Beta Decays as Probes of Sterile Neutrinos

Pranava Teja Surukuchi

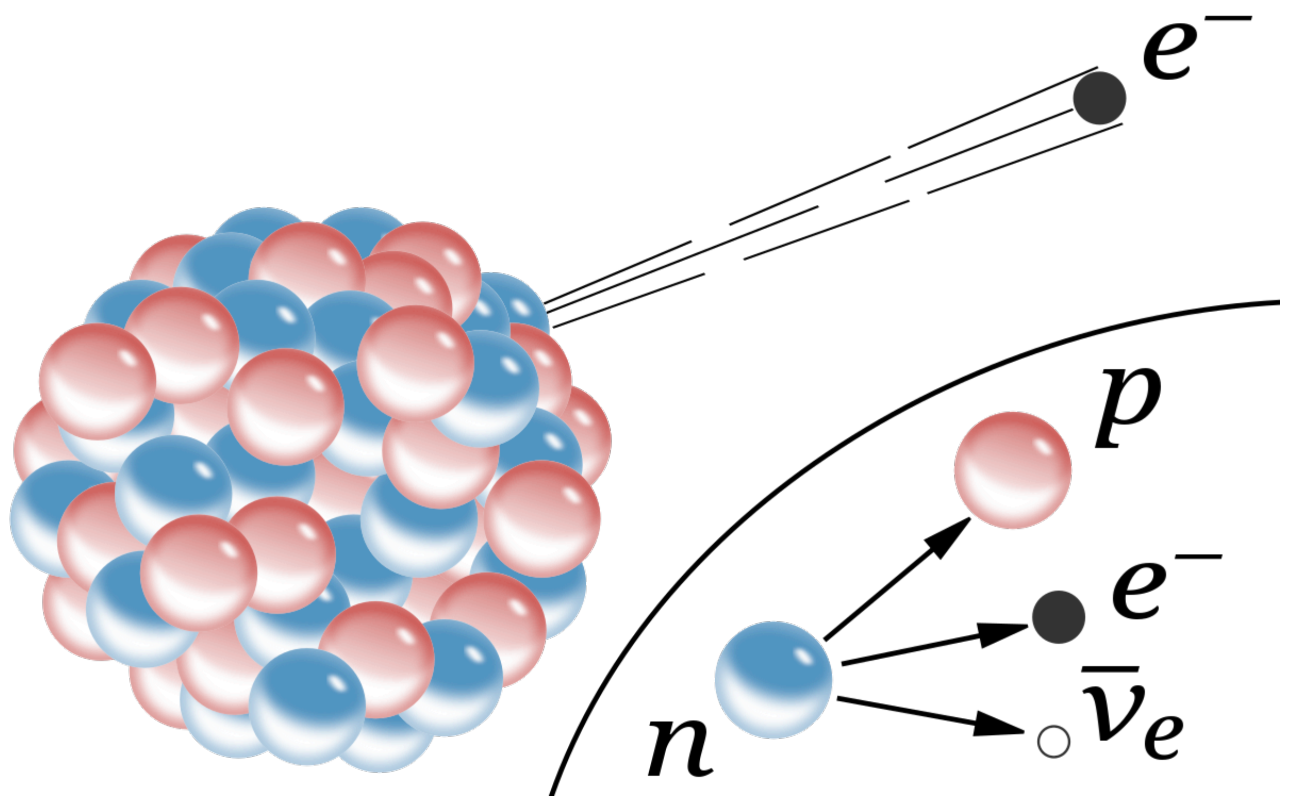
July 24, 2022

Snowmass Community Summer Study

Yale

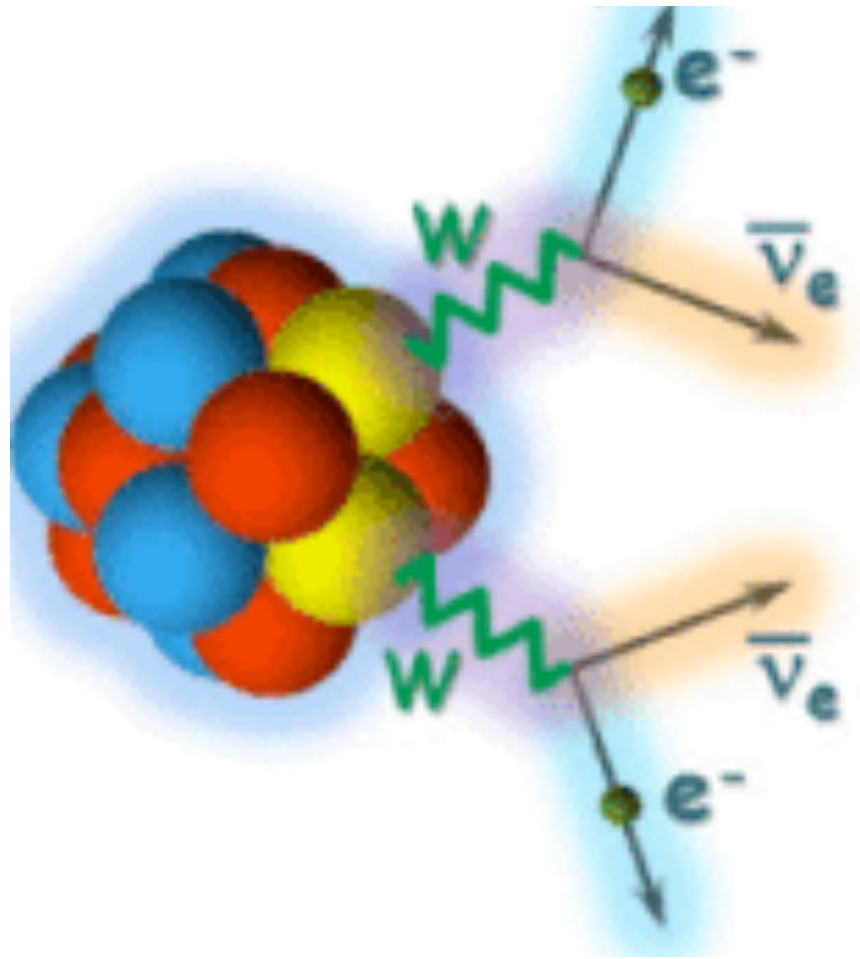
Wright Laboratory

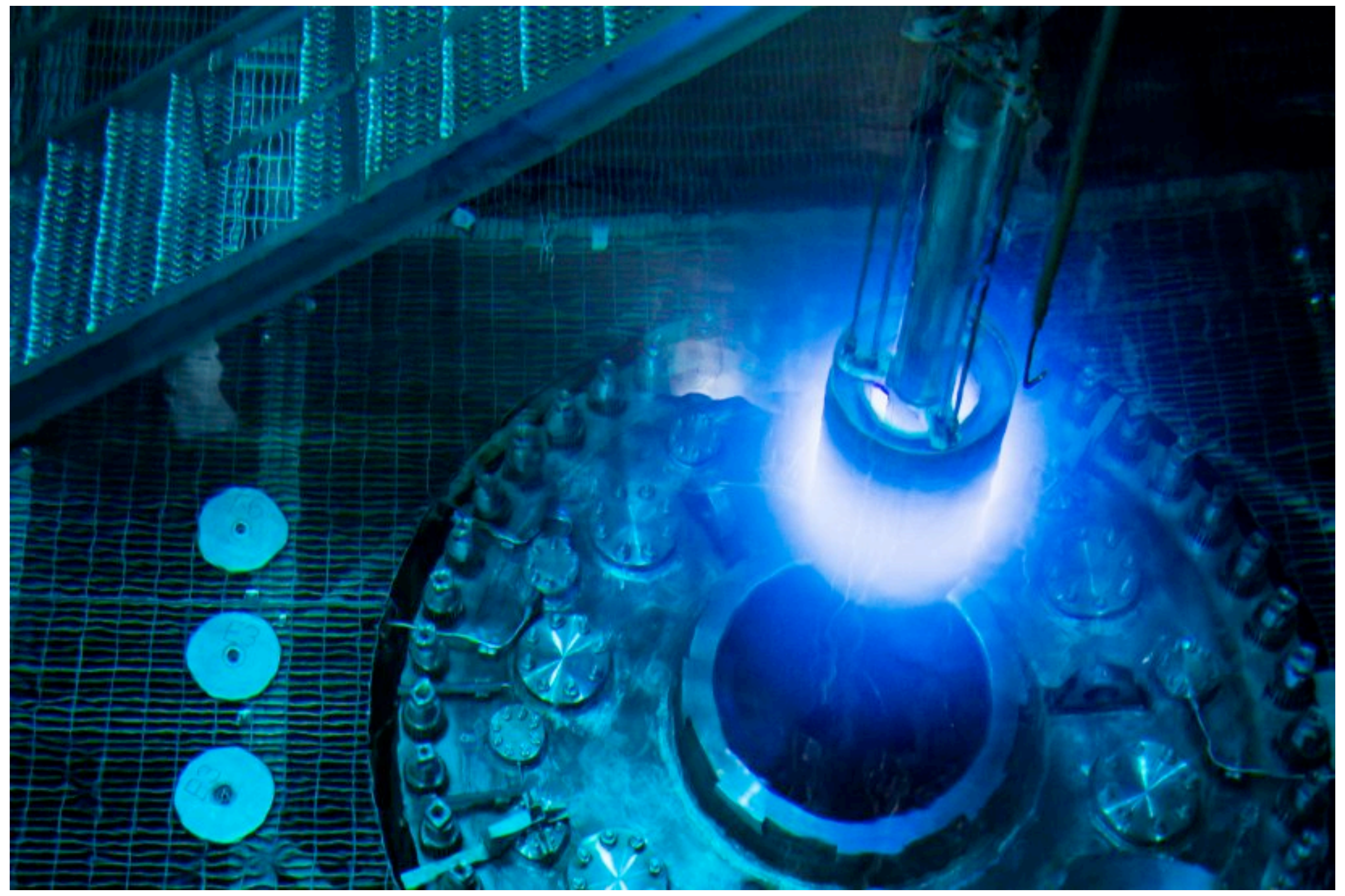
BSM with β Decays



Single Decays: Beta decay/electron capture

Double beta decays

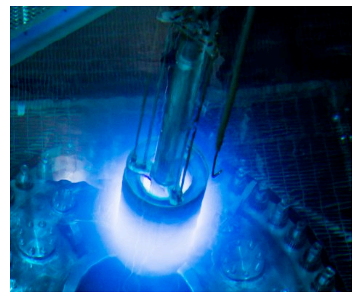




Multi-isotope beta decays: reactors

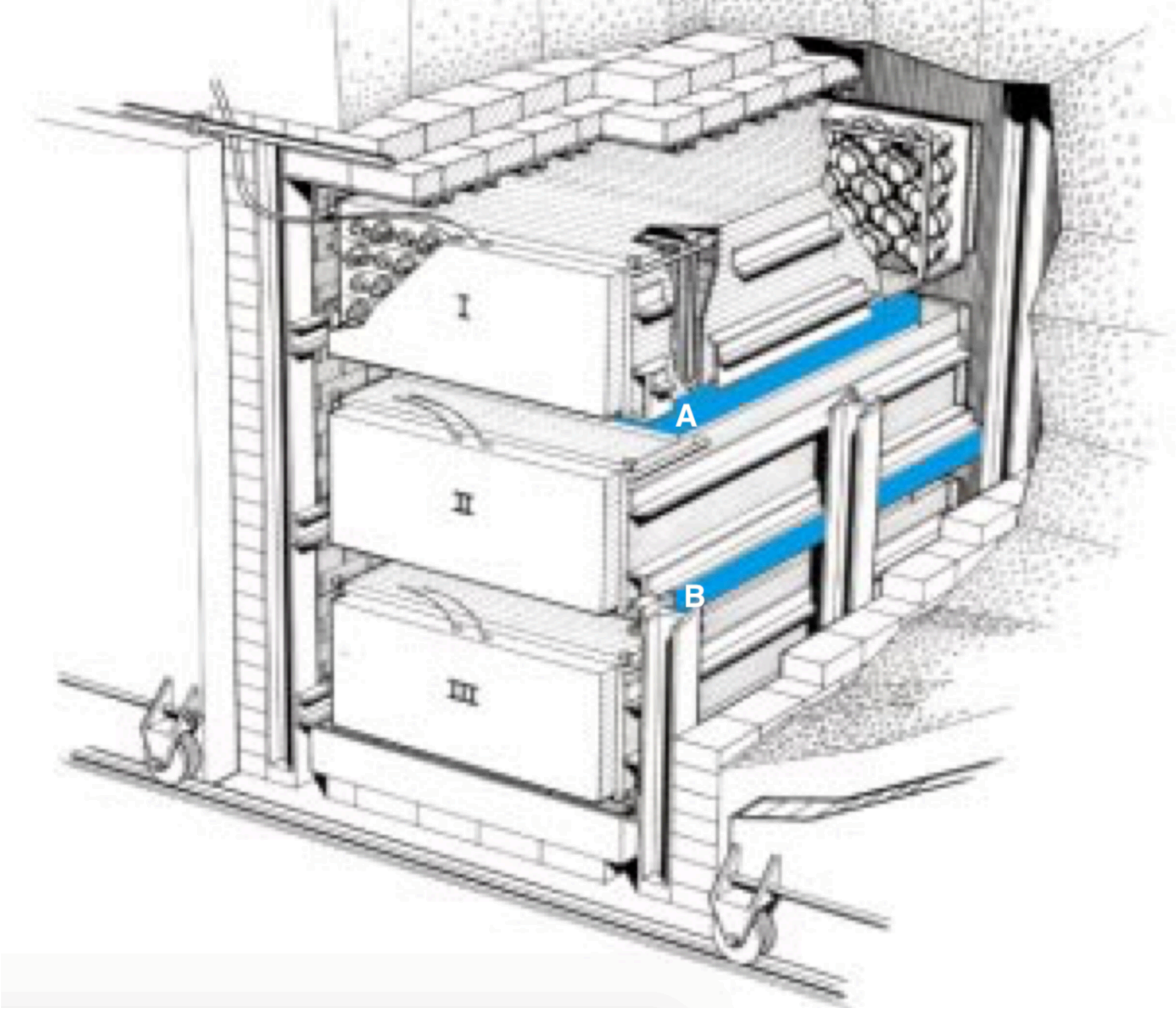
Yale

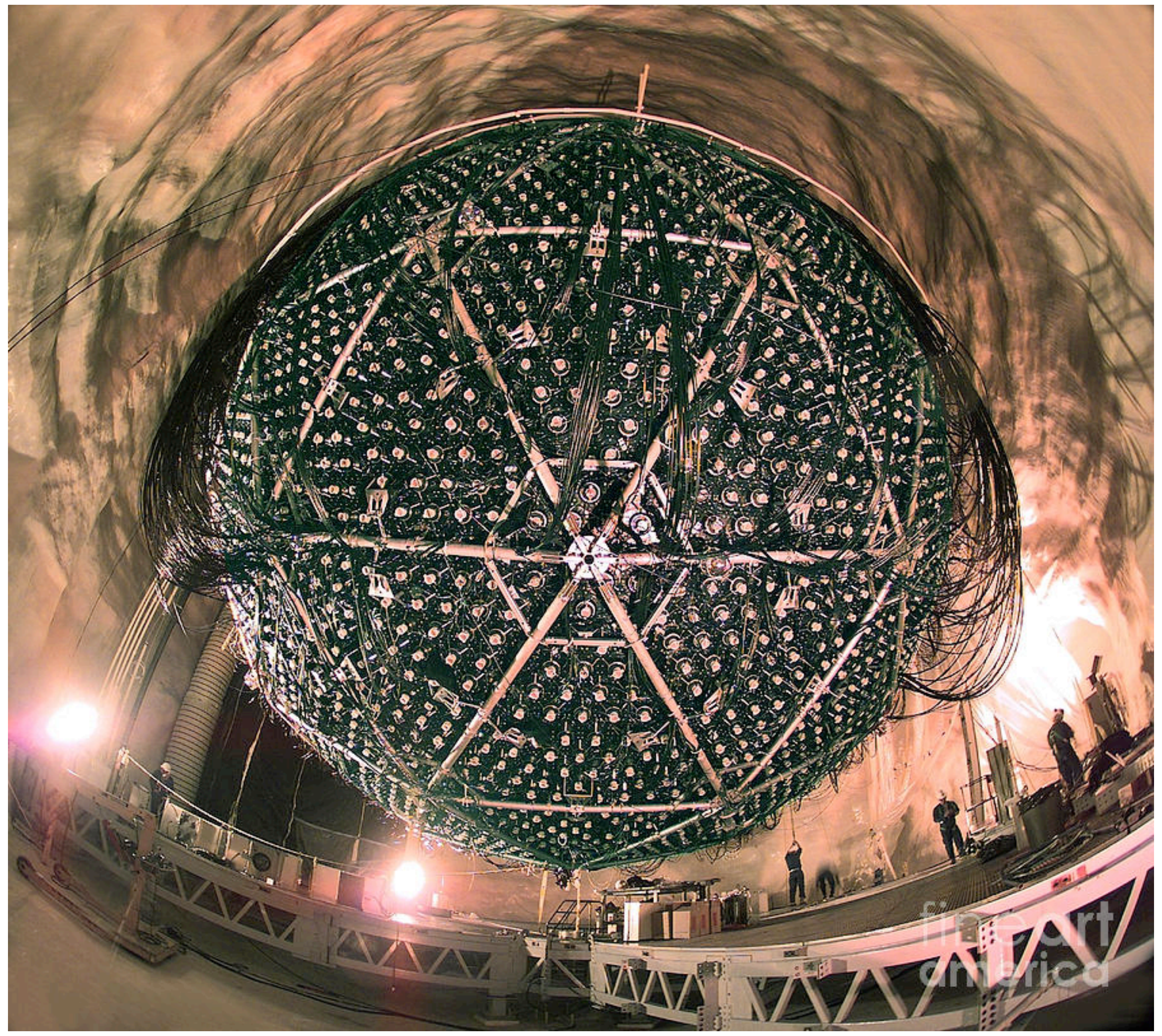
(Extended) SM with β Decays: Reactors



- Reactors are copious sources of β decays
- Beta decays can directly access neutrino properties
- Reactors played a crucial role in understanding neutrino properties

Savannah River Neutrino Detector



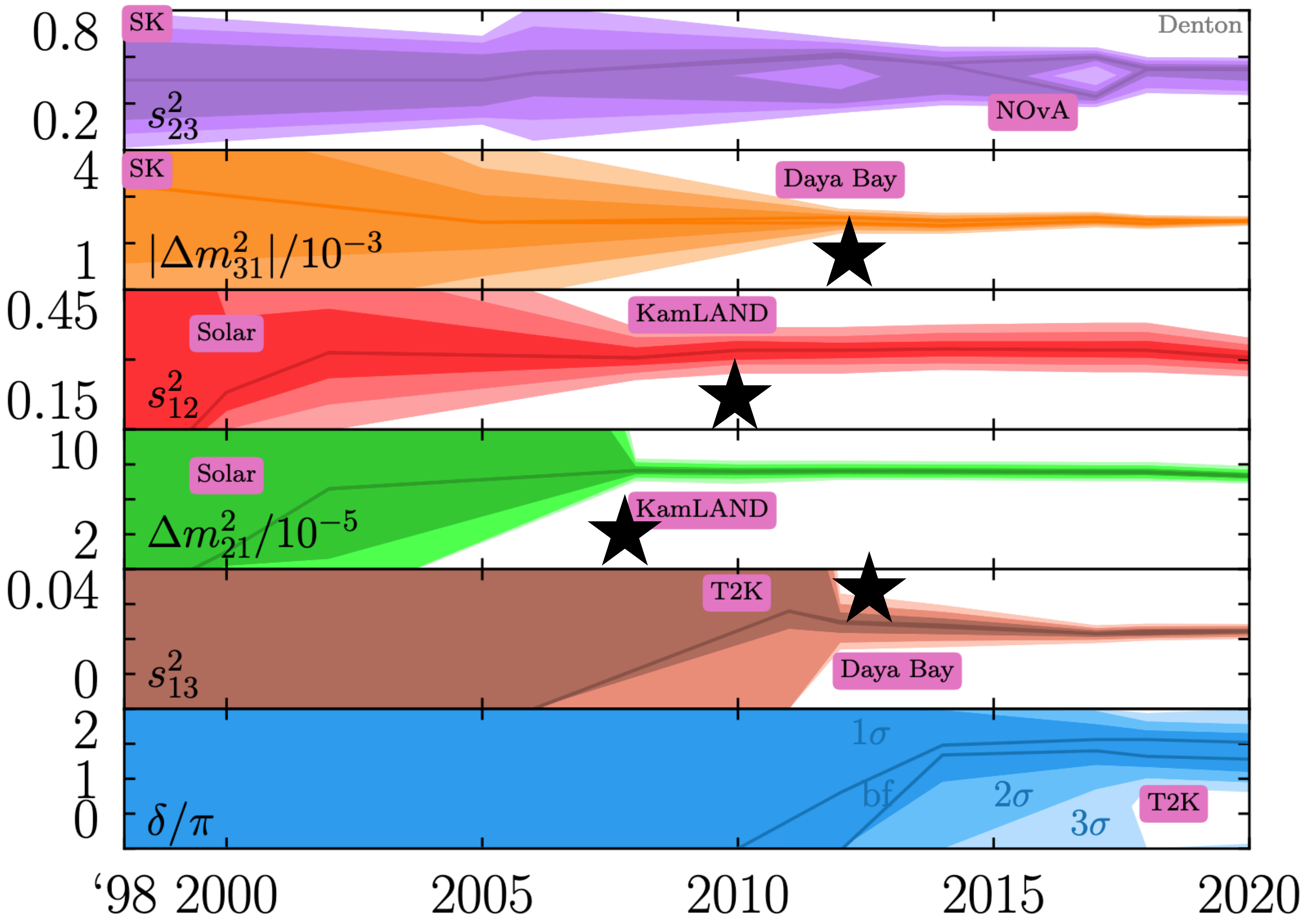


KamLAND

Daya Bay

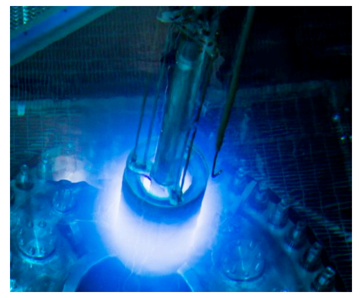
(Extended) SM with β Decays: Oscillation Physics

