The Short-Baseline Neutrino Anomalies

Joachim Kopp (CERN & Uni Mainz)
Seminar at Sydney–CPPC | 23 April 2020

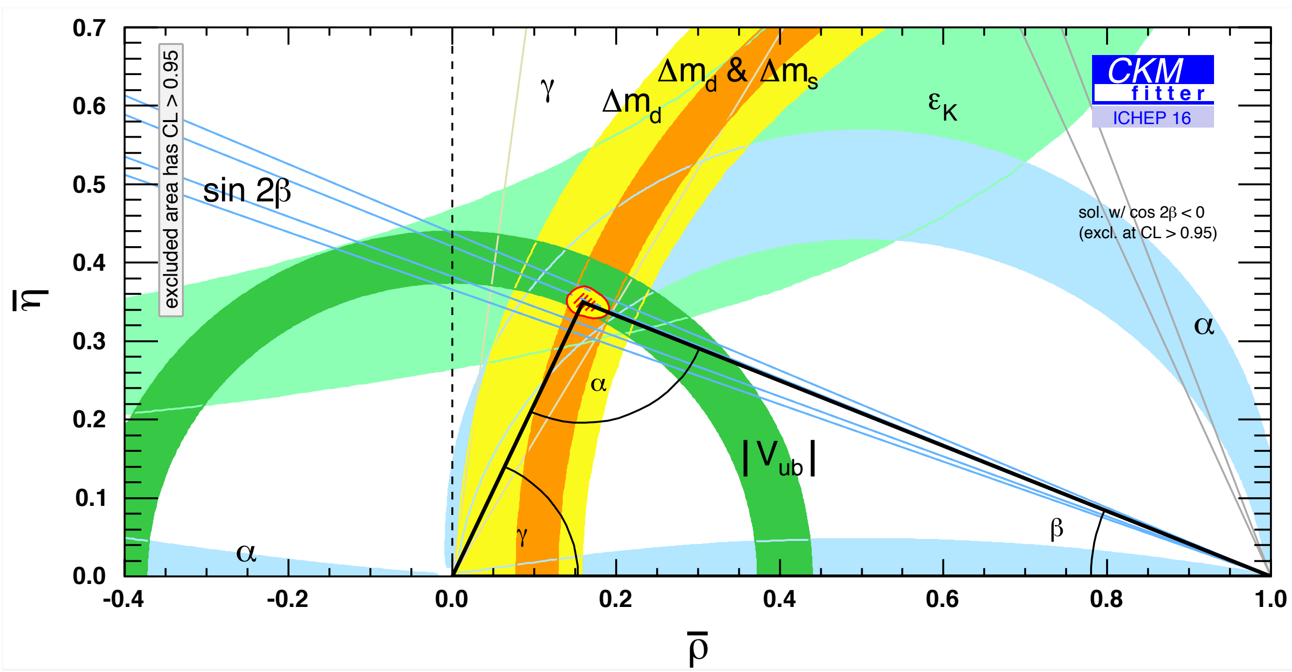
Outline

- ☑ Neutrino Oscillations
- ☑ Short-Baseline Anomalies
- ☑ Sterile Neutrinos?
- ☑ Standard Model Explanations
- ☑ Sterile Neutrino Decay

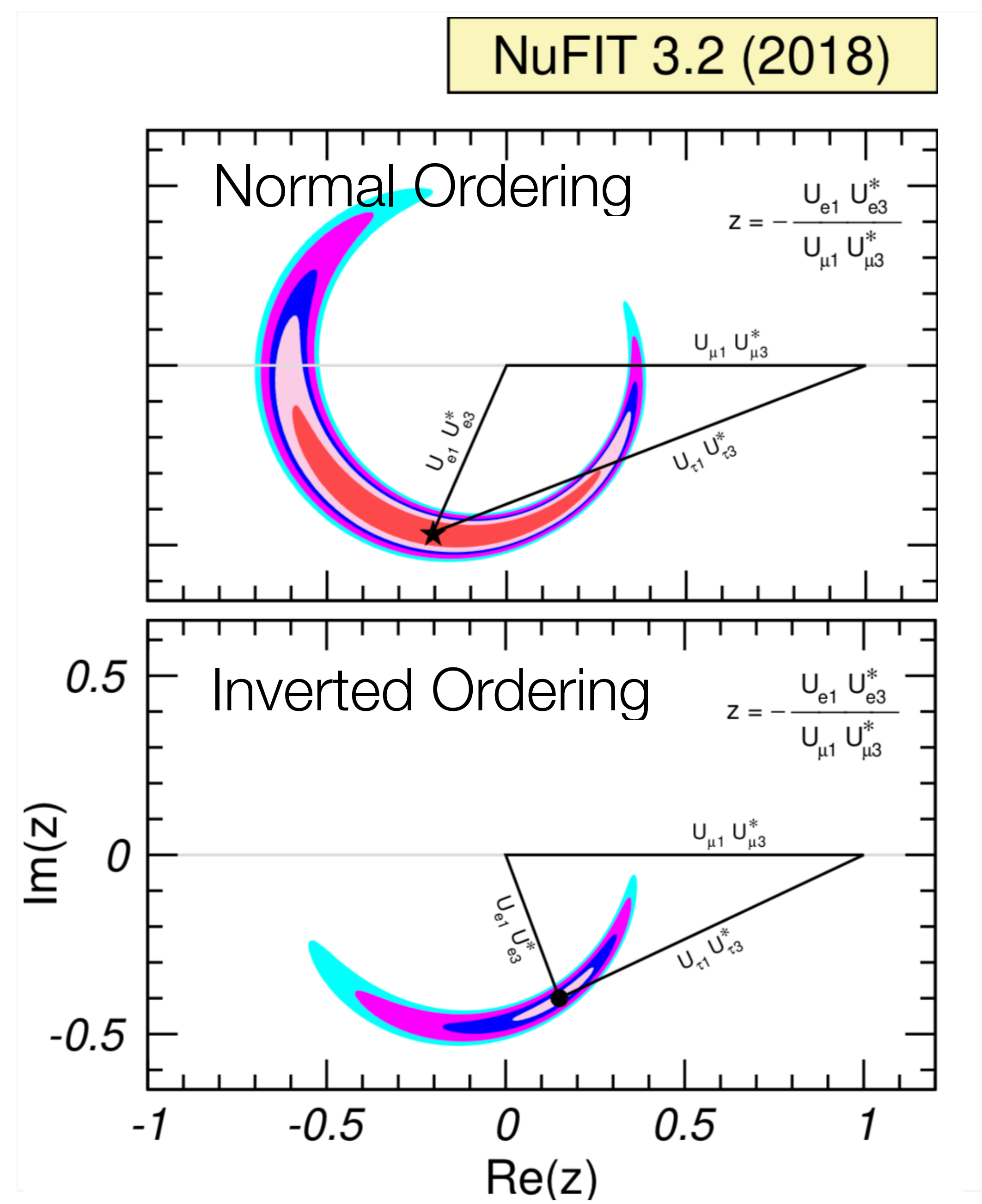
Neutrino Oscillations

Precision Flavour Physics

Quarks



Leptons



Precision Flavour Physics

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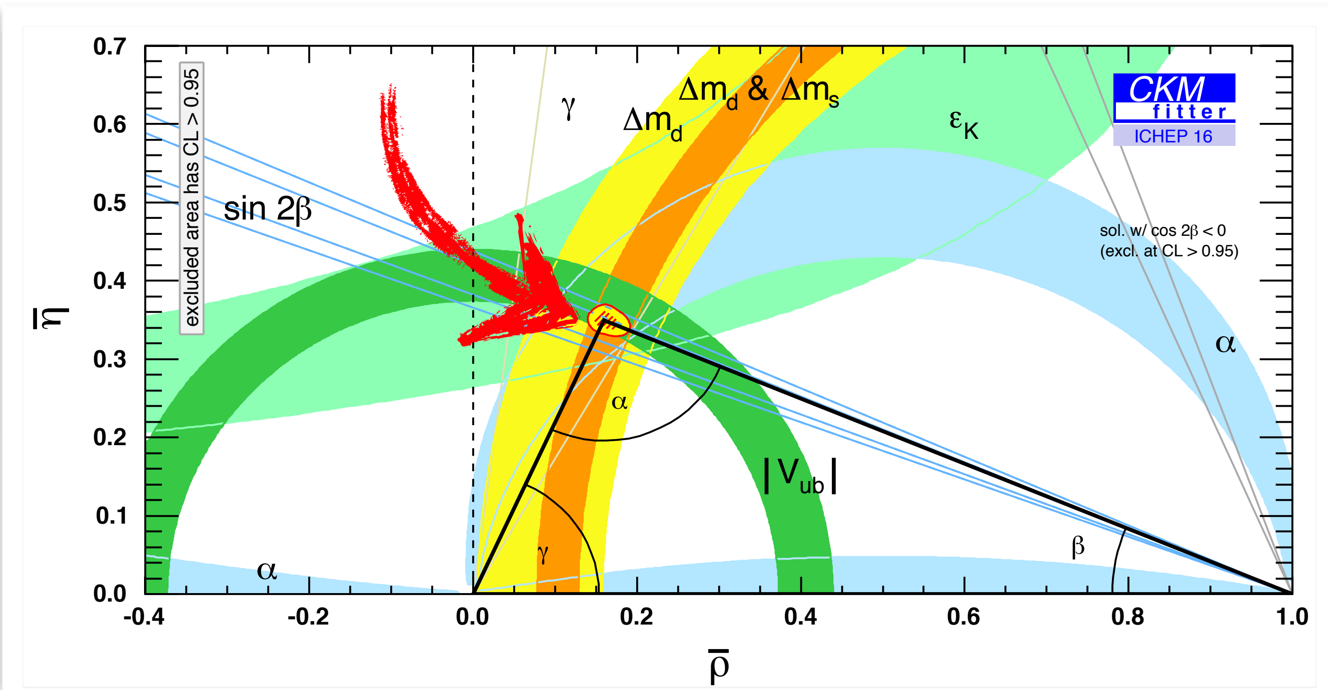

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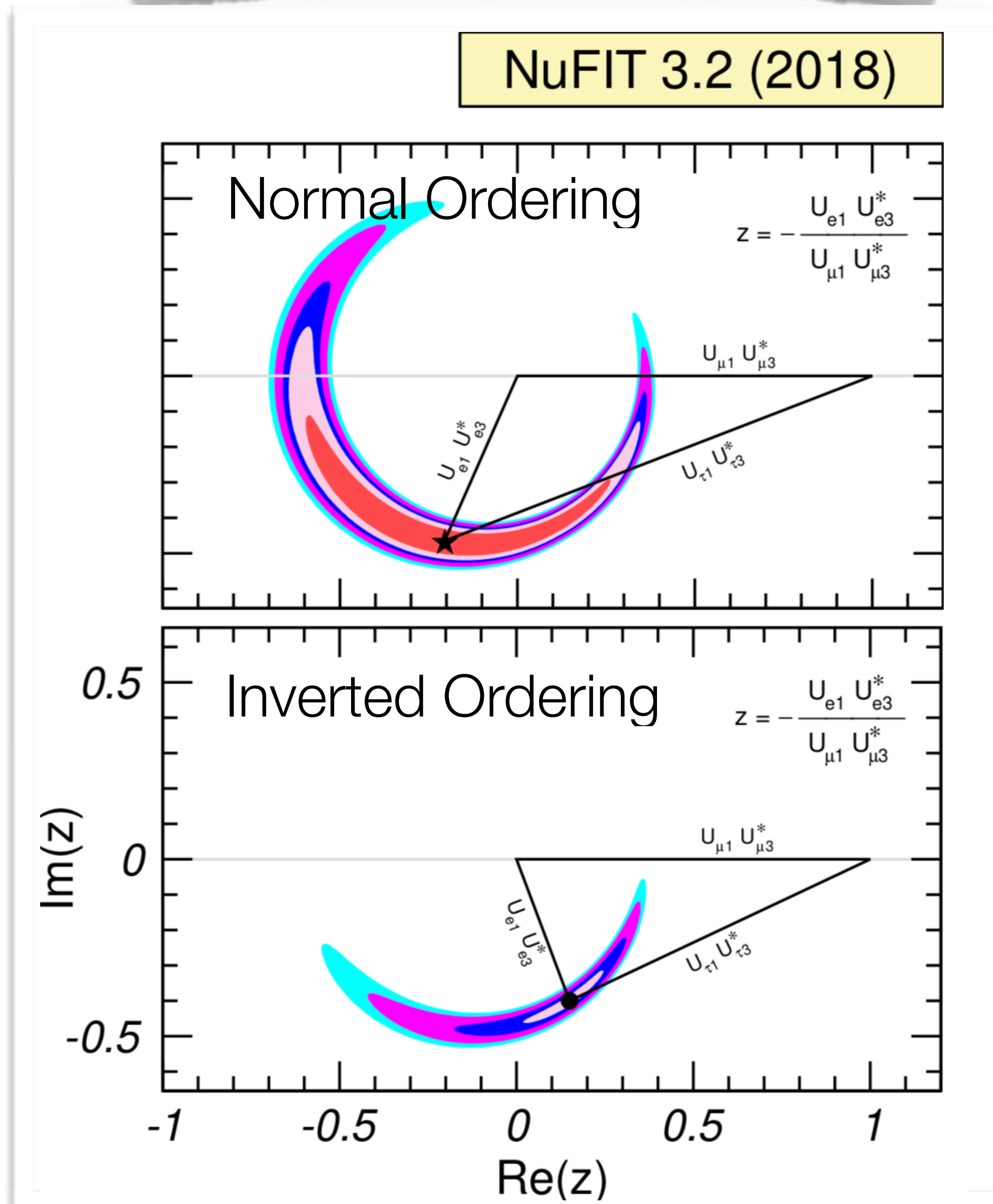

Precision Flavour Physics

$$|\nu_\alpha\rangle = \sum_j U^*_{\alpha j}|\nu_j\rangle$$

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Mass Eigenstate
(well-defined energy)

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Mixing Matrix
(3x3, unitary)

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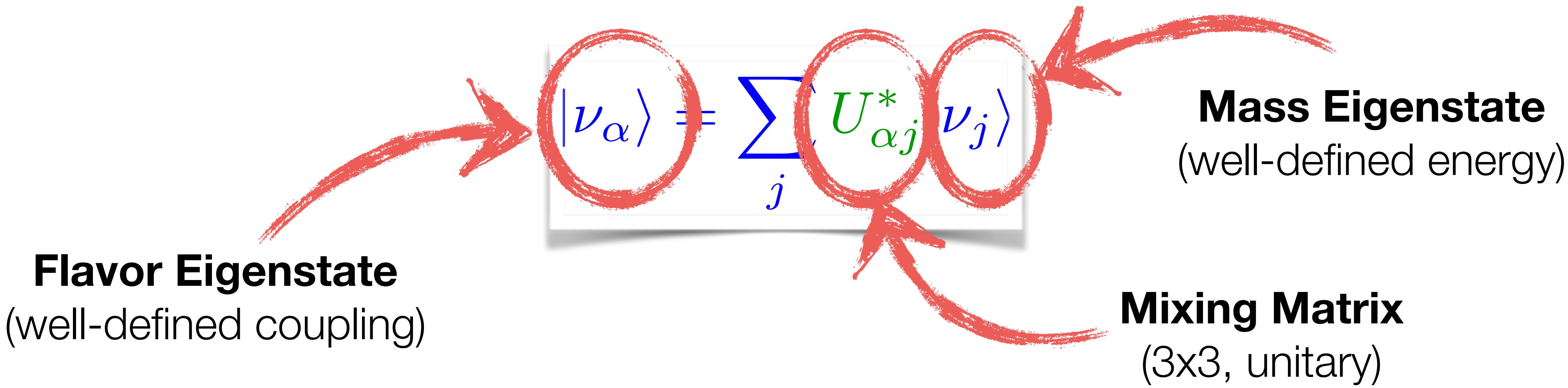
Precision Flavour Physics



☑ Mixing Matrix:

$$U = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}$$

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Large
close to maximal

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Large
but non-maximal

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Large
close to maximal

Small
but non-negligible (~0.1)

Large
but non-maximal

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Mixing Matrix:

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Large
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Small
but non-negligible (~0.1)

