

First Search for High-Energy Neutrino Emission from Galaxy Mergers

Subhadip Bouri, Priyank Parashari, Mousumi Das, Ranjan Laha

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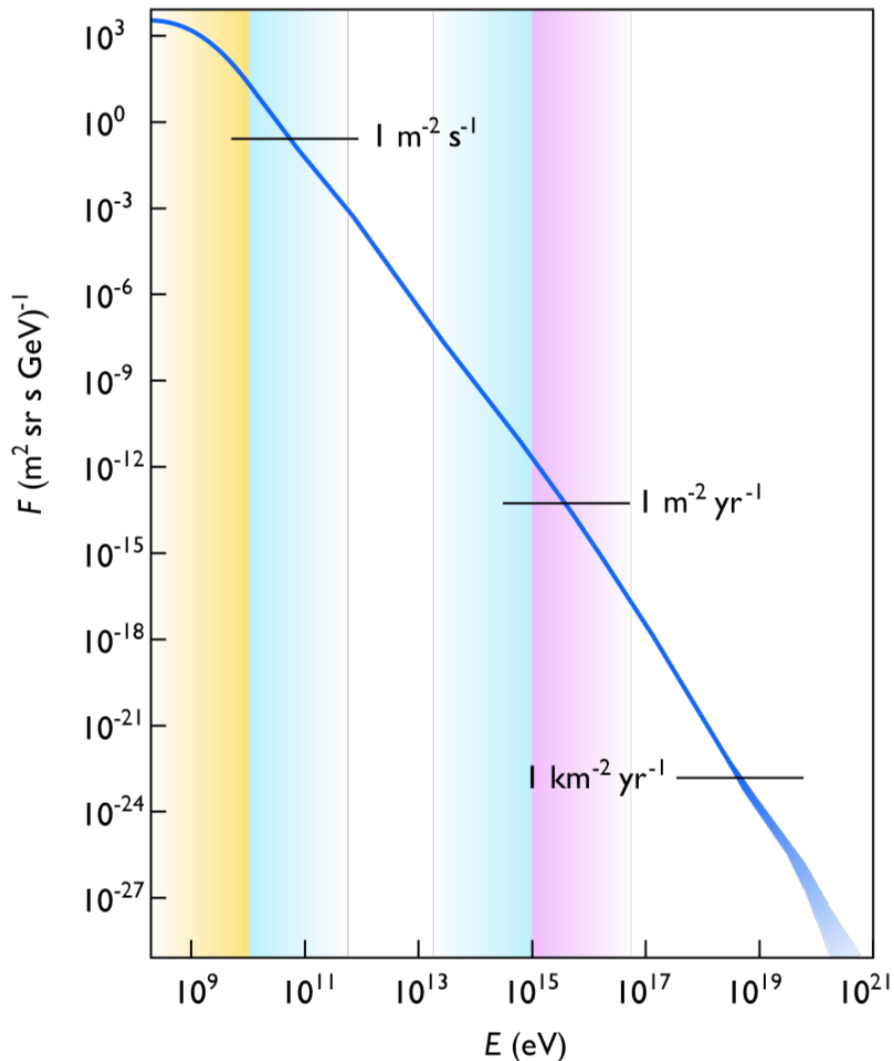
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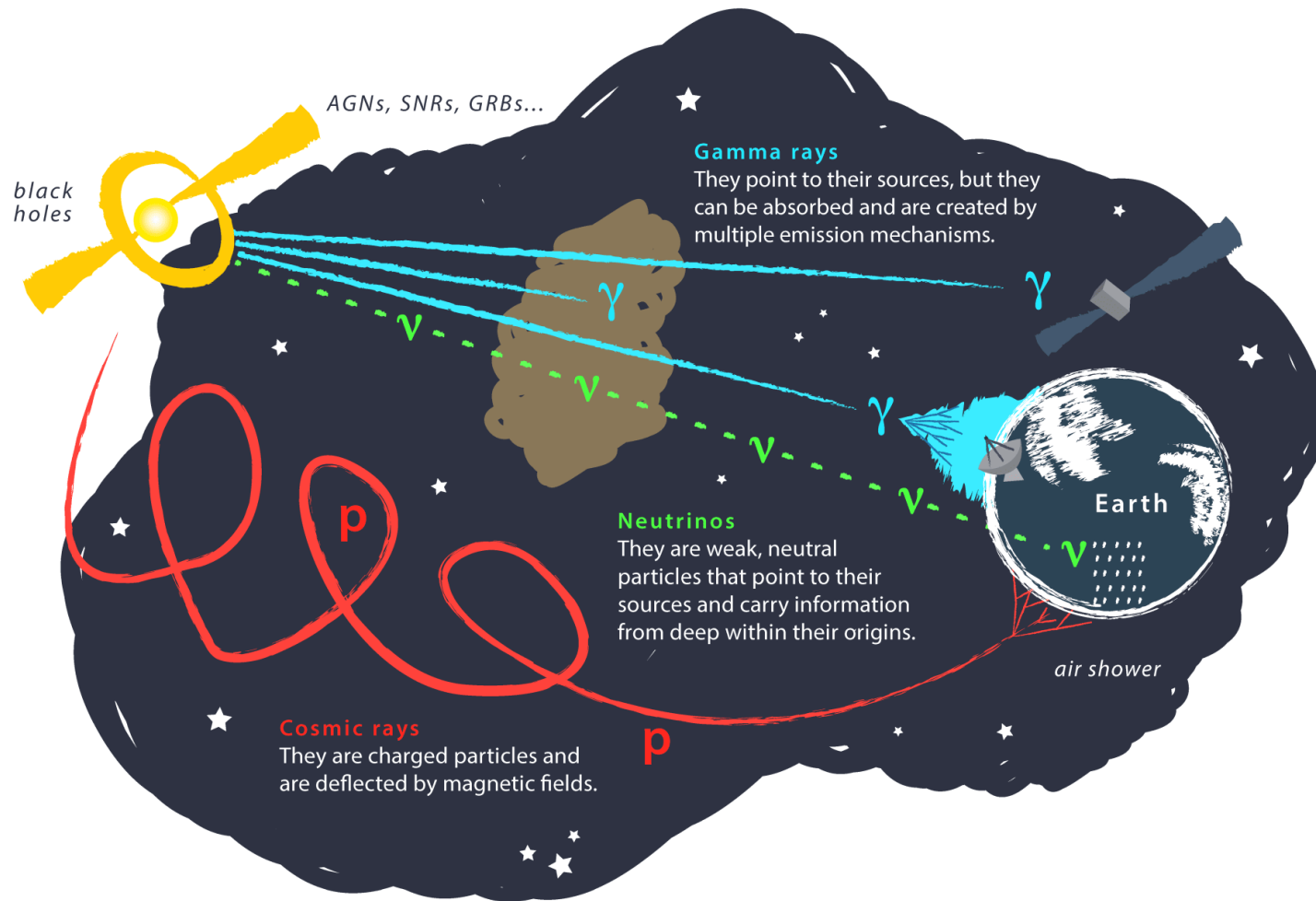
What are the sources of Cosmic Rays?



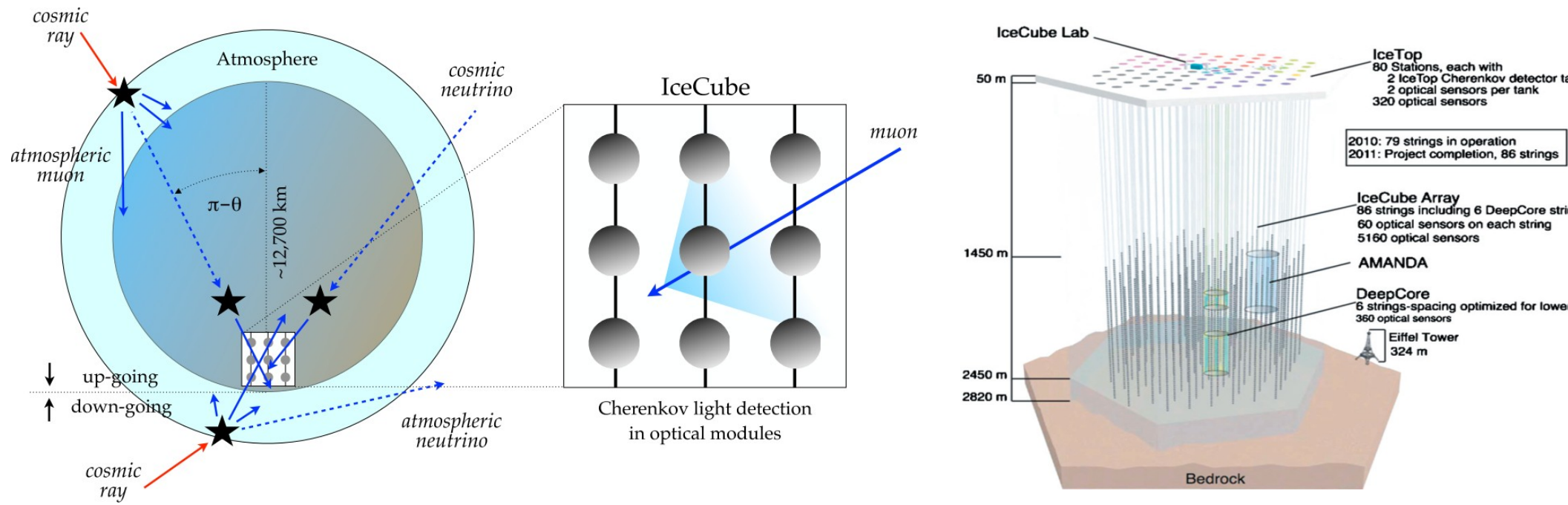
What are the sources of the highest energy particles in our universe, the high-energy ($\geq 10^{15}$ eV) cosmic rays?

Fig: Cosmic flux versus particle energy at the top of Earth's atmosphere (credit: wikipedia)

Neutrinos and gamma rays, a partnership to explore the extreme universe



How IceCube detects Neutrino?



Similar types of interactions happen for anti-neutrinos.

