Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

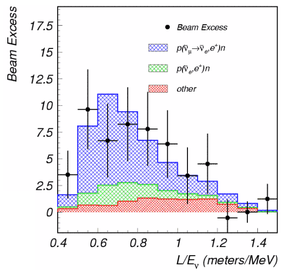
Sterile Neutrino Global Picture

Pedro A. N. Machado

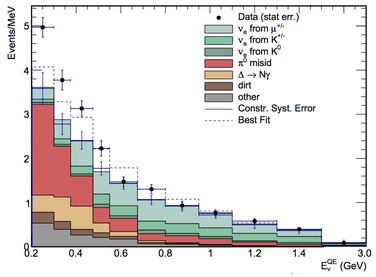
NEUTRINO 2020

July 2nd, 2020

LSND



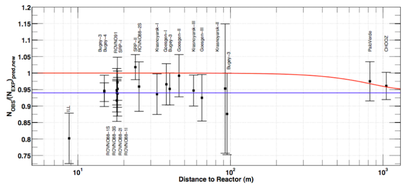
MiniBooNE



4 anomalies

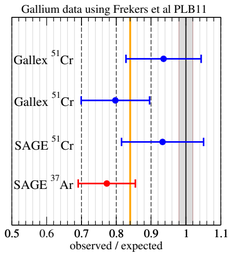
and their interpretation in terms of sterile neutrinos

Reactor



*I am a theorist and I do not represent any experiment

Gallium



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LSND

VERY intense proton beam

$$p + X \rightarrow \pi^+ + X'$$

(800 MeV) $\hookrightarrow \mu^+ \nu_\mu$ (DAR)

$\hookrightarrow e^+ \nu_e \bar{\nu}_\mu$

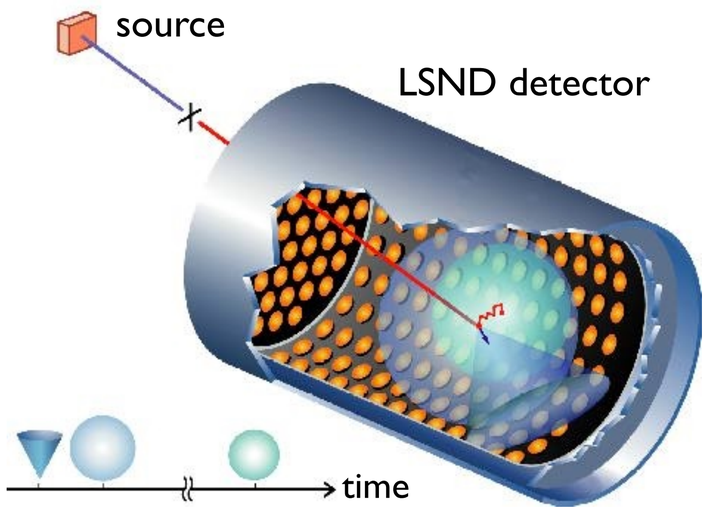
Detection signature:
IBD ($\bar{\nu}_e\, p \rightarrow e^+ n$)

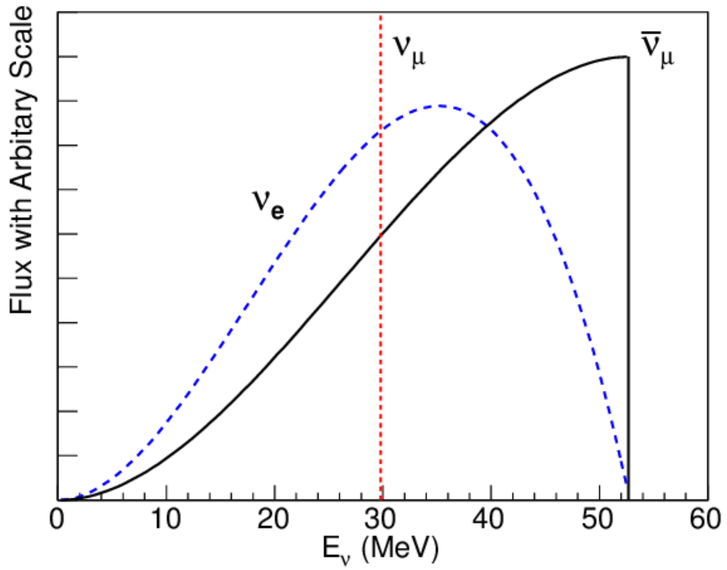
LSND detected more $\bar{\nu}_e$
than expected: 87.9 ± 23.2 events
(3.8σ excess)

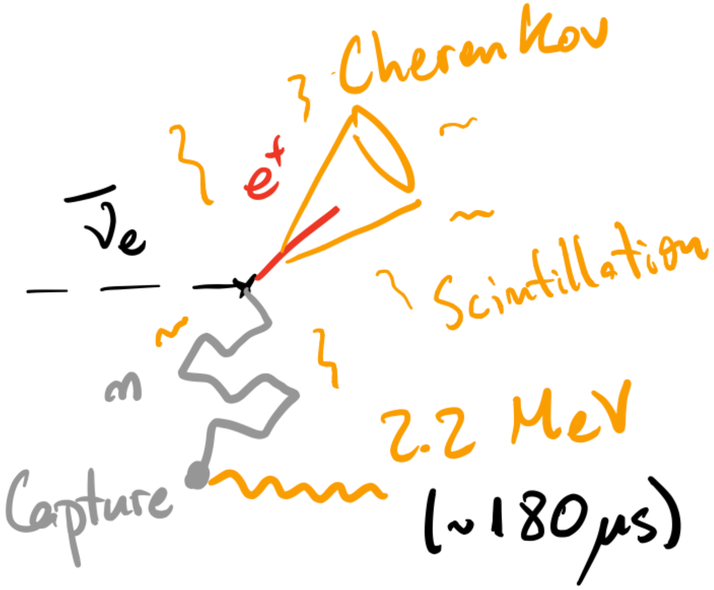
L ~ 30 m
E ~ 30 MeV

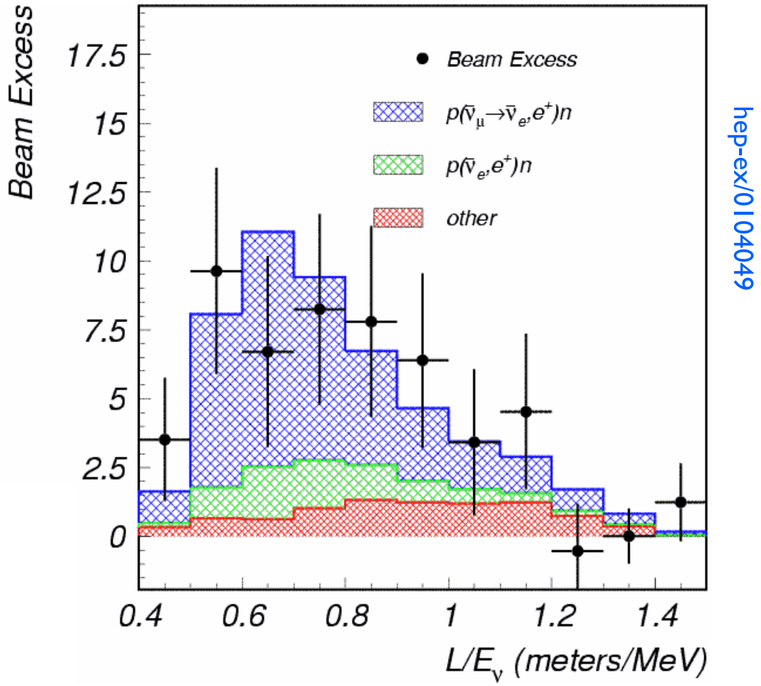
$\Delta m^2 \sim 1\ eV^2$???

Main backgrounds:
anti-nue contamination
π^- decay in flight + μ mis-id









hep-ex/0104049

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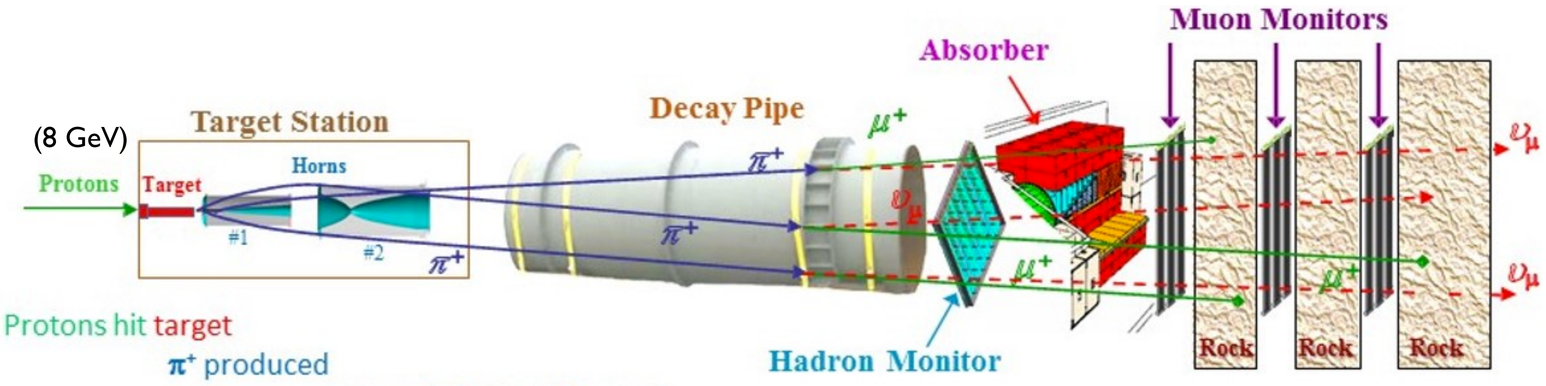
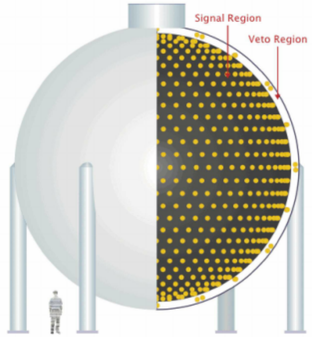
The MiniBooNE Collaboration

arXiv:1805.12028v1 [hep-ex]

Observation of a Significant Excess of Electron-Like Events in the MiniBooNE Short-Baseline Neutrino Experiment

New MB result to be discussed soon!!!





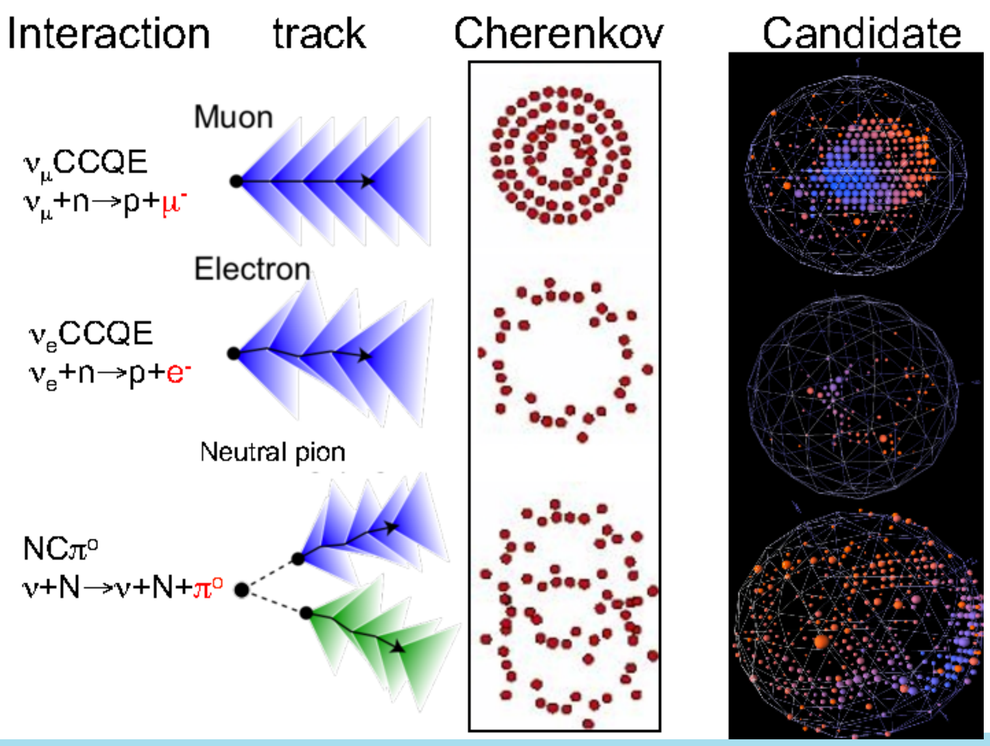
Signal:

Scintillation light (isotropic)

Cherenkov light (directed)

Cherenkov light distribution allows for particle identification

Photons are invisible until they convert to collimated e^+e^- pairs (e-like signature)



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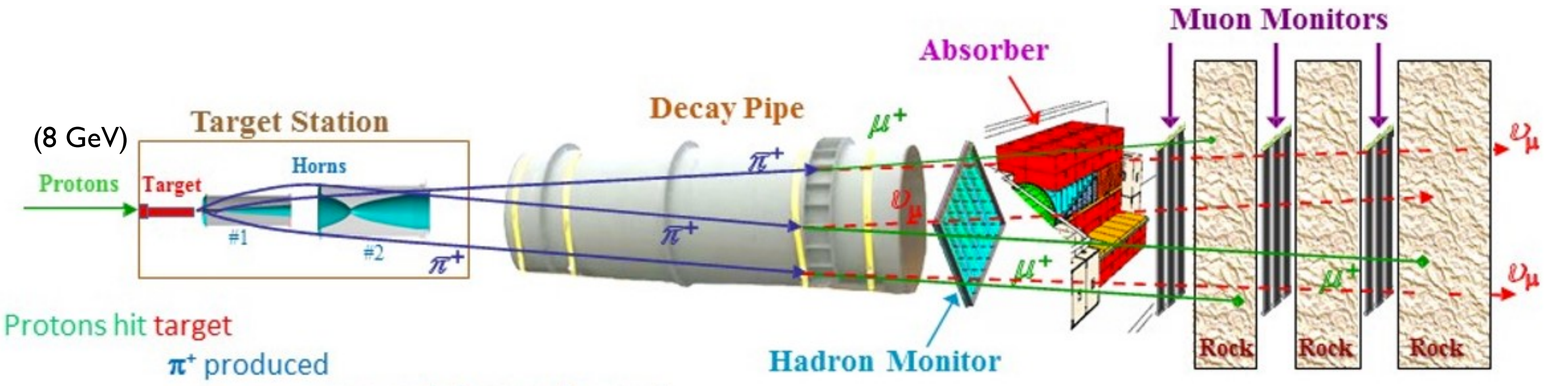
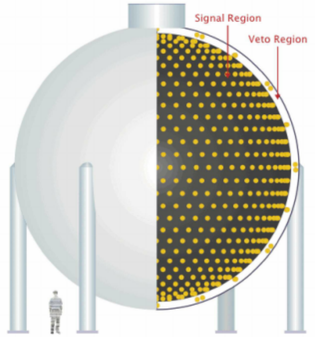




Double neutrino-mode data

($6.46\times10^{20} + 6.38\times10^{20}$ POT)

Event excess: 381.2 ± 85.2 (4.5σ)

L ~ 500 m

E ~ 500 MeV

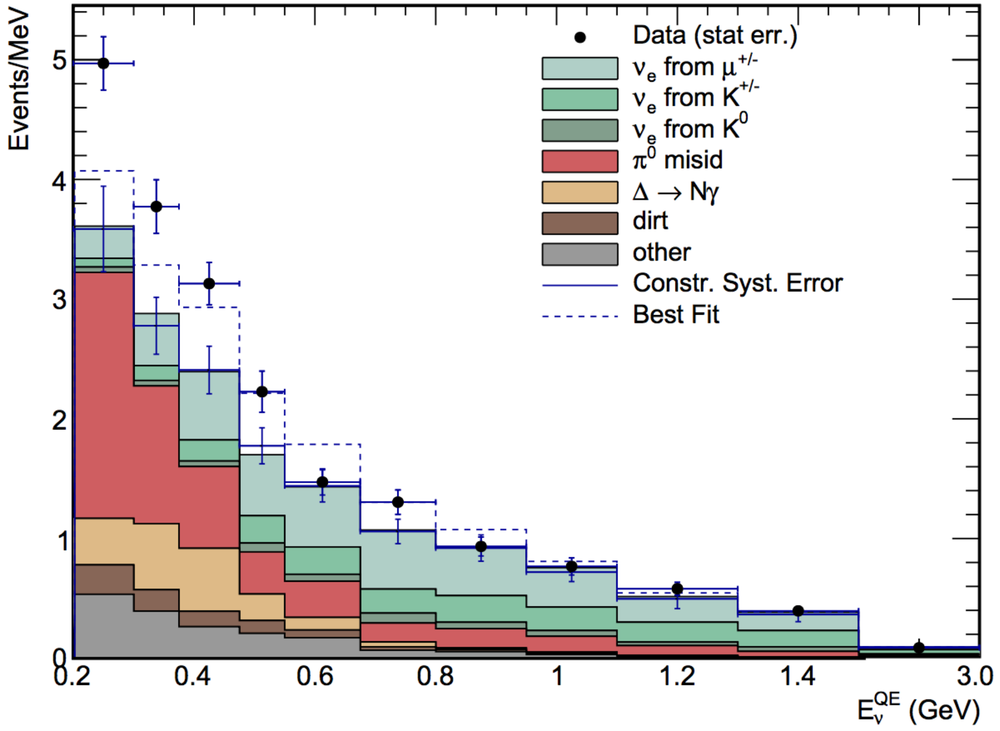
$\Delta m^2 \sim 1\ eV^2$???

Main backgrounds:

π^0 mis-id

ν_e from kaons and muons

γ production via Δ resonance



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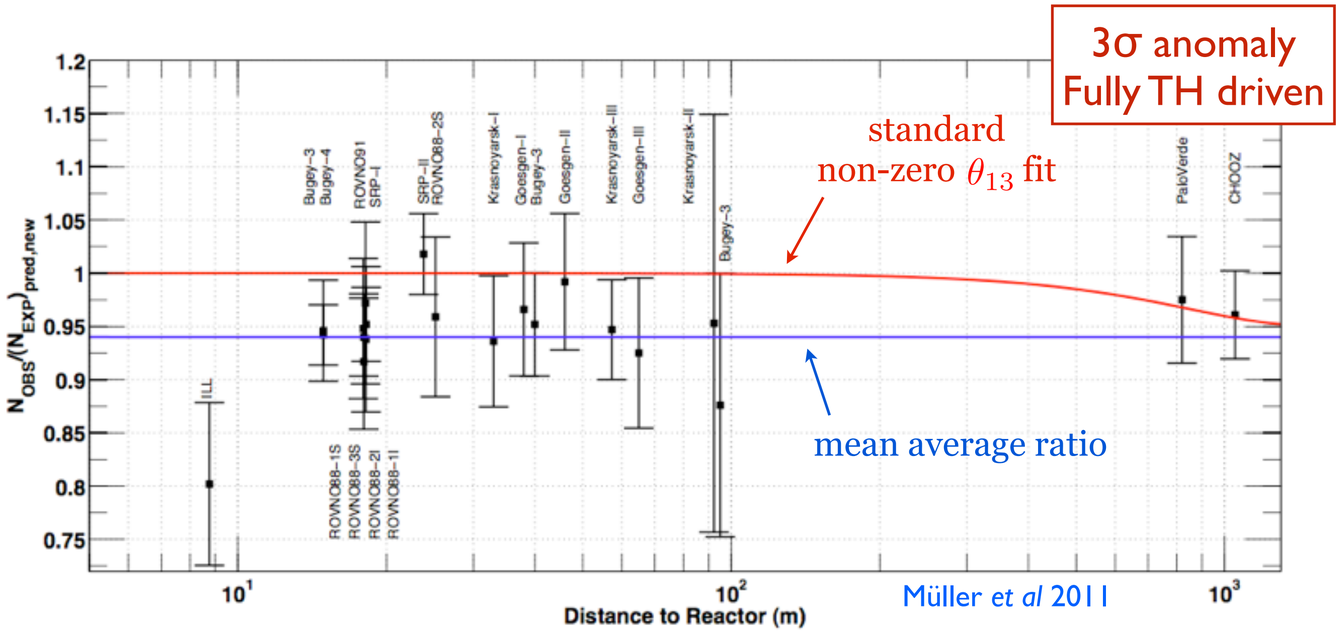
Reactor antineutrino anomaly

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



Müller *et al* 2011

But others say that the error bar should be more like 5%

Hayes et al 2013

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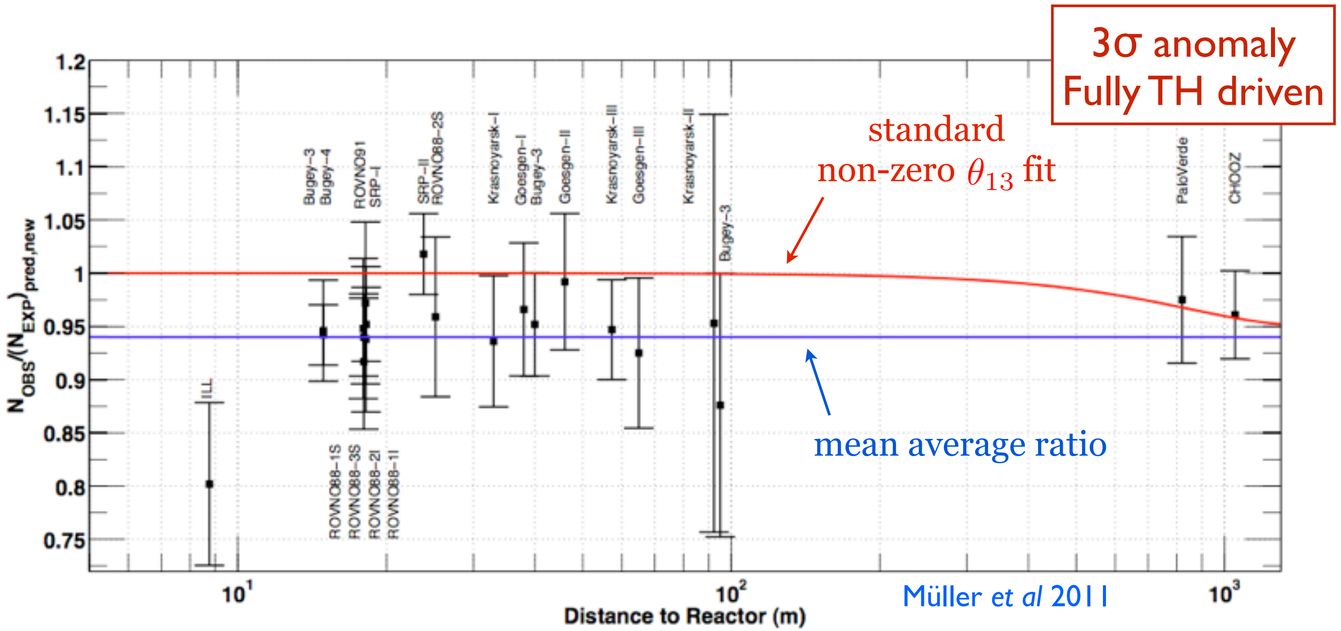

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Issues with theory predictions:

Very hard problem,
thousands of beta branches

Asking to extrapolate what has not been measured…

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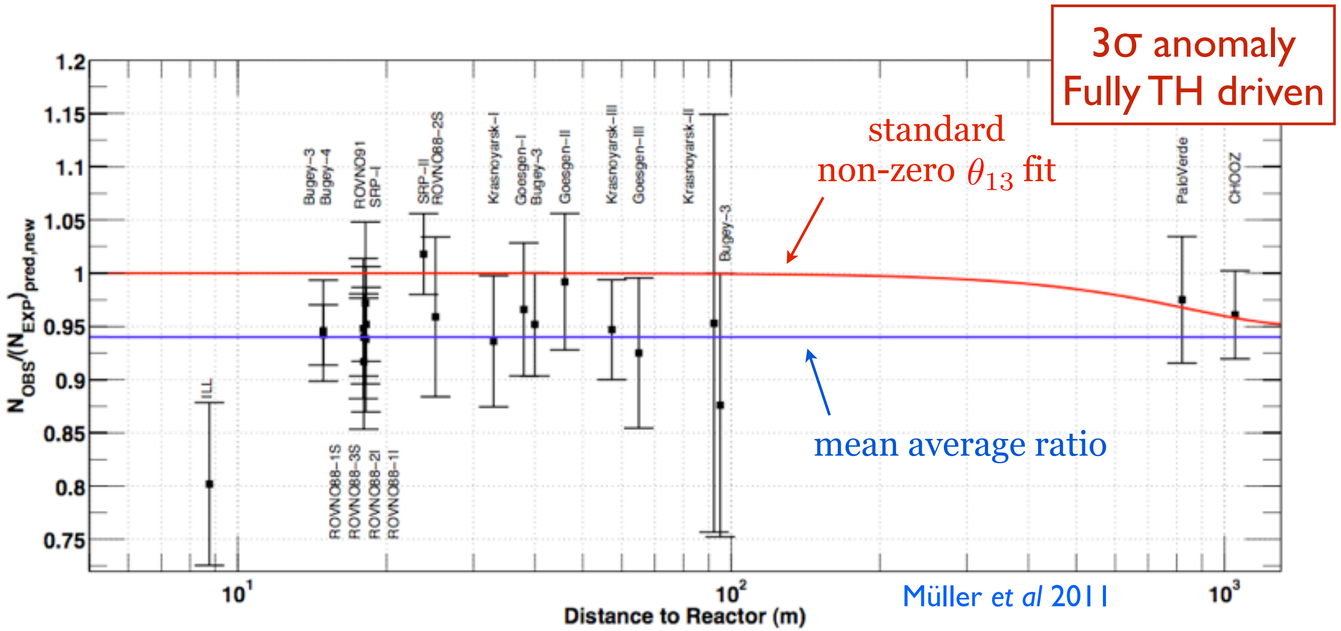

