Beyond Vanilla Sterile Neutrinos and other Scenarios

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Outline

- Why go beyond vanilla sterile neutrinos?
- The garden of forking paths
- Non-vanilla sterile neutrinos
- Other explanations of MiniBoonE:
    - Single electron
    - Single photon
    - Di-electron
- Future

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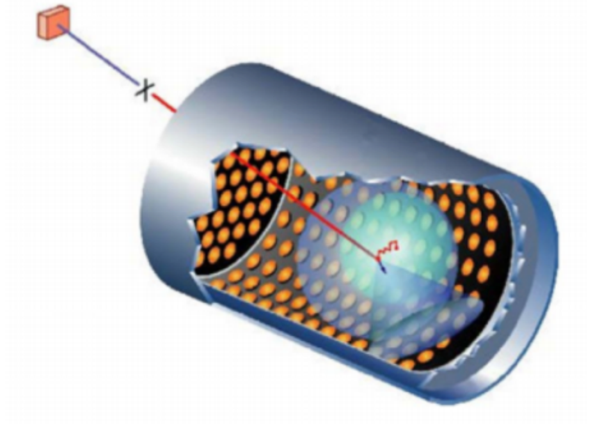
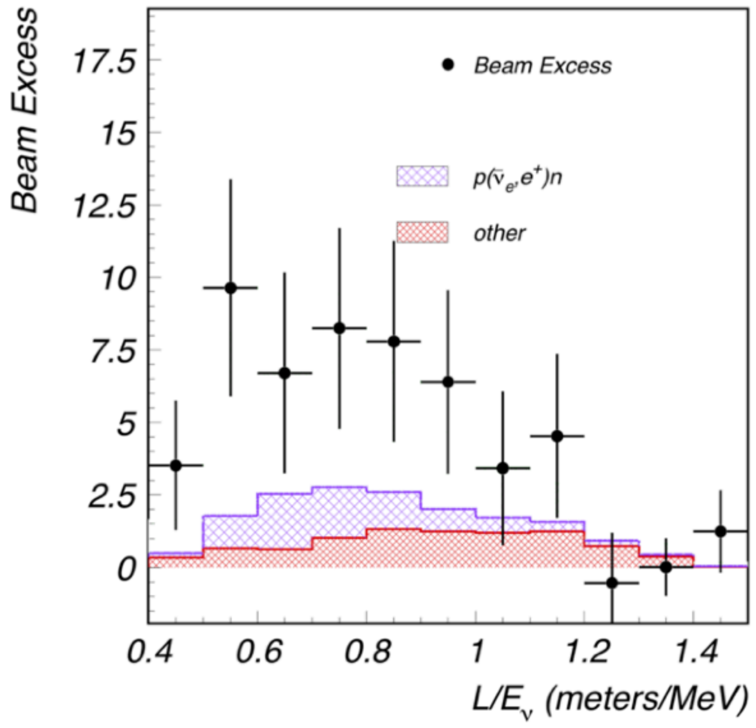
The pieces that do not fit: short-baseline anomalies

LSND

(3.8σ!)

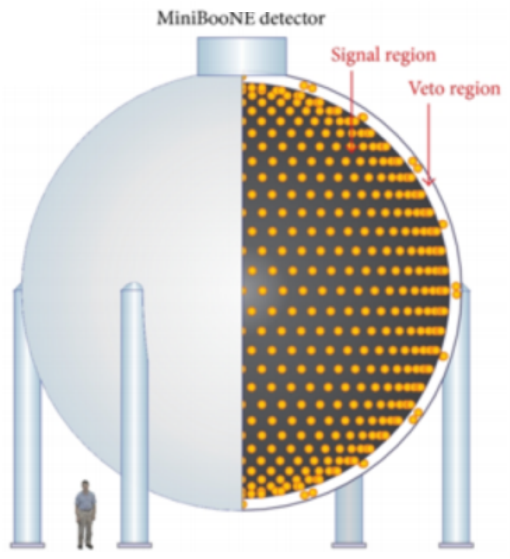


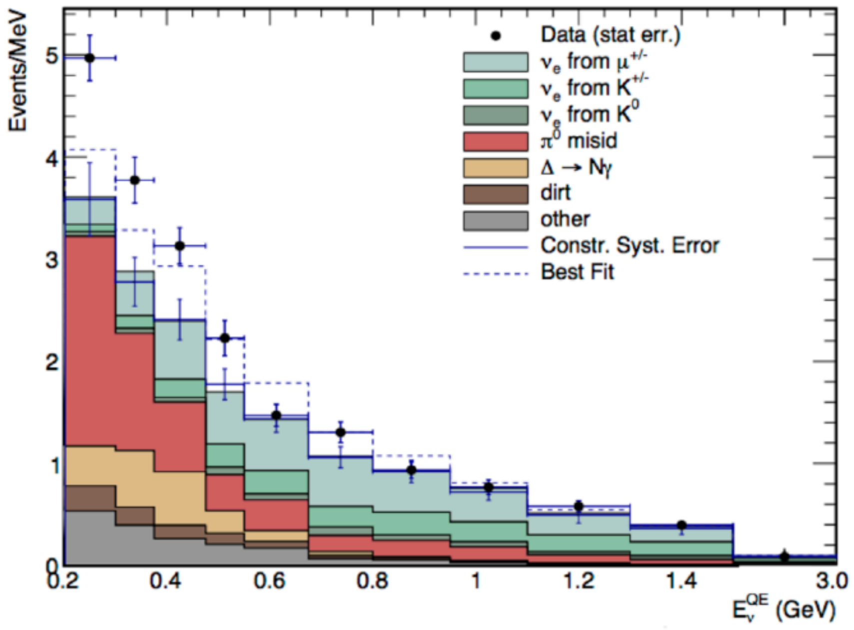


These experiments observe ν_e appearance at L/E ~ 1 km/GeV!

MiniBooNE

(4.8σ!)





This points to

Δm^2~1eV^2

These are not alone, other interesting observations

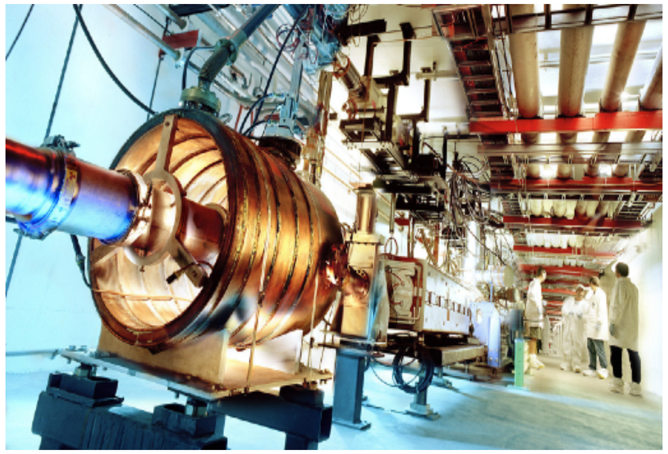
See talk by Joachim Kopp for detailed summary

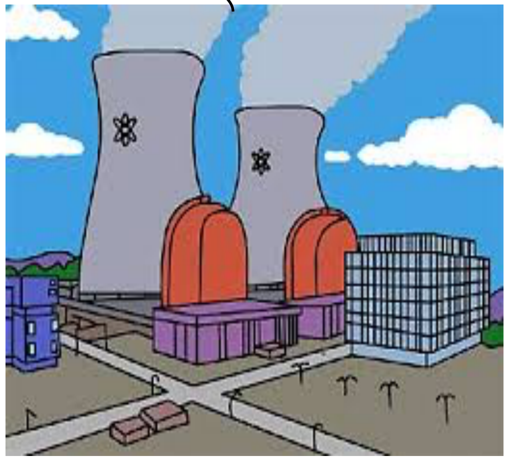
	$\nu_\mu \to \nu_e$	$\nu_\mu \to \nu_\mu$	$\nu_e \to \nu_e$
Neutrino	MiniBooNE (BNB) *	SciBooNE/MiniBooNE	KARMEN/LSND Cross Section
	MiniBooNE(NuMI)	CCFR	Gallium *
	NOMAD	CDHS	BEST *
	MicroBooNE (BNB) (*?)	MINOS IceCube	
Antineutrino	LSND *	SciBooNE/MiniBooNE	Bugey Daya Bay
	KARMEN	CCFR	NEOS PROSPECT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

🟥 ✳ $\Longrightarrow$ >2σ “signal”

🟨 ✳ $\Longrightarrow$ unclear “signal”

See posters by:
Vitalii Zavadskyi on *JUNO-TAO* (P0076)
Leonard Köllenberg on *Katrin* (P0191)
Pablo Del Amo Sanchez on *STEREO* (P0195)
Dongha Lee on *JSNS2* (P0410)
Alba Domi on *Km3NET/ORCA* (P0609)
Alfonso Garcia-Soto on *IceCube Tracks* (P0342)
Benjamin Smithers on *IceCube Cascades* (P0394)
V. Hewes on *ICARUS* (P0591)

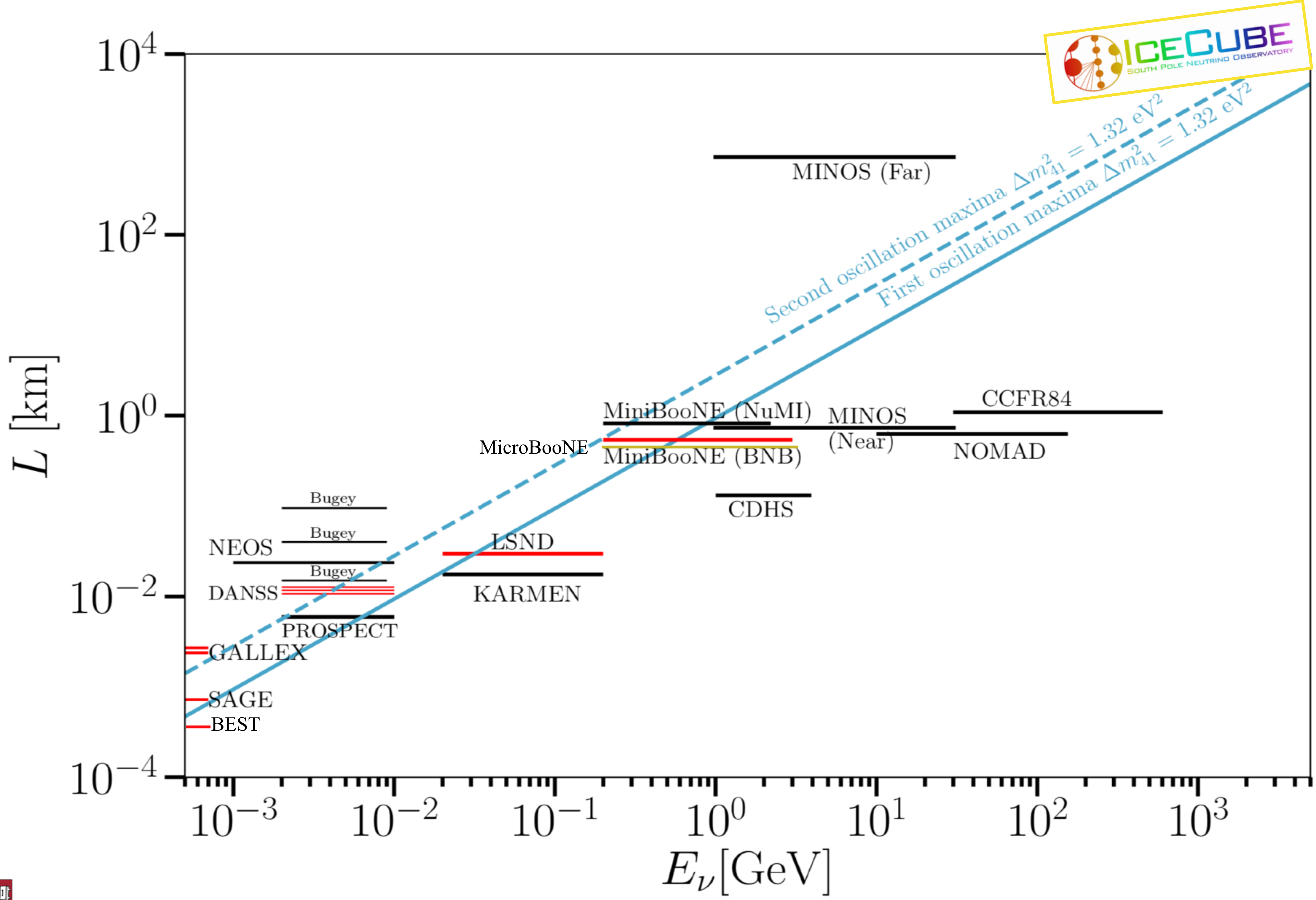




Daniel Winklehner on *ISODAR* (P0689)
Ivan Martinez-Soler on *MicroBooNE PH* (P0617)
Katie Mason on *MicroBooNE QE* (P0719)
Joshua Mills on *MicroBooNE muon-neutrino* (P0720)

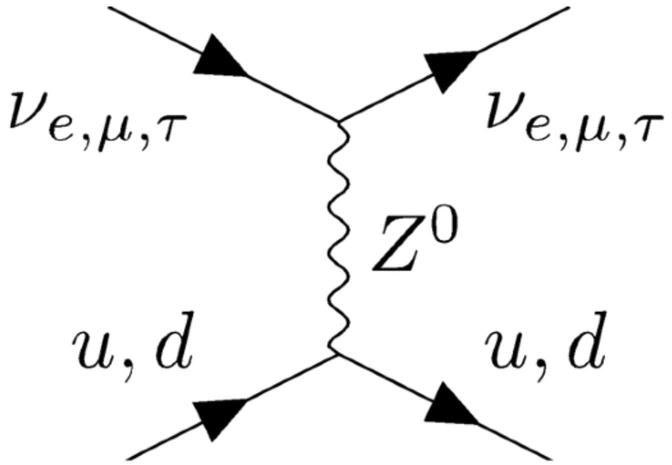
Xiangpan Ji on *MicroBooNE BNB+NuMI* (P0753)
Ivan Caro Terrazas on *MicroBooNE* (P0735)

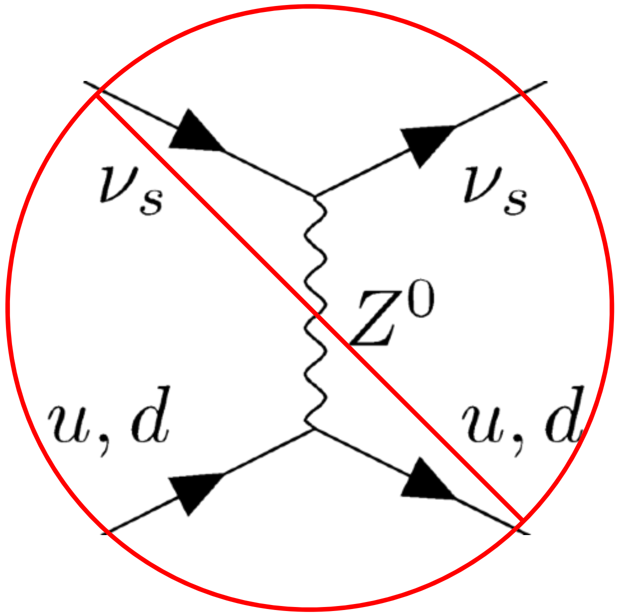
The anomalies lie ~ in a line



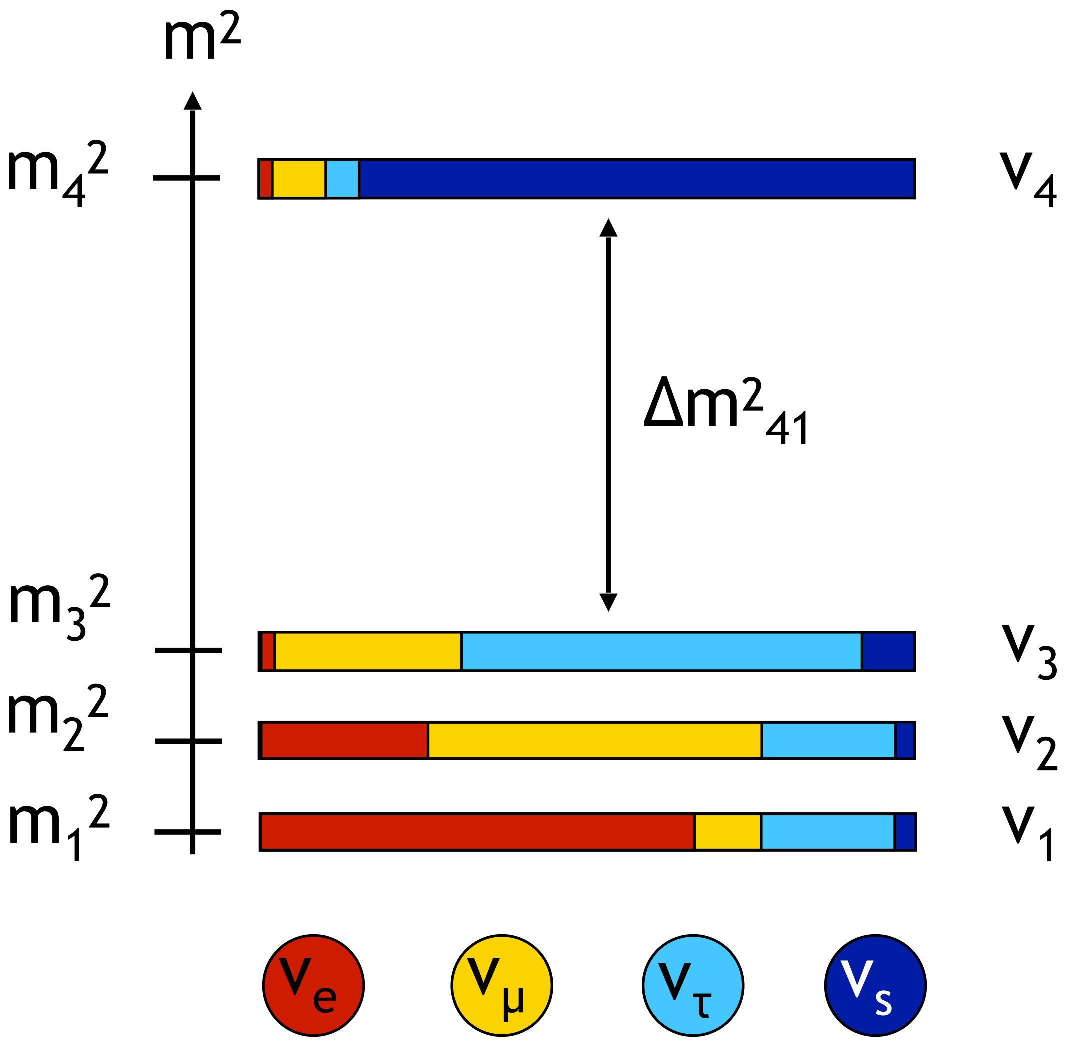
Diaz *et al.* arXiv:1906.00045

Introducing a sterile neutrino





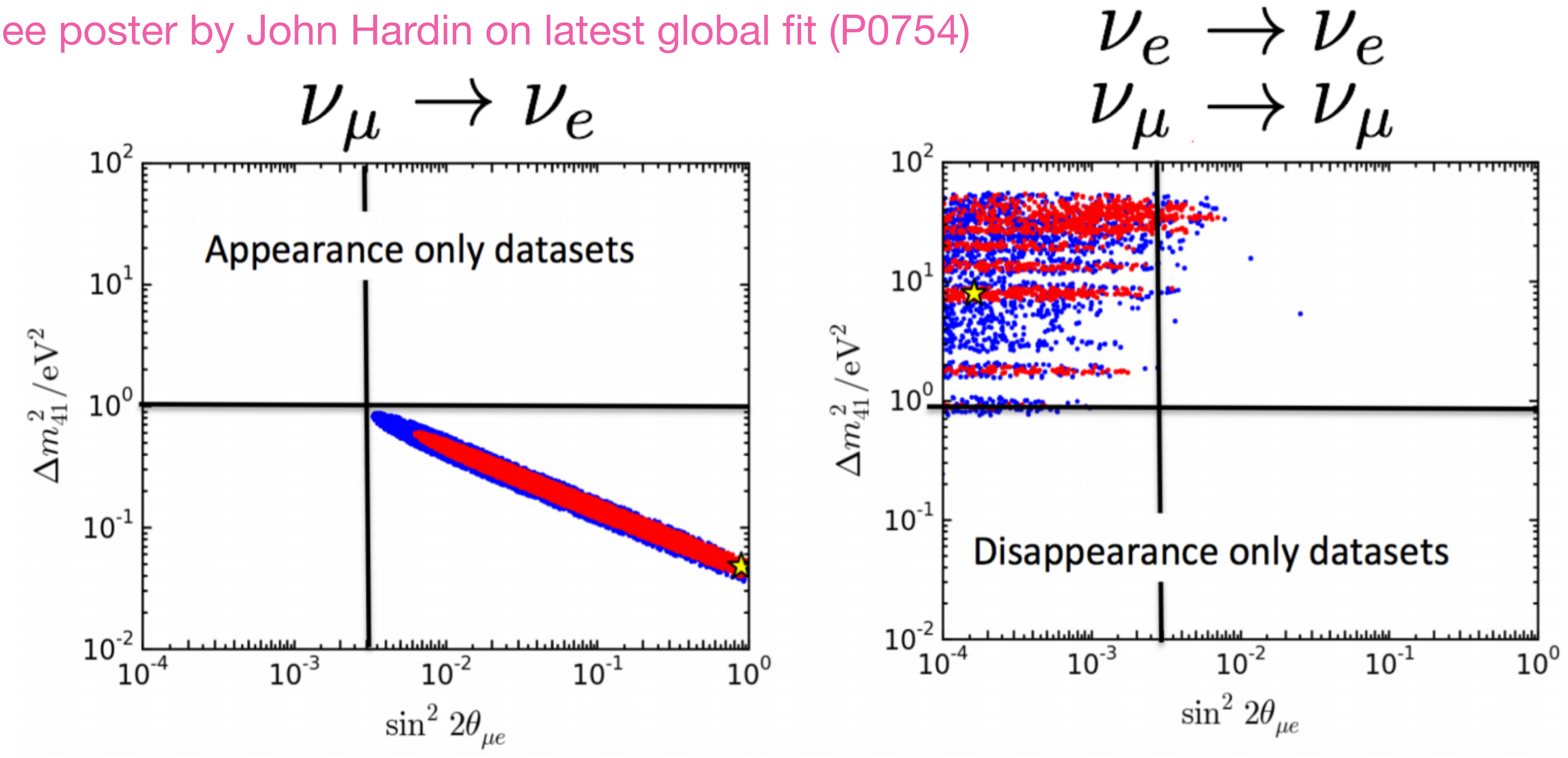
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2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



Assuming Normal Ordering

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

See poster by John Hardin on latest global fit (P0754)



LSND/MB Driven

Reactor, Long-Baseline Driven

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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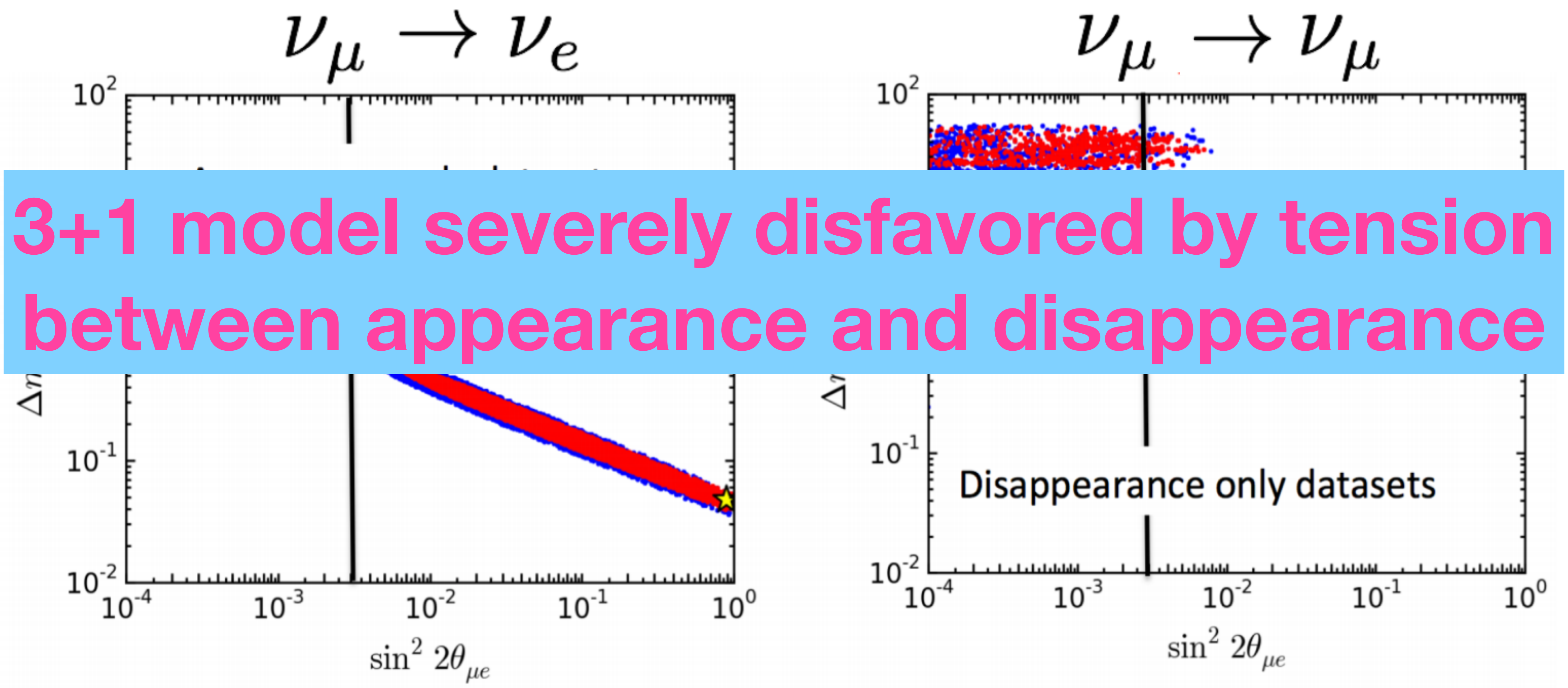
$\nu_e \rightarrow \nu_e$



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

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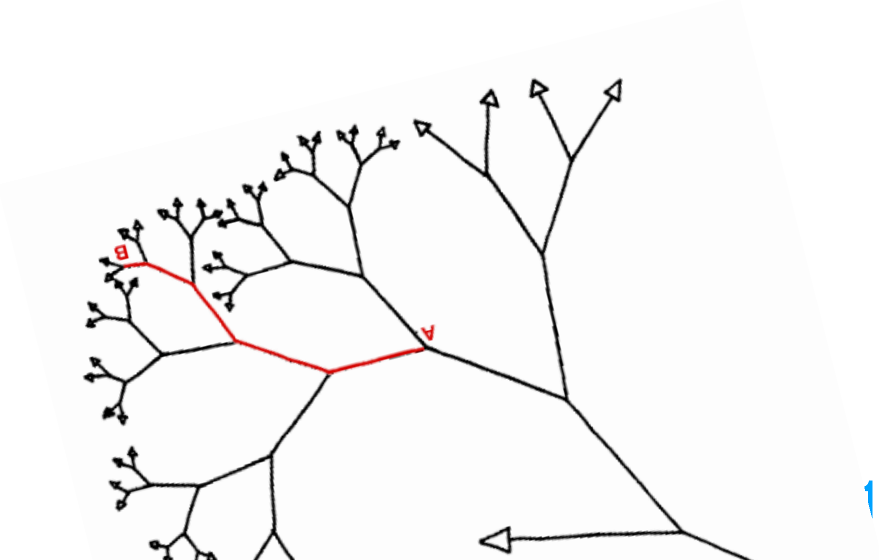
From here: The Garden of Forking Paths*

- 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?



*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.
- MicroBooNE saw no single photons; electron results need further discussion.
- 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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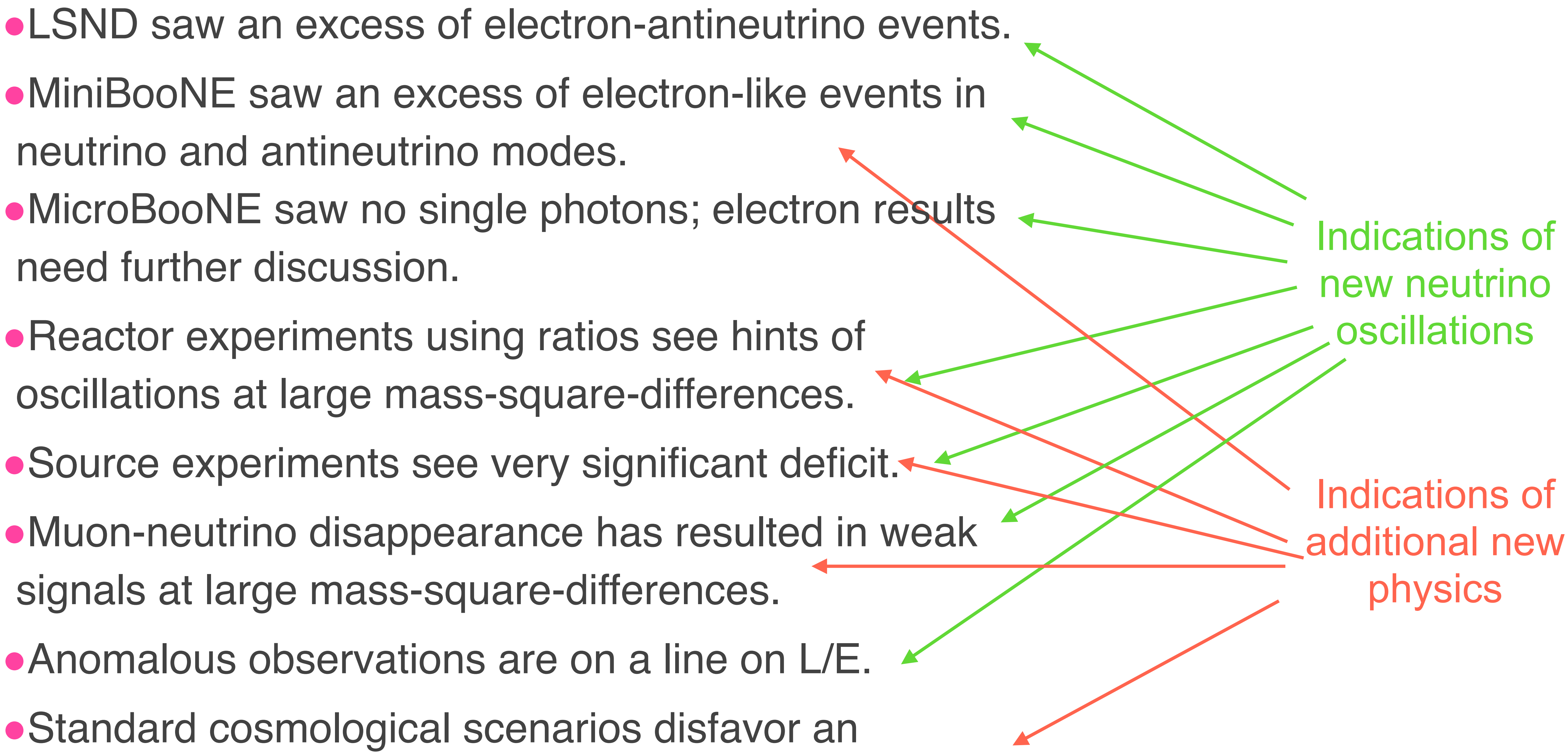

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Indications of new neutrino oscillations

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

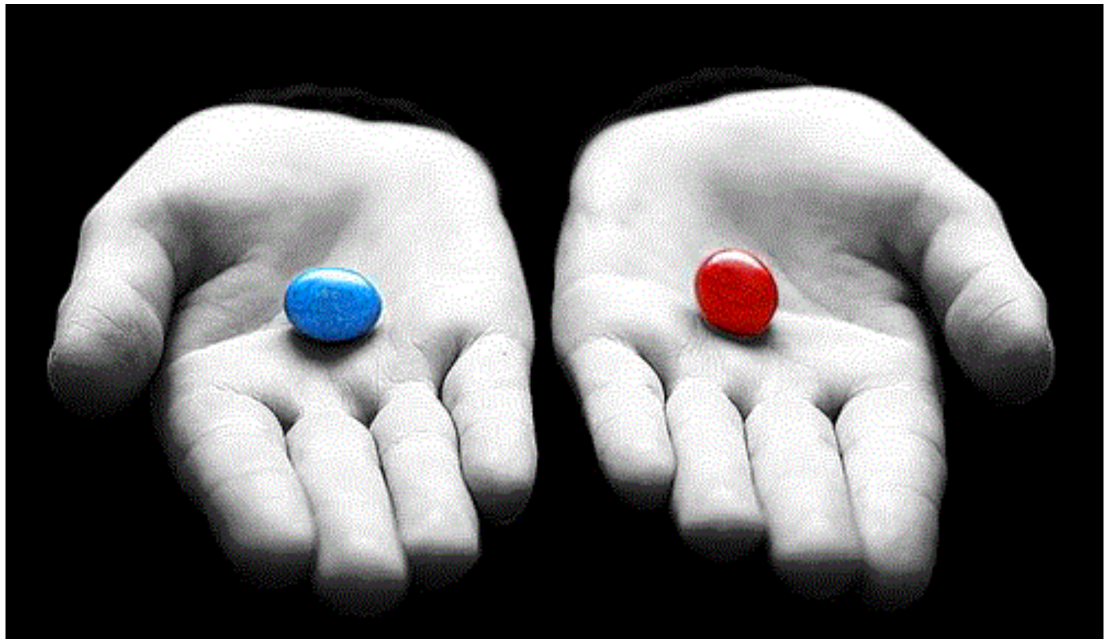
The anomalies are related.

