First Search for High-Energy Neutrino Emission from Galaxy Mergers

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arXiv: 2404.06539

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ISAPP School „Neutrinos and Dark Matter – in the lab and in the Universe"

What are the sources of Cosmic Ray?

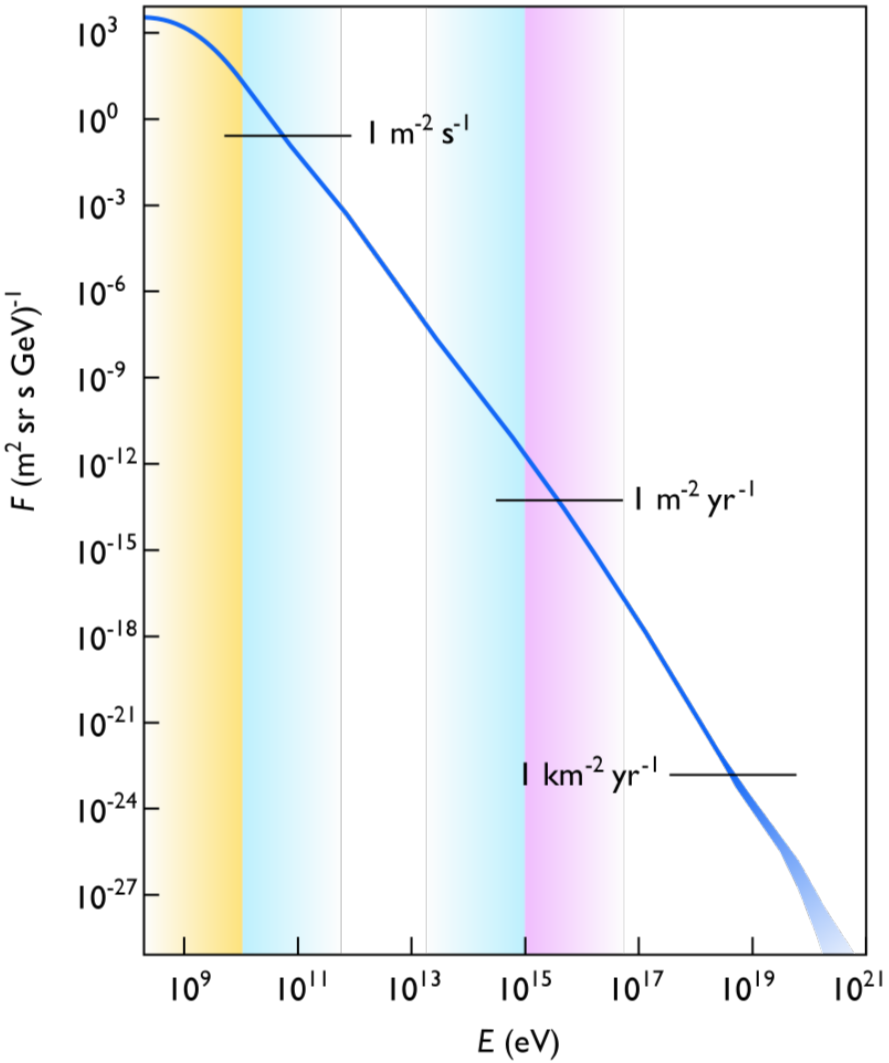


Fig: Cosmic flux versus particle energy at the top of Earth's atmosphere (credit: wikipedia)

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

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

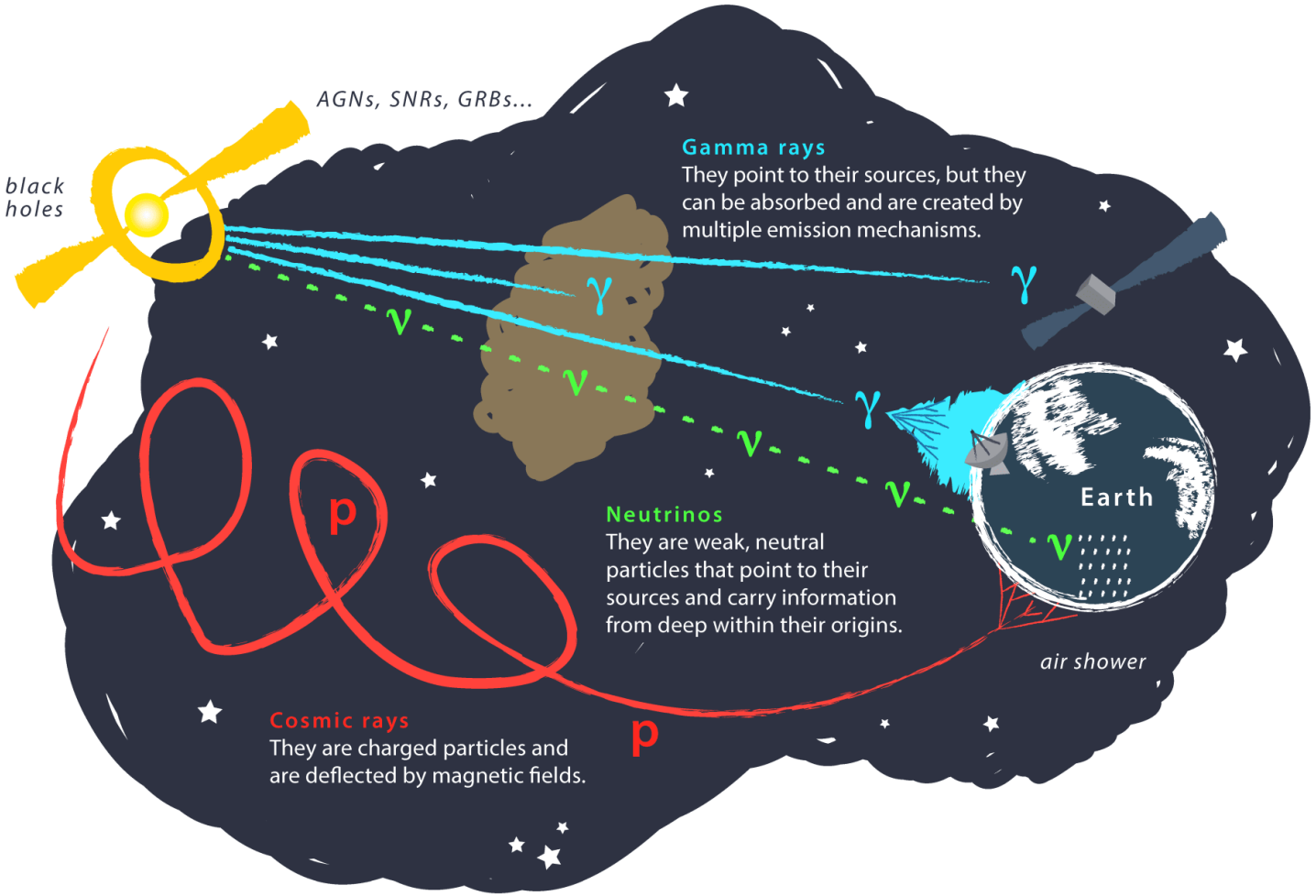
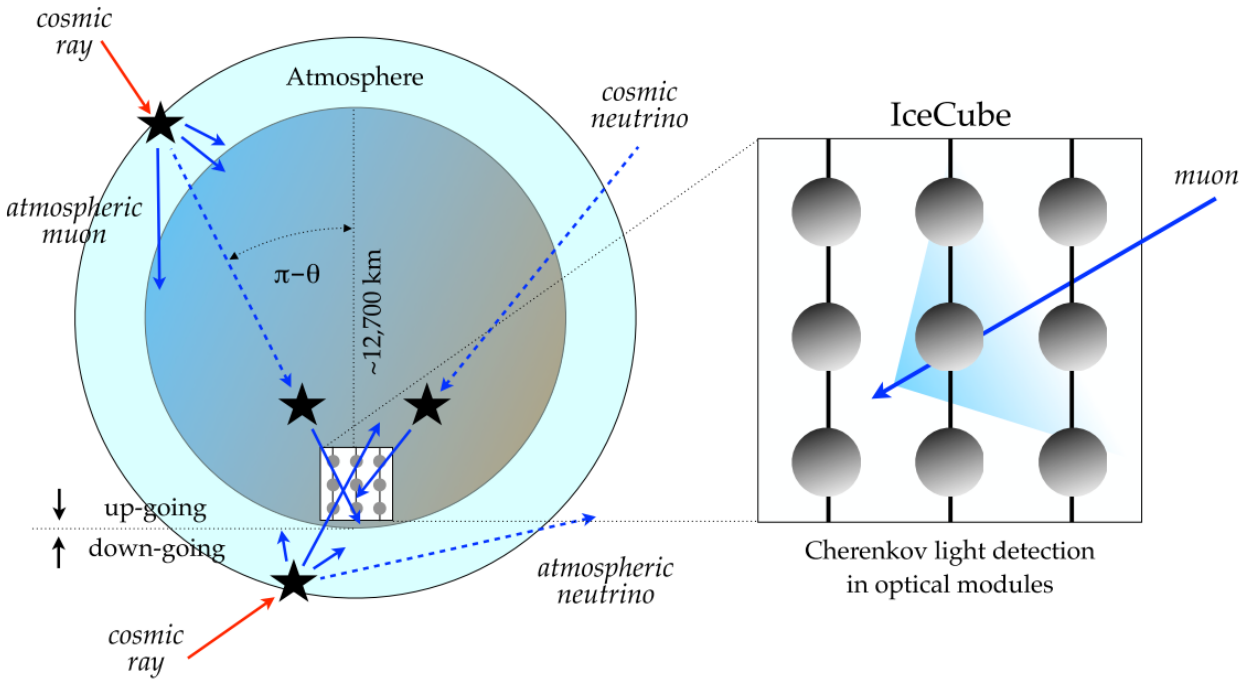
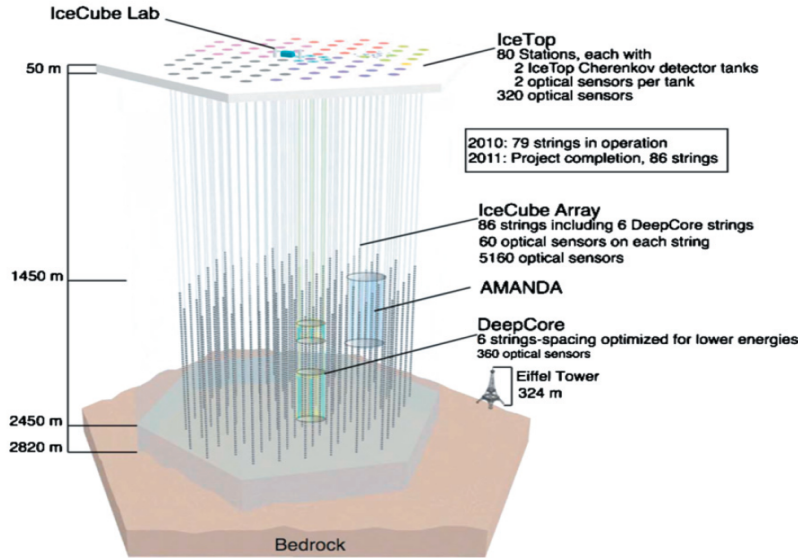


