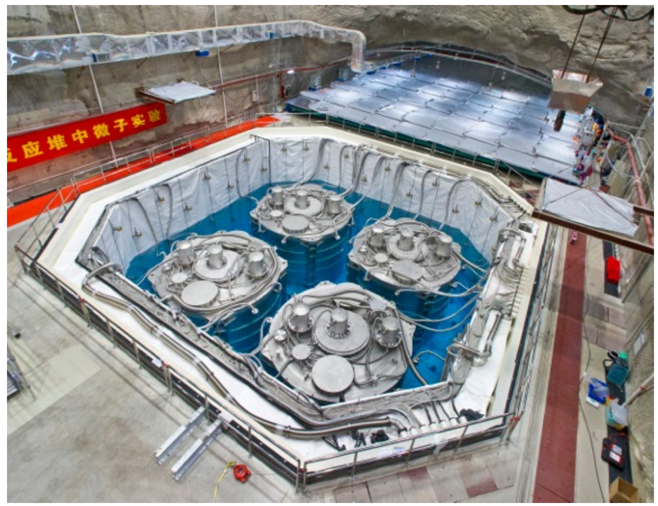
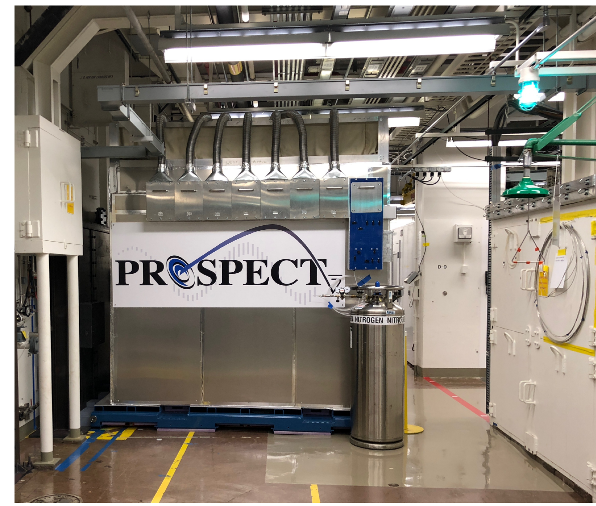
Reactor Neutrinos at Short Baselines





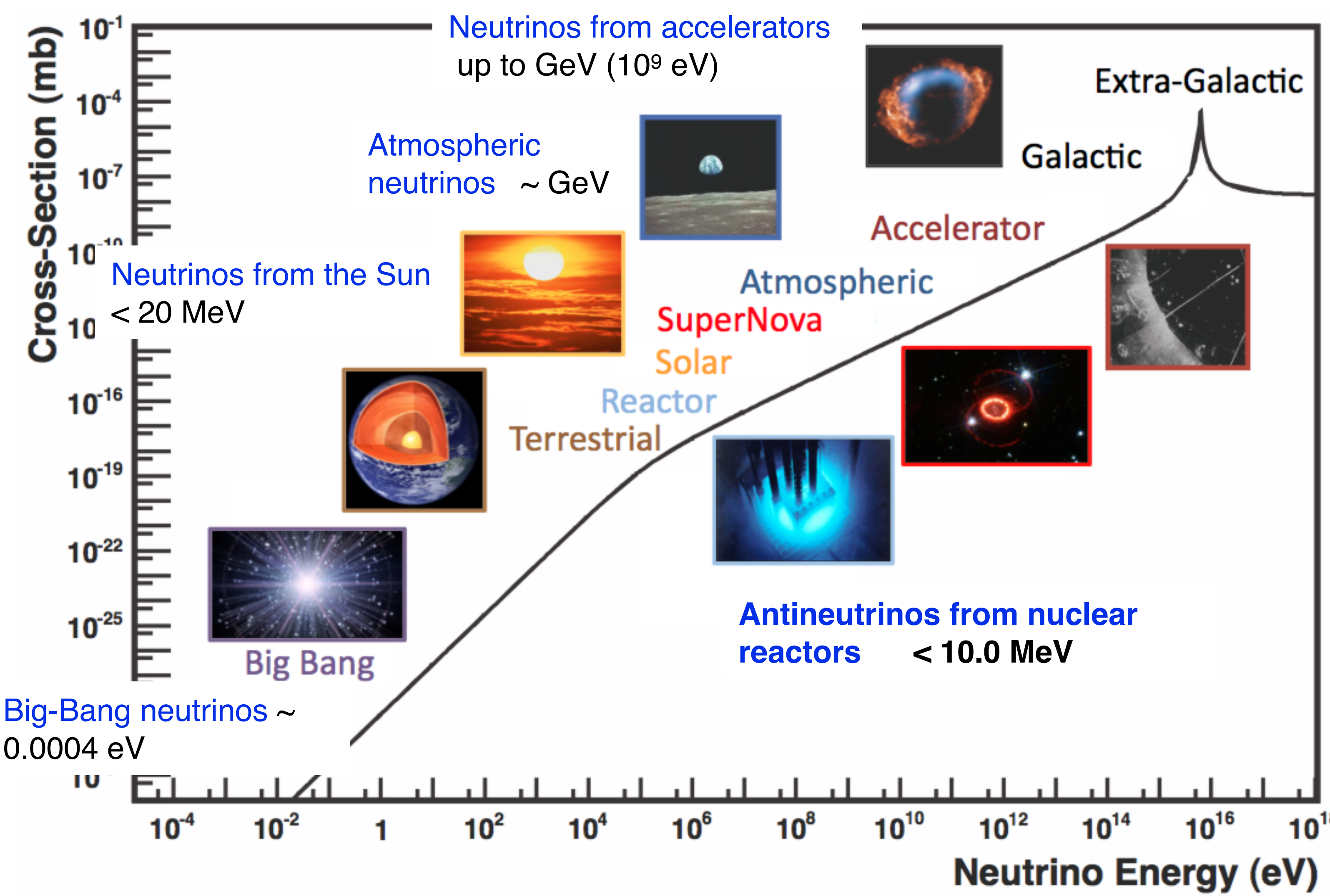
Karsten M. Heeger
Yale University

March 30, 2022

Wright Laboratory

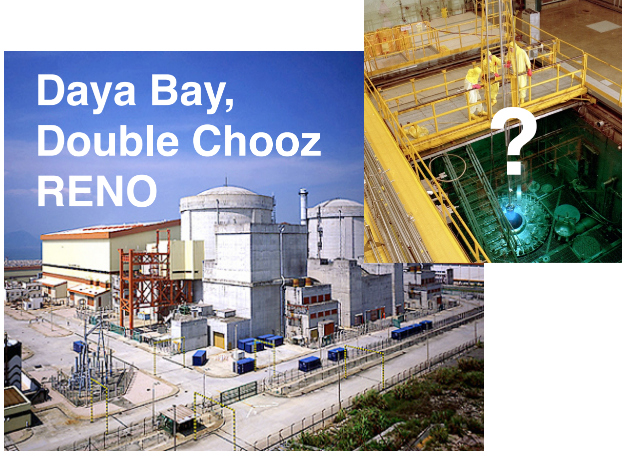
Yale

Neutrino Sources

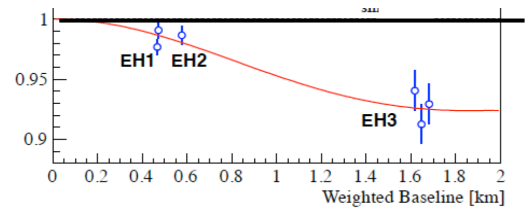


Reactor Antineutrinos

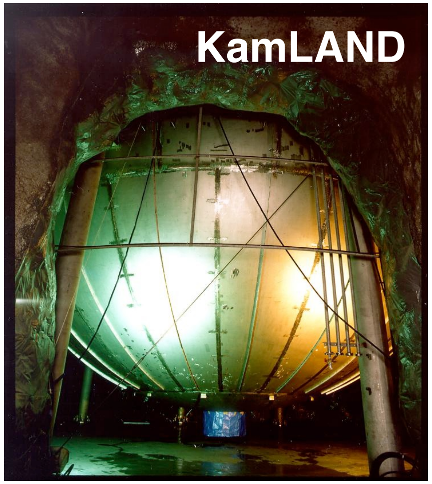
A Tool for Discovery

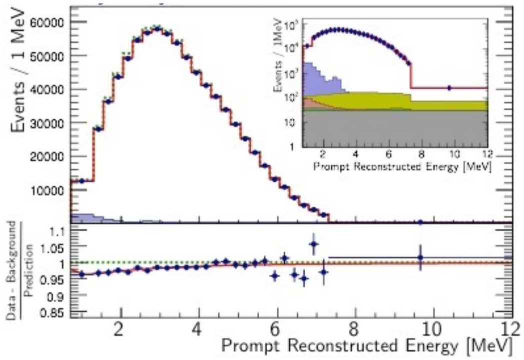


2012 - Measurement of θ_{13} with Reactor Neutrinos



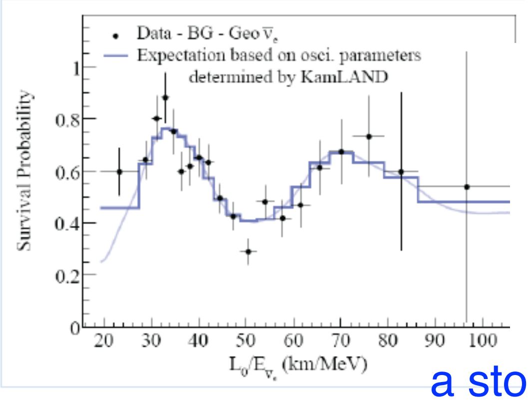
2003 - First observation of reactor antineutrino disappearance

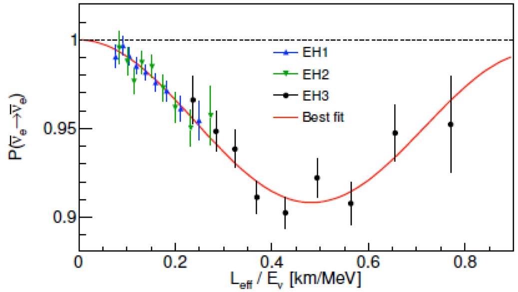




1995 - Nobel Prize to Fred Reines at UC Irvine

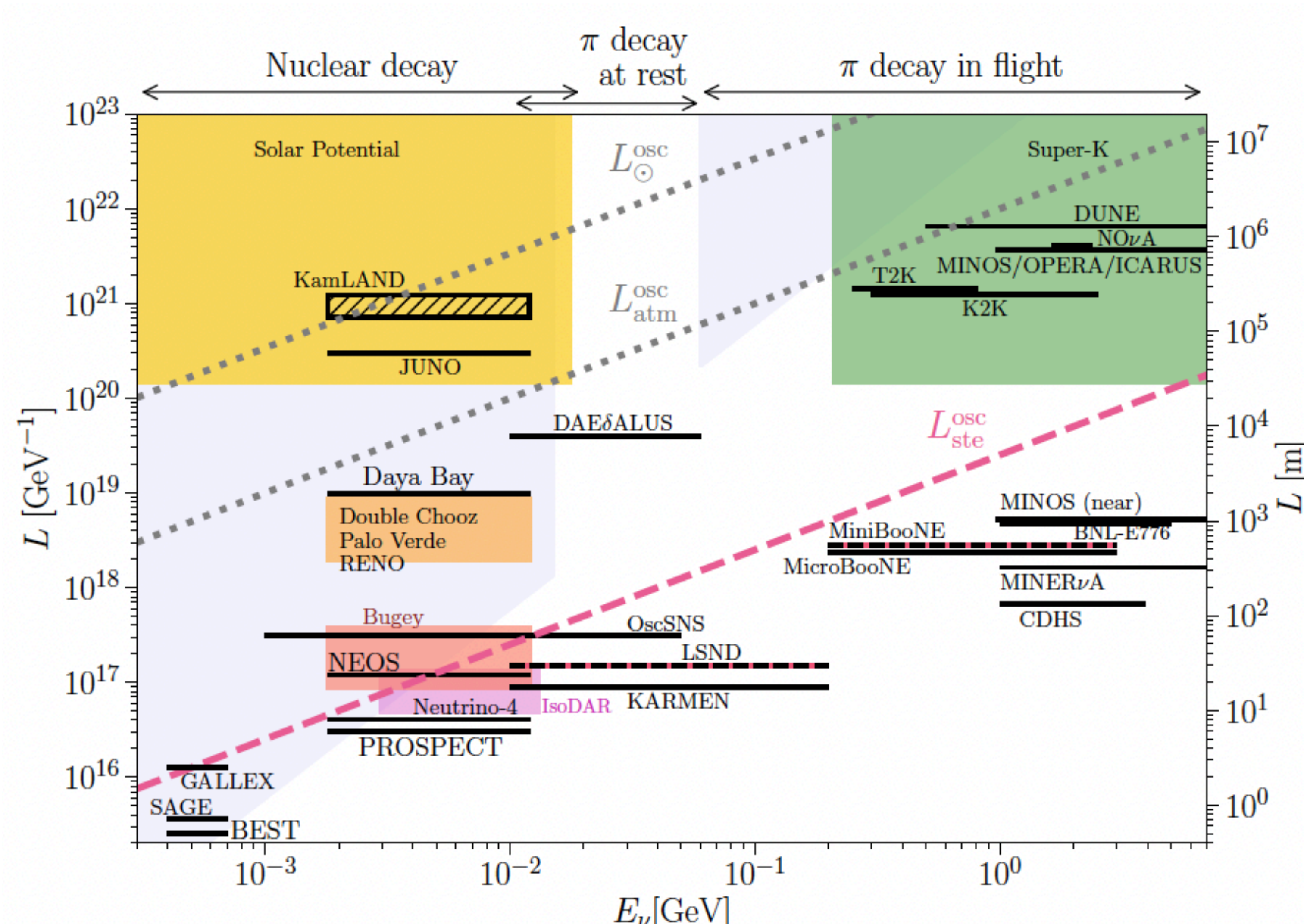
1956 - First observation of (anti)neutrinos





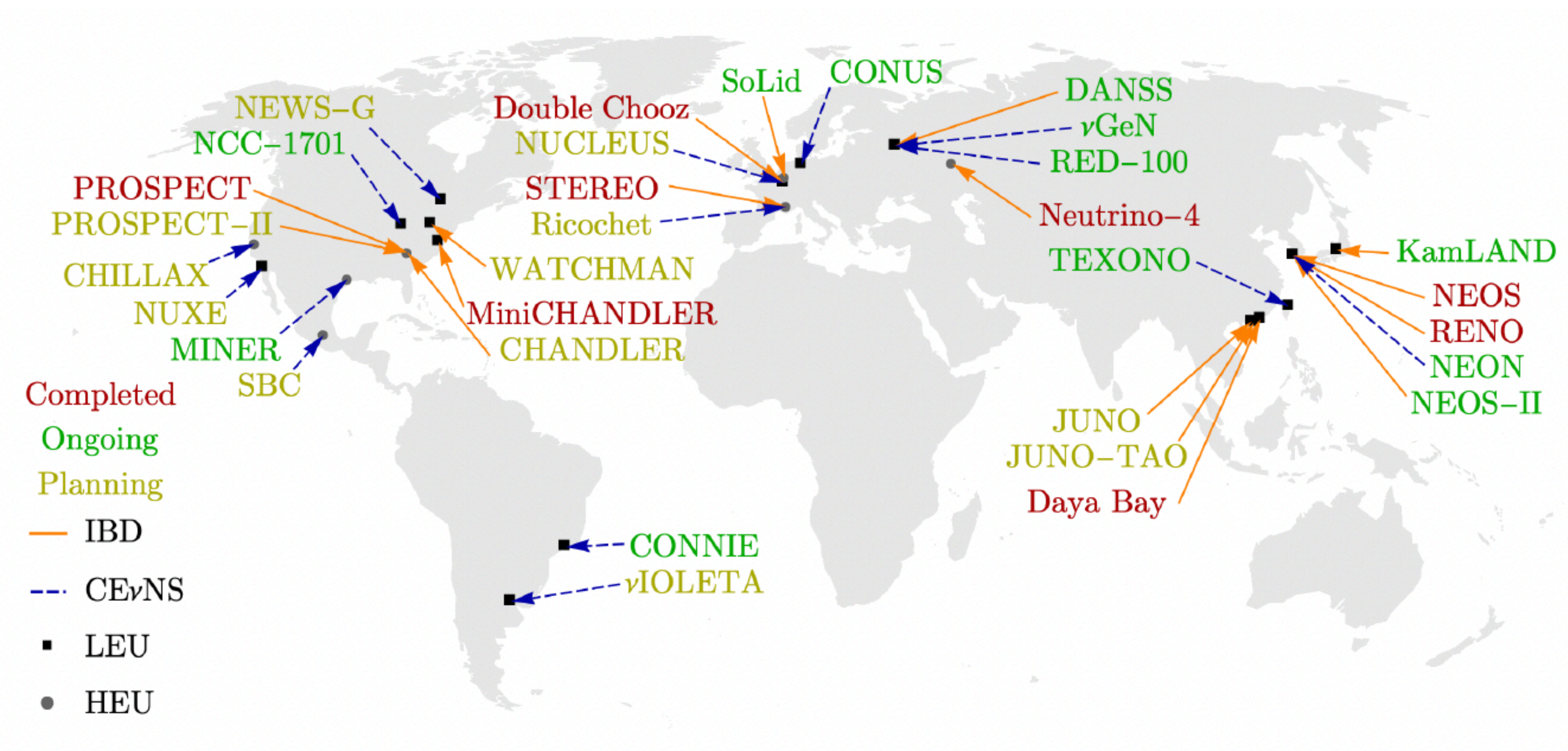
a story of varying baselines...

