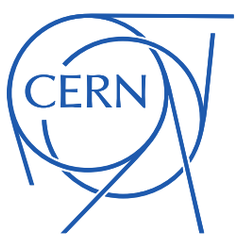
Hunting for New Physics in Neutrino Oscillation Experiments

Joachim Kopp (CERN & Uni Mainz)

Chung-Ang University BSM Workshop | 1st February 2021



Outline

- ☑ Neutrino Oscillation Experiments
- ☑ Sterile Neutrinos
- ☑ New Neutrino Interactions
- ☑ Near Detectors

Neutrino Oscillation Experiments

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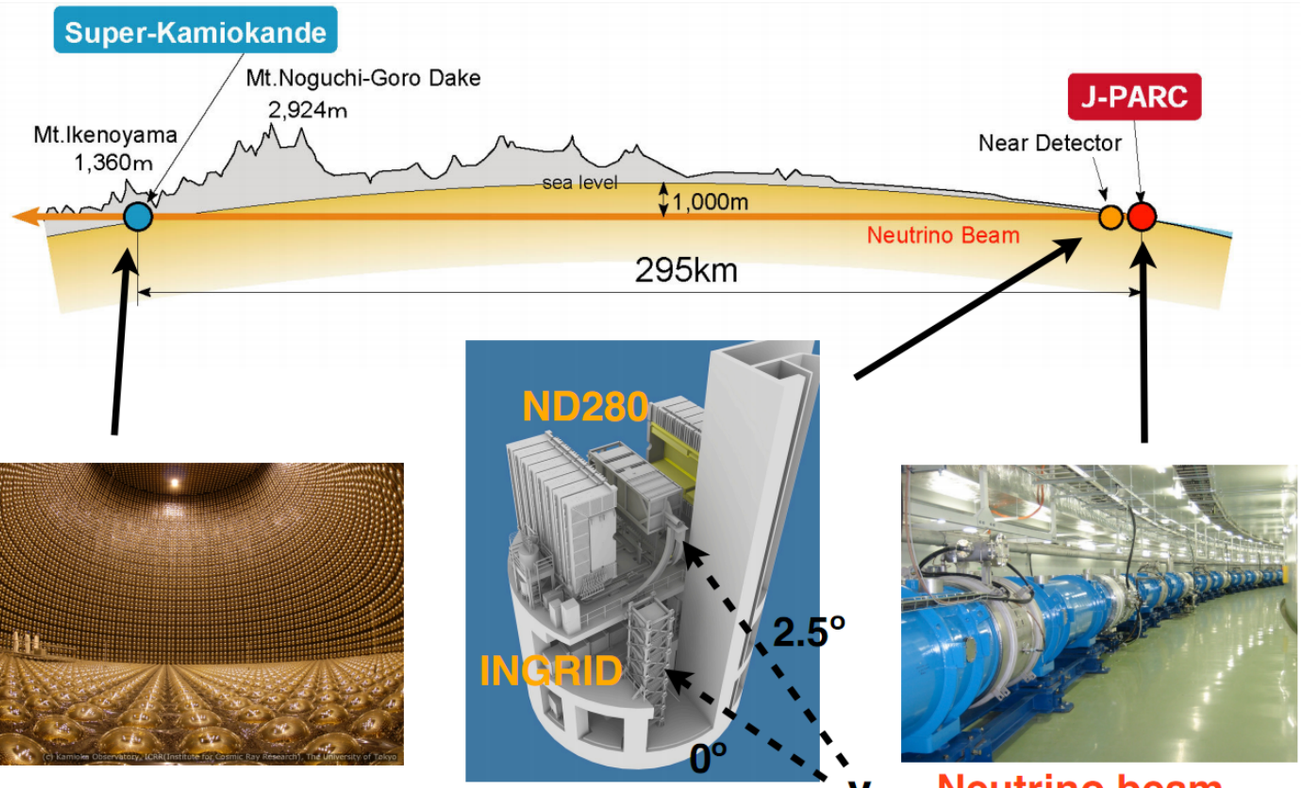
Current Neutrino Flagships

T2K

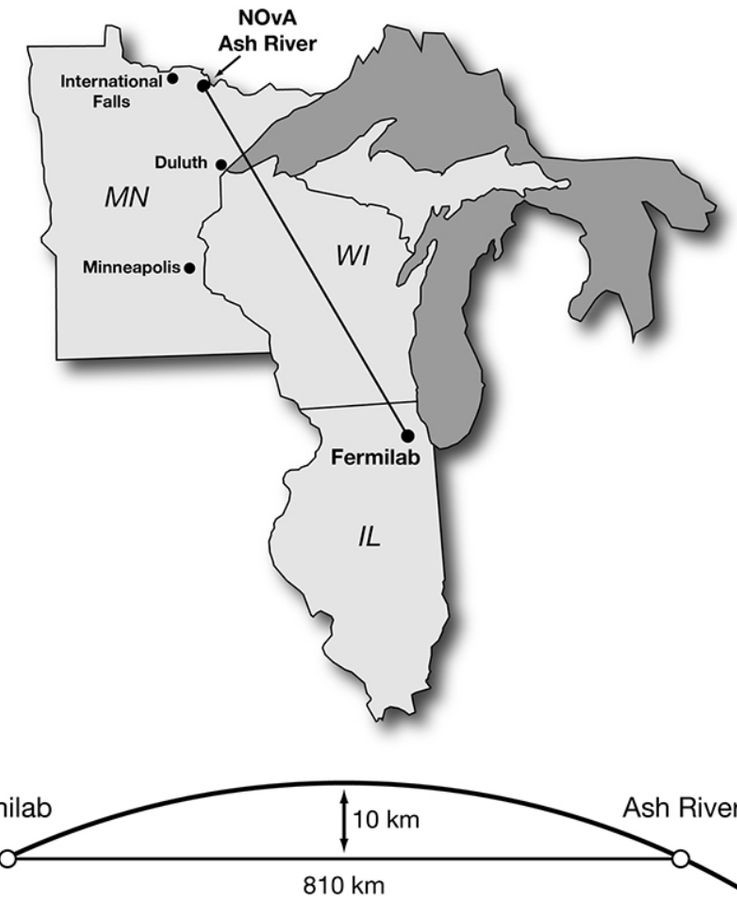


Super-Kamiokande

INGRID (on-axis) and ND280 (off-axis)

Neutrino beam created at J-PARC main ring

NOνA



Blair (T2K) 1509.08889

What we Know About Neutrino Oscillations

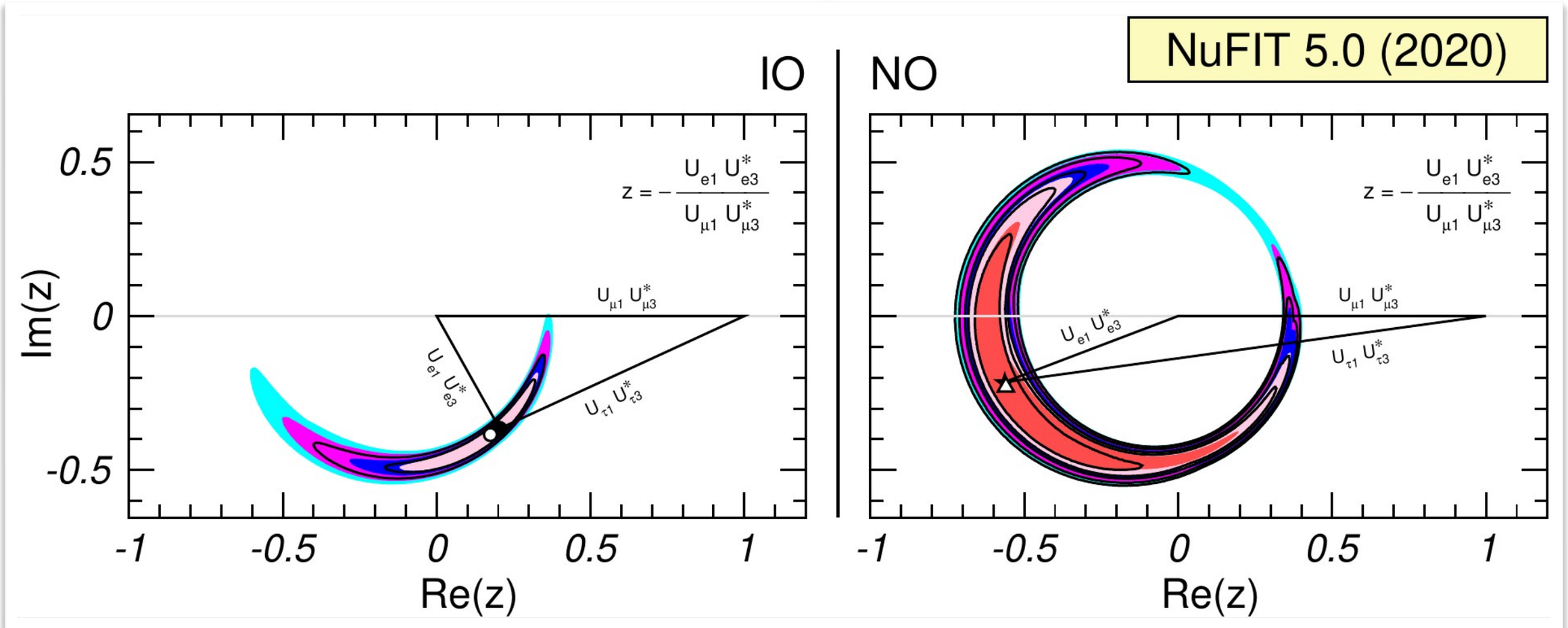


image credit: NuFit 5.0

What we Know About Neutrino Oscillations

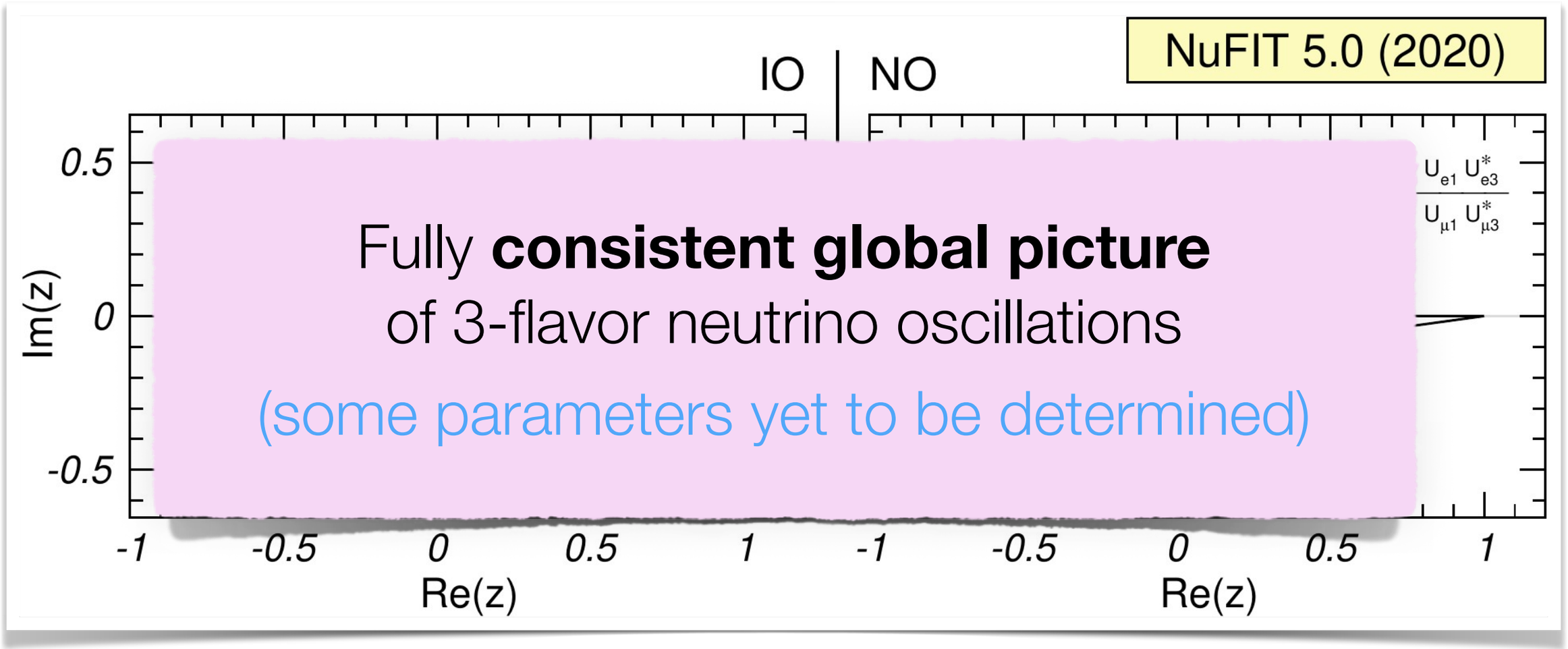


image credit: NuFit 5.0

BSM Searches

In this talk we will look for
dents in this picture

Sterile Neutrinos?

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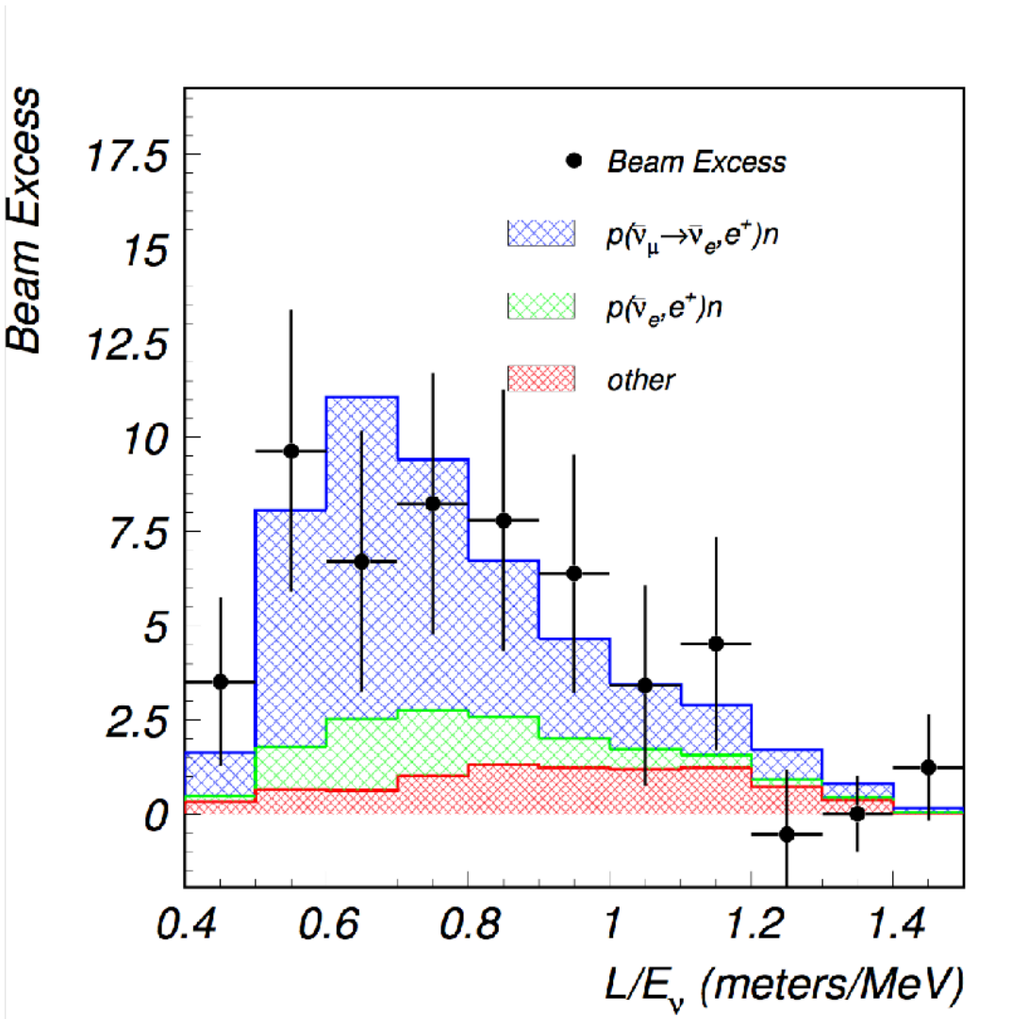
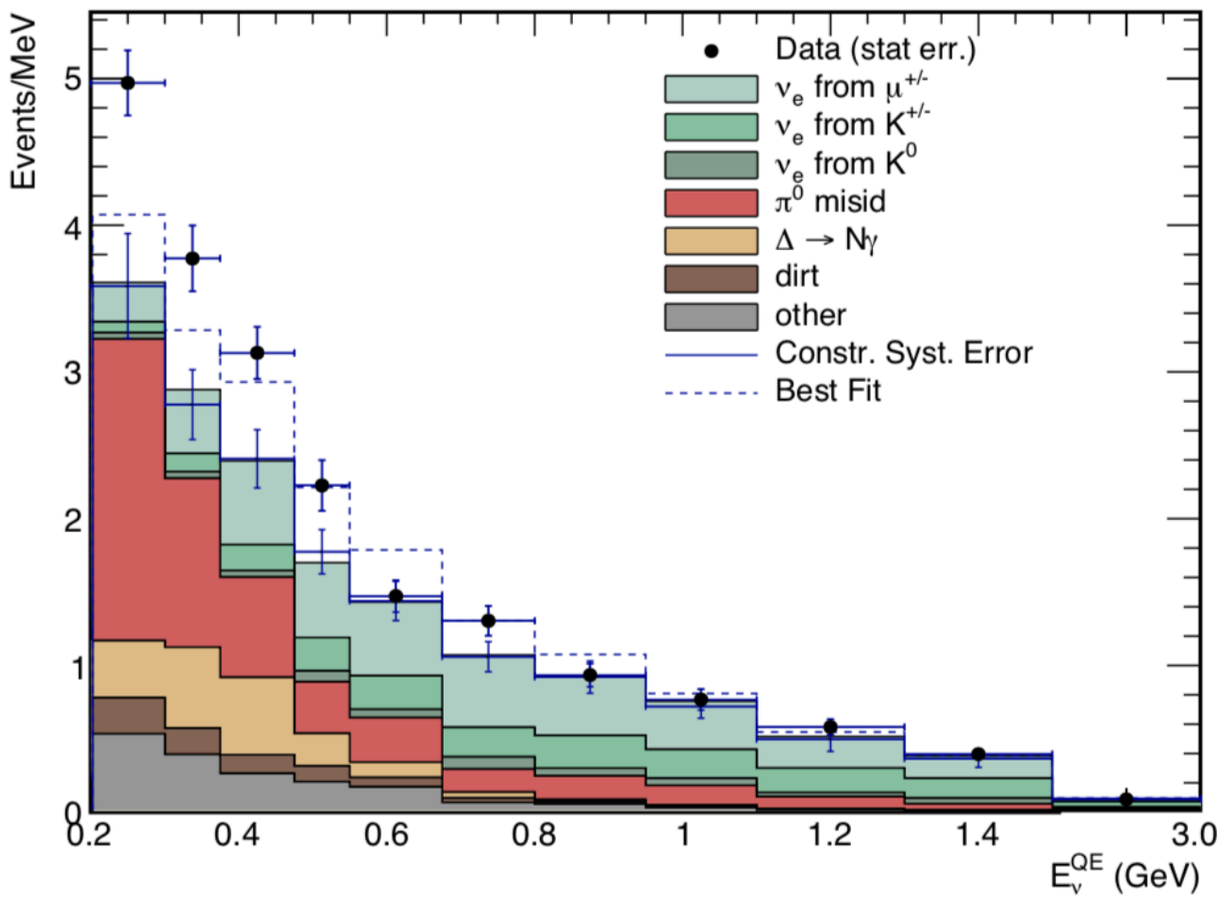
Anomalies in Short Baseline Oscillations