Large
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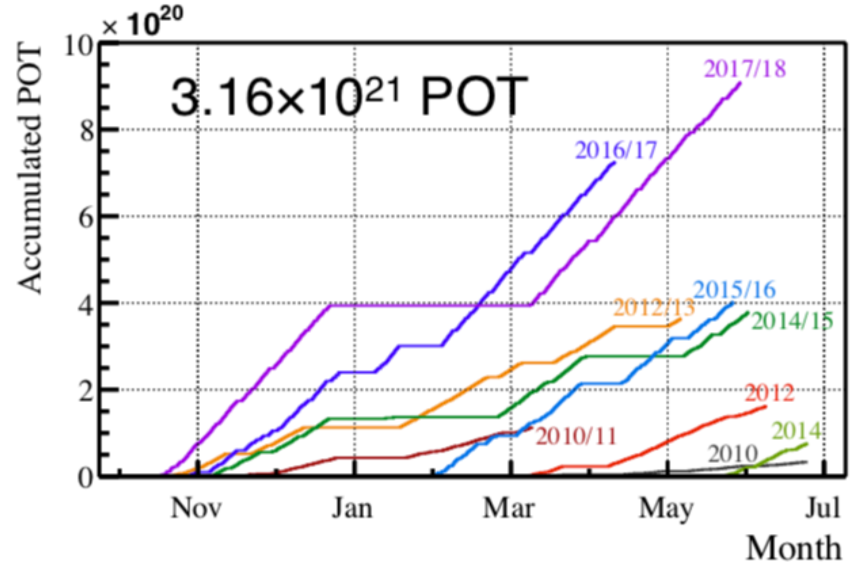
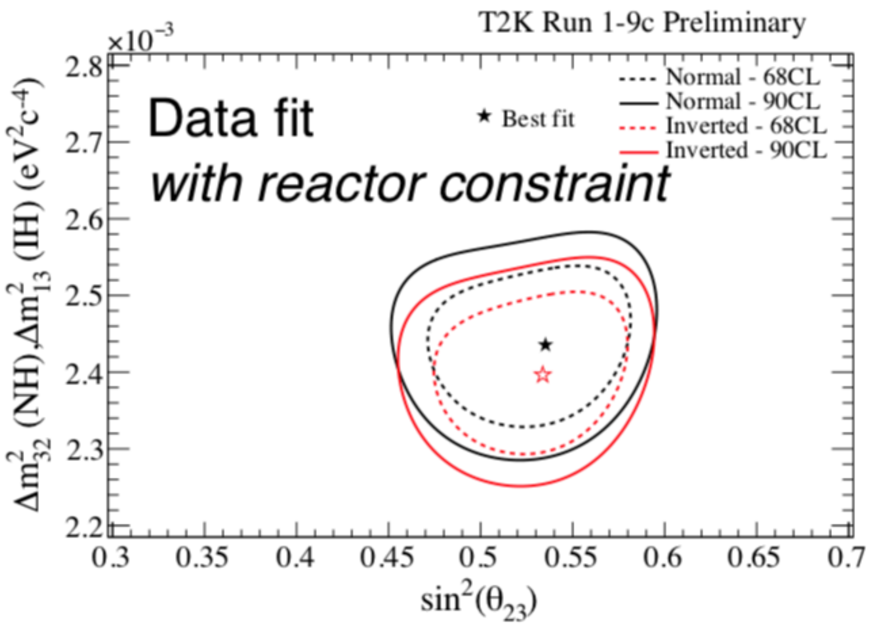
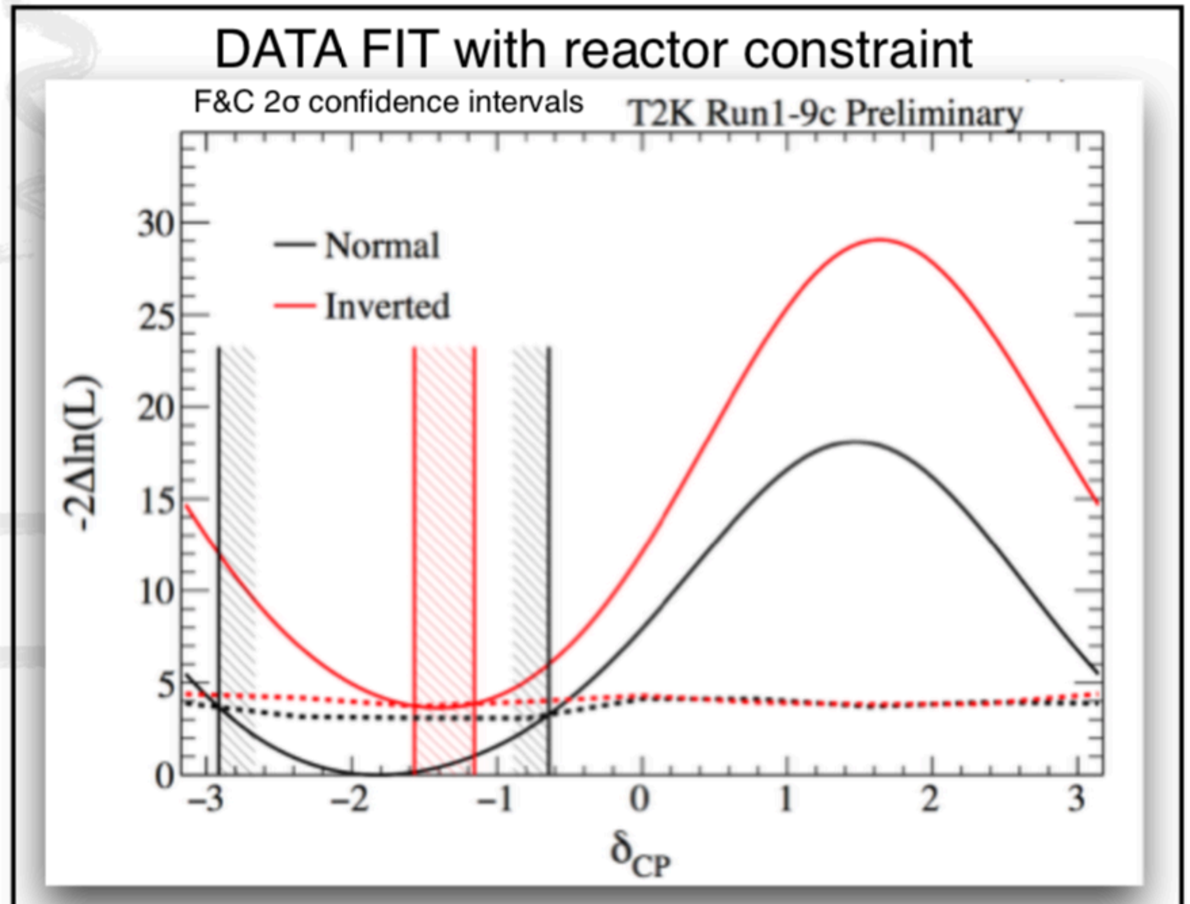
Status of 3-Flavor Oscillations: T2K Results



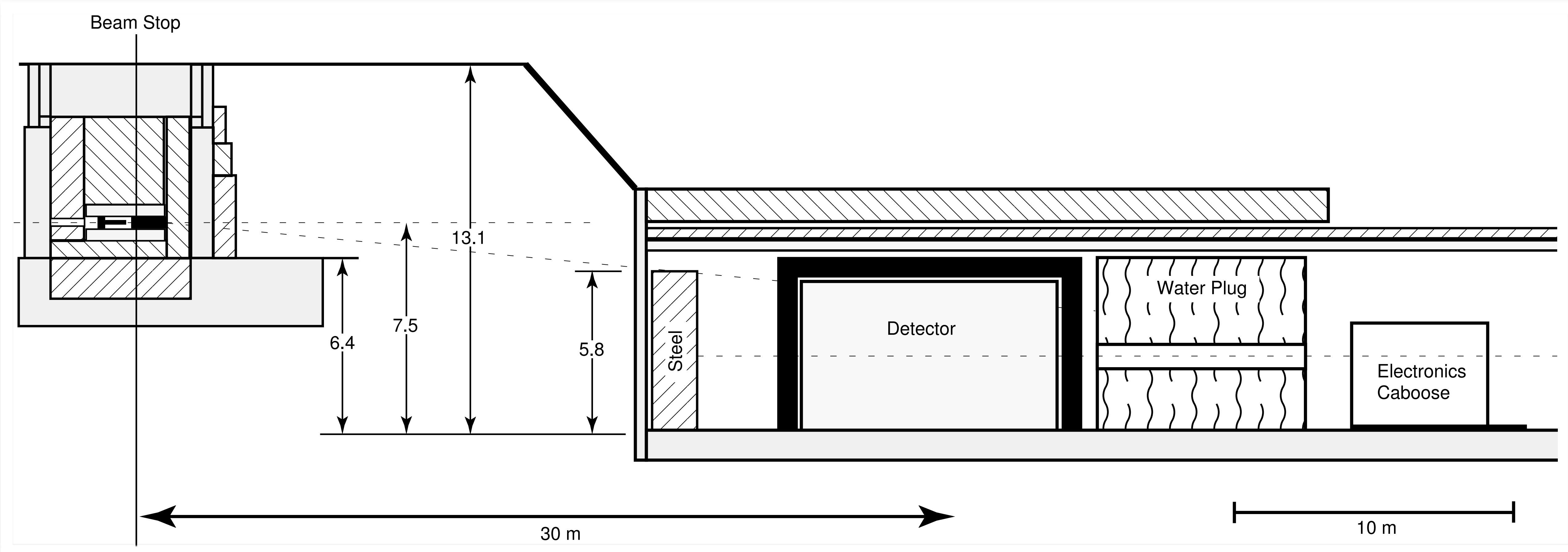
	$\sin^2\theta_{23}\leq 0.5$	$\sin^2\theta_{23}>0.5$	SUM
NH ($\Delta m^2_{32}>0$)	0.204	0.684	0.888
IH ($\Delta m^2_{31}<0$)	0.023	0.089	0.112
SUM	0.227	0.773	1





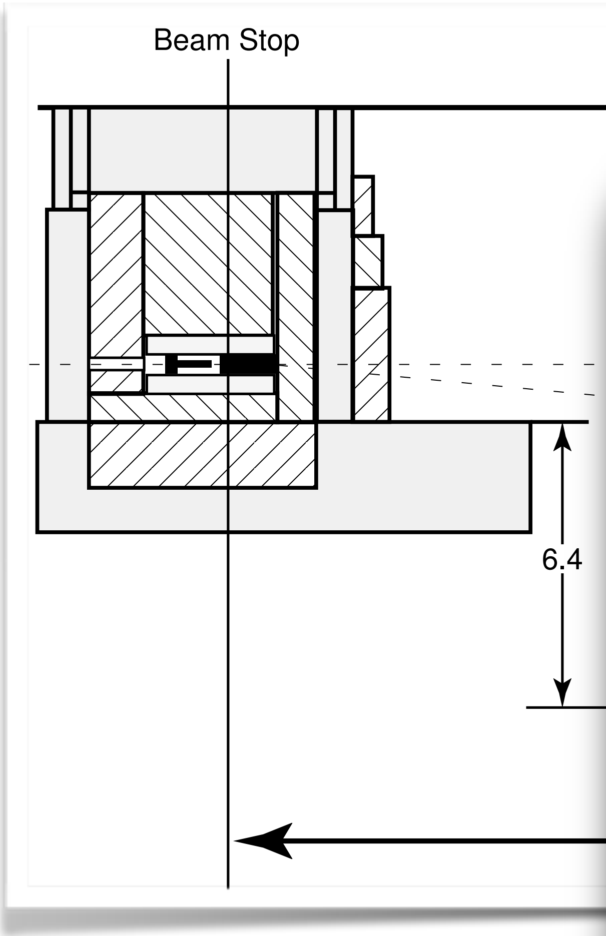
Short-Baseline Anomalies

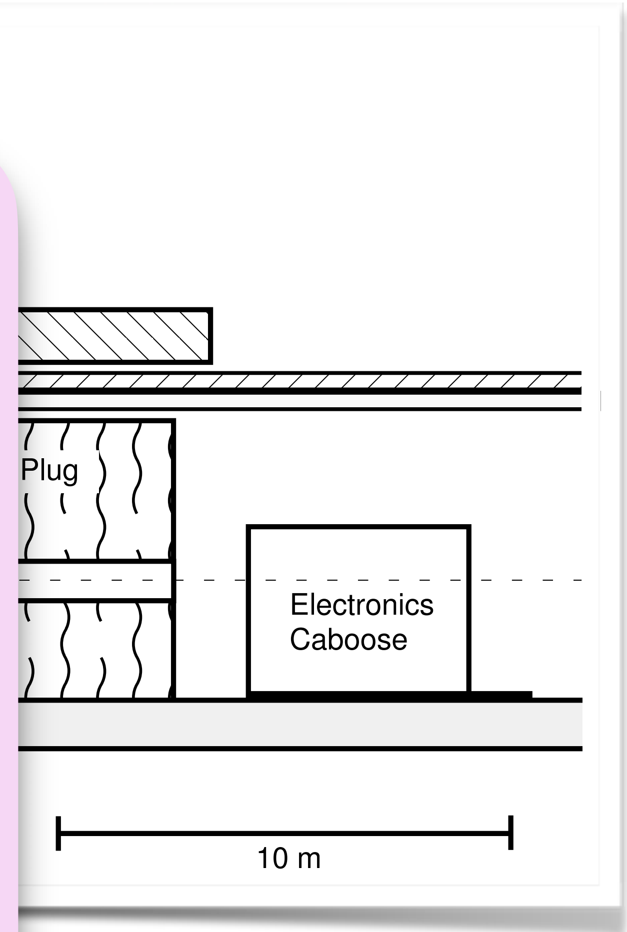
Anomaly #1: LSND

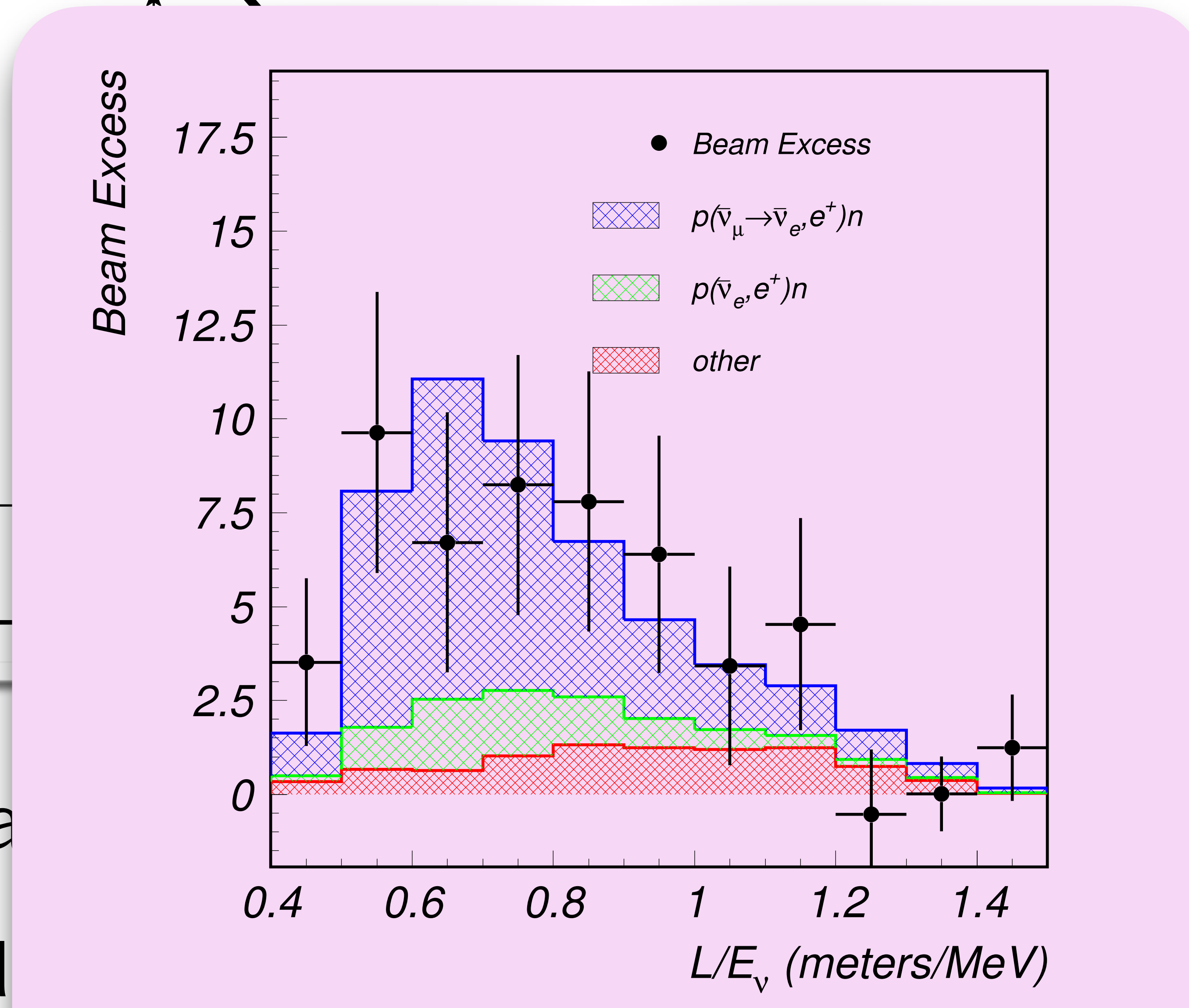


- $\bar{\nu}_e$ appearance in a $\bar{\nu}_\mu$ beam
- Source—detector distance ("baseline") ~ 30 m
- $\nu_\mu \rightarrow \nu_e$ oscillations?

Anomaly #1: LSND







LSND Collaboration, [hep-ex/0104049](hep-ex/0104049)

- ☑ $\bar{\nu}_e$ appeara
- ☑ Source—d m
- ☑ $\nu_\mu \to \nu_e$ osc

Light Sterile Neutrinos

Definition: sterile neutrino = SM singlet fermion

- ☑ Very generic extension of SM
  - can be leftover of extended gauge multiplet
- ☑ Useful phenomenological tool
  - can explain ν masses (seesaw mechanism, m ~ TeV…M_{Pl})
  - can explain cosmic baryon asymmetry (leptogenesis, m≫100 GeV)
  - can explain dark matter (m ~ keV)
  - can explain oscillation anomalies (m ~ eV)
    Promote mixing matrix to 4 x 4, oscillation formula unchanged:

$$P_{\alpha\to\beta} = \sum_{j,k} U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k} \exp\left[-i(E_j - E_k)T\right]$$

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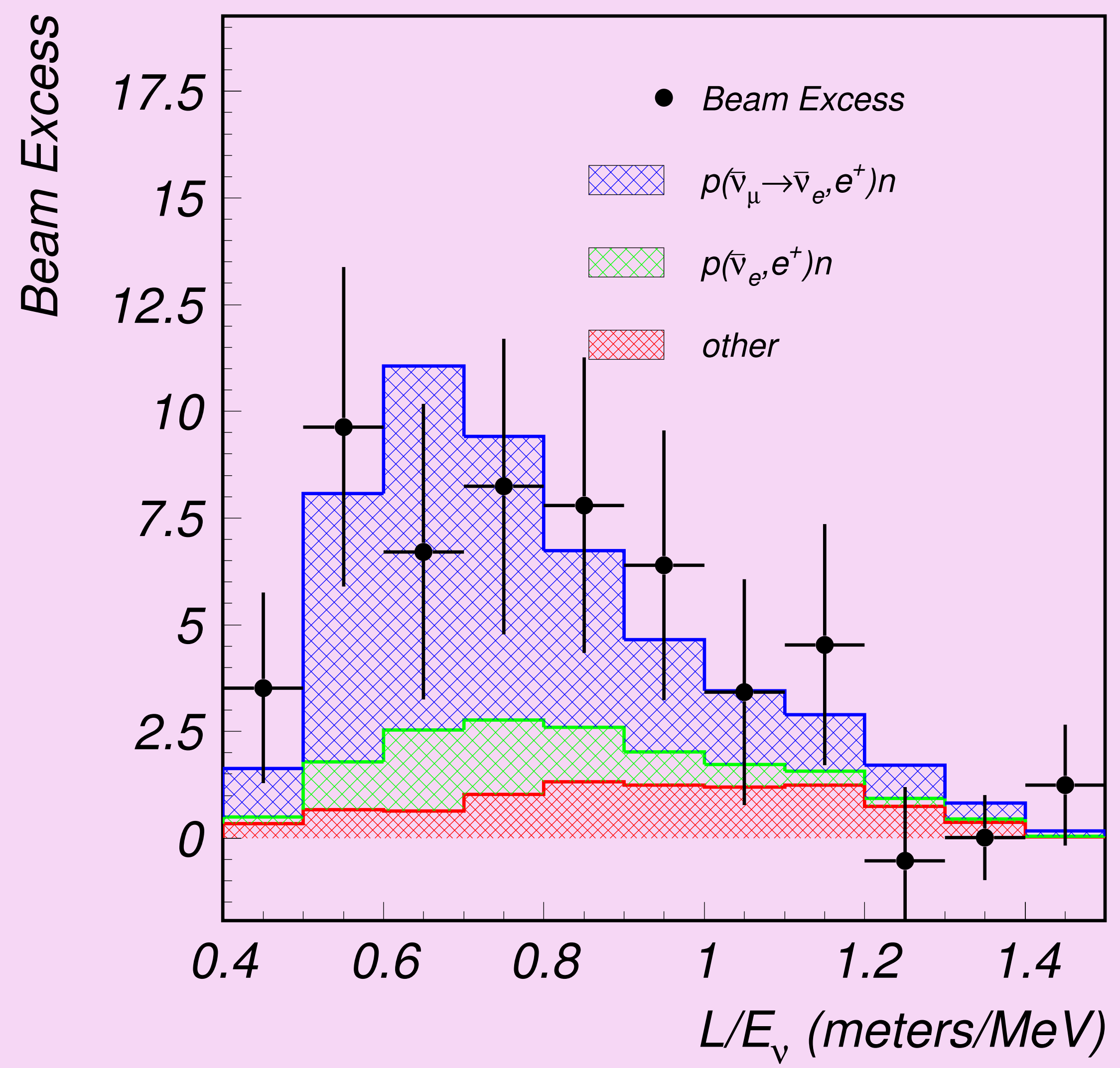
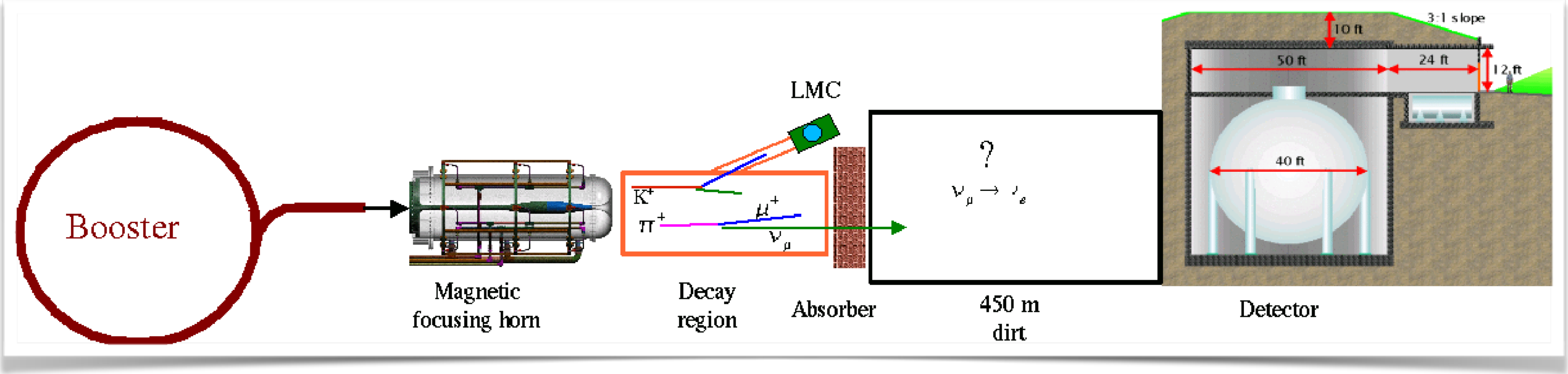
LSND Data



