Probing BSM Physics with Multi-Messenger Astronomy

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PPC 2024

IIT Hyderabad

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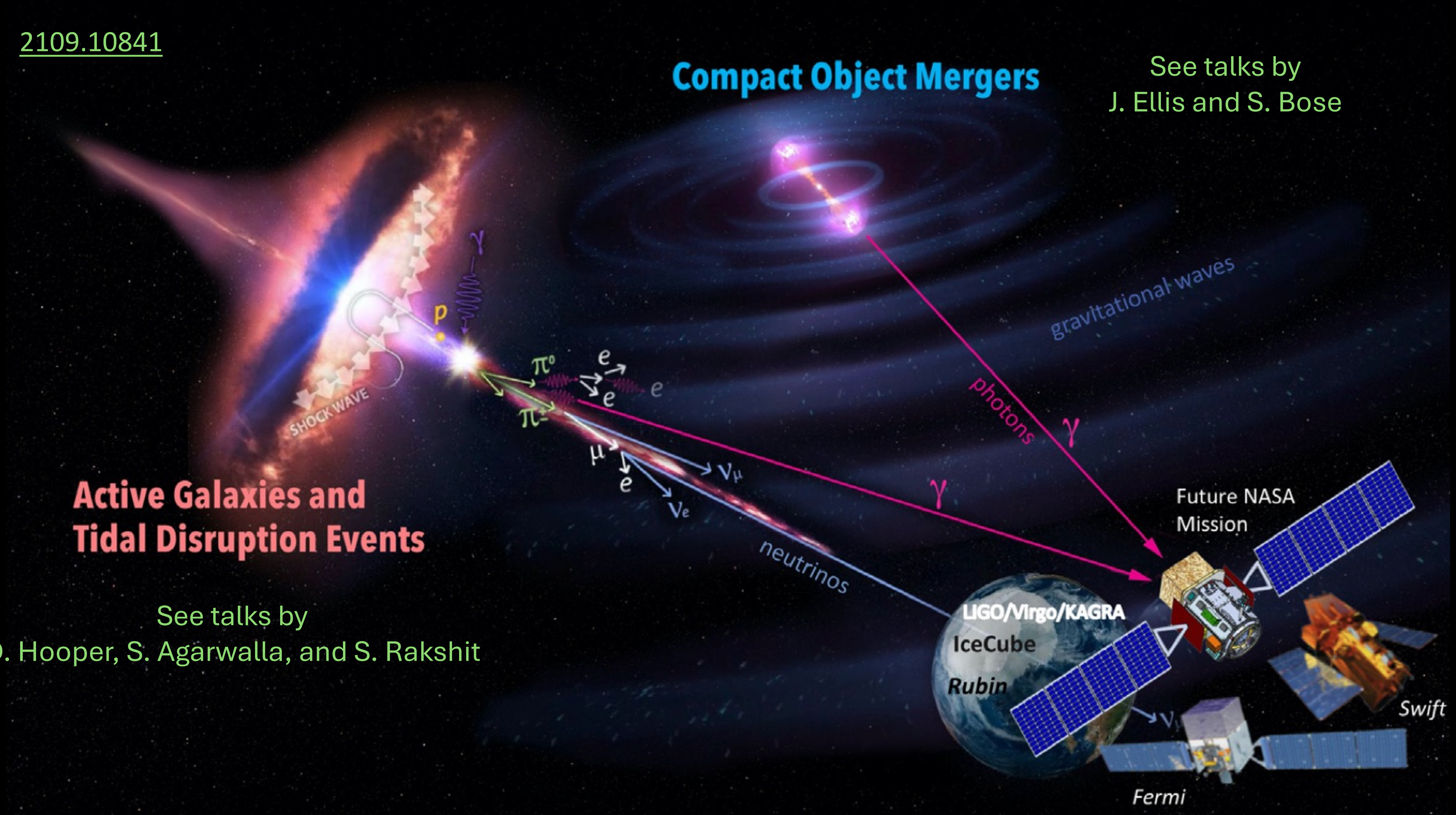
A New Era of Multi-Messenger Astronomy

2109.10841

See talks by
J. Ellis and S. Bose



See talks by
D. Hooper, S. Agarwalla, and S. Rakshit

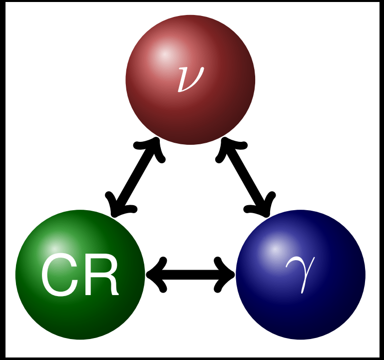
Great news for *both* Astrophysics and Particle Physics.

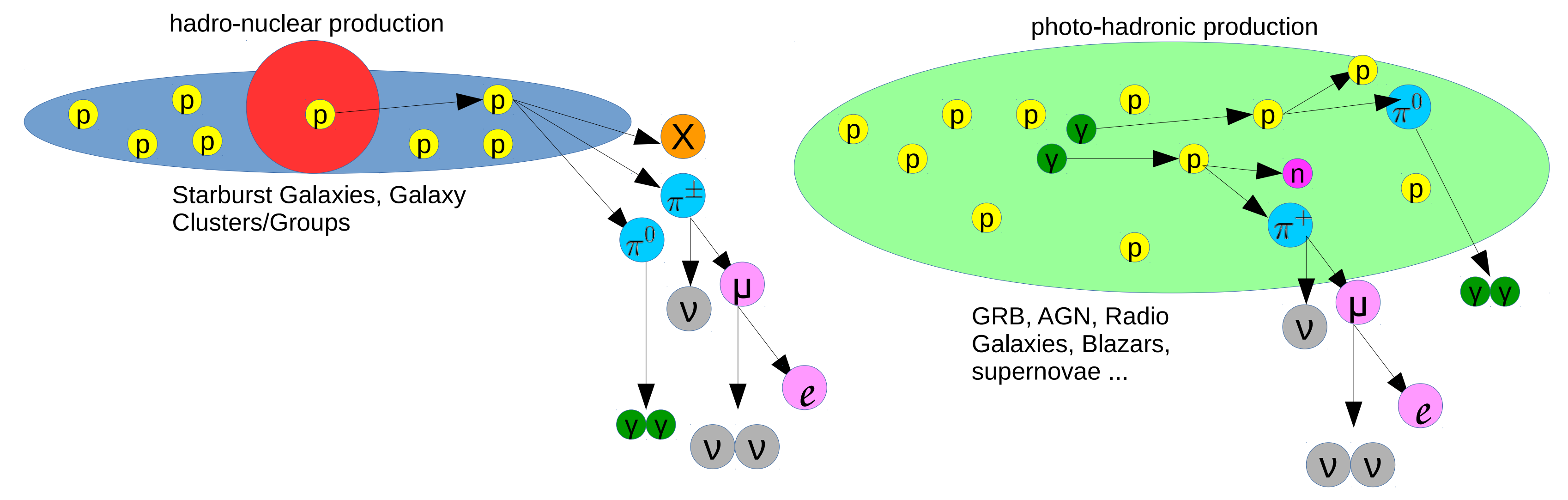
Outline

New Multi-Messenger Probes of (B)SM Physics

- Decaying Heavy Dark Matter [Sui, BD, 1804.04919 (JCAP);
  Brdar, BD, Maitra, Suliga (*in preparation*)]
- New (B)SM Resonances [Babu, BD, Jana, Sui, 1908.02779 (PRL);
  Brdar, BD, Plestid, Soni, 2207.02860 (PLB);
  BD, Jana, Porto, 2312.17315]
- Pseudo-Dirac Neutrinos [Carloni, Martinez-Soler, Arguelles, Babu, BD, 2212.00737 (PRDL);
  BD, Machado, Martinez-Soler, 2406.18507]
- Axion-like Particles [BD, Fortin, Harris, Sinha, Zhang, 2305.01002 (PRL) and *work in progress*]

HENs: Multi-Messenger Connection





hadro-nuclear production

Starburst Galaxies, Galaxy Clusters/Groups

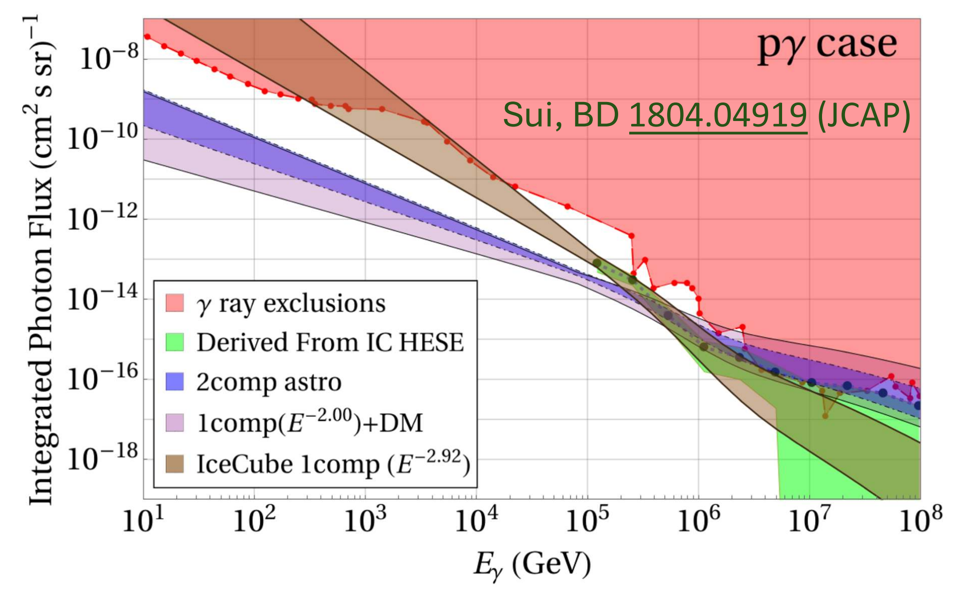
photo-hadronic production

GRB, AGN, Radio Galaxies, Blazars, supernovae ...

$$E_\gamma^2 \Phi_\gamma \simeq \frac{4}{K} E_\nu^2 \frac{\Phi_{(\nu+\bar{\nu})\mathrm{tot}}}{3}\Big|_{E_\nu = 0.5 E_\gamma}$$

Meszaros 1708.03577 (ARNPS)

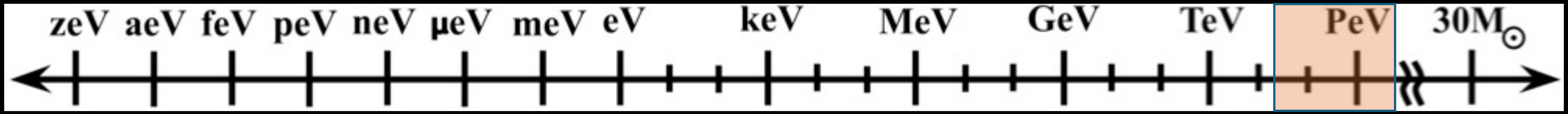
- IceCube best-fit in tension with gamma-ray constraints.
- **Alternatives:** Broken power-law, 2-component flux, neutrinophilic BSM contribution

