Frontiers in Particle Physics 2024

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Probing the cosmic sterile-neutrino background with IceCube

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BITS Pilani

based on an upcoming manuscript with Priyank Parashari (IISc)

Introduction

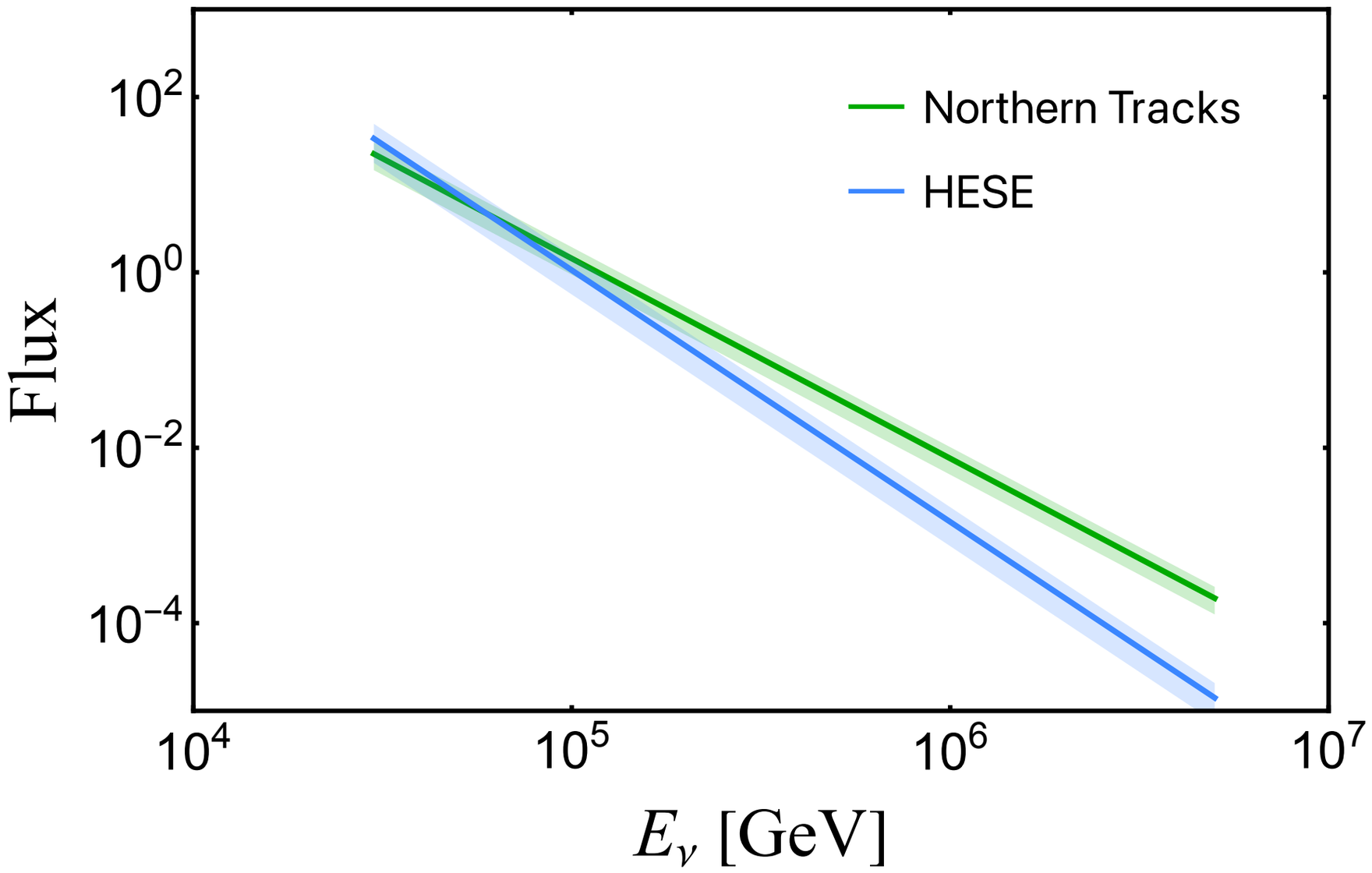
- In the last decade, the IceCube neutrino observatory has detected neutrinos of astrophysical origin in the TeV - PeV range
- Some, but not all, sources have been identified
- The diffuse flux is *mostly* consistent with a single power-law (SPL):

$$\frac{d\Phi_{6\nu}}{dE_\nu} = \Phi_{\text{astro}} \left(\frac{E_\nu}{E_0}\right)^{-\gamma_{\text{astro}}} \cdot 10^{-18}\,\text{GeV}^{-1}\,\text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}$$

