Probing BSM Physics with Multi-Messenger Astronomy

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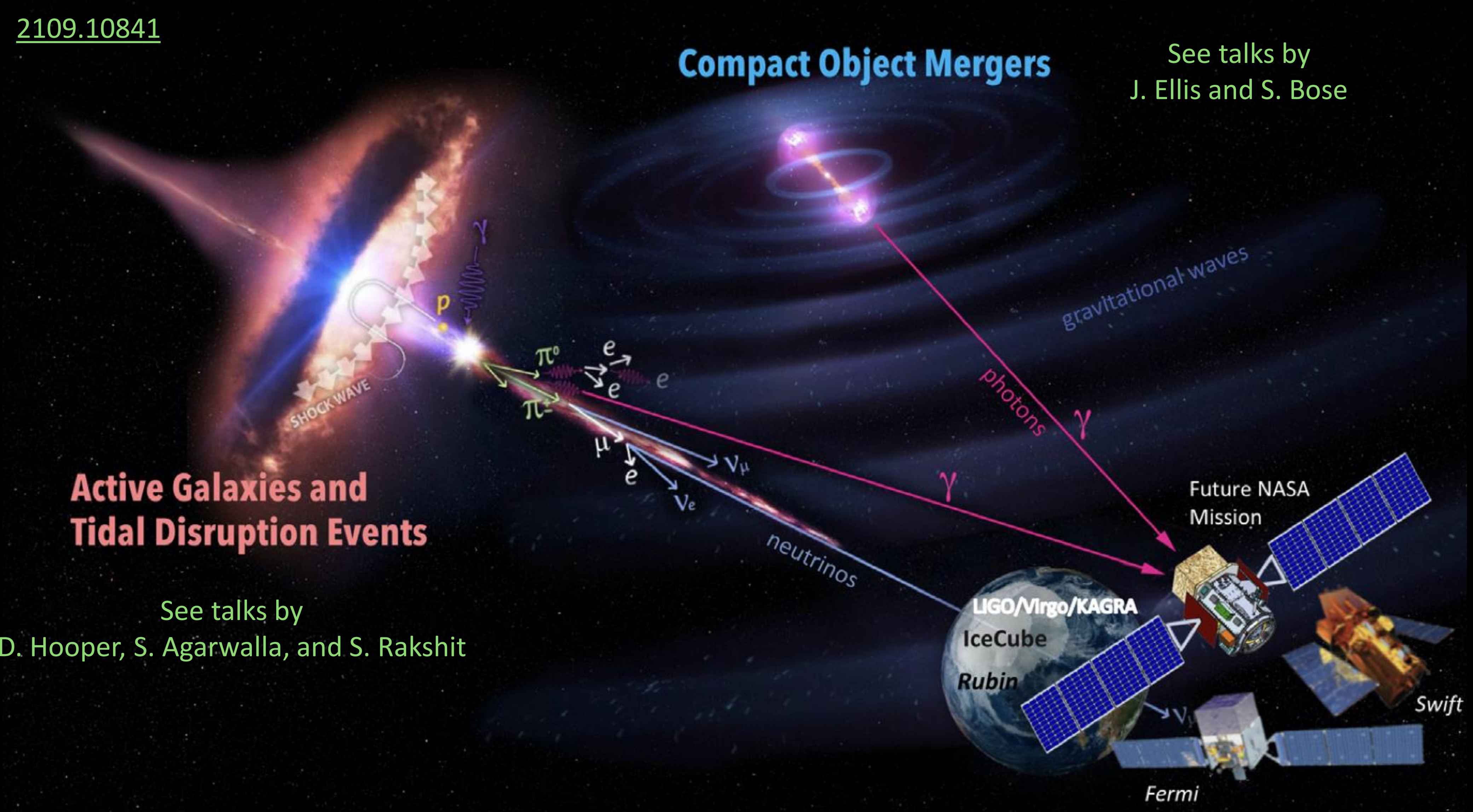
A New Era of Multi-Messenger Astronomy

2109.10841

See talks by
J. Ellis and S. Bose



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

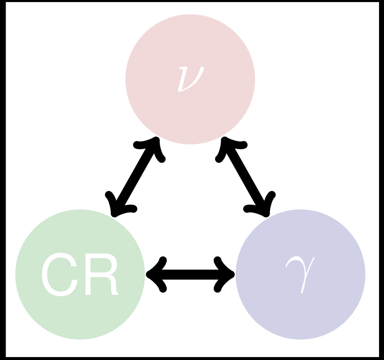
Great news for *both* Astrophysics and Particle Physics.

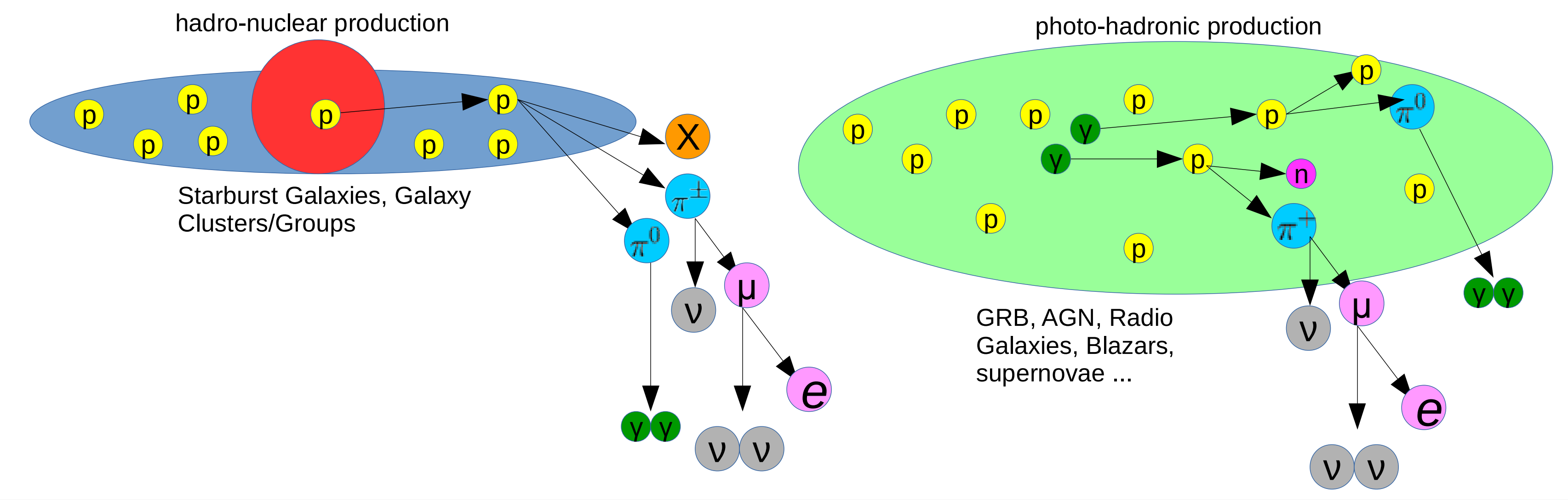
Outline

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

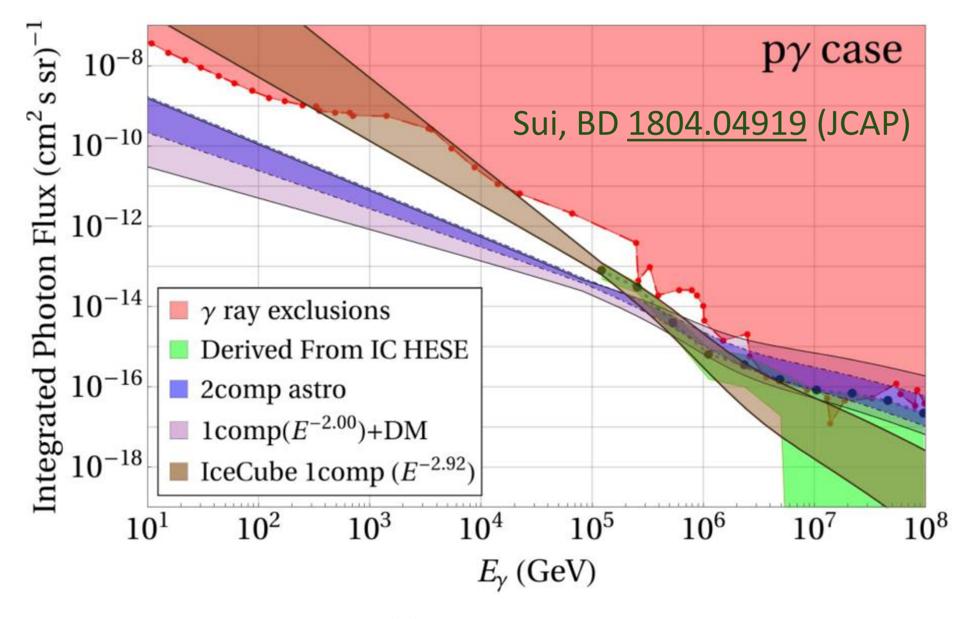




$$E_\gamma^2\Phi_\gamma \simeq \frac{4}{K}E_\nu^2\frac{\Phi_{(\nu+\bar{\nu})\mathrm{tot}}}{3}\Bigg|_{E_\nu=0.5E_\gamma}$$

Meszaros 1708.03577 (ARNPS)

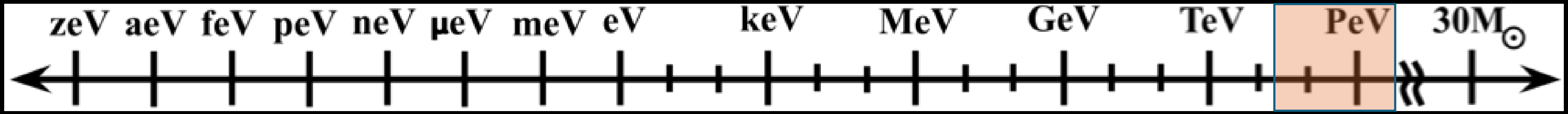
- IceCube best-fit in tension with gamma-ray constraints.
- **Alternatives:** Broken power-law, 2-component flux, neutrinophilic BSM contribution

