A New Idea for Relic Neutrino Detection

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with V. Brdar, R. Plestid and A. Soni, arXiv: 2206.abcde

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Why Relic Neutrinos?

- ‘Holy Grail’ of Neutrino Physics.
- Detection of cosmic neutrino background (CνB) will provide strong validation of our current cosmological model.
- And provide a window into the first second of creation.
- Indirect evidence for CνB from CMB, BBN and large-scale structure data.
- But direct detection remains a challenge.

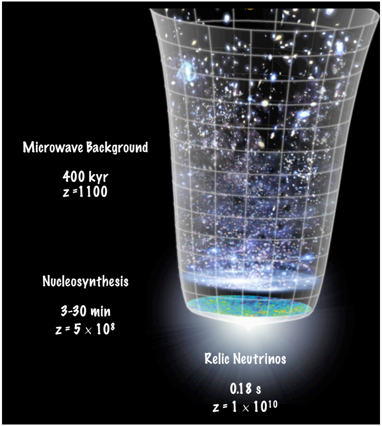

Figure from J. Formaggio

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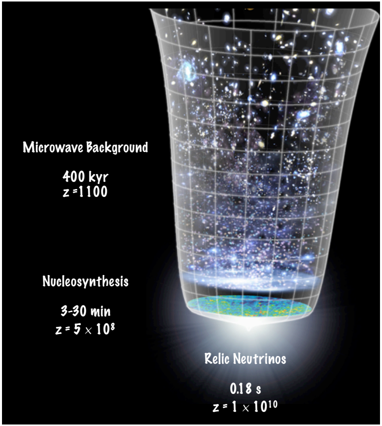
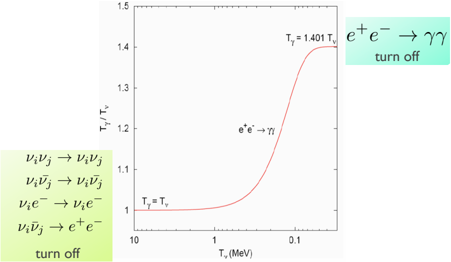


Figure from J. Formaggio

Why is it so hard?

CνB Characteristics

- CνB inherently connected to CMB: $T_{\nu,0} = \left(\frac{4}{11}\right)^{1/3} T_{\gamma,0} = 1.945\ \mathrm{K} = 1.7 \times 10^{-4}\ \mathrm{eV}$.
- Essentially a fermion gas obeying Fermi-Dirac statistics.
- Number density: $n_{\nu,0} = \frac{3}{4}\frac{\zeta(3)}{\pi^2} g T_{\nu,0}^3 = \mathbf{56/cm^3}$ per flavor (and similarly for $\bar{\nu}$).
- Most intense natural neutrino source.



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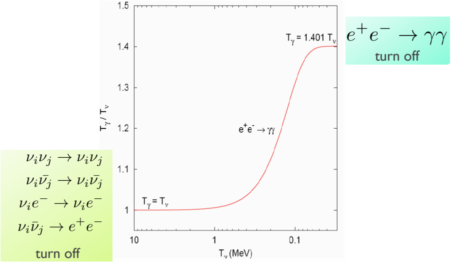

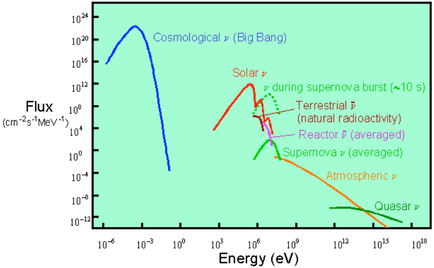

Flux on earth of neutrinos from various sources, in function of energy

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$\nu_i \nu_j \to \nu_i \nu_j$
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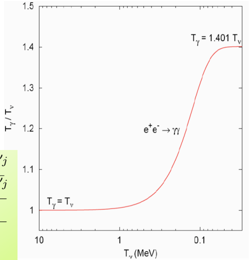
$\nu_i e^- \to \nu_i e^-$
$\nu_i \bar{\nu}_j \to e^+ e^-$
turn off



