The Cosmic Neutrino Background is within Reach of Future Neutrino Telescopes

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arXiv: 2601.09790; 2405.14946

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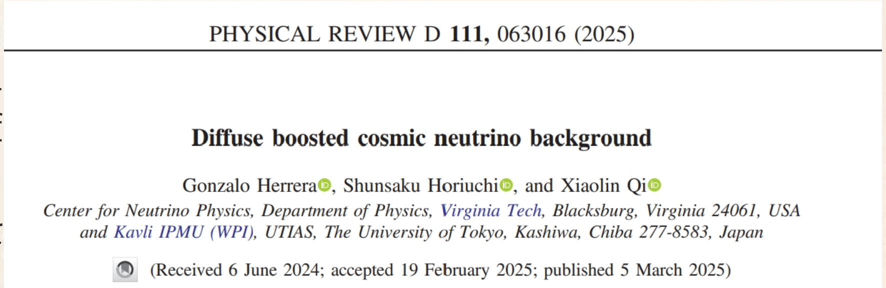

PHYSICAL REVIEW D **111,** 063016 (2025)

Diffuse boosted cosmic neutrino background

Gonzalo Herrera, Shunsaku Horiuchi, and Xiaolin Qi

Center for Neutrino Physics, Department of Physics, Virginia Tech, Blacksburg, Virginia 24061, USA
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The Cosmic Neutrino Background is within Reach of Future Neutrino Telescopes

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[5] *Kavli IPMU (WPI), UTIAS, The University of Tokyo, Kashiwa, Chiba 277-8583, Japan*

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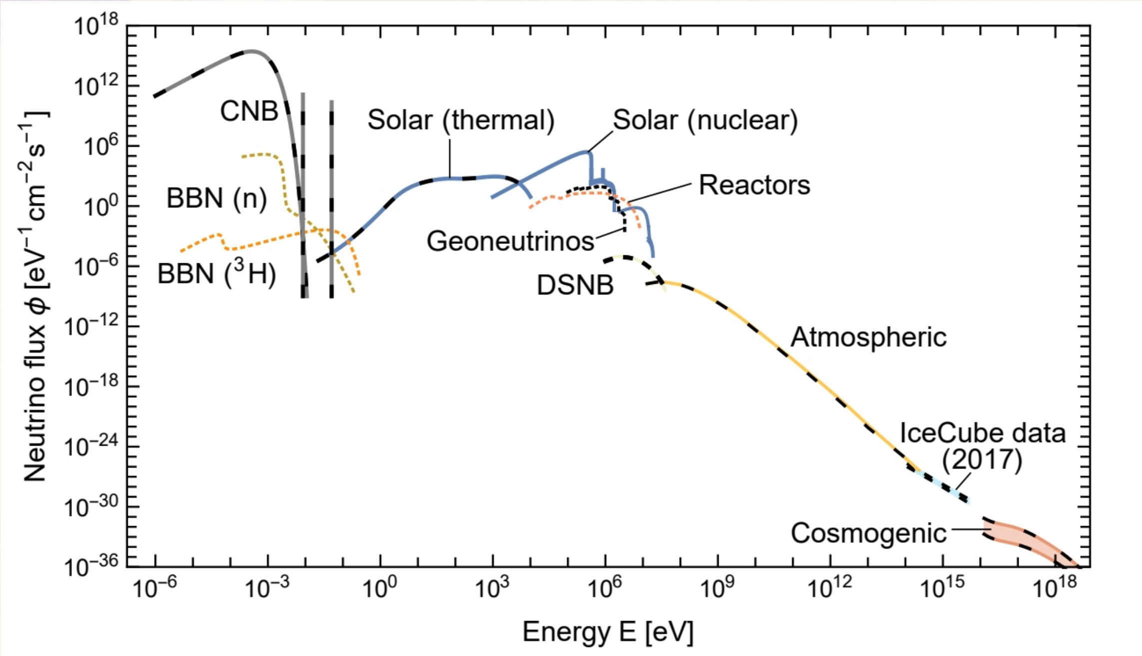

Figure: Vitagliano, Tamborra, and Raffelt 2020

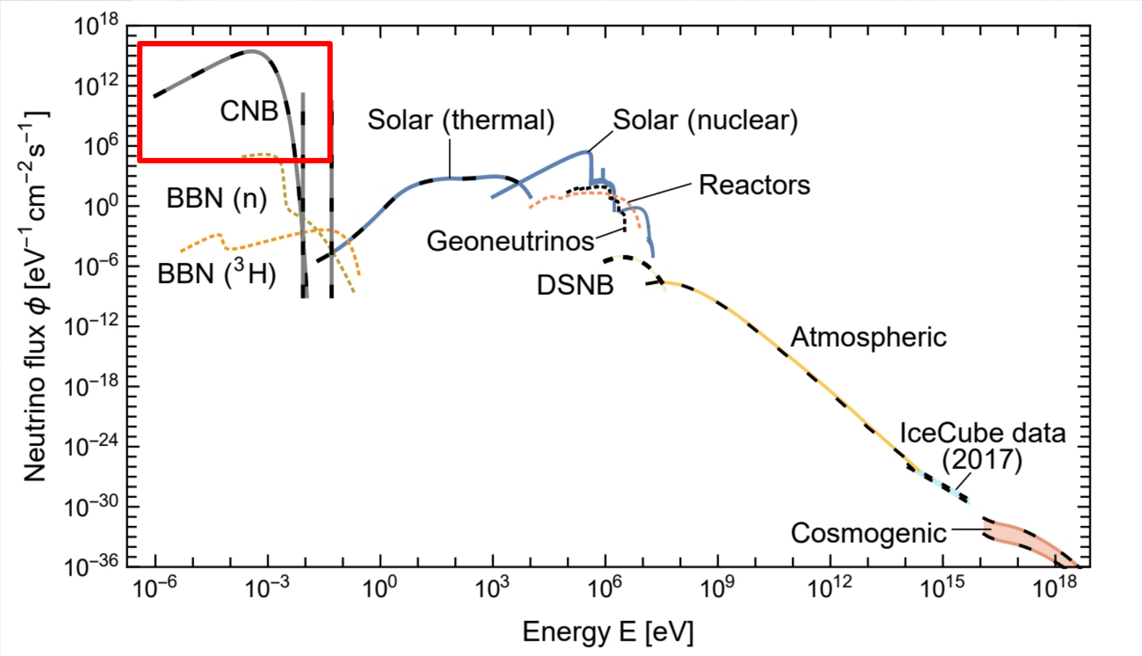

Figure: Vitagliano, Tamborra, and Raffelt 2020

CνB (relic neutrinos) decoupled from matter at the early universe (~ 1 second old).

As the universe expanded, it further cooled down (~ 1.95K).

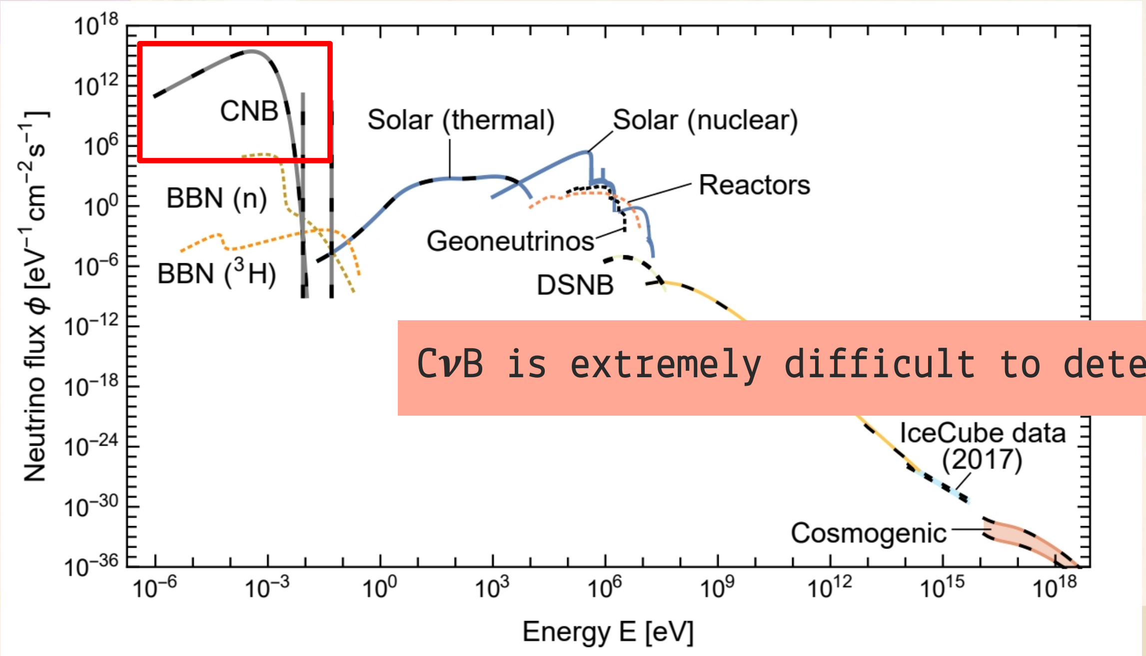

Figure: Vitagliano, Tamborra, and Raffelt 2020

CνB is extremely difficult to detect!

CνB (relic neutrinos) decoupled from matter at the early universe (~ 1 second old).

universe expanded, it further cooled down (~ 1.95K).

Outline

Previous Work

why did we want to do this?

Theory

how did we do this?

Results

what did we get?

Conclusion and Outlook

Outline

Previous Work

why did we want to do this?

Outline

Previous Work

why did we want to do this?

- Limits on overdensity: Katrin constraint;
- Boosting CνB from UHECRs idea.