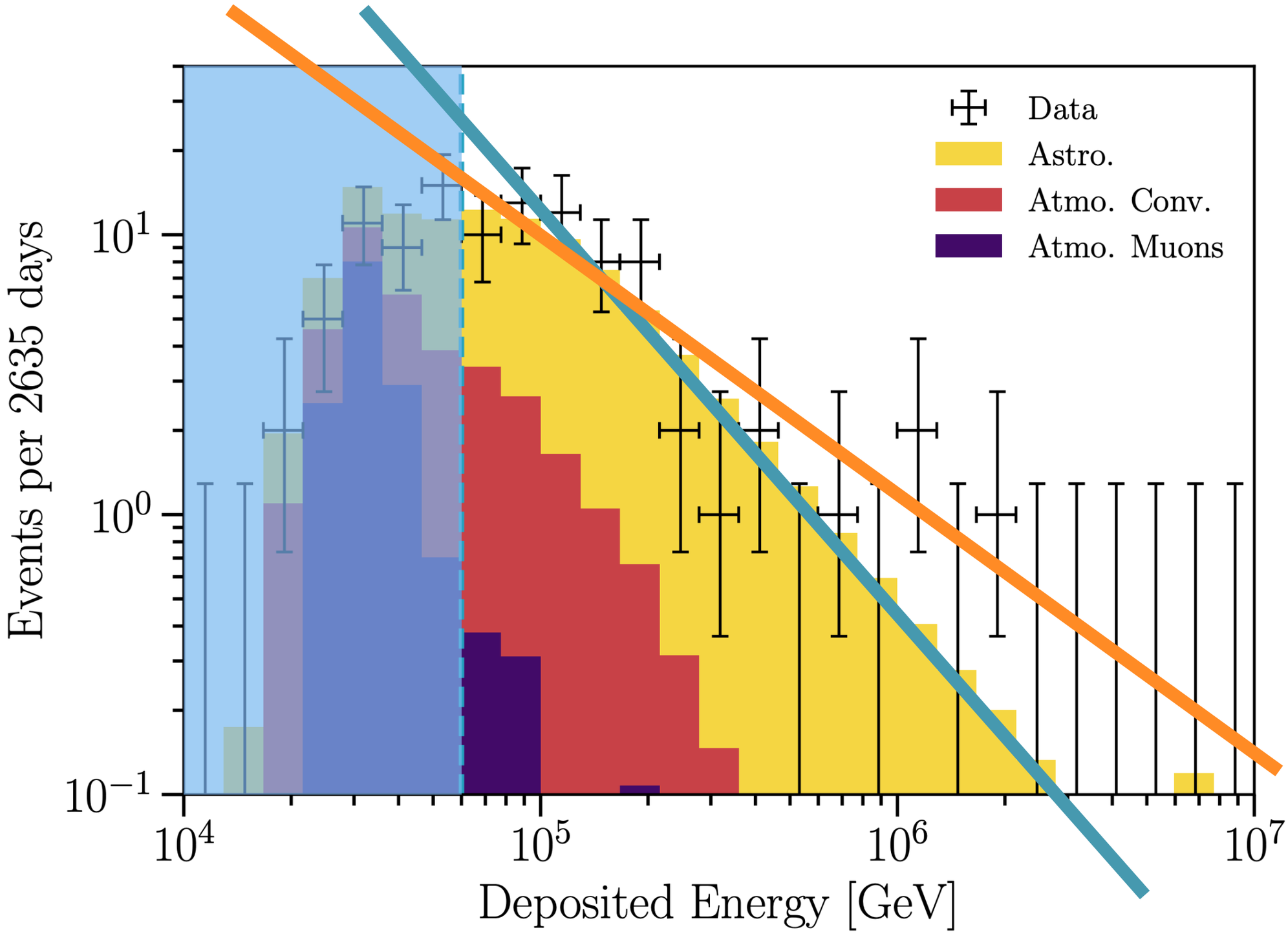
- In this talk, we will focus on the following datasets:
  - 7.5 years high energy starting events (HESE)
  - 9.5 year through-going muon tracks from northern hemisphere (Northern Tracks)
  - 4.5 year PeV energy partially-contained events (PEPE)

A hint of discrepancy

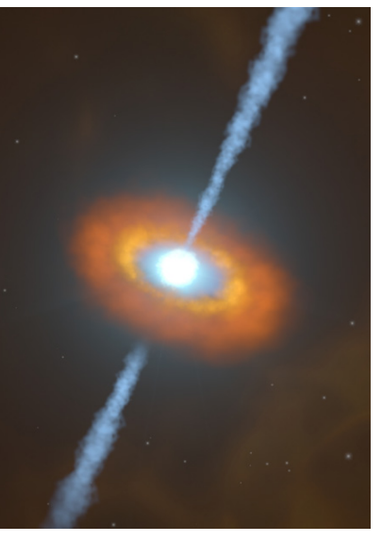
$$\gamma_{\text{astro}}^{\text{HESE}} = 2.87^{+0.20}_{-0.19} \quad \text{and} \quad \gamma_{\text{astro}}^{\text{Nor.Tr.}} = 2.28^{+0.08}_{-0.09}$$

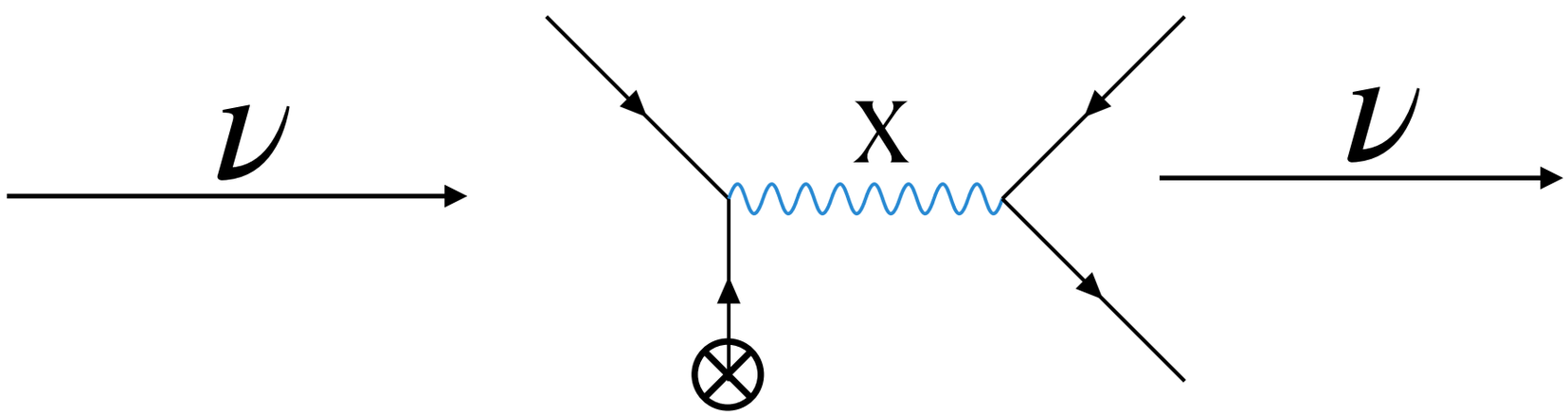


Motivation


Data
Astro.
Atmo. Conv.
Atmo. Muons
Events per 2635 days
10^1
10^0
10^{-1}
10^4
10^5
10^6
10^7
Deposited Energy [GeV]

