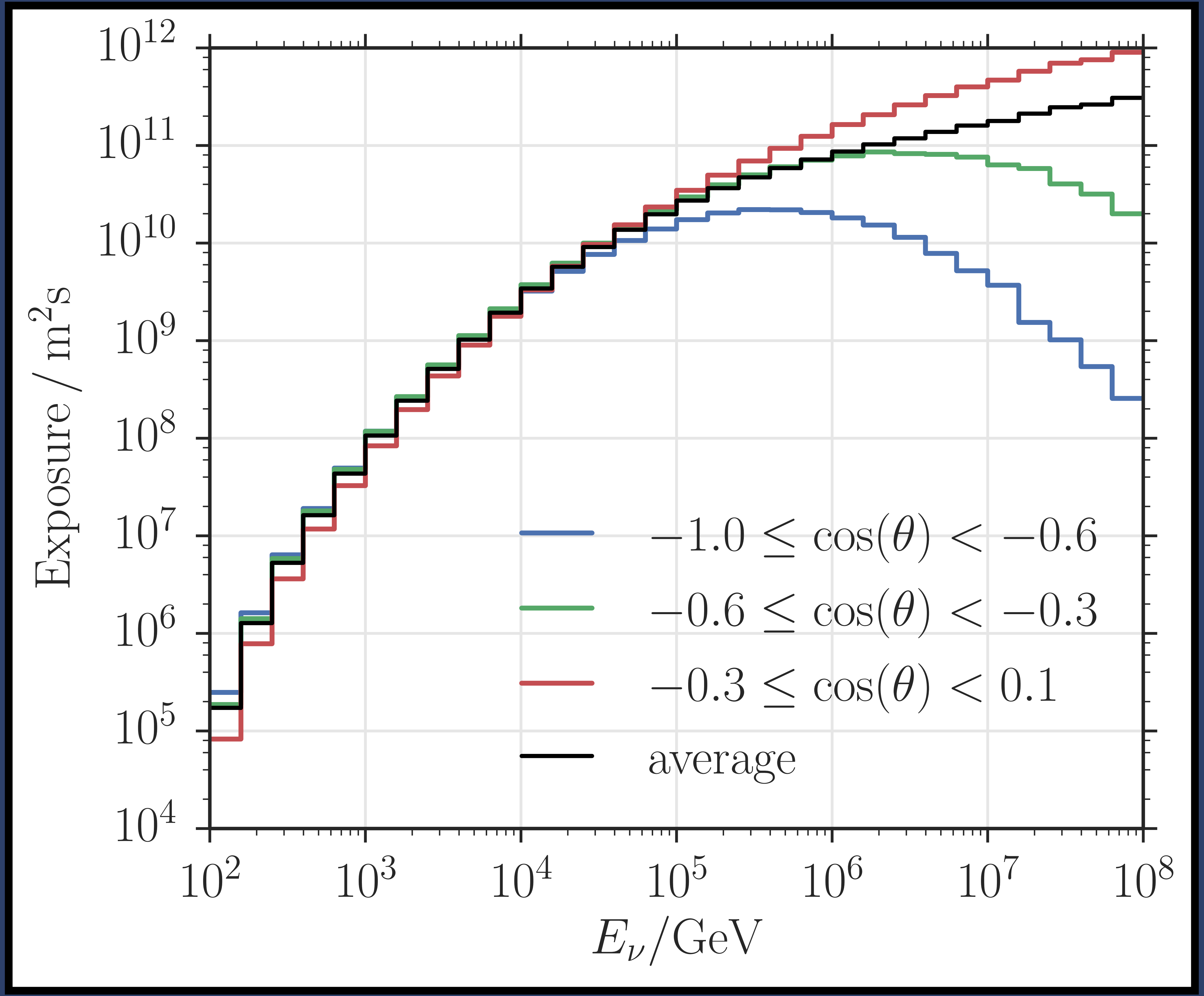
BACKUP SLIDES: ICECUBE EFFECTIVE AREAS (2/2)

Effective areas for **cascades**, solid angle avg.



H. Niederhausen, PoS ICRC17 **301** p. 968

Exposure for **through-going muons**
(2060 days ~ 1.78 × 10^8 s)



M. G. Aartsen et al., APJ **833** (2016) n° 1, 3

BACKUP SLIDES: A TWO-COMPONENT MODEL

THE BACKGROUNDS TO THE ICECUBE ANALYSES

Backgrounds to cosmic neutrino searches:

- atmospheric muons
- atmospheric (conventional + prompt) neutrinos

BACKUP SLIDES: A TWO-COMPONENT MODEL

THE BACKGROUNDS TO THE ICECUBE ANALYSES

Backgrounds to cosmic neutrino searches:
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How to avoid it?
- HESE: IceTop tags atm. showers + veto
- through-μ: Earth filter + cut in energy

BACKUP SLIDES: A TWO-COMPONENT MODEL

THE BACKGROUNDS TO THE ICECUBE ANALYSES

Backgrounds to cosmic neutrino searches:

- atmospheric muons
- atmospheric (conventional + prompt) neutrinos

How to avoid it?

- HESE: IceTop tags atm. showers + veto
- through-μ: Earth filter + cut in energy

Leftover background in 5.7 years:

- through-μ: 9/29 events due to atmospheric ν (A. Palladino, F. Vissani, A&A **604** (2017) A18)
- HESE: see table

	tracks	showers	sum
b_μ	23 ± 7	2 ± 1	25 ± 7
$b_{\rm conv}$	10^{+10}_{-5}	4^{+4}_{-2}	15^{+11}_{-5}
$b_{\rm pr}$	< 1	< 4	< 5
$b_{\rm tot}$	34^{+12}_{-9}	9^{+4}_{-3}	43^{+13}_{-9}
HESE	22	58	82

BACKUP SLIDES: A TWO-COMPONENT MODEL

THE BACKGROUNDS TO THE ICECUBE ANALYSES

Backgrounds to cosmic neutrino searches:

- atmospheric muons
- atmospheric (conventional + prompt) neutrinos

How to avoid it?

- HESE: IceTop tags atm. showers + veto
- through-μ: Earth filter + cut in energy

Leftover background in 5.7 years:

- through-μ: 9/29 events due to atmospheric ν (A. Palladino, F. Vissani, A&A **604** (2017) A18)
- HESE: see table

misidentification

	tracks	showers	sum
b_μ	23 ± 7	$\boxed{2 \pm 1}$	25 ± 7
$b_{\rm conv}$	10^{+10}_{-5}	4^{+4}_{-2}	15^{+11}_{-5}
90% CL { $b_{\rm pr}$	< 1	< 4	< 5
$b_{\rm tot}$	34^{+12}_{-9}	9^{+4}_{-3}	43^{+13}_{-9}
HESE	22	58	$\boxed{82}$

2 not classified
as coincident

BACKUP SLIDES: A TWO-COMPONENT MODEL

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HESE tracks are dominated by background

BACKUP SLIDES: A TWO-COMPONENT MODEL

THE SHAPE OF THE COSMIC NEUTRINO SPECTRUM (1/2)

Spectral tension: HESE and through-μ agree above 200 TeV, but not at lower energies
➡ extend with two-component model

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$$\frac{d\Phi_{\mathrm{bpl}}}{dE} = N_{\mathrm{bpl}} \times 10^{-18}\,\mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1} \begin{cases} (E/200\,\mathrm{TeV})^{-2.93} & E < 200\,\mathrm{TeV} \\ (E/200\,\mathrm{TeV})^{-2.13} & E \geq 200\,\mathrm{TeV} \end{cases}$$

From through-μ flux at 200 TeV: $N_{\mathrm{bpl}} = 0.206$

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From through-μ flux at 200 TeV: $N_{\rm bpl}$ = 0.206

Choice of break at 200 TeV:

- minimal modification to reconcile HESE and through-μ
- most conservative, close to through-μ energy threshold
- checked that break at 100 TeV does not change results

BACKUP SLIDES: A TWO-COMPONENT MODEL

THE SHAPE OF THE COSMIC NEUTRINO SPECTRUM (2/2)

Assume smooth spectrum ➡ define benchmark two-component muon neutrino flux as:

$$\frac{d\Phi_\mu}{dE} = \frac{N_\mu}{2} \times 10^{-18}\,\mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1} \left[\left(\frac{E}{100\,\mathrm{TeV}} \right)^{-\alpha} + \left(\frac{E}{100\,\mathrm{TeV}} \right)^{-\beta} \right]$$

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Find N_μ, α and β from minimisation of distance to bpl flux:

$$d(N_\mu, \alpha, \beta) = \int_{30\,\mathrm{TeV}}^{10\,\mathrm{PeV}} \frac{|d\Phi_\mu/dE - d\Phi_{\mathrm{bpl}}/dE|}{d\Phi_{\mathrm{bpl}}/dE}\, d\log E$$

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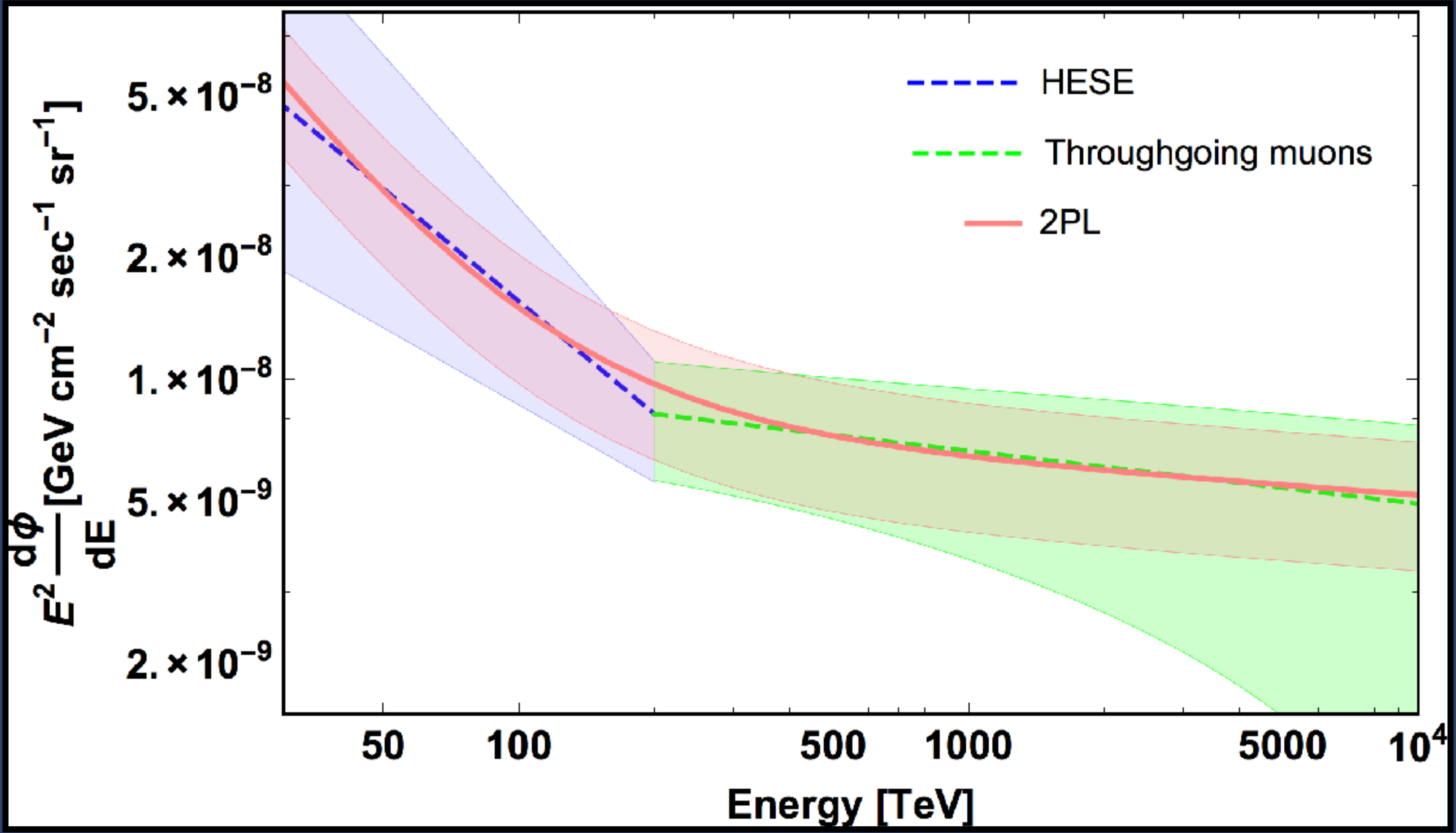
➡ $N_\mu = 1.5(1 \pm 0.3)$, $\alpha = 2.08$, $\beta = 3.05$.

