Sometimes vanilla is not enough!

Sterile Neutrinos: theory opportunities!

Carlos Argüelles

HARVARD UNIVERSITY

Lots of great LoIs

Indirect Detection Aspects of Hidden Sector Dark

Neutrino Non-Standard Interactions

Direct Probes of the Matter Effect in Neutrino Oscillations

Opportunities and signatures of non-minimal Heavy Neutral Leptons

NuSte: Global Light Sterile Neutrino Fits

BSM Physics at the Electron Ion Collider: Searching for Heavy Neutral Leptons

Ultralight dark matter and neutrinos

Dark Sector Studies With Neutrino Beams

Large Extra-Dimension Searches

Exploration of a new model for neutrino oscillations using a kiloton-scale neutrino detector at the Advanced Instrumentation Testbed in Boulby England

Non-Unitarity of the neutrino mixing matrix

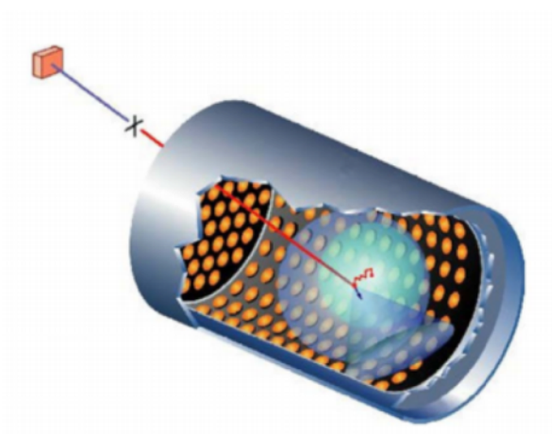
Testing quasi-Dirac leptogenesis through neutrino oscillations

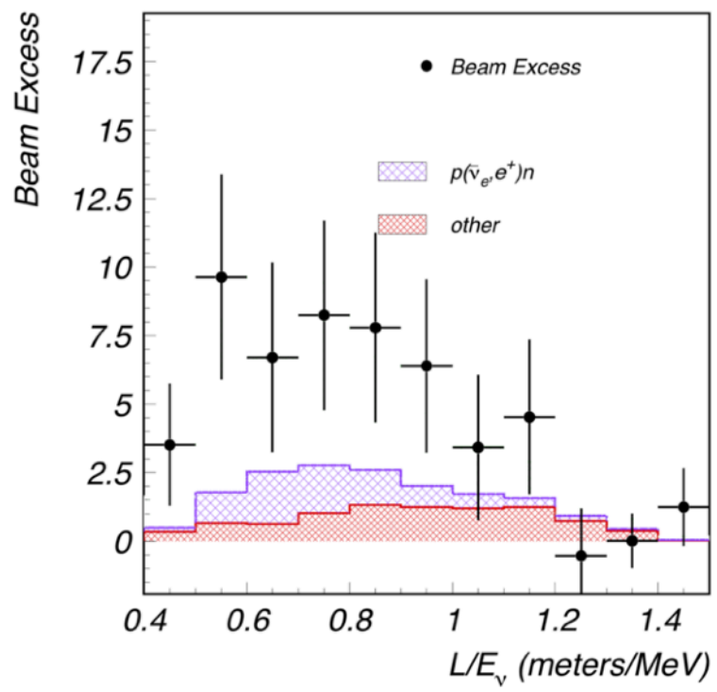
THREE STERILE NEUTRINOS IN E 6

Neutrino Decay as a Solution to the Short-Baseline Anomalies

Big common point: the short-baseline anomalies

LSND

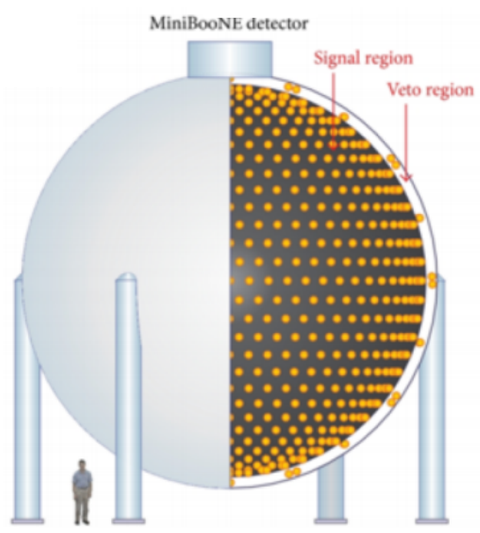


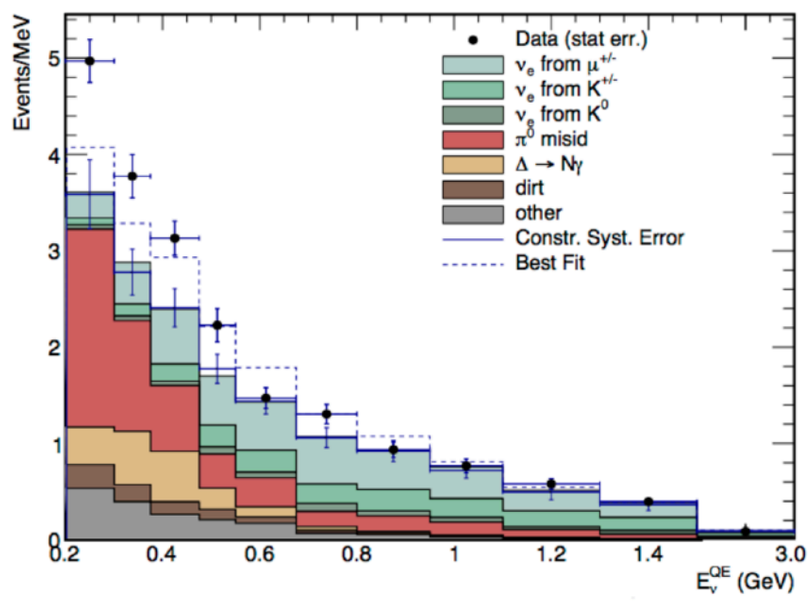


These experiments observe ν_e appearance at L/E ~ 1 km/GeV!

