A multi-messenger probe of the nature of neutrino mass

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in collaboration with
Kiara Carloni, Ivan Martínez-Soler, Carlos Argüelles, and Kaladi Babu,

arXiv: 2212.00737 [astro-ph.HE]

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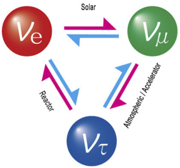
Texas A&M University, College Station

May 17, 2023

Nature of neutrino mass remains unknown!



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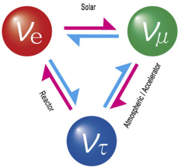

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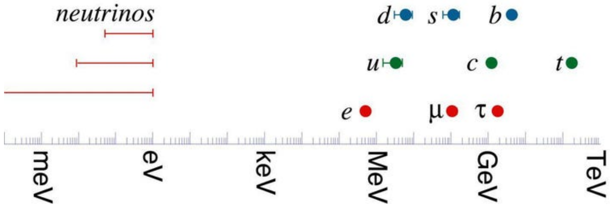

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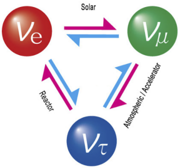

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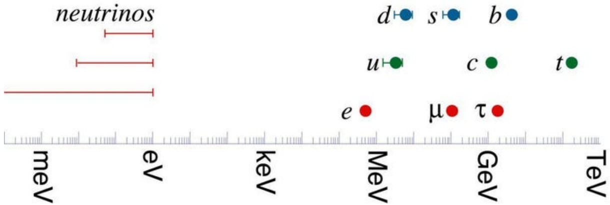

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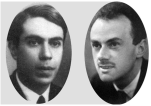
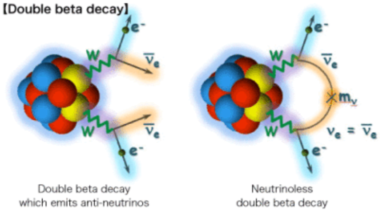
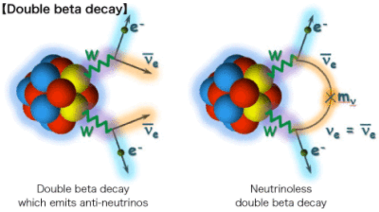


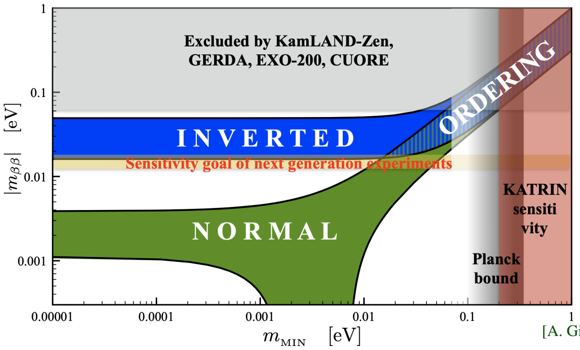
Majorana or Dirac (or something in between)?

Only experiments can tell.

$0\nu\beta\beta$ experiments ... maybe?







[A. Giuliani *et al.*, 1910.04688]

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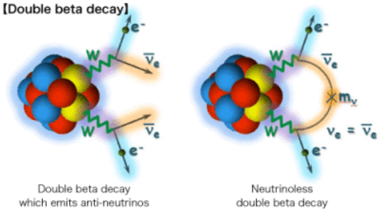

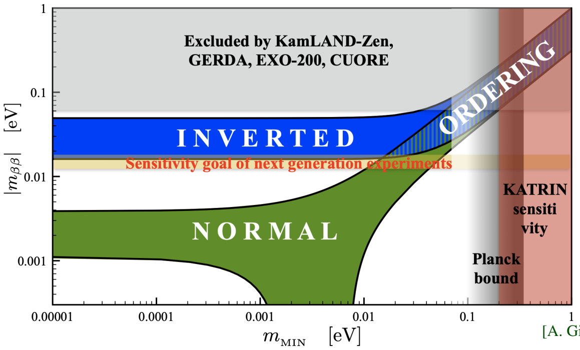

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- Simplest possibility: Add SM-singlet Dirac partners ν_R to write Dirac mass.
- Also allows for a Majorana mass term $M_R \bar{\nu}_R^c \nu_R$.

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  - If $M_R = 0$, lepton number is preserved and neutrinos are **Dirac**.
  - If $M_R \neq 0$, neutrinos are **Majorana**.
  - If $||M_R|| \ll ||m_D||$, neutrinos are **pseudo-Dirac** (small active-sterile mass splitting).
- But isn't it more natural to have $||M_R|| \gg ||m_D||$ (seesaw)?

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- Maybe, but $||M_R|| \ll ||m_D||$ is a logical possibility too.

