DETECTING PROMPT NEUTRINOS AT NEUTRINO TELESCOPES: THEORETICAL PREDICTIONS AND EXPERIMENTAL DATA

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HQHP WORKSHOP, MAINZ

CONTEXT AND MOTIVATION

1. IceCube has provided unique and most important results;

2. conventional neutrinos have been measured for sure, prompt ones yet to be;

3. cosmic neutrino discovered! But spectra resulting from HESE and through-going muons analysis quite at odds below 100 TeV if
   - *standard three-flavour neutrino oscillation*
   - *isotropic cosmic signal*
   - *unbroken power-law cosmic spectrum*

We discuss 2. and 3. on theoretical grounds.

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To compute their spectrum: 1) CR flux model, 2) QCD/numerical code

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

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- Most abundant elements
- E_ν ~ 1/20A of parent's

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Galactic CRs = power laws fitted to AMS-02

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Rigidity-dependent knee fitted to KASCADE-Grande

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Extra-galactic protons fitted to KASCADE-Grande

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Numerical code used: MCEq with SYBILL-2.3c

- computation of conventional and prompt neutrinos for custom CR flux
- average over seasonal atmospheric conditions @ IceCube
- average over azimuthal angle

COSMIC NEUTRINOS: HYPOTHESES AND MEASUREMENTS

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Most recent through-going muons analysis (ICRC 2019, not official yet) not as much:

$$\frac{d\Phi_{\mathrm{IC19},\nu_\mu}}{dE} = 1.44^{+0.25}_{-0.24} \times 10^{-18} \left(\frac{E}{100\ \mathrm{TeV}}\right)^{-2.28^{+0.08}_{-0.09}}$$

COSMIC NEUTRINOS: WHICH SOURCES?

Candidate pp sources: powerful accelerator + lots of hadronic targets, e.g. starburst or star-forming Galaxies. Loeb & Waxman (2006):

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

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(Flaring) blazars could be candidates: neutrino coincidence (formally 3σ, 56.5% cosmic) from TXS 0506+056, but not easy at all to model as (stationary) source of neutrinos > open debate (Palladino, Vissani 2017, …)

COSMIC MUON NEUTRINOS

We combined the flux of Waxman & Loeb and of IceCube 2016 to have a phenomenologically precise cosmic muon neutrino spectrum:

- weighted average of normalisation and spectral index: $\frac{d\Phi_{\mathrm{MV},\nu_\mu}}{dE} = 0.90^{+0.30}_{-0.27} \times 10^{-18} \left(\frac{E}{100 \text{ TeV}}\right)^{-2.14\pm0.08}$
- definition of best fit astrophysical neutrino flux and its 1σ uncertainty considering ρ~0.6 correlation between experimental normalisation @ 100 TeV and slope:

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

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

COSMIC NEUTRINOS: THE OTHER FLAVOURS

Hadronic mechanism > power-law flux of gamma rays and neutrinos are linearly related at the source (Vissani and Villante, 2008):

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

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

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

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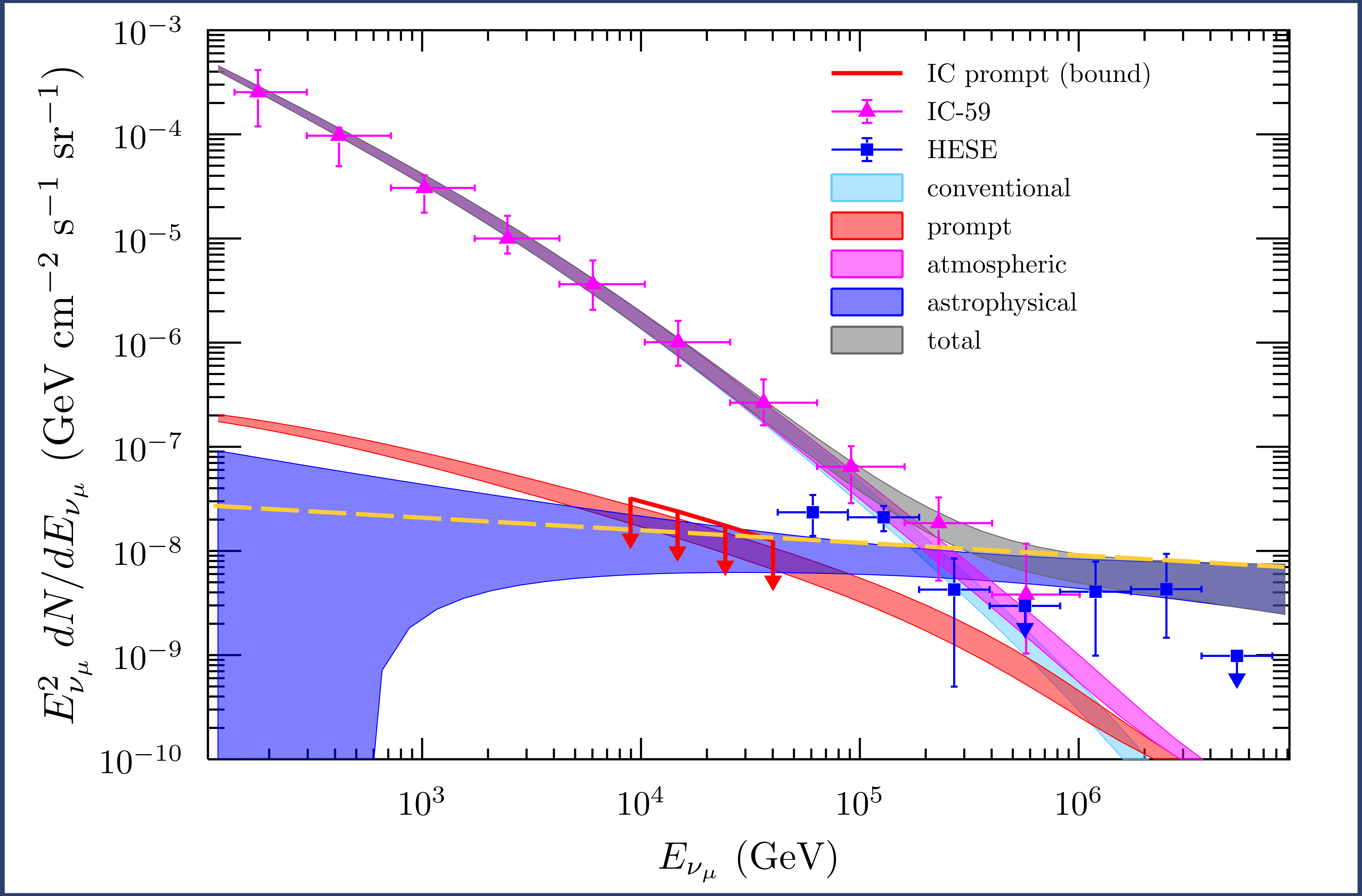
Other possible, less physical, approach: "2:1" approximation, based only upon neutrino oscillations and a flavour ratio at the source of (ξ_e:ξ_μ:ξ_τ) = (1:2:0) < pion decay scenario

$$R^{2:1}_{\ell\ell'} = \frac{\sum_{\ell''} P_{\ell\ell''}\xi_{\ell''}}{\sum_{\ell''} P_{\ell'\ell''}\xi_{\ell''}}$$

RESULTS AND DISCUSSION

THE COMPONENTS OF THE MUON NEUTRINO SPECTRUM



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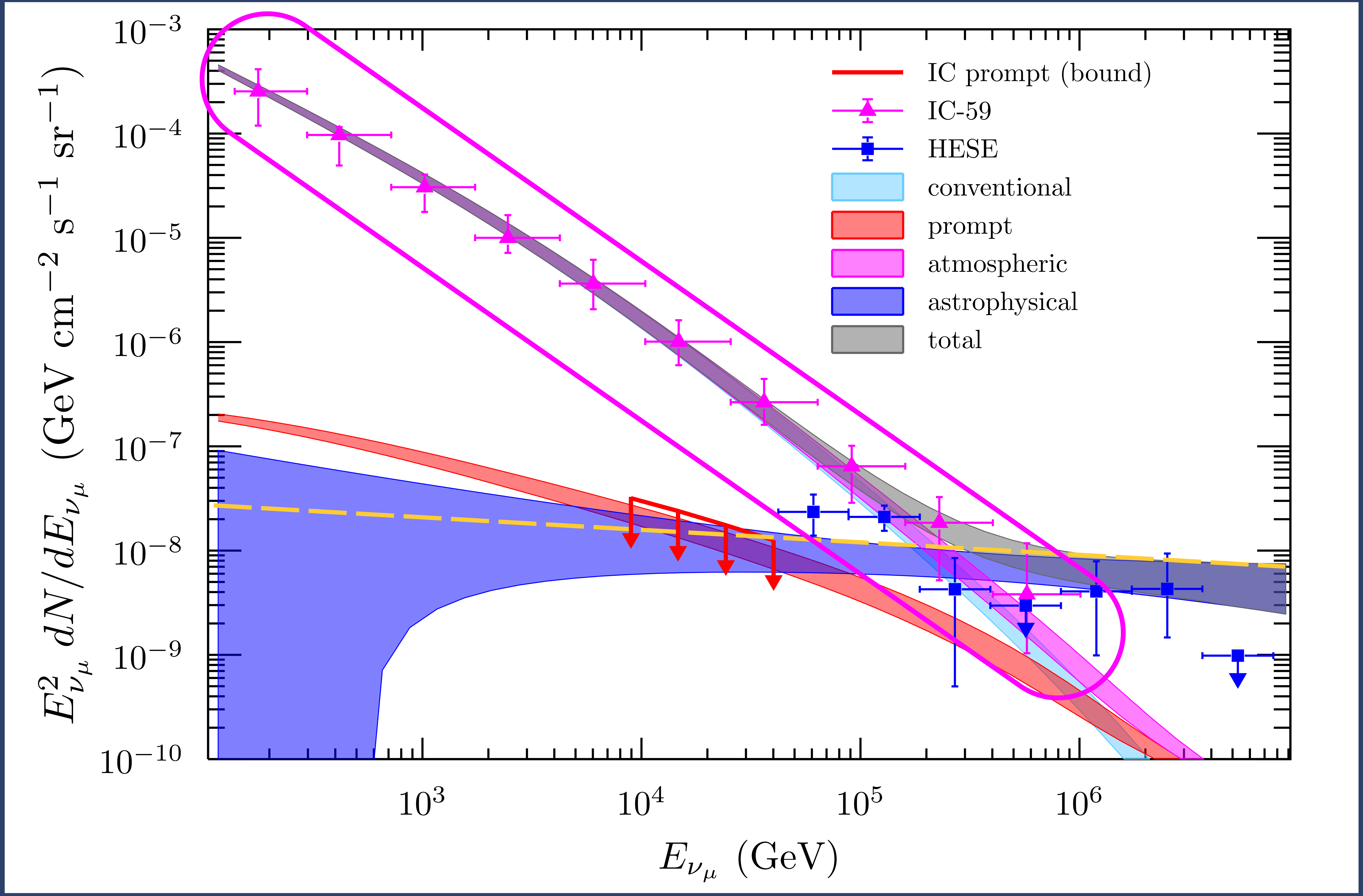

Good agreement between expectations and data for atmospheric neutrinos

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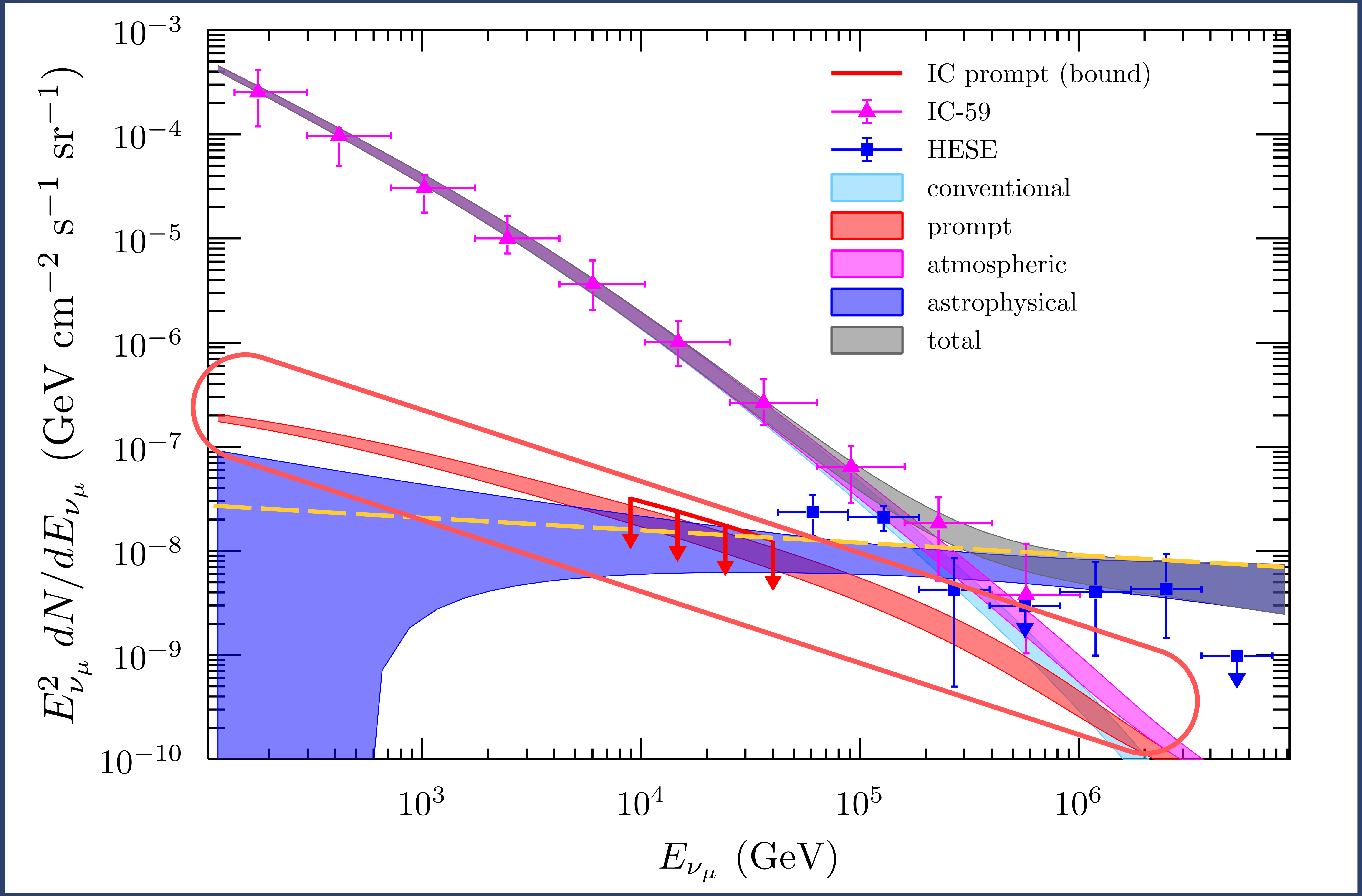