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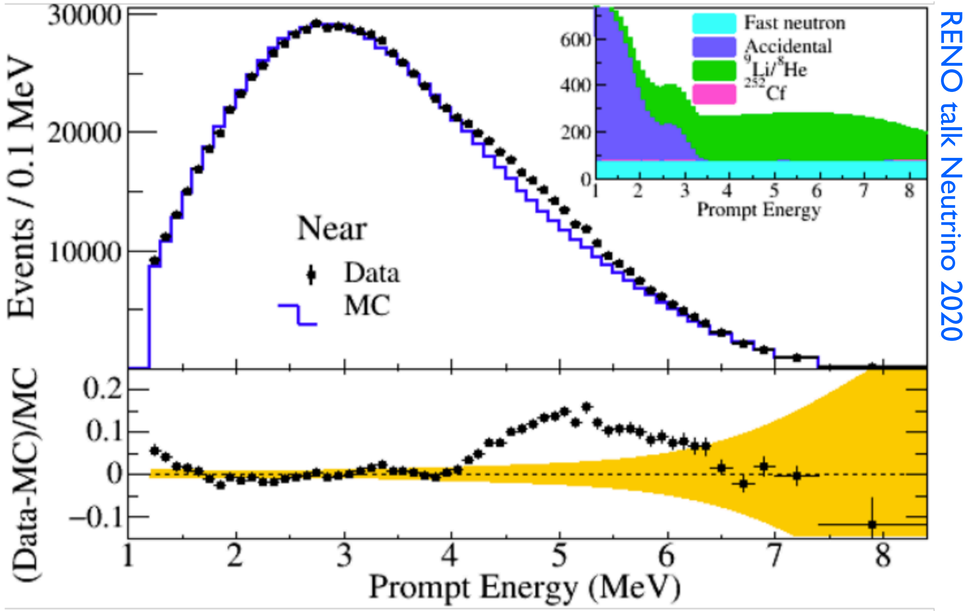
Hayes et al 2013

Issues with theory predictions:

The 5 MeV "bump"



RENO talk Neutrino 2020

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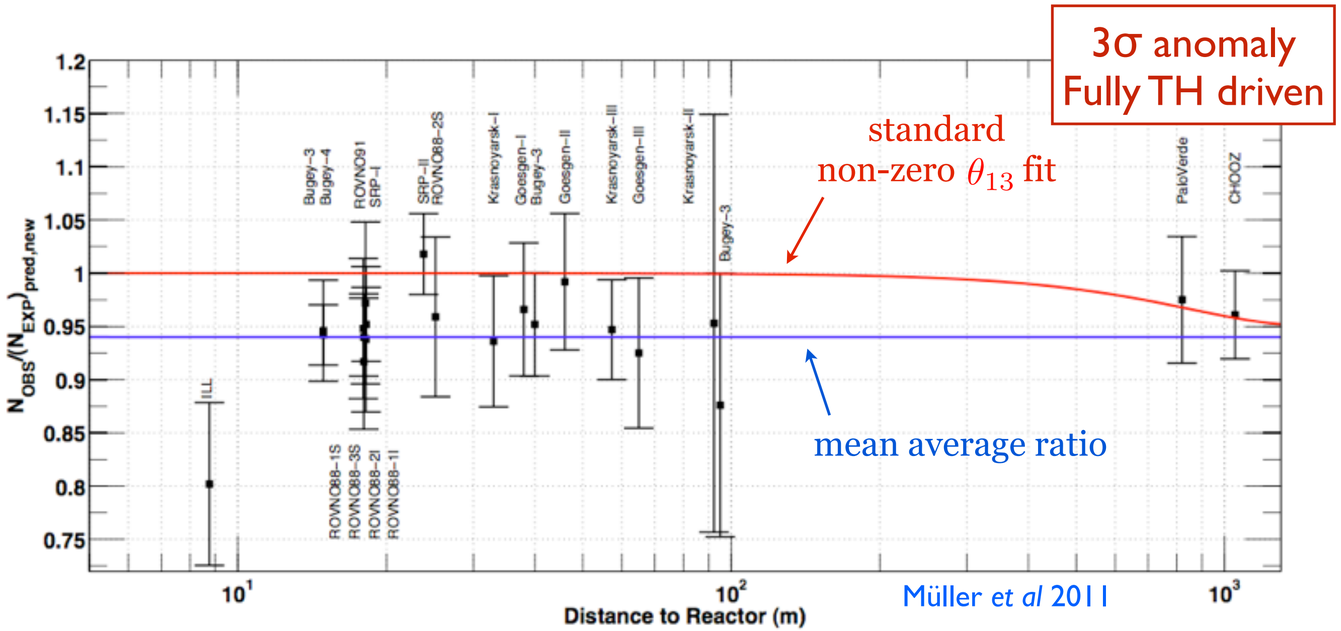

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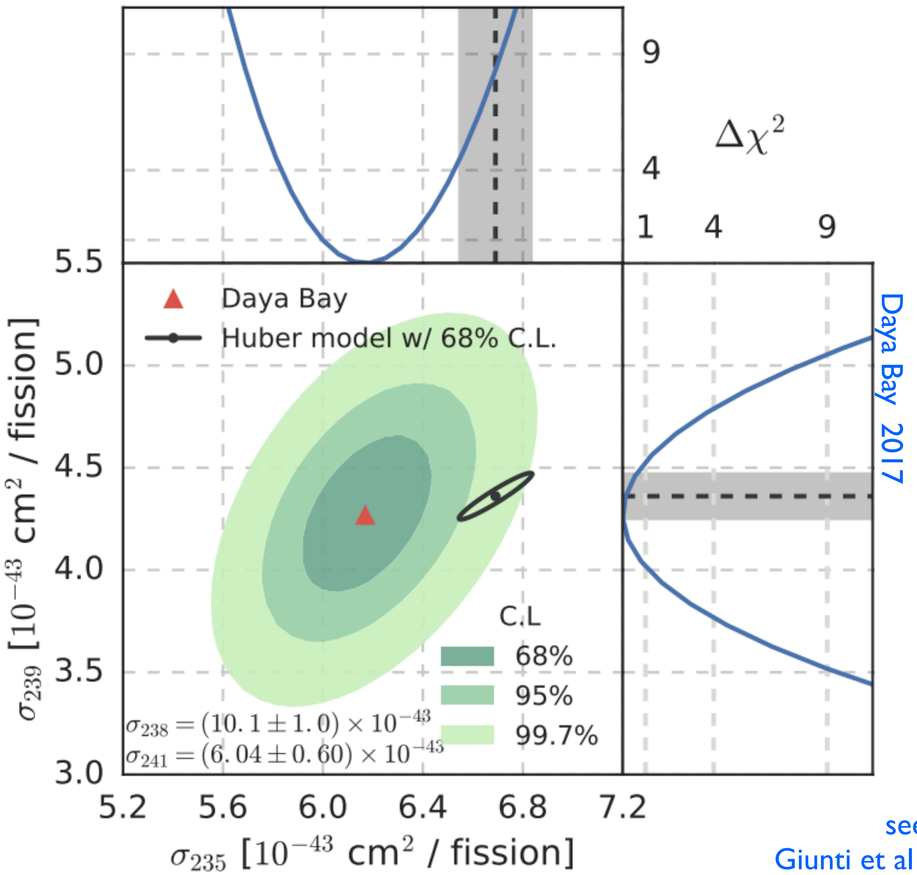
But others say that the error bar should be more like 5%

Hayes et al 2013

Issues with theory predictions:

Isotopes burn, neutrino flux evolves, steriles disfavored at 2.6σ



see also
Giunti et al 2017
Berryman Huber 2020

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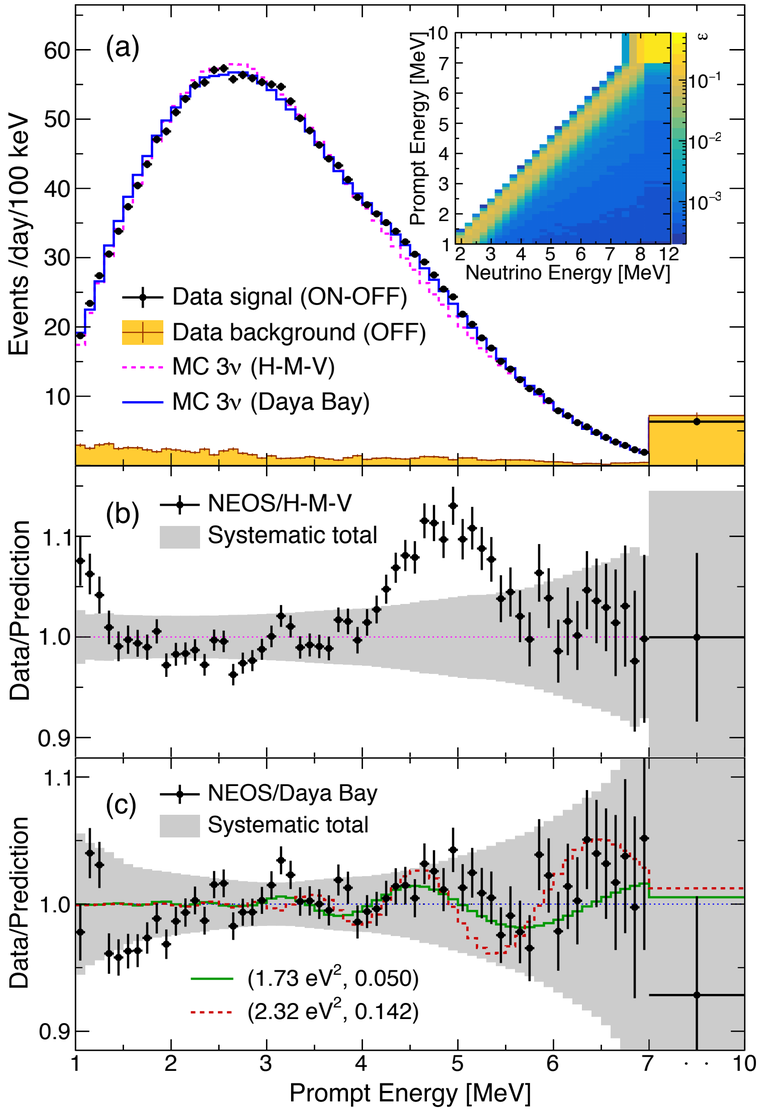
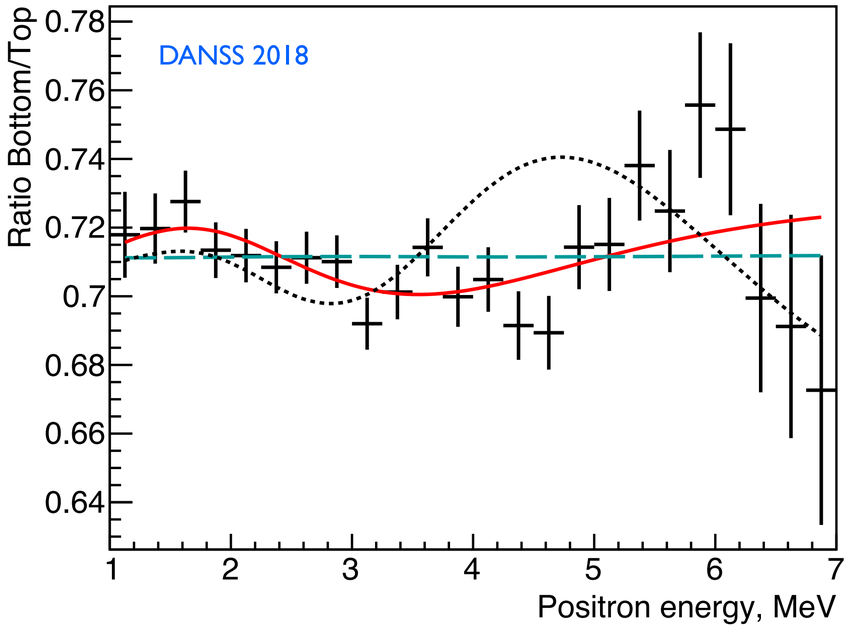
Reactor antineutrino anomaly

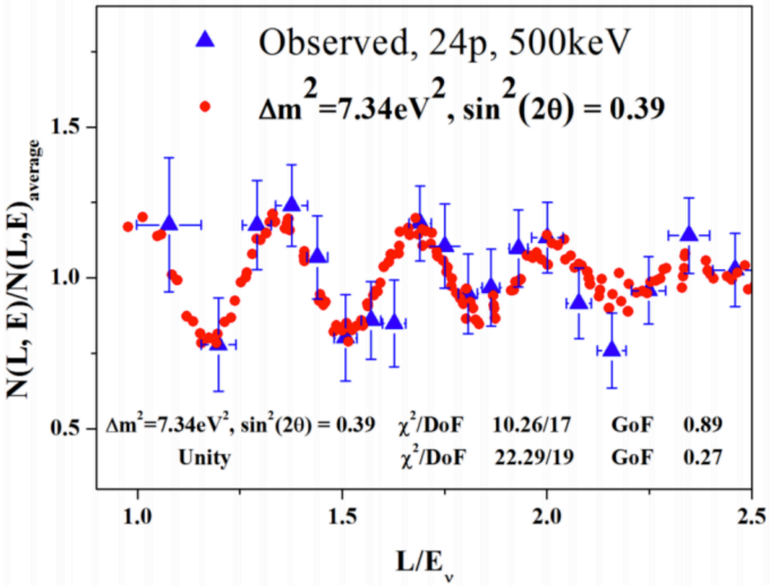
Wiggles in the data???

NEOS 2016





Neutrino-4 2020



Statistics of small wiggles may <u>not be χ^2 distributed</u>!

MC simulation and calibration of test statistics is necessary to state confidence level of claims

se e.g. Giunti 2004.07577

Prospect+Stereo on Neutrino-4:
- statistics may be an issue
- systematics may be an issue

2006.13147

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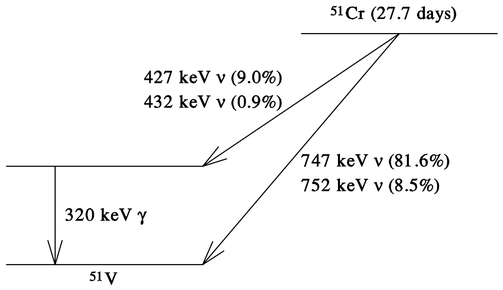
Gallium anomaly

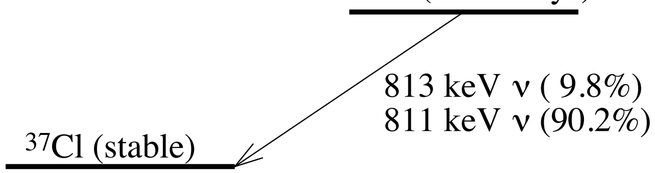
Calibration experiments

Radioactive sources:

$$e^- + {}^{51}\mathrm{Cr} \rightarrow {}^{51}\mathrm{V} + \nu_e$$

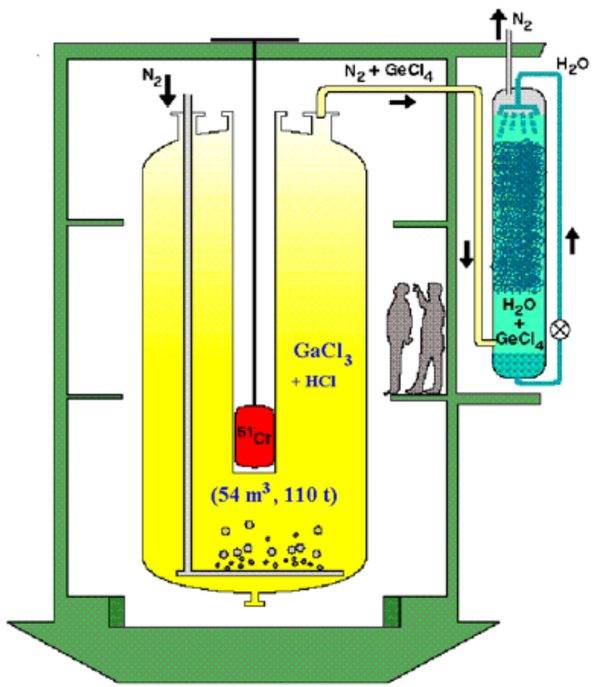


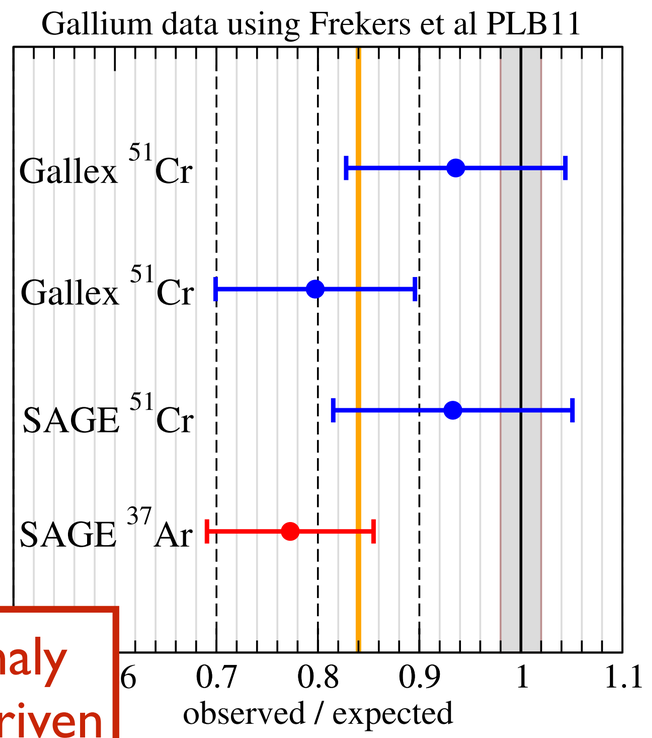
$$e^- + {}^{37}\mathrm{Ar} \rightarrow {}^{37}\mathrm{Cl} + \nu_e$$



Observations disagree with theoretical calculations (deficit of 16% of events)

Hampel *et al* 1998, Kaether *et al* 2010, Abdurashitov *et al* 1998, Abdurashitov *et al* 2005





Schwetz@Neutrino 2012

3σ anomaly
Fully TH driven

New estimates using new nuclear shell-model wave functions diminish significance to 2.3σ…

Kostensalo et al 2019

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Reactor and Gallium anomalies may be theory problem
(though there may be wiggles…)

LSND and MiniBooNE anomalies: same L/E, no obvious culprits, difficult to imagine correlated background

All four anomalies come from **very** different experiments

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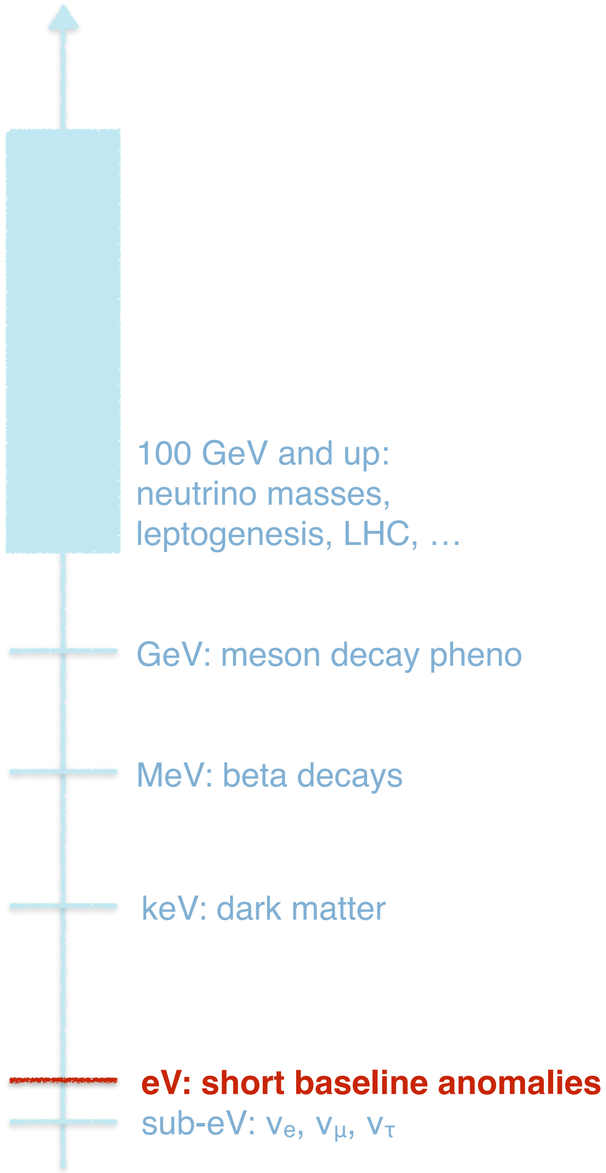
Very schematically:



What is going on???

Simplest non-standard explanation:
Oscillation physics via an extra neutrino state,
not gauge under weak interactions
(that is, a sterile neutrino)

for details, check Dentler et al 1803.10661

*The results that I will show (Dentler et al 2018) are in good agreement with those obtained by other groups (Diaz et al 2019, Gariazzo et al 2017)

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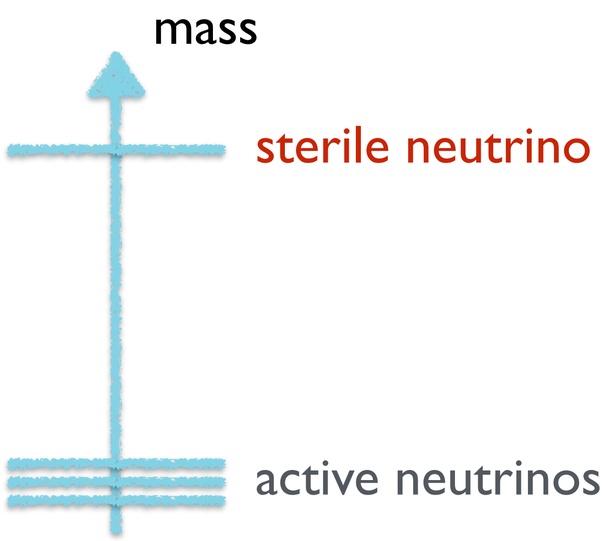
The physics in a nutshell

Add 4th neutrino with mixing

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

*Last line in 4x4 PMNS is unphysical



Δm^2_{21}, $|\Delta m^2_{31}|$ << Δm^2_{41} allows for approximate oscillation formula:

$$P_{\alpha\beta} \simeq \delta_{\alpha\beta} - 4|U_{\alpha\beta}|^2(\delta_{\alpha\beta} - |U_{\alpha\beta}|^2)\sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$\nu_\mu \to \nu_e : \sin^2 2\theta_{\mu e} \equiv 4|U_{\mu 4}|^2|U_{e4}|^2$ → LSND, MiniBooNE, OPERA, …

$\nu_e \to \nu_e : \sin^2 2\theta_{ee} \equiv 4|U_{e4}|^2(1 - |U_{e4}|^2)$ → Reactors, solar, Gallium, …

$\nu_\mu \to \nu_\mu : \sin^2 2\theta_{\mu\mu} \equiv 4|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2)$ → MiniBooNE, MINOS, IceCube, …

We can overconstrain the model

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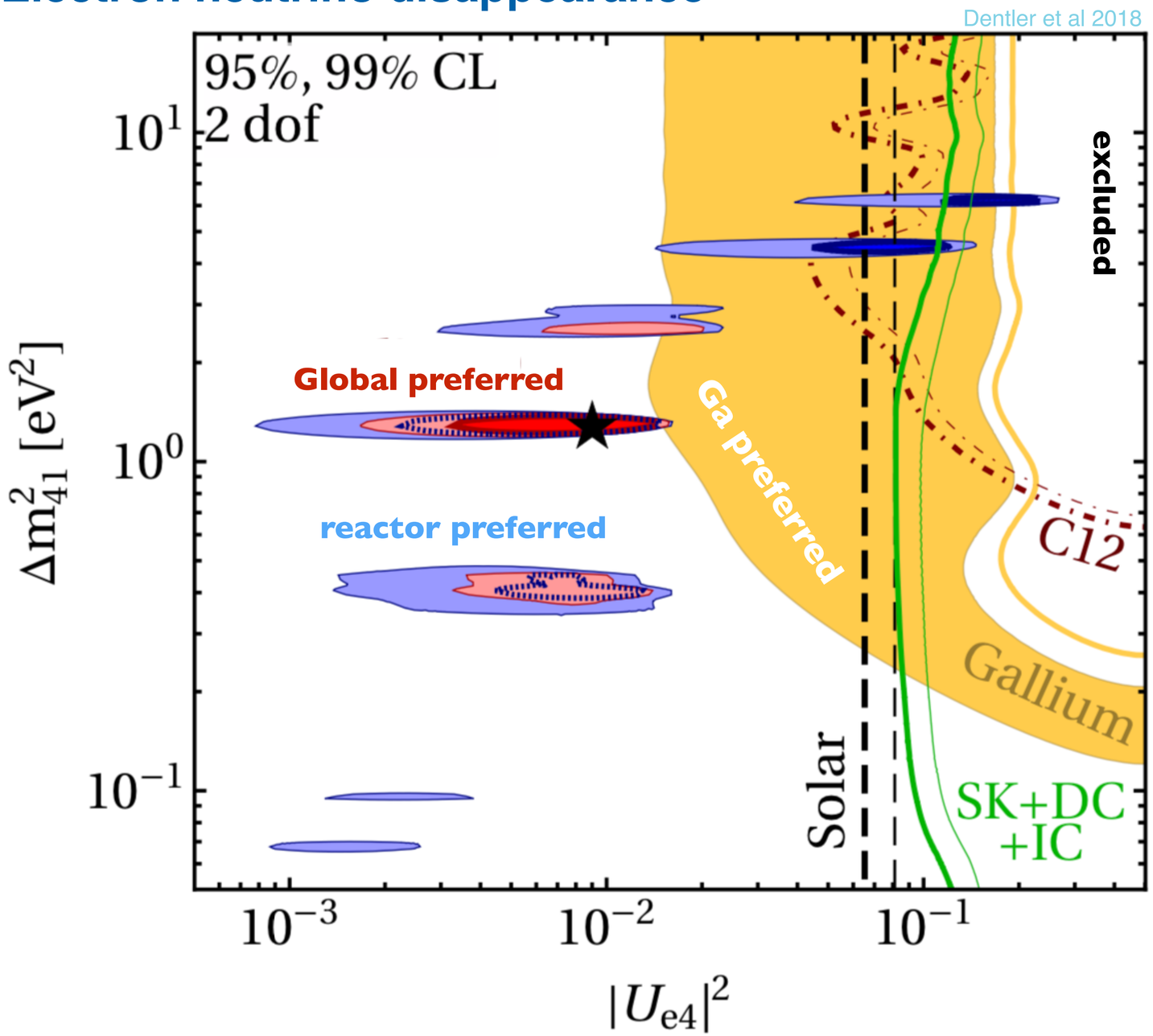
Electron neutrino disappearance



