Theory and Phenomenology

Particle Physics Advisor Panel

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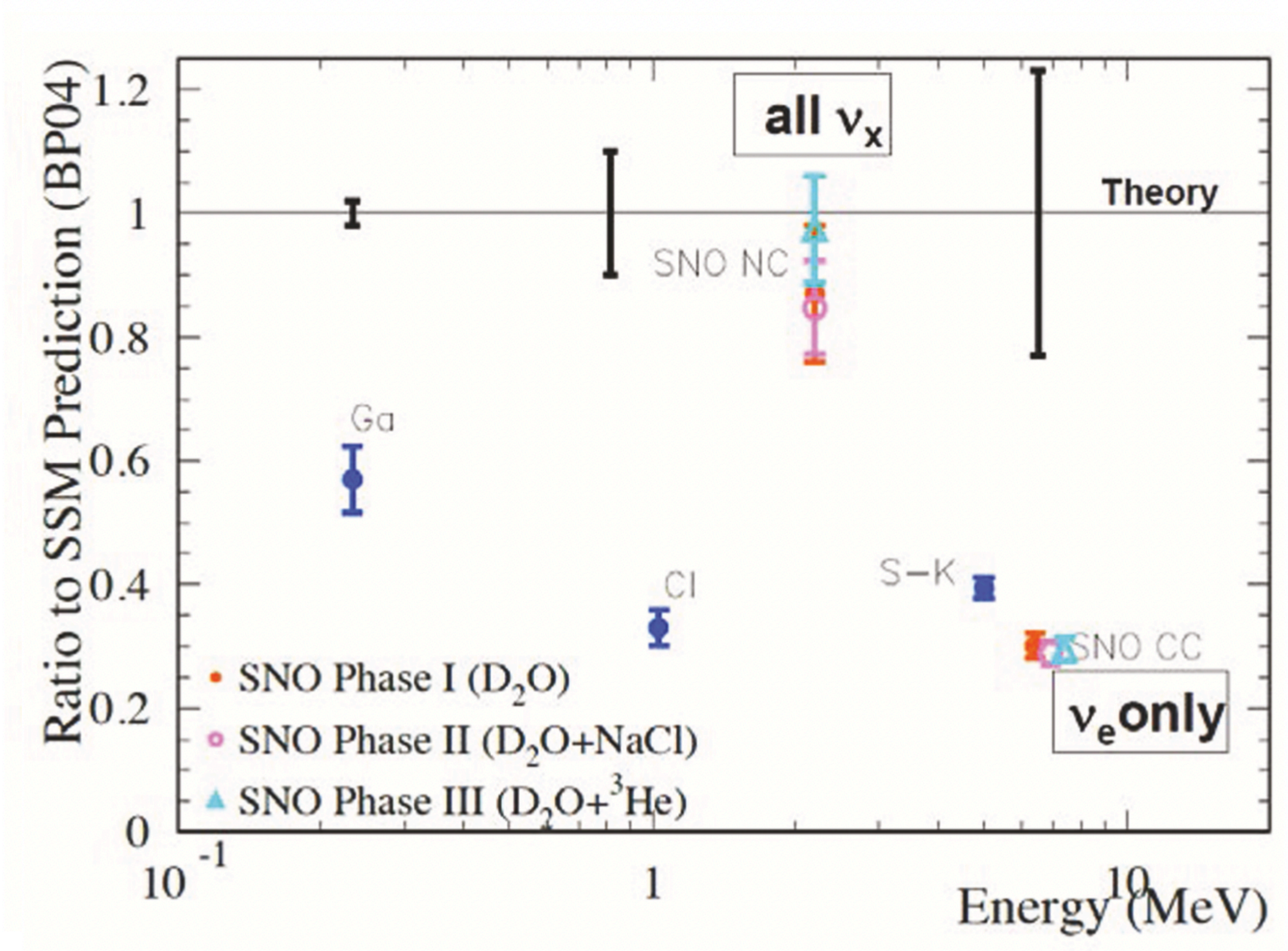
IP3

June 25, 2024

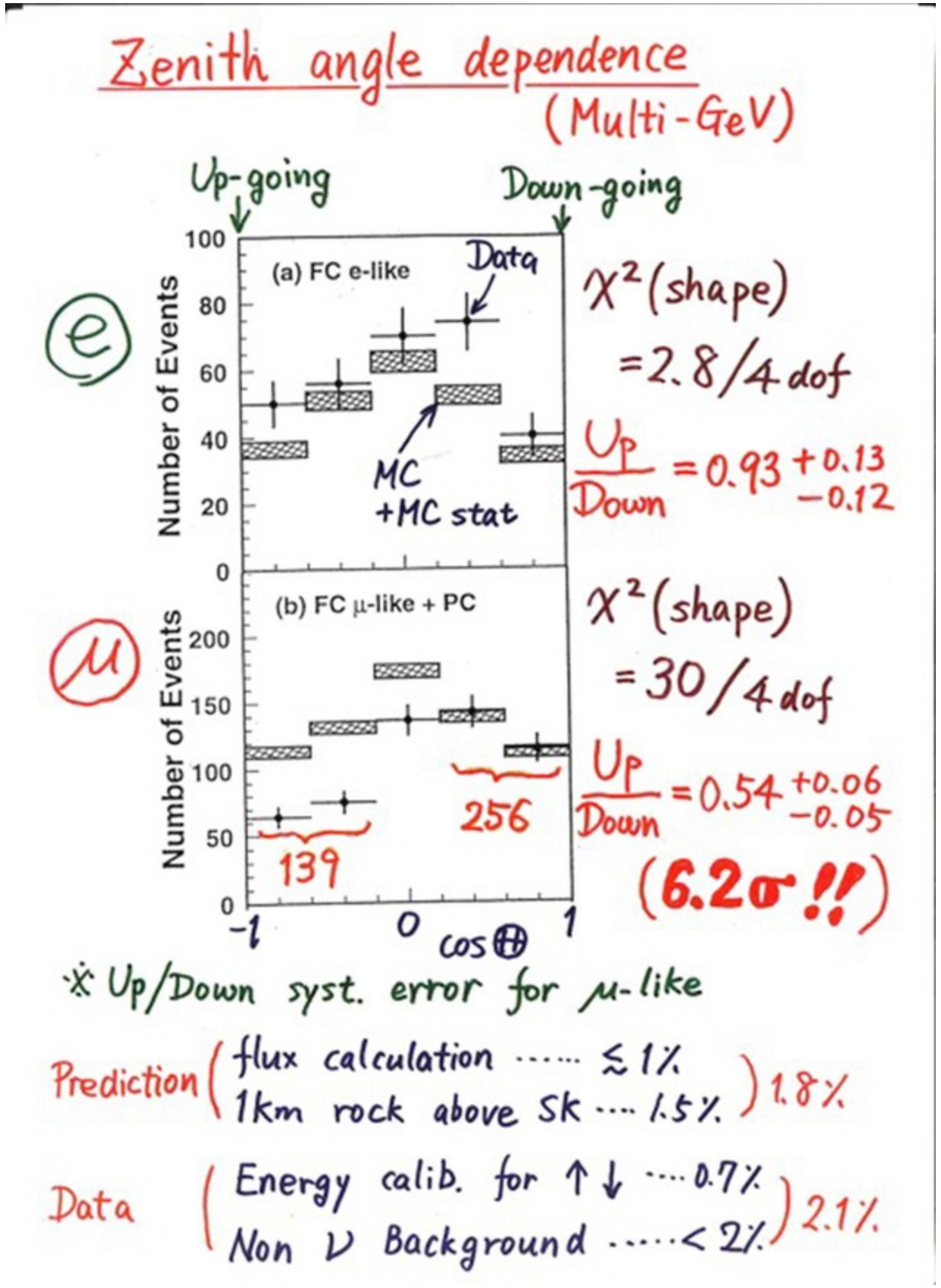
Neutrinos have mass!

In the **SM**, neutrinos are **massless particles**

There are experimental **evidence** showing that neutrinos are massive particles



Arthur MacDonald. Nobel lecture



Takaaki Kajita (Super-kamiokande) Neutrino 98

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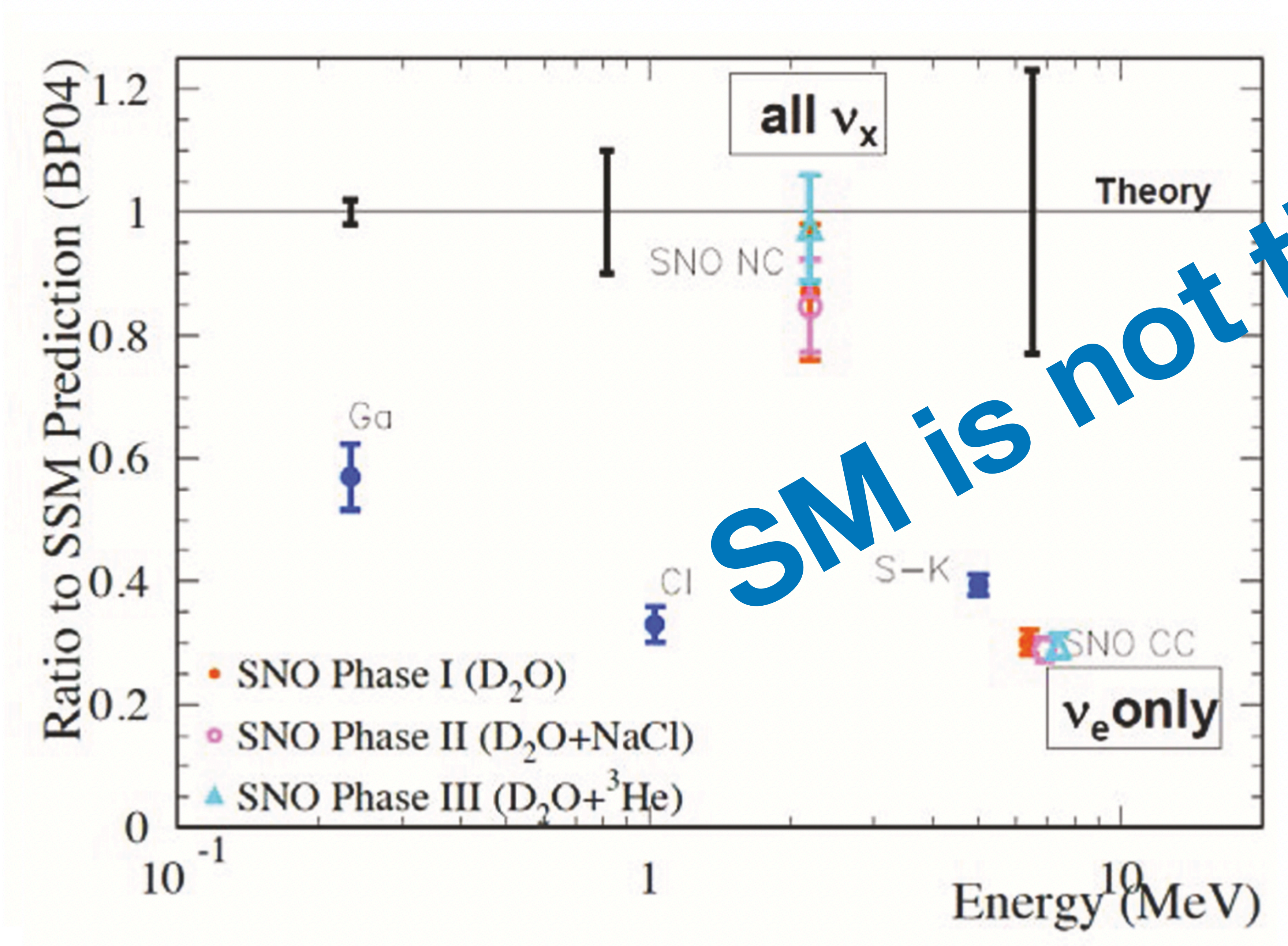
There are experimental **evidence** showing that neutrinos are massive particles

SM is not the ultimate theory!



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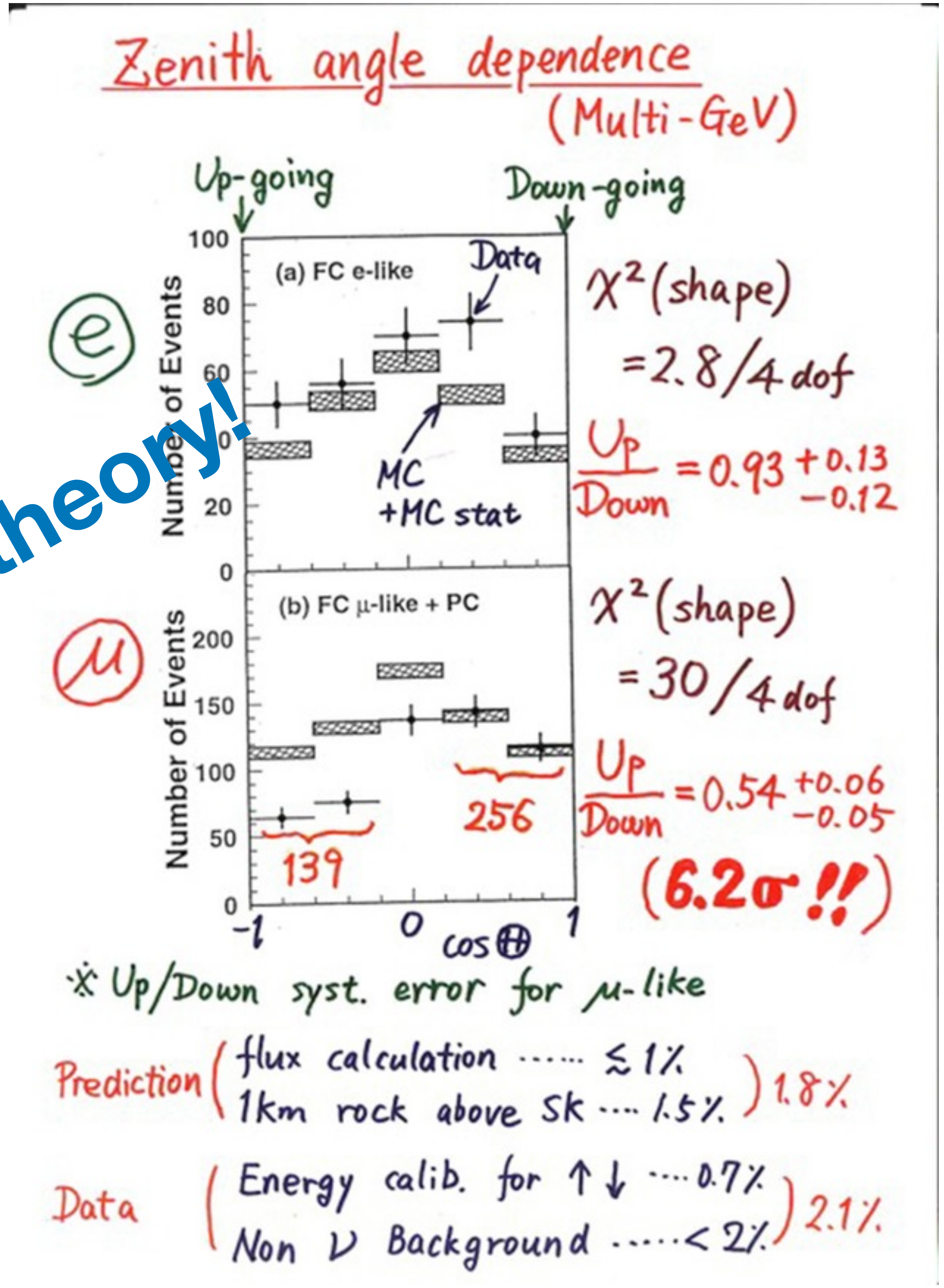

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Neutrinos have mass!