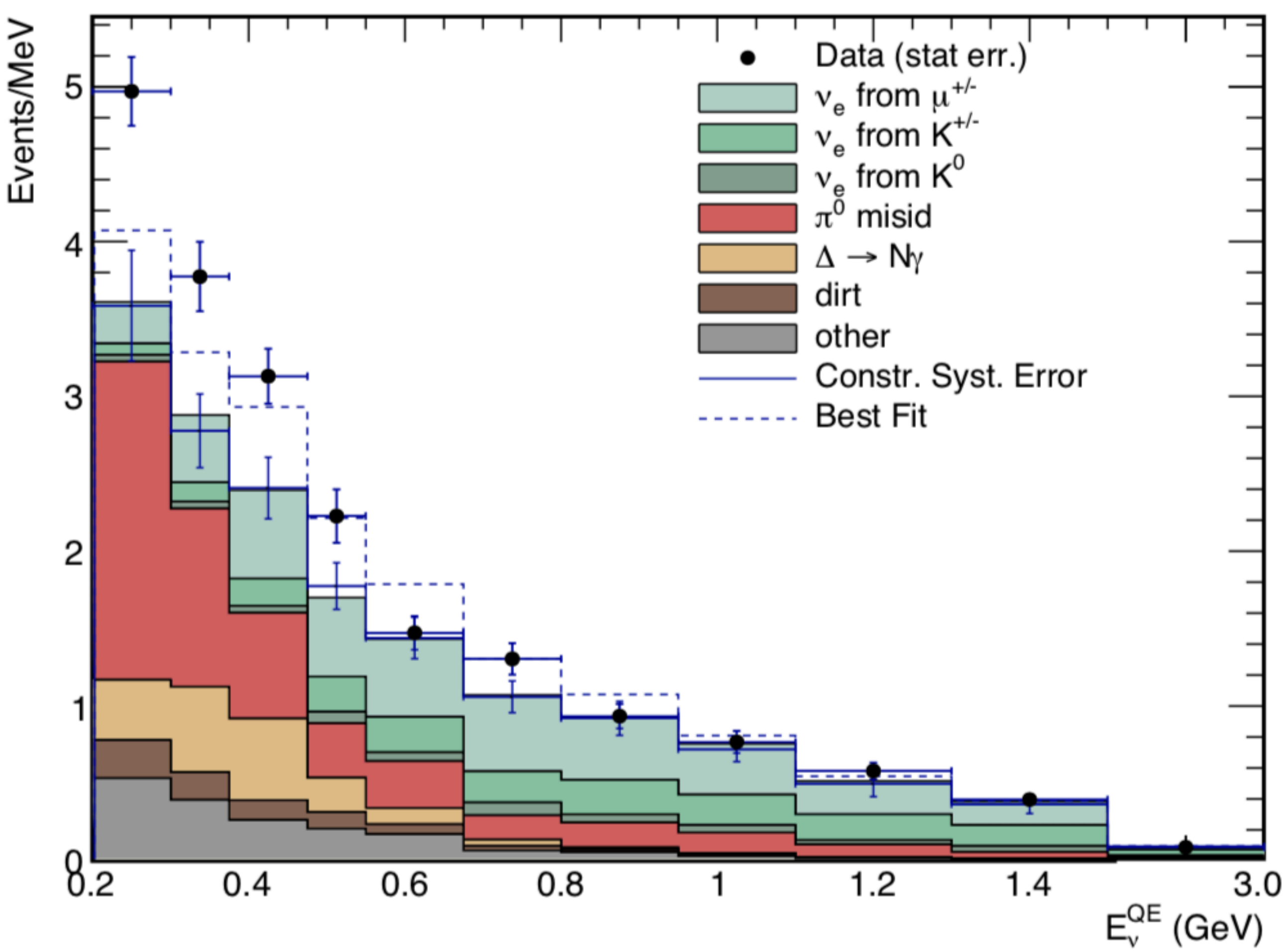
LSND Collaboration, hep-ex/0104049

Anomaly #2: MiniBooNE

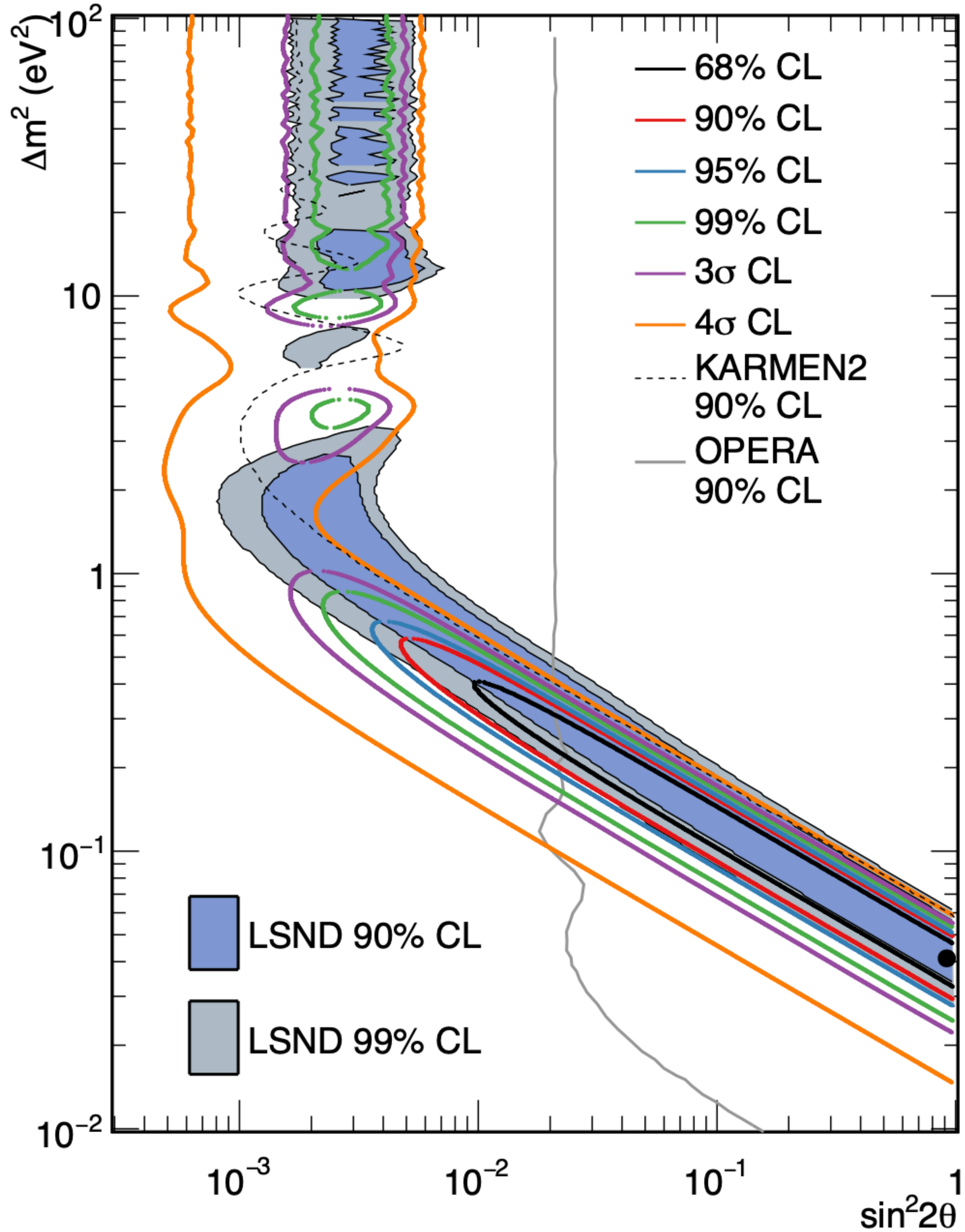


Anomaly #2: MiniBooNE

- ☑ Unexplained low-*E* excess
- ☑ Consistent with LSND
- ☑ L/E too small for 3-flavor framework (wrong Δm^2)



MiniBooNE Collaboration arXiv:1805.12028

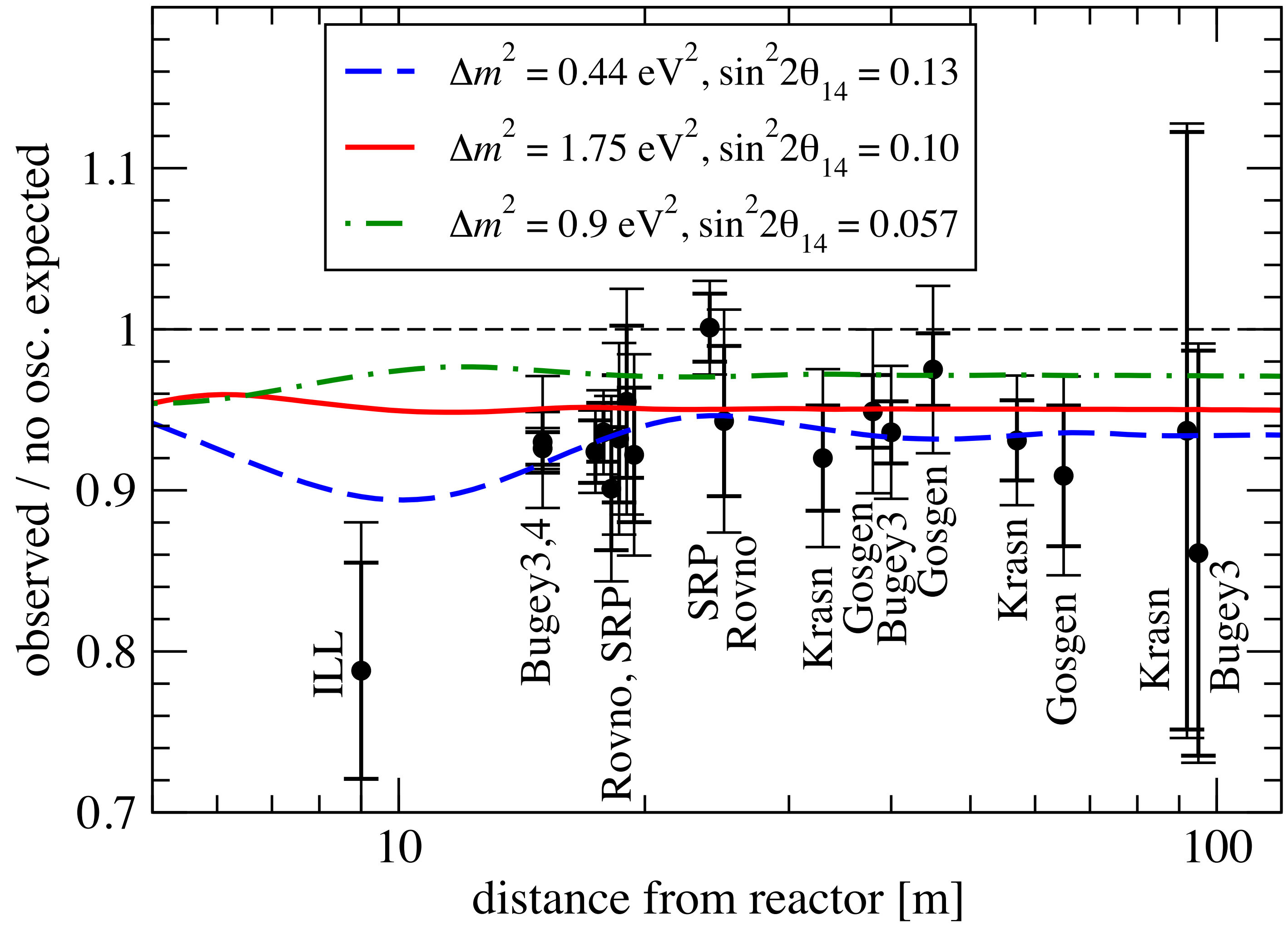


Anomaly #3: The Reactor Anomaly

$\bar{\nu}_e$ flux from nuclear reactors is ~ 3.5% (~ 3σ) below prediction

oscillations of $\bar{\nu}_e$ into sterile neutrinos $\bar{\nu}_s$?

Mueller *et al.* 1101.2663, Huber 1106.0687

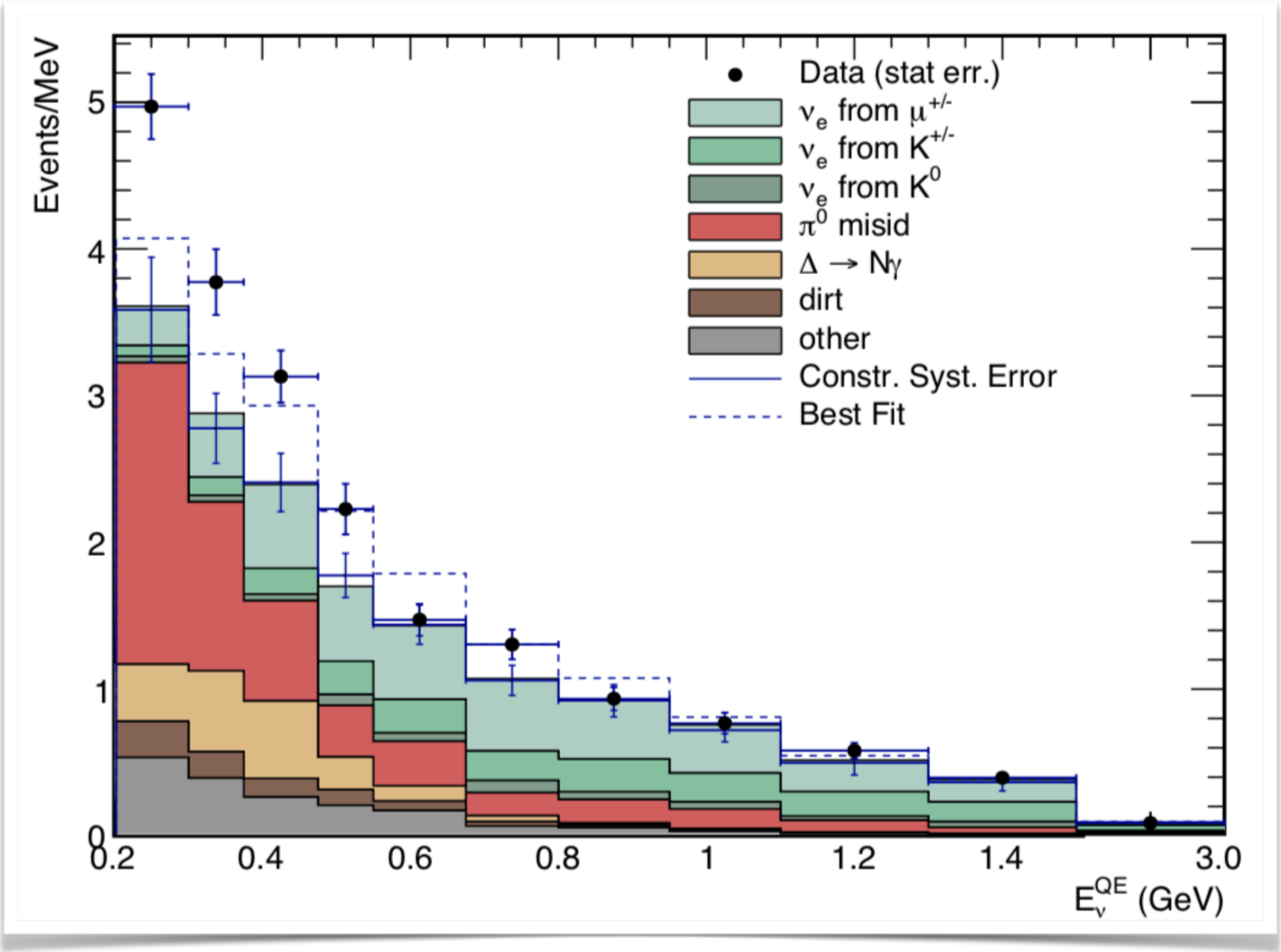


Take-Home Message

- Three Independent Anomalies ($> 3\sigma$)
  - LSND: $\nu_\mu \to \nu_e$ at stopped pion source
  - MiniBooNE: $\nu_\mu \to \nu_e$ in horn-focused beam
  - Reactors: ν_e disappearance
  - + some less significant anomalies not mentioned here, but included in our fits

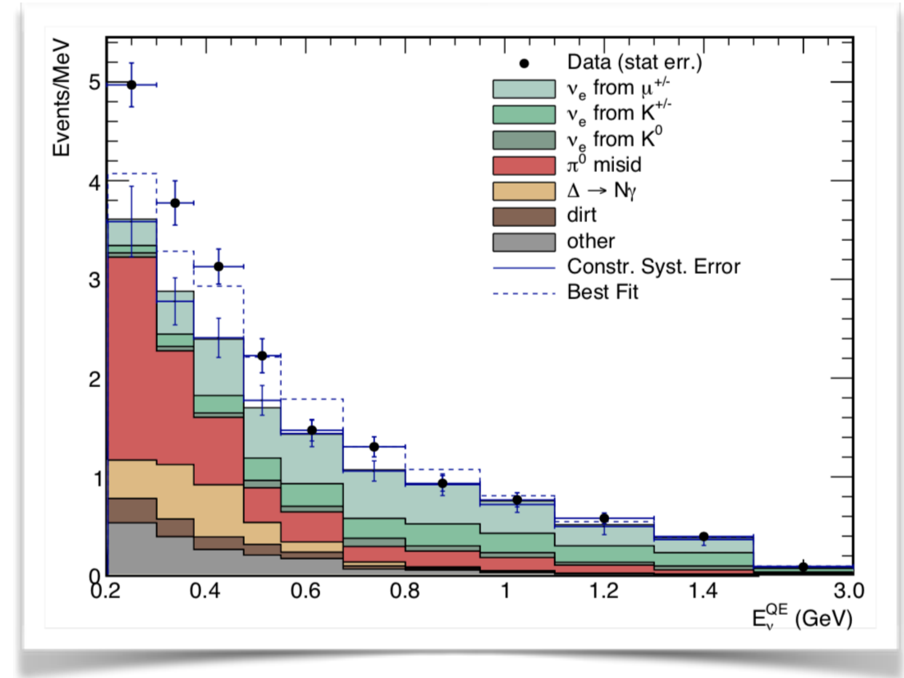
Standard Model Explanations for MiniBooNE