Prompt component always subdominant: very hard to see prompts in ν_μ

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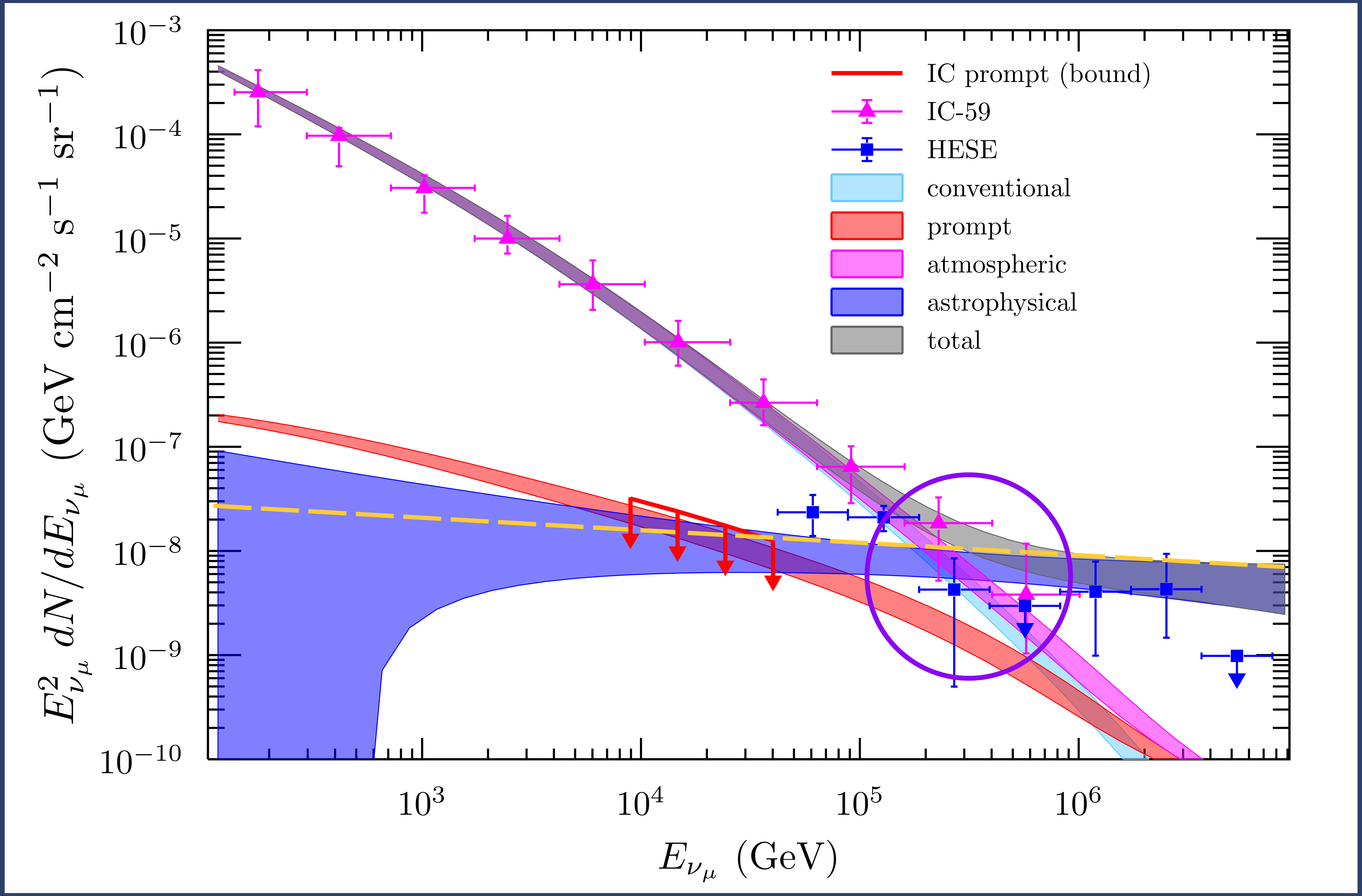
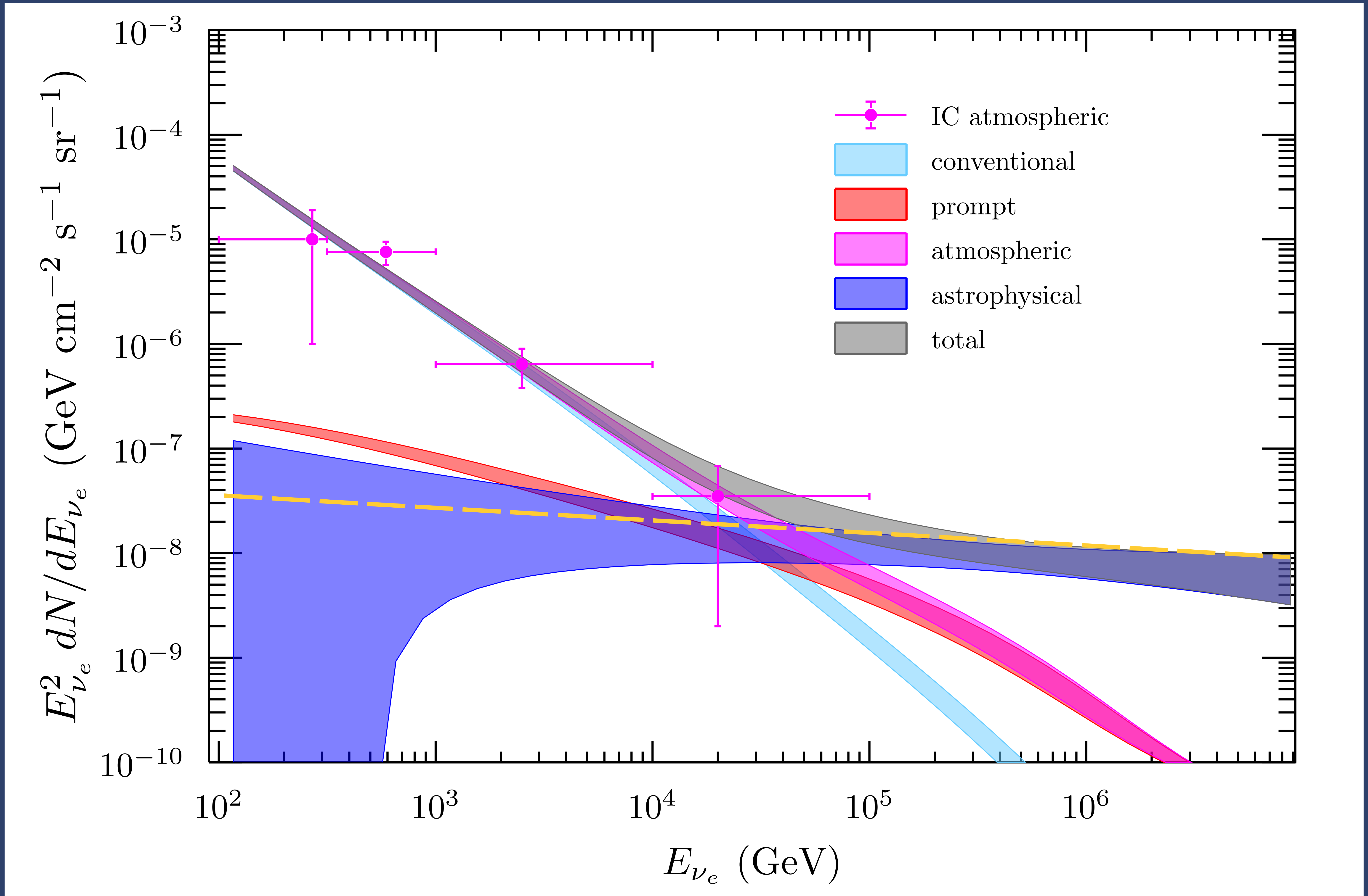


Atmospheric and cosmic neutrinos cross at about 250 TeV ~ $E_{knee}/20$

THE COMPONENTS OF THE ELECTRON NEUTRINO SPECTRUM



$$R_{e\mu} = 1.30 \pm 0.05 \qquad \left(R^{2:1}_{e\mu} = 1.09^{+0.03}_{-0.04}\right)$$

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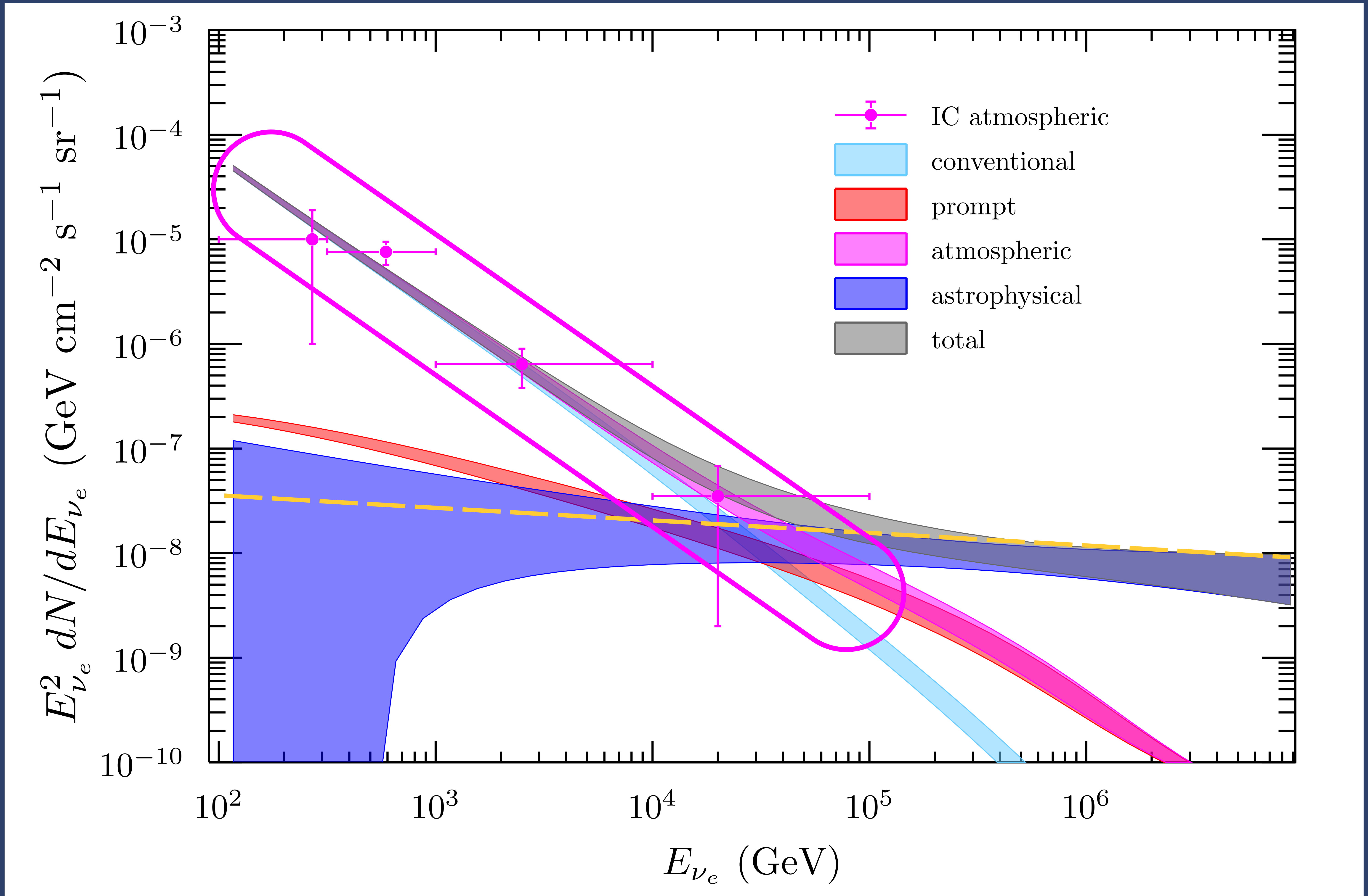

