Quo Vadis, Sterile Neutrino?

The Current Status of Searches for a Fourth Neutrino

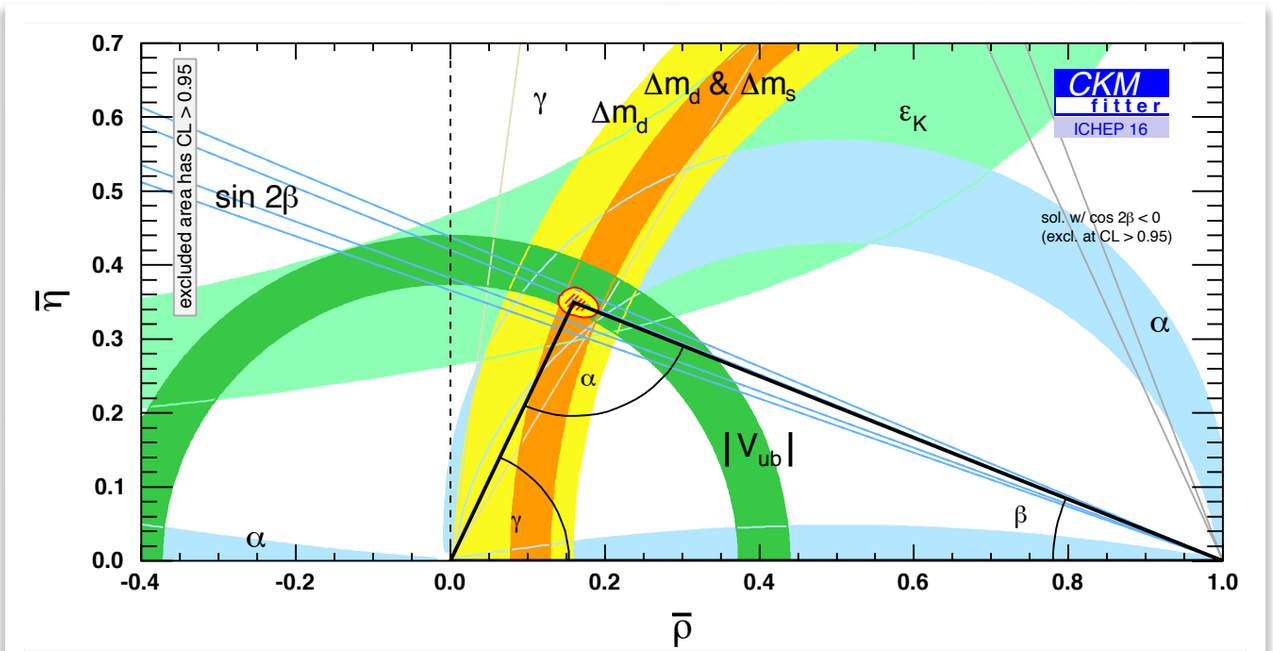
Joachim Kopp (CERN & Uni Mainz)

Neutrino 2022 | 30 May 2022

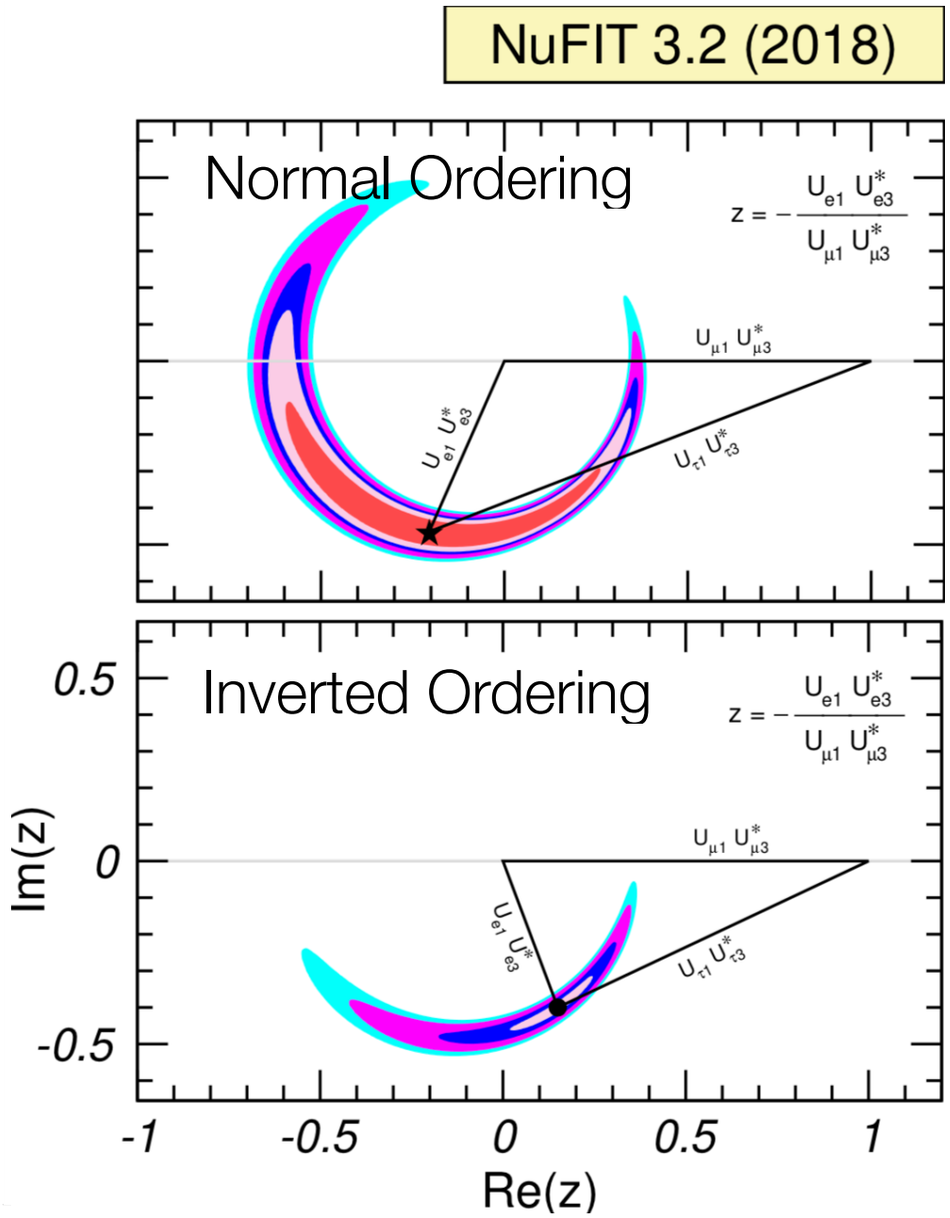
CERN | Neutrino PLATFORM | erc | JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Precision Flavour Physics

Quarks



Leptons



Precision Flavour Physics

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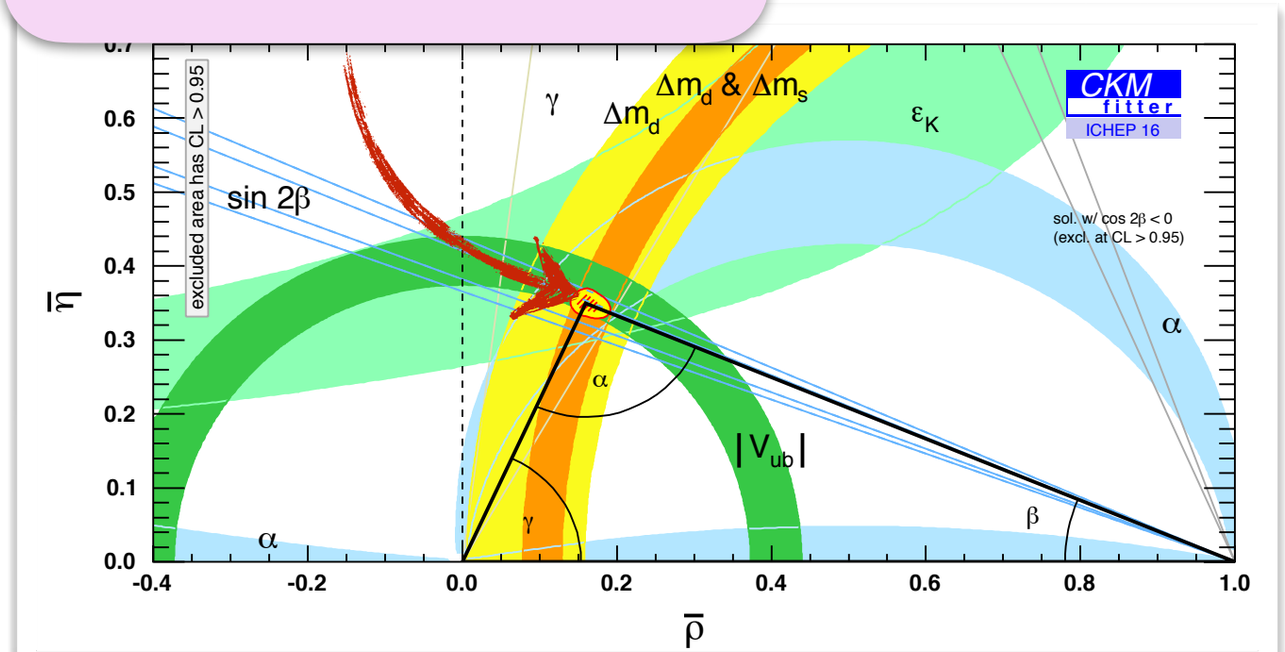
- ☑ superb precision
- ☑ excellent consistency



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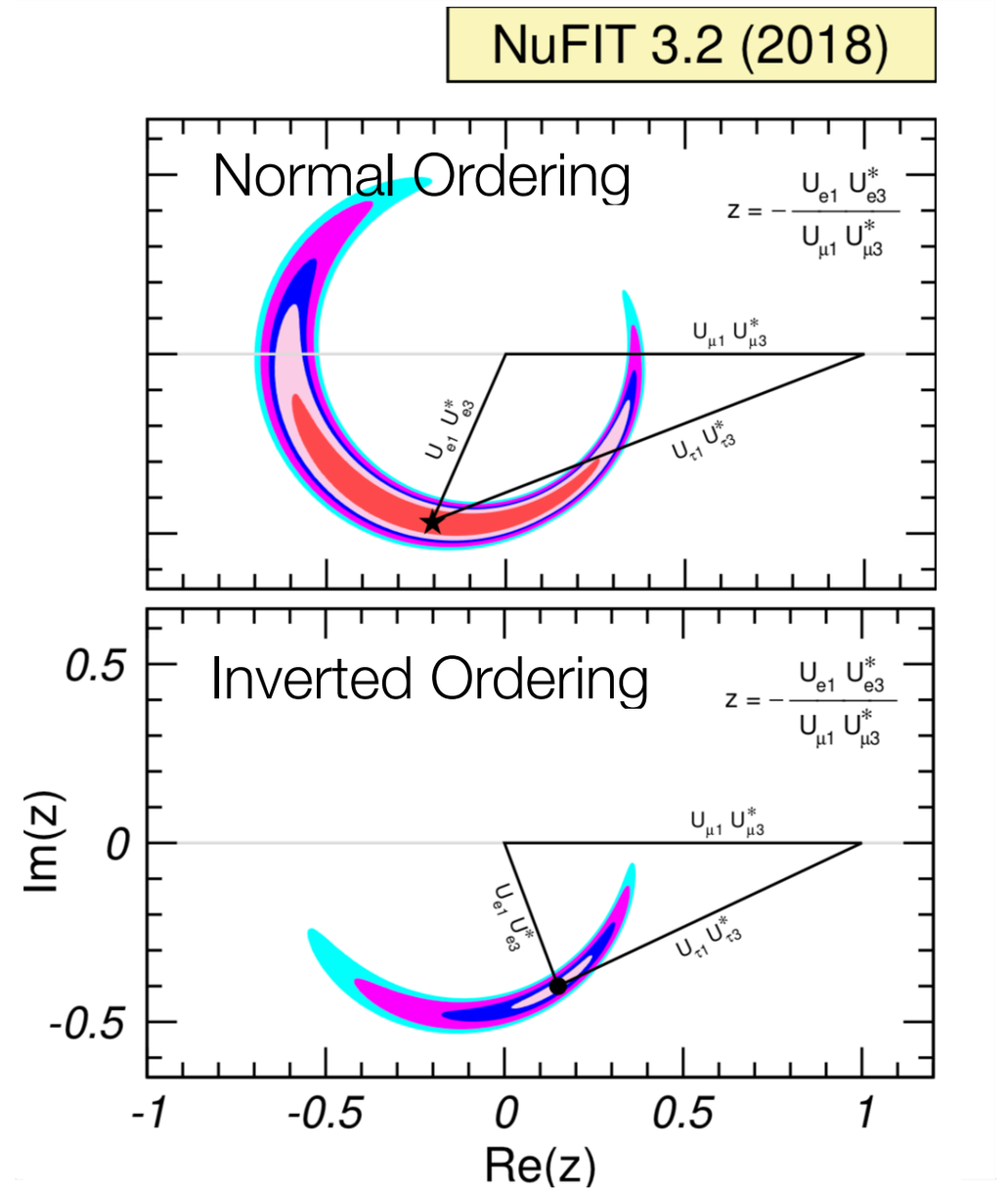

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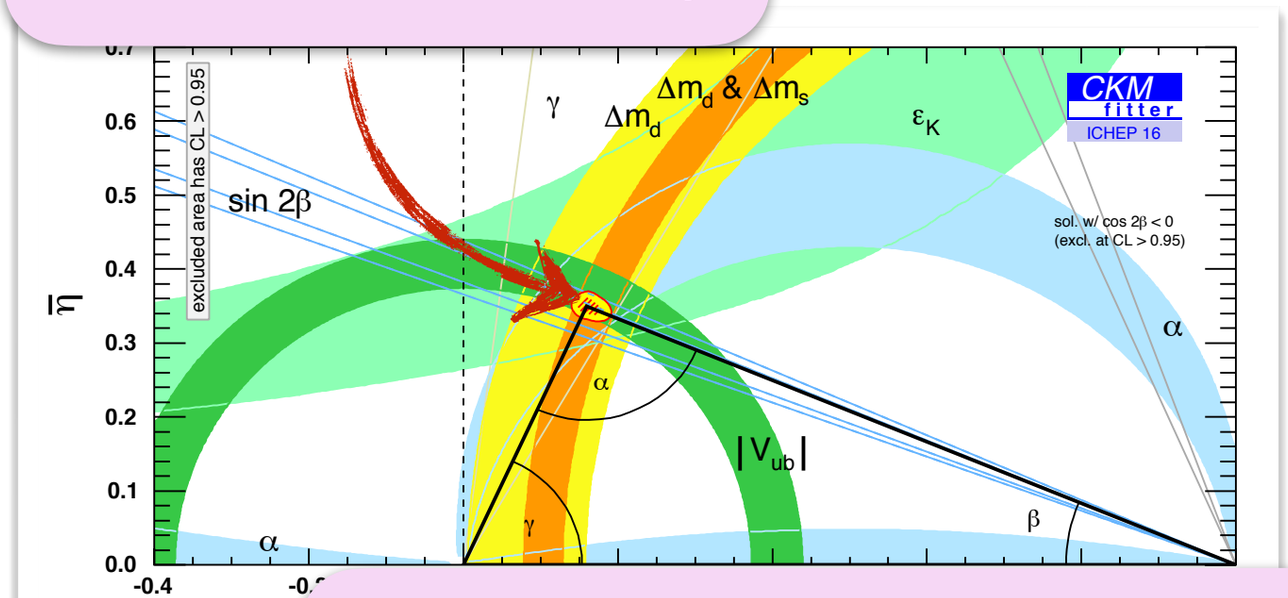
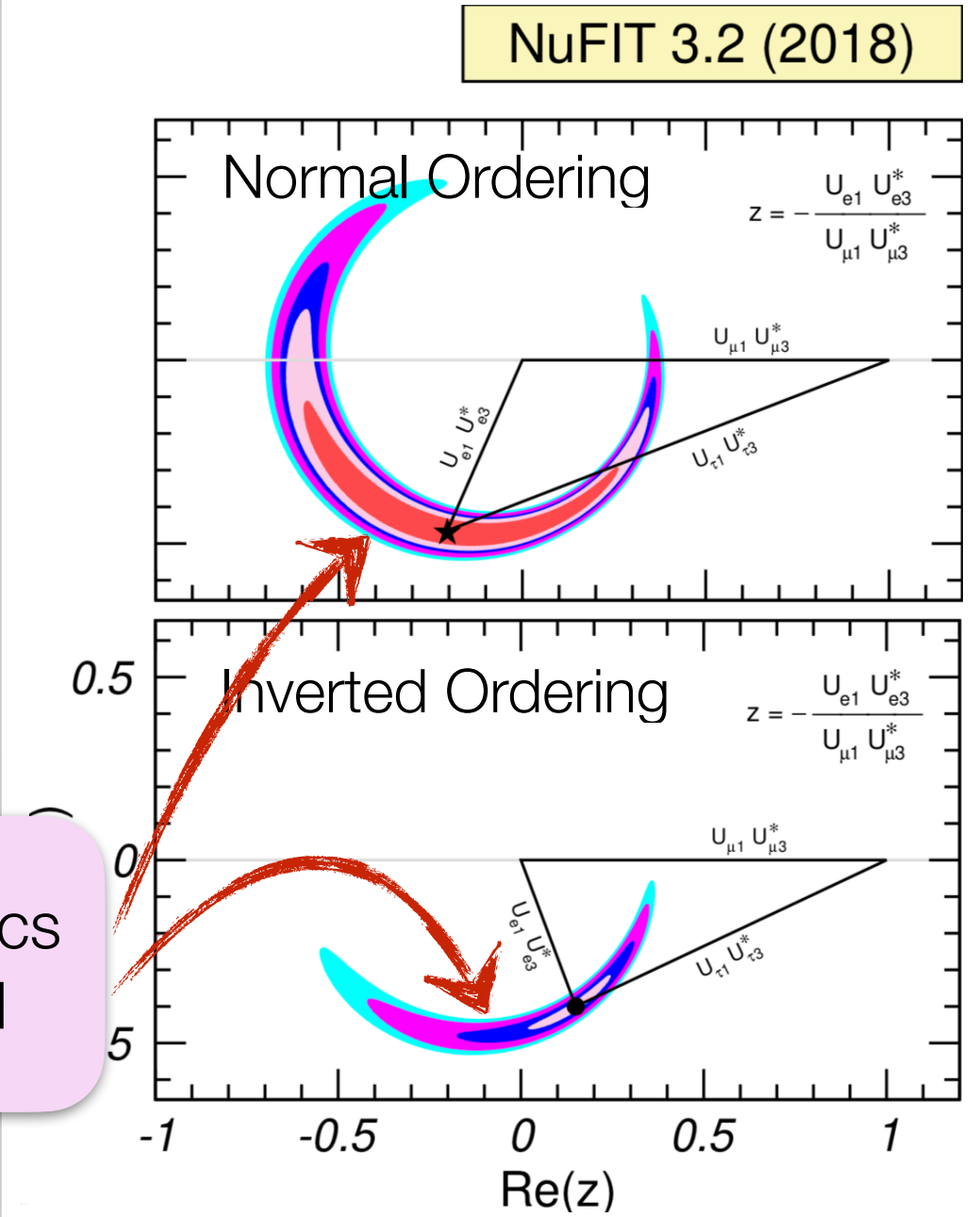


- ☑ < 10% accuracy in spite of tiny x-secs
- ☑ some parameters still unconstrained

Leptons



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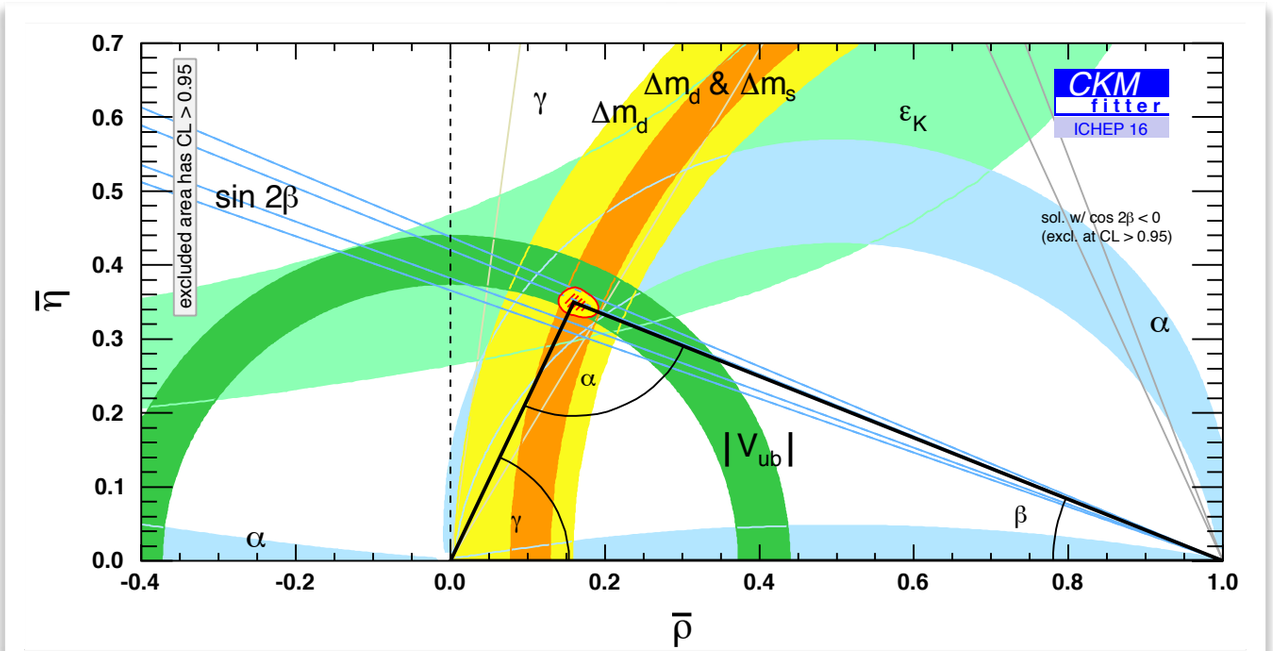

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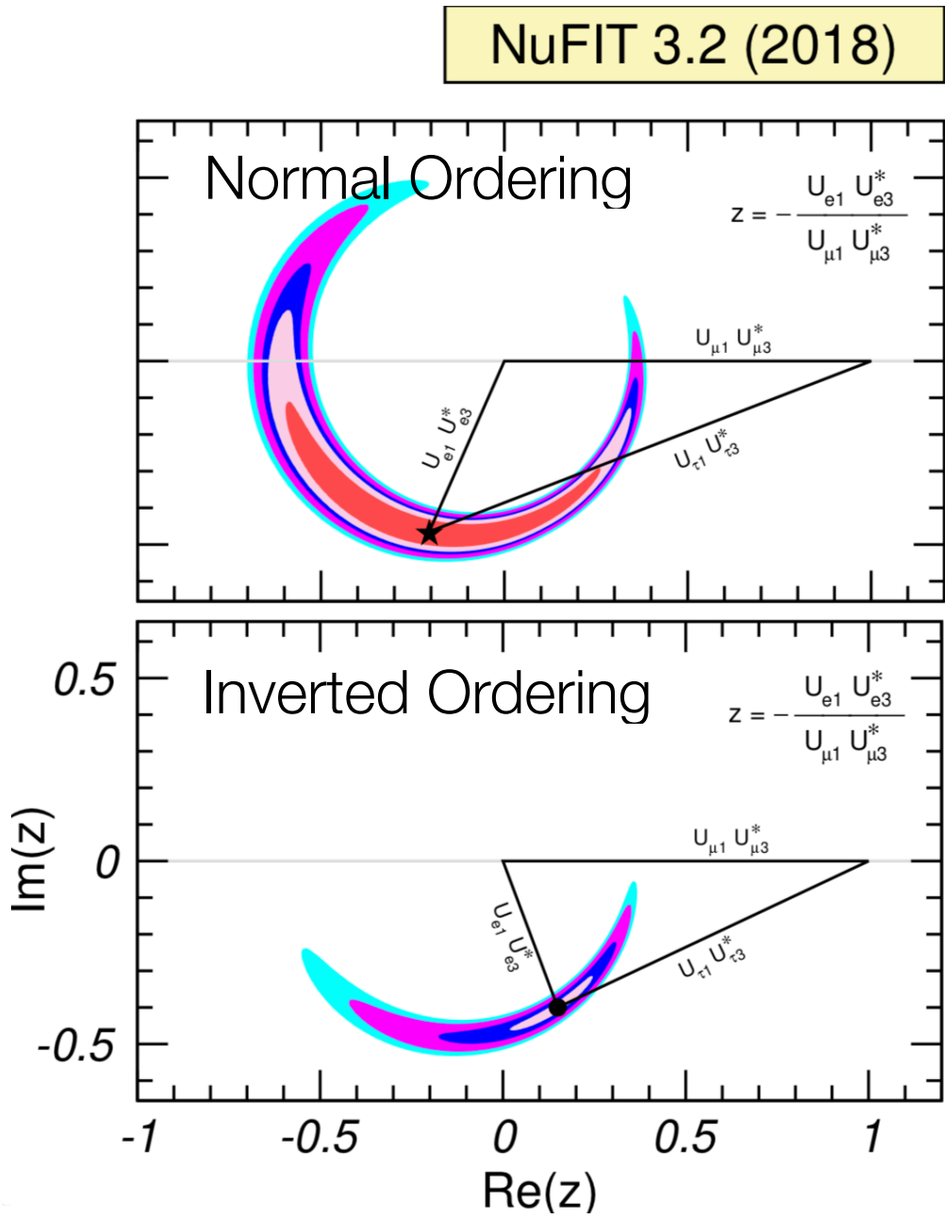

Precision Flavour Physics

Quarks

Leptons

in both sectors:

broadly consistent picture marred by intriguing anomalies

➠ this session

Outline

- ☑ Short-Baseline Anomalies
- ☑ Standard Model Explanations for the MiniBooNE Anomaly?
- ☑ Sterile Neutrinos?

