Status and prospects in the search for light sterile neutrino

Talk given at:
The 7th IBS-ICTP-MultiDark Workshop
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Mehedi Masud
IBS-CTPU
Daejeon, South Korea

Plan of the talk

- Current 3ν scenario & extension to 4ν
- Motivations for light sterile ν: anomalies
- Current status of sterile ν parameter space: global analysis
- Future directions for sterile search at short & long baselines
- Conclusion

Current 3ν status

Table: de Salas, Forero, Gariazzo, Martinez-Mirave, Mena, Ternes, Tortola, Valle: 2006.11237

Oscillation parameter	Best fit value	3σ range
$\theta_{12}/°$	34.3	[31.4, 37.4]
$\theta_{23}/°$	48.8	[41.6, 51.3]
$\theta_{13}/°$	8.6	[8.2, 8.9]
δ_{13}/π	-0.8	$[-1, 0] \cup [0.8, 1]$
$\Delta m^2_{21}/10^{-5}$ eV^2	7.5	[6.9, 8.1]
$\Delta m^2_{31}/10^{-3}$ eV^2	2.6	[2.5, 2.7]

Talk by S.H. Seo

Outstanding questions:

- Leptonic CP violation
- Neutrino mass ordering
- θ_{23}-octant
- ….

$$
\begin{aligned}
P_{\mu e} \quad &\simeq \quad \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \Delta \\
&+ \quad \alpha\Delta \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin \Delta \cos(\delta + \Delta)
\end{aligned}
$$

where, $A = \dfrac{2\sqrt{2}EG_F n_E}{\Delta m^2_{31}}$ $\quad \alpha = \dfrac{\Delta m^2_{21}}{\Delta m^2_{31}}$ $\quad \Delta = \dfrac{\Delta m^2_{31} L}{4E}$

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- ….

$$\simeq 1.27 \times \frac{\Delta m^2[eV^2]\,.\,L[m]}{E[MeV]} \simeq \pi/2$$

(For maximal oscillation)

$$\frac{L[m]}{E[MeV]} \sim (\Delta m^2[eV^2])^{-1}$$

Main Principle for oscillation expts.

$$\begin{aligned} P_{\mu e} \quad &\simeq \quad \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \Delta \\ &+ \quad \alpha\Delta \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin \Delta \cos(\delta + \Delta) \end{aligned}$$

where, $A = \dfrac{2\sqrt{2}EG_F n_E}{\Delta m^2_{31}}$ $\qquad \alpha = \dfrac{\Delta m^2_{21}}{\Delta m^2_{31}}$ $\qquad \Delta = \dfrac{\Delta m^2_{31} L}{4E}$

3+1 case :basics

$$P_{\alpha\beta} = \delta_{\alpha\beta} - \sum_{k>j} \mathrm{Re}[U^*_{\alpha k} U^*_{\beta j} U_{\alpha j} U_{\beta k}] \sin^2 \Delta_{kj} - \sum_{k>j} \mathrm{Im}[U^*_{\alpha k} U^*_{\beta j} U_{\alpha j} U_{\beta k}] \sin 2\Delta_{kj}$$

$$\text{where } \Delta_{ij} = 1.27 \times \frac{\Delta m^2_{ij}[\mathrm{eV}^2] \times L[\mathrm{km}]}{E[\mathrm{GeV}]}$$

- 3 more mixing angles and 2 additional CP phases
- Unitarity in 4x4 sector : $\sum_{k=1,2,3,4} U_{\alpha k} U^*_{\beta k} = \delta_{\alpha\beta}$
- $\Delta m^2_{41} \sim 1\ \mathrm{eV}^2, \Delta m^2_{21} \approx 7.5 \times 10^{-5}\ \mathrm{eV}^2, \Delta m^2_{31} \approx 2.5 \times 10^{-3}\ \mathrm{eV}^2$

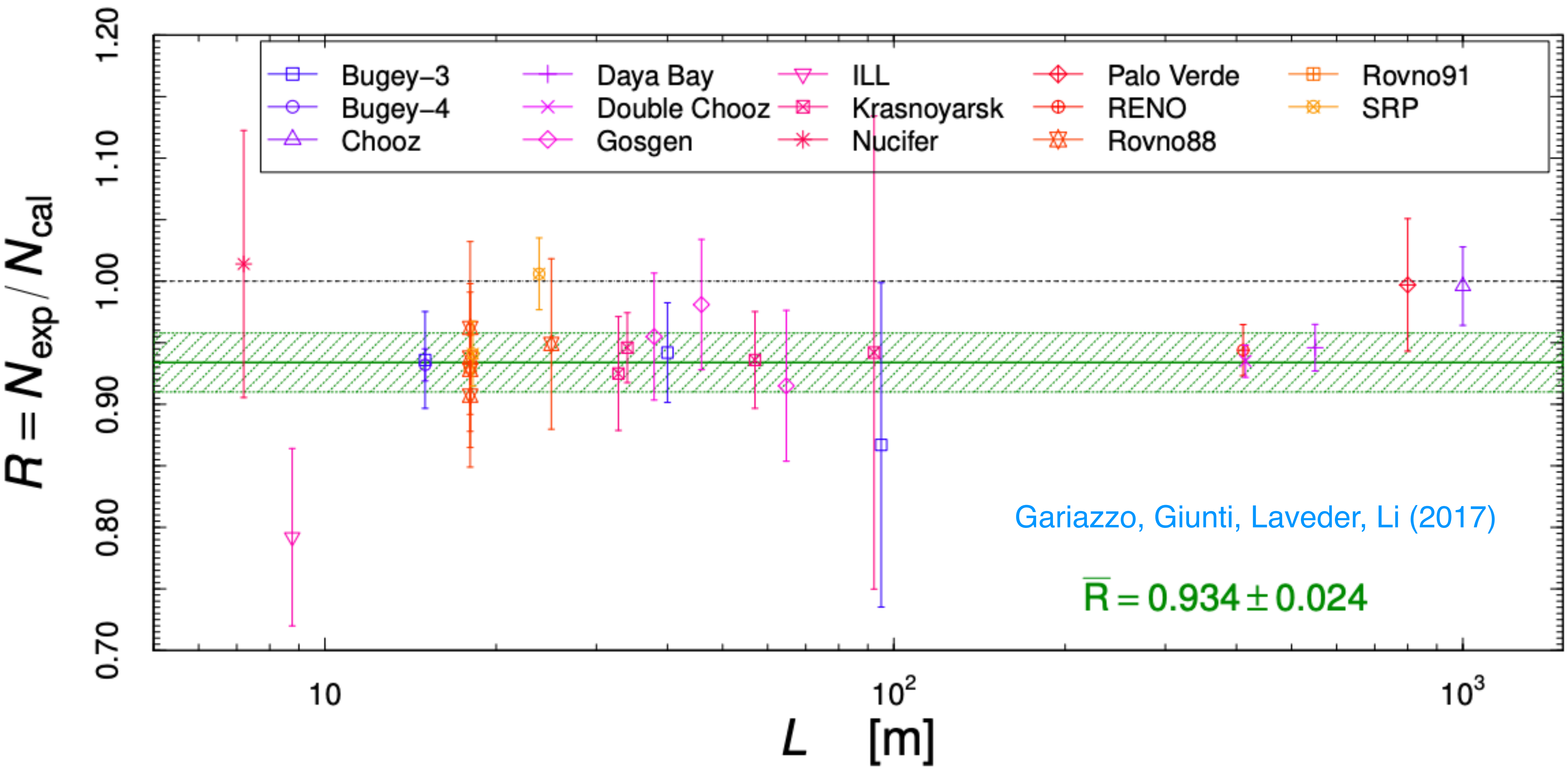
  $\Delta m^2_{41} \approx \Delta m^2_{42} \approx \Delta m^2_{43} >> \Delta m^2_{31} >> \Delta m^2_{21}$

$$P_{\alpha\beta} \approx P^{3+0}_{\alpha\beta} + \underbrace{|U_{\alpha 4}|^2 |U_{\beta 4}|^2}_{\sin^2\theta_{\alpha\beta}} \sin^2 \Delta_{41} \quad (\alpha \neq \beta)$$

$$P_{\alpha\alpha} \approx P^{3+0}_{\alpha\alpha} - \underbrace{|U_{\alpha 4}|^2 (1 - |U_{\alpha 4}|^2)}_{\sin^2\theta_{\alpha\alpha}} \sin^2 \Delta_{41}$$

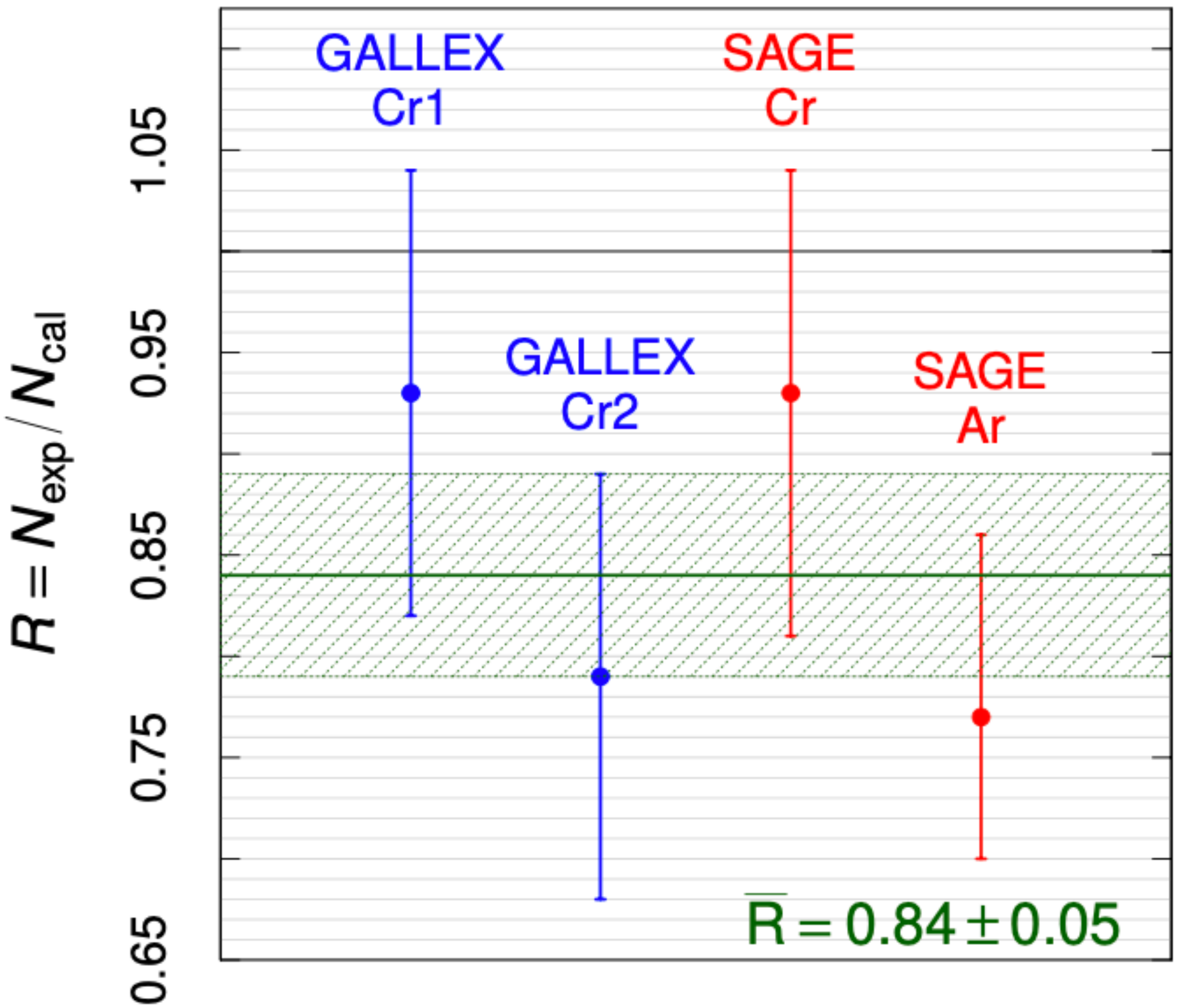
Gandhi, Kayser, MM,Prakash (2015)

Hints: Reactor antineutrino anomaly (RAA)



- Detection via IBD: $\bar{\nu}_e + p \to n + e^+$
- Deficit of total event rates compared to expectation ($\sim 2.8\sigma$)
- Current analysis seems to have reduced the anomaly a lot

Hints: Galium anomaly



Kaether et al: GALLEX collab. (2010)

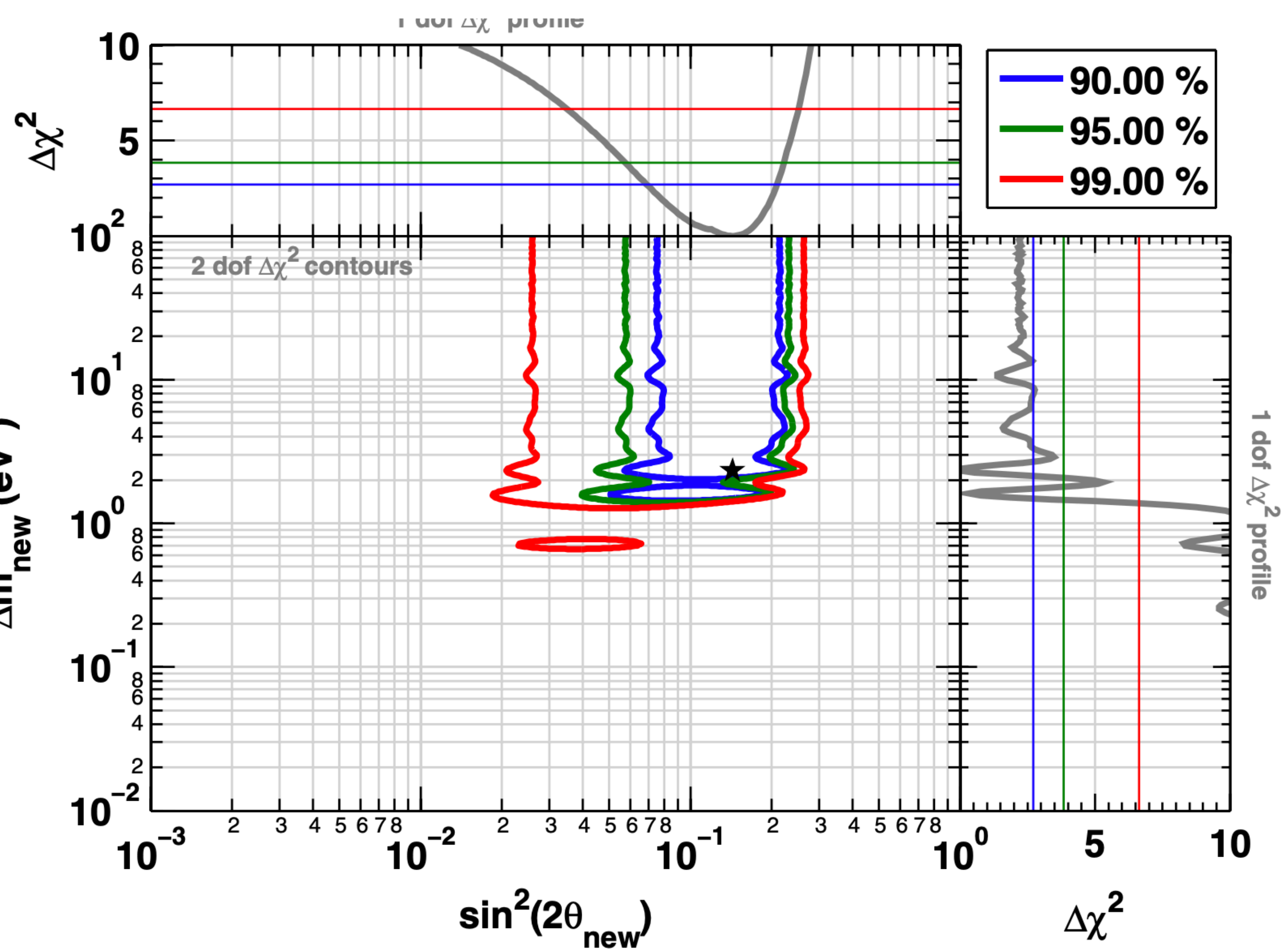
Abdurashitov et al: SAGE collab. (2006)