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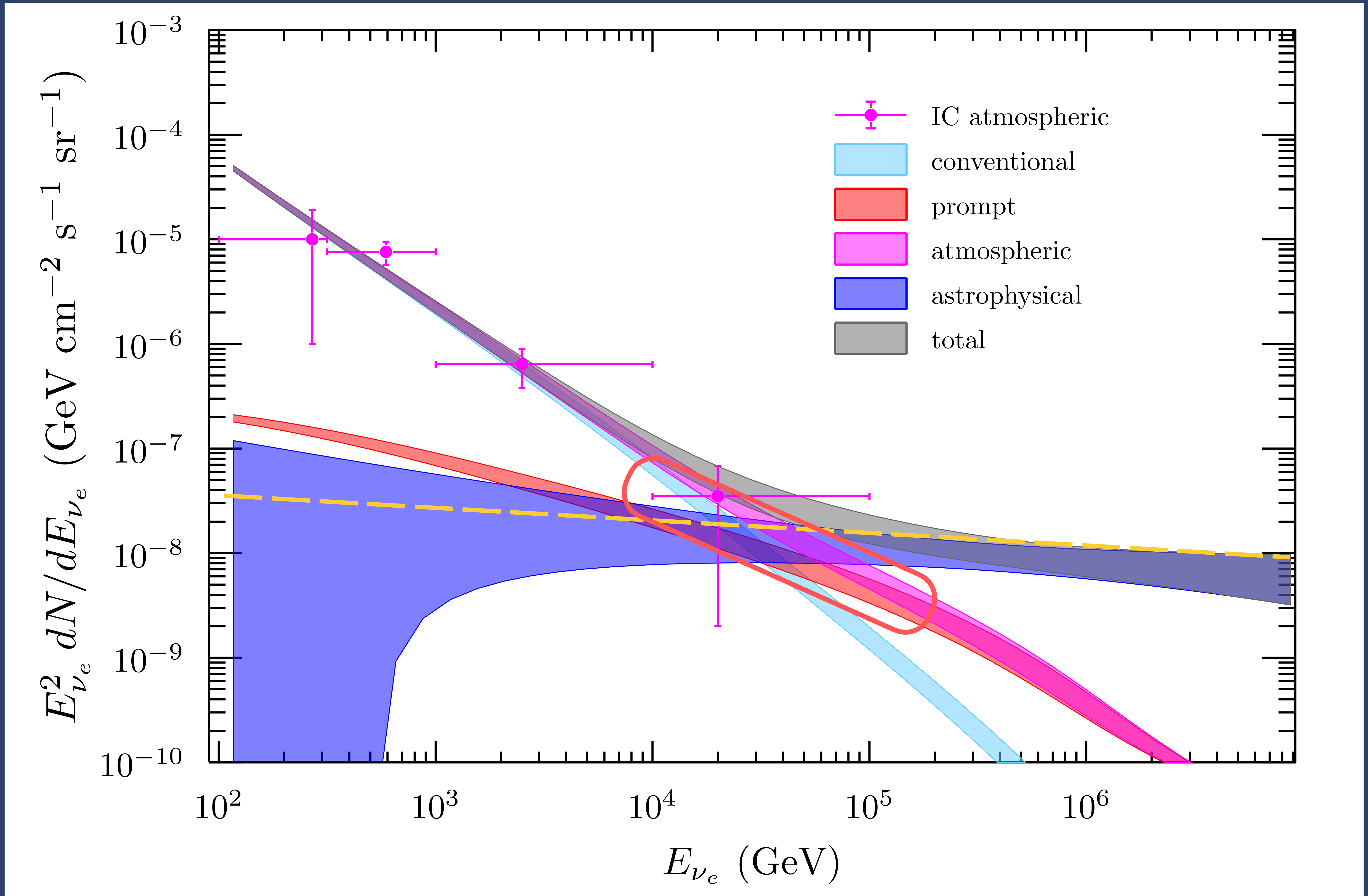

Prompt component relevant for 10 TeV ≤ E ≤ 100 TeV

IS IT POSSIBLE TO EXTRACT THE PROMPT SIGNAL?

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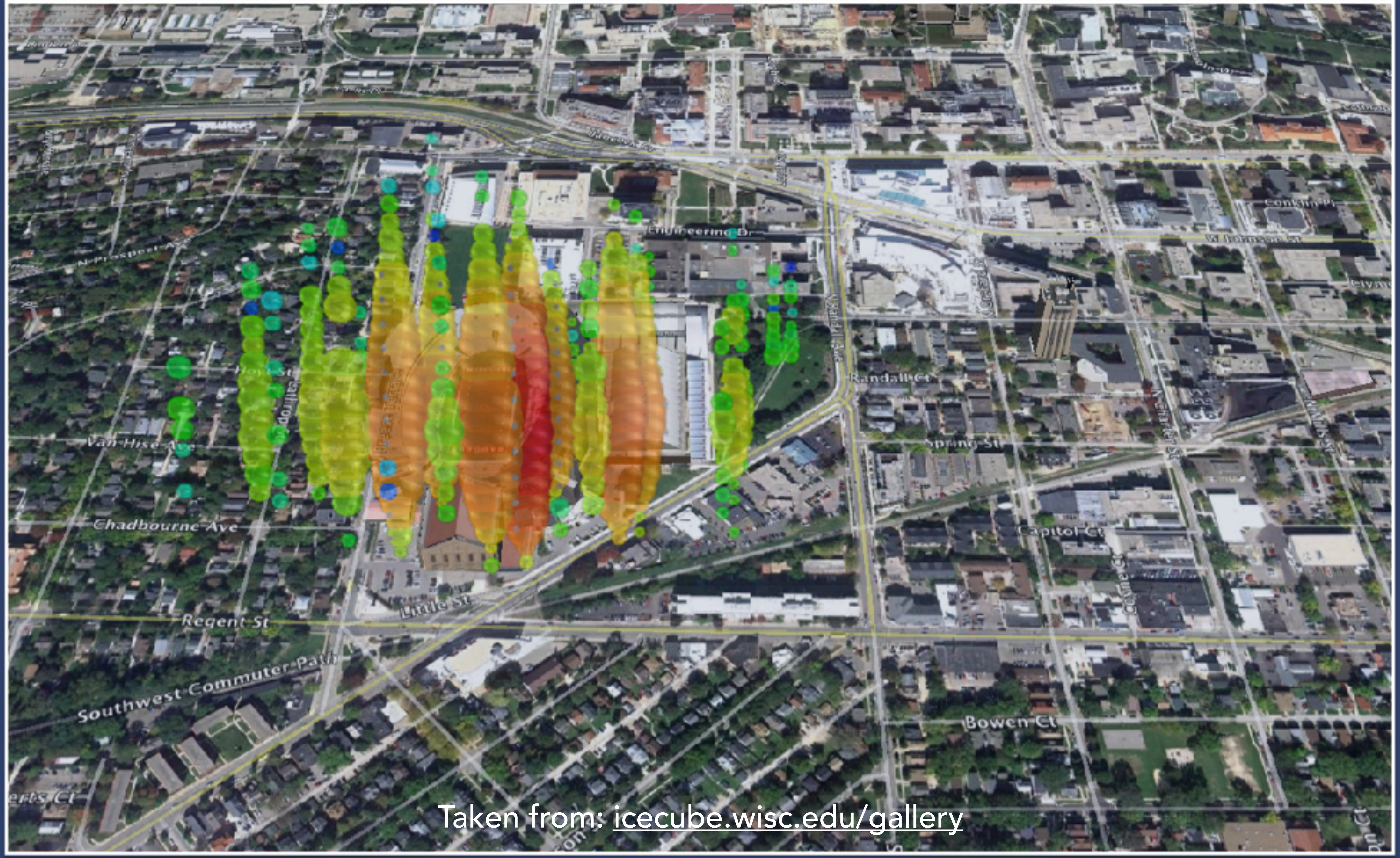
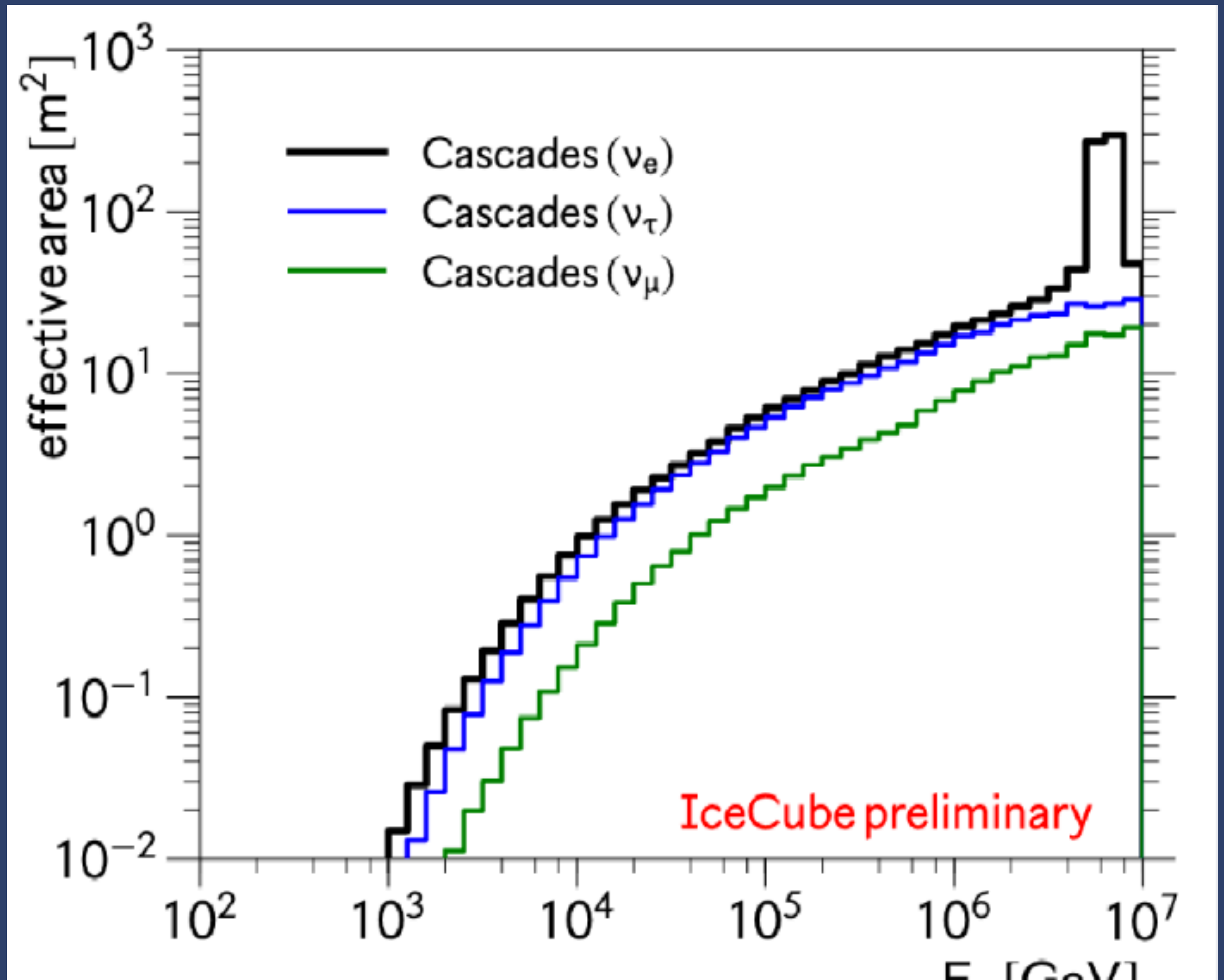
Ideal search: ν_e events. Best dataset: cascades, smallest contribution of ν_μ.



Taken from: icecube.wisc.edu/gallery



ICRC17, averaged over θ

HOW MANY CASCADE EVENTS DUE TO PROMPTS?

Estimation assuming no atmospheric veto:

$$N_{\nu_\ell} = 4\pi \times 1\,\text{year} \times \int_{1\,\text{TeV}}^{10\,\text{PeV}} dE\, \mathcal{A}_{\nu_\ell}(E)\, \frac{d\Phi_{\nu_\ell}}{dE}$$

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Inclusion of veto: passing fraction functions $P_\nu(E,\cos\theta)$ (Argüelles et al. 2018) for conventional and prompt (anti-)neutrinos