MiniBooNE Backgrounds



MiniBooNE 2018

$\Delta \to \gamma N$



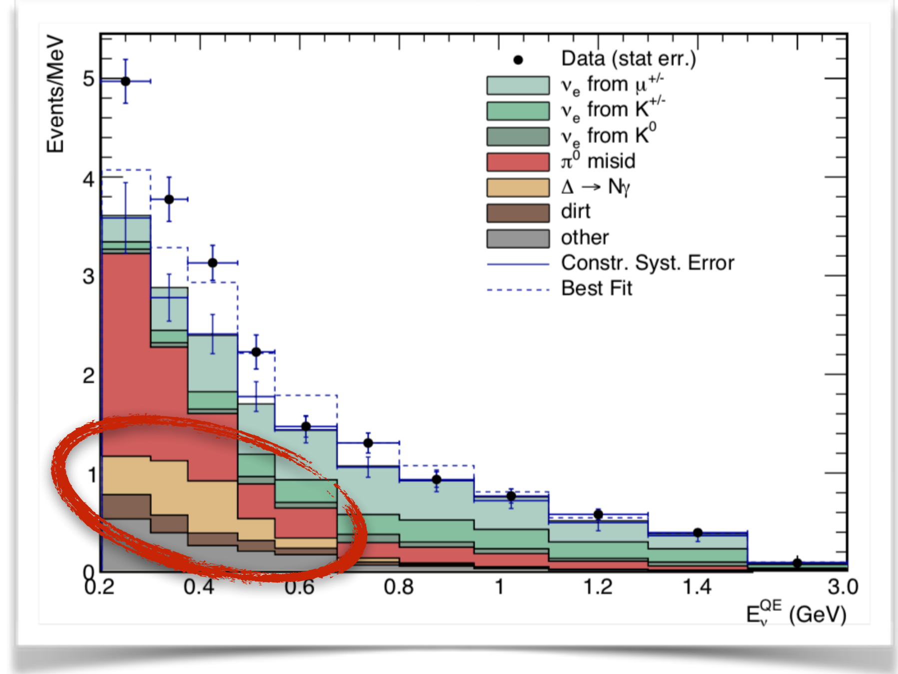
- ☑ Δ production rate measured in $\Delta \to \pi N$ background
- ☑ Pions may be absorbed on their way out of the nucleus
  - may excite another Δ resonance
    ➠ $\Delta \to \gamma N$ enhanced by ~factor 2
  - or may be absorbed
    ➠ control region suppressed by ~factor 2

Ioannisian 1909.08571
Giunti Ioannisian Ranucci 1912.01524

- ☑ This factor 2 has been taken into account by MiniBooNE

private communication from Bill Louis

$\Delta \rightarrow \gamma N$



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Ioannisian [1909.08571]
Giunti Ioannisian Ranucci [1912.01524]

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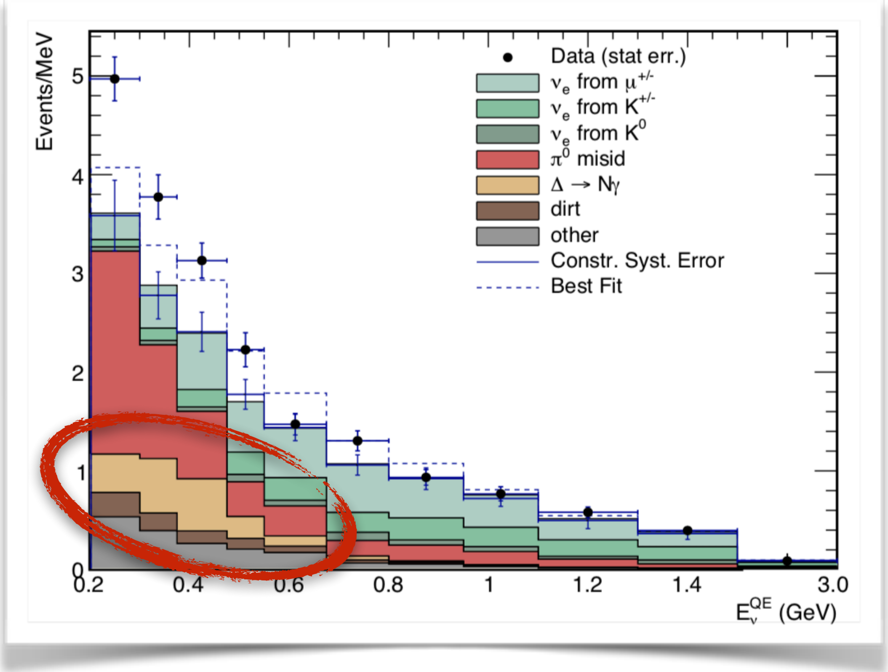
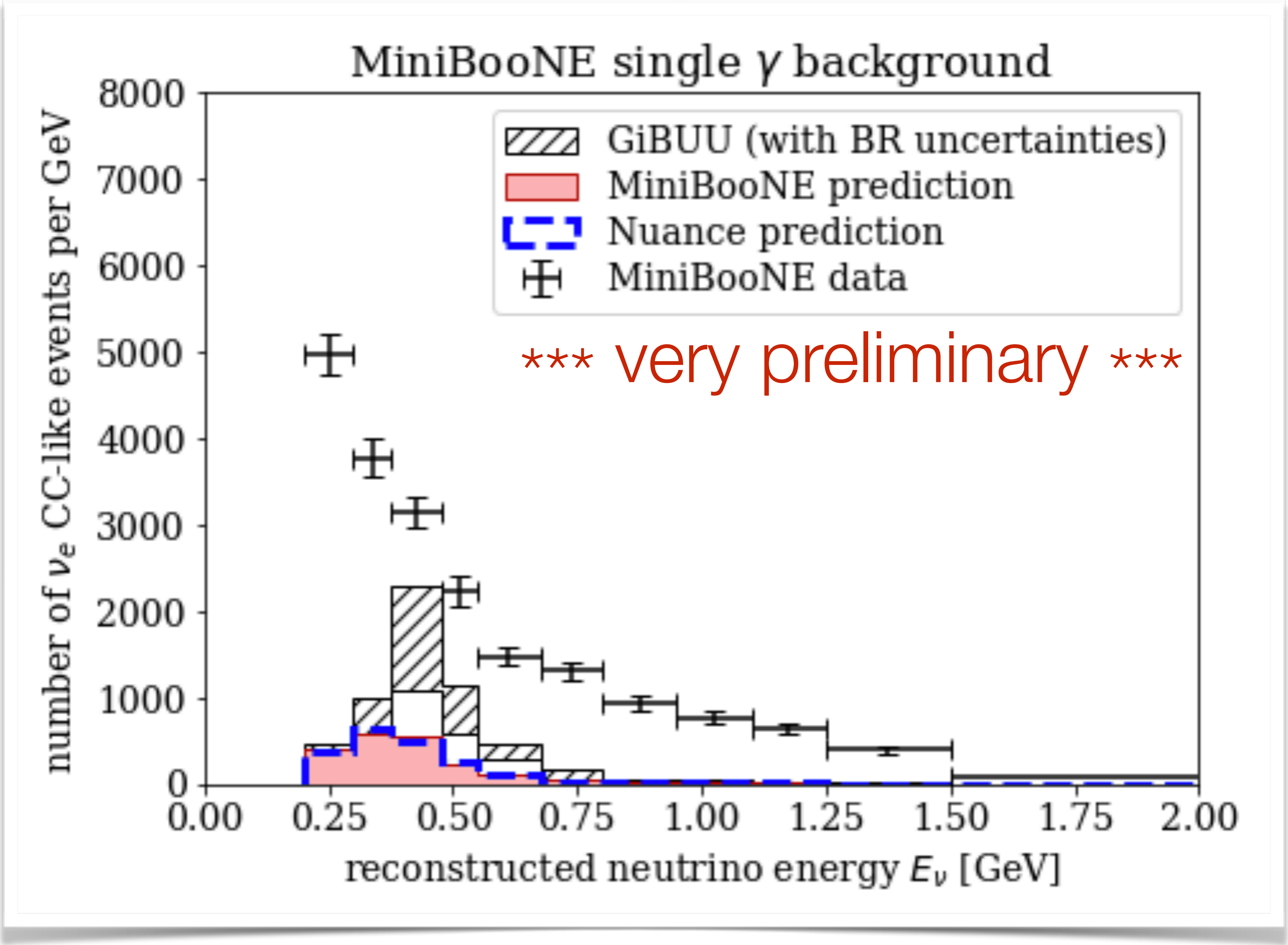
$\Delta \to \gamma N$

- Uncertainty in BR($\Delta \to \gamma N$)
  - PDG: 0.55–0.65%
  - no measurements
- Even larger uncertainties for heavier resonances



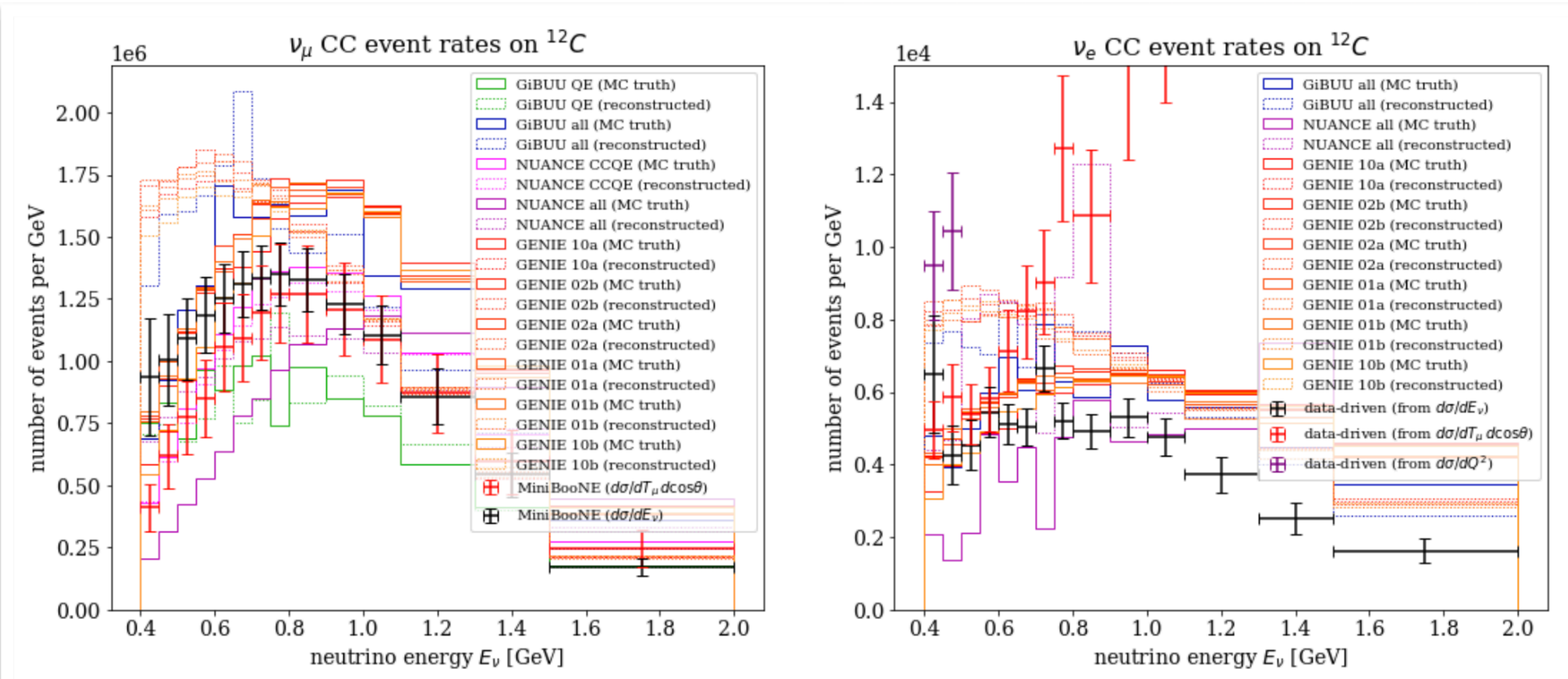
$\Delta \to \pi \gamma$



Brdar JK, *in preparation*

Differences Between Generators

*** very preliminary ***



Brdar JK, *in preparation*

Standard Model Explanations for the Reactor Anomaly

Predicting Reactor Neutrino Fluxes

$\bar{\nu}_e$ flux from nuclear reactors is ~ 3.5% (~ 3σ) below prediction

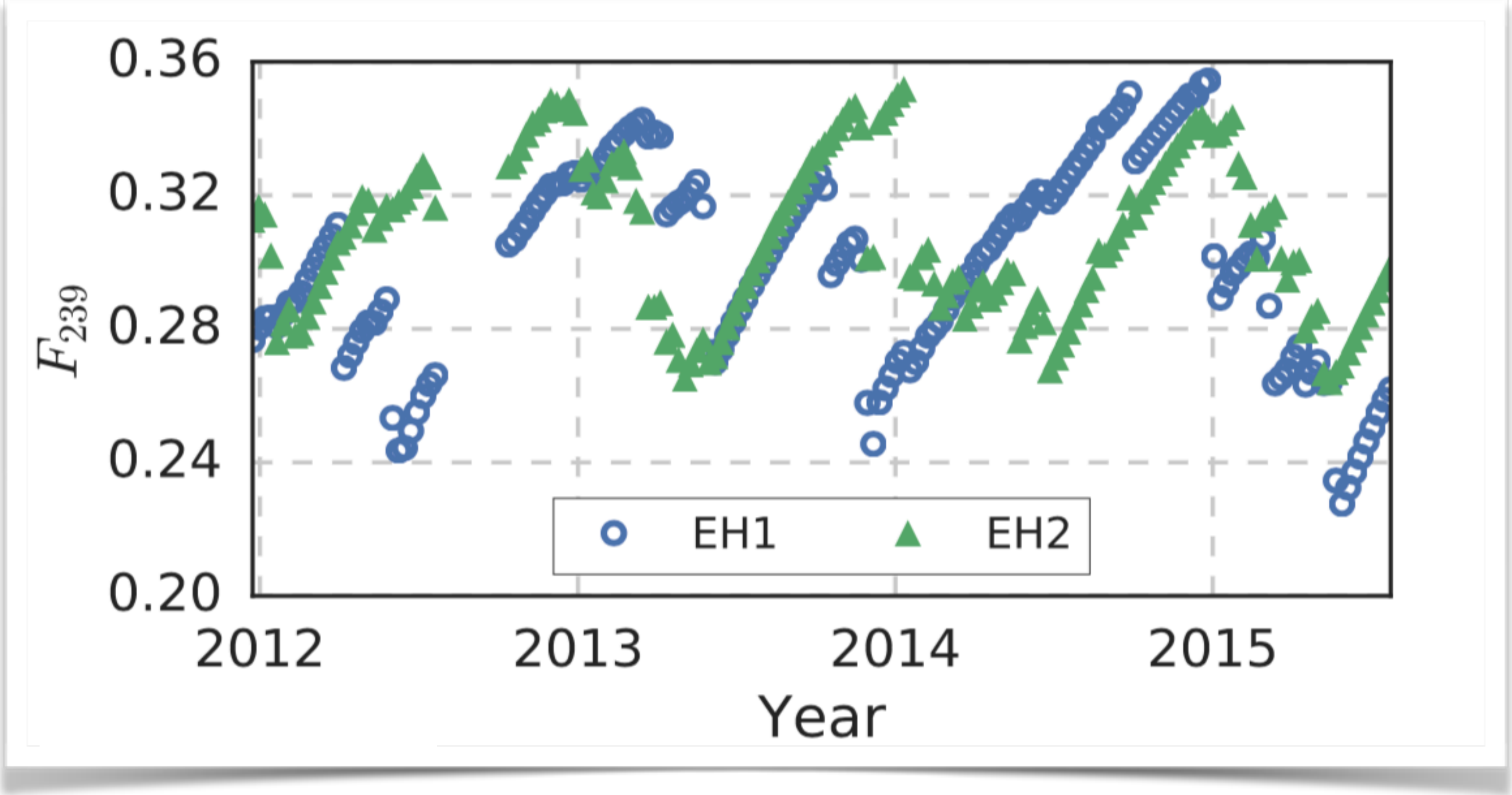
- Predicting reactor $\bar{\nu}_e$ fluxes:
  - Use measured β spectra from ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu fission
  - Convert to $\bar{\nu}_e$ spectrum
  - For single β decay: $E_\nu = Q - E_e$
  - Reality: thousands of decay branches, many not known precisely
  - Use (incomplete) information from nuclear data tables ...
  - ... complemented by a fit to "effective decay branches"

Mueller *et al.* 1101.2663, Huber 1106.0687

Isotope-Dependent Fluxes

Isotope-Dependent Fluxes

☑ Reactor fuel composition evolves with time ("burnup")



