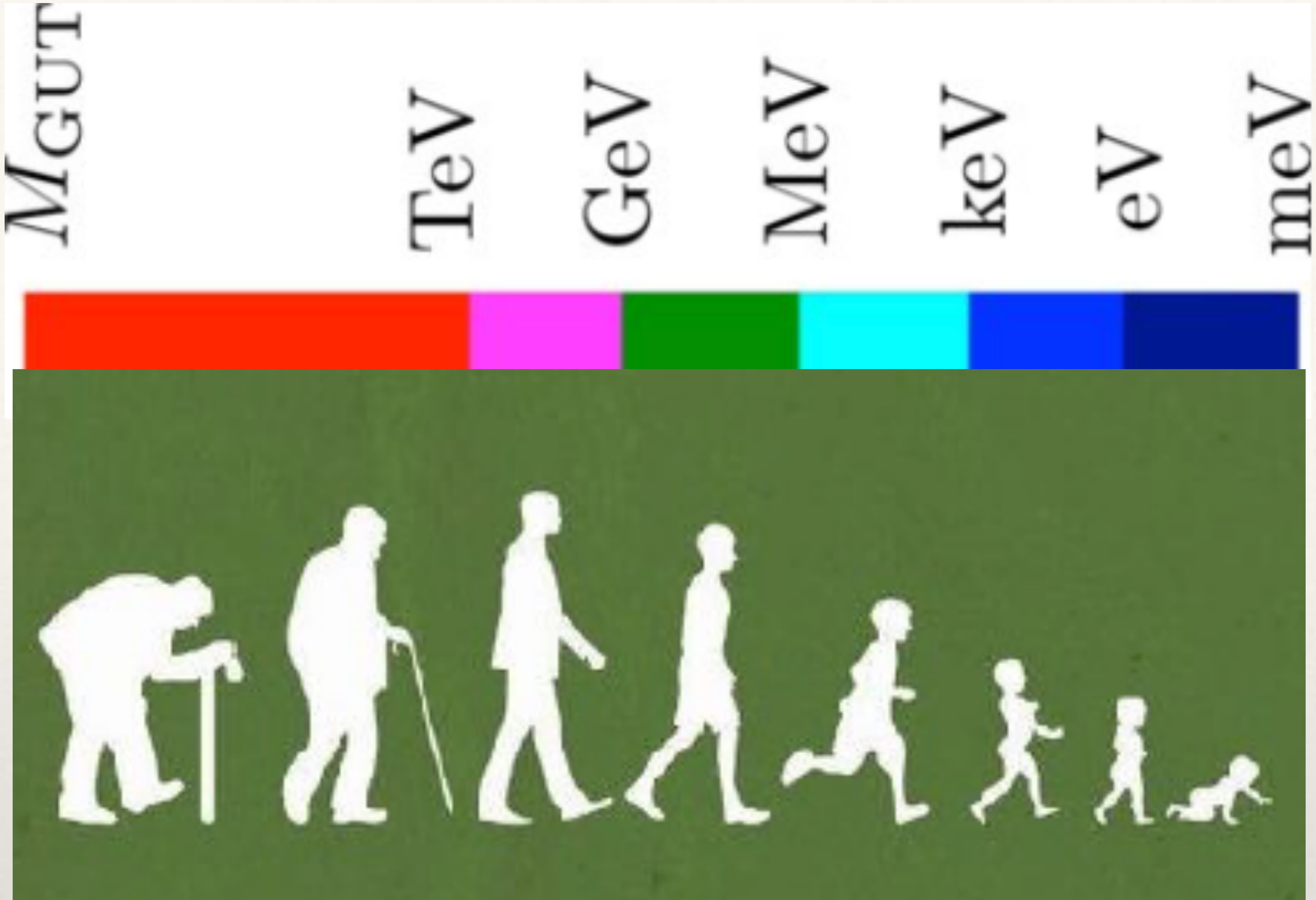

The Curious Case of the Sterile Neutrino

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Physical Research Laboratory
J.C. Bose Fellow, ANRF

Trends in Astro-Particle and Particle Physics, IMSC, Chennai

Neutrinos : What we know

- Neutral leptons with three flavours
- Flavour eigenstates not the same as mass eigenstates
- Leads to neutrino oscillations — have been observed
- Mixing between flavour states governed by U_{PMNS}
- Mass splittings and mixing angles are measured
- The limit on sum of neutrino masses from cosmology

Three Neutrino Paradigm

- Measurement of non-zero θ_{13} in reactor experiments → three neutrino picture

Atm +LBL **Sol+KL**

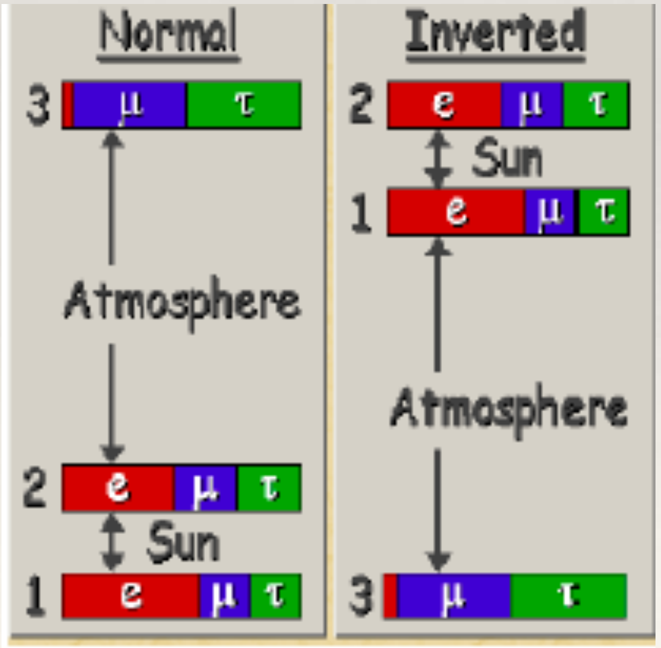
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & e^{-i\delta} s_{13} \\ & 1 & \\ -e^{i\delta} s_{13} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$c_{12} = \cos\theta_{12}$ etc., δ CP-violating phase

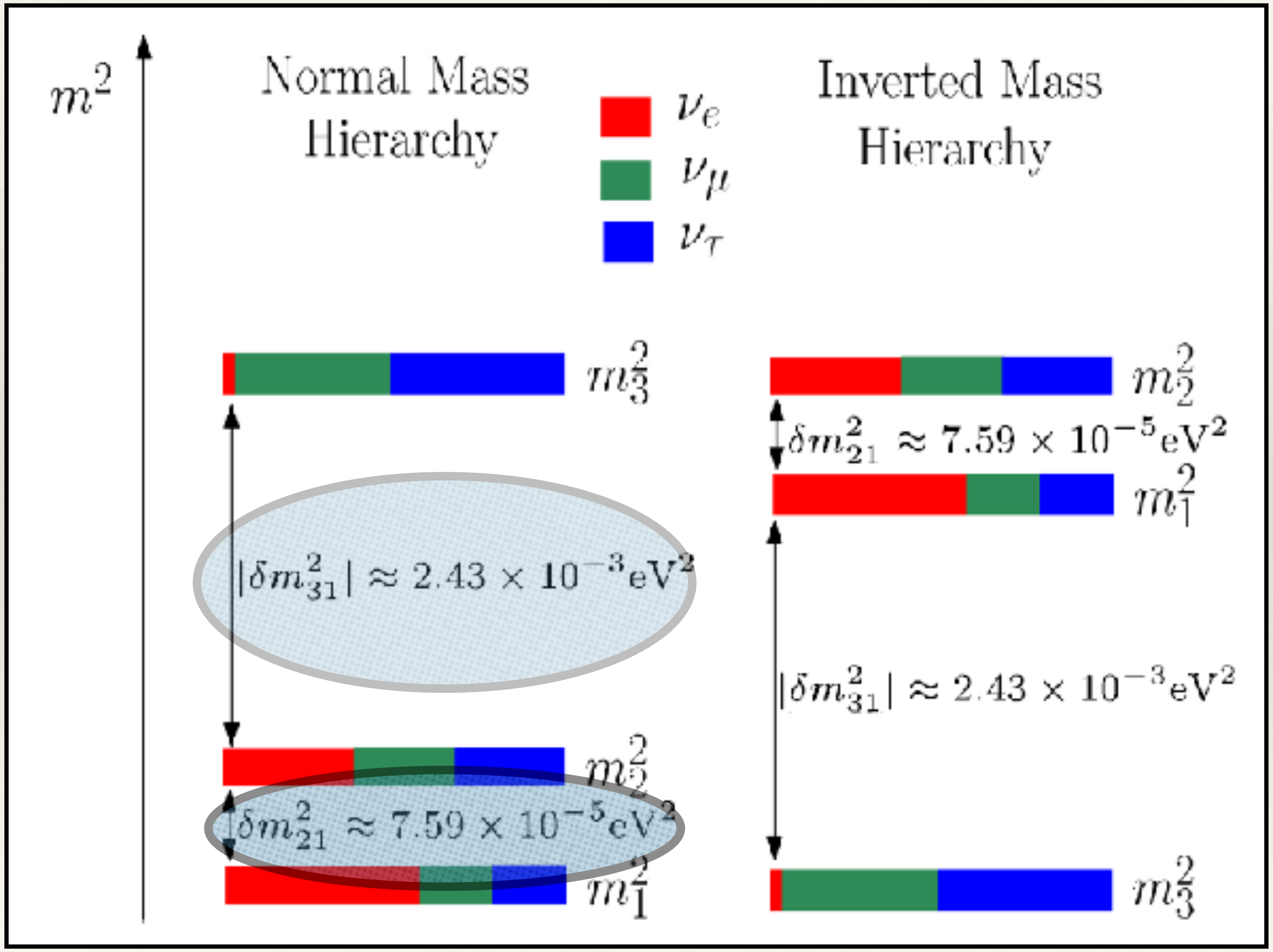
- Δm^2_{21}, θ_{12}, θ_{13} Solar + KamLND
- Δm^2_{31}, θ_{13} Reactor
- Δm^2_{31}, θ_{23}, θ_{13}, δ_{CP} Atm + LBL

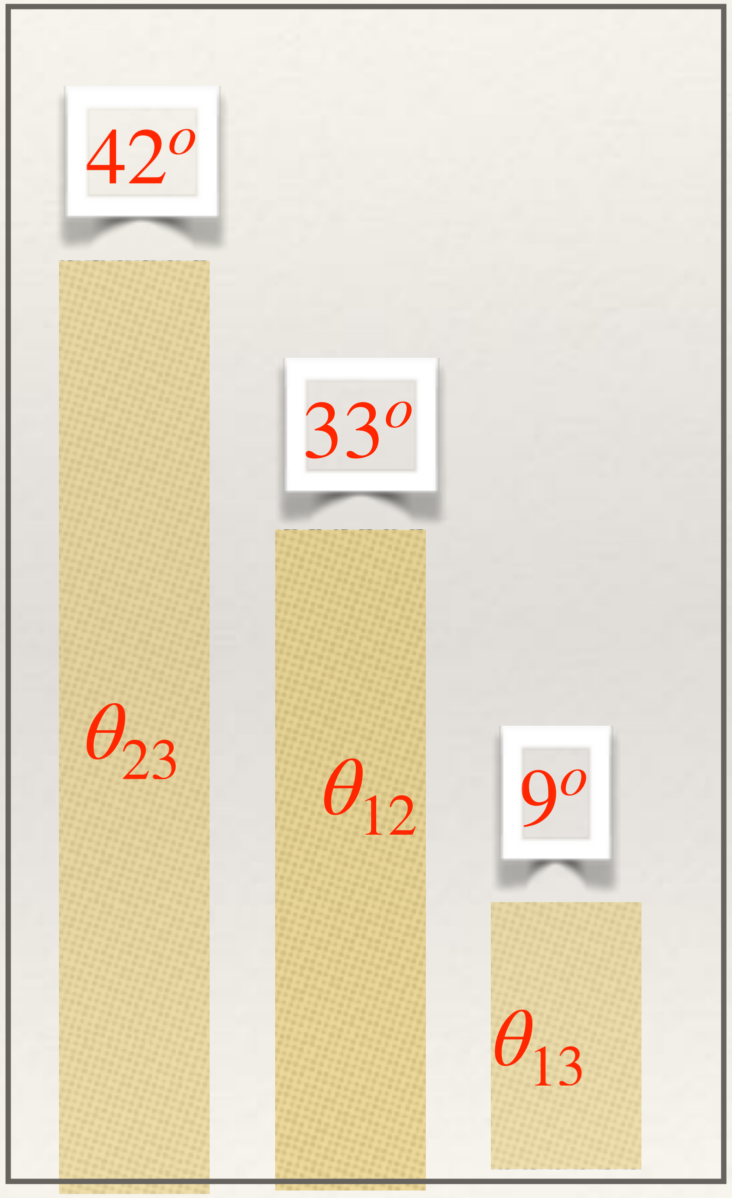
↓

Interplay among different sectors because of θ_{13}



Neutrino Oscillation Parameters



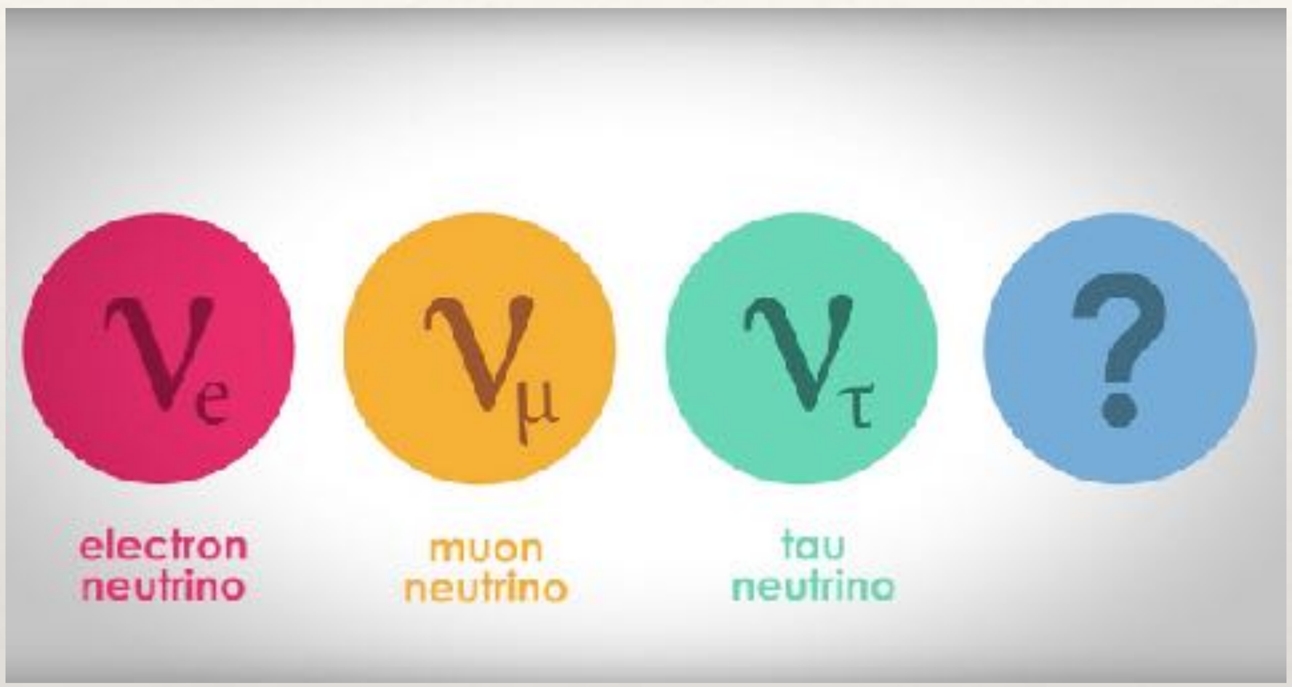


Neutrino Oscillation : from discovery to precision

with SK atmospheric data		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 6.4$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
	$\sin^2\theta_{12}$	$0.303^{+0.012}_{-0.012}$	$0.270 \to 0.341$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$
	$\theta_{12}/^\circ$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$
	$\sin^2\theta_{23}$	$0.451^{+0.019}_{-0.016}$	$0.408 \to 0.603$	$0.569^{+0.016}_{-0.021}$	$0.412 \to 0.613$
	$\theta_{23}/^\circ$	$42.2^{+1.1}_{-0.9}$	$39.7 \to 51.0$	$49.0^{+1.0}_{-1.2}$	$39.9 \to 51.5$
	$\sin^2\theta_{13}$	$0.02225^{+0.00056}_{-0.00059}$	$0.02052 \to 0.02398$	$0.02223^{+0.00058}_{-0.00058}$	$0.02048 \to 0.02416$
	$\theta_{13}/^\circ$	$8.58^{+0.11}_{-0.11}$	$8.23 \to 8.91$	$8.57^{+0.11}_{-0.11}$	$8.23 \to 8.94$
	$\delta_{CP}/^\circ$	232^{+36}_{-26}	$144 \to 350$	276^{+22}_{-29}	$194 \to 344$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.507^{+0.026}_{-0.027}$	$+2.427 \to +2.590$	$-2.486^{+0.025}_{-0.028}$	$-2.570 \to -2.406$

NuFIT 5.2 (2022)

Are there more than 3 neutrinos ?



Sterile =>   No Standard Model Interaction

Can mix with Standard Model Neutrinos

Light ? Heavy ?

Sterile Neutrinos

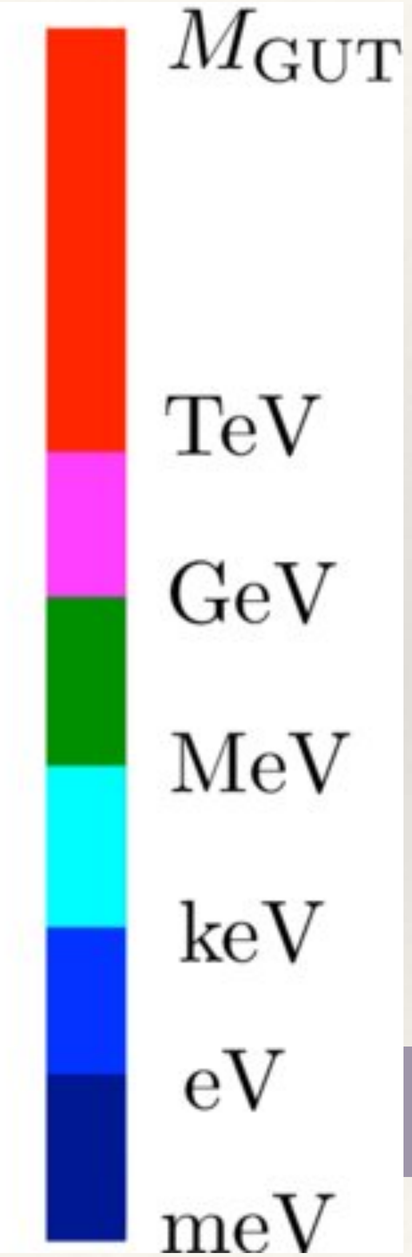
Seesaw, Leptogenesis

Low Scale Seesaw (inverse seesaw, vacuum stability leptogenesis, neutrino less double beta decay, charged lepton flavour violation, dark matter)

Dark Matter

Warm dark matter

LSND/MiniBOONE signal



Colliders, charged lepton flavour violation

Fixed Target Experiments

Meson decays

β Decay

Oscillation Experiments

Sterile Neutrinos

Seesaw, Leptogenesis

Low Scale Seesaw (inverse seesaw, vacuum stability leptogenesis, neutrino less double beta decay, charged lepton flavour violation, dark matter)