  [Wolfenstein (NPB '81); Petcov (PLB '82); Valle (PRD '82); Valle, Singer (PRD '83); Kobayashi, Lim (PRD '01)]

Models of pseudo-Dirac neutrinos

- A good starting point: Dirac neutrino models with m_D naturally small and $M_R = 0$ at renormalizable level, e.g. in **Dirac seesaw**. [Roncadelli, Wyler (PLB '83); Roy, Shanker (PRL '84); Dick, Lindner, Ratz, Wright (PRL '00); Murayama, Pierce (PRL '02); Gu, He (JCAP '06); Joshipura, Mohanty, Pakvasa (PRD '14); Ma, Srivastava (PLB '15); Ma, Popov (PLB '17); Earl, Fong, Gregoire, Tonero (JCAP '20); ...]
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- Global lepton number symmetry.
- Broken by quantum gravity corrections and a small M_R is induced.
- Naturally realized in mirror models. [Berezhiani, Mohapatra (PRD '95)]
- Weinberg operators $(\Psi\Psi HH)/M_{\rm Pl}$ and $(\Psi'\Psi' H' H')/M_{\rm Pl}$ induce small diagonal M_ν entries $\Longrightarrow$ **Pseudo-Dirac neutrinos**.
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- But excluded by BBN and solar neutrino constraints (for maximal mixing). ☹

$\delta m^2 \lesssim 10^{-8}$ eV^2 from BBN, [Barbieri, Dolgov (PLB '90)]
10^{-11} eV^2 from solar. [de Gouvêa, Huang, Jenkins (PRD '09); Ansarifard, Farzan (PRD '23)]

Models of pseudo-Dirac neutrinos

- An alternative is to gauge $B - L$.
- Introduce a singlet scalar S carrying two units of $B - L$.
- Lowest-order quantum gravity corrections are of the form $(\Psi\Psi HHS)/M_{\mathrm{Pl}}^2$.
- For $\langle S \rangle = v_{BL}$, leads to diagonal elements of M_ν of order $v^2 v_{BL}/M_{\mathrm{Pl}}^2$.
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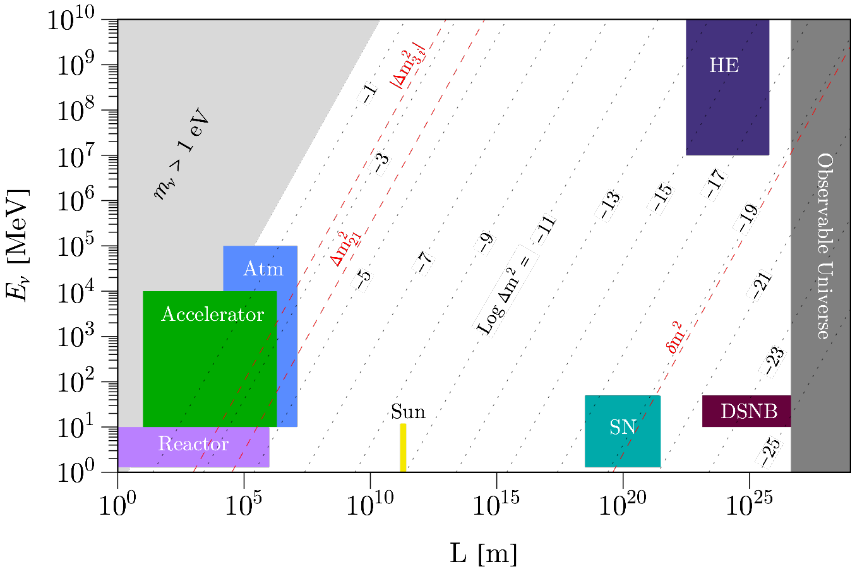
How to probe these tiny δm^2 values?

Oscillation effects are suppressed, unless L and E are such that $\delta m^2 L/E \sim 1$.

Need astrophysical baselines



Beacom, Bell, Hooper, Learned, Pakvasa, Weiler, 0307151 (PRL '04); Martinez-Soler, Perez-Gonzalez, Sen, 2105.12736 (PRD '22)

Supernova neutrino constraints

$$P_{aa}(E_\nu) = \frac{1}{2}\left(1 + e^{-\left(\frac{L}{L_{\rm coh}}\right)^2} \cos\left(\frac{2\pi L}{L_{\rm osc}}\right)\right).$$

$$L_{\rm osc} = \frac{4\pi E_\nu}{\delta m^2} \approx 20 \text{ kpc} \left(\frac{E_\nu}{25 \text{ MeV}}\right)\left(\frac{10^{-19} \text{ eV}^2}{\delta m^2}\right),$$

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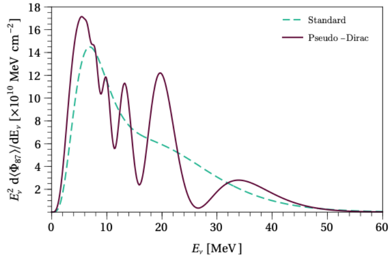

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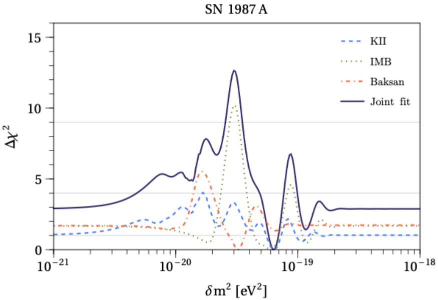

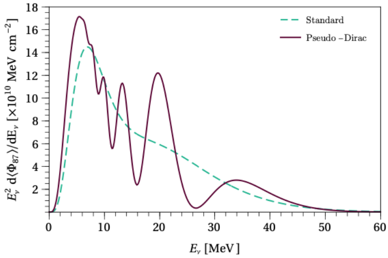

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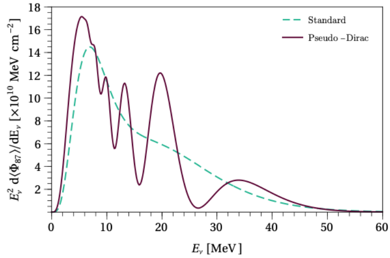