$e^+ e^- \to \gamma\gamma$
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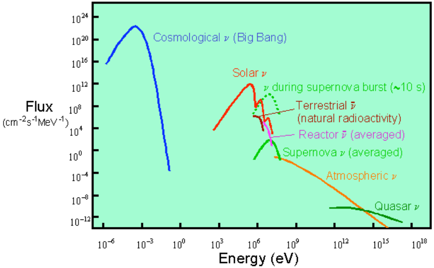
So what's the problem?



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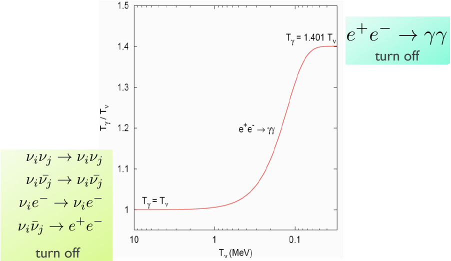

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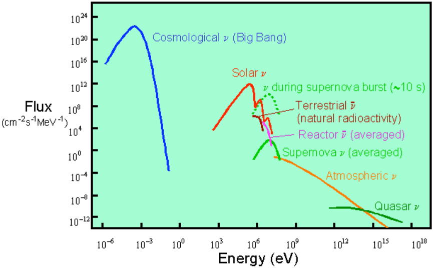
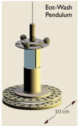
Small kinetic energy.



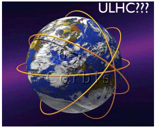
Flux on earth of neutrinos from various sources, in function of energy

Several Ideas on the Table

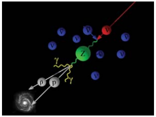
- Mechanical force due to coherent scattering of neutrino wind against a macroscopic object.



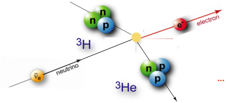
- Scattering on accelerator beam



- Scattering on ultra-high energy neutrinos/cosmic rays

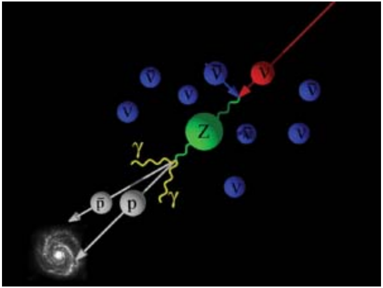


- Neutrino capture on beta nuclei

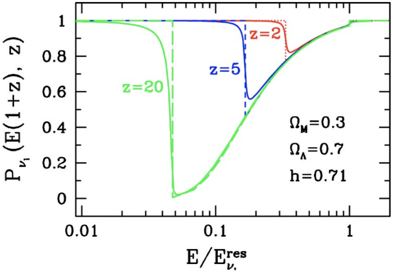


[G. Gelmini (Phys.Scripta ’05); C. Yanagisawa (Front. Phys ’14); P. Vogel (AIP Conf. Proc. ’15)]

Z-burst



[T. Weiler (PRL '82)]

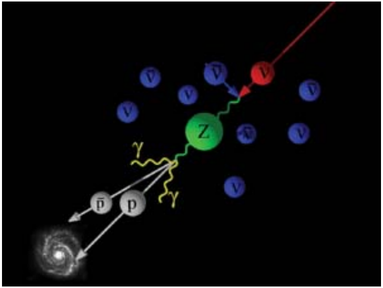


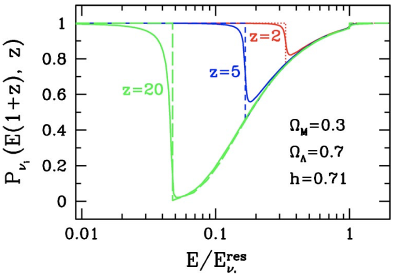
[Eberle, Ringwald, Song, Weiler (PRD '04)]

- Resonant absorption happens at

$$E_\nu^{\rm res} = \frac{m_Z^2}{2m_\nu} = (4.2 \times 10^{22}\ {\rm eV}) \left(\frac{0.1\ {\rm eV}}{m_\nu}\right)$$

Beyond the GZK cut-off!





