Sterile Neutrino Decay Phenomenology

Sterile Neutrino Search at Underground mini-workshop
IBS, Seoul, Korea

Carlos Argüelles

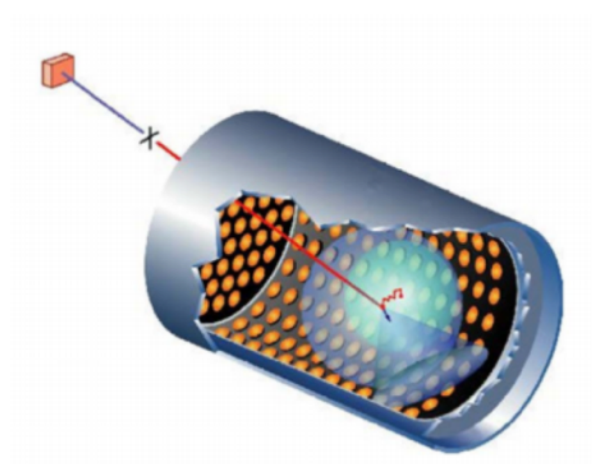
HARVARD UNIVERSITY

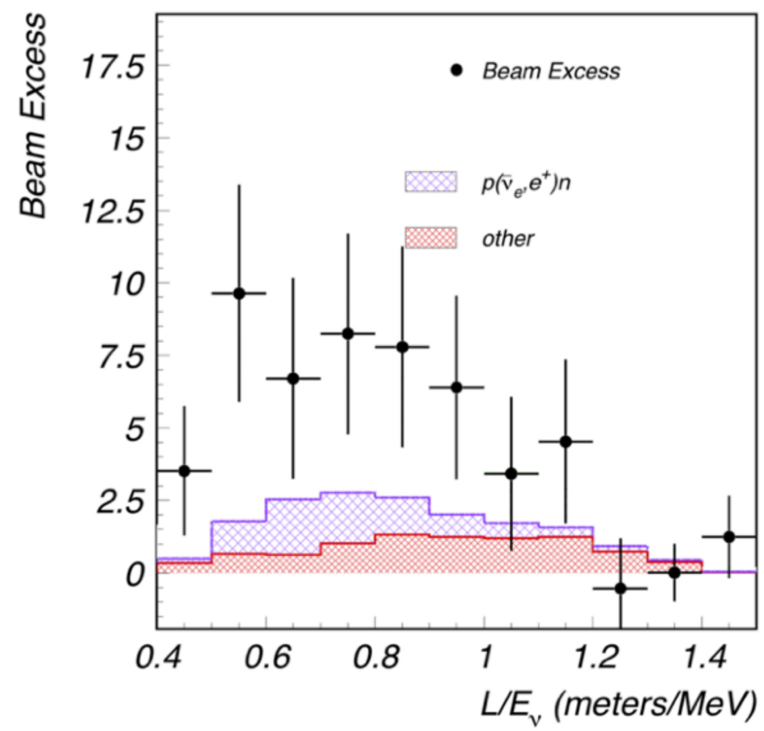
Outline

- Why going beyond 3+1?
- The garden of forking paths
- Opportunities for discovery with IsoDAR@Yemilab

The short-baseline anomalies

LSND

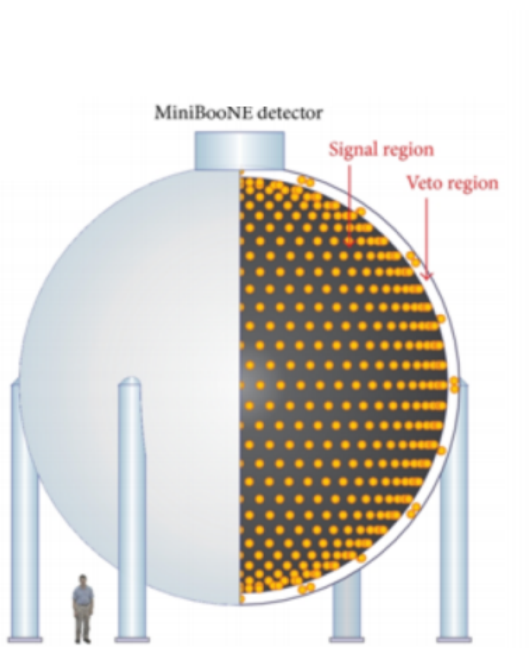


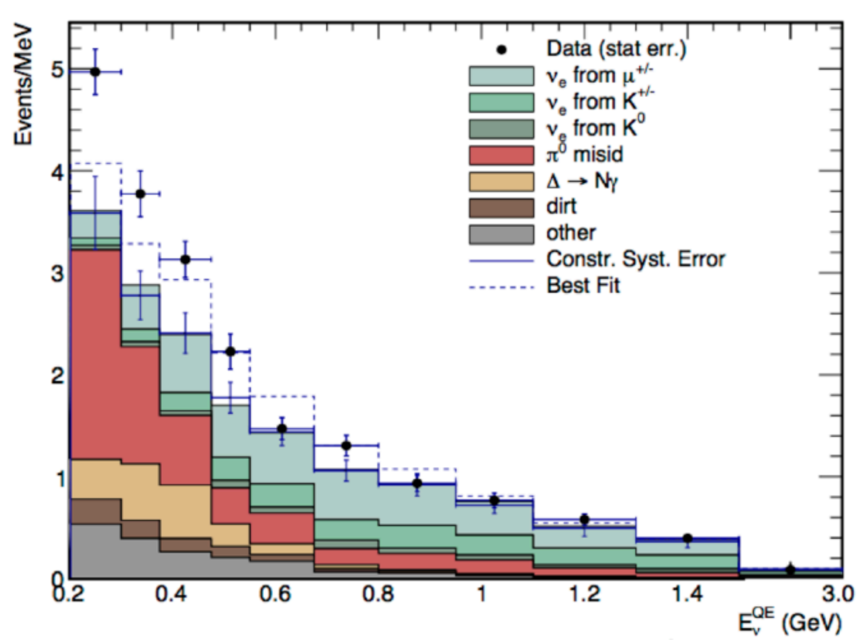


These experiments observe ν_e appearance at L/E ~ 1 km/ GeV!

This points to $\Delta m^2 \sim 1 eV^2$

MiniBooNE

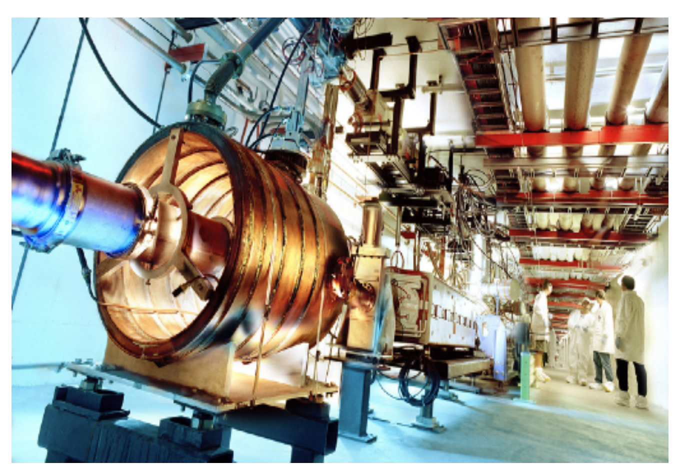


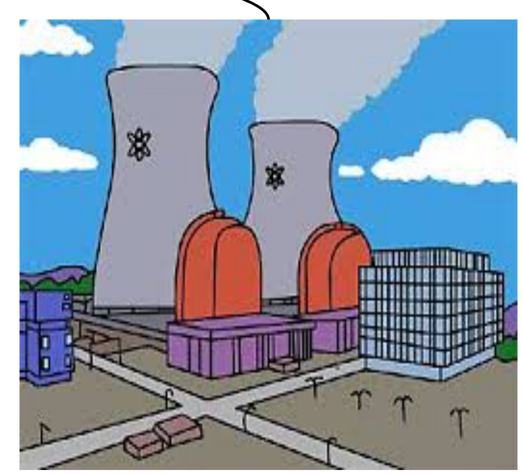


These are not alone, other interesting observations

	$\nu_\mu \to \nu_e$	$\nu_\mu \to \nu_\mu$	$\nu_e \to \nu_e$
Neutrino	MiniBooNE (BNB) * MiniBooNE(NuMI) NOMAD	SciBooNE/MiniBooNE CCFR CDHS MINOS	KARMEN/LSND Cross Section Gallium *
Antineutrino	LSND * KARMEN MiniBooNE (BNB) *	SciBooNE/MiniBooNE CCFR MINOS	Bugey NEOS DANSS * PROSPECT

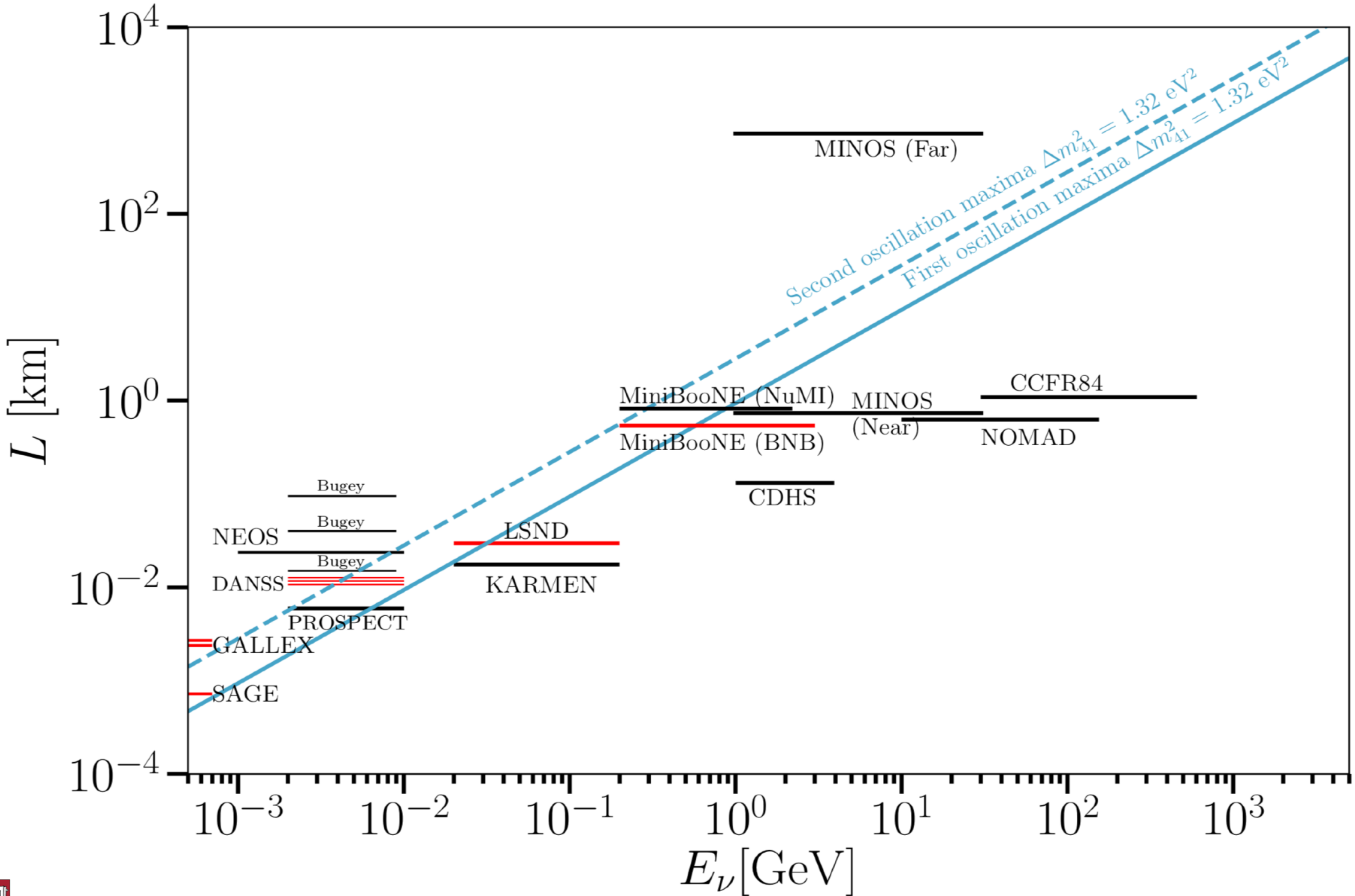
$*$ $\Longrightarrow$ >2σ "signal"





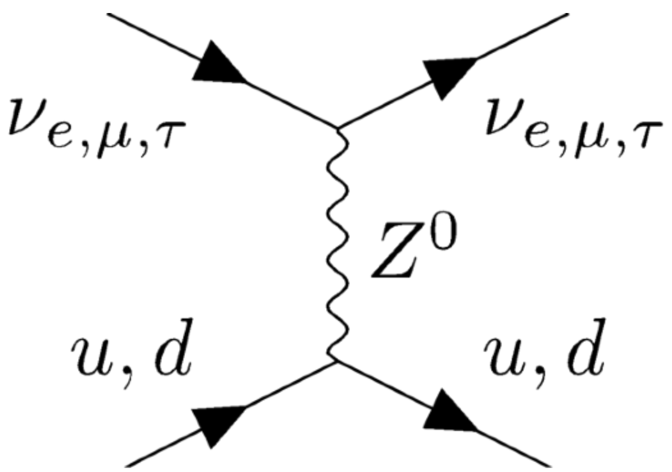
See Berryman & Huber 2021 for a recent discussion on the reactor anomalies.

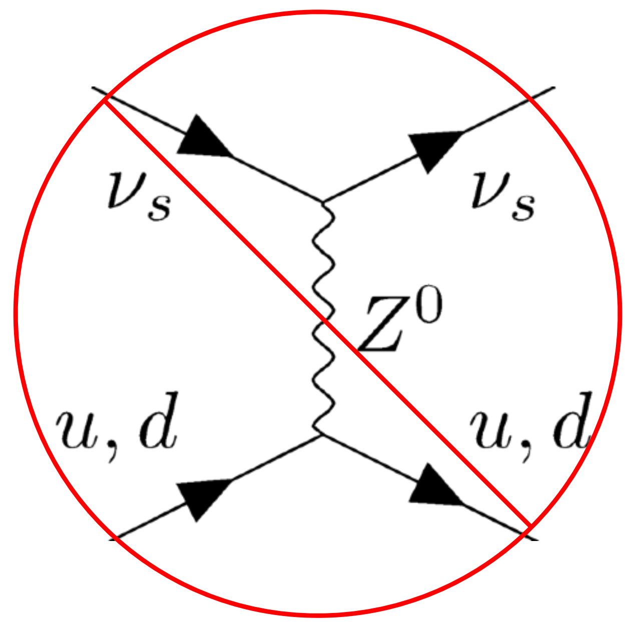
The anomalies lie ~ in a line

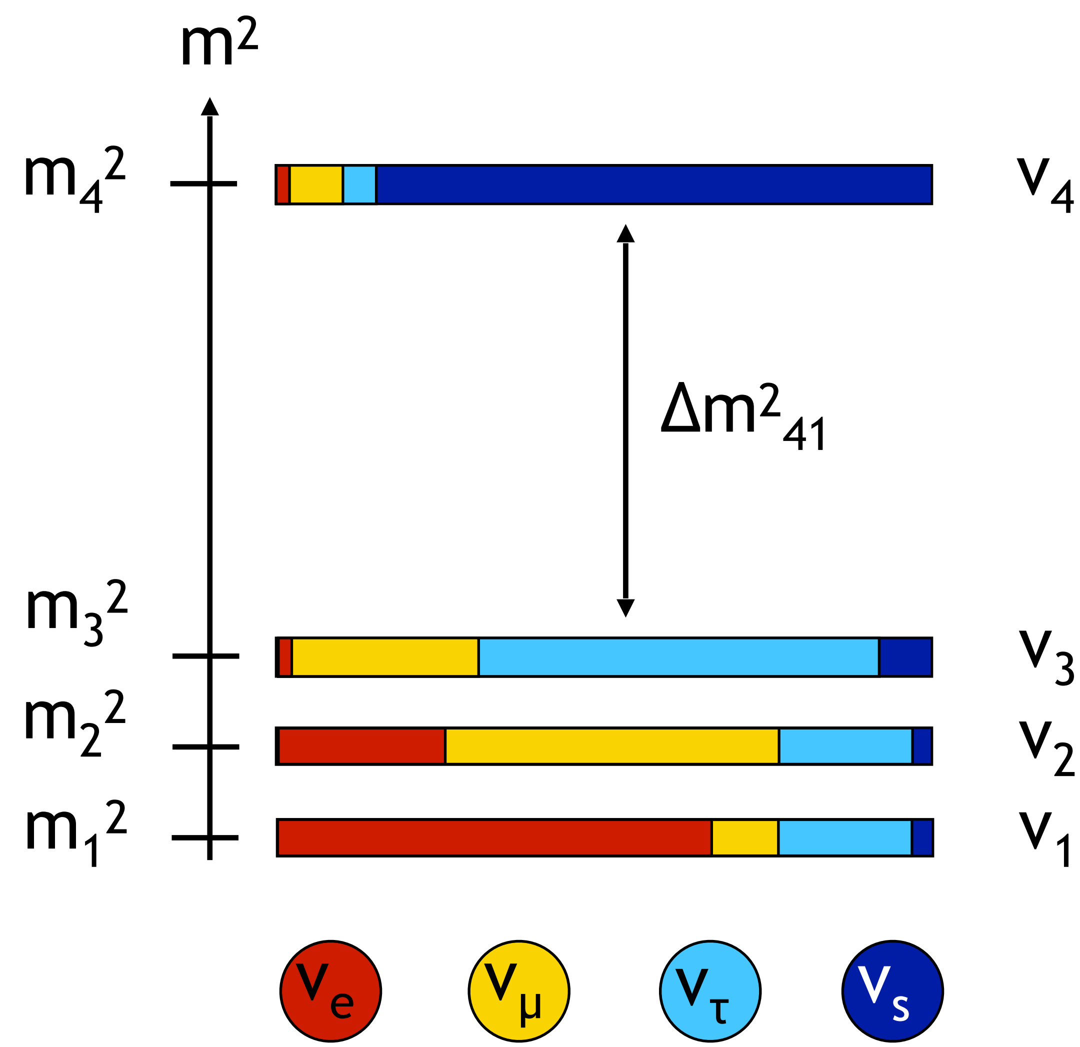


Diaz *et al.* arXiv:1906.00045

Vanilla solution: light sterile neutrino



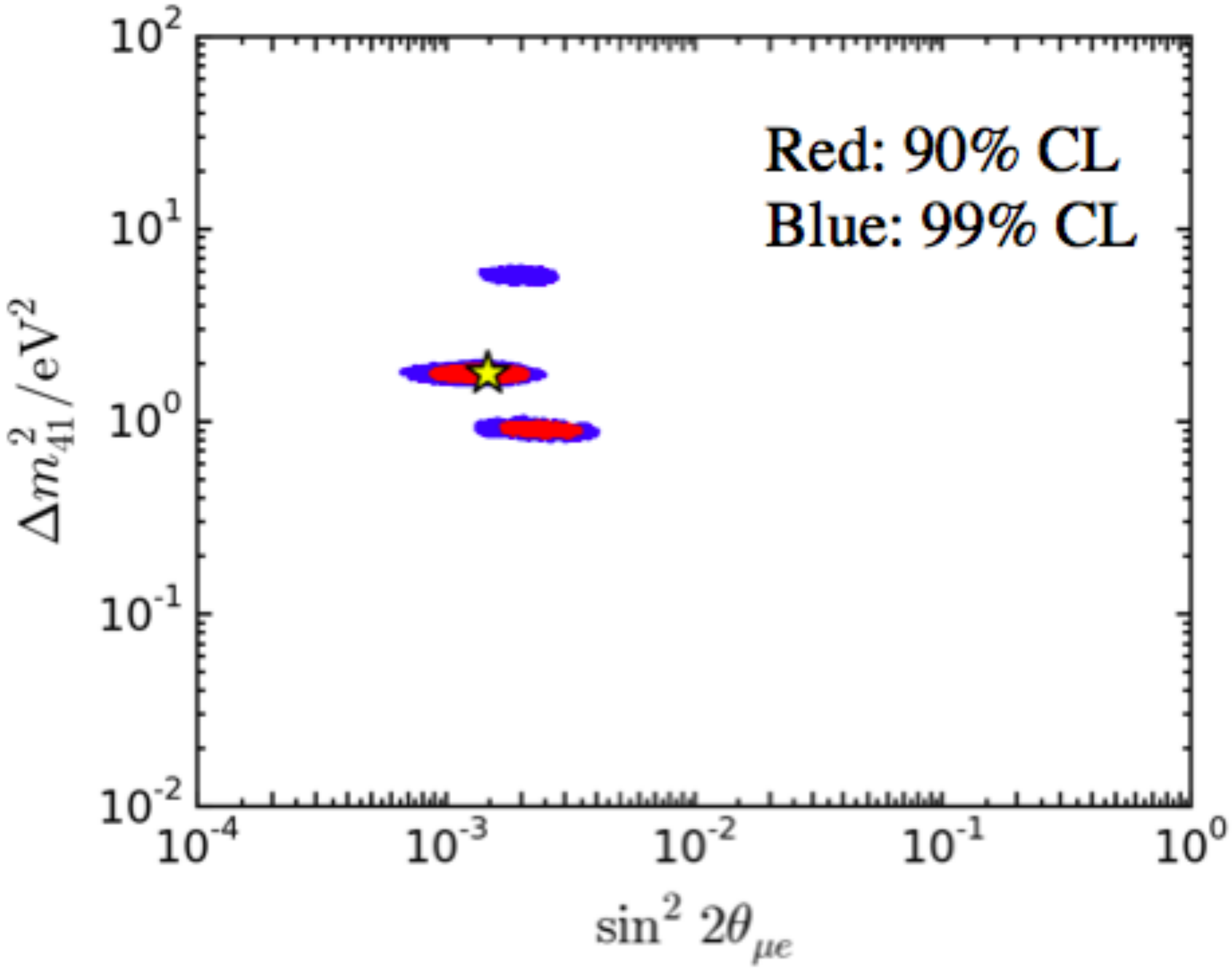




Assuming Normal Ordering

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

Global-fit solution



Best fit point:

Δm^2_{41} : $1.75\ \mathrm{eV}^2$

$\sin^2 2\theta_{\mu e}$: 1.45×10^{-3}

χ^2 : 306.81 (312 dof)

χ^2_{null} : 359.15 (315 dof)

$\Delta\chi^2$: 52.34 (3 dof)

Data strongly prefers
a model with
a sterile neutrino

Collin, CA, Conrad, and Shaevitz Nucl.Phys. B908 (2016) 354-365
arXiv:1602.00671; see also Diaz, CA, Collin, Conrad, Shaevitz arXiv:1906.00045.

Appearance and Disappearance signals should be related!

$\nu_\mu \rightarrow \nu_e$

$\nu_e \rightarrow \nu_e$

$\nu_\mu \rightarrow \nu_\mu$

U_{e4} $U_{\mu4}$ Δm^2

$$P_{\nu_e \rightarrow \nu_e} = 1 - 4(1 - |U_{e4}|^2)|U_{e4}|^2 \sin^2(1.27\Delta m_{41}^2 L/E)$$

$$P_{\nu_\mu \rightarrow \nu_e} = 4|U_{e4}|^2|U_{\mu4}|^2 \sin^2(1.27\Delta m_{41}^2 L/E)$$

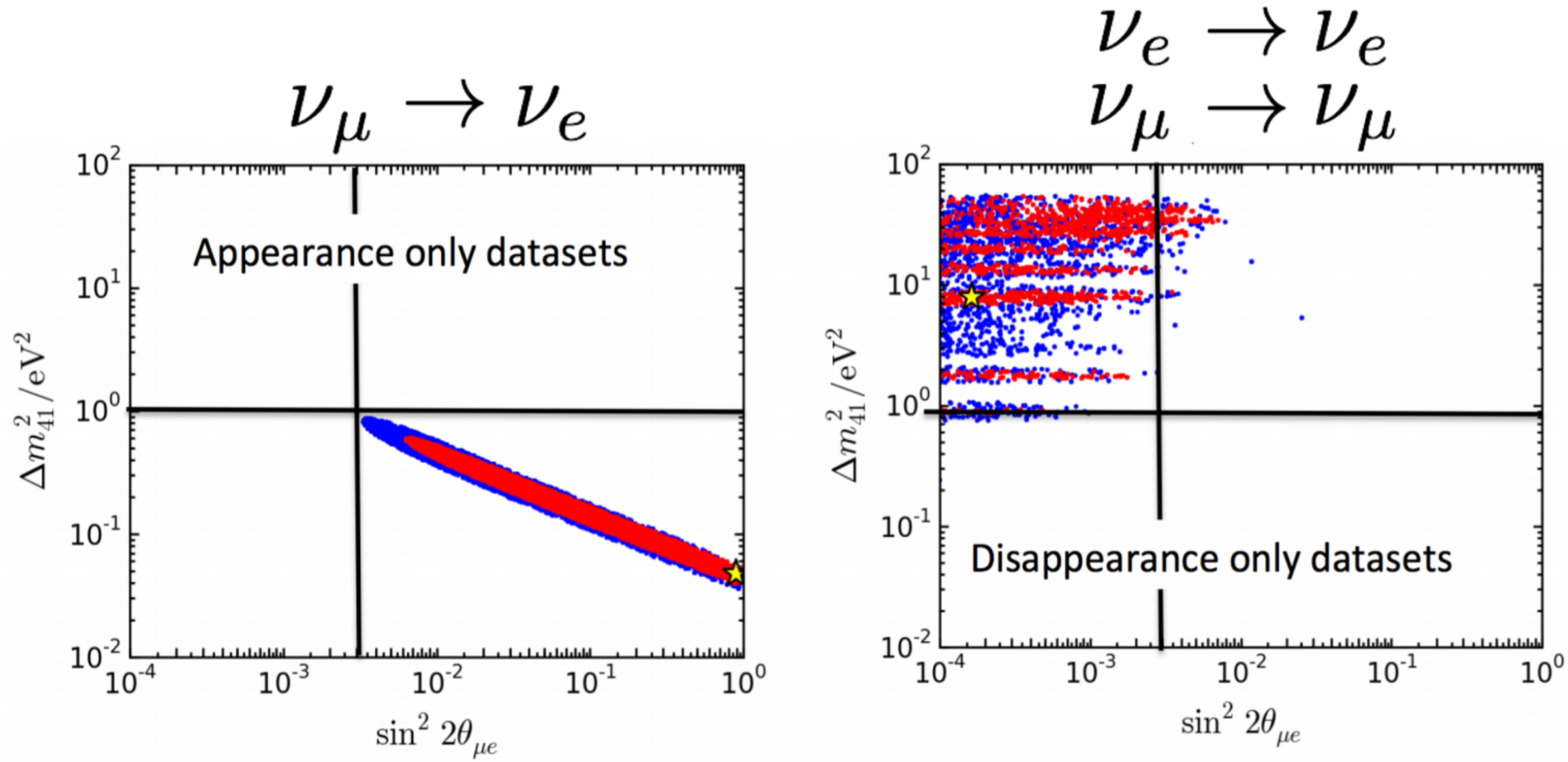
$$P_{\nu_\mu \rightarrow \nu_\mu} = 1 - 4(1 - |U_{\mu4}|^2)|U_{\mu4}|^2 \sin^2(1.27\Delta m_{41}^2 L/E)$$

$$\sin^2 2\theta_{ee} = 4(1 - |U_{e4}|^2)|U_{e4}|^2$$

$$\sin^2 2\theta_{\mu\mu} = 4(1 - |U_{\mu4}|^2)|U_{\mu4}|^2$$

$$\sin^2 2\theta_{\mu e} = 4|U_{\mu4}|^2|U_{e4}|^2$$

Appearance and disappearance “preference regions” don’t overlap!