Precision Oscillation Physics



arXiv: 2203.07214

Reactor Neutrino Experiments Worldwide

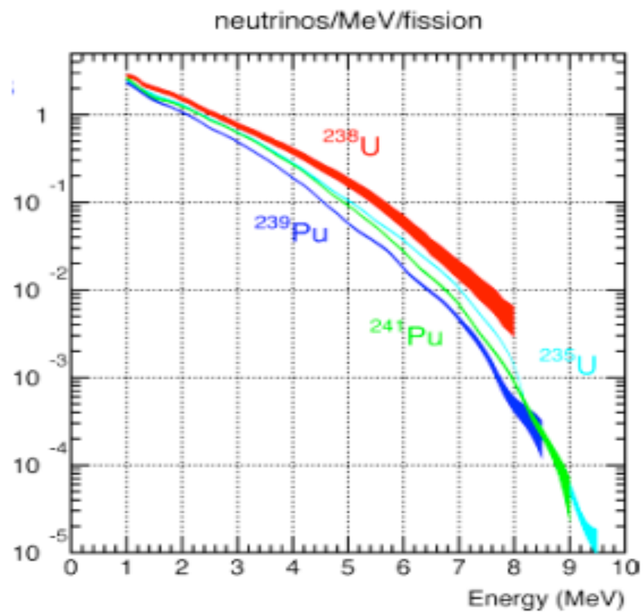


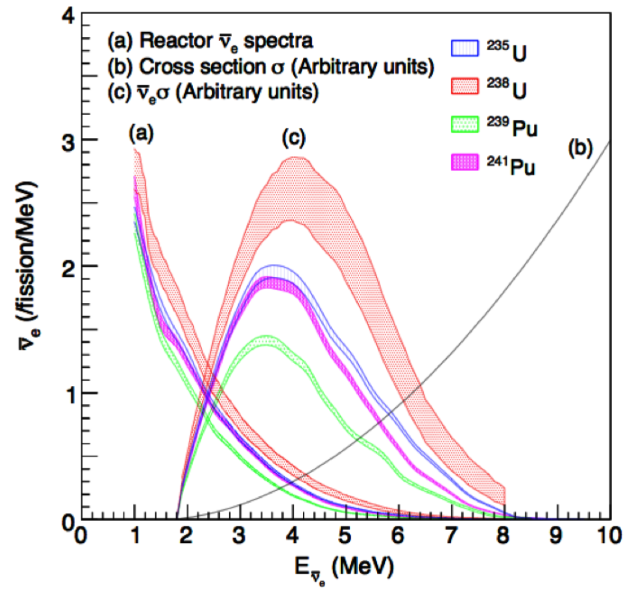
arXiv: 2203.07214

Reactor Antineutrinos

$\bar{\nu}_e$ from β-decays, pure $\bar{\nu}_e$ source

of n-rich fission products
on average ~6 beta decays until stable





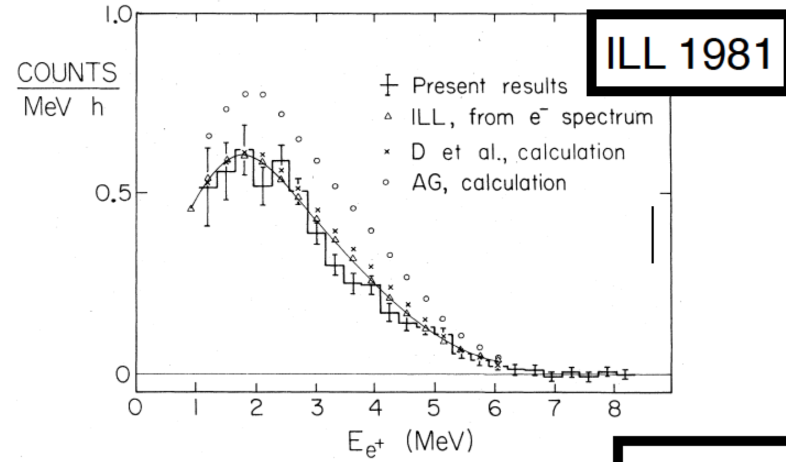
> 99.9% of $\bar{\nu}_e$ are produced by fissions in
^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu

mean energy of $\bar{\nu}_e$: 3.6 MeV

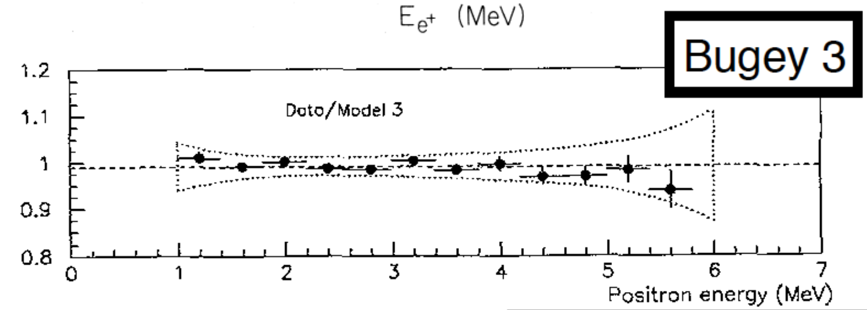
only disappearance
experiments possible

Reactor Neutrino Flux & Spectra

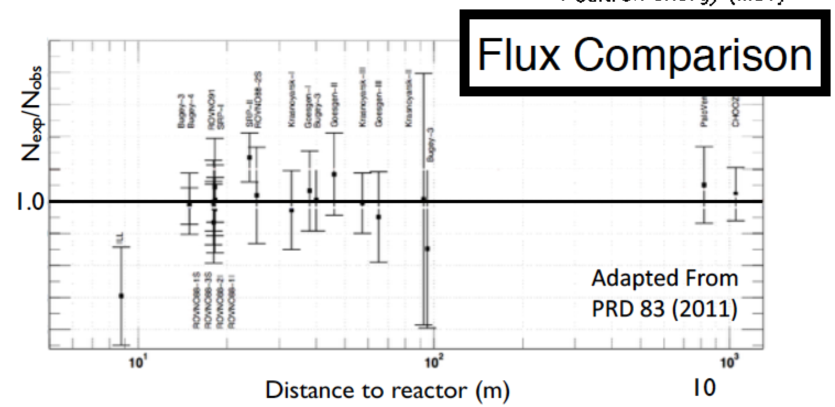
Early 1980s: Measurement of ^{235}U spectrum at ILL
- agrees with ab-initio calculations
- < 5000 neutrinos detected,
- 20% uncertainties



Mid 1980s: Beta conversion measurements at ILL, reduce systematics, improve uncertainties or predictions



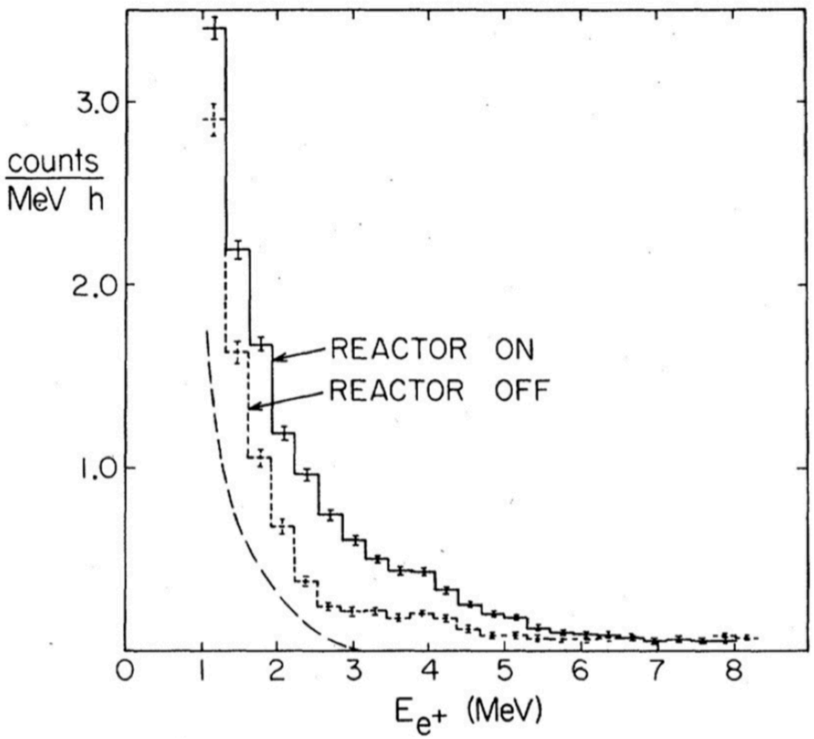
1990s: Bugey PWR spectrum agrees with beta conversion spectra

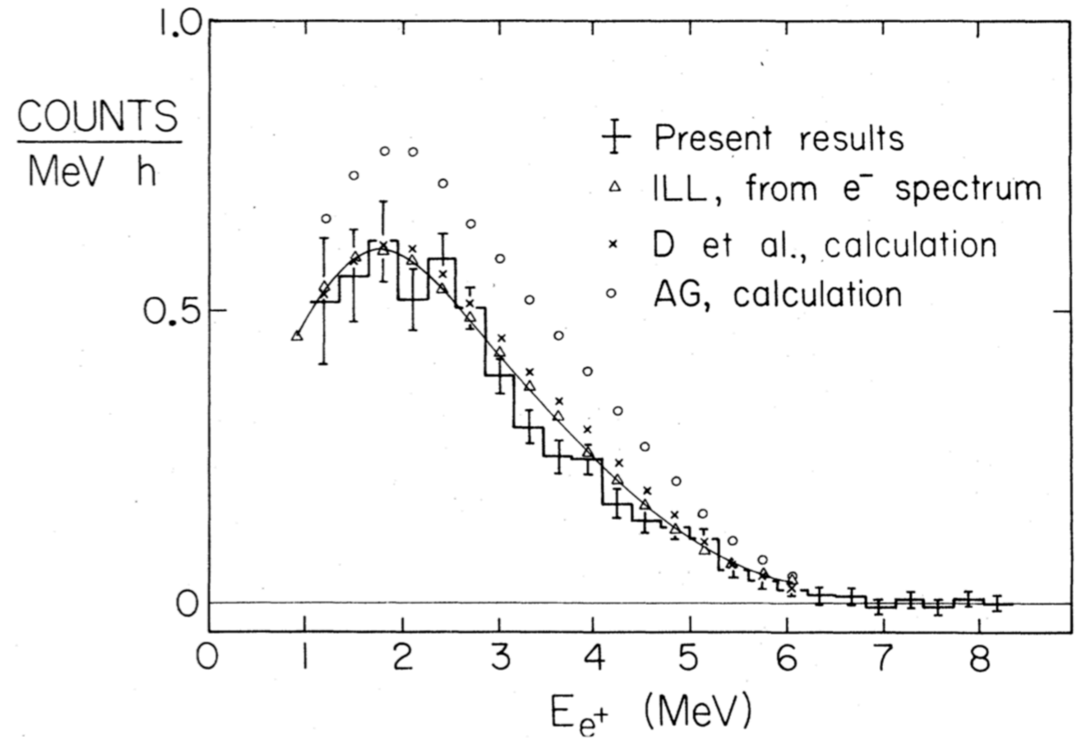


1990-2000s: Measured flux "agrees" with predictions

Reactor ^{235}U Antineutrino Spectrum

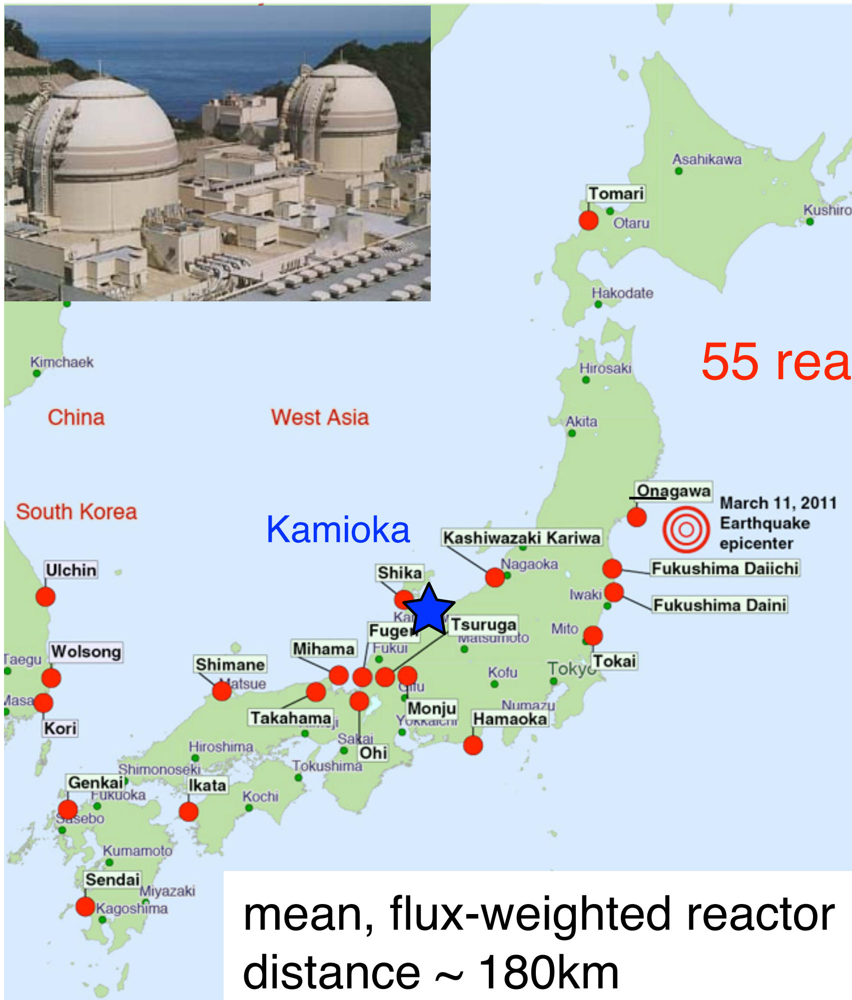
Only existing measurement from 1981 ILL experiment, 5000 events





Reactor Antineutrinos in KamLAND

Japanese Reactors



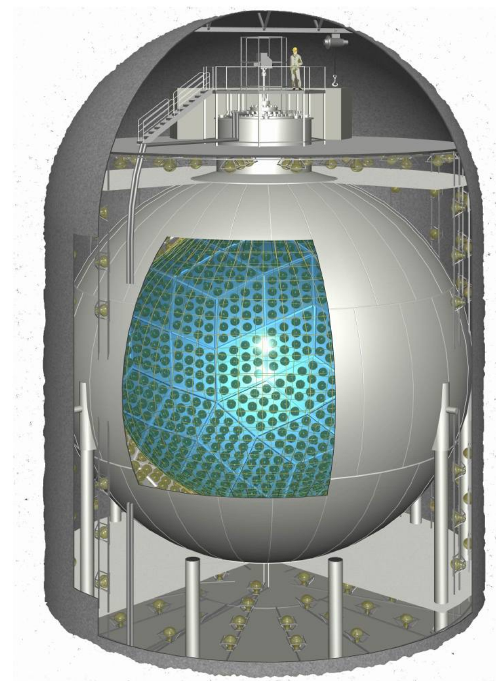
55 reactors

mean, flux-weighted reactor distance ~ 180km

reactor $\bar{\nu}$ flux ~ $6\text{x}10^6/\text{cm}^2/\text{sec}$

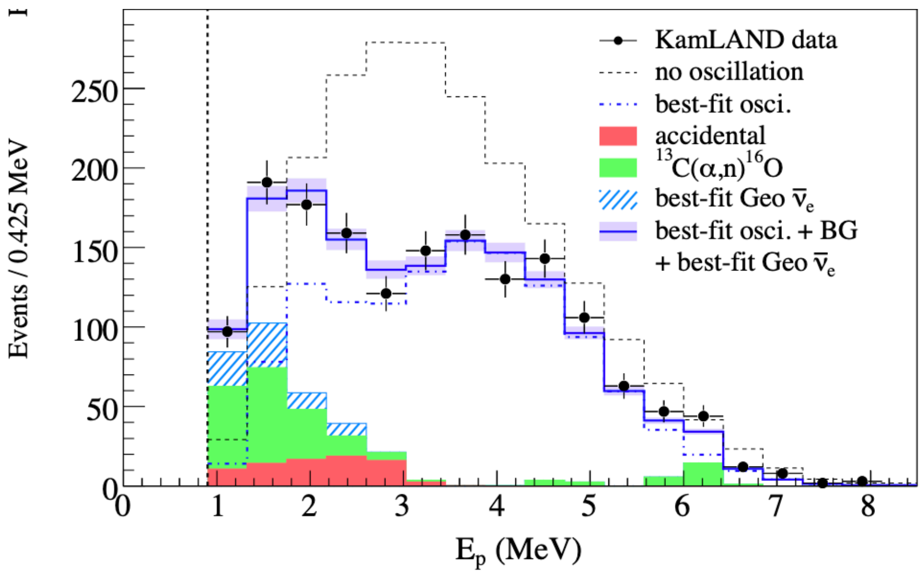
Anti-Neutrino Detection through inverse β-decay