Giunti, Lasserre (2019)

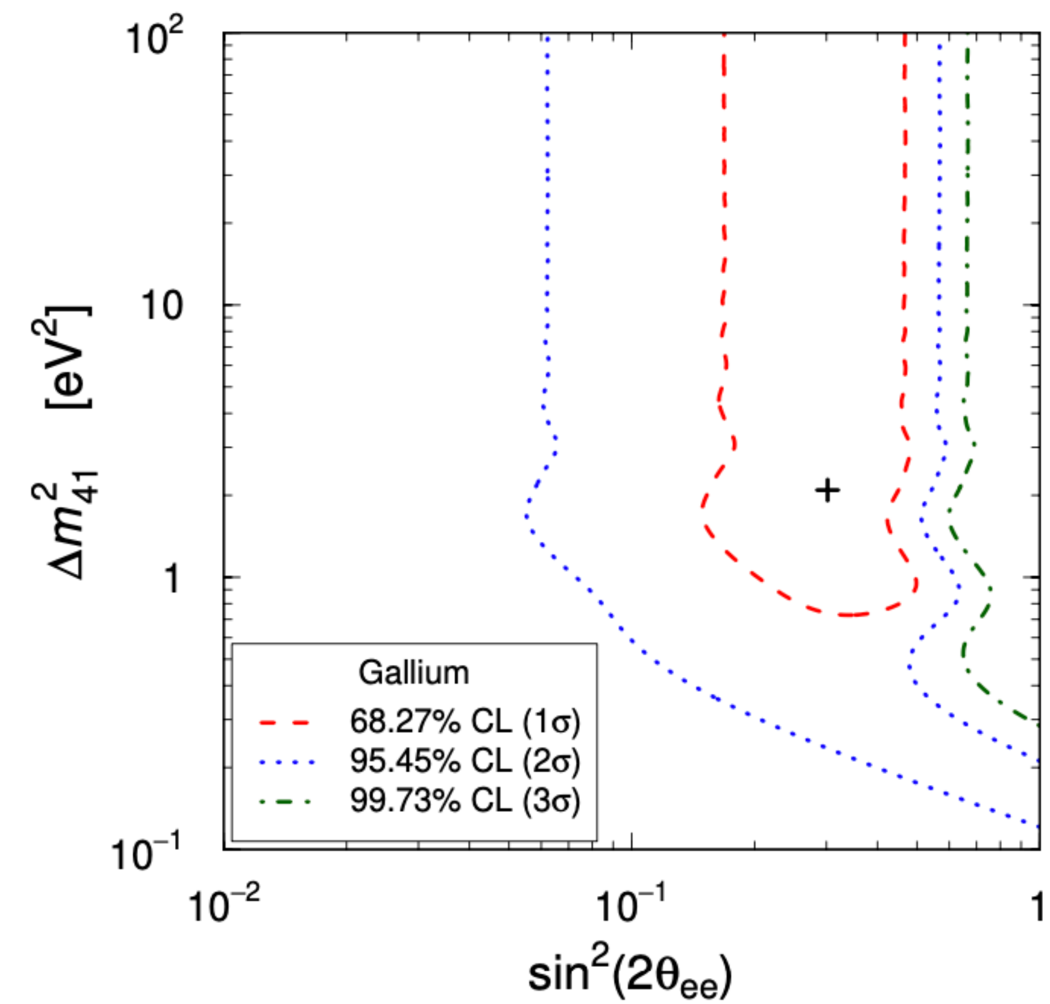
- $\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$
- Deficit of total event rates compared to expectation ($\sim 3\sigma$)
- Recent analysis on cross-sections can reduce the significance to 2.2σ

Hints:RAA & Galium anomaly

Mention et al (2012) RAA

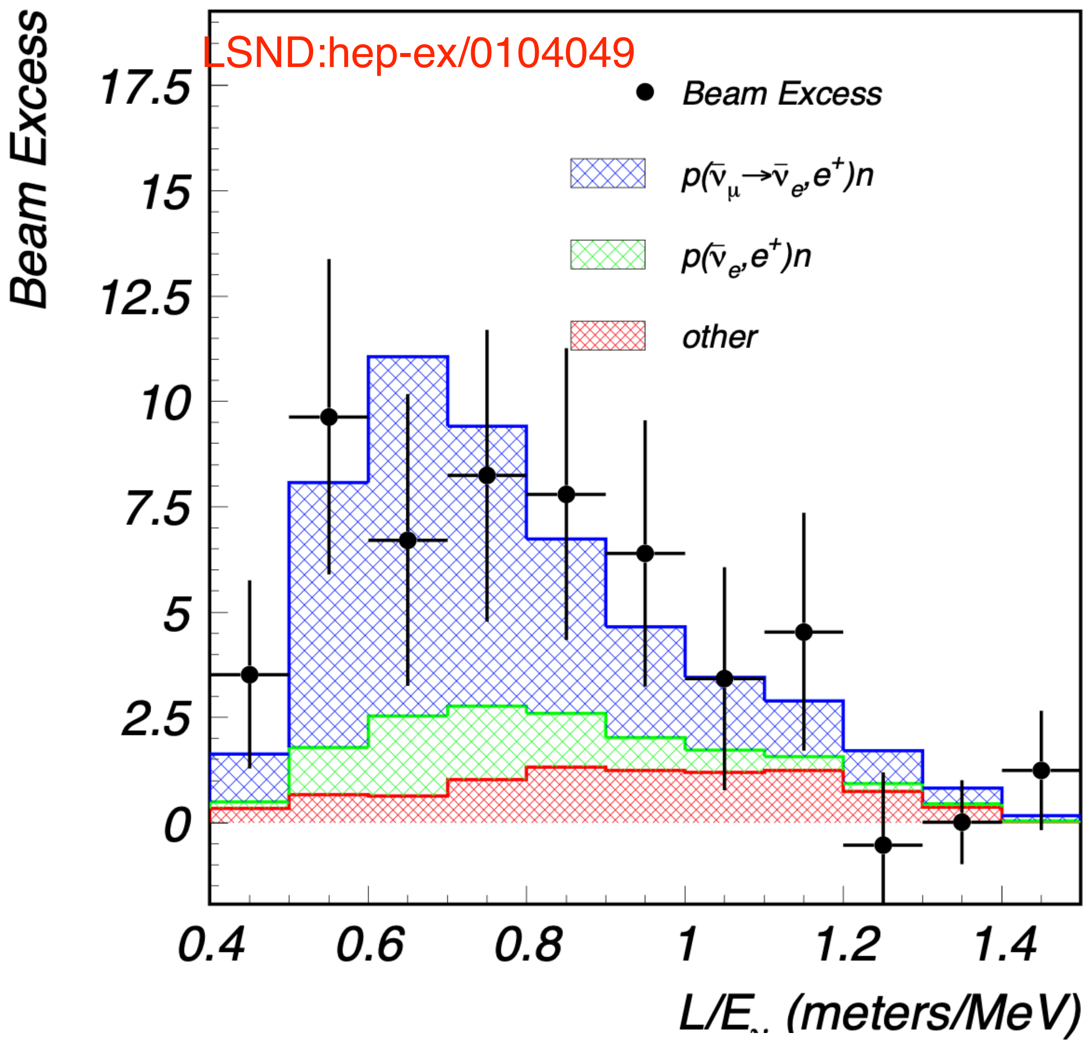


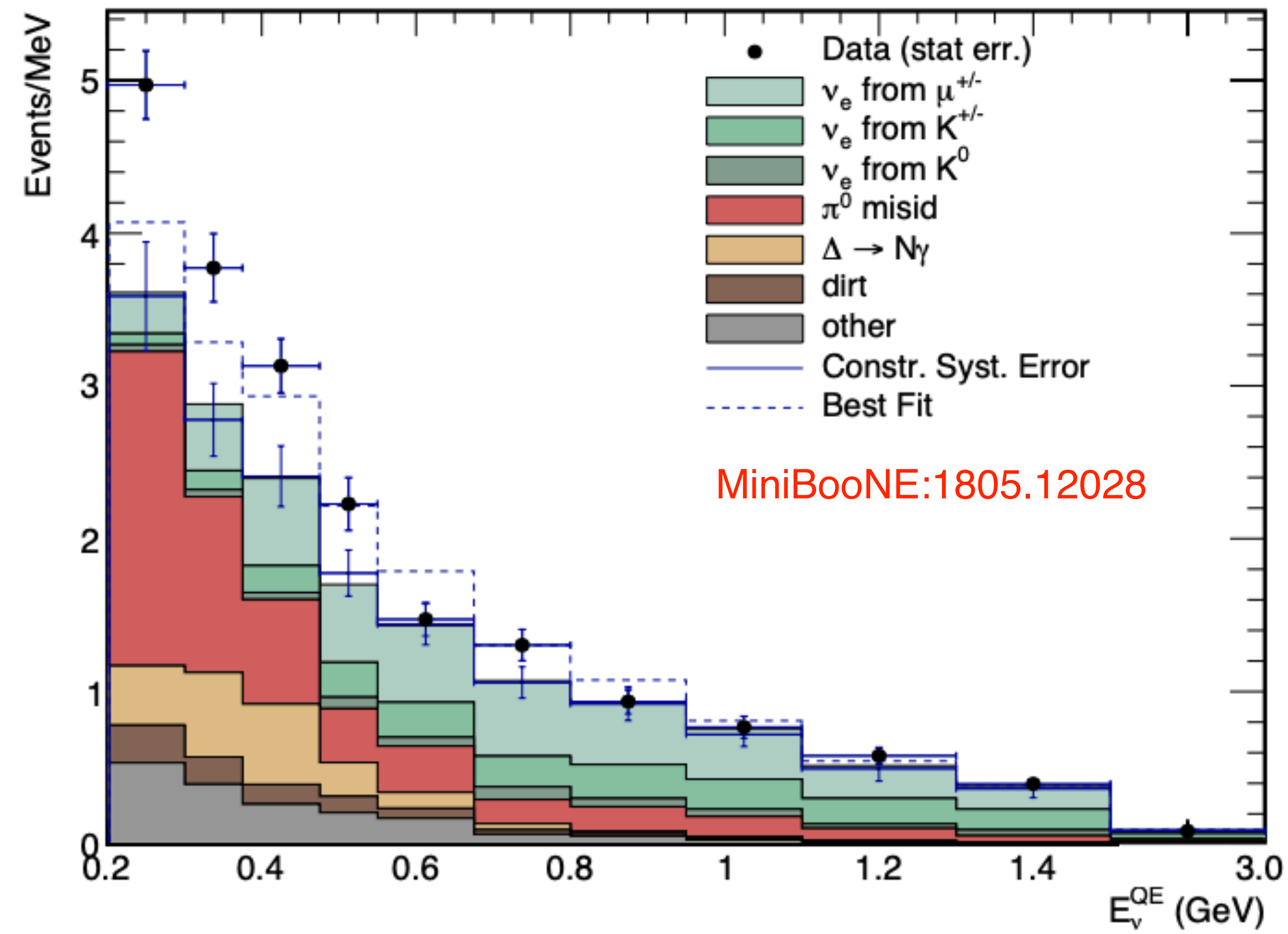
Giunti & Laveder (2011) Galium



- Can be fit by $\Delta m^2 \gtrsim 1$ eV^2 & $\sin^2 2\theta \gtrsim 0.1$

Hints: LSND & MiniBooNE anomaly





VERY intense proton beam

$$p + X \to \pi^+ + X'$$

(800 MeV) $\quad \hookrightarrow \mu^+ \nu_\mu$ (DAR)

$\quad\quad \hookrightarrow e^+ \nu_e \bar{\nu}_\mu$

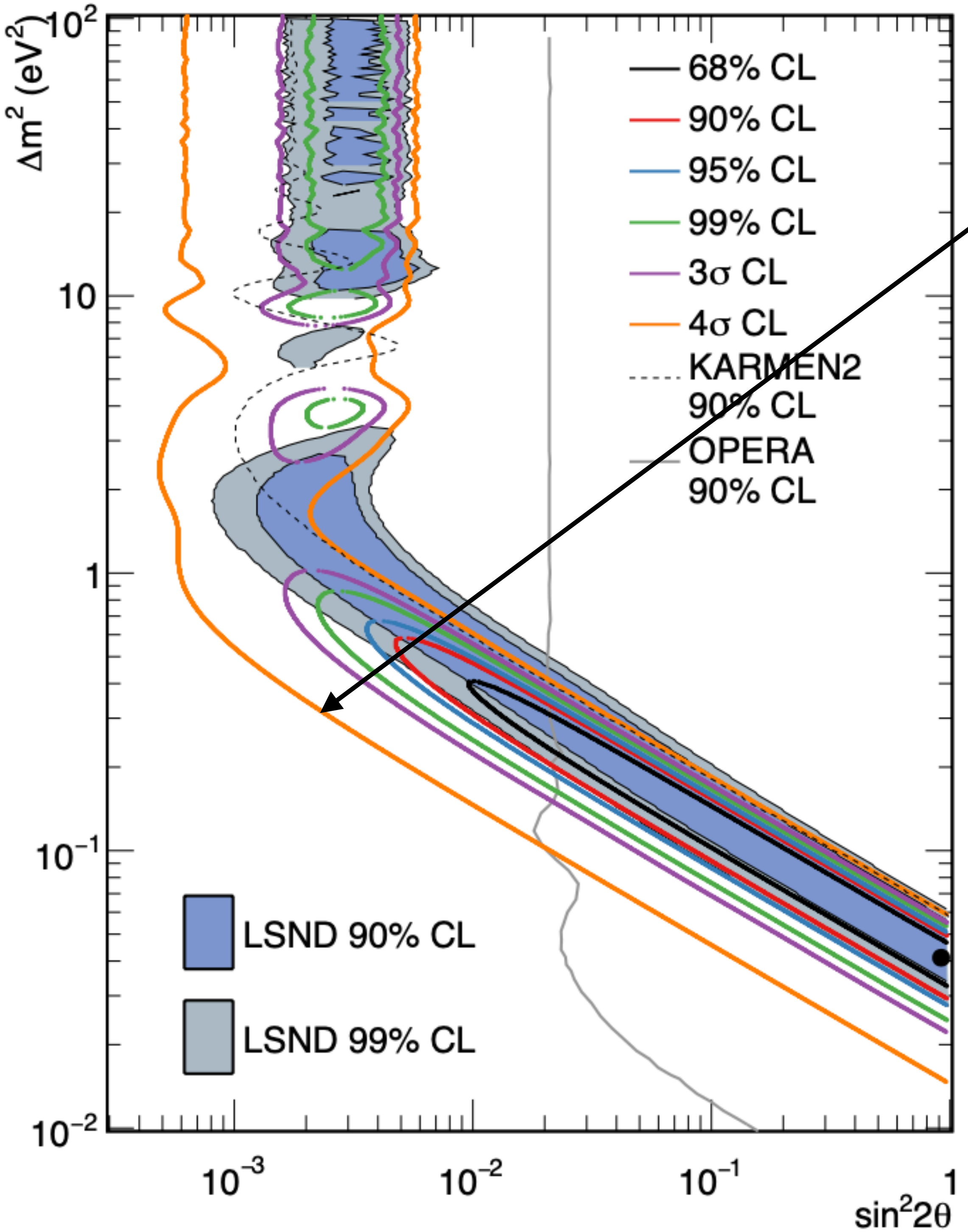
Detection signature:
IBD ($\bar{\nu}_e p \to e^+ n$)

LSND detected more $\bar{\nu}_e$ than expected: 87.9 ± 23.2 events (3.8σ excess)

Measures $\nu_\mu \to \nu_e$ osc.