Short-Baseline Anomalies

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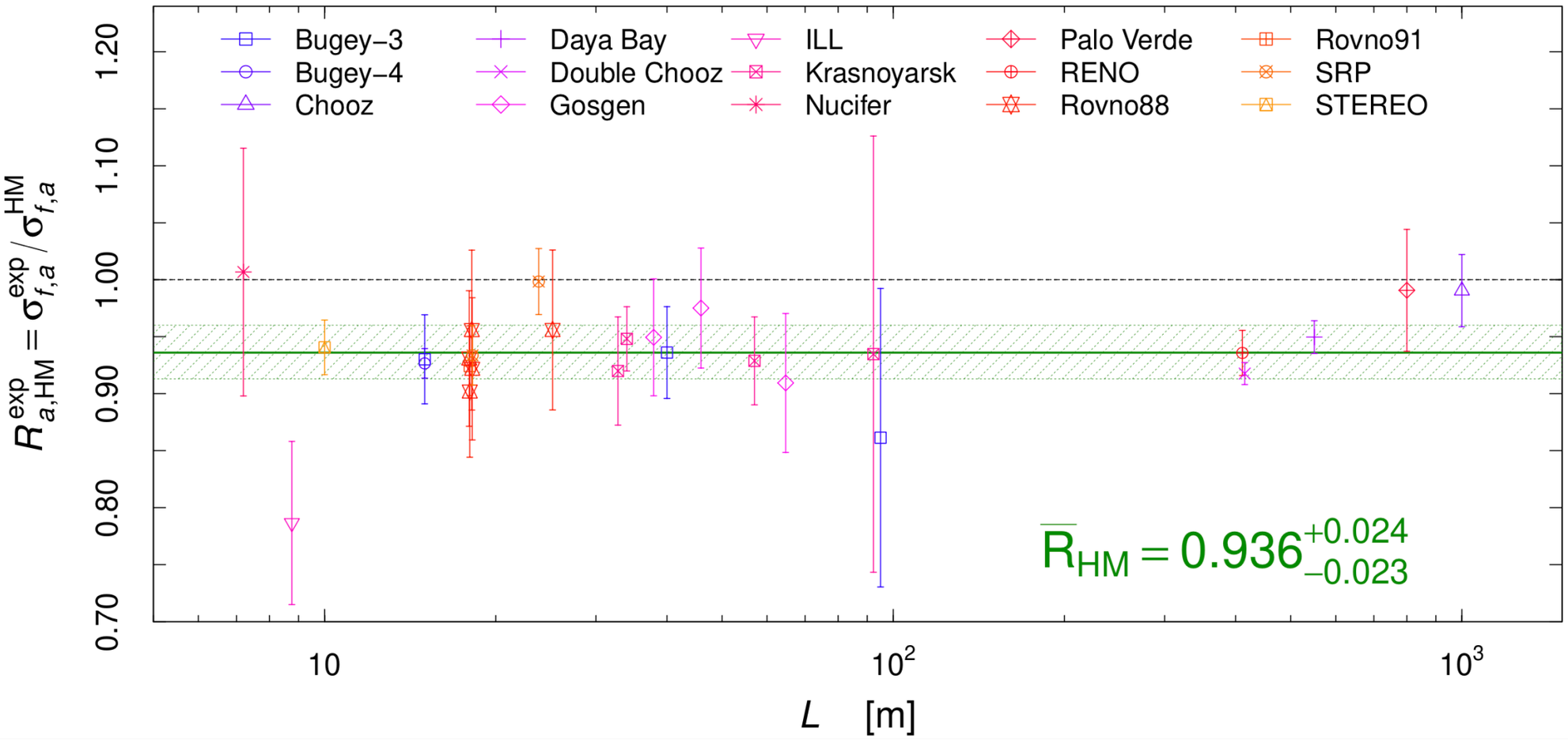
Anomaly #1: Reactor Neutrino Fluxes

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

➠ oscillations of $\bar{\nu}_e$ into **sterile neutrinos** $\bar{\nu}_s$?
(L/E too small for standard oscillations)

Mueller *et al.* 1101.2663, Huber 1106.0687, Giunti *et al.* 2110.06820



Light Sterile Neutrinos

Definition: sterile neutrino = SM singlet fermion

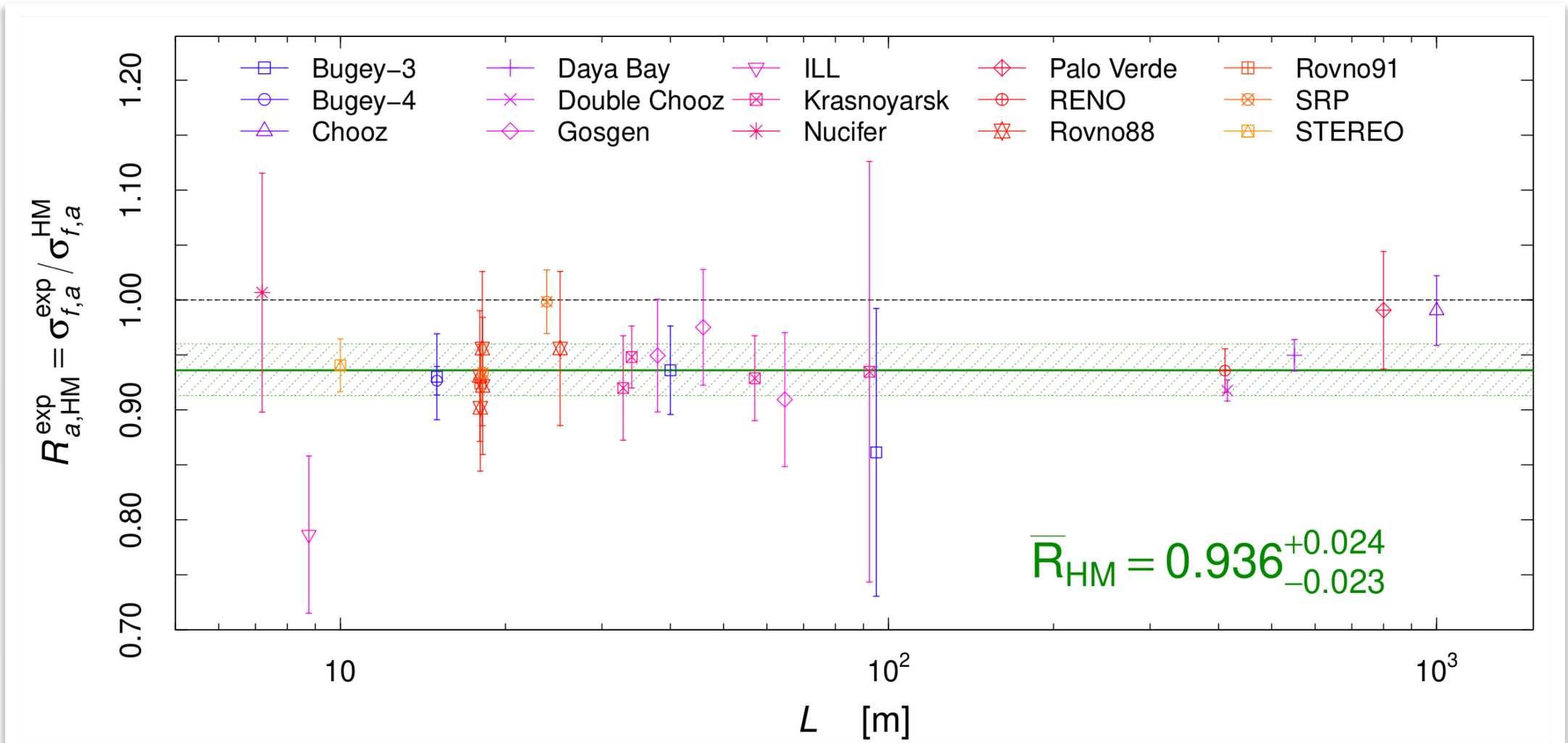
- ☑ Very generic extension of SM
  - can be leftover of extended gauge multiplet

- ☑ 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:

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

Anomaly #1: Reactor Neutrino Fluxes

With updated input data to flux calculation
(new β spectra from ^{235}U fission)



Kopeikin Skorokhvatov Titov arXiv:2103.01684
Berryman Huber arXiv:2005.01756
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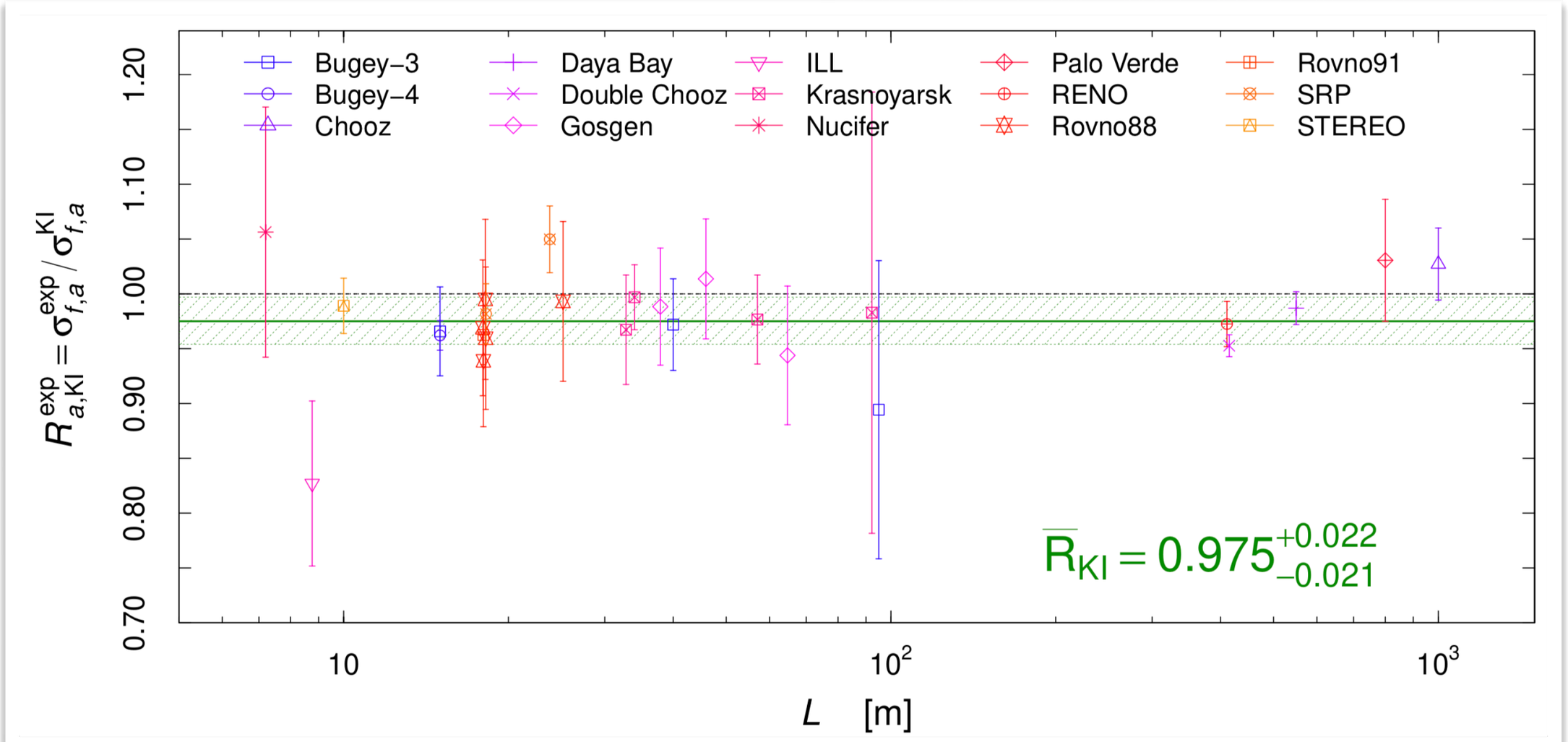

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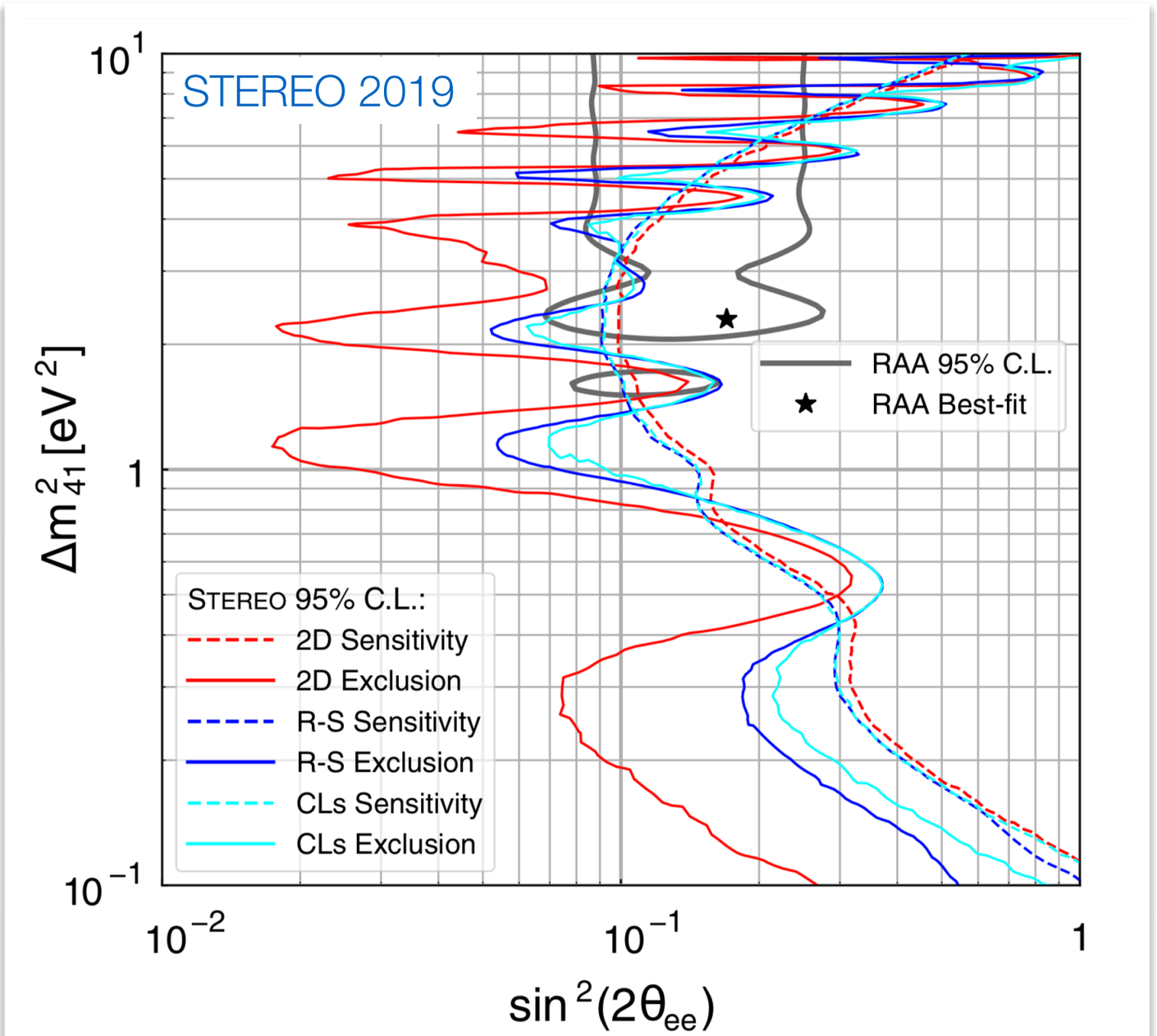


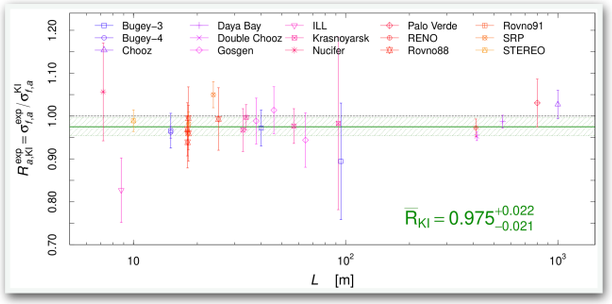
Moreover:

strong constraints from experiments comparing rates at different baselines

➠ independent of flux prediction

➠ see next talk (by Matthieu Licciardi) for updates

Short-Baseline Anomalies



reactor flux anomaly
resolved with new input data
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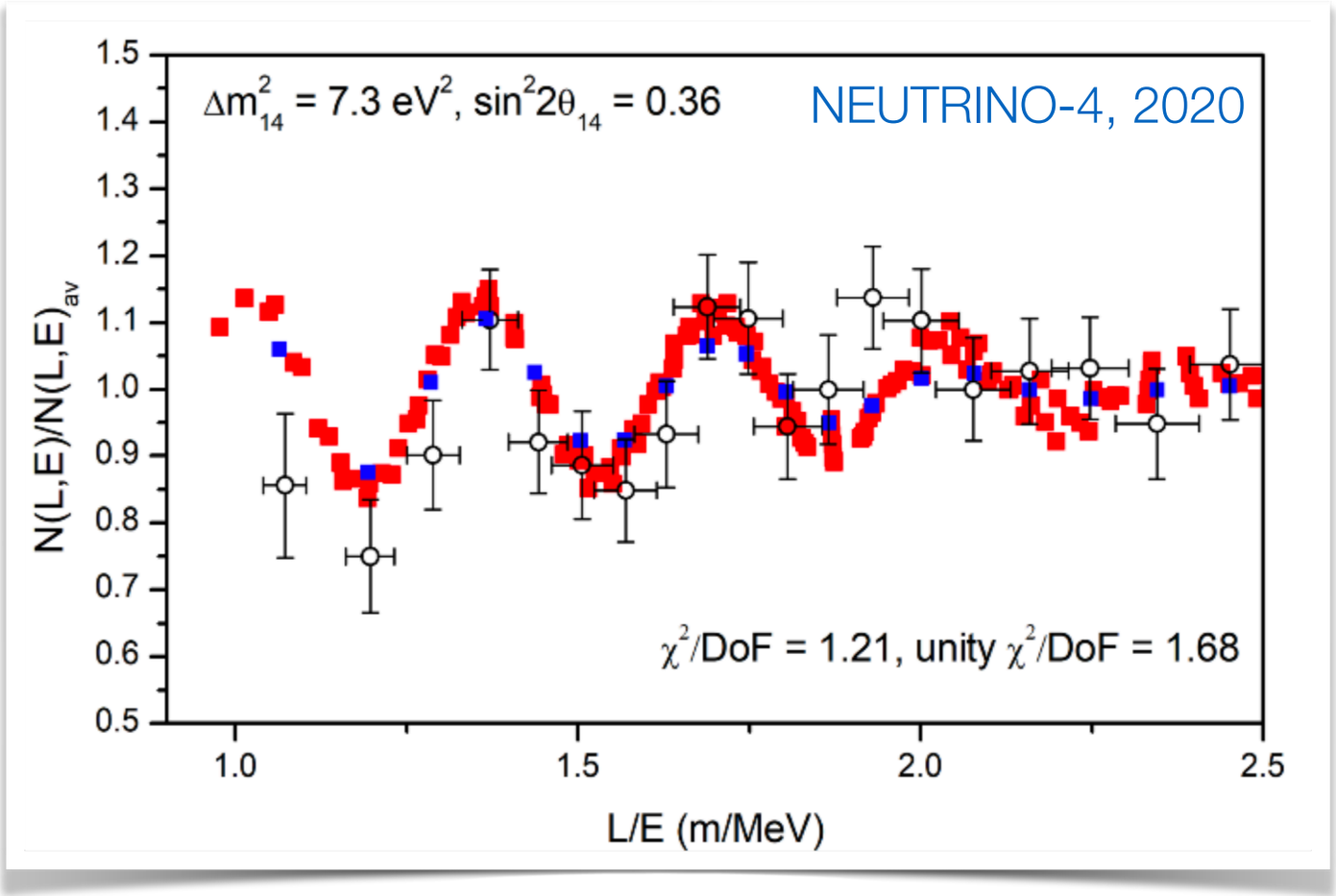
Spectra

Anomaly #2: Reactor Spectra



Almazán *et al.*, arXiv:2006.13147
Berryman Coloma Huber Schwetz Zhou
arXiv:2111.12530

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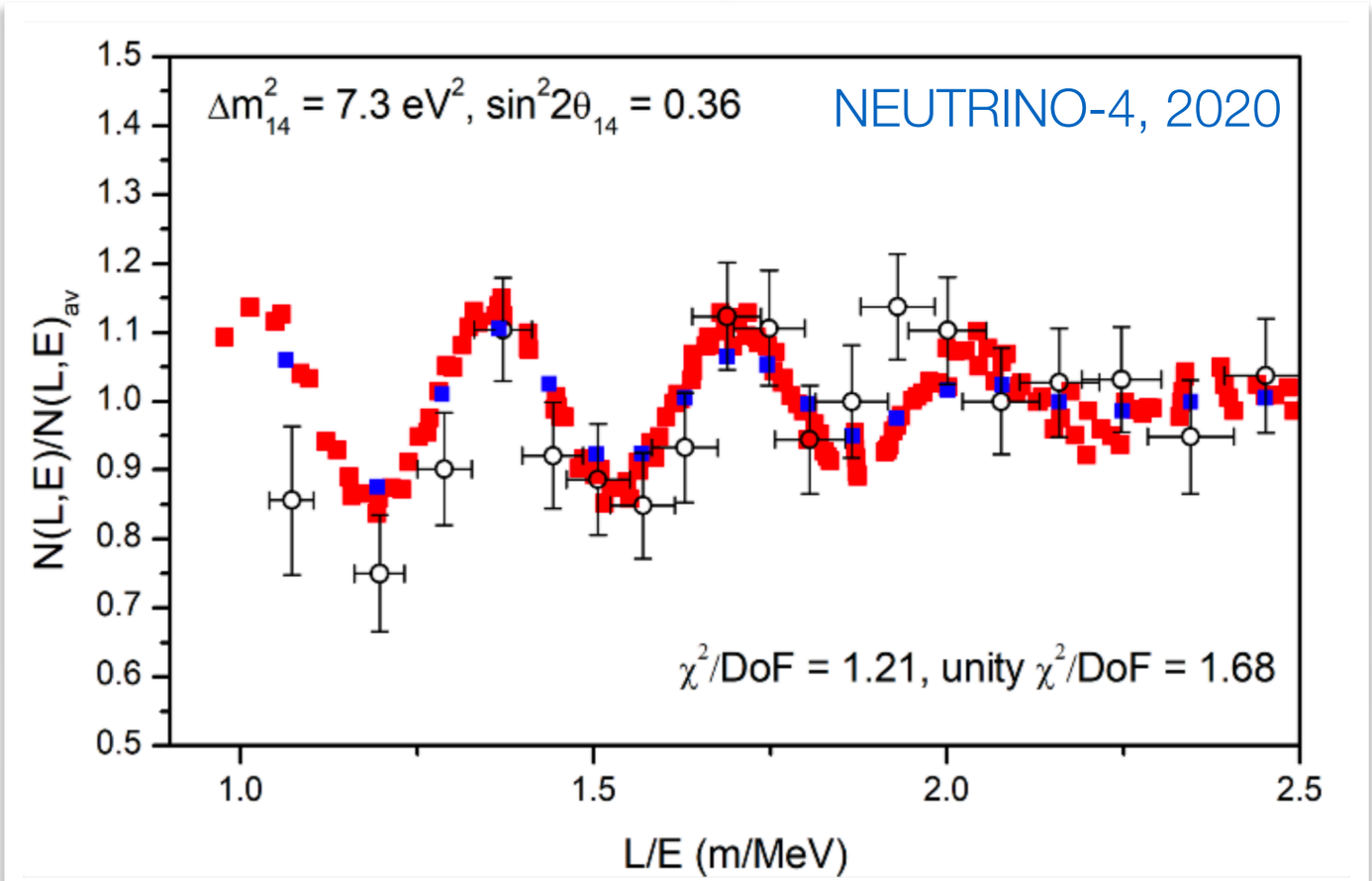

- ☑ spectral "wiggles" in several experiments
  - can be interpreted as neutrino oscillation signal
  - see talks by Matthieu Licciardi and Jinyu Kim
- ☑ Use ratios of spectra at different baselines
  - results independent of flux predictions

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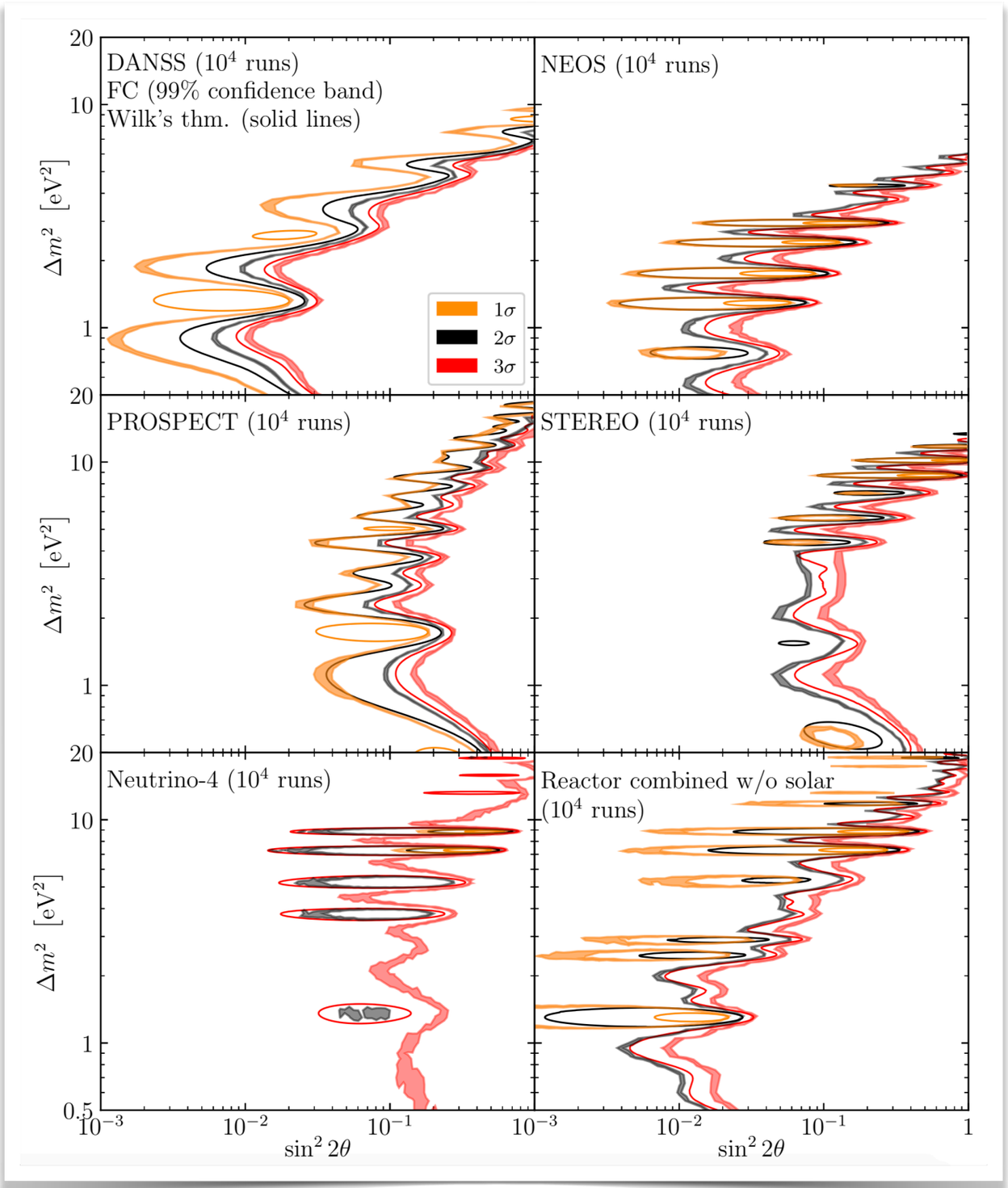

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- ☑ But low statistical significance
  - Wilk's theorem often fails!

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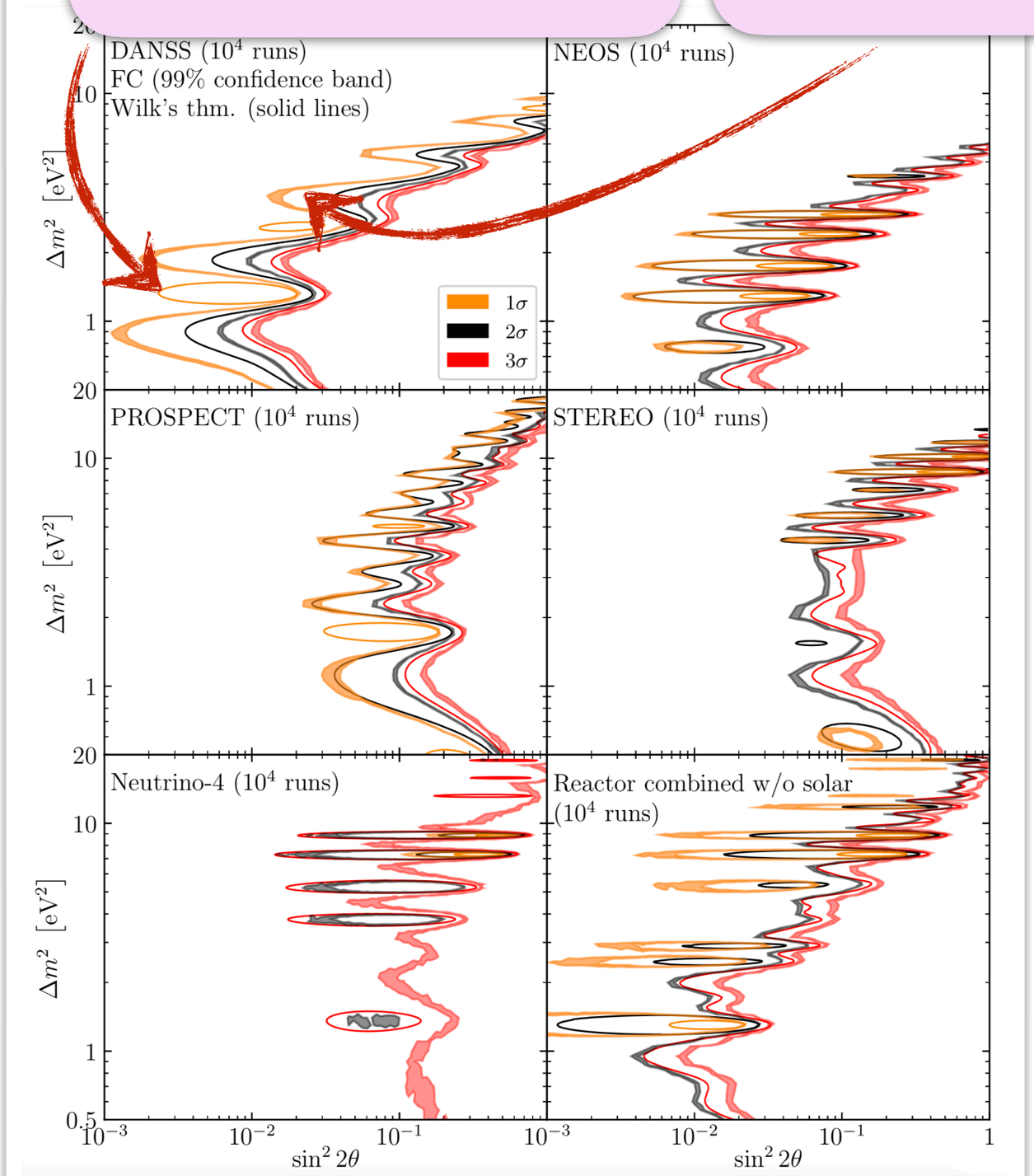
Anomaly #2: Reactor Spectra

contours: Wilk's theorem

bands: Feldman–Cousins



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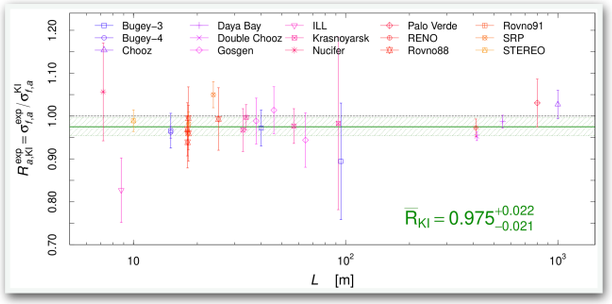
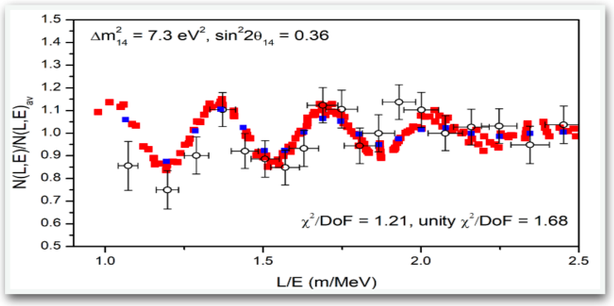




reactor flux anomaly
resolved with new input data
to flux calculation

reactor spectra
is there really an anomaly?