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

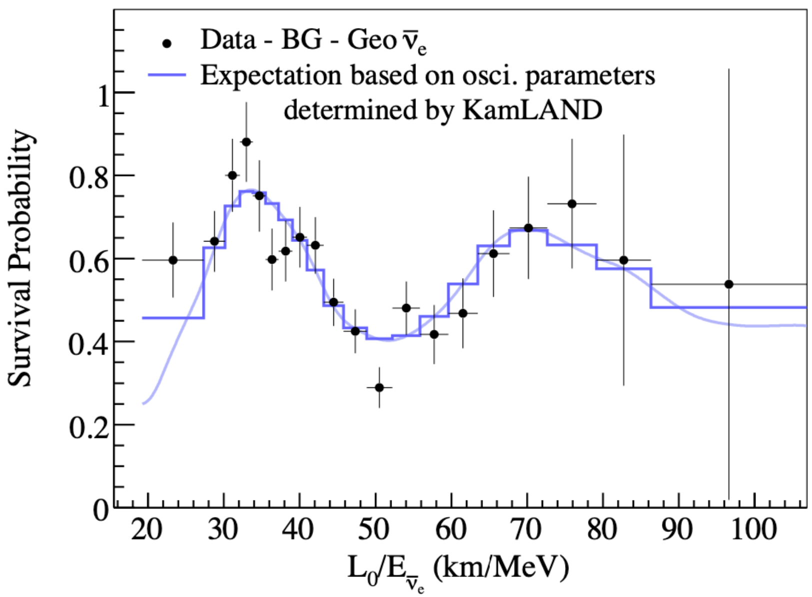


Observation of Reactor $\bar{\nu}_e$ Oscillation

Reactor $\bar{\nu}_e$ Disappearance

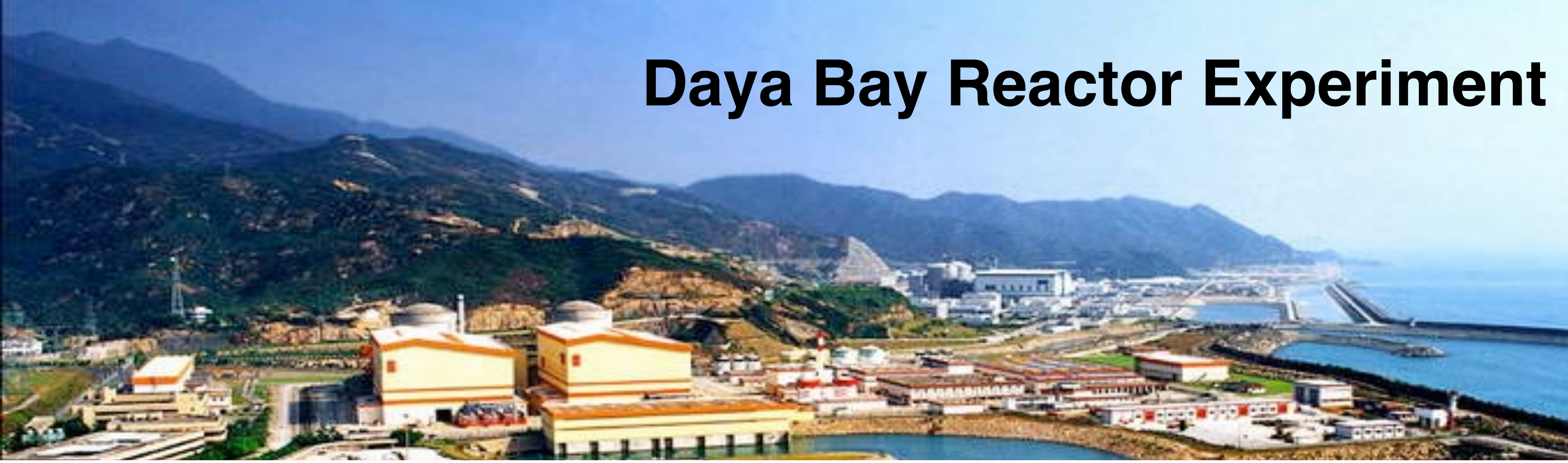


Evidence for Oscillation

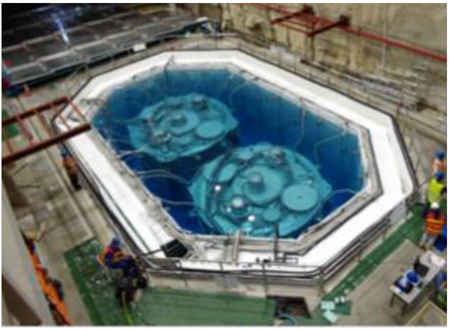


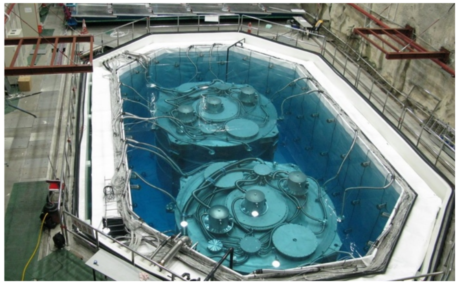
KamLAND Collaboration
Phys.Rev.Lett.100:221803,2008

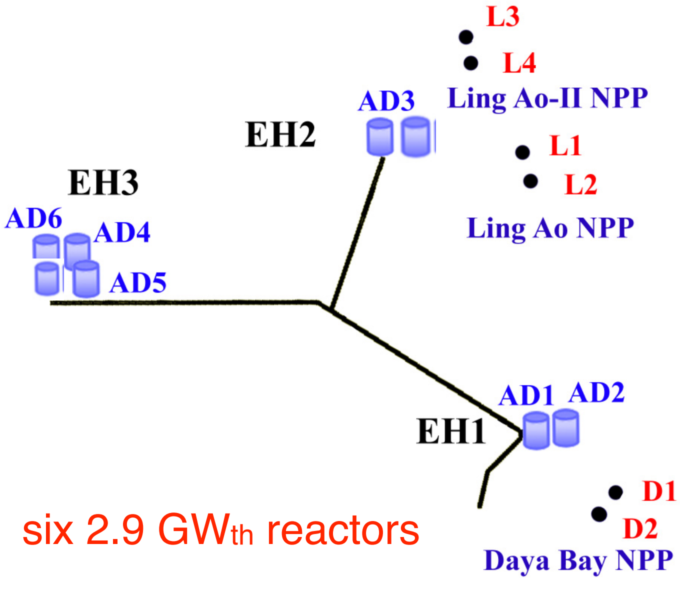
Daya Bay Reactor Experiment



Experimental Hall



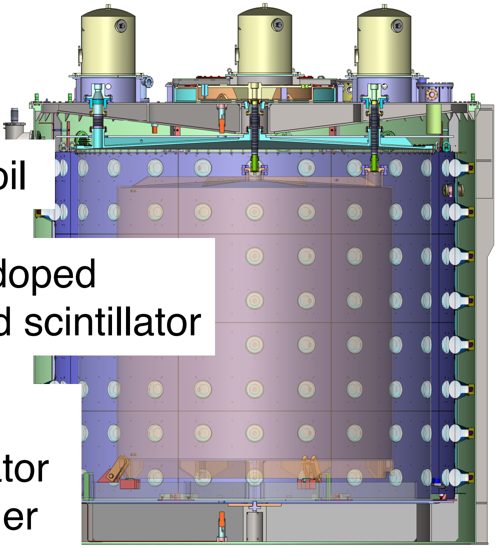




six 2.9 GW_{th} reactors

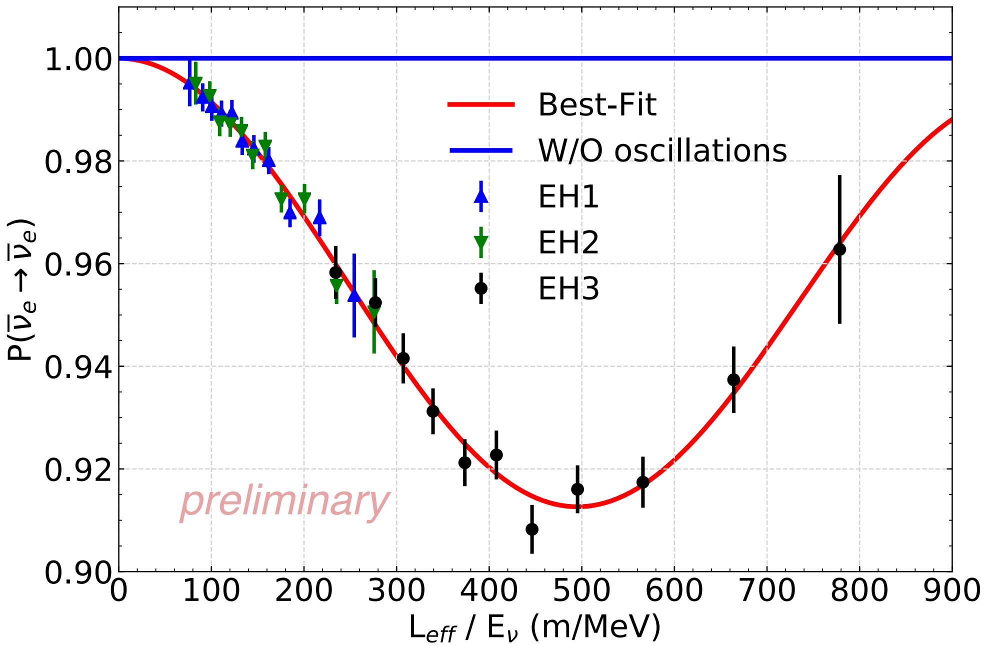
6 detectors, Dec 2011- Jul 2012
then 8 detectors

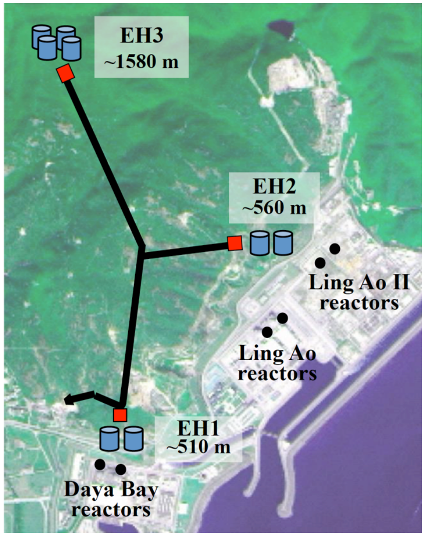
Antineutrino Detector

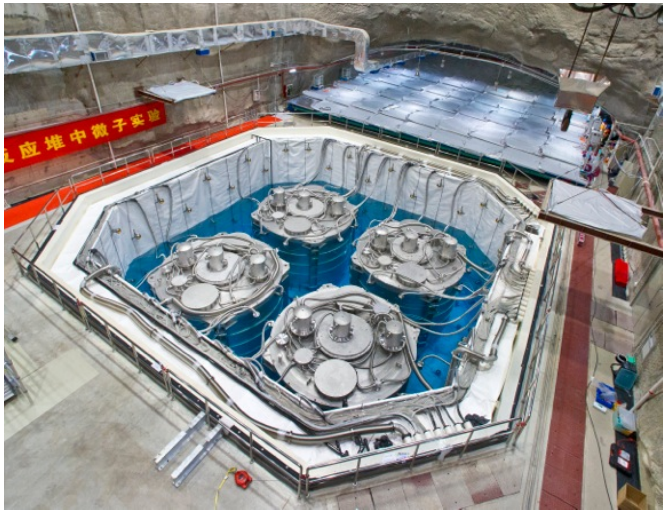


target mass: 20 ton per AD
photosensors: 192 8”-PMTs
energy resolution: $(7.5 / \sqrt{E} + 0.9)\%$

Daya Bay Neutrino Oscillation (1958 Days)







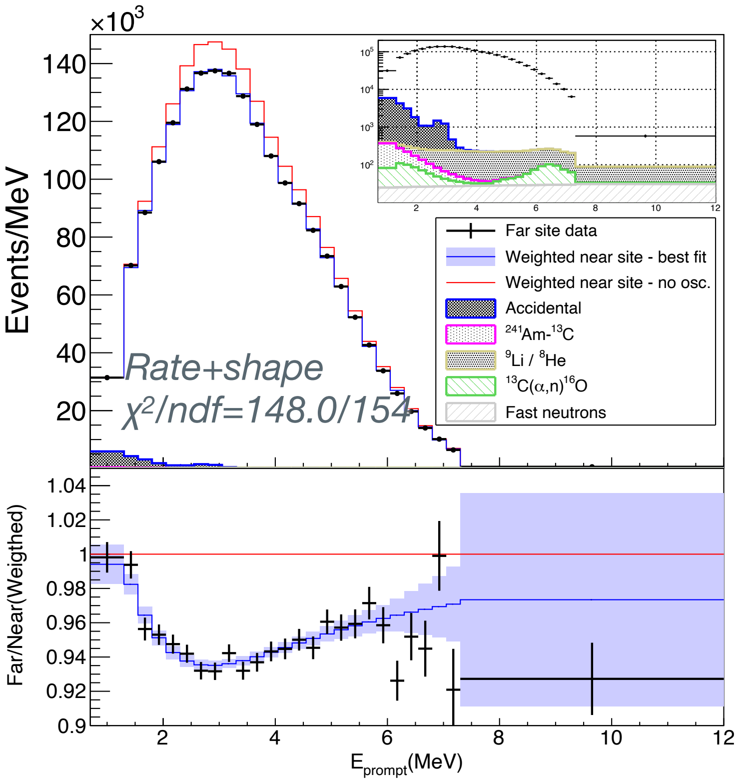
$$P_{i\to j} = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

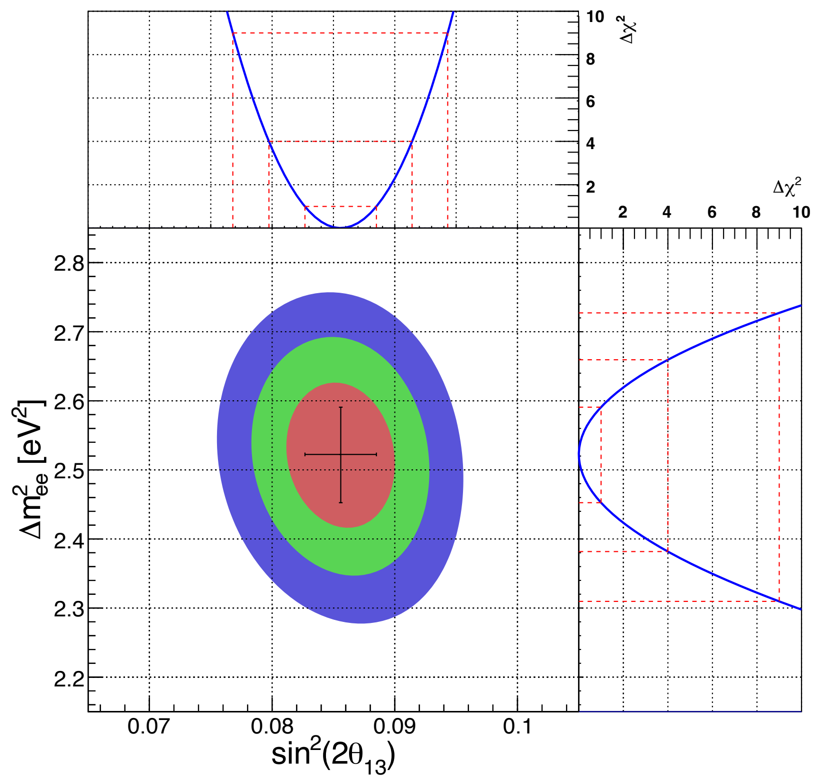
Neutrino oscillation is energy and baseline dependent

Phys. Rev D 95, 072006 (2017).
Daya Bay

Daya Bay Neutrino Oscillation (1958 Days)

nGd Analysis





Daya Bay
Phys.Rev.Lett. 121 (2018) no.24, 241805

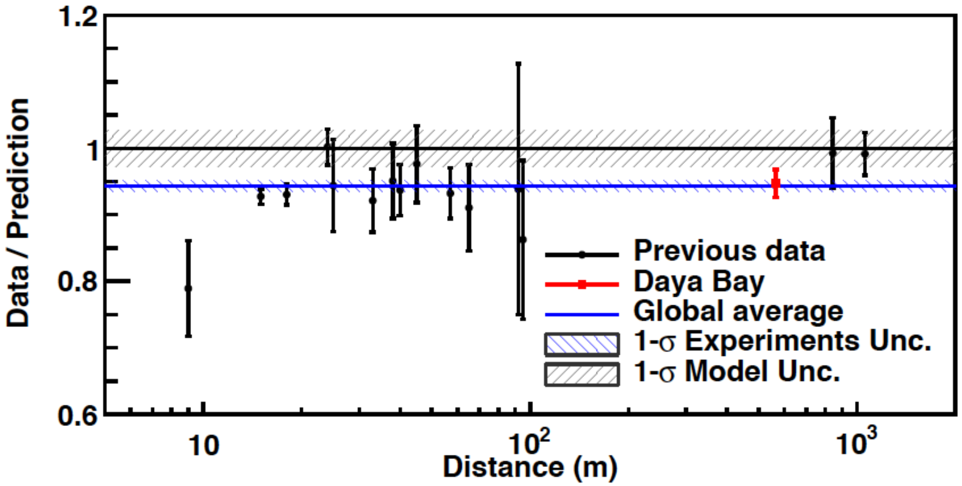
$\sin^2 2\theta_{13}$ uncertainty: 3.4%
$|\Delta m^2_{32}|$ uncertainty: 2.8%

$$\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$$

$$|\Delta m^2_{ee}| = (2.52 \pm 0.07) \times 10^{-3}\ \mathrm{eV}^2$$

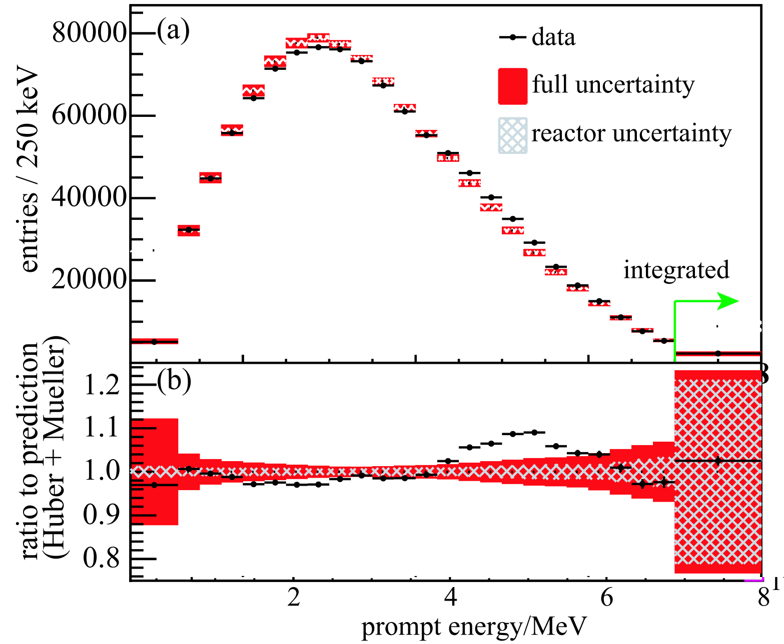
Reactor Antineutrino “Anomalies” (RAA)

Flux Deficit



Deficit due to extra (sterile) neutrino oscillations or artifact of flux predictions?

