Matter Effects on Flavor Composition of Astrophysical Neutrinos

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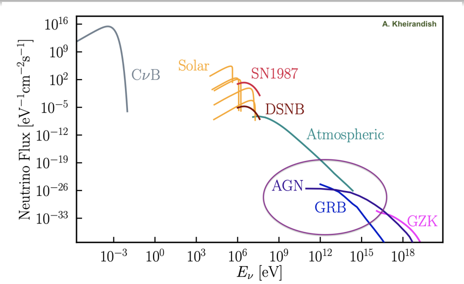
Washington University in St. Louis

w/ Sudip Jana & Yago Porto, arXiv: 2312.17315 [hep-ph];
w/ Pedro Machado & Ivan Martínez-Soler, *to appear (soon)*.

The Mitchell Conference on Collider, Dark Matter, and Neutrino Physics

May 25, 2024

High Energy Neutrinos (HENs)



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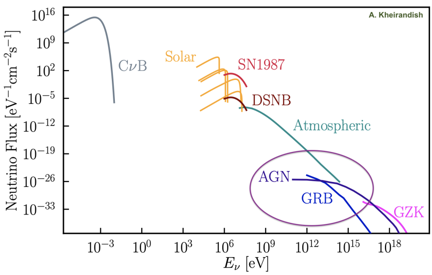
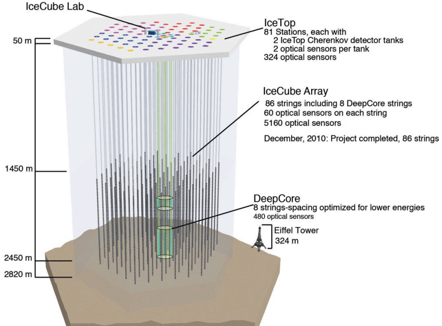
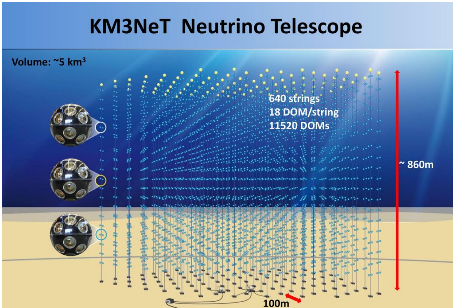


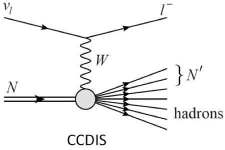
Gigantic detectors to compensate for the tiny flux of HENs.





Detecting HENs at IceCube

$$\nu_\ell + N \quad \rightarrow \quad \begin{cases} \ell + X & \text{(CC)} \\ \nu_\ell + X & \text{(NC)} \end{cases}$$



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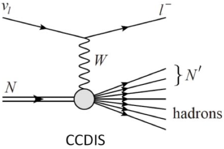

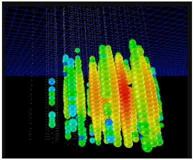

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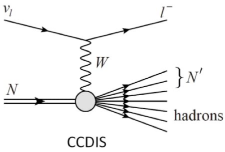

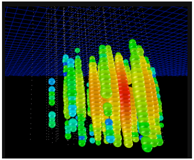

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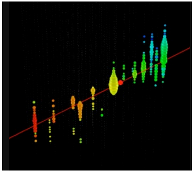

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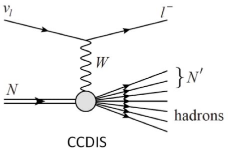

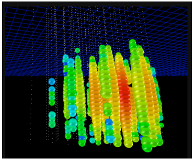

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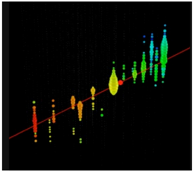

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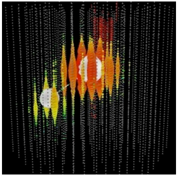

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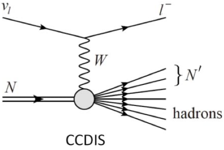

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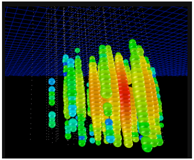

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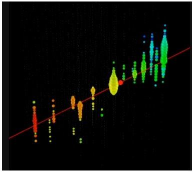

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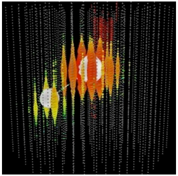

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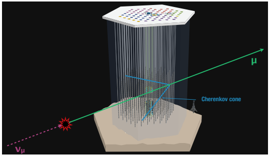

Throughgoing muon (track only, huge statistics)

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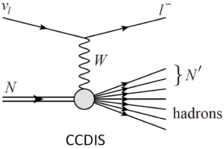

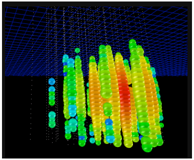

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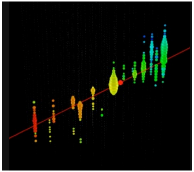

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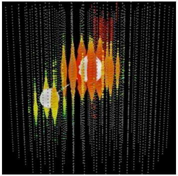