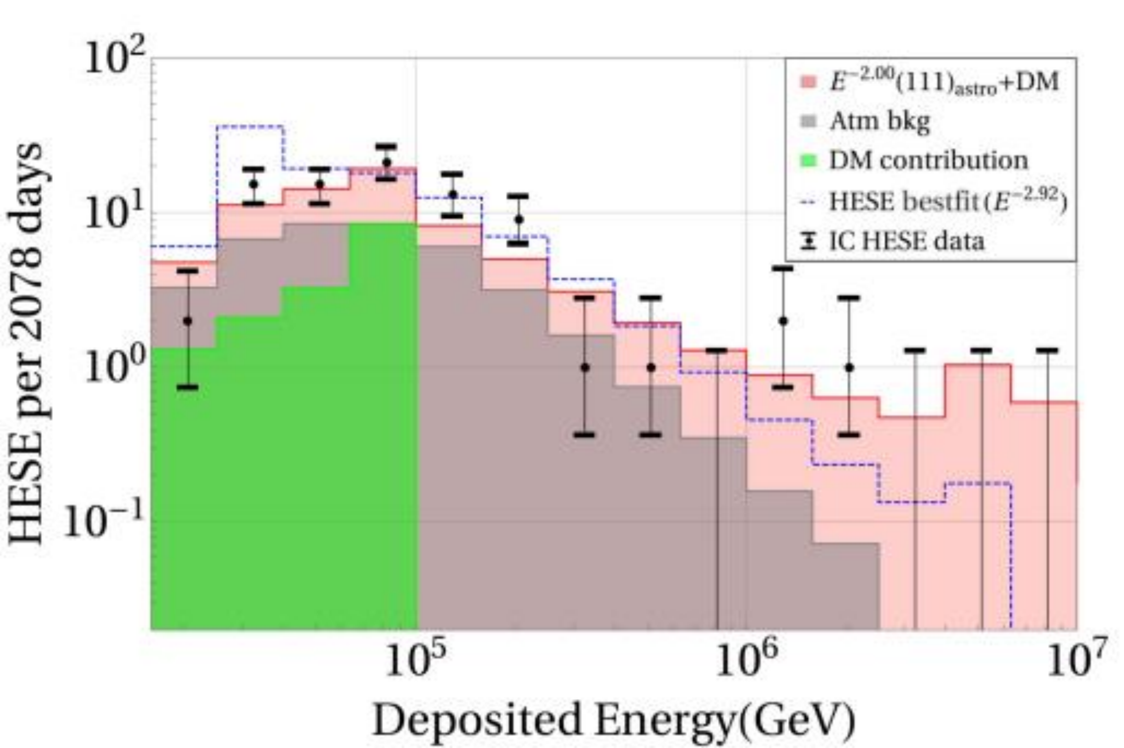


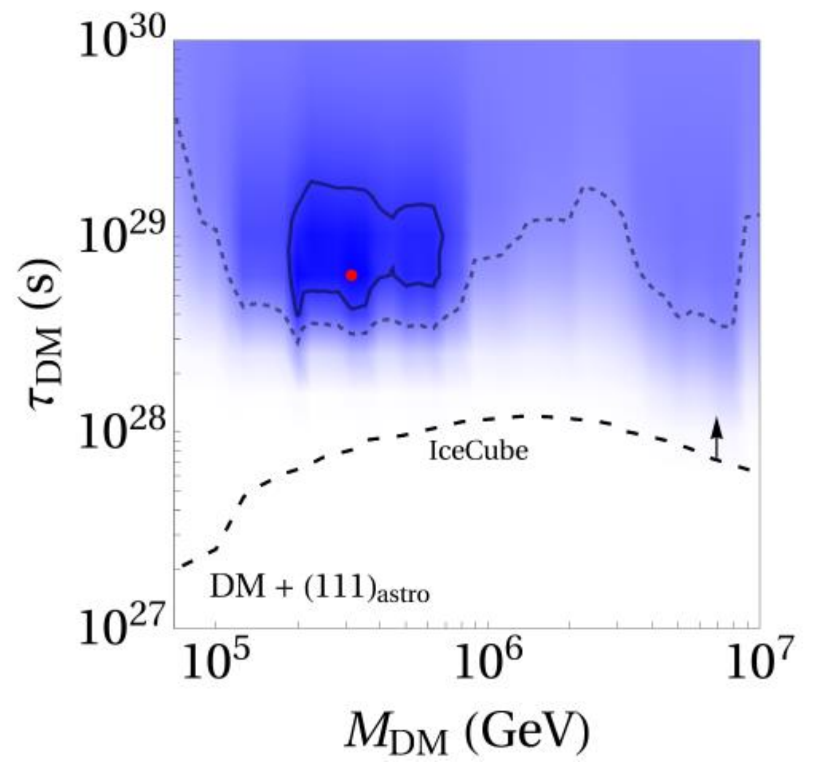
Sui, BD 1804.04919 (JCAP)

(a) $K = 1$ case

Decaying Heavy Dark Matter





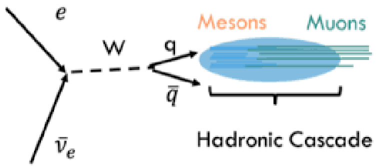


Mild preference for a decaying dark matter component over purely astrophysical unbroken power-law flux

Sui, BD 1804.04919 (JCAP)

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

New SM Resonances with UHE Neutrinos



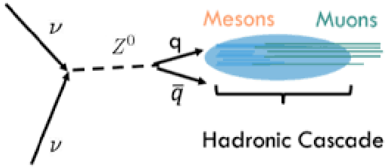
[Glashow (Phys. Rev. '60)]

Glashow resonance

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

Recently observed by IceCube

[Nature 591, 220 (2021)]



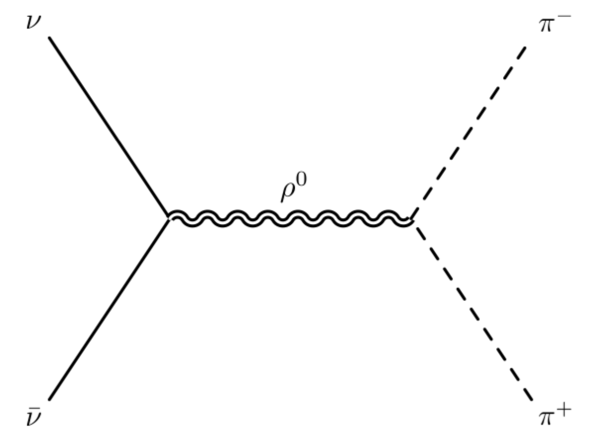
[Weiler (PRL '82)]

***Z*-burst**

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

Beyond GZK cutoff

Unlikely to be seen

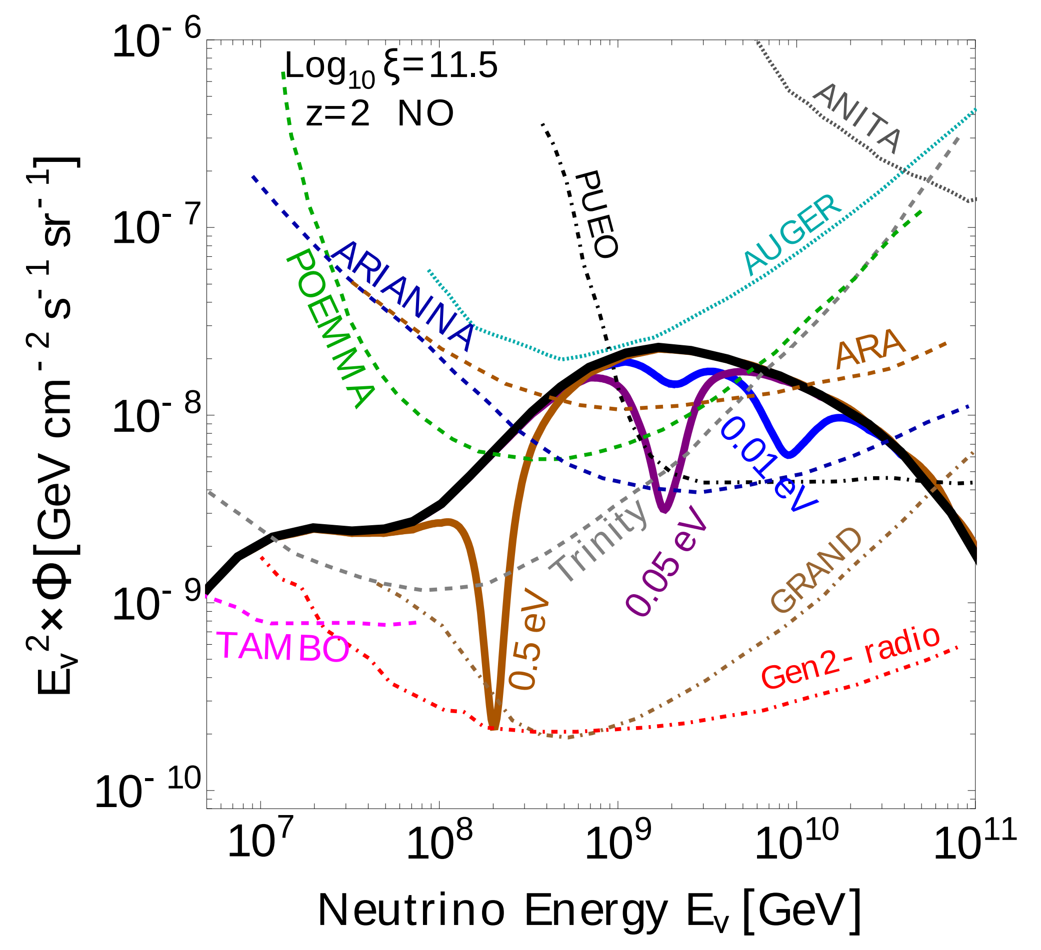


(Axial) vector meson resonance

Paschos, Lalakulich 0206273;
BD, Soni 2112.01424

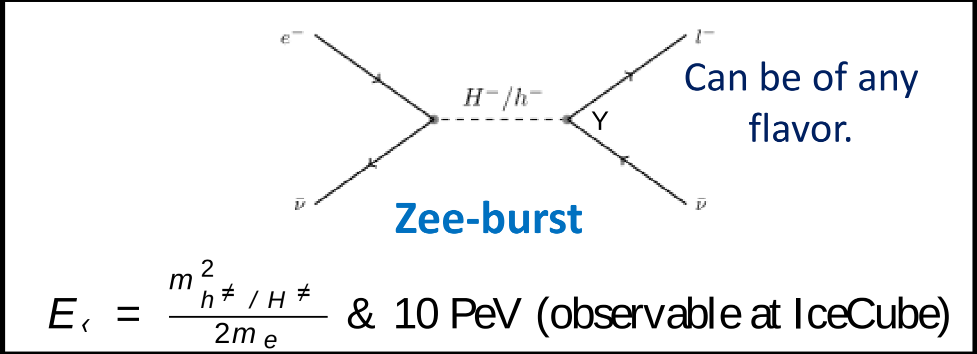
$$E_\nu^{\mathrm{res}} = \frac{m_\rho^2}{2m_\nu(1+z)} = \frac{(3.0\times 10^{18}\ \mathrm{eV})}{(1+z)}^{1}\ \frac{0.1\ \mathrm{eV}}{m_\nu}^{2}$$

Accessible at neutrino telescopes!



