Neutrinos: Majorana or Dirac (or in between)?

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PRISMA Colloquium

Johannes Gutenberg-Universität Mainz

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Career Path and Motivation

- BSc, Utkal University, Bhubaneswar (2001-04)
- MS, Indian Institute of Science, Bangalore (2004-07)
- PhD, University of Maryland, College Park (2007-12)
- Postdoc, University of Manchester (2012-15)
- University Foundation Fellow, Technische Universität München (2015)
- Postdoc, Max-Planck-Institut für Kernphysik, Heidelberg (2015-16)
- Assistant Professor, Washington University in St. Louis (2016-23)
- Associate Professor, Washington University in St. Louis (2023-present)
- Humboldt Fellow, Johannes Gutenberg-Universität Mainz (2025-27)

mitp Mainz Institute for Theoretical Physics

MITP workshops in 2015, 2016, 2022

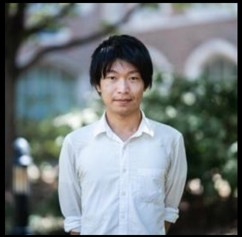
Research Interests and Group at WashU

- BSM Phenomenology
- Neutrino Physics
- Dark Matter/Sector Physics
- Baryogenesis/Leptogenesis
- Multi-messenger Astrophysics

Chris Cappiello
(Jaynes Postdoc)

Anastasia Sokolenko
(Jaynes Postdoc)

Saurav Das
(MCSS Postdoc)



Takuya Okawa
(2020-25)

Writasree Maitra
(2022-)

Diego Lopez Gutierrez
(2023-, MCSS fellow)

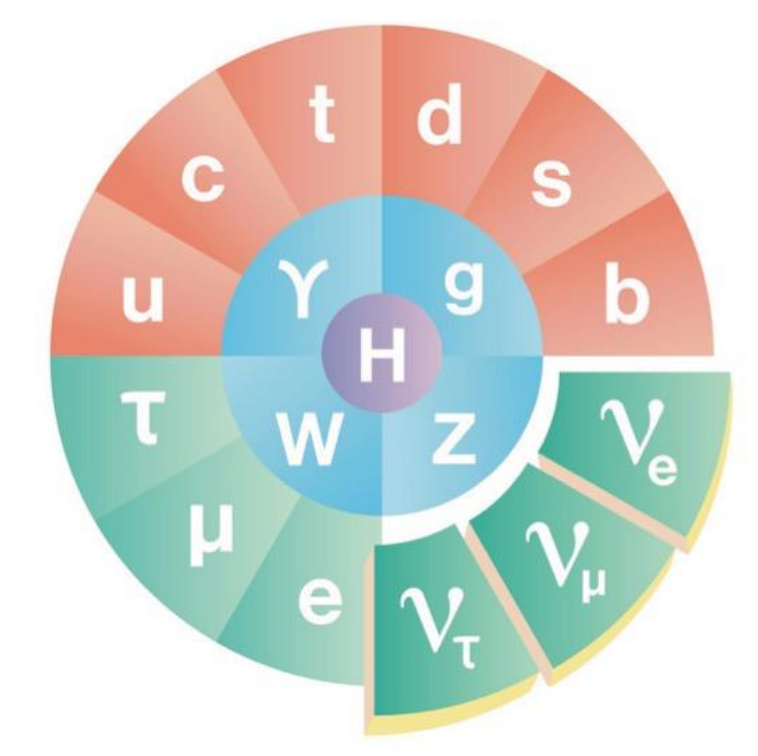
Aaroodd Ramachandran
(2023-)

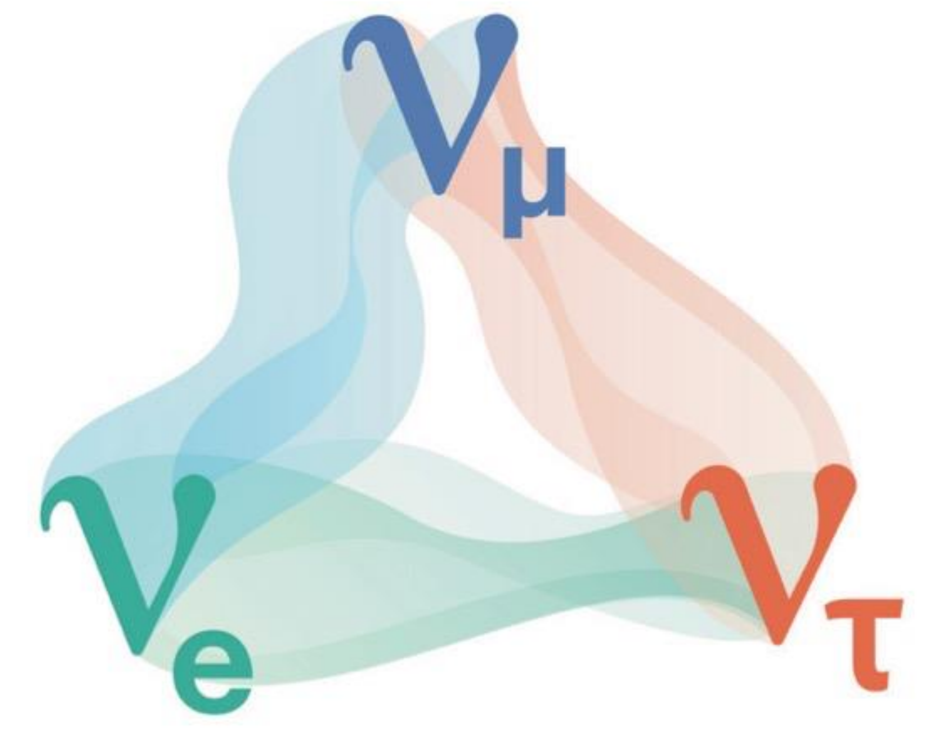
Paul Tang
(undergrad, 2023-25)

Robbie Ellis
(undergrad, 2023-)

We offer two prize postdoctoral fellowships every year: Jaynes (open to all fields) and MCSS (specific to space science)

Neutrinos: The Least Known Sector of the SM





Flavor eigenstates $\neq$ Mass eigenstates.

$$\text{Oscillation Probability} : P_{\alpha\beta} \simeq \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

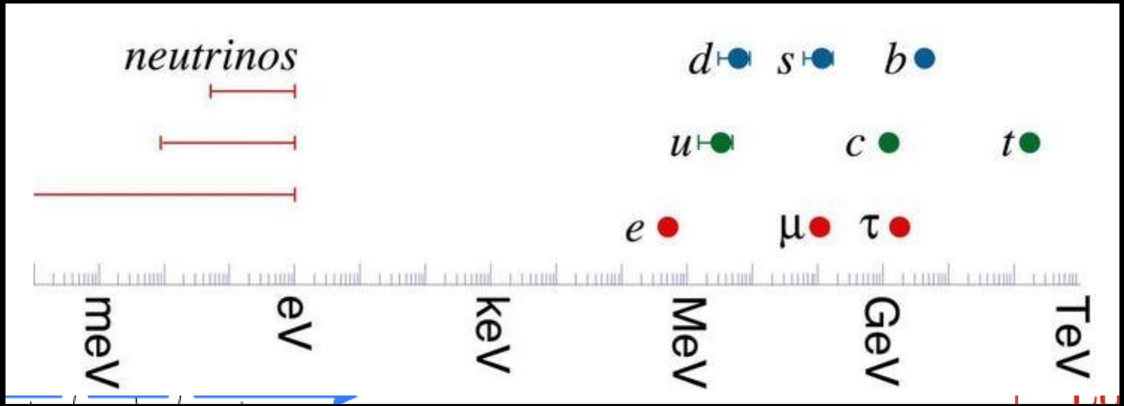
$P_{\alpha\beta} \neq 0 \implies$ **Non-zero neutrino masses and mixing** $\implies$ **BSM physics**

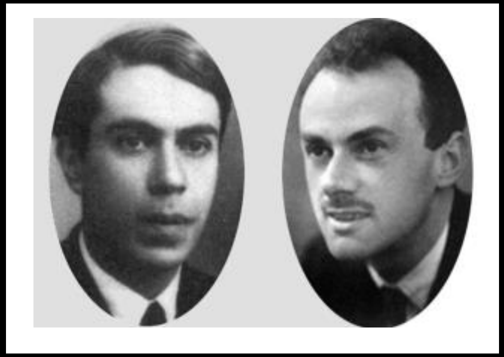
Open Questions in Neutrino Physics

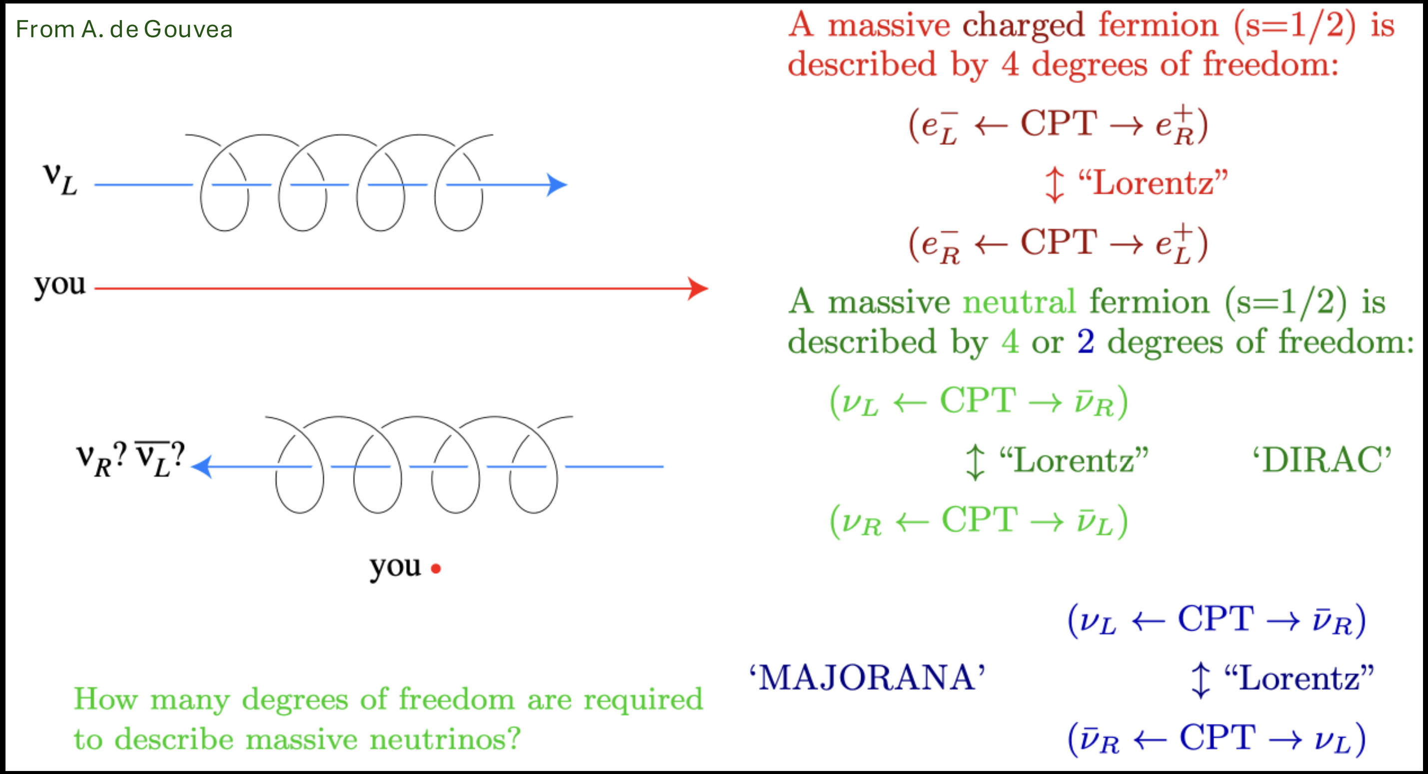
1. What is the neutrino mass ordering? Normal or inverted?
2. In which octant is the atmospheric mixing angle?
3. Is there leptonic CP violation?
4. What is the absolute neutrino mass scale?
5. Are there other species of (sterile) neutrinos?
6. How do neutrinos get mass? Is it Dirac or Majorana?
7. Why neutrino mixing is so different from quark mixing?
8. Do neutrinos decay? What is their lifetime?
9. Do neutrinos have non-standard interactions?
10. Are neutrinos responsible for the observed baryon asymmetry?
11. Do neutrinos have anything to do with Dark Matter (DM)?

BD, 2503.21212

Nature of Neutrino Mass







Majorana or Dirac?

Why is it a difficult question?