Dark Matter

Warm dark matter

LSND/MiniBOONE signal

Colliders, charged lepton flavour violation

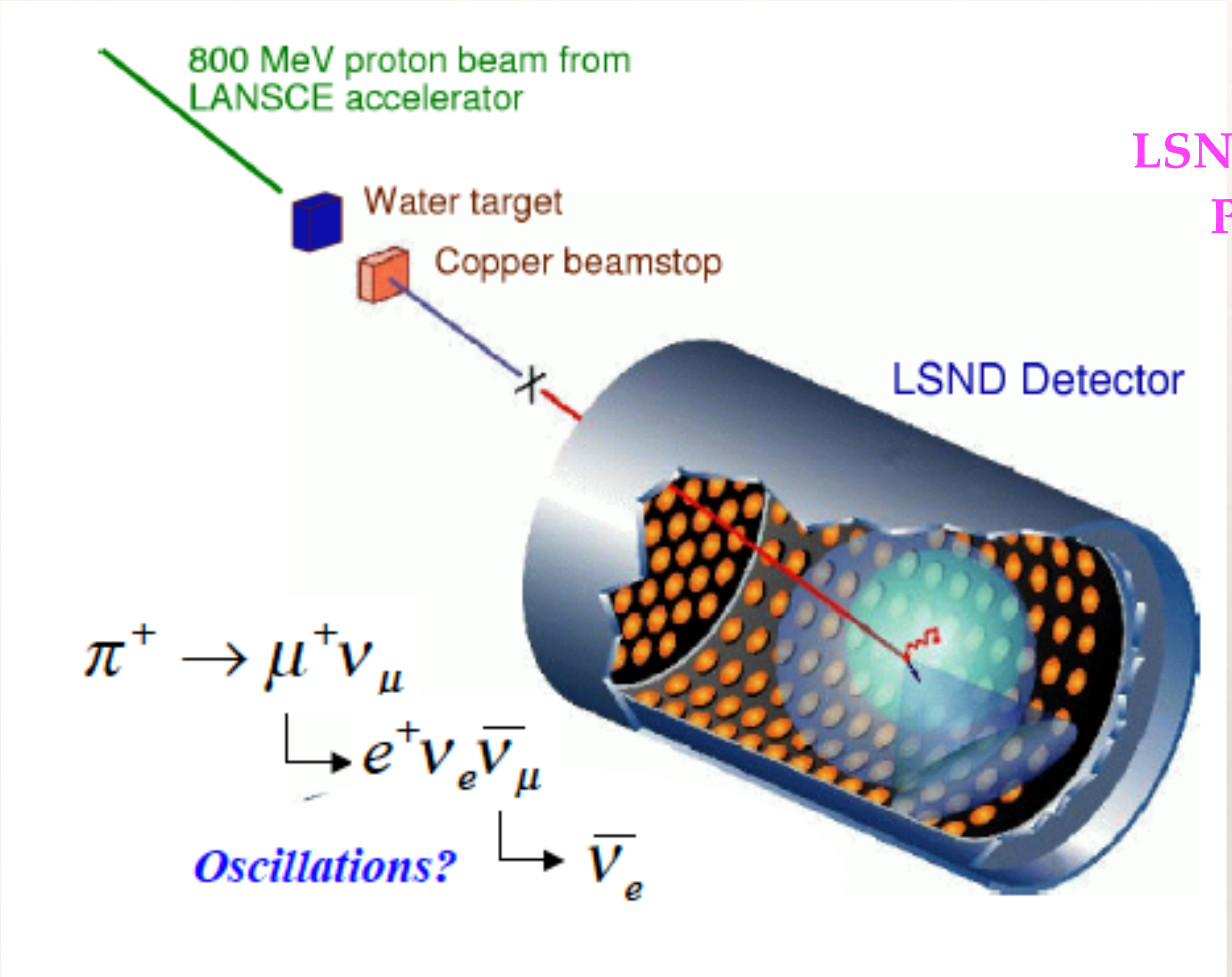
Fixed Target Experiments

Meson decays

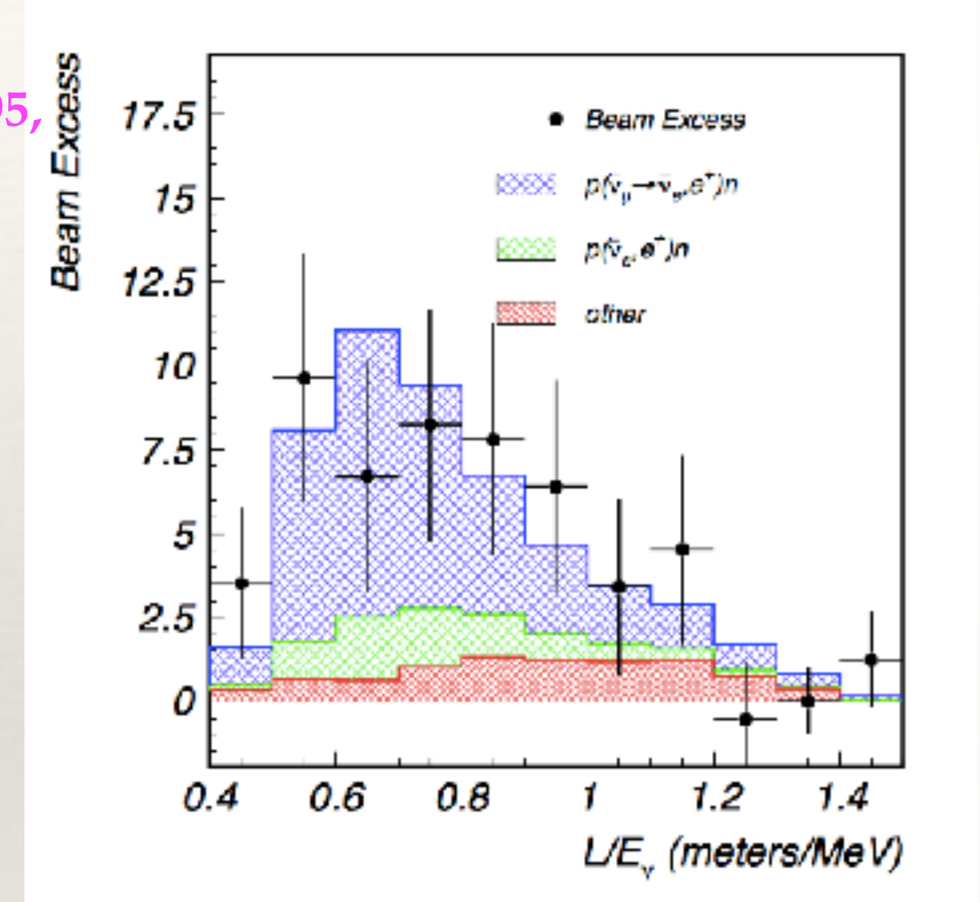
β Decay

Oscillation Experiments

LSND results



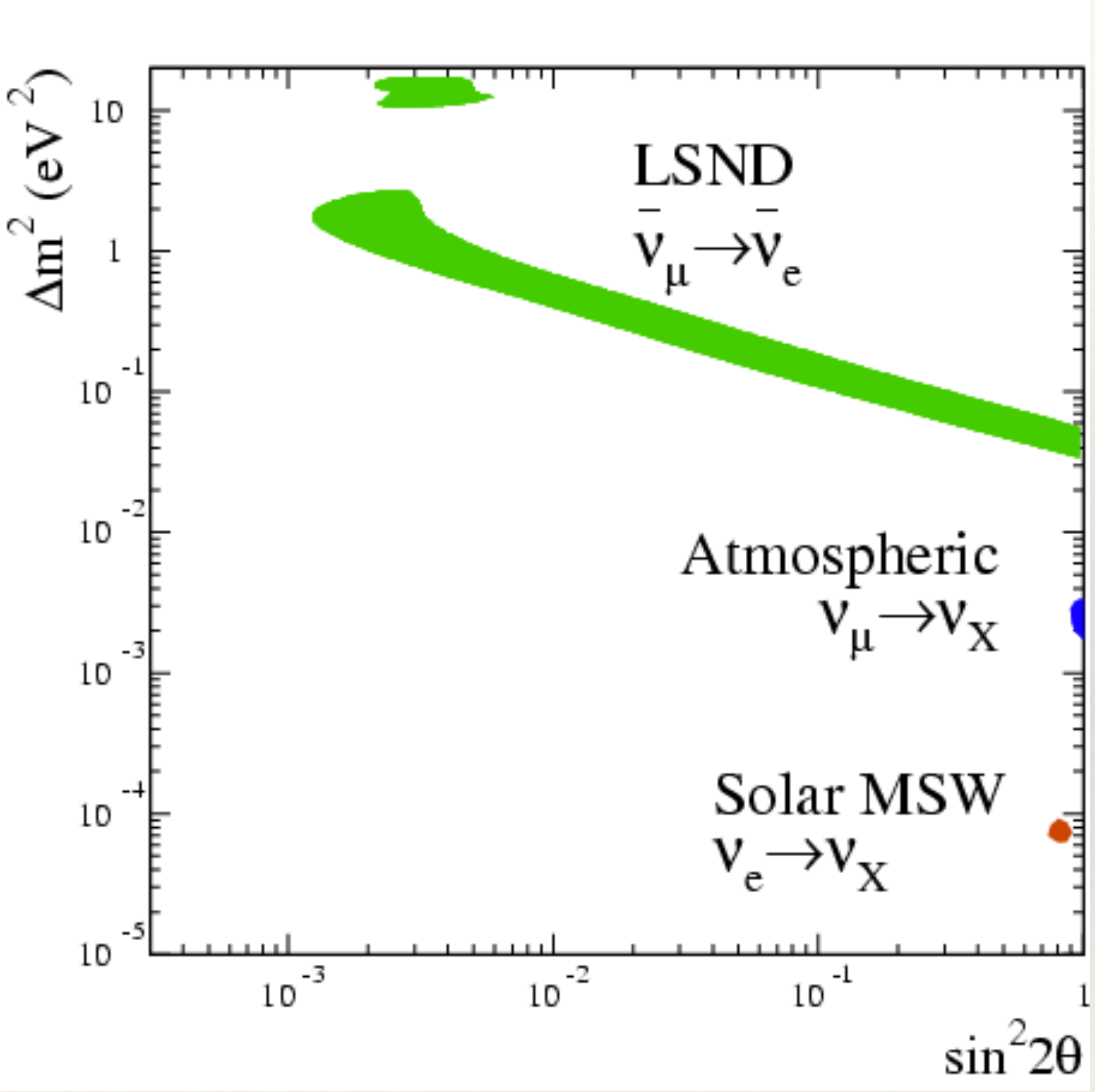
LSND PRL 1995, PRD 2001



$\bar{\nu}_\mu \to \bar{\nu}_e$ $\quad L \simeq 30\,\mathrm{m}$ $\quad 20\,\mathrm{MeV} \le E \le 200\,\mathrm{MeV}$

3.8σ excess $\quad \Delta m^2 \gtrsim 0.2\,\mathrm{eV}^2$

Sterile Neutrino



$$\Delta m^2_{solar} = 10^{-5} eV^2$$
$$\Delta m^2_{atm} = 10^{-3} eV^2$$

Requires at least one additional neutrino (3+1)

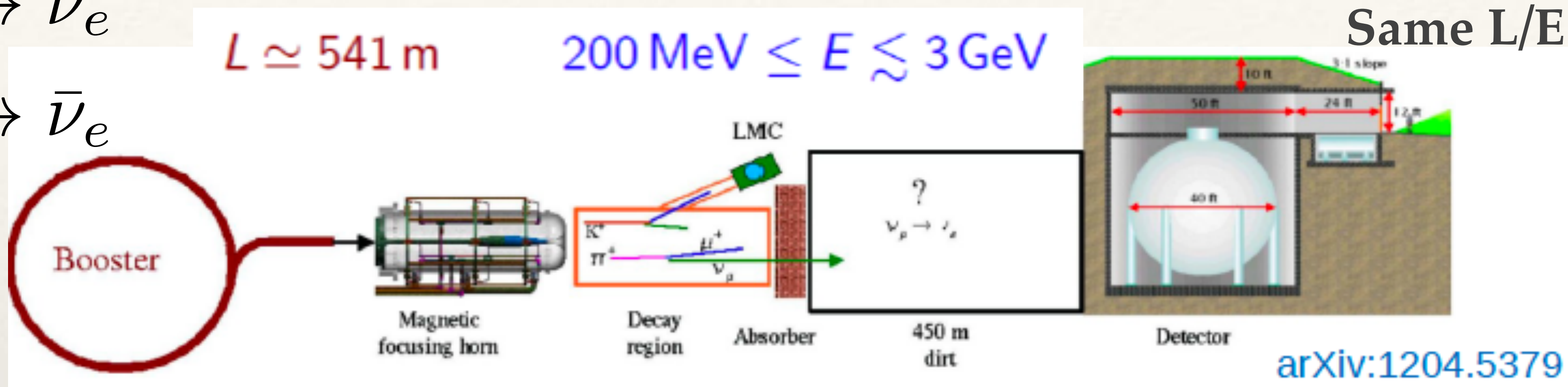
- The constraints from Z decay => the additional neutrino is sterile i.e has no Standard Model gauge interaction
-

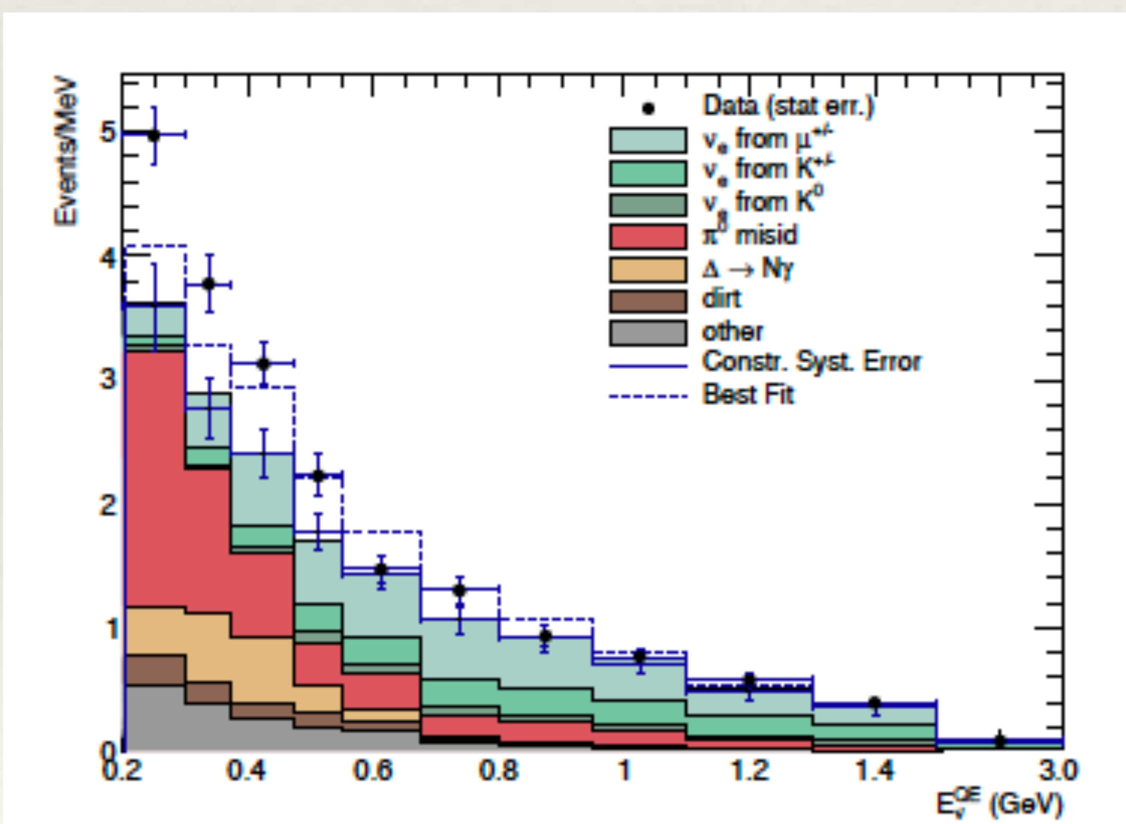
MiniBoone

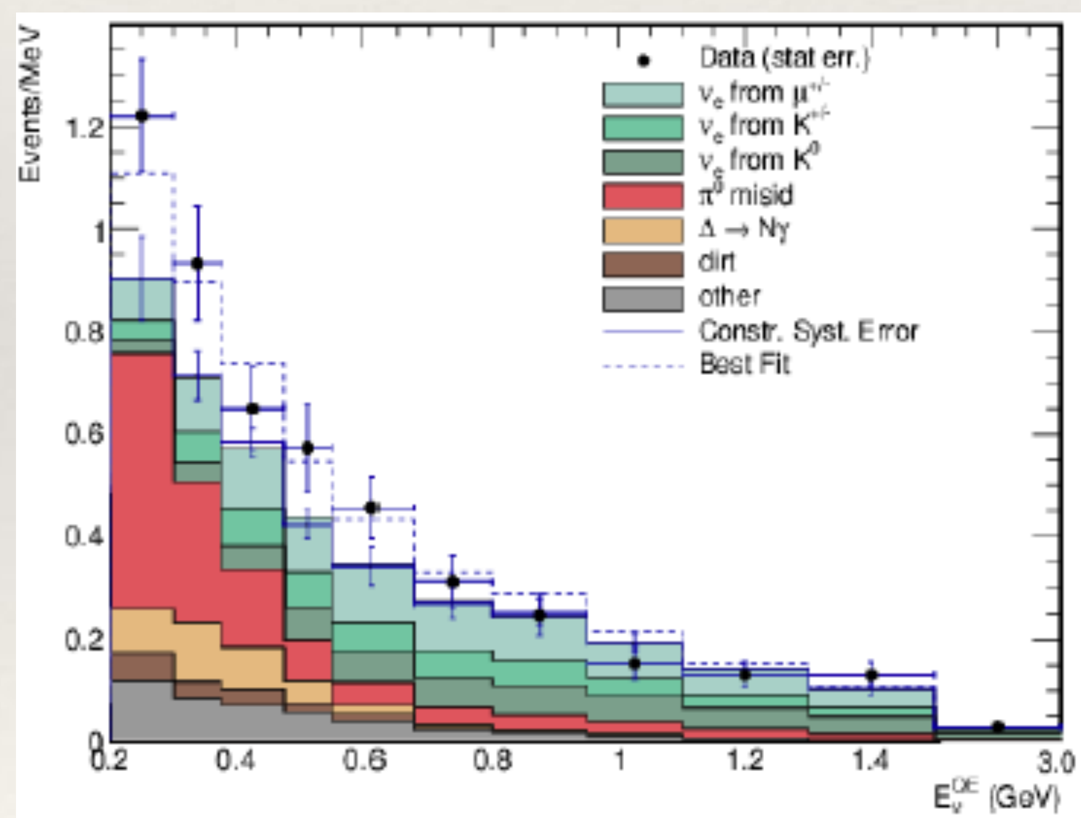
$\nu_\mu \to \nu_e$

$\bar{\nu}_\mu \to \bar{\nu}_e$

Same L/E as LSND

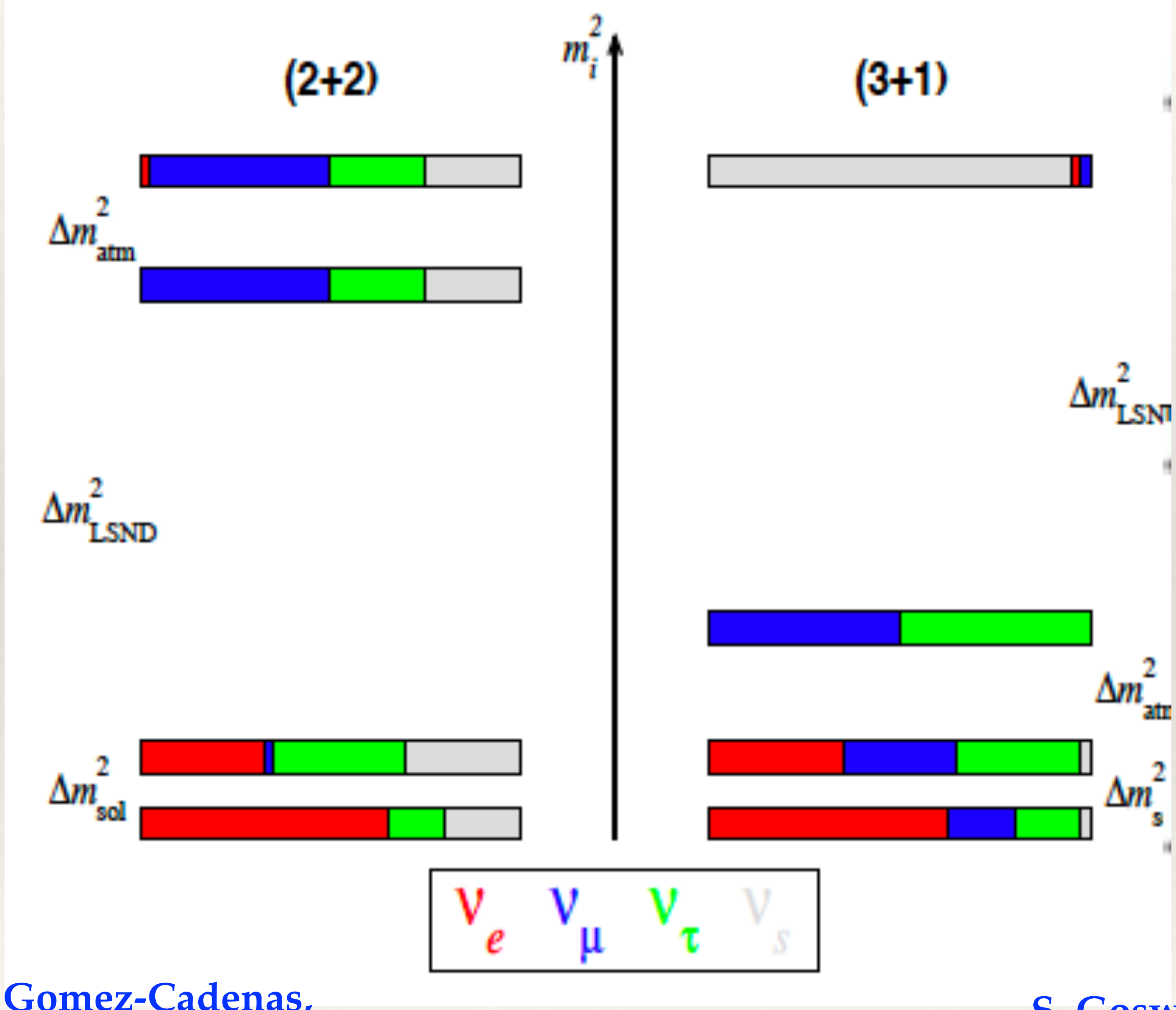






A.A. Aguilar Arevalo, PRL 121, 221801, 2018.