The observation of flavor oscillations has opened new questions, such as the origin of the neutrino masses

To explain the origin of the neutrino mass, we can add a **right-handed state** (N_R)

$$\mathscr{L}^{\nu}_{mass} \supset Y_\nu \bar{L}_L \tilde{\phi} N_R + \frac{1}{2} M_R \bar{N}^c_R N_R + h.c.$$

- The Majorana mass term **breaks Lepton's number**
- For small M_R, neutrinos will behave as **Dirac particles**

$$M_R \ll \frac{Y_\nu v}{\sqrt{2}}$$

Pseudo Dirac Neutrinos

The active states can be written as a supperposition of two almost degenerate mass eigenstates

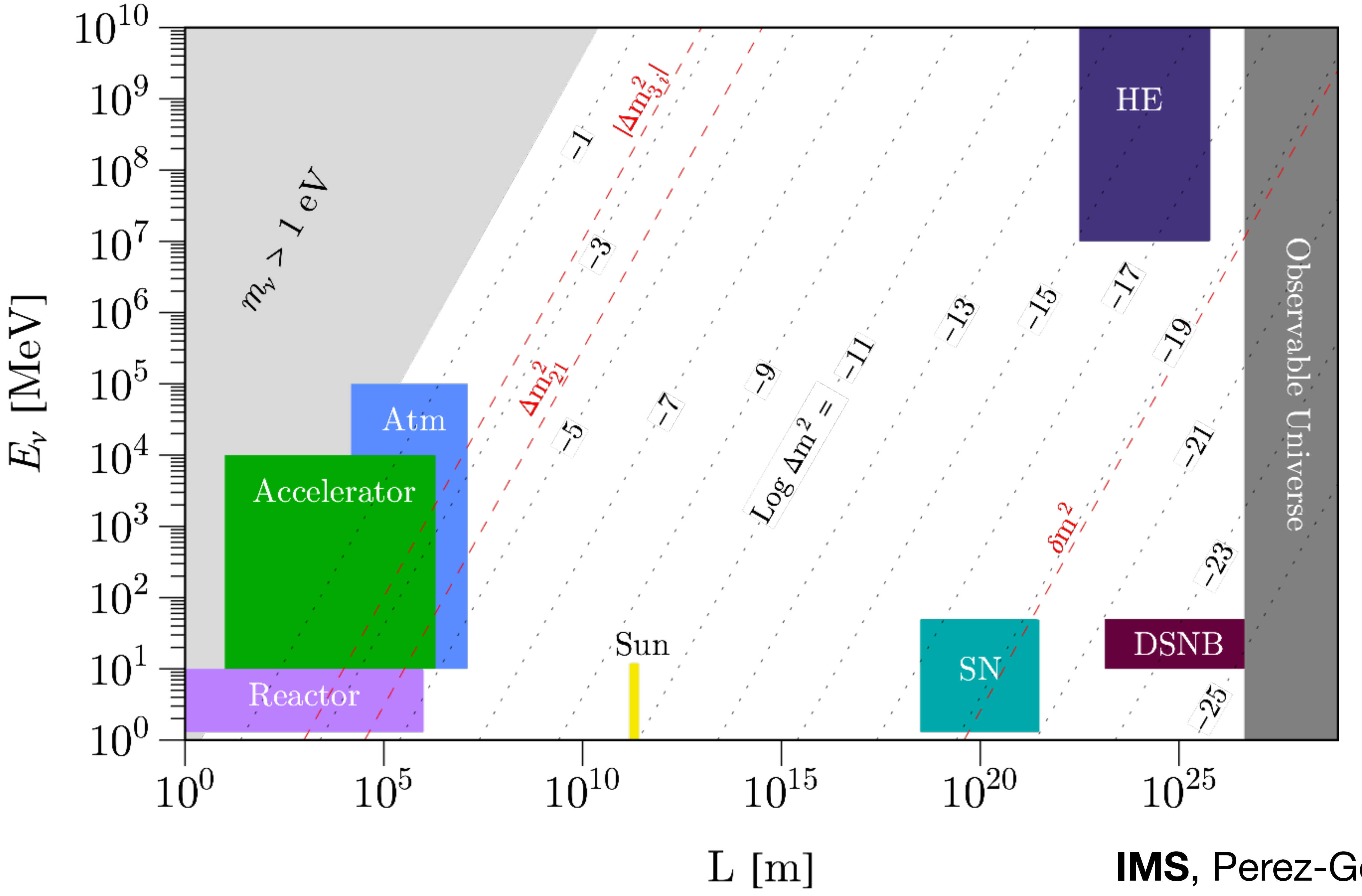
$$\nu_{\alpha L} = \frac{1}{\sqrt{2}} U_{\alpha j}(\nu_{js} + i\,\nu_{ja})$$

The masses of each eigenstate are given by

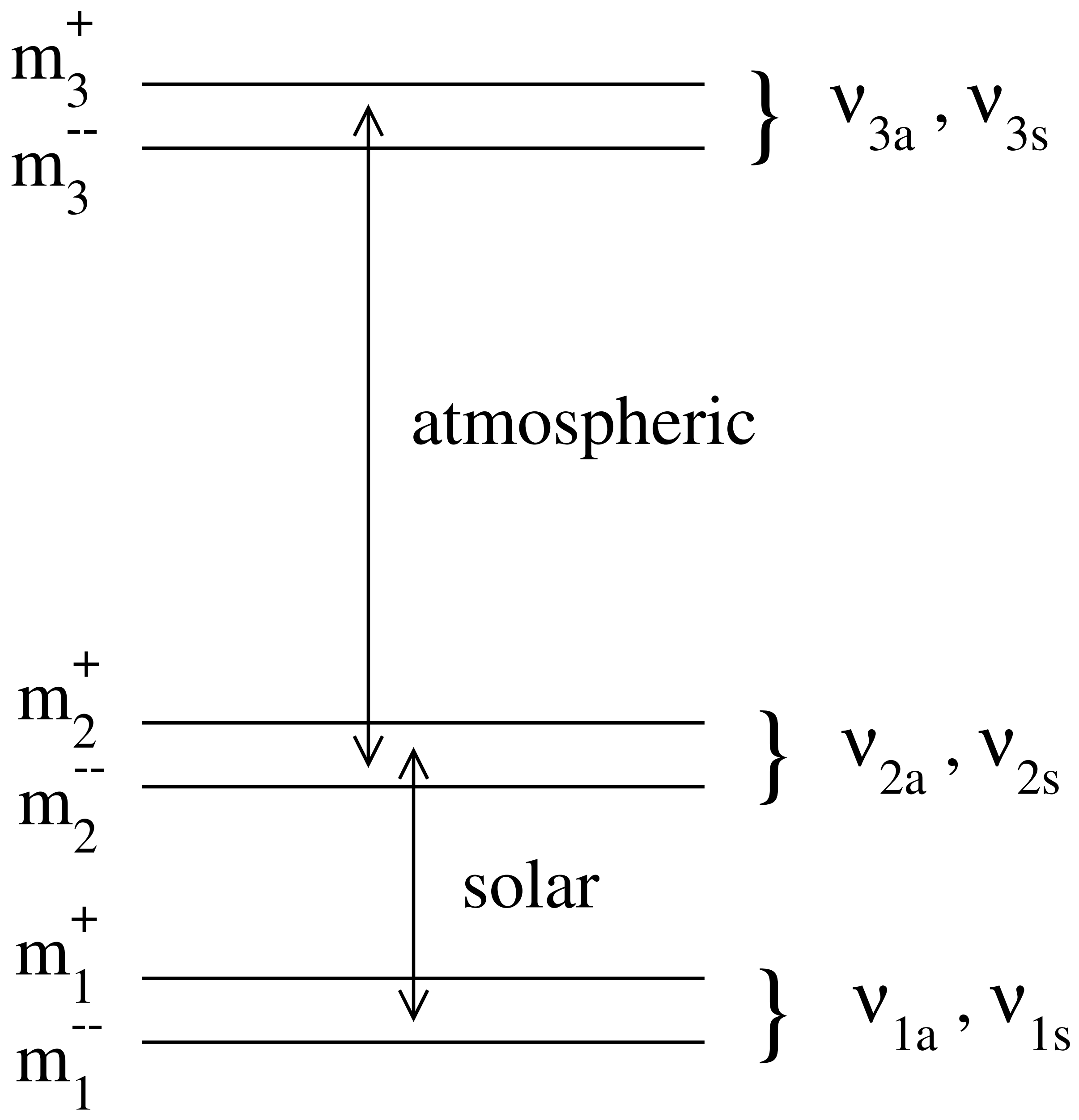
$$m_{ks}^2 = m_k^2 + \frac{1}{2}\delta m_k^2$$

$$m_{ka}^2 = m_k^2 - \frac{1}{2}\delta m_k^2$$

$$\delta m^2 \sim M_D M_R$$



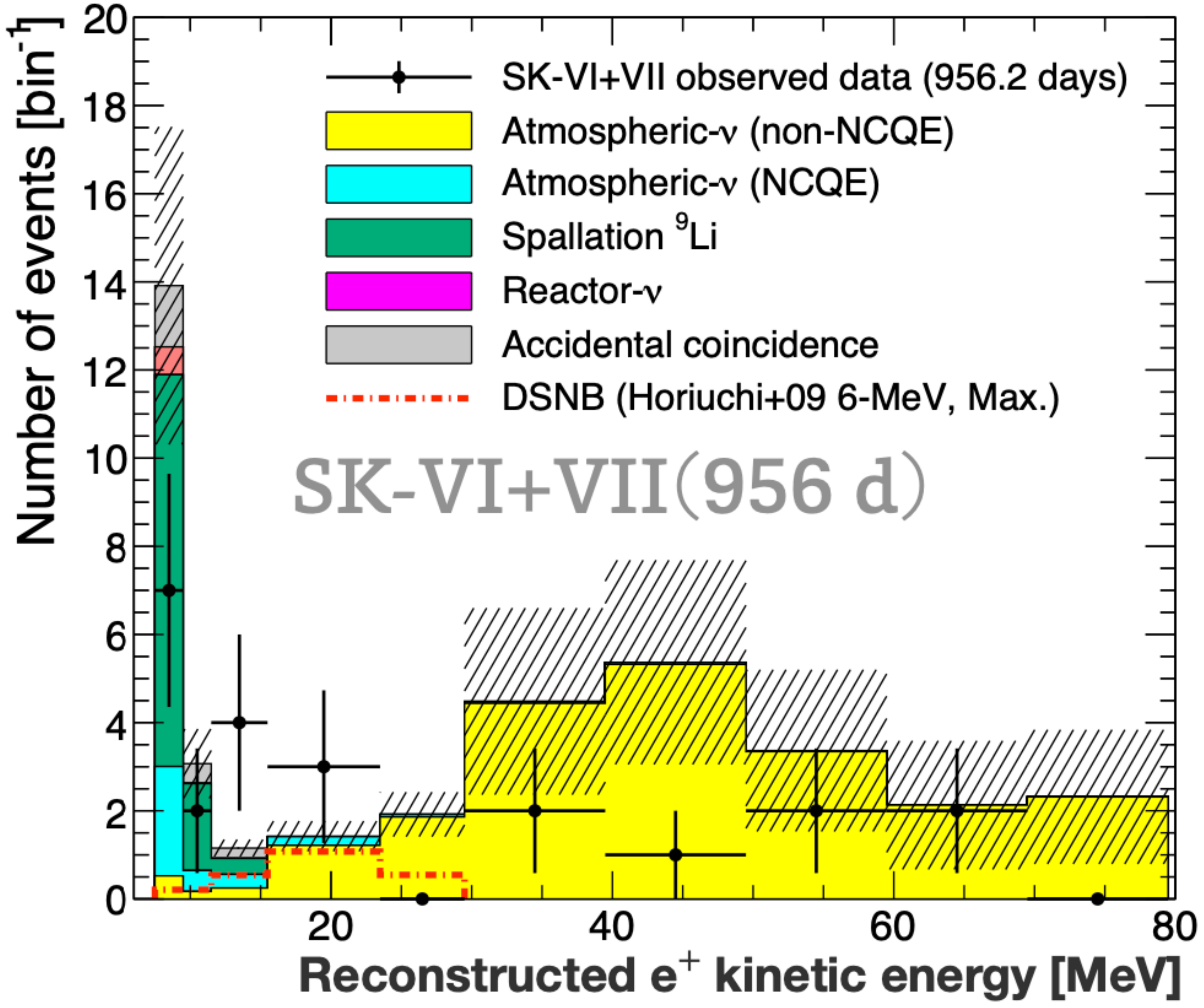
IMS, Perez-Gonzalez, Sen, PRD 105 (2022)