Image courtesy: Juan Antonio Aguilar and Jamie Yang. IceCube/WIPAC

How IceCube detects neutrinos?





Courtesy: IceCube collaboration

courtesy:2202.00694

$$\nu_l + \mathrm{N} \rightarrow l + hadrons \quad \text{(Charged Current interaction)}$$

$$\nu_l + N \rightarrow \nu_l + hadrons \quad \text{(Neutral Current interaction)}$$

Similar types of interactions happen for anti-neutrinos.

Current status of the high-energy astrophysical neutrino sources

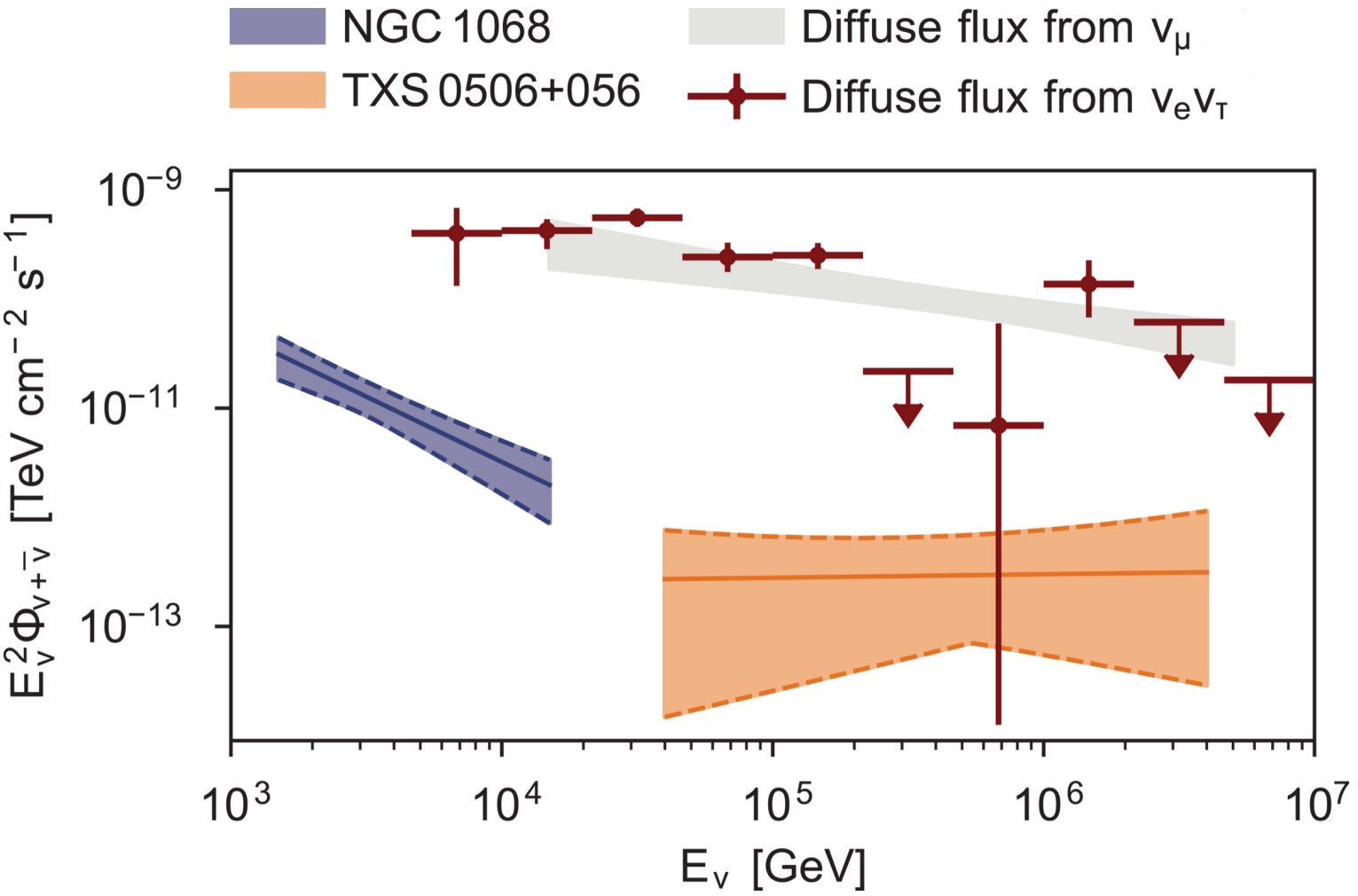


Fig: The high energy neutrino flux observed by IceCube. TXS 0506+056 and NGC 1068 are confirmed high-energy astrophysical neutrino sources till now. We also observe a high-energy diffuse astrophysical neutrino (in all flavors) flux. Currently, we do not know what sources contribute entirely to the high-energy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

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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]

