A Spicy Overview of Global 3+1 Scenario

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HARVARD UNIVERSITY
The NSF Institute for Artificial Intelligence and Fundamental Interactions
the David & Lucile Packard FOUNDATION
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RESEARCH CORPORATION for SCIENCE ADVANCEMENT

Outline

- The long-lasting anomalies and shout-out from string theory
- Where do we stand on 3+1 in 2024?
- The garden of forking paths
- 3+1+X

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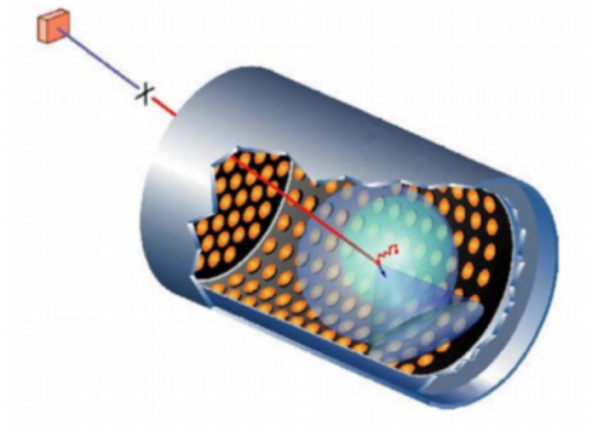
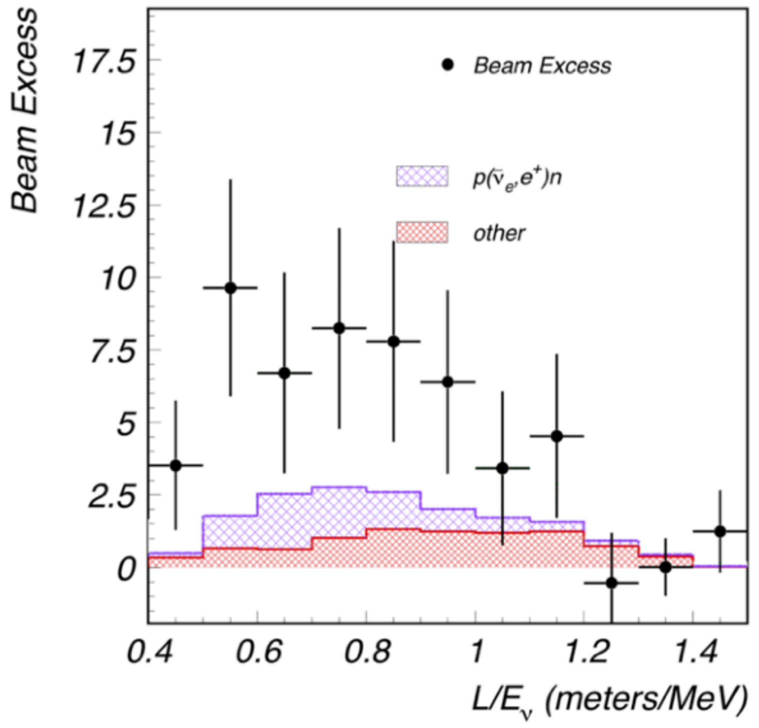
The pieces that do not fit: short-baseline anomalies

LSND

(3.8σ!)

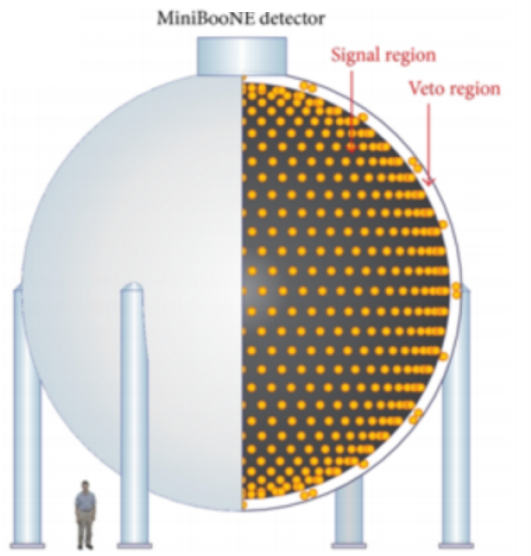


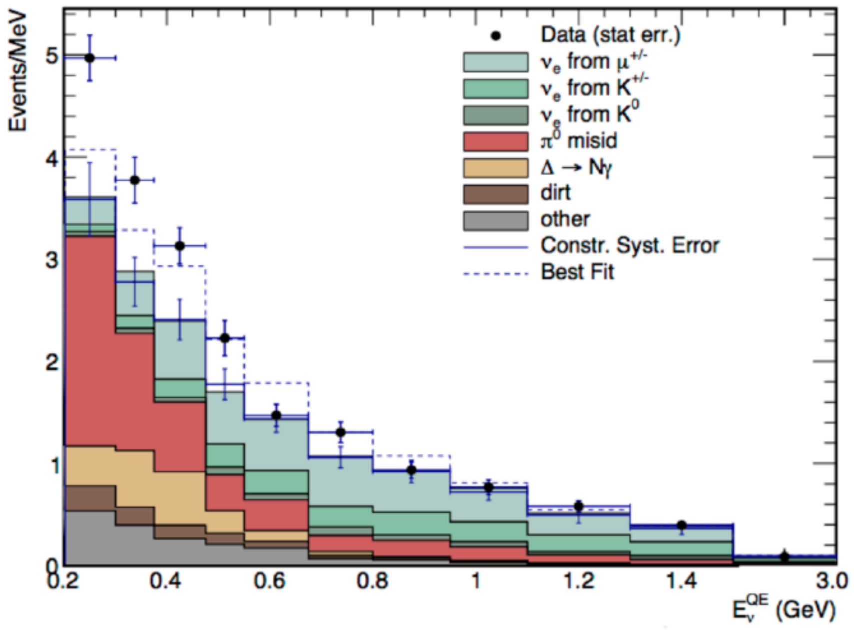


These experiments observe ν_e appearance at L/E ~ 1 km/GeV!

MiniBooNE

(4.8σ!)





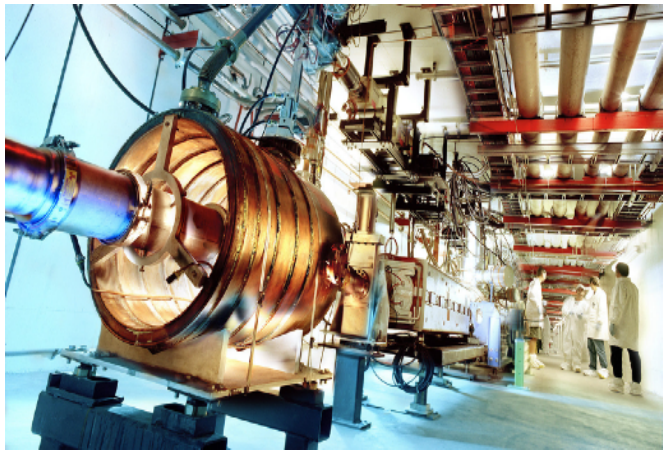
This points to

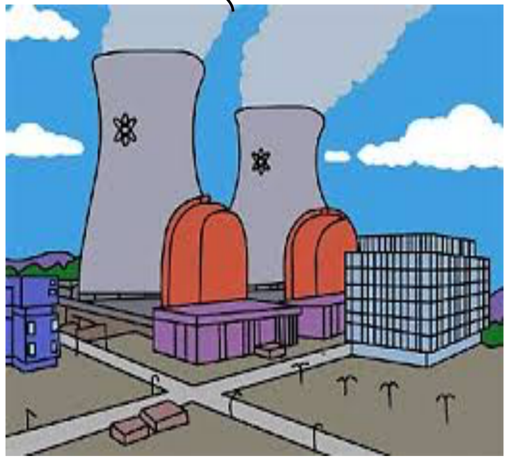
$\Delta m^2 \sim 1 eV^2$

These are not alone, other interesting observations

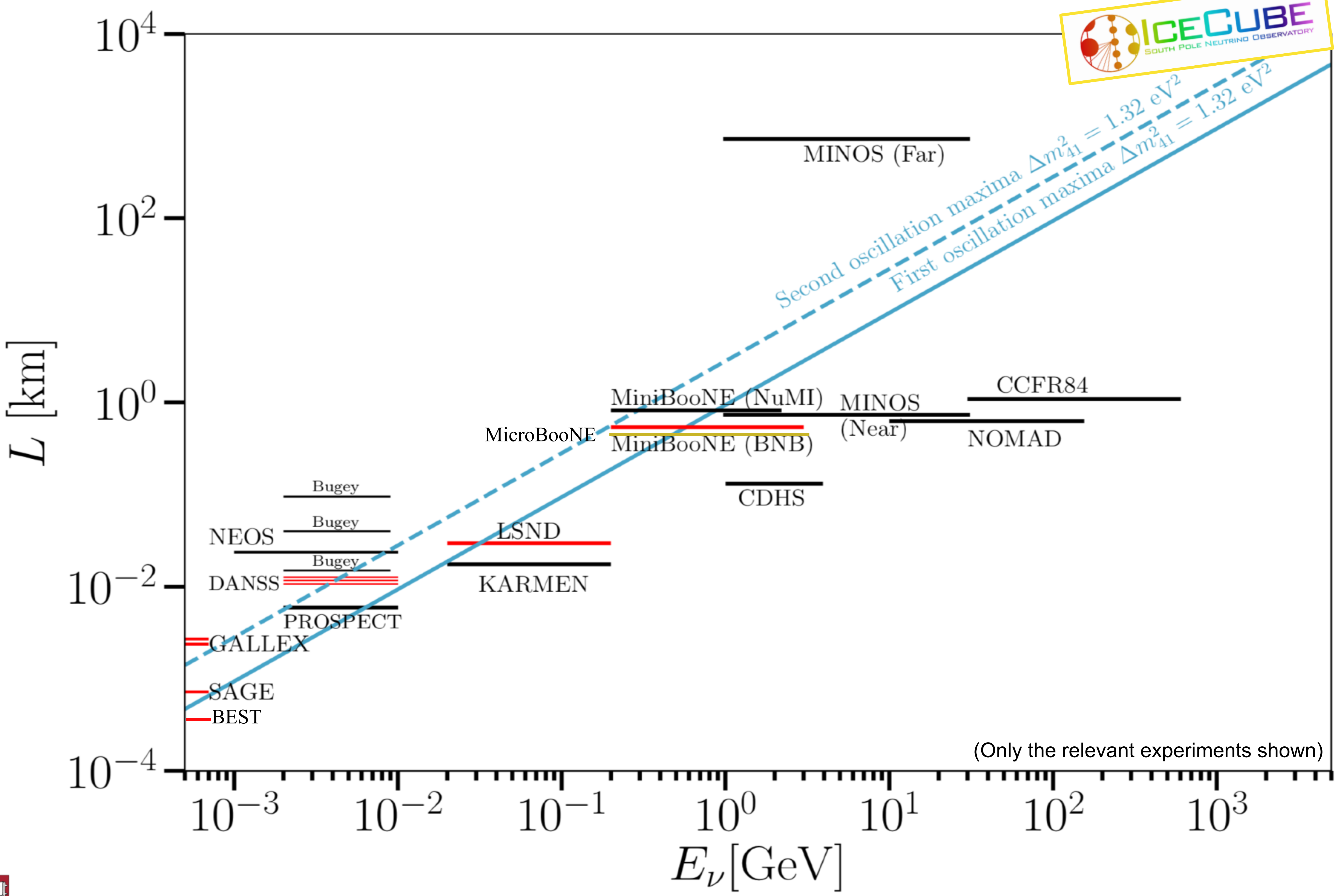
	$\nu_\mu \to \nu_e$	$\nu_\mu \to \nu_\mu$	$\nu_e \to \nu_e$
Neutrino	MiniBooNE (BNB) ∗	SciBooNE/MiniBooNE	KARMEN/LSND Cross Section
	MiniBooNE(NuMI)	CCFR	Gallium ∗
	NOMAD	CDHS	BEST ∗
	MicroBooNE (BNB)	MINOS IceCube	
Antineutrino	LSND ∗	SciBooNE/MiniBooNE	Bugey Daya Bay
	KARMEN	CCFR	NEOS PROSPECT
	MiniBooNE (BNB) ∗	MINOS	DANSS STEREO
		IceCube (∗?)	Neutrino-4 ∗

∗ ⟹ >2σ “signal”





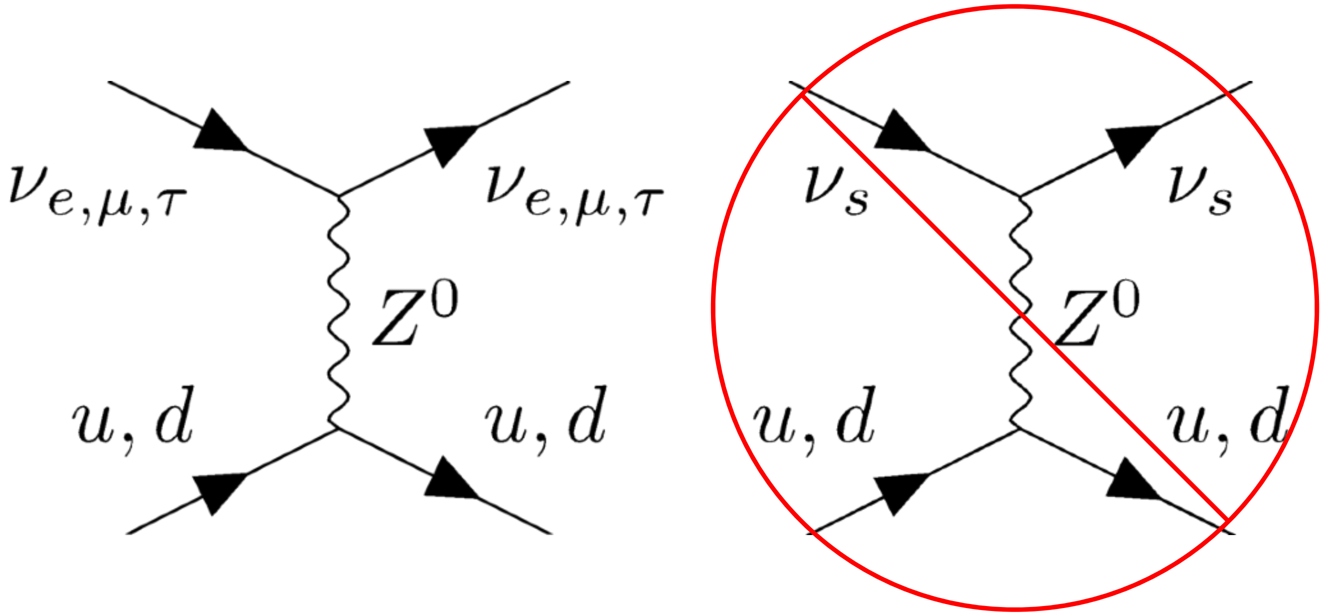
The anomalies lie ~ in a line



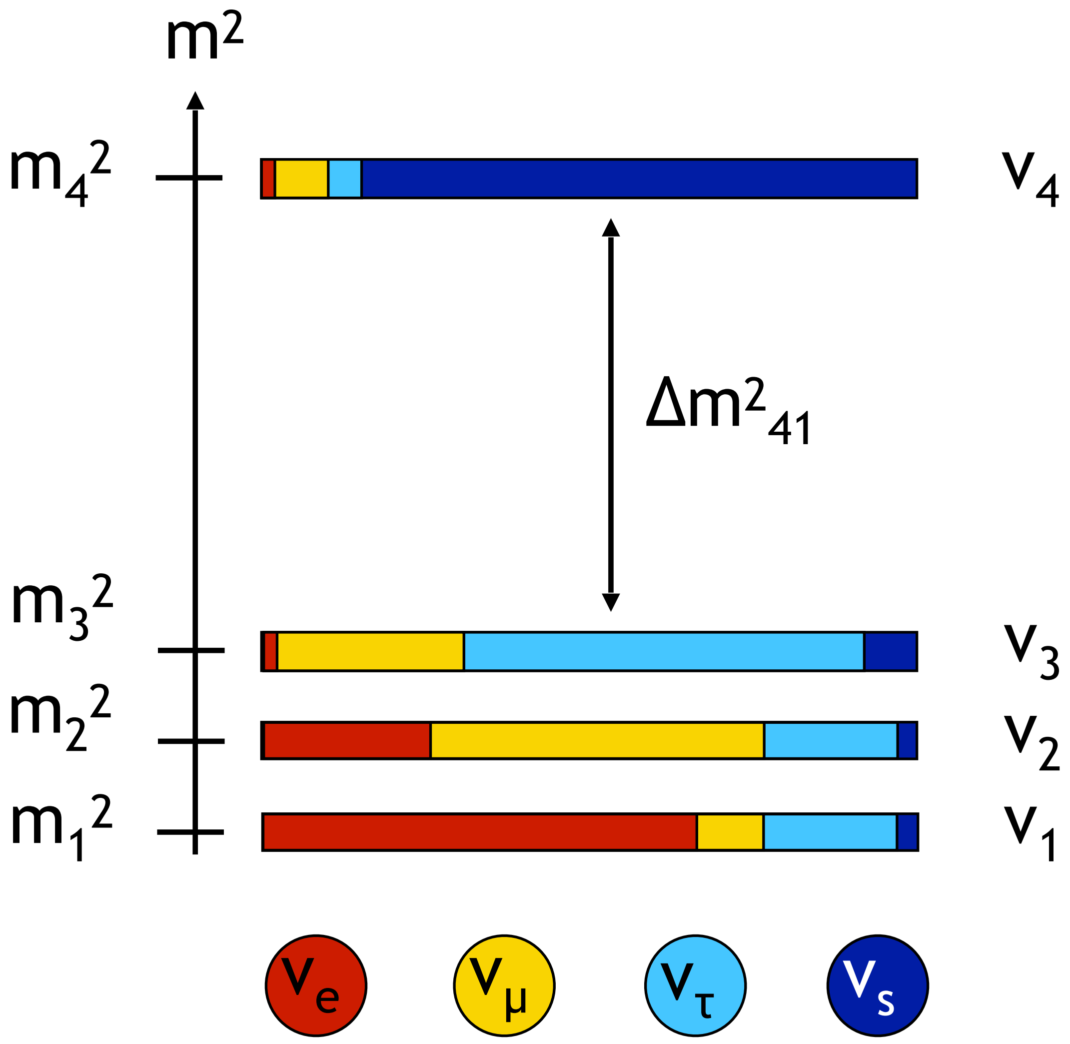
(Only the relevant experiments shown)

Diaz *et al.* arXiv:1906.00045

Introducing a sterile neutrino



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



Assuming Normal Ordering

Why an eV-scale sterile?

Recent developments from string theory

- Swampland program: determine the theory requirement for effective field theories to be Quantum Gravity theories.
- Swampland conjectures (Vafa-Ooguri,1610.01533) and Gonzalo et al (arXiv:2109.10961) require that neutrinos be Dirac particles in minimal model.
- Swampland proposal for dark sector predicts existences of meV - eV sterile neutrinos. Vafa arXiv:2402.00981.

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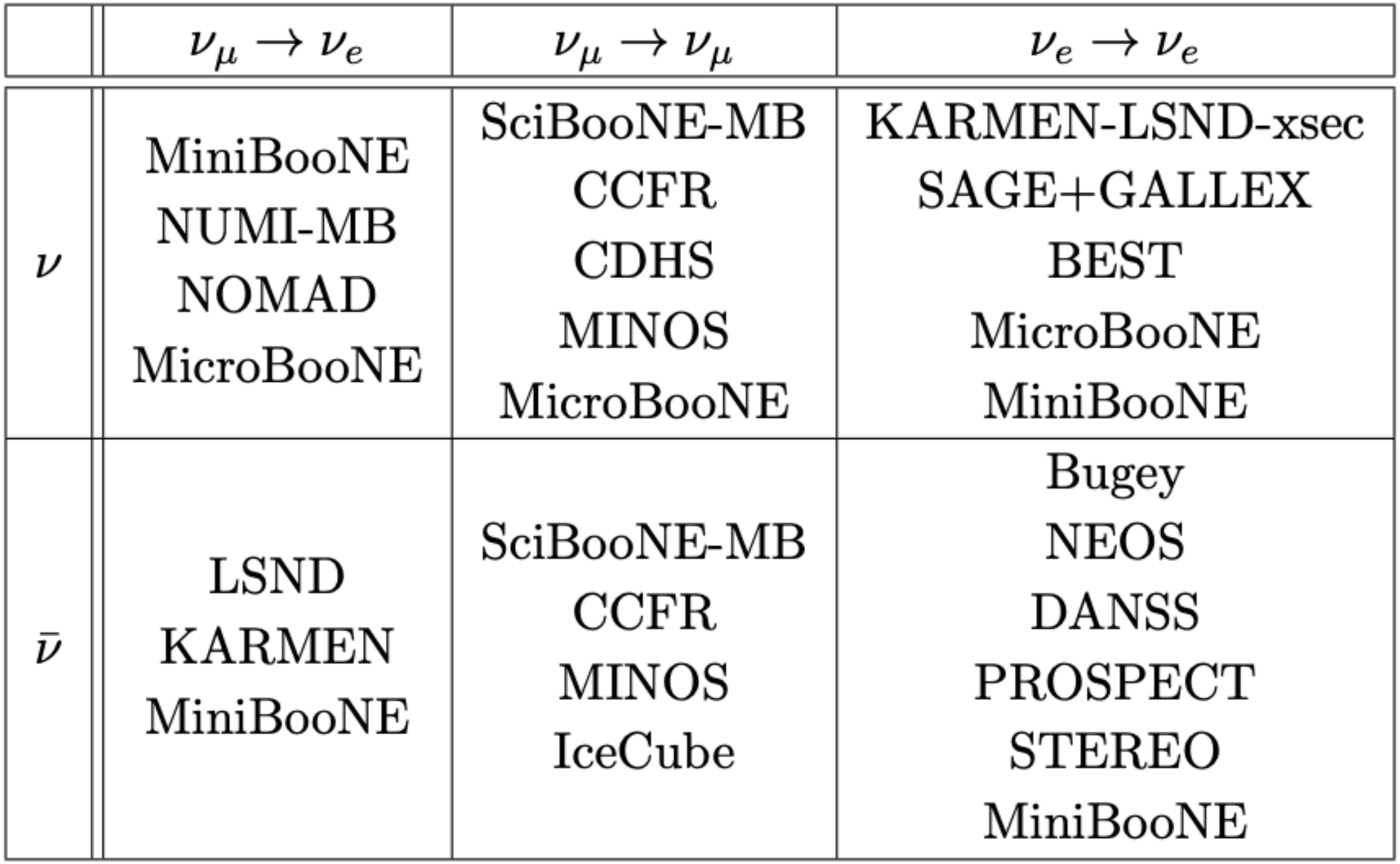
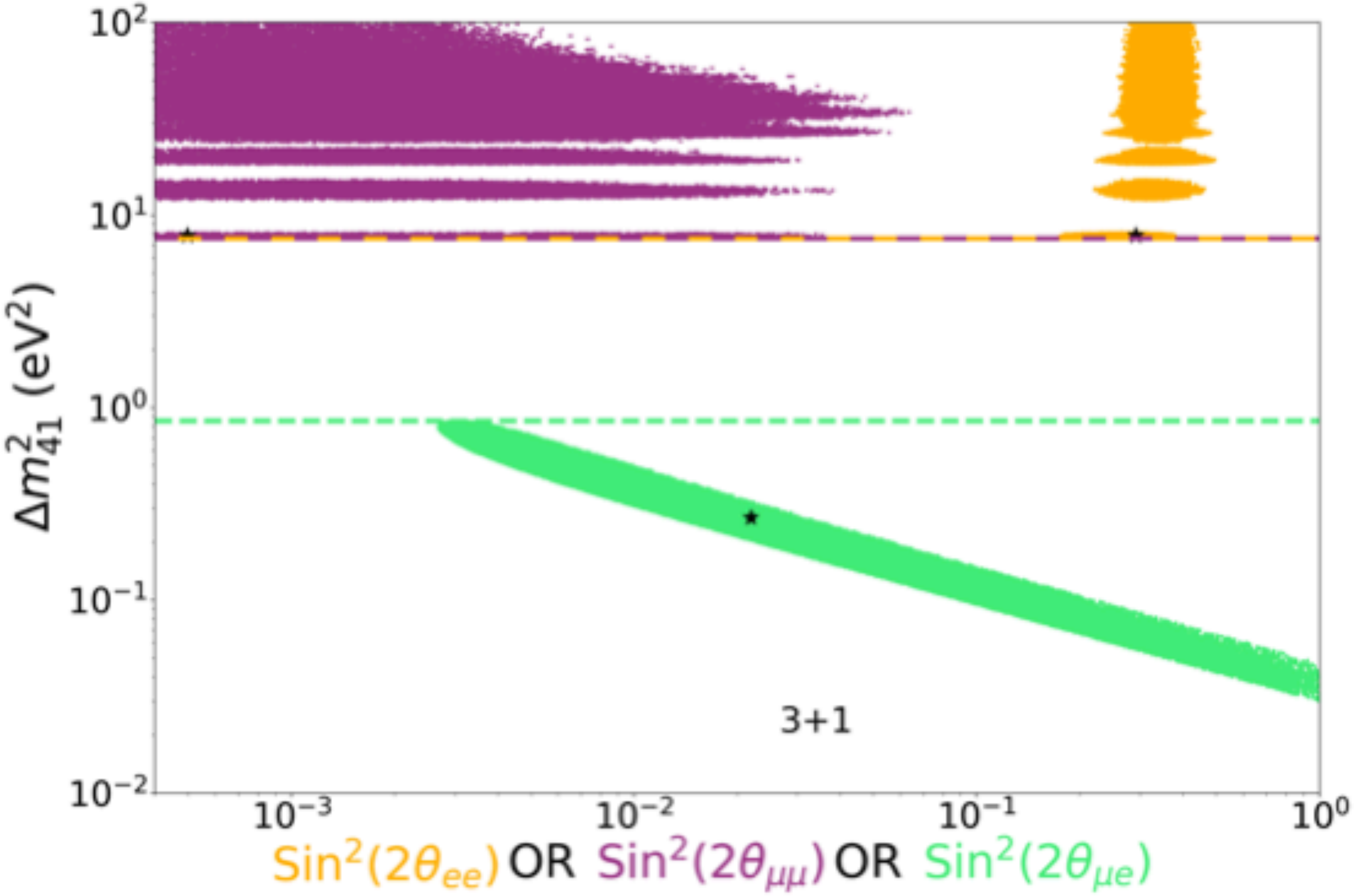
What does the data say?