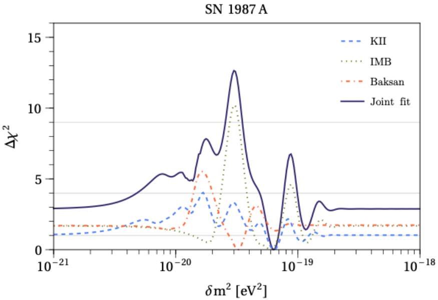

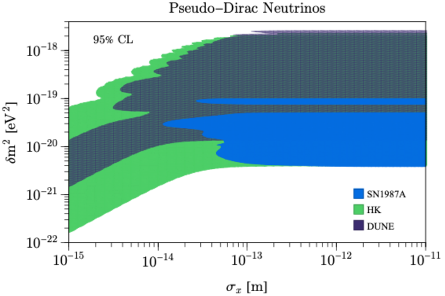

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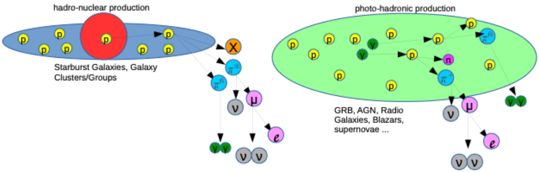
Astrophysical neutrinos



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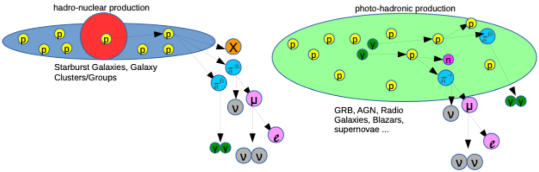

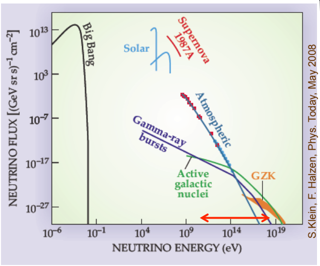

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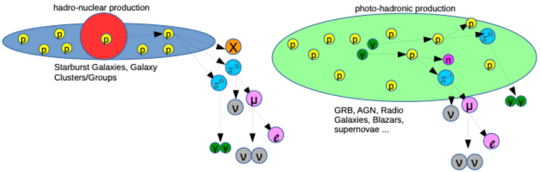
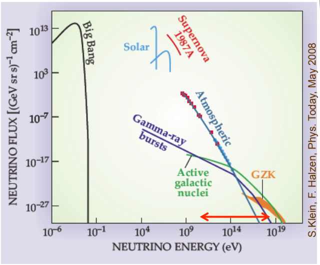
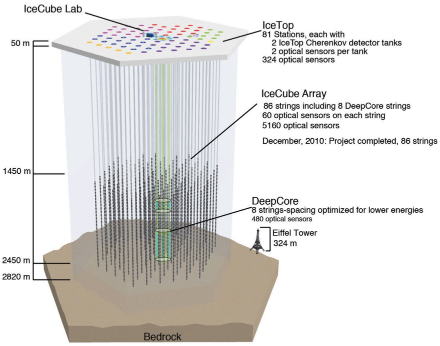




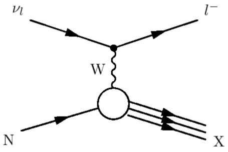
Need gigantic detectors to compensate for the tiny flux.



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

Flavor composition:

$$(\nu_e : \nu_\mu : \nu_\tau) = (1:2:0)_\star \longrightarrow (1:1:1)_\oplus .$$



High-energy neutrino signals at IceCube

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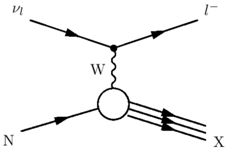

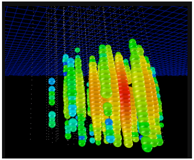

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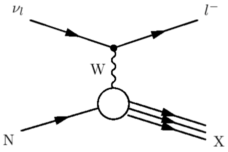

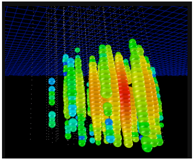

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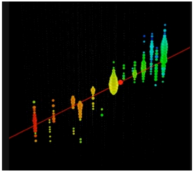

CC Muon (track)

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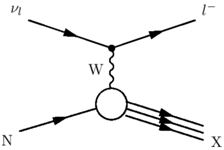
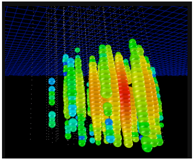
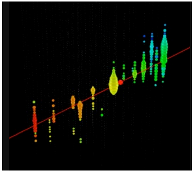


Flavor composition:

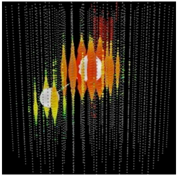
$$(\nu_e : \nu_\mu : \nu_\tau) = (1:2:0)_\star \longrightarrow (1:1:1)_\oplus.$$



CC EM/NC all (shower)



CC Muon (track)



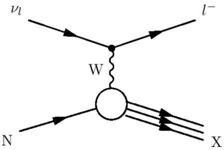
CC tau 'double bang' (only at $E_\nu \gtrsim 100$ TeV)

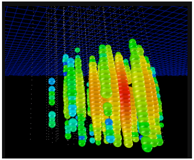
High-energy neutrino signals at IceCube

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

Flavor composition:

$$(\nu_e : \nu_\mu : \nu_\tau) = (1:2:0)_\star \longrightarrow (1:1:1)_\oplus.$$





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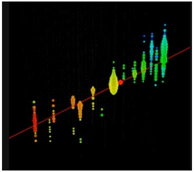