- Reactors also played an important role in neutrino oscillation physics
- Provides some of the tightest bounds on the neutrino oscillation parameters



Plot from P. Denton

Motivation for Sterile Neutrino Searches at Reactors



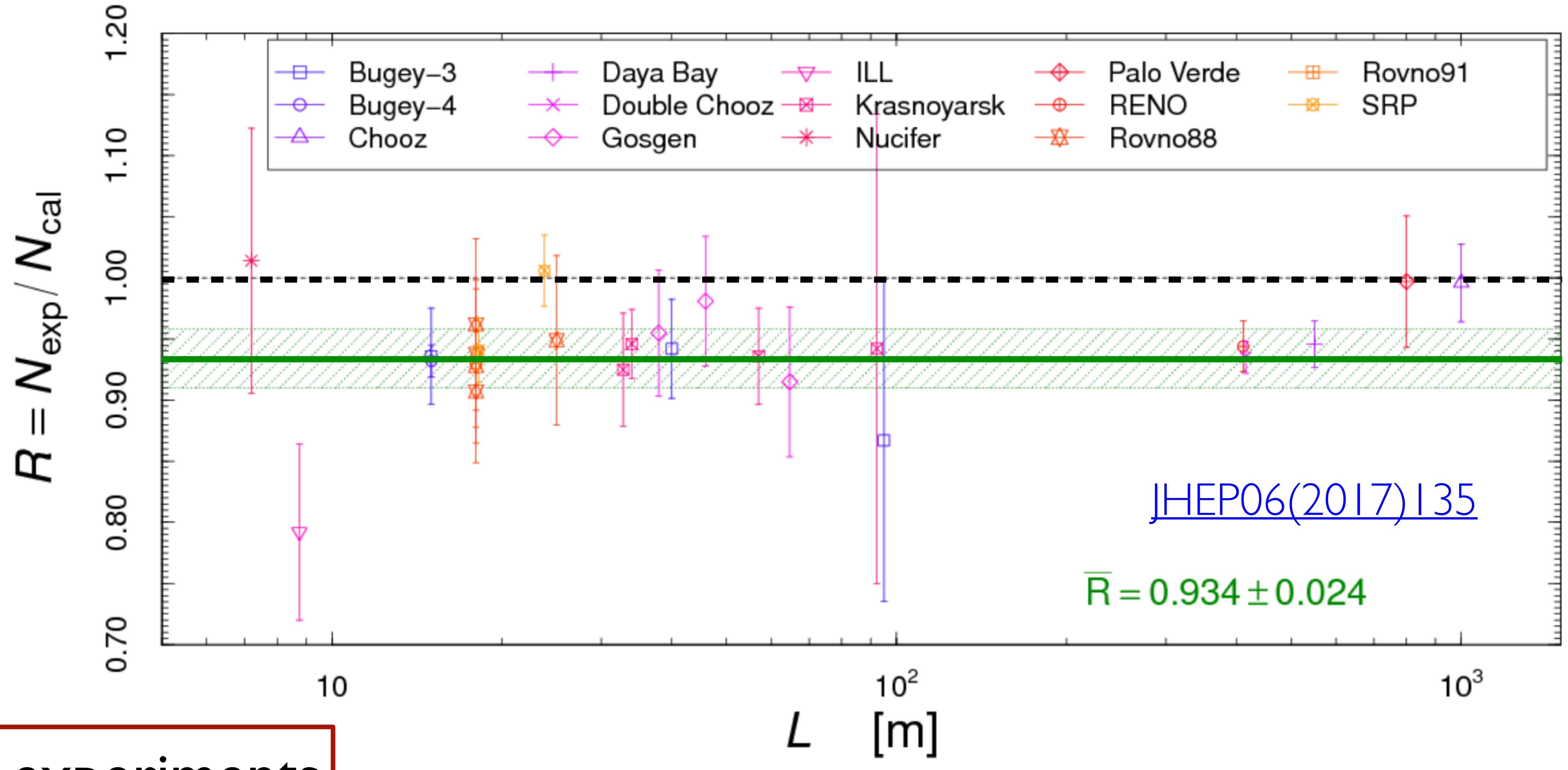
- In 2011, predicted $\bar{\nu}_e$ fluxes were updated
  - Improvement in reactor neutrino model
  - Change in neutron lifetime
  - Inclusion of off-equilibrium effects
- Predicted flux higher with improved model
- ~6% global experimental deficit
- Discrepancy is called Reactor Antineutrino Anomaly (RAA)

Improved predictions of reactor antineutrino spectra

Th. A. Mueller, D. Lhuillier, M. Fallot, A. Letourneau, S. Cormon, M. Fechner, L. Giot, T. Lasserre, J. Martino, G. Mention, A. Porta, and F. Yermia
Phys. Rev. C **83**, 054615 – Published 23 May 2011

Determination of antineutrino spectra from nuclear reactors

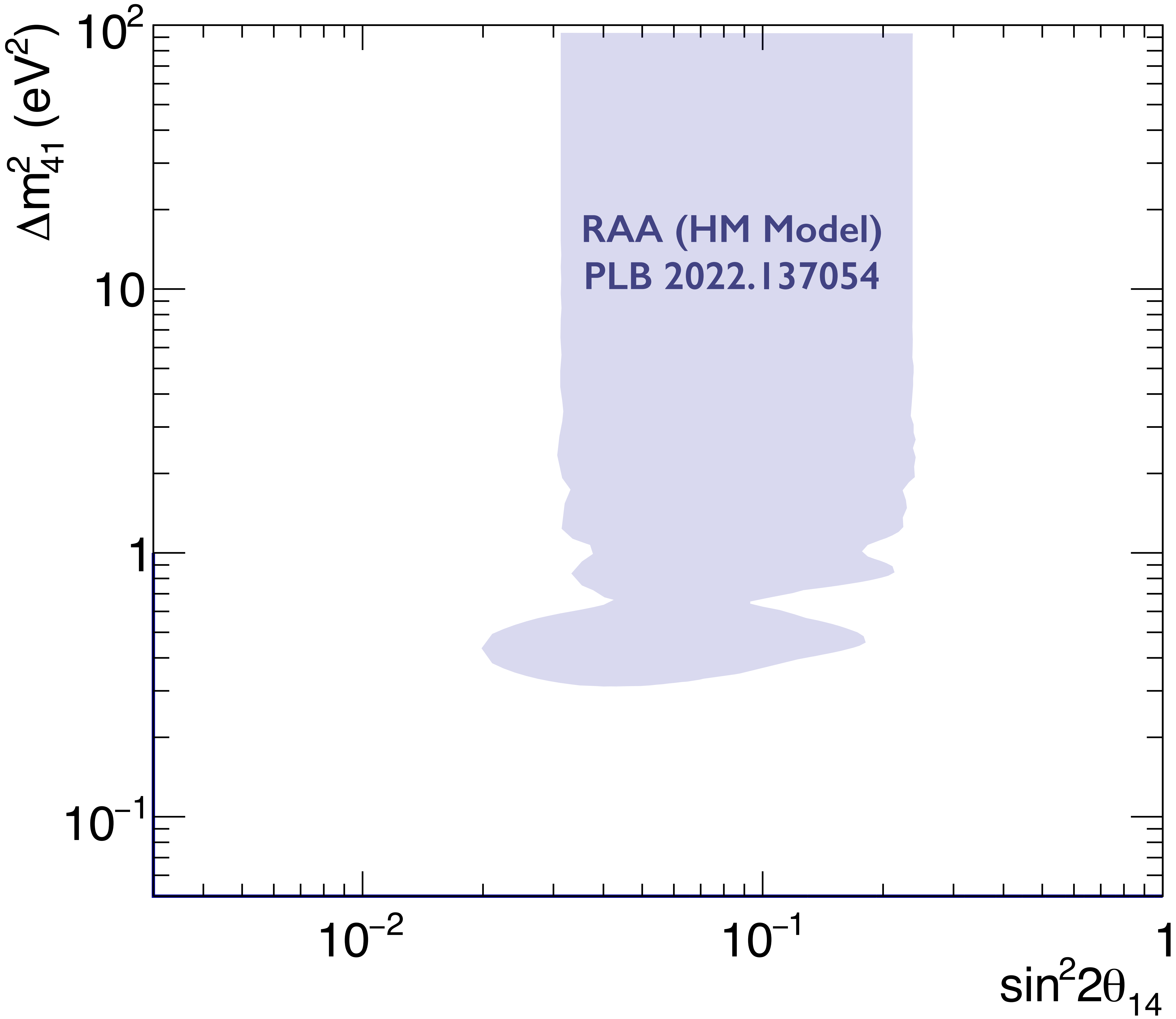
Patrick Huber*
Center for Neutrino Physics, Department of Physics, Virginia Tech, Blacksburg, Virginia 24061, USA
(Received 16 June 2011; published 29 August 2011)



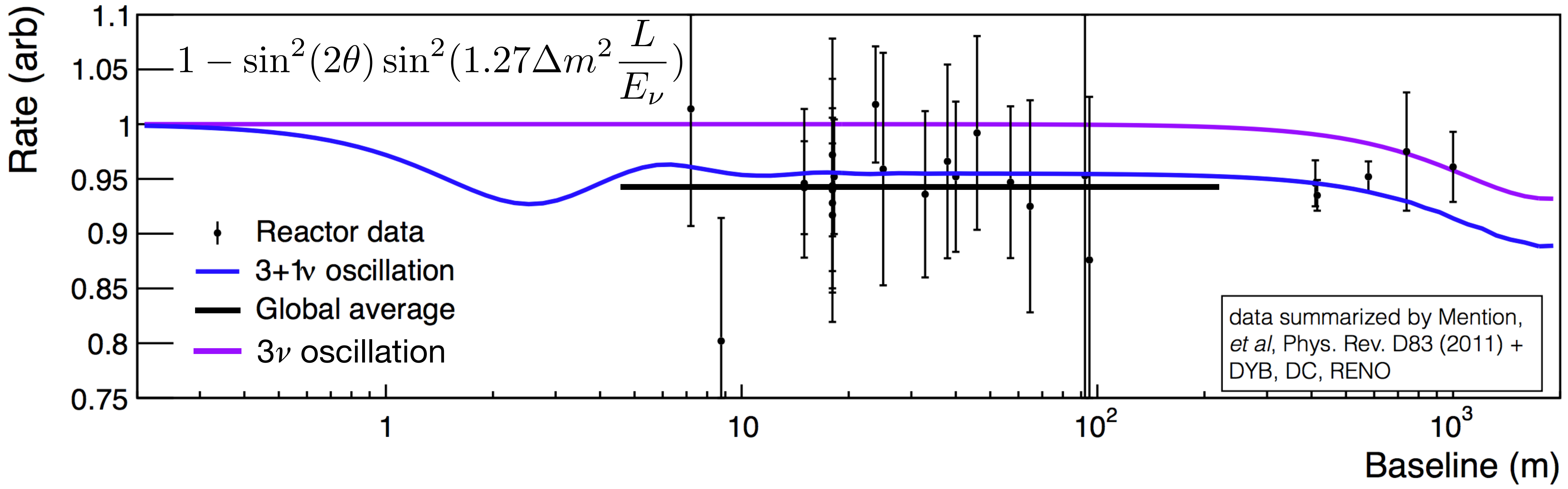
A ~3σ deficit was measured in reactor neutrinos experiments

Interpretation of Anomalies

- RAA could be explained by eV-scale sterile neutrinos
- **Similar parameter space as suggested by the other appearance and disappearance anomalies**
- Catalyzed several reactor neutrino experiments

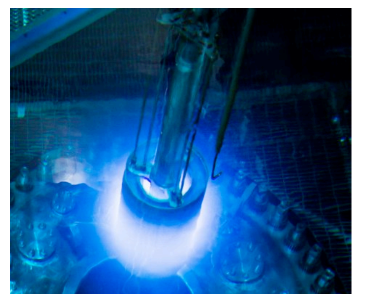


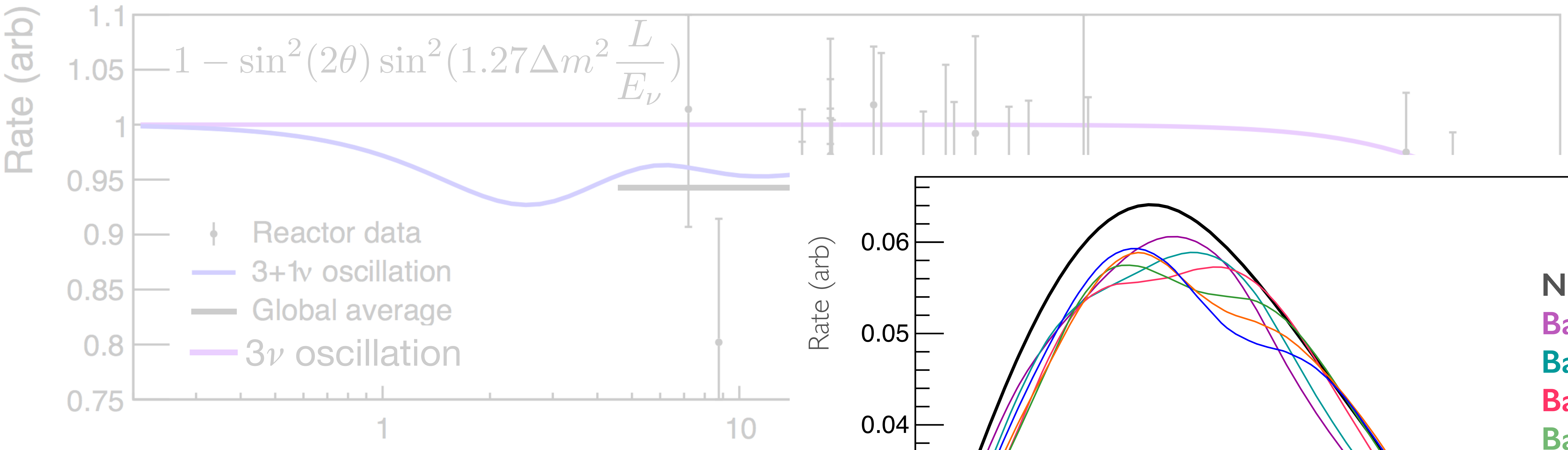
Testing RAA: Searching for Sterile Neutrinos with Reactors

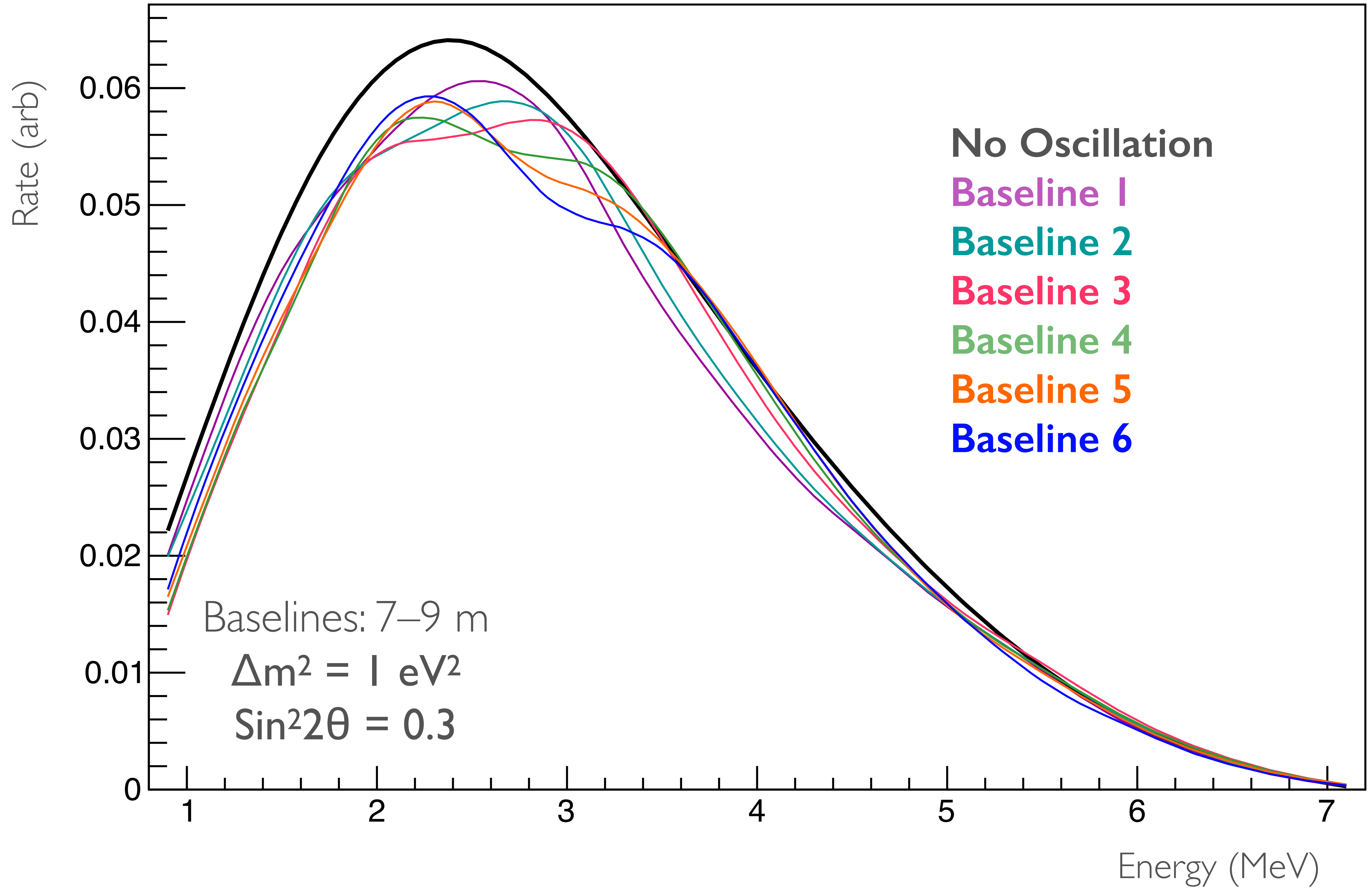


- Sterile neutrinos at eV scale:
  => High frequency oscillations at short distances (<10 m)
- New models and experiments show that RAA is (at least in part) due to mismodeling