The Gallium Anomaly

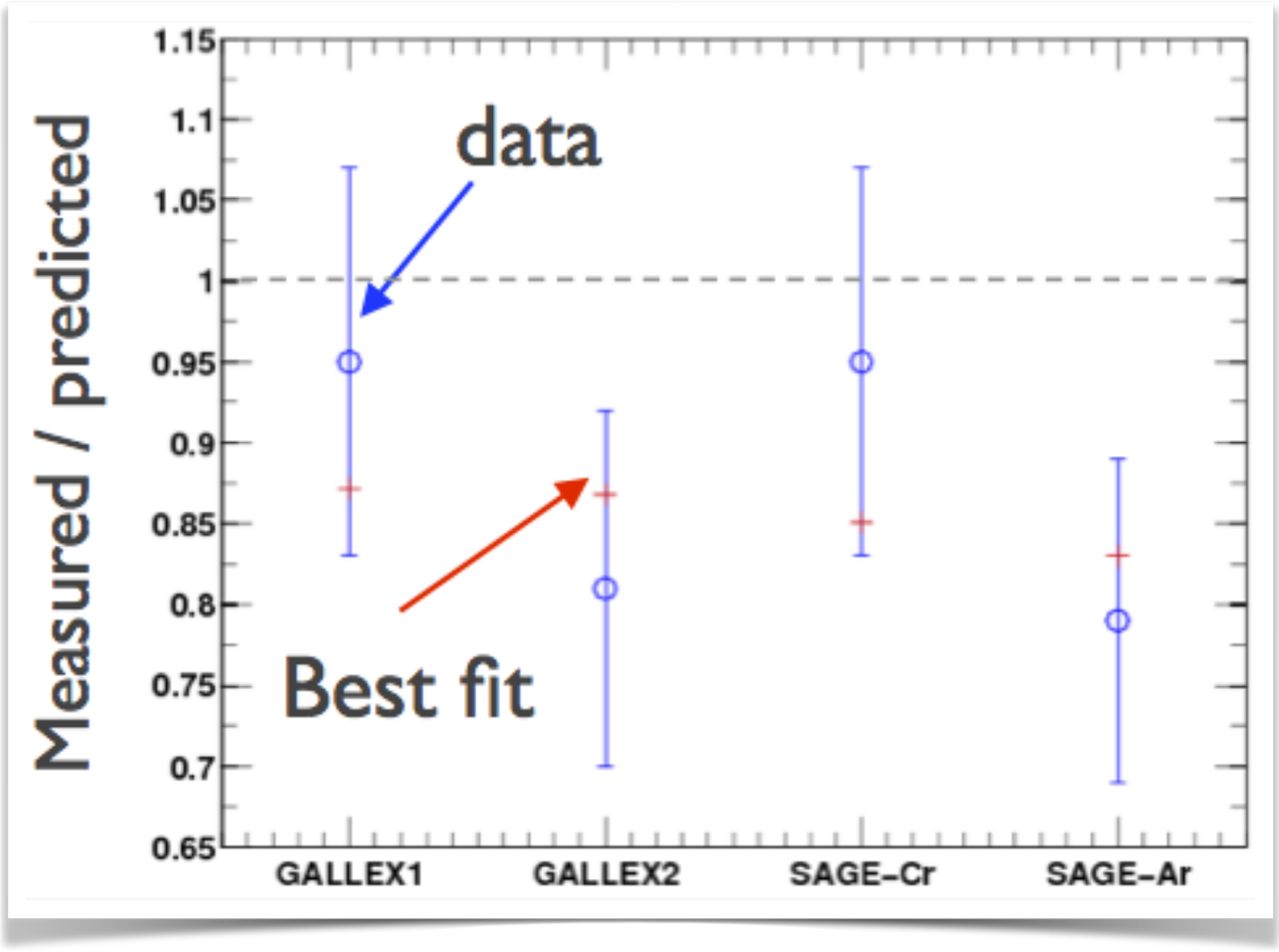
Once Upon a Time in the B.E.S.T.

Anomaly #3: the Gallium Anomaly

- ☑ Experiments with intense radioactive sources
- ☑ Neutrino detection via

$$^{71}\mathrm{Ga} + \nu_e \rightarrow {}^{71}\mathrm{Ge} + e^-$$

- ☑ ~3σ deficit
- ☑ ν_e disappearance into sterile state?
- ☑ would require very large mixing (conflict with reactor observations)



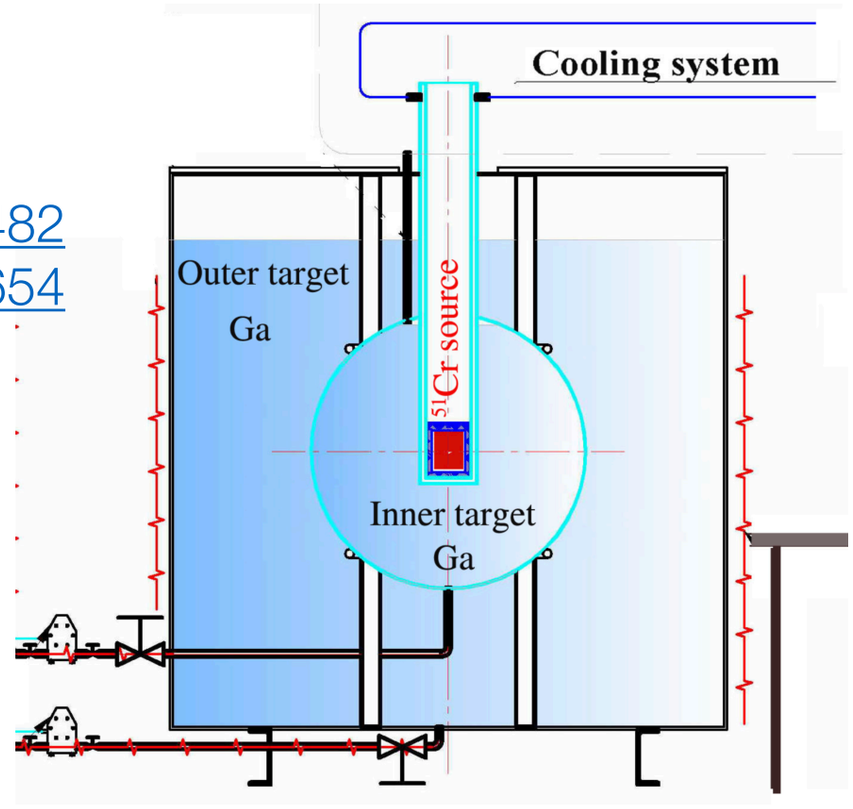
Giunti Laveder 1006.3244

Anomaly #3: the Gallium Anomaly

- ☑ recently confirmed by BEST (~4σ)

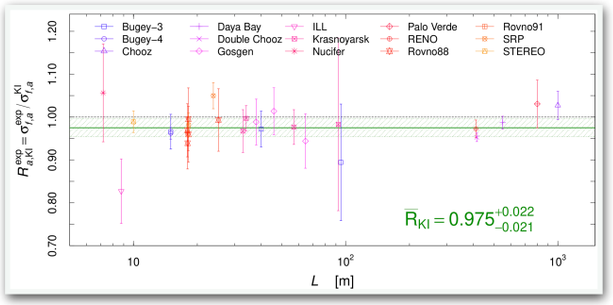
BEST arXiv:2109.11482
Barinov Gorbunov arXiv:2109.14654

- ☑ two independent target volumes
  (hoping to see oscillation pattern)
- ☑ radiochemistry similar to
  other gallium experiments
  (correlated systematics?)



- ☑ but robustness proven by
  - sophisticated calibration Cleveland *et al.* 2015
  - solar *ν* measurements in agreement with other experiments
- ☑ uncertainty in x-sec to excited states of Ge-71
  - but even ignoring excited states altogether, anomaly persists

Short-Baseline Anomalies



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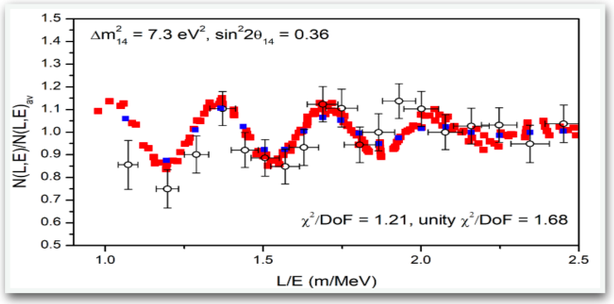

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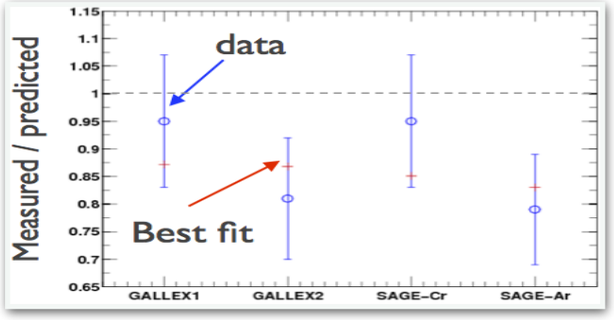
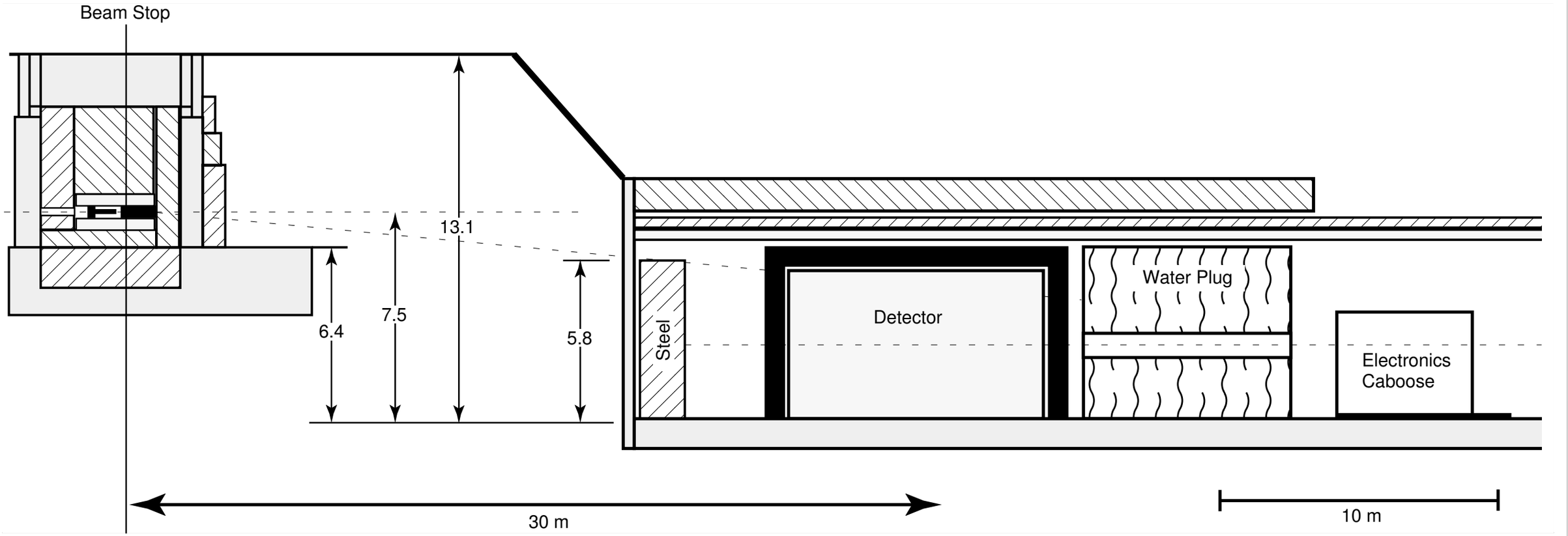


gallium anomaly
unresolved, recently reinforced

LSND

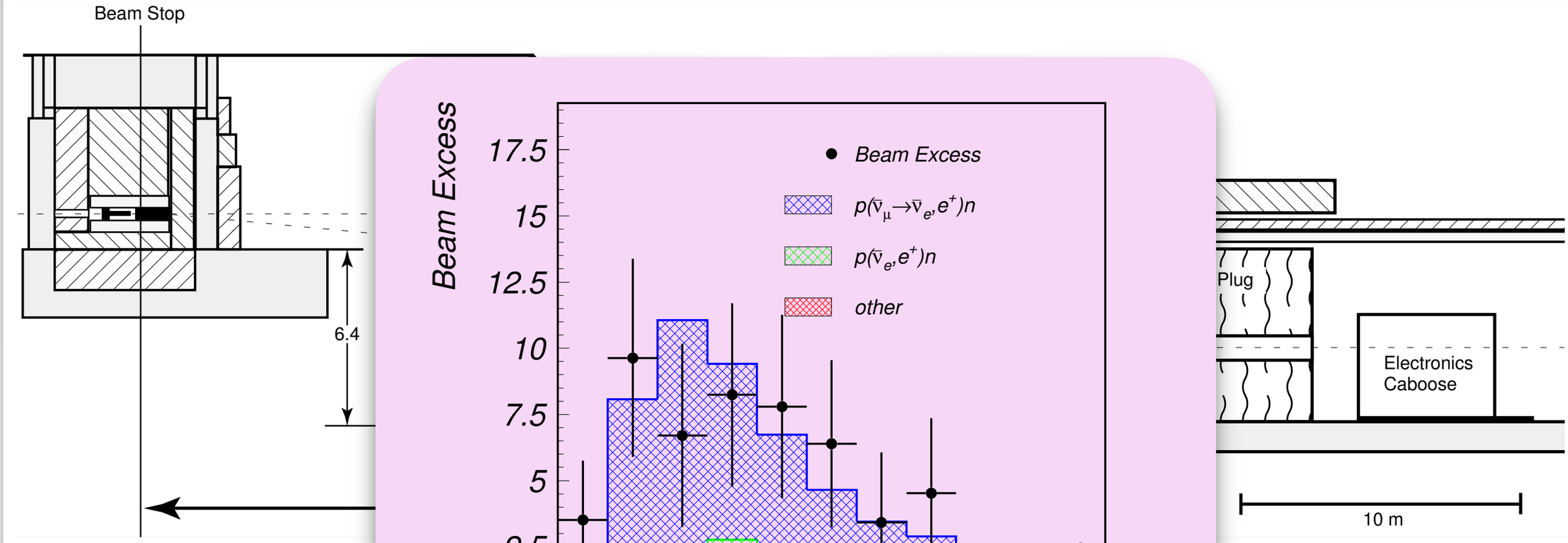
The Los Alamos Chamber of Secrets

Anomaly #4: LSND



- ☑ $\bar{\nu}_e$ appearance in a $\bar{\nu}_\mu$ beam (~3σ)
- ☑ Source—detector distance (“baseline”) ~ 30 m
- ☑ $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations?

Anomaly #4: LSND



LSND Collaboration, hep-ex/0104049

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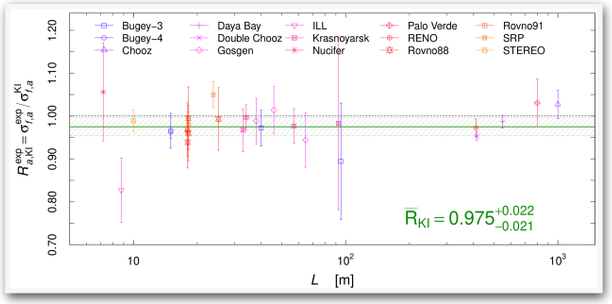
Short-Baseline Anomalies



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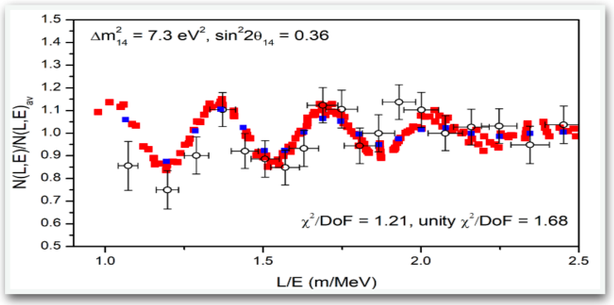

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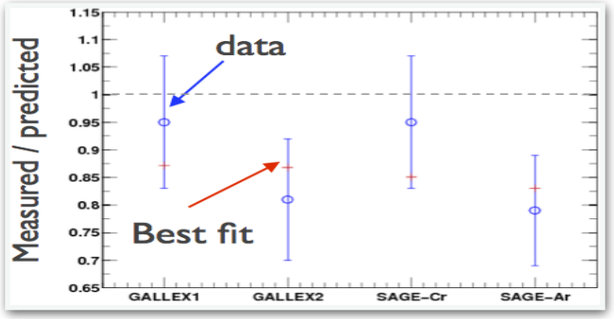

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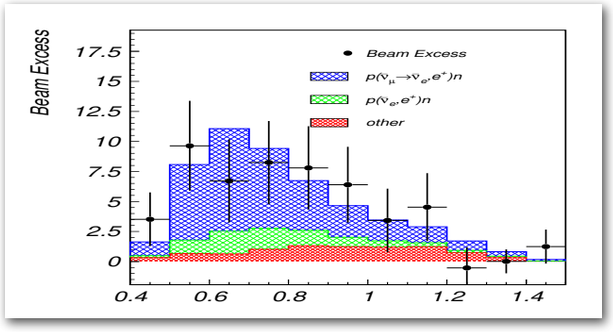

LSND
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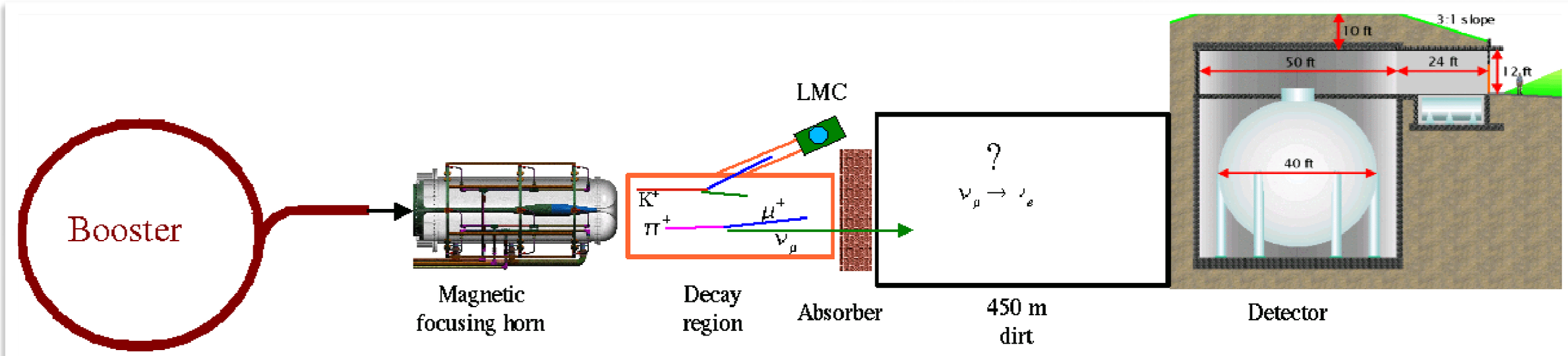
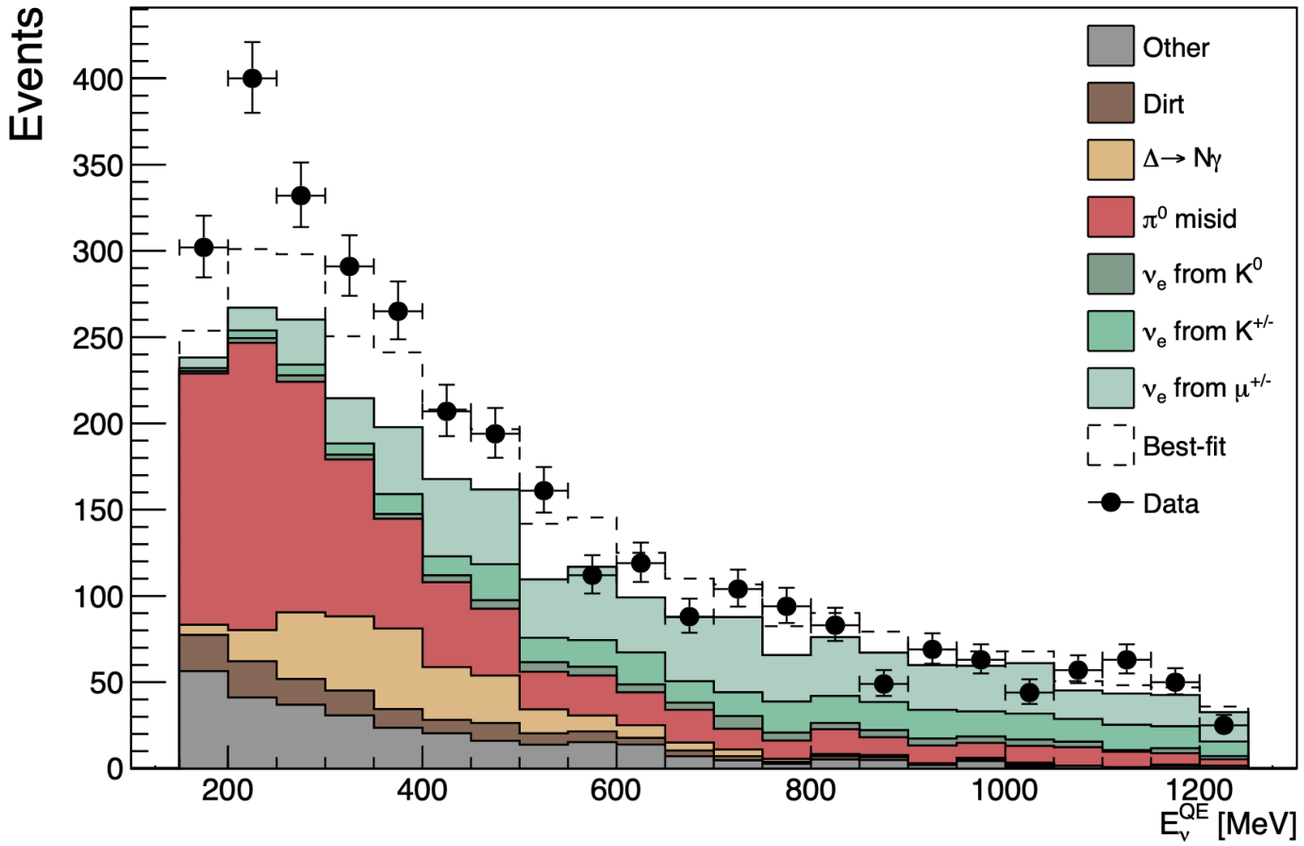
High BooNE

Anomaly #5: MiniBooNE

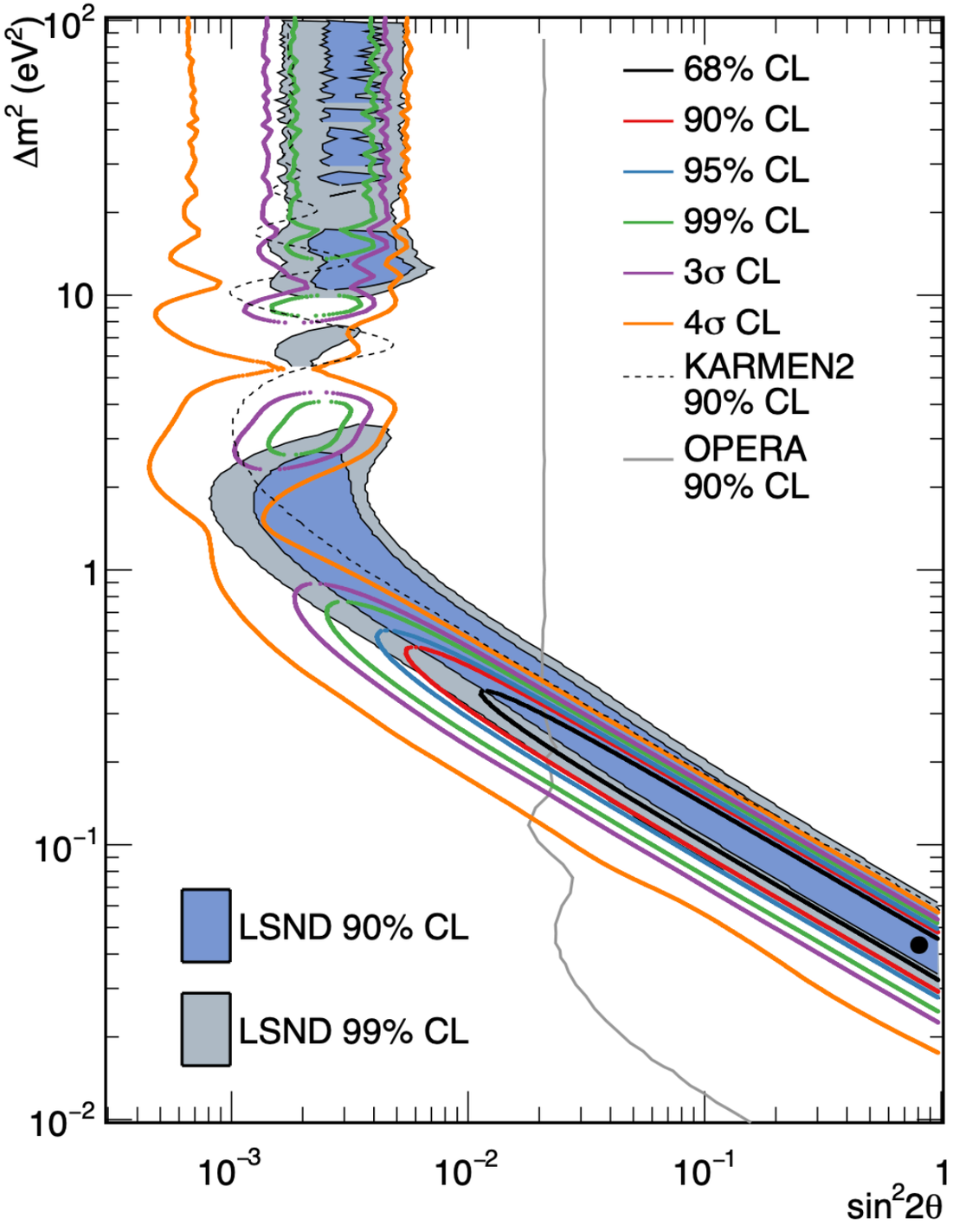


Anomaly #5: MiniBooNE

- ☑ Unexplained low-*E* excess (4.8σ)
- ☑ Consistent with LSND
- ☑ L/E too small for std. oscillations (wrong Δm^2)



MiniBooNE Collaboration arXiv:2006.16883



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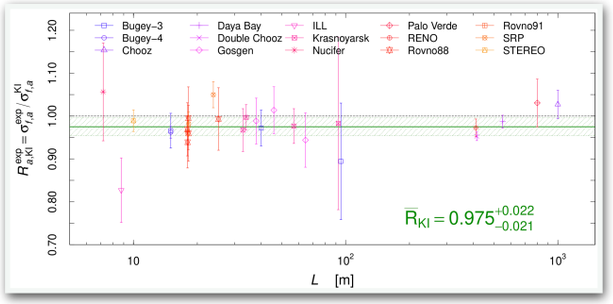

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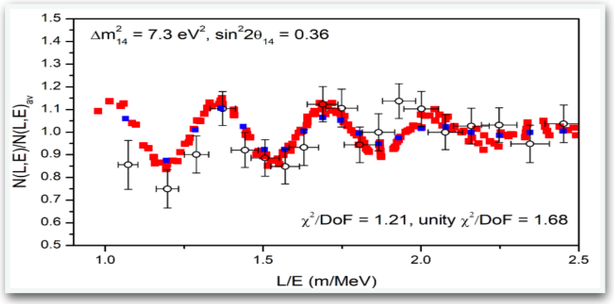

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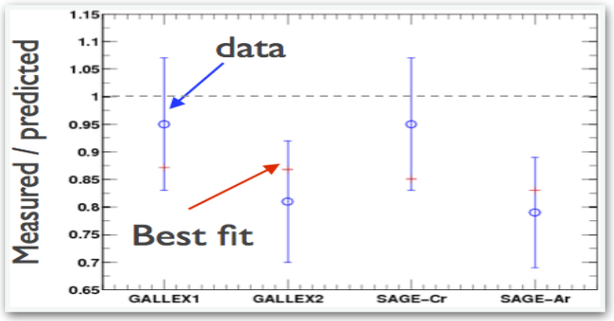

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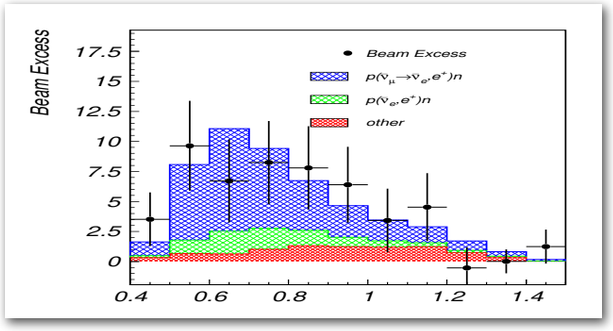

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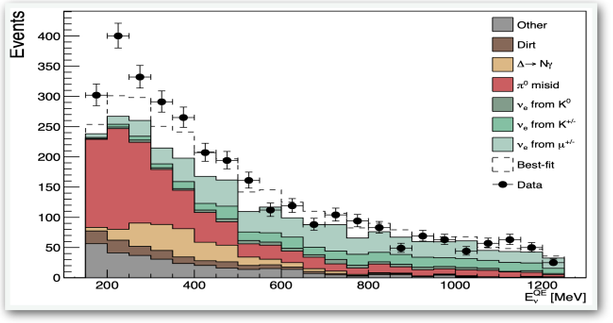

MiniBooNE
unresolved

"With great precision comes great responsibility."