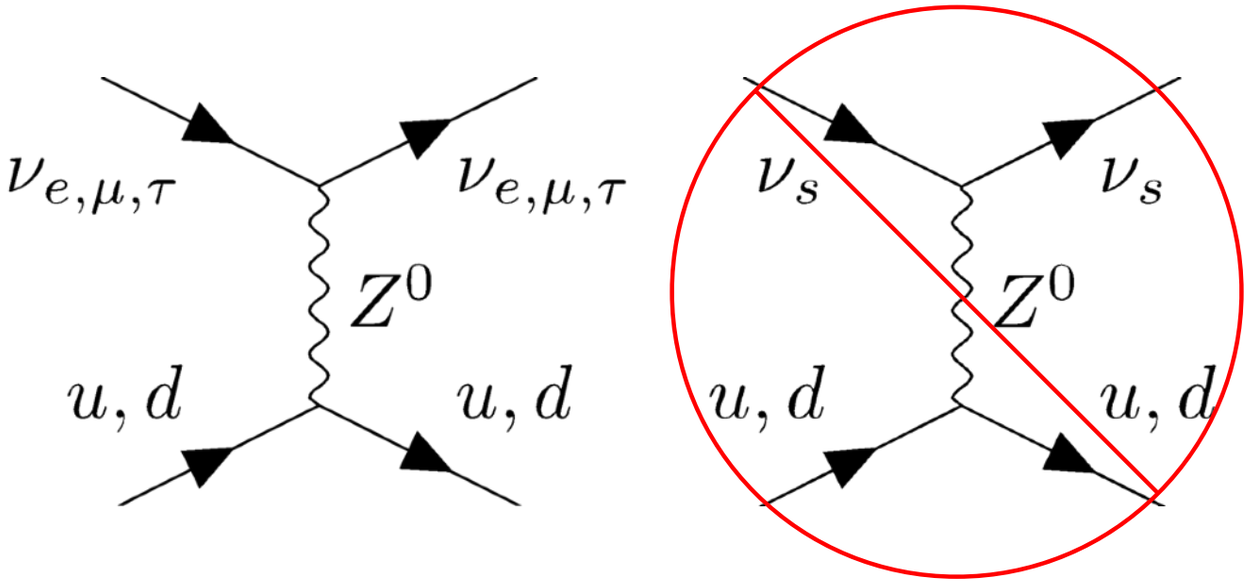
This points to $\Delta m^2 \sim 1 eV^2$

MiniBooNE

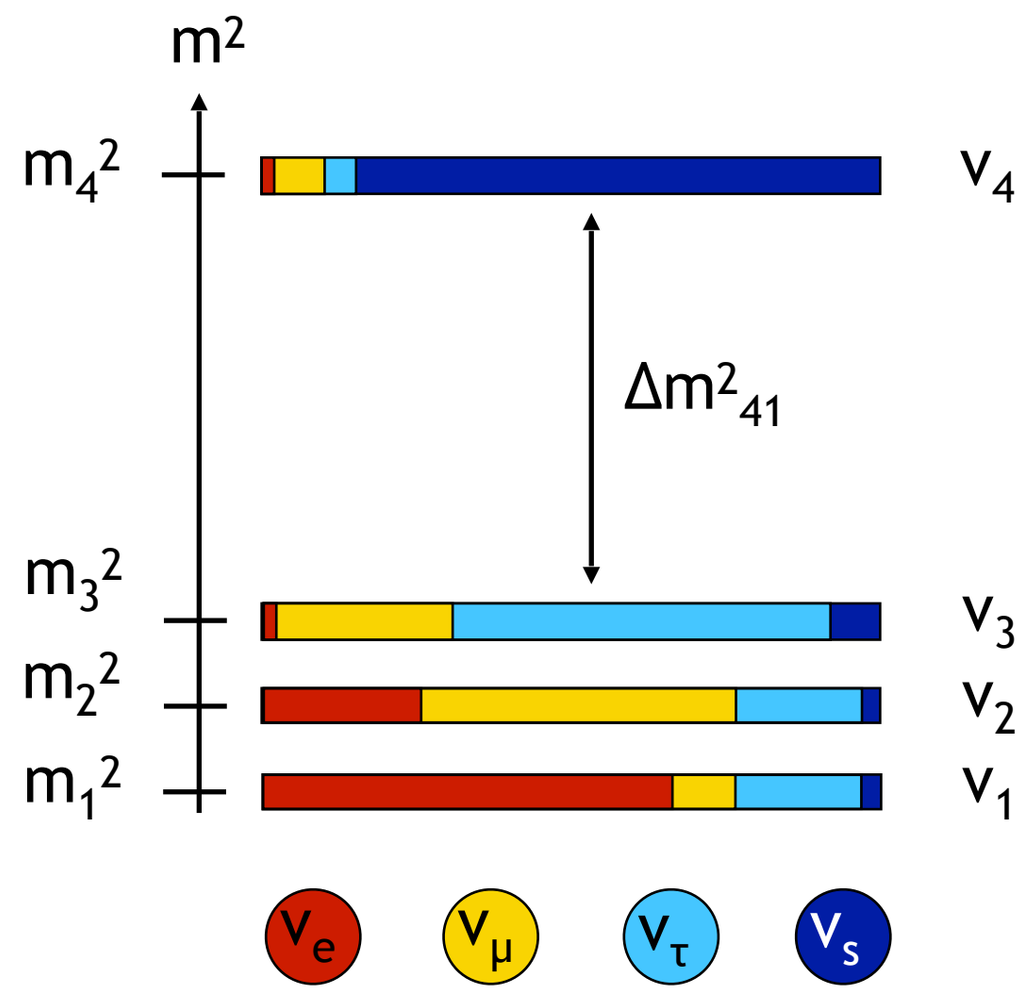




Vanilla solution: light sterile neutrino

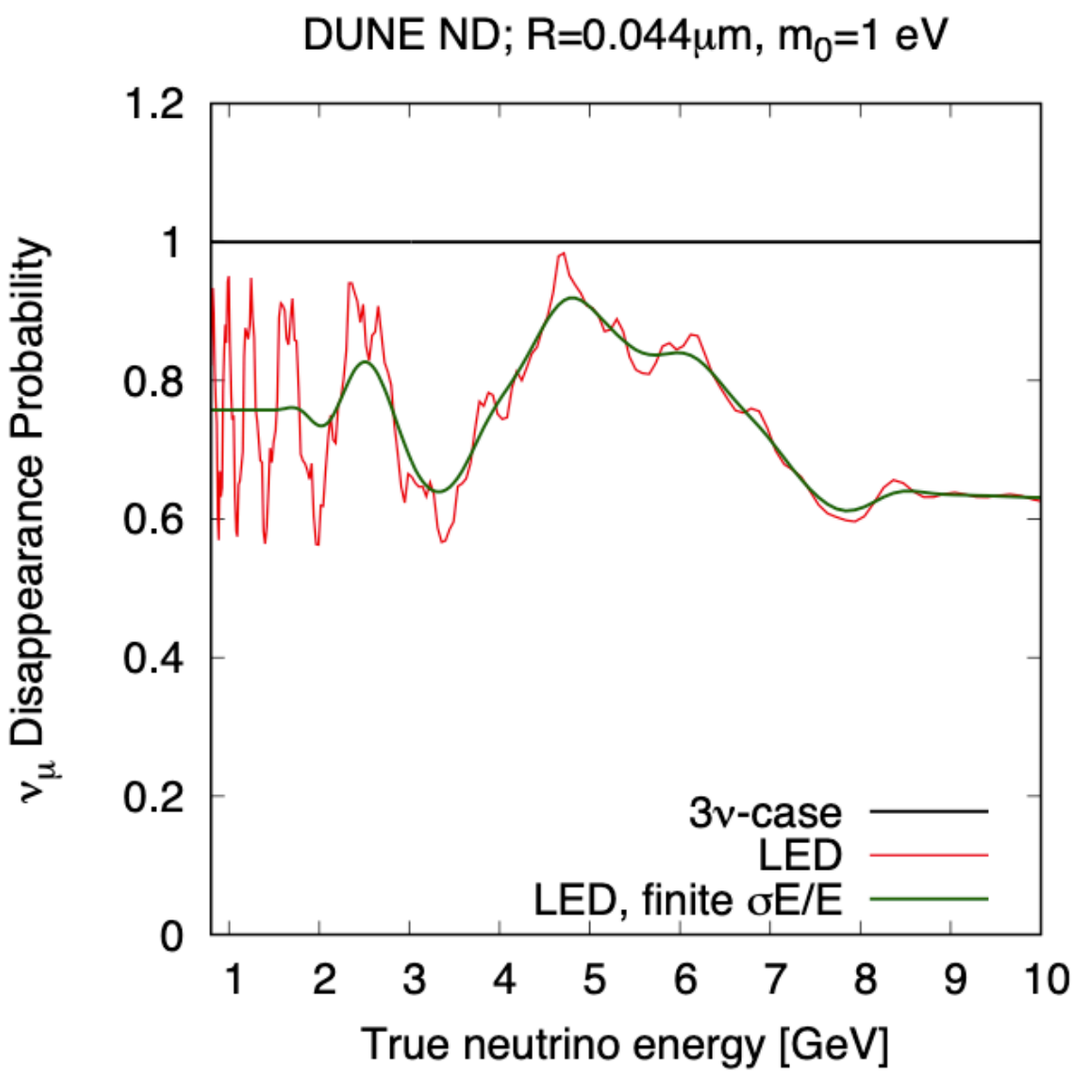


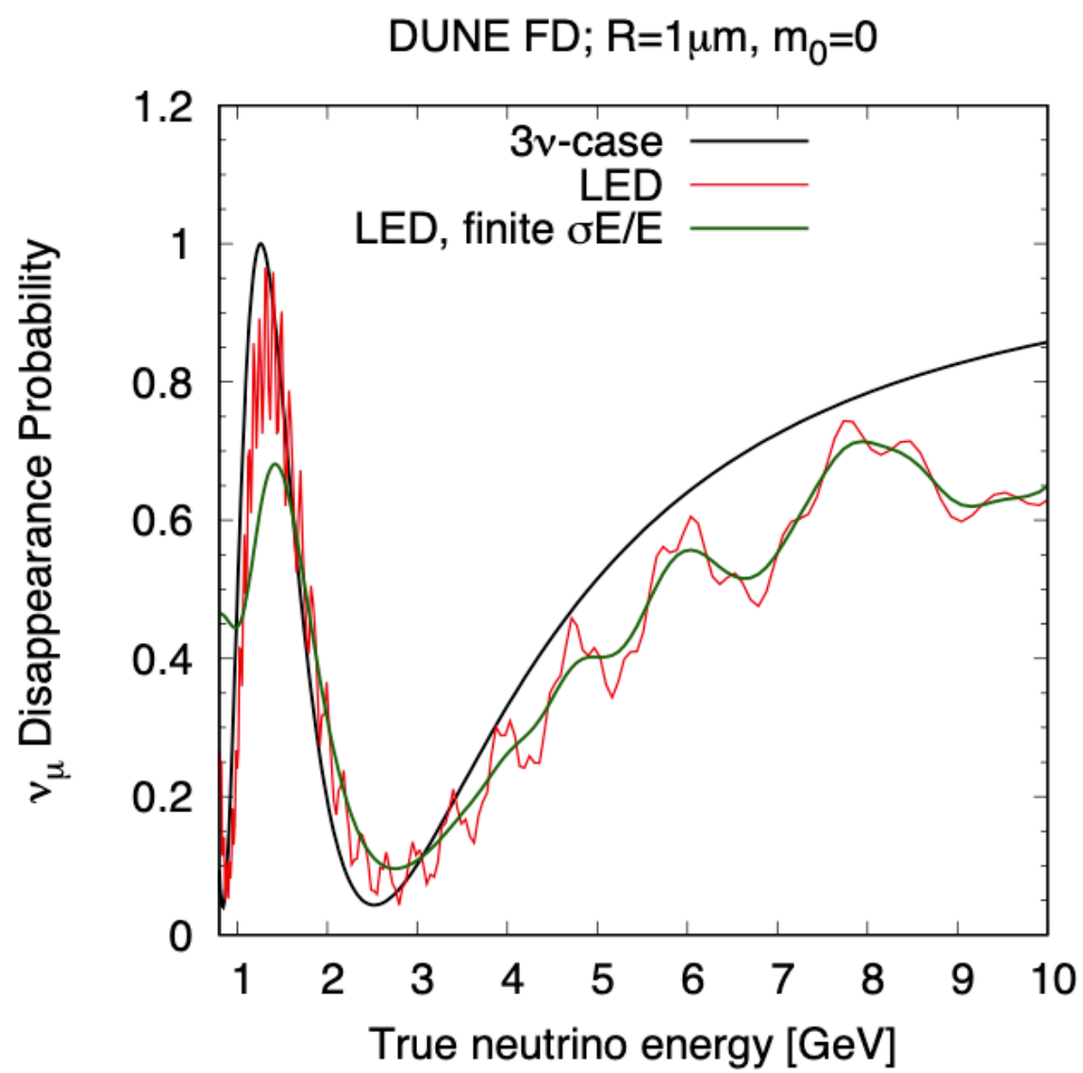
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2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



Assuming Normal Ordering

Large Extra-Dimension





Large Extra-Dimension Searches
(https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF2_NF3-TF11_TF8_D-V-Forero-078.pdf)

Appearance and Disappearance signals should be related!

$\nu_\mu \to \nu_e$

$\nu_e \to \nu_e$

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

$\Rightarrow$ U_{e4} $U_{\mu 4}$ Δm^2

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

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

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

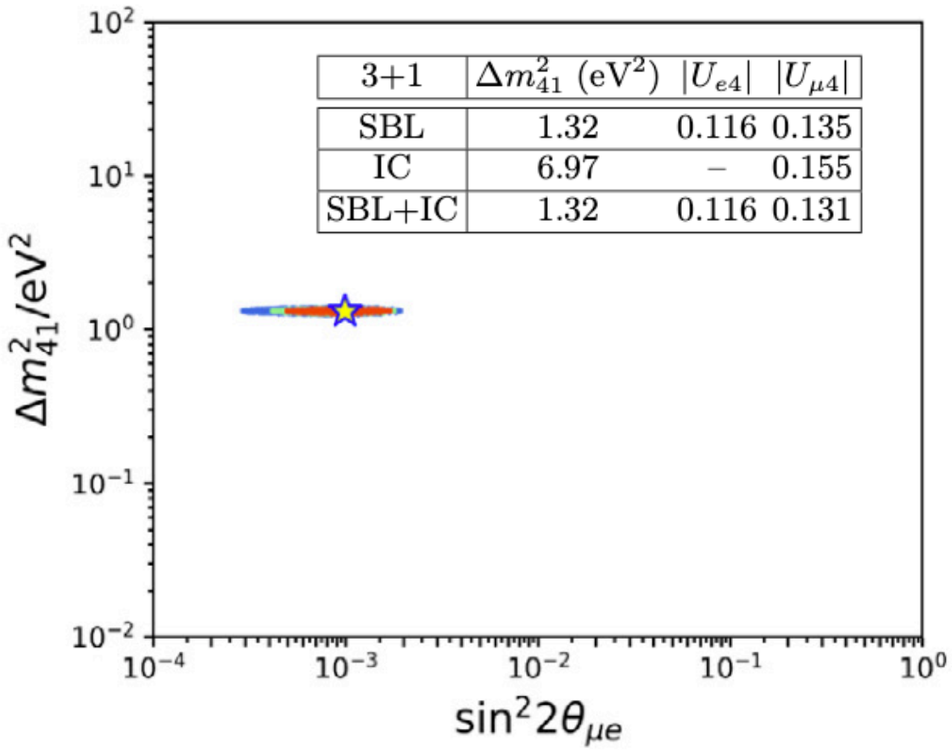
$$\sin^2 2\theta_{ee} = 4(1 - |U_{e4}|^2)|U_{e4}|^2$$

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

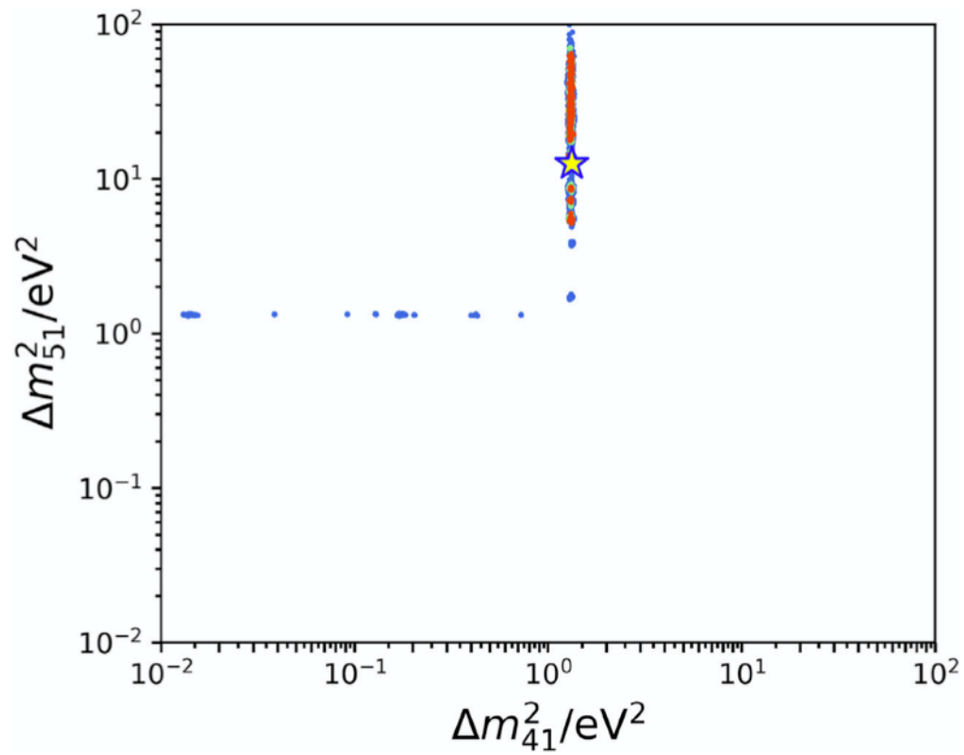
$$\sin^2 2\theta_{\mu e} = 4|U_{\mu 4}|^2|U_{e4}|^2$$

Global fits and the vanilla scenario

Diaz arXiv:1906.00045



3+1	Δm^2_{41} (eV^2)	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 4}\rvert$
SBL	1.32	0.116	0.135
IC	6.97	–	0.155
SBL+IC	1.32	0.116	0.131



Diaz arXiv:1906.00045

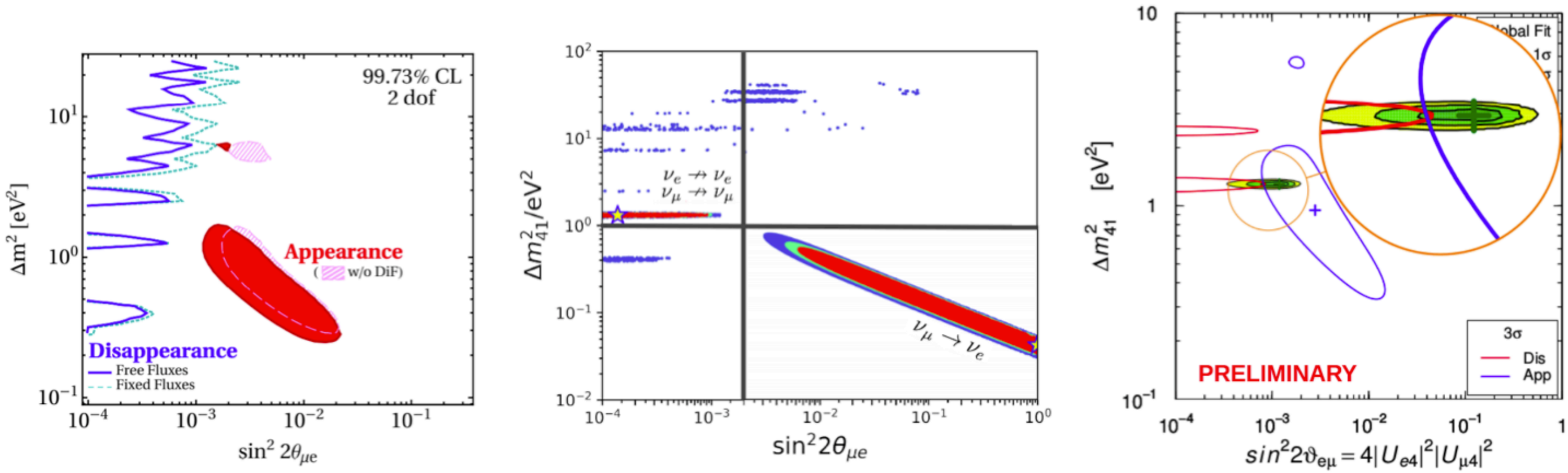
Fit type:	3ν (null)	3+1	3+2
Best Fits			
χ^2	493	458	449
dof	509	506	502
p-value	0.687	0.938	0.957
(Null vs Sterile)			
$\Delta\chi^2$		35	44
Δdof		3	7
p-value		1.2E−07	2.1E−07
$N\sigma$		5.2	5.1

The data prefers beyond the null hypothesis!

Similar conclusions in Collin et al 1602.00671, Gariazzo et al. 1703.00860, and Dentler et al JHEP 1808 (2018)

NuSte: Global Light Sterile Neutrino Fits
(https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF2_NF3_carlo.giunti@to.infn.it-008.pdf)

Global fits and the vanilla scenario



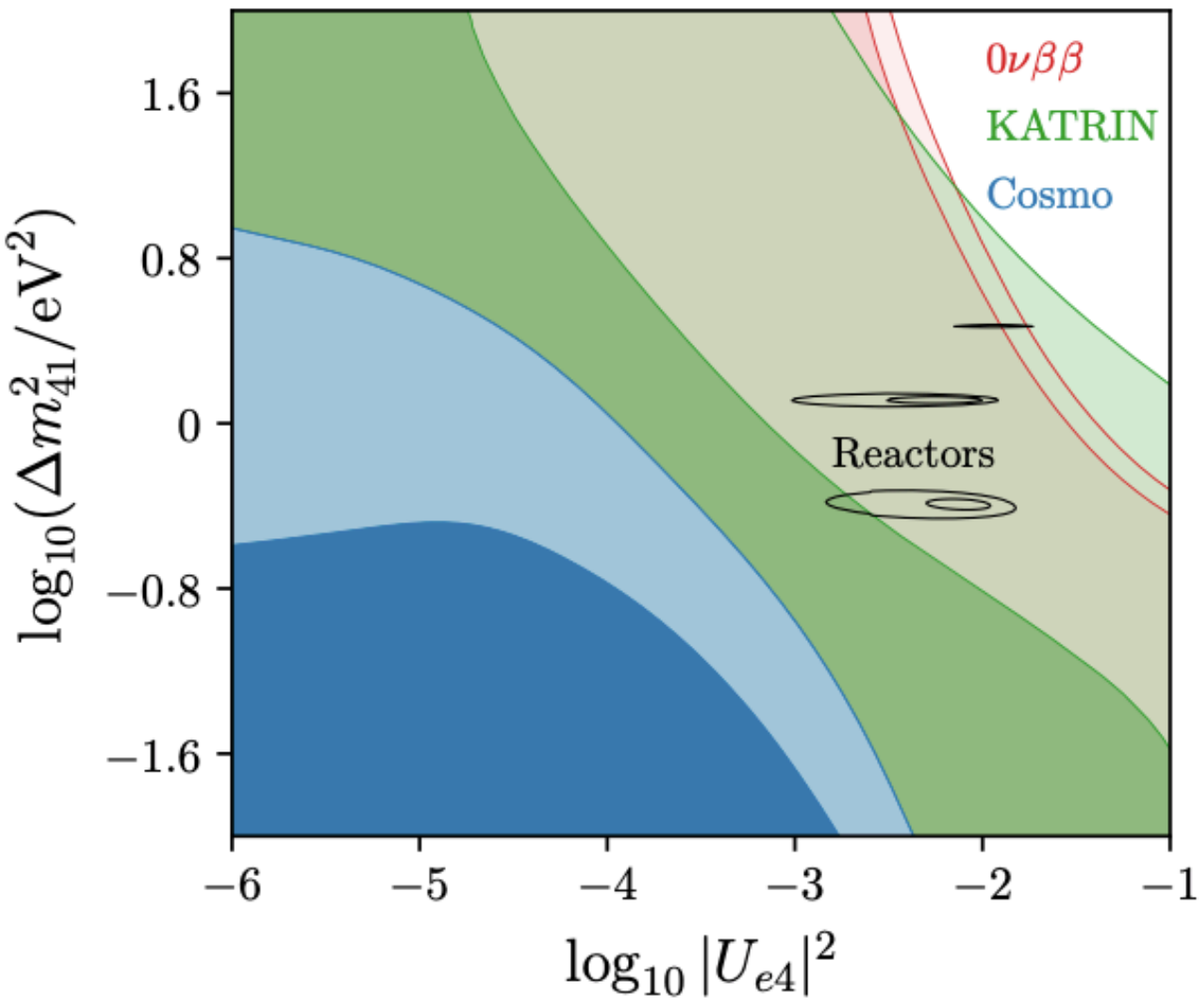
3+1 model severely disfavored by tension between appearance and disappearance

All global fit groups agree in this conclusion Diaz et al arXiv:1906.00045, Gariazzo et al. 1703.00860, and Dentler et al JHEP 1808 (2018)

NuSte: Global Light Sterile Neutrino Fits
(https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF2_NF3_carlo.giunti@to.infn.it-008.pdf)

Let's not forget cosmology!