Testing RAA: Searching for Sterile Neutrinos with Reactors





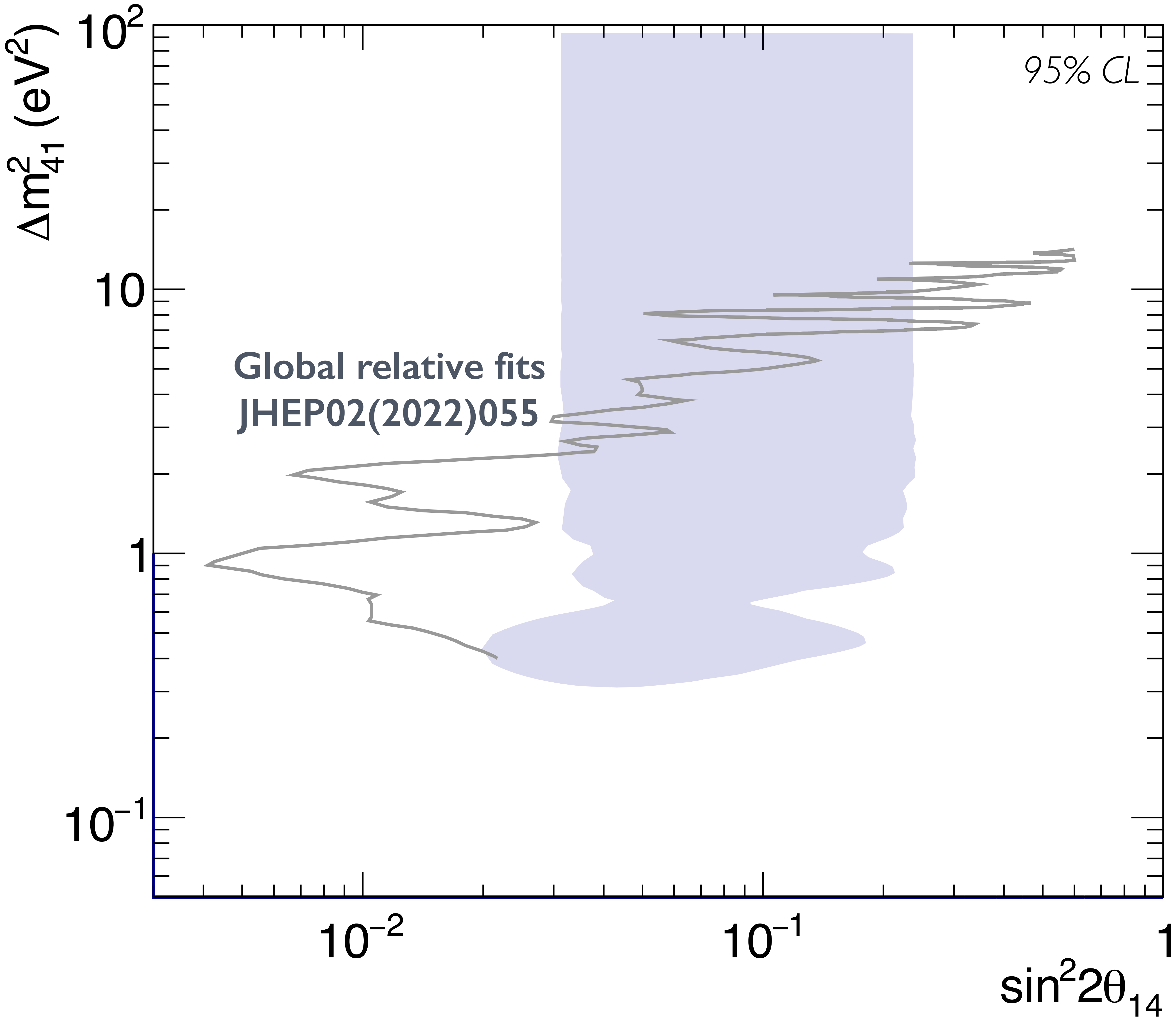


- Sterile neutrinos at eV scale:
  => High frequency oscillations at short distances (<10 m)
- New models and experiments show that RAA is (at least in part) due to mismodeling
- Spectrum measured as a function of baseline would be a smoking gun evidence for sterile neutrino oscillations
- Measure spectrum within a single detector, move the detector, or both

Relative spectral searches essential to irrefutably test eV-scale sterile neutrinos

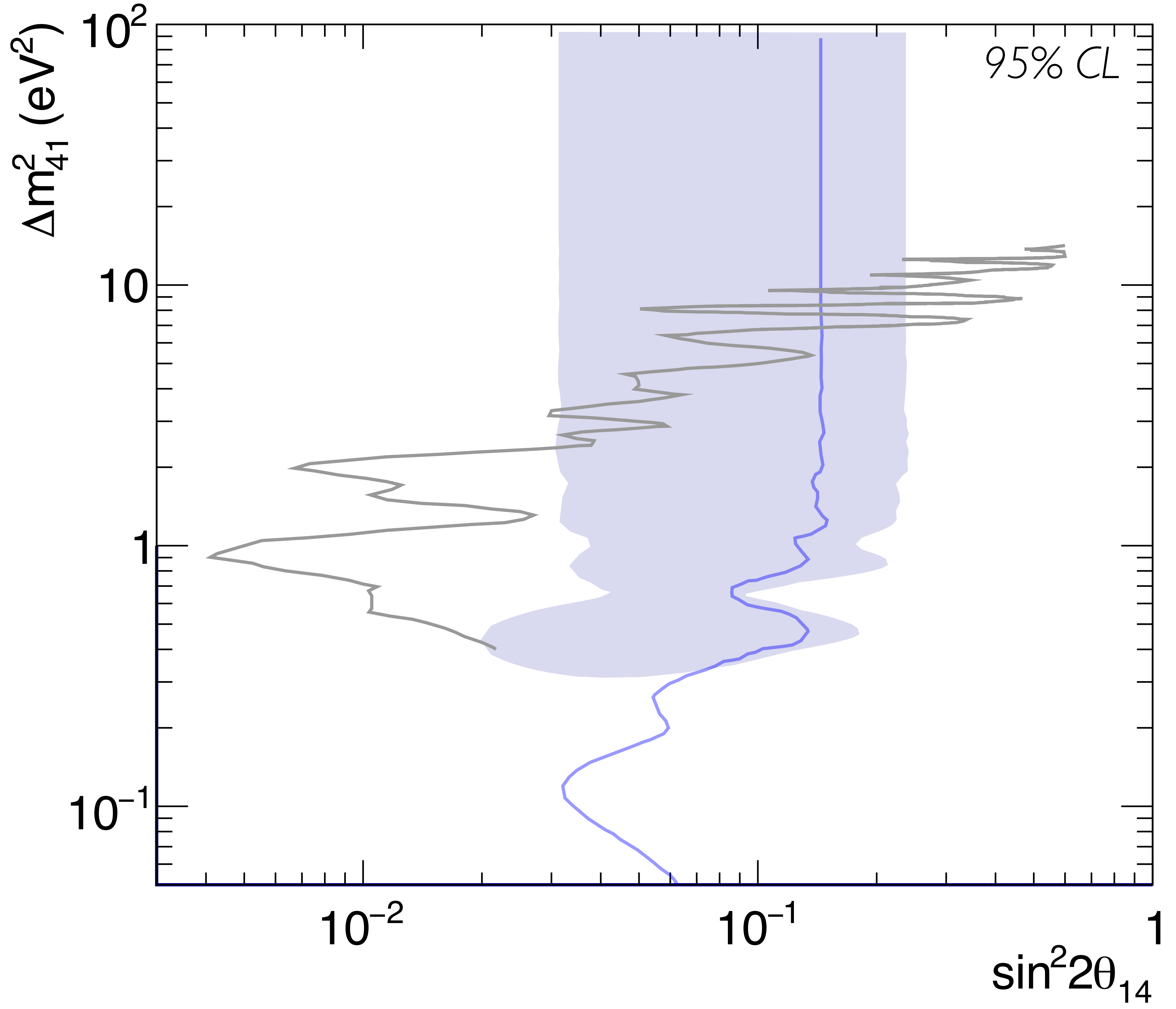
Current Limits on eV-scale sterile neutrinos

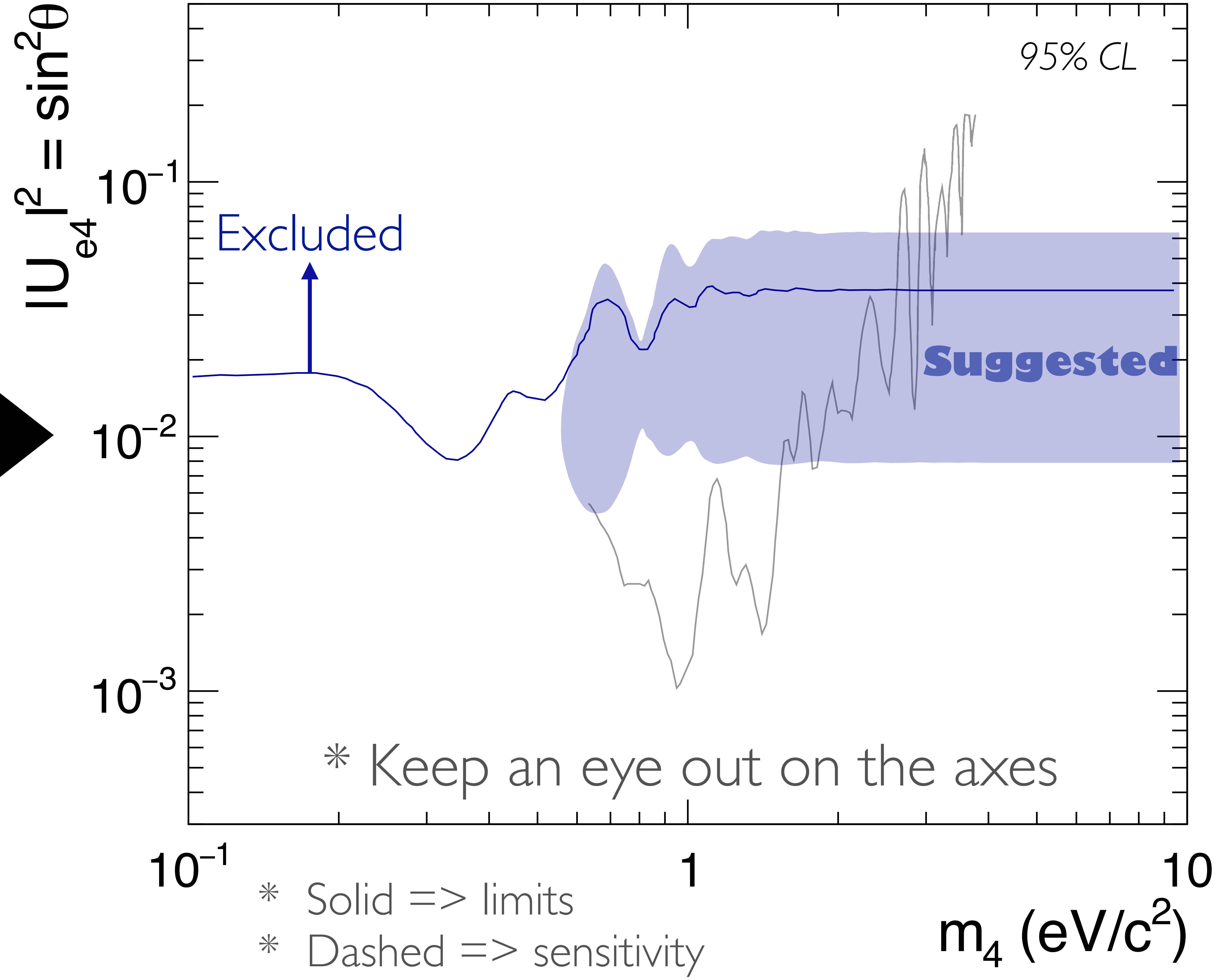
- Several short baseline reactor neutrino experiments placed limits on eV-scale sterile neutrinos
- Fits based solely on relative spectral measurements
- Significant portion of the suggested parameter space excluded: PROSPECT and other global experiments have pushed limits in the last decade
- $\sim\Delta m^2 > 5\ \mathrm{eV}^2$ yet to be excluded



Change of Basis

Change of Basis



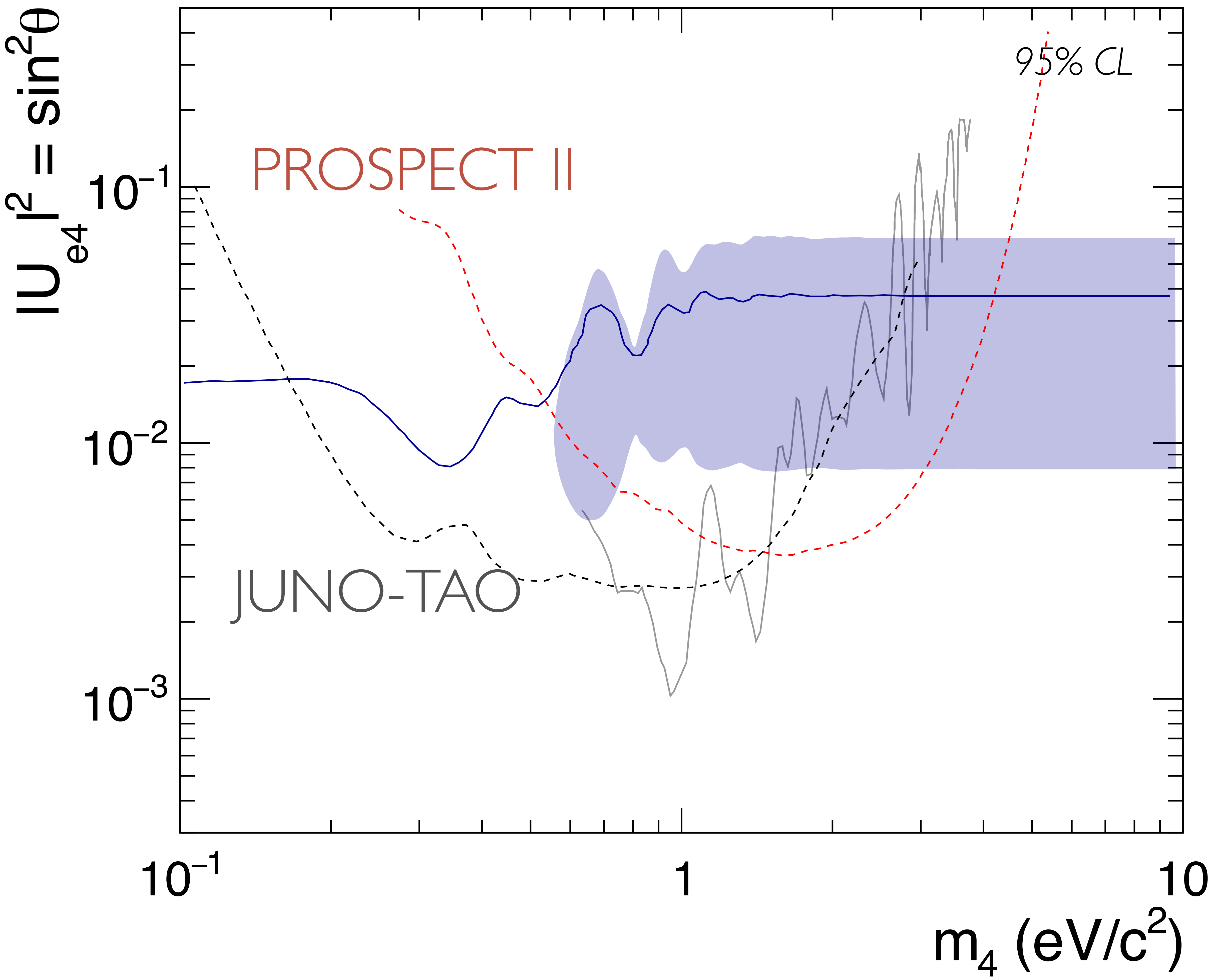


- Change of basis for comparing over scales

* Solid => limits
* Dashed => sensitivity
* Shaded => suggested

Upcoming Experiments

- New experiments planned to cover larger parameter space
- Will constrain larger parameter space to cover larger parameter space relevant to eV-scale anomalies
- PROSPECT II in particular exclude the controversial claim by Neutrino-4 experiment
- Also pertinent to future LBL experiments searching for CP violation

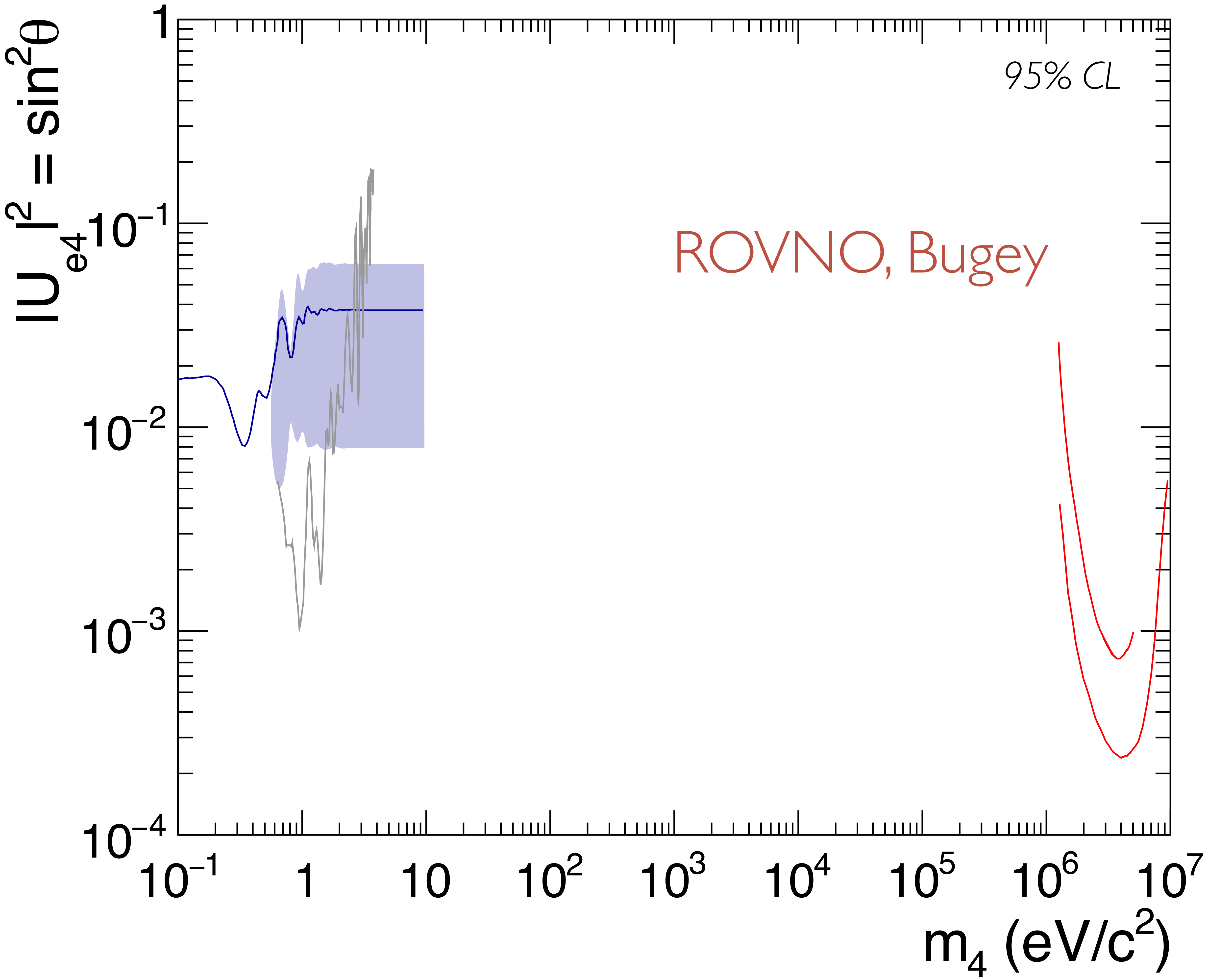


MeV-scale Steriles

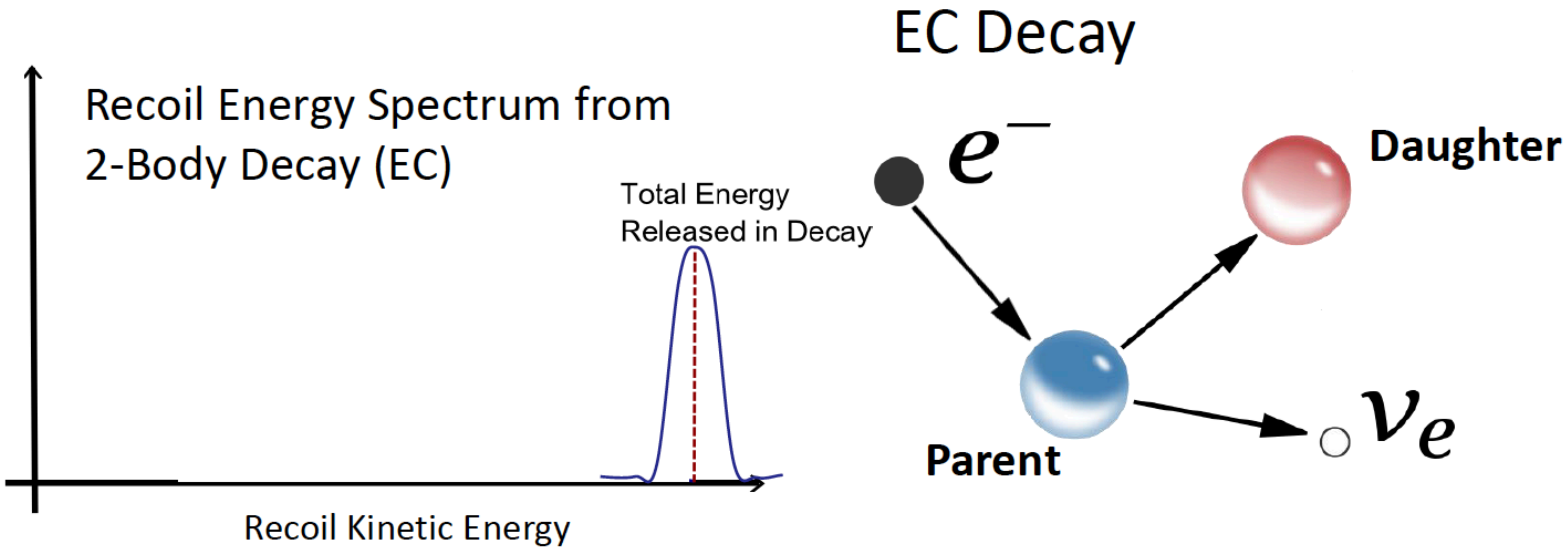
- Neutrino produced in reactors could decay

