# EXPLORING THE ASSUMPTION OF HADRON-HADRON COLLISIONS FOR HIGH-ENERGY NEUTRINO PRODUCTION

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# CONTEXT AND MOTIVATION

1. IceCube has provided unique and most important results;

2. conventional neutrinos have been measured, 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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They are produced in the showering following nucleus-nucleus collisions in the atmosphere: light mesons > conventional neutrinos, heavy > prompt.

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

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

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- Most abundant elements
- $E_\nu$ ~ 1/20A of the 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

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IceCube, through-going muons analysis (2016), supports $E^{-2}$ hypothesis:

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

$$\frac{d\Phi_{\mathrm{LW}}}{dE} = 2 \times 10^{\pm0.5} \times 10^{-18} \left(\frac{E}{100\ \mathrm{TeV}}\right)^{-2.15\pm0.10}$$

# COSMIC NEUTRINOS

We combined the two fluxes to have a phenomenologically precise cosmic muon neutrino spectrum:

$$\frac{d\Phi_{\mathrm{MV},\nu_\mu}}{dE} = 0.90^{+0.30}_{-0.27} \times 10^{-18} \left(\frac{E}{100\ \mathrm{TeV}}\right)^{-2.14\pm0.08}$$

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Hadronic mechanism > power-law flux of gamma rays and neutrinos are linearly related at the source [F. Vissani, F. L. Villante, PRD 78 10 (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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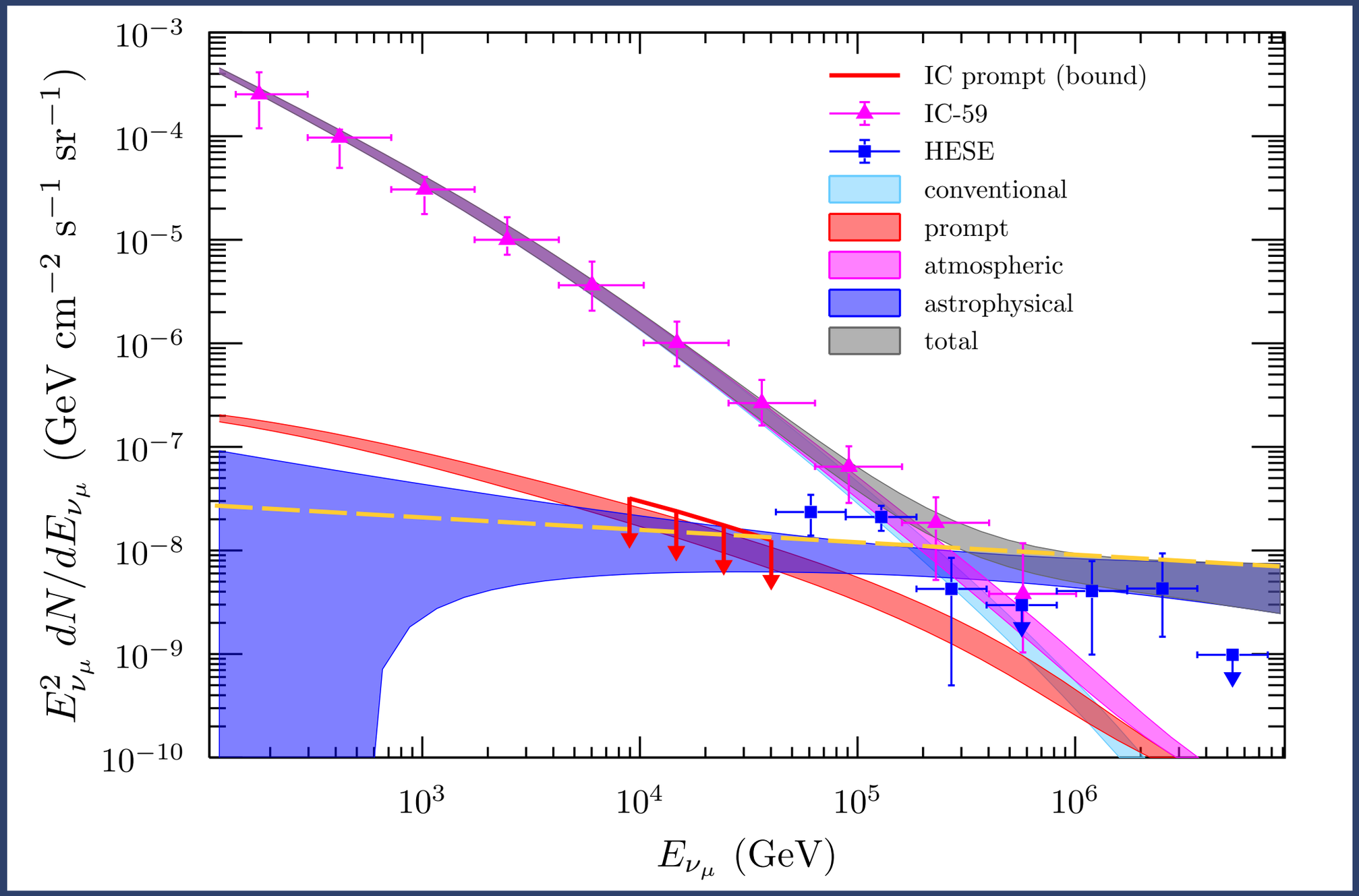
The cosmic neutrino spectra are proportional to each other via $R_{\ell\ell'}$:

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

# THE COMPONENTS OF THE MUON NEUTRINO SPECTRUM



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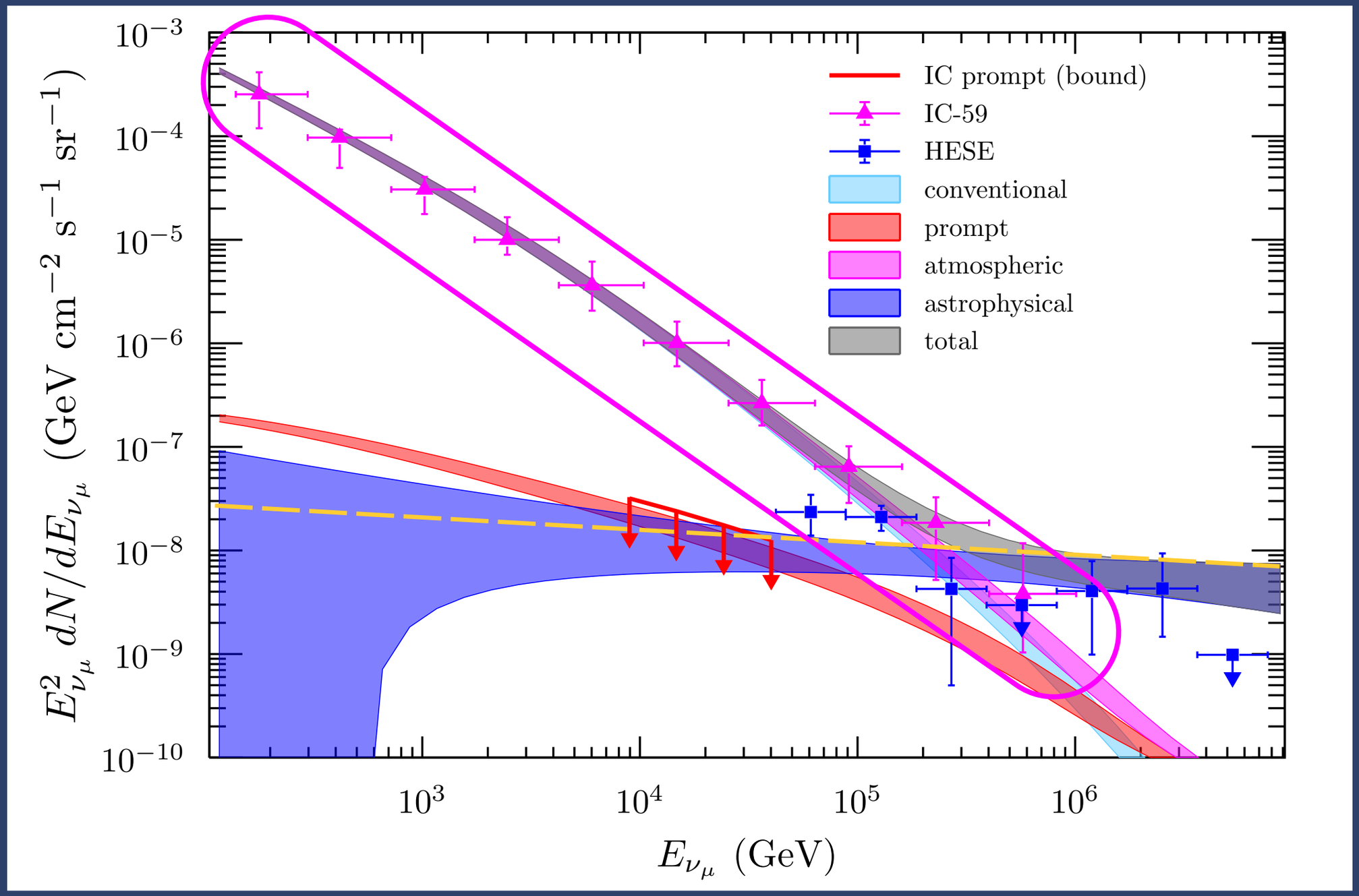