From Collin et al. 1602.00671, 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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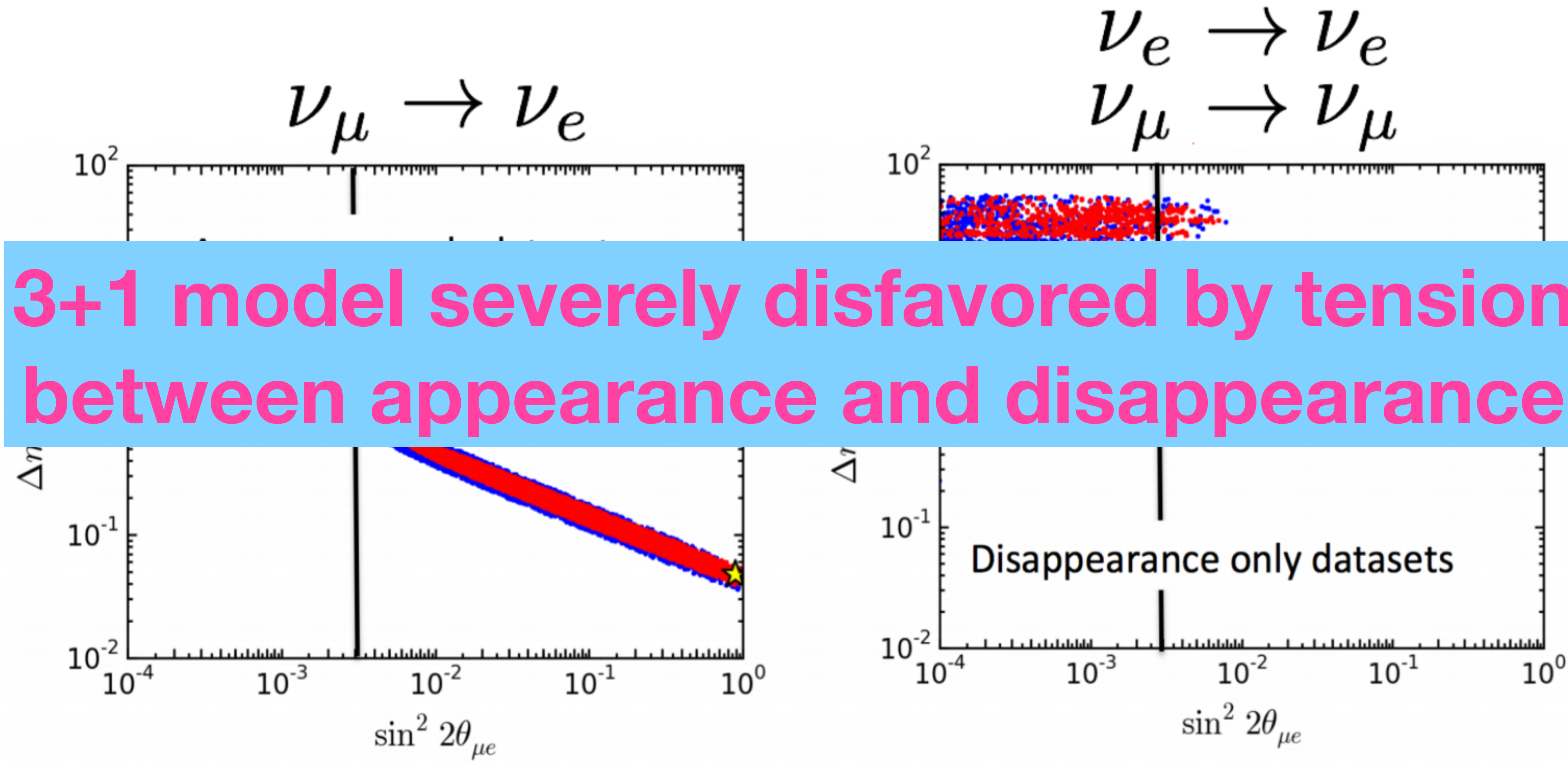
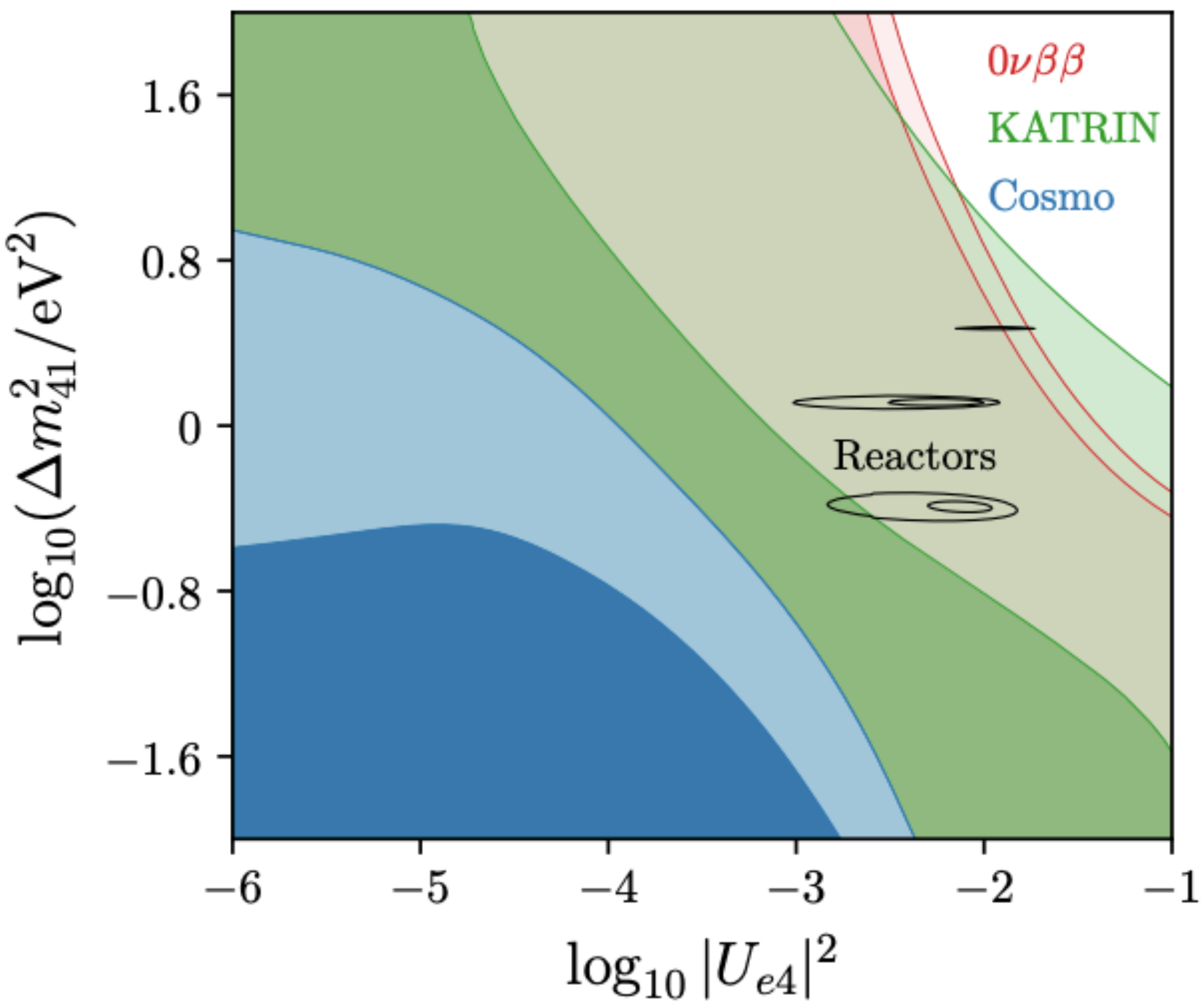


3+1 model severely disfavored by tension between appearance and disappearance

From Collin et al. 1602.00671, 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.

Let's not forget cosmology!

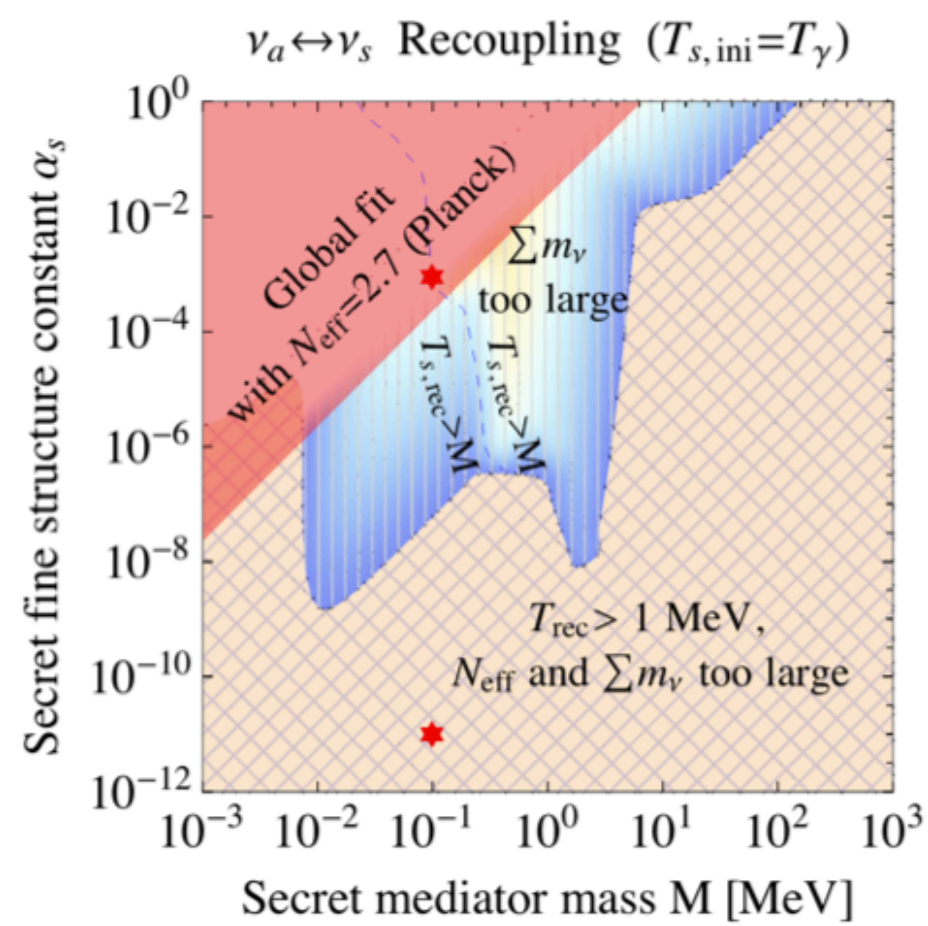
Hagztoz *et al* https://arxiv.org/pdf/2003.02289.pdf



Effective mixing → $\sin^2 2\theta_m = \dfrac{\sin^2 2\theta_0}{\left(\cos^2 2\theta_0 + \frac{2E}{\Delta m^2} V_m\right) + \sin^2 2\theta_0}$ ➡ Keeps N_{eff} at 3

Vacuum mixing ($\sin^2 2\theta_0$); Large ($\frac{2E}{\Delta m^2} V_m$)

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

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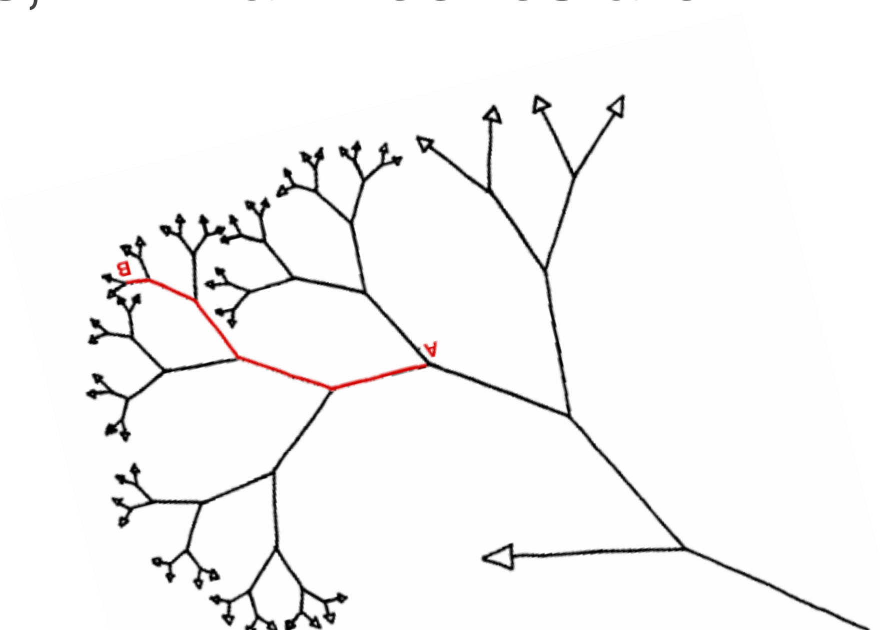
From here: The Garden of Forking Paths*

- Do we understand all SM background/process well enough?
- Are all the anomalies (MB, LSND, reactors) related? Or only some of them? E.g., are LSND and MiniBooNE observing the same physics?
- Since null results are not scrutinized as carefully as anomalous ones. Are all null results reliable?
- Is there a significant signal of electron-neutrino disappearance (e.g. reactors)?
- Is IceCube seeing hints of the missing muon-neutrino disappearance?
- If the anomalies are confirmed as new physics, in what theories are they embedded?



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

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.
- Reactor experiments using ratios see hints of oscillations at large mass-square-differences.
- 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 preference for additional radiation/secret interactions.

Indications of new neutrino oscillations

Indications of additional new physics

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IceCube Hints

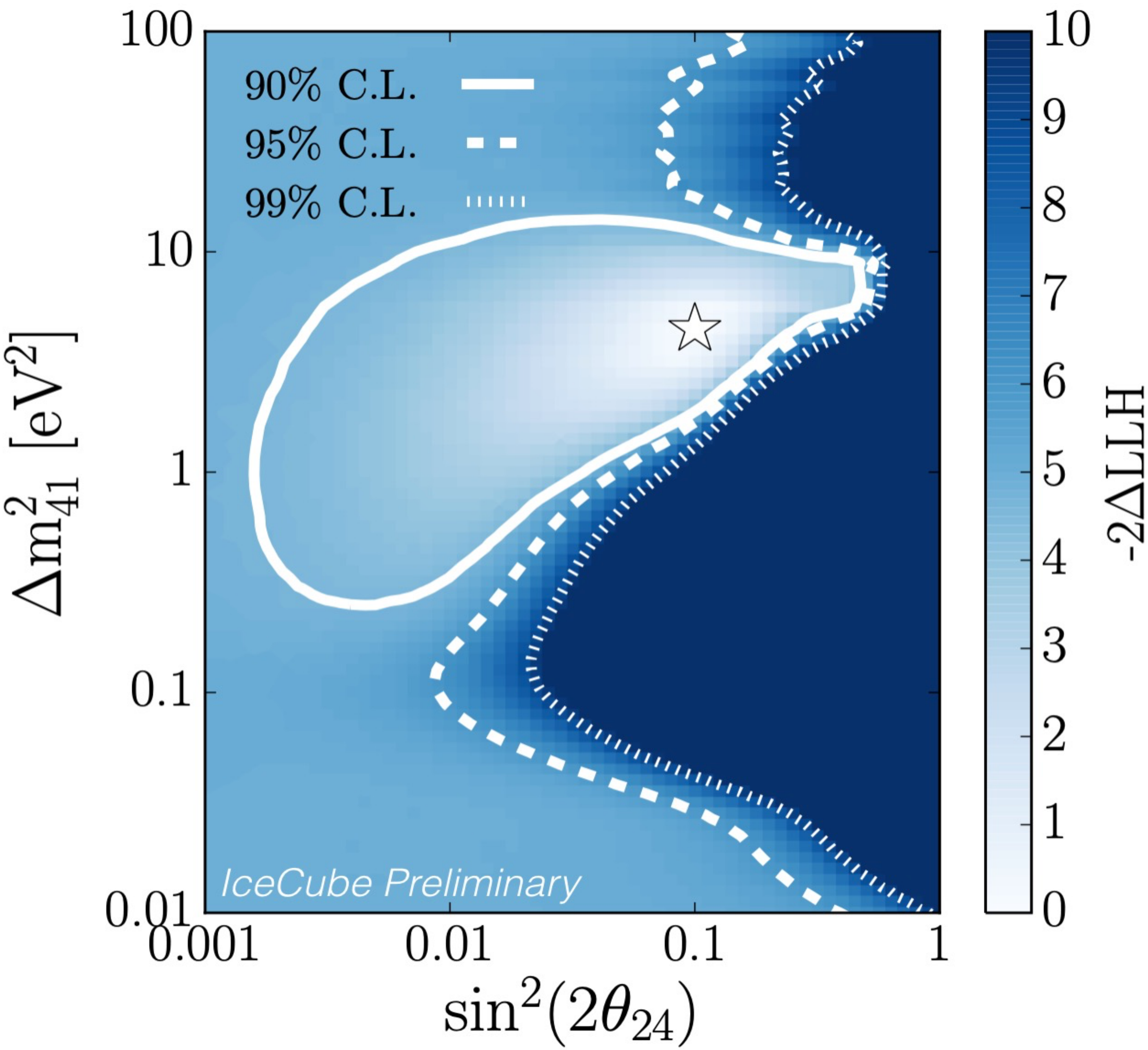
❖Best fit:

$$\Delta m^2_{41} = 4.47^{+3.53}_{-2.08} eV^2$$

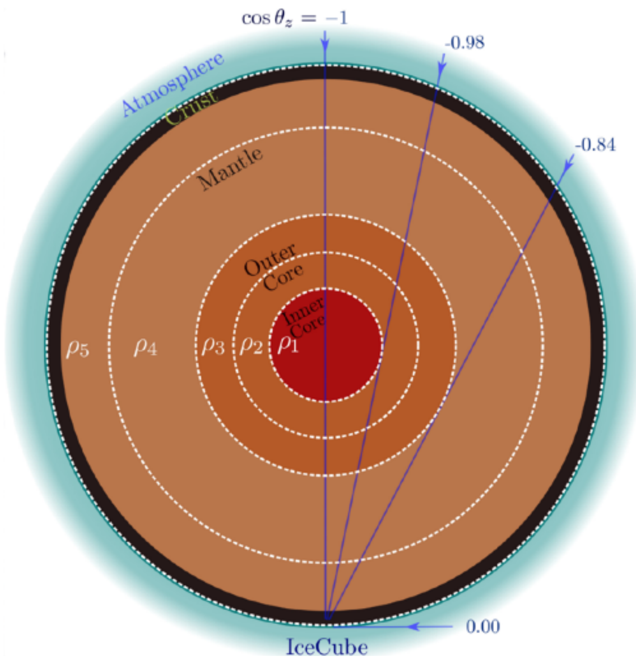
$$\sin^2(2\theta_{24}) = 0.10^{+0.10}_{-0.07}$$

❖Sterile neutrino hypothesis is preferred to null

❖Null is rejected at 8% p-value

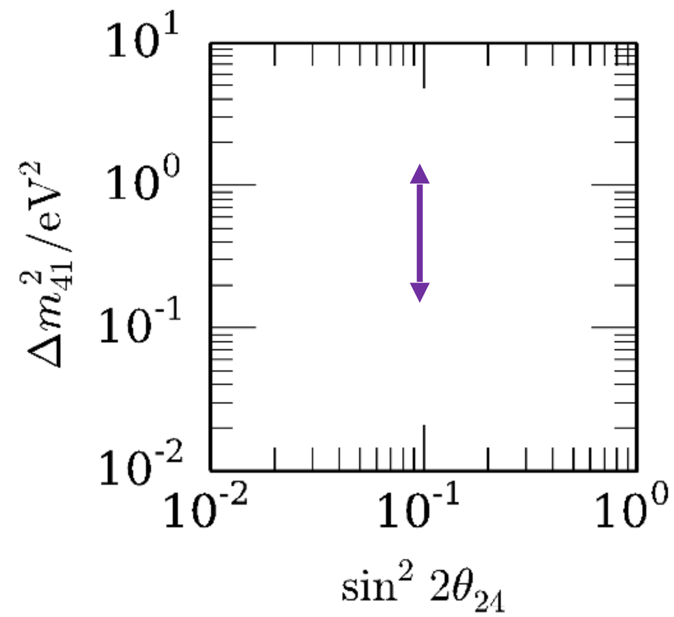


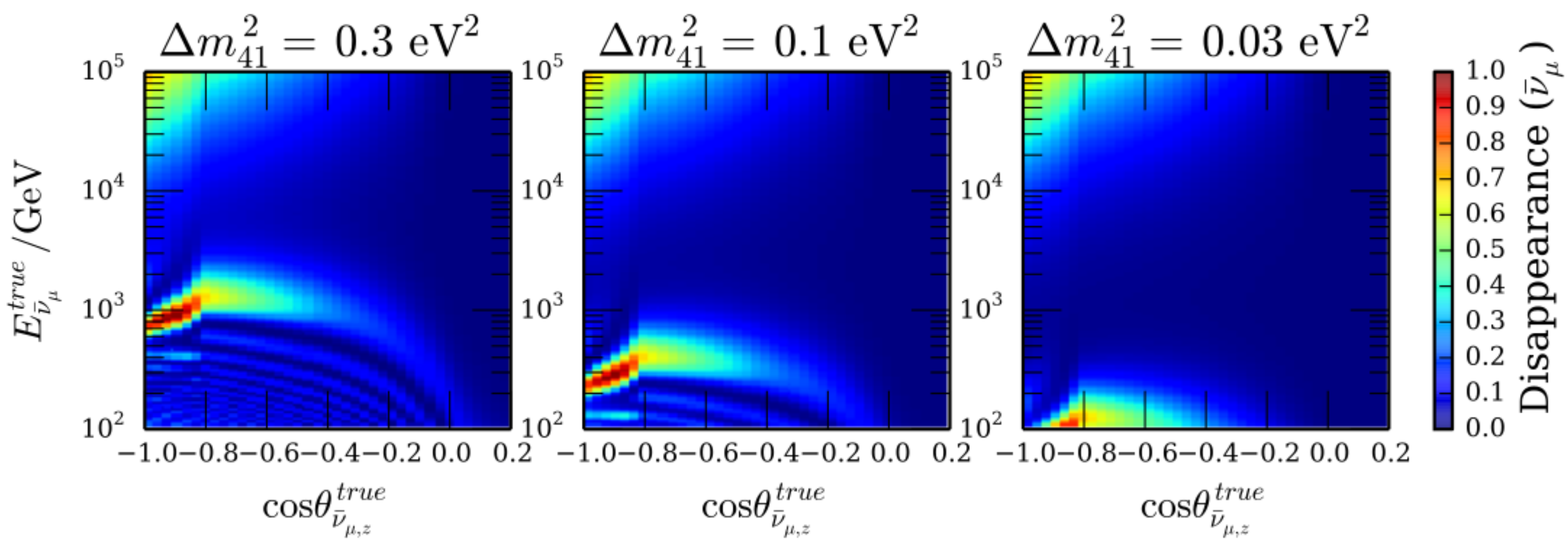
How does the IceCube analysis work?



