Sterile Neutrino Searches

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NuFact
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Cagliari, Italy

Outline

- The need for more than three neutrinos and *more*
- The garden of forking paths
- Outlook

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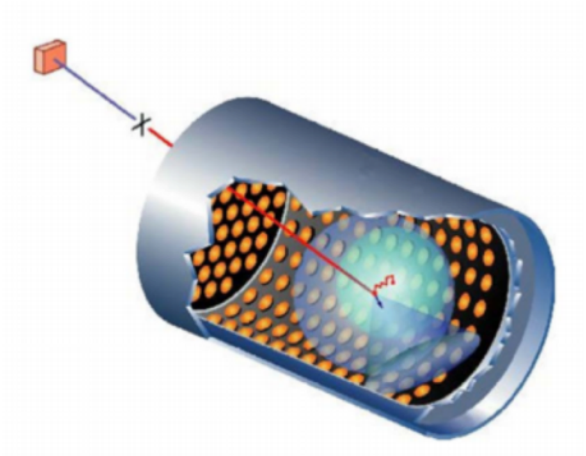
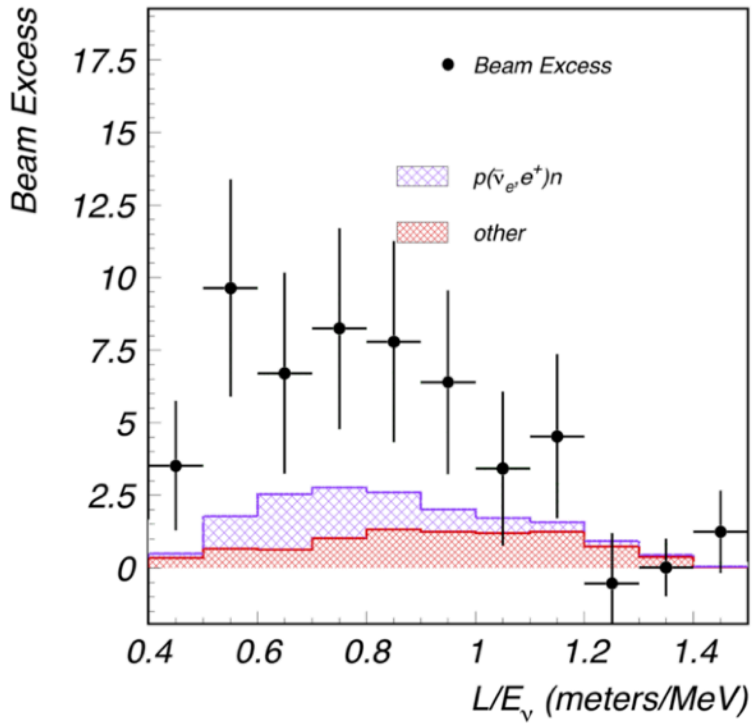
The short-baseline anomalies

LSND (3.8σ)

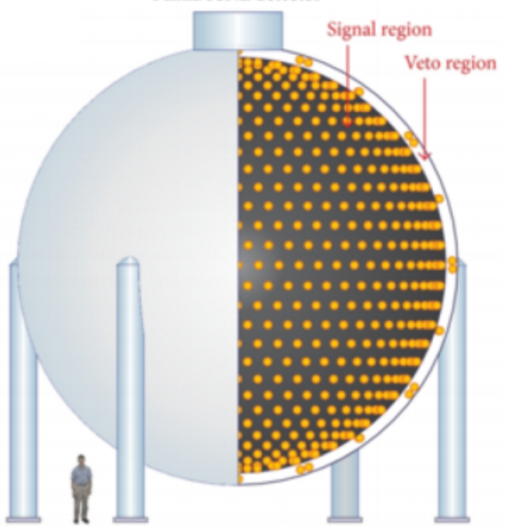


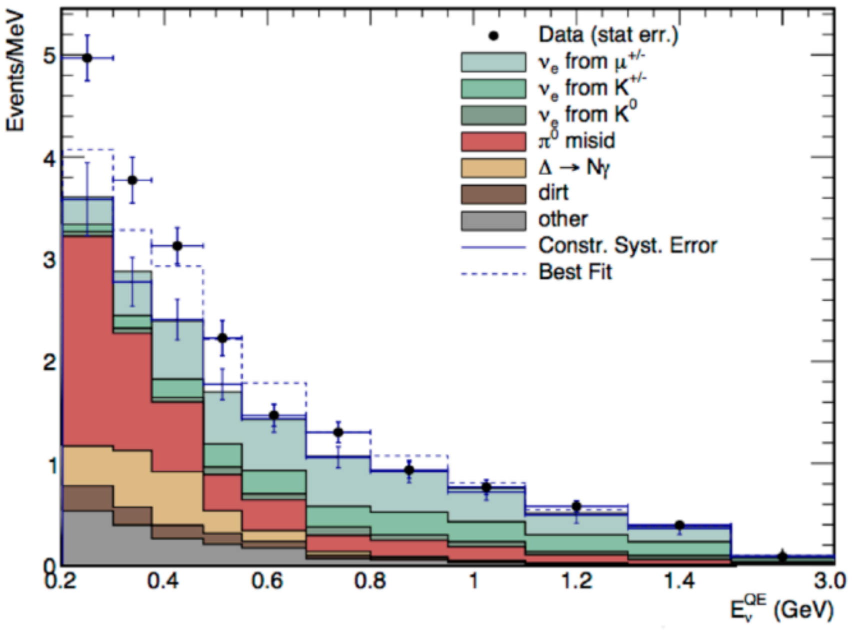


These experiments observe ν_e appearance at L/E ~ 1 km/GeV!

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

MiniBooNE (4.8σ)

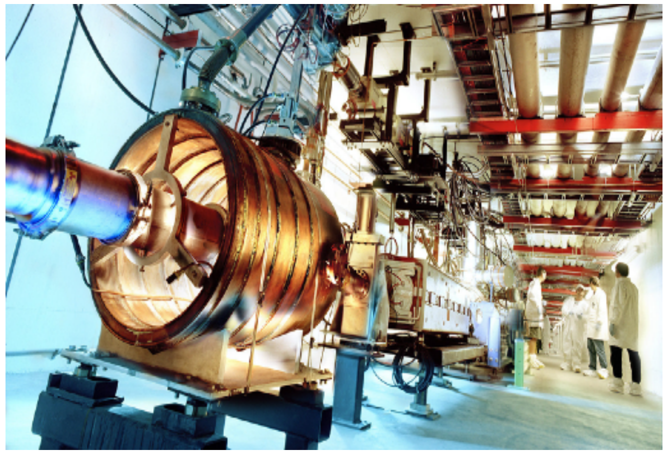


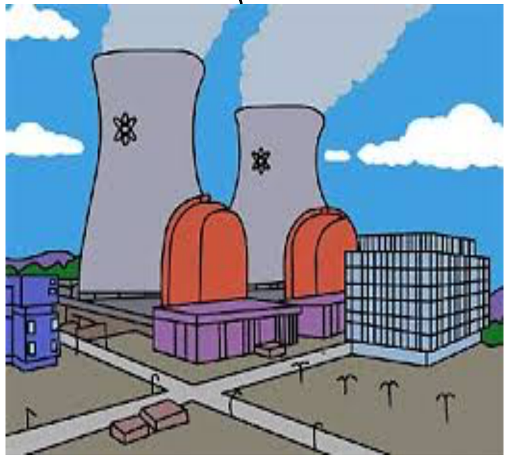


These are not alone, other interesting observations

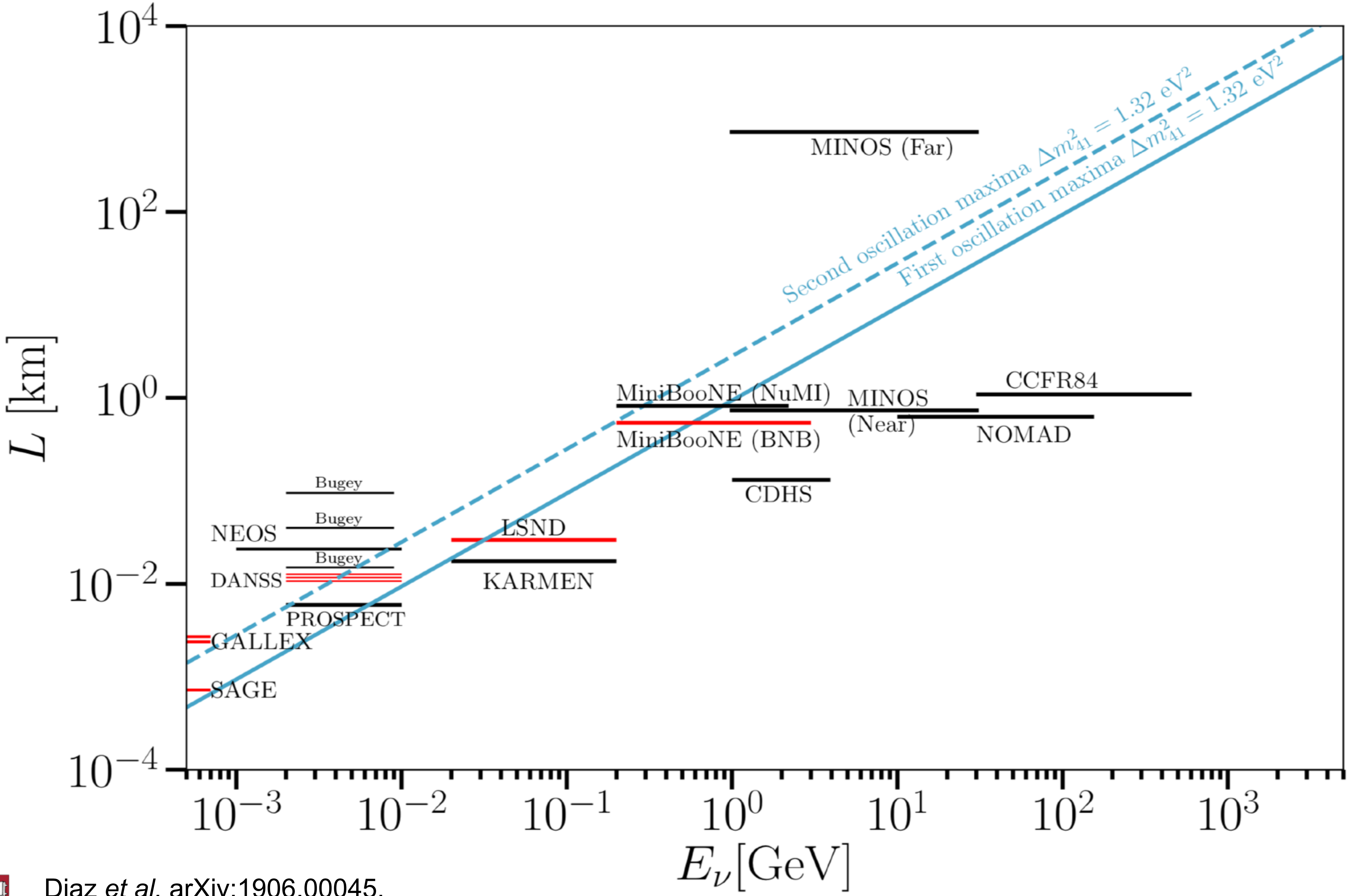
	$\nu_\mu \to \nu_e$	$\nu_\mu \to \nu_\mu$	$\nu_e \to \nu_e$
Neutrino	MiniBooNE (BNB) $\ast$ MiniBooNE(NuMI) NOMAD	SciBooNE/MiniBooNE CCFR CDHS MINOS IceCube	KARMEN/LSND Cross Section Gallium $\ast$
Antineutrino	LSND $\ast$ KARMEN MiniBooNE (BNB) $\ast$	SciBooNE/MiniBooNE CCFR MINOS IceCube	Bugey Daya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

$\ast$ $\Longrightarrow$ >2σ “signal”



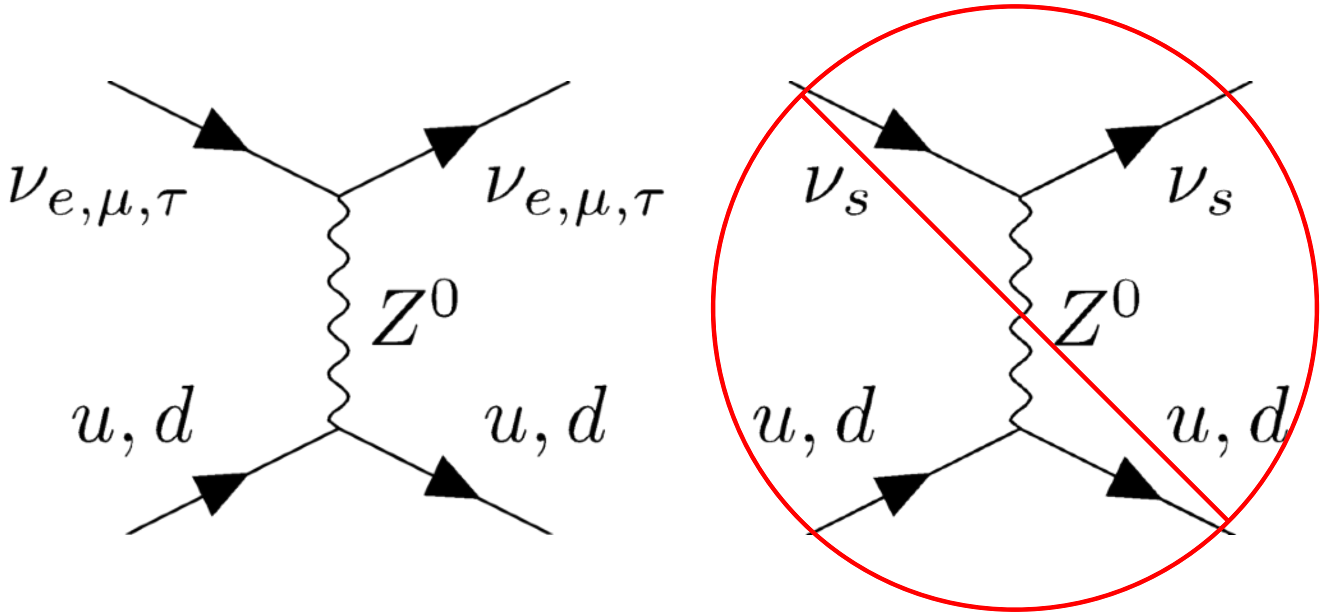


The anomalies lie ~ in a line

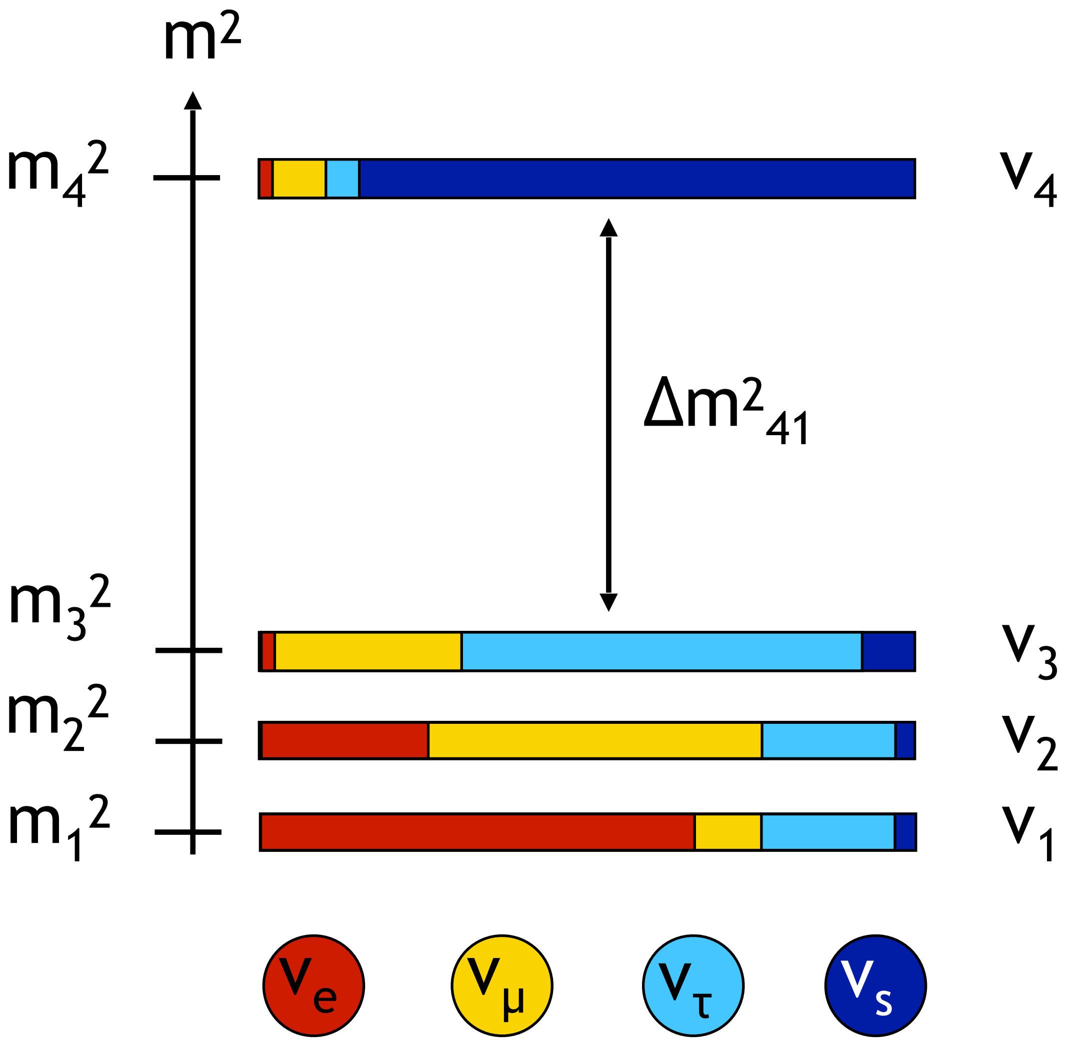


Diaz *et al.* arXiv:1906.00045,
Phys. Rep. 884 (2020) 1-59

Vanilla solution: light sterile neutrino



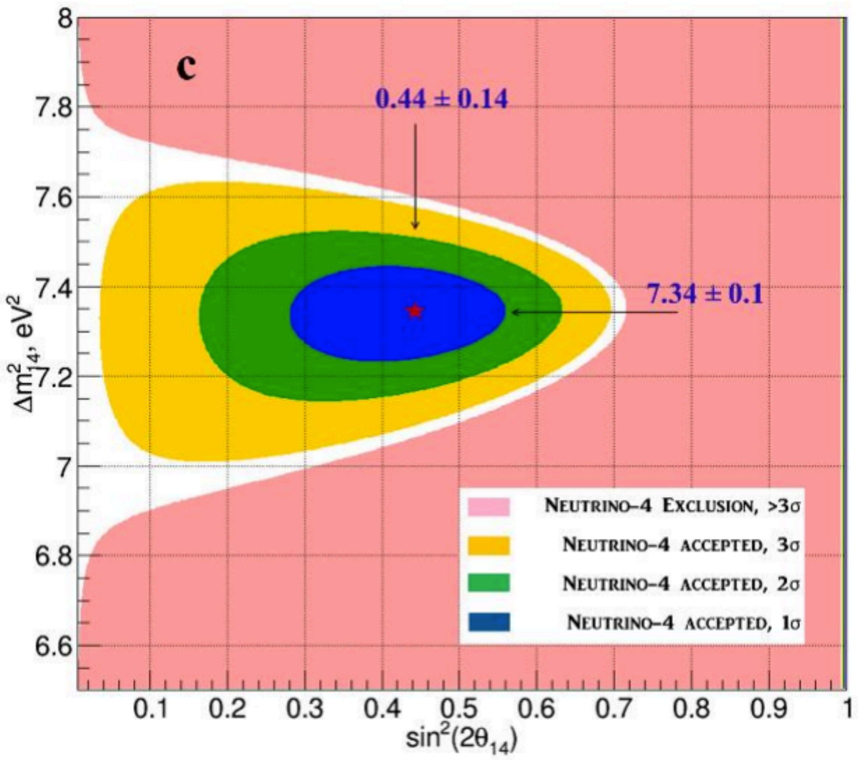
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2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

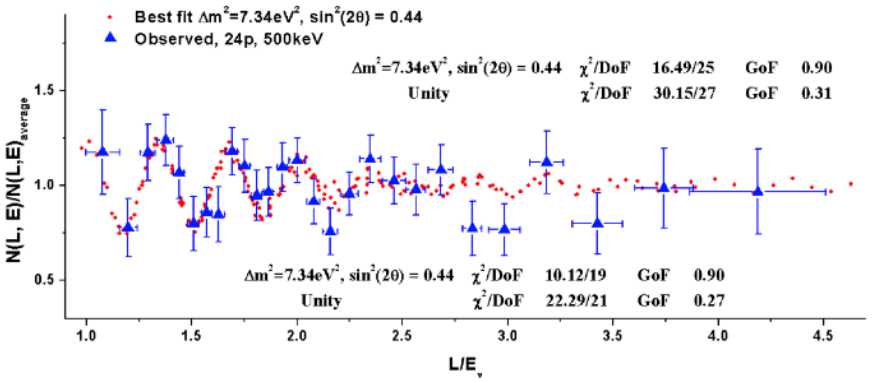


Assuming Normal Ordering

Results from electron-neutrino disappearance

Neutrino-4 arXiv:1809.10561

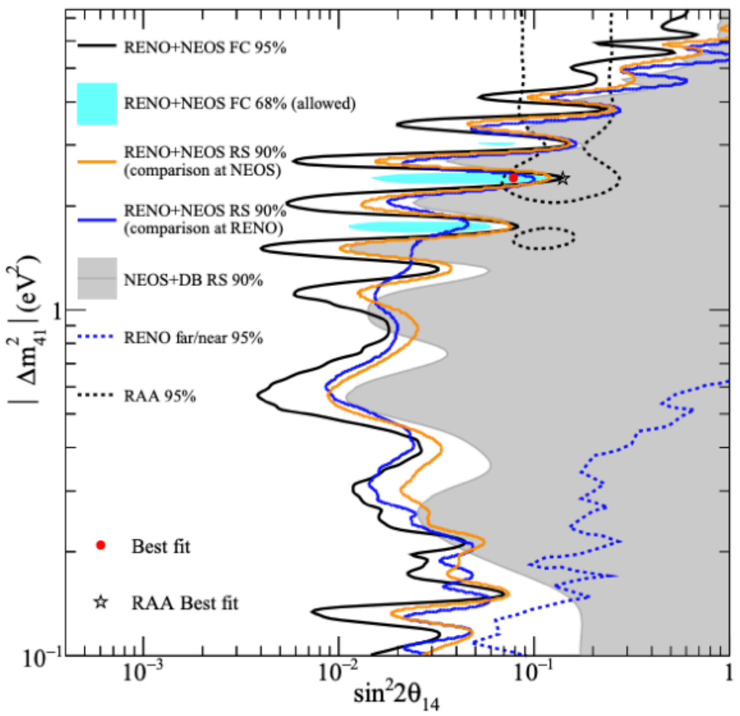




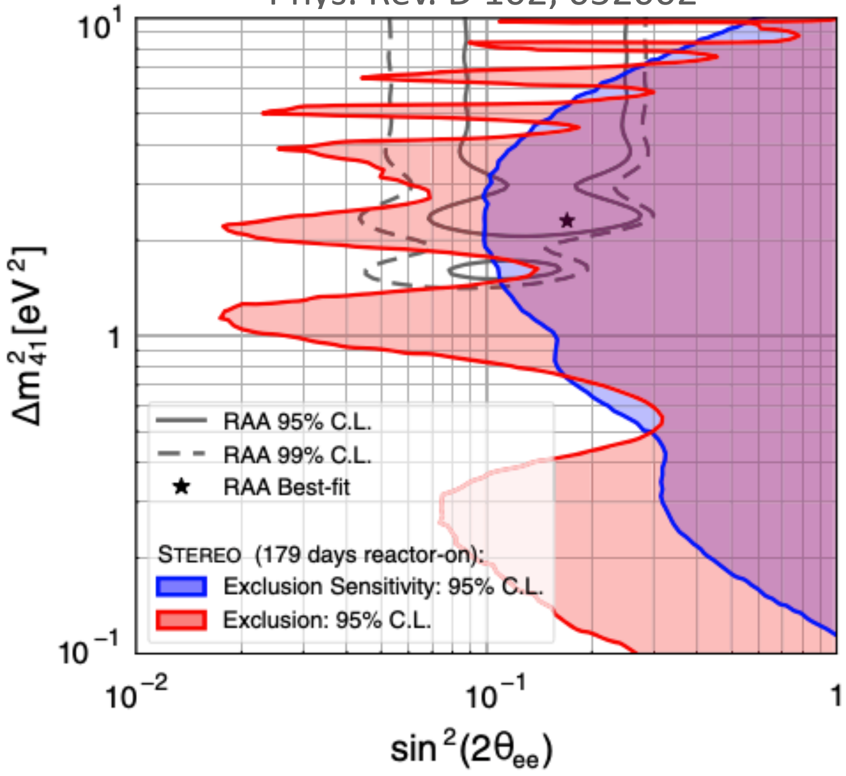
Wiggles or fluctuations?

See C. Giunti arXiv:2101.06785

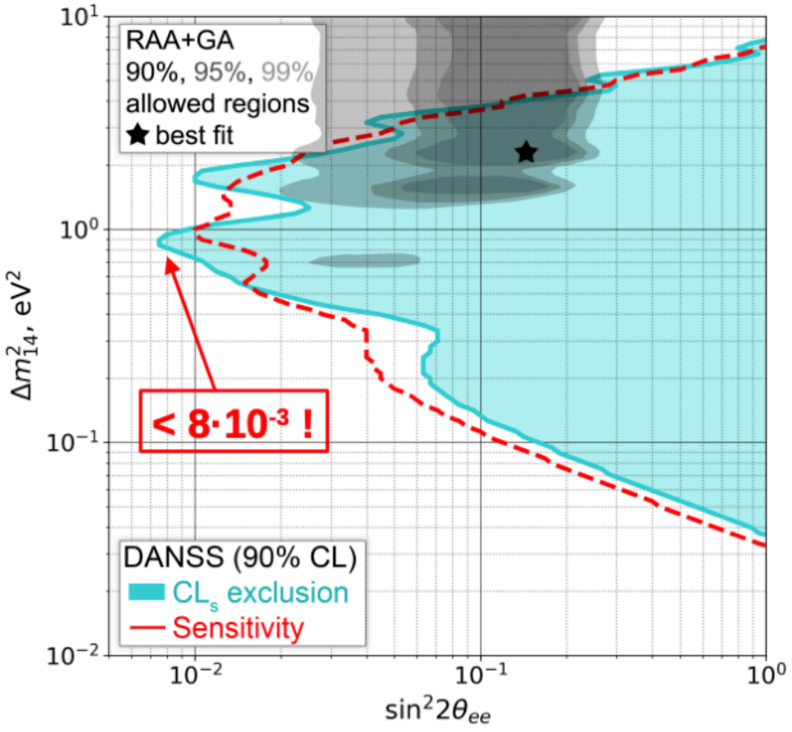
NEOS+RENO
arXiv:2011.00896



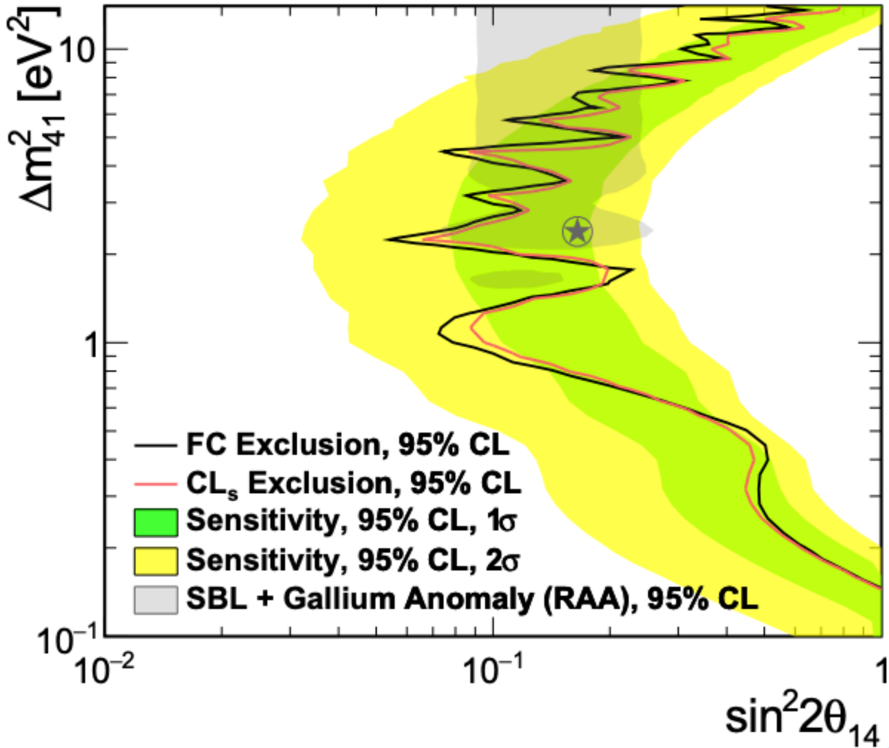
STEREO Collaboration
Phys. Rev. D 102, 052002



DANSS
See talk by Igor Alekseev



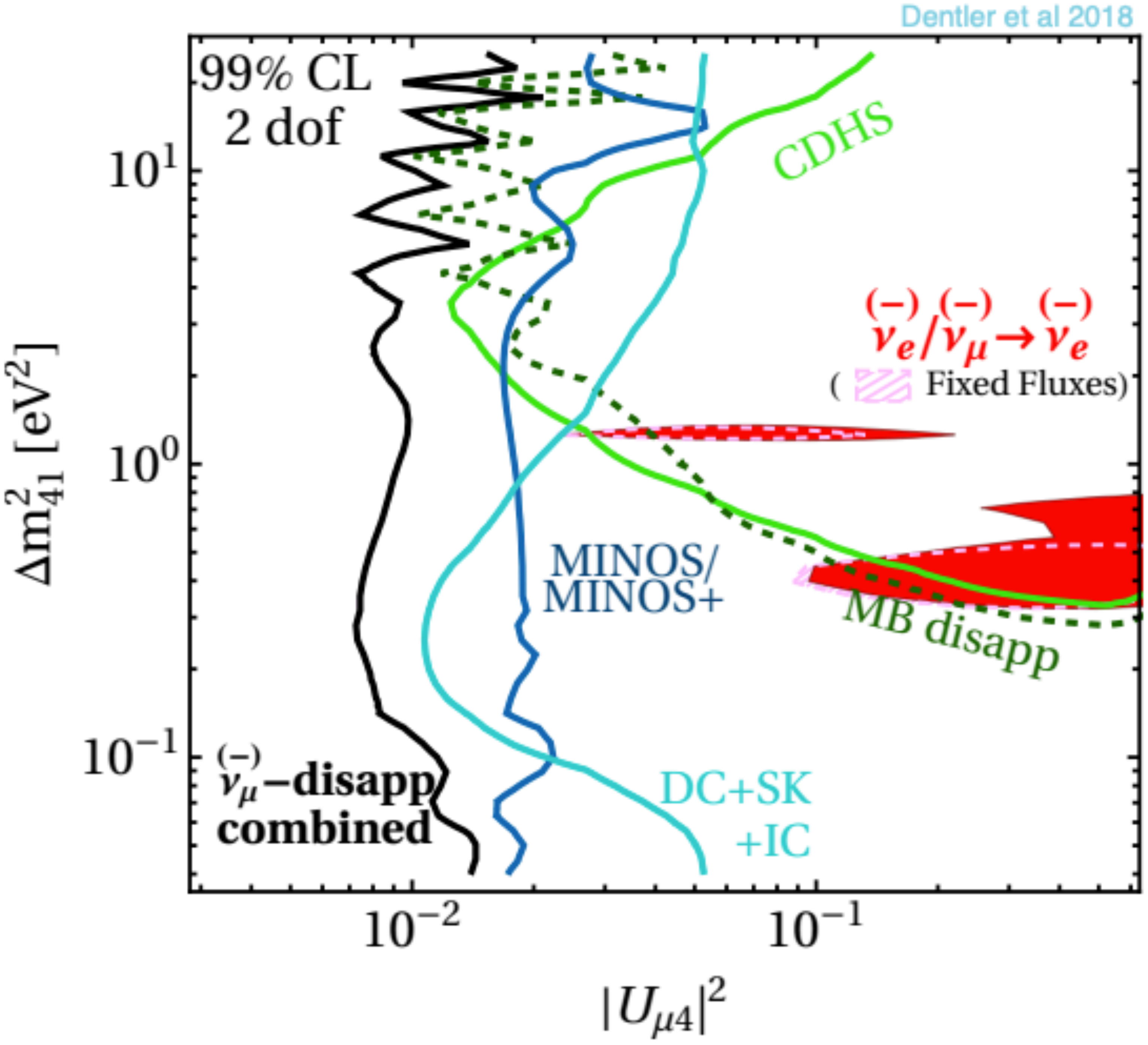
PROSPECT
Phys. Rev. D 103, 032001 (2021)