Current status of the high-energy astrophysical neutrino sources

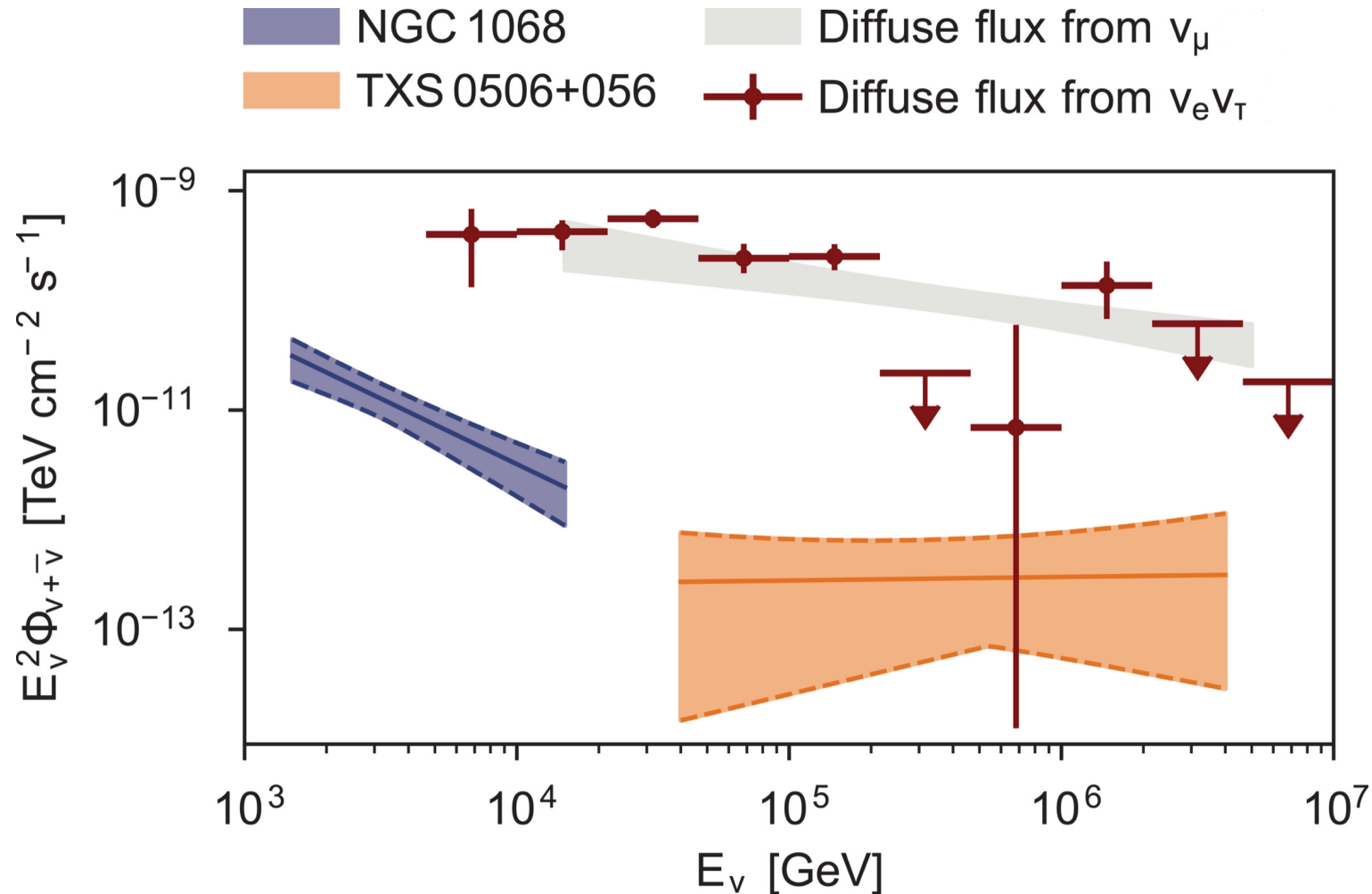


Fig: The high energy neutrino flux observed by IceCube. TXS 0506+056 and NGC 1068 are confirmed high-energy astrophysical neutrino sources till now. We also observe a high-energy diffuse astrophysical neutrino (in all flavors) flux. Currently, we do not know what sources contribute entirely to the high-energy diffuse astrophysical neutrino flux. [courtesy: 2211.09972]

Proposed Neutrino Sources

- Blazars [arXiv: 1904.06371, 2004.09686, 2007.12706, 2309.03115]
- Gamma-ray bursts [arXiv: 1101.1448, 1412.6510, 1601.06484, 1702.06868]
- Radio bright AGN [arXiv: 2103.12813]
- Pulsar wind nebulae [arxiv: 2003.12071]
- Choked Jet Supernovae [arXiv: 1706.02175, 1809.09610]
- Fast radio bursts [arXiv: 1712.06277, 2212.06702]

And many more classes of sources...



What are other powerful hadronic accelerators in the cosmos?



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What if galaxy mergers are emitting high-energy neutrinos?



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What if galaxy mergers are emitting high-energy neutrinos?

Theoretical papers:

1. Kazumi Kashiyama and Peter Meszaros [arXiv:1405.3262]
2. Chengchao Yuan et al. [arXiv: 1712.09754]
3. Chengchao Yuan et al. [arXiv: 1810.04155]

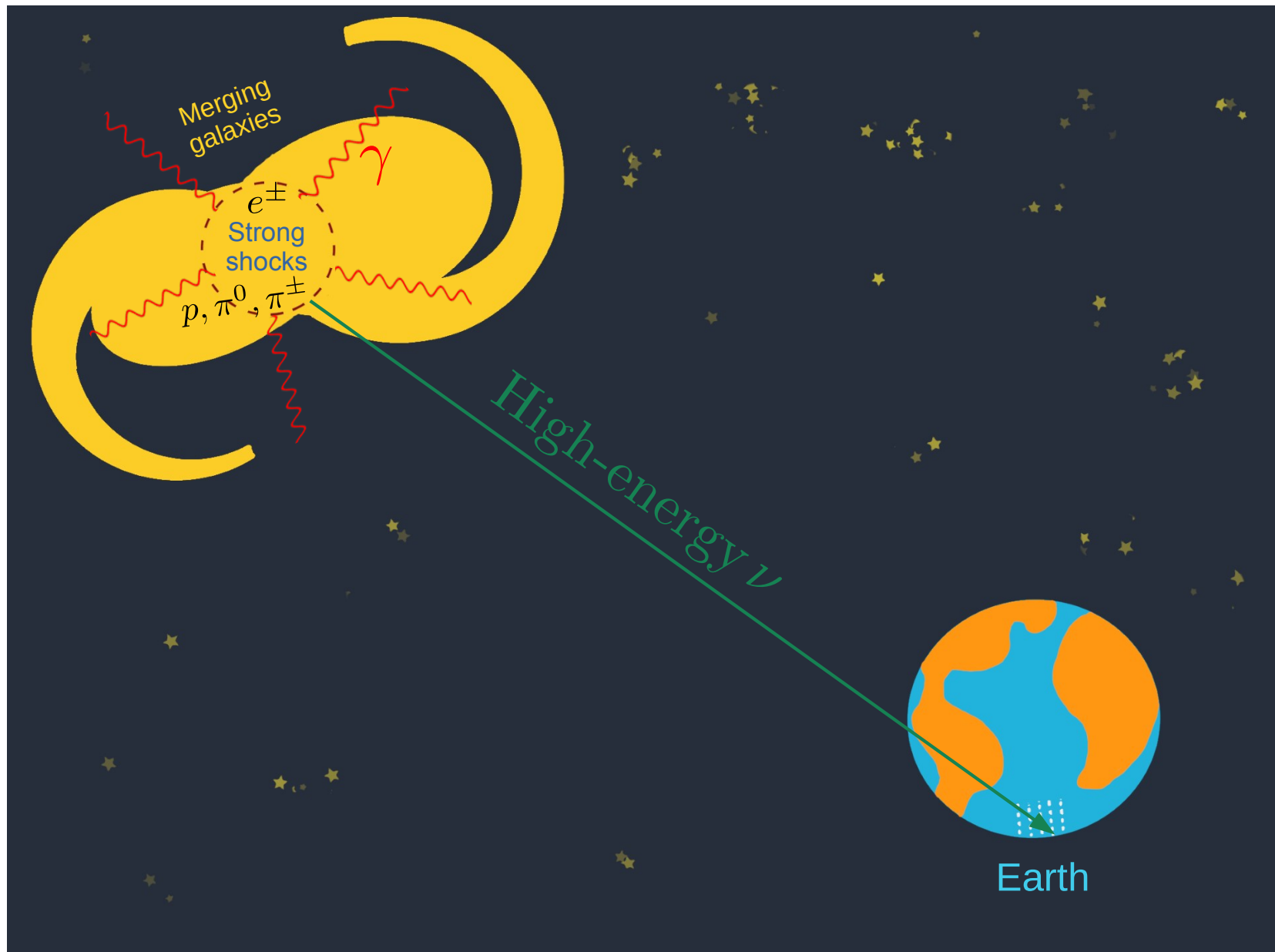
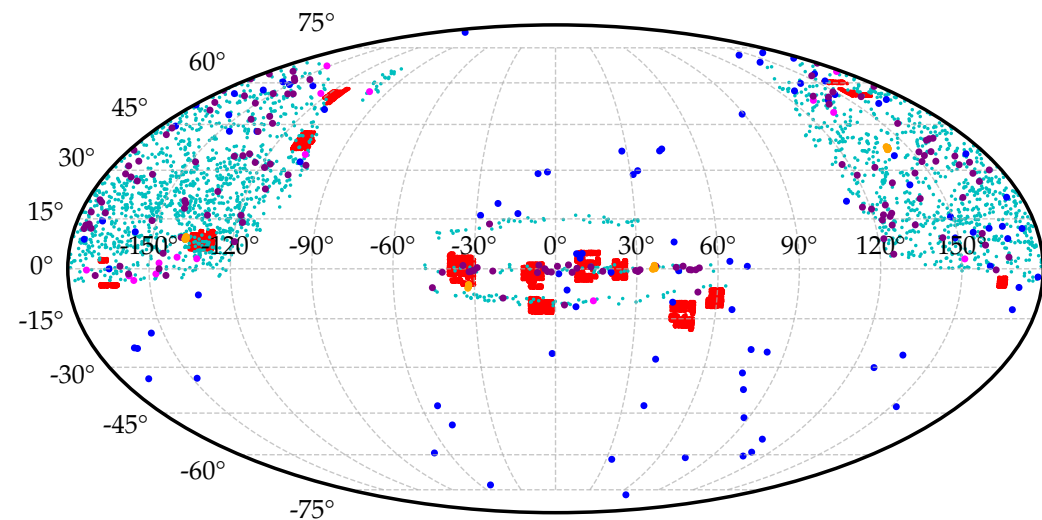
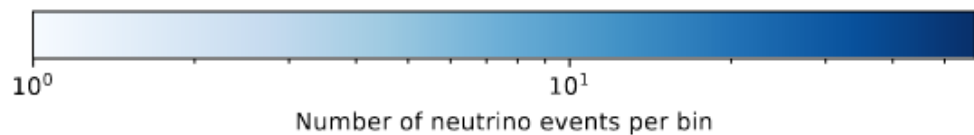
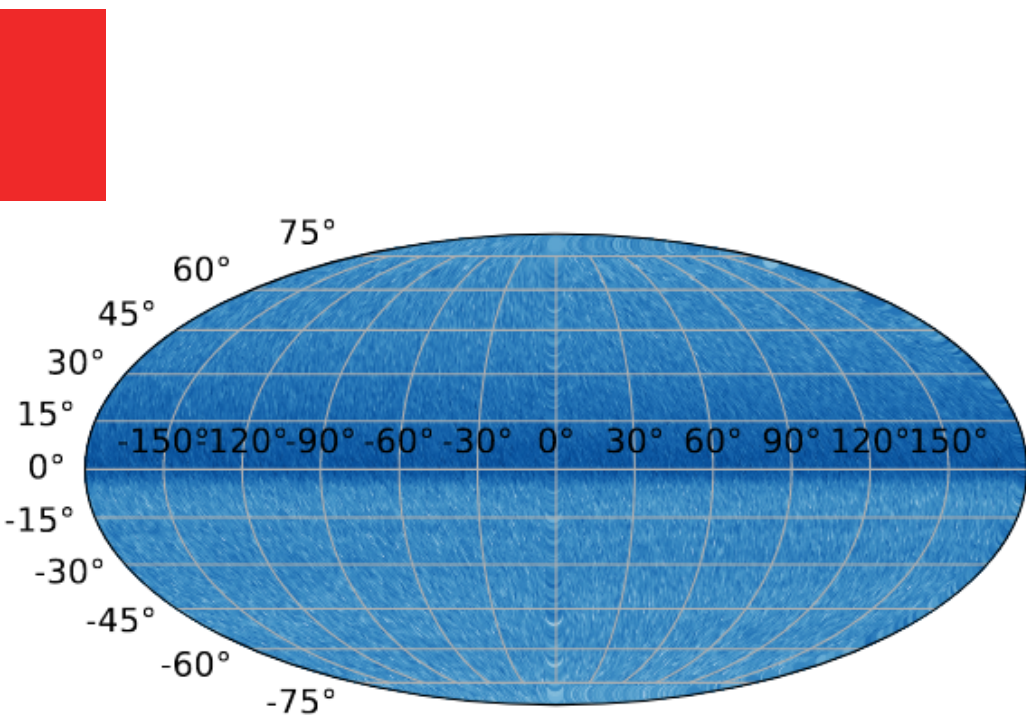


Fig: Schematic figure showing the merger of two galaxies. The shock is in the core region where interactions occur and neutrinos as well as electromagnetic radiation are produced.