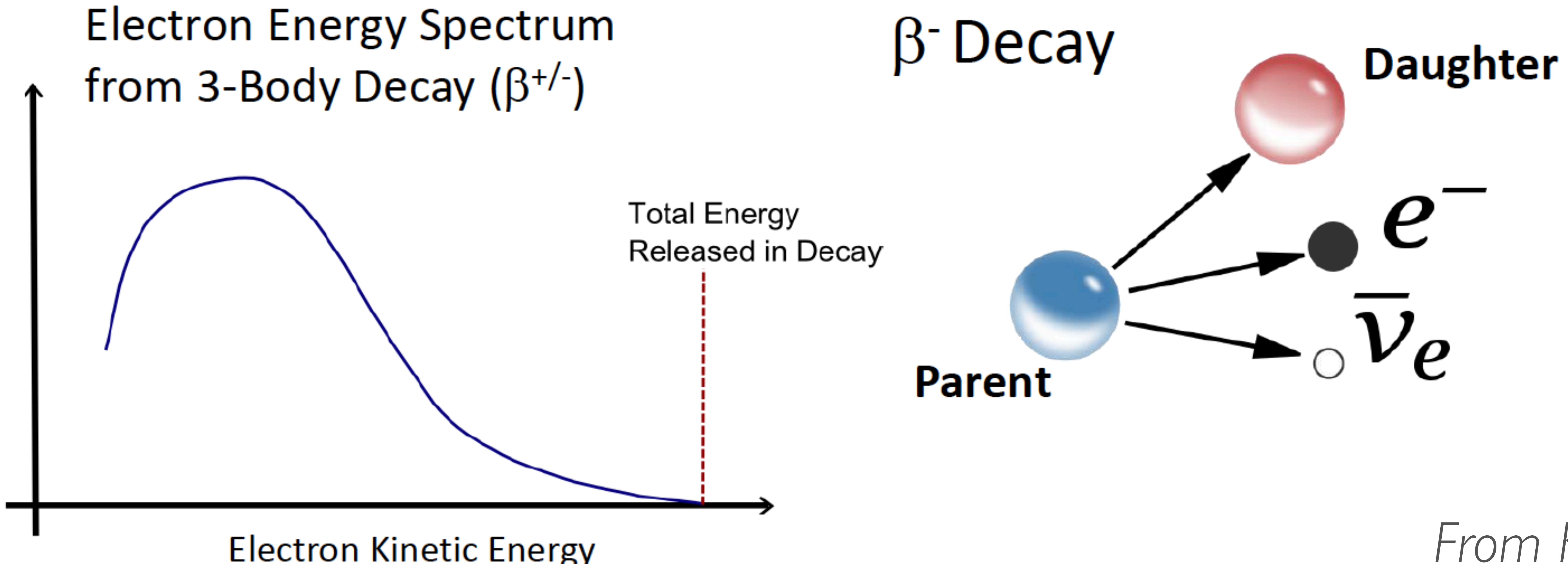
$$\nu_s \rightarrow e^+ + e^- + \nu$$

- Lower threshold from electron mass
- Search for electron and positrons in the detectors
- Covers much higher neutrino mass unto an order of magnitude



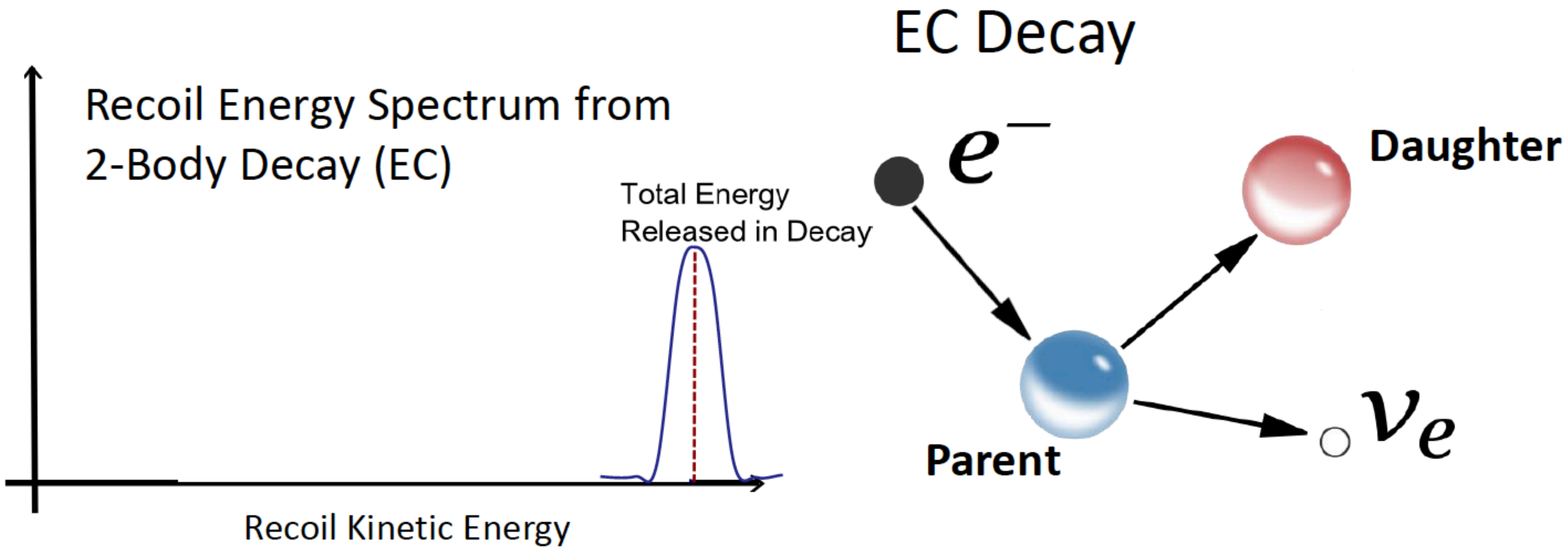
Single Isotope Decays





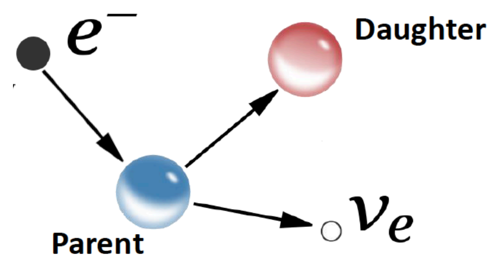
From K. Leach at Neutrino 2022

Single Isotope Decays



From K. Leach at Neutrino 2022

EC with Single Isotope: Rate Based



- Solar neutrino experiments GALLEX and SAGE used ^{51}Cr and ^{37}Ar as calibration sources
- Only few β decay peaks - Cleaner signature
- ^{71}Ga captures neutrino and produces ^{71}Ge
- ^{71}Ge chemically extracted and counted

Radioactive sources

747 keV (81.6%)
427 keV (9.0%)
752 keV (8.5%)
432 keV (0.9%)

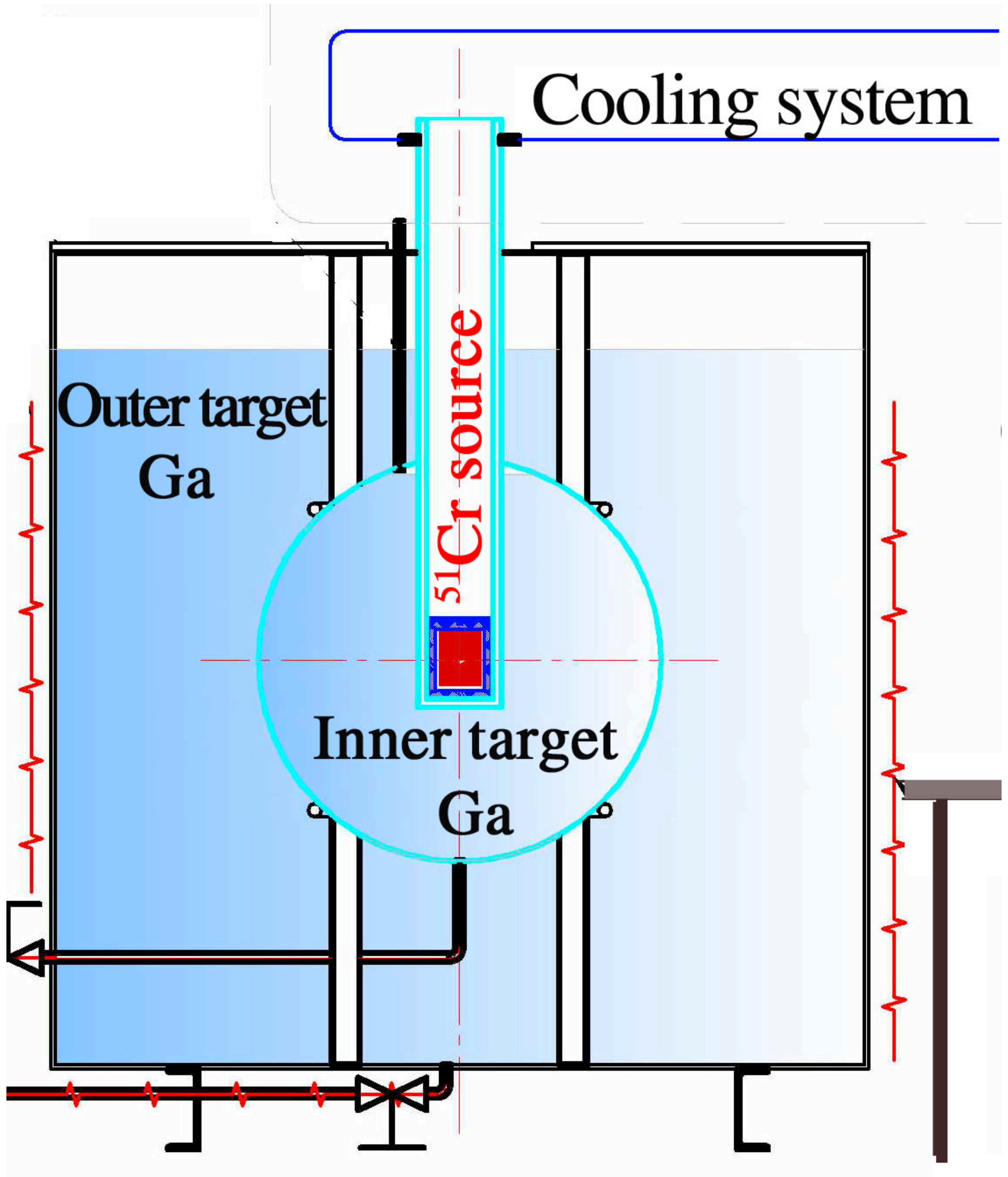
$$e^- + \boxed{^{51}\mathrm{Cr}} \rightarrow {}^{51}\mathrm{V} + \boxed{\nu_e}$$

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

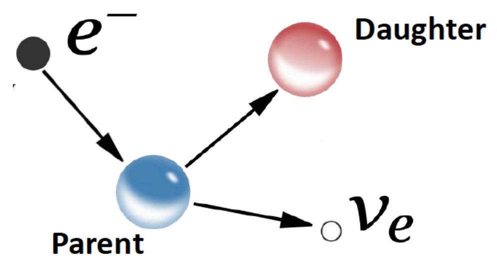
813 keV (9.8 %)
811 keV (90.2 %)

Detection:

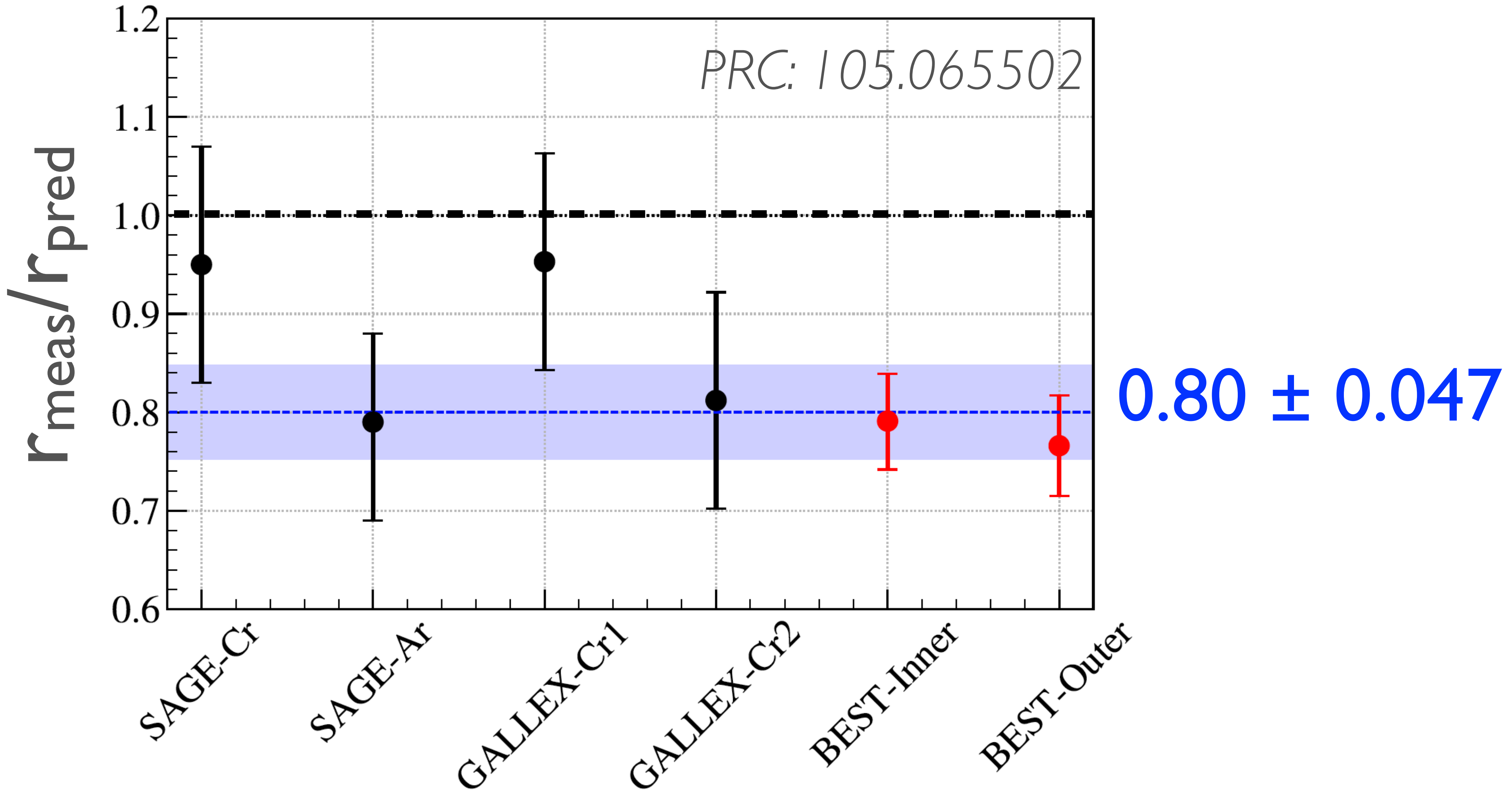
$$\boxed{\nu_e} + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + \mathrm{e}^-$$

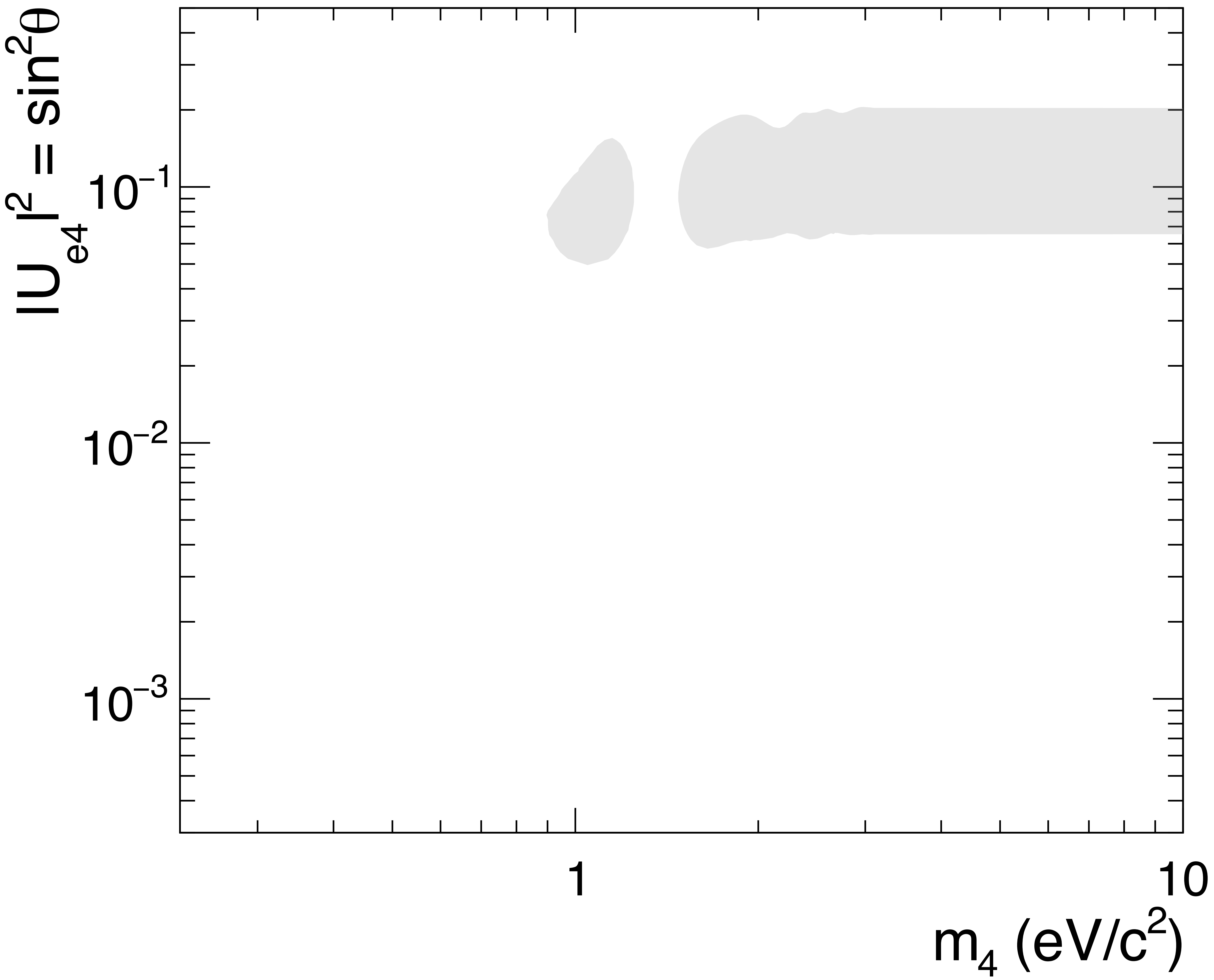


Gallium Anomaly

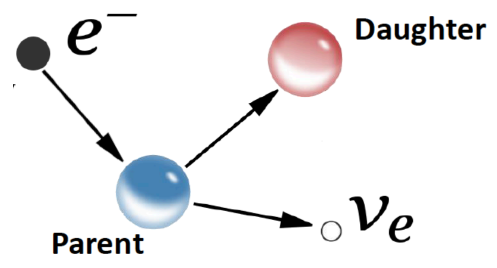


- Measured rate lower than expected in three different experiments
- Combined measured rate: 0.80 ± 0.047 (> 4σ)
- Includes measurement in a two-zone setup by BEST
- Conventional nuclear physics can't resolve the large discrepancy