Difusse Supernova Neutrino Background

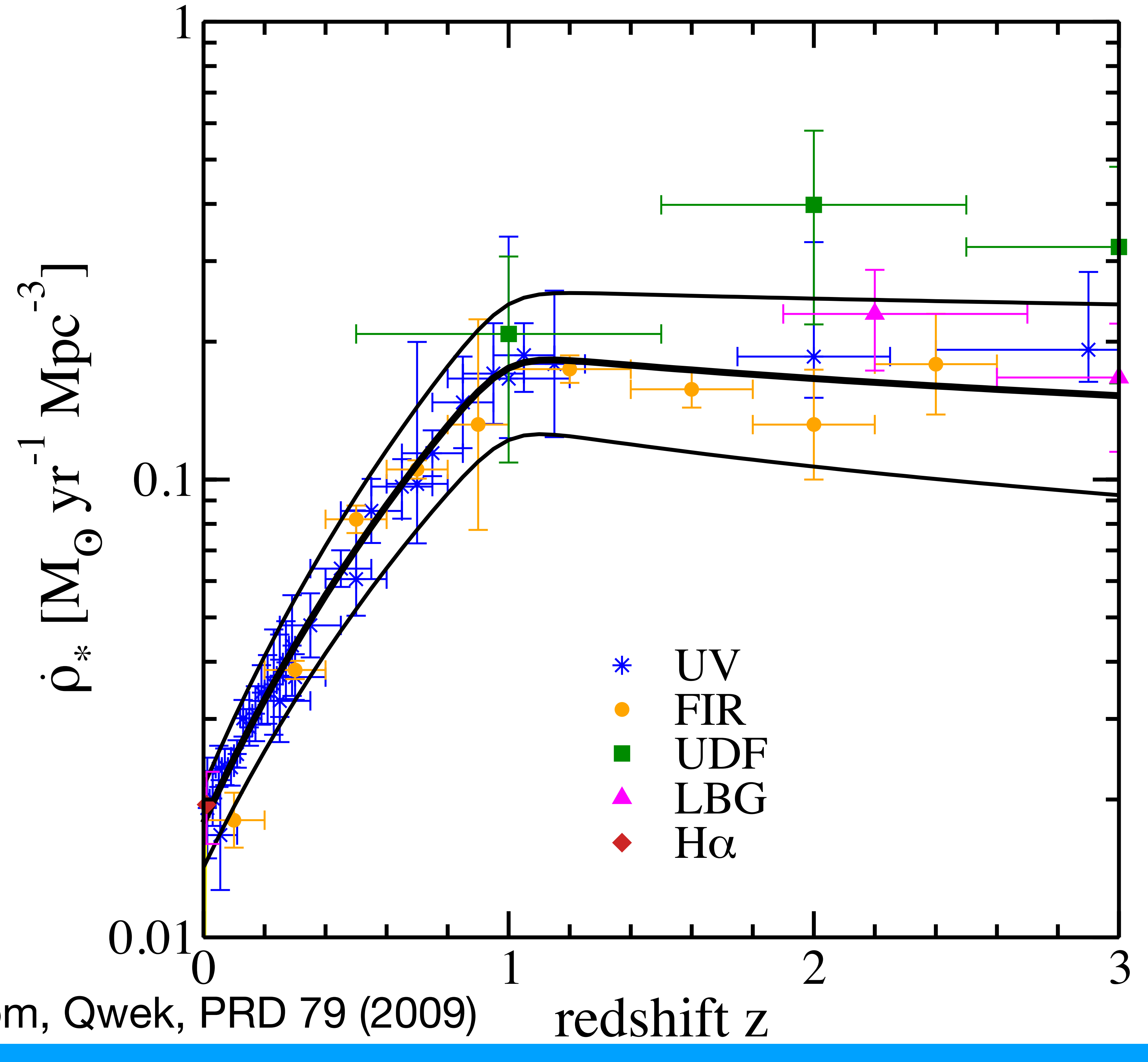
Super-Kamiokande has presented the **first evidence** of the DSNB

$$\Phi_\nu(E) = \int_0^{z_{\max}} \frac{dz}{H(z)} R_{CCSN}(z) F_\nu(E')$$



Harada (Super-Kamiokande) Neutrino2024

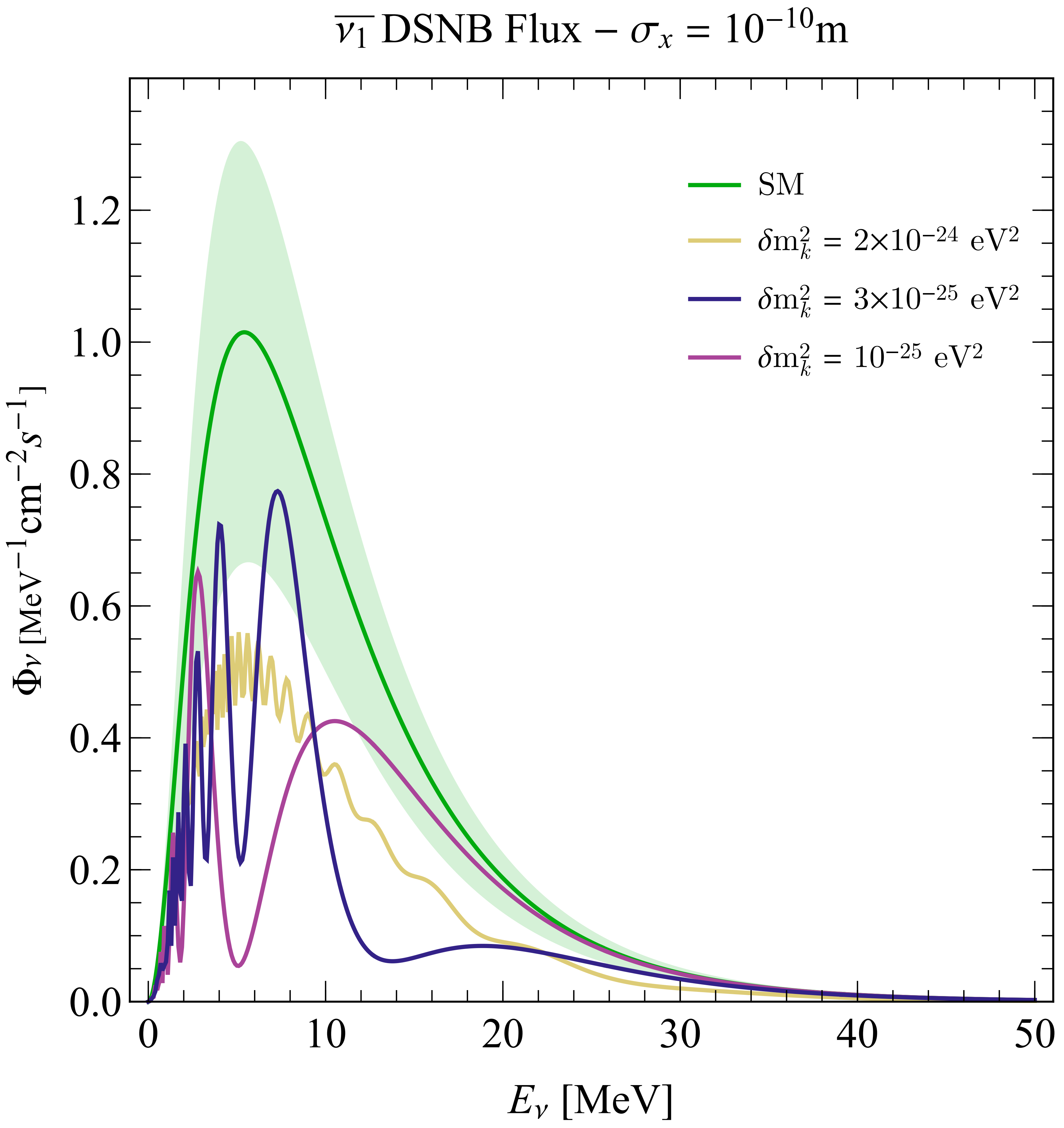
Supernova rate



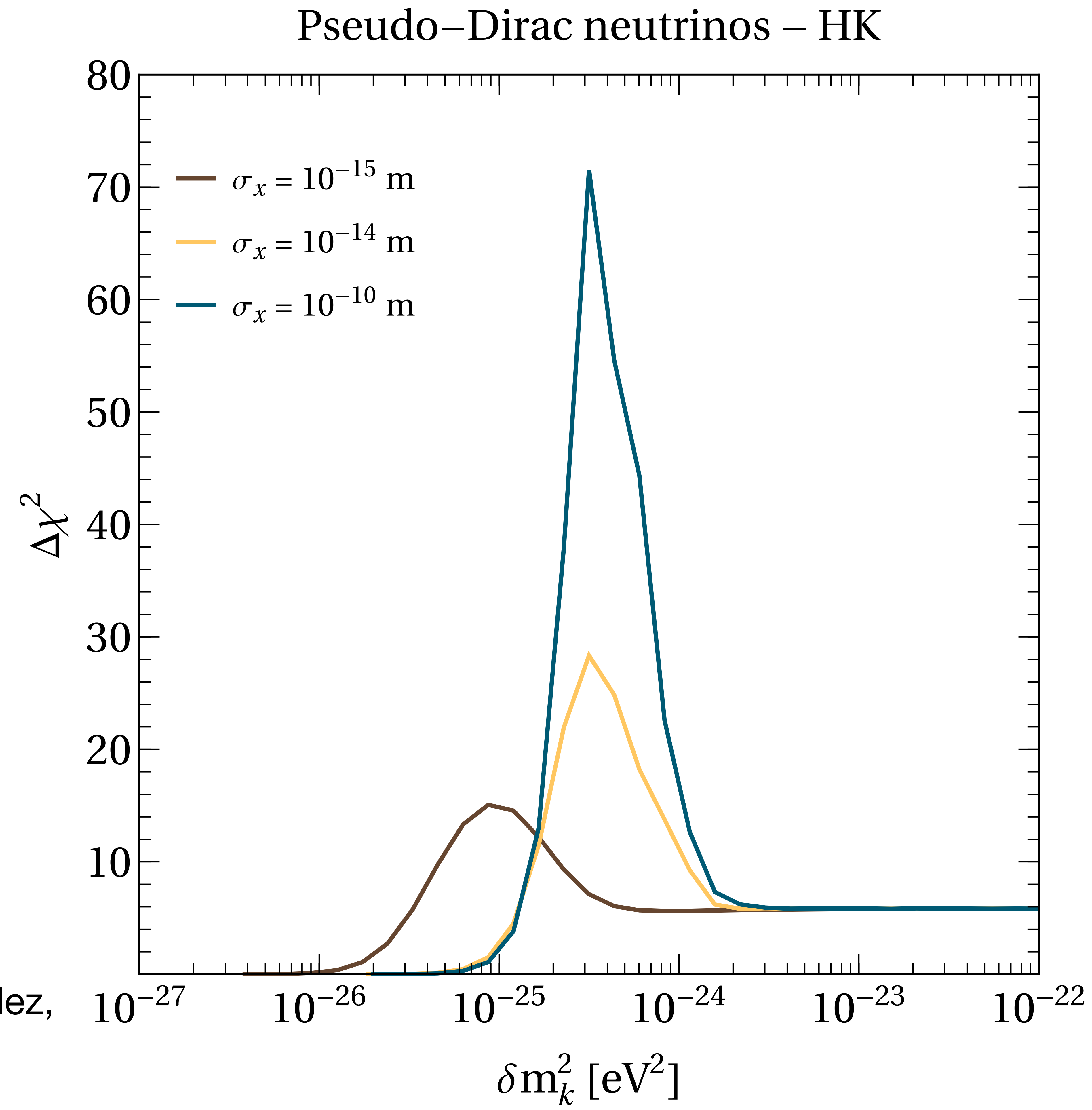
Horiuchi, Beacom, Qwek, PRD 79 (2009)