Good agreement between expectations and data for atmospheric neutrinos

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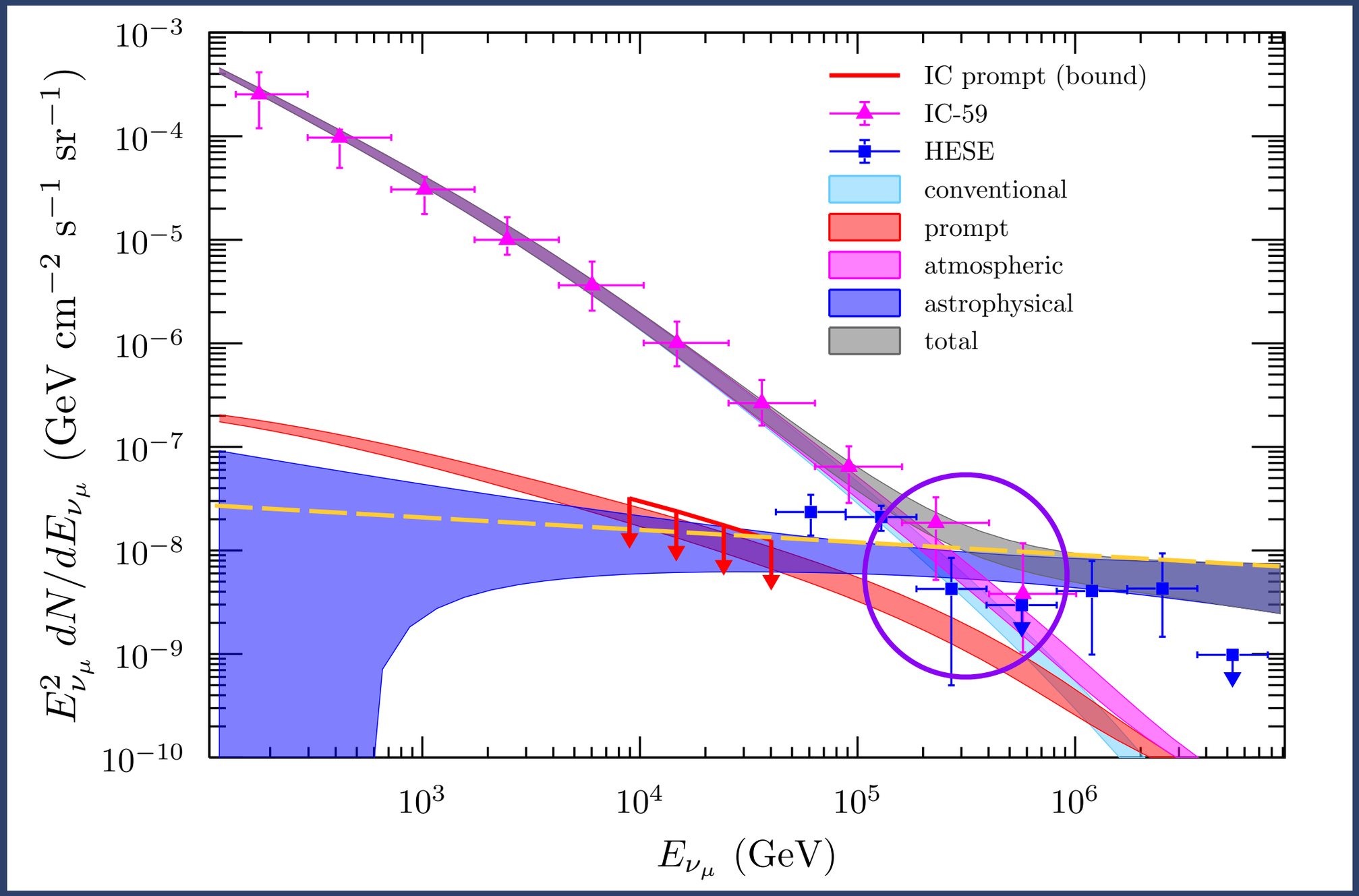