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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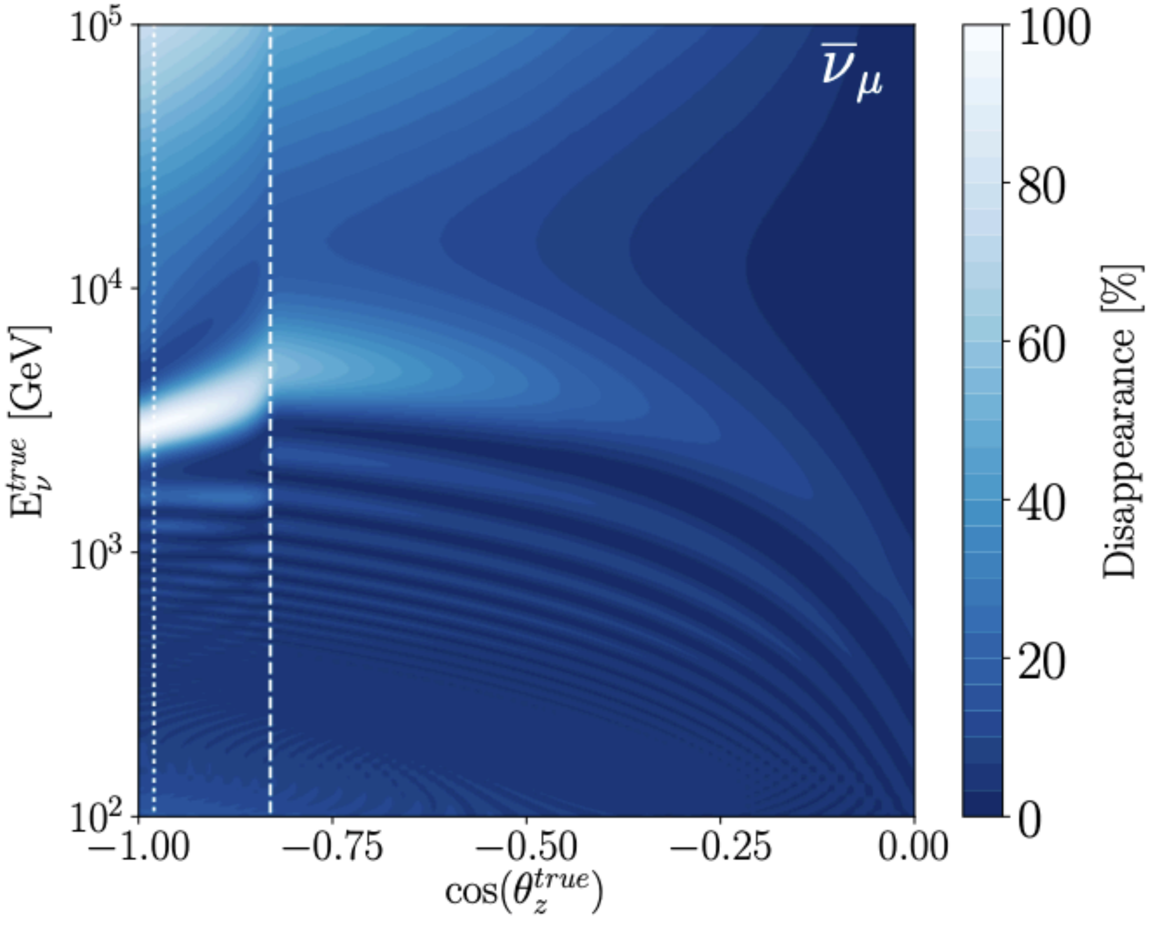
Path One

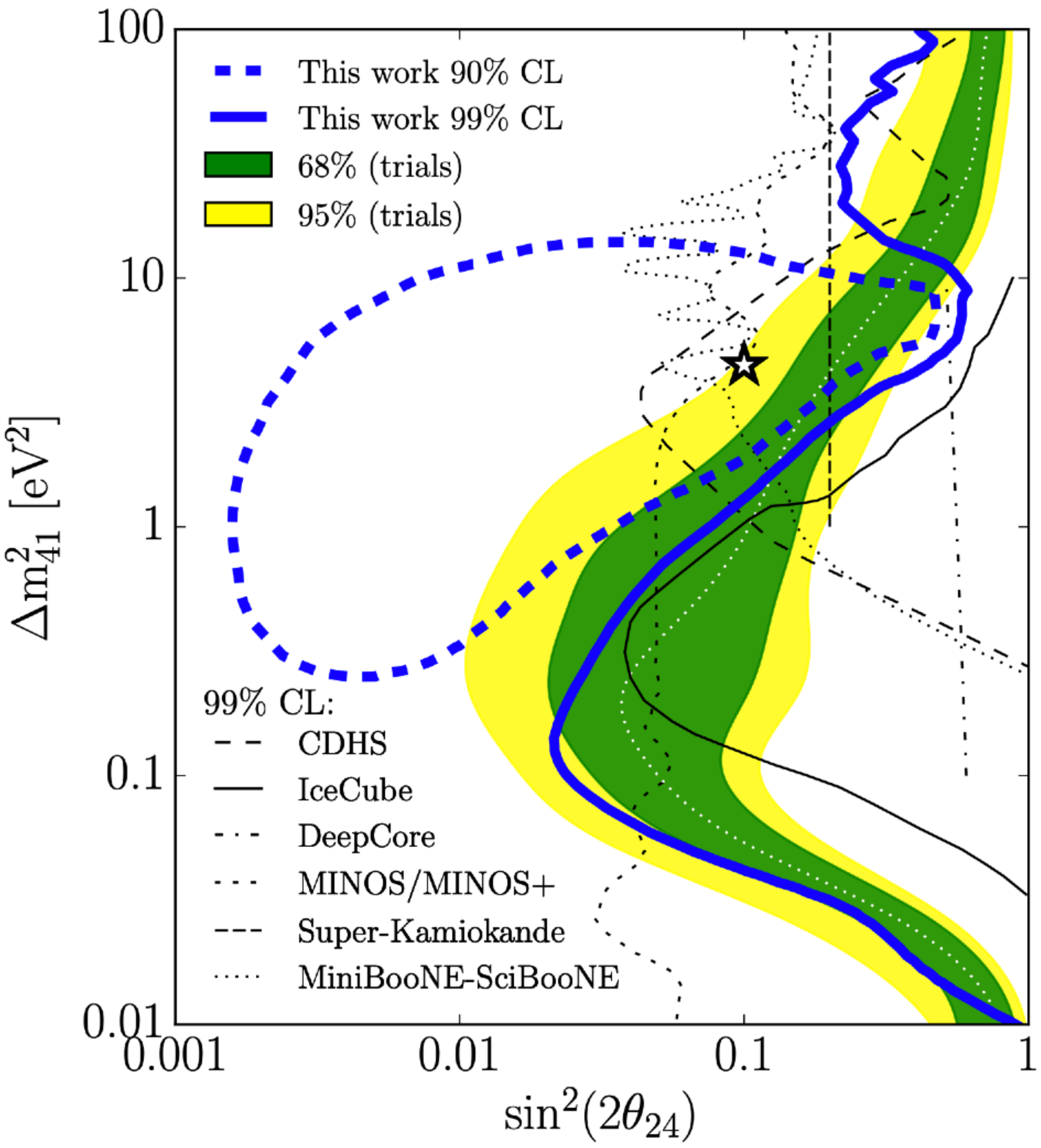
Idea 1: Sterile Neutrinos Plus NSI

The context

See poster by Alfonso Garcia-Soto (P0342) and Ben Smithers P0394) on upcoming IceCube analyses using high-energy neutrinos.

IceCube exploits matter effects for their results





IceCube and MINOS+ dominate muon-neutrino disappearance in ROI

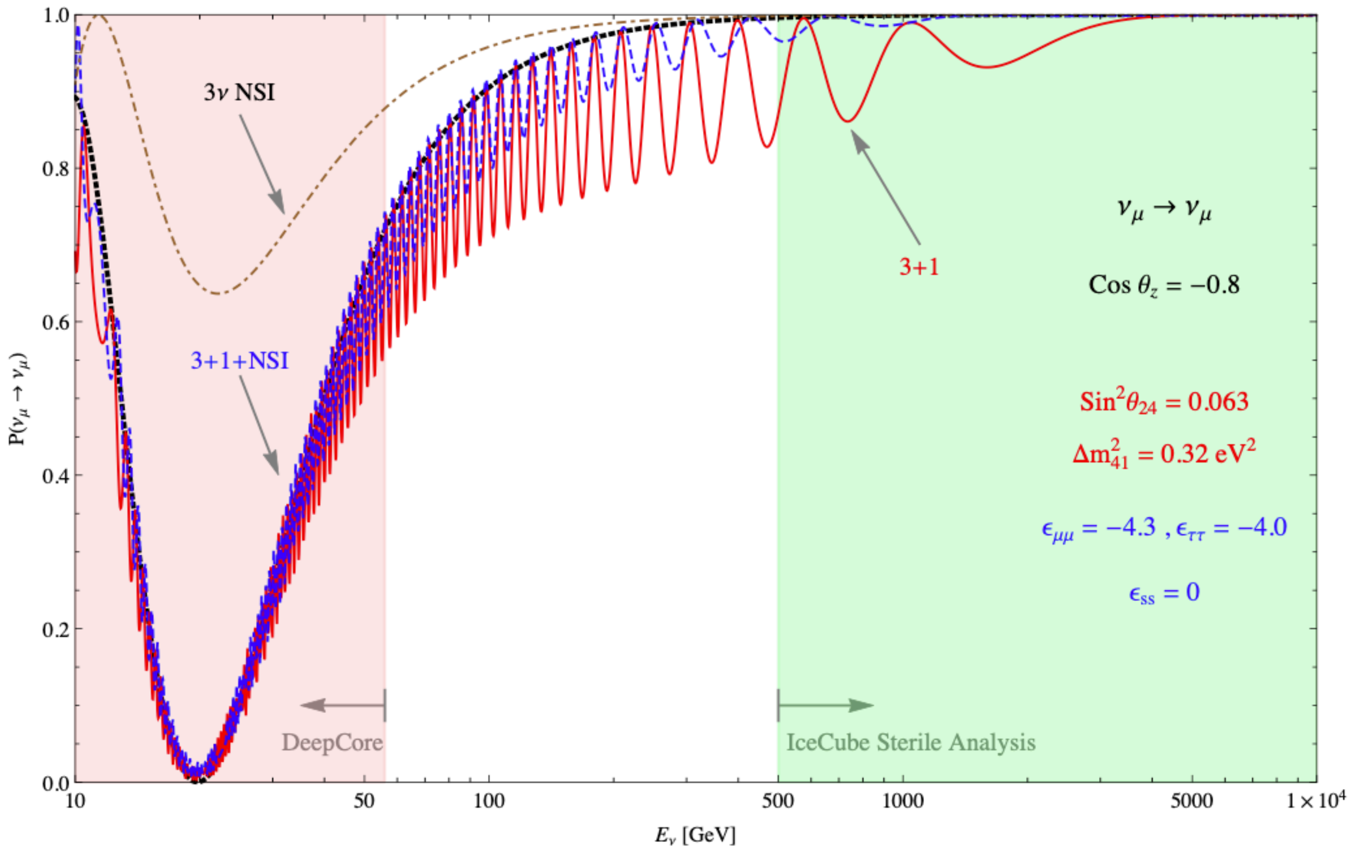
IceCube coll. 2005.12942 and 2005.12943

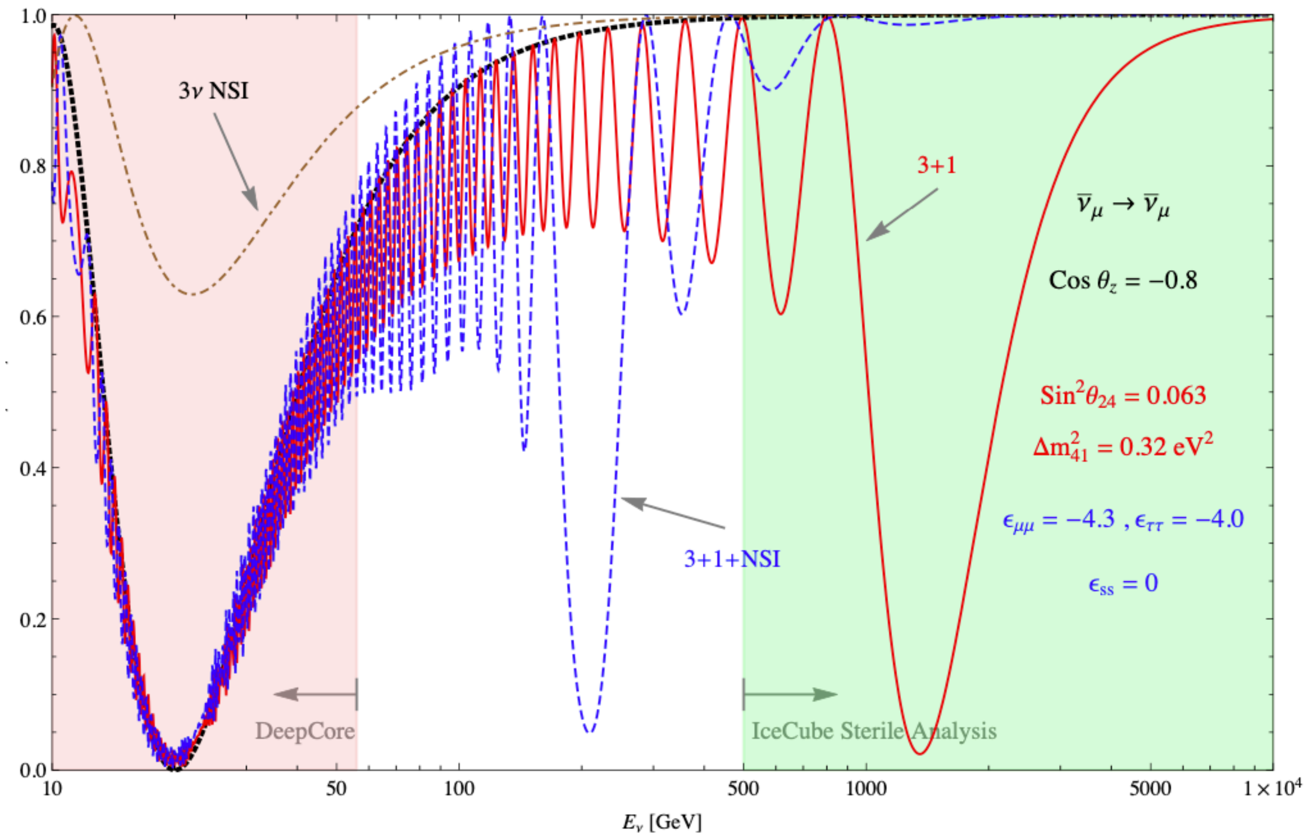
Idea 1: Sterile Neutrinos Plus NSI

Introduction of NSI shifts the resonance and weakens constraint

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

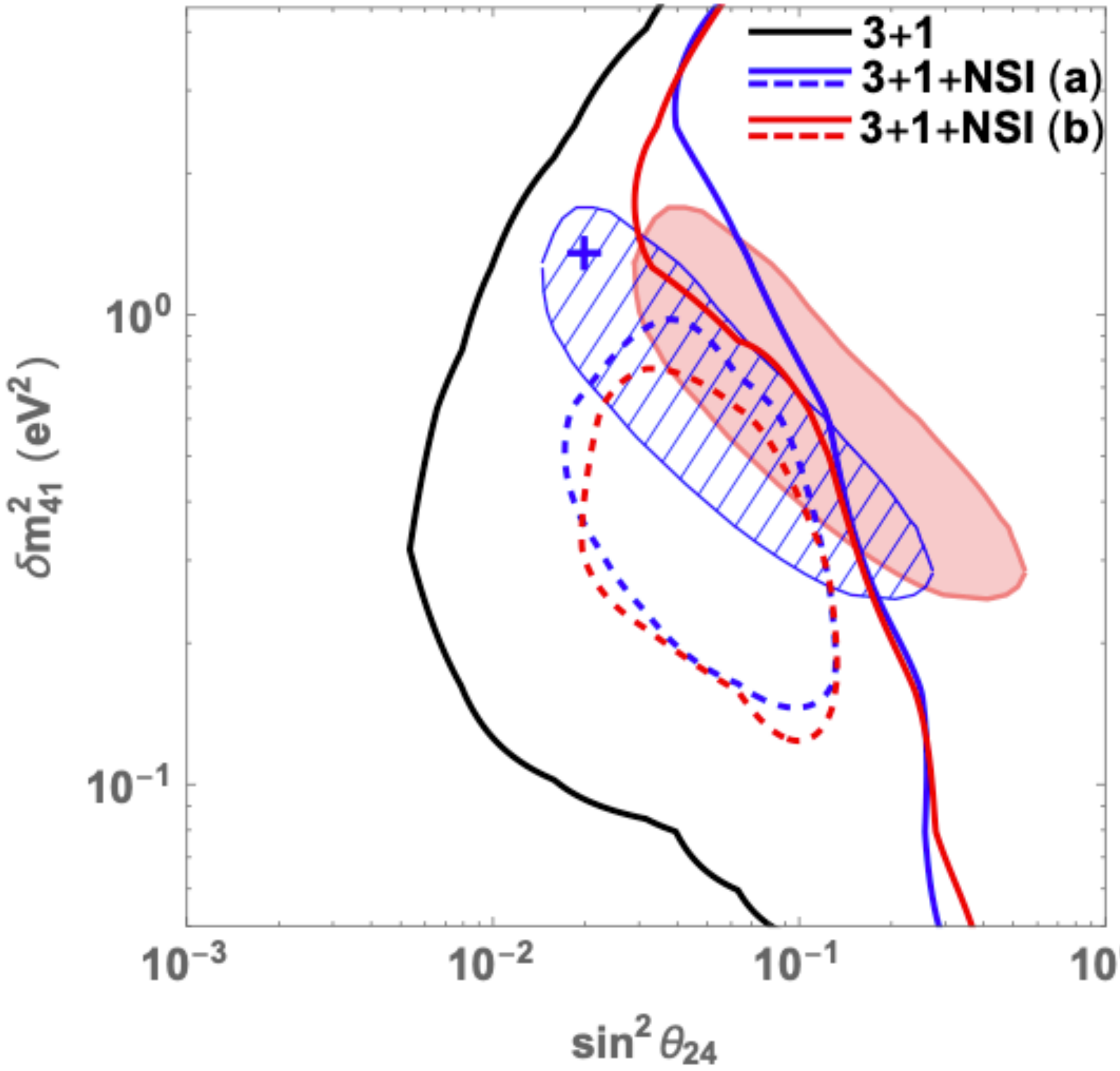
A. Esmaili et al https://arxiv.org/abs/1810.11940

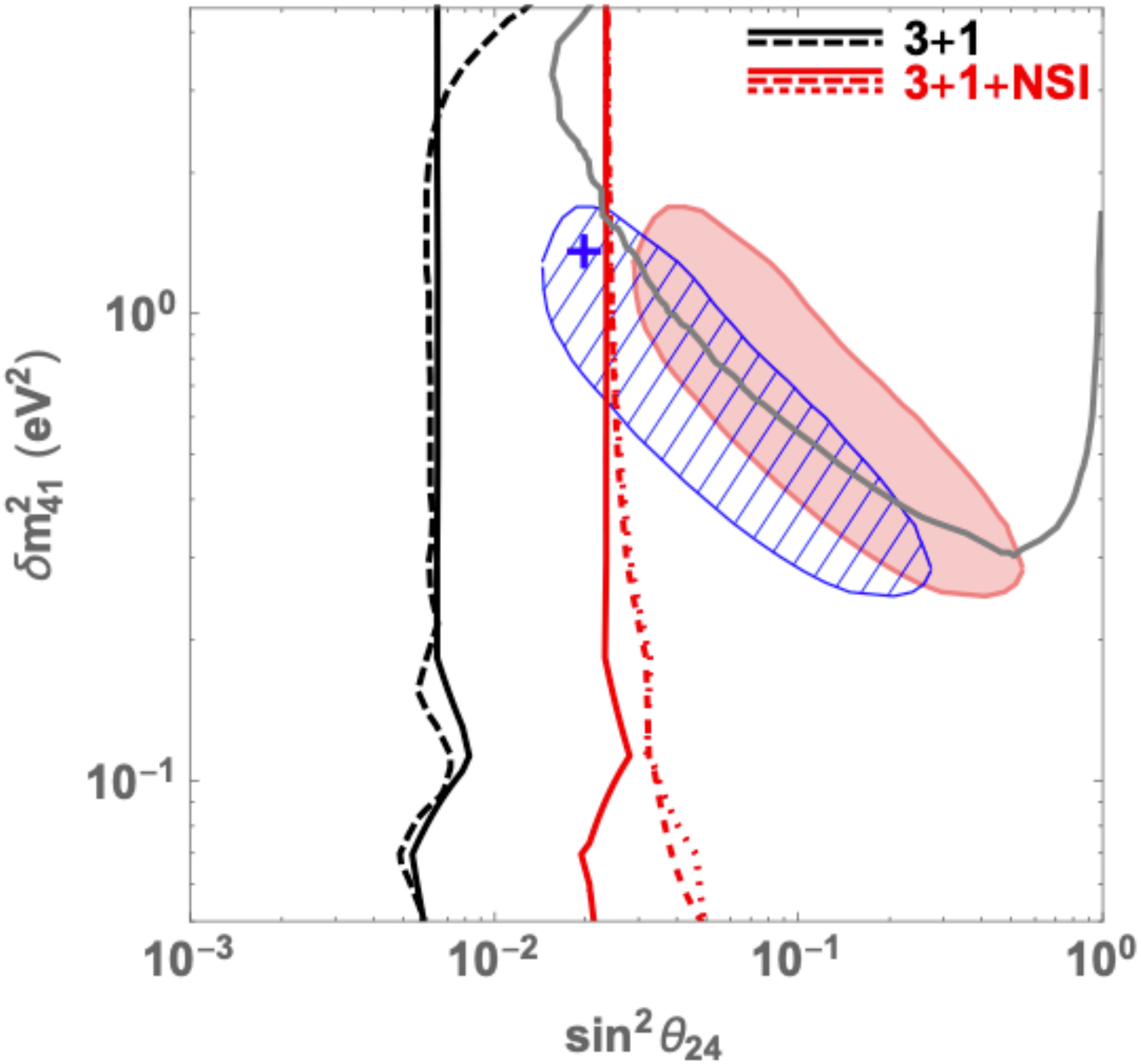




Idea 1: Sterile Neutrinos Plus NSI

NSI affects both long baseline experiments


IceCube modified by NSI


MINOS modified by NSI

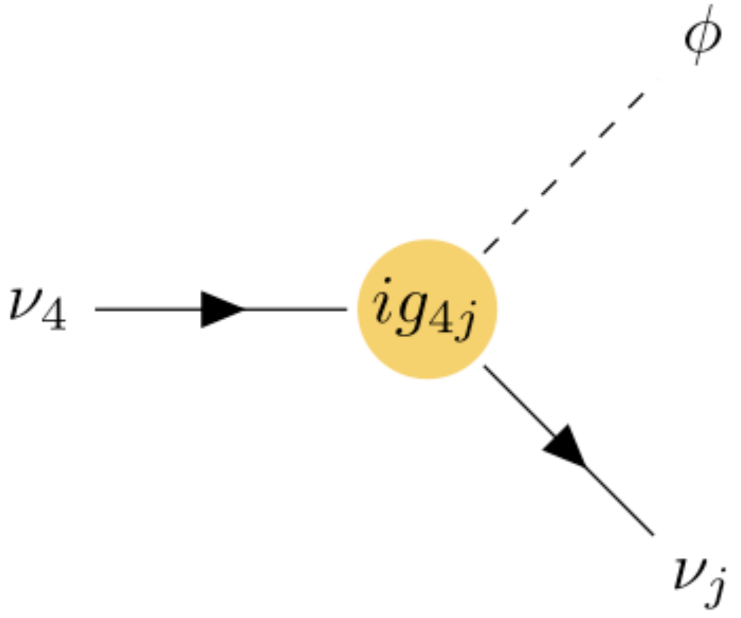
Check out poster by Grant Parker (P0777) for updated IceCube NSI constraints

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

Idea 2: Sterile Neutrinos Plus Decay

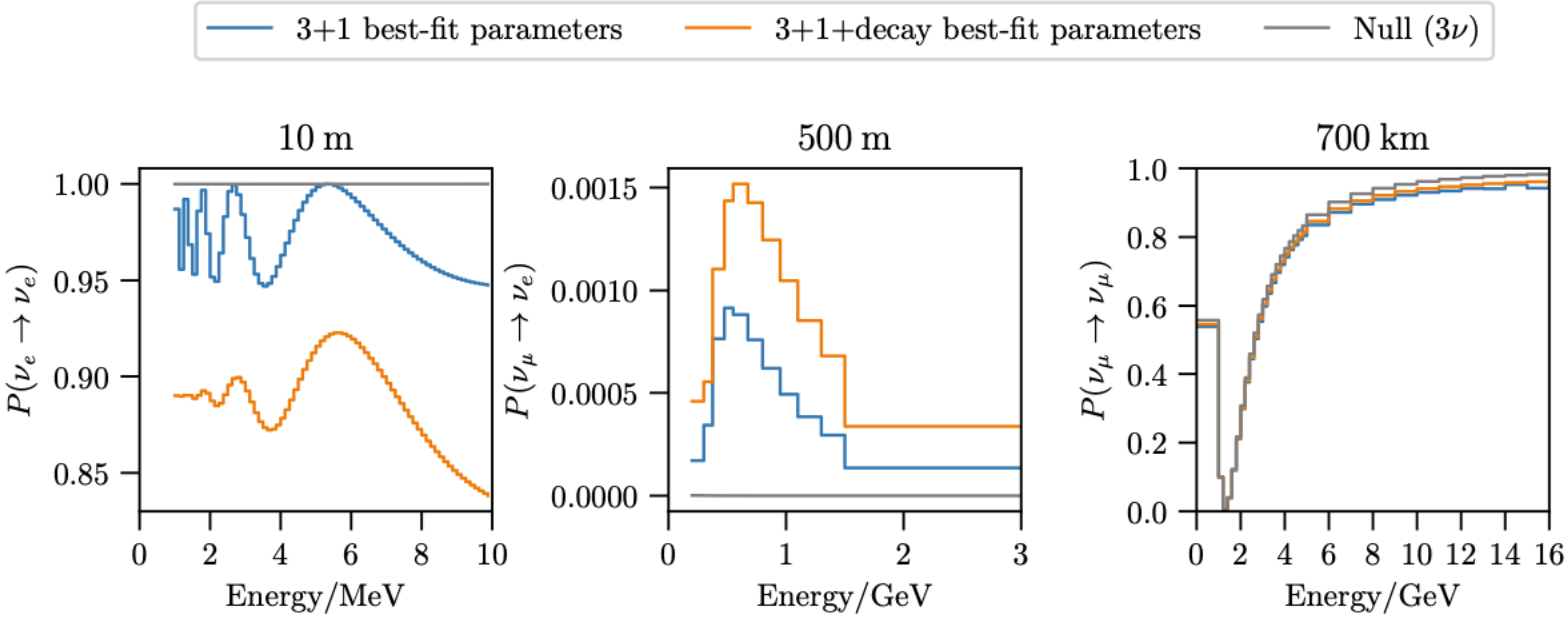
Moss et al 1711.05921
Palomares-Ruiz et al hep-ph/0505216

The model



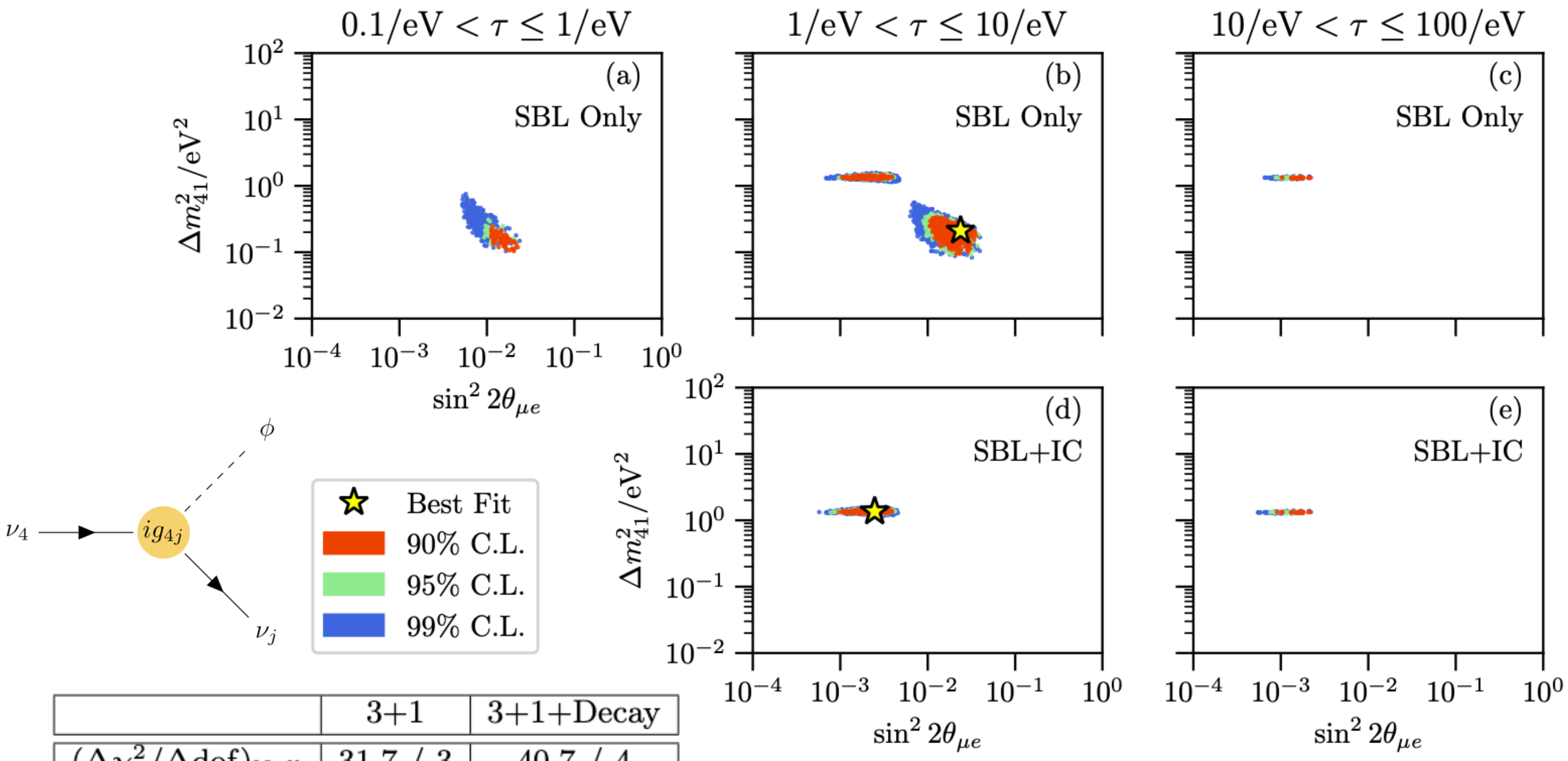
Decay can be visible or invisible.

