Pseudo-Dirac Neutrinos at IceCube

Bhupal Dev

Washington University in St. Louis

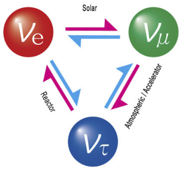
arXiv: 2212.00737 [astro-ph.HE]

with K. Carloni, I. Martínez-Soler, C. Argüelles, and K. S. Babu

CERN Neutrino Platform Pheno Week

March 16, 2023

Nature of neutrino mass remains unknown!



$\Longrightarrow$ **Nonzero Neutrino Mass** $\Longrightarrow$ **BSM Physics**

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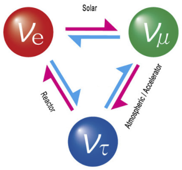

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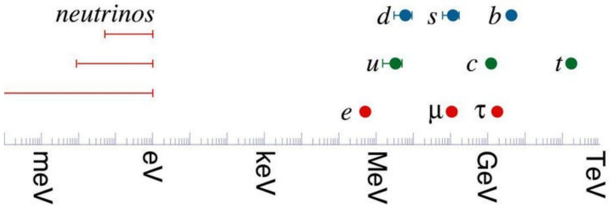

Perhaps something beyond the standard Higgs mechanism?

[see talk by Babu for a review]

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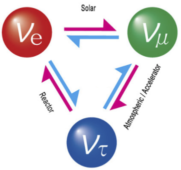

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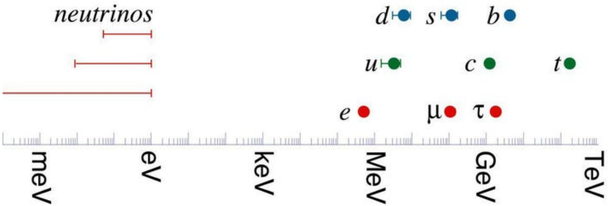

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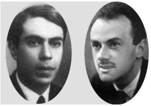
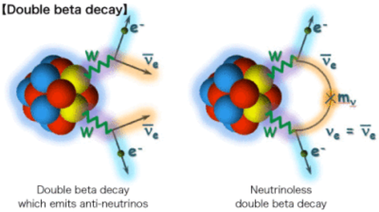
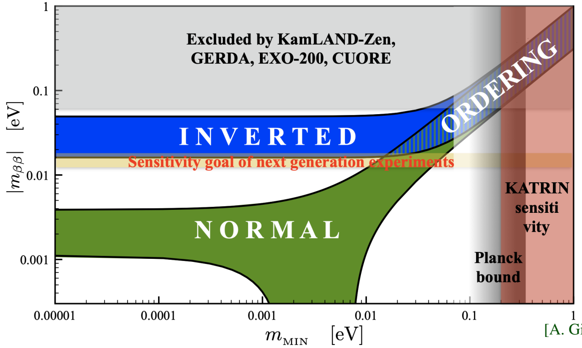


Majorana or Dirac (or something in between)?

Only experiments can tell.

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





[A. Giuliani *et al.*, 1910.04688]
[see talk by Pompa]

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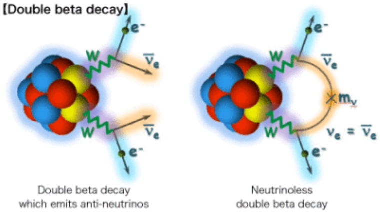

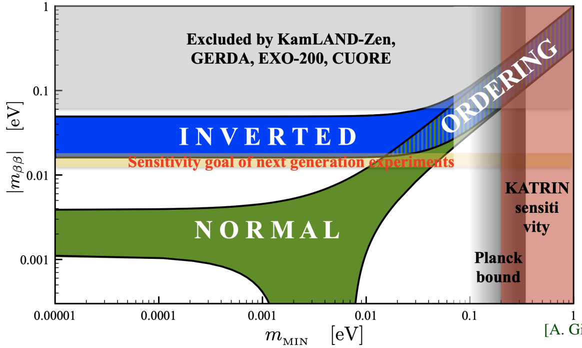

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What if the Majorana mass is small?