Anomalies in Short Baseline Oscillations

☑ LSND / MiniBooNE: anomalous $\nu_\mu \rightarrow \nu_e$ oscillations



LSND 2001

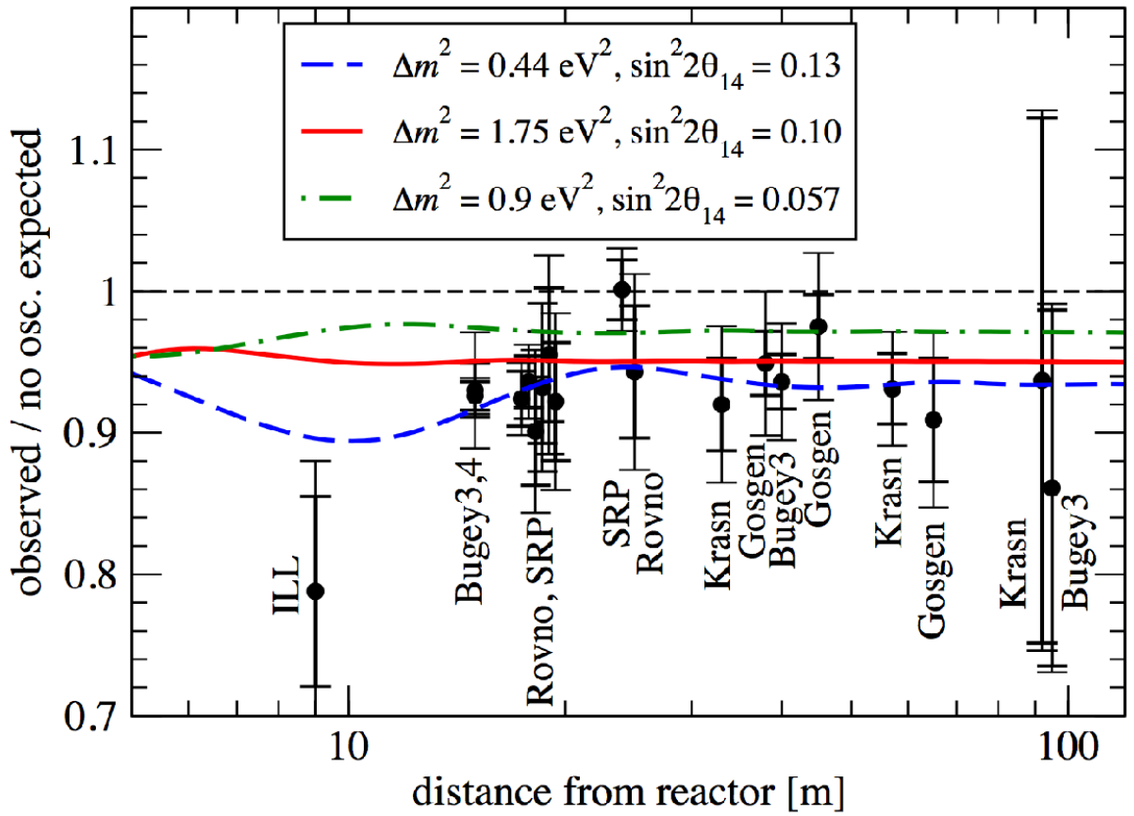


MiniBooNE 2018

Anomalies in Short Baseline Oscillations

☑ LSND / MiniBooNE: anomalous $\nu_\mu \to \nu_e$ oscillations

☑ Reactor & Gallium Experiments:
anomalous ν_e disappearance



Mention et al., 1101.2755

Anomalies in Short Baseline Oscillations

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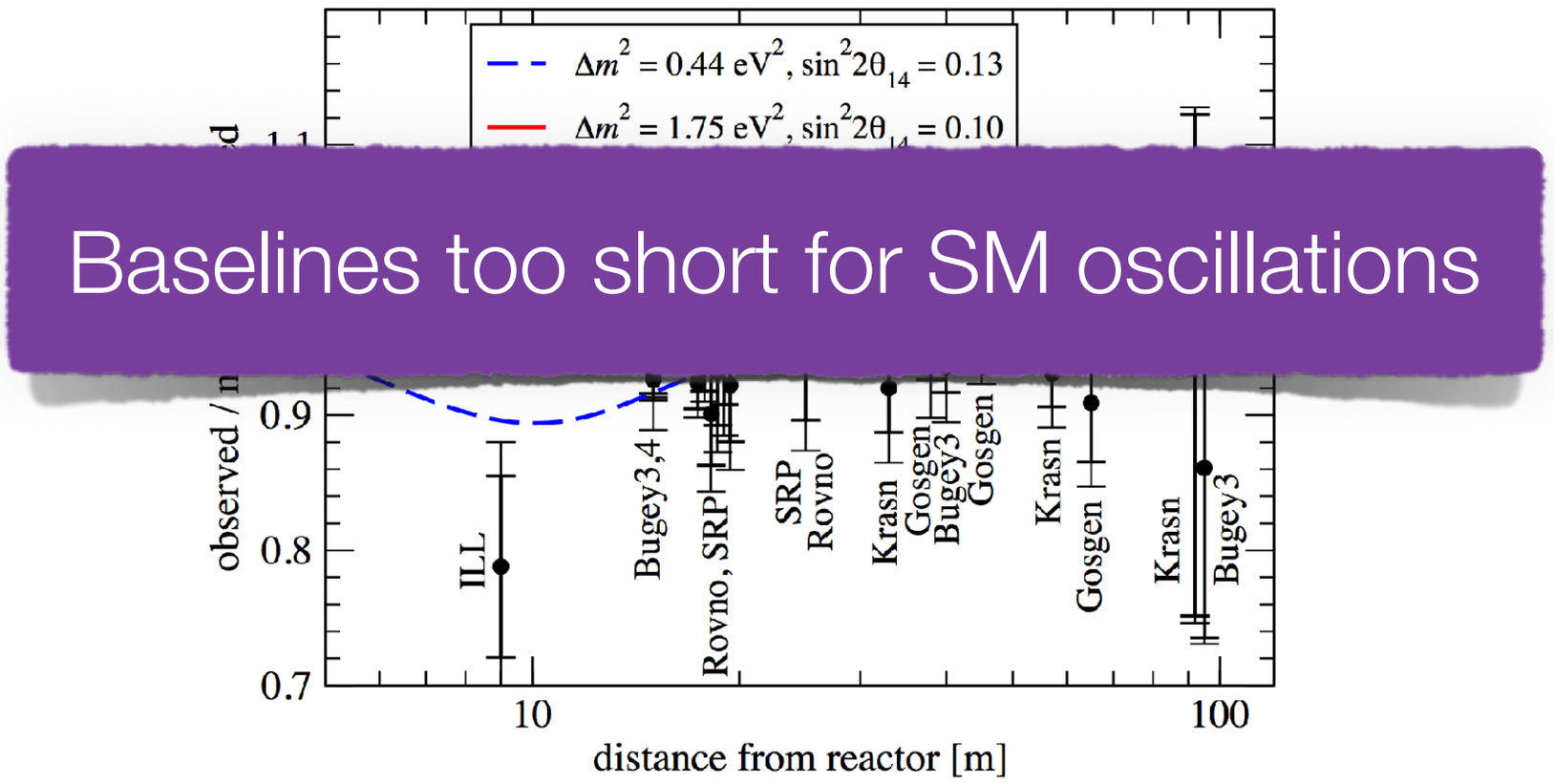


Baselines too short for SM oscillations

Mention et al., 1101.2755

Light Sterile Neutrinos?

☑ Add extra neutrino flavor, promote mixing matrix to 4×4

☑ Oscillation channels are related:

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

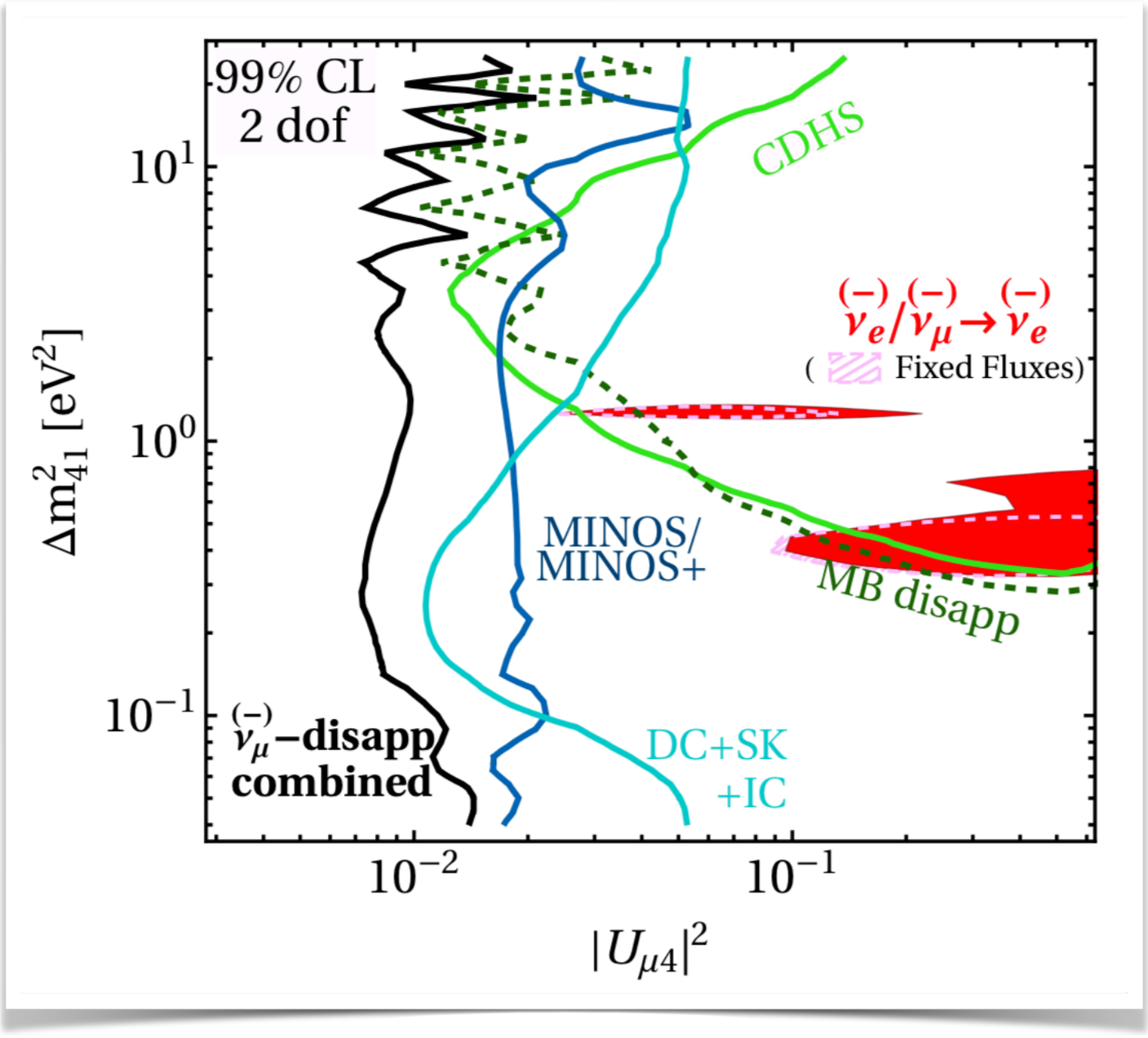
$$P_{\nu_\mu \to \nu_\mu} \simeq 1 - 2|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2)$$

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

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

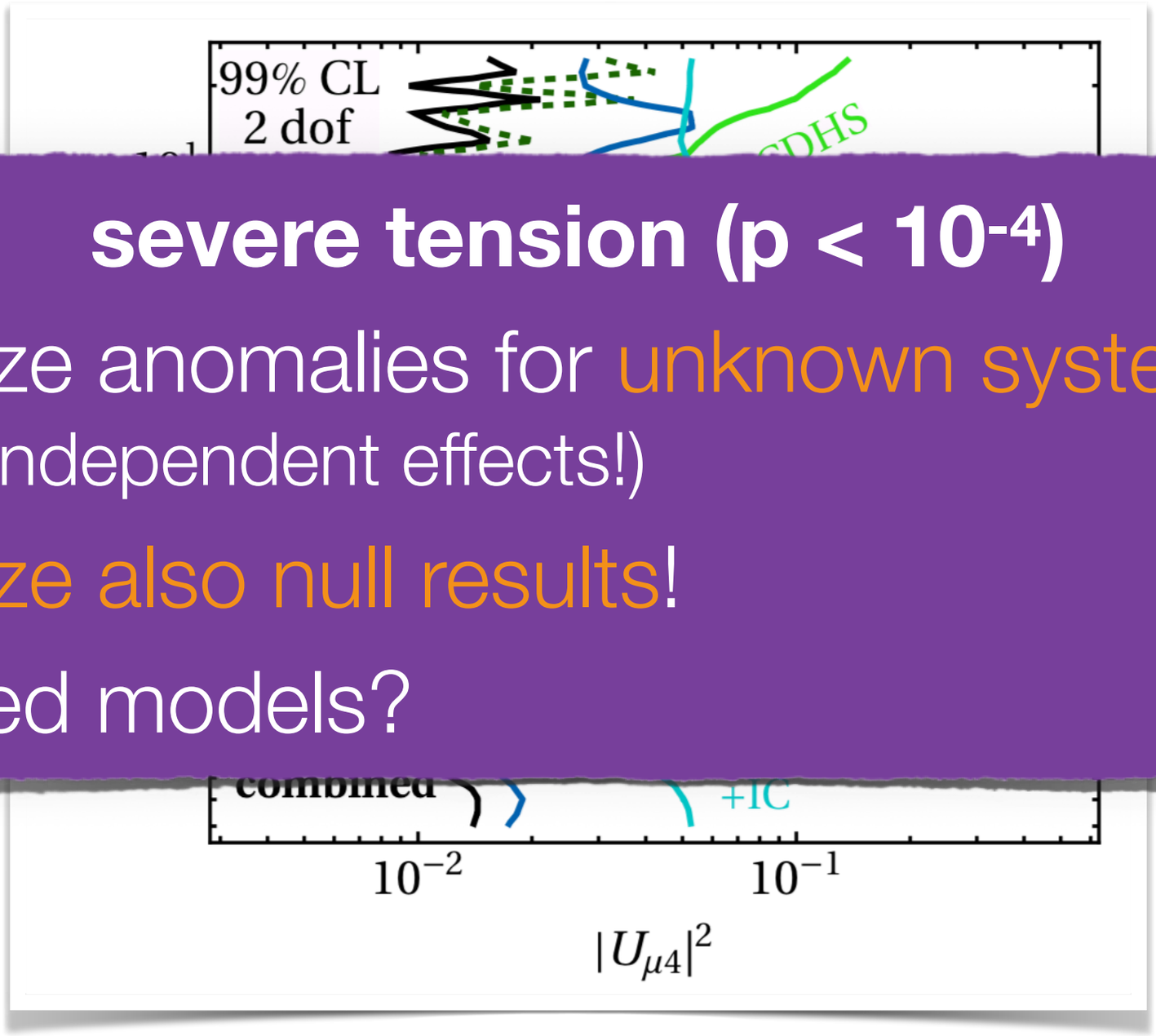
☑ Models can be over-constrained.

Global Fit in 3+1 Model



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

Global Fit in 3+1 Model



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

- ★ scrutinize anomalies for unknown systematics (need 4 independent effects!)
- ★ scrutinize also null results!
- ★ extended models?

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Extended Sterile Neutrino Models

☑ Sterile Neutrino production in the target, followed by $\nu_s \rightarrow \nu + \gamma$ decay in the detector
(MiniBooNE cannot distinguish $e^{\pm}$ and γ)

Fischer Hernández-Cabezudo Schwetz, 1909.09561

☑ Sterile Neutrino production in the detector, followed by $\nu_s \rightarrow \nu + \gamma$ decay

Gninenko, 1009.5536

☑ Sterile Neutrino production in the detector, followed by $\nu_s \rightarrow \nu + (A' \rightarrow e^+e^-)$ decay (on-shell or off-shell)

Bertuzzo Jana Machado Zukanovich-Funchal, 1807.09877
Ballett Pascoli Ross-Lonergan, 1808.02915

☑ Sterile Neutrino production in the target, followed by $\nu_s \rightarrow \nu_{e,\mu,\tau} + \varphi$ decay in flight

Dentler Esteban JK Machado, 1911.01427

Extended Sterile Neutrino Models

difficulty reproducing
angular distribution
of MiniBooNE events

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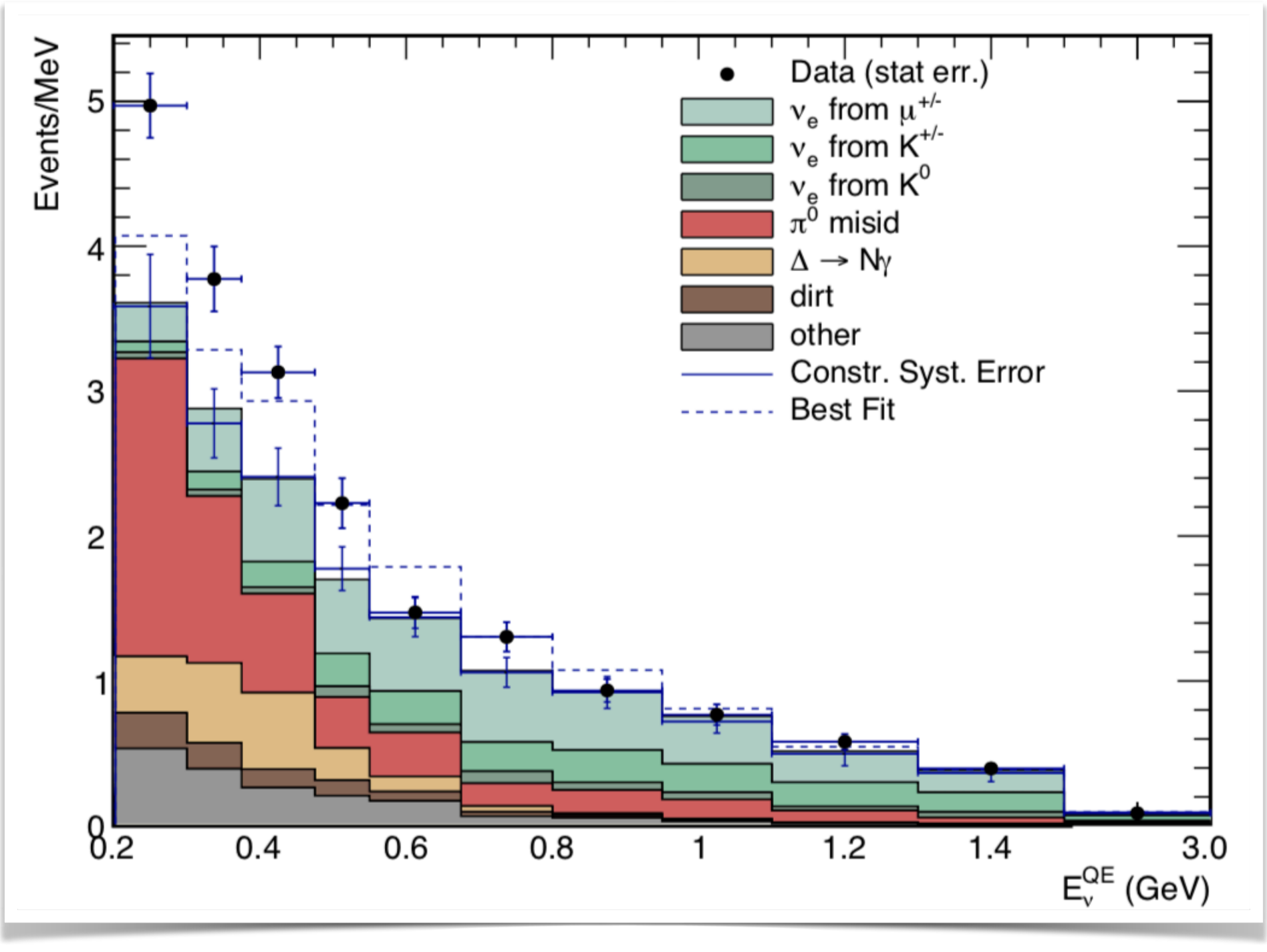
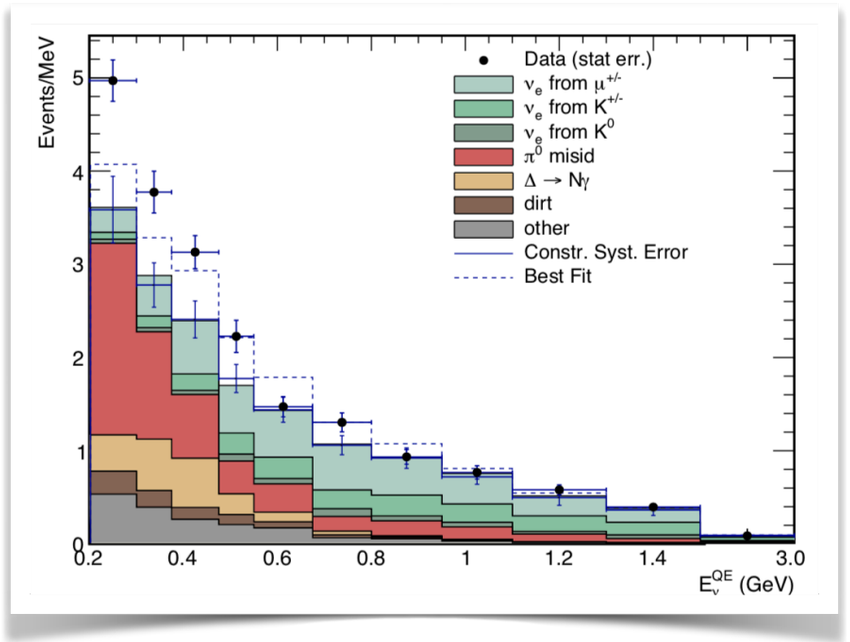
MiniBooNE Backgrounds