Limits on **Overdensity**

CνB can reach higher density via gravitational effect or some beyond standard model mechanisms --> overdensity

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KATRIN placed an upper limit on neutrino overdensity Aker et al. 2022: 10^{11}

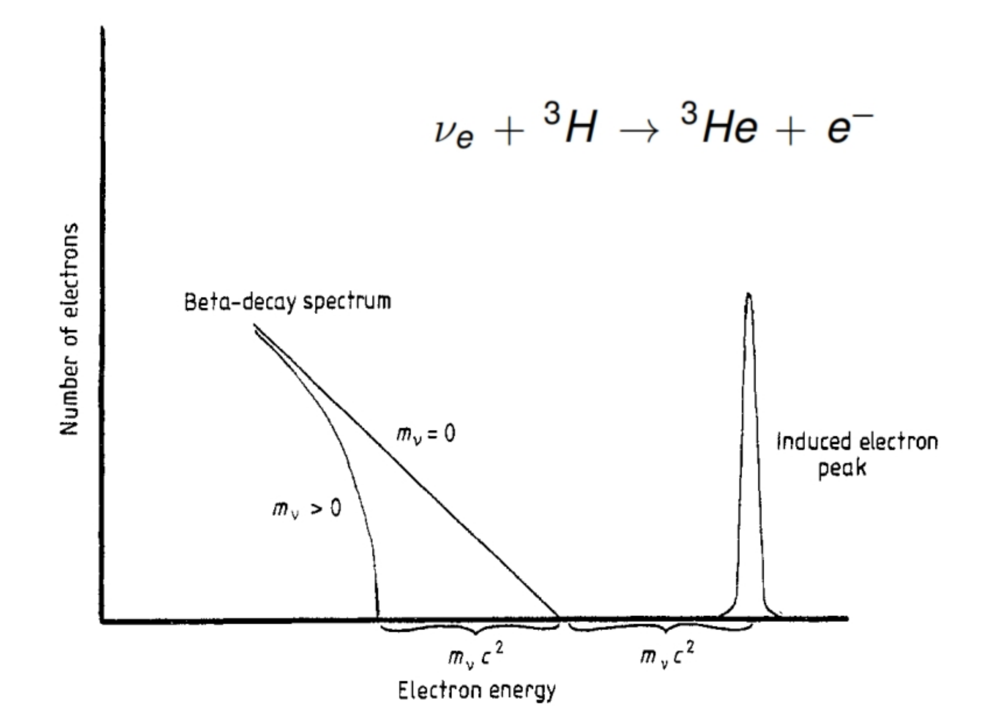

Figure: Irvine and Humphreys 1983

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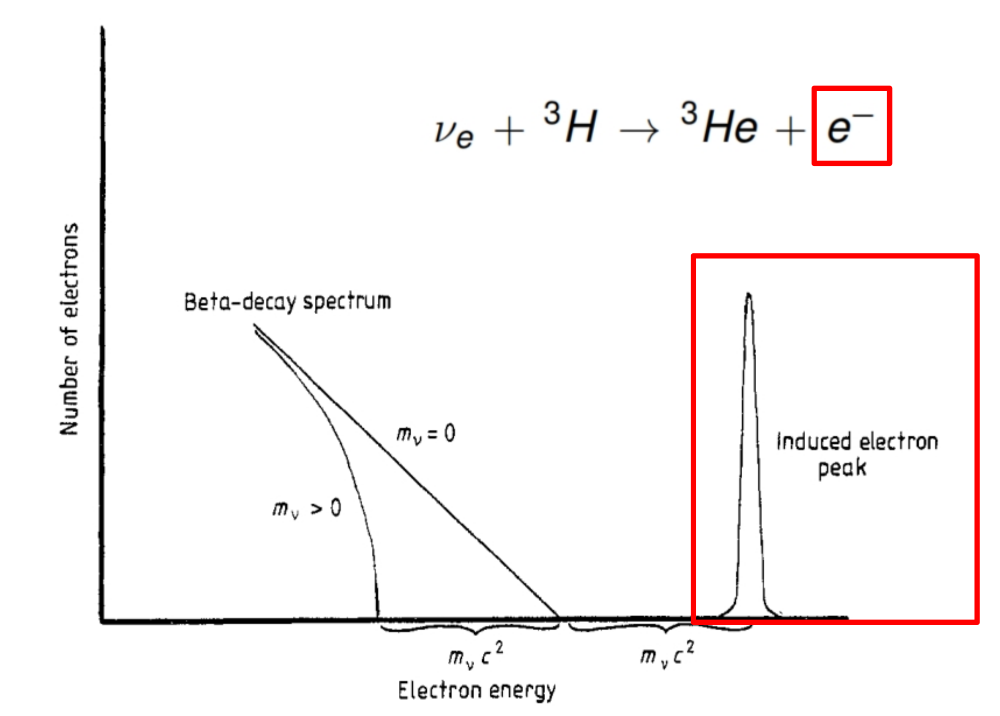

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$$\nu_e + {}^3H \rightarrow {}^3He + e^-$$

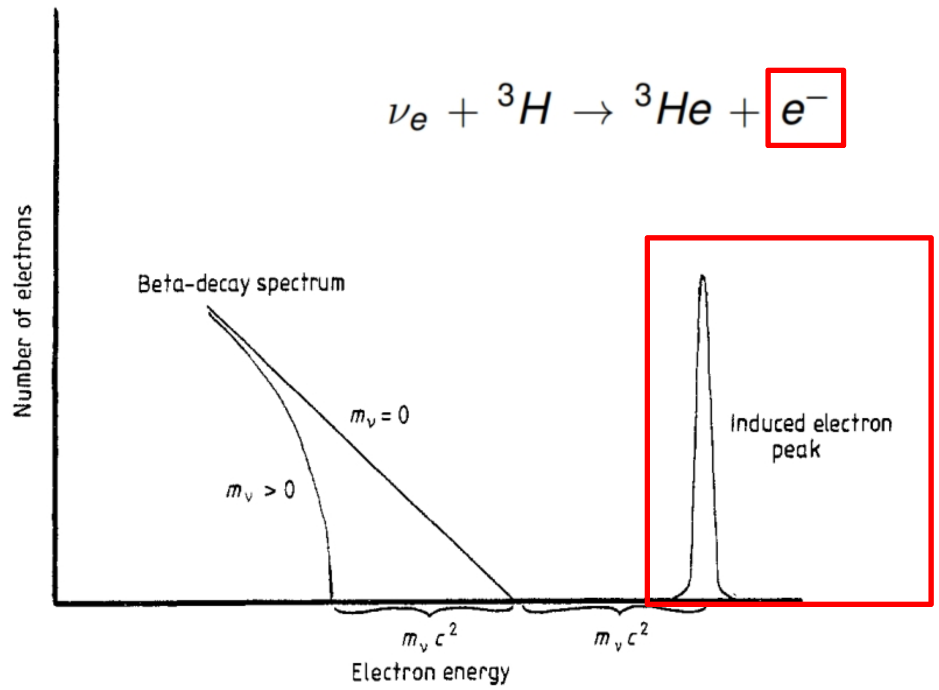


Figure: Irvine and Humphreys 1983

Is it possible for $C\nu B$ to be boosted to higher energies?

Is it possible for CνB to be boosted to higher energies?

YES!

Is it possible for $C\nu B$ to be boosted to higher energies?

YES!

Cosmic rays scattering off relic neutrinos $\longrightarrow$ **boost!**

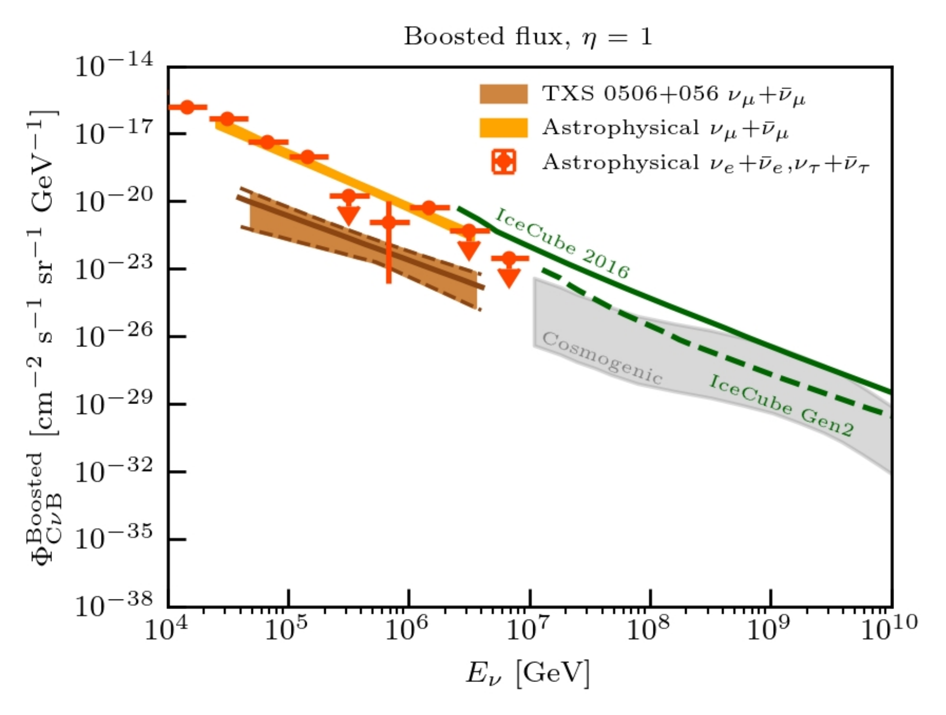
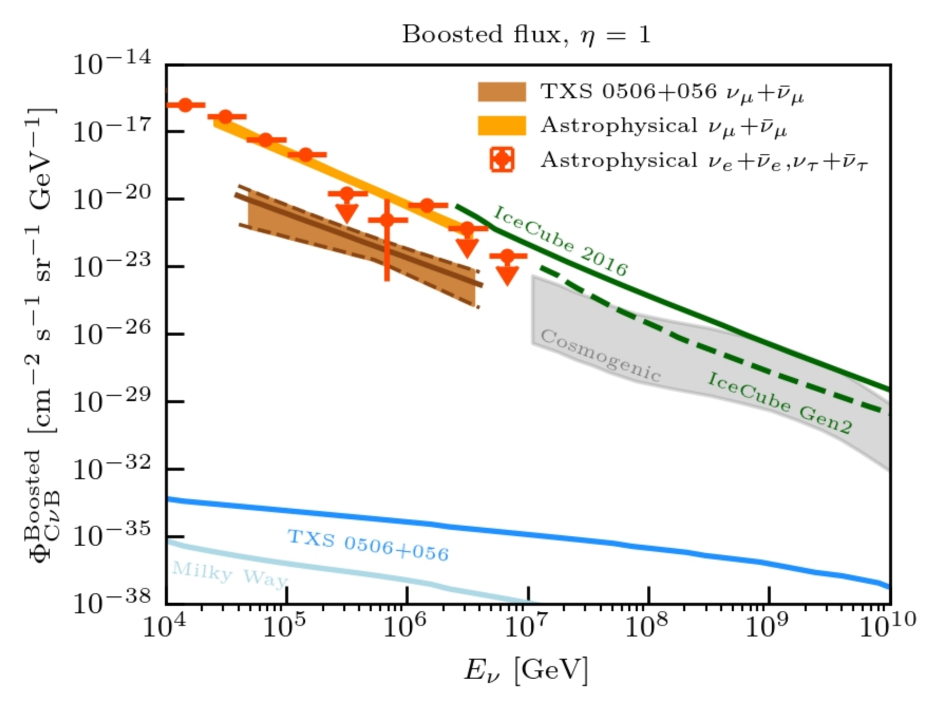


Figure: C´ıscar Monsalvatje, Herrera, and Shoemaker 2024



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Boosted flux by the Milky Way and TXS 0506+056