Possible Scenarios



2+2 disfavoured by solar and atmospheric neutrino data

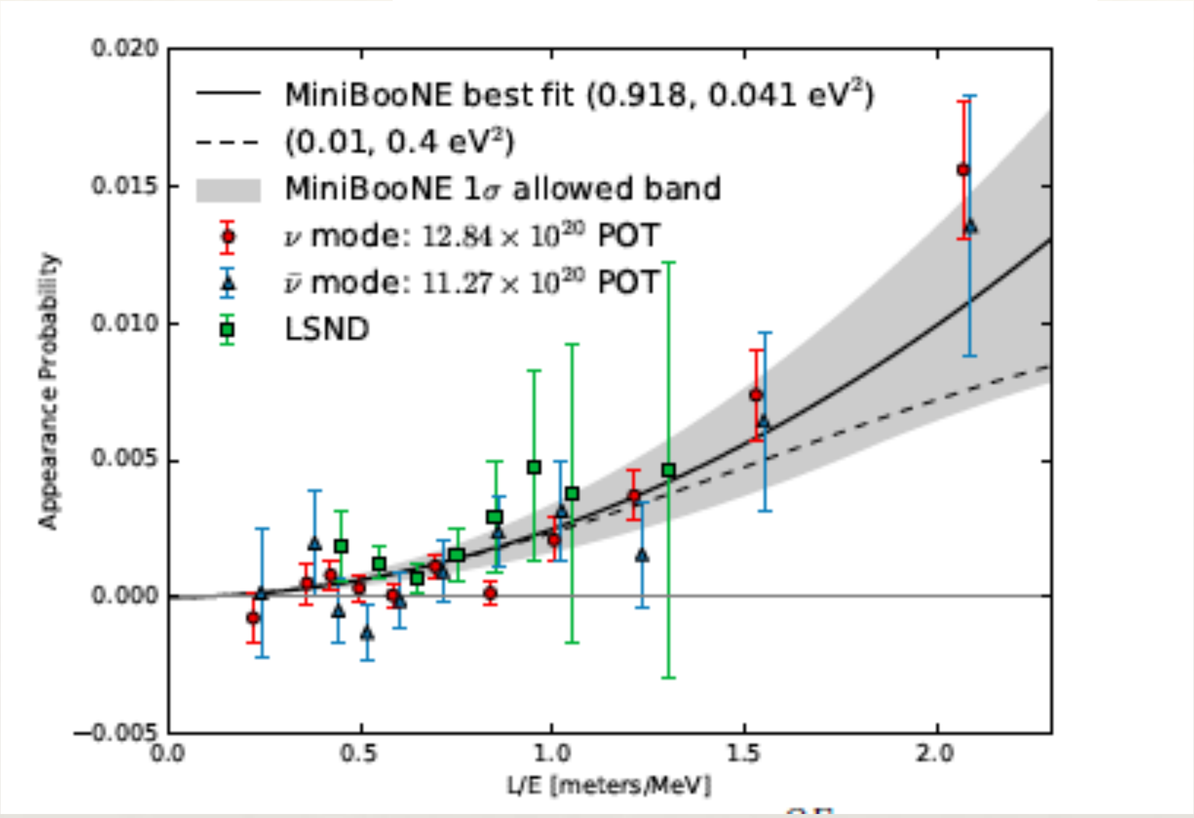
3+1 minimal scheme — strong tension

Gomez-Cadenas, Gonzalez-Garcia, PRD 1995

S. Goswami, Phys. Rev. D, 1996

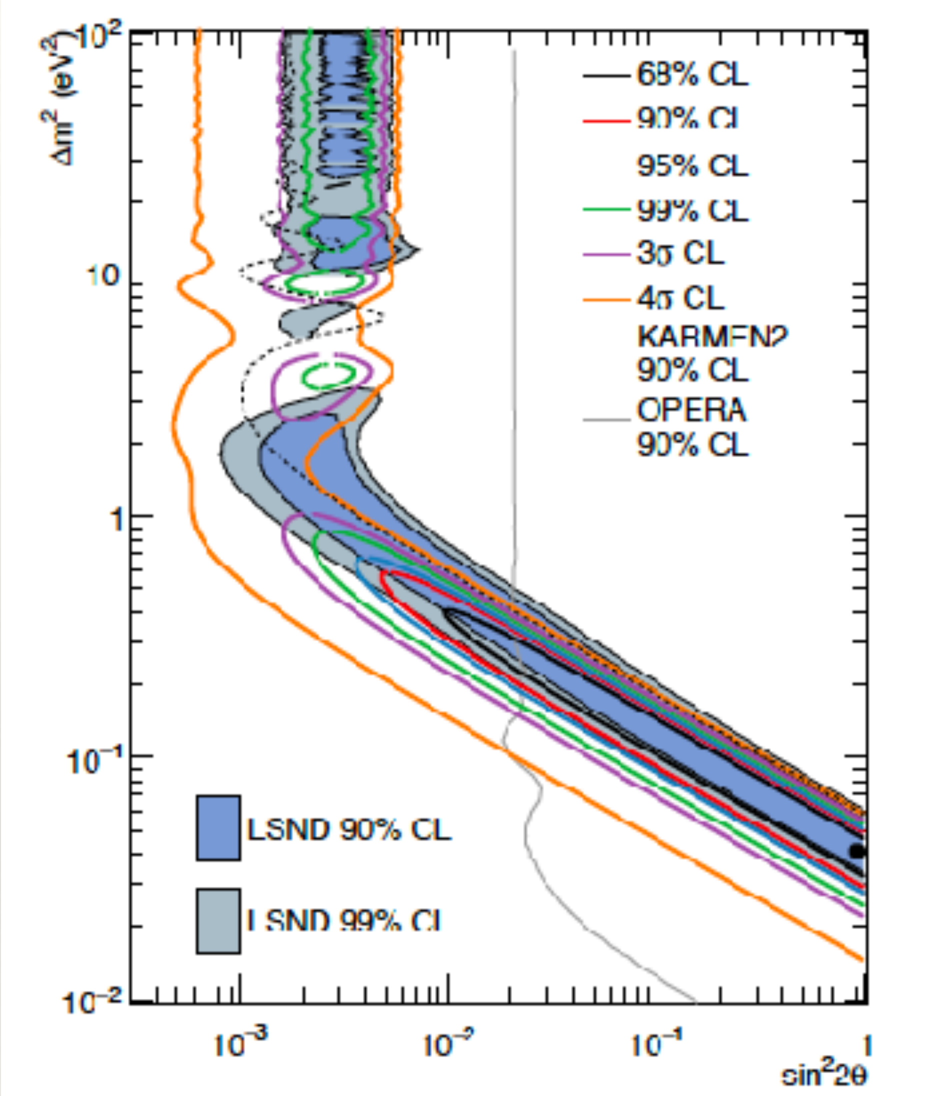
LSND and MiniBoone

$200 < E_\nu^{QE} < 3000$ MeV



Combined significance $\sim 6\sigma$

A.A. Aguilar Arevalo, PRL 121, 221801, 2018.



Two neutrino fit

MiniBoone : neutrino + antineutrino

3+1 mixing framework

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} u_{e1} & u_{e2} & u_{e3} & u_{e4} \\ u_{\mu 1} & u_{\mu 2} & u_{\mu 3} & u_{\mu 4} \\ u_{\tau 1} & u_{\tau 2} & u_{\tau 3} & u_{\tau 4} \\ u_{s1} & u_{s2} & u_{s3} & u_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

$$U = \mathbb{R}_{34}(\theta_{34})\, \mathbb{S}_{24}(\theta_{24}, \delta_{24})\, \mathbb{S}_{14}(\theta_{14}, \delta_{14})\, \mathbb{R}_{23}(\theta_{23})\, \mathbb{S}_{13}(\theta_{13}, \delta_{13})\, \mathbb{R}_{12}(\theta_{12})\, \mathbb{P}$$

$$\mathbb{P} = \mathrm{diag}\{1, e^{i\frac{\alpha}{2}}, e^{i\frac{\beta}{2}}, e^{i\frac{\gamma}{2}}\}$$

Disappearance and appearance tension

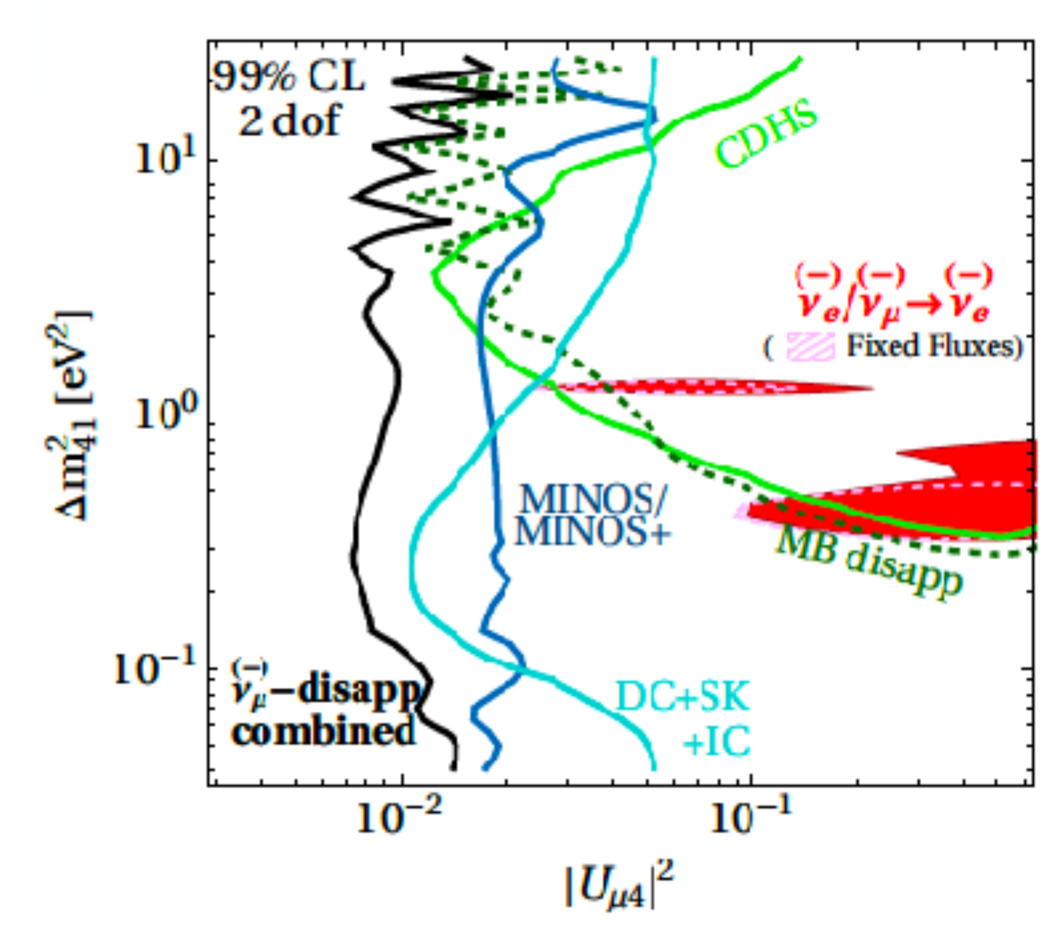
$$P^{\rm SBL}_{\alpha\alpha} = 1 - 4|U_{\alpha 4}|^2(1-|U_{\alpha 4}|^2)\sin^2\left(\frac{\Delta m^2_{41}L}{4E}\right)$$

$$P^{\rm SBL}_{\alpha\beta} = 4|U_{\alpha 4}|^2|U_{\beta 4}|^2\sin^2\left(\frac{\Delta m^2_{41}L}{4E}\right).$$

P_{ee} **depends on** $|U_{e4}|^2$

$P_{\mu\mu}$ **depends on** $|U_{\mu 4}|^2$

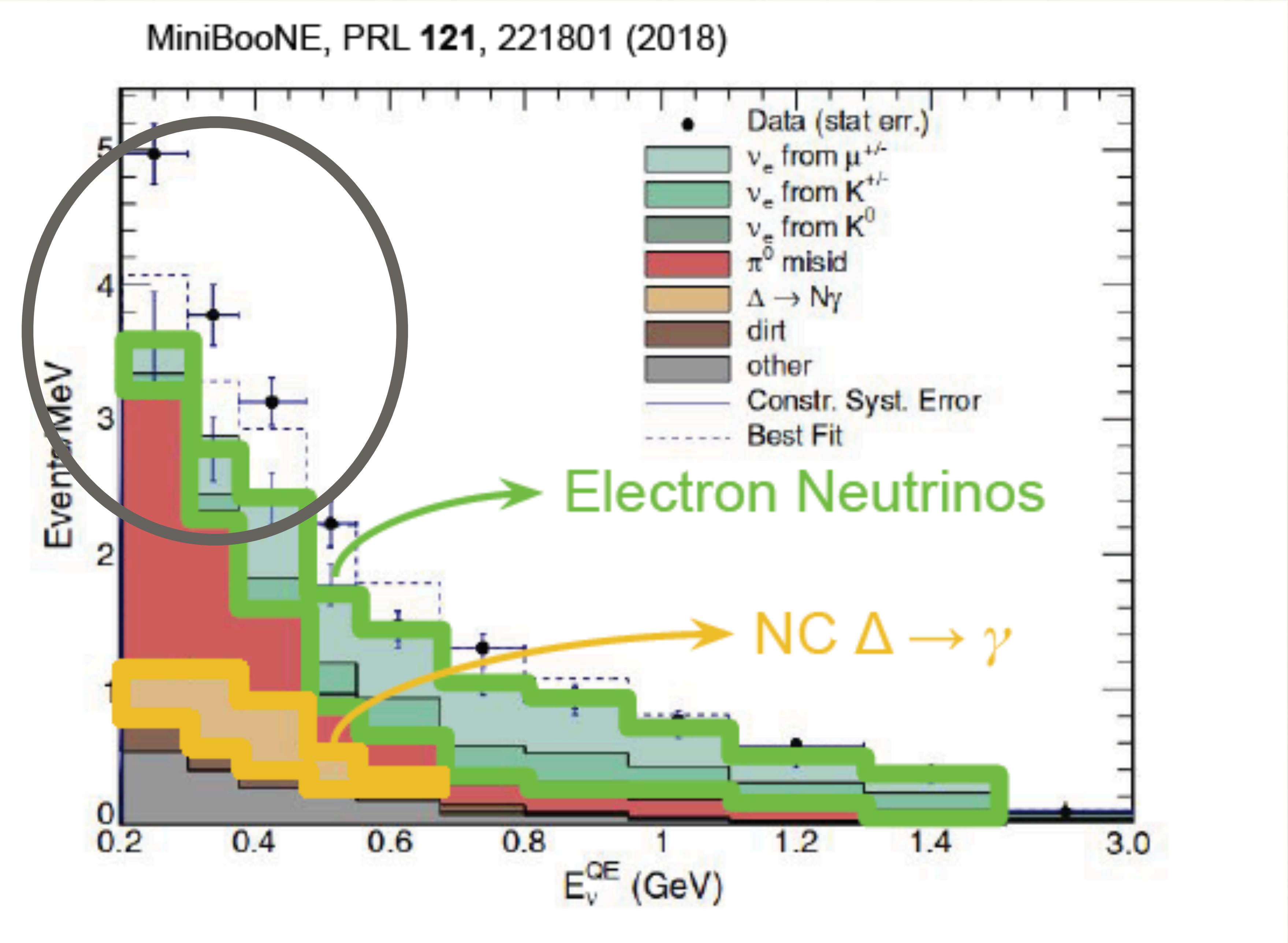
$P_{\mu e}$ **depends on** $|U_{\mu 4}|^2|U_{e4}|^2$



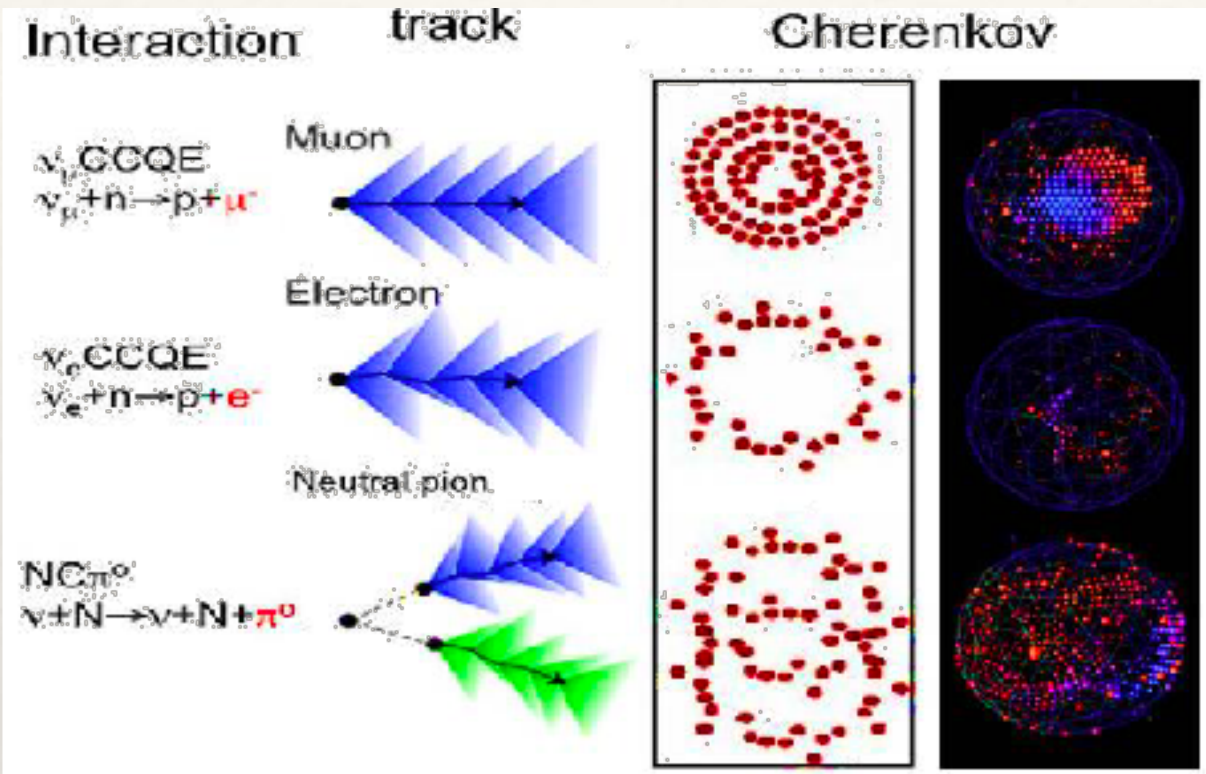
Dentler, Hernandez-Cabezudo,Kopp, Maltoni, Schwetz,JHEP 2017

Low Energy Excess in MiniBoone

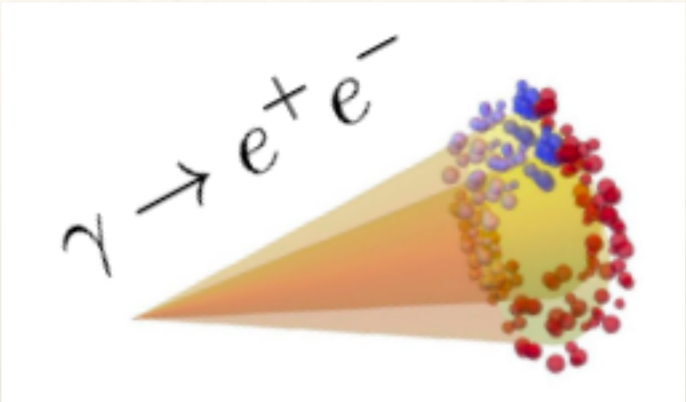
4.5σ
Excess

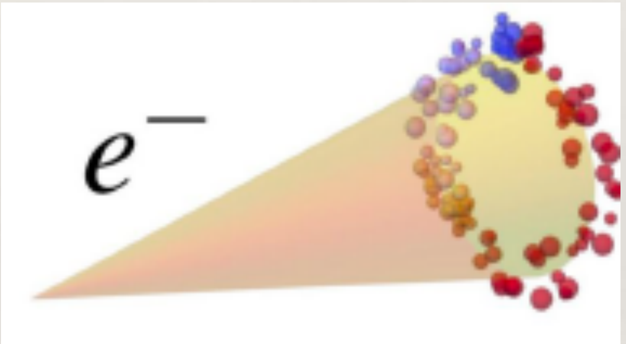


Is it due to background effect ?