MiniBooNE 2018

$\Delta \rightarrow \gamma N$

- ☑ Neutral current neutrino interaction:
  $\nu + N \rightarrow \nu + \Delta(1232)$
- ☑ $\Delta(1232)$ mostly decays to $\pi + N$
- ☑ But a rare decay exists to $\gamma + N$
- ☑ MiniBooNE cannot distinguish γ from e^-



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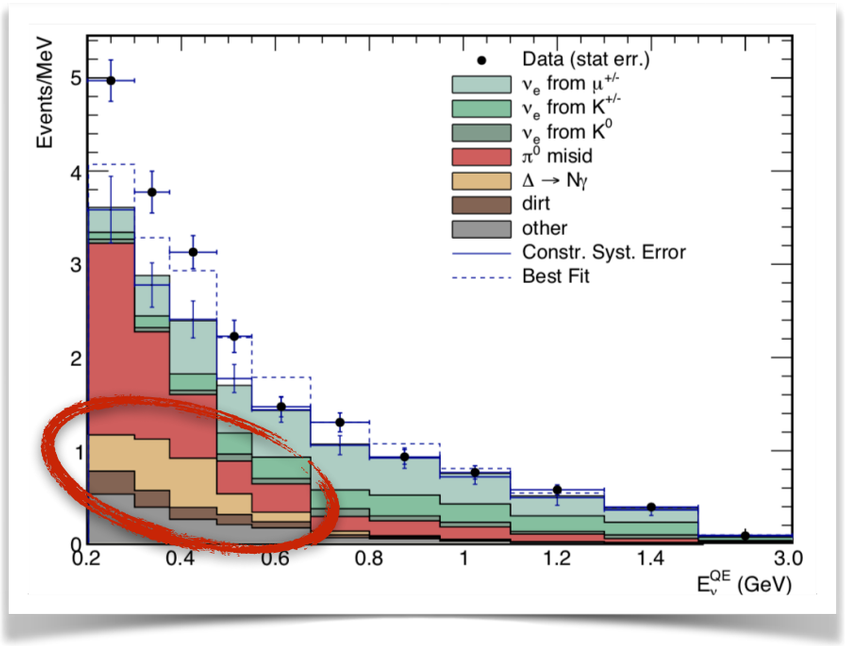
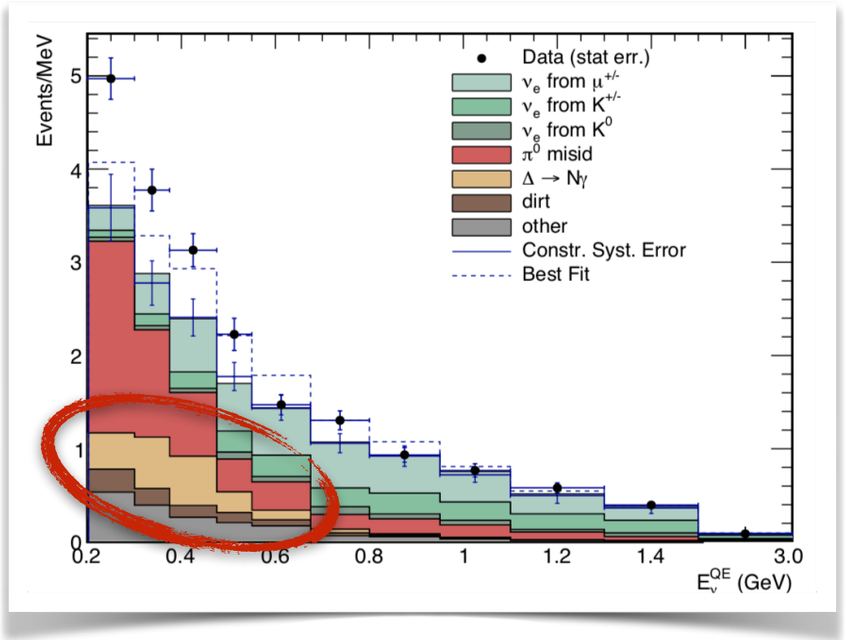


$\Delta \rightarrow \gamma N$

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

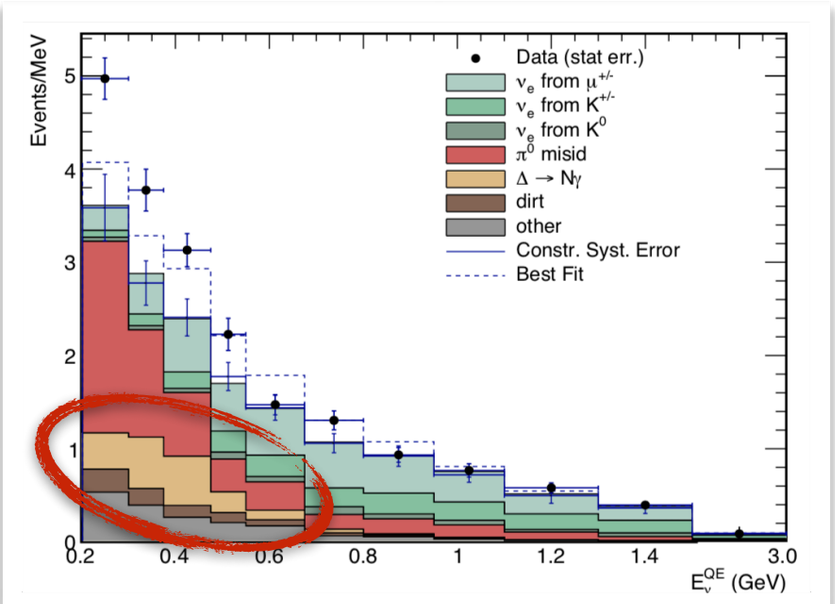


Ioannisian 1909.08571
Giunti Ioannisian Ranucci 1912.01524

☑ These effects have been modelled and have been taken into account by MiniBooNE

$\Delta \rightarrow \gamma N$

- ☑ Uncertainty in BR($\Delta \rightarrow \gamma N$)
  - PDG: 0.55–0.65%
  - no measurements
- ☑ Even larger uncertainties for heavier resonances
- ☑ How reliable is the background estimate?



$\Delta \rightarrow \gamma N$

No successful explanation
for the anomaly exists

But **theory uncertainties** are
large and difficult to quantity

New Neutrino Interactions

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Weak Effective Field Theory

Coloma Esteban Gonzalez-Garcia Maltoni arXiv:1911.09109
Biggio Blennow Fernandez-Martinez arXiv:0907.0097

Weak Effective Field Theory

☑ EFT valid below the electroweak scale

$$\mathcal{L}_{\text{NSI,NC}} = \sum_{f,\alpha,\beta} 2\sqrt{2} G_F \varepsilon^{f,P}_{\alpha\beta} (\bar{\nu}_\alpha \gamma_\mu P_L \nu_\beta)(\bar{f} \gamma^\mu P f) + \text{h.c.}$$

$$\mathcal{L}_{\text{NSI,CC}} = \sum_{f,f',\alpha,\beta} 2\sqrt{2} G_F \varepsilon^{f f',P}_{\alpha\beta} (\bar{\nu}_\alpha \gamma_\mu P_L \ell_\beta)(\bar{f}' \gamma^\mu P f) + \text{h.c.}$$

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dim-6 operators

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dimensionless coefficients

(strength of new interactions
relative to SM weak interactions)

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☑ NC: non-standard matter effects

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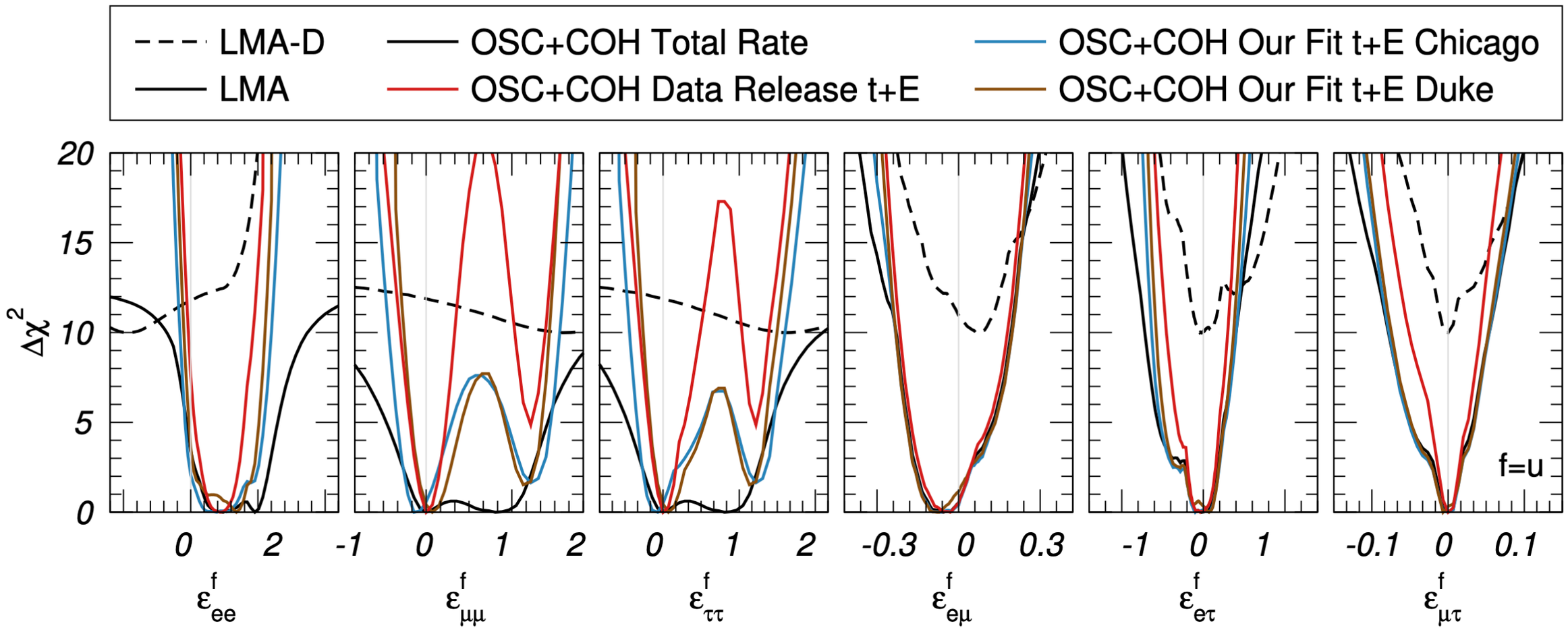
☑ NC: non-standard matter effects

☑ CC: anomalous production and detection

Coloma Esteban Gonzalez-Garcia Maltoni arXiv:1911.09109
Biggio Blennow Fernandez-Martinez arXiv:0907.0097