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



Effective mixing

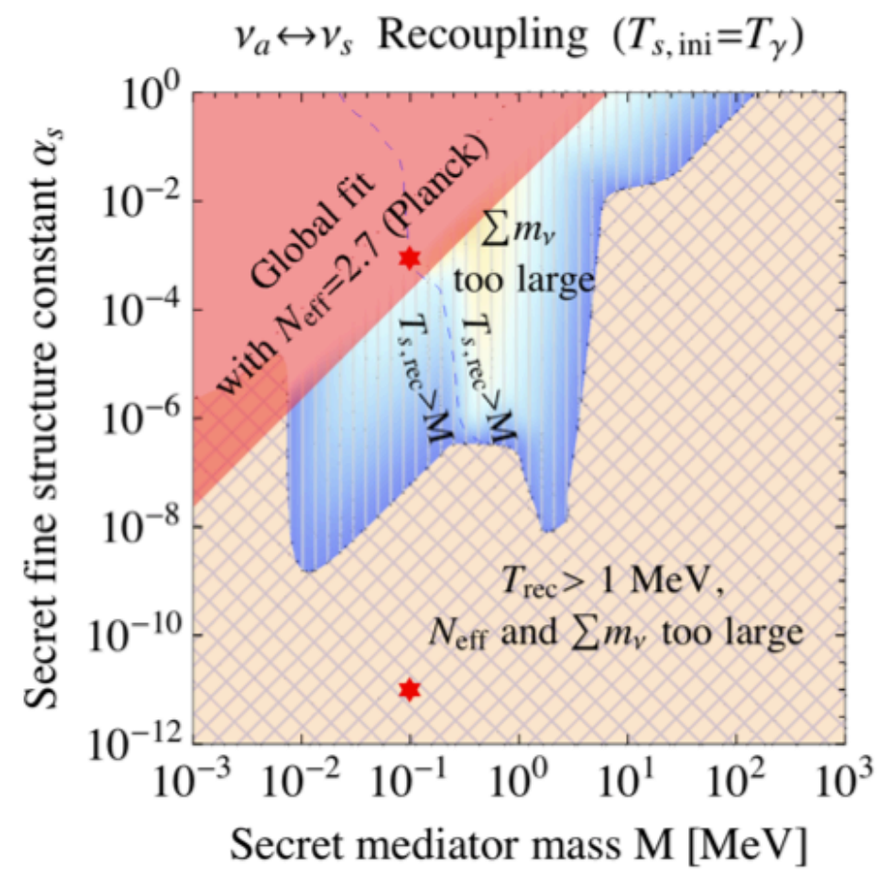
$$\sin^2 2\theta_m = \frac{\sin^2 2\theta_0}{\left(\cos^2 2\theta_0 + \frac{2E}{\Delta m^2} V_m\right) + \sin^2 2\theta_0}$$

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

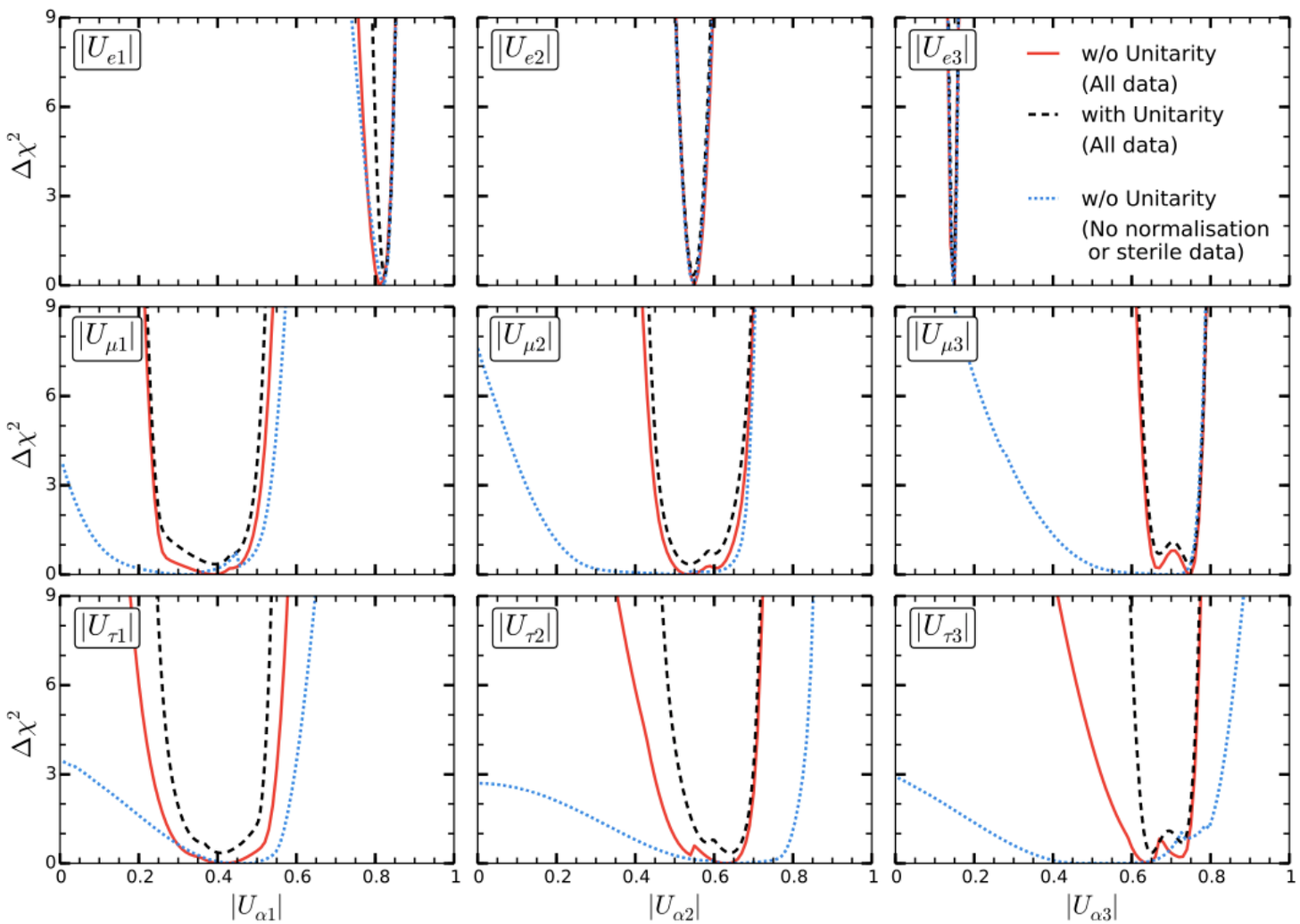
Sterile Neutrinos With Non Standard Interactions (In Cosmology)
(https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF2_NF0-CF7_CF0-TF9_TF11-200.pdf)

From here: The Garden of Forking Paths

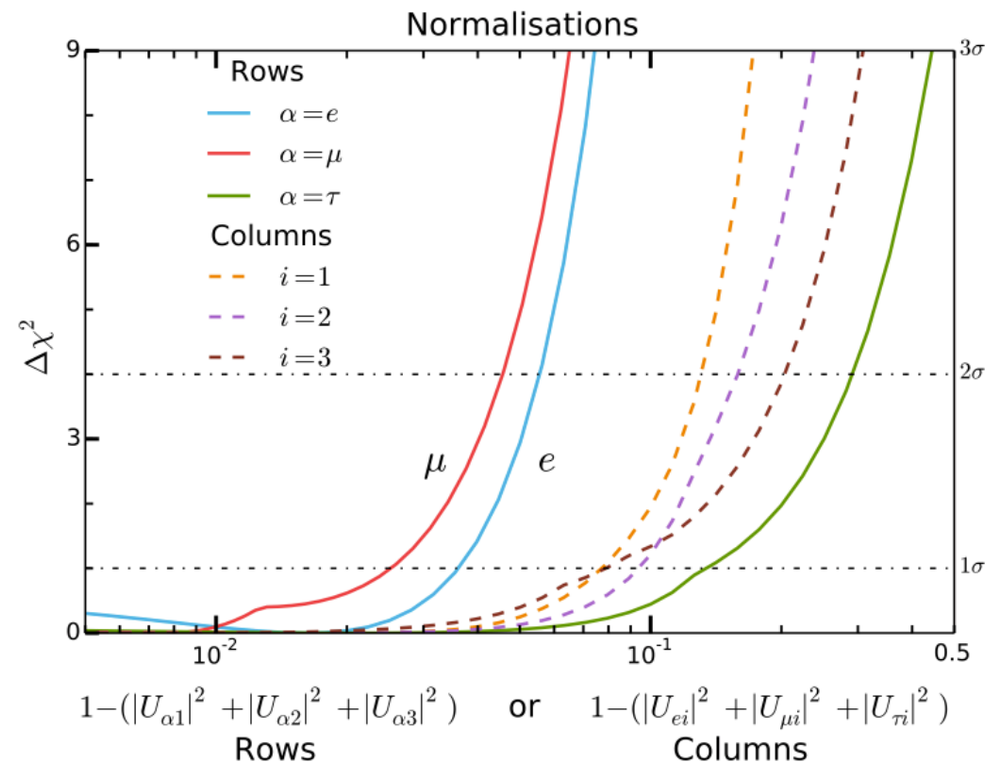
- Do we understand all SM background/process well enough?
- Are all the anomalies (MB, LSND, reactors) related? Or only some of them?
- E.g., are LSND and MiniBooNE observing the same physics?
- Since null results are not scrutinized as carefully as anomalous ones. Are all null results reliable?
- Is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

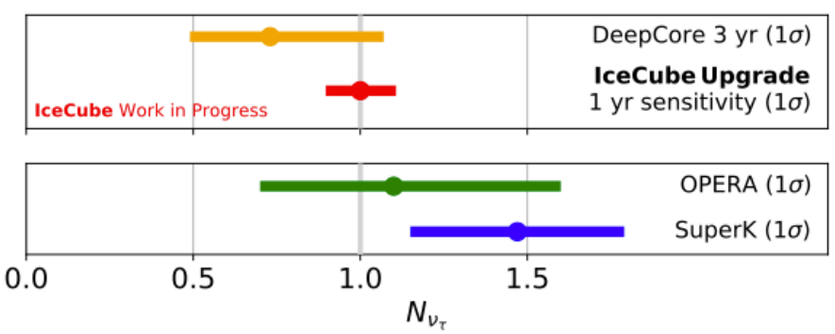
A broad net: testing unitarity

Parke & Ross-Lonergan https://arxiv.org/abs/1508.05095



2015



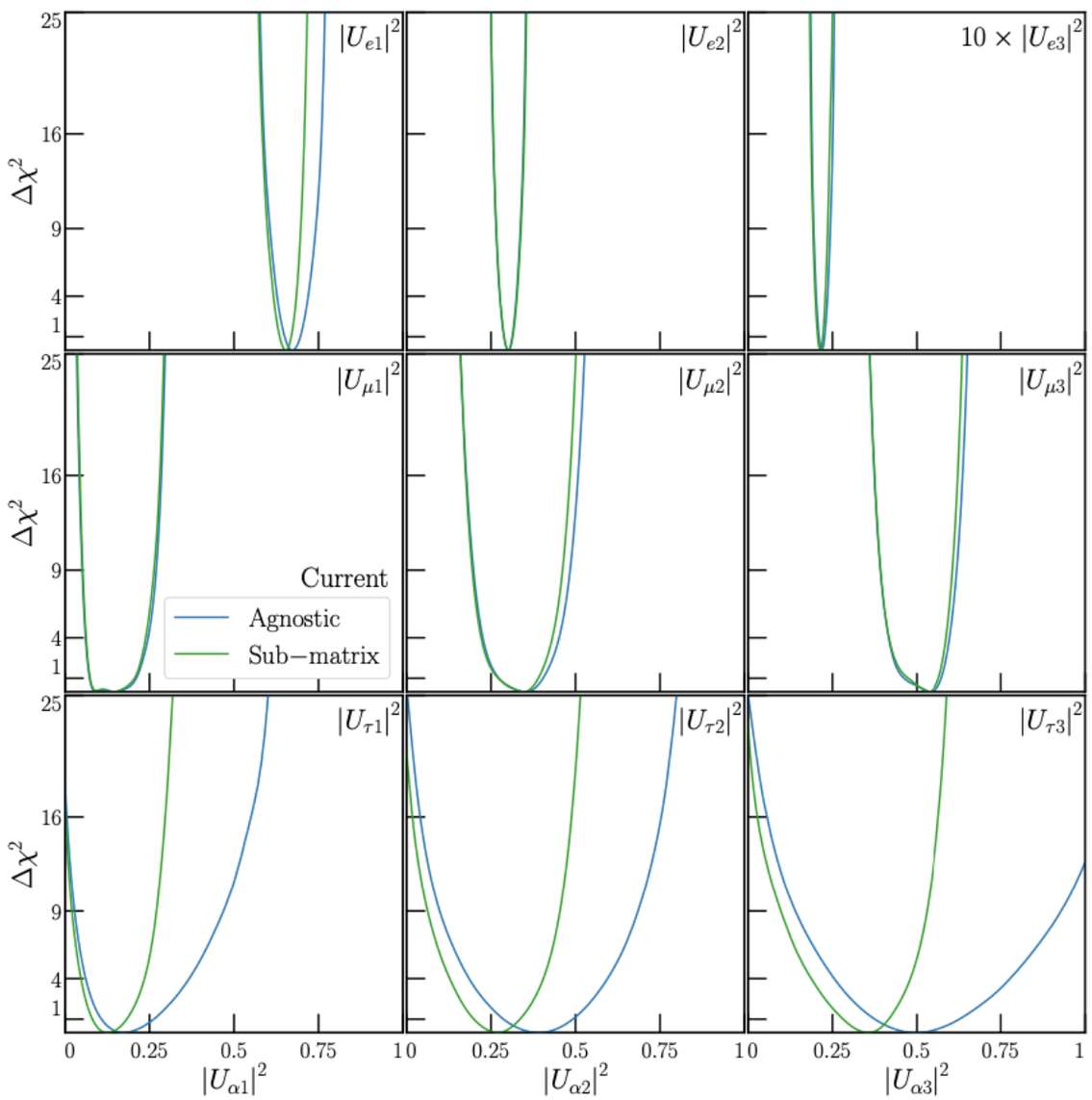


A. Ishihara for IceCube https://arxiv.org/pdf/1908.09441.pdf

See also Ellis et al https://arxiv.org/abs/2008.01088; and nuFIT website

Non-unitarity of the Neutrino PMNS Matrix
(https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF3_NF2_Celio_Moura-063.pdf)