Astrophysical neutrino attenuation by background





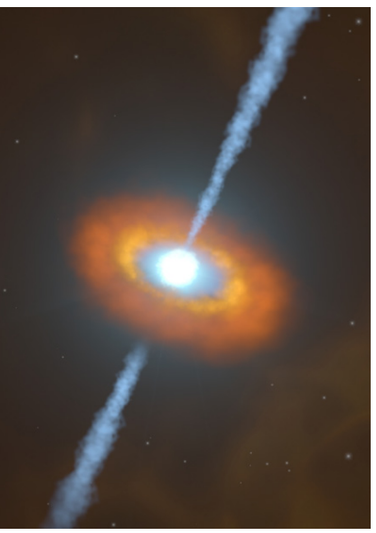
$$E_\nu^{\rm res} = \frac{M_X^2}{2m_T}$$

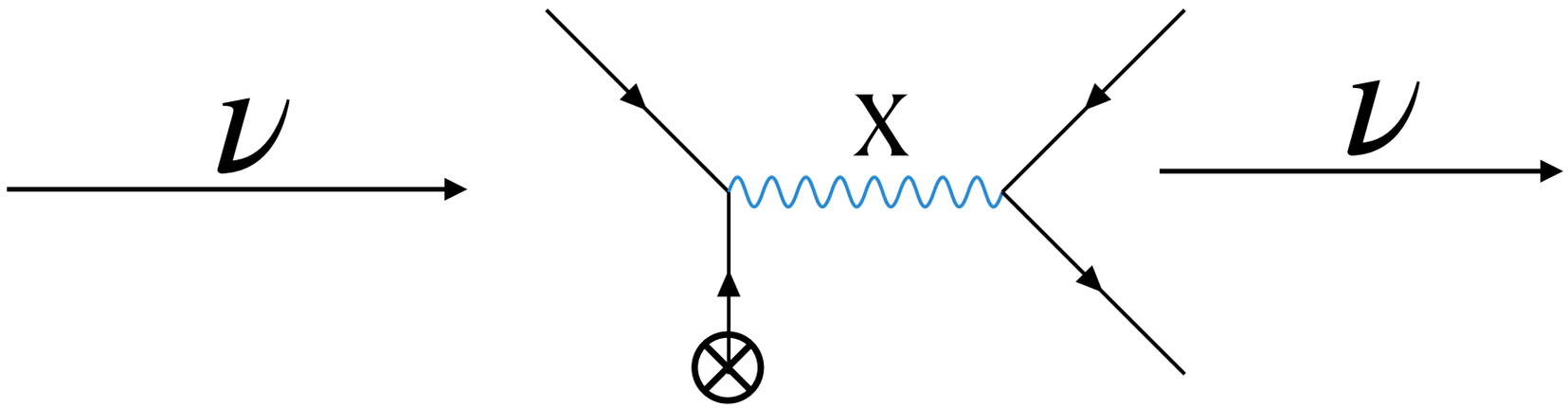
$$\frac{\partial \tilde{n}_i(t,E_\nu)}{\partial t} = \frac{\partial}{\partial E_\nu}\left[H(t)\,E_\nu\,\tilde{n}_i(t,E_\nu)\right] + \mathscr{L}_i(t,E_\nu) - \tilde{n}_i(t,E_\nu)\sum_j n_j^t \sigma_{ij}(E_\nu)$$

$$+ \sum_{j,k,l} n_j^t \int_{E_\nu}^{\infty} dE'_\nu\,\tilde{n}_k(t,E'_\nu)\frac{d\sigma_{jk\to il}}{dE_\nu}(E'_\nu,E_\nu)$$

Ng and Beacom Phys. Rev. D 90, 065035 (2014)

Astrophysical neutrino attenuation by background





$$E_\nu^{\rm res} = \frac{M_X^2}{2m_T}$$

Expansion Source Attenuation

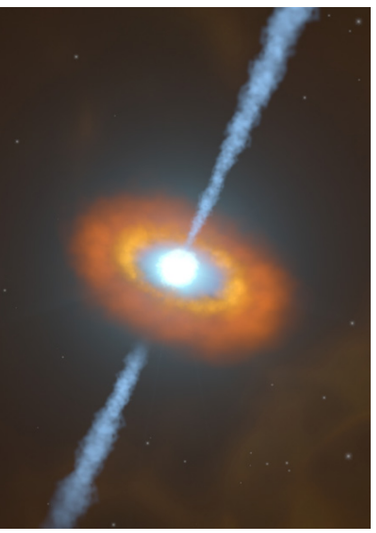
$$\frac{\partial \tilde{n}_i(t,E_\nu)}{\partial t} = \frac{\partial}{\partial E_\nu}\left[H(t)\,E_\nu\,\tilde{n}_i(t,E_\nu)\right] + \mathscr{L}_i(t,E_\nu) - \tilde{n}_i(t,E_\nu)\sum_j n_j^t \sigma_{ij}(E_\nu)$$

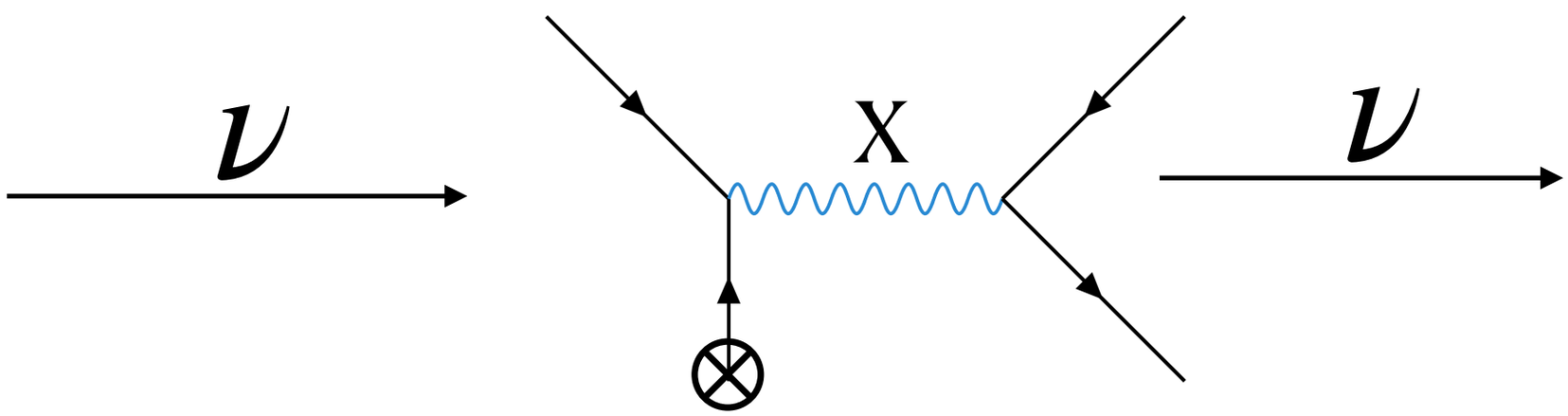
$$+ \sum_{j,k,l} n_j^t \int_{E_\nu}^{\infty} dE'_\nu\, \tilde{n}_k(t,E'_\nu)\frac{d\sigma_{jk\to il}}{dE_\nu}(E'_\nu,E_\nu)$$