We look into the statistical correlation between the 10 years IceCube skymap and six galaxy mergers catalogs

Analysis Formalism

- Single Source Analysis

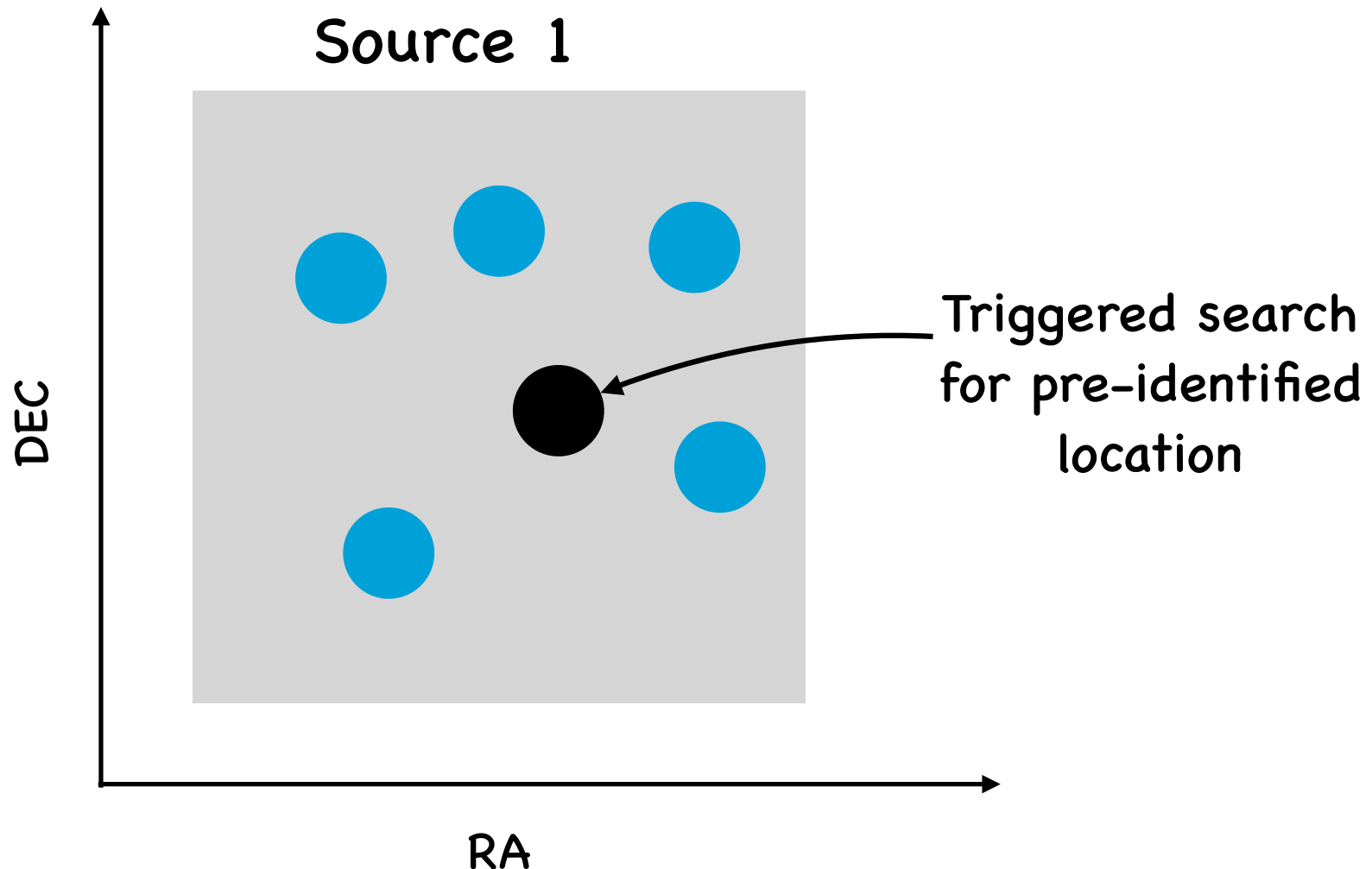


Fig: schematic representation of Single source analysis

Analysis Formalism

- Stacking Analysis

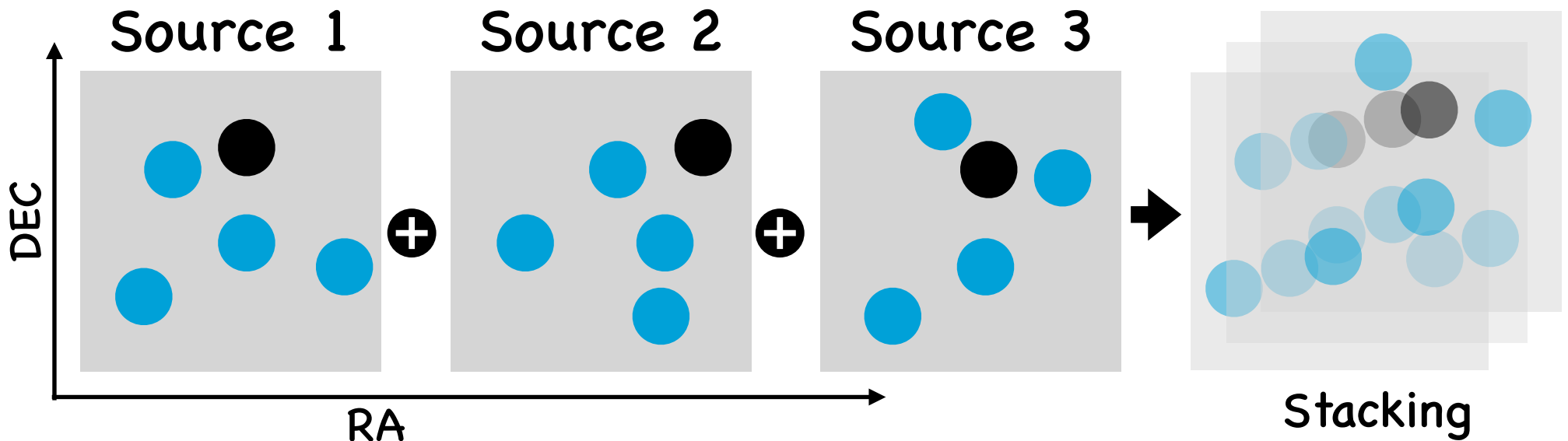


Fig: Schematic representation of Stacking analysis, search for collective neutrino emission from a catalog/class of sources

Analysis Formalism

- Test Statistic:

$$TS(n_s) = 2 \log \frac{\mathcal{L}(n_s)}{\mathcal{L}(n_s = 0)}$$

Hypothesis: neutrino events are coming from galaxy mergers

Null Hypothesis: all the events come from the background

- If the background hypothesis is true, the probability distribution for TS_{max} is approximately a χ^2 distribution.

$$\text{PDF}(TS_{max}) \approx \chi_1^2(TS_{max})$$

Results: Single Source analysis

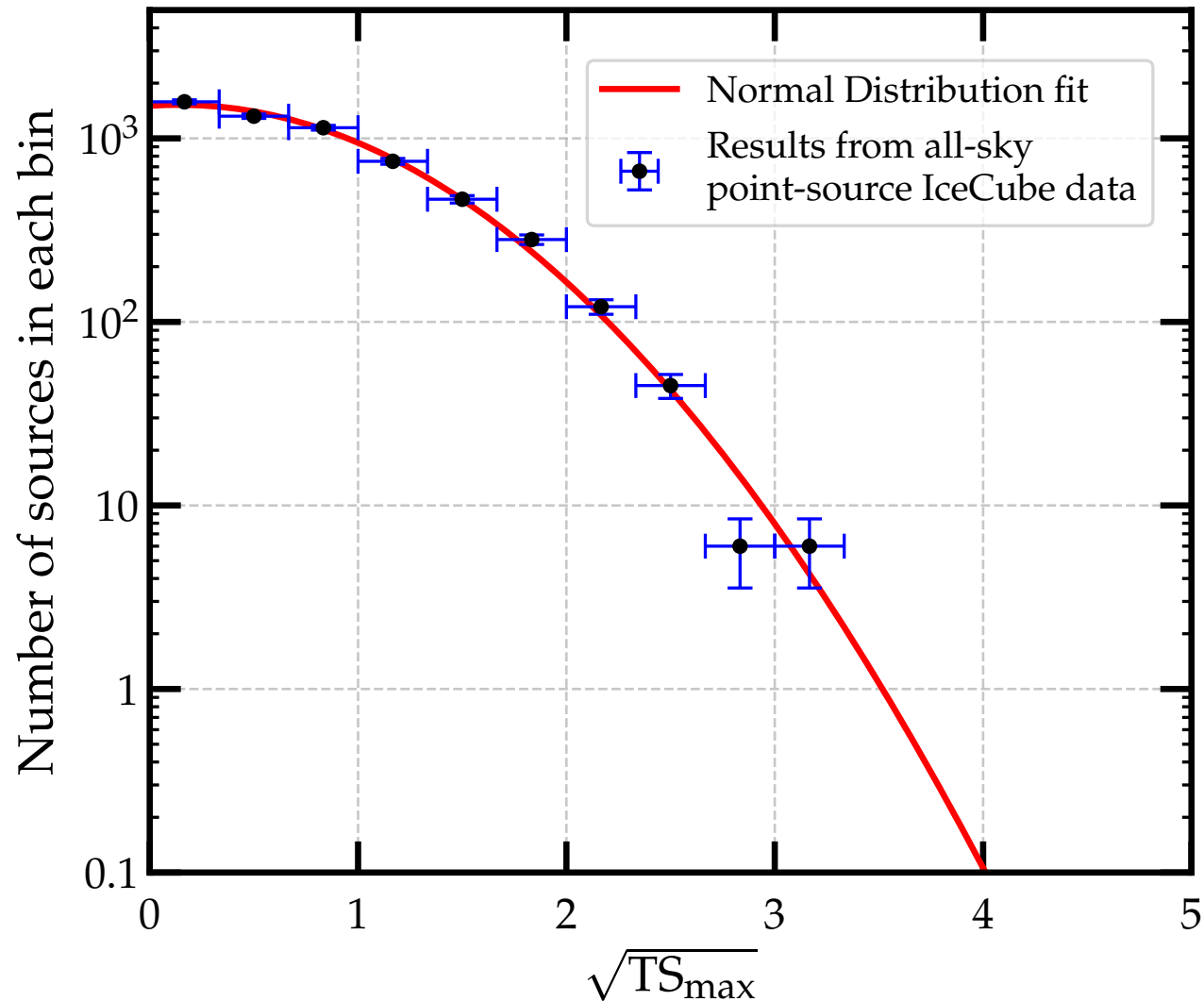


Fig: Distribution of square root of maximized TS values for all galaxy mergers from our likelihood analysis with 10 years of IceCube muon-track data. The normal distribution favours the null hypothesis implying high-energy astrophysical neutrinos are not coming from galaxy mergers. (Our work)