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- Observable effect, depending on redshift and source energy distribution of the (unknown) super-GZK cosmic ray sources.

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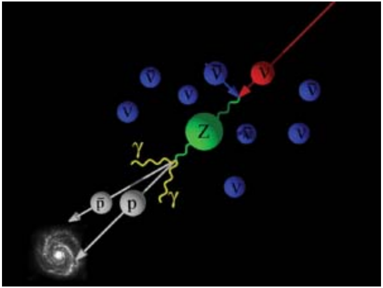

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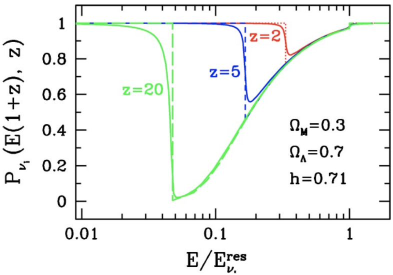

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- Observable effect, depending on redshift and source energy distribution of the (unknown) super-GZK cosmic ray sources.
- Resonance energy can be sub-GZK for secret neutrino interactions with light mediators.

[Ioka, Murase (PTEP '14); Araki et al (PRD '15); DiFranzo, Hooper (PRD '15); Cherry, Friedland, Shoemaker (1605.06506); Altmannshofer, Chen, BD, Soni (PLB '16); Barenboim, Denton, Oldengott (PRD '19); Esteban, Pandey, Brdar, Beacom (PRD '21);...]

New Idea: Use SM Meson Resonances

- Recall vector meson resonances in e^+e^- scattering. [Lee, Zumino (PR '67); Gounaris, Sakurai (PRL '68)]
- Apply it to UHE neutrino scattering off CνB. [Bander, Rubinstein (PRD '95); Paschos, Lalakulich (hep-ph/0206273); BD, Soni (2112.01424)]
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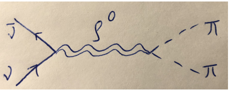

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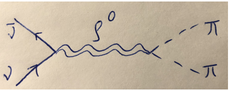

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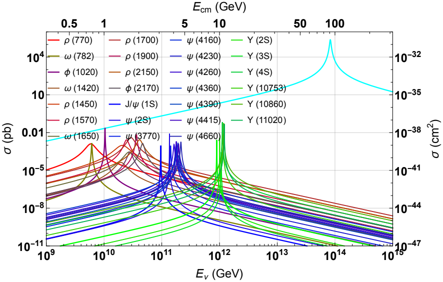

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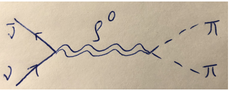

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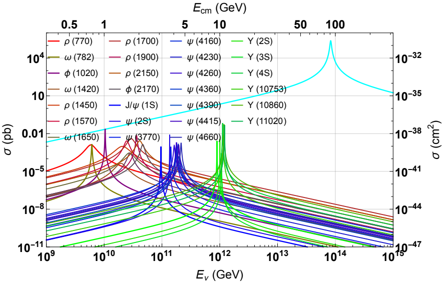
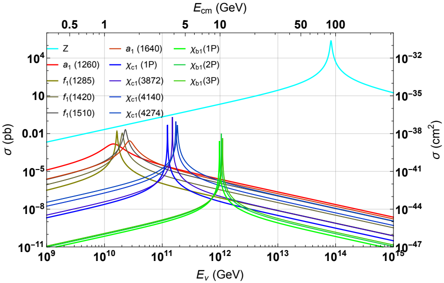
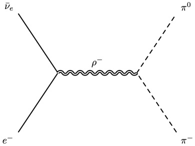