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

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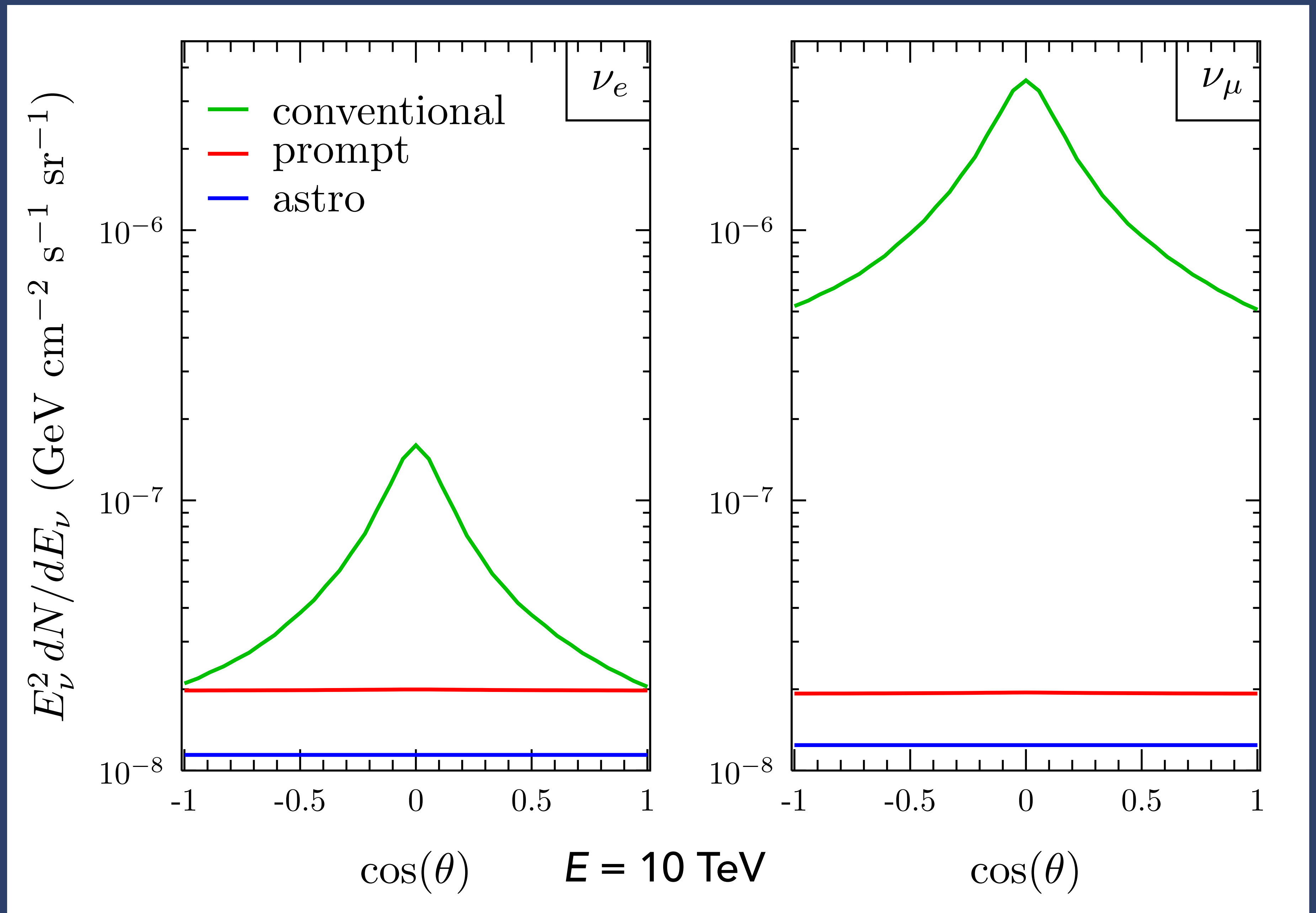
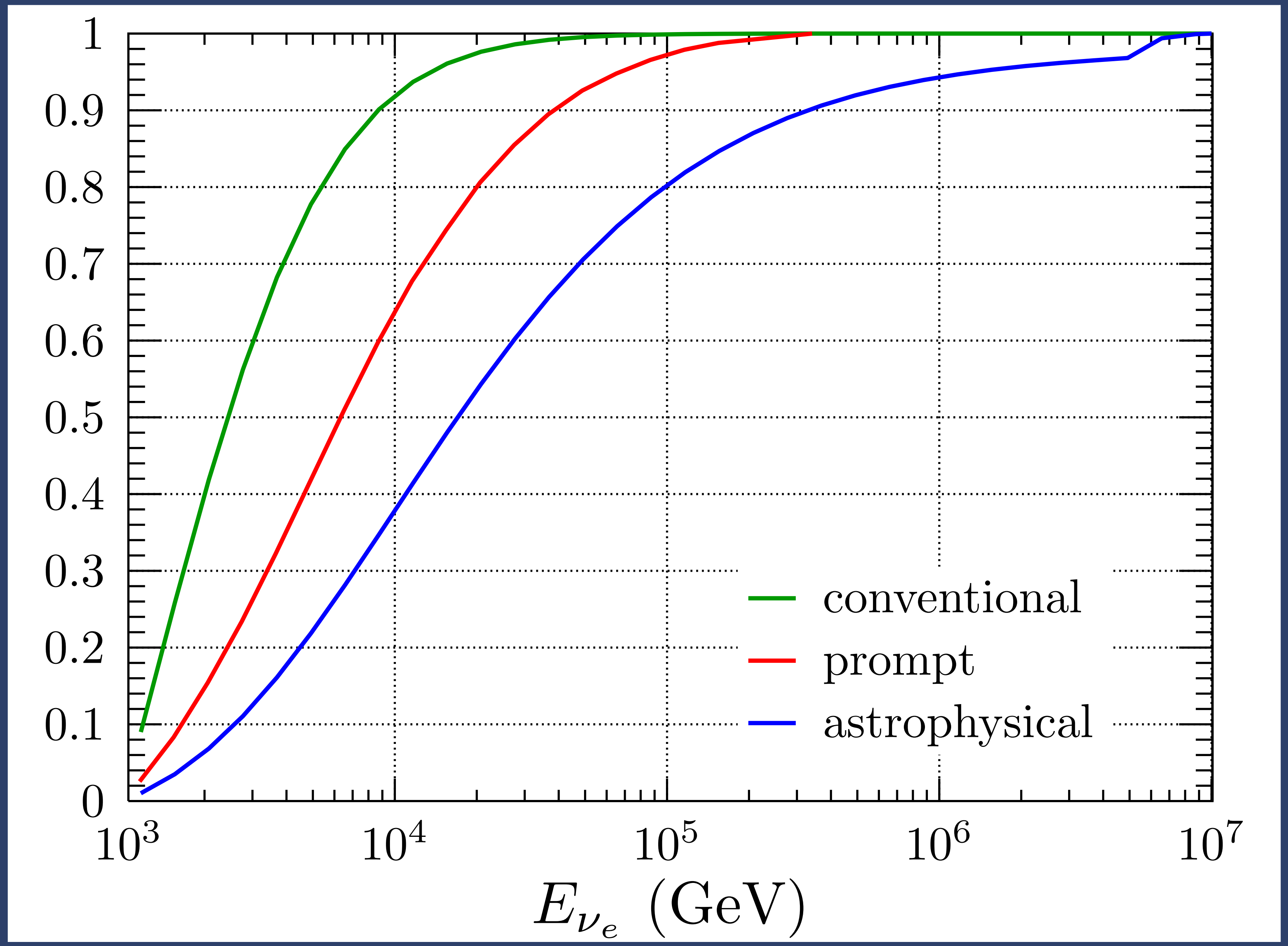


Not easy, but: angular selection, higher energy threshold could help!

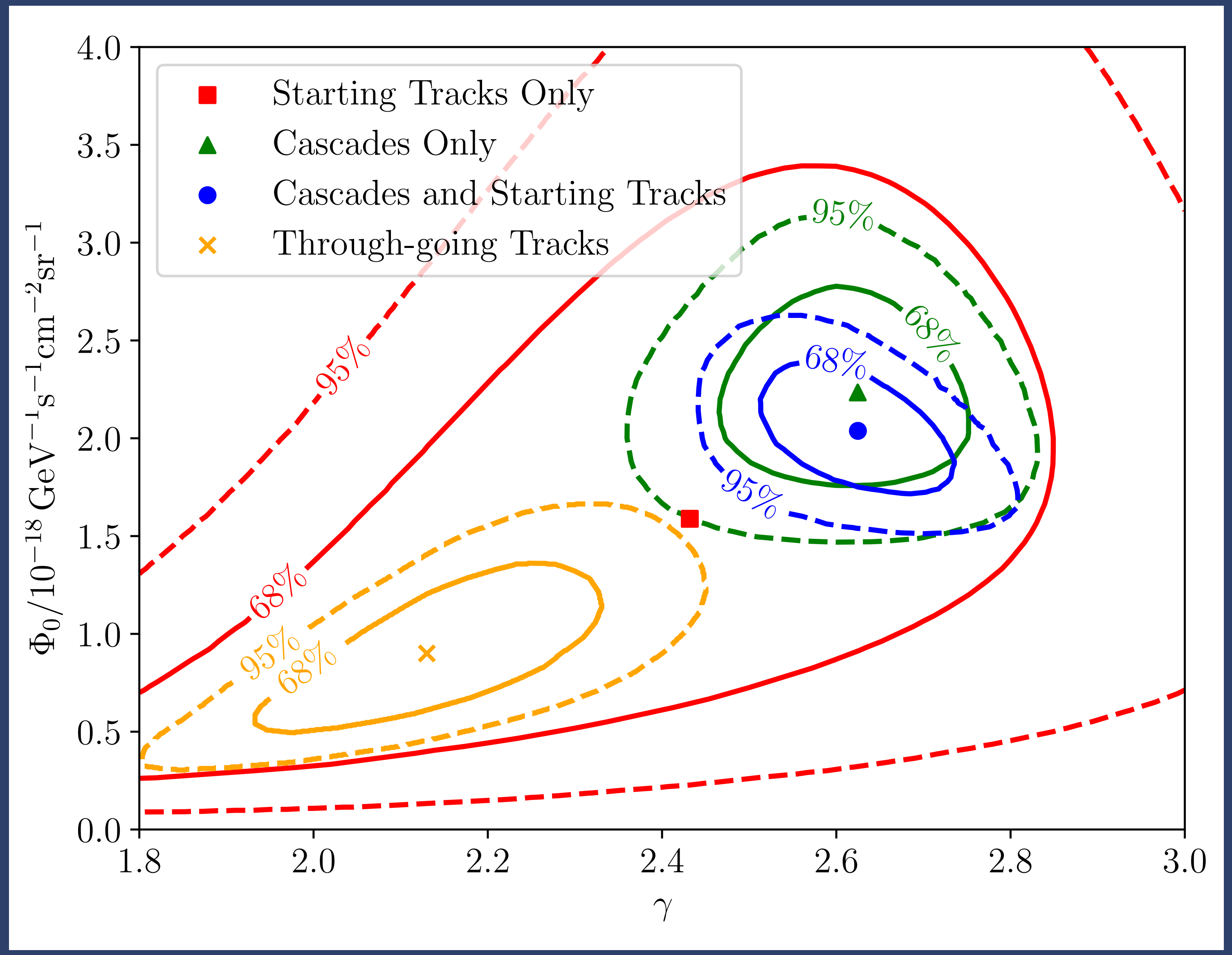


Component	Veto	N_{ν_e}	N_{ν_μ}	N_{ν_τ}	N_{tot}
Conventional	×	150 – 190	410 – 510	–	560 – 700
	✓	140 – 180	385 – 485	–	525 – 665
Prompt	×	18 – 24	3 – 4	1 – 2	22 – 30
	✓	16 – 21	2 – 3	1 – 2	19 – 26
Cosmic	–	10 – 40	2 – 6	5 – 20	15 – 65

IS THERE A SPECTRAL ANOMALY?

Spectral anomaly: different IC datasets suggest different cosmic neutrino spectra.

Plot from IC Coll., PRD**99** 032004 (2019), prompts best fit = 0



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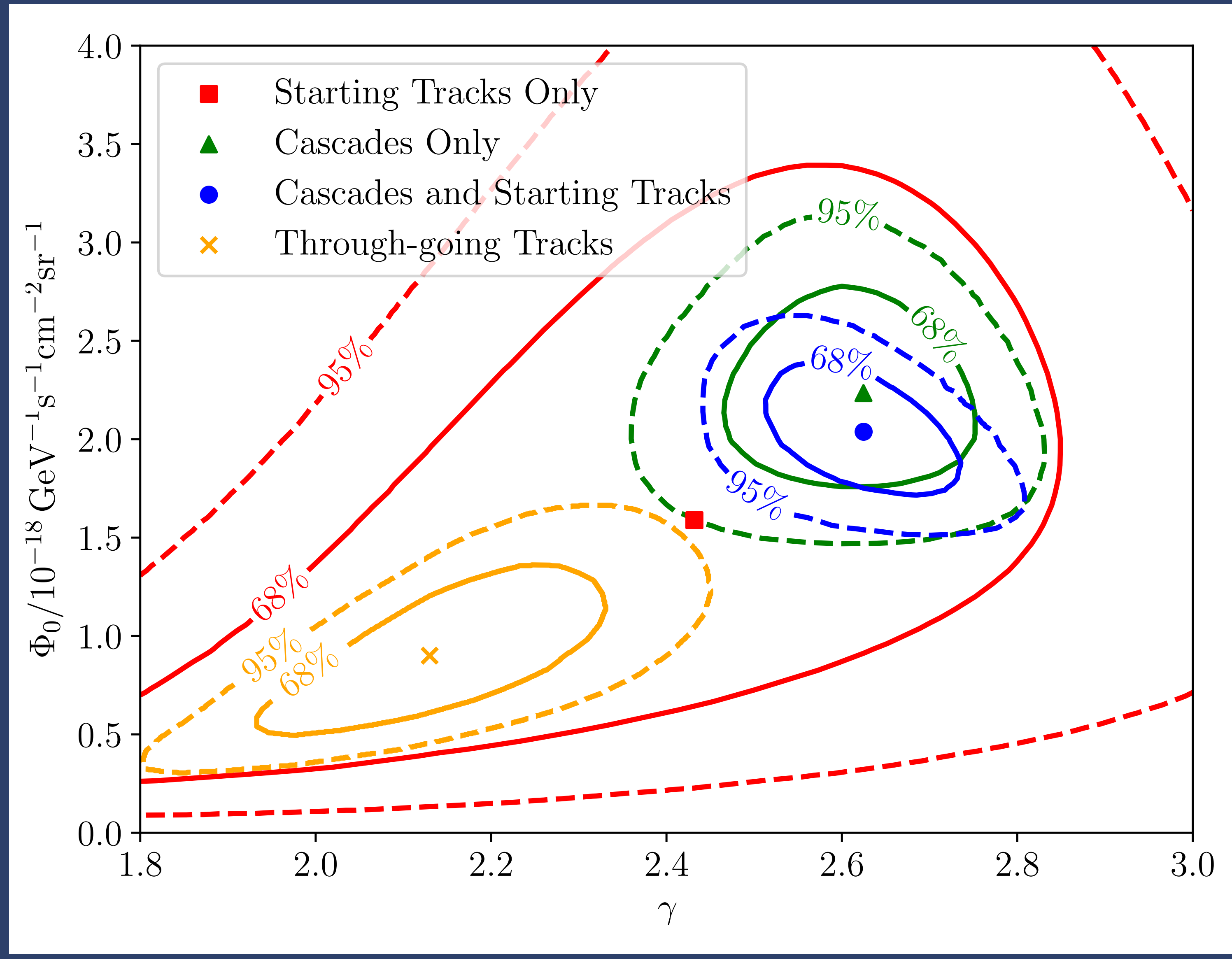

Analysis	2017	2018	2019
Cascades	$(2.48 \pm 0.08; 1.57^{+0.23}_{-0.22})$	$(2.62 \pm 0.08; 2.2^{+0.6}_{-0.5})$	
HESE	$(2.92^{+0.33}_{-0.29}; 2.46 \pm 0.8)$		$(2.89^{+0.20}_{-0.19}; 2.15^{+0.49}_{-0.15})$
Starting tracks		$(2.43^{+0.28}_{-0.30}; 1.6^{+1.6}_{-1.0})$	
Through-going muons	$(2.19 \pm 0.10; 1.01^{+0.26}_{-0.23})$		$(2.28^{+0.08}_{-0.09}; 1.44^{+0.25}_{-0.24})$

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Similar number of events + same isotropic distribution = difficult to distinguish…can prompts play a role in cosmic neutrino analyses?