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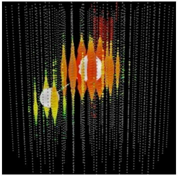

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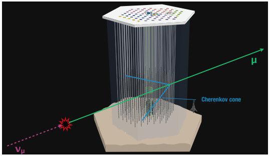


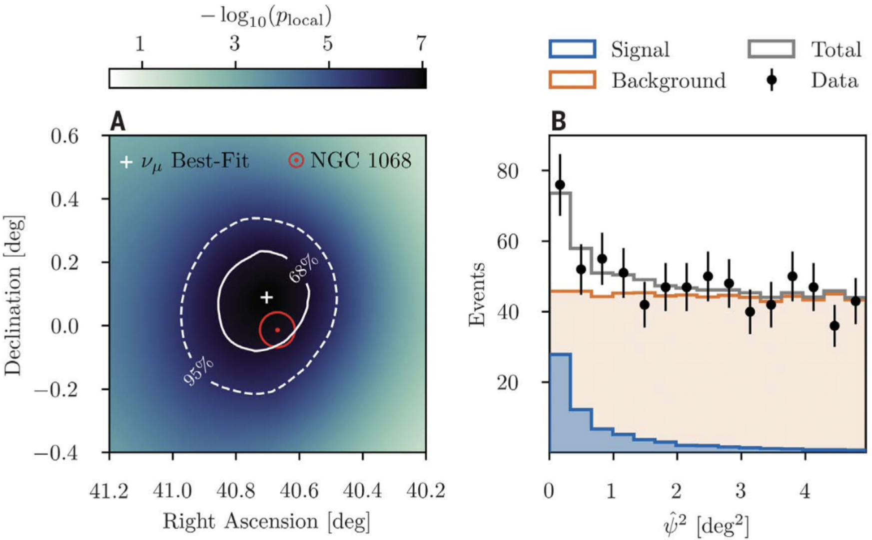
Throughgoing muon (track only, huge statistics)

[Picture courtesy: C. Kopper]

Showers: Good energy resolution, but poor angular resolution

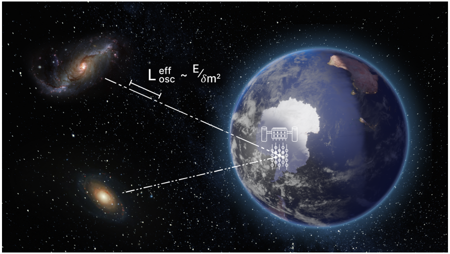
Tracks: Excellent angular resolution ($< 1^\circ$), but modest energy resolution ($\sim 30\%$)

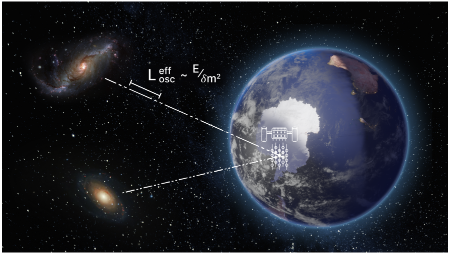
Track events are ideal for astrophysical source identification.

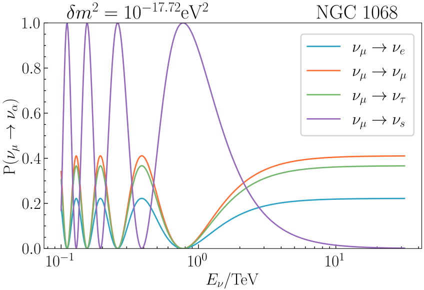


[IceCube Collaboration, 2211.09972 (Science '22)]

A new probe of pseudo-Dirac neutrinos





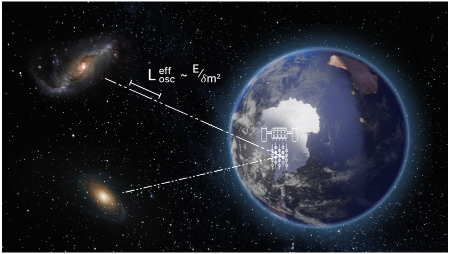


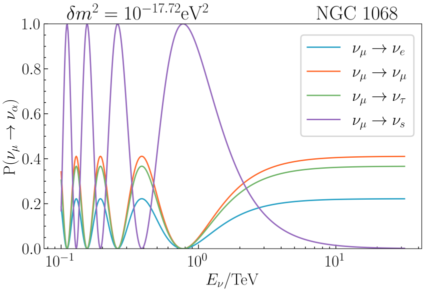
Carloni, Martínez-Soler, Argüelles, Babu, BD, 2212.00737

- Oscillation probability:

$$P_{\alpha\beta} = \frac{1}{2}\sum_{j=1}^{3} |U_{\beta j}|^2 |U_{\alpha j}|^2 \left[1 + \cos\left(\frac{\delta m_j^2 L_{\rm eff}}{2E_\nu}\right)\right],$$

with $L_{\rm eff} = \int \frac{dz}{H(z)(1+z)^2}$ and $H(z) = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda + (1-\Omega_m-\Omega_\Lambda)(1+z)^2}$.