Regeneration

Ng and Beacom Phys. Rev. D 90, 065035 (2014)

Astrophysical neutrino attenuation by background





$$E_\nu^{\text{res}} = \frac{M_X^2}{2m_T}$$

The target can be any *background* -
dark matter, active neutrinos, or sterile neutrinos!

The cosmic sterile neutrino background

- In the neutrino oscillation experiments, there are hints in **favor** of and **against** the sterile neutrino
- What is clear is that a fully thermalized eV-scale sterile neutrino is incompatible with cosmology
- A possible resolution is to introduce self-interactions in sterile neutrinos, which delays their production

The Methods

- The interaction Lagrangian:

$$\mathscr{L}_{\text{int}} = g_X \bar{\nu}_s \gamma_\mu P_L \nu_s X^\mu$$

Dasgupta and Kopp Phys.Rev.Lett. 112 (2014) 3, 031803

- For solving the transport equation, we modify nuSIprop to account for four flavors

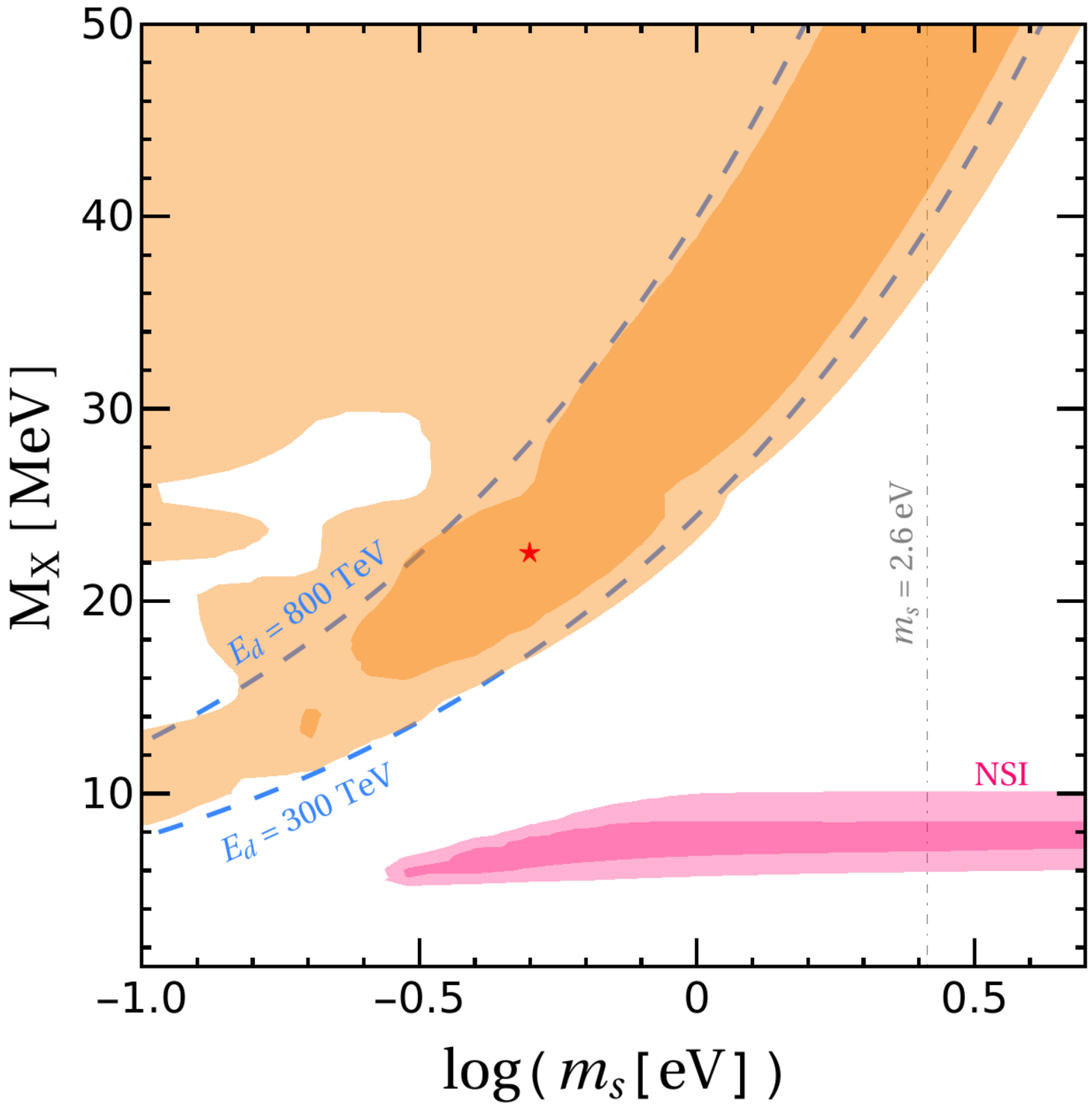
Esteban et. al. Phys.Rev.D 104 (2021) 12, 123014