What do we know from theory?

- Neutrinos are massless in the SM, because
  - There are no right-handed partners to write the Dirac mass term $m_D \bar{\nu}_L \nu_R$.
  - Majorana mass term $m_M \bar{\nu}_L^c \nu_L$ is forbidden by $SU(2)_L$-gauge invariance.

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- Simplest possibility is to add Dirac partners ν_R (SM-singlets).
- Can allow for a Majorana mass term $m_R \bar{\nu}_R^c \nu_R$.
- Mass matrix (with multiple flavors):

$$M_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & m_R \end{pmatrix}.$$

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  - If $m_R \neq 0$, neutrinos are **Majorana**.
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- Isn't it more natural to have $||m_R|| \gg ||m_D||$, as motivated by the seesaw mechanism?

[Minkowski (PLB '77); Mohapatra, Senjanović (PRL '80); Yanagida '79; Gell-Mann, Ramond, Slansky '79]

[talks by Bolton, Marcano, Fernández-Martínez, Schmidt]

- Maybe, but $||m_R|| \ll ||m_D||$ remains a logical possibility.

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

Models of pseudo-Dirac neutrinos

- A good starting point: Dirac neutrino models in which 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); ...]

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- E.g., Weinberg operators of the type $(\Psi\Psi HH)/M_{\rm Pl}$ [and $(\Psi'\Psi'H'H')/M_{\rm Pl}$ in mirror models] induce small diagonal M_ν entries $\Longrightarrow$ **Pseudo-Dirac neutrinos**.
- Gives $\delta m^2 \approx 2m\delta m \sim 10^{-6}$ eV^2 (for $m_a \simeq 0.05$ eV).

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- But excluded by BBN and solar neutrino constraints. ☹

$\delta m^2 \lesssim 10^{-8}$ eV^2 from BBN, [Barbieri, Dolgov (PLB '90)]

10^{-11} eV^2 from solar. [de Gouvêa, Huang, Jenkins, 0906.1611 (PRD '09); Ansarifard, Farzan, 2211.09105]

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 $(\Psi\Psi HHS)/M_{\rm Pl}^2$.
- For $\langle S \rangle = v_{BL}$, leads to diagonal elements of M_ν of order $v^2 v_{BL}/M_{\rm Pl}^2$.
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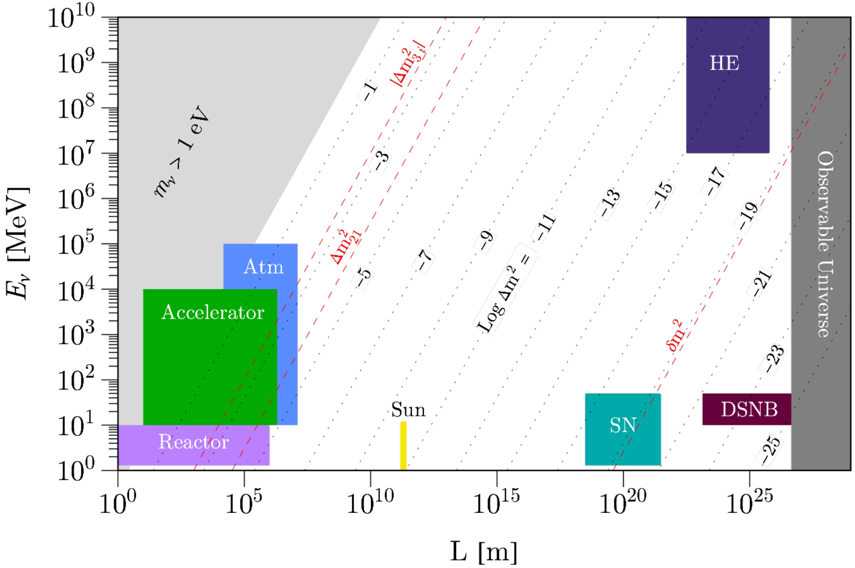
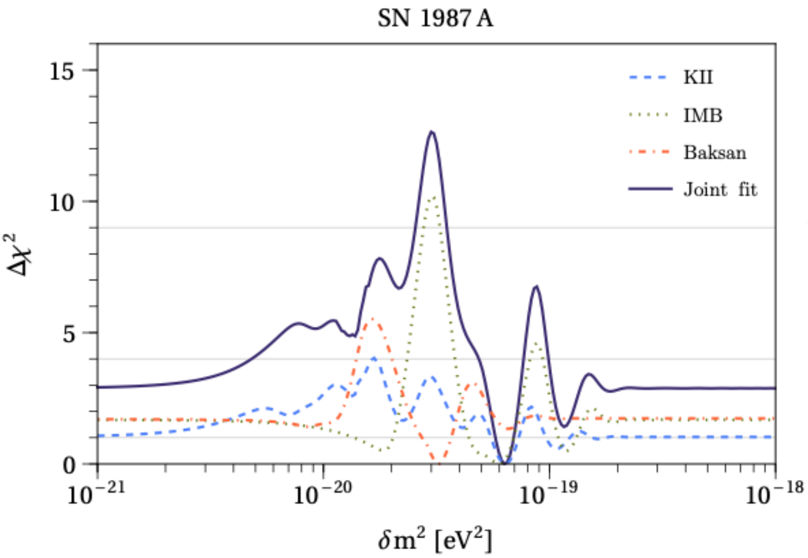
How to probe these tiny δm^2 values?