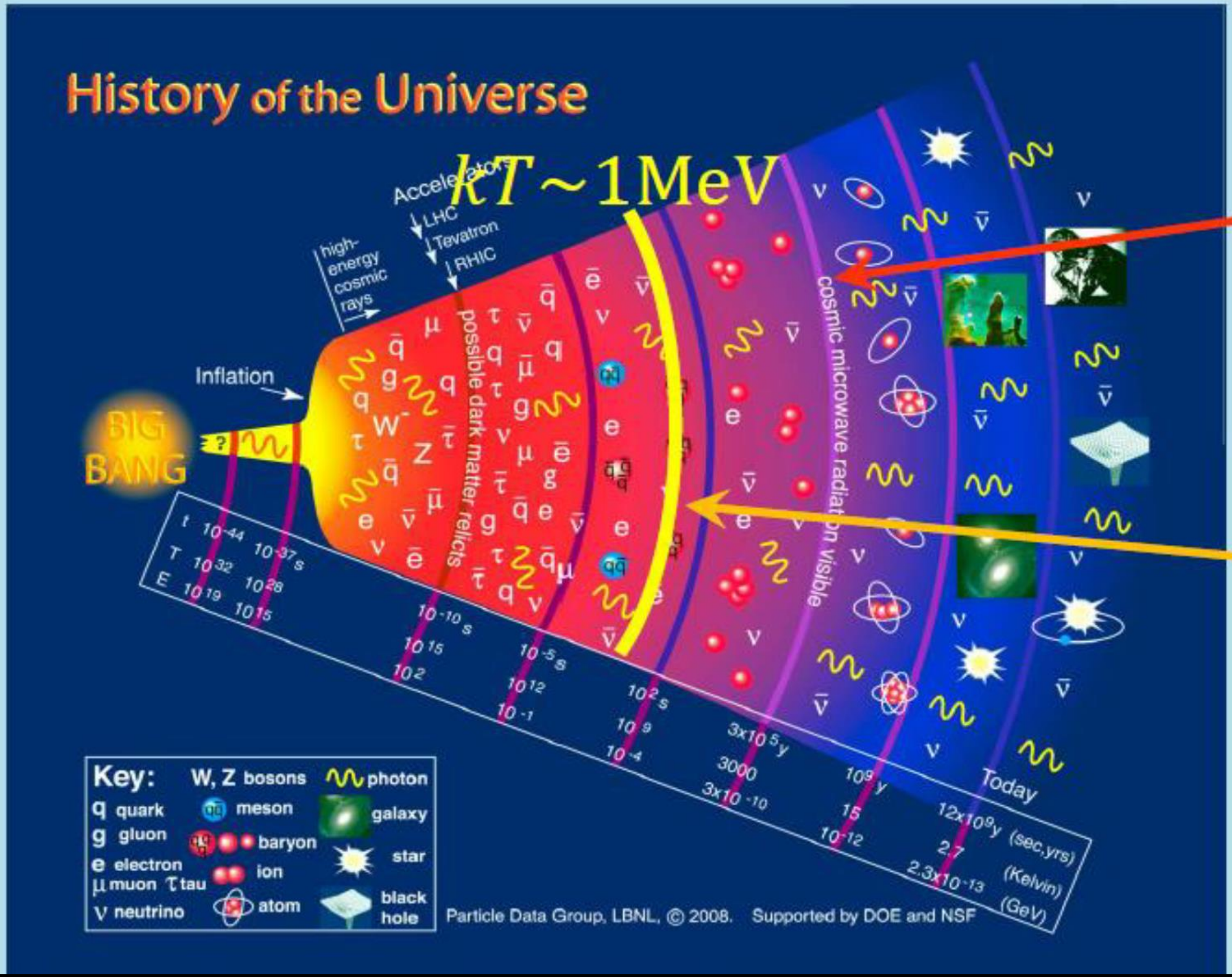
Because the Majorana nature is suppressed by the tiny neutrino mass itself.

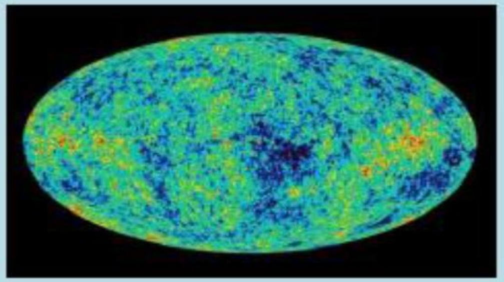
$$A \propto (m_\nu / E)^n$$

Two ways around:

- Find a process that violates *L*.
- Find non-relativistic neutrinos.

Non-relativistic Neutrinos





CMB

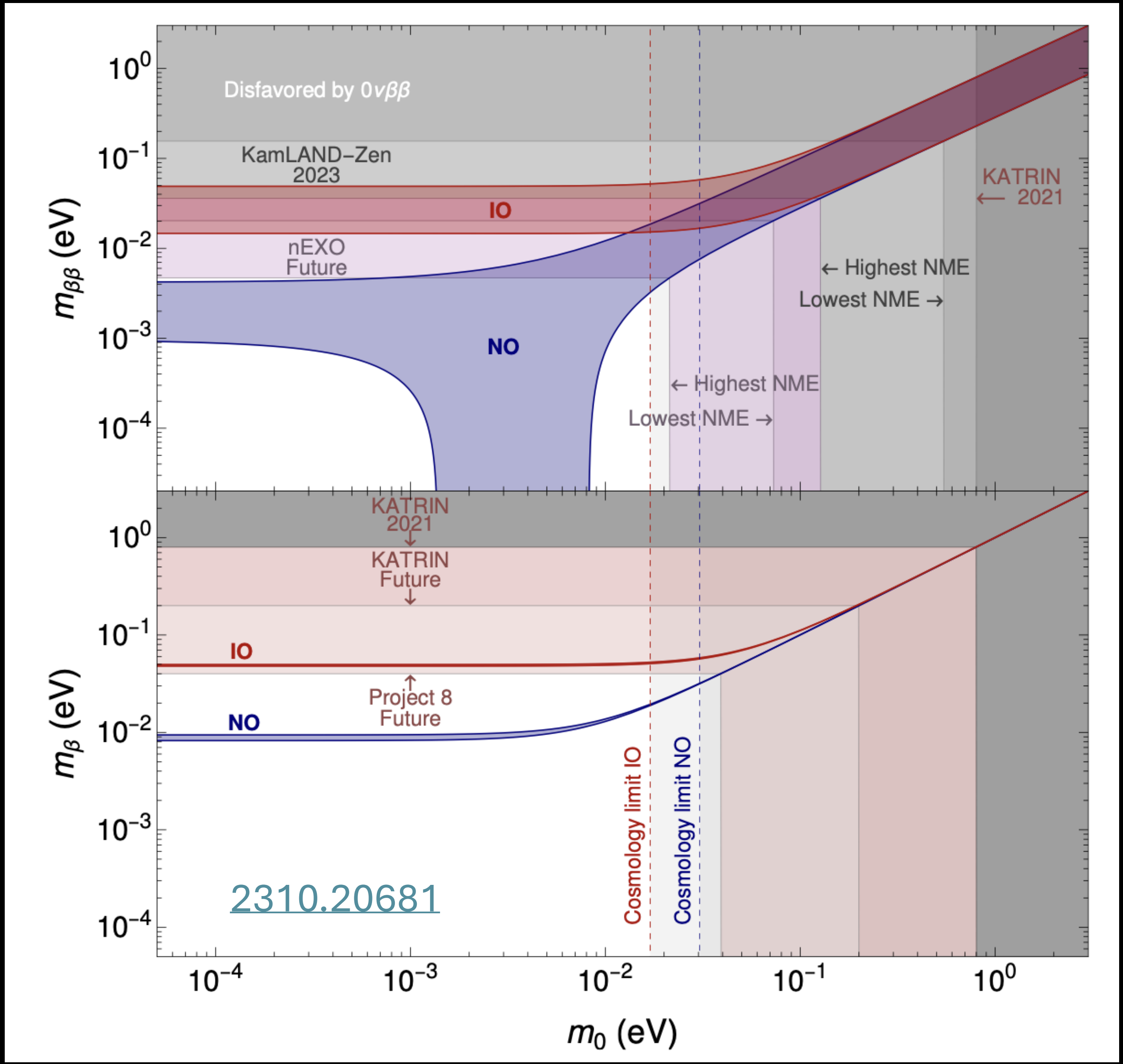
$$n_\gamma = 411/\text{cm}^3$$
$$T_\gamma = 2.73\ \text{K}$$

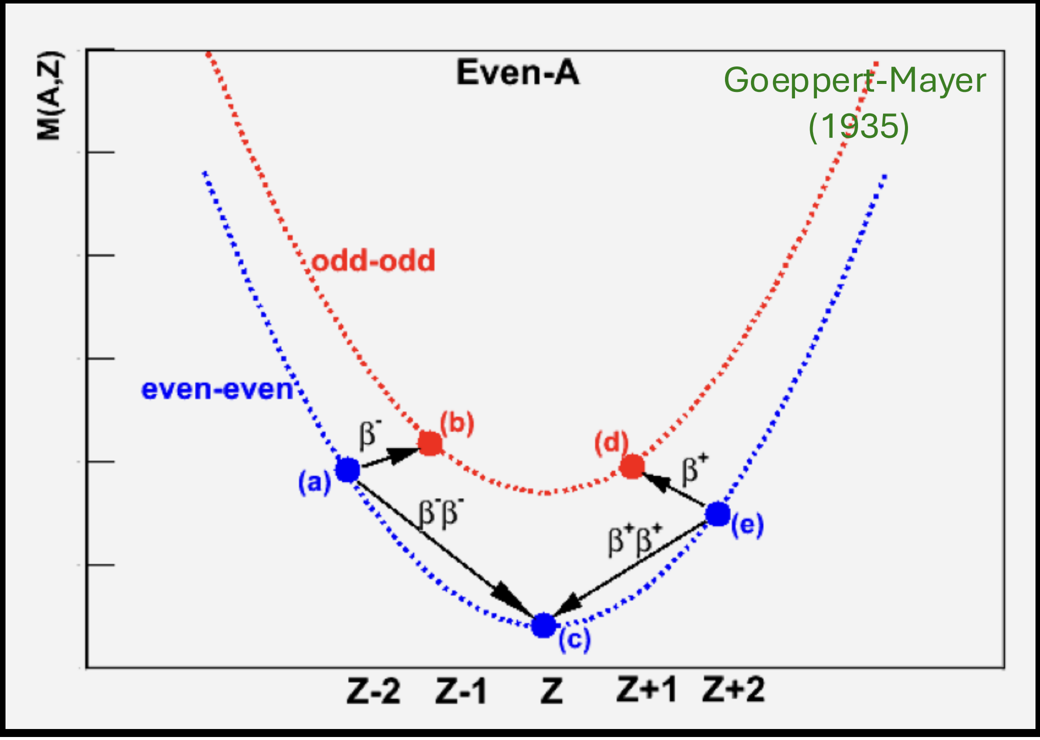
CνB

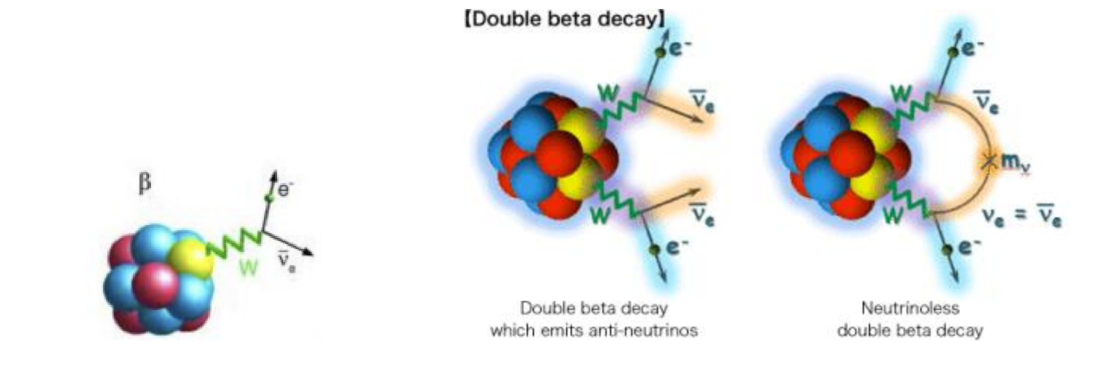
$$n_\nu = n_{\bar{\nu}} = \frac{3}{4}\left(\frac{T_\nu}{T_\gamma}\right)^3 \frac{n_\gamma}{2}$$
$$= 56/\text{cm}^3$$
$$T_\nu = \left(\frac{4}{11}\right)^{\frac{1}{3}} T_\gamma = 1.95\text{K}$$

Extremely challenging task, but worth trying.