Tim Linden, WIN 2021

Standard Model Explanations for the MiniBooNE Anomaly?

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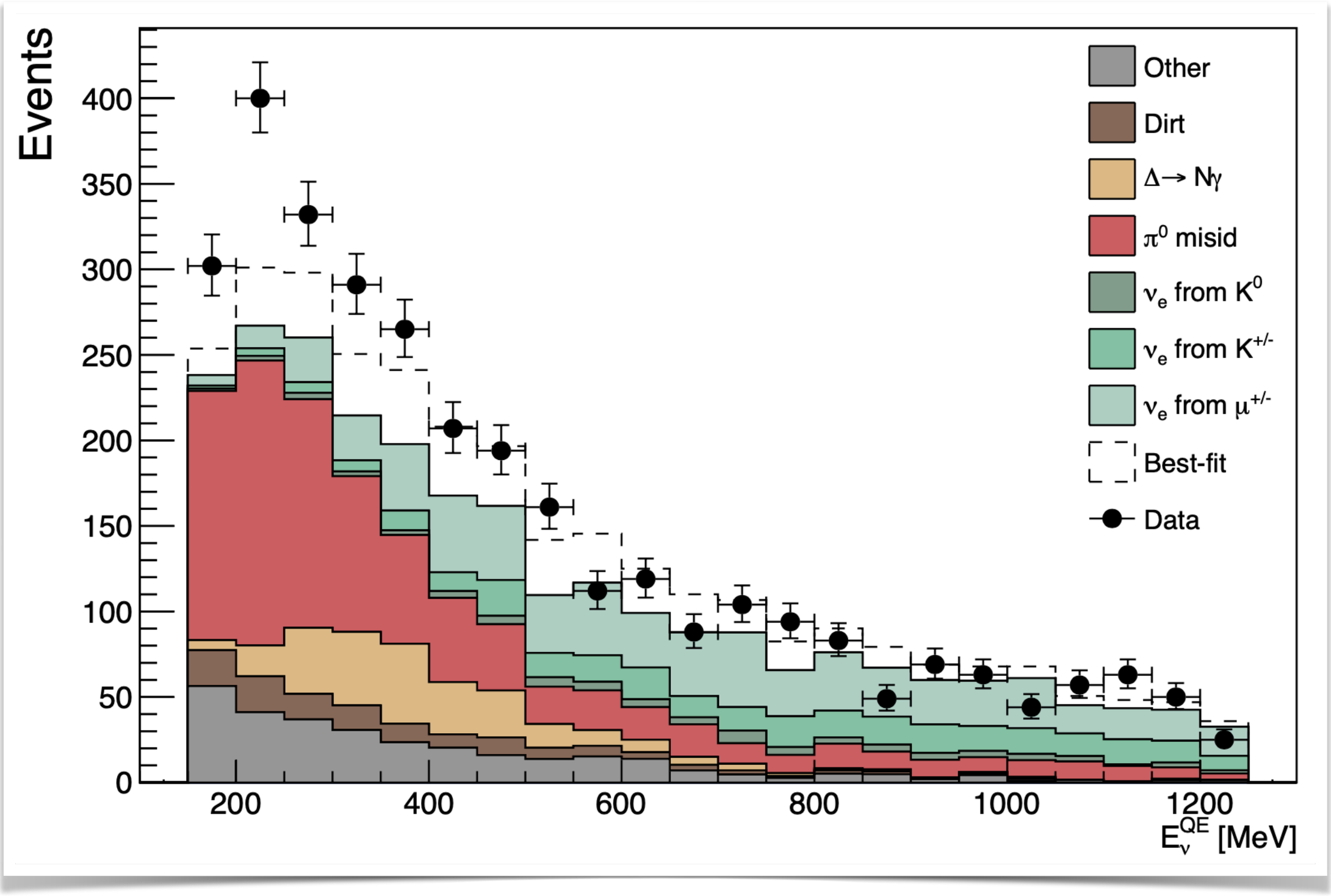
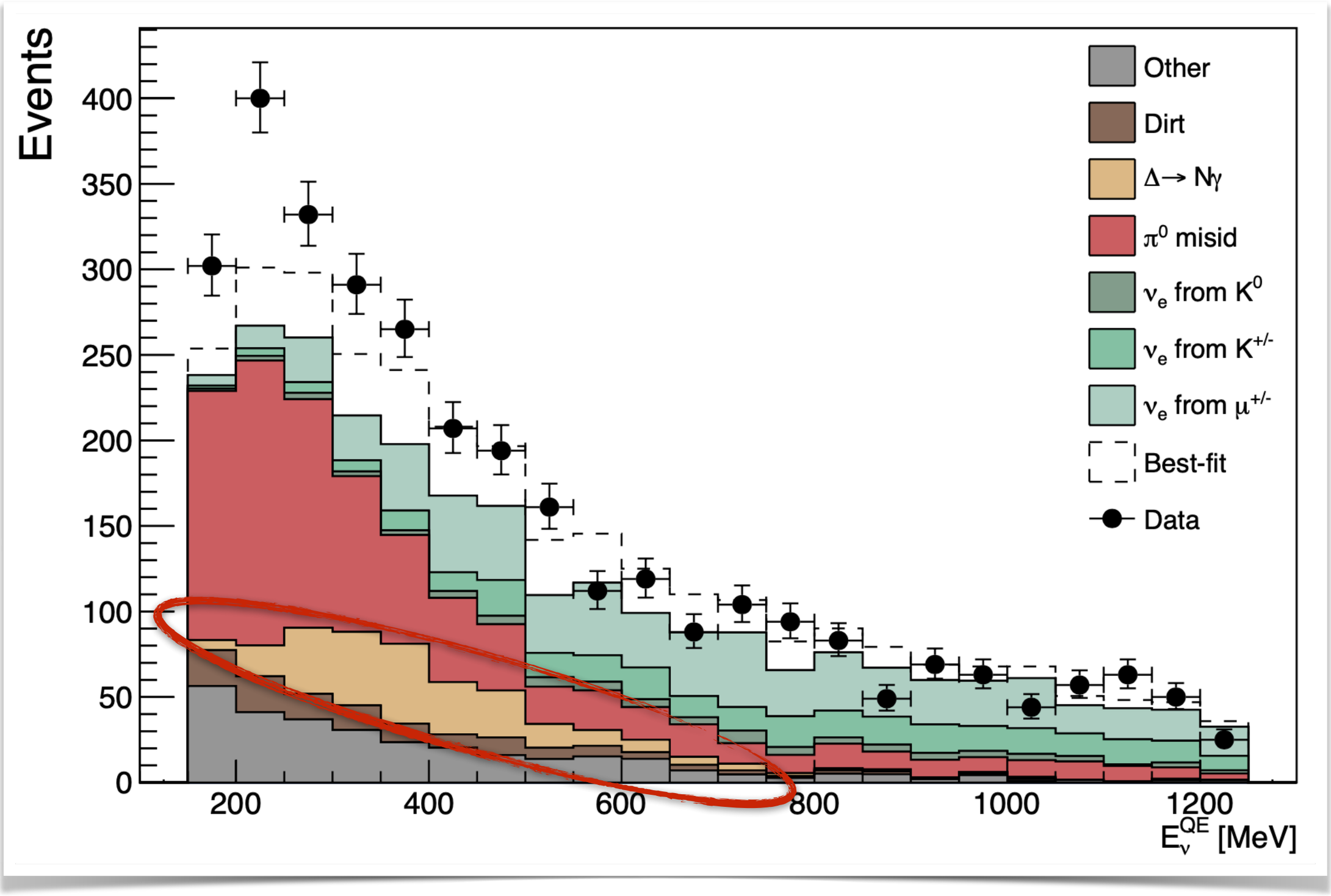
MiniBooNE Backgrounds



MiniBooNE 2020

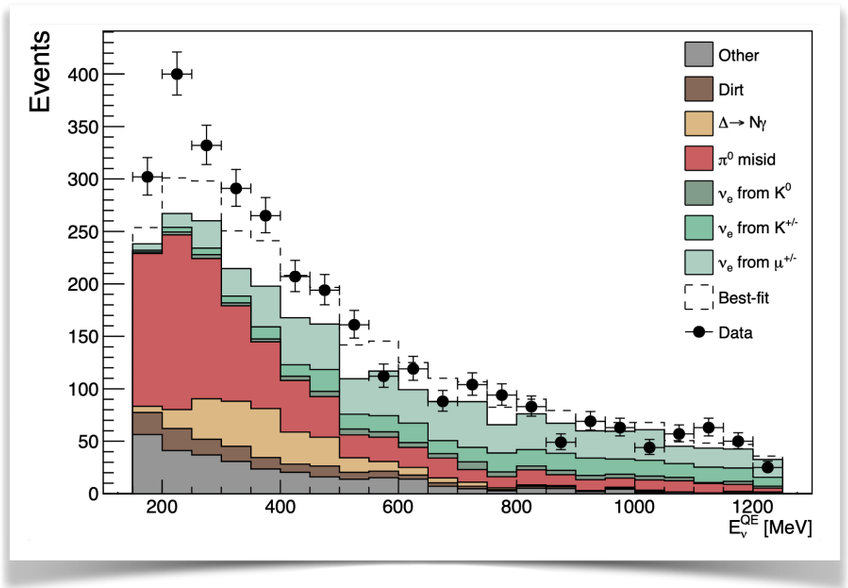
MiniBooNE Backgrounds



MiniBooNE 2020

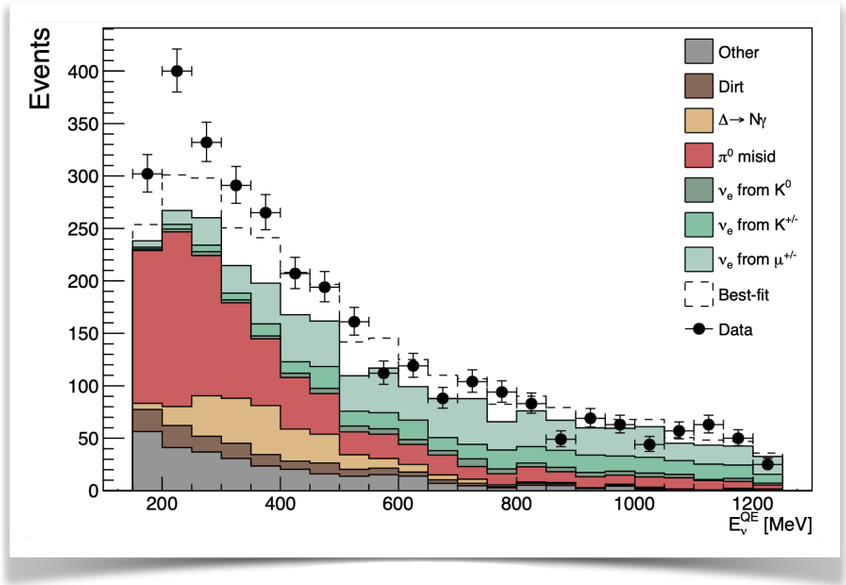
Δ → γ N

- ☑ Neutral current neutrino interaction:
  ν + N → ν + Δ(1232)
- ☑ Δ(1232) mostly decays to π + N
- ☑ But a rare decay exists to γ + N
- ☑ MiniBooNE cannot distinguish γ from e^-



Δ → γ N

- ☑ Δ production rate can be estimated from Δ → πN
- ☑ Pions may be absorbed on their way out of the nucleus
  - may excite another Δ resonance
    - ➠ Δ → γN enhanced by ~factor 2
  - or may be absorbed
    - ➠ control region suppressed by ~factor 2

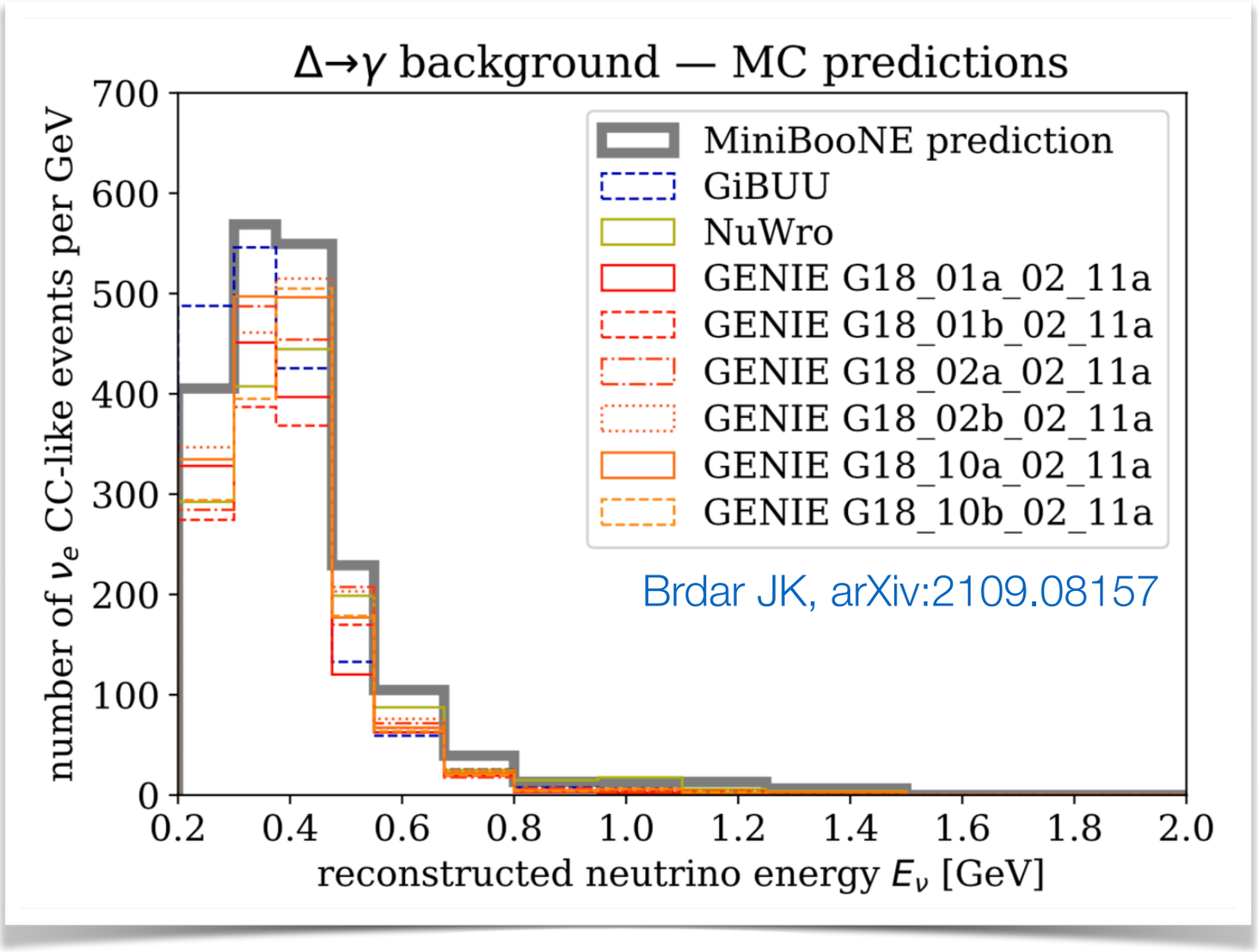


Ioannisian 1909.08571
Giunti Ioannisian Ranucci 1912.01524

☑ This factor 2 has been taken into account by MiniBooNE

MiniBooNe, arXiv:2006.16883

Δ → γ N: Comparison of Generators

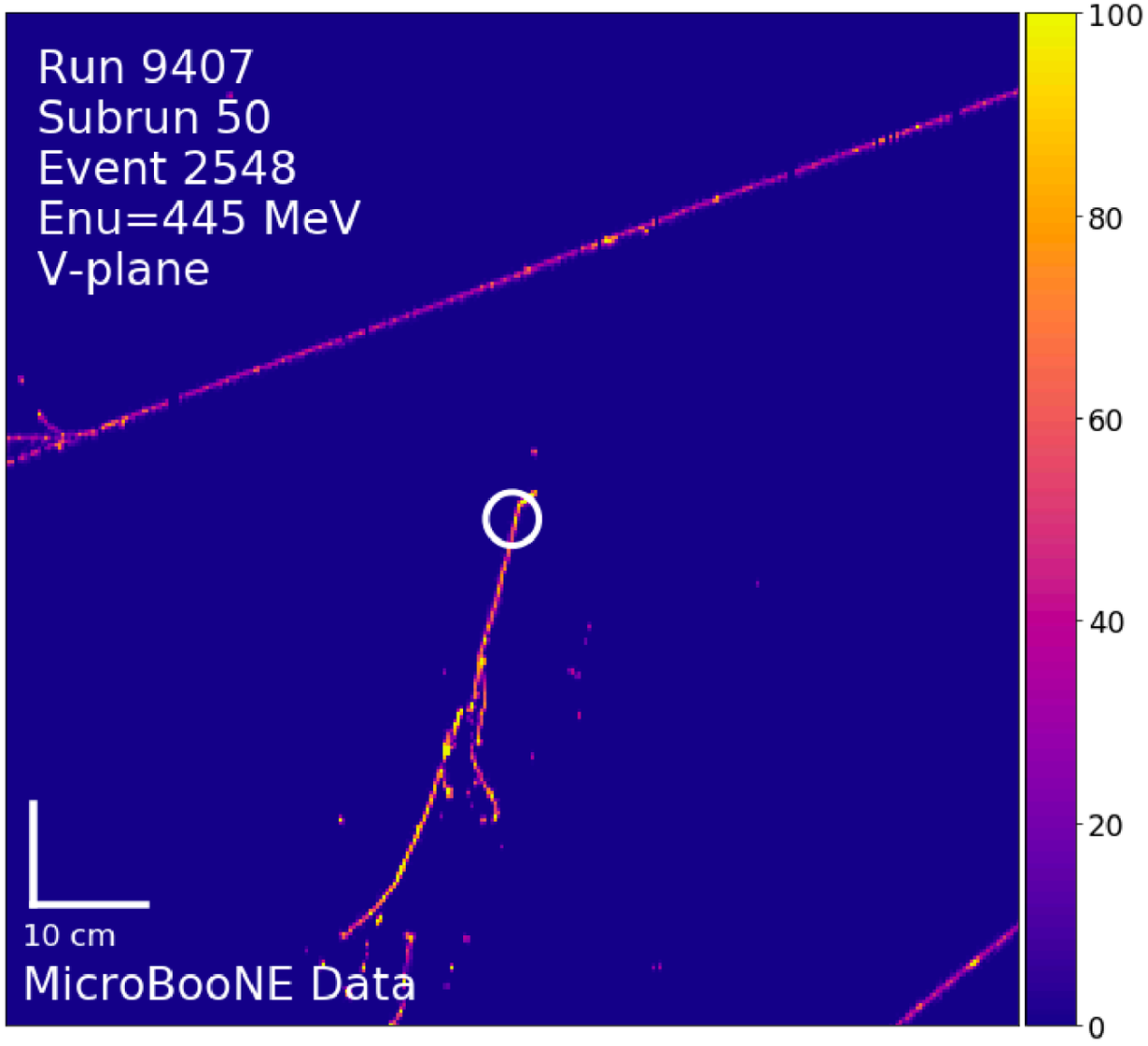


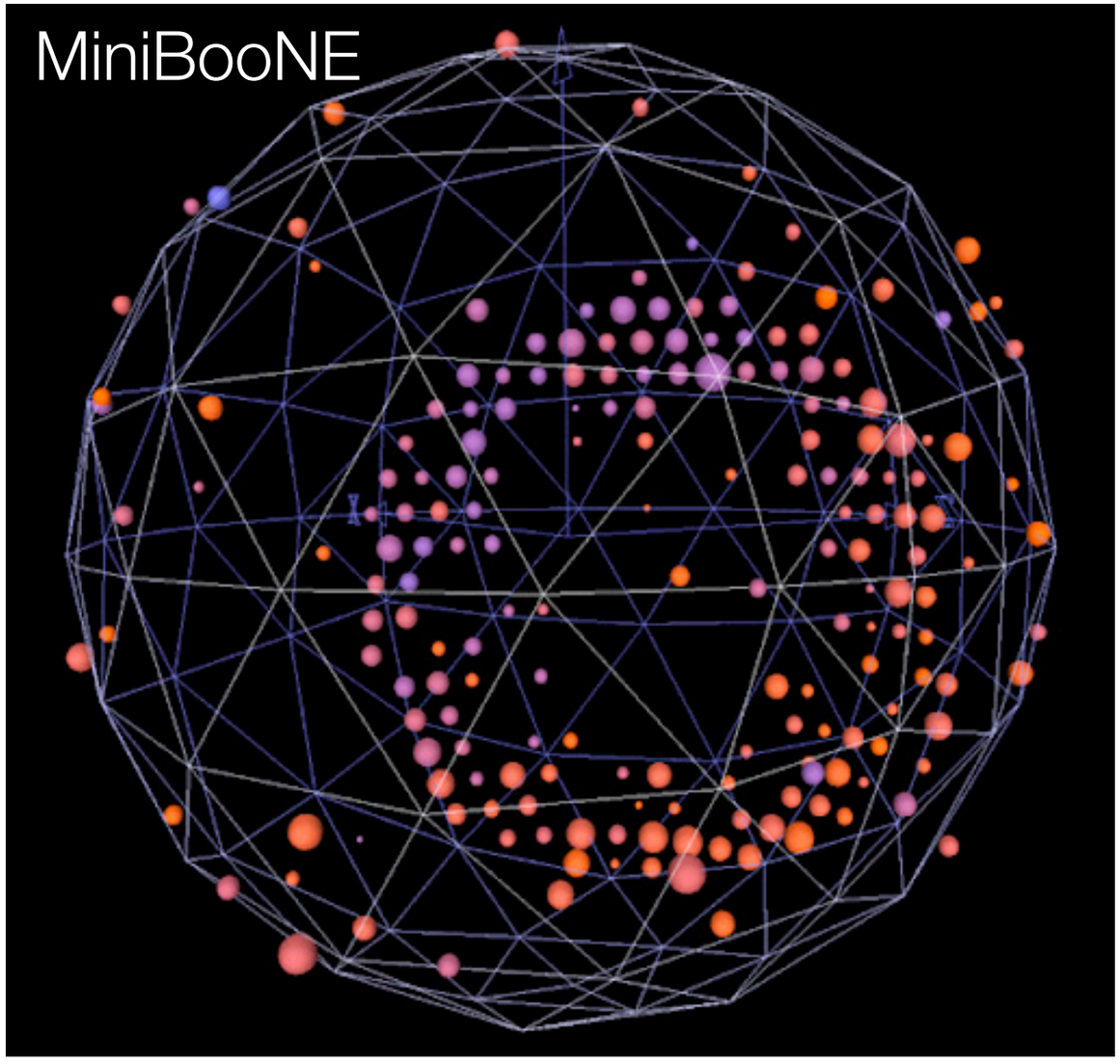
- ☑ histograms calibrated to NUANCE
  (the generator used by MiniBooNE)
- ☑ using our own implementation of radiative resonance decays
  in GiBUU, NuWro, NUANCE

MicroBooNE

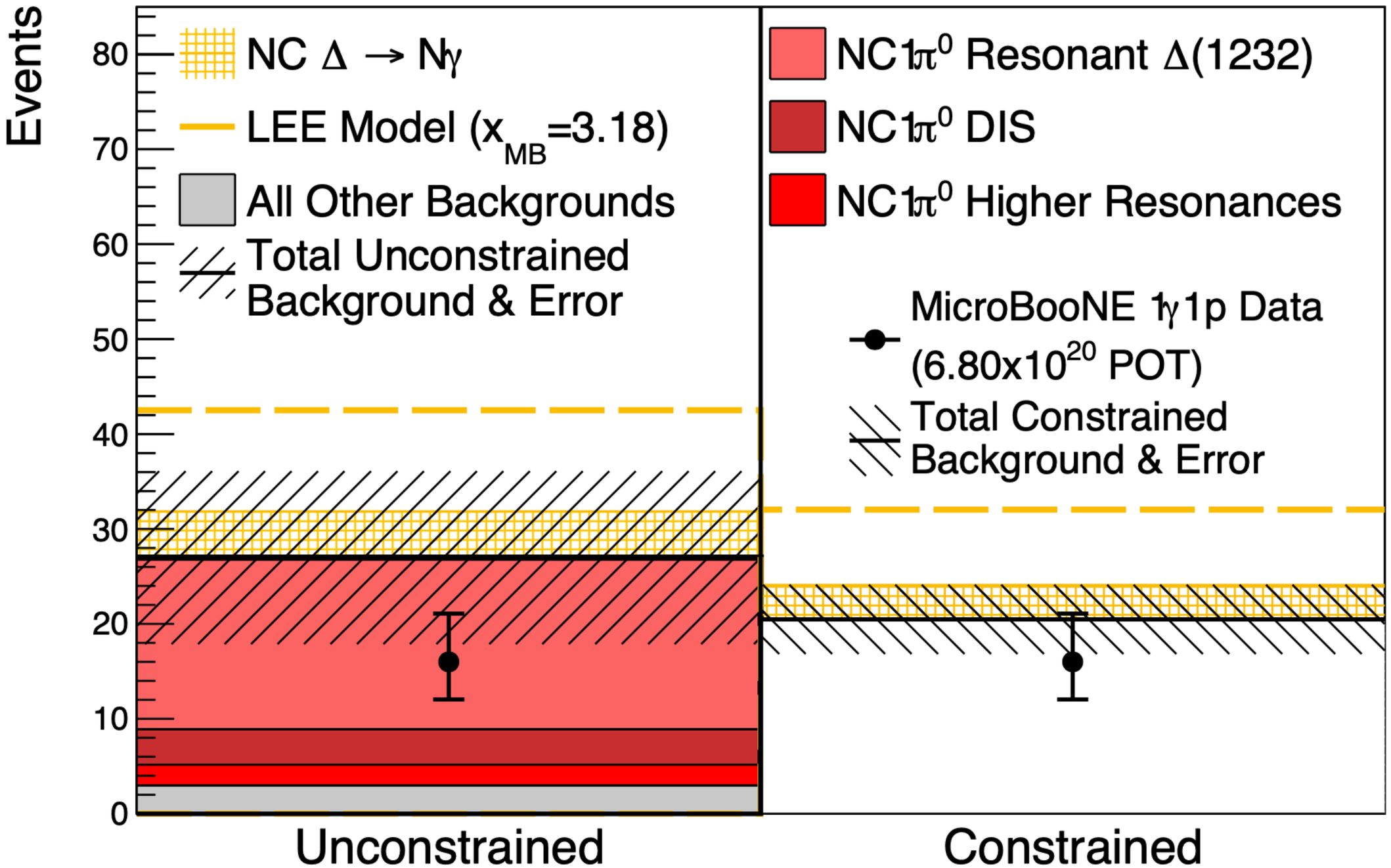
- ☑ 80 ton LAr TPC
- ☑ Very good event reconstruction capabilities
  - can distinguish $e^{\pm}$ from γ