Results: Stacking Analysis

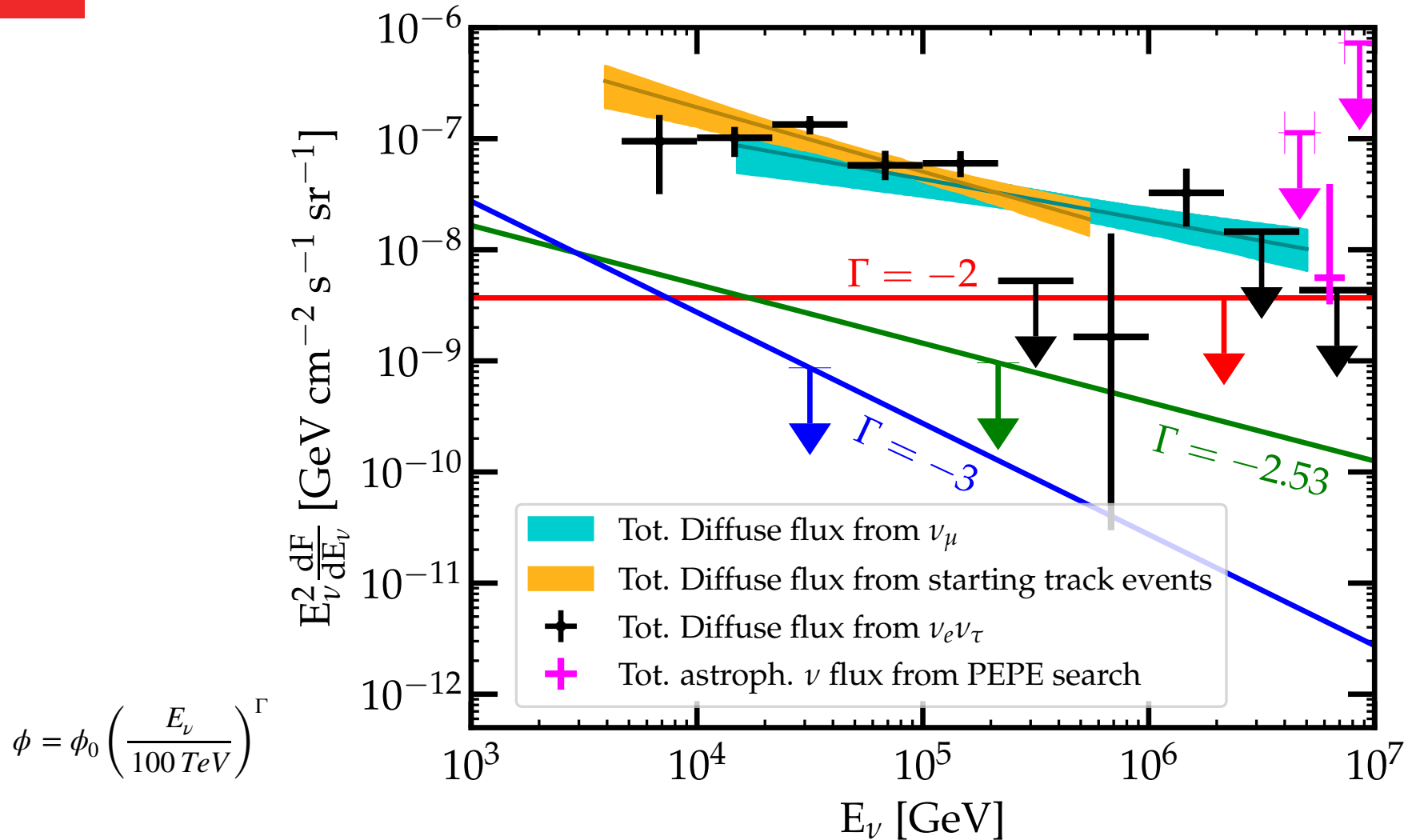


Fig: All six-flavor neutrino energy fluxes vs. neutrino energy combining all the galaxy mergers in the six catalogs for the luminosity distance weighting scheme. The spectral index of signal neutrinos is Γ . (our work)


Conclusion

- We analyze the significance of each galaxy merger location in the six catalogs and find that none of the galaxy mergers in all six catalogs have a large global significance.
- Our stacking analyses show no significant correlation between our selected galaxy mergers and IceCube neutrinos with the current data set. For luminosity distance weighting, with $\Gamma = -2$, the upper limits can contribute no more than 8.55%, 7.42% and 7.33% of the total astrophysical diffuse flux observed by IceCube measured from muon-neutrino events, combined electron and tau neutrino cascade channels, and starting track events, respectively.

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Thank you!
subhadipb@iisc.ac.in



Back Up Slides!

Results: Single Source analysis

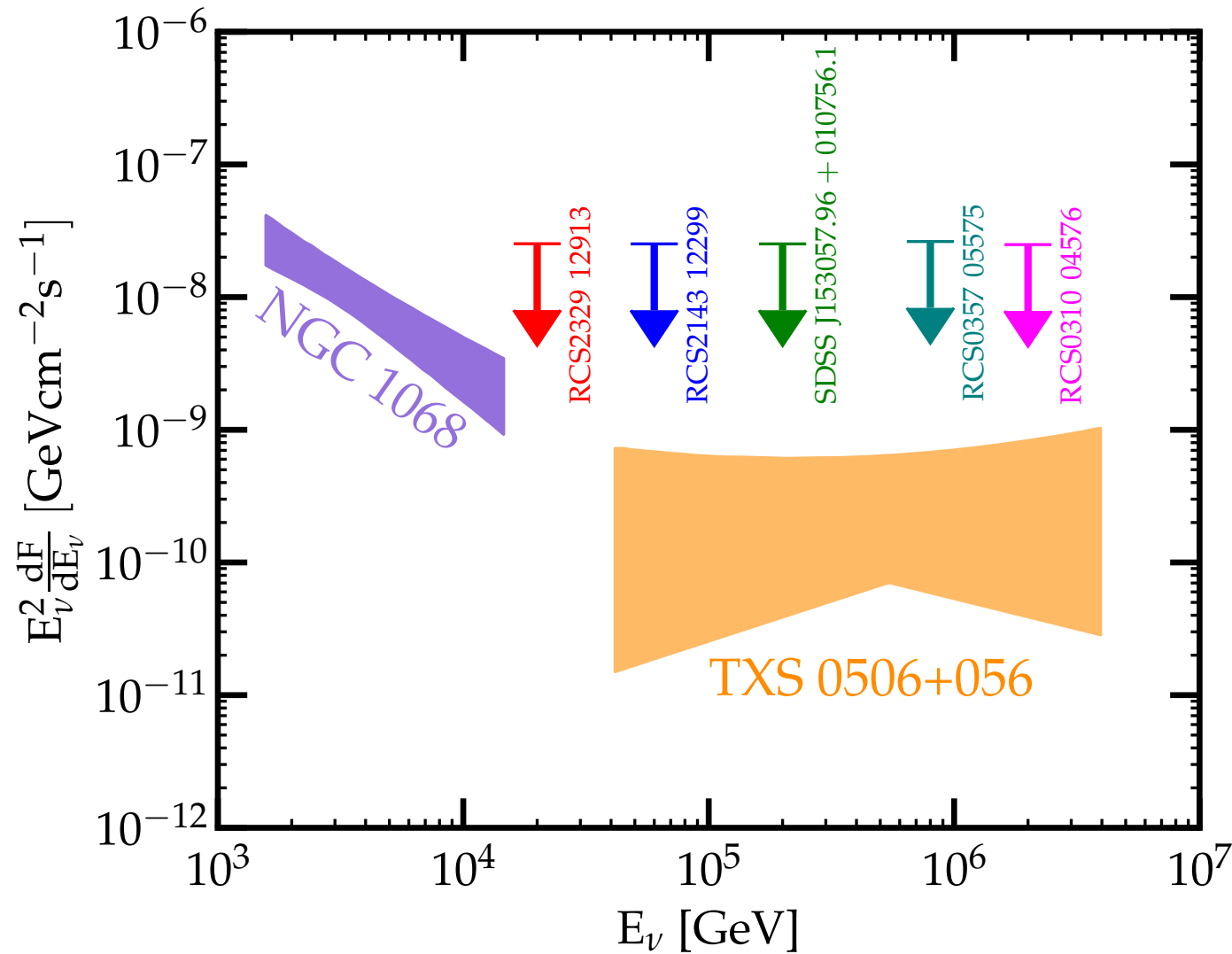


Fig: Upper limits on the total flux of high-energy neutrinos with $\Gamma = -2$ at various energies for the five most significant sources among all the considered galaxy mergers within six catalogs. (Our work)

Results: Single Source analysis

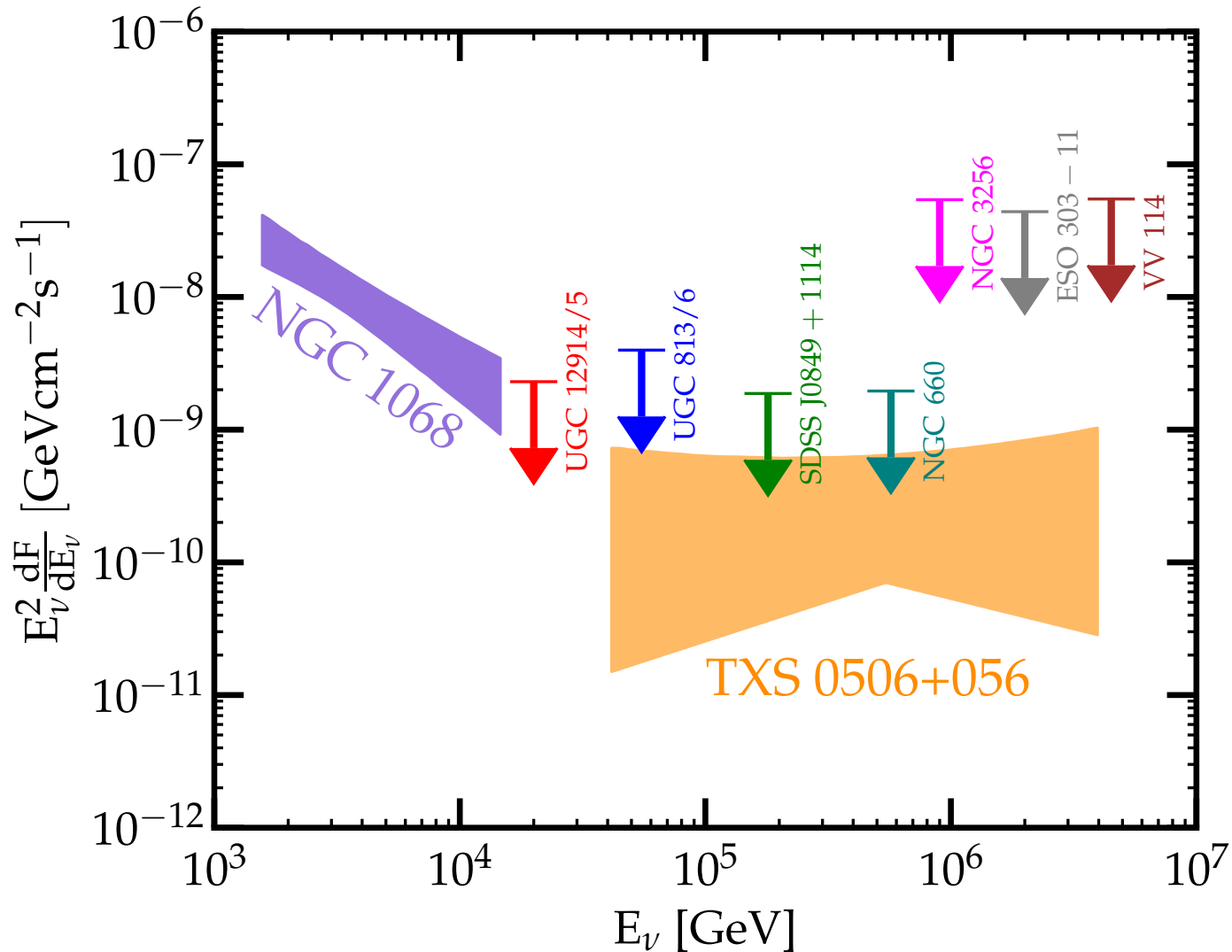


Fig: Upper limits on the total flux of high-energy neutrinos with $\Gamma = -2$ at various energies for seven interesting galaxy mergers mentioned in various references. (Our work)