Spectral Deviation



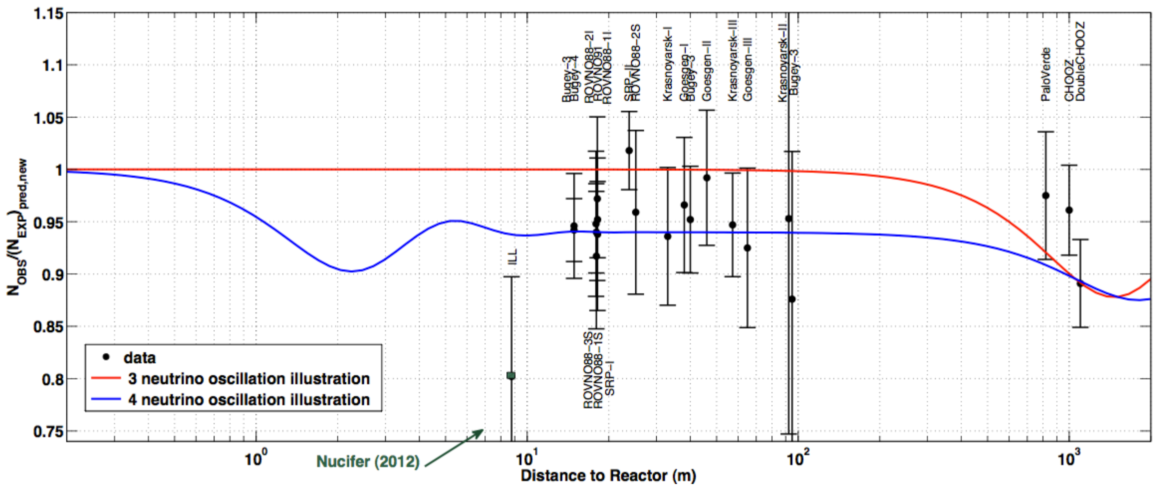
Measured spectrum does not agree with predictions.

Daya Bay,
CPC 41, No. 1 (2017)

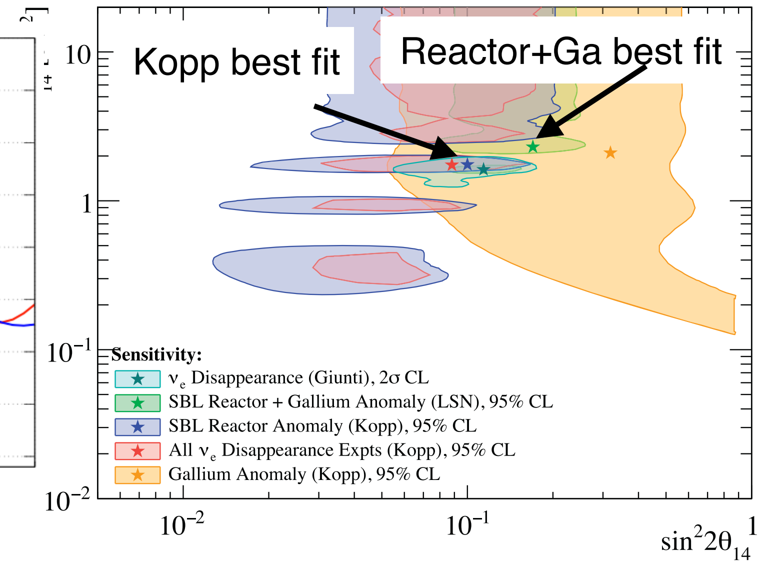
Understanding reactor flux and spectrum anomalies requires additional data

Reactor Antineutrino Flux Deficit

Reactor $\overline{\nu}_e$ flux measurements



$\overline{\nu}_e$ disappearance data



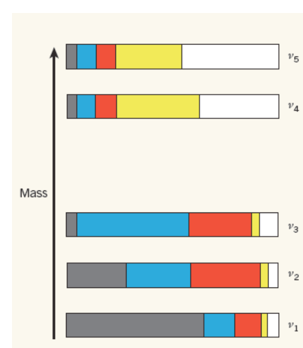
PROSPECT J. Phys. G: 43 (2016)

2011 reanalysis of the predicted reactor flux in tension with global data

Measurements of neutrino source with SAGE/Gallex also show a deficit

new oscillation signal requires:

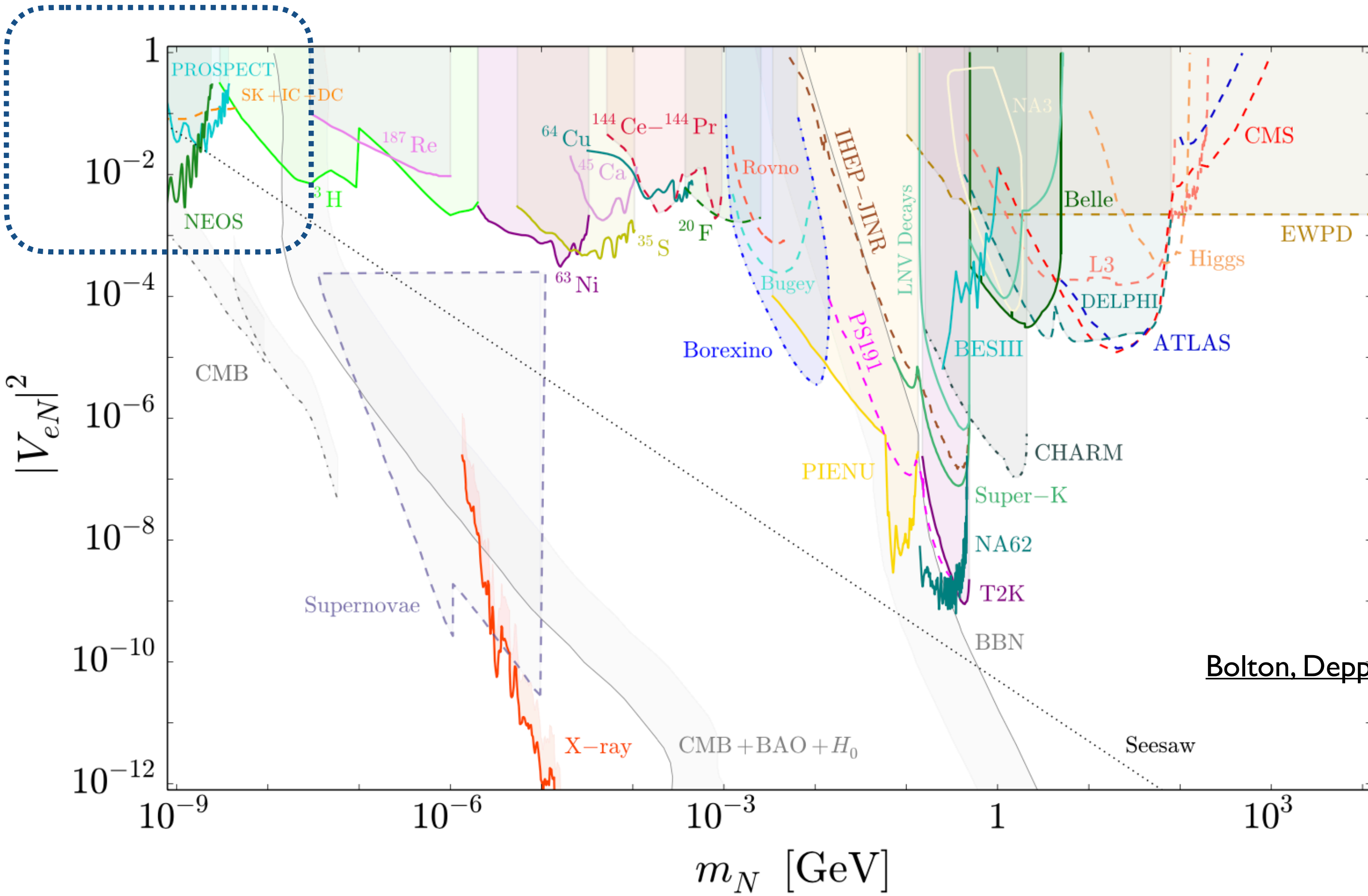
$\Delta m^2 \sim O(1 eV^2)$ and $\sin^2 2\theta > 10^{-3}$
"sterile" neutrino states



$\Delta m^2_{new} \sim 1\ eV^2$

Search for Sterile Neutrinos and BSM Physics

Constraints on the mass m_N of the sterile neutrino and its squared mixing $|V_{eN}|^2$ with the electron neutrino.

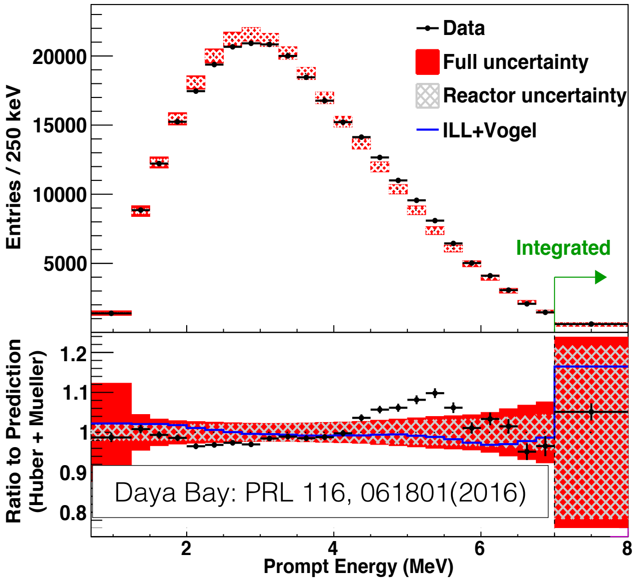


Bolton, Deppsih, Dev, JHEP 170 (2020)

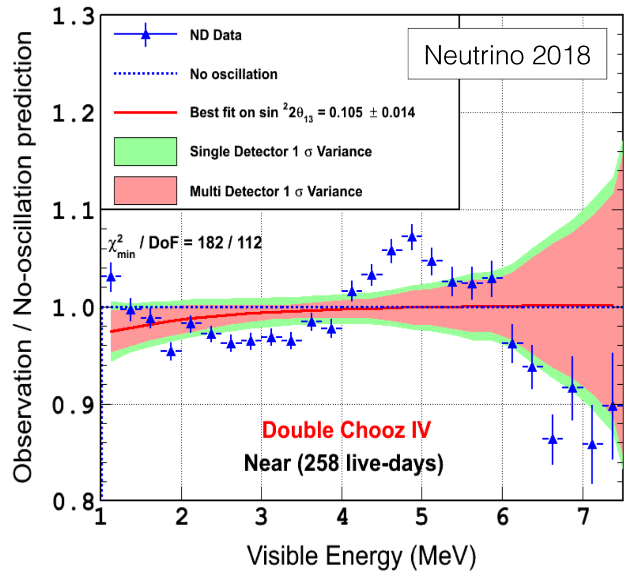
No strong preference for mass scale or coupling strength

Spectral Deviation θ_{13} in Experiments

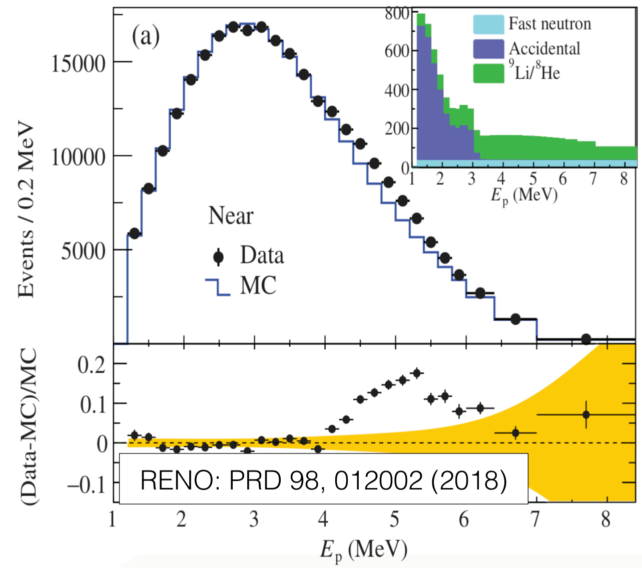
Daya Bay, **China**



Double Chooz, **France**



RENO, **Korea**



all Θ_{13} experiments observe deviations

tracks with reactor power (LEU power), appears in near and far detectors

Most likely an issue with nuclear models?

Predicting the Antineutrino Flux and Spectrum

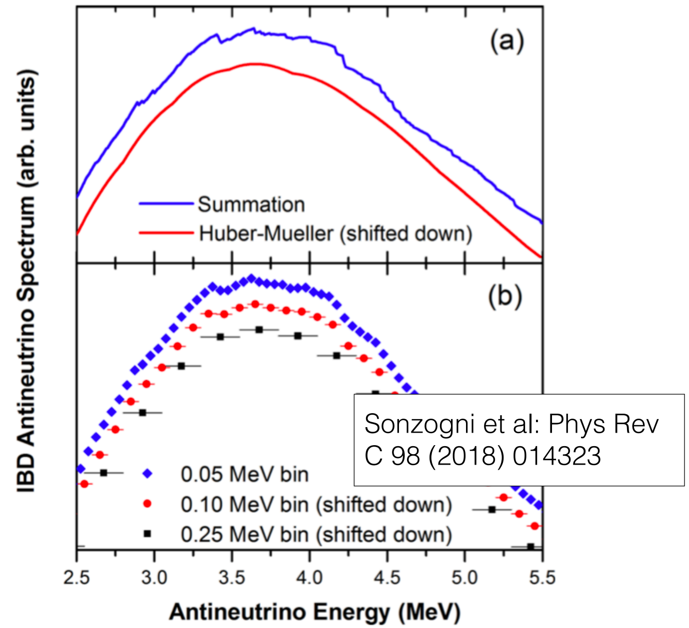
Two major approaches

1. ***Ab-initio***
   - sum the spectrum from thousands of beta branches using nuclear databases
   - databases incomplete and large uncertainties

Decay Rate **Branching Fraction**

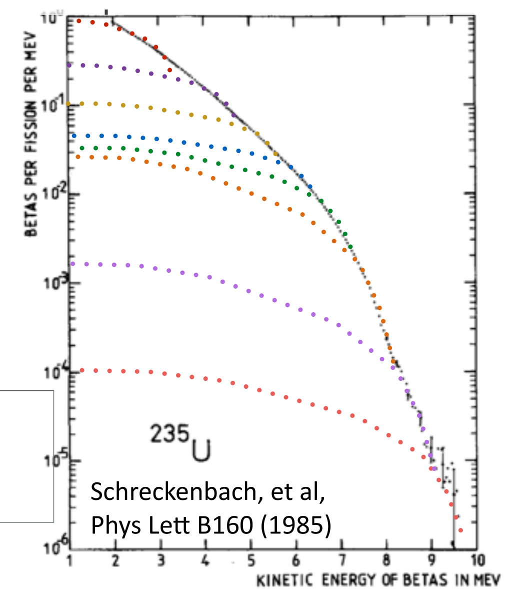
$$S(E_{\bar{\nu}}) = \sum_{i=0}^{n} R_i \sum_{j=0}^{m} f_{ij} S_{ij}(E_{\bar{\nu}}).$$

Spectrum



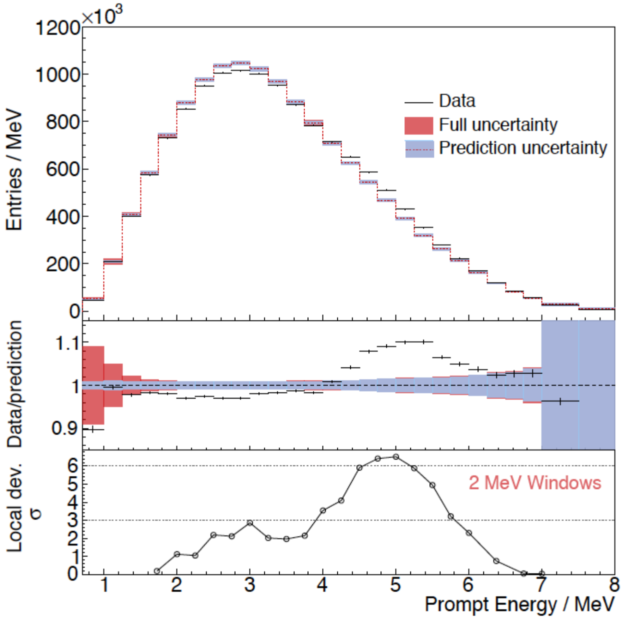
2. **Beta conversion**
   - empirical measurements of beta spectra for each isotope (foils, 1980's)
   - fit with 'virtual branches' and kinematically convert to antineutrino spectra

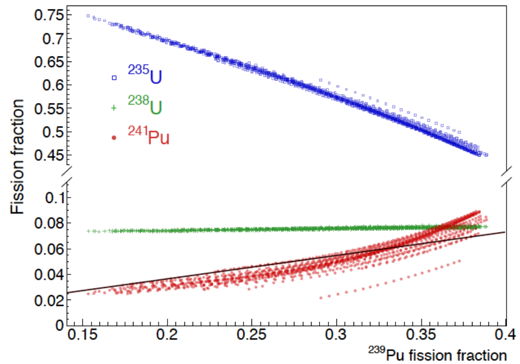
Huber-Mueller model used as benchmark to experiment at LEU reactors: Phys. Rev. C 85, 029901 (2012) and Phys. Rev. C 83 (2011)

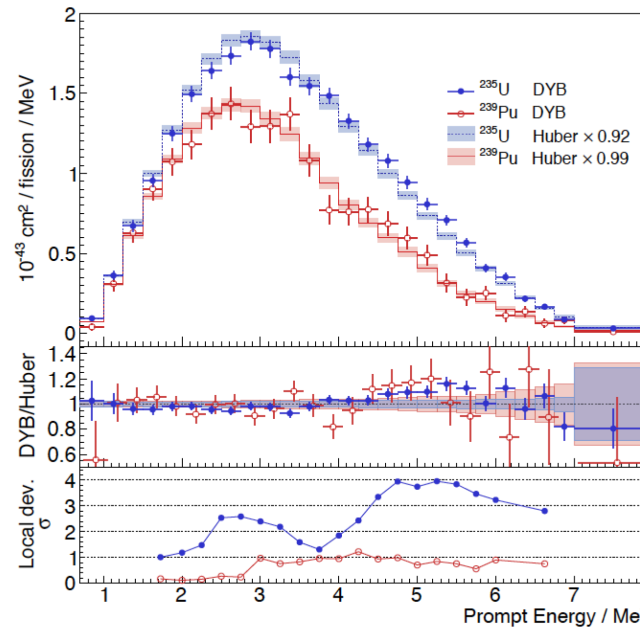


predicting reactor spectra is complicated, nuclear physics uncertainties

Measured Spectra from ^{235}U and ^{239}U







Daya Bay, arXiv:1904.07812

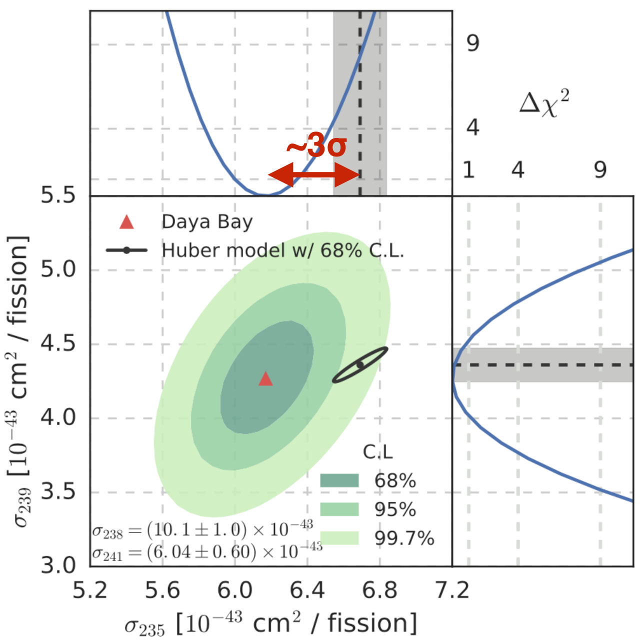
Comparison of the measured and predicted ^{235}U and ^{239}Pu IBD yields prefers an incorrect prediction of the ^{235}U flux as the primary source of the reactor antineutrino rate anomaly.