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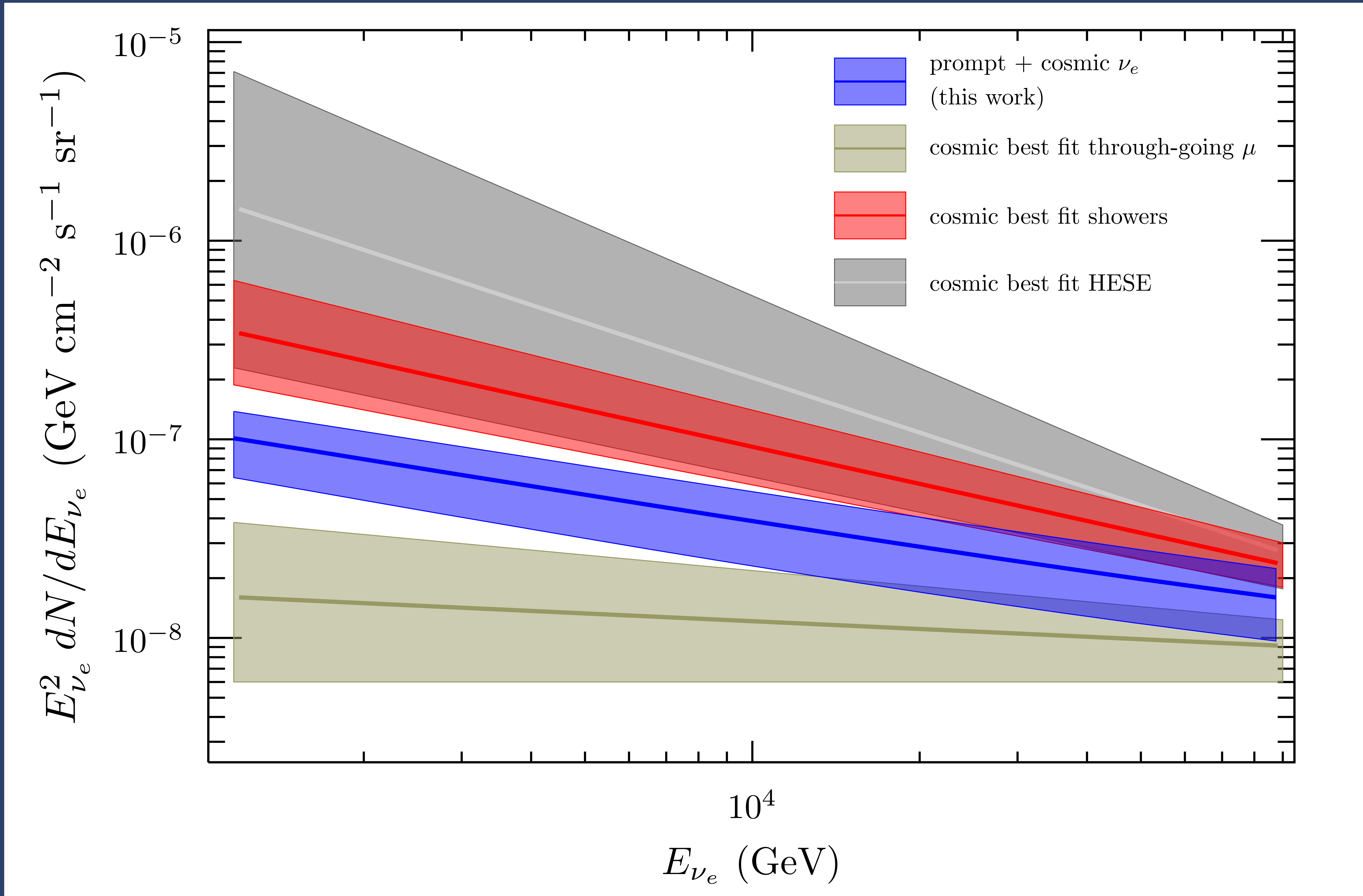

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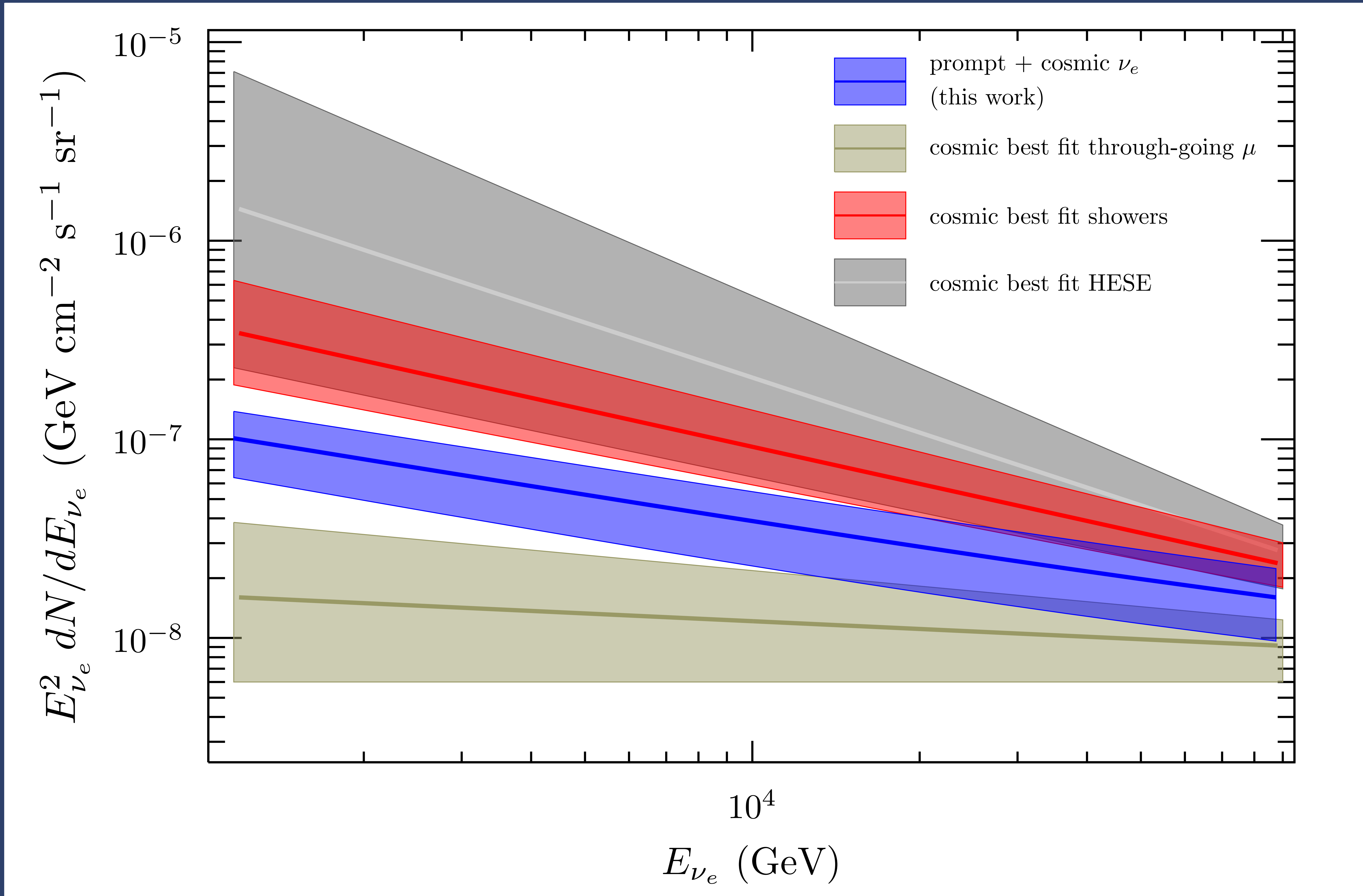

Prompt + cosmic spectrum closer to HESE/showers spectrum

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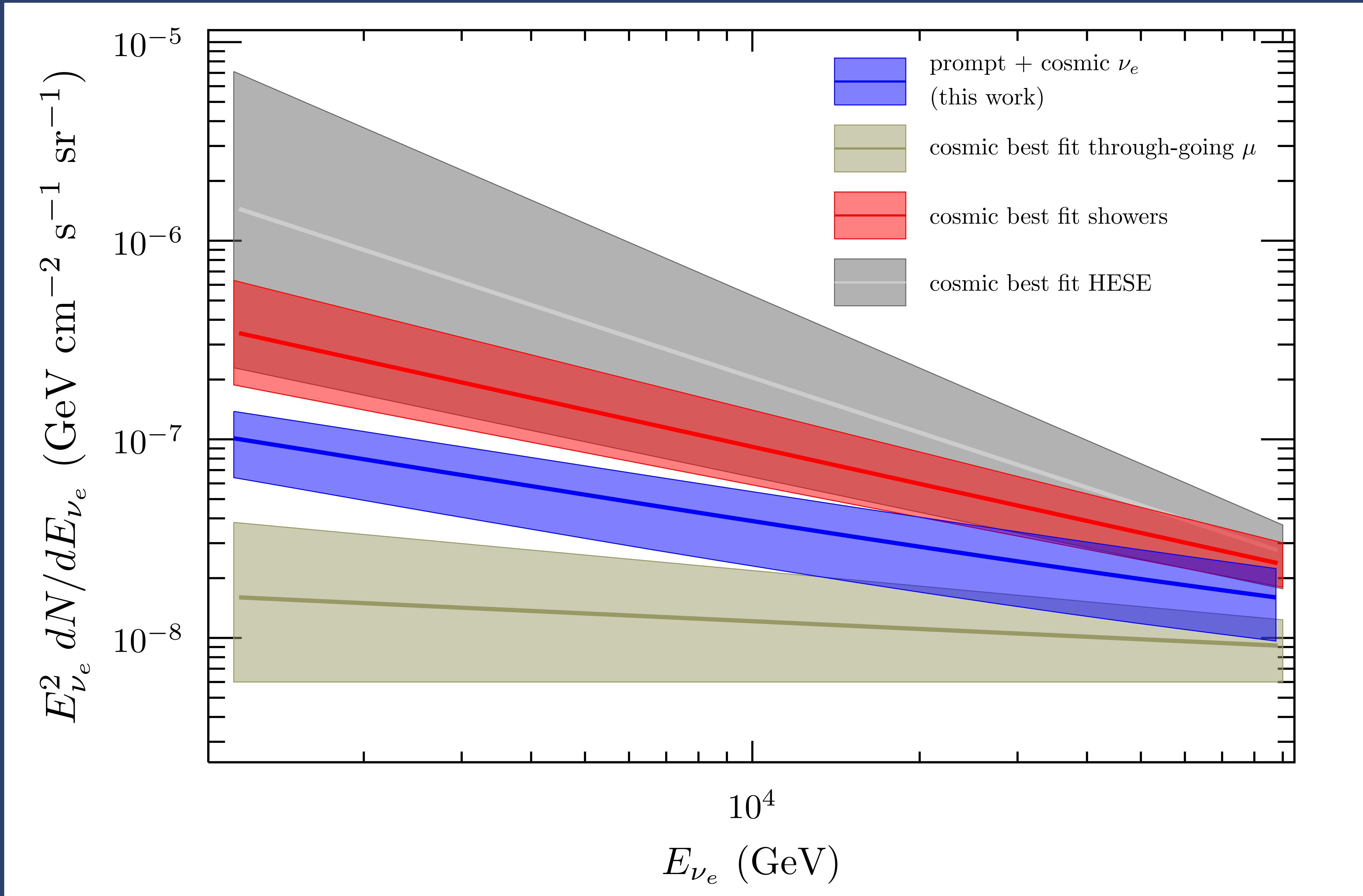

Anomaly attributable to: prompts in cascades, background tracks in HESE.
This in the "minimal" proposal = no other hypothetical physical ingredients