Atmospheric and cosmic neutrinos cross at about 250 TeV ~ $E_{knee}/20$

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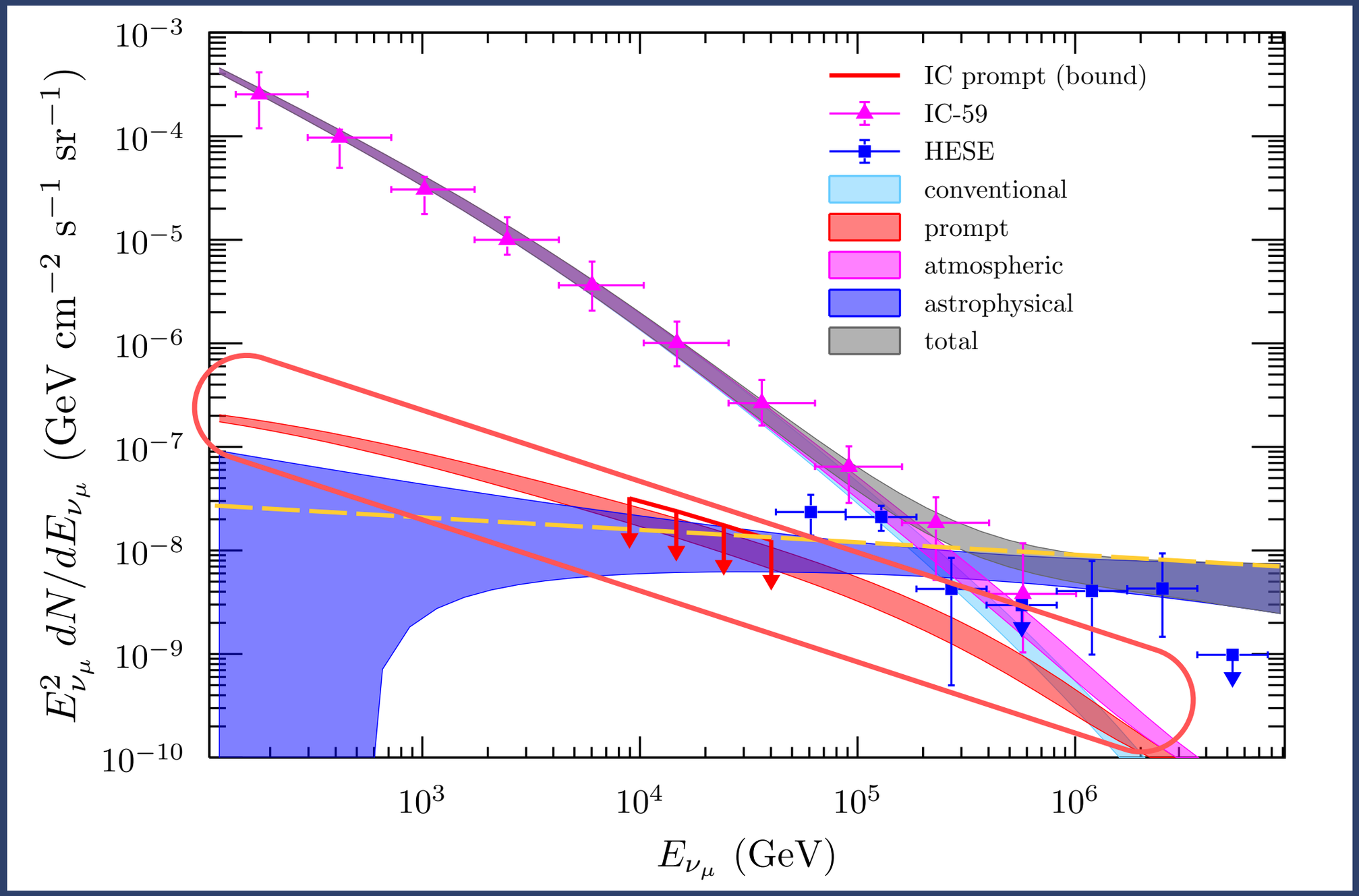
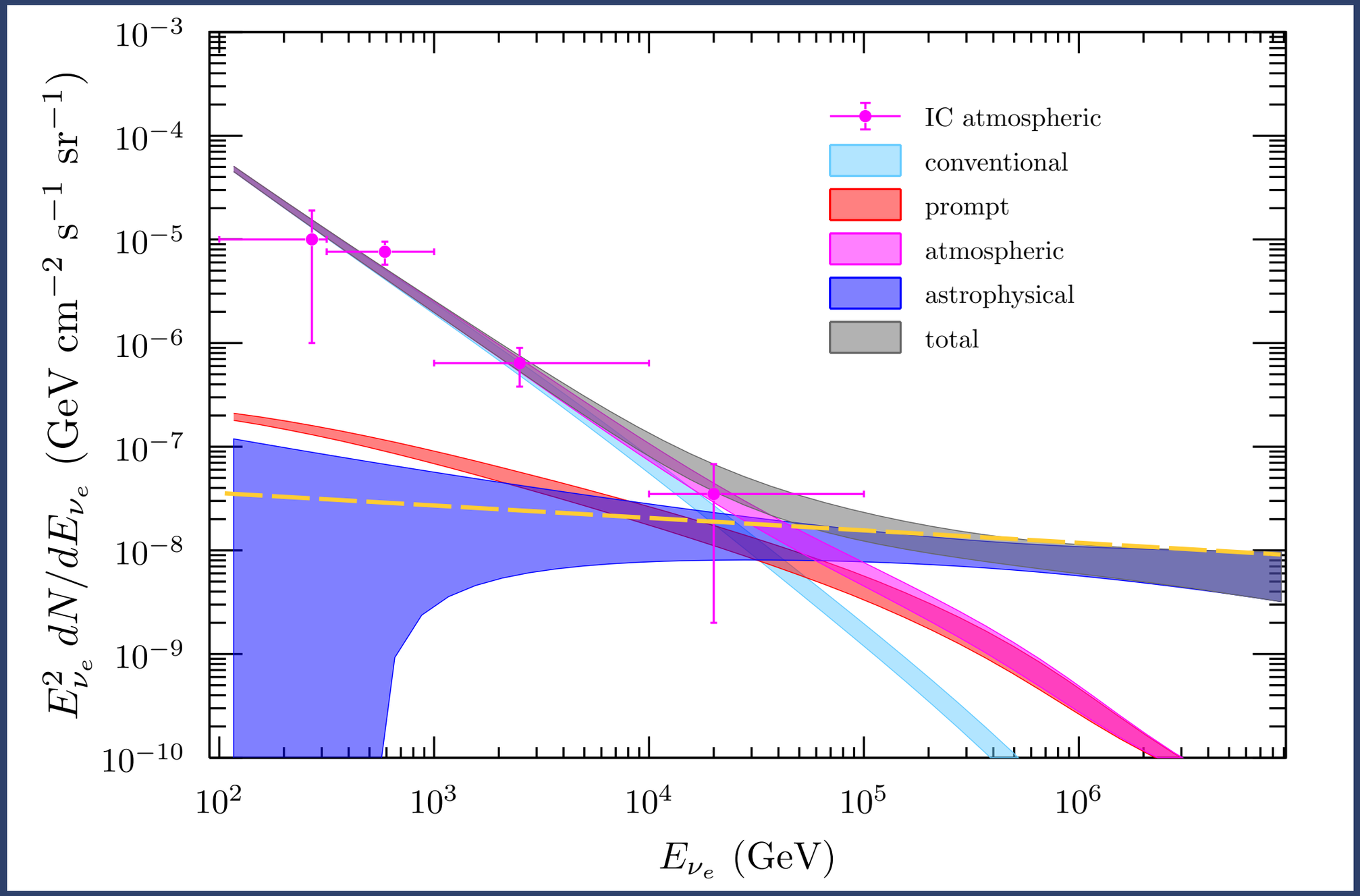



Prompt component always subdominant: impossible to see prompts in $\nu_\mu$

# THE COMPONENTS OF THE ELECTRON NEUTRINO SPECTRUM




$$R_{e\mu} = 1.30 \pm 0.05$$

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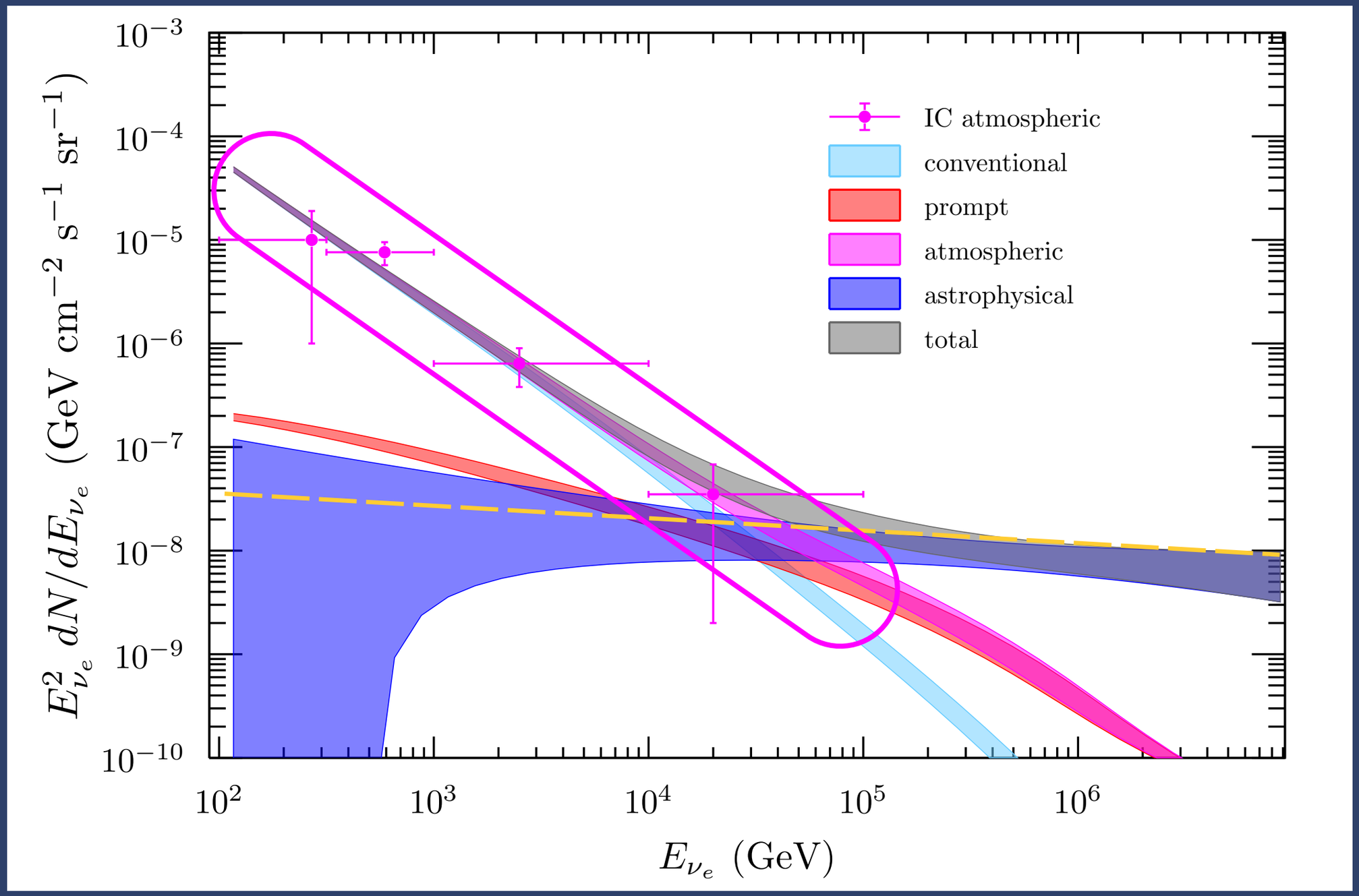