Need astrophysical baselines



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

Constraint from supernova neutrinos



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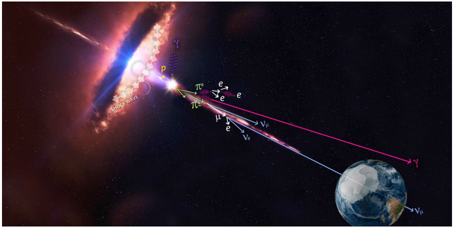
[see talk by Perez-Gonzalez]

Astrophysical neutrinos

[see talks by Beacom and Murase]



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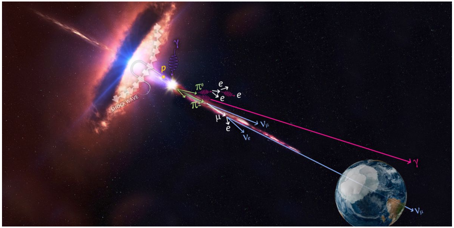

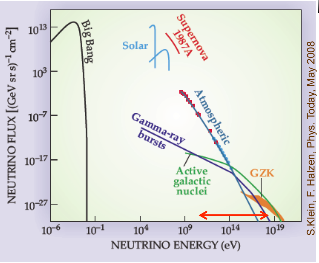

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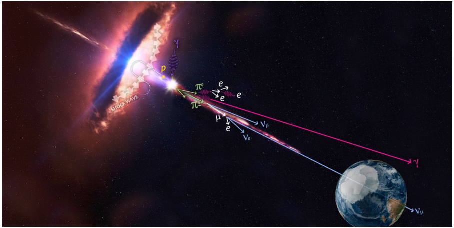
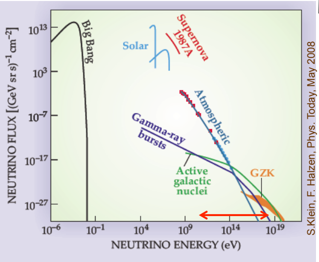
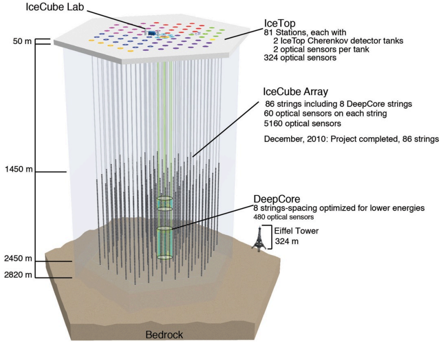
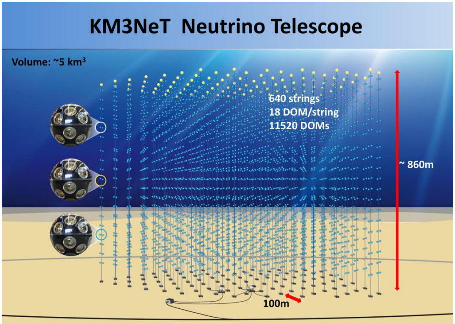