Daya Bay 1704.01082

Isotope-Dependent Fluxes

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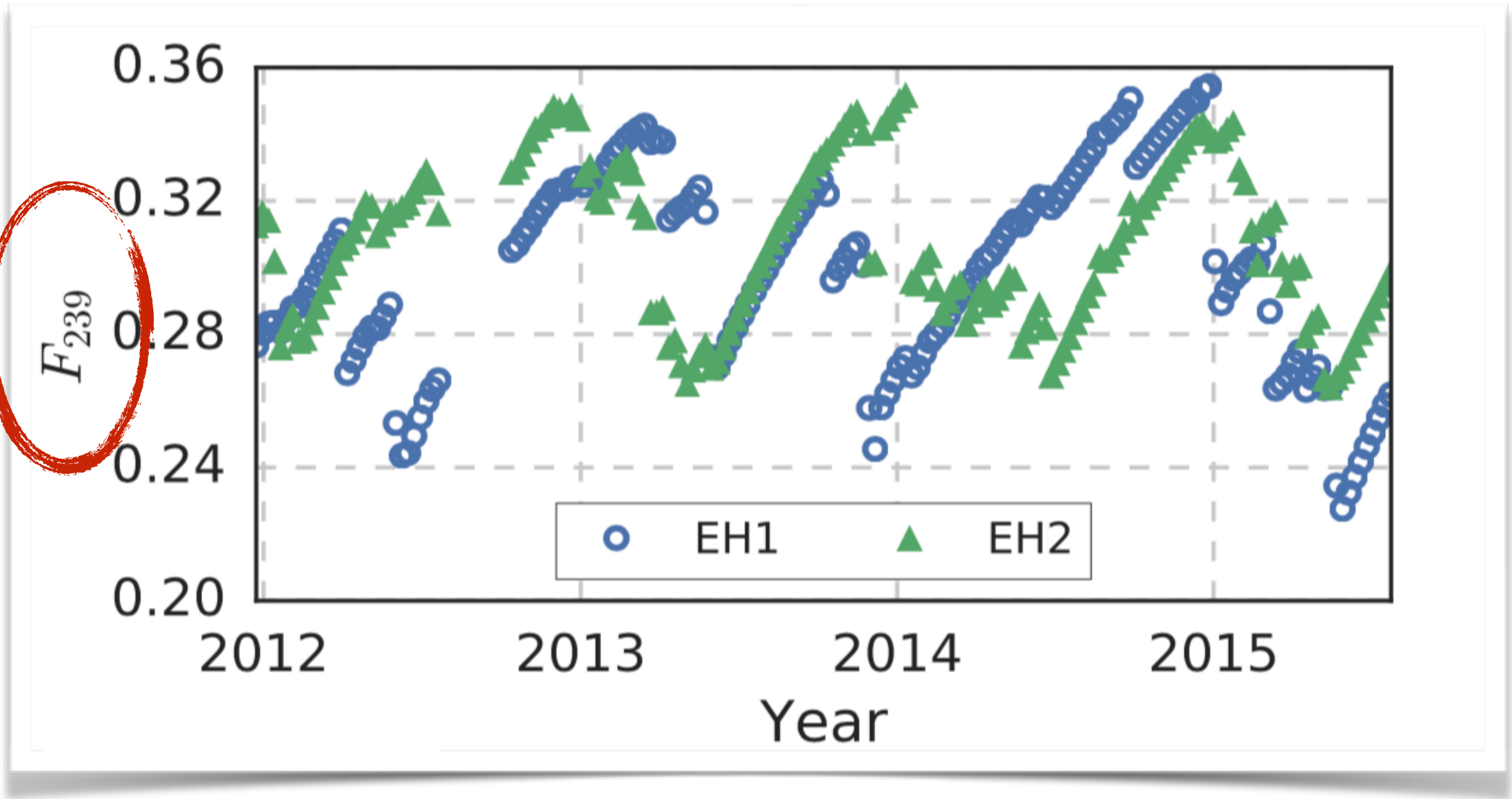


Effective fraction of ^{239}Pu fissions

$$F_i(t) = \frac{\sum_{r=1}^{6} \frac{W_{\mathrm{th,r}} \bar{P}_{ee,r} f_{i,r}(t)}{L_r^2 \overline{E}_r(t)}}{\sum_{r=1}^{6} \frac{W_{\mathrm{th,r}} \bar{P}_{ee,r}}{L_r^2 \overline{E}_r(t)}}$$

4.01082

Isotope-Dependent Fluxes

- ☑ Reactor fuel composition evolves with time ("burnup")
- ☑ Measure inverse β decay rate as function of F_{239}

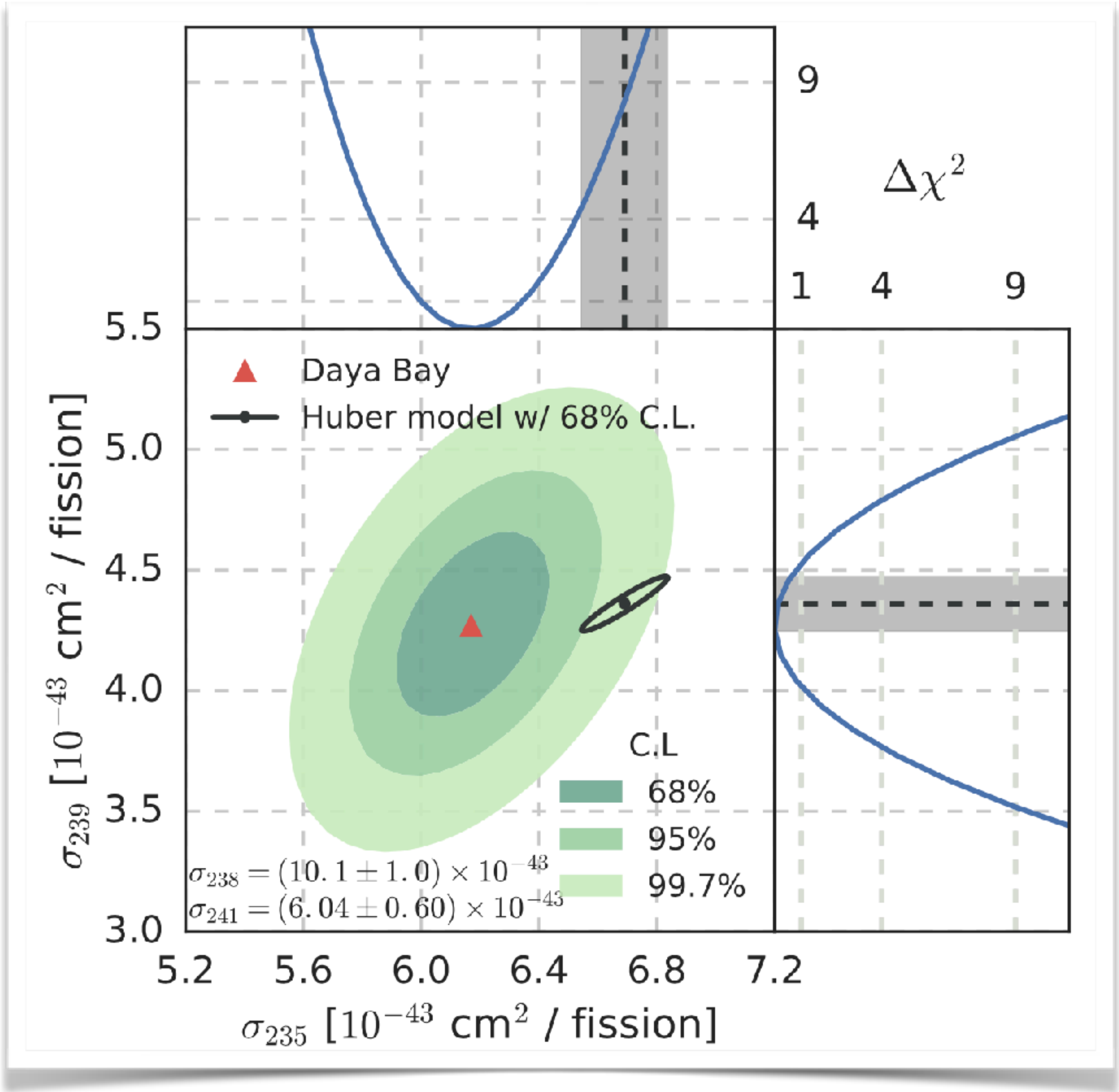
Daya Bay 1704.01082

Isotope-Dependent Fluxes

- ☑ Reactor fuel composition evolves with time ("burnup")
- ☑ Measure inverse β decay rate as function of F_{239}
- ☑ Sterile Neutrino: same deficit for all isotopes
  Flux Misprediction: isotope-dependent deficits

Daya Bay 1704.01082

Sterile Neutrinos or Flux Uncertainty



Daya Bay 1704.01082

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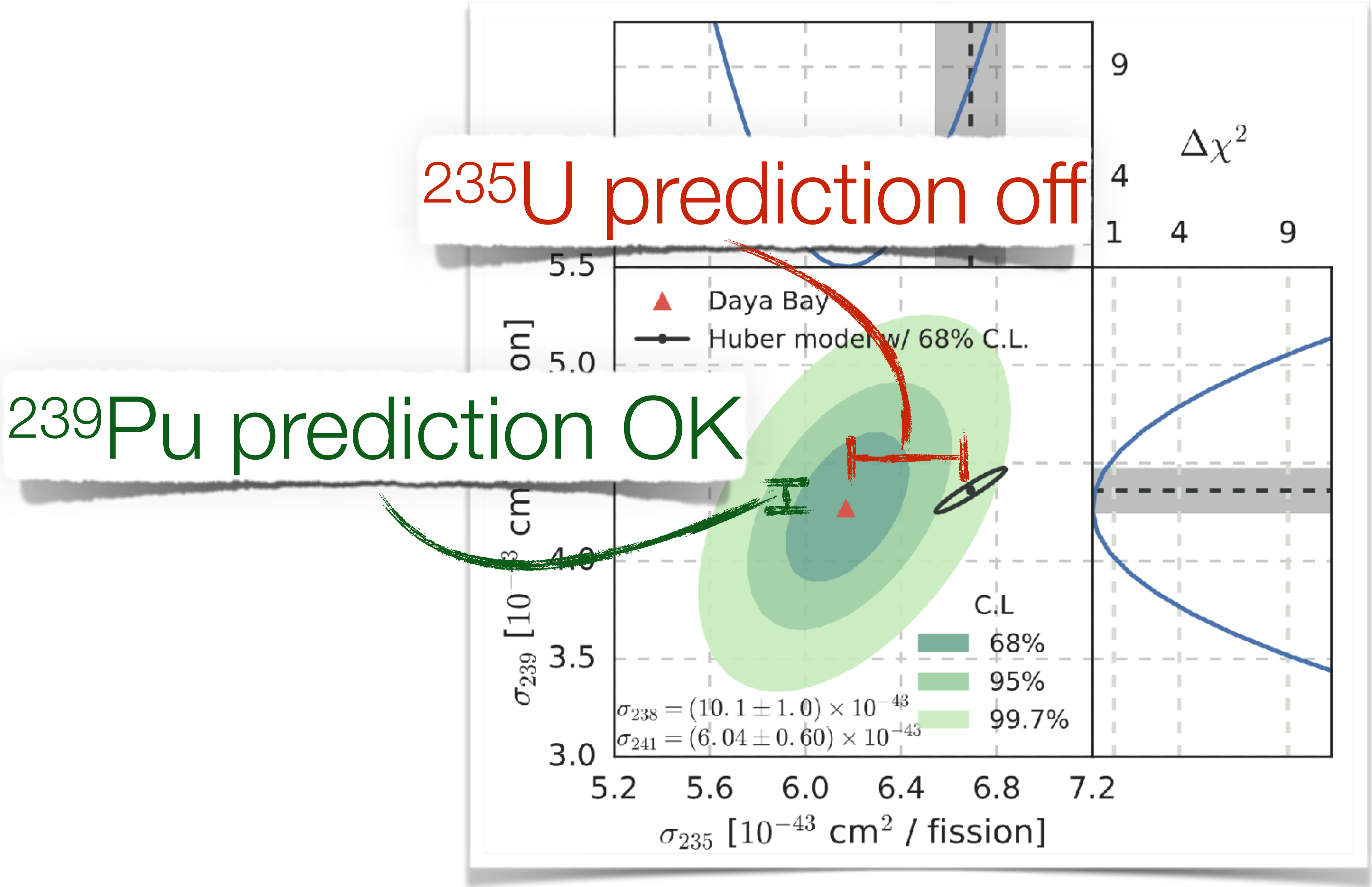

Daya Bay 1704.01082

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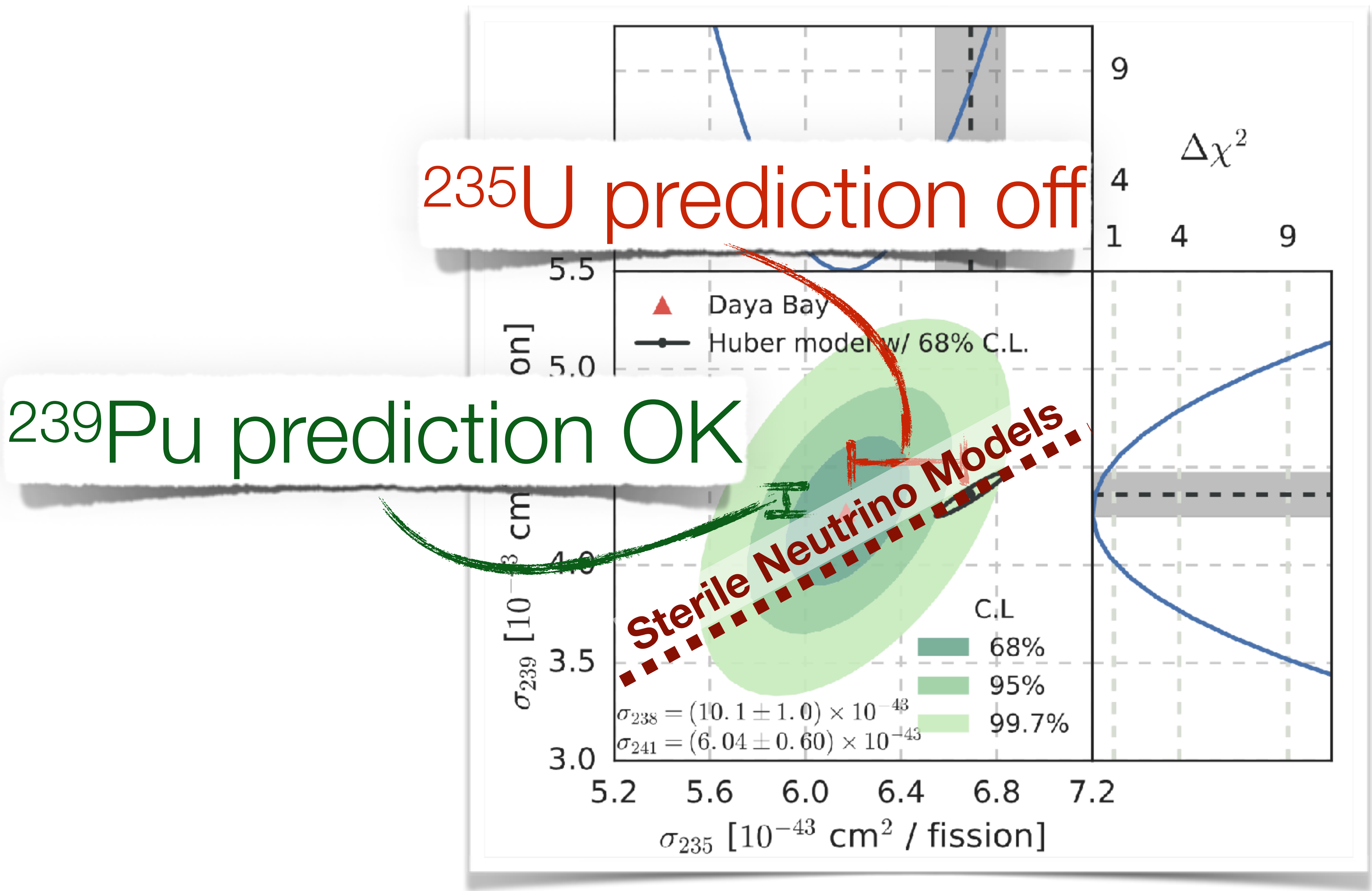

Daya Bay 1704.01082

Sterile Neutrinos or Flux Uncertainty?

- ☑ Full analysis:
  - Compare fit with free ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu fluxes to fit with fixed fluxes + ν_s

- ☑ But both hypothesis yield excellent goodness of fit

Sterile Neutrinos or Flux Uncertainty?

- Full analysis:
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$$\Delta\chi^2 = 7.9$$

- But both hypothesis yield excellent goodness of fit

Sterile Neutrinos or Flux Uncertainty?

- Full analysis:
  - Compare fit with free ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu fluxes to fit with fixed fluxes + ν_s

$\Delta\chi^2 = 6.3$ (with theoretical uncertainties)

- But both hypothesis yield excellent goodness of fit

Fluxes within errors + ν_s	: $p = 0.18$
Fluxes free	: $p = 0.73$
$\Delta\chi^2$ (sterile neutrino vs. free fluxes)	: $p = 0.007$

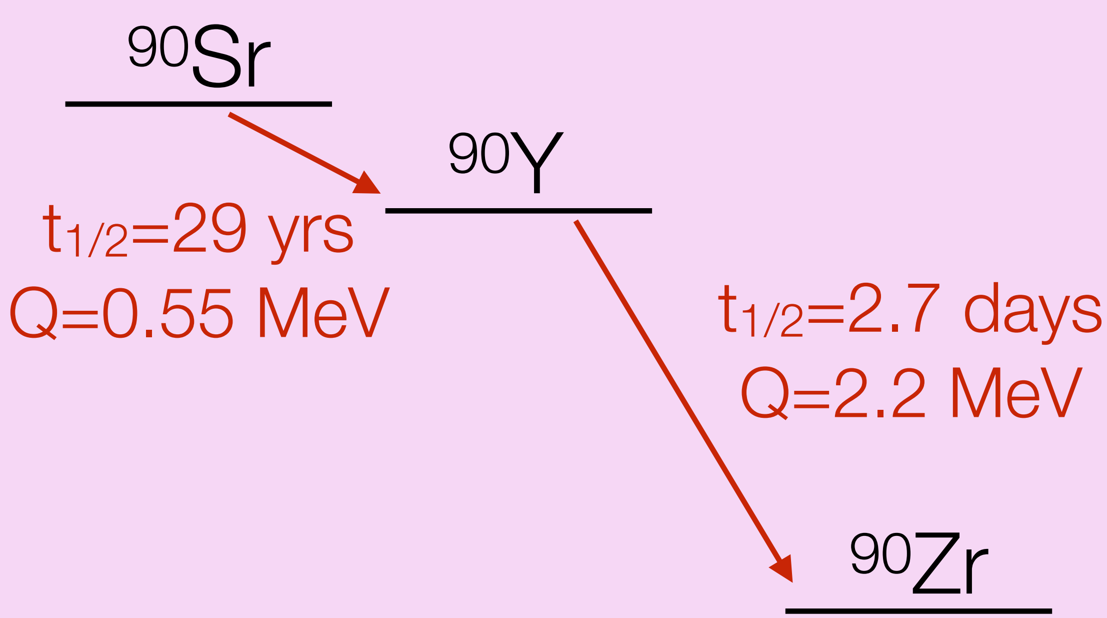
Dentler Hernández JK Maltoni Schwetz 1709.04294

Caveats

Daya Bay method assumes flux from each isotope is time and burnup-independent.