Carloni, Martínez-Soler, Argüelles, Babu, BD, 2212.00737

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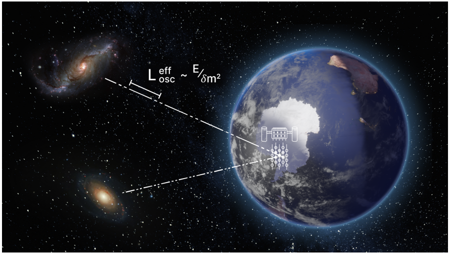
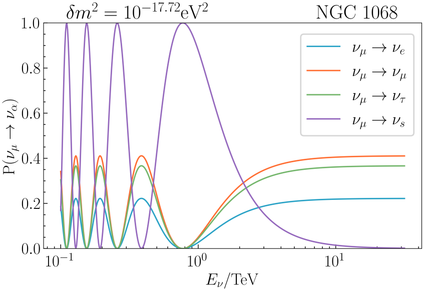
- Typical oscillation length: $L_{\rm osc} = \frac{2E_\nu}{\delta m^2} \approx 6.4\ \mathrm{Mpc}\left(\frac{E_\nu}{1\ \mathrm{TeV}}\right)\left(\frac{2\times10^{-18}\ \mathrm{eV}^2}{\delta m^2}\right)$.

A new probe of pseudo-Dirac neutrinos





Carloni, Martínez-Soler, Argüelles, Babu, BD, 2212.00737

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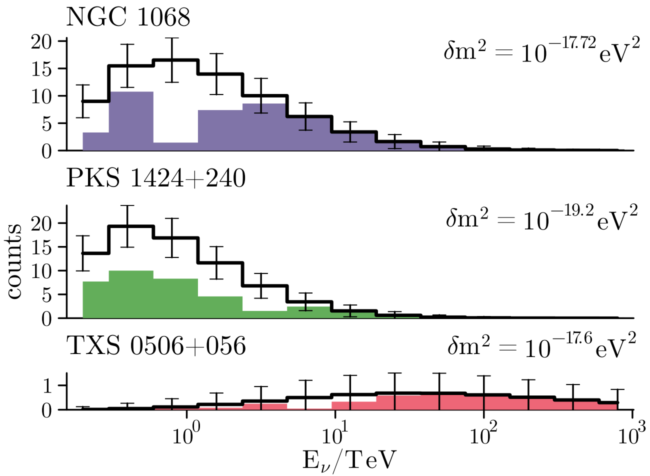
- Typical coherence length: [Kersten, Smirnov, 1512.09068 (EPJC '16); Rink, Sen, 2211.16520]

$L_{\rm coh} = \frac{4\sqrt{2}E_\nu^2}{|\delta m^2|} \approx 10^{10}\ \mathrm{Mpc}\left(\frac{E_\nu}{1\ \mathrm{TeV}}\right)^2\left(\frac{2\times 10^{-18}\ \mathrm{eV}^2}{|\delta m^2|}\right)\left(\frac{\sigma_x}{10^{-10}\ \mathrm{m}}\right) \gg L_{\rm osc}$.

Event Distributions

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 (16 Mpc)
PKS 1424+240	BLL	4.0 (3.7σ)	77	3.5	0.6047 (2.6 Gpc)
TXS 0506+056	BLL/FSRQ	3.6 (3.5σ)	5	2.0	0.3365 (1.4 Gpc)



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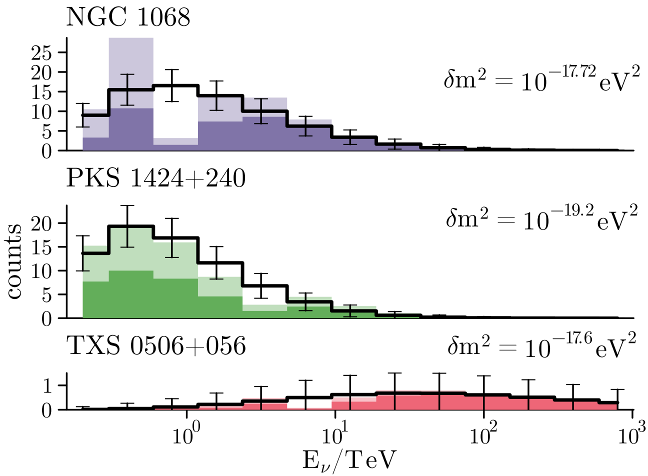
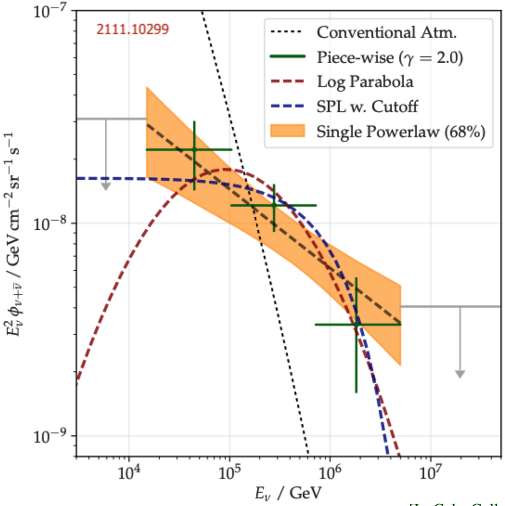


Power-law flux



[IceCube Collaboration, 2111.10299 (ApJ '22)]

$$\Phi(E_\nu) = \begin{cases} \Phi_0 (E_\nu/E_0)^{-\gamma} & \text{(single power law)} \\ \Phi_0' (E_\nu/E_0)^{-\gamma'} e^{-E_\nu/E_{\rm cutoff}} & \text{(SPL with cutoff)} \\ \Phi_0'' \cdot (E/E_0)^{-(\alpha+\beta\log(E/E_0))} & \text{(log parabola)} \end{cases}$$