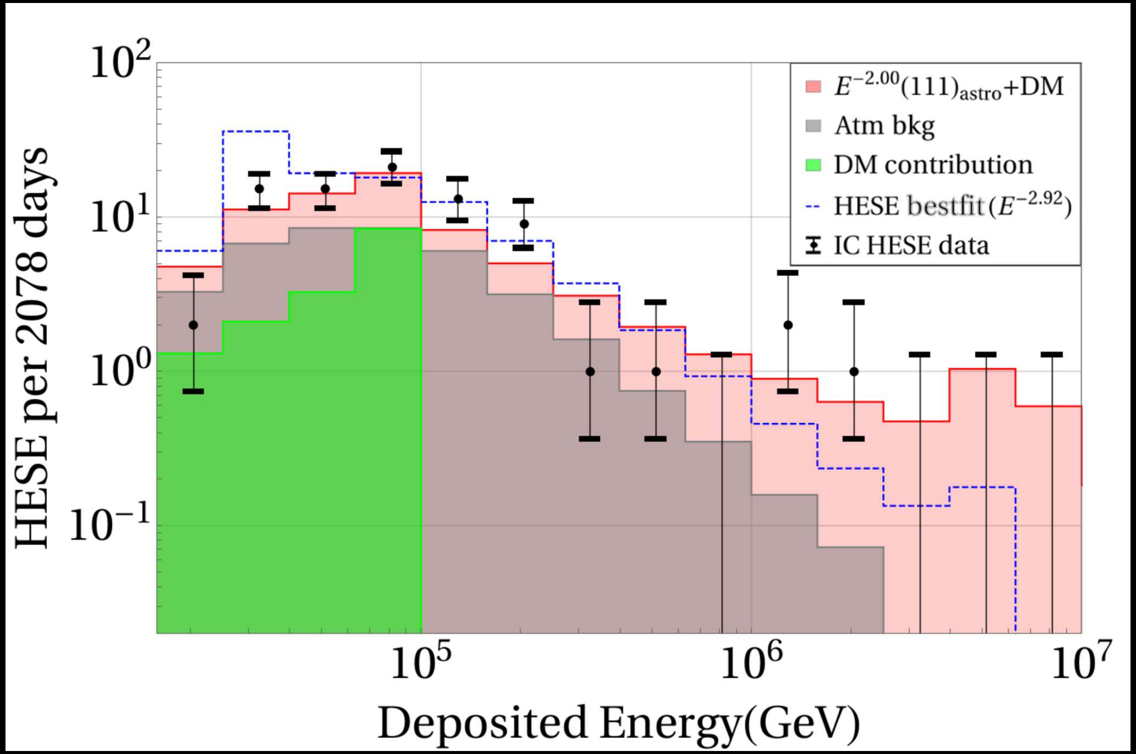


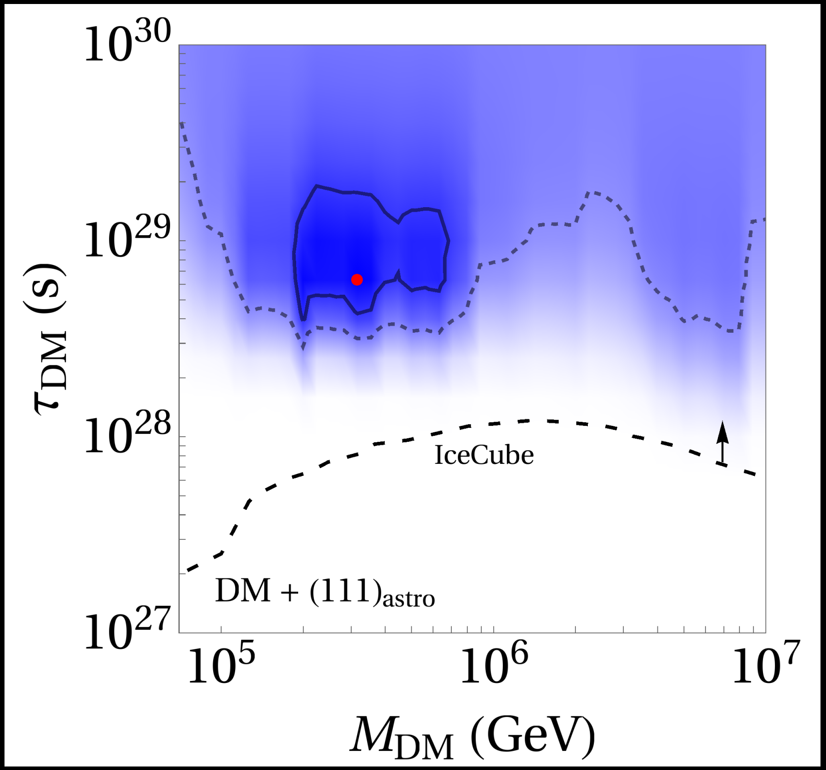
Sui, BD 1804.04919 (JCAP)

(a) $K = 1$ case

Decaying Heavy Dark Matter





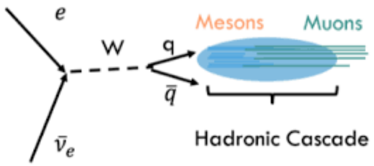


Mild preference for a decaying dark matter component over purely astrophysical unbroken power-law flux

Sui, BD 1804.04919 (JCAP)

For a recent update, see Fiorillo, Valera, Bustamante, Winter 2307.02538 (PRD)

New SM Resonances with UHE Neutrinos



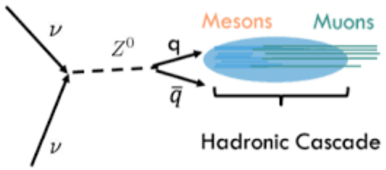
[Glashow (Phys. Rev. '60)]

Glashow resonance

$$E_\nu = \frac{m_W^2}{2m_e} = 6.3\ \text{PeV}$$

Recently observed by IceCube

[Nature **591**, 220 (2021)]



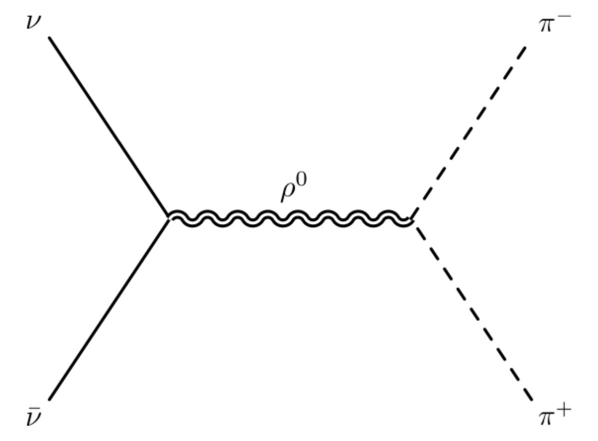
[Weiler (PRL '82)]

***Z*-burst**

$$E_\nu = \frac{m_Z^2}{2m_\nu} > 10^{14}\ \text{GeV}$$

Beyond GZK cutoff

Unlikely to be seen

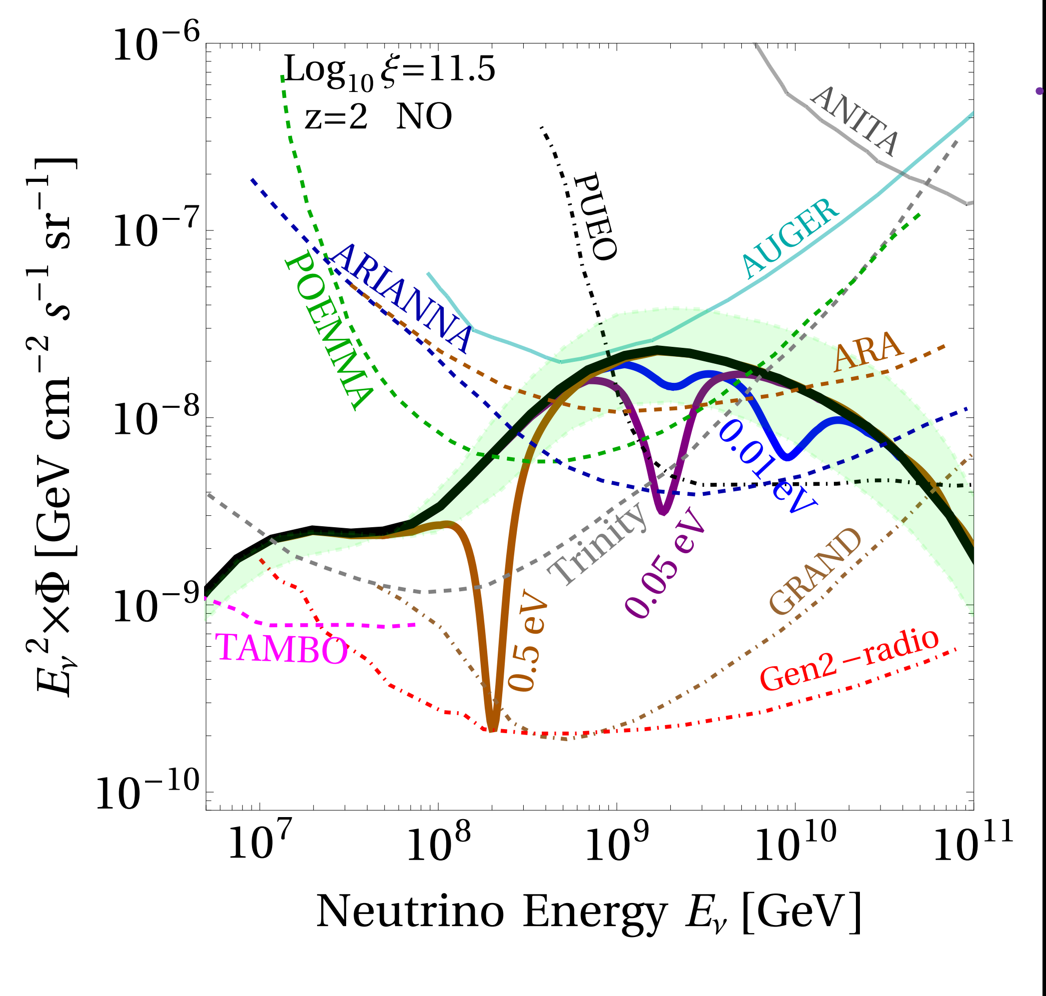


(Axial) vector meson resonance

Paschos, Lalakulich 0206273;
BD, Soni 2112.01424

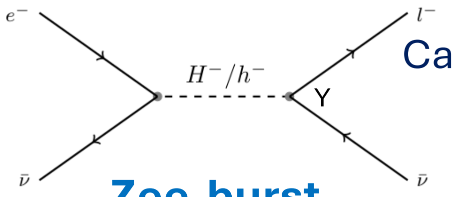
$$E_\nu^{\text{res}} = \frac{m_\rho^2}{2m_\nu(1+z)} = \frac{(3.0 \times 10^{18}\ \text{eV})}{(1+z)}\left(\frac{0.1\ \text{eV}}{m_\nu}\right)$$

Accessible at neutrino telescopes!



Brdar, BD, Plestid, Soni, 2207.02860 (PLB)

New BSM Resonances with UHE Neutrinos



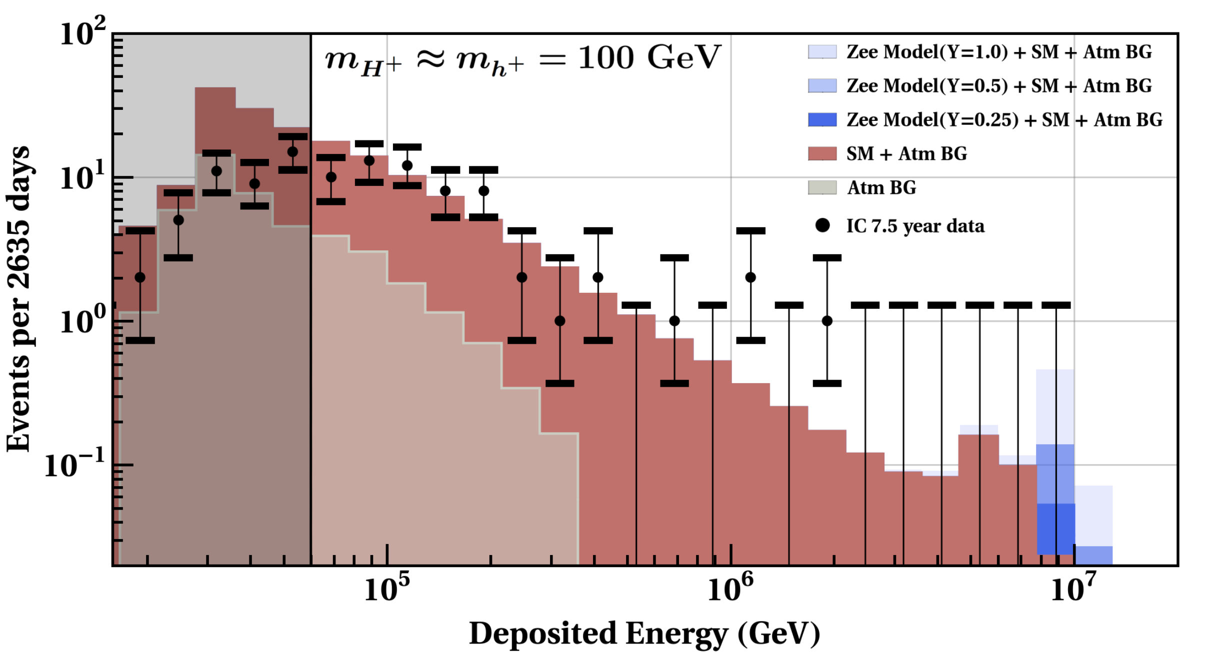
Can be of any flavor.