Find a Lepton Number Violating Process

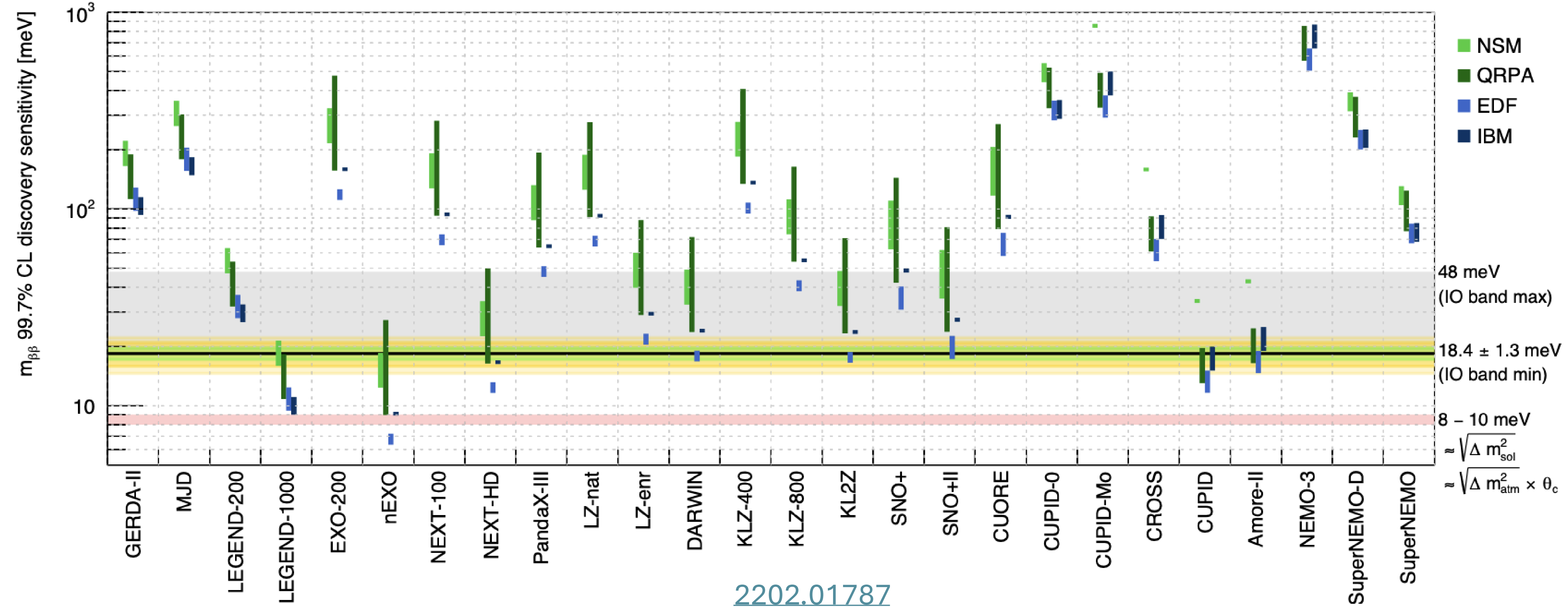






Over 40 nuclei can do this. Only 10 experimentally feasible

Future Prospect of 0νββ



2202.01787

What if there is no positive signal in 0νββ? Need to find alternative probes of the nature of neutrino mass.

Guidance from Theory

- Neutrinos are massless in the SM, because
  - No right-handed partners for Dirac mass term $m_D \bar{\nu}_L \nu_R$.
  - Majorana mass term $m_M \bar{\nu}_L^c \nu_L$ breaks $SU(2)_L$-gauge invariance.
  - Non-perturbative sphaleron effects preserve $B - L$.
  - Gravitational effects are at most $\mathcal{O}(v^2/M_{\rm Pl}) \sim 10^{-5}$ eV.

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

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

Dirac, Majorana or Quasi-Dirac

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

- 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 **quasi-Dirac** (small active-sterile mass splitting).

- But isn't it more natural to have $||M_R|| \gg ||m_D||$ (seesaw)?

  [Minkowski (PLB '77); Mohapatra, Senjanovic (PRL '80); Yanagida '79; Gell-Mann, Ramond, Slansky '79]
- Maybe, but $||M_R|| \ll ||m_D||$ is a logical possibility too.

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

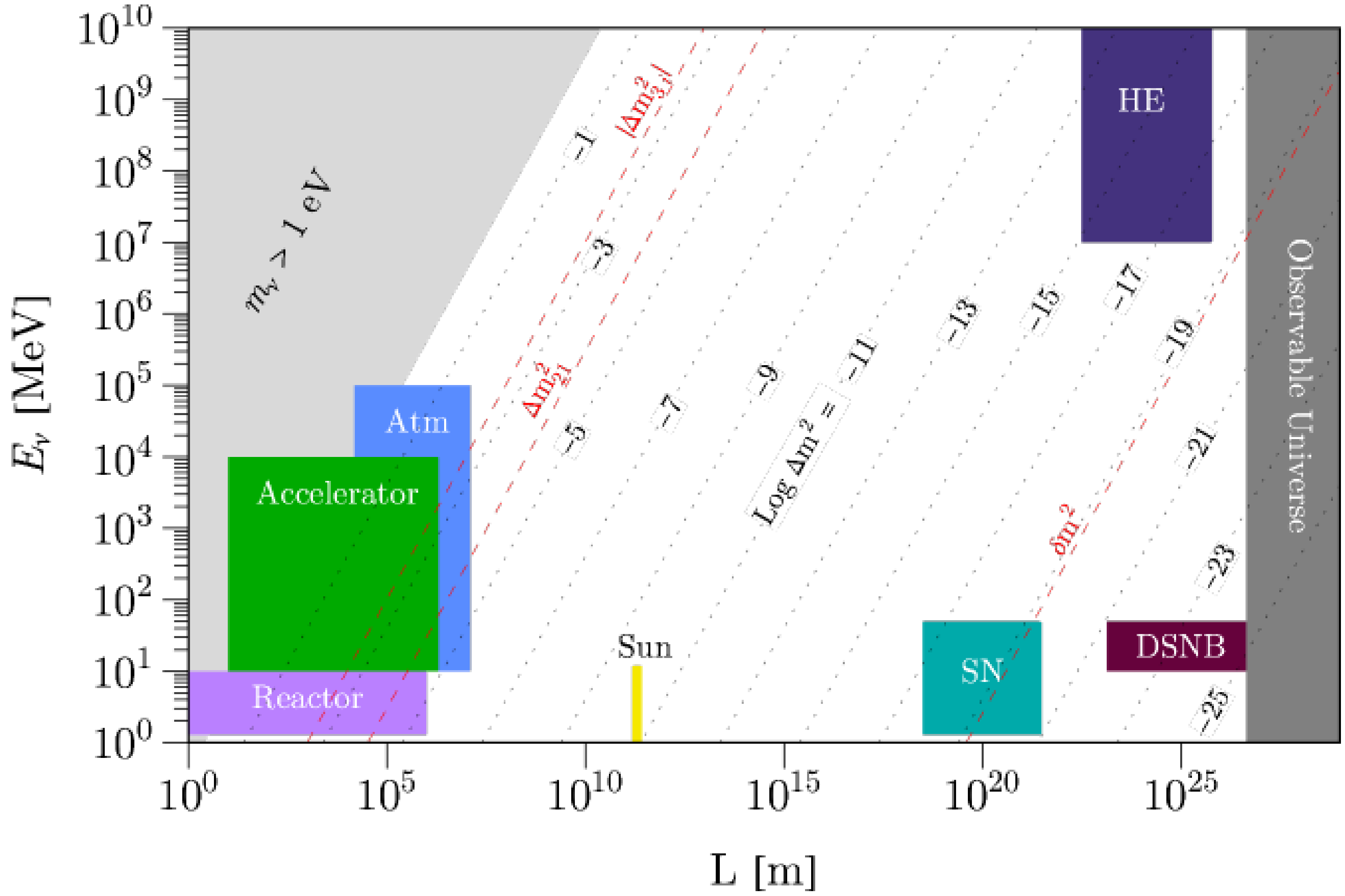
- Any model of Dirac neutrinos with Planck-suppressed operators would predict quasi-Dirac neutrinos.
- Dirac neutrinos preferred by the swampland conjecture in string theory. [Ooguri, Vafa (ATMP '16), Ibanez, Martın-Lozano, Valenzuela (JHEP '17); Gonzalo, Ibanez, Valenzuela (JHEP '22); Casas, Ibanez, Marchesano, 2406.14609]

Different from Quasi (Pseudo)-Dirac SM Singlets

$$-\mathcal{L}'_{\rm mass} = \frac{1}{2}\overline{[\nu_{\rm L}\ \ (N_{\rm R})^c\ \ (S_{\rm R})^c]}\begin{pmatrix} 0 & M_{\rm D} & \varepsilon \\ M_{\rm D}^T & M_{\rm R} & M_S \\ \varepsilon^T & M_S^T & \mu \end{pmatrix}\begin{pmatrix} (\nu_{\rm L})^c \\ N_{\rm R} \\ S_{\rm R} \end{pmatrix} + \text{h.c.}$$

- Inverse seesaw: $M_{\rm R} = 0 \text{ and } \varepsilon = 0$ Mohapatra, Valle (PRD 1986)
- Linear Seesaw: $M_{\rm R} = 0 \text{ and } \mu = 0$ Malinsky, Romao, Valle, 0506296 (PRL)
- Radiative Inverse Seesaw: $\varepsilon = 0$ BD, Pilaftsis, 1209.4051 (PRD)
- In each case, light neutrinos are still purely Majorana.
- Unless we consider superlight steriles. BD, Pilaftsis, 1212.3808 (PRD)

How to Probe Quasi-Dirac Neutrinos (*Qdinos*)



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

Active-sterile oscillations suppressed, unless

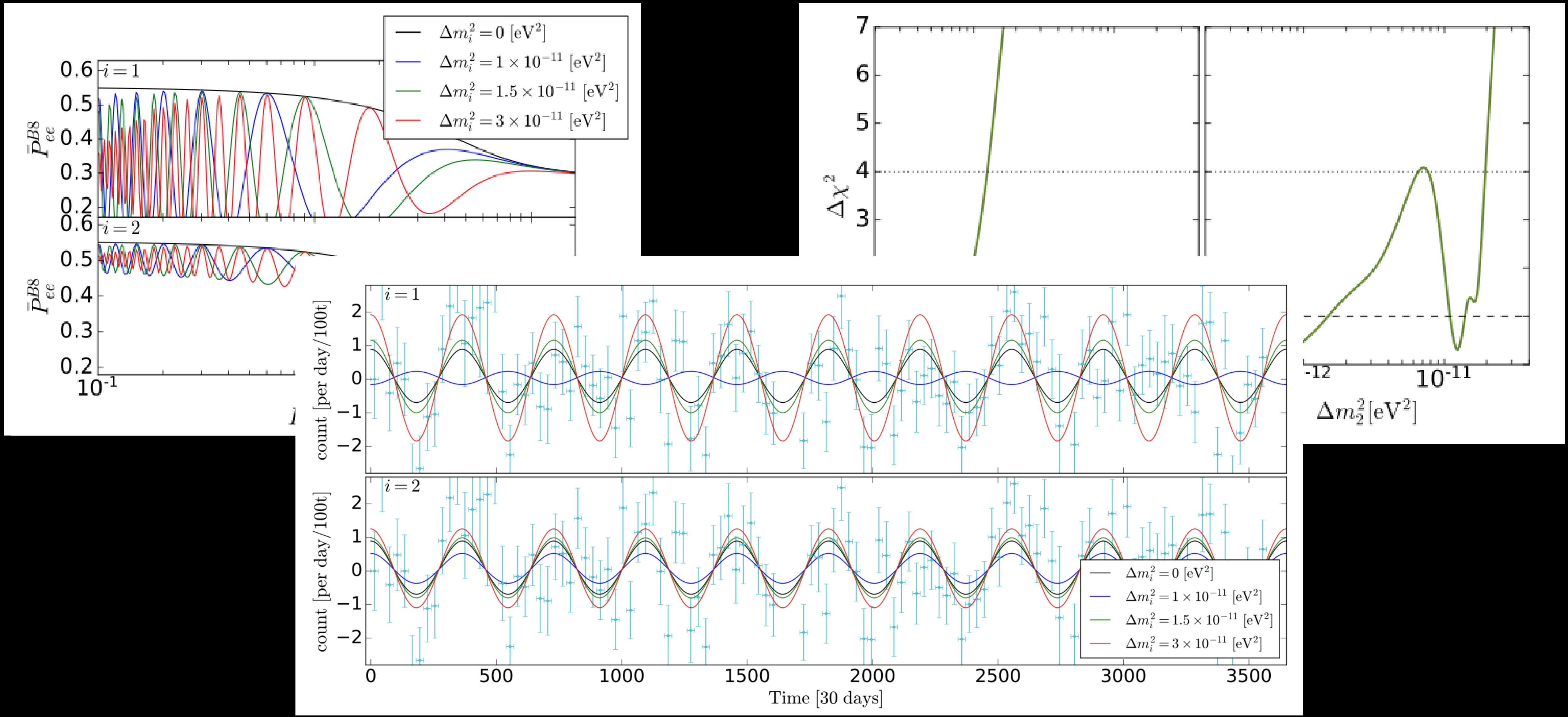
$$\delta m^2 \frac{L}{E} \sim 1$$

Need astrophysical baselines

$\delta m^2 \lesssim 10^{-8}$ eV^2 from BBN,
10^{-11} eV^2 from solar.