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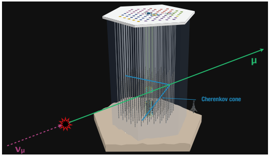
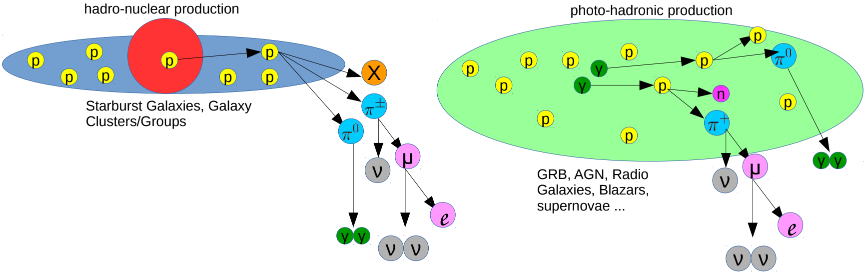


Throughgoing muon (track only, huge statistics)

Showers: Good energy resolution, but poor angular resolution
Tracks: Excellent angular resolution, but modest energy resolution

Track events are ideal for astrophysical source identification.

Astrophysical Sources and Multimessenger Connection



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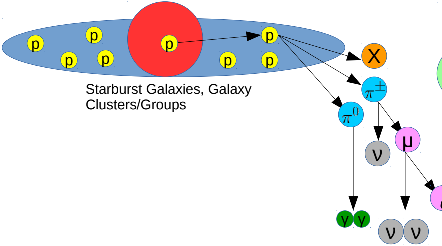
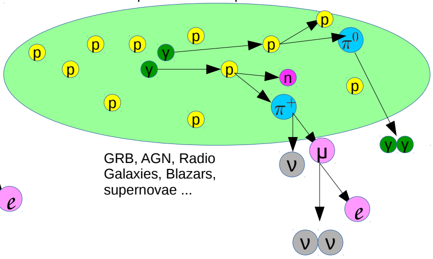
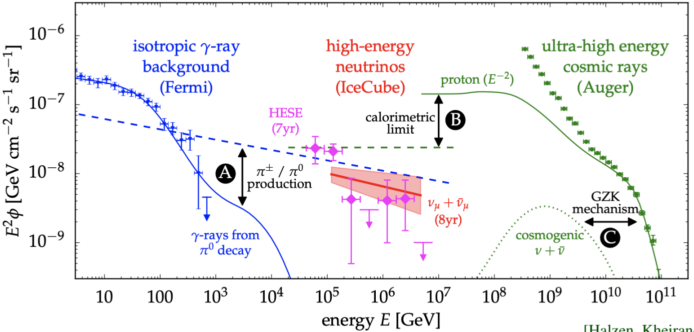
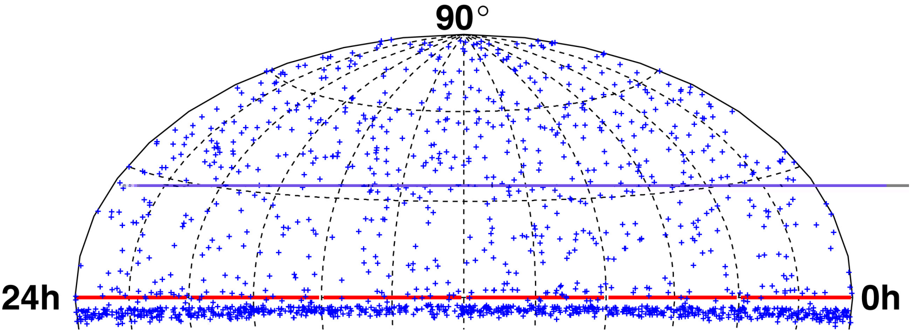






[Halzen, Kheirandish, 2202.00694]

Numerous Neutrino Sources



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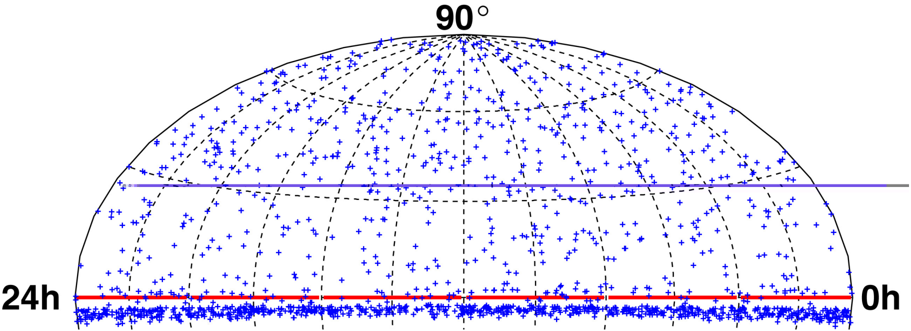