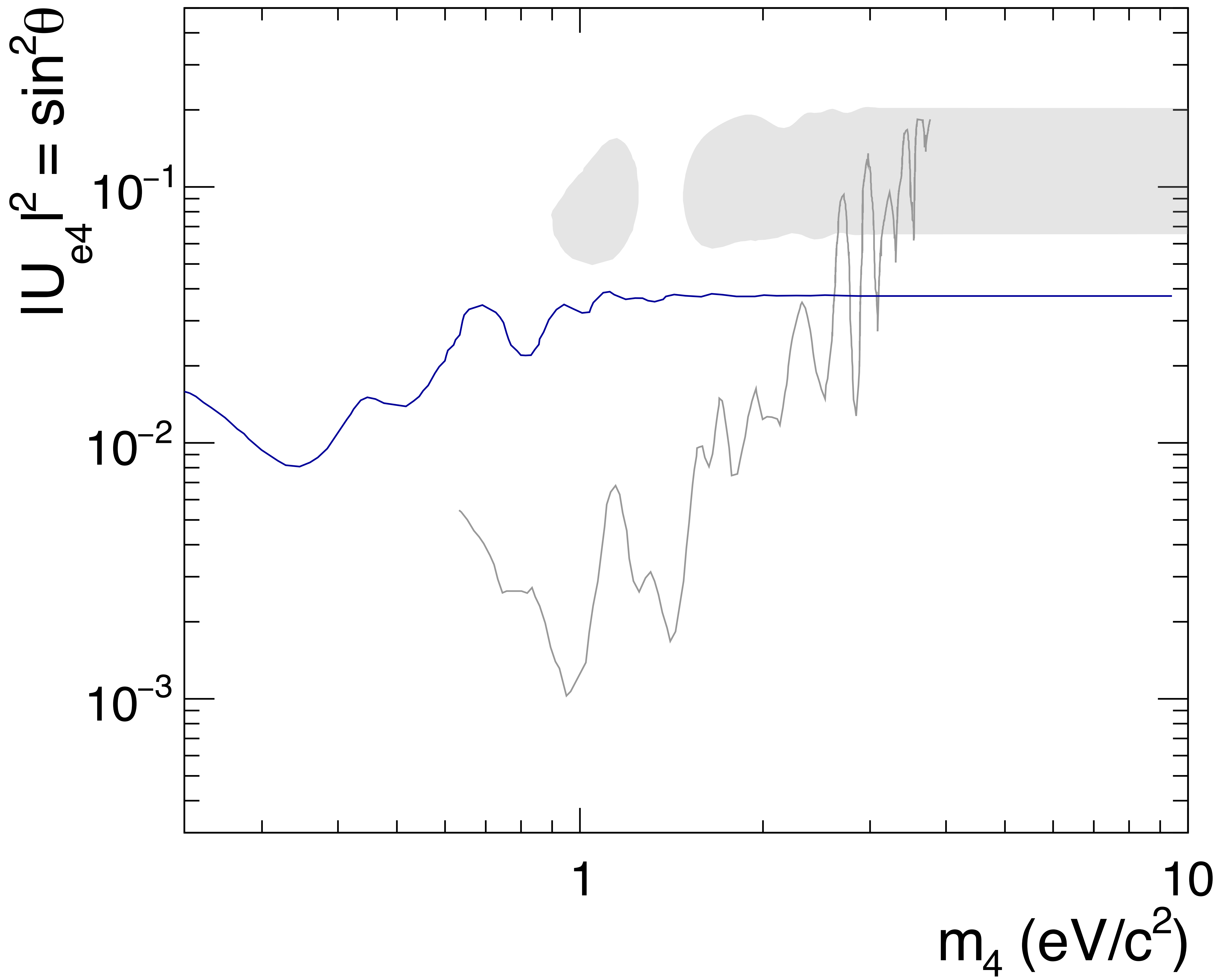




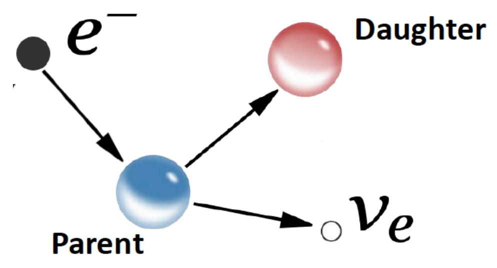
Comparison in Reactor and Gallium Experiments



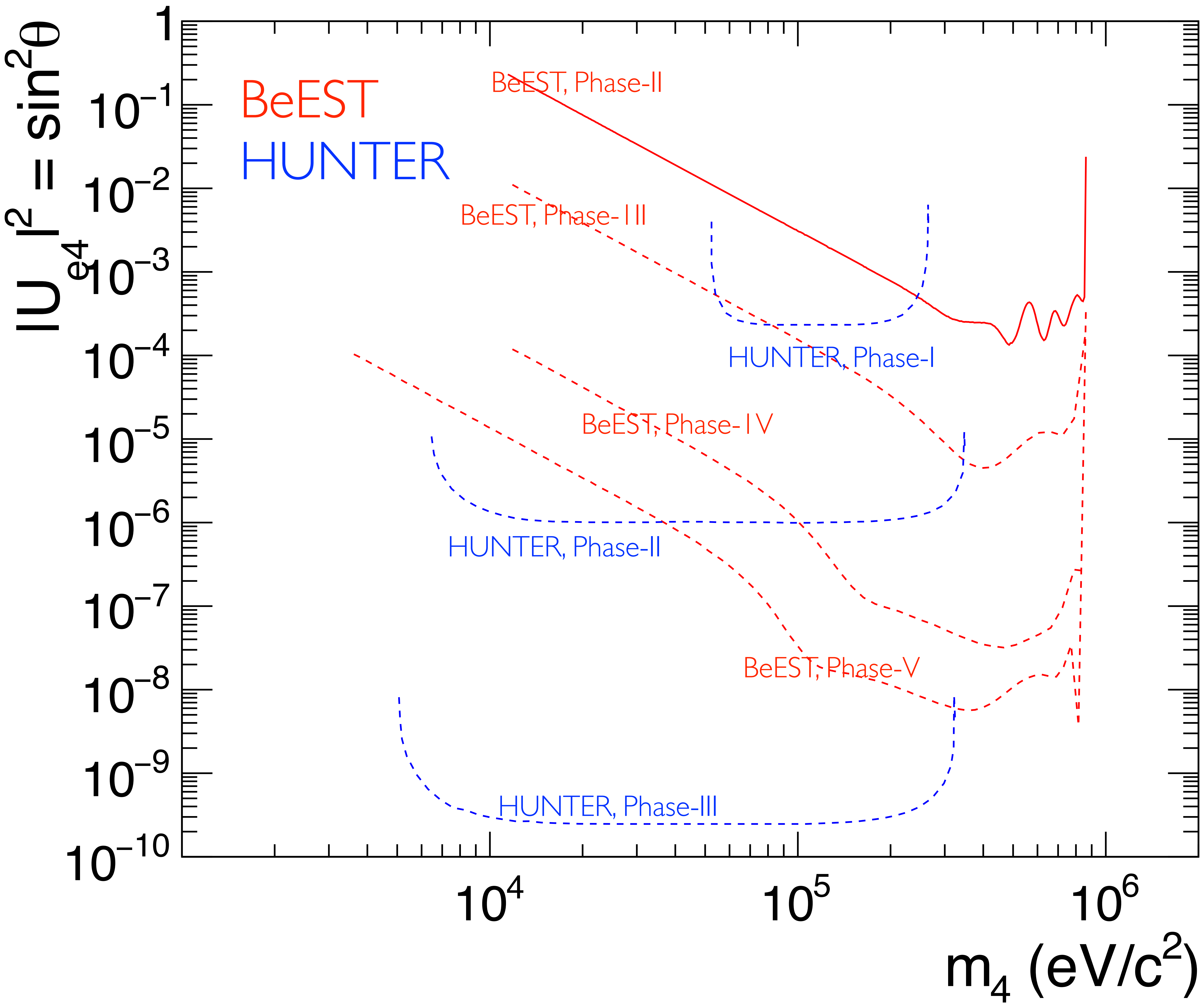
- The deficit from GA is too high to be compatible with reactor rates
- Also major portions of 3+1 suggested parameter space by GA excluded by relative reactor spectral data
- BEST experiment with two zones still saw similar deficit
- Plans in future to look at a higher energy isotope
  - Valuable for high frequency oscillations



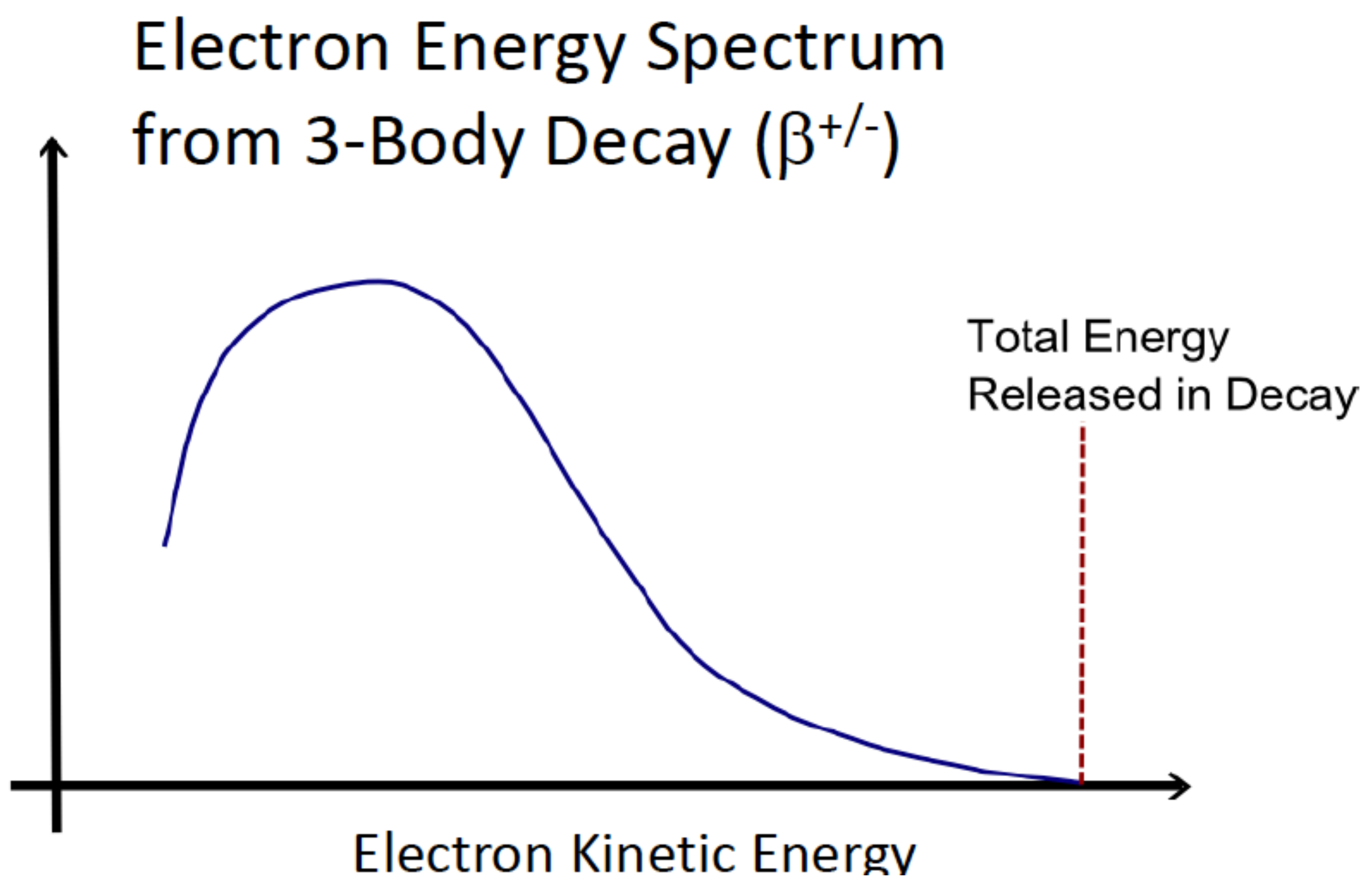
EC with Single Isotope: Recoil Measurements: keV-scale

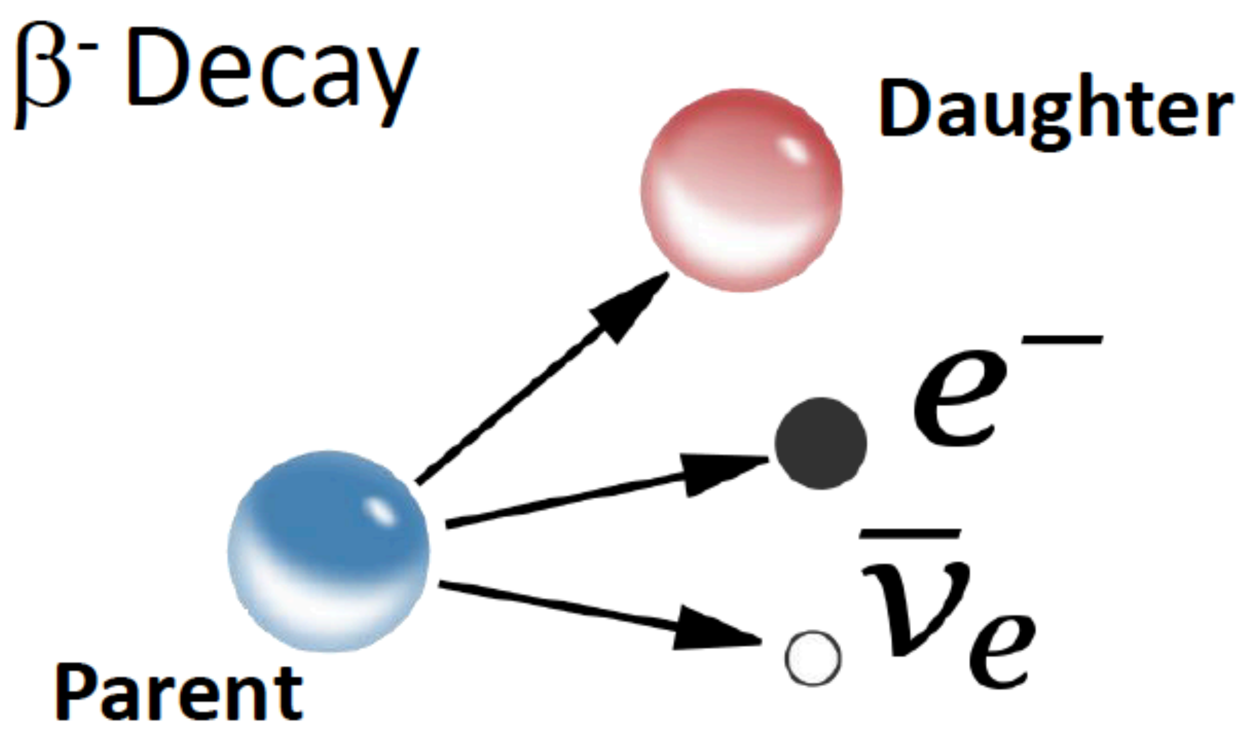


- EC to search for keV-scale steriles
- Two body decay: Peaks (vs spectrum in β decays)
- Nuclear recoils carry all the information of neutrino mass
- More details in K. Leach's talk
- Major ongoing efforts to cover upto 10 orders in mixing in a phased approach



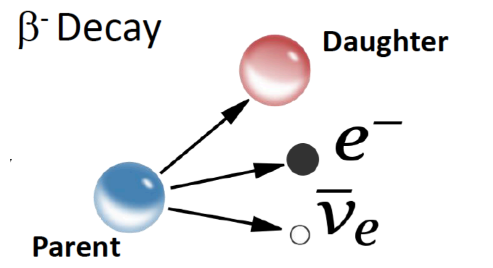
Single Isotope Decays



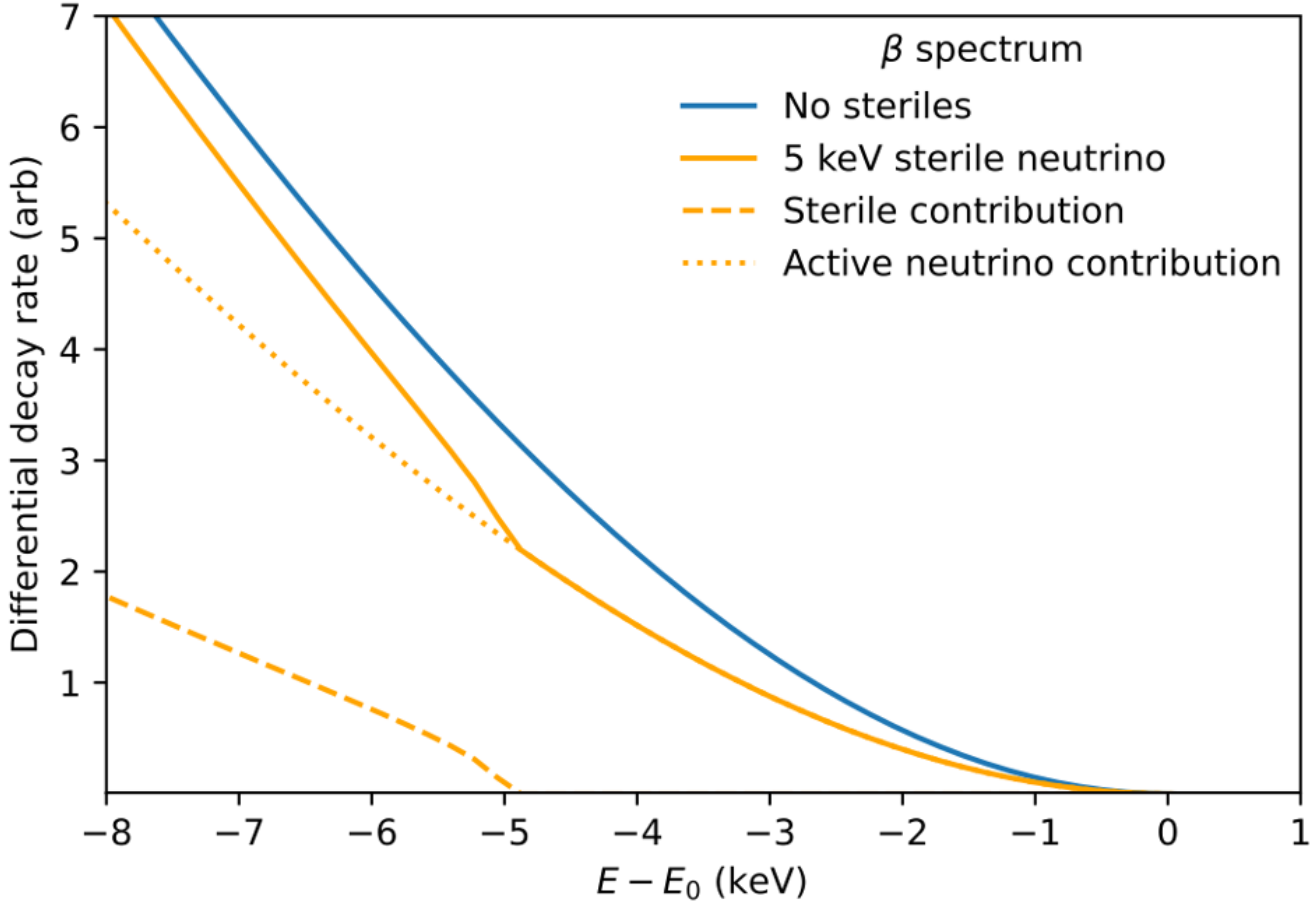


From K. Leach at Neutrino 2022

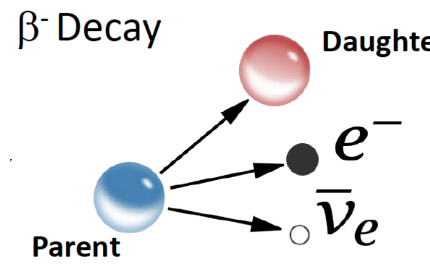
Sterile Searches with Beta Decay Spectrum