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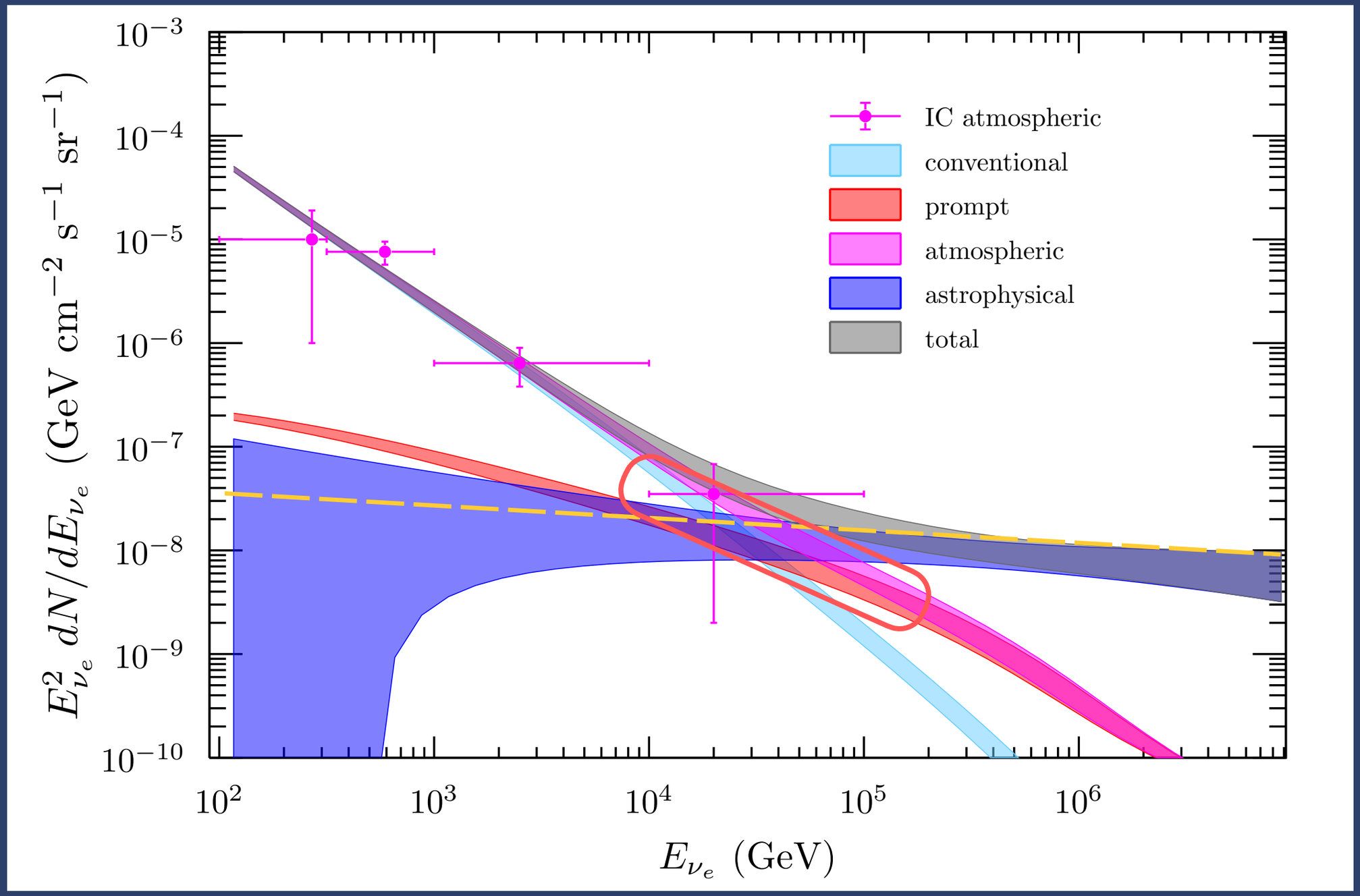
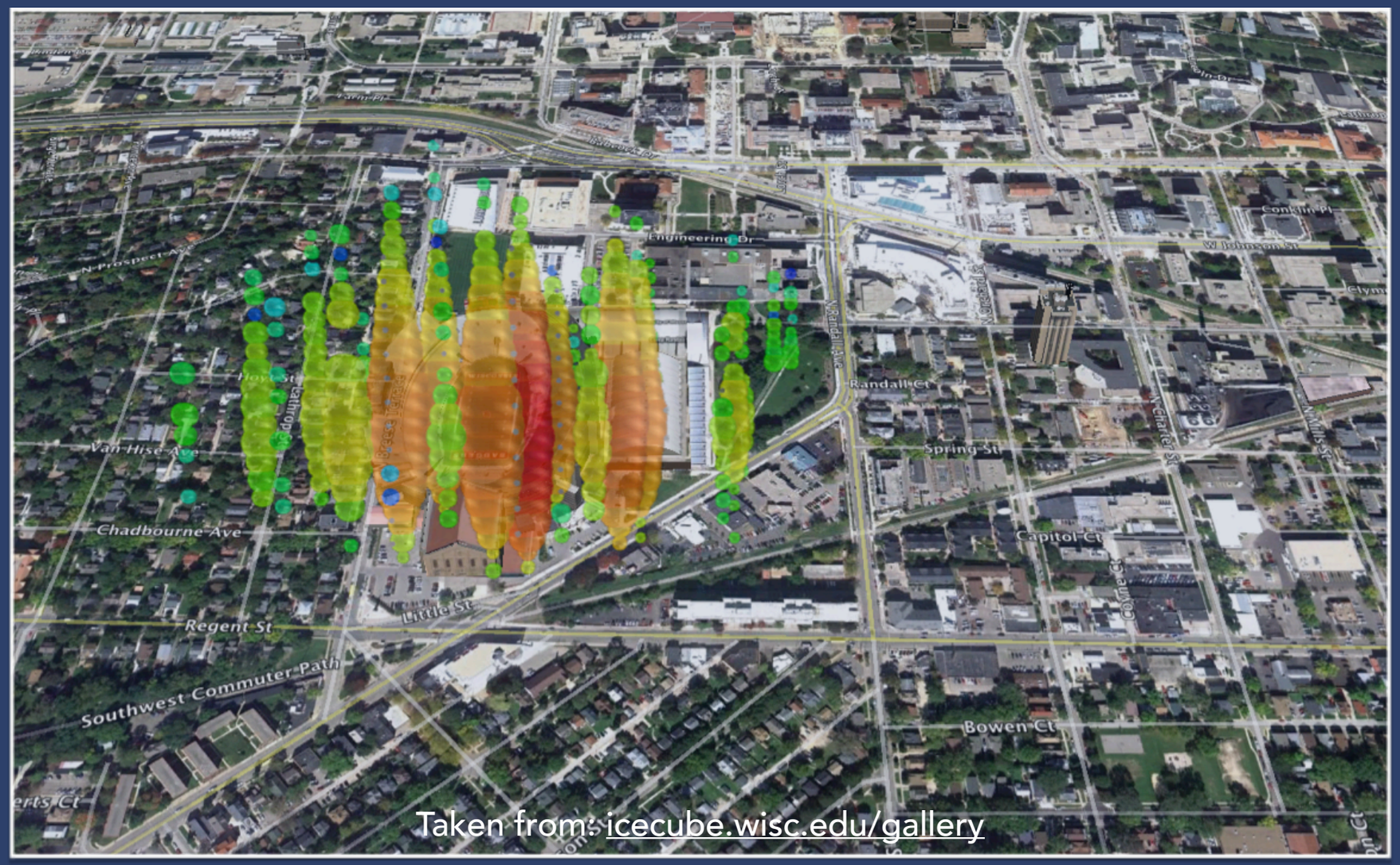