- We use the public HESE Monte Carlo simulation to calculate event rates

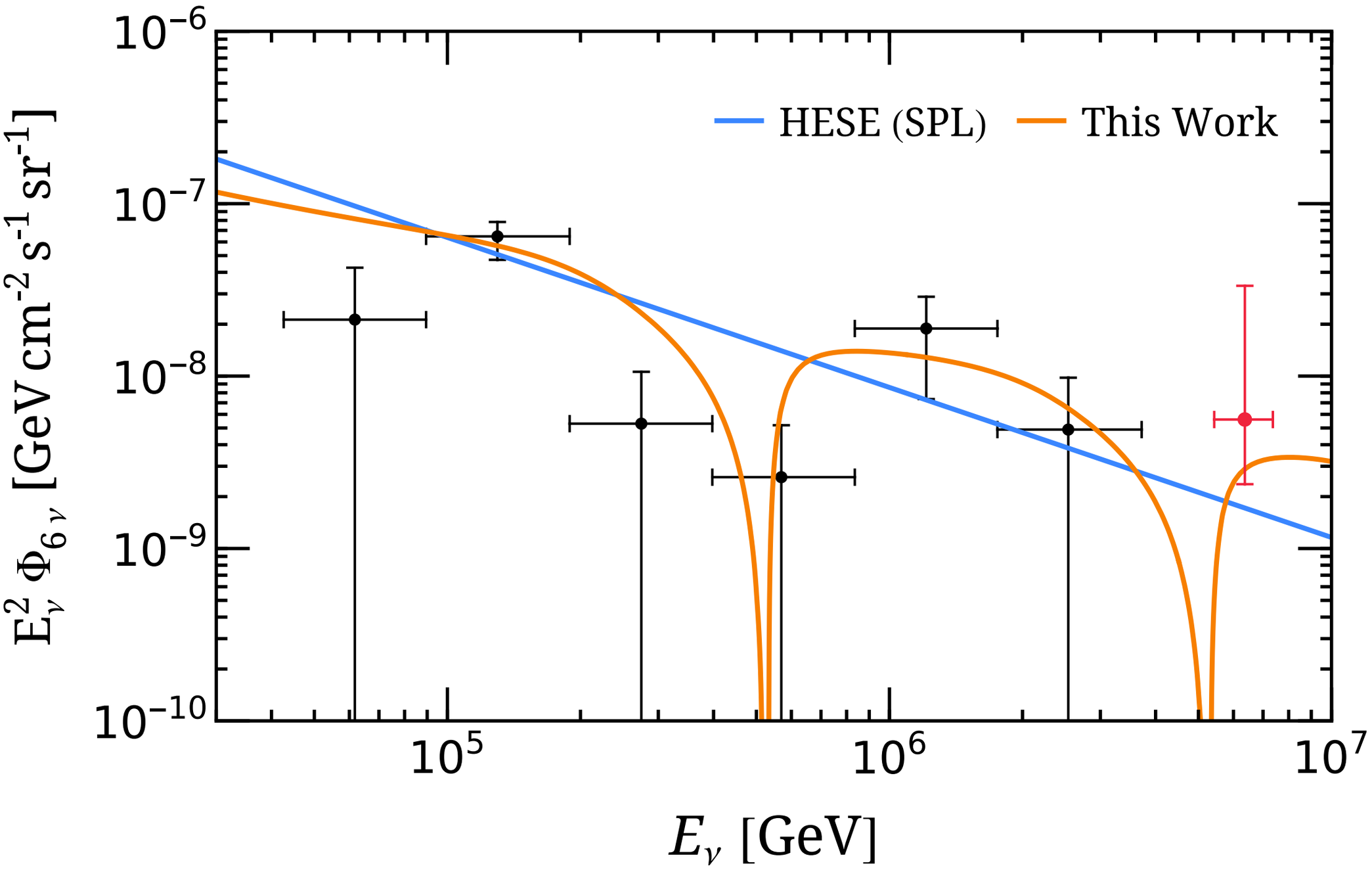
IceCube Phys.Rev.D 104 (2021) 022002

github.com/icecube/HESE-7-year-data-release

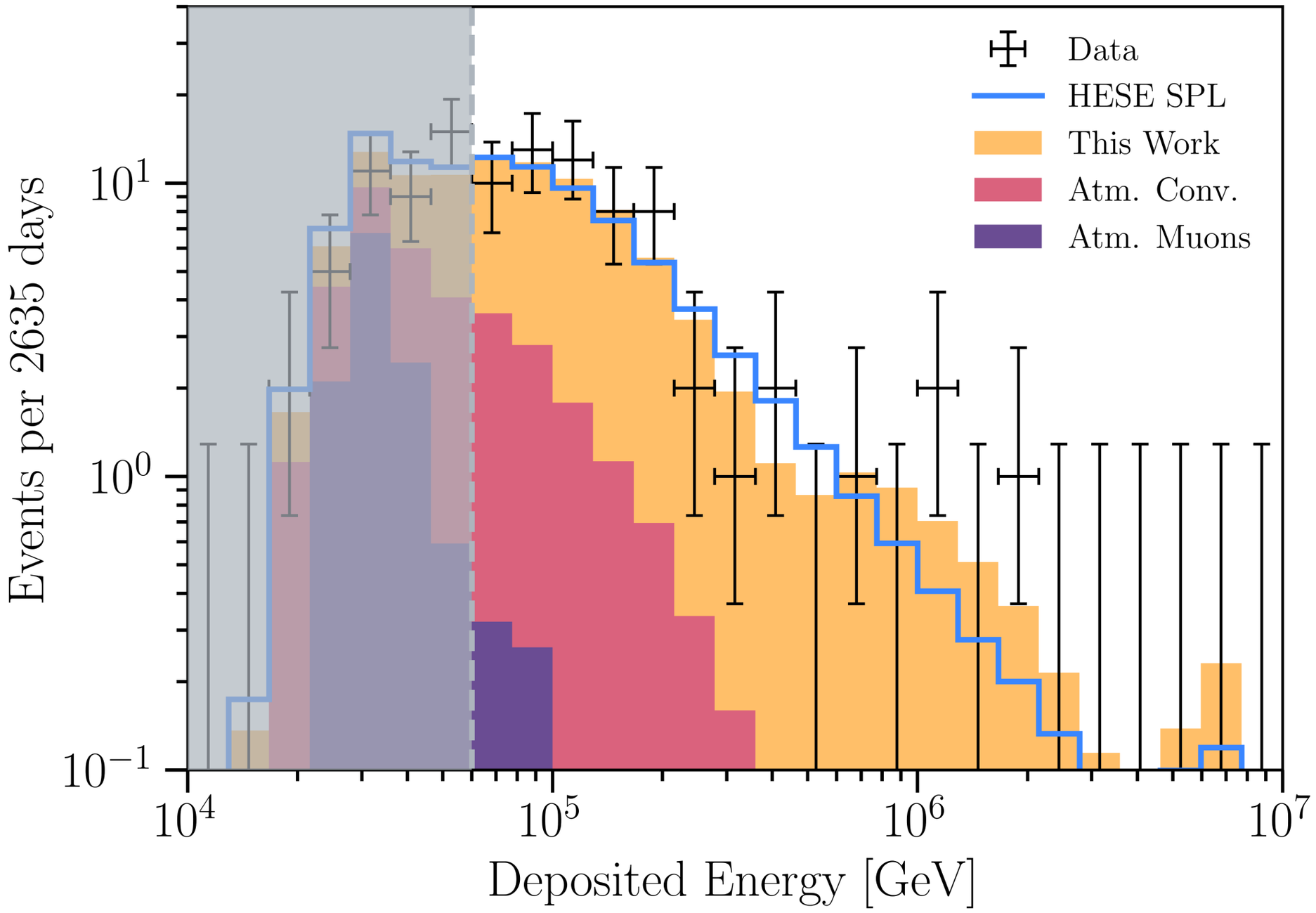
Results


50
40
30
20
10
M_X [MeV]
$E_d = 800$ TeV