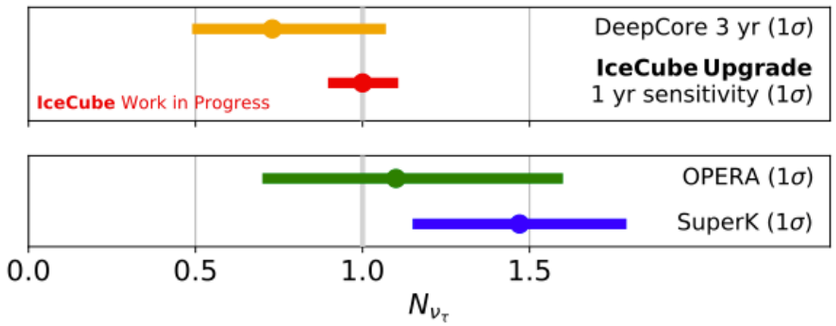
A broad net: testing unitarity



2020!!!

Ellis et al https://arxiv.org/abs/2008.01088

Conclusion remains the same:
we need to study the tau row



A. Ishihara for IceCube https://arxiv.org/pdf/1908.09441.pdf

See also Gouvêa et al https://arxiv.org/abs/1904.07265 for DUNE insight

Non-unitarity of the Neutrino PMNS Matrix
(https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF3_NF2_Celio_Moura-063.pdf)

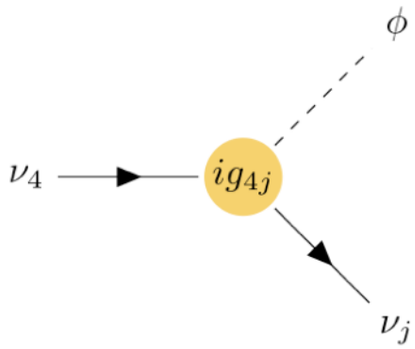
Resolving the Short-baseline Anomaly Puzzle

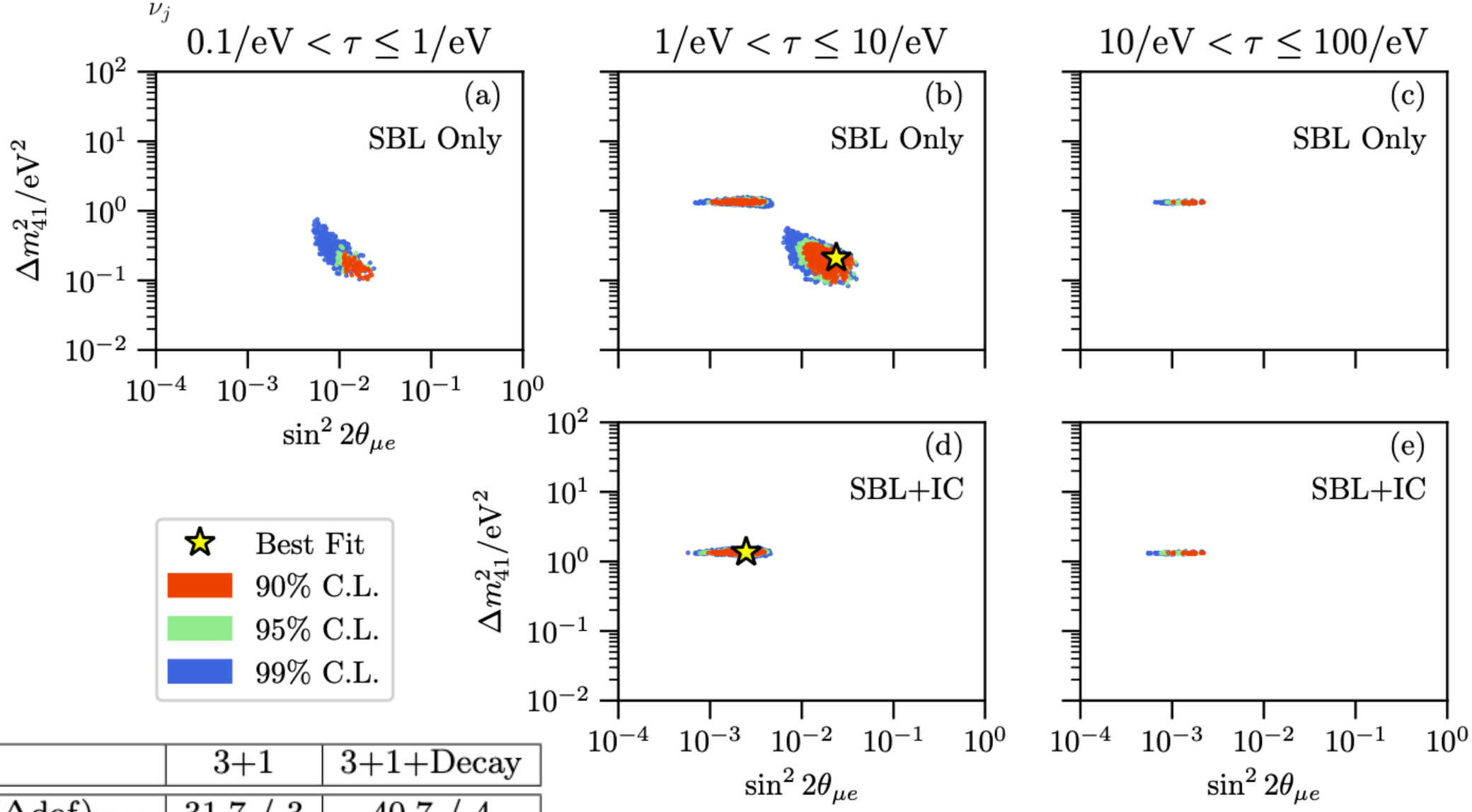
Active experimental and theoretical program:

- **Many on-going and proposed experiments proposed:**
  - Reactor experiments: NEOS, DANSS, STEREO, ...
  - Redoing LSND: JSNS2
  - Fermilab Short Baseline Program (SBND, MicroBooNE, and ICARUS)
  - Atmospherics: SK, HK, DUNE, IceCube, IceCube-Upgrade
  - New beams: IsoDAR, nuSTORM
  - ...
- **New ideas to explain the anomalies and resolve the tension**:
  - New neutrino interactions
    Liao *et al* 1810.01000, Bertuzzo *et al.* 1807.09877, Ballett *et al.* 1808.02915, Ballett *et al.* 1903.07589, CA *et al.* 1812.08768, ...
  - Unstable neutrinos
    Palomares-Ruiz *et al.* hep-ph/0505216, Moss *et al.* 1711.05921, Fisher *et al* 1909.09561, Moulai *et al.* 1910.13456, Dentler *et al.* 1911.01427, Gouvea *et al.* 1911.01447, ...
  - More sterile neutrinos
    Giunti *et al.* 1107.1452, Diaz *et al.* 1906.00045, …
  - …

Sorry for the incomplete list!

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





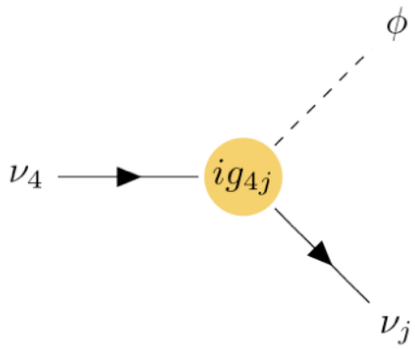
	3+1	3+1+Decay
$(\Delta\chi^2/\Delta\text{dof})_{\text{Null}}$	31.7 / 3	40.7 / 4
$(\Delta\chi^2/\Delta\text{dof})_{3+1}$	–	9.1 / 1

Global data prefers 3+1+Decay!

Moss 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

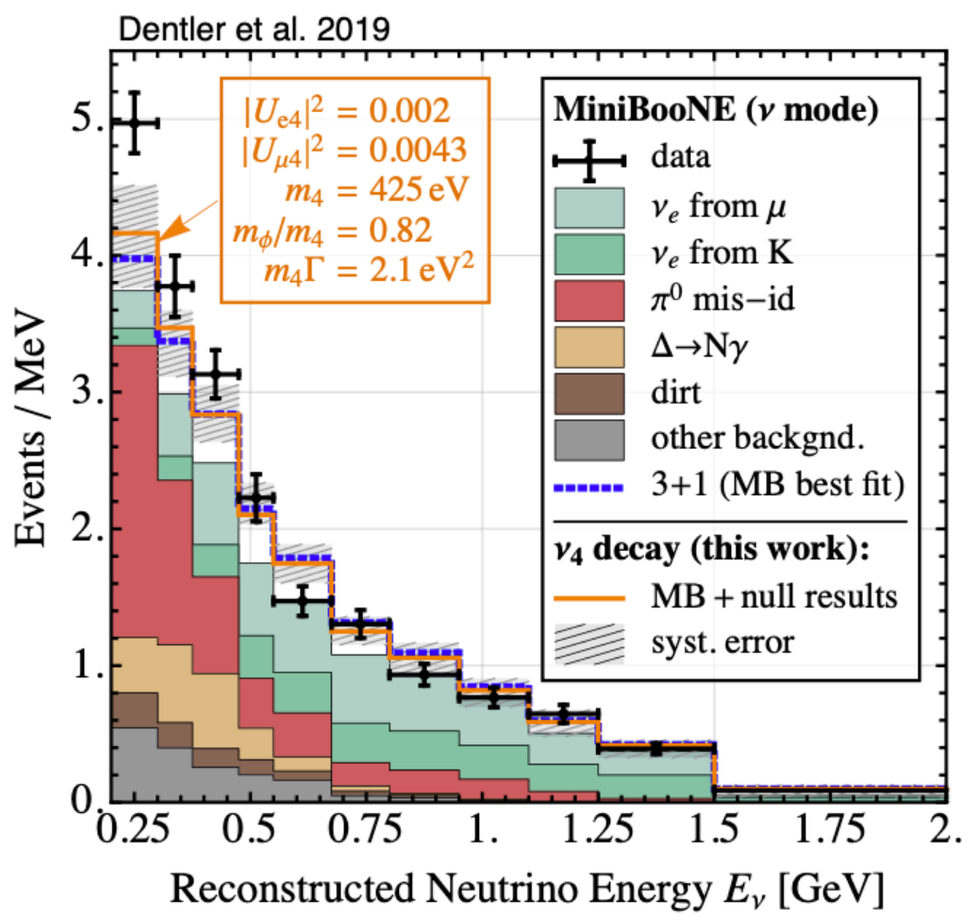
Neutrino Decay as a Solution to the Short-Baseline Anomalies
(https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF2_NF3_G_V_Stenico-131.pdf)

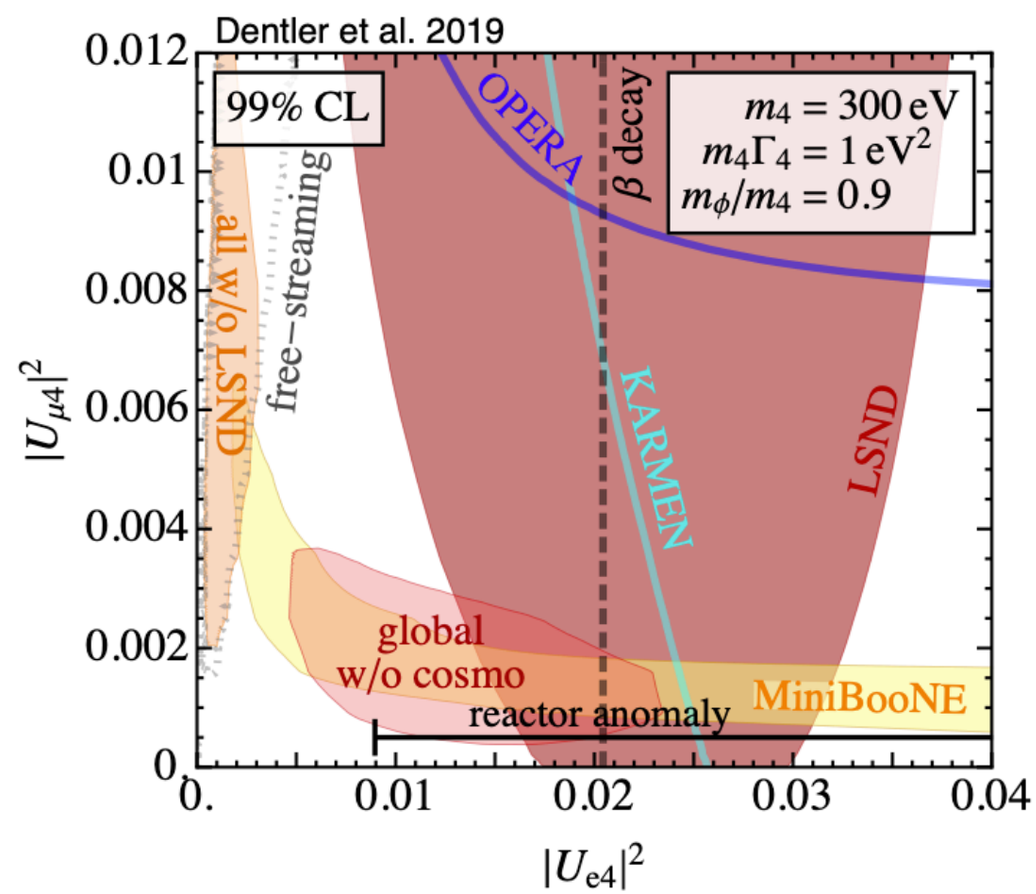


Sterile Neutrino Decay (3+1+Visible-Decay)