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

New BSM Resonances with UHE Neutrinos



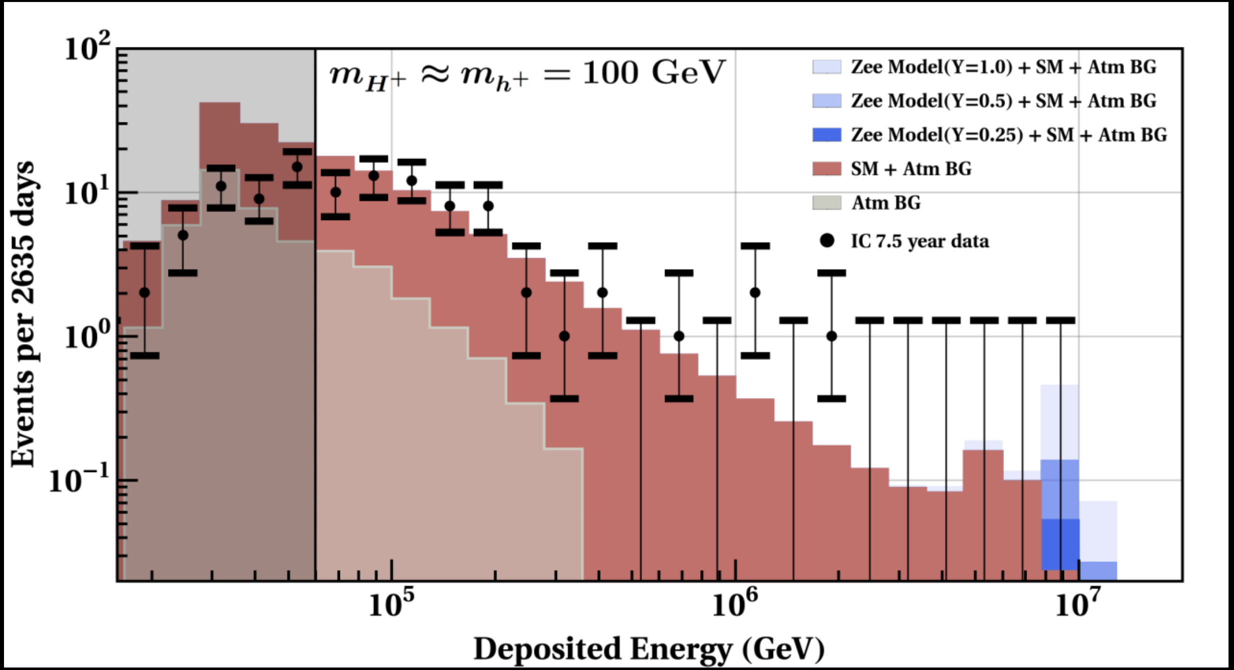
Can be of any flavor.

Zee-burst

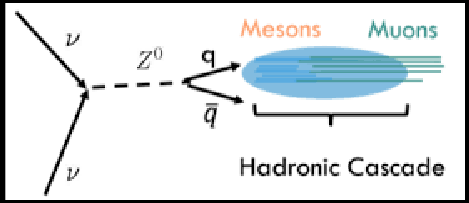
$E_\nu = \frac{m^2_{h^\pm/H^\pm}}{2m_e} \simeq 10$ PeV (observable at IceCube)

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

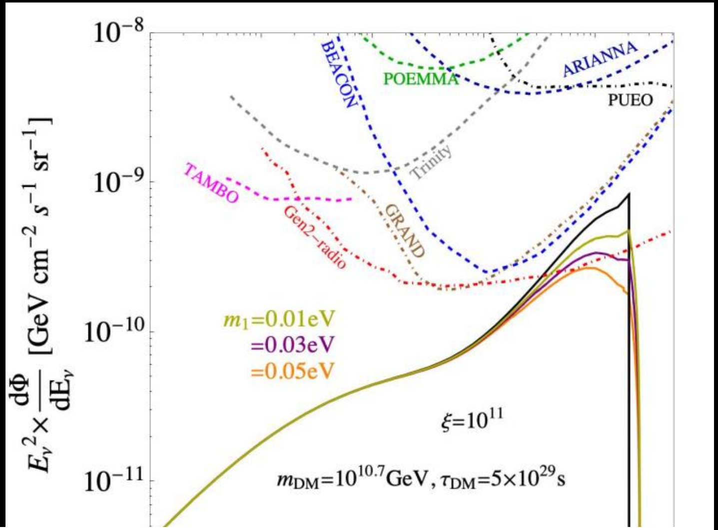
A. Zee (PLB '80)

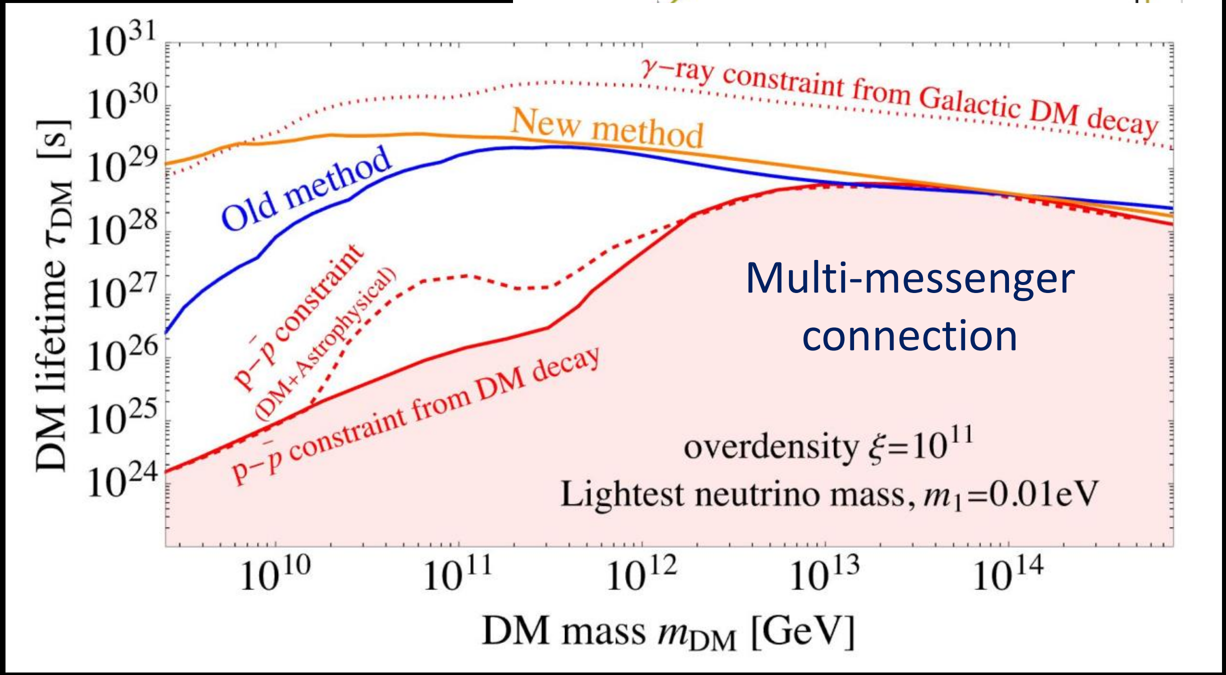


Babu, BD, Jana, Sui 1908.02779 (PRL)



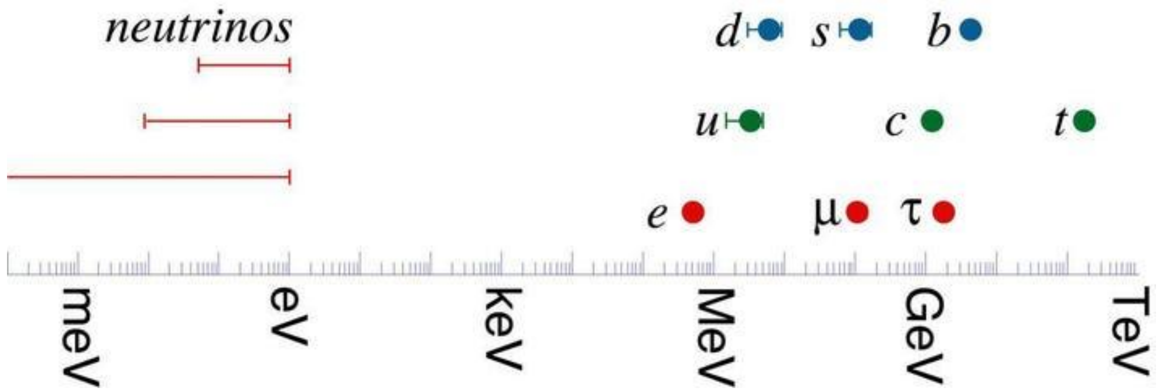
DM decay-induced *Z*-burst (or ρ-burst)





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

Probing the Nature of Neutrino Mass

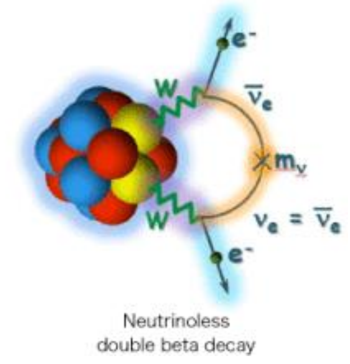


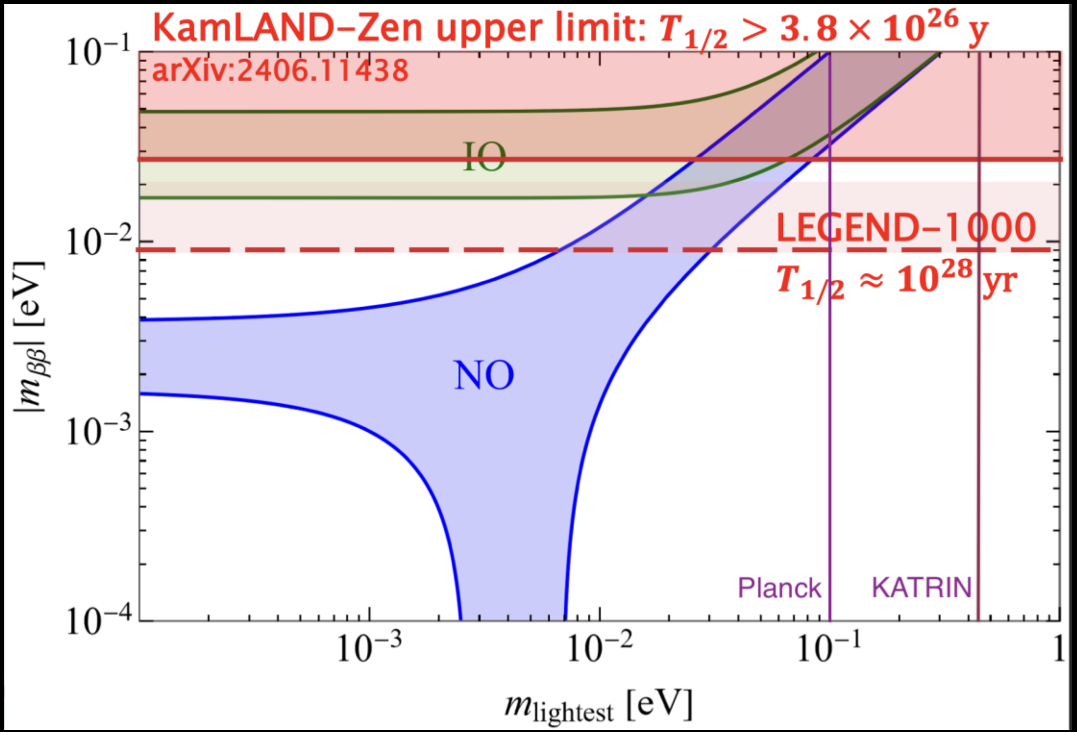
Perhaps something beyond the standard Higgs mechanism?