$E_d = 300$ TeV
$m_s = 2.6$ eV
NSI
−1.0
−0.5
0
0.5
$\log(m_s[\mathrm{eV}])$

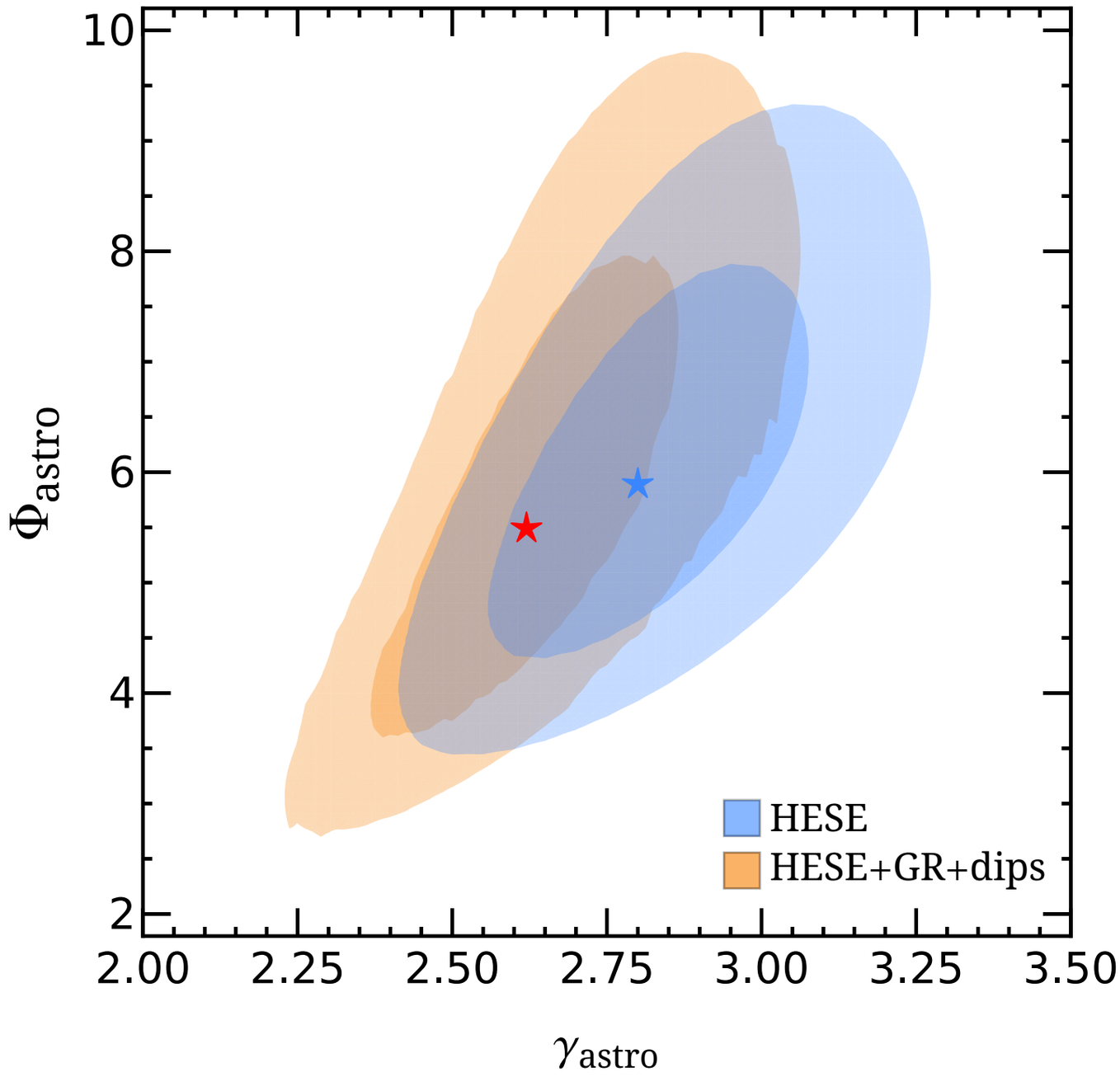
Results


HESE (SPL)
This Work
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{5}
10^{6}
10^{7}
$E_\nu^2\,\Phi_{6\,\nu}$ [GeV cm^{-2} s^{-1} sr^{-1}]
E_ν [GeV]