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

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



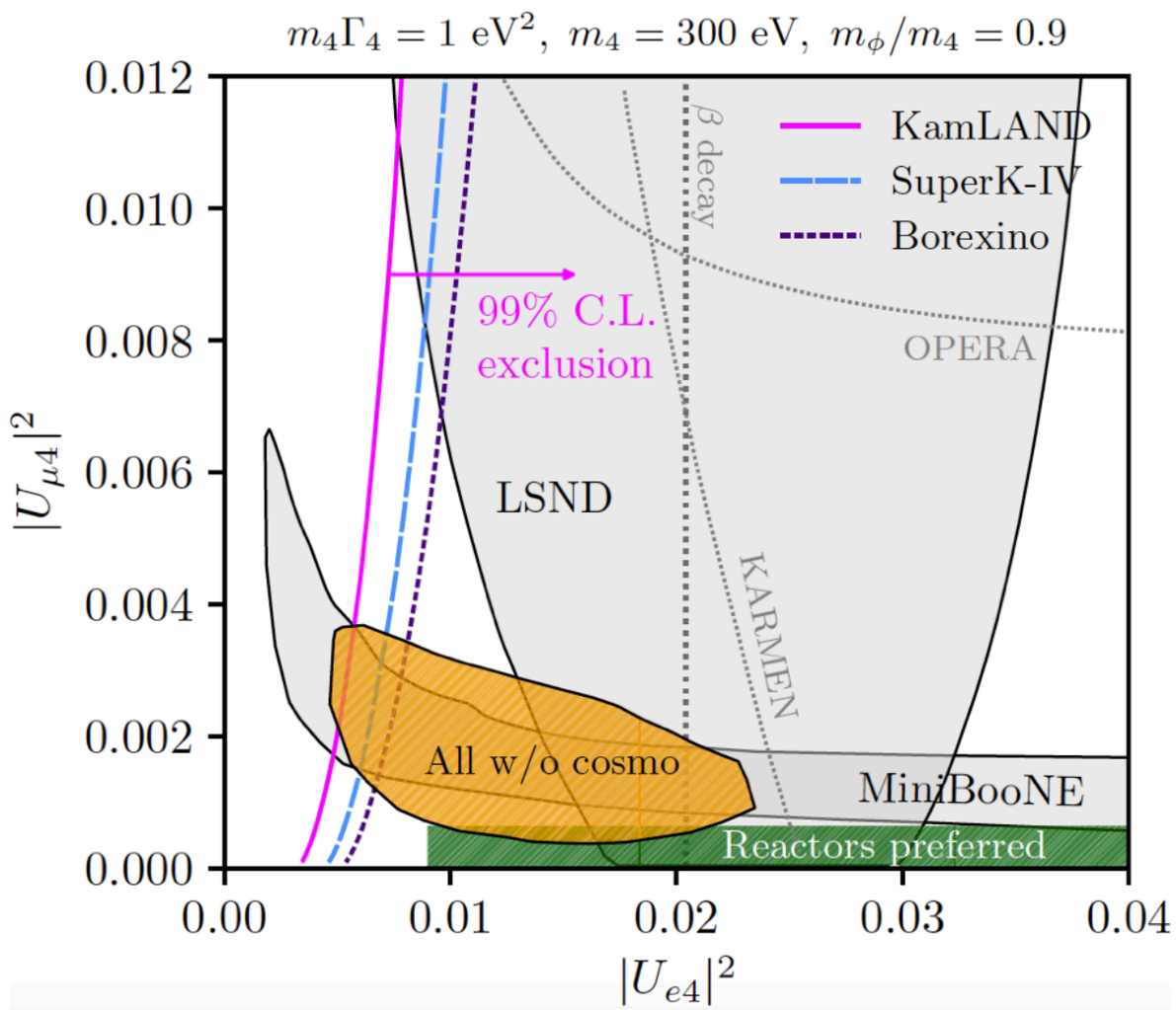


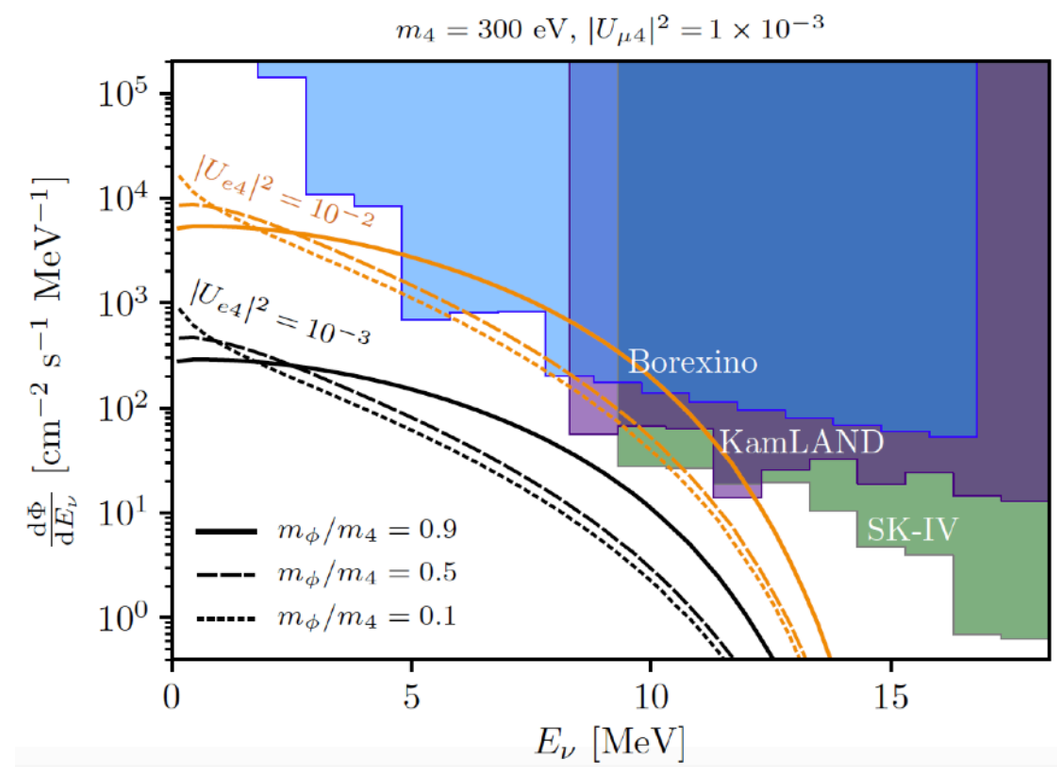
See also Palomares-Ruiz *et al* http://xxx.lanl.gov/abs/hep-ph/0505216, Gninekov https://arxiv.org/abs/0902.3802, Fisher *et al* https://arxiv.org/abs/1909.09561

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

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

$$-\mathscr{L} = g_\varphi \overline{\nu_s} \nu_s \varphi + \sum_{\alpha,\beta} m_{\alpha\beta} \overline{\nu_\alpha} \nu_\beta$$





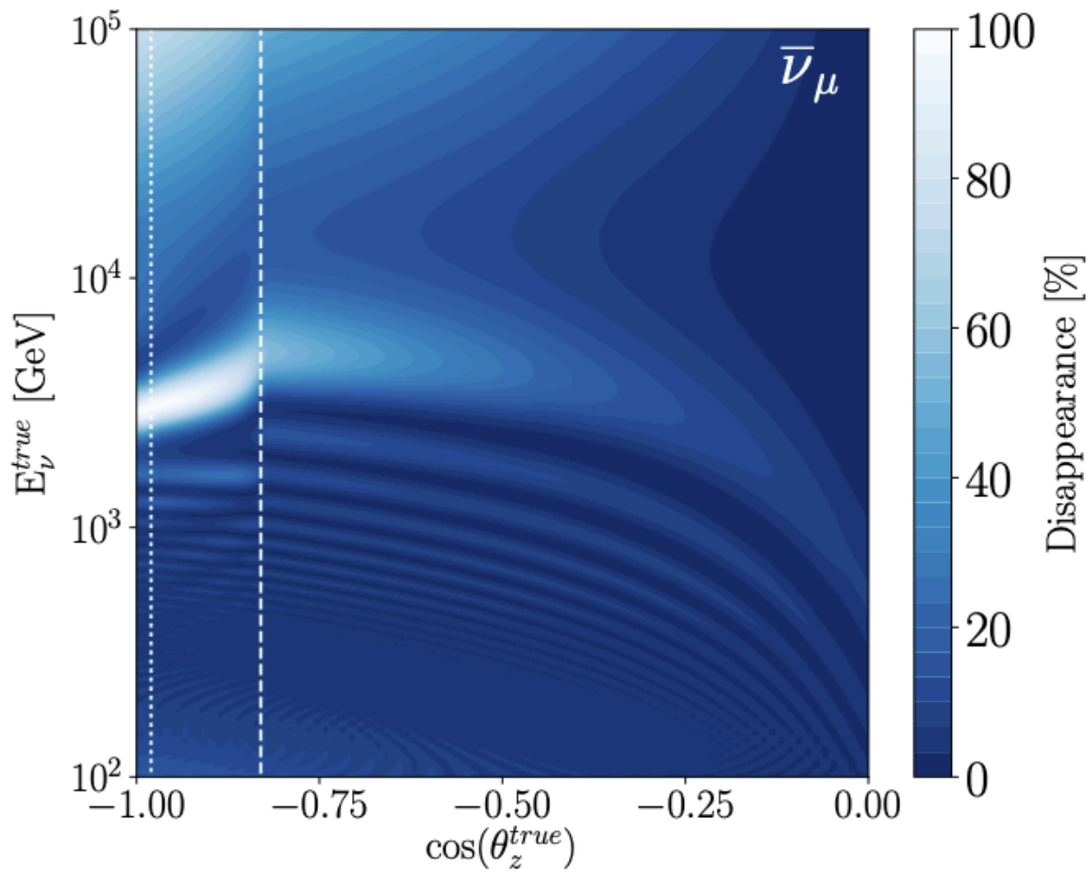
Visible decay predicts emission of antineutrinos from the Sun!

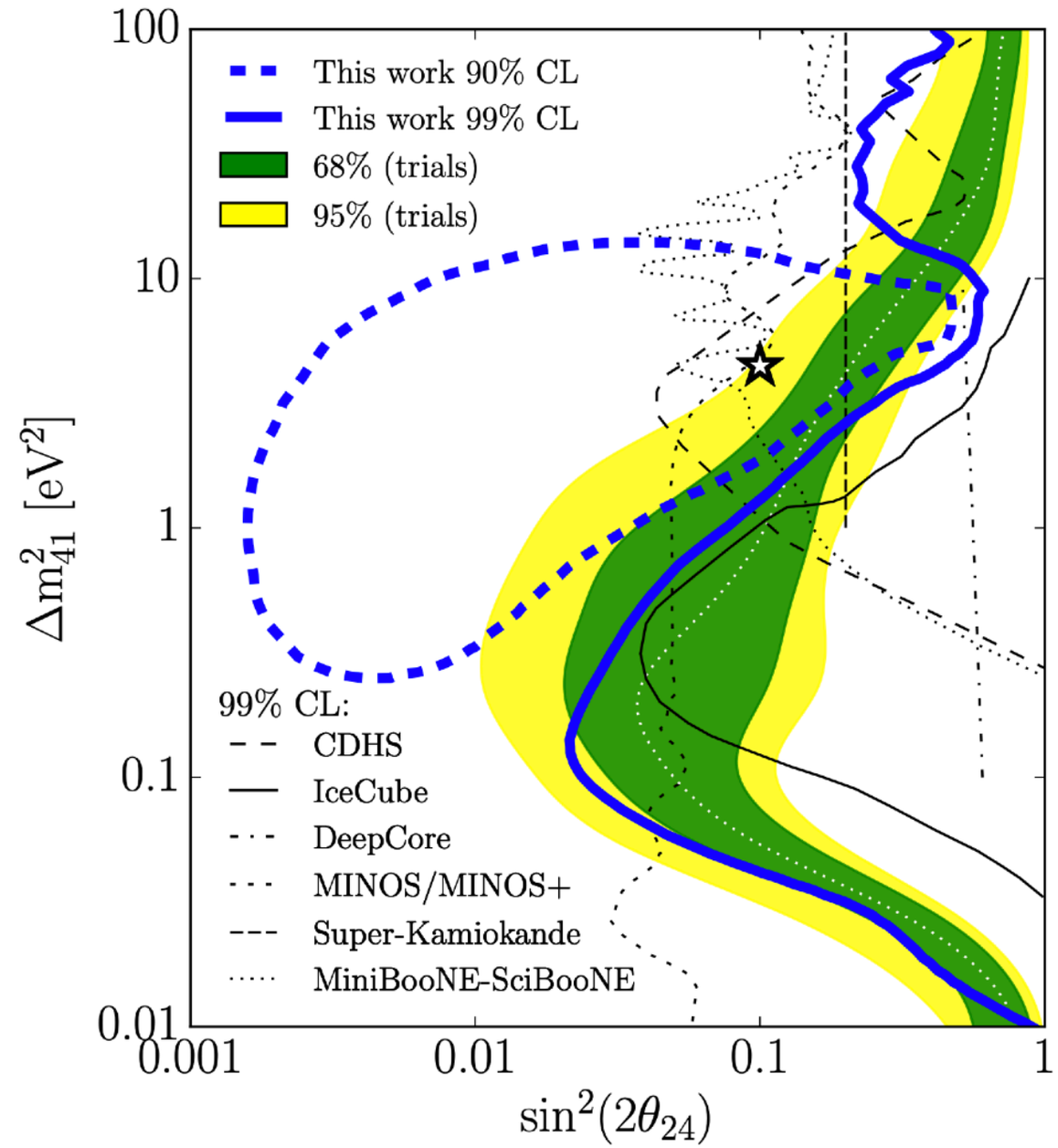
Neutrino Decay as a Solution to the Short-Baseline Anomalies
(https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF2_NF3_G_V_Stenico-131.pdf)