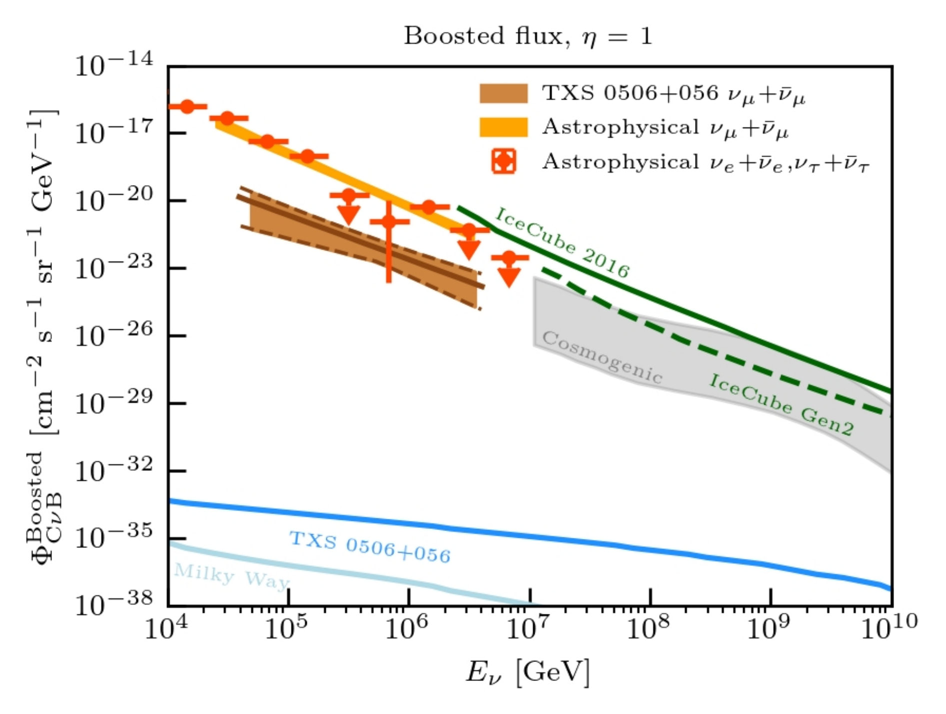

Figure: C´ıscar Monsalvatje, Herrera, and Shoemaker 2024

Boosted flux by the Milky Way and TXS 0506+056

Overdensity limits

Milky Way → ~ 10^{13}
TXS 0506+056 → ~ 10^{10}

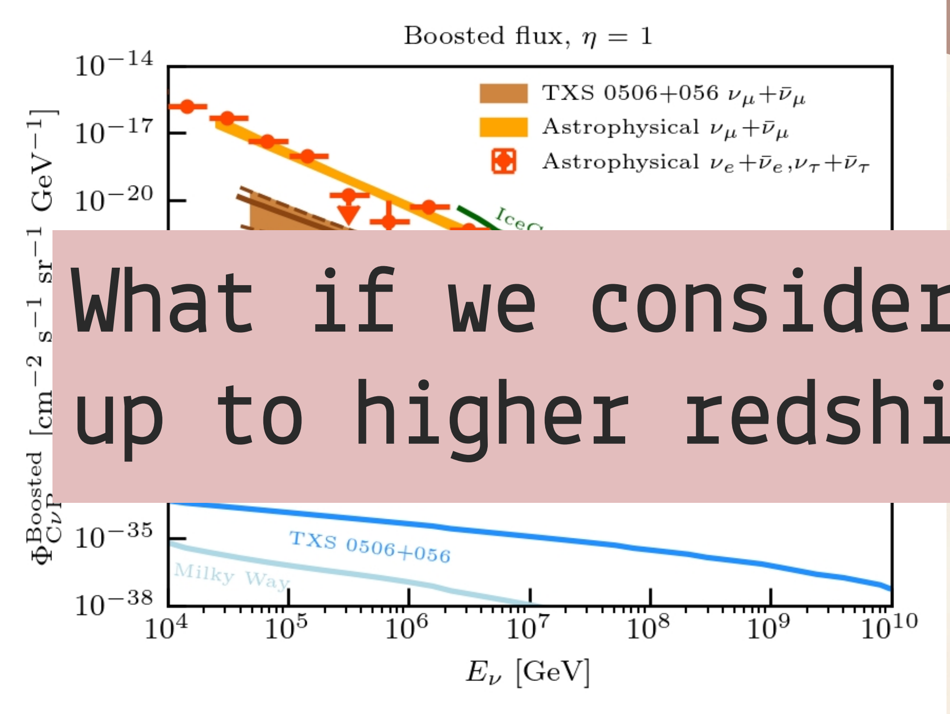

Figure: C´ıscar Monsalvatje, Herrera, and Shoemaker 2024

Boosted flux by the Milky Way and TXS

Milky Way → ~ 10^{13}
TXS 0506+056 → ~ 10^{10}

What if we consider ALL galaxies up to higher redshift?

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Outline

Previous Work

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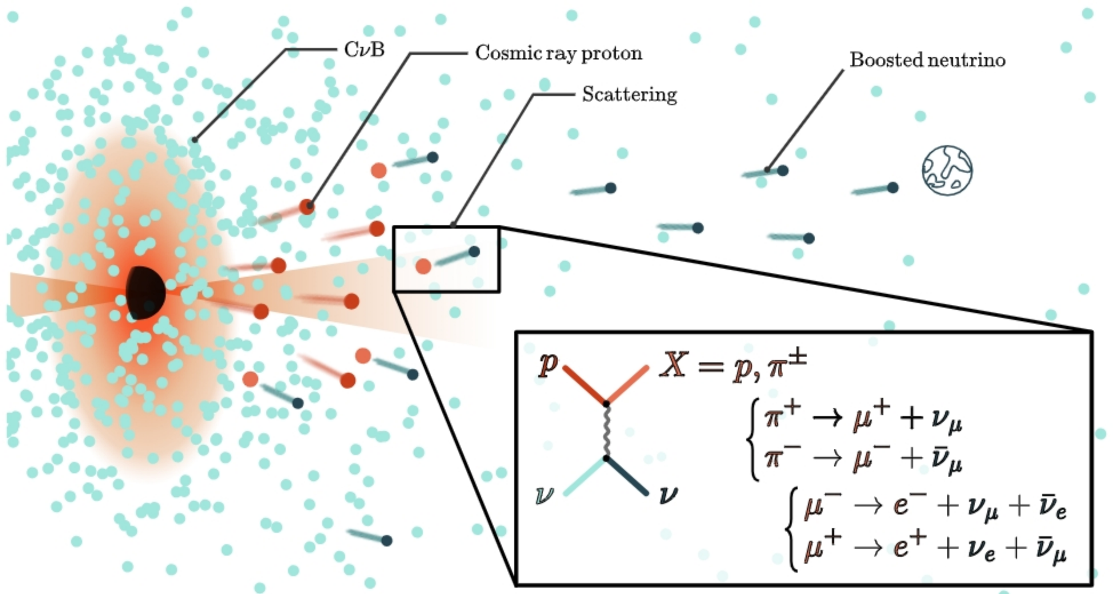
how did we do this?



NC Elastic scattering:

$$p + \nu \to p + \nu$$

NC Deep inelastic regime:

$$p + \nu \to X + \nu$$

CC quasi-elastic scattering:

$$p + \bar{\nu}_\mu \to \mu^+ + n$$

etc.

A schematic plot

Figure: Herrera, Horiuchi, Qi, and Shoemaker 2026

We need some **Simplifications**

To make the calculation simpler, we:

- assumed Cosmic Rays are made of protons
- considered NC elastic regime below $\sqrt{s} = 2$ GeV, and NC deep inelastic regime above the threshold.

Double integral

$$\frac{d\phi_\nu}{dT_\nu} = \int_{z_{\min}}^{z_{\max}} \frac{c}{H_0} \frac{1}{\sqrt{(1+z)^3\Omega_m + \Omega_\Lambda}} f_i(z)\, n_\nu (1+z)^3 \int_0^\infty dT_p \, \frac{d\sigma_{p\nu}}{dT_\nu}(T_p, T_\nu) \, \frac{d\phi_p}{dT_p} \, \Theta\left[T_\nu^{\max}(T_p) - T_\nu(1+z)\right]$$

Double integral

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Redshift evolution of Cosmic Ray flux

Double integral

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Redshift evolution of Cosmic Ray flux

$$f_i(z) = \frac{N_i(z)}{N_i(z_{min})}$$

$N_i(z)$ is the distribution of:

- SFR
- GRB
- QSO

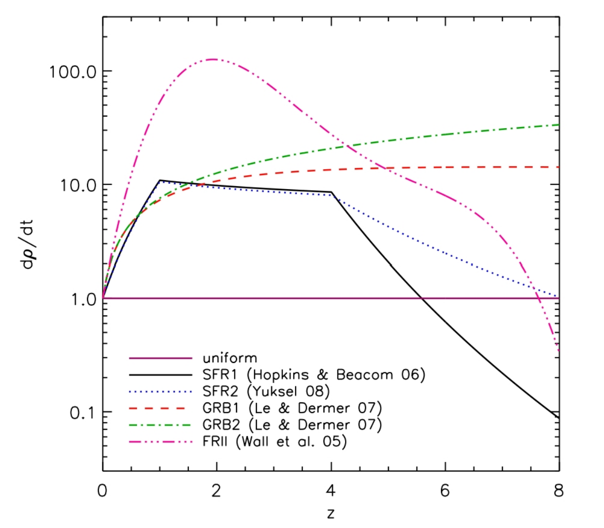

Figure: Kotera, Allard, and Olinto 2010

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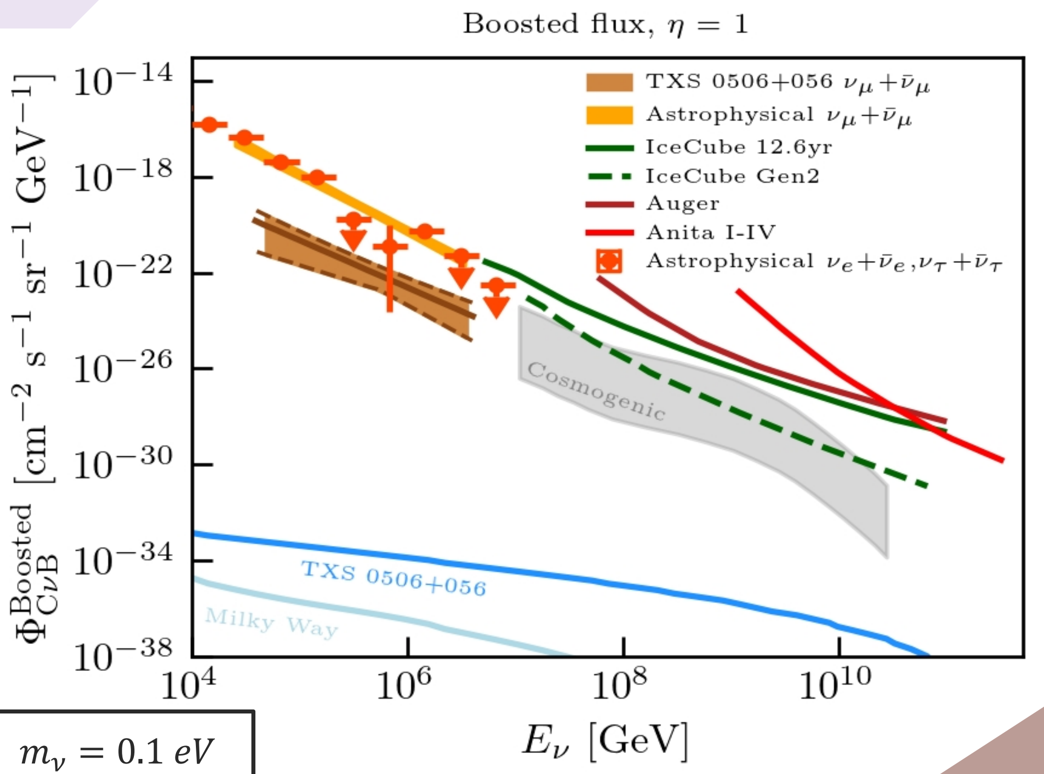