Zee-burst

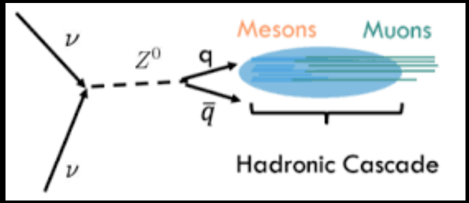
$$E_\nu = \frac{m^2_{h^-/H^-}}{2m_e} \gtrsim 10 \text{ PeV (observable at IceCube)}$$

Motivated by the **Zee model** for neutrino mass

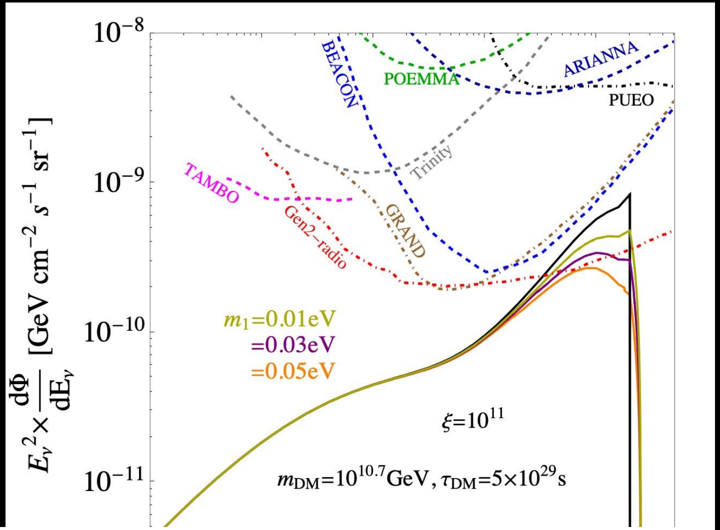
A. Zee (PLB '80)

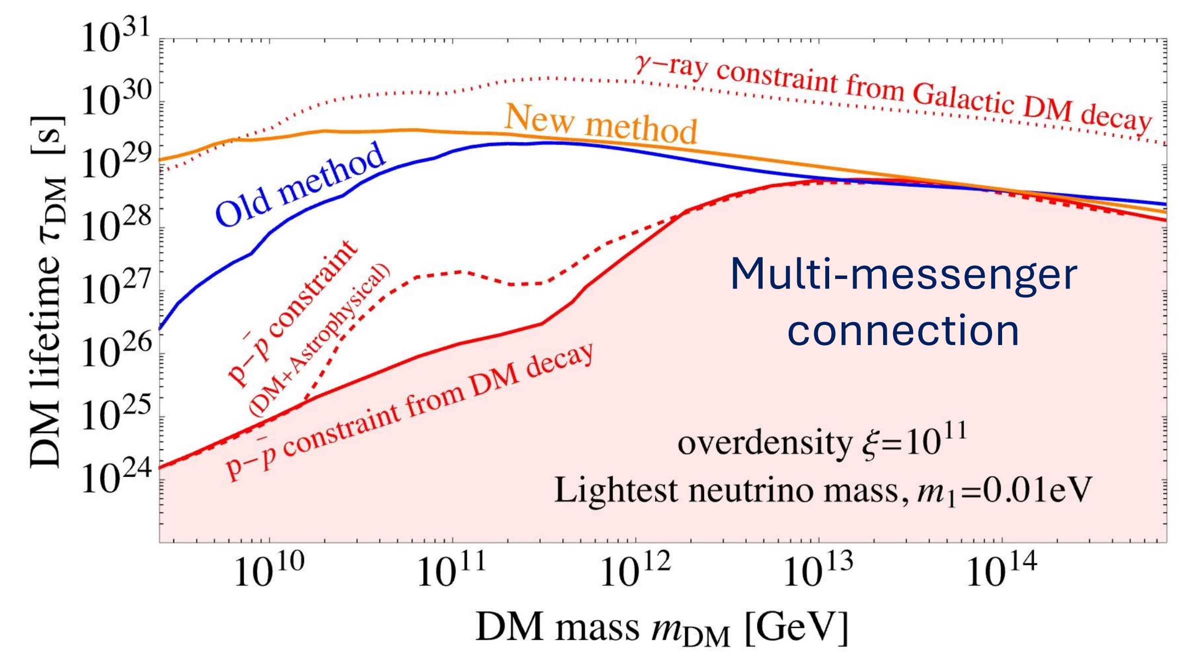


Babu, BD, Jana, Sui 1908.02779 (PRL)



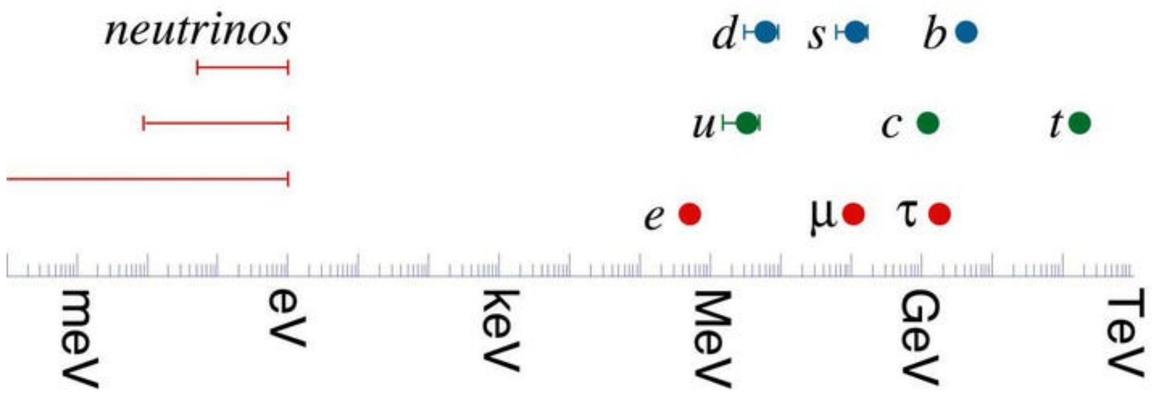
DM decay-induced *Z*-burst (or ρ-burst)





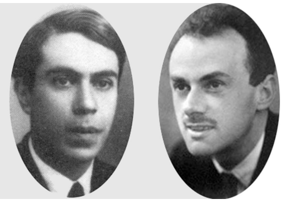
Brdar, BD, Maitra, Suliga (*in preparation*)

Probing the Nature of Neutrino Mass



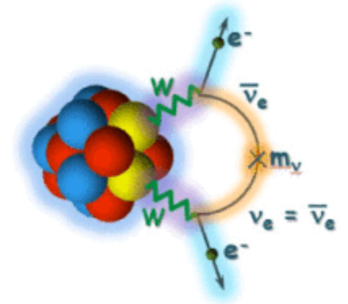
Perhaps something beyond the standard Higgs mechanism?

See talk by S. Goswami

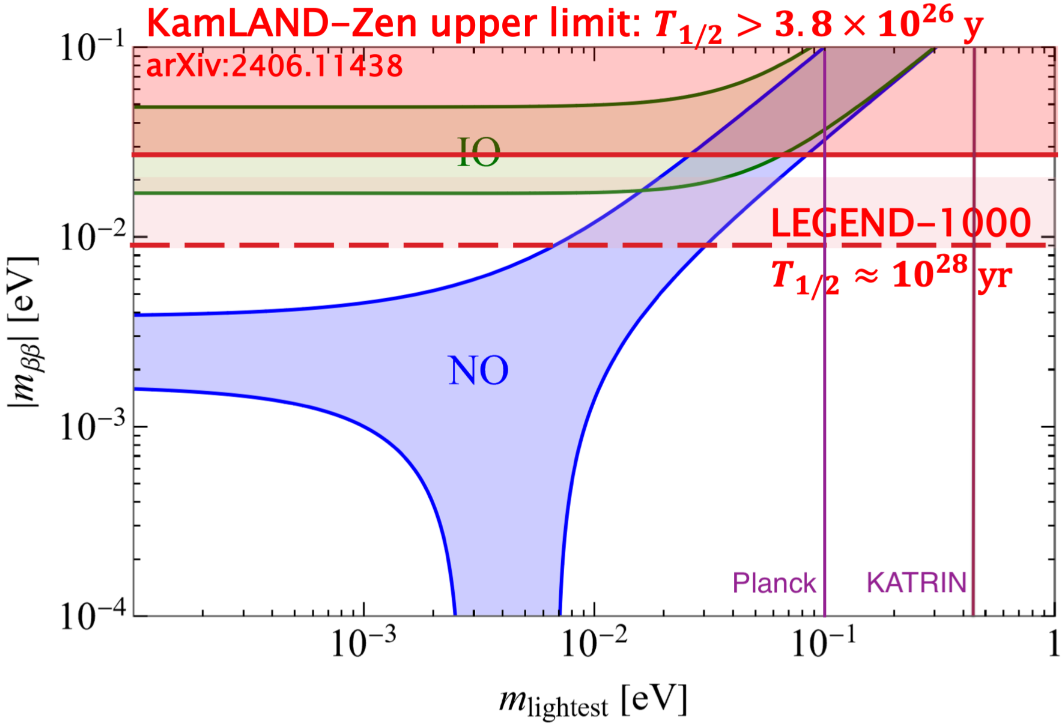


Majorana or Dirac (or something in between)?

Only experiments can tell.



Neutrinoless double beta decay



- What if there is no signal in NDBD experiments?
- Time to think about alternative probes.

See talk by F. Deppisch

What do we know from Theory?

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

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

  - 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 **pseudo-Dirac** (small active-sterile mass splitting).
- But isn't it more natural to have $||M_R|| \gg ||m_D||$ (seesaw)?