Weighting Schemes for Stacking Analysis

- $w_{j,\text{model}} = 1$

- $w_{j,\text{model}} \propto 1/d_L(z)^2$

Luminosity Distance

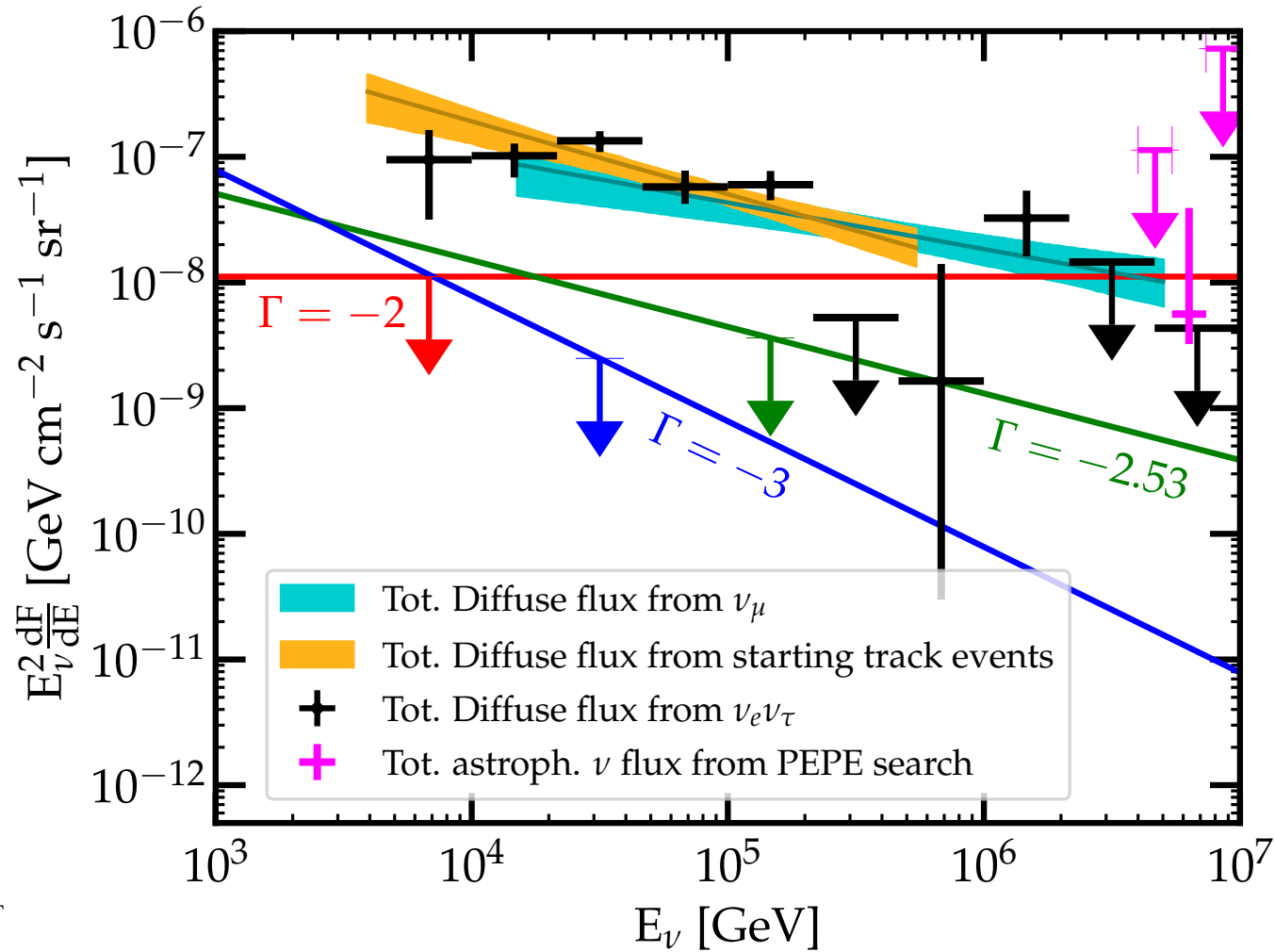
- $w_{j,\text{model}} \propto \frac{\epsilon_\nu Q_\nu^{(g)}}{(1+z)^2 H(z)}$

All flavour luminosity density

Hubble parameter

[Taken from Yuan, Murase and Mészáros (arXiv: 1810.04155)]

Results: Stacking Analysis



$$\phi = \phi_0 \left(\frac{E_\nu}{100 \text{ TeV}} \right)^\Gamma$$

Fig: All six-flavor neutrino energy fluxes vs. neutrino energy combining all the galaxy mergers in the six catalogs for equal weighting scheme. The spectral index of signal neutrinos is Γ . (our work)

Results: Stacking Analysis

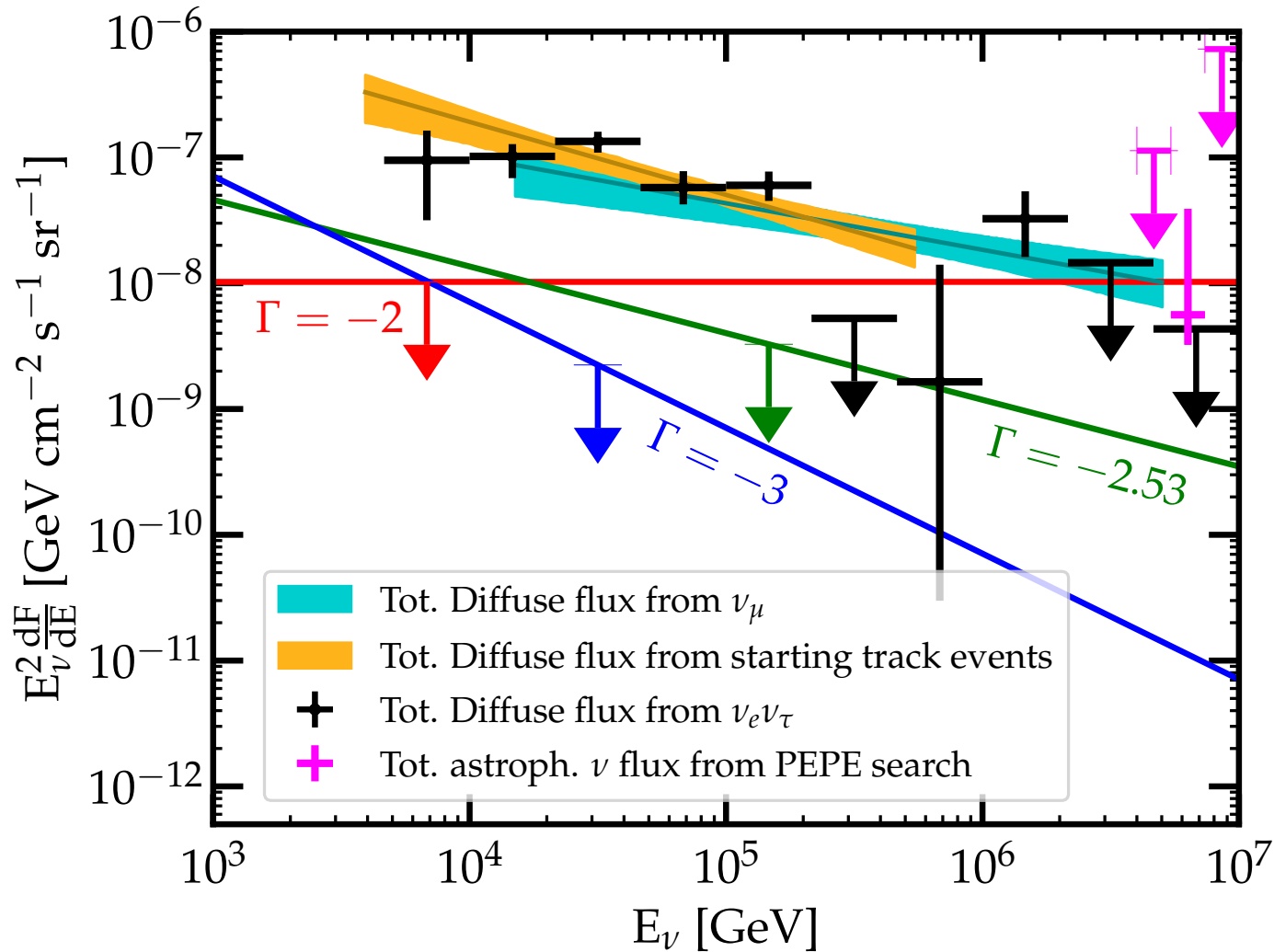
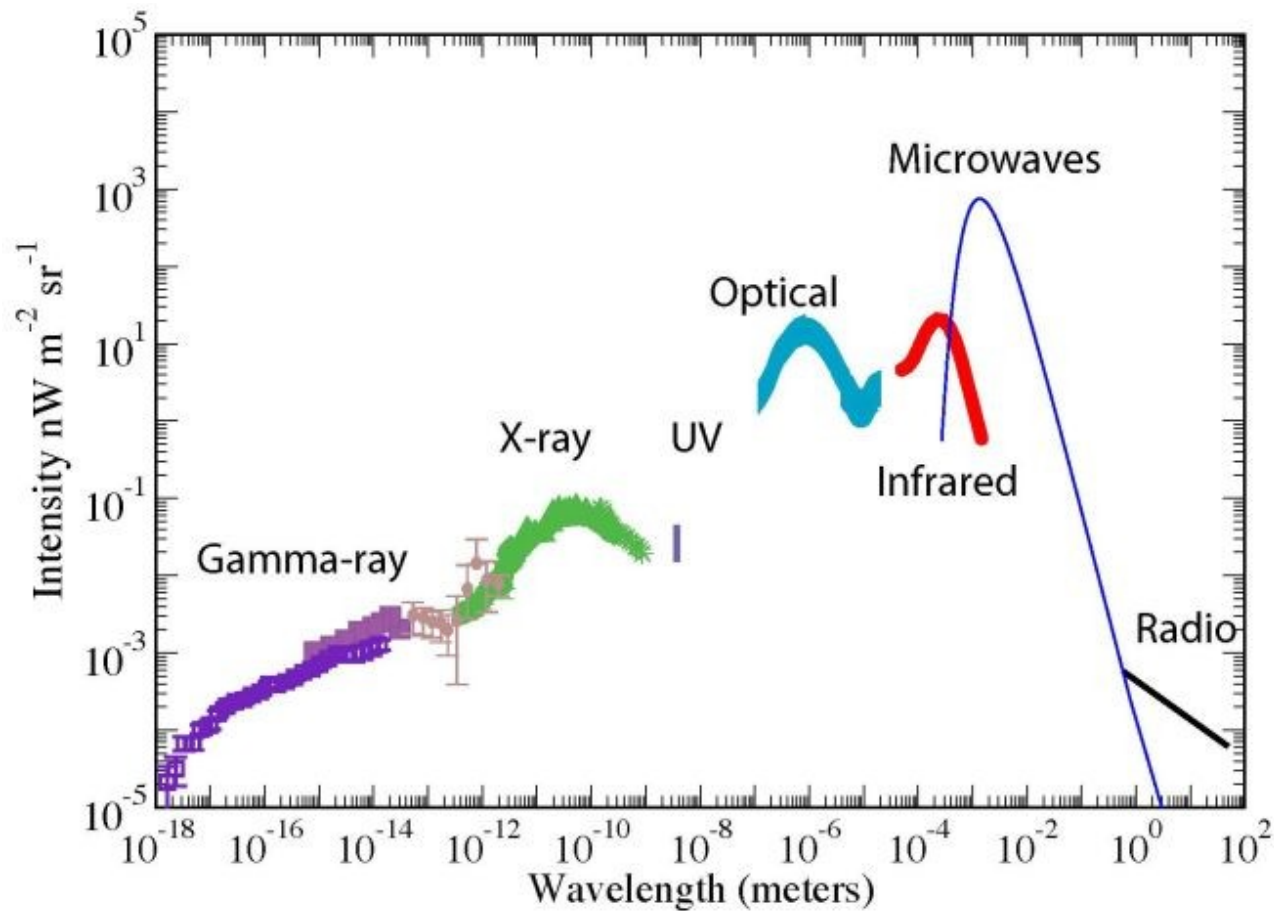


Fig: All six-flavor neutrino energy fluxes vs. neutrino energy combining all the galaxy mergers in the six catalogs for the Yuan et al. weighting scheme. The spectral index of signal neutrinos is Γ . (our work)

EBL



Courtesy: NASA

Pair production CC

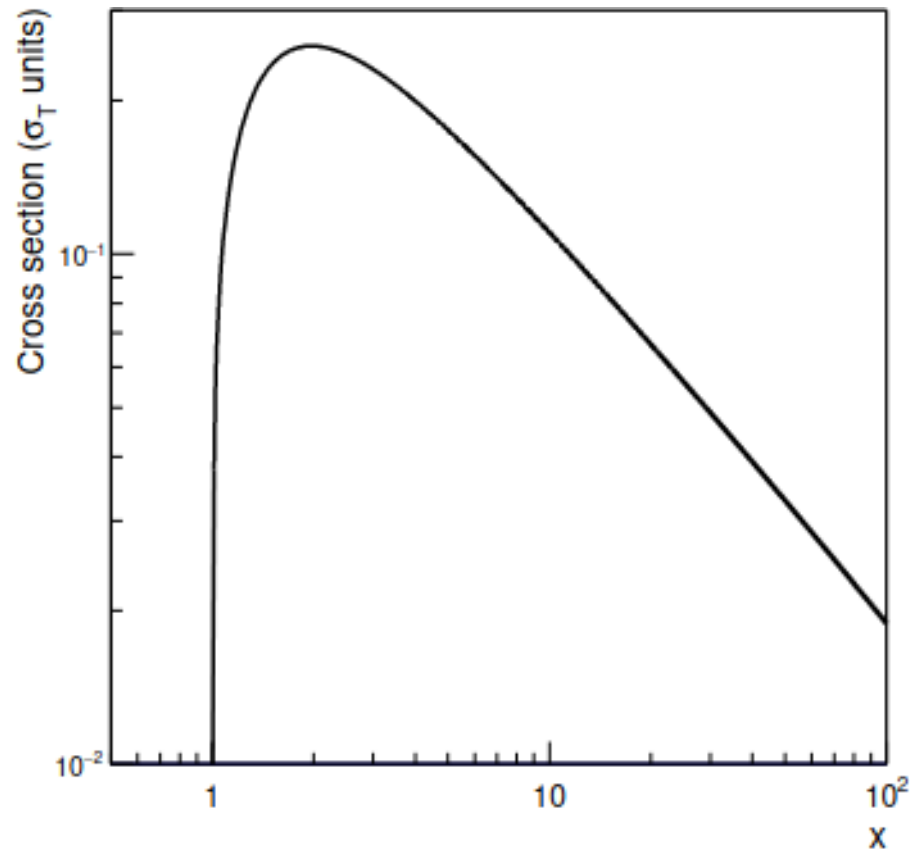


FIG. 1: Pair production cross section plotted as a function of the variable $x = s/(4m_e^2)$. σ_T is the Thomson cross section.