	$\nu_\mu \to \nu_e$	$\nu_\mu \to \nu_\mu$	$\nu_e \to \nu_e$
ν	MiniBooNE NUMI-MB NOMAD MicroBooNE	SciBooNE-MB CCFR CDHS MINOS MicroBooNE	KARMEN-LSND-xsec SAGE+GALLEX BEST MicroBooNE MiniBooNE
$\bar{\nu}$	LSND KARMEN MiniBooNE	SciBooNE-MB CCFR MINOS IceCube	Bugey NEOS DANSS PROSPECT STEREO MiniBooNE

Will show results from the latest Columbia-Harvard-MIT Global Fit
Hardin arXiv:2211.02610

Appearance and disappearance "preference regions" don't overlap!



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Similar conclusions from other groups see Gariazzo et al. 1703.00860, and Dentler et al JHEP 1808 (2018). See Diaz et al. arXiv:1906.00045 for more discussion.

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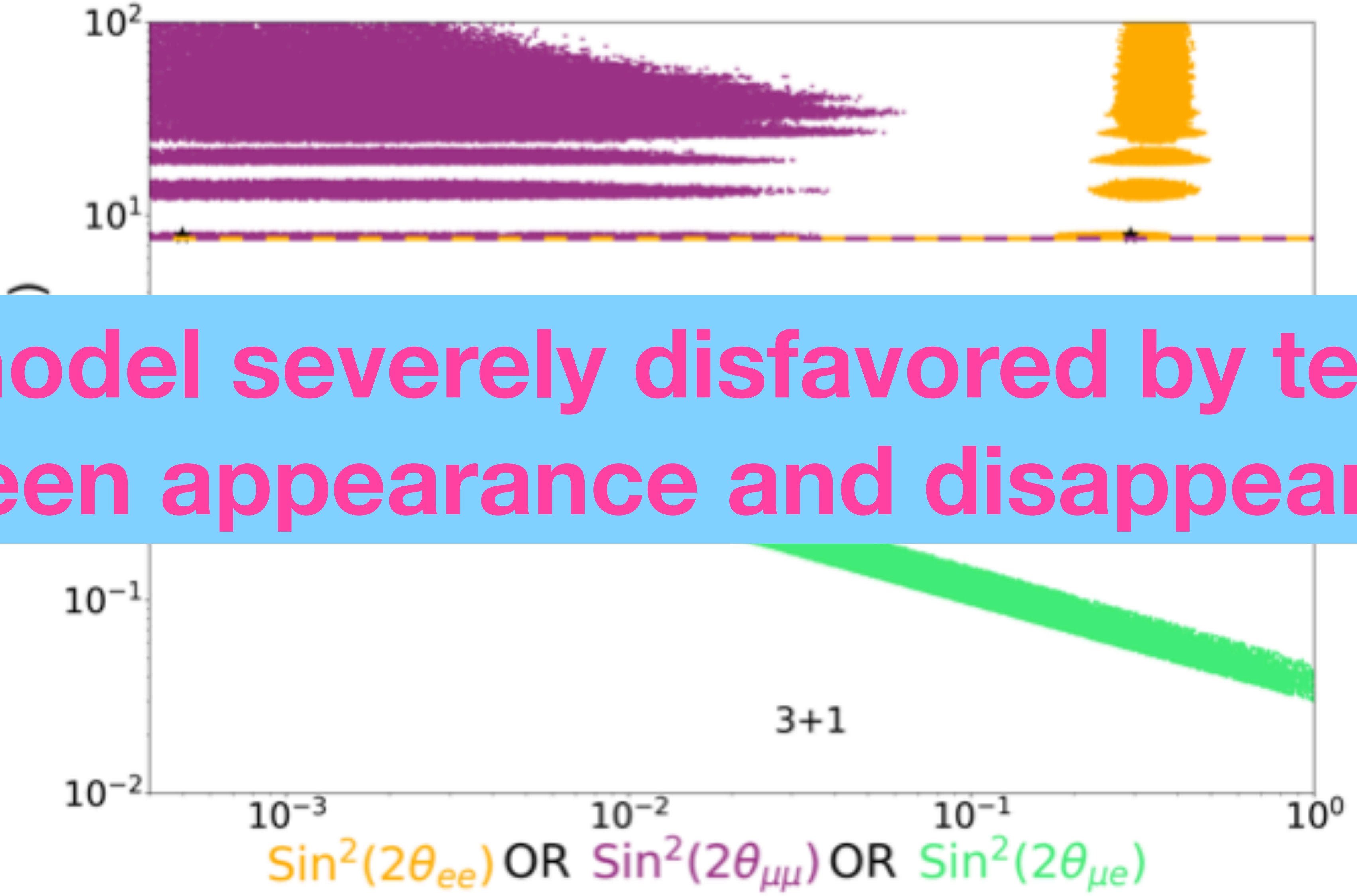

3+1 model severely disfavored by tension between appearance and disappearance

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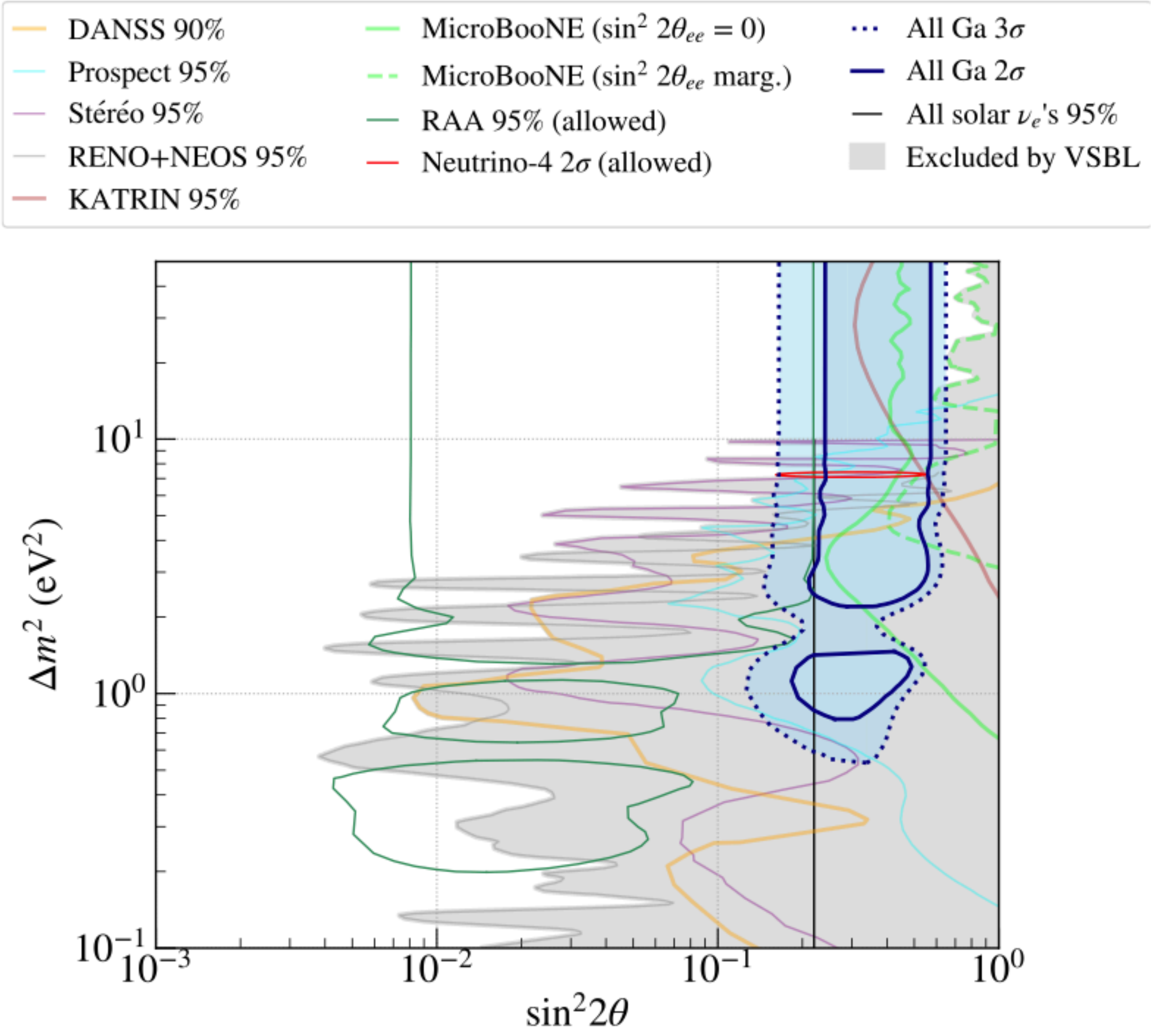
Highlights $P(\nu_e \rightarrow \nu_e)$: Solar, Reactors, and BEST

BEST Collaboration, 2201.07364



- -BEST confirms long-standing “Gallium" anomalies at 5 sigma level.
- -Mixing angle required is large.
- -Tension with reactor and solar data.

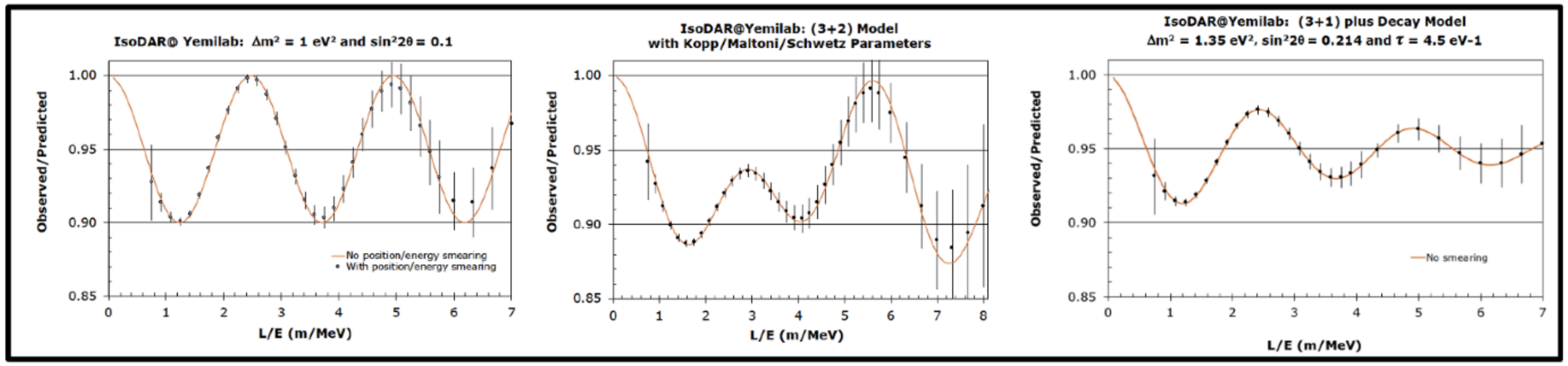
See also detailed analysis by Berryman et al. arXiv:2111.12530

Highlights $P(\nu_e \to \nu_e)$: IsoDAR!

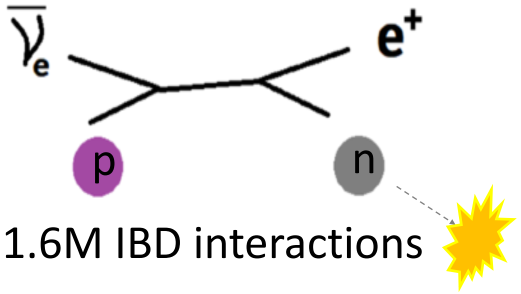
IsoDAR@Yemilab:

Combining the first high-power,
underground accelerator
with a large scintillator detector
for Beyond Standard Model Physics

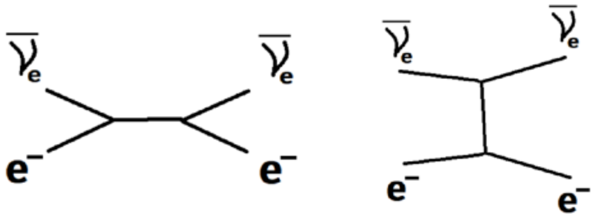
1DOI:0.1103/PhysRevD.105.052009



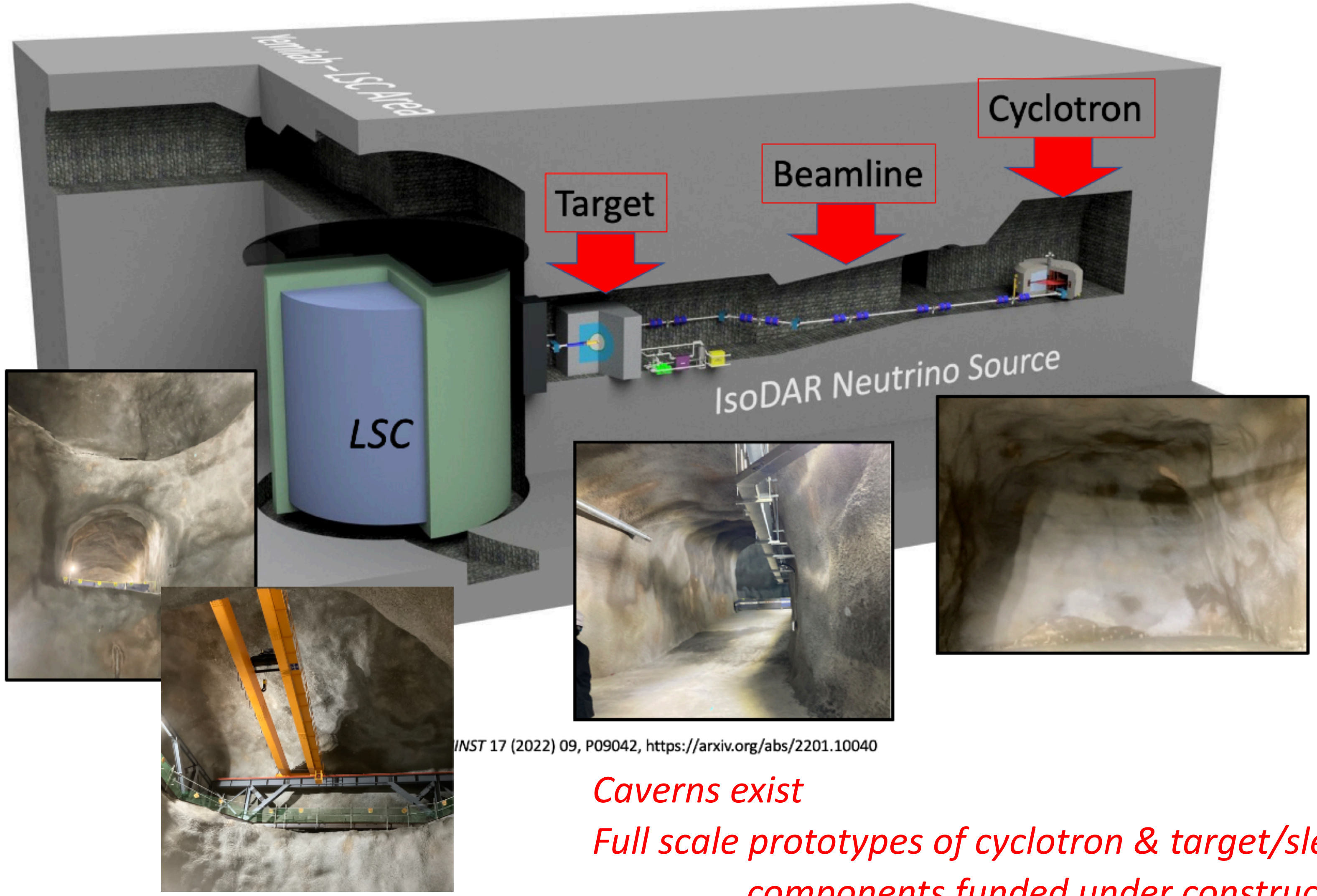
Much larger samples than exist today!
in 5 years (4 years of live time)....



1.6M IBD interactions



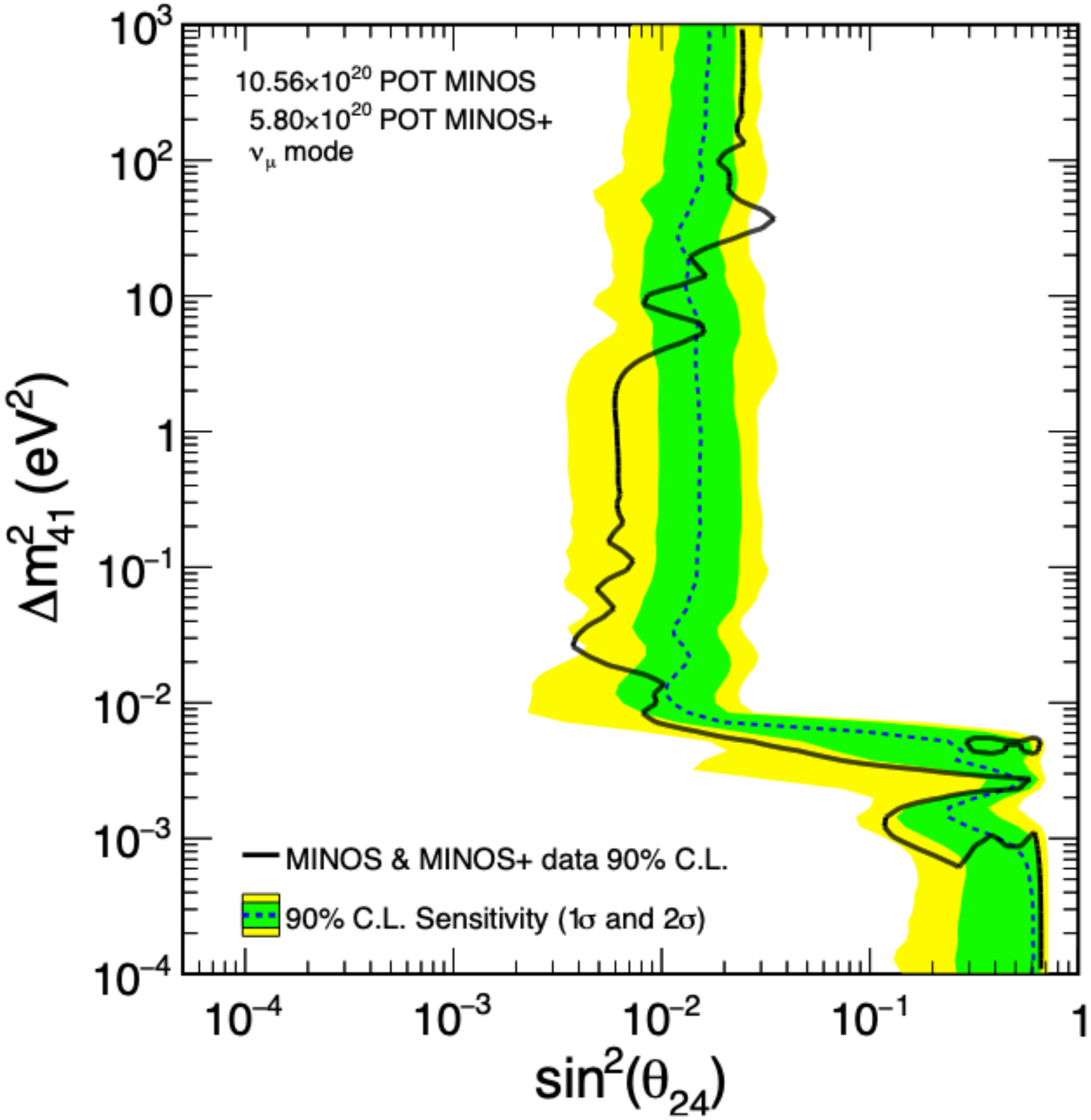
7000 ν_e-electron elastic scatters
(a lepton-lepton collider!)



JINST 17 (2022) 09, P09042, https://arxiv.org/abs/2201.10040

Caverns exist
Full scale prototypes of cyclotron & target/sleeve components funded under construction

Highlights $P(\nu_\mu \to \nu_\mu)$:
MINOS+



Overall normalization

Near-detector dominated

Far-detector dominated

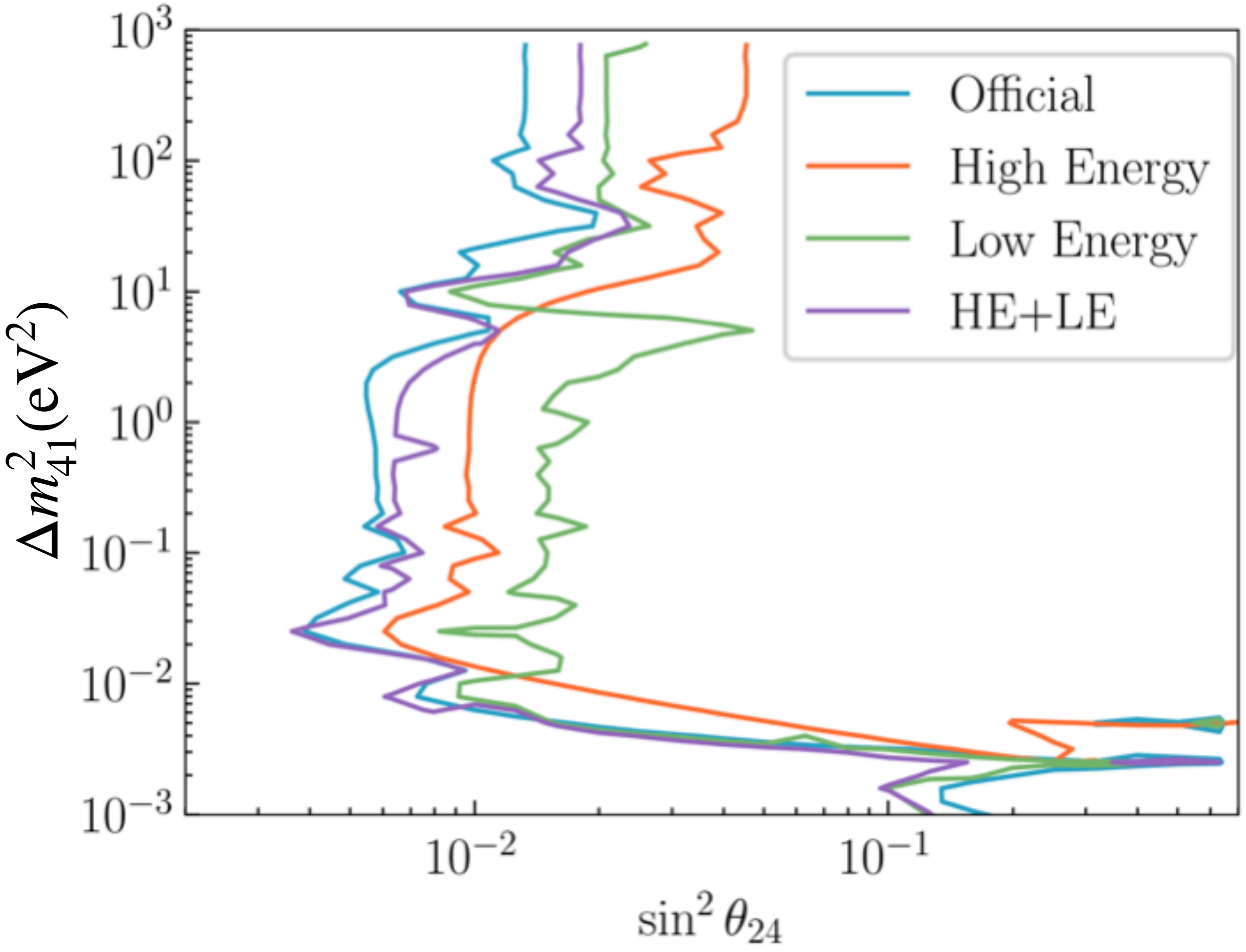
Large mass-squared-limit corresponds to ~ 4% flux normalization uncertainty.