Event excess: 381.2 ± 85.2 (4.5σ)

Hints: LSND & MiniBooNE anomaly

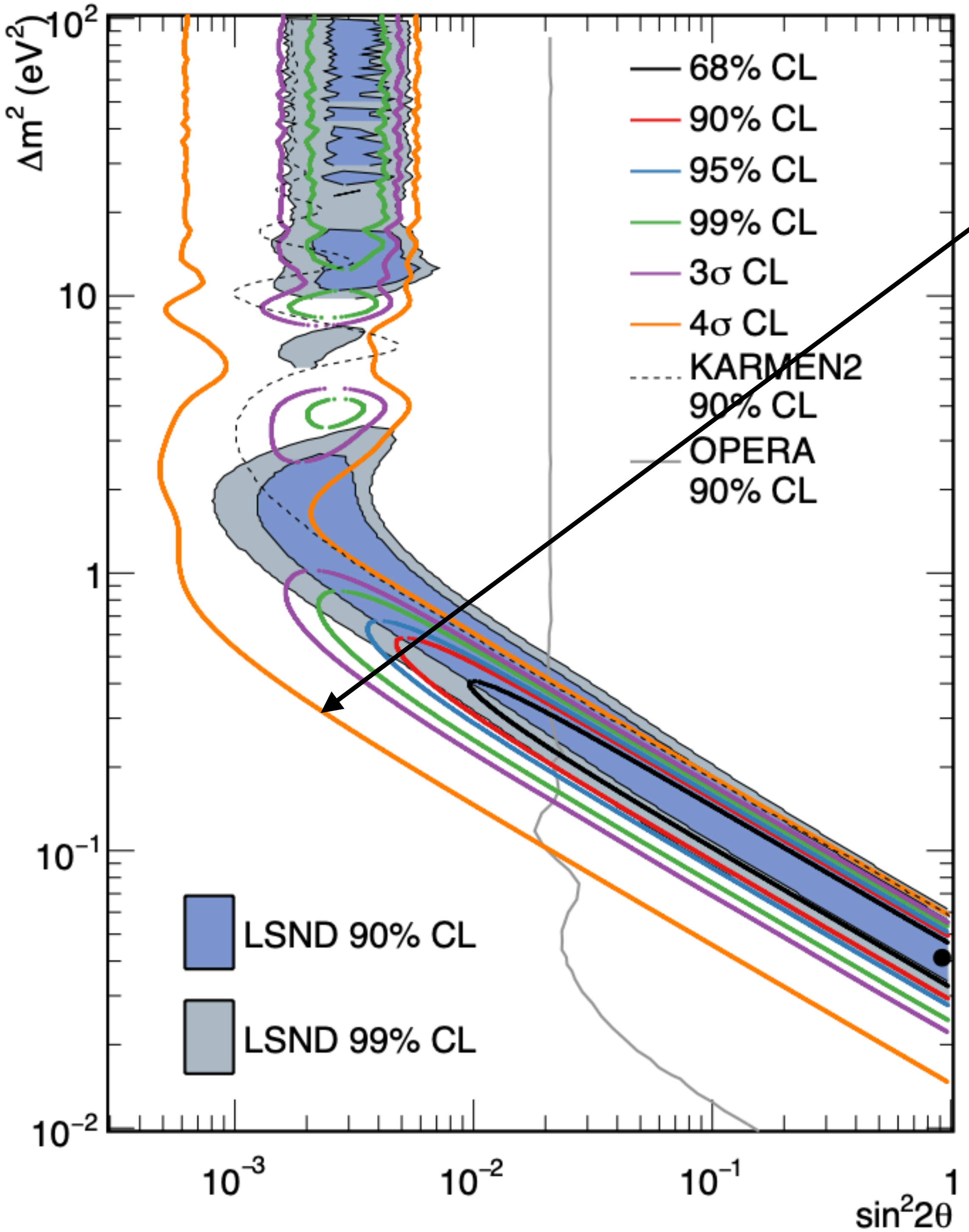


4σ by MiniBooNE

MB + LSND $\sim 6\sigma$ excess

MiniBooNE:1805.12028

Hints: LSND & MiniBooNE anomaly



4σ by MiniBooNE

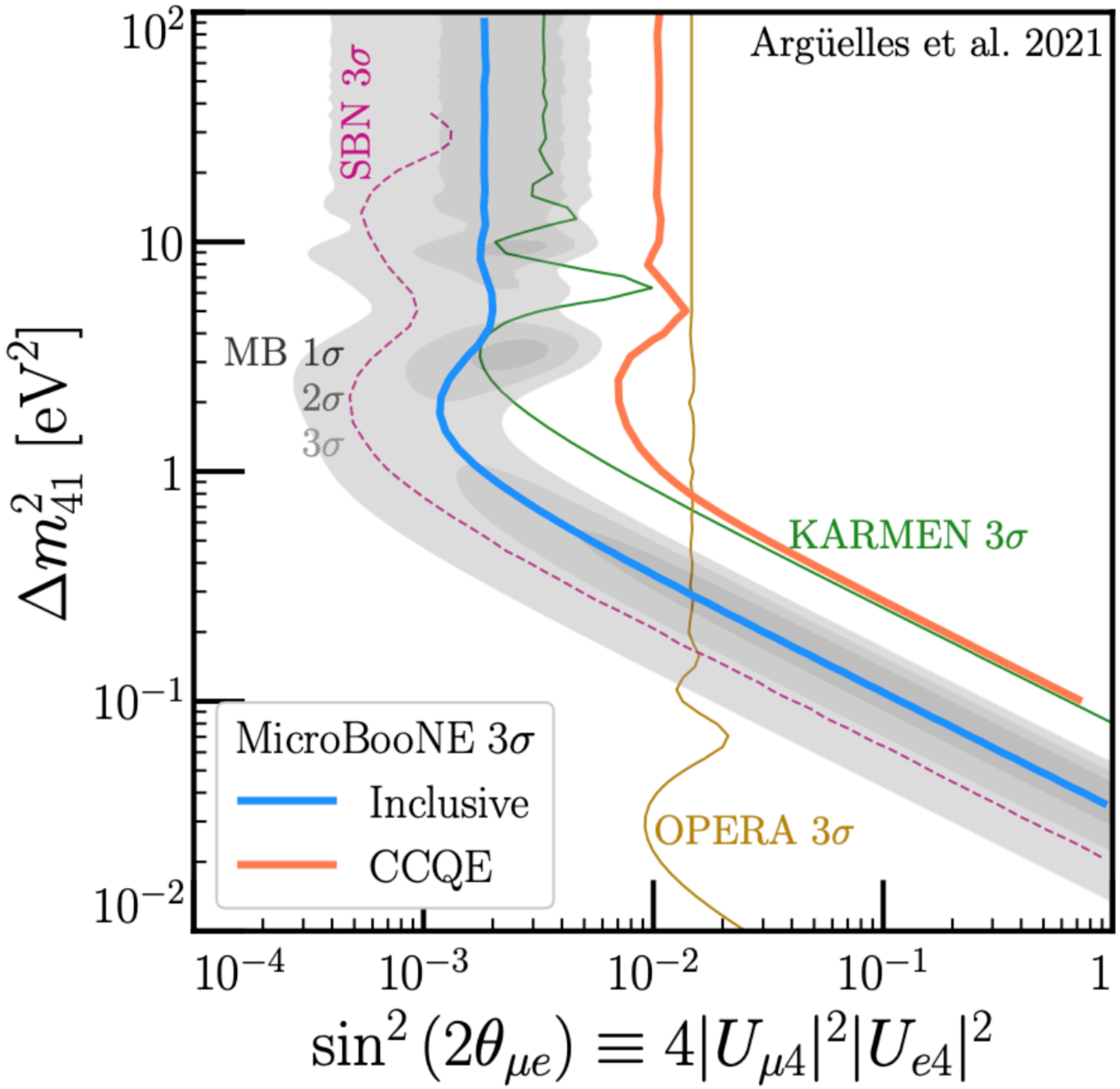
MB + LSND $\sim 6\sigma$ excess

Plethora of other possible explanations:

- γ from misidentified π^0
- Dark photons
- Dark sector decay to e^+e^-
- …….

MiniBooNE:1805.12028

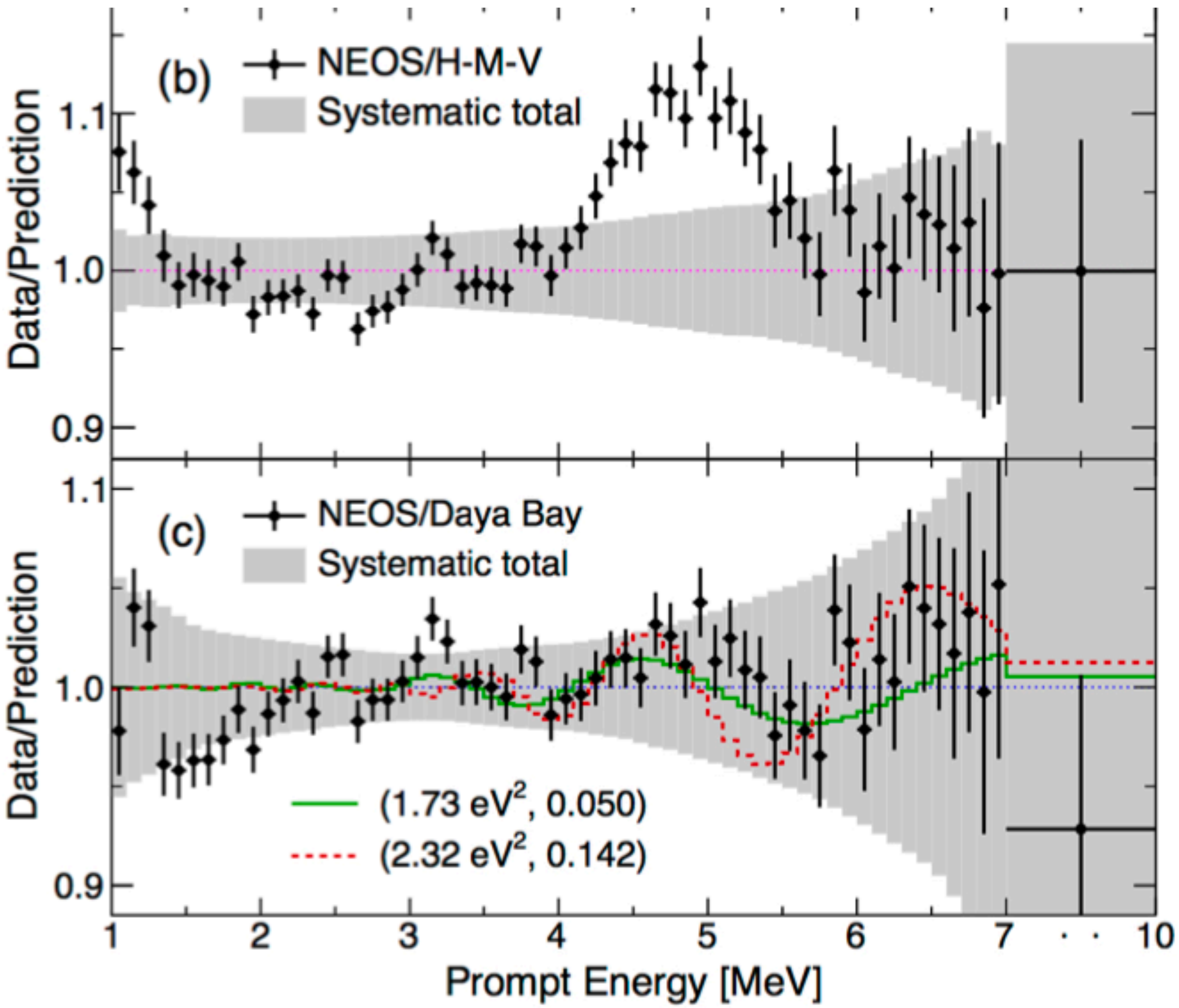
Hints: LSND & MiniBooNE anomaly



- Though MicroBooNE has not observed the anomalous excess, it has not yet completely ruled out 3+1 scenario

Current status: Reactor data

Ko et al: NEOS collaboration (2017)



- Comparison with predictions (Huber-Mueller-Vogel calculations)
- "Bump" at 5 MeV: shape anomaly