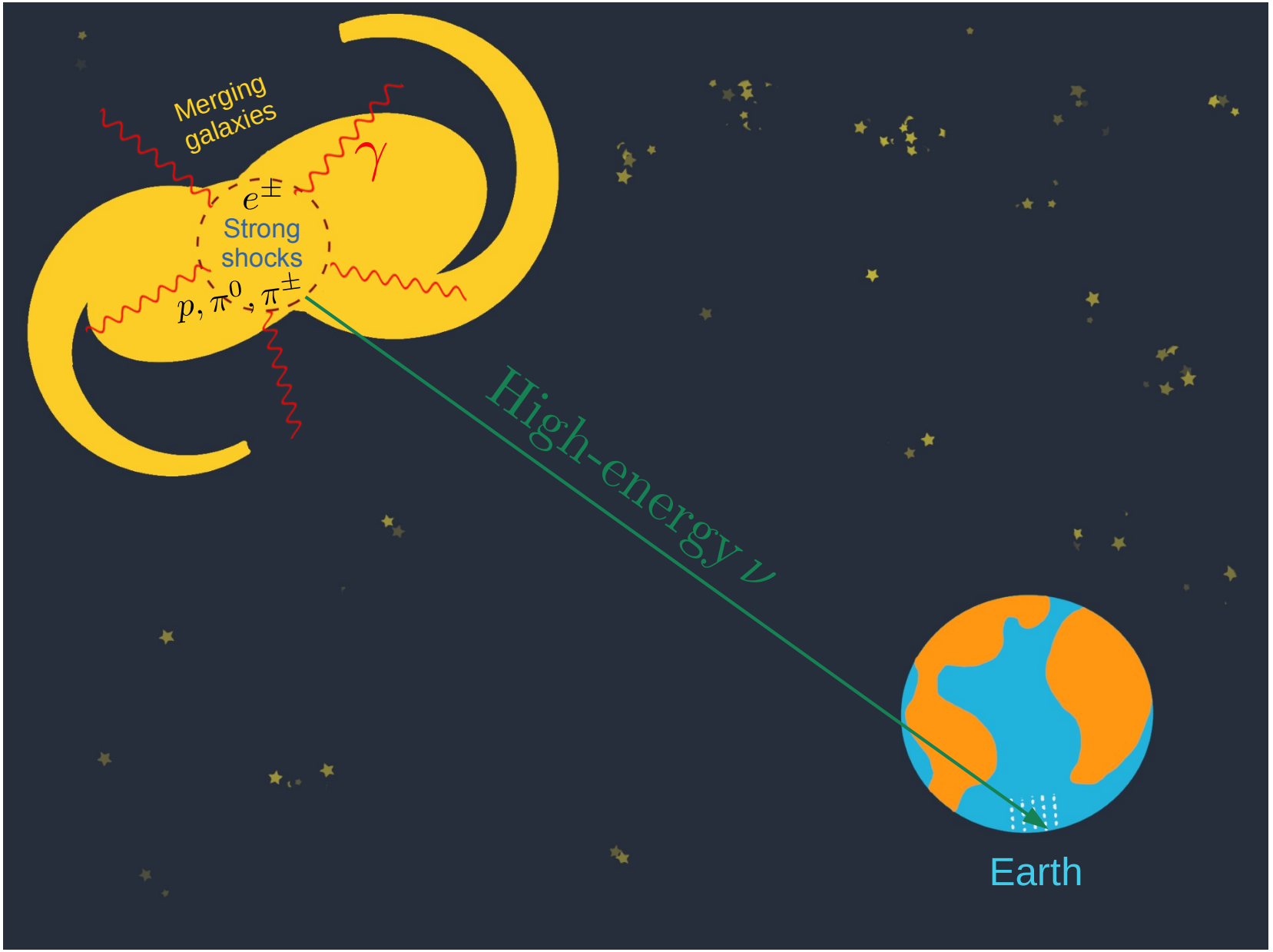
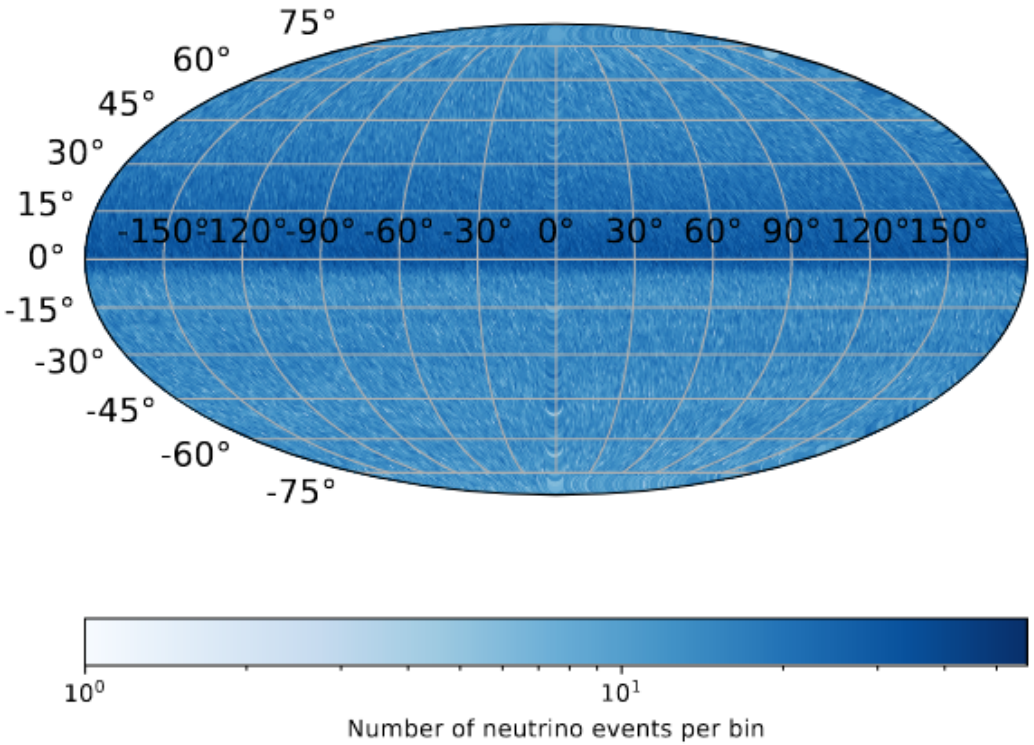
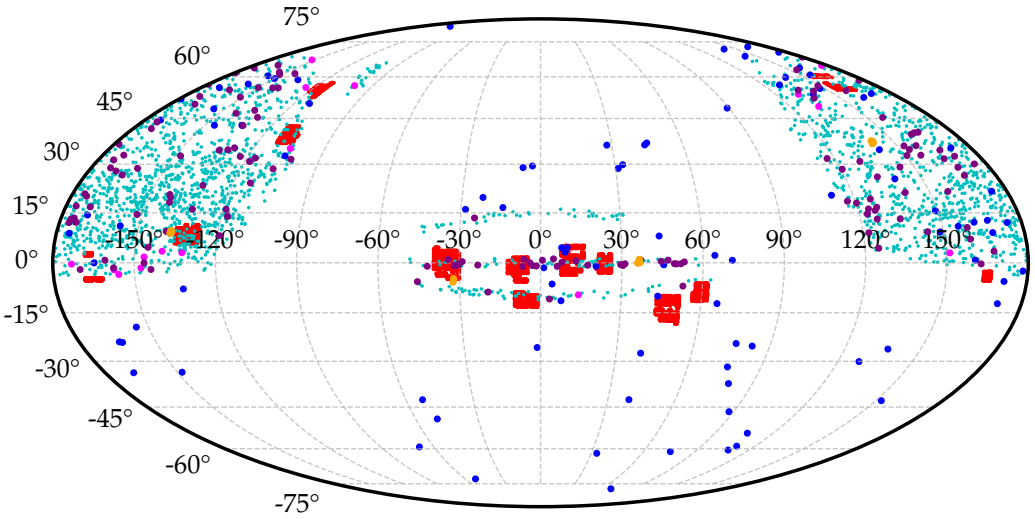


Fig: Schematic figure showing the merger of two galaxies. The shock is in the core region where interactions occur and neutrinos as well as electromagnetic radiation are produced.