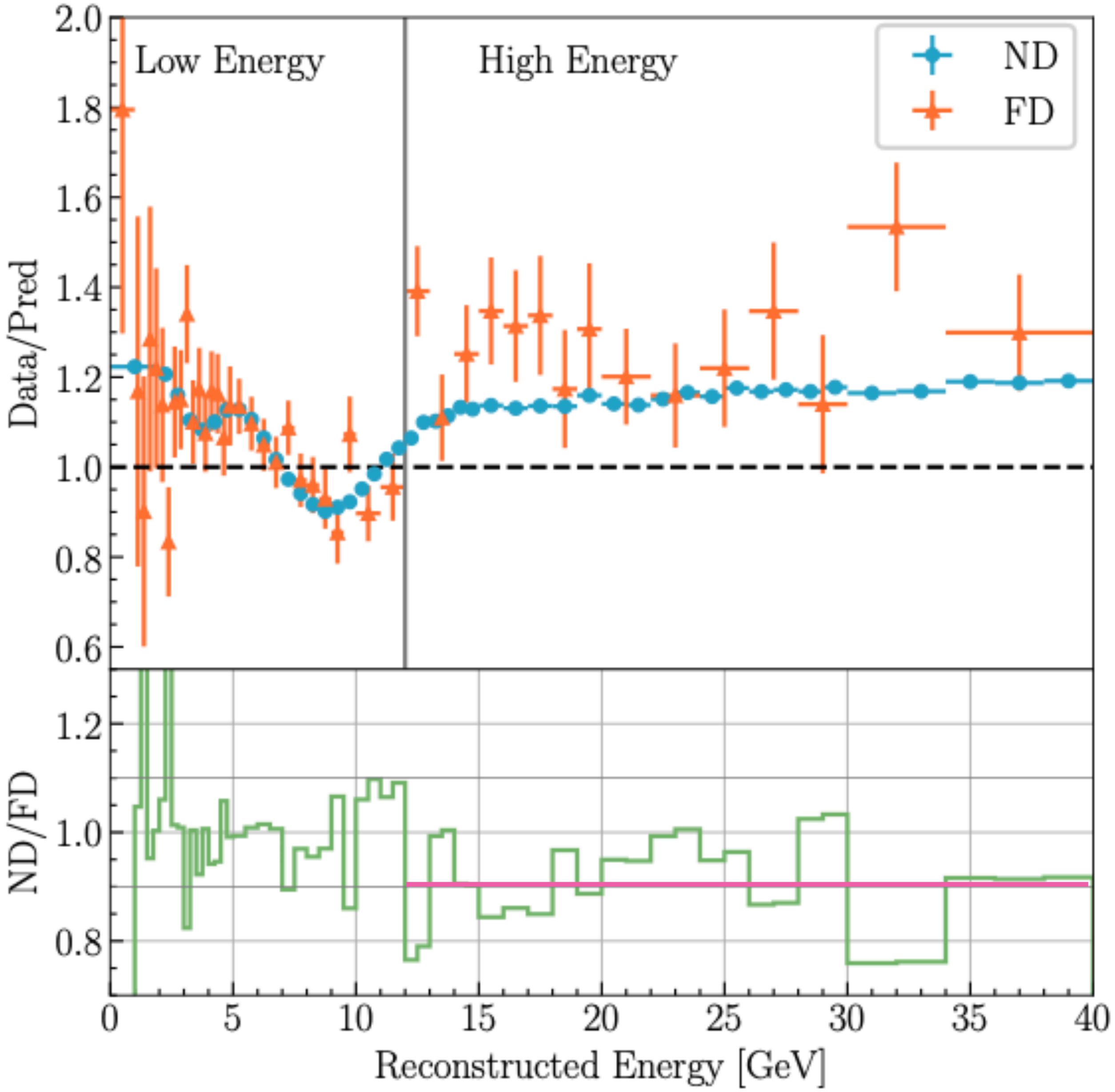
Factor of ~2 smaller than nominal error.

W. Louis arXiv:1803.11488

MINOS Collaboration Phys. Rev. Lett. 122, 091803 (2019)
arXiv:1710.06488v6

Highlights $P(\nu_\mu \rightarrow \nu_\mu)$: MINOS+



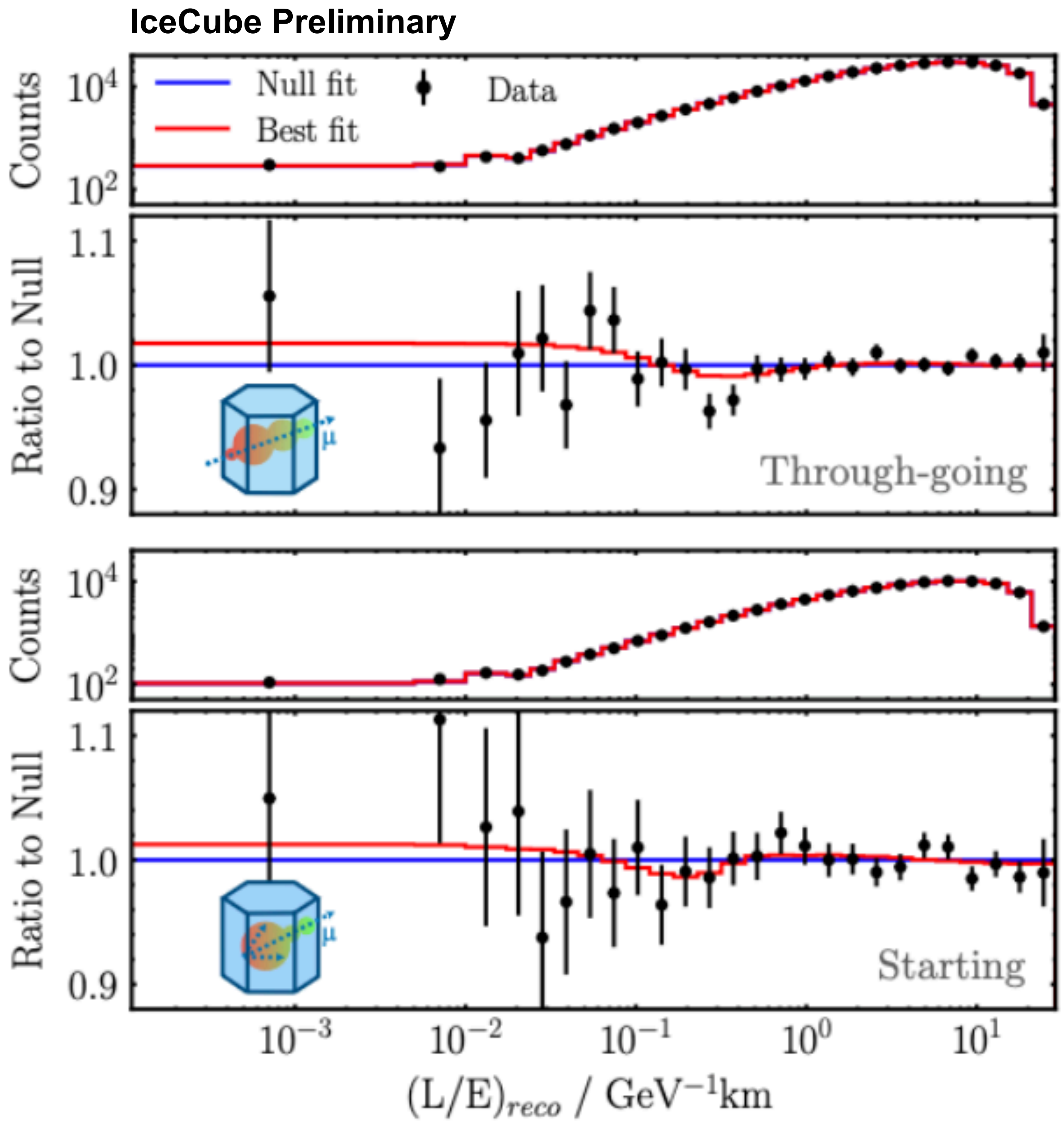


We studied the MINOS/MINOS+ using their official data release in search for clues.

Hardin et al arXiv:2211.02610v1

Highlights $P(\nu_\mu \to \nu_\mu)$: IceCube

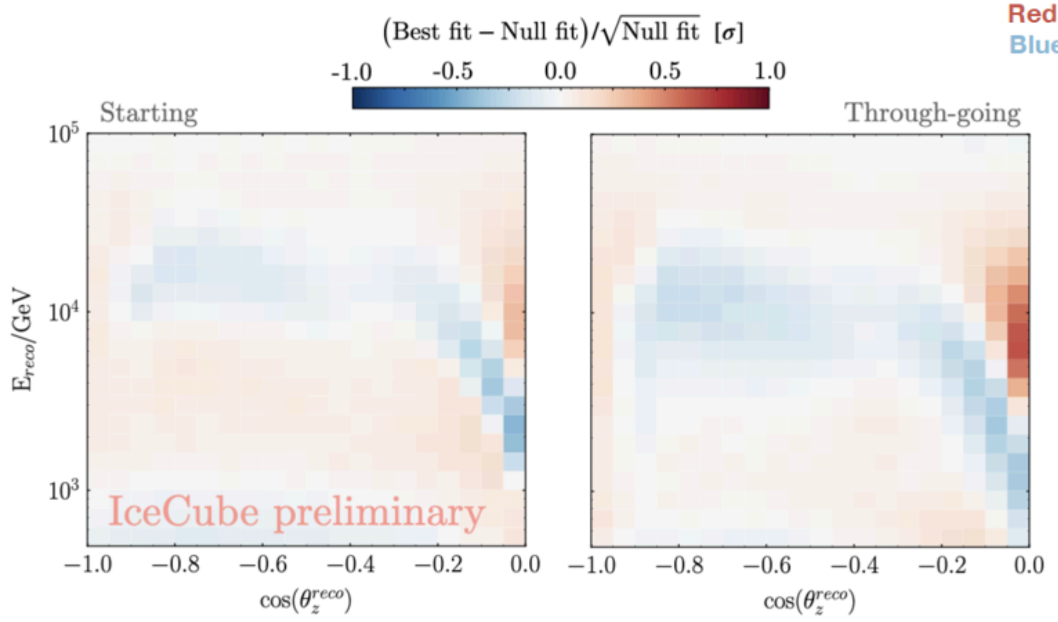
N. Kamp, 2024, this workshop

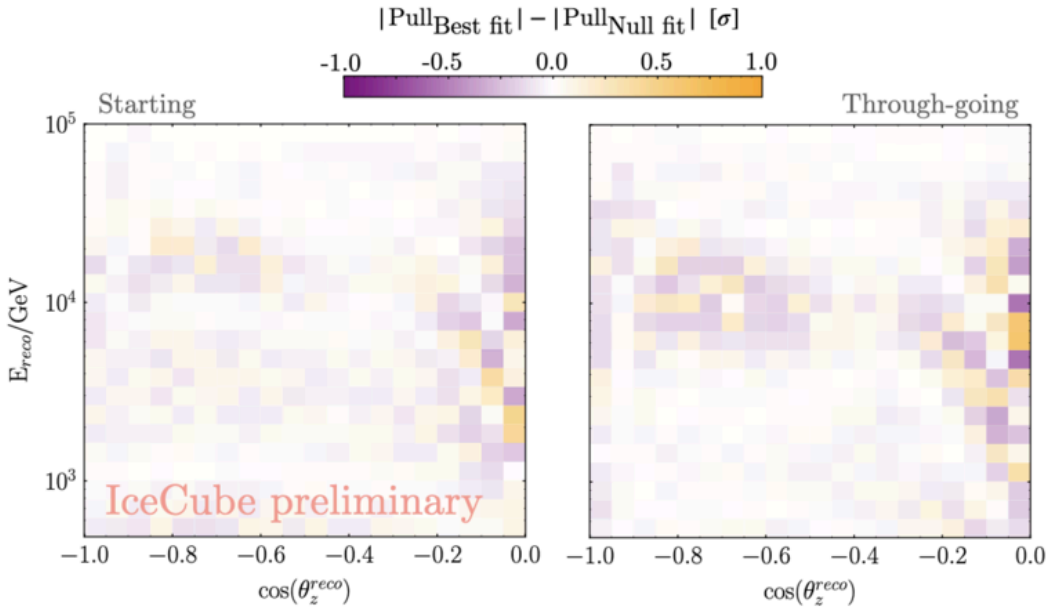


$$\text{Pull} \equiv \frac{\text{Best fit} - \text{Null fit}}{\sqrt{\text{Null fit}}}$$

Red: excess in best fit v.s. null

Blue: deficit in best fit v.s. null





Significance dominated by through-going events and vertical component

$$\text{Pull} \equiv \frac{\text{Data} - \text{Fit}}{\sqrt{\text{Fit}}}$$

Yellow: data prefers null fit

Purple: data prefers oscillation fit

Highlights $P(\nu_\mu \rightarrow \nu_\mu)$: IceCube

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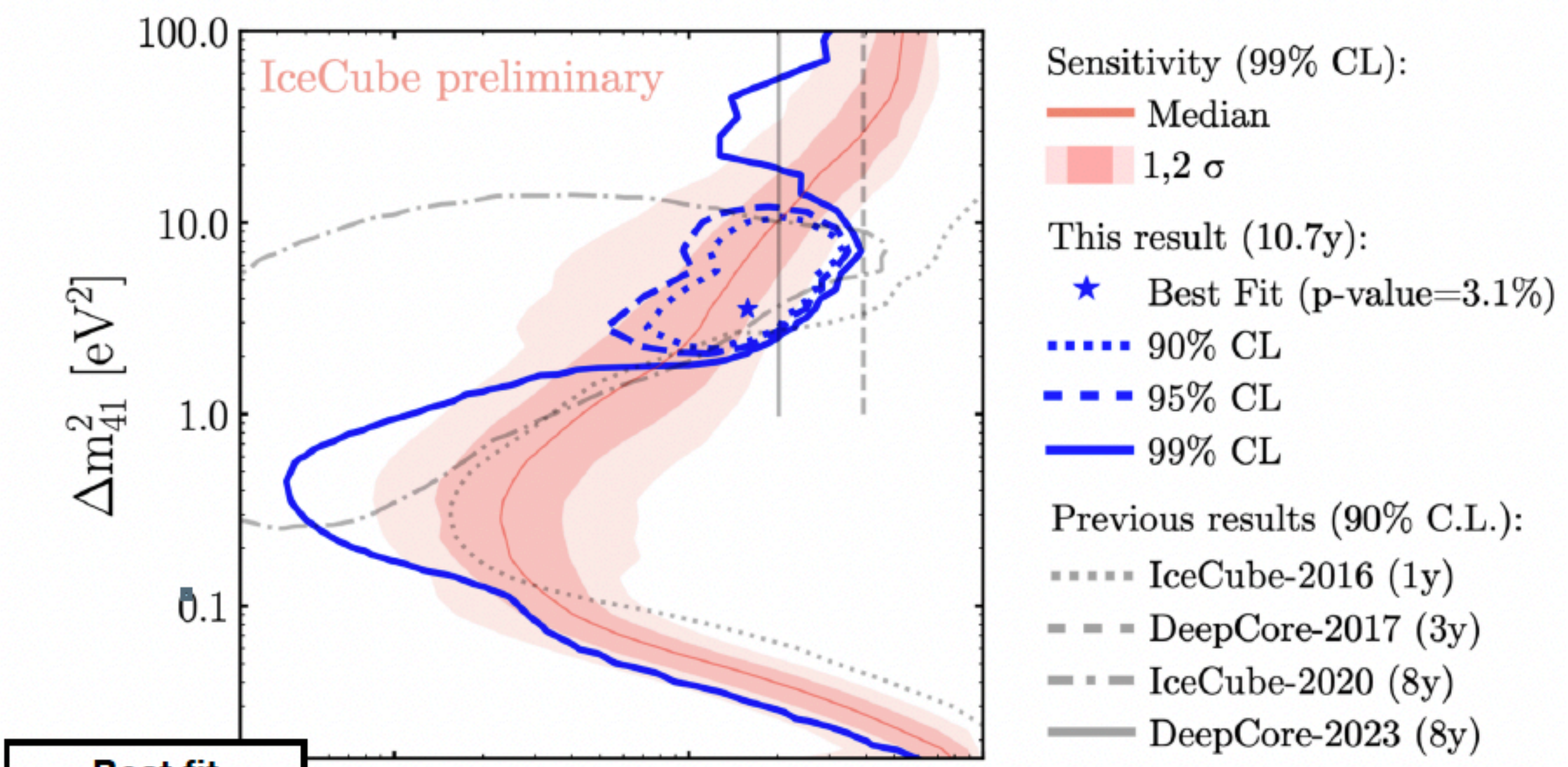
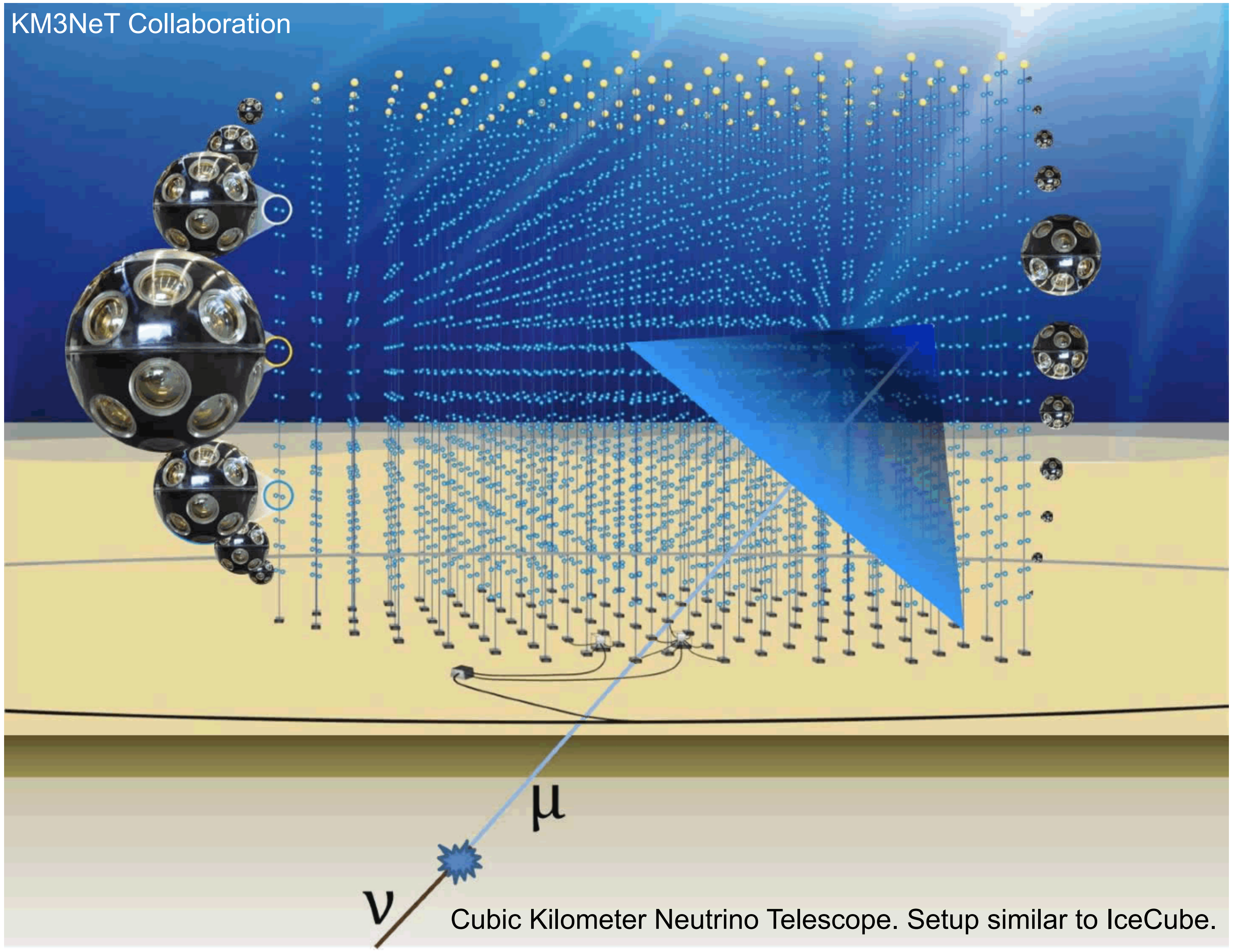


Best fit
$\Delta m^2 = 3.5\ \mathrm{eV}^2$
$\sin^2 2\theta_{24} = 0.16$

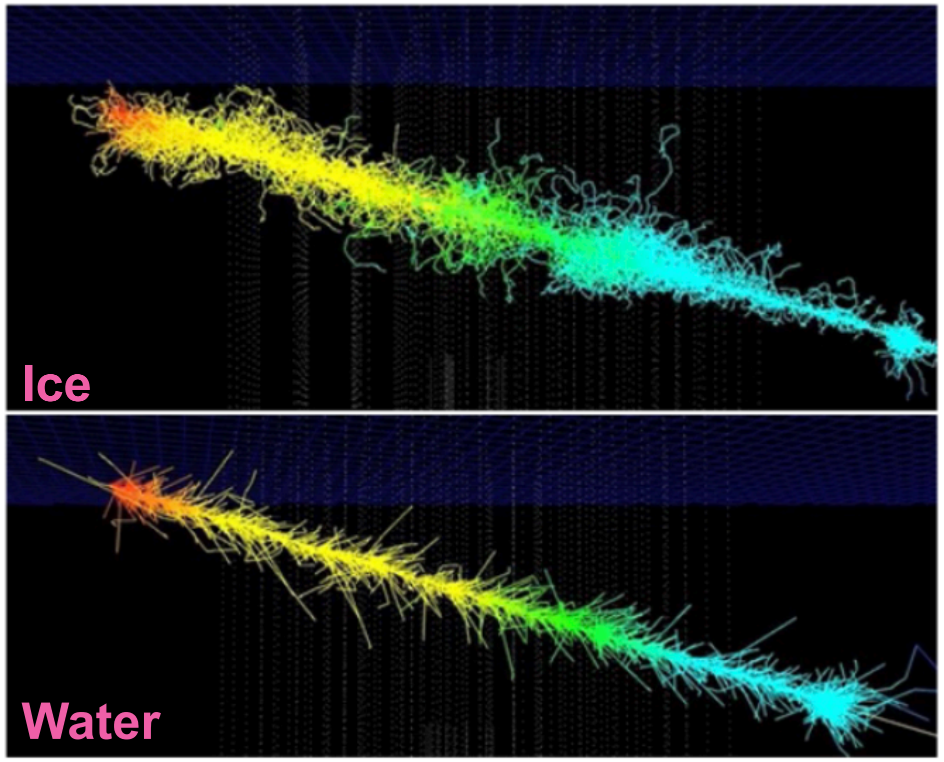
Increased statistics and improved systematic treatment shows persistent preference for non-null model at 2 sigma level.
Most significant observation in the muon-neutrino channel!

