Short Baseline Neutrino Experiments

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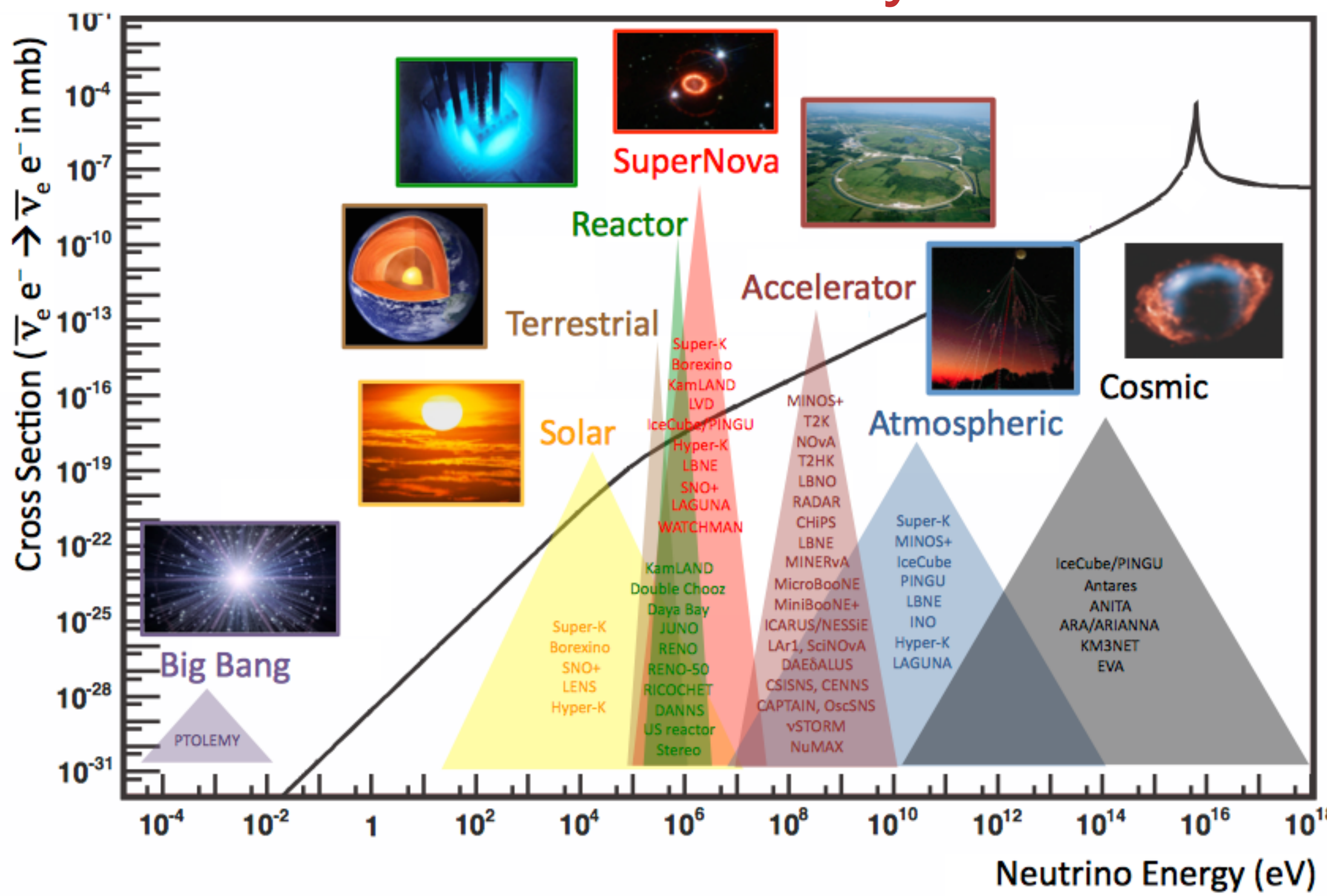
Neutrinos Matter!

- We need to understand neutrinos if we want to understand our universe!

Neutrinos are everywhere!

  - They are **invaluable astronomical (and terrestrial) messengers**
  - They are the **second most abundant particle in the universe**



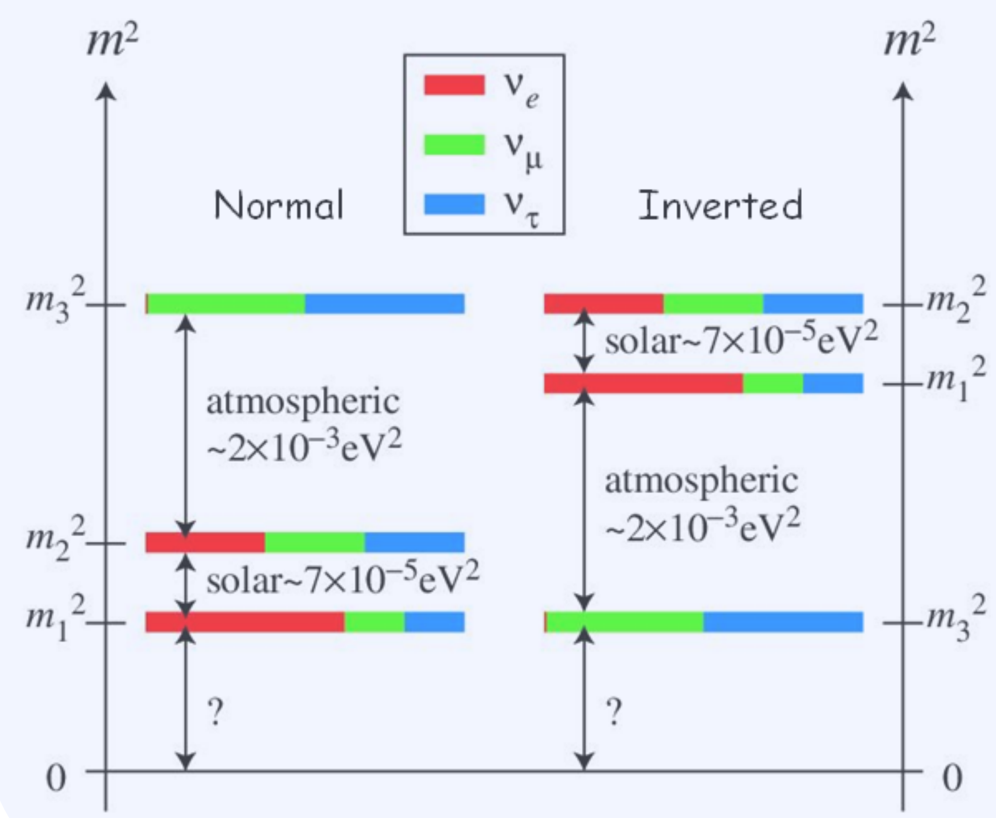
  - **They are guiding the way to new physics**

Short Baseline Neutrino Experiments

- Short baseline (SB) neutrino experiments are at the forefront of our field:
  - Performing precision measurement of neutrino oscillation parameters
  - Tackling open questions:
    - What is the neutrino mass ordering?
    - Are there more than 3 neutrinos (and/or other new physics)?
  - Studying a variety of neutrino sources and processes
  - Producing important flux and cross-section measurements