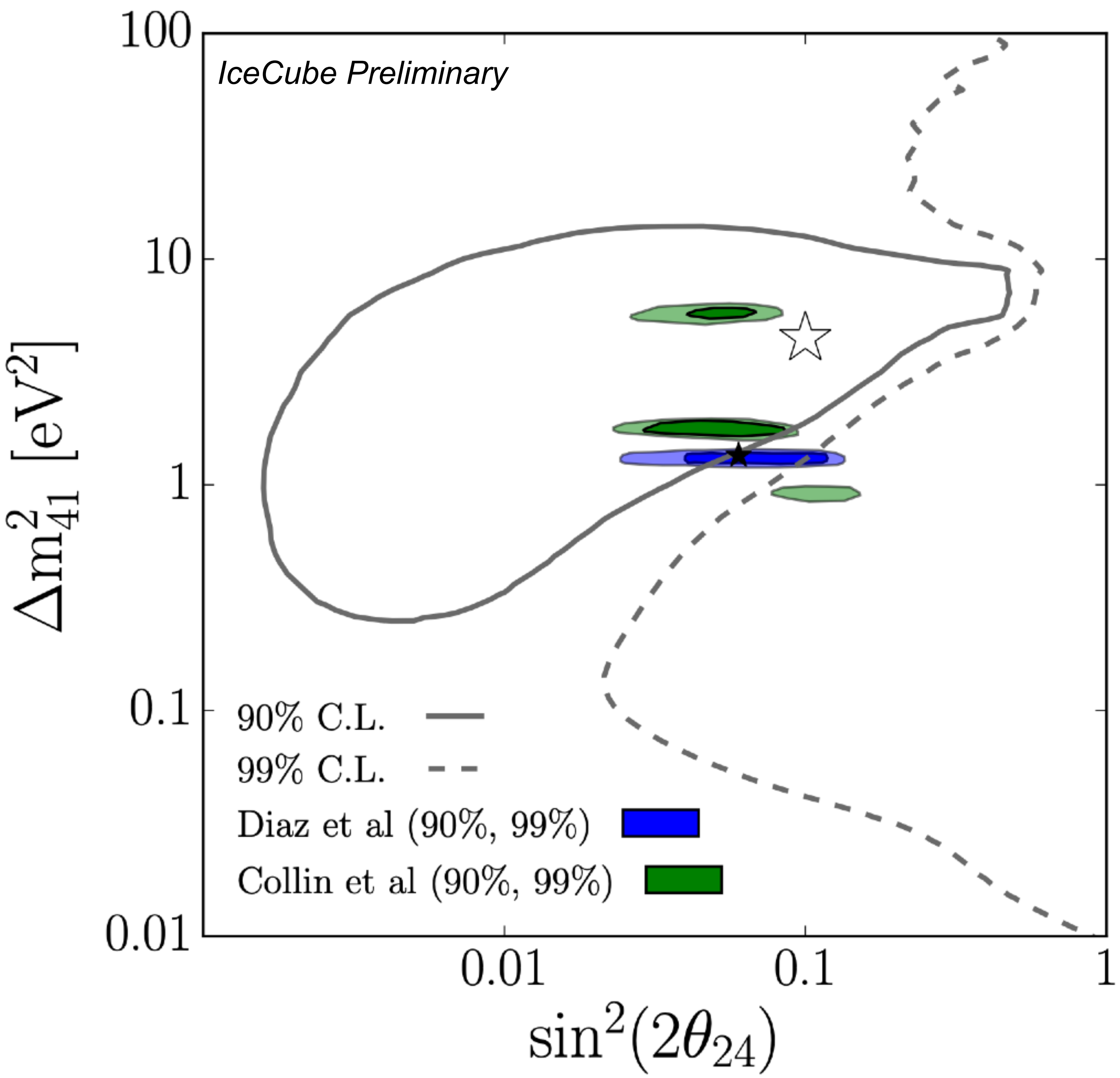
We measure two things:
- length (direction)
- energy

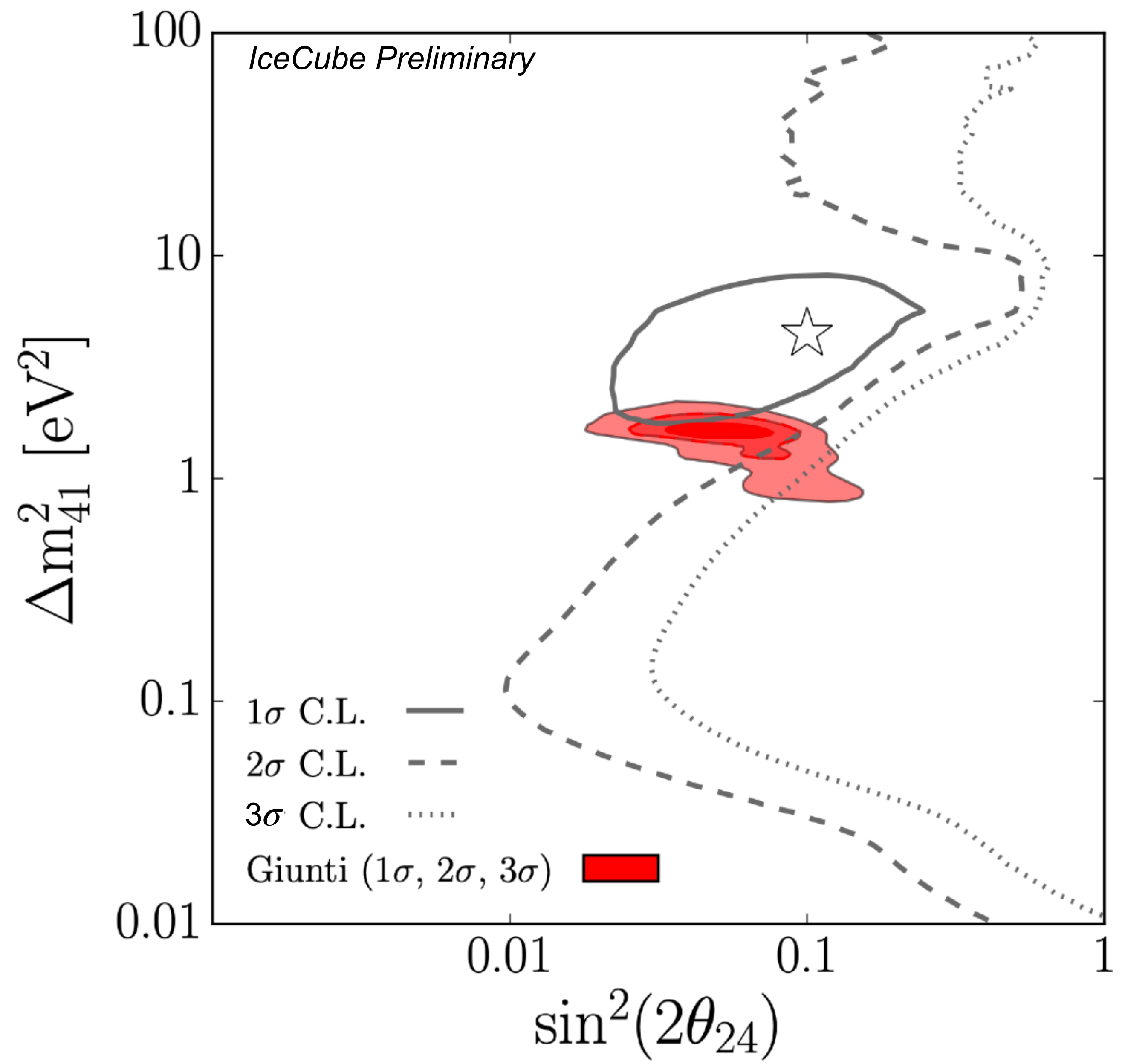
We extract two parameters:
- squared mass difference
- mixing angle





Comparison to global-fit solutions





IceCube muon-neutrino disappearance result is in a very interesting part of parameter space, but has low significance

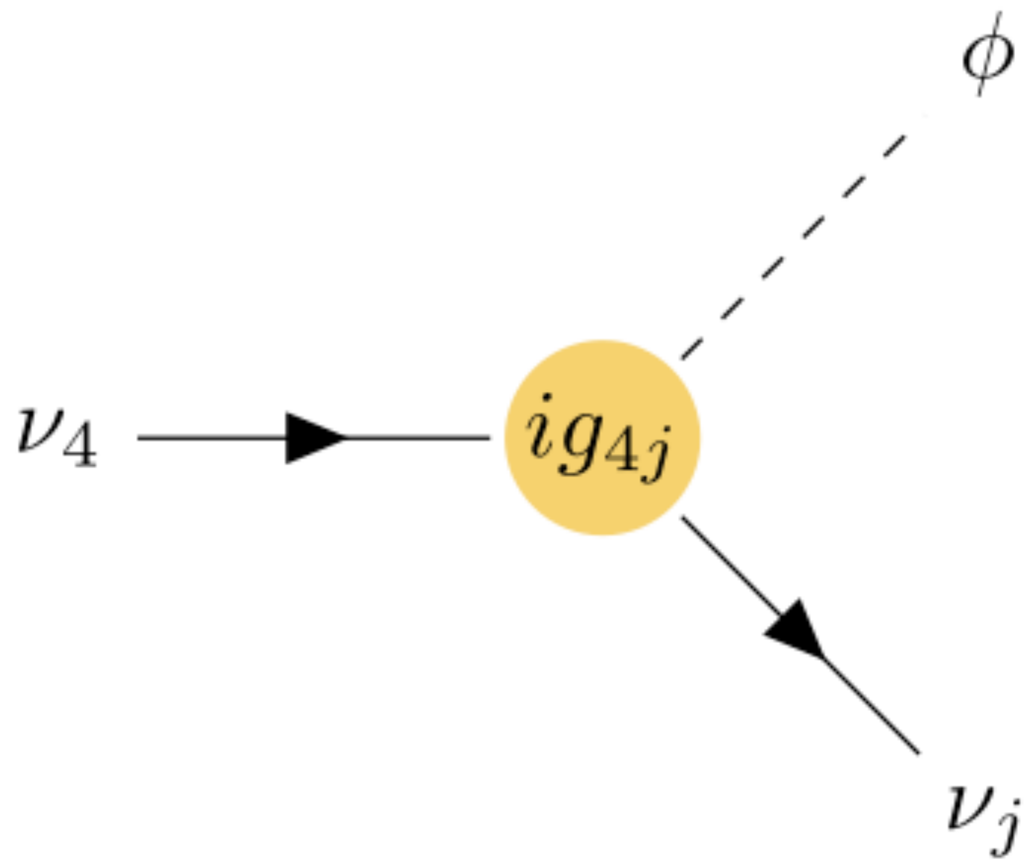
Reexamining IceCube

IceCube muon-neutrino disappearance result is in a very interesting part of parameter space, but has low significance.

Is IceCube significance low because we are not looking for the right model?

“Sterile” Neutrino Decay

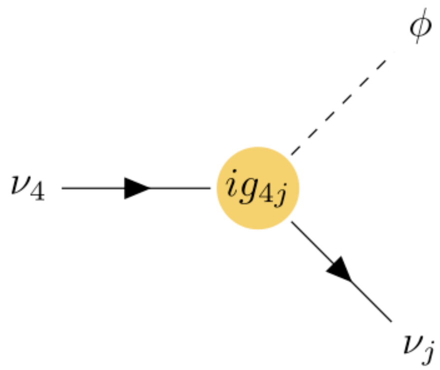
Moss et al https://arxiv.org/abs/1711.05921
Dentler *et al* https://arxiv.org/abs/1911.01427
Gouvea *et al* https://arxiv.org/abs/1911.01447



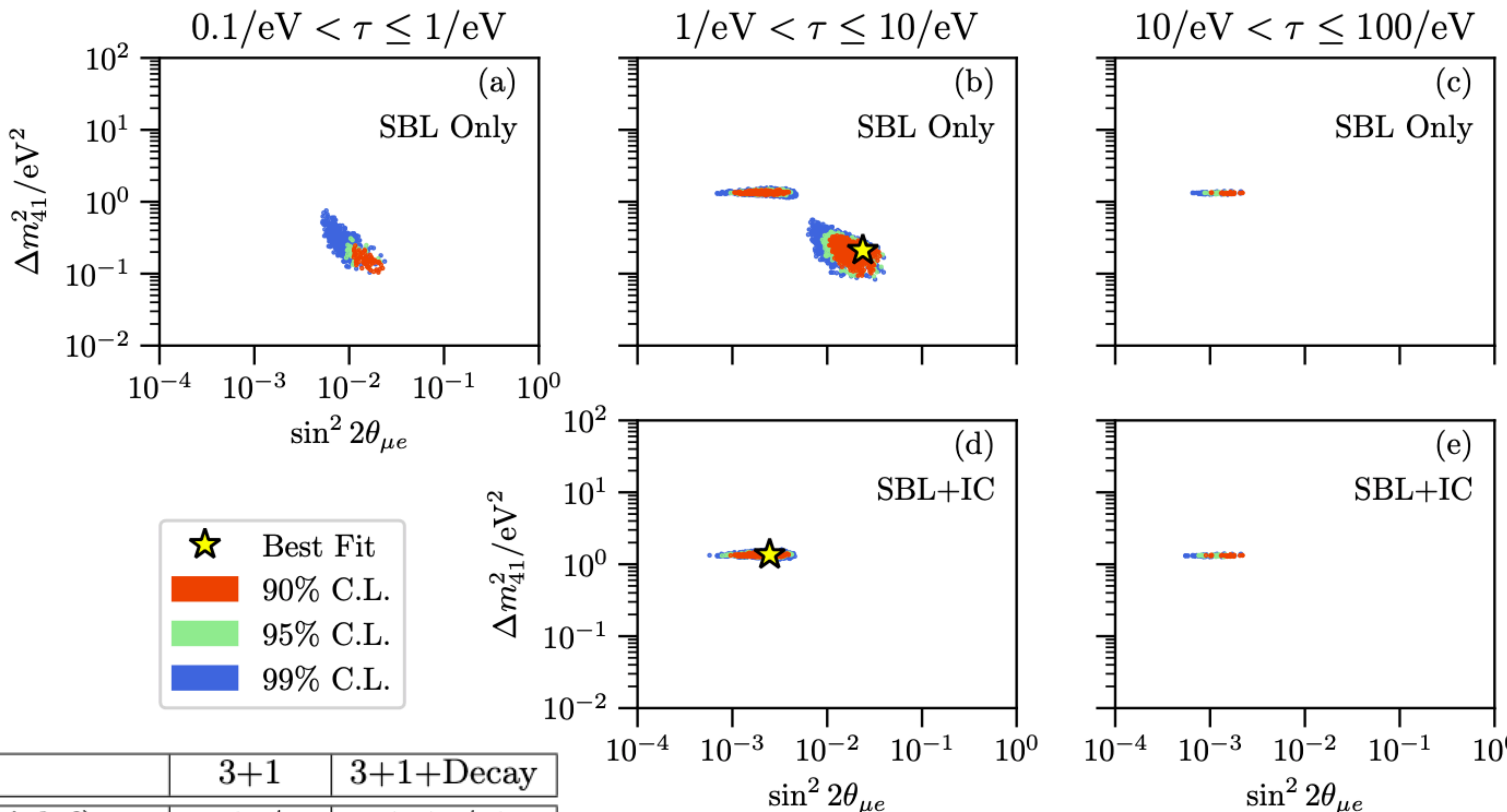
$$\tau = \frac{16\pi}{g^2 m_4}$$

Decay can be visible or invisible.

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



Sterile Neutrino Decay (3+1+Invisible-Decay)

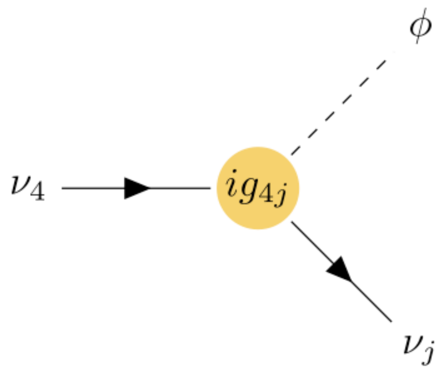


	3+1	3+1+Decay
$(\Delta\chi^2/\Delta\mathrm{dof})_{\mathrm{Null}}$	31.7 / 3	40.7 / 4
$(\Delta\chi^2/\Delta\mathrm{dof})_{3+1}$	–	9.1 / 1

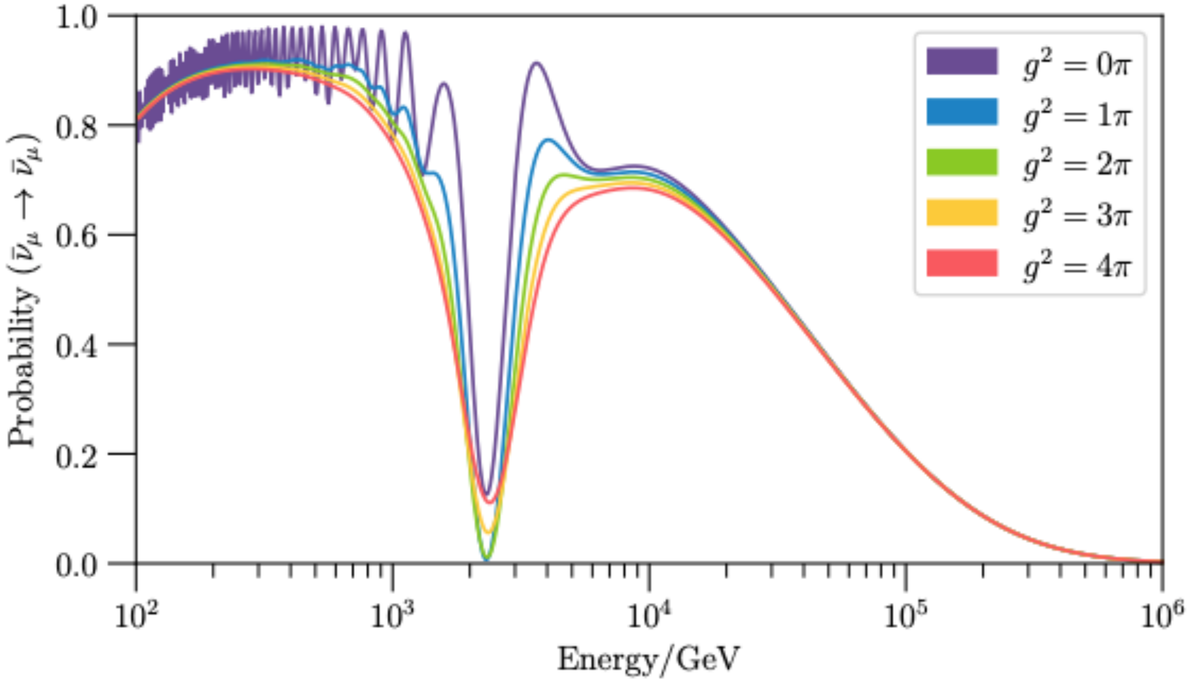
Moss et al https://arxiv.org/abs/1711.05921
Moulai et al https://arxiv.org/abs/1910.13456

See also Berryman *et al* https://arxiv.org/abs/1407.6631

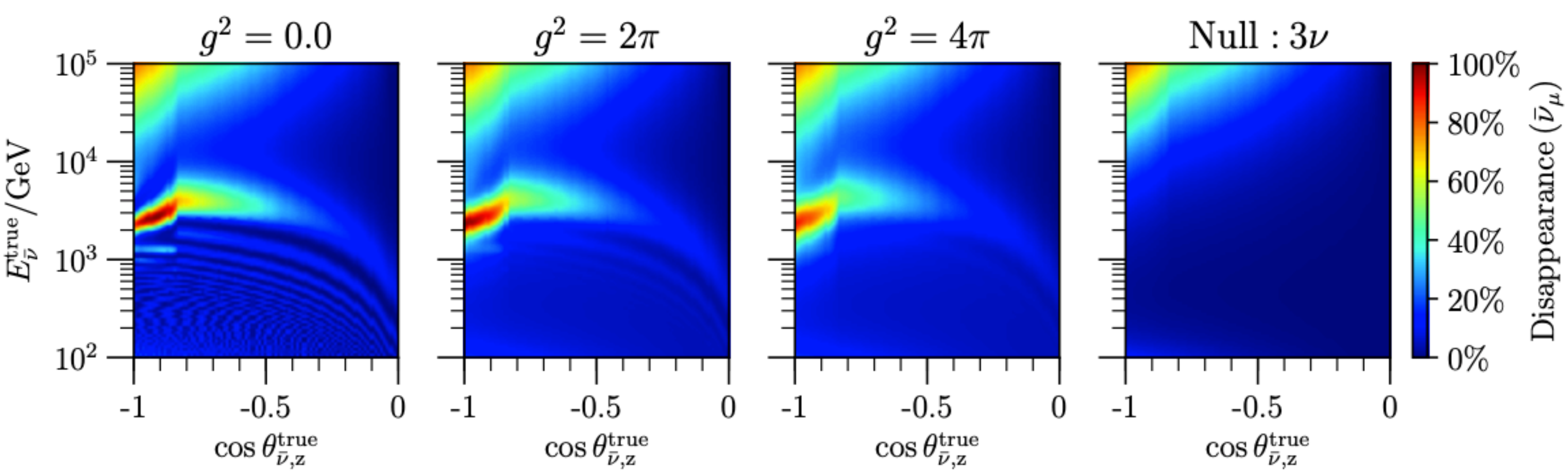
Global data prefers 3+1+Decay! Does IceCube prefer it?

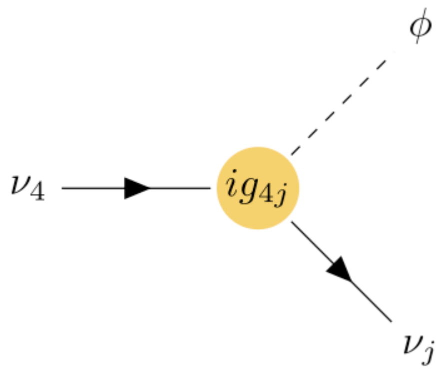


3+1+Decay In IceCube

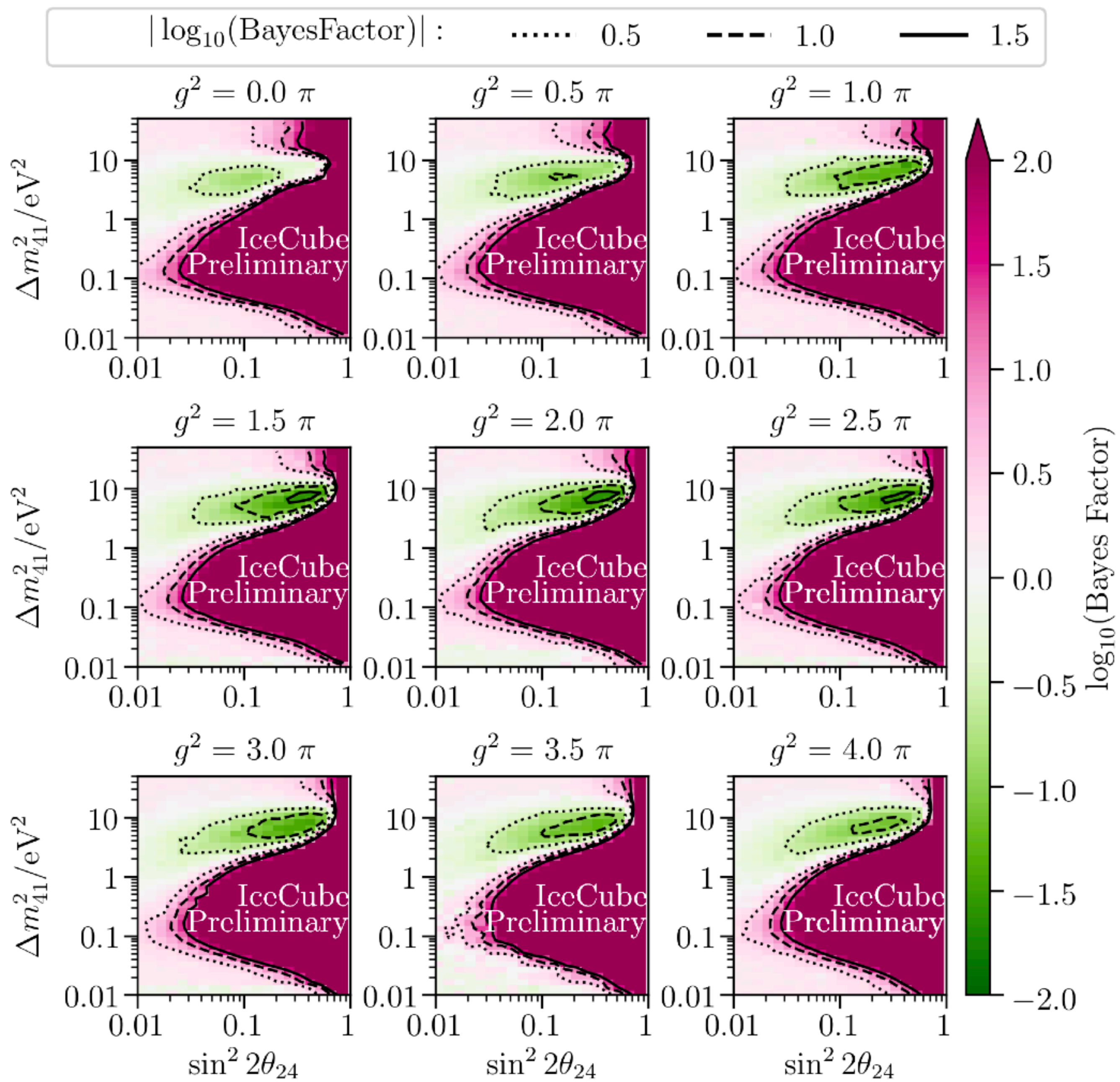


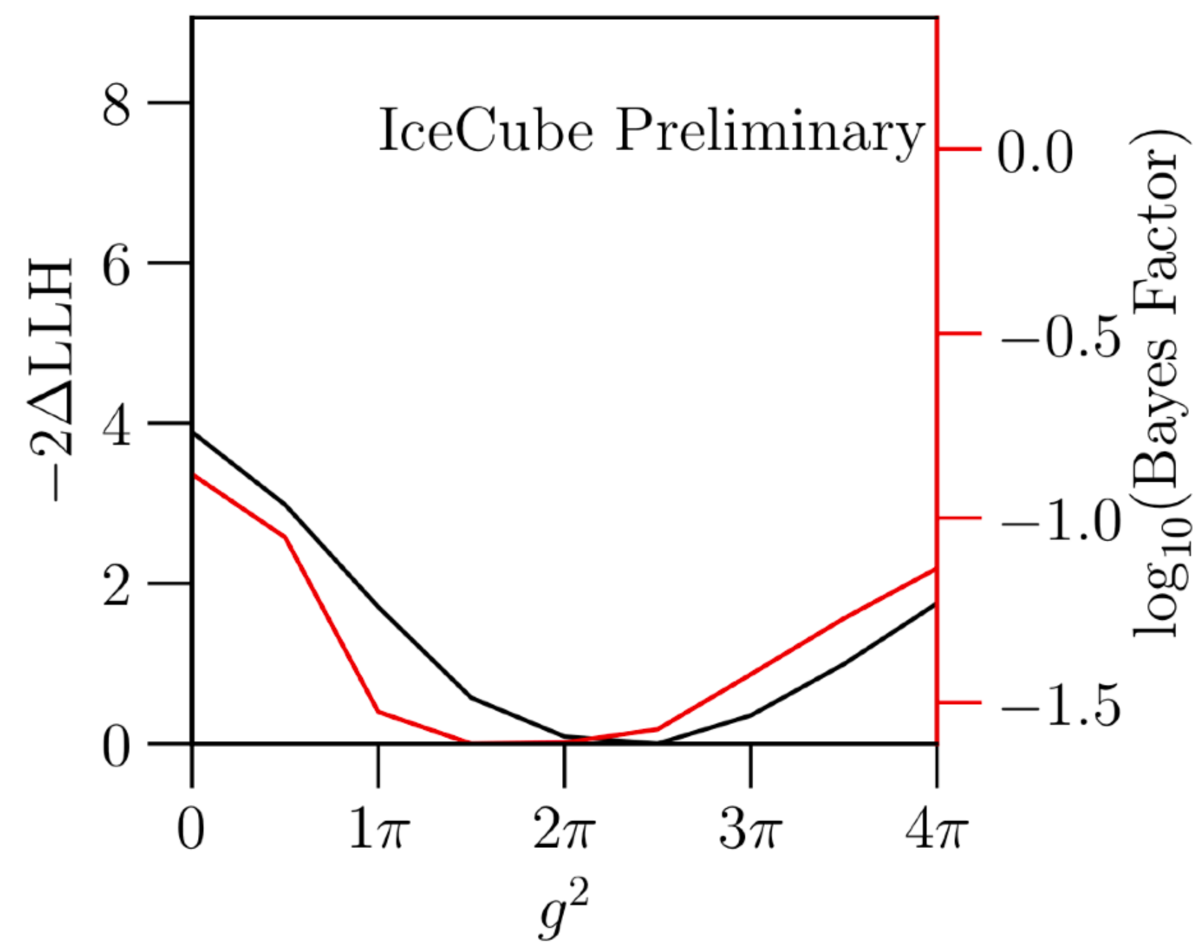
3+1+Decay model compared to 3+1 produces broader and smoother muon-neutrino disappearance.