Highlights $P(\nu_\mu \rightarrow \nu_\mu)$:
Future KM3NeT



Cubic Kilometer Neutrino Telescope. Setup similar to IceCube.

Argüelles, Kurahashi, Halzen (2024, to appear)

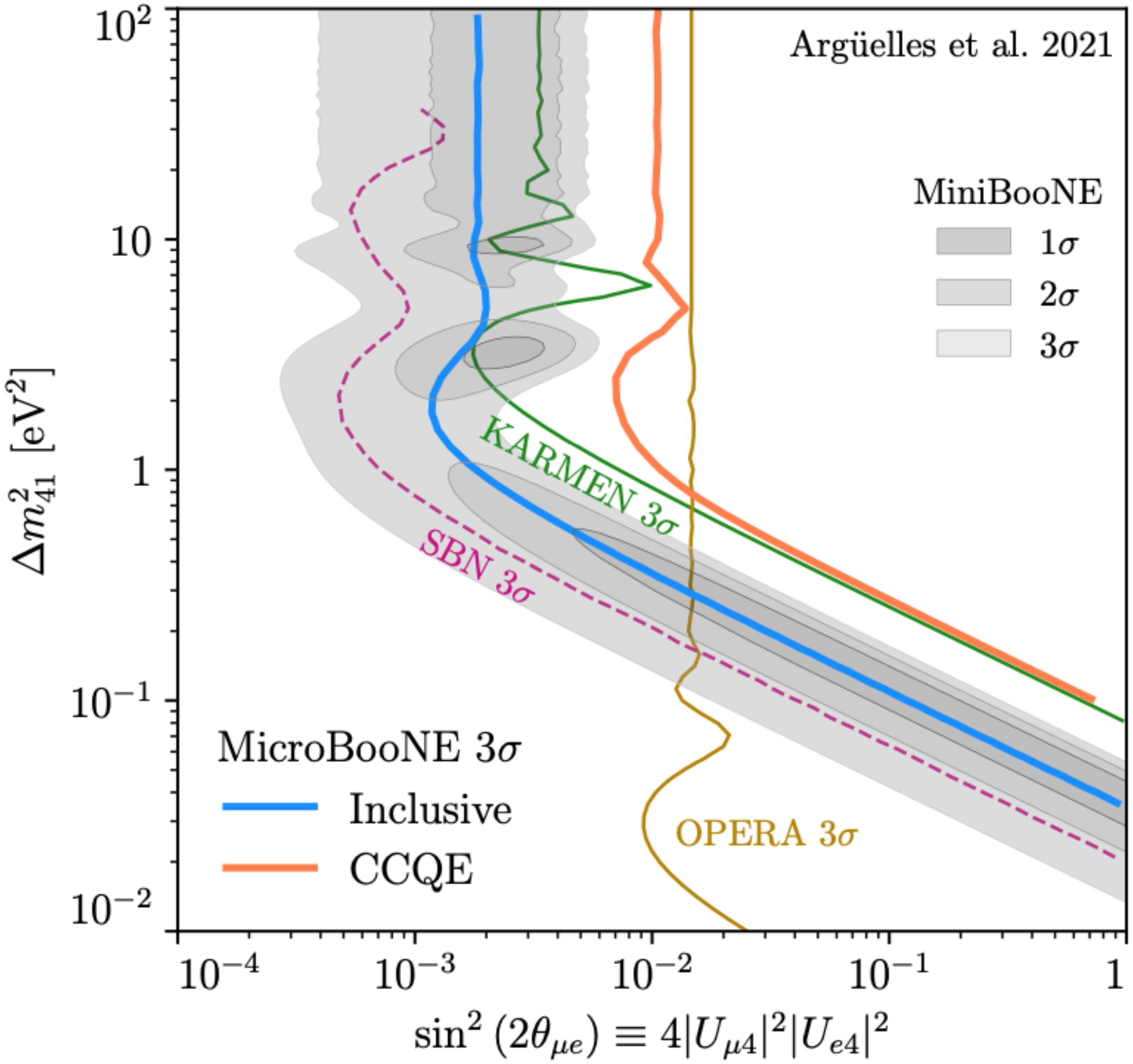


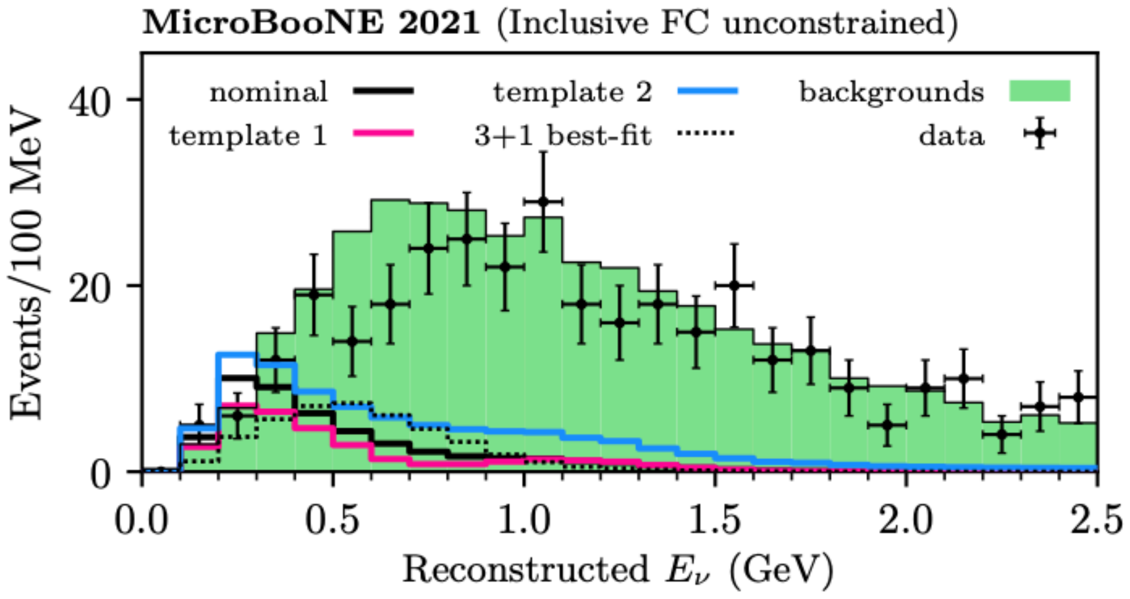
Event reconstruction is expected to be better in water than ice.

KM3NeT is funded and under construction on the mediterranean sea (~ 20% completed, expected 2027)

Highlights $P(\nu_\mu \to \nu_e)$: MicroBooNE

Thank to the MicroBooNE and MiniBooNE collaborations for making their data and MC available for studies!



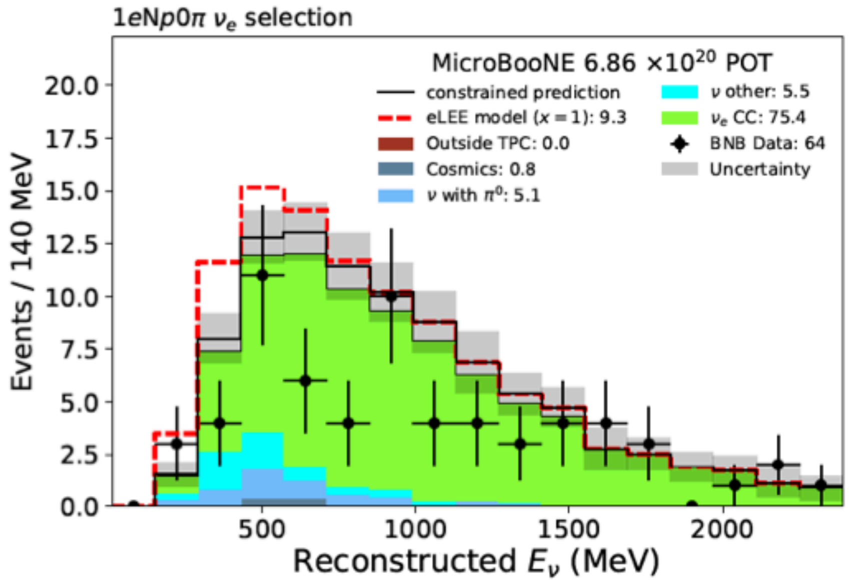


Two important messages:

- Given the large electron mixing angle suggested by best full 3+1 analysis needed to properly understand data.
- MiniBooNE+MicroBooNE combination does not significantly impact prefer region, see MiniBooNE (arXiv:2201.01724)

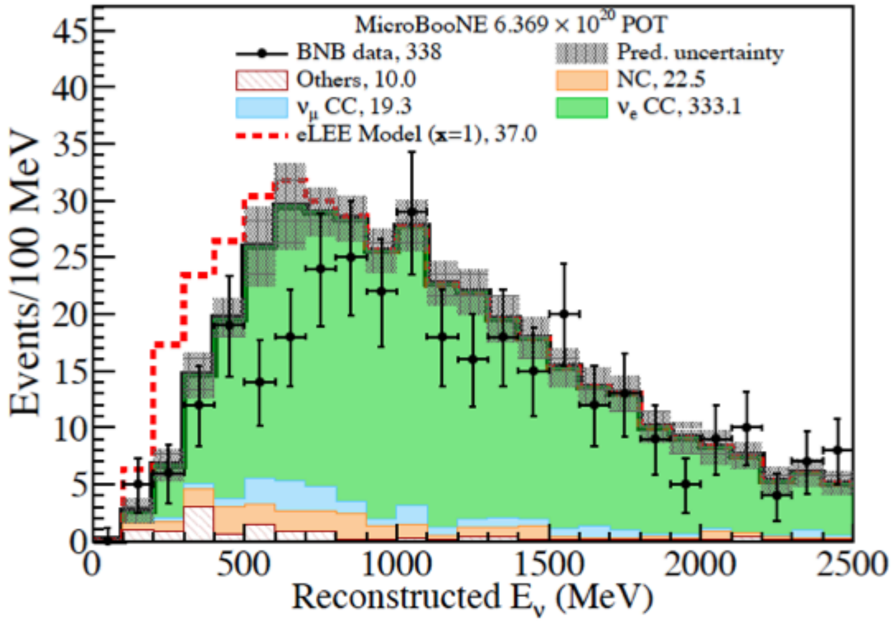
See CA, I. Esteban, M. Hostert, K. J. Kelly, J. Kopp, P. A. N. Machado, I. Martinez-Soler, and Y. F. Perez-Gonzalez (arXiv:2111.10359)
See also P. Denton (arXiv:2111.05793), MicroBooNE (arXiv:2210.10216), and MiniBooNE (arXiv:2201.01724)

Highlights $P(\nu_\mu \to \nu_e)$: MicroBooNE



Electron neutrino data in MicroBooNE seems low.

P. Denton (arXiv:2111.05793) claims 2σ hint that matches BEST.



CA et al (arXiv:2111.10359) agree on best-fit point, but do not find it significant.

MicroBooNE says compatible with error bars.

I think it will be very interesting to see if this low event rate continues in next, unanalyzed MicroBooNE data! This would support BEST mixing angle.

See CA, I. Esteban, M. Hostert, K. J. Kelly, J. Kopp, P. A. N. Machado, I. Martinez-Soler, and Y. F. Perez-Gonzalez (arXiv:2111.10359)
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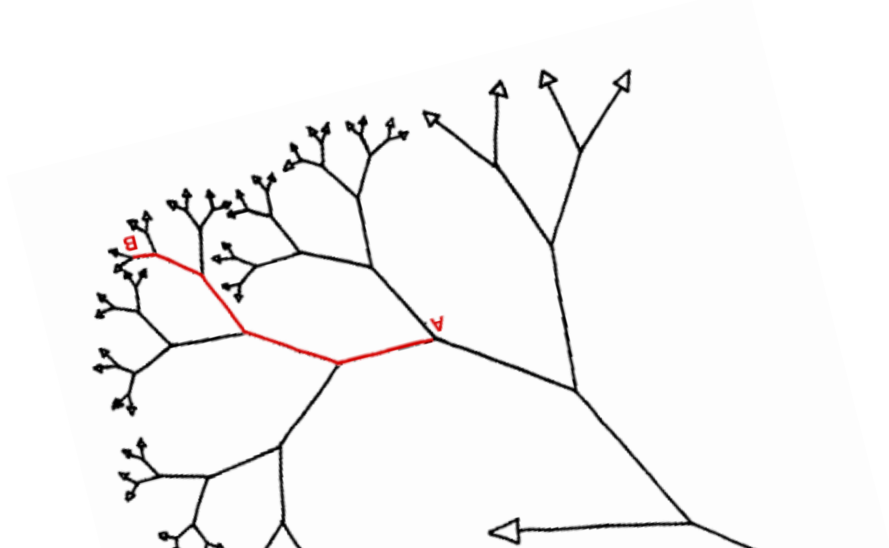
From here: The Garden of Forking Paths*

- Do we understand all SM background/process well enough?
- Do we understand how neutrino oscillations work?
- Are all the anomalies (MB, LSND, reactors) related? Or only some of them?
- Since null results are not scrutinized as carefully as anomalous ones
- Why is there a very significant signal for ν_e disappearance in sources, but not in reactors?
- How do we interpret MicroBooNE data? Electron-neutrino disappearance? Nothing?
- Is IceCube seeing hints of the missing muon-neutrino disappearance?
- If the anomalies are confirmed as new physics, in what theories are they embedded?



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*Garden of Forking Paths is spy/mystery short story by Jorge Luis Borges

From here: The Garden of Forking Paths*

The garden maybe actually a spiky garden full of cactuses … we need to walk with care

Stepping back: What do we know?

- LSND saw an excess of electron-antineutrino events.
- MiniBooNE saw an excess of electron-like events in neutrino and antineutrino modes.
- MicroBooNE saw no single photons; electron results yield no significant observation.
- Reactor experiments using ratios see hints of oscillations at large mass-square-differences.
- Source experiments see very significant deficit.
- Muon-neutrino disappearance has resulted in weak signals at large mass-square-differences.
- Anomalous observations are on a line on L/E.
- Standard cosmological scenarios disfavor an additional neutrino. Though tensions in the Hubble parameter indicate that something is missing.

Indications of new neutrino oscillations

Indications of additional new physics

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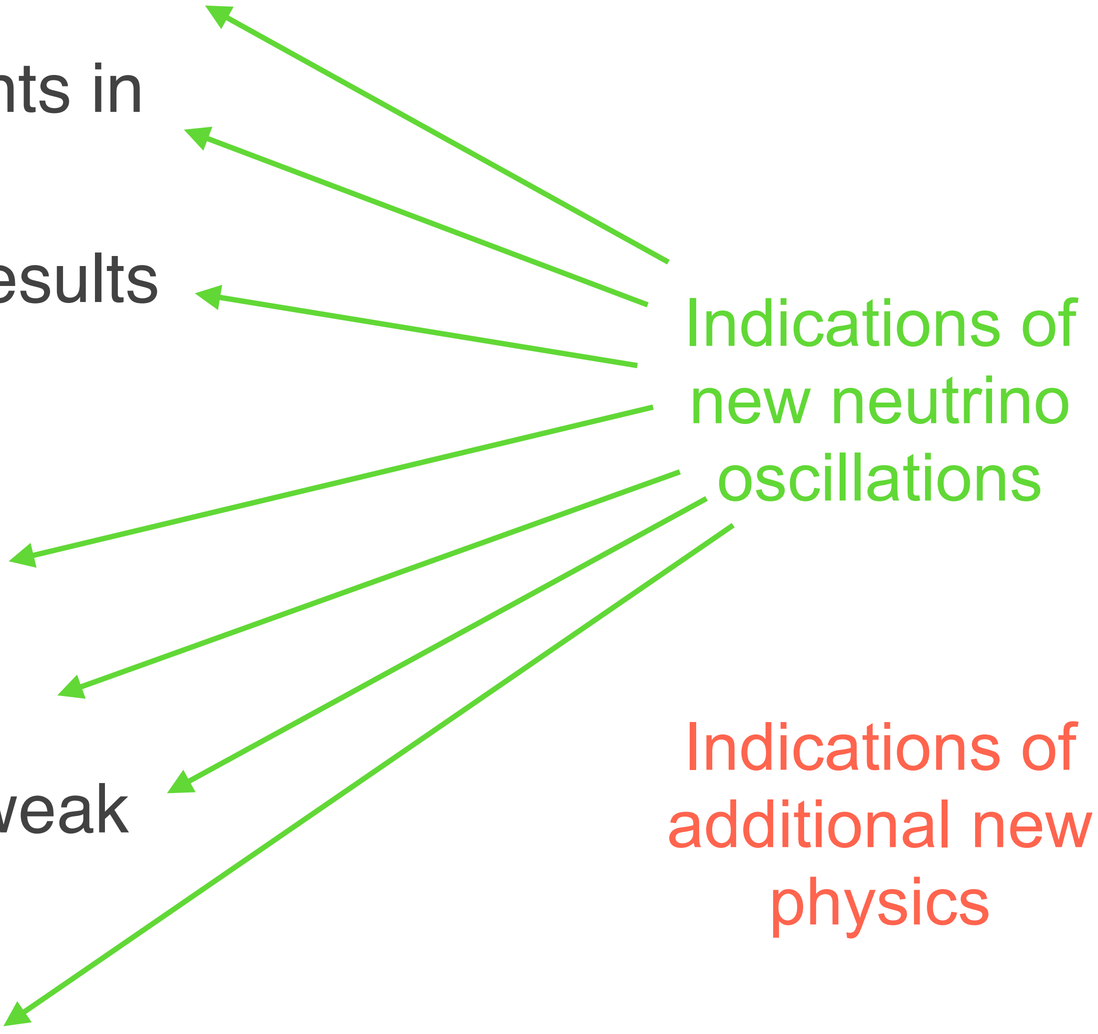

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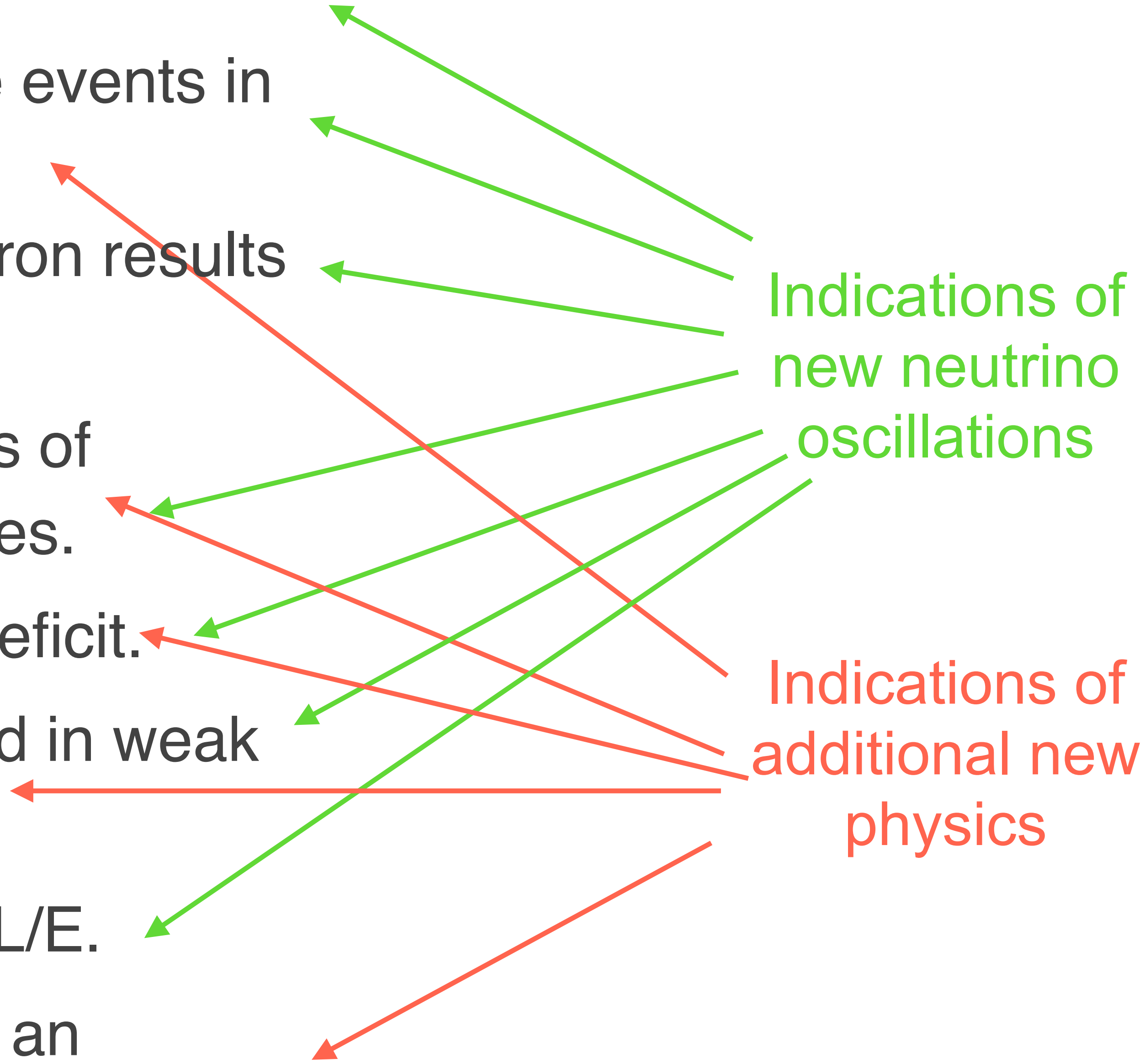

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Many elements suggest something like 3+1, but something else is hinted by observations and tensions in the data sets.

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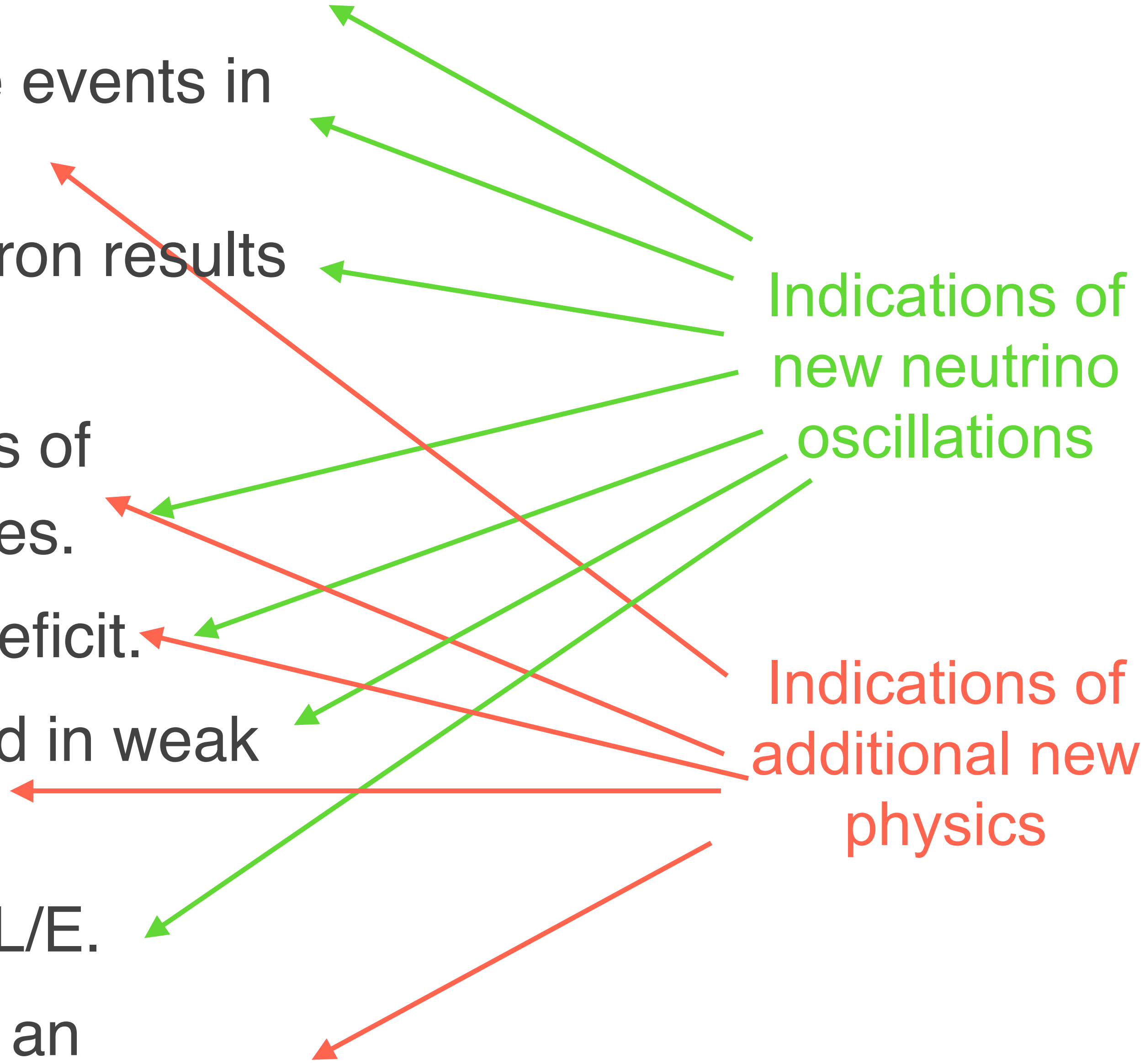


Indications of new neutrino oscillations

Indications of additional new physics

Many elements suggest something like 3+1, but something else is hinted by observations and tensions in the data sets.