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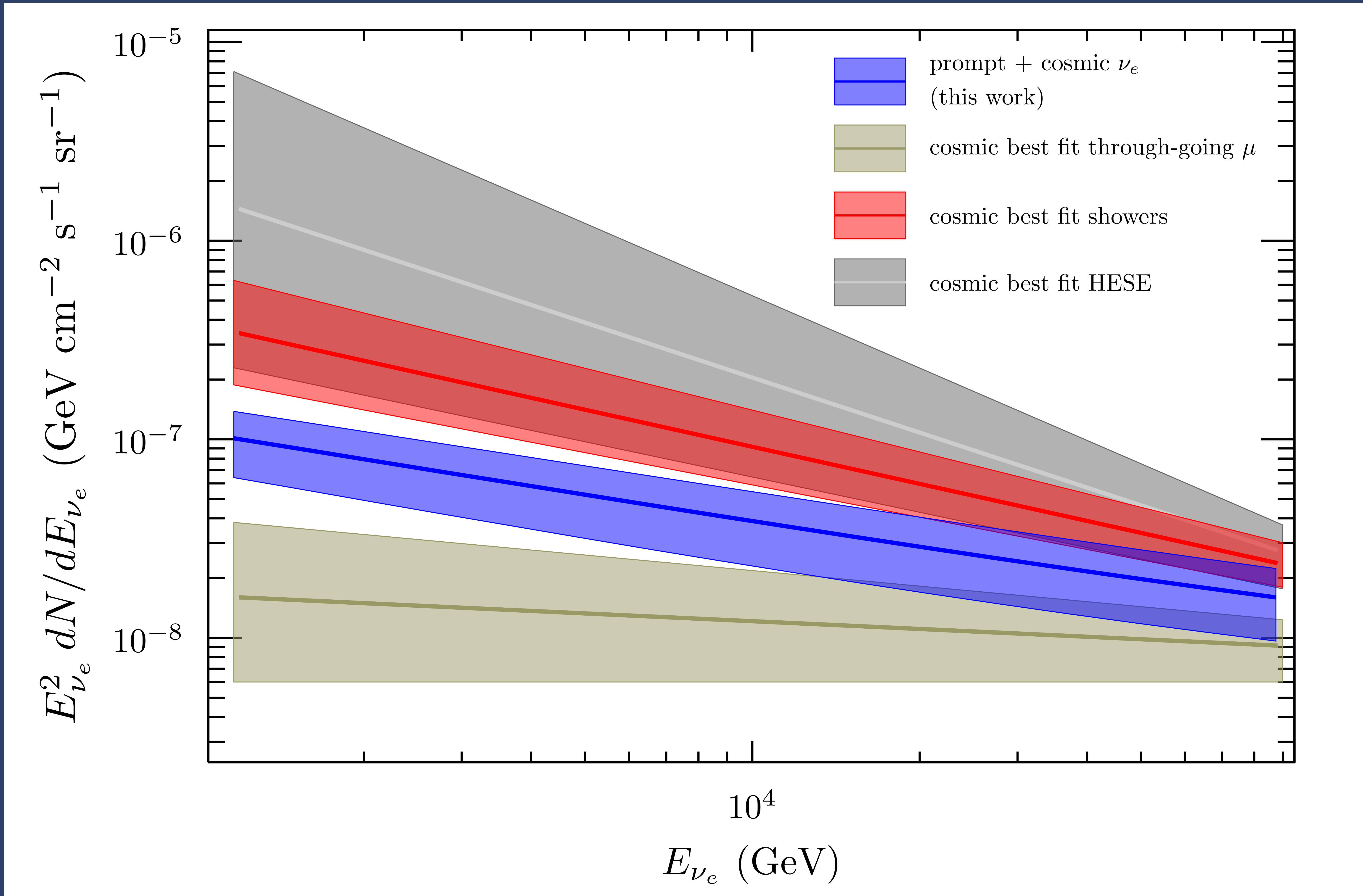


Other contributions to the low-energy HESE spectrum are not ruled out

CONCLUSIONS

Within our assumptions and modelling, we can conclude that:

- it is not surprising that no prompt neutrino evidence has been found in the through-going muons dataset;
- the prompt signal could be relevant for the showers dataset - still not easy to extract;
- the low-energy discrepancy between HESE and through-going muons spectra can be due to the presence of prompts and/or atmospheric background.

We argue that a theory-driven analysis of all datasets is the optimal procedure to obtain information about the whole neutrino spectrum.

THANKS FOR YOUR ATTENTION!

BACKUP SLIDES

Few more details on the primary CR spectrum. For even more see MC, P. Blasi and C. Evoli, *Astr. Phys.* 114 (2020) 22-29

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

$\propto E^{-2.7}$

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

Model	$R_{\rm knee}$	N_p	γ_p	$N_{\rm He}$	$\gamma_{\rm He}$	$N_{\rm eg}$
`exp2-cut`	15.1 ± 0.7 PV	1.5 ± 0.2	2.71 ± 0.04	1.5 ± 0.1	2.64 ± 0.03	6.0 ± 0.2
`delta-slope`	5.8 ± 0.6 PV					5.0 ± 0.5

N_p, $N_{\rm He}$: x 10^{-7} GeV^{-1} m^{-2} s^{-1} sr^{-1} @ 10 TeV

$N_{\rm eg}$: x 10^{-19} GeV^{-1} m^{-2} s^{-1} sr^{-1} @ 100 PeV

BACKUP SLIDES

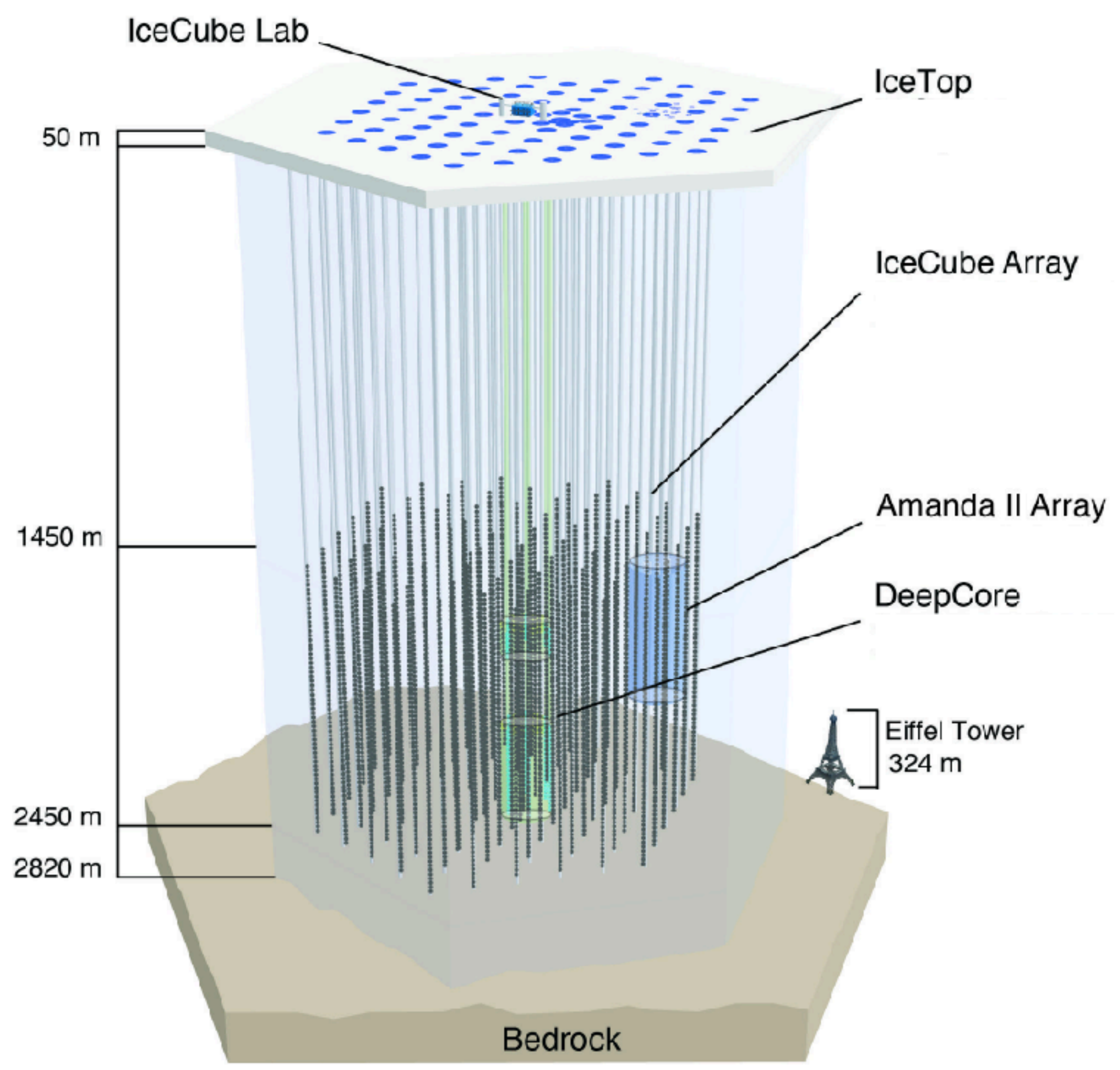
More about the kernel formalism from F. Vissani & F. L. Villante, PRD**78** 10 (2008):

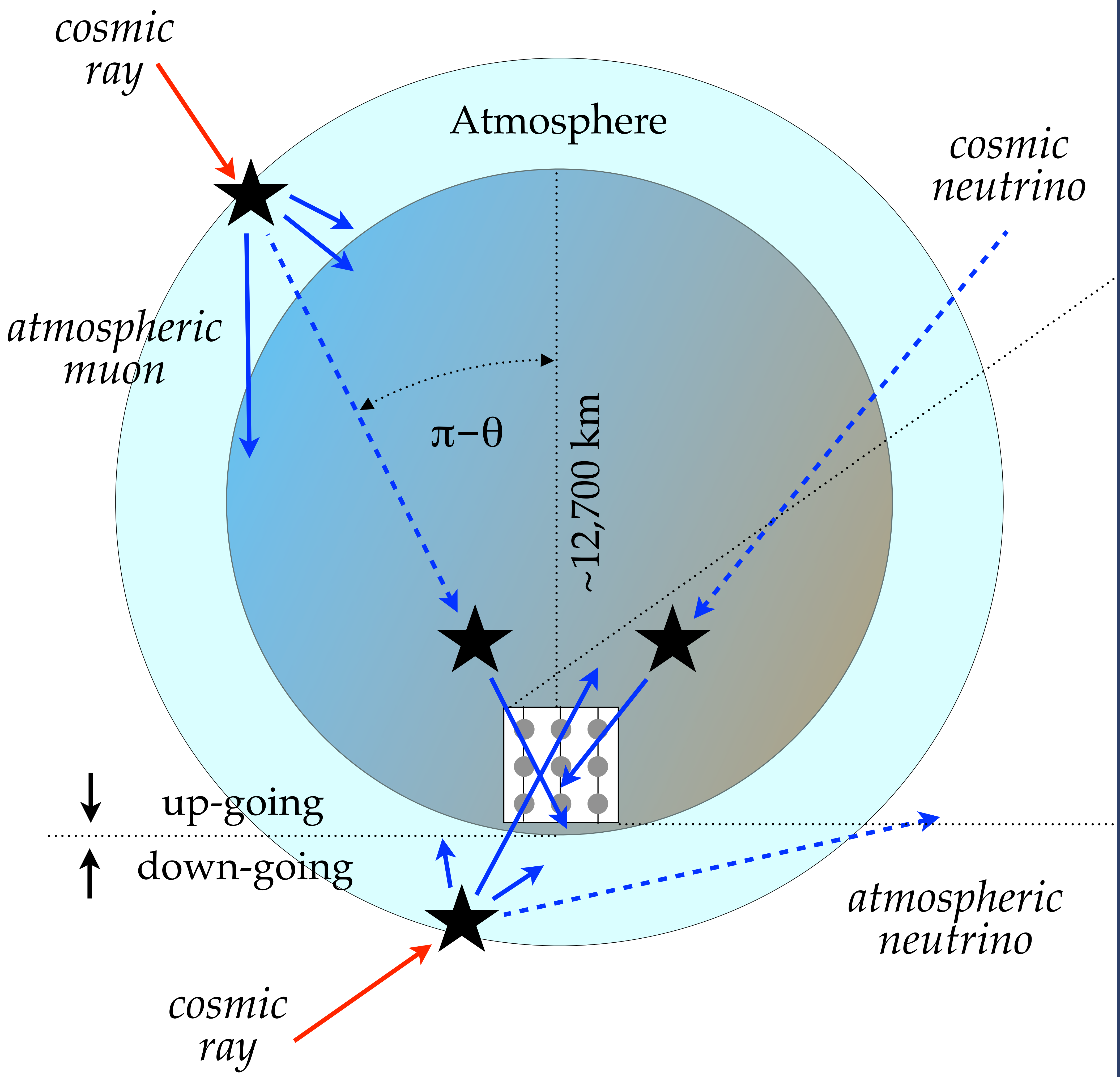
$$\tilde{K}_{\nu_\ell} = \sum_{\ell'=e,\mu} P_{\ell\ell'} K_{\nu_{\ell'}} \qquad \ell = e, \mu, \tau$$