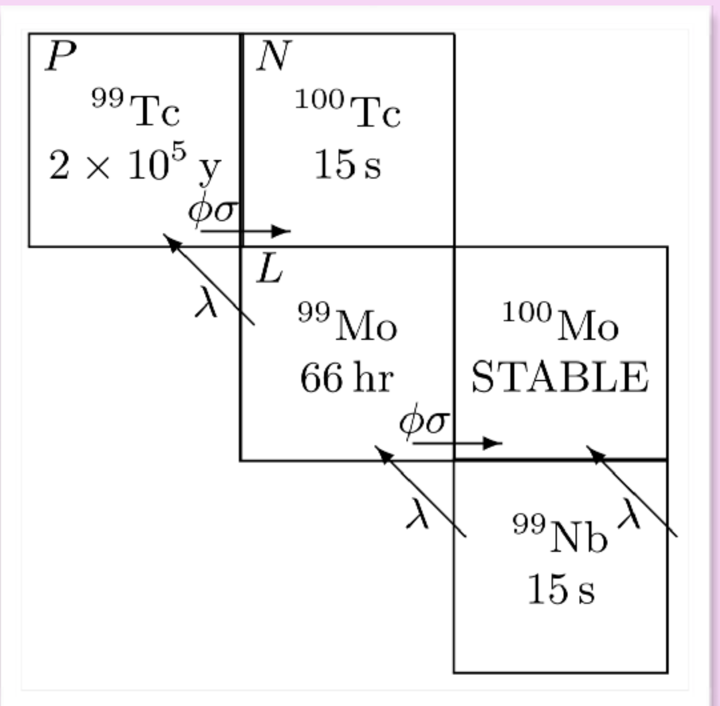
Caveats

Non-Equilibrium



Non-Linear Isotopes

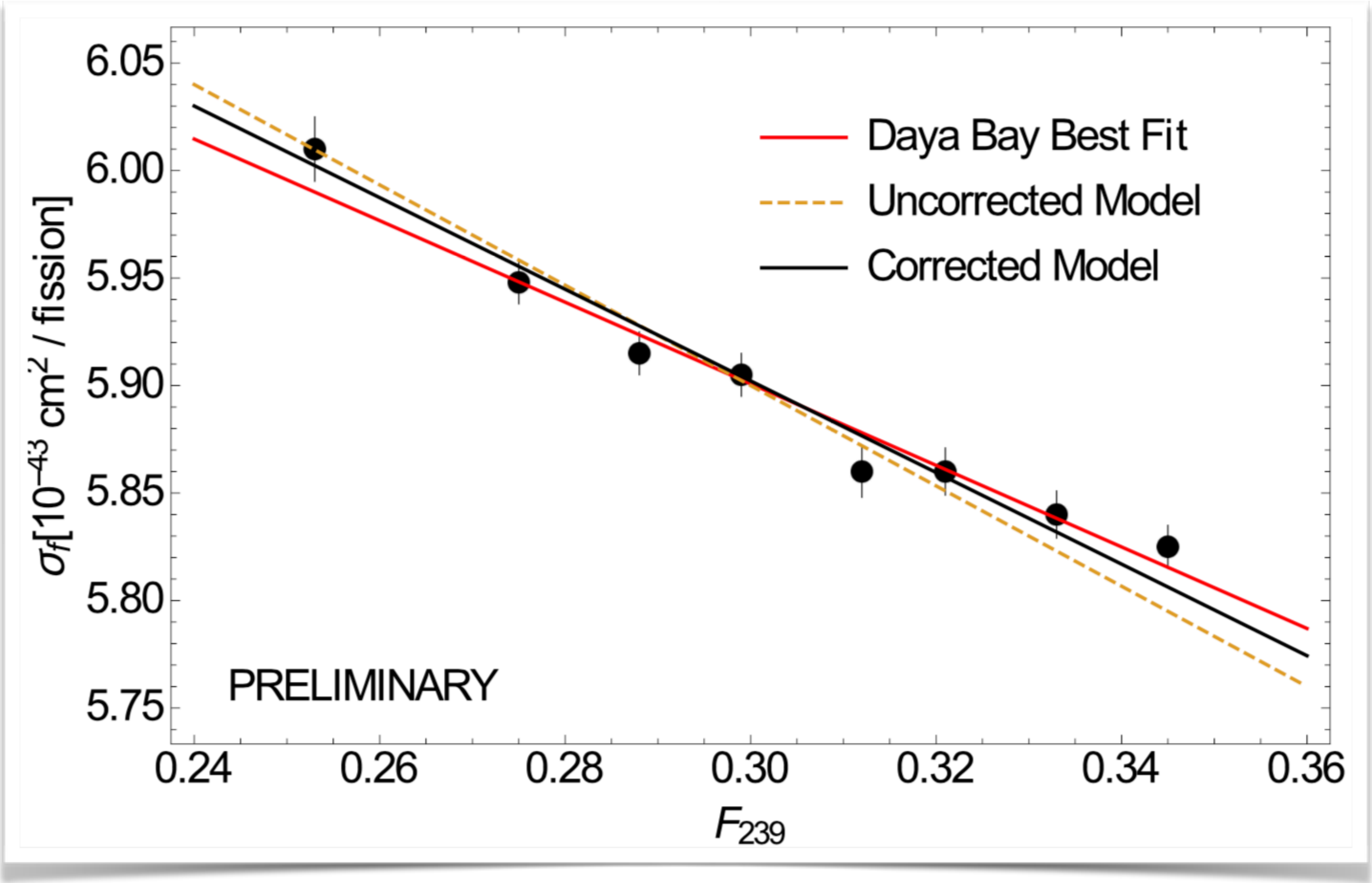
- ☑ Neutron capture on fission products



- ☑ Extra neutron flux/burnup dependence in ν flux

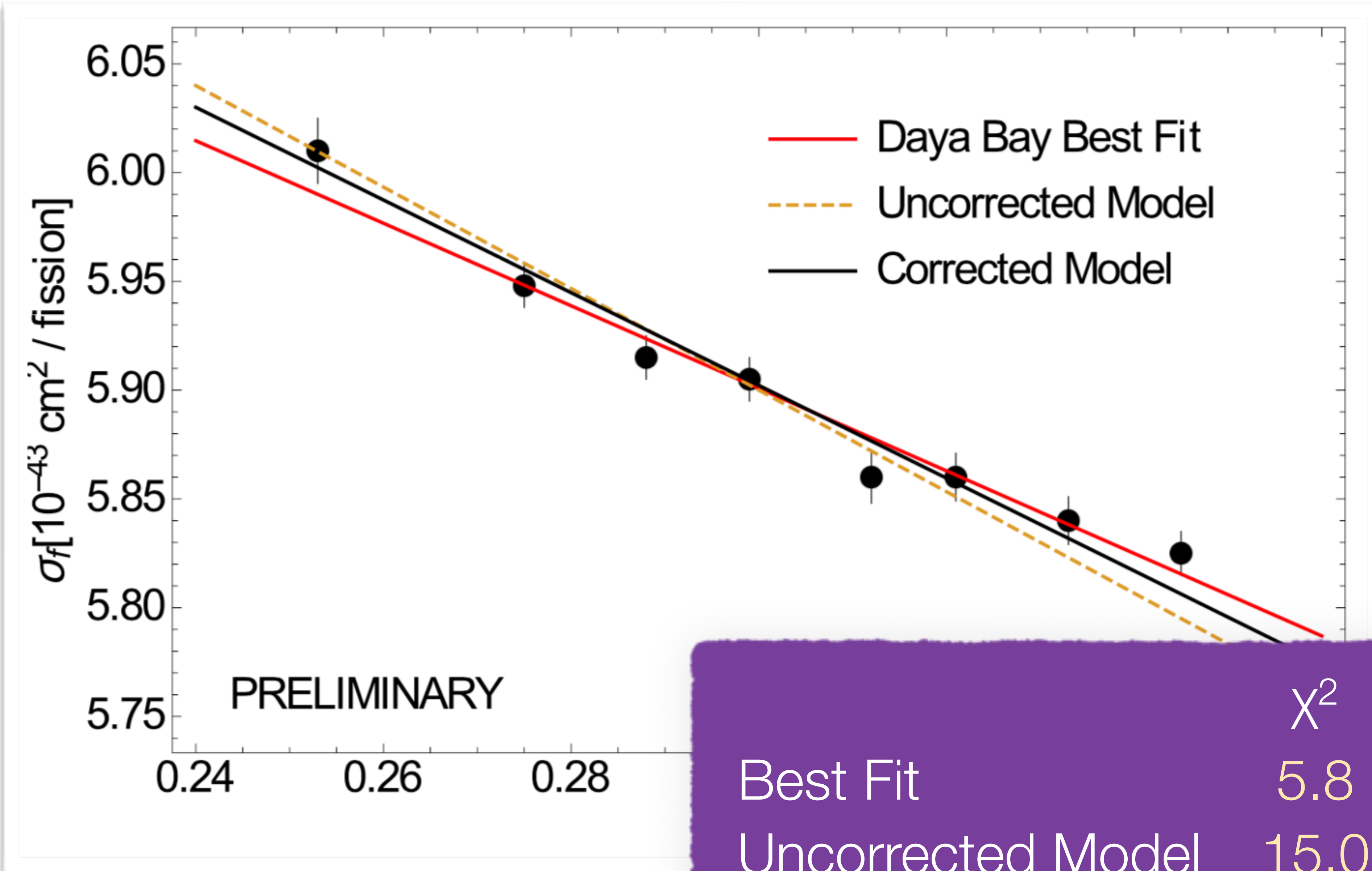
Jaffke Huber [1510.08948](), Huber Sharma, *in preparation*

Improved Analysis



Huber Sharma, *in preparation*

Improved Analysis



Huber Sharma, *in preparation*

	χ^2	$(\Delta\chi^2)^{1/2}$
Best Fit	5.8	
Uncorrected Model	15.0	3σ
Corrected Model	8.5	1.6σ

Sterile Neutrinos?

Light Sterile Neutrinos

- Promote mixing matrix to 4x4
- Oscillation channels are related:

$$P_{\nu_e \to \nu_e} \simeq 1 - 2|U_{e4}|^2(1 - |U_{e4}|^2)$$

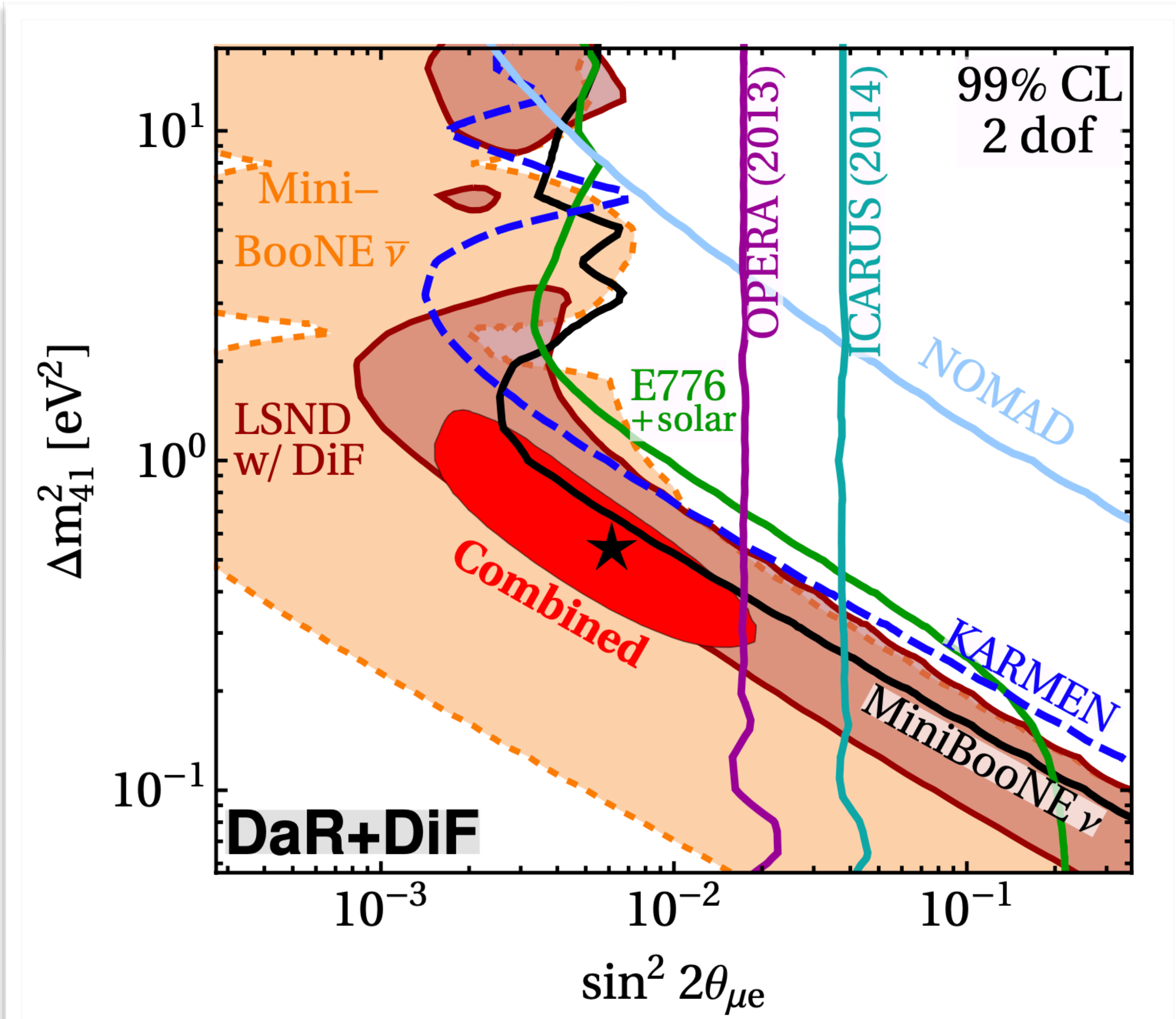
$$P_{\nu_\mu \to \nu_\mu} \simeq 1 - 2|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2)$$

$$P_{\nu_\mu \to \nu_e} \simeq 2|U_{e4}|^2|U_{\mu 4}|^2$$

(for $4\pi E/\Delta m^2_{41} \ll L \ll 4\pi E/\Delta m^2_{31}$)

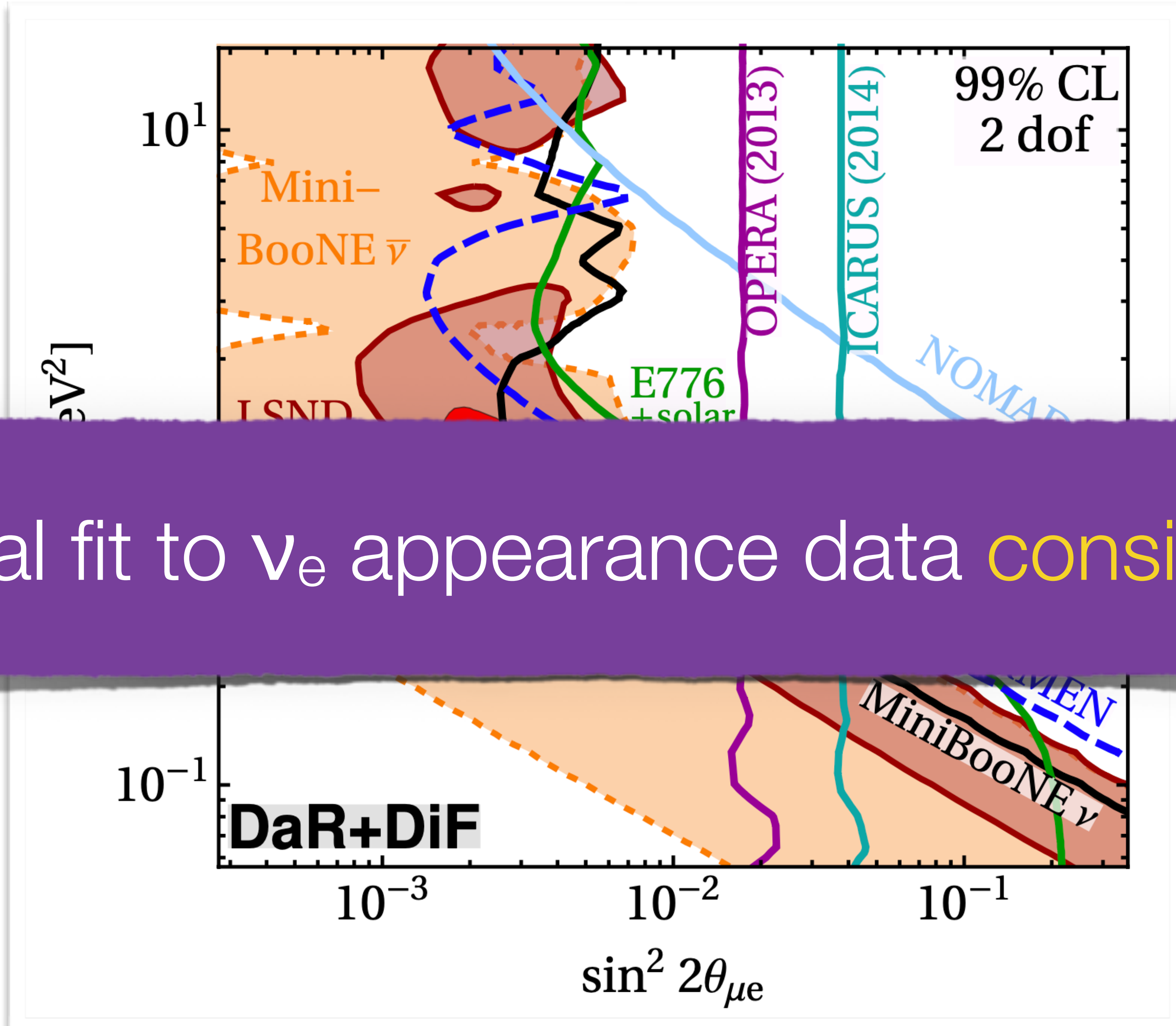
- Models can be over-constrained.

Global Fit to ν_e Appearance Data



Dentler *et al.*, 1803.10661

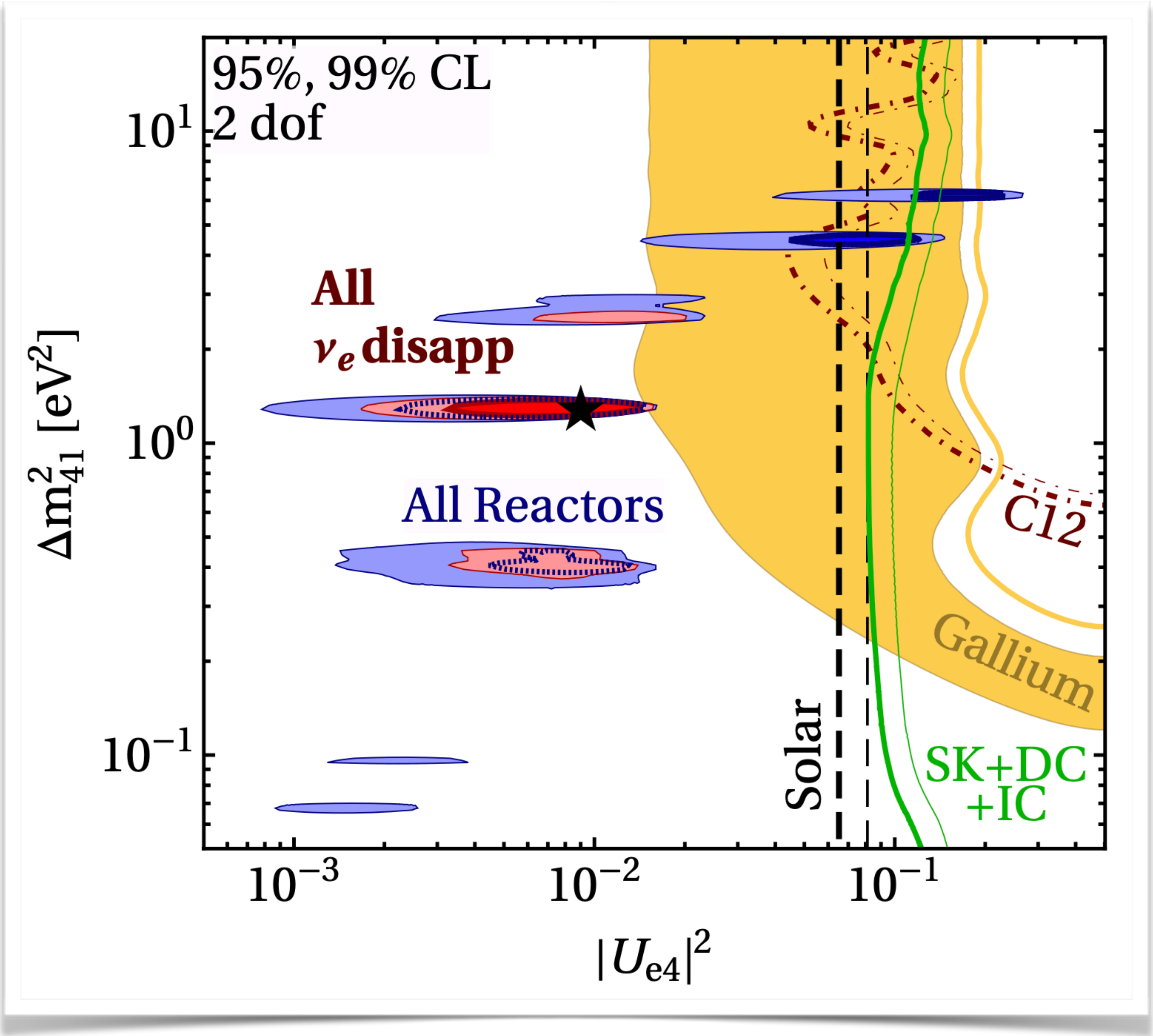
Global Fit to ν_e Appearance Data



Global fit to ν_e appearance data consistent.