Diffuse Supernova Neutrino Background

The DSNB probes Gpc scales



Considering a detector like Hyper-Kamiokande doped with Gd



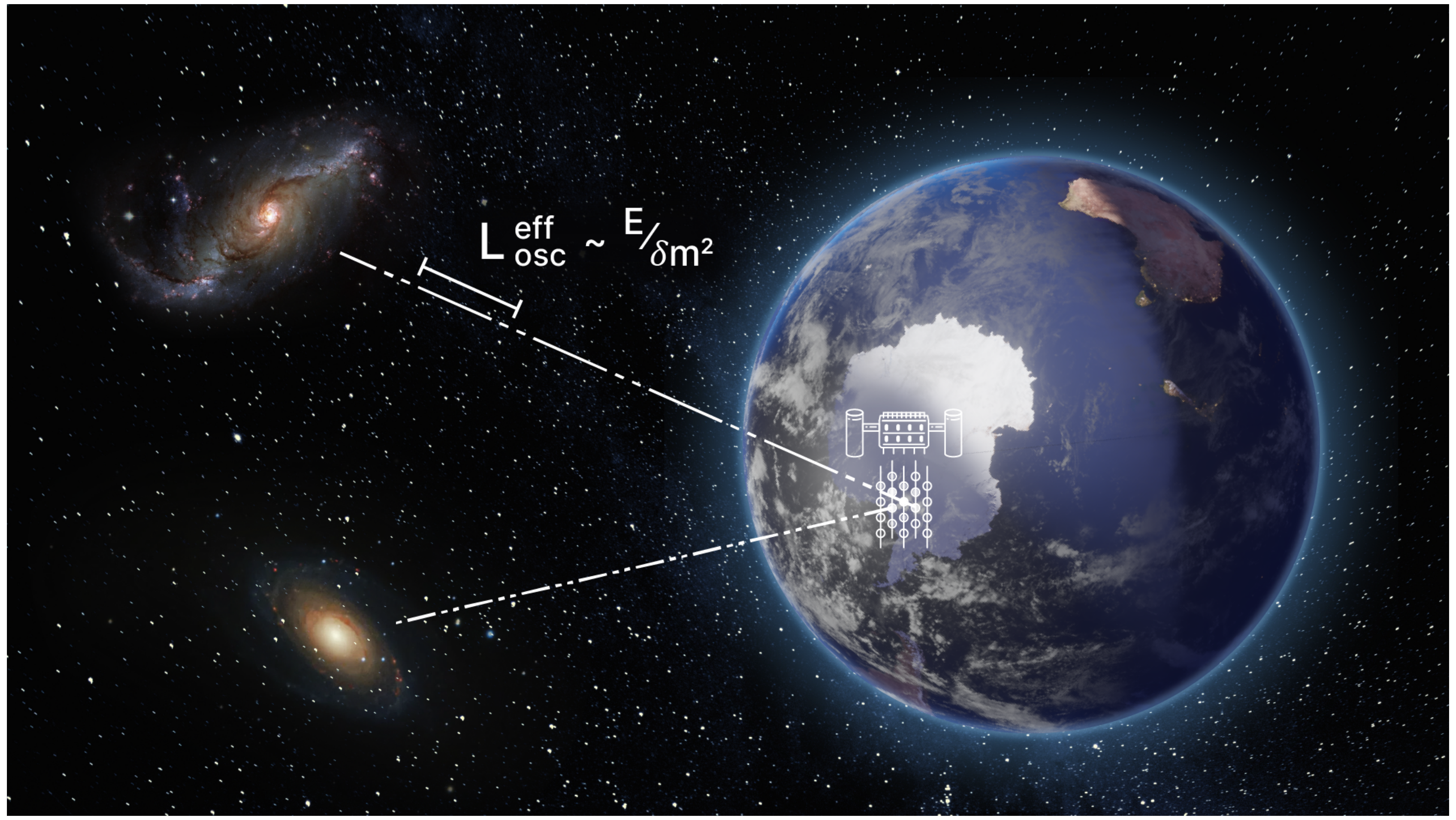
de Gouvêa, **IMS**, Perez-Gonzalez, Sen, PRD 102 (2020)

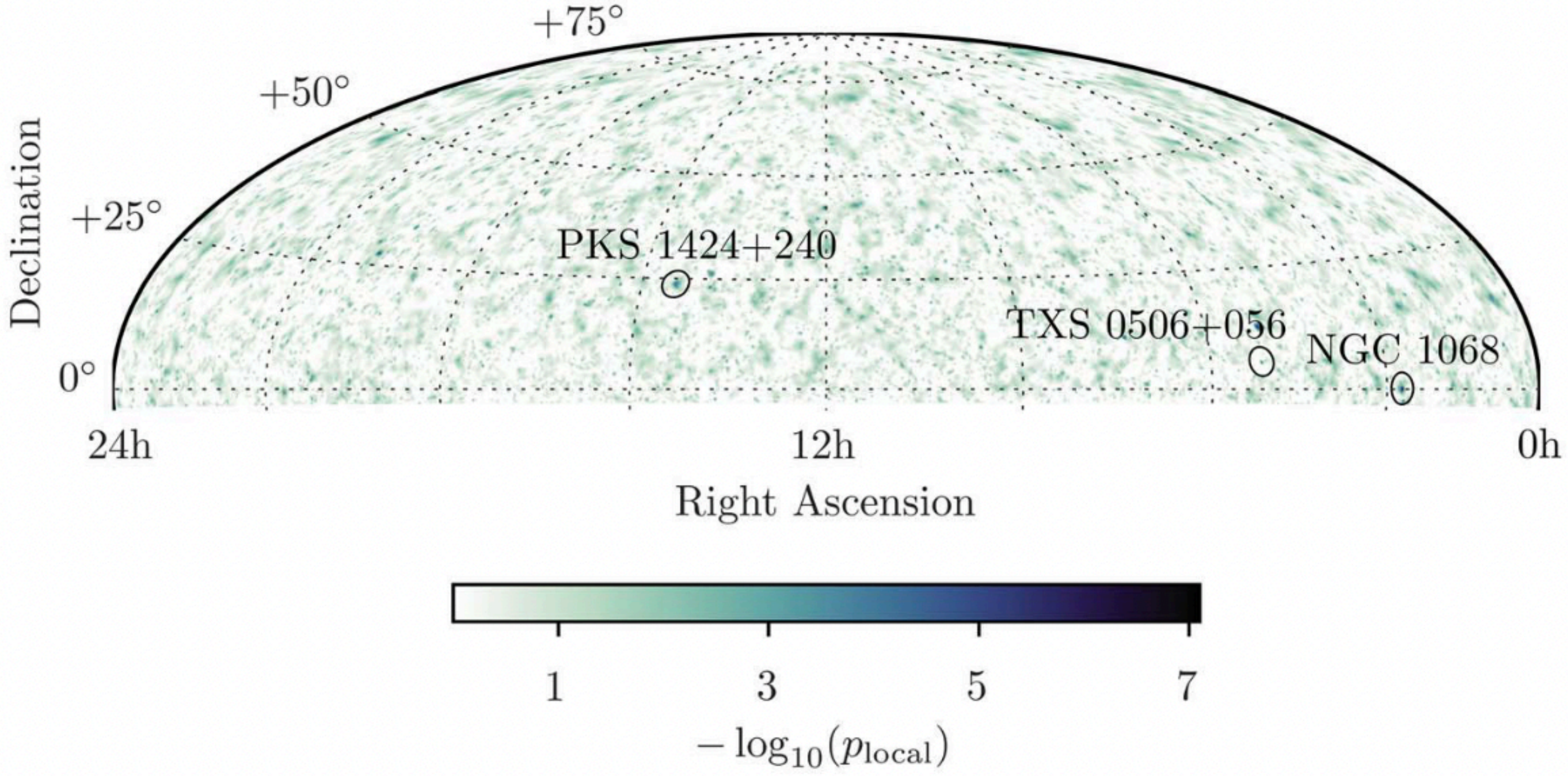
Pseudo Dirac Neutrinos with Astrophysical Sources

IceCube has identified several candidate sources that can be used to search for pseudo-Dirac neutrinos

- Combining multiple sources allow us to explore a wide range of δm^2 and increase the significance.

Source	$-\log_{10} p$	$\hat{\gamma}$	z
NGC 1068	7.0	3.2	0.0038
PKS 1424+240	4.0	3.5	0.6047
TXS 0506+056	3.6	2.0	0.3365

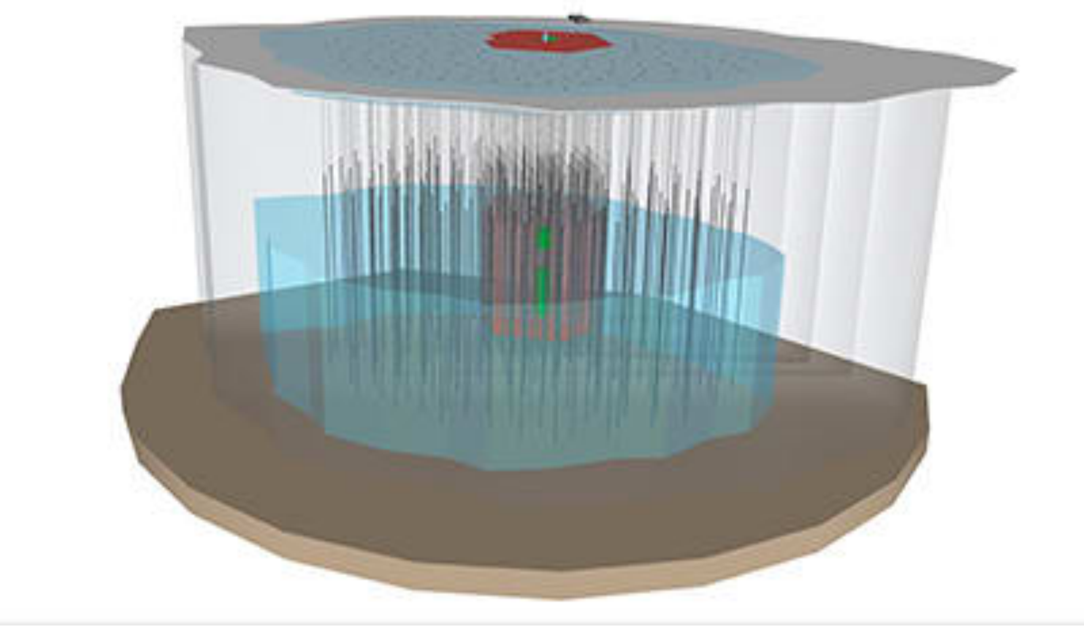




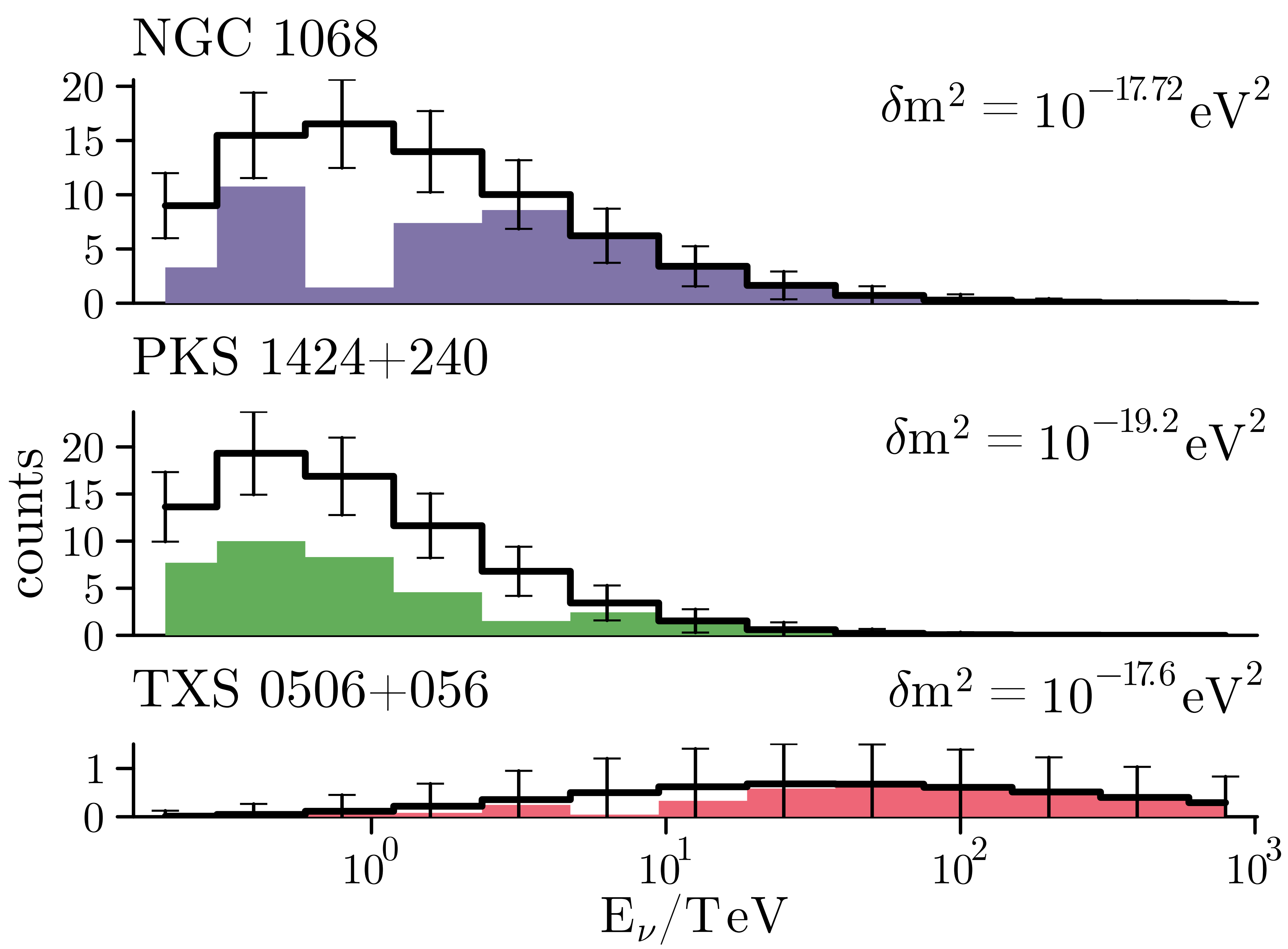
Abbasi et al. (IceCube) Science 378, 538 (2022)