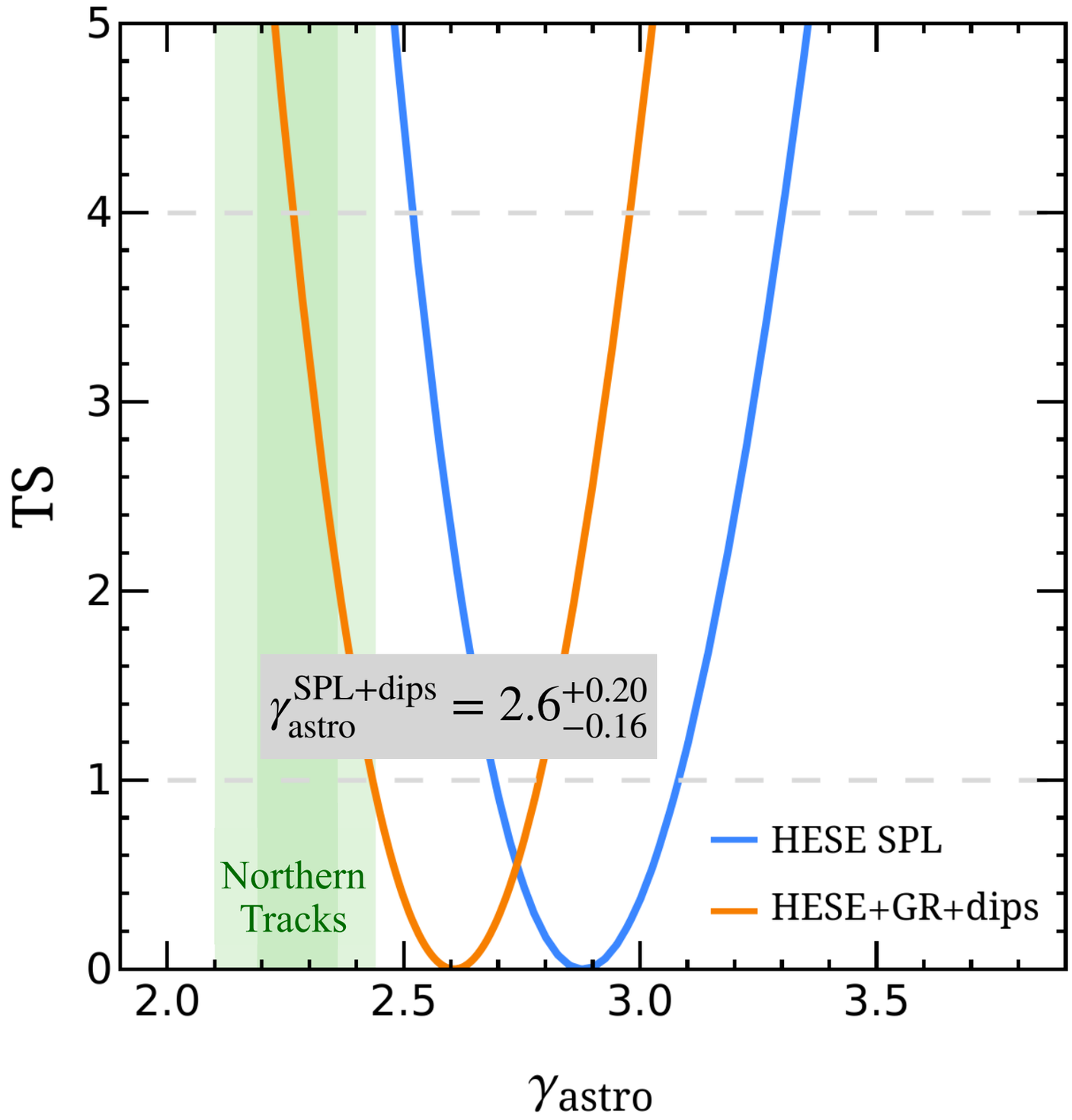
Results


Data
HESE SPL
This Work
Atm. Conv.
Atm. Muons
Events per 2635 days
Deposited Energy [GeV]
10^{1}
10^{0}
10^{-1}
10^{4}
10^{5}
10^{6}
10^{7}

Results


10
8
6
4
2
Φ_{astro}
2.00
2.25
2.50
2.75
3.00
3.25
3.50
γ_{astro}
HESE
HESE+GR+dips

Results


5
4
3
2
1
0
TS
2.0
2.5
3.0
3.5
γ_{astro}
$\gamma_{\text{astro}}^{\text{SPL+dips}} = 2.6^{+0.20}_{-0.16}$
Northern Tracks
HESE SPL
HESE+GR+dips