- $\sigma = \left(\frac{3}{16}\right) \sigma_{Th} (1 - \beta^2) [(3 - \beta^4) \log\left(\frac{1+\beta}{1-\beta}\right) - 2\beta (2 - \beta^2)]$, with $\sigma_{Th} = \frac{8\pi}{3} \left(\frac{\alpha}{m_e}\right)^2 = 6.63081 \times 10^{-29} m^2$.
- β is the speed of the outgoing electrons in the center of mass frame of the process.
- β depends on the energy of the high energy photon, E , the background photon energy, ϵ , and the angle between their momenta θ and the mass of the electron.

More quantitatively,

$$\beta = \sqrt{1 - \frac{2m_e^2}{\epsilon E(1 - \cos\theta)}} = \sqrt{1 - \frac{4m_e^2}{s}}$$

The cross-section has a threshold for the background field photon energy $\epsilon_{th} = \frac{2m_e^2}{E(1 - \cos\theta)}$. Cross-section peaks at $\beta = 0.701317$ or $s = 1.9679 (4m_e^2)$.

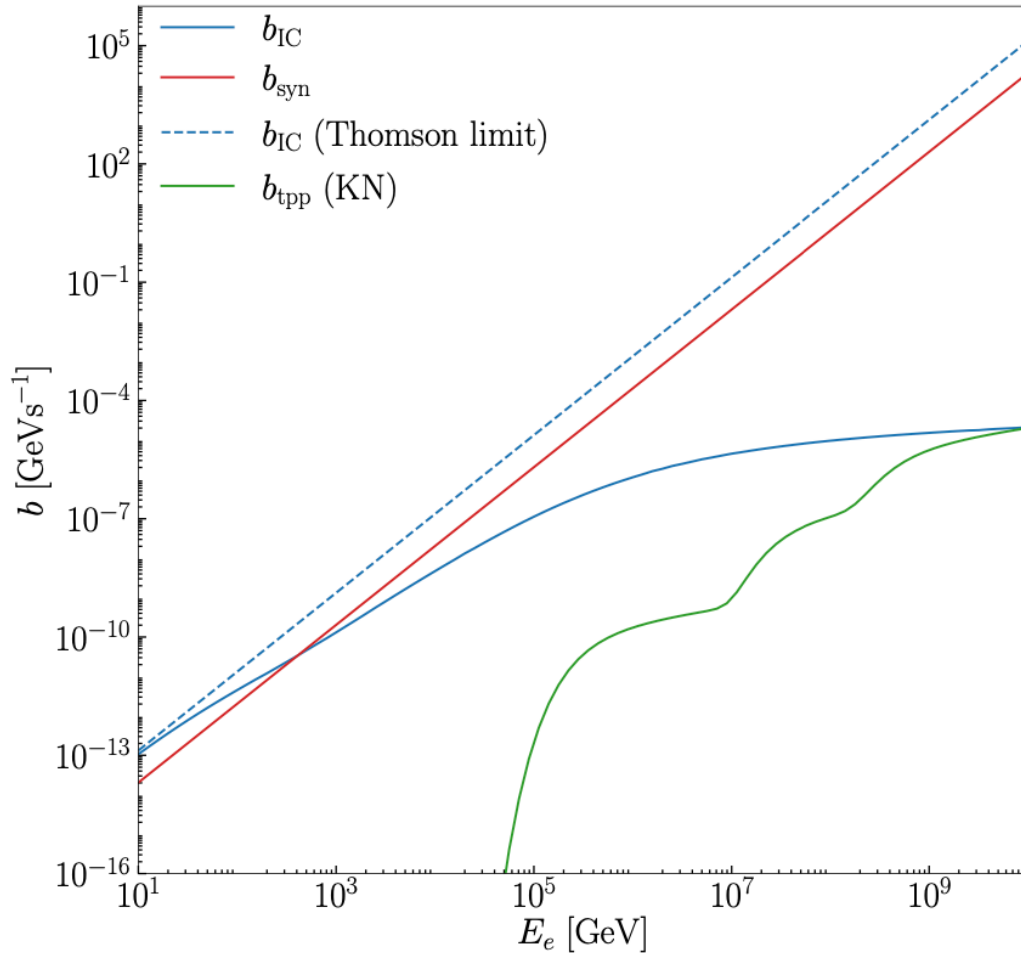


FIG. 1. Energy losses from synchrotron emission (b_{syn}) from the Galactic Center, Inverse Compton emission (b_{IC}), Inverse Compton emission in the Thomson limit (b_{IC} Thomson) and triplet pair production processes in the Klein-Nishina regime (b_{tpp} KN). At ultrarelativistic electron energies E_e close to half the DM mass $m_\chi/2$, synchrotron emission vastly dominates over IC and TPP emission.

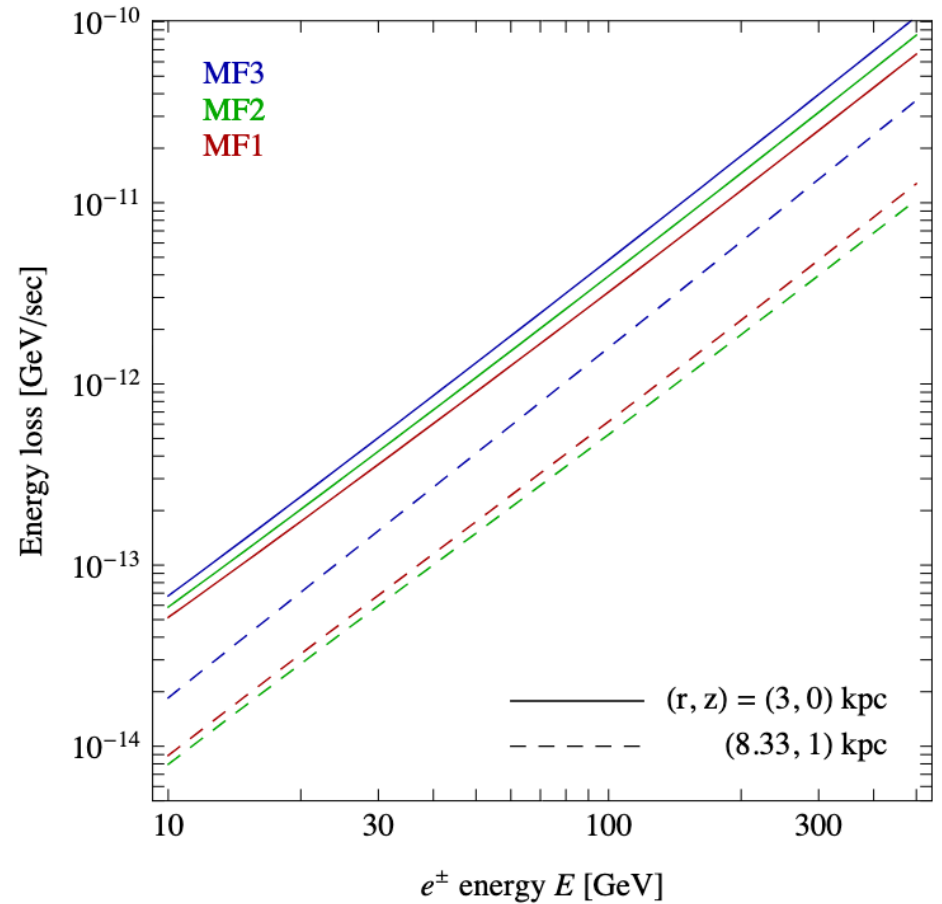
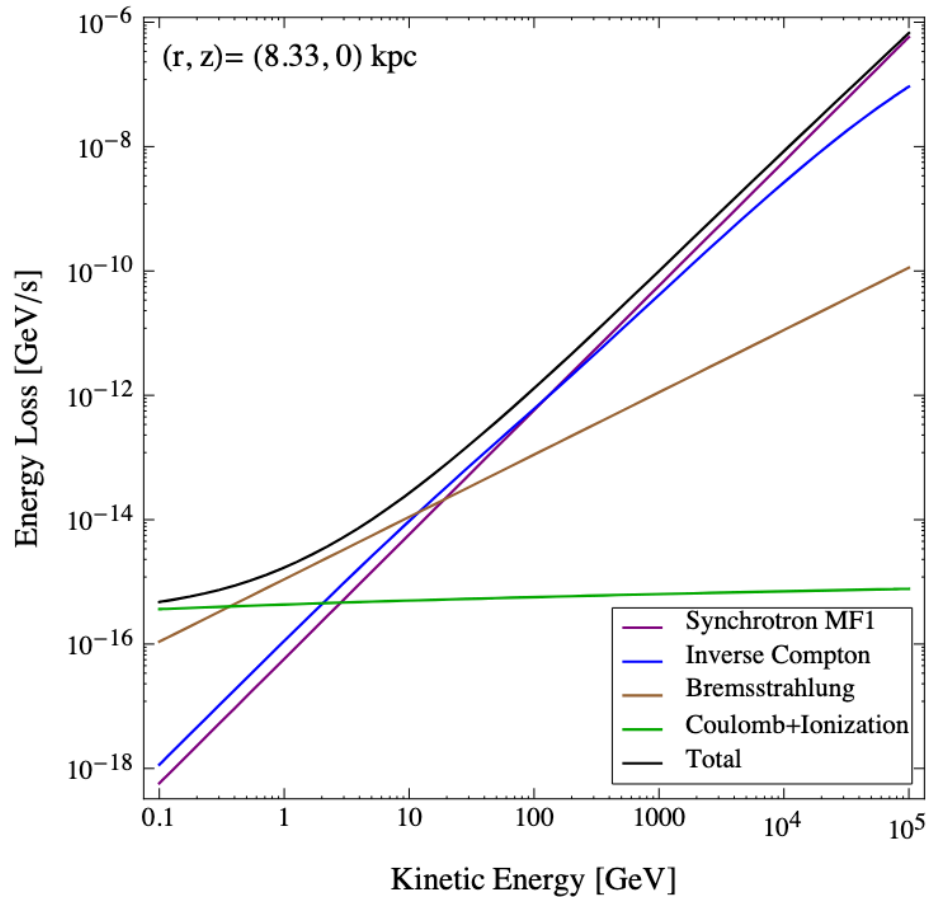


Figure 3: *Left panel: the **different processes** contributing to the energy loss function, at the location of the Earth. Right panel: the dependence of the energy loss coefficient function on the choice of magnetic field model, in two locations.*