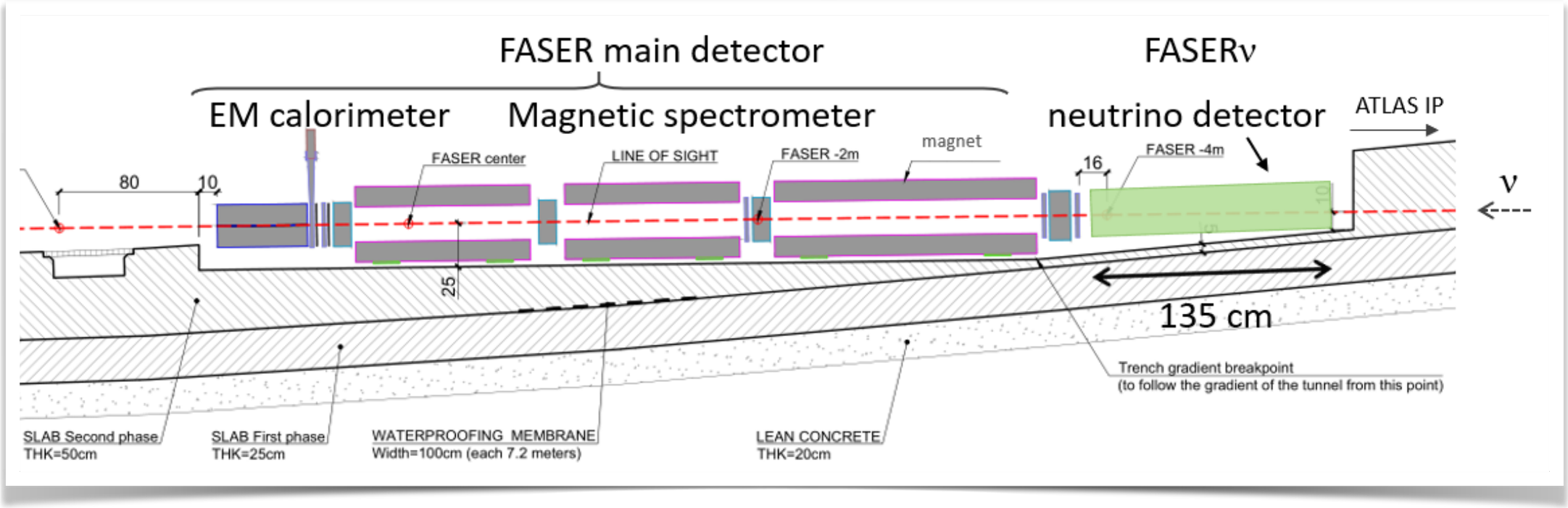
Anomalous Neutral Currents



Coloma Esteban Gonzalez-Garcia Maltoni arXiv:1911.09109

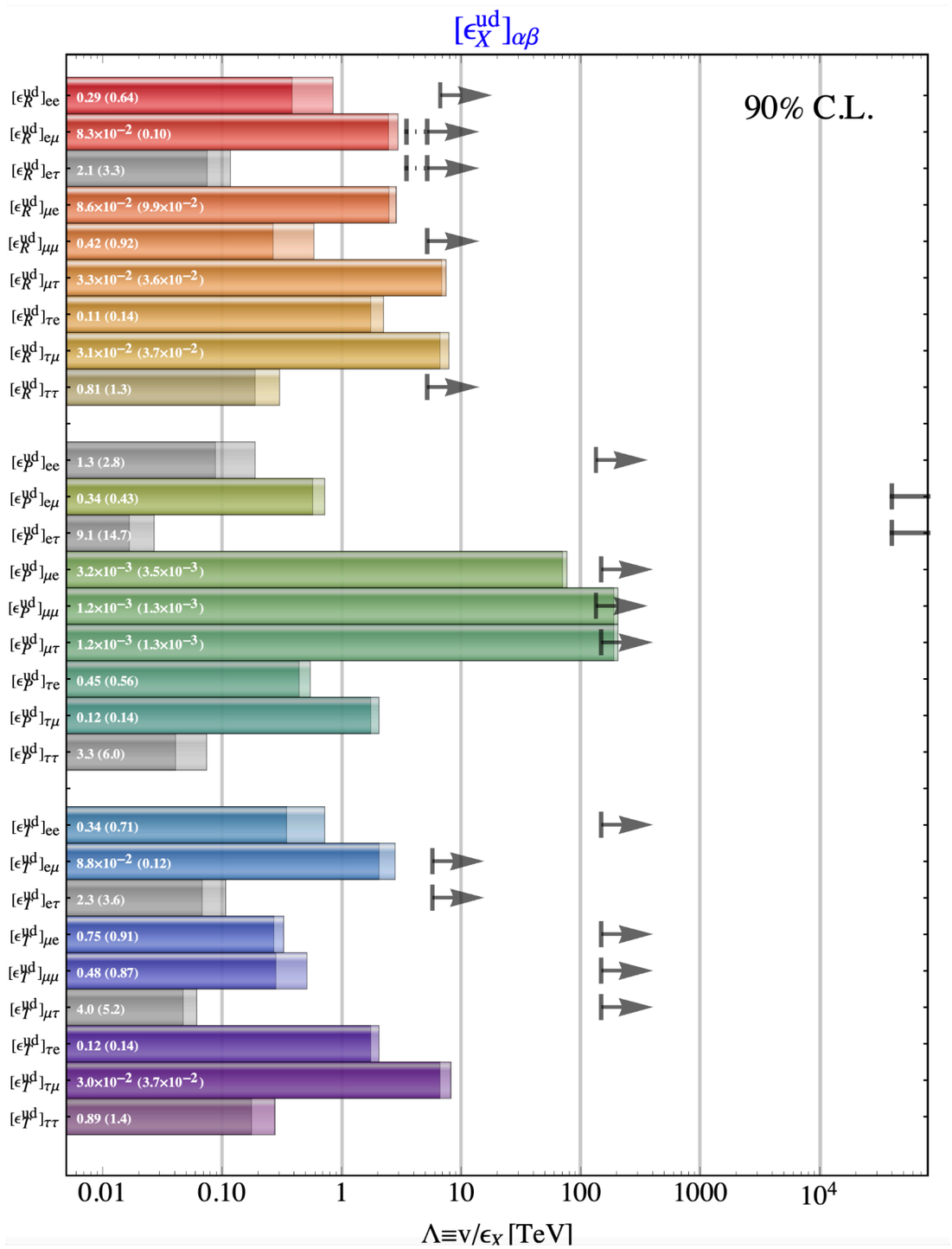
Anomalous Charged Currents

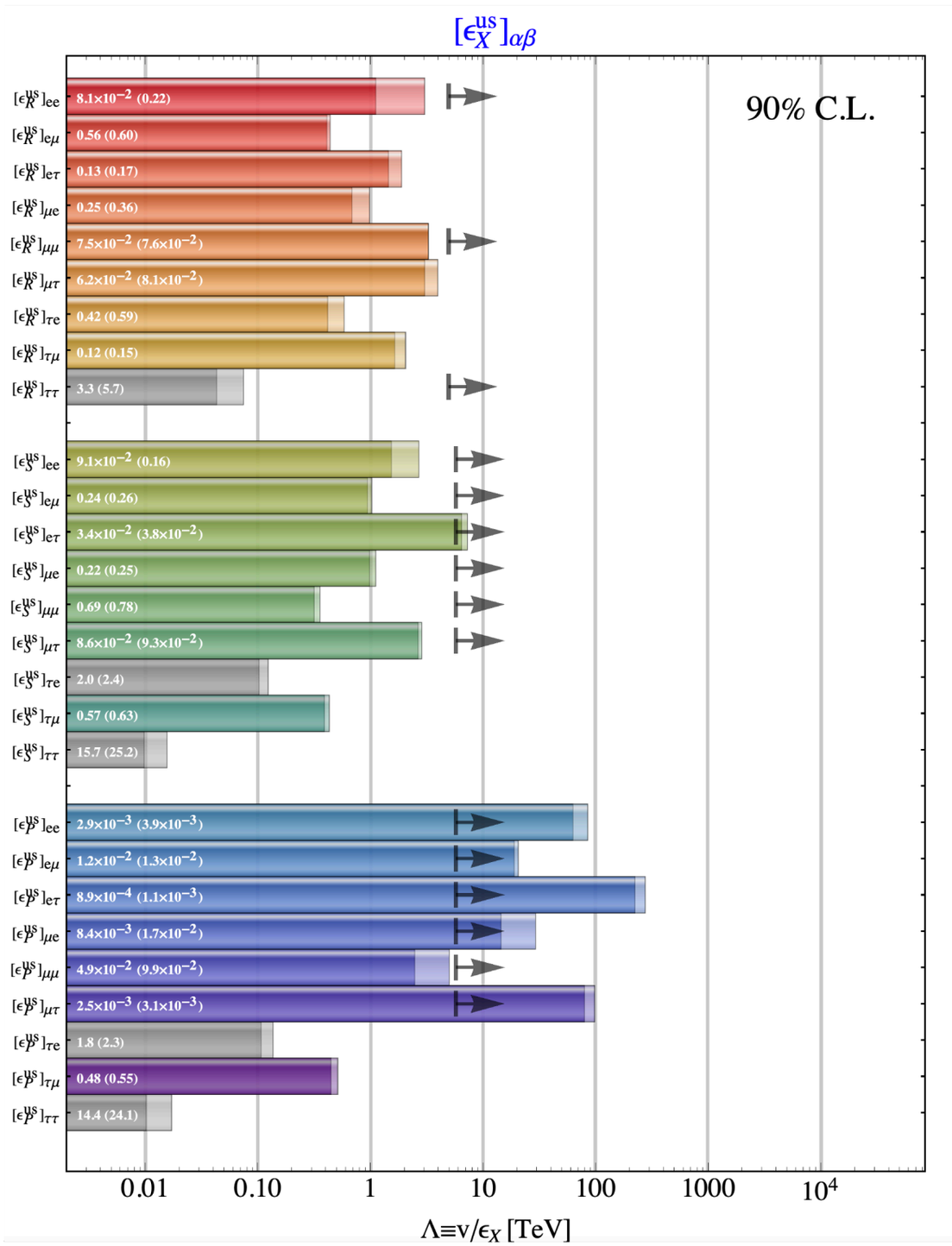
☑ Interesting new opportunity: FASERν at the LHC



https://faser.web.cern.ch/about-the-experiment/detector-design/fasernu

Anomalous Charged Currents





Falkowski Gonzalez-Alonso
JK Soreq Tabrizi, *in preparation*

Near Detectors

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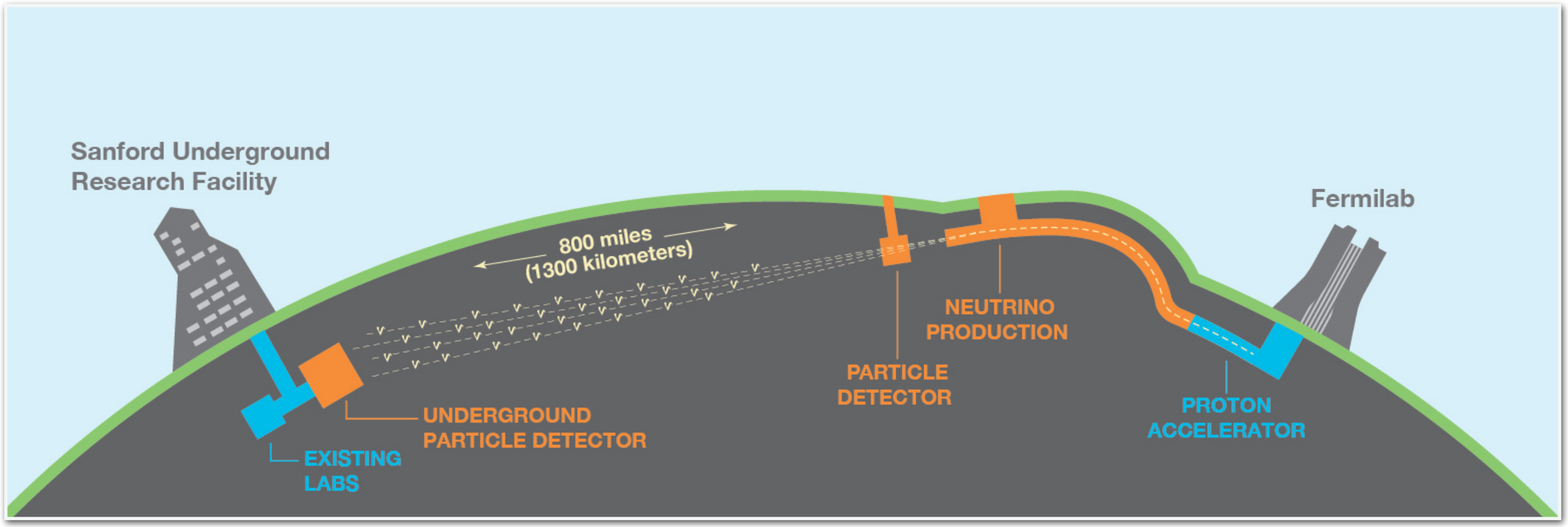
The Need for Near Detectors

- ☑ Large systematic uncertainties in
  - Composition of neutrino beam
  - Neutrino interaction cross sections
- ☑ Dedicated detectors close to the source (“near detectors”) measure the unoscillated neutrino event rate.



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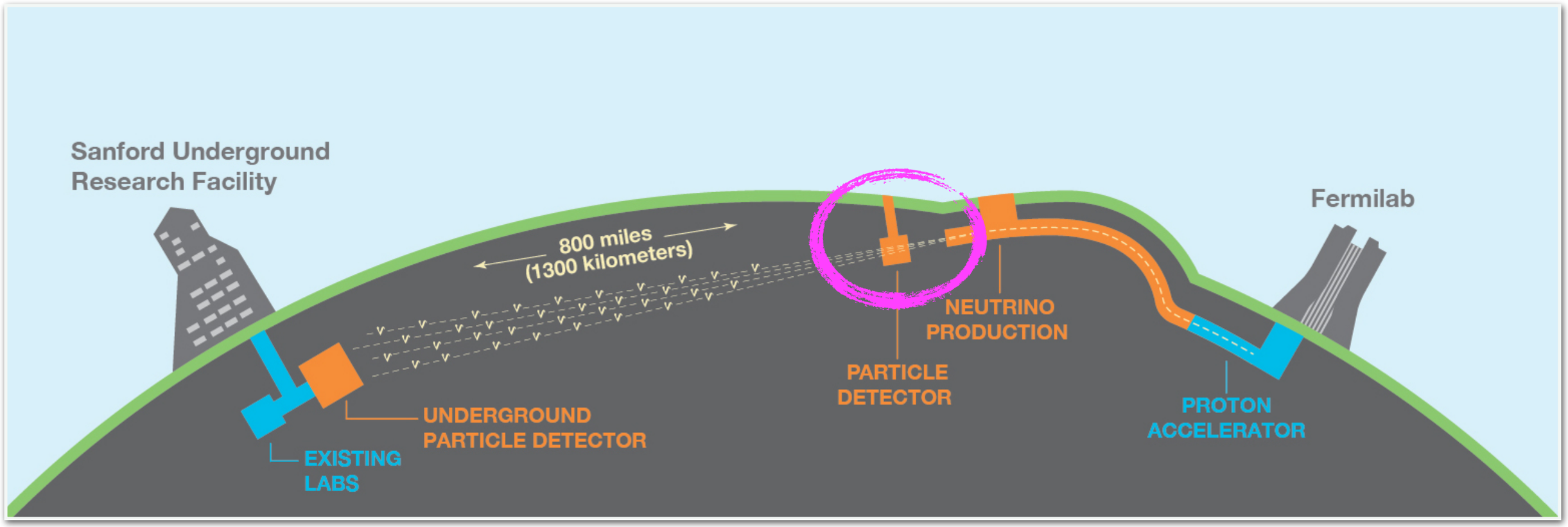
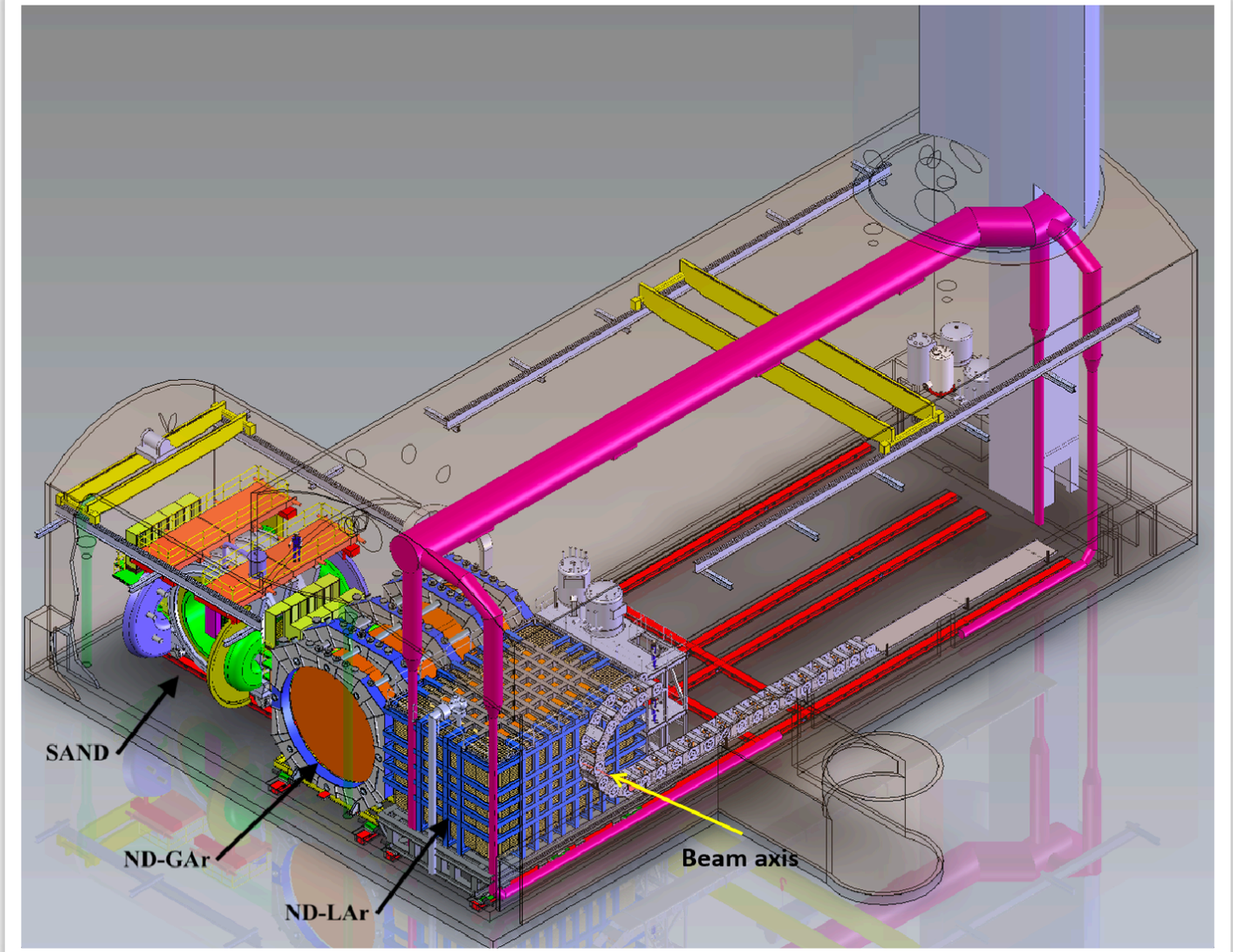


The DUNE Near Detectors



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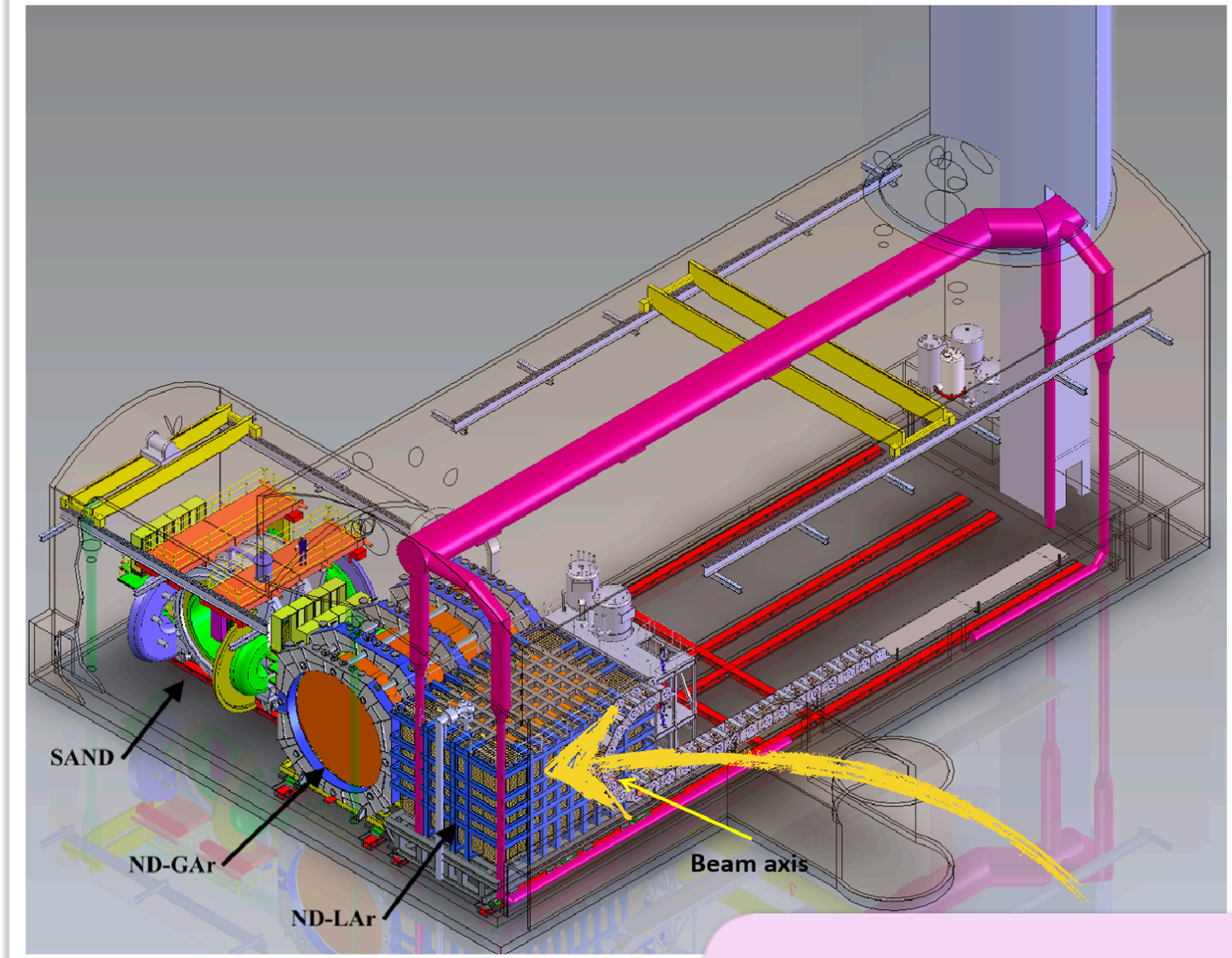
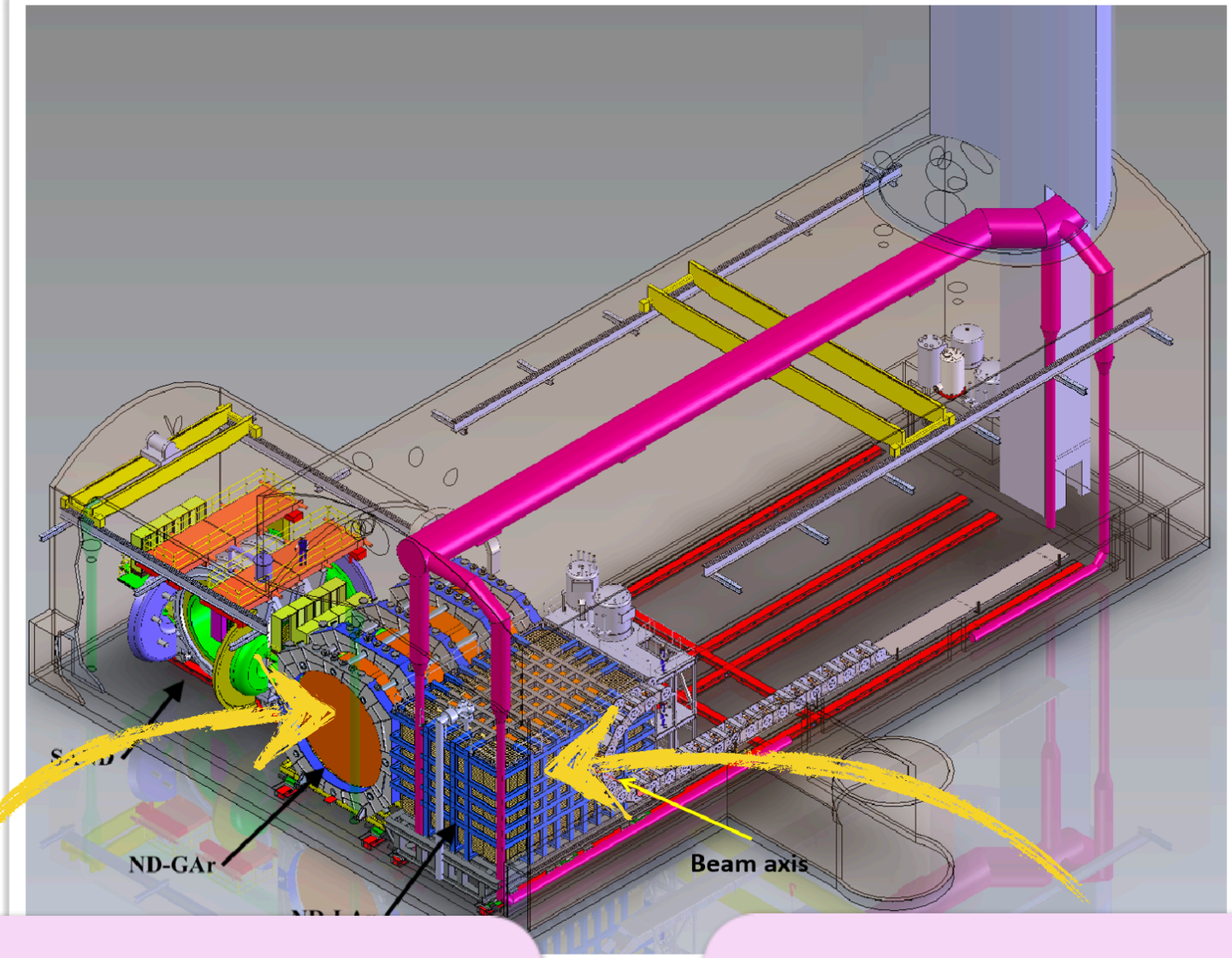