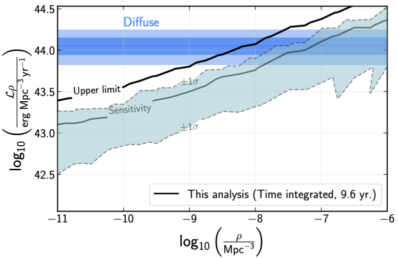

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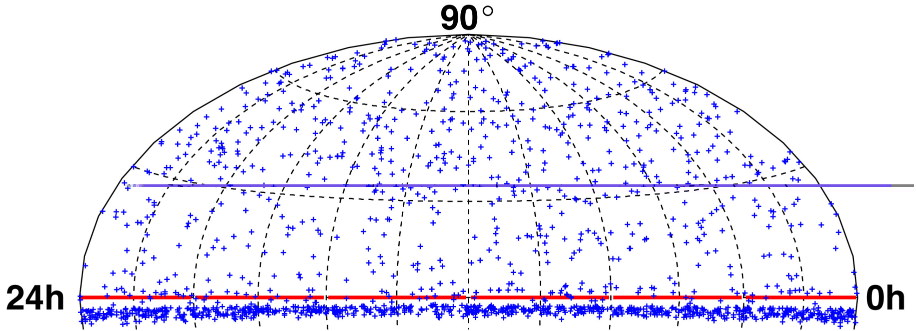
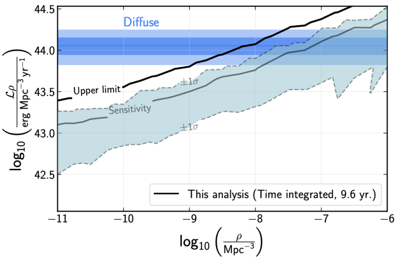
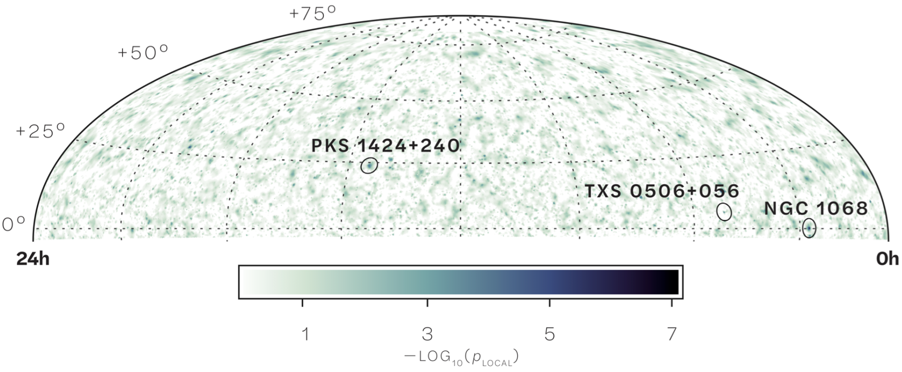




- Expect numerous population of neutrino sources to account for the observed diffuse flux.
- Following star-formation rate, inferred population density $\gtrsim 7 \times 10^{-9}\ \mathrm{Mpc}^{-3}$.

[IceCube Collaboration, 2210.04930 (ApJ)]

But why do we see so few in the EM Spectrum?



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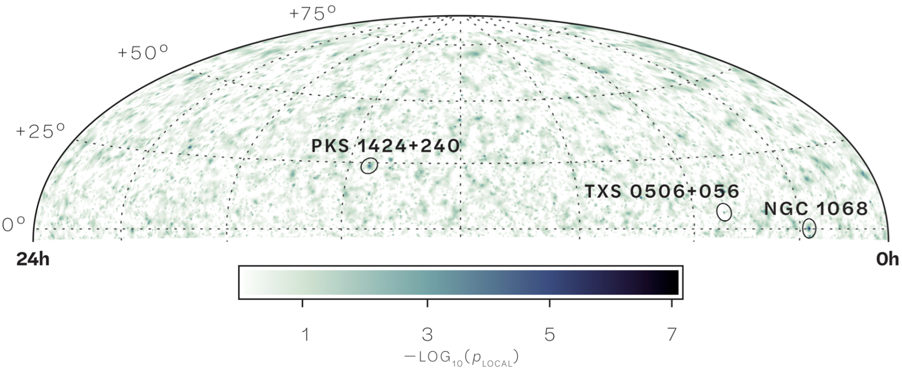

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Source	Source Type	$-\log_{10} p_{\rm local}$	$\hat{n}_s$	$\hat{\gamma}$	z
NGC 1068	SBG/AGN	7.0 (5.2σ)	79	3.2	0.0038 (14.4 Mpc)
PKS 1424+240	BLL	4.0 (3.7σ)	77	3.5	0.6047 (2.6 Gpc)
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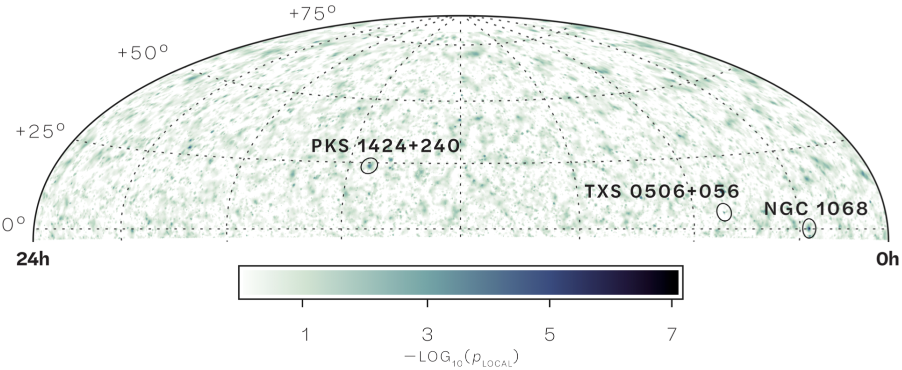