Hillas Formula

$$E \approx ZevBR$$

$$Z = 26$$

$$E = 10^{20} \text{ eV}$$

$$v = 0.99c$$

$$B = 10 \times 10^{-6} \times 10^{-4} \text{ T}$$

$$10^{20} \text{ eV} = 26 \times 1 \times 0.99 \times 10^8 \times 3 \times 10^{-9} \times R$$

$$\Rightarrow R \approx 1.25 \times 10^{21} \text{ m}$$

$$\approx 41.96 \text{ kpc}$$

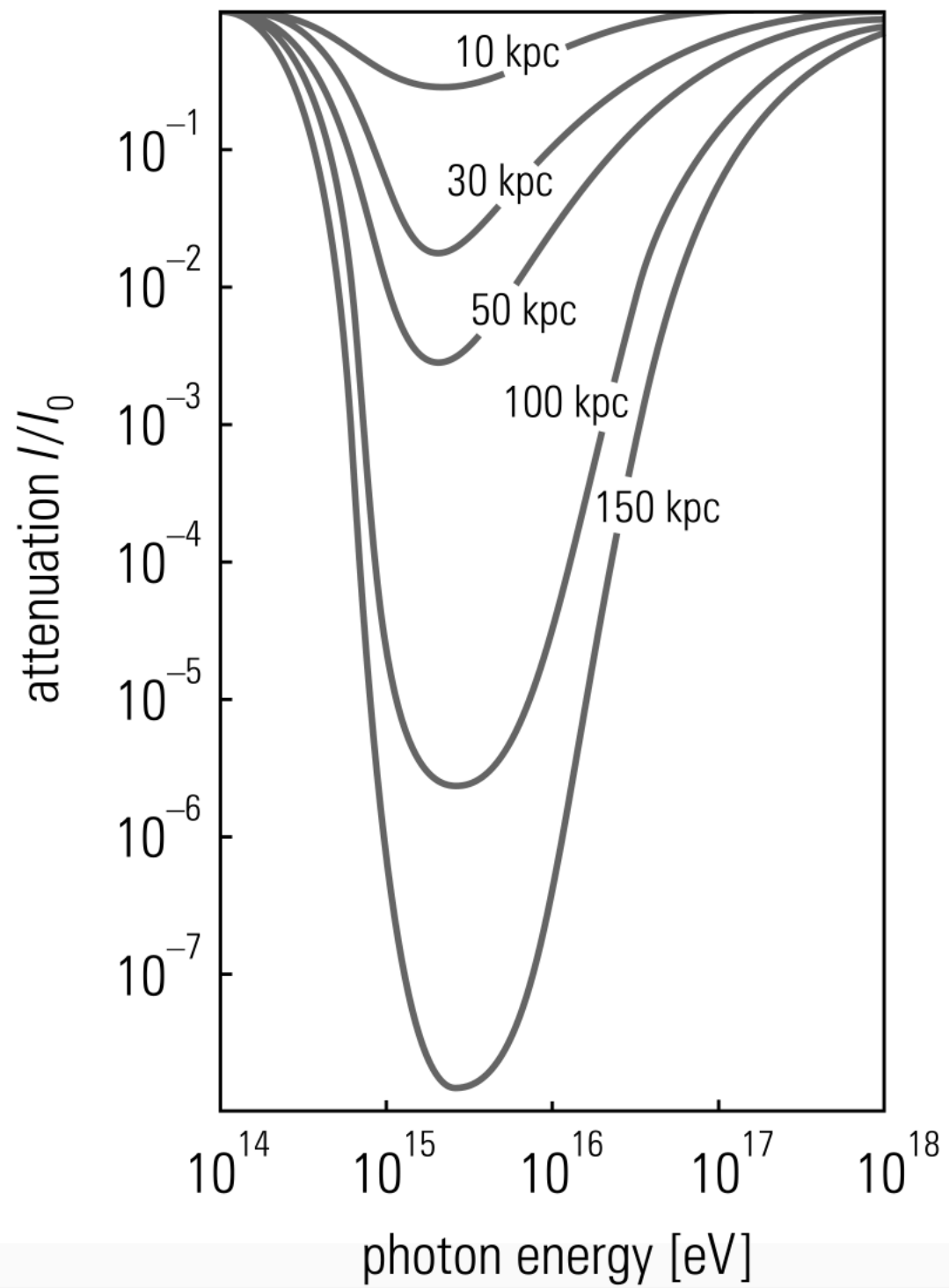
$$\approx 8 \text{ kpc}$$

$$\approx 16 \text{ kpc}$$

$$\begin{aligned}\varepsilon_\nu Q_{\varepsilon_\nu}^{(g)} &= \frac{1}{2} (1 - e^{-f_{pp}^g}) \varepsilon_p Q_{\varepsilon_p}^{(LM)} \\ \varepsilon_\nu Q_{\varepsilon_\nu}^{(cl)} &= \frac{1}{2} [(1 - e^{-f_{pp}^{cl}}) \varepsilon_p Q_{\varepsilon_p}^{(HM)} \\ &\quad + \eta (1 - e^{-f_{pp}^{cl}}) e^{-f_{pp}^g} \varepsilon_p Q_{\varepsilon_p}^{(LM)}],\end{aligned}$$

$$\varepsilon_\nu^2 \Phi_{\varepsilon_\nu} = \frac{c}{4\pi} \int \frac{\varepsilon_\nu Q_{\varepsilon_\nu}^{(g)} + \varepsilon_\nu Q_{\varepsilon_\nu}^{(cl)}}{(1+z)} \left| \frac{dt}{dz} \right| dz, \quad (18)$$

2018). Then, the effective pp optical depth is estimated to be $f_{pp}^g = \kappa_{pp} c g(z) n_{g,0} \sigma_{pp} \min[t_{\text{dyn}}, t_{\text{diff}}] \simeq 0.24 g(z) \left(\frac{n_{g,0}}{1 \text{ cm}^{-3}}\right) \left(\frac{\sigma_{pp}}{50 \text{ mb}}\right) \left(\frac{\min[t_{\text{dyn}}, t_{\text{diff}}]}{10 \text{ Myr}}\right)$ in the merging galaxy system. The ambient magnetic field en-