MiniBooNE vs. MicroBooNE



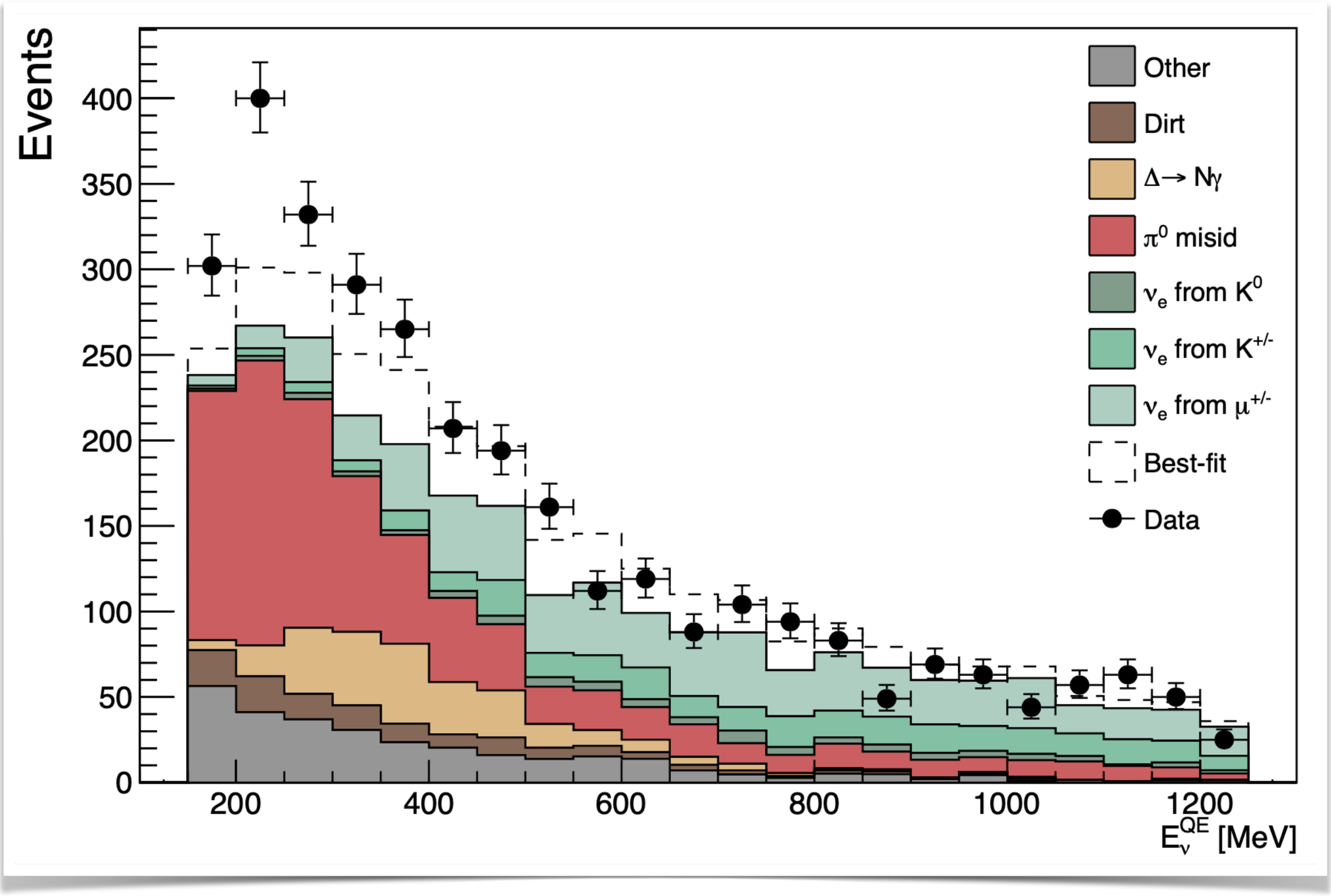


Δ → γ N: MicroBooNE



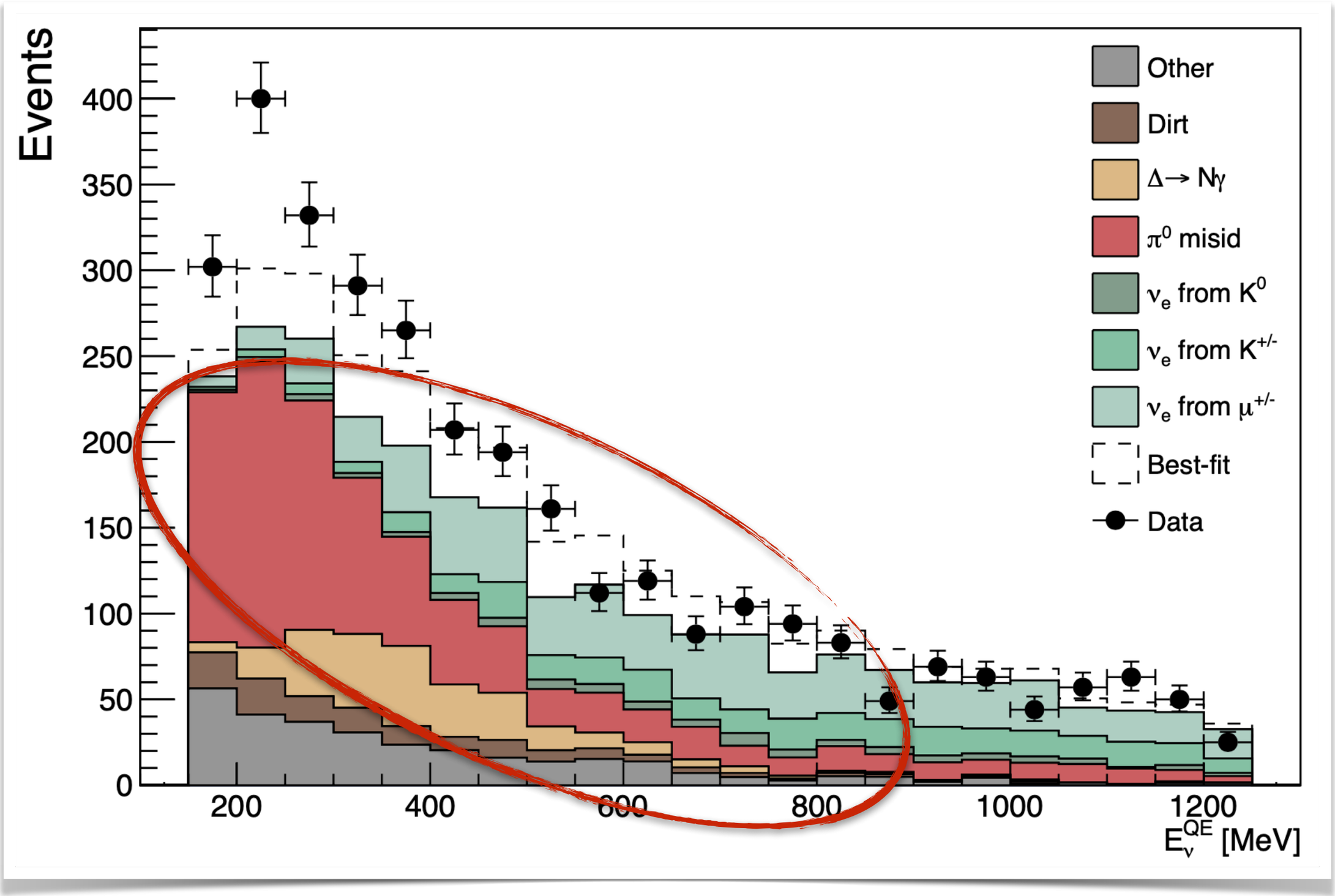
MicroBooNE arXiv:2110.00409

NC π^0 Production in MiniBooNE



MiniBooNE 2020

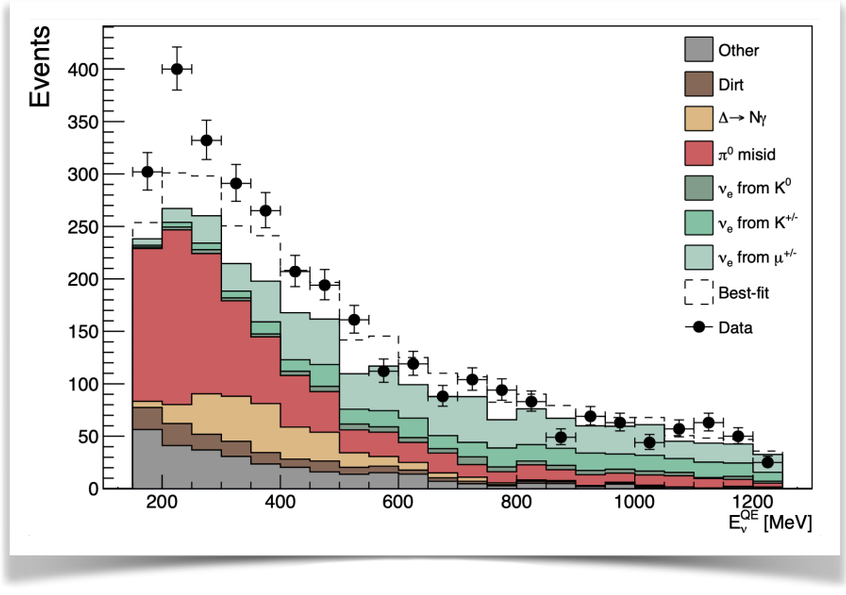
NC π^0 Production in MiniBooNE



MiniBooNE 2020

NC π^0 Production in MiniBooNE

- ☑ $\nu + N \rightarrow \nu + N + \pi^0$
- ☑ $\pi^0 \rightarrow \gamma\gamma$ is observable
  → π^0 production rate *measured*
- ☑ Rarely, one photon from $\pi^0 \rightarrow \gamma\gamma$ is missed
  - conversion outside active volume
    - ➠ disfavored by uniform distribution of excess events
  - decay may be asymmetric
  - boosted/collimated photons
    - ➠ not at low energies, where the excess is
  - photon absorbed on nucleus before converting



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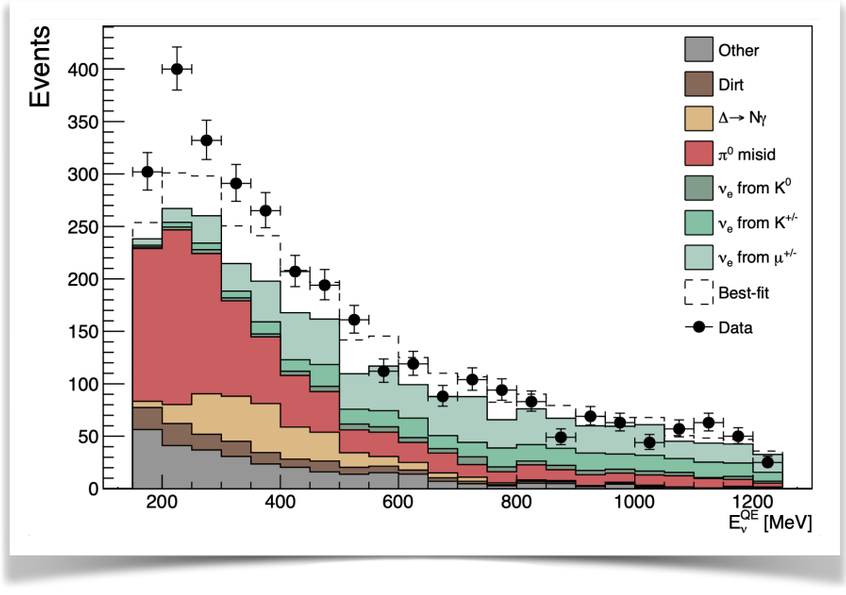
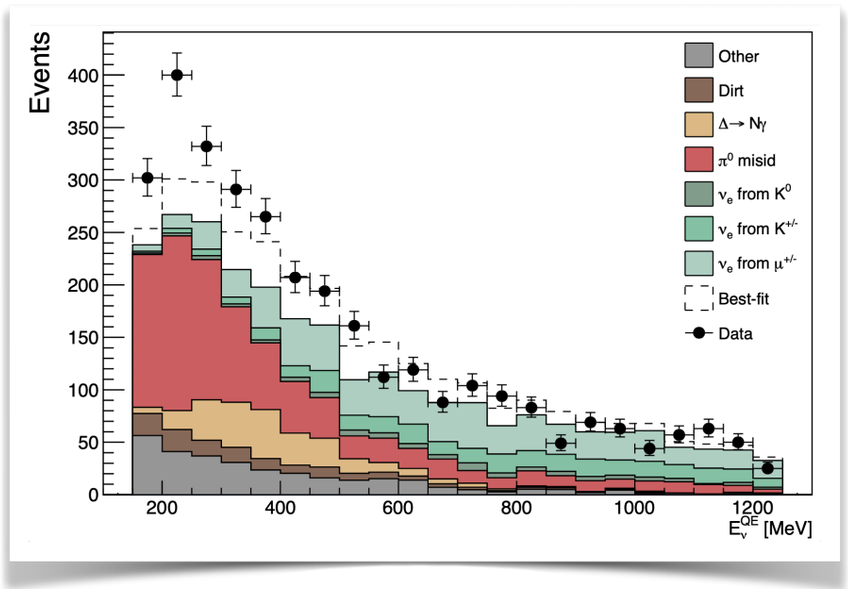


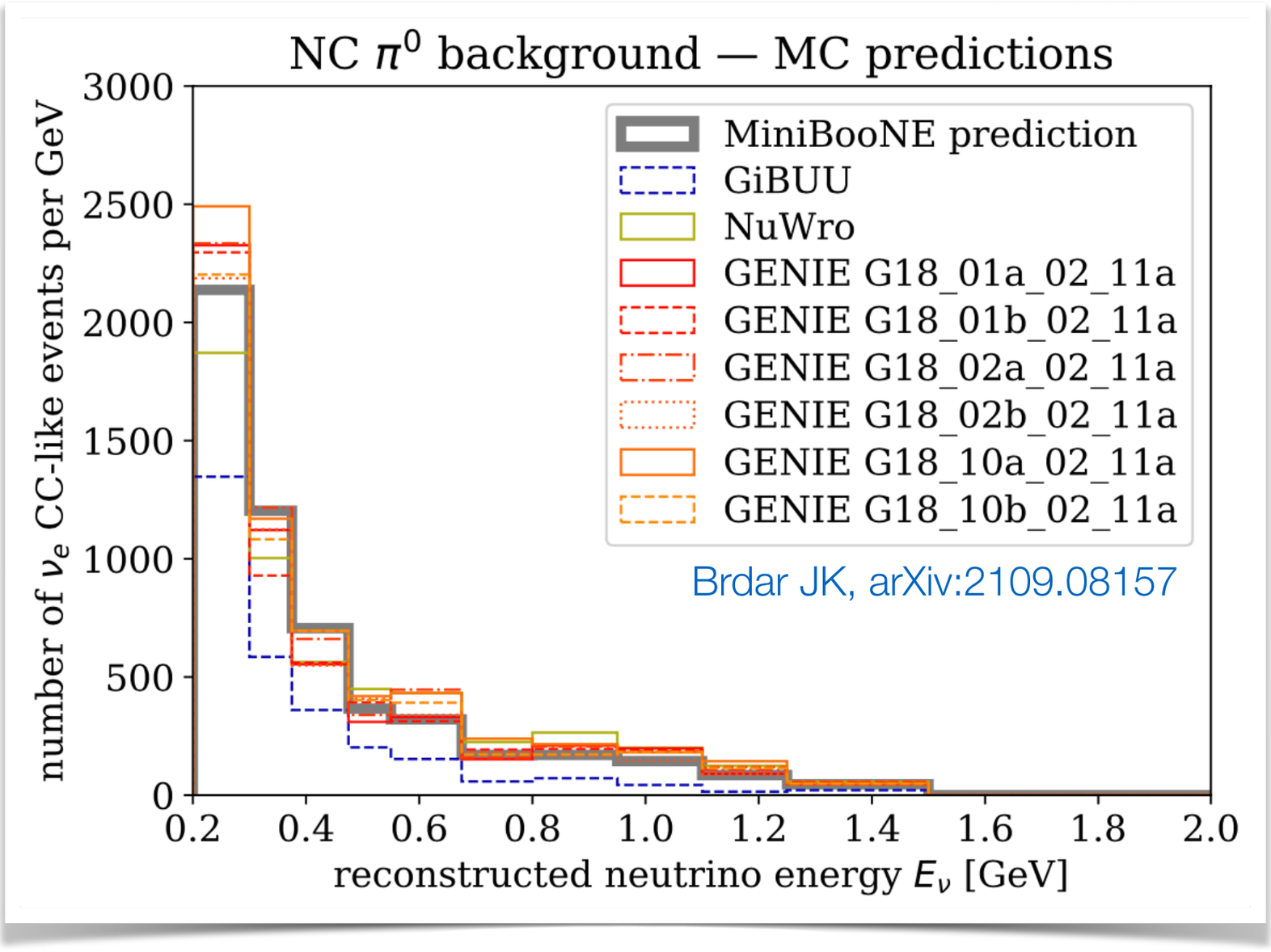
NC π^0 Production in MiniBooNE

- Problem with translation from control sample to signal region?
  - unlikely after >10 years
  - but probability for missing one γ is determined based on MC only



- One possible cross-check: CC ν_μ + π^0 production
  - compare rate of μ + 1 shower and μ + 2 shower events

π^0 in MiniBooNE: Comparison of Generators



☑ histograms calibrated to NUANCE
(the generator used by MiniBooNE)

Sterile Neutrinos after all?
Global Fits

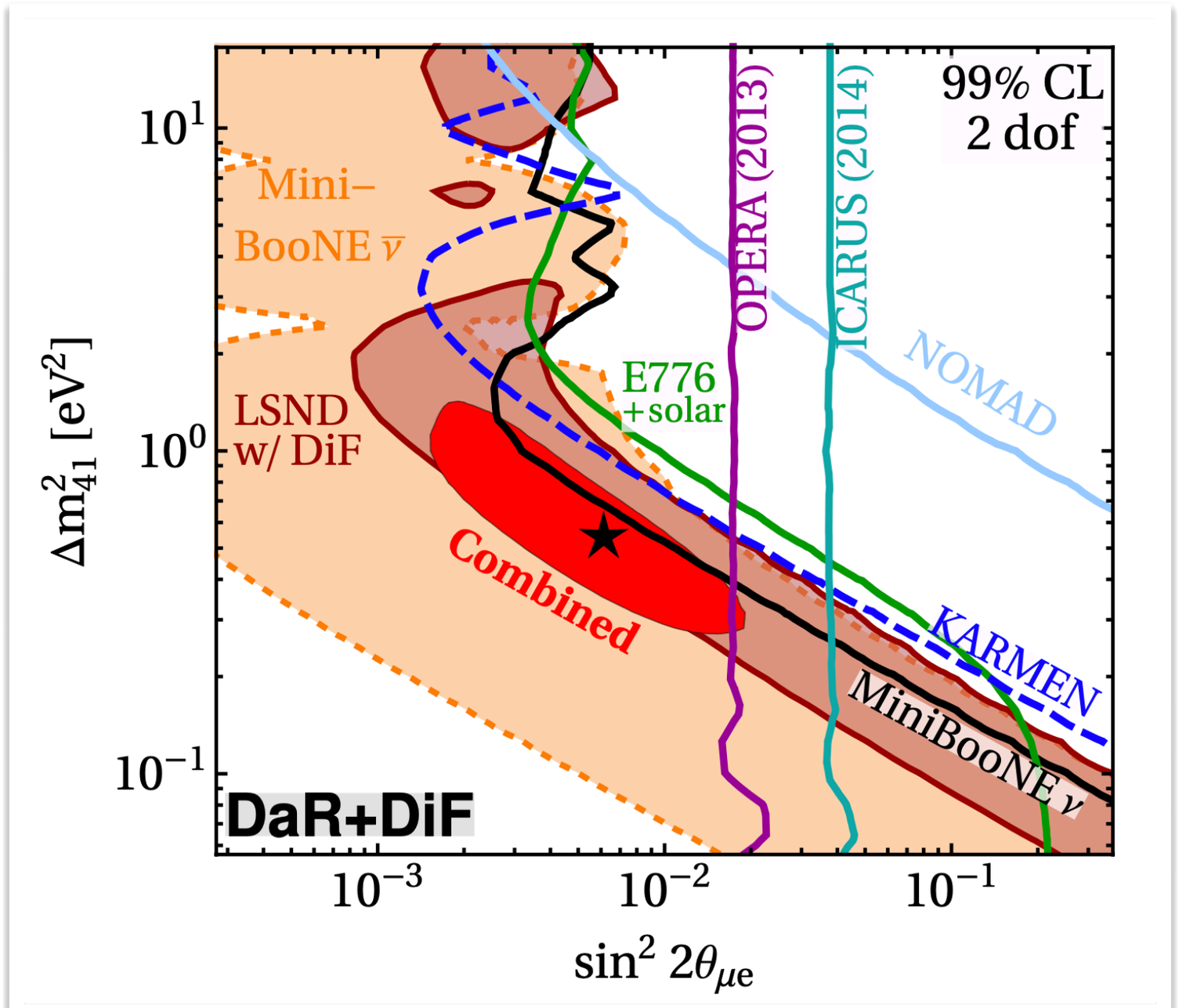
CERN

Neutrino PLATFORM

erc

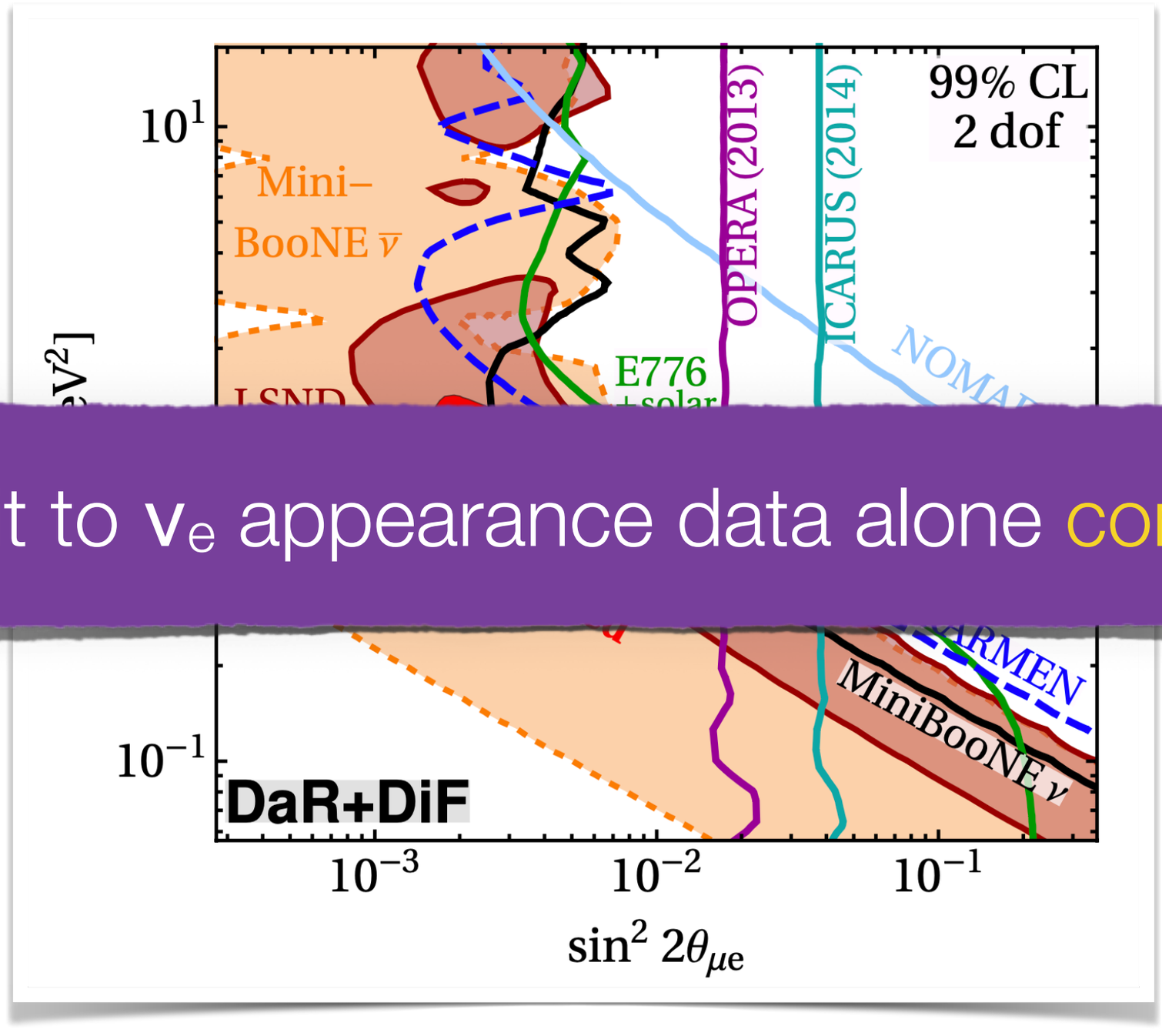
JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Global Fit to ν_e Appearance Data



Dentler *et al.*, 1803.10661

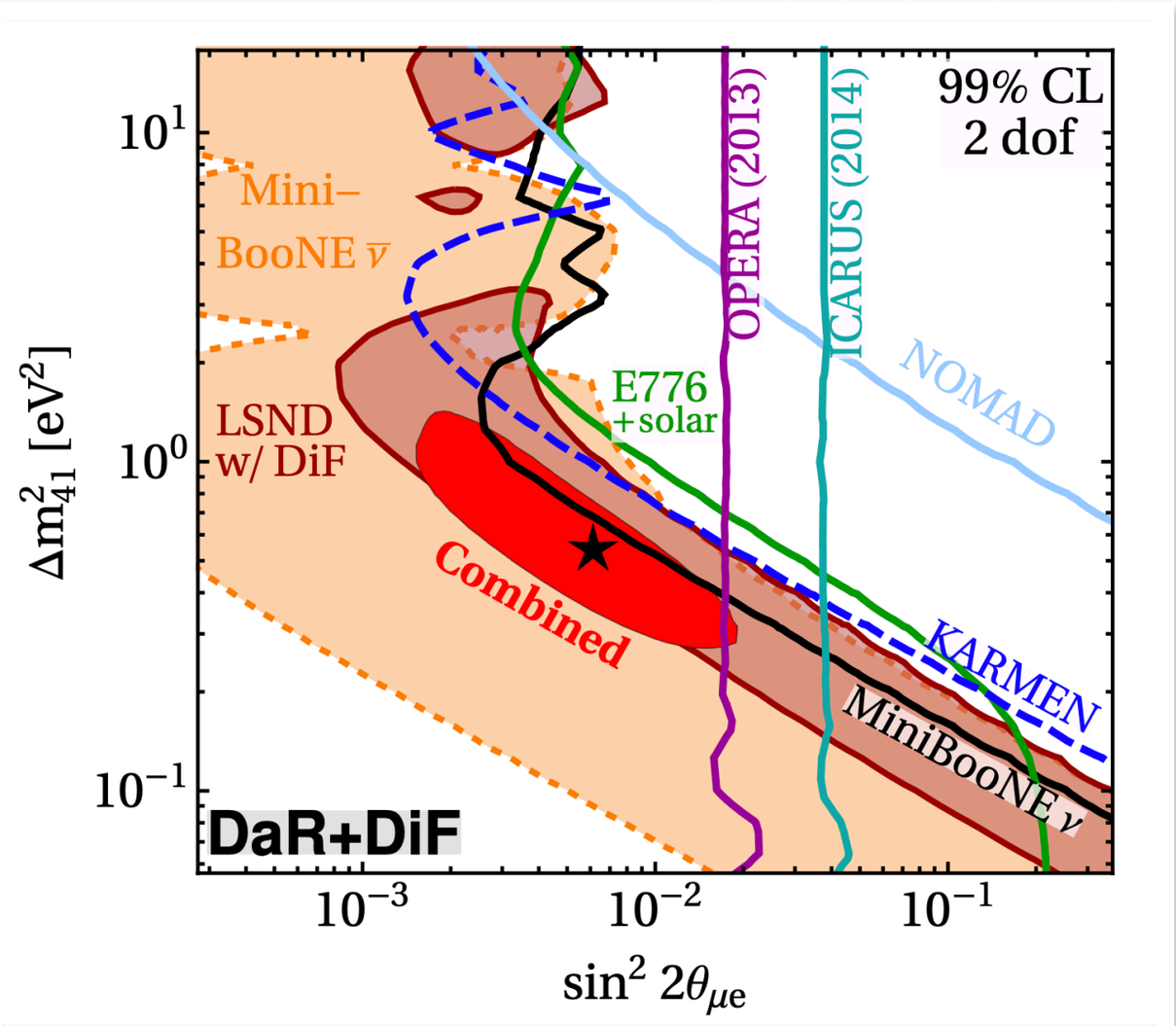
Global Fit to ν_e Appearance Data

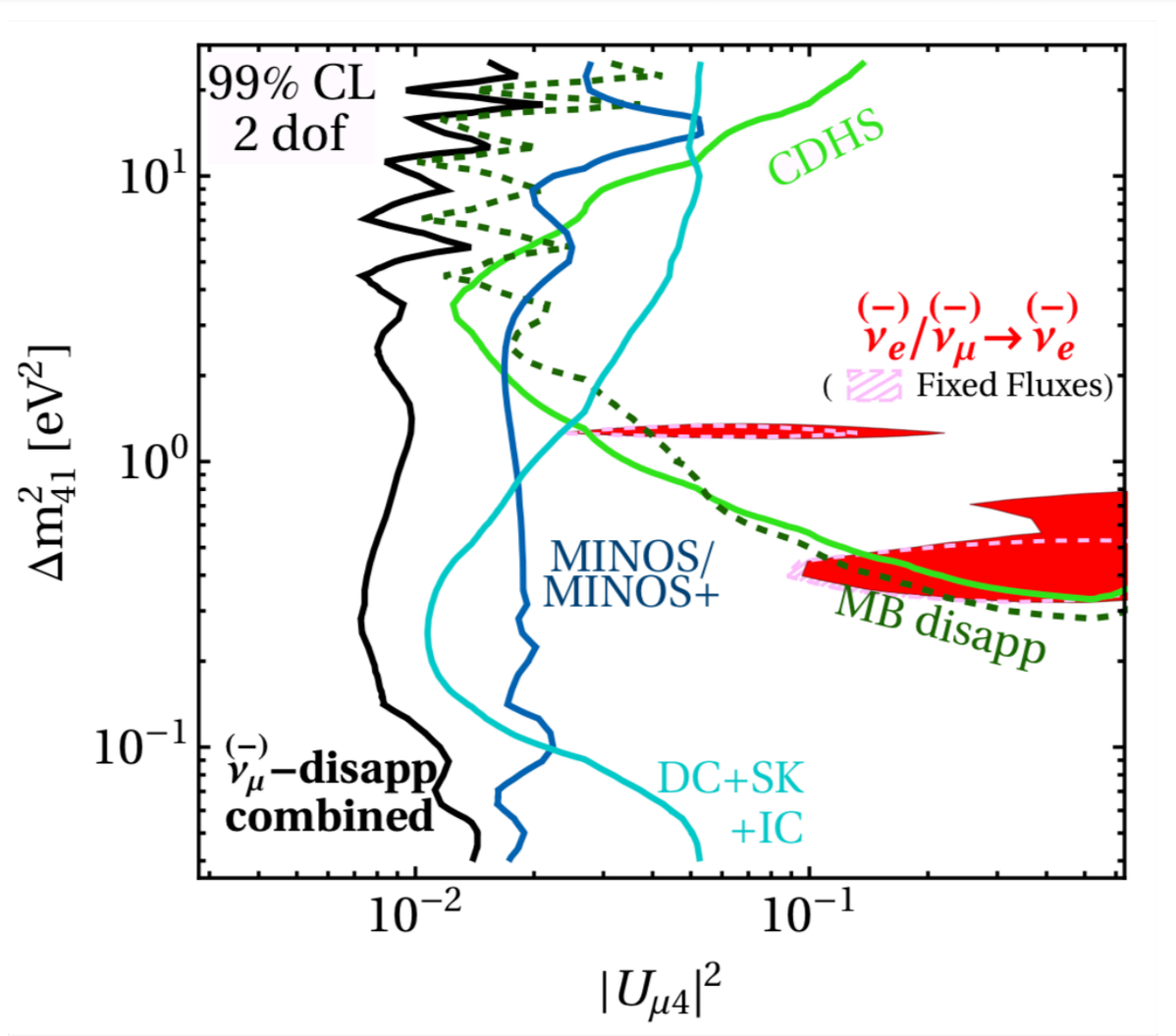


Global fit to ν_e appearance data alone consistent.