Two hypothesis we will pursue

Path One

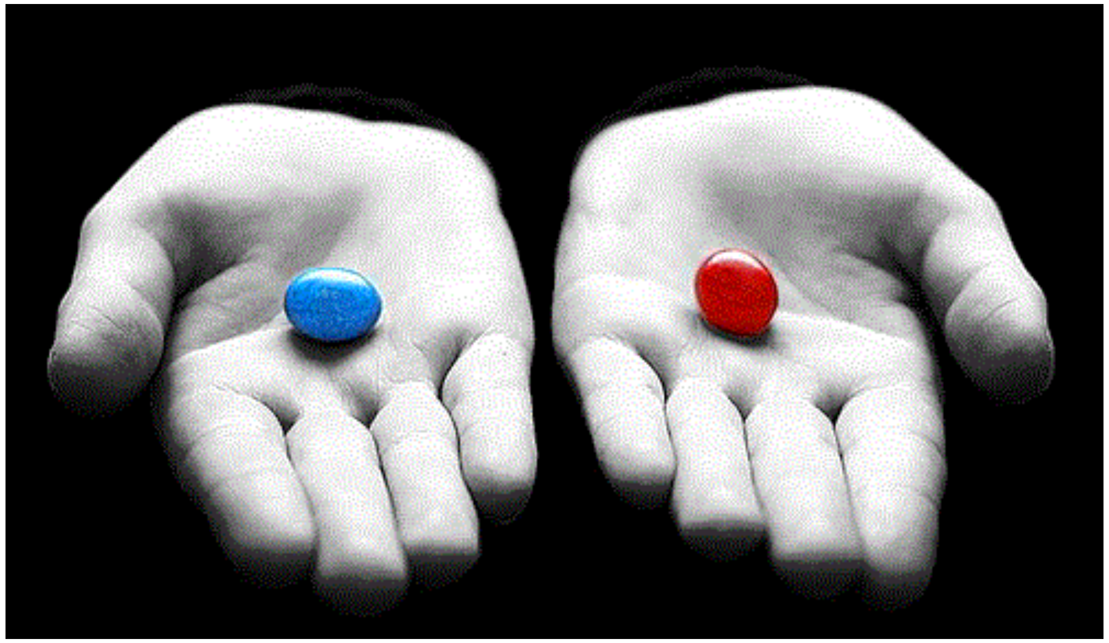
The anomalies are related.

Light sterile neutrino exists, but something is missing

Path Two

The anomalies are not related.
Reactors are statistical fluctuations,
BEST is systematic, …

What can MiniBooNE be?



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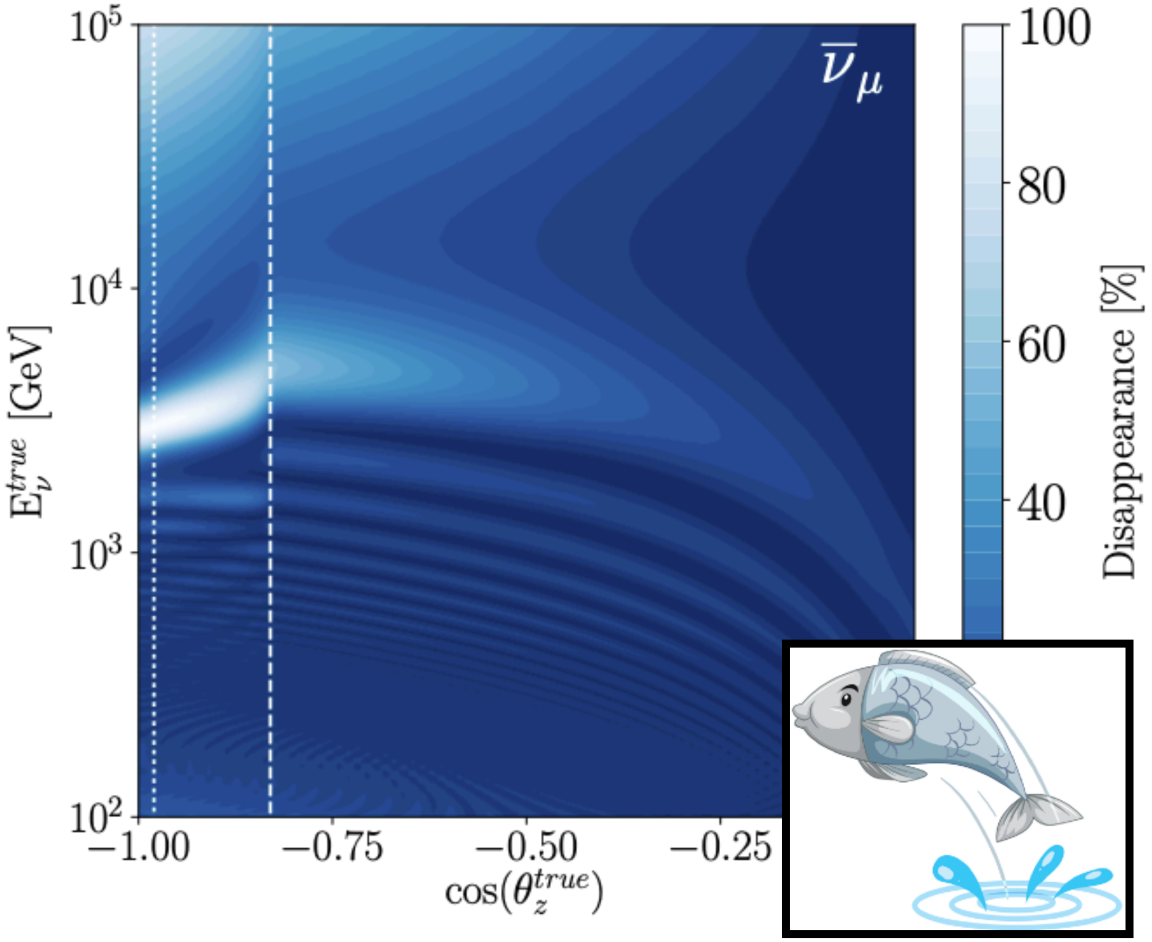
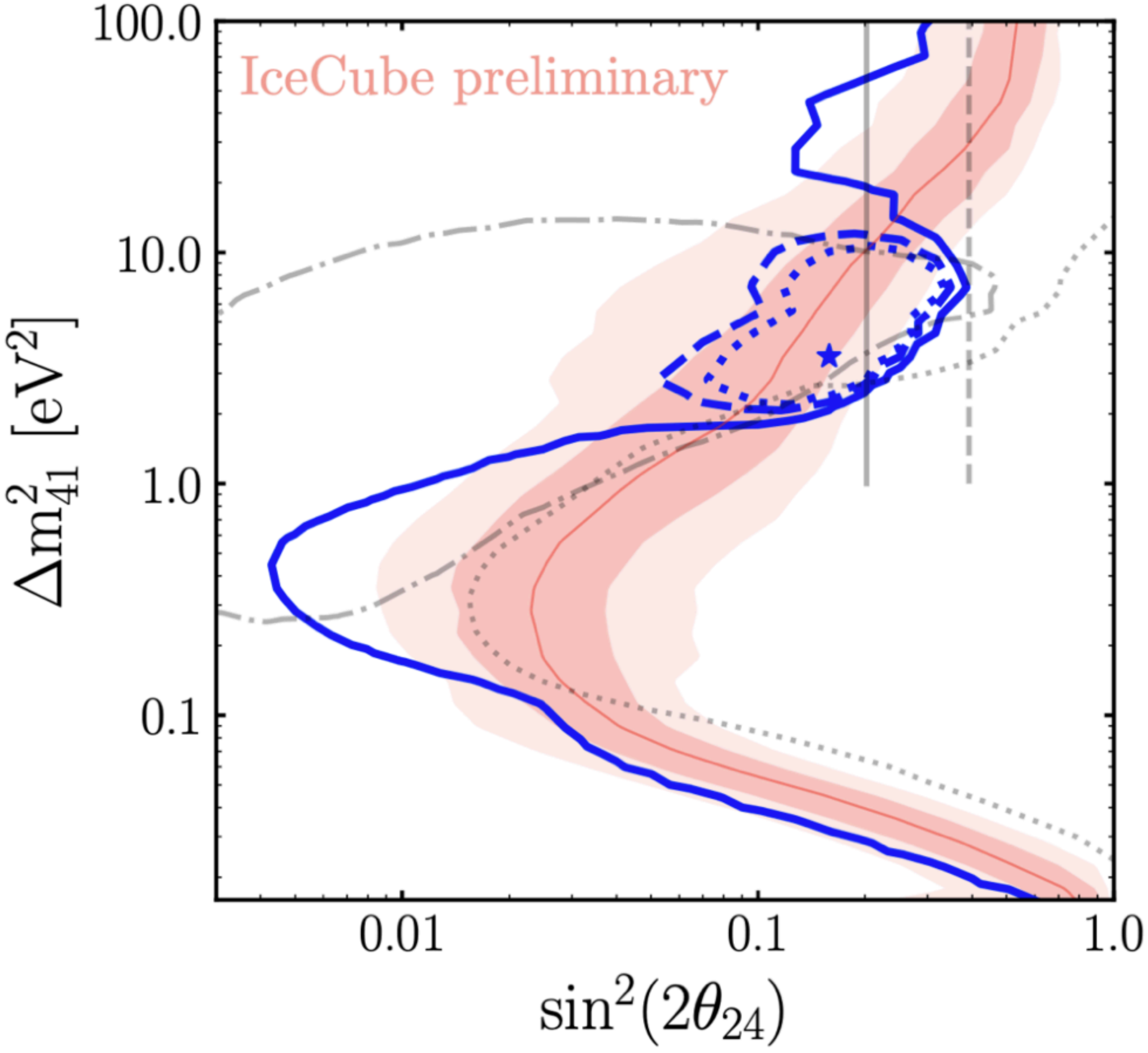
Idea 1: Sterile Neutrinos Plus NSI

The context

IceCube exploits matter effects for their results



N. Kamp, 2024, this workshop



IceCube and MINOS+ dominate muon-neutrino disappearance in ROI

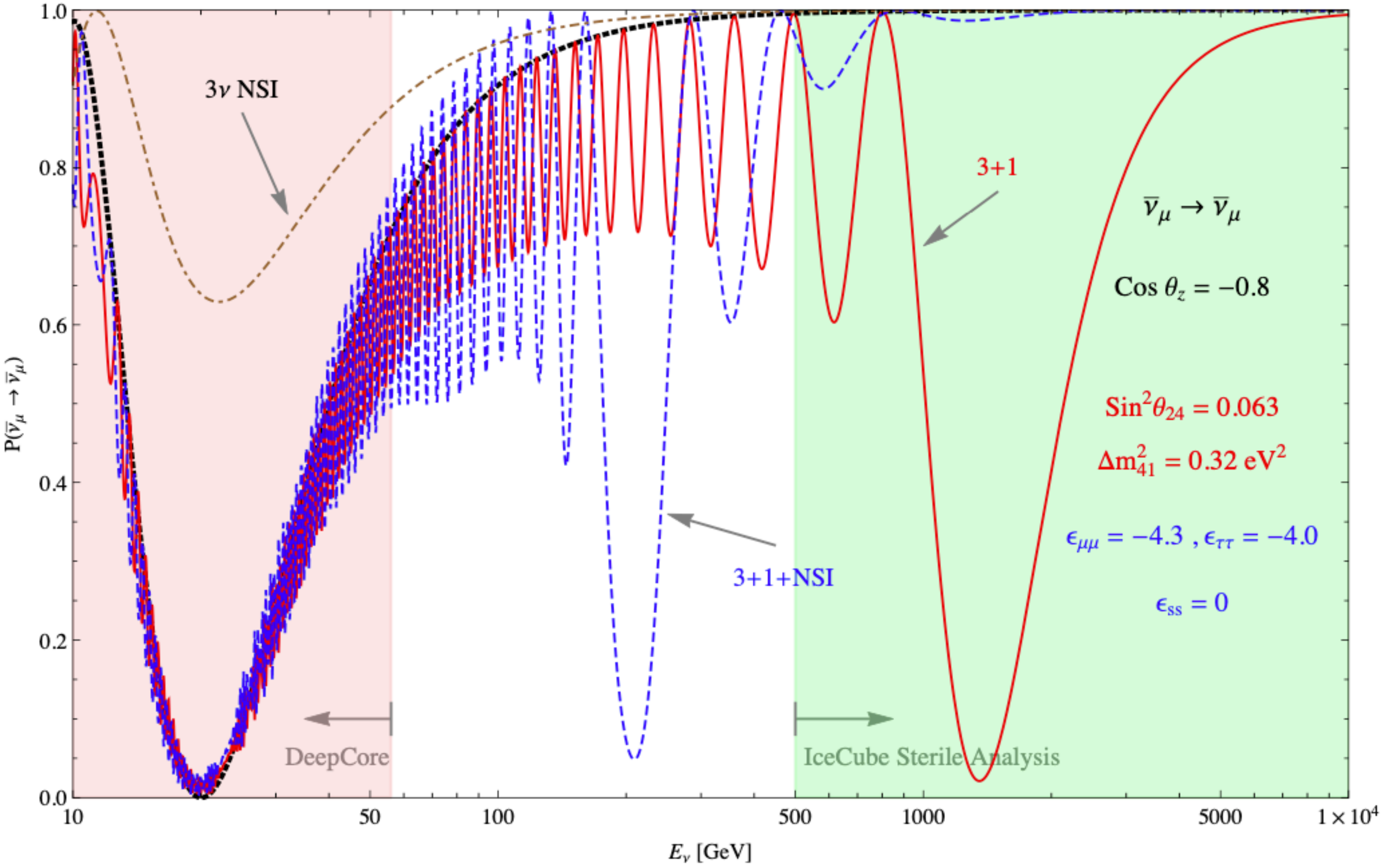
IceCube coll. 2005.12942 and 2005.12943

Idea 1: Sterile Neutrinos Plus NSI

Introduction of NSI shifts the resonance and weakens constraint

J. Liao et al 1810.01000

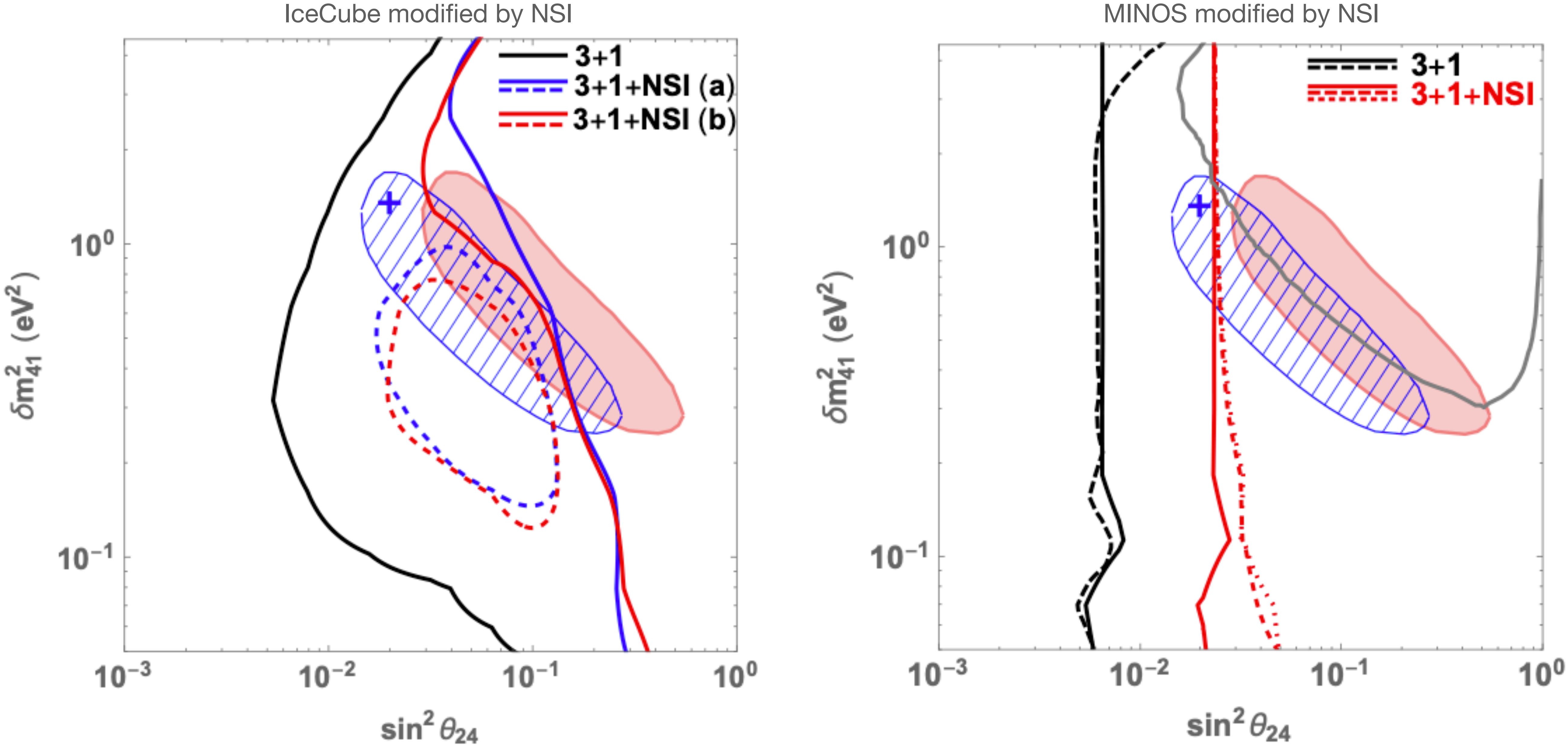
A. Esmaili et al 810.11940



Idea 1: Sterile Neutrinos Plus NSI

NSI affects both long baseline experiments

J. Liao et al 1810.01000

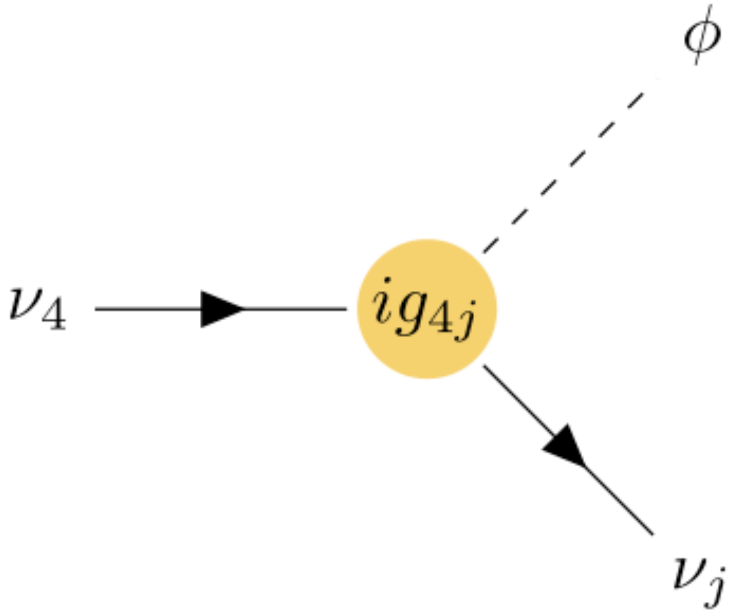


This scenario needs to be reassess with updated NSI constraints, and IceCube and MINOS+ data

Idea 2: Sterile Neutrinos Plus Decay

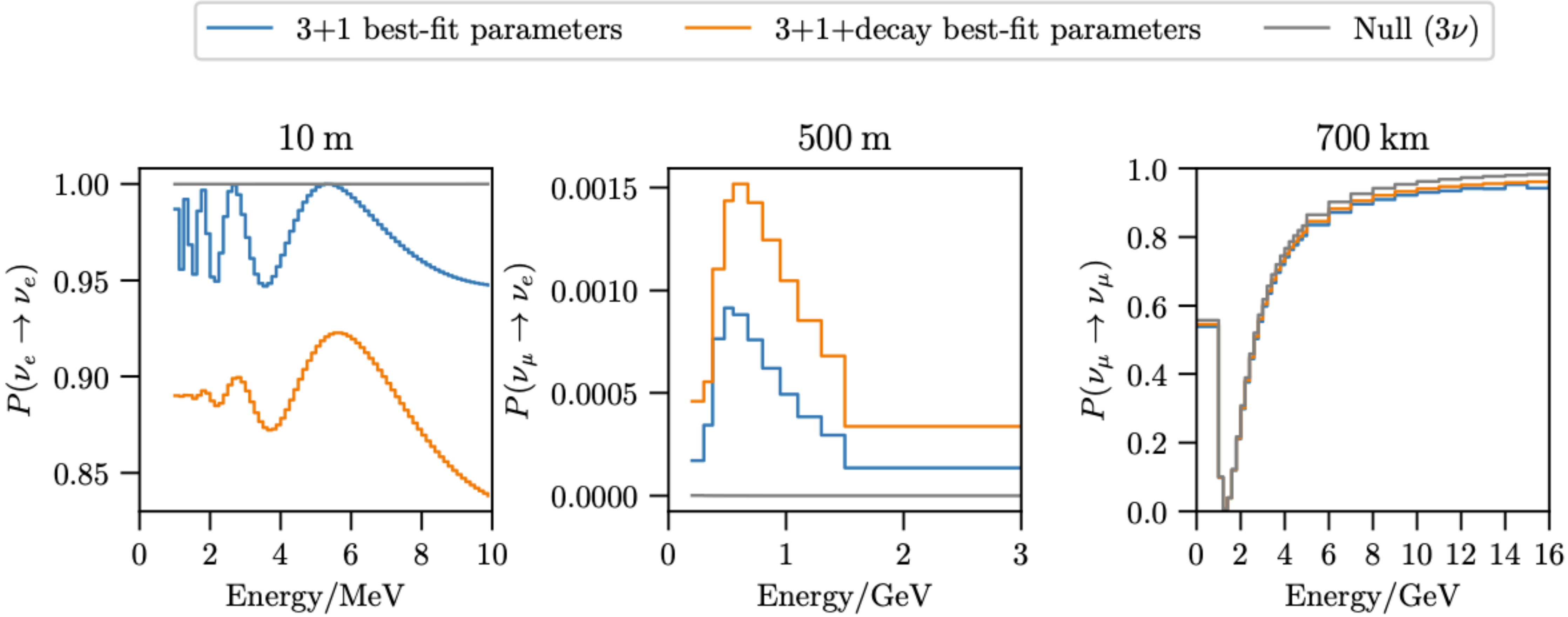
Moss et al 1711.05921
Palomares-Ruiz et al hep-ph/0505216

The model



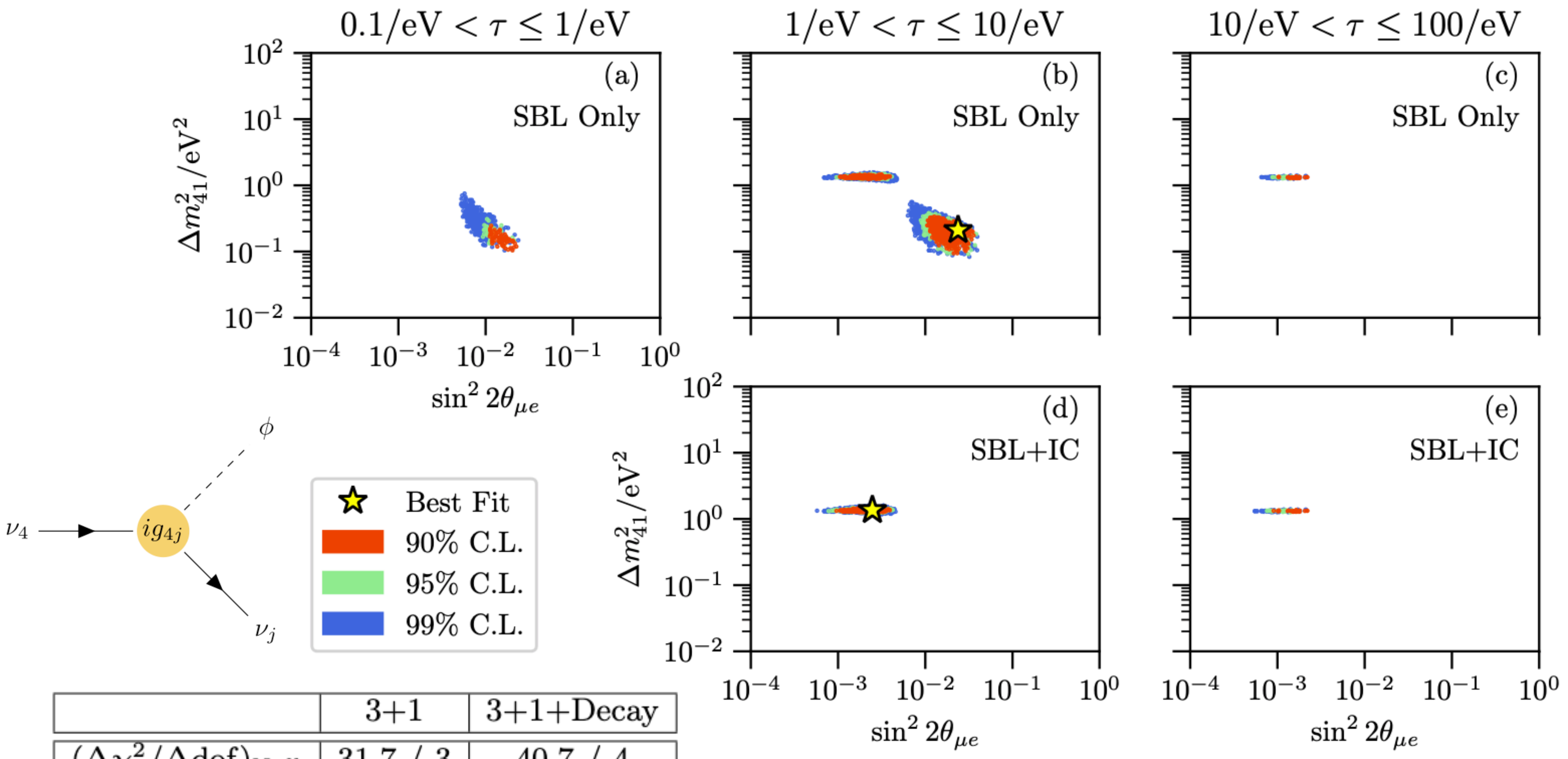
Decay can be visible or invisible.