Interlude: Charged Meson Resonances

[Brdar, de Gouvea, Machado, Plestid, 2112.03283 (PRD '22)]



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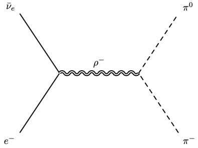

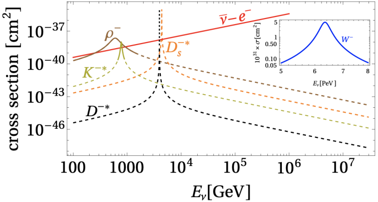

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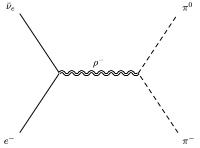

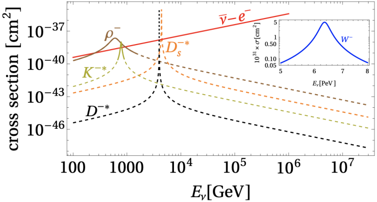

$$N_{\rm res} = N_e \int_{\frac{(M-n\Gamma/2)^2}{(2m_e)}}^{\frac{(M+n\Gamma/2)^2}{(2m_e)}} \Phi(E_\nu)\sigma_{\rm res}(E_\nu)dE_\nu$$

Experiment	ρ^-, $\pm\Gamma/2$	ρ^-, $\pm 2\Gamma$	K^{-*}, $\pm\Gamma/2$	K^{-*}, $\pm 2\Gamma$
FASERν	0.3	0.5	–	–
FASERν2	23	37	0.7	3
FLArE-10	11	19	0.3	2
FLArE-100	63	103	2	8
DeepCore	3 (1)	5 (2)	–	–
IceCube	8 (40)	17 (83)	–	–

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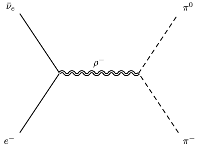

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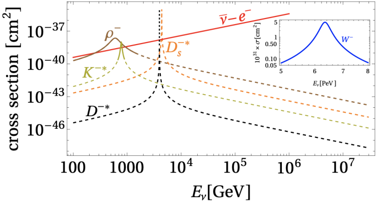

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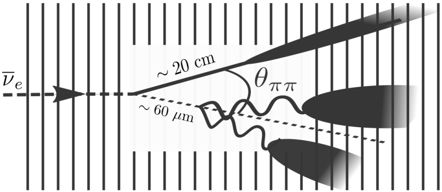

But not enough for CνB Detection ☹

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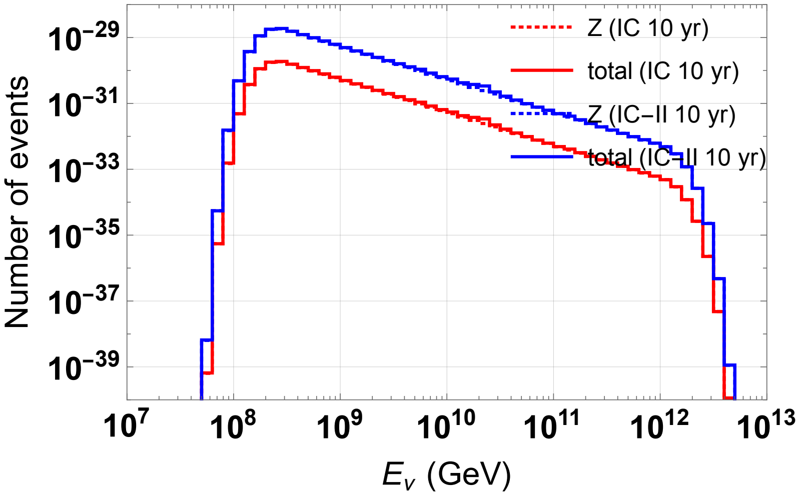