Current status: Reactor data

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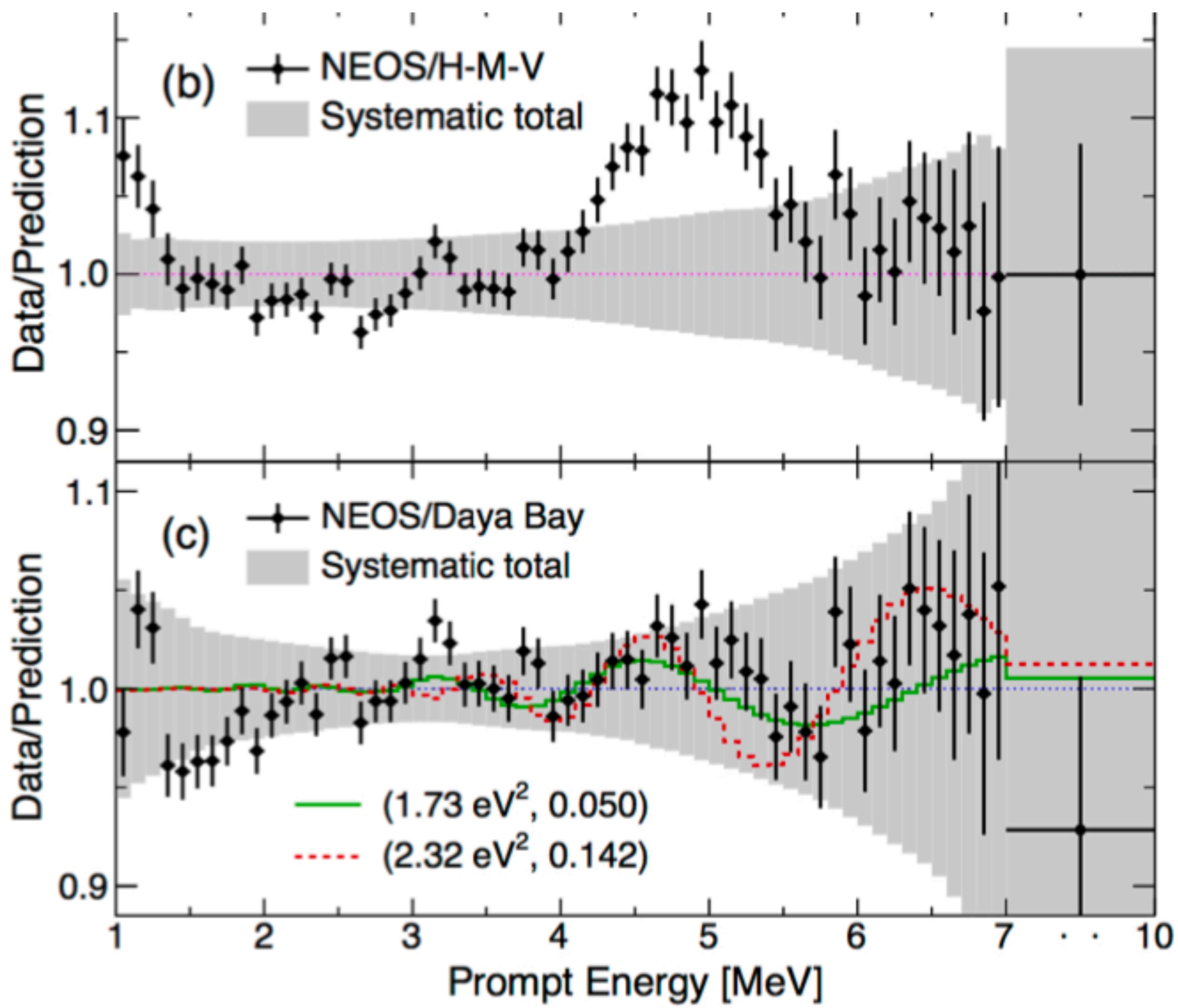
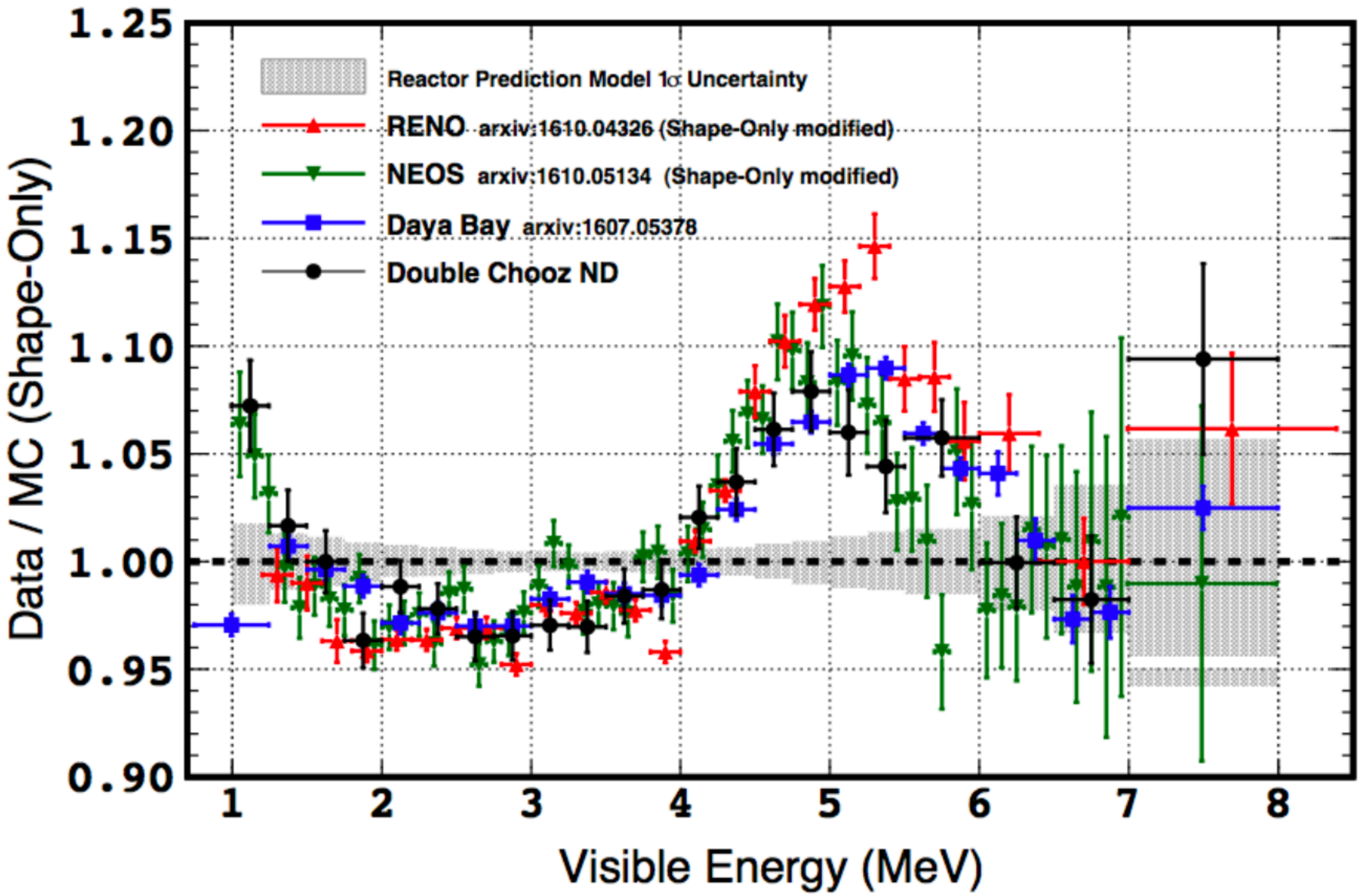


- Comparison with predictions (Huber-Mueller-Vogel calculations)
- “Bump” at 5 MeV: shape anomaly
- Comparison with DayaBay spectrum
- 3+1 bestfit
  RAA bestfit

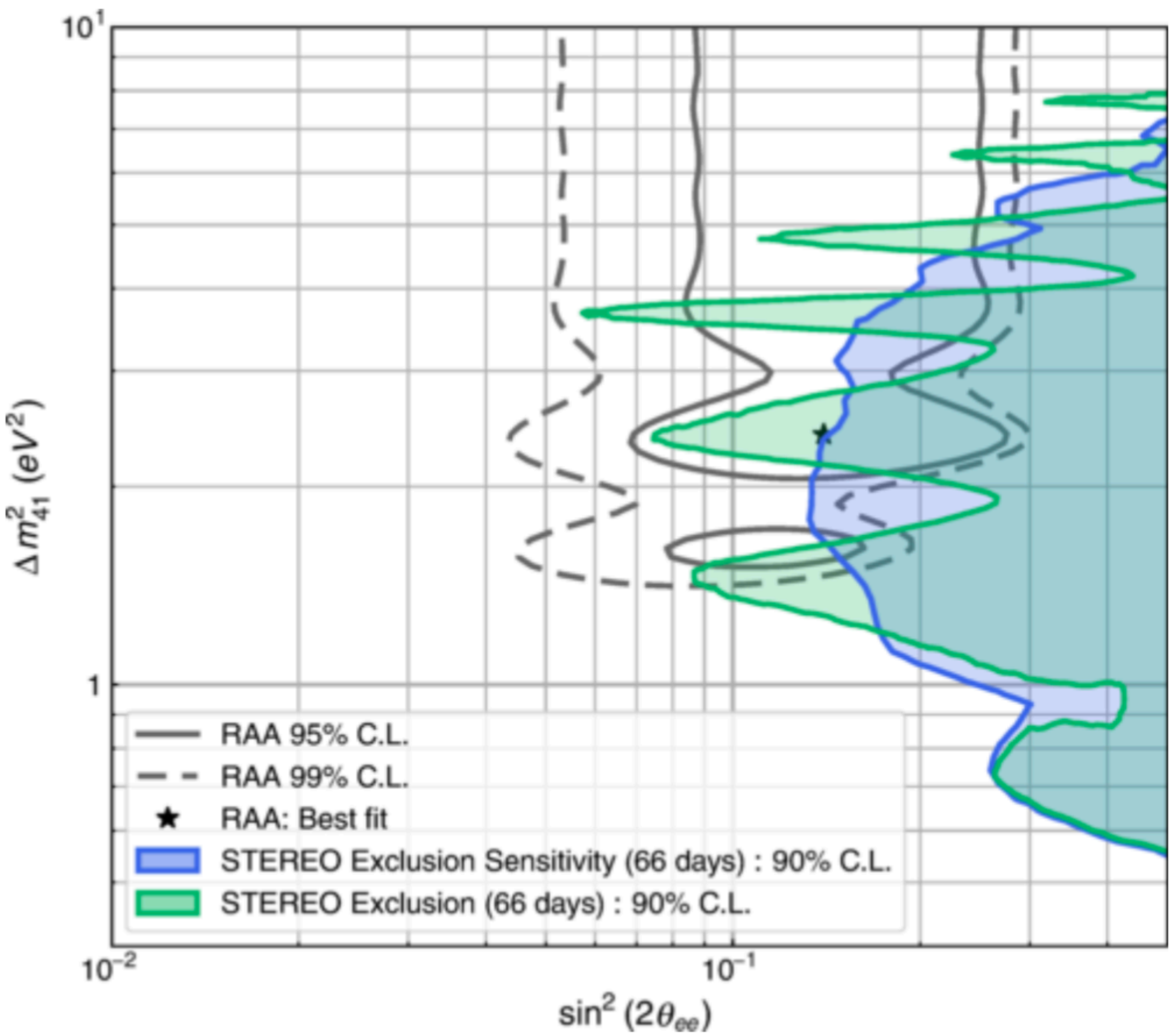
No strong evidence for sterile neutrino

Current status: Reactor data (5 MeV bump)



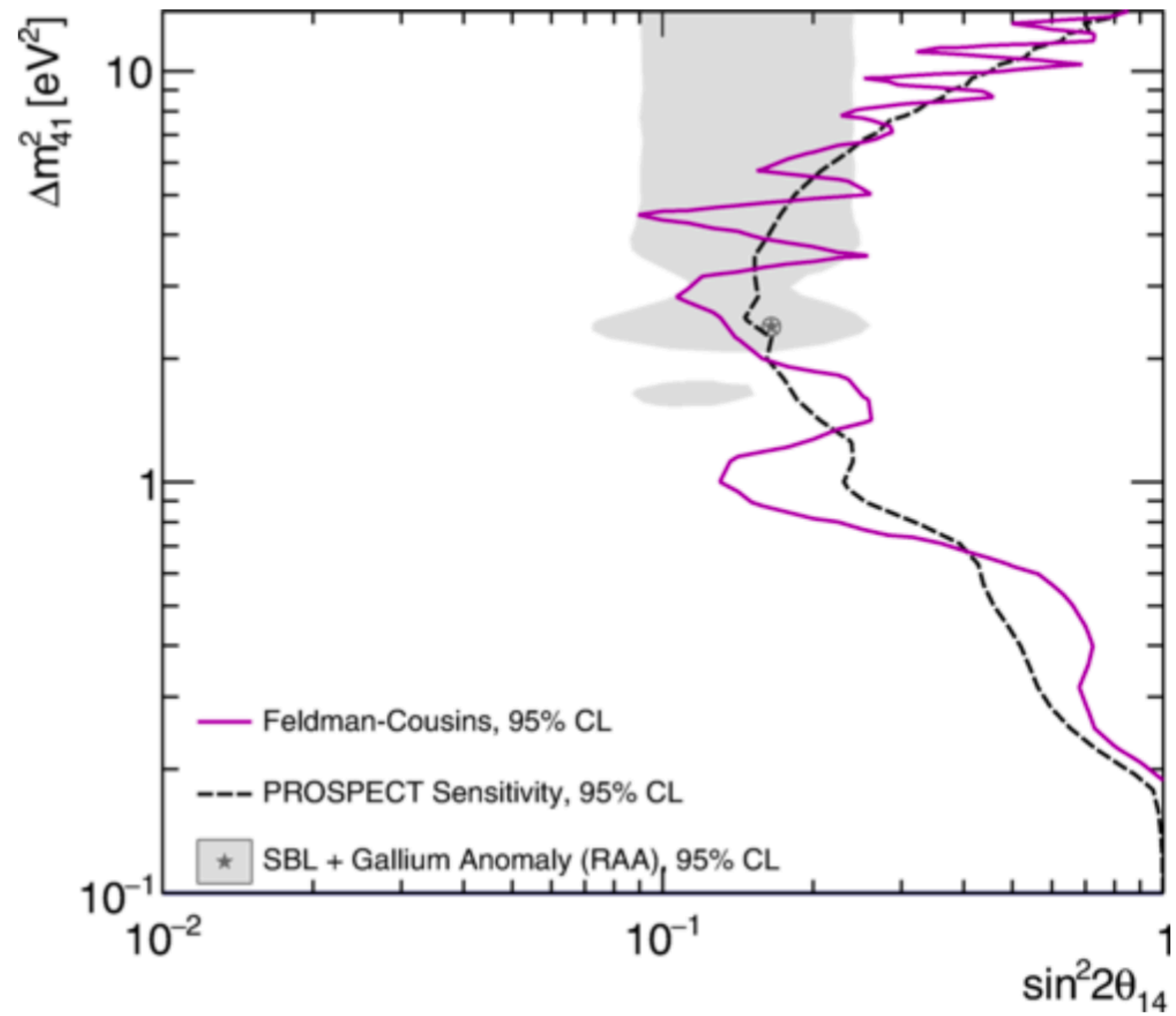
Current status: Reactor data

Almazan et al: STEREO collaboration (2018)



- 10 m baseline with a Gd-doped LS detector
- No significant evidence of sterile
- Can exclude RAA at 97.5% C.L.