BACKUP SLIDES: A TWO-COMPONENT MODEL

PART 2: THE SHAPE OF THE COSMIC NEUTRINO SPECTRUM (2/2)



BACKUP SLIDES: A TWO-COMPONENT MODEL

PART 3: CONSTRAINTS ON THE COSMIC NEUTRINO SPECTRUM

Normalisations of the other flavours: $R_{e\mu}$, $R_{\tau\mu}$ for a generic production mechanism

$$N_e = R_{e\mu} N_\mu \qquad N_\tau = R_{\tau\mu} N_\mu$$

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$$\mathcal{L}_{\text{osc}}(N_\ell) = \int dN_\mu \, \mathcal{L}_{\text{exp}}(N_\mu) \, \frac{dR_{\ell\mu}}{dN_\mu} \qquad \ell = e, \tau$$

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➡ Poissonian likelihood functions to include experimental constraints

BACKUP SLIDES: A TWO-COMPONENT MODEL

PART 3: EXPERIMENTAL CONSTRAINTS ON N_τ

Expected number of double cascade events in 5.7 years of IceCube DAQ:

$$N_{\mathrm{dc}} = 4\pi \Delta T \int_0^\infty dE\, A_{\mathrm{eff,dc}}(E)\, \frac{d\Phi_\tau}{dE} = 0.44 N_\tau$$

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A. Palladino et al.,
EPJ **C76** (2016) 2

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Approximately Gaussian: $N_\tau = 1.48 \pm 0.54$ similar to $R_{\tau\mu}N_\mu = 1.50 \pm 0.46$!

BACKUP SLIDES: A TWO-COMPONENT MODEL

PART 3: EXPERIMENTAL CONSTRAINTS ON N_e (1/2)

Expected number of Glashow resonances in 5.7 years of IceCube DAQ:

$$N_\mathrm{G}(N_e, \epsilon) = 4\pi \Delta T \int_0^\infty dE\, A_{\mathrm{eff,G}}(E)\, \frac{d\Phi_e}{dE} = 2.3\, N_e\, \epsilon$$

where $\epsilon = \Phi_{\overline{\nu}_e} / (\Phi_{\nu_e} + \Phi_{\overline{\nu}_e})$

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BACKUP SLIDES: A TWO-COMPONENT MODEL

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Atmospheric background in cascades: $b_s = 9^{+4}_{-3}$ with likelihood: $\mathcal{L}_{\mathrm{bg}}(b_s)$

BACKUP SLIDES: A TWO-COMPONENT MODEL

PART 3: EXPERIMENTAL CONSTRAINTS ON N_e (2/2)

Observed HESE cascades: $N_{\rm obs} = 58$.

Fix $N_\tau = 1.48$; HESE showers likelihood:

$$\mathcal{L}_{\rm HESE}(N_e, \epsilon) \propto \left[b_s + N_c(N_e, \epsilon)\right]^{N_{\rm obs}} \exp\left[-b_s - N_c(N_e, \epsilon)\right]$$

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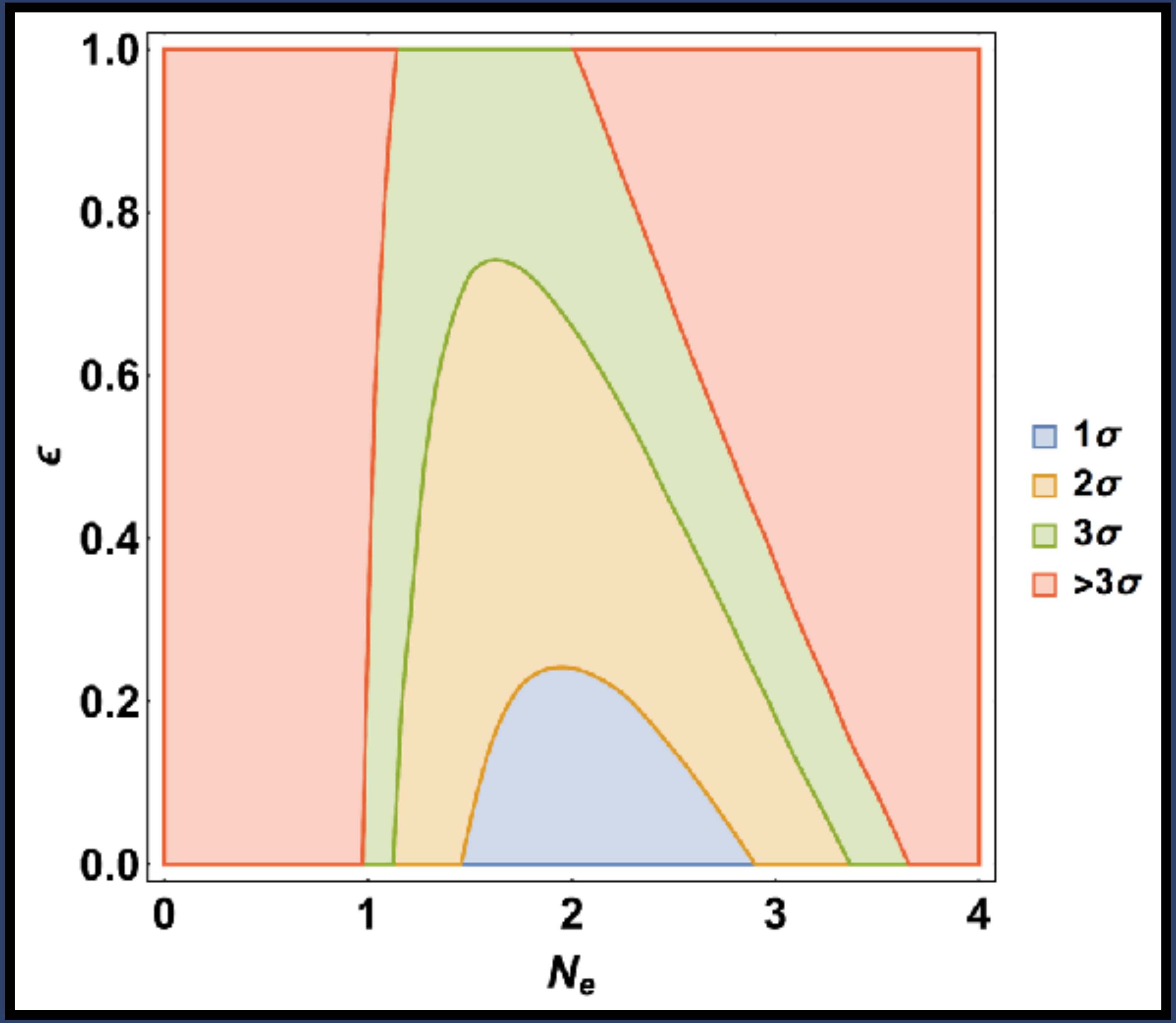
Total likelihood for electron neutrinos:

$$\mathcal{L}(N_e, \epsilon) \propto \mathcal{L}_{\text{G}} \int db_s \mathcal{L}_{\text{bg}}(b_s) \mathcal{L}_{\text{HESE}} \int dN_\mu \, \mathcal{L}_{\exp}(N_\mu) \frac{dR_{e\mu}}{dN_\mu}$$



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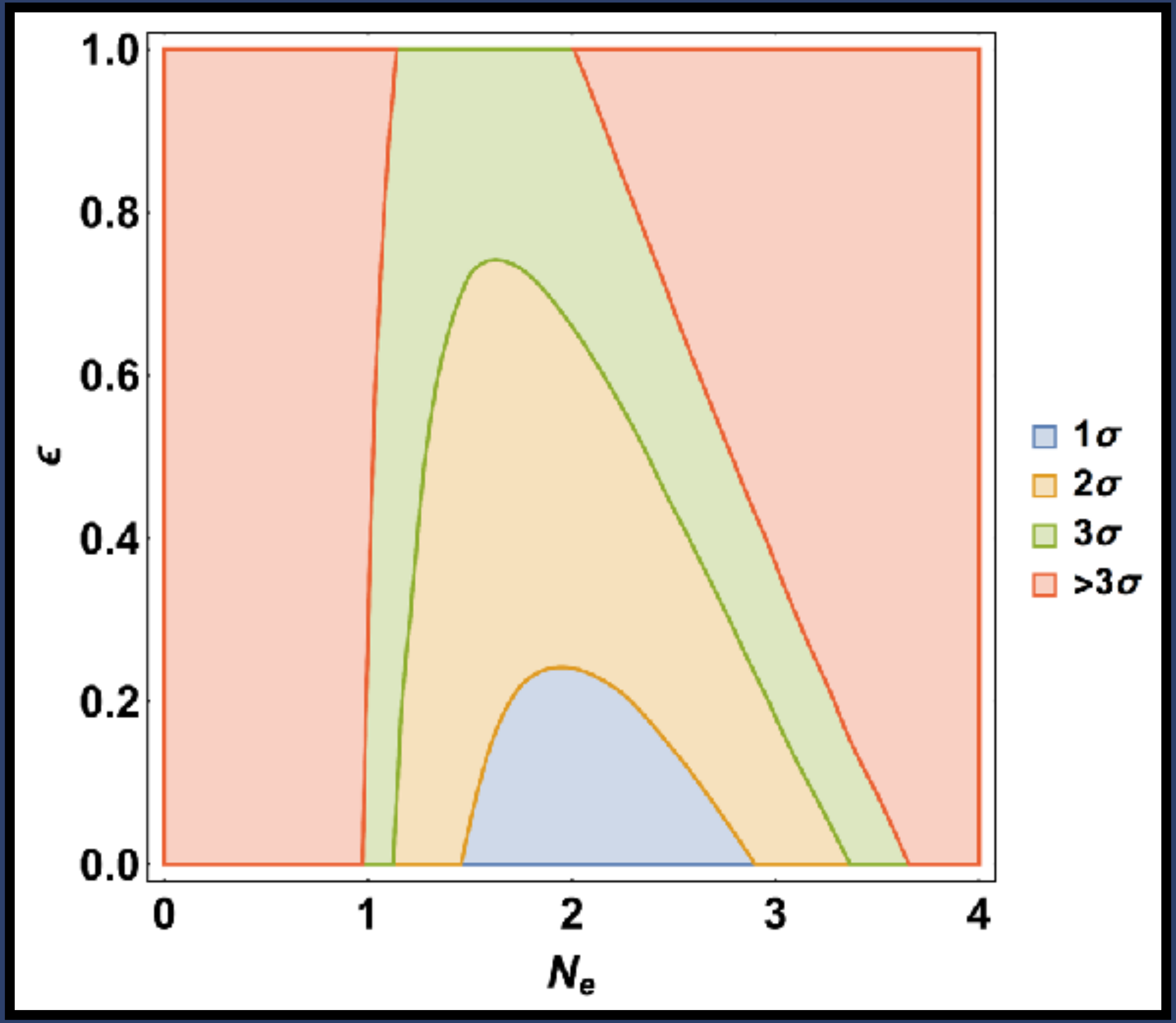
Marginalising separately:

- $N_e = 1.83 \pm 0.44$ vs $R_{e\mu}N_\mu = 1.17^{+0.73}_{-0.45}$
- $\epsilon < 0.25$ at 68% CL



BACKUP SLIDES: A TWO-COMPONENT MODEL

PART 4: PREDICTIONS OF THE MODEL (1/2)

Normalisations of cosmic neutrino flux:

- $N_\mathrm{e} = 1.98 \pm 0.45$
- $\epsilon < 0.25$ (68% CL), 0.52 (90% CL)
- $N_\mu = 1.50 \pm 0.50$
- $N_\tau = 1.48 \pm 0.54$

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Small ϵ ➡ preference for $p\gamma$