Discrepancy in the comparison of spectrum shape for ^{235}U suggests incorrect spectral shape prediction for the ^{235}U spectrum.

Fuel Evolution and $\overline{\nu}_e$ Fluxes

Daya Bay Fuel Evolution Analysis

Daya Bay, PRL 118 251801 (2017)



Daya Bay reported IBD yields of ^{235}U and ^{239}Pu using evolution of LEU reactors.

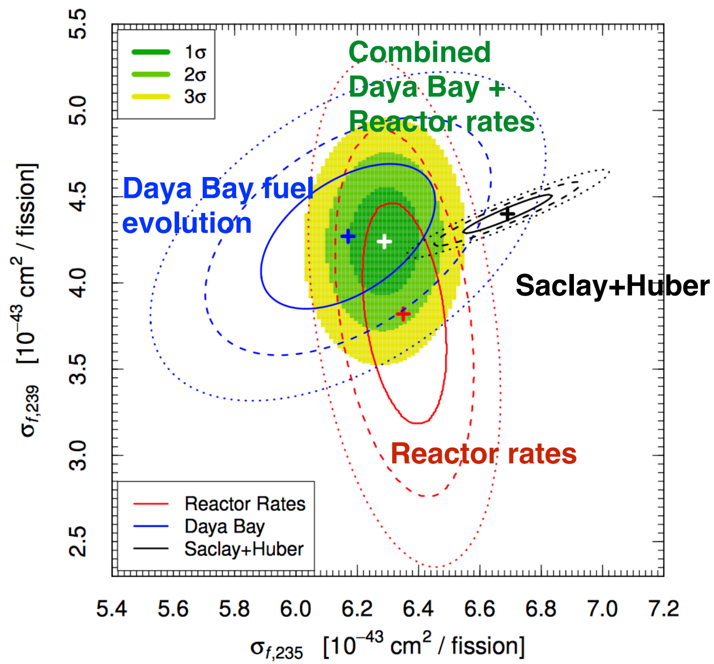
Fitted ^{235}U lower than model.

Analysis of Daya Bay with Fuel Burnup

Hayes et al, Phys.Rev.Lett. 120 (2018) no.2, 022503

Improved Determination of Fluxes

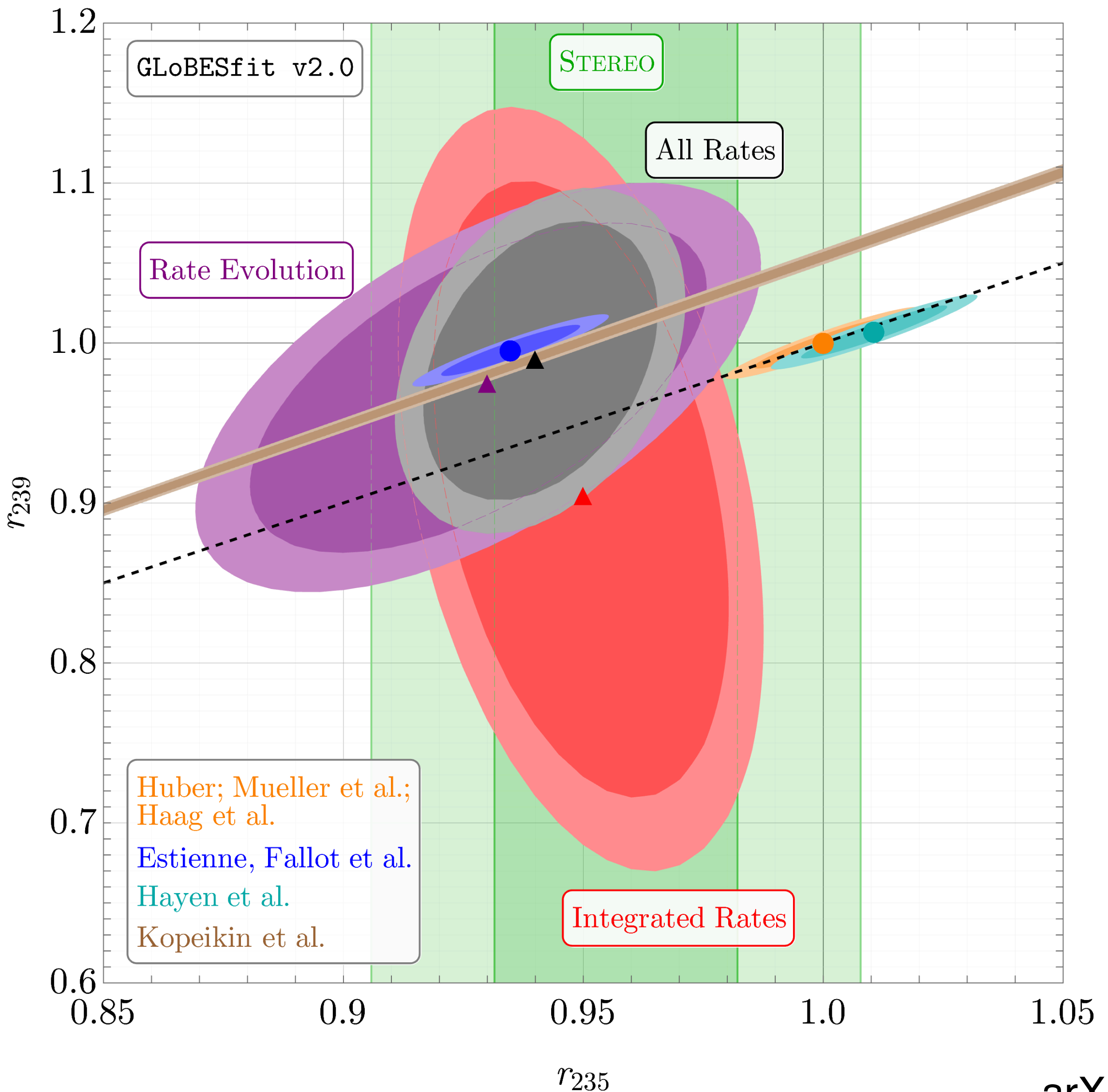
Giunti et al, Phys.Rev. D96 (2017) no.3, 033005



IBD yields calculated from reactor rates (of 26 reactor experiments) do not agree with Daya Bay measurement.

"not enough information to use the antineutrino flux changes to rule out the possible existence of sterile neutrinos"

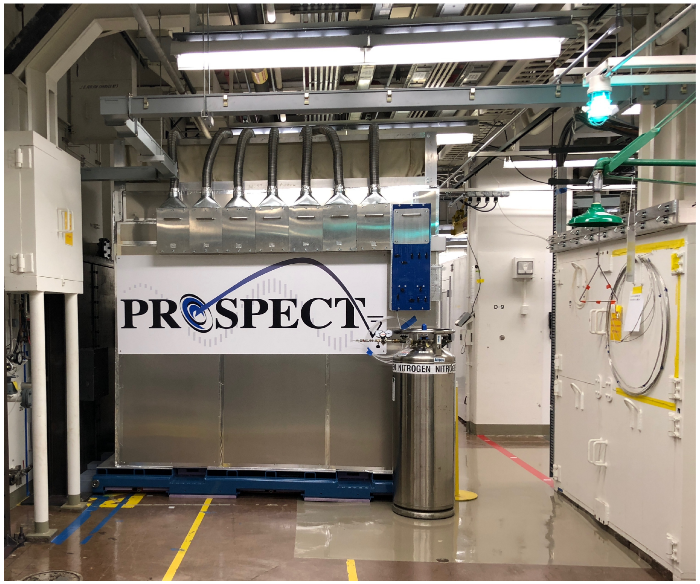
Fuel Evolution and $\overline{\nu}_e$ Fluxes

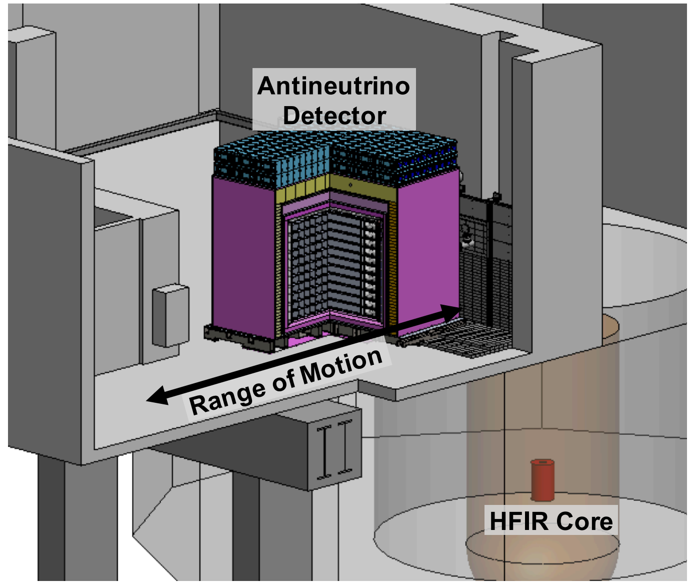


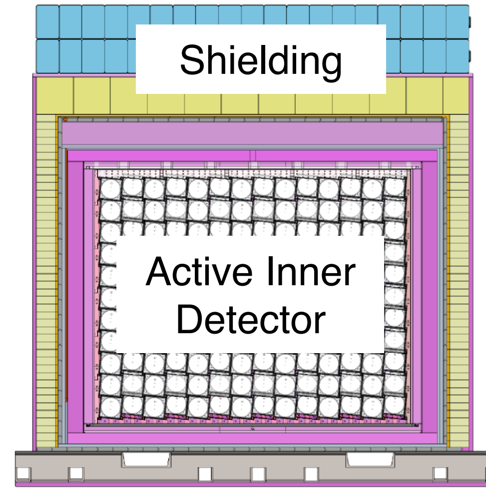
arXiv: 2003.07214

Precision Oscillation and Spectrum Experiment

PROSPECT



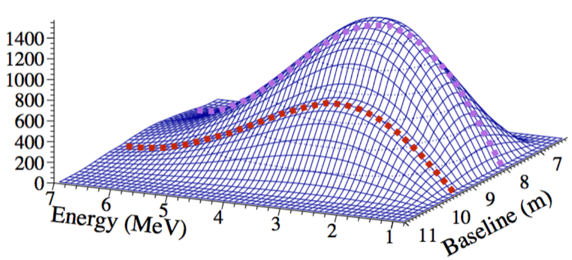




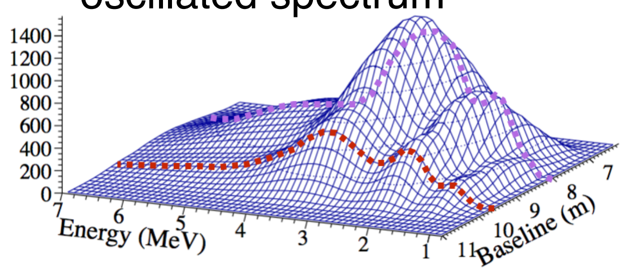
Objectives **Search for short-baseline oscillation at <10m**
Precision measurement of ^{235}U reactor $\overline{\nu}_e$ spectrum

Relative Spectrum Measurement
relative measurement of L/E and spectral shape distortions

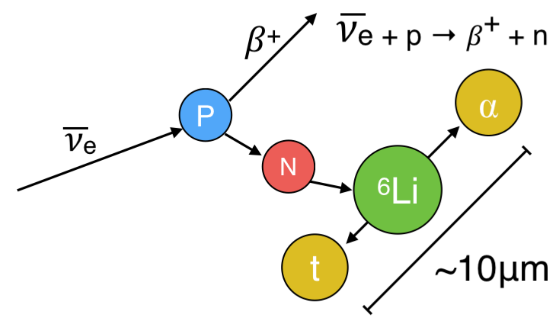
unoscillated spectrum



oscillated spectrum



Segmented, ^{6}Li-loaded Detector

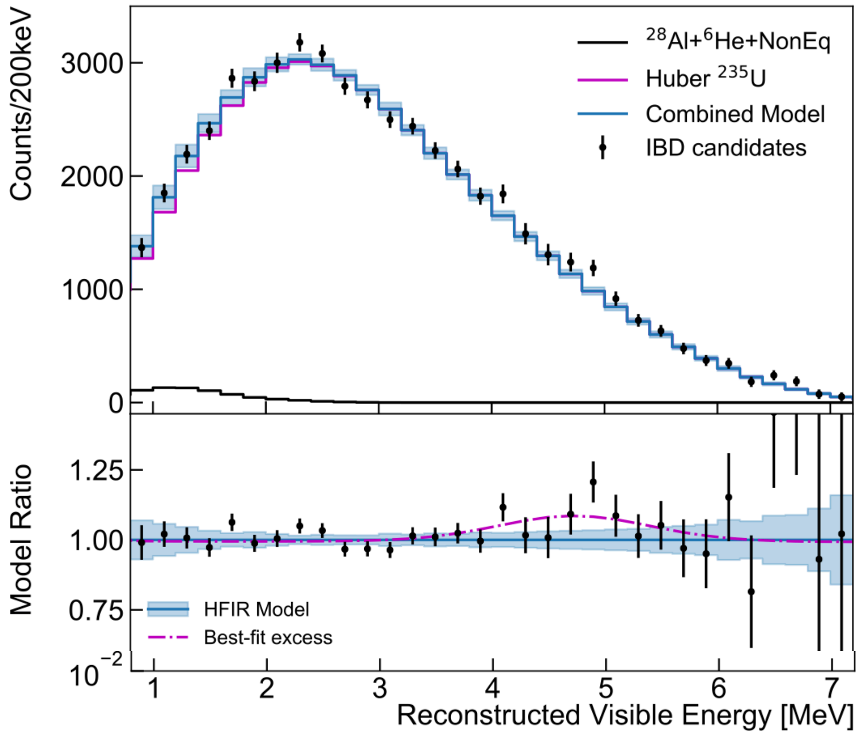


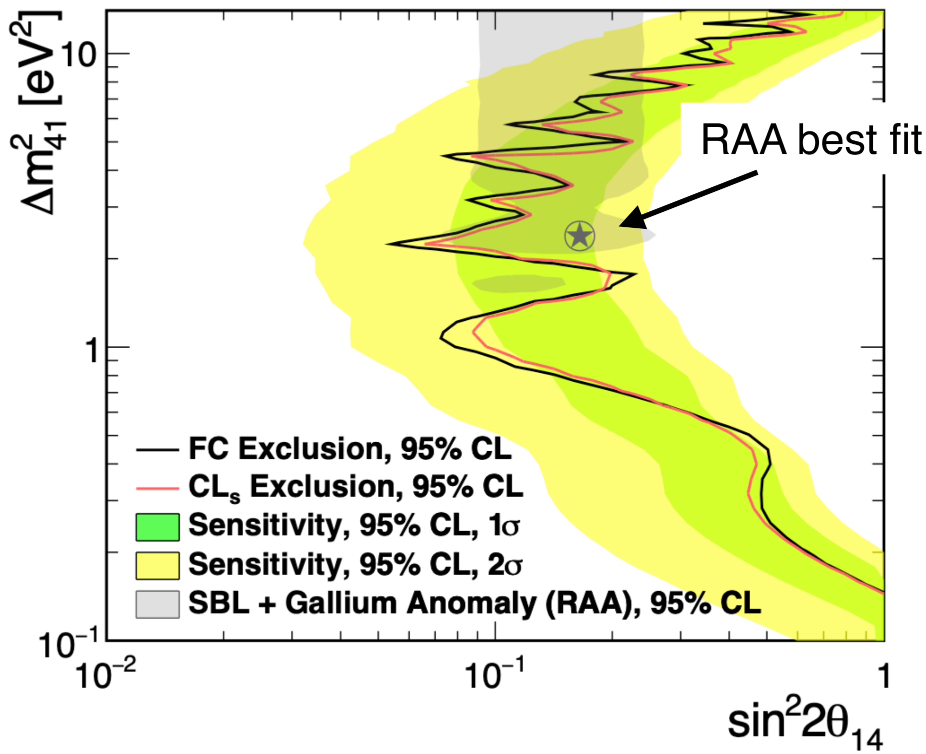

Final Row Installation
November 17, 2017
Wright
Laboratory

Short-Baseline Reactor Experiments at HEU Reactors

	Size	Material	Overburden	Events / Day	Signal-to-background ratio
STEREO	1600 kg	Gd-loaded liquid scintillator	15 m.w.e.	400 IBDs	0.9
SoLid	1400 kg	^{6}Li-layered plastic scintillator	30 m.w.e.	300 IBDs (expected)	3 (expected)
Neutrino-4	1700 kg	Gd-loaded liquid scintillator	5 m.w.e.	600 IBDs	0.5
PROSPECT	4300 kg	^{6}Li-loaded liquid scintillator	<1 m.w.e.	530 IBDs	1.4

Oscillation Search Results





χ^2/NDF =30.79/31 for shape-only comparison with model

PROSPECT feature size with respect to Daya Bay: 84% ± 39%.