Dentler *et al.*, 1803.10661

Tension in Global Sterile Neutrino Fits





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

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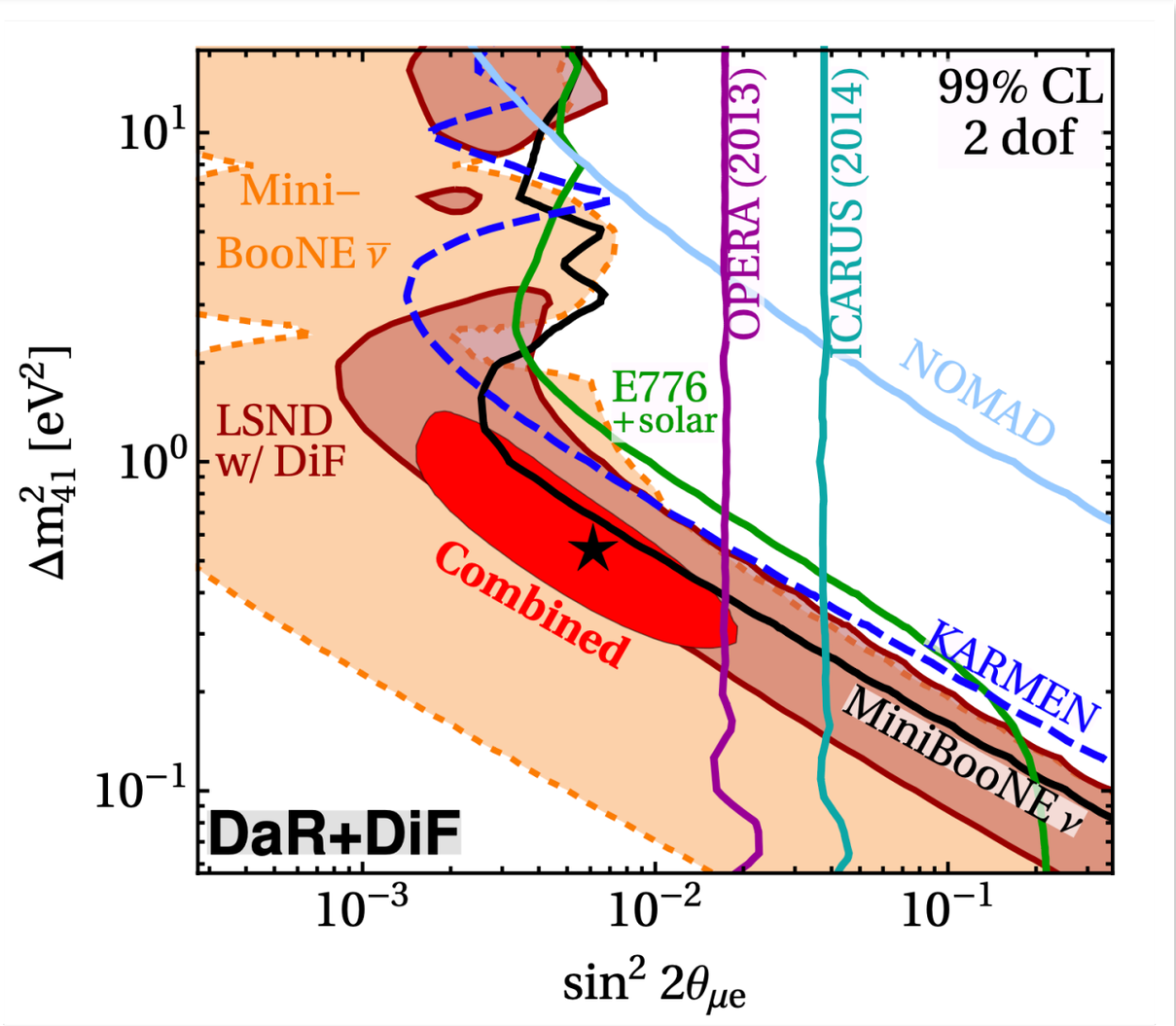

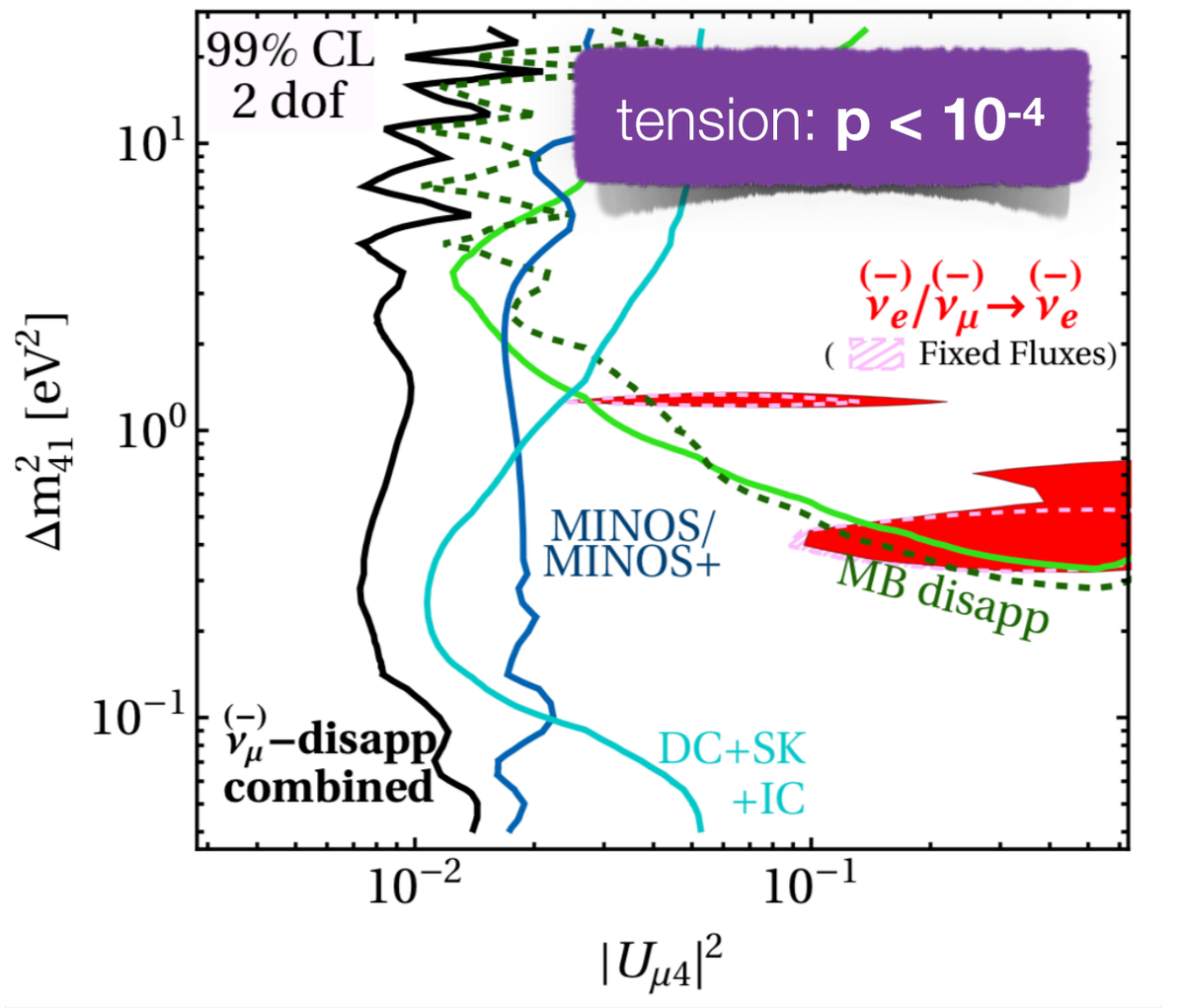

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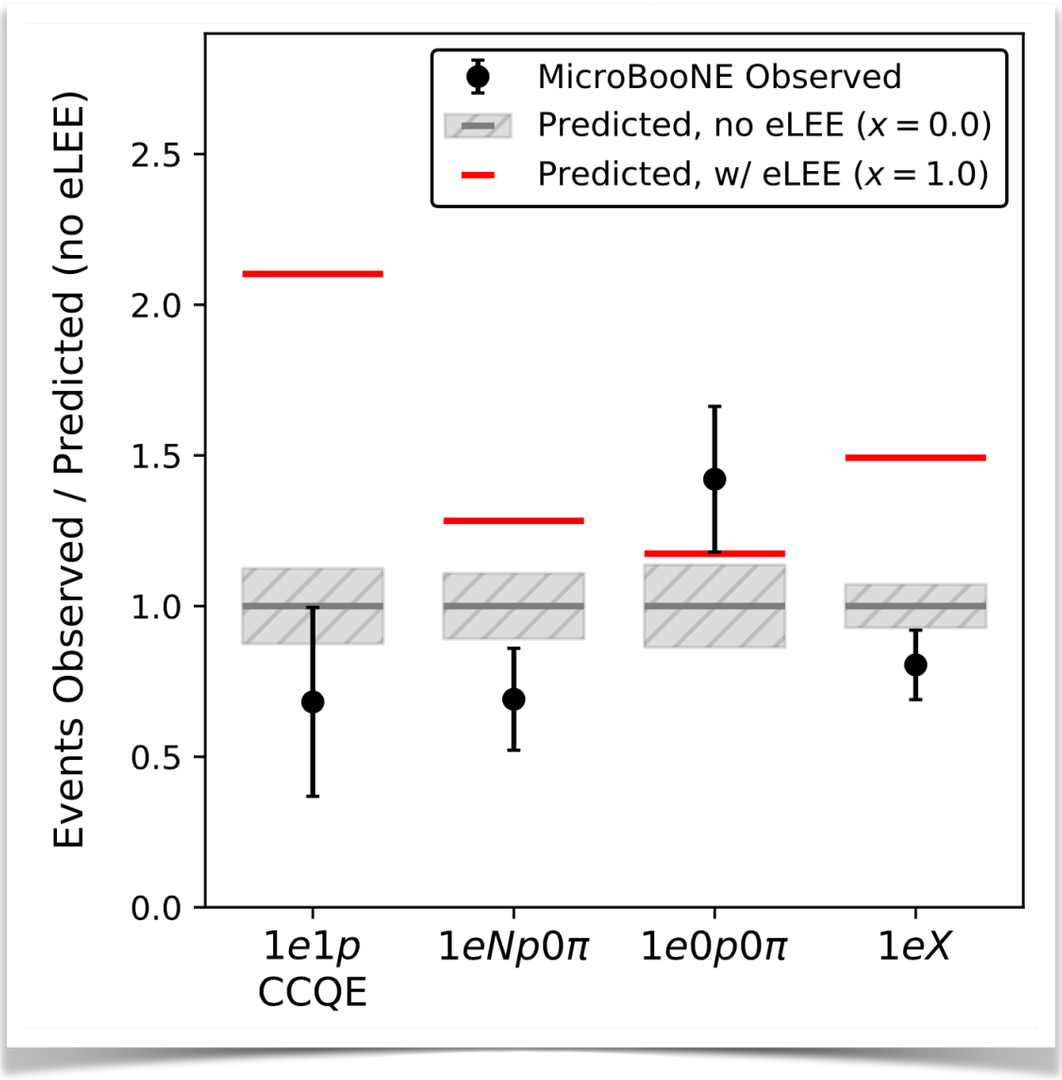
MicroBooNE weighs in

- ☑ anomalous ν_e appearance tested by MicroBooNE in several channels
- ☑ No support for interpretation of MiniBooNE excess as ν_e



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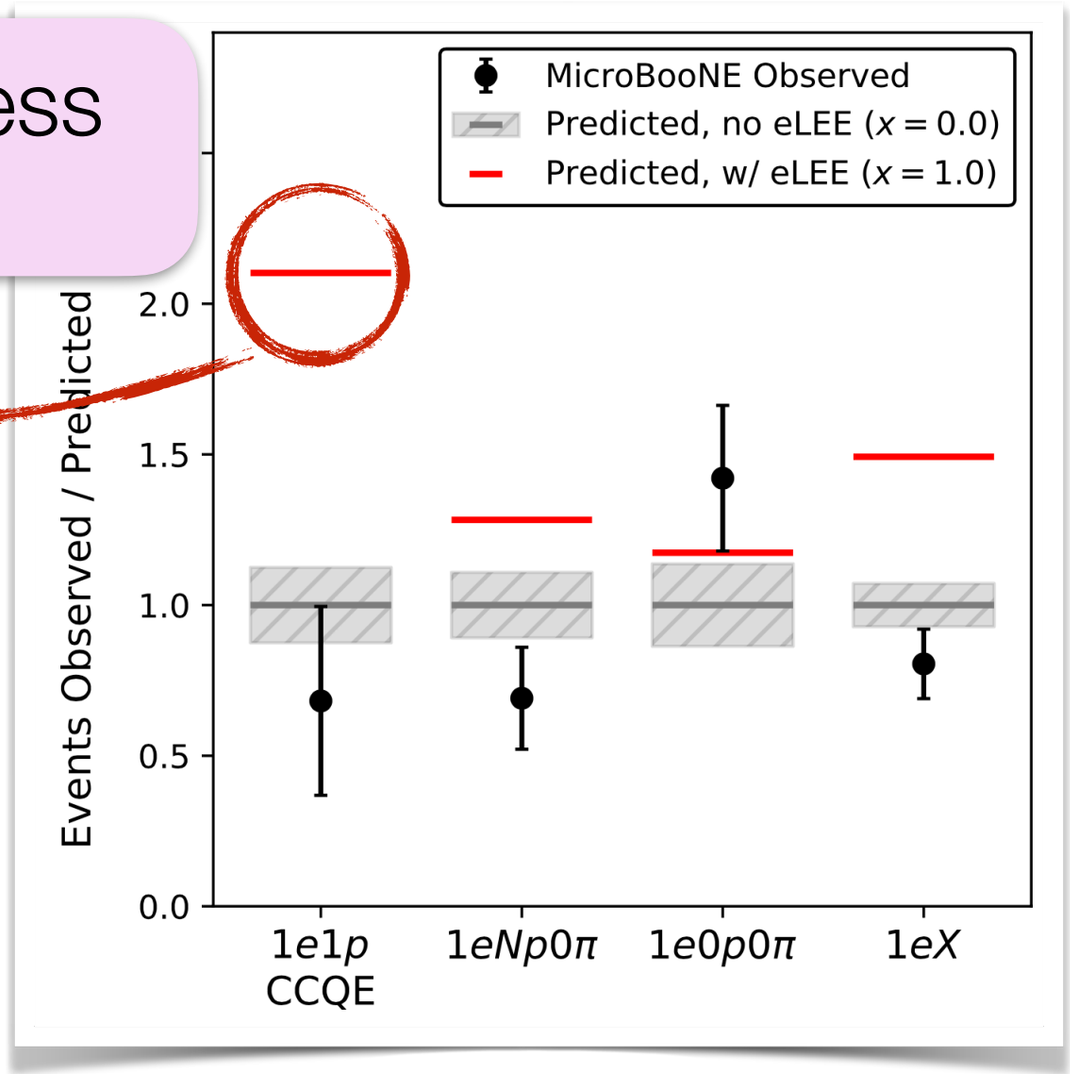
MiniBooNE excess
central value



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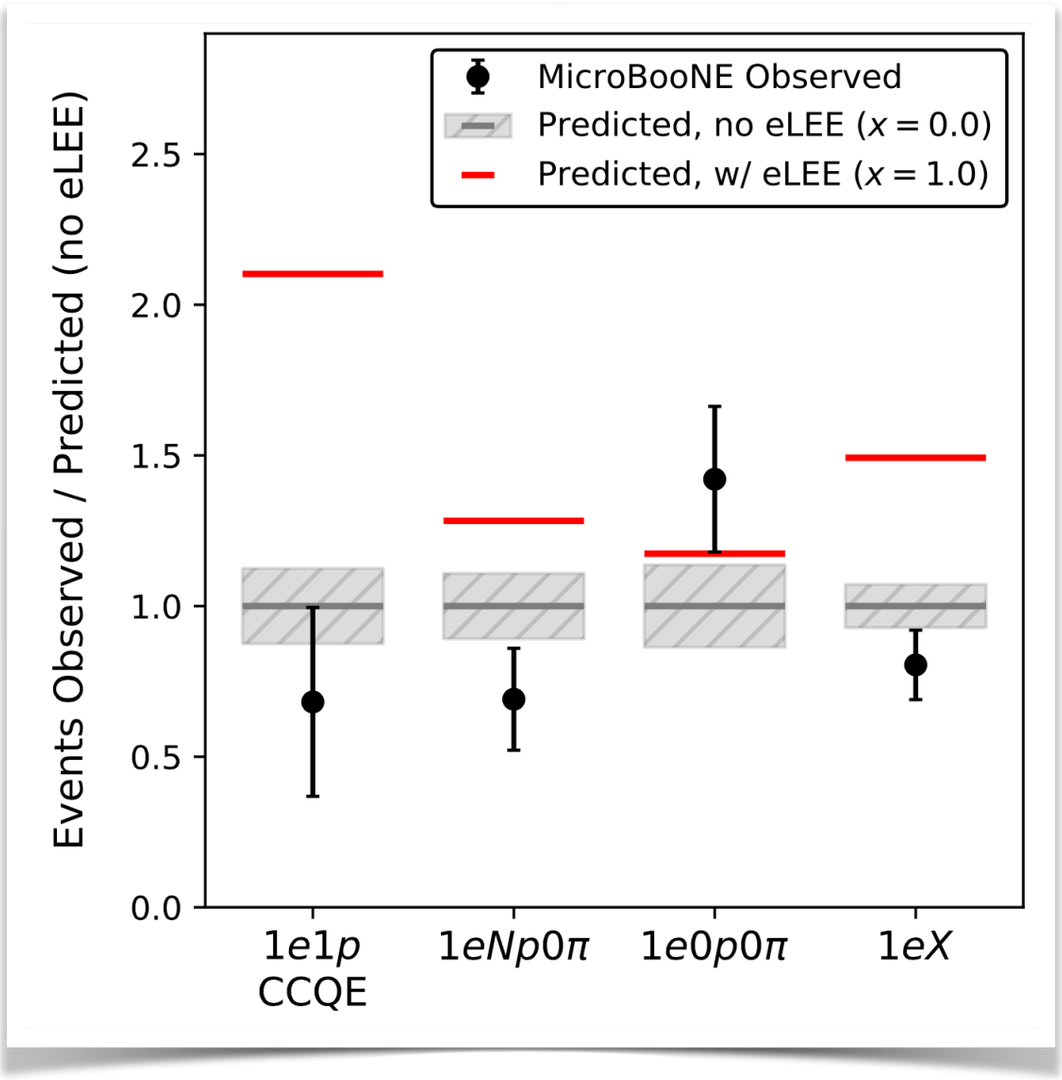
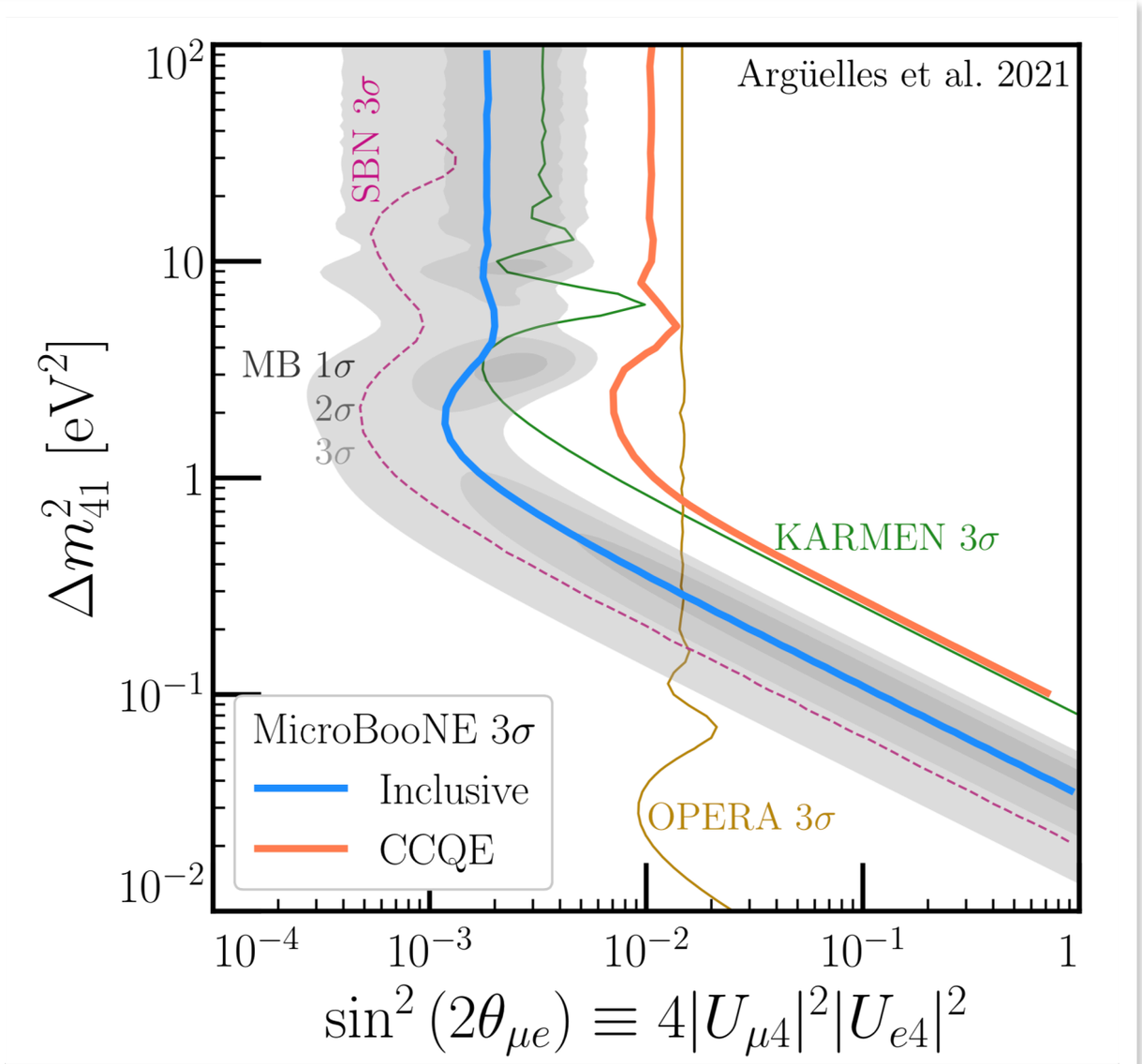


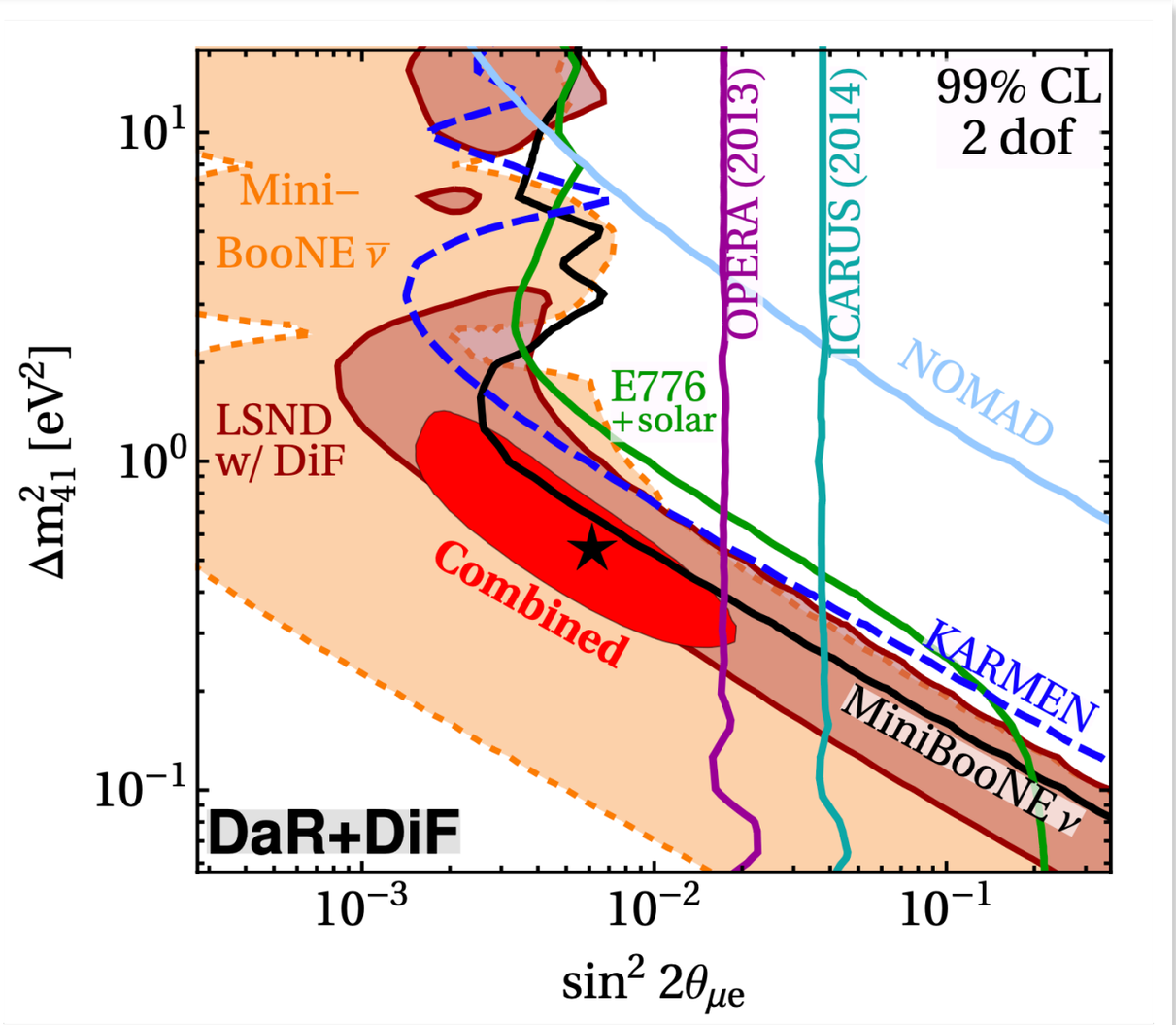
Compatibility Between MiniBooNE and μBooNE