First IceCube constraints on δm^2

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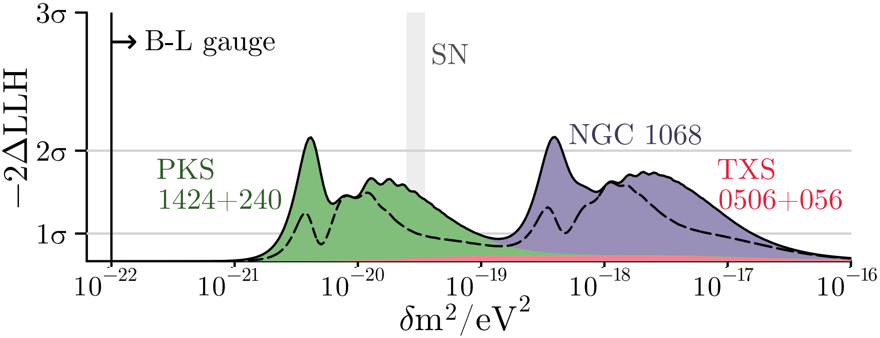
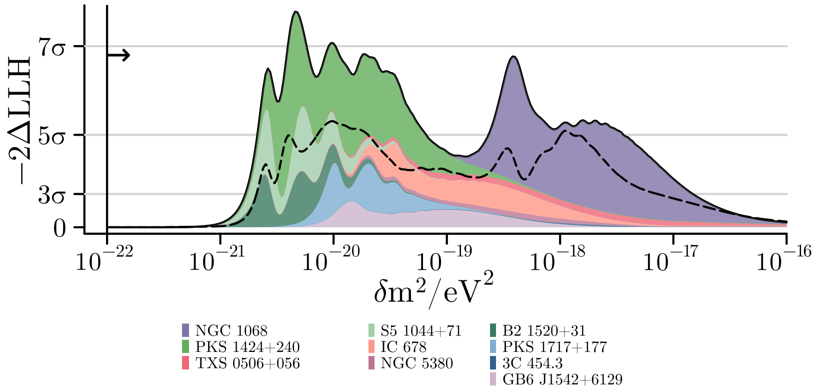


Carloni, Martínez-Soler, Argüelles, Babu, BD, 2212.00737

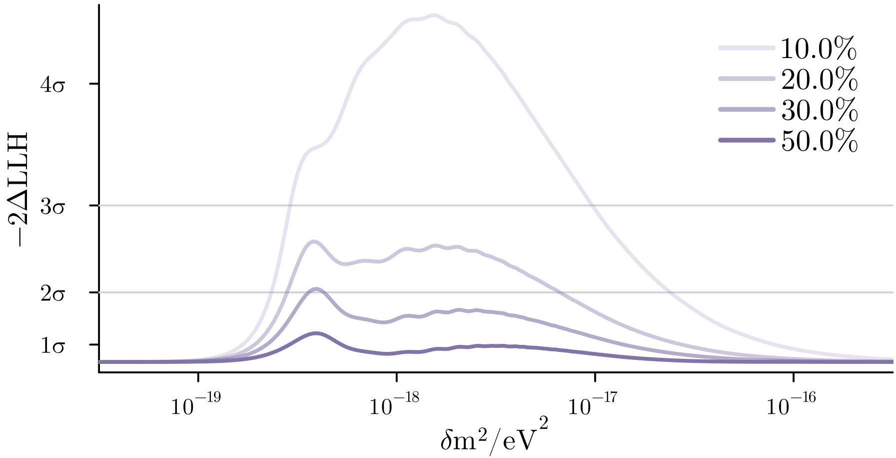
Future IceCube-Gen2 sensitivity

Source	Source Type	$-\log_{10} p_{\text{local}}$	$\hat{n}_s$	$\hat{\gamma}$	z
NGC 1068	SBG/AGN	7.0	79	3.2	0.0038
PKS 1424+240	BLL	4.0	77	3.5	0.6047
TXS 0506+056	BLL/FSRQ	3.6	5	2.0	0.3365
S5 1044+71	FSRQ	1.3	45	4.3	1.1500
IC 678	GAL	0.9	22	3.1	0.04799
NGC 5380	GAL	0.9	4	2.4	0.010584
B2 1520+31	FSRQ	1.0	35	4.3	1.48875
PKS 1717+177	BLL	1.0	34	4.3	0.137
3C 454.3	FSRQ	1.2	1	1.5	0.859
GB6 J1542+6129	BLL	1.9	16	4.3	0.117



Carloni, Martínez-Soler, Argüelles, Babu, BD, 2212.00737

Effect of energy resolution



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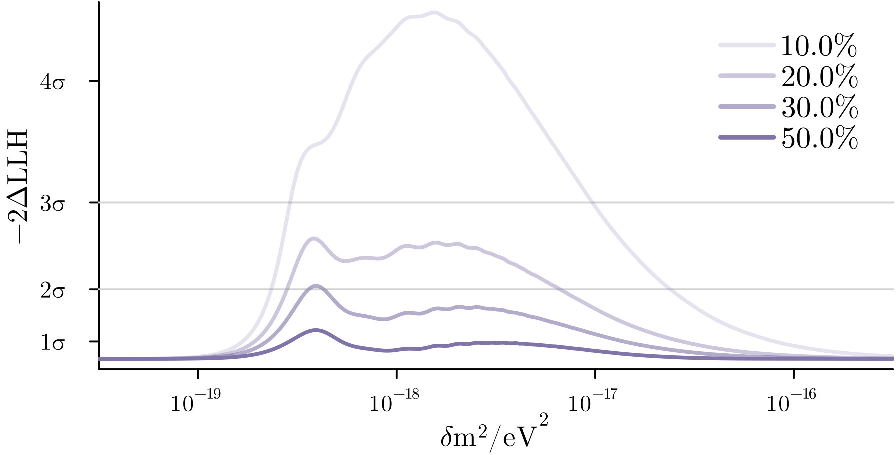