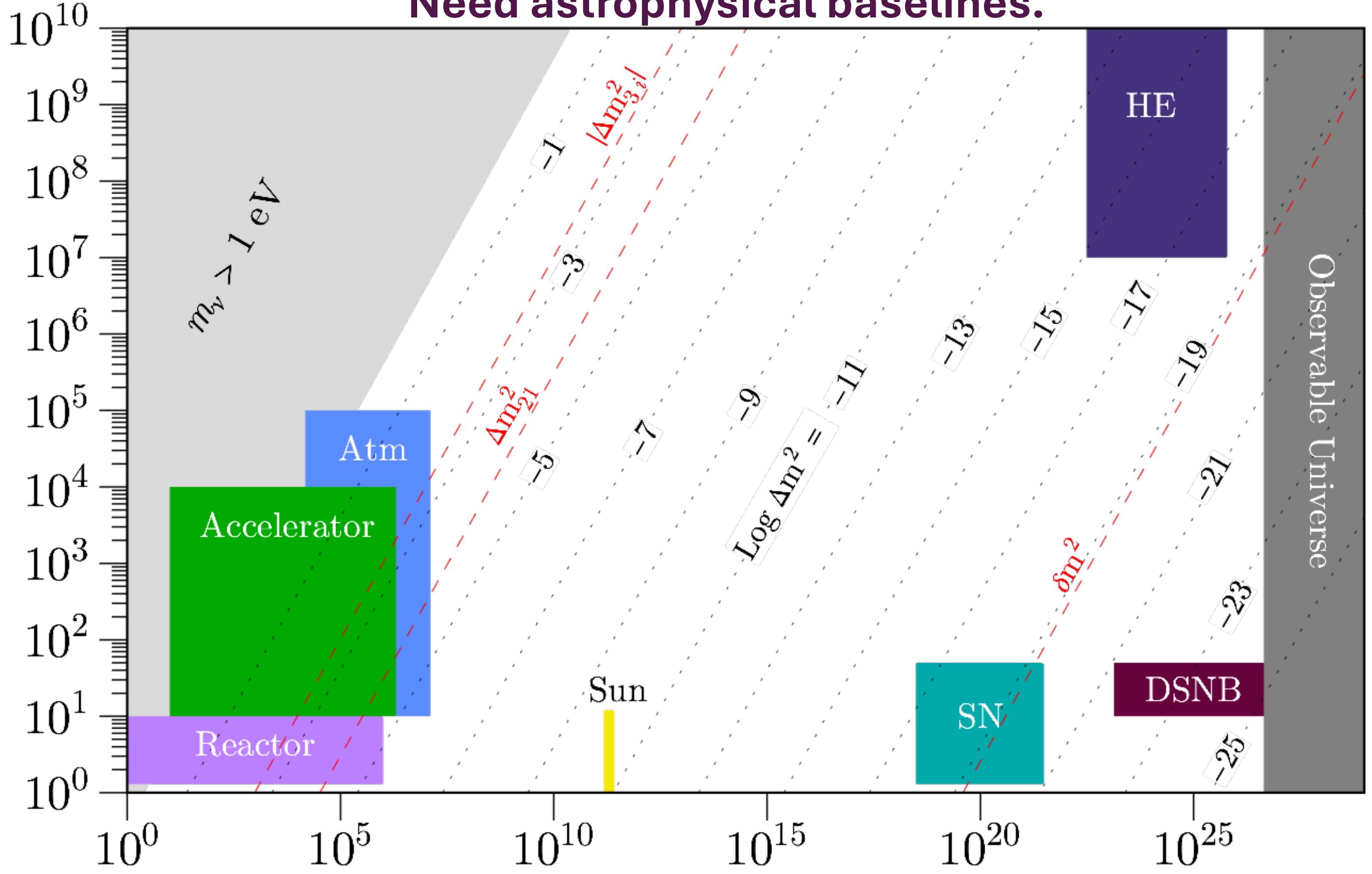
  [Minkowski (PLB '77); Mohapatra, Senjanovic (PRL '80); Yanagida '79; Gell-Mann, Ramond, Slansky '79]
- Maybe, but $||M_R|| \ll ||m_D||$ is a logical possibility too.

  [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 pseudo-Dirac neutrinos.

How to probe Pseudo-Dirac Neutrinos?

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

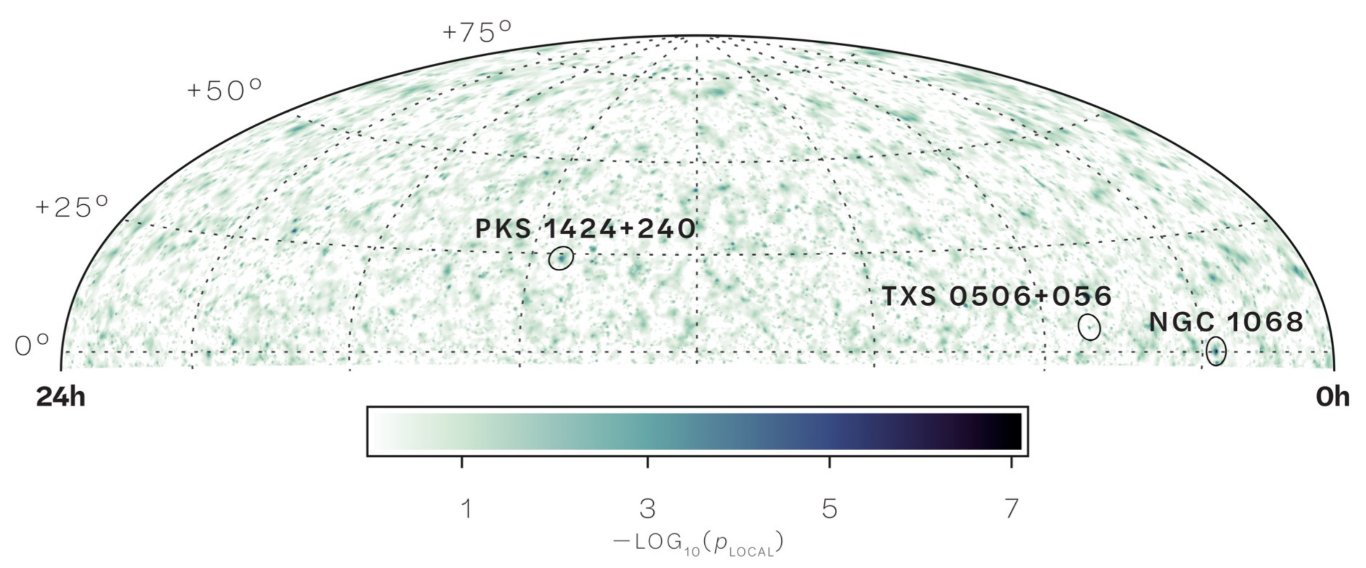
Need astrophysical baselines.

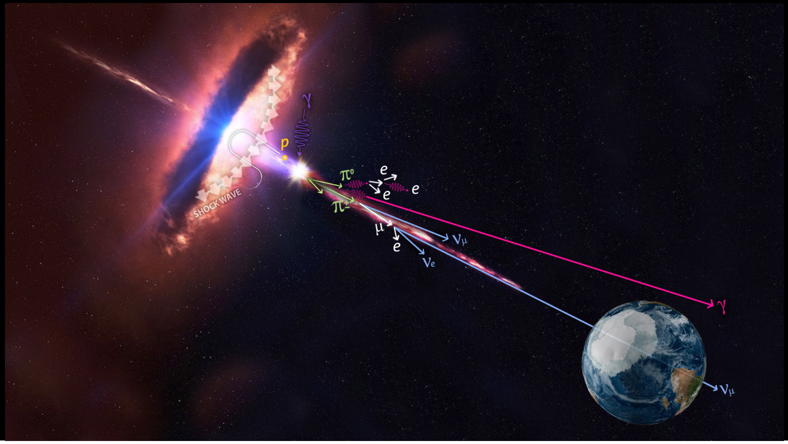


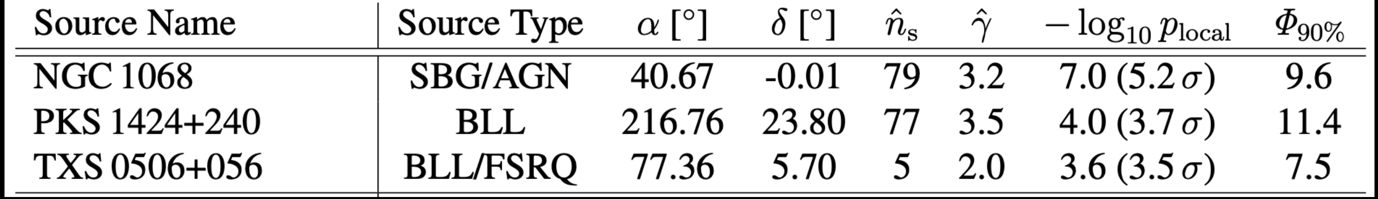
Beacom, Bell, Hooper, Learned, Pakvasa, Weiler 0307151 (PRL)

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

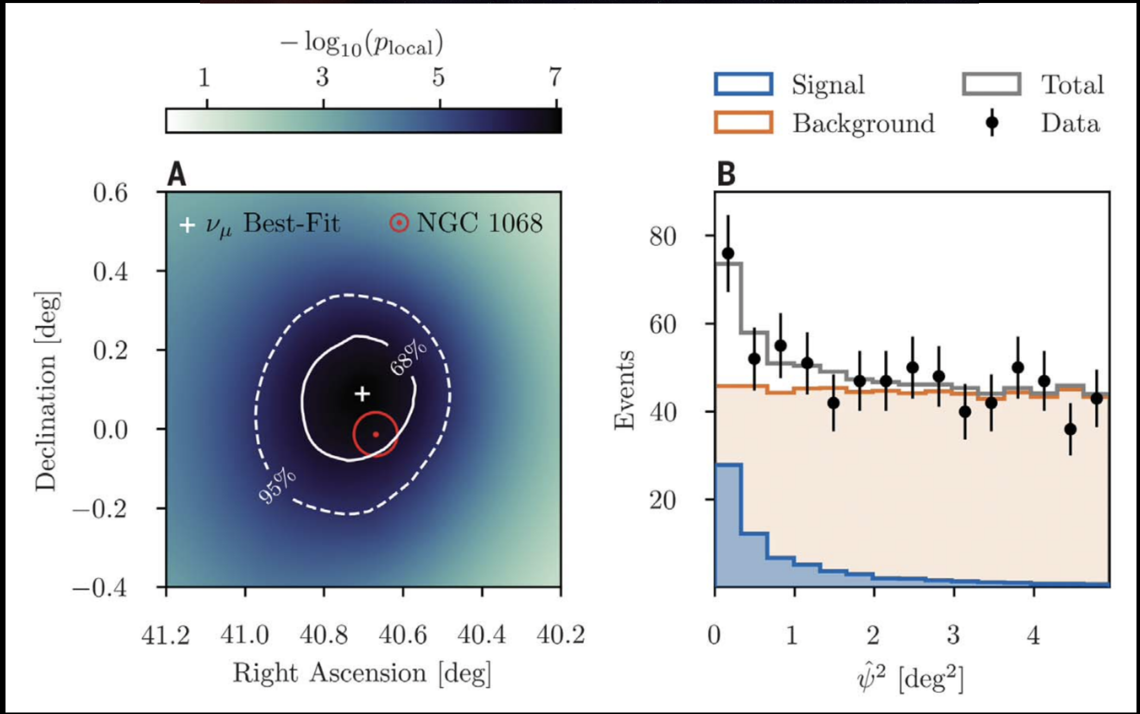
Here comes Multi-Messenger Neutrino Astronomy