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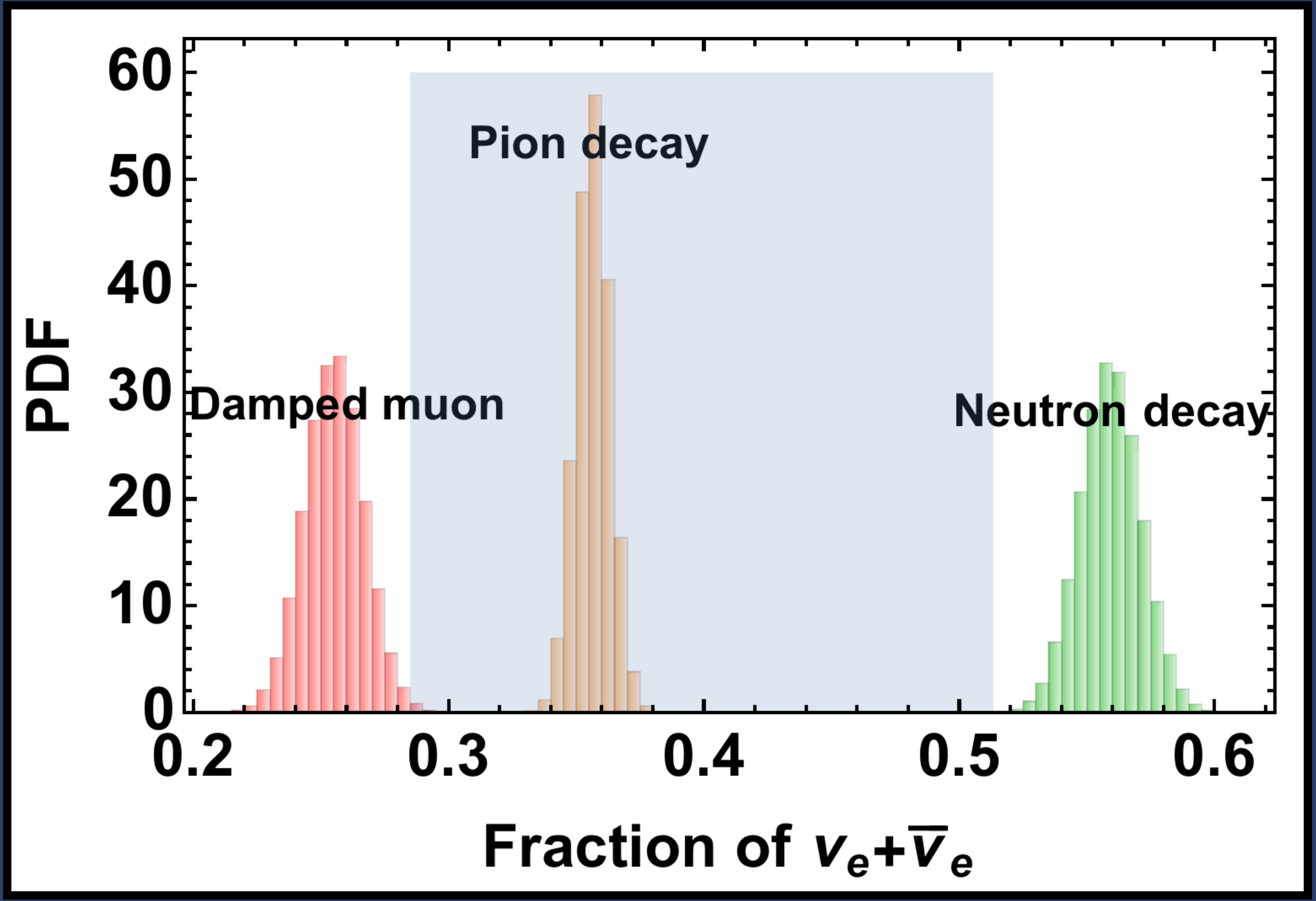
Similar normalisations ➡ pion decay



BACKUP SLIDES: A TWO-COMPONENT MODEL

PART 4: PREDICTIONS OF THE MODEL (2/2)

Number of “special” events in 5.7 years:

$N_G = 2.3\, N_e\, \epsilon$

BACKUP SLIDES: A TWO-COMPONENT MODEL

PART 4: PREDICTIONS OF THE MODEL (2/2)

Number of “special” events in 5.7 years:

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$= 2.28 \pm 0.52$ for $\epsilon = 1/2$, pp production

$= 1.14 \pm 0.26$ for $\epsilon = 1/4$, $p\gamma$ production

- ▶ if there is no energy cutoff

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▶ if there is no energy cutoff

$N_{dc} = 0.44\ N_\tau = 0.65 \pm 0.24$

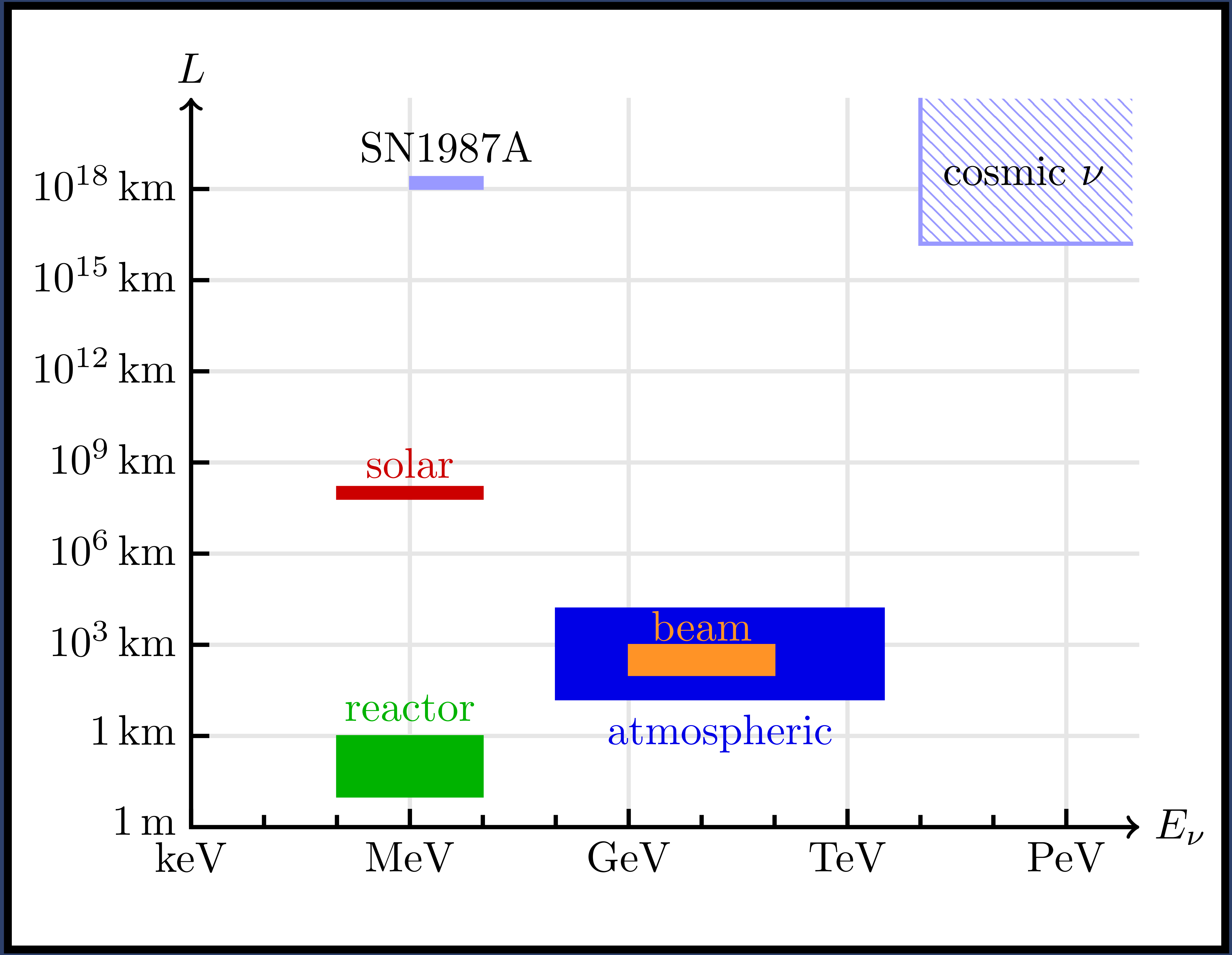
▶ depends only on high-energy part of spectrum

BACKUP SLIDES: STANDARD 3-FLAVOUR NEUTRINO OSCILLATIONS

The three neutrino flavours oscillate with a phase given by:

$$\phi = 1.27\Delta m^2 \frac{L}{E_\nu}$$

Experimental coverage of neutrino oscillations:



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For solar (1 MeV, 1.5 × 10^8 km) and Galactic (100 TeV, 1 kpc) neutrinos the ratio L/E_ν is very similar:

$$\frac{L}{E_\nu} = \begin{cases} 1.5 \times 10^{11}\,\mathrm{km\,GeV^{-1}} & \nu_\odot \\ 3 \times 10^{11}\,\mathrm{km\,GeV^{-1}} & \nu_{\mathrm{Gal.}} \end{cases}$$

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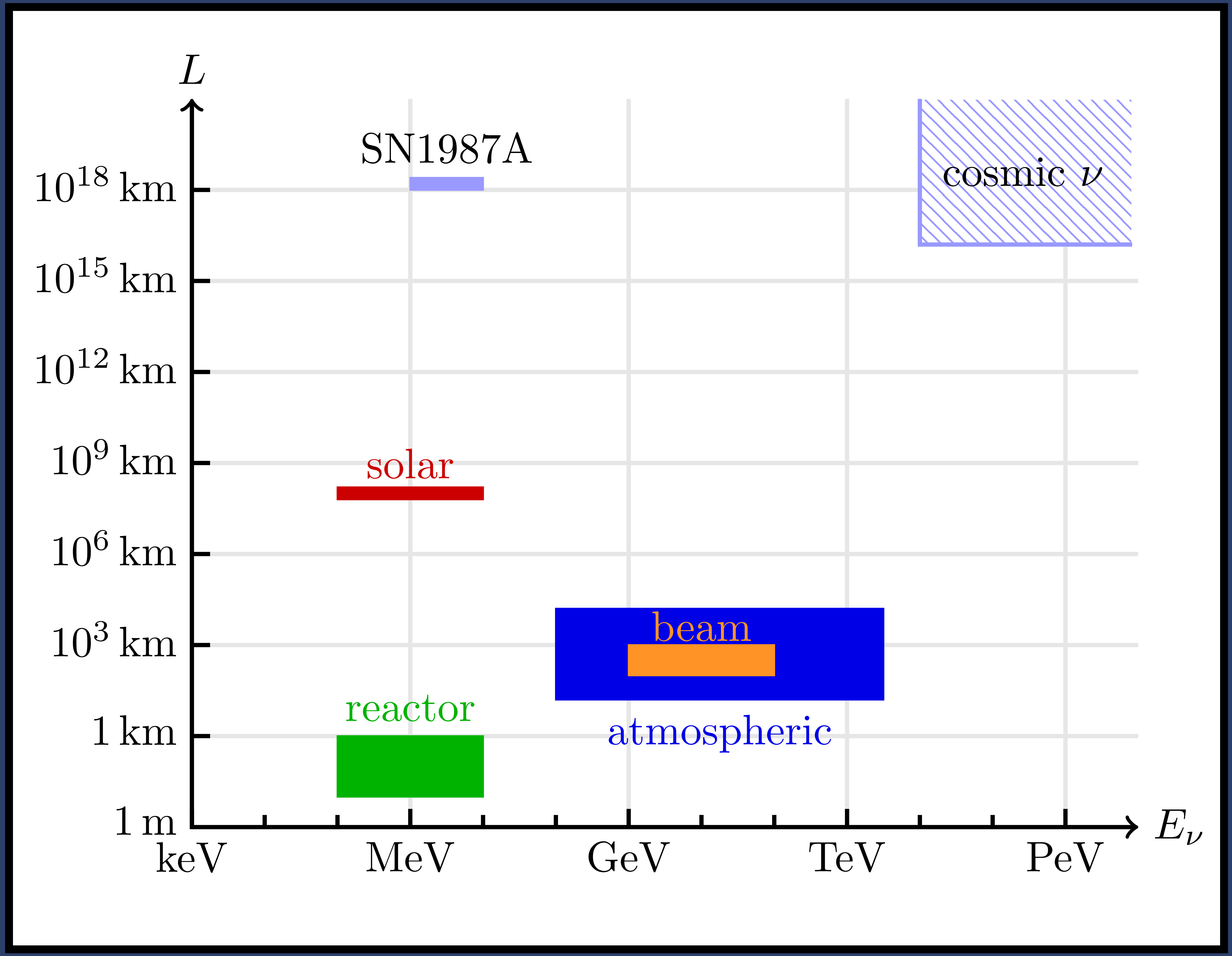

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Occam's razor: high energy neutrinos, propagating along cosmic distances, undergo standard 3-flavour oscillations and nothing else