Matter Effects and Sterile Neutrinos

IceCube coll. https://arxiv.org/abs/2005.12942 https://arxiv.org/abs/2005.12943

IceCube exploits matter effects for their results





IceCube and MINOS+ dominate muon-neutrino disappearance in ROI

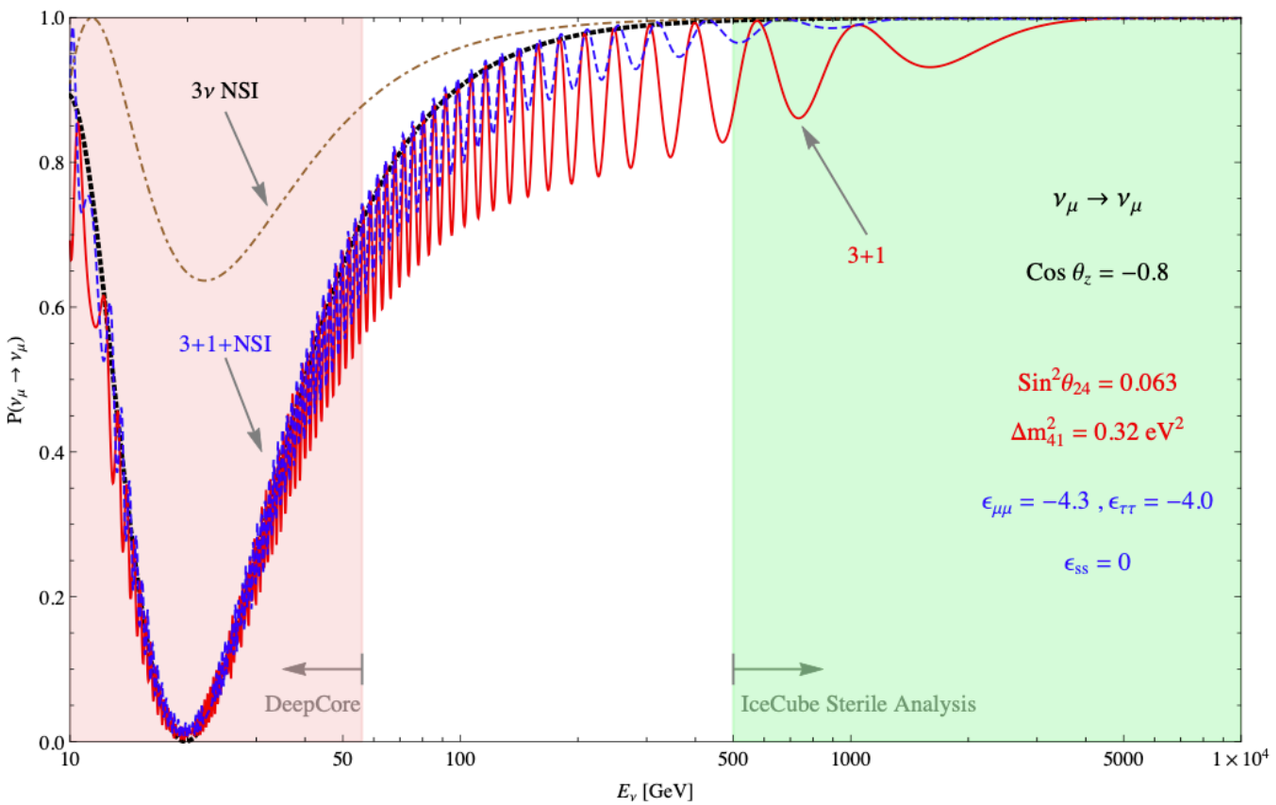
Direct Probes of Matter Effects In Neutrino Oscillations
(https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF1_NF3-TF0_TF0_Peter_Denton-010.pdf)

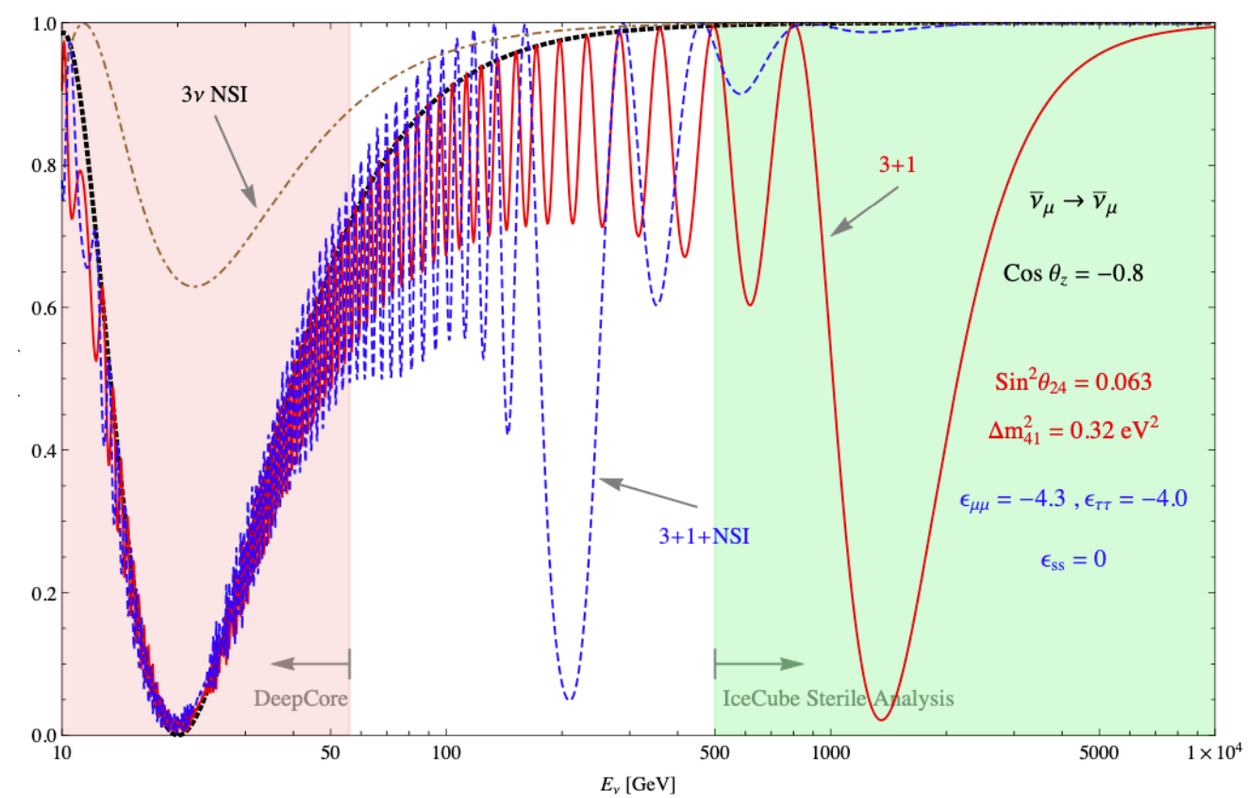
Neutrino NonStandard Interactions
(https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF3_NF1-CF7_CF0-TF11_TF8_Peter_Denton-023.pdf)

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

J. Liao et al https://arxiv.org/abs/1810.01000

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





See also Denton et al https://arxiv.org/pdf/1811.01310.pdf
Bhupal Dev et al https://arxiv.org/pdf/1907.00991.pdf

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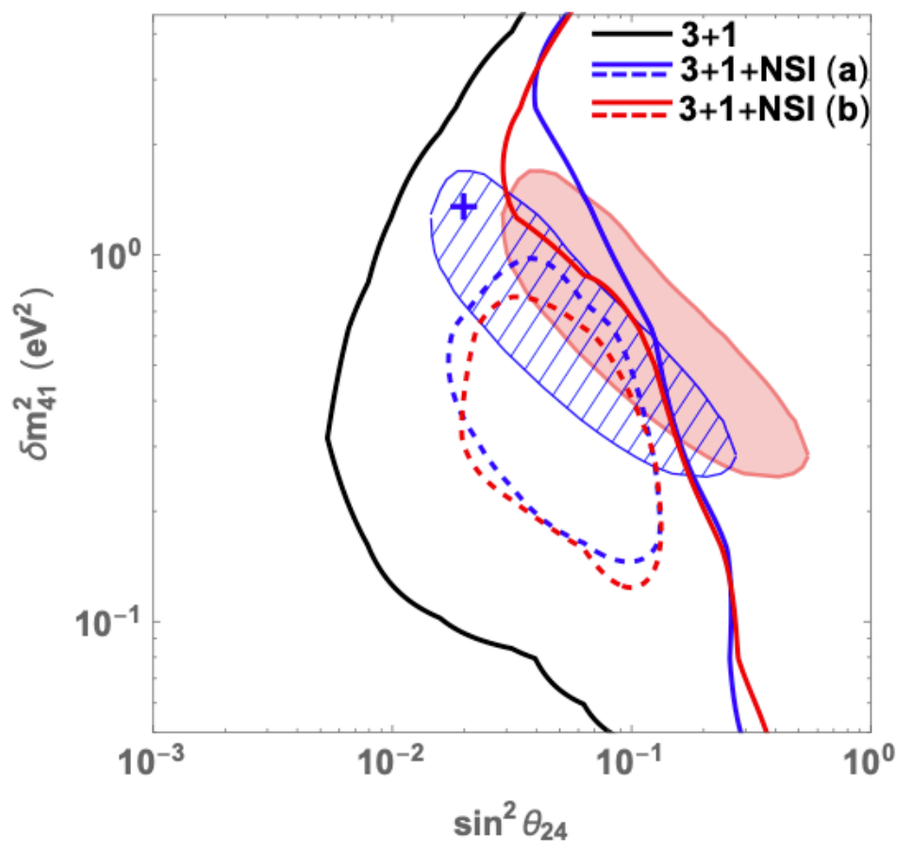
Non-Standard Matter Effects (3+1+NSI)

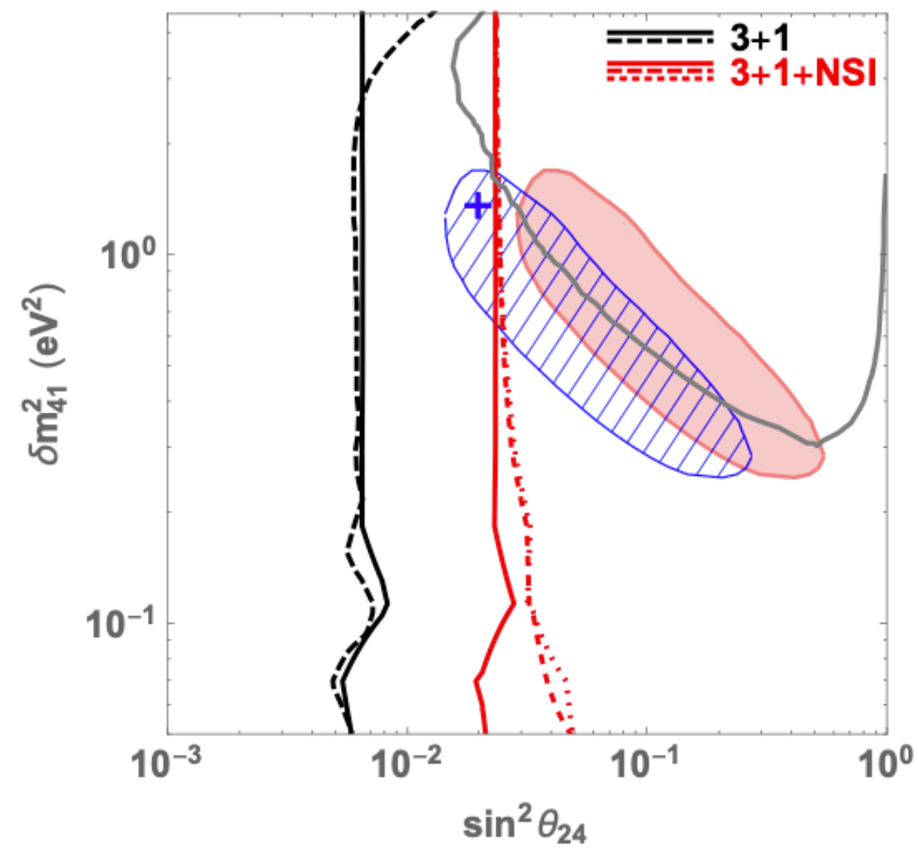
J. Liao et al https://arxiv.org/abs/1810.01000

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

IceCube modified by NSI



MINOS modified by NSI



See also Denton et al https://arxiv.org/pdf/1811.01310.pdf
Bhupal Dev et al https://arxiv.org/pdf/1907.00991.pdf