See talk by S. Goswami

Majorana or Dirac (or something in between)?

Only experiments can tell.





- 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]

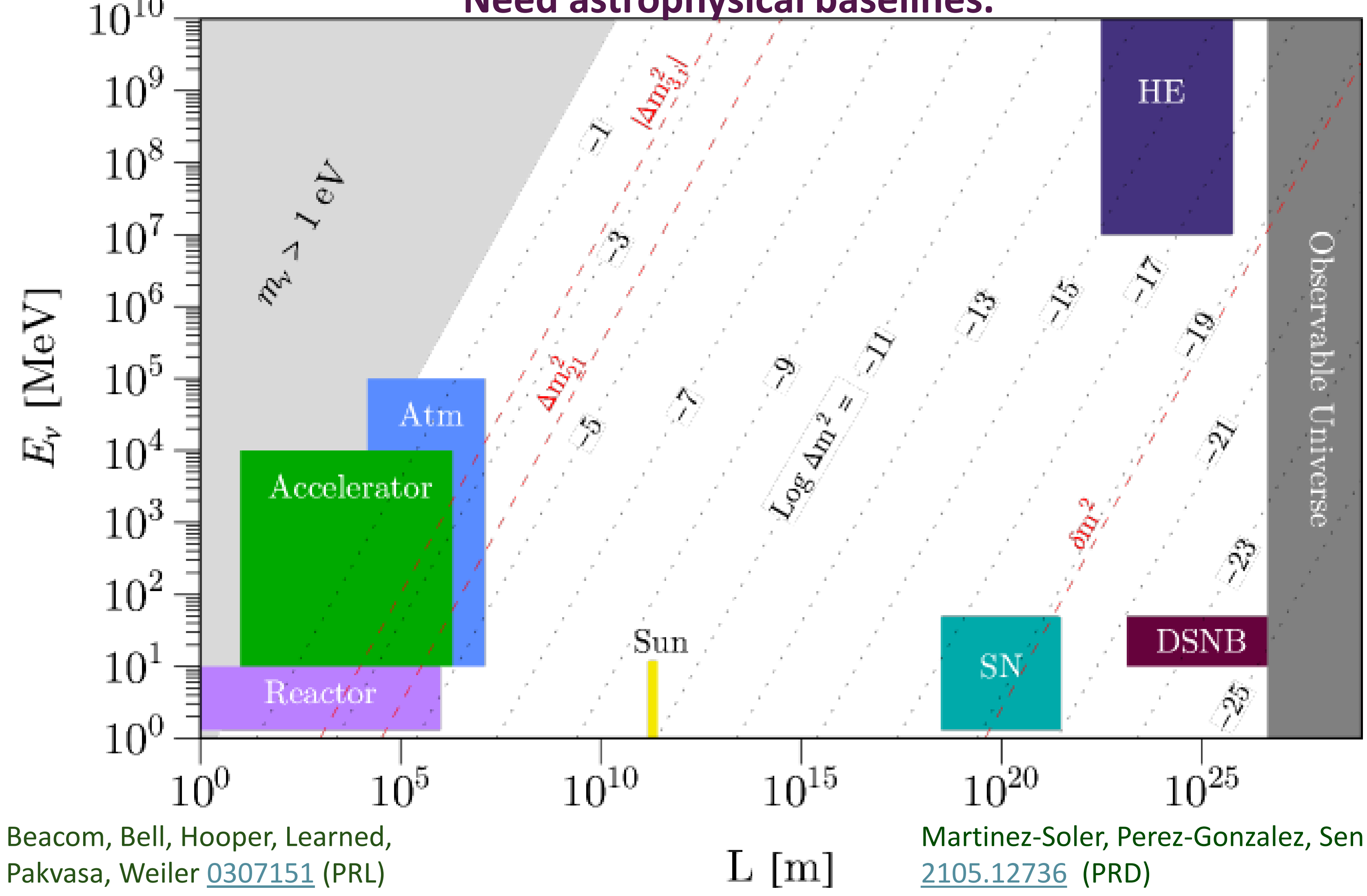
- Maybe, but $||M_R|| \ll ||m_D||$ is a logical possibility too.

[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 $\delta m^2 L/E \sim 1$.

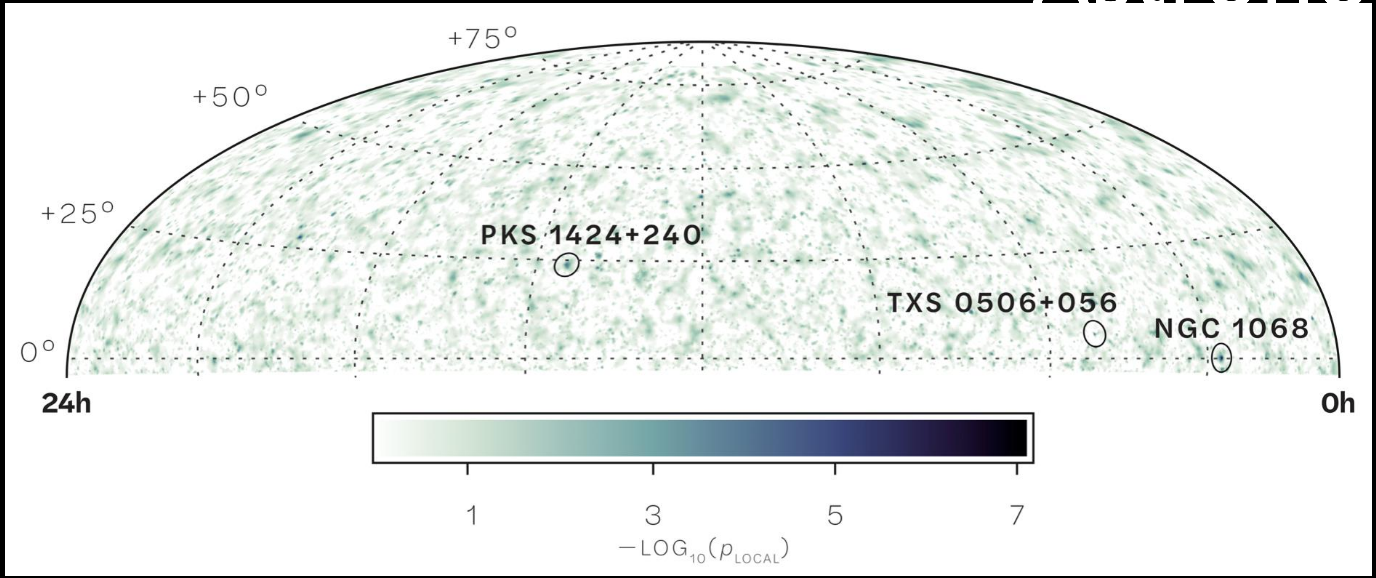


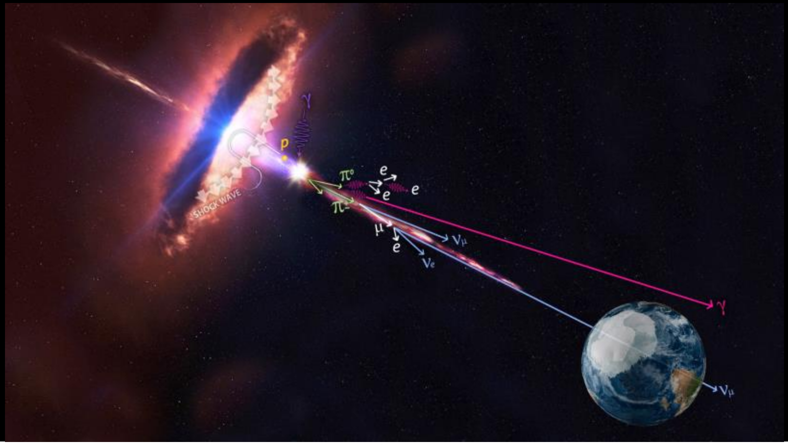
Need astrophysical baselines.

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

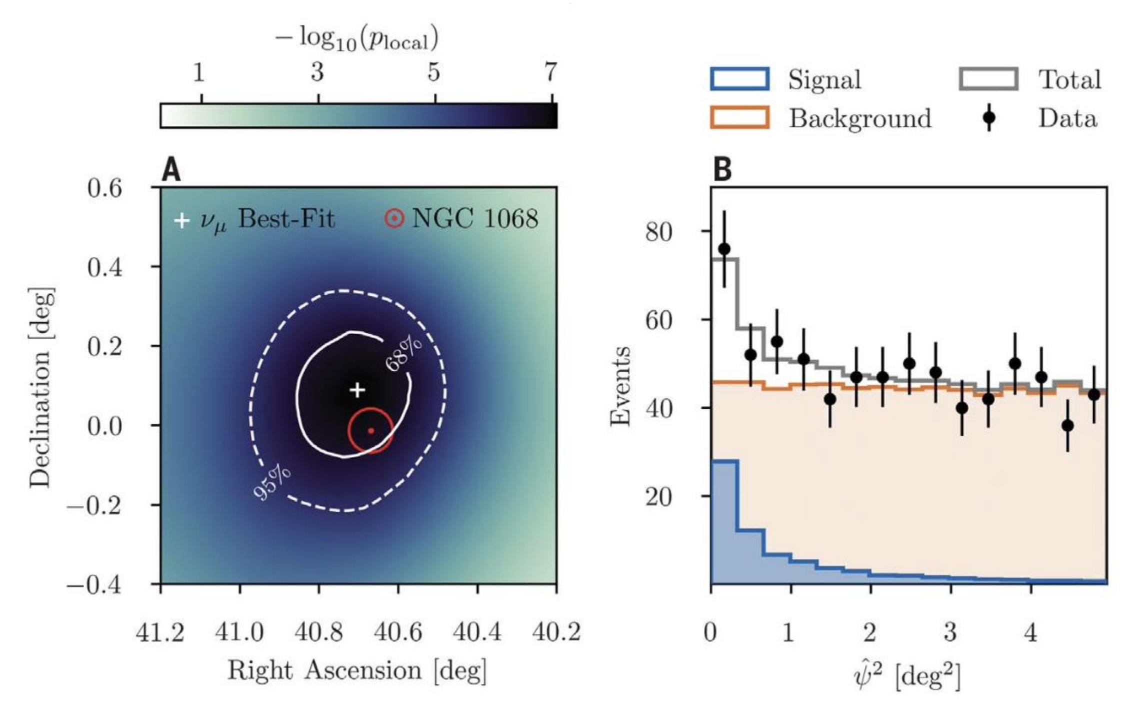
Martinez-Soler, Perez-Gonzalez, Sen 2105.12736 (PRD)