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

Analysis Formalism

- Single Source Analysis

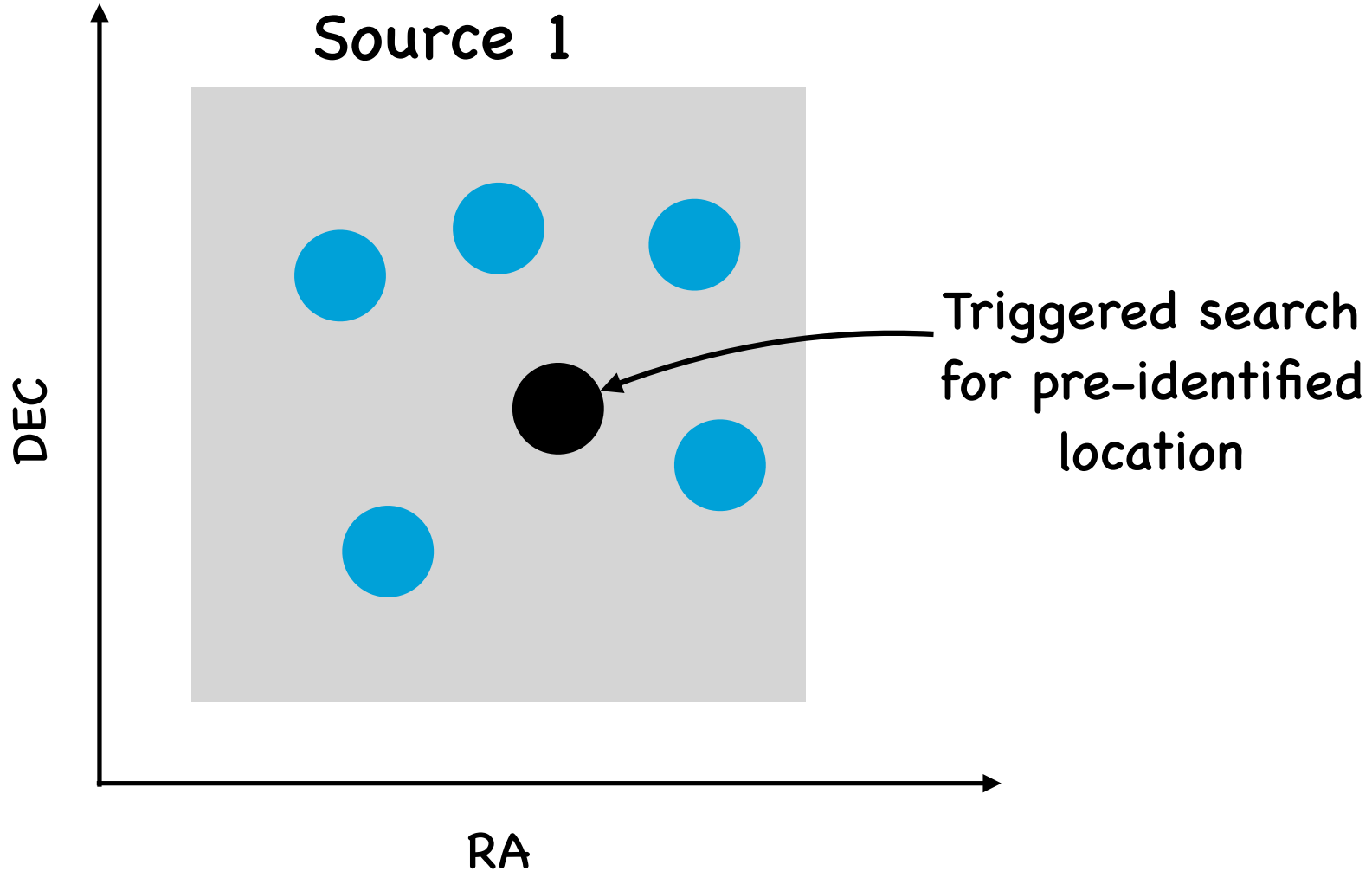


Fig: schematic representation of Single source analysis

Analysis Formalism

- Stacking Analysis

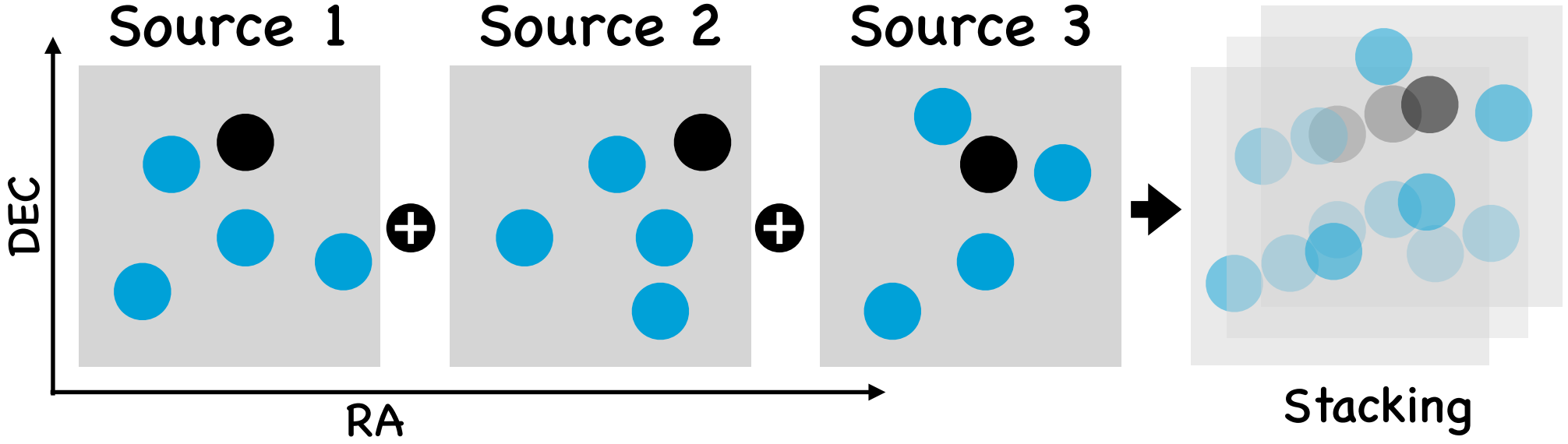


Fig: Schematic representation of Stacking analysis, search for collective neutrino emission from a catalog/class of sources

Analysis Formalism

- Test Statistic:

$$TS(n_s) = 2\,log\,\frac{\mathscr{L}(n_s)}{\mathscr{L}(n_S = 0)}$$

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.