See poster by A. Minotti for a recent summary

See talk by d Galbinski for sensitivity of the Solid experiment

Results from muon-neutrino disappearance



Accelerator neutrinos

CDHS, MiniBooNE, NOvA NC, MINOS/MINOS+

Atmospheric neutrinos

IceCube, SK, DeepCore

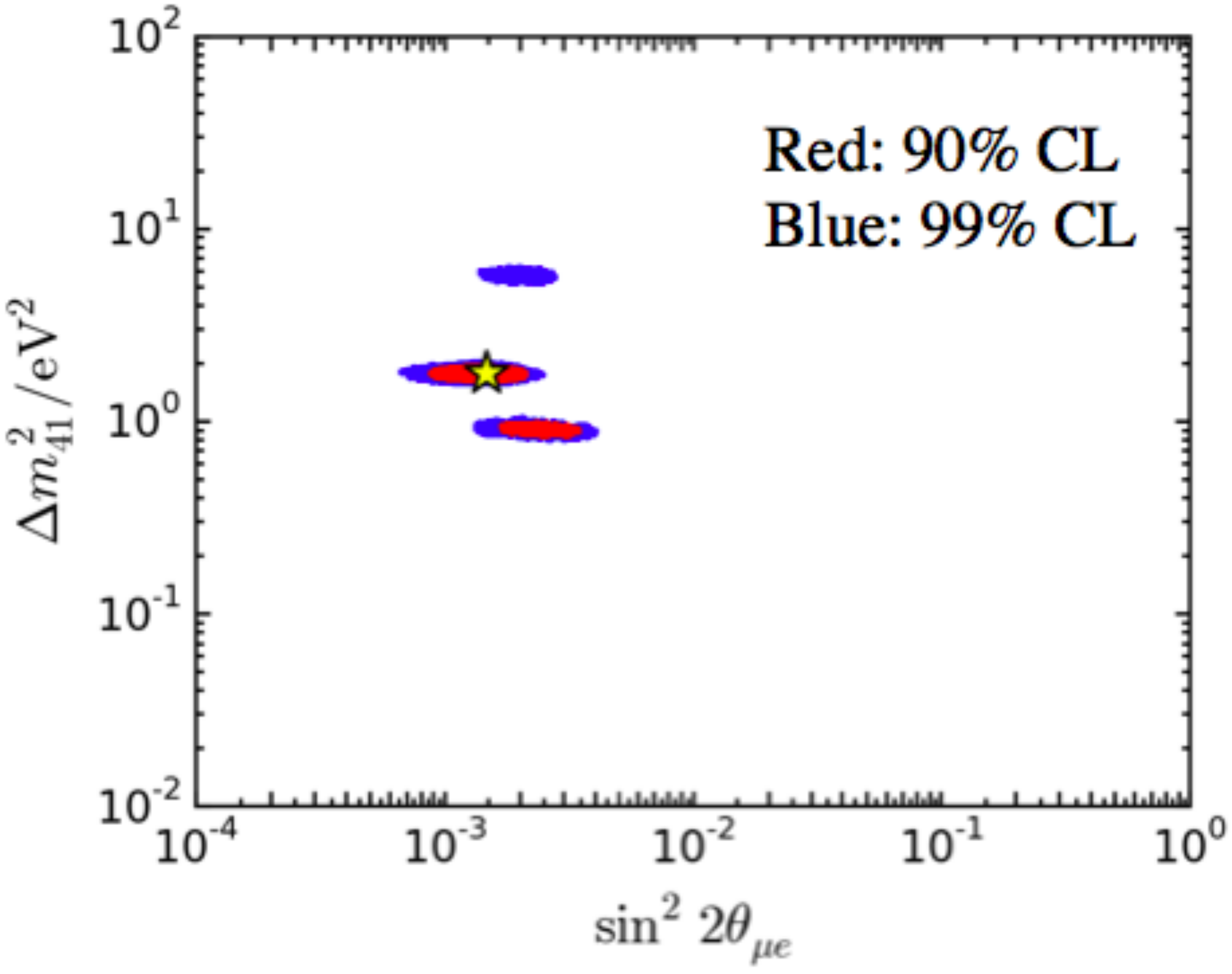
No anomaly there

Very strong constraint

Dominated by IceCube and MINOS/MINOS+, then CDHS and MiniBooNE

See talk by J. Hewes for recent results from Nova

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)

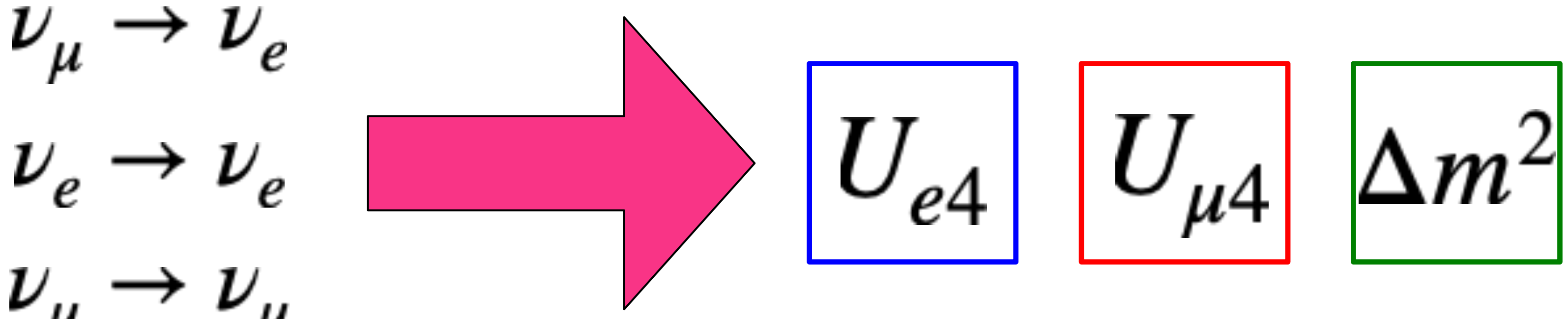
χ^2_{null} : 359.15 (315 dof)

$\Delta\chi^2$: 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!



$\nu_\mu \to \nu_e$

$\nu_e \to \nu_e$

$\nu_\mu \to \nu_\mu$

$\boxed{U_{e4}}$ $\boxed{U_{\mu4}}$ $\boxed{\Delta m^2}$

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

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

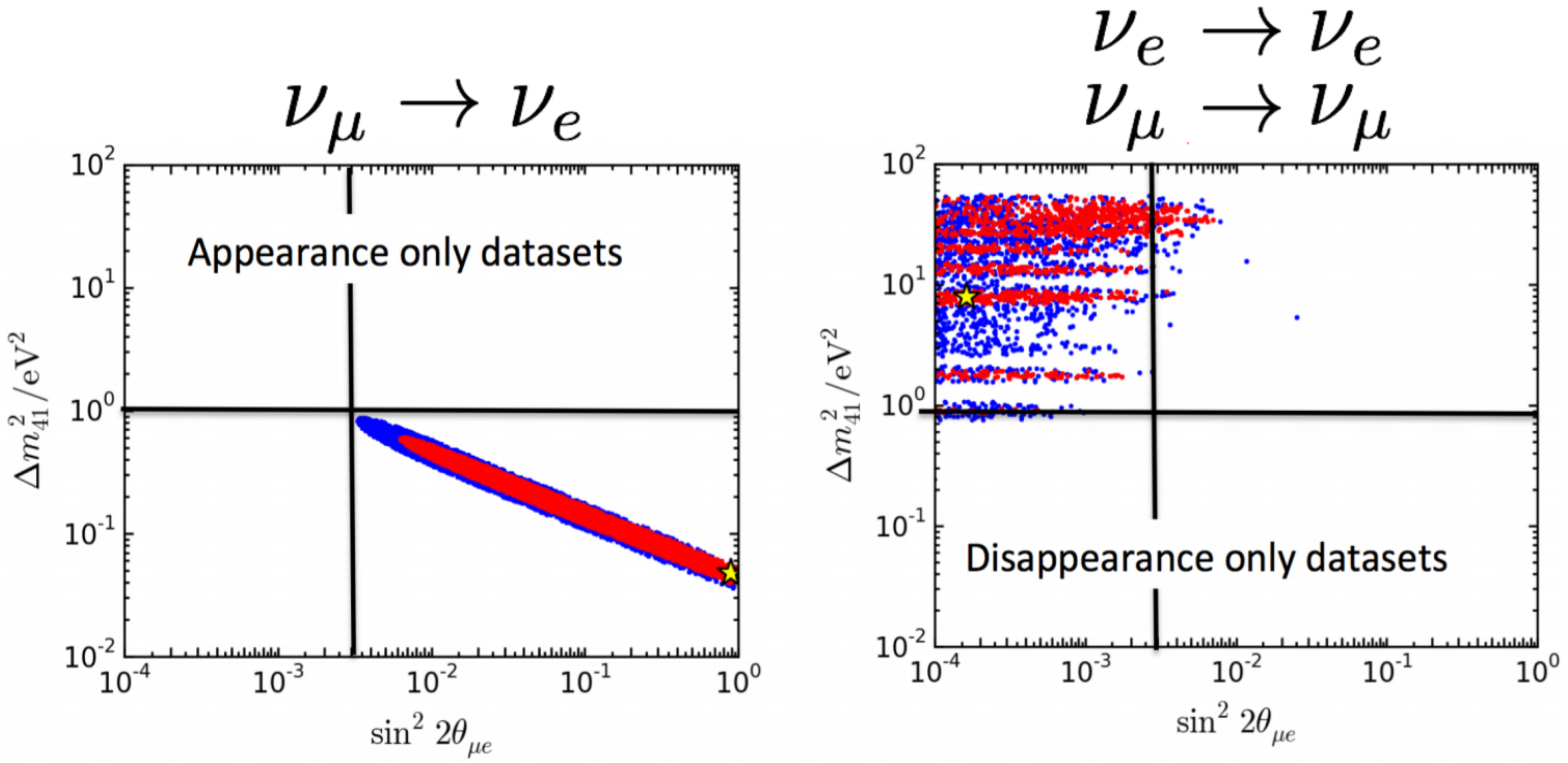
$$P_{\nu_\mu\to\nu_\mu} = 1 - 4\boxed{(1-|U_{\mu4}|^2)|U_{\mu4}|^2}\sin^2(1.27\boxed{\Delta m^2_{41}}L/E)$$

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

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

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

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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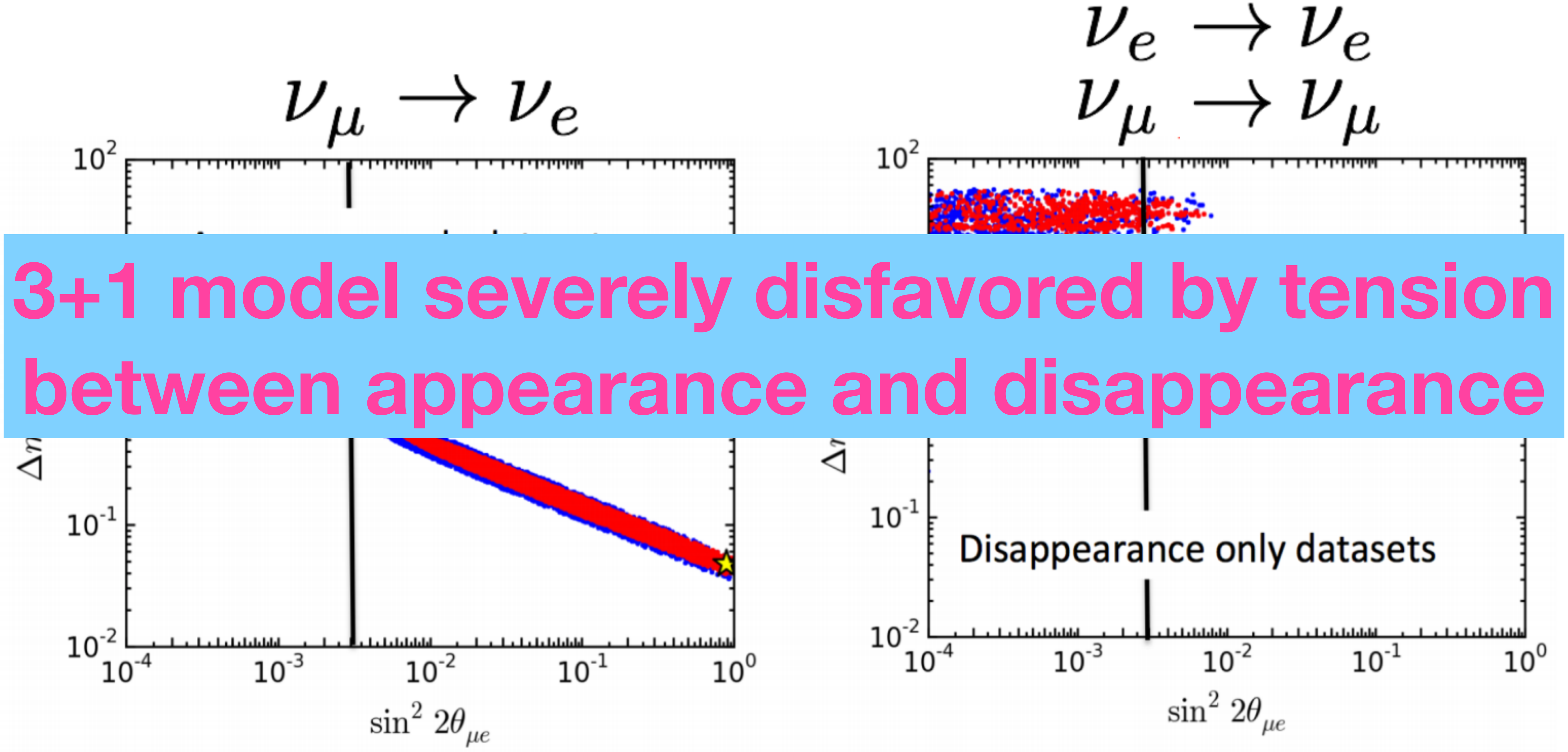
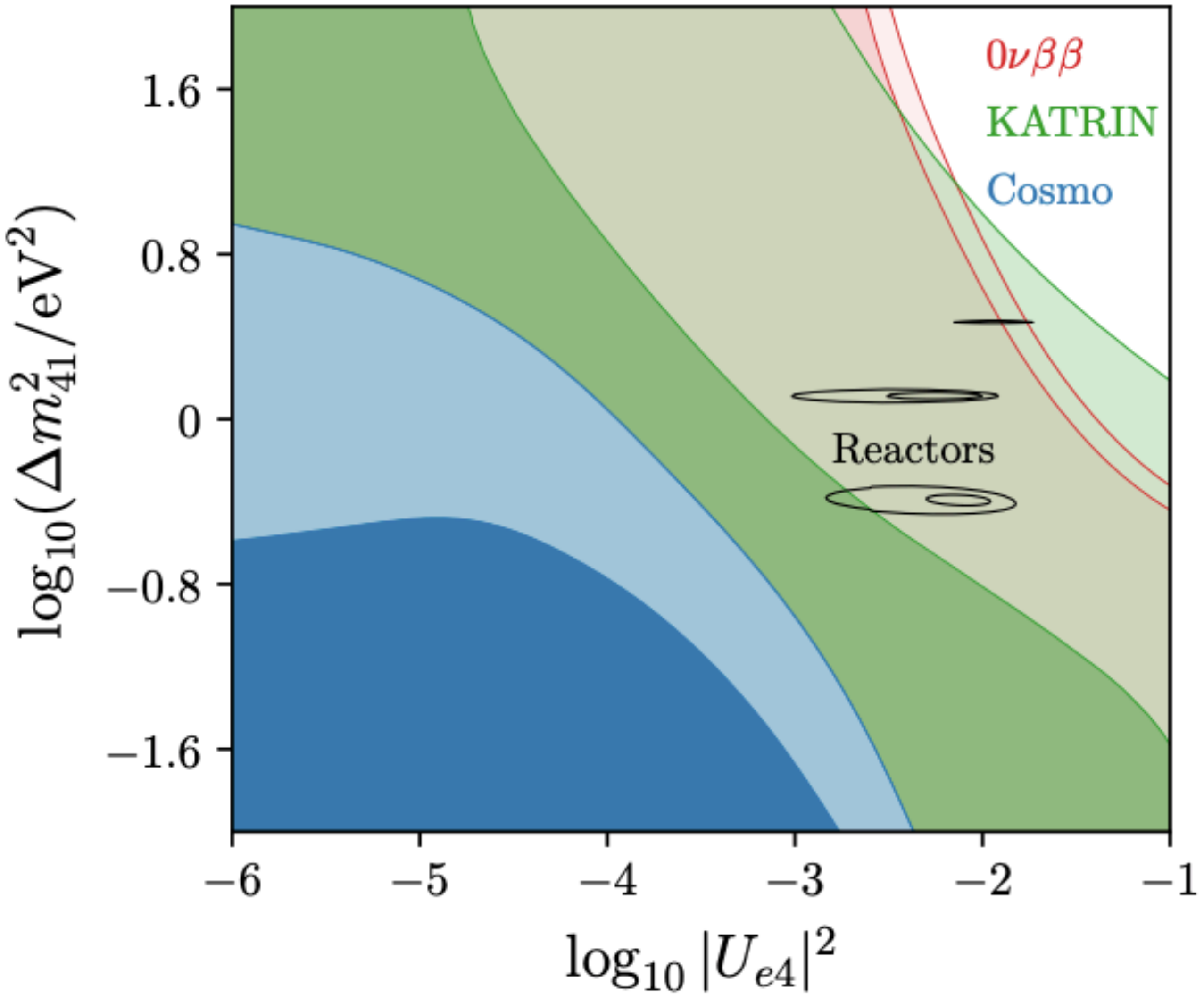


3+1 model severely disfavored by tension between appearance and disappearance

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.

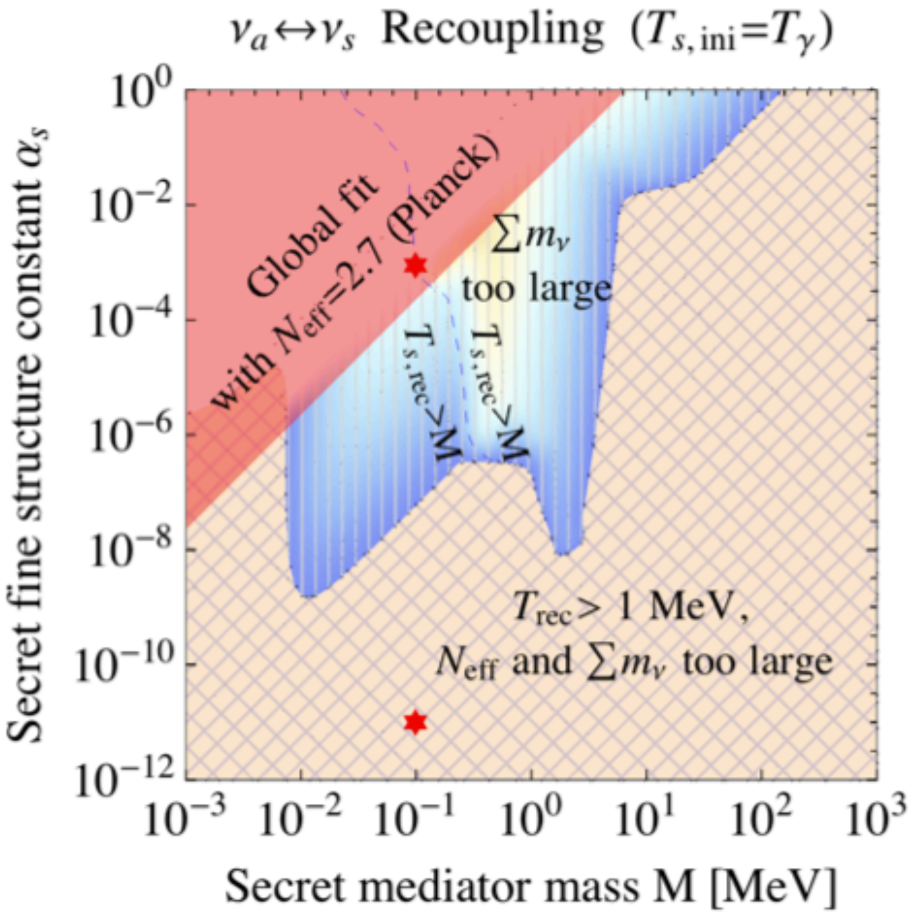
Let’s not forget cosmology!

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



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

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



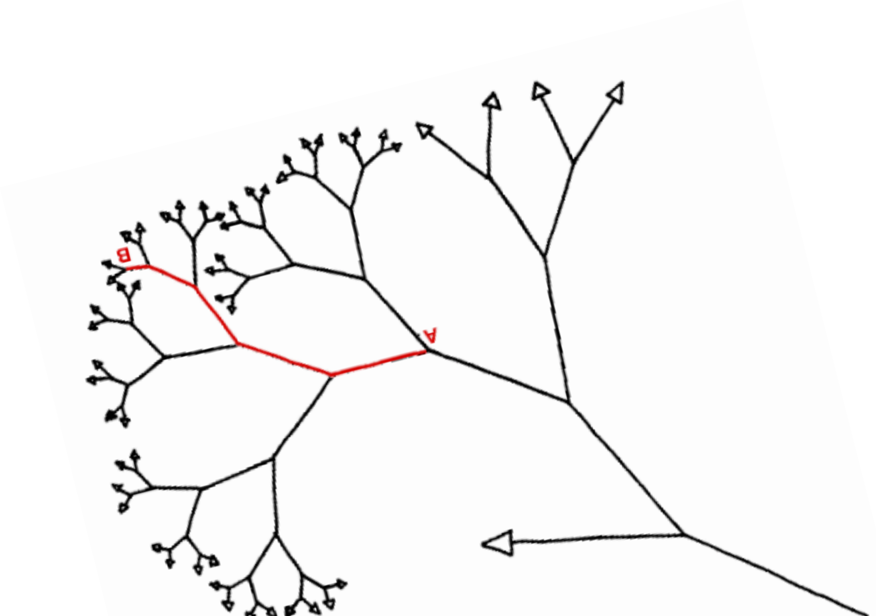
Dasgupta & Kopp 2014; Chu, Dasgupta & Kopp 2015 Saviano et al. 2014; Mirrizi et al. 2015;
Cherry, Friedland & Shoemaker 2016; Chu et al. 2018
<u>See talk by Yvonne Y. Y. Wong at Neutrino 2020 for summary</u>

Outline

- The need for more than three neutrinos and *more*
- The garden of forking paths
- Outlook

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 that something is missing.

Indications of new neutrino oscillations

Indications of additional new physics

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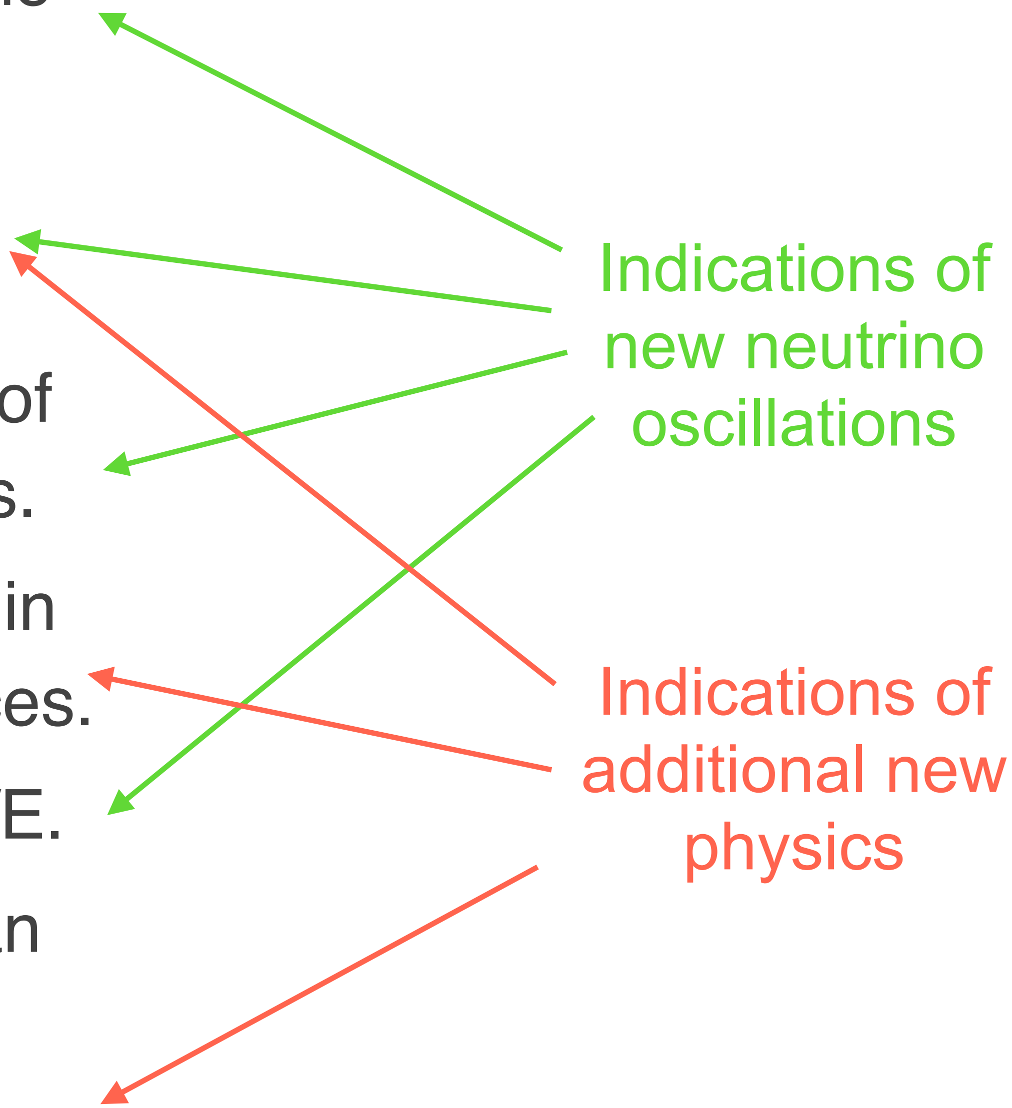
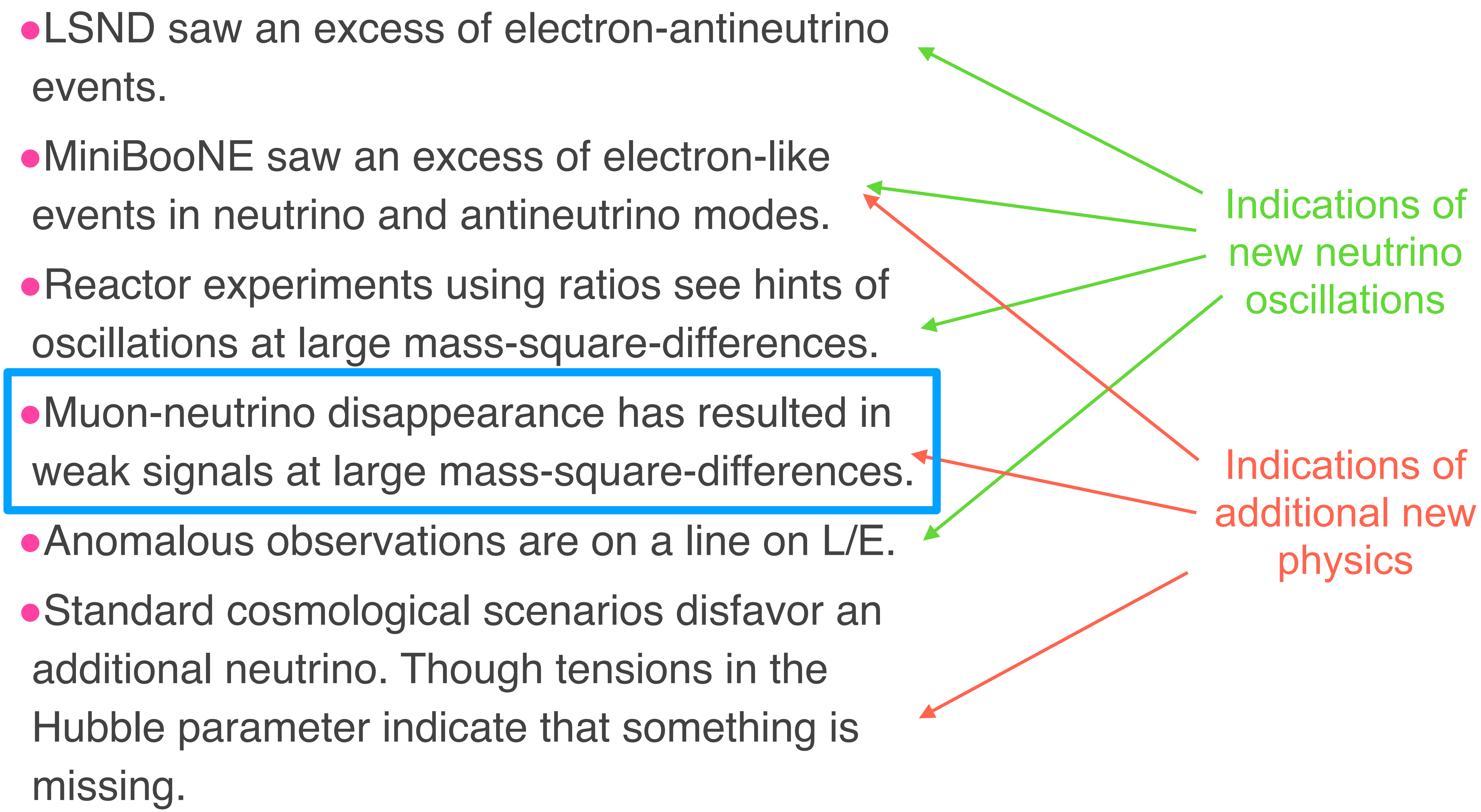


Indications of new neutrino oscillations

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.

Stepping back: What do we know?