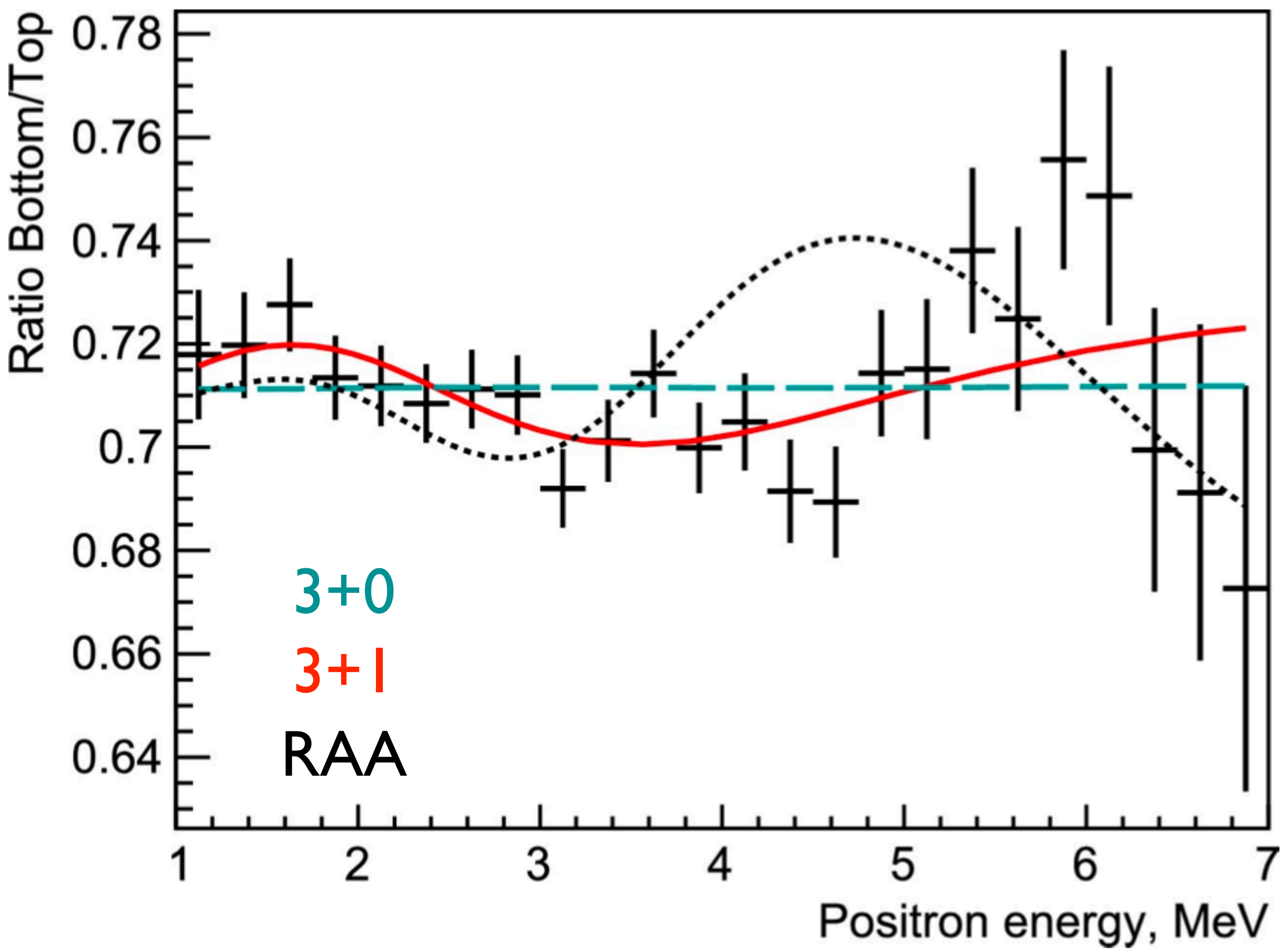
Ashenfelter et al: PROSPECT collaboration (2018)



- Baseline~7-9 m with a Li-doped LS detector
- Can exclude RAA bestfit at 2.2σ
- Limited statistics so far

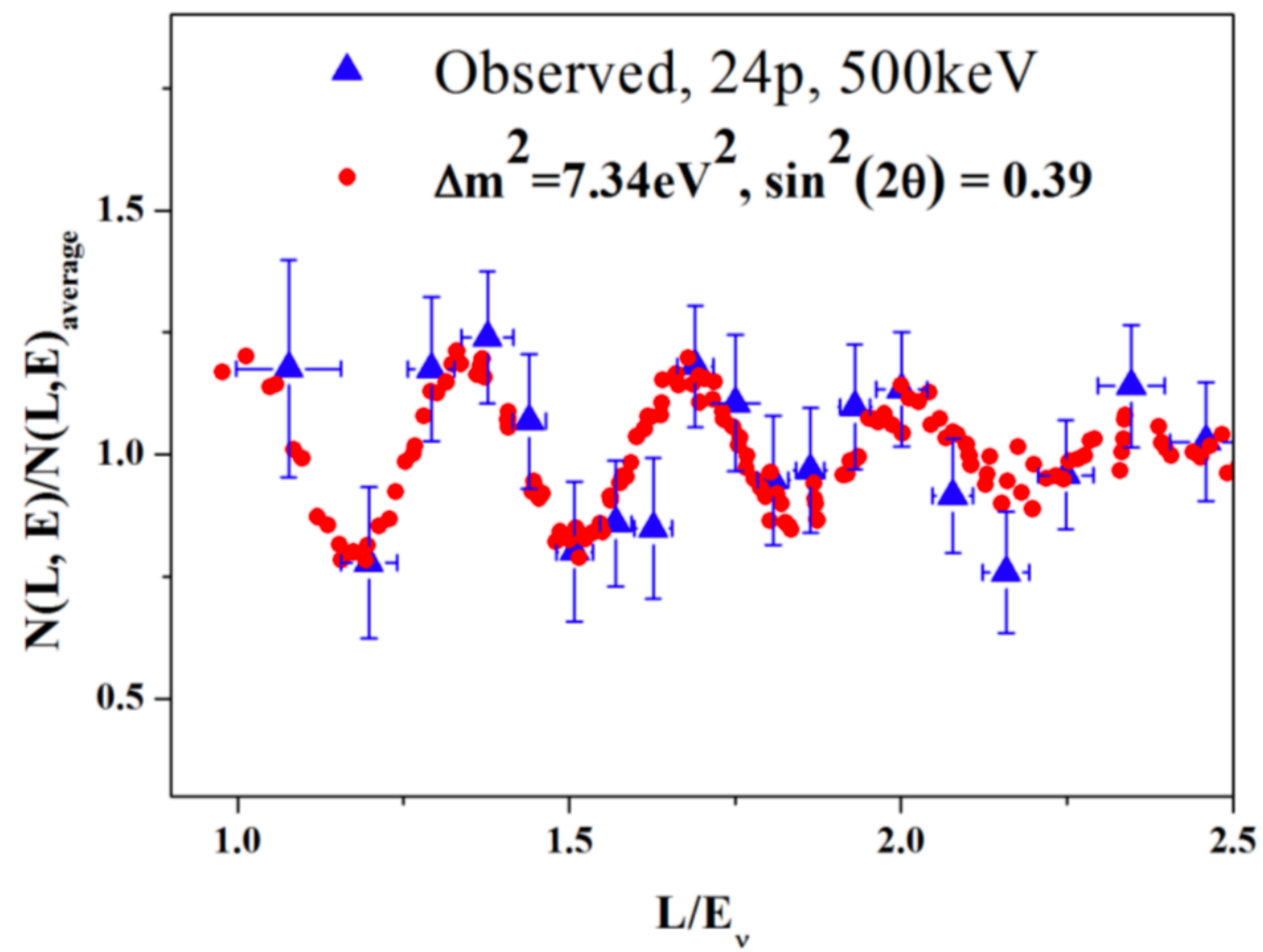
Current status: Reactor data

Alekseev et al: DANSS collaboration (2018)



- Observes spectra at different L (10.7-12.7 m)
- Very high interaction rate and S/B ratio
- Significance of oscillation $\lesssim 2\sigma$

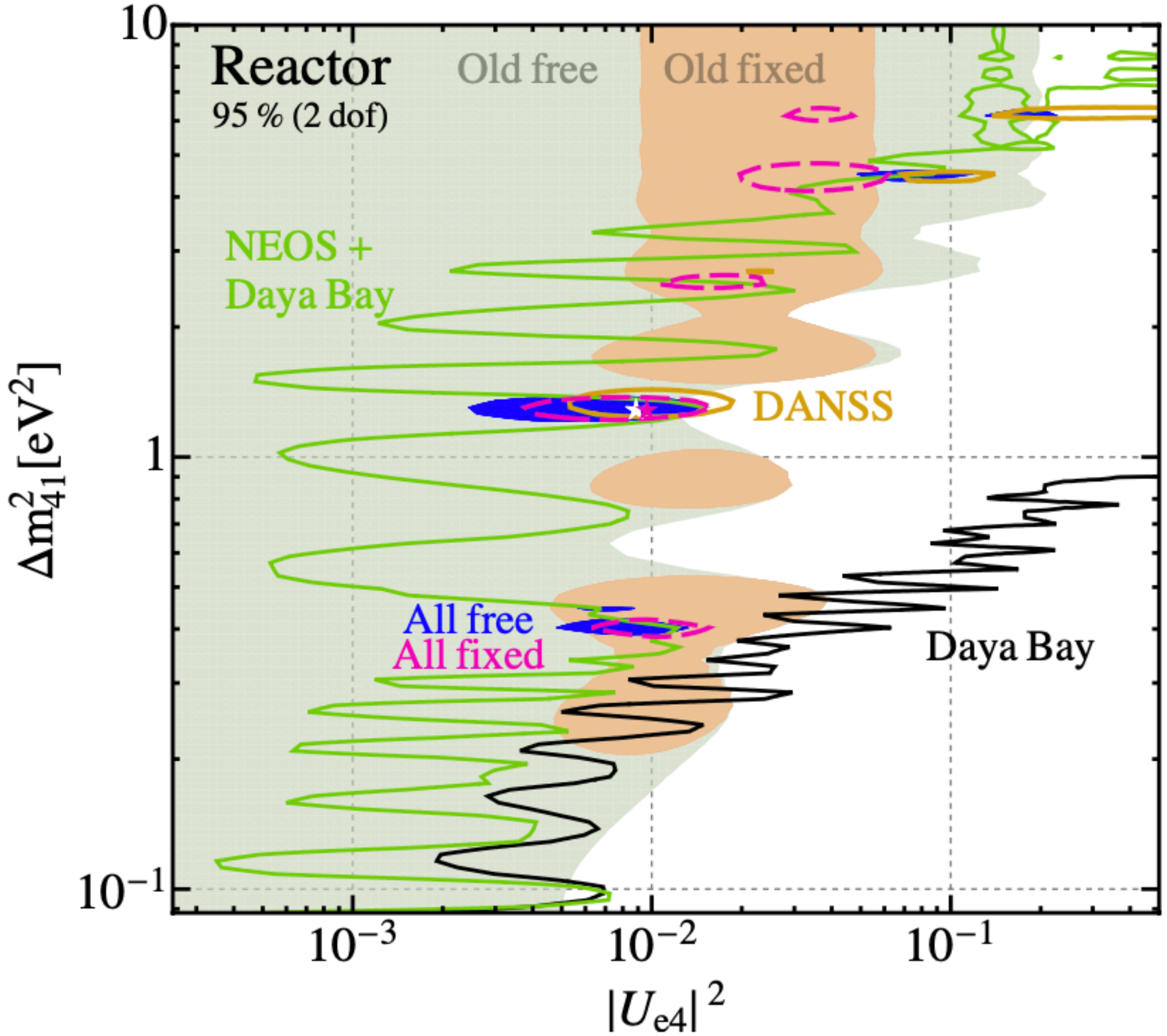
Serebrov et al: Neutrino-4 collaboration (2019)

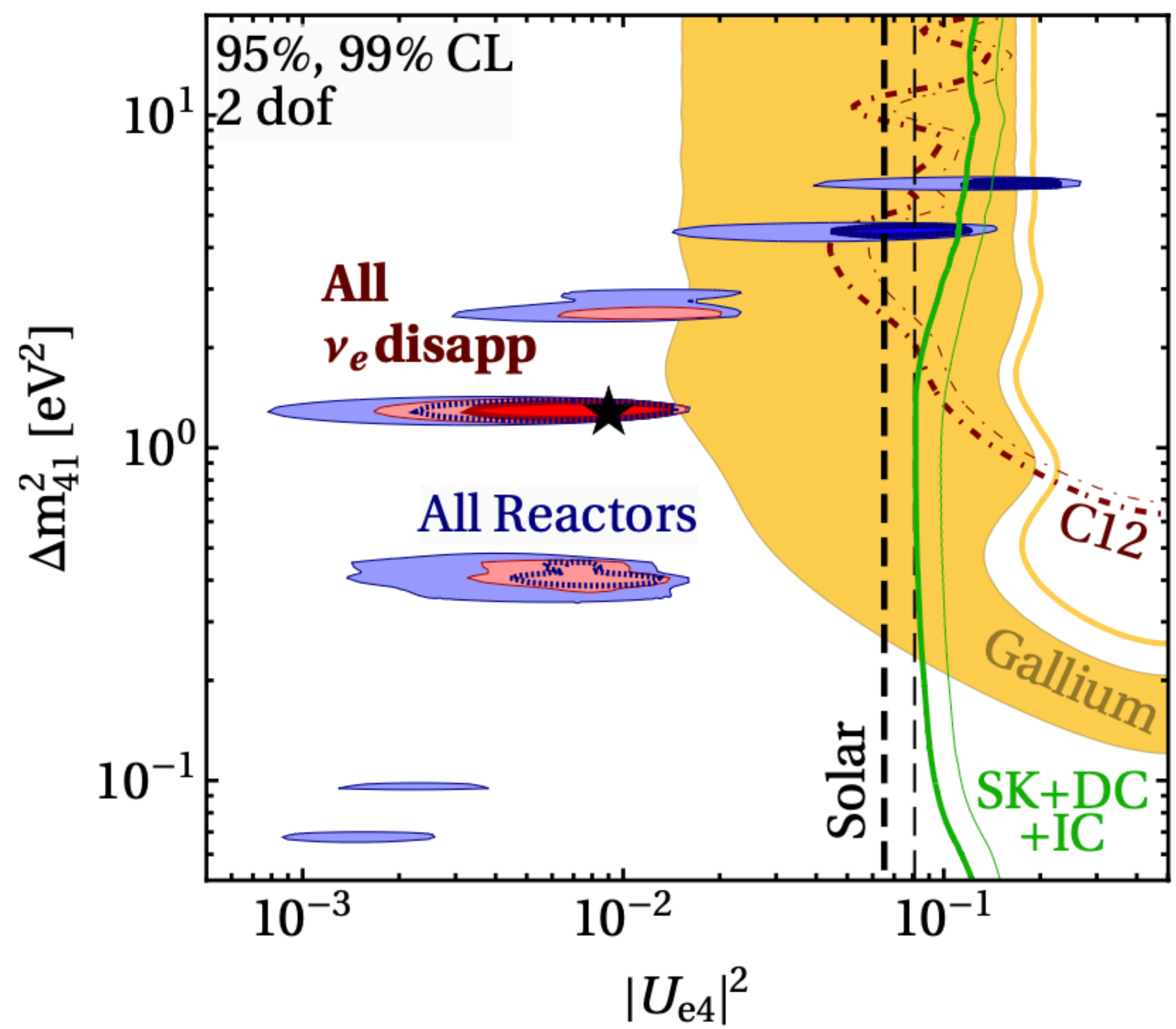


- Observes spectra at different L (6-12 m)
- Has claimed to observe active-sterile oscillation at 3σ