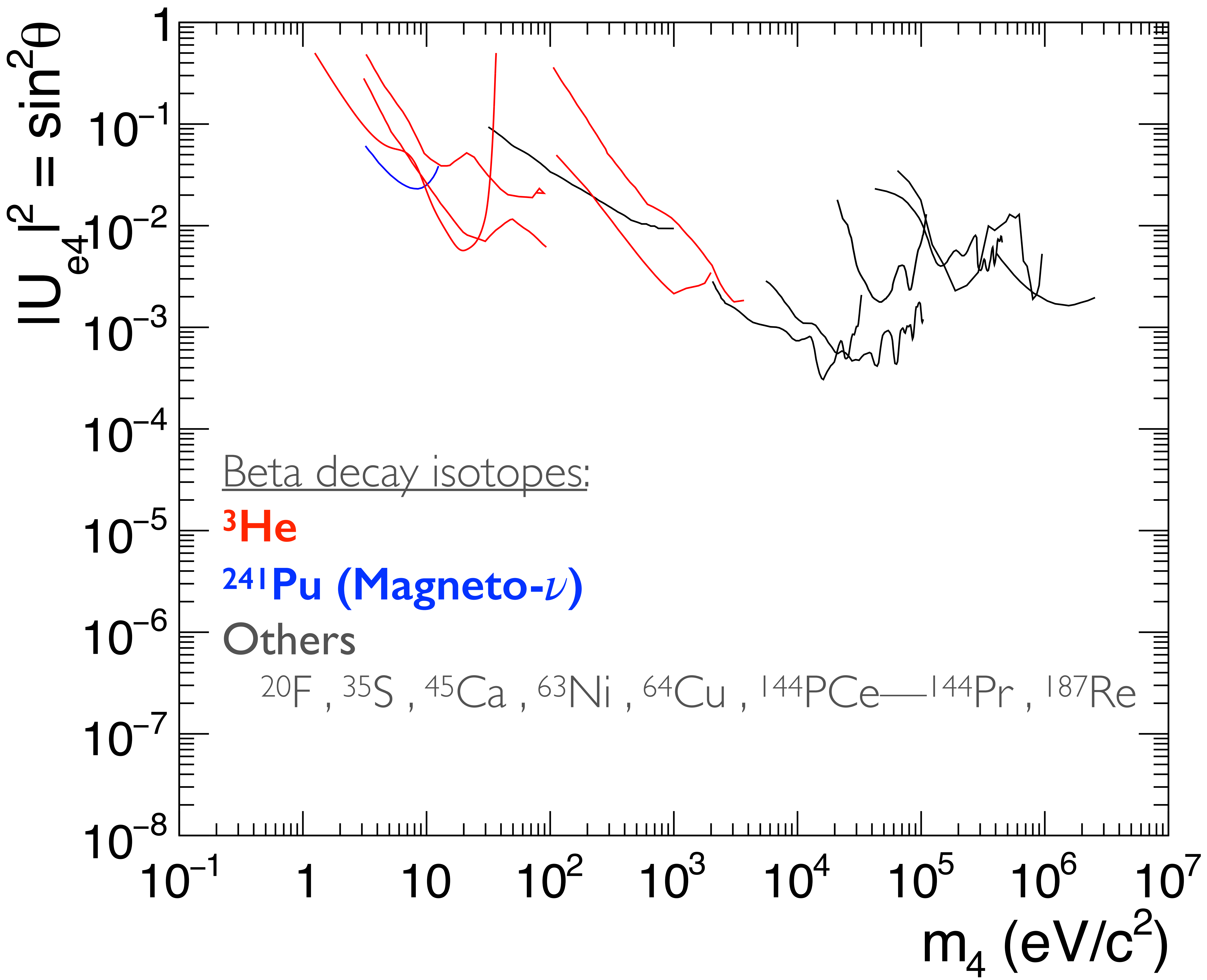
- β decay is a three body problem
- Continuous electron spectrum
- Neutrino mass states cause a distortion (kink) in the beta decay spectrum
- Location of the kink depends on the mass of the sterile state
- Magnitude depends on the mixing angle
- Higher energy limited by the end point energy of the spectrum



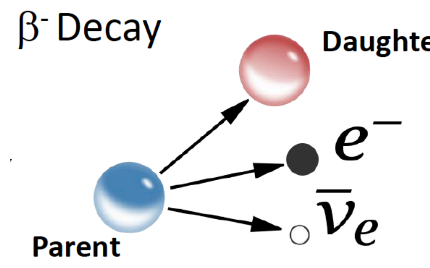
Beta Decay Spectrum Measurements: eV—MeV



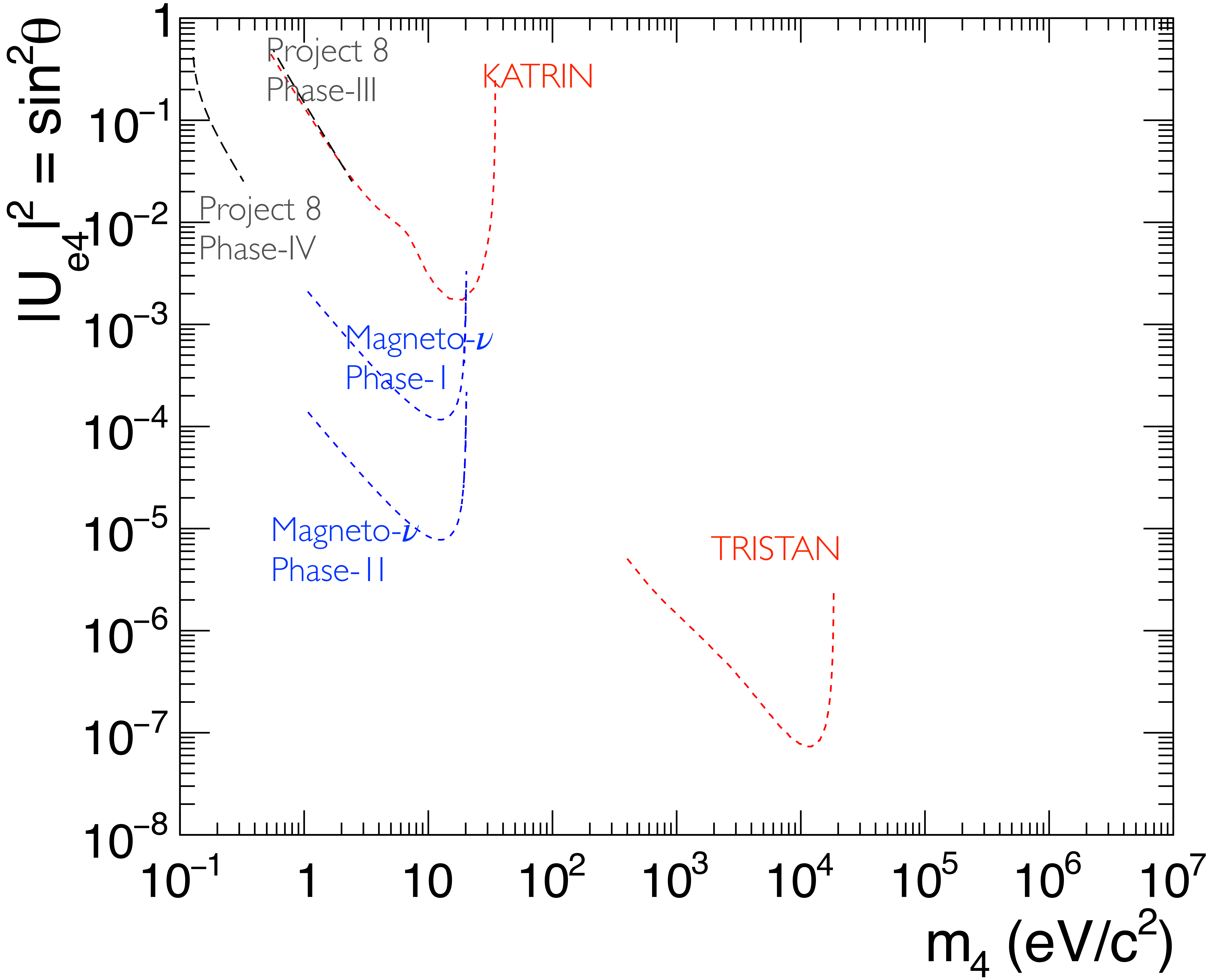
- Several experiments have placed limits using β decay spectra measurements using multiple isotopes
- Six order of magnitude covered in mass scale covered
- In many cases, not the primary goal of the experiment



Beta Decay Spectrum Measurements: Future

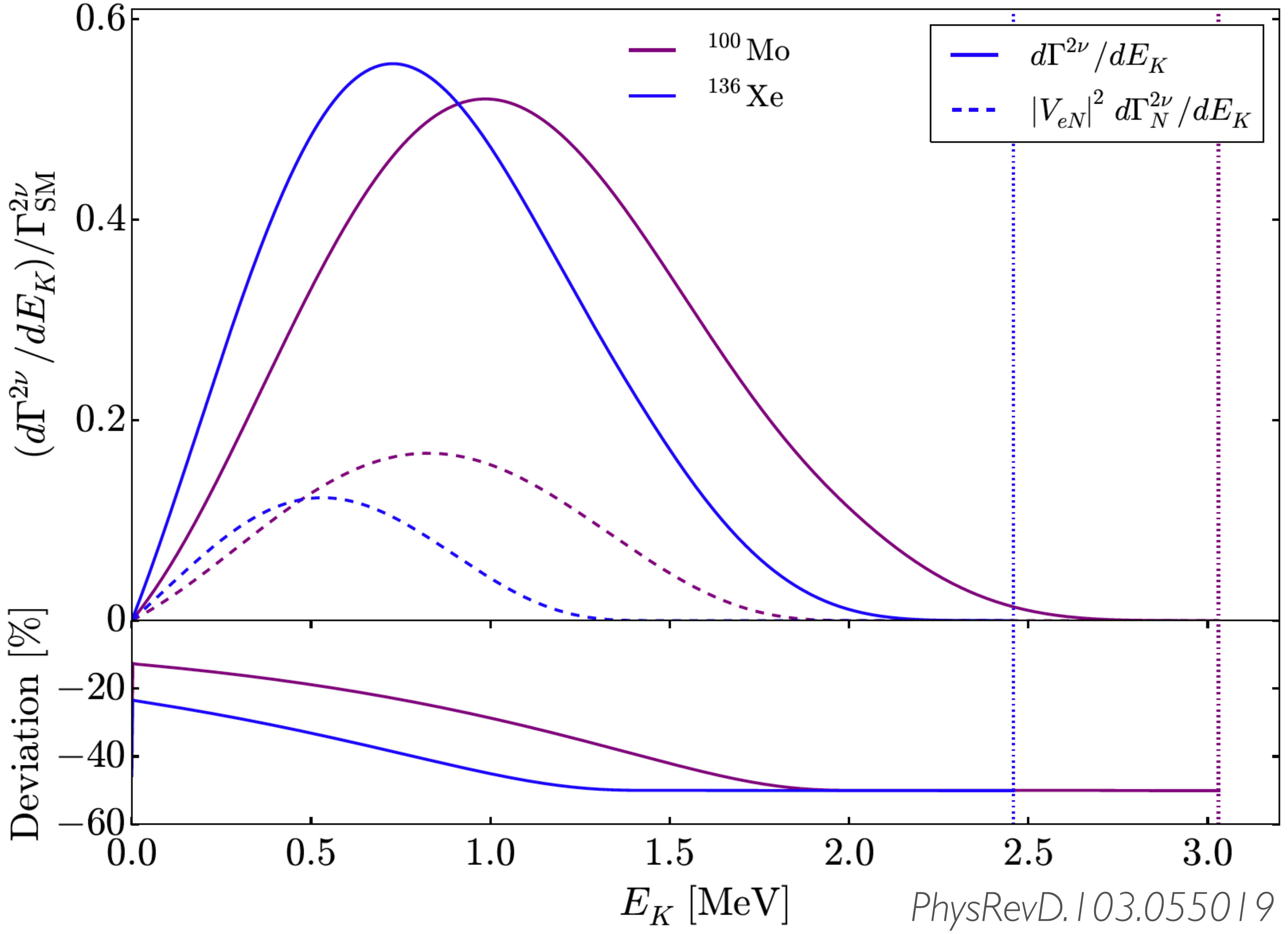


- Several experiments have placed limits using β decay spectra measurements using multiple isotopes
- Six order of magnitude covered in mass scale covered
- In many cases, not the primary goal of the experiment
- Several ongoing, upcoming and future experiments: Increase coverage in mass and mixing



Double Beta Decay Experiments

- Double beta decay experiments search for the Majorana nature of neutrinos
- Focus is on end point region: Look for peak near the end point
- Overall spectrum provides other opportunities
- Sterile neutrinos modifies energy spectrum (in the low energy region)
- Could search for sterile neutrinos by looking for the deviation in the spectrum

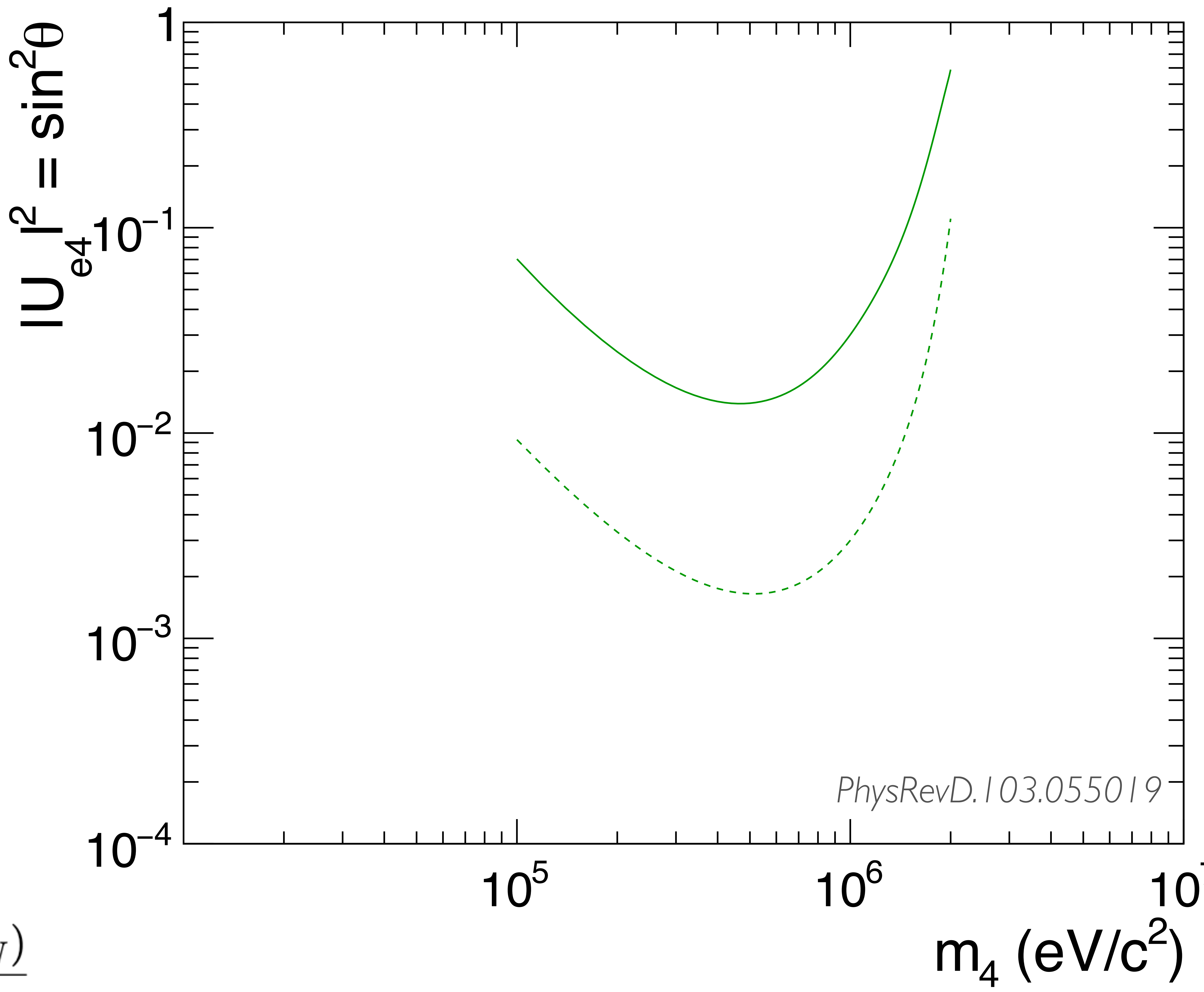


PhysRevD.103.055019

$$\frac{d\Gamma^{2\nu}(\boldsymbol{\xi})}{dE_K} = (1-|V_{eN}|^2)^2\frac{d\Gamma^{2\nu}_{\mathrm{SM}}}{dE_K} + (1-|V_{eN}|^2)|V_{eN}|^2\,\frac{d\Gamma^{2\nu}_N(m_N)}{dE_K}$$

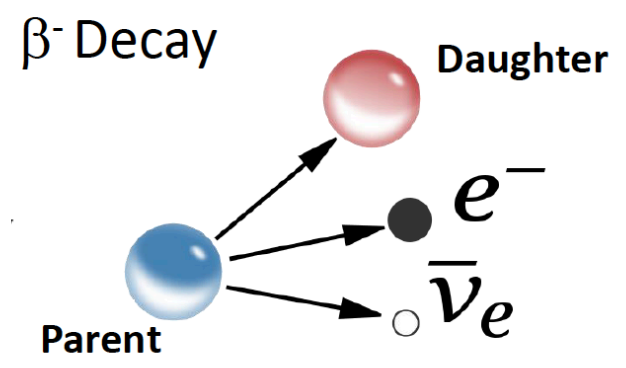
Double Beta Decay Experiments

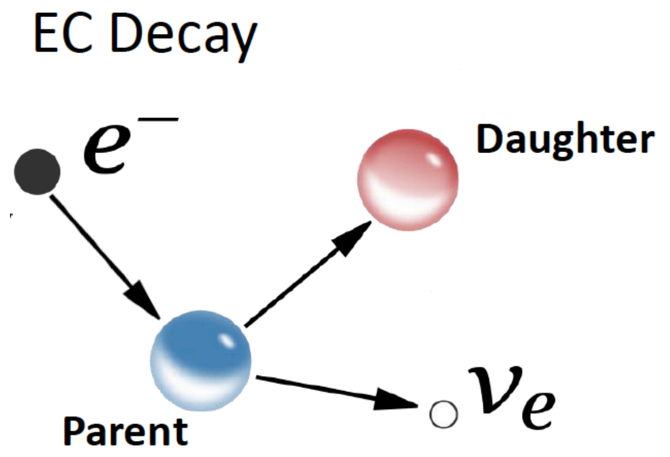
- Double beta decay experiments search for the Majorana nature of neutrinos
- Focus is on end point region: Look for peak near the end point
- Overall spectrum provides other opportunities
- Sterile neutrinos modifies energy spectrum (in the low energy region)
- Could search for sterile neutrinos by looking for the deviation in the spectrum

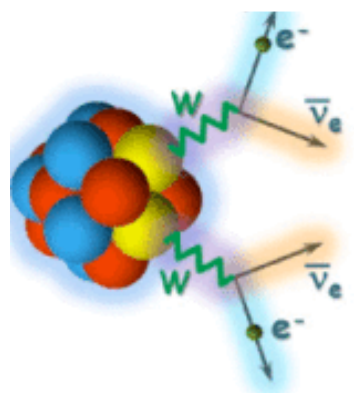


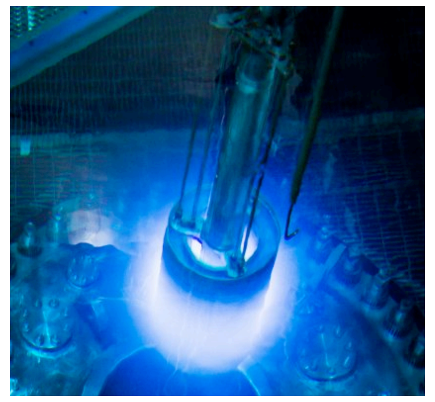
$$\frac{d\Gamma^{2\nu}(\xi)}{dE_K} = (1-|V_{eN}|^2)^2 \frac{d\Gamma^{2\nu}_{\rm SM}}{dE_K} + (1-|V_{eN}|^2)|V_{eN}|^2 \frac{d\Gamma^{2\nu}_N(m_N)}{dE_K}$$