Here comes Multi-Messenger Neutrino Astronomy



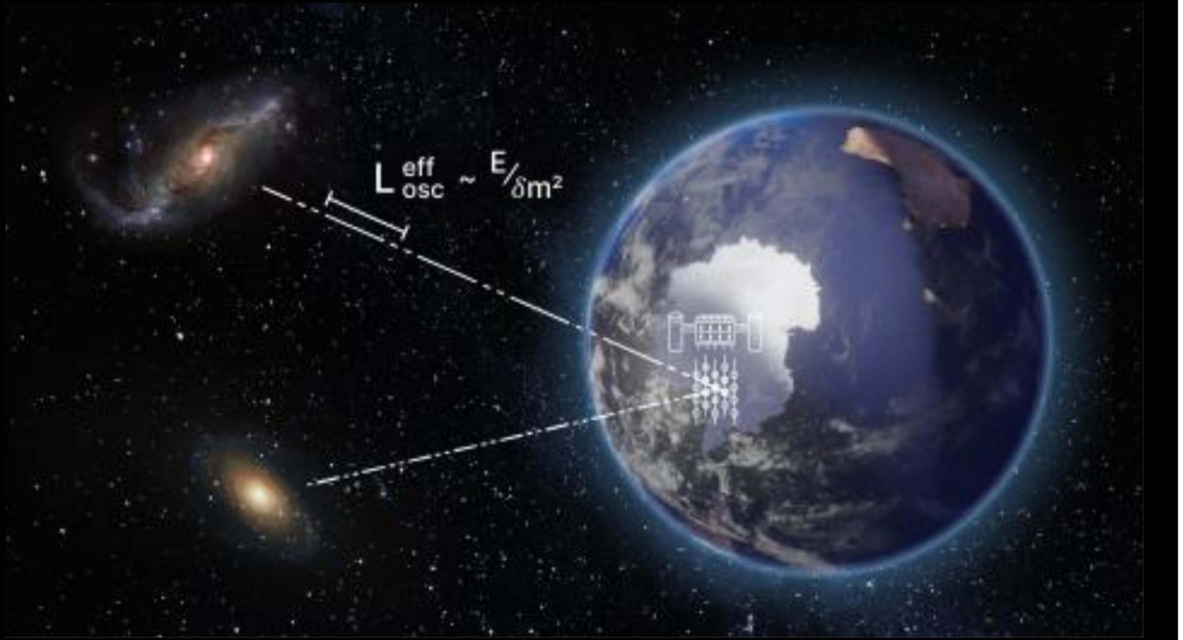


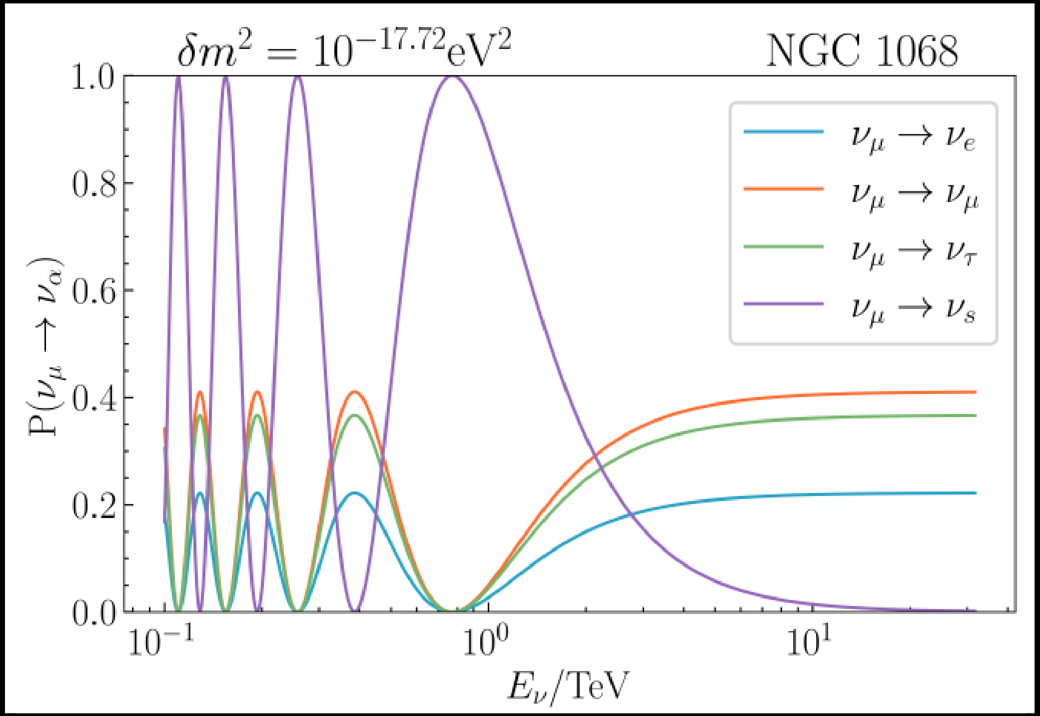
Source Name	Source Type	α [°]	δ [°]	$\hat{n}_s$	$\hat{\gamma}$	$-\log_{10} p_{\mathrm{local}}$	$\Phi_{90\%}$
NGC 1068	SBG/AGN	40.67	-0.01	79	3.2	7.0 (5.2 σ)	9.6
PKS 1424+240	BLL	216.76	23.80	77	3.5	4.0 (3.7 σ)	11.4
TXS 0506+056	BLL/FSRQ	77.36	5.70	5	2.0	3.6 (3.5 σ)	7.5



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

A New Probe of Pseudo-Dirac Neutrinos





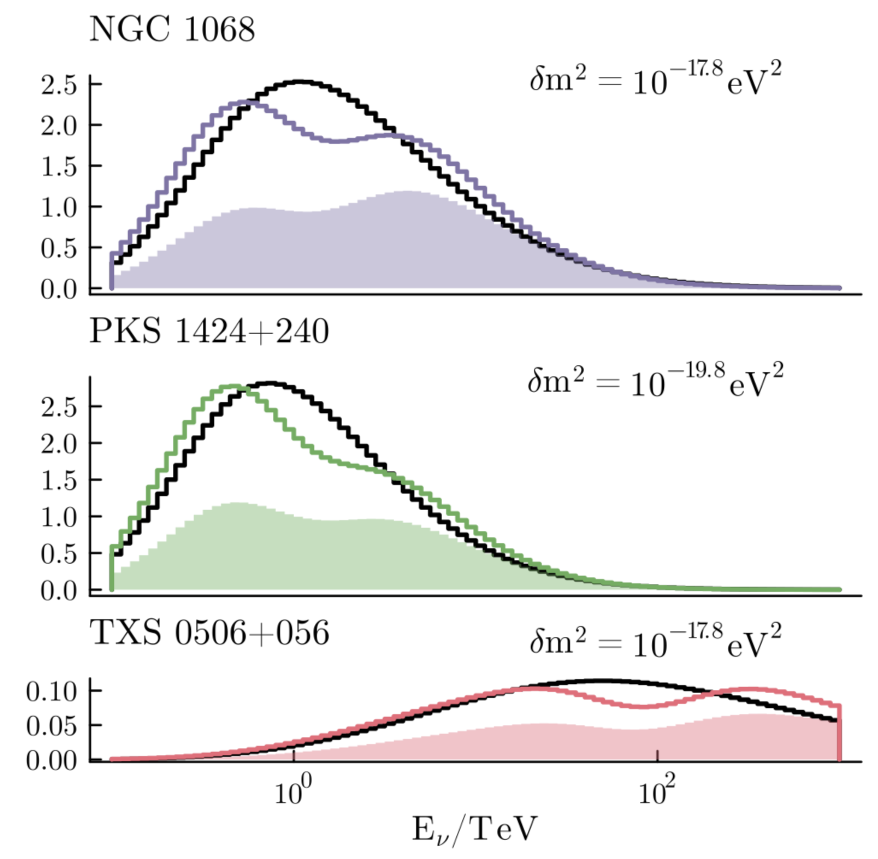
$$P_{\alpha\beta} = \frac{1}{2}\sum_{j=1}^{3} |U_{\beta j}|^2 |U_{\alpha j}|^2 \left[1 + \cos\left(\frac{\delta m_j^2 L_{\rm eff}}{2E_\nu}\right)\right],$$

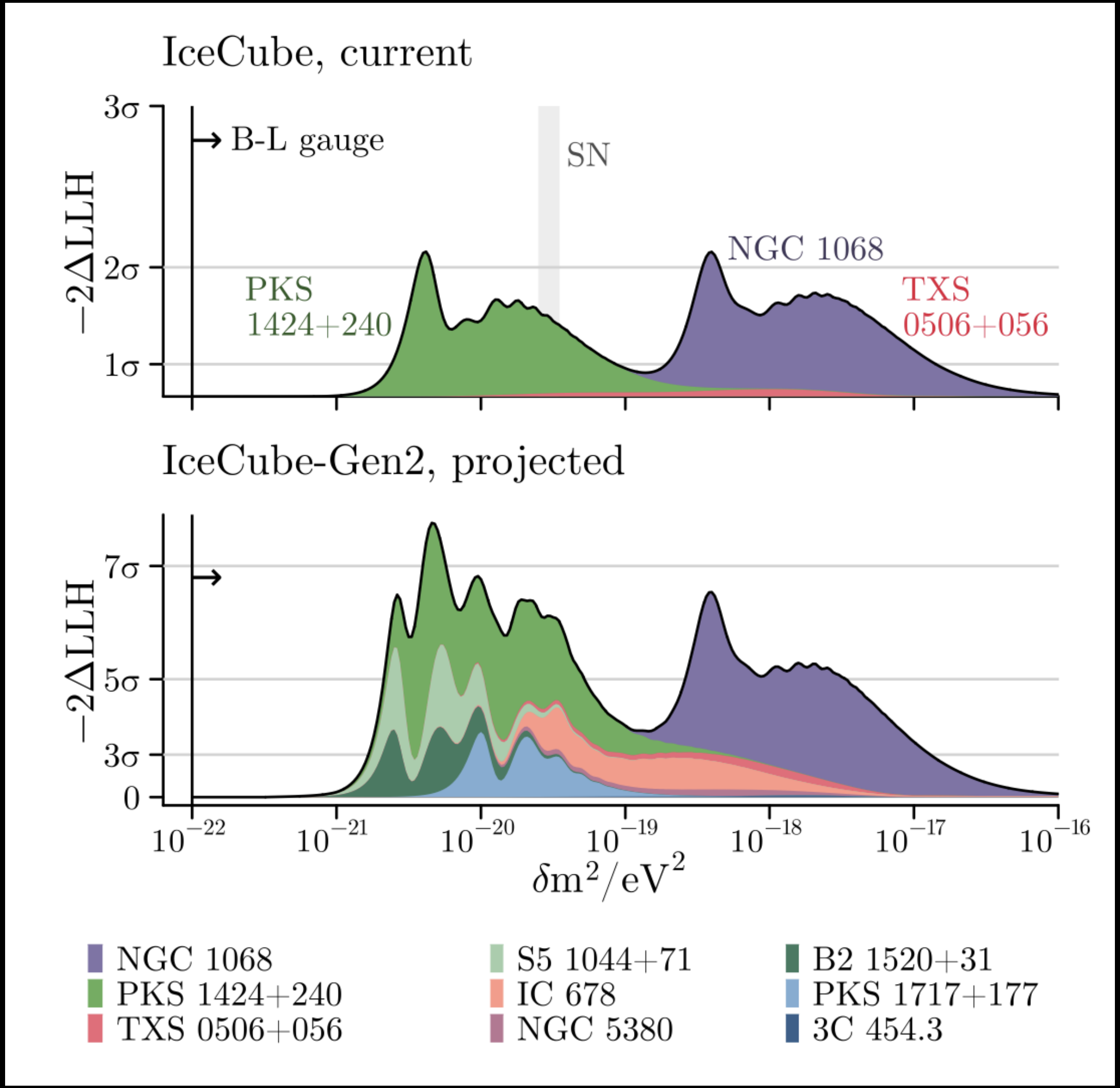
with $L_{\rm eff} = \int \frac{dz}{H(z)(1+z)^2}$ and $H(z) = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda + (1-\Omega_m-\Omega_\Lambda)(1+z)^2}$.