See talk by K. McFarland

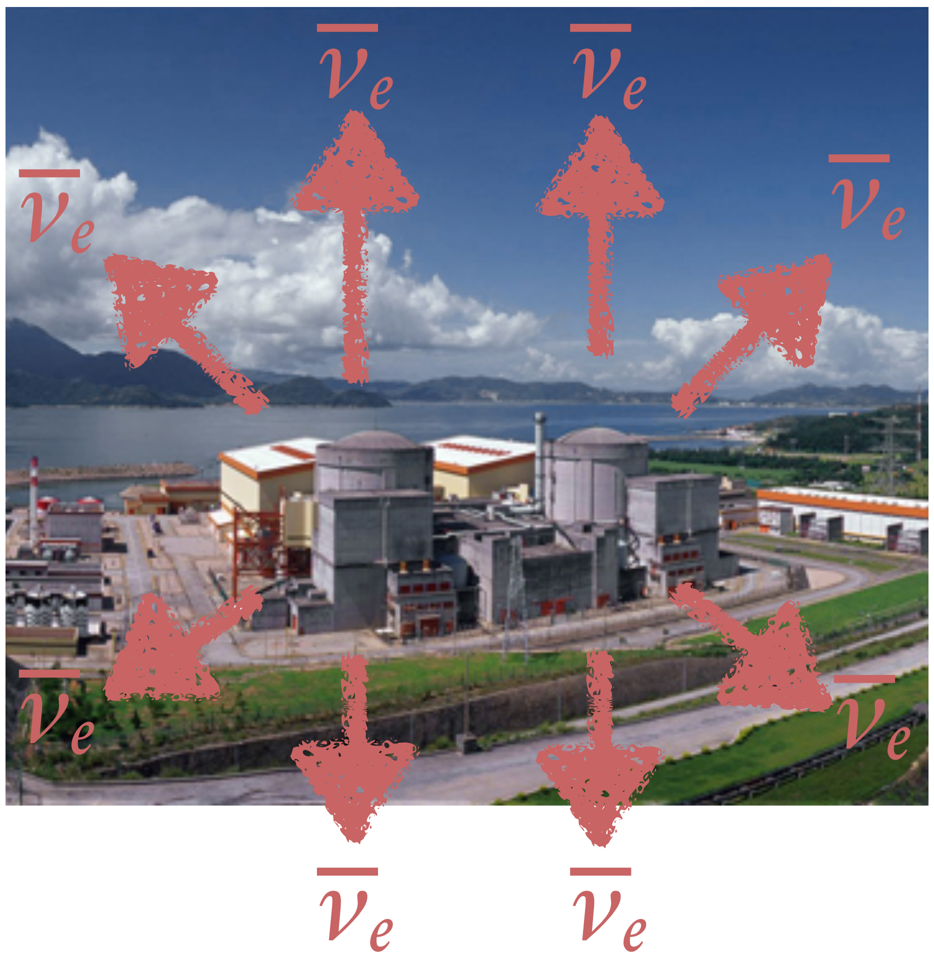
Our current picture of neutrinos



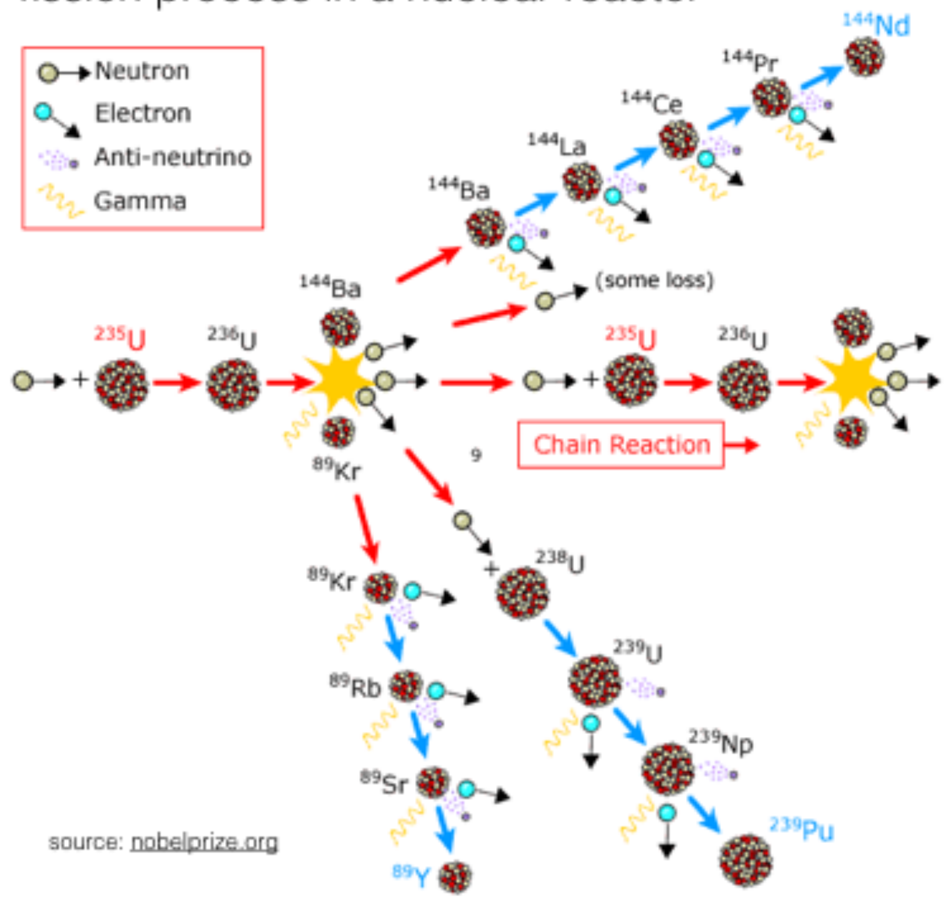
- In this talk I will highlight the contributions of present and future SB experiments with a focus on **reactor experiments**
  - Disclaimer: I am a member of the Daya Bay and JUNO collaborations

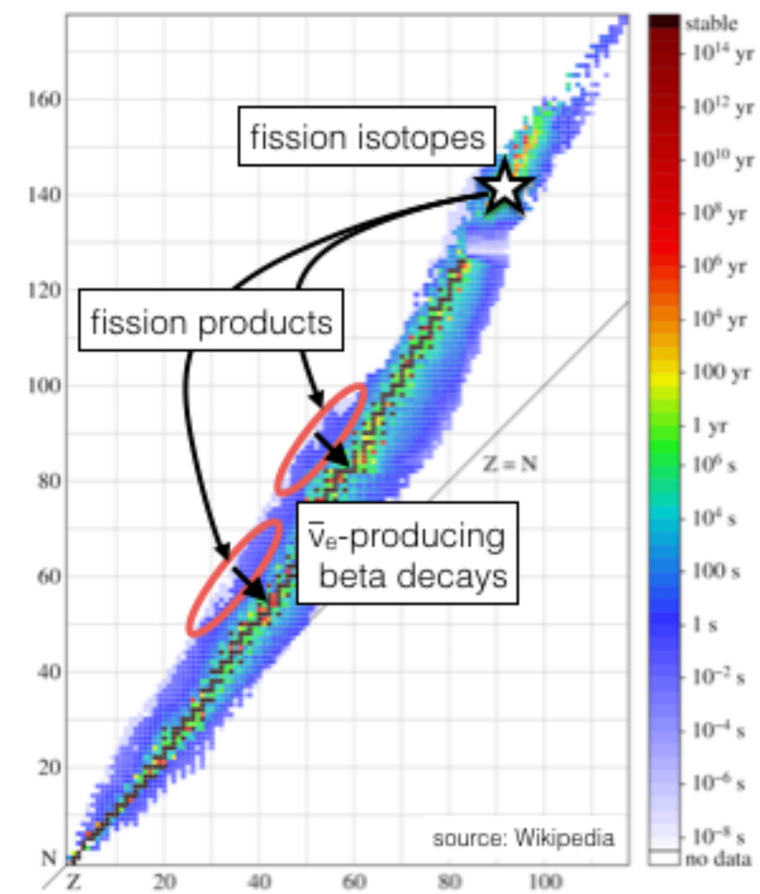
Reactor Antineutrinos

- Nuclear power plants are an **abundant** and **well-understood** source of electron antineutrinos:



fission process in a nuclear reactor





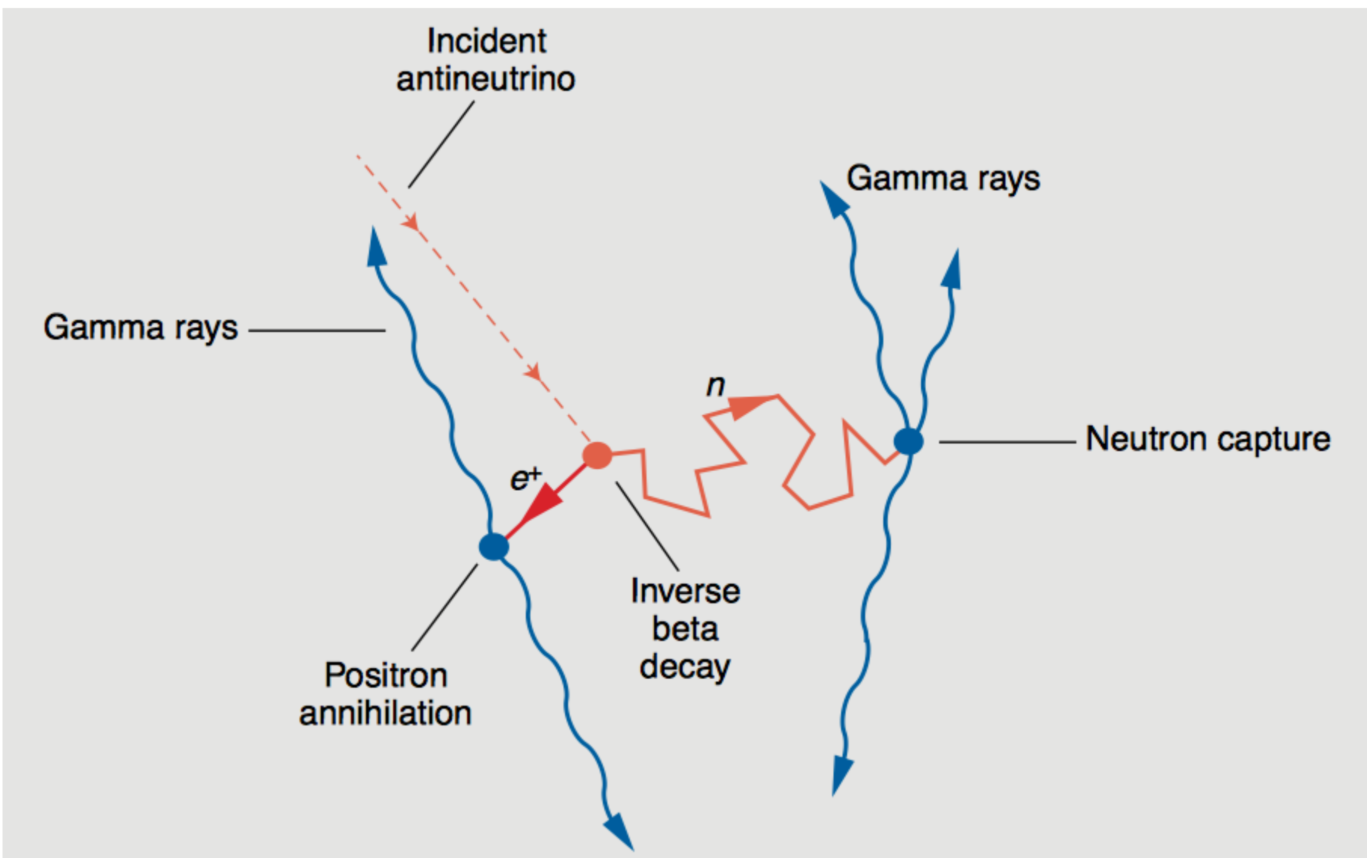
$$n \longrightarrow p + e^- + \overline{\nu}_e$$

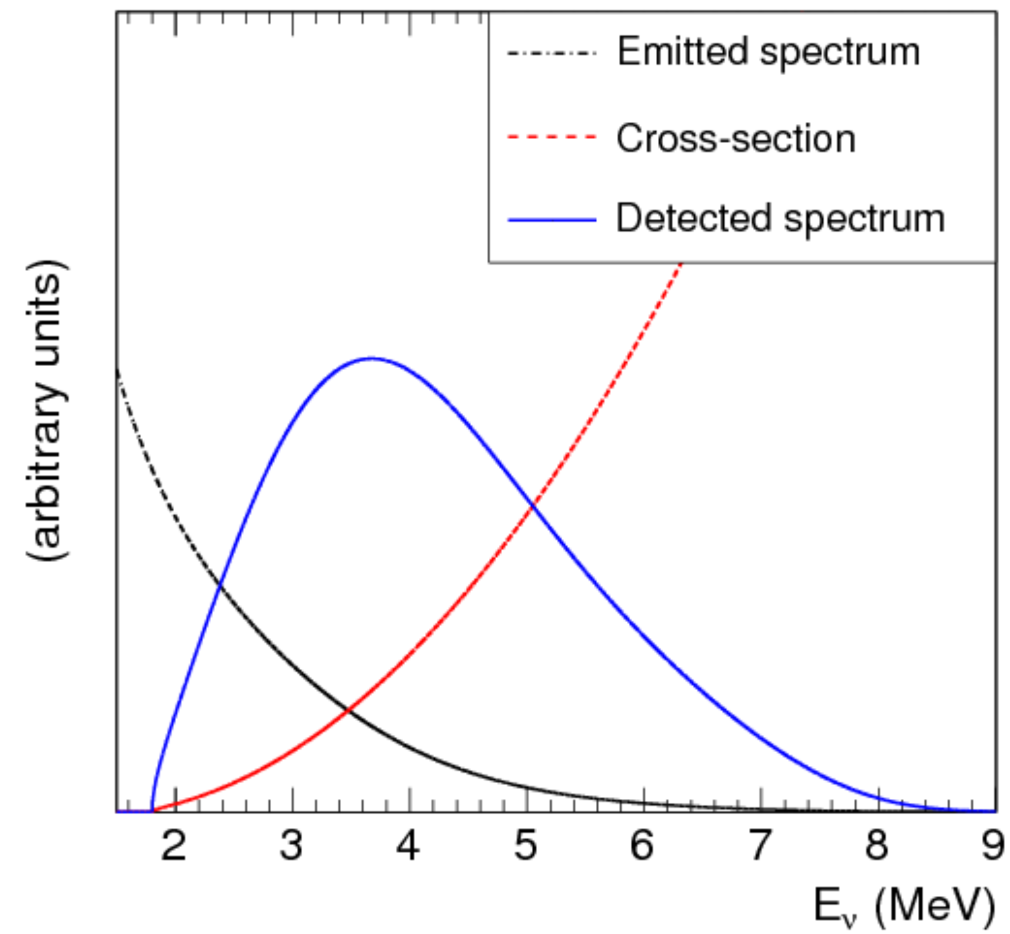
  – Neutrinos originate primarily from fission products of 4 isotopes: ^{235}U, ^{239}Pu, ^{241}Pu and ^{238}U

Detection Essentials

- The primary detection channel in reactor experiments is the inverse beta decay (IBD) reaction:

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





  - Coincidence between positron and neutron signals allows for powerful background rejection
  - Product of flux times IBD cross-section gives spectrum that peaks around 3-4 MeV

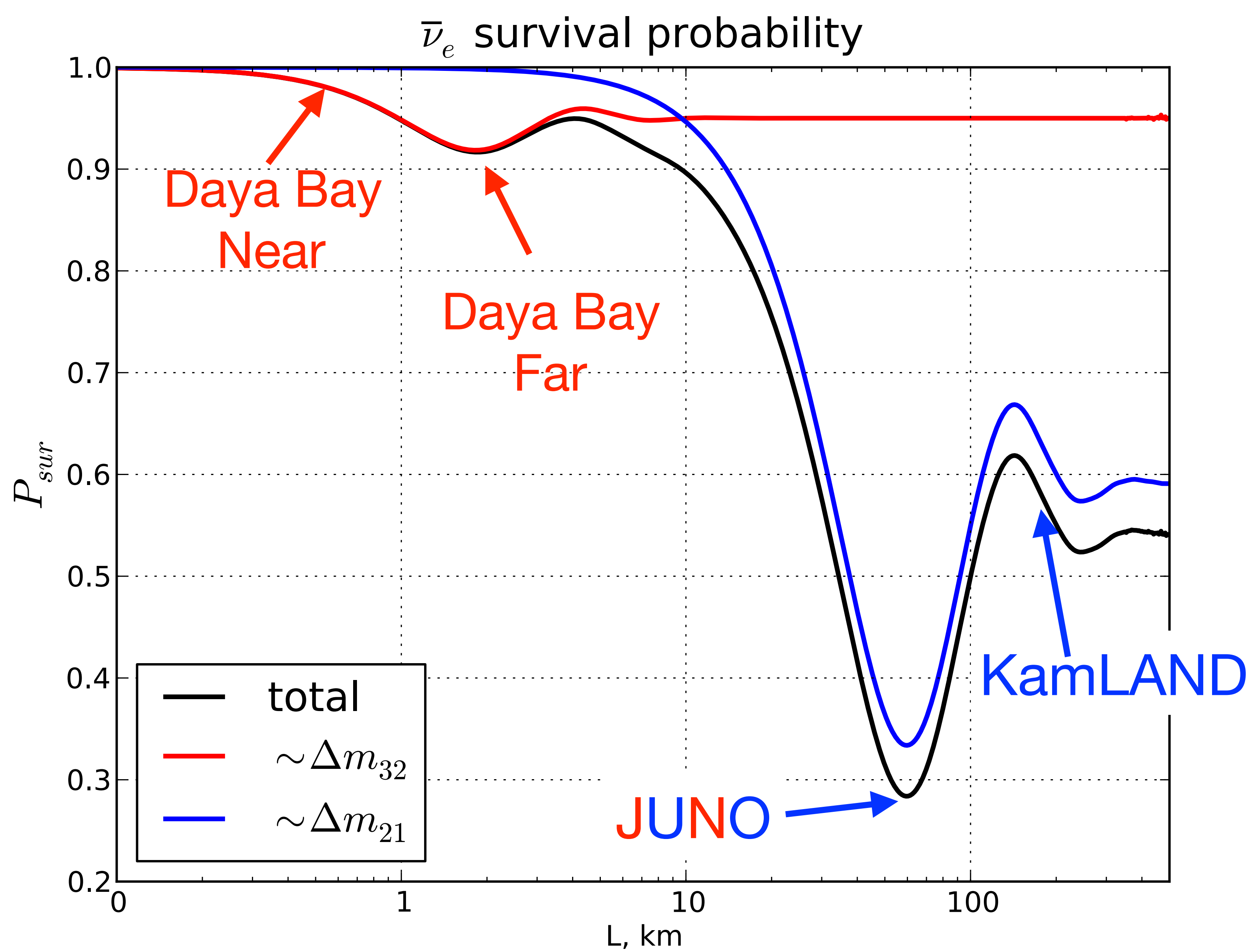
Electron Antineutrino Disappearance

- The disappearance of electron antineutrinos is given by:

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\theta_{13}\left(\cos^2\theta_{12}\sin^2\frac{\Delta m^2_{31}L}{4E} + \sin^2\theta_{12}\sin^2\frac{\Delta m^2_{32}L}{4E}\right) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\frac{\Delta m^2_{21}L}{4E}$$

This channel gives **access to most neutrino oscillation parameters** (θ_{12}, θ_{13}, Δm^2_{21} and Δm^2_{32}), in a way that is independent of θ_{23} and CP effects.

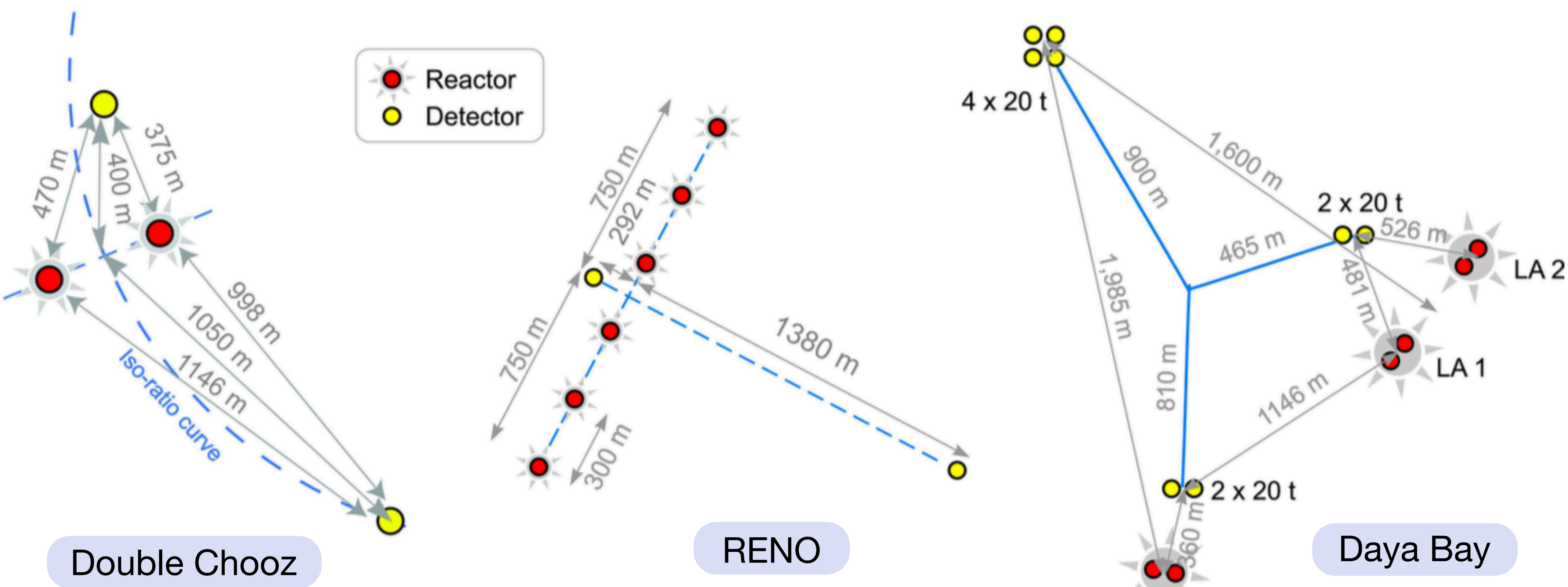
Physics goals drive choice of baseline



(disclaimer: only including a small subset of reactor experiments in this graph)