Current status: Reactor data

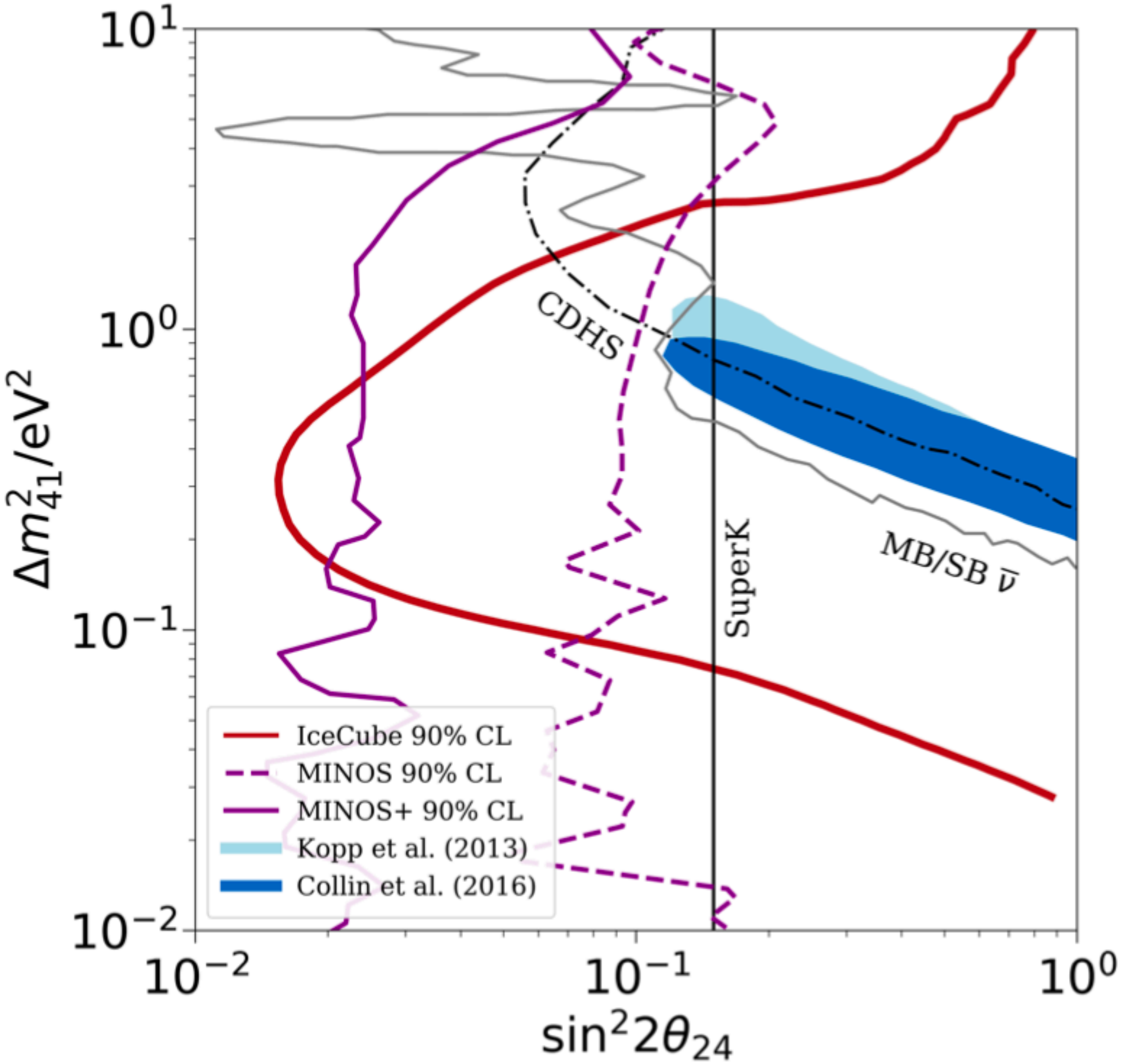
Dentler, Cabezudo, Kopp, Machado, Maltoni, Soler, Schwetz (2018)

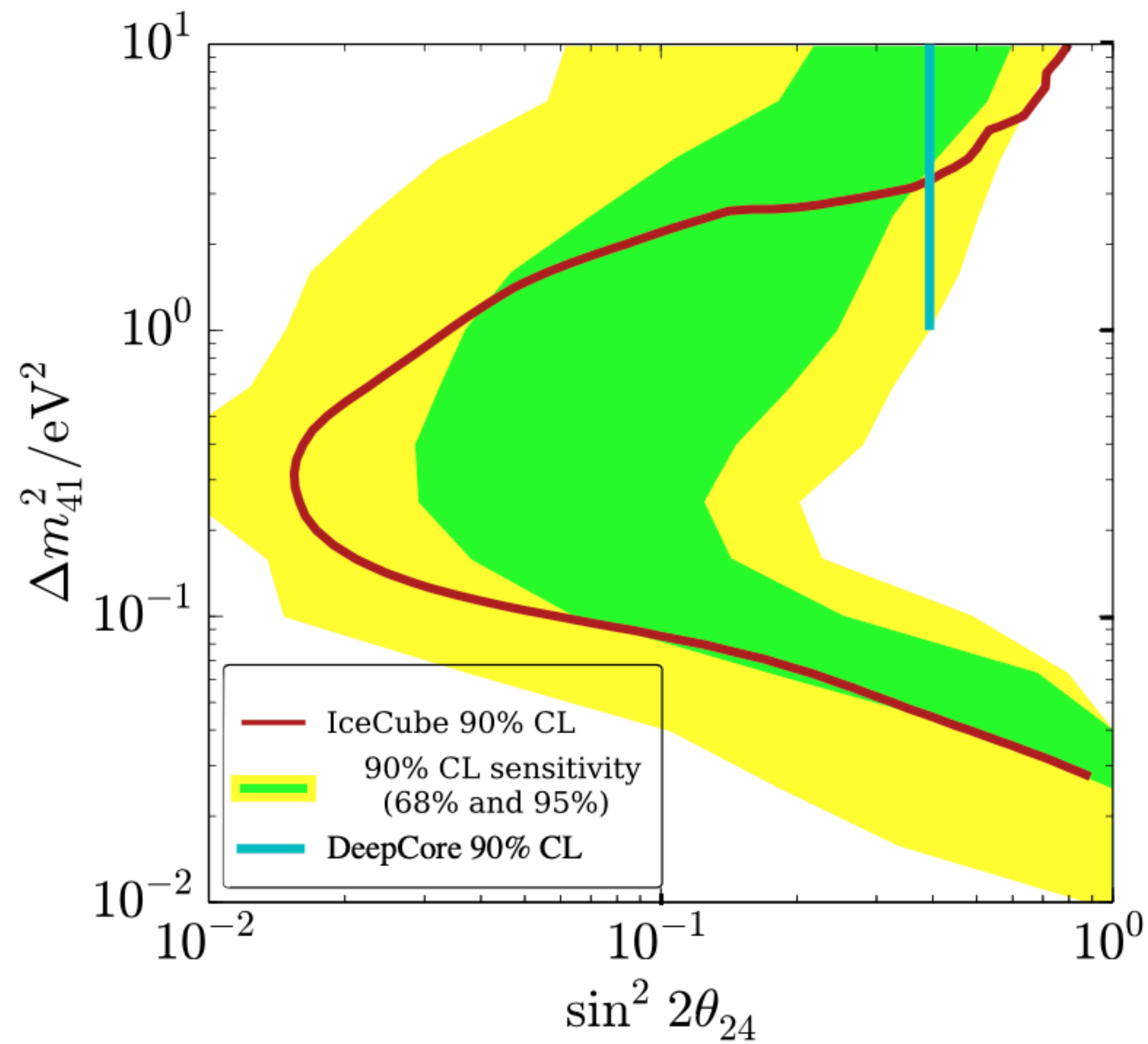




Current status: atmospheric and LBL data

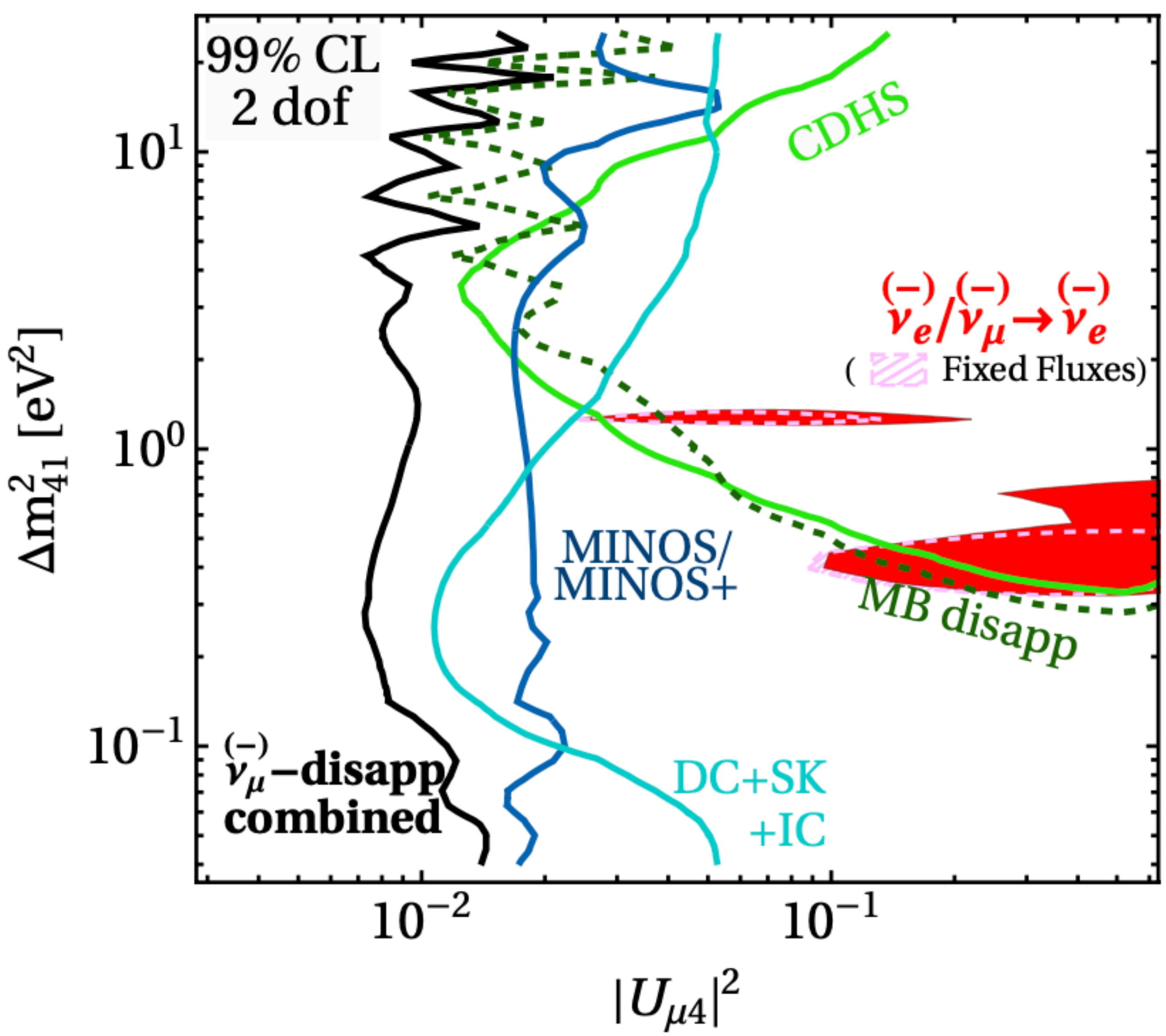
Dentler, Cabezudo, Kopp, Machado, Maltoni, Soler, Schwetz (2018)

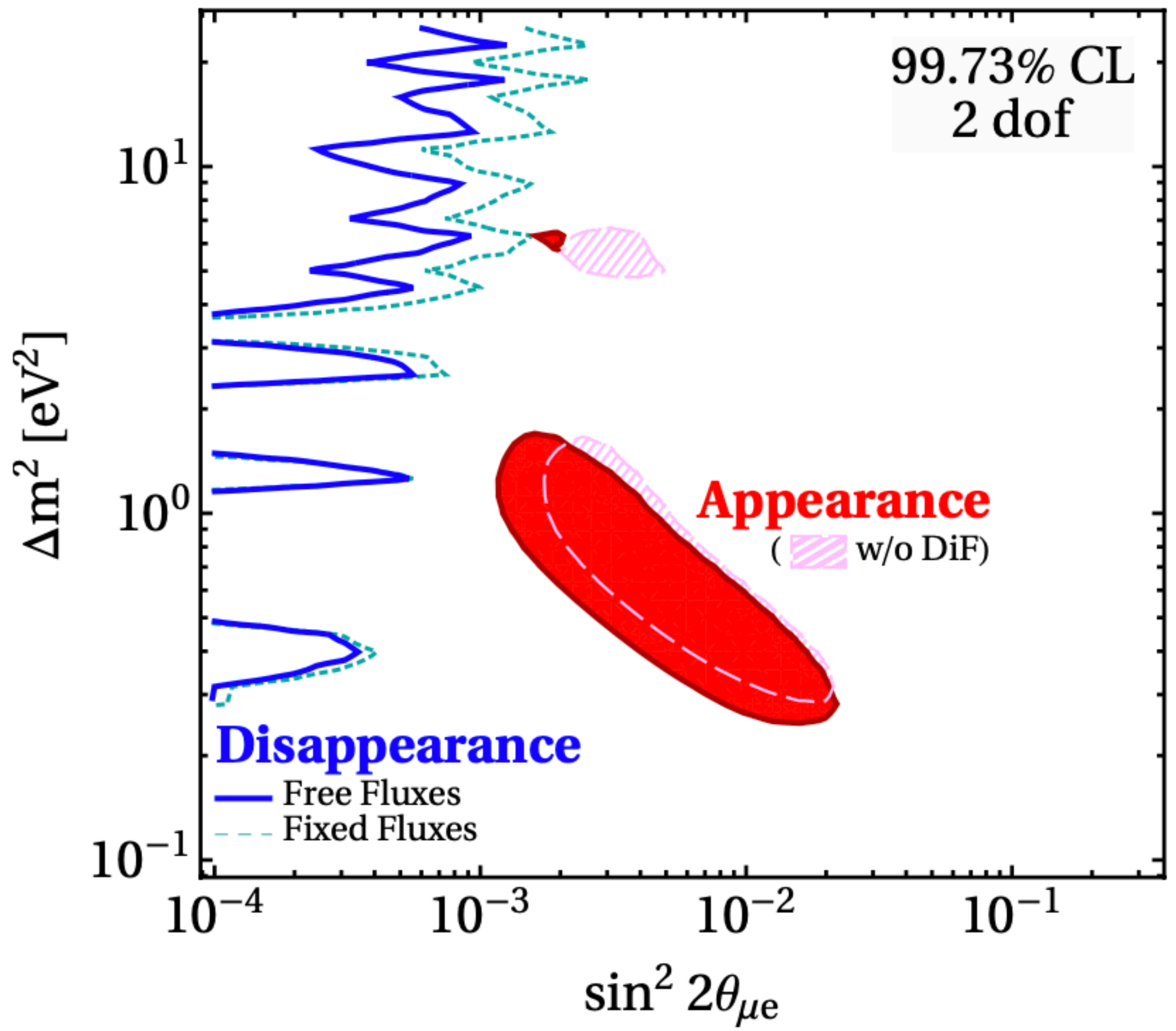




Current status: Another tension

Dentler, Cabezudo, Kopp, Machado, Maltoni, Soler, Schwetz (2018)