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!

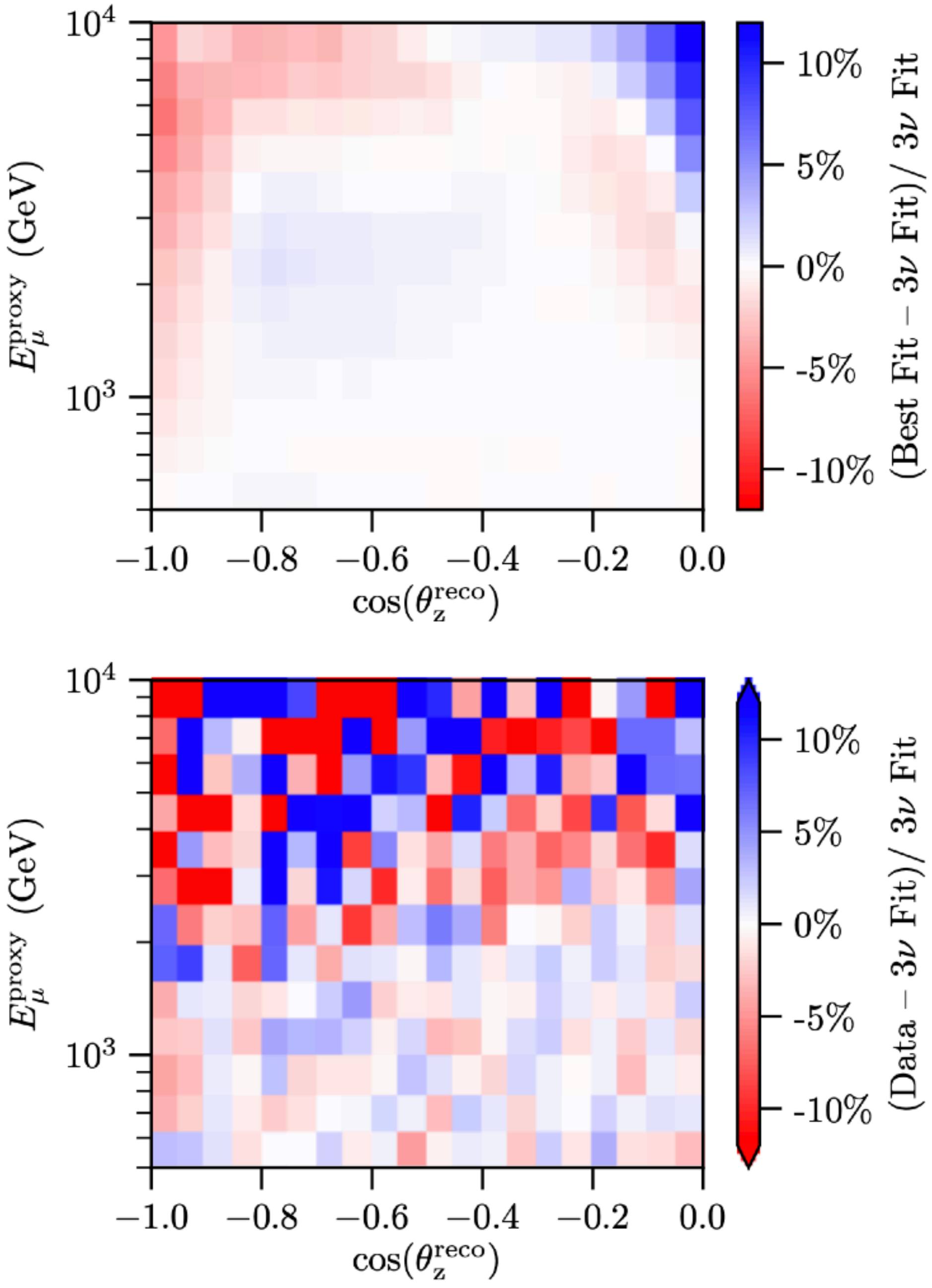
See also Berryman *et al* 1407.6631

Idea 2: Sterile Neutrinos Plus Decay

Breaking news!

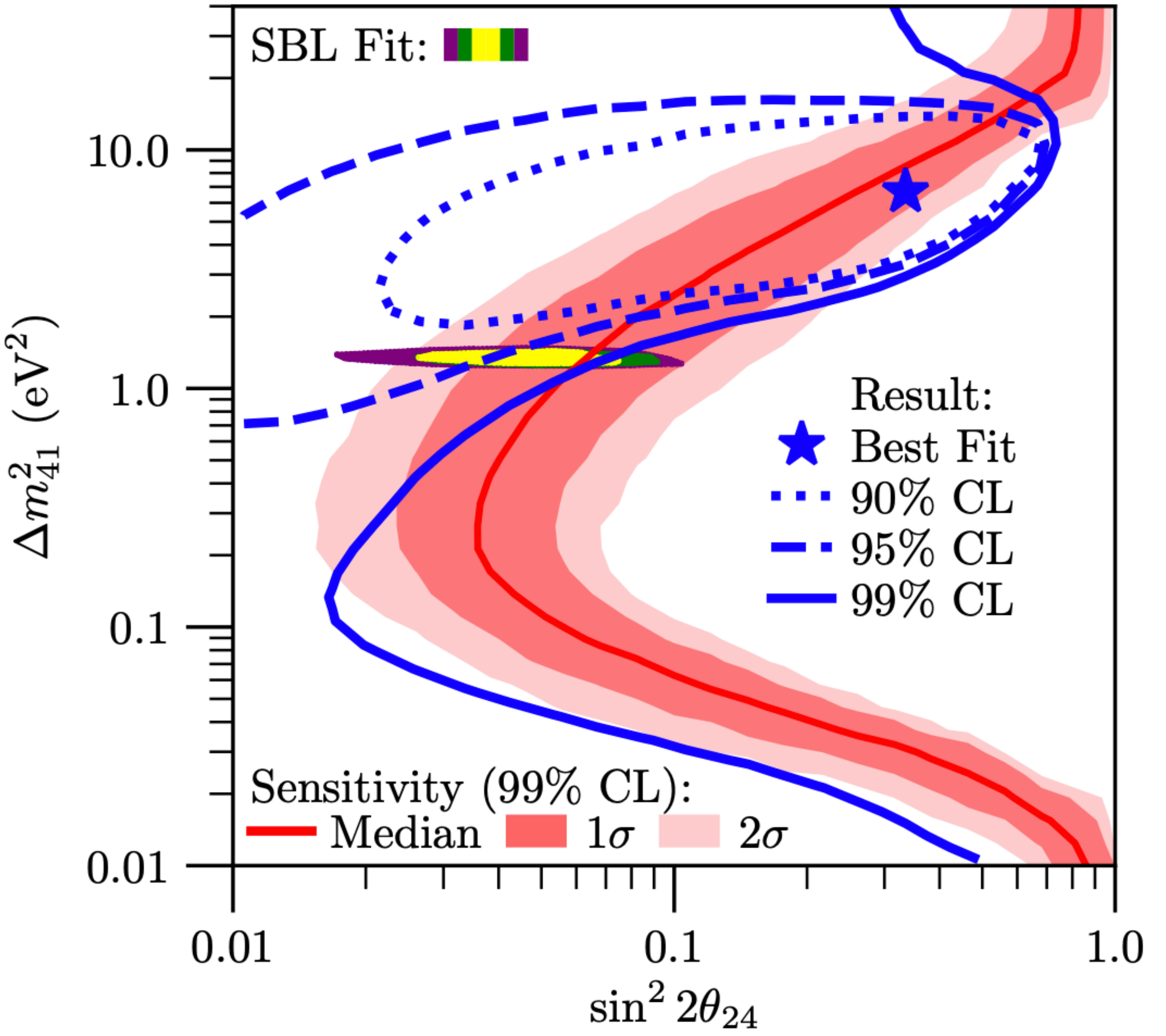
See poster by Marjon Moulai (P0250) for details.

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



IceCube Collaboration arXiv:2204.00612

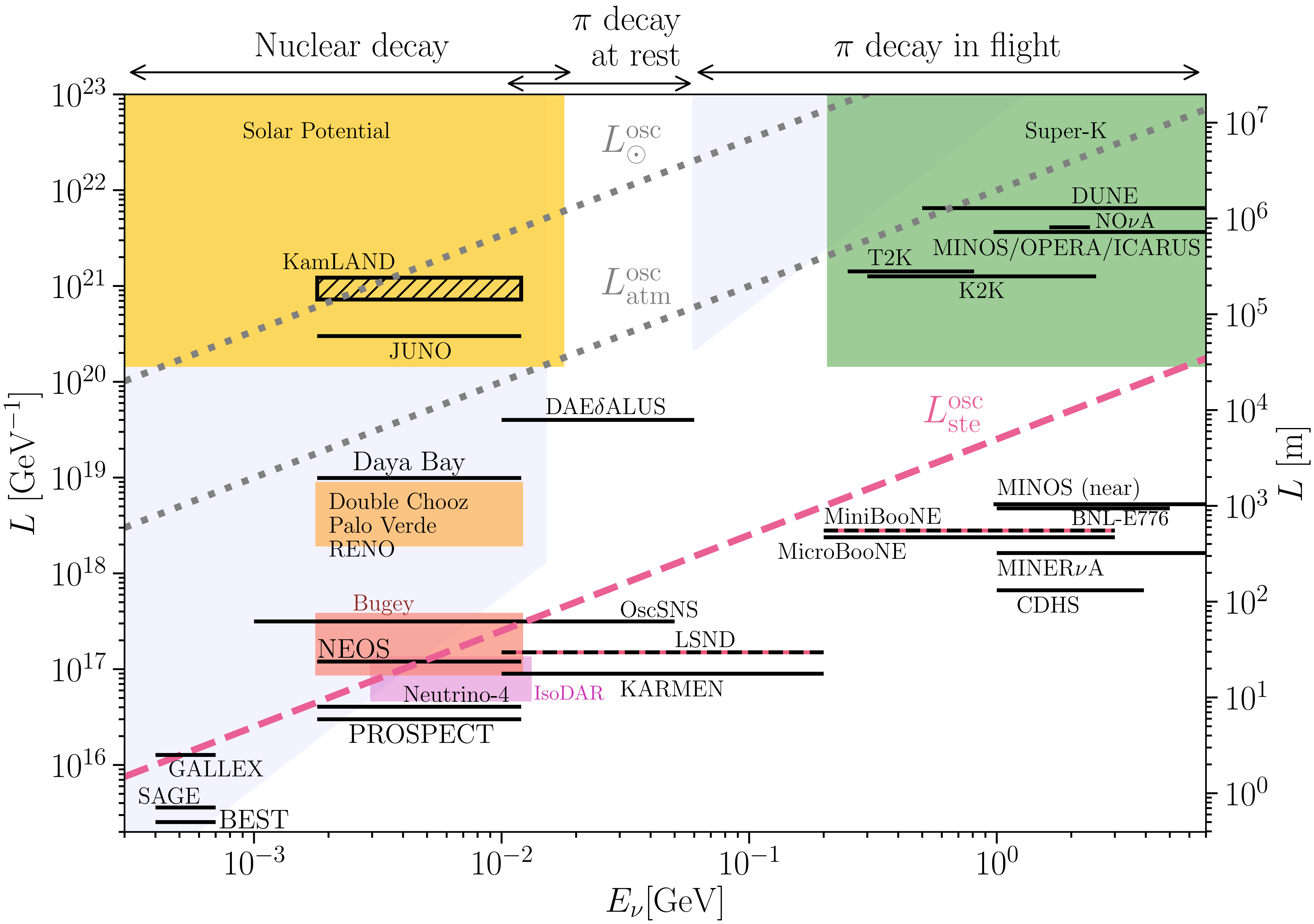
(slice for best-fit decay constant)



IceCube also prefers 3+1+Decay, though at small significance!

Idea 3: Sterile Neutrinos Plus Decoherence

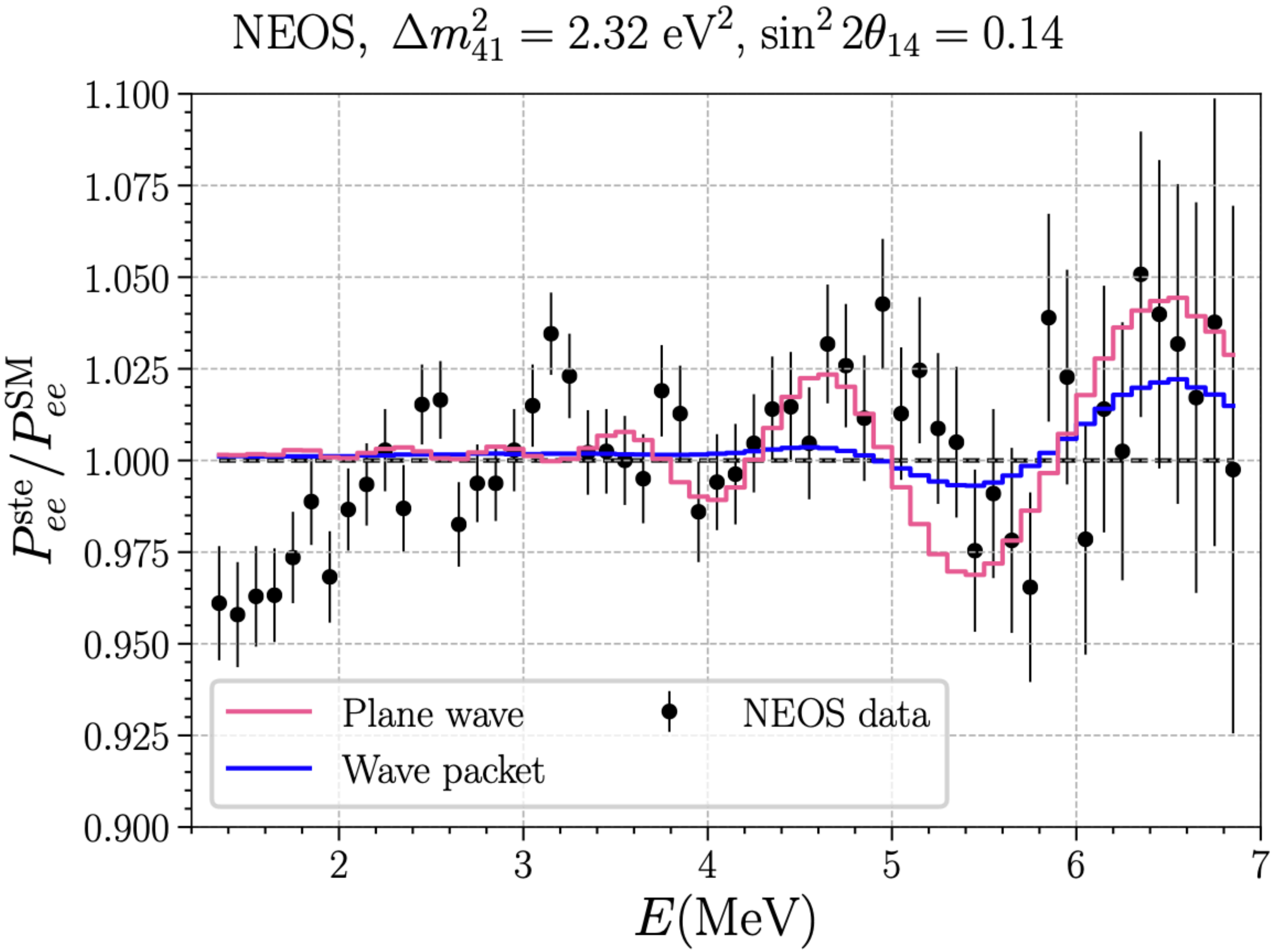
How are our neutrinos produced?

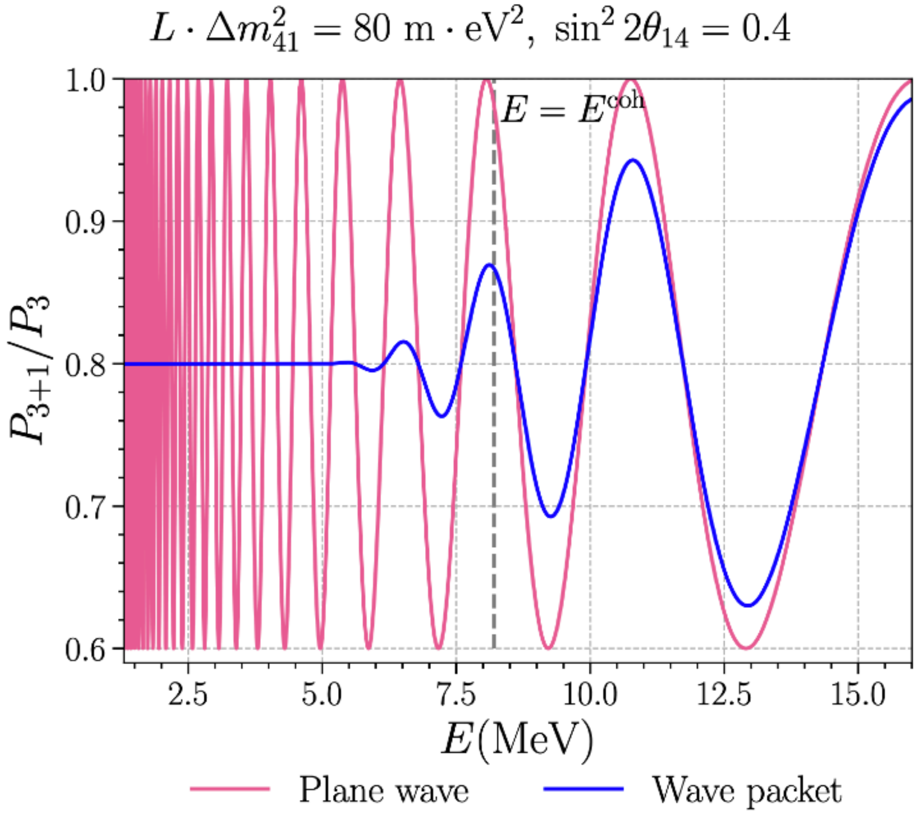


Carlos Argüelles (Neutrino 2022)

Idea 3: Sterile Neutrinos Plus Decoherence

Context: tension between rate (BEST) and spectral measurements

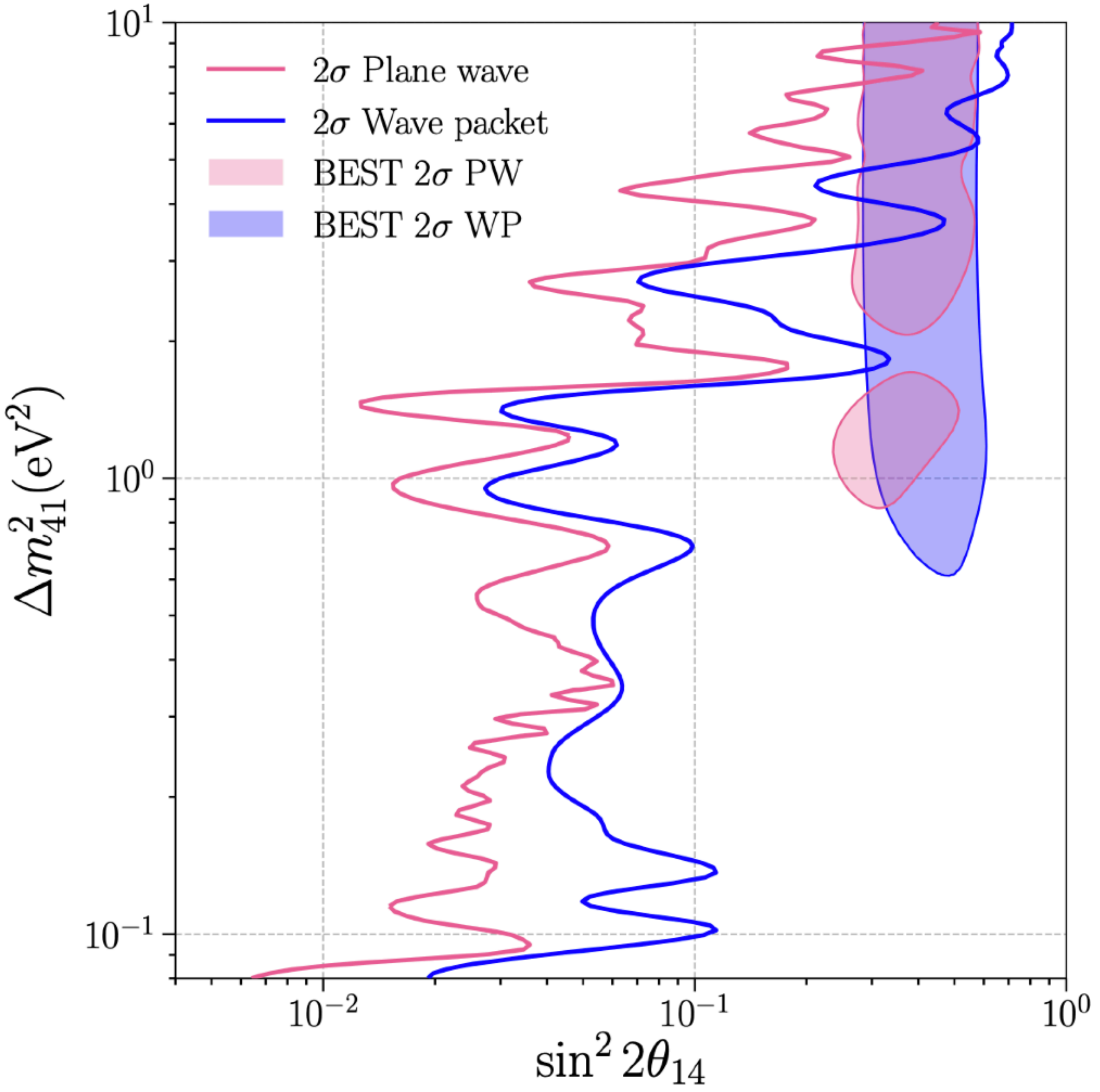


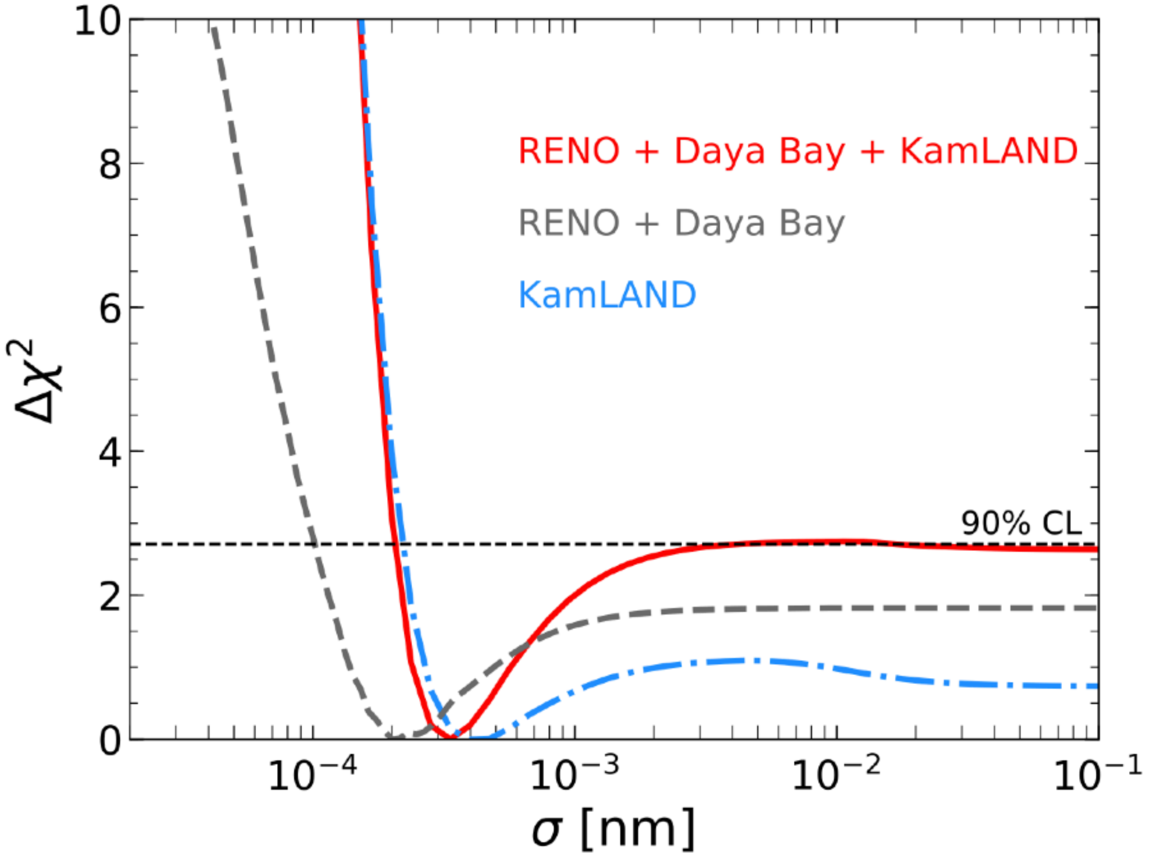


CA, T. Bertólez-Martínez, and J. Salvado 2201.05108
Berryman et al 2111.12530

Idea 3: Sterile Neutrinos Plus Decoherence

Context: Tension between BEST and other reactor measurements





Gouvea arXiv:2104.05806 and Daya Bay Coll. 1608.01661

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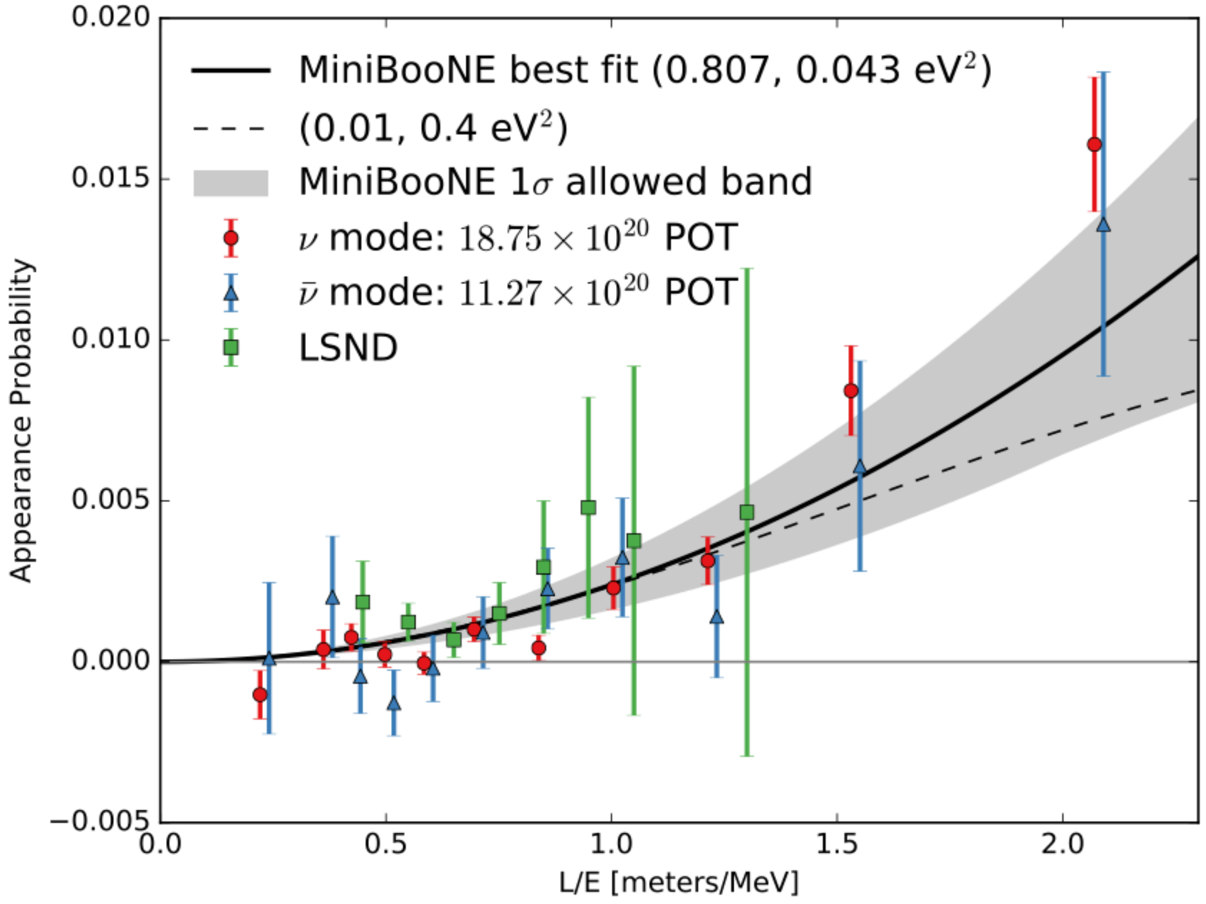
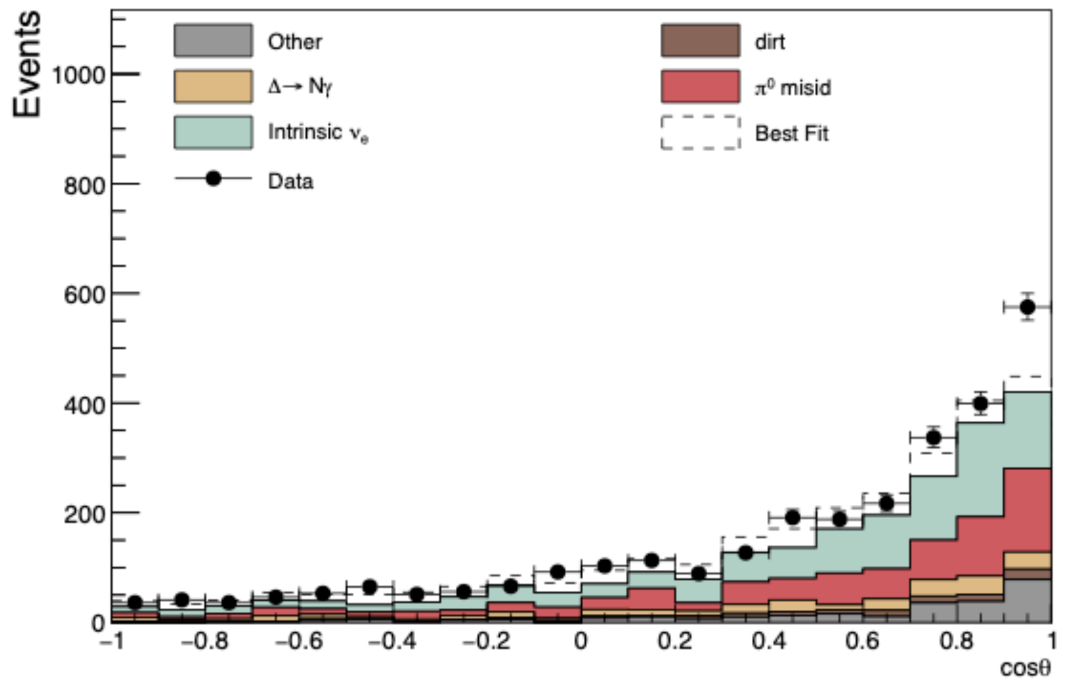
Path Two

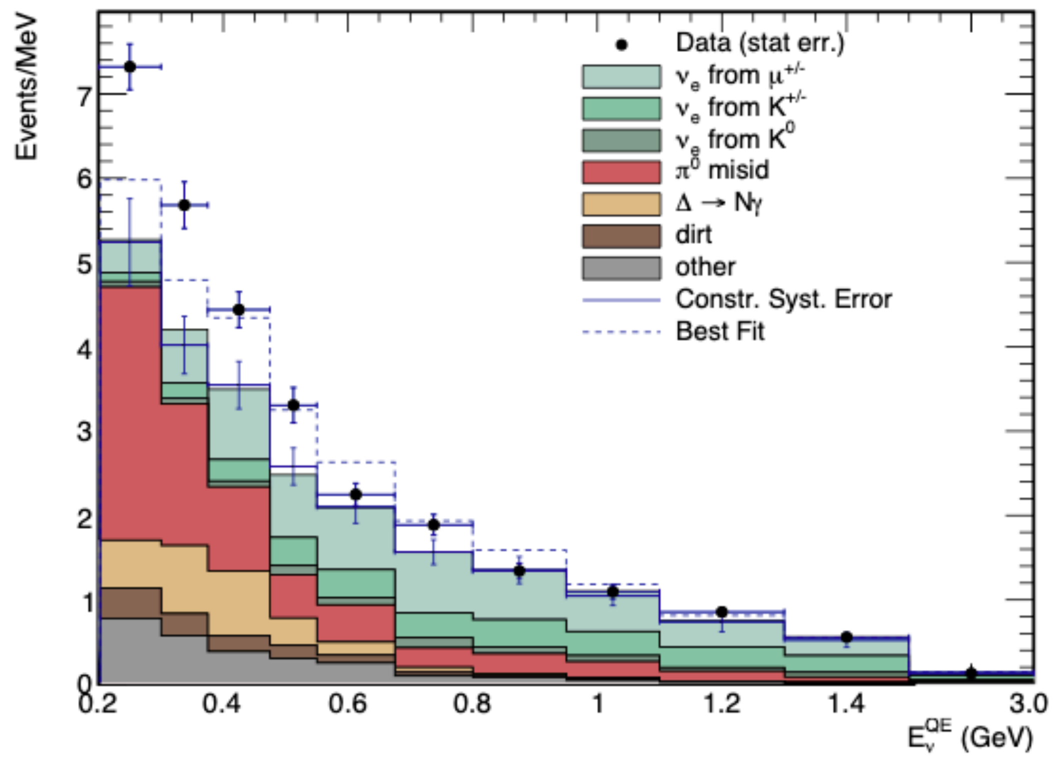
Switching gears: Changing how we look at things

This is useful if we are after an oscillation explanation





In other cases we need to fit these two!