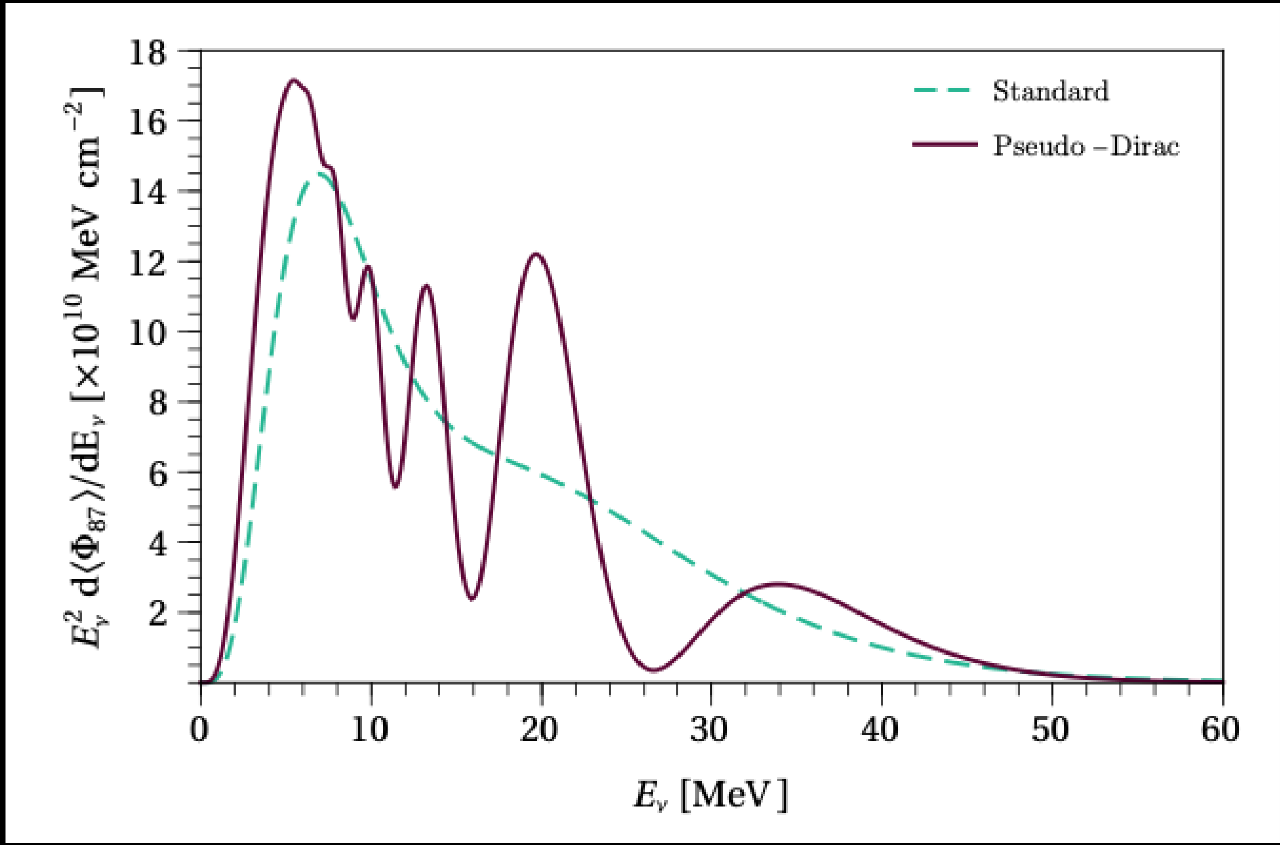
Barbieri, Dolgov (PLB 1990); de Gouvea, Huang, Jenkins, 0906.1611 (PRD)

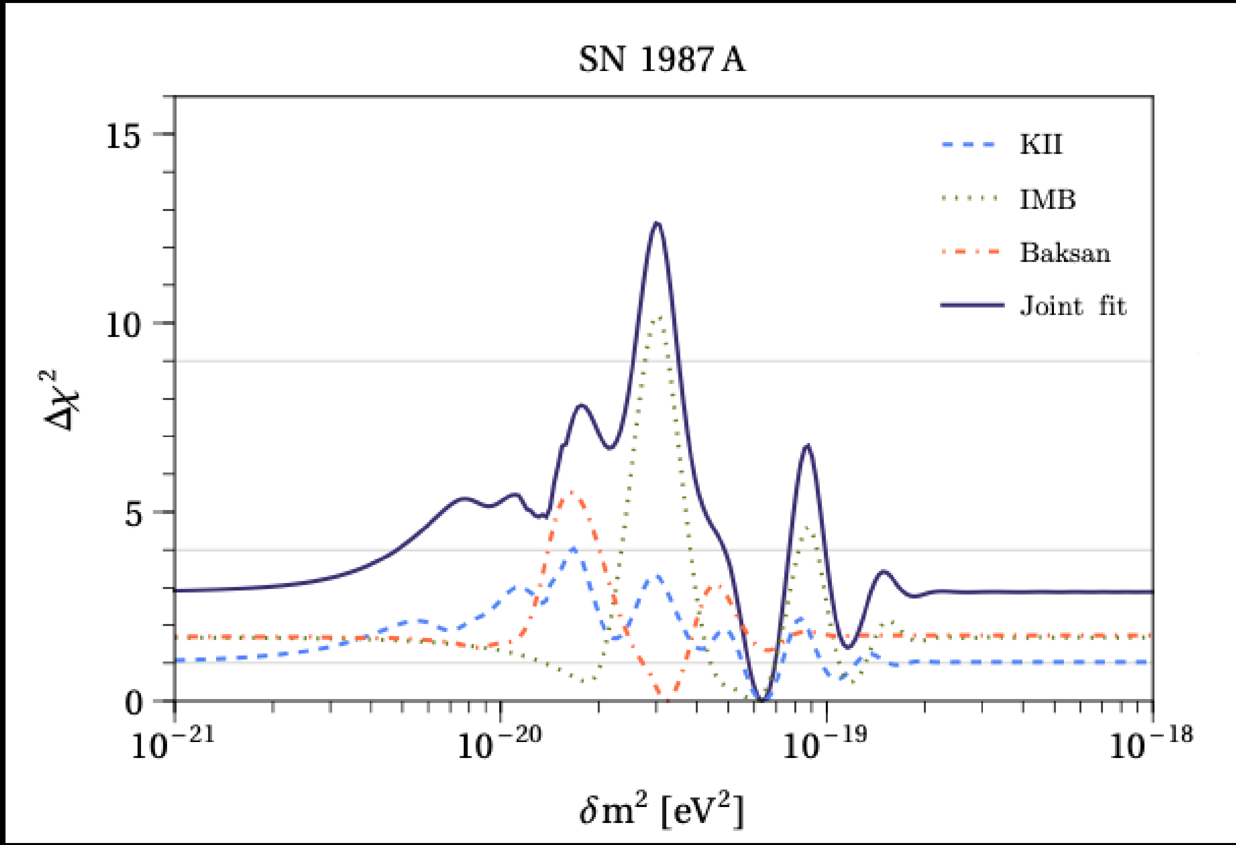
Solar Neutrino Constraint



Ansarifad, Farzan, 2211.09105 (PRD)

SN1987A Constraint



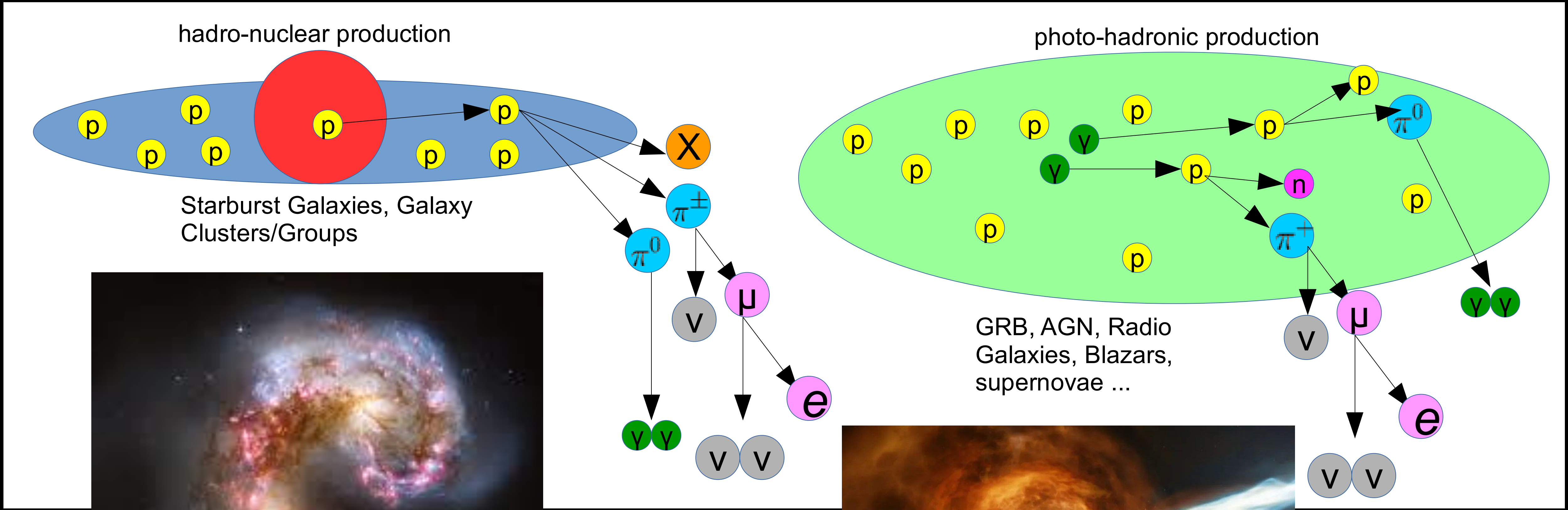


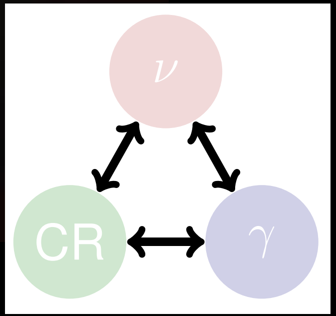
Martinez-Soler, Perez-Gonzalez, Sen, 2105.12736 (PRD)

A New Probe of *Qdinos* using High-Energy Astrophysical Neutrino Data

[1] Karloni, Martinez-Soler, Arguelles, Babu, BD, 2212.00737 (PRDL) – point source analysis
[2] Karloni, Porto, Arguelles, BD, Jana, 2503.19960 – diffuse source analysis
[3] BD, Machado, Martinez-Soler, 2406.18507 (PLB) – all-flavor diffuse + CνB matter effect
[4] BD, Dutta, Martinez-Soler, Verma, in preparation – flavor triangle + scalar NSI