If neutrinos are Dirac -> invisible
If neutrinos are Majorana -> visible



Idea 2: Sterile Neutrinos Plus Decay

The global status



	3+1	3+1+Decay
$(\Delta\chi^2/\Delta\text{dof})_{\text{Null}}$	31.7 / 3	40.7 / 4
$(\Delta\chi^2/\Delta\text{dof})_{3+1}$	–	9.1 / 1

Moss Moss et al 1711.05921
Moulai et al 1910.13456

Global data prefers 3+1+Decay!

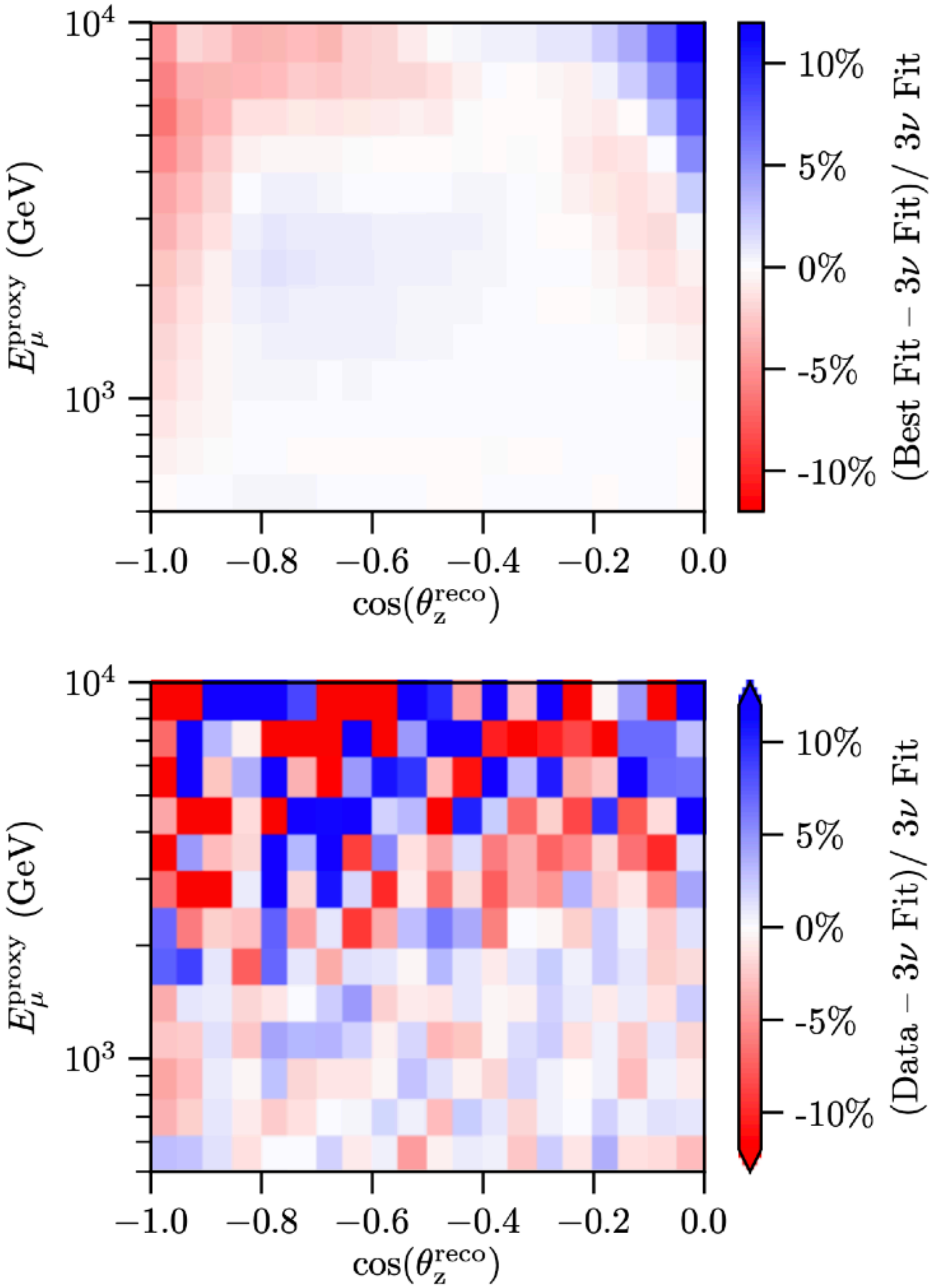
See also Berryman *et al* 1407.6631

See latest fits on this on Hardin et al arXiv:2211.02610

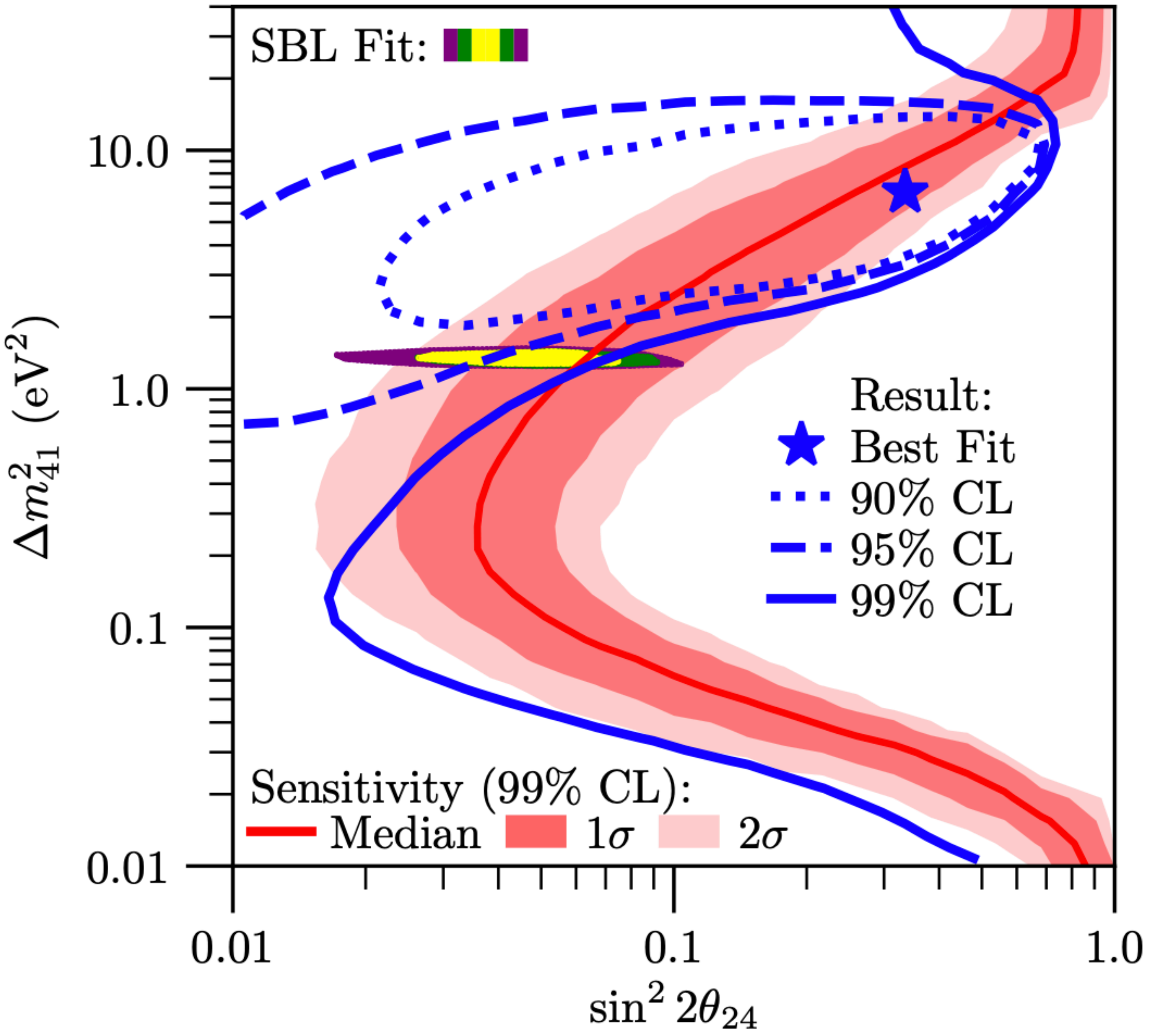
Idea 2: Sterile Neutrinos Plus Decay

$$\Delta m^2_{41} = 6.7^{+3.9}_{-2.5}\mathrm{eV}^2 \;\; \sin^2 2\theta_{24} = 0.33^{+0.20}_{-0.17} \;\; g^2 = 2.5\pi \pm 1.5\pi$$

(slice for best-fit decay constant)



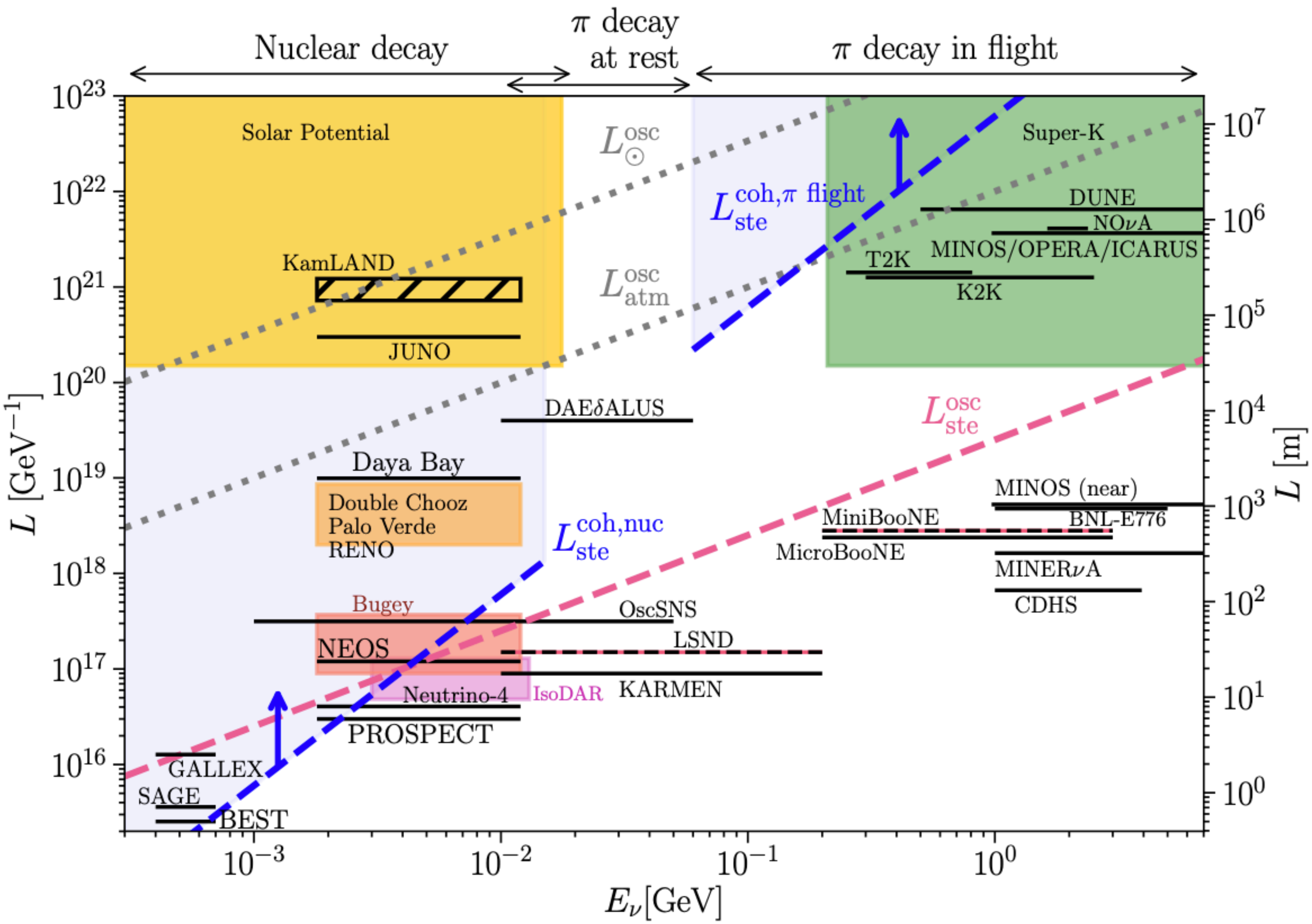
IceCube Collaboration arXiv:2204.00612



IceCube also prefers 3+1+Decay!

Idea 3: Sterile Neutrinos Plus Decoherence

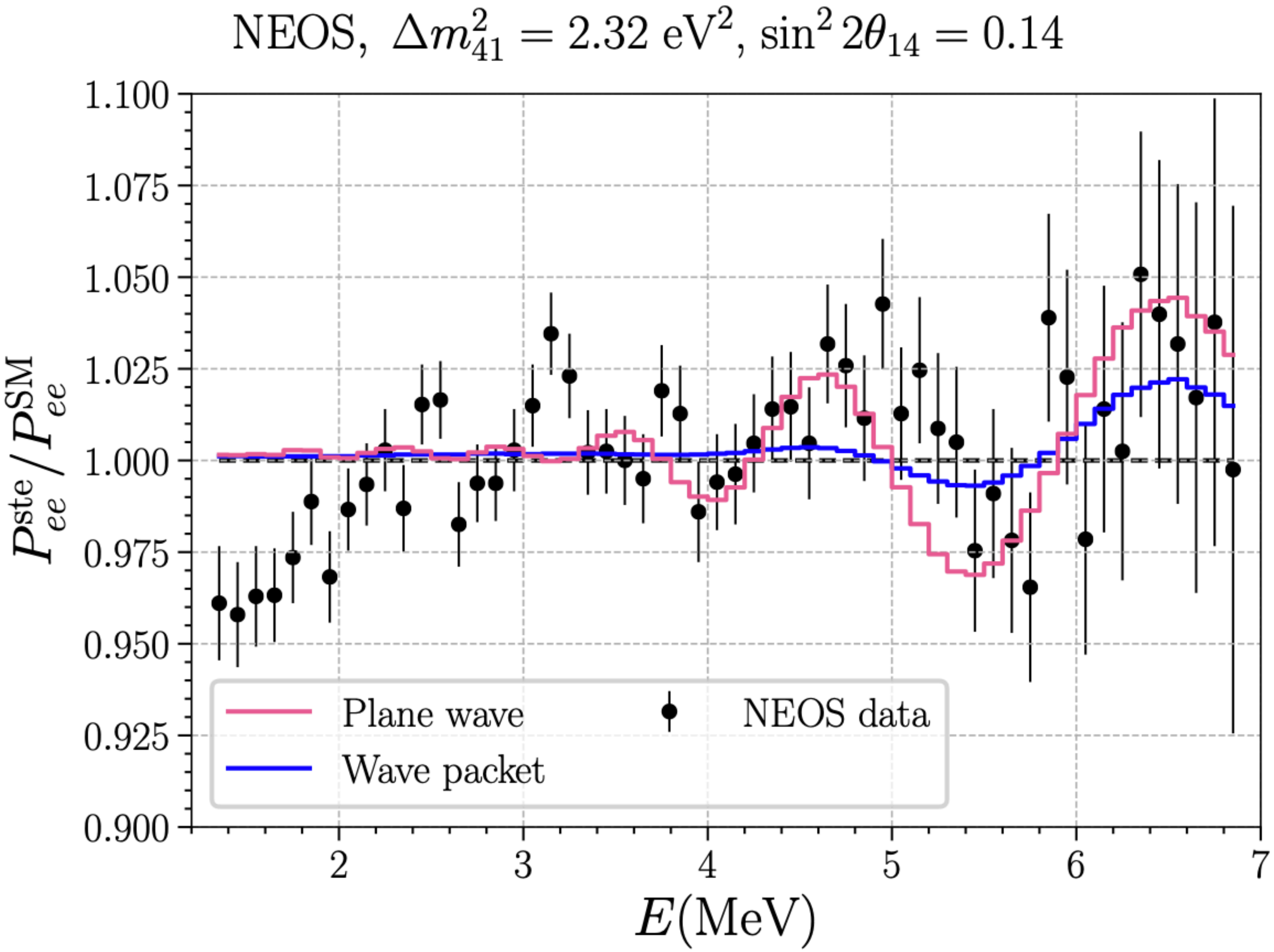
How are our neutrinos produced?