TeV Dark Matter

Single Power Law with dips

Single Power Law

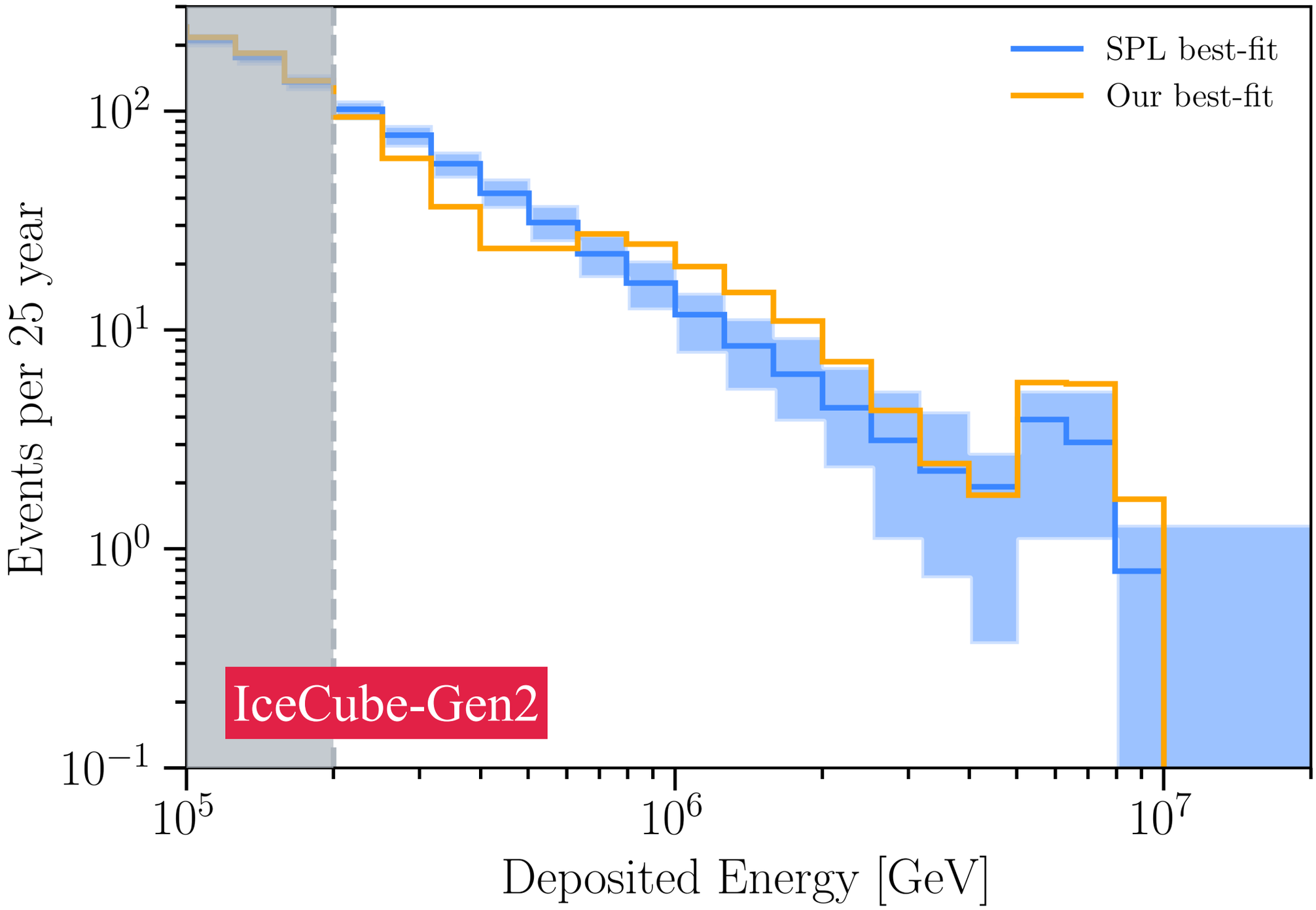
PeV Dark Matter

Leptoquarks

Two component flux

SPL with cutoff

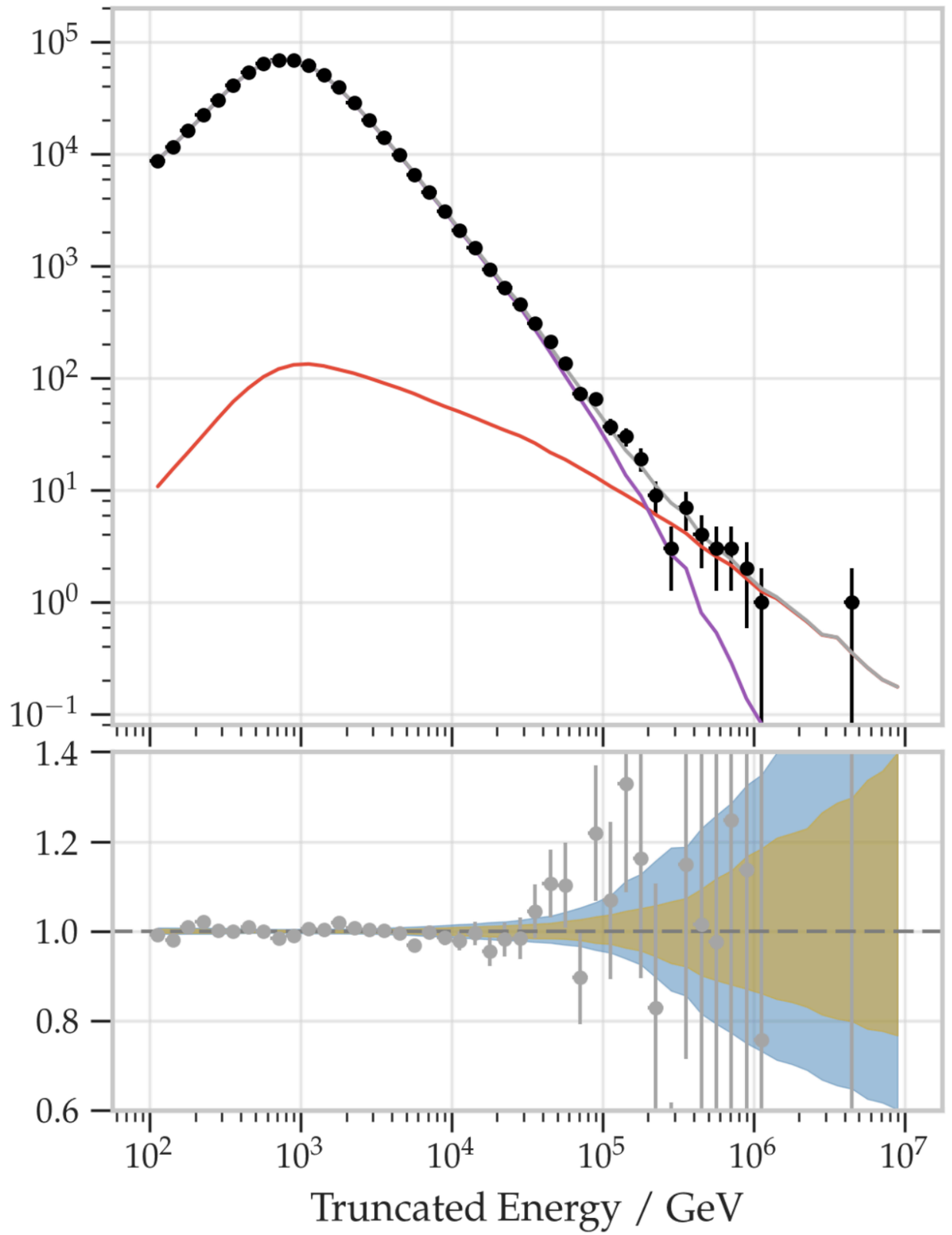
Forecast for IceCube-Gen2



Summary

- Introducing a *dip* in the astrophysical neutrinos can favor a harder spectrum, making HESE compatible with Northern Tracks
- We have considered the dip to originate from interactions with a cosmic sterile neutrino background
- With current data, there is a large overlap in the parameter space and conclusive statements are not possible.
- We look forward to IceCube-Gen2 and additional data from other neutrino telescopes.

Backup


10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
1.4
1.2
1.0
0.8
0.6
10^2
10^3
10^4
10^5
10^6
10^7
Truncated Energy / GeV