Summary and Outlook

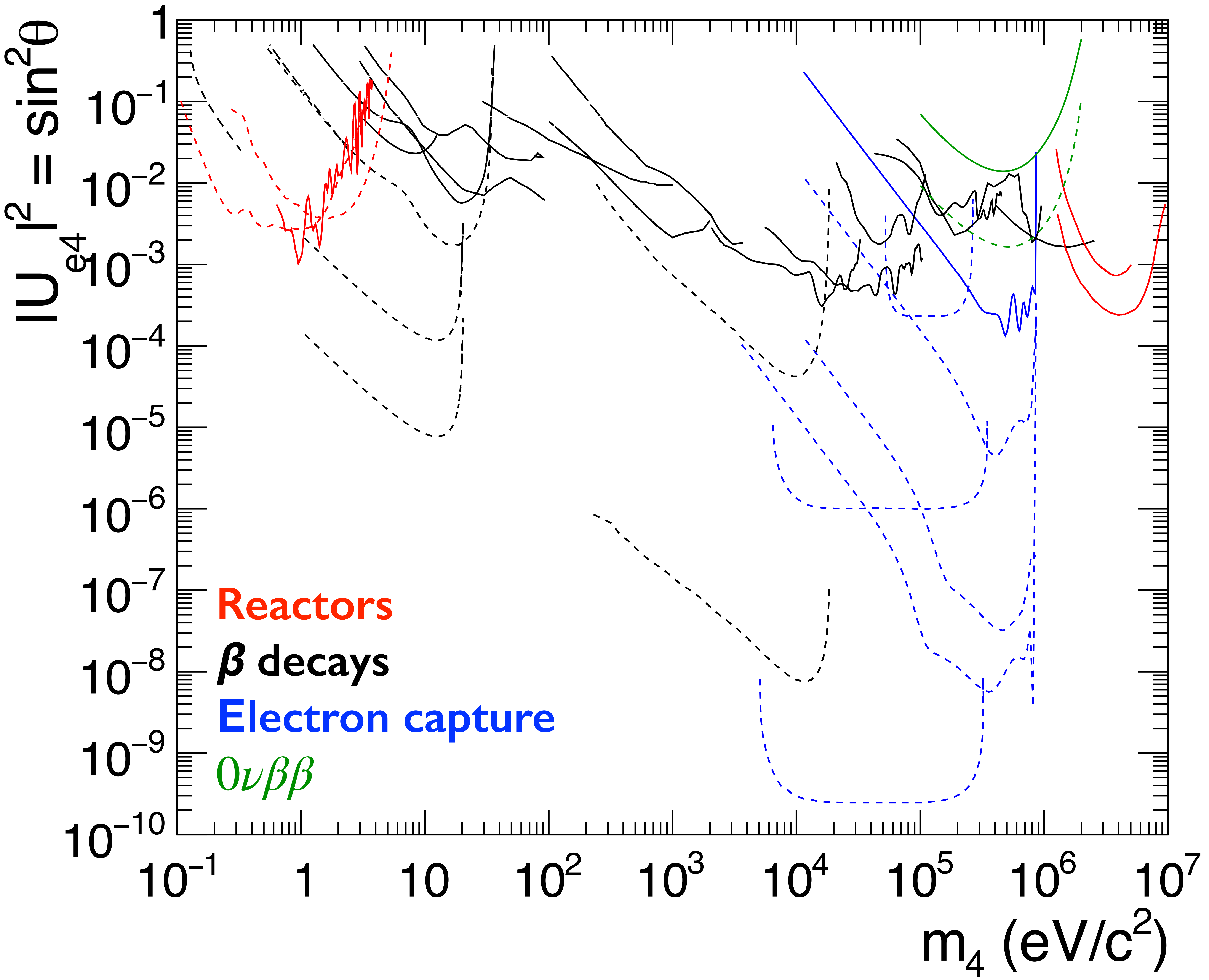








- Beta decay and electron capture are powerful tools to search for sterile neutrinos
- Using a variety of probes and an array of available isotopes, sterile neutrinos could be searched over several orders of magnitude in mass
- Ongoing dedicated efforts are expected to provide sensitivity over a large range of mixing angle
- Using different β-decay related probes provide complementarity and cross-checks



Credits

- Walter Pettus
- Kyle Leach, Vedran Brdar
- Patrick Bolton, Franck Deppisch
  - https://www.hep.ucl.ac.uk/~pbolton
- Jeffrey Berryman, Pilar Coloma, Patrick Huber, Thomas Schwetz, Albert Zhou
  - *https://doi.org/10.1007/JHEP02(2022)055*
- Carlo Giunti, Yufeng Li, Christopher Ternes, Zhao Xi
  - *https://doi.org/10.1016/j.physletb.2022.137054*
- All experimental collaborations, of course

Back up

Motivation for Sterile Neutrino Searches at Reactors

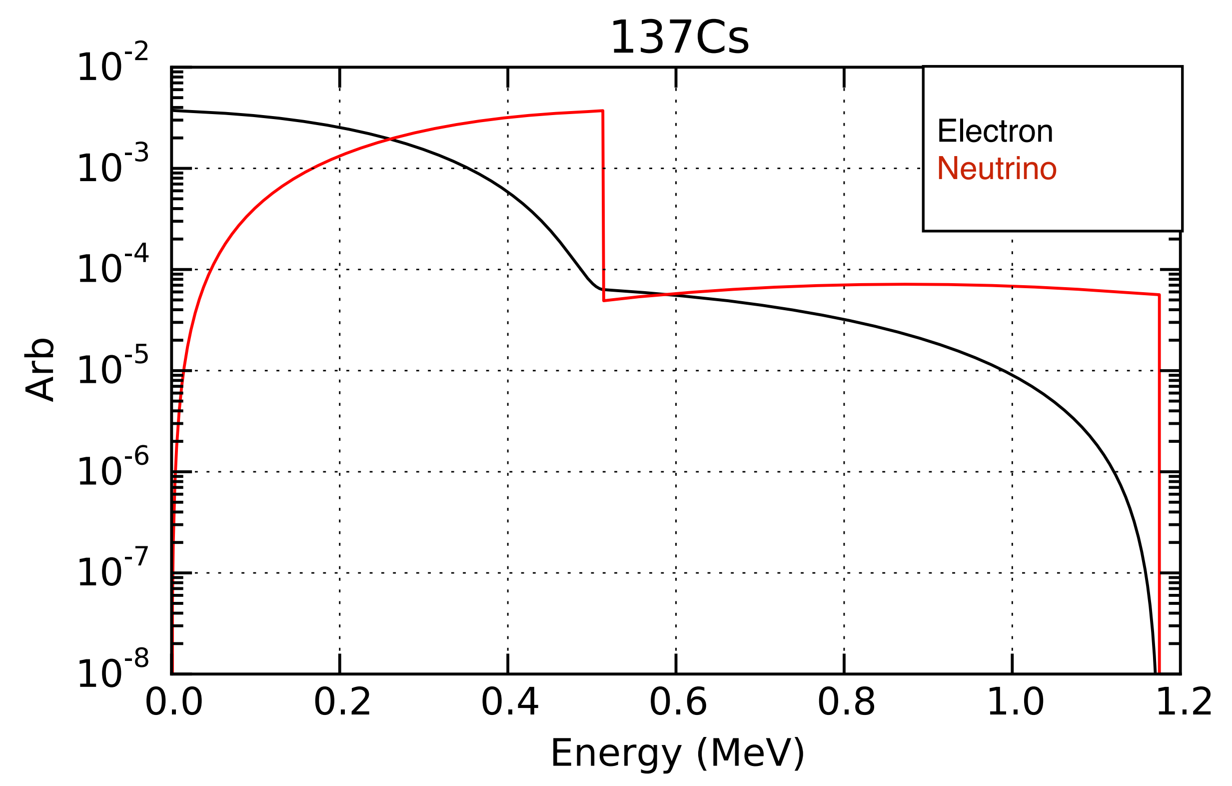
Predicted Spectrum

Decay Rate

Spectrum

$$S(E_{\bar{\nu}}) = \sum_{i=0}^{n} \boxed{R_i} \sum_{j=0}^{m} \boxed{f_{ij}} \boxed{S_{ij}(E_{\bar{\nu}})}$$

Branching Fraction

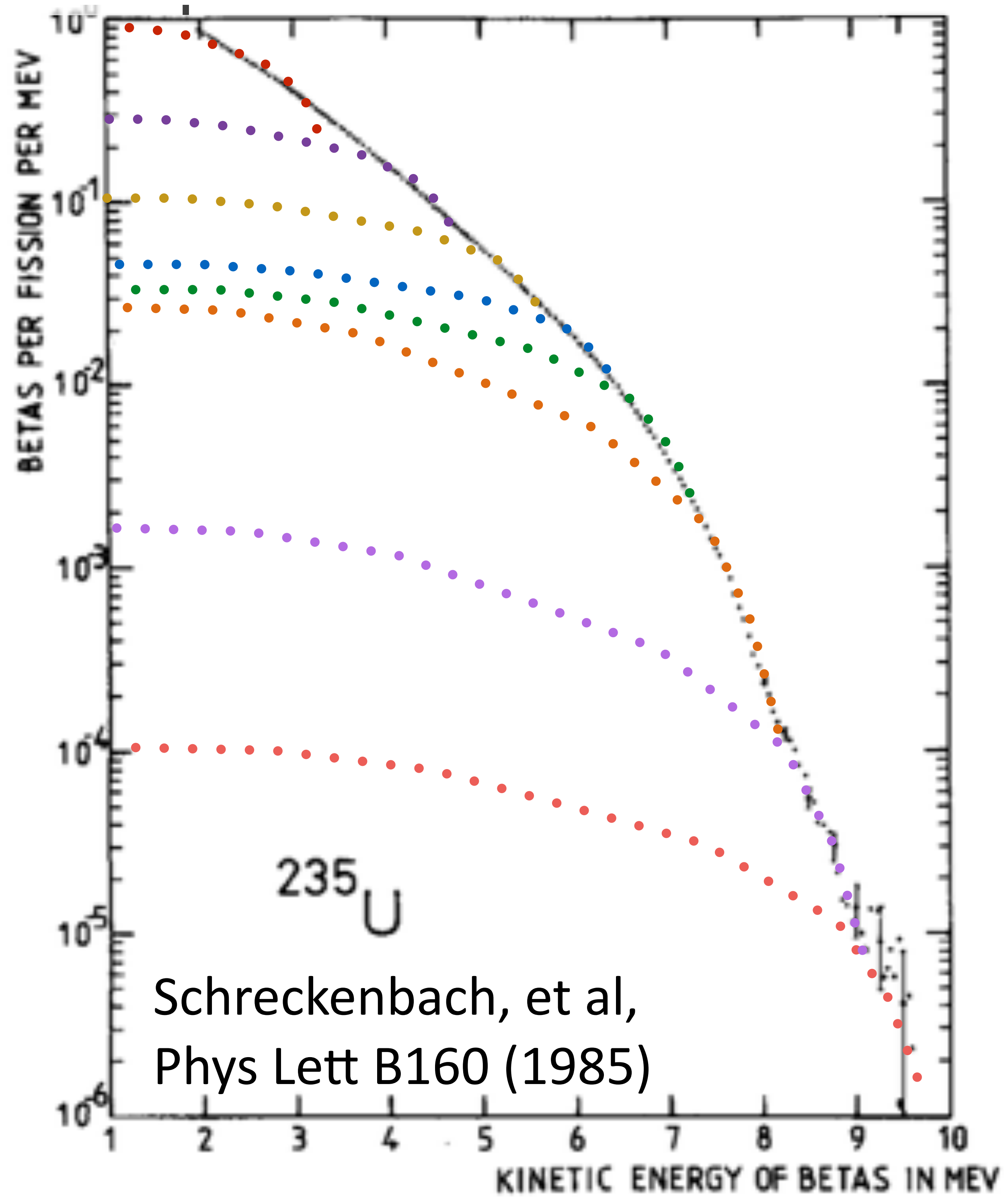


ab initio **approach**

- Use existing databases and sum the spectra from all the beta decay branches
- *1000s of branches; Databases are incomplete/wrong*

Conversion method

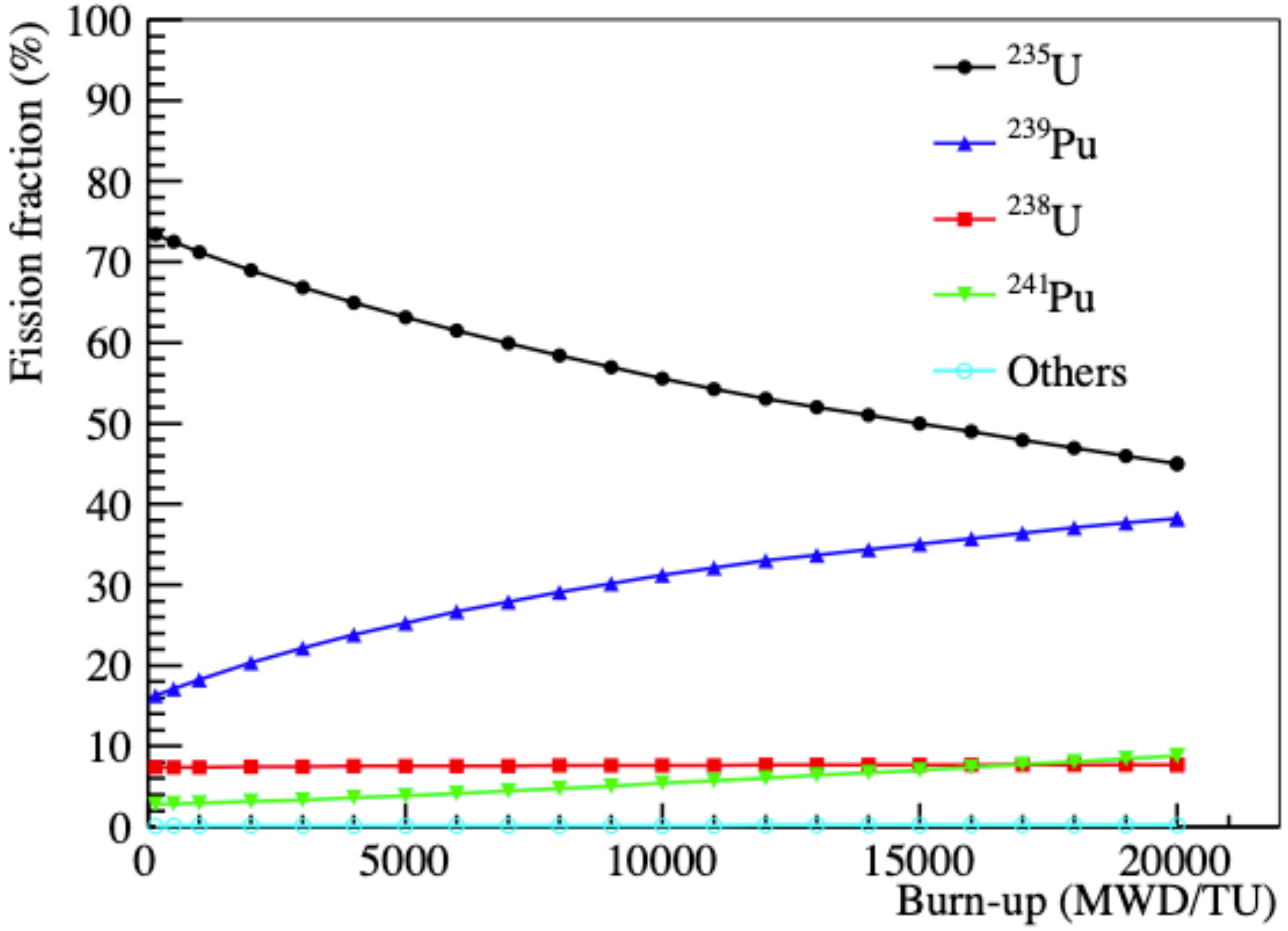
- Measure beta spectrum and fit it to virtual branches to convert to neutrino spectrum
- *Is all relevant physics captured by virtual beta branches*

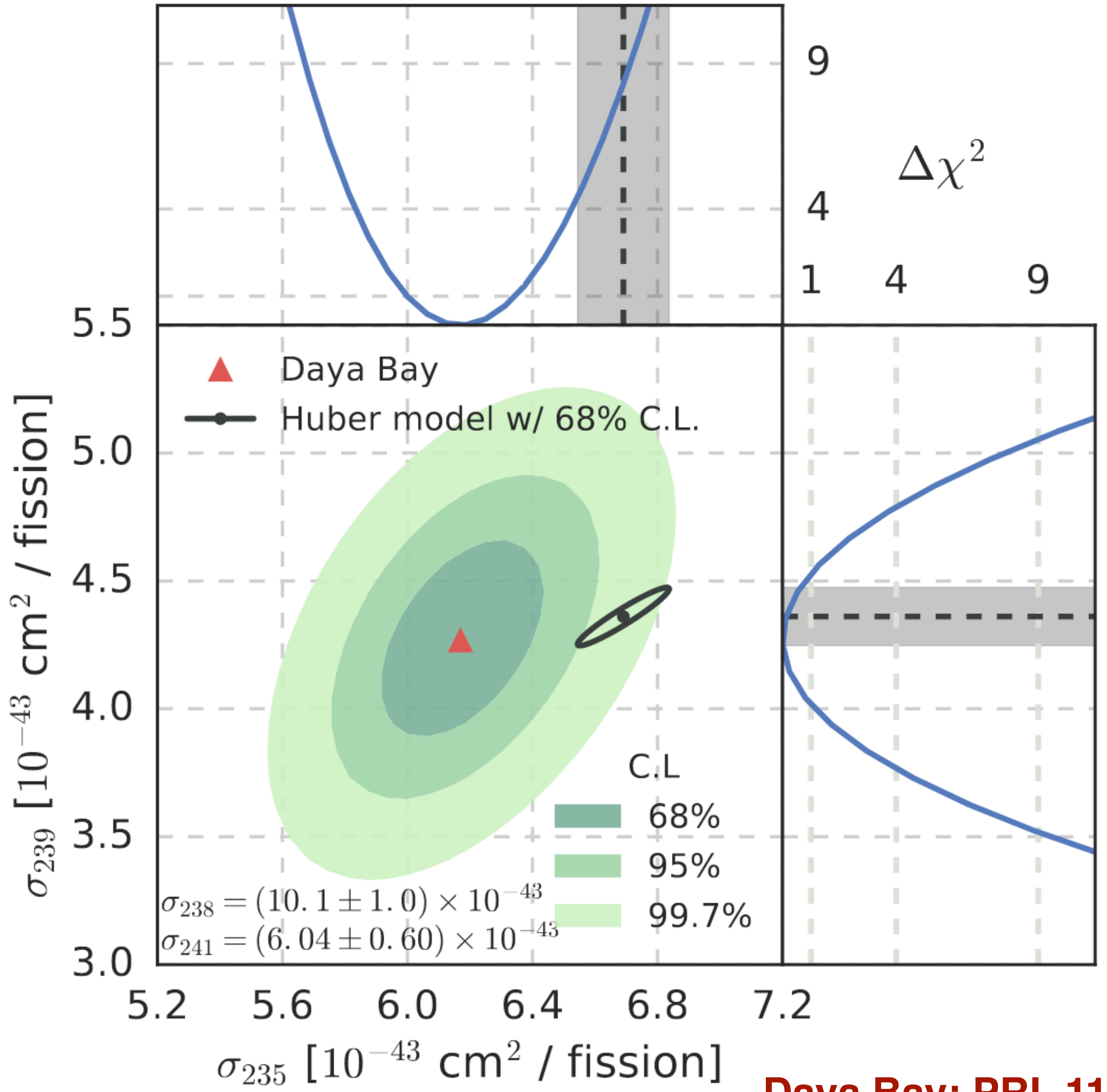


Reactor antineutrino predictions are very complicated

More Reactor Neutrino Context

- Daya Bay measures neutrino flux as a function of fission fractions of ^{235}U/^{239}Pu
- One can extract the contribution (IBD yield) of single isotope to the measured flux
- Measured ^{235}U disagrees but ^{239}Pu agrees well with the predictions
- Similar results from RENO
- **^{235}U seems like the problematic isotope**