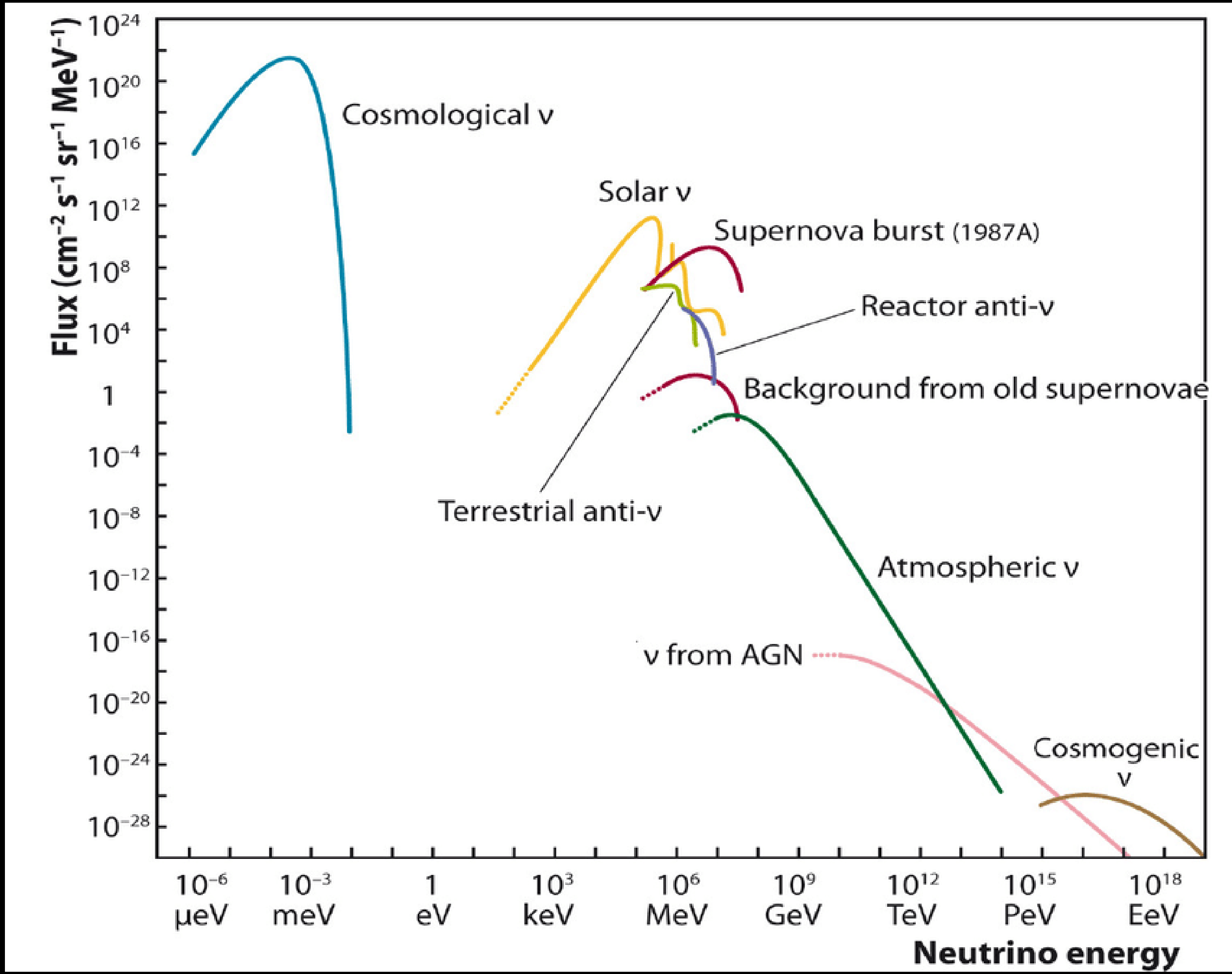
High-Energy Astrophysical Neutrinos

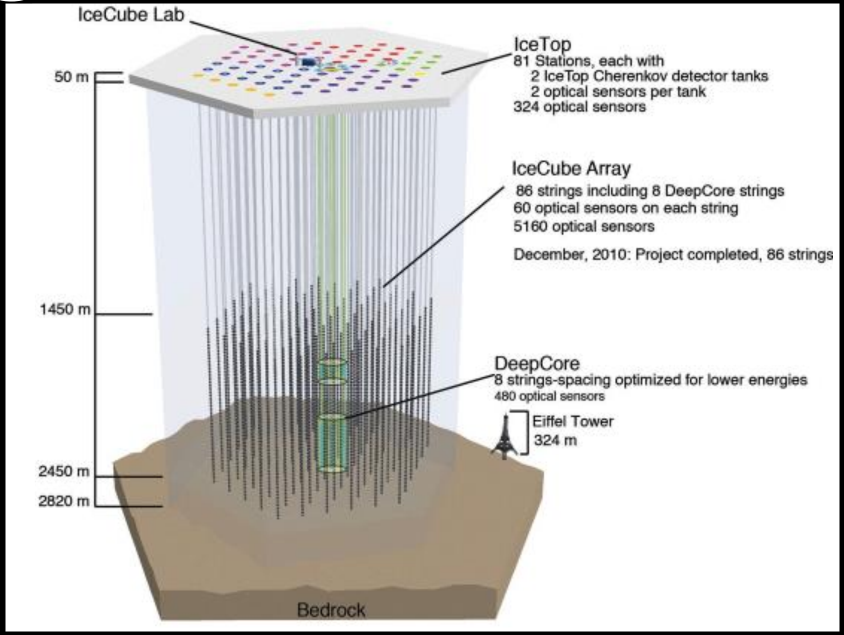


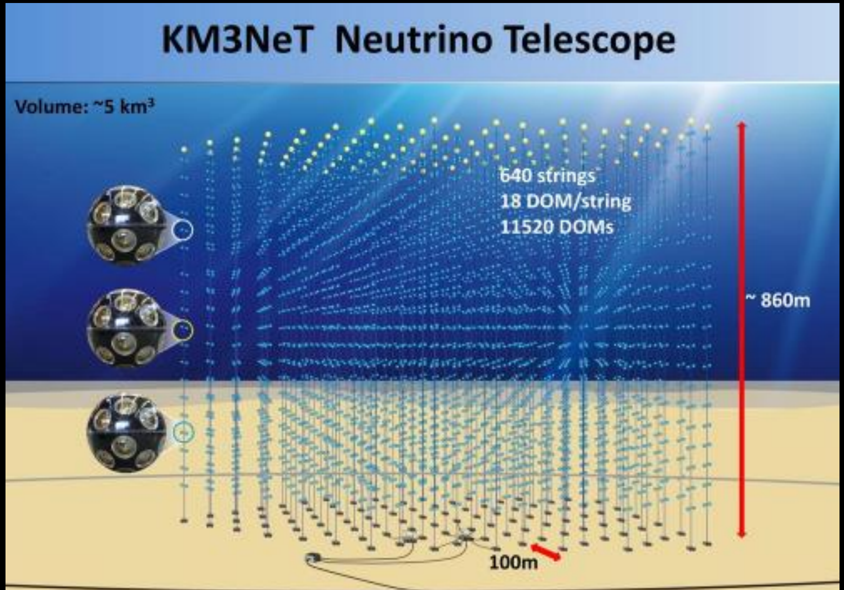


Multi-messenger connection

Small Flux. Need Huge Detectors

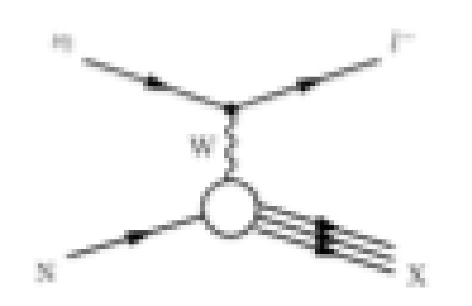




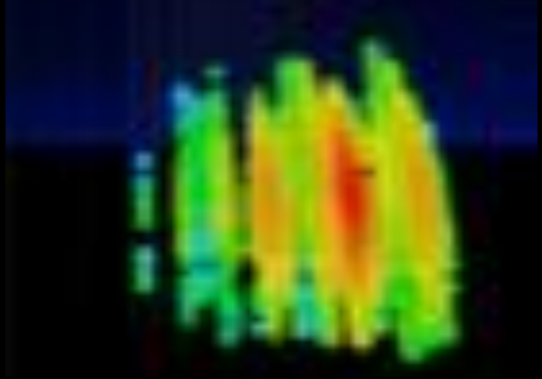


High-Energy Neutrino Signal

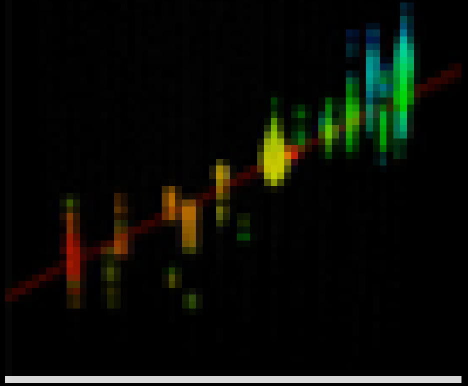
$$\omega_\omega + N \rightarrow \begin{cases} \varepsilon + X & \text{(CC)} \\ \omega_\omega + X & \text{(NC)} \end{cases}$$



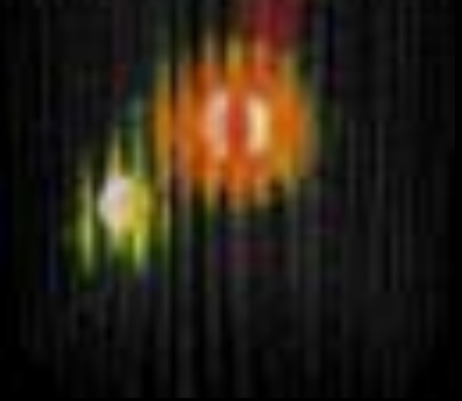
EM/Hadronic showers

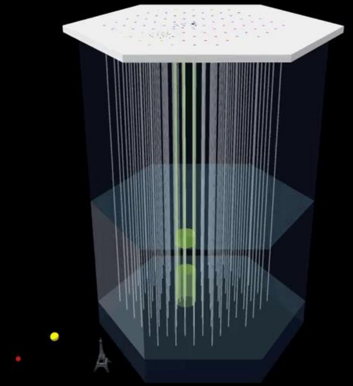


CC Muon track



Tau double-bang



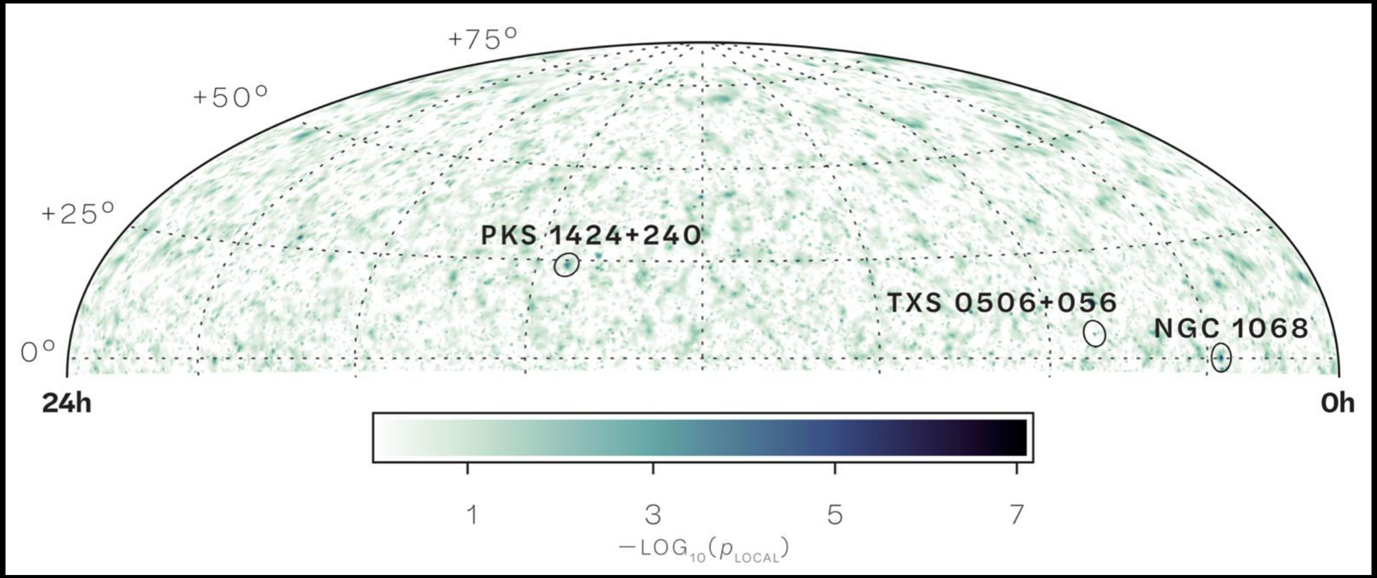


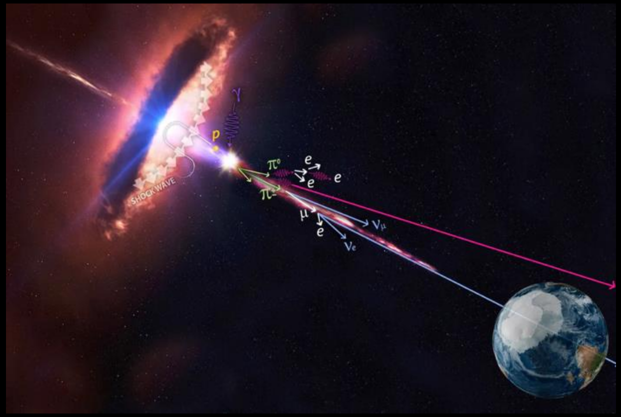
Throughgoing muons, more statistics

Showers: Good energy resolution (~ 15%), but poor angular resolution (~ 10°)
Tracks: Poor energy resolution (~ 30%), but excellent angular resolution (~ 0.5°).

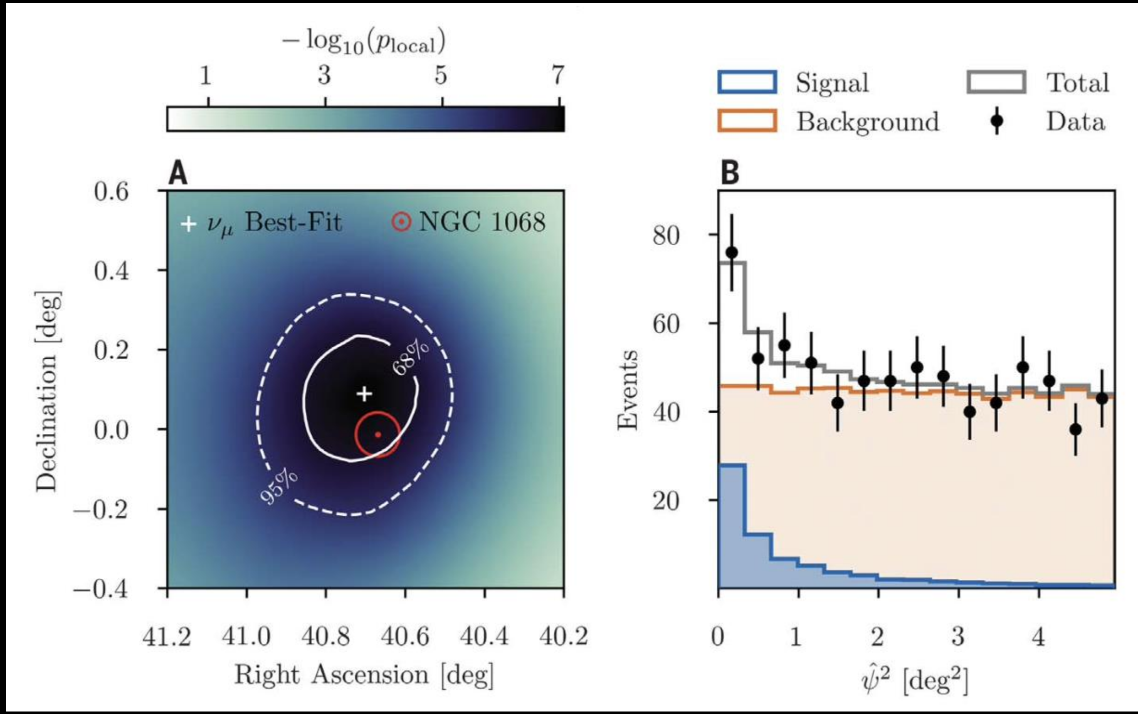
Track events are ideal for astrophysical source identification.