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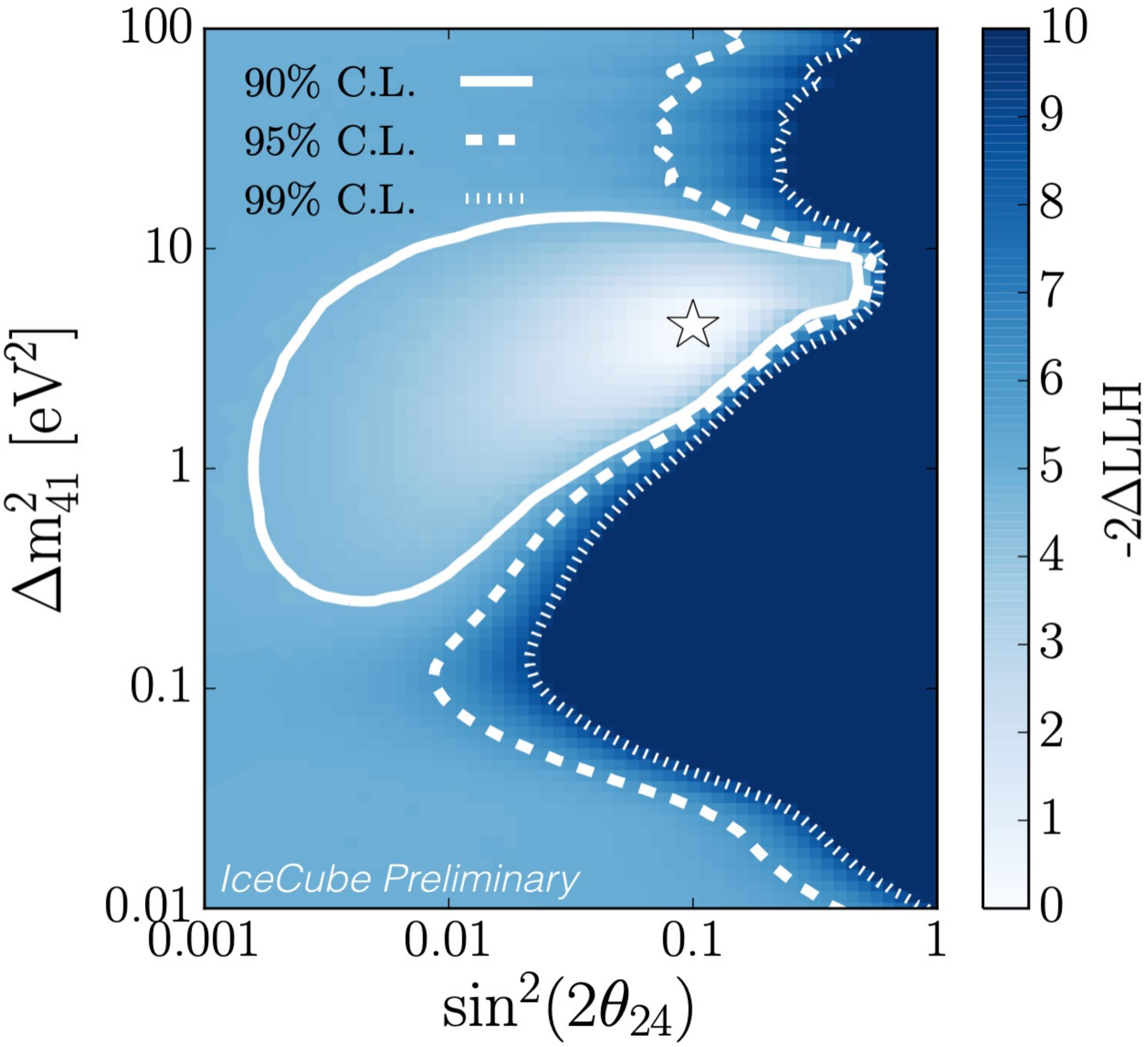
IceCube Hints

- ❖Best fit:

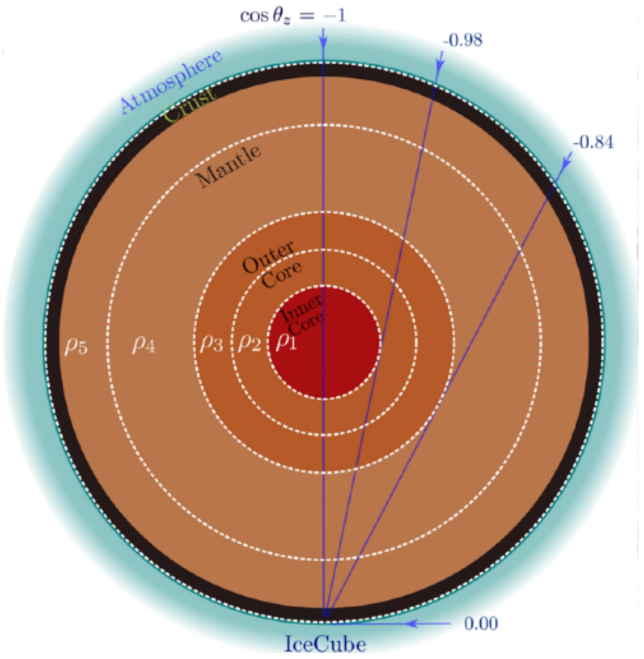
$$\Delta m^2_{41} = 4.47^{+3.53}_{-2.08}\,\mathrm{eV}^2$$

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

- ❖Sterile neutrino hypothesis is preferred to null
- ❖Null is rejected at 8% p-value

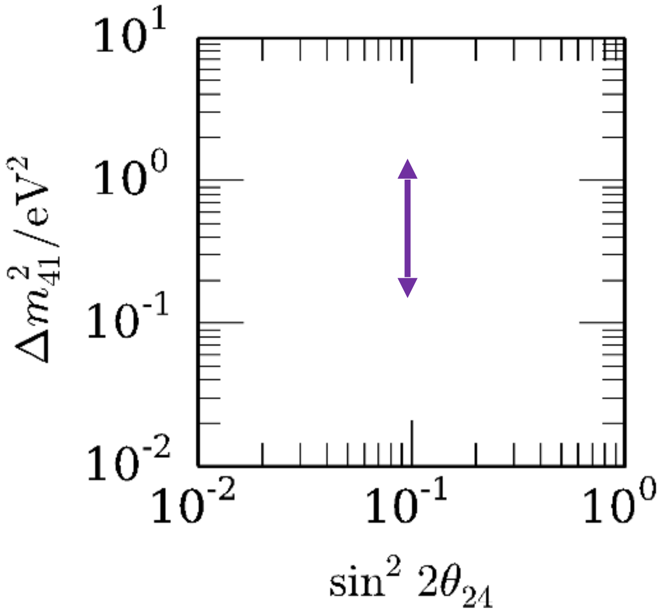


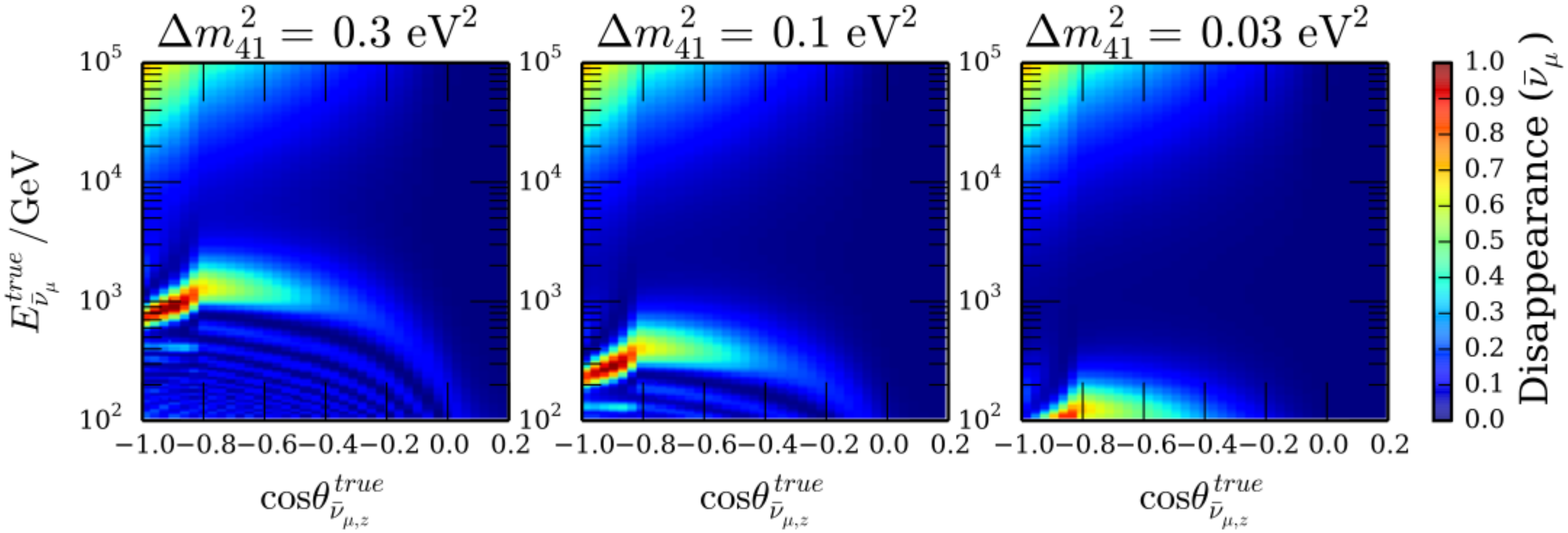
How does the IceCube analysis work?



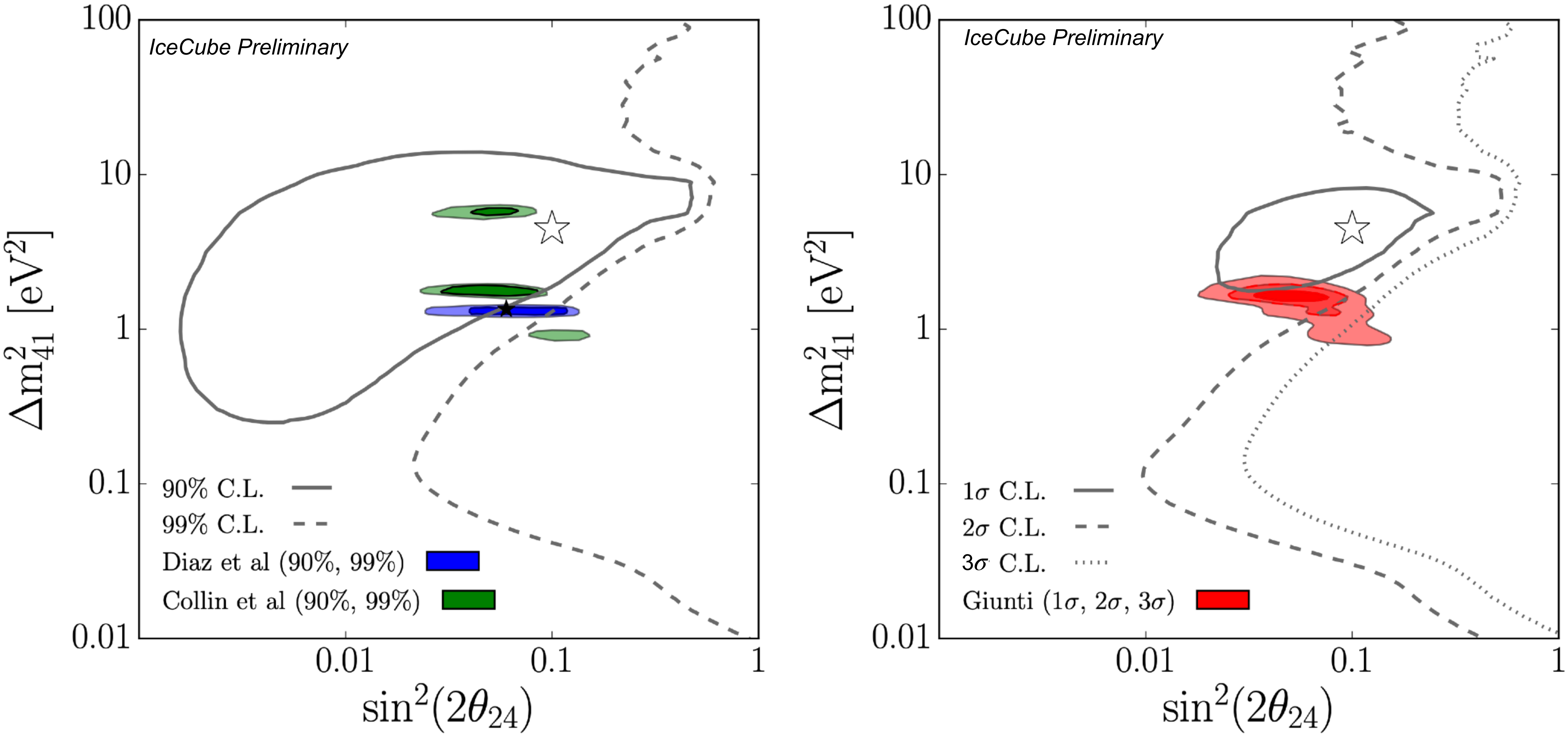
We measure two things:
- length (direction)
- energy

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

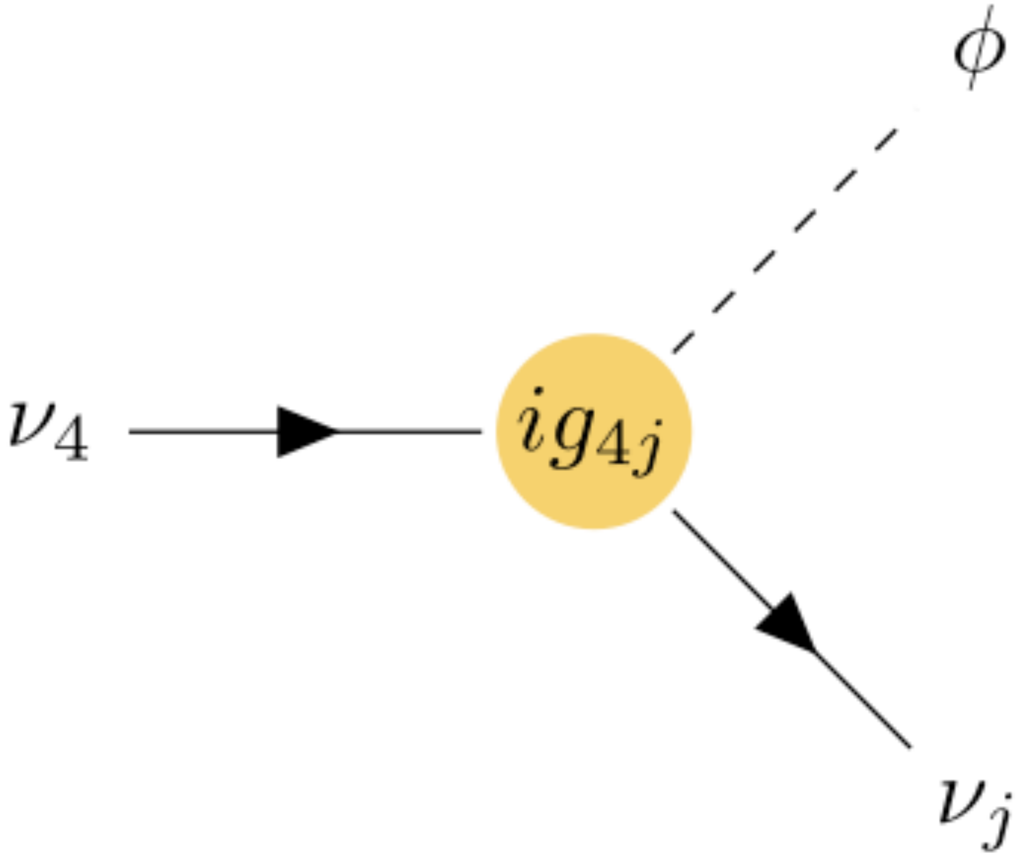
Reexamining IceCube

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

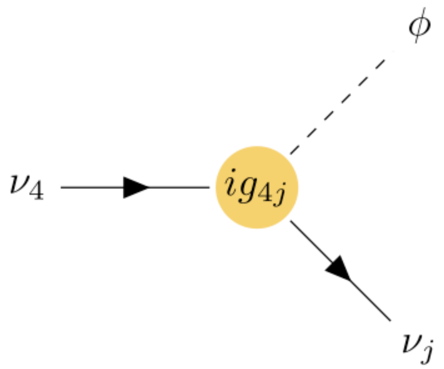
Moss et al https://arxiv.org/abs/1711.05921
Dentler *et al* https://arxiv.org/abs/1911.01427
Gouvea *et al* https://arxiv.org/abs/1911.01447



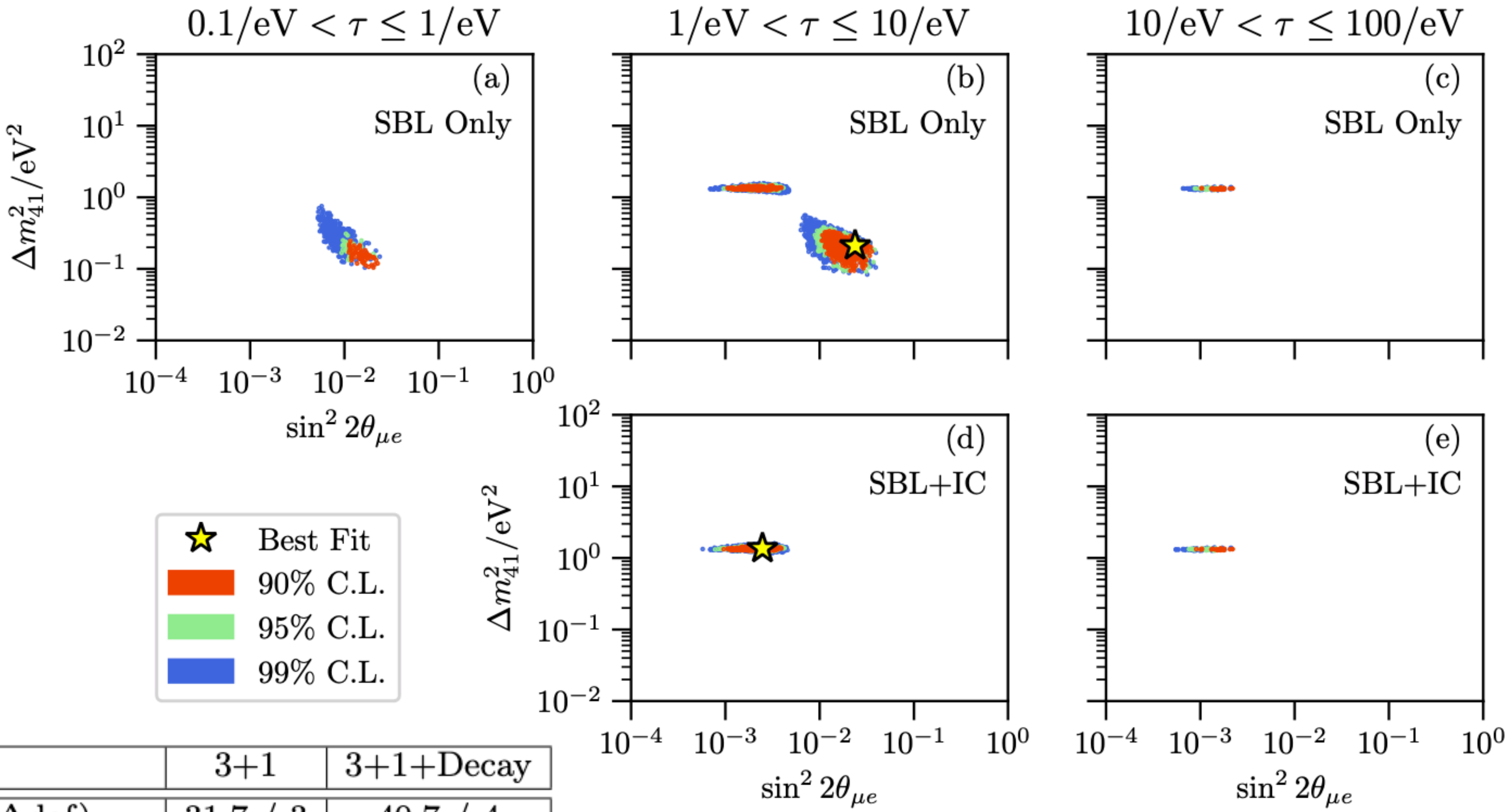
$$\tau = \frac{16\pi}{g^2 m_4}$$

Decay can be visible or invisible.

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



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

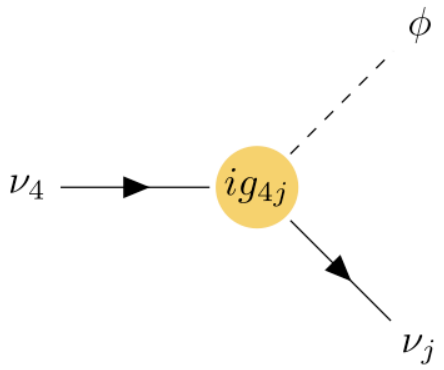


	3+1	3+1+Decay
$(\Delta\chi^2/\Delta\text{dof})_{\text{Null}}$	31.7 / 3	40.7 / 4
$(\Delta\chi^2/\Delta\text{dof})_{3+1}$	–	9.1 / 1

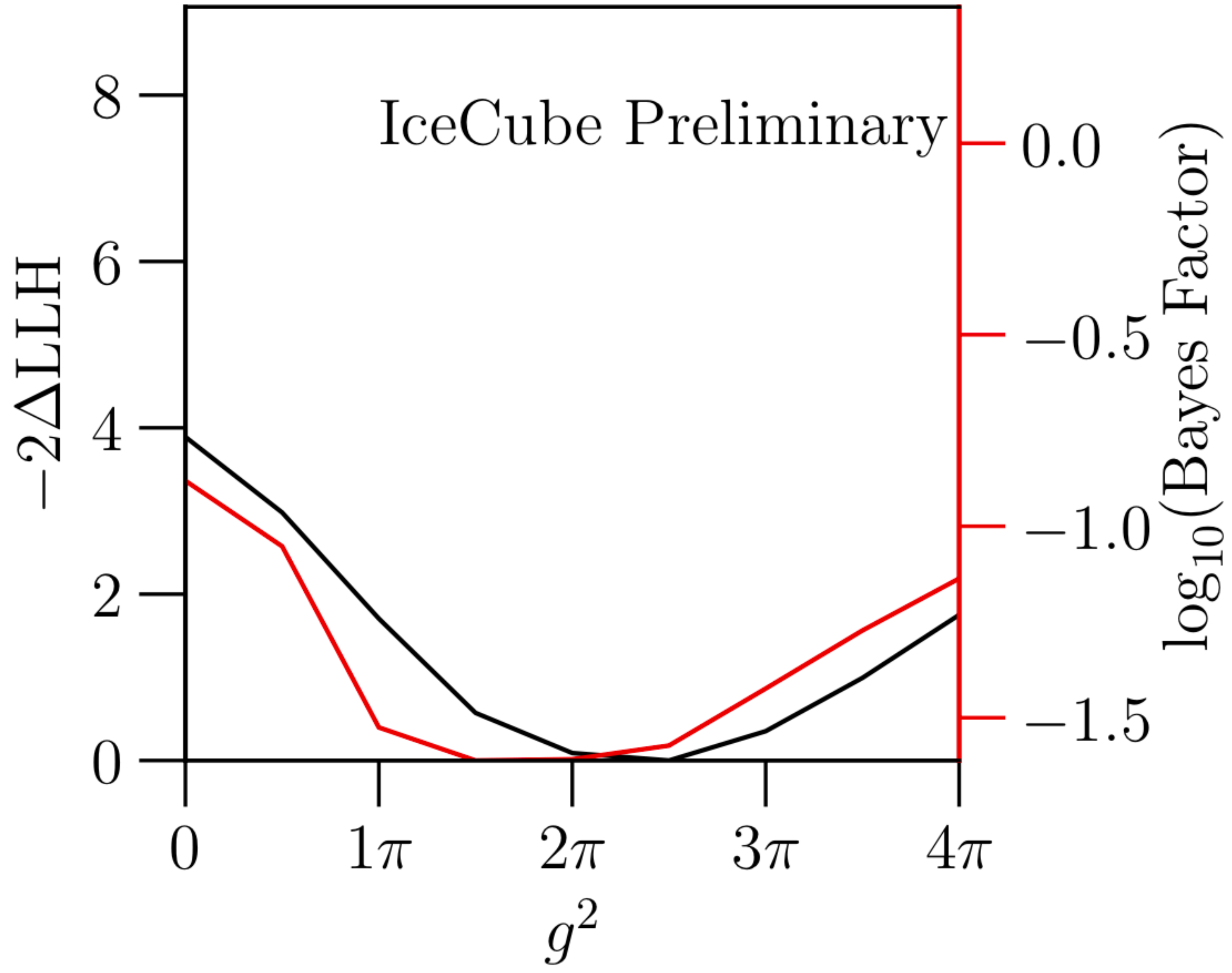
Moss et al https://arxiv.org/abs/1711.05921
Moulai et al https://arxiv.org/abs/1910.13456

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

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



Results of 3+1+Decay in IceCube



No Decay : g = 0

Does IceCube prefer it? YES!

See talk by G. Parker for details

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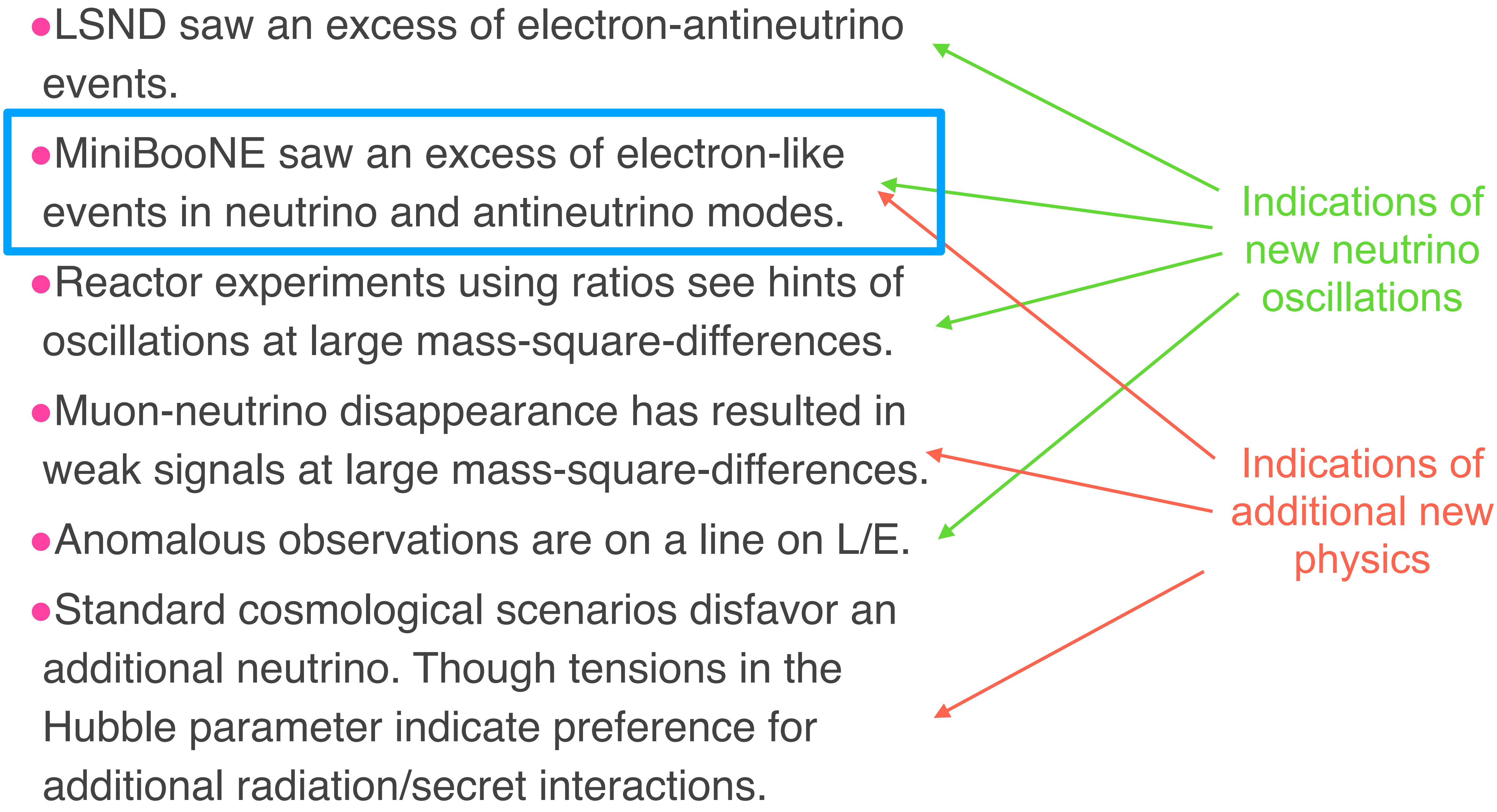

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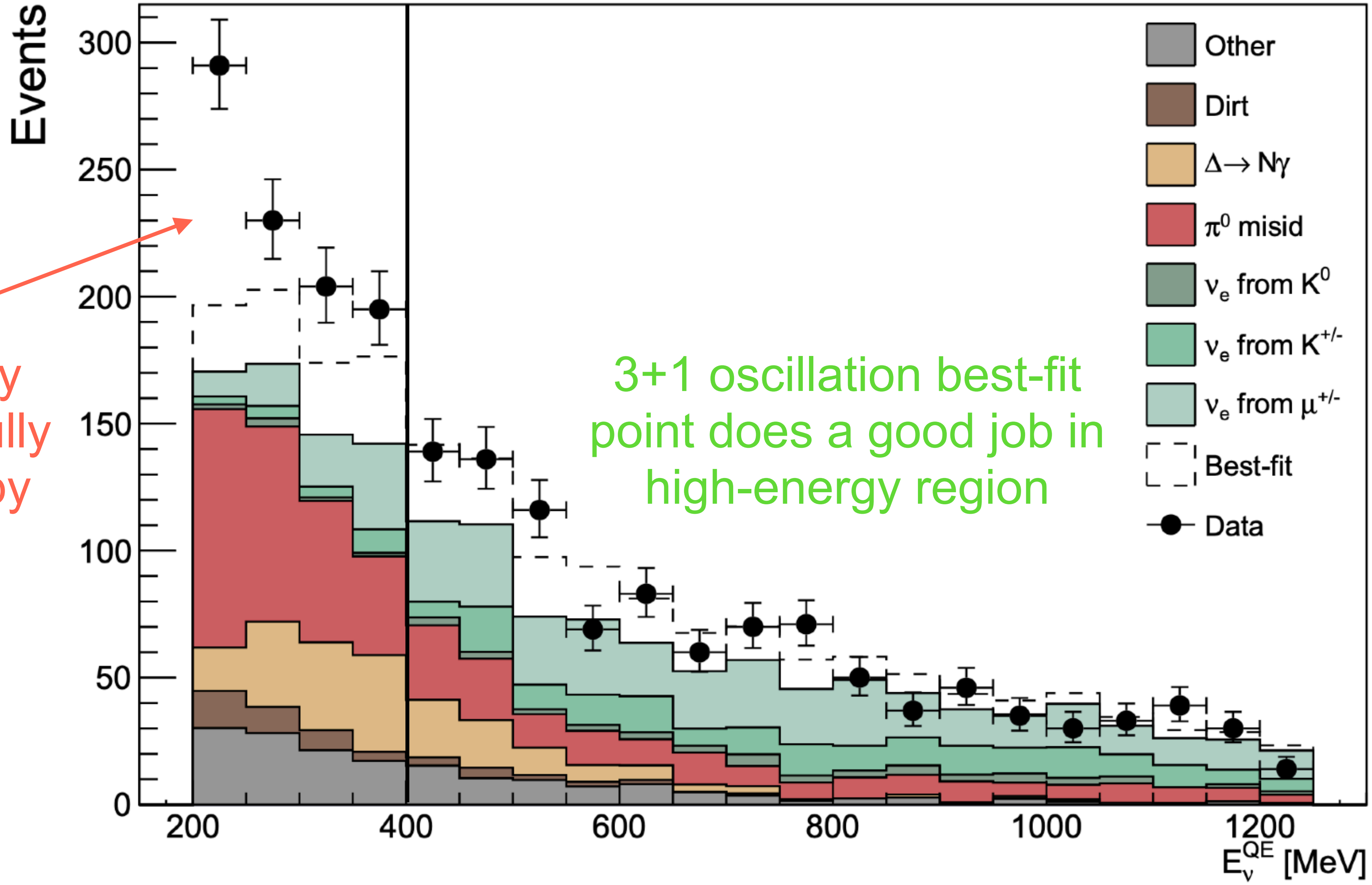
- Anomalous observations are on a line on L/E.
- Standard cosmological scenarios disfavor an additional neutrino. Though tensions in the Hubble parameter indicate preference for additional radiation/secret interactions.