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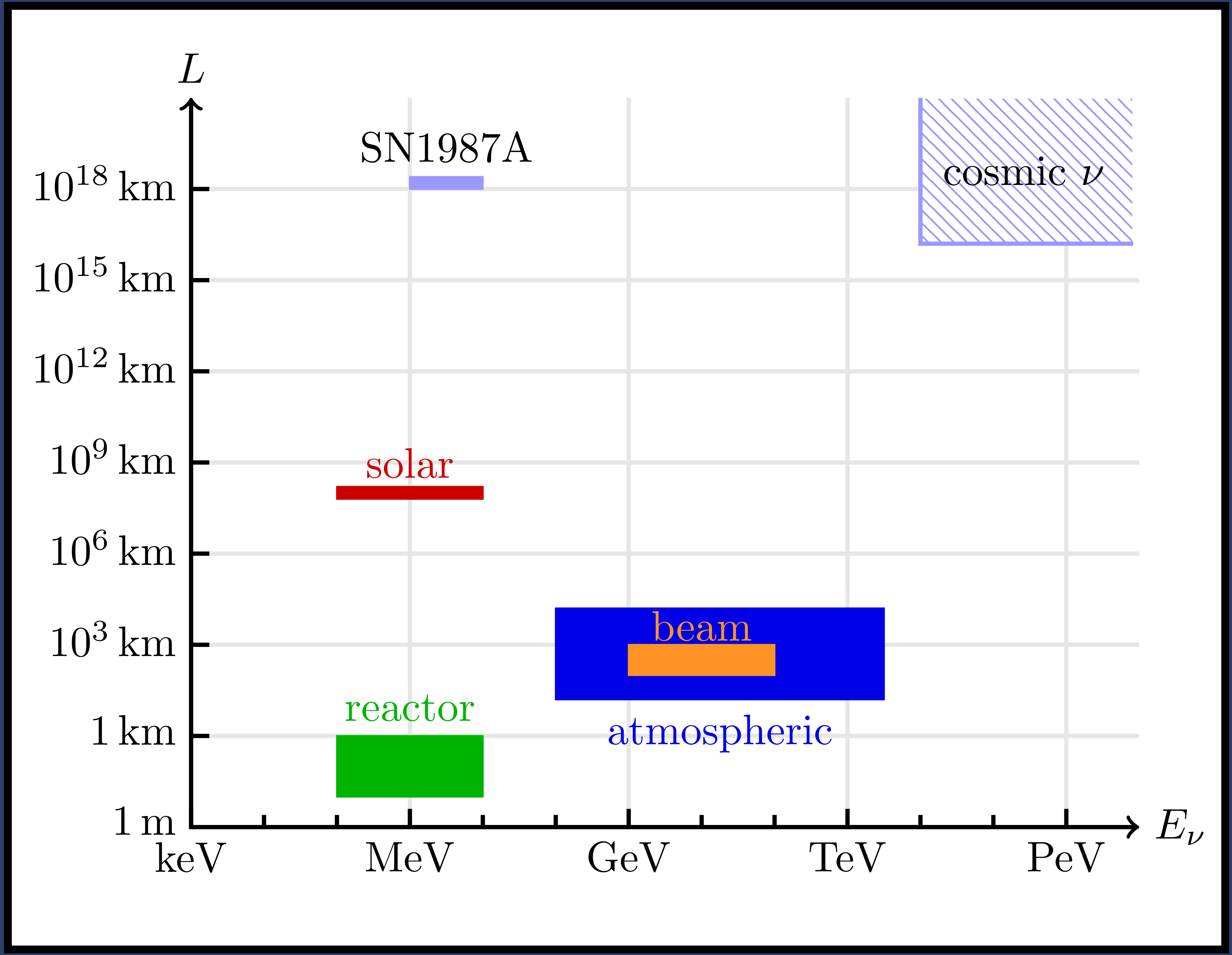

BACKUP SLIDES: DOUBLE BANG EFFECTIVE AREA

$$A_{\rm eff}(E_\nu, E_{\rm min}) = \frac{\rho V}{m} \frac{1+S(E_\nu)}{2} \times \mathrm{BR} \times \sigma_{\rm cc}(E_\nu) \exp\left(-\frac{E_{\rm min}}{E_\nu}\right)$$

For double bangs:

$$E_{\rm min}^{\rm 2b} \simeq \frac{4}{3} \frac{1}{\cos\theta} \left(\frac{\delta}{50\,\mathrm{m}}\right) \mathrm{PeV}$$

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$$\downarrow$$

$E_\tau \sim 3E_\nu/4$

BACKUP SLIDES: DOUBLE BANG EFFECTIVE AREA

$$A_{\mathrm{eff}}(E_\nu, E_{\mathrm{min}}) = \frac{\rho V}{m} \frac{1+S(E_\nu)}{2} \times \mathrm{BR} \times \sigma_{\mathrm{cc}}(E_\nu) \exp\left(-\frac{E_{\mathrm{min}}}{E_\nu}\right)$$

For double bangs:

$$E_{\mathrm{min}}^{2\mathrm{b}} \simeq \frac{4}{3} \underset{\downarrow}{\boxed{\frac{1}{\cos\theta}}} \left(\frac{\delta}{50\,\mathrm{m}}\right) \mathrm{PeV}$$

θ = angle betw.

dir. ν & plane $\perp$

to strings

BACKUP SLIDES: DOUBLE BANG EFFECTIVE AREA

$$A_{\mathrm{eff}}(E_\nu, E_{\min}) = \frac{\rho V}{m}\frac{1+S(E_\nu)}{2} \times \mathrm{BR} \times \sigma_{\mathrm{cc}}(E_\nu)\exp\left(-\frac{E_{\min}}{E_\nu}\right)$$

For double bangs:

$$E^{2\mathrm{b}}_{\min} \simeq \frac{4}{3}\frac{1}{\cos\theta}\left(\frac{\boxed{\delta}}{50\,\mathrm{m}}\right)\mathrm{PeV}$$

$$\text{inter-string distance} = \begin{cases} 120\,\mathrm{m} & \text{IC-86} \\ 240\,\mathrm{m} & \text{IC-gen2} \\ 90\,\mathrm{m} & \text{KM3NeT} \end{cases}$$

(inter-DOM distance = 22 m for all)

BACKUP SLIDES: DOUBLE BANG EFFECTIVE AREA

$$A_{\mathrm{eff}}(E_\nu, E_{\mathrm{min}}) = \frac{\rho V}{m} \frac{1+S(E_\nu)}{2} \times \mathrm{BR} \times \sigma_{\mathrm{cc}}(E_\nu) \exp\left(-\frac{E_{\mathrm{min}}}{E_\nu}\right)$$

For double bangs:

$$E^{\mathrm{2b}}_{\mathrm{min}} \simeq \frac{4}{3} \frac{1}{\cos\theta} \left(\frac{\delta}{50\,\mathrm{m}}\right) \mathrm{PeV}$$

inter-string distance

$$= \begin{cases} 120\,\mathrm{m} & \text{IC-86} \\ 240\,\mathrm{m} & \text{IC-gen2} \\ 90\,\mathrm{m} & \text{KM3NeT} \end{cases}$$

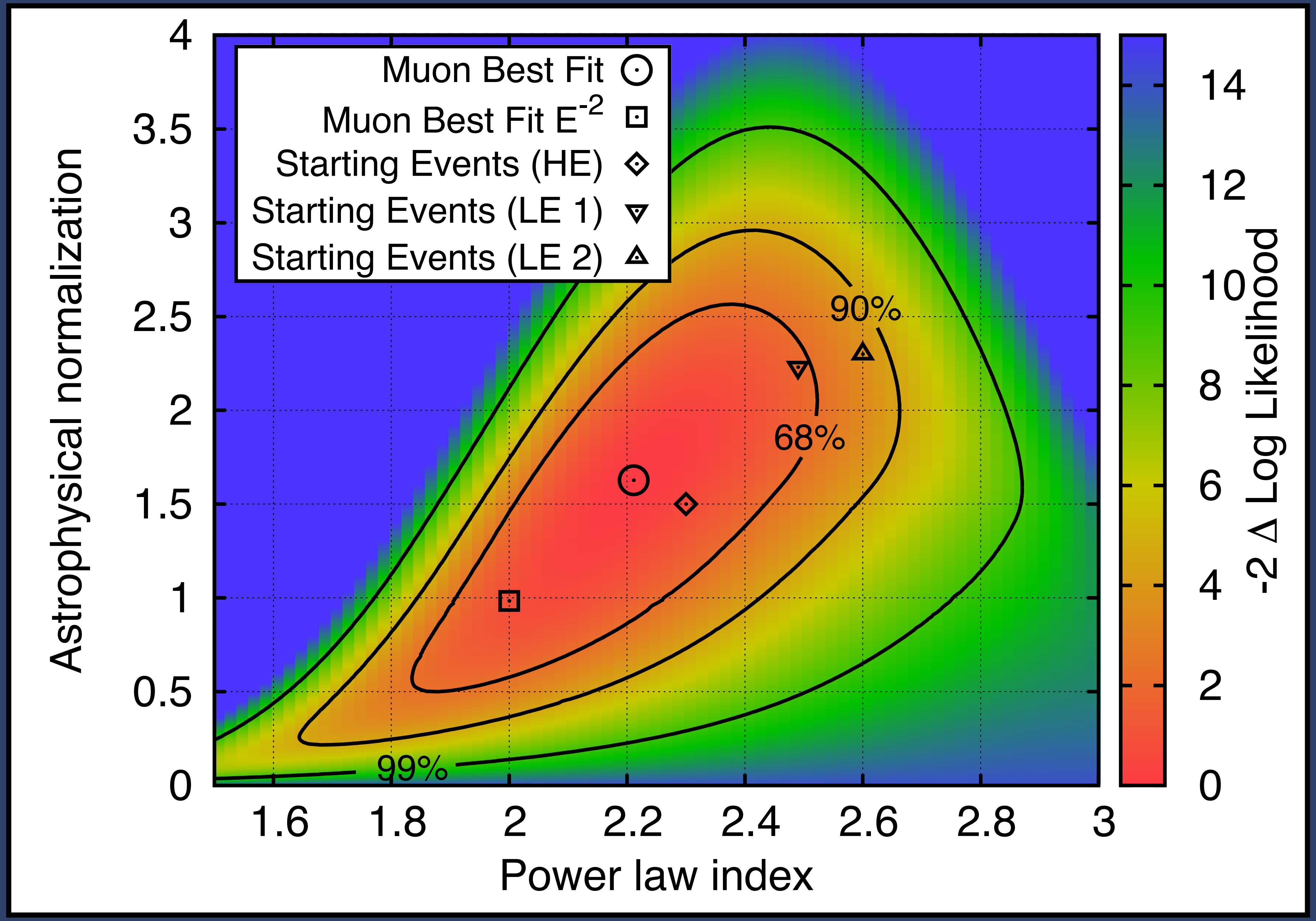
For isotropic cosmic neutrino flux:

$$A^{\mathrm{2b}}_{\mathrm{eff}}(E_\nu, E^{\mathrm{2b}}_{\mathrm{min}}) = \frac{1}{\pi} \int_{-\pi/2}^{\pi/2} d\theta \;\, A_{\mathrm{eff}}\left(E_\nu, E^{\mathrm{2b}}_{\mathrm{min}}\right)$$

BACKUP SLIDES: THE IMPORTANCE OF OBSERVING COSMIC TAU NEUTRINOS

YEARLY RATES OF DOUBLE CASCADE EVENTS

Spectral uncertainties: correlate γ and normalisation of cosmic ν flux, $N = N(\gamma)$



IceCube Coll. PRL 115 (2015) 081102

BACKUP SLIDES: THE IMPORTANCE OF OBSERVING COSMIC TAU NEUTRINOS

YEARLY RATES OF DOUBLE CASCADE EVENTS

Spectral uncertainties: correlate γ and normalisation of cosmic ν flux, $N = N(\gamma)$

$$N_{\rm 2c} = 4\pi \Delta T \int_0^\infty dR_{\tau\mu} \, \frac{dP}{dR_{\tau\mu}} \int_0^\infty d\gamma \, \frac{dP}{d\gamma} \int_0^\infty dE \, R_{\tau\mu} N(\gamma) E^{-\gamma} A_{\rm eff,2c}(E)$$

BACKUP SLIDES: THE IMPORTANCE OF OBSERVING COSMIC TAU NEUTRINOS

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gaussian:
$\gamma = 2.19 \pm 0.19$

BACKUP SLIDES: THE IMPORTANCE OF OBSERVING COSMIC TAU NEUTRINOS

YEARLY RATES OF DOUBLE CASCADE EVENTS

Spectral uncertainties: correlate γ and normalisation of cosmic ν flux, $N = N(\gamma)$

$$N_{2\mathrm{c}} = 4\pi \Delta T \int_0^\infty dR_{\tau\mu} \frac{dP}{dR_{\tau\mu}} \int_0^\infty d\gamma \frac{dP}{d\gamma} \int_0^\infty dE\, R_{\tau\mu} N(\gamma) E^{-\gamma} A_{\mathrm{eff},2\mathrm{c}}(E)$$

ΔT = 1 year ➡

Experiment	N_{2bang}	N_{2p}	N_{2casc}	$T_{\mathrm{year}}^{\mathrm{P}>90\%}$	$T_{\mathrm{year}}^{\mathrm{P}>99\%}$	$T_{\mathrm{year}}^{\mathrm{P}>5\sigma}$
IC86	0.07	0.25	0.32	5.1	10.1	31.7
IC-gen2	0.29	1.78	2.07	0.8	1.6	5.0
KM3NeT	0.10	0.44	0.54	3.1	6.1	19.1

Background ~ 40% = misidentified double cascades (M. Usner, PoS ICRC17 **301** 974)