$m_\nu = 0.1\ eV$

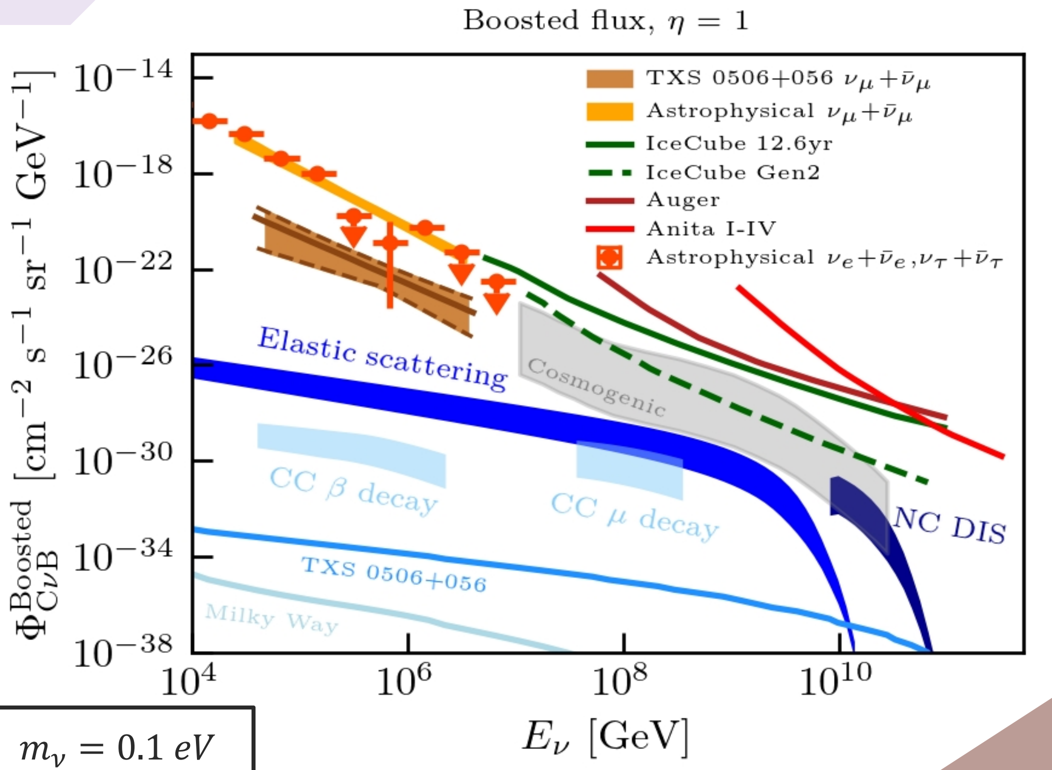

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Figure: Herrera, Horiuchi, Qi, and Shoemaker 2026

→ huge enhancement

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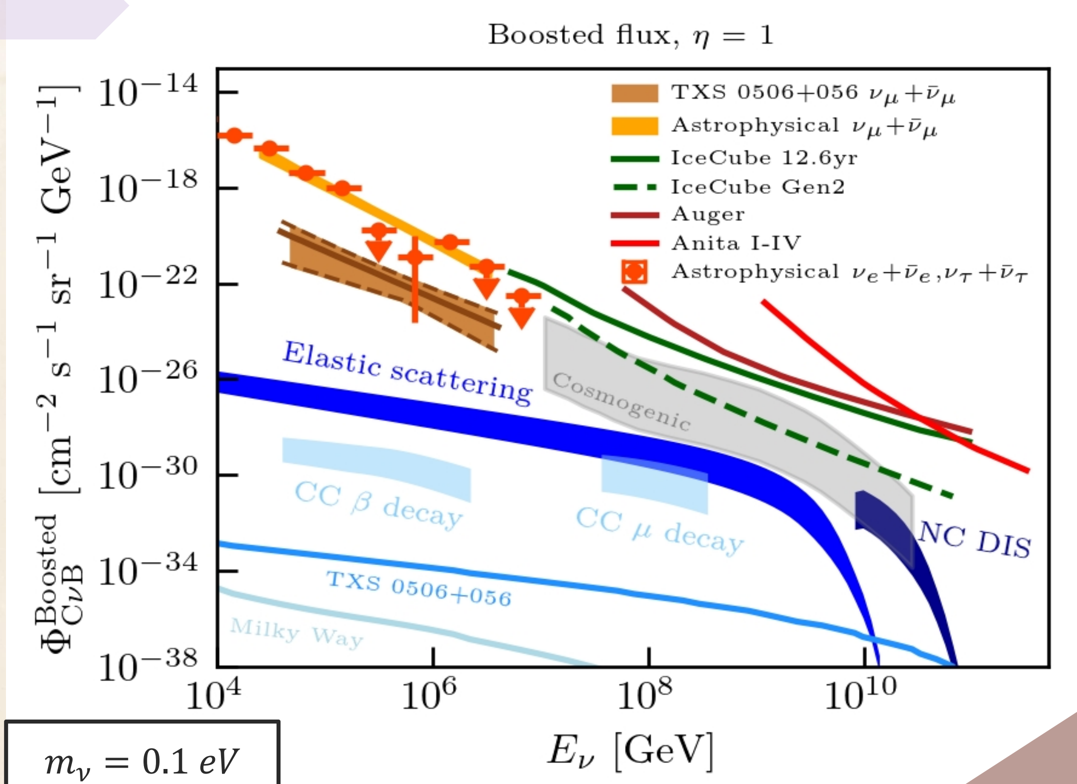

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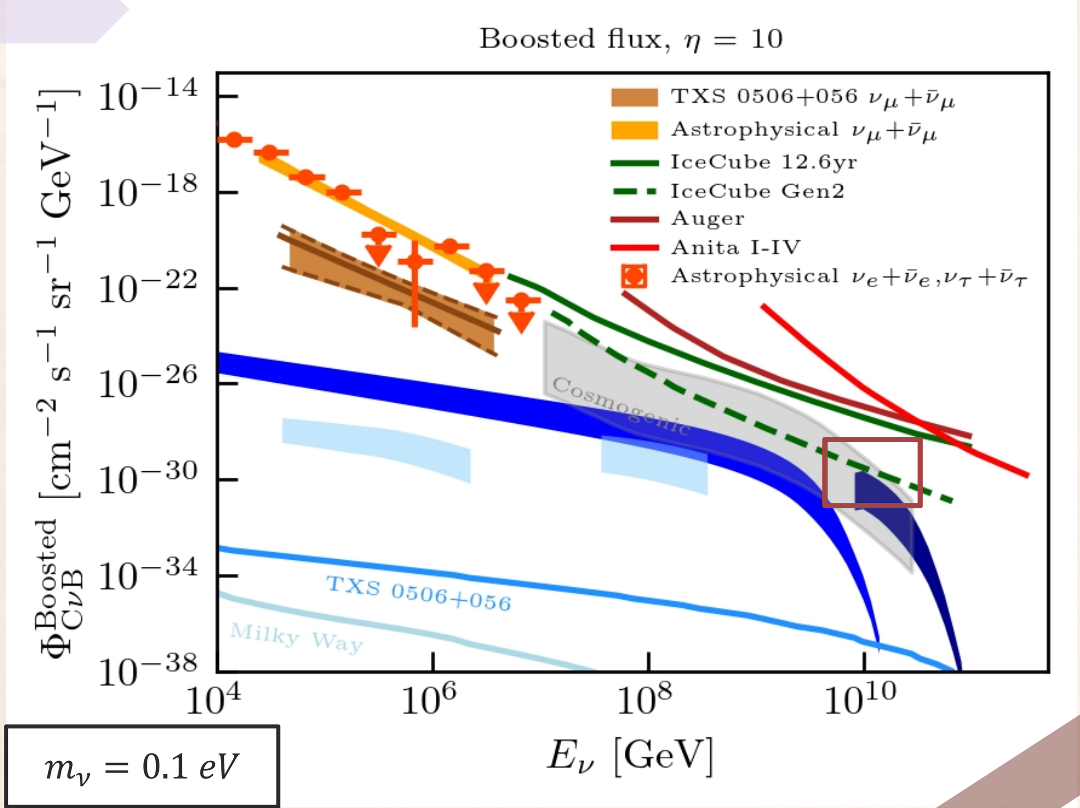

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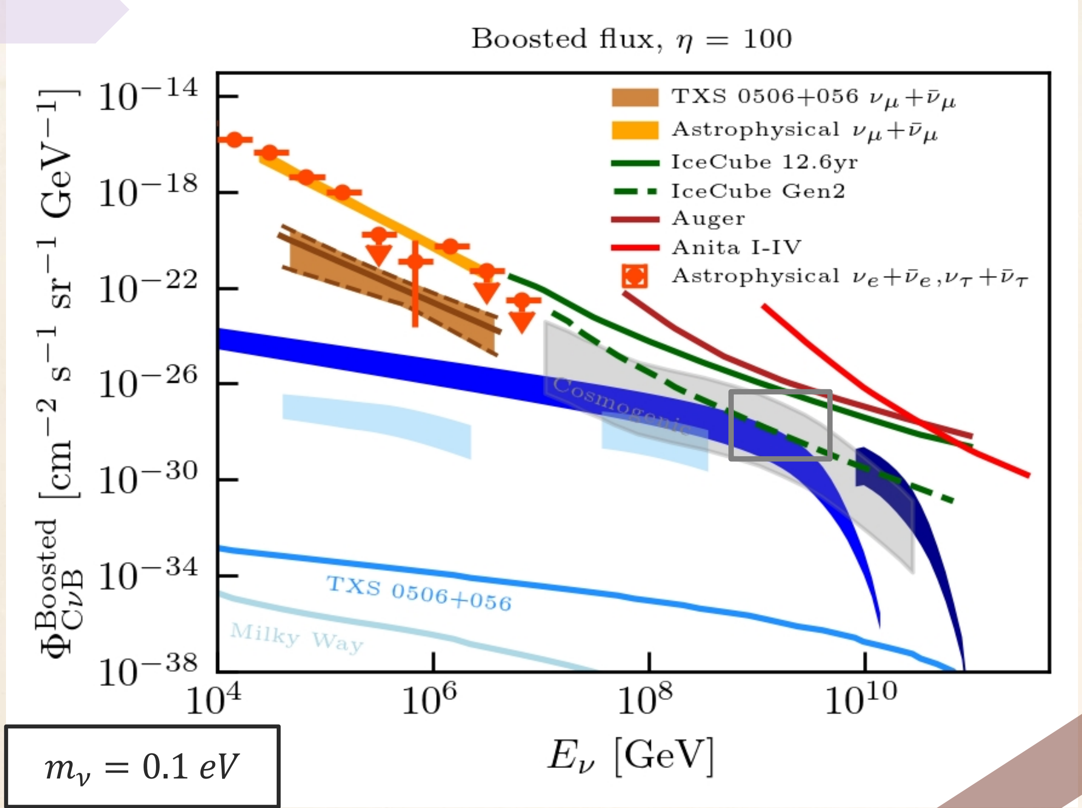
huge enhancement