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

3+1 oscillation best-fit point does a good job in high-energy region

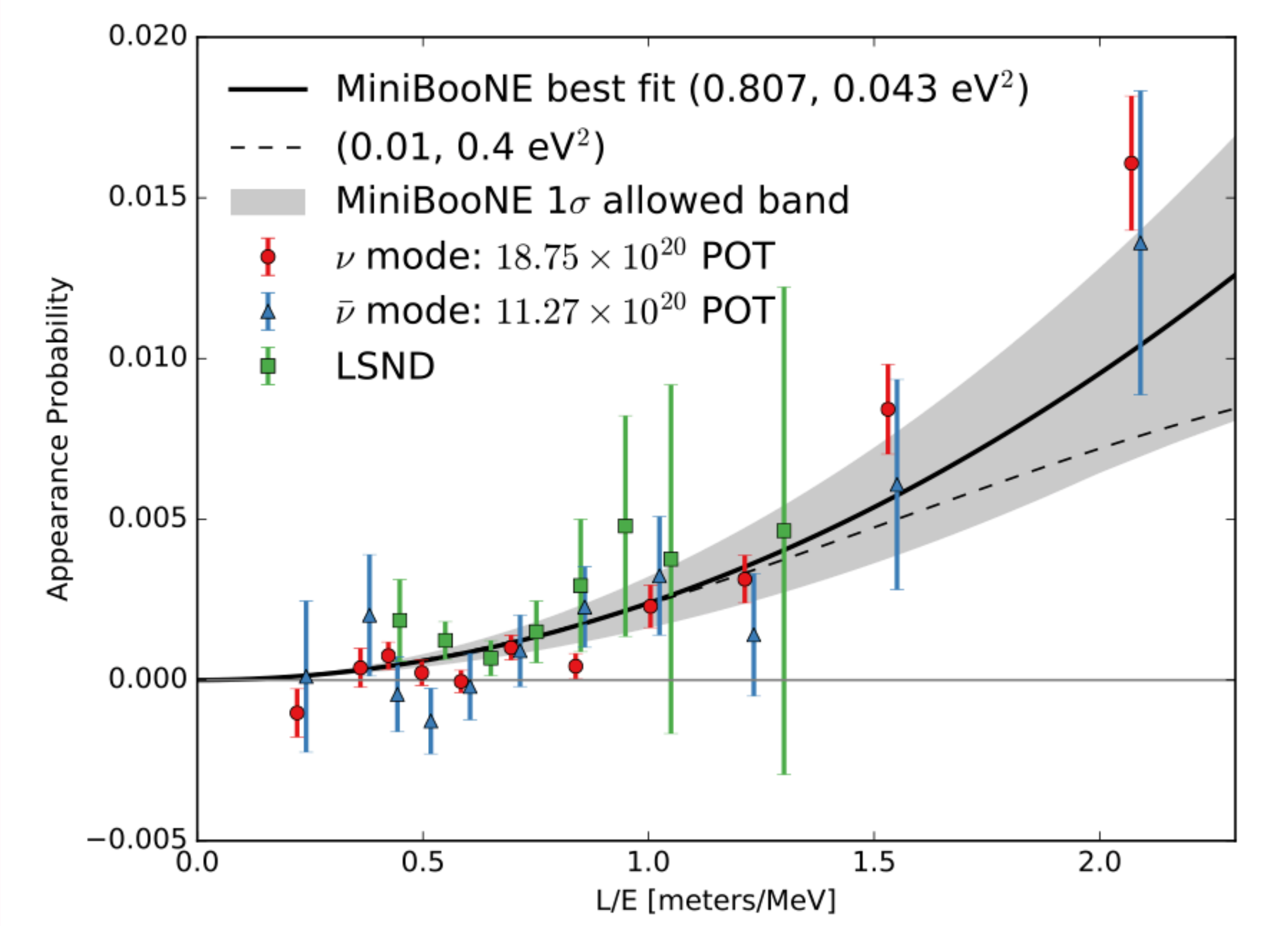
MiniBooNE Collaboration 2006.16883

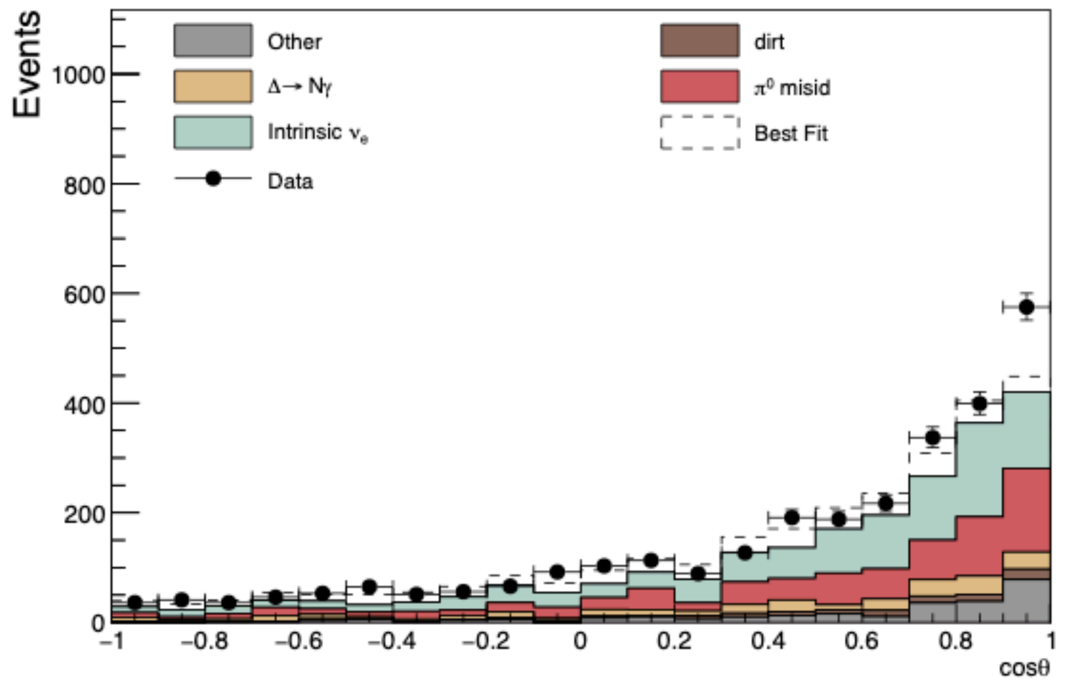
Indications of additional new physics?

Indications of new neutrino oscillations?

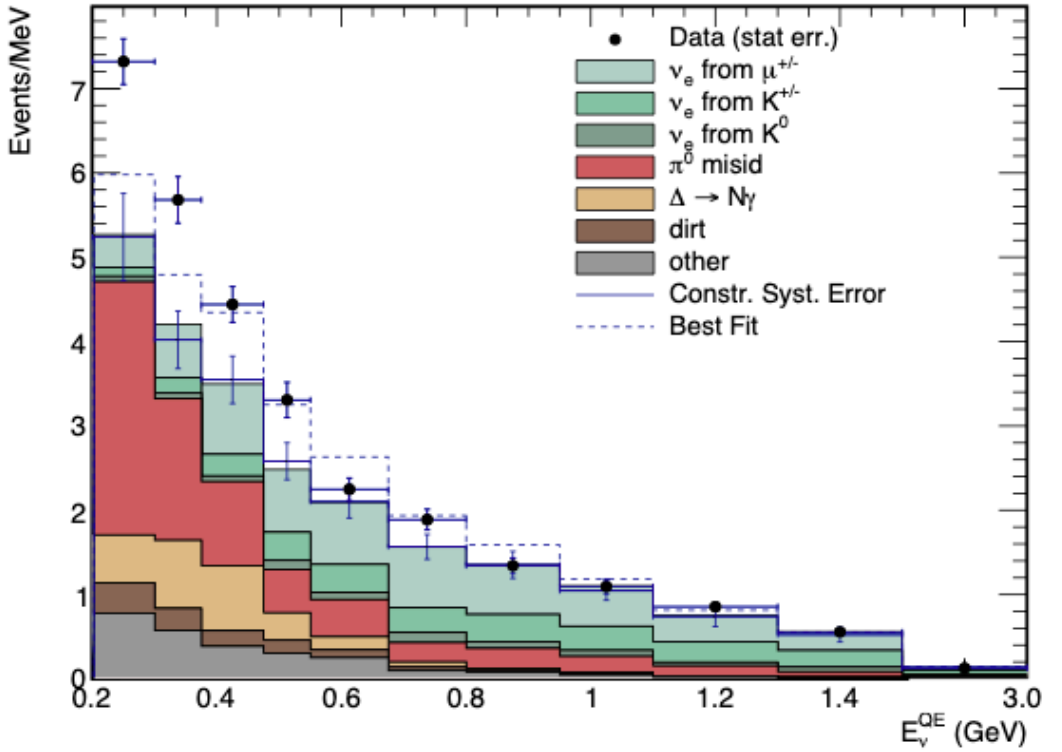
Switching gears: Changing how we look at things

This is useful if we are after an oscillation explanation





In other cases we need to fit these two!

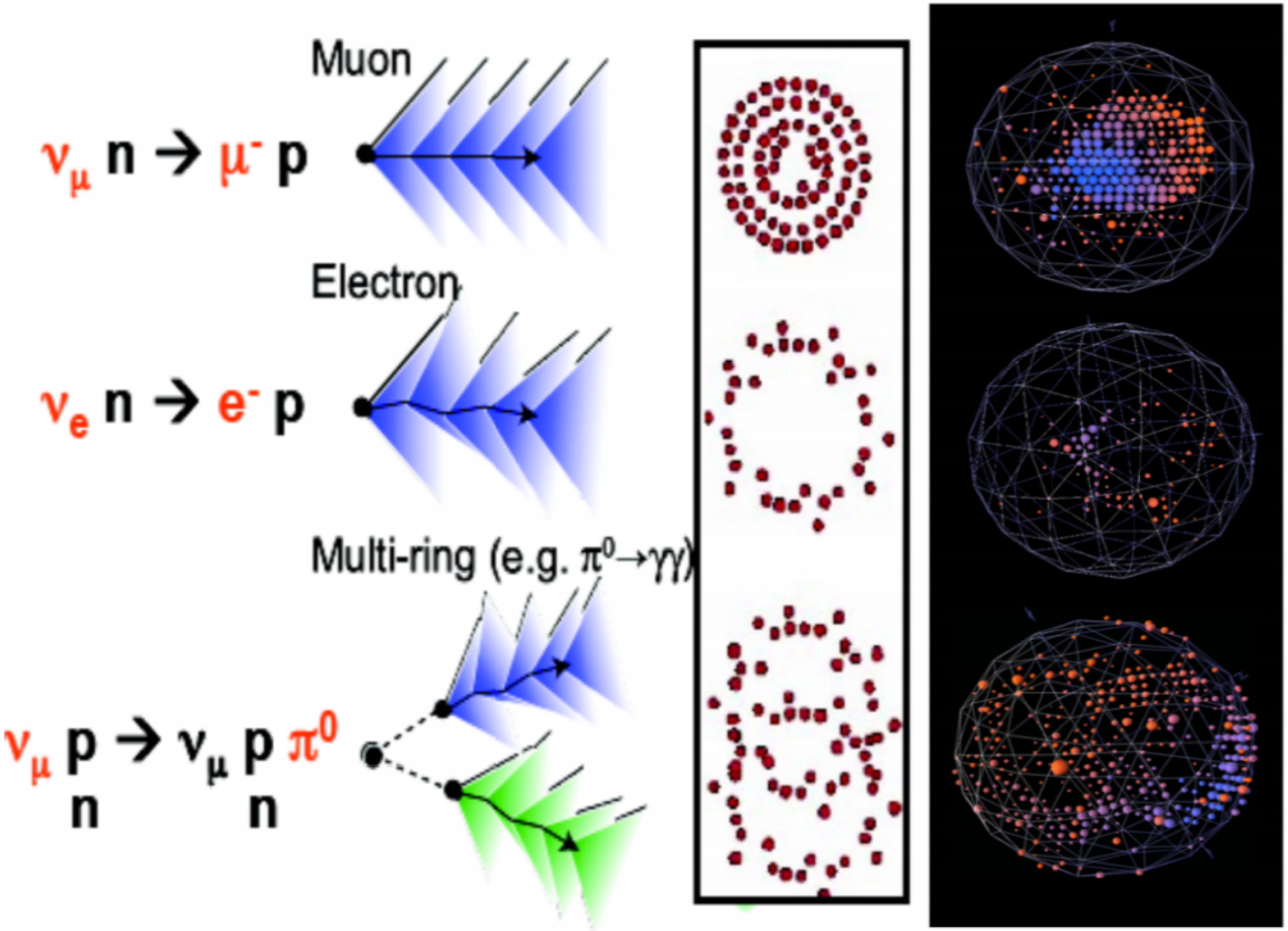


MiniBooNE Collaboration https://arxiv.org/abs/2006.16883

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!

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

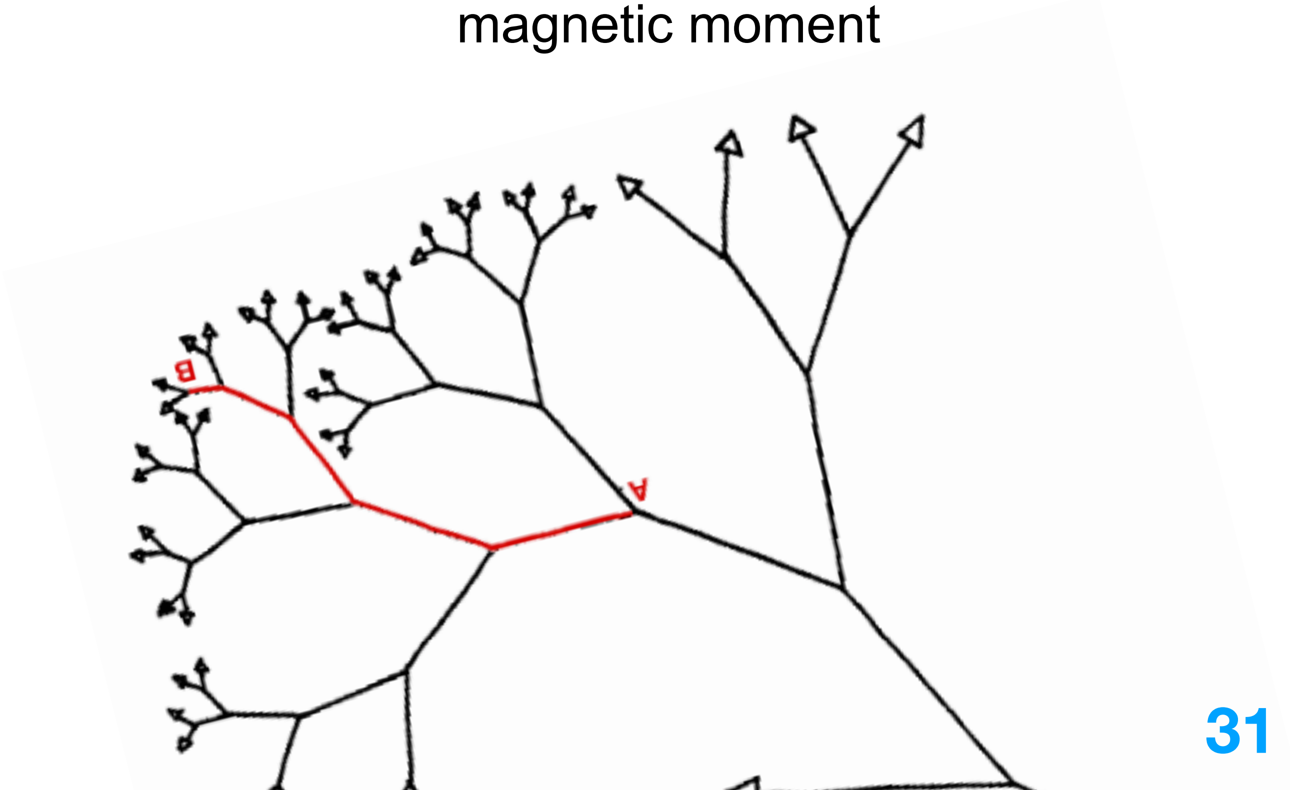
Assadi et al 1712.08019
Resonant matter effect

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



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,
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Hostert & Pospelov 2008.11851

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Fisher et al 1909.0956,
CA, Foppiani, Hostert 2109.03831

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Steriles + NCNSI + CCNSI

More than one at a time

S. Vergani et al arXiv:2105.06470
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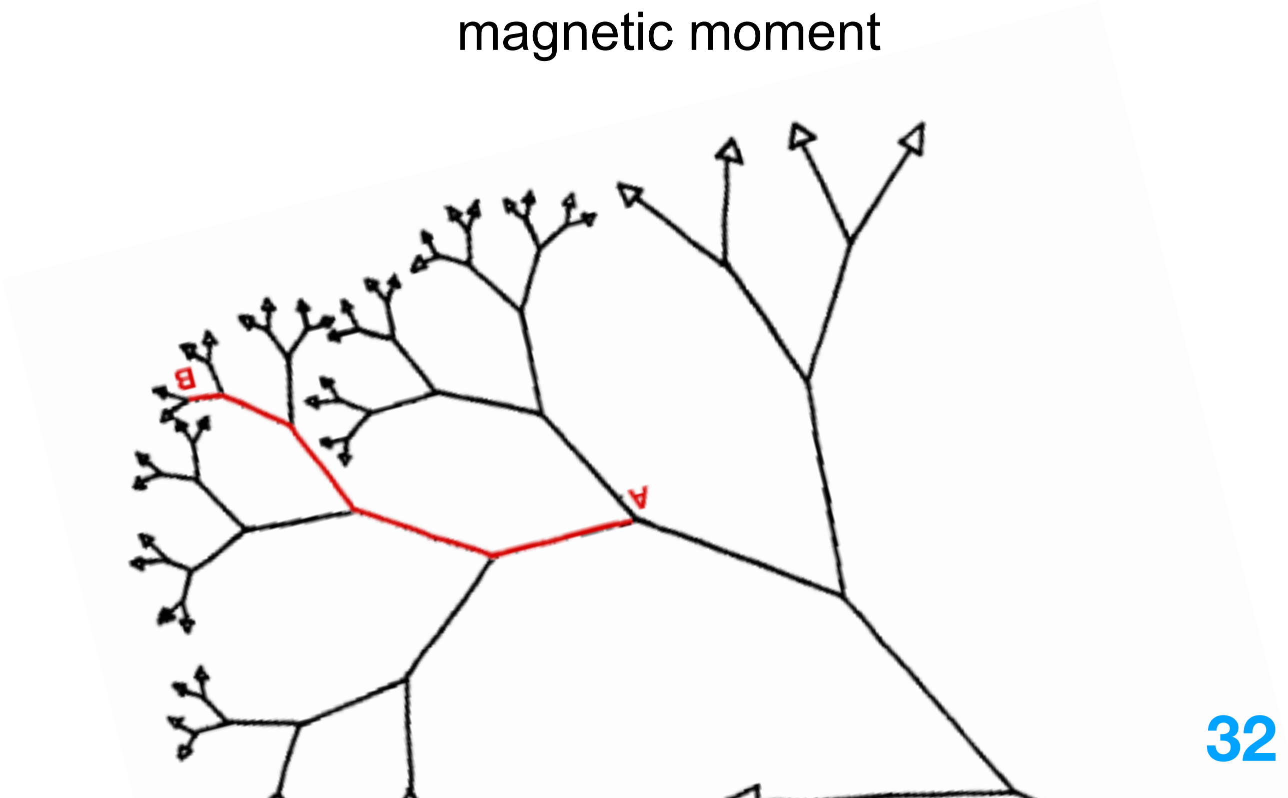
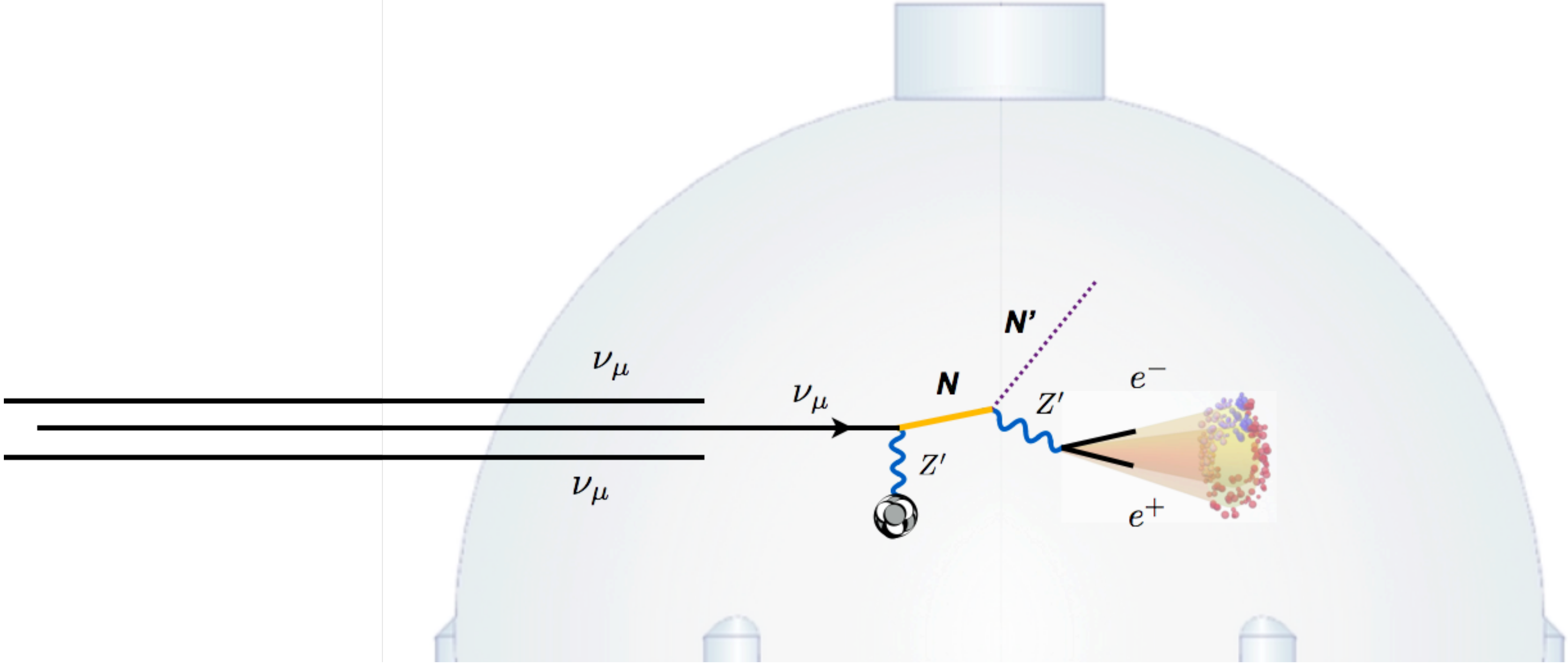


Non-Minimal HNL: di-electron scenario

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



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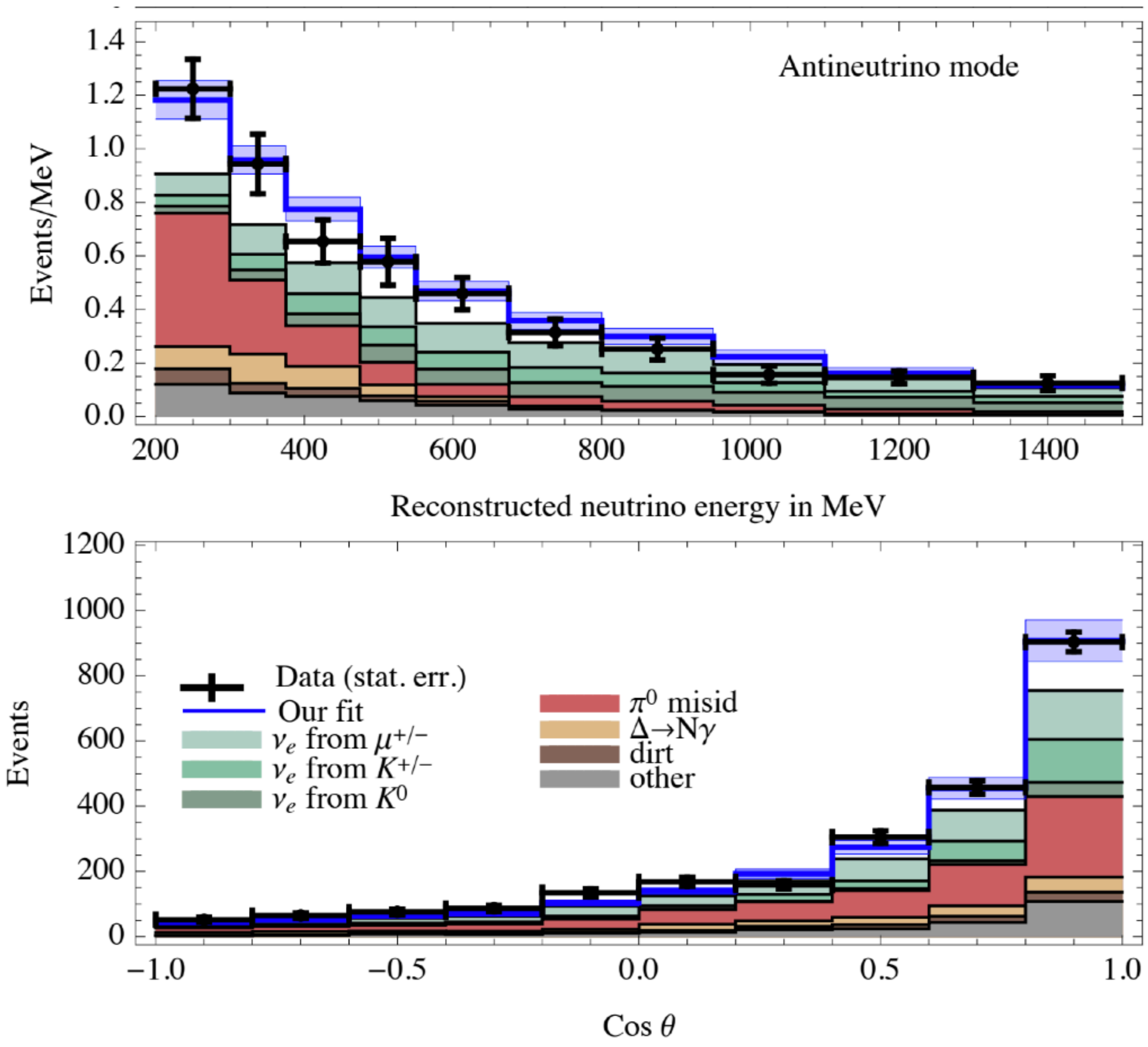
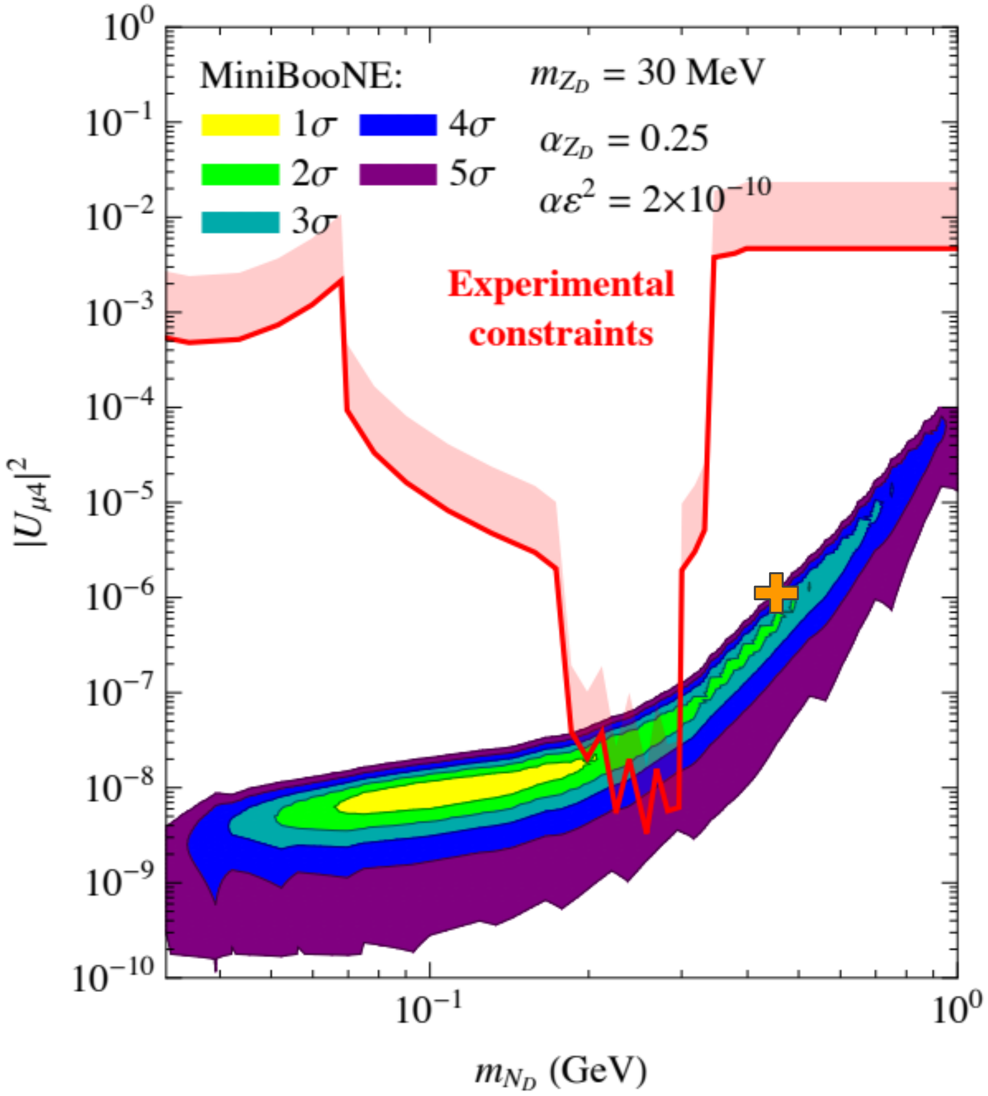
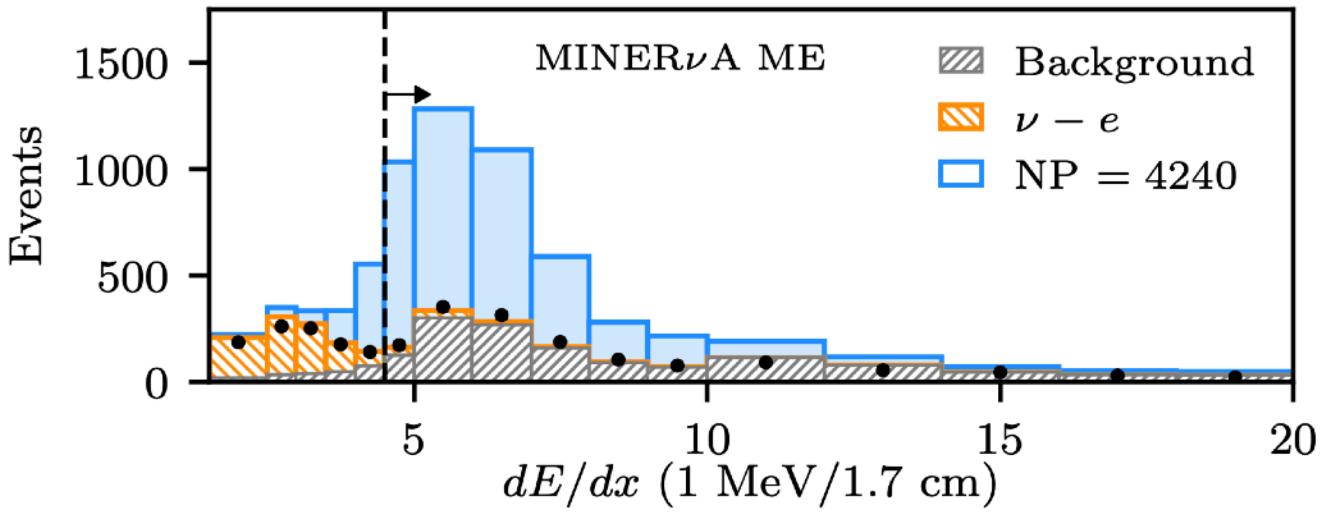