$$\mathrm{PDF}\,(TS_{max}) \approx \chi^2_1(TS_{max})$$

Results: Single Source analysis

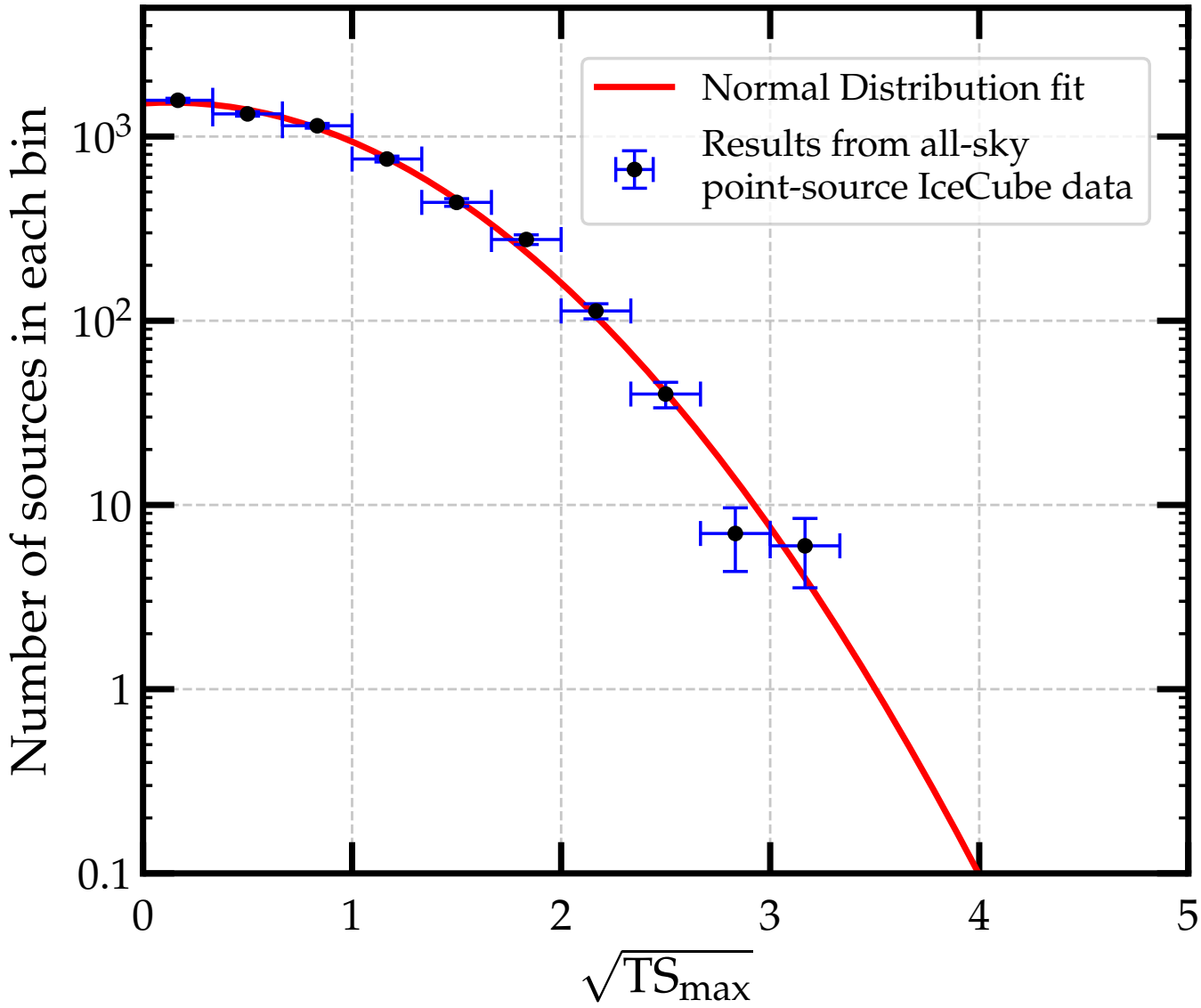
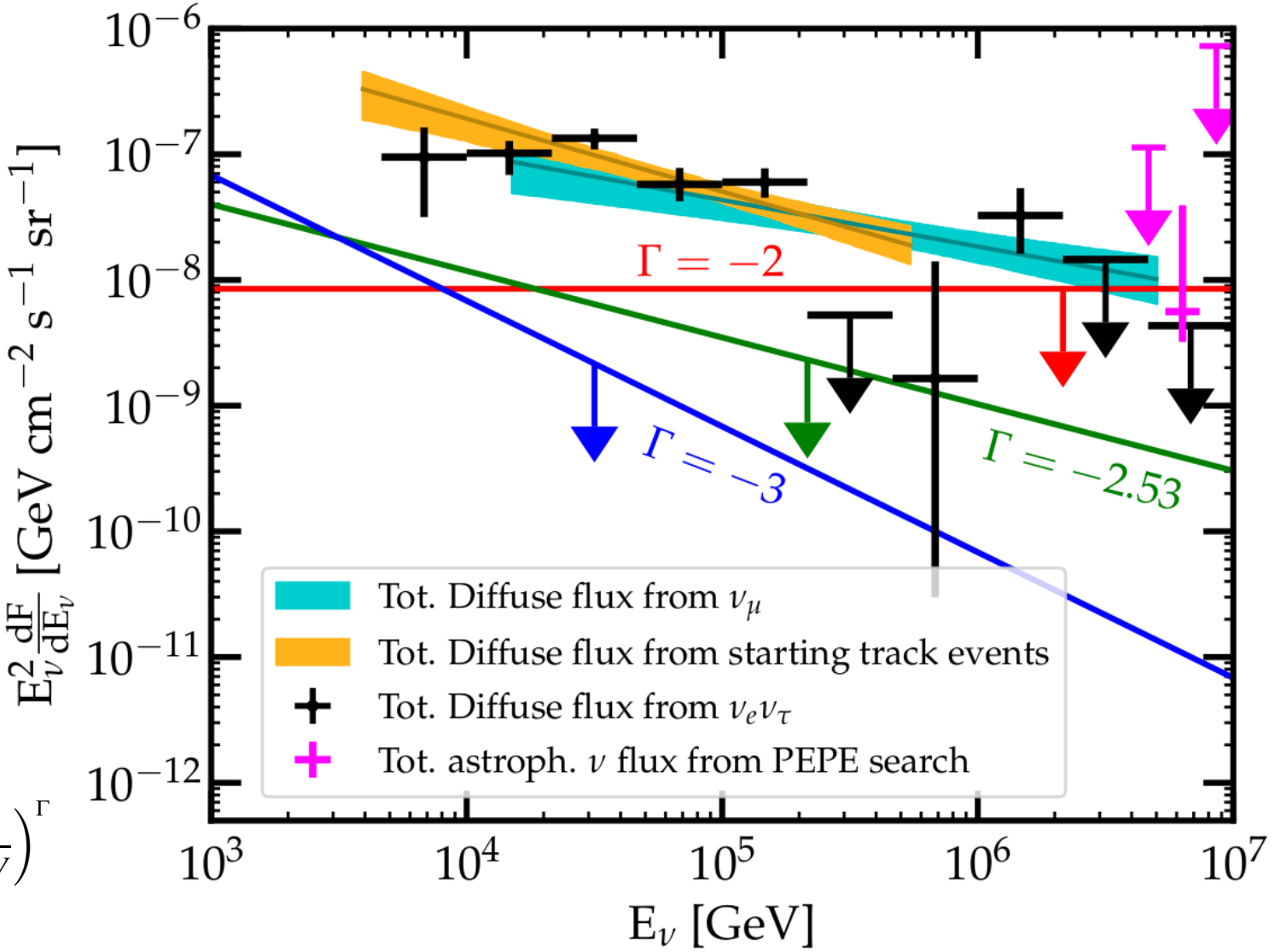


Fig: Distribution of square root of maximized TS values for all galaxy mergers from our likelihood analysis with 10 years of IceCube muon-track data. The normal distribution favours the null hypothesis implying high-energy astrophysical neutrinos are not coming from galaxy mergers. (Our work)

Results: Stacking Analysis



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

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 19.69%, 17.08% and 16.88% 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.
- We conclude that known galaxy mergers from the six catalogs do not contribute significantly to the diffuse neutrino flux detected by IceCube. Our study implies strong constraints on very high-energy hadronic cosmic-ray acceleration in galaxy mergers. Near future searches of neutrinos from galaxy mergers can either discover their neutrino production or produce even more stringent constraints on their very high-energy hadronic acceleration mechanism.

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Thank you!

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Back Up Slides!

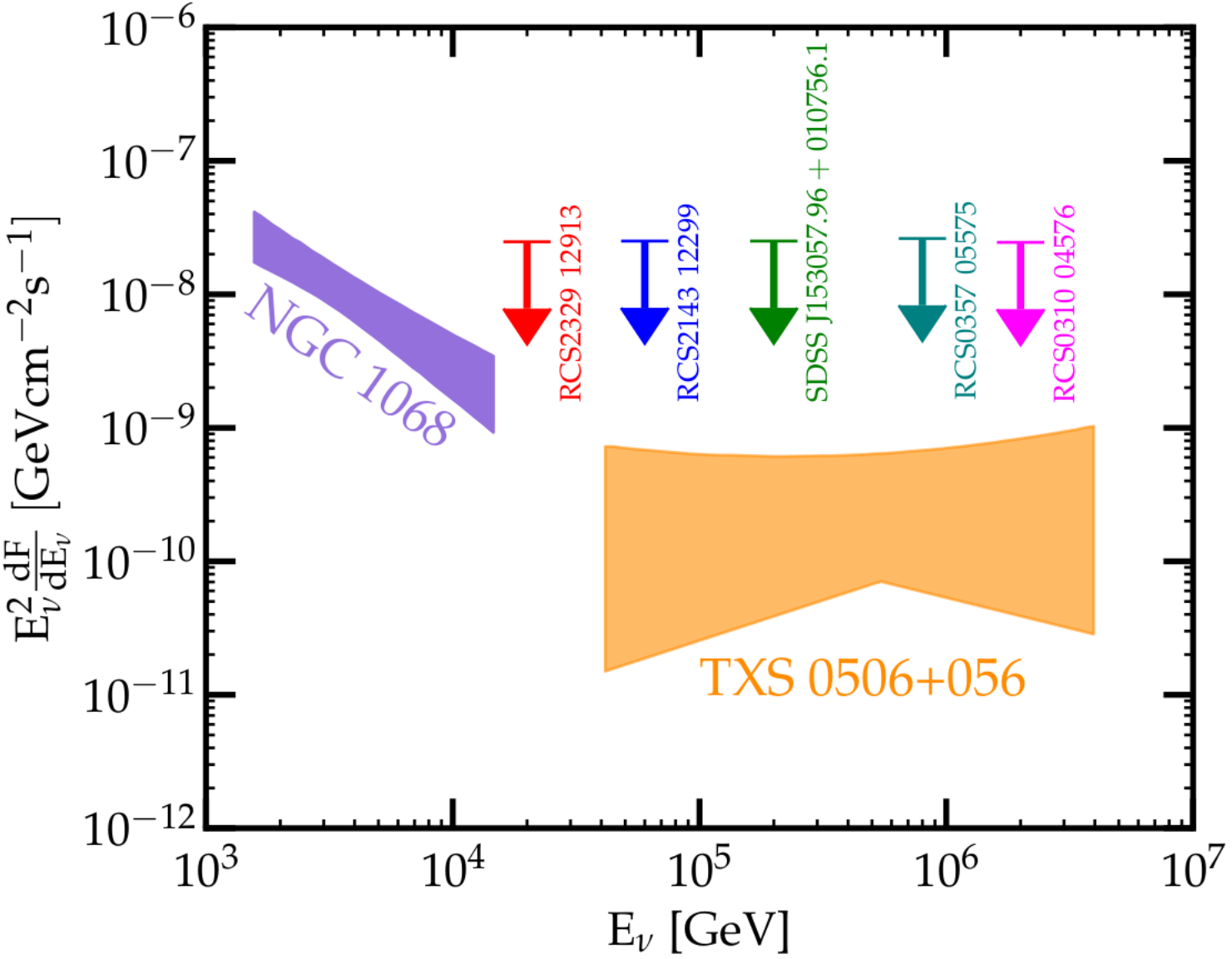
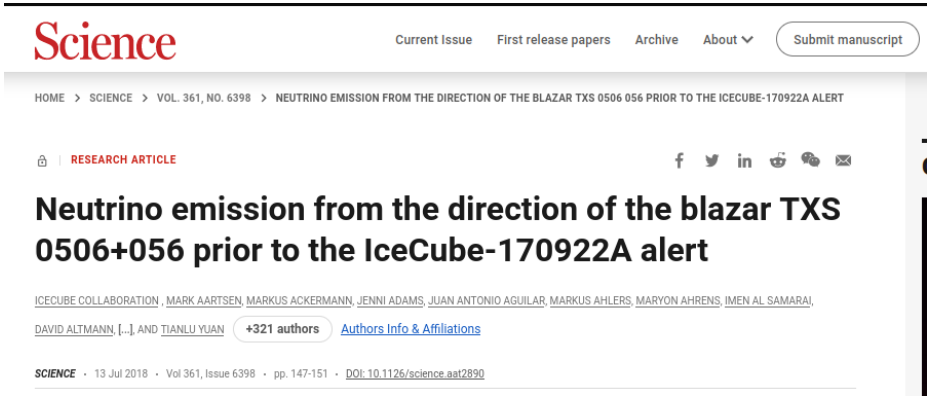