Results of 3+1+Decay in IceCube



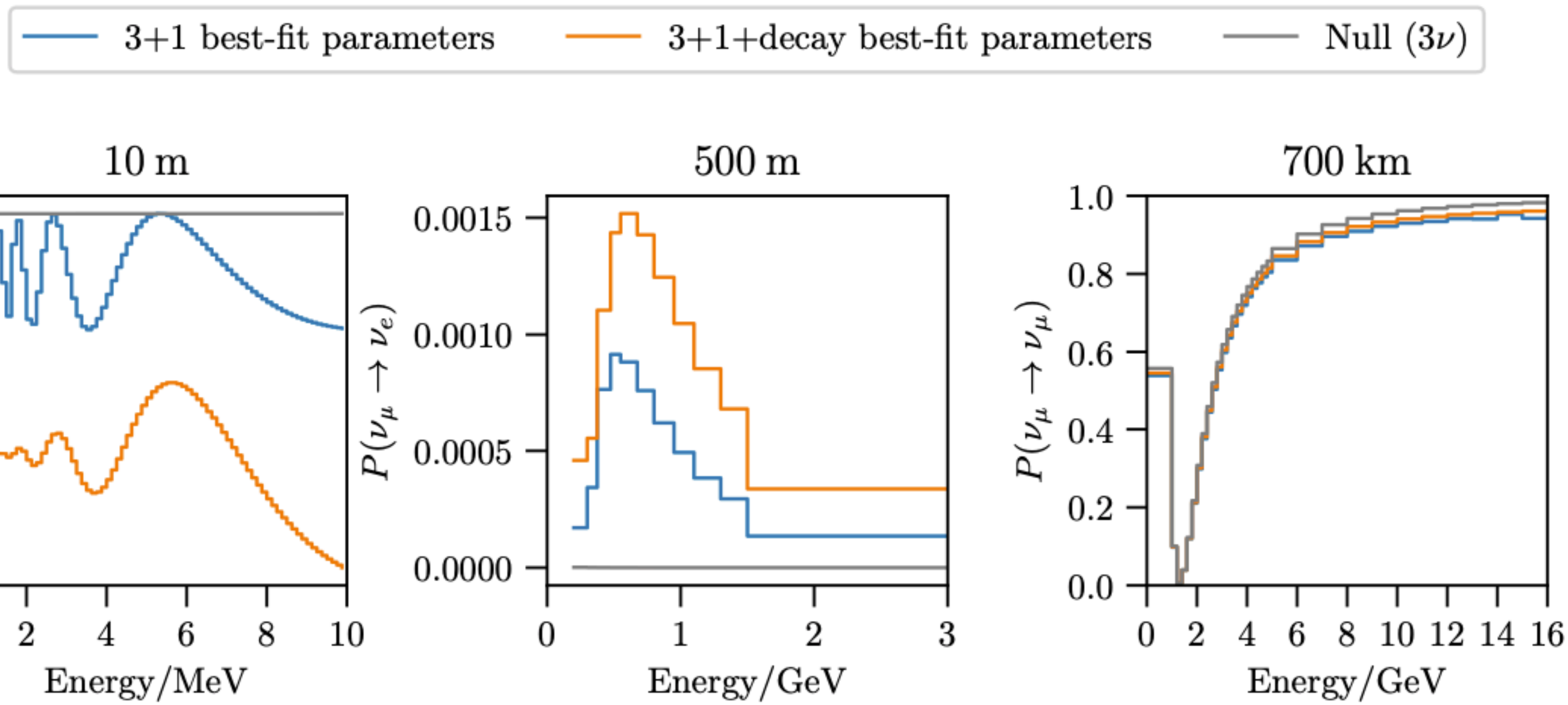


No Decay : g = 0

Does IceCube prefer it? YES!

Phenomenological implications of 3+1+Decay

Moulai et al https://arxiv.org/abs/1910.13456



Reactors | MiniBooNE | Long-baseline

- Reactor experiments experience reduced oscillations features.
- Oscillation probability at MiniBooNE slightly shifted to higher energies.

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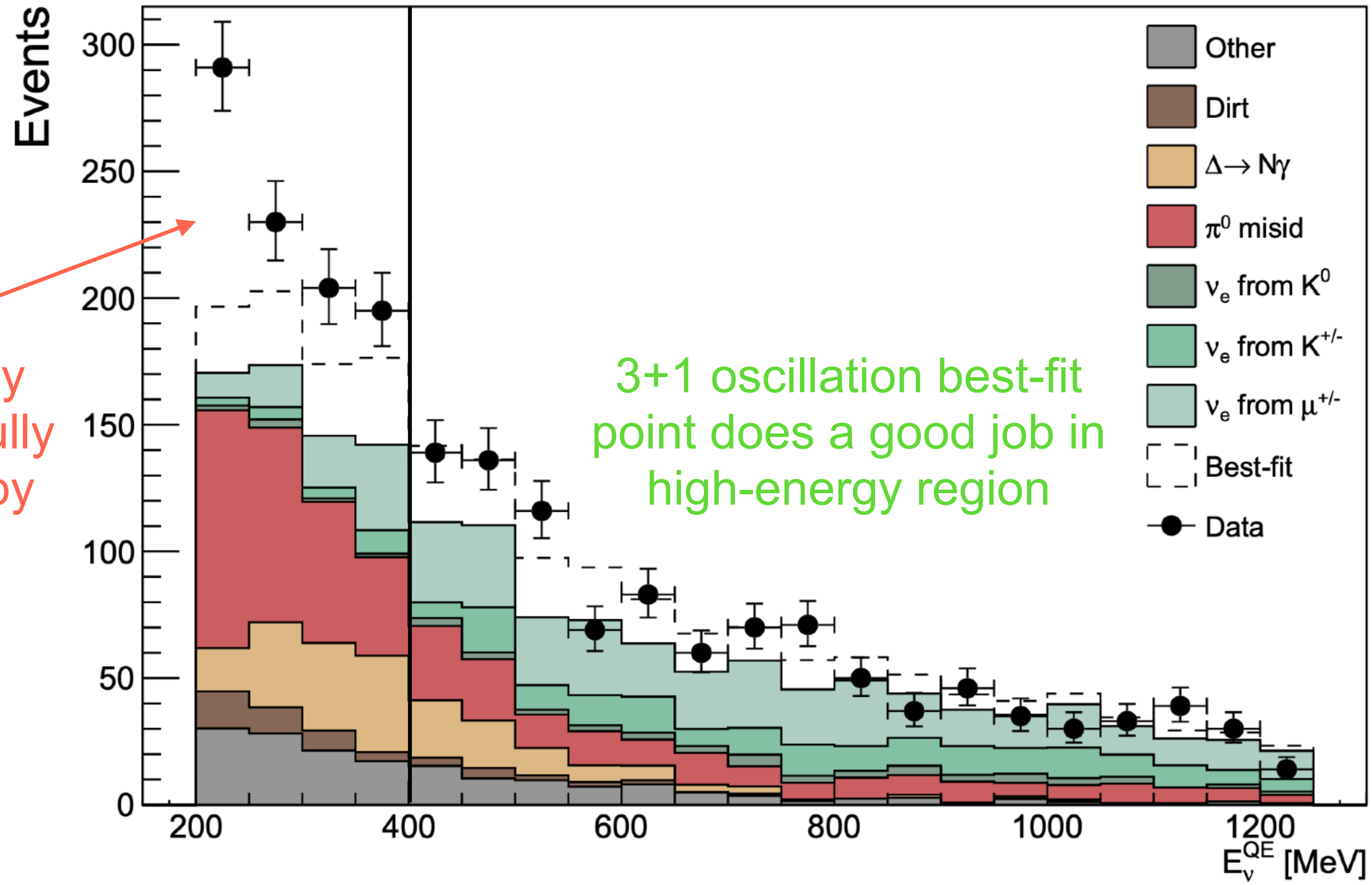
Indications of new neutrino oscillations

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.

Reexamining MiniBooNE

Low-energy part is not fully explained by 3+1



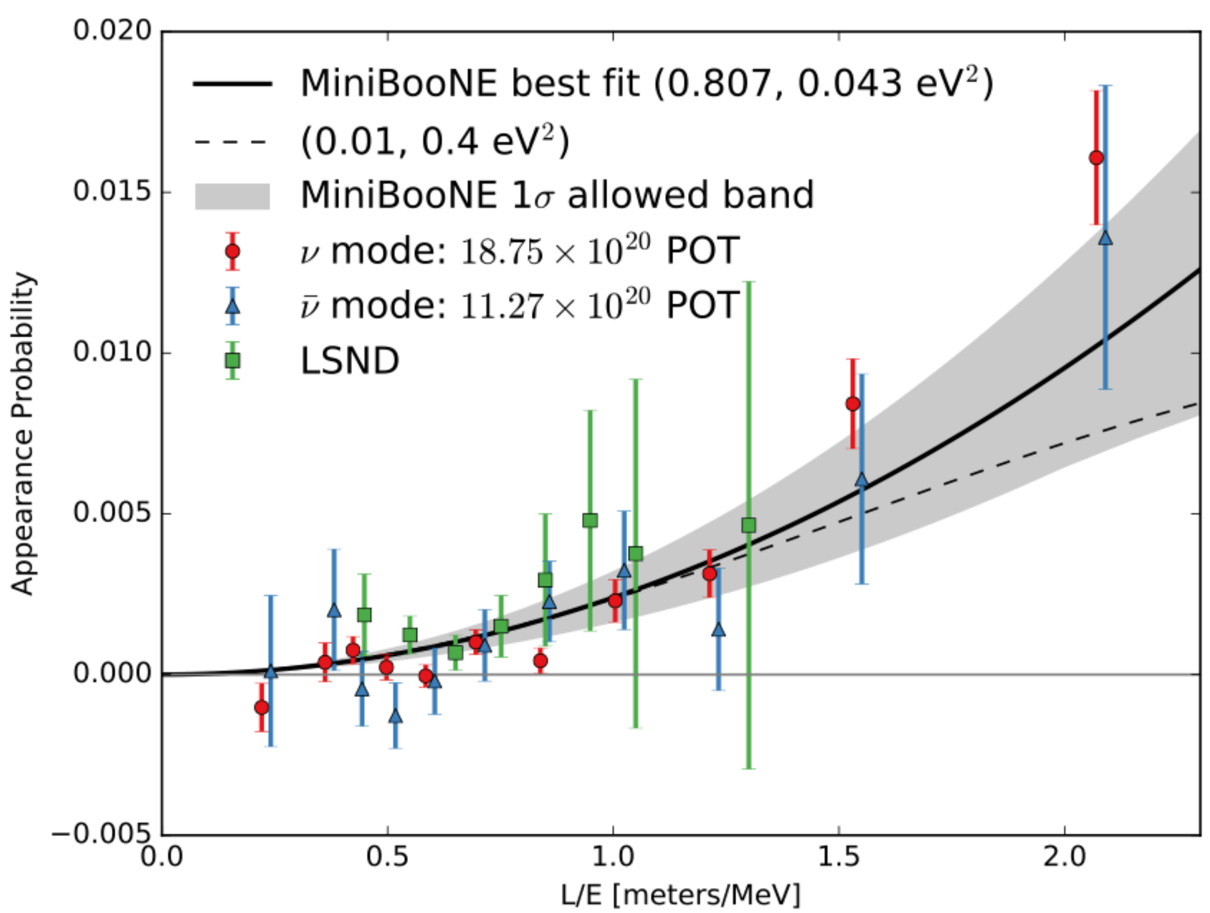
MiniBooNE Collaboration 2006.16883

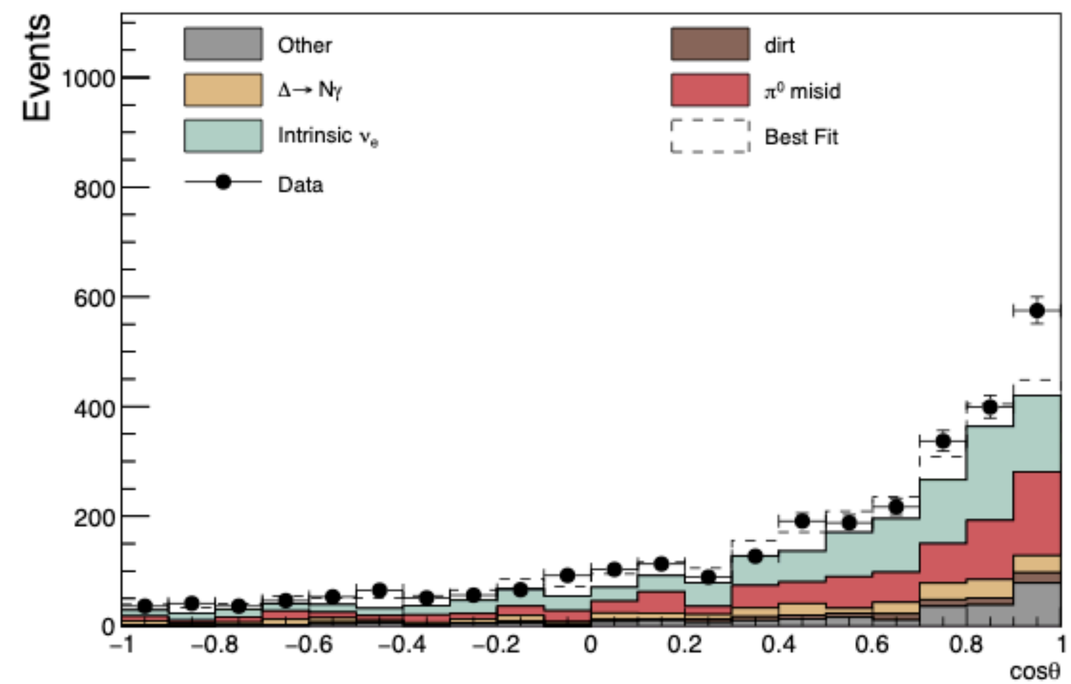
Indications of additional new physics

Indications of new neutrino oscillations

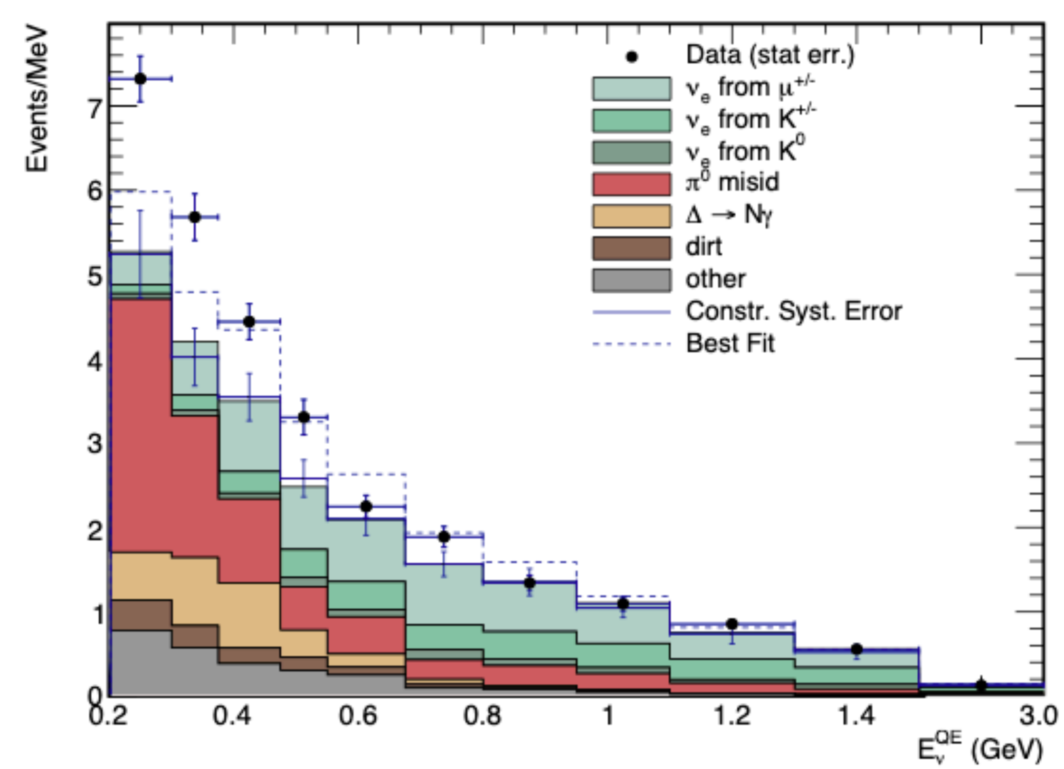
Switching gears: Changing how we look at things

This is useful if we are after an oscillation explanation





In other cases we need to fit these two!

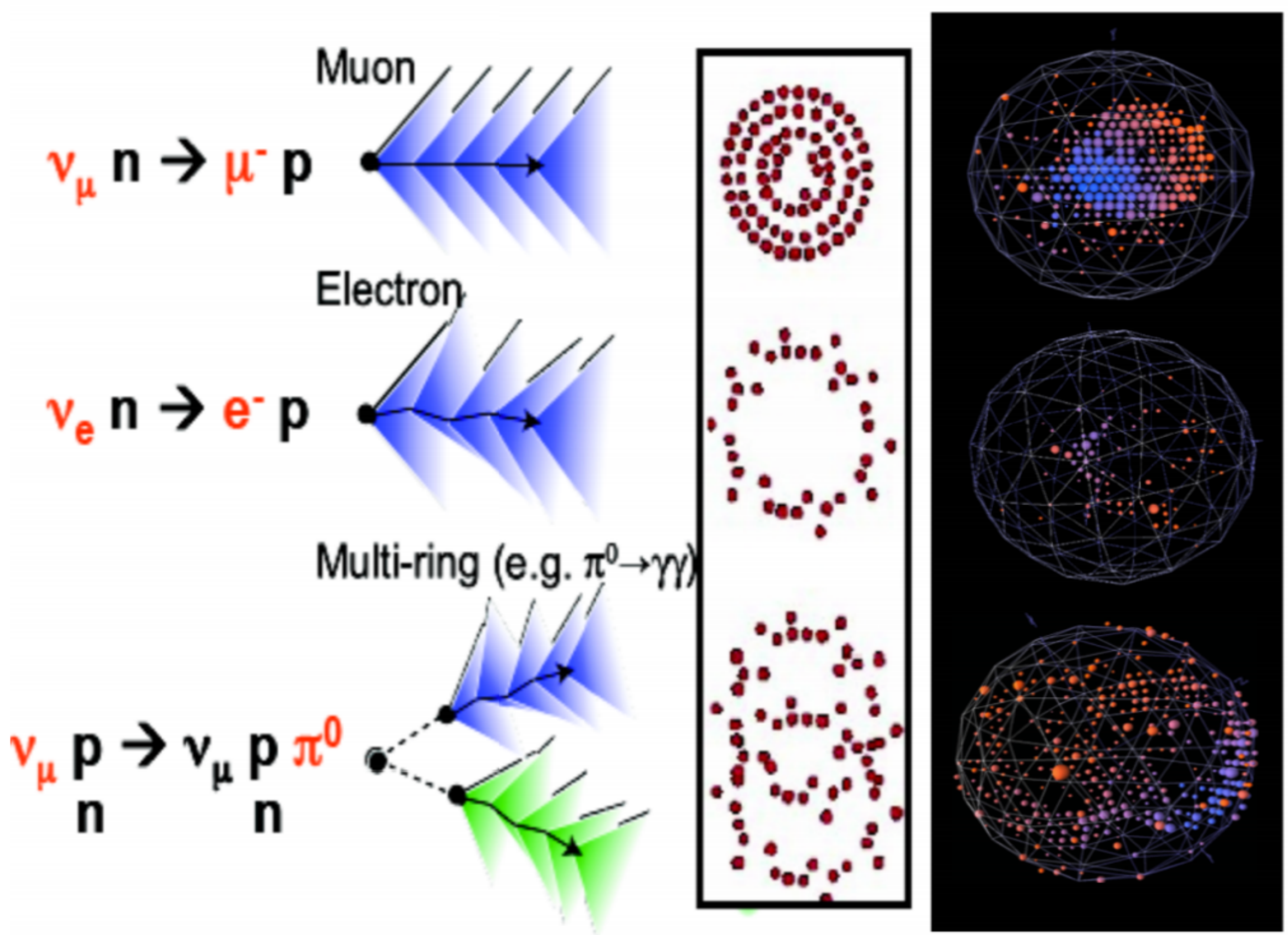


MiniBooNE Collaboration https://arxiv.org/abs/2006.16883

MiniBooNE event identification

Three typical event signatures:

- Muon-neutrino CCQE produces sharp photon ring on PMTS,
- Electron-neutrino CCQE events produces fuzzy ring,
- Muon-neutrino NC can produce pi0: two gammas -> two fuzzy rings.



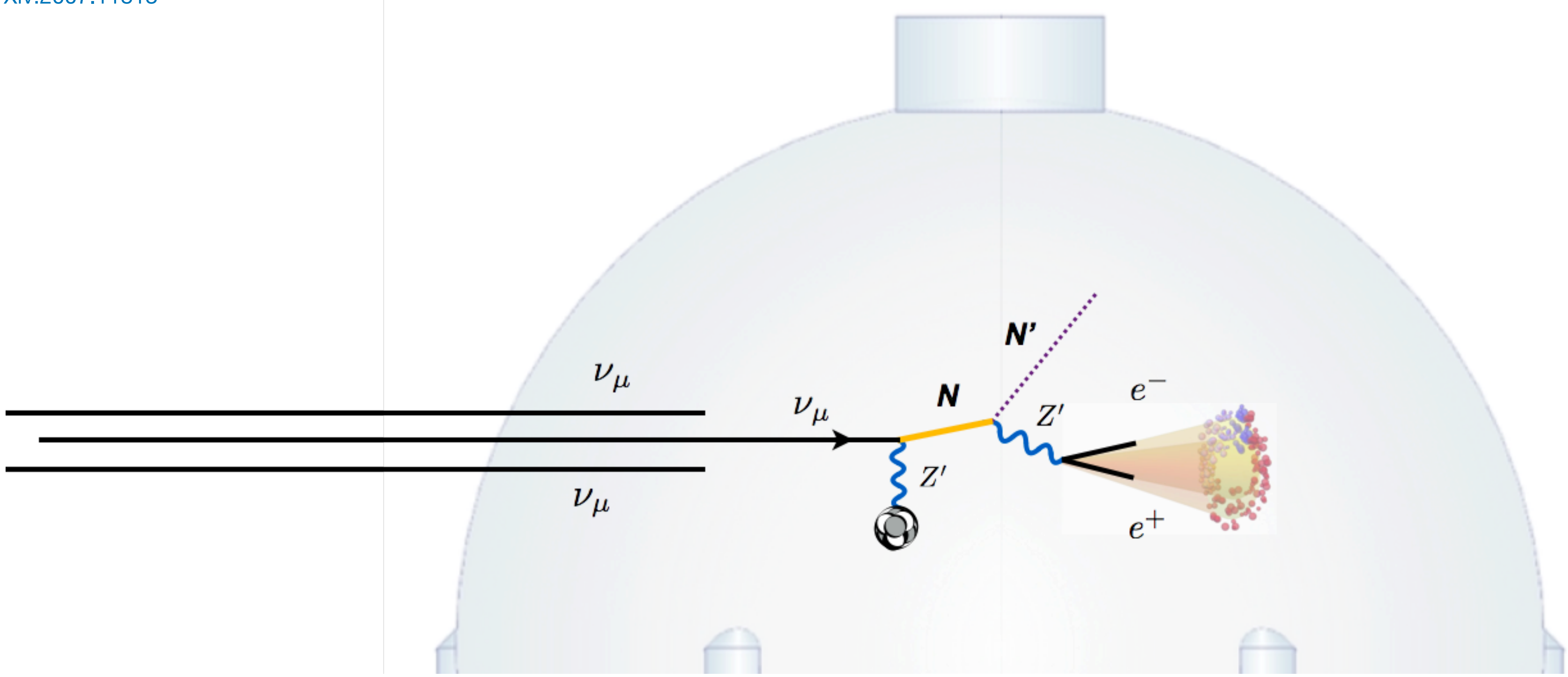
Cannot distinguish between electrons and photons!