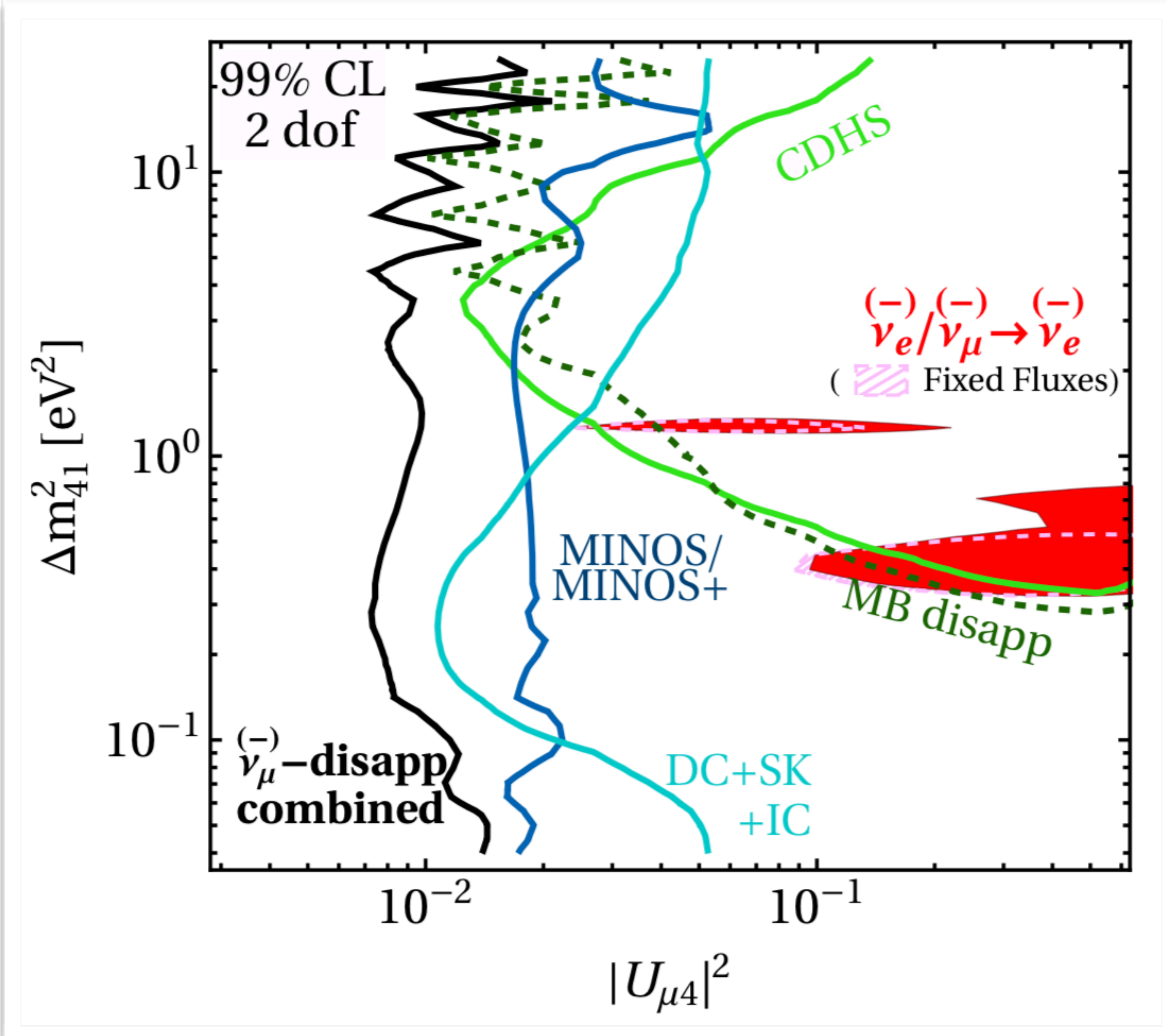
Dentler *et al.*, [1803.10661]

Global Fit to ν_e Disappearance



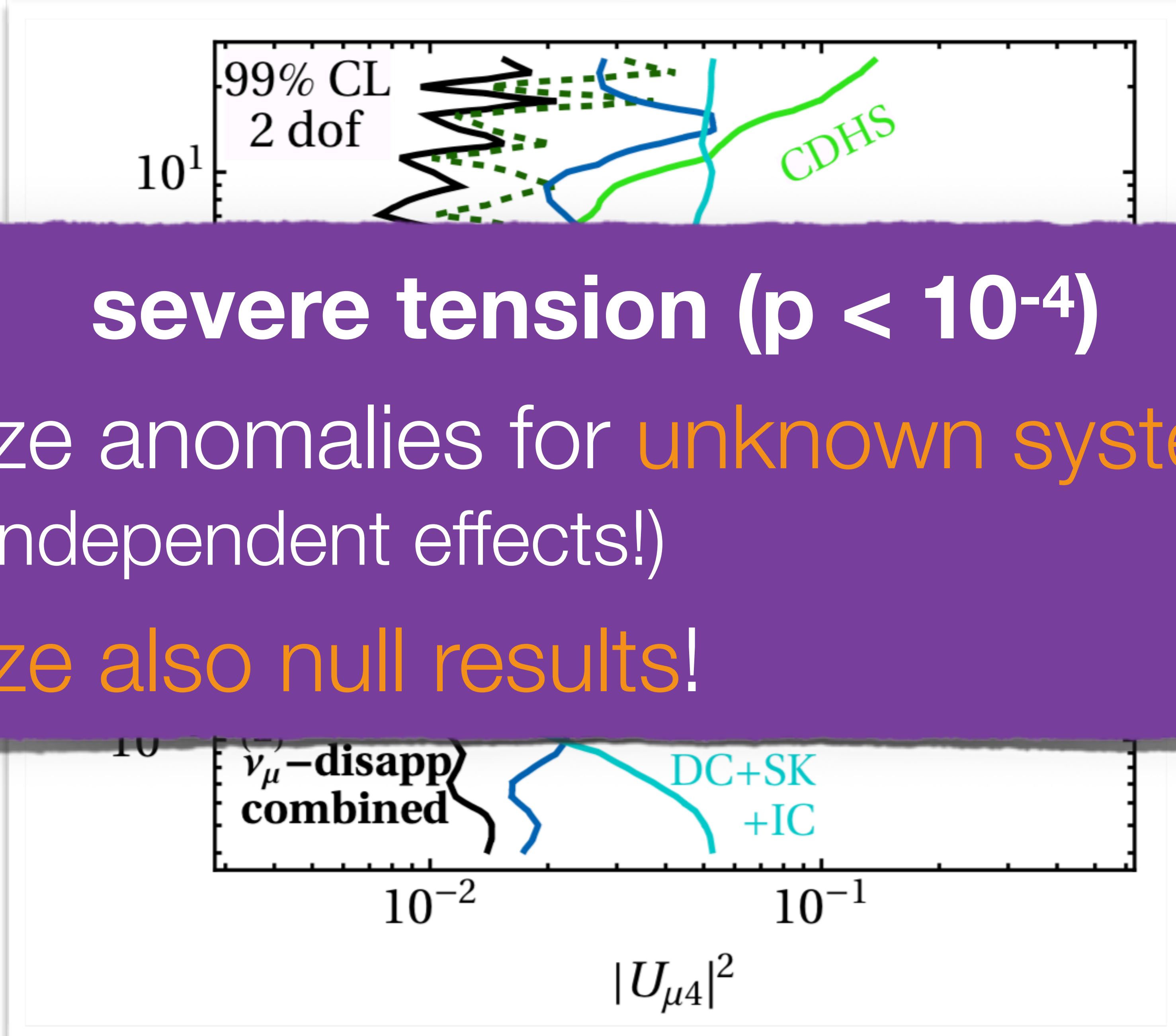
Dentler *et al.*, 1803.10661

Including ν_μ Disappearance



Dentler Hernandez JK Machado Maltoni Martinez Schwetz, 1803.10661
see also works by Collin Argüelles Conrad Shaevitz, 1607.00011
Gariazzo Giunti Laveder Li, 1703.00860

Including ν_μ Disappearance



severe tension ($p < 10^{-4}$)

- ☆ scrutinize anomalies for unknown systematics (need 4 independent effects!)
- ☆ scrutinize also null results!

Dentler Hernandez JK Machado Maltoni Martinez Schwetz, 1803.10661
see also works by Collin Argüelles Conrad Shaevitz, 1607.00011
Gariazzo Giunti Laveder Li, 1703.00860

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Sterile Neutrino Decay

Decaying Sterile Neutrinos

Dentler Esteban JK Machado, 1911.01427

Decaying Sterile Neutrinos

- Idea: production of sterile neutrinos that quickly decay back into active neutrinos (+ light new scalar): $\nu_s \to \nu_a + \Phi$

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

Dentler Esteban JK Machado, 1911.01427

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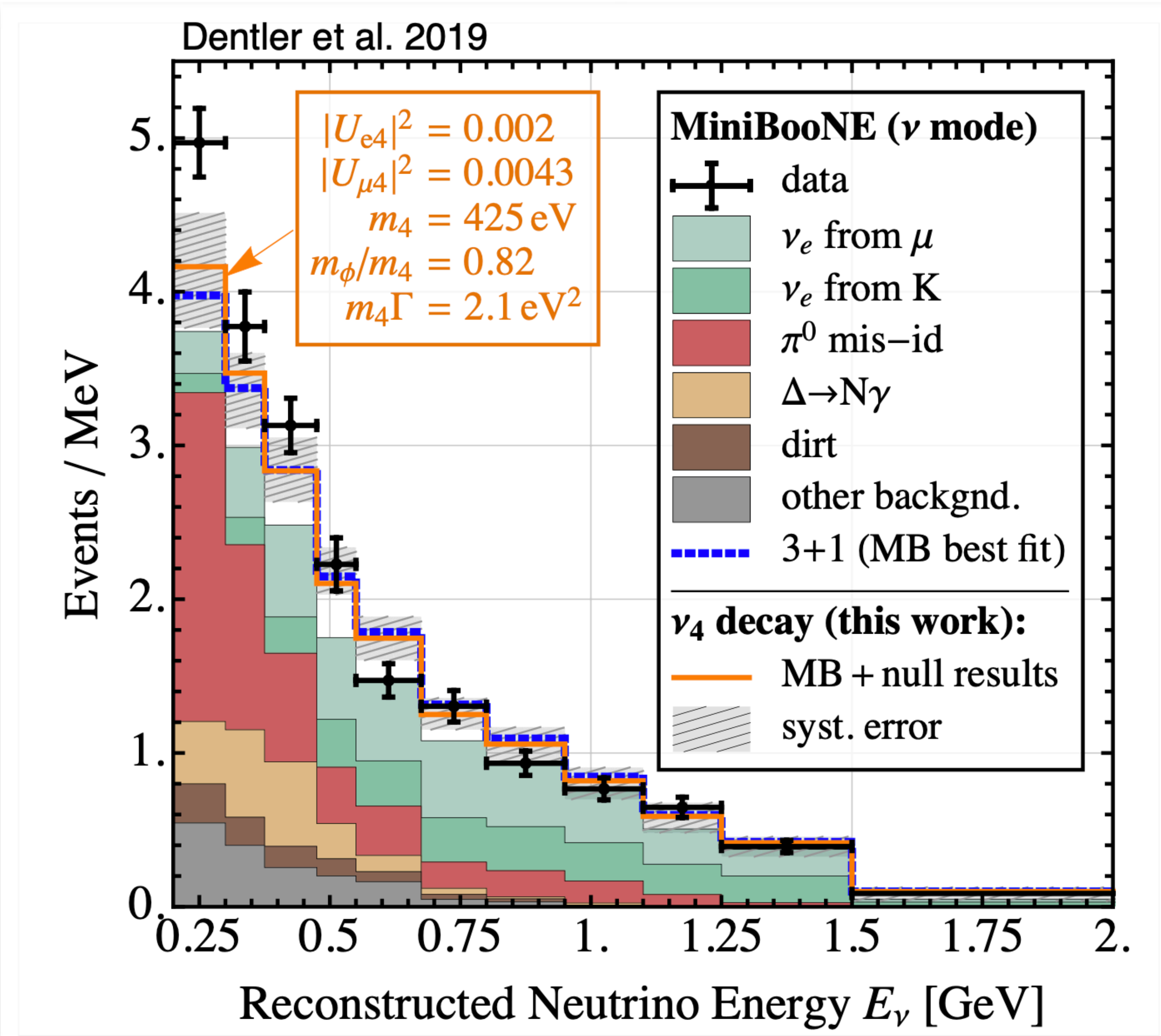
- Excellent fit to MiniBooNE data



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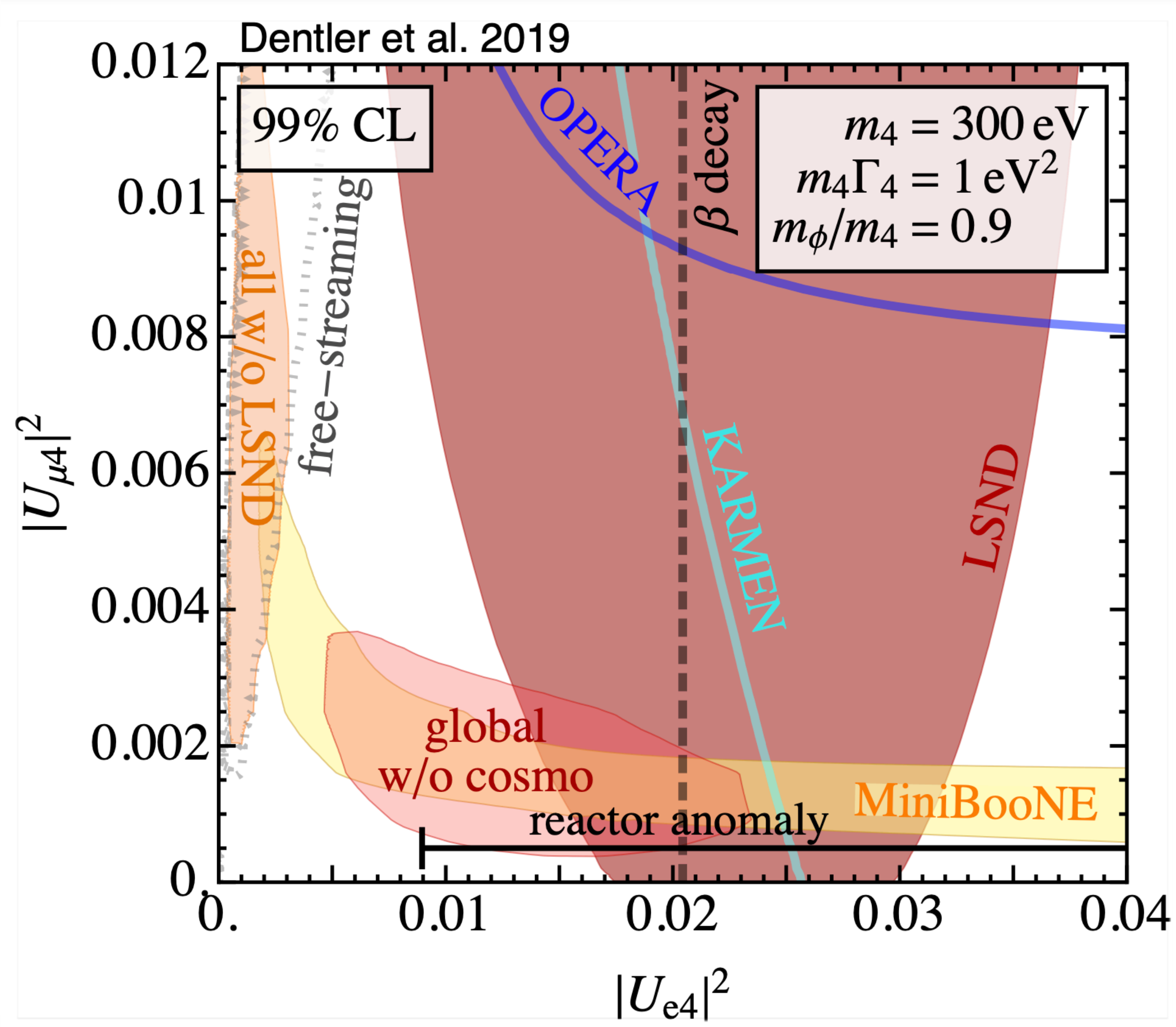