Radioactive source exps
GALLEX, SAGE

Reactor experiments
ILL, Goesgen, Krasnoyarsk, Rovno, Bugey-3, Bugey-4, SRP, NEOS, DANSS, Double Chooz, RENO, Daya Bay, KamLAND

ν_e scattering on carbon
KARMEN, LSND

Solar experiments
Chlorine, GALLEX/GNO, SAGE, Super-Kamiokande, SNO, Borexino

Atmospheric neutrinos
Super-Kamiokande, DeepCore, IceCube

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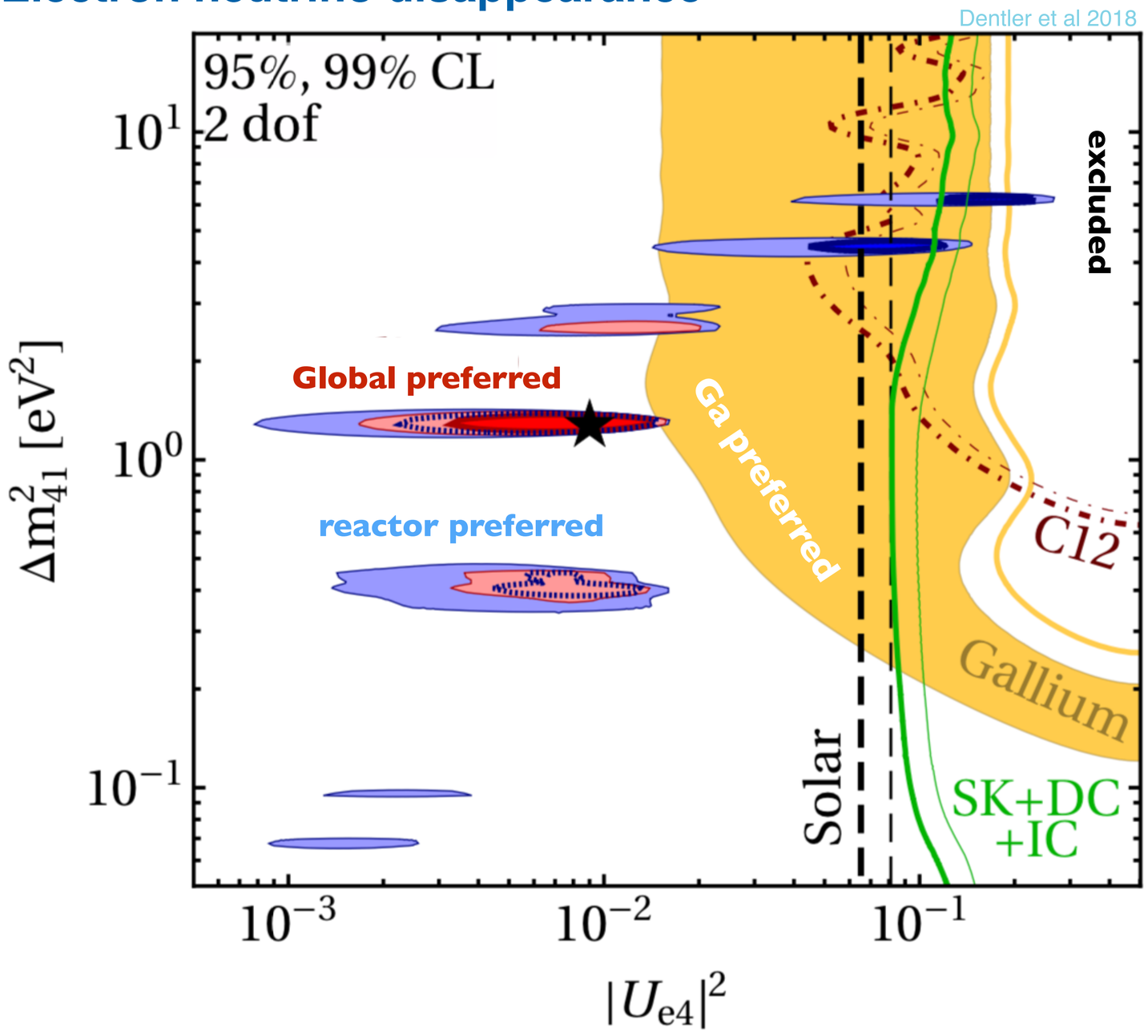
Electron neutrino disappearance



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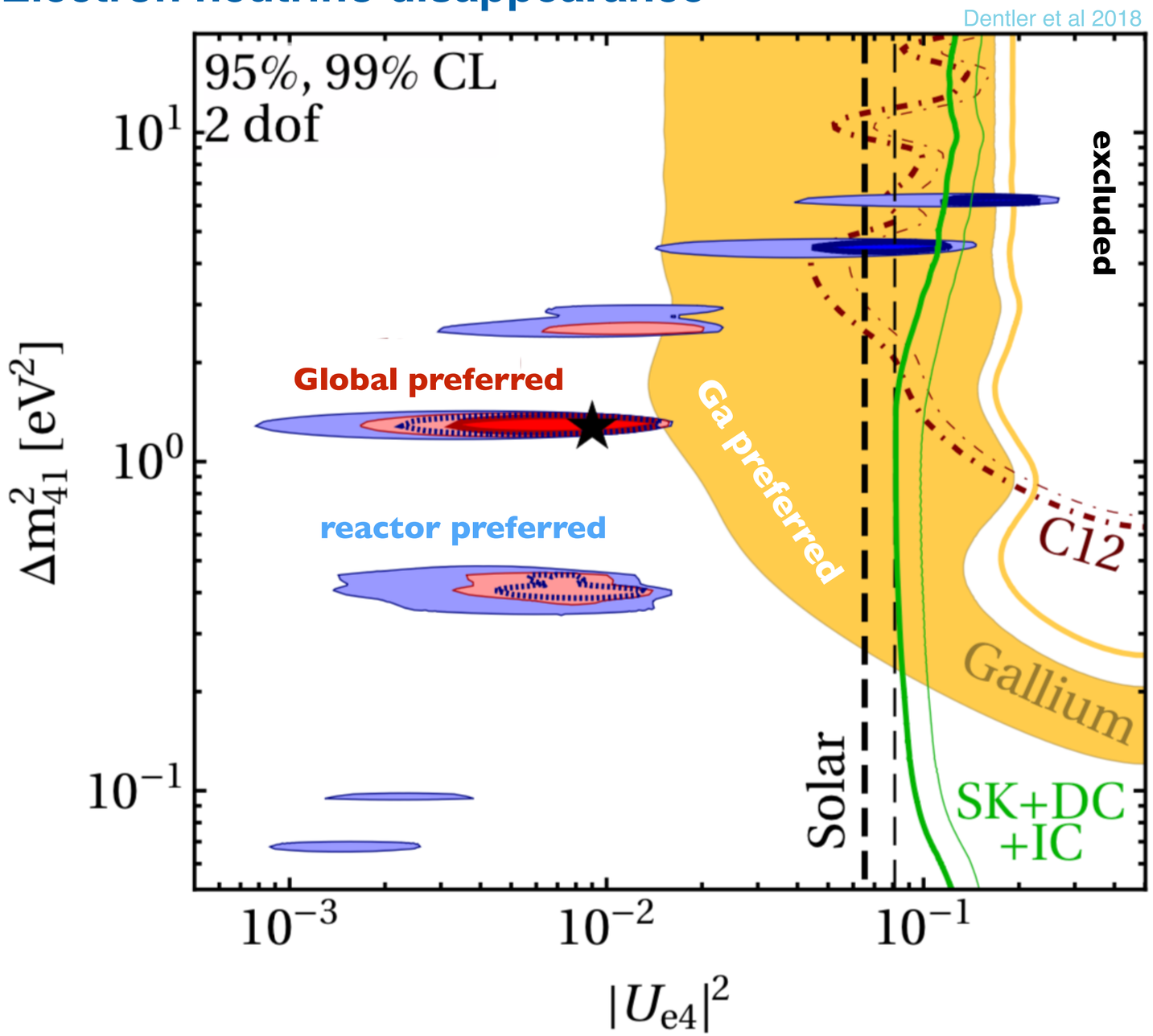
Atmospheric neutrinos
Super-Kami
DeepCore, I

Analysis with free reactor flux prediction
Best fit:
$\Delta m^2 = 1.3$ eV^2, $|U_{e4}|^2 = 0.009$
"3.2σ"
Dominated by DANSS/NEOS

Electron neutrino disappearance



Radioactive source exps
GALLEX, SAGE

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ILL, Goesgen, Krasnoyarsk, Rovno, Bugey-3, Bugey-4, SRP, NEOS, DANSS, Double Chooz,

ν_e

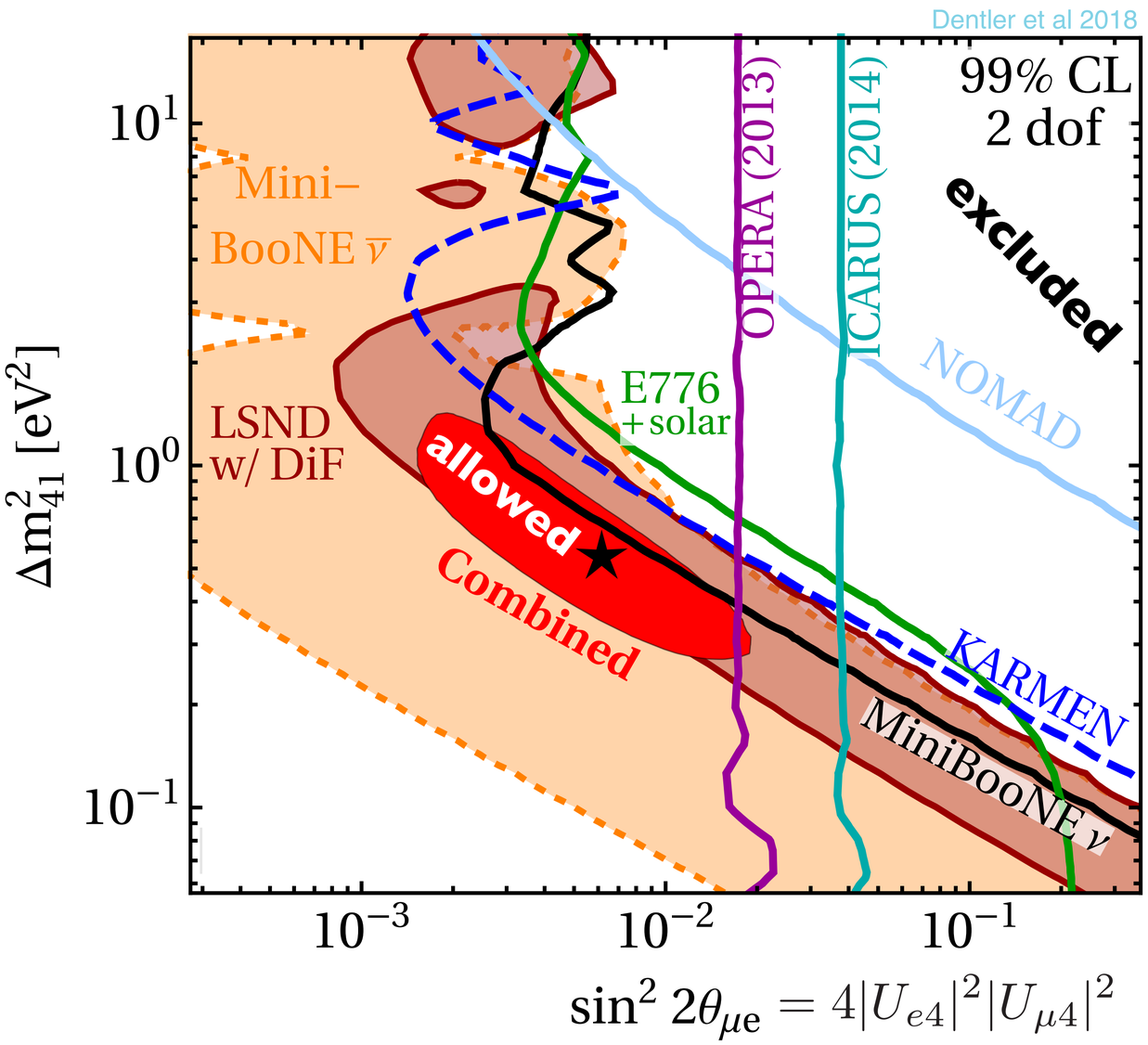
O,
de,
SNO, Borexino

Atmospheric neutrinos
Super-Kami
DeepCore, I

CAVEAT
We have assumed the test statistics to be χ^2 distributed.
Interpret this with a grain of salt!
("3.2σ" <==> $\Delta\chi^2$ = 13.3)
This will not change the final results on the tension between APP-DIS.

Analysis with free reactor flux prediction
Best fit:
Δm^2 = 1.3 eV^2, $|U_{e4}|^2$ = 0.009
"3.2σ"
Dominated by DANSS/NEOS

Electron neutrino appearance



Accelerator neutrinos
LSND, MiniBooNE, KARMEN, NOMAD, E776, ICARUS, OPERA

> 5σ

Dominated by LSND, then MiniBooNE

Not a large difference between 2012 MiniBooNE data and 2018

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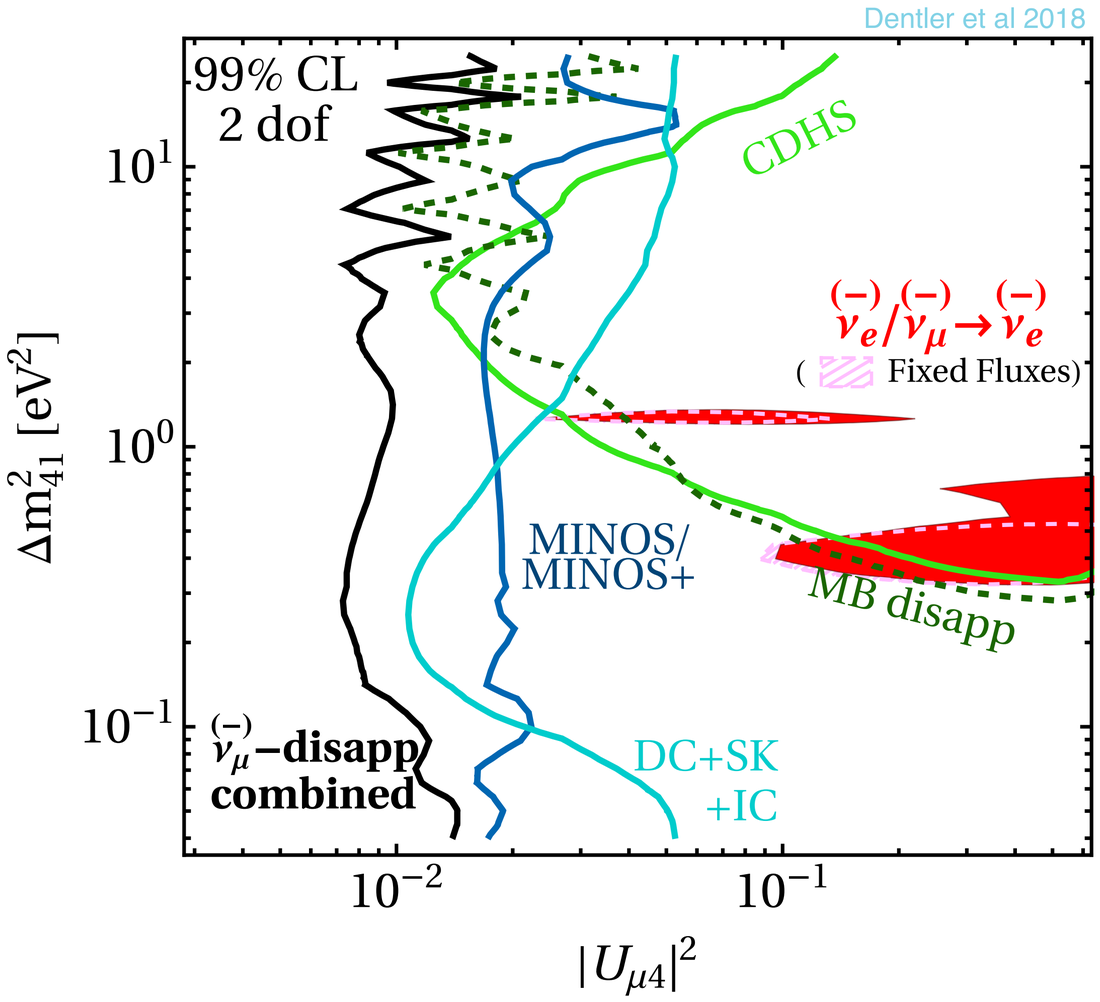
Muon neutrino disappearance



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

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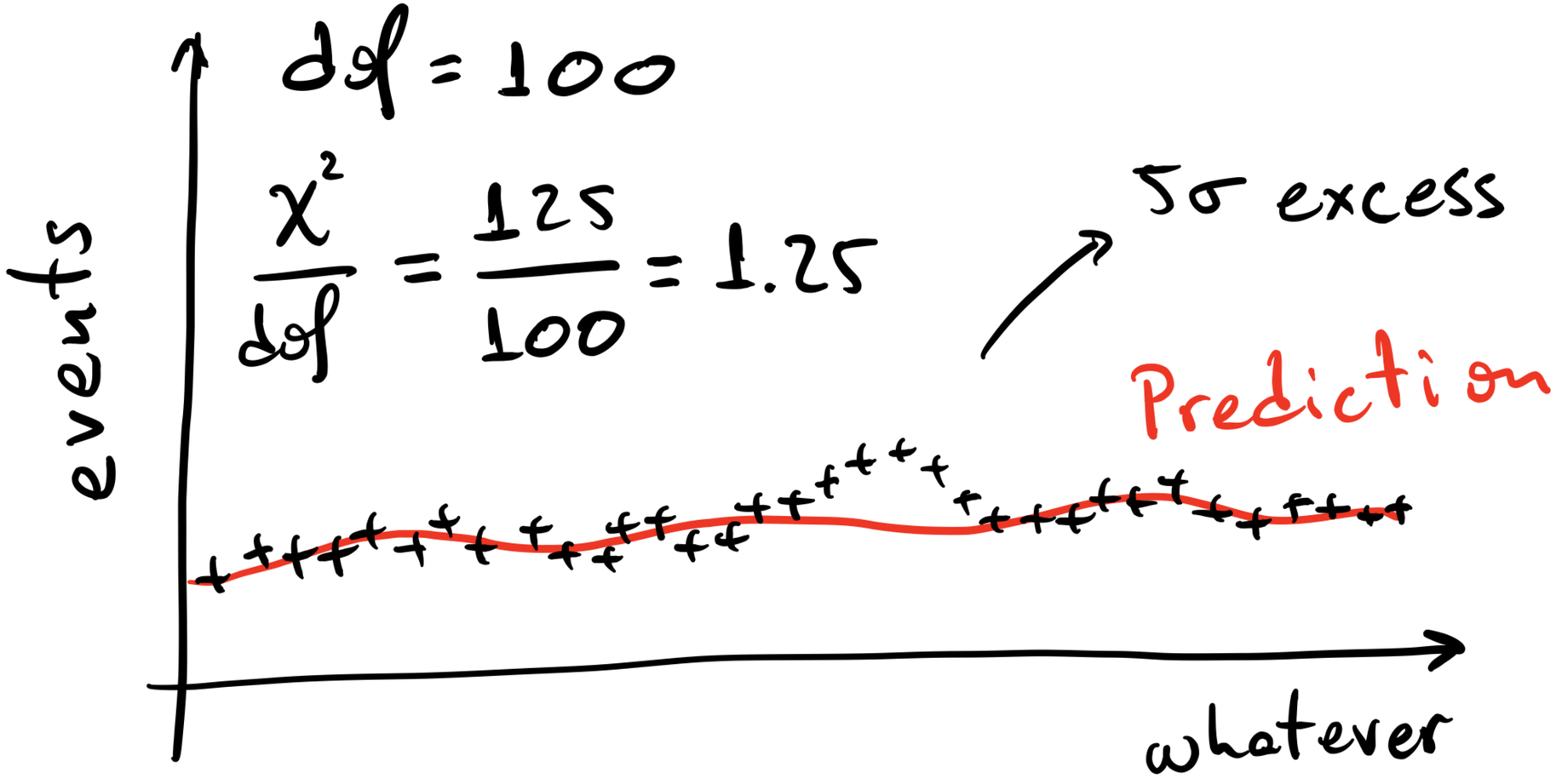
Global analysis

How well the model fits the data?

χ^2/dof ✗



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Global analysis

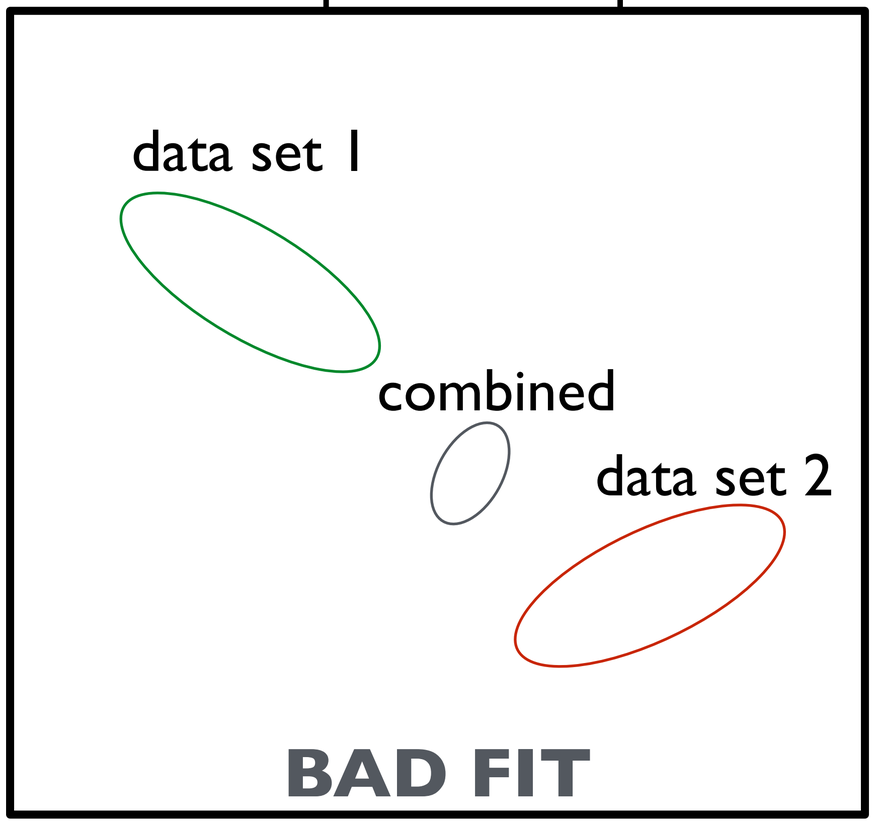
How well the model fits the data?