BACKUP SLIDES: THE IMPORTANCE OF OBSERVING COSMIC TAU NEUTRINOS

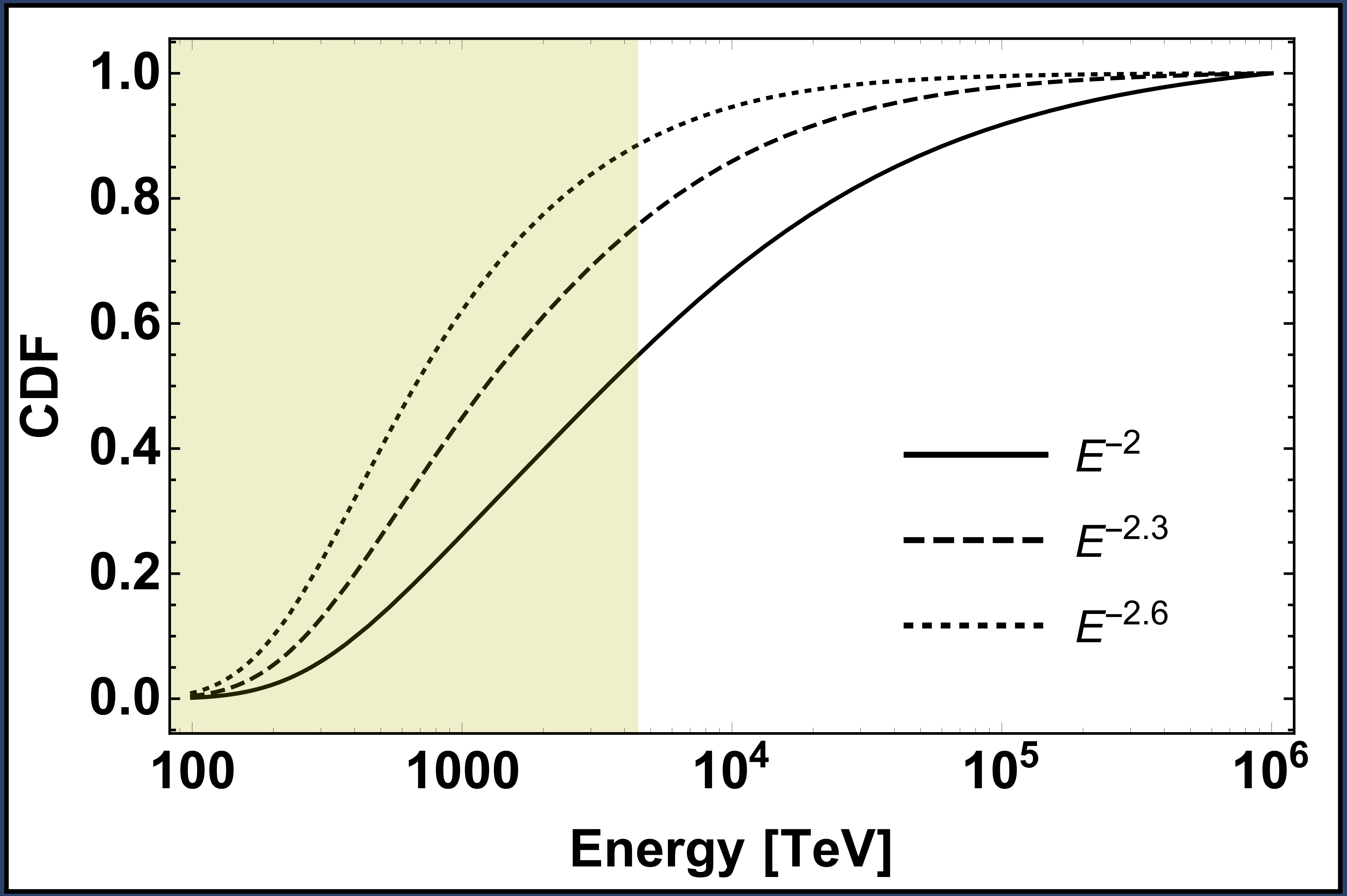
ENERGY DISTRIBUTION OF DOUBLE CASCADE EVENTS

Cumulative distribution function for variable spectral index γ:

$$\mathrm{CDF}(E,\gamma) = \frac{\int_0^E d\varepsilon\, \varepsilon^{-\gamma} A_{\mathrm{eff}}(\varepsilon, E_{\mathrm{min}})}{\int_0^\infty d\varepsilon\, \varepsilon^{-\gamma} A_{\mathrm{eff}}(\varepsilon, E_{\mathrm{min}})}$$

➡ no contribution for $E < 200$ TeV

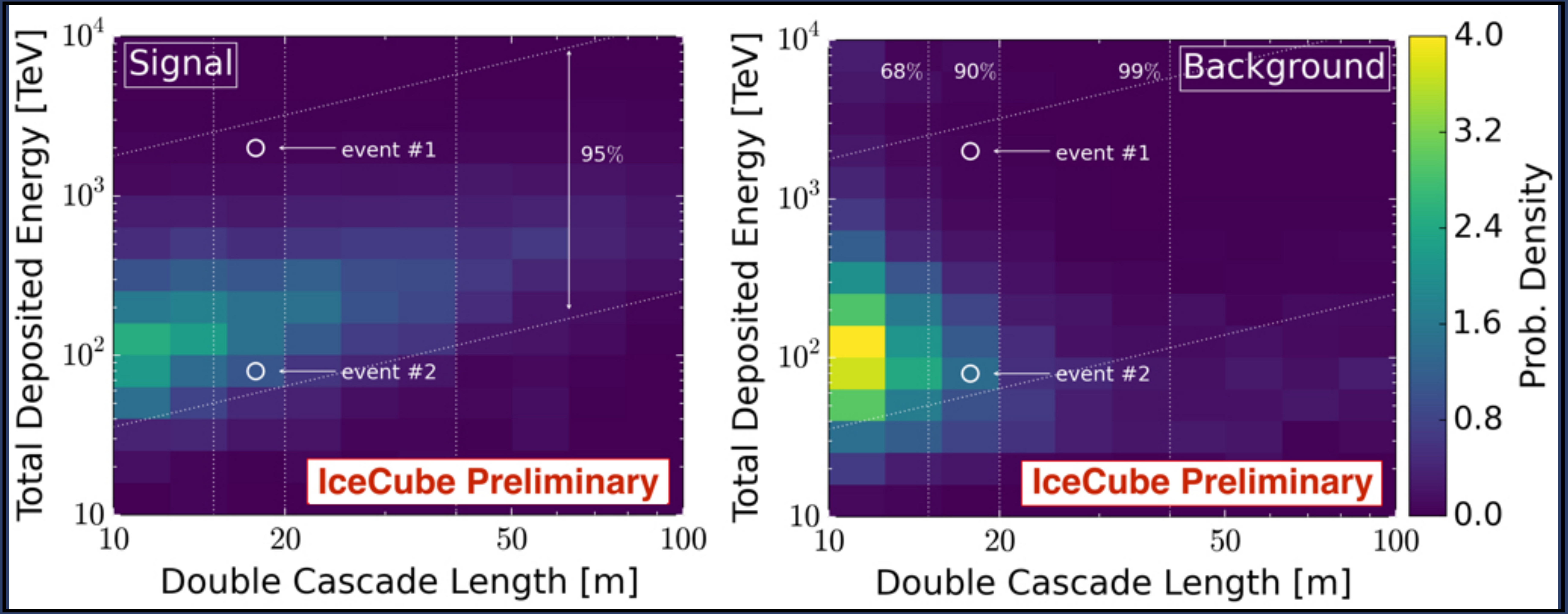
➡ the relevant energy range is already **probed**



BACKUP SLIDES: THE IMPORTANCE OF OBSERVING COSMIC TAU NEUTRINOS

TWO CANDIDATES

IceCube announcement of two double cascade candidates: J. Stachurska, PoS ICRC19 **358** 1015



BACKUP SLIDES: COMBINATION OF NEUTRINO FLUXES

Combine the two Loeb-Waxman and through-going muon fluxes:

- weighted average of normalisation and spectral index ➡ best fit (bf) values
- likelihood $\mathcal{L}(\Phi,\gamma)$ to consider ρ~0.6 correlation between normalisation and slope
- average and 1σ interval: integrate with likelihood

$$\mathcal{L}(\mathbf{v}) = \frac{1}{2\pi\sqrt{\det\Sigma^2}} \exp\left[-\frac{1}{2}(\mathbf{v}-\mathbf{v}^{\mathrm{best}})^T\Sigma^{-2}(\mathbf{v}-\mathbf{v}^{\mathrm{best}})\right] \qquad \mathbf{v} = \begin{pmatrix}\Phi\\ \gamma\end{pmatrix} \qquad \Sigma^2 = \begin{pmatrix}\sigma_\Phi^2 & \rho\sigma_\Phi\sigma_\gamma\\ \rho\sigma_\Phi\sigma_\gamma & \sigma_\gamma^2\end{pmatrix}$$

$$\left\langle \frac{d\Phi}{dE} \right\rangle = \int_{\Phi_{\mathrm{bf}}-5\sigma_\Phi}^{\Phi_{\mathrm{bf}}+5\sigma_\Phi} d\Phi \int_{\gamma_{\mathrm{bf}}-5\sigma_\gamma}^{\gamma_{\mathrm{bf}}+5\sigma_\gamma} d\gamma\, \mathcal{L}(\Phi,\gamma)\,\frac{d\Phi}{dE}, \qquad \delta\left(\frac{d\Phi}{dE}\right) = \sqrt{\left\langle\left(\frac{d\Phi}{dE}\right)^2\right\rangle - \left(\left\langle\frac{d\Phi}{dE}\right\rangle\right)^2}$$

BACKUP SLIDES: THE KERNEL FORMALISM

Kernel formalism from F. Vissani & F. L. Villante, PRD**78** 10 (2008):

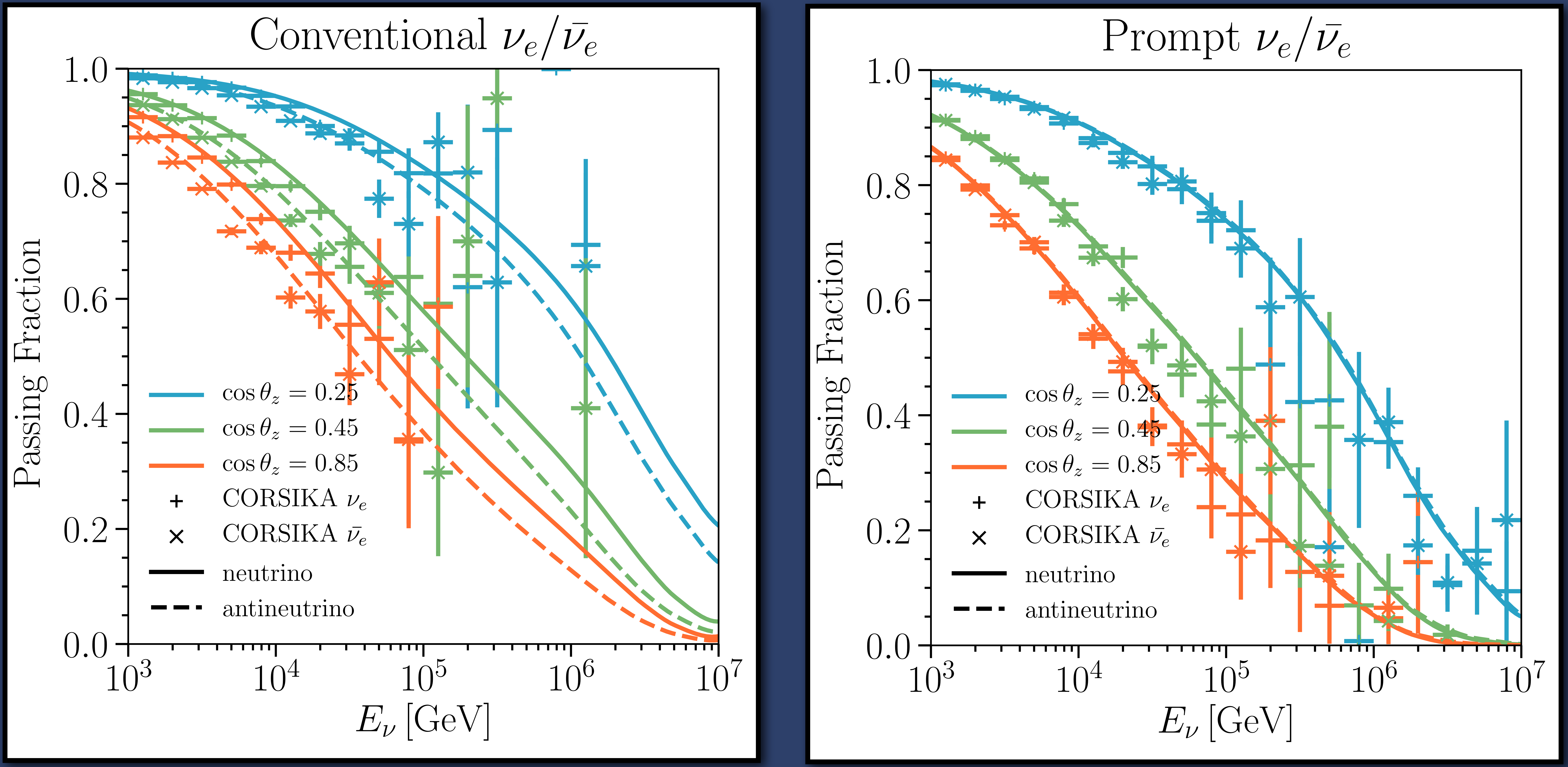
$$\tilde{K}_{\nu_\ell} = \sum_{\ell'=e,\mu} P_{\ell\ell'} K_{\nu_{\ell'}} \qquad \ell = e, \mu, \tau$$

$$K_{\nu_\ell}(x) = \alpha_\pi \delta\left(x - (1 - r_\pi)\right) + \alpha_K \delta\left(x - (1 - r_K)\right) + \begin{cases} x^2(\beta_0 + \beta_1 x) & x \leq r_K \\ \displaystyle\sum_{n=0}^{3} \chi_n x^n & r_K < x < r_\pi \\ (1 - x)^2(\delta_0 + \delta_1 x) & x \geq r_\pi \end{cases}$$