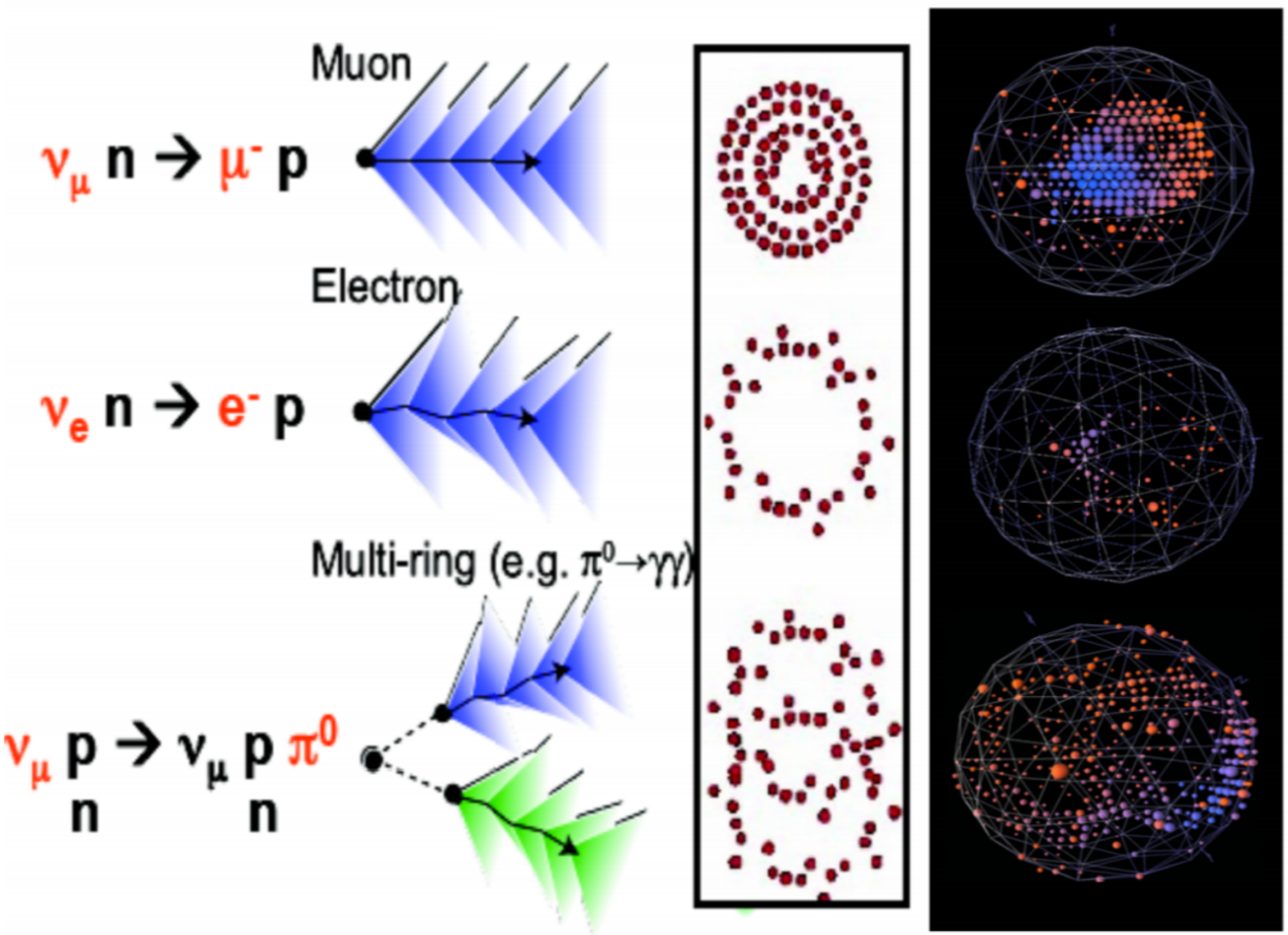


MiniBooNE Collaboration 2006.16883

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 π_0: two gammas -> two fuzzy rings.

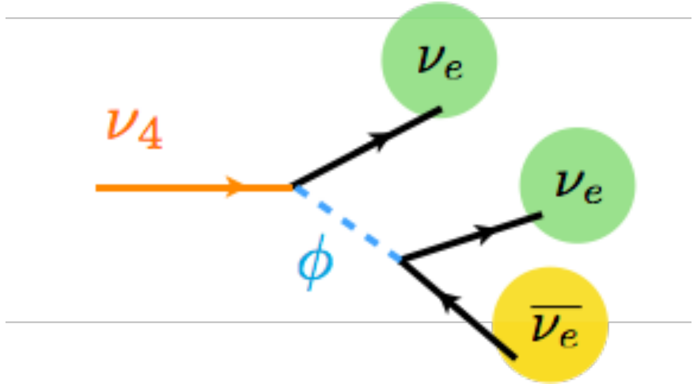


Cannot distinguish between electrons and photons!

Electron

Idea 4: Visible Neutrino Decay in Beam

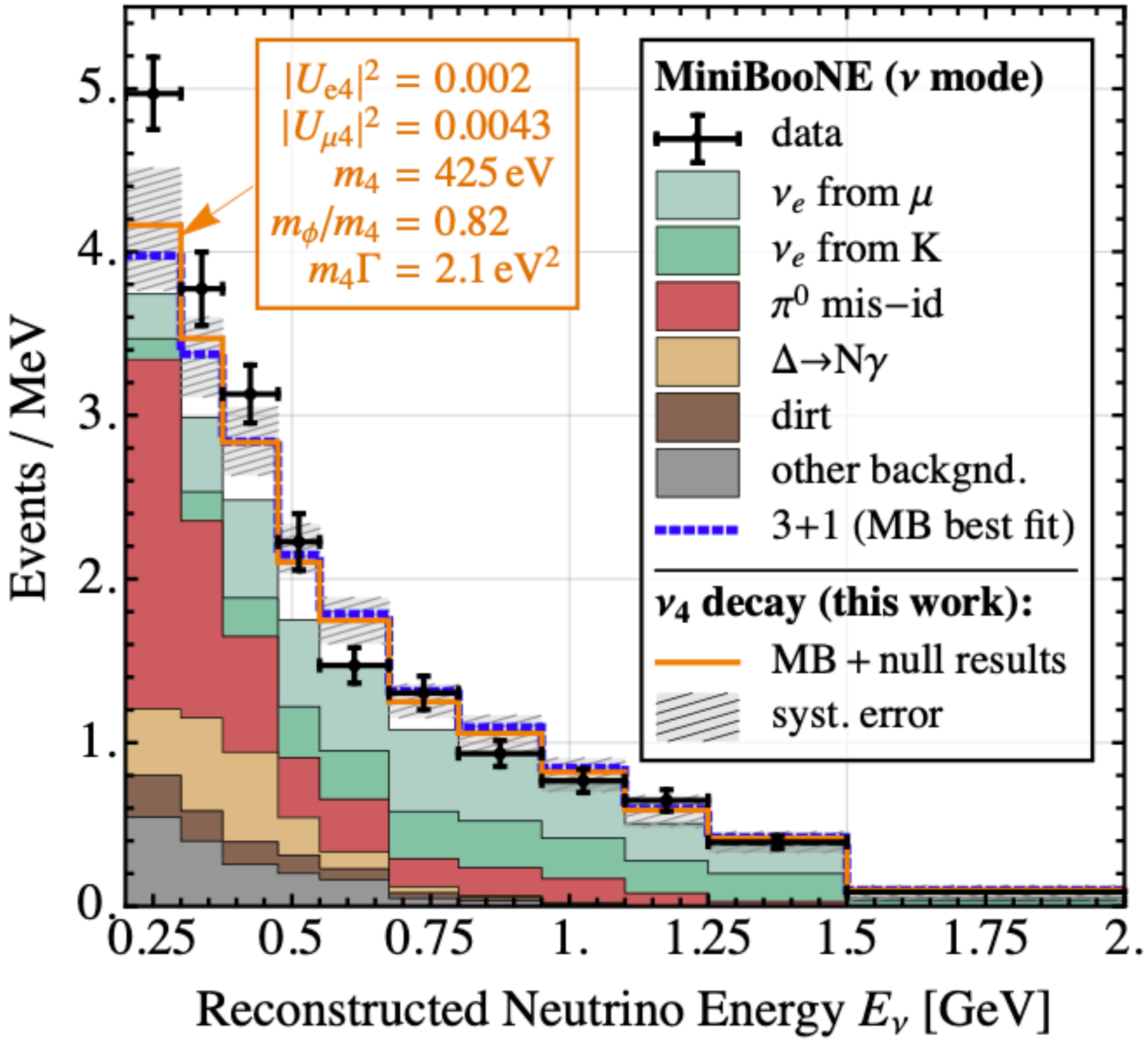
Dentler *et al* 1911.01427
Gouvea *et al* 1911.01447



Heavy neutrino component in the neutrino beam decays into lighter less energetic neutrinos.

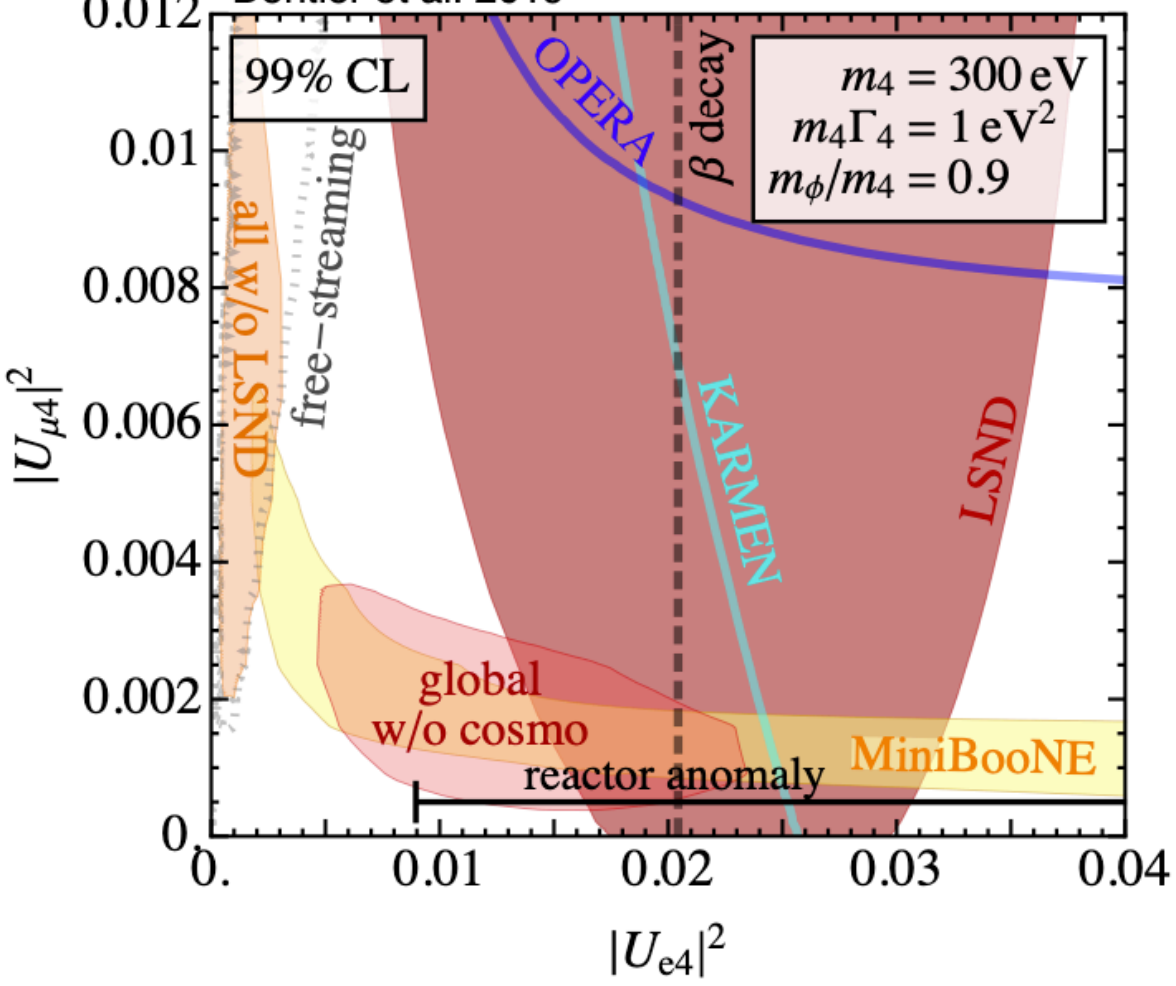
These neutrinos interact in the detector and produce the excess.

Dentler et al. 2019



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

Dentler et al. 2019



See also Fisher *et al* 1909.09561

Electron

Idea 4: Visible Neutrino Decay in Beam

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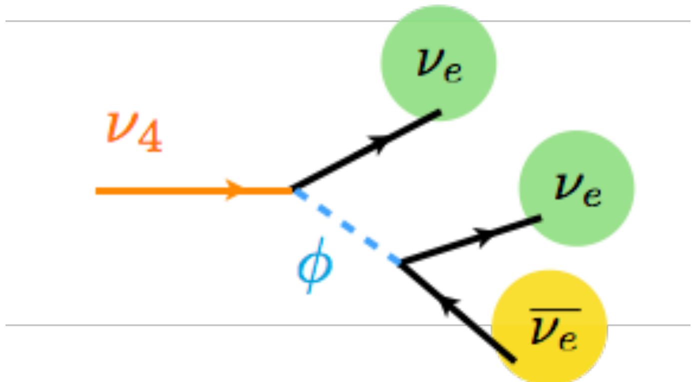
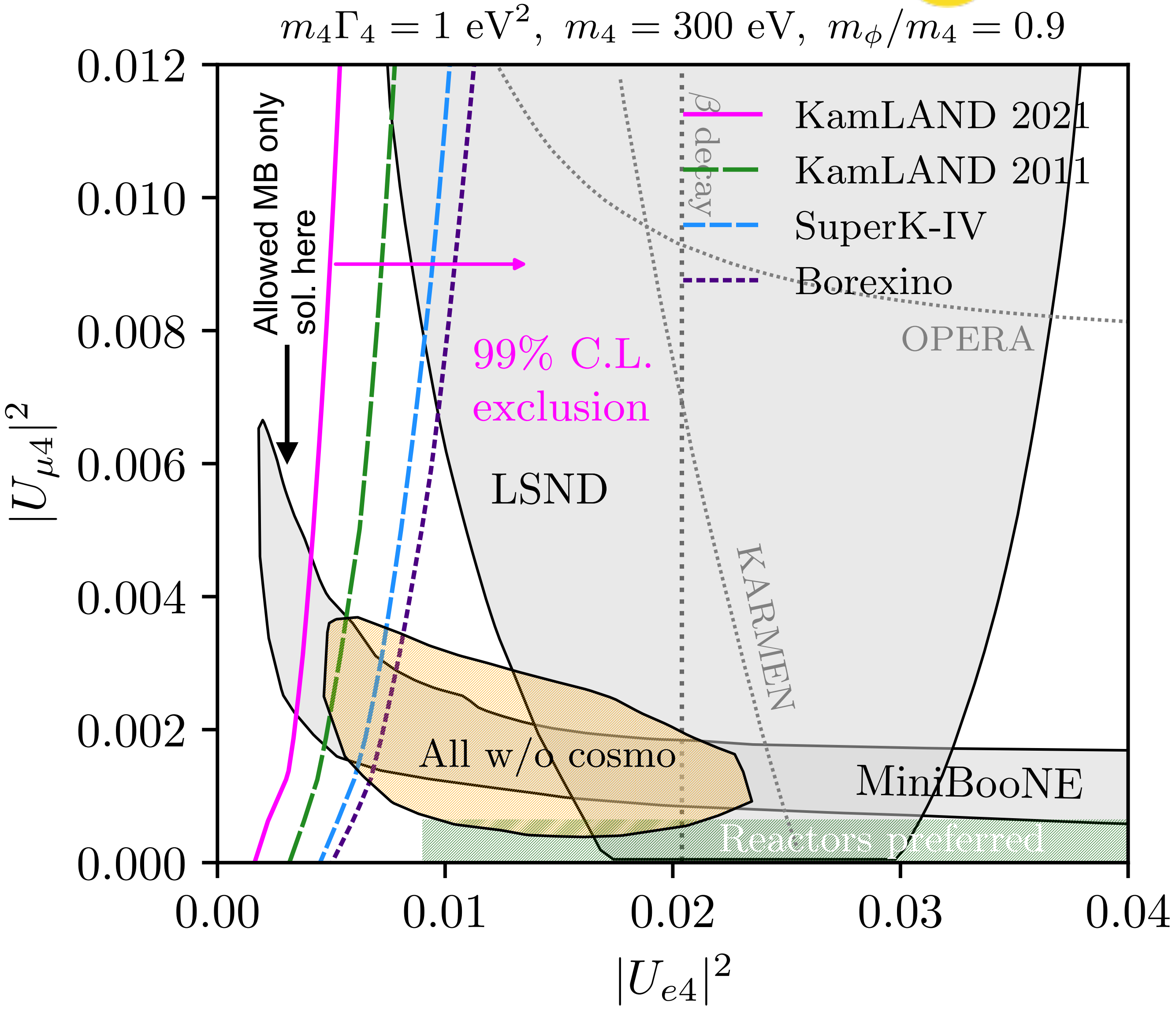
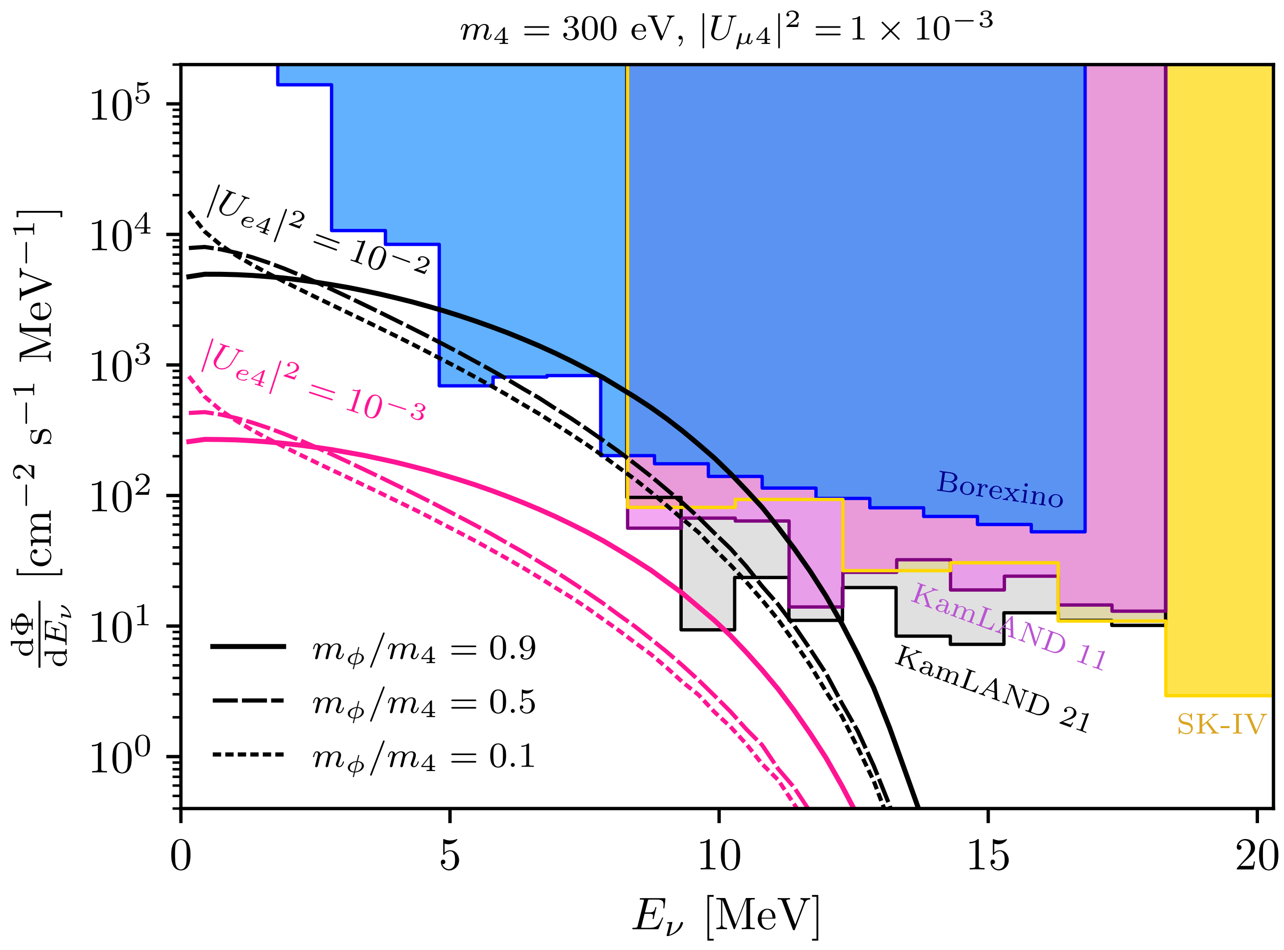


Constrains from antineutrinos from the Sun do not allow this to be a global solution of the anomalies.

MiniBooNE alone can be explained.



M. Hostert & M. Pospelov 2008.11851



Visible decay predicts emission of antineutrinos from the Sun!

Gamma

Idea 5: Scalar With “Primakoff” Upscattering

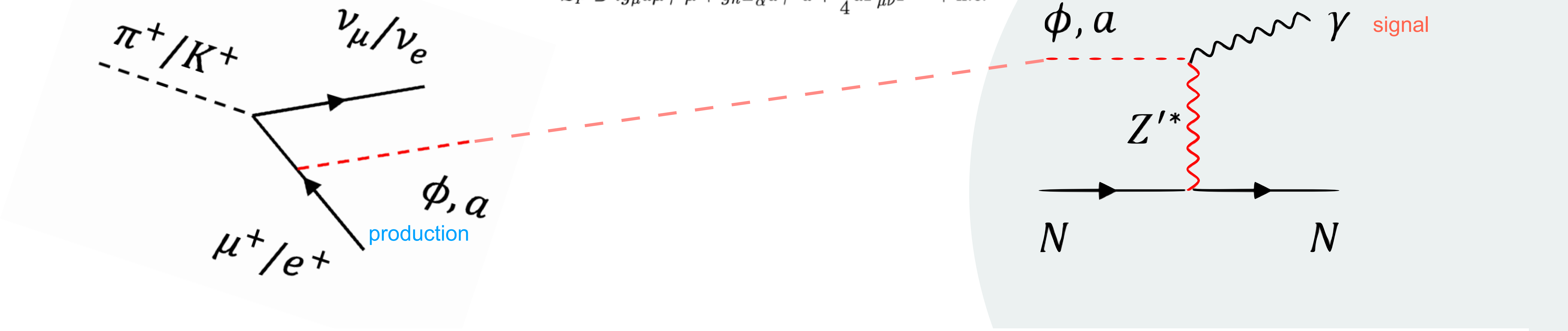
B. Dutta et al. 2110.11944
See also Abdallah et al 2202.09373

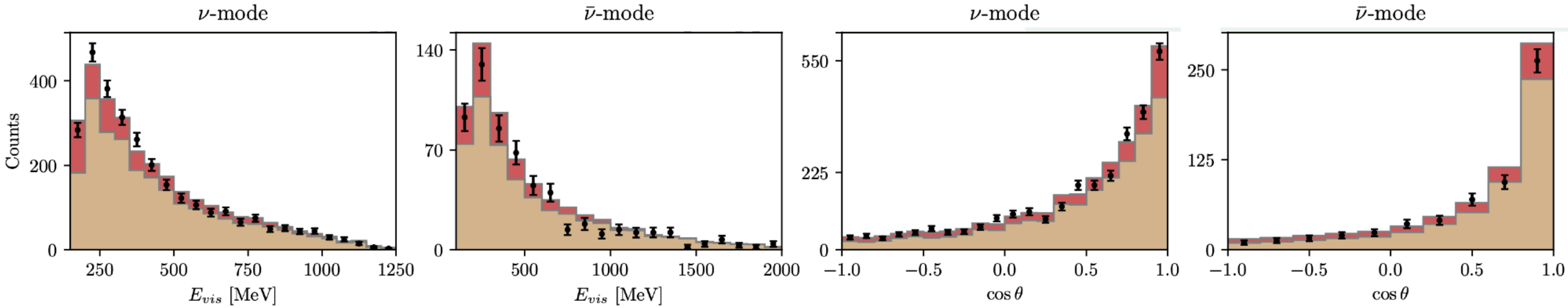
Booster Beam

$$\mathcal{L}_S \supset g_\mu \phi \bar{\mu}\mu + g_n Z'_\alpha \bar{u}\gamma^\alpha u + \frac{\lambda}{4}\phi F'_{\mu\nu}F^{\mu\nu} + \text{h.c.},$$

$$\mathcal{L}_P \supset i g_\mu a \bar{\mu}\gamma^5\mu + g_n Z'_\alpha \bar{u}\gamma^\alpha u + \frac{\lambda}{4} a F'_{\mu\nu}\tilde{F}^{\mu\nu} + \text{h.c.}$$

MiniBooNE detector





Energy distribution

Angular distribution

🟥 ϕ/a Dark Primakoff

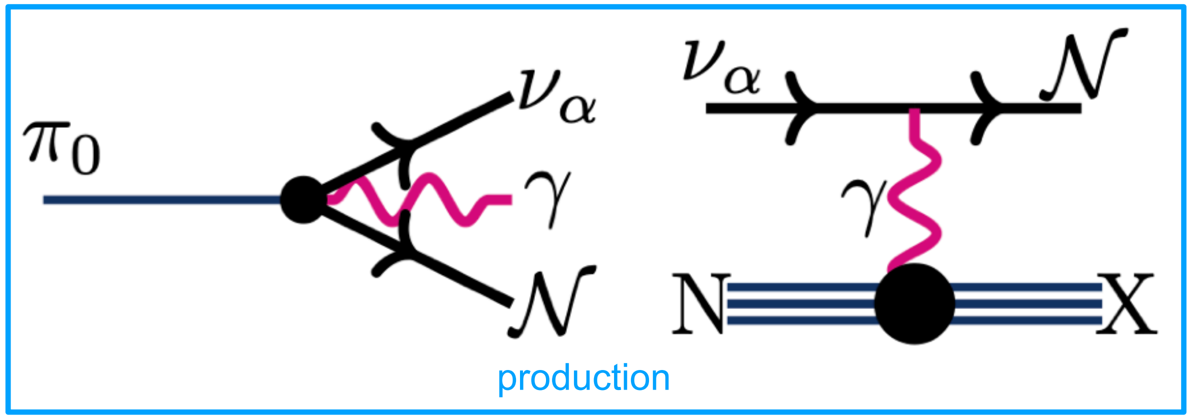
🟫 MiniBooNE Background

Long-lived (pseudo)scalar

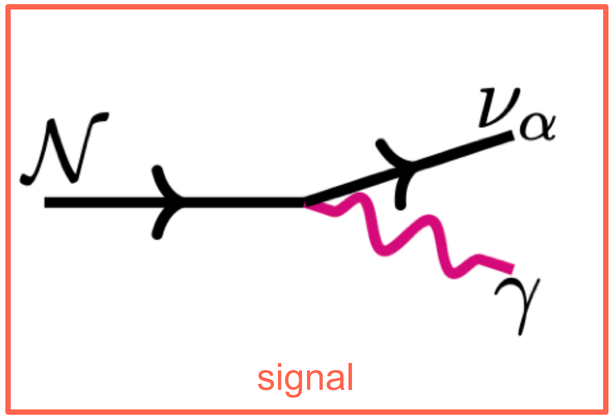
Scenario	$(m_{Z'}, m_{\phi/a})$	$(g_\mu g_n \lambda)$ [MeV^{-1}]	χ^2/dof
Scalar	(49, 1)	2.2×10^{-8}	1.6
Pseudoscalar	(85, 1)	5.9×10^{-7}	1.6

Gamma

Idea 6: Heavy Neutrino With Trans. Mag. Mom.