Fig: Upper Limit of the total neutrino flux of the five most significant mergers

Sources of High Energy Astrophysical neutrinos?



Sources: GRB, FRB, AGN, Radio Pulsars??

Radio bright AGNs can account for at most 30% (95% CL) of the diffuse astrophysical neutrino flux measured by IceCube!

Other sources?

What are other powerful hadronic accelerators in the cosmos?

- Galaxy mergers: can host powerful hadronic collision and photohadronic processes when galaxies collide.

- Are neutrinos detected by IceCube coming from Galaxy mergers?

Fig: Galaxy merger [Credit: International Gemini Observatory]

Galaxy mergers: source of Astrophysical neutrino?

- By the shock acceleration of particles in massive galaxy mergers or collisions cosmic rays (CRs) can be accelerated up to the second knee energy 0.1-1 EeV.

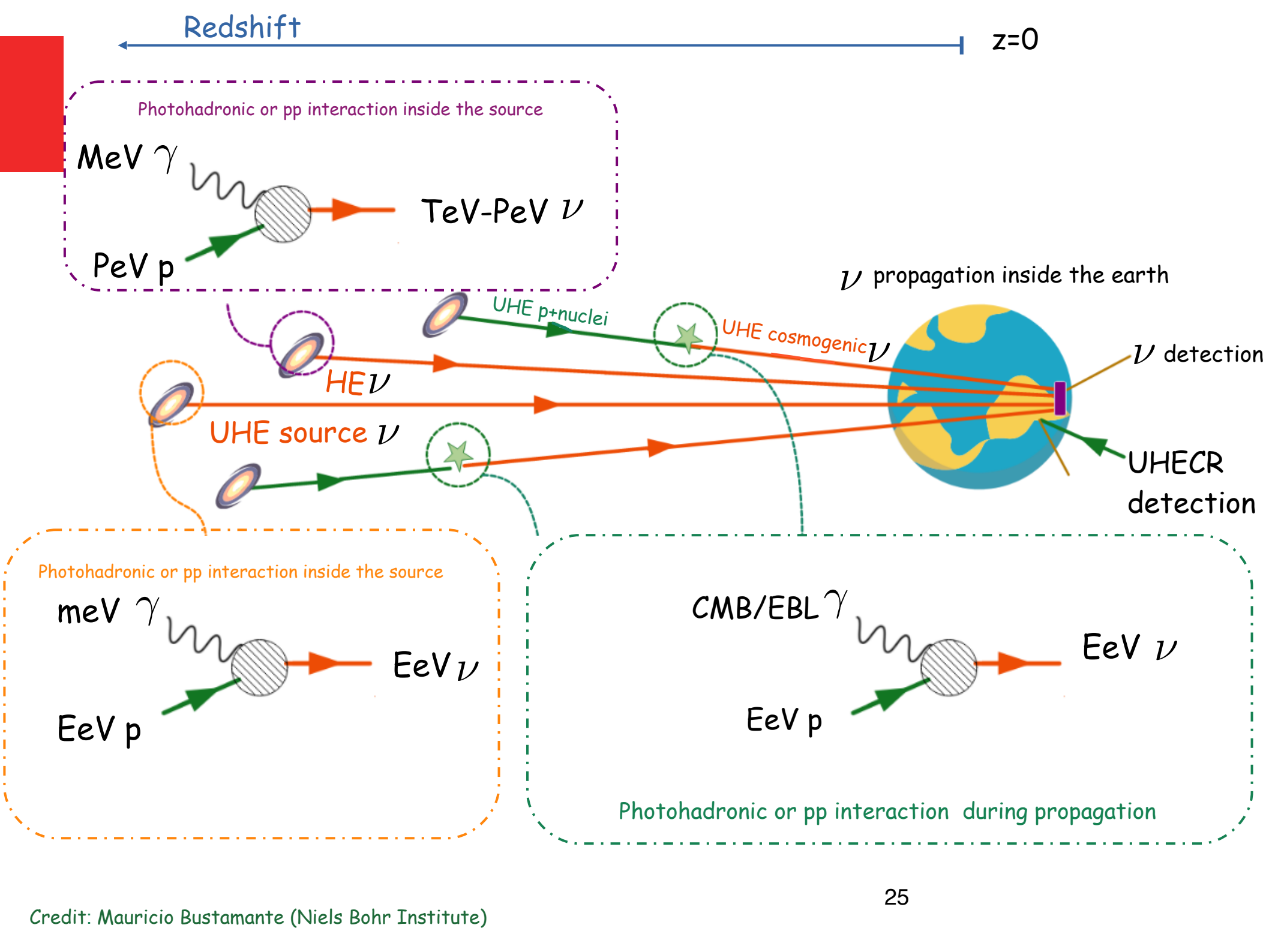
- Such CRs lose their energy via hadronuclear interactions within a dynamical timescale of the merger shock, producing gamma rays and neutrinos as a by-product.

1. Kazumi Kashiyama and Peter Meszaros [arXiv:1405.3262]
2. Yuan, Mészáros and Murase , and Donghui Jeong [arXiv:1712.09754]