Non-Minimal HNL: di-electron scenario

E. Bertuzzo et al., PhysRevLett.121.241801

P. Ballett, M. Ross-Lonergan, S. Pascoli, PhysRevD.99.071701

A. Abdullahi, M. Hostert, S. Pascoli, arXiv:2007.11813



Option 1: HNL produced in the neutrino interaction that makes a pair of electrons.

Non-Minimal HNL: di-electron scenario

E. Bertuzzo et al., PhysRevLett.121.241801

A. Abdullahi, M. Hostert, S. Pascoli, arXiv:2007.11813

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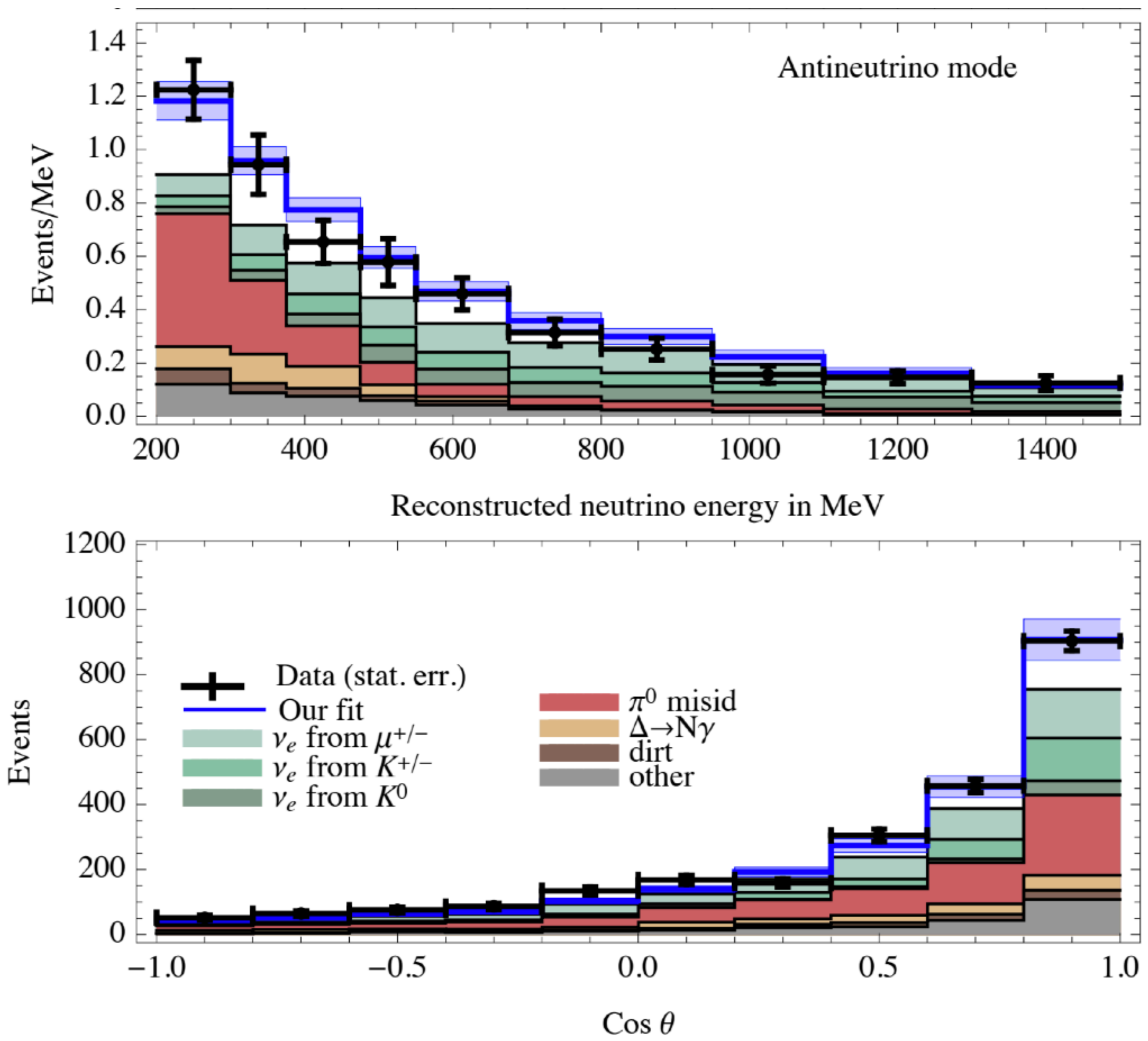
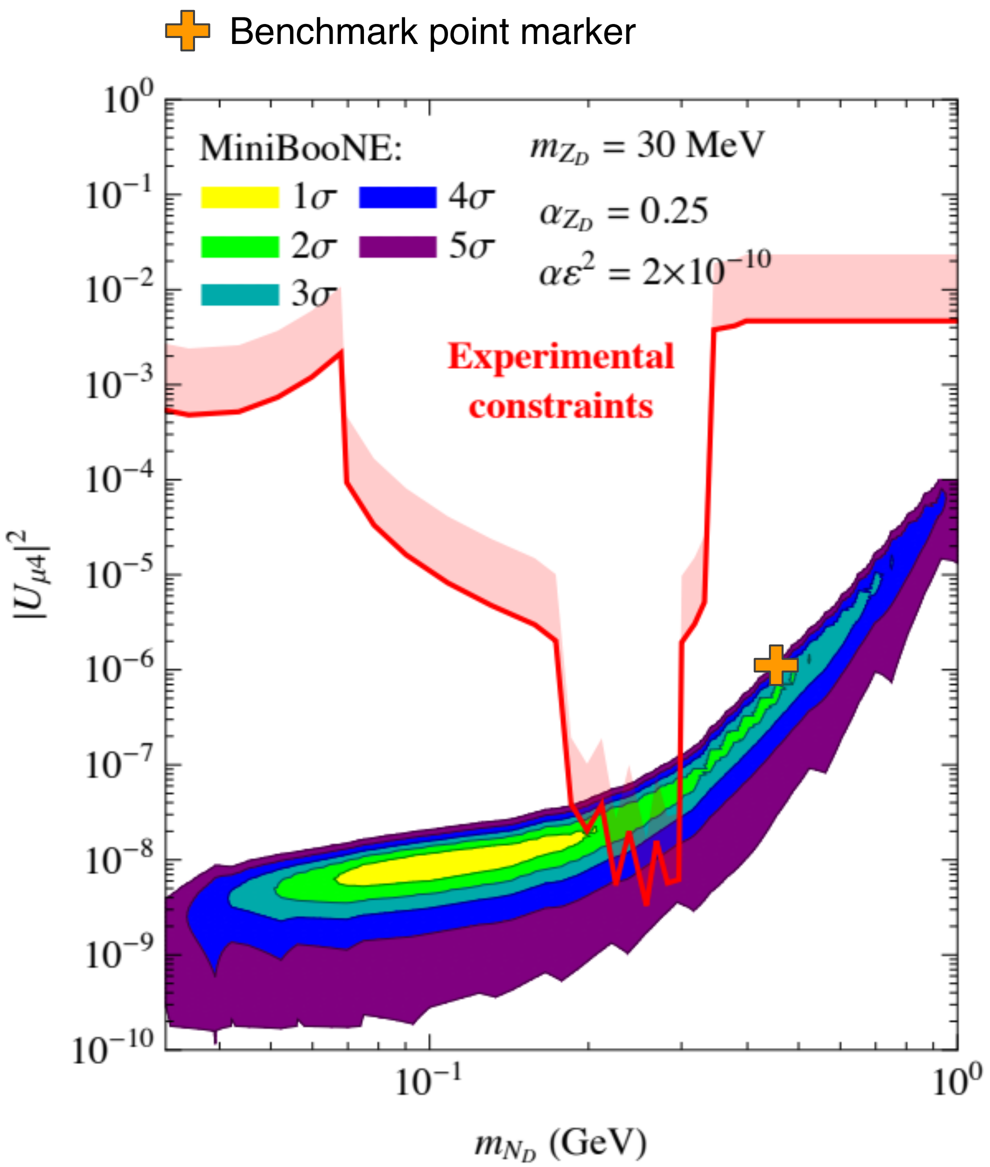
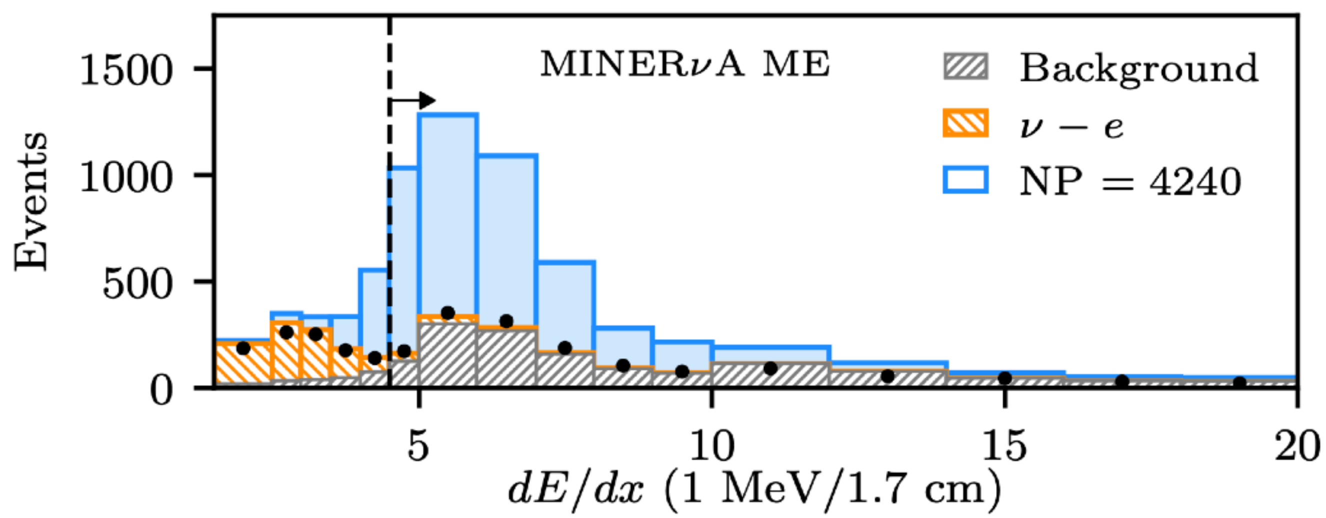
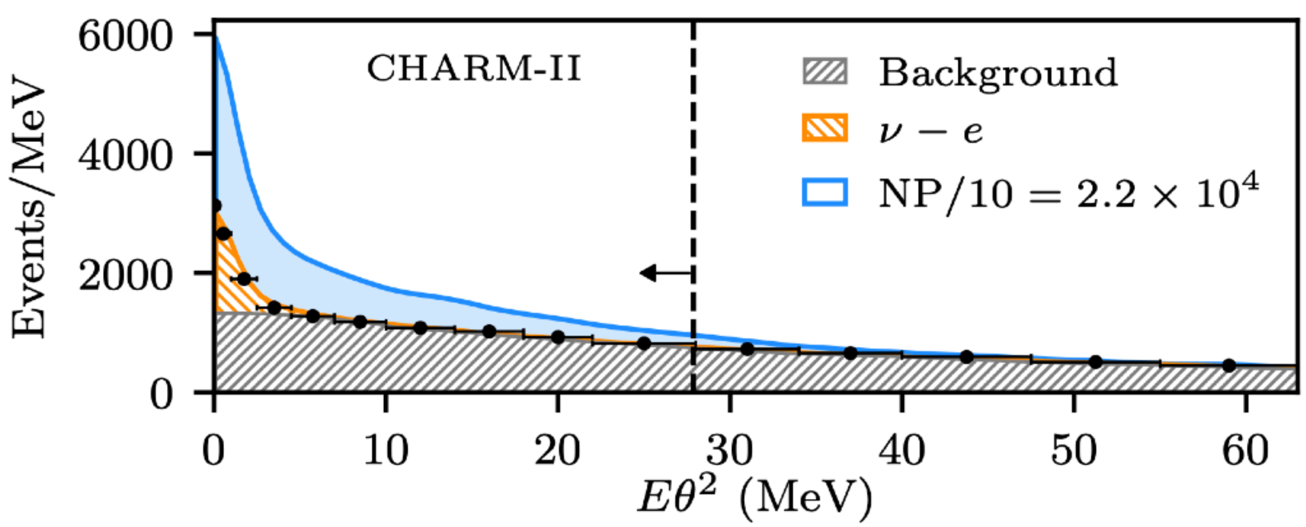




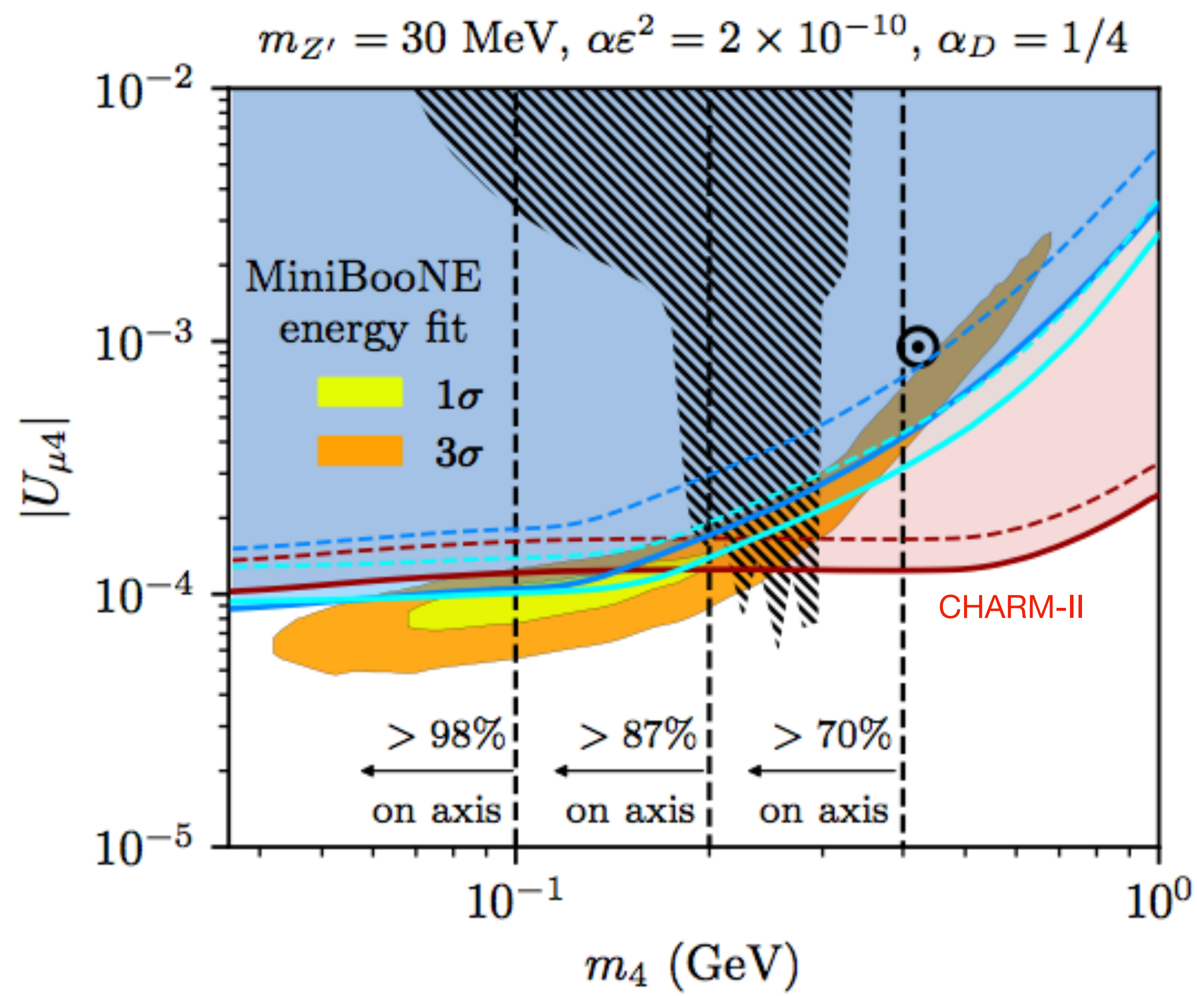
Good fit to the energy and angular distribution.

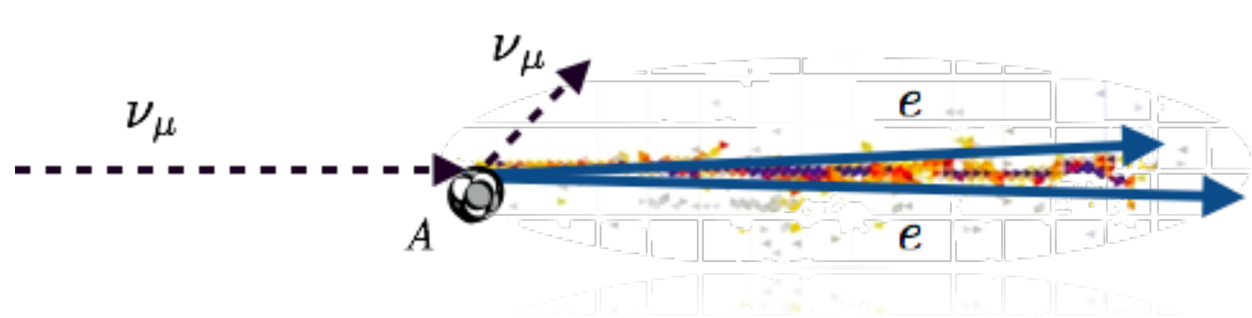
Non-Minimal HNL: di-electron scenario





CA, M. Hostert, Y. Tsai, PhysRevLett. 123, 261801 (2019)

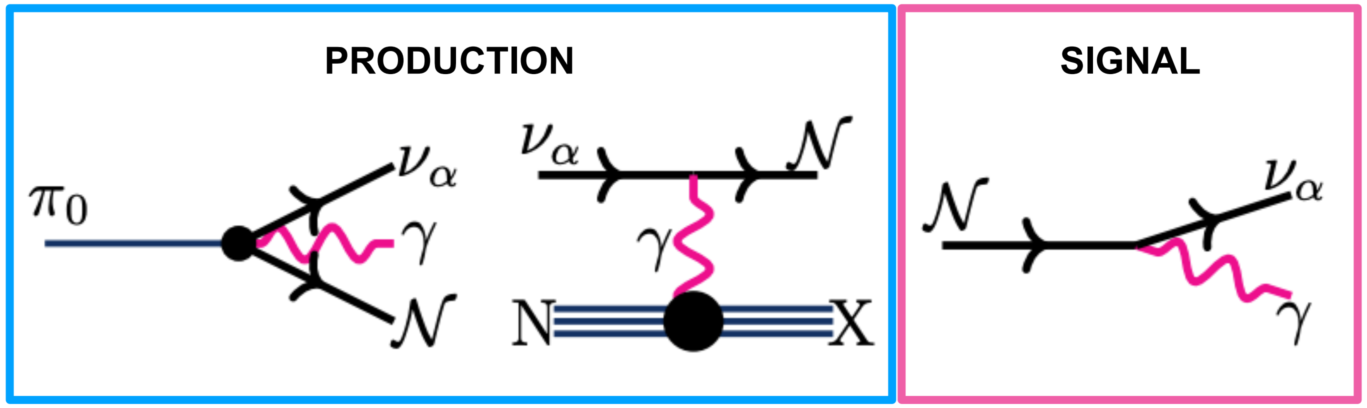


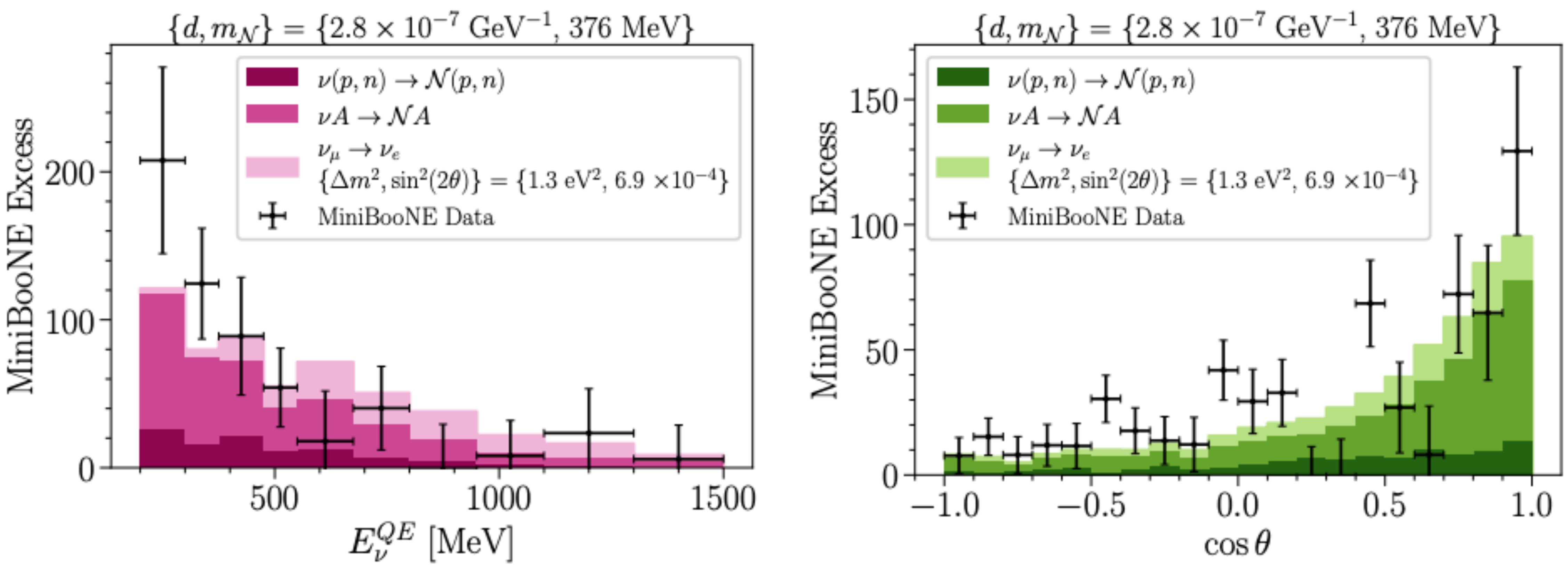


In tension with measurements of electron-neutrino scattering

Non-Minimal HNL: photon scenario

$$\sum_{j=1}^{3} \bar{\mathcal{N}}_j (i\partial\!\!\!/ - M_j)\mathcal{N}_j + \sum_{i=1}^{3} (d_{i,j}\bar{\nu}_i \sigma_{\mu\nu} F^{\mu\nu} \mathcal{N}_j + h.c.)$$





Option 2: HNL produced in the neutrino interaction that decays into a photon and a neutrino

A global solution: 3+1+HNL-photon

Used to Test	References (Flux Type)	Type of Fit
$\bar{\nu}_e$ disappearance	[39–43] (Reactor)	
ν_e disappearance	[44–46] (Source)	↑
$\bar{\nu}_\mu \to \bar{\nu}_e$ appearance	[47, 48](π/μ DAR)	3+1-only
$\nu_\mu \to \nu_e$ appearance	[49](π/μ DIF)	
$\bar{\nu}_\mu$ disappearance	[50–53] (π/μ DIF)	↓
ν_μ disappearance	[51, 54–56] (π/μ DIF)	
$3+1+\mathcal{N}$	[8] (MiniBooNE BNB ν)	$\mathcal{N}$