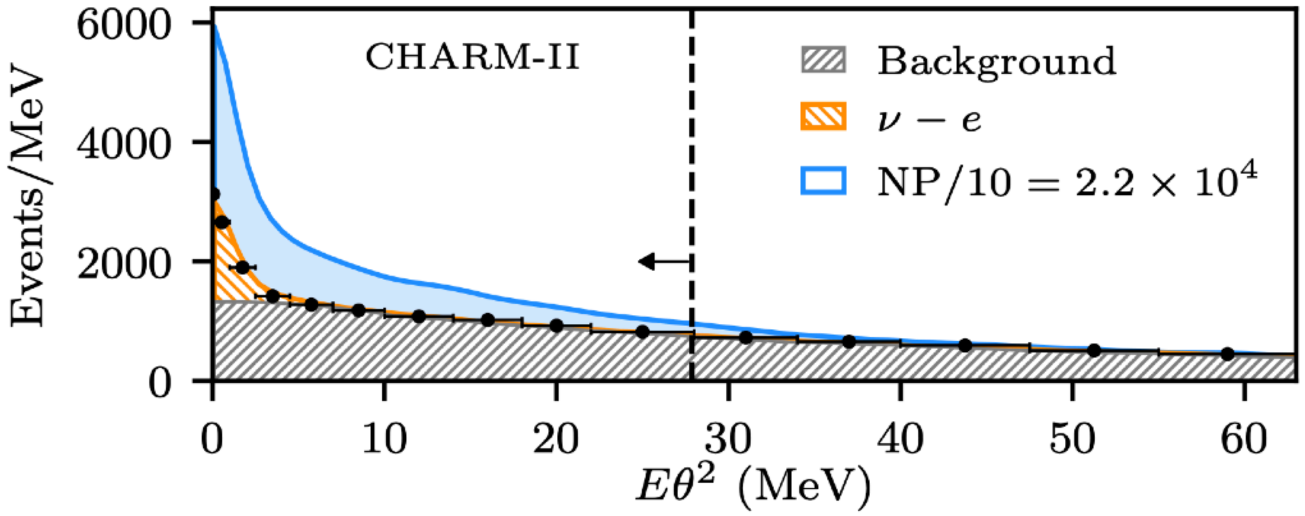
Benchmark point marker



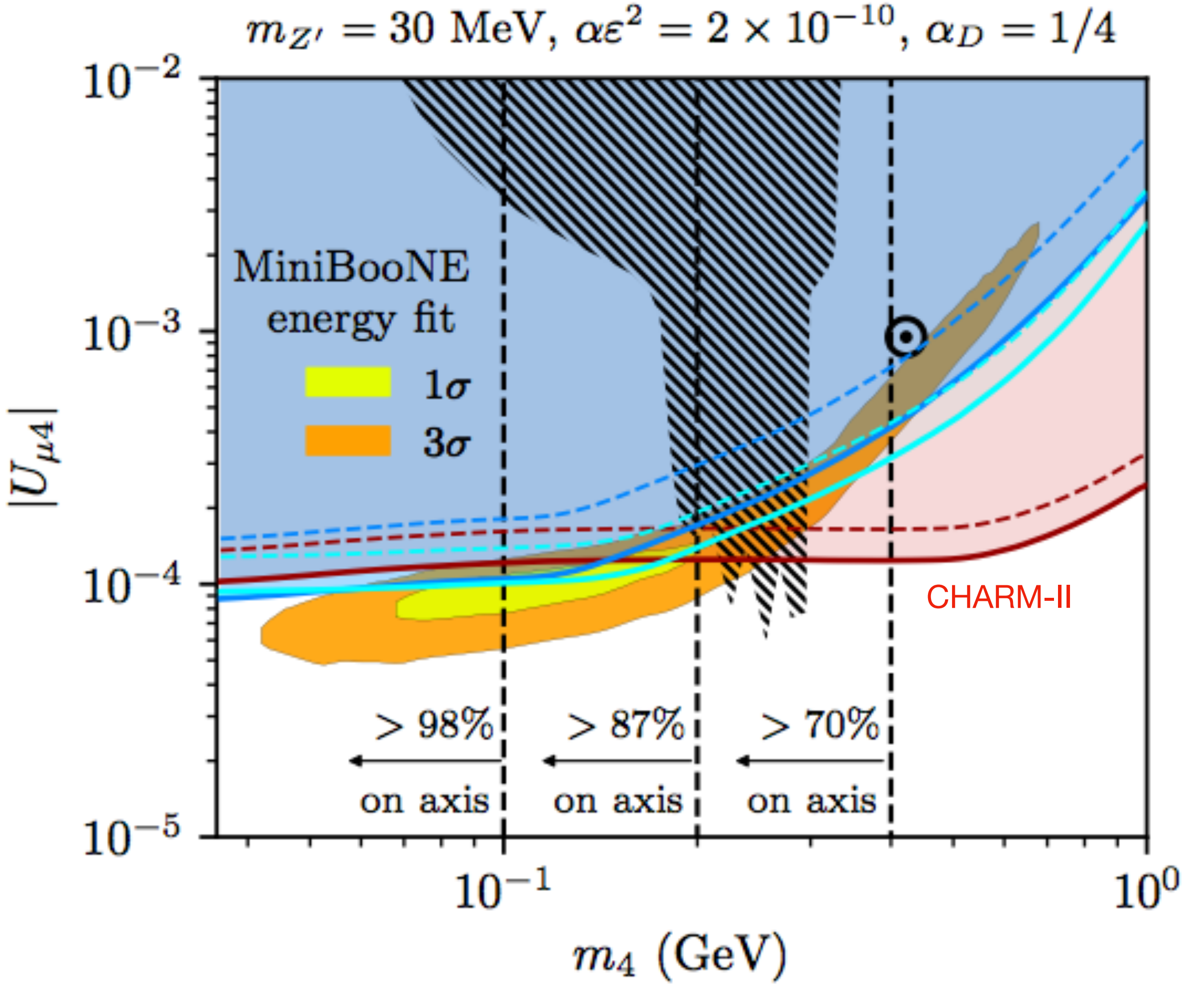
Good fit to the energy and angular distribution.

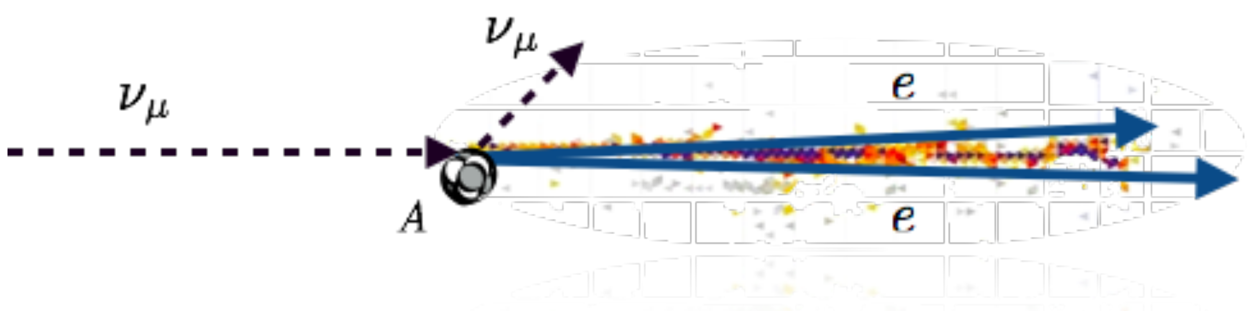
Non-Minimal HNL: di-electron scenario





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





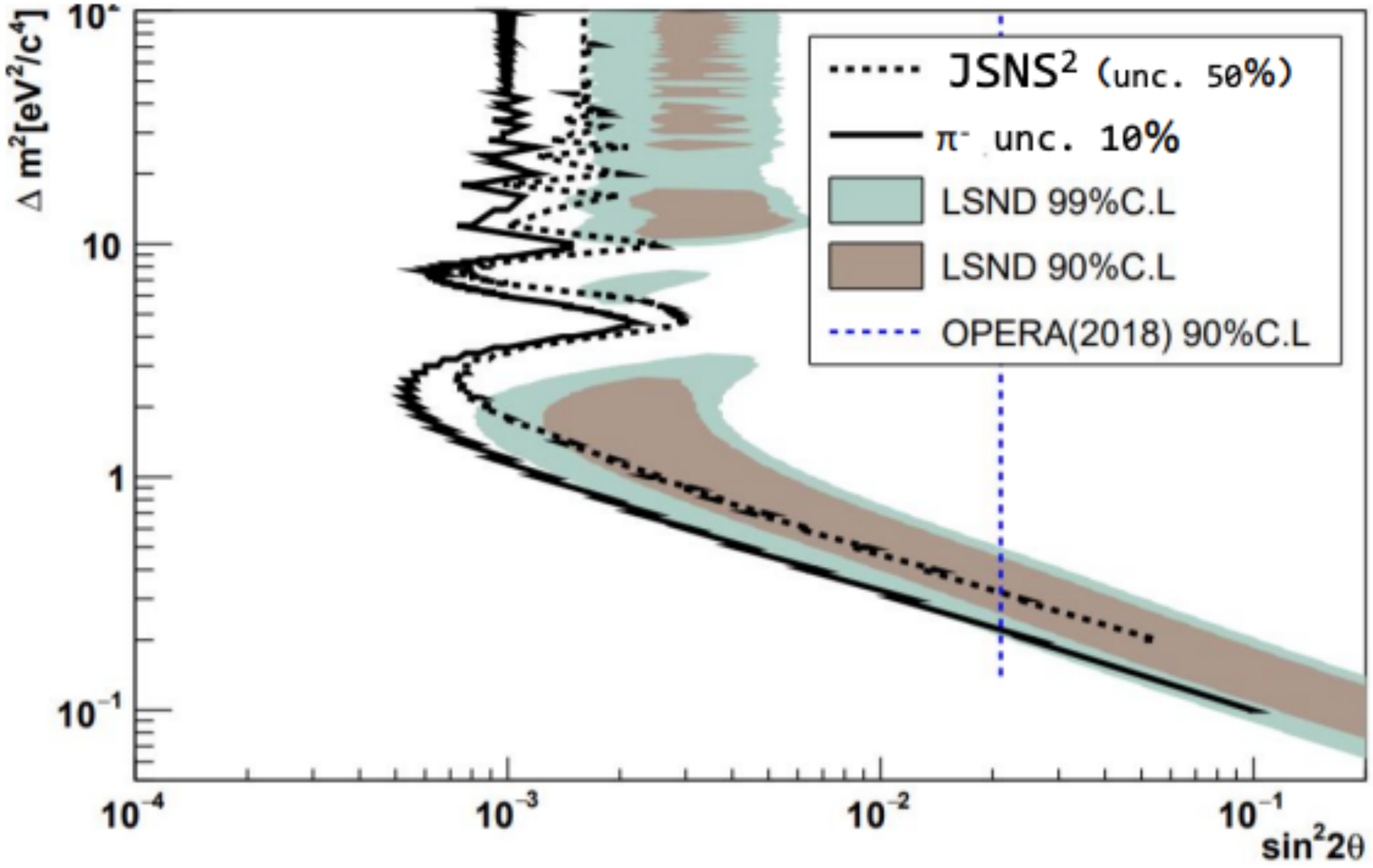
In tension with measurements of electron-neutrino scattering

Outline

- The need for more than three neutrinos and *more*
- The garden of forking paths
- Outlook

JSNS^2@J-PARC

JSNS2 Collaboration arXiv:2012.10807
See talk by T. Maruyama

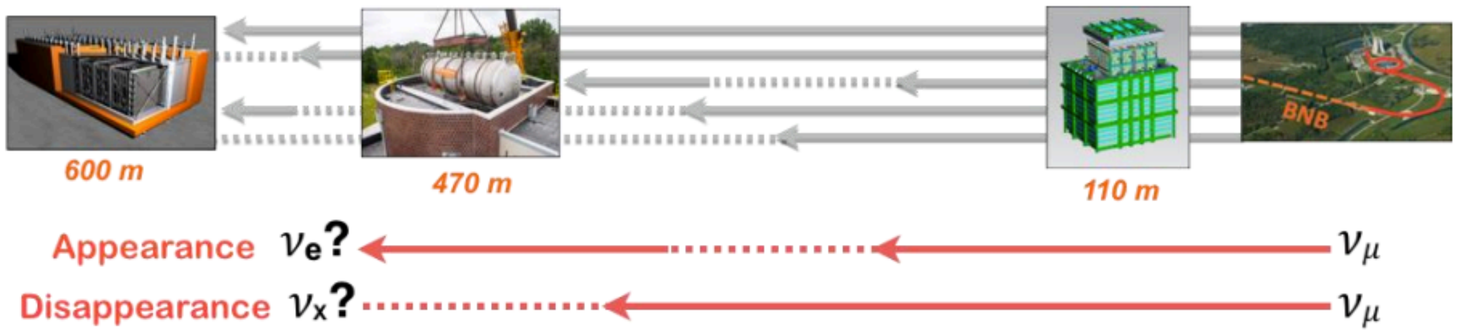


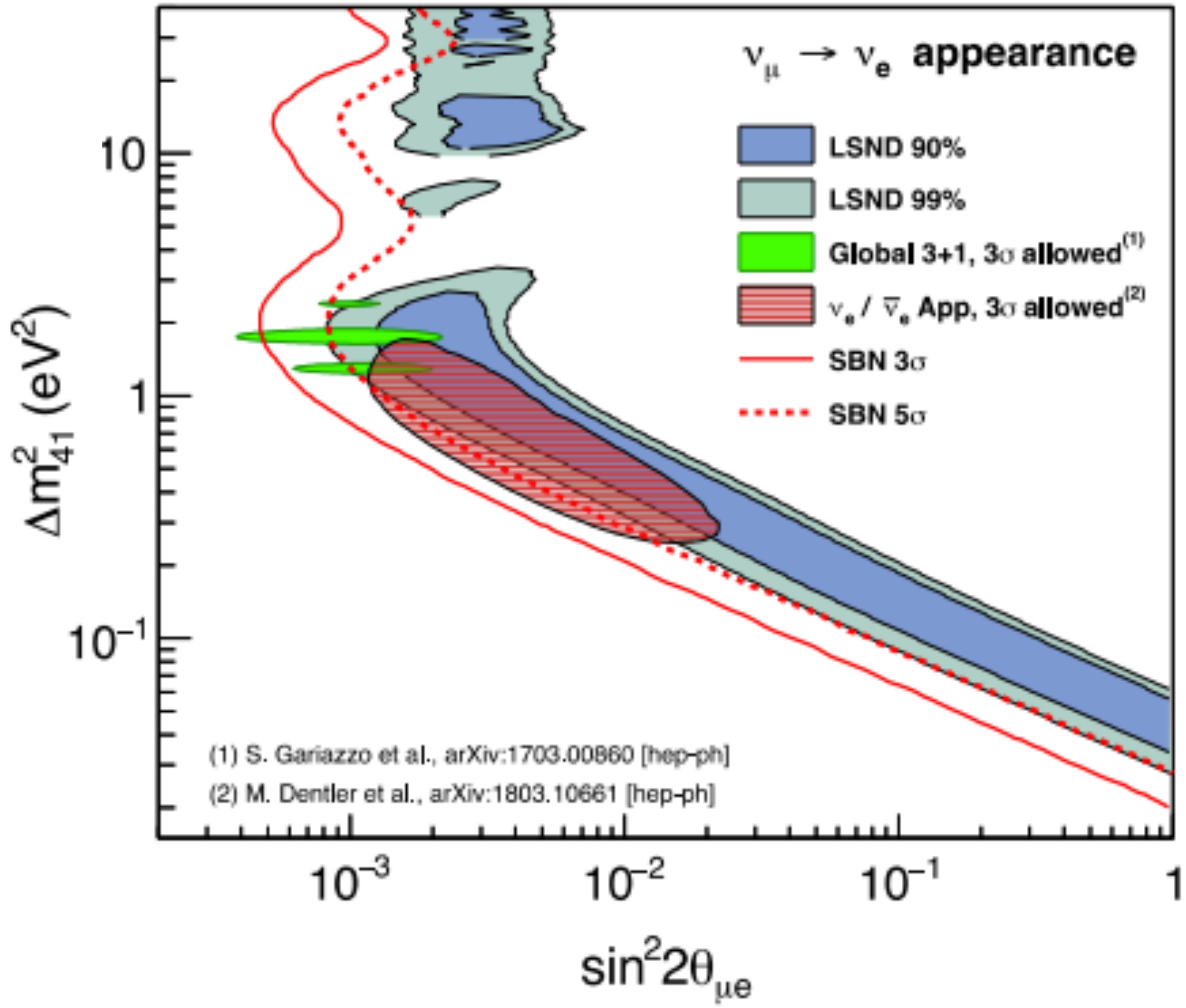
JSNS^2@J-PARC will directly test LSND

Pion decay at rest beam
and
IBD detection

Short Baseline Program@FNAL

M. Bonesini





SBND@FNAL Program

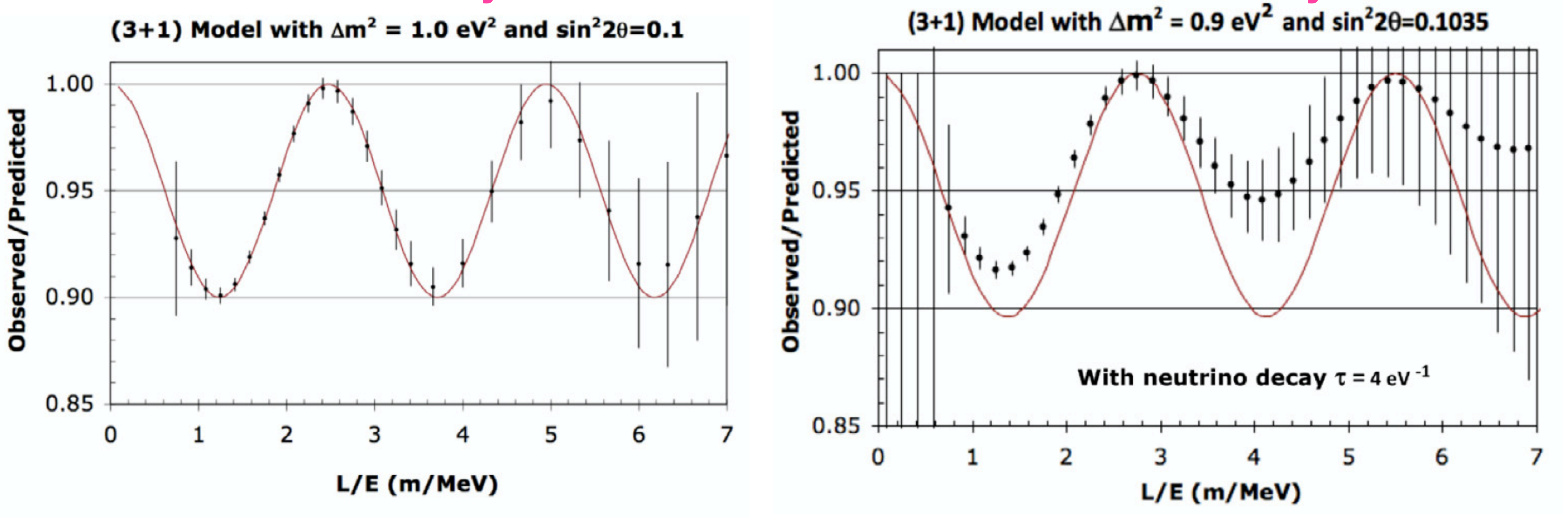
Will test the MiniBooNE low-energy excess

&

Perform new searches for electron neutrino appearance

See upcoming talk by V. Gustavo
See talk by M. Bonesini for SBN Program Summary
See talk by M Torti for plans for ICARUS
See talk by Kathryn Sutton for uBooNE photon analysis

IsoDAR@Yemilab



No decay

With decay

IsoDAR with O(1M) events

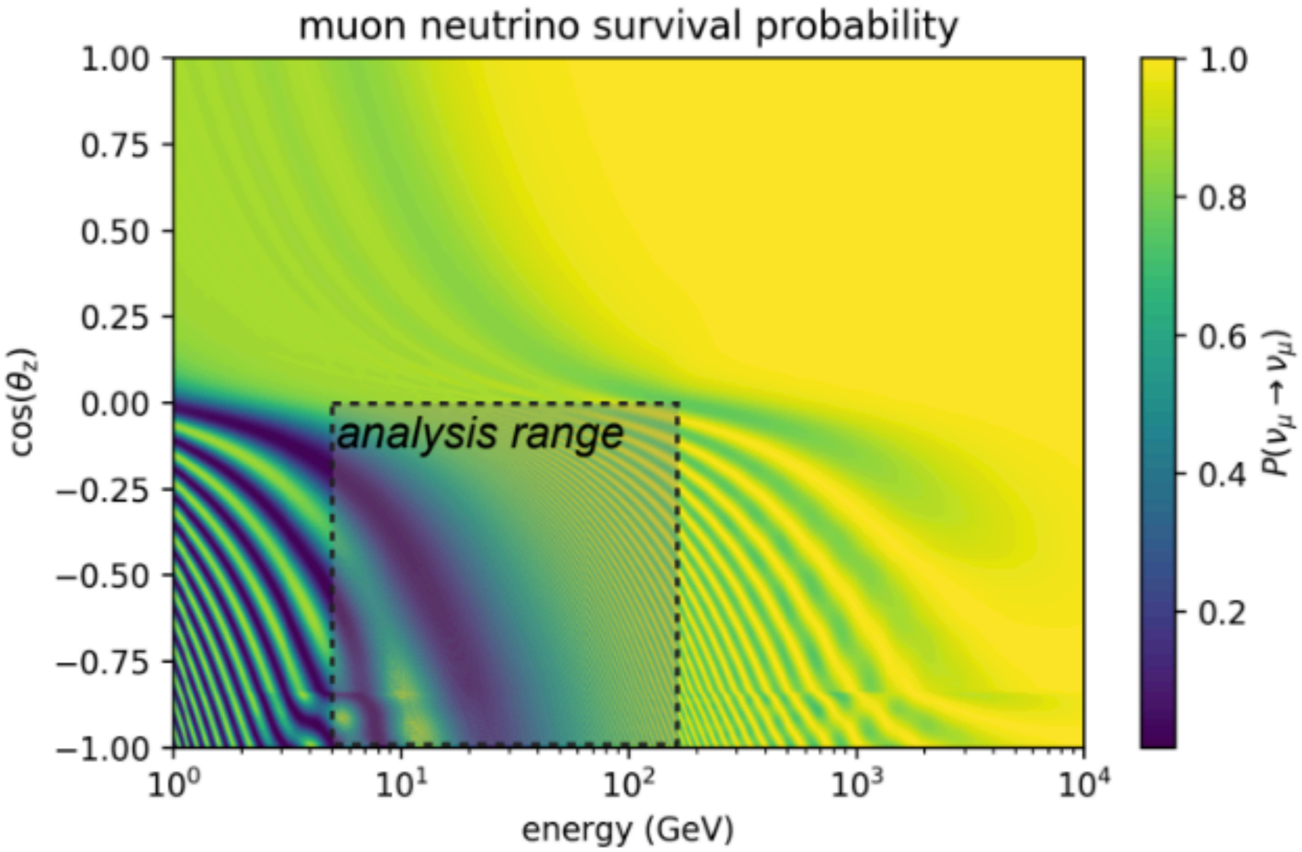
IsoDAR@Yemilab will conclusively rule out the 3+1 model, but also due to its ability to trace the oscillation wave see variants on this model such as 3+1+Decay

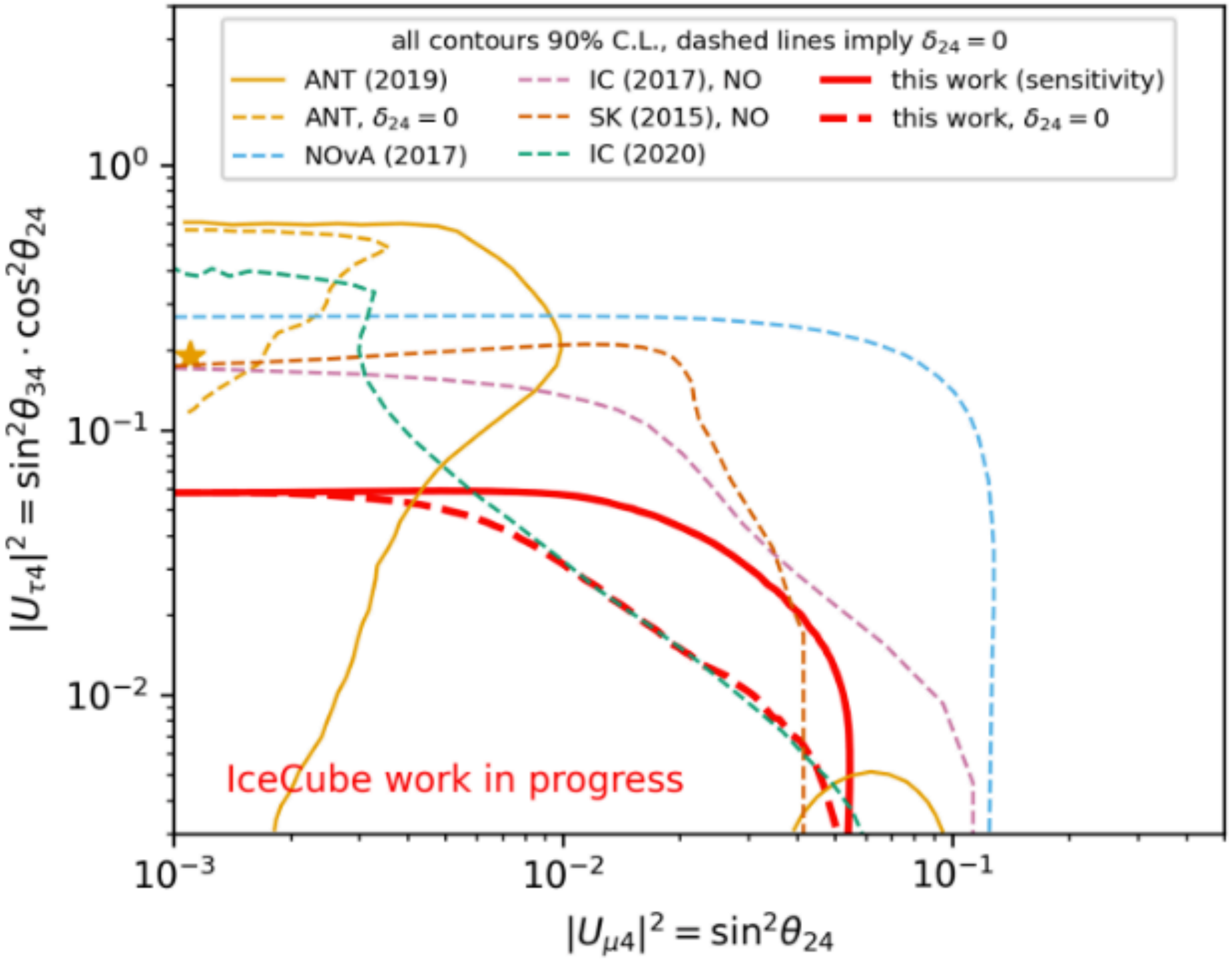
See talk by L. Waites

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 $|U_{\mu 4}|^2$!

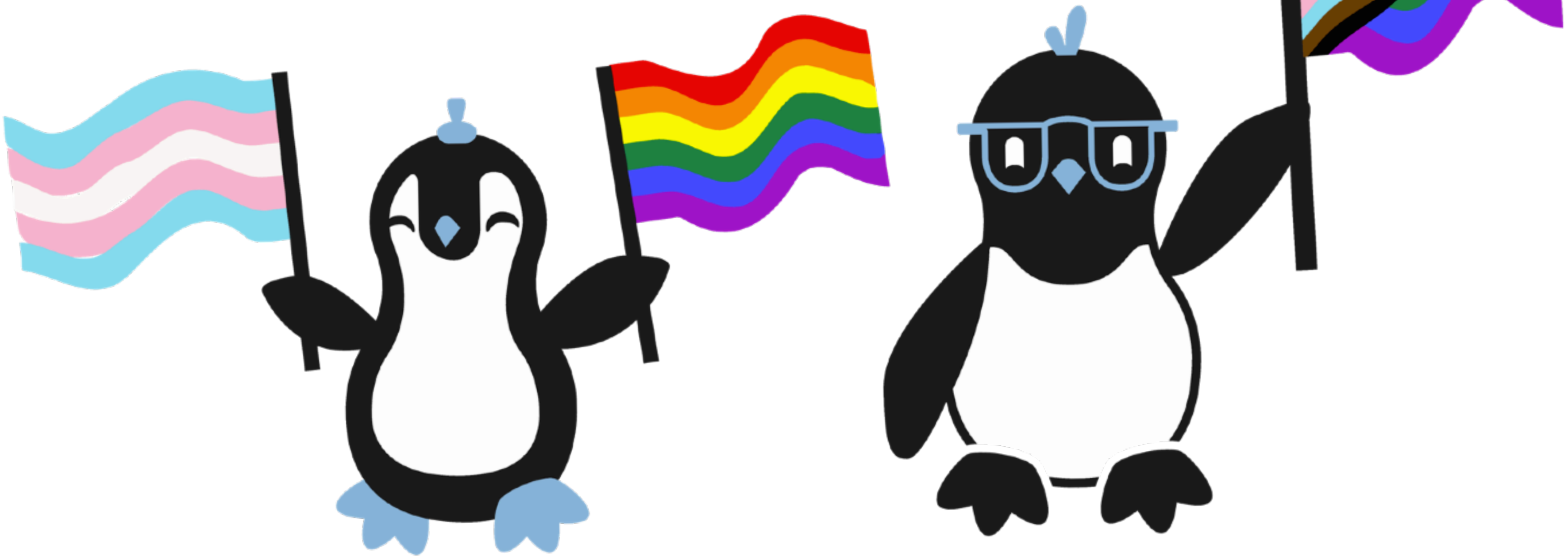
IceCube will continue improving muon neutrino disappearance searches.
“Low energy” sample (<100 GeV) still not studied.

See talk by K. Leonard DeHolton for more details

Take home messages

- 3+1 model is disfavored as a global solution.
- Alternative explanations of the short baseline anomalies have been proposed: 3+1+Decay, 3+1+NSI, non-minimal heavy neutral leptons, etc.
- The low-energy part of the MiniBooNE hints points to a non-oscillation explanation.
- Lots of ideas out there. We need more data to solve the short-baseline puzzle.

Thanks!