Liquid Argon TPC

- similar to far detector (cancel systematic uncertainties)

The DUNE Near Detectors



High Pressure Gas TPC + ECal

- excellent event reconstruction
- magnetic field

Liquid Argon TPC

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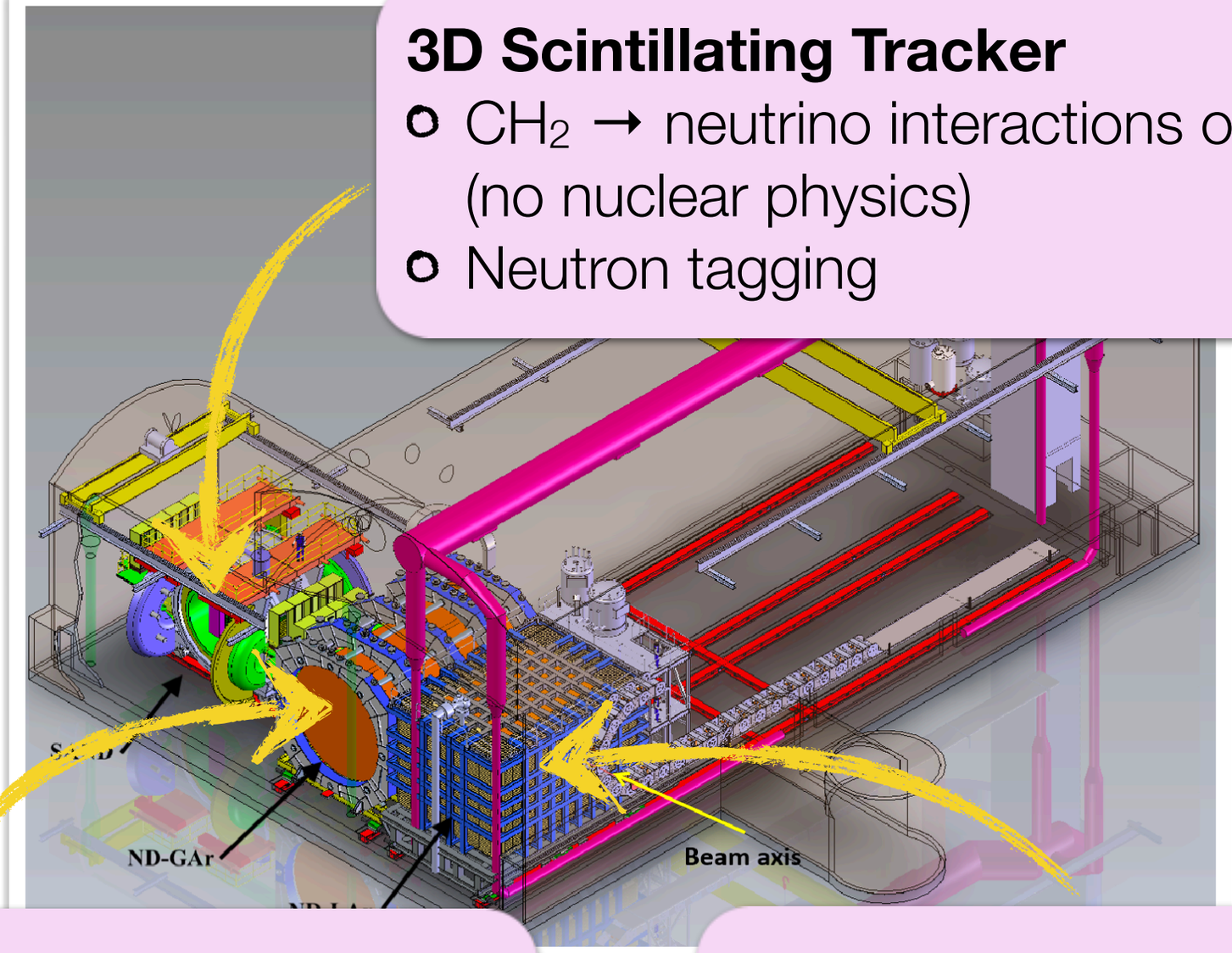
The DUNE Near Detectors



3D Scintillating Tracker

- CH_2 → neutrino interactions on free protons (no nuclear physics)
- Neutron tagging

High Pressure Gas TPC + ECal

- excellent event reconstruction
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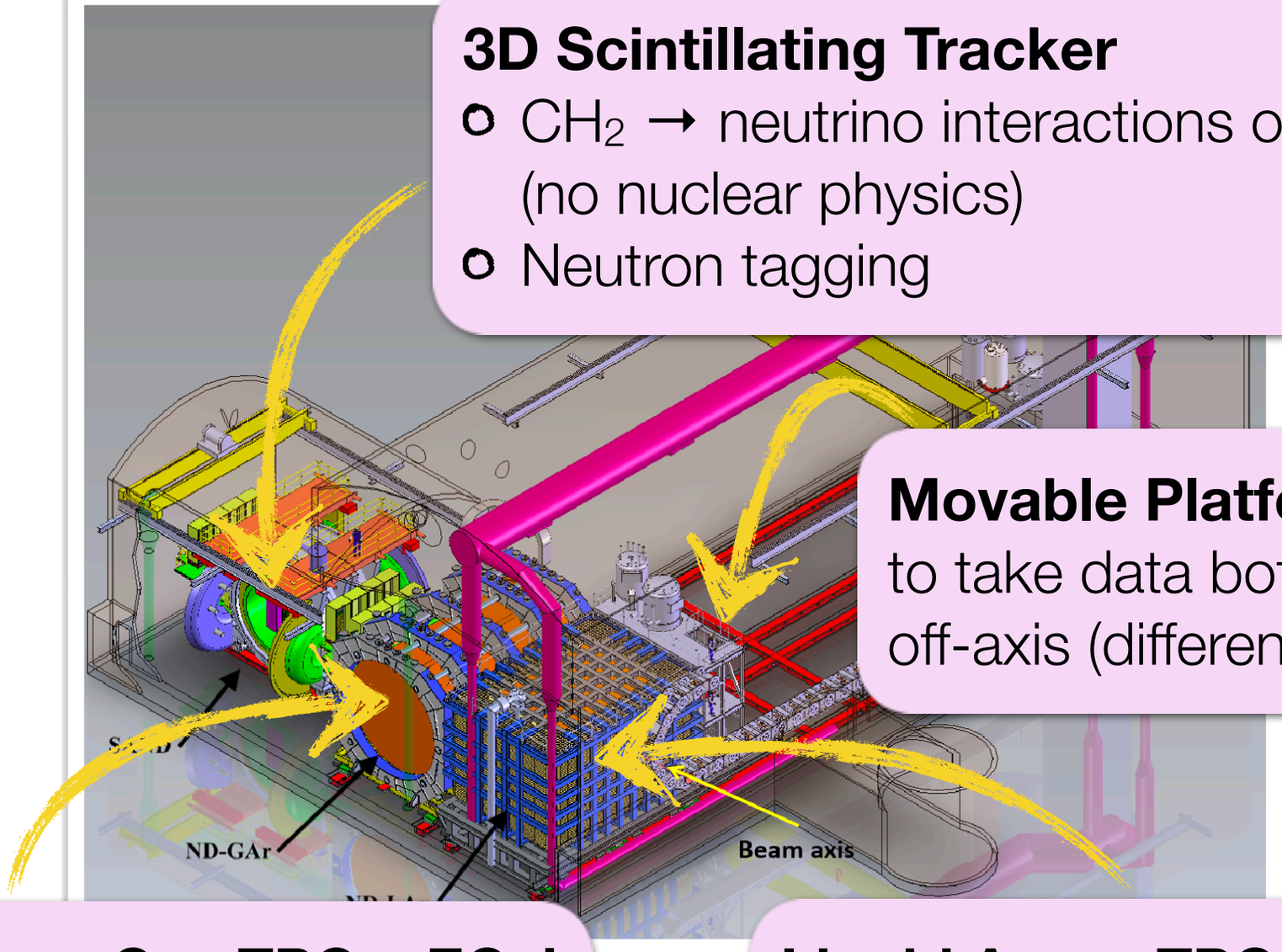

3D Scintillating Tracker

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Movable Platform

to take data both on-axis and off-axis (different beam spectra)

High Pressure Gas TPC + ECal

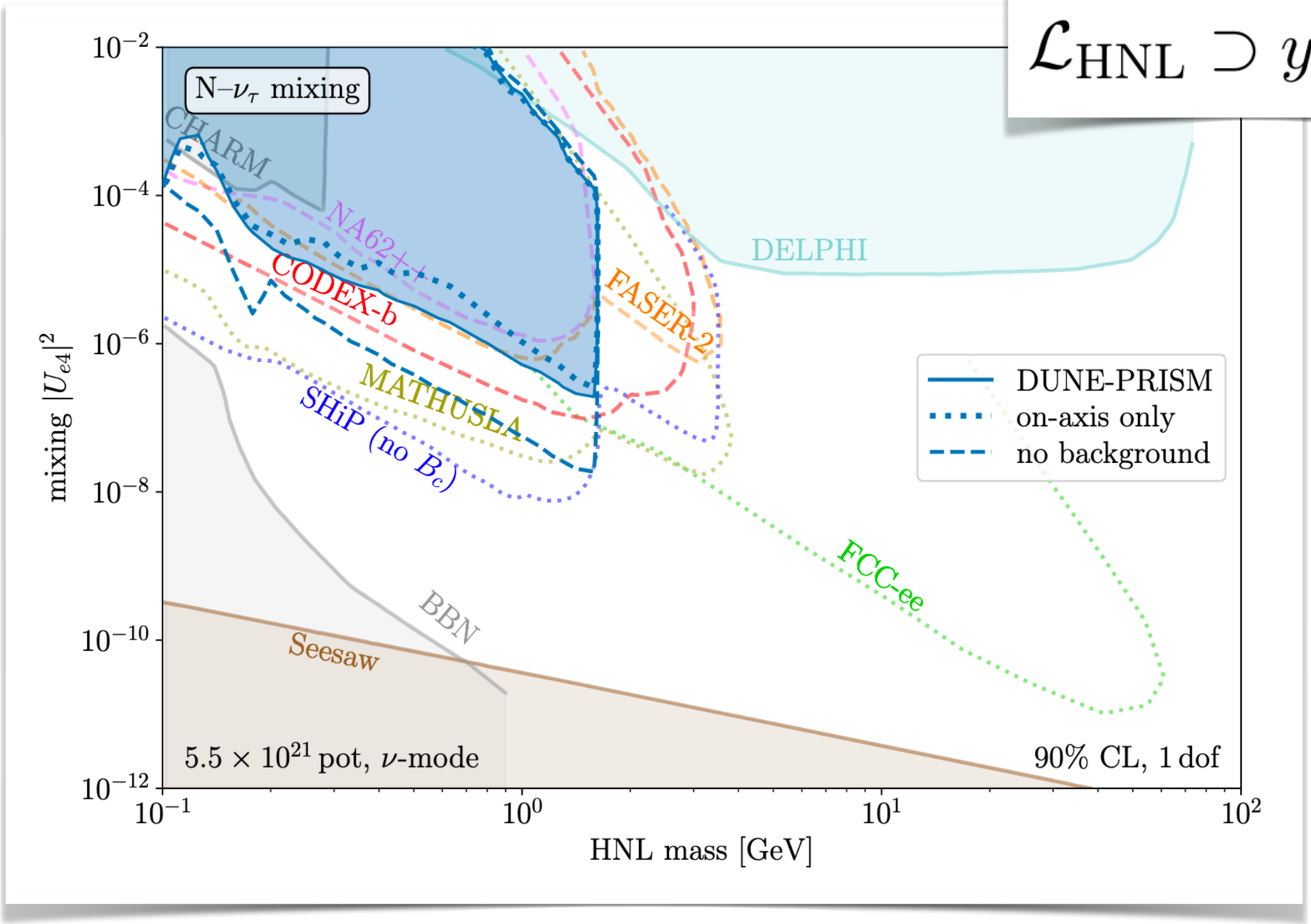
- excellent event reconstruction
- magnetic field

Liquid Argon TPC

- similar to far detector (cancel systematic uncertainties)

Example: Heavy Neutral Leptons

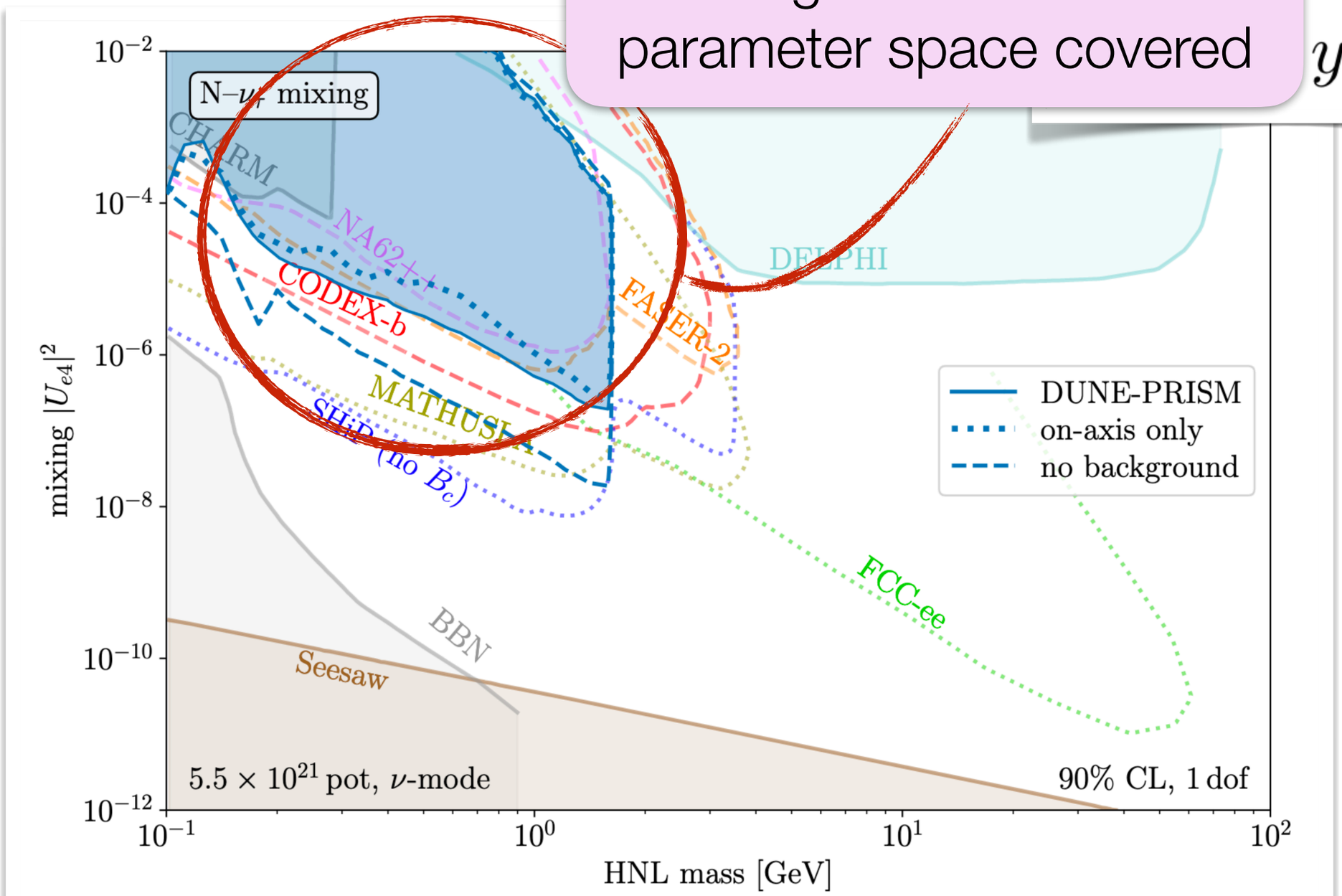
$$\mathcal{L}_{\text{HNL}} \supset y\bar{L}\tilde{H}N$$



Example: Heavy Neutral Leptons

significant new
parameter space covered

$$y\bar{L}\tilde{H}N$$



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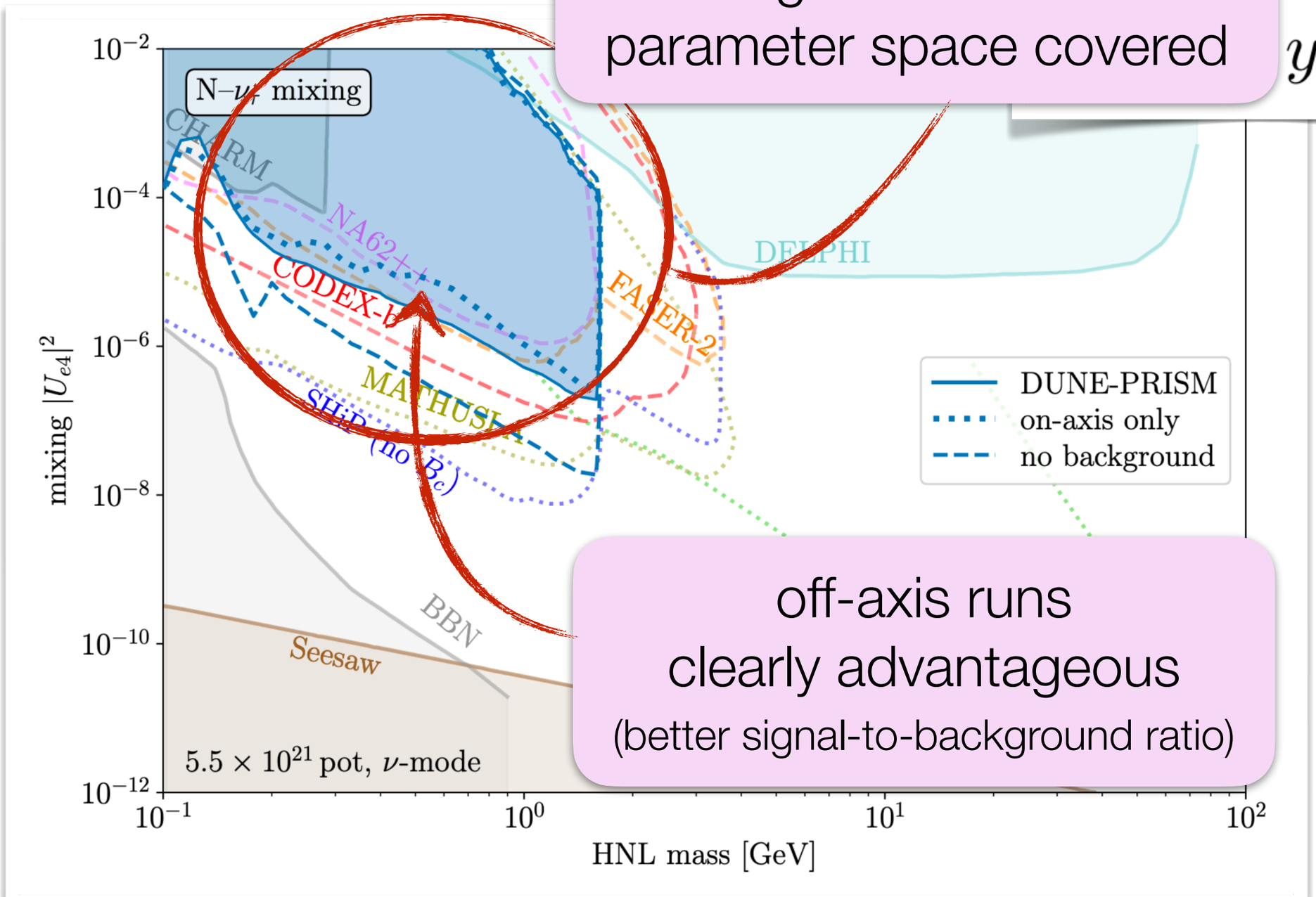