Need gigantic detectors to compensate for the tiny flux.





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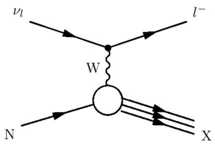

High-energy neutrino signals at IceCube

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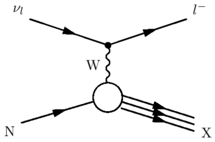

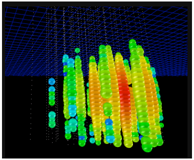

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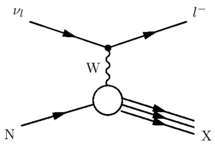

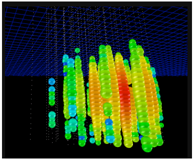

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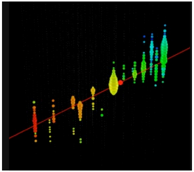

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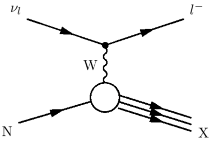

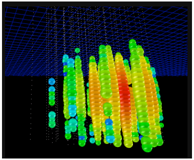

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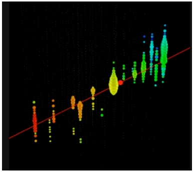

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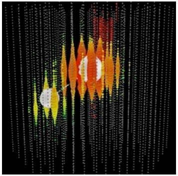

CC tau 'double bang' (only at $E_\nu \gtrsim 100$ TeV)

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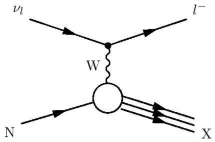

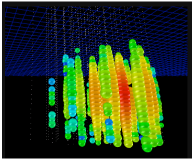

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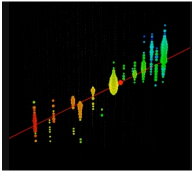

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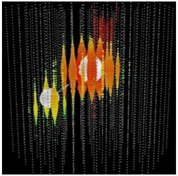

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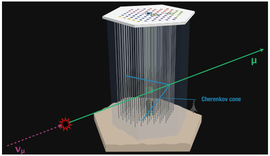


Throughgoing muon (track only, huge statistics)

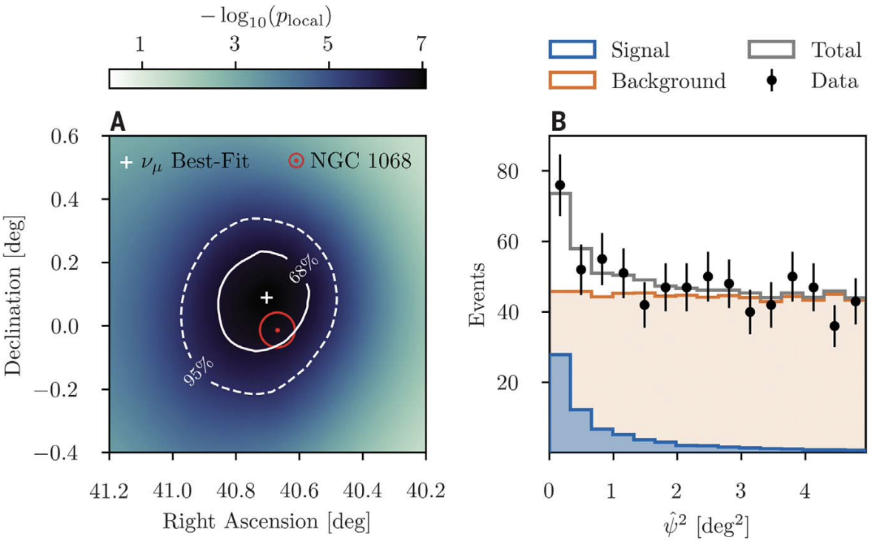
[Picture courtesy: C. Kopper]