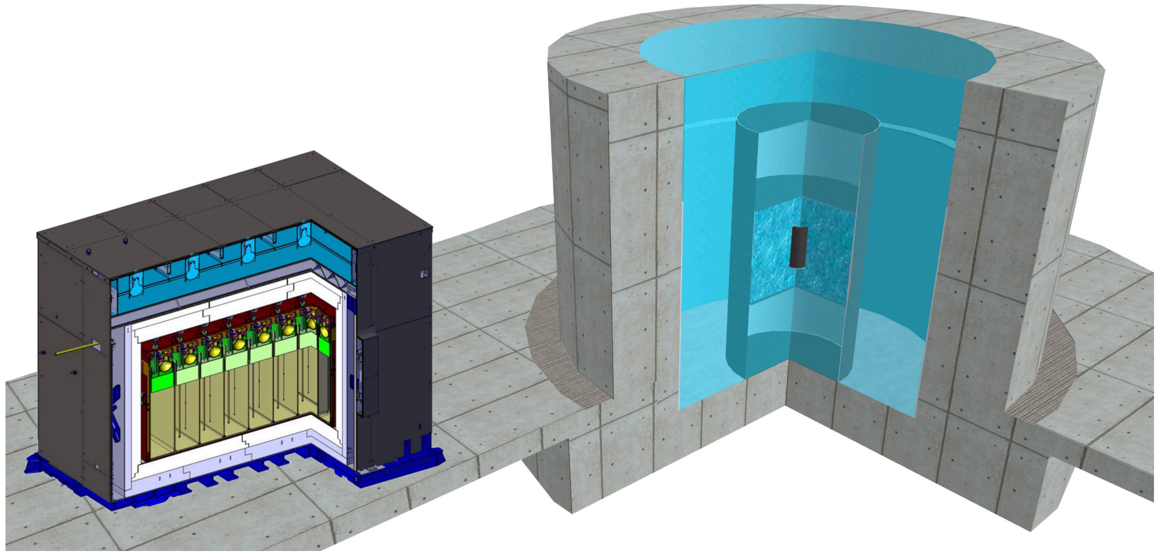
(No ^{235}U bump disfavored at 2.2σ CL, all ^{235}U is disfavored at 2.4σ CL)

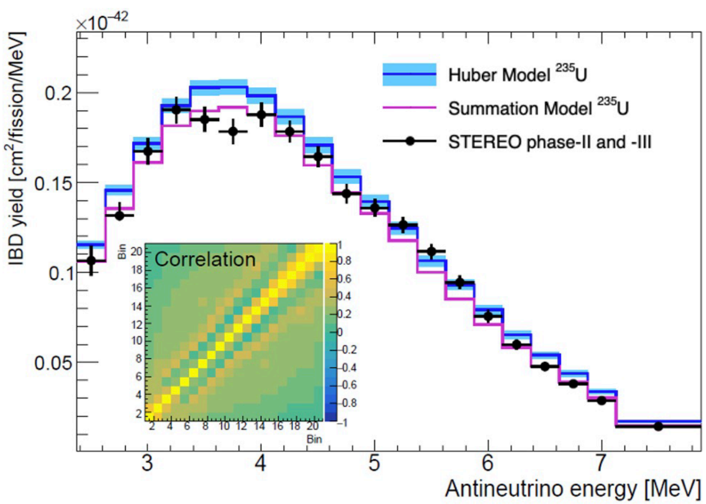
95.65 reactor-on calendar days, 73.09 reactor-off

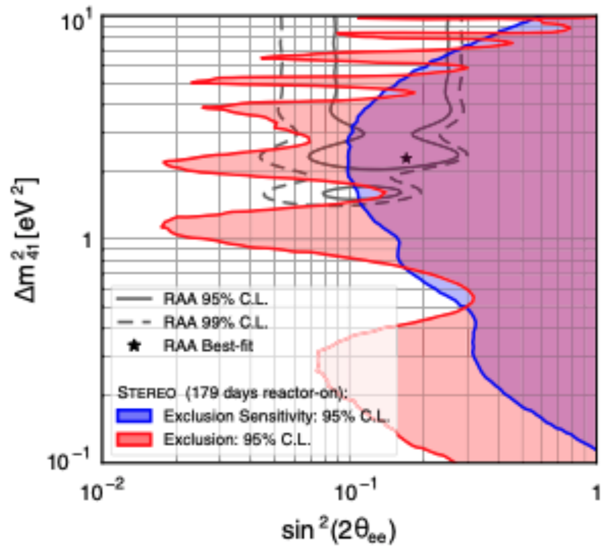
RAA best-fit excluded: 98.5% CL, data is compatible with null oscillation hypothesis (p=0.57)

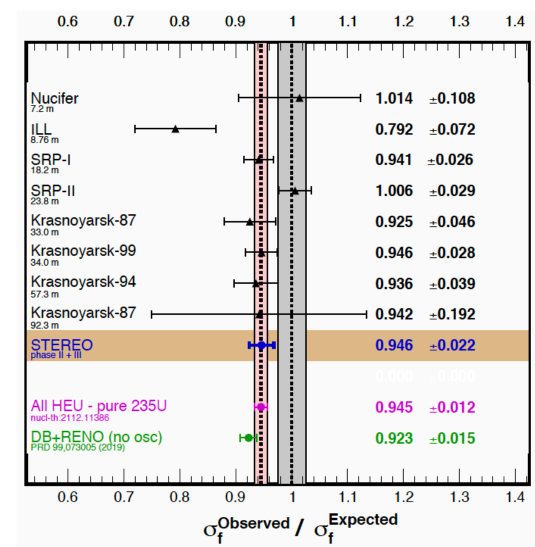
PROSPECT Collaboration
Phys.Rev.D 103 (2021) 3, 03200

STEREO





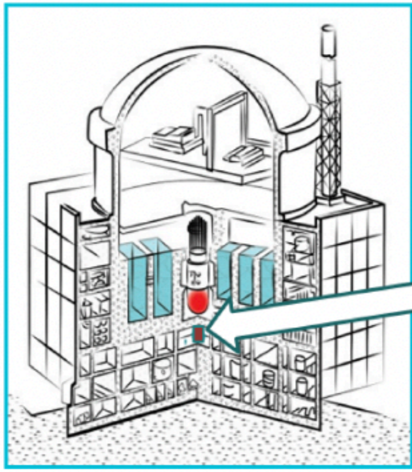


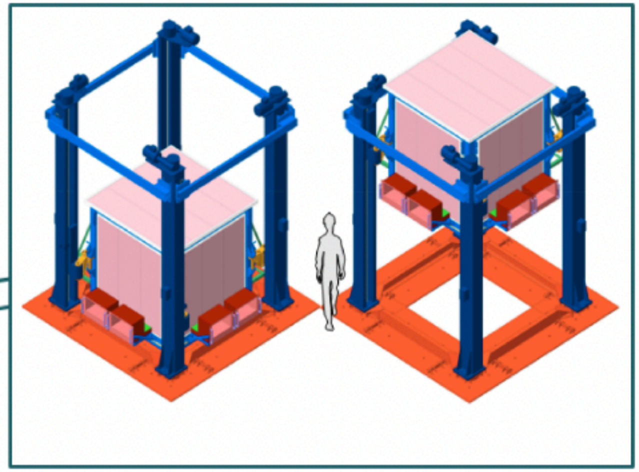


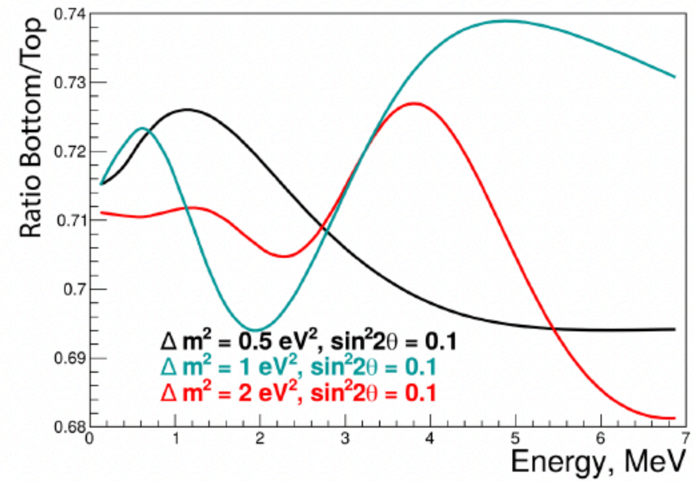
Reported deficit wrt. Huber predicted neutrino rate [2.375MeV, 7.875MeV]:

$\mathbf{0.946 \pm 0.022\ [stat + syst]}$

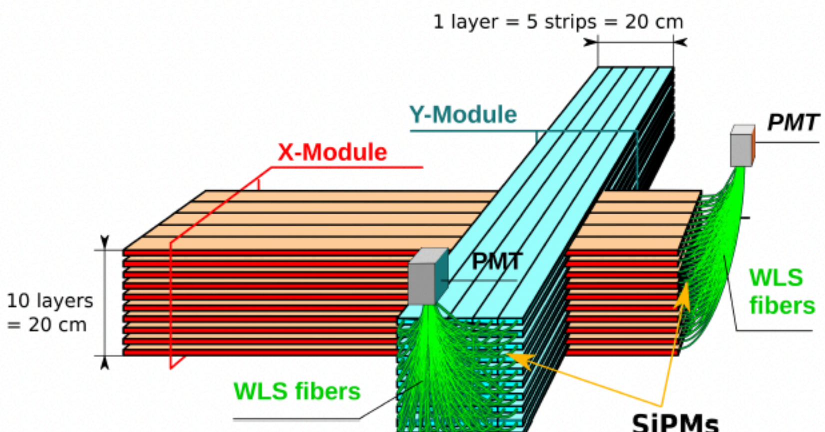
DANSS

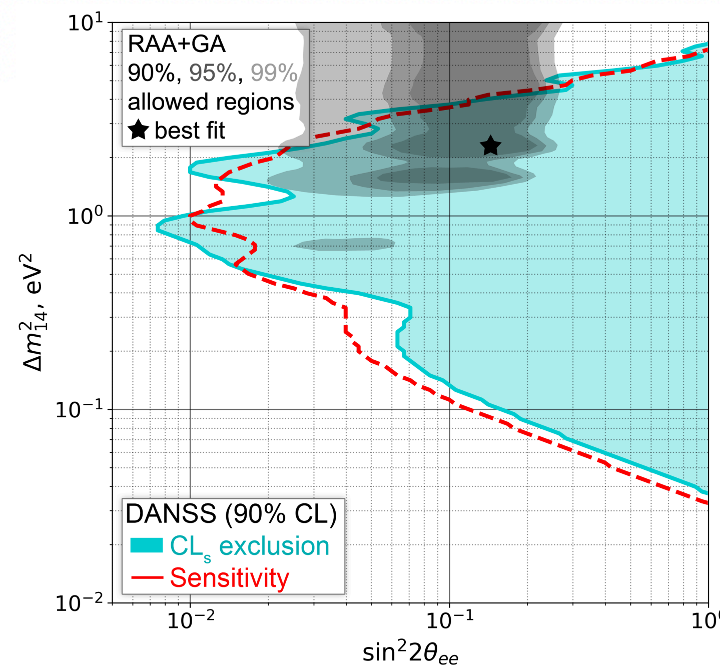




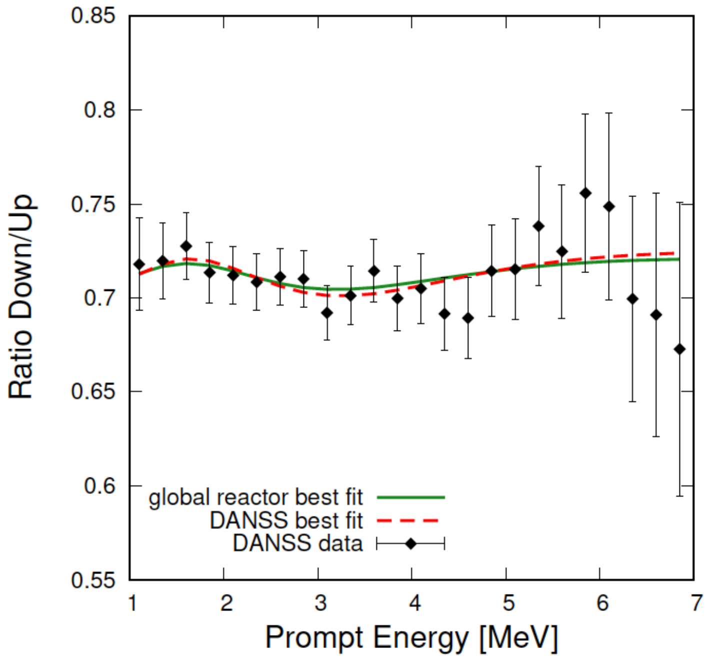


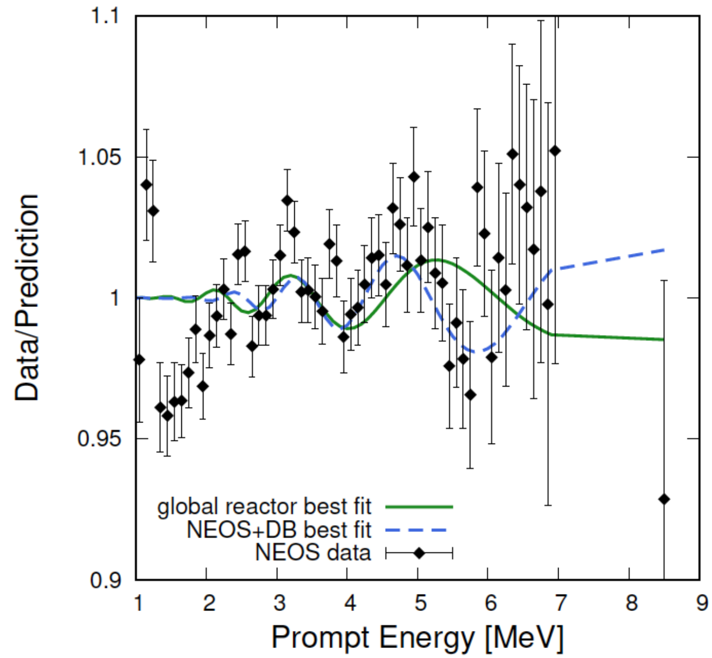
Position changes twice a week





DANSS, NEOS





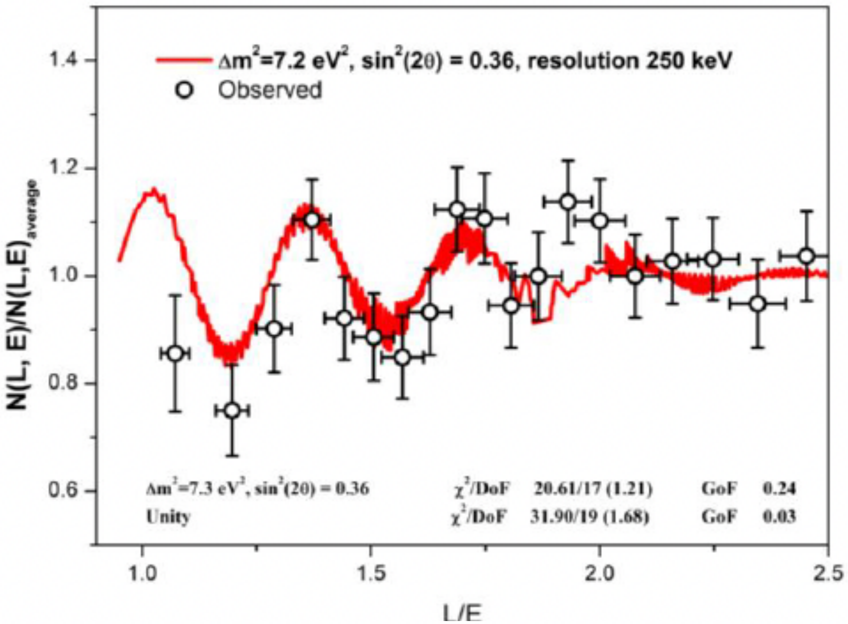
DANSS: relative spectra @ detector locations with $L = 10.7$ and 12.7 m

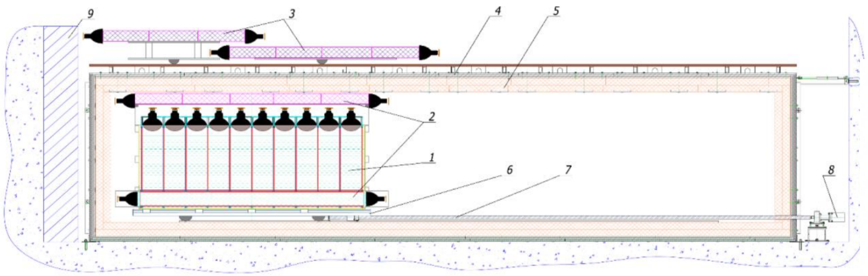
NEOS: spectrum at $L = 24$ m, relative to prediction based on Daya Bay near detector spectrum