CC: marginal effect

overdensity limit from DIS: ~ 10

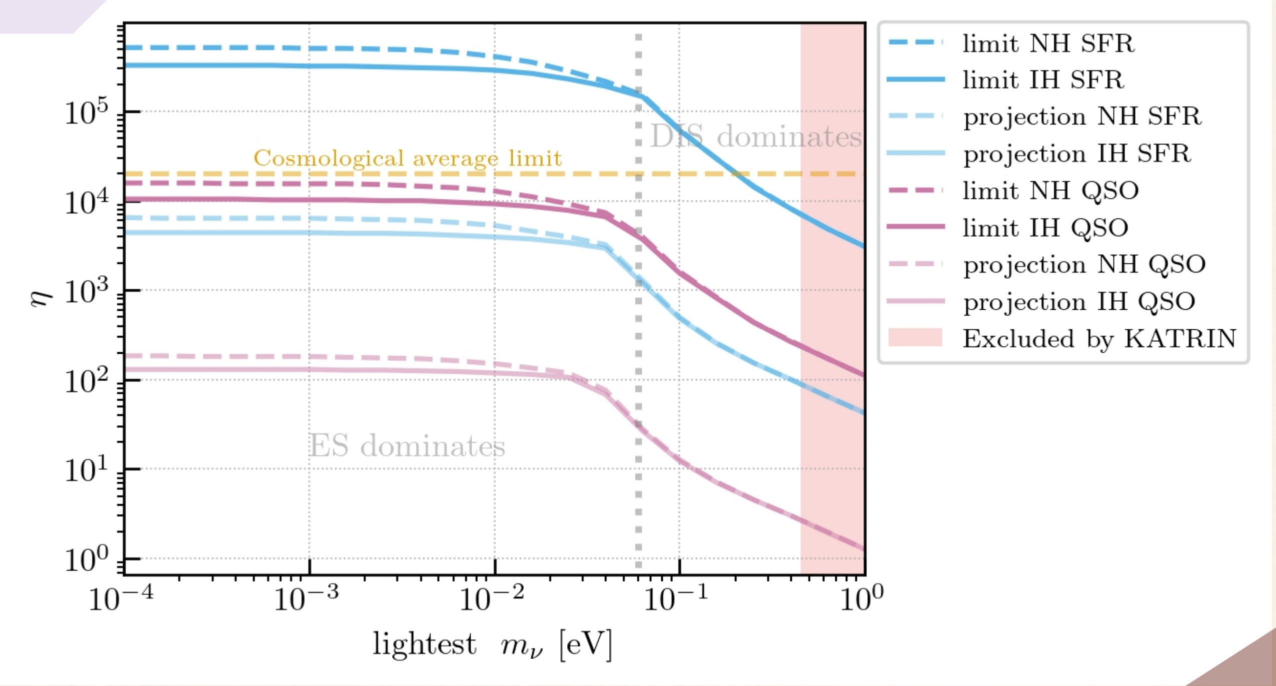
Figure: Herrera, Horiuchi, Qi, and Shoemaker 2026



$m_\nu = 0.1\ eV$

- huge enhancement
- CC: marginal effect
- overdensity limit from DIS: ~ 10
- overdensity limit from ES: ~ 100

Figure: Herrera, Horiuchi, Qi, and Shoemaker 2026



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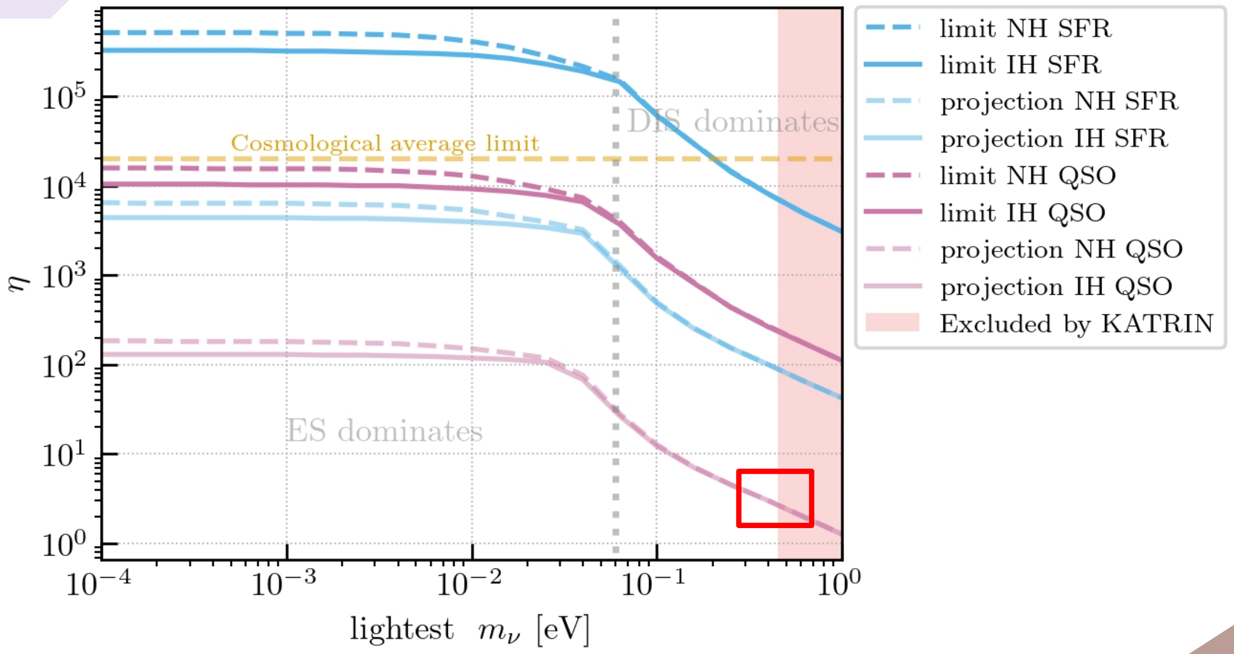

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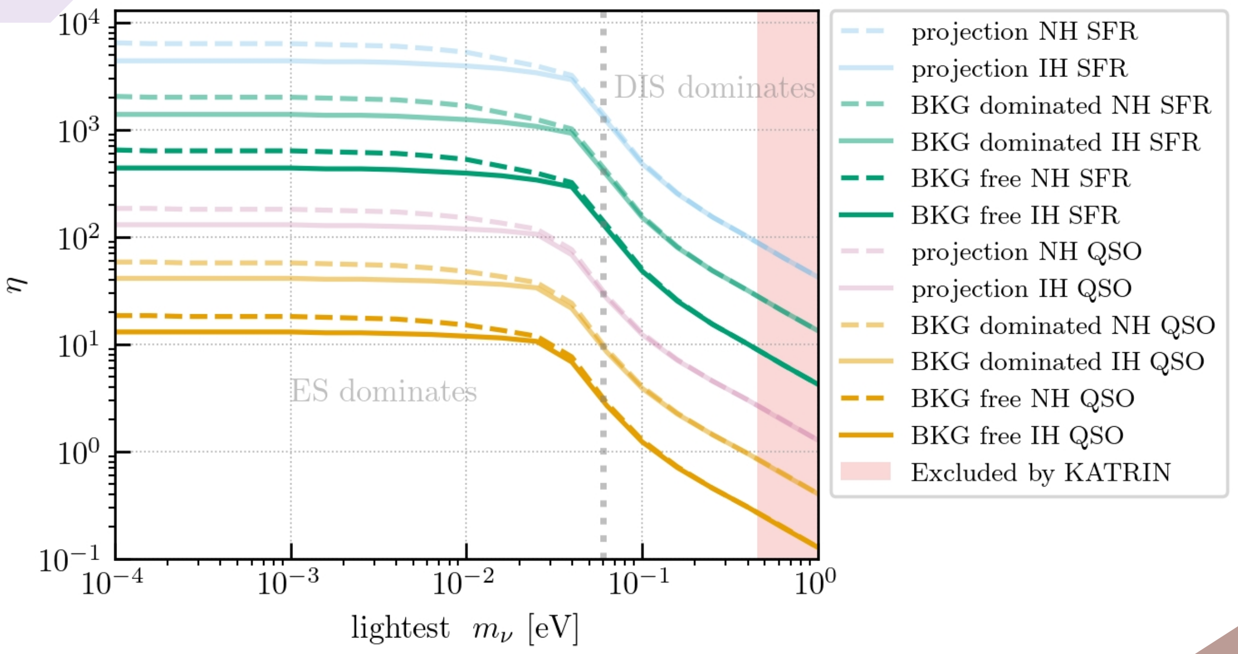