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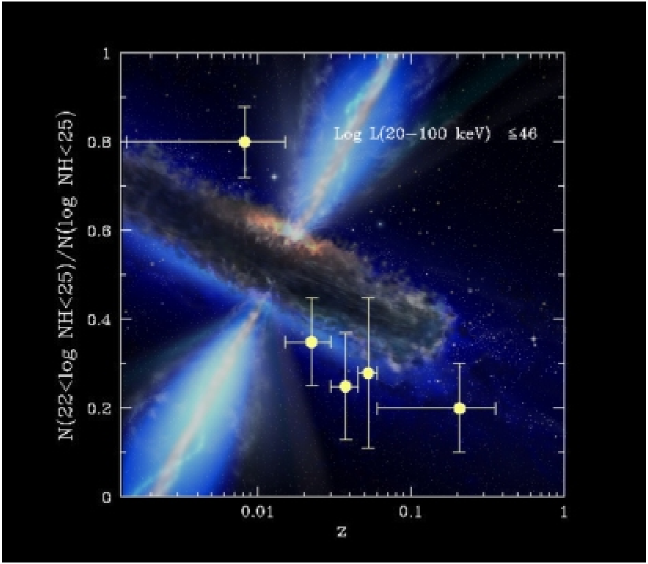
Obscured (Compton-thick) AGNs: Hidden neutrino sources?

[Murase, Kimura, Meszaros, 1904.04226 (PRL); Fang, Gallagher, Halzen, 2205.03740 (ApJ)]

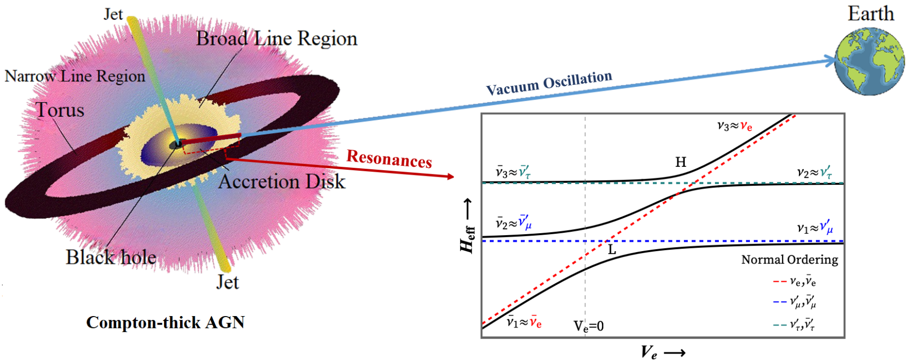
One in Four AGNs is Compton Thick in the Local Universe



[Malizia *et al.*, 0906.5544 (MNRAS)]

Column density $N_{\mathrm{H}} = \int n_e dr \geq \sigma_T^{-1} \simeq 1.5 \times 10^{24}\ \mathrm{cm}^{-2}$ corresponds to unity optical depth.

Neutrinos from Compton-thick AGNs *must* undergo Matter Effect



[BD, Jana, Porto, 2312.17315]

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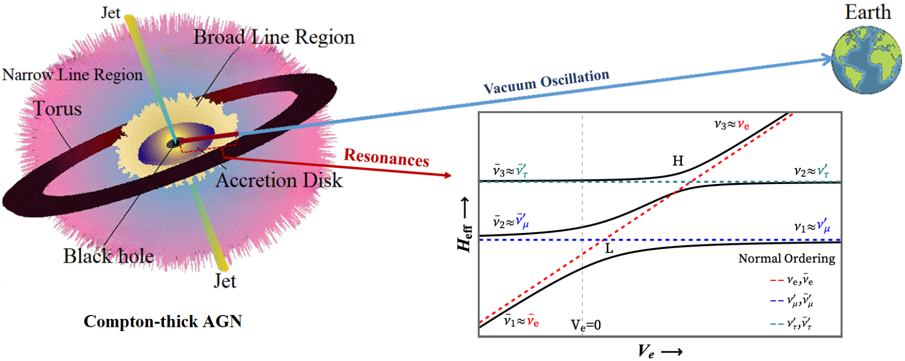

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- **Resonant flavor conversion**, analogous to supernova case: [Dighe, Smirnov, hep-ph/9907423 (PRD)]

$$\sqrt{2} G_F n_e^{\rm res} = \frac{\Delta m_{i1}^2}{2E_\nu} \cos 2\theta_{1i}.$$