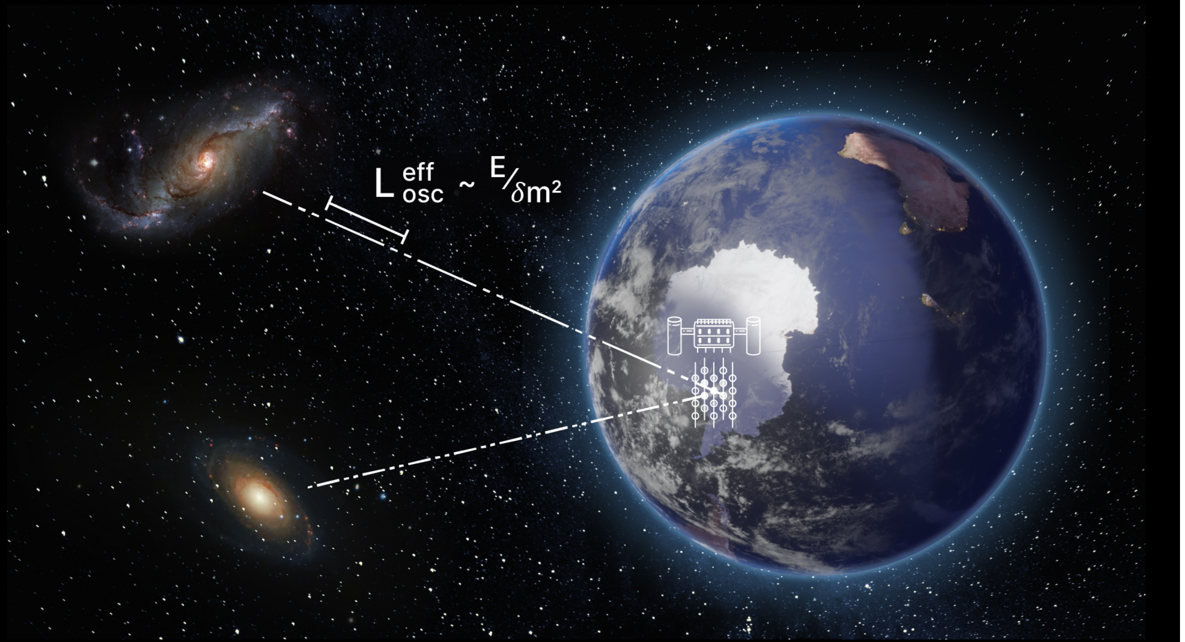


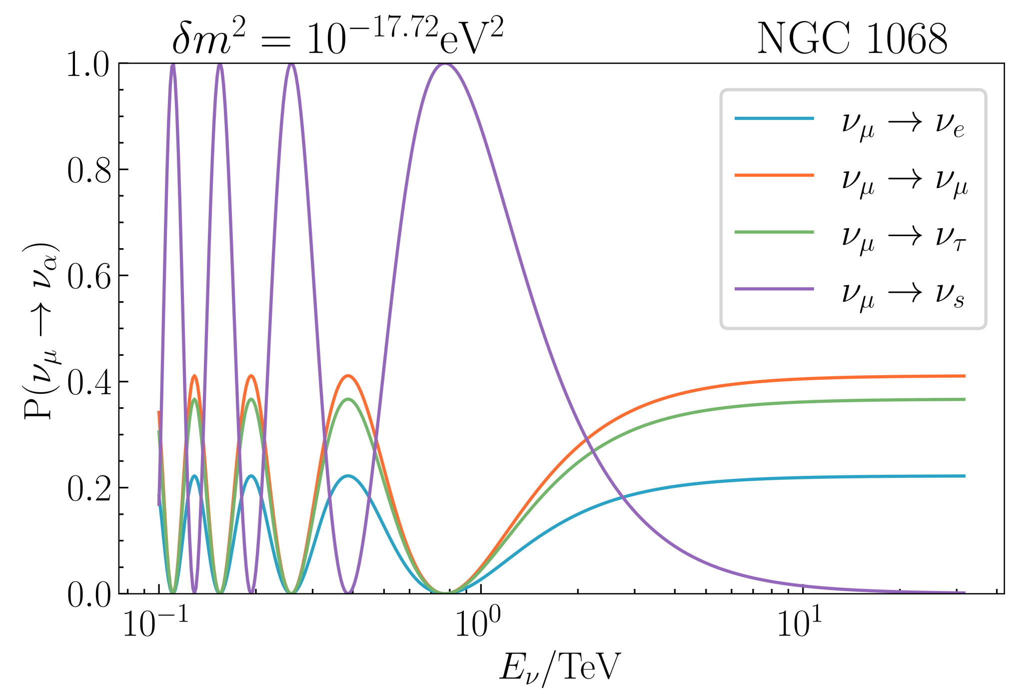
Source Name	Source Type	α [°]	δ [°]	$\hat{n}_s$	$\hat{\gamma}$	$-\log_{10} p_{\mathrm{local}}$	$\Phi_{90\%}$
NGC 1068	SBG/AGN	40.67	-0.01	79	3.2	7.0 (5.2 σ)	9.6
PKS 1424+240	BLL	216.76	23.80	77	3.5	4.0 (3.7 σ)	11.4
TXS 0506+056	BLL/FSRQ	77.36	5.70	5	2.0	3.6 (3.5 σ)	7.5



IceCube Collaboration, 2211.09972 (Science);
1807.08794 (Science).
Padovani *et al.*, 2405.20146 (Nature Astron.)

A New Probe of Pseudo-Dirac Neutrinos



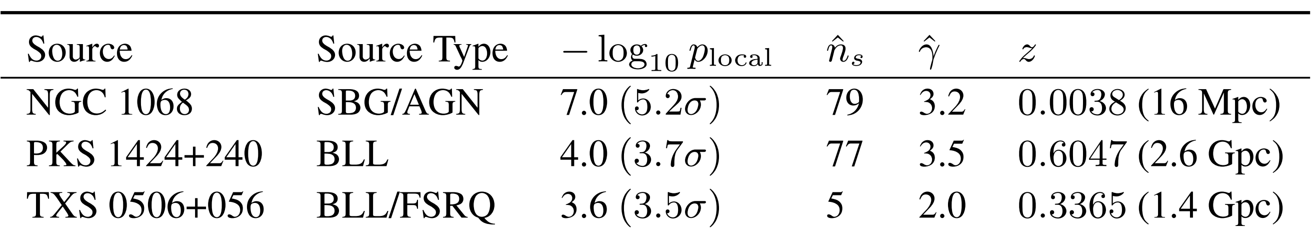


$$P_{\alpha\beta} = \frac{1}{2}\sum_{j=1}^{3} |U_{\beta j}|^2 |U_{\alpha j}|^2 \left[1 + \cos\left(\frac{\delta m_j^2 L_{\mathrm{eff}}}{2E_\nu}\right)\right],$$

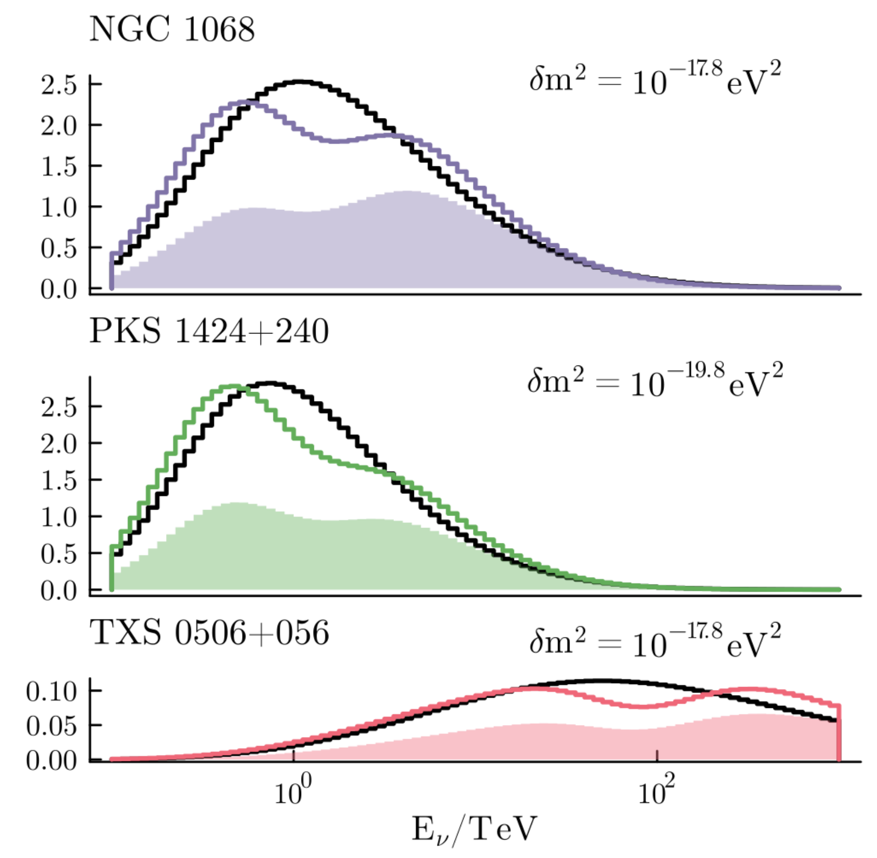
with $L_{\mathrm{eff}} = \int \frac{dz}{H(z)(1+z)^2}$ and $H(z) = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda + (1-\Omega_m-\Omega_\Lambda)(1+z)^2}$.

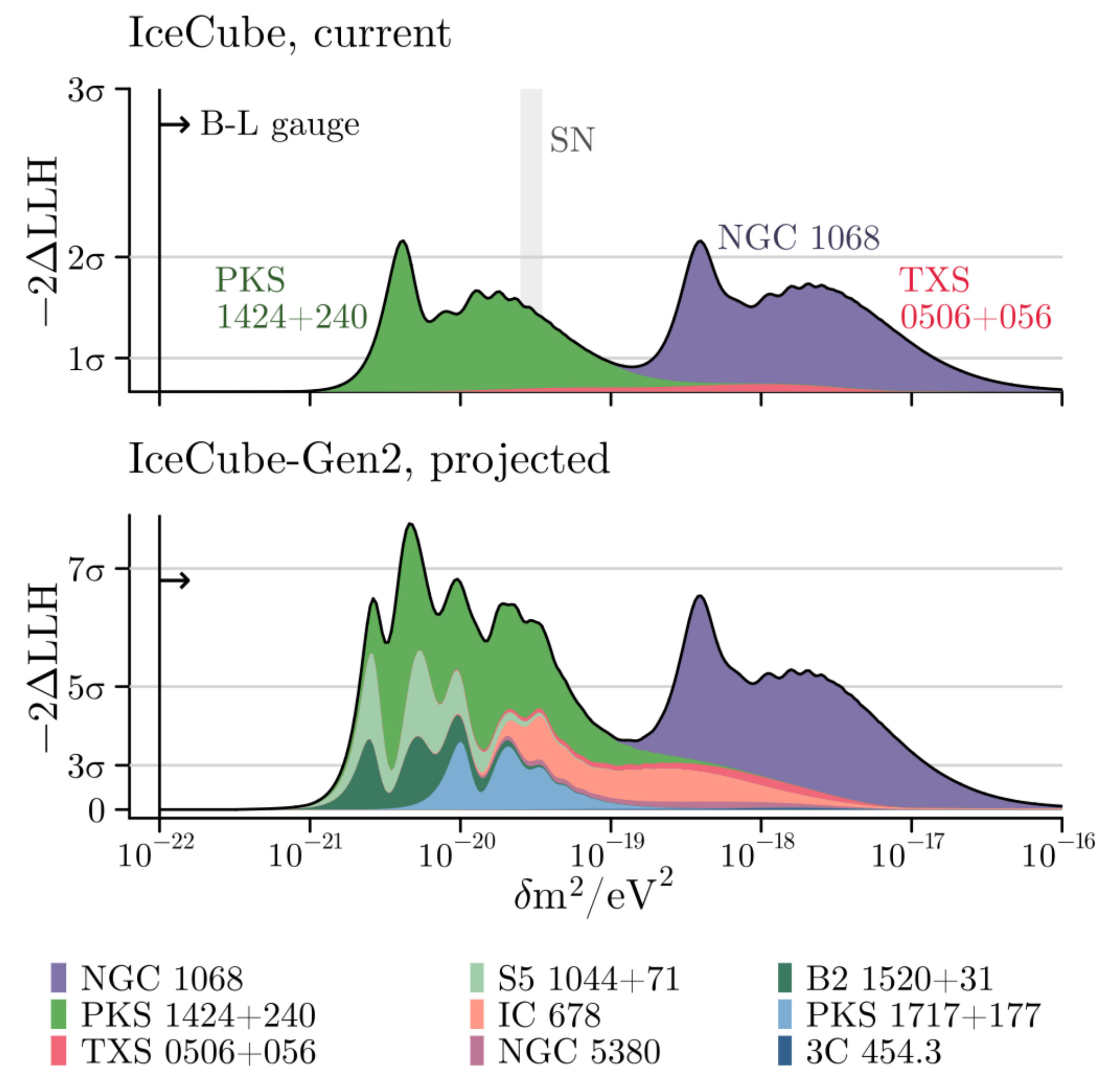
Carloni, Martinez-Soler, Arguelles, Babu, BD, 2212.00737 (PRDL)