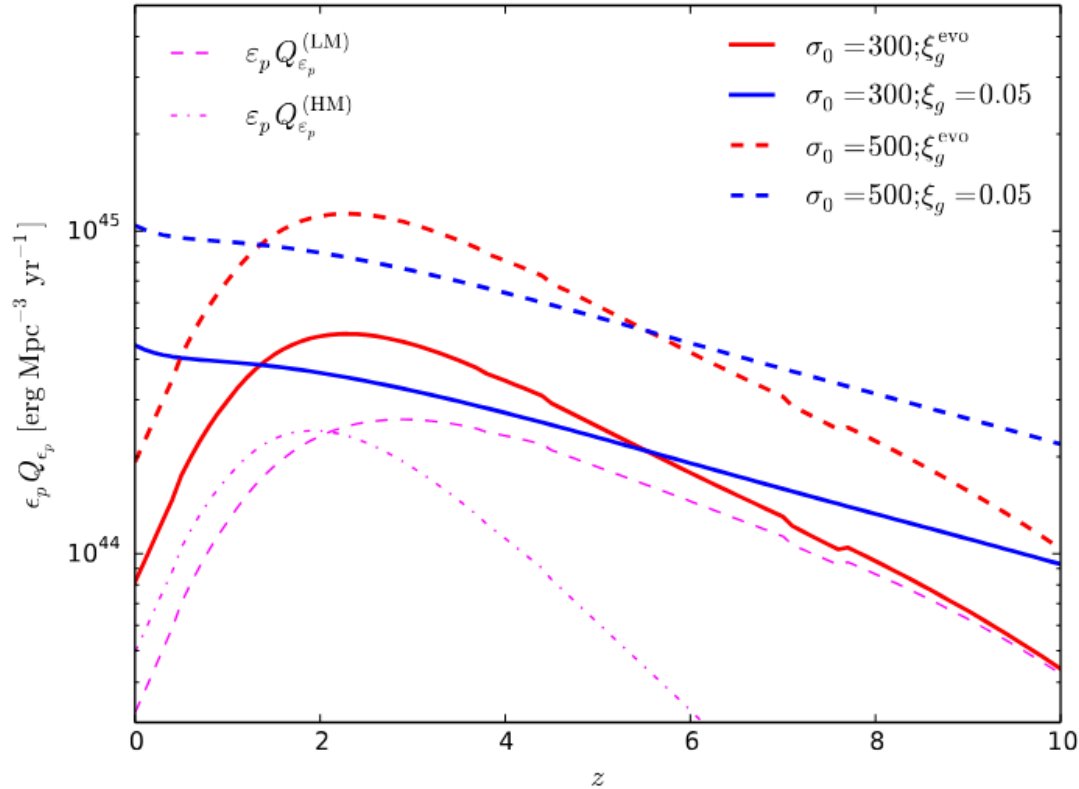
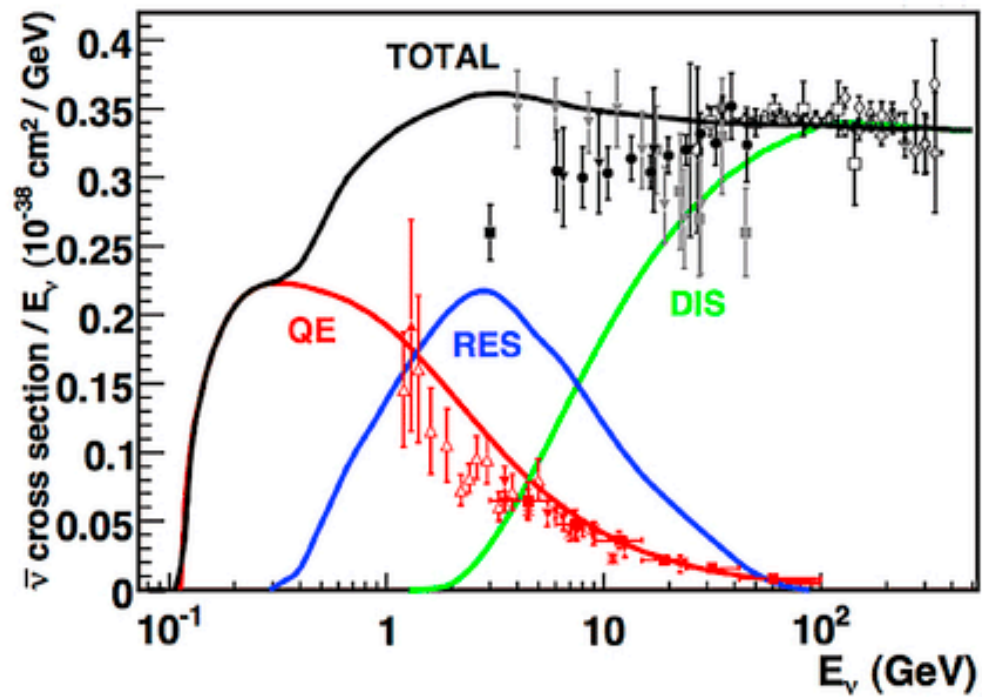
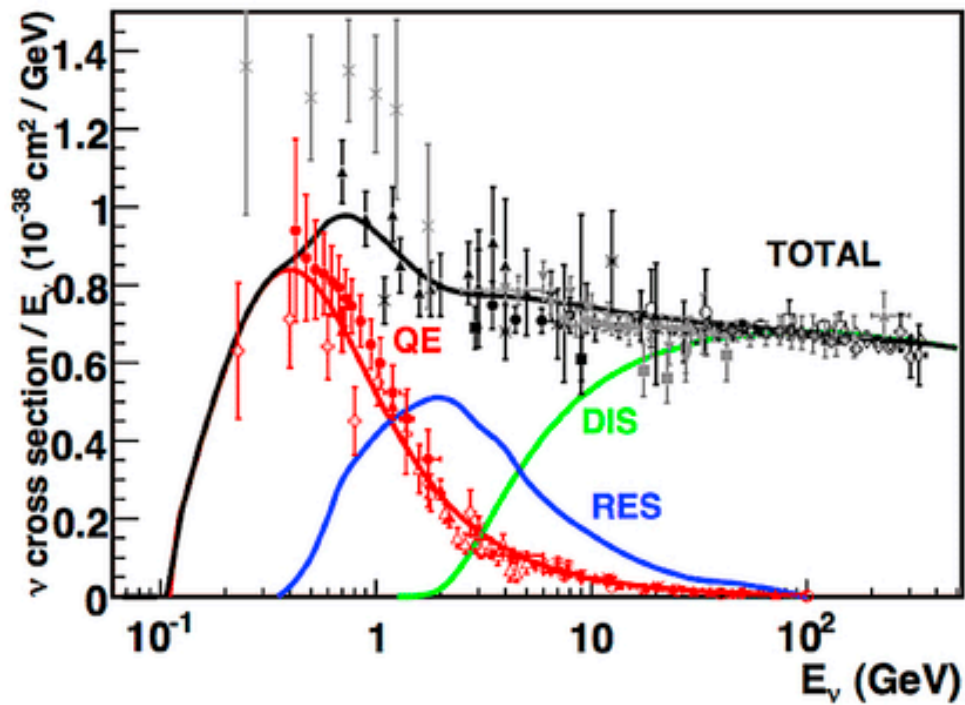
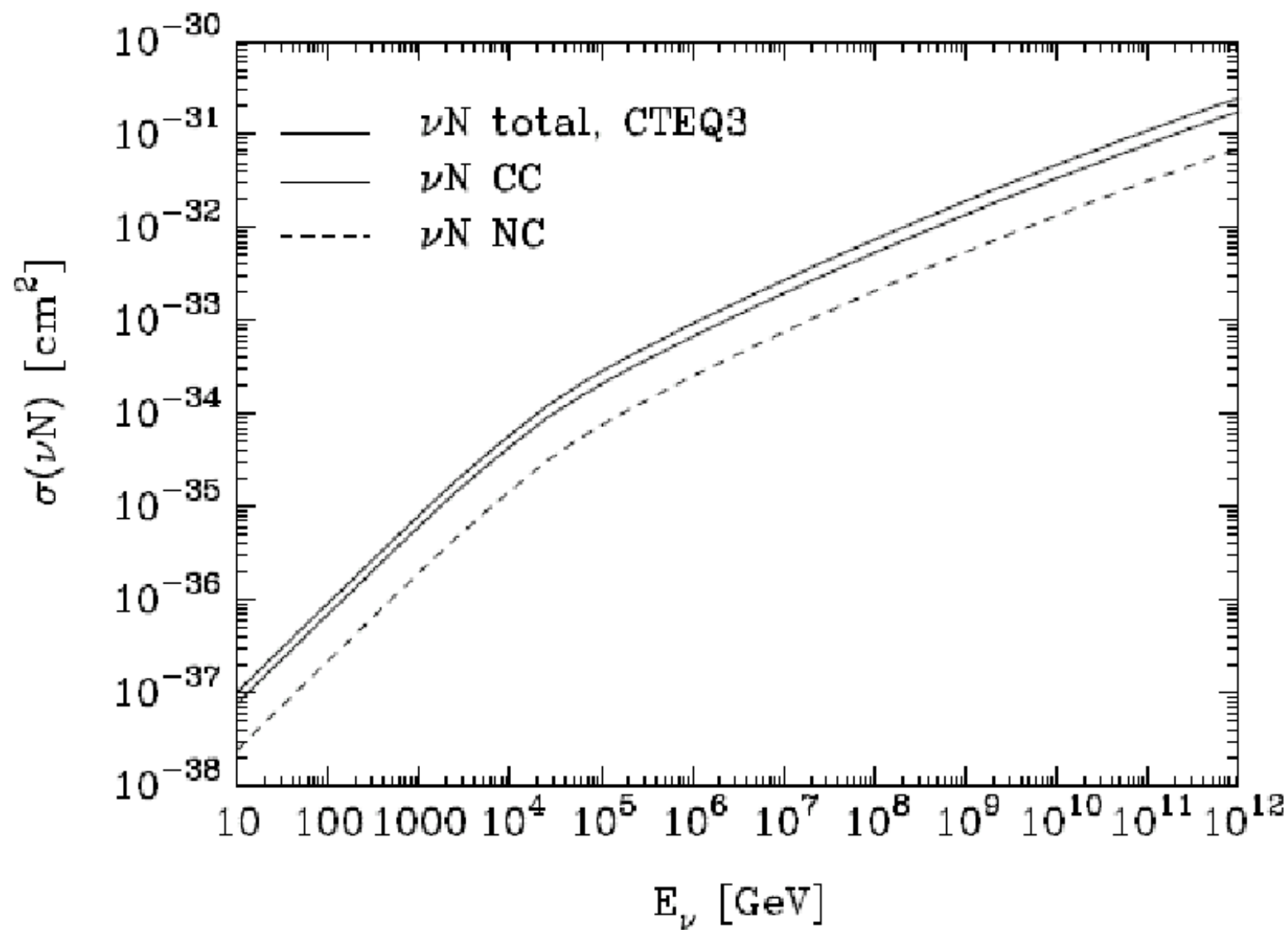
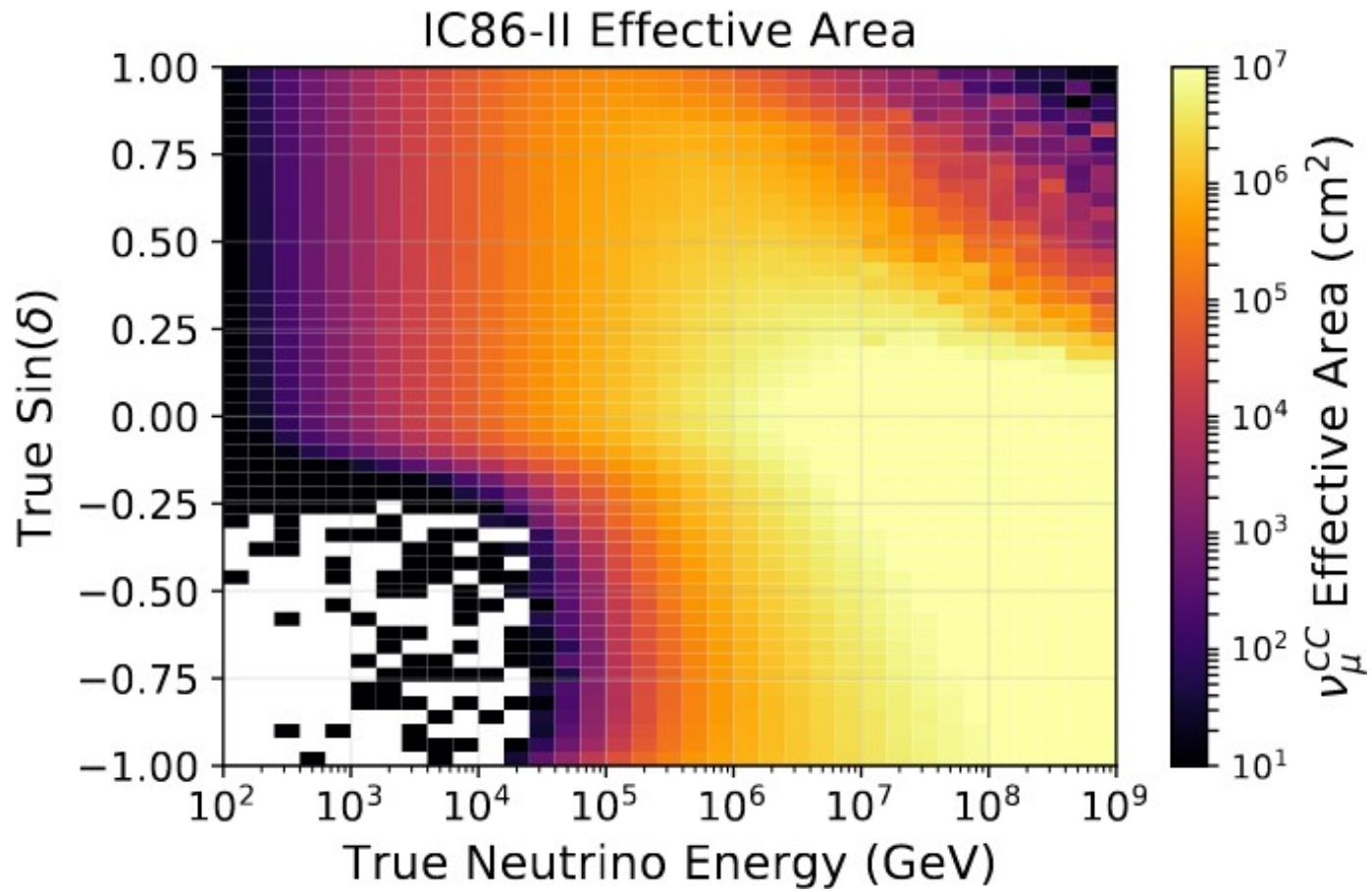


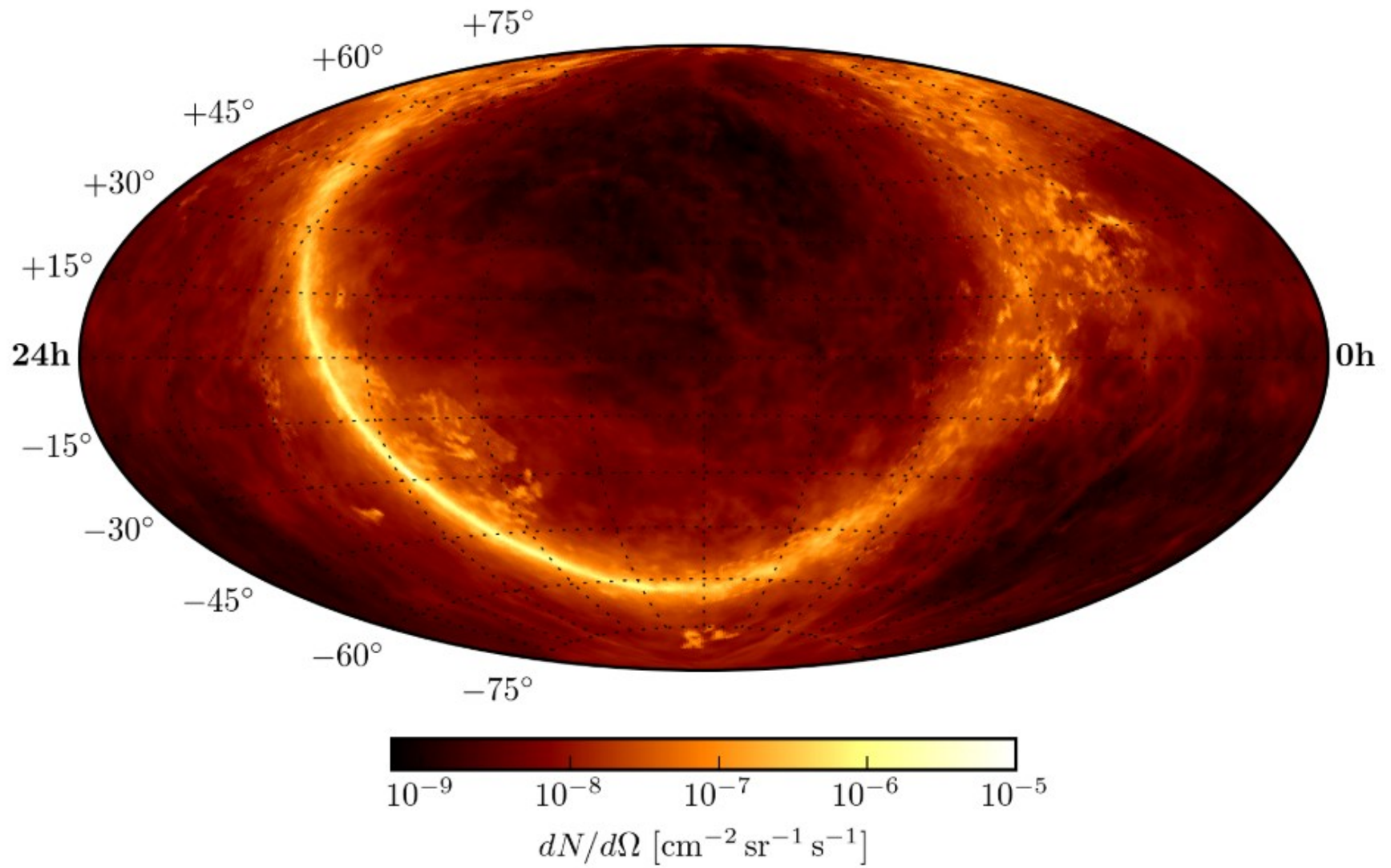
Figure 3. CR energy input rate versus redshift. The red lines correspond to a redshift-dependent gas fraction ξ_g^{evo} and the blue lines are for a redshift-independent gas fraction $\xi_g = 0.05$, while the solid lines are for $\sigma_0 = 300$ and the dashed are for $\sigma_0 = 500$, respectively. The dashed and dash-dotted magenta lines are LM and HM components of $(\sigma_0 = 300, \xi_g^{\text{evo}})$ scenario. Here LM and HM denote the low-mass ($10^{10} M_\odot - 10^{13} M_\odot$) and high-mass ($10^{13} M_\odot - 10^{15} M_\odot$) intervals, respectively.







Courtesy: IceCube collab.



Diffuse galactic gamma ray flux