From : S. Jana , Pheno 2019

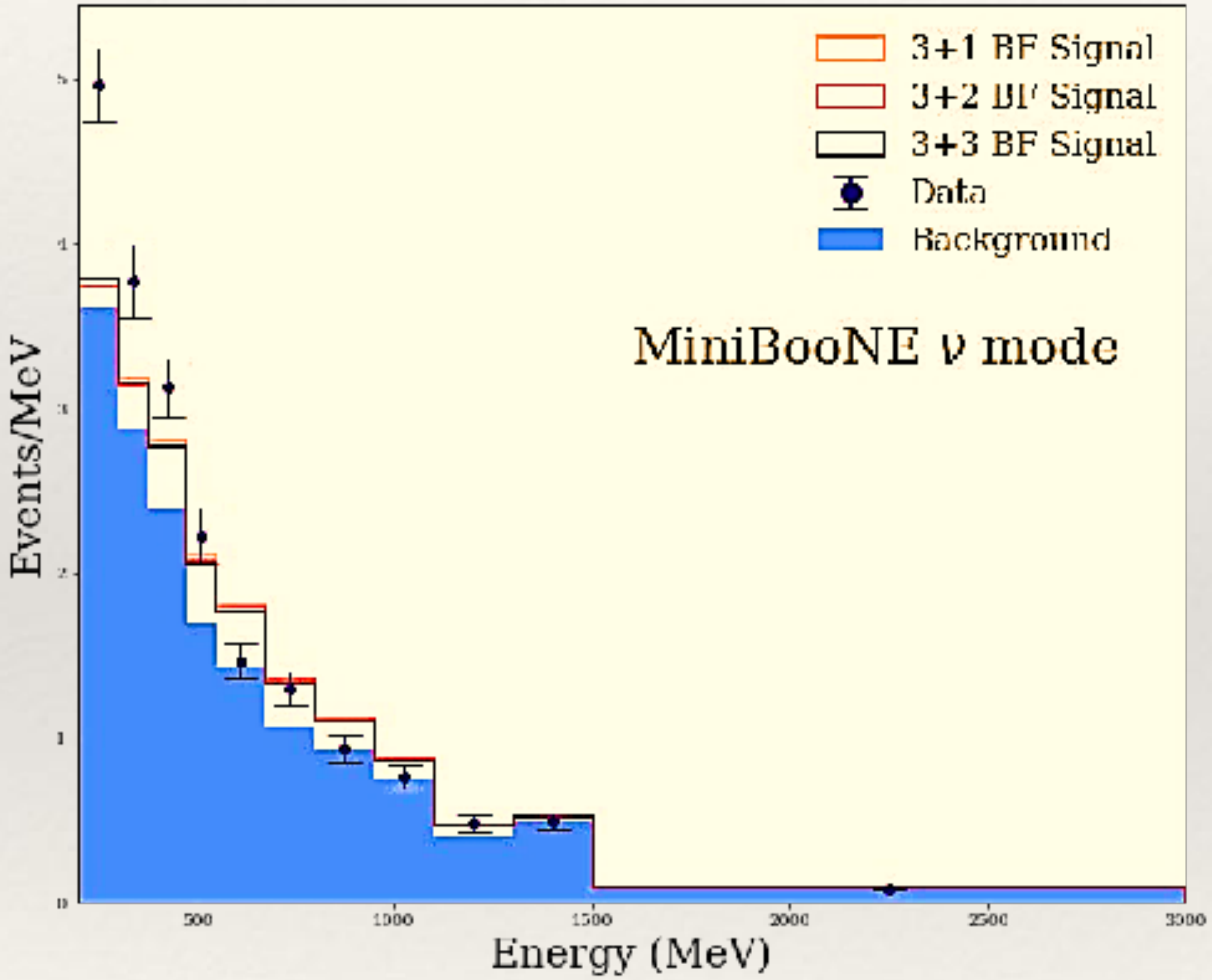




Cannot distinguish between Cherenkov cone of electrons and single photon

The single photons coming from NC background cannot explain the excess

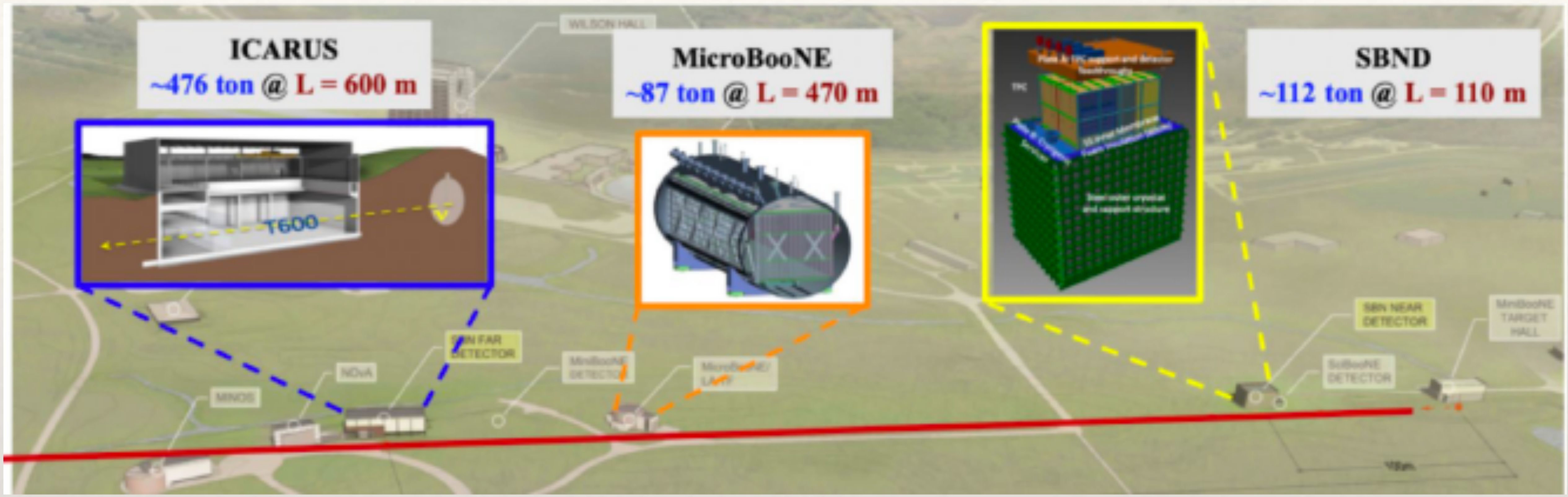
Sterile neutrinos and low energy excess

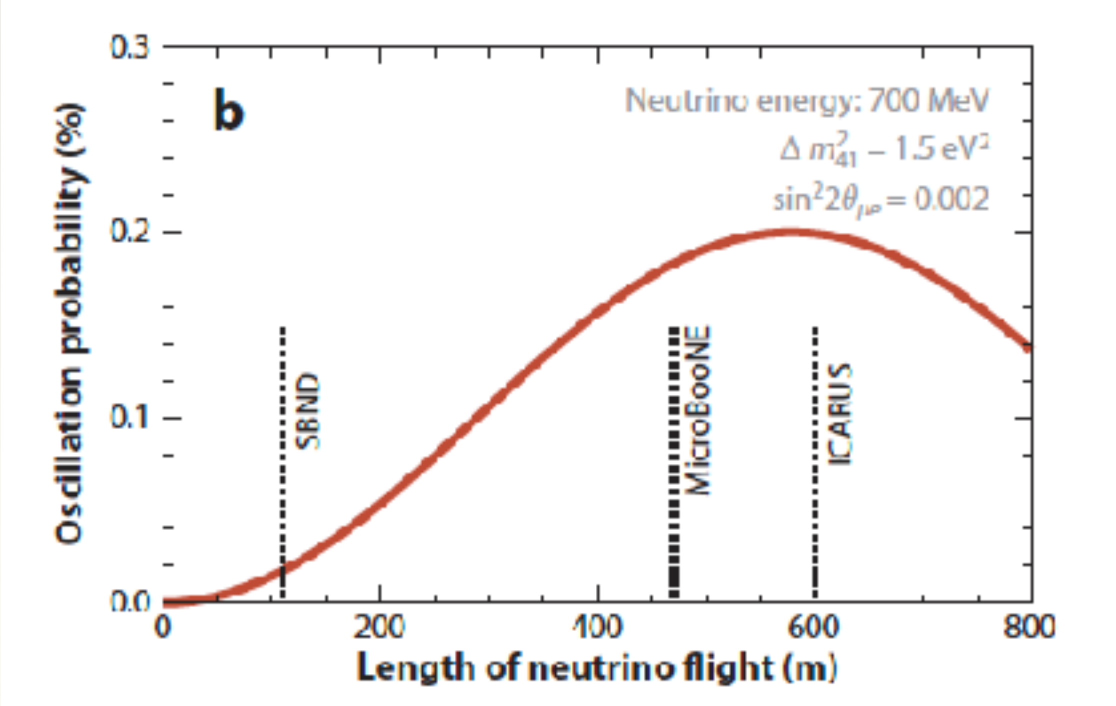


3+N sterile neutrino scenario cannot explain the MiniBoone low energy excess

D. Cianci , talk at Applied Antineutrino Physics Workshop 2018

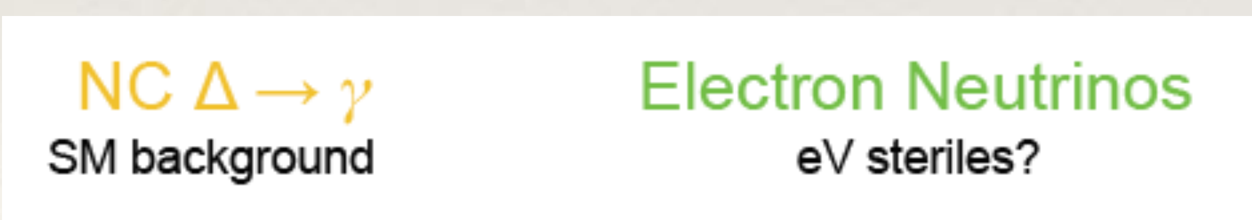
SBN@FermiLab



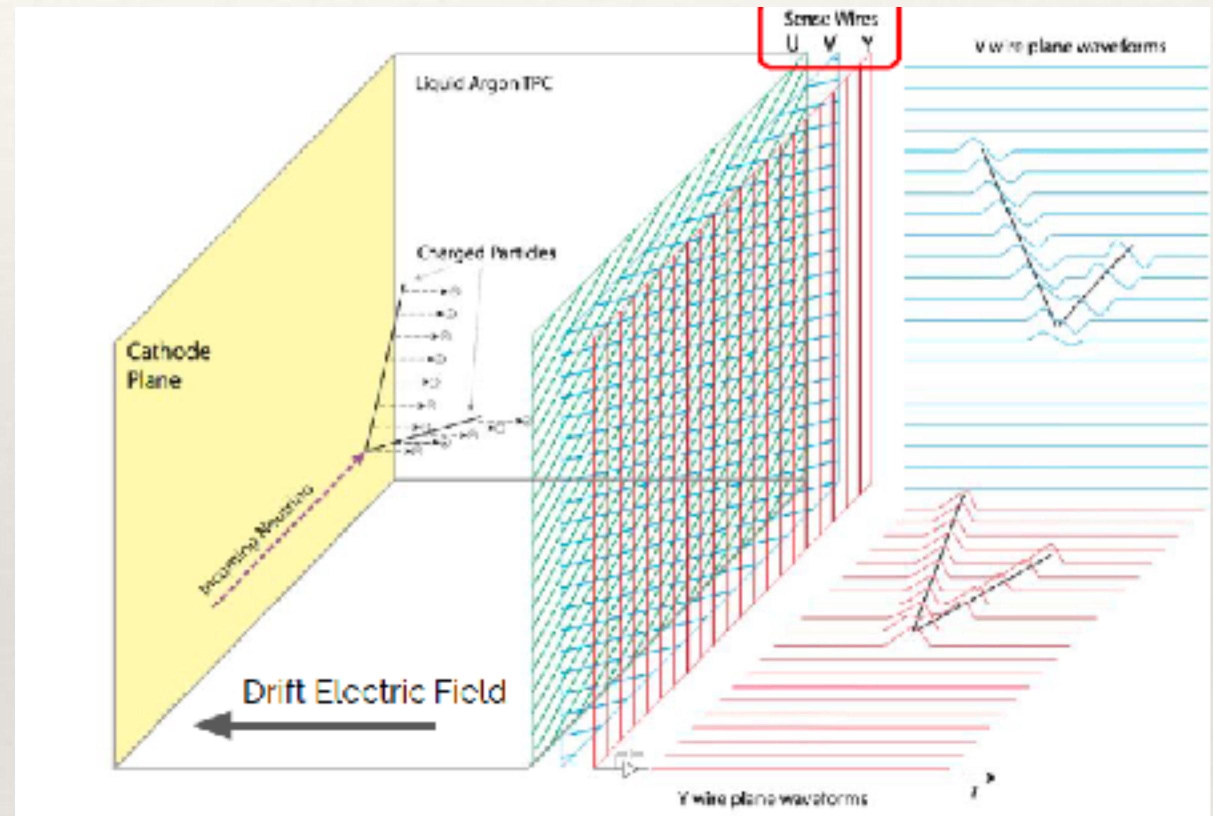


MicroBoone

- 8 ton surface based LArTPC detector
- Taking data since 2015
- Primary goal is to identify if the MiniBoone LEE is



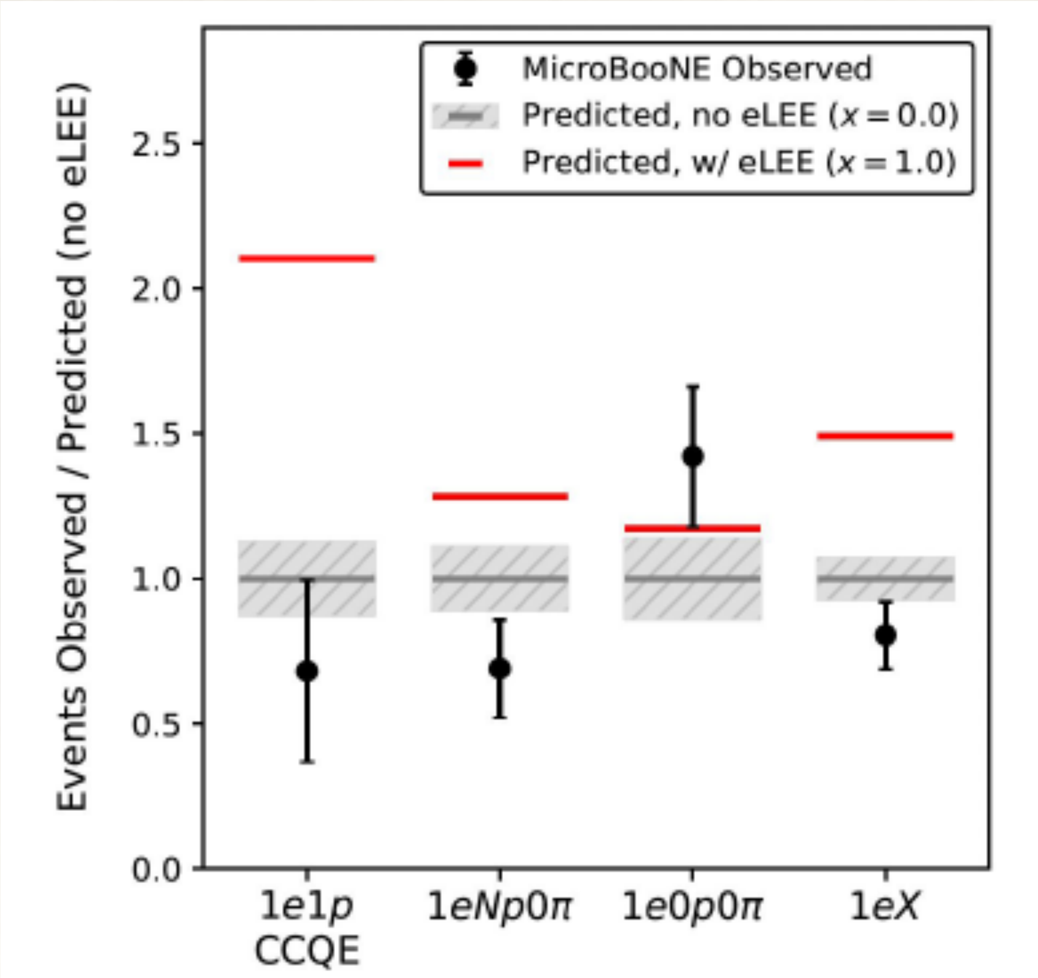
Same beam and similar baseline but different detector technology



- Can separate electrons and photons because of excellent resolution of LiqAr detectors

MicroBoone Results

- Disfavour NC $\Delta \to \gamma$ as origin of LEE 94.8% C.L.
- No electron neutrino excess in data



https://arxiv.org/pdf/2110.14054.pdf

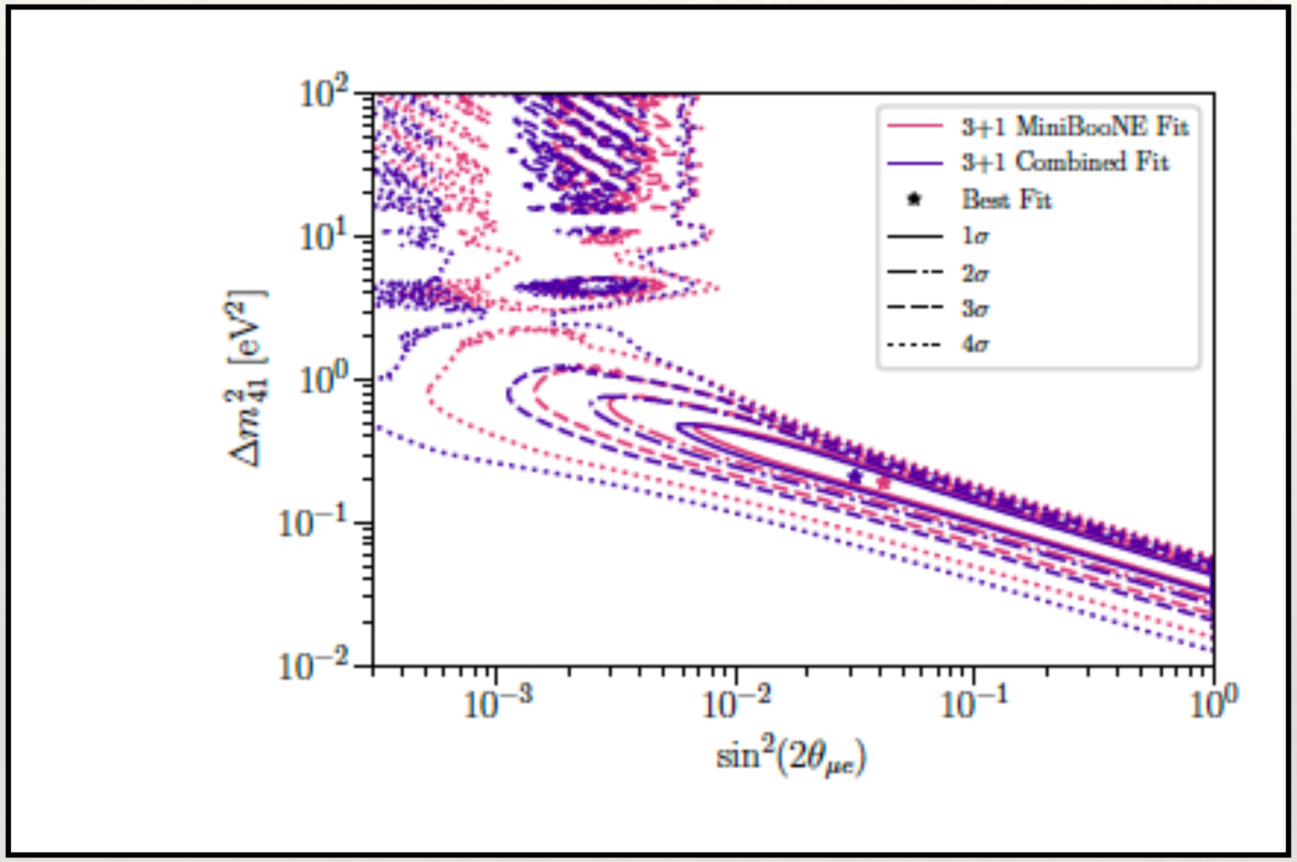
See however
.https://arxiv.org/pdf/2111.10359.pdf

The electron neutrino excess cannot be excluded in a model independent way

New physics ?