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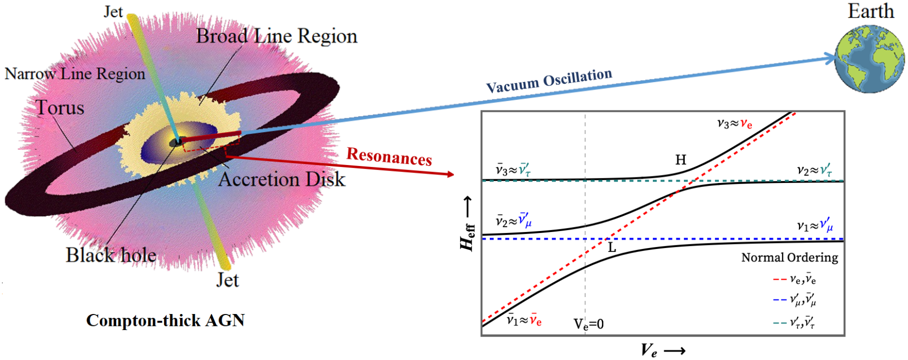

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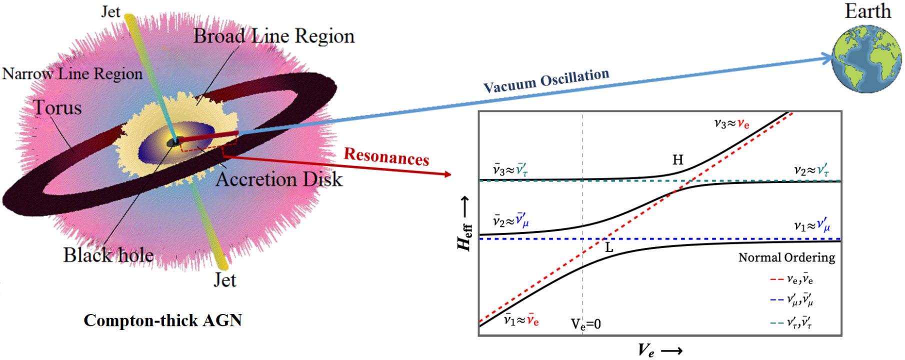

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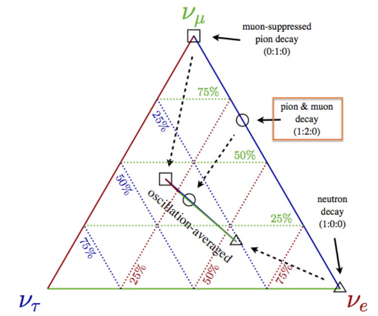
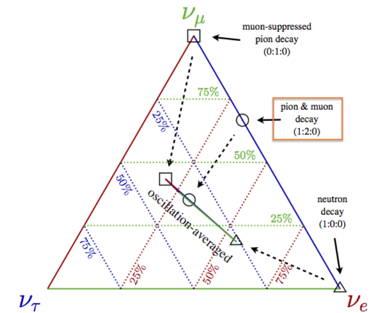
- Are these number densities realistic for AGNs? **YES.** [1406.4502; 1411.0670; 1511.03503; 1806.04680]

Modifies the Flavor Composition of HENs





Vacuum Oscillations (NO)	
π-decay	$(1/3, 2/3, 0)_S \to (0.30, 0.37, 0.33)_\oplus$
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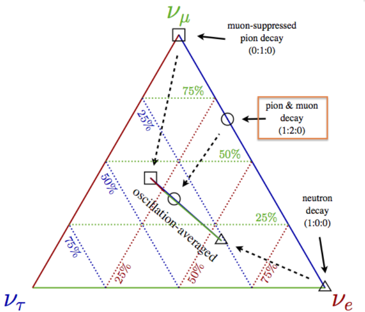

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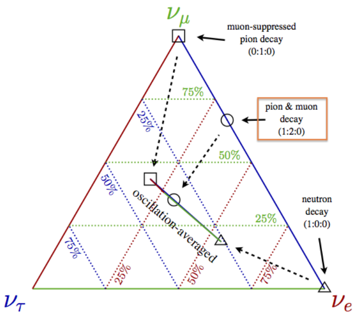

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Matter Effect (NO), $p\gamma$ production	
π-decay	$(1/3, 2/3, 0)_S \rightarrow (0.23, 0.40, 0.37)_\oplus$
μ-damped	$(0, 1, 0)_S \rightarrow (0.50, 0.20, 0.30)_\oplus$
n-decay	$(1, 0, 0)_S \rightarrow (0.67, 0.08, 0.25)_\oplus$