Direct Probes of Matter Effects In Neutrino Oscillations
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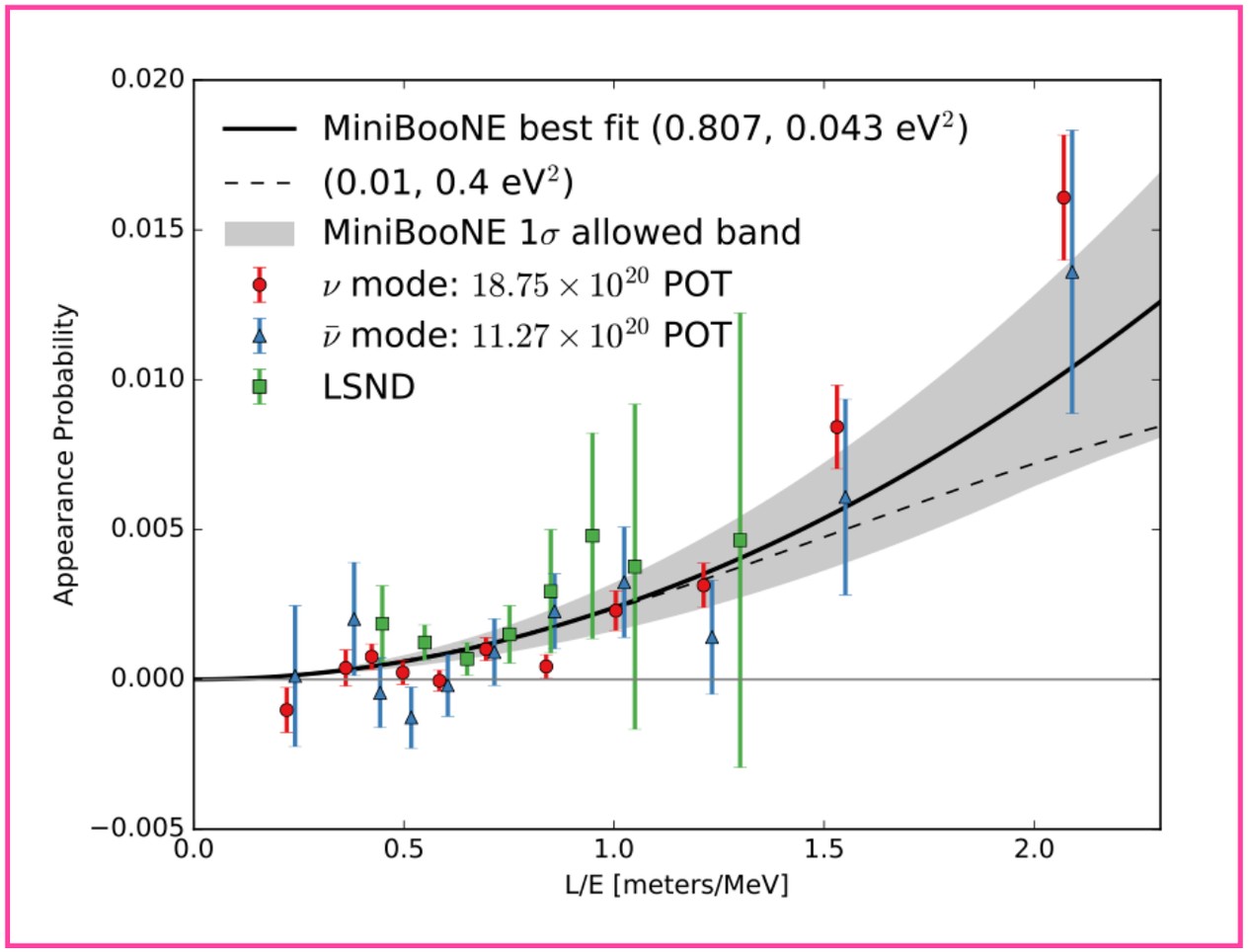
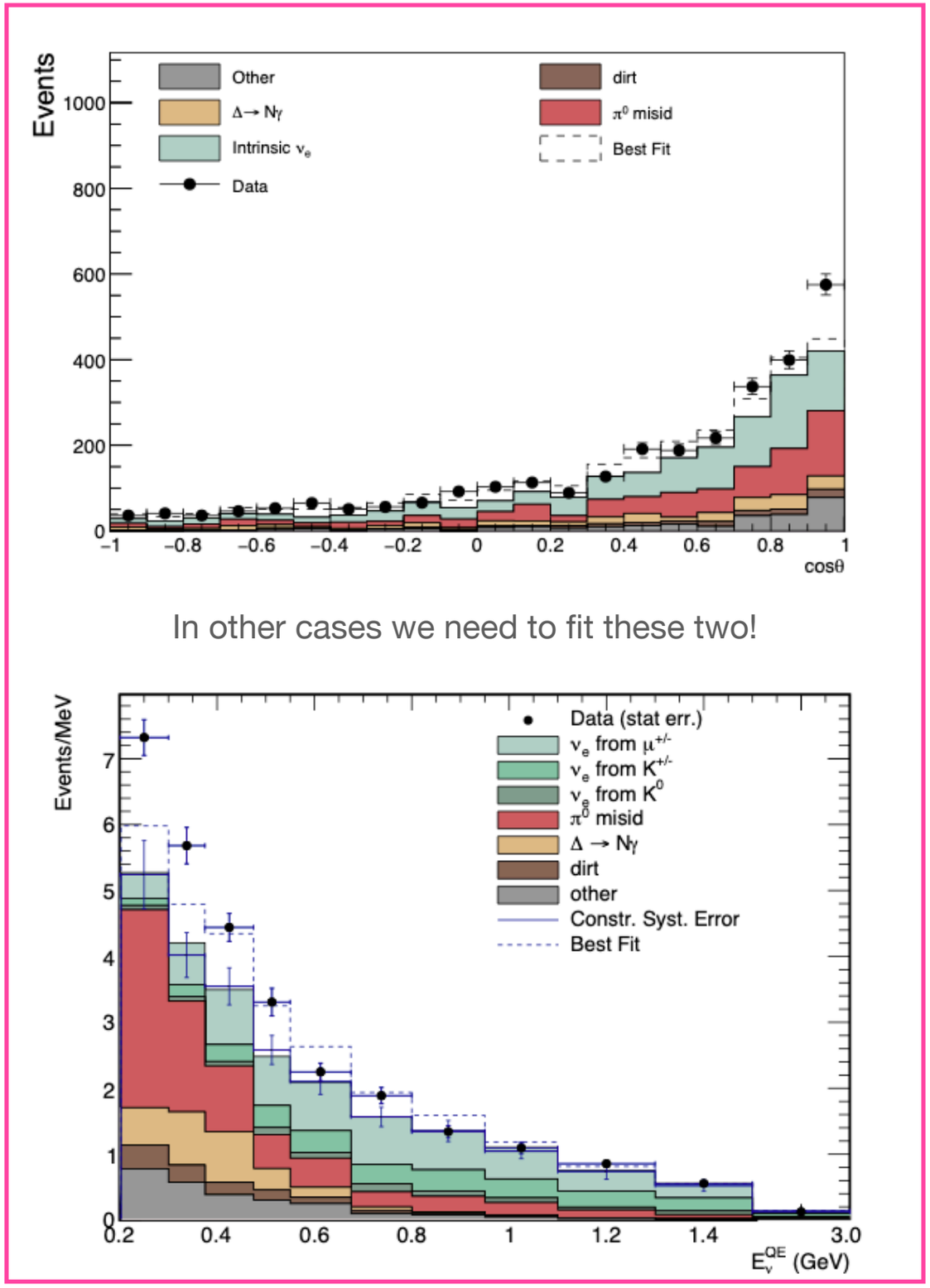
Neutrino NonStandard Interactions
(https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF3_NF1-CF7_CF0-TF11_TF8_Peter_Denton-023.pdf)

Switching gears: Changing how we look at things

This is useful if we are after an oscillation explanation

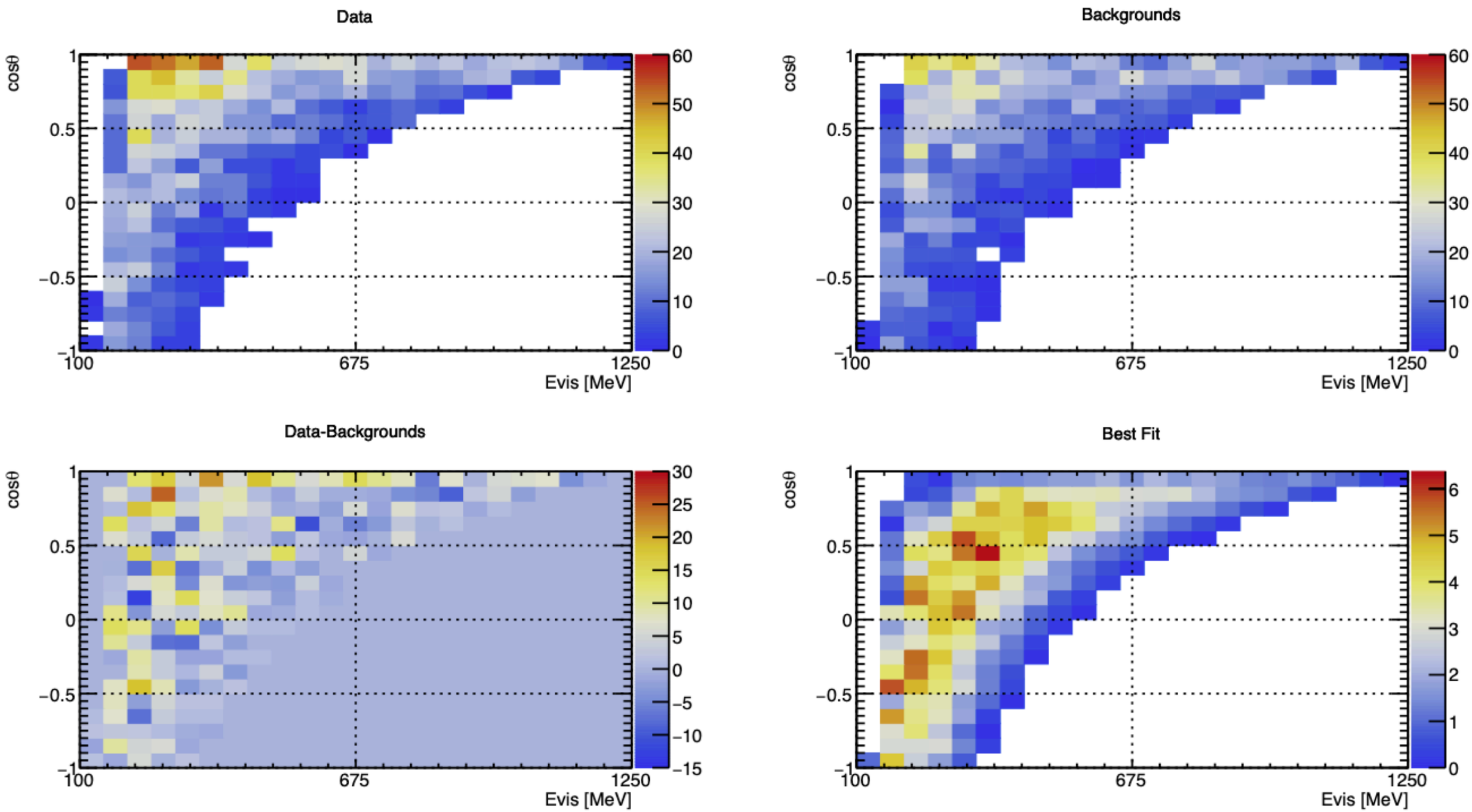




In other cases we need to fit these two!

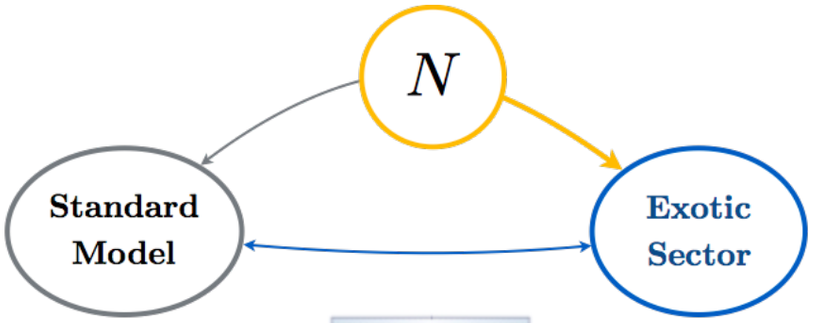
MiniBooNE Collaboration https://arxiv.org/abs/2006.16883

More information & a new perspective!

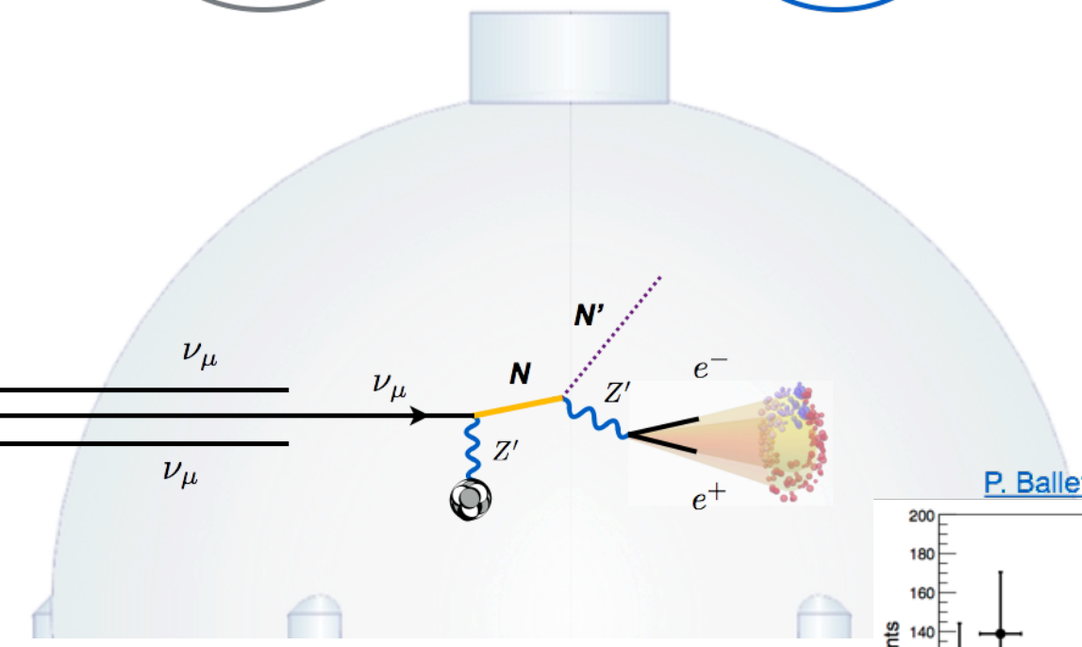


MiniBooNE Collaboration https://arxiv.org/abs/2006.16883

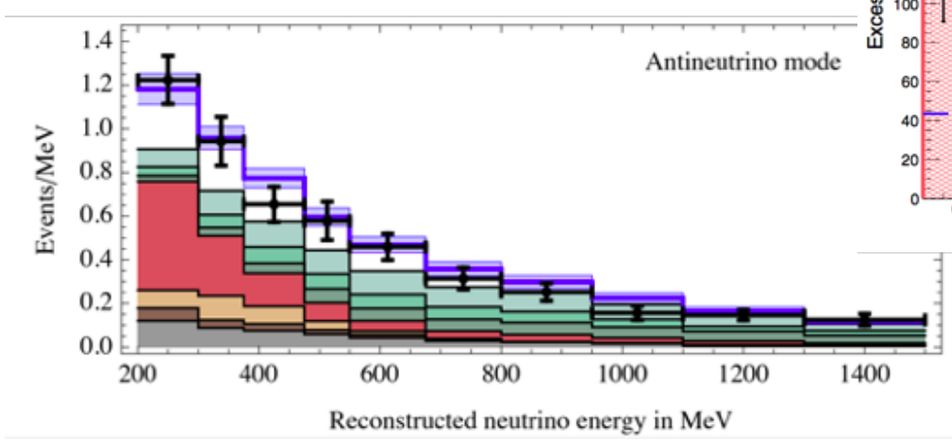
Non-Minimal HNL



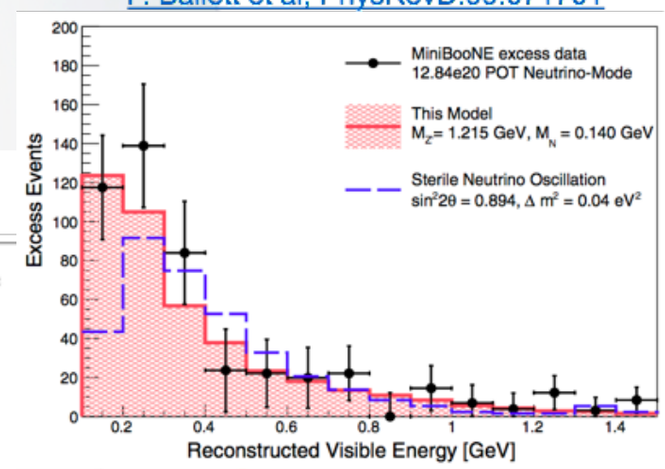
Neutrino mass models from a dark sector → Upscattering + decay