Ongoing Reactor Experiments

- Three running experiments (Daya Bay, RENO and Double Chooz) were designed to make a **precision measurement of the θ_{13} mixing angle**
- Strategy: look for disappearance at **short (~1-2 km) baselines:**
  - Need "small" detectors (tens or hundreds of tons)
  - Looking for a small effect, so **key is keeping systematics under control**

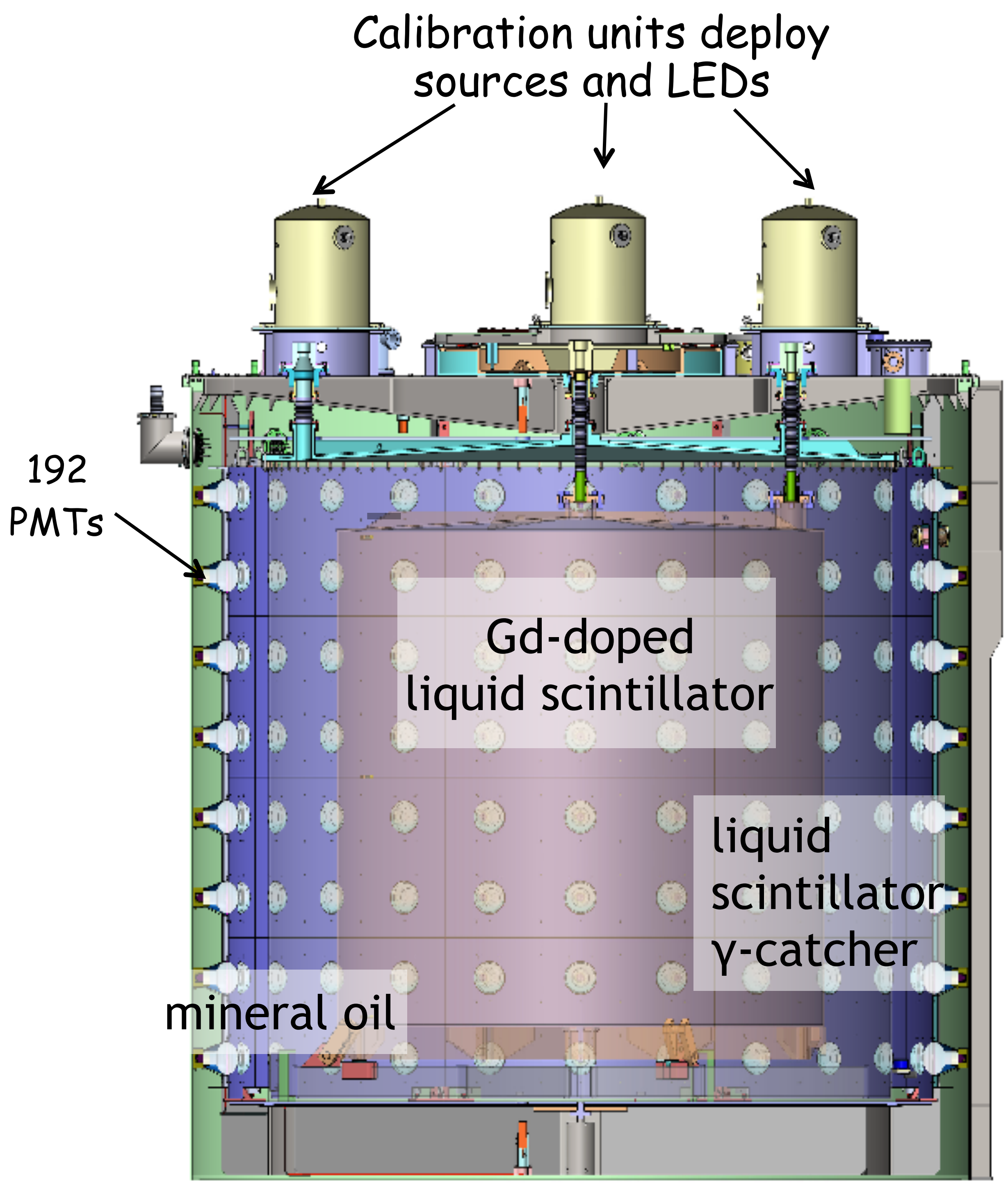


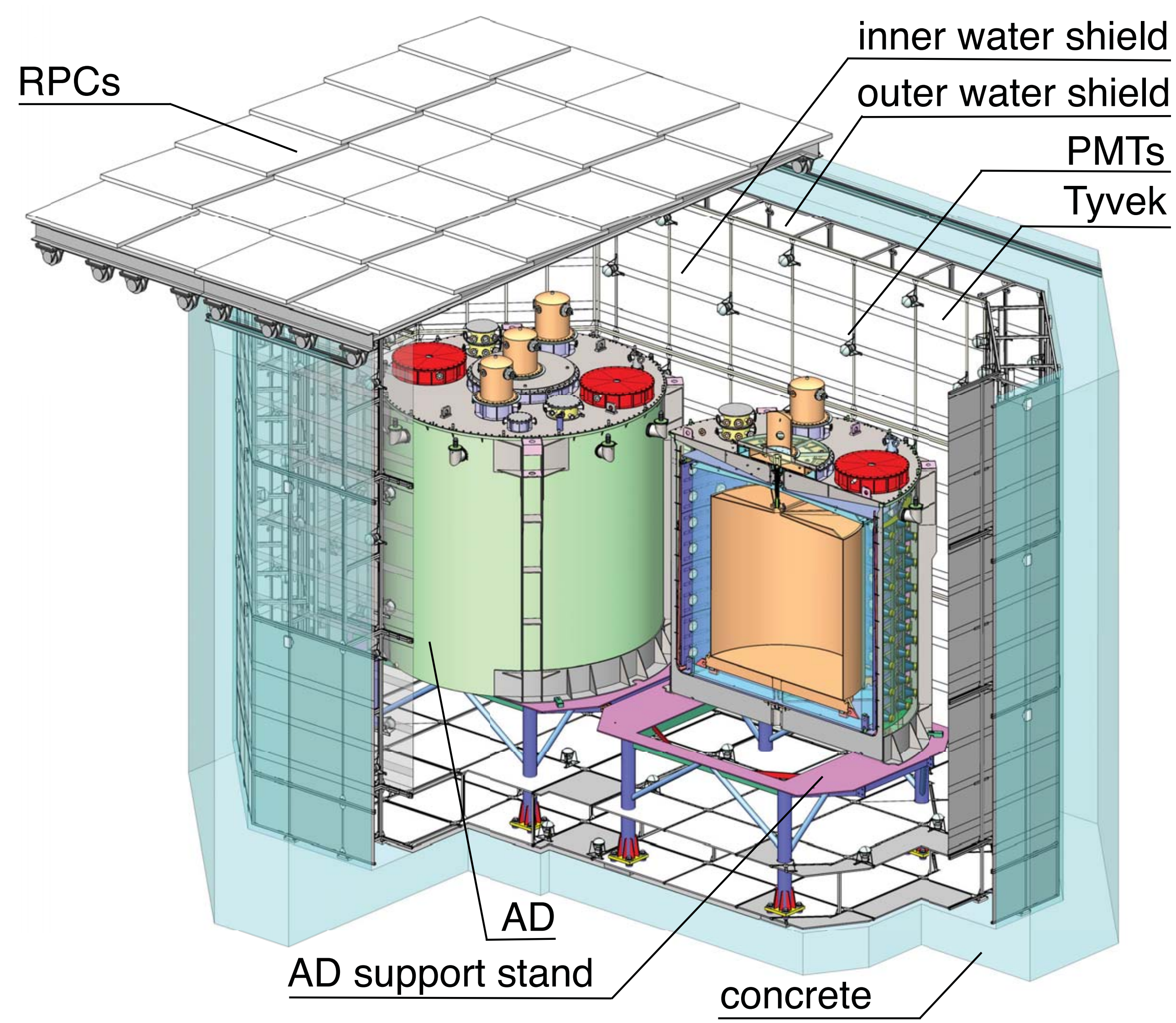
Note: Double Chooz just stopped running recently