χ^2/dof ✗

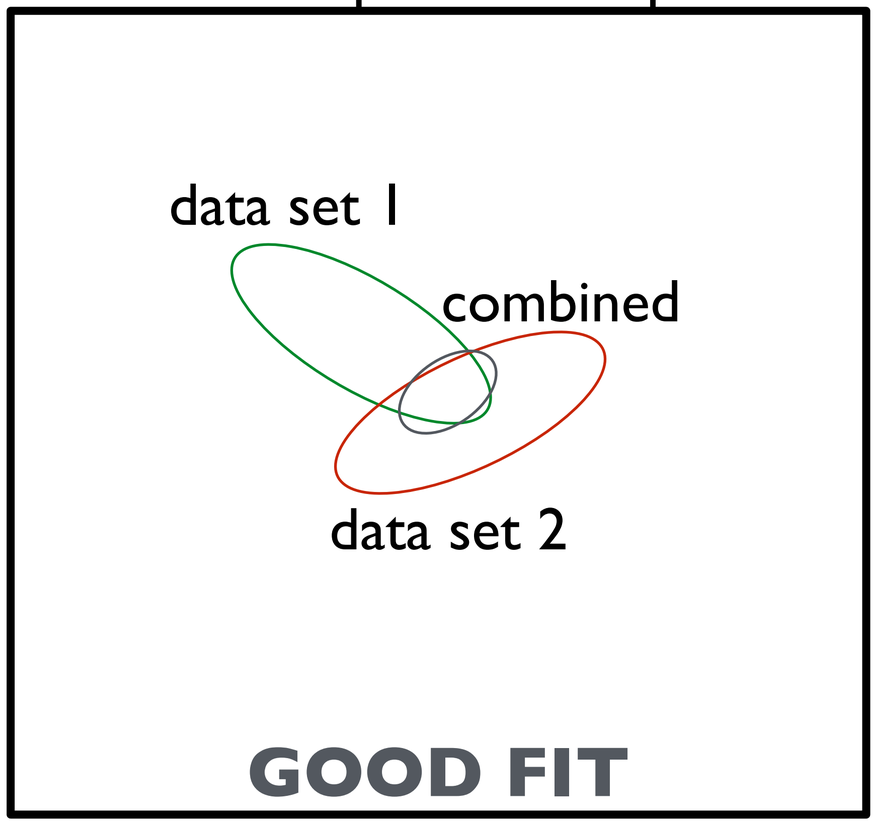
goodness of fit ✓

see Maltoni Schwetz 2007

Model parameter space



Model parameter space



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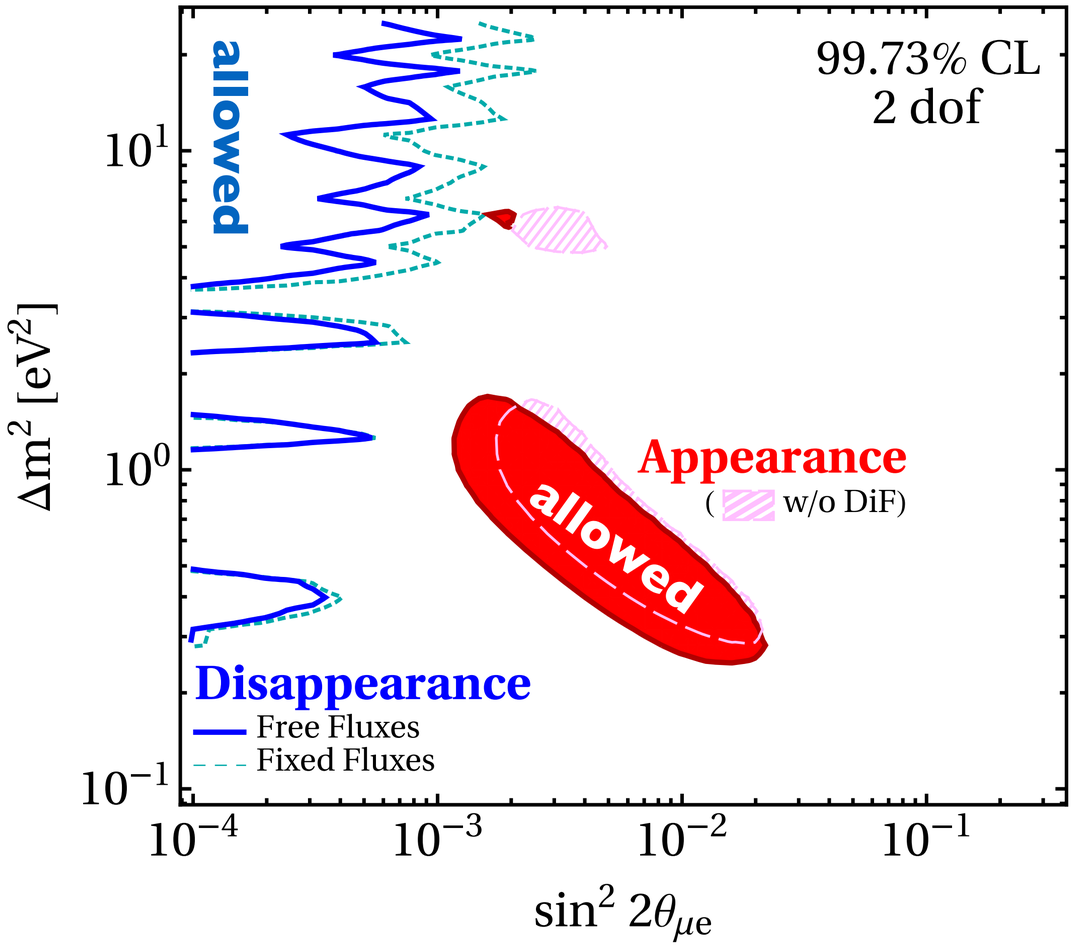
Global analysis

How well the model fits the data?

χ^2/dof ✗

goodness of fit ✓

see Maltoni Schwetz 2007



ν_μ to ν_e appearance

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

ν_e disappearance ν_μ disappearance

Data sets:

ν_e and ν_μ disappearance

vs.

ν_e appearance

4.7 σ tension

between DISAPP and APP data sets under eV sterile interpretation

Exercise: remove each experiment and see if agreement improves

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Global analysis

Taking out any single experiment does not lead to a good fit

Analysis	$\chi^2_{\text{min,global}}$	$\chi^2_{\text{min,app}}$	$\Delta\chi^2_{\text{app}}$	$\chi^2_{\text{min,disapp}}$	$\Delta\chi^2_{\text{disapp}}$	$\chi^2_{\text{PG}}/\text{dof}$	PG
Global							3.71×10^{-7}
Removing anomalous data sets							
w/o LSND							1.6×10^{-3}
w/o MiniBooNE							5.2×10^{-6}
w/o reactors							3.8×10^{-5}
w/o gallium							4.4×10^{-8}
Removing constraints							
w/o IceCube							4.2×10^{-7}
w/o MINOS(+)							4.7×10^{-6}
w/o MB disapp							6.0×10^{-7}
w/o CDHS							7.5×10^{-7}
$\overset{(-)}{\nu}_\mu$ dis + solar vs app							7.4×10^{-6}

MiniBooNE 2012 data set

Taking out reactor and Ga experiments does not improve the fit

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Some thoughts

Is there any background that may explain LSND and MiniBooNE?

MiniBooNE: photon background? Not motivated by theory…

see e.g. R. Hill 2011

LSND: some nuclear physics? unexpected background??

No background can explain both, the energies are too different

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Some thoughts

Is there any background that may explain LSND and MiniBooNE?

Does cosmology rule out sterile neutrinos?

Standard cosmology: Yes Yvonne Wong's talk

Observing steriles would imply non-standard cosmology
(maybe learn about pre-BBN cosmology?) see e.g. Gelmini 2004

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Some thoughts

Is there any background that may explain LSND and MiniBooNE?

Does cosmology rule out sterile neutrinos?

Is there an explanation for the anomalies that is not ruled out?

Maybe, if

(1) non-minimal models (beyond oscillations) more on this later

(2) very baroque standard BSM scenarios (NSI+steriles) Liao et al 1810.01000

Explaining both LSND and MiniBooNE is typically a challenge

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Some thoughts

Is there any background that may explain LSND and MiniBooNE?

Does cosmology rule out sterile neutrinos?

Is there an explanation for the anomalies that is not ruled out?

Is there a strong theoretical motivation for eV steriles?

No. Yes. Maybe. Depends on who you ask…

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Some thoughts

Is there any background that may explain LSND and MiniBooNE?

Does cosmology rule out sterile neutrinos?

Is there an explanation for the anomalies that is not ruled out?

Is there a strong theoretical motivation for eV steriles?

Why do we need to solve this issue?

1) Because it could be new physics, we cannot miss any chance

2) Part of the future neutrino program depend on correctly estimating the backgrounds!

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Alternative explanations

New signatures:

Gninenko 1107.0279 No LSND

Heavy neutrino O(MeV), magnetic moment, decay

Bertuzzo et al 1807.09877, Ballett et al 1808.02916, Arguelles et al 1812.08768

Heavy neutrino O(1-100MeV), light Z', decay No LSND

Oscillations+:

Asaadi et al 1712.08019

Resonant matter effect UV challenge

Doring et al 1808.07460, Barenboim et al 1911.02329

eV steriles and extra dimensional shortcuts not clear

Liao et al 1810.01000

Steriles + NCNSI + CCNSI Baroque

Decay:

Bai et al 1512.05357, Dentler et al 1911.01427, de Gouvêa et al 1911.01447

Heavy sterile O(keV-MeV) decay to ν_e May work...

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Alternative explanations

New signatures:
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Heavy neutrino O(MeV), magnetic moment, decay

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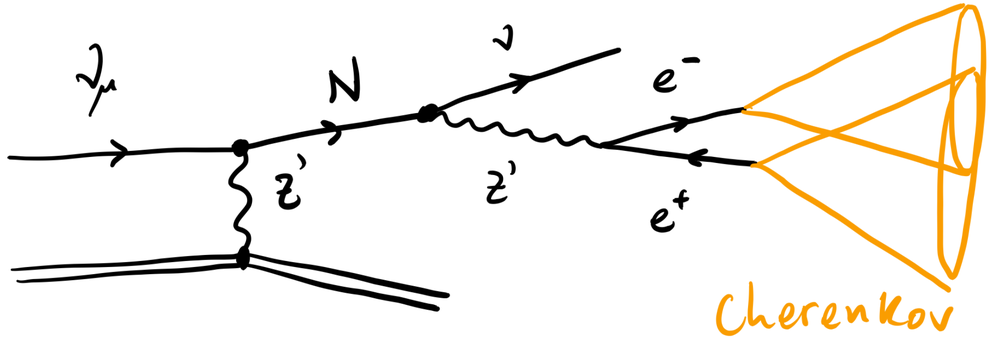
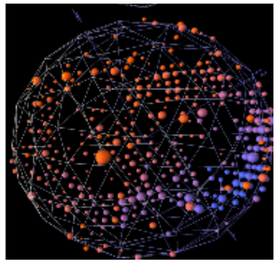
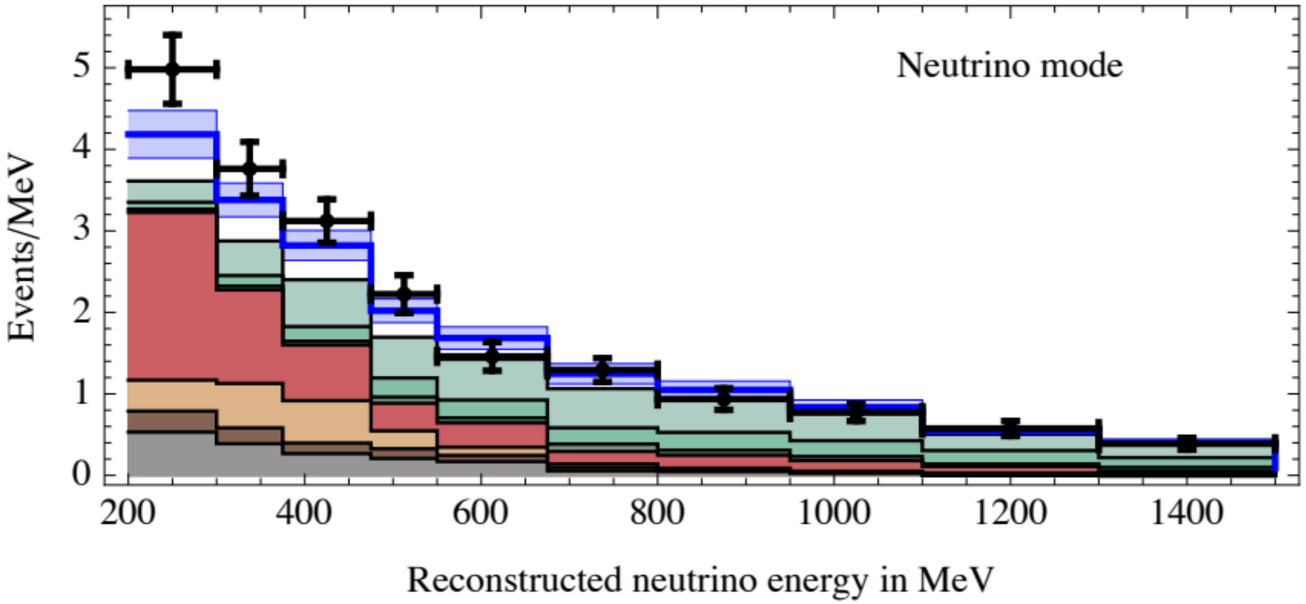




Explains only MiniBooNE avoiding tensions

UV complete scenario

MiniBooNE angular distribution? Epicycles to avoid large ν_e signals in LBL exps?



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Decay:
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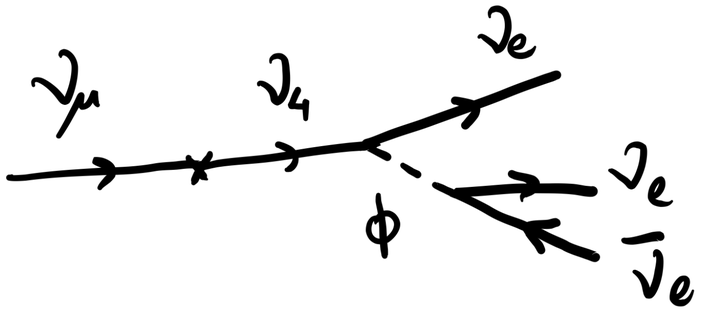
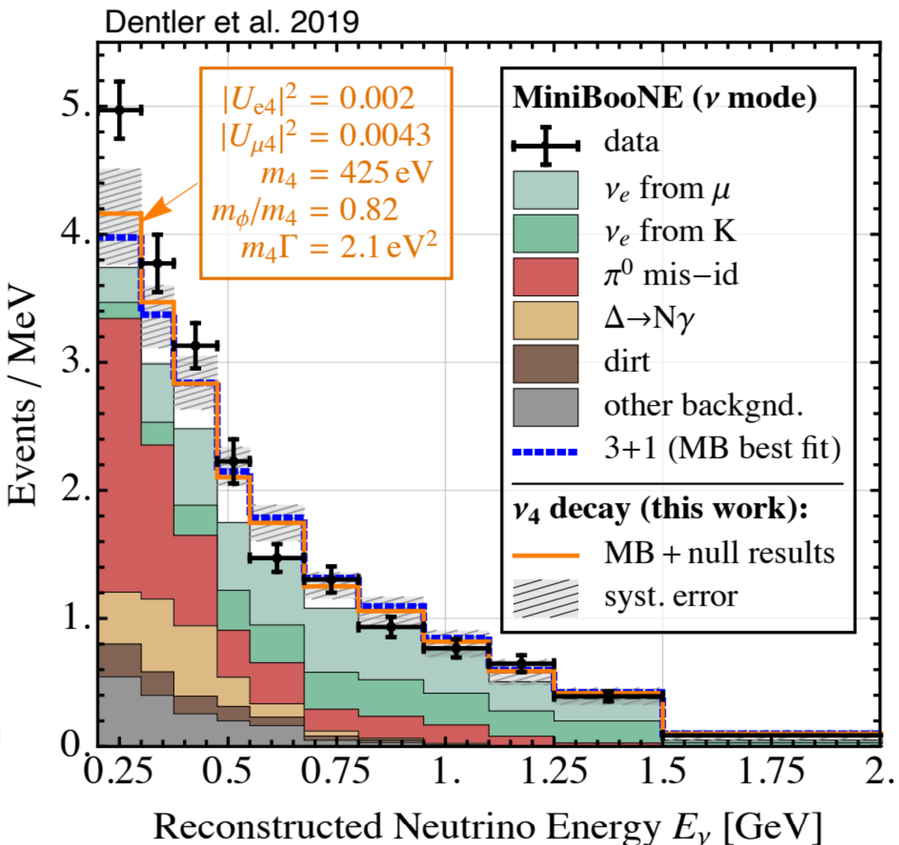
Heavy sterile O(keV-MeV) decay to ν_e



Explains MiniBooNE avoiding tensions

May explain MB + LSND + RAA (rate) and avoid tensions if NP is added to fix cosmology



See Moss et al 1711.05921

See Palomares-Ruiz Pascoli Schwetz hep-ph/0505216 for original proposal

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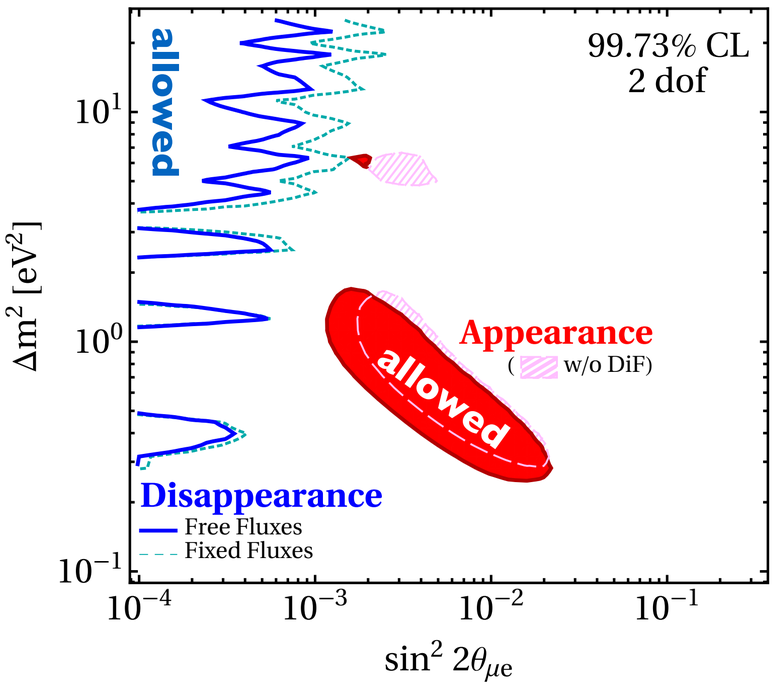
LSND and MiniBooNE anomalies remain unresolved



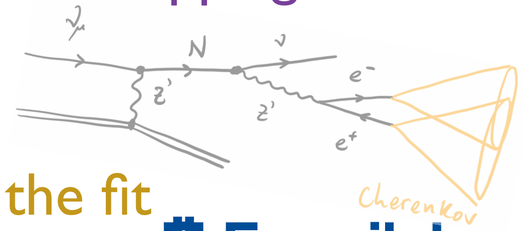
Calculations of reactor flux and gallium cross section may have **larger error bars than expected**
(did you see wiggles?)

Anomalies come from very diverse experiments, no common systematics or calculation can explain them

Sterile neutrino interpretation presents a **robust tension** between appearance and disappearance experiments that **does not depend on any single experiment**

Cosmology poses strong constraints on most models

Solutions are non-trivial or require dropping LSND
(why?)

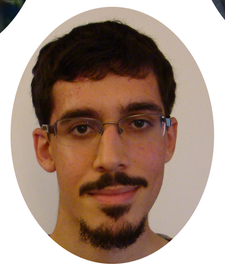


More steriles do not help the fit

Dentler

Hernández

Martínez



Esteban

Jana

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Backup

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Mixing with tau neutrinos

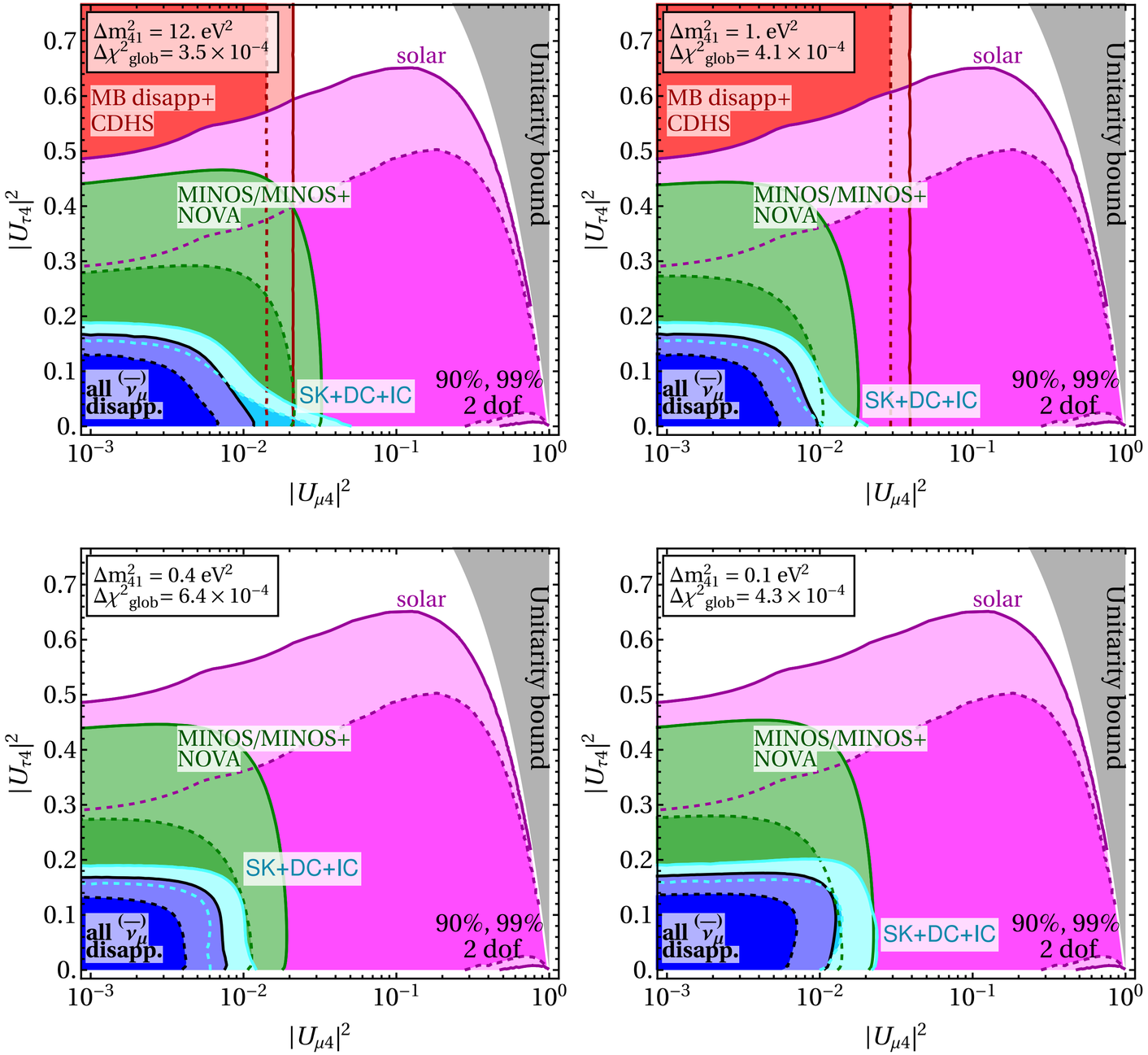
Fairly independent of Δm^2

Dominated by atmospherics

Allows for $|U_{\tau 4}|^2 \sim 0.15$,
that is $\sin^2\theta_{\tau\tau} \sim 0.5$

Consistent with
tau cross section determinations which
have a precision of ~20% @ 1σ

SK 1711.09436



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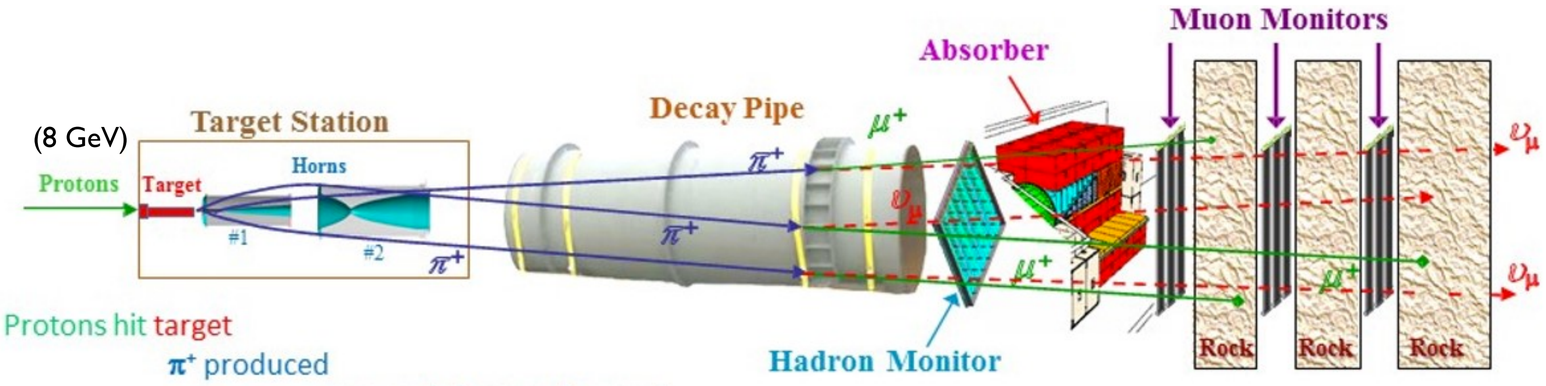
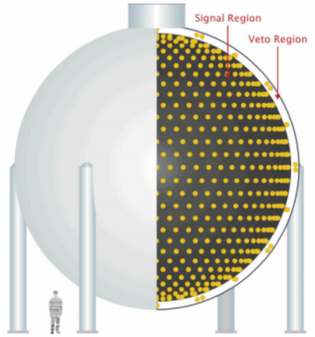
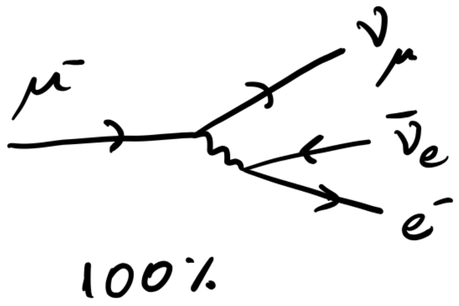
The MiniBooNE Collaboration

arXiv:1805.12028v1 [hep-ex]