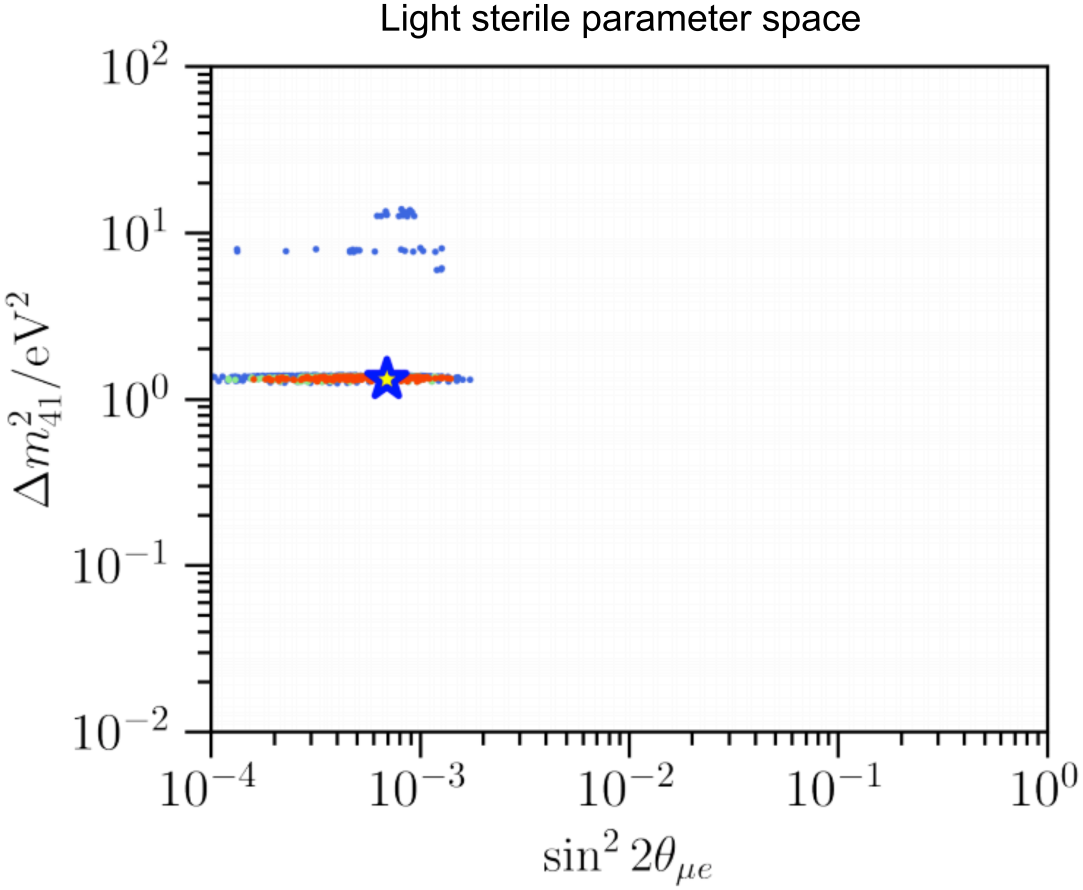
Explained by eV-sterile

Explained by MeV-HNL

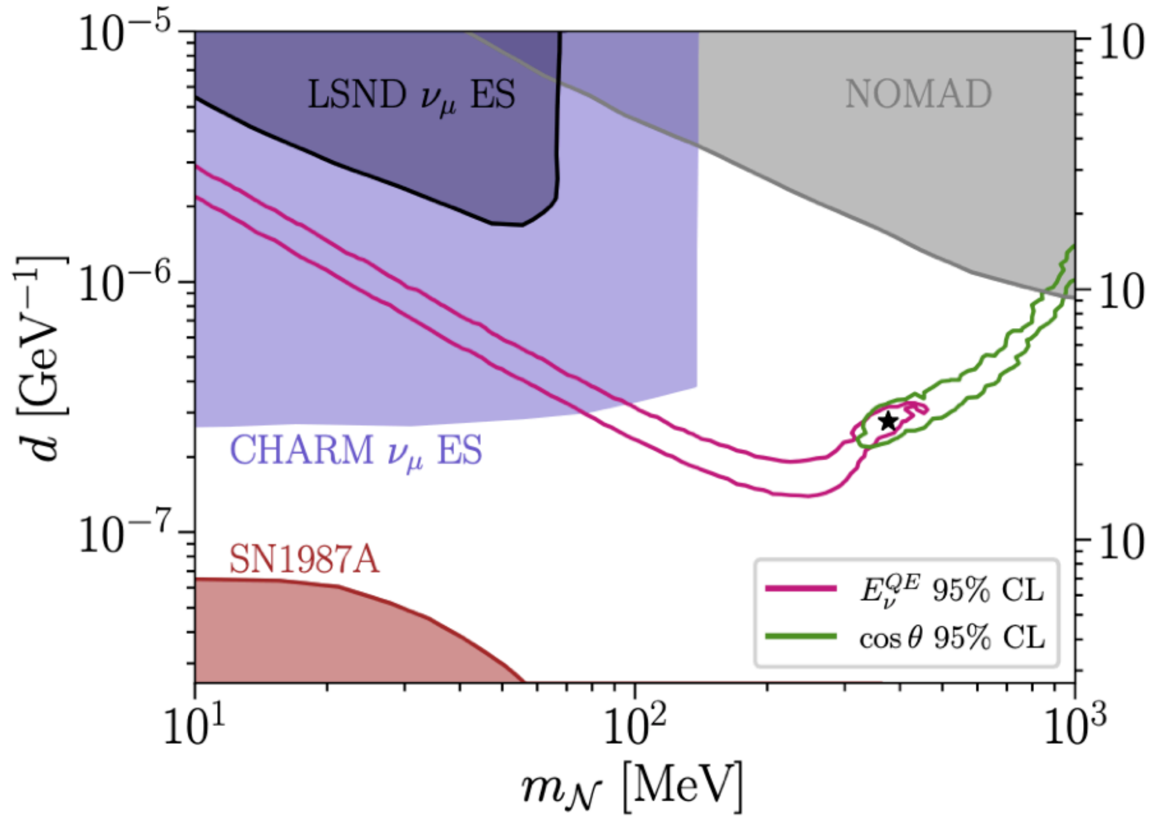
Fit type:	3+1-only	3+1-complete
χ^2_{app}	48	79
N_{app}	2	2
χ^2_{dis}	557	557
N_{dis}	3	3
χ^2_{glob}	615	664
N_{glob}	3	3
χ^2_{PG}	10	28
N_{PG}	2	2
p-value	7E-03	8E-07
$N\sigma$	2.7σ	4.8σ

Tension

Light sterile parameter space



Heavy "sterile" parameter space



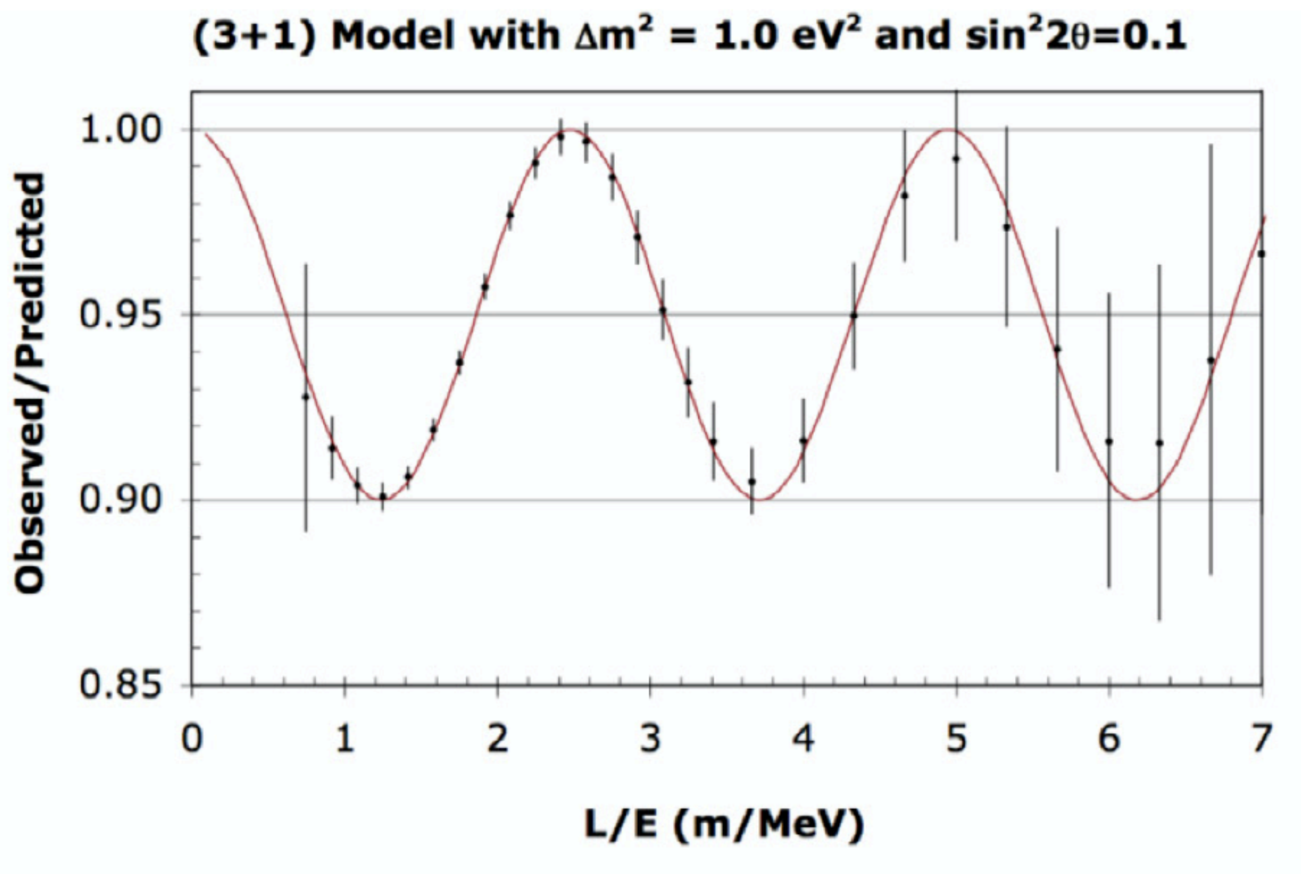
S. Vergani, N. Kamp, Diaz, CA, J. M. Conrad, M. H. Shaevitz, M. A. Uchida, arXiv:2105.06470

Outline

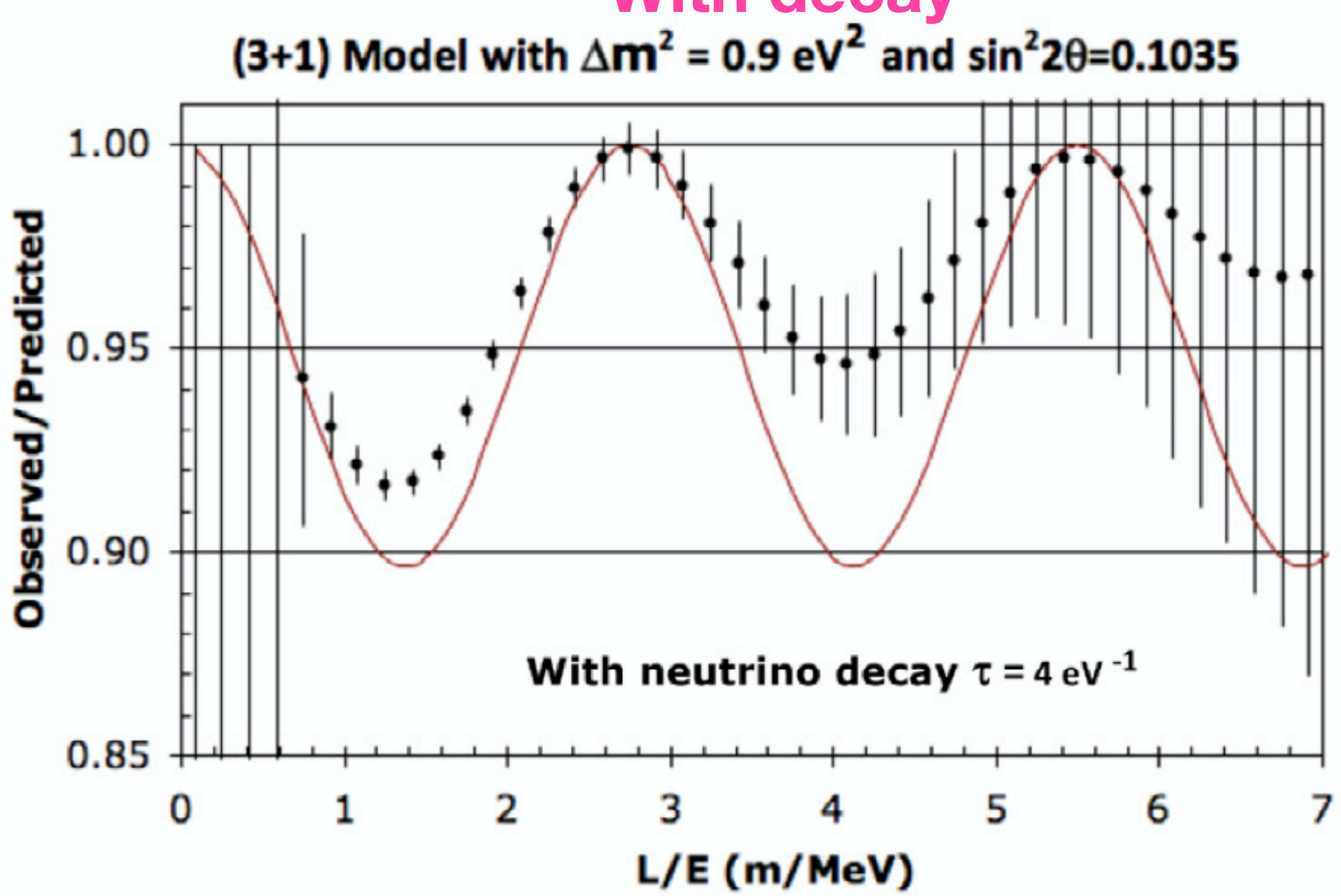
- Why going beyond 3+1?
- The garden of forking paths
- Opportunities for discovery with IsoDAR@Yemilab

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

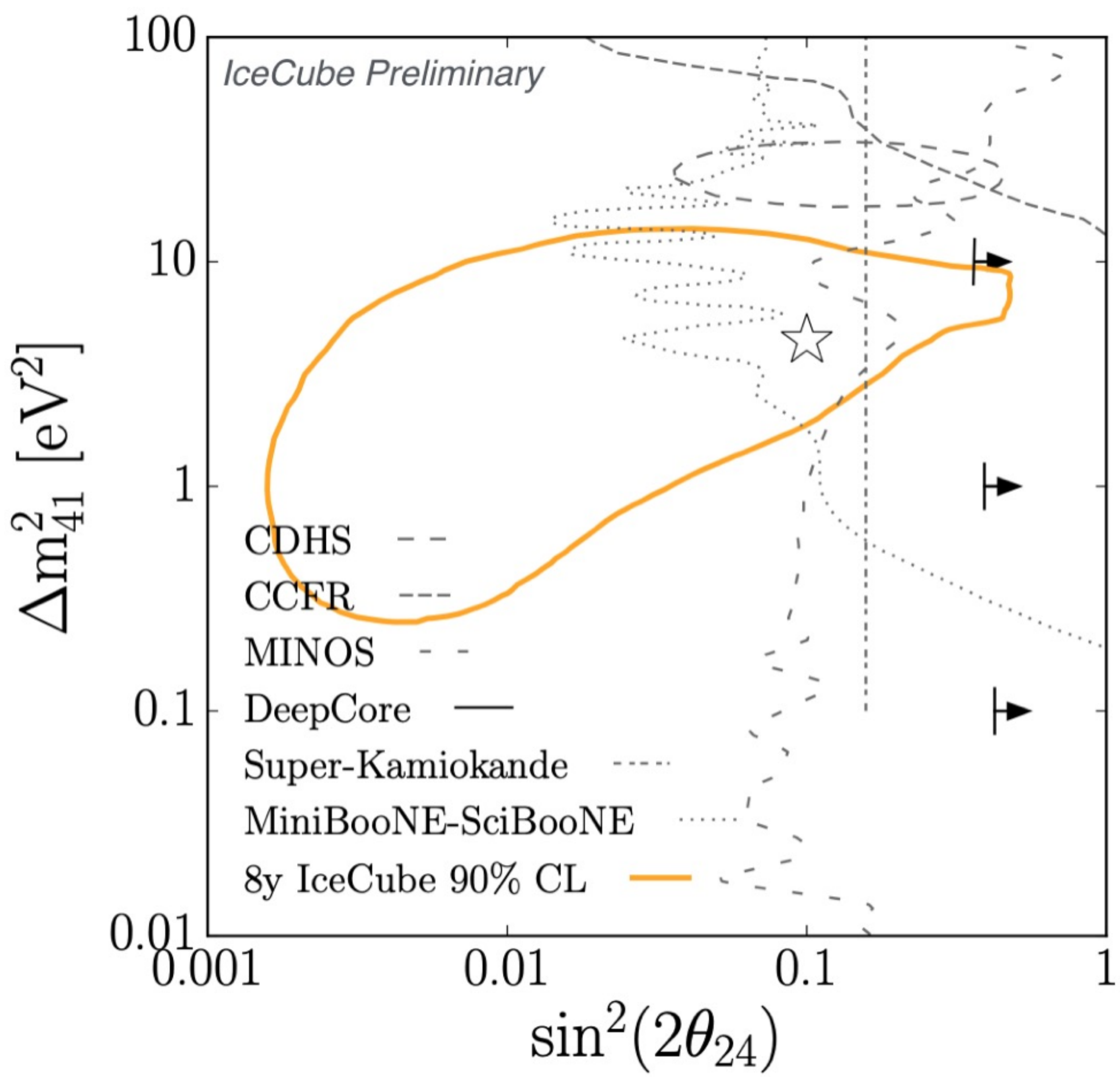
Take home messages

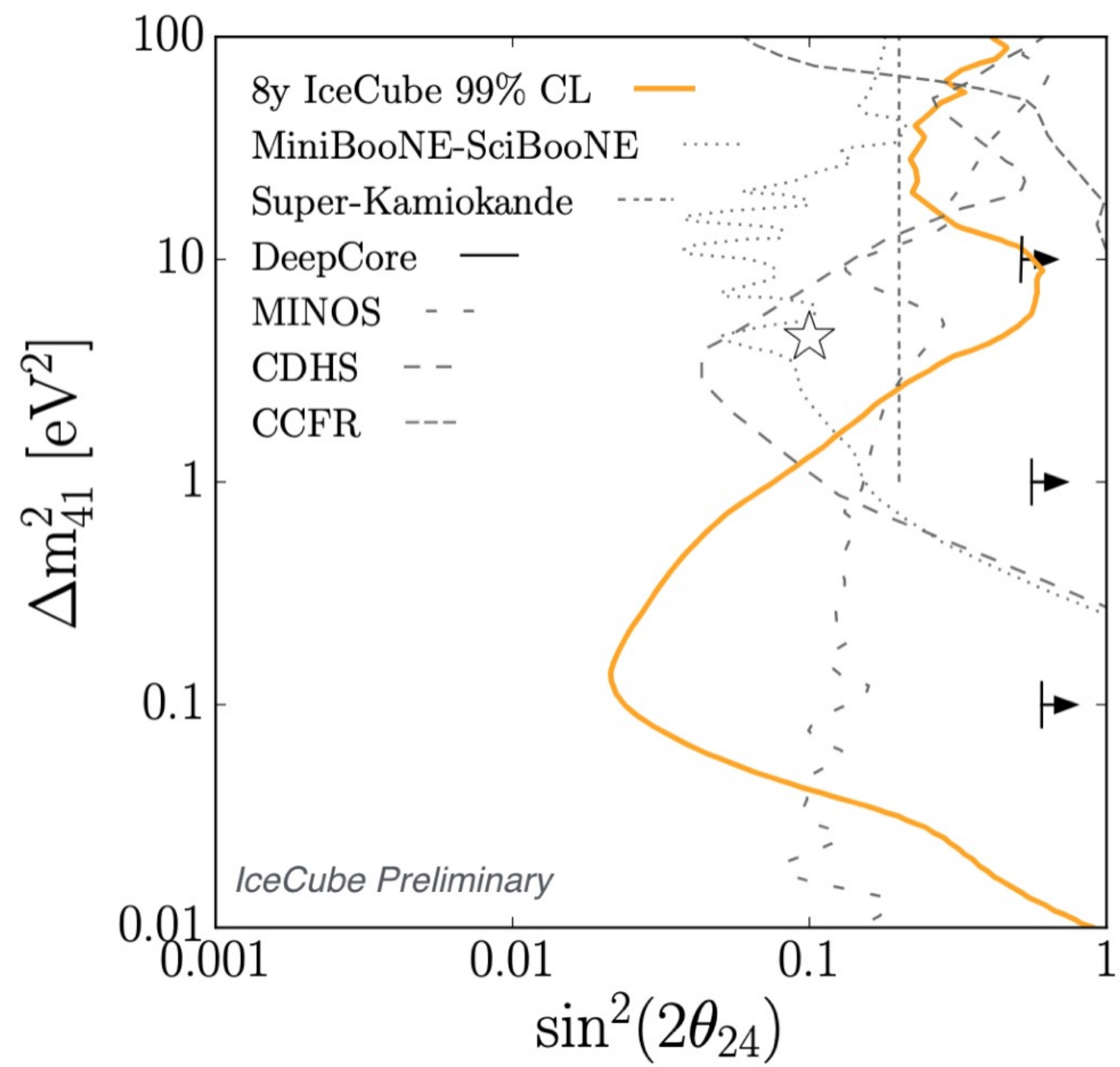
- 3+1 model is disfavored as a global solution.
- 3+1+Decay provides a better explanation of the global data set.
- 3+1+Decay is preferred over 3+1 by IceCube.

- The low-energy part of the MiniBooNE excess points to a second component.
- Non-minimal HNLs provide a good explanation for the low-energy excess.
- Measurement of electron-neutrino cross section will be important to test these scenarios.

Bonus slides

Compare to other muon-neutrino disappearance results

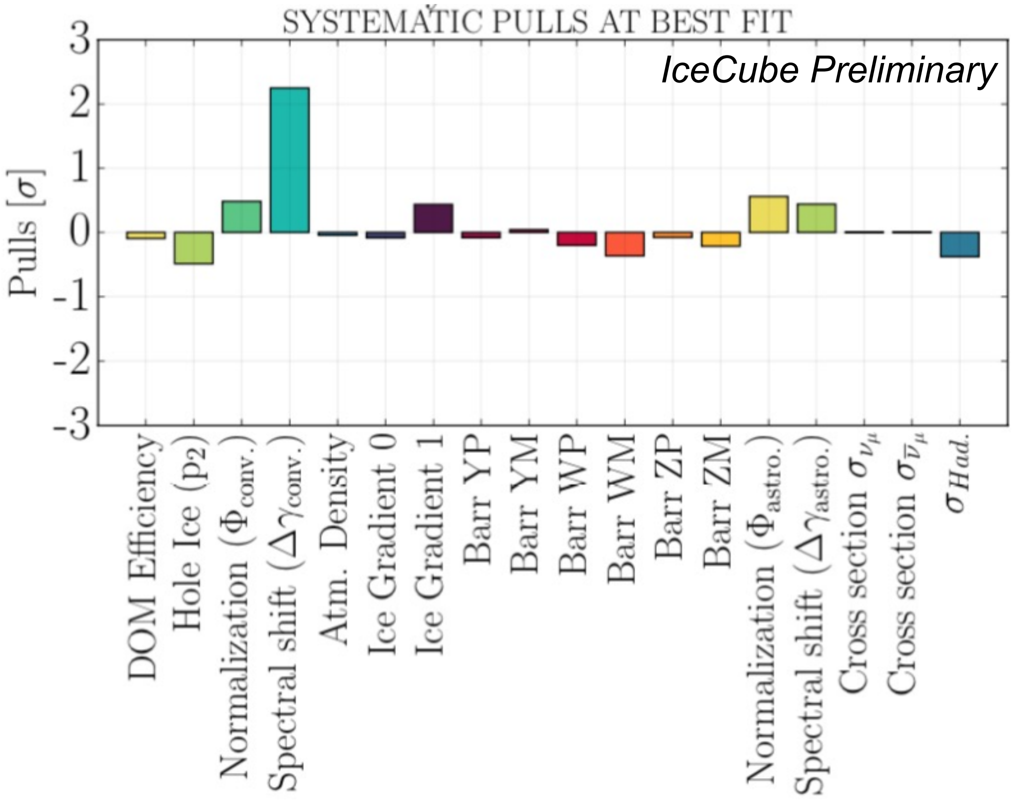


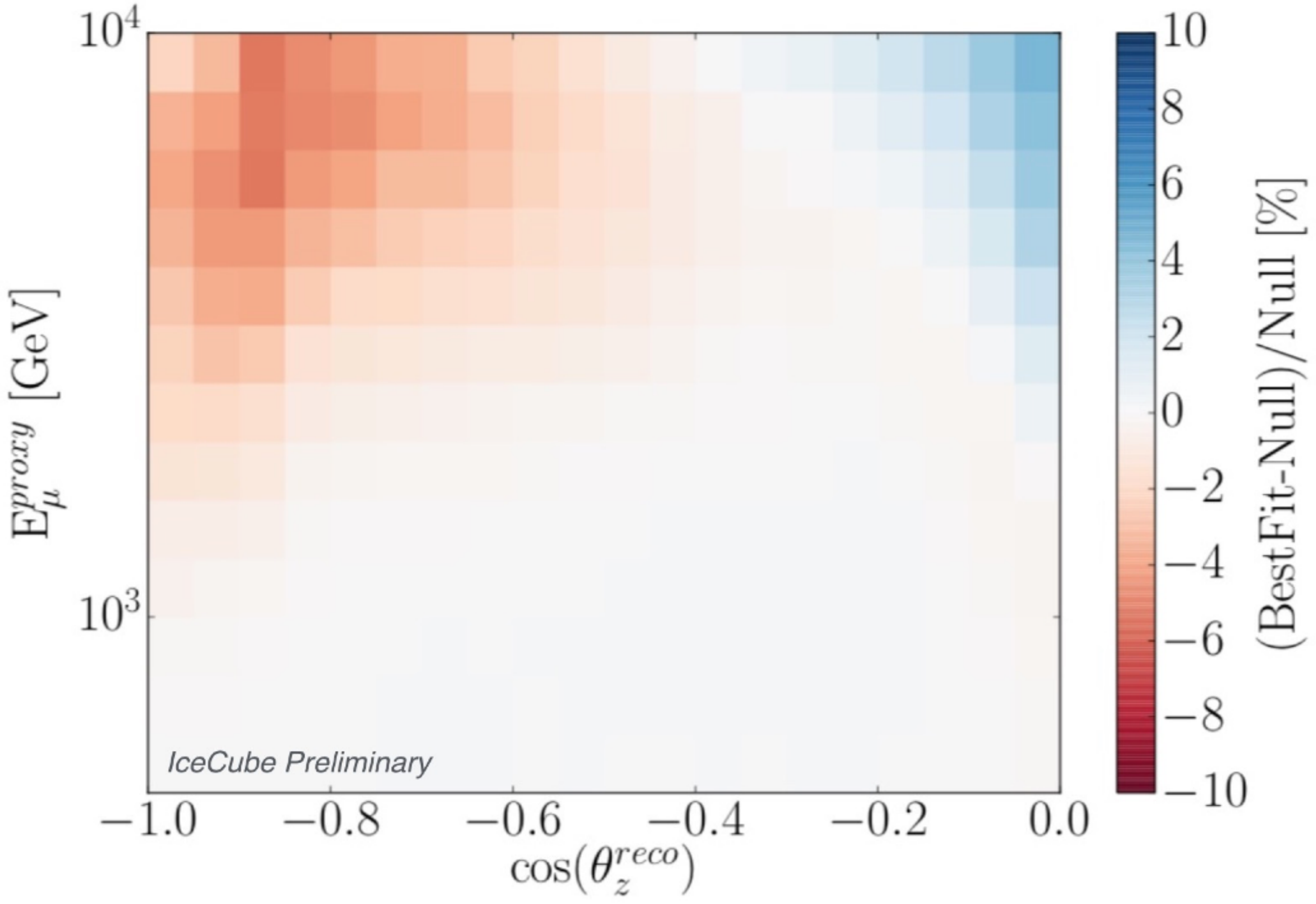


Best-fit point (data) and signal shape (Monte Carlo)