Showers: Good energy resolution, but poor angular resolution

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

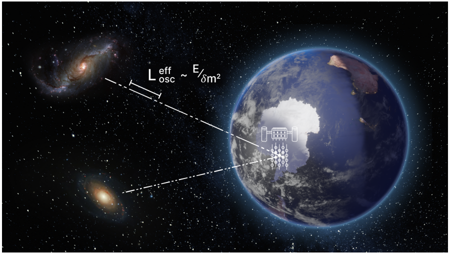
Track events are ideal for astrophysical source identification.

NGC 1068



[IceCube Collaboration, 2211.09972 (Science '22)]

A new probe of pseudo-Dirac neutrinos



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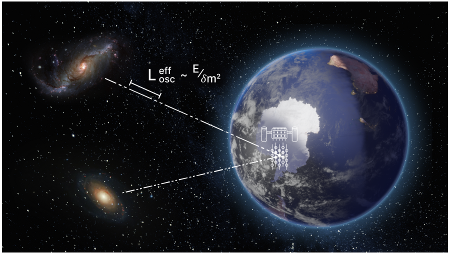

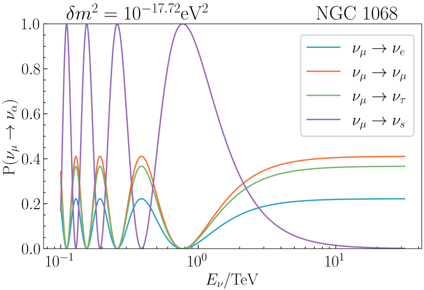

Carloni, Martínez-Soler, Argüelles, Babu, BD, 2212.00737

- 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 $H(z) = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda + (1-\Omega_m-\Omega_\Lambda)(1+z)^2}$.

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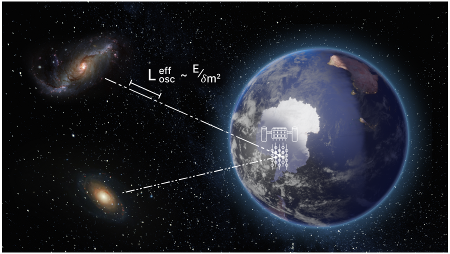

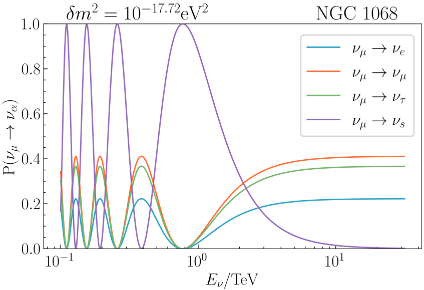

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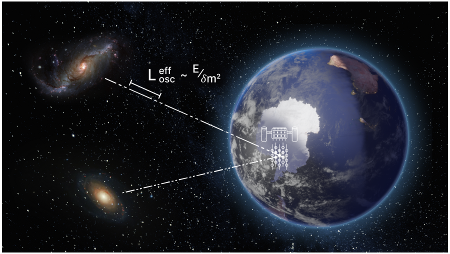
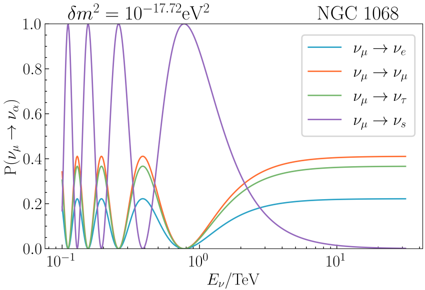
- Typical oscillation length: $L_{\rm osc} = \frac{2E_\nu}{\delta m^2} \approx 6.4\ {\rm Mpc}\left(\frac{E_\nu}{1\ {\rm TeV}}\right)\left(\frac{2\times10^{-18}\ {\rm eV}^2}{\delta m^2}\right)$.