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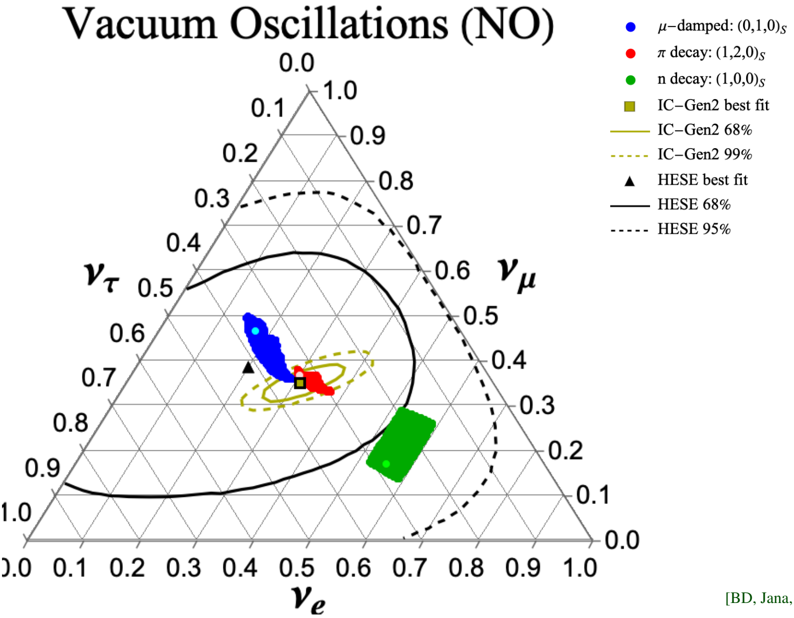
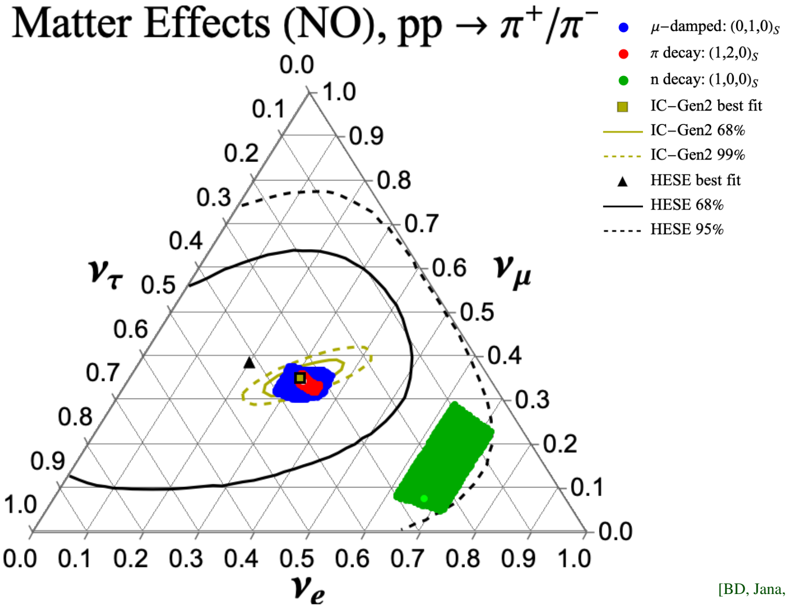


[BD, Jana, Porto, 2312.17315]



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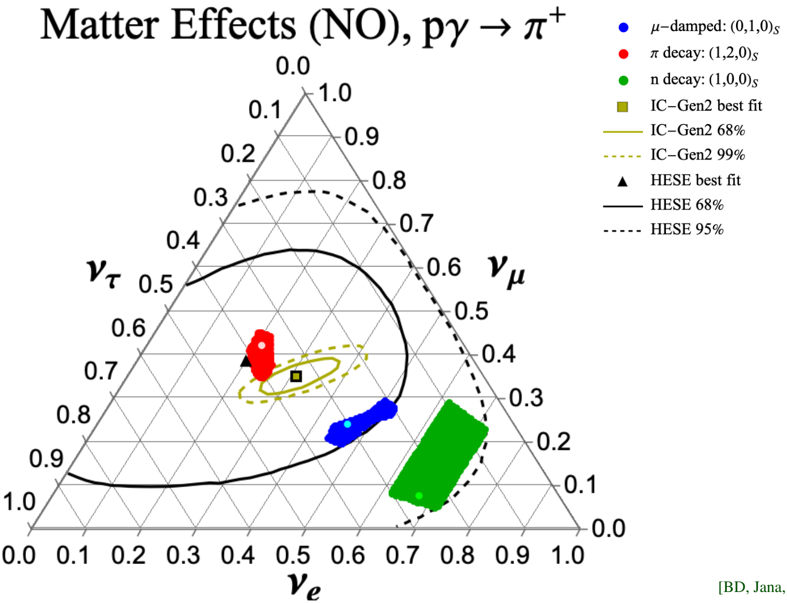

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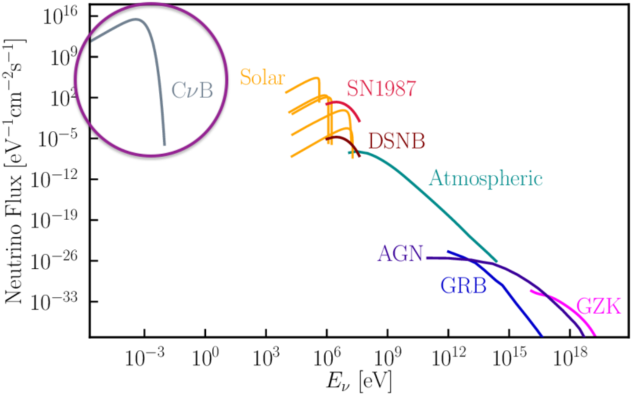
Another Matter Effect due to CνB