Multi-Messenger Neutrino Astronomy



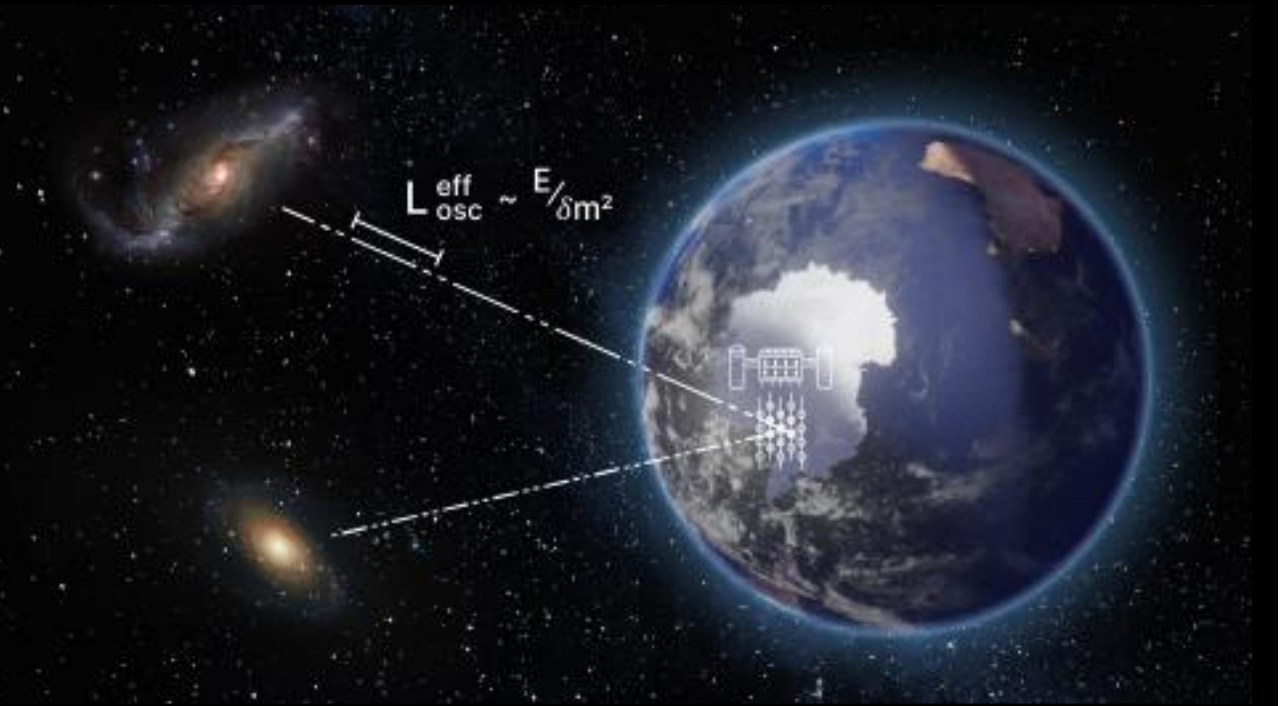


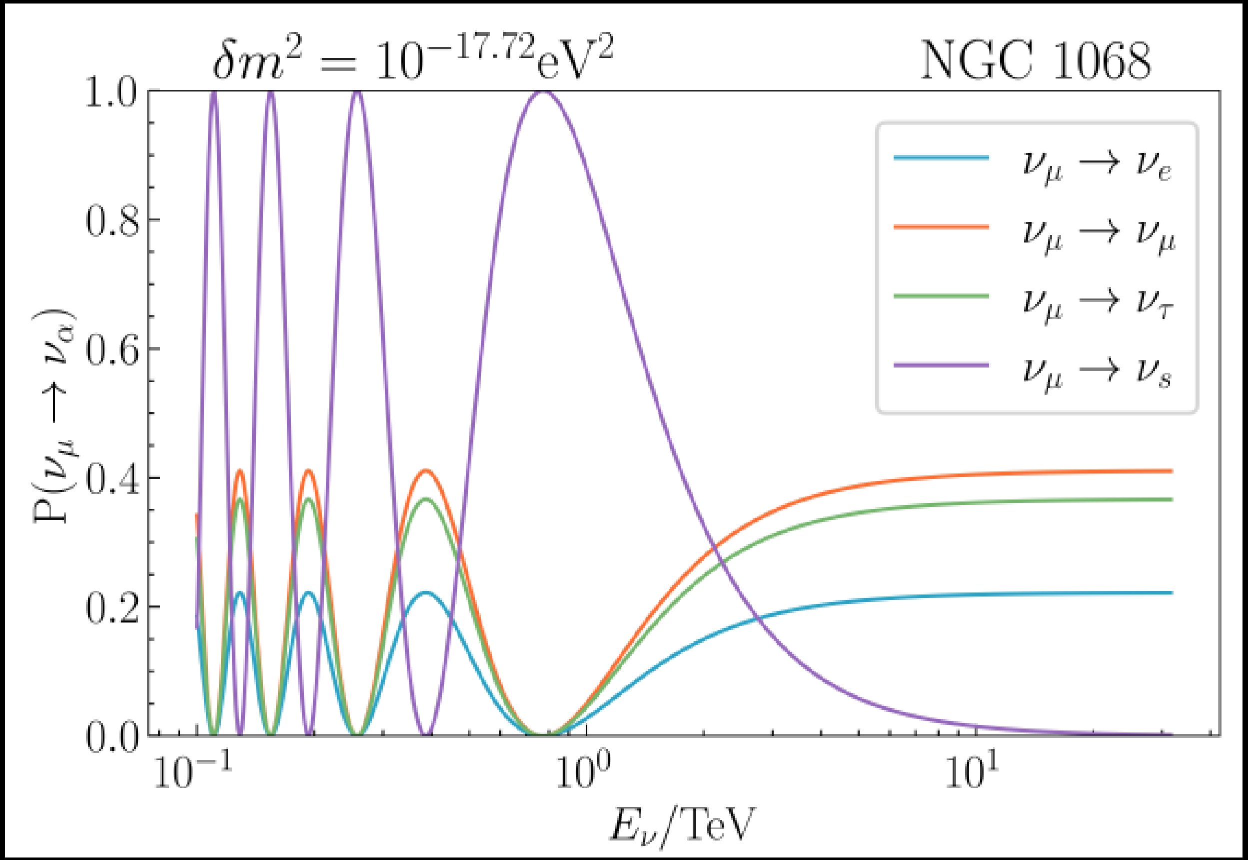
Source Name	Source Type	α [°]	δ [°]	$\hat{n}_s$	$\hat{\gamma}$	$-\log_{10} p_{\mathrm{local}}$	$\Phi_{90\%}$
NGC 1068	SBG/AGN	40.67	-0.01	79	3.2	7.0 (5.2 σ)	9.6
PKS 1424+240	BLL	216.76	23.80	77	3.5	4.0 (3.7 σ)	11.4
TXS 0506+056	BLL/FSRQ	77.36	5.70	5	2.0	3.6 (3.5 σ)	7.5



IceCube Collaboration, 2211.09972 (Science); 1807.08794 (Science).

Probing *Qdino* Oscillations





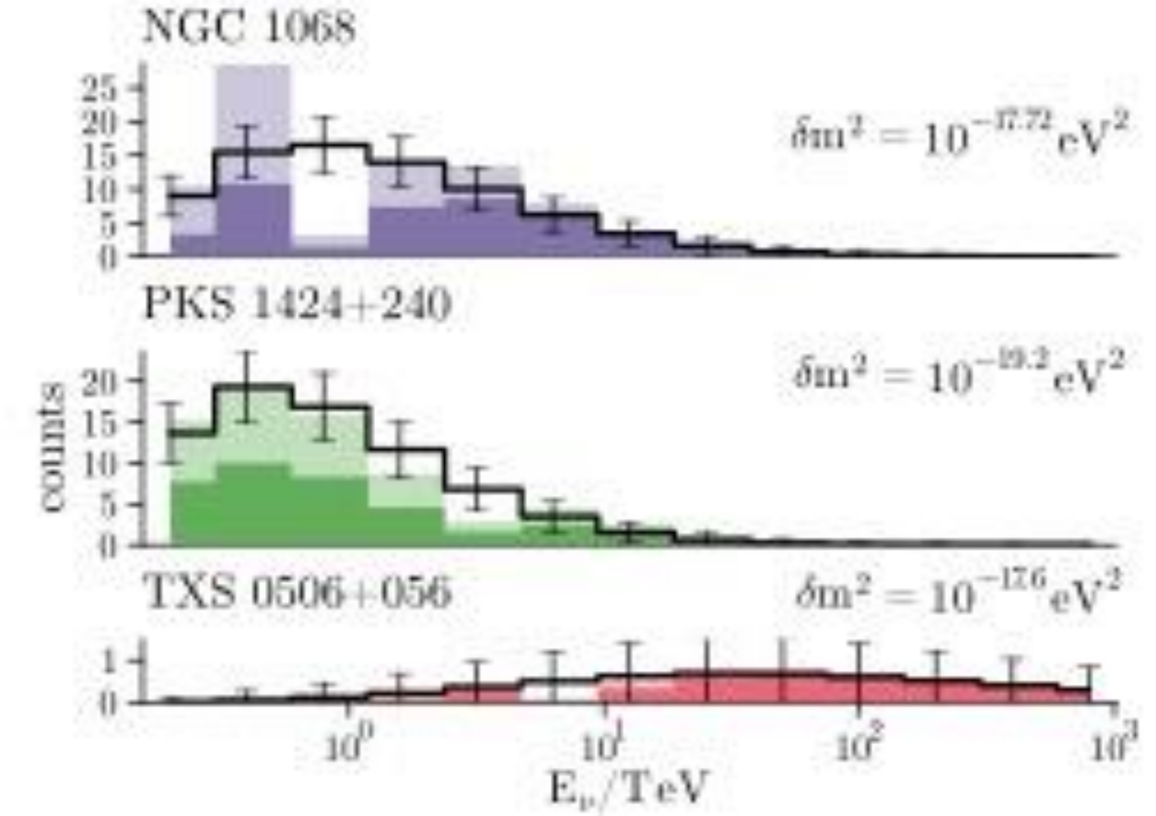
Carloni, Martinez-Soler, Arguelles, Babu, BD, 2212.00737