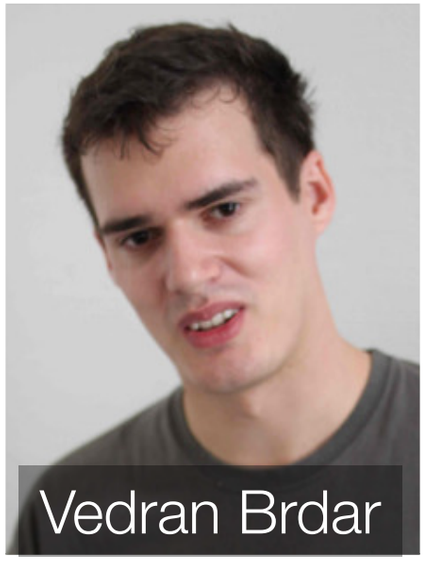
off-axis runs
clearly advantageous
(better signal-to-background ratio)

Summary

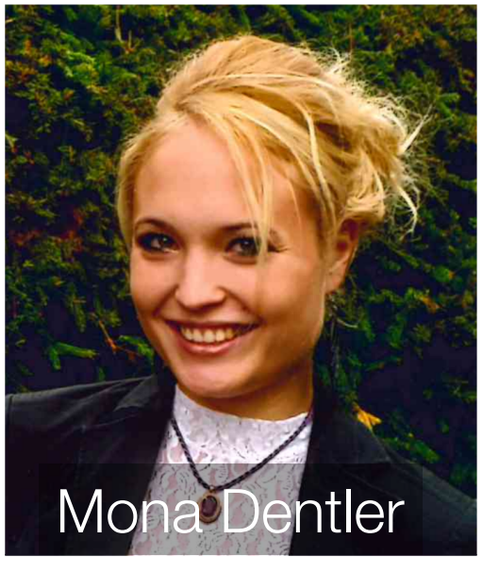
Summary

- ☑ Sterile Neutrinos:
  - interesting hints, but inconsistent with null results
  - extended models?
  - SM explanations?
- ☑ New Neutrino Interactions
  - anomalous matter effects
  - new CC interactions: opportunities with LHC neutrinos
- ☑ Near Detectors
  - parasitical “beam-dump” program
  - DUNE-PRISM: improved S/B ratio off-axis

Thank You!


Vedran Brdar

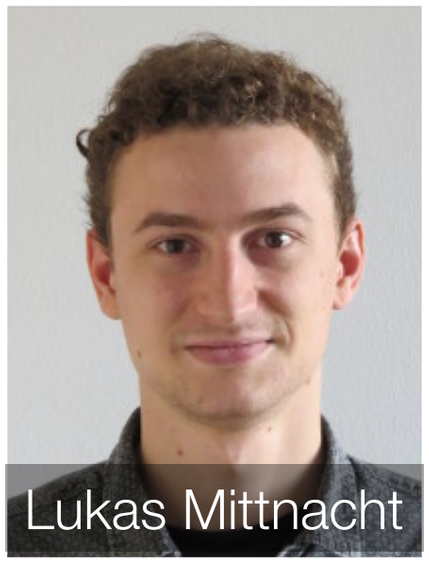

Moritz Breitbach


Mona Dentler


Ivan Esteban


Álvaro Hernández


Ivan Martinez


Lukas Mittnacht


Ninetta Saviano


Zahra Tabrizi

Bonus Slides

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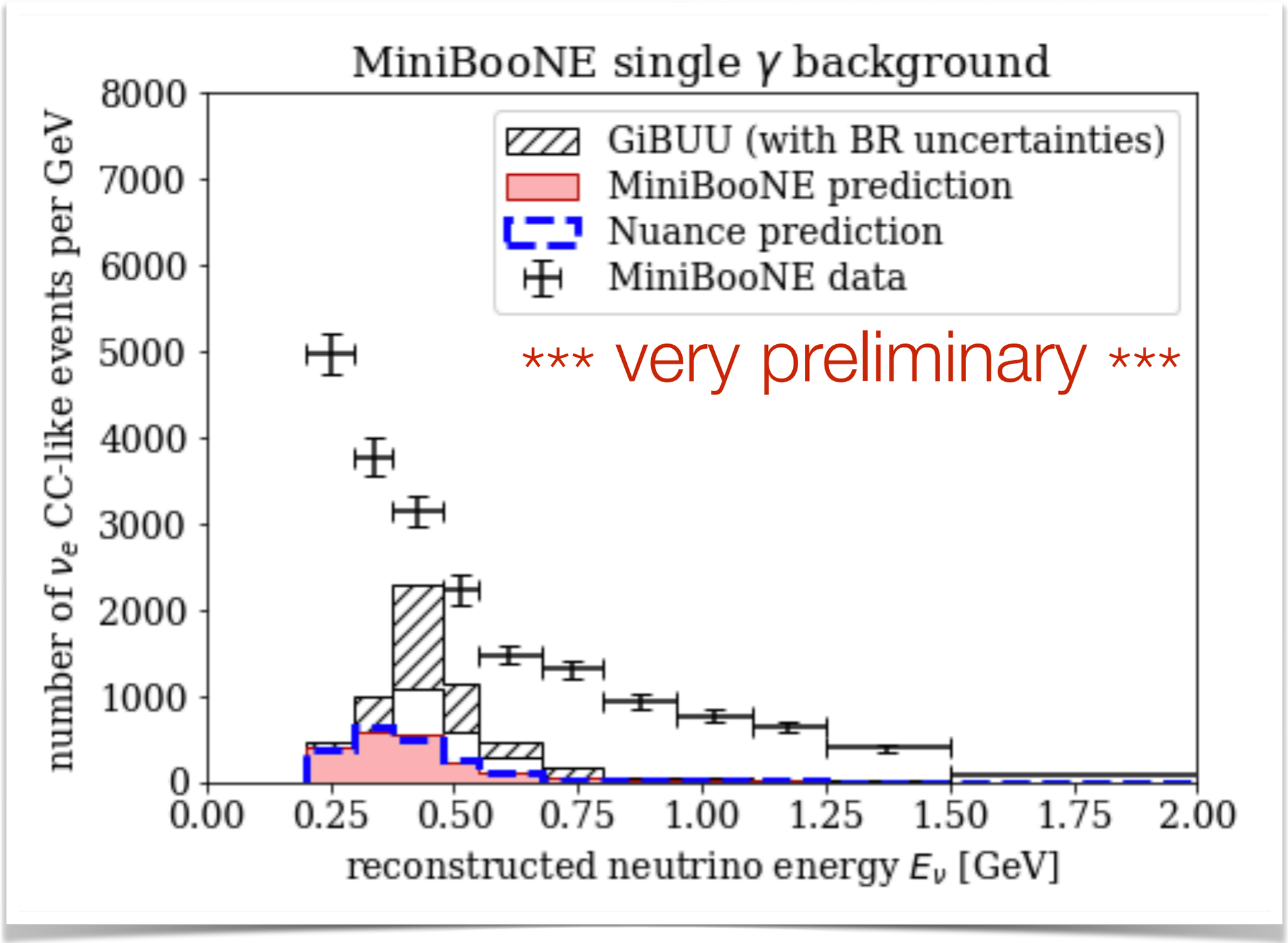
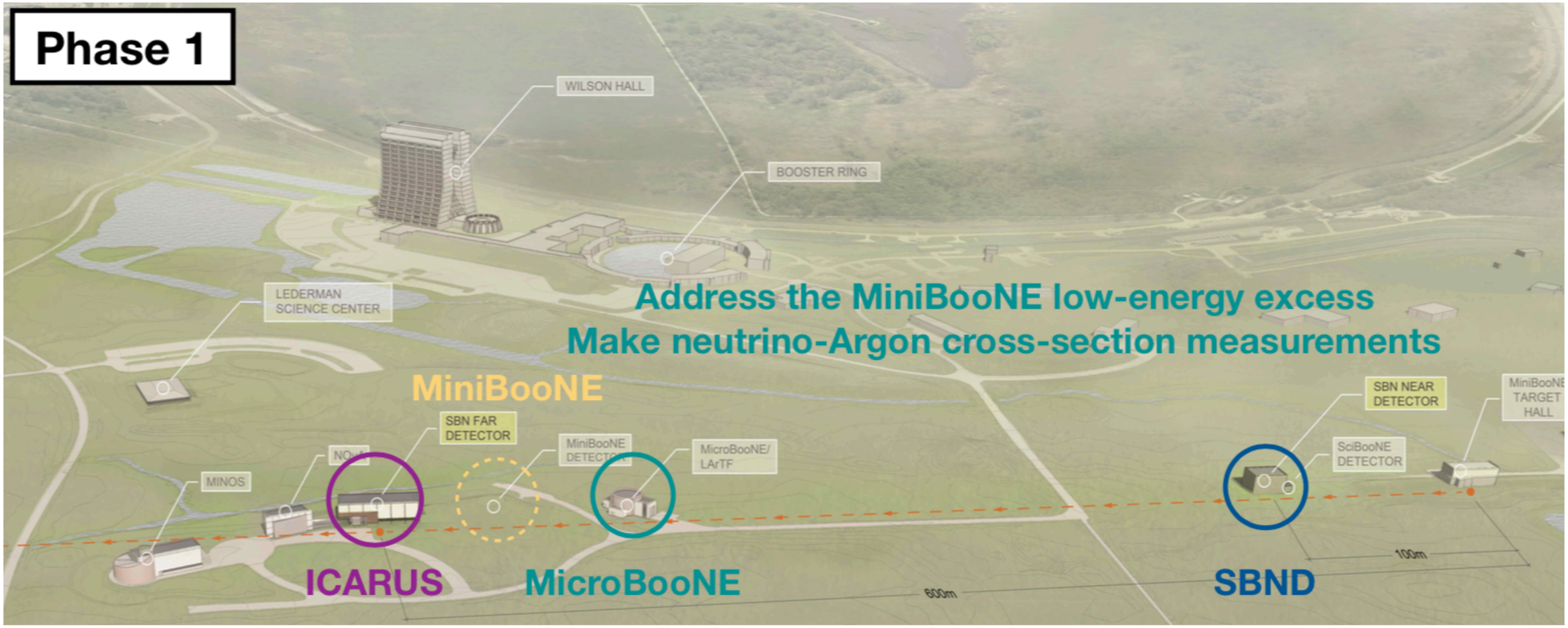
$\Delta \rightarrow \pi\gamma$



Brdar JK, *in preparation*

Testing the MiniBooNE Anomaly



- ☑ FNAL Short-Baseline Program: 3 LAr detectors
- ☑ Can distinguish γ (background) from $e^{\pm}$ (signal)

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): $\nu_s \rightarrow \nu_a + \Phi$

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

Dentler Esteban JK Machado, 1911.01427

Decaying Sterile Neutrinos?

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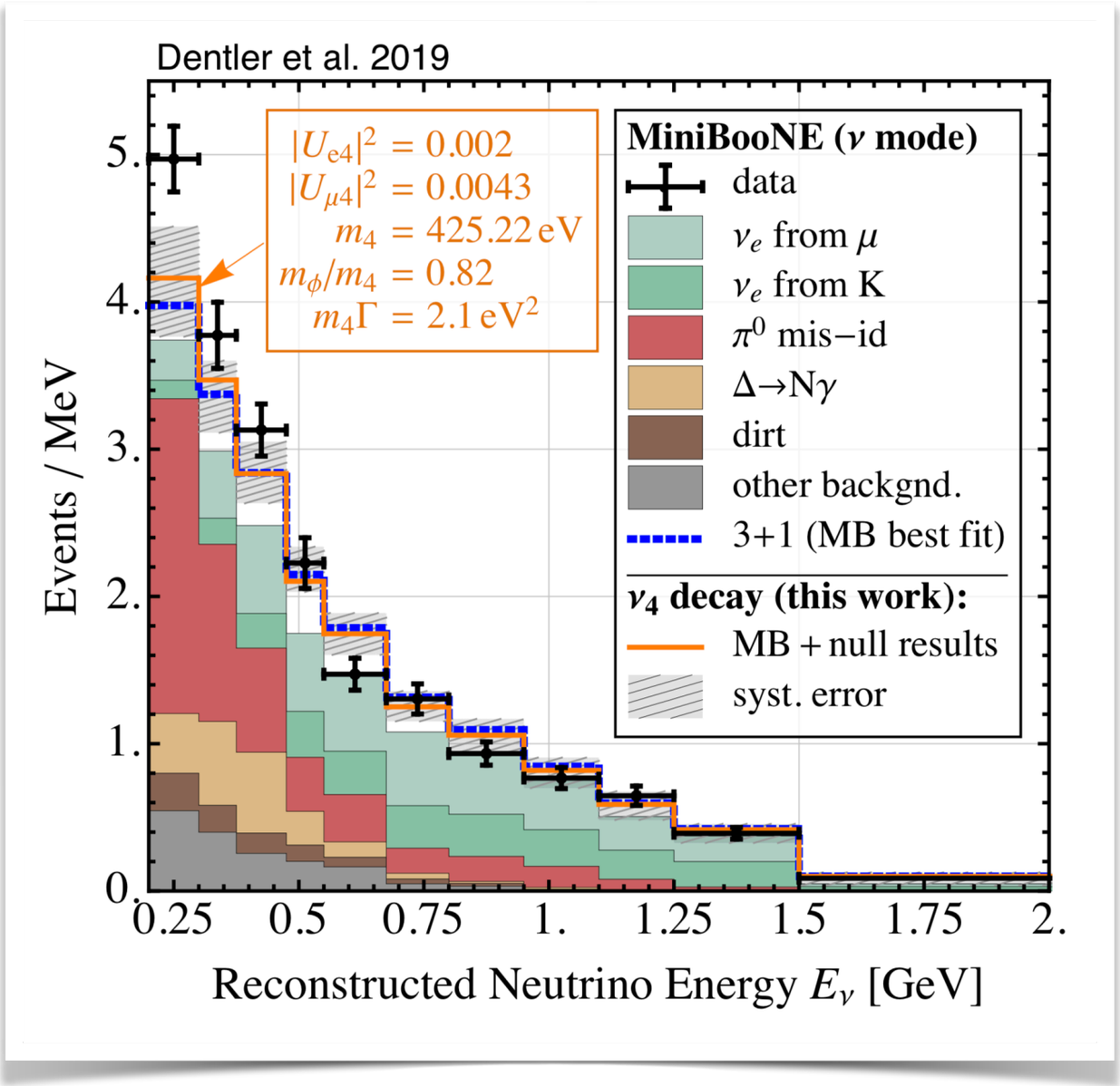
☑ Excellent fit to MiniBooNE data



Dentler Esteban JK Machado, 1911.01427

Decaying Sterile Neutrinos?

- ☑ Idea: production of sterile neutrinos that quickly decay back into active neutrinos (+ light new scalar): $\nu_s \rightarrow \nu_a + \Phi$
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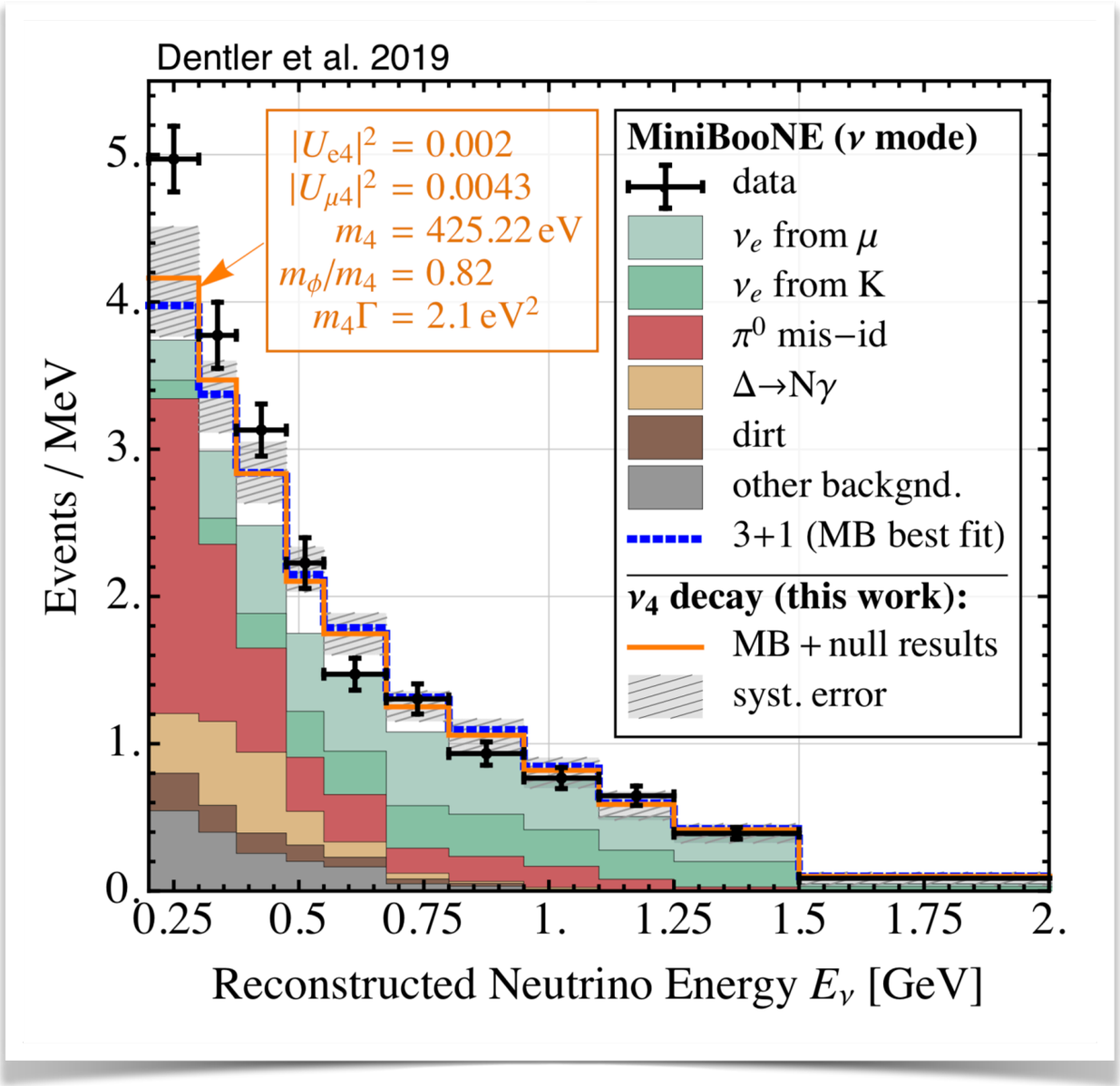
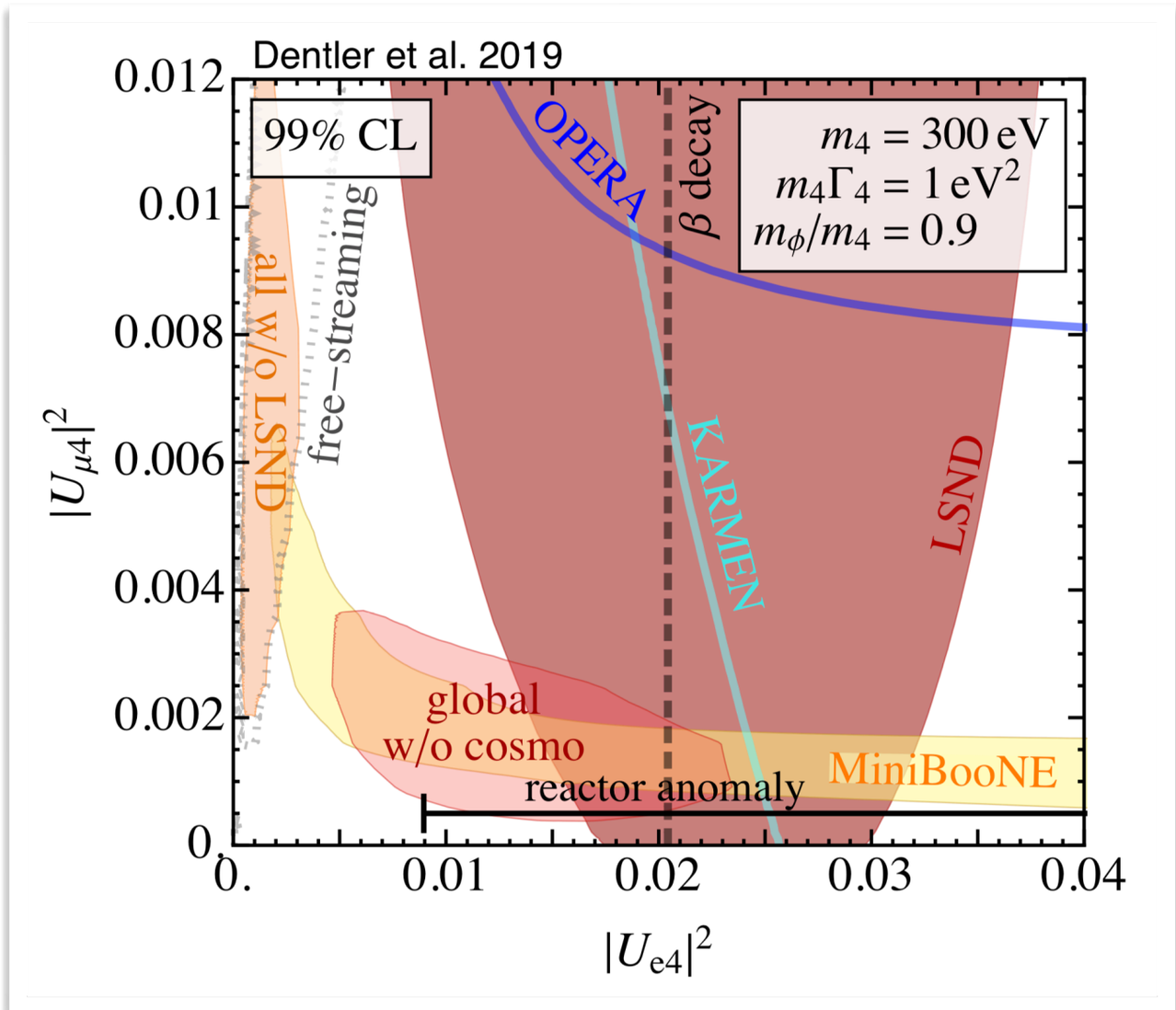
- ☑ Consistent with all null results (incl. cosmology)