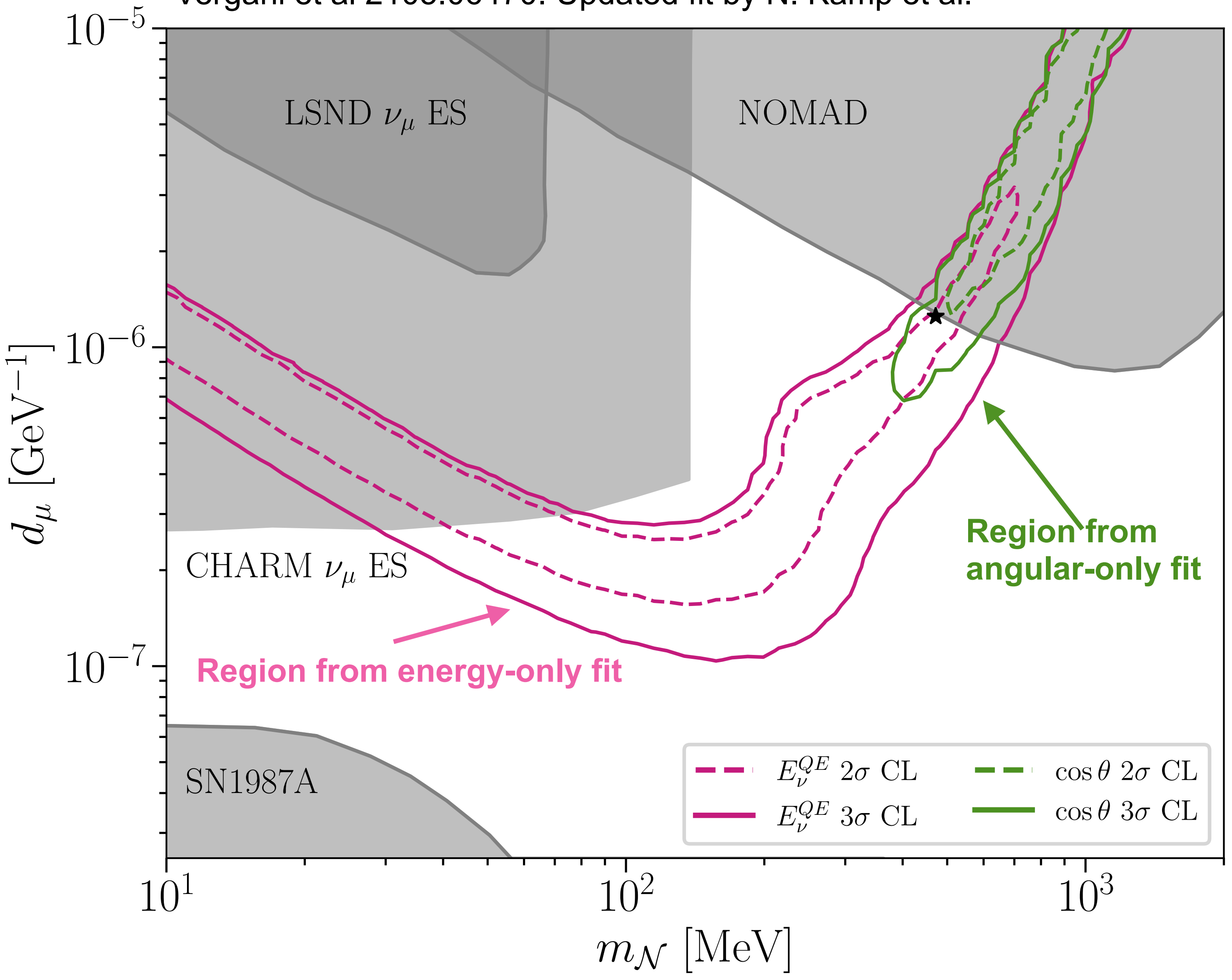


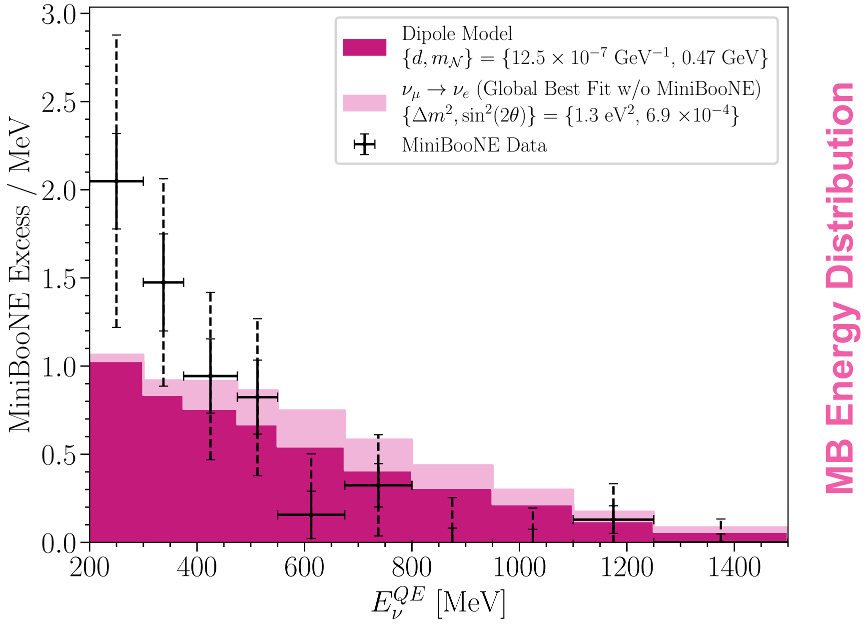
production

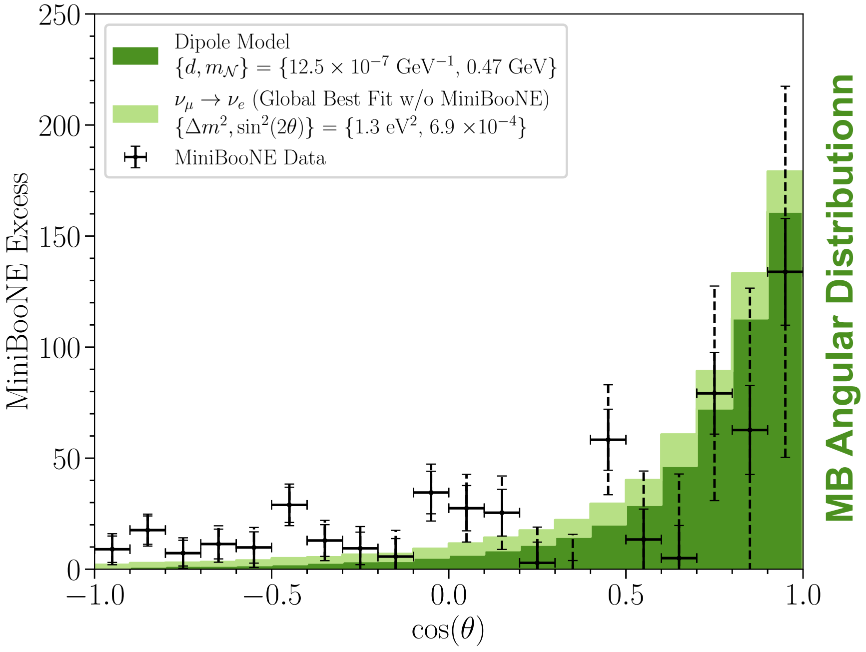


signal

Vergani et al 2105.06470. Updated fit by N. Kamp et al.







See Vergani et al 2105.06470, Magill et al 1803.03262, and Brdar et al 2007.15563.
See poster by N. Kamp (P0665) for updated regions.

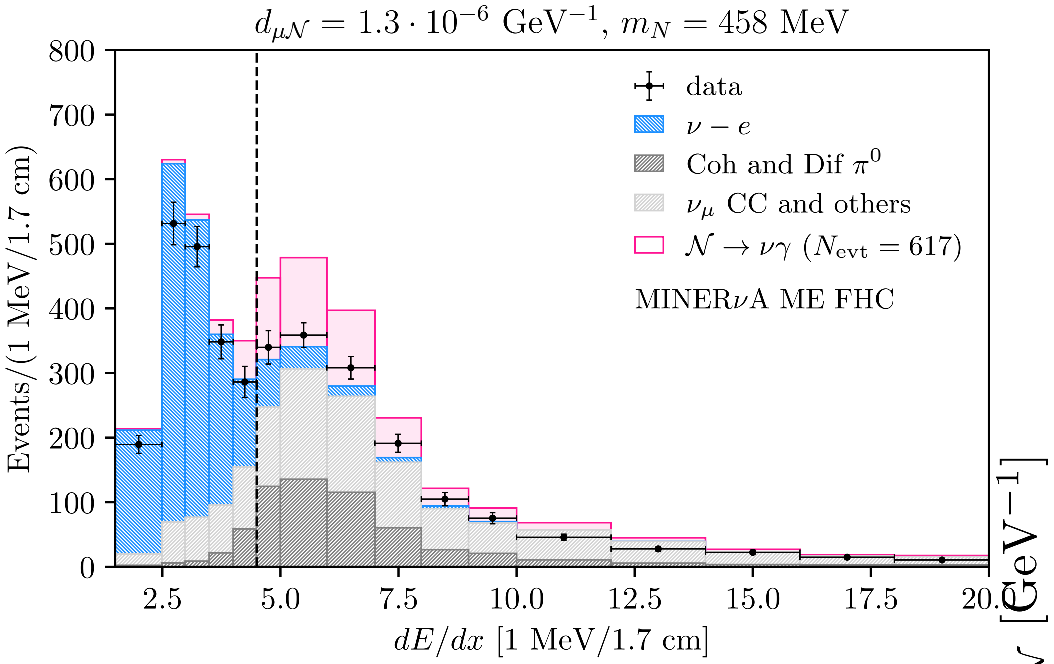
Gamma

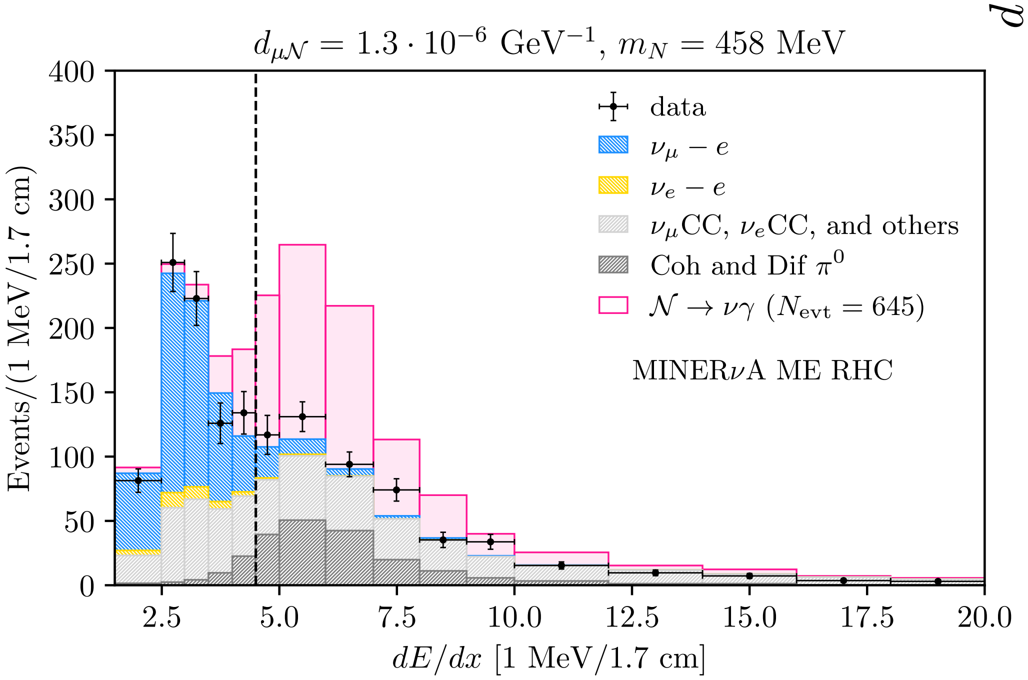
Idea 6: Heavy Neutrino With Trans. Mag. Mom.

This model can be constraint by Minerva neutrino-electron scattering data sets.

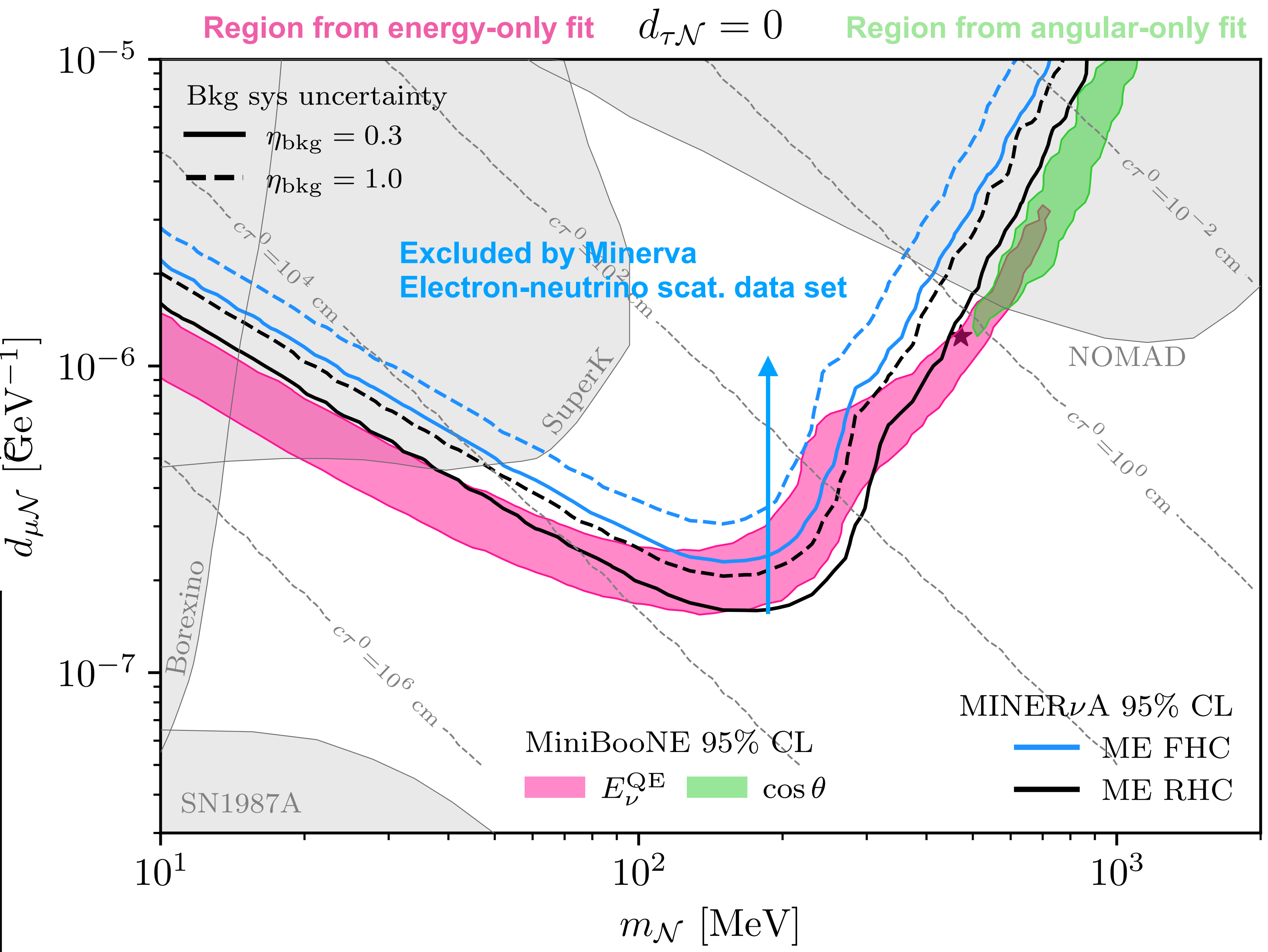
Neutrino mode

Medium Energy NuMI Beam





Antineutrino mode



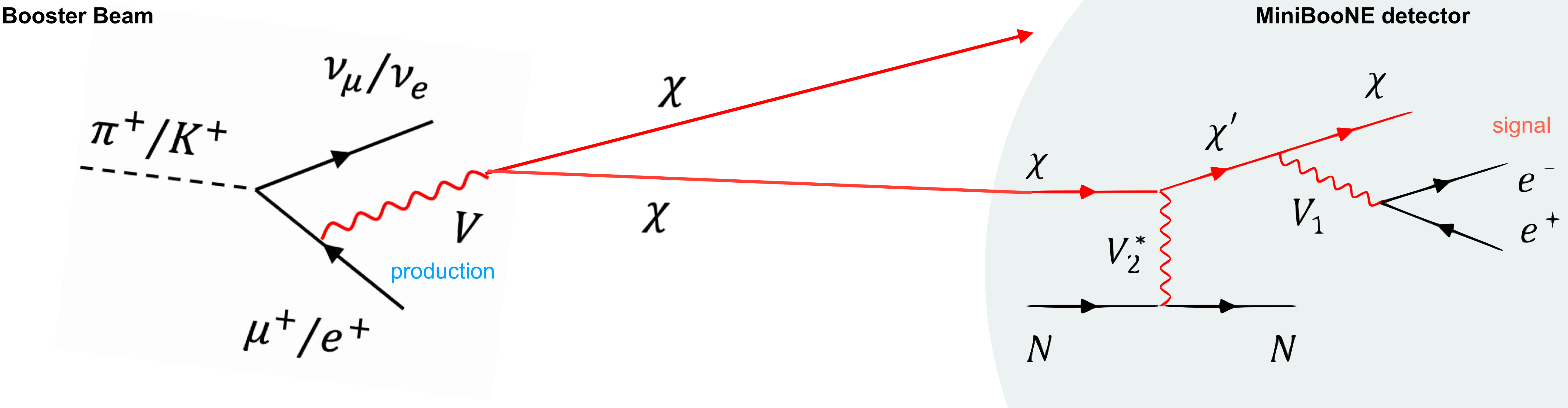
A dedicated Minerva analysis should be sensitive to the entire MiniBooNE a preferred region.

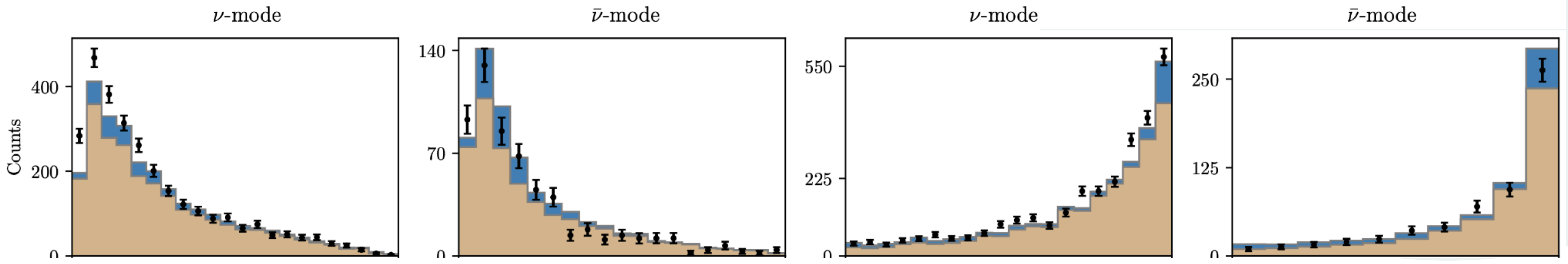
See poster by Nick Kamp (P0665).

Dielectron

Idea 7: Dark Photon With Upscattering

B. Dutta et al. 2110.11944





Energy distribution

Angular distribution

🟦 χ Upscattering

🟫 MiniBooNE Background

Vector-portal dark matter			
Scenario	$(m_{V_1}, m_{V_2}, m_\chi, m_{\chi'})$	$\epsilon_1\epsilon_2 g_2'^2/(4\pi)$	χ^2/dof
Single	$(17, -, 8, 40)$	3.6×10^{-9}	2.5
Double	$(17, 200, 8, 50)$	1.3×10^{-7}	2.2

Dielectron

Idea 8: Dark Neutrino

E. Bertuzzo et al., PhysRevLett.121.241801

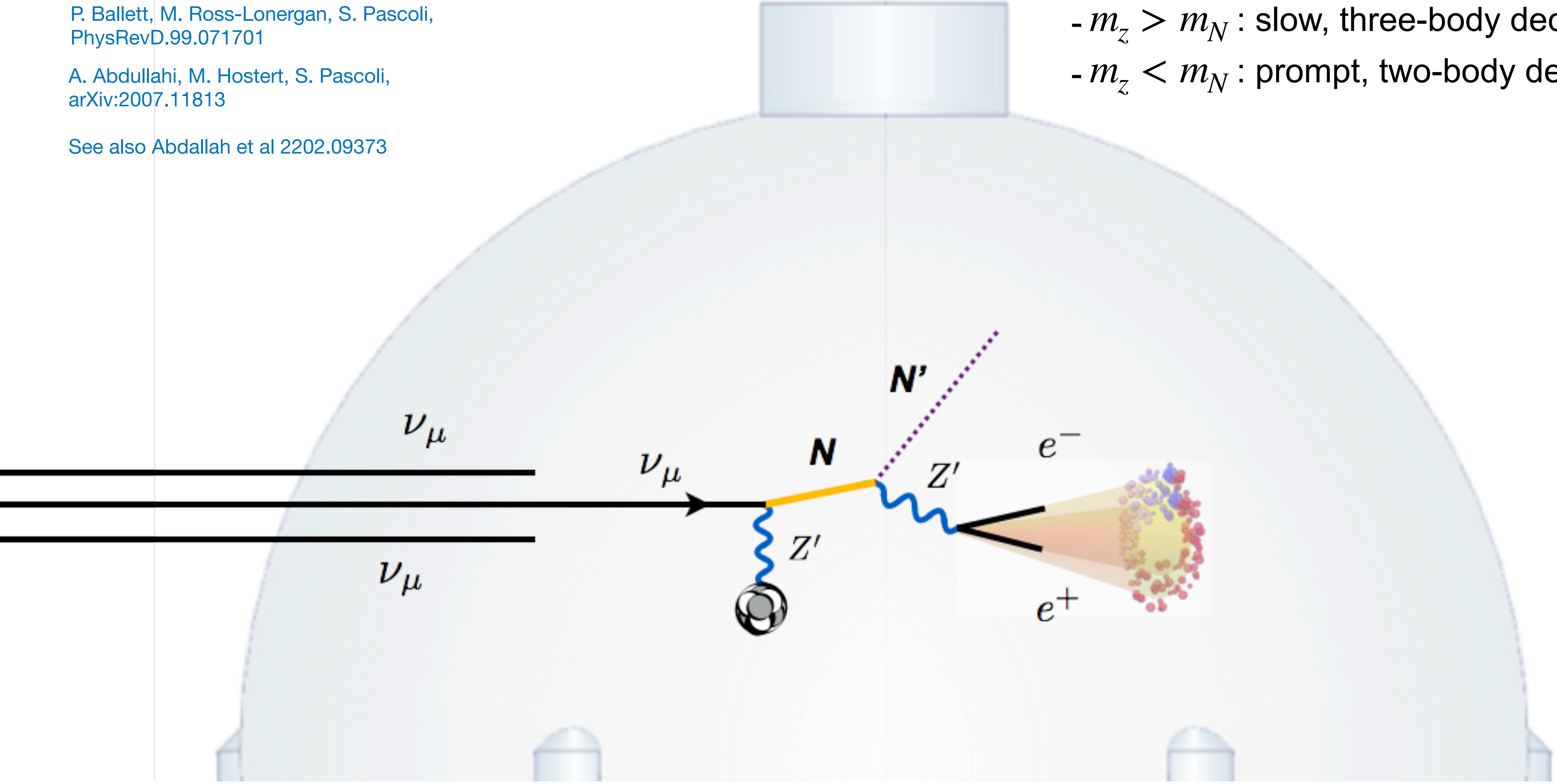
P. Ballett, M. Ross-Lonergan, S. Pascoli, PhysRevD.99.071701

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

See also Abdallah et al 2202.09373

Two phenomenologically distinct scenarios:

- $m_z > m_N$: slow, three-body decays.
- $m_z < m_N$: prompt, two-body decays.



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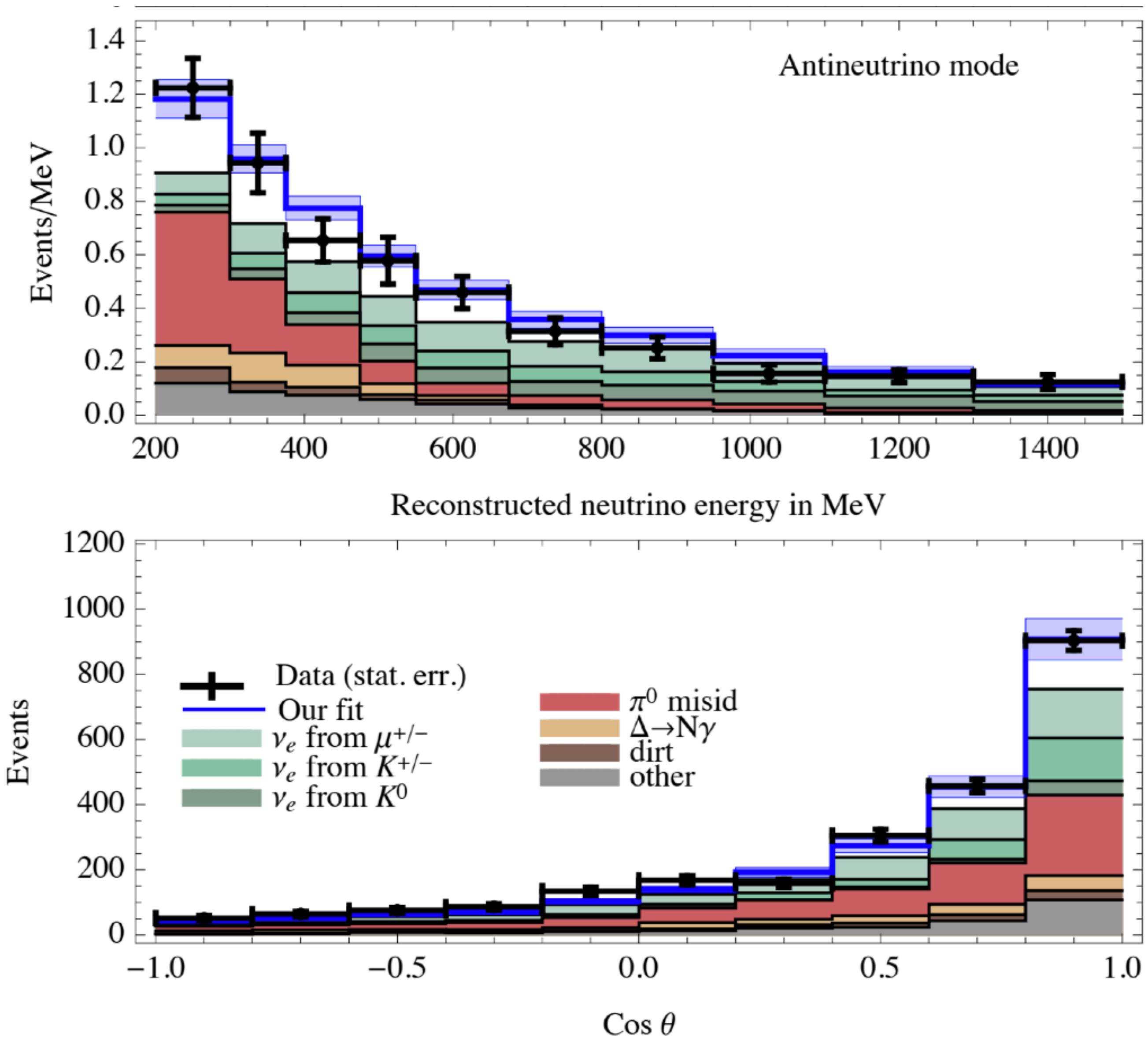
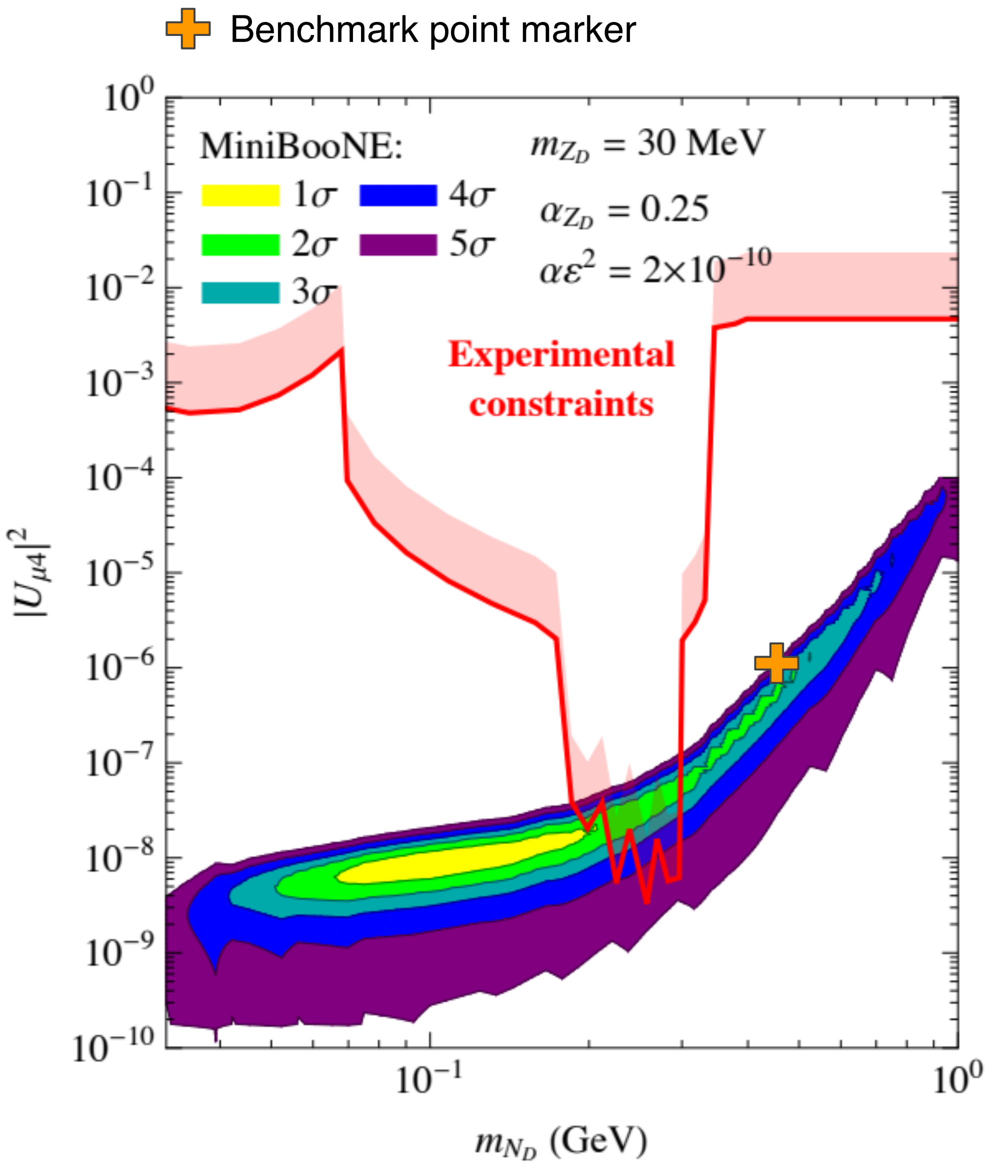
Idea 8: Dark Neutrino

E. Bertuzzo et al., PhysRevLett.121.241801

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

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



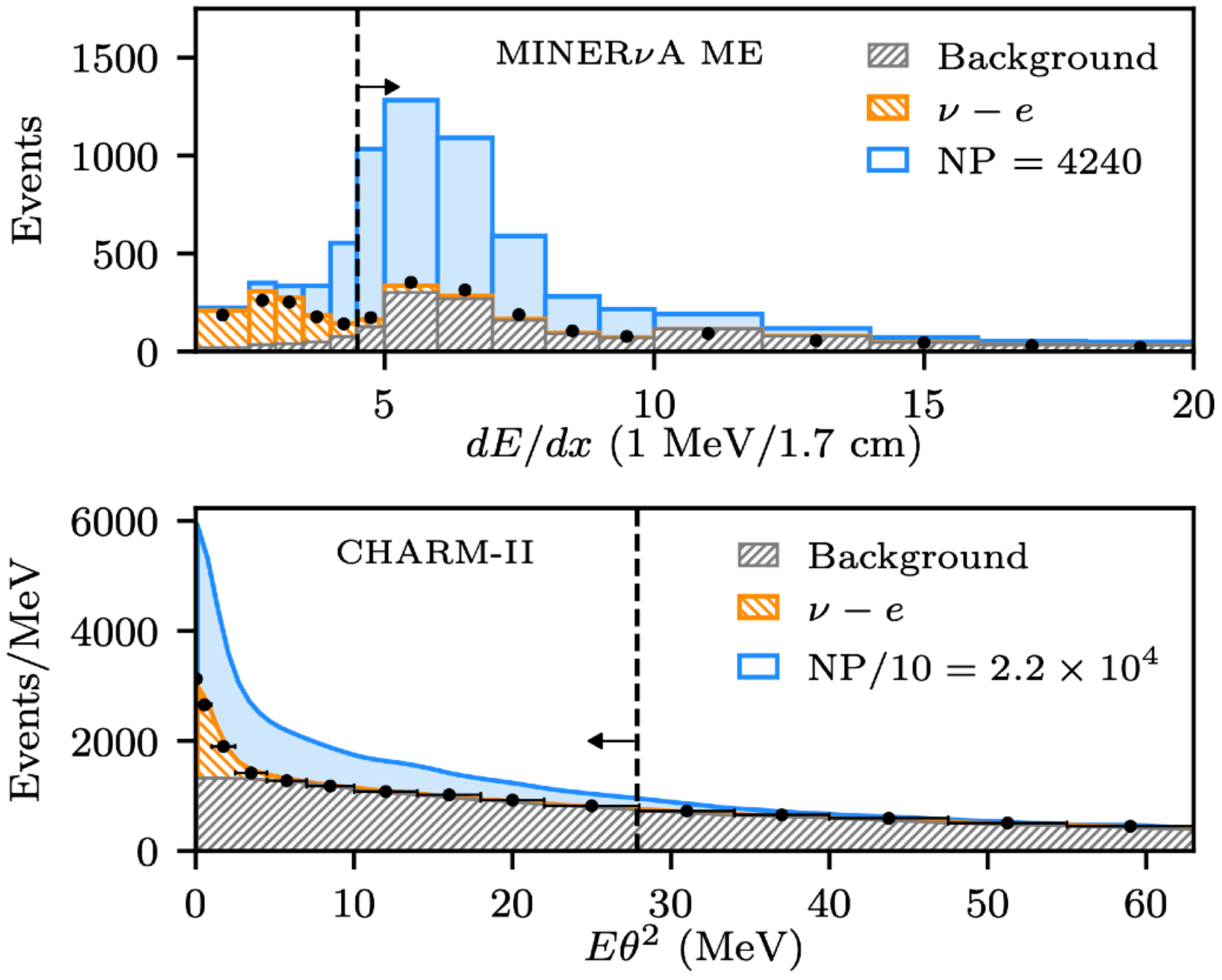


Good fit to the energy and angular distribution.