Bonus slides

Menu of other explanations

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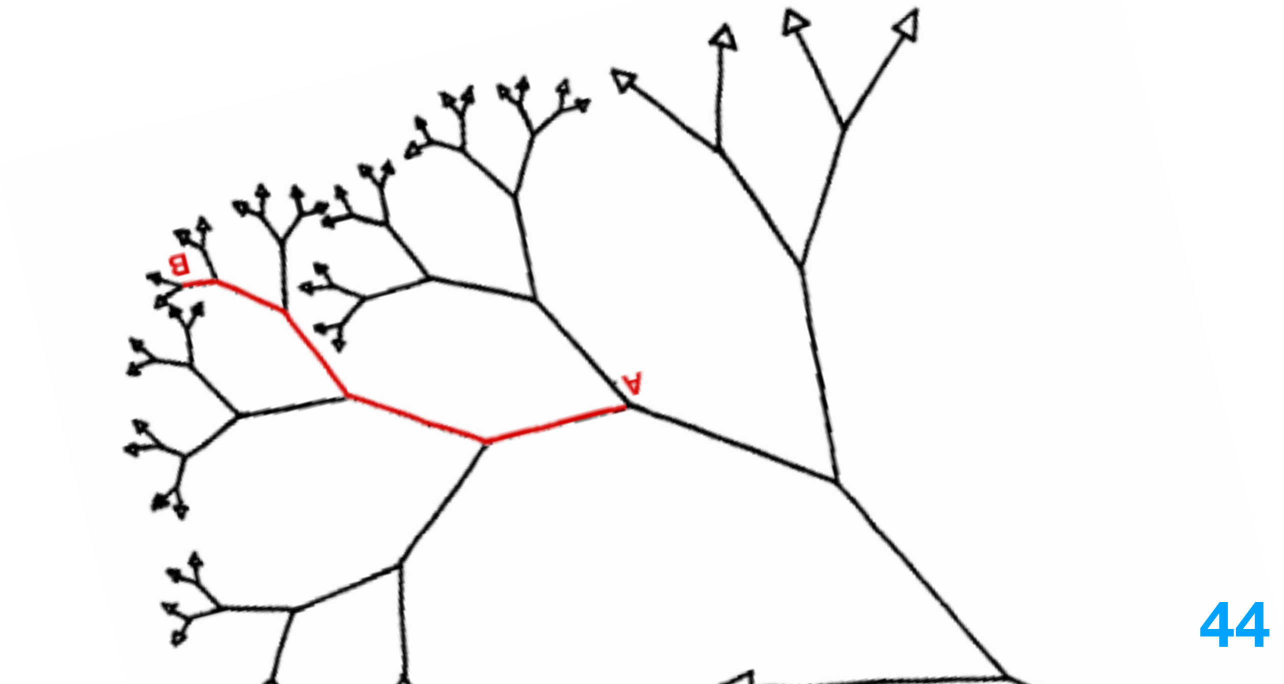
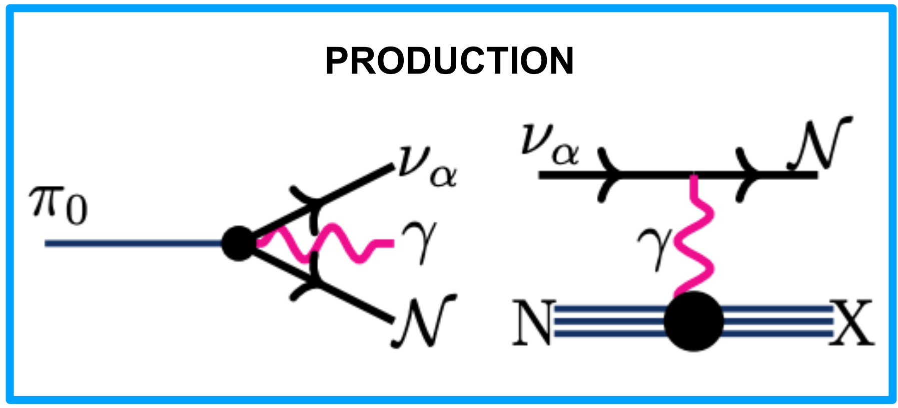
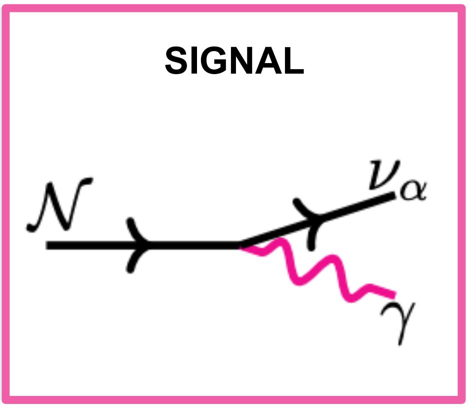
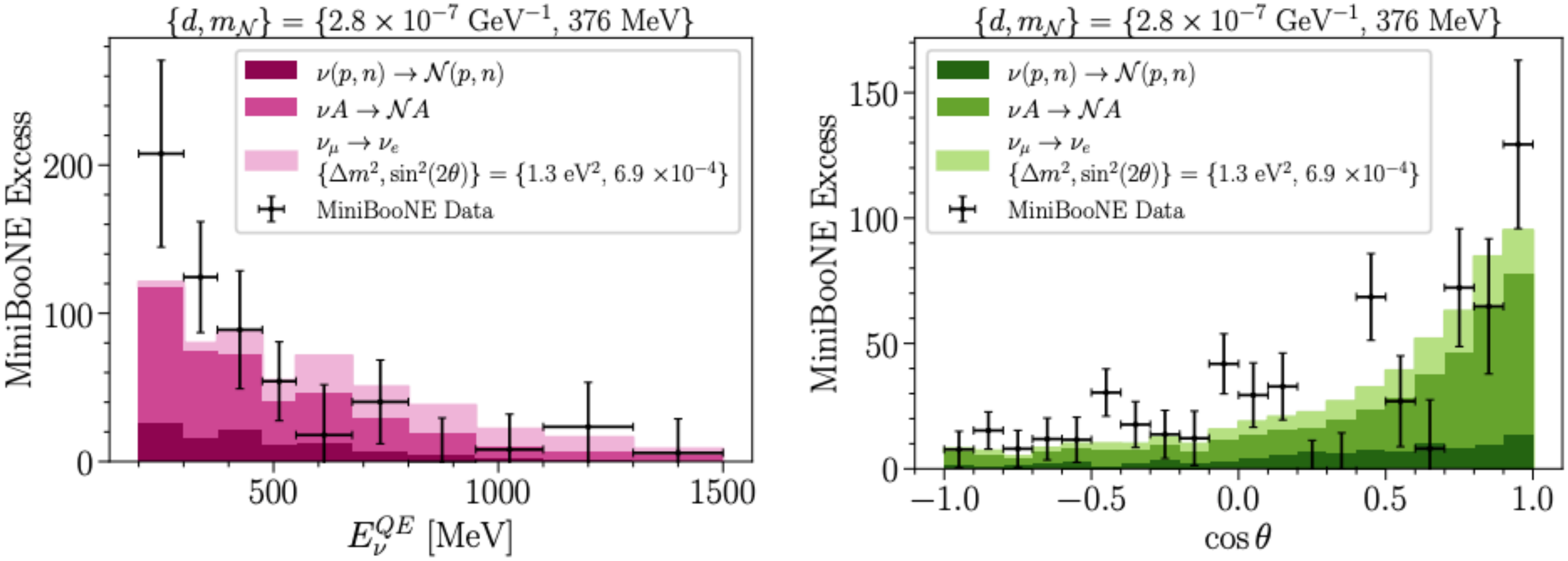


Non-Minimal HNL: photon scenario

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


PRODUCTION


SIGNAL



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)	
$\nu_\mu \to \nu_e$ appearance	[49](π/μ DIF)	3+1-only
$\bar{\nu}_\mu$ disappearance	[50–53] (π/μ DIF)	↓
ν_μ disappearance	[51, 54–56] (π/μ DIF)	
$3+1+\mathcal{N}$	[8] (MiniBooNE BNB ν)	$\mathcal{N}$

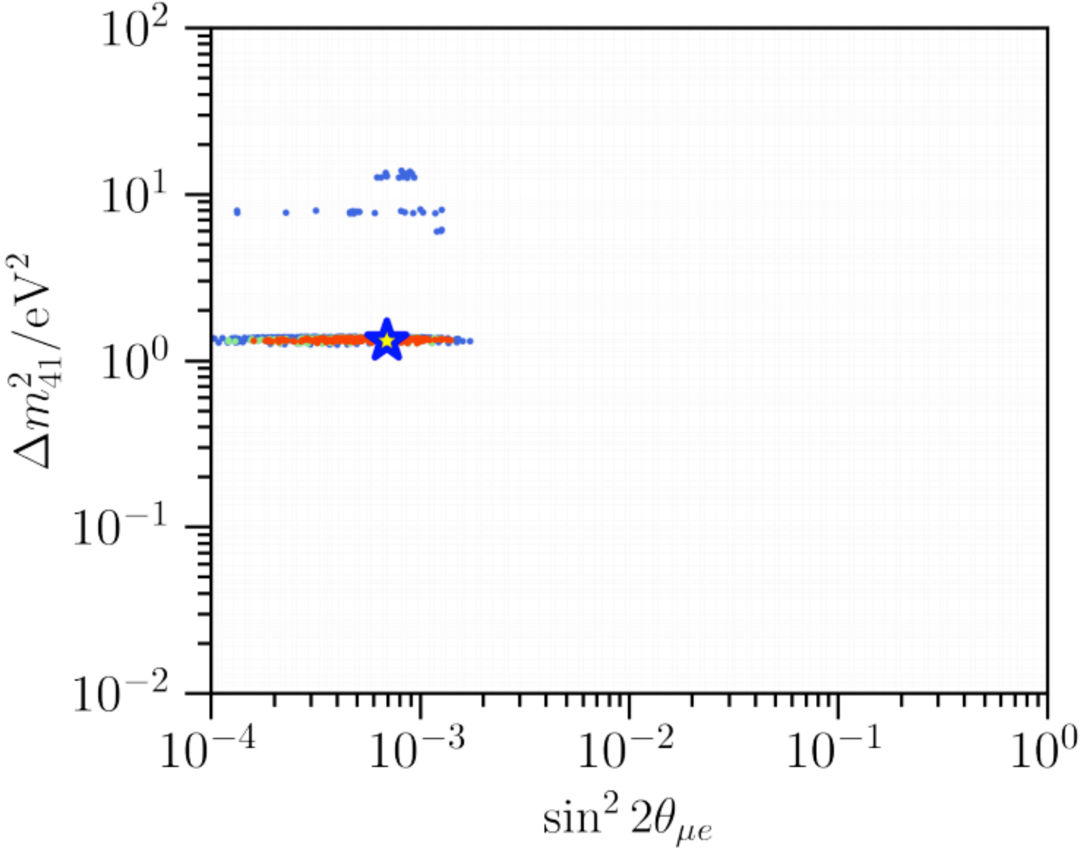
Explained by eV-sterile

Explained by MeV-HNL

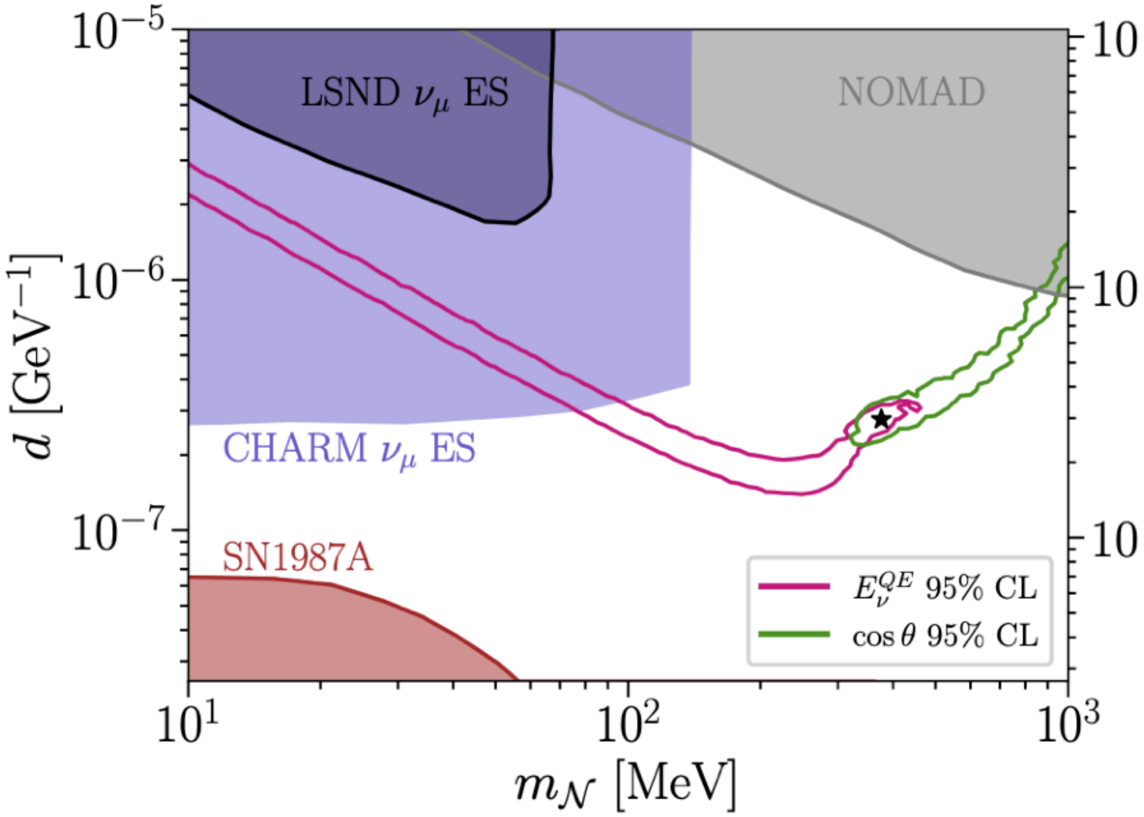
Fit type:	3+1-only	3+1-complete
χ^2_{app}	48	79
N_{app}	2	2
χ^2_{dis}	557	557
N_{dis}	3	3
χ^2_{glob}	615	664
N_{glob}	3	3
χ^2_{PG}	10	28
N_{PG}	2	2
p-value	7E-03	8E-07
$N\sigma$	2.7σ	4.8σ

Tension

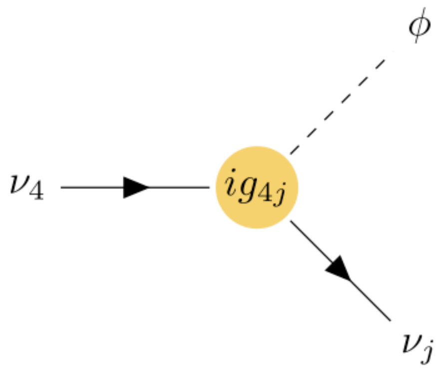
Light sterile parameter space



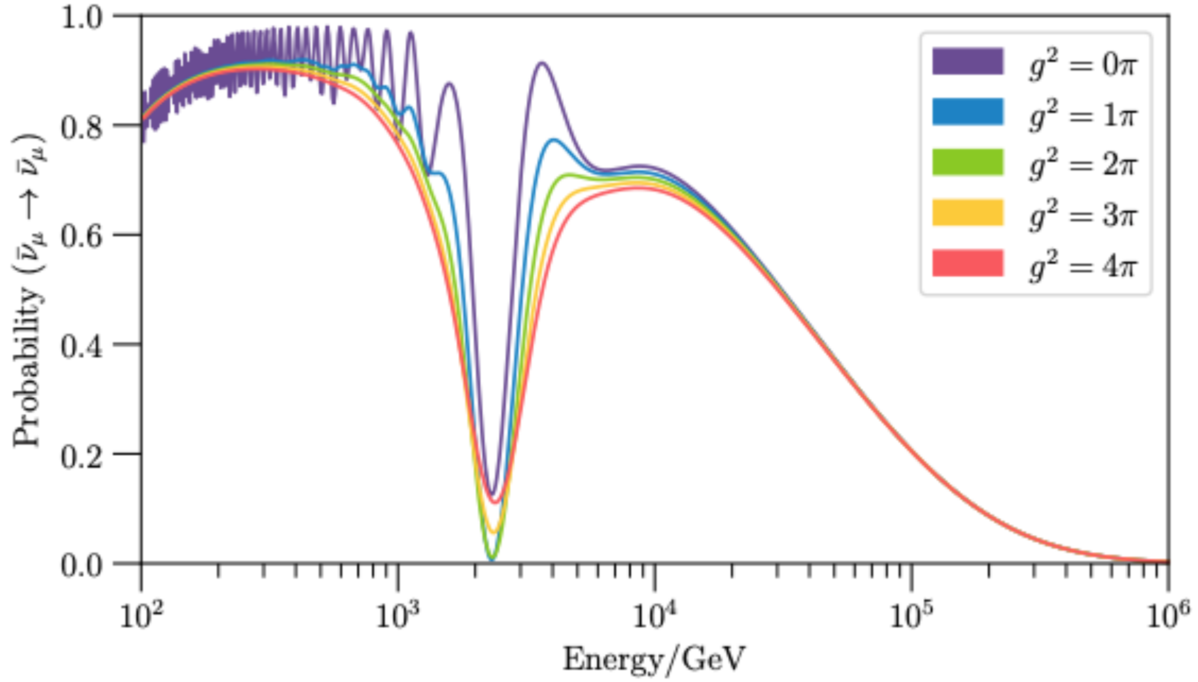
Heavy "sterile" parameter space



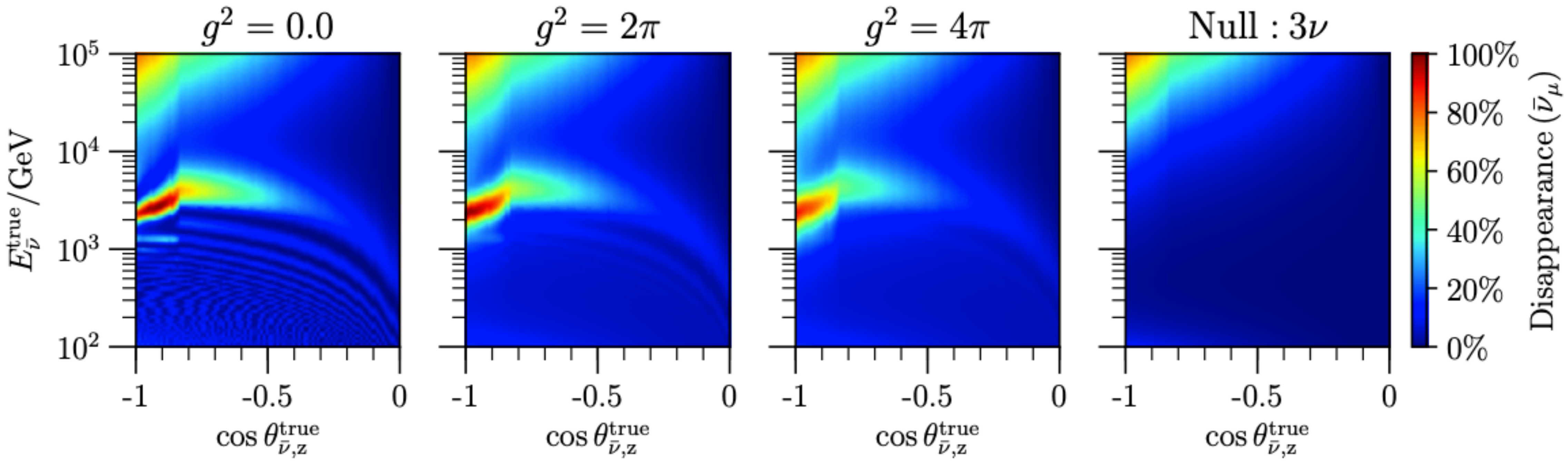
Magill et al Phys. Rev. D 98, 115015 (2018)
S. Vergani, N. Kamp, Diaz, CA, J. M. Conrad, M. H. Shaevitz, M. A. Uchida, arXiv:2105.06470



3+1+Decay In IceCube

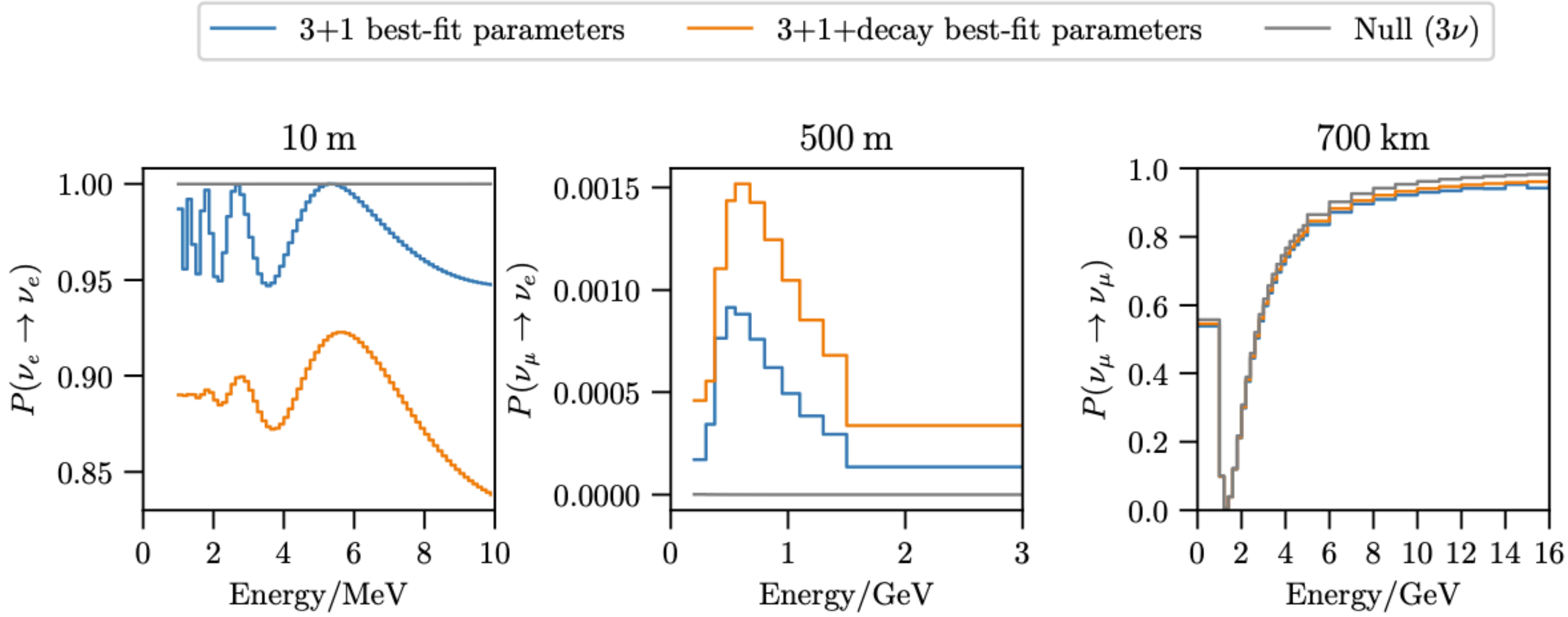


3+1+Decay model compared to 3+1 produces broader and smoother muon-neutrino disappearance.



Phenomenological implications of 3+1+Decay

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



Reactors

MiniBooNE

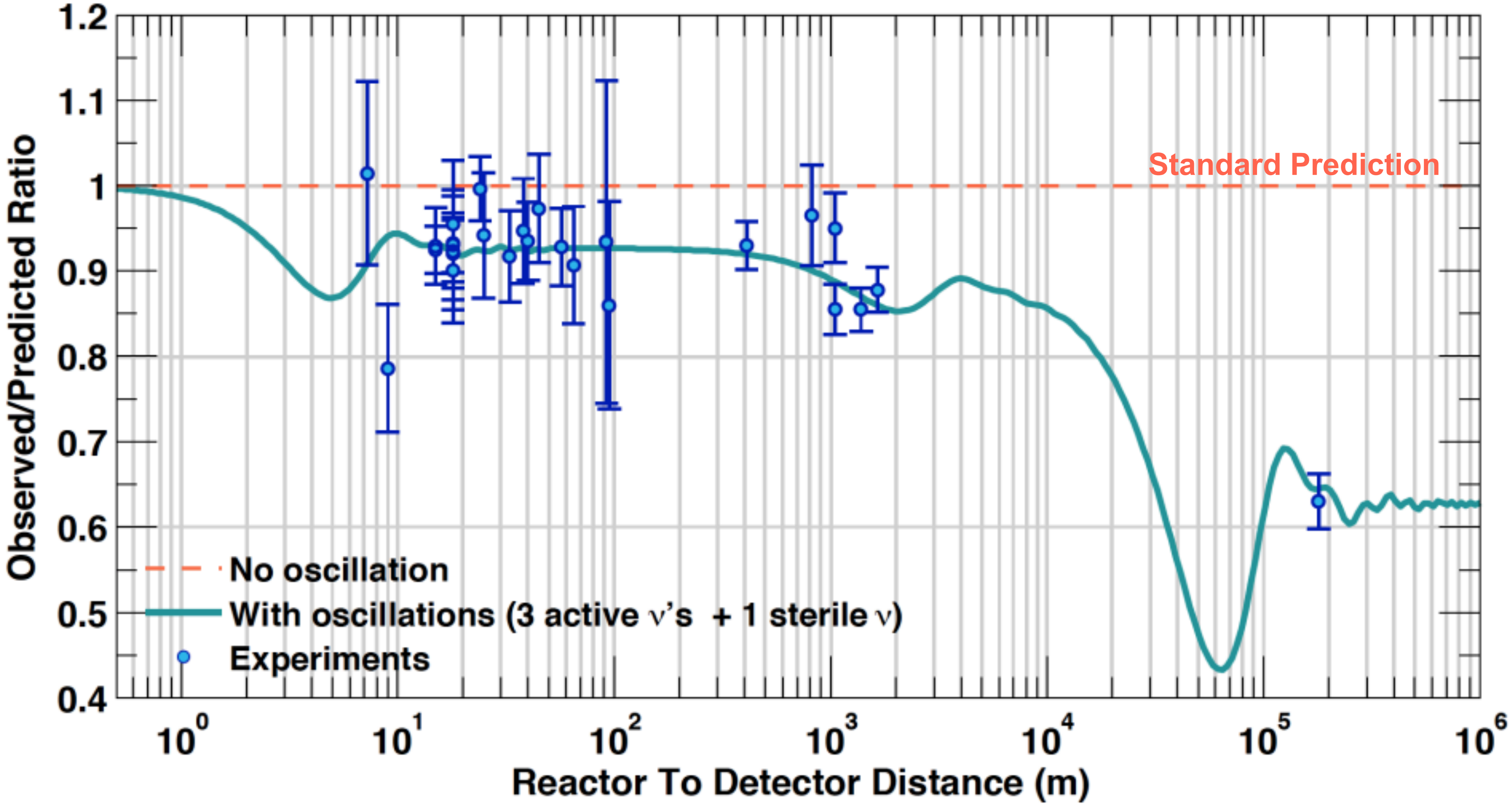
Long-baseline

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

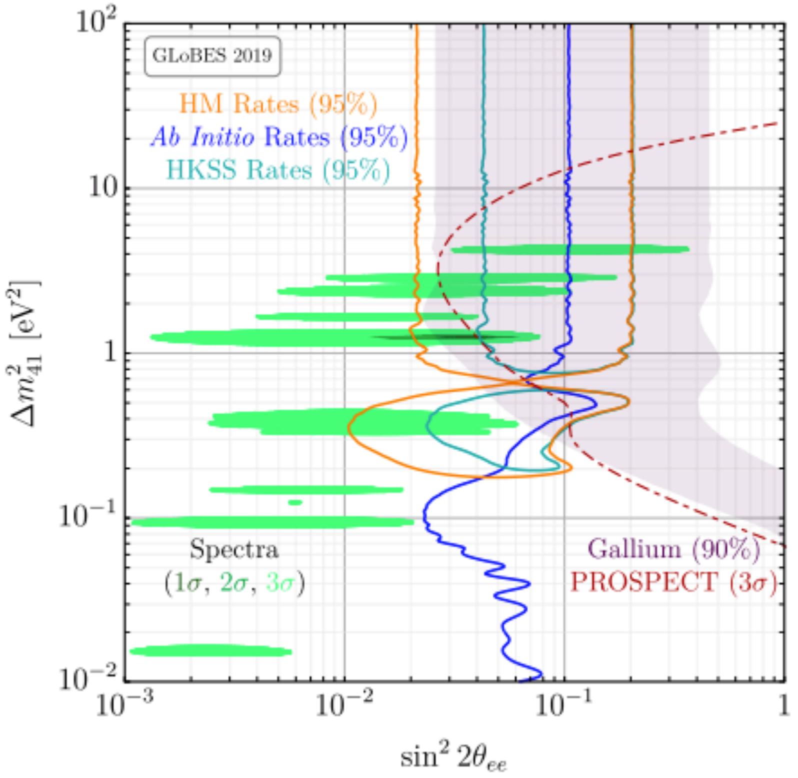
Reactor Antineutrino Anomaly (RAA)

Nuclear reactors: electron spectra from ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu are translated to $\bar{\nu}_e$ flux Schreckenbach 82, 85

A recalculation of fluxes lead to ~ 6% discrepancy with 2% error bars Müller *et al* 2011, Huber 2011



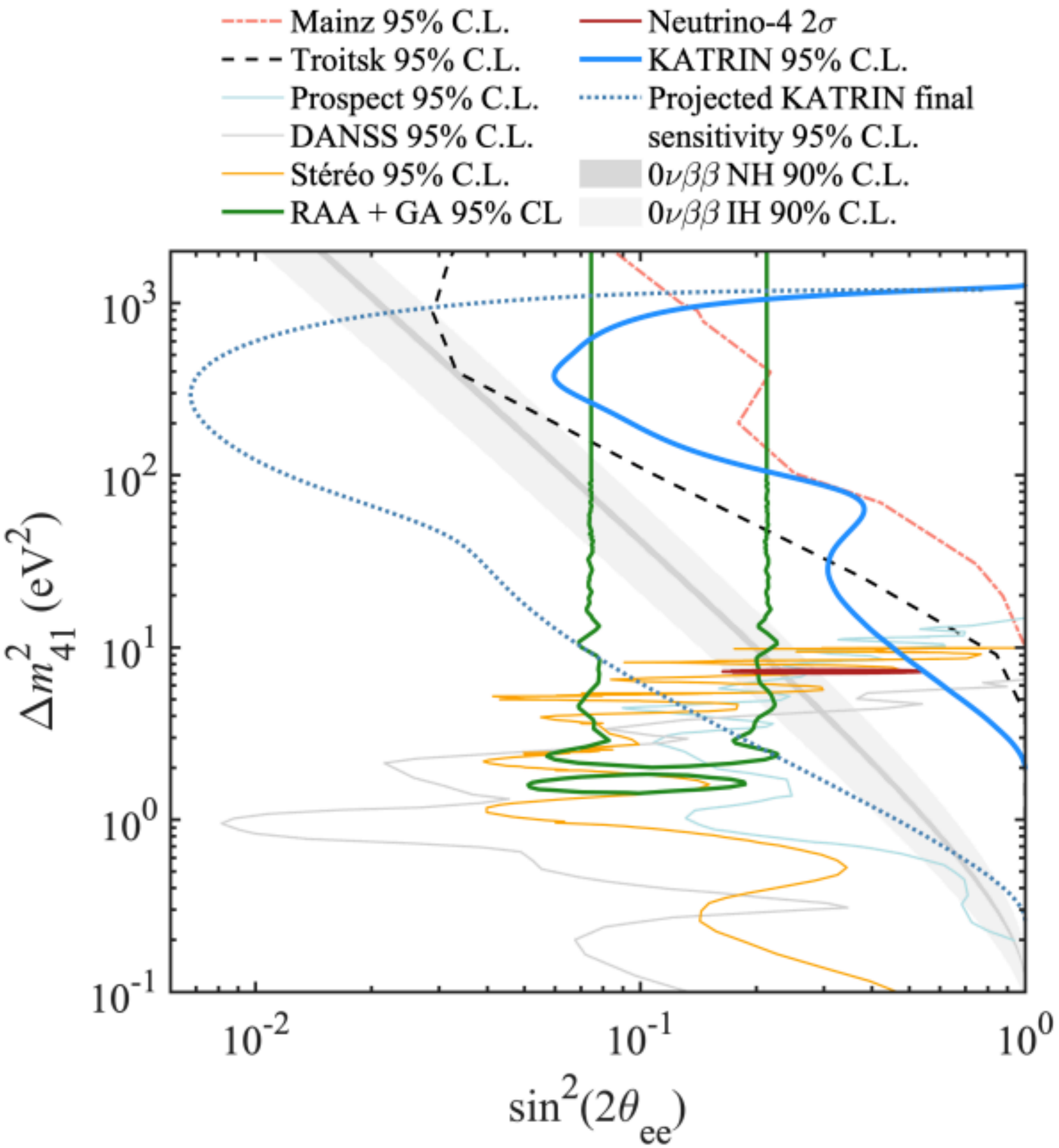
Berryman & Huber
Phys. Rev. D 101, 015008

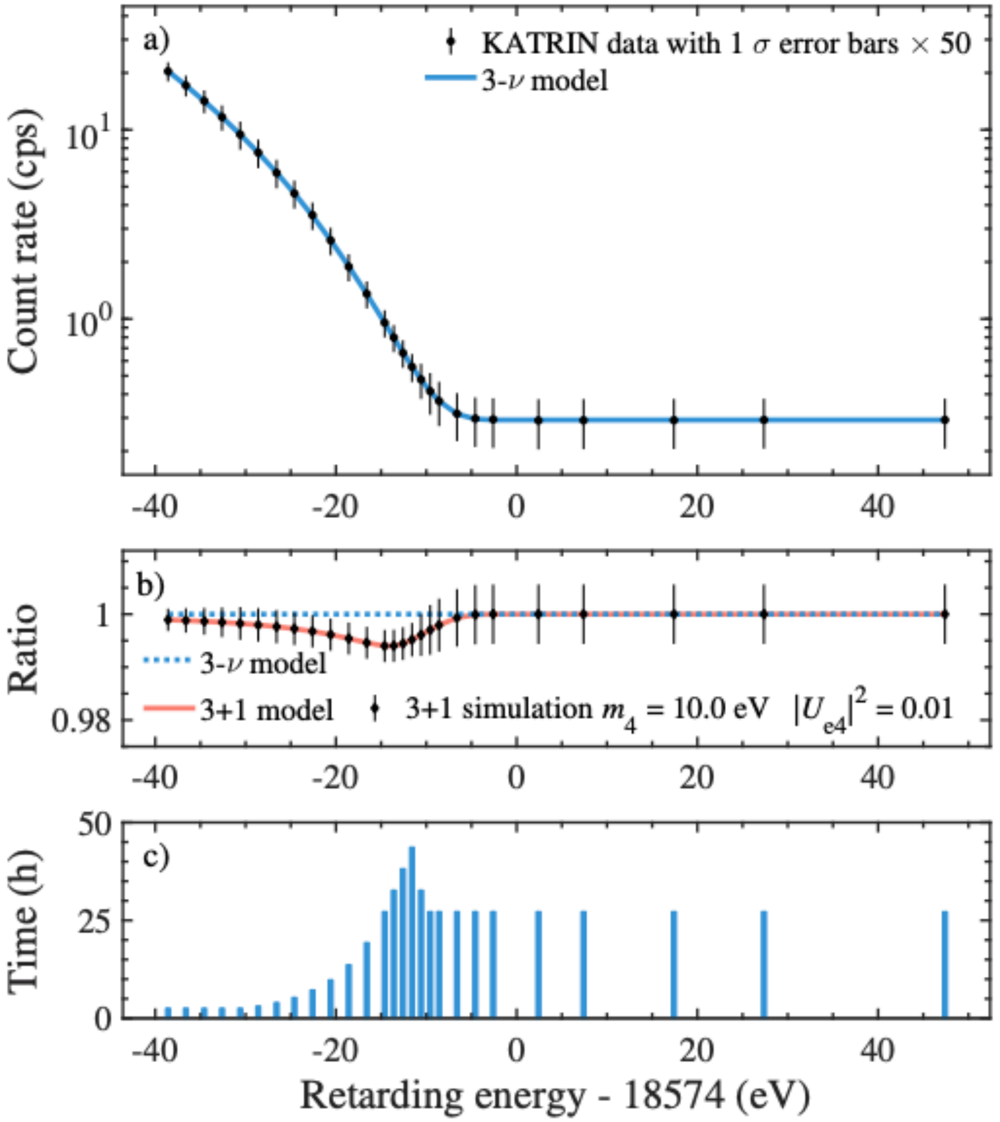


3σ significance, but fully driven by theoretical prediction.