First IceCube Constraints on Pseudo-Dirac Neutrinos



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



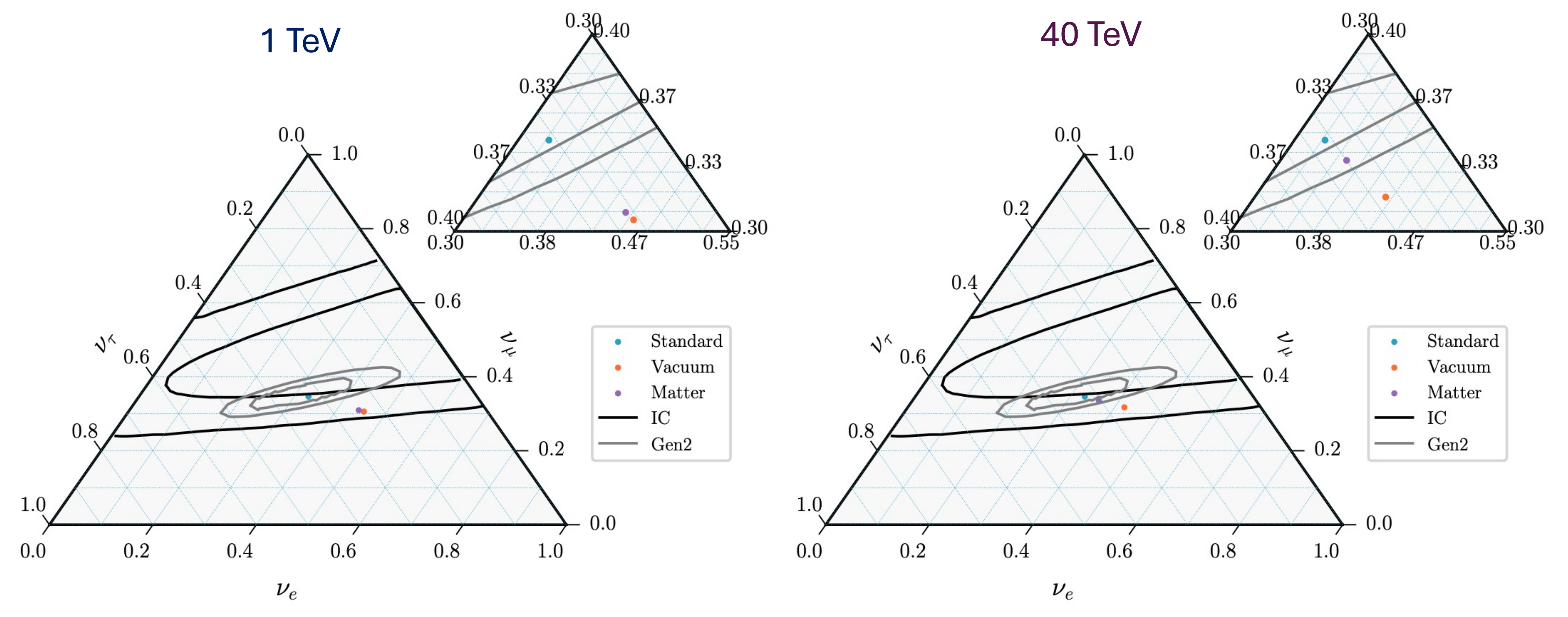


Carloni, Martinez-Soler, Arguelles, Babu, BD, 2212.00737 (PRDL)

Energy-dependent Flavor Triangles

CvB matter effect: $V_{\nu_\alpha} = \sqrt{2} G_F (1 + \delta_{\alpha\beta})(n_{\nu_\beta} - n_{\bar{\nu}_\beta})$ Notzold, Raffelt (NPB '88)

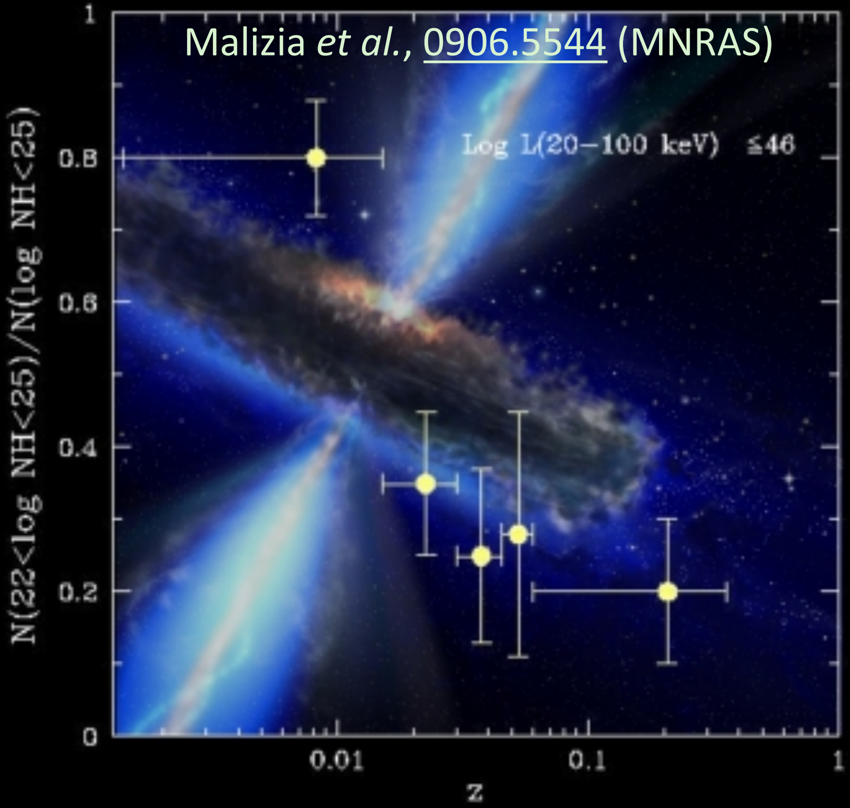
$$P_{\alpha\beta} = \frac{1}{2} \sum_j |U_{\alpha j}|^2 |U_{\beta j}|^2 \left[1 + \cos 2\widetilde{\theta}_j^i \cos 2\widetilde{\theta}_j^f \cos\left(\frac{\delta m_j^2 L_{\text{eff}}}{4E_\nu} \right) + \sin 2\widetilde{\theta}_j^i \sin 2\widetilde{\theta}_j^f \cos\left(\int dx \frac{\delta \widetilde{m}_j^2}{4E_\nu} + \frac{\delta m_j^2 L_{\text{eff}}}{4E_\nu} \right) \right].$$



BD, Machado, Martinez-Soler, 2406.18507

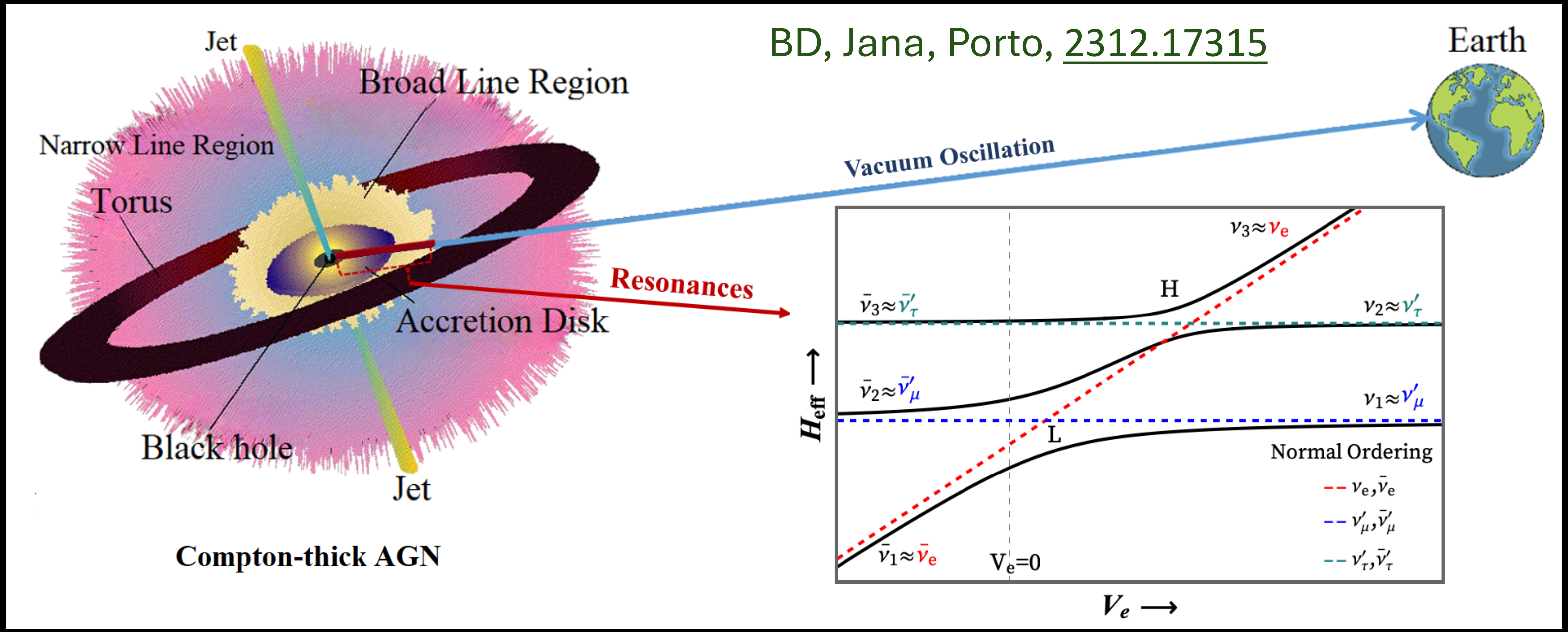
MSW Resonance in Hidden Neutrino Sources

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



Malizia *et al.*, 0906.5544 (MNRAS)

- Roughly one in four AGNs is Compton thick.
- Maybe the reason why most of the HEN sources are unknown.



BD, Jana, Porto, 2312.17315

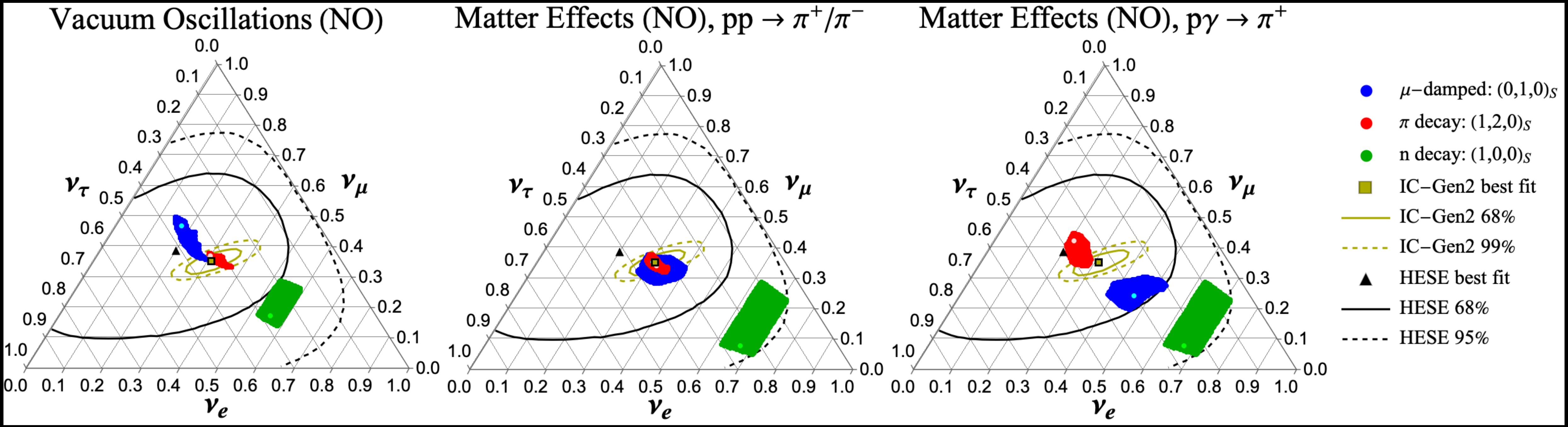
- Neutrinos from Compton-thick AGNs *must* undergo source matter effect.
- Resonant flavor conversion, analogous to the supernova case.