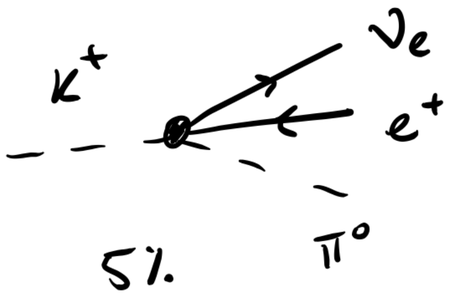
Observation of a Significant Excess of Electron-Like Events in the MiniBooNE Short-Baseline Neutrino Experiment

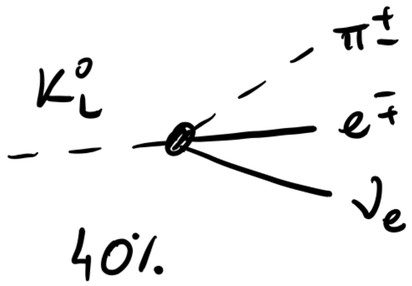


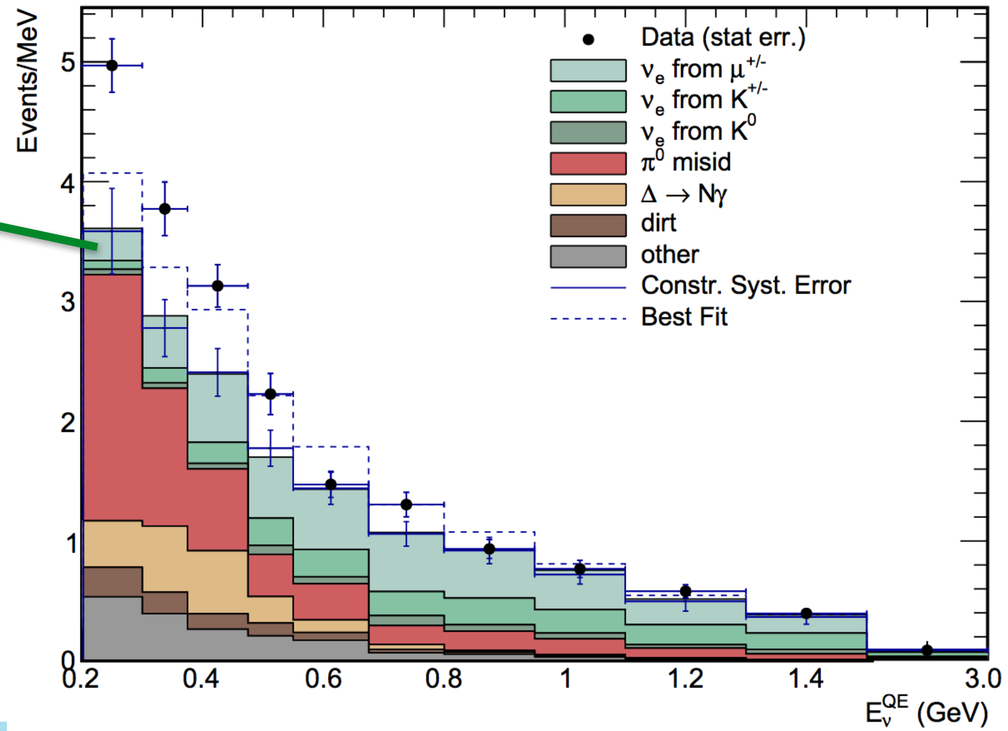




Constrained by Kaon production and SciBooNE data







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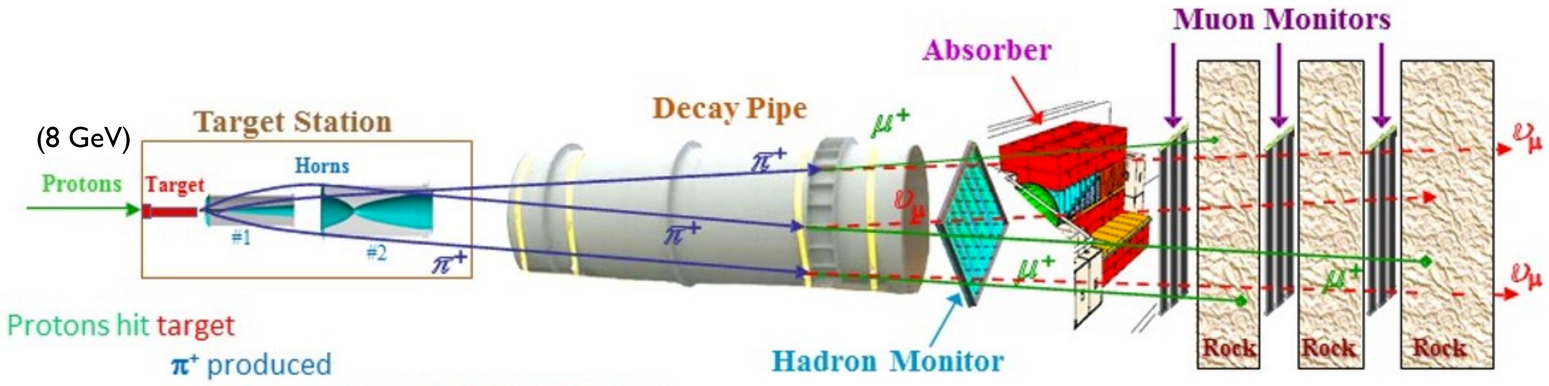
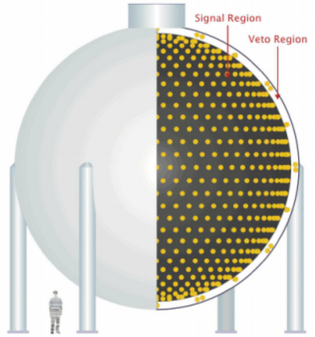
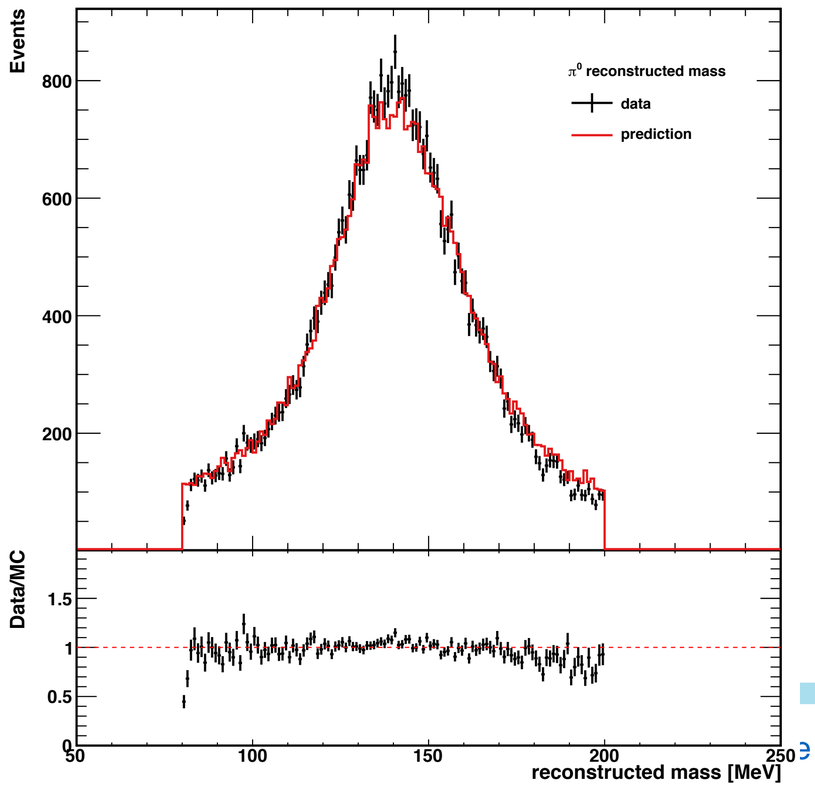
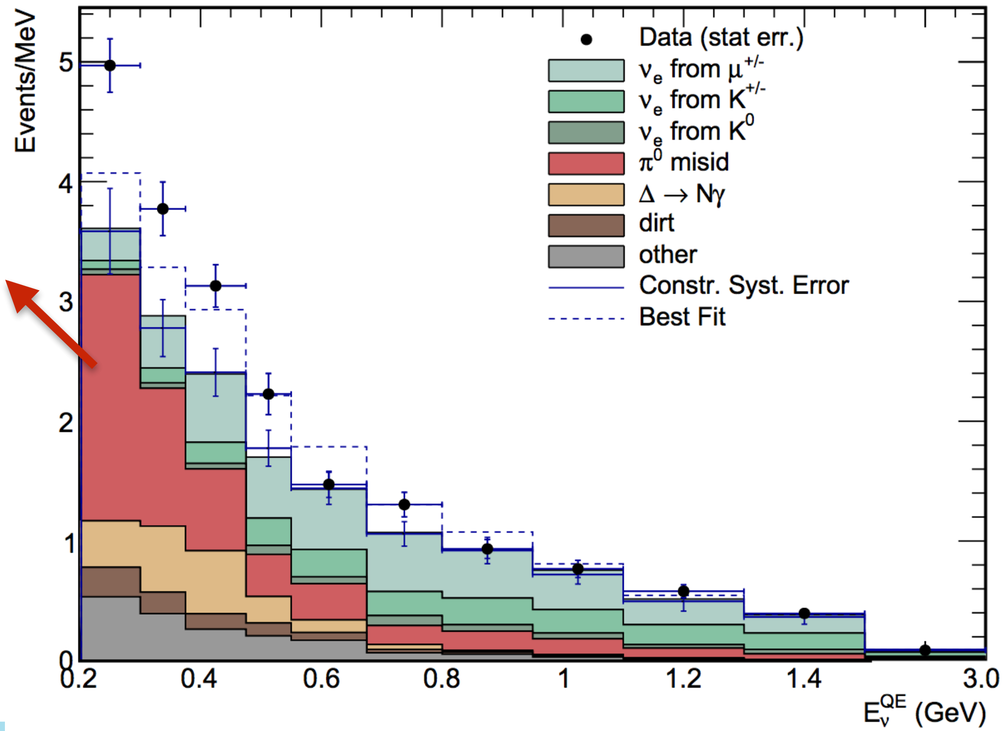






Constrained by double gamma sample in MiniBooNE using π^0 measurements



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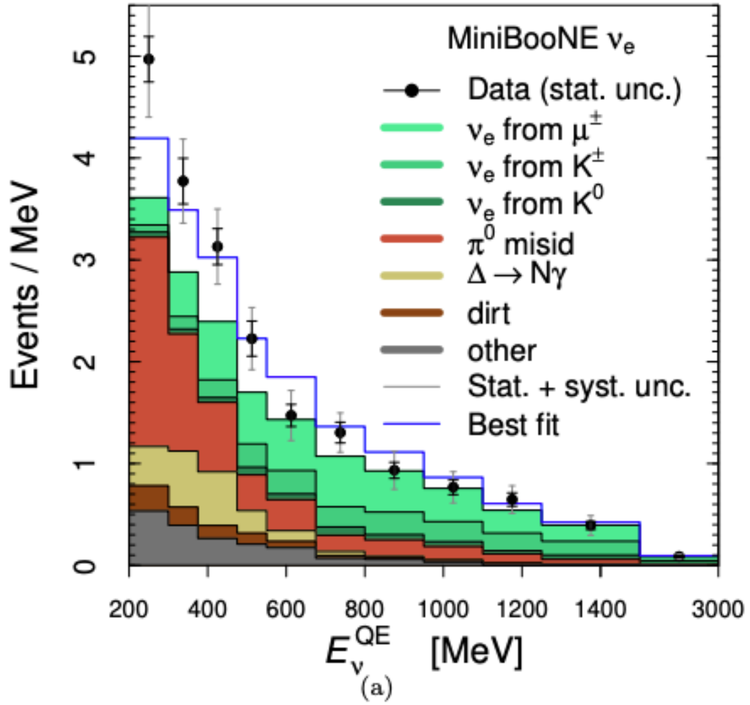
Criticism from Ioannisian 1909.08571 and Giunti et al 1912.01524 on Δ background

π^0 from Δ decay may excite another Δ or be absorbed in nucleus

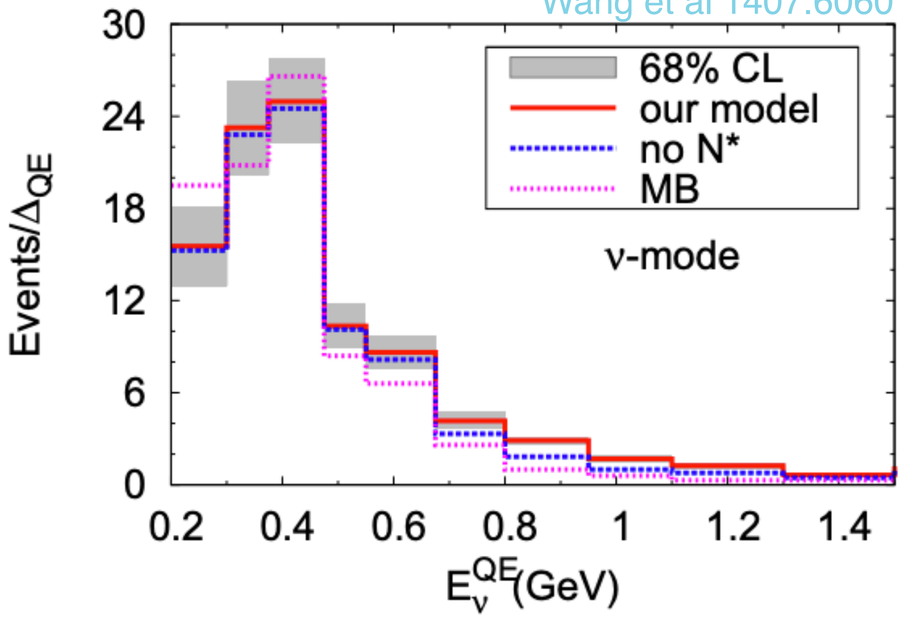
This could enhance the Δ background by a factor 2

MiniBooNE collaboration took this into account

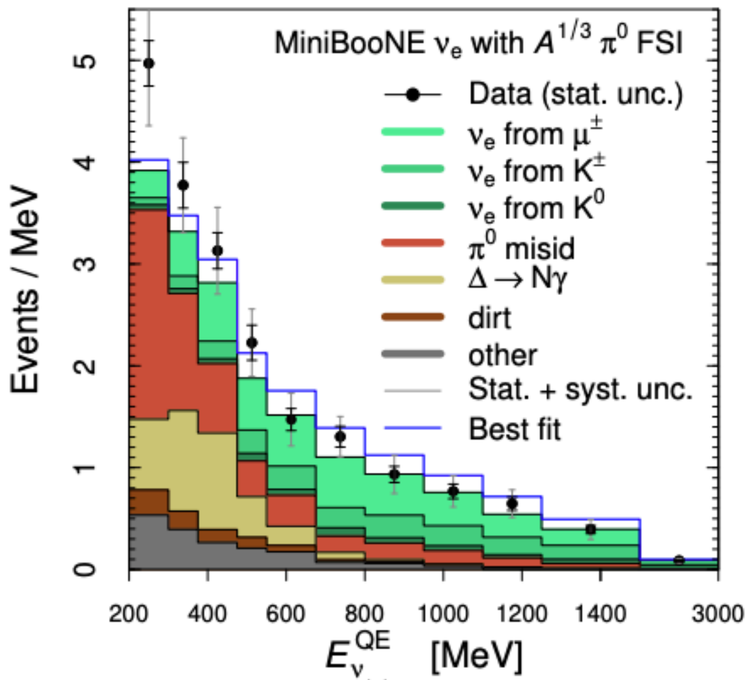
Nuclear TH calculations agree with MB estimate of Δ background



Wang et al 1407.6060



Ioannisian 1909.08571



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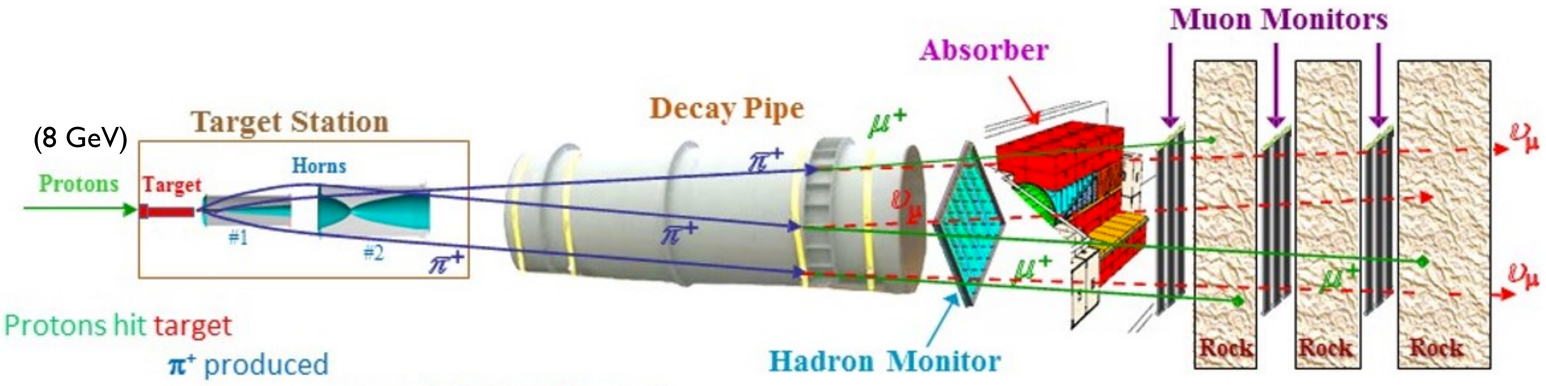

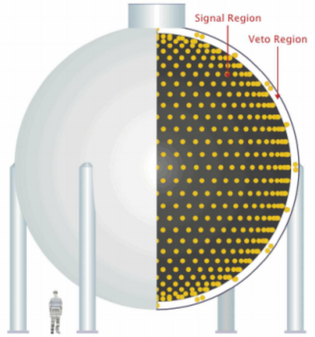

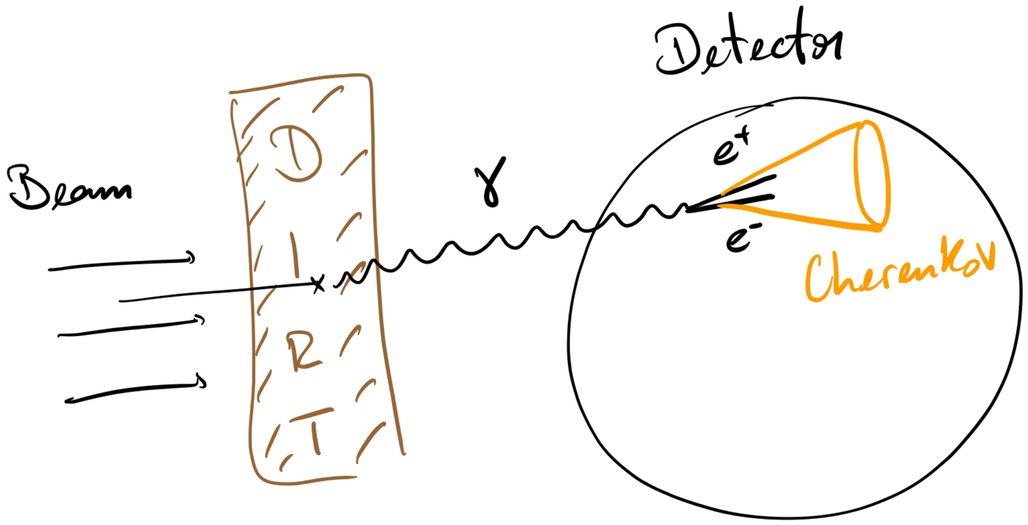

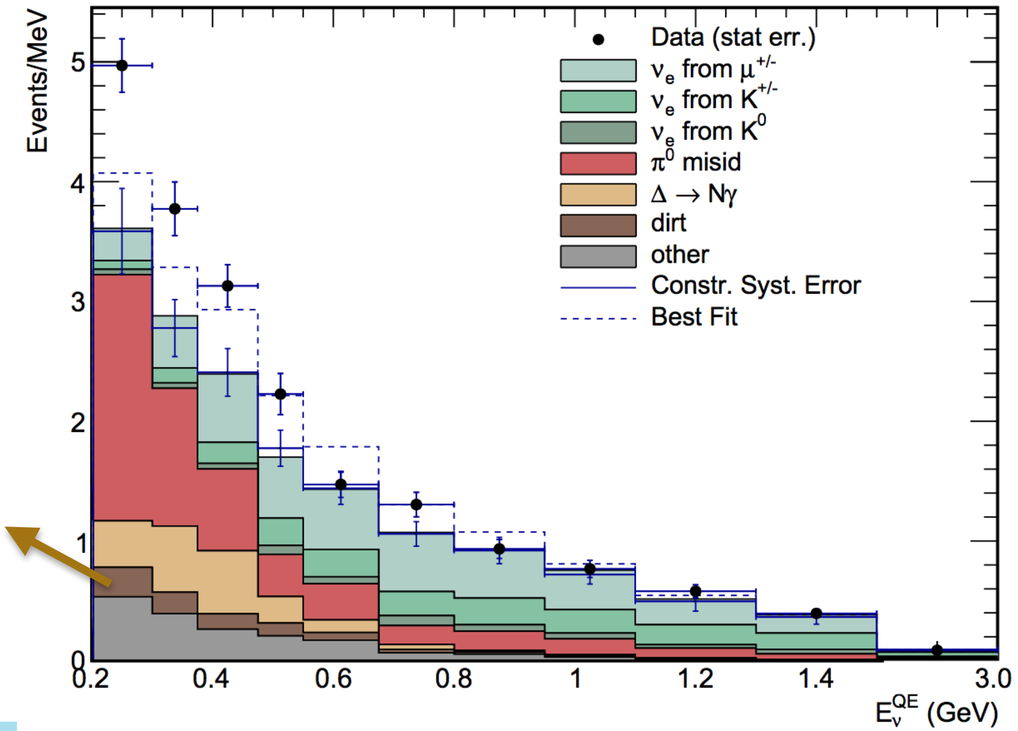

Topological cuts

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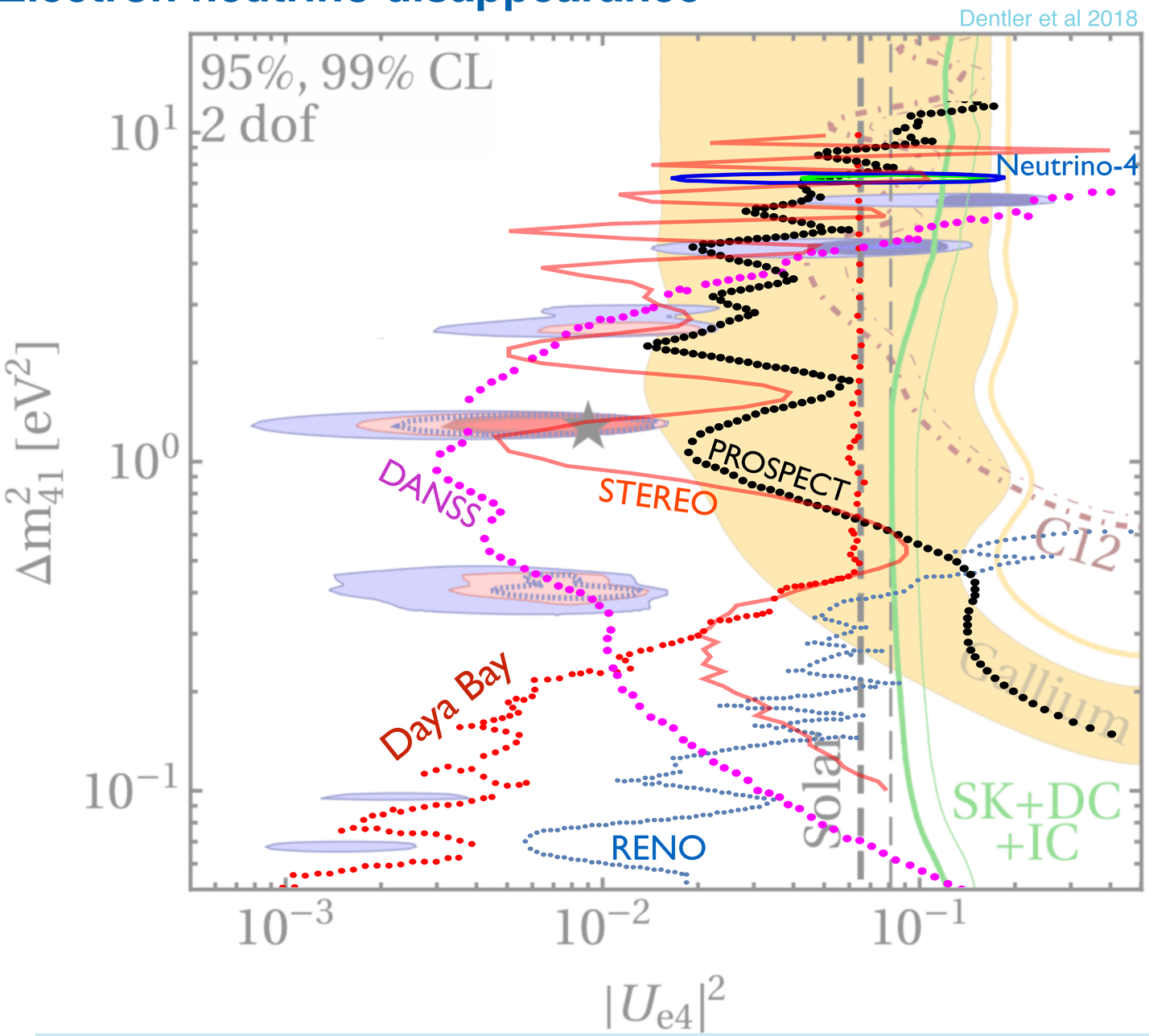
Electron neutrino disappearance