JPhysG37,103001 (2010)

Detector Technology

- Similar detection technologies:
  - Three-zone detectors
  - Surrounded by instrumented shields (water or LS) that also veto muons

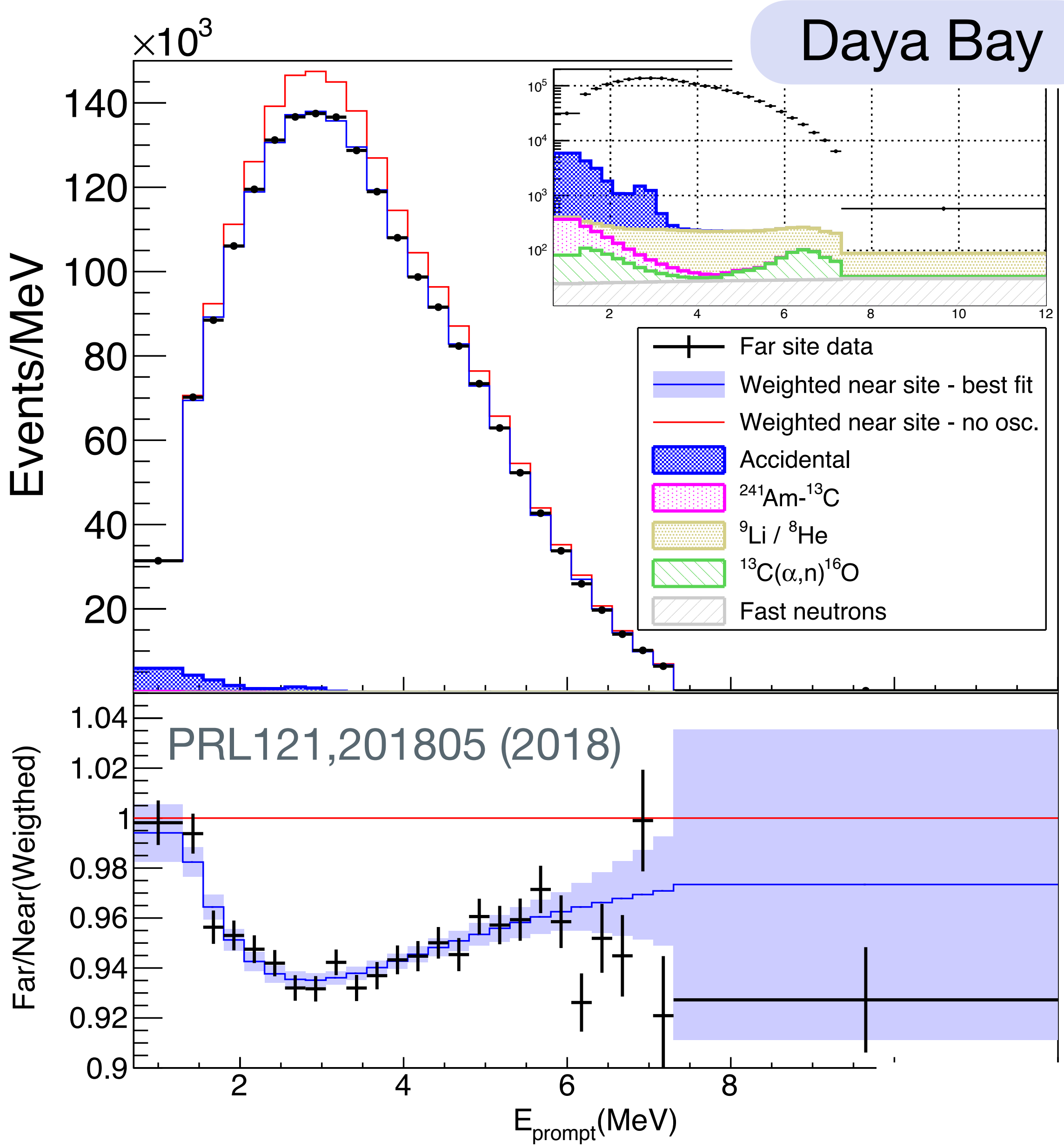


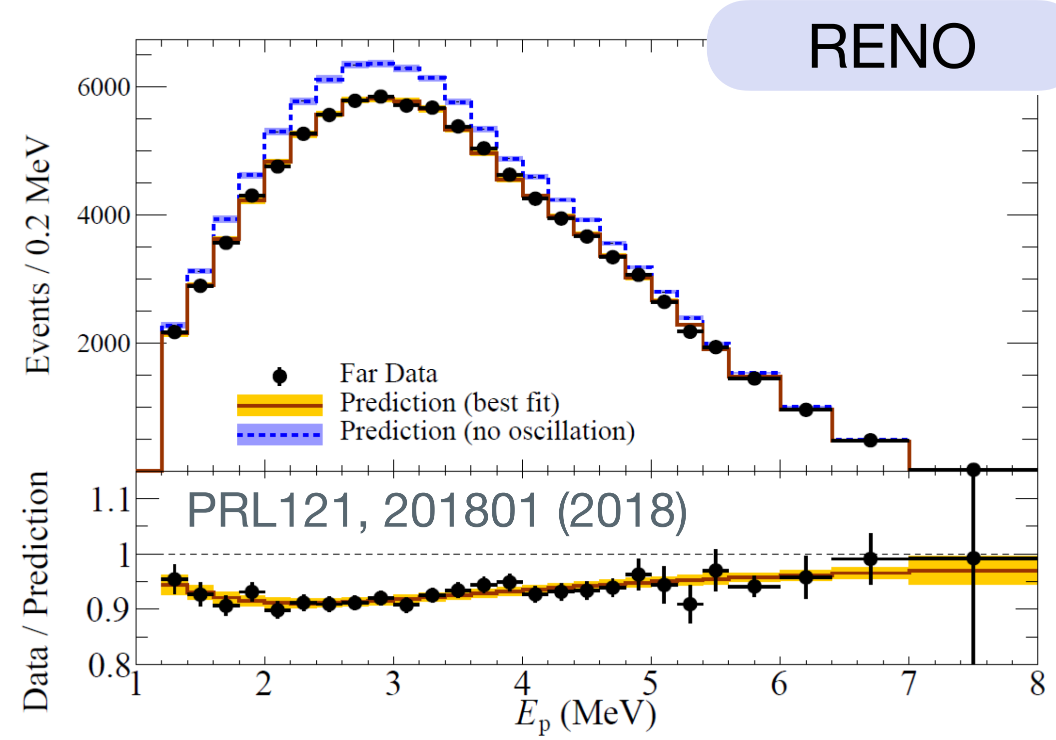


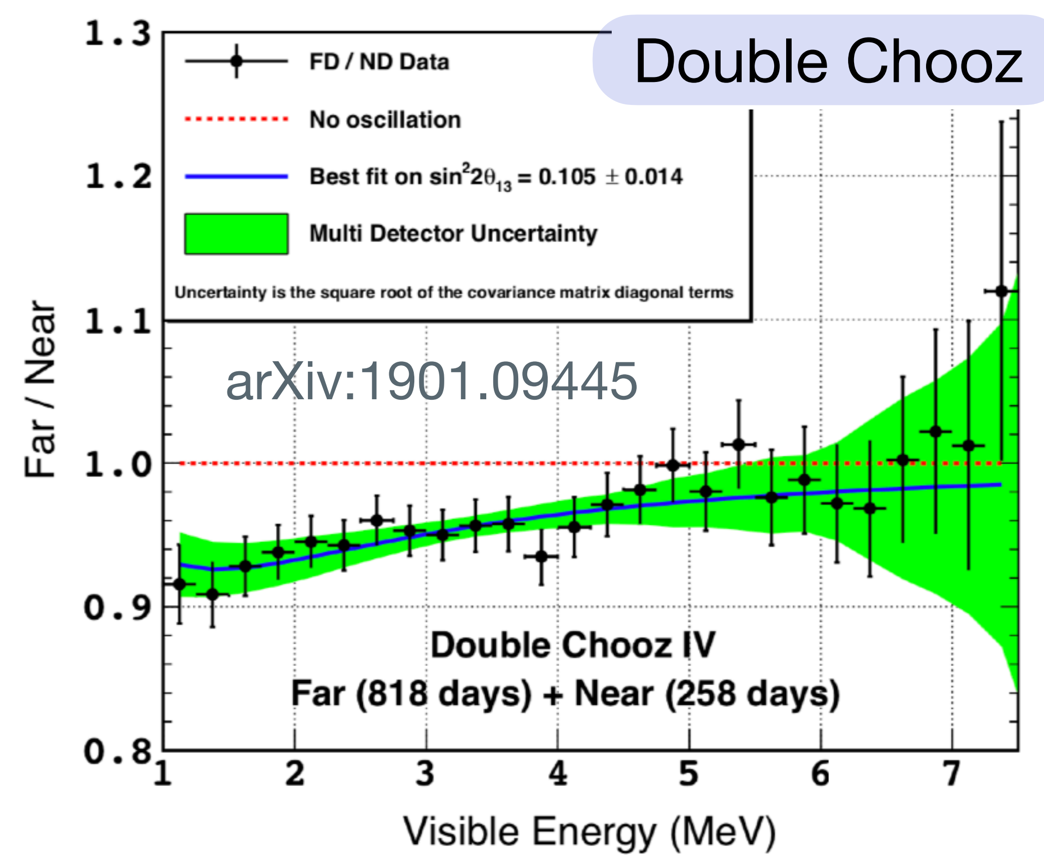
(using Daya Bay as an illustration)

Clear Oscillation Signal

- The three experiments see a clear oscillation signal consistent with 3-flavor oscillations:



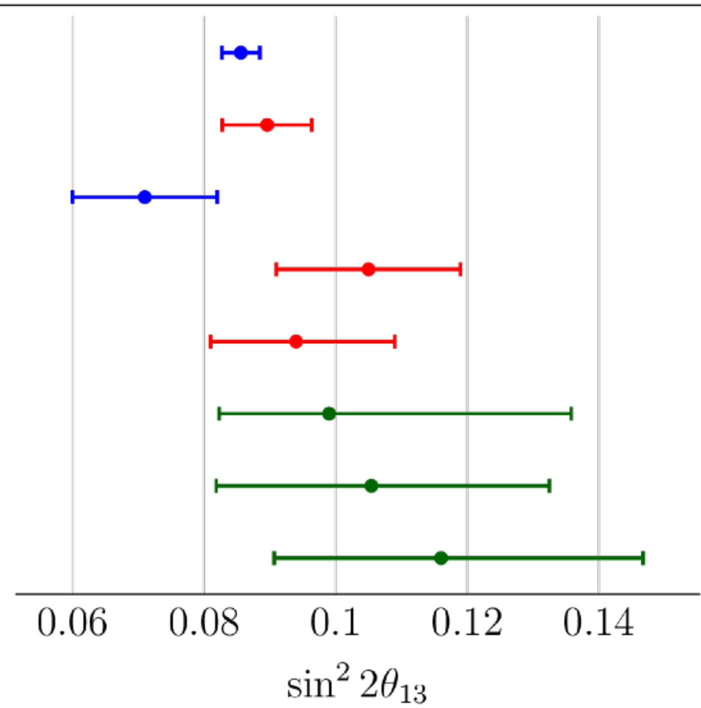