B. Dasgupta *Phys.Rept.* 928 (2021) 1-63

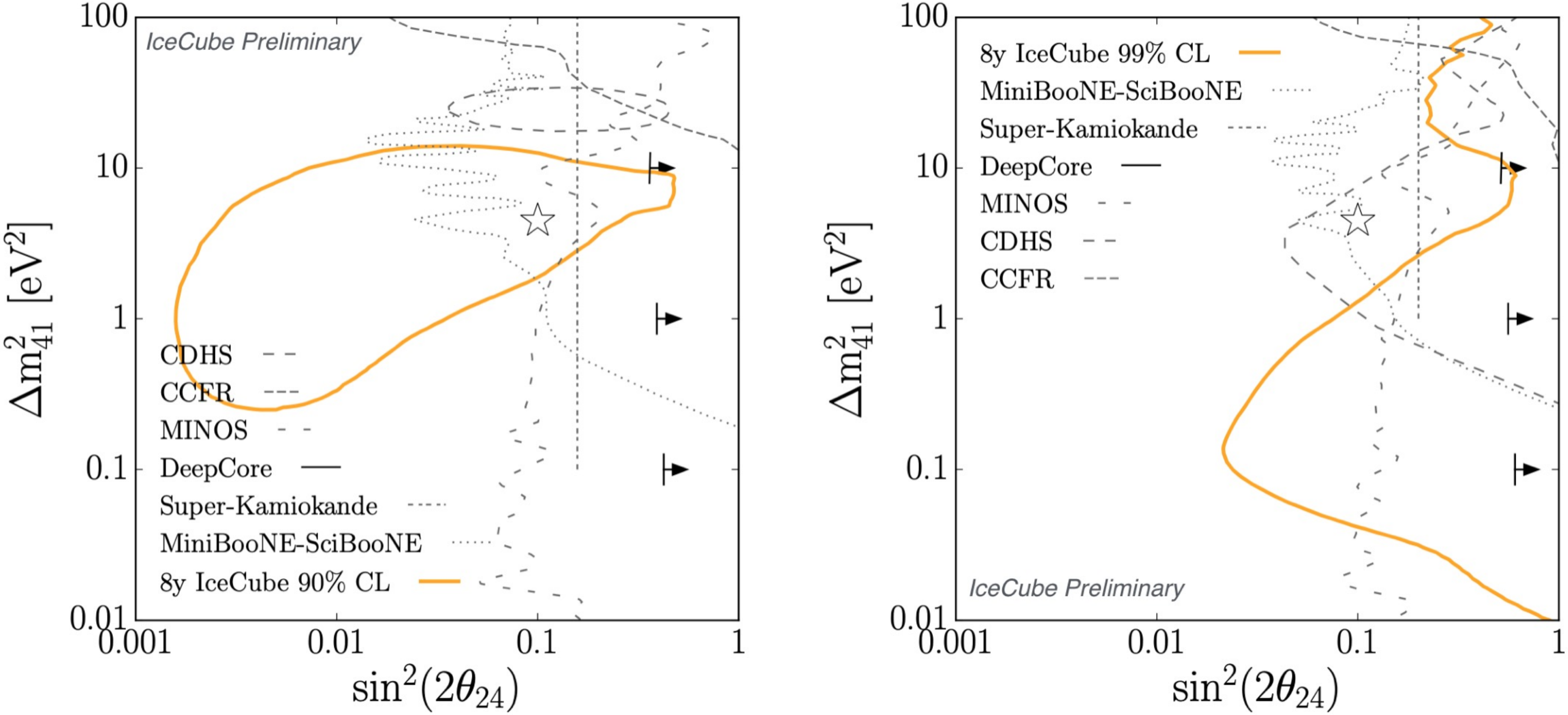
Constraints from Direct Mass Measurements





Katrin Collaboration Phys. Rev. Lett. 126, 091803 (2021)

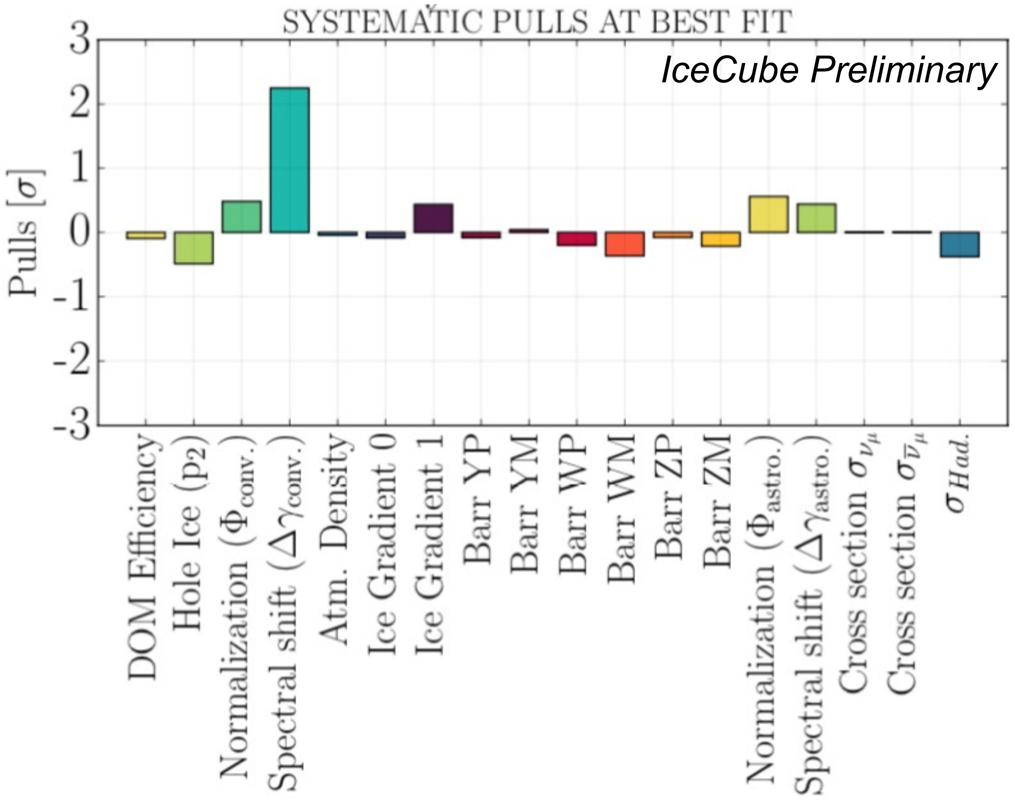
Compare to other muon-neutrino disappearance results

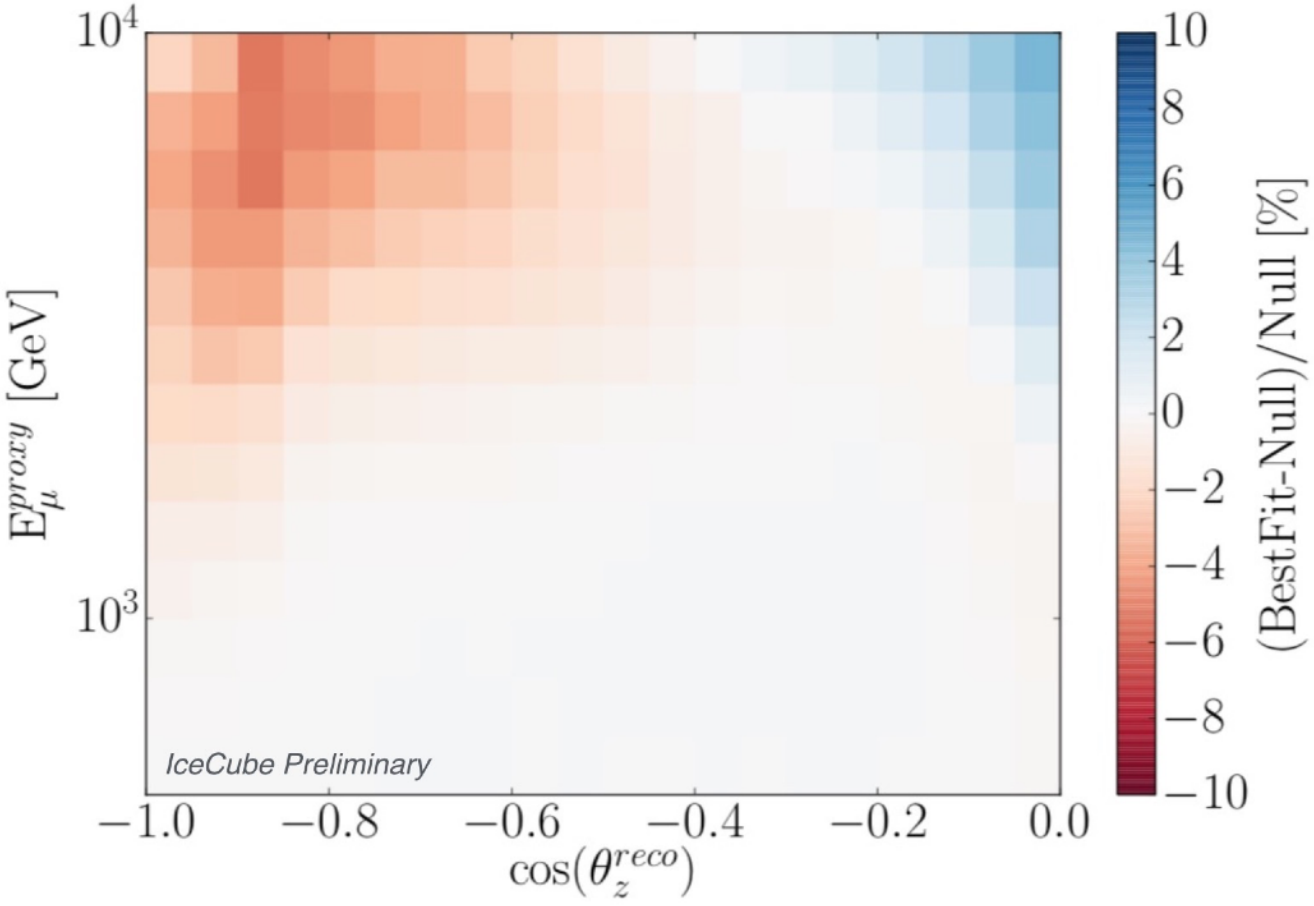


Best-fit point (data) and signal shape (Monte Carlo)

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

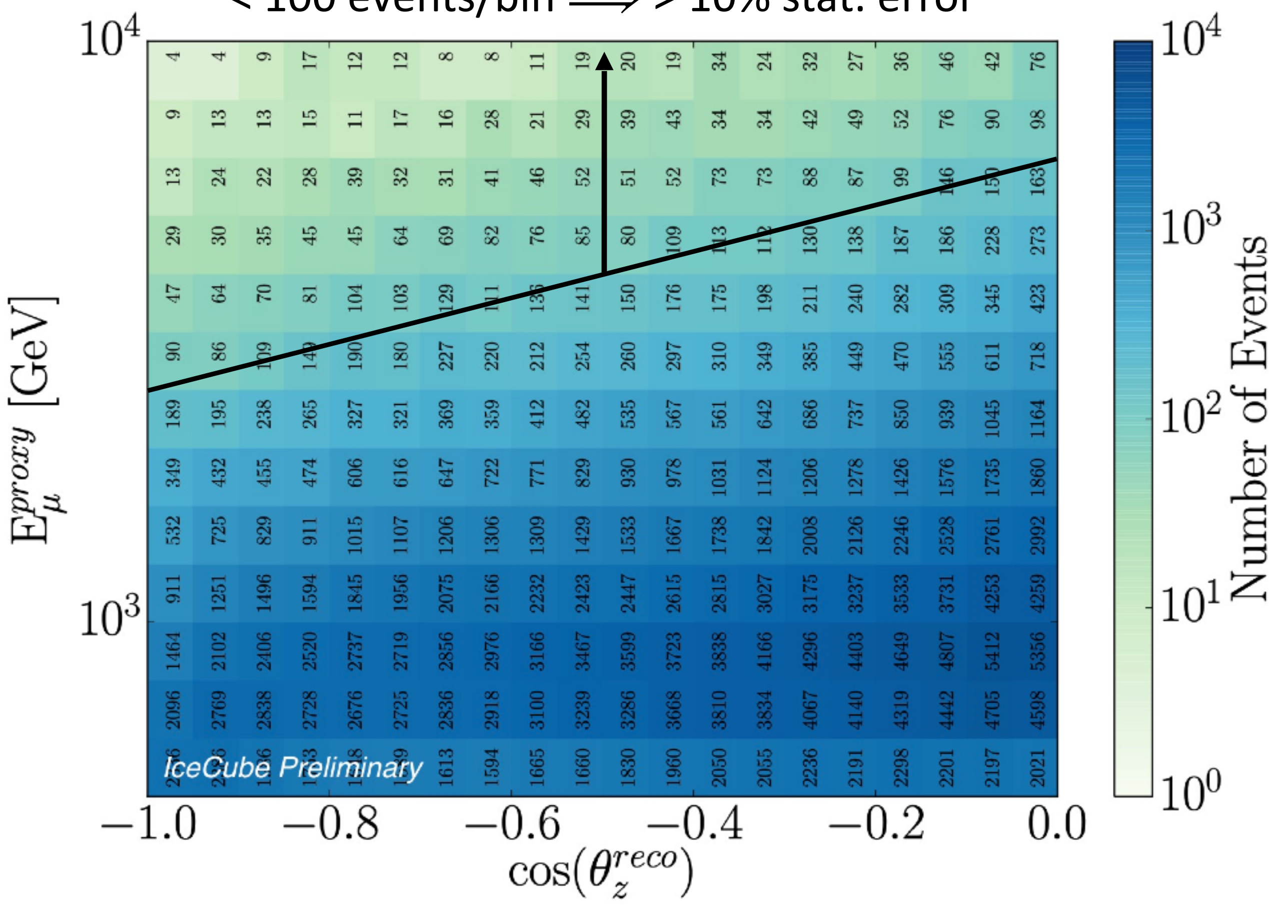
$$\sin^2(2\theta_{24}) = 0.10^{+0.10}_{-0.07}$$





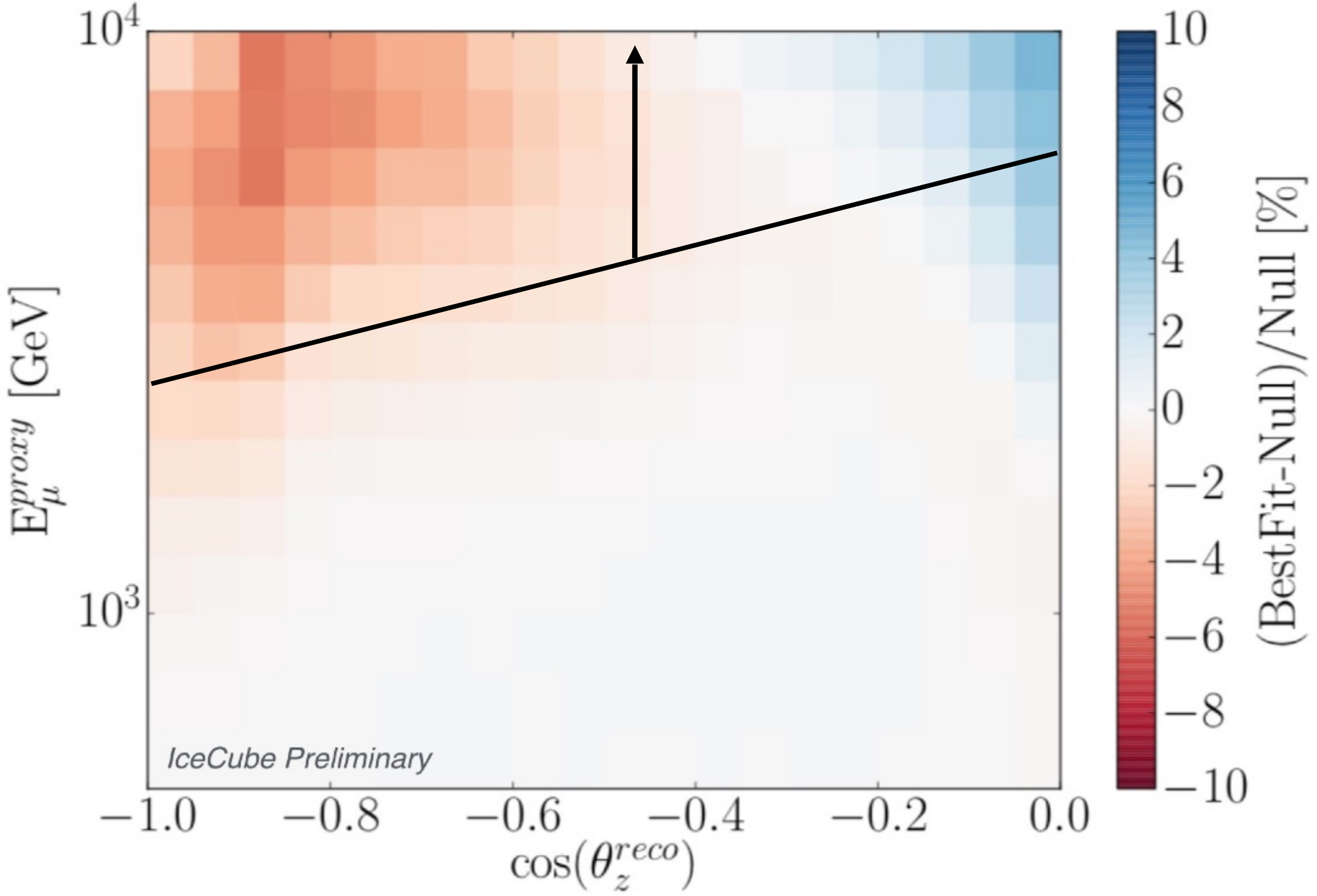
Event distribution (data) and best-fit shape (Monte Carlo)

- ❖ 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



< 100 events/bin ⟹ > 10% stat. error

4	4	9	17	12	12	8	8	11	19	20	19	34	24	32	27	36	46	42	76
9	13	13	15	11	17	16	28	21	29	39	43	34	34	42	49	52	76	90	98
13	24	22	28	39	32	31	41	46	52	51	52	73	73	88	87	99	146	150	163
29	30	35	45	45	64	69	82	76	85	80	109	113	112	130	138	187	186	228	273
47	64	70	81	104	103	129	111	135	141	150	176	175	198	211	240	282	309	345	423
90	86	109	149	190	180	227	220	212	254	260	297	310	349	385	449	470	555	611	718
189	195	238	265	327	321	369	359	412	482	535	567	561	642	686	737	850	939	1045	1164
349	432	455	474	606	616	647	722	771	829	930	978	1031	1124	1206	1278	1426	1576	1735	1860
532	725	829	911	1015	1107	1206	1306	1309	1429	1533	1667	1738	1842	2008	2126	2246	2528	2761	2992
911	1251	1496	1594	1845	1956	2075	2166	2232	2423	2447	2615	2815	3027	3175	3237	3533	3731	4253	4259
1464	2102	2406	2520	2737	2719	2856	2976	3166	3467	3599	3723	3838	4166	4296	4403	4649	4807	5412	5356
2096	2769	2838	2728	2676	2725	2836	2918	3100	3239	3286	3668	3810	3834	4067	4140	4319	4442	4705	4598
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1613	1594	1665	1660	1830	1960	2050	2055	2236	2191	2298	2201	2197	2021



< 6% shape effect

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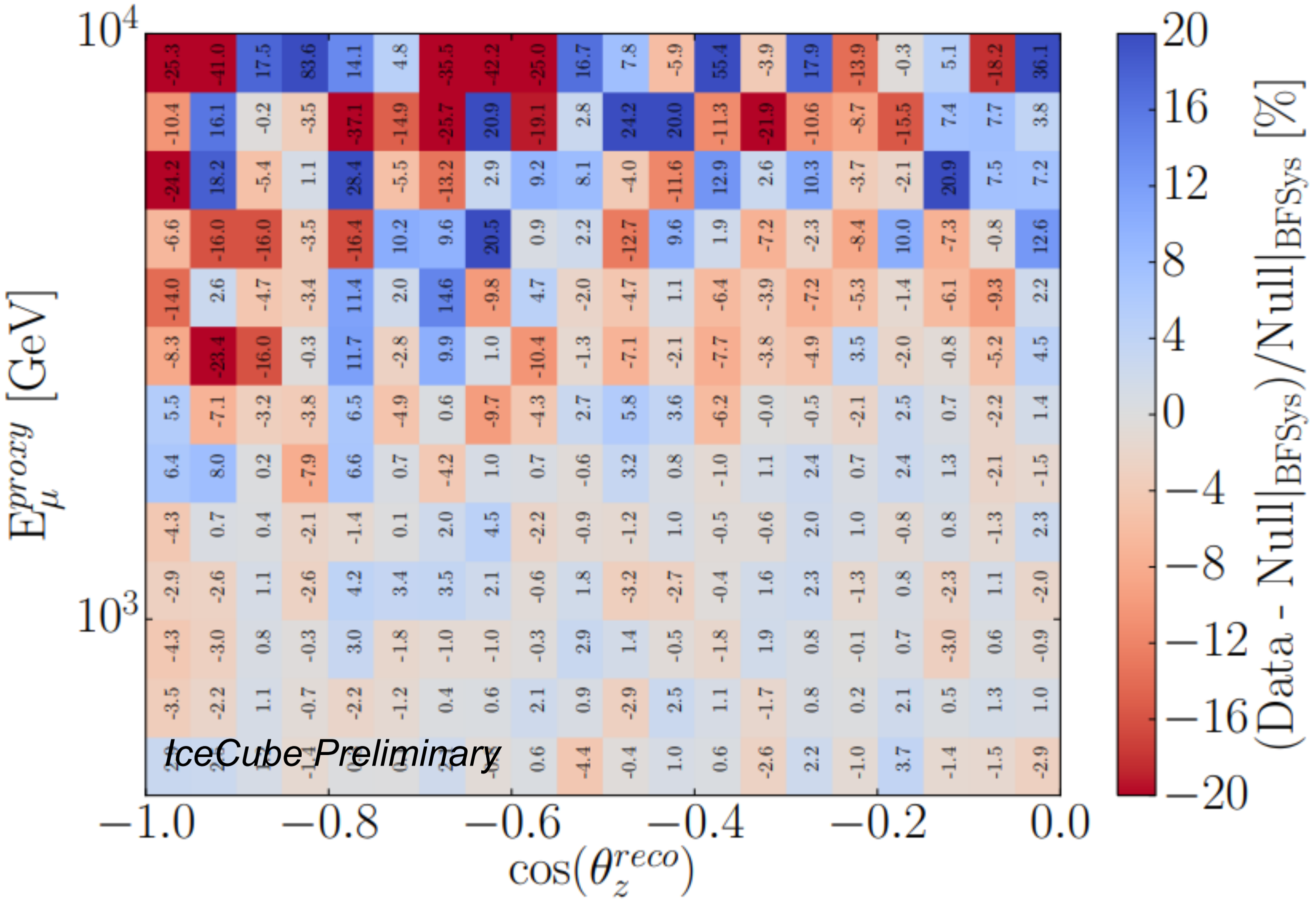
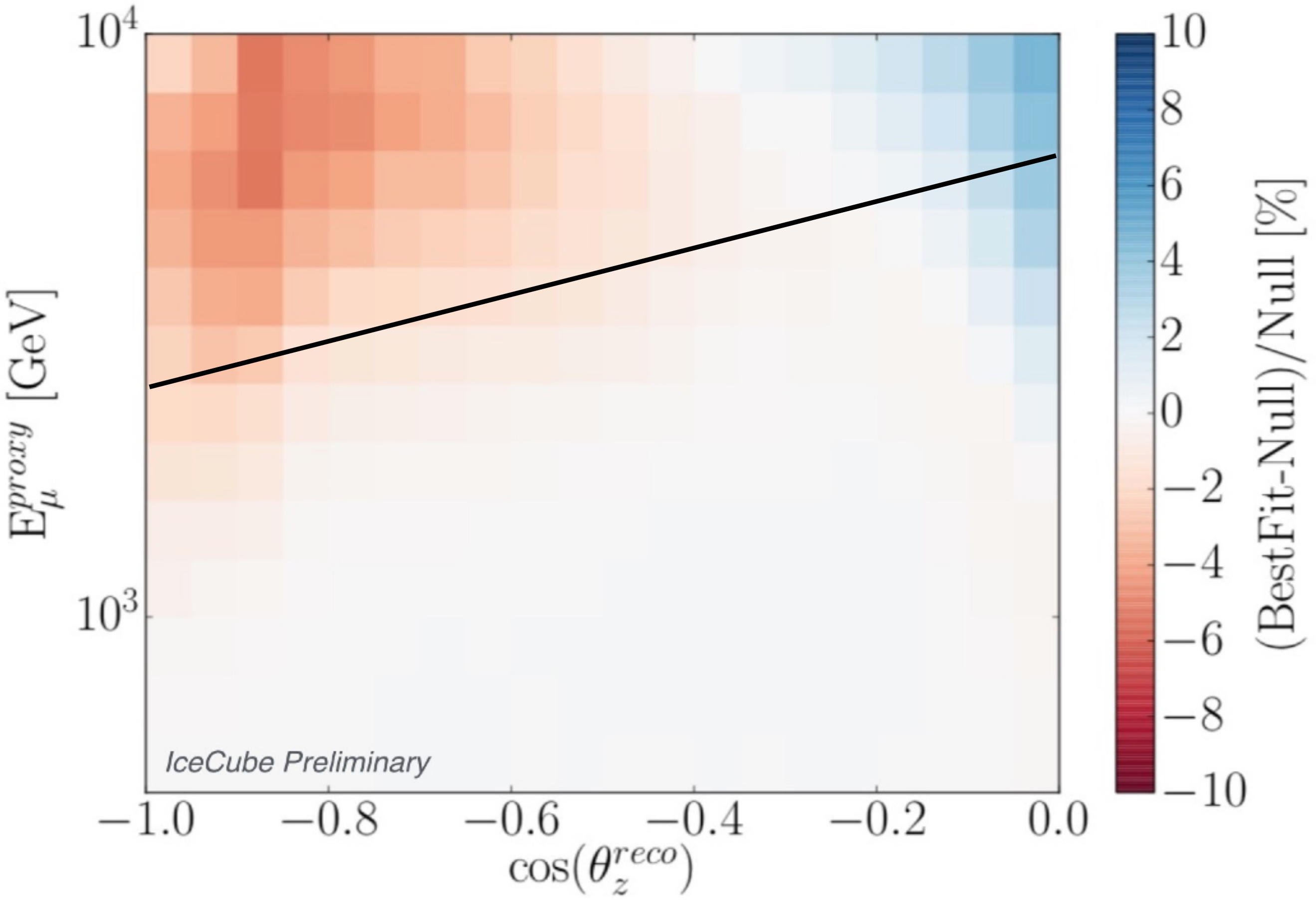
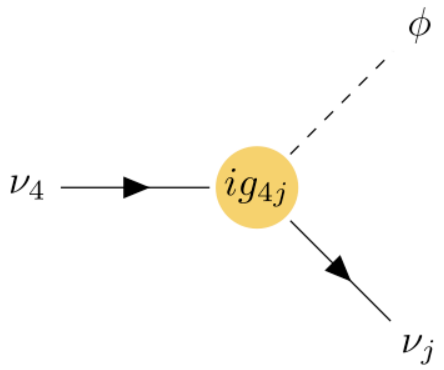


-25.3	-41.0	17.5	83.6	14.1	4.8	-35.5	-42.2	-25.0	16.7	7.8	-5.9	55.4	-3.9	17.9	-13.9	-0.3	5.1	-18.2	36.1
-10.4	16.1	-0.2	-3.5	-37.1	-14.9	-25.7	20.9	-19.1	2.8	24.2	20.0	-11.3	-21.9	-10.6	-8.7	-15.5	7.4	7.7	3.8
-24.2	18.2	-5.4	1.1	28.4	-5.5	-13.2	2.9	9.2	8.1	-4.0	-11.6	12.9	2.6	10.3	-3.7	-2.1	20.9	7.5	7.2
-6.6	-16.0	-16.0	-3.5	-16.4	10.2	9.6	20.5	0.9	2.2	-12.7	9.6	1.9	-7.2	-2.3	-8.4	10.0	-7.3	-0.8	12.6
-14.0	2.6	-4.7	-3.4	11.4	2.0	14.6	-9.8	4.7	-2.0	-4.7	1.1	-6.4	-3.9	-7.2	-5.3	-1.4	-6.1	-9.3	2.2
-8.3	-23.4	-16.0	-0.3	11.7	-2.8	9.9	1.0	-10.4	-1.3	-7.1	-2.1	-7.7	-3.8	-4.9	3.5	-2.0	-0.8	-5.2	4.5
5.5	-7.1	-3.2	-3.8	6.5	-4.9	0.6	-9.7	-4.3	2.7	5.8	3.6	-6.2	-0.0	-0.5	-2.1	2.5	0.7	-2.2	1.4
6.4	8.0	0.2	-7.9	6.6	0.7	-4.2	1.0	0.7	-0.6	3.2	0.8	-1.0	1.1	2.4	0.7	2.4	1.3	-2.1	-1.5
-4.3	0.7	0.4	-2.1	-1.4	0.1	2.0	4.5	-2.2	-0.9	-1.2	1.0	-0.5	-0.6	2.0	1.0	-0.8	0.8	-1.3	2.3
-2.9	-2.6	1.1	-2.6	4.2	3.4	3.5	2.1	-0.6	1.8	-3.2	-2.7	-0.4	1.6	2.3	-1.3	0.8	-2.3	1.1	-2.0
-4.3	-3.0	0.8	-0.3	3.0	-1.8	-1.0	-1.0	-0.3	2.9	1.4	-0.5	-1.8	1.9	0.8	-0.1	0.7	-3.0	0.6	-0.9
-3.5	-2.2	1.1	-0.7	-2.2	-1.2	0.4	0.6	2.1	0.9	-2.9	2.5	1.1	-1.7	0.8	0.2	2.1	0.5	1.3	1.0
[illegible]	[illegible]	[illegible]	-1.4	[illegible]	[illegible]	[illegible]	[illegible]	0.6	-4.4	-0.4	1.0	0.6	-2.6	2.2	-1.0	3.7	-1.4	-1.5	-2.9