ν	α_π	α_K	β_0	β_1	χ_0	χ_1	χ_2	χ_3	δ_0	δ_1
ν_e	0	0	18.611	−84.173	−0.0070	0.4579	8.6140	−11.426	−5.7189	18.921
$\overline{\nu}_e$	0	0	13.257	−58.739	−0.0048	0.3170	6.3360	−8.3753	−4.1830	13.823
ν_μ	0.4541	0.0347	47.980	−103.75	0.0442	0.4579	12.802	−14.218	−3.4151	23.528
$\overline{\nu}_\mu$	0.3322	0.0241	55.343	−86.796	0.0692	0.3170	12.049	−12.184	−1.0295	20.129

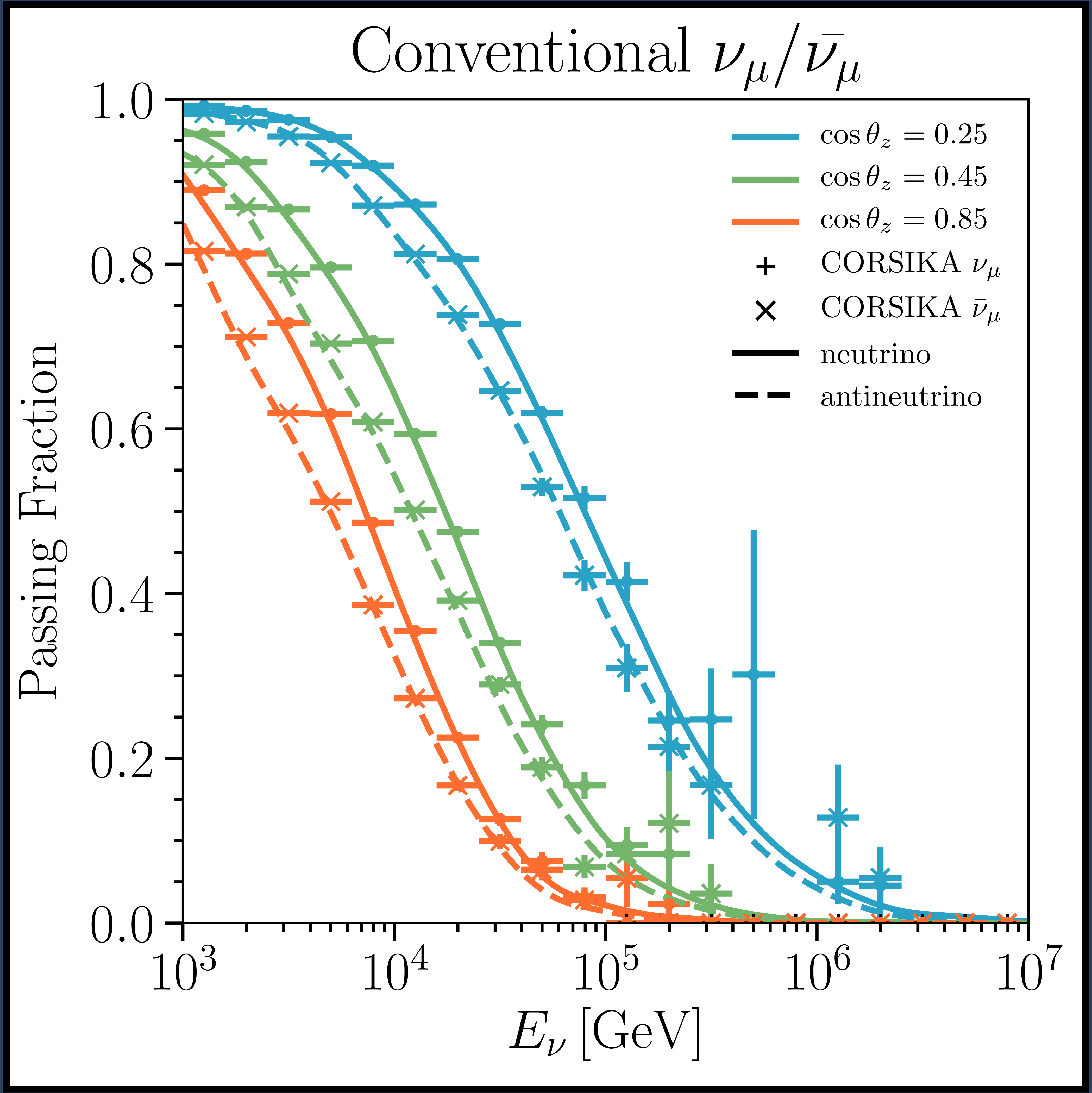
BACKUP SLIDES: ELECTRON NEUTRINO PASSING FRACTIONS

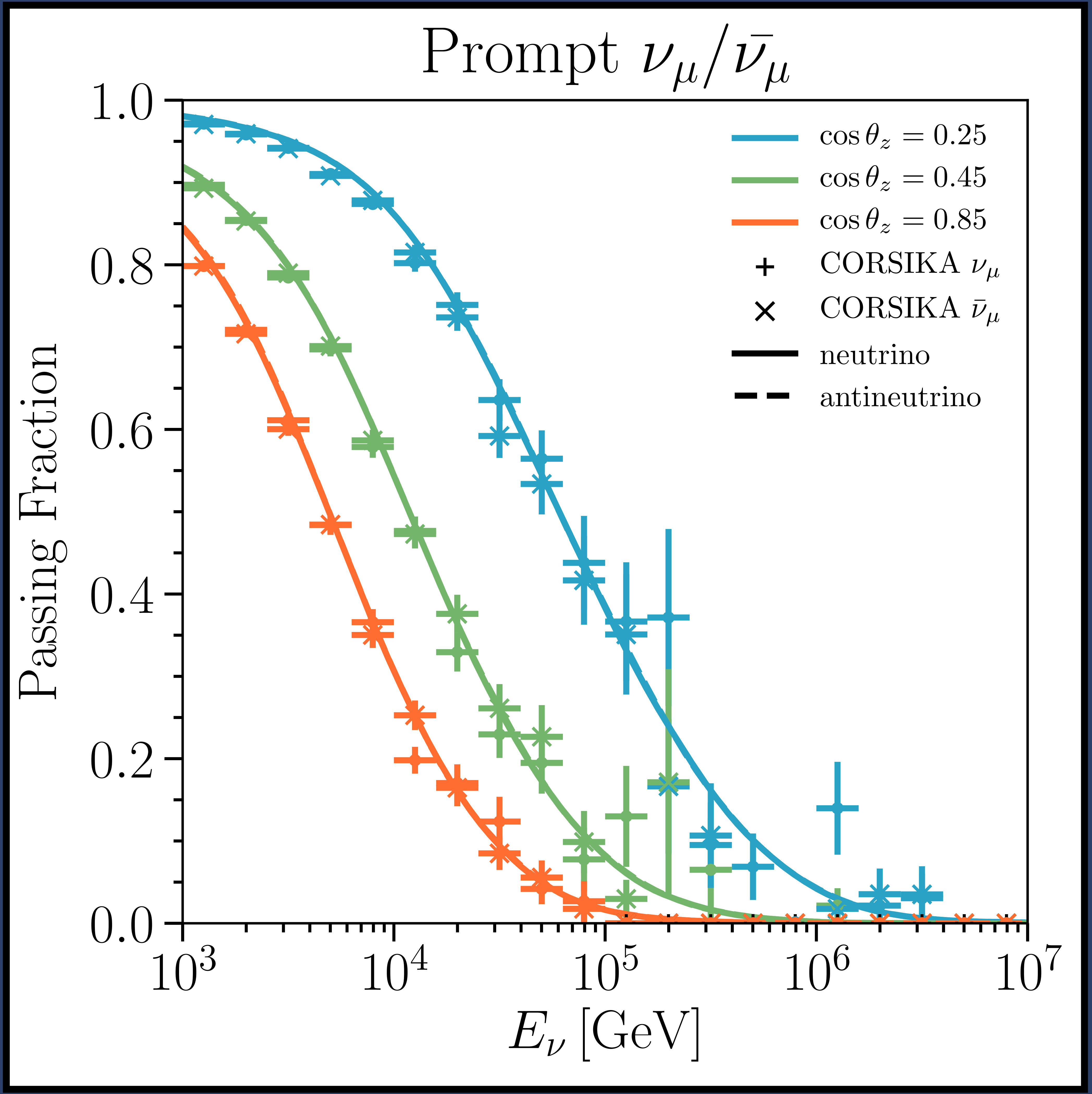
Taken from C. A. Argüelles et al., JCAP **07** (2018) 047



BACKUP SLIDES: MUON NEUTRINO PASSING FRACTIONS

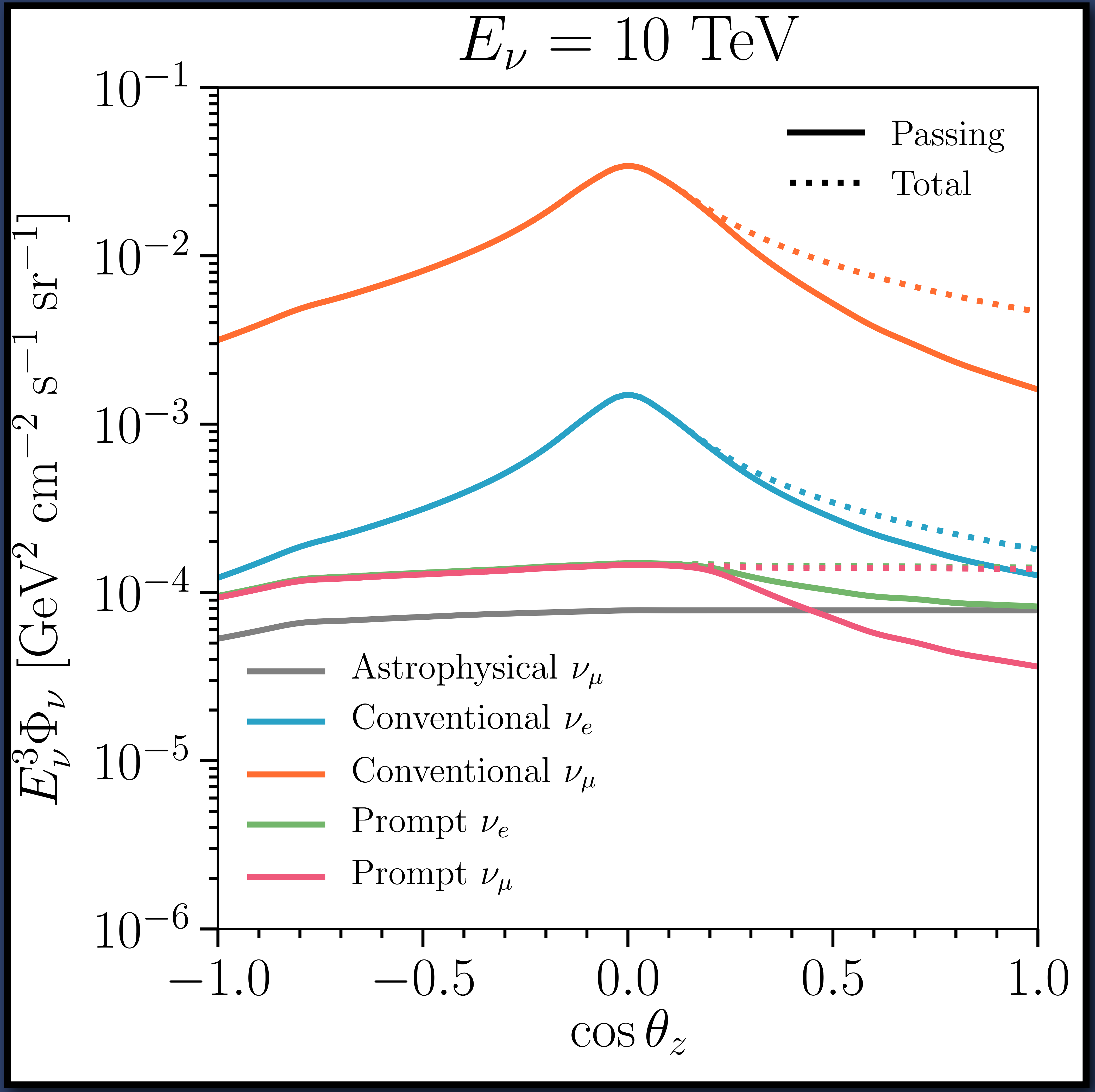
Taken from C. A. Argüelles et al., JCAP **07** (2018) 047