Global Landscape

- The most precise measurements of θ_{13} come from reactor experiments:

Experiment		Value
Daya Bay	nGd	0.0856 ± 0.0029
RENO	nGd	0.0896 ± 0.0068
Daya Bay	nH	0.071 ± 0.011
D-CHOOZ	nGd+nH	0.105 ± 0.014
RENO	nH	$0.094^{+0.015}_{-0.013}$
	bayessian	$0.099^{+0.037}_{-0.017}$
T2K	NH	$0.105^{+0.027}_{-0.024}$
	IH	$0.116^{+0.031}_{-0.025}$

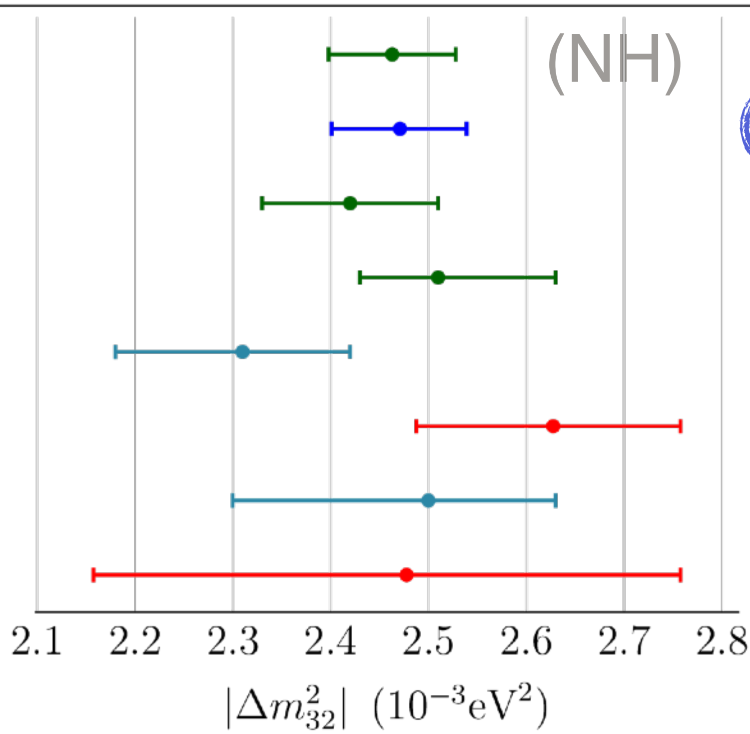


~3.4% precision in $\sin^2 2\theta_{13}$!

Best known angle in the Pontecorvo Maki Nakagawa Sakata (PMNS) matrix!