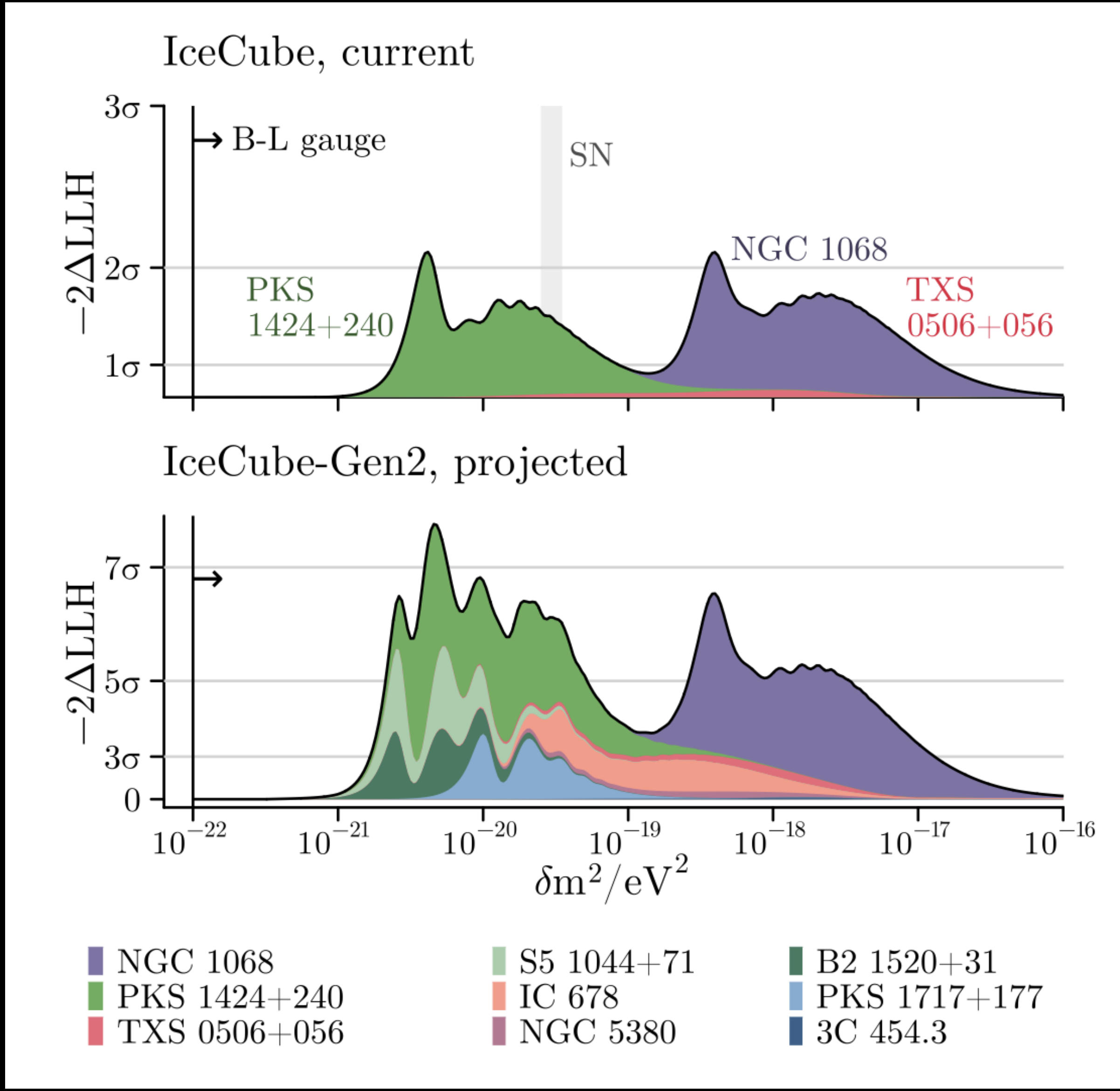
$$P_{\alpha\beta} = \frac{1}{2}\sum_{j=1}^{3} |U_{\beta j}|^2 |U_{\alpha j}|^2 \left[1 + \cos\left(\frac{\delta m_j^2 L_{\text{eff}}}{2E_\nu}\right)\right],$$

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

First IceCube Constraints on Qdinos

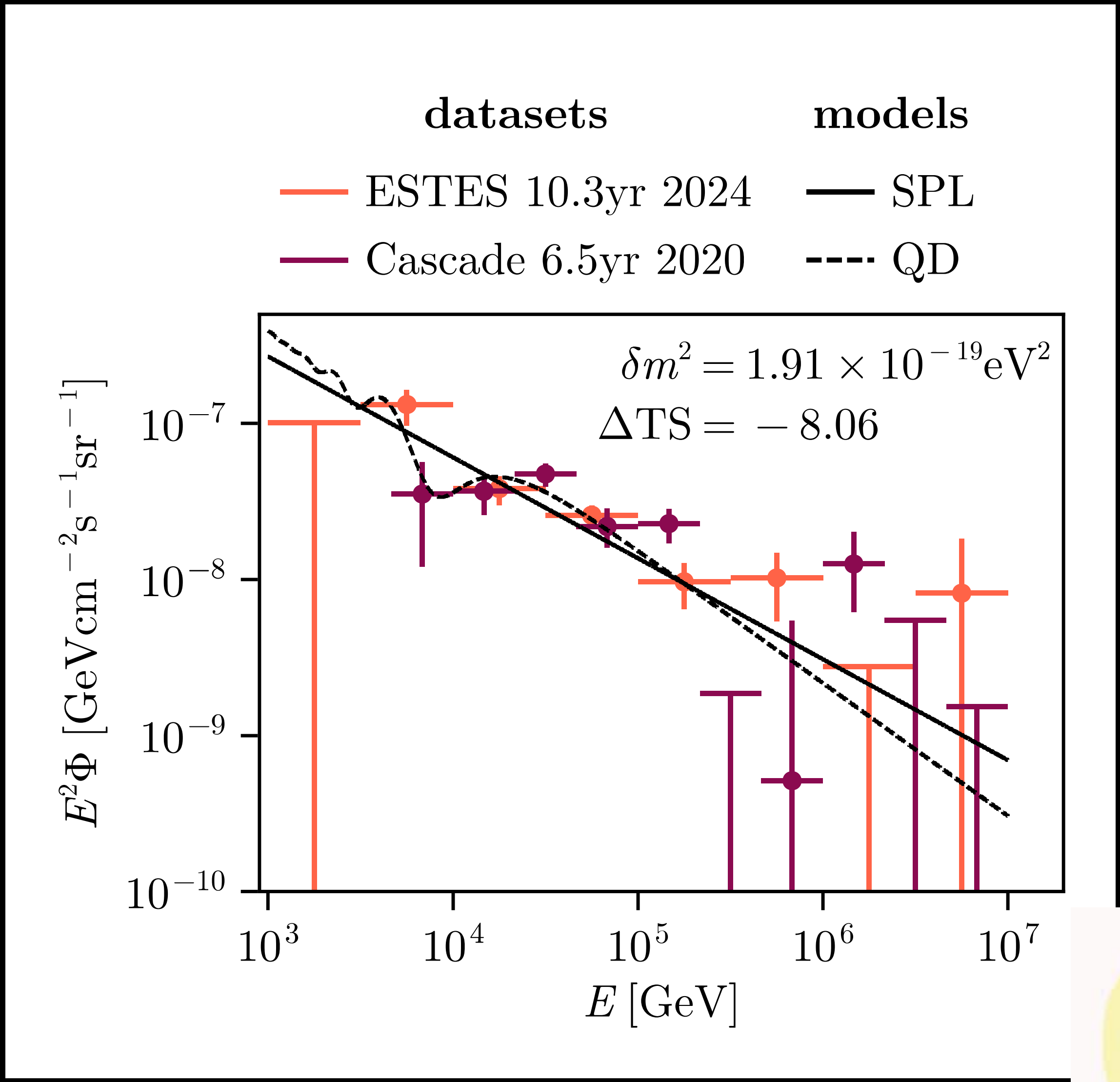
Source	Source Type	$-\log_{10} p_{\text{local}}$	$\hat{n}_s$	$\hat{\gamma}$	z
NGC 1068	SBG/AGN	7.0 (5.2σ)	79	3.2	0.0038 (16 Mpc)
PKS 1424+240	BLL	4.0 (3.7σ)	77	3.5	0.6047 (2.6 Gpc)
TXS 0506+056	BLL/FSRQ	3.6 (3.5σ)	5	2.0	0.3365 (1.4 Gpc)