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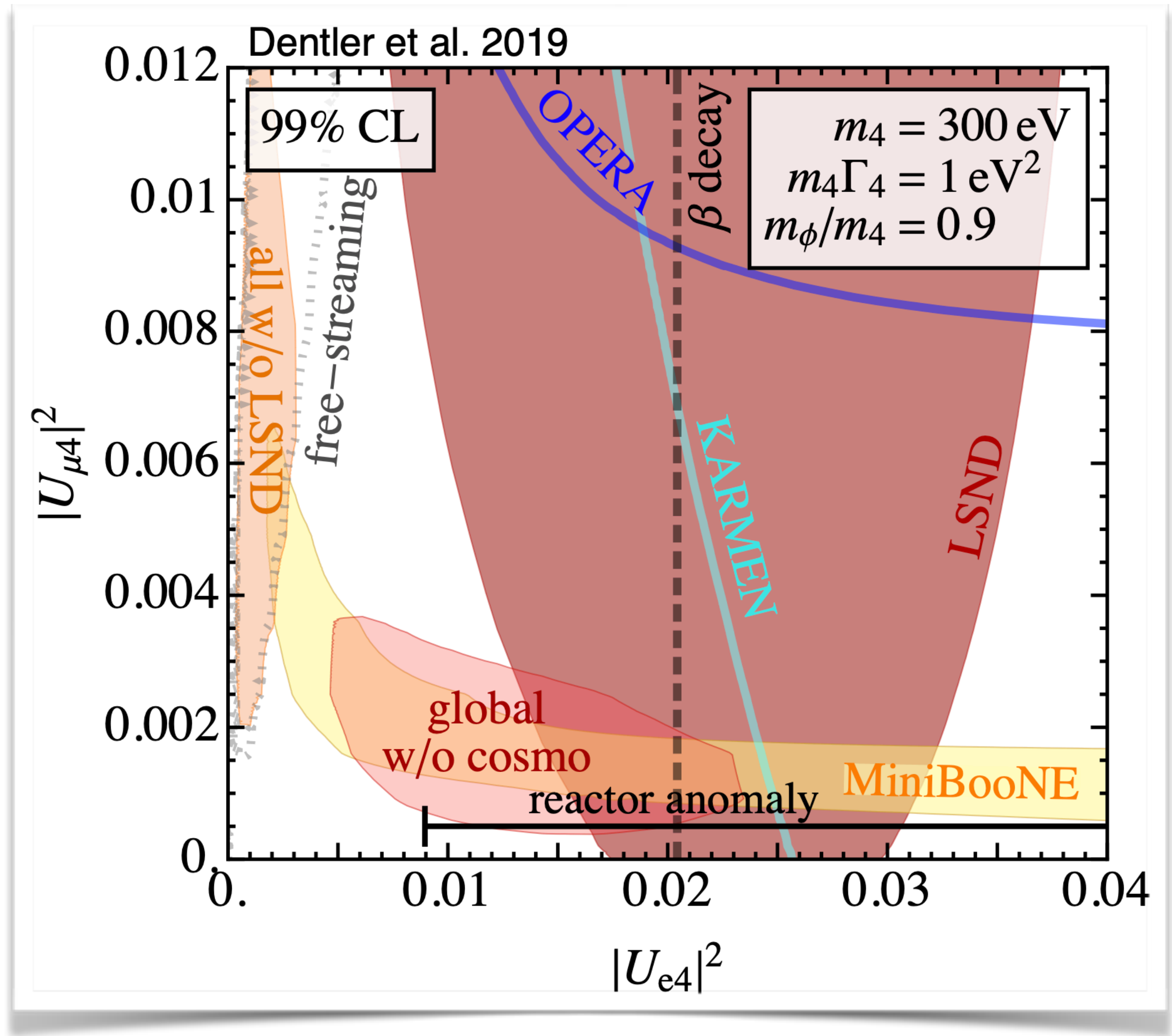
- with small extensions: consistent also with LSND + reactors + gallium



Dentler Esteban JK Machado, 1911.01427

Summary

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- ☑ 3+n sterile neutrino models cannot explain all data
- ☑ MiniBooNE
  - data-driven background estimates
  - but large uncertainties in translating to signal region
  - differences between event generators
- ☑ Reactor Anomaly
  - origin can be tested via isotope/time-dependence
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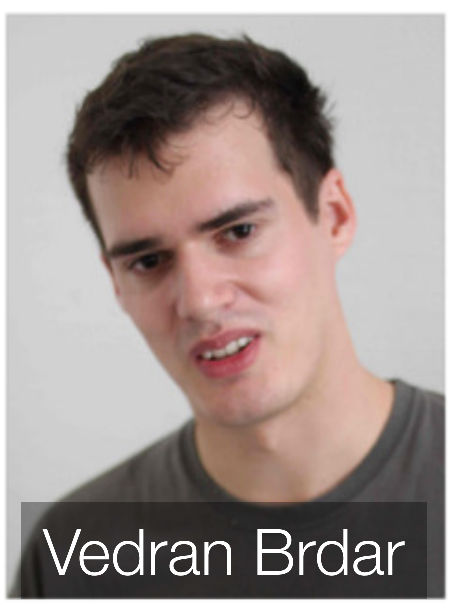

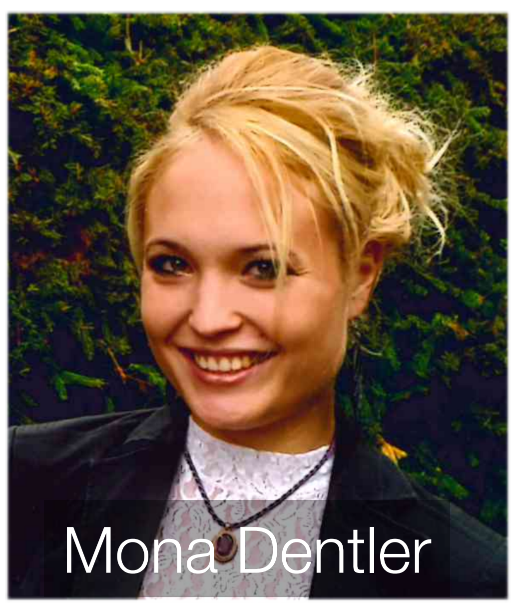

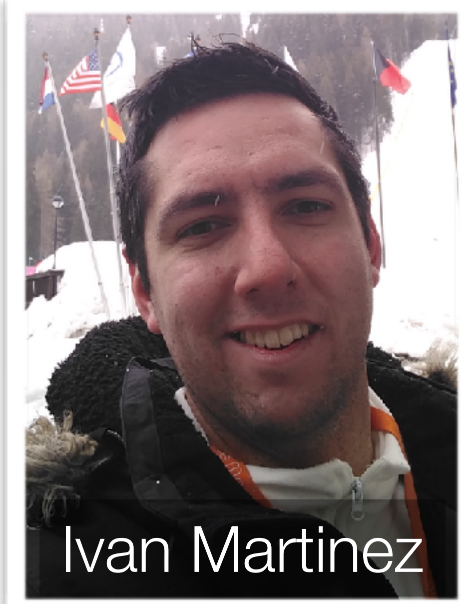

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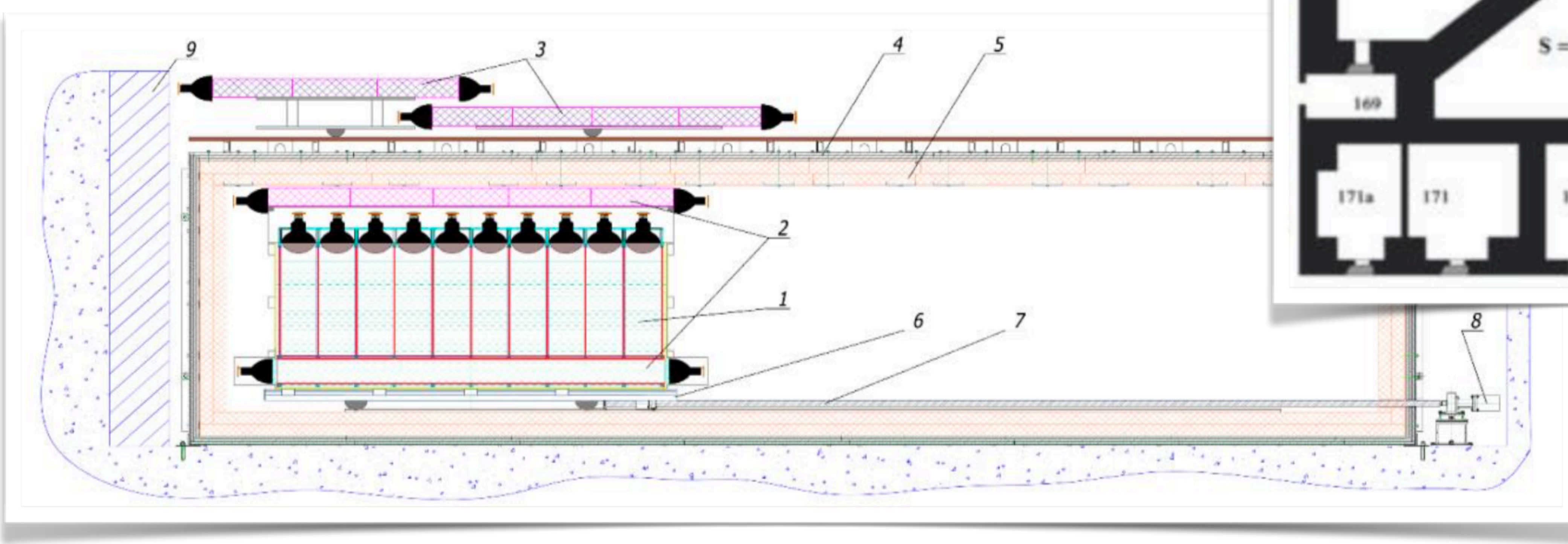
Thank You!

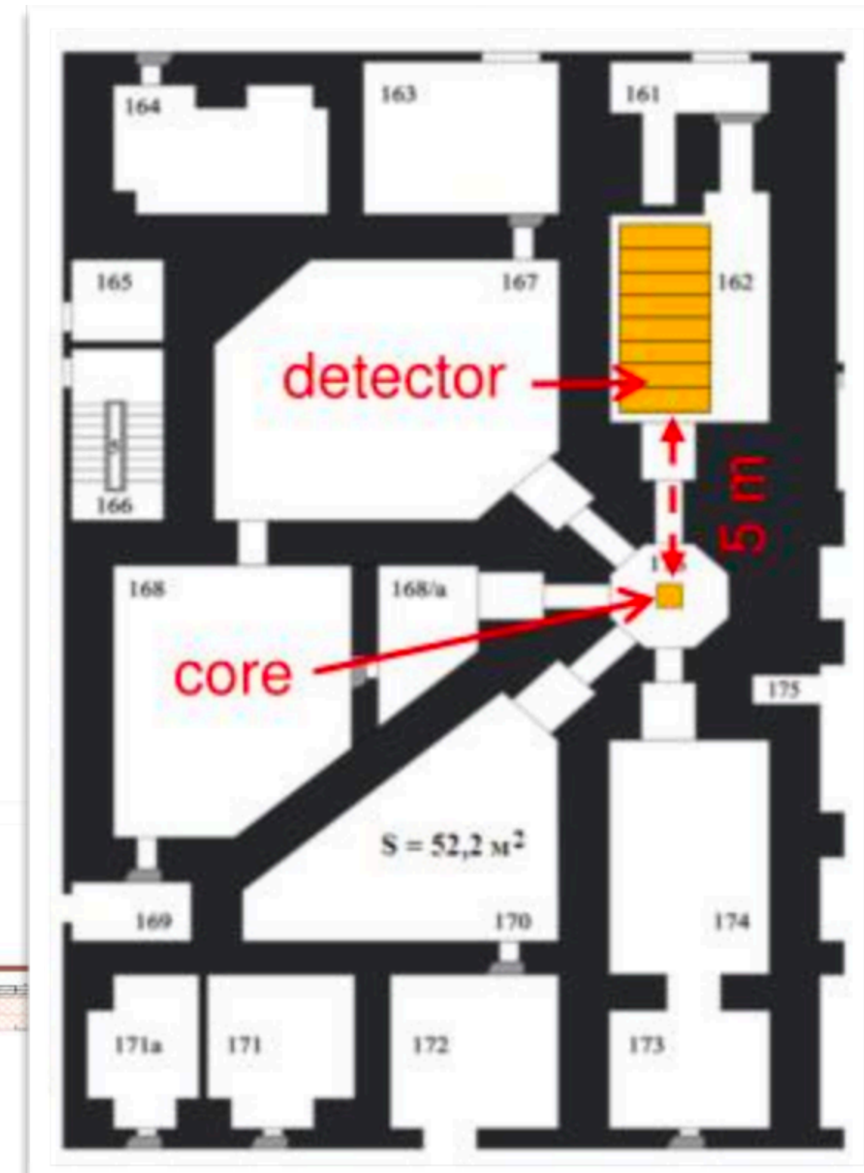
Bonus Slides

Neutrino-4

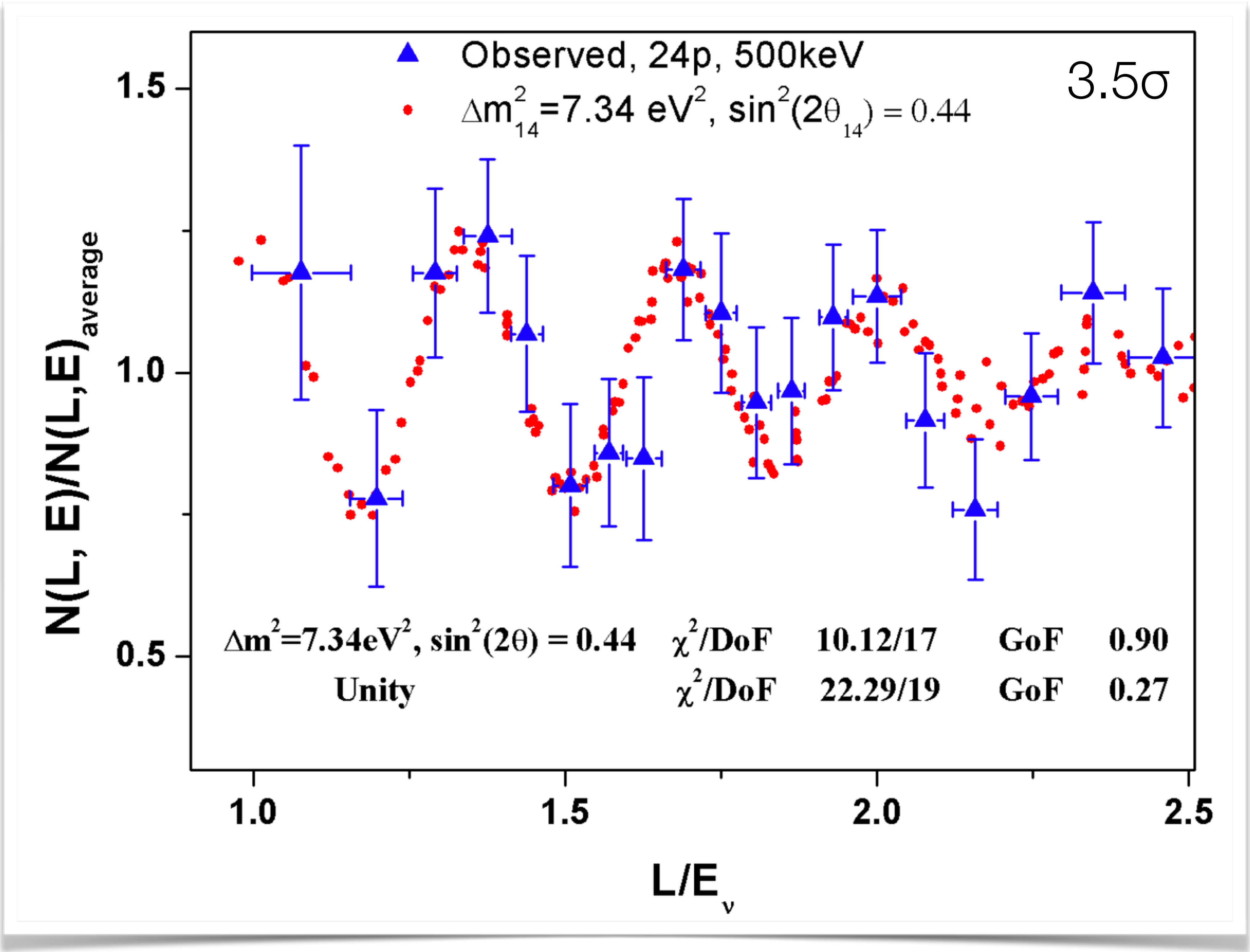
Neutrino-4

- ~1.5 ton detector at research reactor in Dimitrovgrad, Russia
- 480 days of reactor-ON data



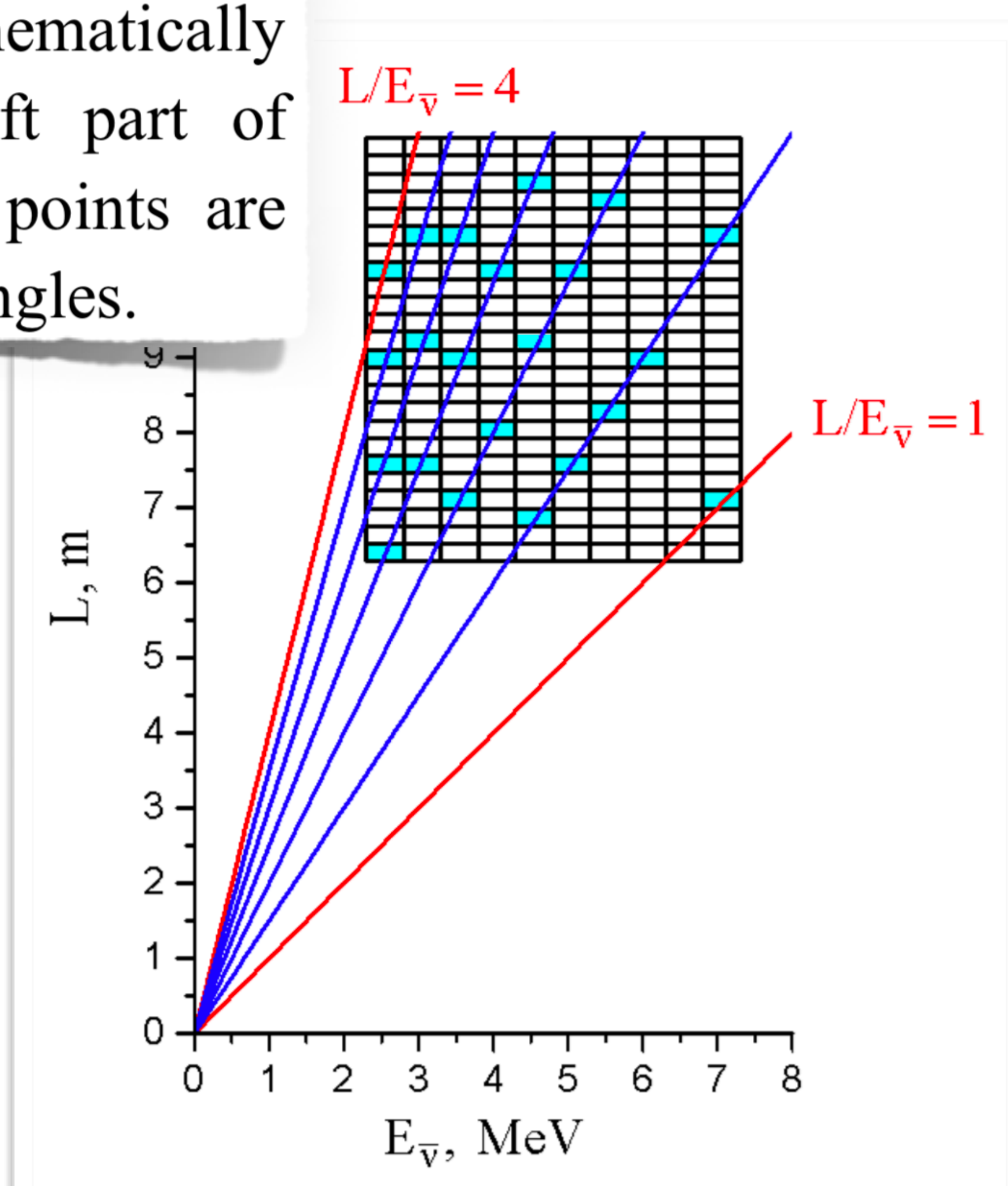


The DAMA of Neutrino Physics?



Questions about Binning

For this purpose, we used 24 distance points (with 23 cm interval) and 9 energy points (with 0.5MeV interval). The corresponding matrix is schematically shown in Fig. 11. The selection for left part of equation (2) (of total 216 points each 8 points are averaged) is shown in Fig. 12 with blue triangles.



- ☑ binning could introduce artefacts