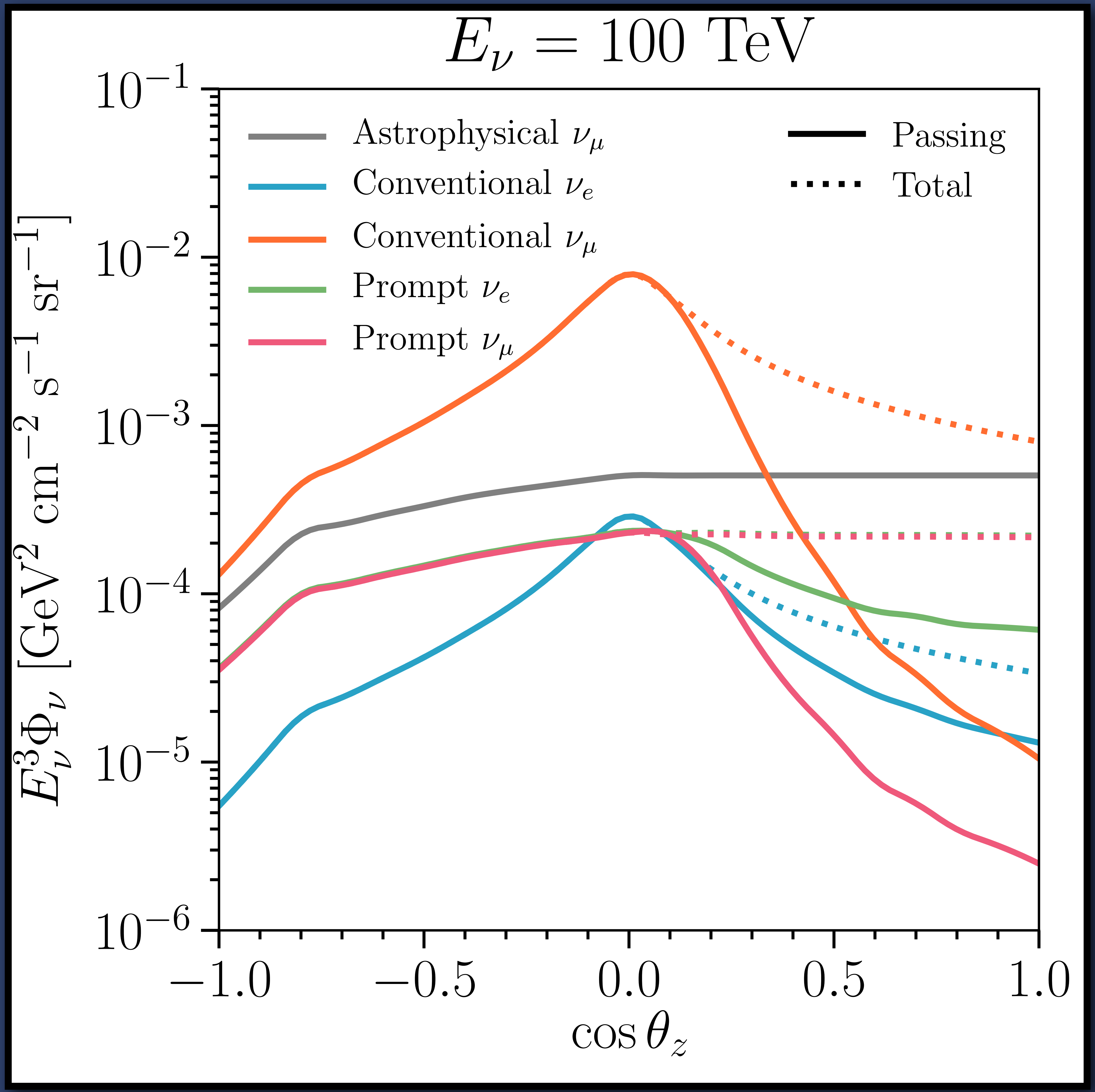




BACKUP SLIDES: ANGULAR DEPENDENCE PASSING FRACTIONS

Taken from C. A. Argüelles et al., JCAP **07** (2018) 047





BACKUP SLIDES: ATMOSPHERIC NEUTRINO FLUXES

$$\frac{d\Phi_\nu^{\text{conv}}}{dE\,d\cos\theta} = \frac{1.1 N_\nu^{\text{conv}}}{|\cos\theta| + 0.1}\left(\frac{E}{100\text{ TeV}}\right)^{-3.7}\ \text{GeV}^{-1}\,\text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}$$

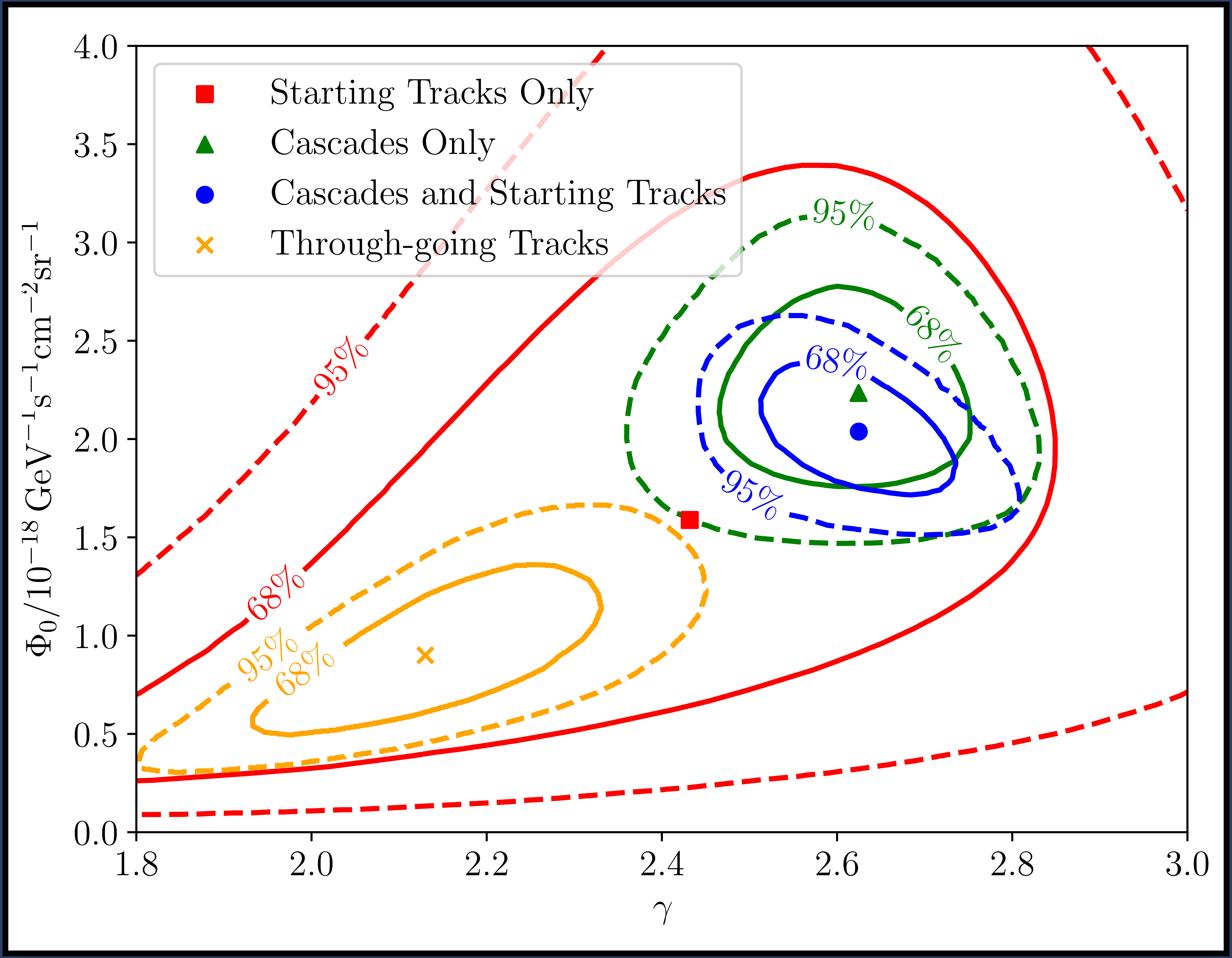
$$\frac{d\Phi_\nu^{\text{prompt}}}{dE\,d\cos\theta} = N_\nu^{\text{prompt}}\left(\frac{E}{100\text{ TeV}}\right)^{-2.7}\ \text{GeV}^{-1}\,\text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}$$

KG primary CR flux model + SIBYLL-2.3c

ν	N_ν^{conv}	N_ν^{prompt}
ν_e	$(0.086 - 0.108) \times 10^{-15}$	$(6.85 - 9.03) \times 10^{-17}$
$\overline{\nu}_e$	$(0.067 - 0.086) \times 10^{-15}$	$(6.70 - 8.86) \times 10^{-17}$
ν_μ	$(2.19 - 2.71) \times 10^{-15}$	$(6.67 - 8.80) \times 10^{-17}$
$\overline{\nu}_\mu$	$(1.30 - 1.66) \times 10^{-15}$	$(6.53 - 8.62) \times 10^{-17}$
ν_τ	-	$(0.89 - 1.18) \times 10^{-17}$
$\overline{\nu}_\tau$	-	$(0.92 - 1.21) \times 10^{-17}$

BACKUP SLIDES: IC ANALYSES OF TRACKS AND CASCADES

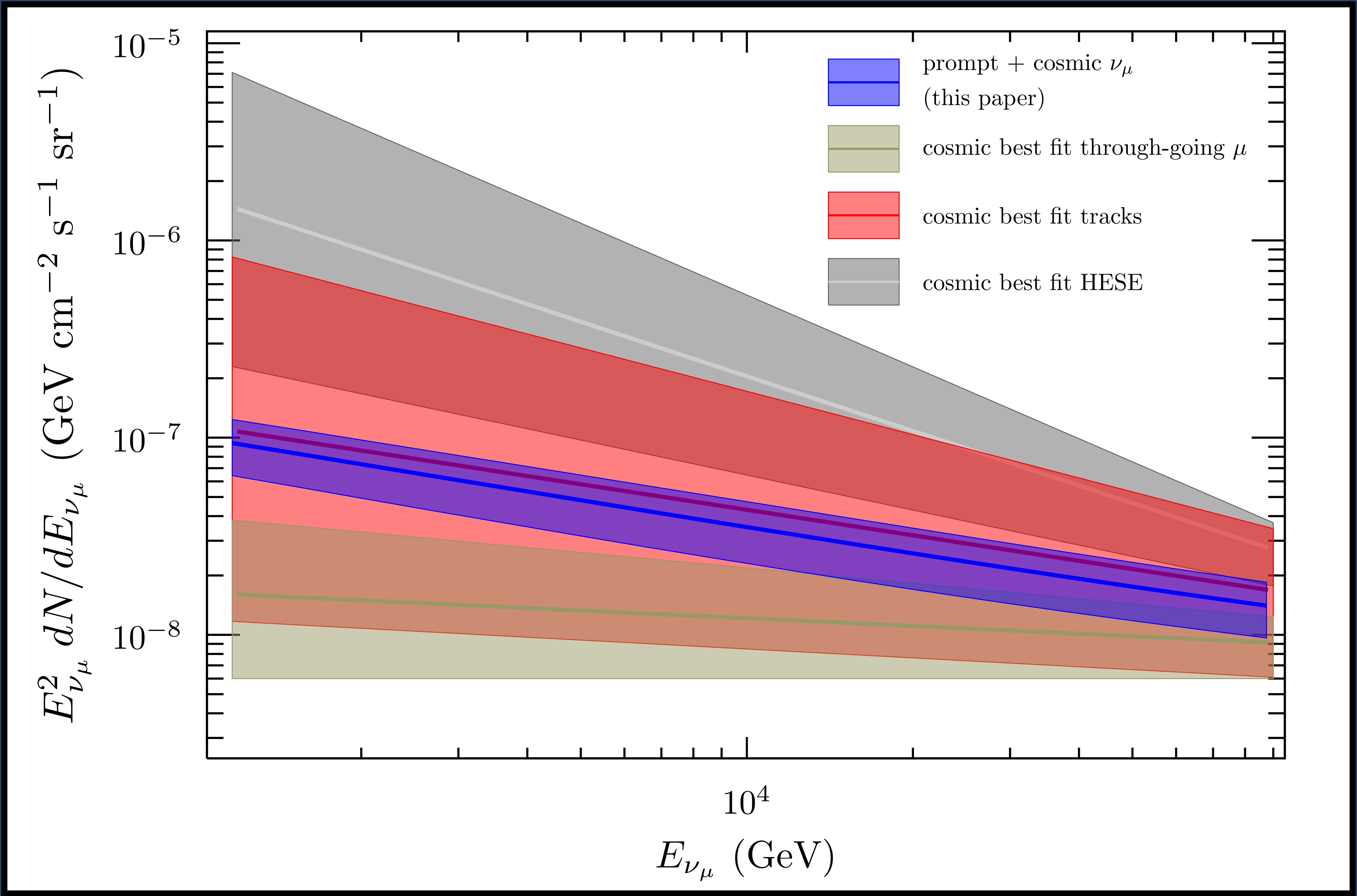
IC Coll., PR **D99** (2019) 032004
prompts best fit = 0