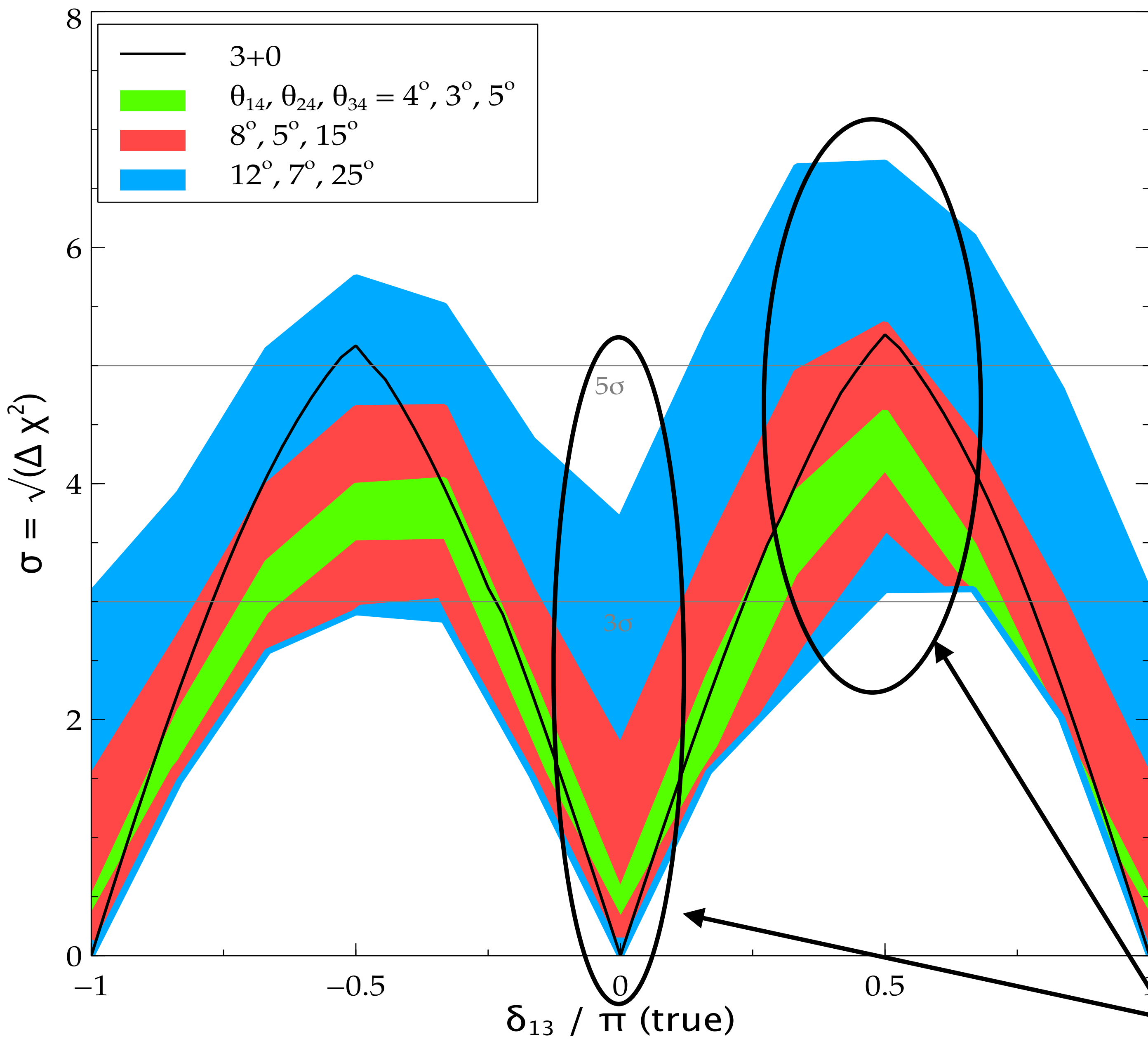




- $\sin^2 2\theta_{\alpha\beta} = 4\,|U_{\alpha4}|\,|^2 U_{\beta4}|^2;\ \sin^2 2\theta_{\alpha\alpha} = 4\,|U_{\alpha4}|^2(1 - |U_{\alpha4}|^2)$
- $\sin^2 2\theta_{\alpha\beta} \simeq \dfrac{1}{4}\sin^2 2\theta_{\alpha\alpha}\sin^2 2\theta_{\beta\beta}$ (for small $U_{\alpha4}$, $U_{\beta4}$)

3+1 case: Impact on crucial measurements

Dutta, Gandhi, Kayser, **MM**, Prakash (2016)

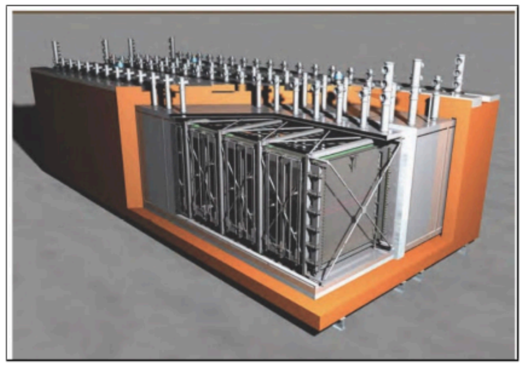


- Can potentially jeopardize attempts to resolve hierarchy, CPV, octant significantly

CP conservation/ violation?

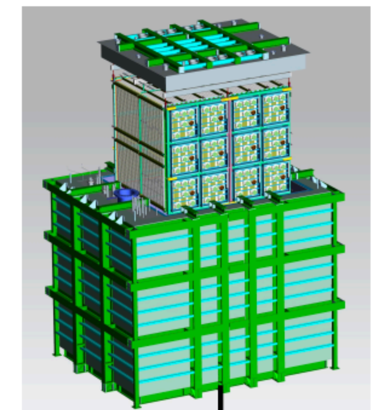
3+1 case: Future roadmap

ICARUS-T600 (476 t)
at L = 600 m

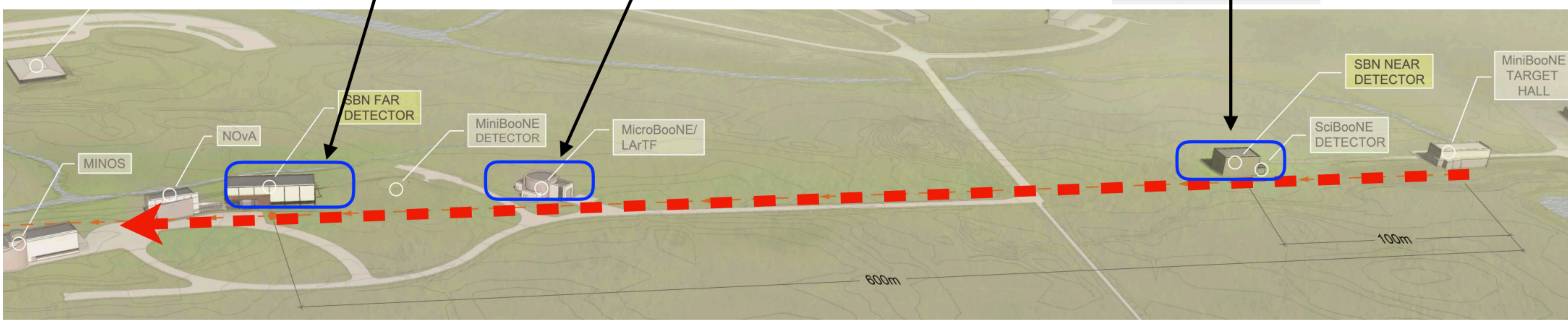


MicroBooNE (89 t)
at L = 470 m

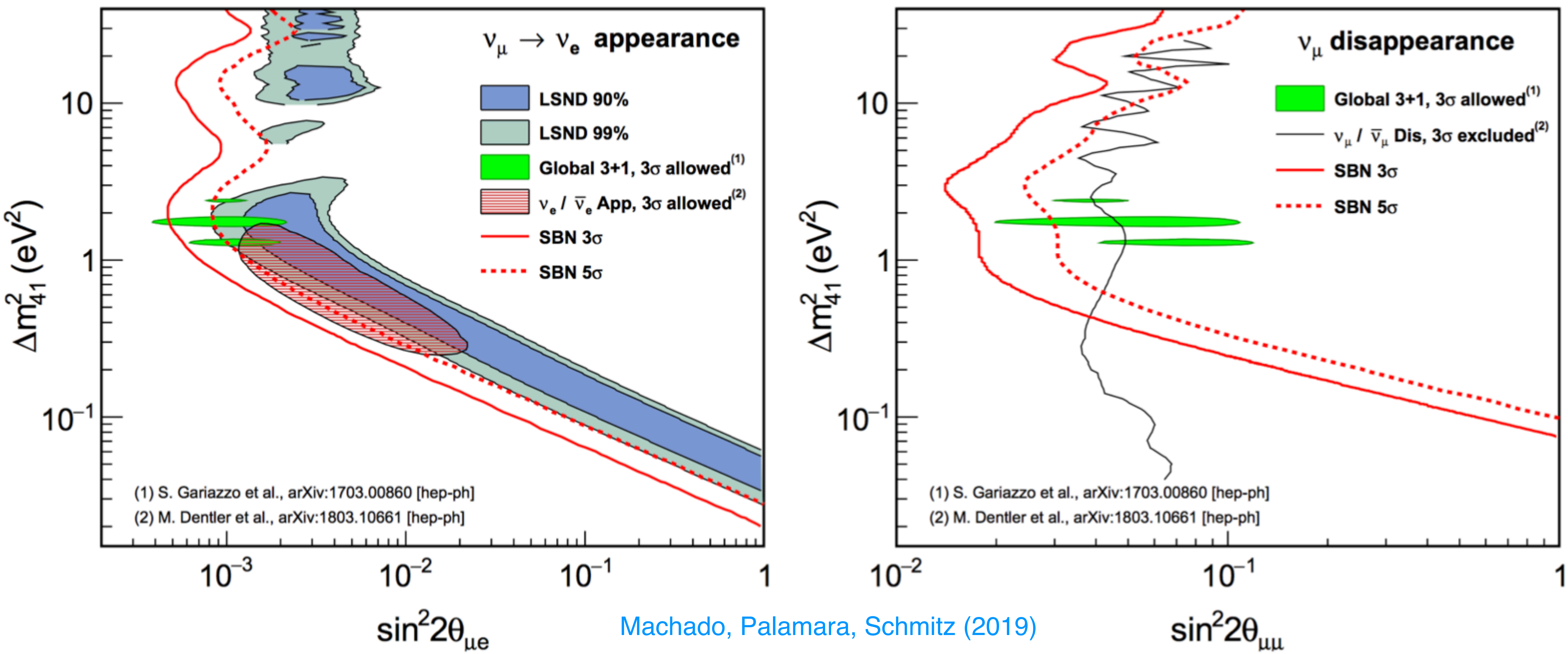
SBND (112 t)
at L = 110 m



Antonello et al (2015)



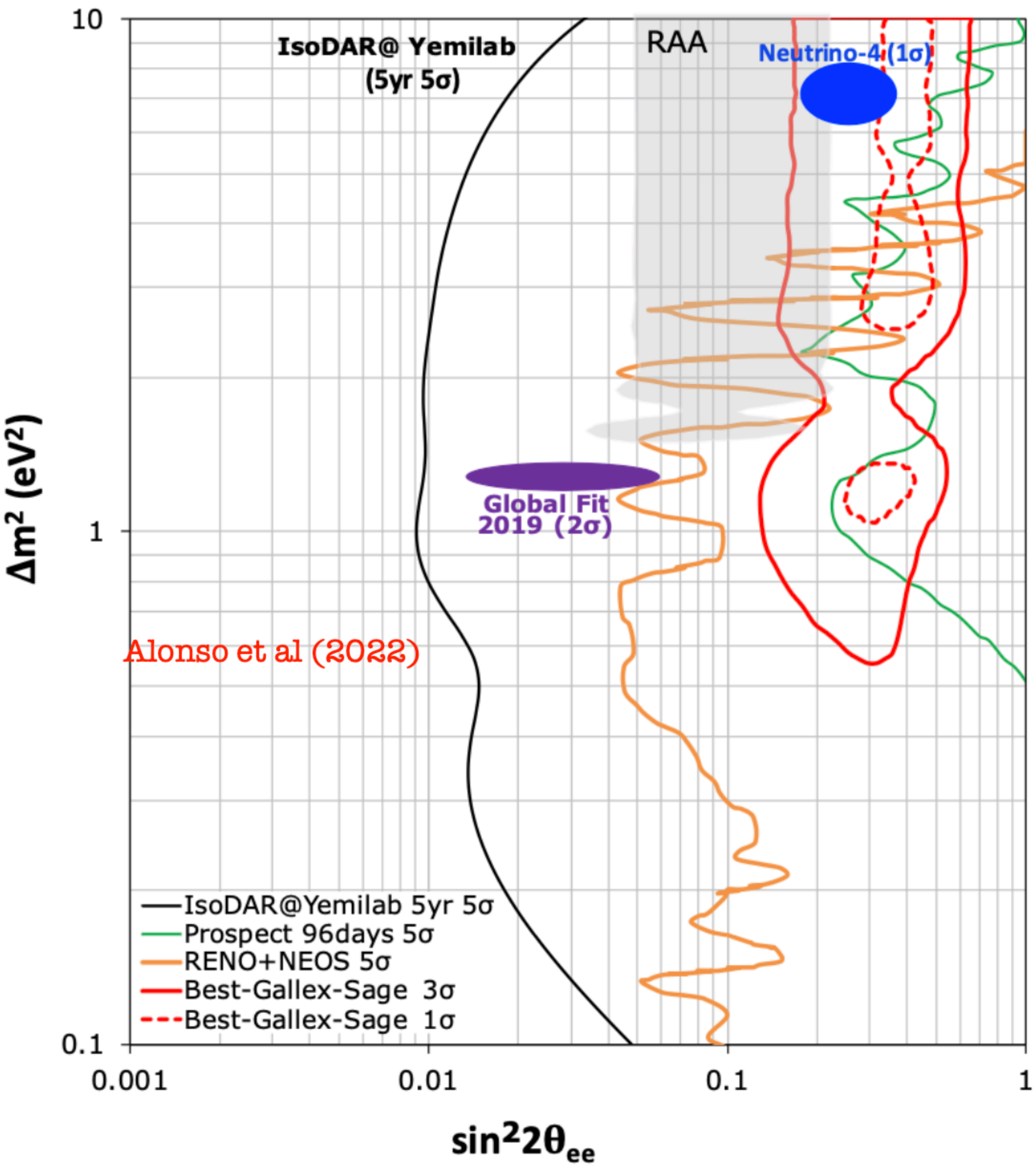
3+1 case: Future roadmap



Machado, Palamara, Schmitz (2019)