Prompt component relevant for 10 TeV ≤ $E$ ≤ 100 TeV

# IS IT POSSIBLE TO EXTRACT THE PROMPT SIGNAL?

Ideal search: $\nu_e$ events. Best dataset: cascades, smallest contribution of $\nu_\mu$.




Taken from: icecube.wisc.edu/gallery

# HOW MANY EVENTS DUE TO PROMPTS?

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

| Component | $N_{\nu_e}$ | $N_{\nu_\mu}$ | $N_{\nu_\tau}$ | $N_{\text{tot}}$ |
|---|---|---|---|---|
| Conventional | 160 – 210 | 420 – 570 | 0 | 580 – 780 |
| Prompt | 20 – 30 | 3 – 5 | 2 – 3 | 25 – 40 |
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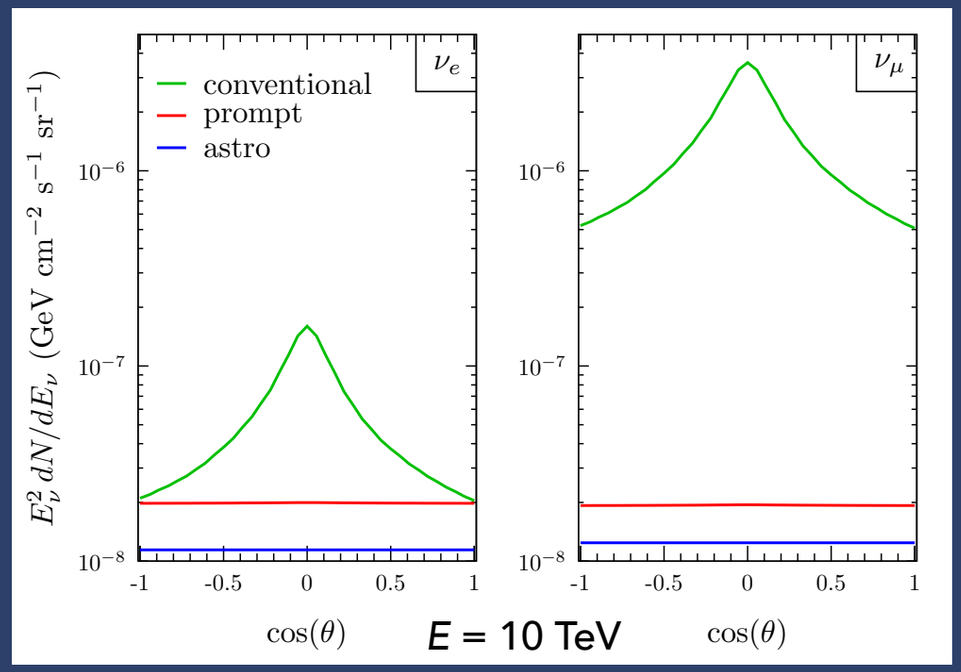
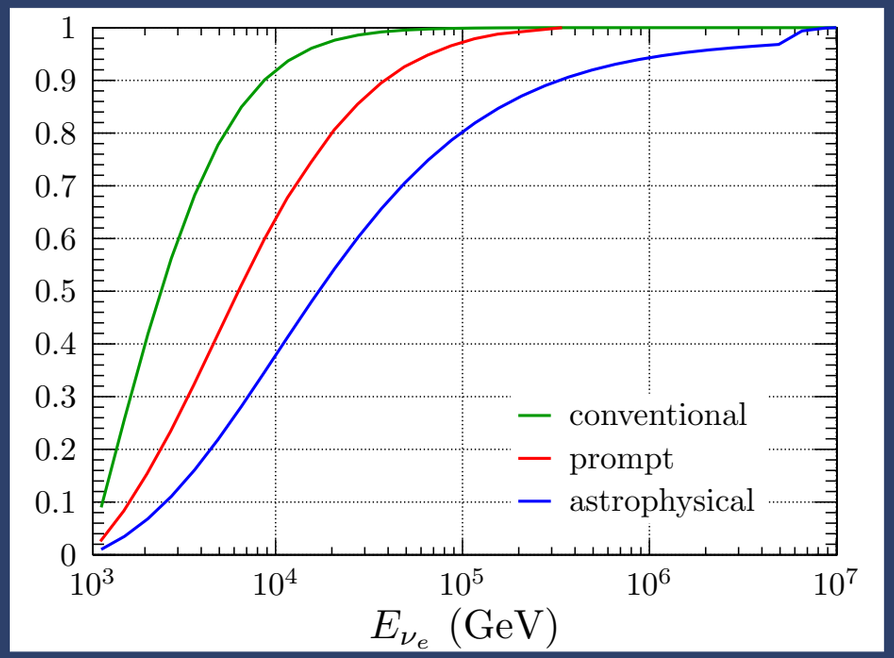
Not easy, but: angular selection, higher energy threshold could help!