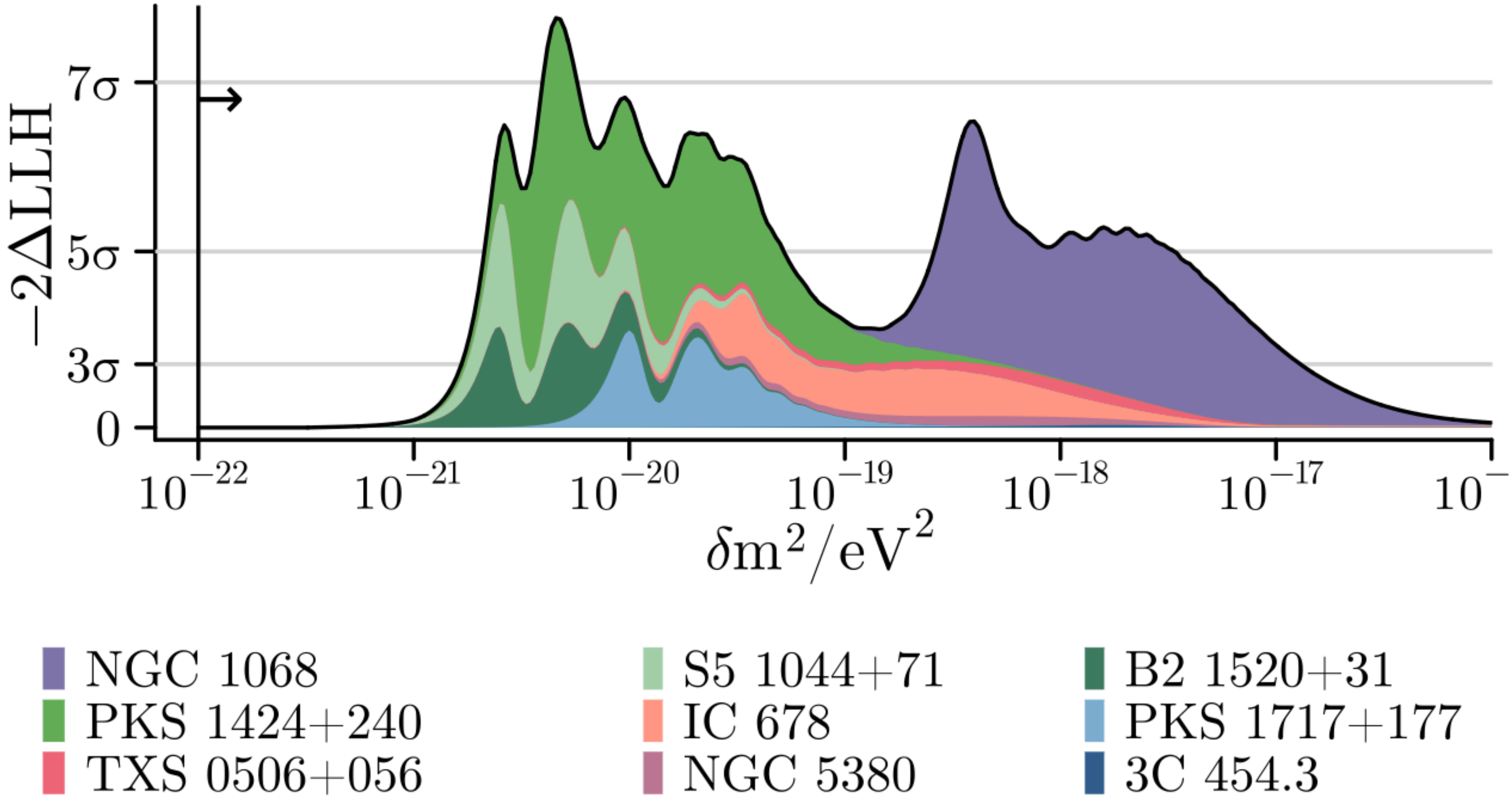
Pseudo Dirac Neutrinos with Astrophysical Sources

IceCube is planning an upgrade corresponding to a volume ~10 times larger, allowing the observation of new sources.



- A dip in the neutrino spectra of several sources will robustly indicate this scenario.





Carloni, **IMS**, Arguelles, Babu, Bhupal, PRD 109 (2024)

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The observation of flavor oscillations has opened new questions, such as the origin of the neutrino masses

To explain the origin of the neutrino mass, we can add a right-handed state (N_R)

$$\mathscr{L}^{\nu}_{mass} \supset Y_\nu \bar{L}_L \tilde{\phi} N_R + \frac{1}{2} M_R \bar{N}^c_R N_R + h.c.$$

- Large values of M_R can explain the smallness of the neutrino mass (Seesaw)

$$m_\nu \sim \frac{Y^\dagger_\nu Y_\nu v^2}{M_R} \qquad m_N \approx M_R + \mathcal{O}\left(m_\nu\right)$$

- The masses predicted by the Type I seesaw are hard to test
- There are other scenarios where the Majorana mass can take smaller values

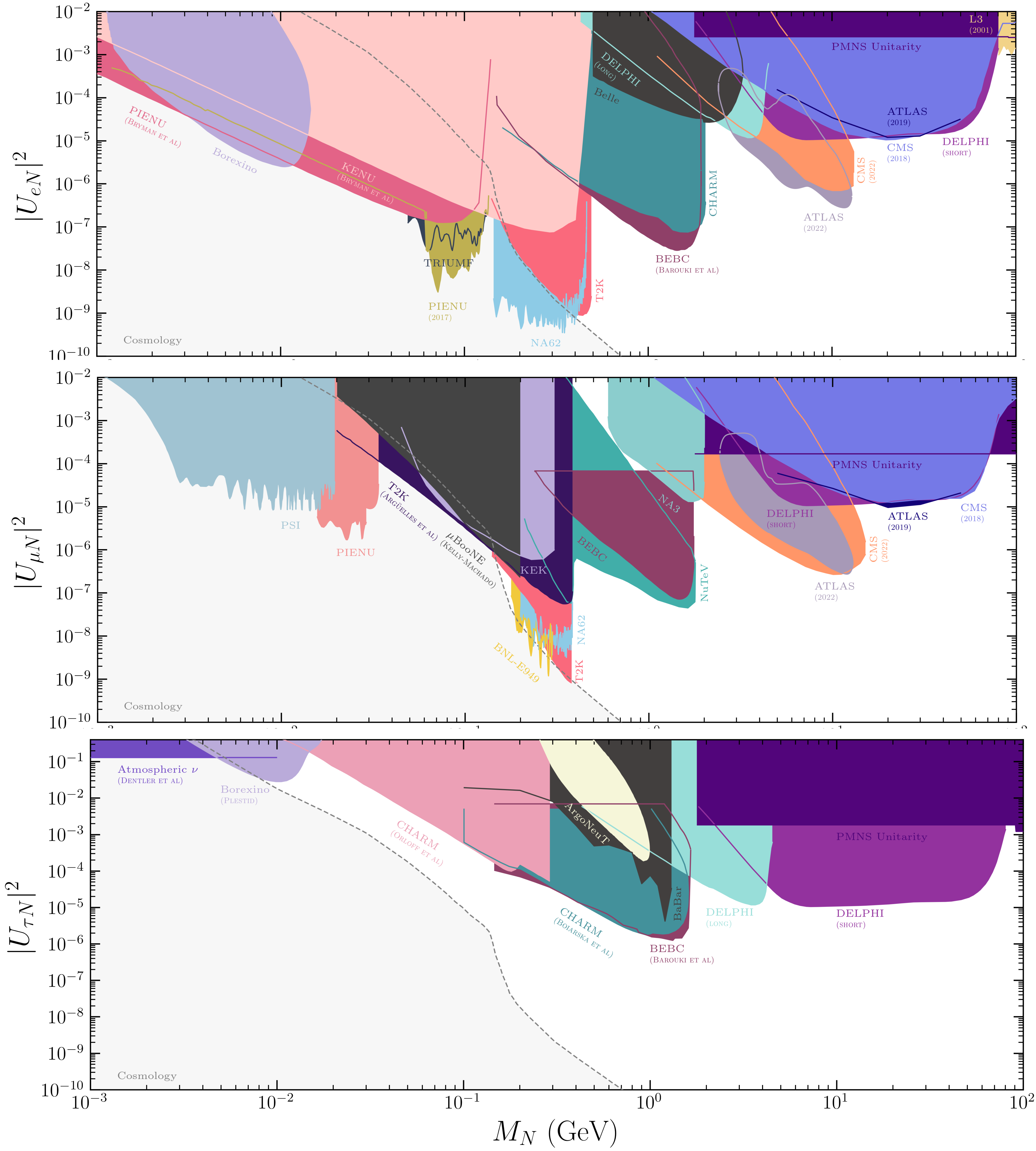
HNLs

In the presence of N_R, the flavor states can be written as a superposition of massive states as

$$\nu_{\alpha L} = \sum U_{\alpha m}\nu_{mL} + U_{\alpha 4}N_{4L}$$

Several analysis has searched for HNLs

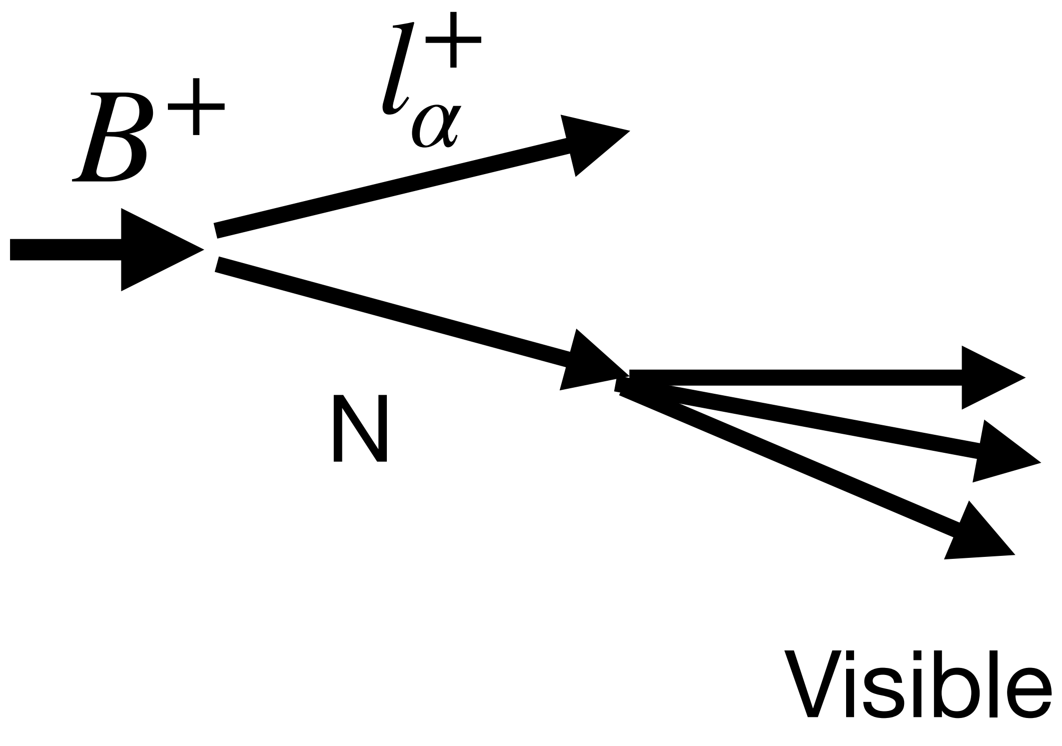
Fernandez-Martinez, Gonzalez-Lopez, Hernandez-Garcia, Hostert, Lopez-Pavon, arXiv:2304.06772



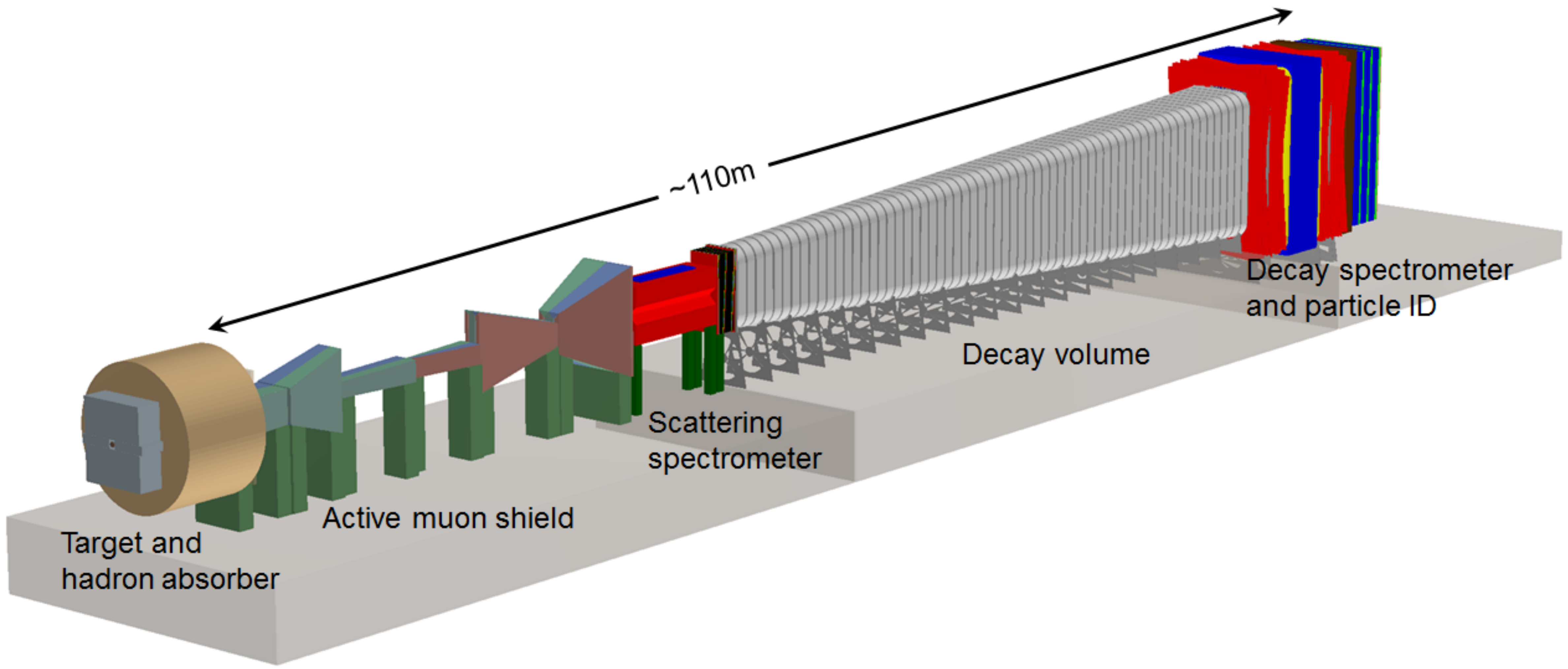
HNLs

The copling of the HNLs with the SM fermions via mixing makes that they can be produced in meson decays

- Accelerators or beam dump experiments
- The typical signal expected is a displaced vertex