A new probe of pseudo-Dirac neutrinos





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- 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 $H(z) = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda + (1-\Omega_m-\Omega_\Lambda)(1+z)^2}$.

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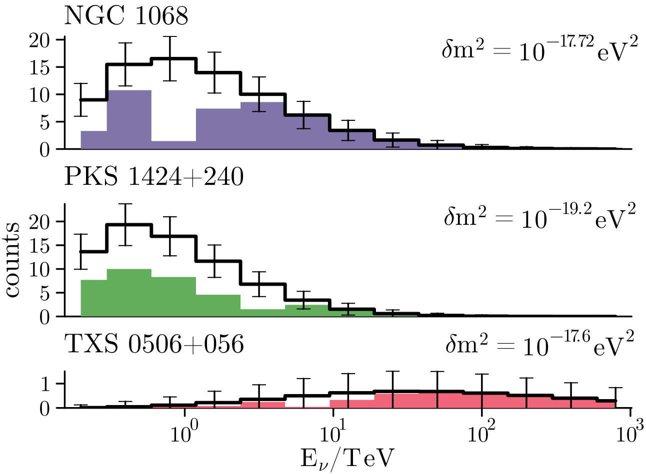
- Typical coherence length: [Kersten, Smirnov, 1512.09068 (EPJC '16); Rink, Sen, 2211.16520]

$$L_{\rm coh} = \frac{4\sqrt{2}E_\nu^2}{|\delta m^2|} \approx 10^{10}\ {\rm Mpc}\left(\frac{E_\nu}{1\ {\rm TeV}}\right)^2\left(\frac{2\times10^{-18}\ {\rm eV}^2}{|\delta m^2|}\right)\left(\frac{\sigma_x}{10^{-10}\ {\rm m}}\right) \gg L_{\rm osc}.$$

Event Distributions

Source	Source Type	$-\log_{10} p_{\text{local}}$	$\hat{n}_s$	$\hat{\gamma}$	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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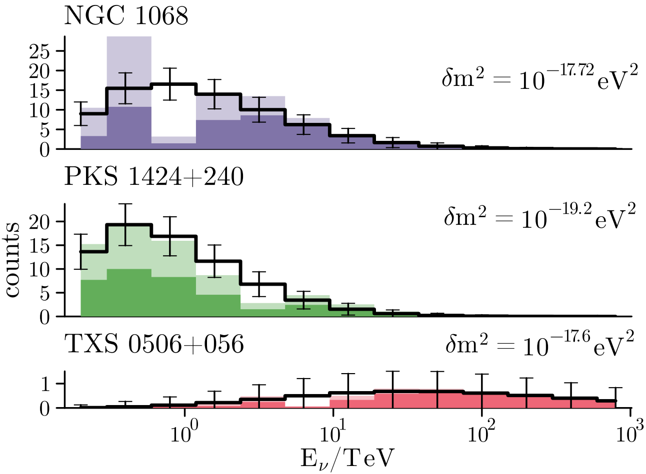