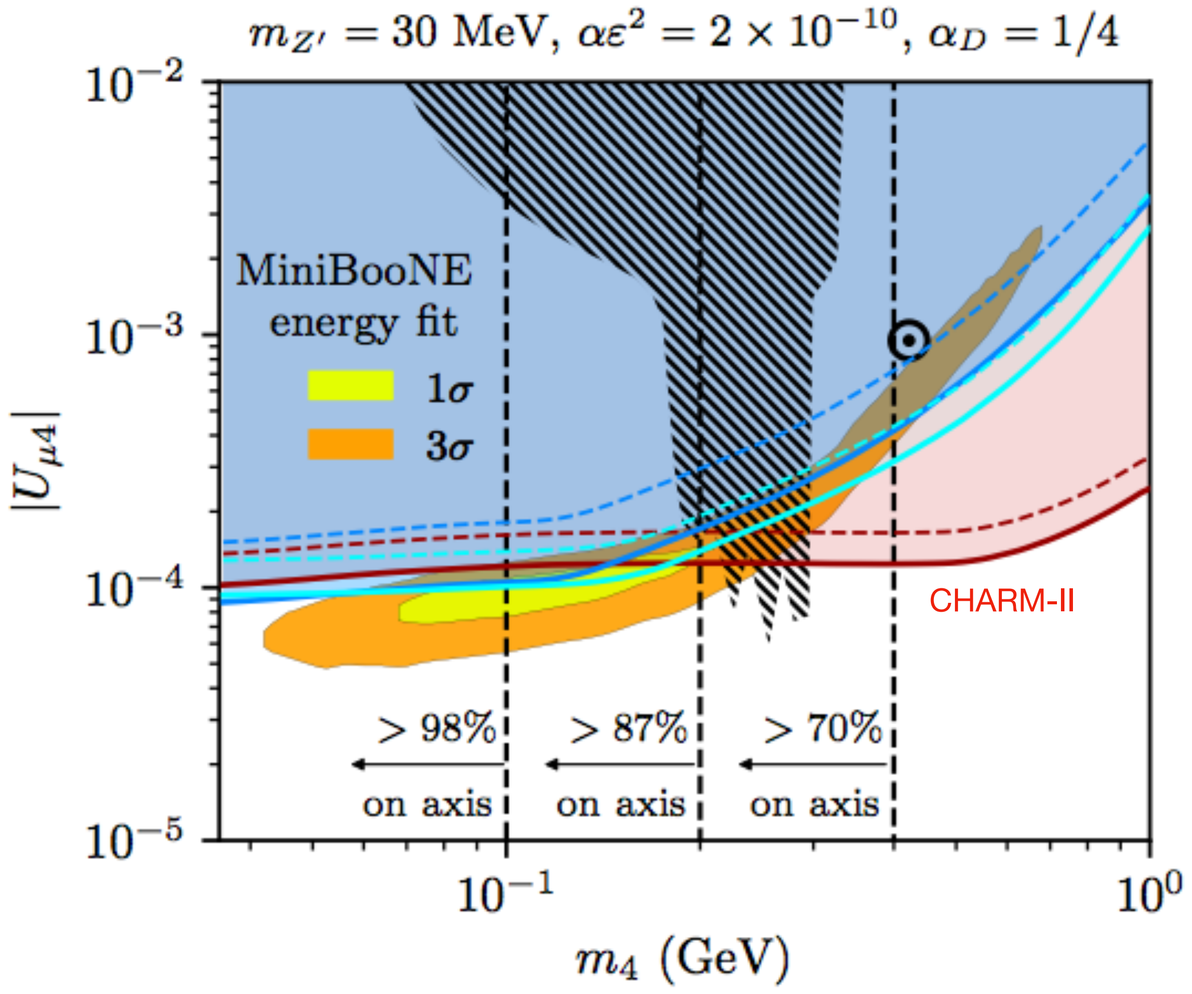
Dielectron

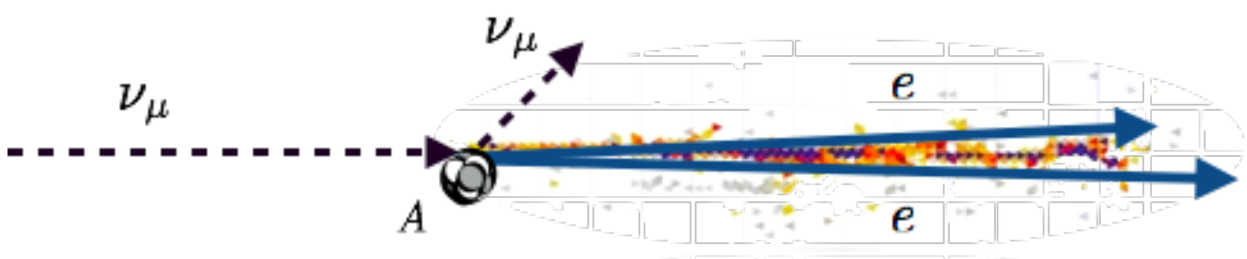
Idea 8: Dark Neutrino

This model can be constraint by Minerva electron-neutrino scattering data sets.



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





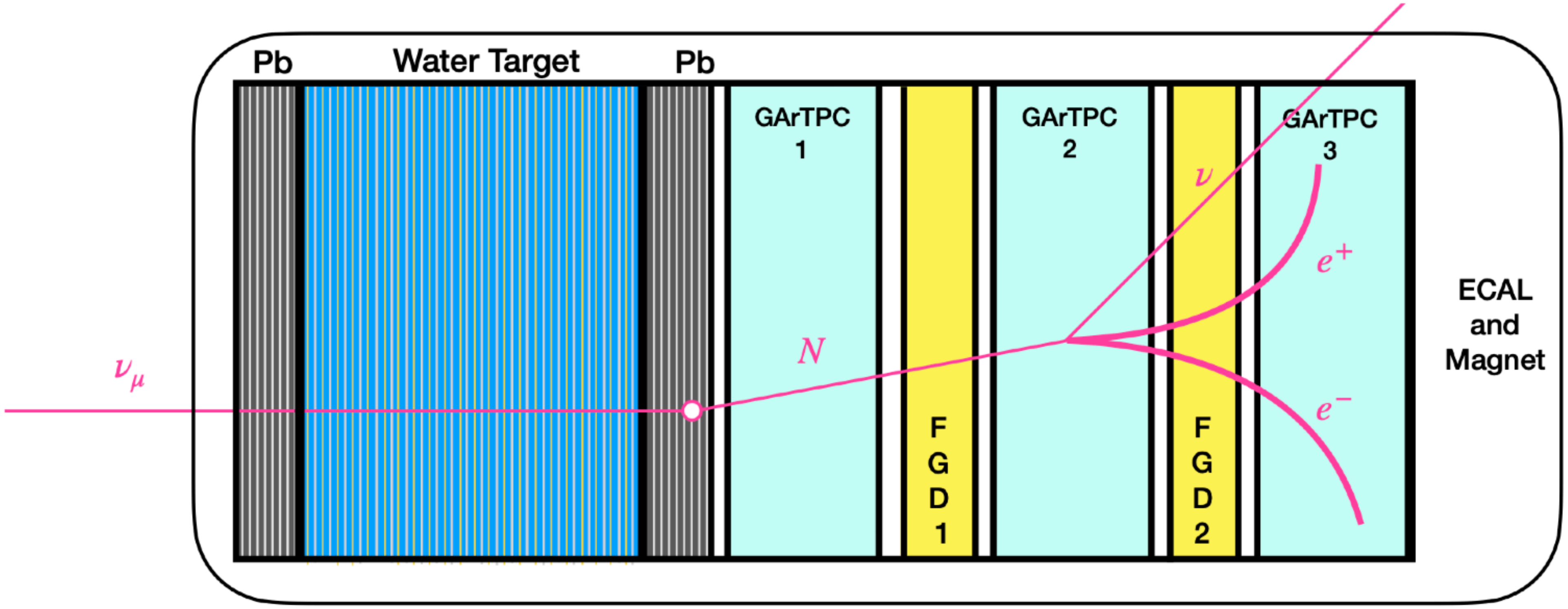
In tension with measurements of electron-neutrino scattering

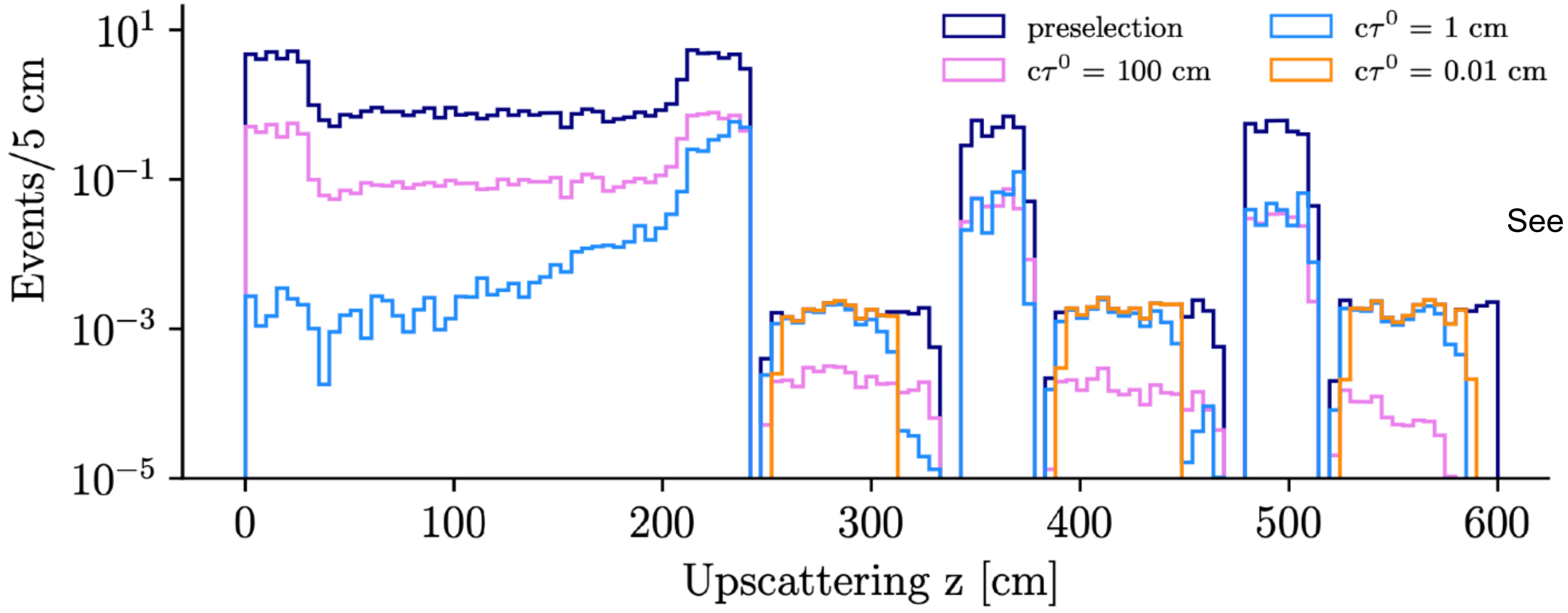
Dielectron

Idea 8: Dark Neutrino

CA, Foppiani, Hostert 2205.12273

Also constraints from T2K ND280 HNL search





See poster by N. Foppiani (P0244)

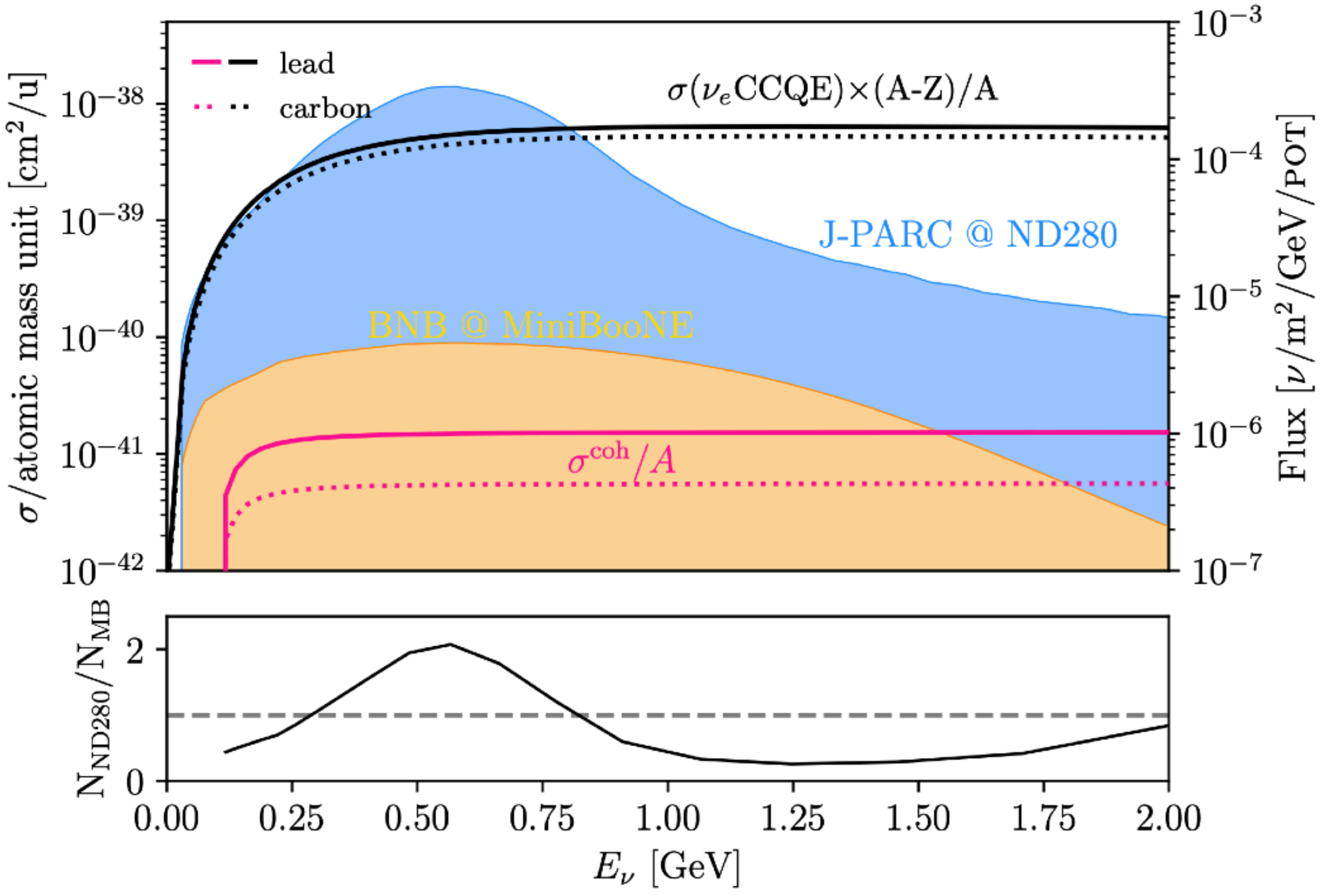
Dielectron

Idea 8: Dark Neutrino

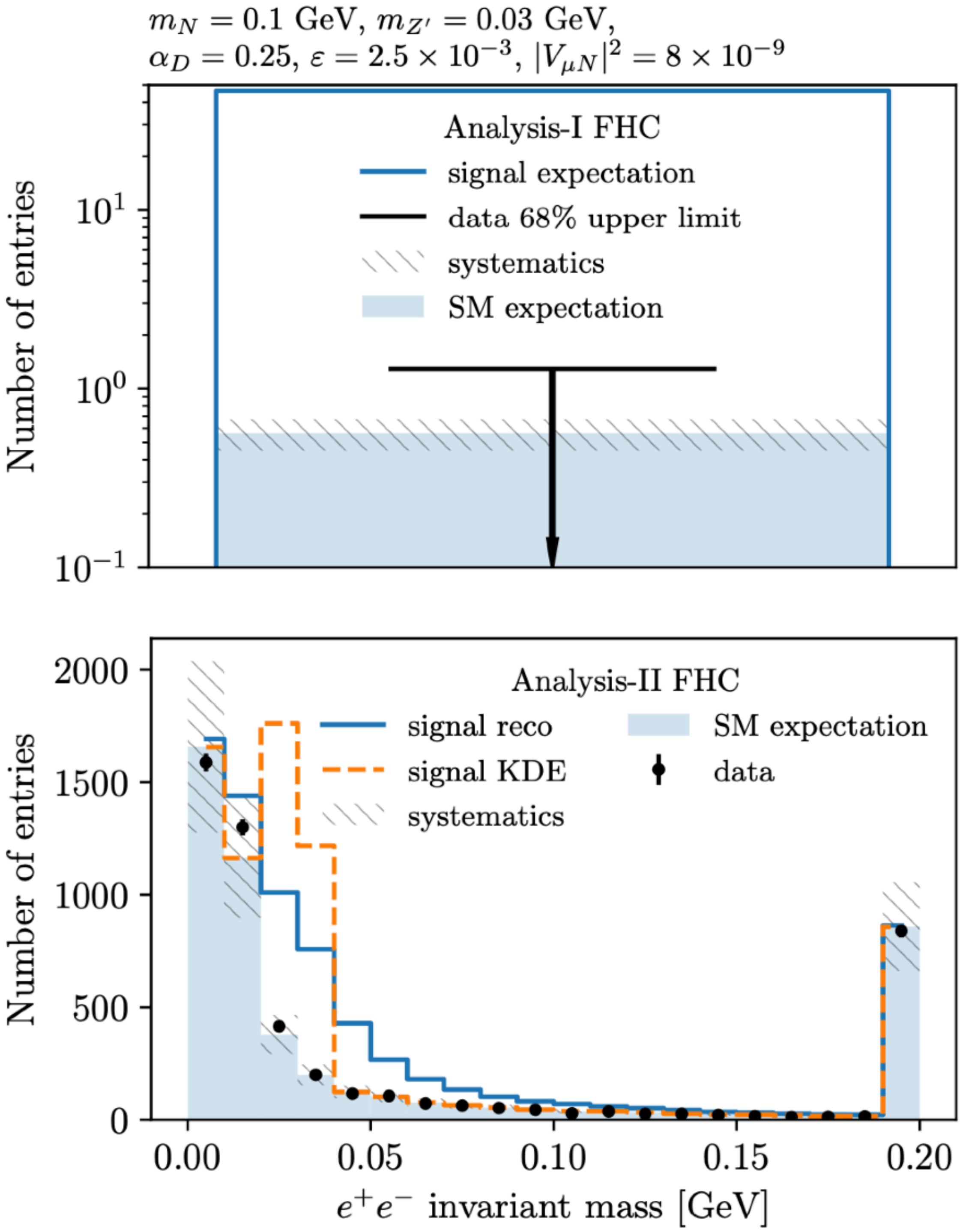
Also constraints from T2K ND280 HNL search

CA, Foppiani, Hostert 2205.12273

T2K ND280 detector is smaller, but flux at T2K
Is much more intense than at MB. Rates event out.



See poster by N. Foppiani (P0244)



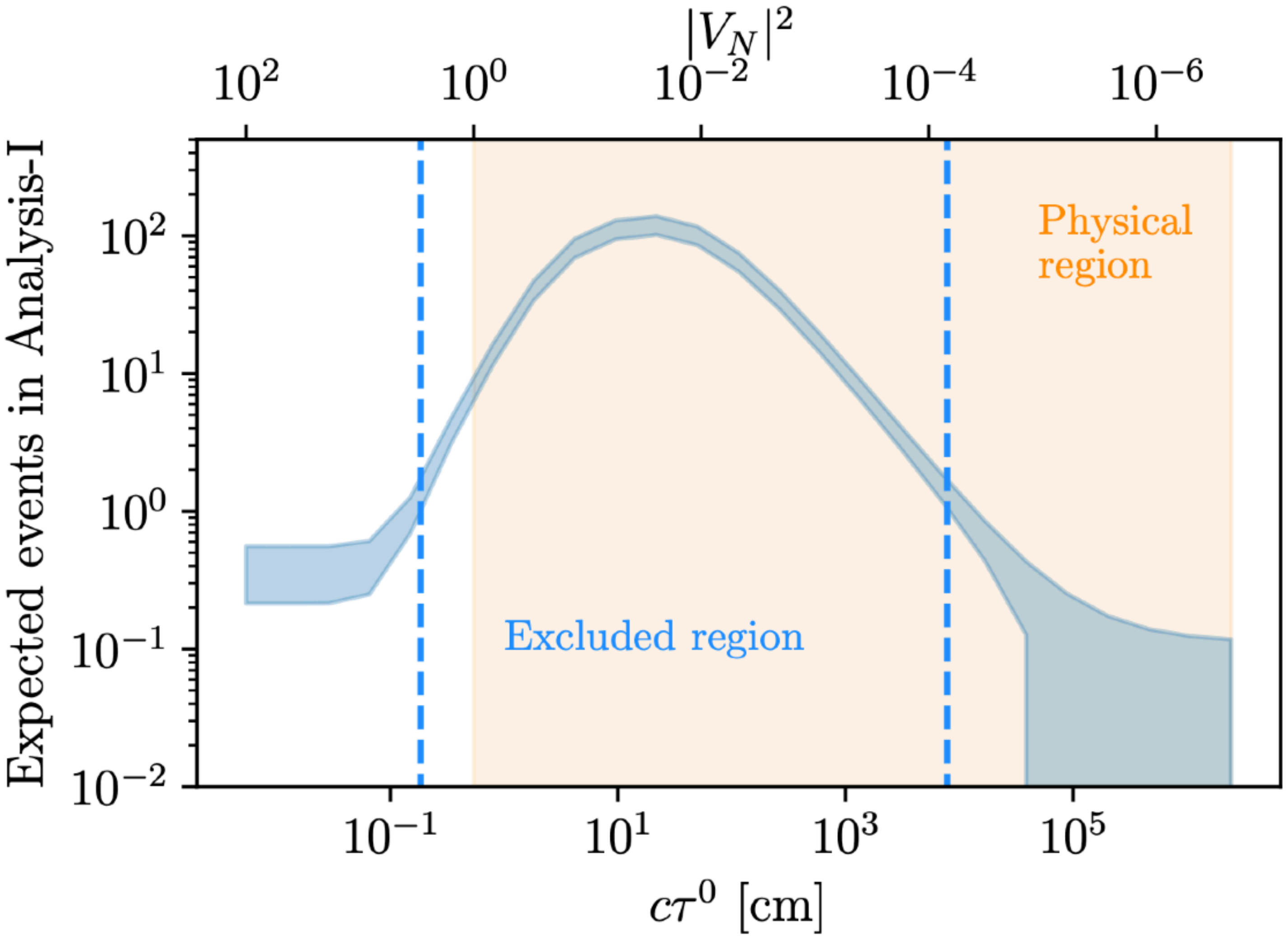
Dielectron

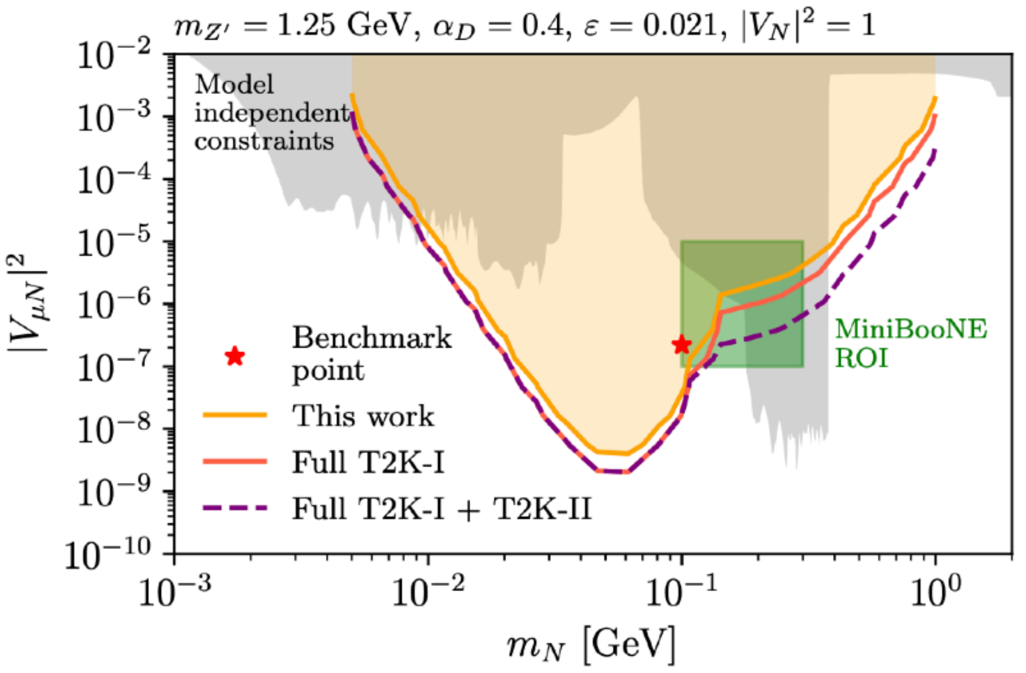
Idea 8: Dark Neutrino

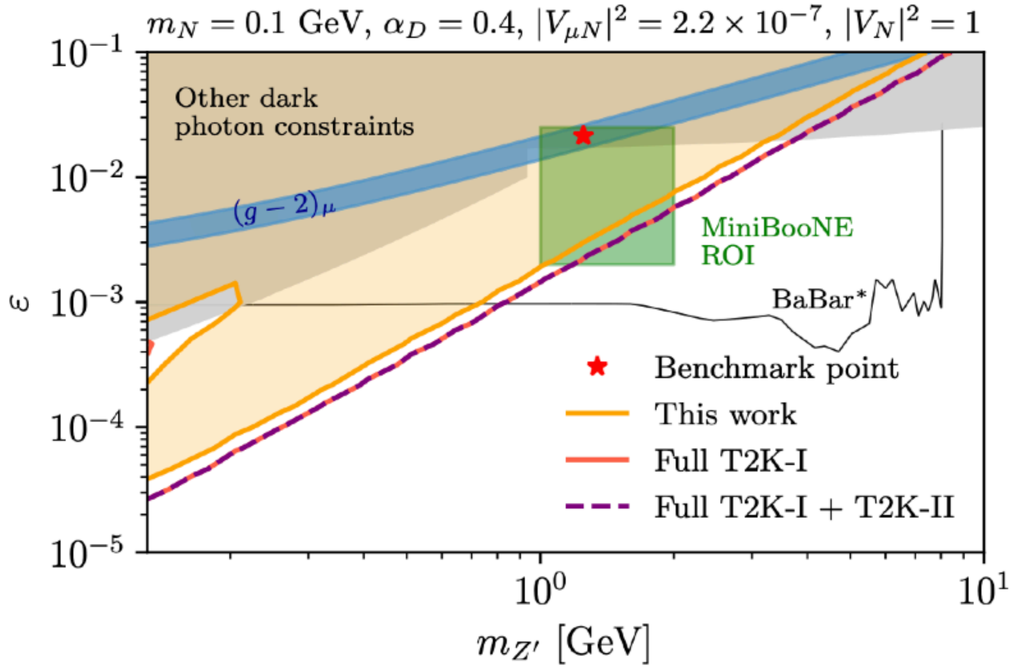
Constraints from T2K are powerful when the mediator is heavier, in the light case dominated by Minerva bounds.

CA, Foppiani, Hostert 2205.12273

See poster by N. Foppiani (P0244)







Dedicated T2K analysis should significantly improve these constraints.