Set oscillation limits, no claim for signal

T. Schwetz

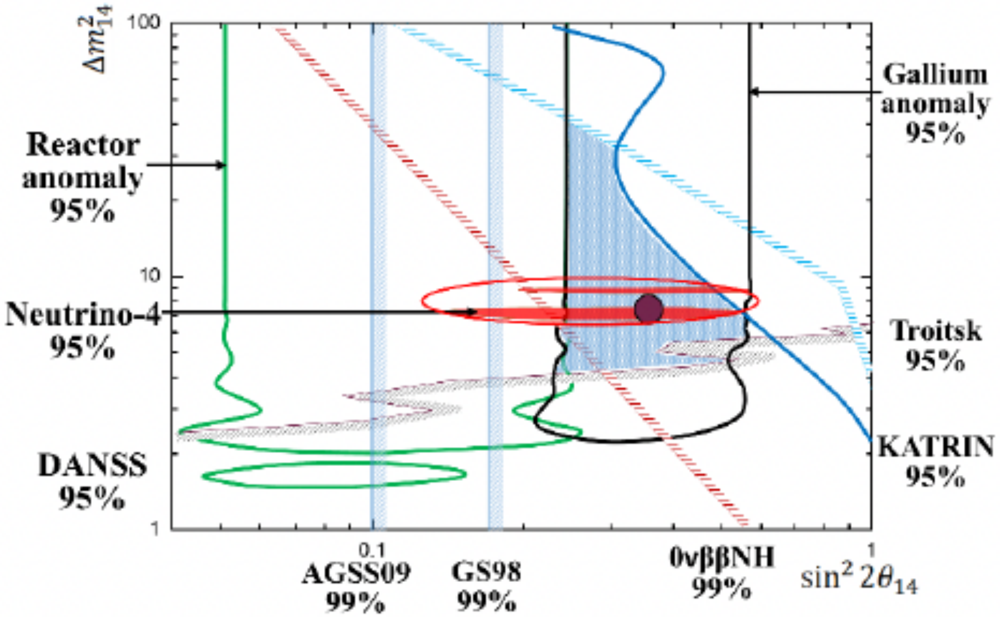
Neutrino-4





Poor agreement between measured and predicted spectrum

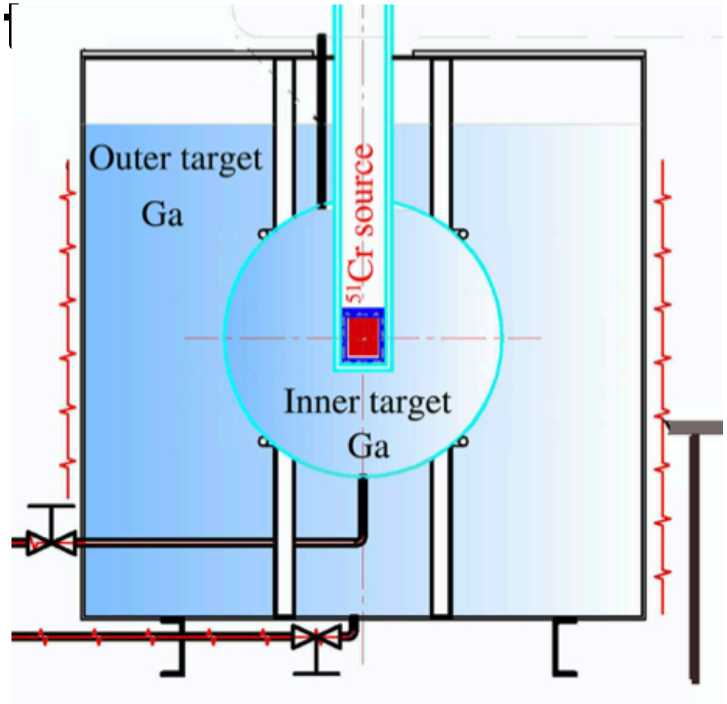
Non-linear effects of detector response are not taken into account

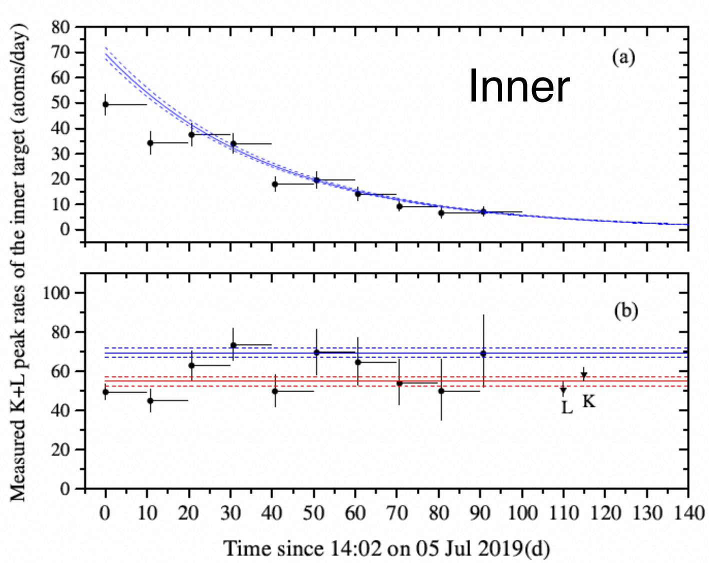


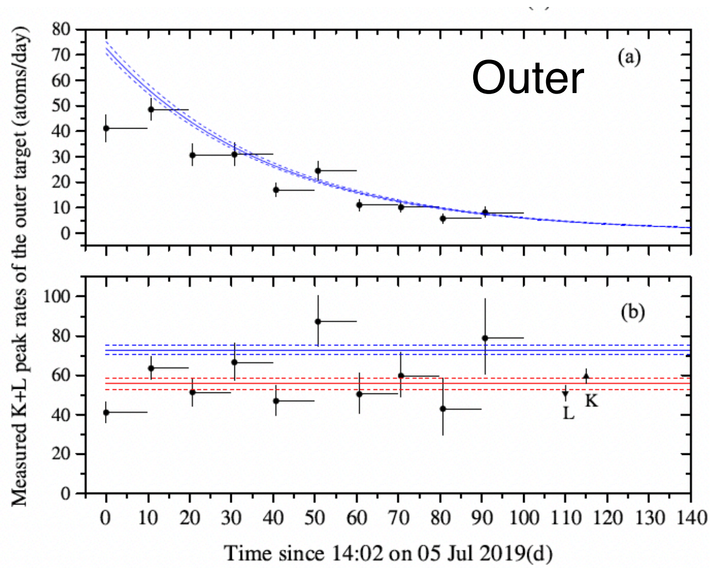
arXiv:2003.09401

BEST Radiochemical Experiment

- 3.4 MCi ^{51}Cr source irradiates nested volumes of gallium
- $R_{in} = 0.791 \pm 0.05$ and $R_{out} = 0.766 \pm 0.05$
- significant deficit implies large mixing

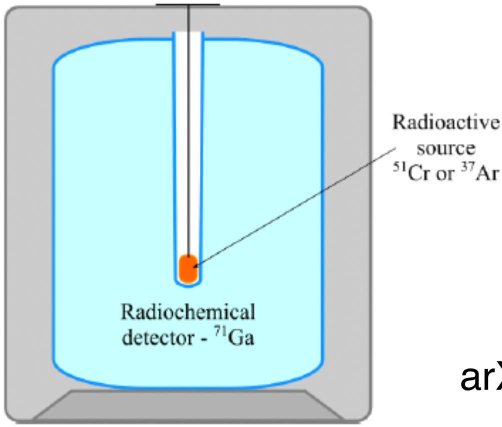






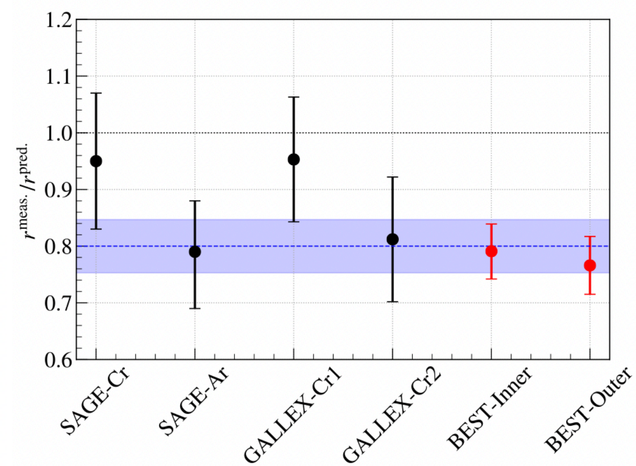
arXiv:2109.11482

Gallium and BEST Experiment

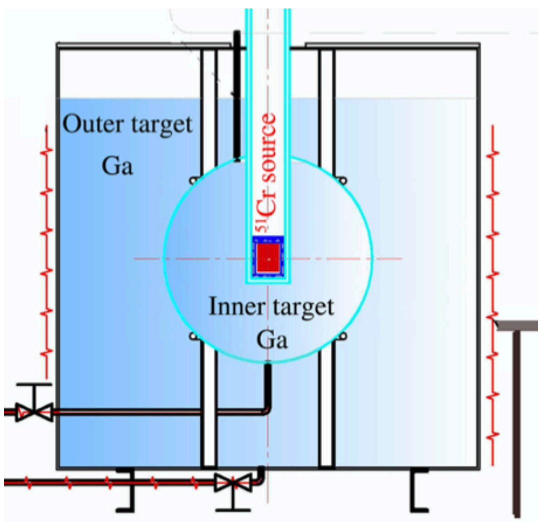


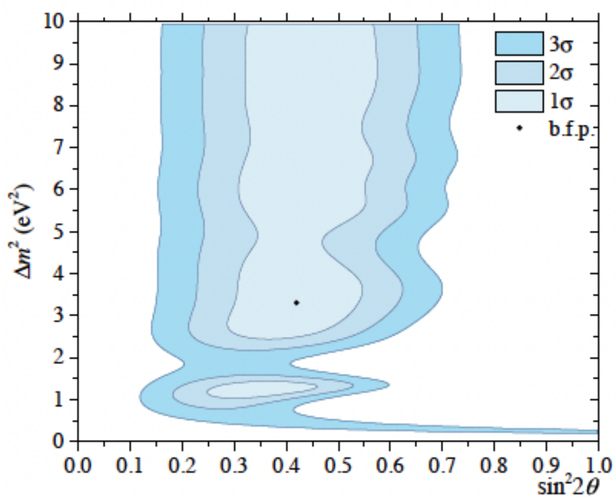
GALLEX	SAGE	
0.953 ± 0.11	0.95 ± 0.12	Predicted rate
$0.812^{+0.10}_{-0.11}$	$0.791^{+0.084}_{-0.078}$	Observed rate

arXiv:2203.07323



arXiv:2201.07364

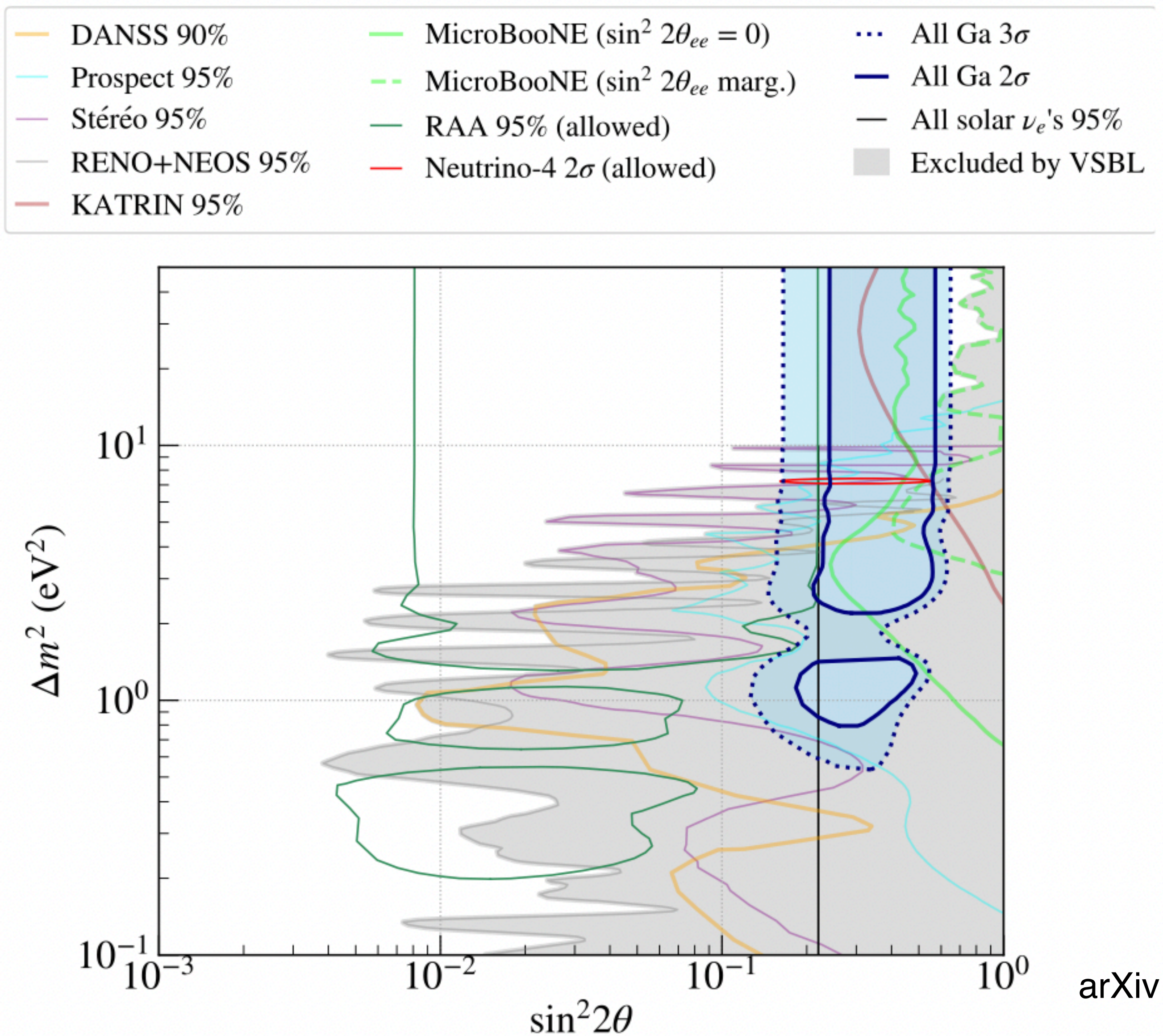




arXiv:2109.11482

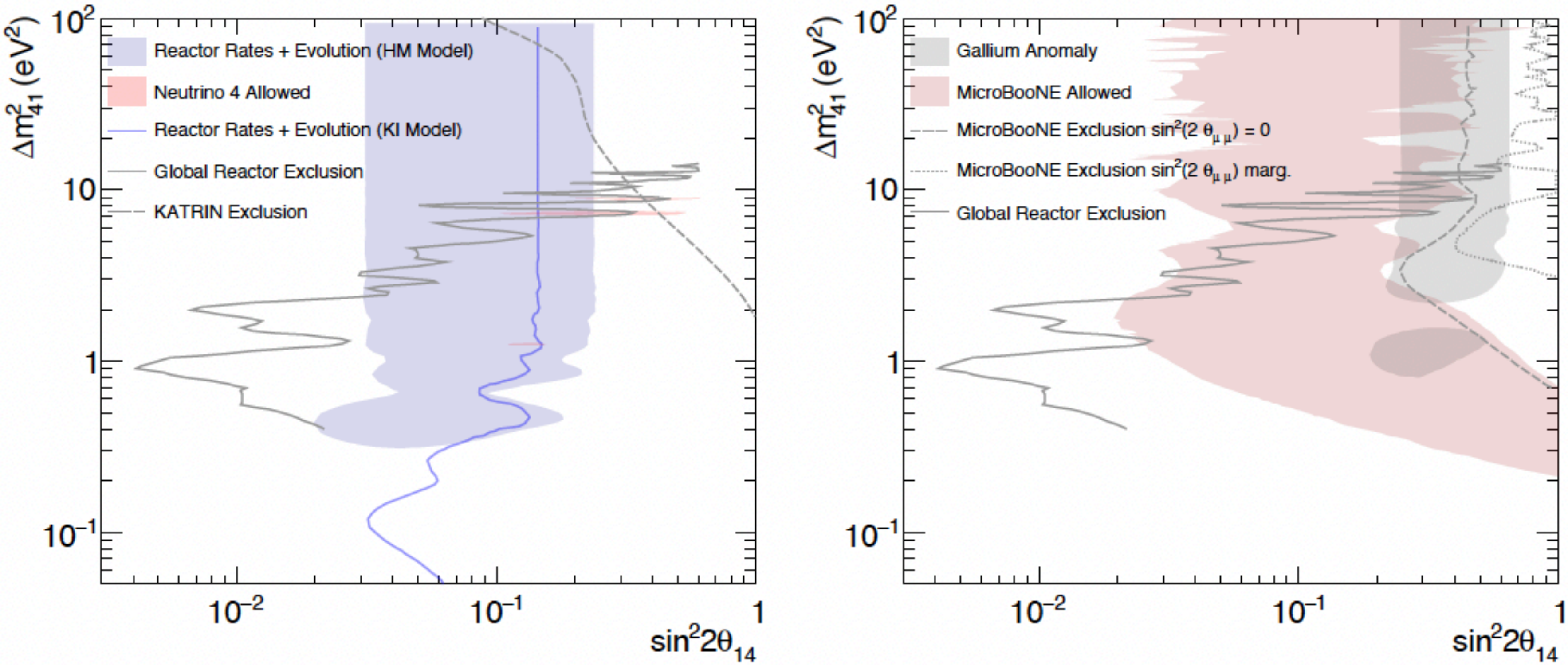
BEST consistent with earlier experiments (SAGE + GALLEX)

BEST, Gallium, and other SBL experiments



arXiv:2201.07364

RAA, Neutrino-4, Gallium and MicroBooNE



arXiv: 2022.12343

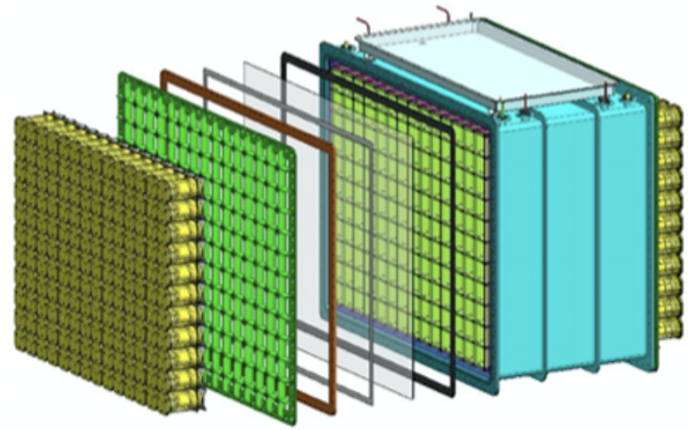
Extended Short Baseline Program with PROSPECT-II