IceCube constraints on δm^2

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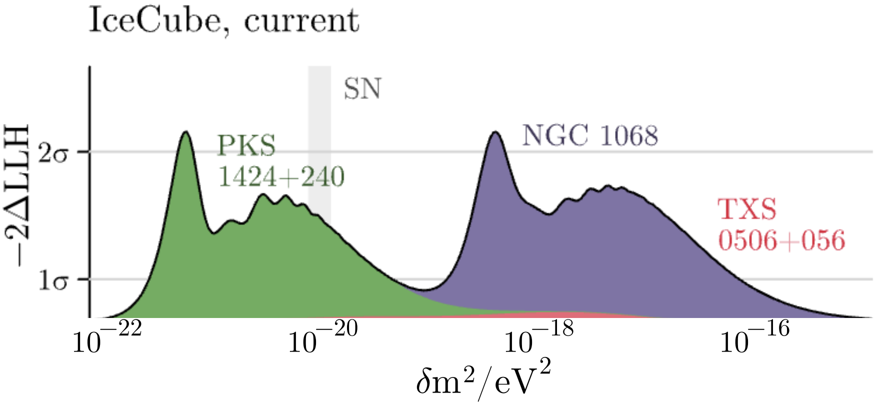

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Future IceCube-Gen2 sensitivity

Source	Source Type	$-\log_{10} p_{\mathrm{local}}$	$\hat{n}_s$	$\hat{\gamma}$	z
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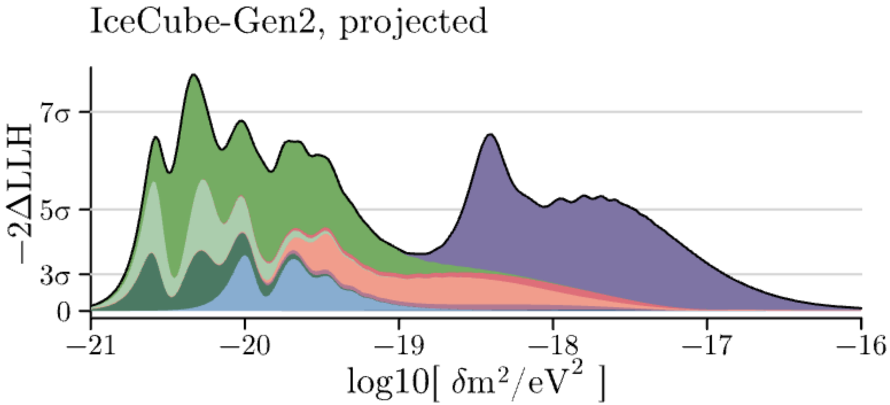
TXS 0506+056	BLL/FSRQ	3.6	5	2.0	0.3365
S5 1044+71	FSRQ	1.3	45	4.3	1.1500
IC 678	GAL	0.9	22	3.1	0.04799 ± 0.00002
NGC 5380	GAL	0.9	4	2.4	0.010584
B2 1520+31	FSRQ	1.0	35	4.3	1.48875
PKS 1717+177	BLL	1.0	34	4.3	0.137
3C 454.3	FSRQ	1.2	1	1.5	0.859



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 astrophysical baselines.

- 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 $10^{-20} - 10^{-16}$ eV^2 with up to 2σ significance.

- Including additional sources and assuming more statistics at IceCube-Gen2, a larger range of δm^2 can be probed in the future.

- Modification of flavor ratios is a promising way to probe distinct mass splittings.

  [Keranen, Maalampi, Myyrylainen, Riittinen, 0307041 (PLB '03); Beacom, Bell, Hooper, Learned, Pakvasa, Weiler, 0307151 (PRL '04); Shoemaker, Murase, 1512.07228 (PRD '16)]