Outline

- Why go beyond vanilla sterile neutrinos?
- The garden of forking paths
- Non-vanilla sterile neutrinos
- Other explanations of MiniBoonE:
    - Single electron
    - Single photon
    - Di-electron
- Future

The MiniBooNE Lens

Single photon

Single electron

Di-electron

(3+1) + vis. decay

Dark sectors w/ pseudo -scalar

3+1 oscillations

Dark sectors w/ dark matter

Large Extra Dim

Neutrino dipole portal

(3+1) + inv-ν decay

Dark neutrinos

(3+1) + vis-ν decay

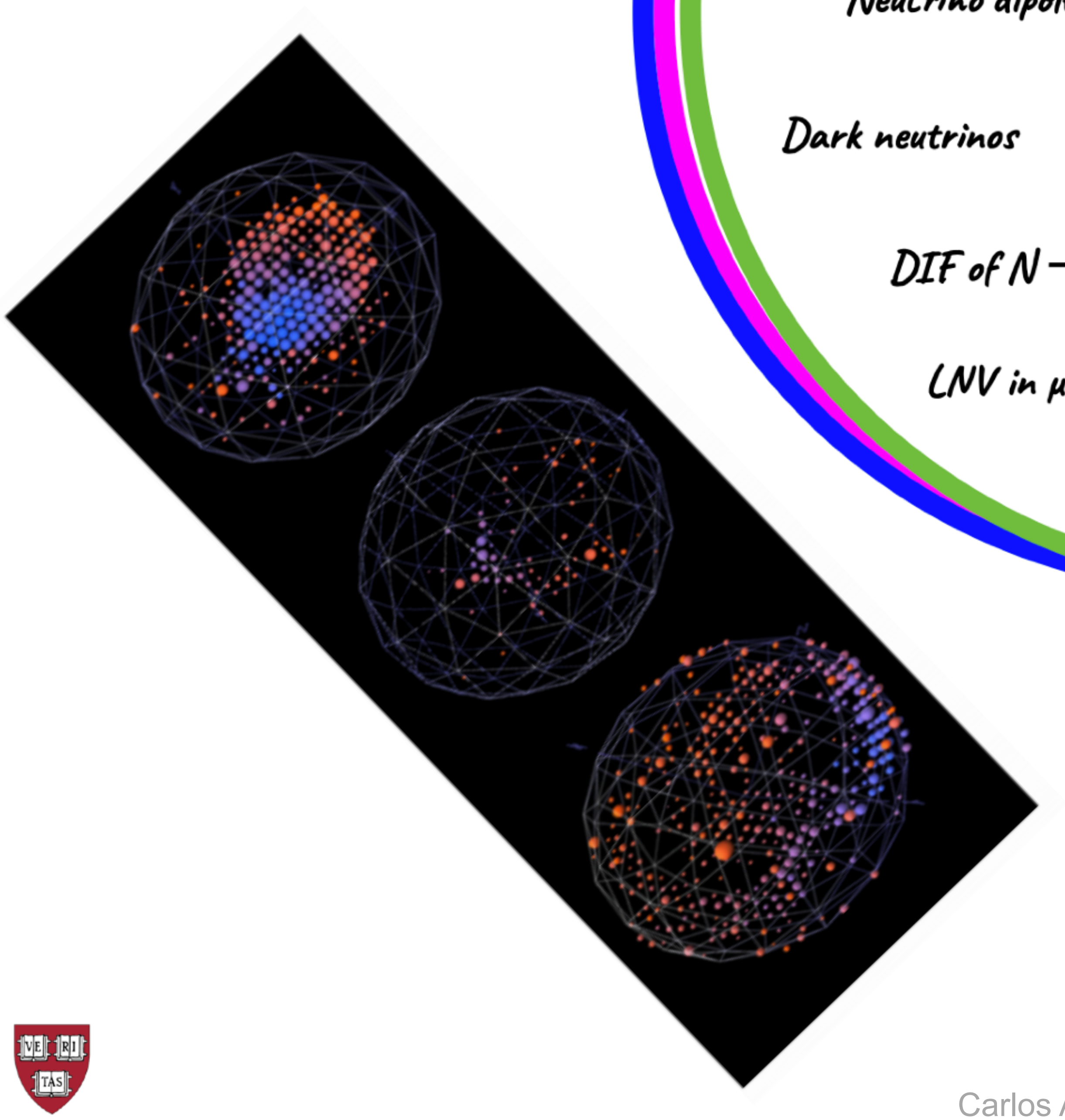
Lorentz Violation

DIF of $N \rightarrow \nu\gamma$

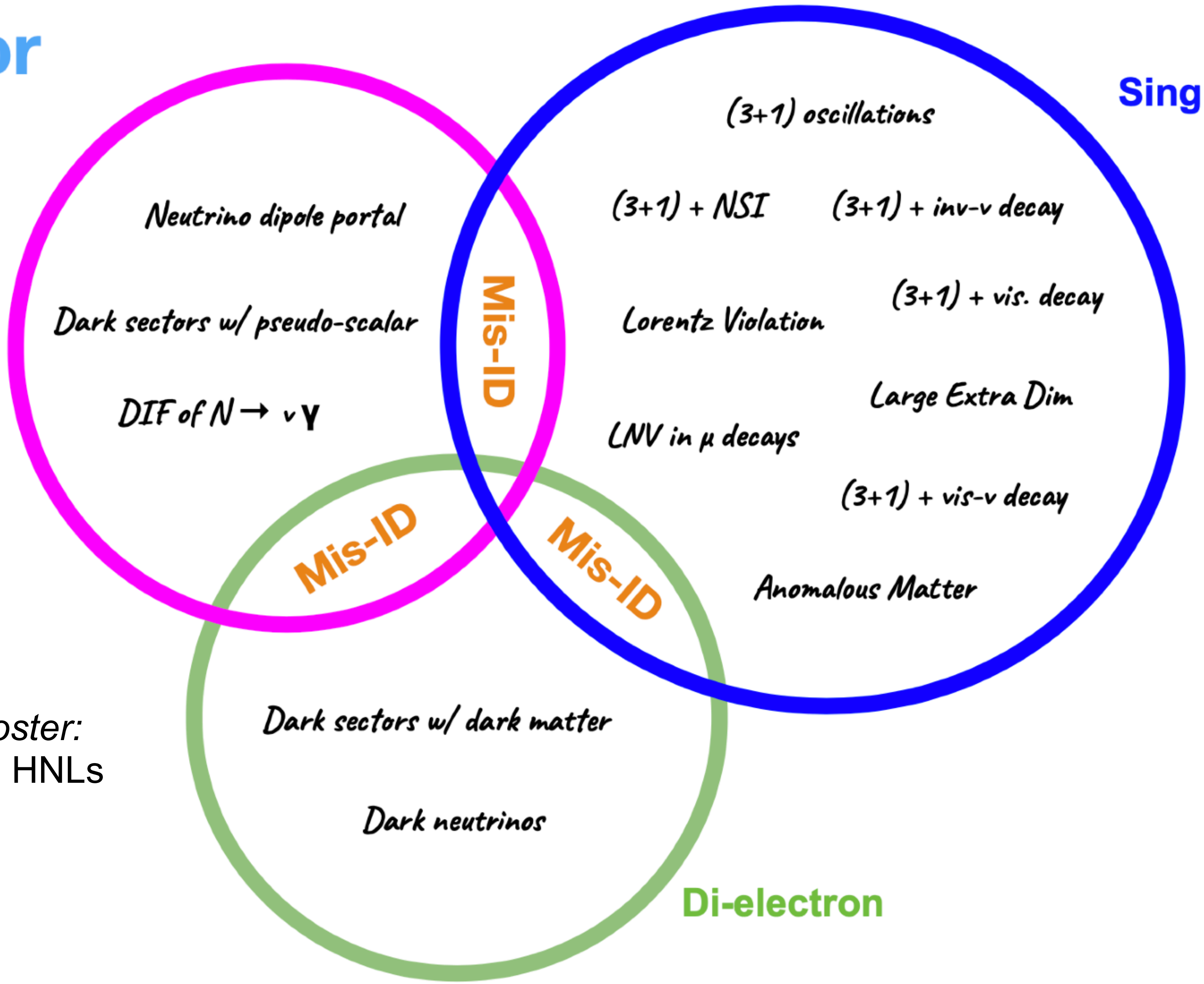
Anomalous Matter

LNV in μ decays

(3+1) + NSI



SBN Tricolor Lens



Single photon

Single electron

Di-electron

Neutrino dipole portal

Dark sectors w/ pseudo-scalar

DIF of $N \rightarrow \nu\gamma$

Mis-ID

Mis-ID

Mis-ID

(3+1) oscillations

(3+1) + NSI

(3+1) + inv-ν decay

Lorentz Violation

(3+1) + vis. decay

Large Extra Dim

LNV in μ decays

(3+1) + vis-ν decay

Anomalous Matter

Dark sectors w/ dark matter

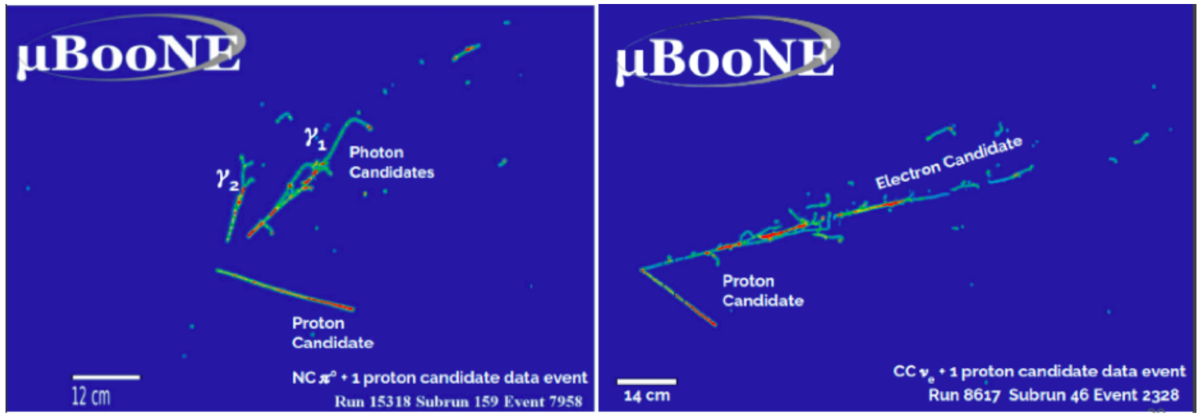
Dark neutrinos

Check out IceCube poster:

- Julia Book P0047 on HNLs

Check out MicroBooNE posters:

- Erin Yandel P0722
- Lee Hagaman P0764
- Guanqun Ge P0765
- Mark Ross-Longerman P0767
- Asli Abdullahi P0615



Take home message

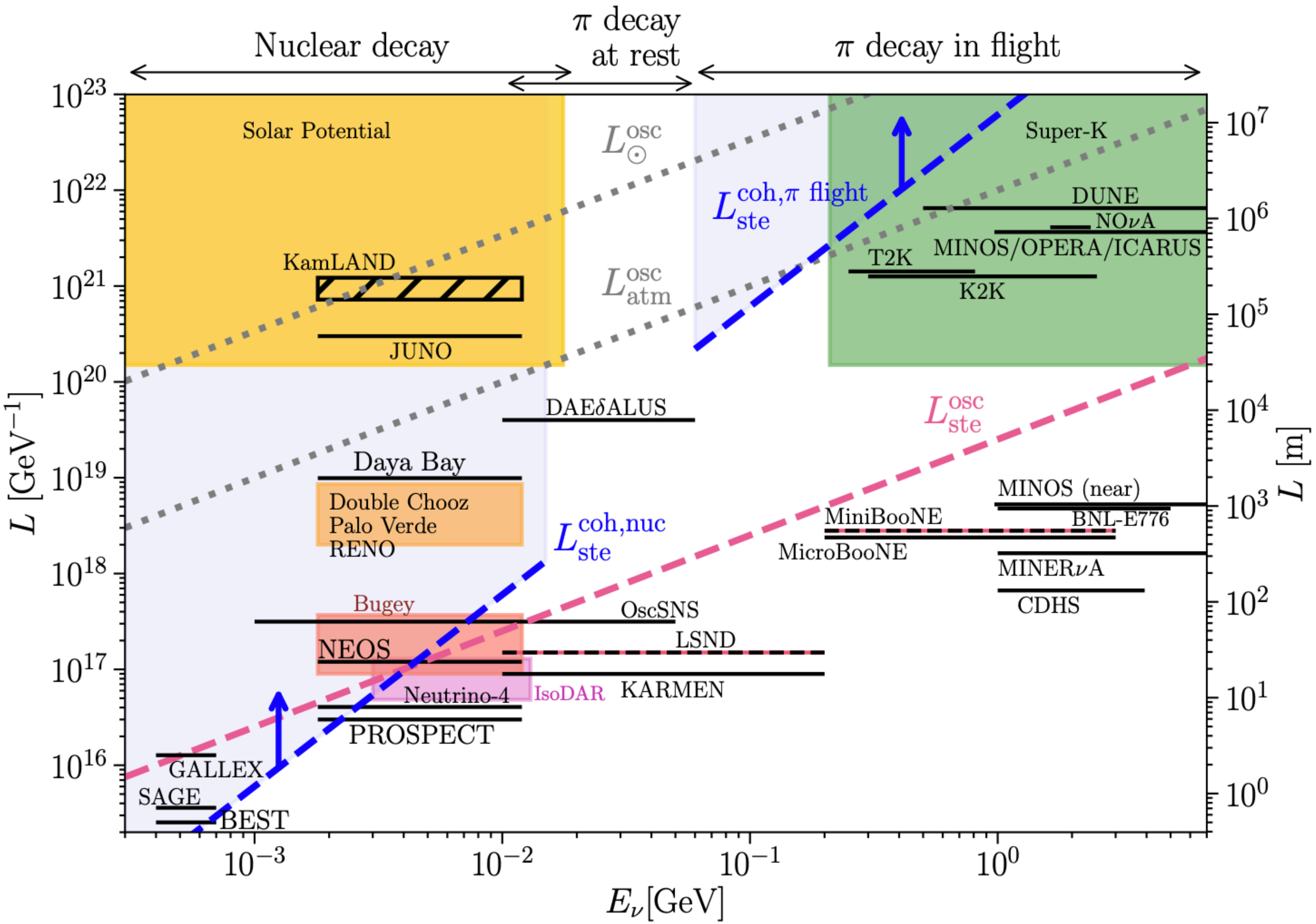
- ❖The short-baseline anomalies are an unresolved puzzled in neutrino physics
- ❖Need to keep doing oscillation searches for 3+1+other scenarios in electron-neutrino and muon-neutrino .
- ❖Minerva and T2K offer already important constraints on new models. Gas Argon TPC of T2K specially useful.
- ❖Upcoming results from MicroBooNE, ICARUS, and others will help constraint these models.
- ❖Current constraints only by phenomenologist. Need experiments to do these analyses!
- ❖Need to think how all of these models would fit in the greater picture and cosmology.


May your physics be BSM!

Thank you!

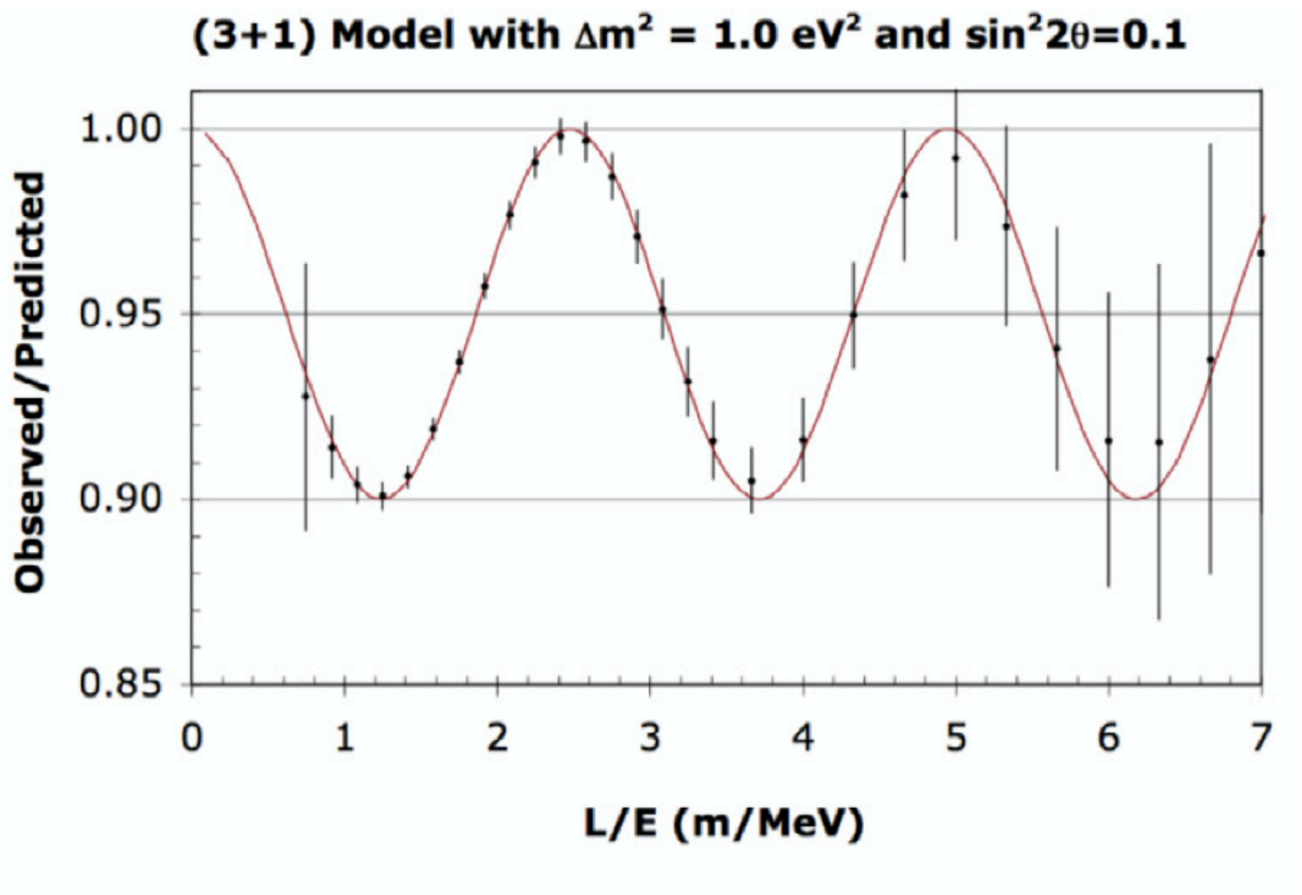
Bonus slides

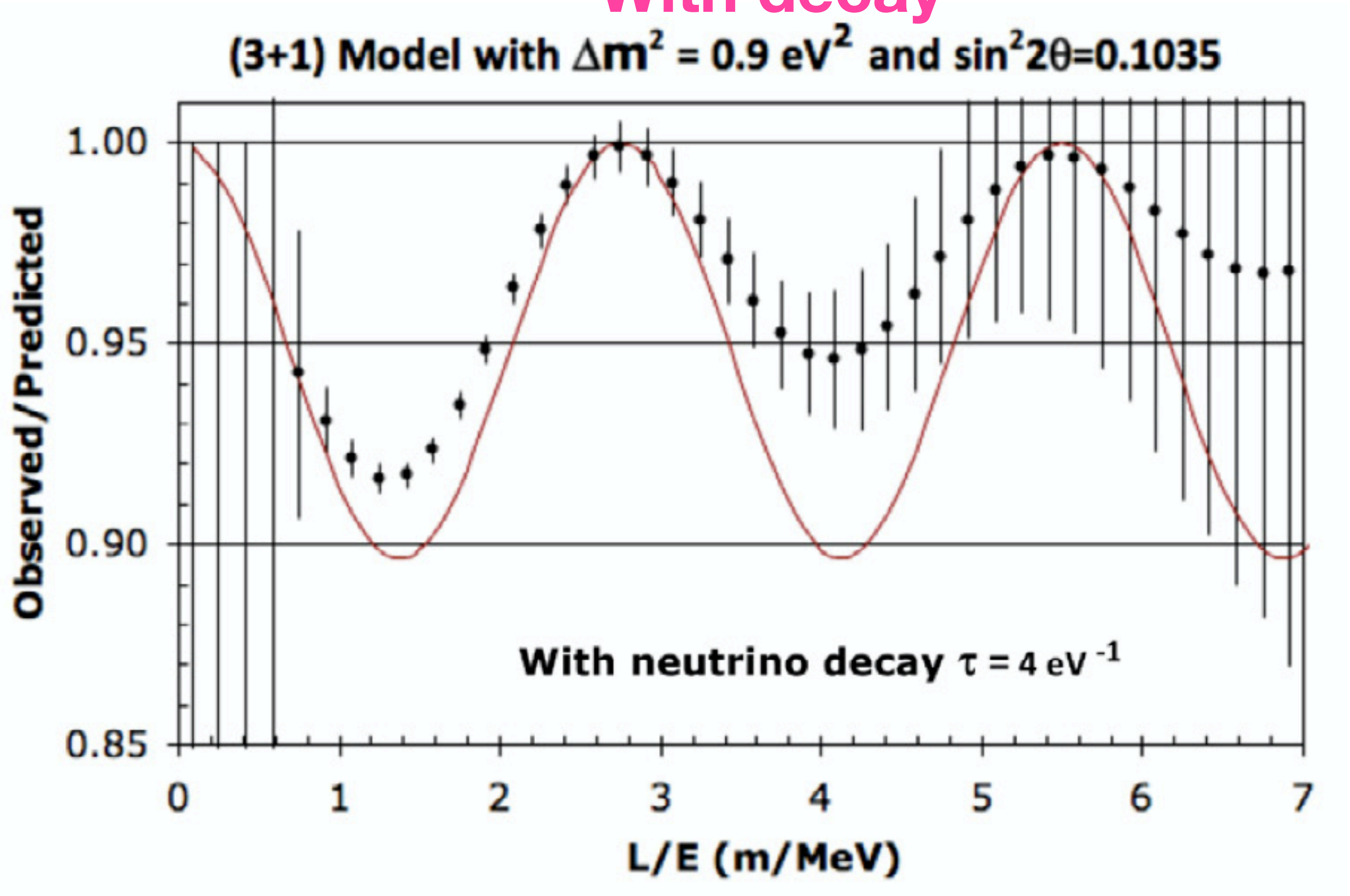
Where does it matter?



IsoDAR@Yemilab

No decay **With decay**





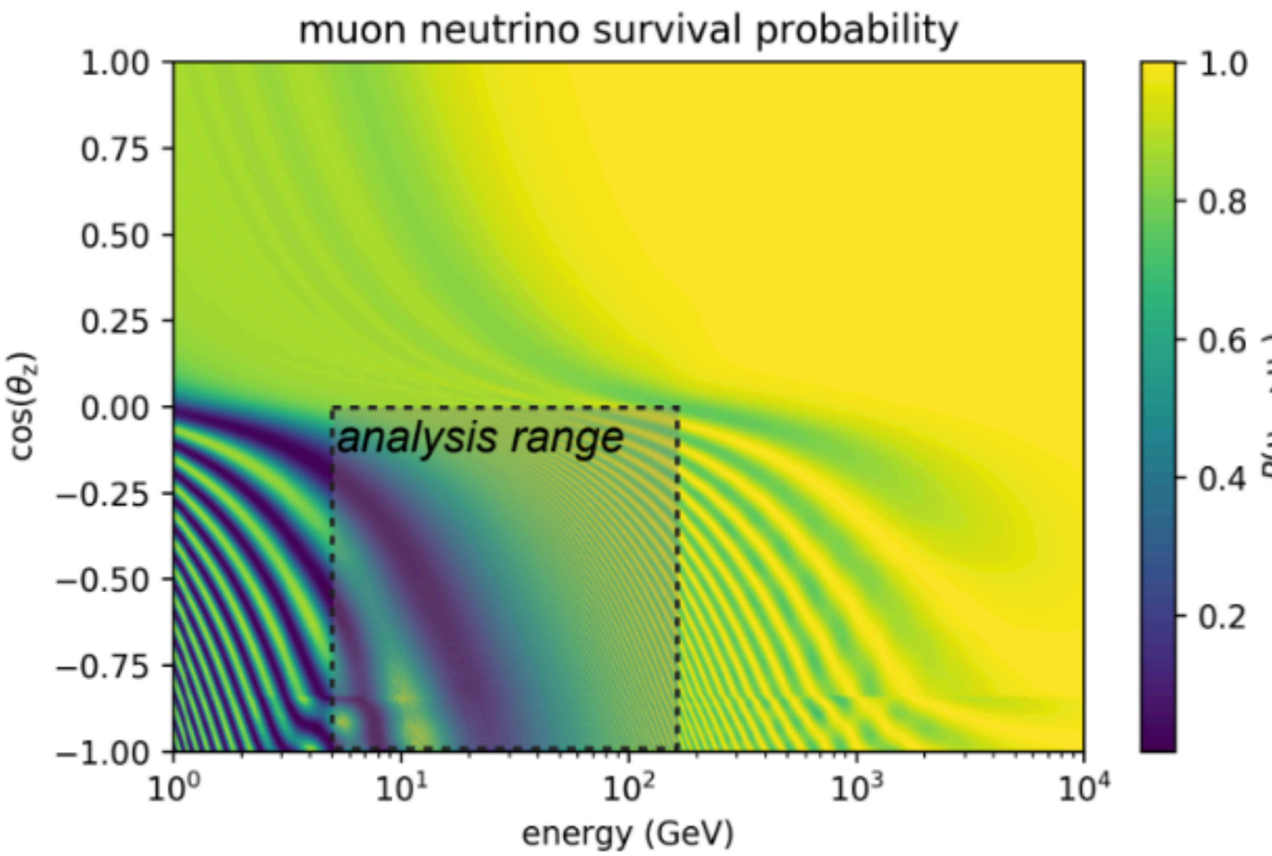
IsoDAR with O(1M) events

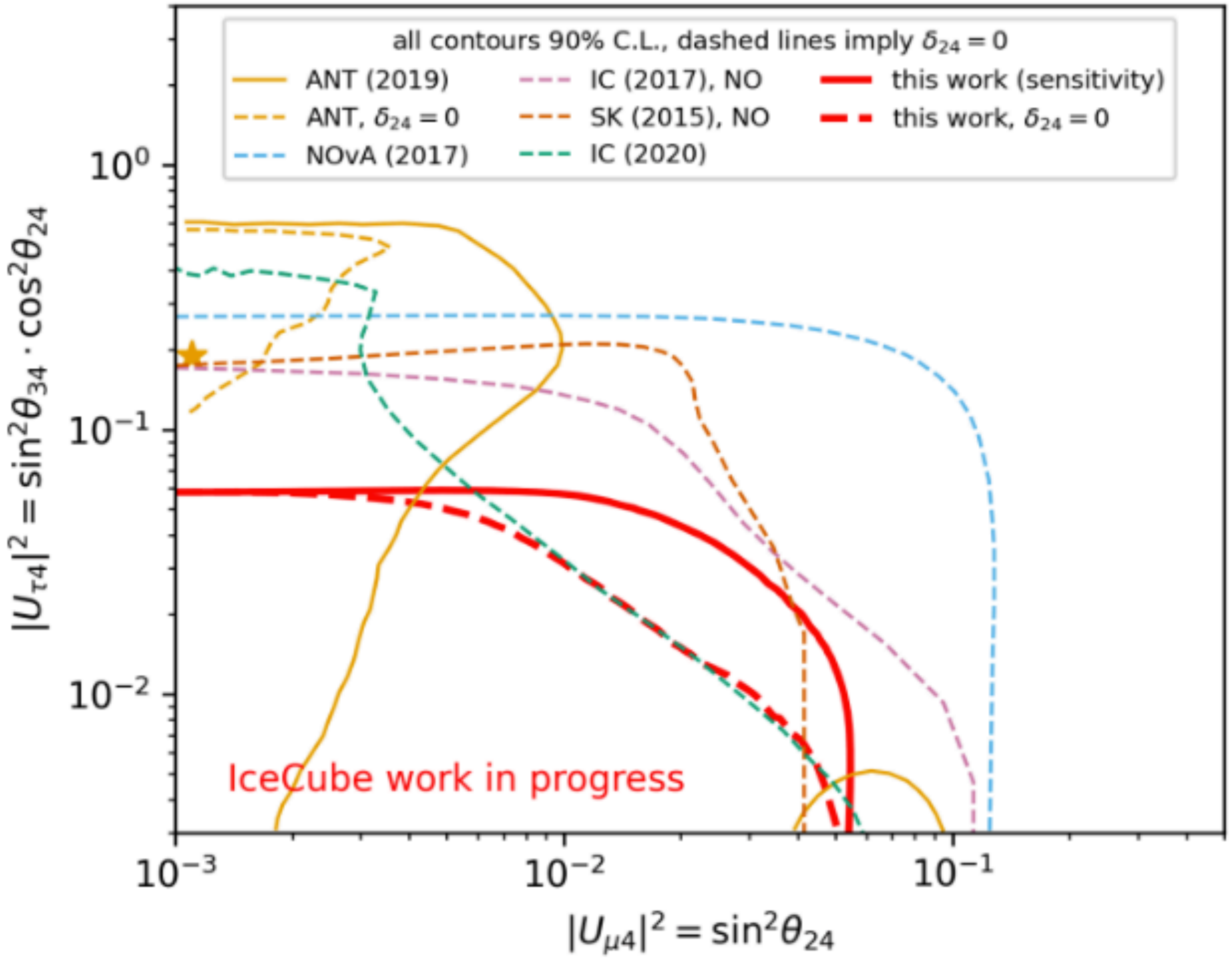
IsoDAR@Yemilab will conclusively rule out the 3+1 model, but also due to its ability to trace the oscillation wave see variants on this model such as 3+1+Decay

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

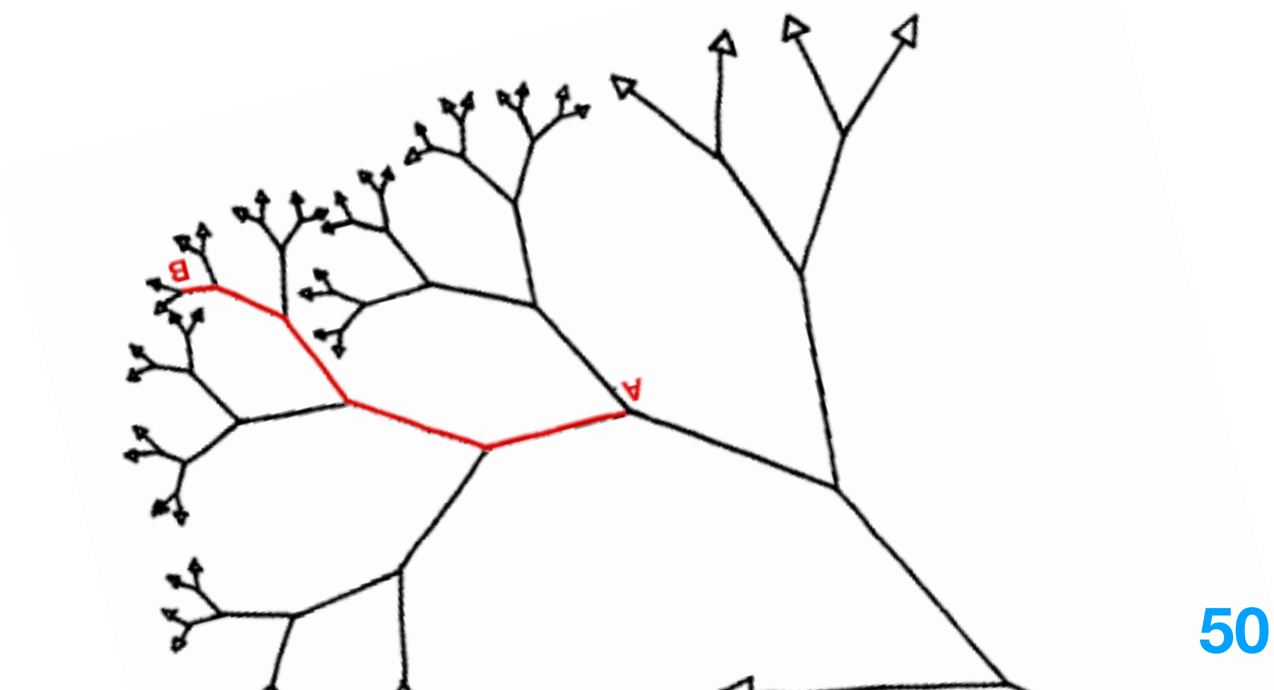
Assadi et al 1712.08019
Resonant matter effect

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

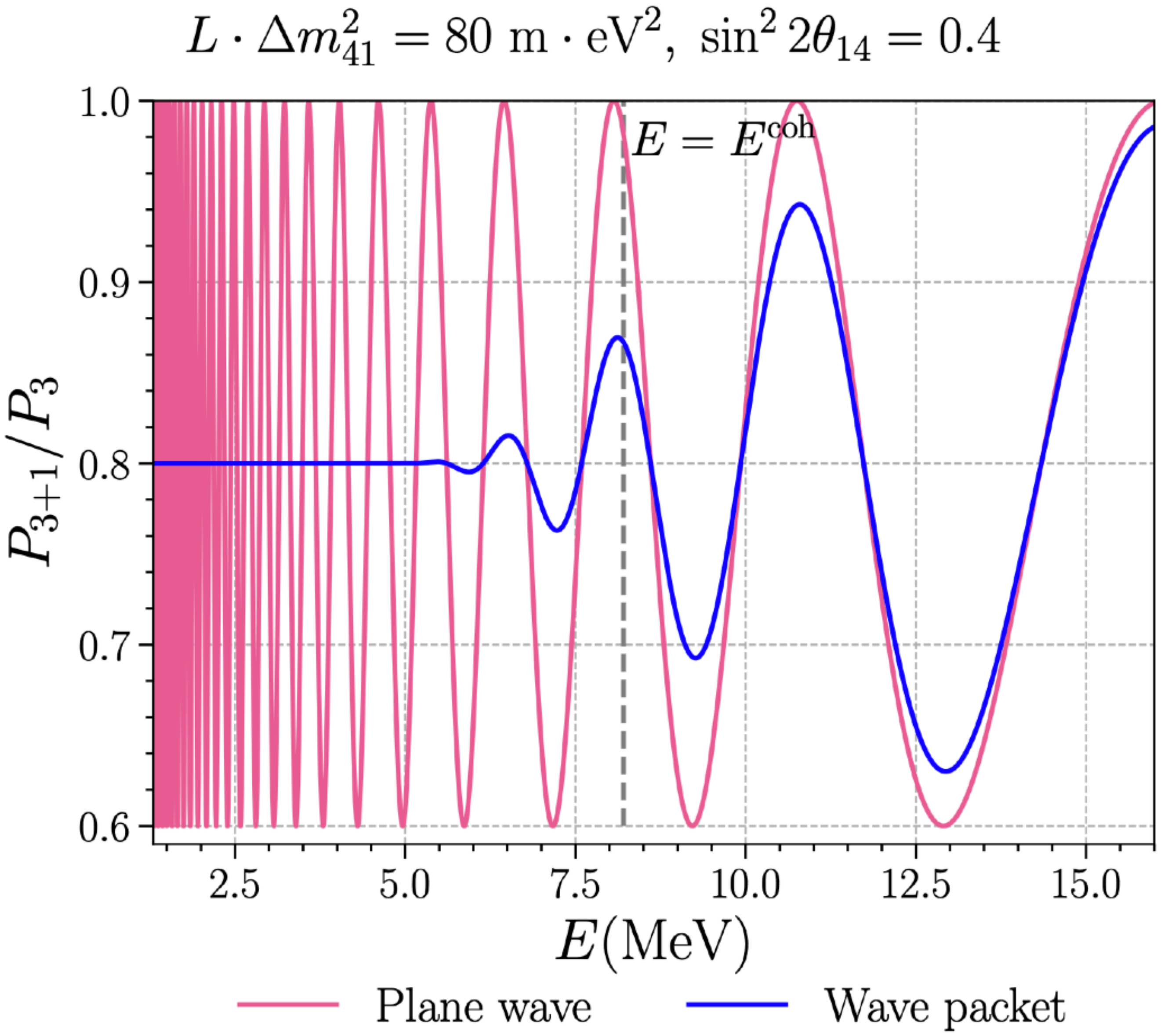
Liao et al 1810.01000
Steriles + NCNSI + CCNSI