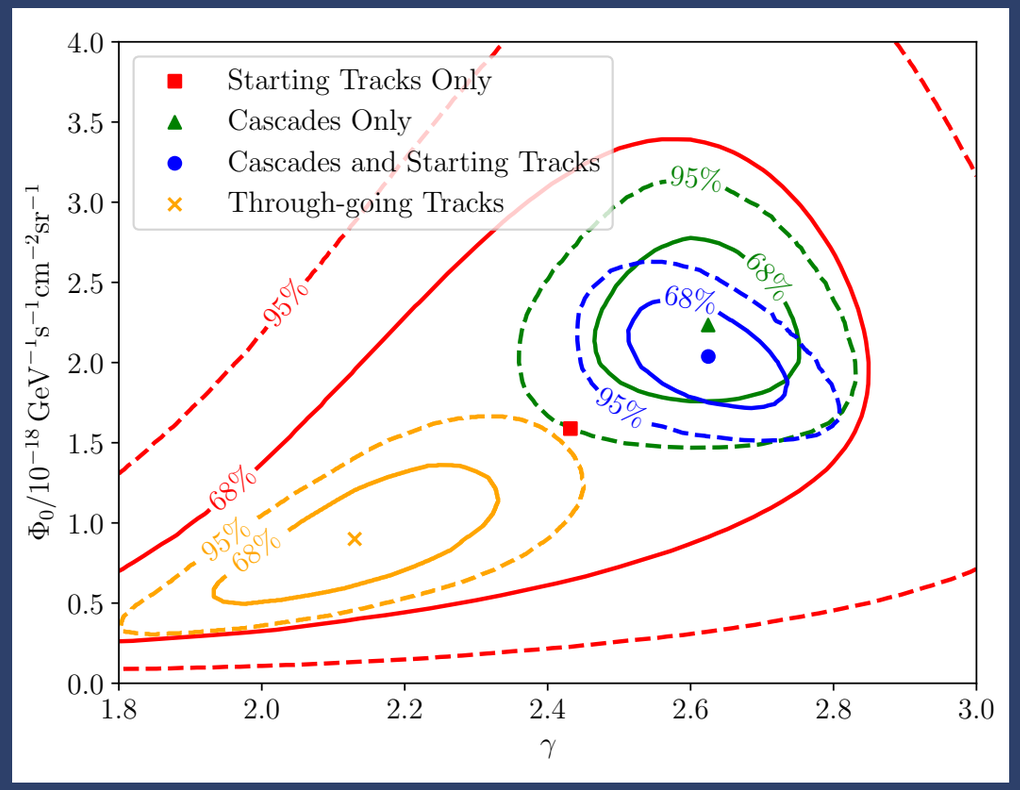


# IS THERE A SPECTRAL ANOMALY?

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

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



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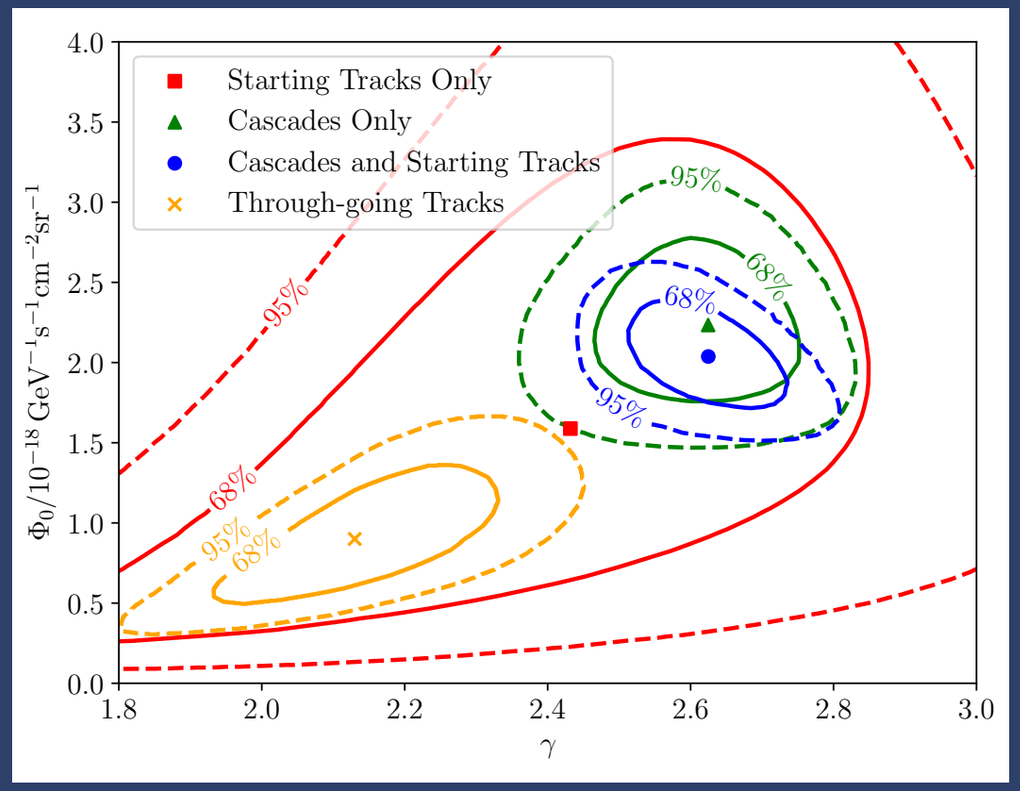


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Similar number of events + same isotropic distribution = difficult to distinguish…can prompts play a role in cosmic neutrino analyses?

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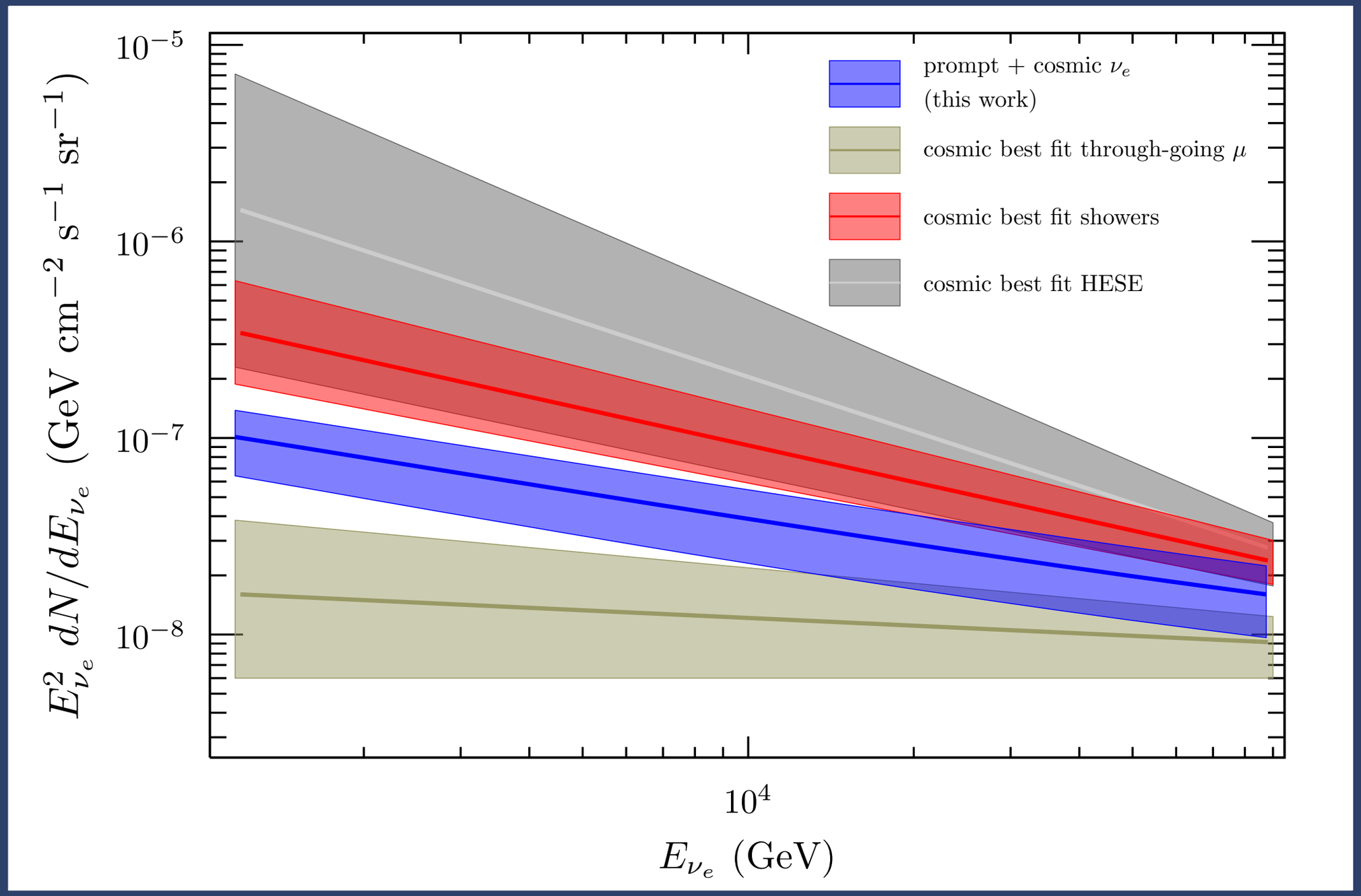