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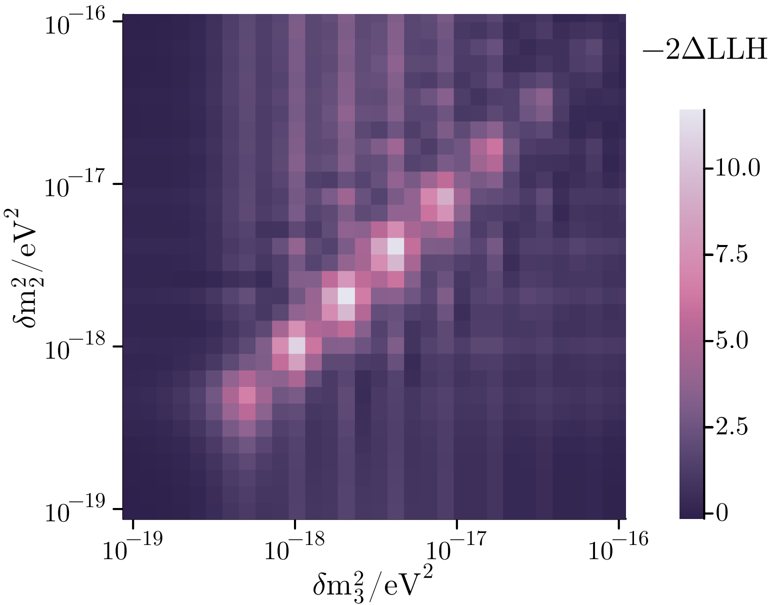
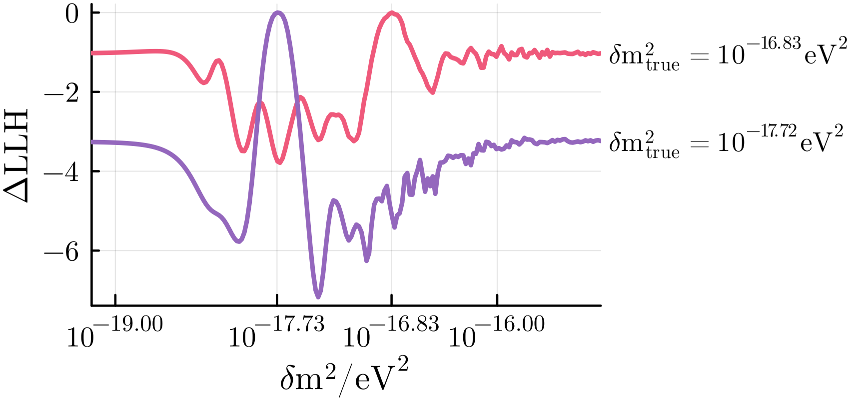
Thank You.

Backup Slides

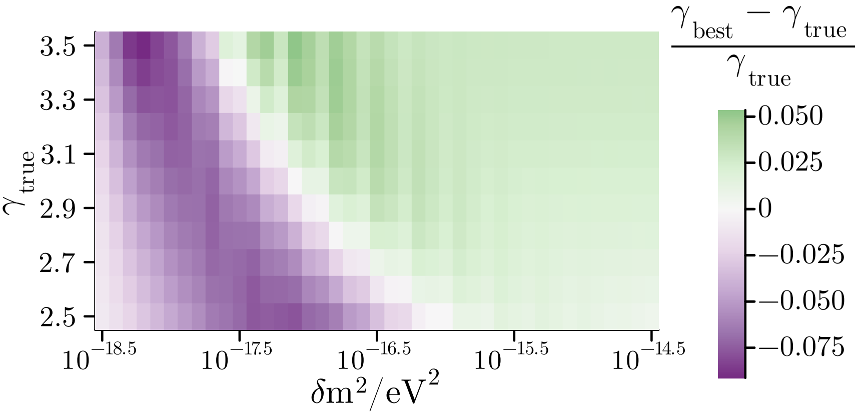
Sensitivity to distinct mass splittings



Recovery of true pseudo-Dirac parameters



Standard Model fits to pseudo-Dirac reality



With additional sterile interactions

- Consider $SU(2)_L$-singlet charged scalars, $\mathcal{L} \supset Y^s_{\alpha\beta}\overline{\nu^c_{s\alpha}}\eta^+\ell_{\beta R} + \text{H.c.}$.
- Glashow-like new resonance at IceCube: $\bar{\nu}_{s\alpha}e_R \to \eta^+$.