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

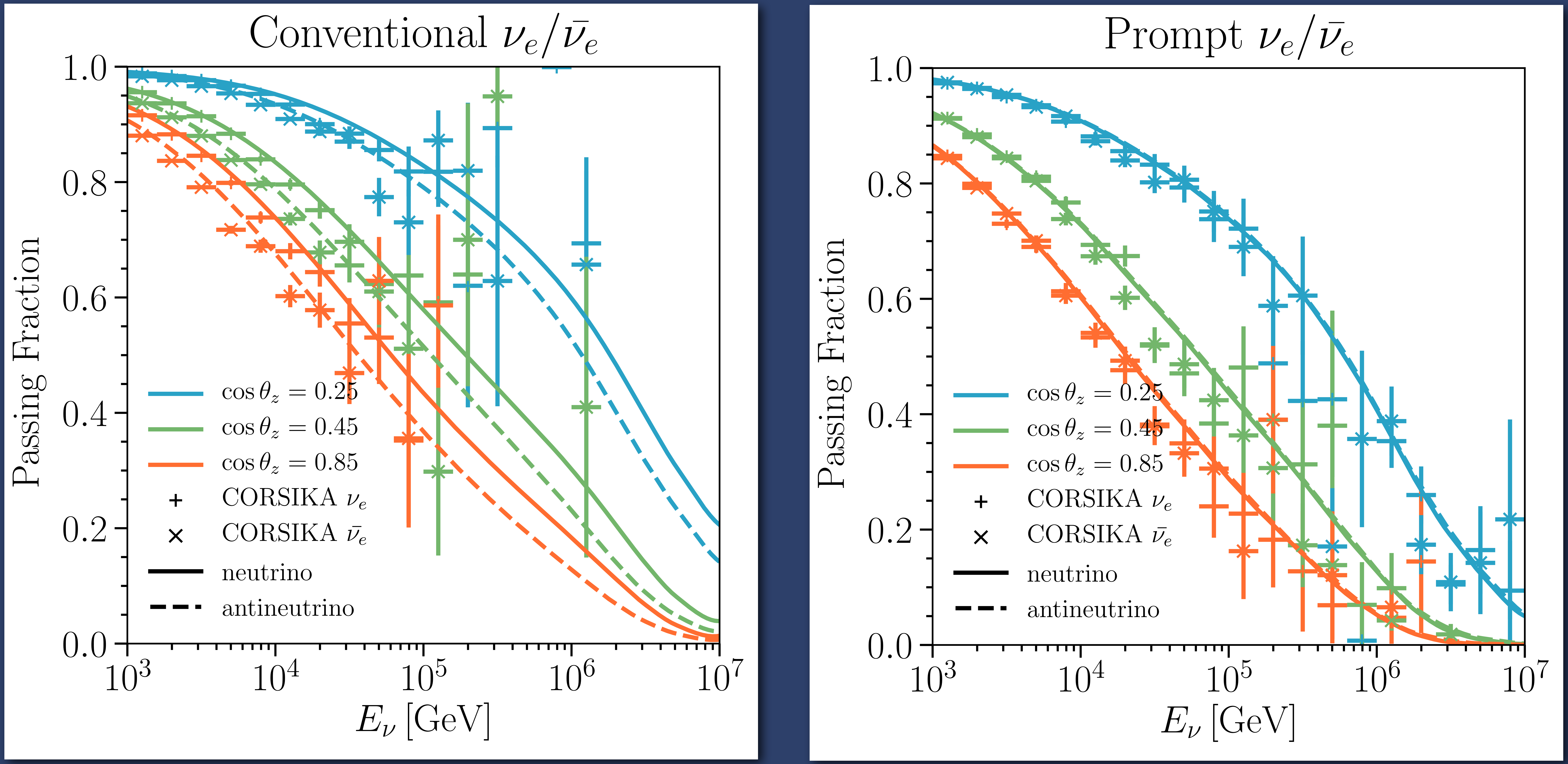
ν	α_π	α_K	β_0	β_1	χ_0	χ_1	χ_2	χ_3	δ_0	δ_1
ν_e	0	0	18.611	−84.173	−0.0070	0.4579	8.6140	−11.426	−5.7189	18.921
$\overline{\nu}_e$	0	0	13.257	−58.739	−0.0048	0.3170	6.3360	−8.3753	−4.1830	13.823
ν_μ	0.4541	0.0347	47.980	−103.75	0.0442	0.4579	12.802	−14.218	−3.4151	23.528
$\overline{\nu}_\mu$	0.3322	0.0241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

BACKUP SLIDES: ICECUBE

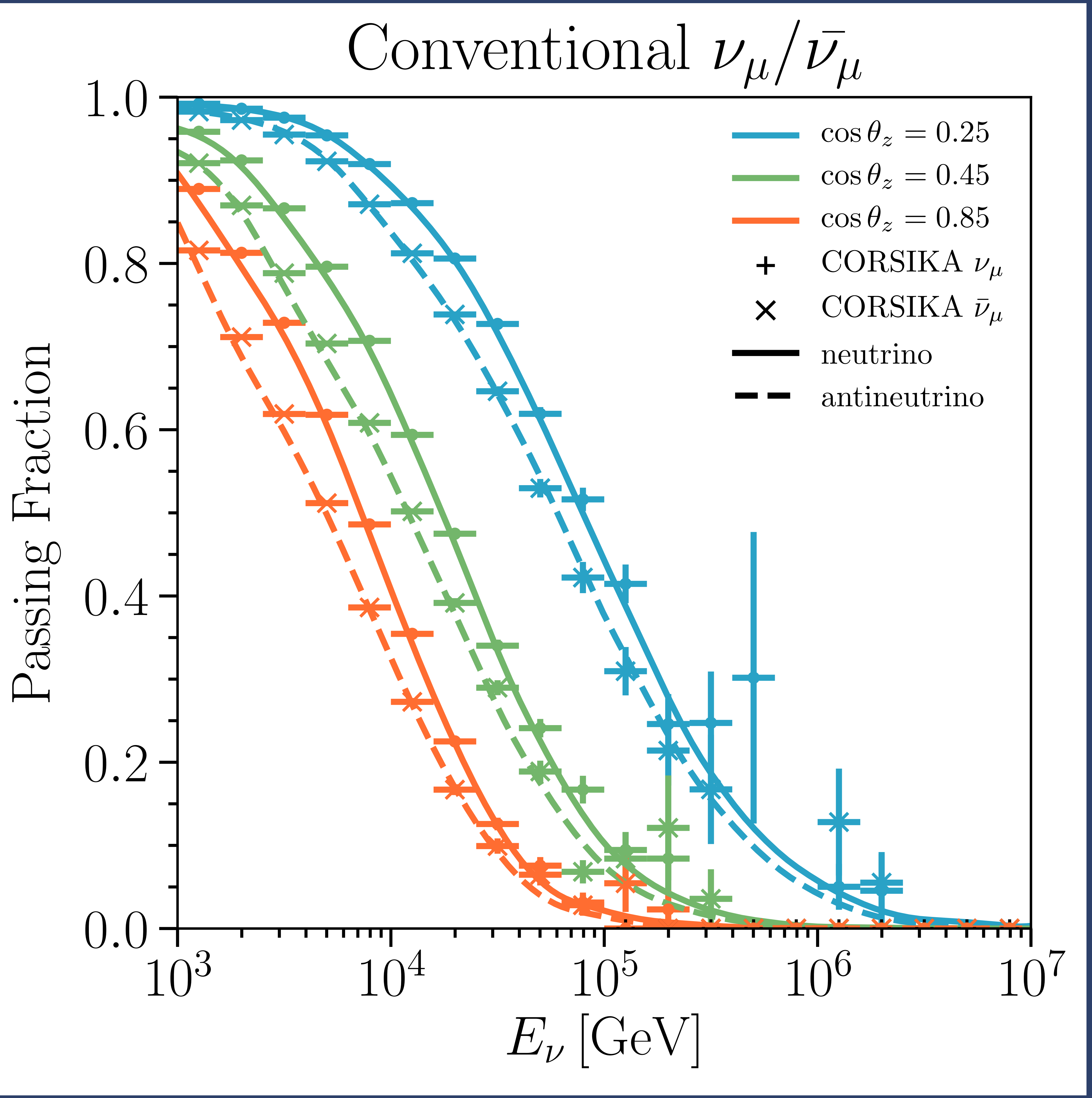


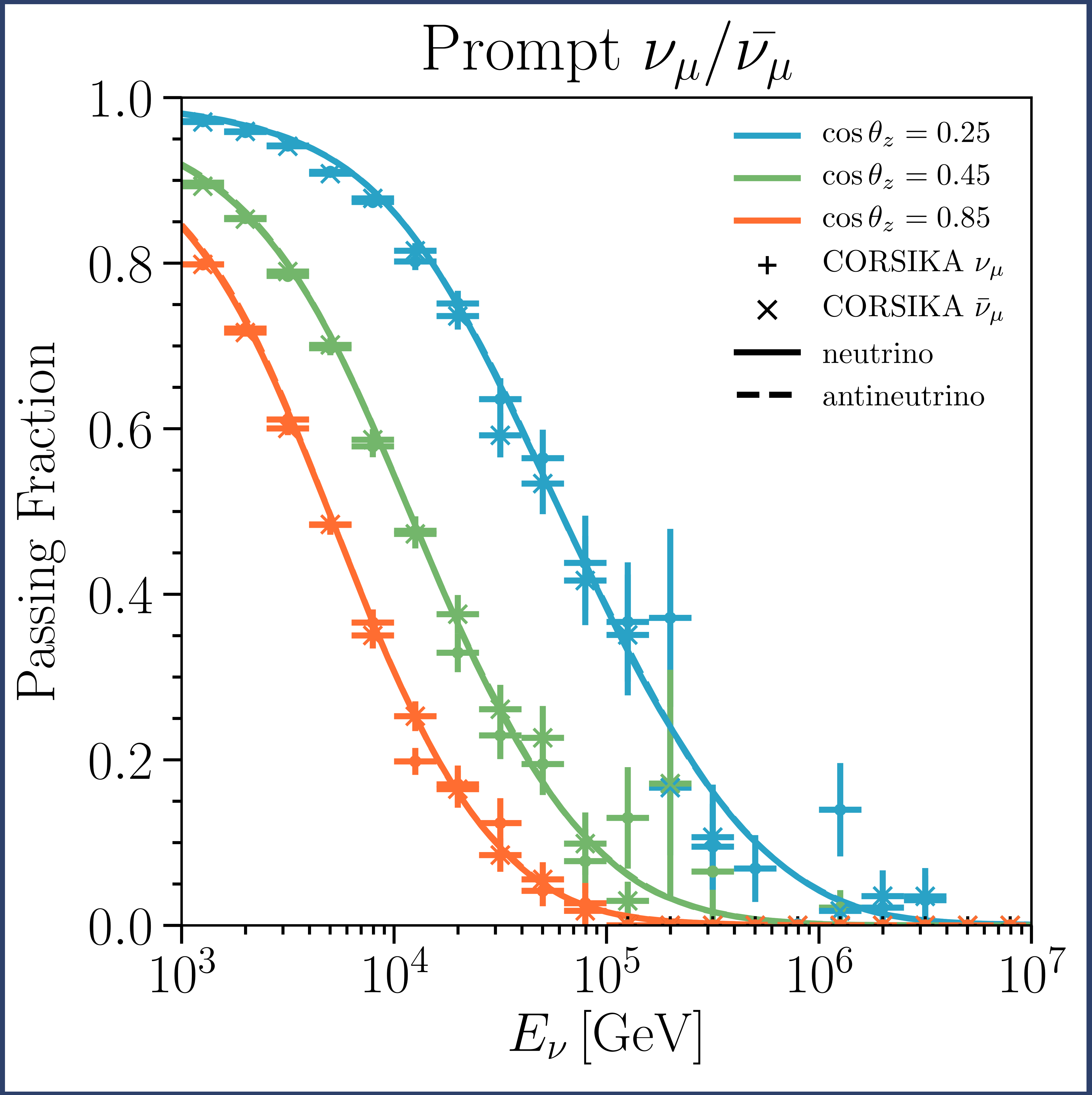


BACKUP SLIDES: ELECTRON NEUTRINO PASSING FRACTIONS (ARGÜELLES+18)