Wilk's Theorem

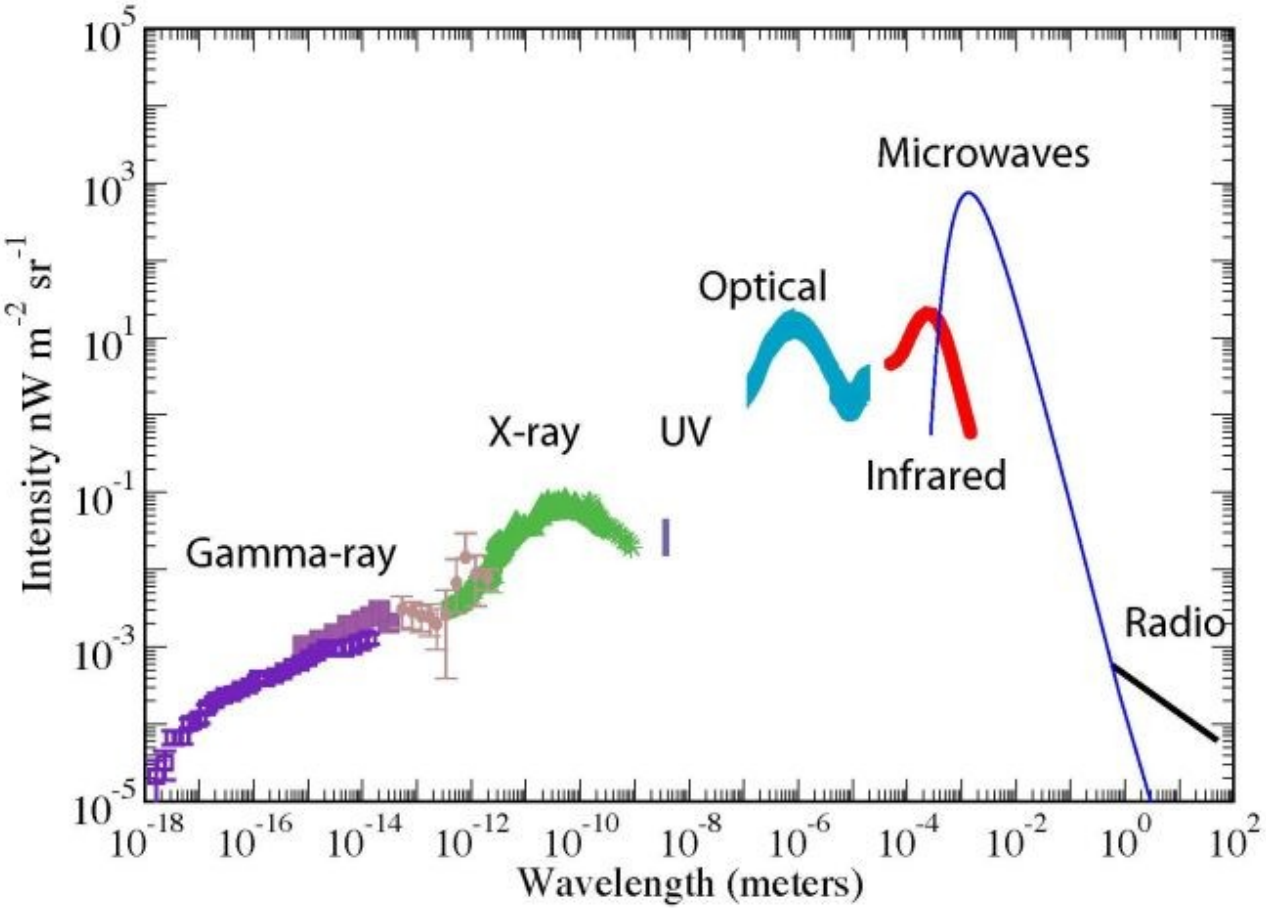
- If the background hypothesis is true, the probability distribution for TS_{max} is approximately a χ^2 distribution.

$$\mathrm{PDF}(\mathrm{TS}_{max}) \approx \chi^2_1(\mathrm{TS}_{max})$$



Credit: Mauricio Bustamante (Niels Bohr Institute)

EBL



Courtesy: NASA

Pair production CC

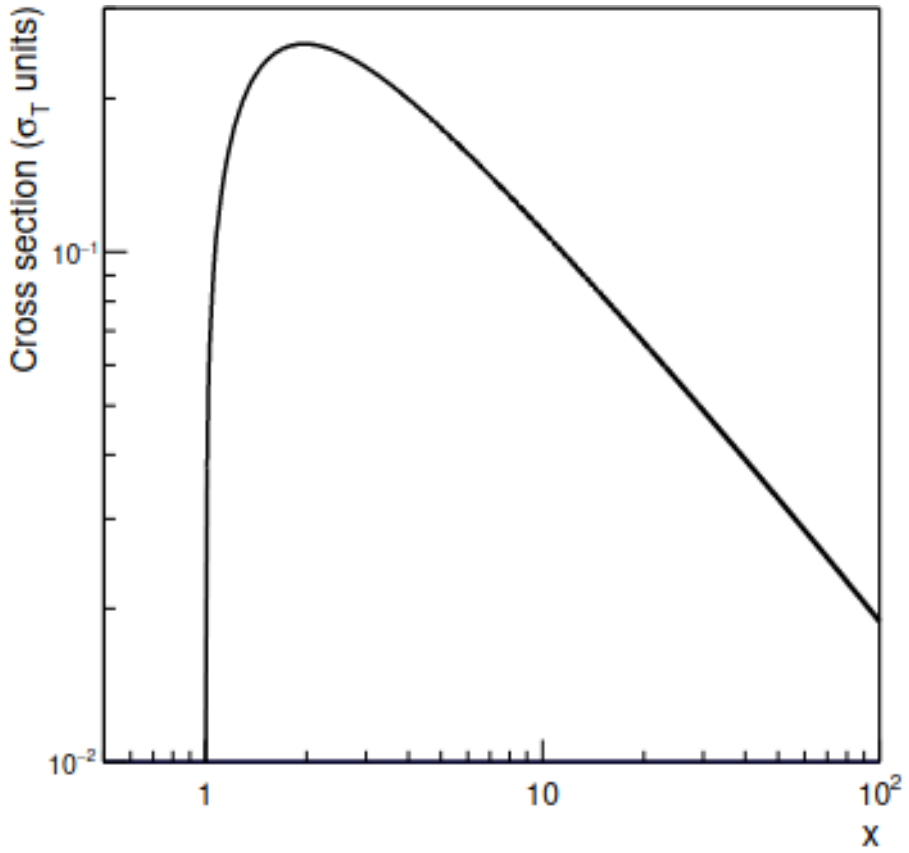
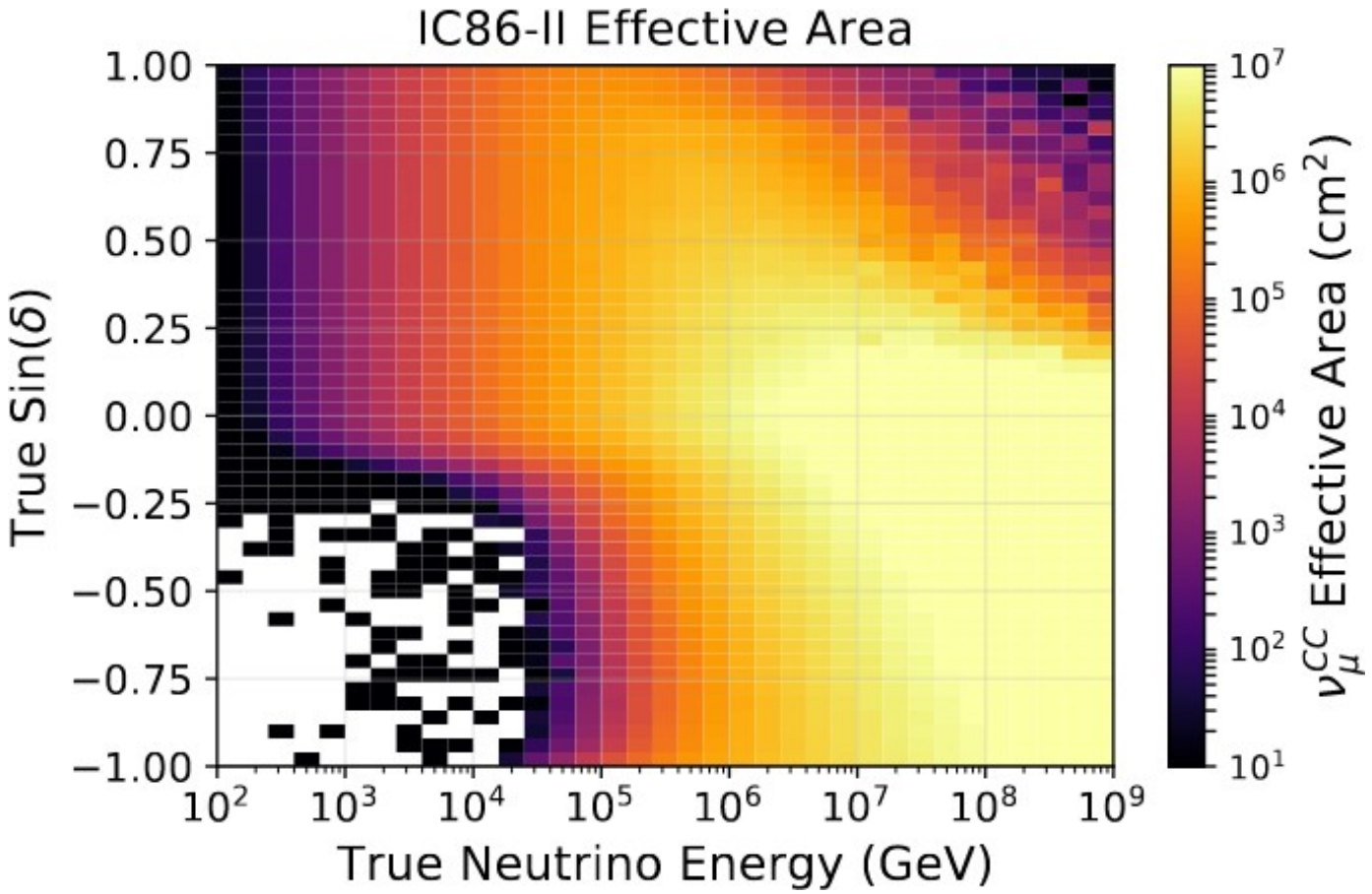
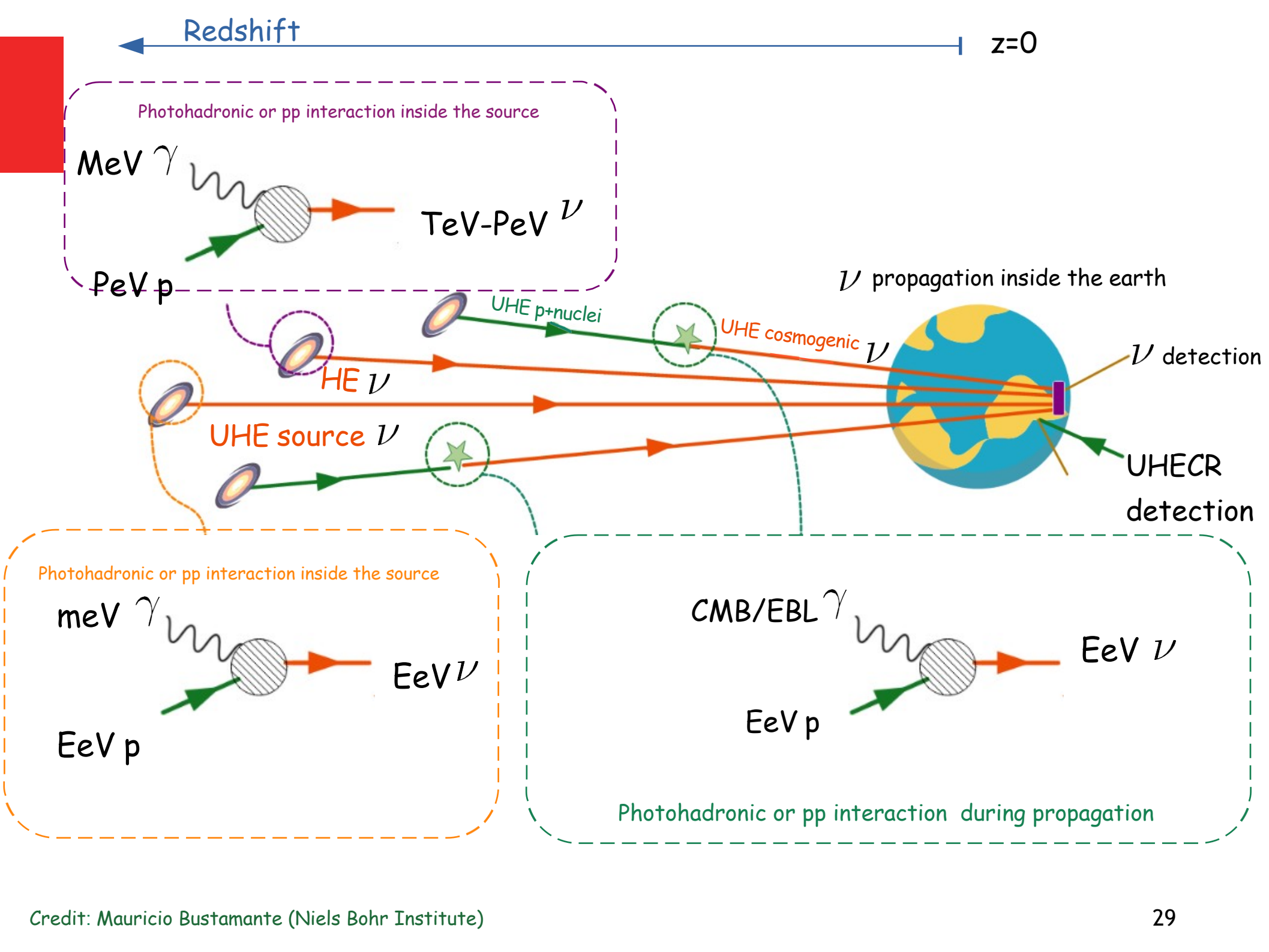