Radioactive source exps
GALLEX, SAGE

Reactor experiments
ILL, Goesgen, Krasnoyarsk, Rovno, Bugey-3, Bugey-4, SRP, NEOS, DANSS, Double Chooz,

ν_e

CAVEAT
We have assumed the test statistics to be χ^2 distributed.
Interpret this with a grain of salt!
This will not change the final results.
("3.2σ" <==> $\Delta\chi^2$ = 13.3)

SNO, Borexino

Atmospheric neutrinos
Super-Kami
DeepCore,

Analysis with free reactor flux prediction
Best fit:
Δm^2 = 1.3 eV^2, $|U_{e4}|^2$ = 0.009
"3.2σ"
Dominated by DANSS/NEOS

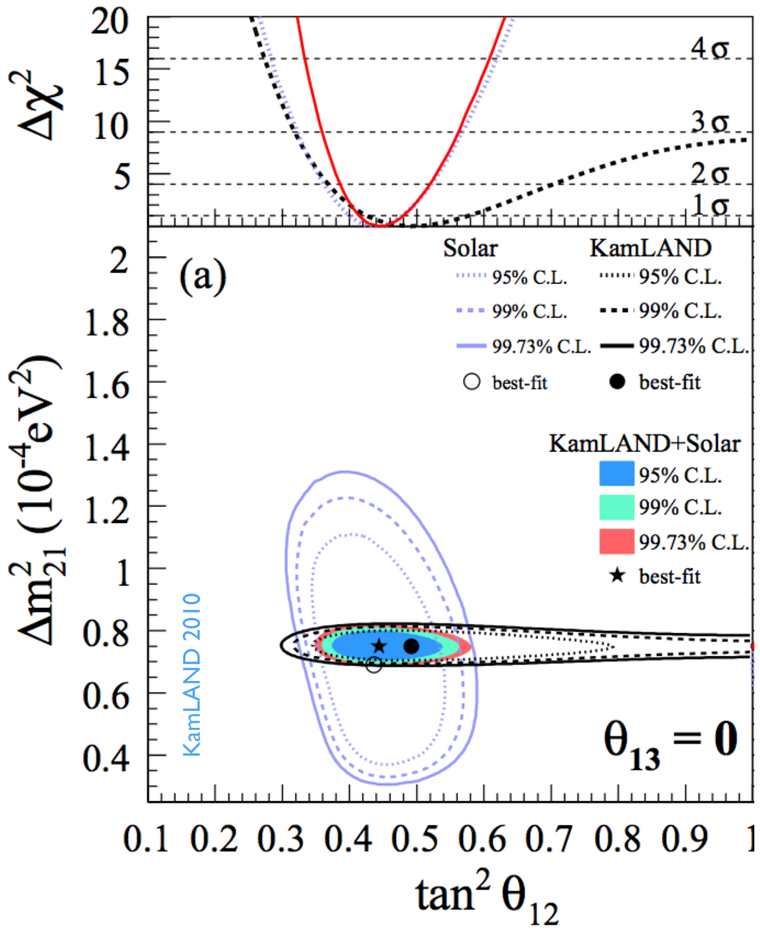
Electron neutrino disappearance

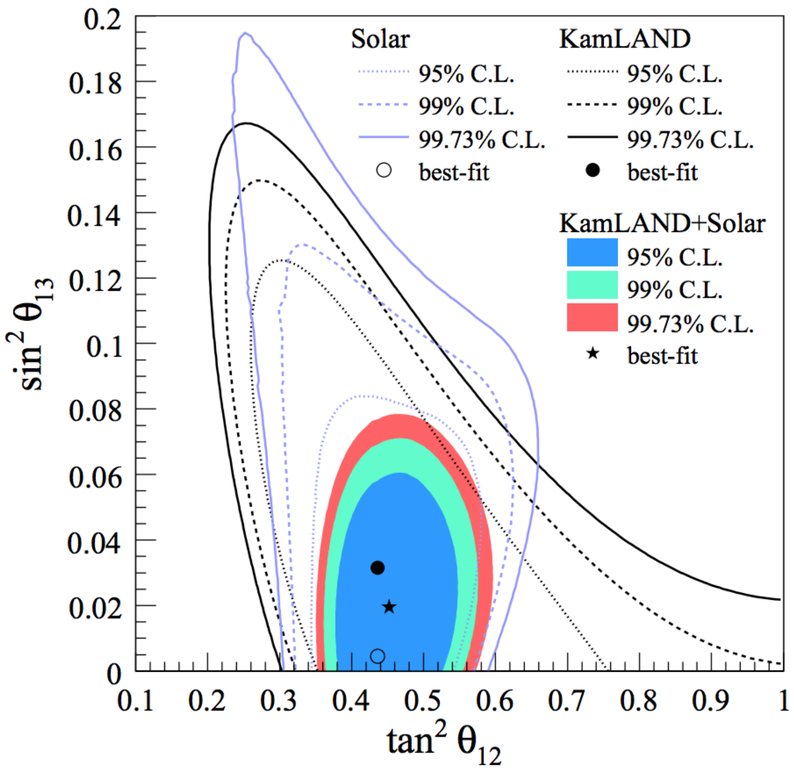
For ^{8}B solar ν:

$$P_{ee}^{sun} \simeq |U_{e2}|^2$$

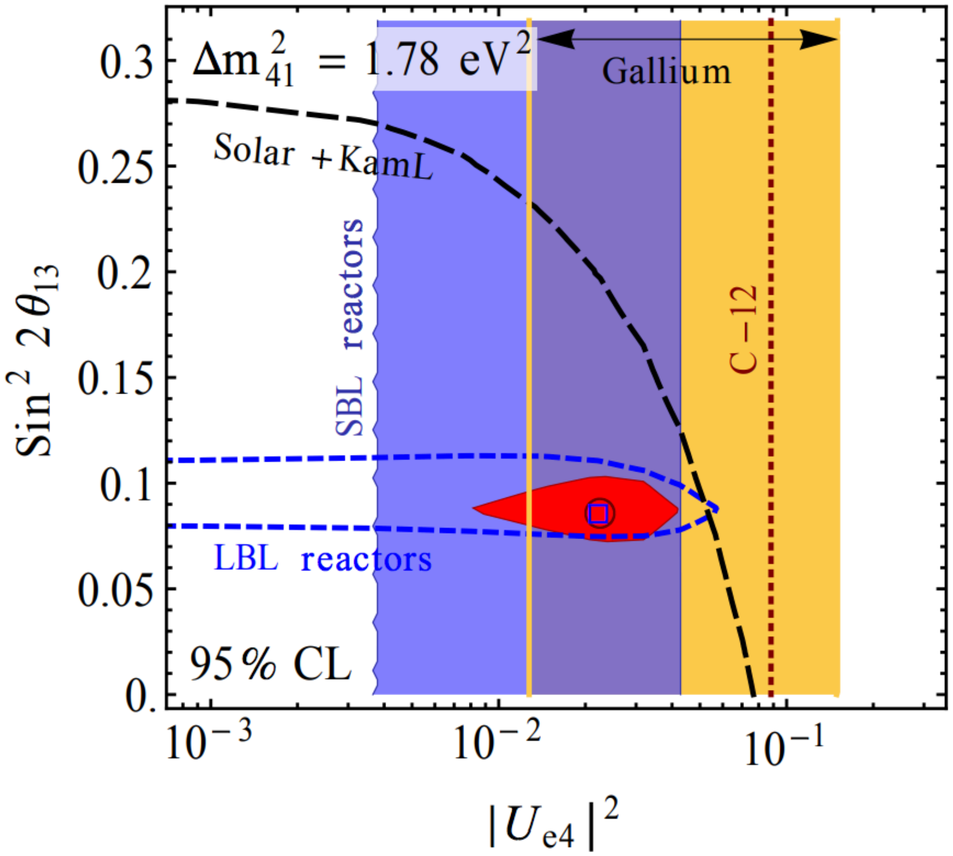
At KamLAND:

$$P_{ee}^{KL} \approx 1 - 4|U_{e1}U_{e2}|^2 \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right) - 2\left(|U_{e3}|^2 + |U_{e4}|^2\right) + \ldots$$





Dentler et al 2018



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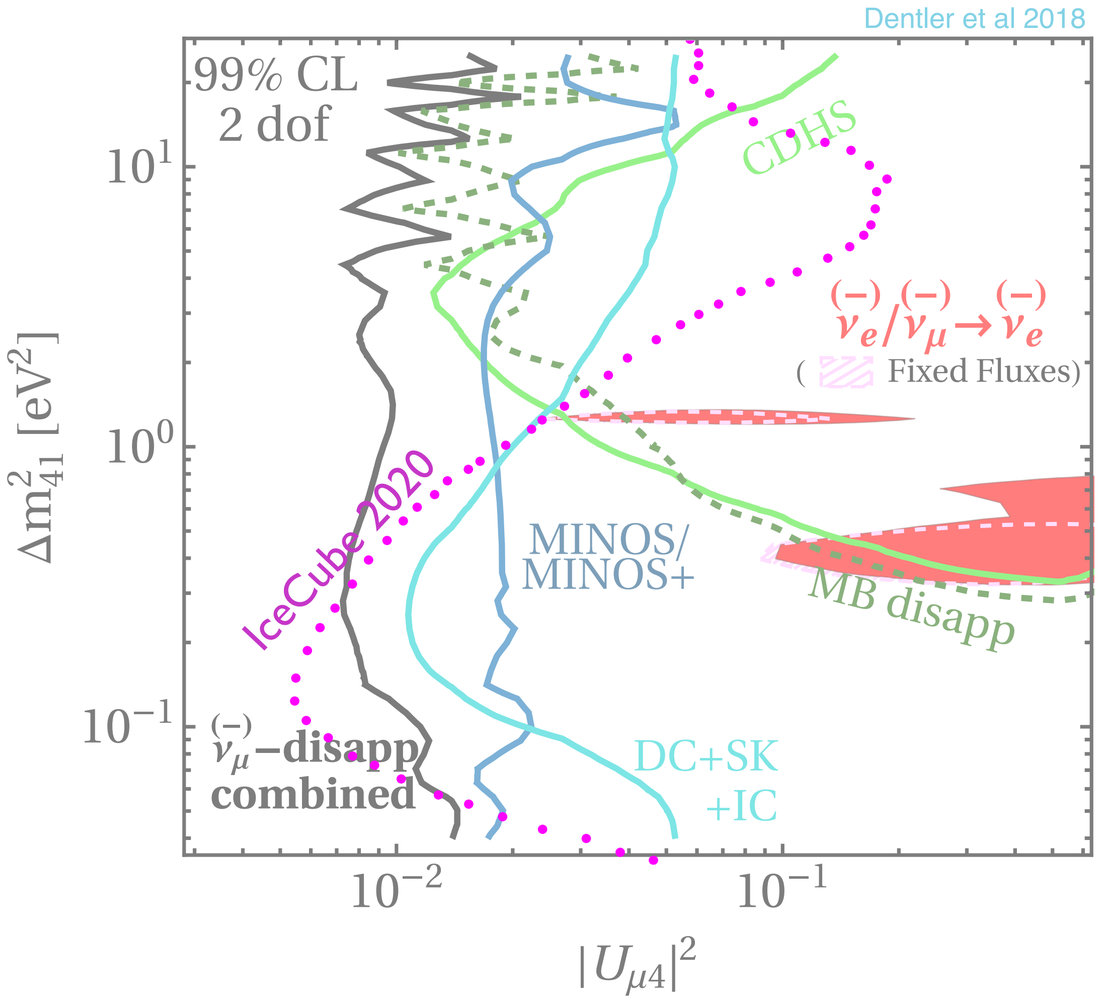
Muon neutrino disappearance



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

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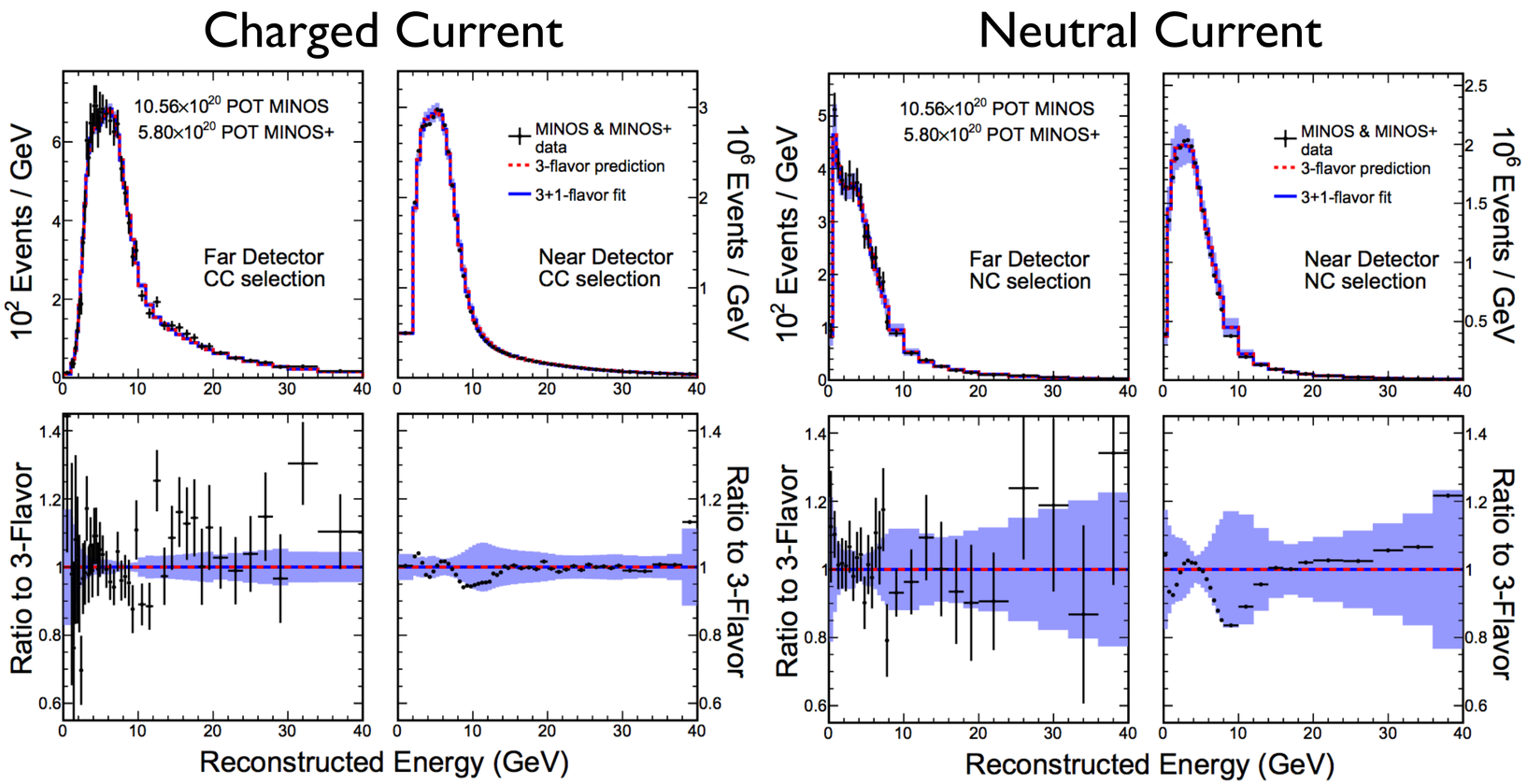
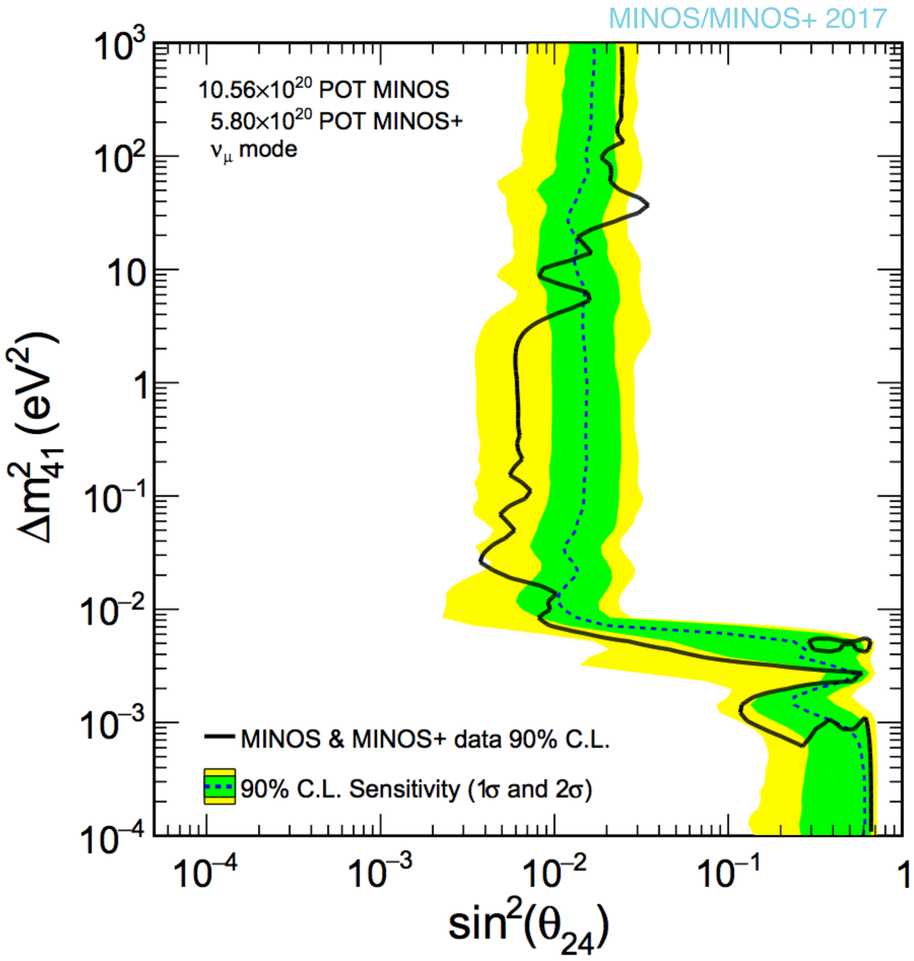
Muon neutrino disappearance





Though criticisms from Louis 1803.11488

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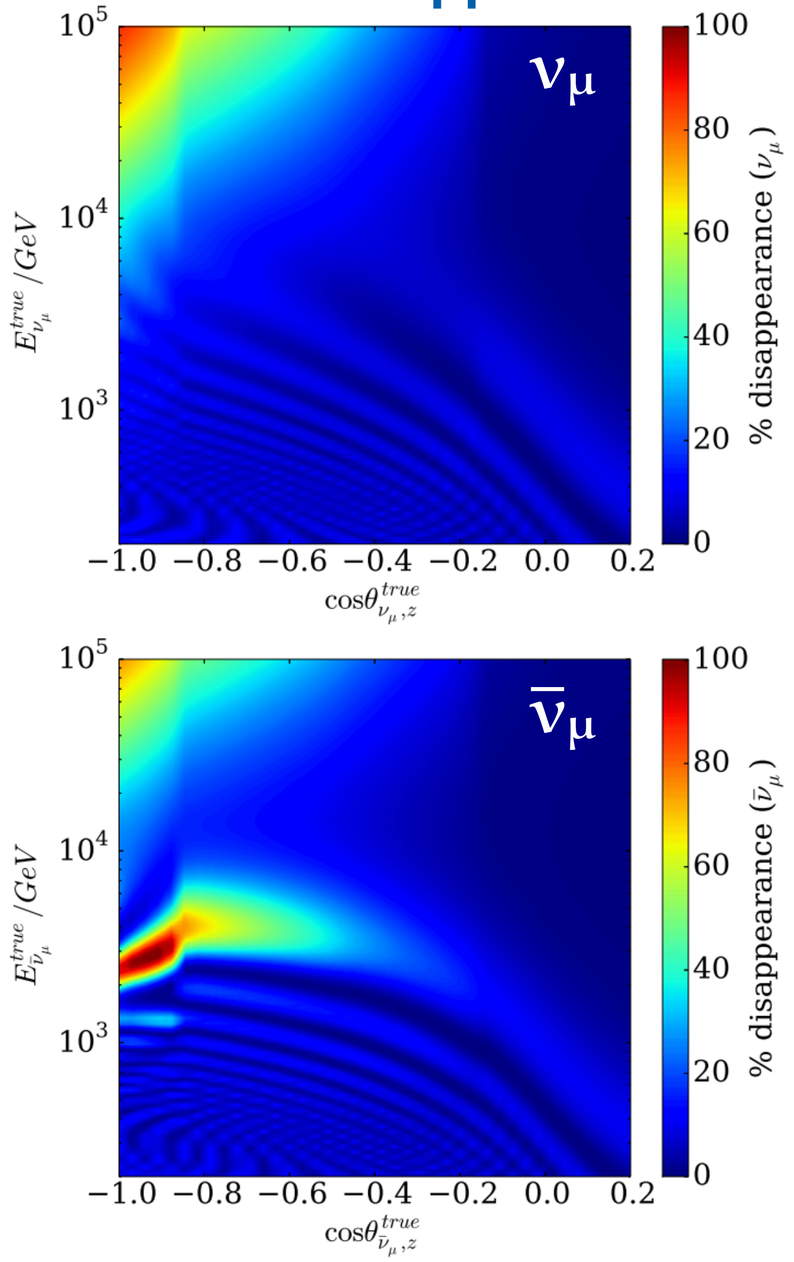
Muon neutrino disappearance



Standard oscillations

$$1.27 \frac{\Delta m^2/eV^2 \; L/km}{E/GeV}$$

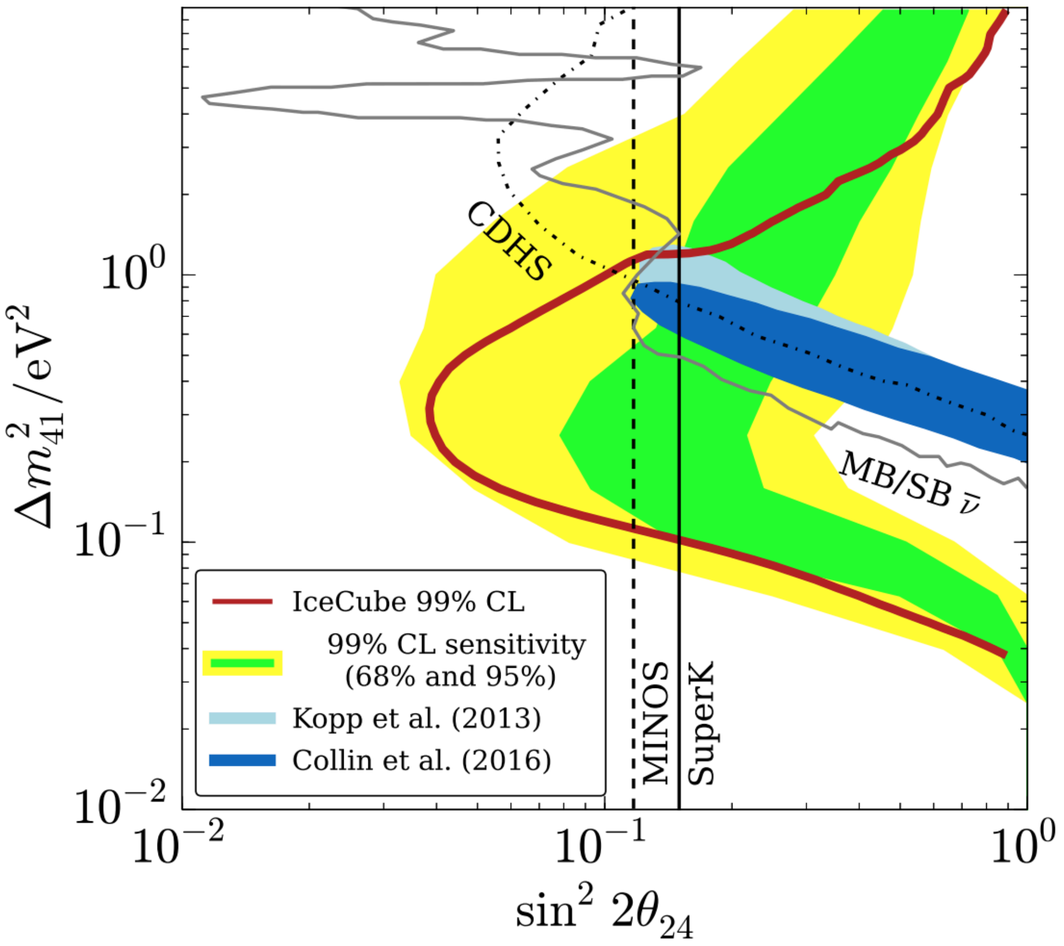
$$= 1.27 \frac{2.5\times10^{-3} \times 10^4}{10^3}$$

→ zero!