Result from all 3 detectors in SBN

3+1 fit : MiniBoone and MicroBoone



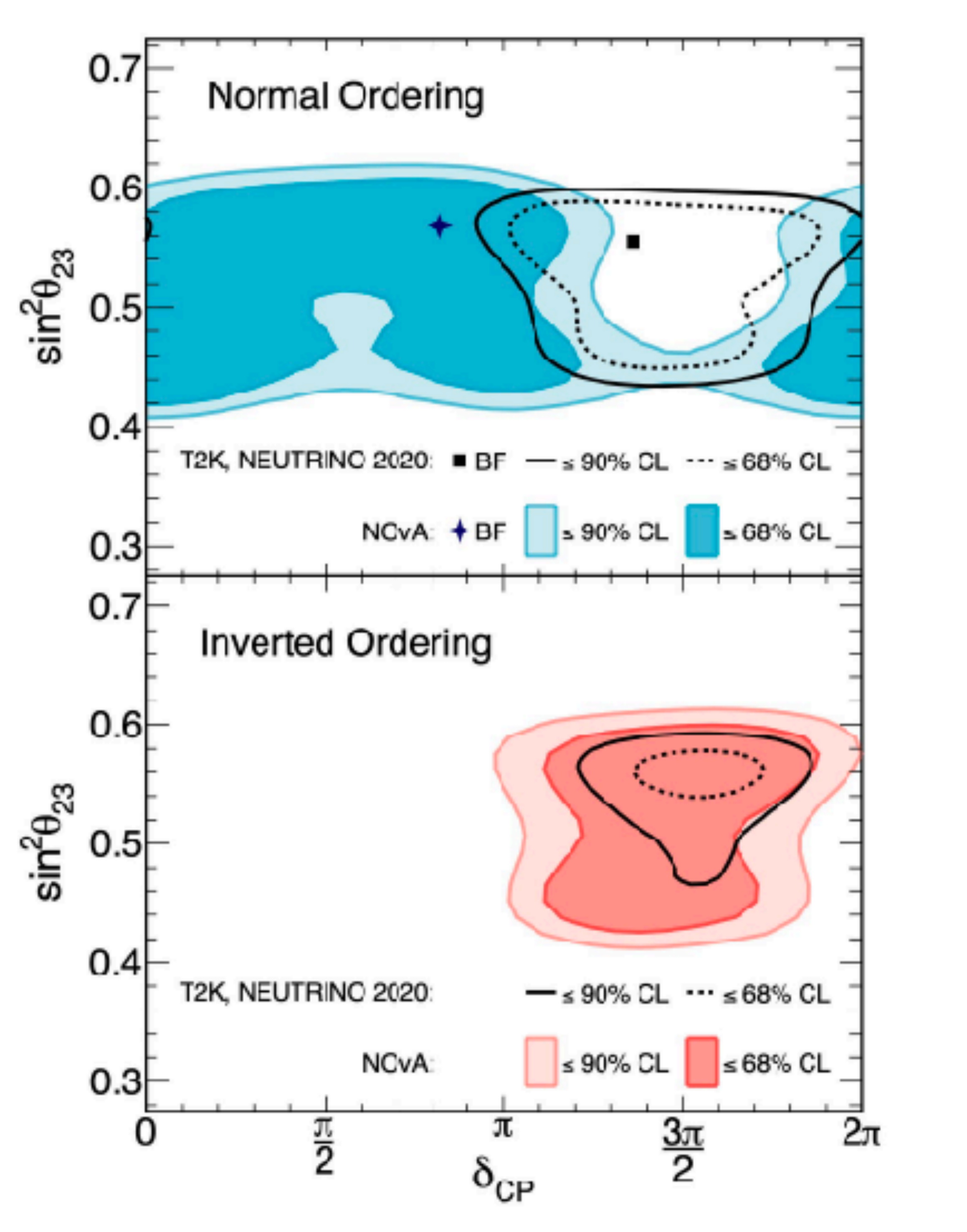
3+1 Fit	$\lvert U_{e4}\rvert^2$	$\lvert U_{\mu 4}\rvert^2$	Δm^2	$\Delta\chi^2$/ dof
MiniBooNE only	0.508	0.0205	0.191	27.8 / 3
Combination	0.502	0.0158	0.209	24.7 / 3

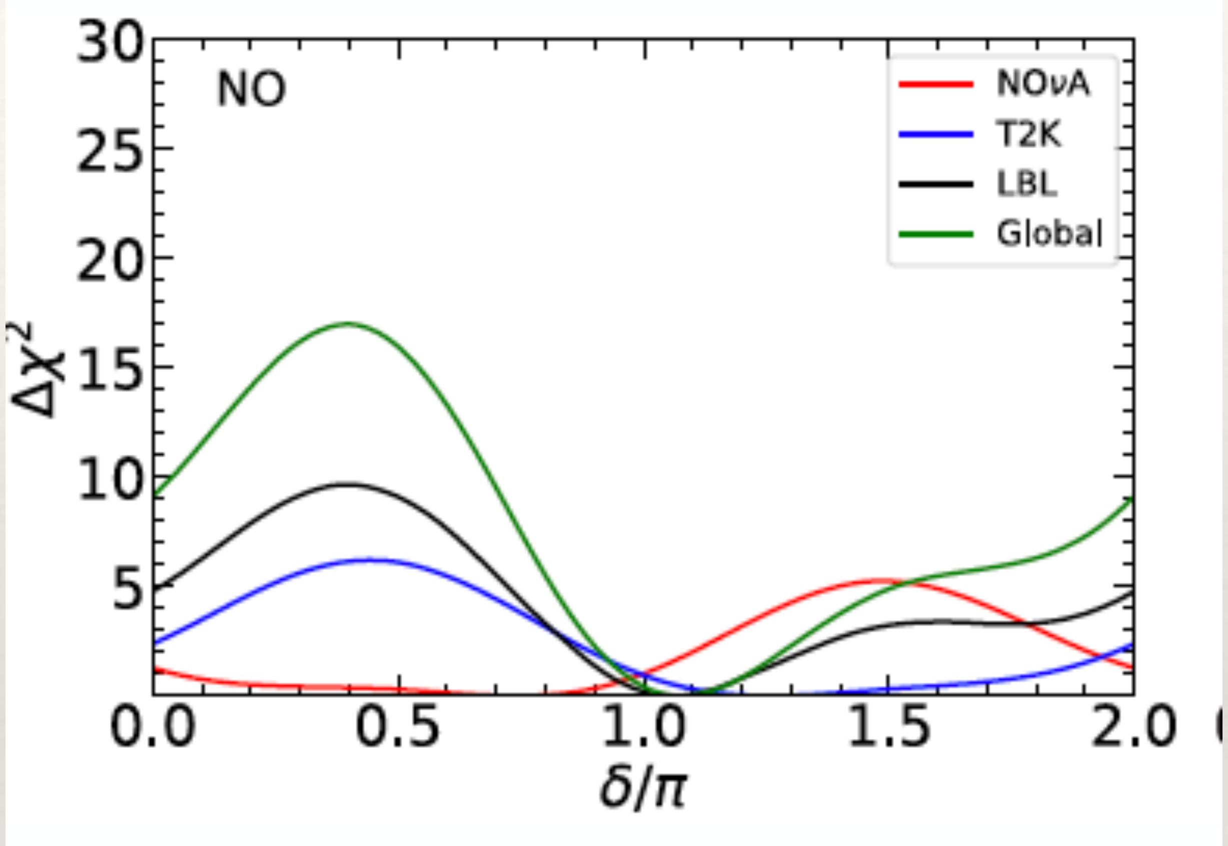
TABLE I. Summary of results. The $\Delta\chi^2$/dof in the last column compares the $3+1$ model to the no-oscillation model.

A.A. Aguilar-Arevalo et al. [MiniBooNE], Phys. Rev. Lett. 129 (2022) 201801

Can we have lighter sterile neutrinos ?

T2K and NOνA and CP

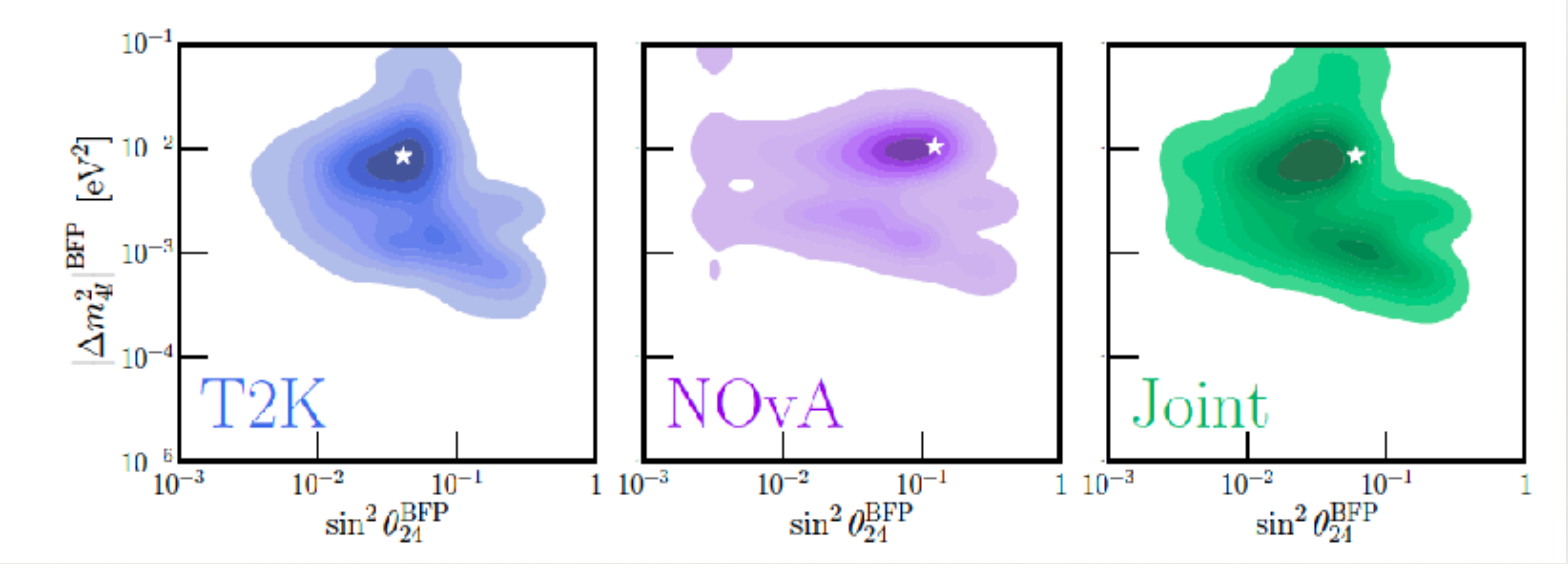




Tension between T2K and NOVA for NO

Very light sterile neutrinos

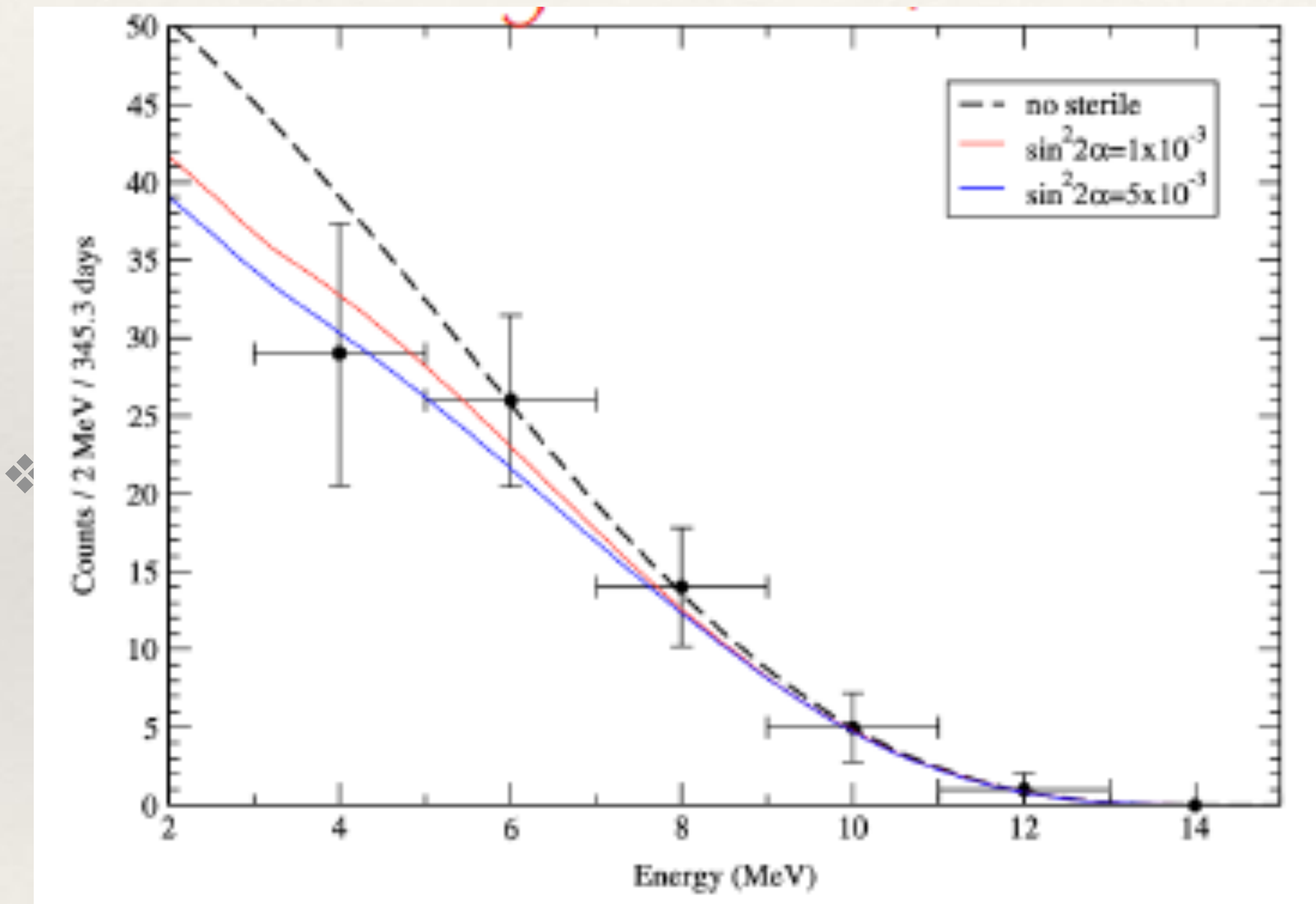
- Hint of eV scale sterile neutrinos to explain LSND/MiniBoone anomaly
- Can there be lighter sterile neutrinos ?



$$U_s = \tilde{R}_{34}(\theta_{34}, \delta_{34}) R_{24}(\theta_{24}) \tilde{R}_{14}(\theta_{14}, \delta_{14}) R_{23}(\theta_{23}) \tilde{R}_{13}(\theta_{13}, \delta_{13}) R_{12}(\theta_{12})$$

Additional parameters give improved fit

Spectral upturn in solar neutrino data



[PhysRevD. 83,113011]

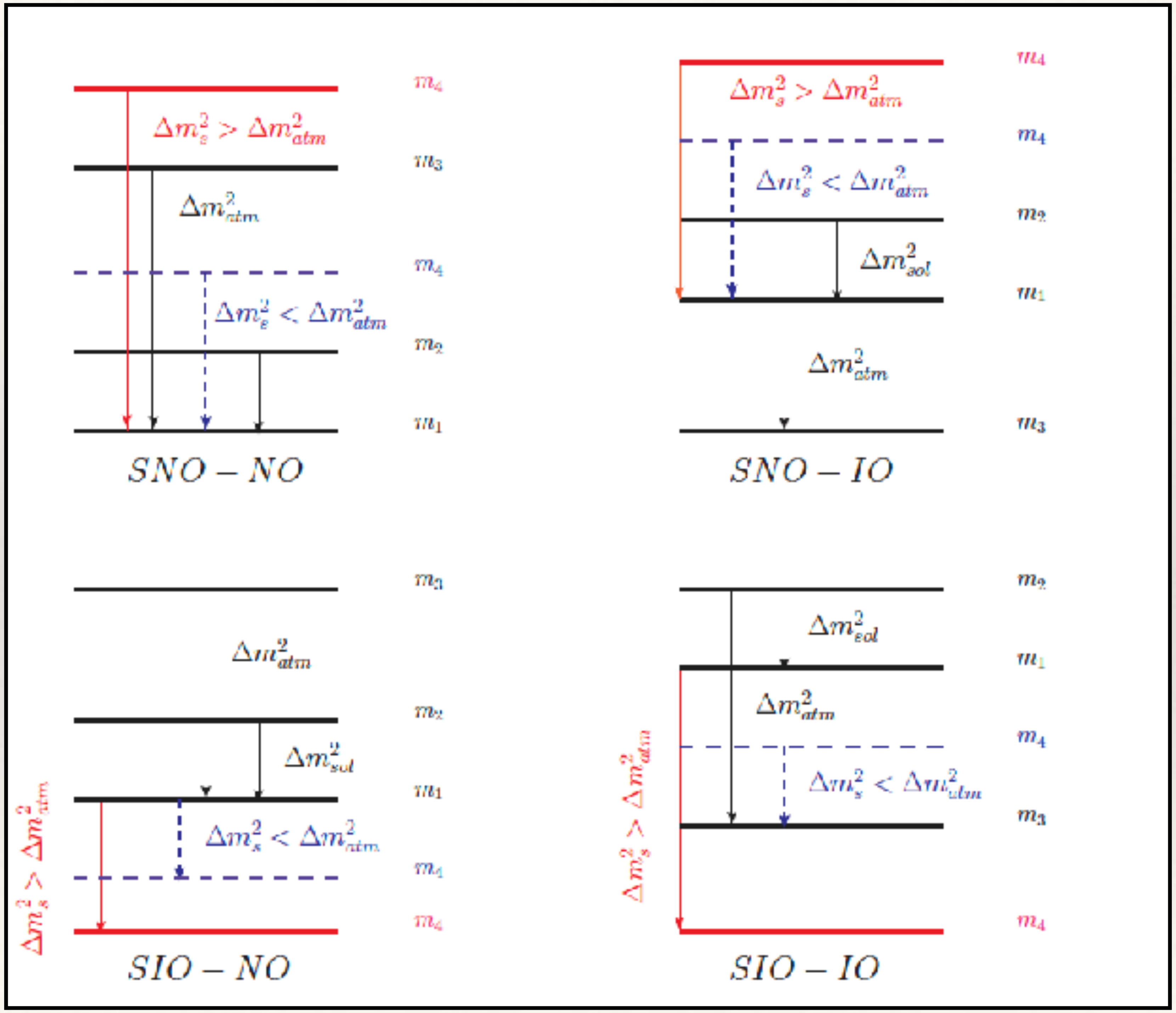
The predicted spectral upturn from MSW effect not seen in data

Ultra light sterile neutrinos with

$\Delta_s \sim 10^{-5}\,\mathrm{eV}^2$ $\sin^2 2\alpha \sim 10^{-5} : 10^{-3}$

explain this

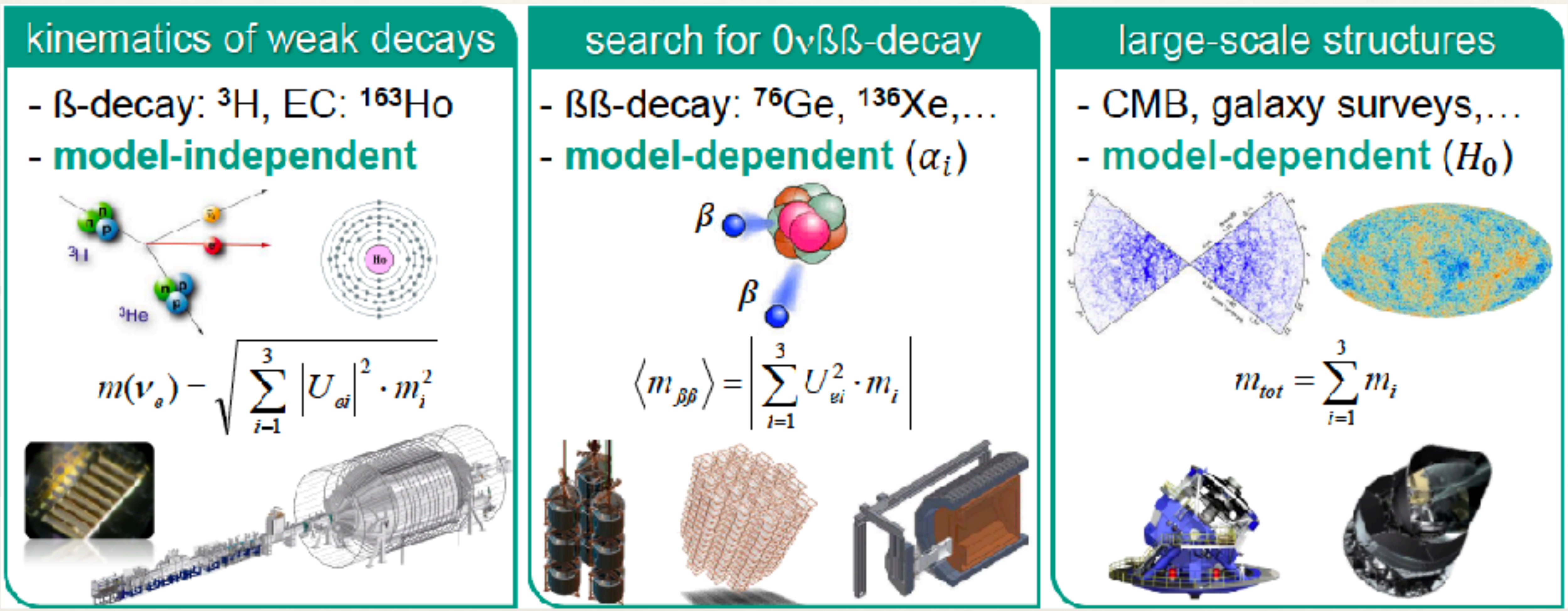
Mass Spectra for 3+1 Picture



Absolute neutrino mass

Information can come from three different sectors

Courtsey: G. Drexlin, NOW 2022



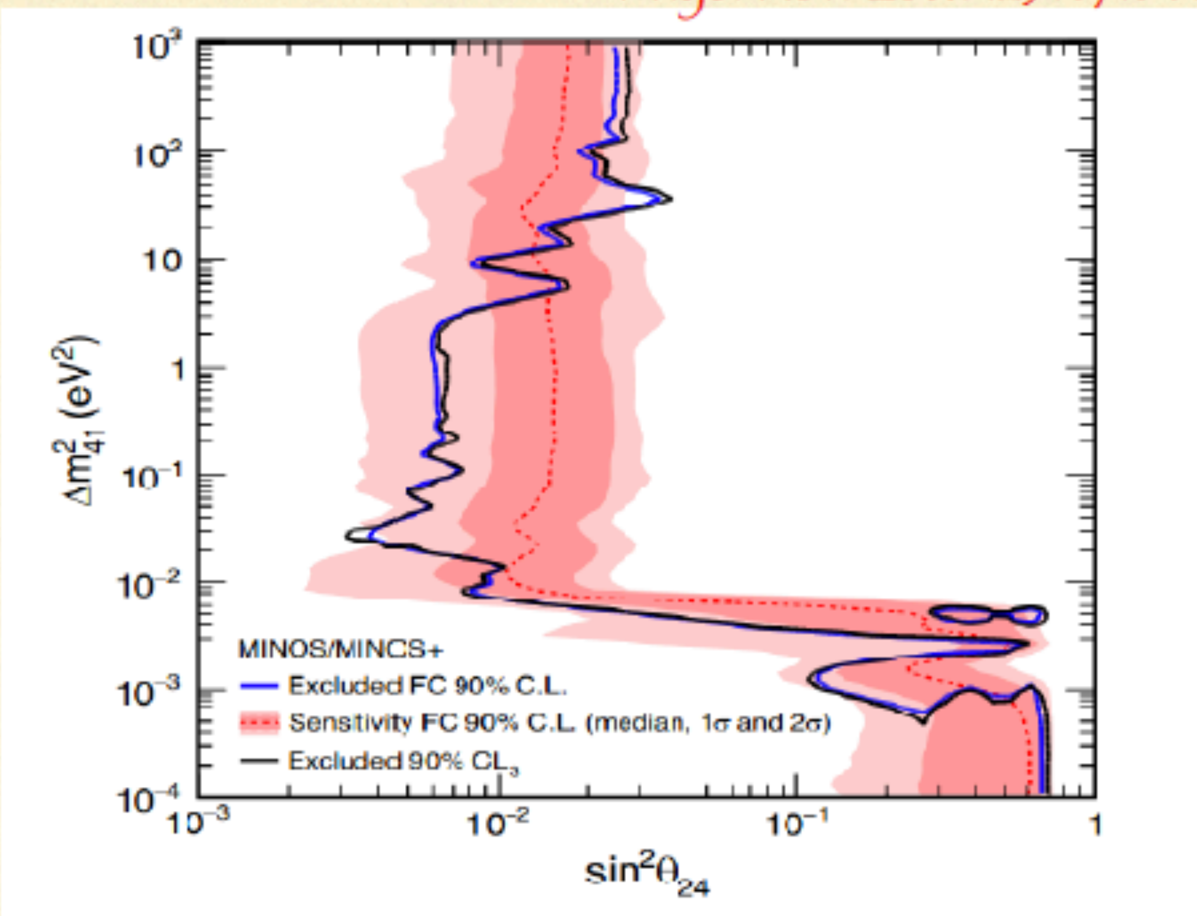
Present Limit < 0.8 eV, 90% C.L. from Katrin experiment