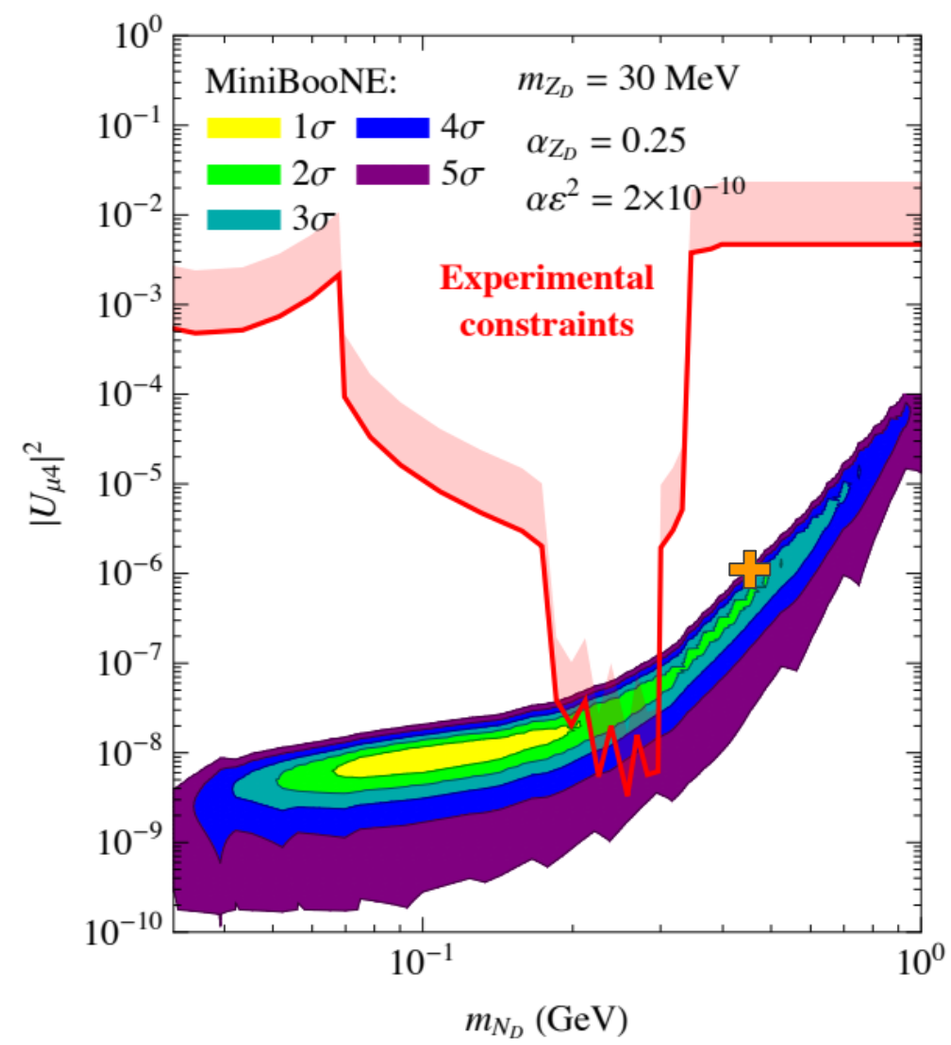
E. Bertuzzo et al., PhysRevLett.121.241801



P. Ballett et al, PhysRevD.99.071701



Benchmark point marker

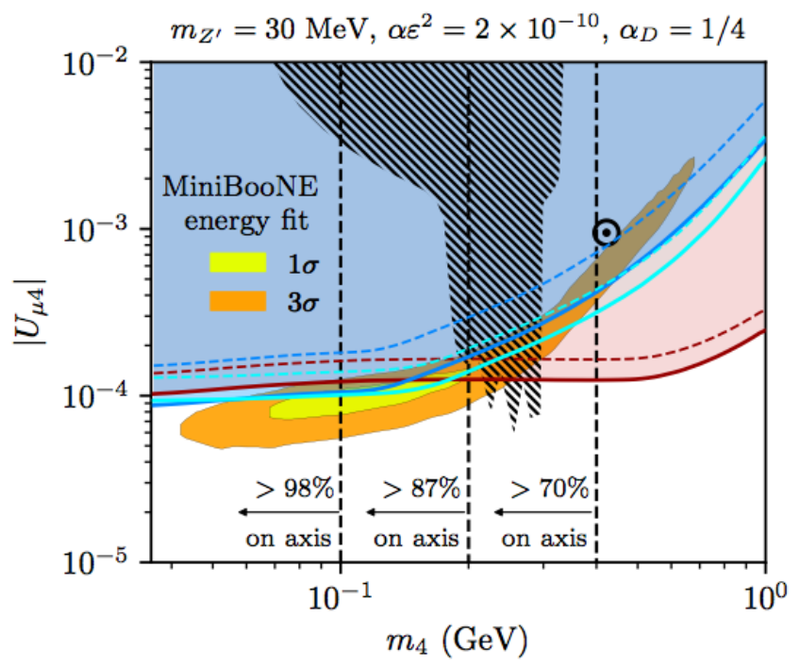


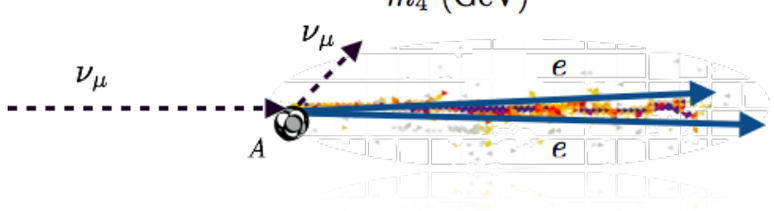
Opportunities and signatures of non-minimal Heavy Neutral Leptons
(www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF2_NF3-EF9_EF0-RF4_RF6-CF1_CF0-TF8_TF11_Matheus_Hostert-041.pdf)

Non-Minimal HNL - Testability

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

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

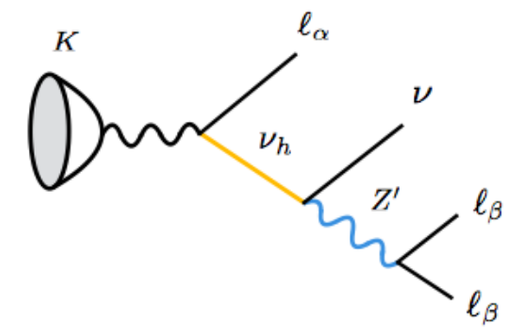




More data from: MINERvA, NOvA, and SBN program to come soon!

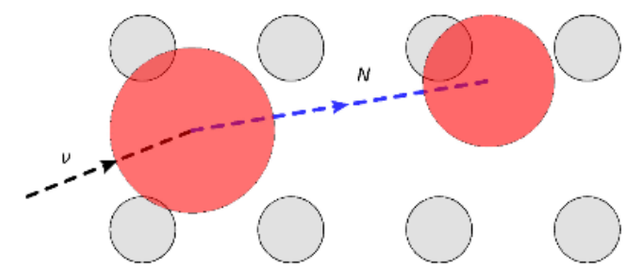
Rare kaon decays

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



Connections to
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

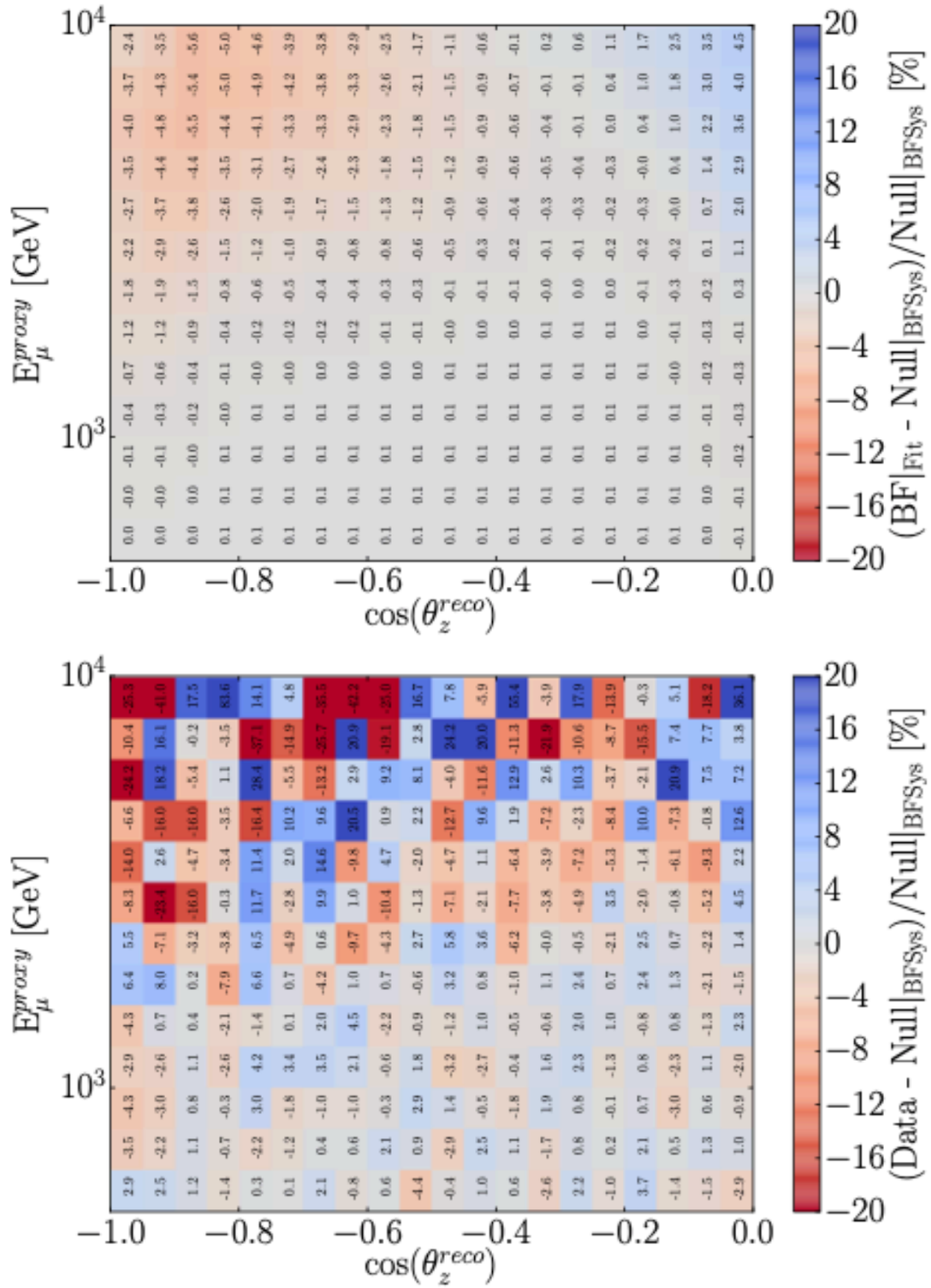
BSM Physics at the Electron Ion Collider: Searching for Heavy Neutral Leptons
(https://www.snowmass21.org/docs/files/summaries/EF/SNOWMASS21-EF7_EF0-NF2_NF3-RF4_RF0_Brian_Batell-114.pdf)
Dark Sector With Neutrino Beams
(https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF3_NF0-RF6_RF0-CF1_CF3-TF9_TF11-148.pdf)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

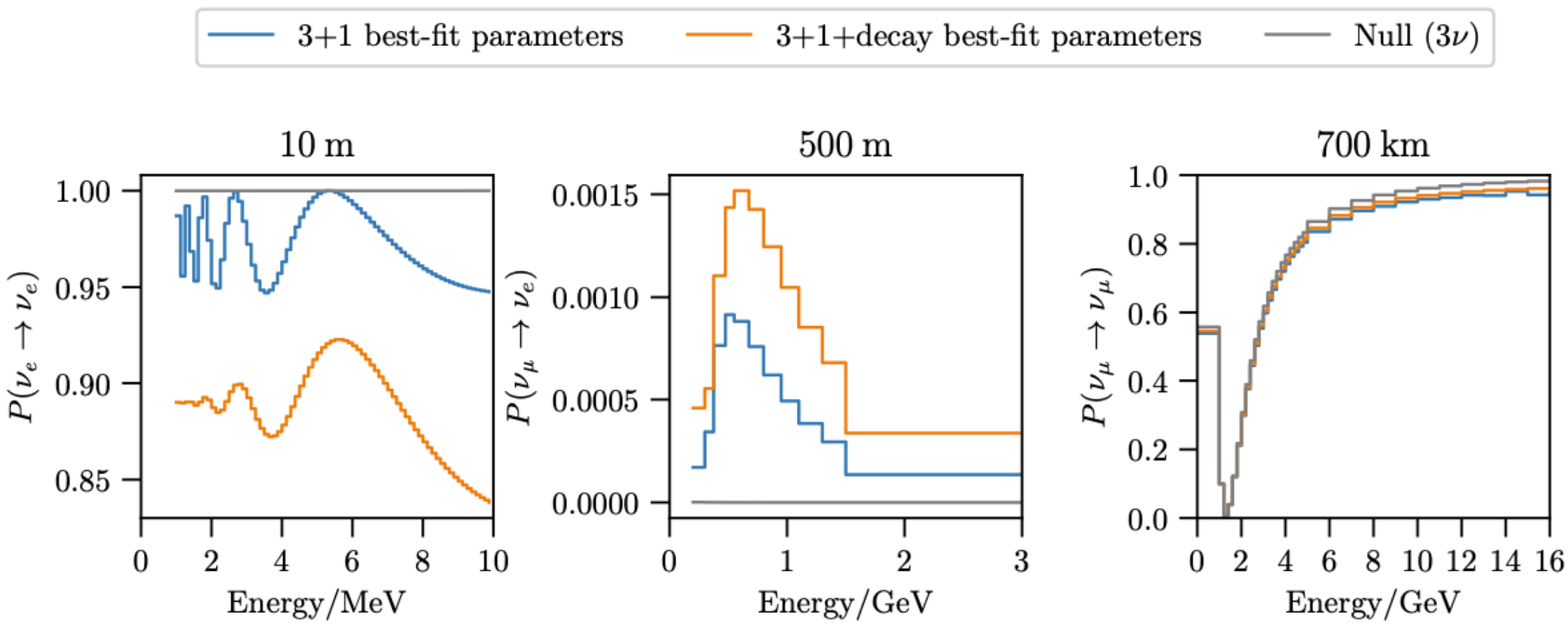
Take home message

- Vanilla eV sterile neutrino is extremely disfavored as a solution, but is still a very important benchmark point.
- Very exciting times to be doing theory and phenomenology related to the MB/LSND anomalies. We have a very high-significance signal to explain!
- MiniBooNE is proving new information that can guide our intuition.
- No clear solution around. All proposals have problems one way or another.
- New proposals imply that we need to think about new ways of testing them and consider new sources of constraints, *e.g.* solar neutrinos, electron neutrino scattering, etc.
- Solving the MB/LSND anomalies, especially in the non-vanilla scenarios, will need efforts from the whole neutrino community! Very important complementarity between accelerator based searches, reactors, atmospheric, and solar experiments.

Gracias!

Bonus Slides



IceCube coll. https://arxiv.org/abs/2005.12942 https://arxiv.org/abs/2005.12943

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