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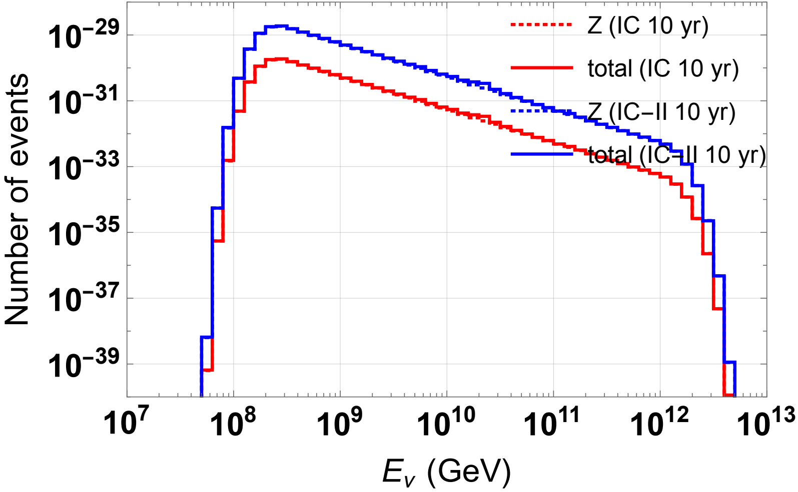
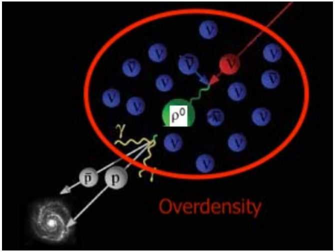


Any hope?

Attenuation of GZK Neutrinos



Attenuation: $\mathcal{R} = e^{-L/\lambda}$.
Inverse MFP: $\lambda^{-1} = \sigma n_\nu = \sigma n_{\nu,0} \xi (1+z)^3$.
Cloud length: $L = \frac{c}{H_0} \xi^{-1/3}$.

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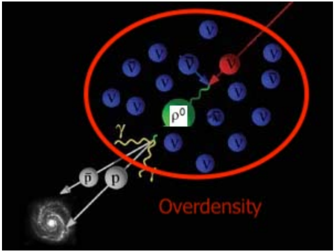