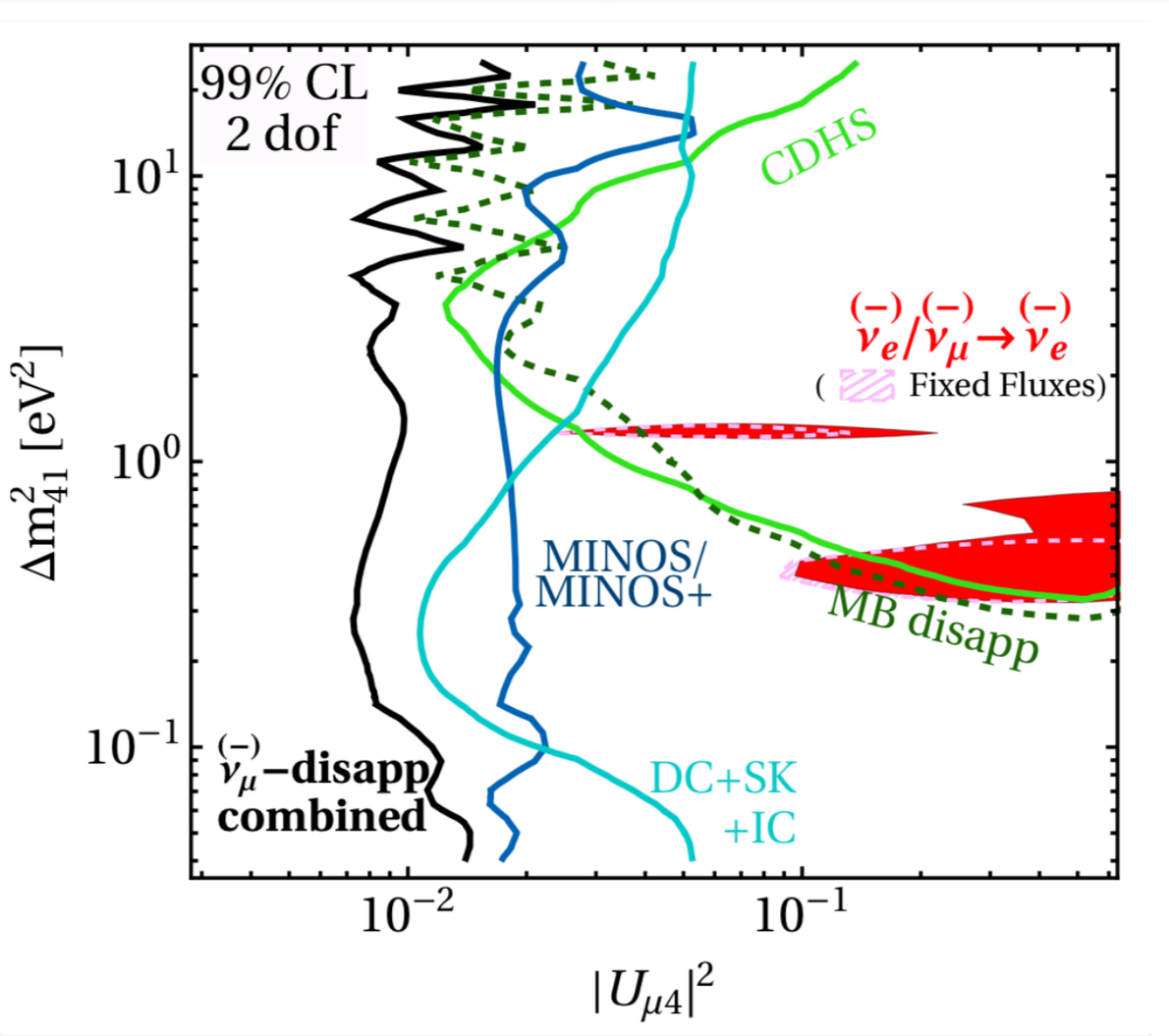


- ☑ 2σ regions overlap
  - ➠ poster #667 by Ivan Martinez-Soler and poster #152 by Nick Kamp
- ☑ good sensitivity due to downward fluctuation in ν_e, upward fluctuation in ν_μ
- ☑ more conservative / robust limits from CLs method
  - ➠ poster #152 by Nick Kamp
- ☑ stay tuned for Hanyu Wei's talk tomorrow

Argüelles Esteban Hostert Kelly
JK Machado Martinez-Soler Perez-Gonzalez
arXiv:2111.10359

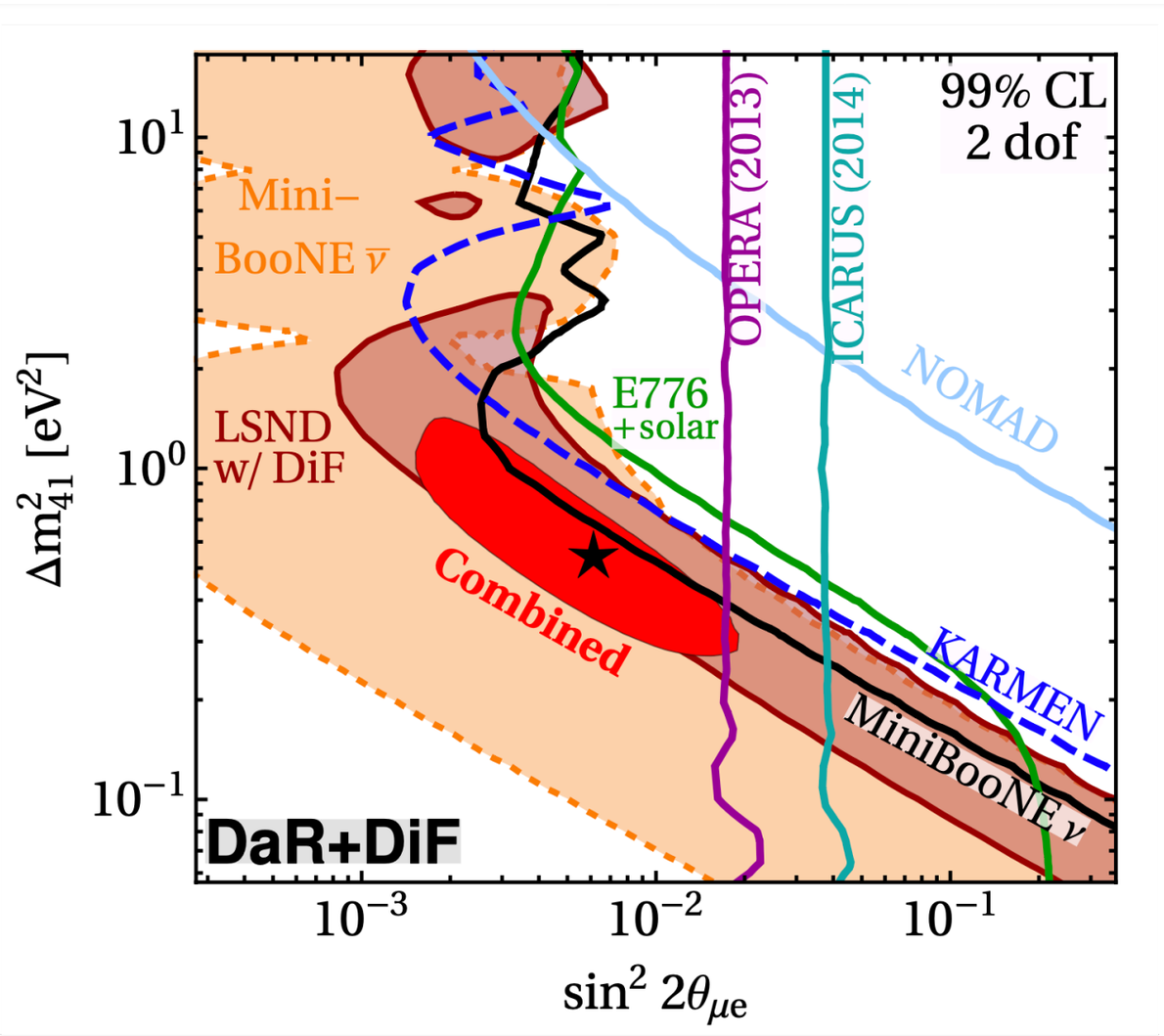
Recent Updates

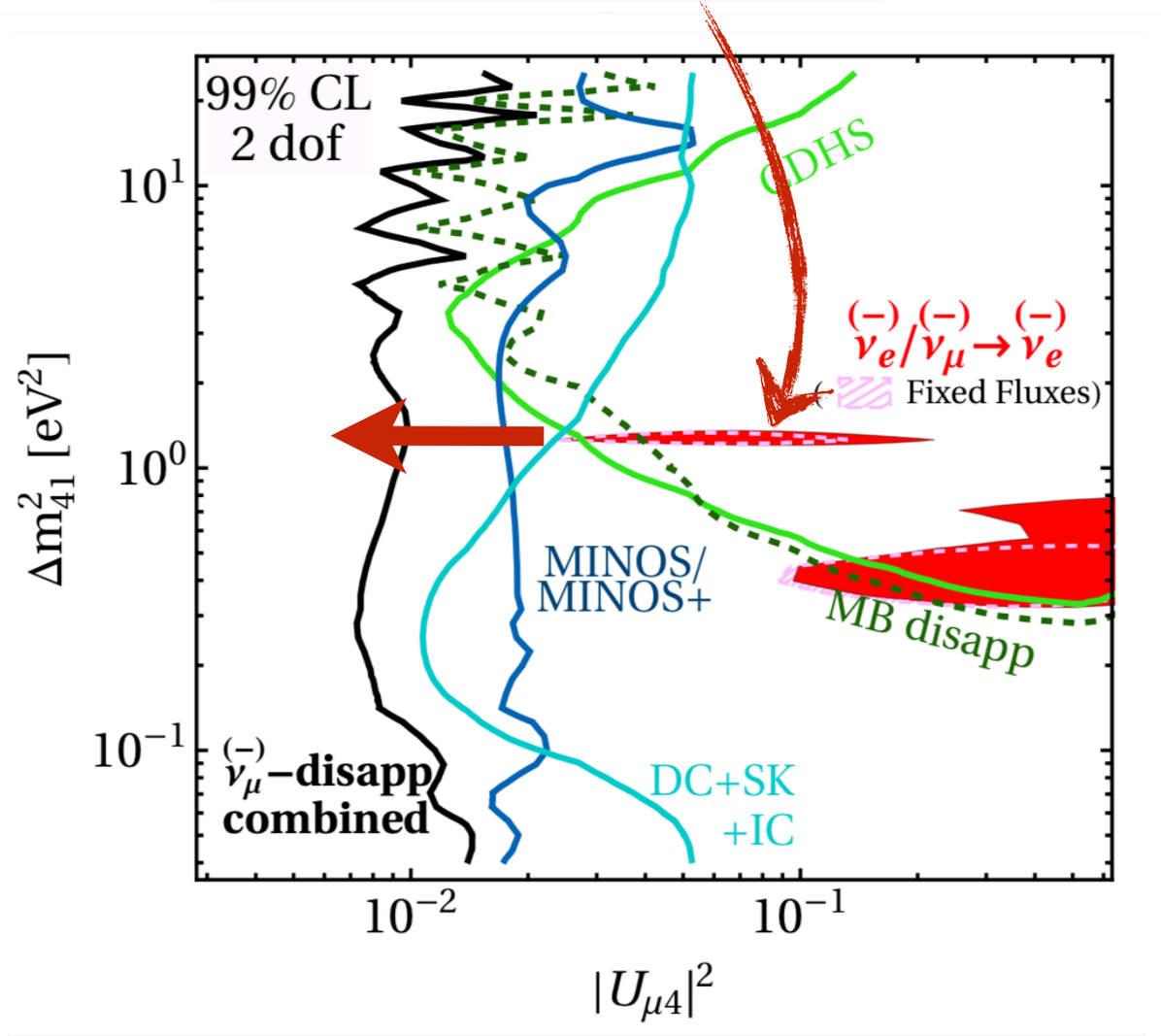




Recent Updates

BEST and **μBooNE** push towards lower $|U_{\mu 4}|^2$

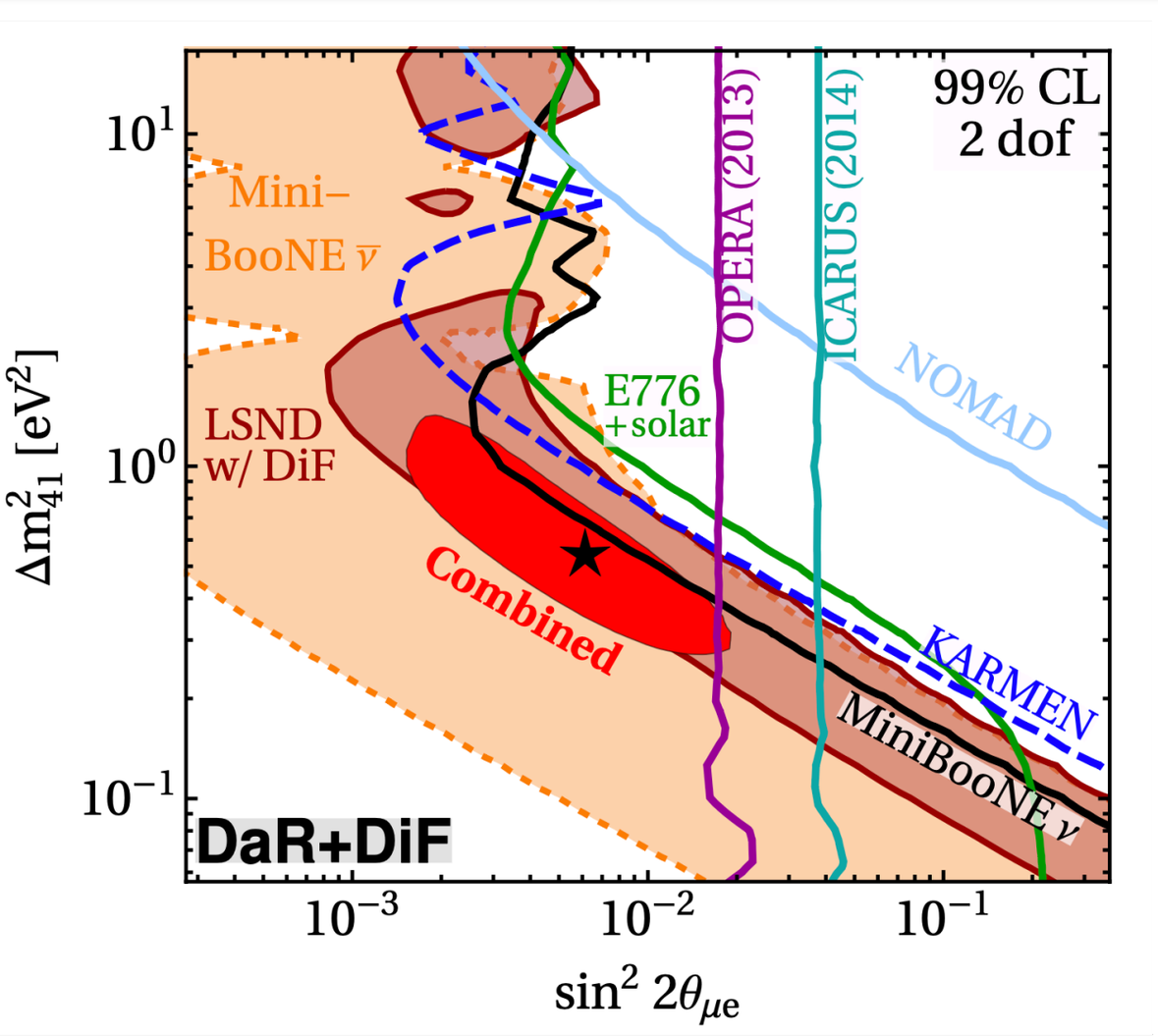


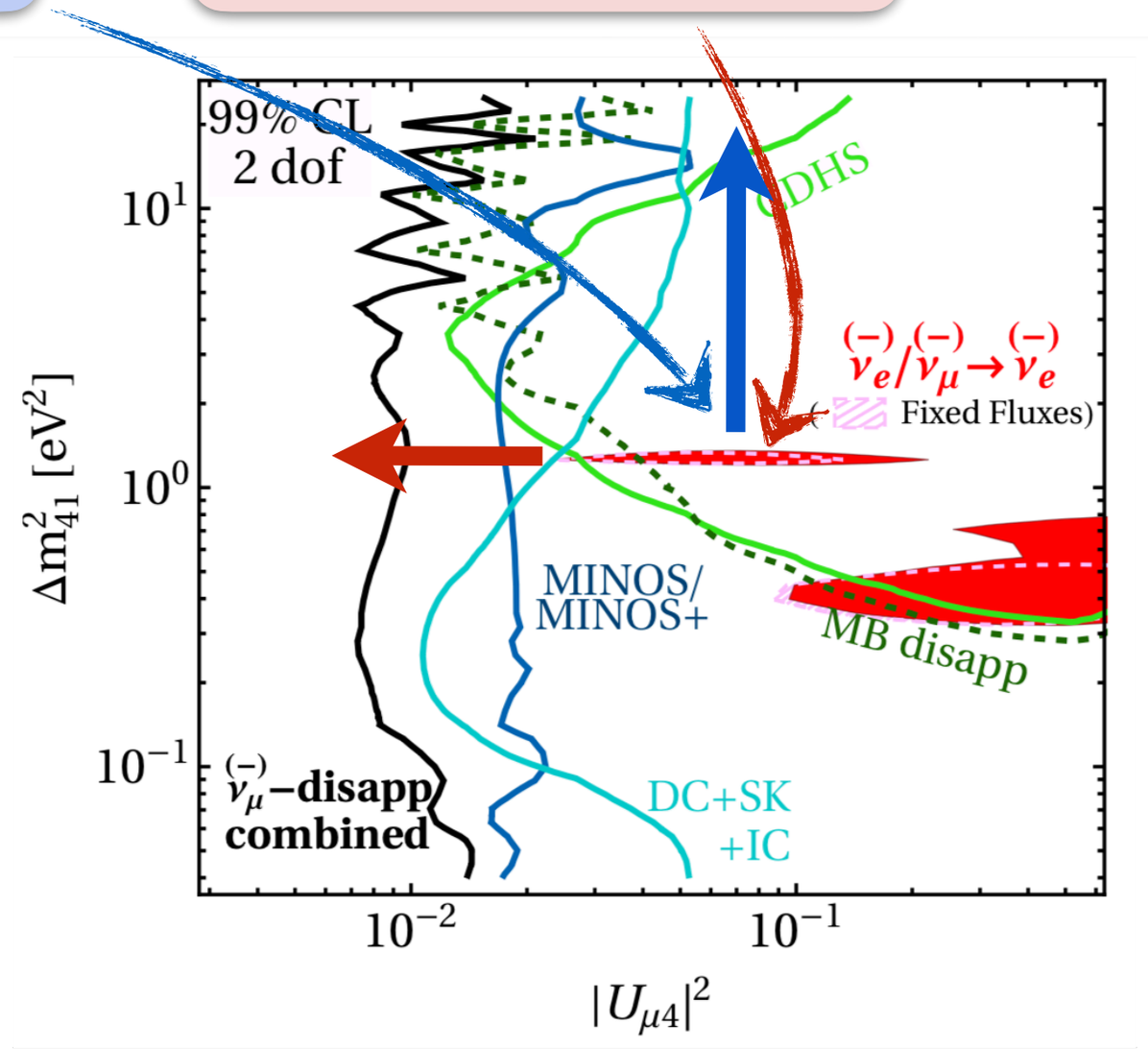


Recent Up

BEST and **Neutrino-4** push towards larger $|\Delta m_{41}|^2$

BEST and **μBooNE** push towards lower $|U_{\mu 4}|^2$





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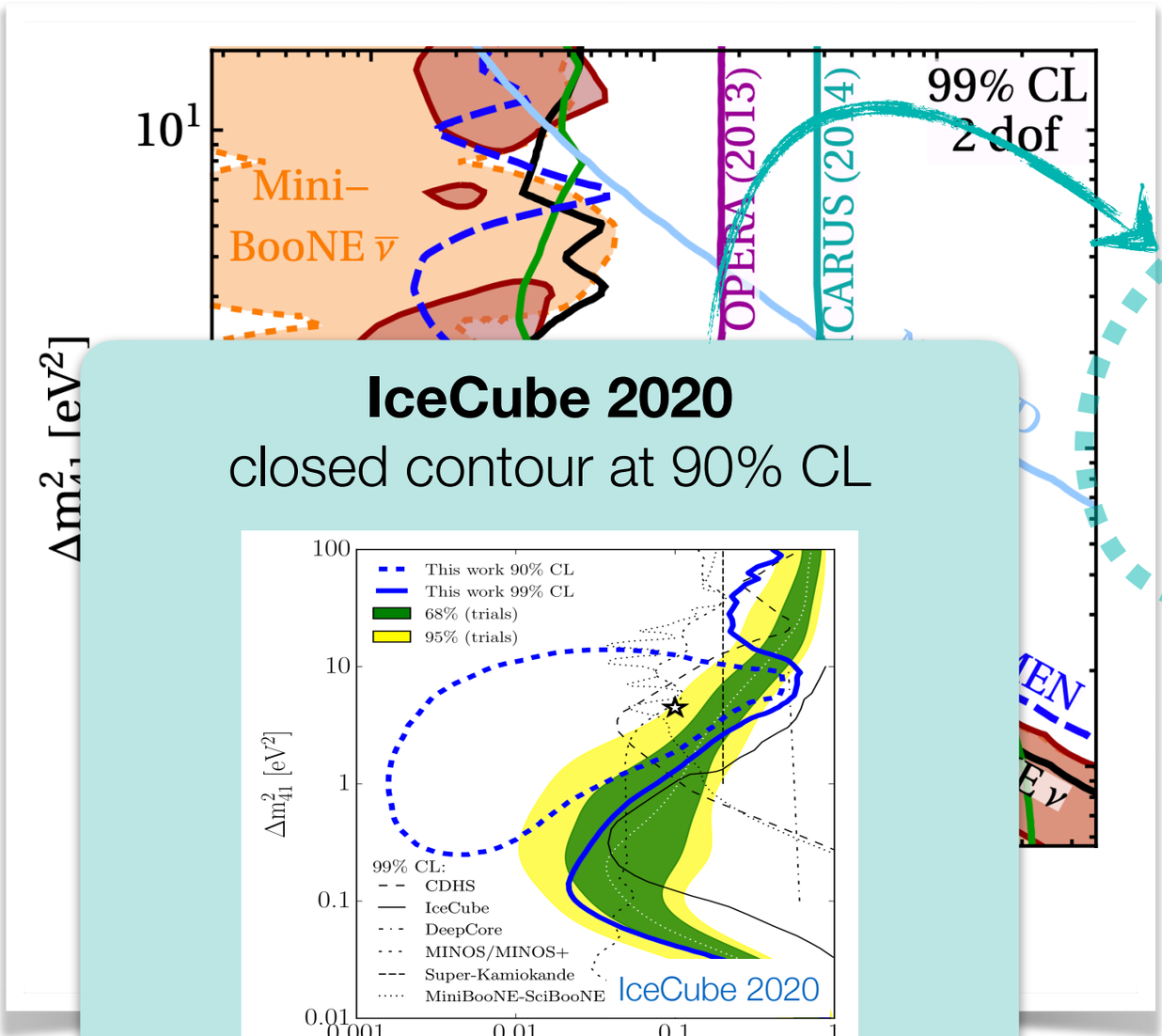
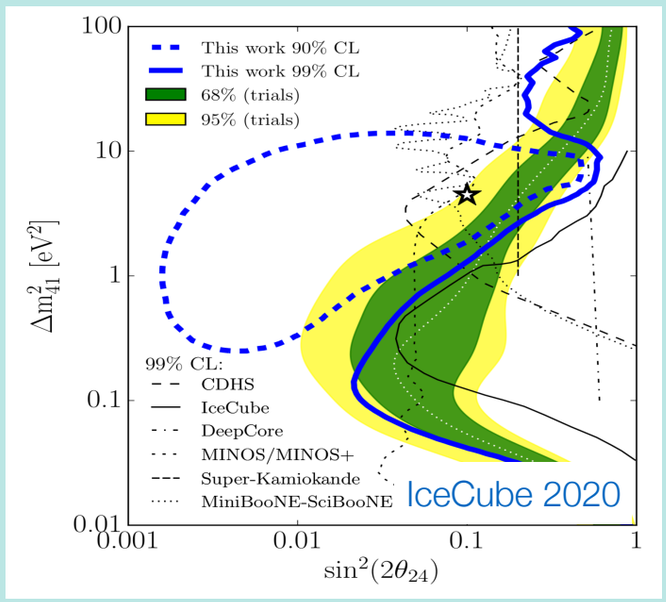
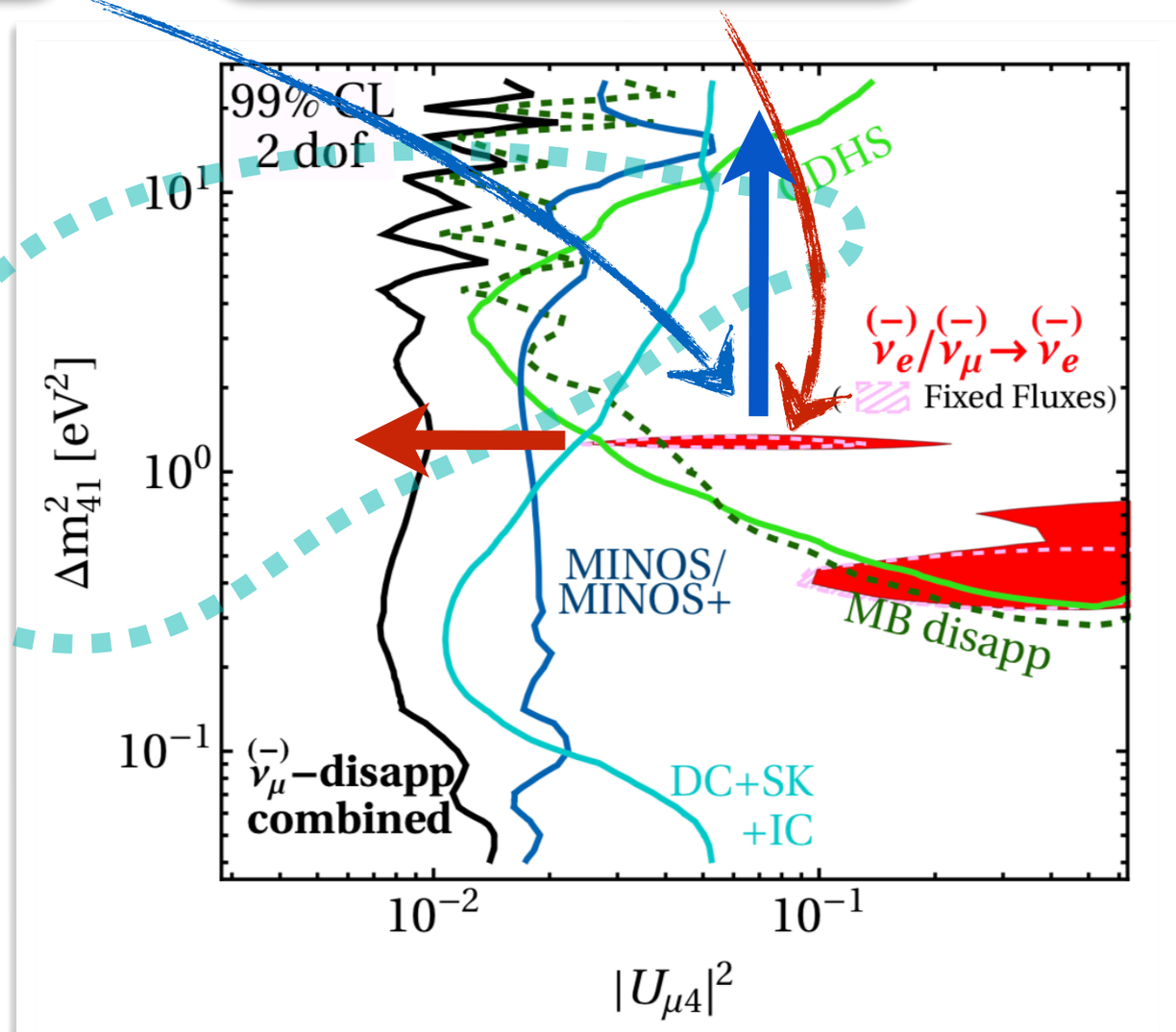


IceCube 2020
closed contour at 90% CL



➠ posters #105 (Bejnamin Smithers)
& #279 (Alfonso Garcia-Soto)



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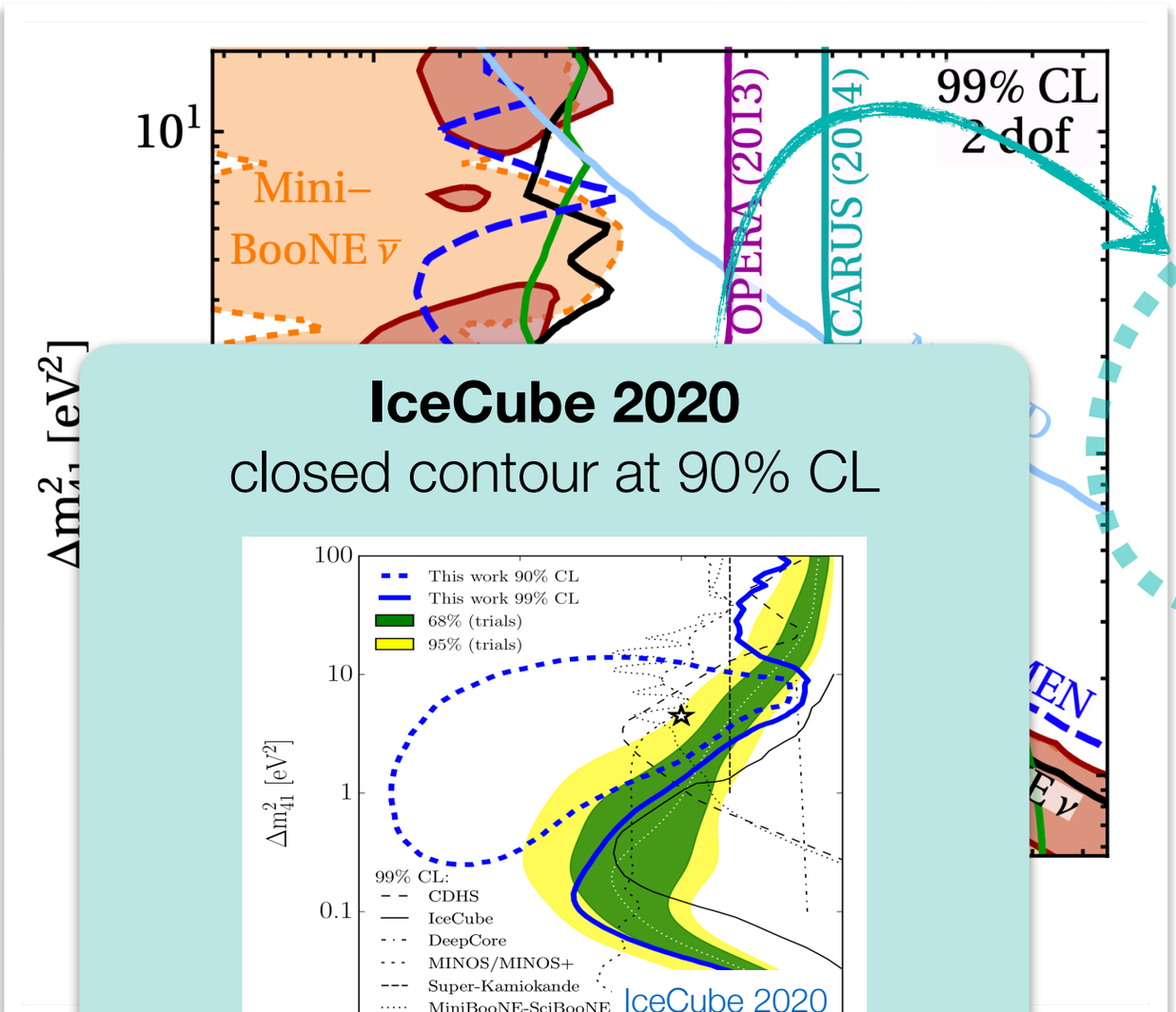