Present Limit < 36-156 meV, 95% C.L. from GERDA experiment

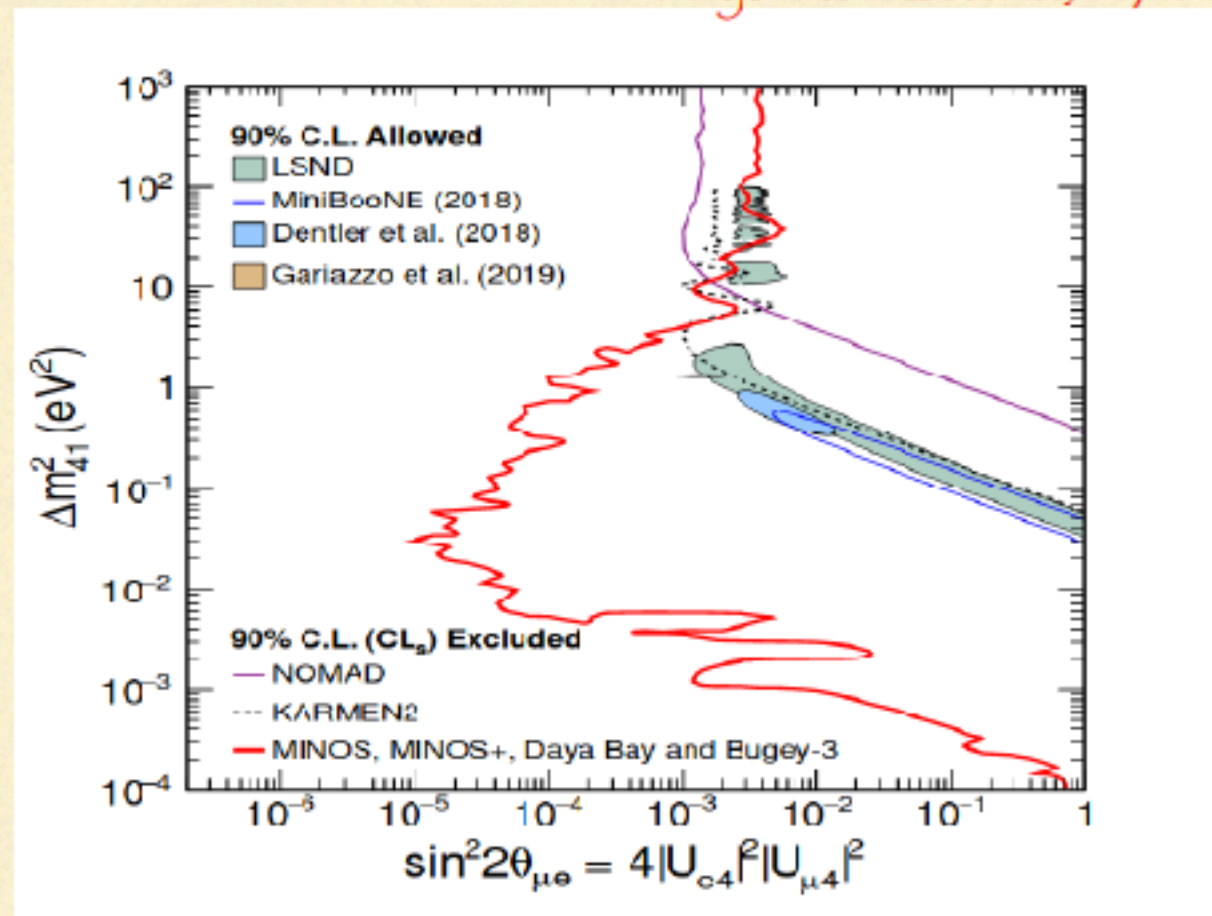
Present Limit < 0.12 eV, 95% C.L. from Plank

Allowed parameters from experiment

Phys. Rev. Lett. 125.071801



Phys. Rev. Lett. 125.071801



Δm_s^2	10^{-4} eV^2	0.01 eV^2	1.3 eV^2
$\sin^2\theta_{14}$	0.1-0.2	0.0005-0.005	0.001-0.01

Effective Number of Neutrinos in Cosmology

Radiation Density :

$$\rho_r = \rho_\gamma \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right)$$

$$\sum_{\nu_e,\nu_\mu,\nu_\tau,} \rho_{\nu_\alpha} + \rho_{\rm other} = N_{\rm eff} \times \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} \rho_\gamma$$

$$N_{\rm eff} = N_{\rm eff}^{\rm SM} + \Delta N_{\rm eff}$$

Photon Energy Density

energy density of relativistic neutrinos

$$\Delta N_{eff} = N_{eff} - N_{eff}^{SM}$$

N_{eff}^{SM}: 3.044 ± 0.002

Big Bang Nucleosynthesis
Large Scale Structures
Cosmic Microwave Background

Sterile Neutrinos and Cosmology

Sterile neutrinos contribute to N_{eff} and Σ

For massive neutrinos : N_{eff} and m_s^{eff}

$$\Sigma = m_1 + m_2 + m_3 + m_s^{\rm eff}$$

energy density of non-relativistic neutrinos

- 10 parameter Cosmological Model

$$N_{\rm eff} = 3.11^{+0.37}_{-0.36}$$

$$\Sigma m_i < 0.16\,\mathrm{eV}$$

2203.07323

$$\Lambda\mathrm{CDM} + N_{\rm eff} + \sum m_\nu + w_0 + n_{\rm run}$$

Fully thermalised neutrinos => $\Delta N_{eff} \approx 1$

(active and sterile states in equilibrium)

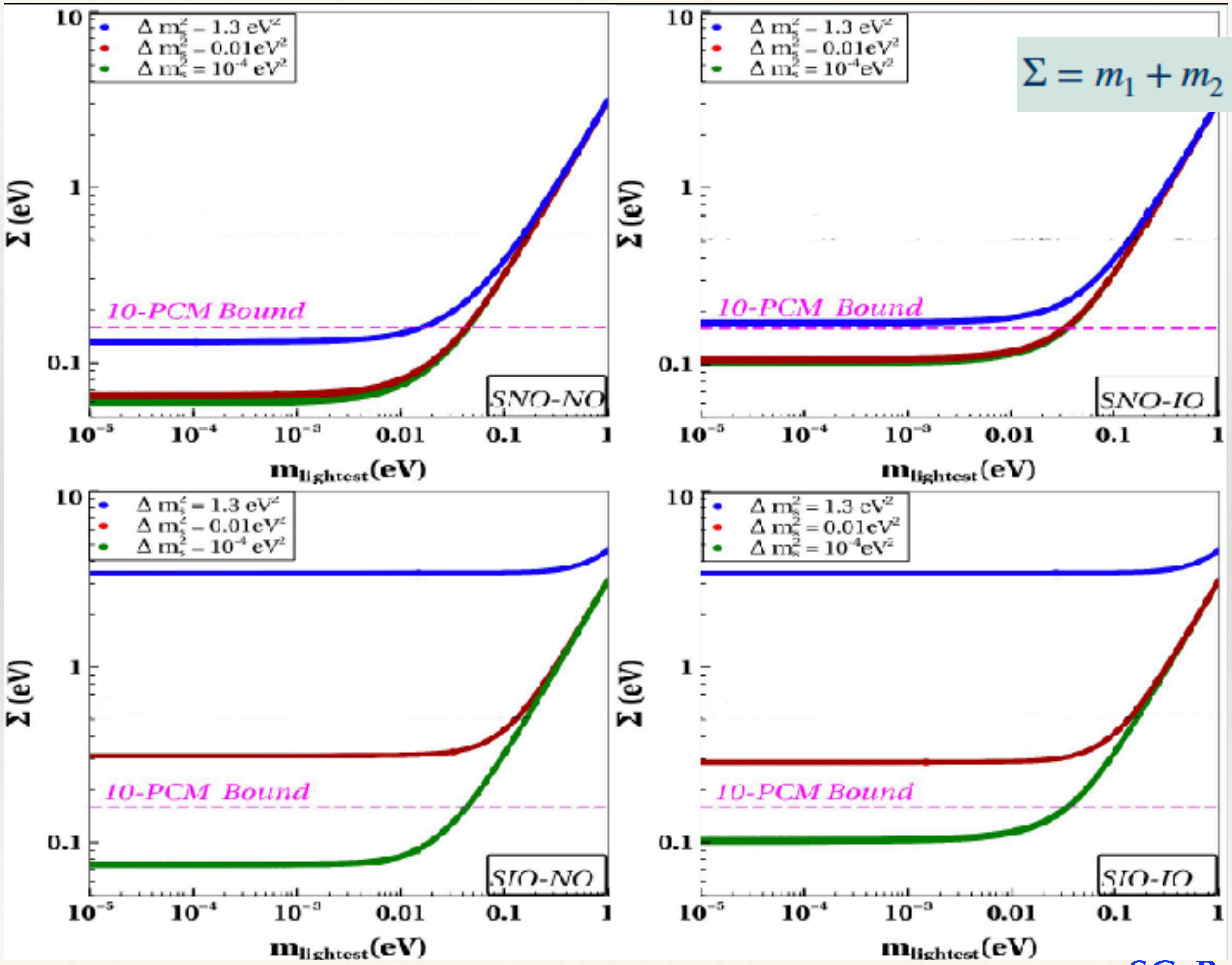
→ Non-thermal or partially thermal

$$m_s^{eff} = \Delta N_{eff} m_4$$

Hagstotz et al. , PRD , 2021

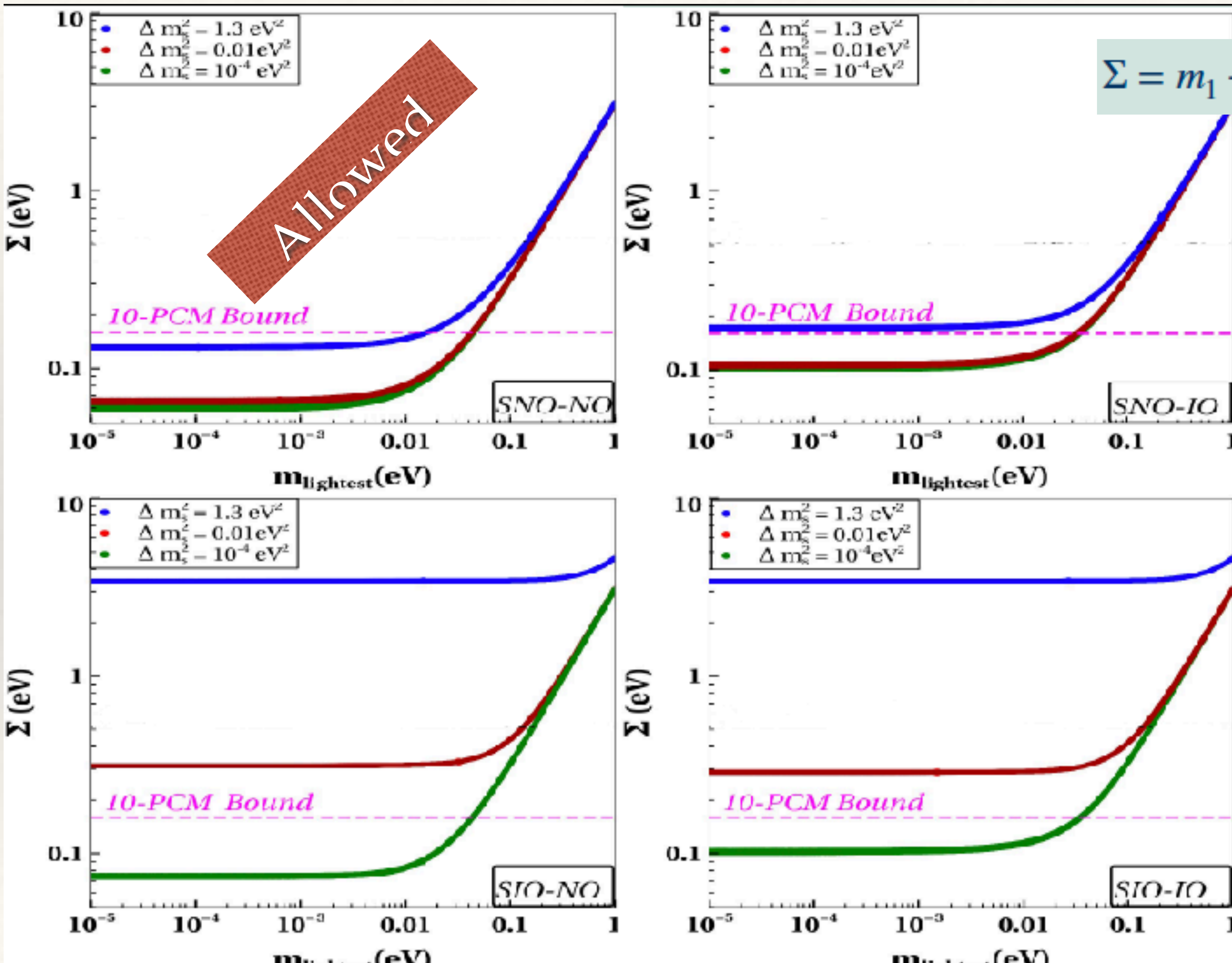
Cosmological mass bound

$$\Sigma = m_1 + m_2 + m_3 + \left(m_4 \times \Delta N_{eff}\right)$$



SG, Pan, Pachhar,, PRD, 2024

Cosmological mass bound



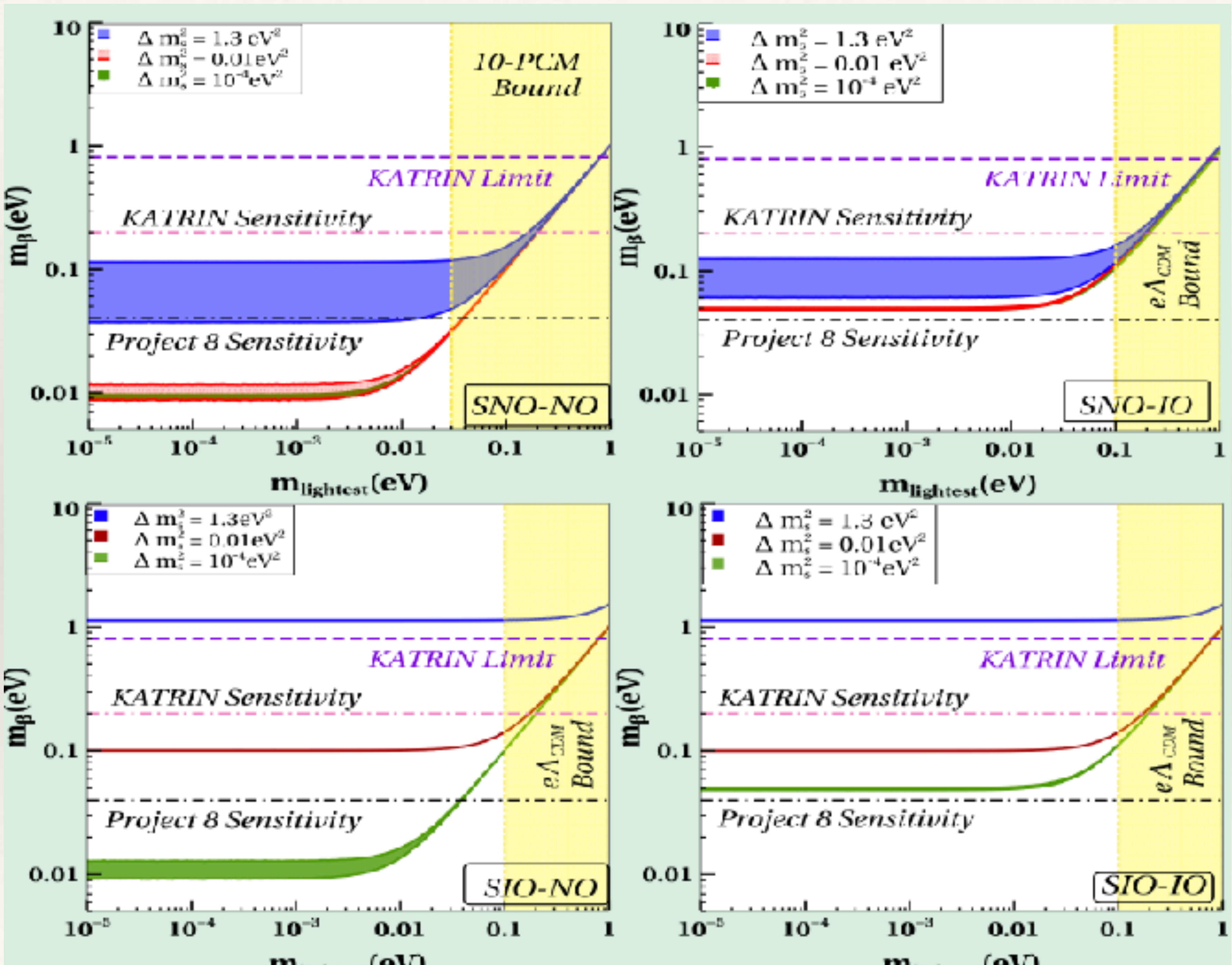
$$\Sigma = m_1 + m_2 + m_3 + \left(m_4 \times \Delta N_{eff} \right)$$