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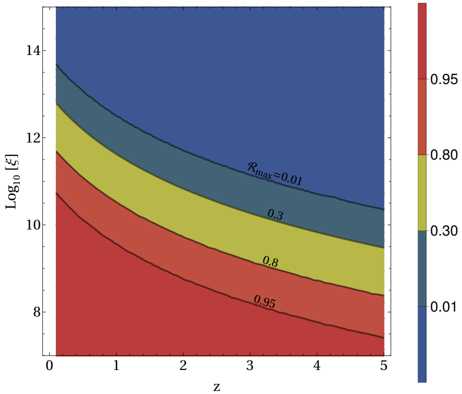
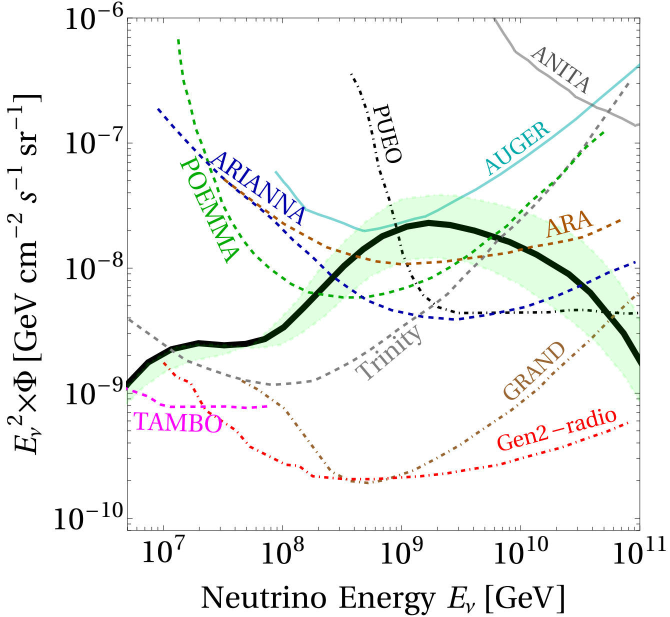
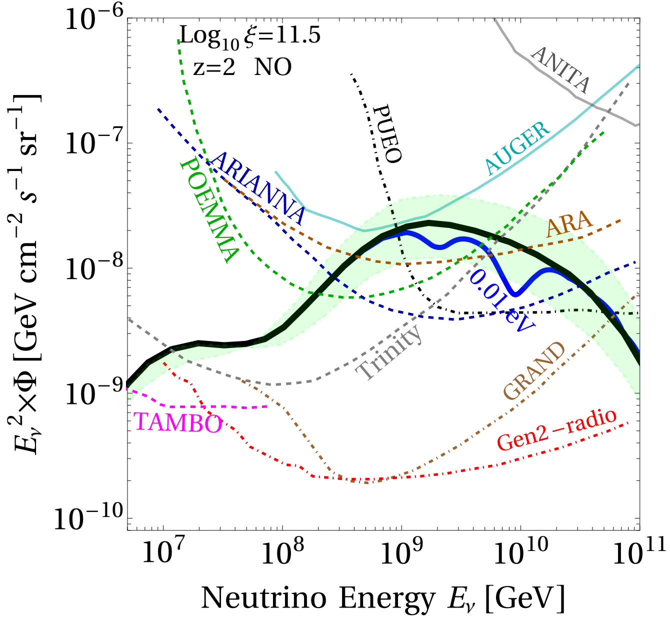




[GZK flux: Ahlers, Anchordoqui, Gonzalez-Garcia, Halzen, Sarkar (1005.2620); Sensitivity curves: 2203.08096]



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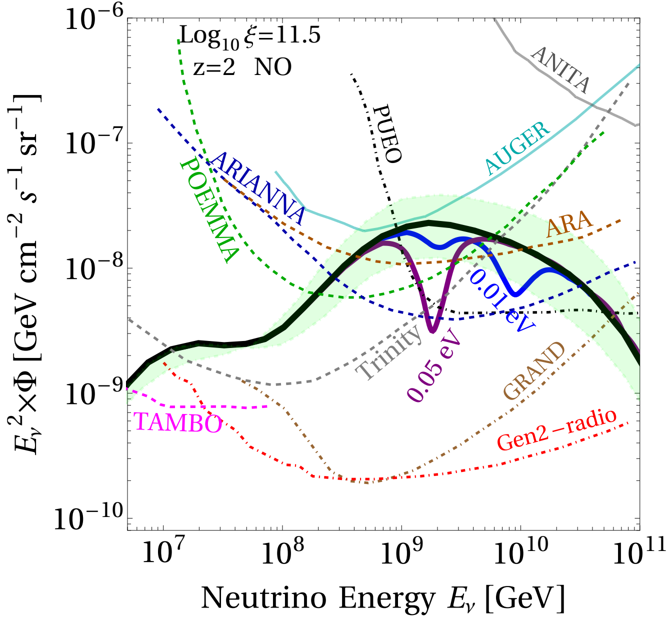
Observable Effect in GZK Neutrino Flux