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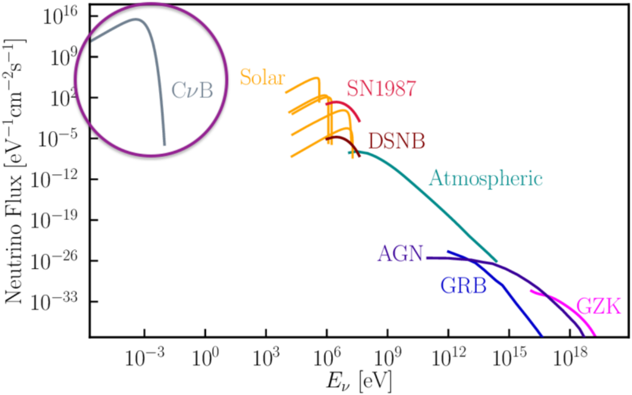

- CνB matter potential: $V = \sqrt{2}G_F n_\nu \sim 10^{-35}$ eV.
- Resonance condition: $\delta m^2 \cos(2\theta) = 2E_\nu V_{\rm res}$.
- For $E_\nu \sim 10$ TeV, resonance condition is satisfied with $\delta m^2 \sim 10^{-22}$ eV^2.
- **Pseudo-Dirac neutrinos**! [Carloni, Martínez-Soler, Argüelles, Babu, BD, 2212.00737 (PRD L)]
- Flavor composition of HENs will be modified by CνB matter effect if neutrinos are pseudo-Dirac. [BD, Machado, Martínez-Soler, *to appear*]

Oscillation Probability

$$P_{\alpha\beta} = \sum_j |U_{\alpha j}|^2 |U_{\beta j}|^2 \Bigg[\cos^2 \tilde{\theta}^i_j \cos^2 \tilde{\theta}^f_j + \sin^2 \tilde{\theta}^i_j \sin^2 \tilde{\theta}^f_j$$

$$+ \frac{1}{2} \sin 2\tilde{\theta}^i_j \sin 2\tilde{\theta}^f_j \cos \left(\int dx \frac{\delta \tilde{m}^2_j}{4E_\nu} \right) \Bigg] .$$

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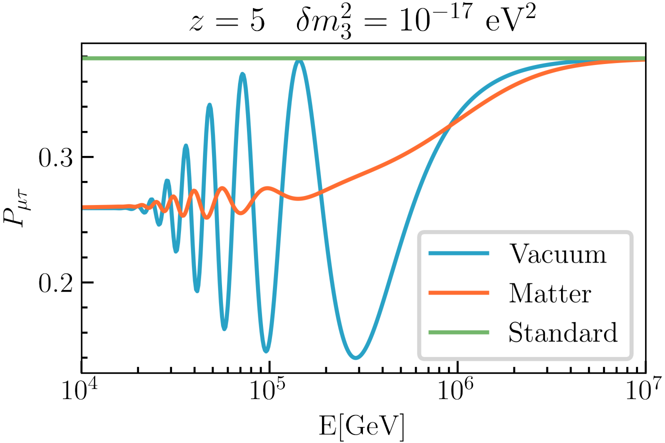
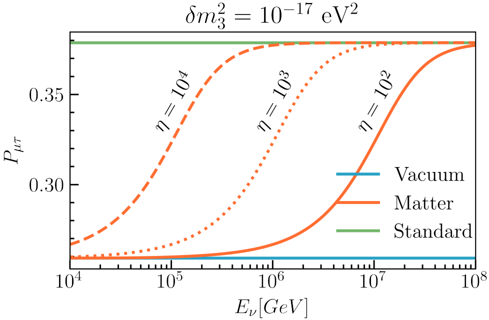
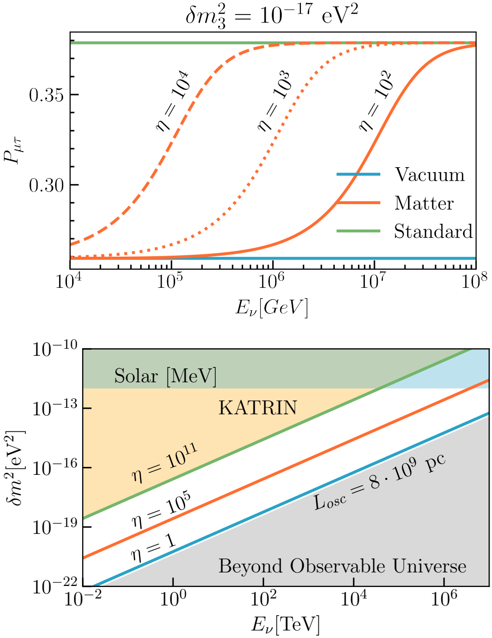
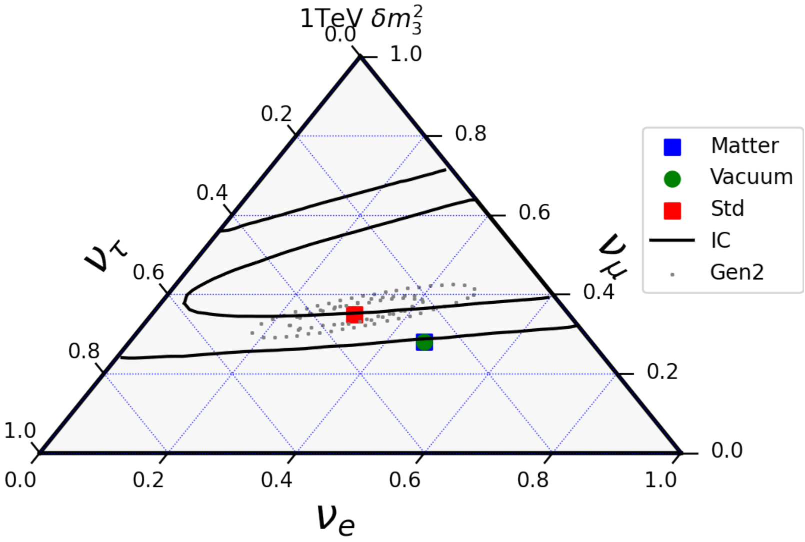