3.5 TeV to 2.6 PeV

BACKUP SLIDES: MUON PROMPT + COSMIC COMPONENTS

Prompt + cosmic contribution in the case of muon neutrinos: little to see…



BACKUP SLIDES: THE SOURCES OF COSMIC NEUTRINOS

Experimentally known, near and with VHE emission starburst Galaxy nuclei: (E. Peretti et al., MNRAS **487** (2019) 1)

$$\gamma_i = 2.25, 2.3, 2.45 \qquad i = \mathrm{M82},\ \mathrm{NGC253},\ \mathrm{Arp220^*}$$

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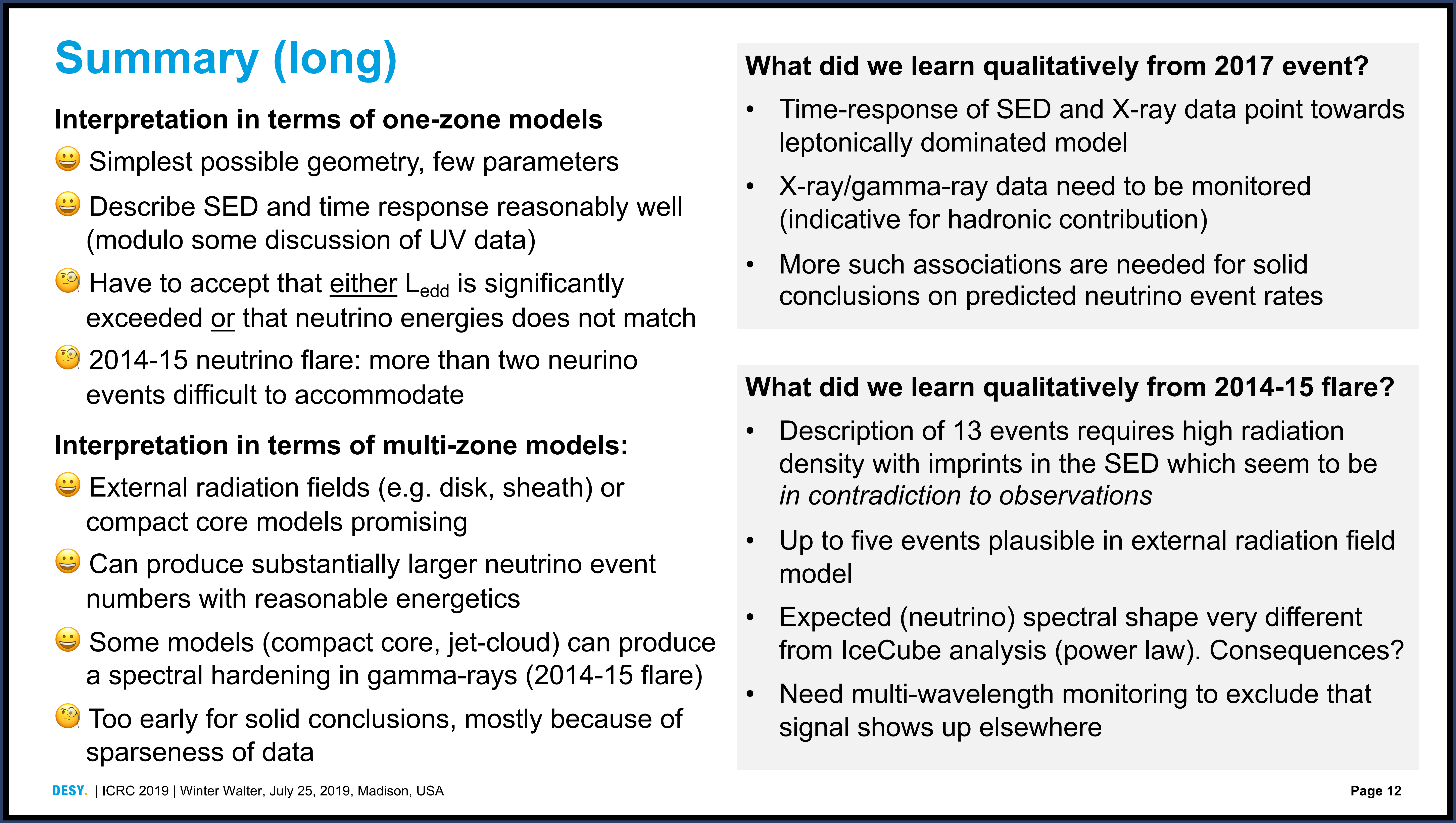
GRBs and (flaring) blazars could also be candidates:

- neutrino coincidence (formally 3σ, 56.5% cosmic) from TXS 0506+056
- not easy at all to model as (stationary) source of neutrinos
- open debate

BACKUP SLIDES: THEORETICAL DESCRIPTION OF TXS



Summary (long)

Interpretation in terms of one-zone models

- 😀 Simplest possible geometry, few parameters
- 😀 Describe SED and time response reasonably well (modulo some discussion of UV data)
- 🧐 Have to accept that either L_{edd} is significantly exceeded or that neutrino energies does not match
- 🧐 2014-15 neutrino flare: more than two neurino events difficult to accommodate

Interpretation in terms of multi-zone models:

- 😀 External radiation fields (e.g. disk, sheath) or compact core models promising
- 😀 Can produce substantially larger neutrino event numbers with reasonable energetics
- 😀 Some models (compact core, jet-cloud) can produce a spectral hardening in gamma-rays (2014-15 flare)
- 🧐 Too early for solid conclusions, mostly because of sparseness of data

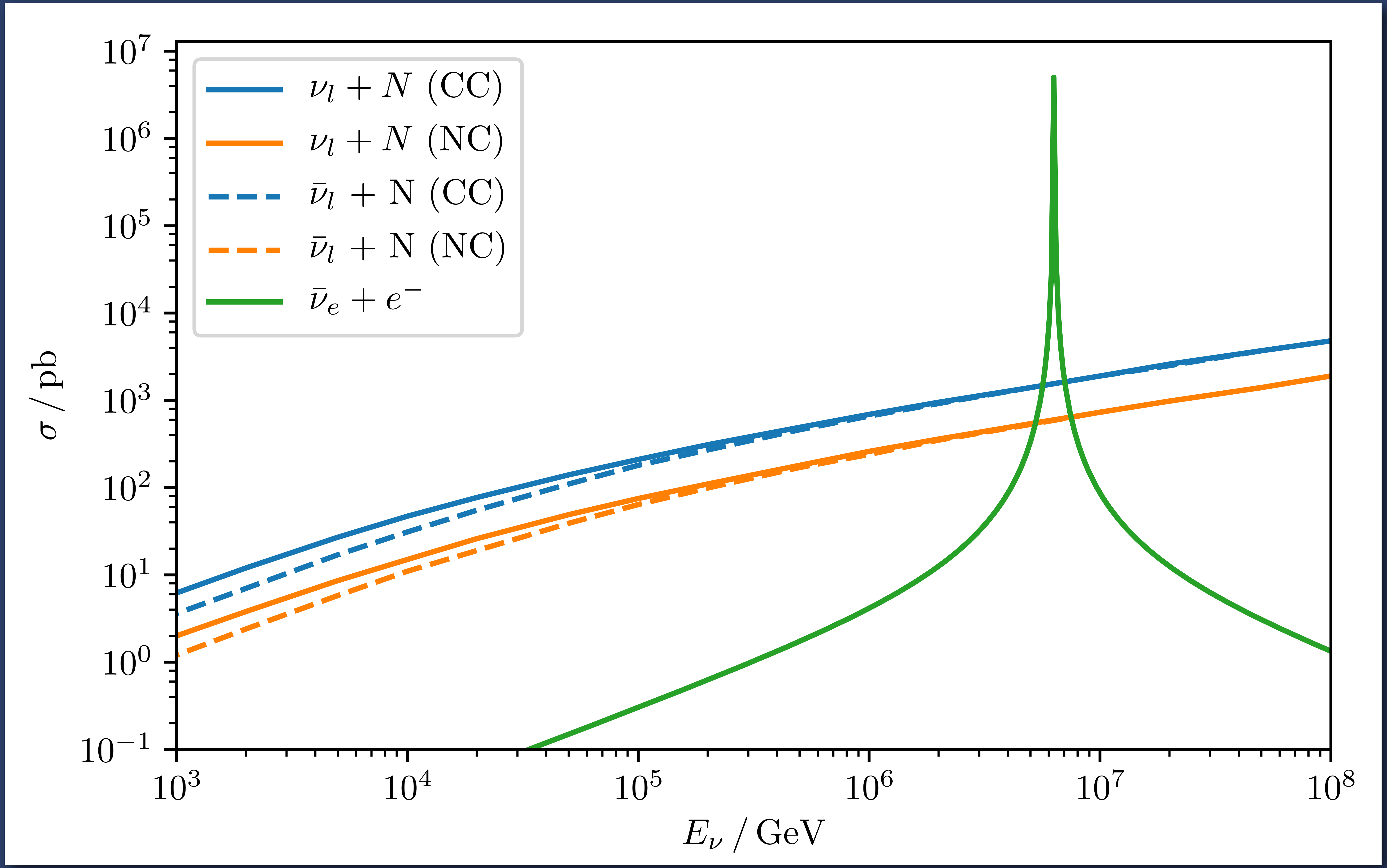
What did we learn qualitatively from 2017 event?

- Time-response of SED and X-ray data point towards leptonically dominated model
- X-ray/gamma-ray data need to be monitored (indicative for hadronic contribution)
- More such associations are needed for solid conclusions on predicted neutrino event rates

What did we learn qualitatively from 2014-15 flare?

- Description of 13 events requires high radiation density with imprints in the SED which seem to be *in contradiction to observations*
- Up to five events plausible in external radiation field model
- Expected (neutrino) spectral shape very different from IceCube analysis (power law). Consequences?
- Need multi-wavelength monitoring to exclude that signal shows up elsewhere

BACKUP SLIDES: NEUTRINO CROSS SECTION



M. Rongen, “Calibration of the IceCube Neutrino Observatory”, arXiv:1911.02016

BACKUP SLIDES: GZK NEUTRINOS

$$\frac{dN}{dE} \propto \begin{cases} E^{-2.7} & 10^{10}\,\mathrm{eV} < E < 10^{15}\,\mathrm{eV} \\ E^{-3.1} & 10^{15}\,\mathrm{eV} < E < 10^{18}\,\mathrm{eV} \\ E^{-2.6} & 10^{18}\,\mathrm{eV} < E < 10^{20}\,\mathrm{eV} \end{cases}$$

Apparent cutoff of spectrum at about 10^{20} eV: resonant interactions of CR protons with CMB?

$$p + \gamma_{\mathrm{CMB}} \to \Delta^+ \to \begin{cases} p + \pi^0 \\ n + \pi^+ \end{cases} \qquad E_{p,\mathrm{th}} \approx 5 \times 10^{19}\,\mathrm{eV},\, E_{\gamma_{\mathrm{CMB}}} \simeq 0.235\,\mathrm{meV}$$

Search of GZK neutrinos with Auger, Askaryan detectors: so far only upper limits

$$E^2 \Phi_\nu \leq 4.4 \times 10^{-9}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}} \qquad 100\,\mathrm{PeV} \leq E \leq 25\,\mathrm{EeV}$$

Auger Coll., JCAP 10 (2019), assuming an E^{-2} spectrum

BACKUP SLIDES: ICRC19 AUGER SPECTRUM