$1.3\ eV^2$, $0.01\ eV^2$
Allowed

$1.3\ eV^2$, $0.01\ eV^2$
Disallowed

SG, Pan, Pachhar,, PRD, 2024

Constraints from Beta decay



$$m_\beta^2 = \sum_{i=1,4} |U_{ei}|^2 m_i^2$$

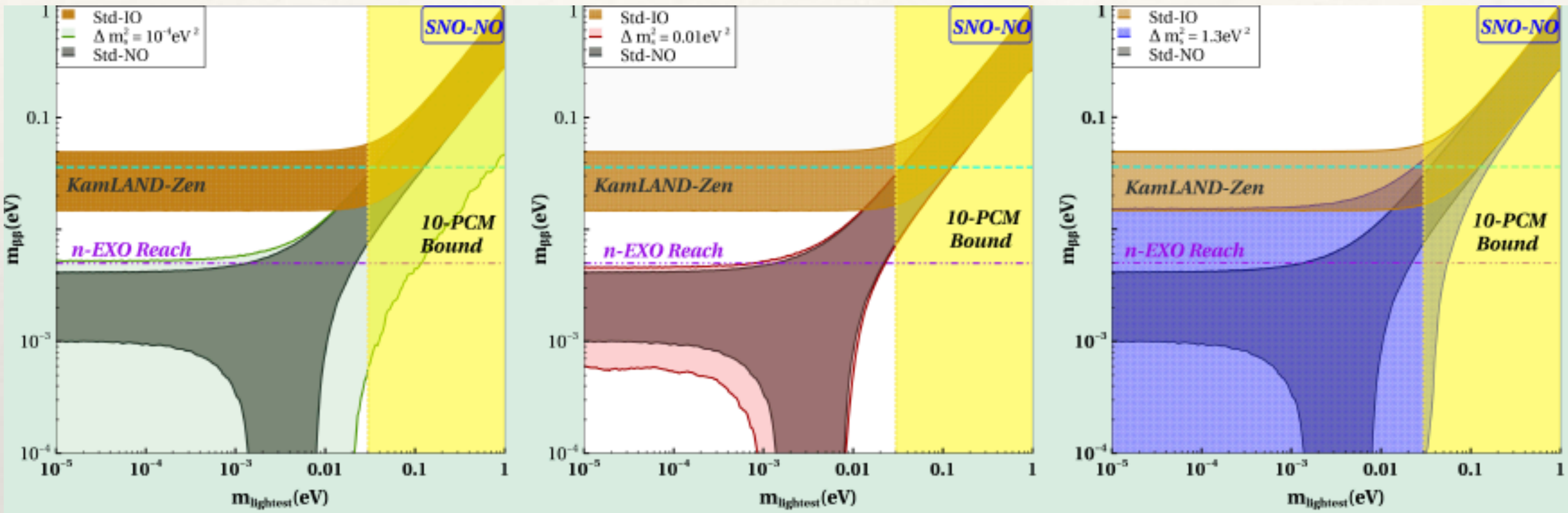
SNO allowed

SIO disfavoured for 1.3 eV^2

SG, Pan, Pachhar,, PRD, 2024

Neutrinoless double beta decay (SNO-NO)

$10^{-4} eV^2$ $\quad$ $0.01\ eV^2$ $\quad$ $1.3\ eV^2$



$lightest \rightarrow m_1$

$$m_2 = \sqrt{m_1^2 + \Delta m_{sol}^2}$$

$$m_3 = \sqrt{m_1^2 + \Delta m_{atm}^2}$$

$$m_4 = \sqrt{m_1^2 + \Delta m_s^2}$$

$$m_{\beta\beta}^{\text{SNO-NO}} = \left| \sum_i u_{ei}^2 m_i \right|$$

$$m_{\beta\beta}^{\text{SNO-NO}} = c_{14}^2 \left| m_{\beta\beta}^{std-NO} + t_{14}^2 m_4 e^{i\gamma} \right|$$

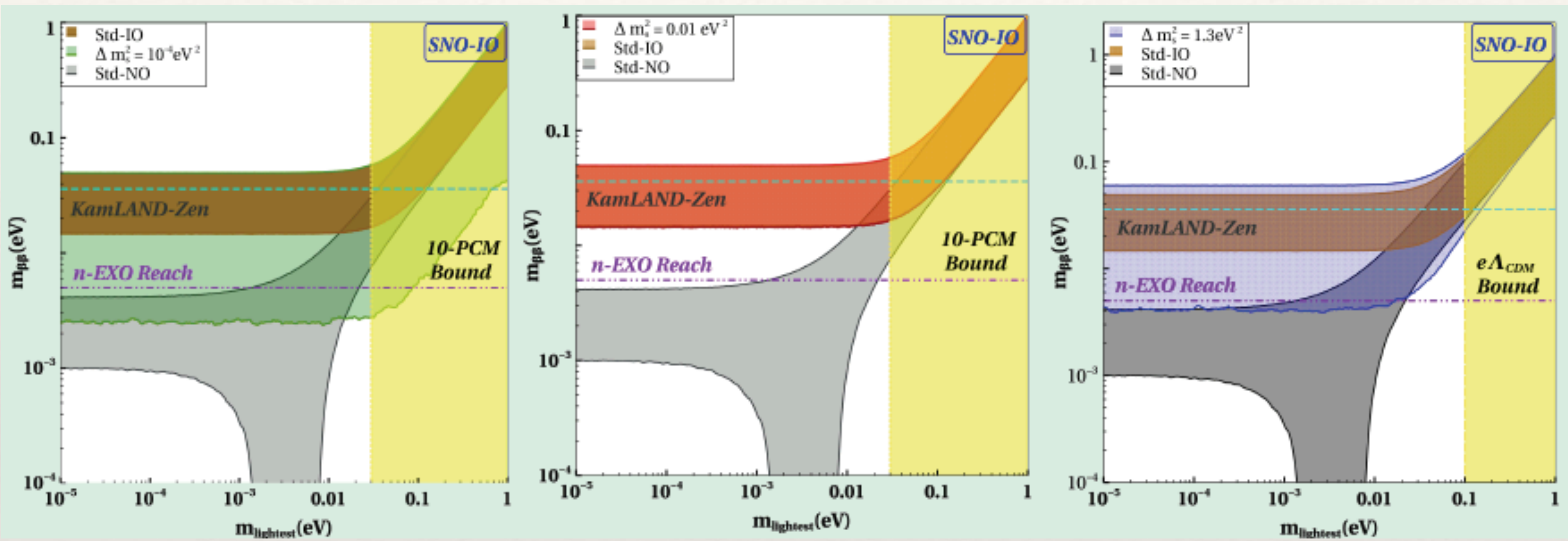
Δm^2

SNO-NO allowed for all

SG, Pan, Pachhar,, PRD, 2024

Neutrinoless double beta decay (SNO-IO)

$10^{-4} eV^2$ $\quad$ $0.01\ eV^2$ $\quad$ $1.3\ eV^2$



$$m_{\beta\beta}^{\text{SNO-IO}} = c_{14}^2 \left| m_{\beta\beta}^{std-IO} + t_{14}^2\, m_4\, e^{i\gamma} \right|$$

Part of parameter space disfavoured for all the mass squared differences

SG, Pan, Pachhar,, PRD, 2024

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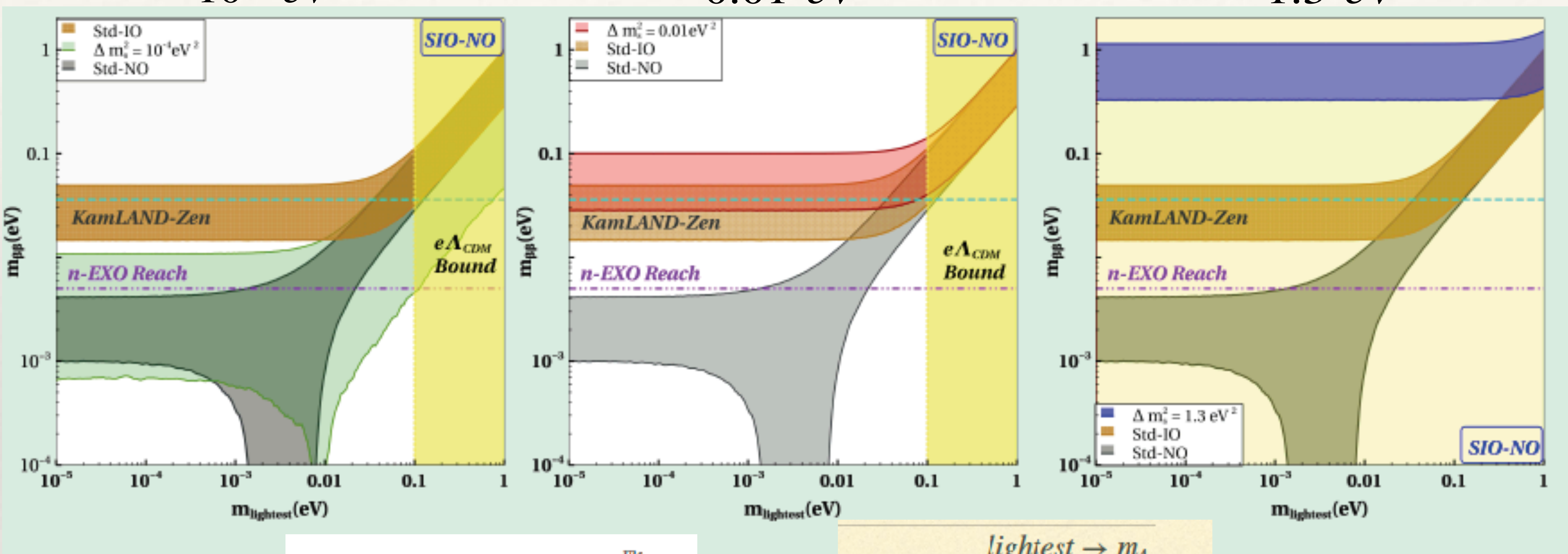

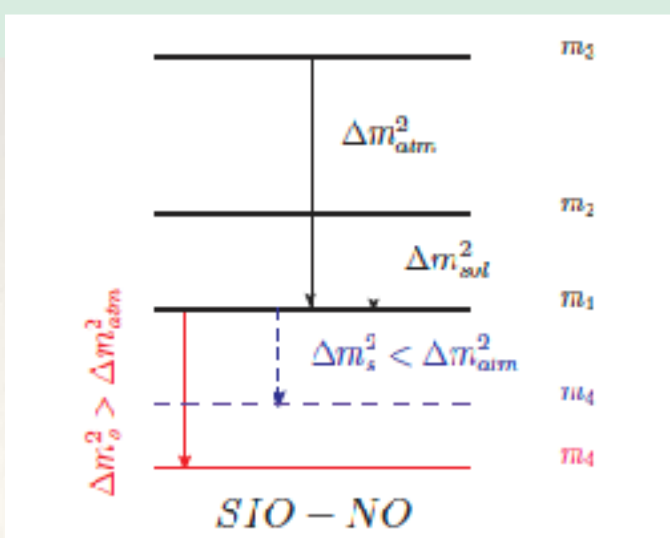

$$lightest \to m_4$$

$$m_1 = \sqrt{m_4^2 + \Delta m_{sol}^2}$$

$$m_2 = \sqrt{m_1^2 + \Delta m_{sol}^2}$$

$$m_3 = \sqrt{m_1^2 + \Delta m_{atm}^2}$$

SG, Pan, Pachhar,,
PRD, 2024

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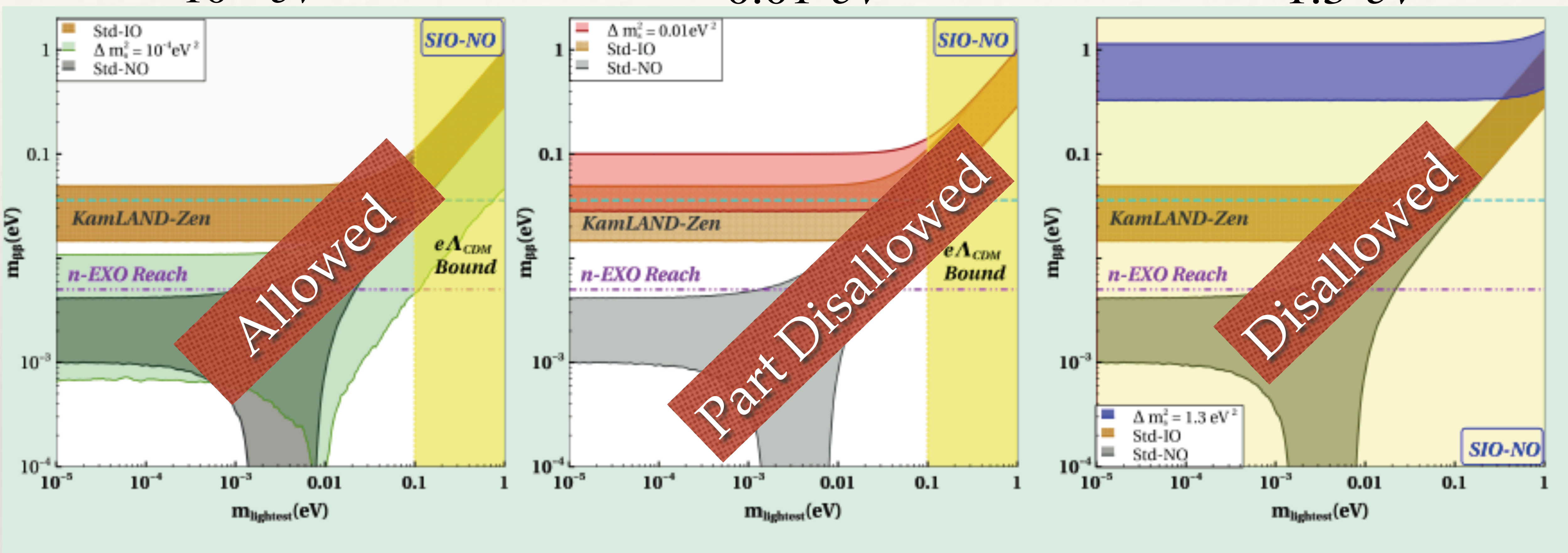

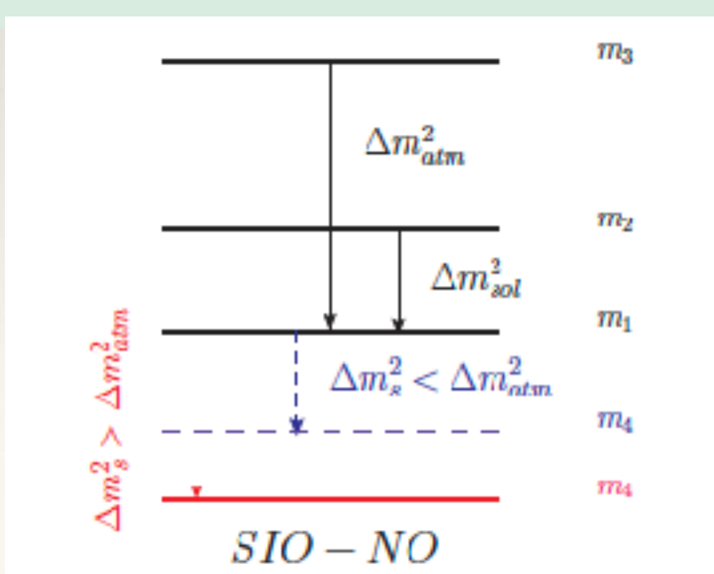

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SG, Pan, Pachhar,, PRD, 2024

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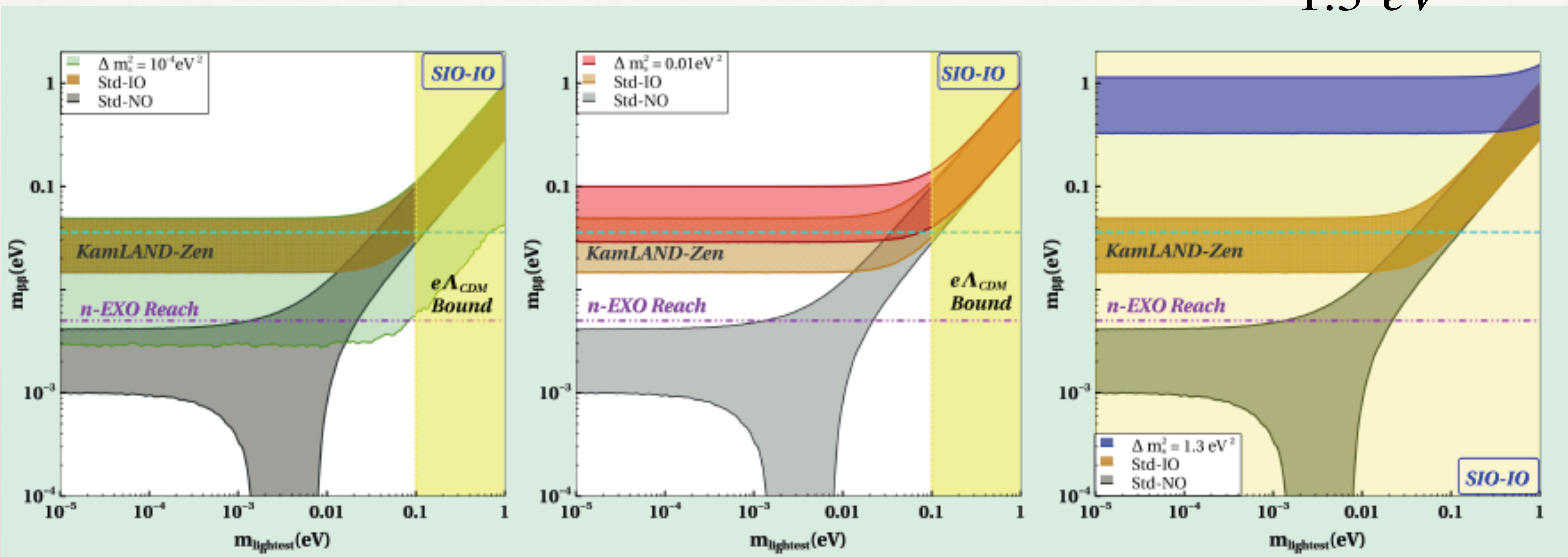
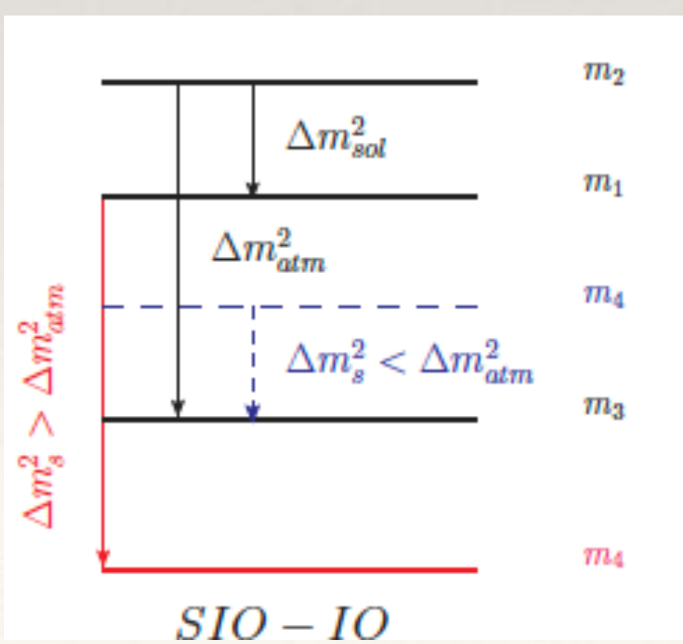




$lightest \rightarrow m_4/m_3$

$$m_3/m_4 = \sqrt{m_{3/4}^2 + \Delta m_{atm}{}^2}$$

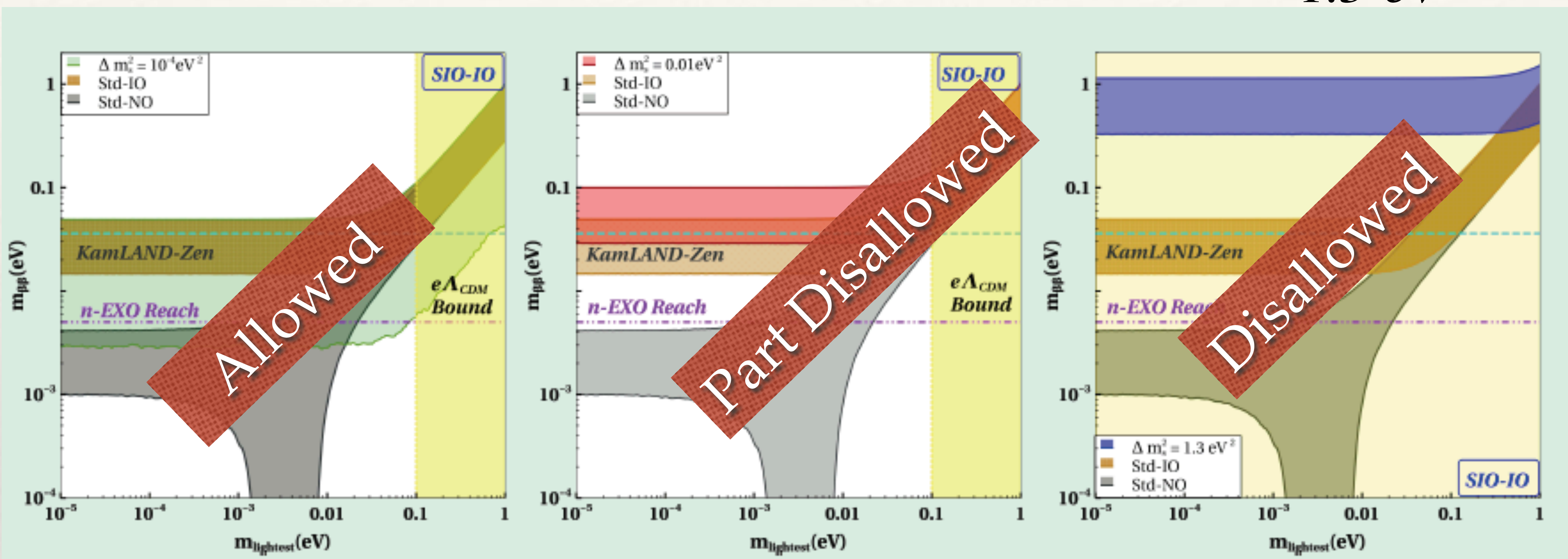
$$m_2 = \sqrt{m_3^2 + \Delta m^2_{atm}}$$