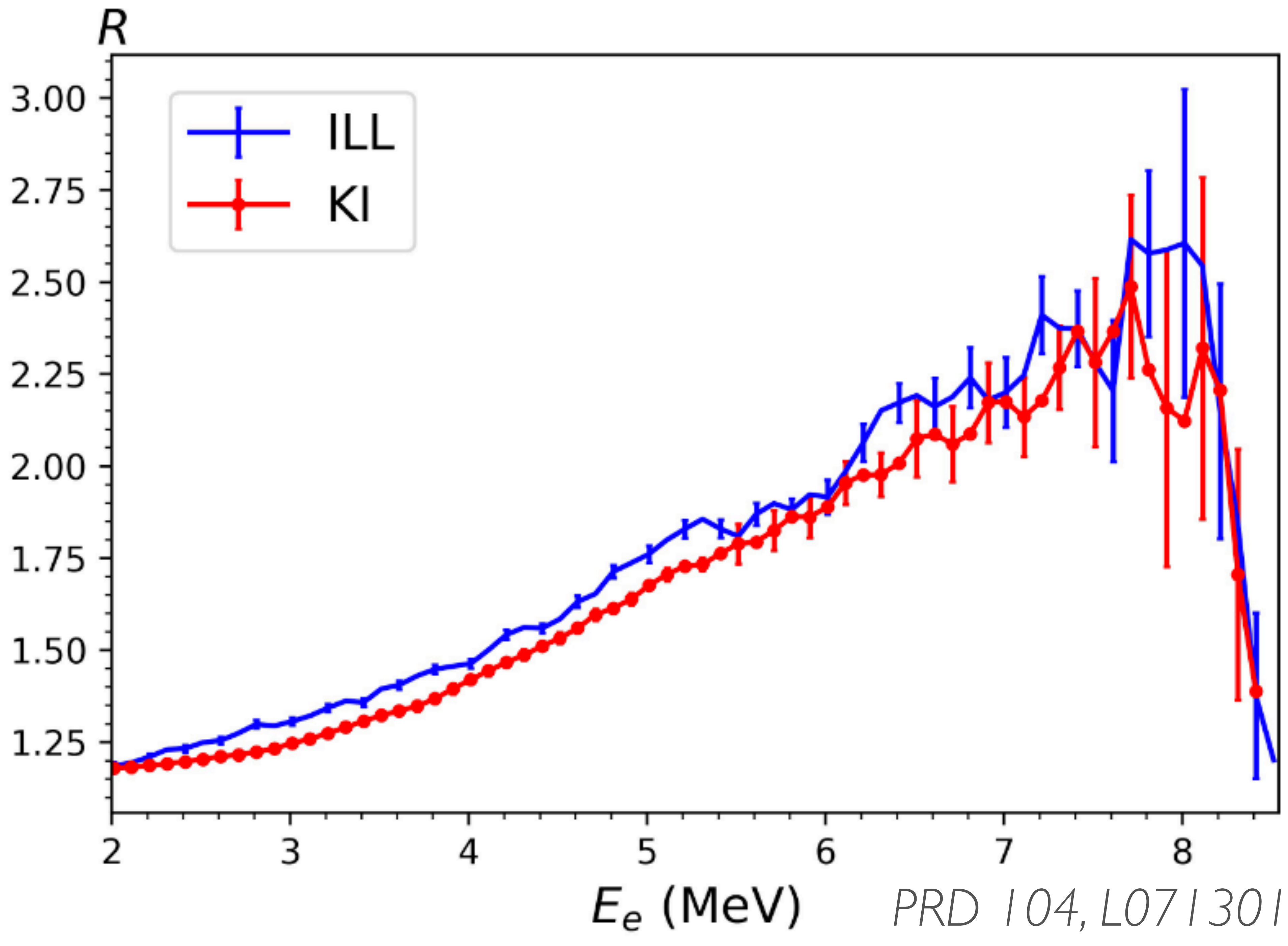


Daya Bay: PRL 118 (2017)

Even More Reactor Neutrino Context

$$R \equiv \frac{{}^eS_5}{{}^eS_9} = \frac{\sigma_9}{\sigma_5} \cdot \frac{N_9}{N_5} \cdot \frac{n_5}{n_9},$$

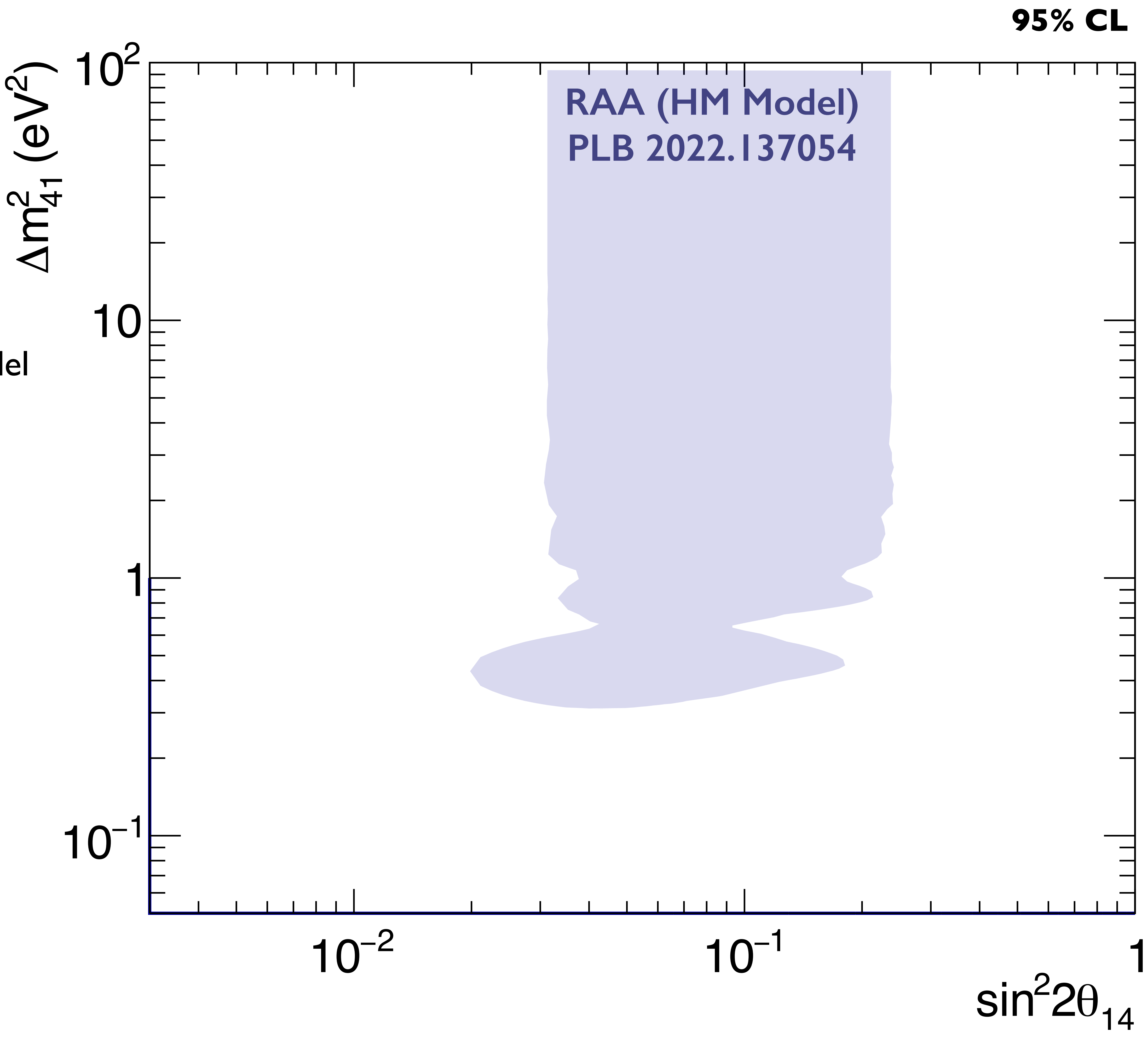
- Conversion method is reliant on the β-decay measurements done at ILL, France in 1980s
- Recent claim: Issue with calibration for the original ILL β-decay measurements
- New measurement of ^{235}U/^{239}Pu β-decay spectra performed at Kurchatov Institute
- Shows that ^{235}U normalization was overestimated (assuming ^{239}Pu normalization is correct)
- No systematic uncertainties presented and peer-reviewed results not yet published



PRD 104, L071301

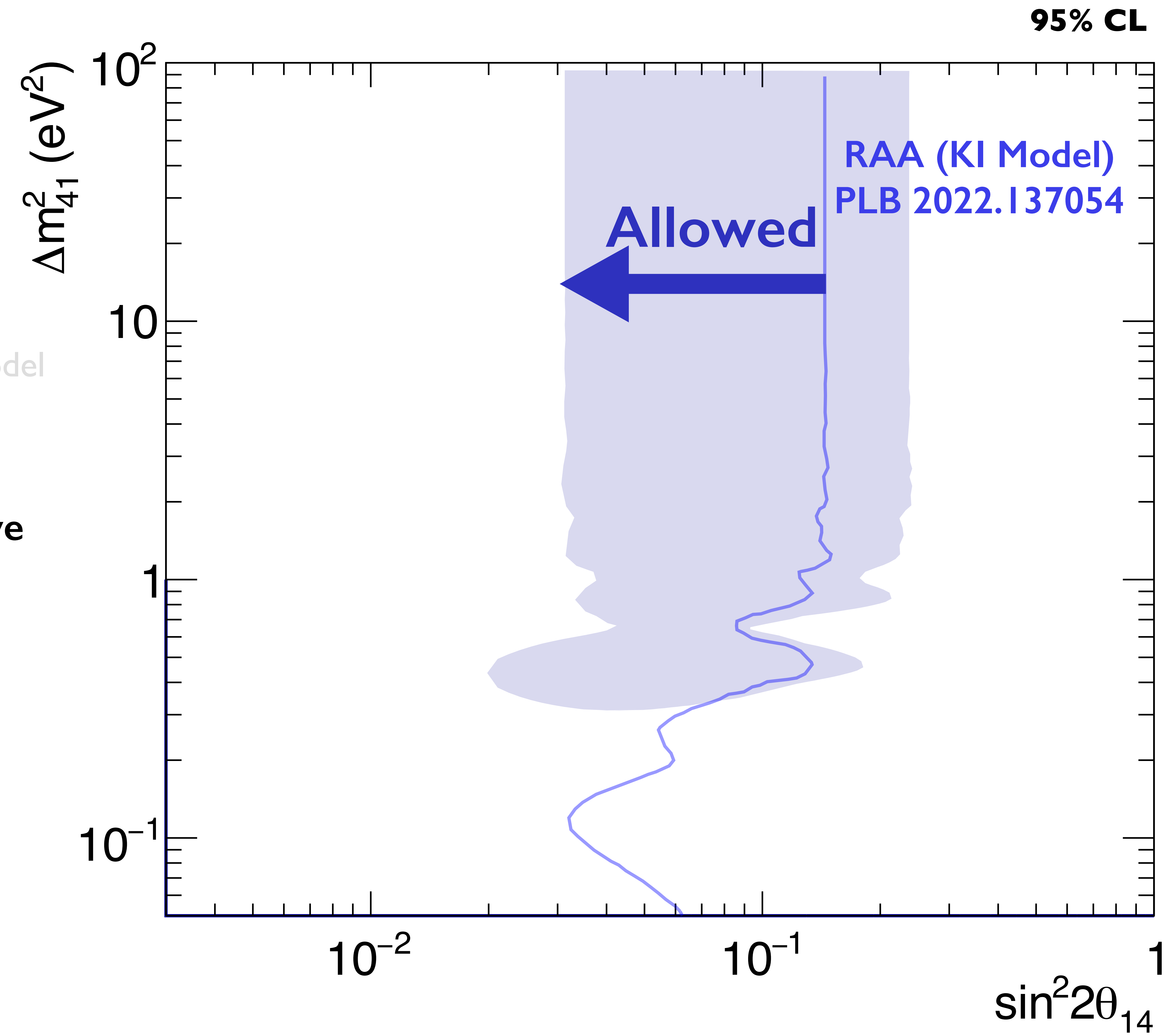
Current Reactor Neutrino Status

- Updated models:
  - KI model: Conversion based on updated beta decay measurements; smaller deficit
  - EF model: Summation based on improved nuclear databases; smaller deficit
- New models don't agree with canonical Huber-Mueller (HM) conversion model
- New data: Daya Bay + RENO evolution + STEREO prefer KI and EF models



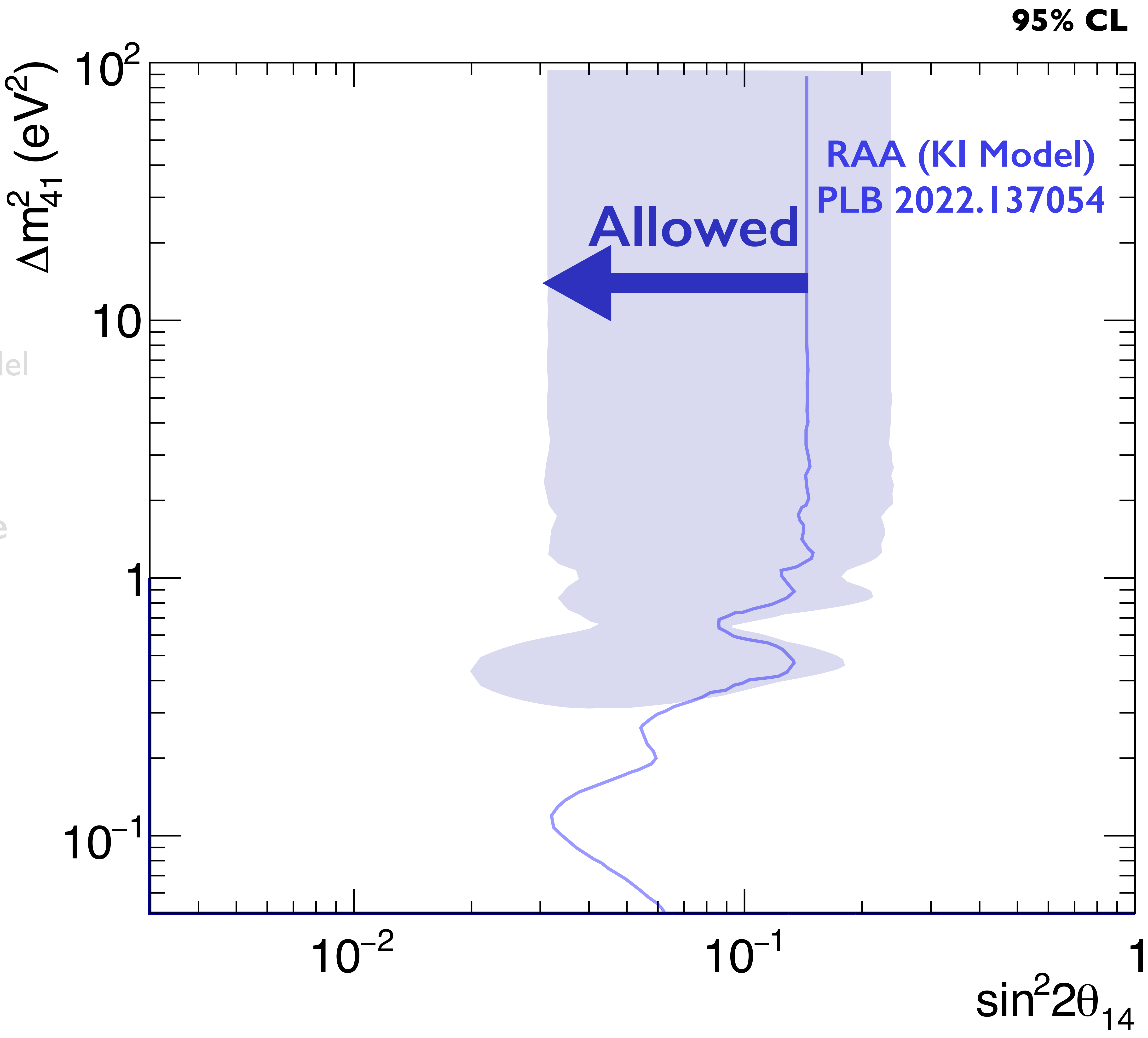
Current Reactor Neutrino Status

- Updated models:
  - KI model: Conversion based on updated beta decay measurements; smaller deficit
  - EF model: Summation based on improved nuclear databases; smaller deficit
- New models don't agree with canonical Huber-Mueller (HM) conversion model
- New data: Daya Bay + RENO evolution + STEREO prefer KI and EF models
- **Reactor mismodeling and sterile neutrinos not mutually exclusive**



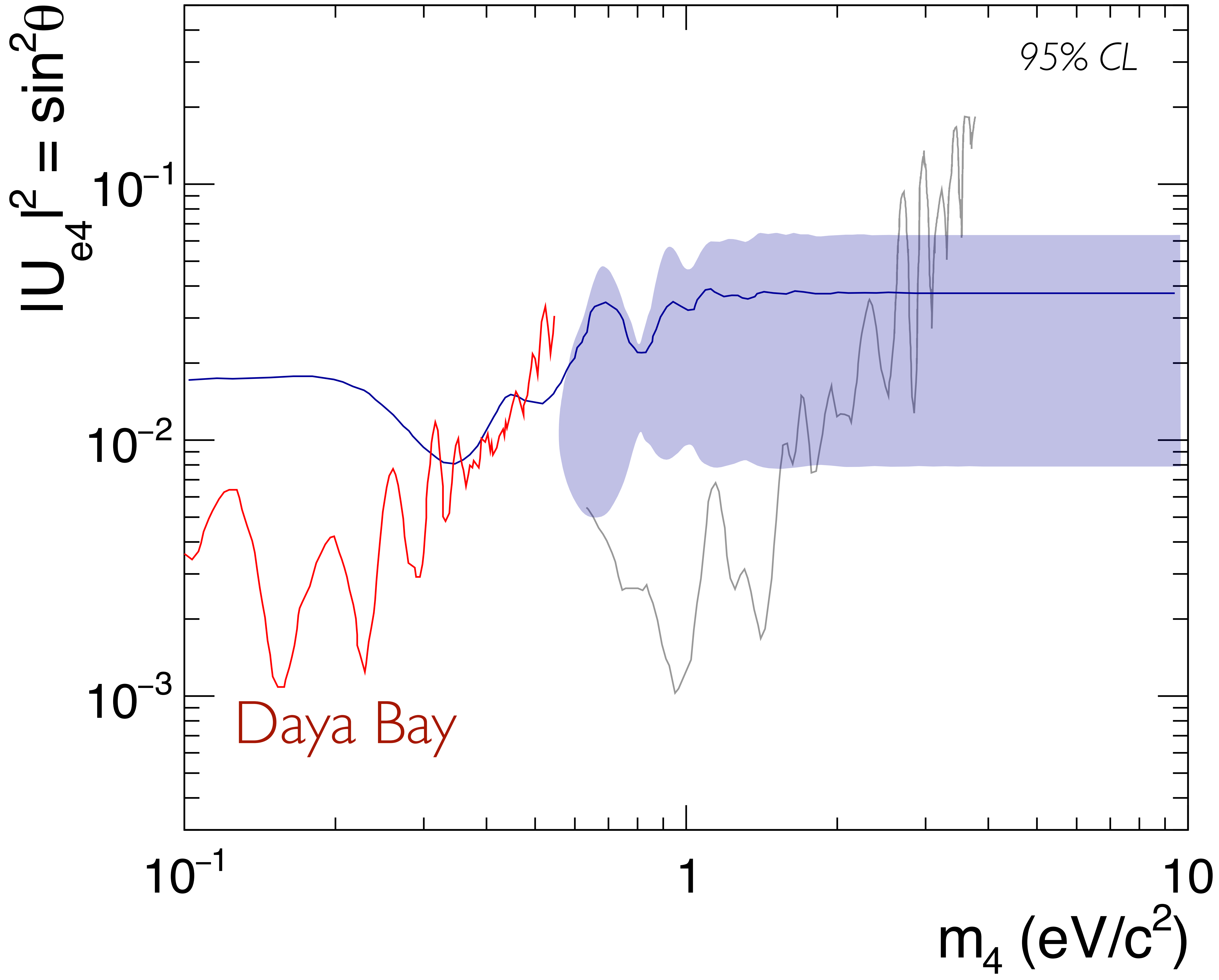
Current Reactor Neutrino Status

- Updated models:
  - KI model: Conversion based on updated beta decay measurements; smaller deficit
  - EF model: Summation based on improved nuclear databases; smaller deficit
- New models don't agree with canonical Huber-Mueller (HM) conversion model
- New data: Daya Bay + RENO evolution + STEREO prefer KI and EF models
- **Reactor mismodeling and sterile neutrinos not mutually exclusive**
- **Rely on baseline-dependent spectral measurements to mitigate model-dependence**



Long Baseline Reactor Experiment

- (Relatively) long baseline reactor experiments designed to measure θ_{13} could also search for sterile neutrinos
- Could use relative spectral comparison between detectors placed at different baselines
- Due to the baseline, sensitive to lower masses



Double Beta Decay Experiments

- Double beta decay experiments search for the Majorana nature of neutrinos
- Focus is on end point region: Look for peak near the end point
- Overall spectrum provides other opportunities
- Sterile neutrinos modifies energy spectrum (in the low energy region)
- Could search for sterile neutrinos by looking for the deviation in the spectrum
-

$$\frac{d\Gamma^{2\nu}(\boldsymbol{\xi})}{dE_K} = (1-|V_{eN}|^2)^2 \frac{d\Gamma^{2\nu}_{\rm SM}}{dE_K} + (1-|V_{eN}|^2)|V_{eN}|^2 \frac{d\Gamma^{2\nu}_{N}(n}{dE_K}$$