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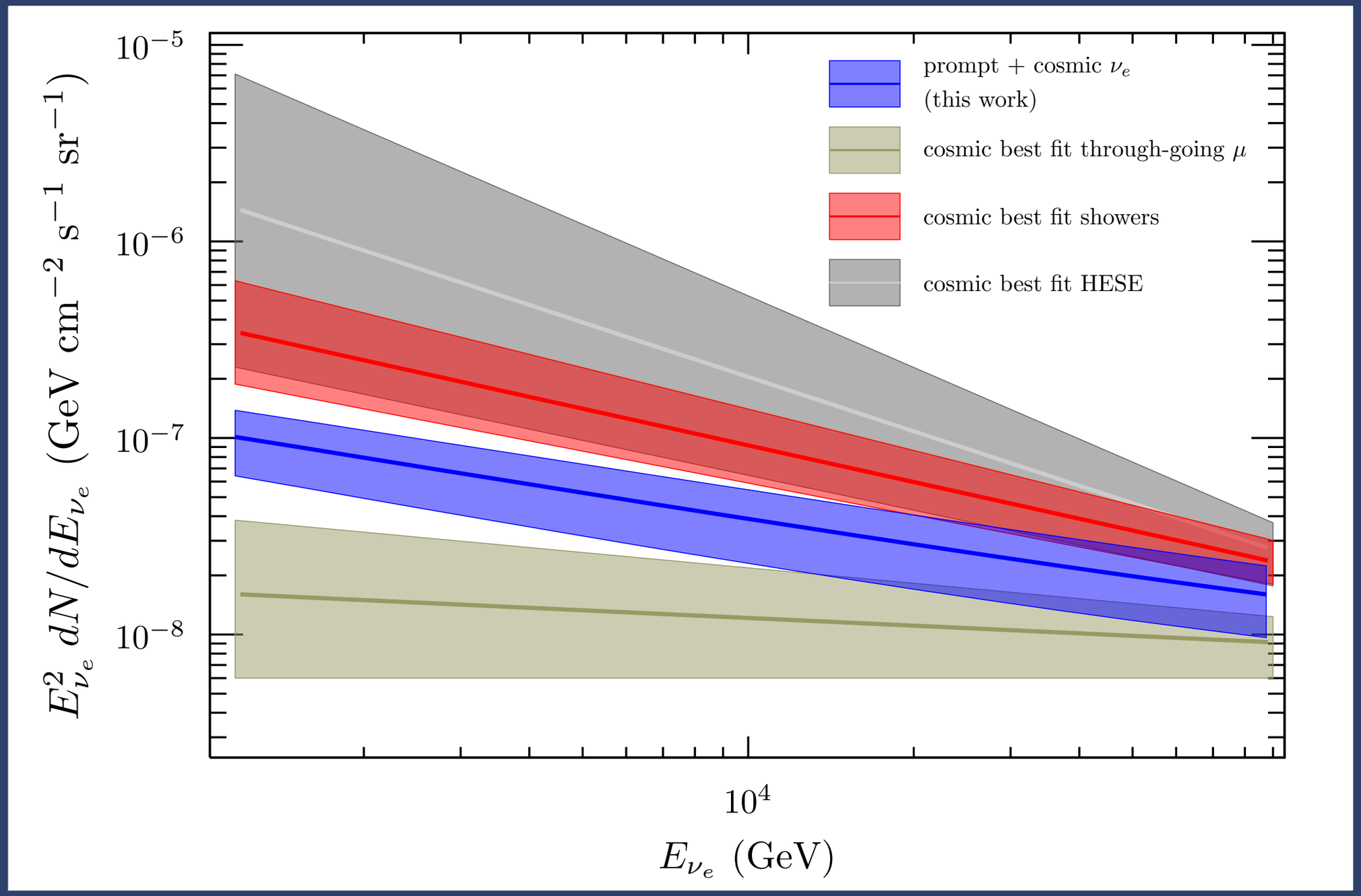


Prompt + cosmic spectrum closer to HESE/showers spectrum

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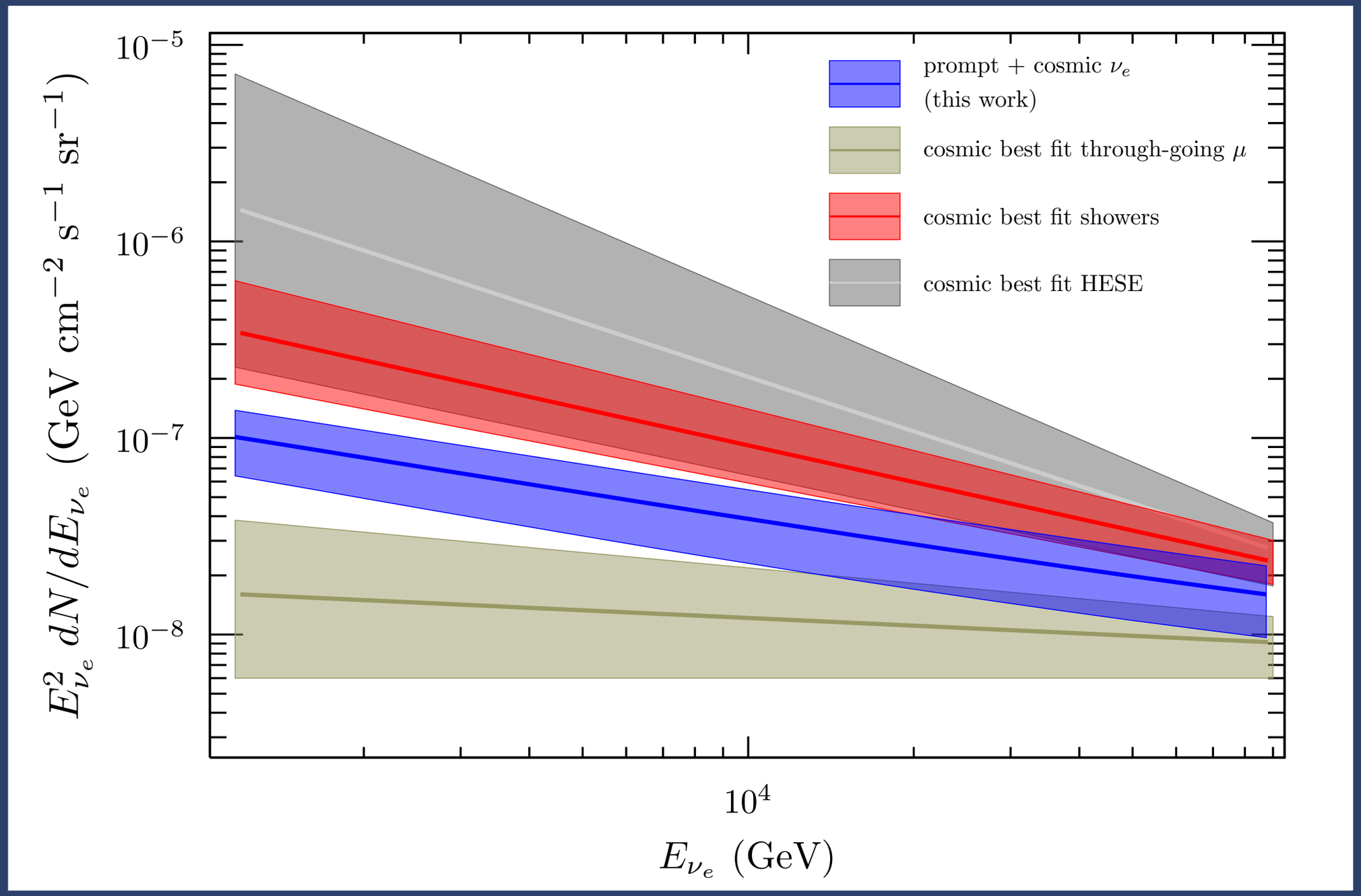


Anomaly attributable to: prompts in cascades, background tracks in HESE.
This in the "minimal" proposal = no other hypothetical physical ingredients