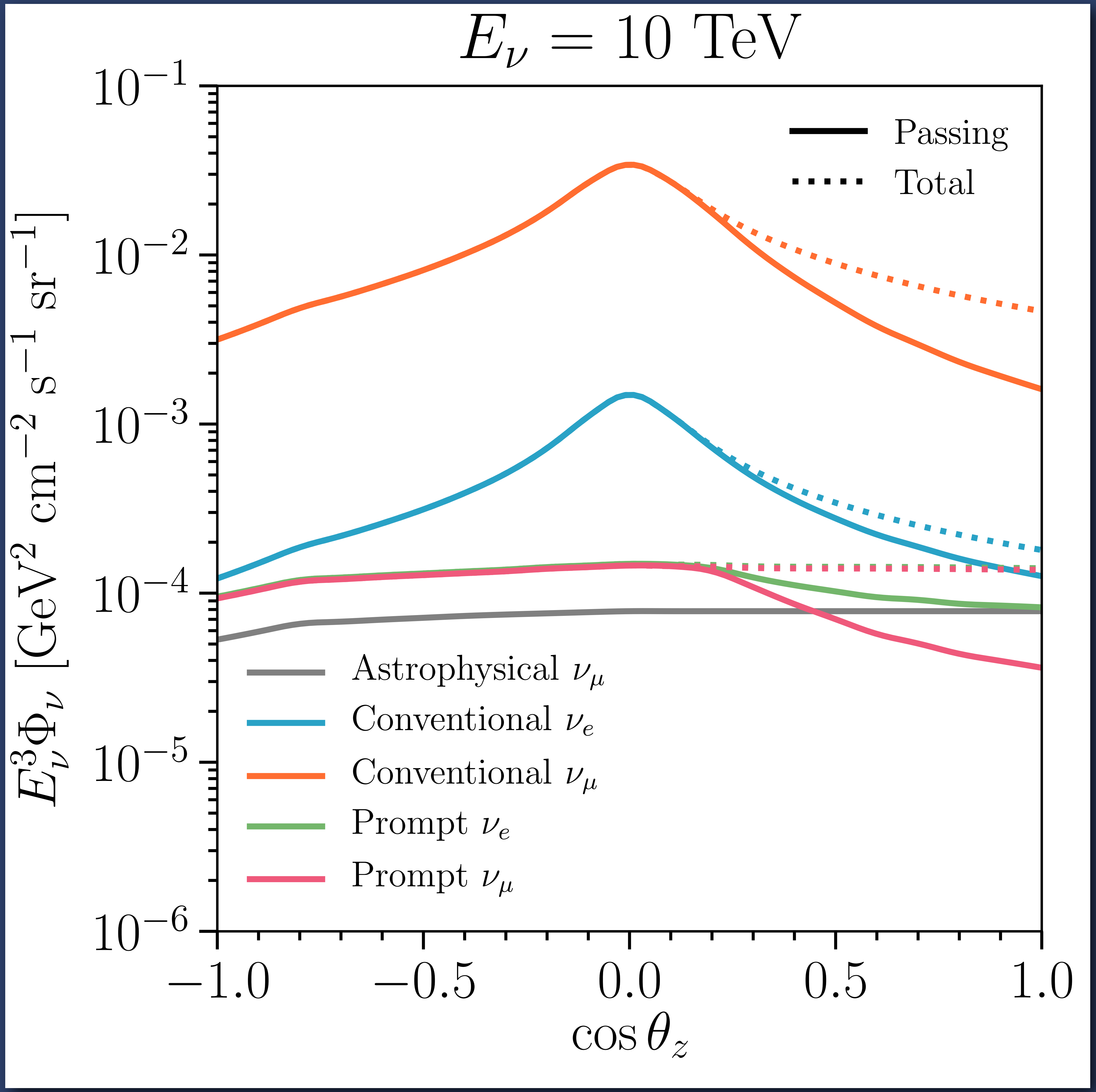


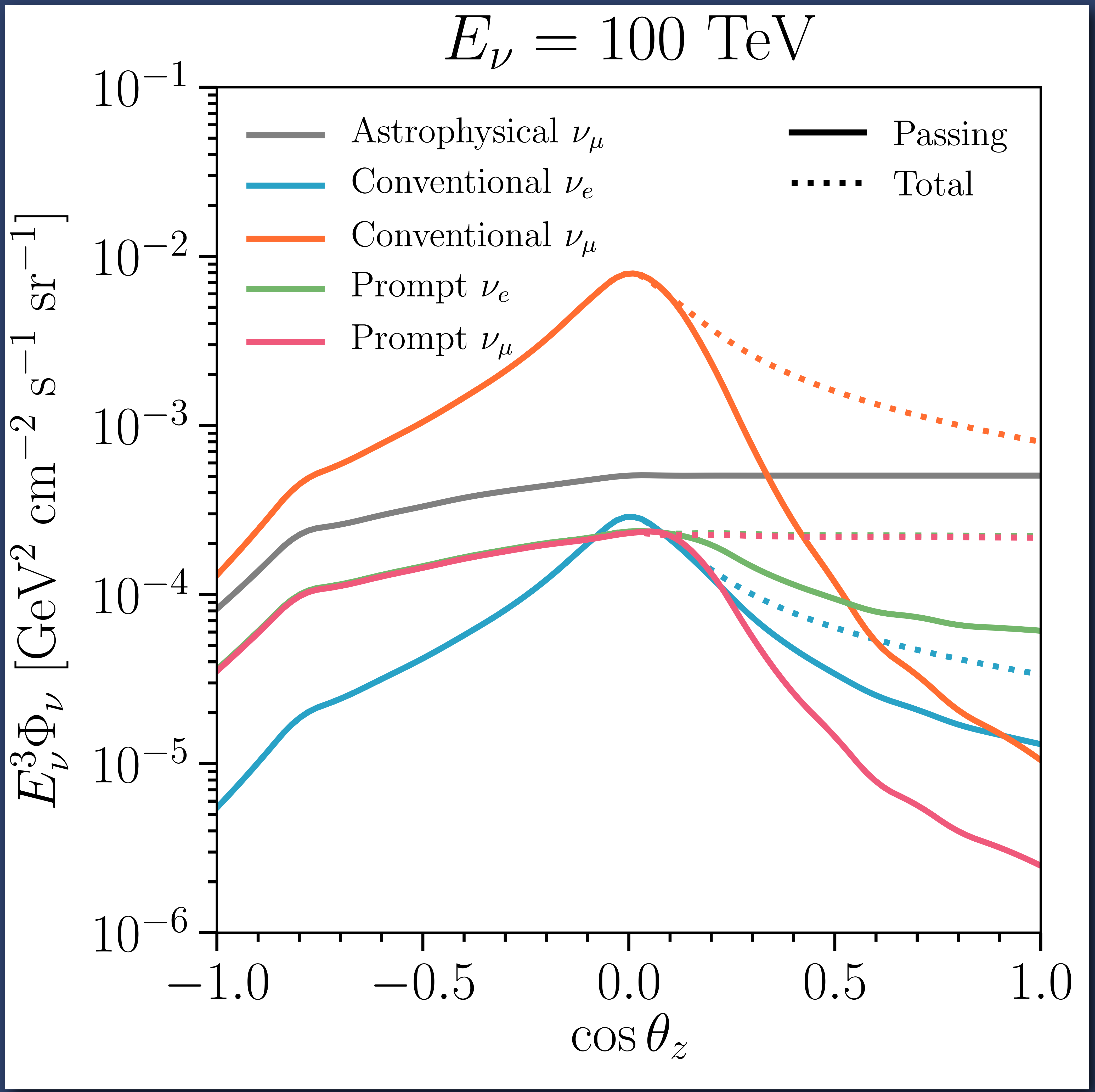
BACKUP SLIDES: MUON NEUTRINO PASSING FRACTIONS (ARGÜELLES+18)





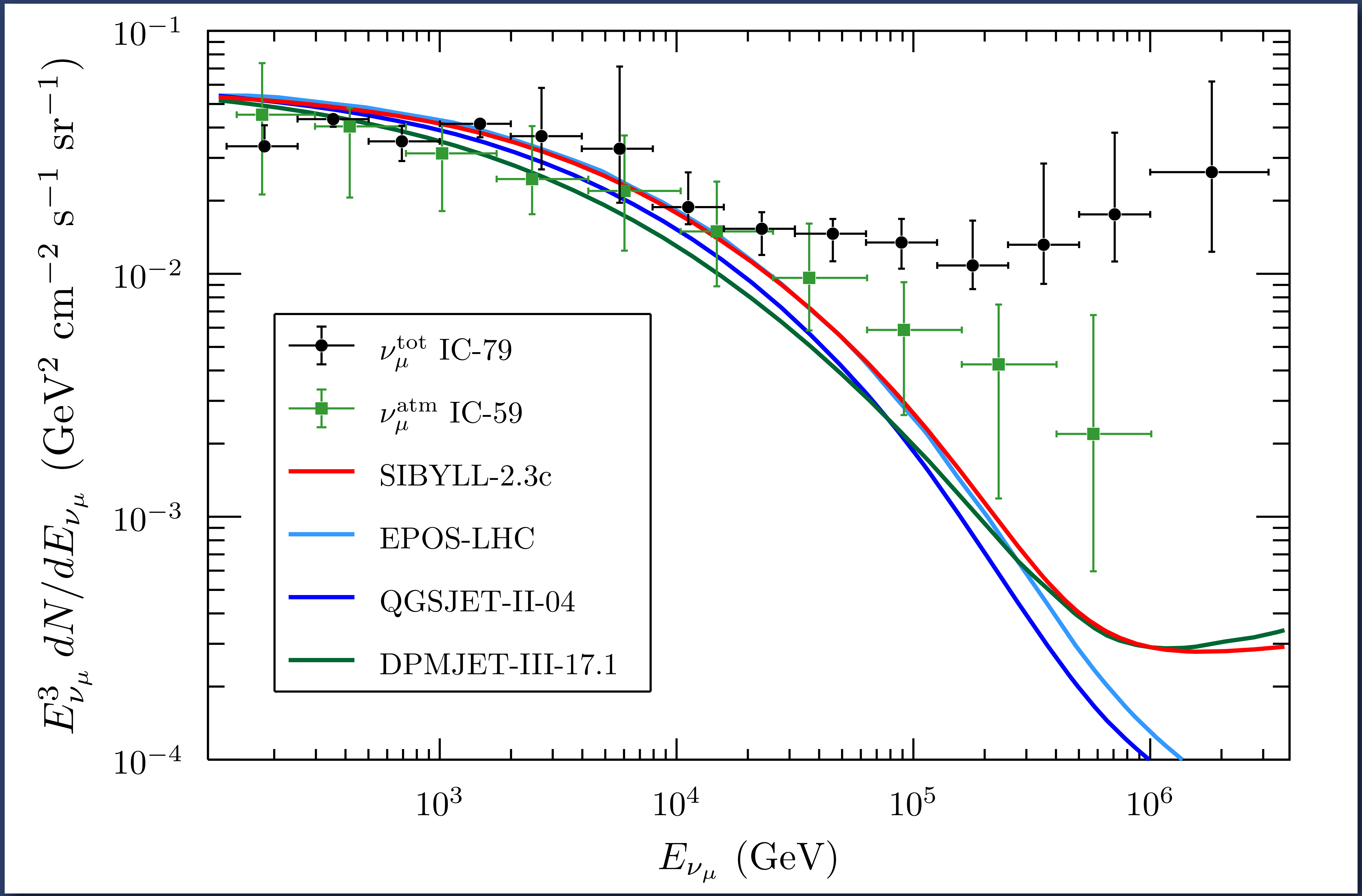
BACKUP SLIDES: ELECTRON NEUTRINO PASSING FLUXES (ARGÜELLES+18)





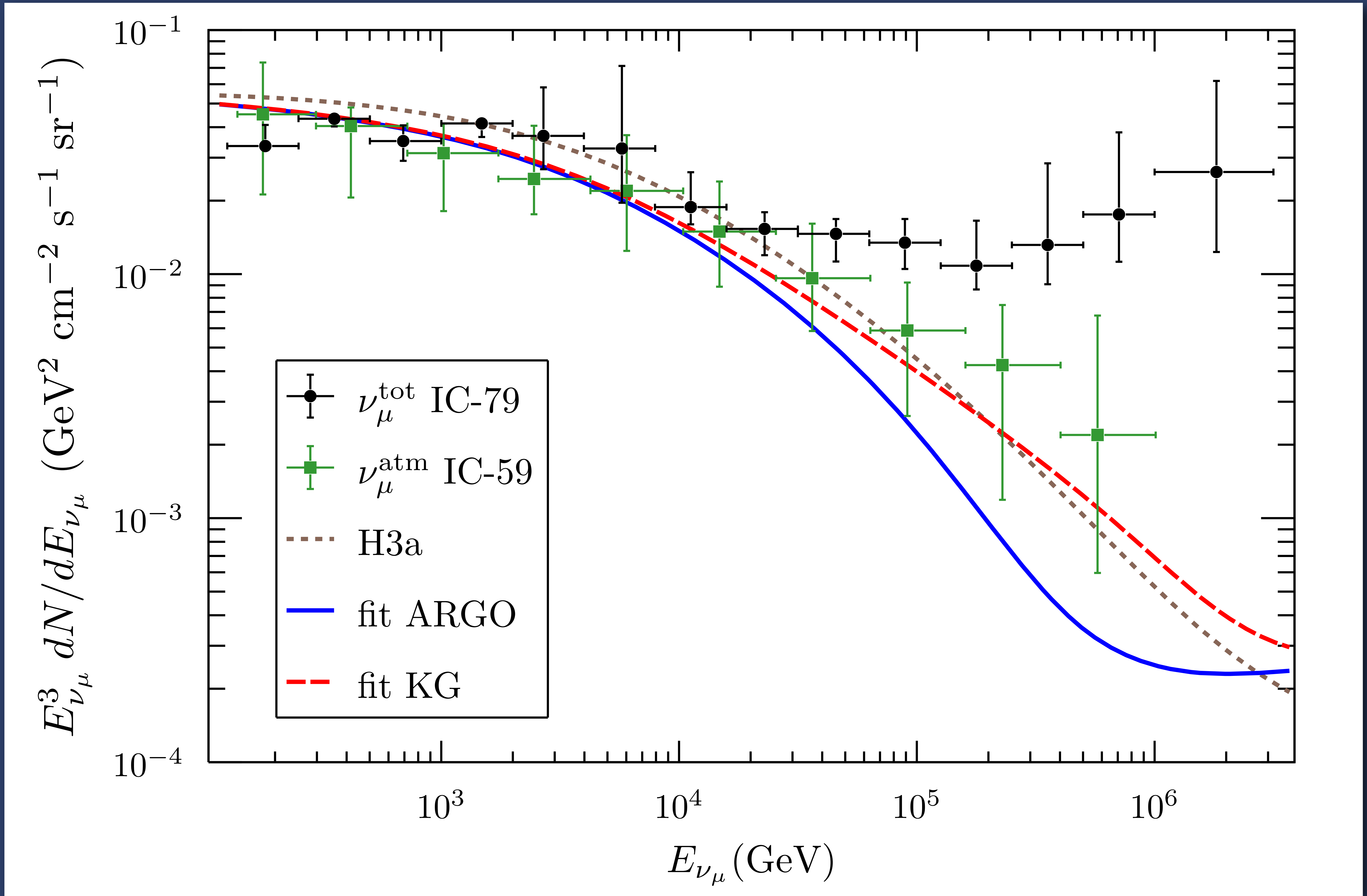
BACKUP SLIDES

Dependence on the hadronic interaction model



BACKUP SLIDES

Dependence on the CR flux model



BACKUP SLIDES

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