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

First IceCube Constraints on Pseudo-Dirac Neutrinos

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





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

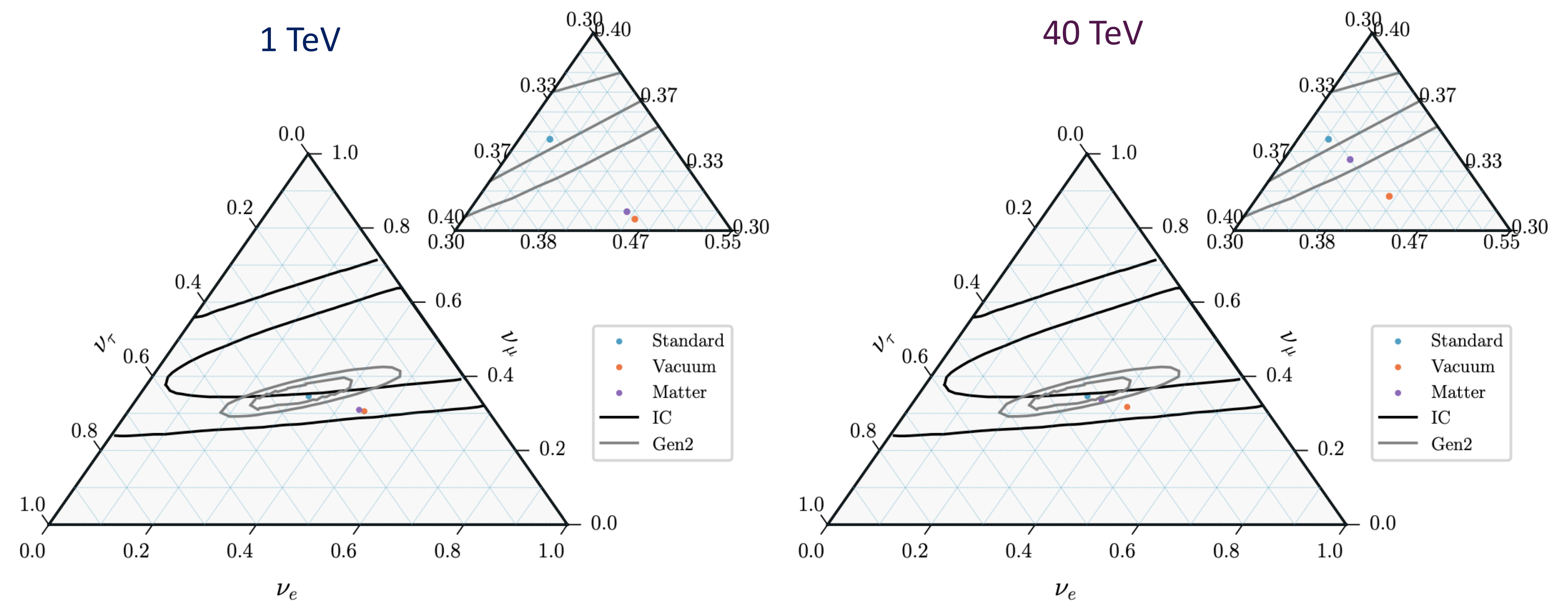
Energy-dependent Flavor Triangles

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)

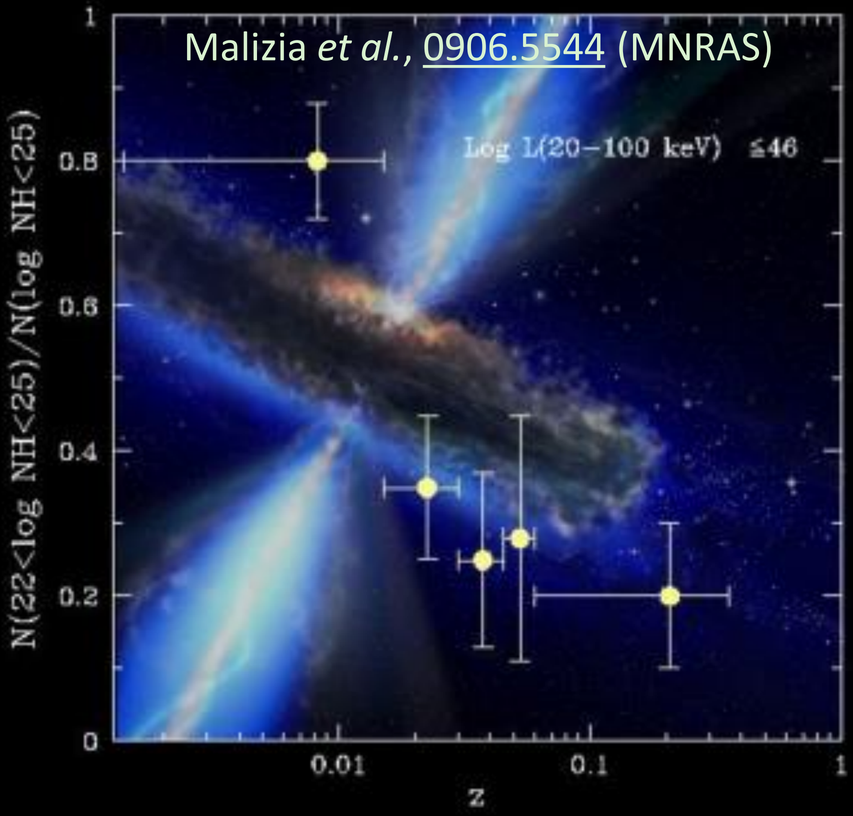
$$P_{\alpha\beta} = \frac{1}{2} \sum_j |U_{\alpha j}|^2 |U_{\beta j}|^2 \left[1 + \cos 2\widetilde{\theta}_j^i \cos 2\widetilde{\theta}_j^f \cos\left(\frac{\delta m_j^2 L_{\rm eff}}{4E_\nu} \right) + \sin 2\widetilde{\theta}_j^i \sin 2\widetilde{\theta}_j^f \cos\left(\int dx \frac{\delta \widetilde{m}_j^2}{4E_\nu}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



BD, Machado, Martinez-Soler, 2406.18507

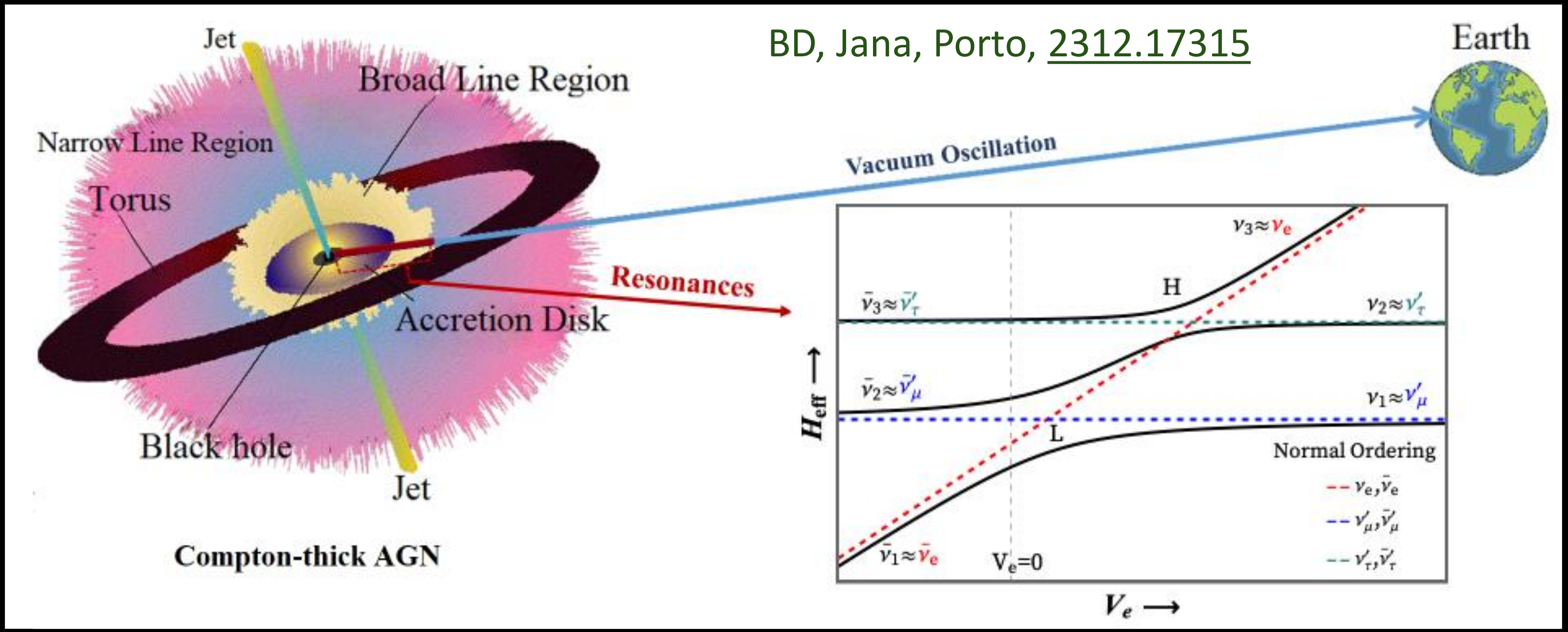
MSW Resonance in Hidden Neutrino Sources