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

Dighe, Smirnov, 9907423 (PRD)

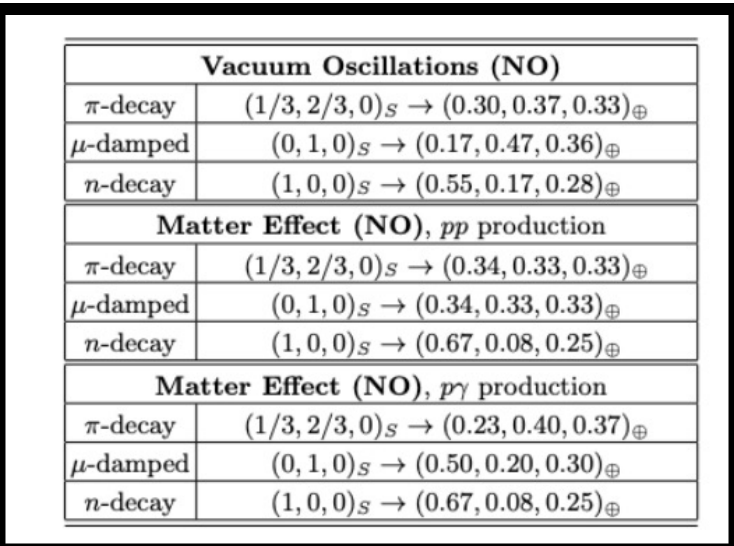
Can drastically change the flavor composition of HENs.

Flavor Matters but Matter Flavors HENs


Vacuum Oscillations (NO)

Matter Effects (NO), pp → π^+/π^-

Matter Effects (NO), pγ → π^+



Vacuum Oscillations (NO)	
π-decay	$(1/3, 2/3, 0)_S \to (0.30, 0.37, 0.33)_\oplus$
μ-damped	$(0, 1, 0)_S \to (0.17, 0.47, 0.36)_\oplus$
n-decay	$(1, 0, 0)_S \to (0.55, 0.17, 0.28)_\oplus$
Matter Effect (NO), pp production	
π-decay	$(1/3, 2/3, 0)_S \to (0.34, 0.33, 0.33)_\oplus$
μ-damped	$(0, 1, 0)_S \to (0.34, 0.33, 0.33)_\oplus$
n-decay	$(1, 0, 0)_S \to (0.67, 0.08, 0.25)_\oplus$
Matter Effect (NO), $p\gamma$ production	
π-decay	$(1/3, 2/3, 0)_S \to (0.23, 0.40, 0.37)_\oplus$
μ-damped	$(0, 1, 0)_S \to (0.50, 0.20, 0.30)_\oplus$
n-decay	$(1, 0, 0)_S \to (0.67, 0.08, 0.25)_\oplus$

BD, Jana, Porto, 2312.17315

- Might be the *only* way to probe heavily Compton-thick neutrino sources with no electromagnetic counterparts.
- Important implications for modeling of cosmic *X*-ray background, black hole growth and galaxy evolution.

GW170817: Another Multi-Messenger Frontier

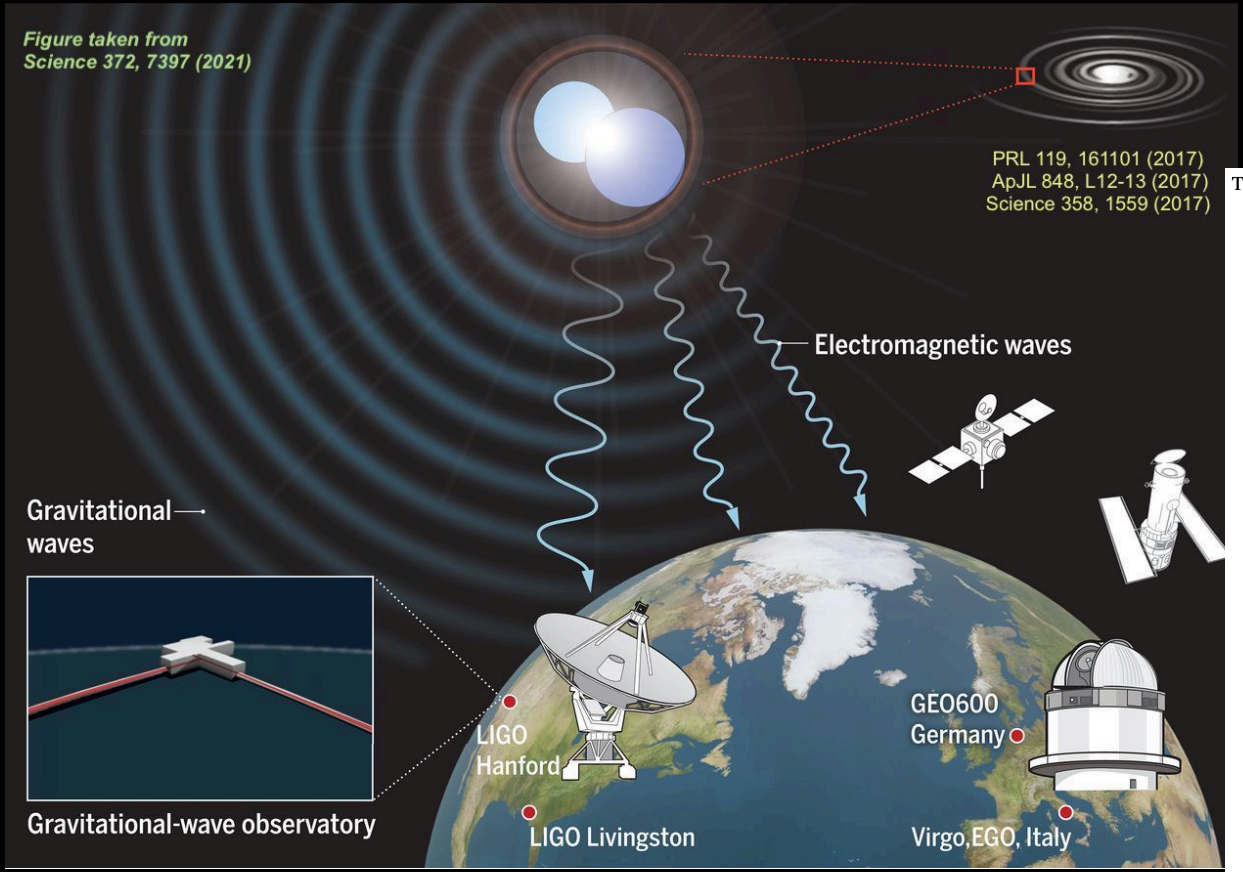
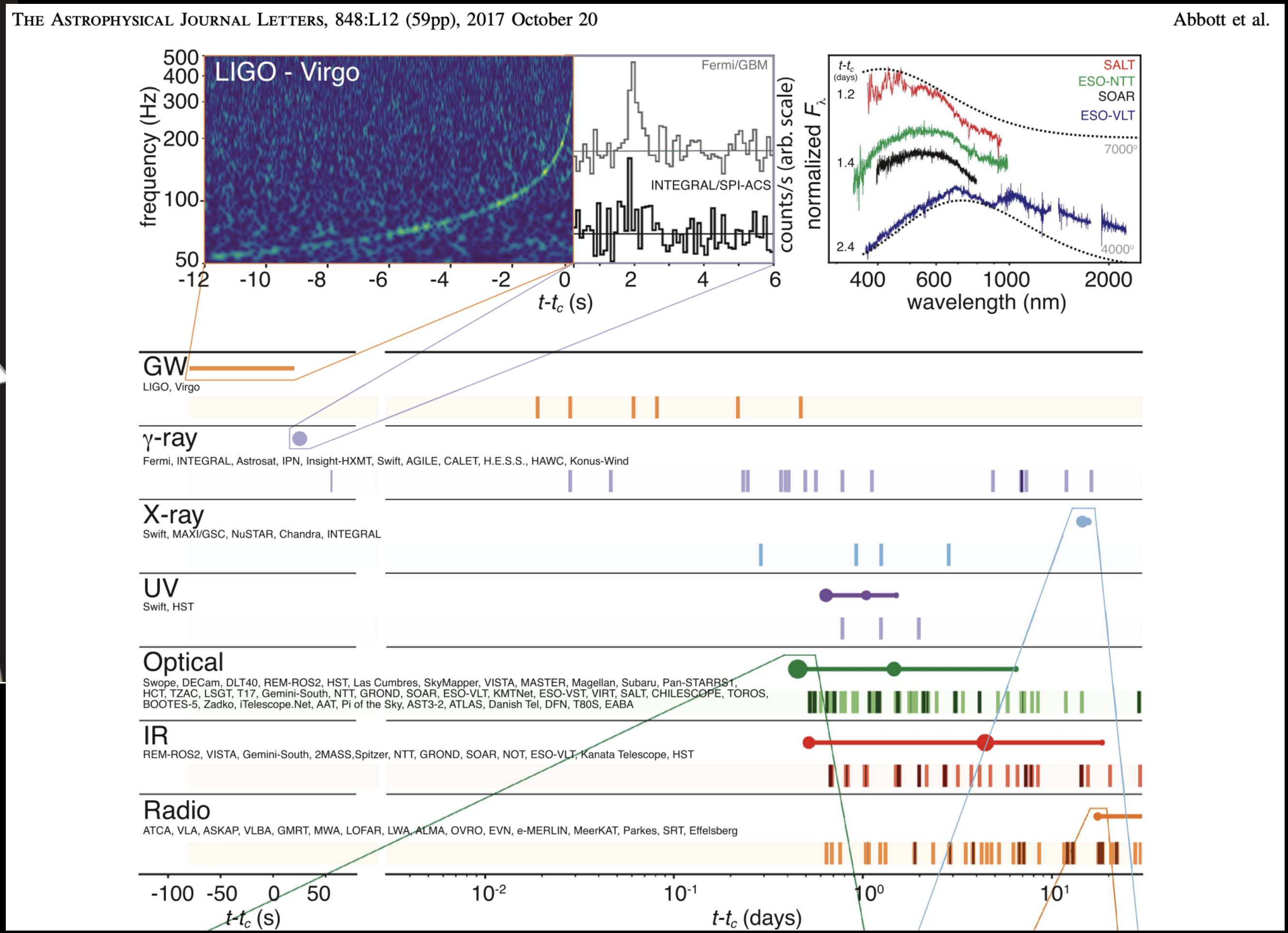


Figure taken from
Science 372, 7397 (2021)

PRL 119, 161101 (2017)
ApJL 848, L12-13 (2017)
Science 358, 1559 (2017)



The Astrophysical Journal Letters, 848:L12 (59pp), 2017 October 20 Abbott et al.