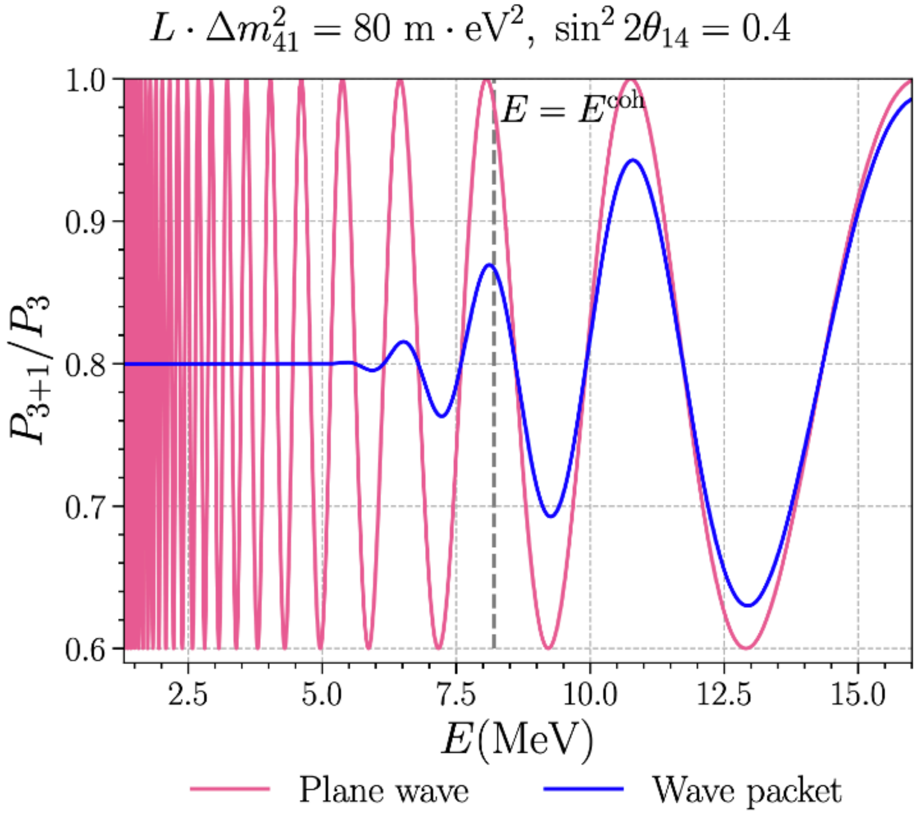


CA, Bertólez-Martínez, Salvado arXiv:2201.05108

Idea 3: Sterile Neutrinos Plus Decoherence

Context: tension between rate (BEST) and spectral measurements

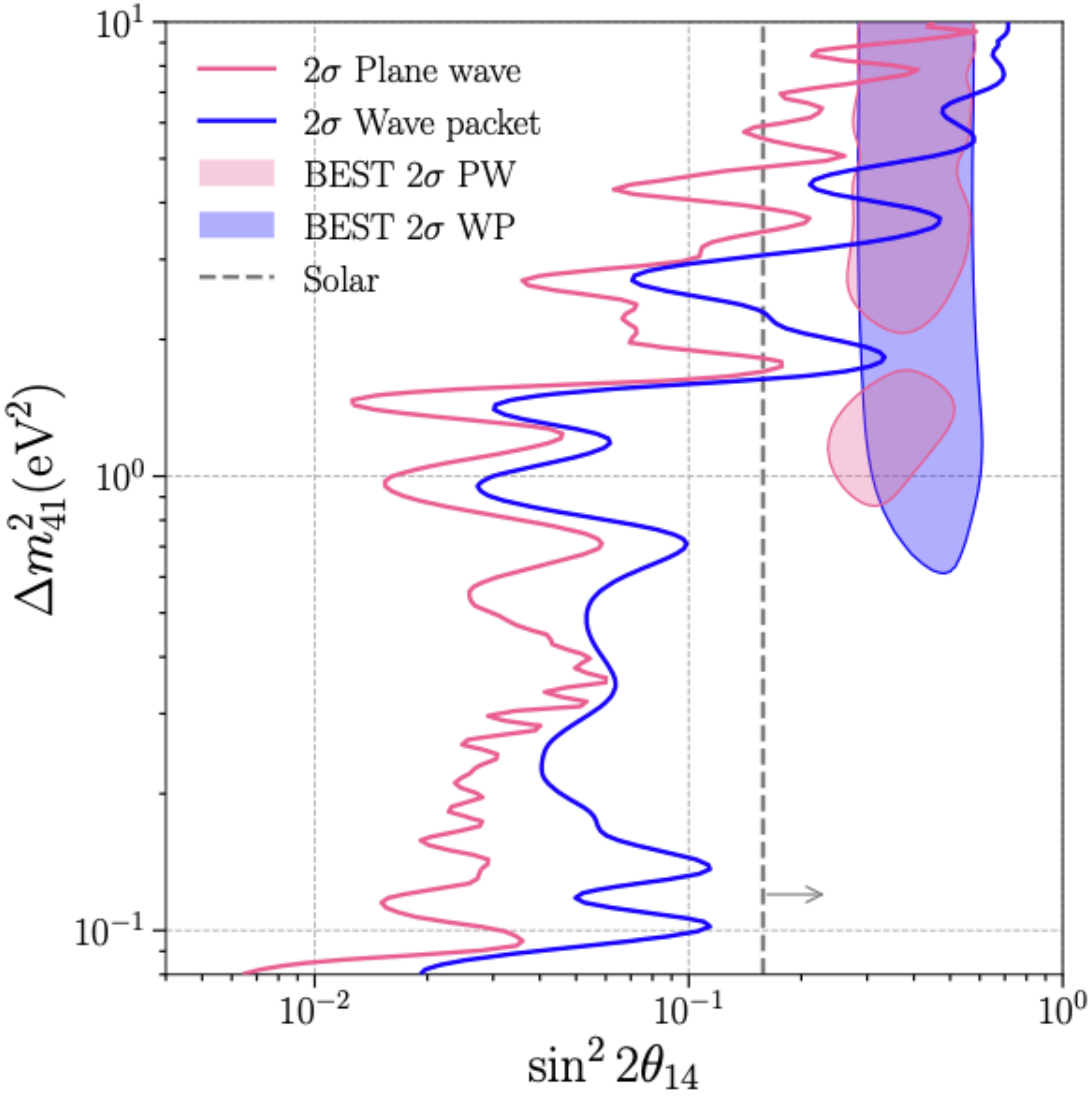


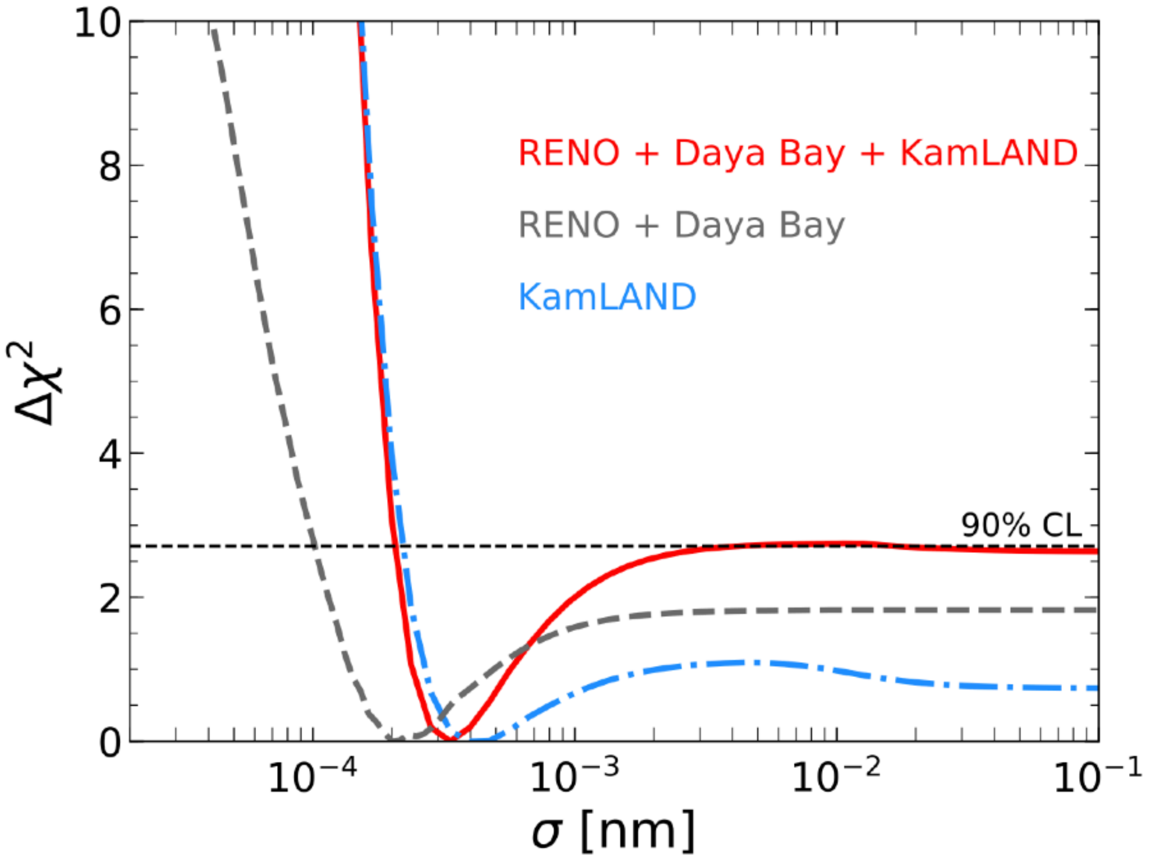


CA, T. Bertólez-Martínez, and J. Salvado 2201.05108
Berryman et al 2111.12530

Idea 3: Sterile Neutrinos Plus Decoherence

Context: Tension between BEST and other reactor measurements



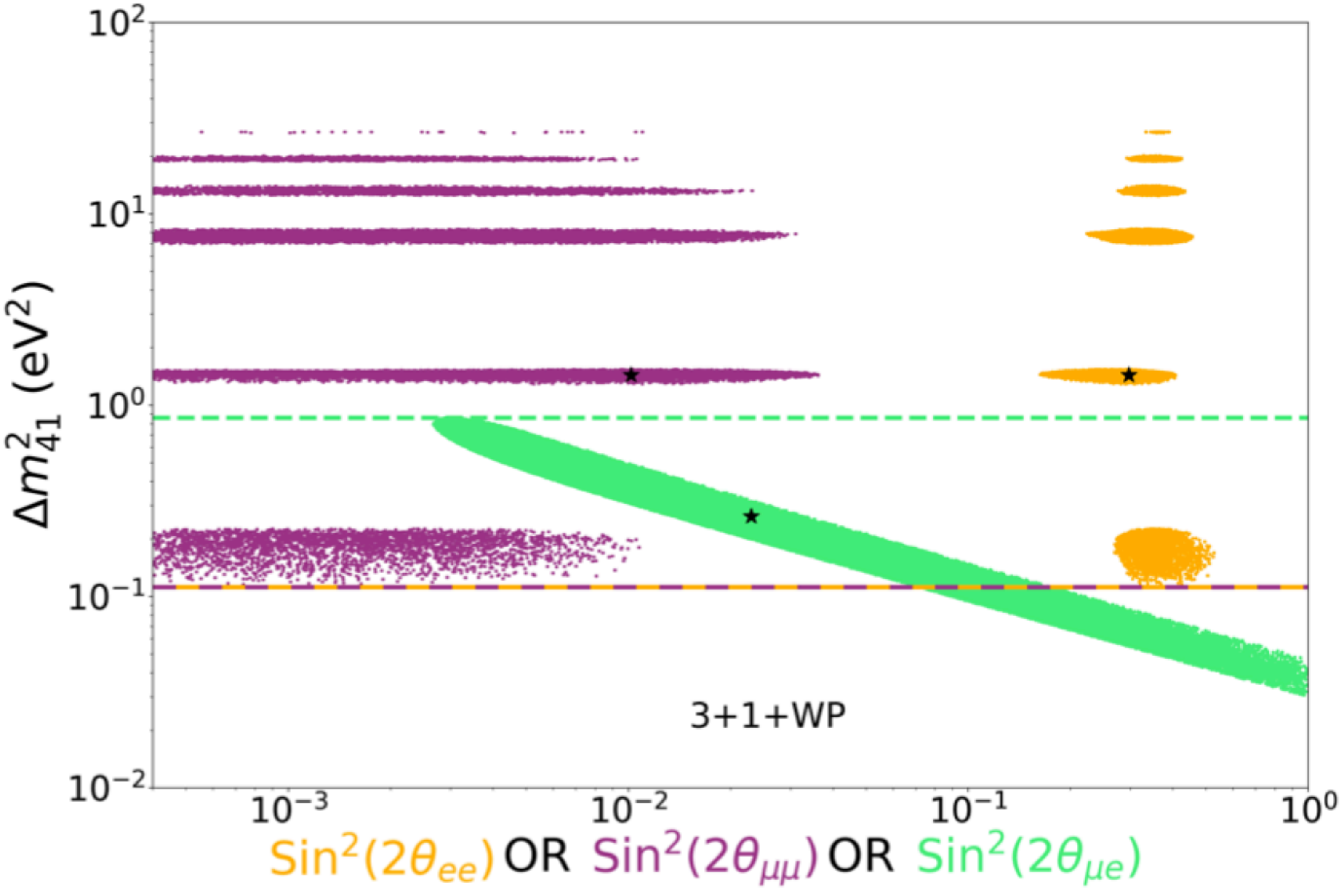


Gouvea arXiv:2104.05806 and Daya Bay Coll. 1608.01661

CA, T. Bertólez-Martínez, and J. Salvado 2201.05108
Berryman et al 2111.12530

Idea 3: Sterile Neutrinos Plus Decoherence

Fit	App vs. Dis tension	Δm^2 best fit (eV^2) App., Dis, Global
3+1	4.9σ	0.24, 7.8, 13
3+1+WP	3.5σ	0.24, 1.4, 1.4
3+1+WP, No MiniBooNE	2.1σ	0.84, 1.4, 1.4



WP solution in severe tension with estimation by Ahkmedov & Smirnov (arXiv:2208.03736)

Ok with estimation from Jones, Marzec & Spitz (2211.00026)

See also comment by Jones (2209.00561)

BSM proposal:
Banks et al (2209.11270)

Hardin et al arXiv:2211.02610

Take home message

- The short-baseline anomalies are an unresolved puzzled in neutrino physics
- Need to keep doing oscillation searches for 3+1+other scenarios in electron-neutrino and muon-neutrino.
- Need to think how all of these models would fit in the greater picture and cosmology.

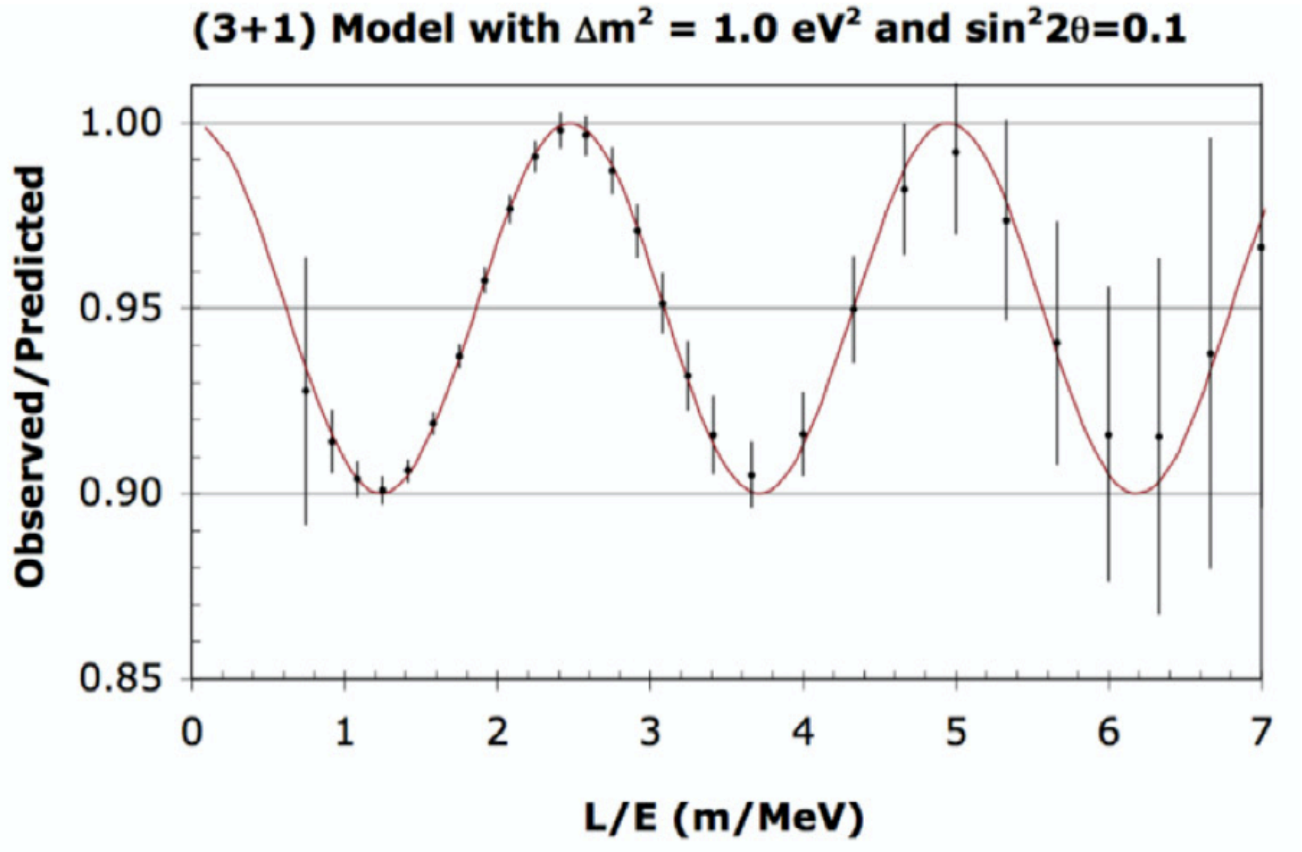
May your physics be BSM!

Thank you!

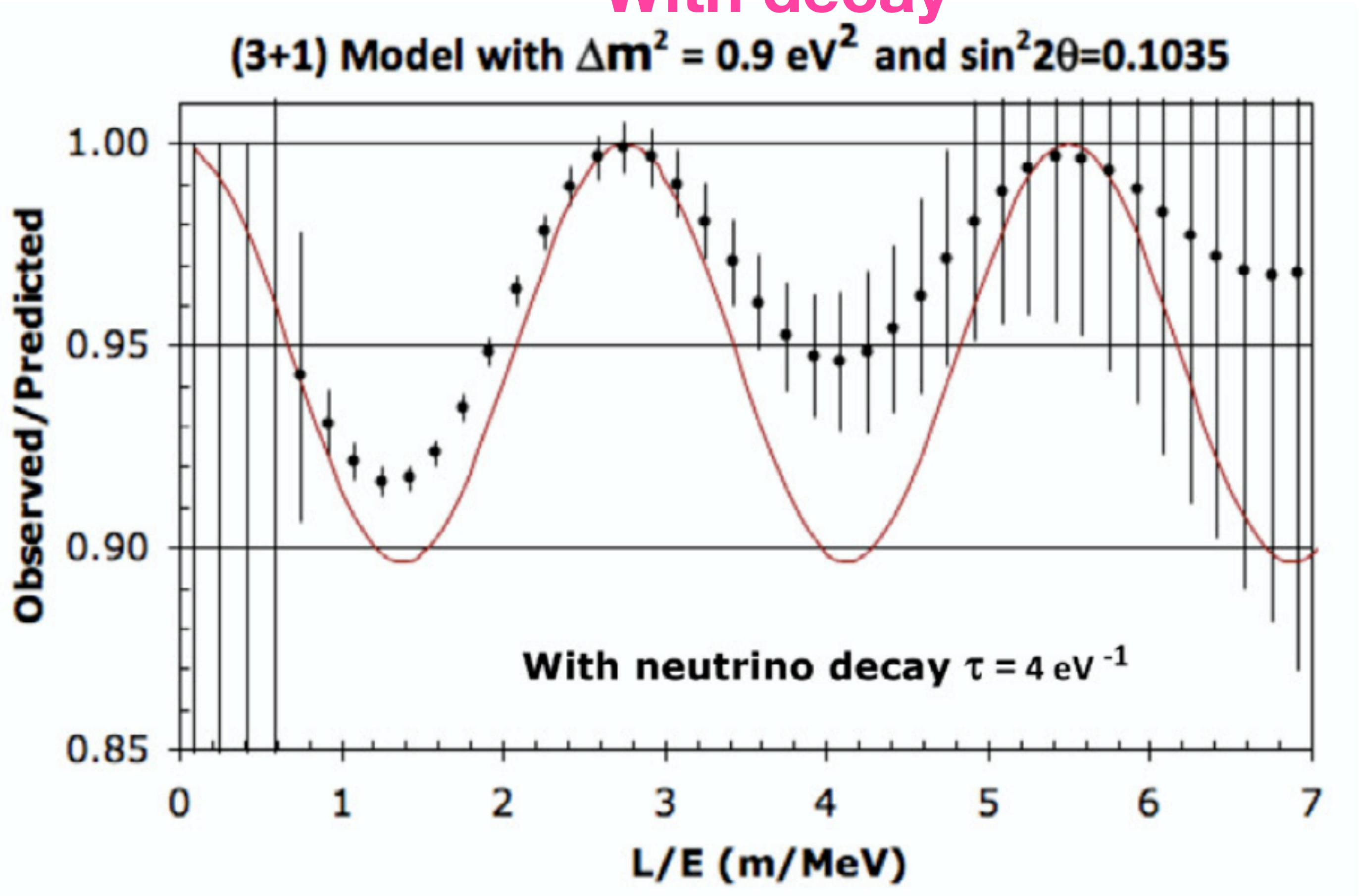
Bonus slides

IsoDAR@Yemilab

No decay



With decay



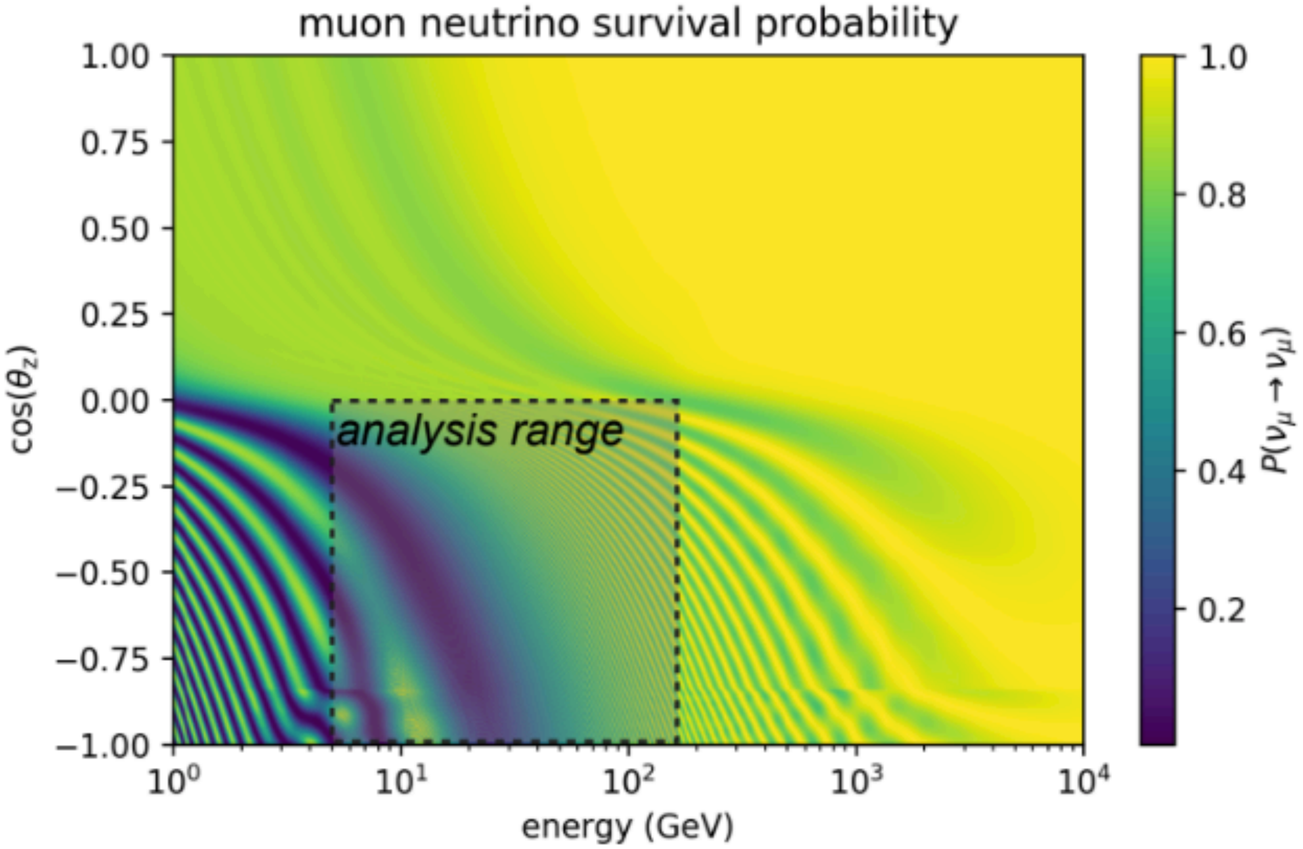
IsoDAR with O(1M) events

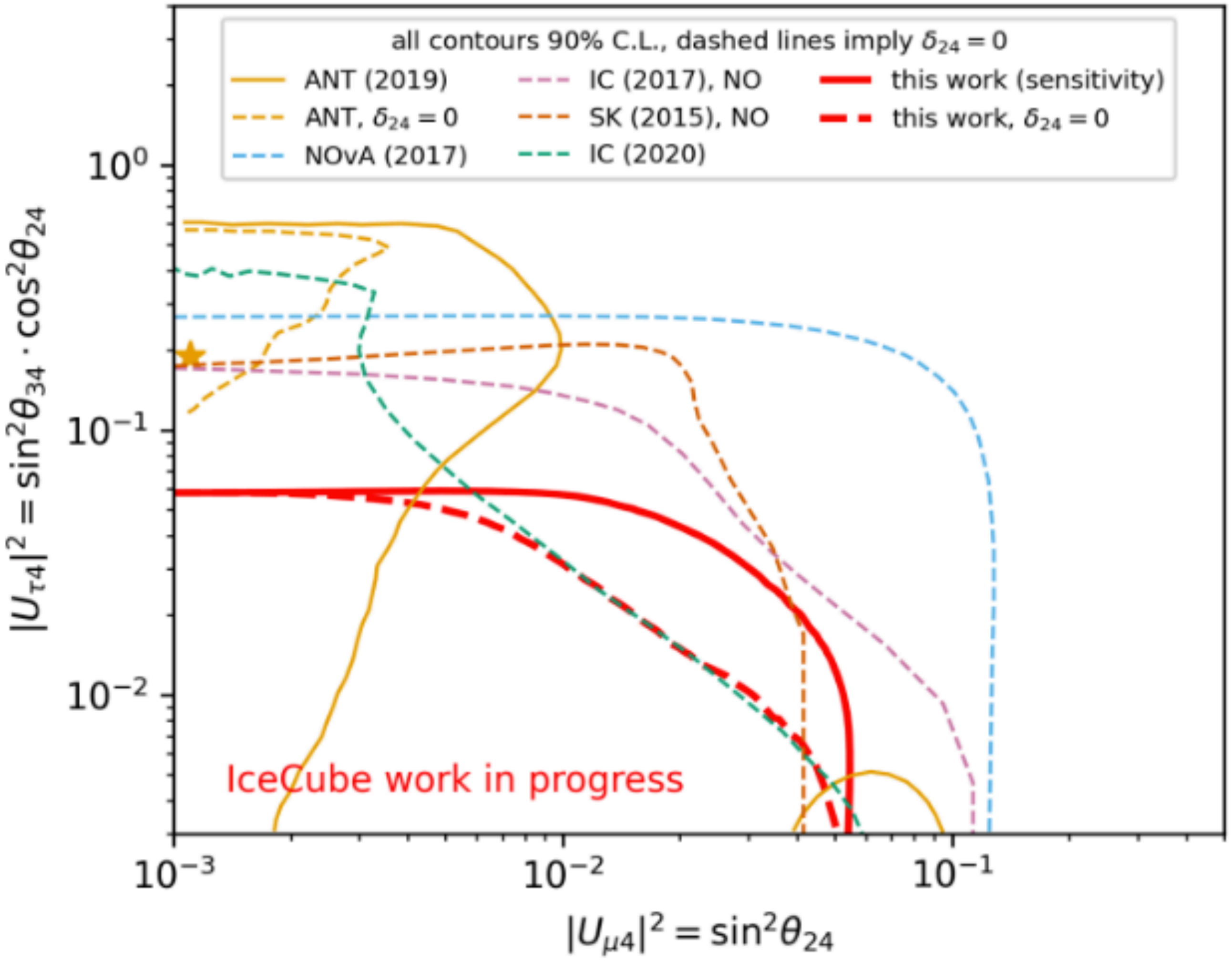
IsoDAR@Yemilab will conclusively rule out the 3+1 model, but also due to its ability to trace the oscillation wave see variants on this model such as 3+1+Decay

IceCube@Antartica

Talk by A. Trettin@PANIC2021

“Low” energies: 5 - 150 GeV





Projected sensitivity of sterile search with 8 years of DeepCore data

- \> very fast, unresolvable oscillations + distortion
- \> IceCube: World-leading limits on $|U_{\tau 4}|^2$ and $|U_{\mu 4}|^2$!