Dentler Esteban JK Machado, 1911.01427

Decaying Sterile Neutrinos?

- ☑ Idea: production of sterile neutrinos that quickly decay back into active neutrinos (+ light new scalar): $\nu_s \to \nu_a + \Phi$
- ☑ Excellent fit to MiniBooNE data
- ☑ Consistent with all null results (incl. cosmology)
- ☑ with small extensions: consistent also with LSND + reactors + gallium



Dentler Esteban JK Machado, 1911.01427

More on the Reactor Anomaly

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Predicting Reactor Neutrino Fluxes

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

☑ Predicting reactor $\overline{\nu}_e$ fluxes:

- Use measured β spectra from ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu fission
- Convert to $\overline{\nu}_e$ 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

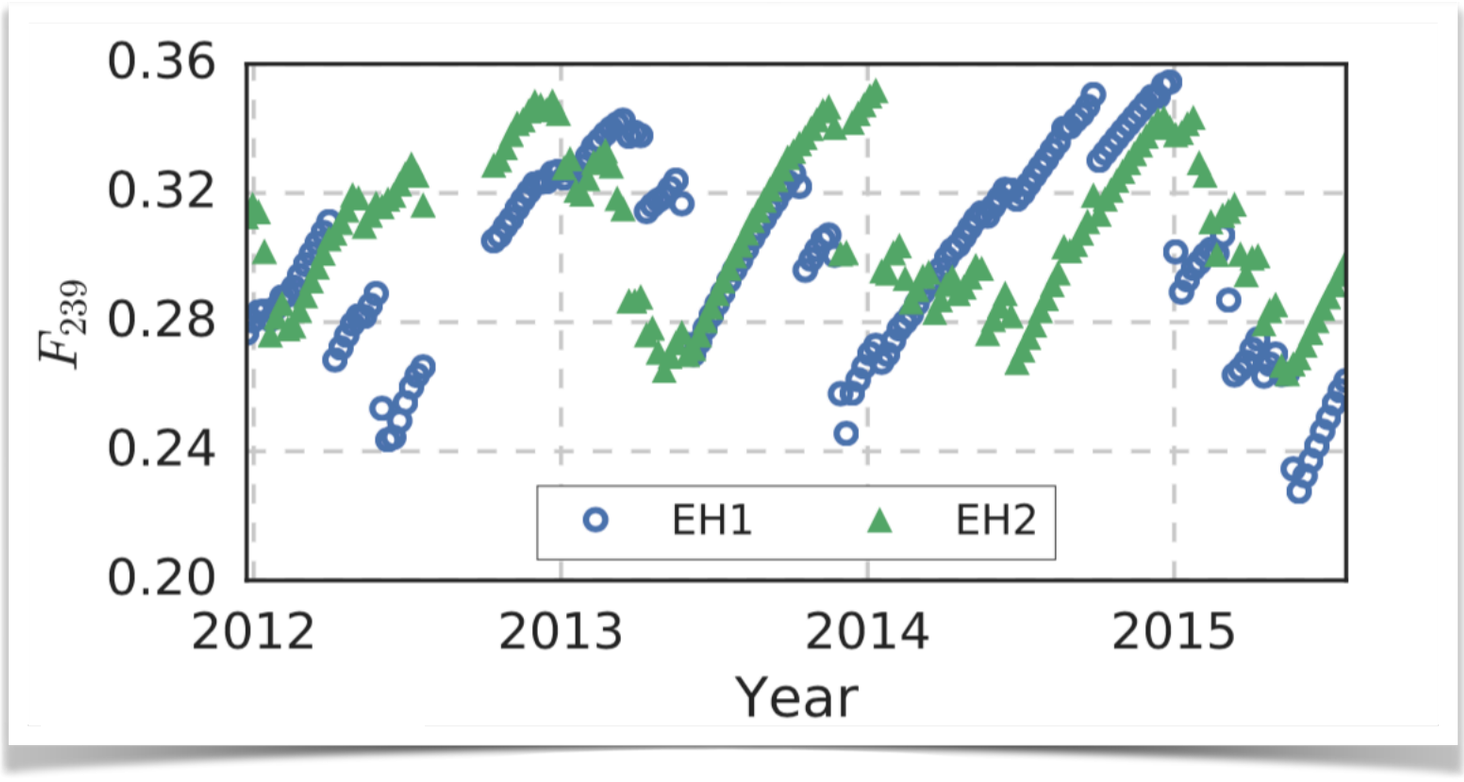
Testing the Reactor Anomaly

- ☑ Four fissile isotopes in a reactor: ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu
- ☑ Different fission product distributions + secondary decays
- ☑ Analyze isotope-dependence of the anomaly
  - “New Physics” would be isotope-independent
  - Problems with flux prediction are typically different for different isotopes

Isotope-Dependent Fluxes

Isotope-Dependent Fluxes

☑ Reactor fuel composition evolves with time (“burnup”)



Daya Bay 1704.01082

Isotope-Dependent Fluxes

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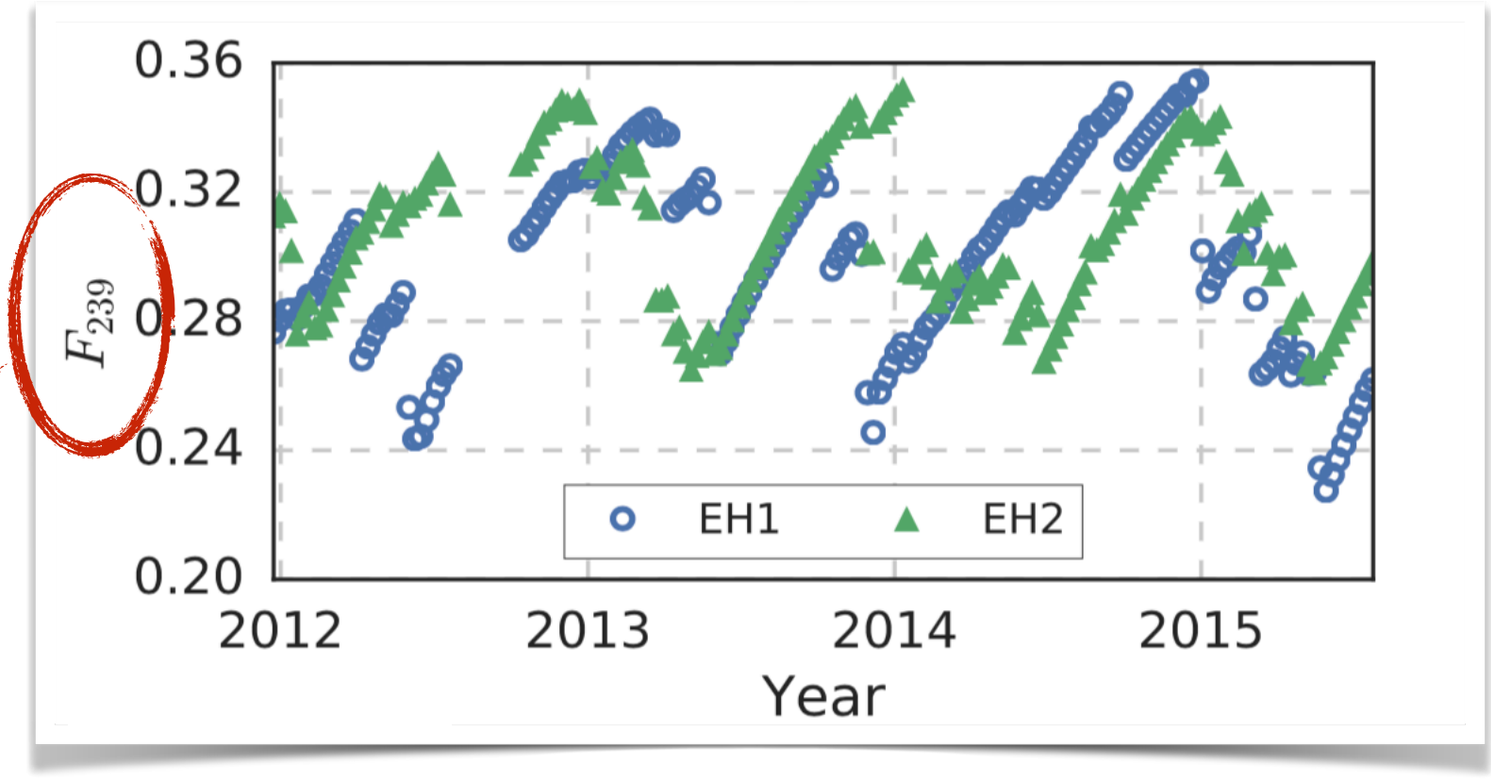

Effective fraction of ^{239}Pu fissions

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Isotope-Dependent Fluxes

- ☑ Reactor fuel composition evolves with time (“burnup”)
- ☑ Measure neutrino event rate as function of F_{239}

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Isotope-Dependent Fluxes

- ☑ Reactor fuel composition evolves with time (“burnup”)
- ☑ Measure neutrino event rate as function of F_{239}
- ☑ New Physics: same deficit for all isotopes
  Flux Misprediction: isotope-dependent deficits

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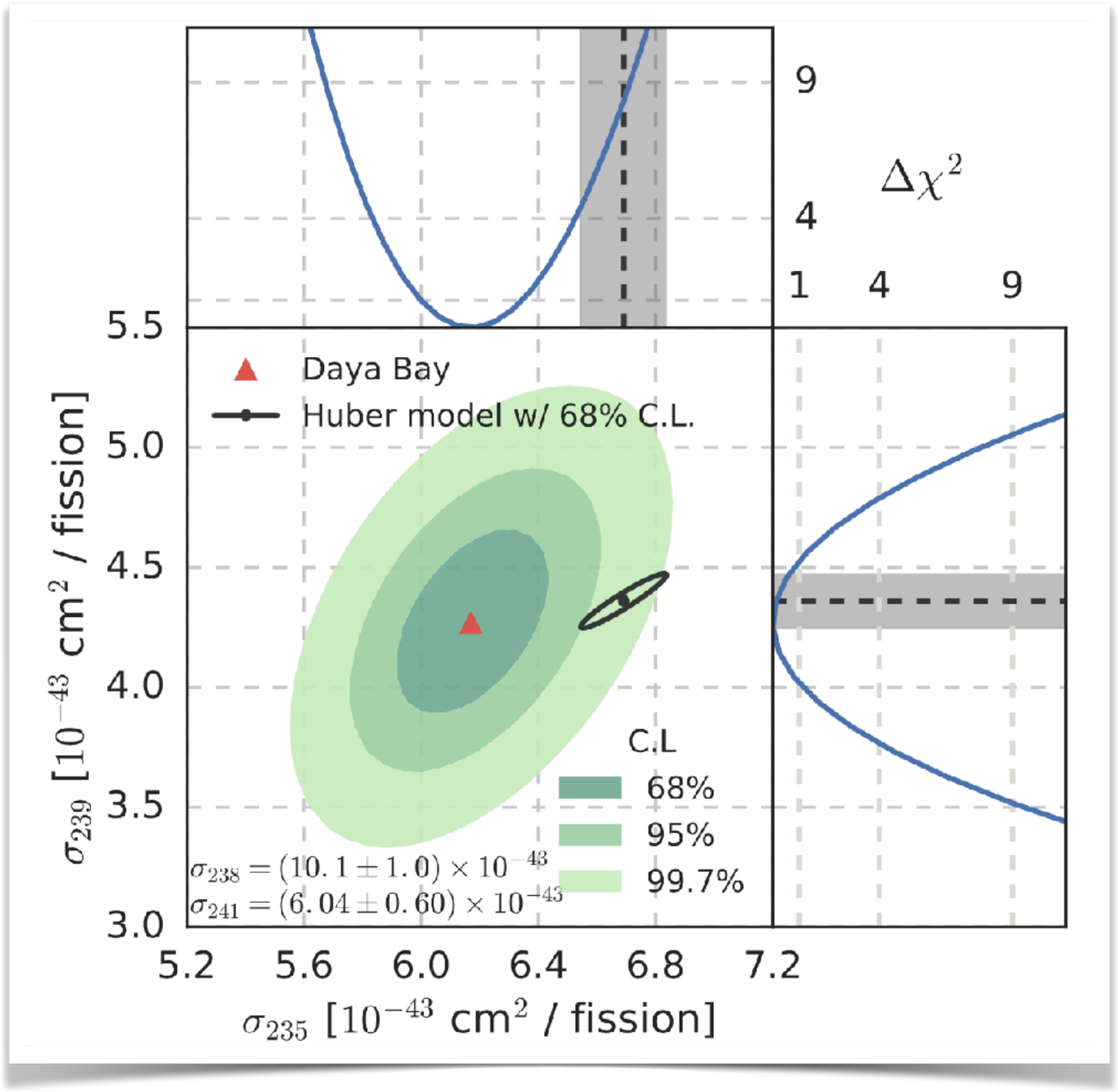
New Physics or Flux Uncertainty?



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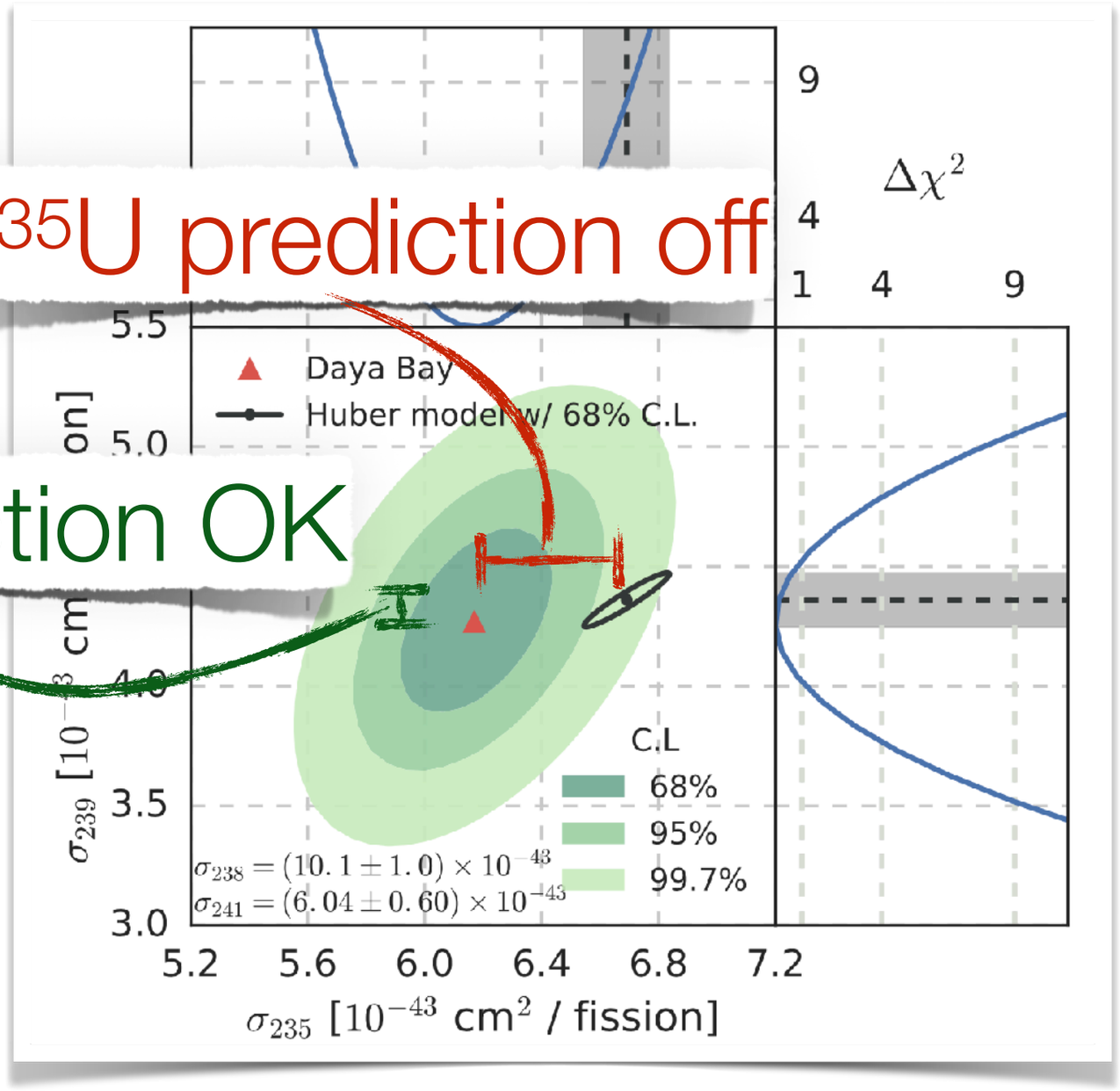
New Physics or Flux Uncertainty?