- Lot of room for improvement with better technology.
- Showers can do much better, if the angular resolution can be improved somehow.
- Possible with KM3NeT or P-ONE (or something even bigger and better).

Conclusion

- The nature of neutrino mass (Majorana, Dirac, or pseudo-Dirac) has to be *experimentally* determined.

- We proposed a new experimental probe of pseudo-Diracness of neutrinos using high-energy astrophysical neutrinos.

- Made possible by recent breakthroughs in multi-messenger neutrino astrophysics.

- **Current IceCube data on the three most significant astrophysical neutrino sources already constrain δm^2 in the range of $10^{-21} - 10^{-16}$ eV^2 with up to 2σ significance.**

- With additional sources and more statistics at IceCube-Gen2 (+KM3NeT), a larger range of δm^2 can be probed with higher significance.

- Robust against astrophysical flux and flavor ratio uncertainties.

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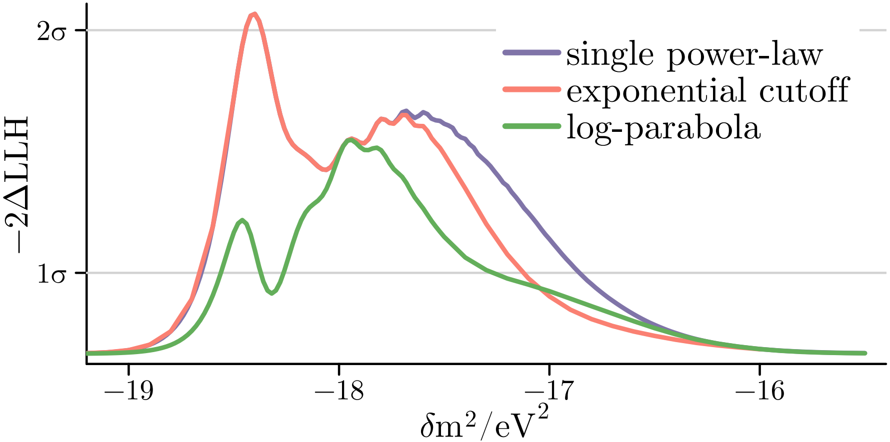
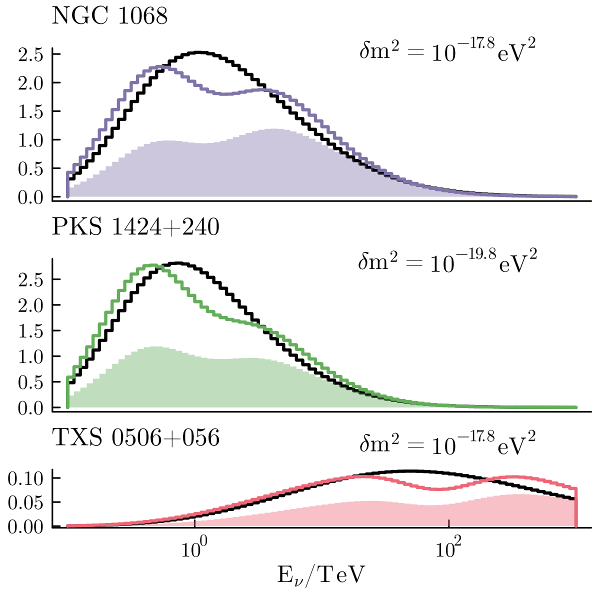
Thank You.