IceCube will continue improving muon neutrino disappearance searches.
“Low energy” sample (<100 GeV) still not studied.

Menu of other explanations

New signatures

Gninenko 1107.0279
Magill et al 1803.03262
Heavy neutrino O(MeV), magnetic moment, decay

Bertuzzo et al 1807.09877, Ballett et al 1808.02916,
CA, Hostert, Tsai et al 1812.08768
Heavy neutrino O(1-100MeV), light Z’, decay

Heavy Neutrino Decay

Bai et al 1512.05357

Dentler et al 1911.01427,
de Gouvea et al 1911.01447,
Hostert & Pospelov 2008.11851

Heavy O(100MeV) decay to ν_e

Fisher et al 1909.0956,
CA, Foppiani, Hostert 2109.03831

Heavy O(100MeV) decay to photon

Oscillations+X

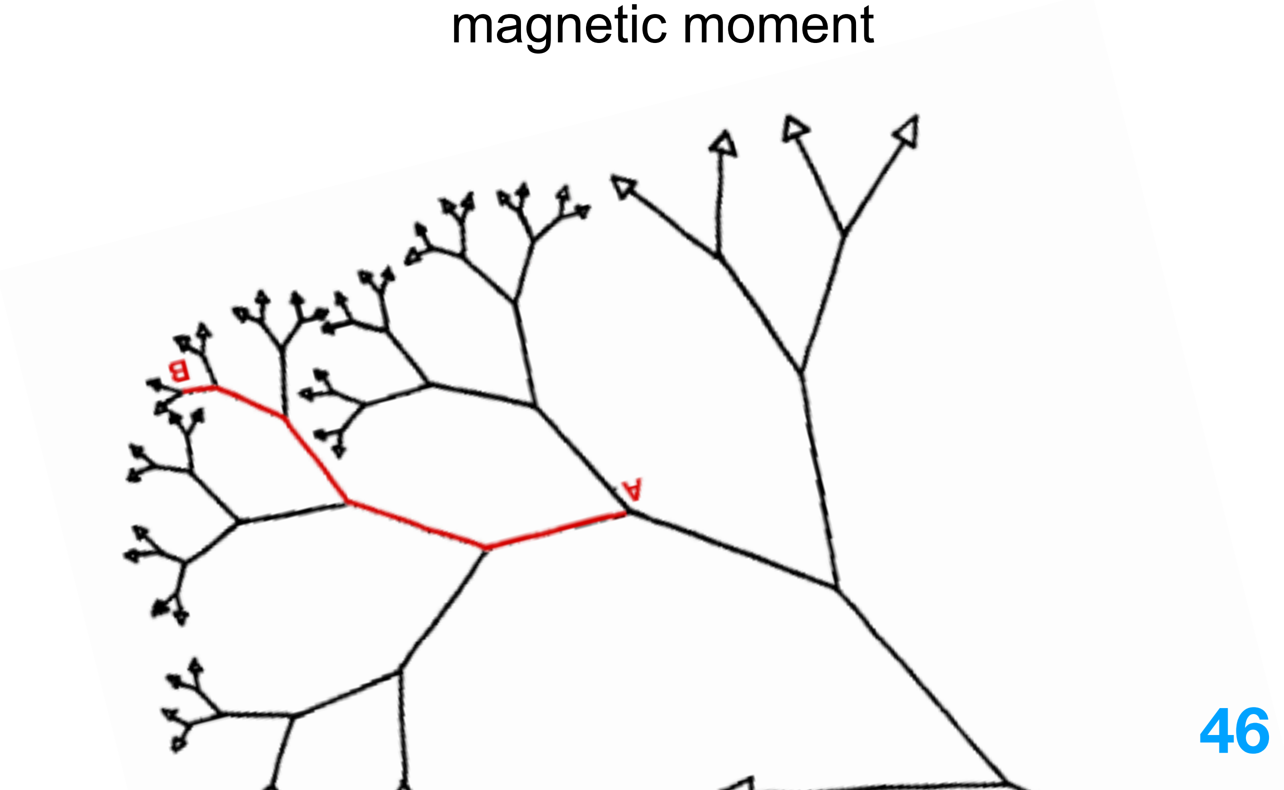
Assadi et al 1712.08019
Resonant matter effect

Moss et al 1711.05921, Moulai et al 1910.13456
Steriles +decay

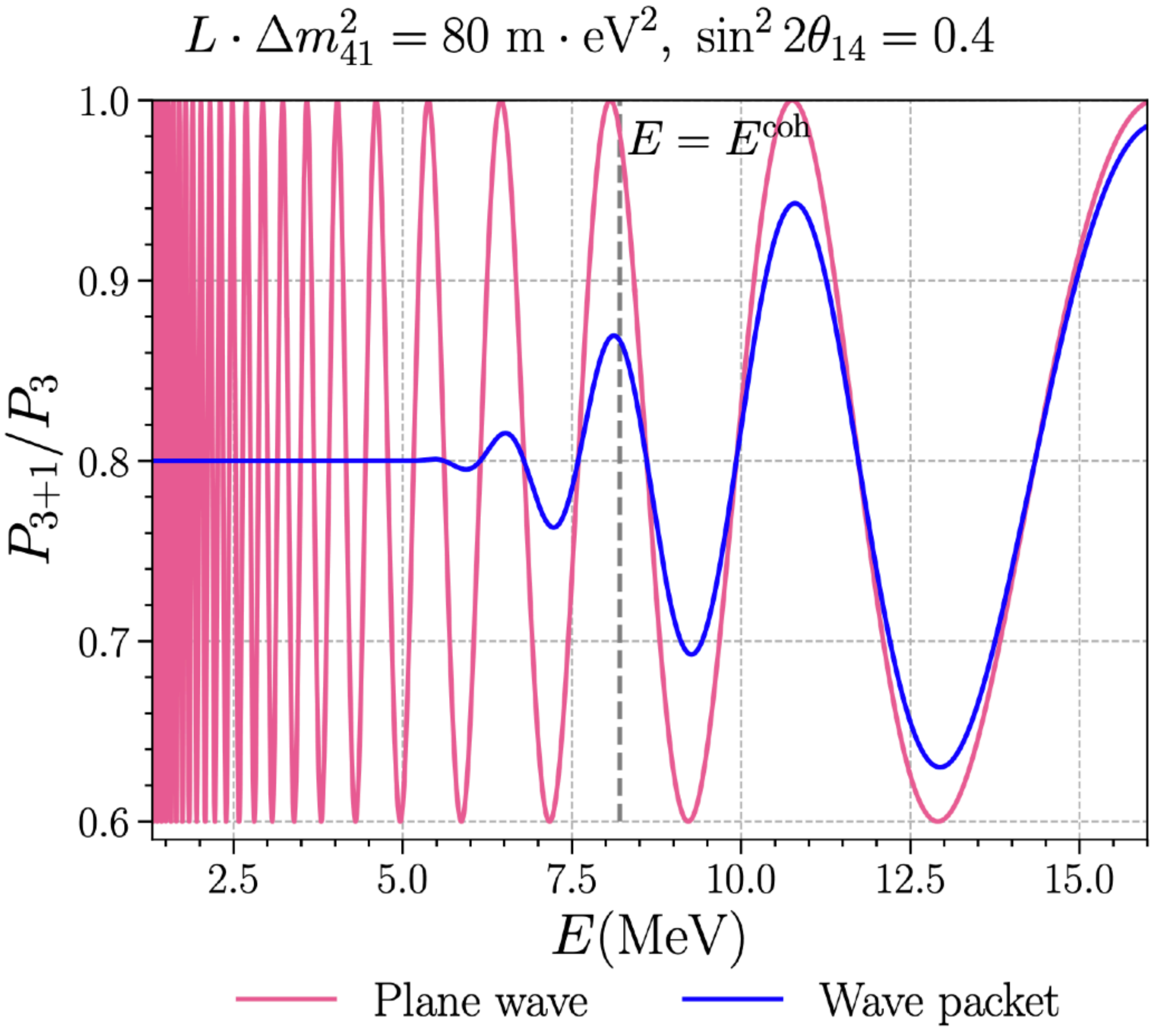
Liao et al 1810.01000
Steriles + NCNSI + CCNSI

More than one at a time

S. Vergani et al arXiv:2105.06470
Light Sterile + Heavy neutrino O(100MeV),
magnetic moment



Oscillation probability in the Wave Packet formalism



$$P_{\alpha\beta} = \sum_{i=1}^{n} |U_{\alpha i}|^2 |U_{\beta i}|^2 + 2\mathrm{Re} \sum_{j>i} U_{\alpha i} U^*_{\alpha j} U^*_{\beta i} U_{\beta j} \times$$

$$\times \exp\left\{ -2\pi i \frac{L}{L^{ij}_{\mathrm{osc}}} - 2\pi^2 \left(\frac{\sigma_x}{L^{ij}_{\mathrm{osc}}} \right)^2 - \left(\frac{L}{L^{ij}_{\mathrm{coh}}} \right)^2 \right\}$$

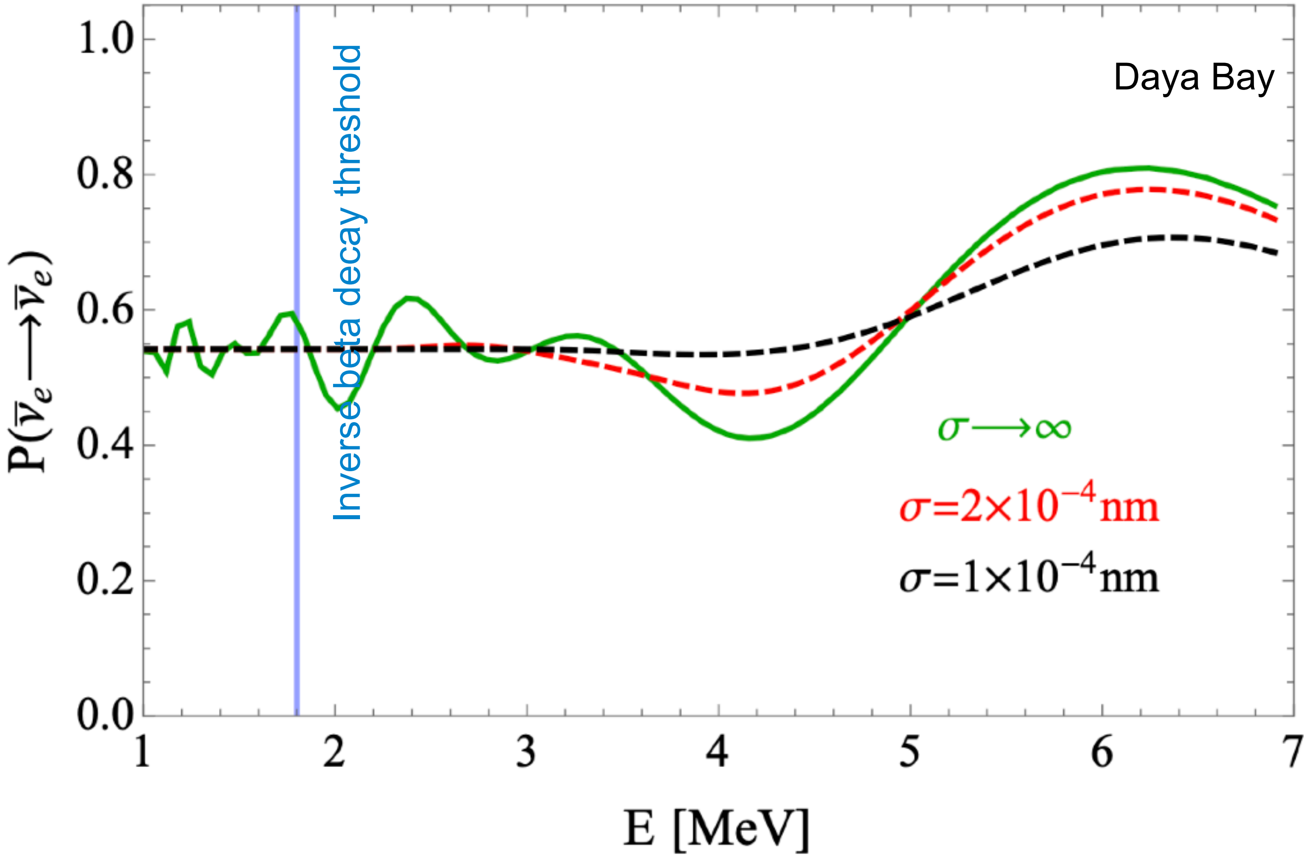
$$L^{ij}_{\mathrm{osc}} = \frac{4\pi E}{\Delta m^2_{ji}} \quad \text{and} \quad L^{ij}_{\mathrm{coh}} = \frac{4\sqrt{2} E^2 \sigma_x}{\Delta m^2_{ji}}$$

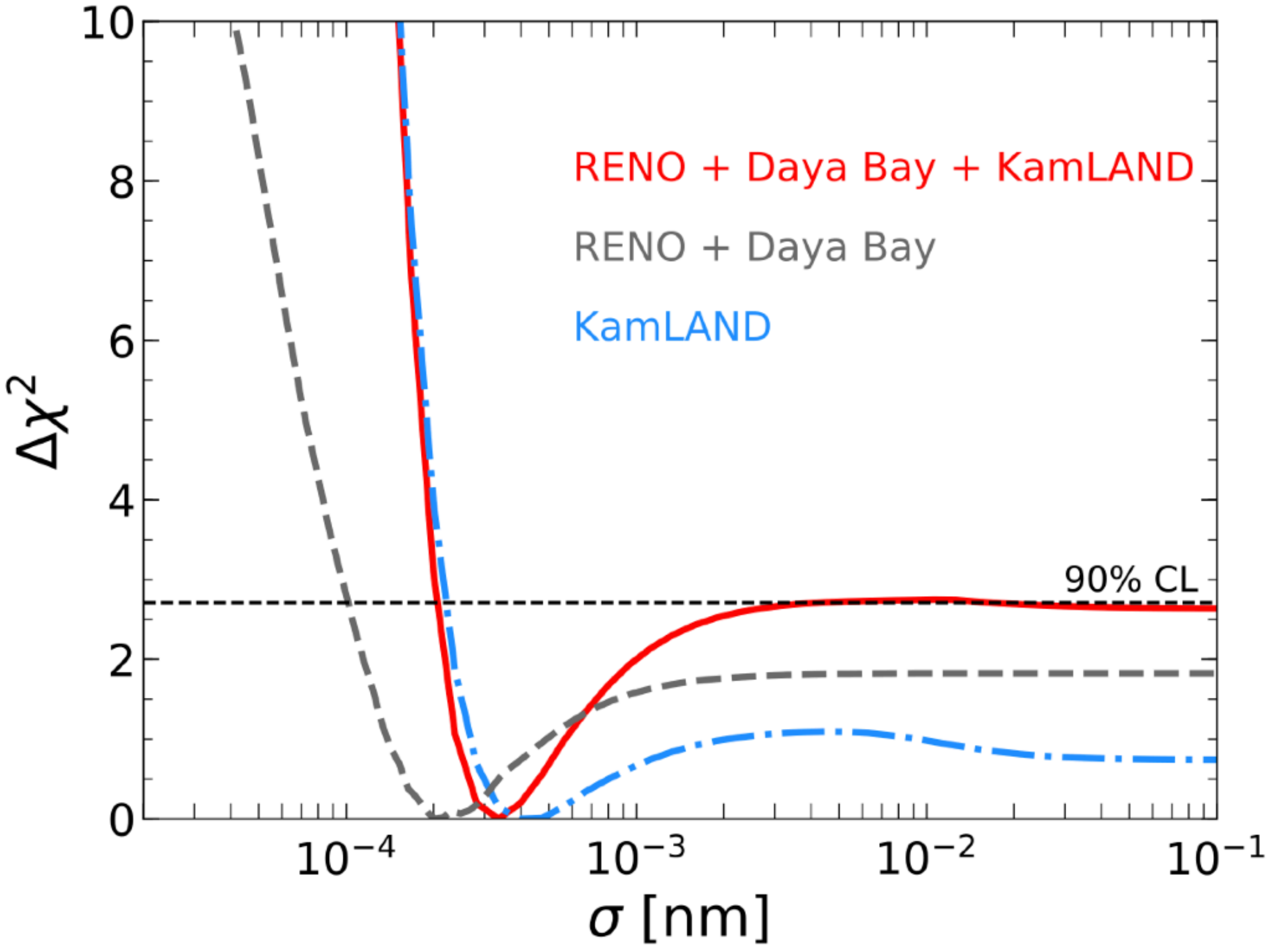
σ_x is the wave packet size

Oscillations are damped due to the added uncertainty in the neutrino energy

Can we measure/constraint its size?

Yes! We can look at the distortions on the reactor neutrino measurements of standard oscillations!



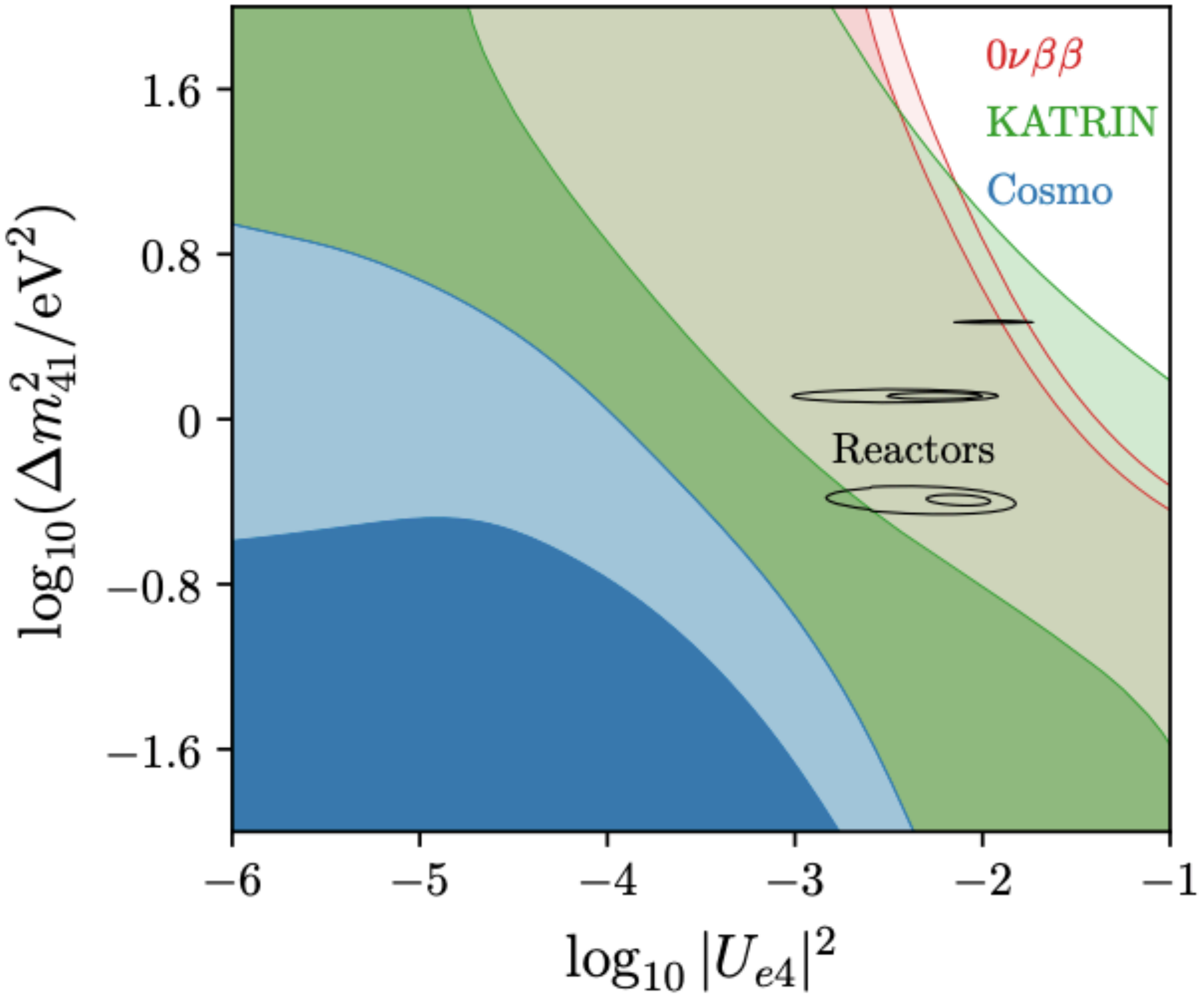


Reactor wave packet size to be constraint to be greater than 2.1×10^{-4}nm at 90% CL.

Gouvea arXiv:2104.05806 and Daya Bay Coll. 1608.01661

Let’s not forget cosmology!

Hagztoz *et al* https://arxiv.org/pdf/2003.02289.pdf



Effective mixing

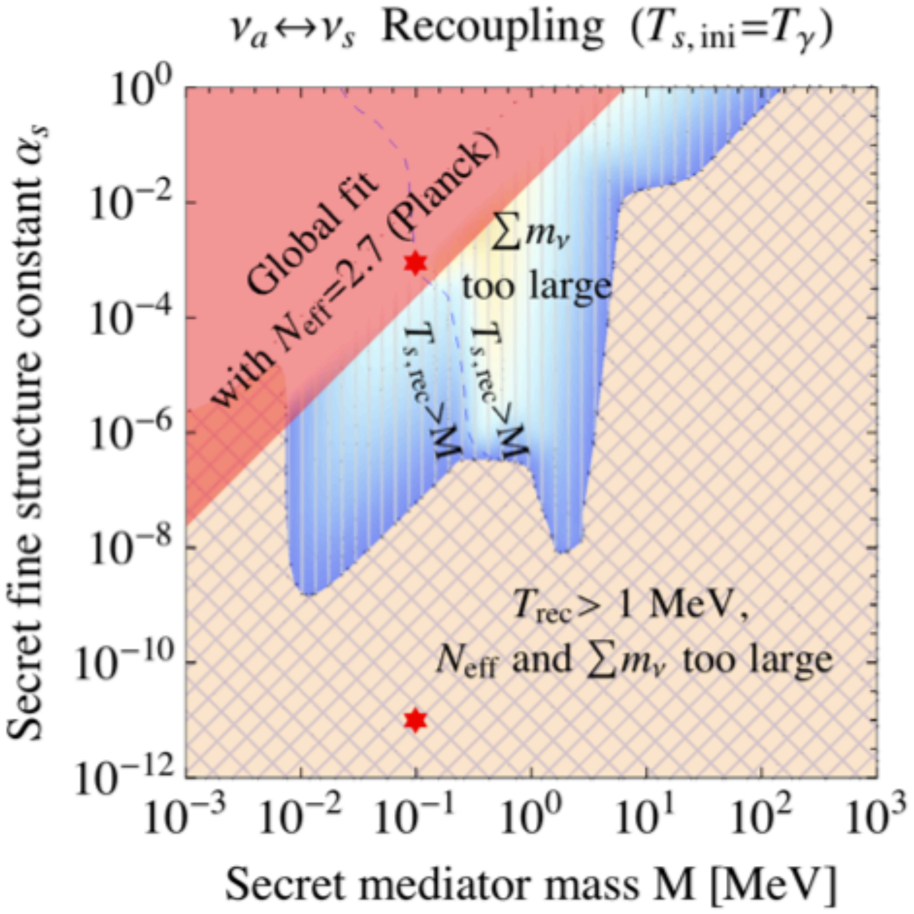
$$\sin^2 2\theta_m = \frac{\sin^2 2\theta_0}{\left(\cos^2 2\theta_0 + \frac{2E}{\Delta m^2} V_m\right) + \sin^2 2\theta_0}$$

Vacuum mixing

Large

Keeps N_{eff} at 3

Chu et al. https://arxiv.org/pdf/1806.10629.pdf



Dasgupta & Kopp 2014; Chu, Dasgupta & Kopp 2015 Saviano et al. 2014; Mirrizi et al. 2015;
Cherry, Friedland & Shoemaker 2016; Chu et al. 2018
See talk by Yvonne Y. Y. Wong at Neutrino 2020 for summary