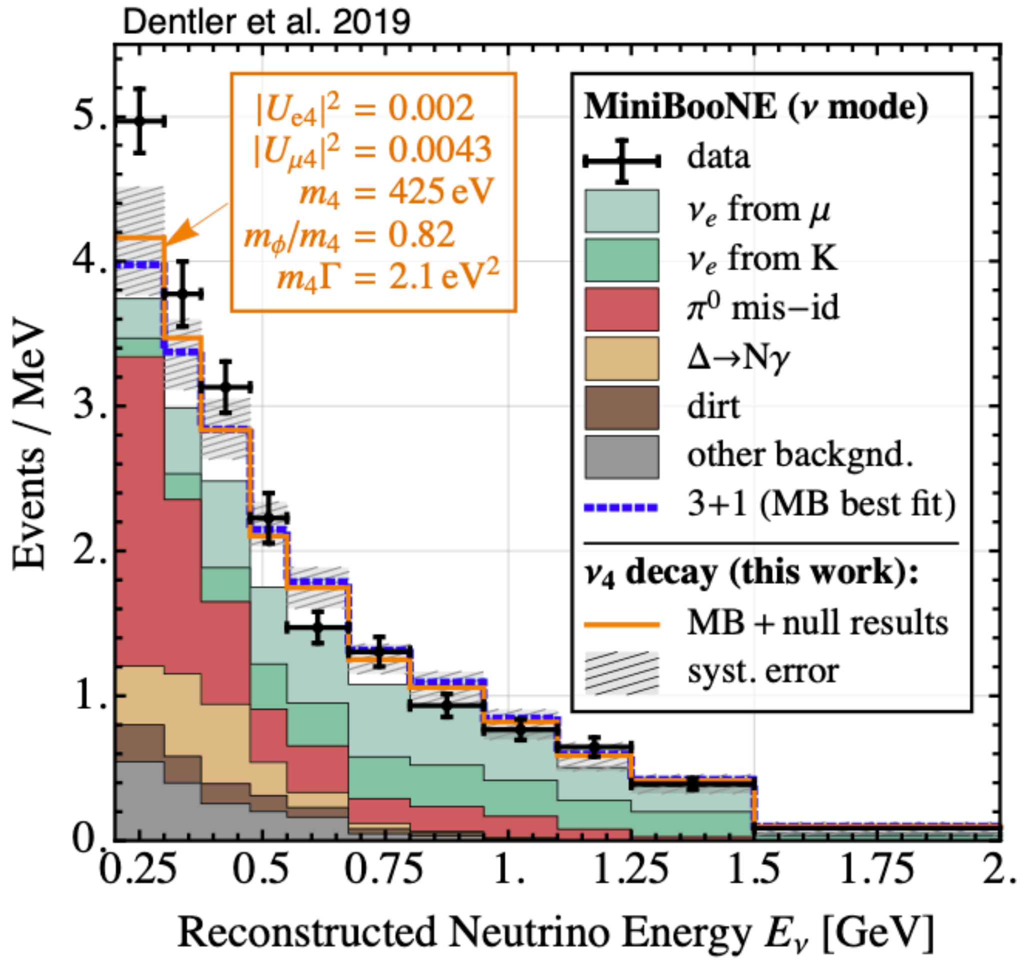


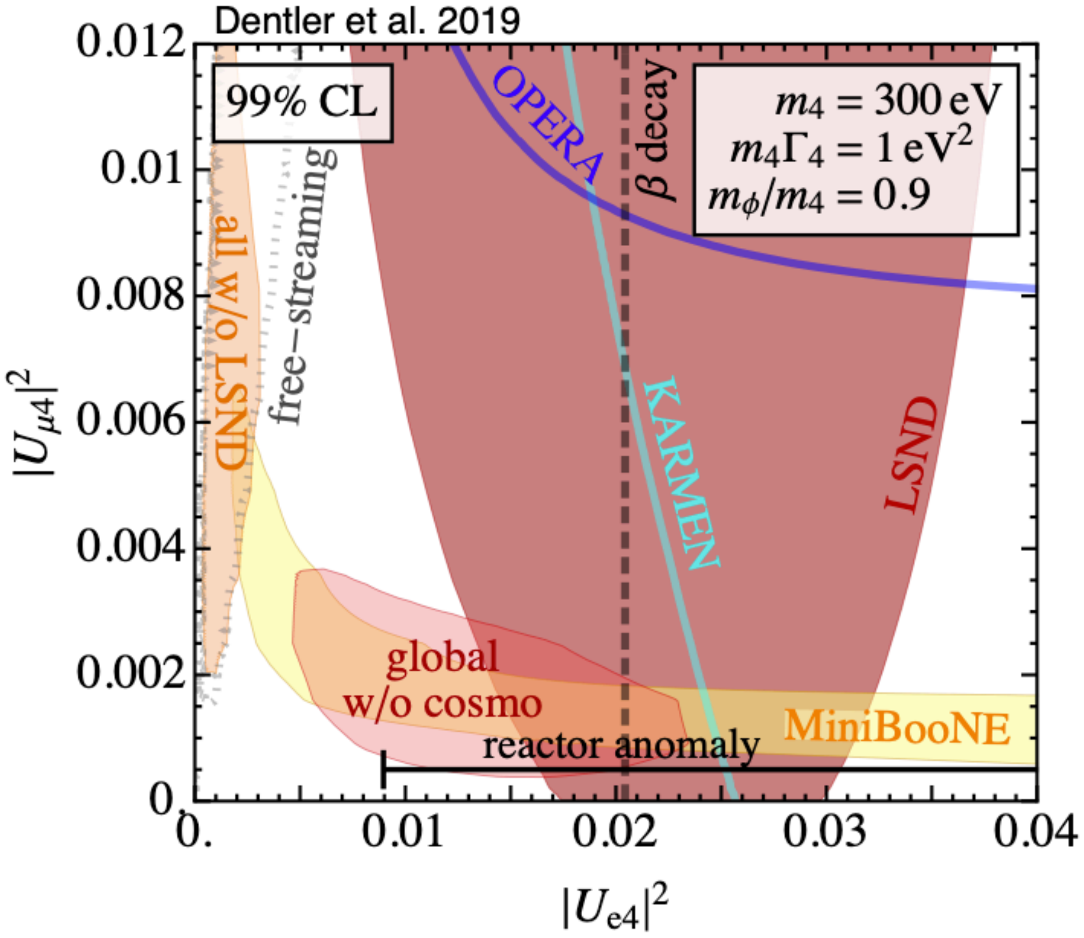


Sterile Neutrino Decay (3+1+Visible-Decay)

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

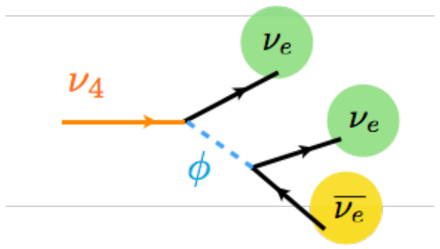
$$\mathcal{L} \supset -g\,\bar{\nu}_s\nu_s\phi - \sum_{a=e,\mu,\tau,s} m_{\alpha\beta}\,\bar{\nu}_\alpha\nu_\beta$$





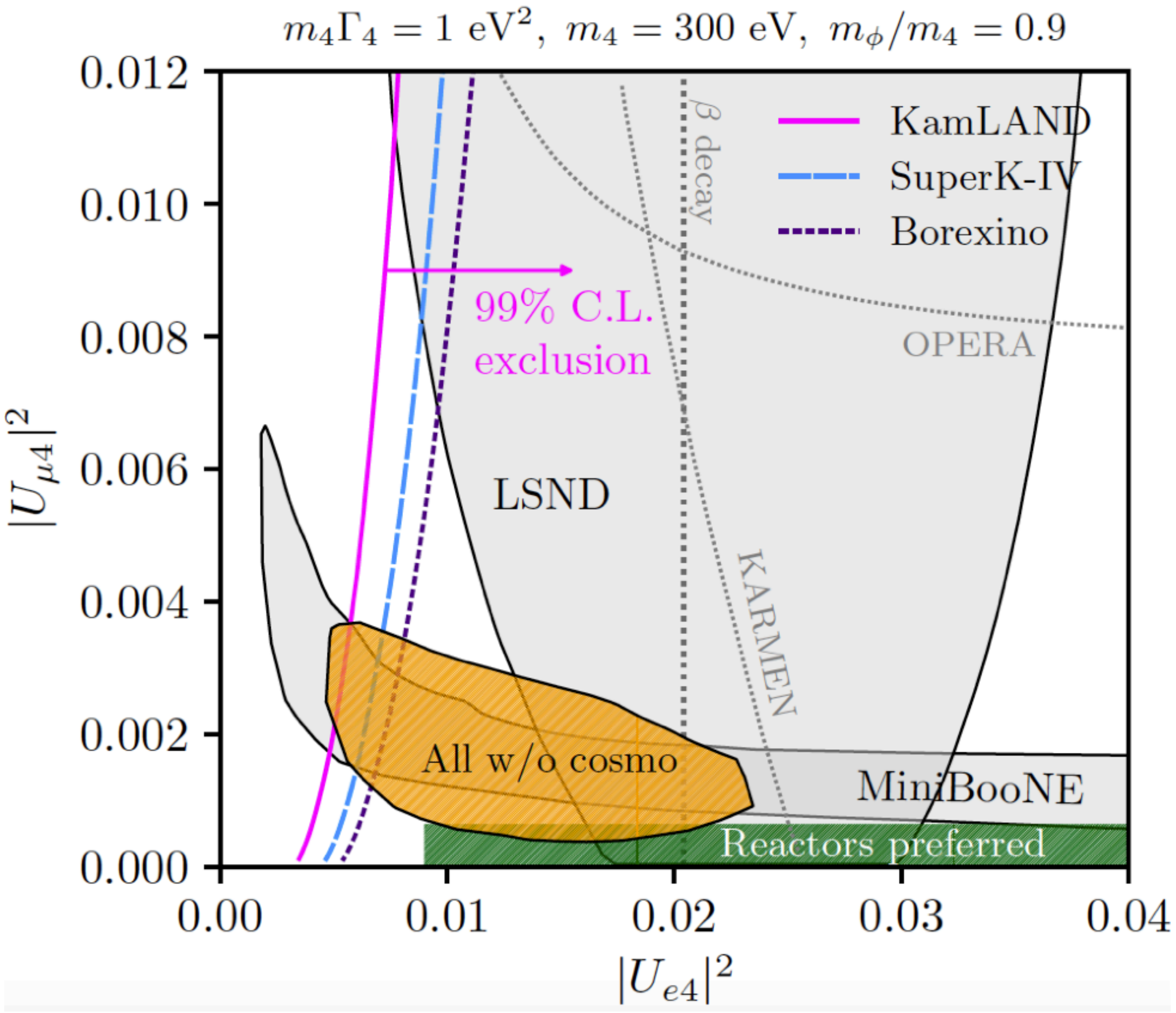
See also Palomares-Ruiz et al http://xxx.lanl.gov/abs/hep-ph/0505216, Gninekov https://arxiv.org/abs/0902.3802, Fisher et al https://arxiv.org/abs/1909.09561

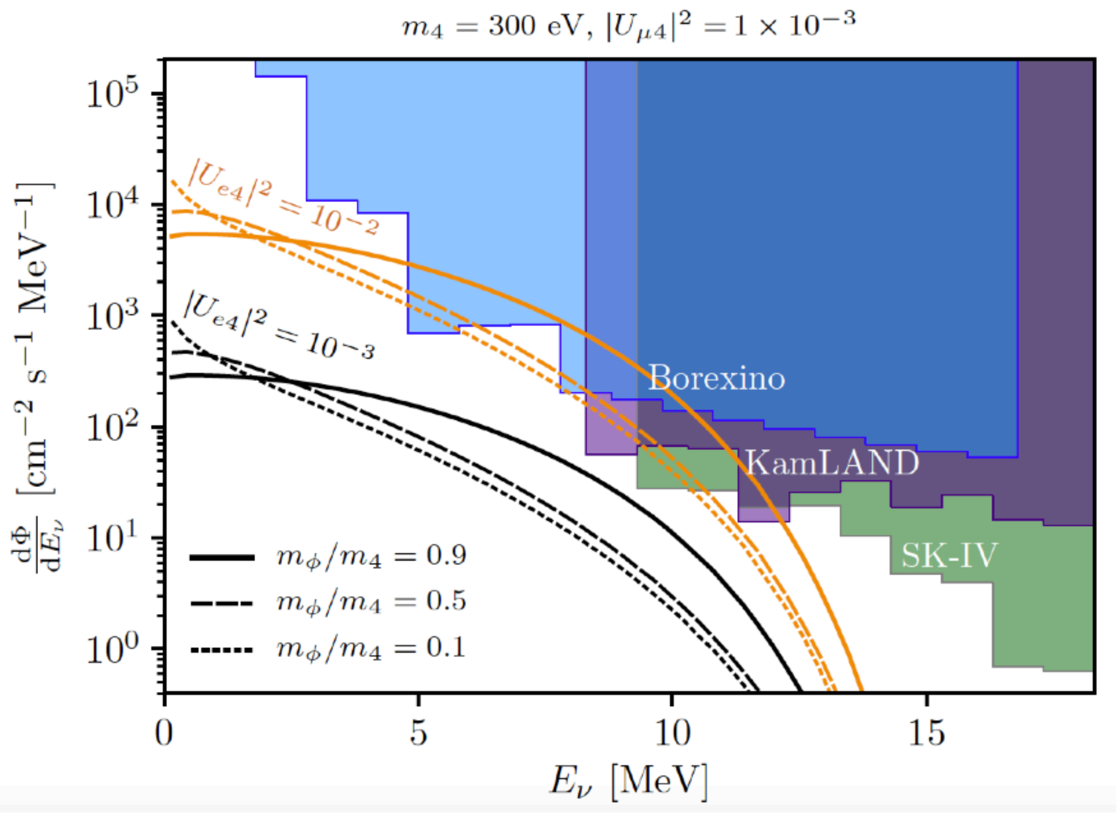
Neutrino Decay as a Solution to the Short-Baseline Anomalies
(https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF2_NF3_G_V_Stenico-131.pdf)



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

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





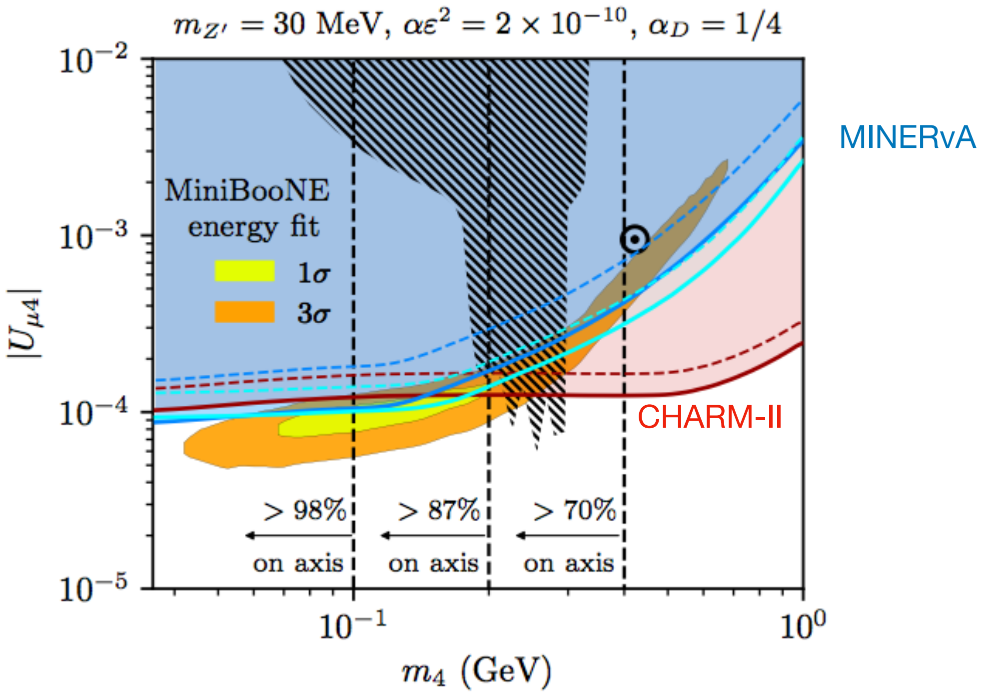
Visible decay predicts emission of antineutrinos from the Sun!

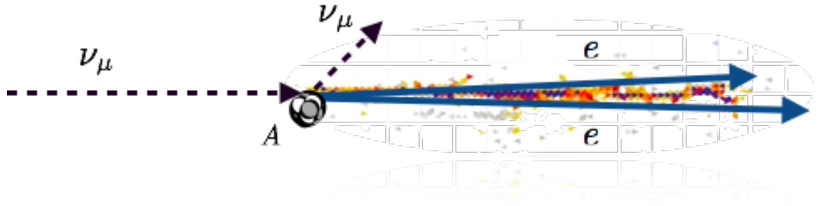
Neutrino Decay as a Solution to the Short-Baseline Anomalies
(https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF2_NF3_G_V_Stenico-131.pdf)

Non-Minimal HNLs - Testability

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

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

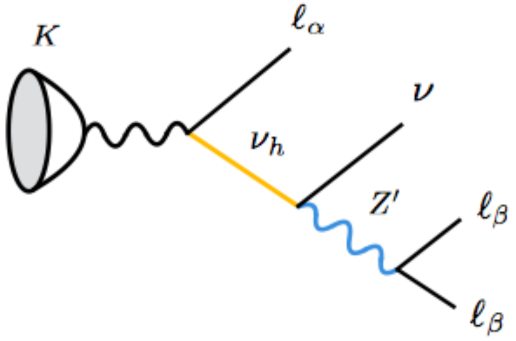




More data from: MINERvA, NOvA, and SBN program to come soon!

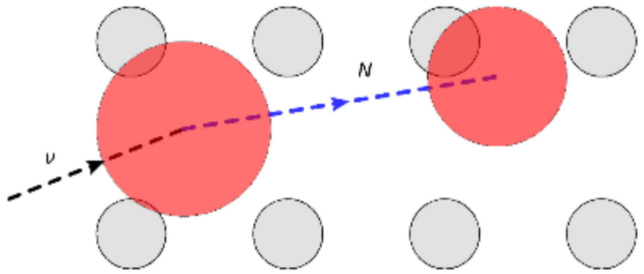
Rare kaon decays

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

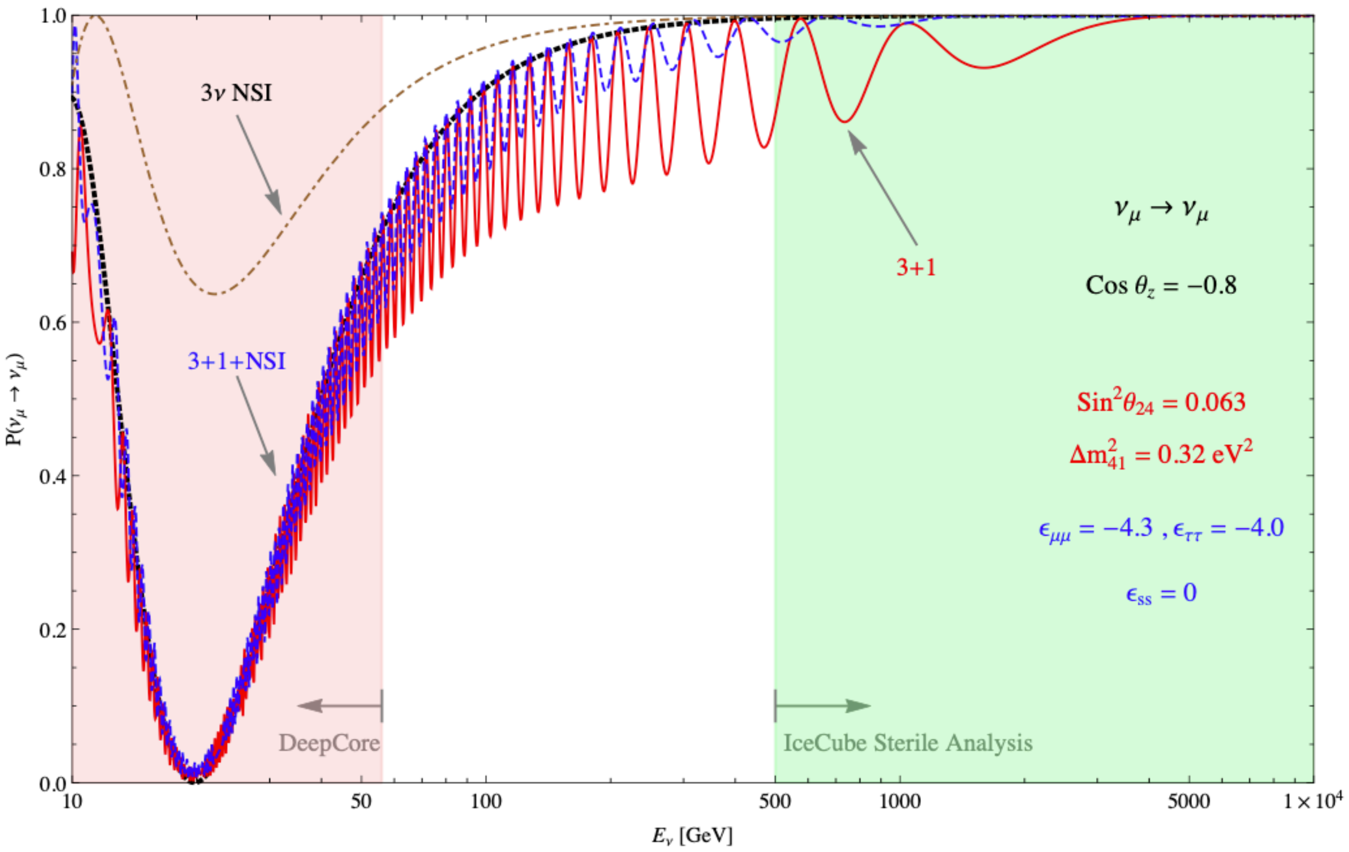
A. Abdullahi, M. Hostert, S. Pascoli, arXiv:2007.11813

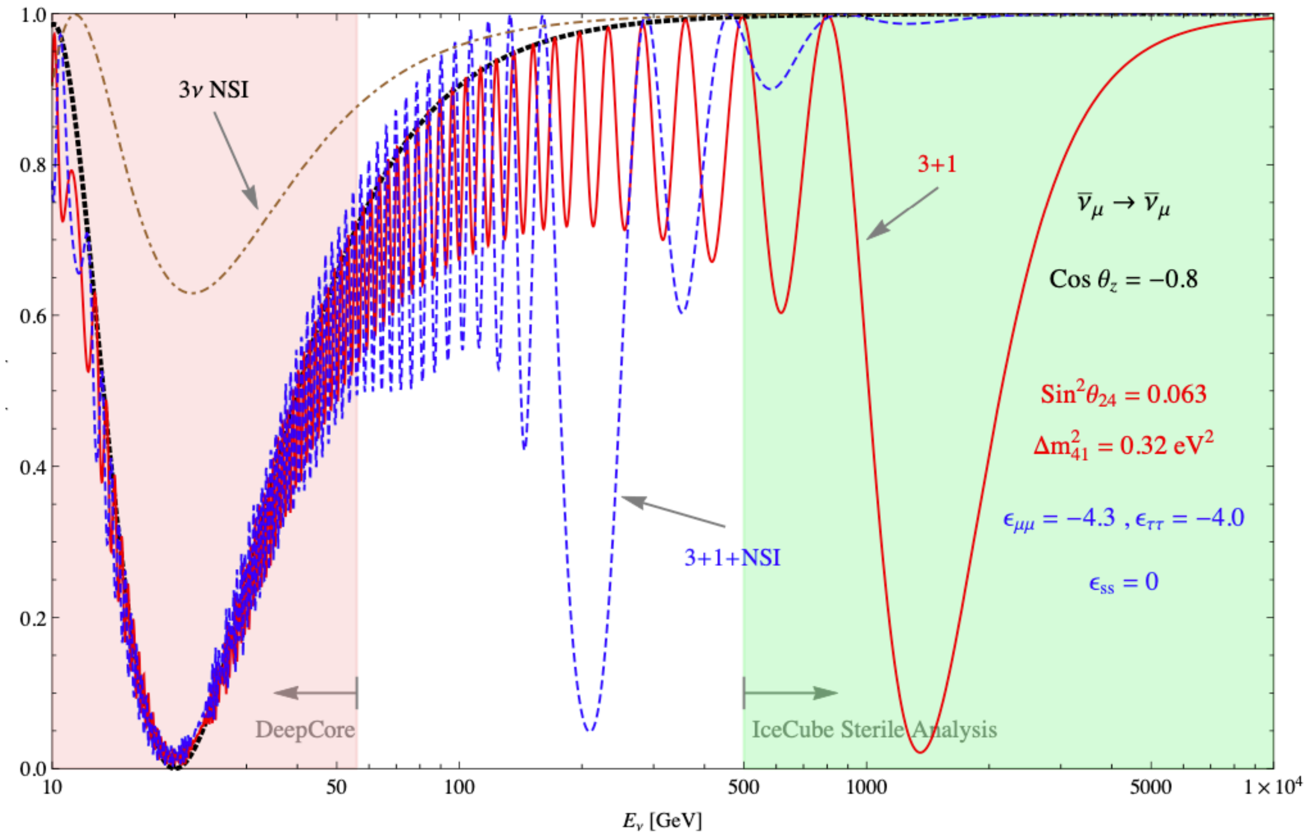
BSM Physics at the Electron Ion Collider: Searching for Heavy Neutral Leptons
(https://www.snowmass21.org/docs/files/summaries/EF/SNOWMASS21-EF7_EF0-NF2_NF3-RF4_RF0_Brian_Batell-114.pdf)
Dark Sector With Neutrino Beams
(https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF3_NF0-RF6_RF0-CF1_CF3-TF9_TF11-148.pdf)
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)

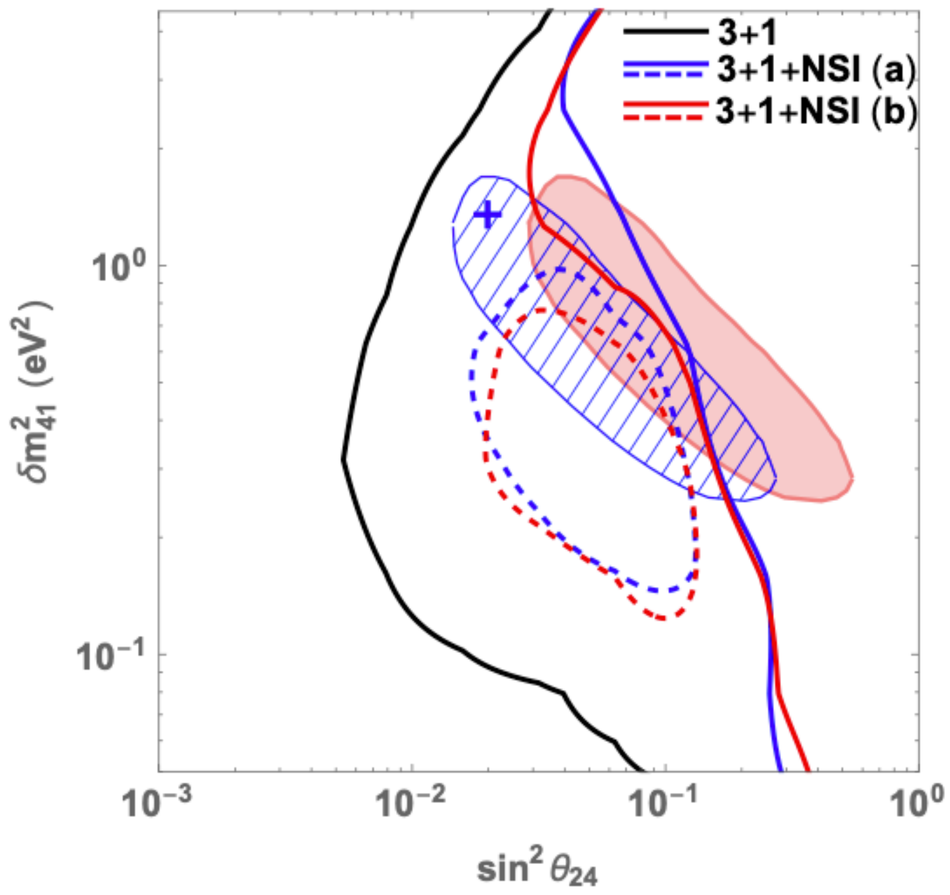
Neutrino NonStandard Interactions
( )

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

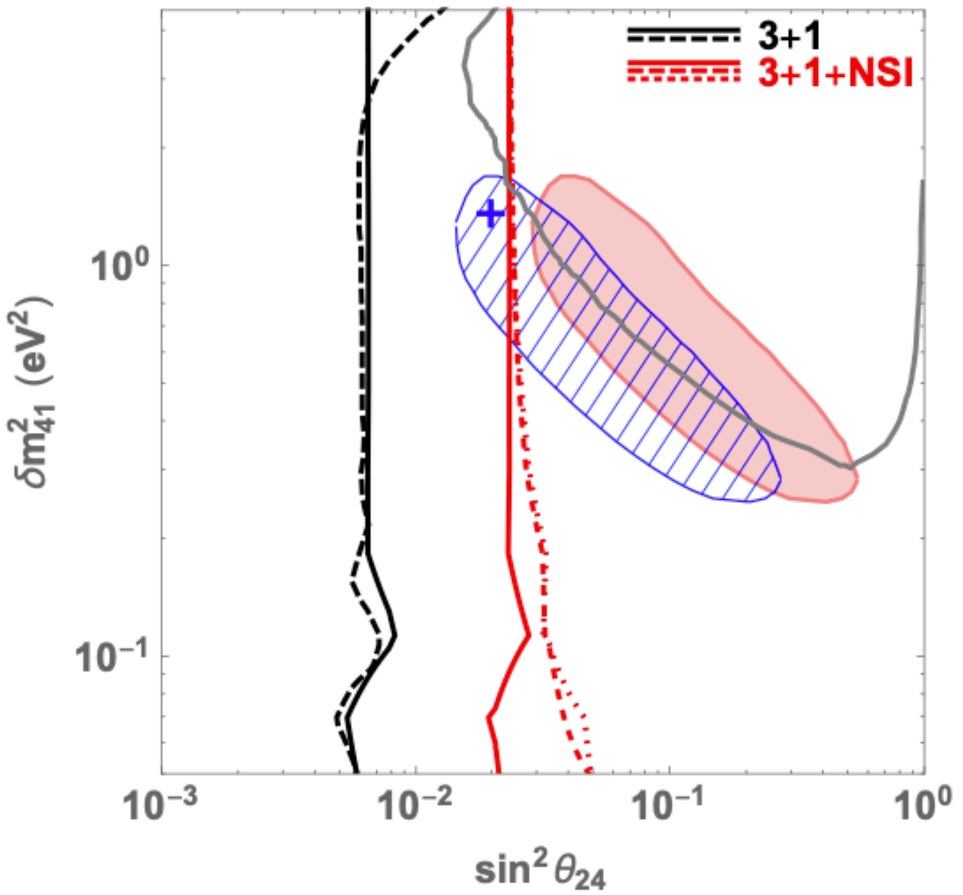
J. Liao et al

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

IceCube modified by NSI



MINOS modified by NSI



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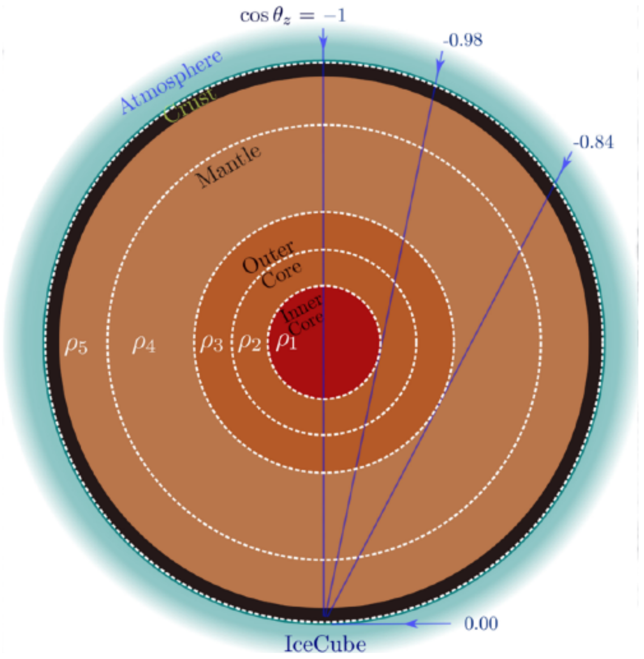
(https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF1_NF3-TF0_TF0_Peter_Denton-010.pdf)

Position of resonance maps onto sterile parameter space



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

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