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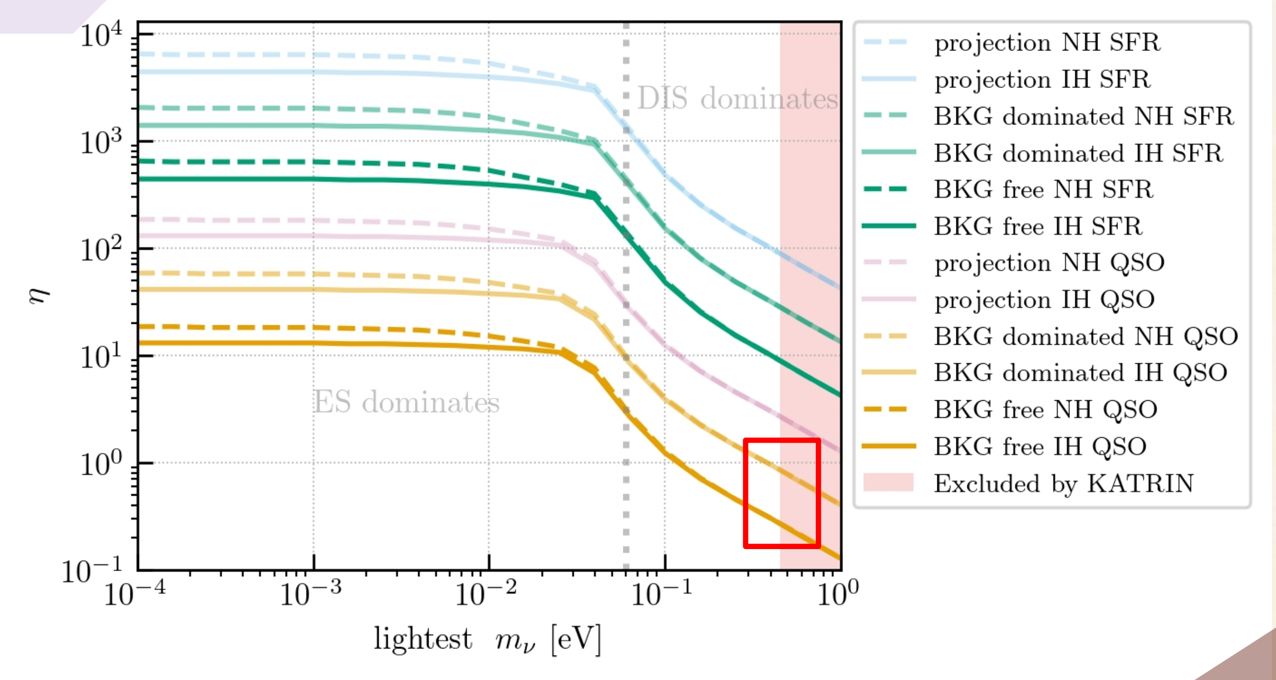

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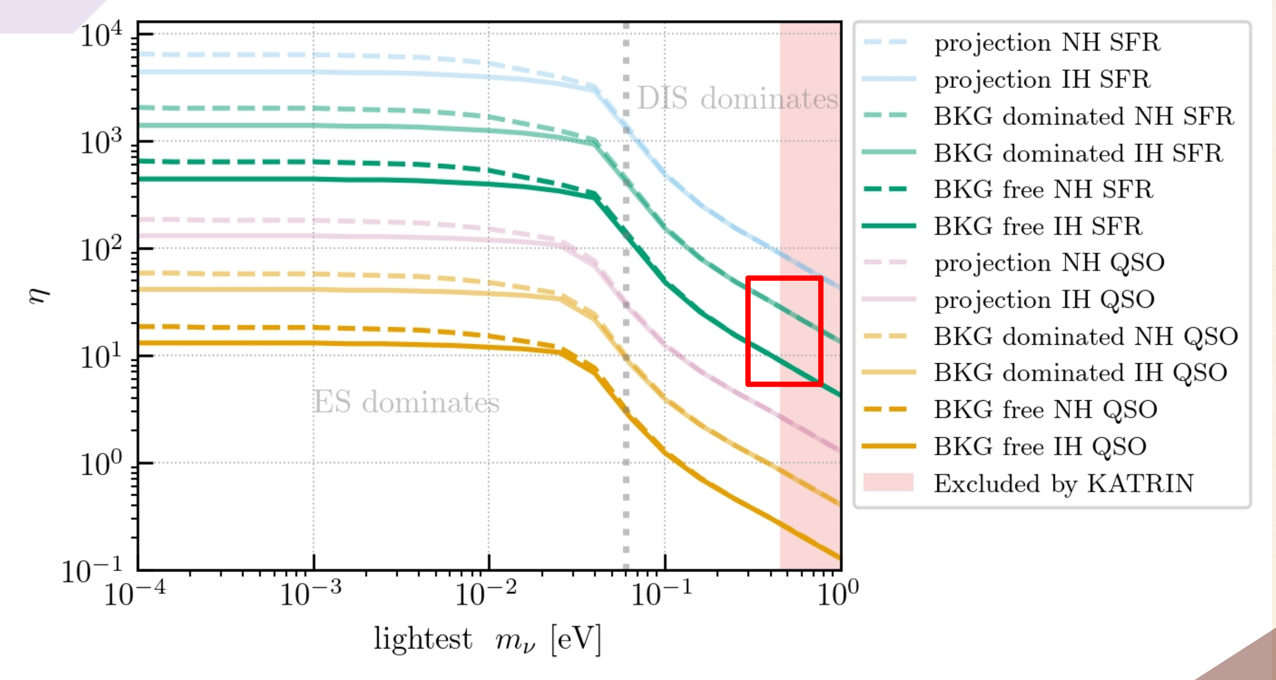

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Relic neutrinos can reach $O(10^{10})$ GeV by boosting.

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IceCube Gen2 can set a strong overdensity upper limit to be ~ O(1)-O(1000).

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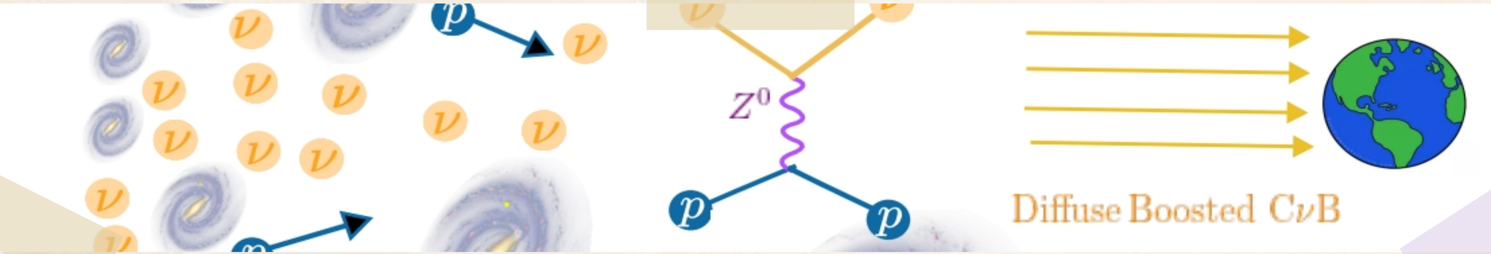
IceCube Gen2 can set a strong overdensity upper limit to be ~ O(1)-O(1000).

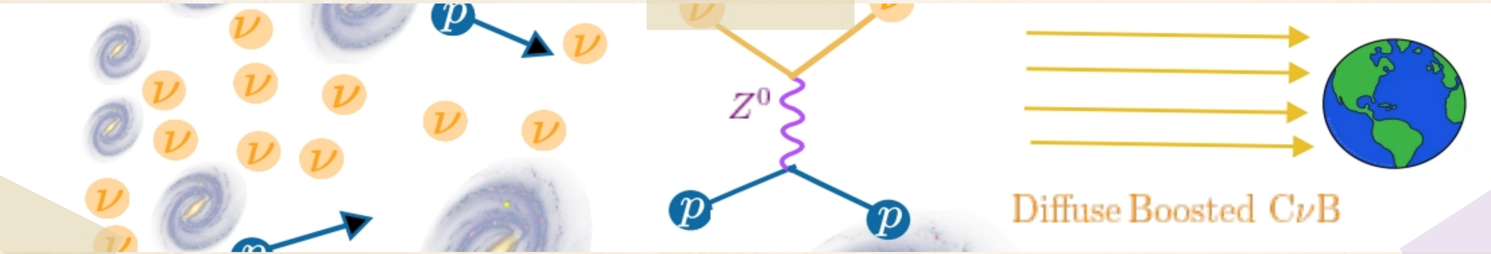
CνB is within reach by combining 10 future, IceCube Gen2-like neutrino detectors!

Outlook



Outlook

- Heavy nuclei?
- Compare with Cosmogenic neutrinos?
- Simulation?
- Much more to explore!



Outlook

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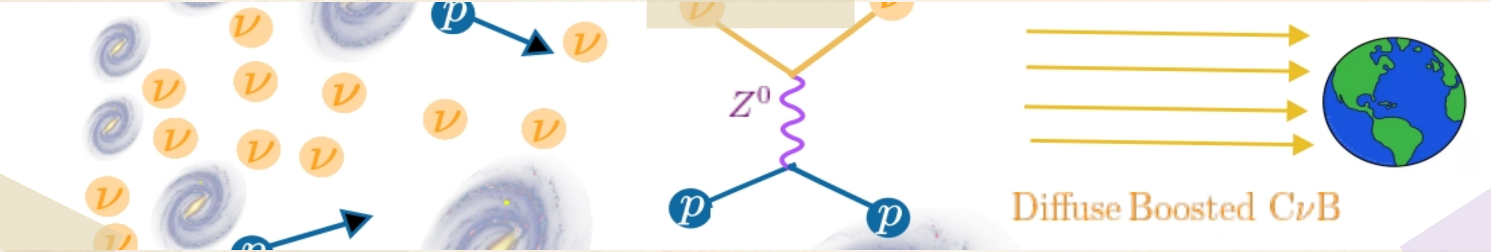
Work in progress...

Project members: Gonzalo Herrera, Shunsaku Horiuchi, Daniel Naredo, Xiaolin Qi, Ian Shoemaker.



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Thanks!

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Figure: https://www.phys.vt.edu/Undergraduate/a-day-in-the-life-of-physics-major-registratioin.html

Any Questions?

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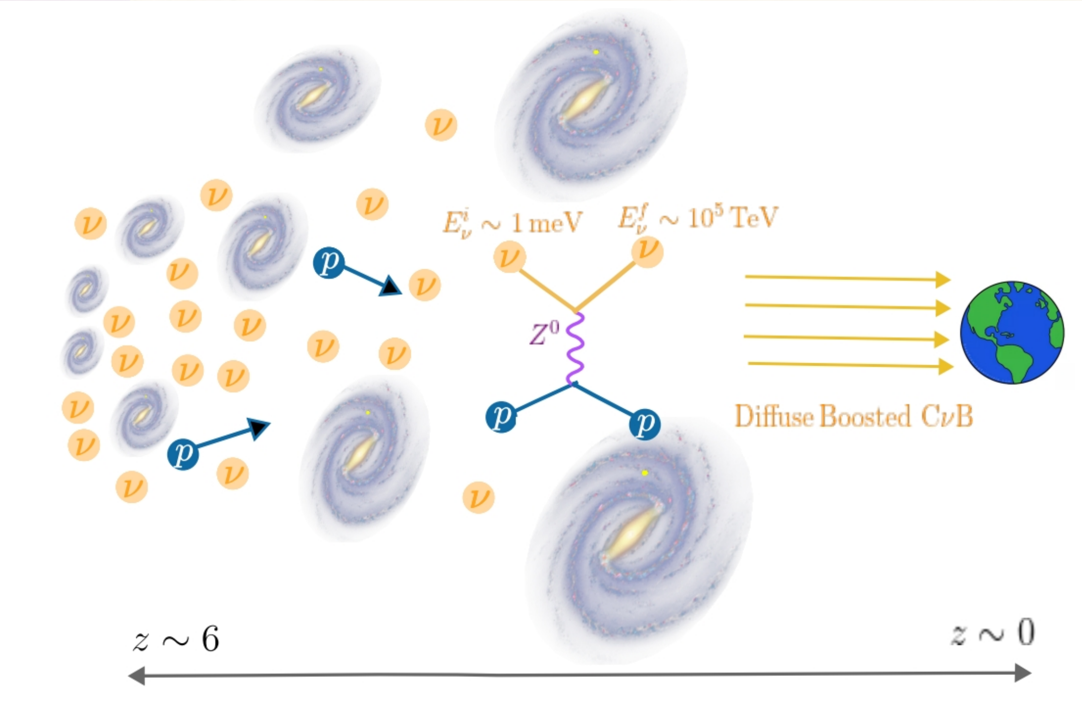
Backup Slides