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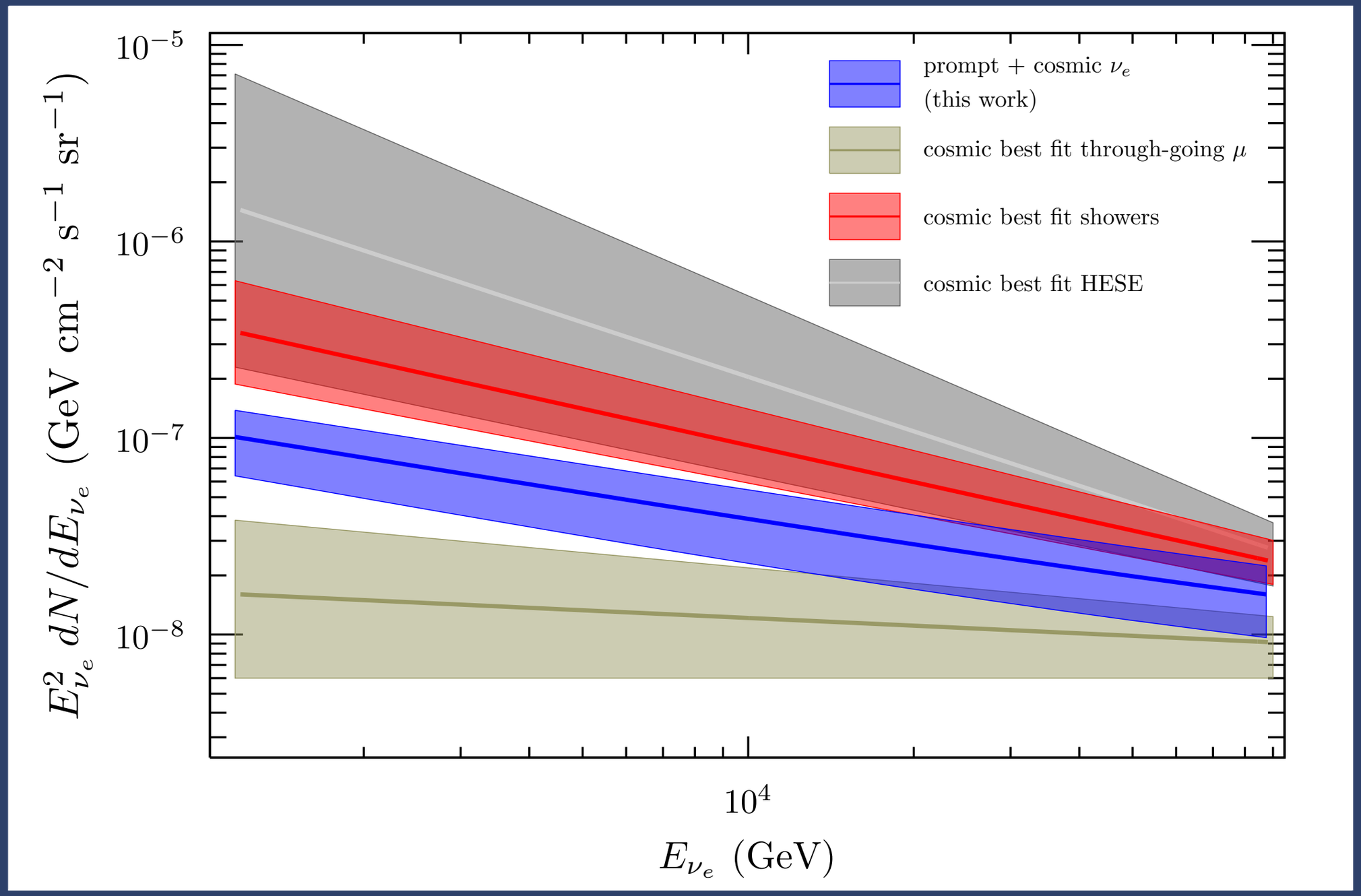


Other scenarios: Galactic (or other) origin of the low-energy HESE spectrum

# 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 <u>all datasets</u> is the optimal procedure to obtain information about the whole neutrino spectrum.

# THANKS FOR YOUR ATTENTION!




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# 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

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$\propto E^{-2.7}$

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

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

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

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):

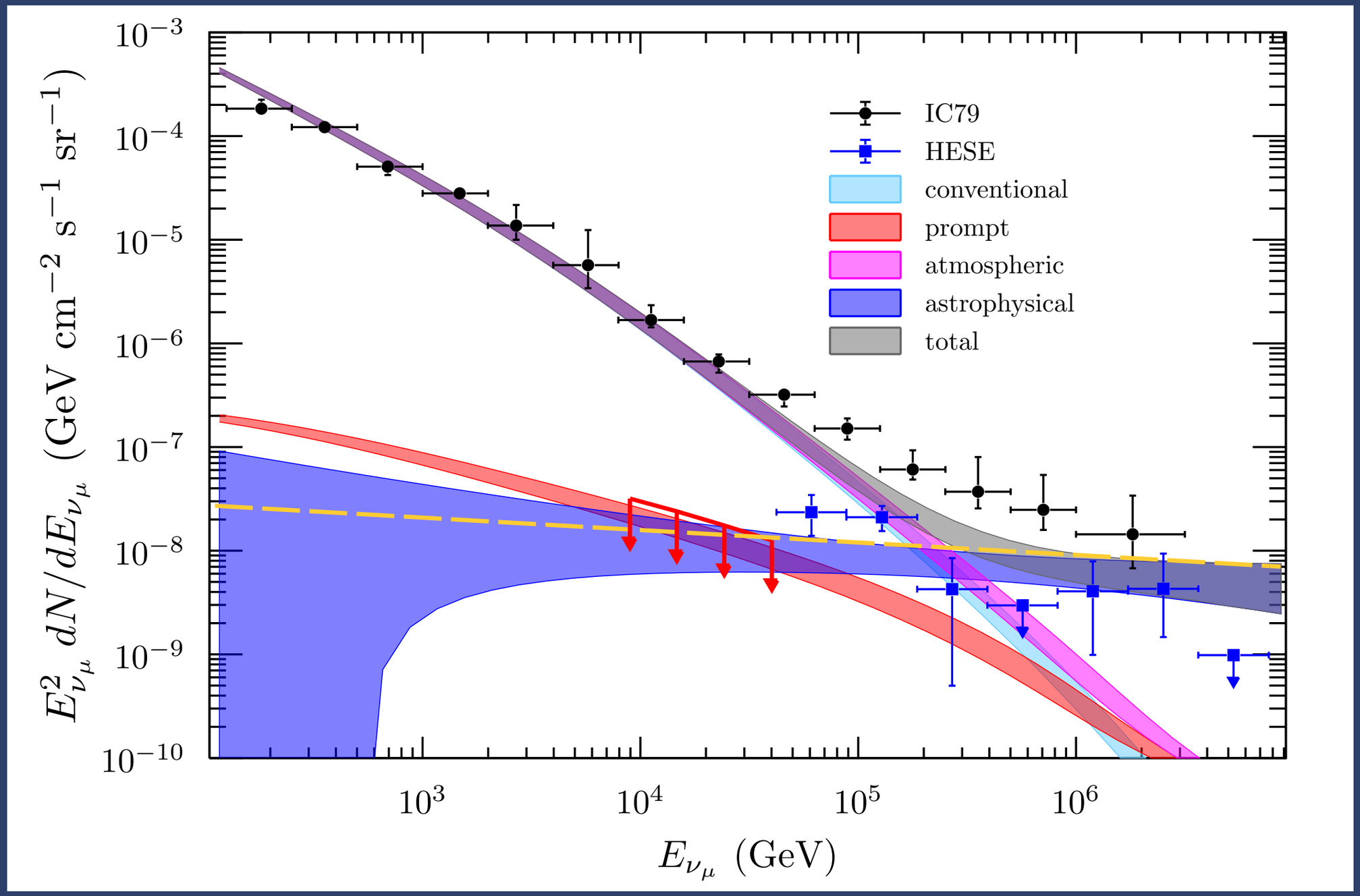
$$\tilde{K}_{\nu_\ell} = \sum_{\ell'=e,\mu} P_{\ell\ell'} K_{\nu_{\ell'}} \qquad \ell = e, \mu, \tau$$

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

| $\nu$ | $\alpha_\pi$ | $\alpha_K$ | $\beta_0$ | $\beta_1$ | $\chi_0$ | $\chi_1$ | $\chi_2$ | $\chi_3$ | $\delta_0$ | $\delta_1$ |
|---|---|---|---|---|---|---|---|---|---|---|
| $\nu_e$ | 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 |
| $\nu_\mu$ | 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

The muon neutrino spectrum with the IC-79 data:



# BACKUP SLIDES

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