SBN programme is expected to bring us closest to a definitive answer

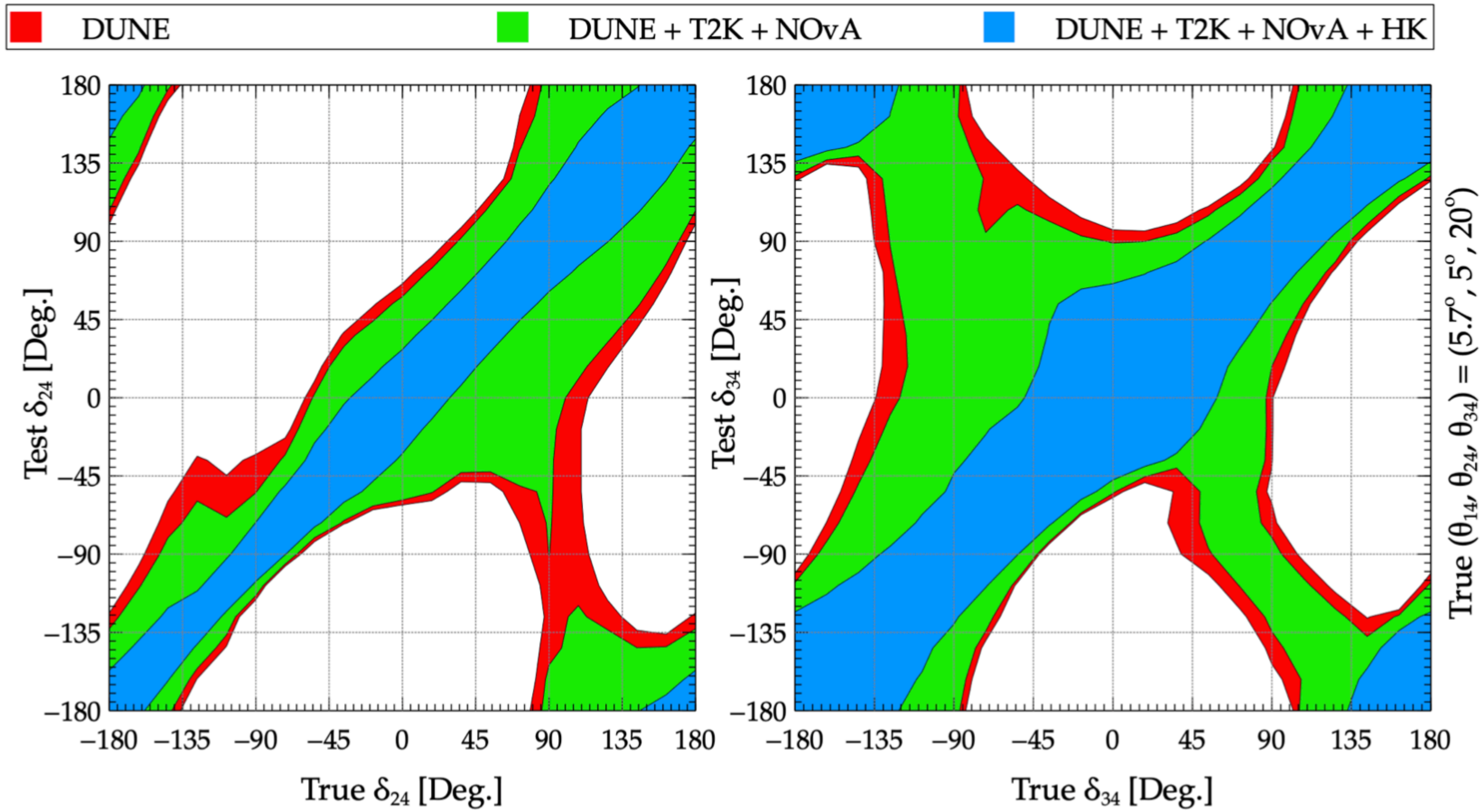
3+1 case: Future roadmap



IsoDAR@Yemilab is sensitive to all current allowed regions with 5 yrs. of runtime

3+1 case: Future roadmap

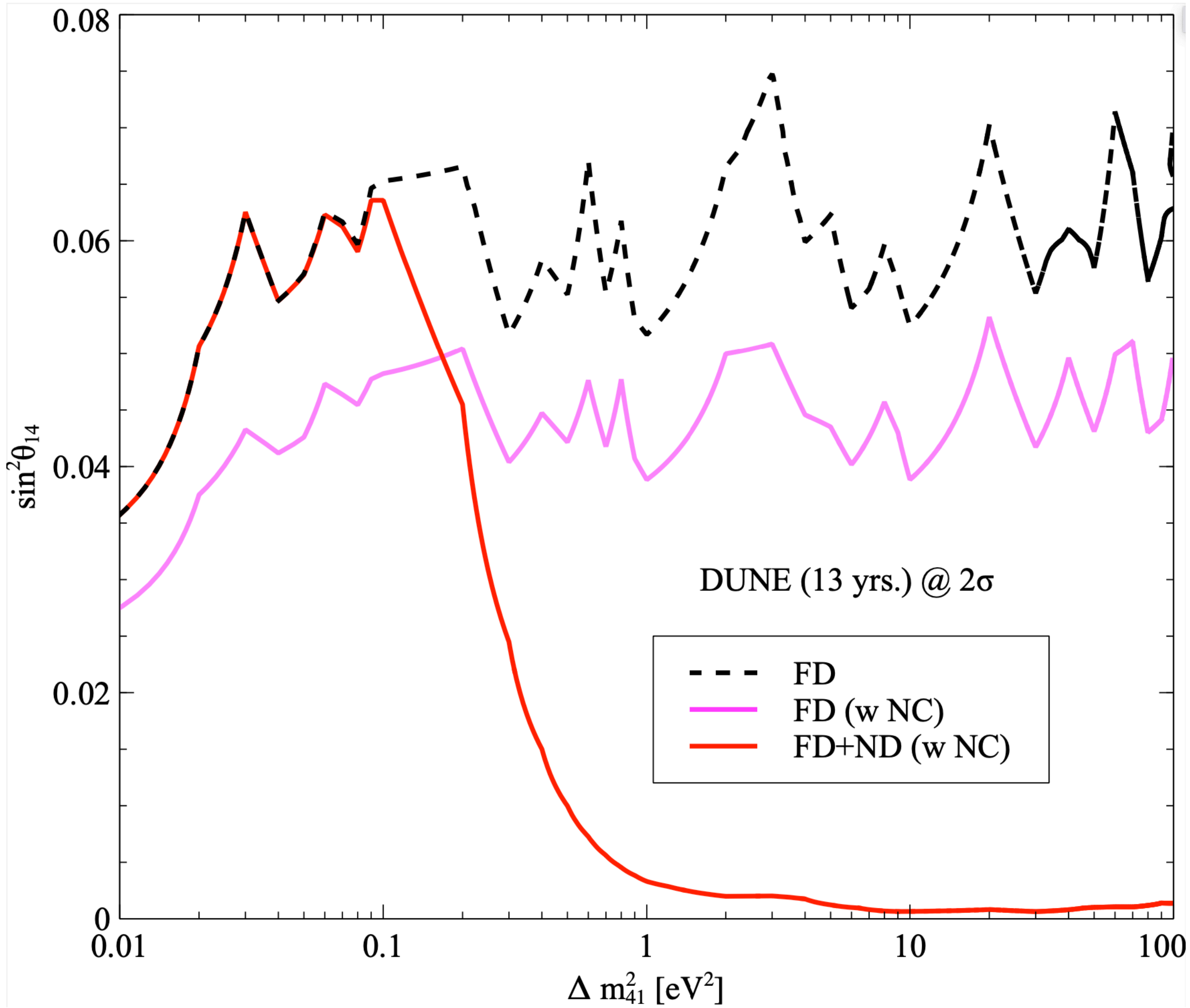
Fiza, **MM**, Mitra (2021)



Estimation of capabilities of measuring sterile CP phases at T2K,NoVA, DUNE,HK

3+1 case: Future roadmap

Parveen, **MM**, Mehta (To appear soon)



Constraining sterile parameter space with near detector and NC channels

Summary

- Short baseline anomalies (Reactor, Galium, LSND/MiniBooNE): hint for a light sterile neutrino

- Constraining the sterile parameter space by data from reactor (NEOS, DANSS, Neutrino-4..), accelerator SBL, atmospheric expts.

- Mild tension of appearance and diappearance searches

- Impact of sterile neutrino on standard measurements

- Future directions: Fermilab SBN programme, IsoDAR@Yemilab, LBL expts..

Thank you!

3+1 case :Global analysis

$$|U_{e4}|^2 \lesssim 0.1, \quad |U_{\mu 4}|^2 \lesssim 0.01, \quad |U_{\tau 4}|^2 \lesssim 0.17$$

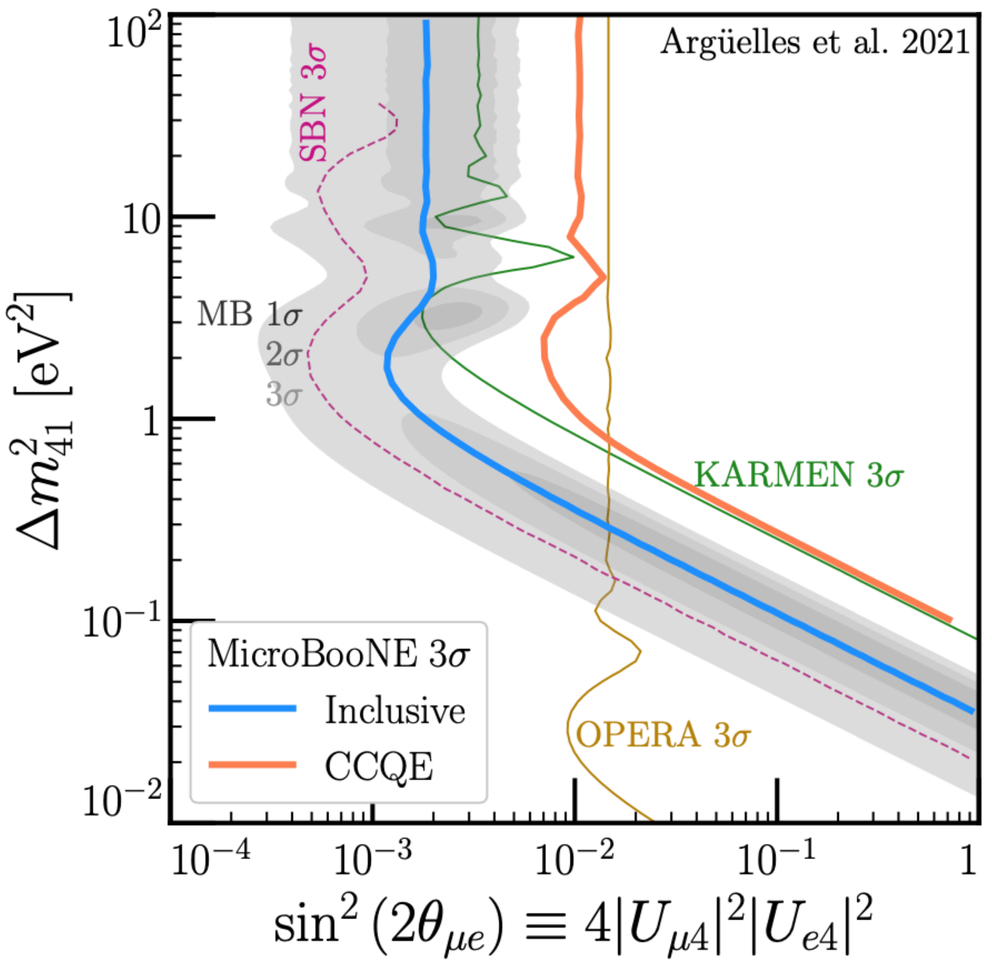
$$\theta_{14} \lesssim 18.4^\circ, \quad \theta_{24} \lesssim 6.05^\circ, \quad \theta_{34} \lesssim 25.6^\circ$$

Phases are unconstrained

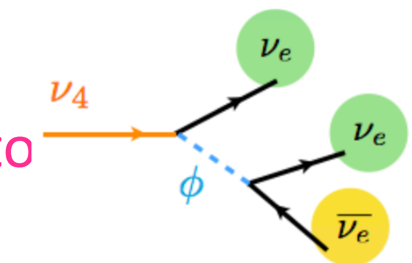
Dentler, Kopp, Harnandez, Machado, Maltoni, Martinez-Soler, Schwetz (2018)

Future research plans
(Sterile neutrino)

- Attempt towards resolving MiniBooNE anomaly:
  - No "excess" seen at μBooNE
  - But MiNiBooNE parameter space is not fully ruled out yet

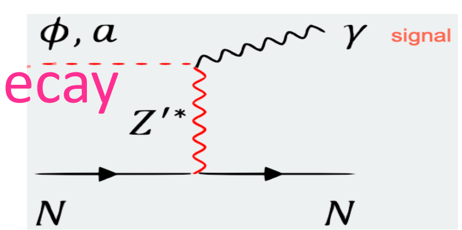


1. Light sterile ν: Further probes by Fermilab SBN (μBooNE+ICAR
2. Decay of heavy neutral lepto



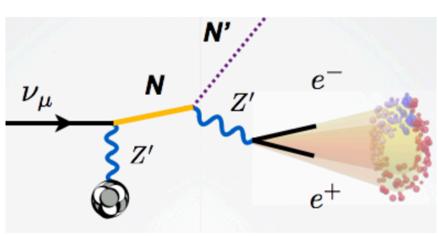
Dentler et al (201

3. Long-lived pseudo(scalar) decay



Abdallah et al

4. Dark neutrinos



Bertuzzo et al

....??