MSW effect when atmospheric neutrinos traverse the Earth induces a resonance to steriles

Nunokawa Peres Zukanovich-Funchal 2003

IceCube 2016



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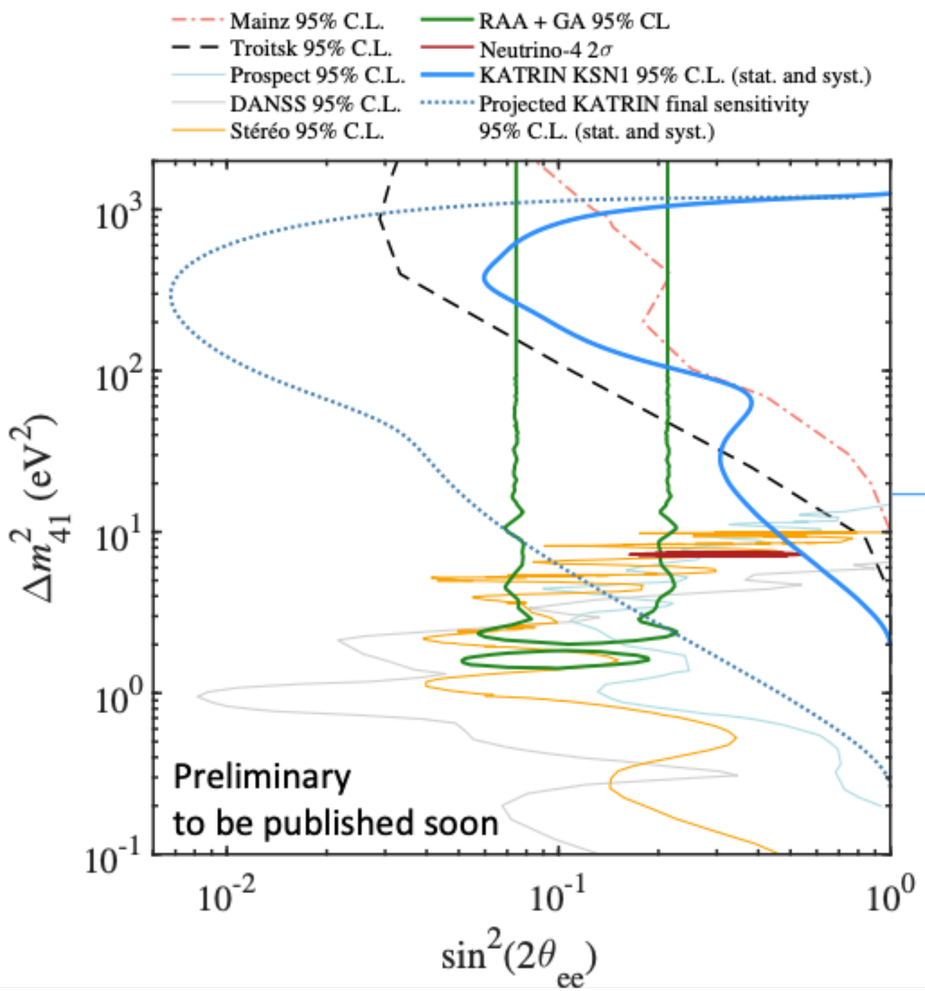
Susanne Mertens last Monday:

eV-scale sterile neutrino search

Poster #108
T. Lasserre et al



High Δm_{41} region:

- ✓ Improve exclusion with respect to DANSS, PROSPECT, and STEREO
- ✓ Exclude parameter space of Reactor Anomaly (RAA)

Low Δm_{41} region:

- ✓ Improve MAINZ and TROITSK limit
- ✓ The NEUTRINO-4 hint at the edge of exclusion limit

26

Data set	Reference	Data points	Relevant parameters
$\overset{(-)}{\nu}_e$ disappearance	Table I	594	Δm^2_{31}, Δm^2_{41}, θ_{12}, θ_{14}, θ_{24}, θ_{34}
$\overset{(-)}{\nu}_\mu$ disappearance	Table IV	504	Δm^2_{31}, Δm^2_{41}, θ_{23}, θ_{14}, θ_{24}, θ_{34}
$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ appearance (w/o LSND DiF)	Table III	69	Δm^2_{41}, $\lvert U_{e4}U_{\mu4}\rvert$
Total number of data points:		1167	

ν_e APP

Experiment	References	Comments	Data points
LSND	[1]	$\bar{\nu}_\mu$ from stopped pion source (DaR)	11
LSND	[1]	combined DaR and DiF data ($\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$)	N/A
MiniBooNE	[2, 99]	ν_μ and $\bar{\nu}_\mu$ from high-energy Fermilab beam	22
KARMEN	[94]	$\bar{\nu}_\mu$ from stopped pion source	9
NOMAD	[95]	ν_μ from high-energy CERN beam	1
E776	[96]	ν_μ from high-energy Brookhaven beam	24
ICARUS	[97, 98]	ν_μ from high-energy CERN beam	1
OPERA	[40]	ν_μ from high-energy CERN beam	1

ν_μ DIS

Experiment	References	Comments	Data points
IceCube (IC)	[52–54]	MSW resonance in high-E atmospheric $\bar{\nu}_\mu$	189
CDHS	[101]	accelerator ν_μ	15
MiniBooNE	[102, 103, 107]	accelerator ν_μ and $\bar{\nu}_\mu$	15 + 42
Super-Kamiokande (SK)	[48, 104]	low-E atmospheric neutrinos	70
DeepCore (DC)	[49, 50]	low-E atmospheric neutrinos	64
NOνA	[44]	NC data	1
MINOS/MINOS+	[43]	accelerator ν_μ, CC & NC event spectra	108

ν_e DIS

Experiment	References	Comments	(Data points)
Reactor experiments			(233)
ILL	[59]		
Gösgen	[60]		
Krasnoyarsk	[61–63]		
Rovno	[64, 65]		
Bugey-3	[66]	spectra at 3 distances with free bin-by-bin normalization	
Bugey-4	[67]		
SRP	[68]		
NEOS	[23, 29]	ratio of NEOS and Daya Bay spectra	
DANSS	[26]	ratios of spectra at two baselines (updated w.r.t. [21])	
Double Chooz	[33]	near detector rate	
RENO	[69, 70]	near detector rate	
Daya Bay spectrum	[71]	spectral ratios EH3/EH1 and EH2/EH1	
Daya Bay flux	[37]	individual fluxes for each isotope (EH1, EH2)	
KamLAND	[72]	very long-baseline reactor experiment ($L \gg 1\,\mathrm{km}$)	
Solar neutrino experiments			(325)
Chlorine	[73]		
GALLEX/GNO	[74]		
SAGE	[75]		
Super-Kamiokande	[45, 76–78]	Phases I–IV	
SNO	[79–81]	Phases 1–3 (CC and NC data)	
Borexino	[46, 82, 83]	Phases I and II	
ν_e scattering on carbon ($\nu_e + {}^{12}\mathrm{C} \to \mathrm{e}^- + {}^{12}\mathrm{N}$)			(32)
KARMEN	[84–86]		
LSND	[86, 87]		
Radioactive source experiments (gallium)			(4)
GALLEX	[74, 88]	ν_e from ^{51}Cr source	
SAGE	[89, 90]	ν_e from ^{51}Cr and ^{37}Ar sources	

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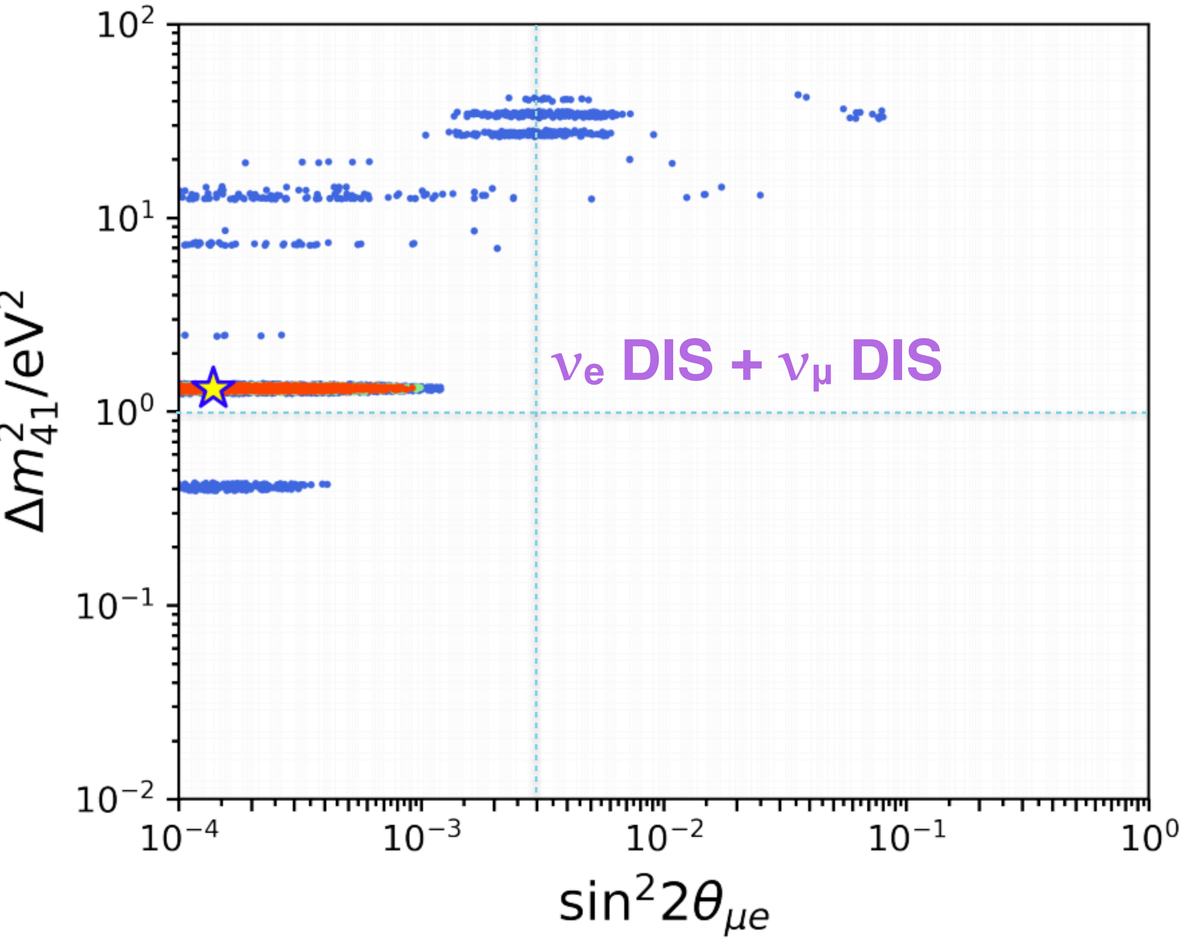
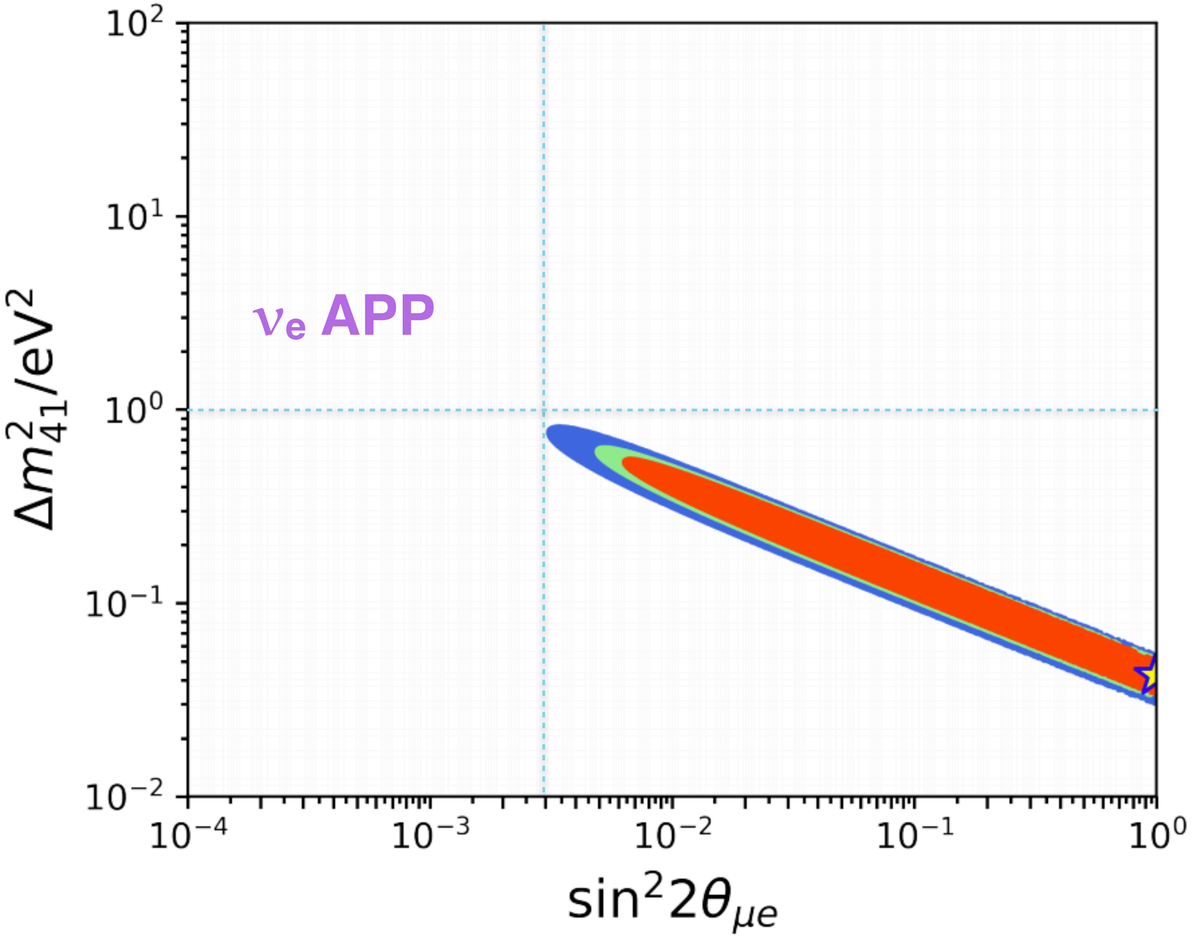
Where Are We With Light Sterile Neutrinos?

A. Diaz[1], C.A. Argüelles[1], G.H. Collin[1], J.M. Conrad[1], M.H. Shaevitz[2]
[1] *Massachusetts Institute of Technology, Cambridge, MA 02139, USA and*
[2] *Columbia University, New York, NY 10027, USA*





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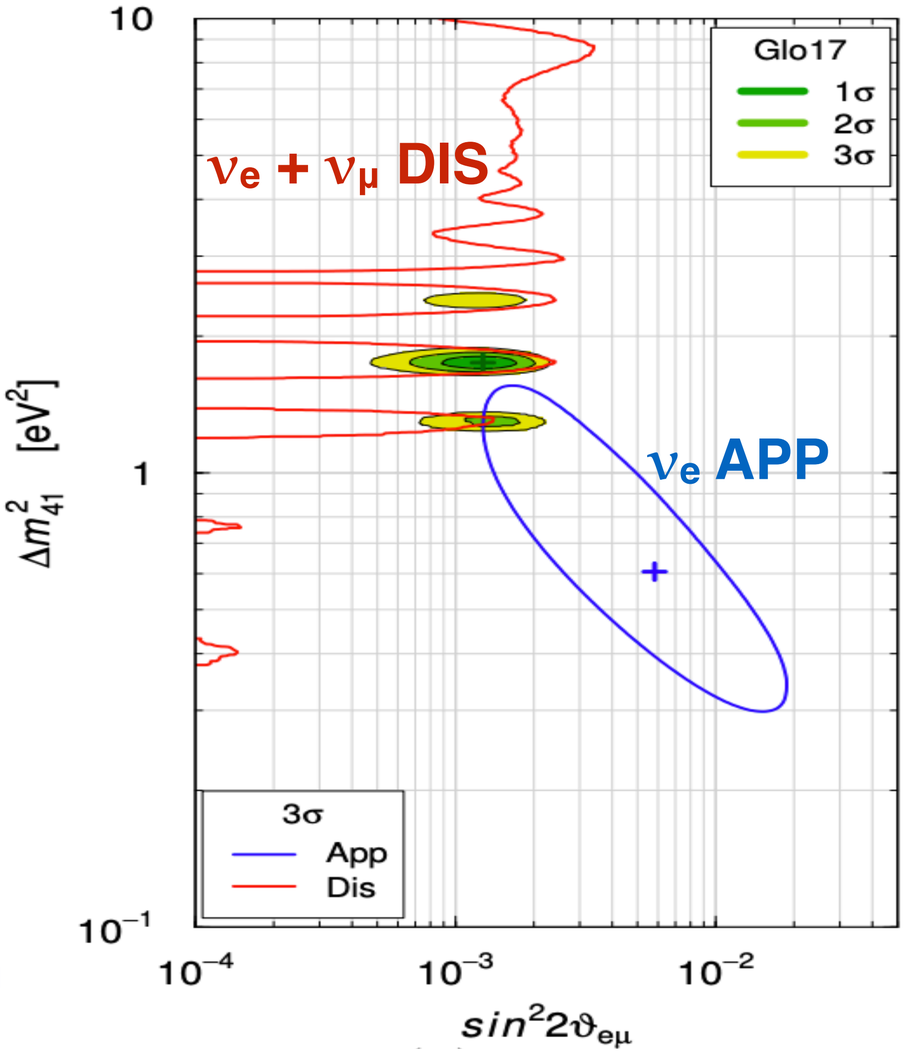
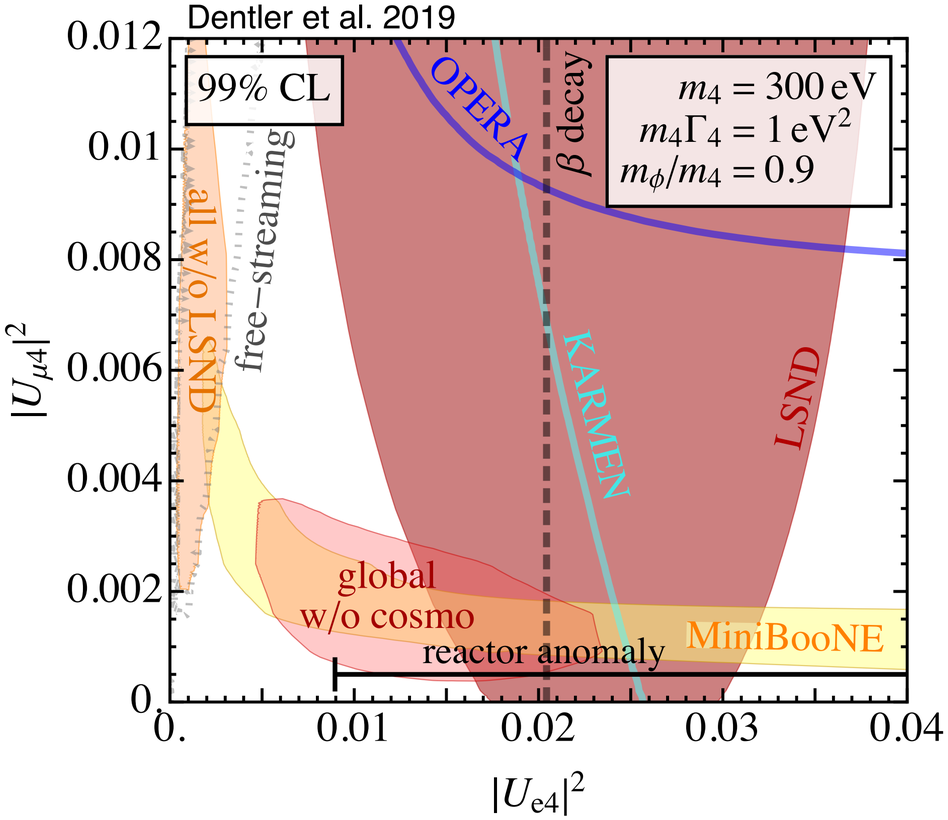
Updated Global 3+1 Analysis of Short-BaseLine Neutrino Oscillations

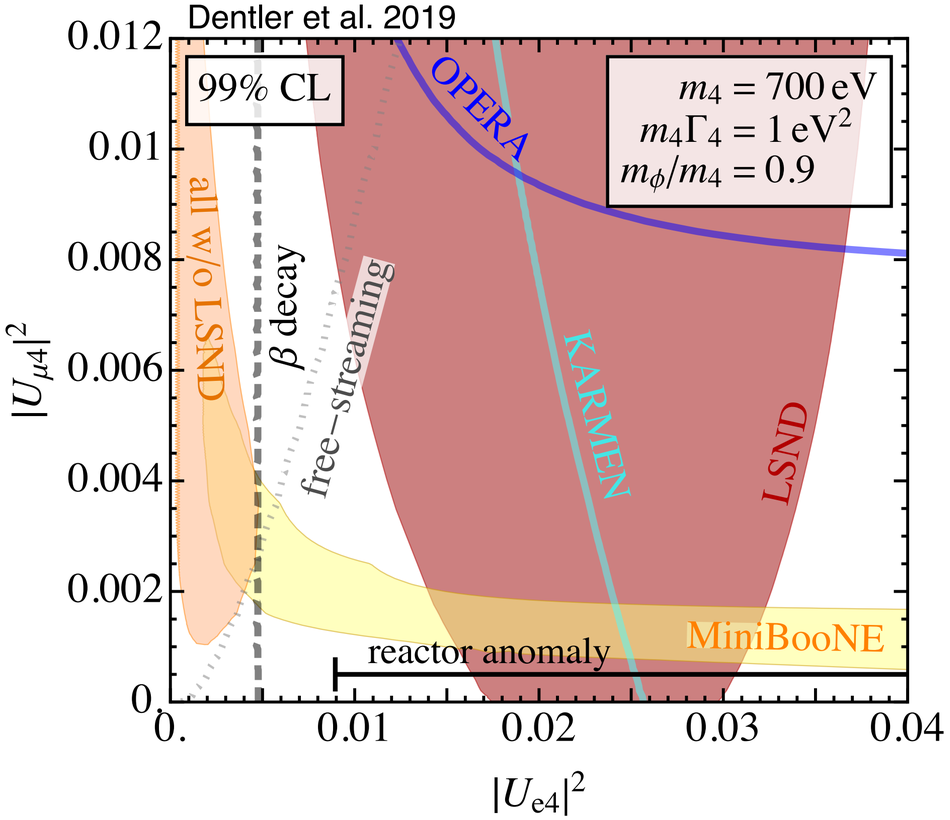
S. Gariazzo,[a] C. Giunti,[b] M. Laveder,[c,d] and Y.F. Li[e]

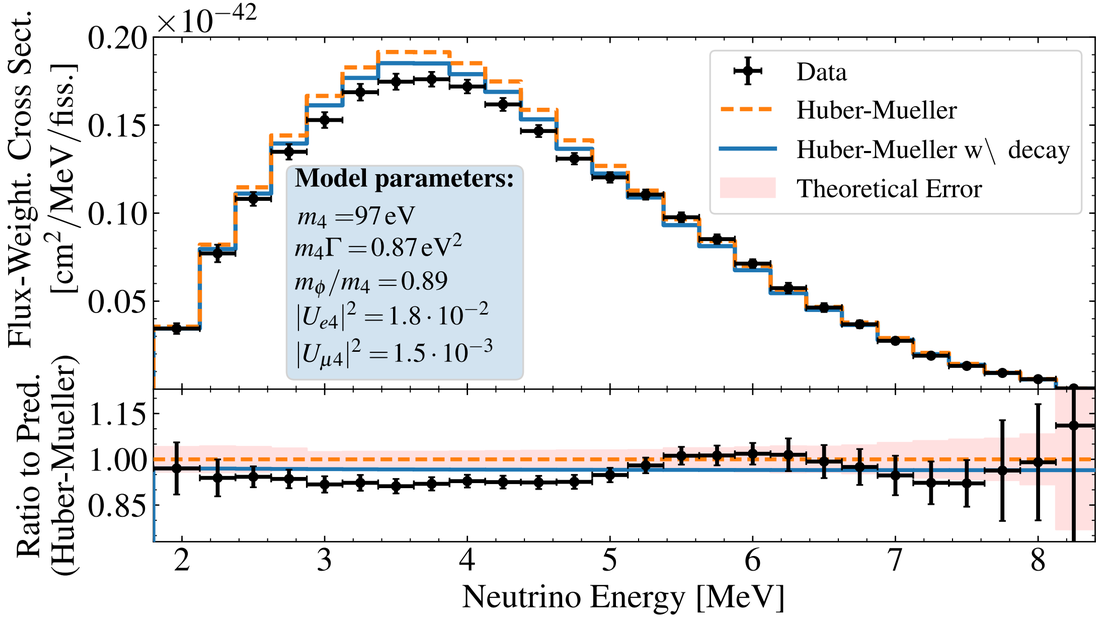


PG = 0.019%

	Glo16A	Glo16B	Glo17	PrGlo17
$\chi^2_{\rm min}$	288.4	556.9	622.1	595.1
NDF	250	525	585	579
GoF	4.8%	16%	14%	31%
Δm^2_{41}	1.6	1.6	1.7	1.7
$\lvert U_{e4}\rvert^2$	0.027	0.028	0.021	0.020
$\lvert U_{\mu4}\rvert^2$	0.015	0.014	0.016	0.015
$\sin^2 2\vartheta_{e\mu}$	0.0015	0.0015	0.0013	0.0012
$\sin^2 2\vartheta_{ee}$	0.10	0.11	0.080	0.079
$\sin^2 2\vartheta_{\mu\mu}$	0.058	0.054	0.062	0.058
$\Delta\chi^2_{\rm NO}$	53.1	51.9	51.7	47.4
$\rm NDF_{NO}$	3	4	4	4
$n\sigma_{\rm NO}$	6.7	6.4	6.4	6.1
$(\chi^2_{\rm min})_{\rm App}$	94.3	94.3	94.3	77.3
$\rm NDF_{App}$	84	84	84	78
$\rm GoF_{App}$	21%	21%	21%	50%
Δm^2_{41}	0.61	0.61	0.61	0.97
$\sin^2 2\vartheta_{e\mu}$	0.0058	0.0058	0.0058	0.0026
$(\chi^2_{\rm min})_{\rm Dis}$	180.8	448.3	510.6	510.6
$\rm NDF_{Dis}$	163	439	499	499
$\rm GoF_{Dis}$	16%	37%	35%	35%
Δm^2_{41}	1.7	1.7	1.7	1.7
$\lvert U_{e4}\rvert^2$	0.025	0.025	0.017	0.017
$\lvert U_{\mu4}\rvert^2$	0.011	0.0088	0.0073	0.0073
$\sin^2 2\vartheta_{e\mu}$	0.0011	0.00086	0.00048	0.00048
$\sin^2 2\vartheta_{ee}$	0.097	0.097	0.065	0.065
$\sin^2 2\vartheta_{\mu\mu}$	0.042	0.035	0.029	0.029
$\Delta\chi^2_{\rm PG}$	13.4	14.4	17.2	7.2
$\rm NDF_{PG}$	2	2	2	2
$\rm GoF_{PG}$	0.13%	0.075%	0.019%	2.7%