$$\Delta m^2_{41} = 4.47^{+3.53}_{-2.08}\,\mathrm{eV}^2$$

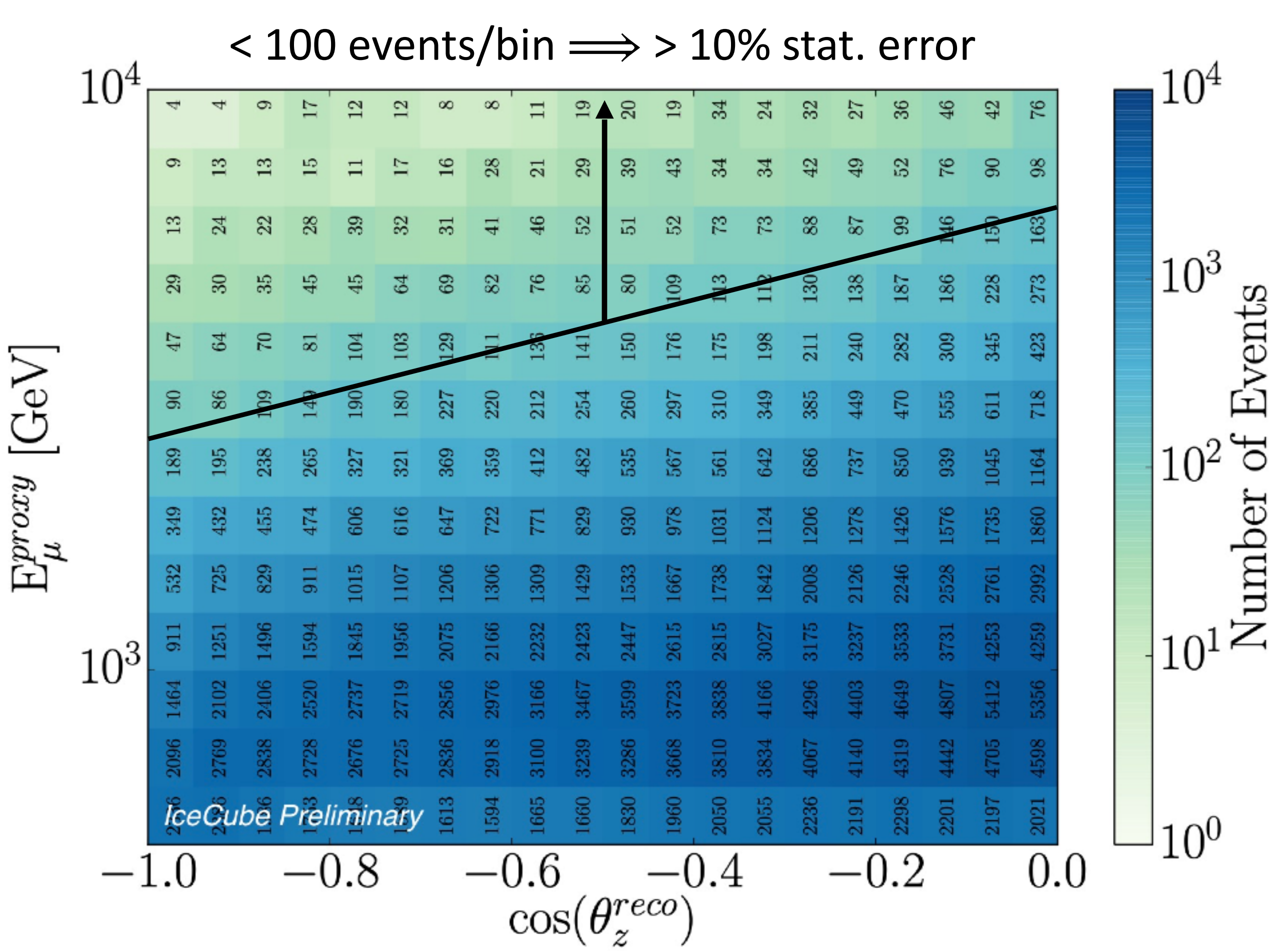
$$\sin^2(2\theta_{24}) = 0.10^{+0.10}_{-0.07}$$

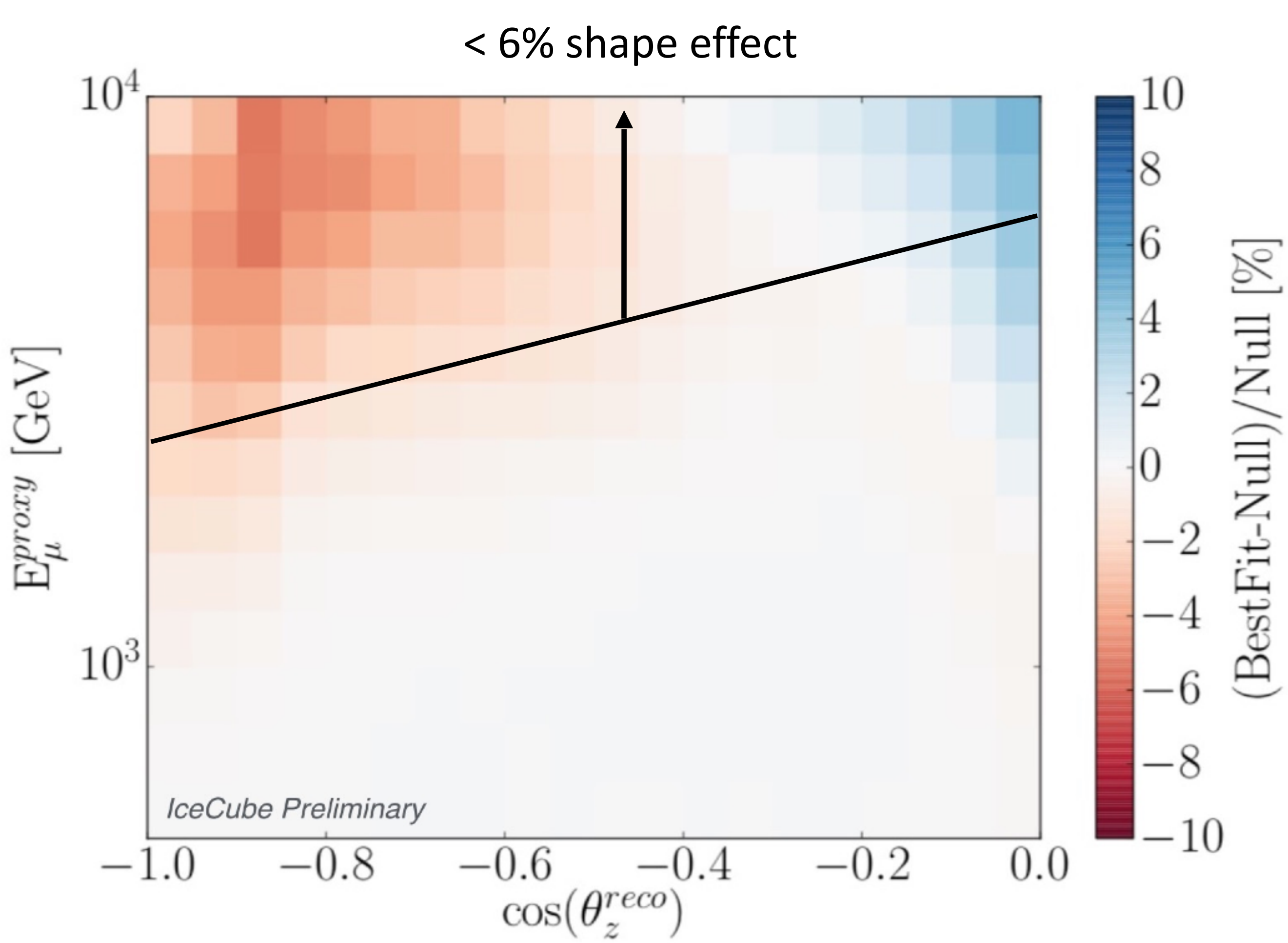




Event distribution (data) and best-fit shape (Monte Carlo)

- Best-fit shape effect is in a low-statistics regime
  - Hard to see by eye in the data
- But the result does not seem to be a statistical fluctuation
  - Consistent year-to-year





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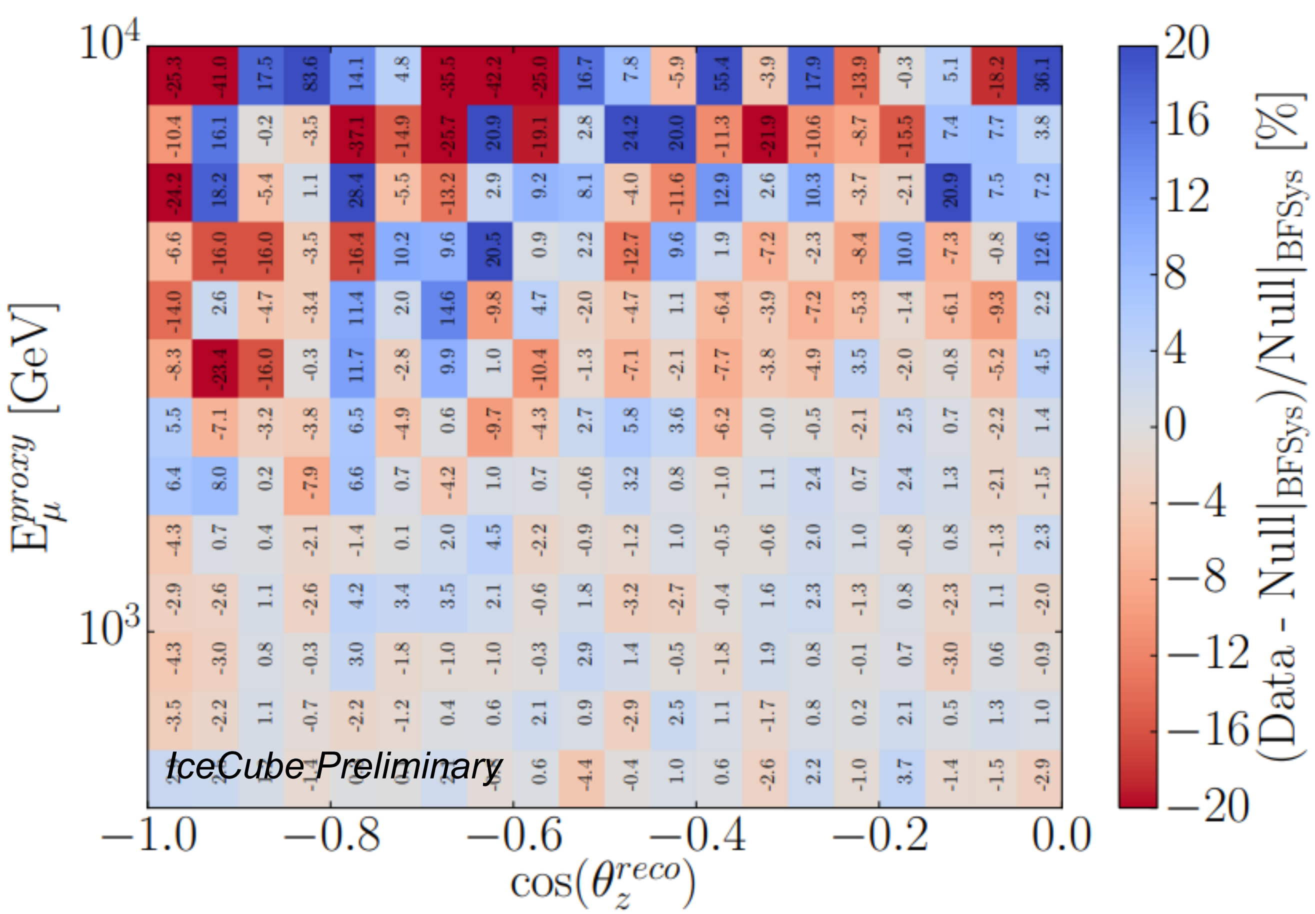
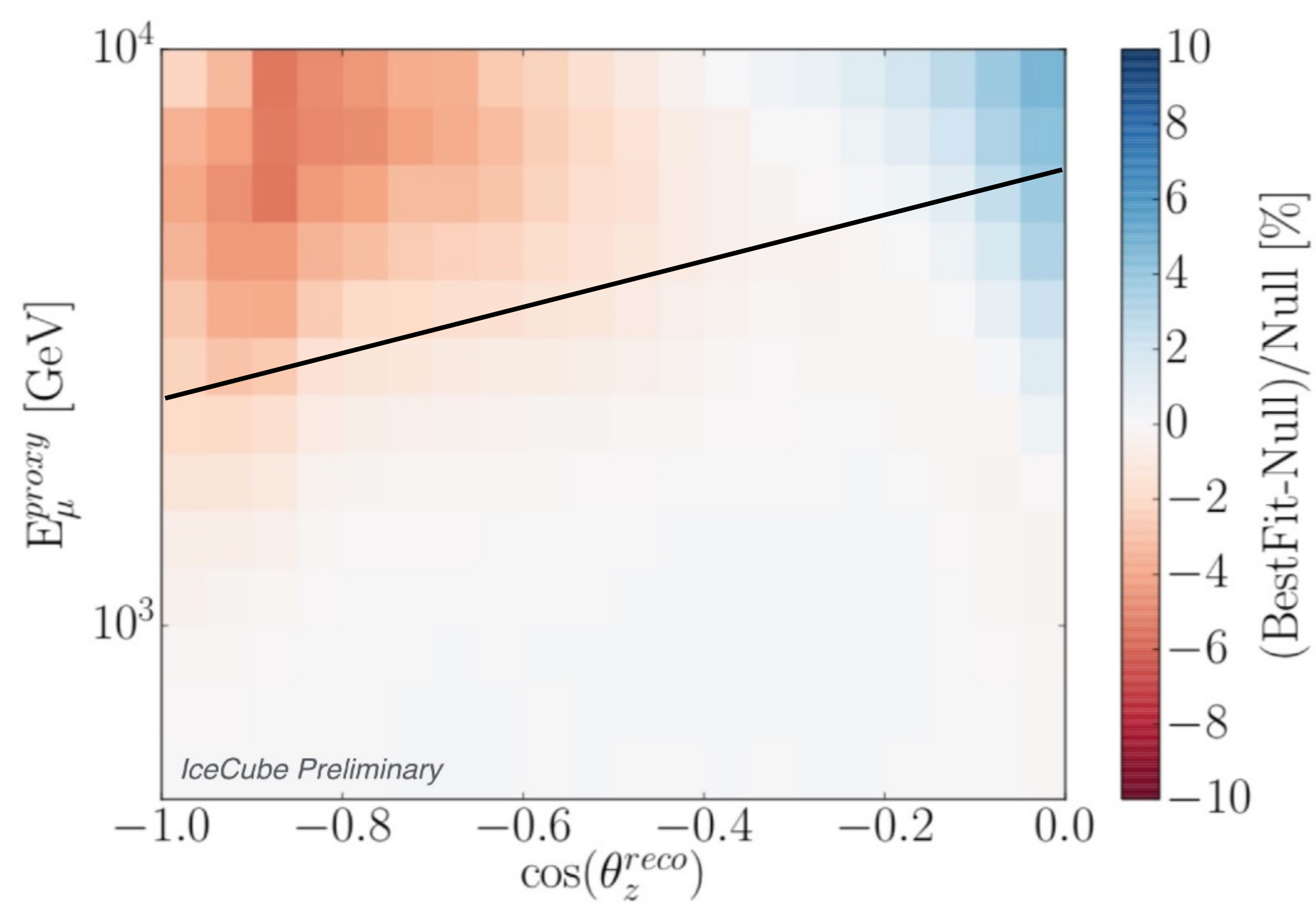
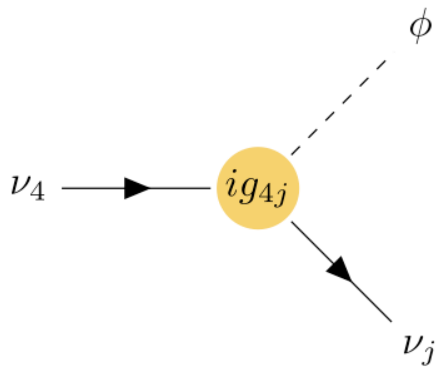


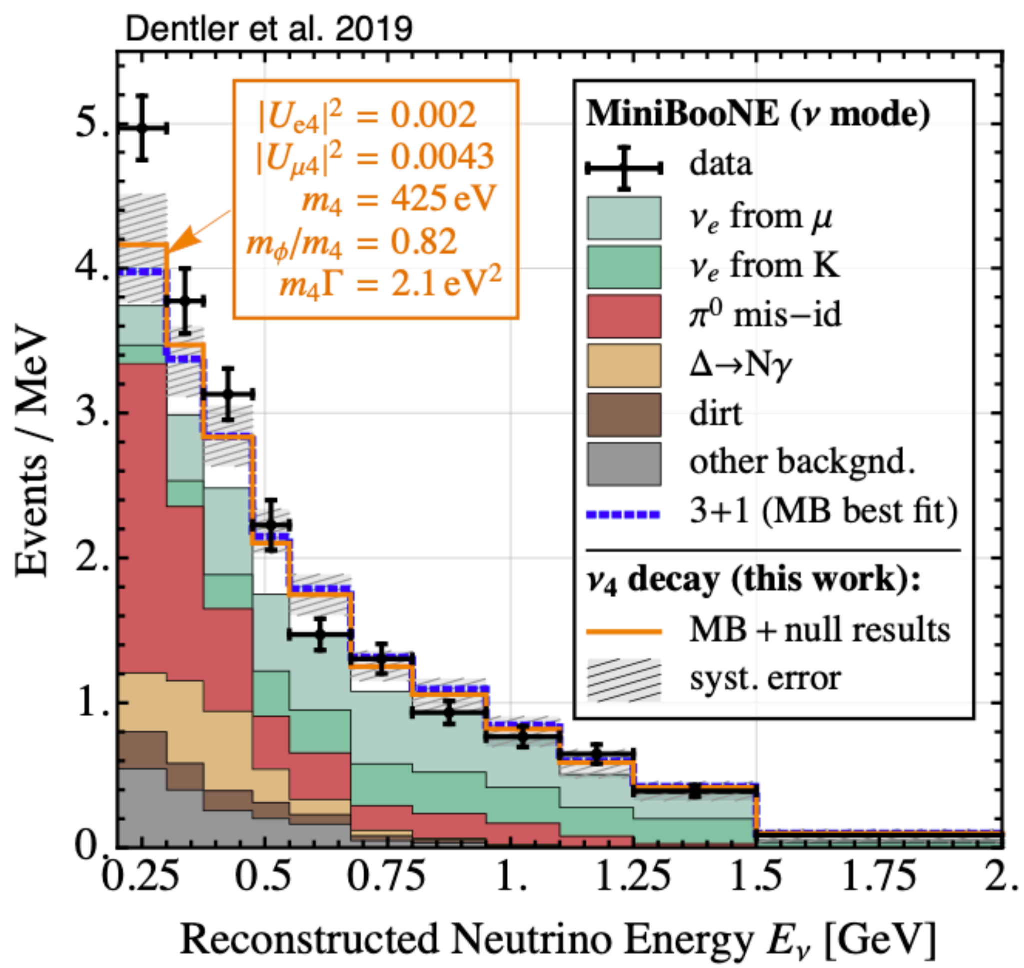


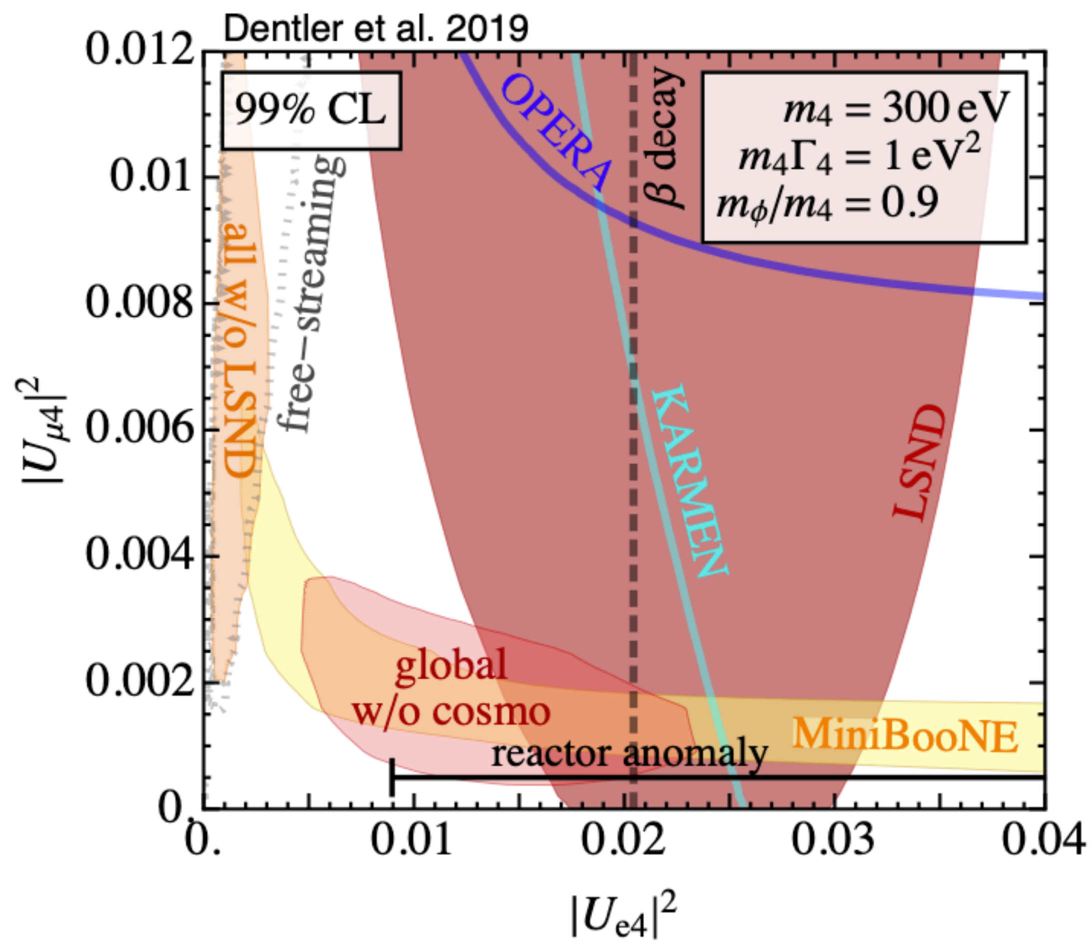


Sterile Neutrino Decay (3+1+Visible-Decay)

Dentler *et al* https://arxiv.org/abs/1911.01427
Gouvea *et al* https://arxiv.org/abs/1911.01447

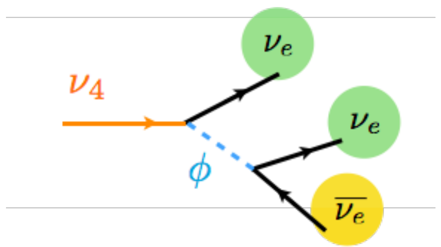
$$\mathcal{L} \supset -g\,\bar{\nu}_s \nu_s \phi - \sum_{a=e,\mu,\tau,s} m_{\alpha\beta}\,\bar{\nu}_\alpha \nu_\beta$$