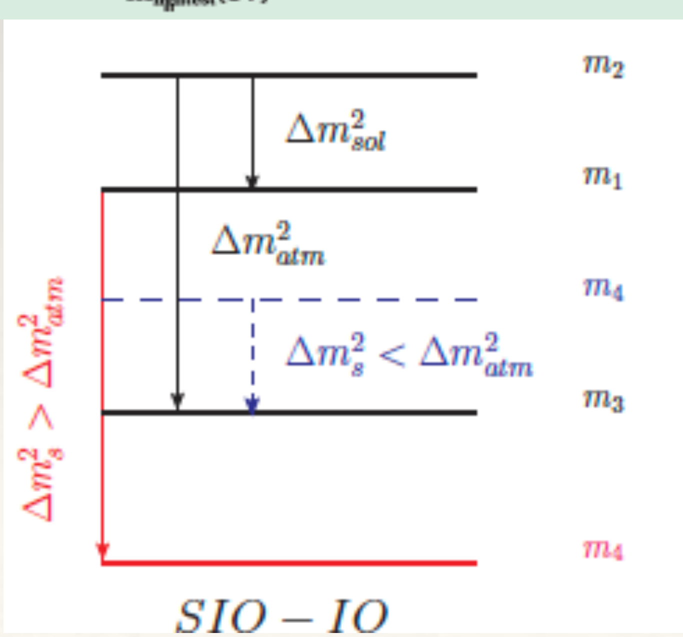
$$m_1 = \sqrt{m_2^2 - \Delta m^2_{sol}}$$

SG, Pan, Pachhar,,
PRD, 2024

Neutrinoless double beta decay (SIO-IO)

$10^{-4} eV^2$ $0.01\ eV^2$ $1.3\ eV^2$





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SG, Pan, Pachhar,,
PRD, 2024

Sterile Neutrinos and Seesaw Model

Type I Seesaw :

$$\mathcal{L} = \frac{1}{2}(\bar{\nu}_L, \bar{N}_R^c)\begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix}\begin{pmatrix} \nu_L^c \\ N_R \end{pmatrix}$$

Diagonalized by

$$\mathcal{U}_\nu \simeq \begin{pmatrix} 1-\frac{1}{2}BB^\dagger & B \\ -B^\dagger & 1-\frac{1}{2}B^\dagger B \end{pmatrix}\begin{pmatrix} U & 0 \\ 0 & V_R \end{pmatrix} \quad \text{with } B = m_D M_R^{-1}$$

Light Neutrino Mass Matrix

$$m_\nu = -m_D\, M_R^{-1}\, m_D^T = U\, \mathrm{diag}(m_1, m_2, m_3)\, U^T$$

Heavy Neutrino Mass Matrix

$$M_R = V_R\, \mathrm{diag}(M_1, M_2, M_3)\, V_R^T$$

Non-unitary UPMNS

$$N = (1-\tfrac{1}{2}BB^\dagger)\, U$$

How to generate eV scale sterile ?

Extended Seesaw (ν_L^c, N_R) to (ν_L^c, N_R, S) 3 N_R, 1 S

7X7 mass matrix

$$\mathcal{M} = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & M_R & m_{RS}^T \\ 0 & m_{RS} & 0 \end{pmatrix}$$

$M_R \gg m_{RS} > m_D$

$$m_\nu = m_D M_R^{-1} m_{RS}^T (m_{RS} M_R^{-1} m_{RS}^T)^{-1} m_{RS} (M_R^{-1})^T m_D^T - m_D M_R^{-1} m_D^T$$

$$m_4 = -m_{RS} M_R^{-1} m_{RS}^T$$

$$U_{\alpha 4} = m_D M_R^{-1} m_{RS}^T (M_S M_R^{-1} m_{RS}^T)^{-1} = \mathcal{O}(m_D/m_{RS})$$

Barry, Rodejgohann, Zhang

10.1007/JHEP07(2011)091

How can one generate eV scale sterile mass ?

Light sterile neutrinos from large extra dimensions

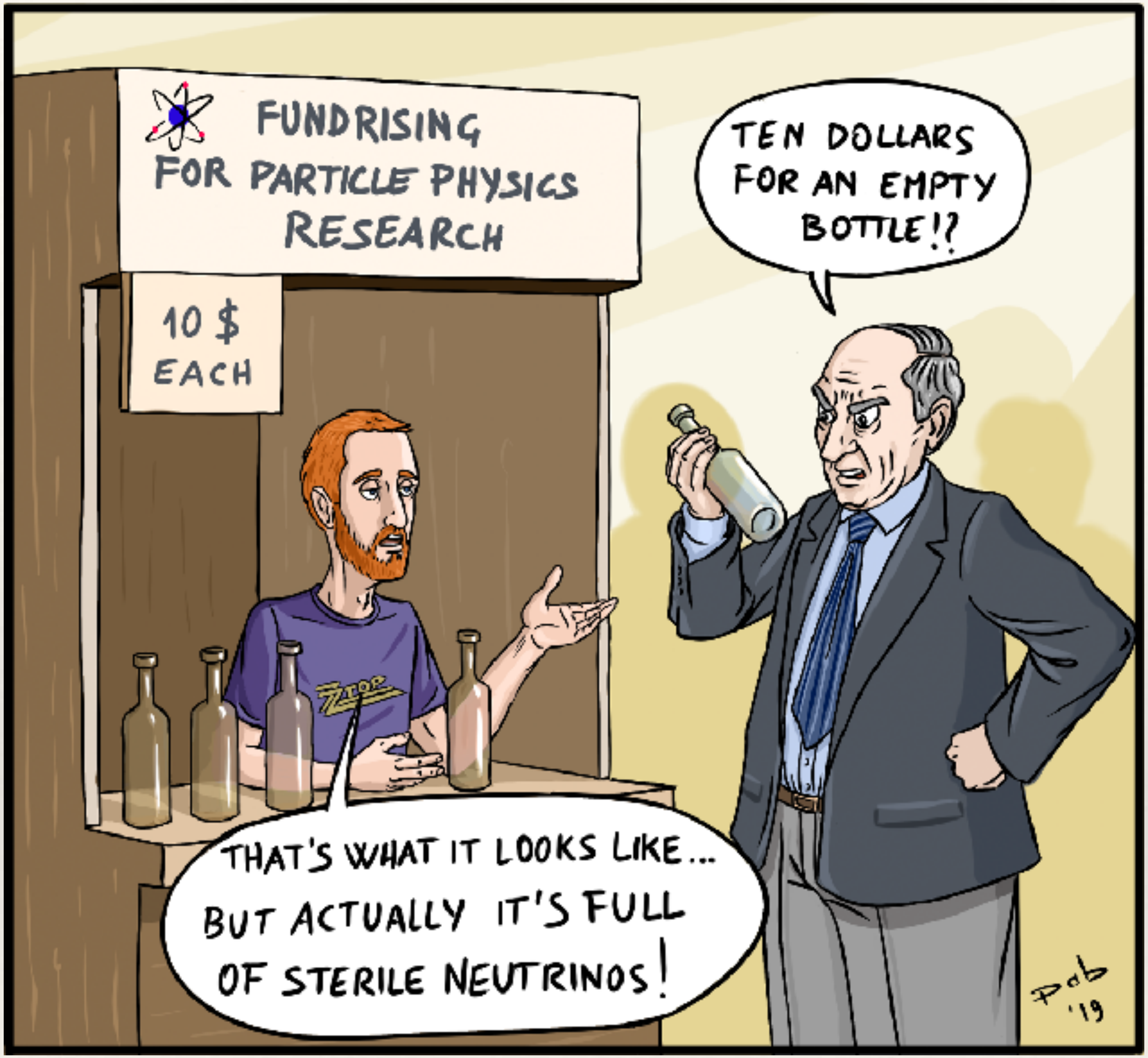
Ernest Ma [a], G. Rajasekaran [b], Utpal Sarkar [c]

[a] *Department of Physics, University of California, Riverside, CA 92521, USA*
[b] *Institute of Mathematical Sciences, Madras 600 113, India*
[c] *Physical Research Laboratory, Ahmedabad 380 009, India*

Received 29 September 2000; accepted 13 October 2000
Editor: M. Cvetič

Summary

- Sterile neutrinos can exist ar all energy scales
- Some hints in favour of eV scale sterile neutrino
- Strong tension in data
- eV scale sterile constrained from cosmology, beta decay, neutrino less double beta decay
- Are lighter than eV sterile neutrinos allowed ?
- Four different mass spectra
- Constraints from cosmology, neutrino less double beta decay disfavour some of these mass spectra

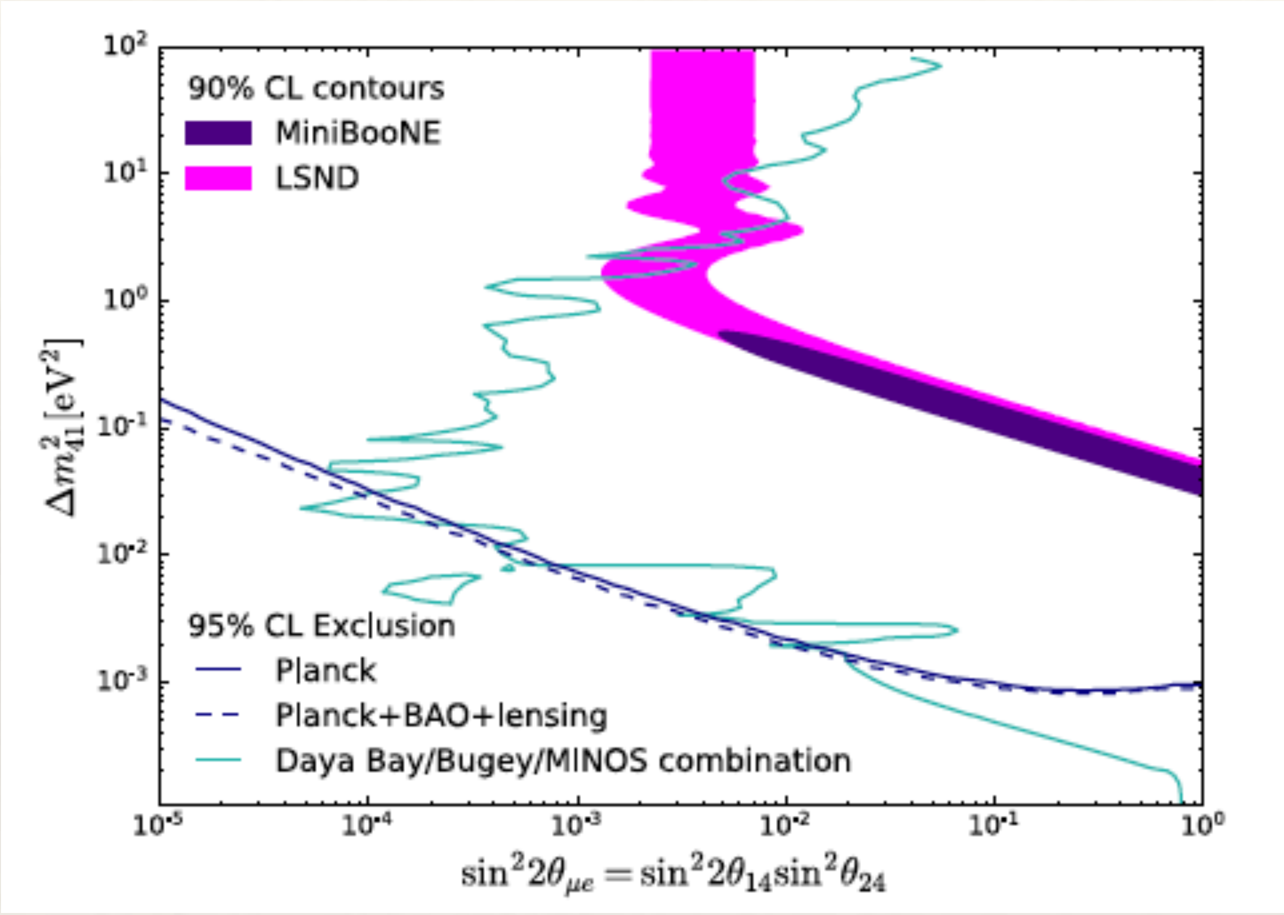


10 Dollars or Million Dollars ?


Thank
you!!

Back Up

Evading Cosmological Constraints



M.Adams et al. Eur. Phys. J.80 (2020)

Interactions with an ultralight scalar

Y. Farzan, Phys. Lett. B. 2019
J.M. Cline, Phys. Lett. B 2020

Large lepton anti-lepton asymmetry in the Universe

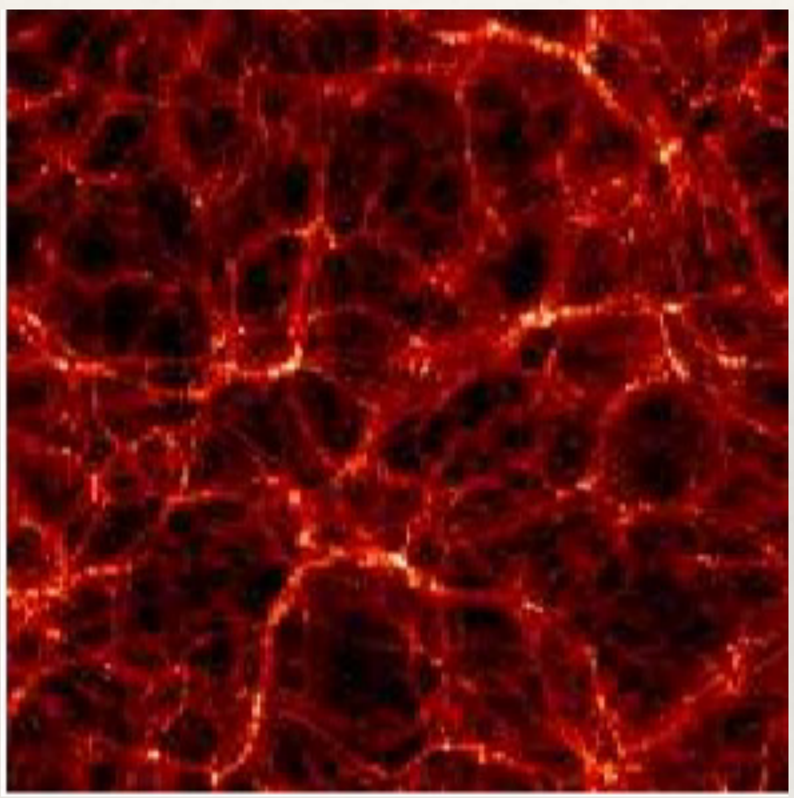
Foot and Volkas, PRL 1995

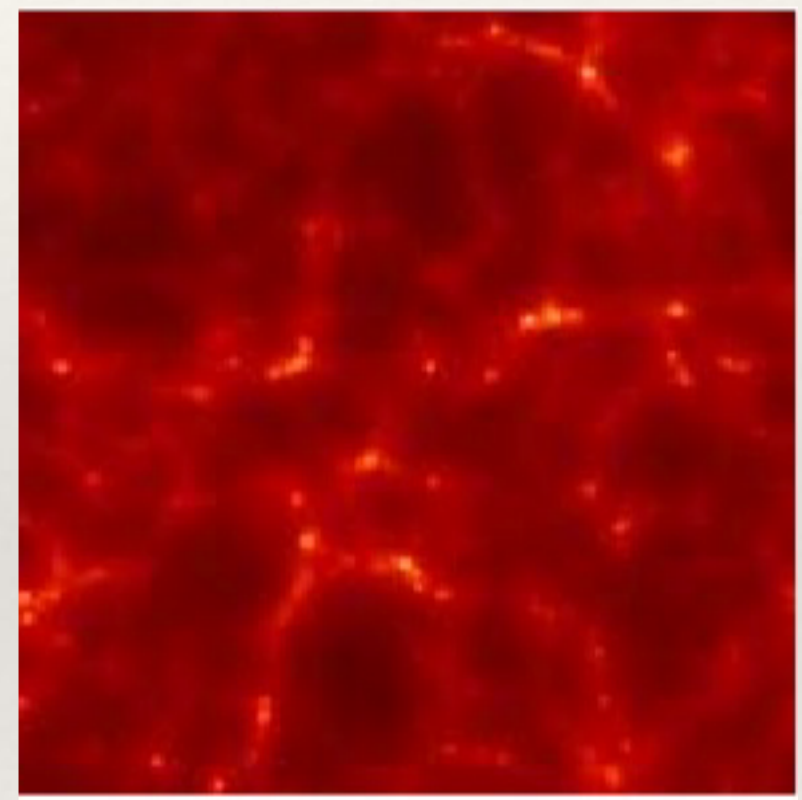
Low reheating temperature

Gelmini, Palomarez-Ruis, Pascoli, PRL 2004

LSS and neutrino mass

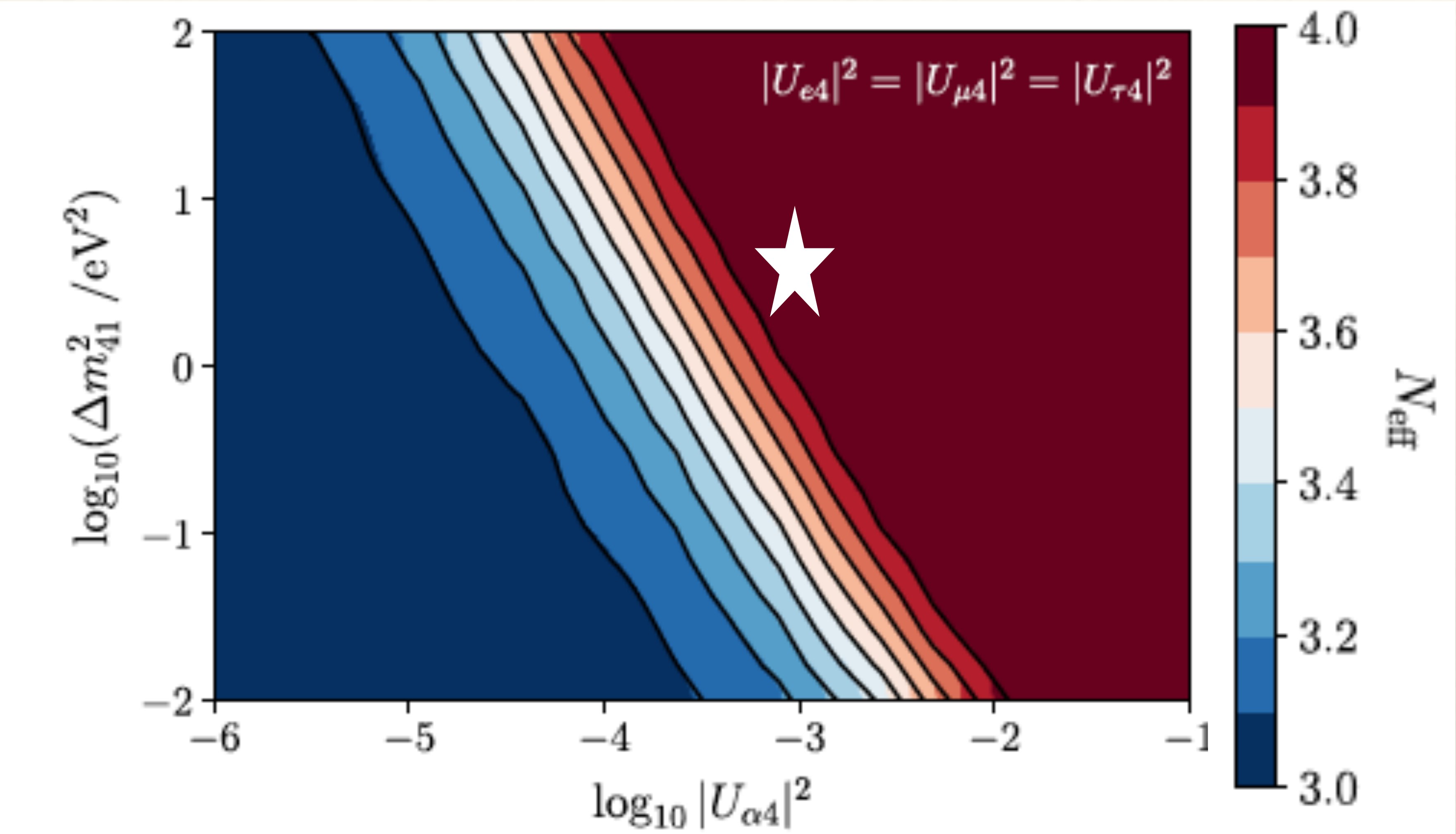
$m_\nu = 0.5\ eV$





Neutrino free streaming erases structures

Effective Number of Neutrinos



Solving Boltzman Equations for 3+1 picture

- The parameter space for SBL anomalies => $\Delta N_{\mathrm{eff}} \approx 1$

= > Fully thermalised neutrinos