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



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

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

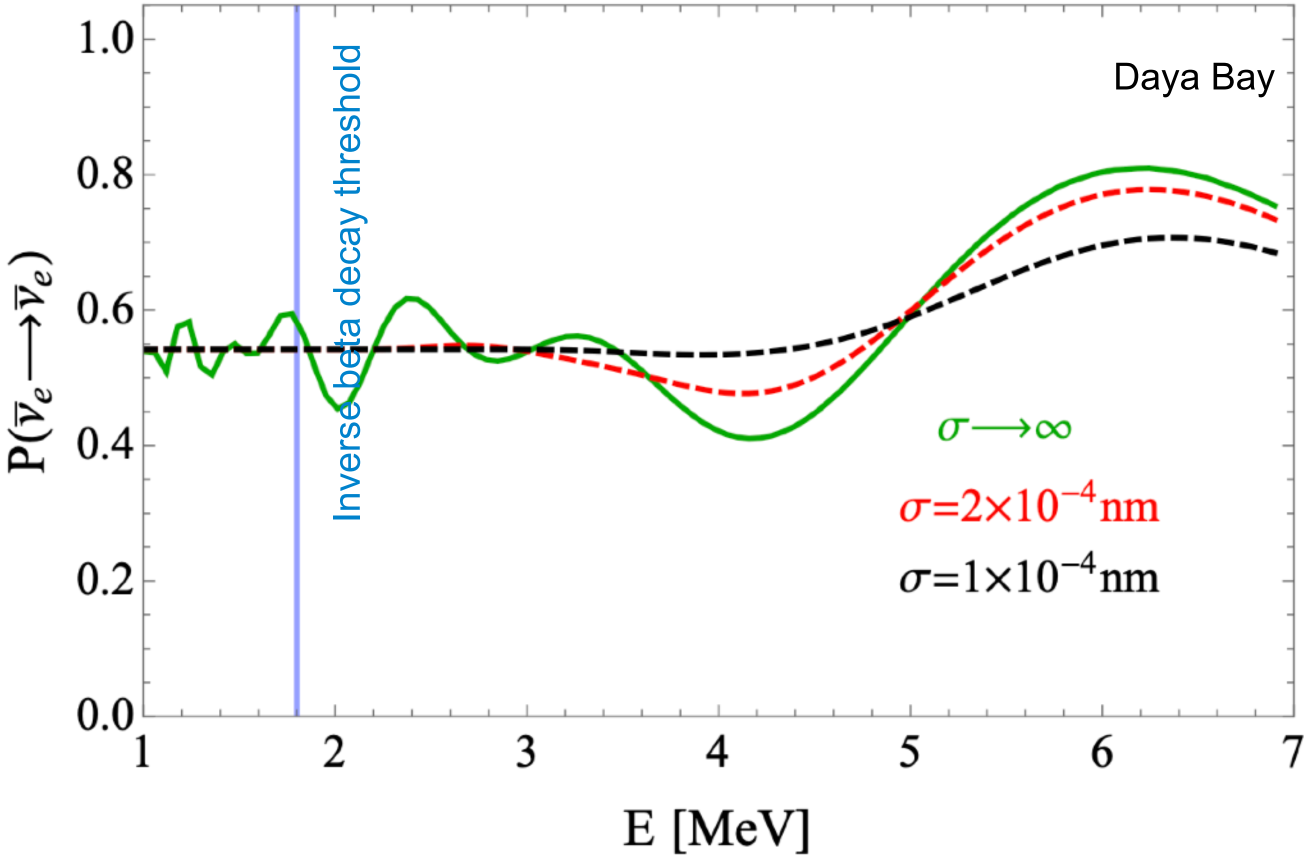
$$L^{ij}_{\mathrm{osc}} = \frac{4\pi E}{\Delta m^2_{ji}} \quad \text{and} \quad L^{ij}_{\mathrm{coh}} = \frac{4\sqrt{2}E^2\sigma_x}{\Delta m^2_{ji}}$$

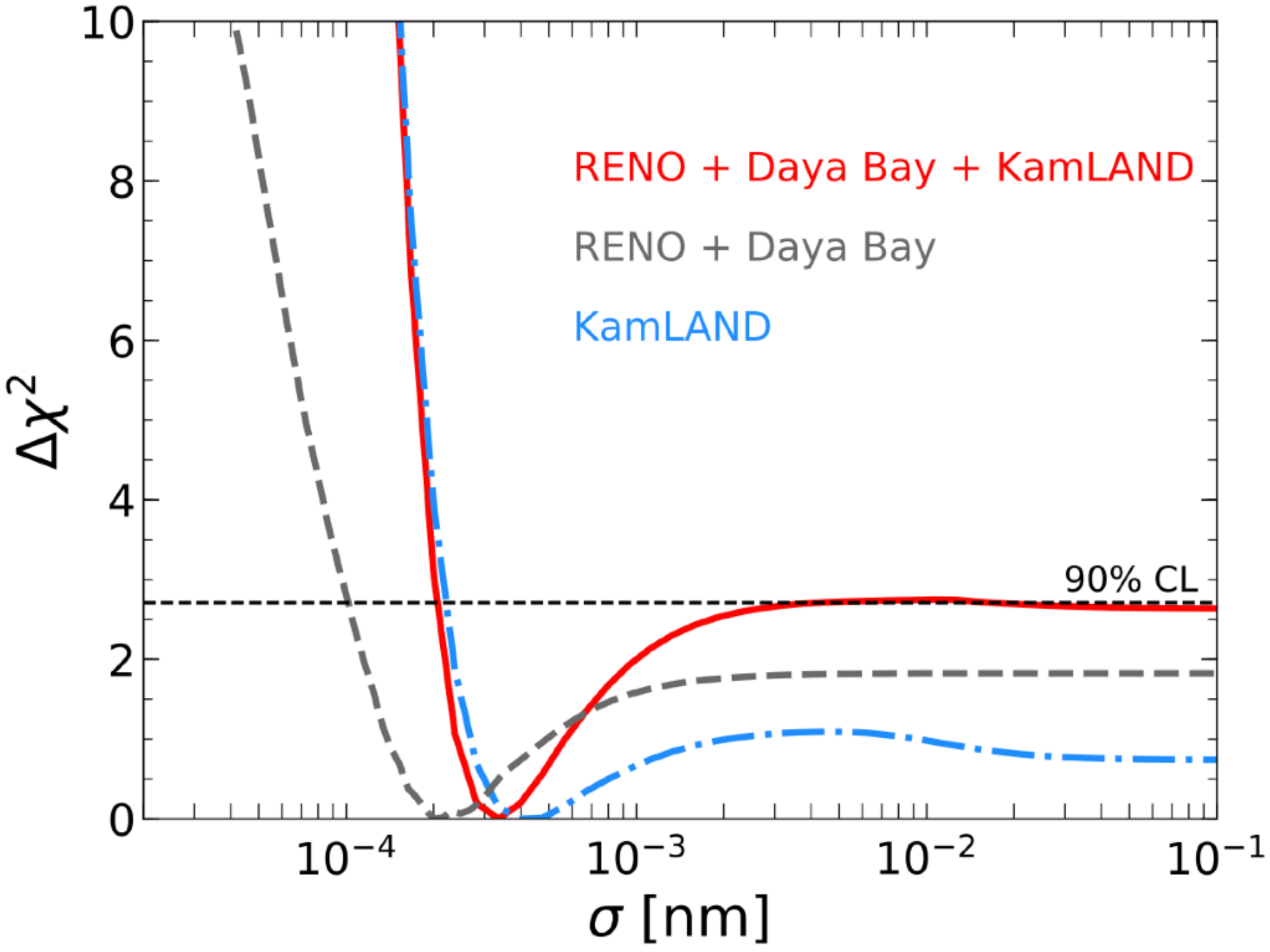
σ_x is the wave packet size

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

What is the size of the wave packet?

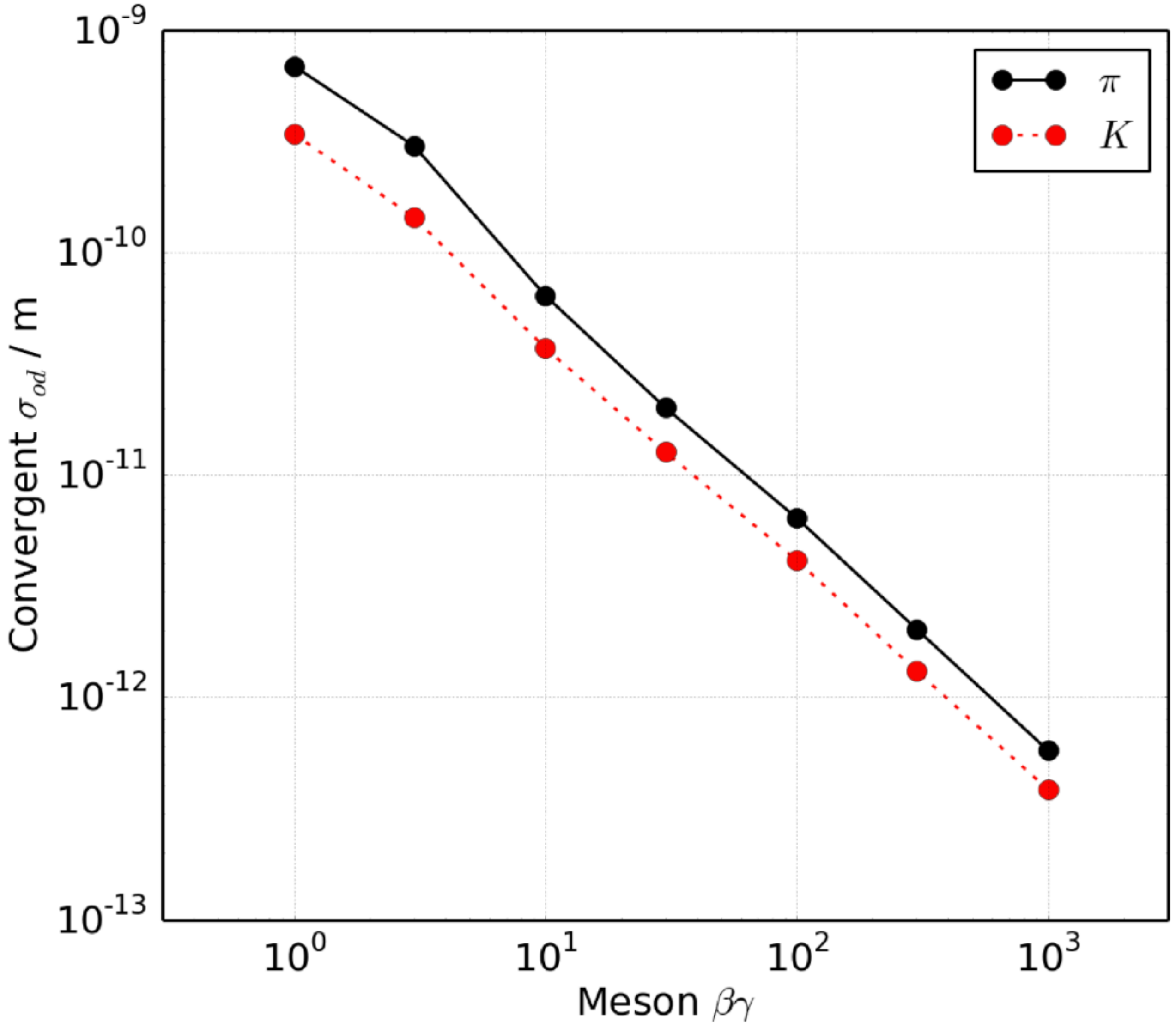
No detail calculation exists for neutrinos produced in reactors or radioactive sources. The following scales seem plausible:

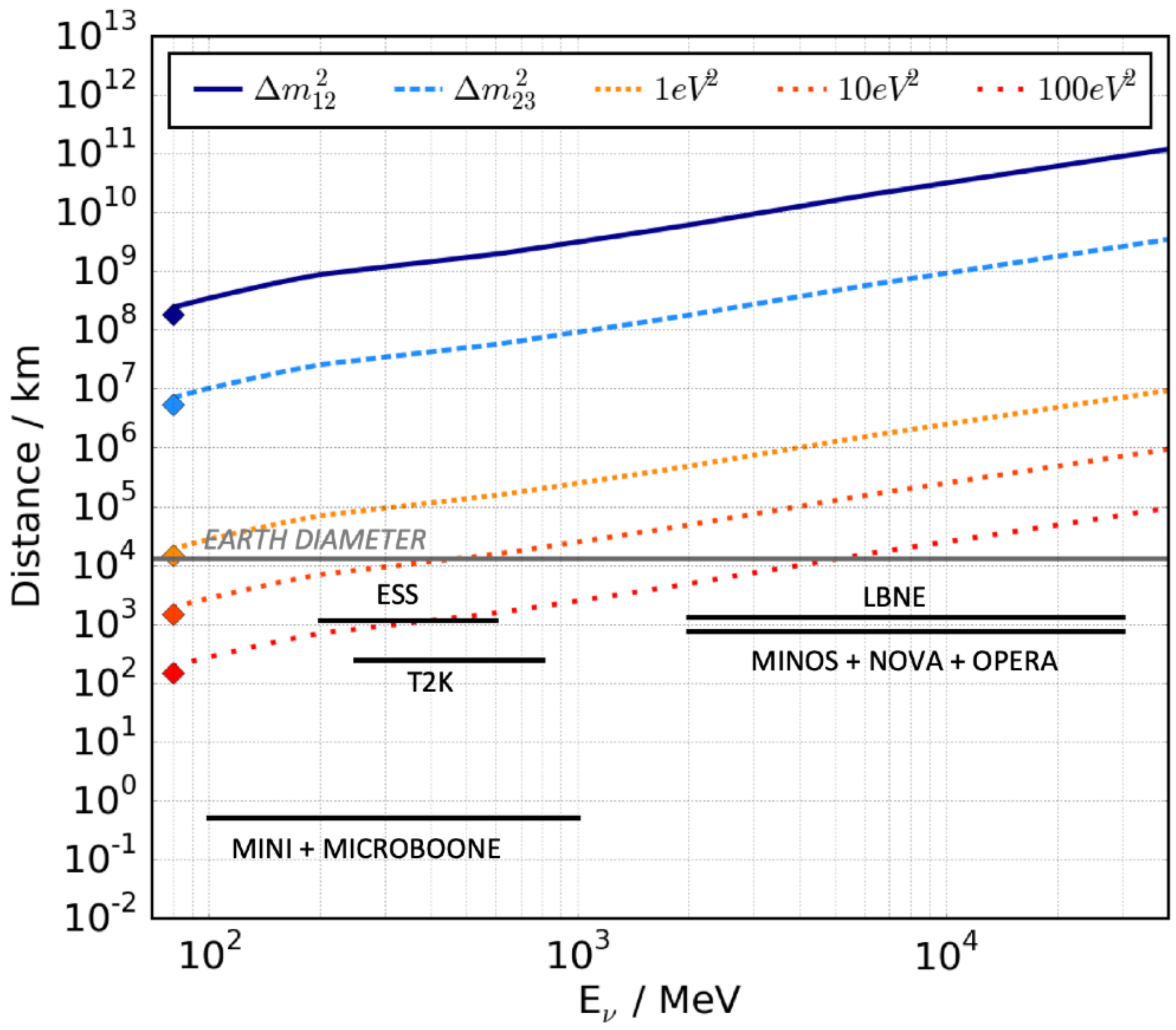
- Typical size of beta-decaying nuclei $(10^{-5}\mathrm{nm})$
- Interatomic spacing on reactor fuel $(0.1-1\mathrm{nm}$ for uranium)
- Inverse of the neutrino energy $(10^{-4}\mathrm{nm})$
- Inverse of detector energy resolution

The smaller the scale of the neutrino wave packet the larger the neutrino energy resolution effect.

What is the size of the wave packet?

Depends on production and detection process. This has been computed for pion decay in flight.

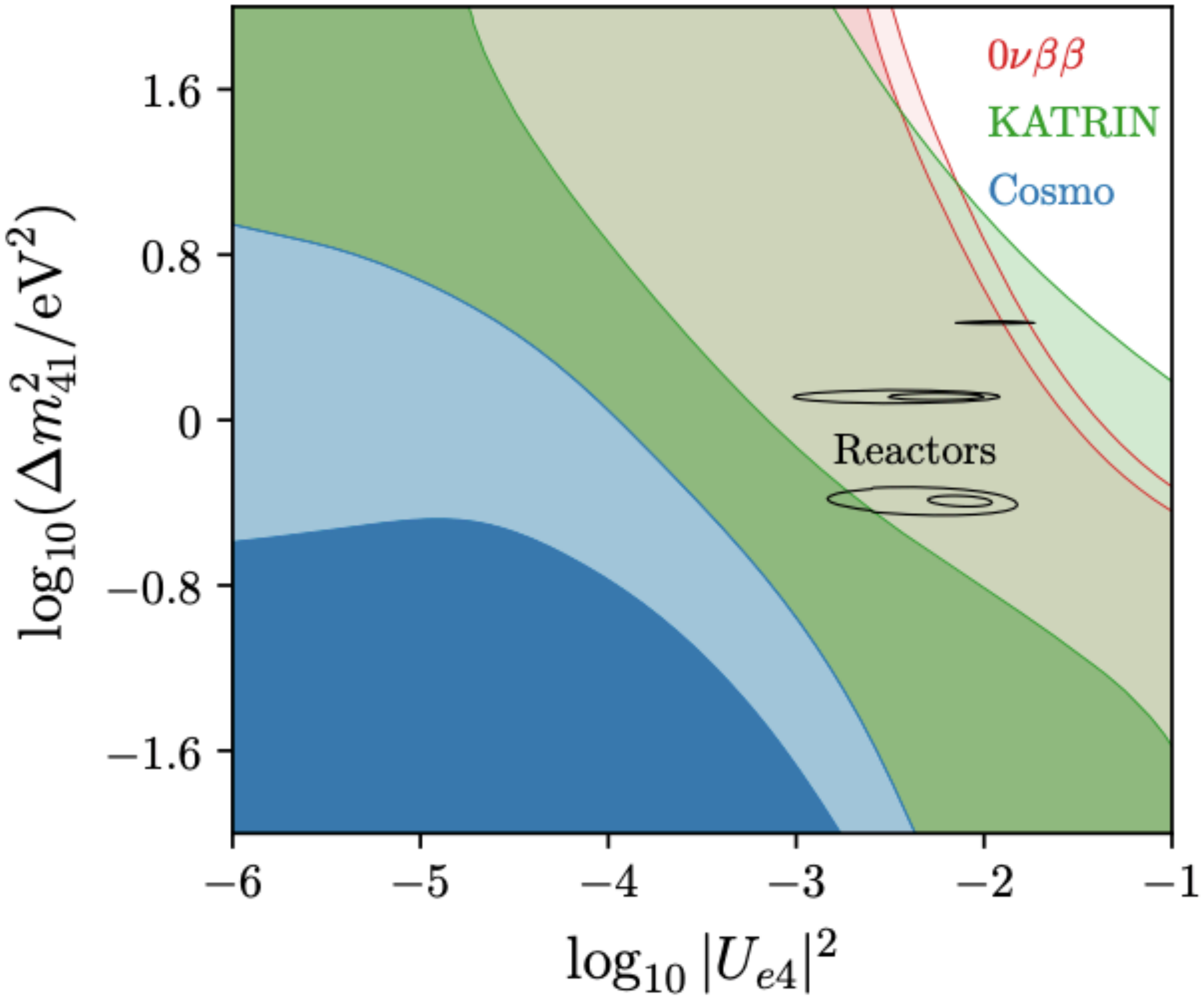




BJP Jones arXiv:1412.2264

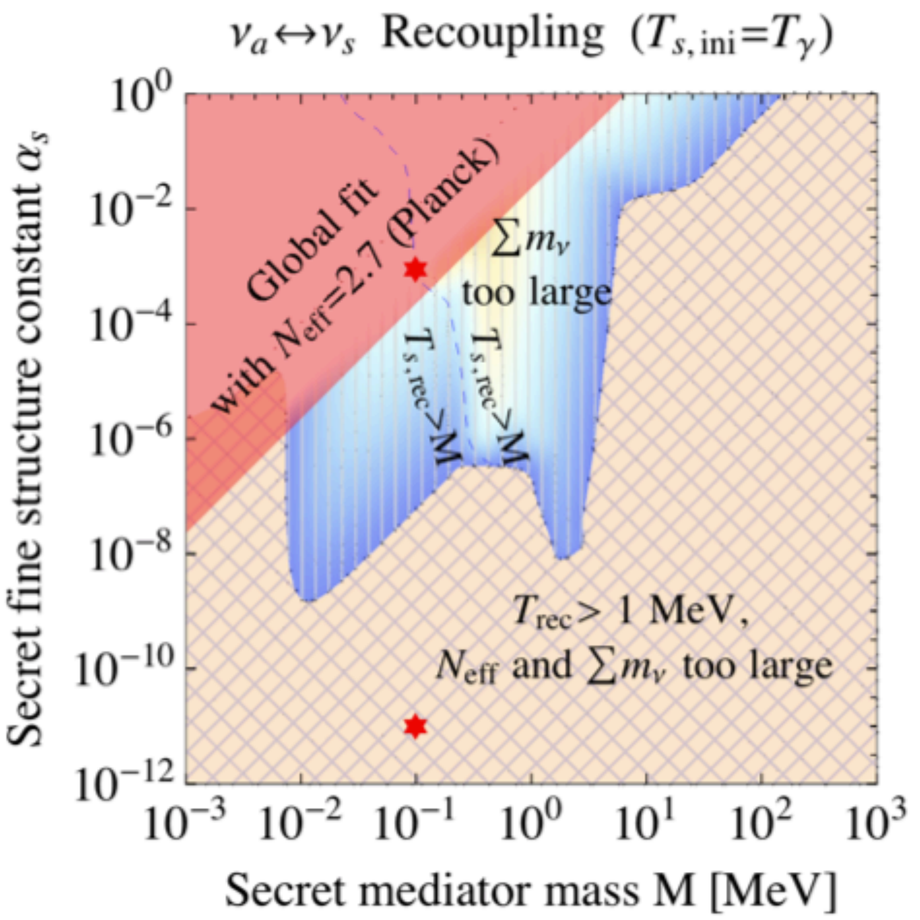
Let’s not forget cosmology!

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



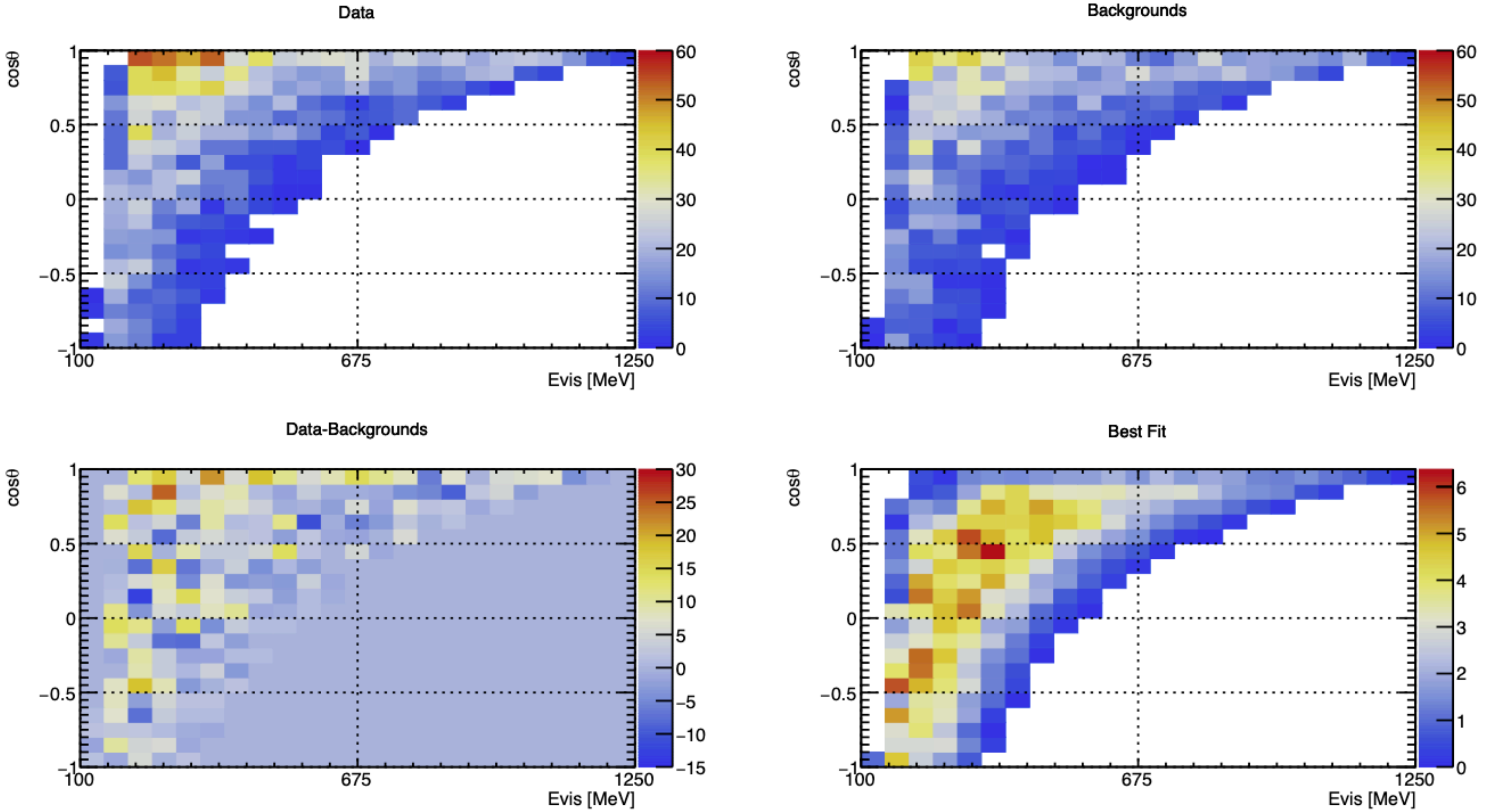
$$\underset{\text{Effective mixing}}{\sin^2 2\theta_m} = \frac{\overset{\text{Vacuum mixing}}{\sin^2 2\theta_0}}{\left(\cos^2 2\theta_0 + \underset{\text{Large}}{\frac{2E}{\Delta m^2}V_m}\right) + \sin^2 2\theta_0} \Rightarrow \text{Keeps } N_{\mathrm{eff}} \text{ at } 3$$

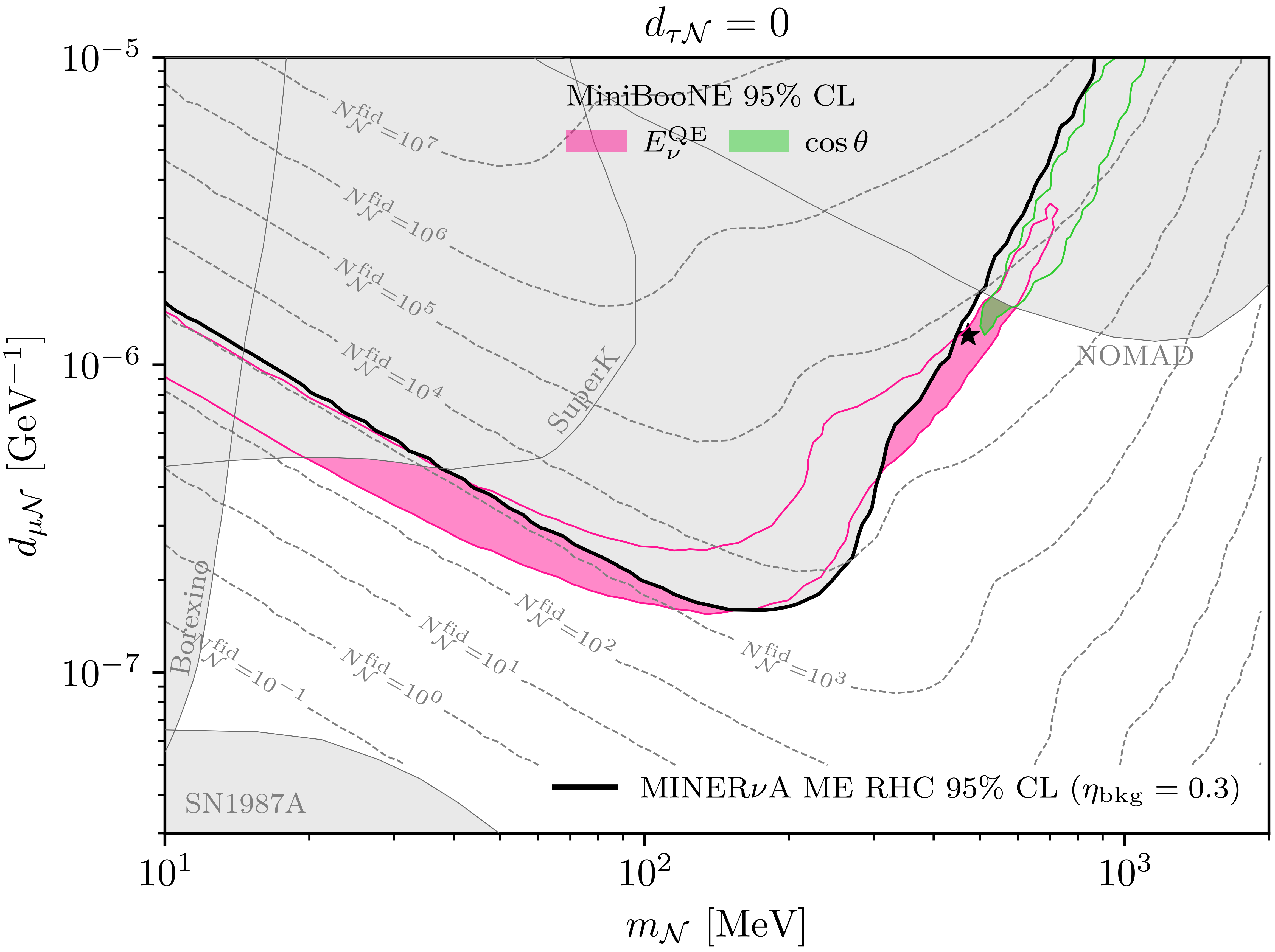
Chu et al. https://arxiv.org/pdf/1806.10629.pdf



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

More information & a new perspective!




$d_{\tau\mathcal{N}} = 0$
MiniBooNE 95% CL
$E_\nu^{\rm QE}$
$\cos\theta$
$N_\mathcal{N}^{\rm fid}=10^7$
$N_\mathcal{N}^{\rm fid}=10^6$
$N_\mathcal{N}^{\rm fid}=10^5$
$N_\mathcal{N}^{\rm fid}=10^4$
$N_\mathcal{N}^{\rm fid}=10^3$
$N_\mathcal{N}^{\rm fid}=10^2$
$N_\mathcal{N}^{\rm fid}=10^1$
$N_\mathcal{N}^{\rm fid}=10^0$
$N_\mathcal{N}^{\rm fid}=10^{-1}$
SuperK
NOMAD
Borexino
SN1987A
MINERνA ME RHC 95% CL ($\eta_{\rm bkg} = 0.3$)
10^{-5}
10^{-6}
10^{-7}
$d_{\mu\mathcal{N}}$ [GeV^{-1}]
10^1
10^2
10^3
$m_\mathcal{N}$ [MeV]