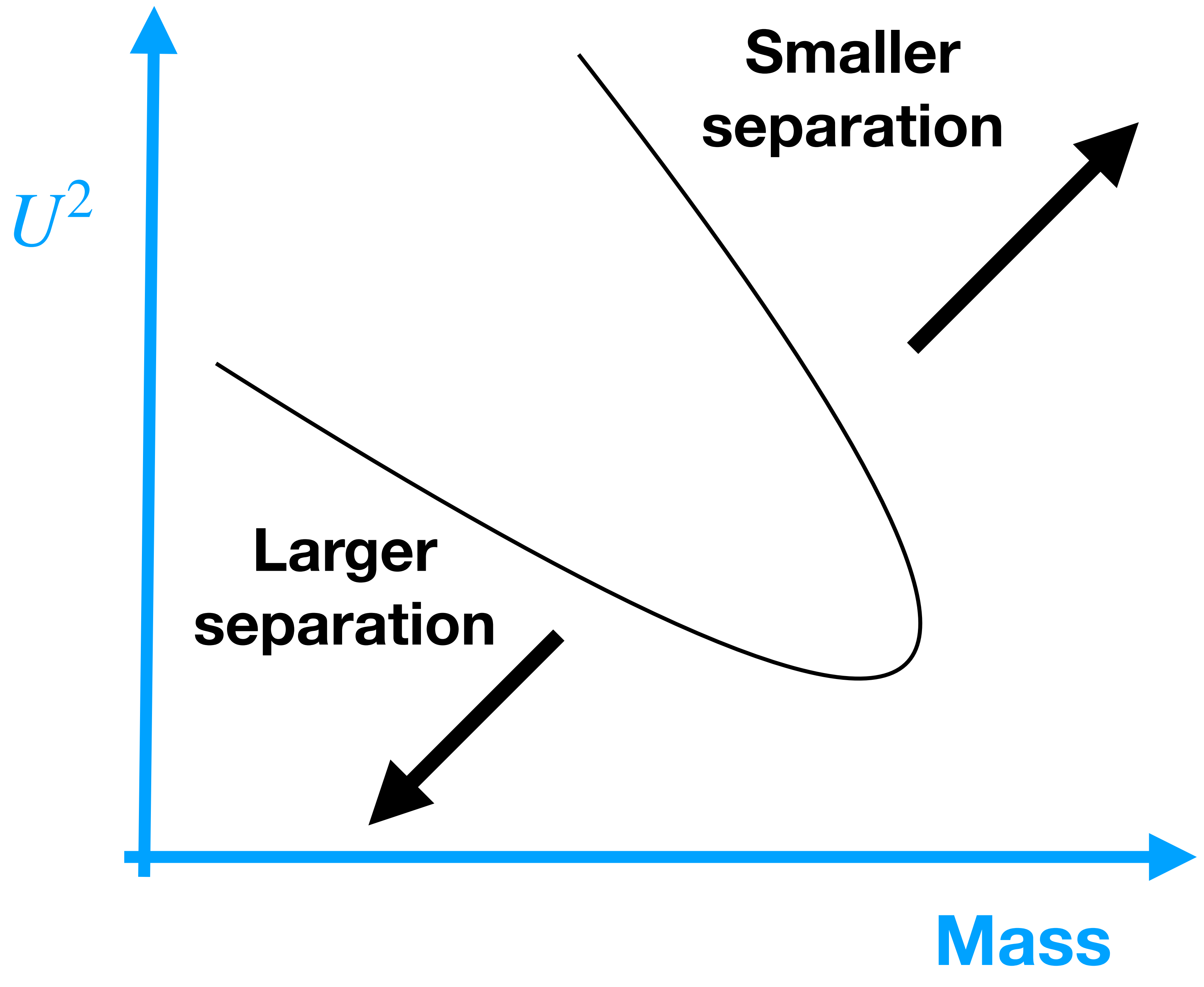
Several experiments have been proposed (SHIP, Sadows…)

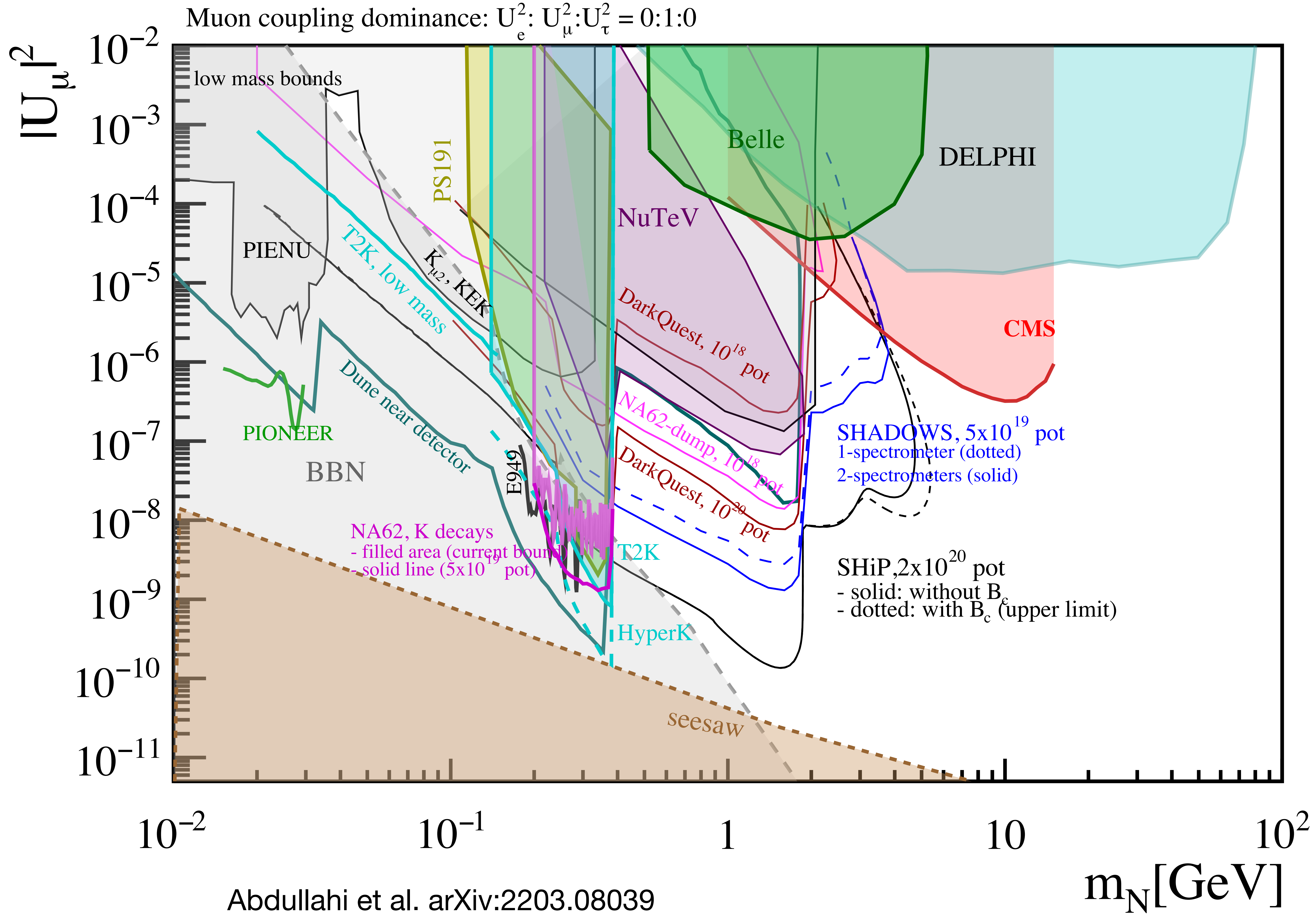


Ahdida et al (SHIP), JHEP 04 (2019)

HNLs

Beam dump experiments can increase the sensitivity

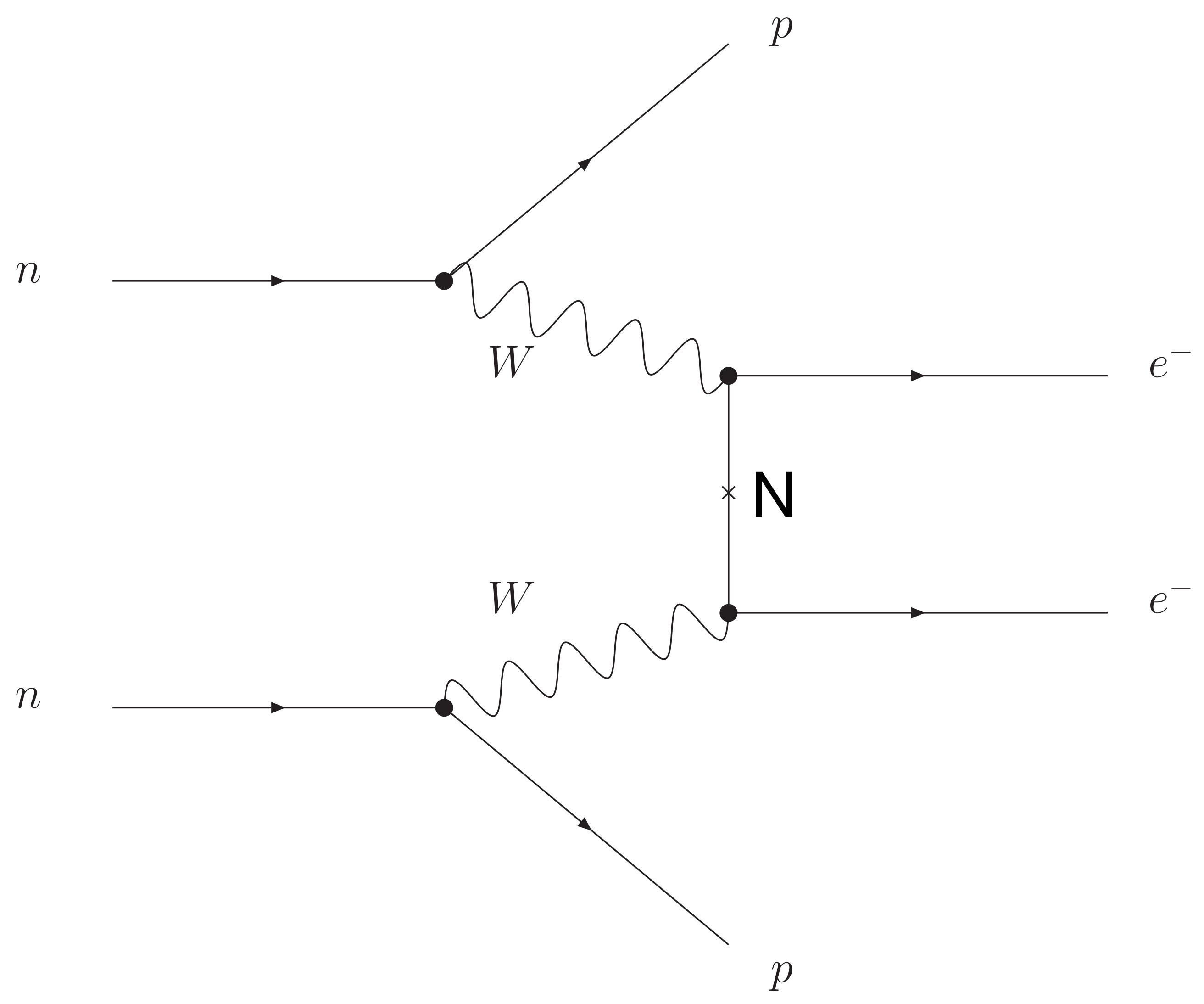


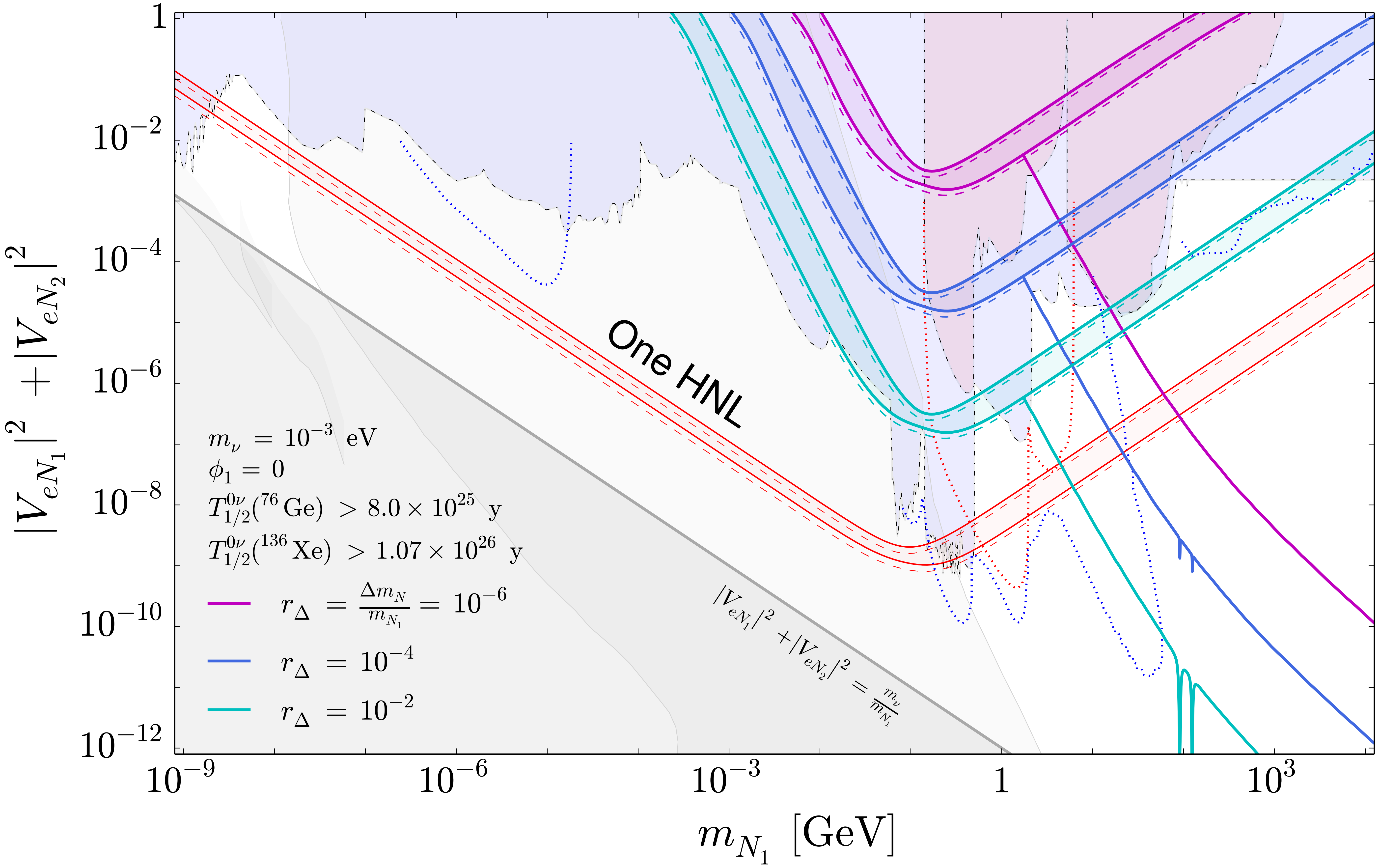


Abdullahi et al. arXiv:2203.08039

HNLs

The coupling of HNLs with electron neutrinos can be searched for in $0\nu\beta\beta$ experiments