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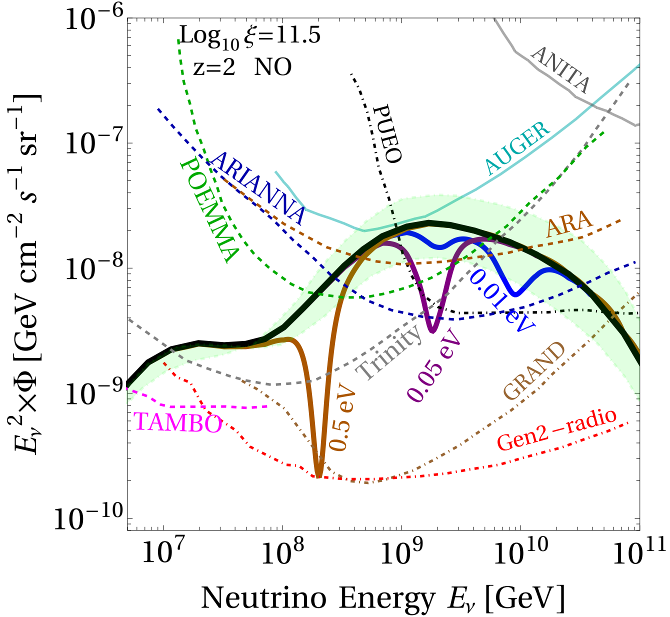
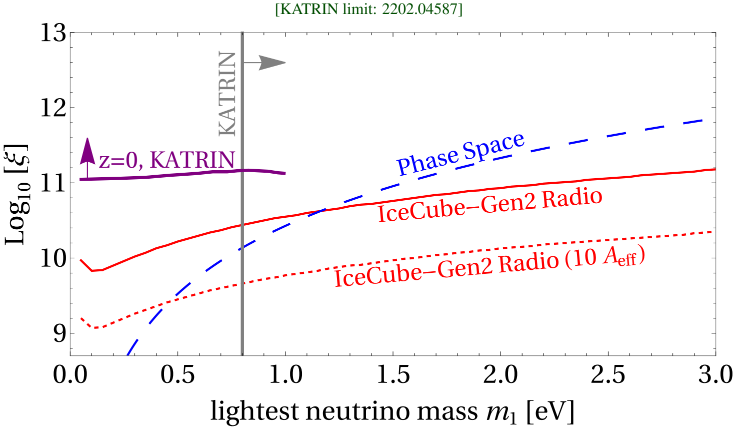
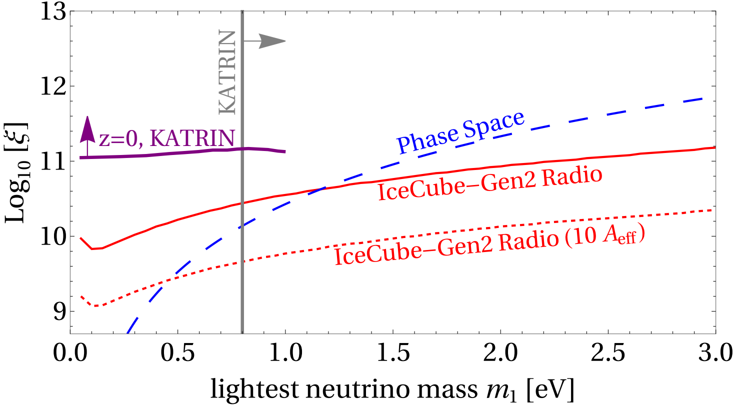


[GZK flux: Ahlers, Anchordoqui, Gonzalez-Garcia, Halzen, Sarkar (1005.2620); Sensitivity curves: 2203.08096]

Complementary to KATRIN



[KATRIN limit: 2202.04587]

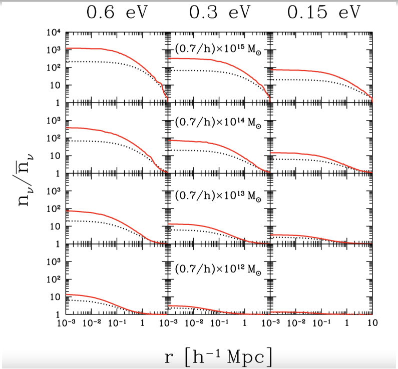


What are we asking for?