Elastic scattering:

$$p + \nu \to p + \nu$$

Deep inelastic regime:

$$p + \nu \to X + \nu$$

A schematic plot

Figure: Herrera, Horiuchi, and Qi 2024

Double integral

$$\frac{d\phi_\nu}{dT_\nu} = \int_{z_{\min}}^{z_{\max}} \frac{c}{H_0} \frac{1}{\sqrt{(1+z)^3\Omega_m + \Omega_\Lambda}} f_i(z)\, n_\nu (1+z)^3 \int_0^\infty dT_p \frac{d\sigma_{p\nu}}{dT_\nu}(T_p, T_\nu) \frac{d\phi_p}{dT_p} \Theta\left[T_\nu^{\max}(T_p) - T_\nu(1+z)\right]$$

Cosmological terms

Differential cross section

Neutrino density at redshift z

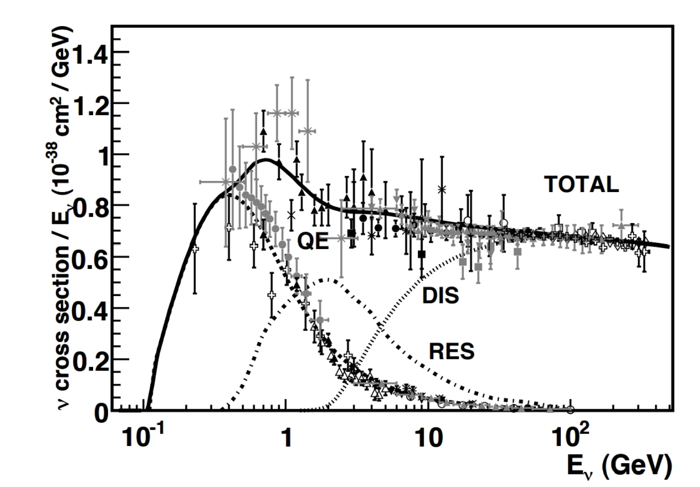
Cosmic ray spectrum

Maximal energy transferred to a neutrino in one scattering

Redshift evolution of Cosmic Ray flux

Neutrino energy at redshift z

Cross section



$$\frac{d\sigma_{\nu N}^{\mathrm{ES}}}{dE_\nu} = \frac{2G_F^2 m_\nu m_N^4}{\pi(s-m_N^2)^2}\left[A_N(Q^2) + C_N(Q^2)\frac{(s-u)^2}{m_N^4}\right]$$

$$\frac{d\sigma_{\nu N}^{\mathrm{DIS}}}{dE_\nu} \simeq \sum_{a=q,\bar{q}} \frac{G_F^2[(g_V^a)^2+(g_A^a)^2]}{2\pi E_N} \times \int_{y_{\min}}^{1} \frac{dy}{y^2}\,\frac{Q^2 f_a^N(x,Q^2)}{[1+Q^2/M_Z^2]^2}\, g(y,Q^2,m_N)$$

[2] Zhang, J., Sandrock, A., Liao, J. and Yue, B., 2025. Impact of coherent scattering on relic neutrinos boosted by cosmic rays. arXiv preprint arXiv:2505.04791.

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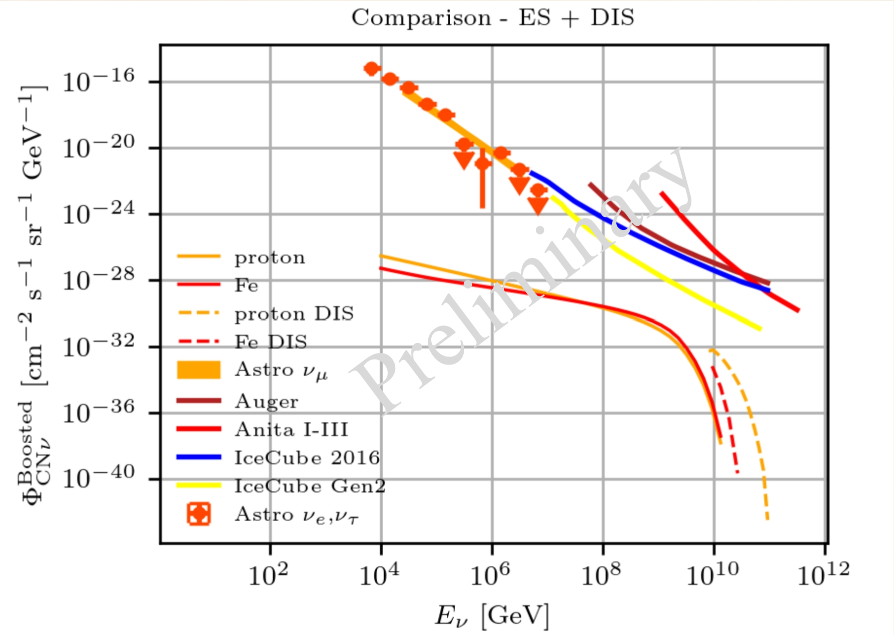
Heavy nuclei effect...



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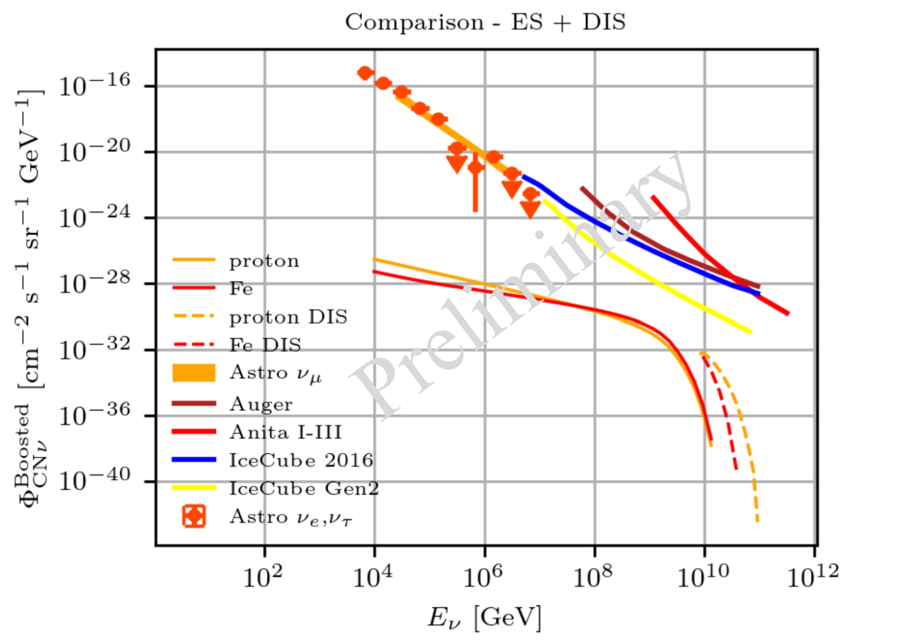


More results

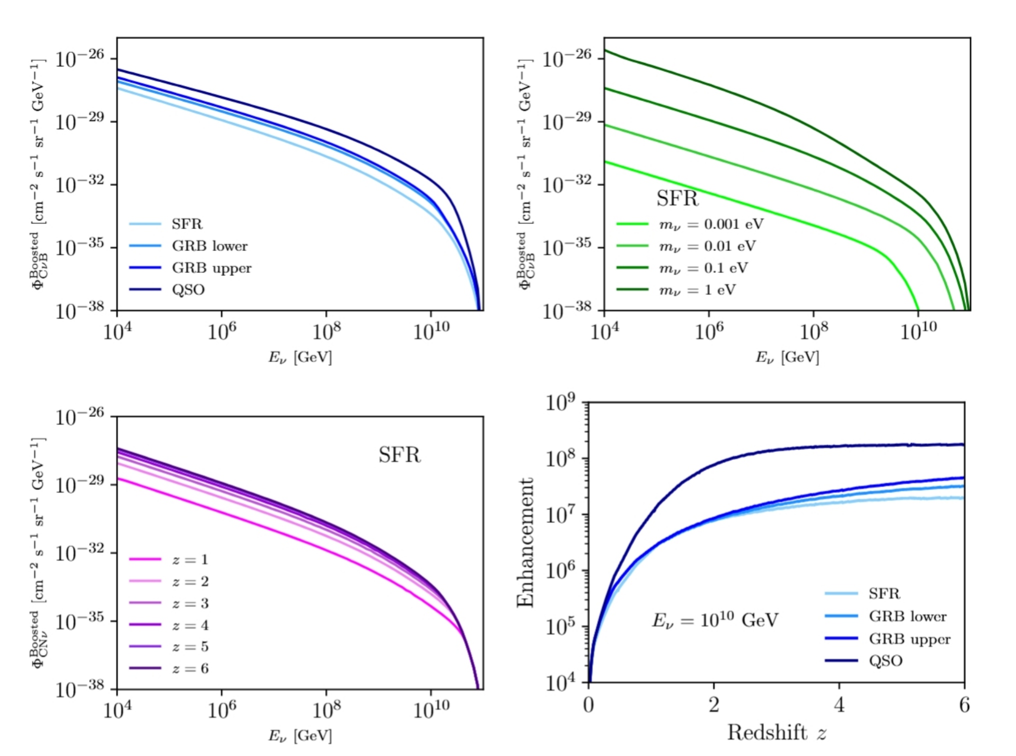
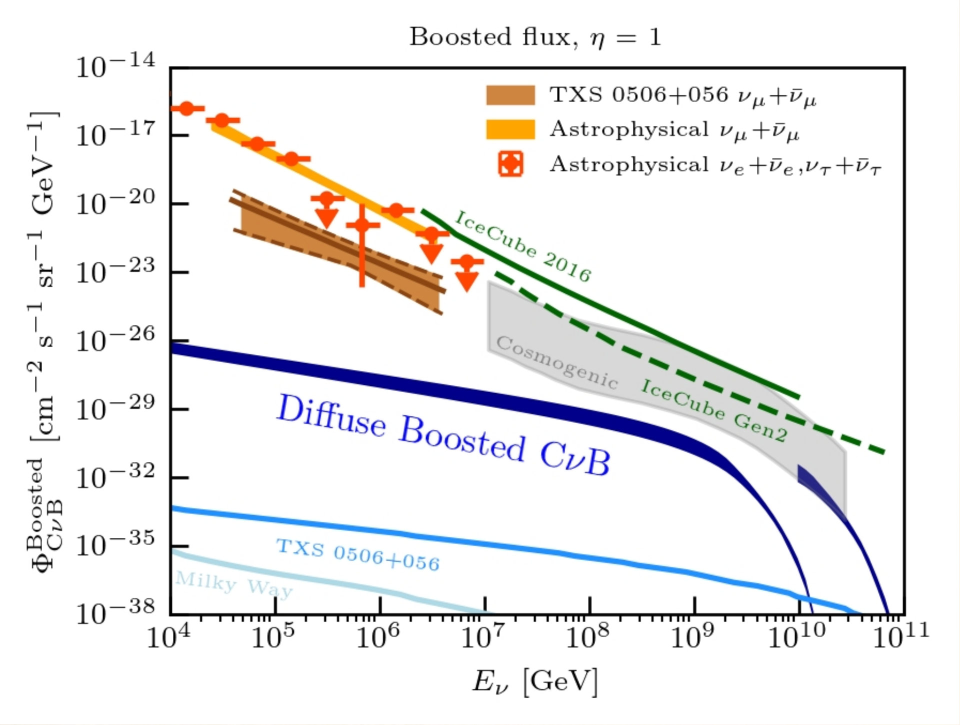