Sensitive to CνB Overdensity

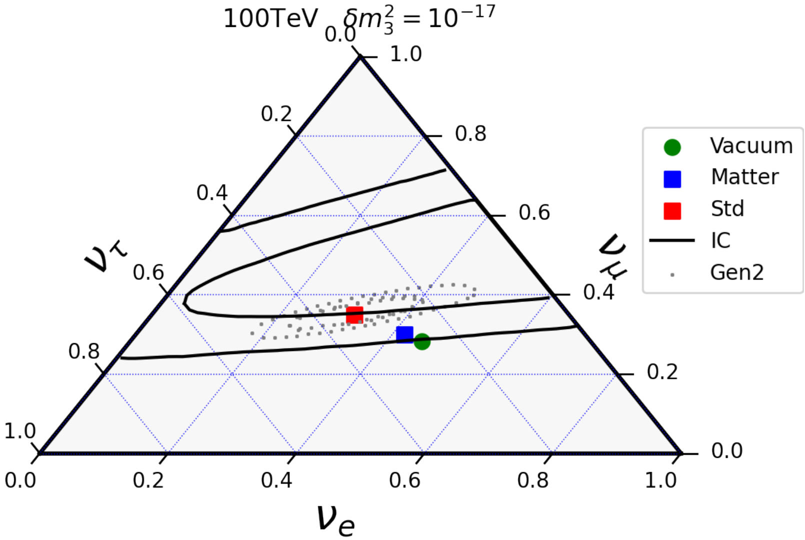


Sensitive to CνB Overdensity




1TeV δm_3^2
0.0
0.2
0.4
0.6
0.8
1.0
ν_τ
1.0
0.8
0.6
0.4
0.2
0.0
ν_μ
0.0
0.2
0.4
0.6
0.8
1.0
ν_e
Matter
Vacuum
Std
IC
Gen2

Energy-dependent Flavor Effect



Conclusions

- The sources of HENs are largely unknown.
- Precision measurements of their flavor composition will give crucial information.
- It is essential to include the source matter effect, which is non-negligible for Compton-thick sources.
- Might be the ONLY way to discover heavily Compton-thick sources (with $N_{\rm H} \gg 10^{25}$ cm^{-2}), which are neutrino bright, but EM dark.
- If neutrinos are pseudo-Dirac, CνB can induce additional, energy-dependent matter effect on the flavor composition.
- Sensitive to (local) CνB overdensity.

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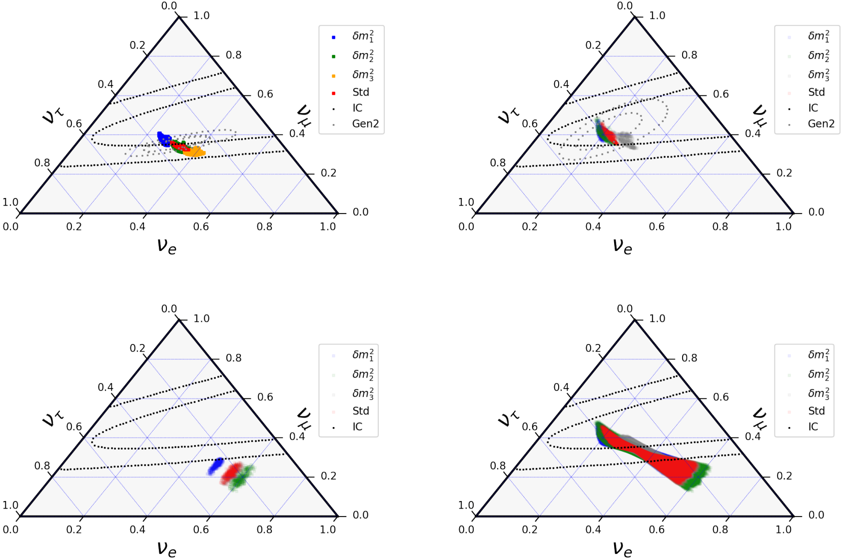
Thank You!

Flavor Triangles for Pseudo-Dirac Neutrinos



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