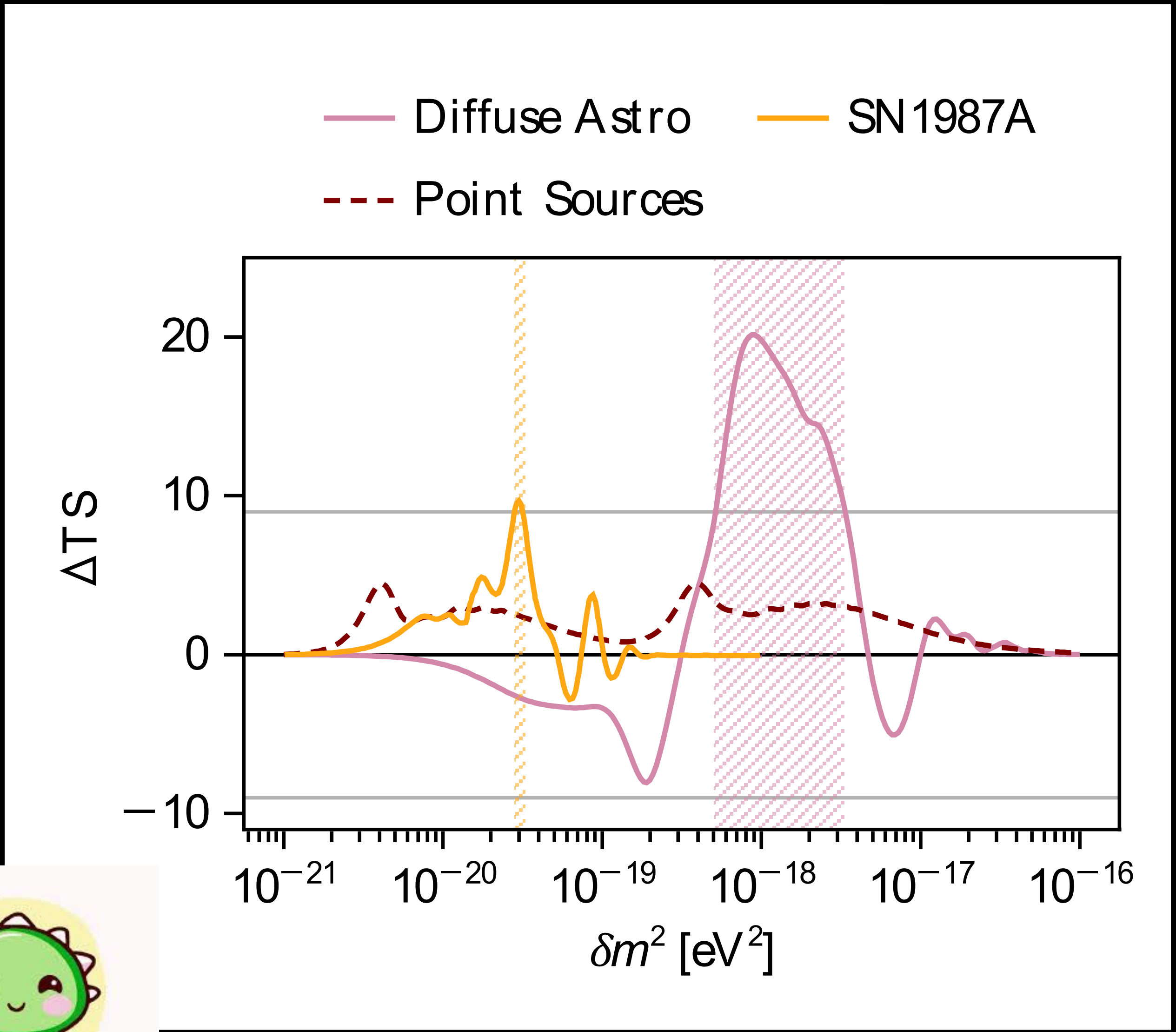




Carloni, Martinez-Soler, Arguelles, Babu, BD, 2212.00737

Hint of Qdinos in IceCube All-Sky Data

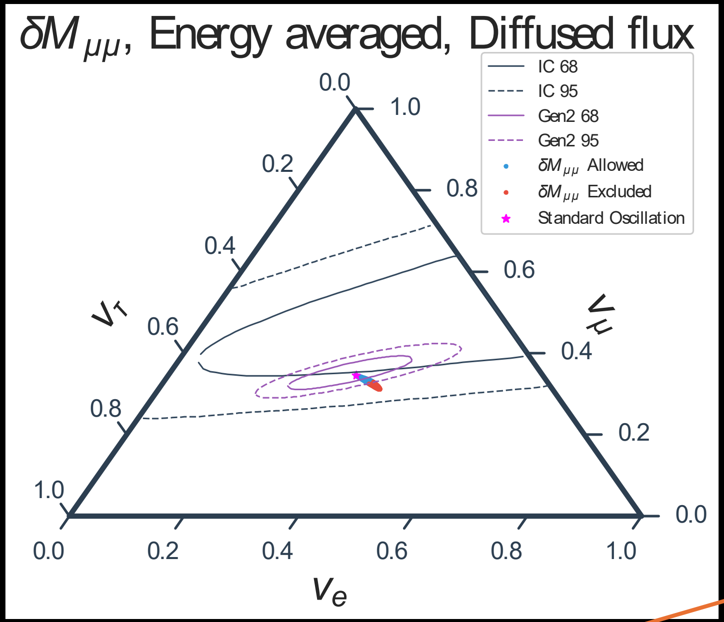


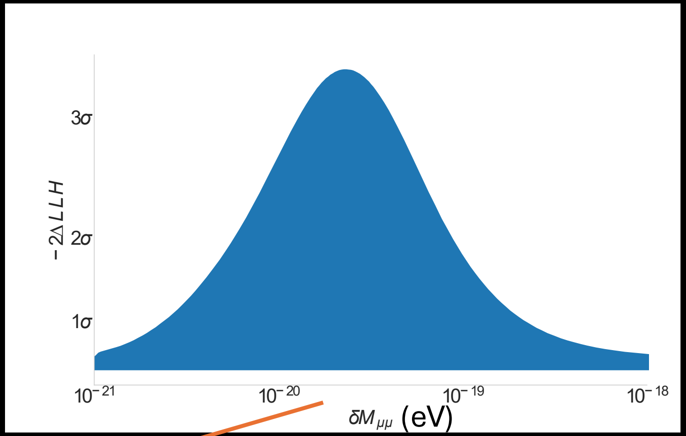


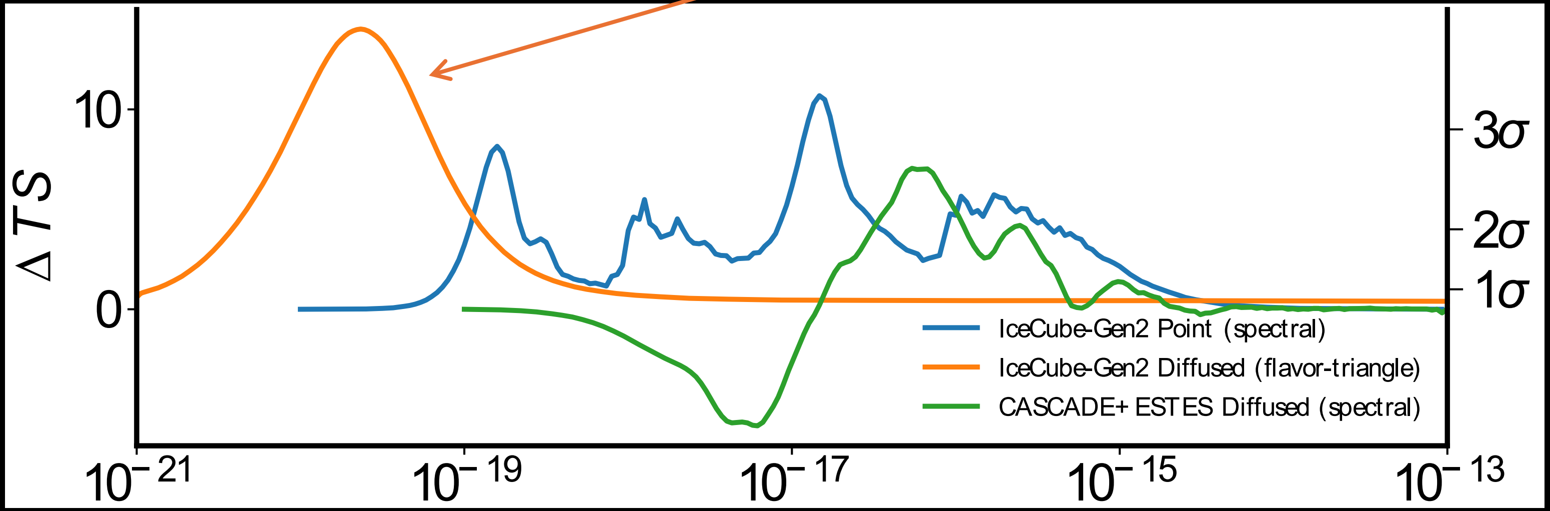
Carloni, Porto, Arguelles, BD, Jana, [2503.19960](https://arxiv.org/abs/2503.19960)

Under reasonable assumptions on SFR distribution

Flavor Triangle Analysis

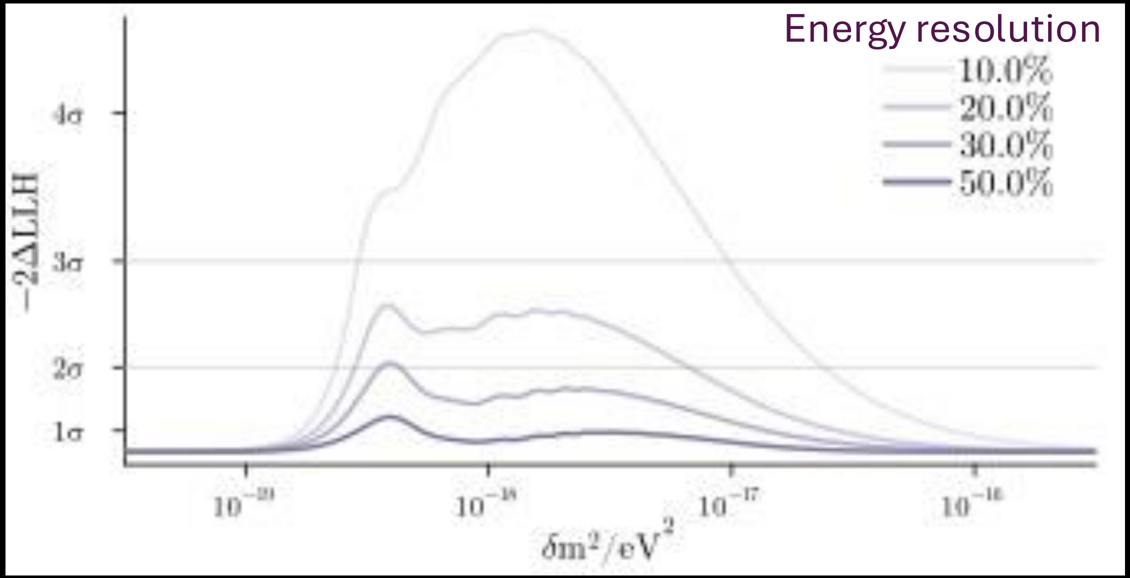


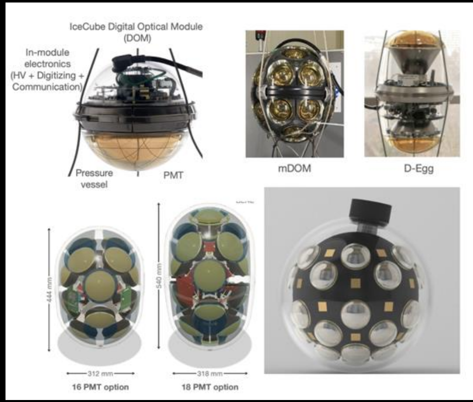


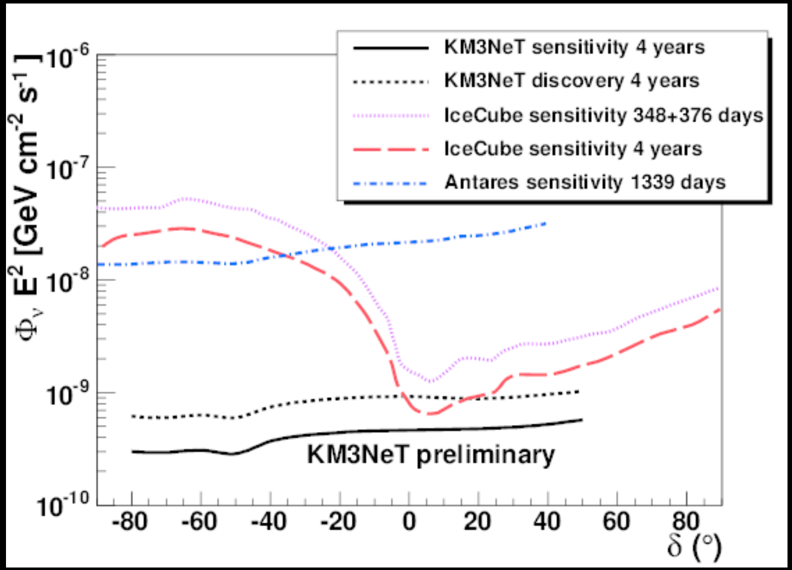


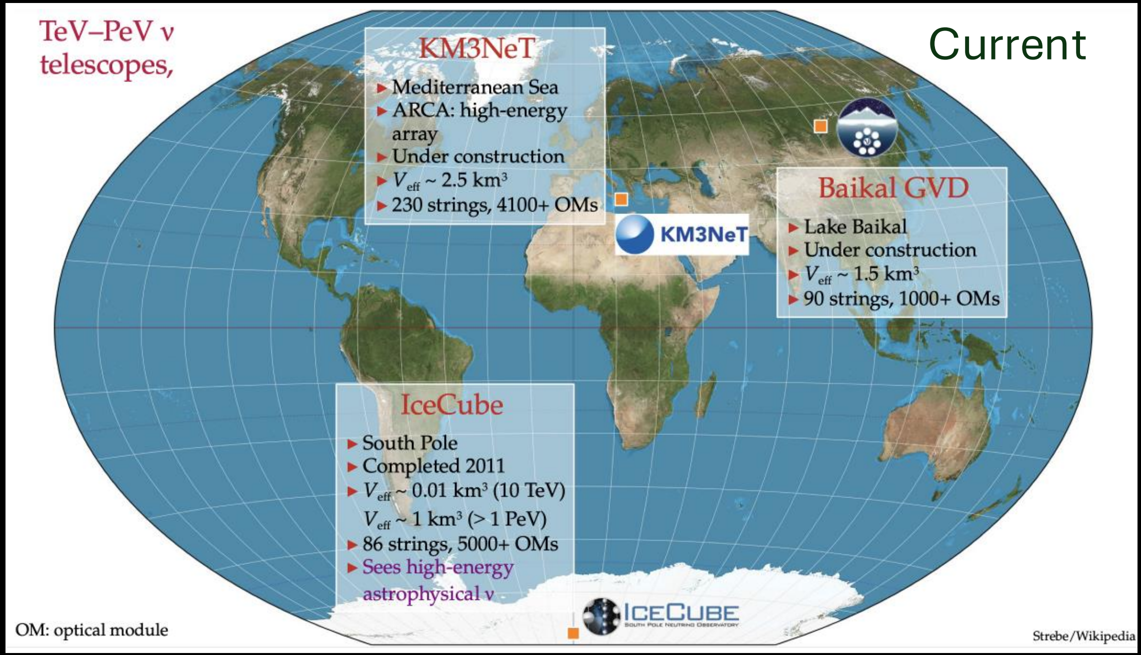
BD, Dutta, Martinez-Soler, Verma (*in preparation*)

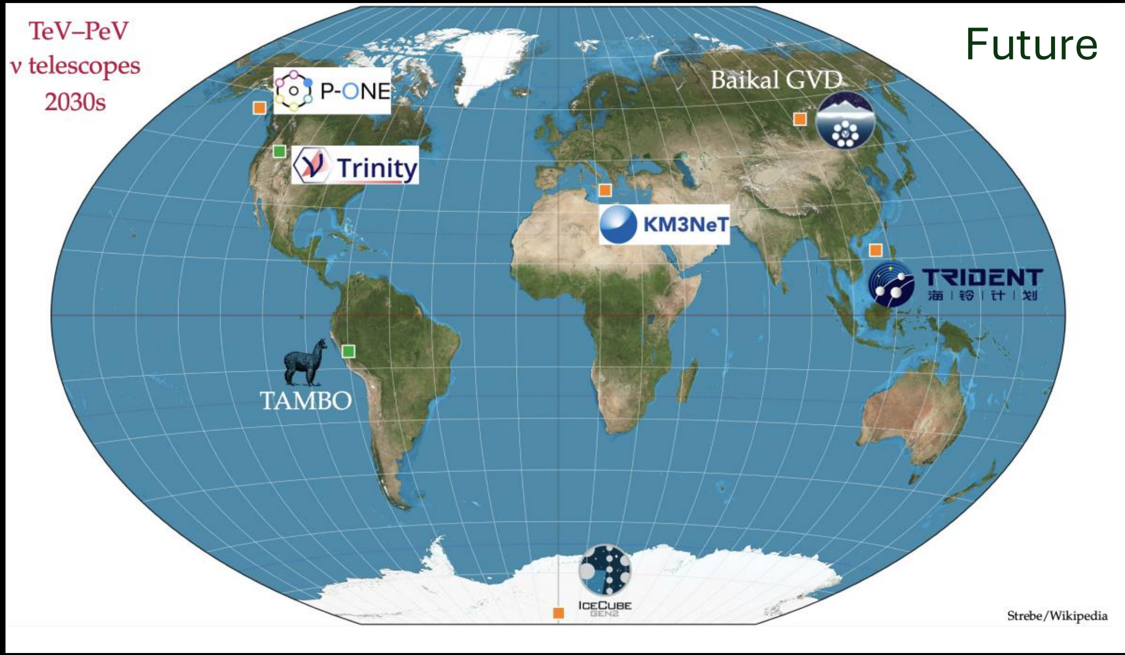
Future is Promising







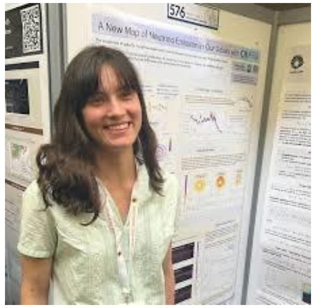




Conclusions

- Nature of neutrino mass (Majorana, Dirac or quasi-Dirac) is an open question of fundamental importance.
- Neutrinoless double beta decay may (or may not) address it.
- An alternative probe of quasi-Dirac neutrinos using astrophysical baselines.
- Enabled by recent breakthroughs in high-energy neutrino astrophysics.
- Future is promising.

Acknowledgments



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