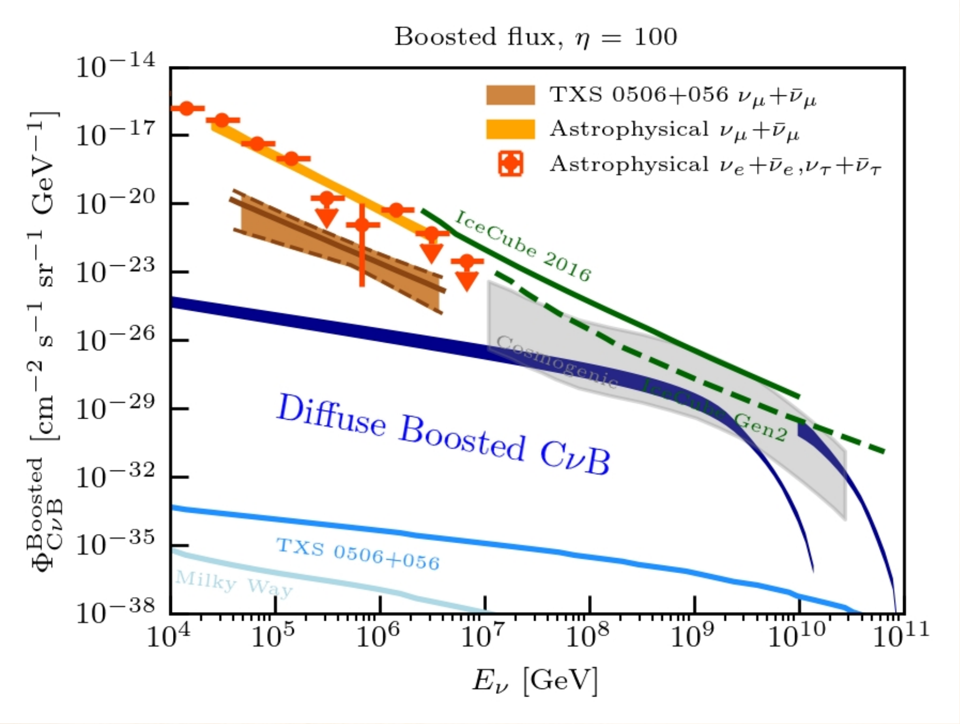
Figure: Herrera, Horiuchi, and Qi 2025

Exclude QSO



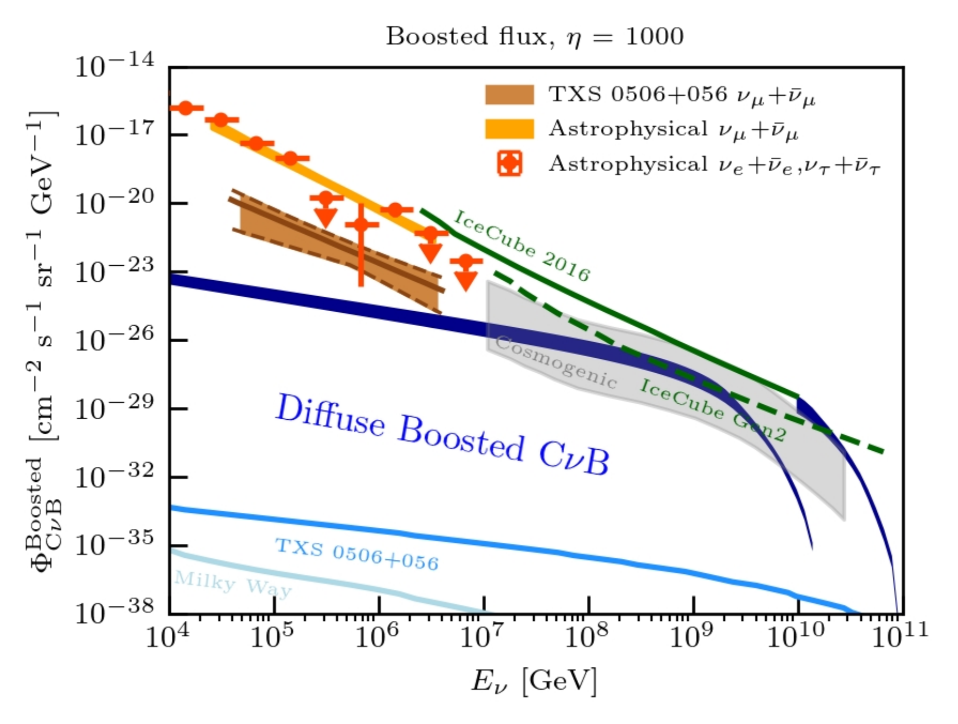
Boosted flux, $\eta = 1$
TXS 0506+056 $\nu_\mu + \bar{\nu}_\mu$
Astrophysical $\nu_\mu + \bar{\nu}_\mu$
Astrophysical $\nu_e + \bar{\nu}_e, \nu_\tau + \bar{\nu}_\tau$
IceCube 2016
Cosmogenic
IceCube Gen2
Diffuse Boosted CνB
TXS 0506+056
Milky Way
$\Phi^{\text{Boosted}}_{\text{C}\nu\text{B}}$ [cm^{-2} s^{-1} sr^{-1} GeV^{-1}]
E_ν [GeV]
10^{-14} 10^{-17} 10^{-20} 10^{-23} 10^{-26} 10^{-29} 10^{-32} 10^{-35} 10^{-38}
10^4 10^5 10^6 10^7 10^8 10^9 10^{10} 10^{11}

Exclude QSO



Boosted flux, $\eta = 100$
TXS 0506+056 $\nu_\mu+\bar{\nu}_\mu$
Astrophysical $\nu_\mu+\bar{\nu}_\mu$
Astrophysical $\nu_e+\bar{\nu}_e,\nu_\tau+\bar{\nu}_\tau$
IceCube 2016
Cosmogenic
IceCube-Gen2
Diffuse Boosted CνB
TXS 0506+056
Milky Way
$\Phi^{\text{Boosted}}_{\text{C}\nu\text{B}}$ [cm^{-2} s^{-1} sr^{-1} GeV^{-1}]
E_ν [GeV]
10^{-14}
10^{-17}
10^{-20}
10^{-23}
10^{-26}
10^{-29}
10^{-32}
10^{-35}
10^{-38}
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}

Exclude QSO



Boosted flux, $\eta = 1000$
TXS 0506+056 $\nu_\mu+\bar{\nu}_\mu$
Astrophysical $\nu_\mu+\bar{\nu}_\mu$
Astrophysical $\nu_e+\bar{\nu}_e,\nu_\tau+\bar{\nu}_\tau$
IceCube 2016
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IceCube Gen2
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TXS 0506+056
Milky Way
$\Phi^{\rm Boosted}_{\rm C\nu B}$ [cm^{-2} s^{-1} sr^{-1} GeV^{-1}]
E_ν [GeV]
10^{-14}
10^{-17}
10^{-20}
10^{-23}
10^{-26}
10^{-29}
10^{-32}
10^{-35}
10^{-38}
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}

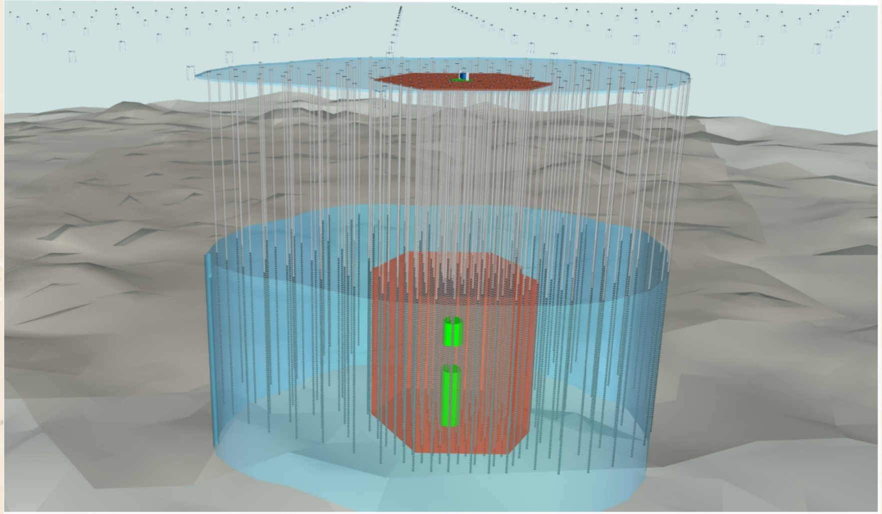
Cosmic Ray Spectrum

$$\frac{d\phi_p}{dT_p} \sim \begin{cases} {T_p}^{-2.7}, \text{ for } T_p < 10^7 \text{ GeV} \\ {T_p}^{-\alpha}, \text{ for } T_p > 10^7 \text{ GeV}, \ and\ \alpha = \begin{cases} 2.5,\ for\ SFR \\ 2.4,\ for\ GRB \\ 2.3,\ for\ QSO \end{cases} \end{cases}$$

[1]

[1] Kotera, K., Allard, D. and Olinto, A.V., 2010. Cosmogenic neutrinos: parameter space and detectabilty from PeV to ZeV. *Journal of Cosmology and Astroparticle Physics*, *2010*(10), p.013.

IceCube Gen2



A 3D rendering of the planned IceCube-Gen2 extension. IceCube-Gen2 encompasses three new arrays—in-ice optical, surface, and extensive radio—that expand the capabilities of the current IceCube Neutrino Observatory. Image credit: IceCube Collaboration

- next-generation South Pole neutrino observatory
- "A core detector will be the IceCube-Gen2 optical array, with a size eight times larger than the current IceCube and optimized to detect neutrinos with energies ranging from hundreds of TeV to tens or even a few hundreds of PeV."

Figure: https://icecube-gen2.wisc.edu/about/icecube-gen2/