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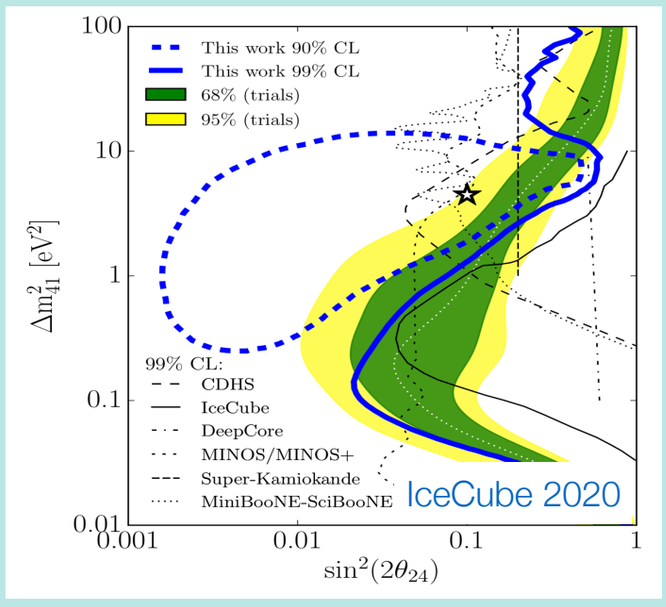

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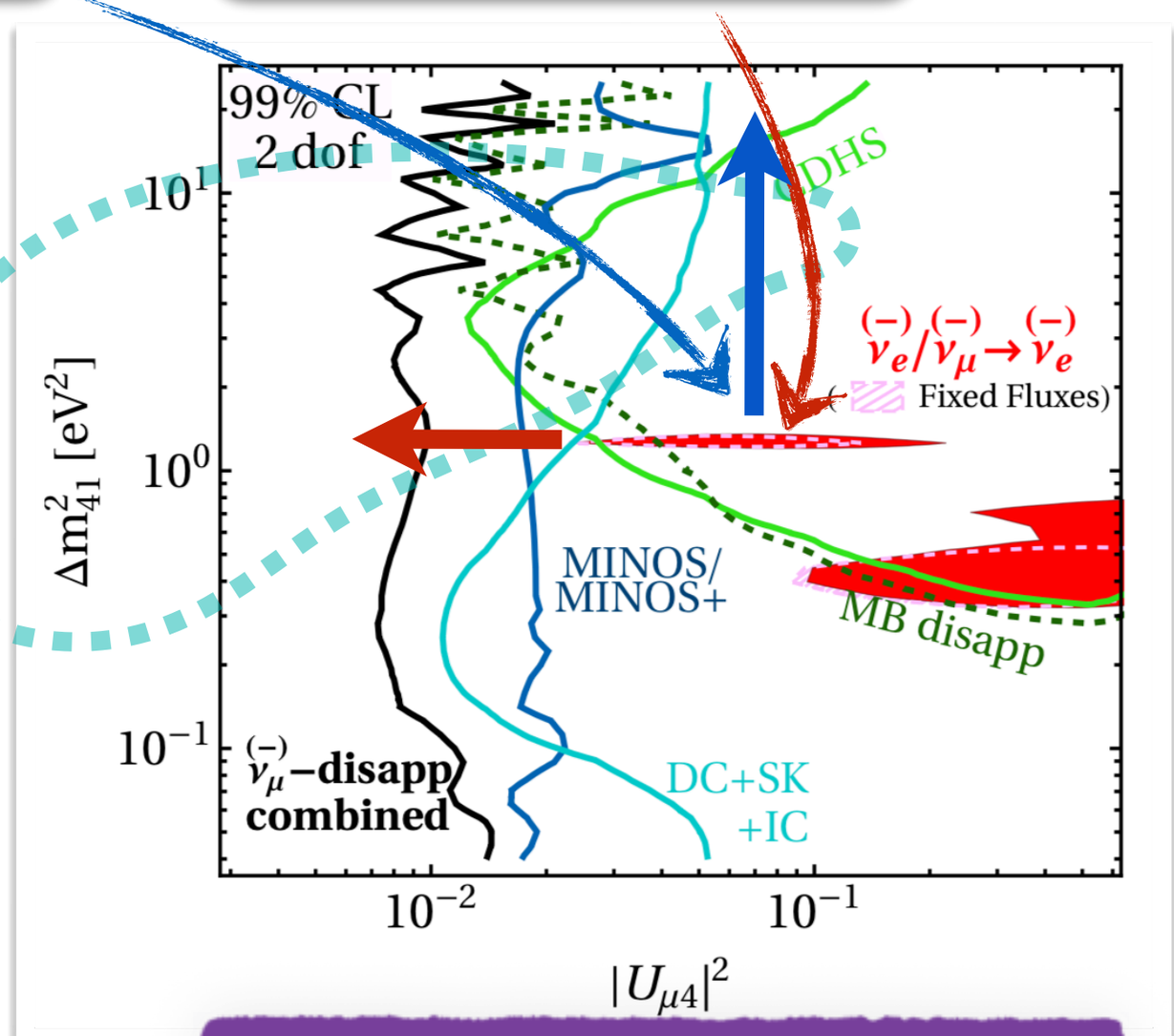
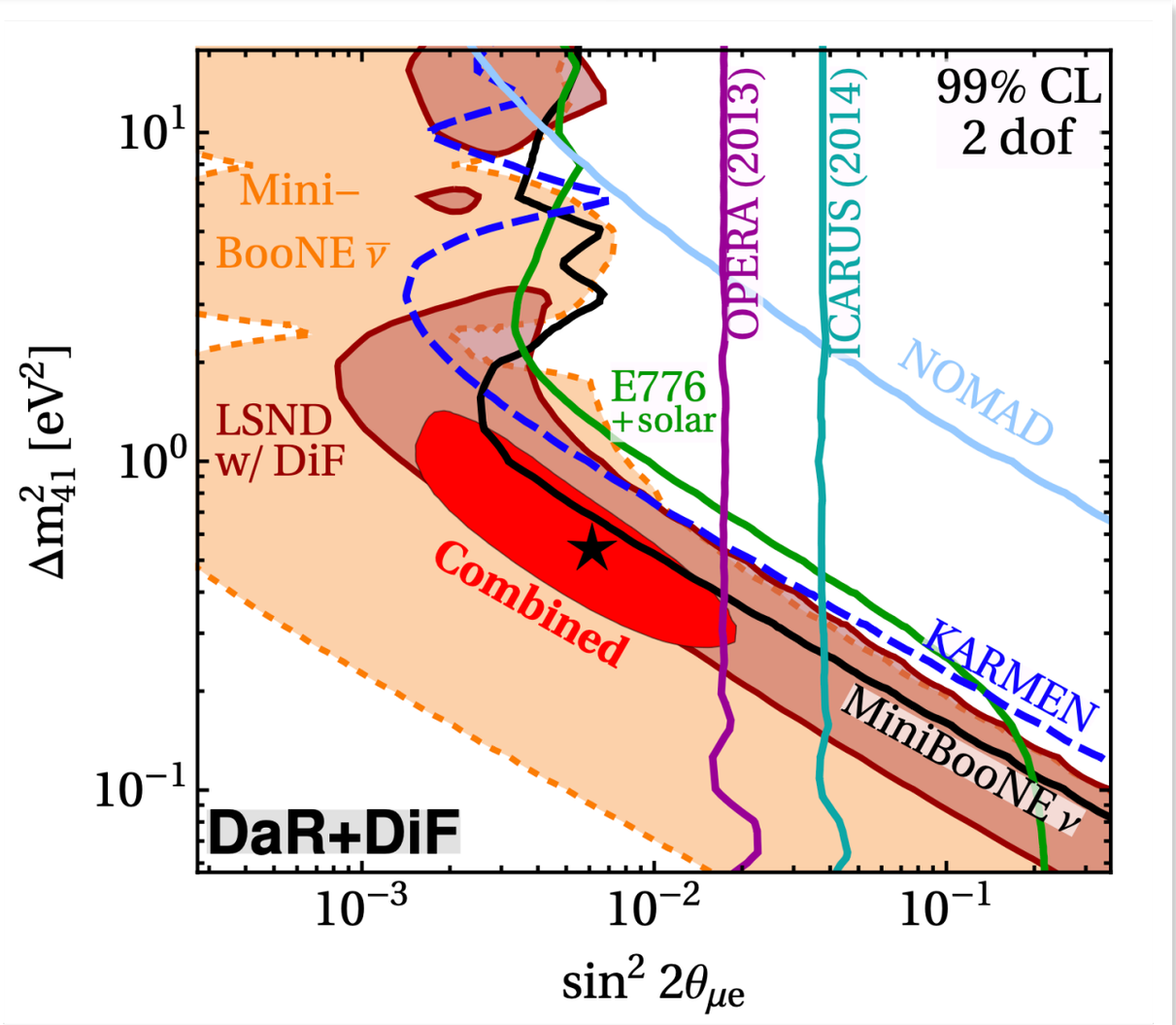
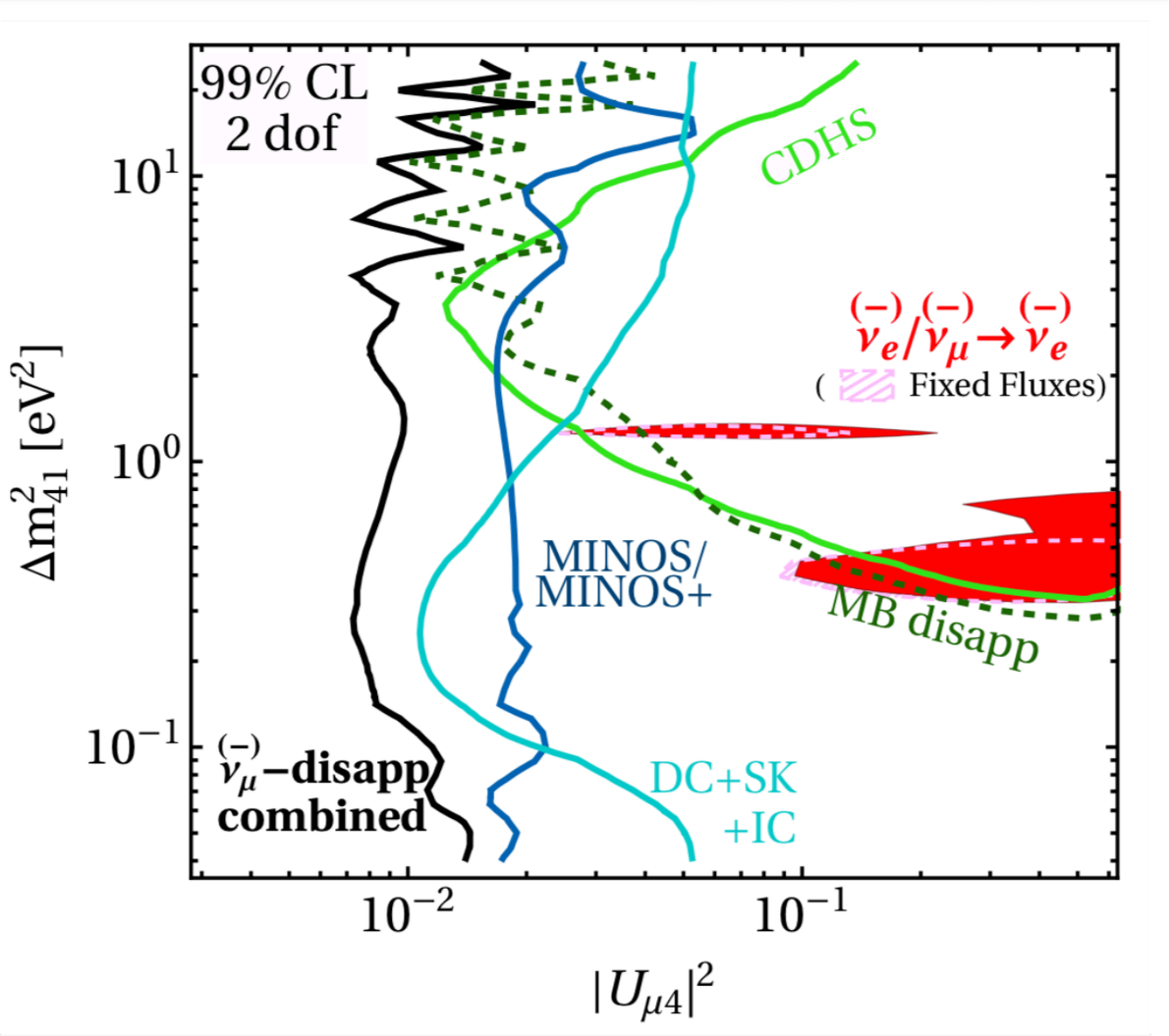


Expect tension to *increase*

- reactor fluxes vs. BEST
- MiniBooNE vs. μBooNE

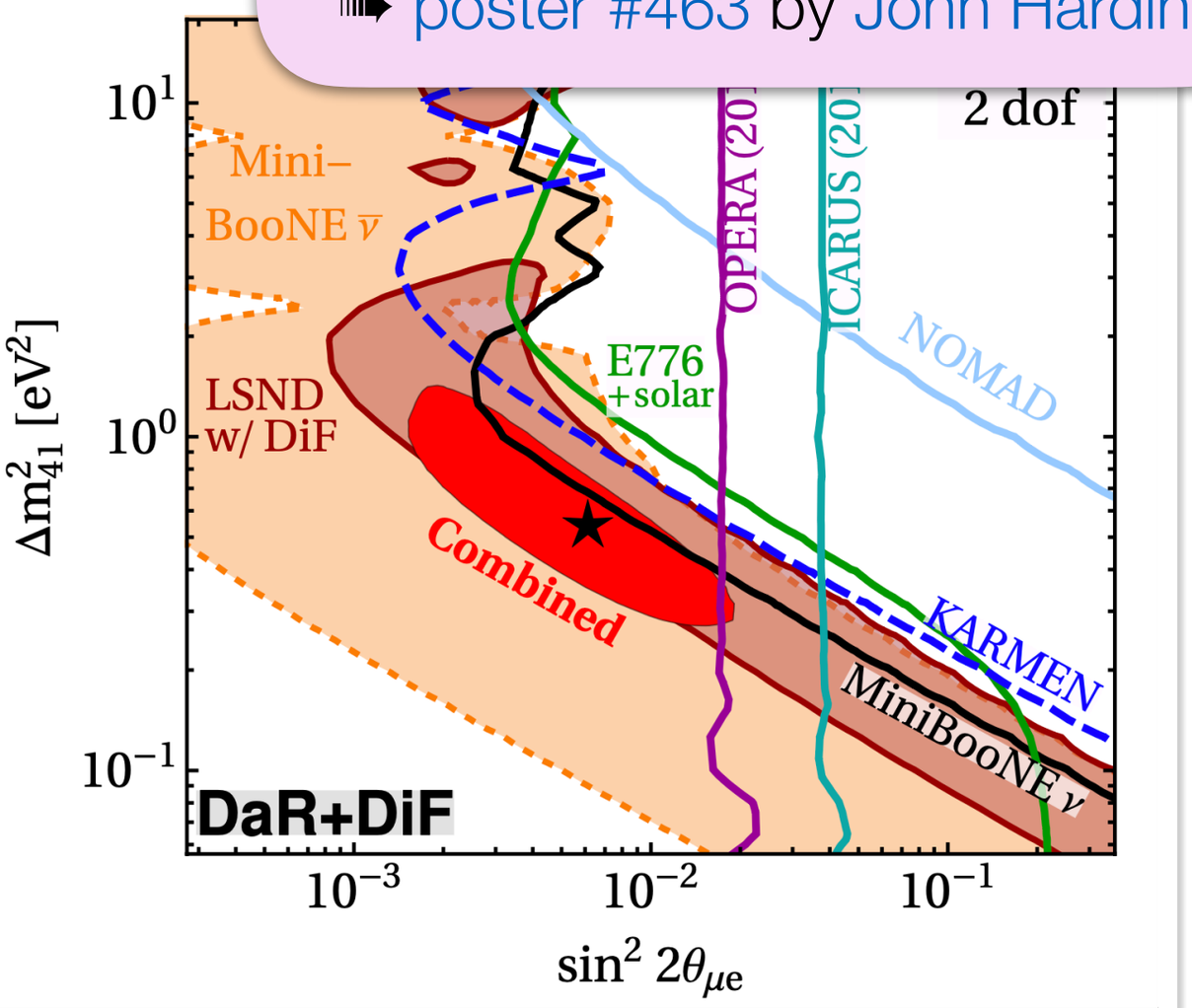
Recent Updates

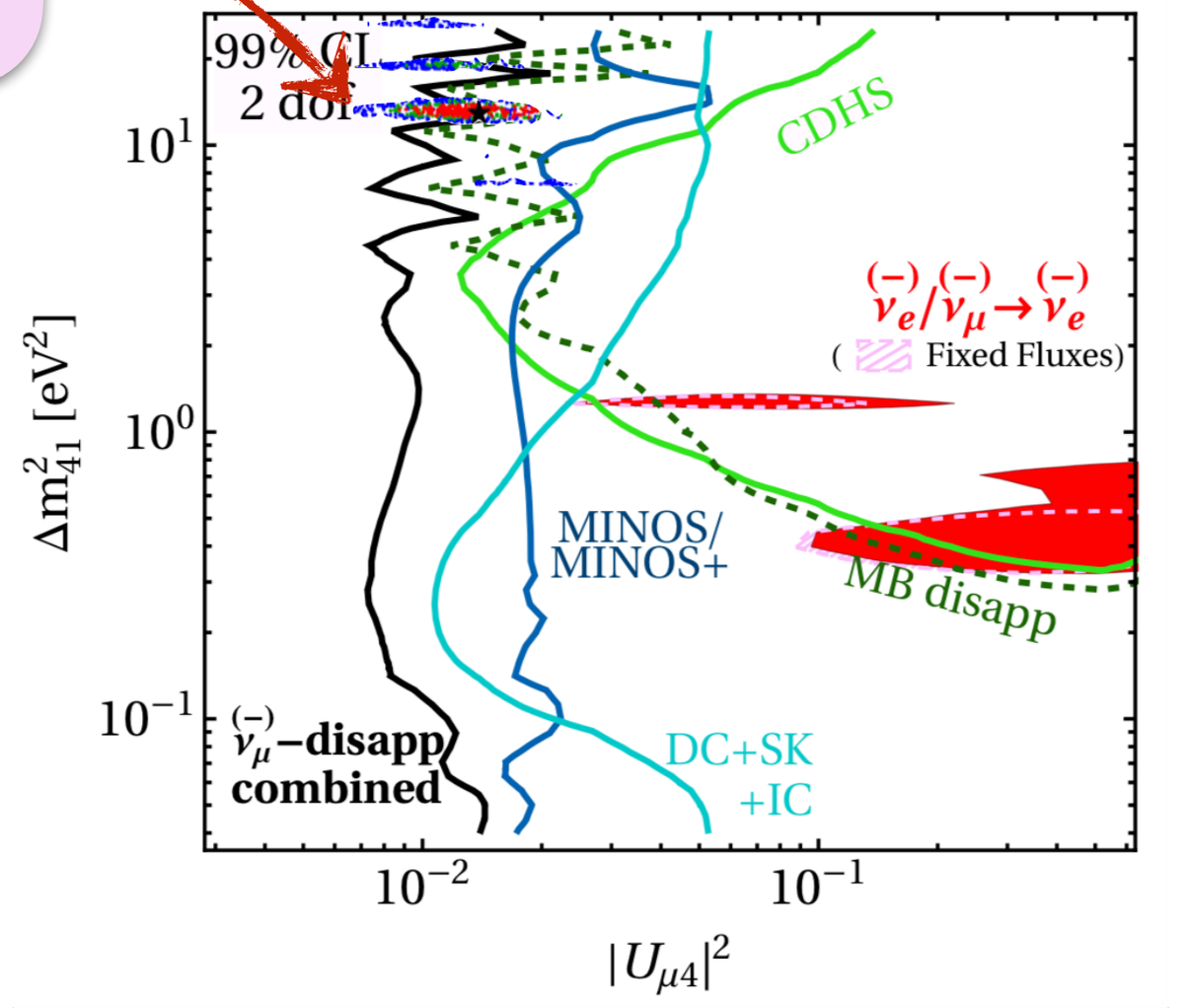




Recent Updates

new global fit
by the Columbia–Harvard–MIT group
➠ poster #463 by John Hardin





Sterile Neutrinos in Cosmology

An extra neutrino species is in severe tension with cosmology.

Standard picture: ν_s production via oscillation at T ≳ MeV

$N_{eff} \lesssim 3.16$ ⚡

$\Sigma m_\nu \lesssim 0.12$ eV ⚡

Planck TT,TE,EE+lowE+lensing+BAO 2018

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measure for the
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extra neutrino species would imply $N_{eff} \sim 4$

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sum of neutrino masses
affects structure formation
sterile neutrino compatible with anomalies
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Planck TT,TE,EE+lowE+lensing+BAO 2018

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would imply $\Sigma m_\nu \sim 1$ eV

potentially solvable in extended models
➠ talk by Olga Mena on Saturday

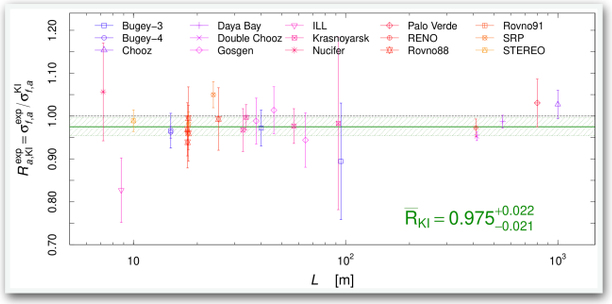
Back to the Future

The Future

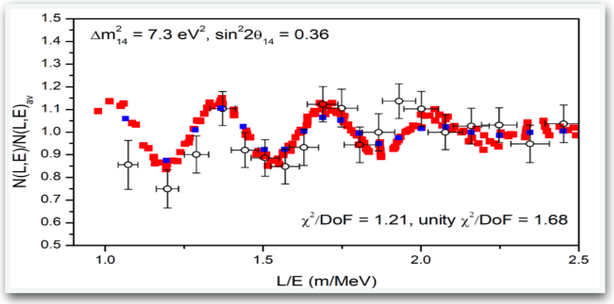
- ☑ Look for more exotic signatures (no know SM candidates)
  - single-γ production unrelated to the Δ(1232)?
  - single electrons unrelated to ν_e?
  - boosted e^+e^- pairs?
  - ➠ talk by Carlos Argüelles tomorrow
- ☑ More data incoming:
  - μBooNE / SBND / ICARUS at Fermilab
    - ➠ talks by Hanyu Wei and Anne Schukraft tomorrow
  - SBL reactor + gallium experiments
    - ➠ Matthieu Licciardi, Jinyu Kim today, Steve Elliott tomorrow
  - JSNS-2 ➠ talk by Jungsic Park tomorrow
  - Long-baseline Experiments, Neutrino Telescopes, ...
  - Future Proposals (IsoDAR, ...) ➠ poster session

Summary

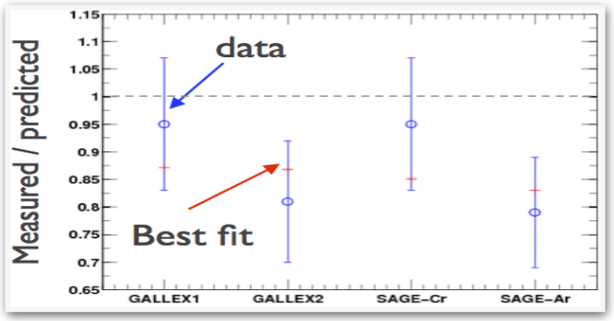
Summary



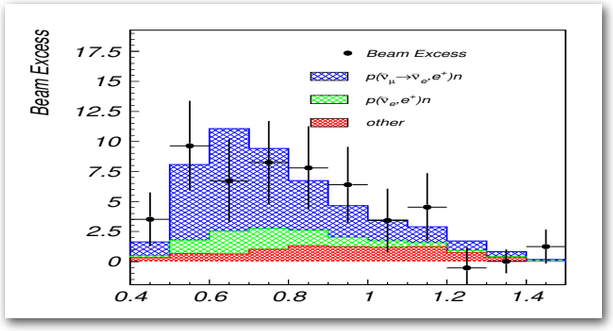
reactor flux anomaly
resolved with new input data
to flux calculation



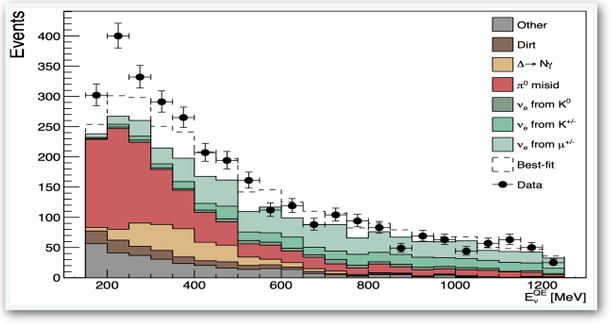
reactor spectra
is there really an anomaly?



gallium anomaly
unresolved, recently reinforced

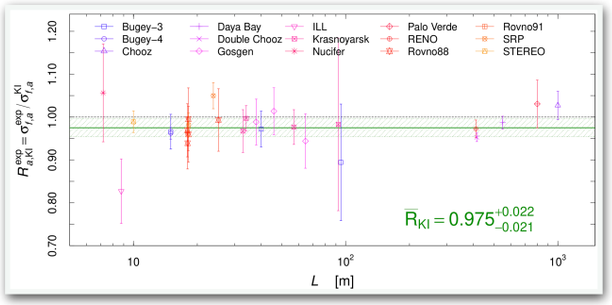


LSND
unresolved

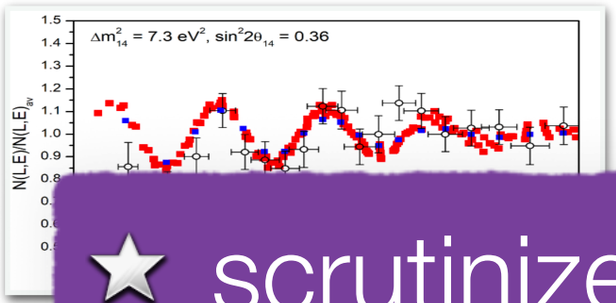


MiniBooNE
unresolved
resolvable by next-gen. SBL experiments

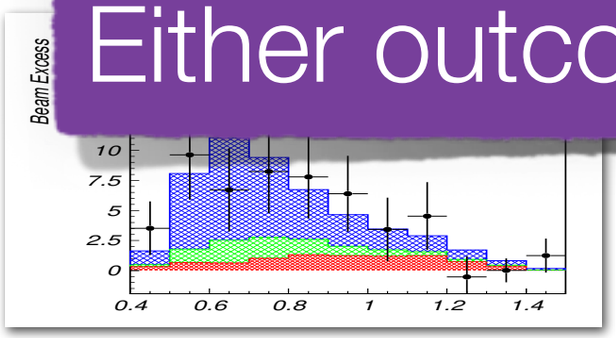
Summary



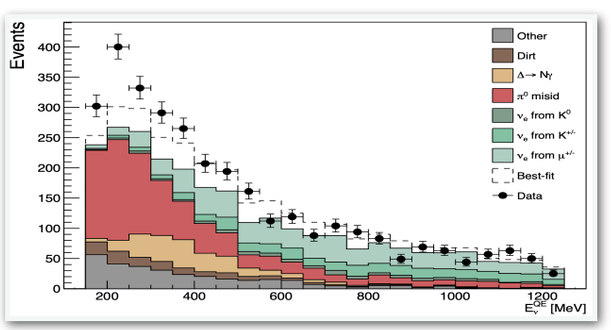
reactor flux anomaly
resolved with new input data
to flux calculation



reactor spectra



LSND
unresolved



MiniBooNE
unresolved
resolvable by next-gen. SBL experiments

★ scrutinize anomalies for unknown systematics
(need 4 independent effects!)

★ scrutinize also null results?

Either outcome **will teach us crucial lessons**.

Thank You!

CERN

Neutrino PLATFORM

erc

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