ALP Searches with NS Mergers

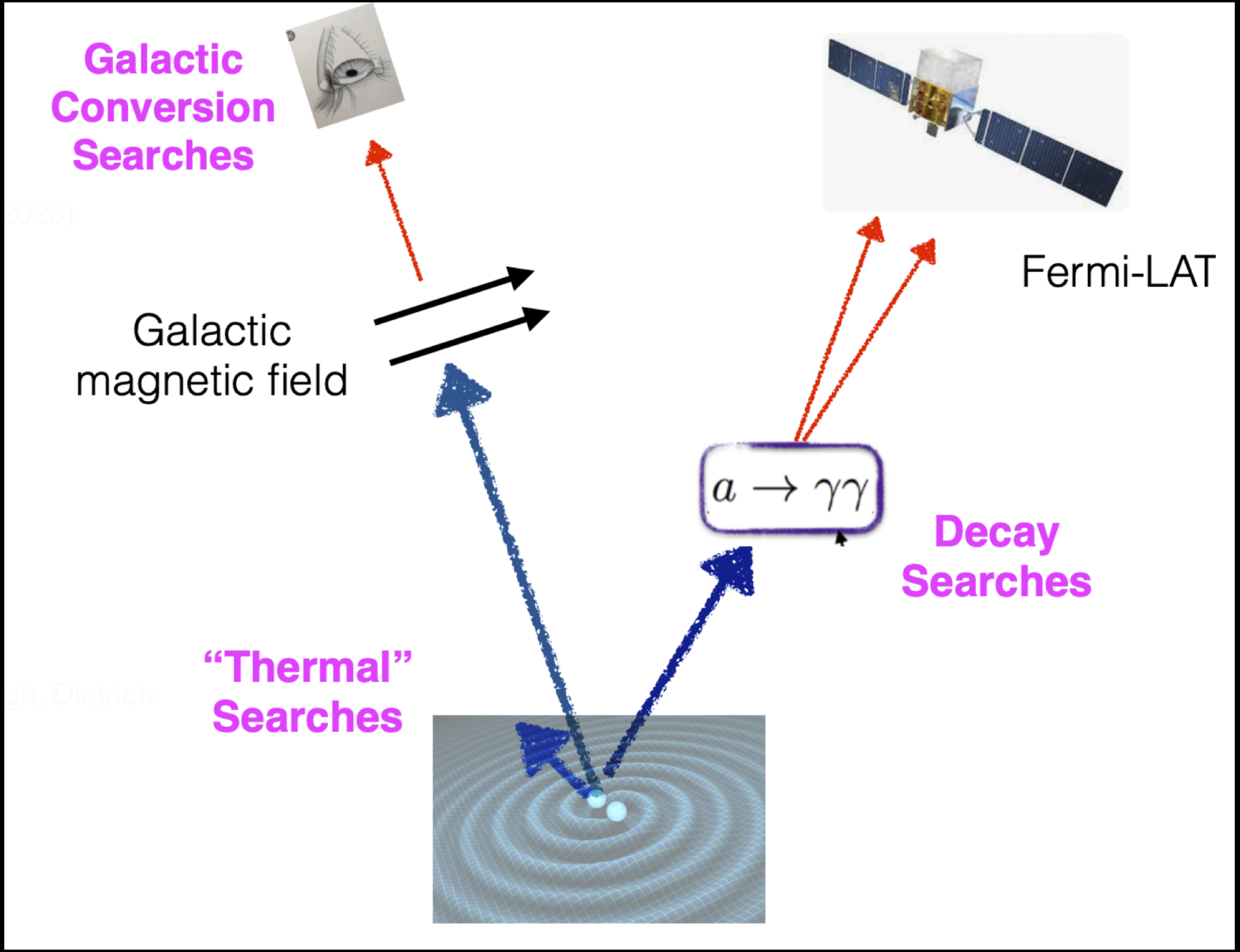
$$\mathcal{L} \supset \frac{1}{2}\partial^\mu a \partial_\mu a - \frac{1}{2} m_a^2 a^2 - \frac{1}{4} g_{a\gamma\gamma} a F^{\mu\nu} \widetilde{F}_{\mu\nu}$$

Fiorillo, Iocco, 2109.10364 (PRD)

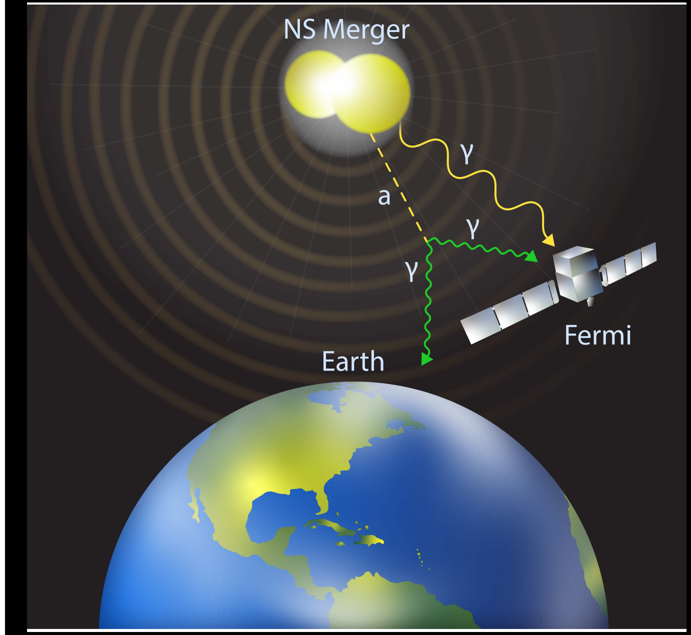
For small ALP mass (below neV)

Dietrich, Clough, 1909.01278 (PRD); Harris, Fortin, Sinha, Alford, 2003.09768 (JCAP)

Negligible effect

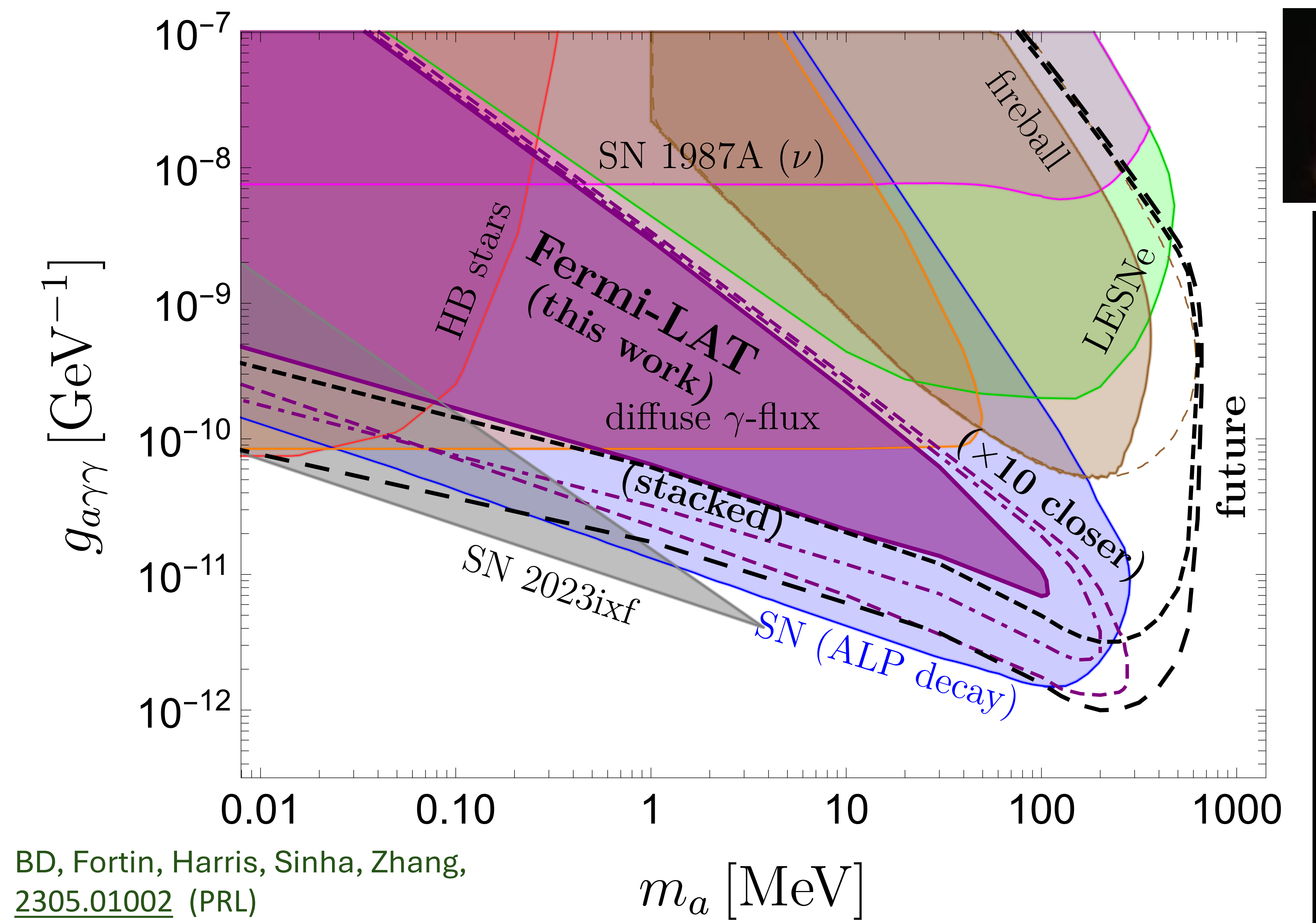


Multi-messenger connection

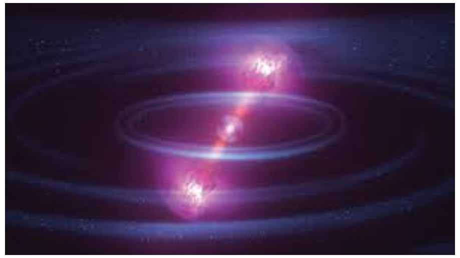


BD, Fortin, Harris, Sinha, Zhang, 2305.01002 (PRL);
Diamond, Fiorillo, Marques-Tavares, Tamborra, Vitagliano, 2305.10327 (PRL)

Supernova vs NS Merger: Which is Better?

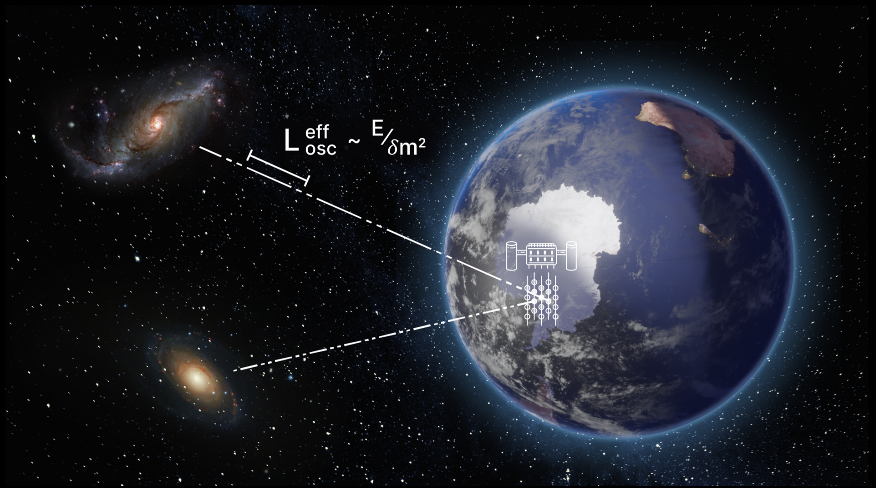


BD, Fortin, Harris, Sinha, Zhang, 2305.01002 (PRL)



- NS merger can reach slightly higher core temperature (40-100 MeV vs 30 MeV for SN).
- SN1987A was 1000 times closer than GW170817.
- Rate of GW-observable NS mergers is higher (10-1700/Gpc^3/yr) than that of local, neutrino-observable SN (~1/50 yr).
- Both can give excellent timing information with early-warning system (AMON/SNEWS).

Conclusions



- An exciting era of Multi-messenger Astronomy.
- Great for *both* Astrophysics and Particle Physics.
- Multi-messenger probes of (B)SM Physics, e.g.
  - Decaying Dark Matter
  - Resonances (ρ meson, new scalars/vectors)
  - New Matter Effects
  - Nature of Neutrino Mass
  - Light Mediators (ALPs, dark photons, Z',…)
- New windows of opportunity into the BSM world.