- Large overdensity $\xi \equiv \frac{n_\nu}{n_{\nu,0}} \gtrsim 10^{10}$.
- Mass-varying neutrinos or non-standard cosmology to avoid $\sum m_\nu \lesssim 0.1$ eV (Planck).

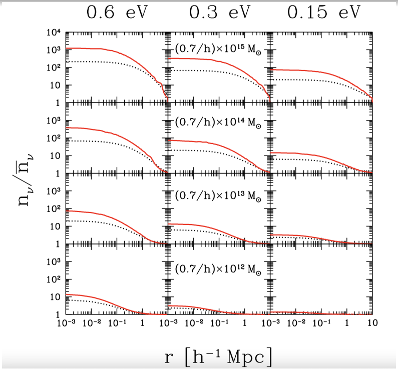
[Fardon, Nelson, Weiner (JCAP '04); Krnjaic, Machado, Necib (PRD '18); Alvey, Escudero, Sabti, Schwetz (PRD '22);...]

Neutrino Clustering



[Ringwald, Wong, hep-ph/0412256]

Gravitational clustering is not enough ☹



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- But new neutrino interactions could help efficient clustering.
- E.g., [Smirnov, Xu (2201.00939)]

$$\mathcal{L} = \frac{1}{2}\partial^\mu \phi \partial_\mu \phi - \frac{1}{2} m_\phi^2 \phi^2 + \bar{\nu} i \partial\!\!\!/ \nu - m_\nu \bar{\nu}\nu - y \bar{\nu}\phi\nu$$

- Condition for bound state: $E_{\rm kin} \lesssim -V \Longrightarrow \frac{y^2}{8\pi}\frac{m_\nu}{m_\phi} \gtrsim 0.7.$
- Strong limits on y_ϕ force $m_\phi \lesssim 10^{-17}$ eV.

[Smirnov, Xu (JHEP '19); Babu, Chauhan, BD (PRD '20)]

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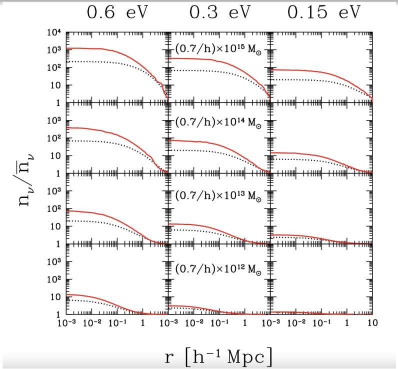

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Table I. Characteristics of final (degenerate) states of neutrino clusters for $y = 10^{-7}$ and $m_\phi = 0$.

N	$2.96 \cdot 10^{21}$	$1.63 \cdot 10^{22}$	$5.96 \cdot 10^{22}$	$9.35 \cdot 10^{23}$	$2.34 \cdot 10^{24}$
$p_{F0}/\tilde{m}_0$	0.10	0.31	0.75	7.0	22
$\tilde{m}_0/m_\nu$	0.991	0.922	0.688	0.060	0.014
p_{F0}/m_ν	0.099	0.286	0.561	0.420	0.308
n_0 [cm^{-3}]	$2.0 \cdot 10^6$	$4.9 \cdot 10^7$	$3.7 \cdot 10^8$	$1.5 \cdot 10^8$	$6.1 \cdot 10^7$
R [km]	1.25	0.75	0.62	1.46	2.41

Conclusion

- Detection of CνB is an important unsolved problem in neutrino physics.
- A new idea for CνB detection via resonant scattering off GZK neutrinos through neutral vector (axial-vector) mesons in the SM.
- Observable effect, provided there is a large overdensity of CνB along the line-of-sight.
- **Can probe CνB overdensity at higher redshifts.**
- Complementary to KATRIN which is only sensitive to local overdensity.

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