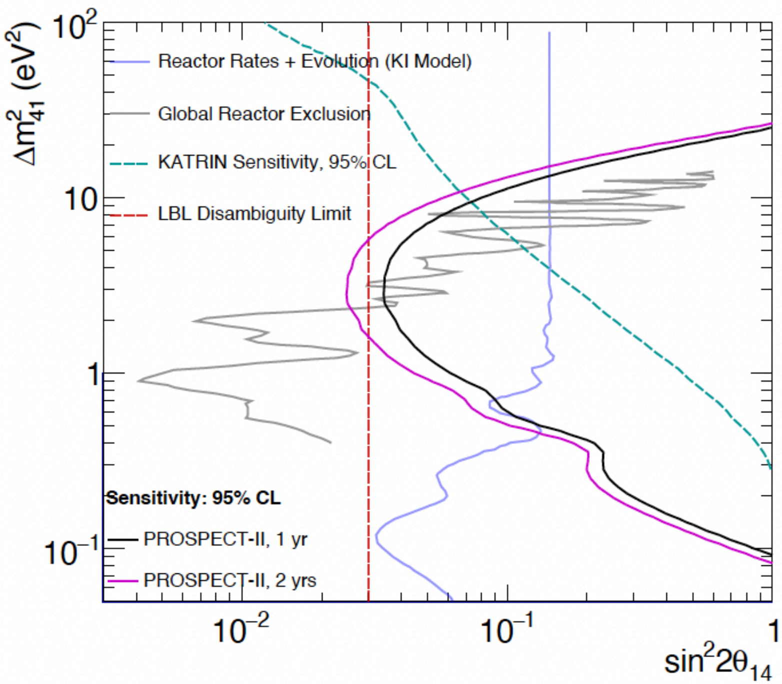
Planned 2 year deployment at HFIR, ORNL

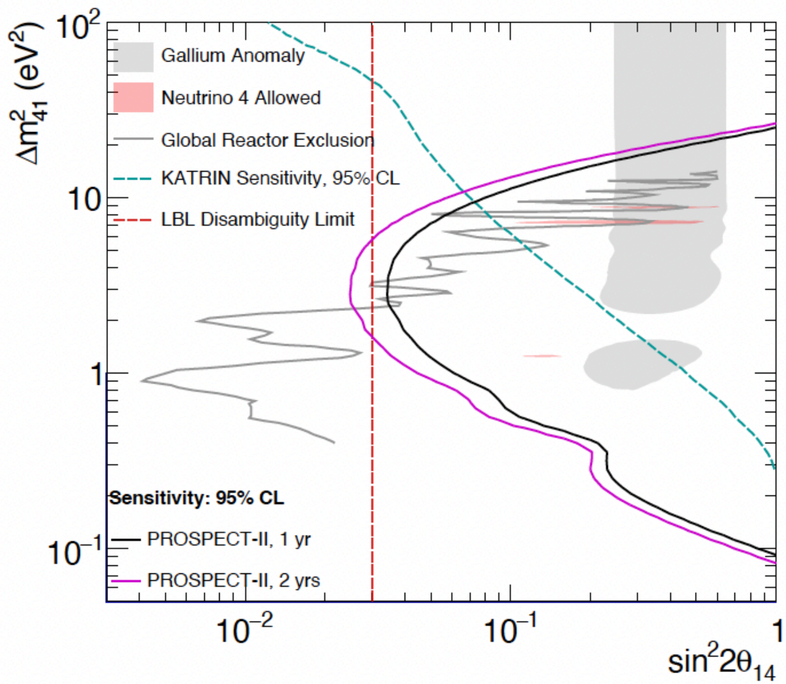
~50% reactor on-time

Detector target mass 30% larger

4:1 signal:background ratio



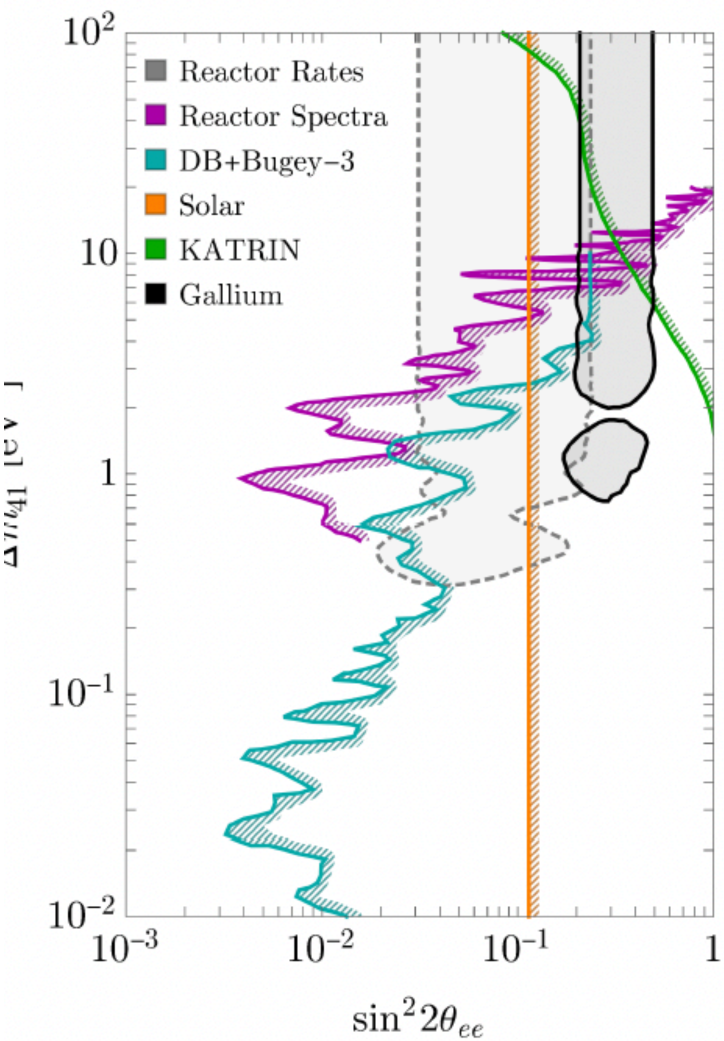




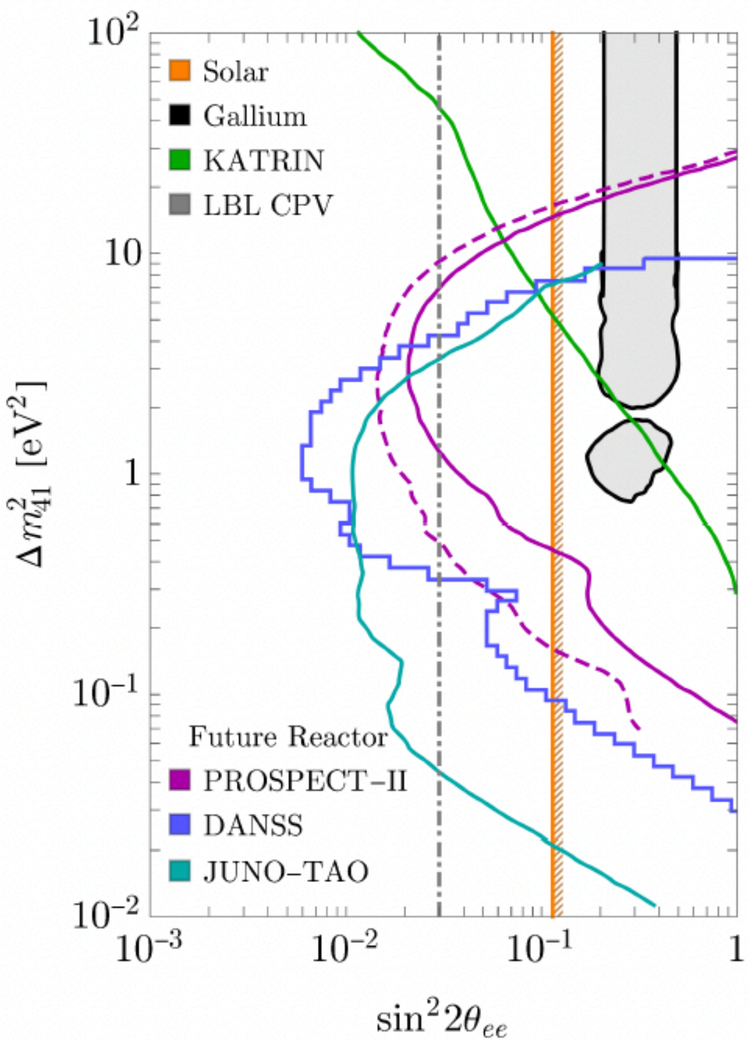
arXiv: 2022.12343

Constraints on ν_e / $\overline{\nu_e}$ Disappearance

Now



Future



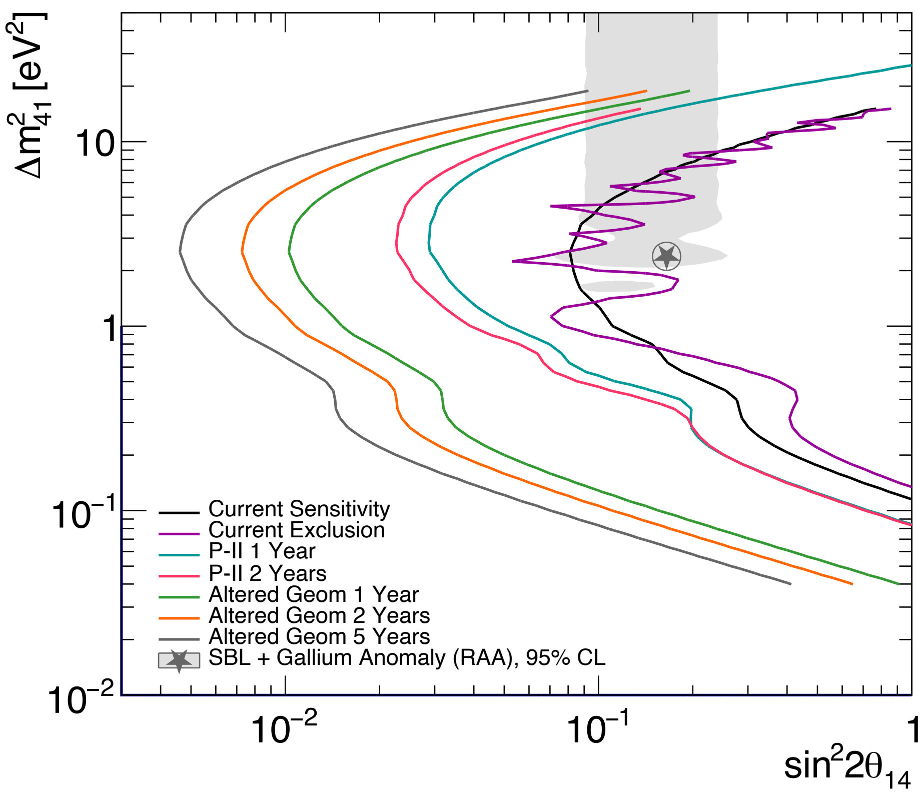
‘Ultimate’ Reactor SBL Experiment at HFIR

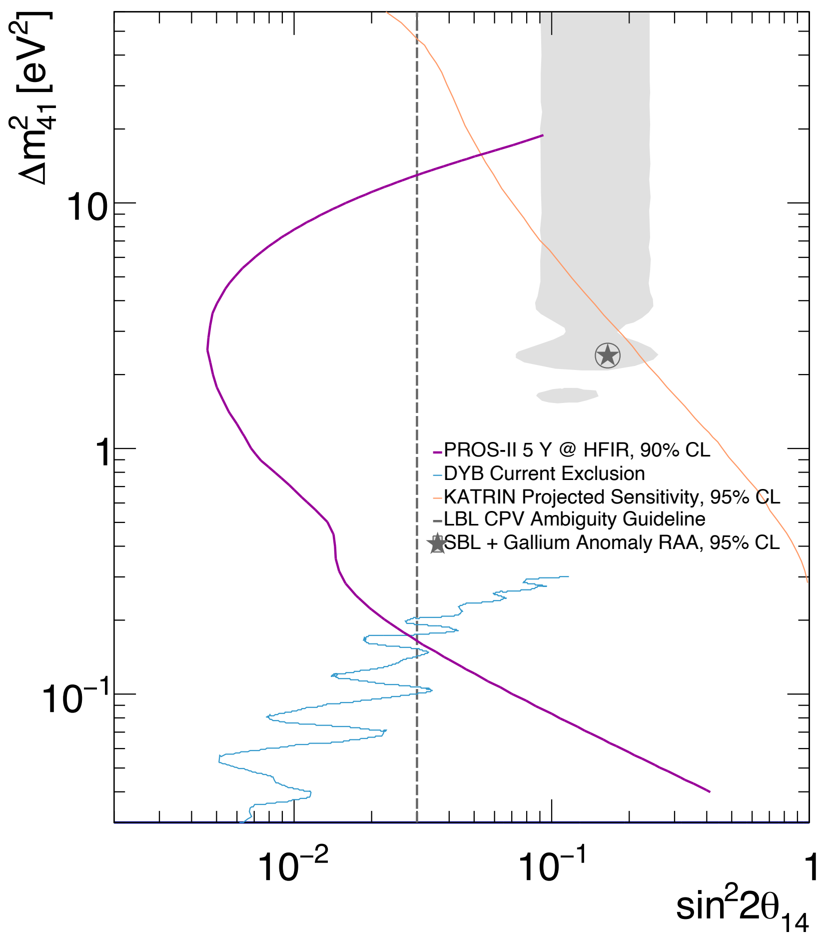
20 k L active volume (5 x PROSPECT)

6 m long (3 x PROSPECT), ~7 m baseline

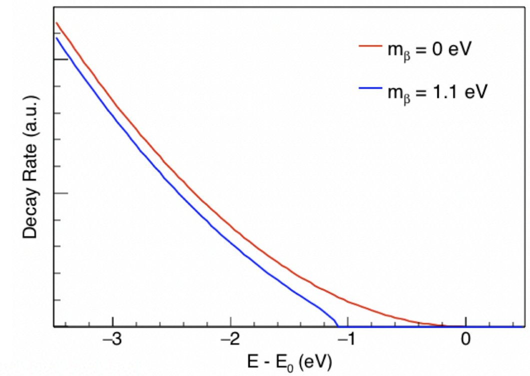
S:B 10:1

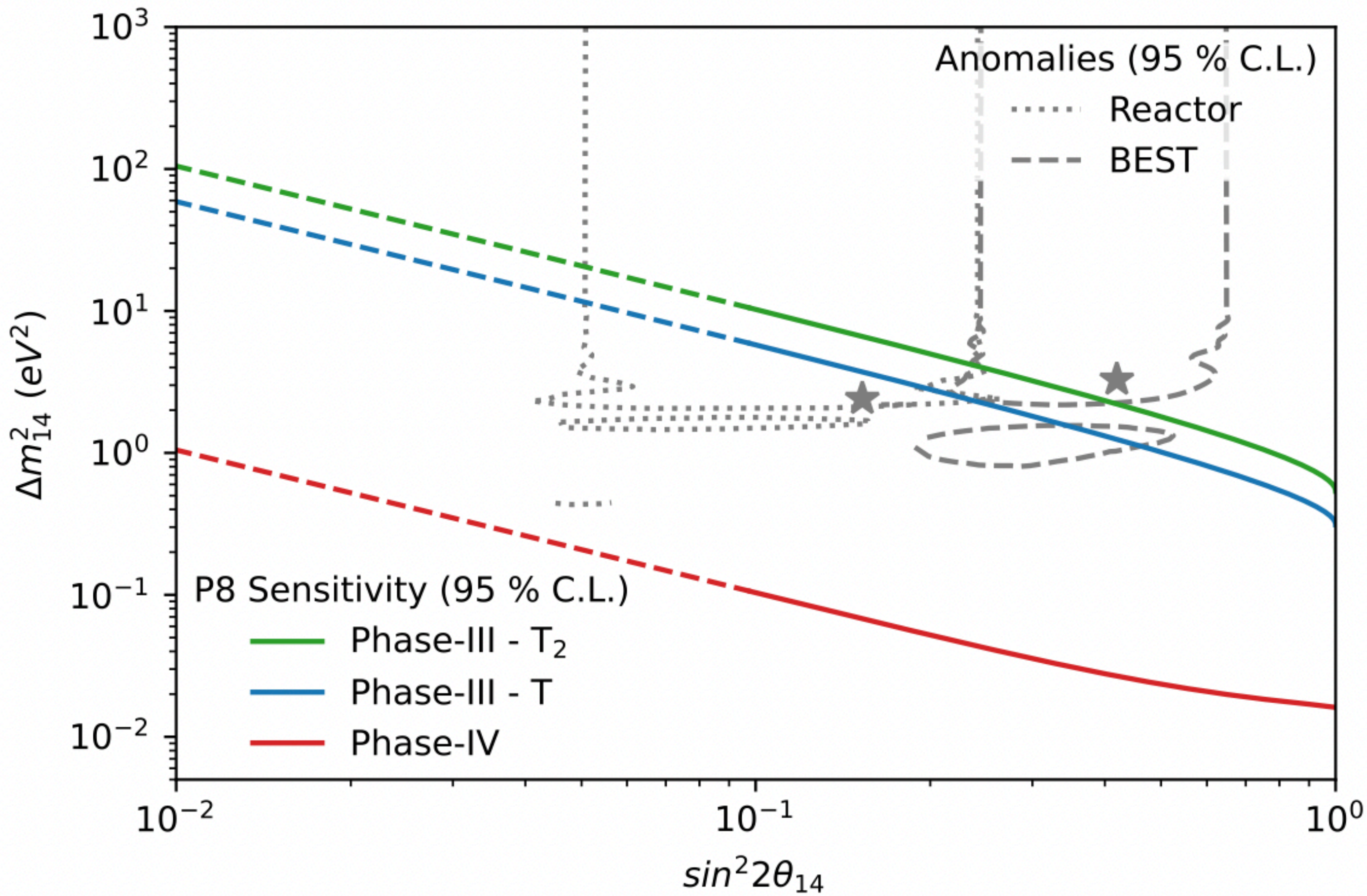
roughly 1 M events/year





Project 8 and Sterile Neutrinos





arXiv:2203.07349

Summary and Outlook

Reactor experiments have made high-precision measurements of the prompt energy spectrum from PWR and HEU reactors.

Incorrect prediction of the ^{235}U flux likely primary source of the reactor antineutrino rate anomaly.

No significant indications of ν_s in reactor experiments, PROSPECT, STEREO, DANSS, NEOS place strong limits.
Except for Neutrino-4, still some concerns about analysis of Neutrino-4.

BEST confirmed GA with high significance, in strong tension with other experiments. SBL reactor experiments, KATRIN, and Project 8 can probe remaining parameter space.

Upgraded plans (e.g. PROSPECT-II) significantly expand SBL program to search for BSM physics.