Bolton, Deppish, Dev, JHEP 03 (2020)

Leptogenesis

The HNLs decay into leptons generates a lepton asymmetry ($N \to Hl$)

$$\mathscr{L}^{\nu}_{mass} \supset Y_\nu \bar{L}_L \tilde{\phi} N_R + \frac{1}{2} M_R \bar{N}^c_R N_R + h.c.$$

Large CP-violation can be generated ($\epsilon \sim 10^{-6}$) for very heavy masses $M_R > (0.1\text{eV}/m_\nu)10^{10} GeV$

$$\epsilon = \frac{\Gamma(N \to lH) - \Gamma(N \to \bar{l}H^\dagger)}{\Gamma_N}$$

Lepton asymmetry is transform to Baryon asymmetry via sphaleron

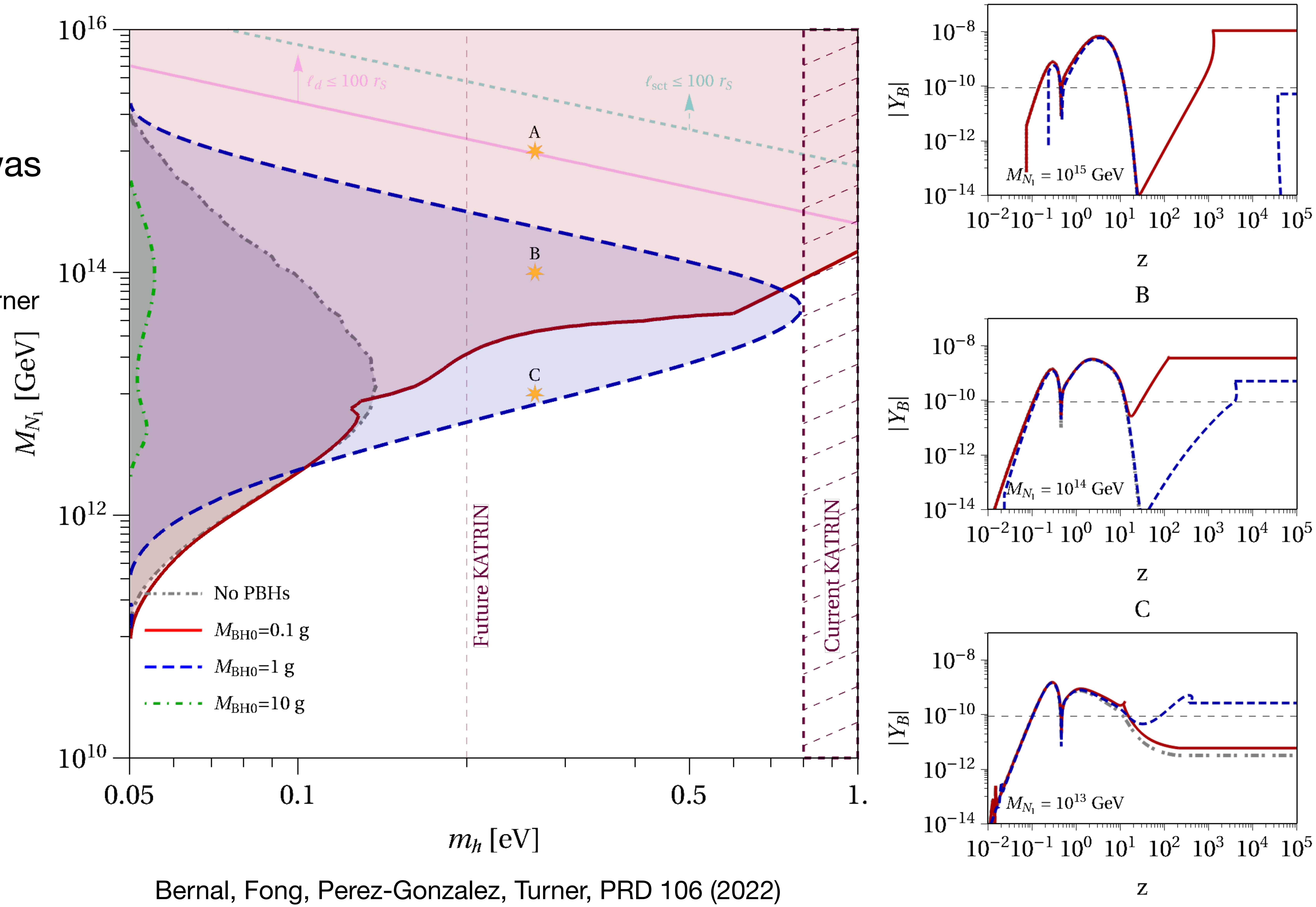
$$\begin{cases} \eta_{CMB} = (6.23 \pm 0.17) \times 10^{-10} \\ \eta_{BBN} = (6.08 \pm 0.06) \times 10^{-10} \end{cases}$$

PBH has got a lot interest in the recent year. It would be interesting to understand their interplay with leptogenesis.

PBH and Leptogenesis

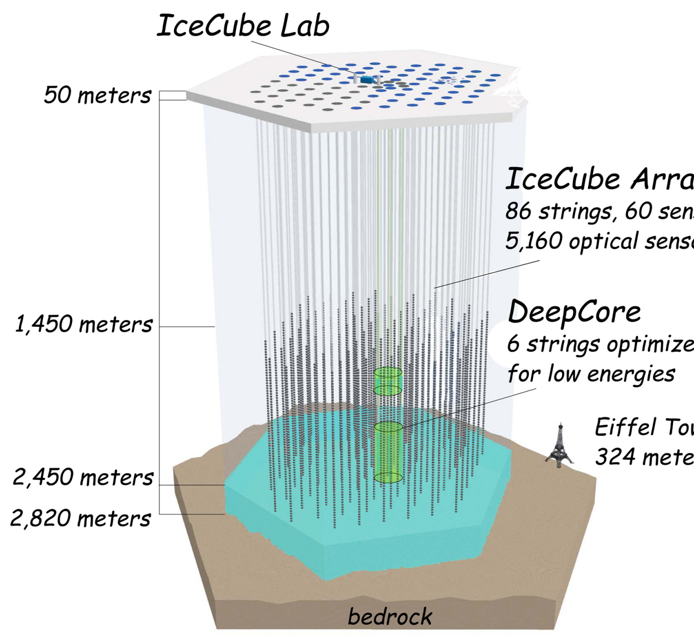
To obtain the baryon asymmetry, it was used **ULYSSES**

Granelli, Leslie, Perez-Gonzalez, Schulz, Shuve, Turner and Walker, Comput.Phys.Commun, 191 (2023)

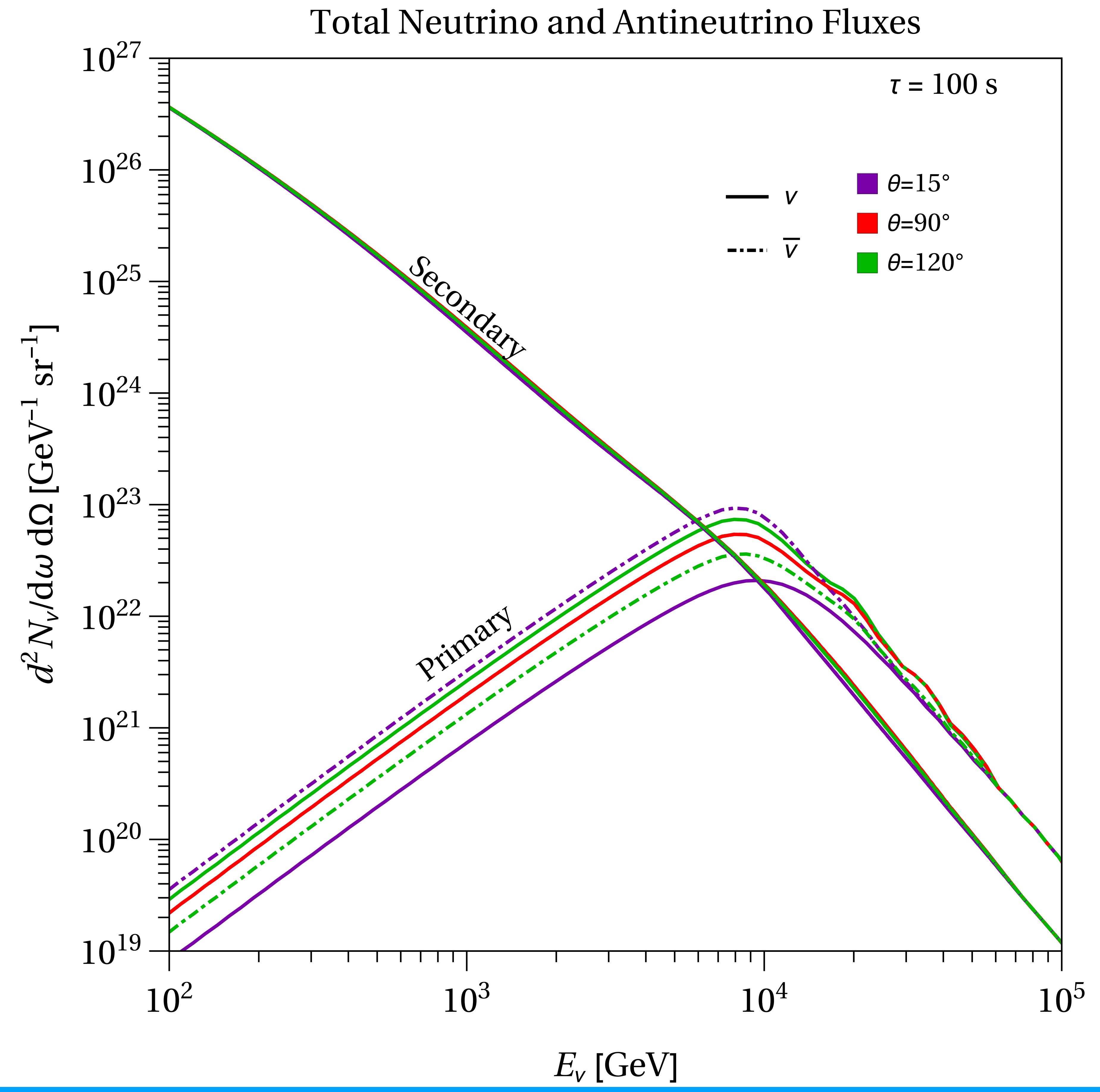


Bernal, Fong, Perez-Gonzalez, Turner, PRD 106 (2022)