FIG. 1: Pair production cross section plotted as a function of the variable $x = s/(4m_e^2)$. σ_T is the Thomson cross section.



Courtesy: IceCube collab.



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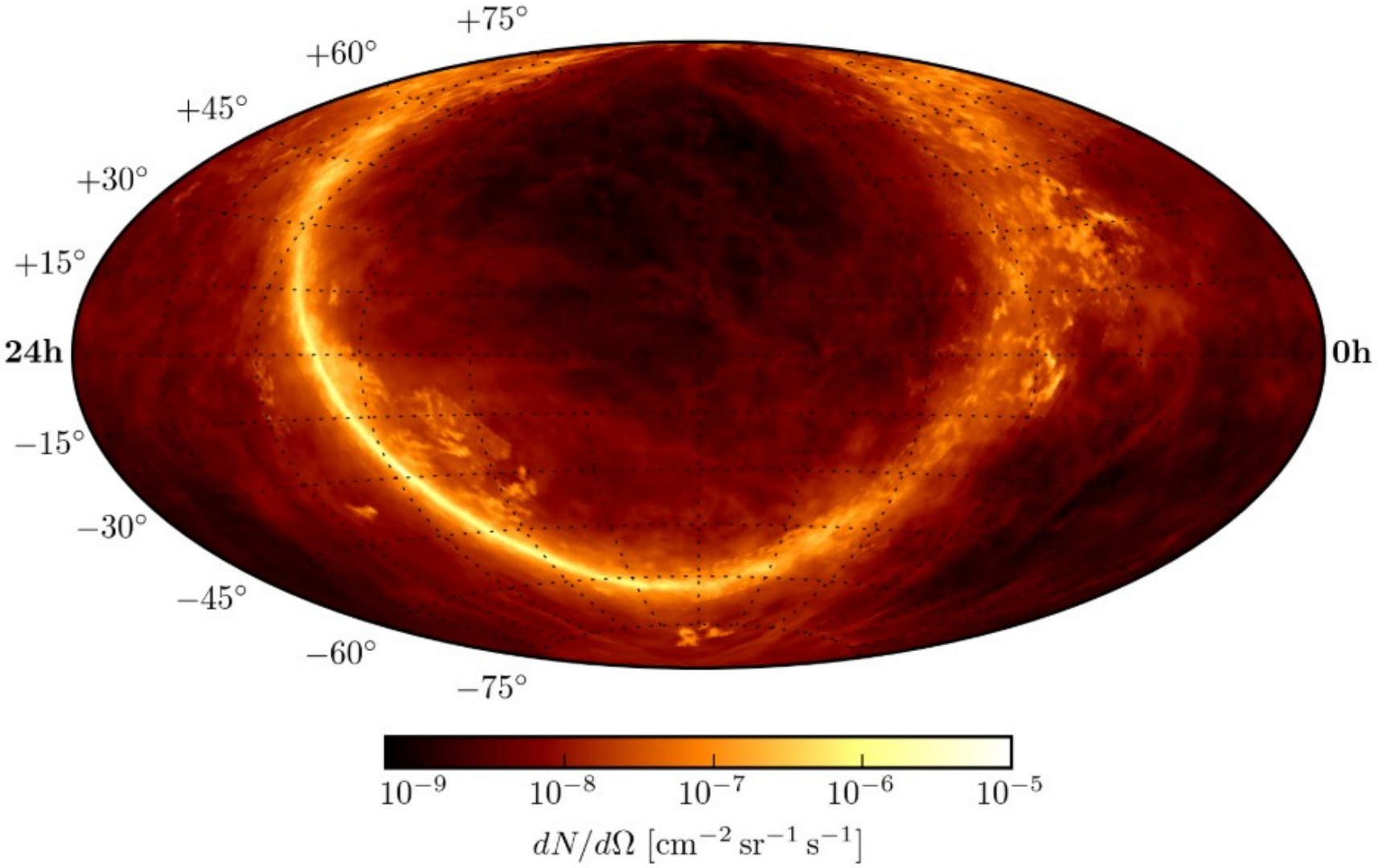

Diffuse galactic gamma ray flux