Decaying Sterile Neutrinos and the Short Baseline Oscillation Anomalies

Mona Dentler,[1,a] Ivan Esteban,[2,b] Joachim Kopp,[3,4,c] and Pedro Machado[5,d]

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

re

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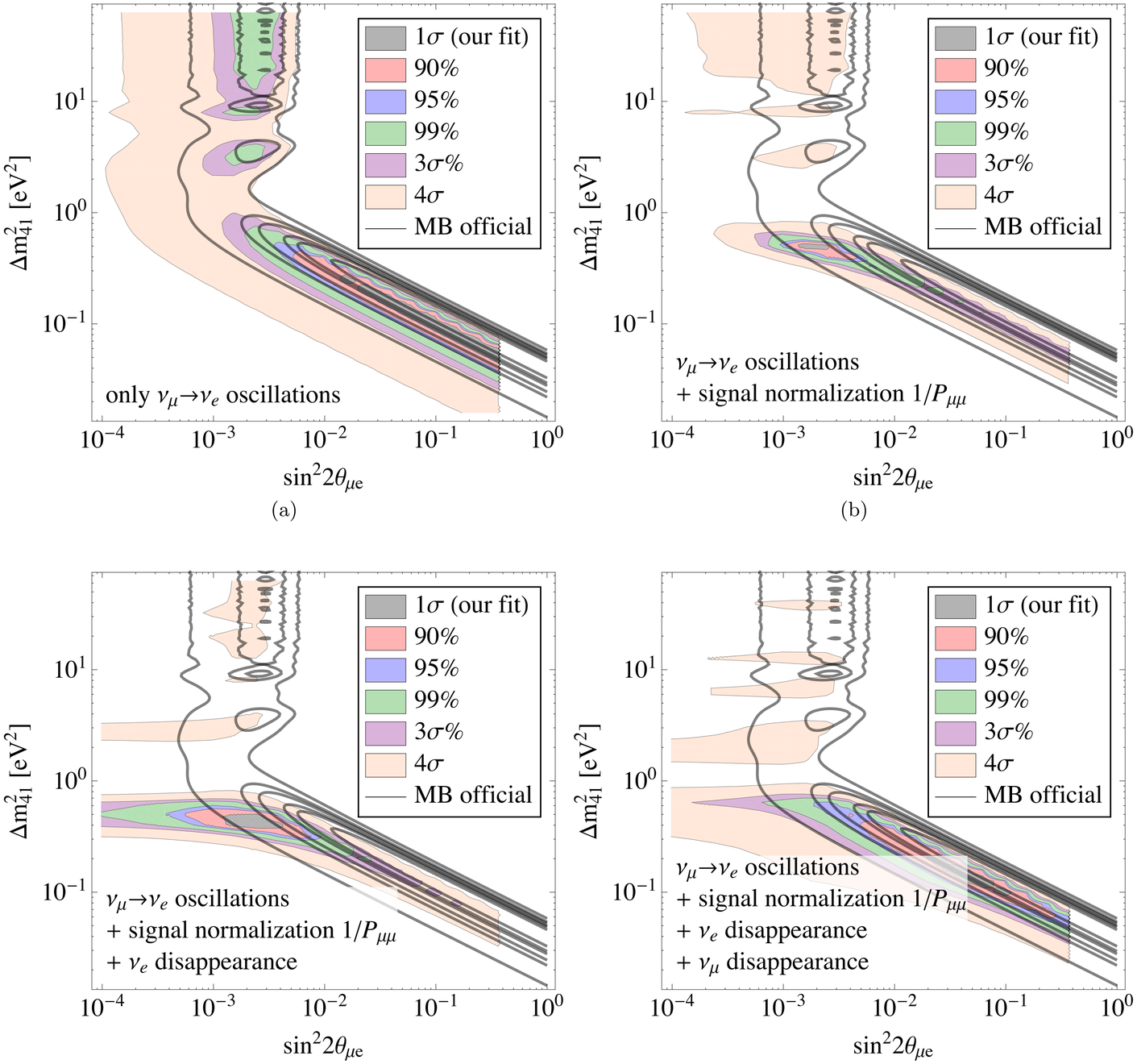

Decaying Sterile Neutrinos and the Short Baseline Oscillation Anomalies

Mona Dentler,[1,a] Ivan Esteban,[2,b] Joachim Kopp,[3,4,c] and Pedro Machado[5,d]

Some MiniBooNE backgrounds oscillate, and that should change the allowed regions.
(This is not taken into account by the collaboration.)

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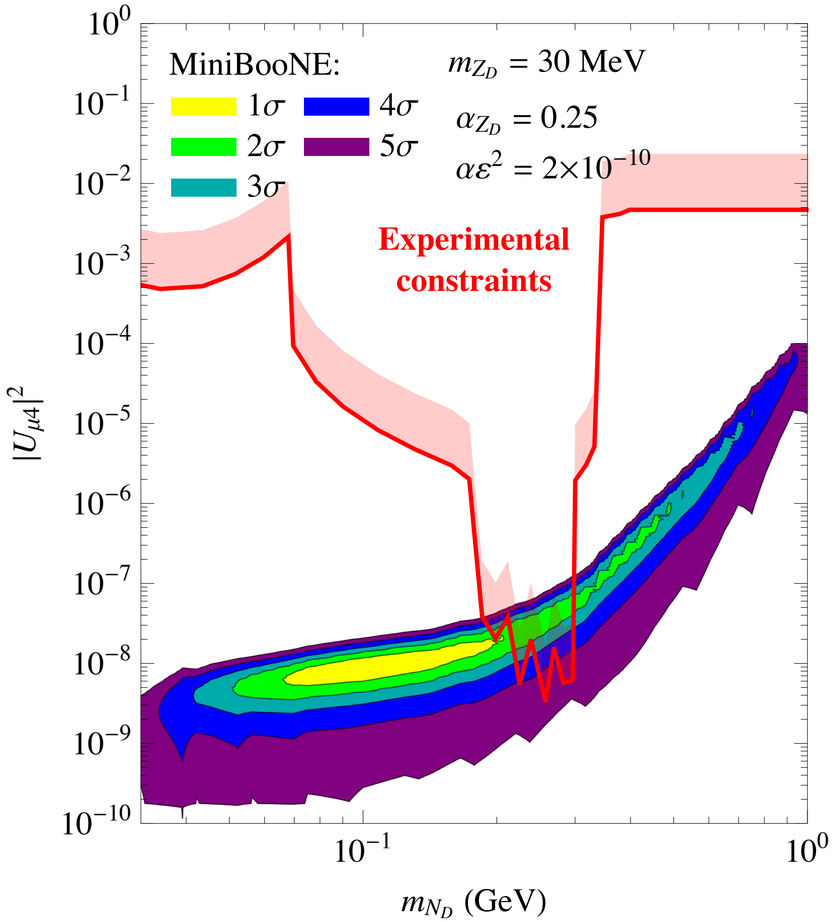
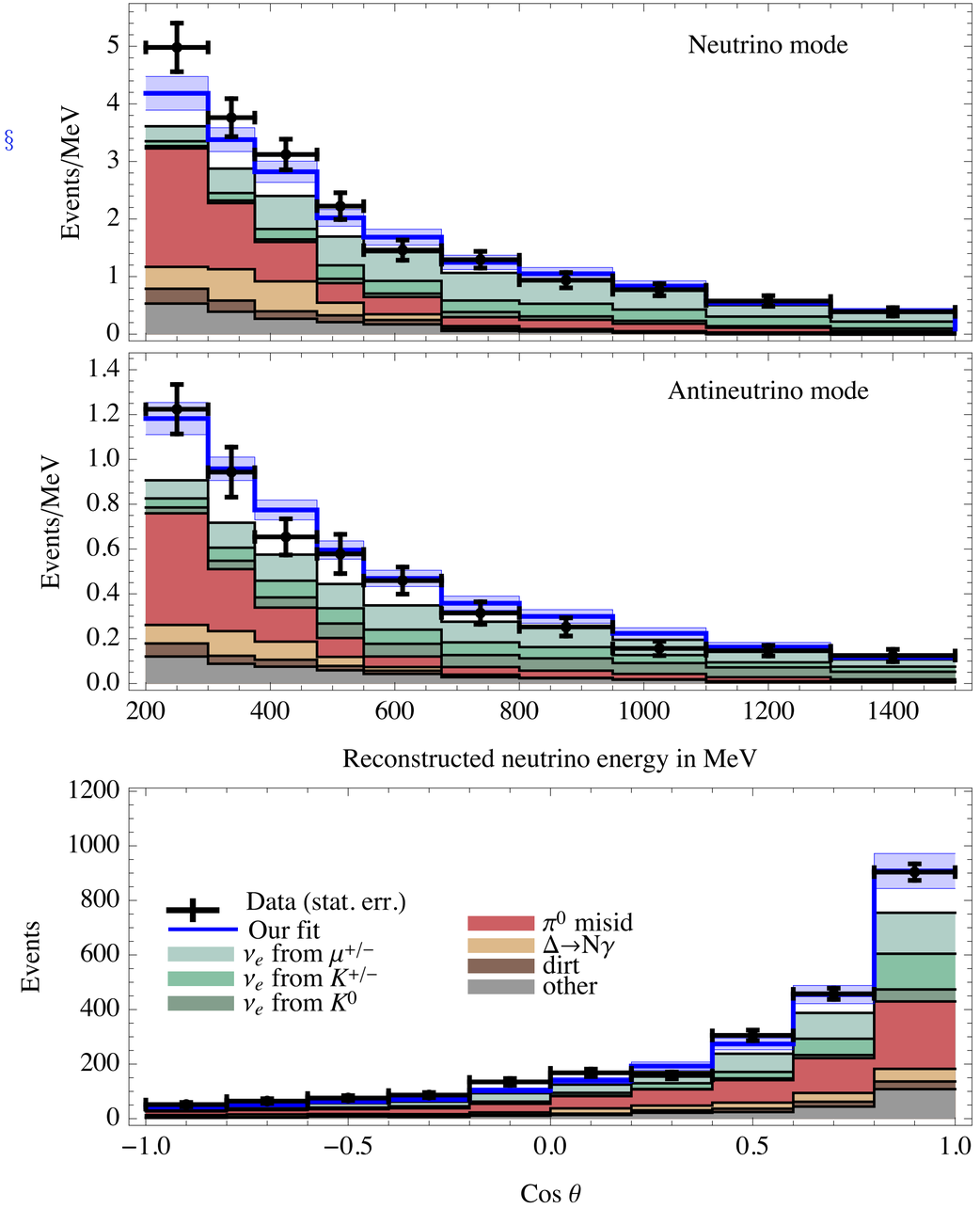
Dark Neutrino Portal to Explain MiniBooNE excess

Enrico Bertuzzo,[1,*] Sudip Jana,[2,3,†] Pedro A. N. Machado,[3,‡] and Renata Zukanovich Funchal[1,§]

$$\mathcal{L}_{\mathcal{D}} \supset \frac{m_{Z_{\mathcal{D}}}^2}{2} Z_{\mathcal{D}\mu} Z_{\mathcal{D}}^{\mu} + g_{\mathcal{D}} Z_{\mathcal{D}}^{\mu} \bar{\nu}_{\mathcal{D}} \gamma_{\mu} \nu_{\mathcal{D}} + e\epsilon\, Z_{\mathcal{D}}^{\mu} J_{\mu}^{\rm em} + \frac{g}{c_W} \epsilon'\, Z_{\mathcal{D}}^{\mu} J_{\mu}^{Z}$$





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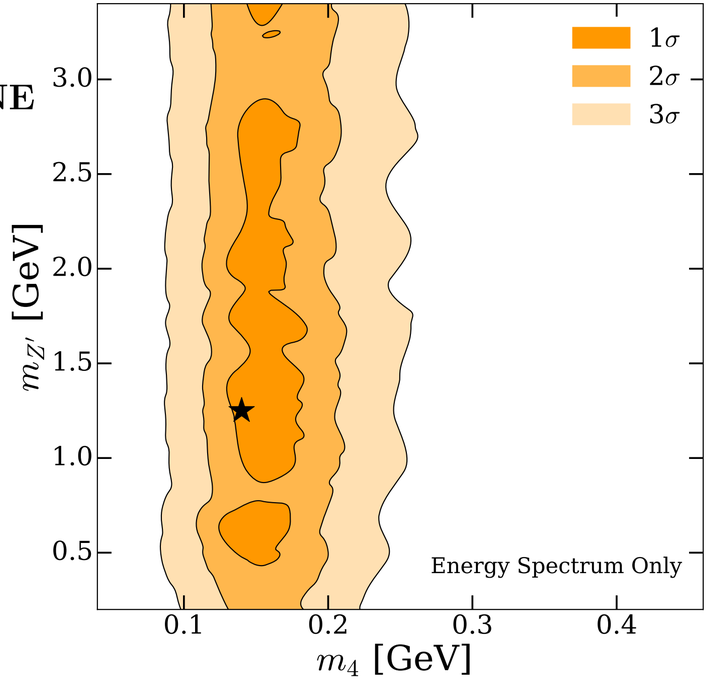
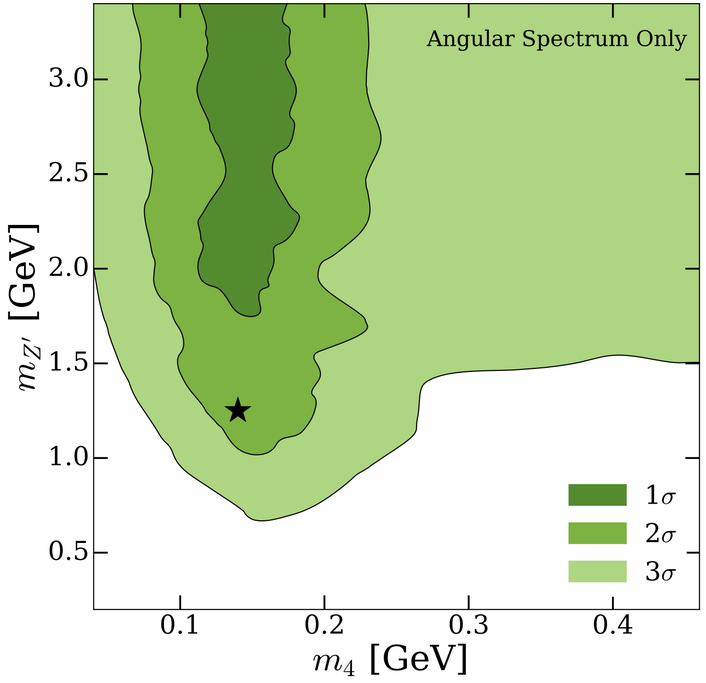
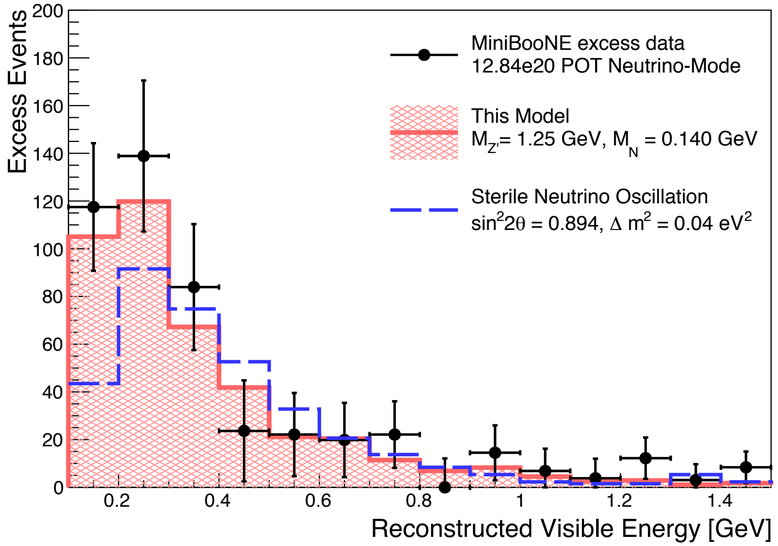
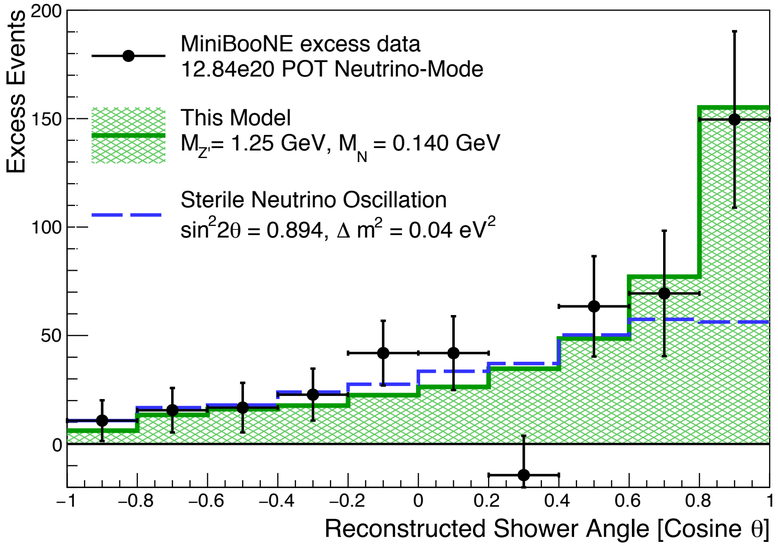
U(1)′ mediated decays of heavy sterile neutrinos in MiniBooNE

Peter Ballett,[1,*] Silvia Pascoli,[1,†] and Mark Ross-Lonergan[2,‡]









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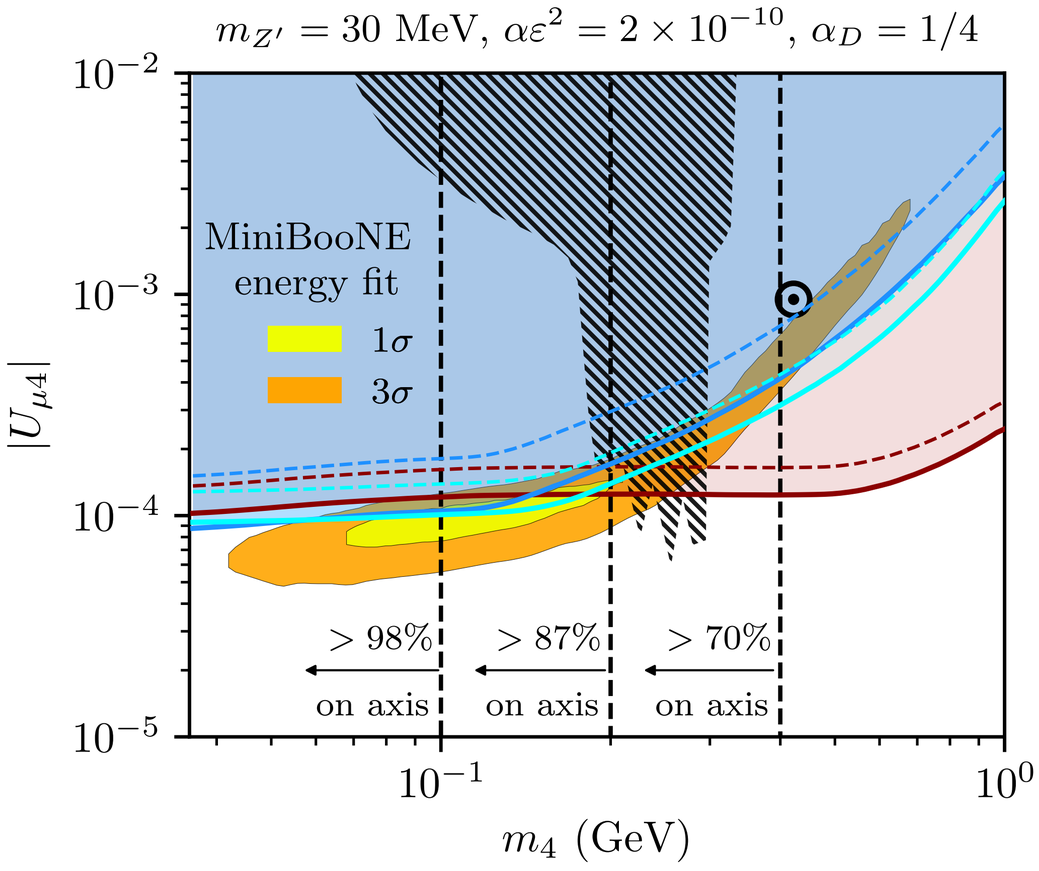
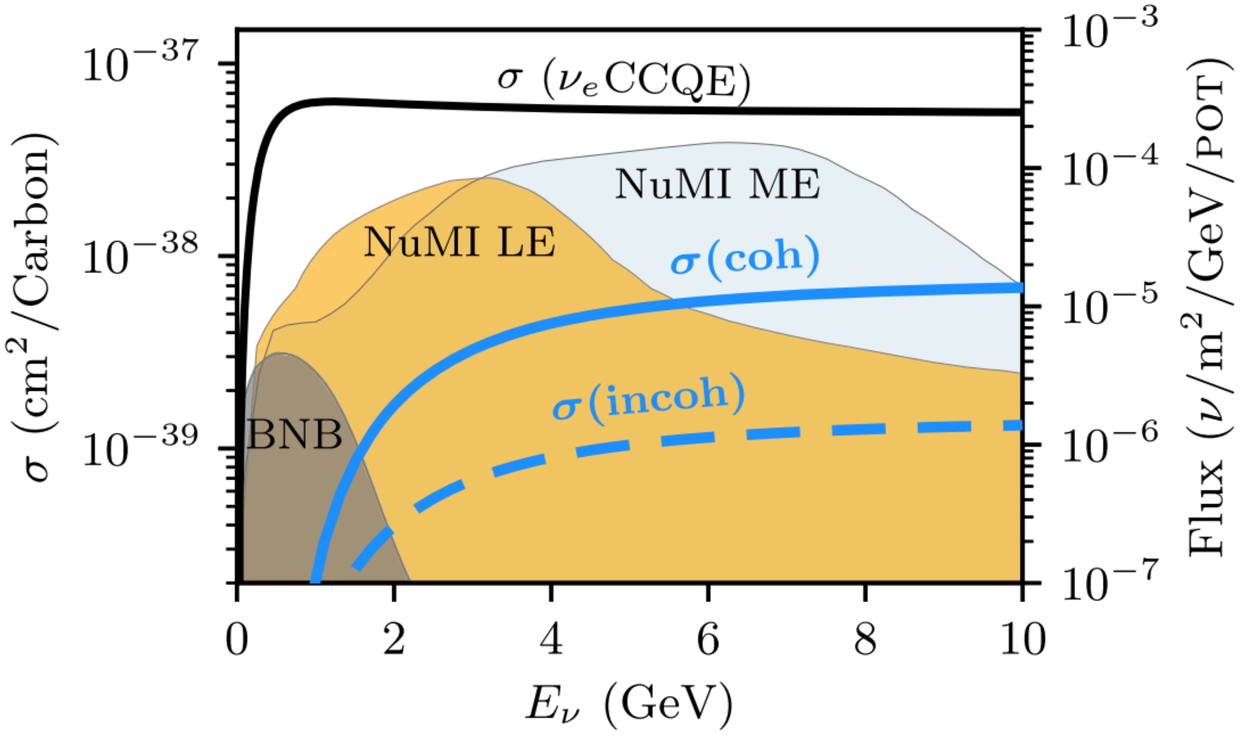
Testing New Physics Explanations of MiniBooNE Anomaly at Neutrino Scattering Experiments

Carlos A. Argüelles,[1,*] Matheus Hostert,[2,†] and Yu-Dai Tsai[3,‡]





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