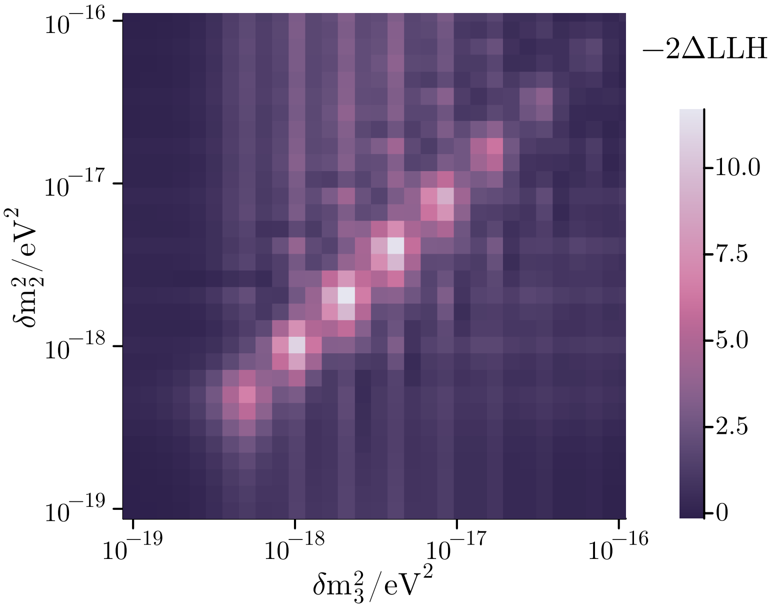
Backup Slides

Different flux models

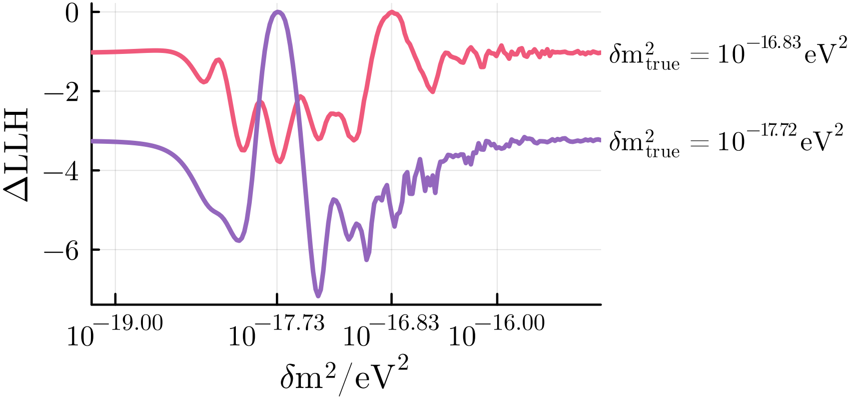


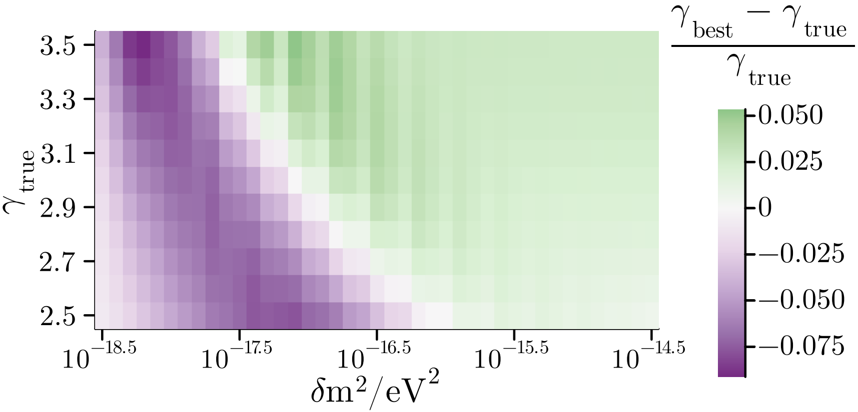
Different binning



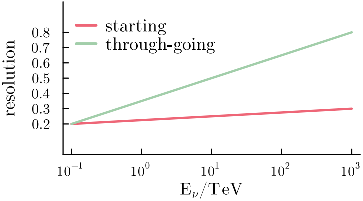

$-2\Delta\mathrm{LLH}$
10.0
7.5
5.0
2.5
0
10^{-16}
10^{-17}
10^{-18}
10^{-19}
$\delta m_2^2/\mathrm{eV}^2$
10^{-19}
10^{-18}
10^{-17}
10^{-16}
$\delta m_3^2/\mathrm{eV}^2$

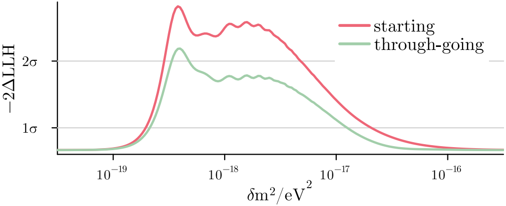
Recovery of true pseudo-Dirac parameters



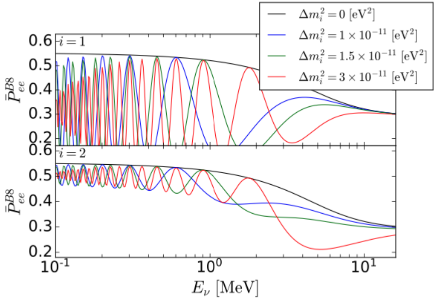

$\frac{\gamma_{best} - \gamma_{true}}{\gamma_{true}}$
0.050
0.025
0
−0.025
−0.050
−0.075
γ_{true}
3.5
3.3
3.1
2.9
2.7
2.5
$10^{-18.5}$
$10^{-17.5}$
$10^{-16.5}$
$10^{-15.5}$
$10^{-14.5}$
$\delta m^2/eV^2$

Linear models for energy resolution

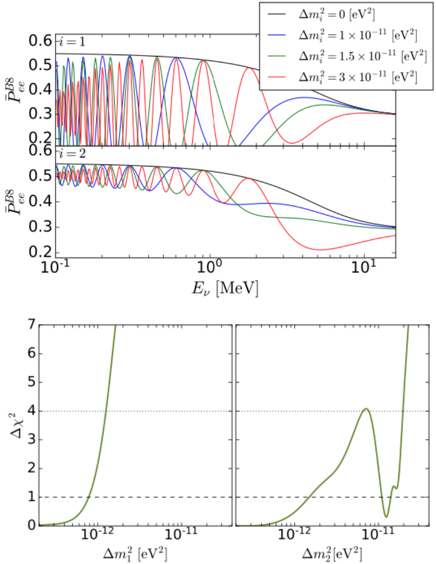




Solar neutrino constraint



Solar neutrino constraint



Ansarifard, Farzan, 2211.09105