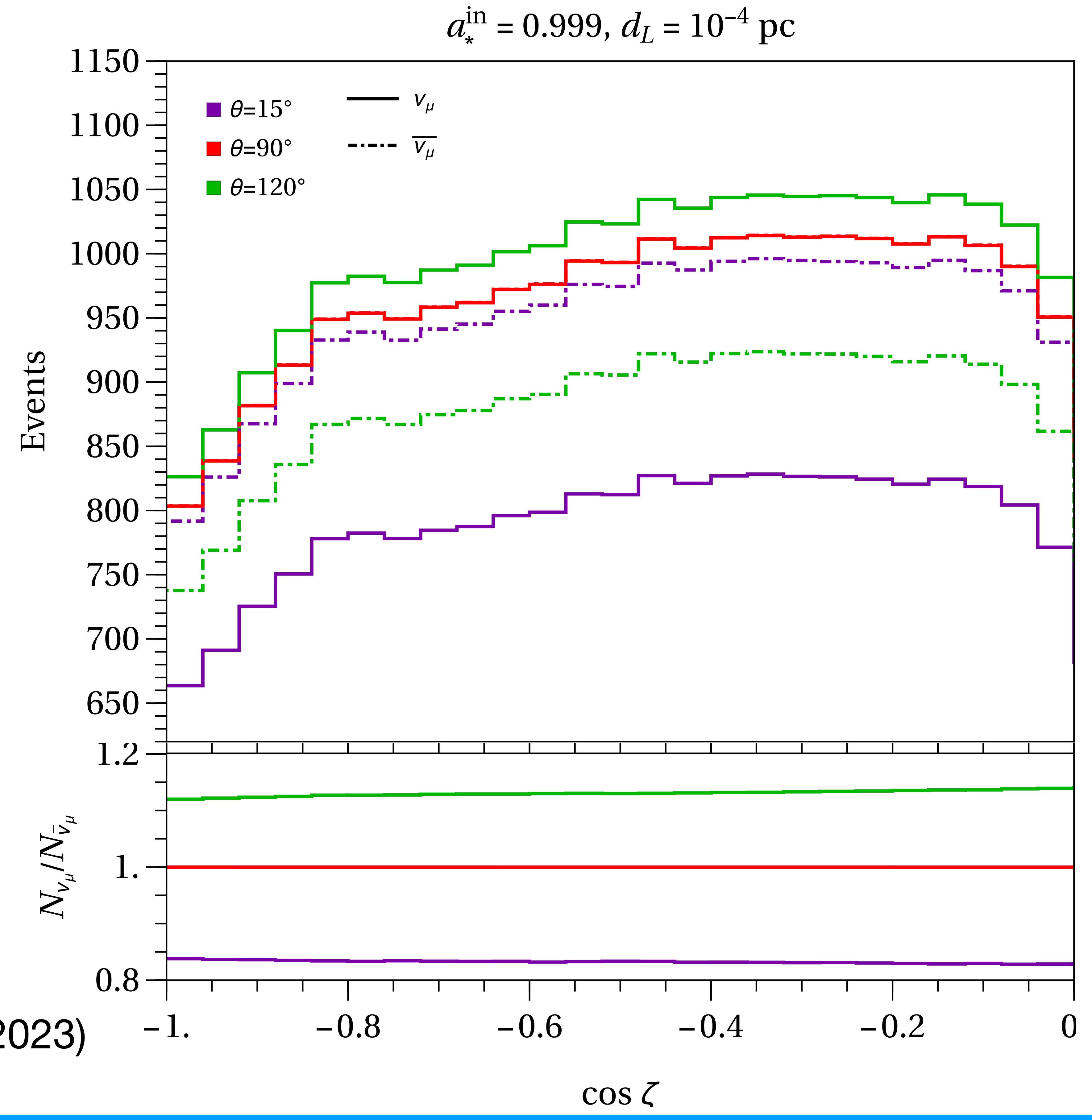
Primordial Black Holes



At the final stage, particle emission intensifies in PBH evaporation



The neutrino burst can be observed by neutrino telescopes



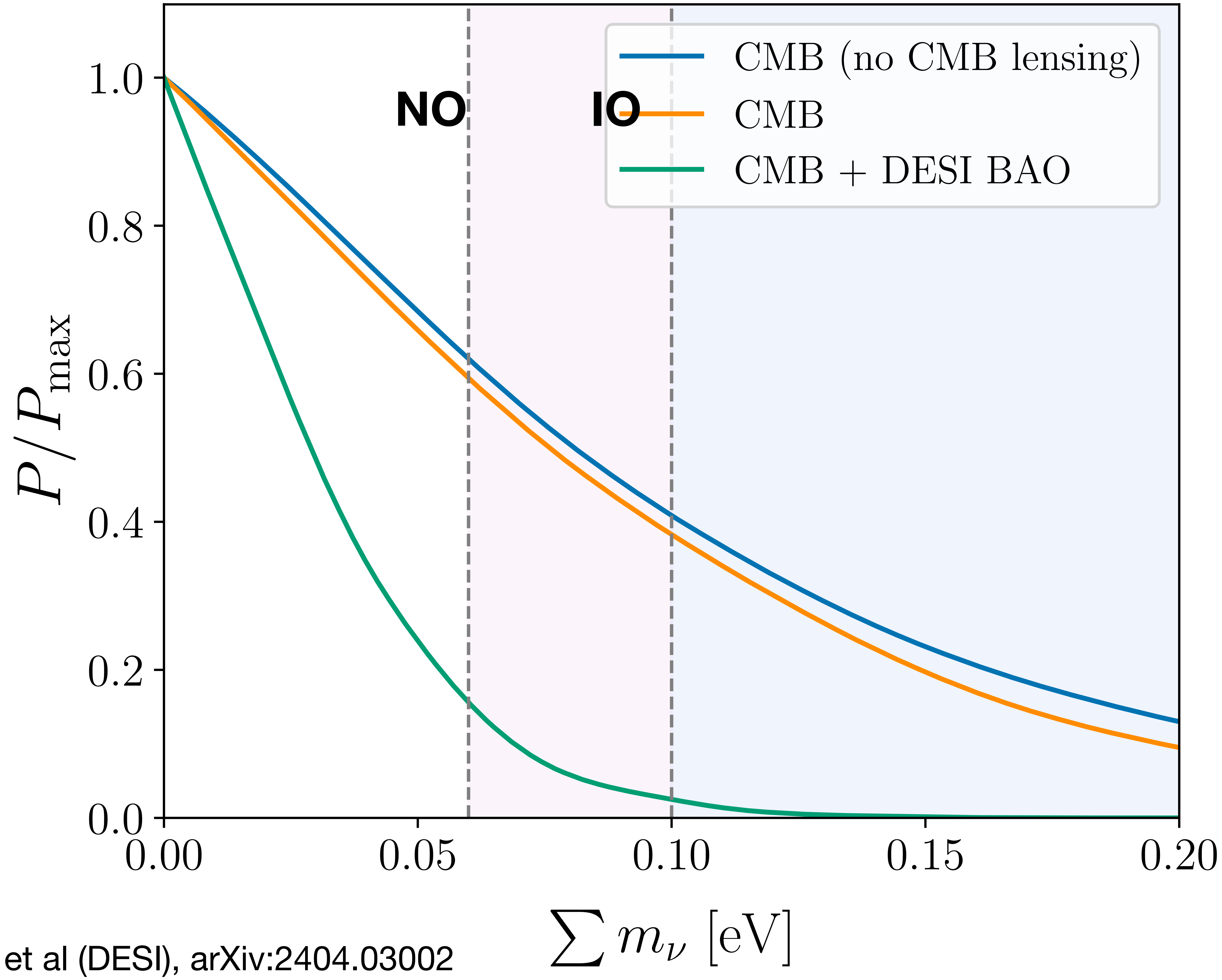
Perez-Gonzalez, PRD 108 (2023)

Neutrino Masses in Cosmology

Neutrino masses affect cosmological measurement through their **free-streaming** and their contribution to **non-relativistic matter density** at low redshift

$\sum m_\nu < 0.21\text{eV}$ 95%, CMB

$\sum m_\nu < 0.072\text{eV}$ 95%, DESI BAO + CMB

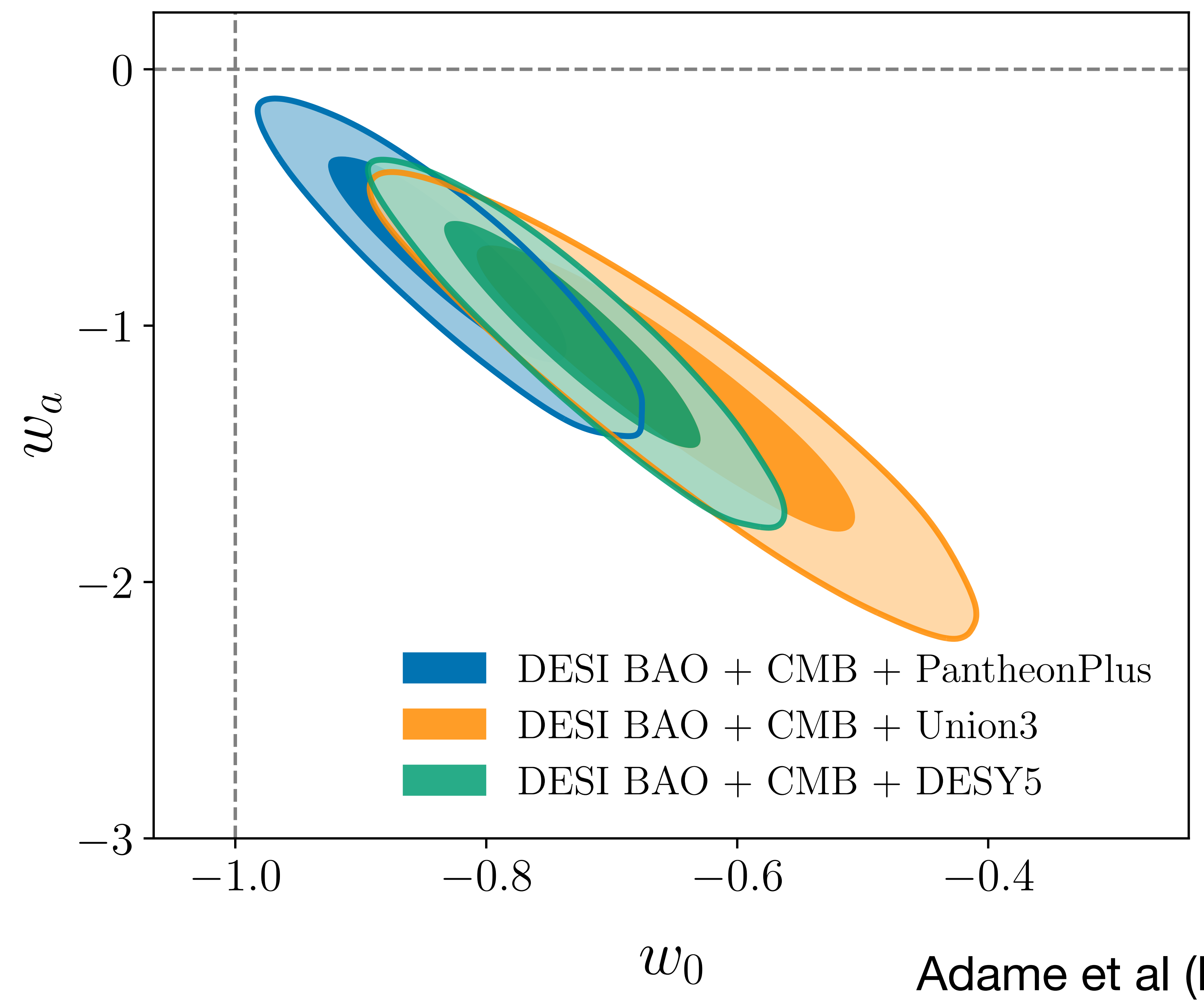


Adame et al (DESI), arXiv:2404.03002

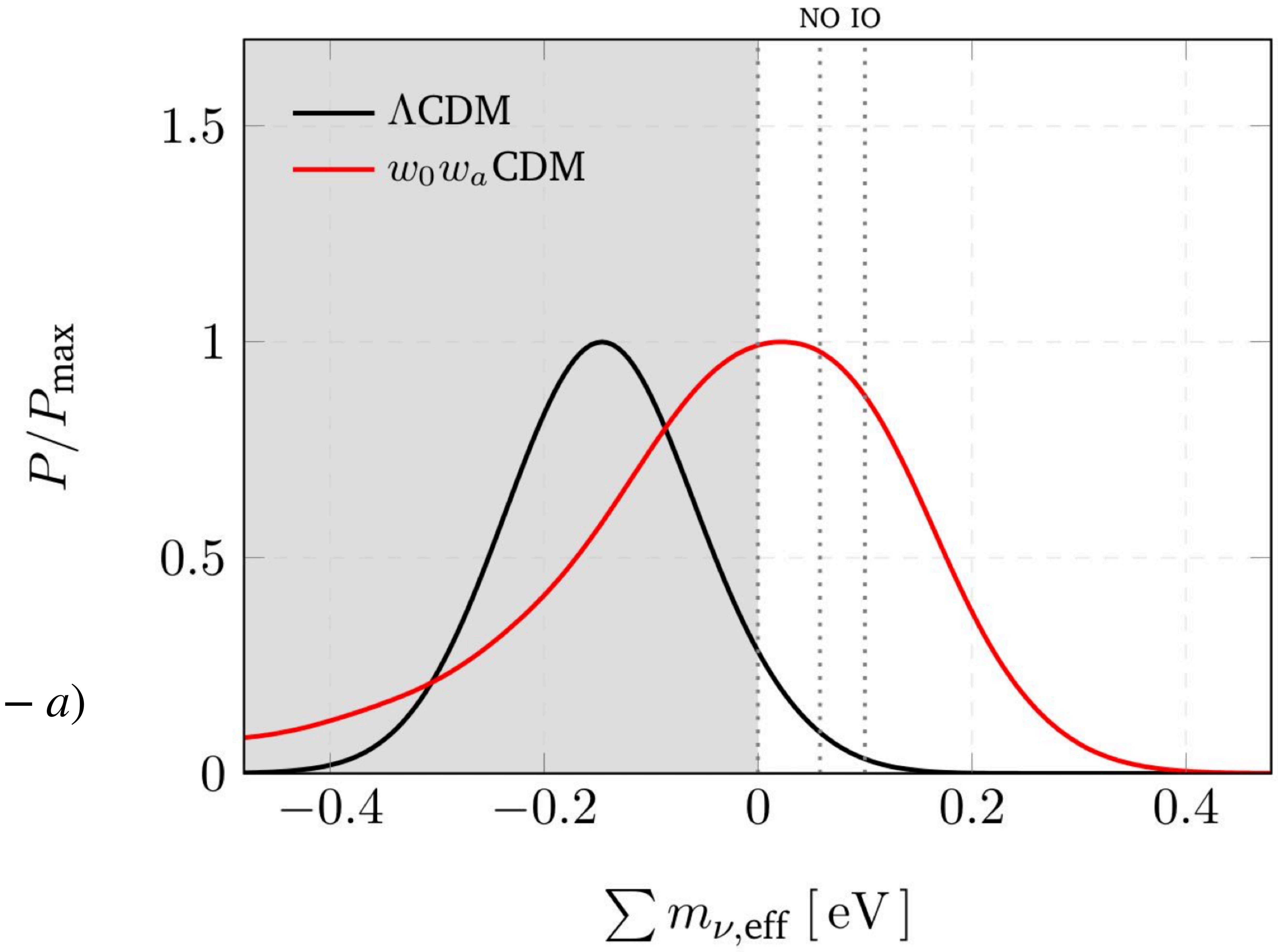
Neutrino Masses in Cosmology

- Considering scenarios other than ΛCDM, the tension with neutrino oscillations is reduced

- Time-varying equation of state for dark energy



$$w(a) = w_0 + w_a(1 - a)$$



Adame et al (DESI), arXiv:2404.03002

Elbers (DESI), Neutrino2024

Conclusions

- The discovery of the neutrino masses has raised new questions about how to explain them.
- One option to explain neutrino masses is to add a right-handed neutrino, which allows for the possibility of Majorana neutrino masses.
- Light values of this mass might leave an imprint on the astrophysical neutrino fluxes through oscillation between active and sterile states.
- Majorana masses on the GeV scale can be investigated in laboratory experiments such as beam dumps or neutrinoless double beta decay.
- Such heavy states could be responsible for the baryon asymmetry observed in the universe.
- Cosmology is also sensitive to neutrino masses. Recent results are intension with neutrino oscillations, raising the question of whether this indicates BSM.