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

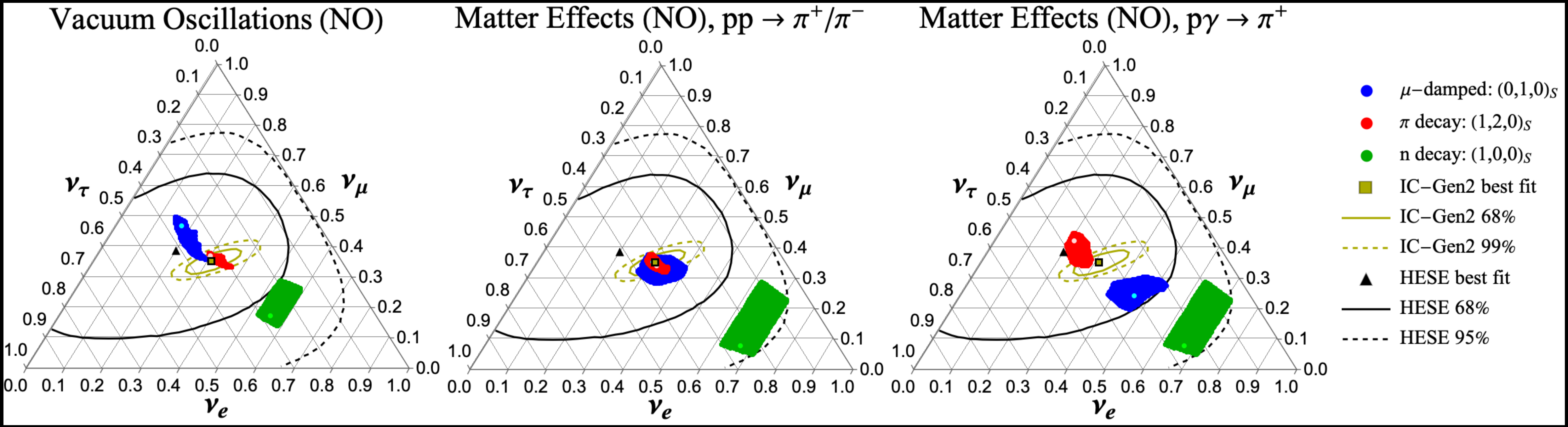
- Neutrinos from Compton-thick AGNs *must* undergo source matter effect.
- Resonant flavor conversion, analogous to the supernova case.

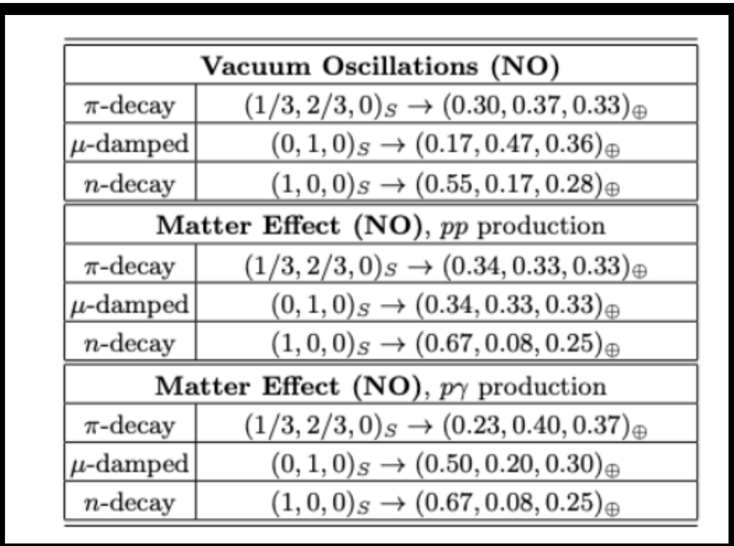
$$\sqrt{2} G_F n_e^{\rm res} = \frac{\Delta m_{i1}^2}{2E_\nu} \cos 2\theta_{1i} \,.$$

Dighe, Smirnov, 9907423 (PRD)

Can drastically change the flavor composition of HENs.

Flavor Matters but Matter Flavors HENs





Vacuum Oscillations (NO)	
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), *pγ* 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

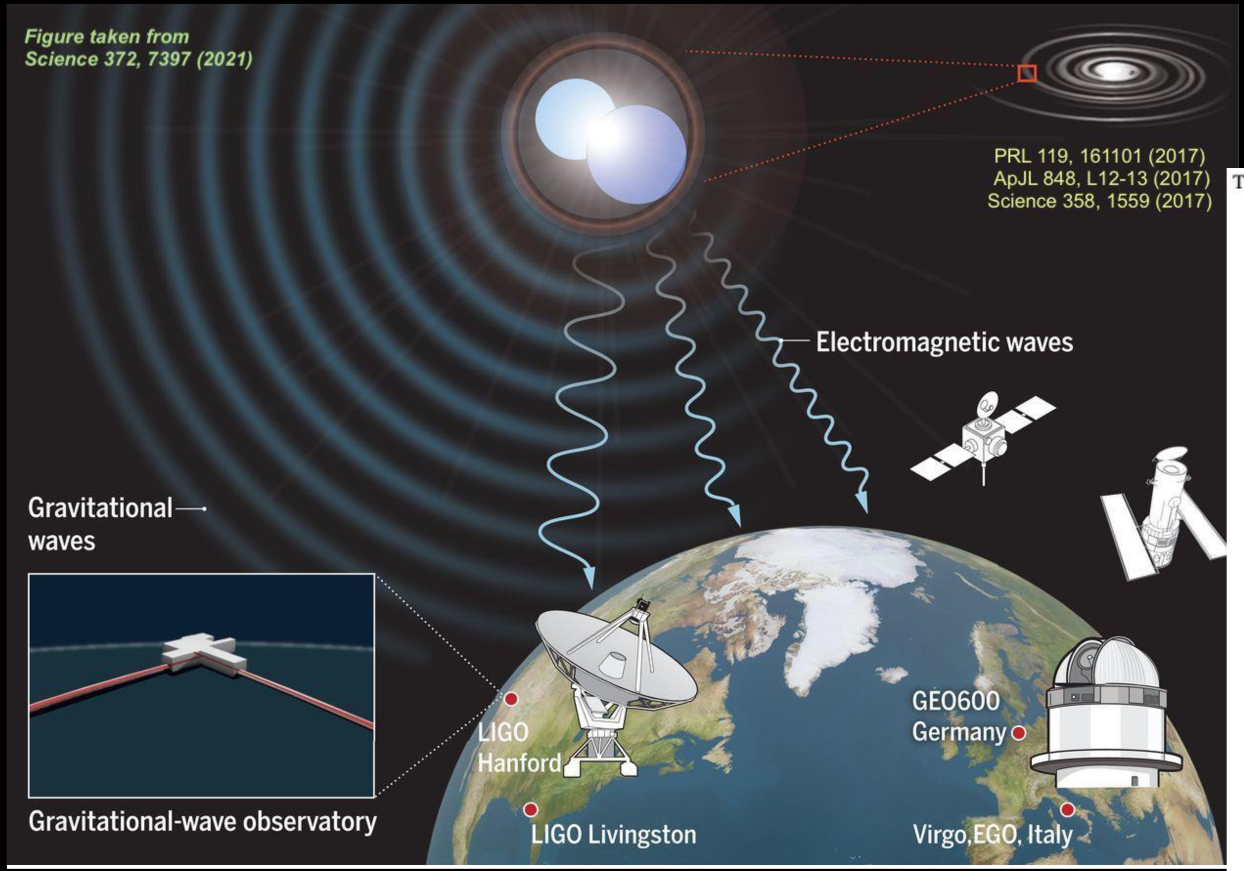
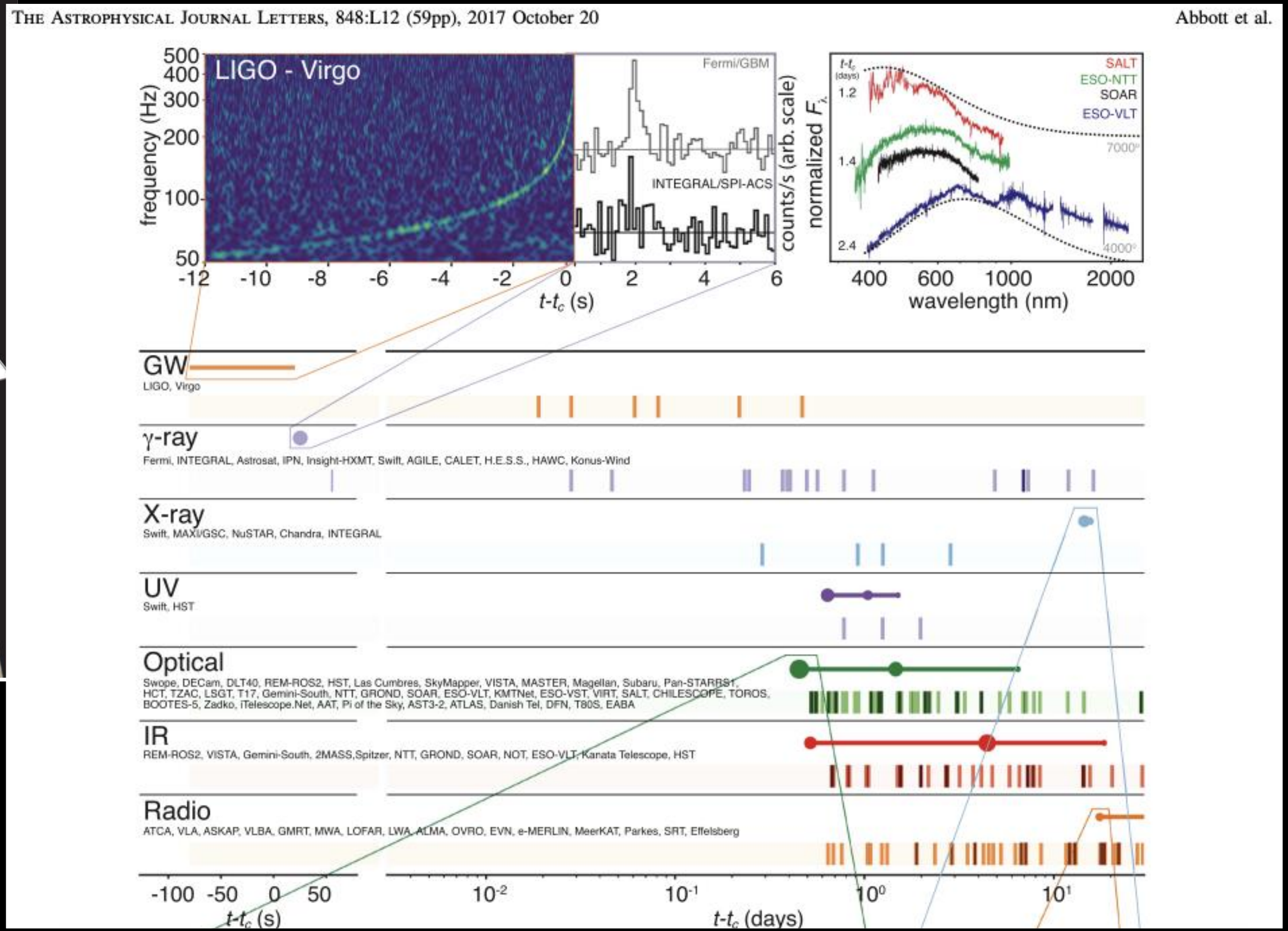