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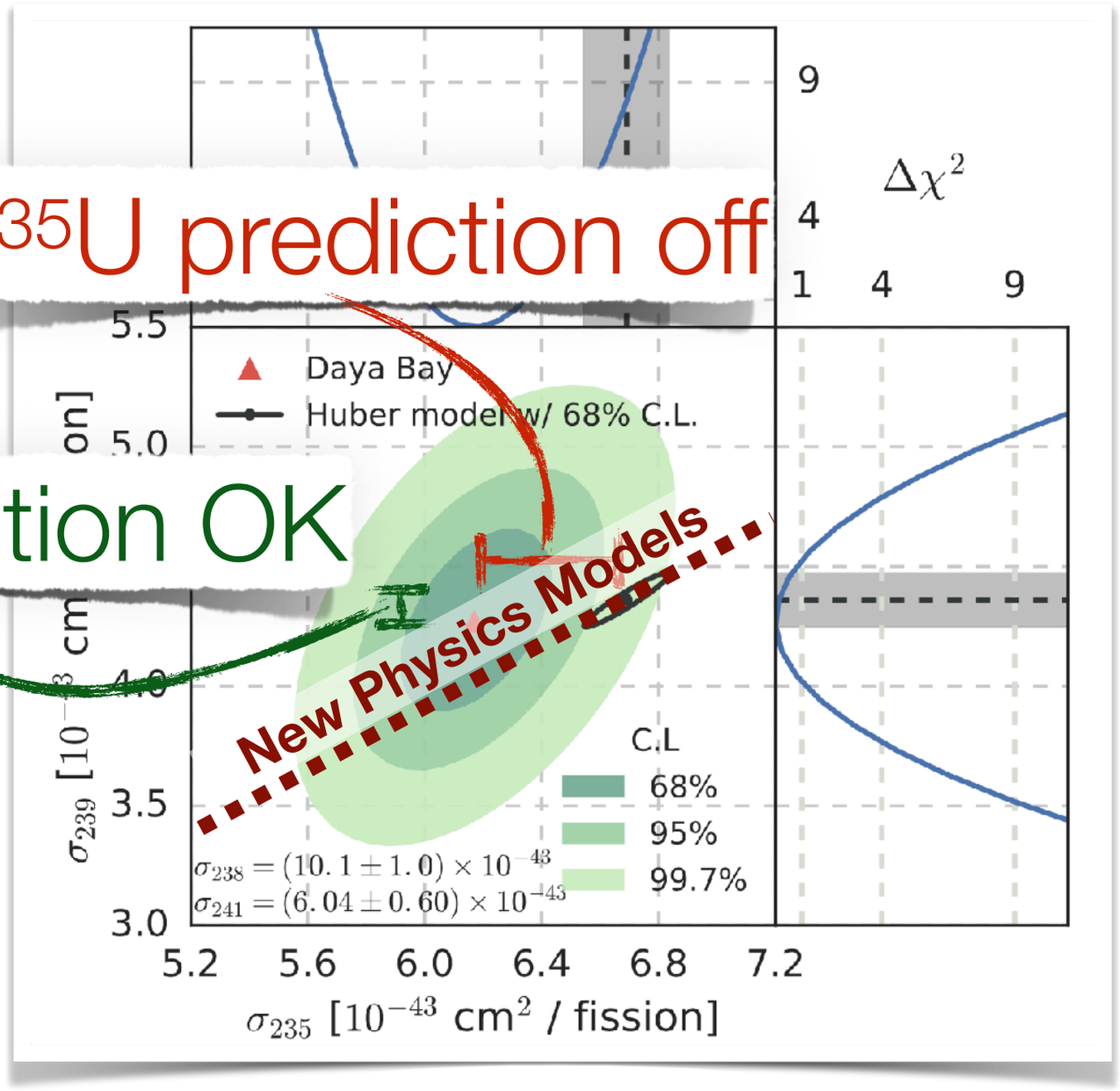
New Physics or Flux Uncertainty?



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Caveats

Is the flux from each isotope really time and burnup-independent?

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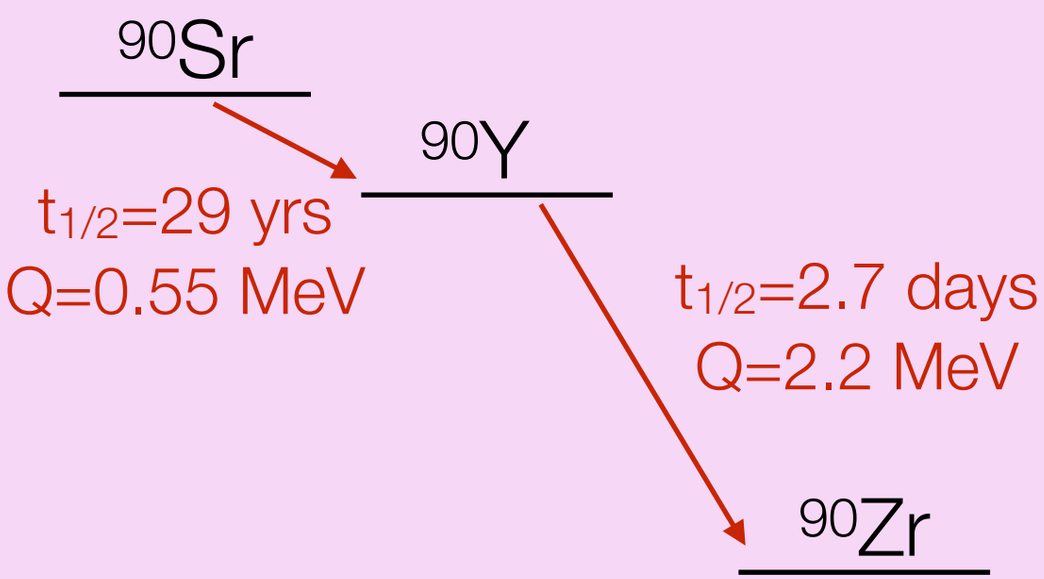
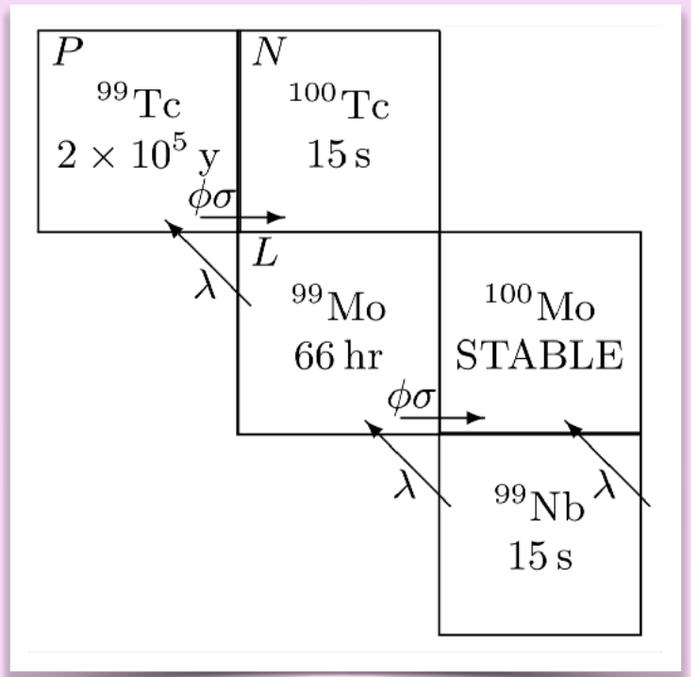
Caveats

Non-Equilibrium Effects



Non-Linear Isotopes

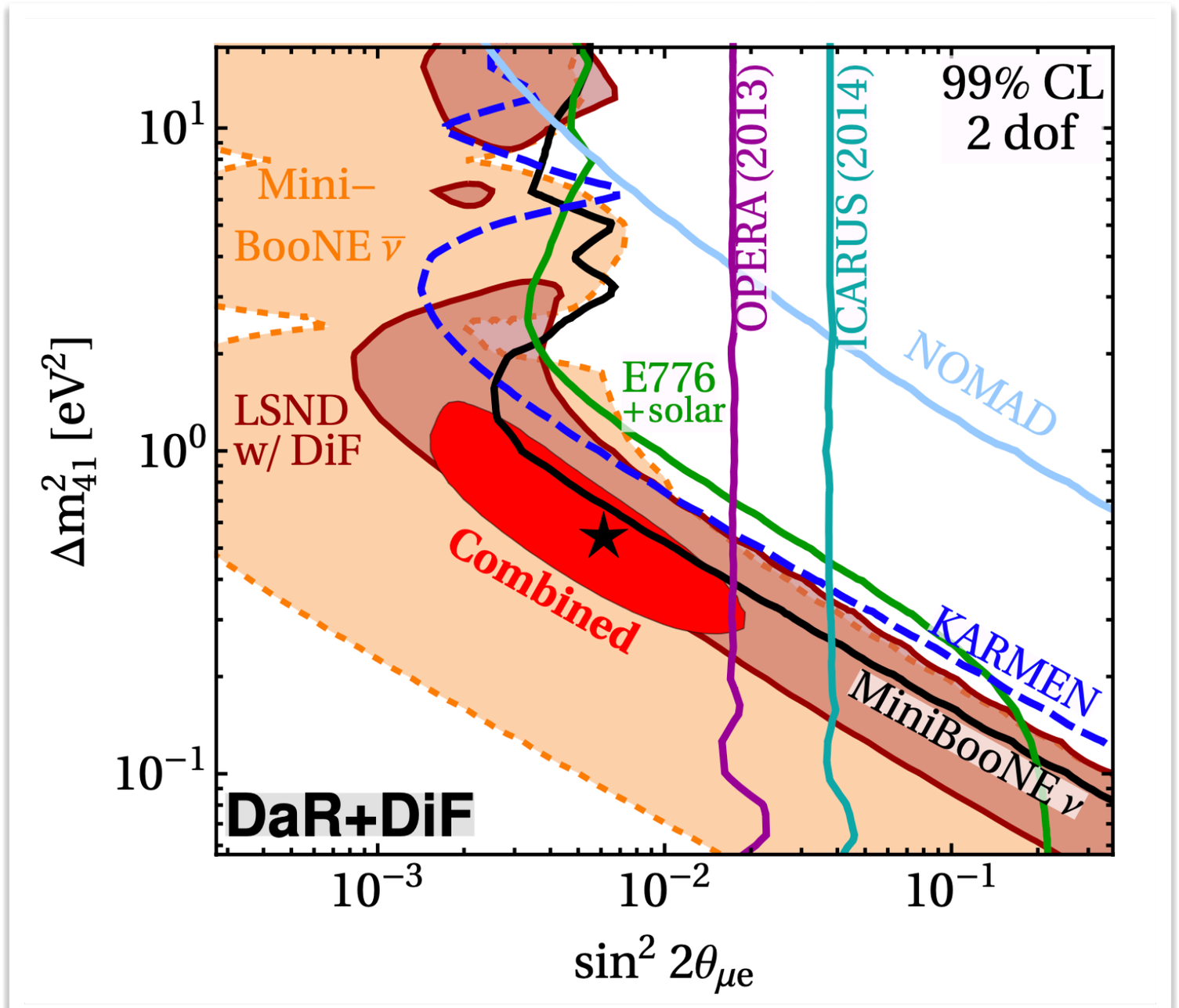
☑ Neutron capture on fission products



☑ Extra neutron flux/burnup dependence in ν flux

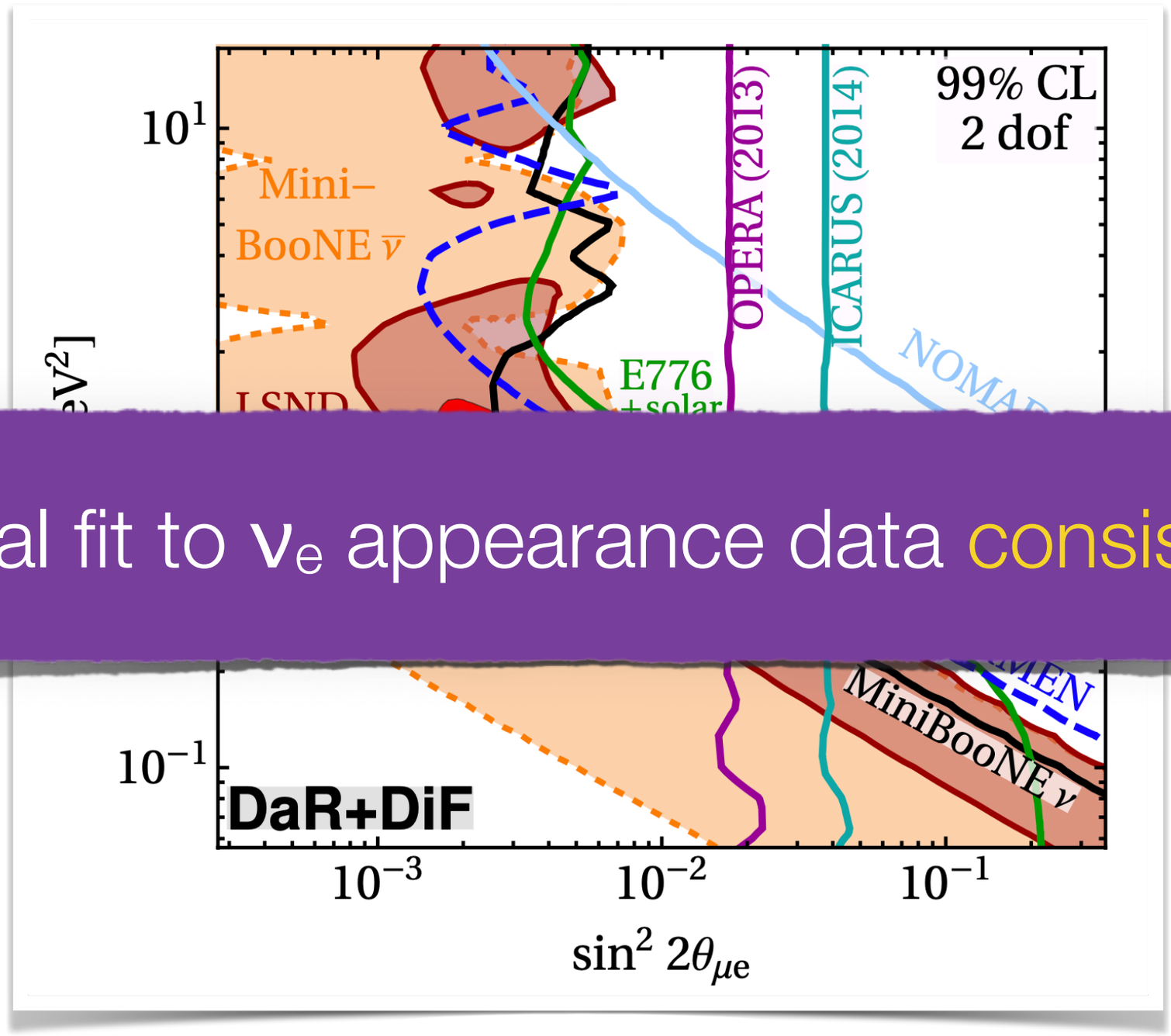
Jaffke Huber 1510.08948, Daya Bay 1904.07812

Global Fit to ν_e Appearance Data



Dentler *et al.*, 1803.10661

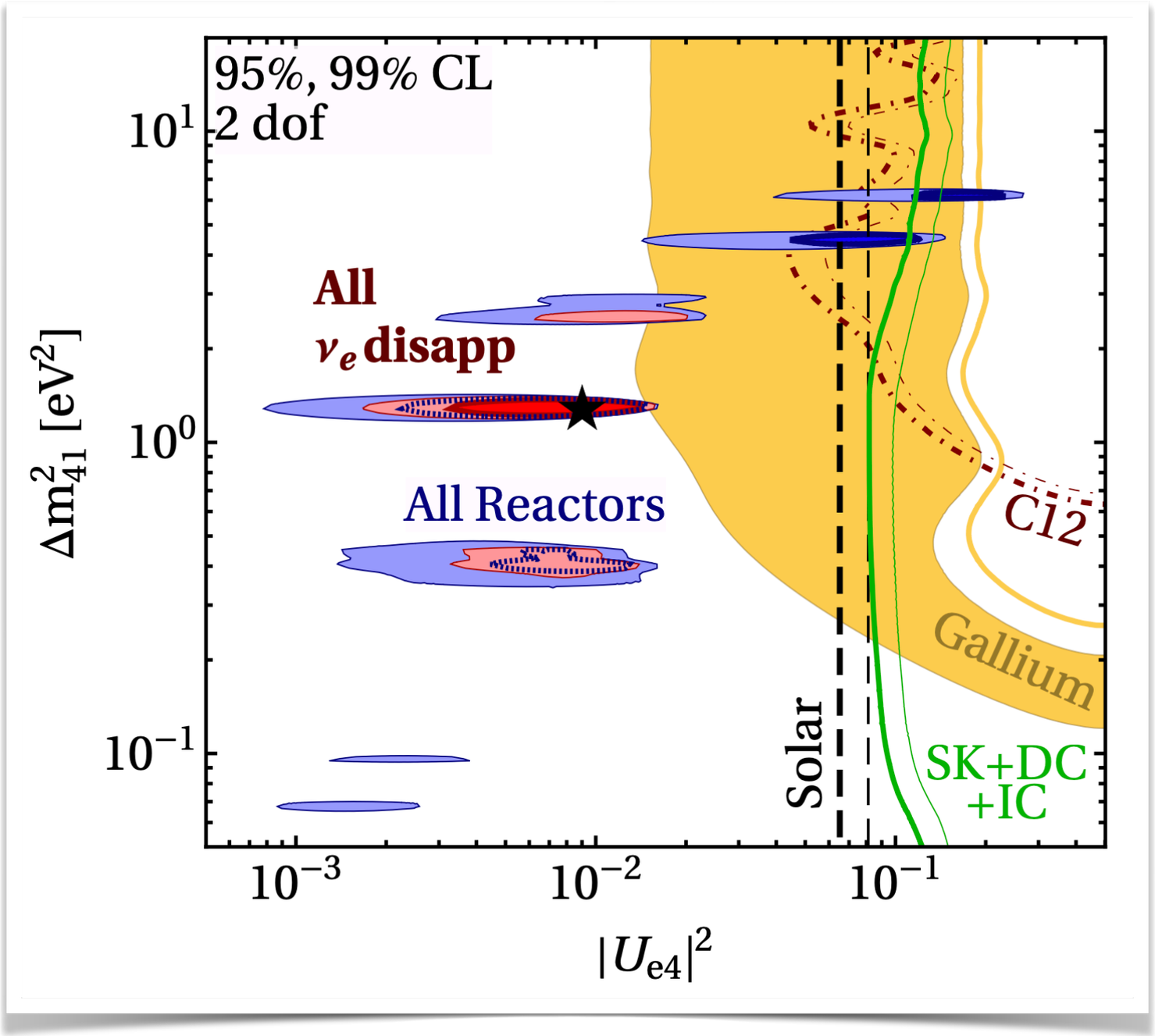
Global Fit to ν_e Appearance Data



Global fit to ν_e appearance data consistent.

Dentler *et al.*, 1803.10661

Global Fit to ν_e Disappearance



Dentler *et al.*, 1803.10661