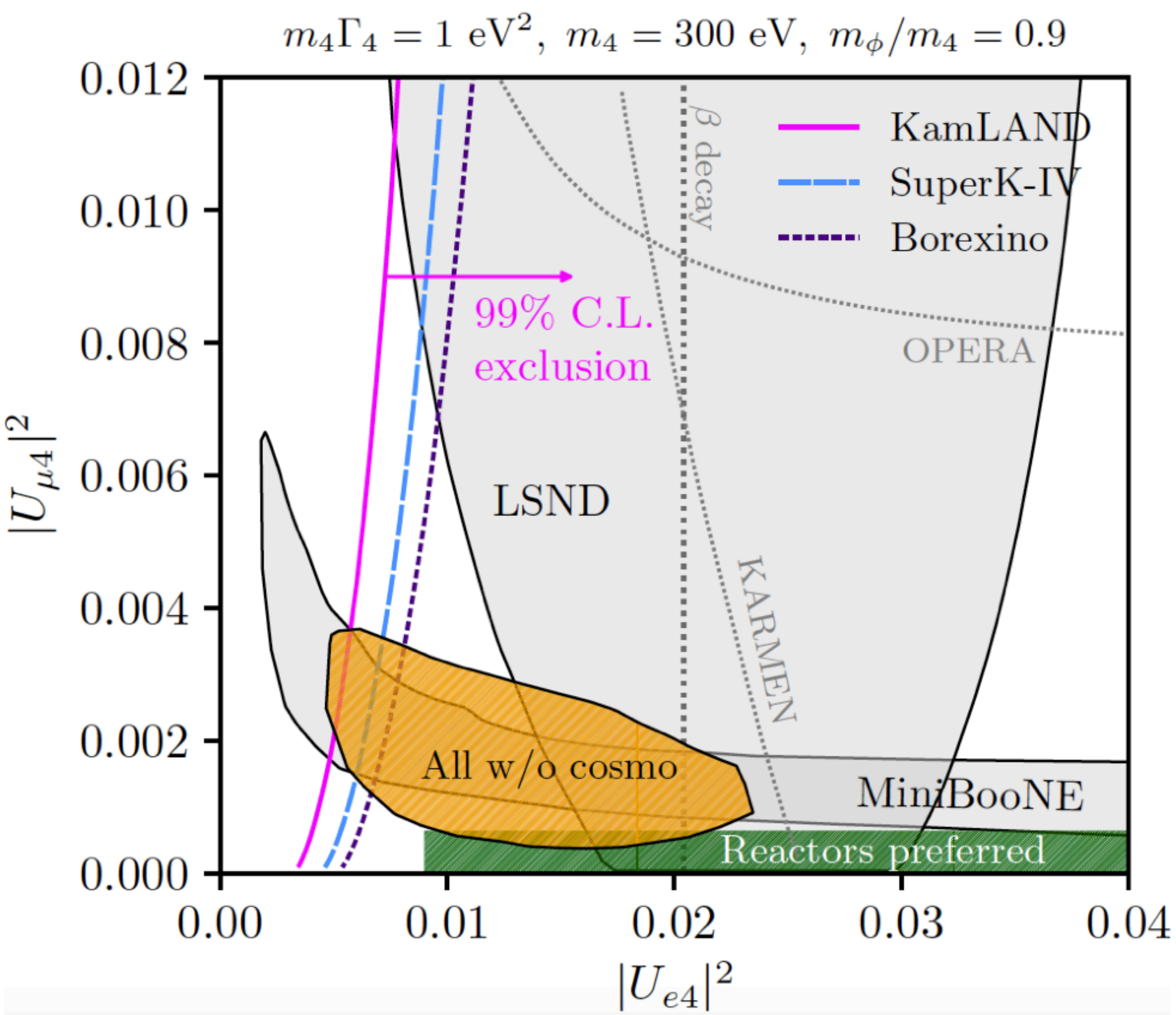
See also Palomares-Ruiz et al http://xxx.lanl.gov/abs/hep-ph/0505216, Gninekov https://arxiv.org/abs/0902.3802, Fisher et al https://arxiv.org/abs/1909.09561

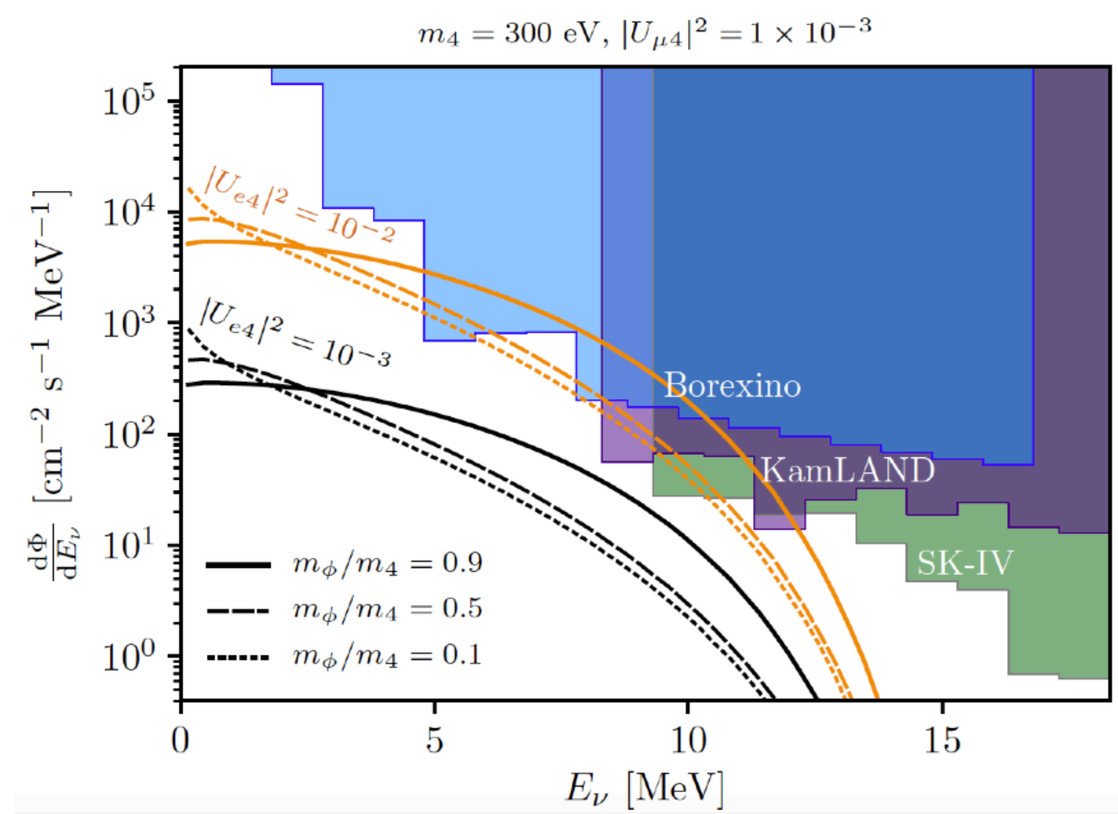
Neutrino Decay as a Solution to the Short-Baseline Anomalies
(https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF2_NF3_G_V_Stenico-131.pdf)



Sterile Neutrino Decay (3+1+Visible-Decay)

M. Hostert & M. Pospelov https://arxiv.org/pdf/2008.11851.pdf





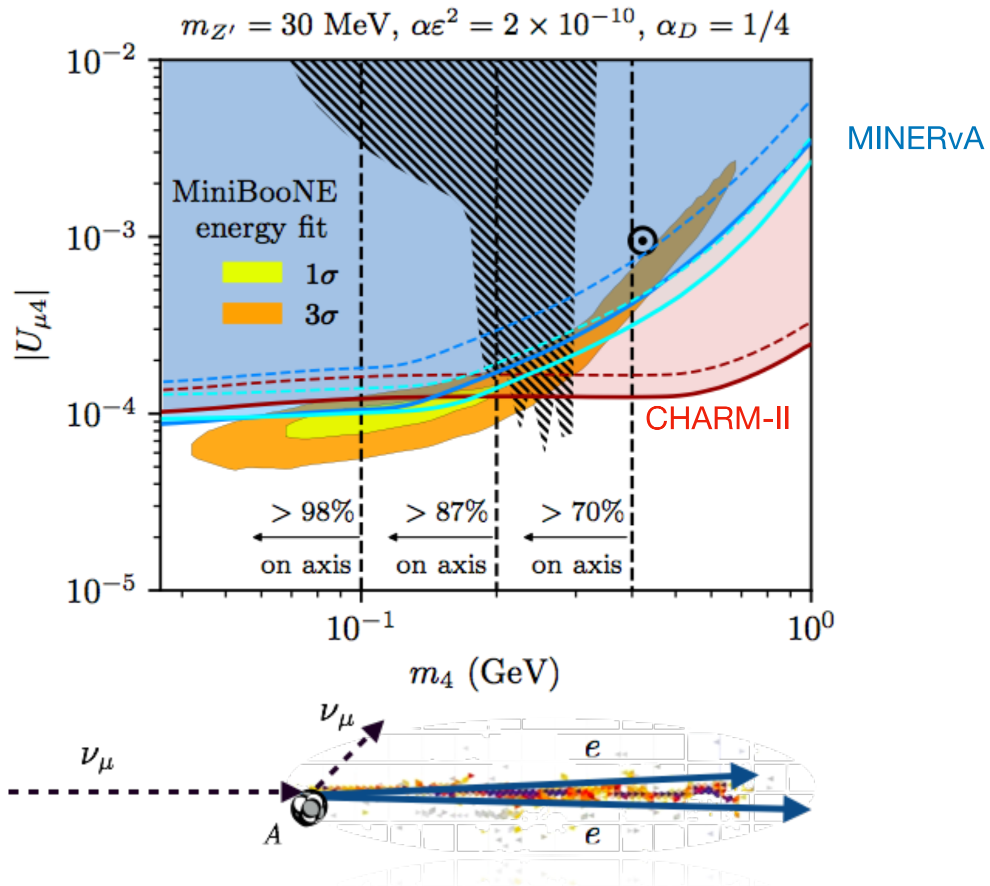
Visible decay predicts emission of antineutrinos from the Sun!

Neutrino Decay as a Solution to the Short-Baseline Anomalies
(https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF2_NF3_G_V_Stenico-131.pdf)

Non-Minimal HNLs - Testability

Photon-like signatures
neutrino-electron scattering
(MINERvA, CHARM-II)

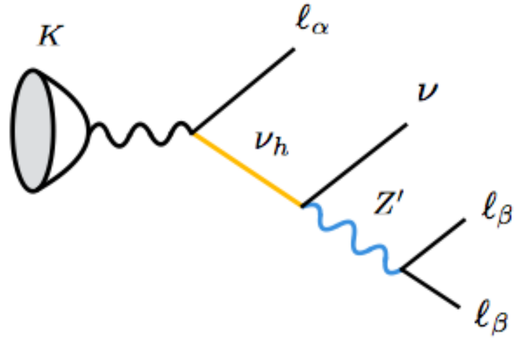
CA, M. Hostert, Y. Tsai, PhysRevLett. 123, 261801 (2019)



More data from: MINERvA, NOvA, and SBN program to come soon!

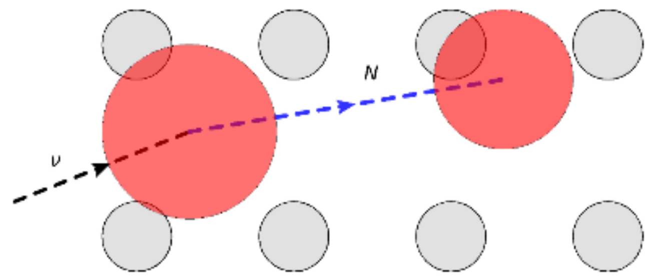
Rare kaon decays

P. Ballet, M. Hostert, S. Pascoli,
Phys. Rev. D 101, 115025 (2020)



Double cascades in IceCube

P. Coloma et al, arxiv:1707.08573,
P. Coloma arxiv:1906.02106



KOTO & muon (g-2) anomalies

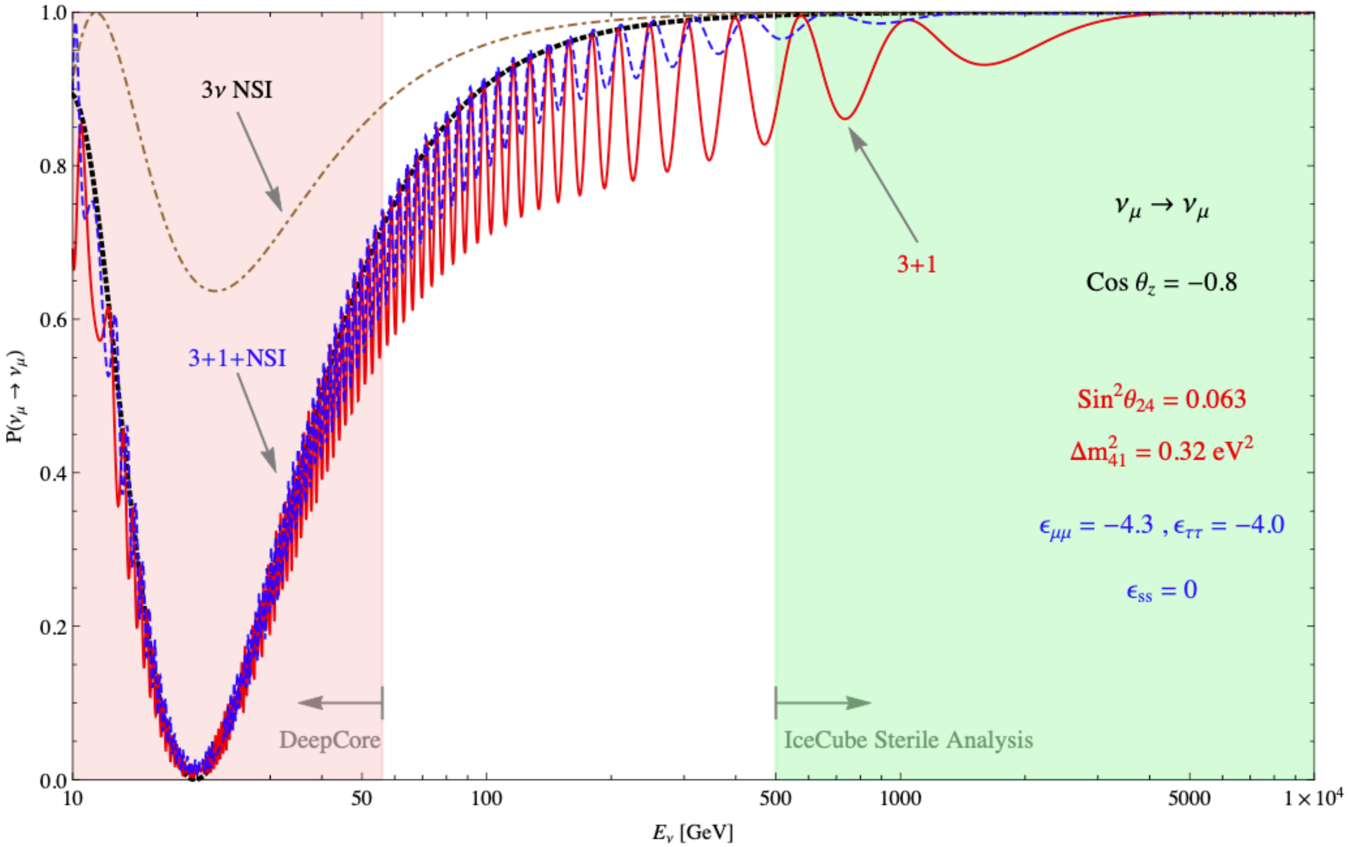
B. Dutta, S. Ghosh, T. Li, PhysRevD.102.055017
W. Abdallah et al, arXiv:2006.01948
A. Datta et al, Phys.Lett.B 807 (2020) 135579
A. Abdullahi, M. Hostert, S. Pascoli, arXiv:2007.11813

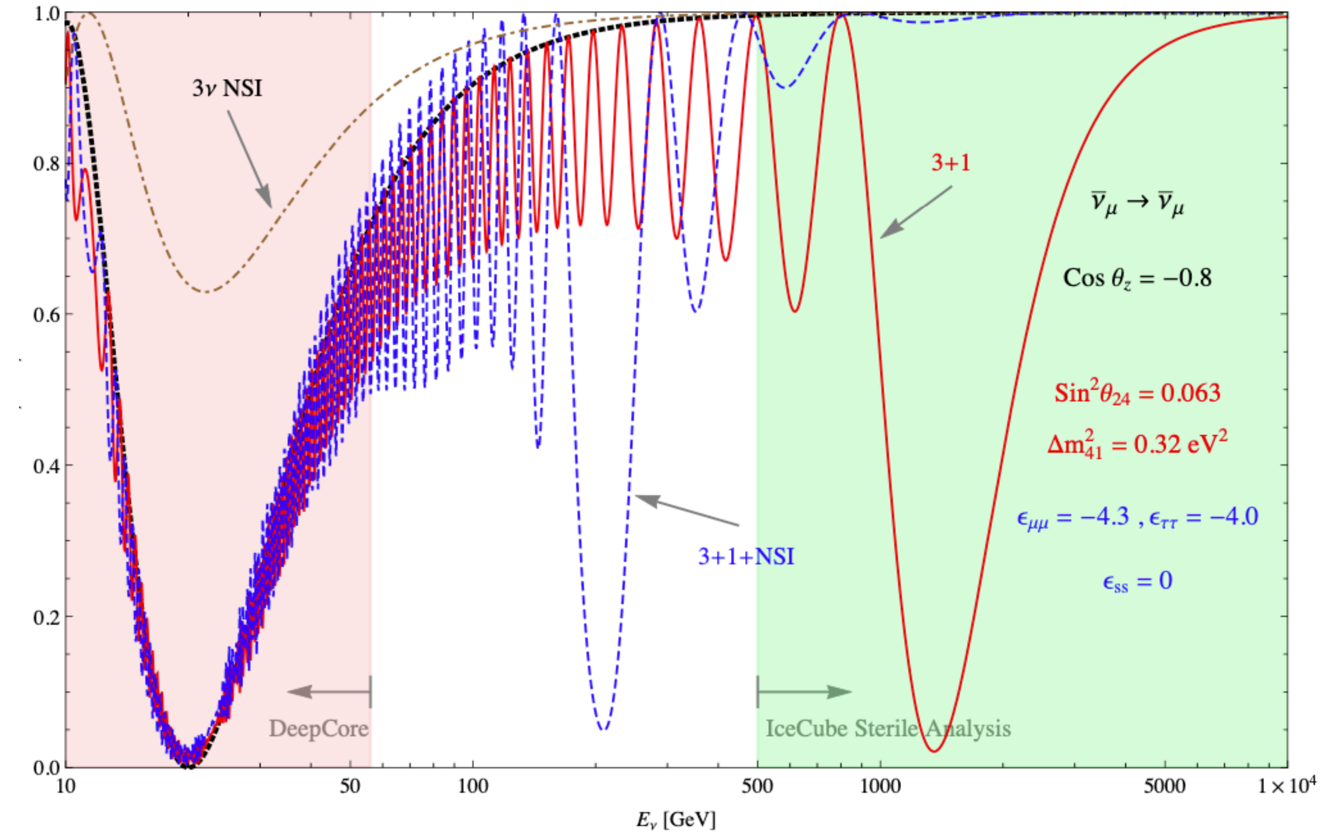
BSM Physics at the Electron Ion Collider: Searching for Heavy Neutral Leptons
(https://www.snowmass21.org/docs/files/summaries/EF/SNOWMASS21-EF7_EF0-NF2_NF3-RF4_RF0_Brian_Batell-114.pdf)
Dark Sector With Neutrino Beams
(https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF3_NF0-RF6_RF0-CF1_CF3-TF9_TF11-148.pdf)
Opportunities and signatures of non-minimal Heavy Neutral Leptons
(https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF2_NF3-EF9_EF0-RF4_RF6-CF1_CF0-TF8_TF11_Matheus_Hostert-041.pdf)

Non-Standard Matter Effects (3+1+NSI)

J. Liao et al

A. Esmaili et al https://arxiv.org/abs/1810.11940





See also Denton et al
Bhupal Dev et al

Direct Probes of Matter Effects In Neutrino Oscillations
(https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF1_NF3-TF0_TF0_Peter_Denton-010.pdf)

Neutrino NonStandard Interactions

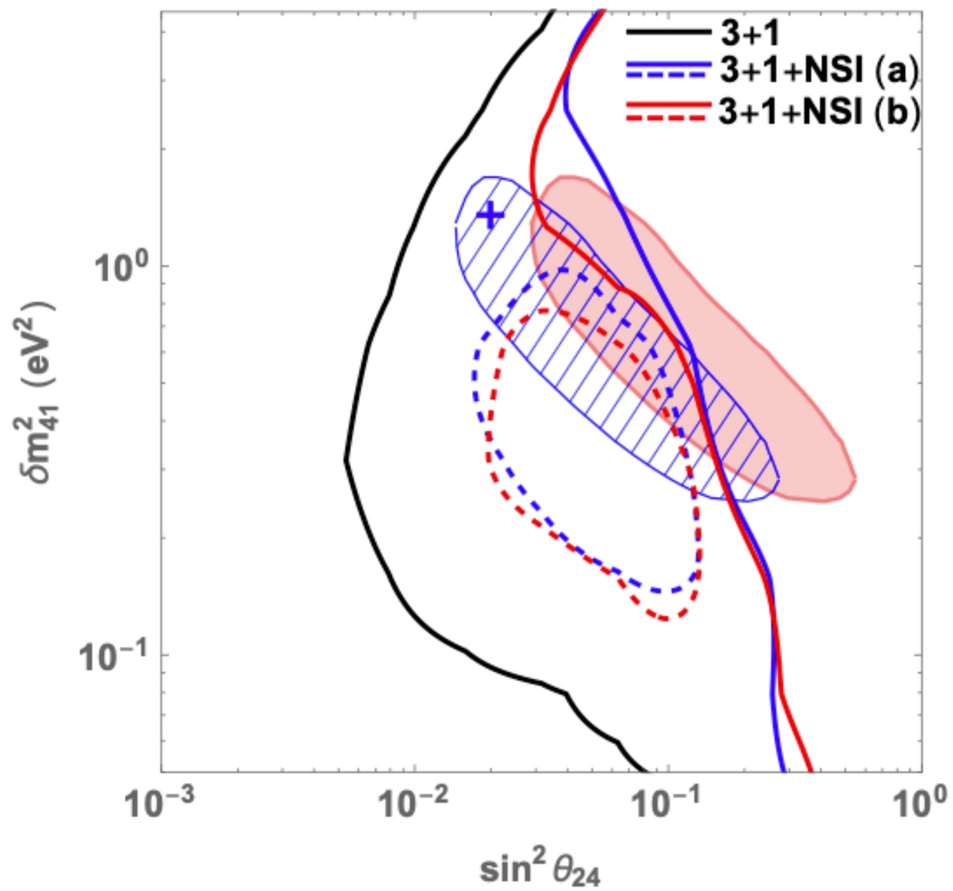
( )

Non-Standard Matter Effects (3+1+NSI)

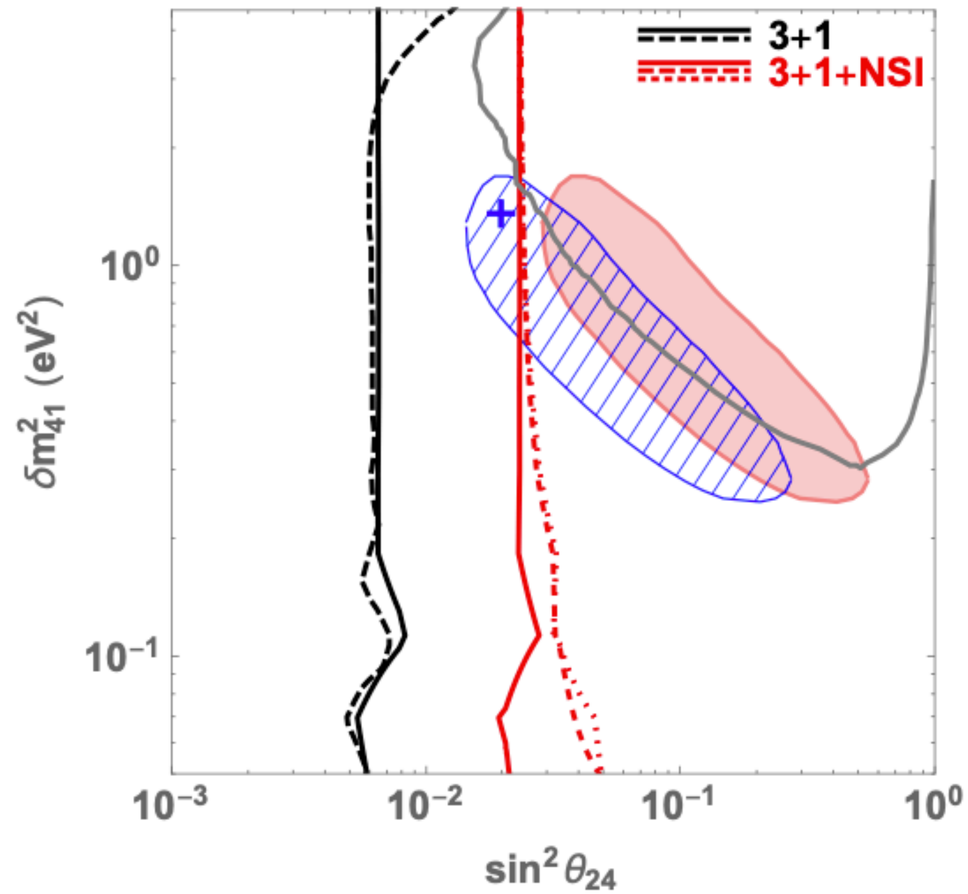
J. Liao et al

A. Esmaili et al https://arxiv.org/abs/1810.11940

IceCube modified by NSI



MINOS modified by NSI



See also Denton et al
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Neutrino NonStandard Interactions

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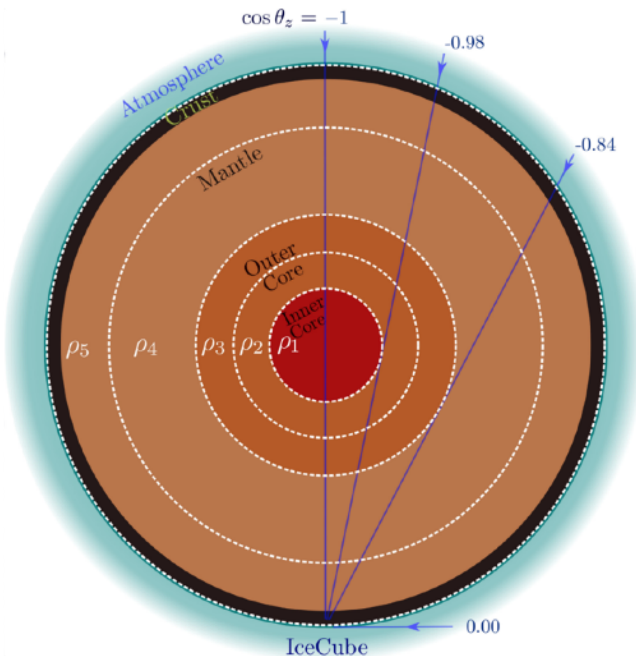
Position of resonance maps onto sterile parameter space



We measure two things:
- length (direction)
- energy

We extract two parameters:
- squared mass difference
- mixing angle