Figure taken from Science 372, 7397 (2021)

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

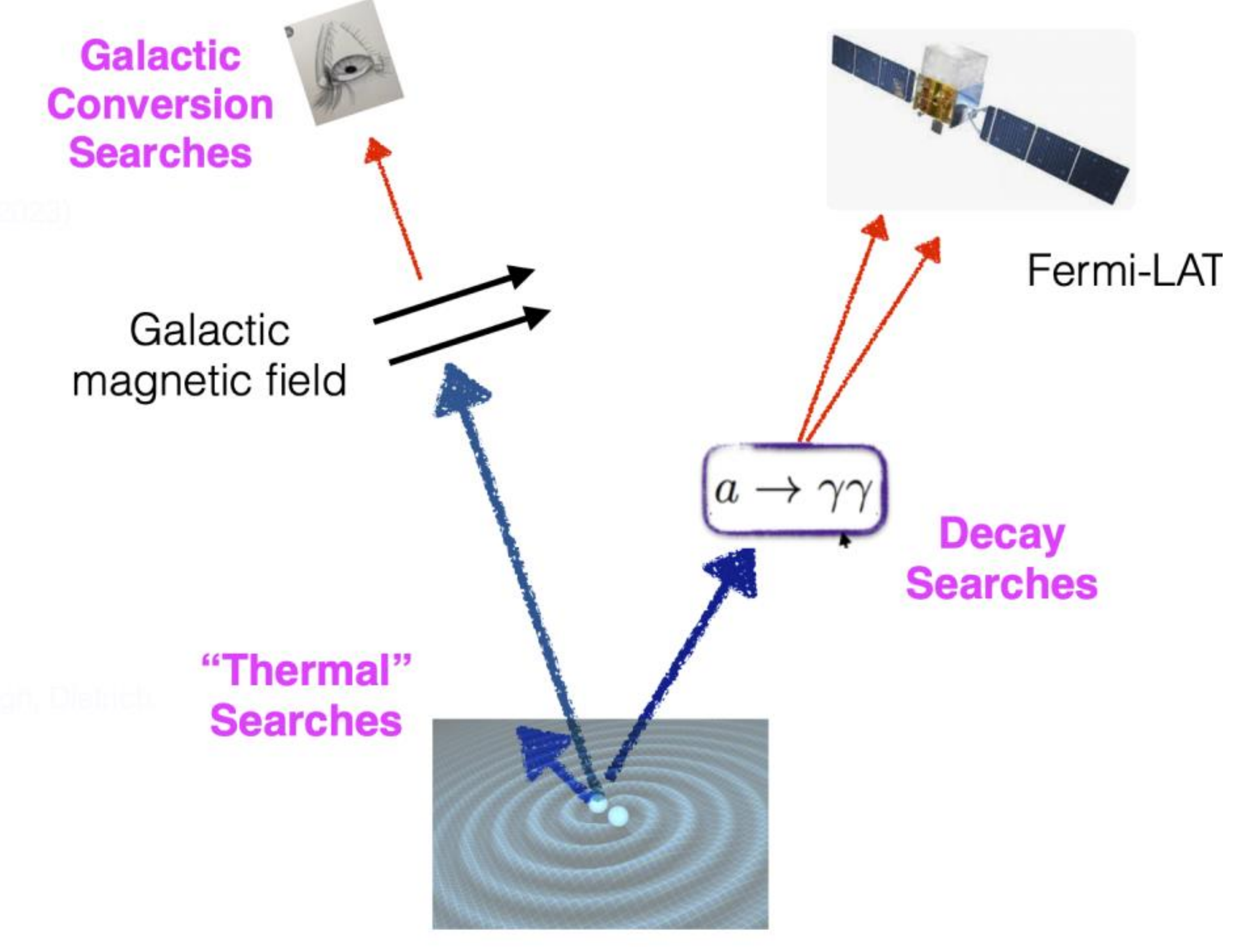


ALP Searches with NS Mergers

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

Fiorillo, Iocco,
2109.10364 (PRD)

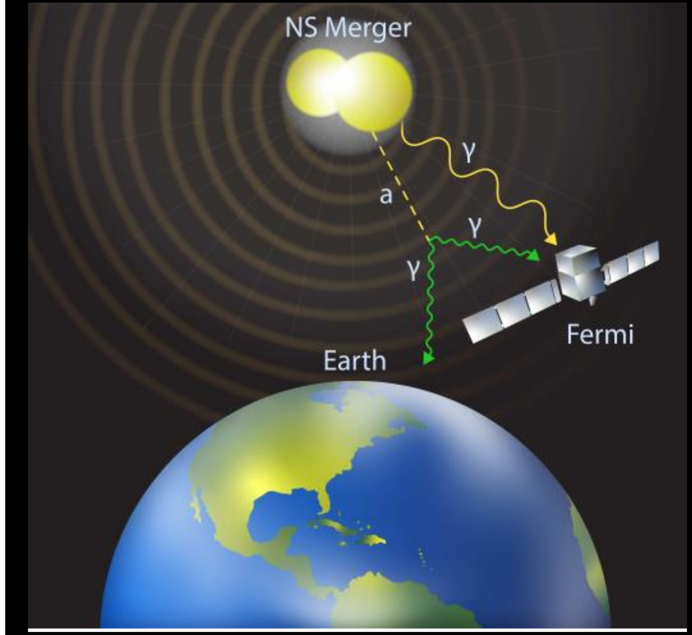
For small ALP mass
(below neV)



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

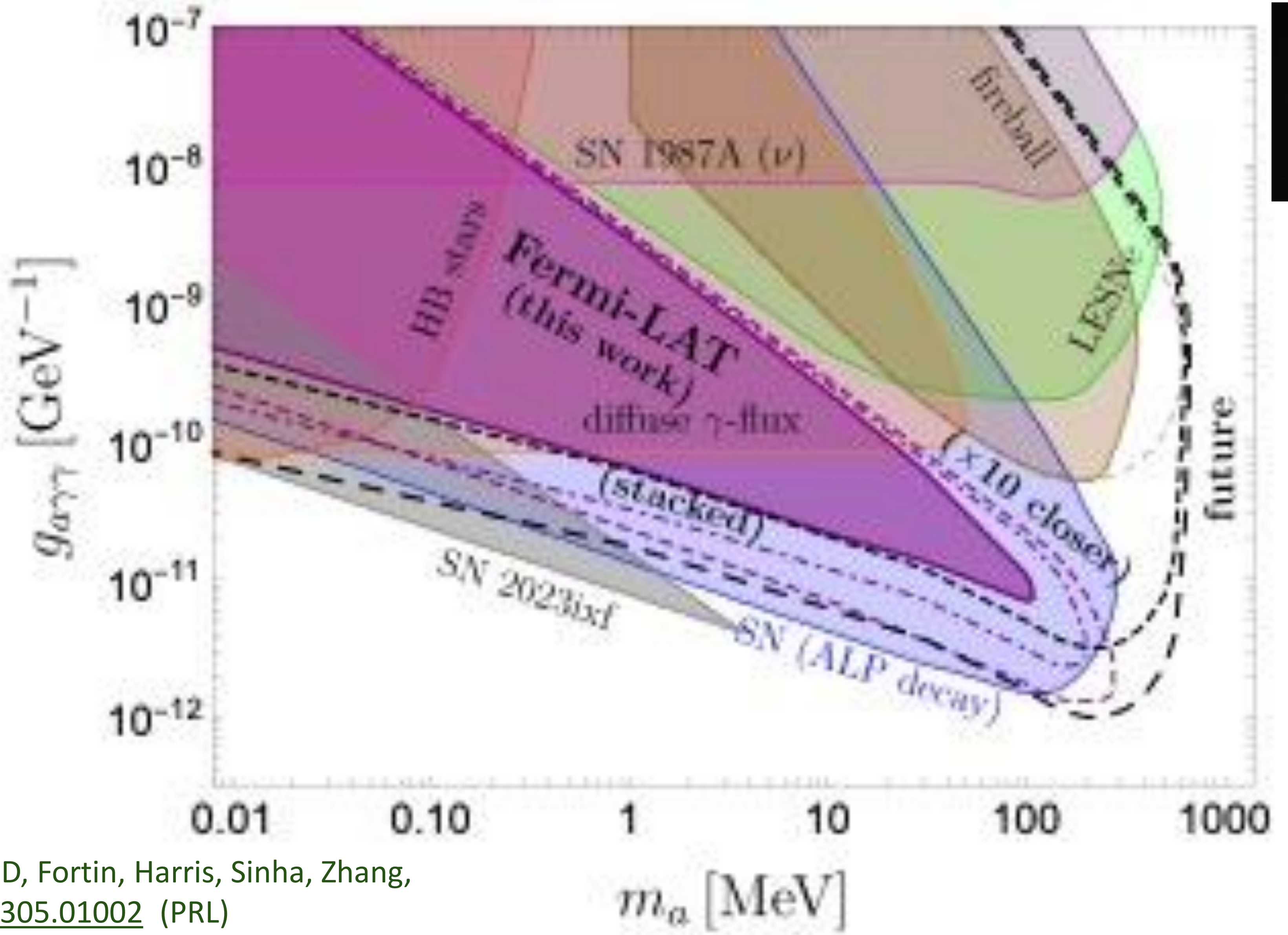
Negligible effect

Multi-messenger connection

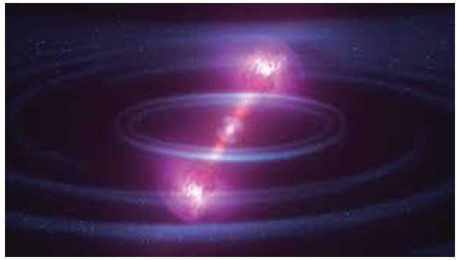


BD, Fortin, Harris, Sinha, Zhang, 2305.01002 (PRL);
Diamond, Fiorillo, Marques-Tavares, Tamborra, Vitagliano, 2305.10327 (PRL)

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.