- Can also measure Δm^2_{32} through the spectral distortion:

Experiment	Value (10^{-3} eV^2)
T2K	2.463 ± 0.065
Daya Bay	$2.471^{+0.068}_{-0.070}$
MINOS	2.42 ± 0.09
NOvA	$2.51^{+0.12}_{-0.08}$
IceCube	$2.31^{+0.11}_{-0.13}$
RENO (nGd)	$2.63^{+0.13}_{-0.14}$
Super-K	$2.50^{+0.13}_{-0.20}$
RENO (nH)	$2.48^{+0.28}_{-0.32}$



Similar precision to that from accelerator experiments

(figures courtesy of M. Gonchar, updated shortly after Neutirno 2018)

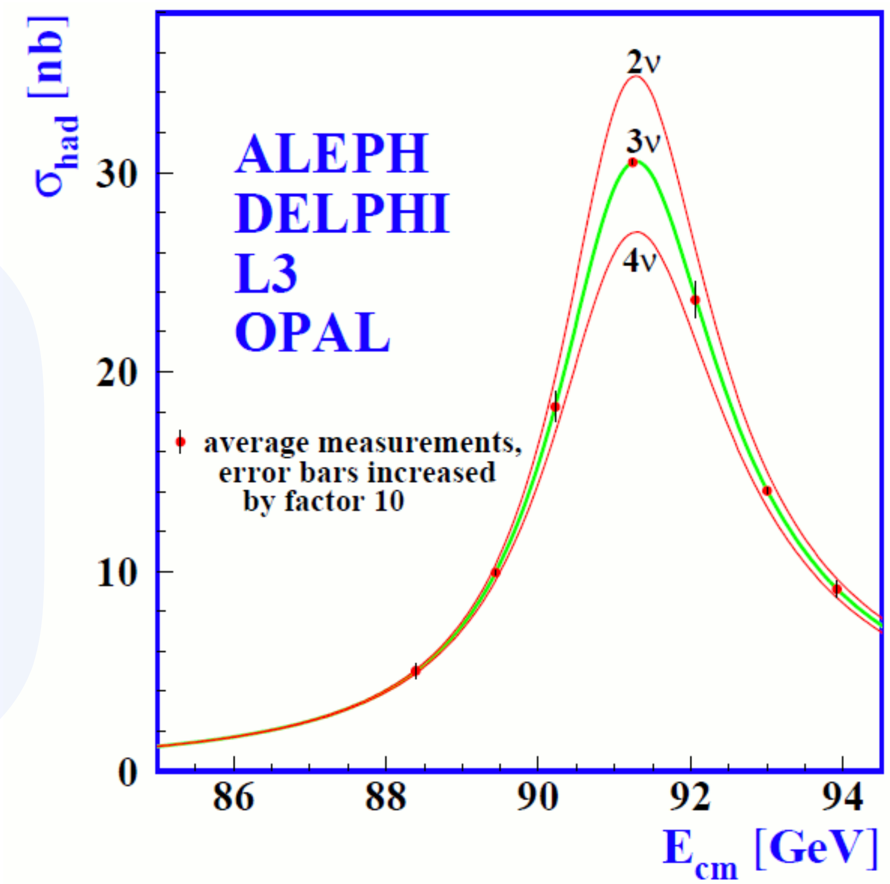
Sterile Neutrinos

- Ongoing reactor experiments are also an ideal ground to search for sterile neutrinos:

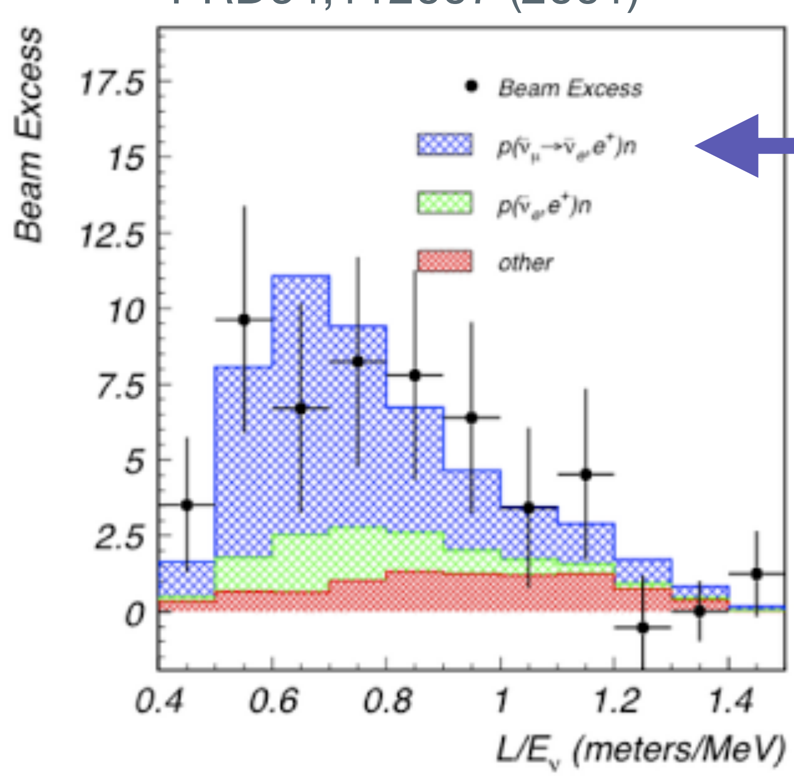
✔ Well-motivated from the theoretical standpoint

✔ Could explain some of the puzzles in astrophysics (e.g. dark matter)

✔ Could explain some of the anomalies seen in neutrino physics



PRD64,112007 (2001)

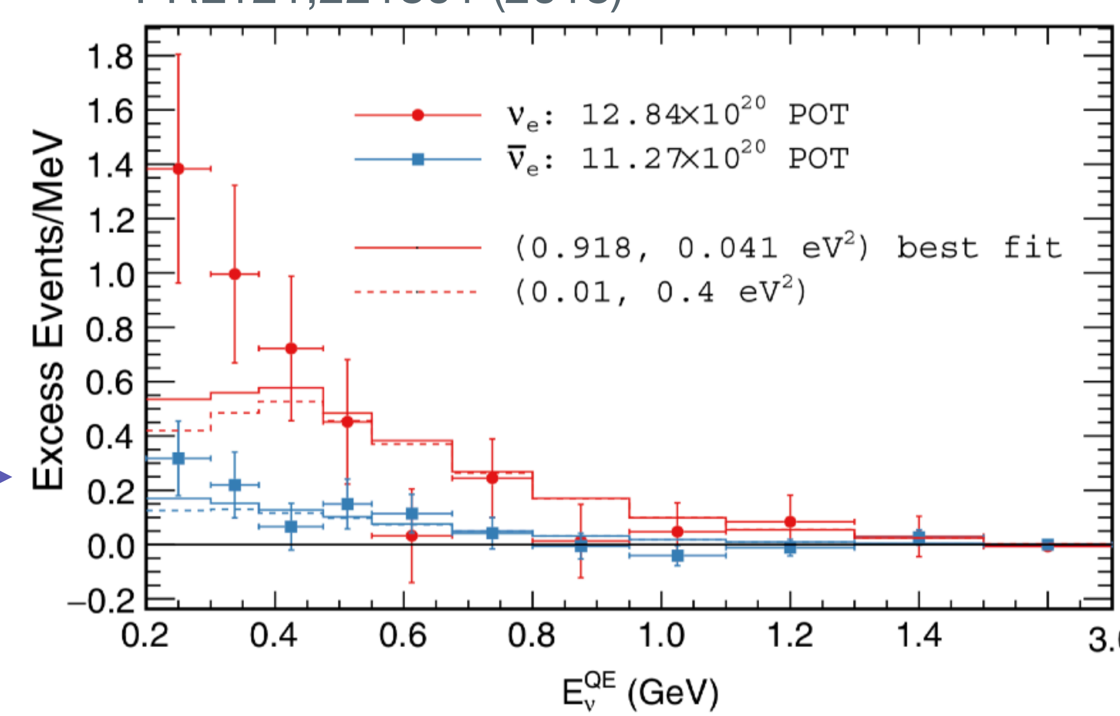


LSND:
3.8σ excess of $\bar{\nu}_e$ in a $\bar{\nu}_\mu$ beam (2001)

MiniBooNE:
4.7σ excess of $\nu_e/\bar{\nu}_e$ in a $\nu_\mu/\bar{\nu}_\mu$ beam (2018)

6.0σ Combined significance!

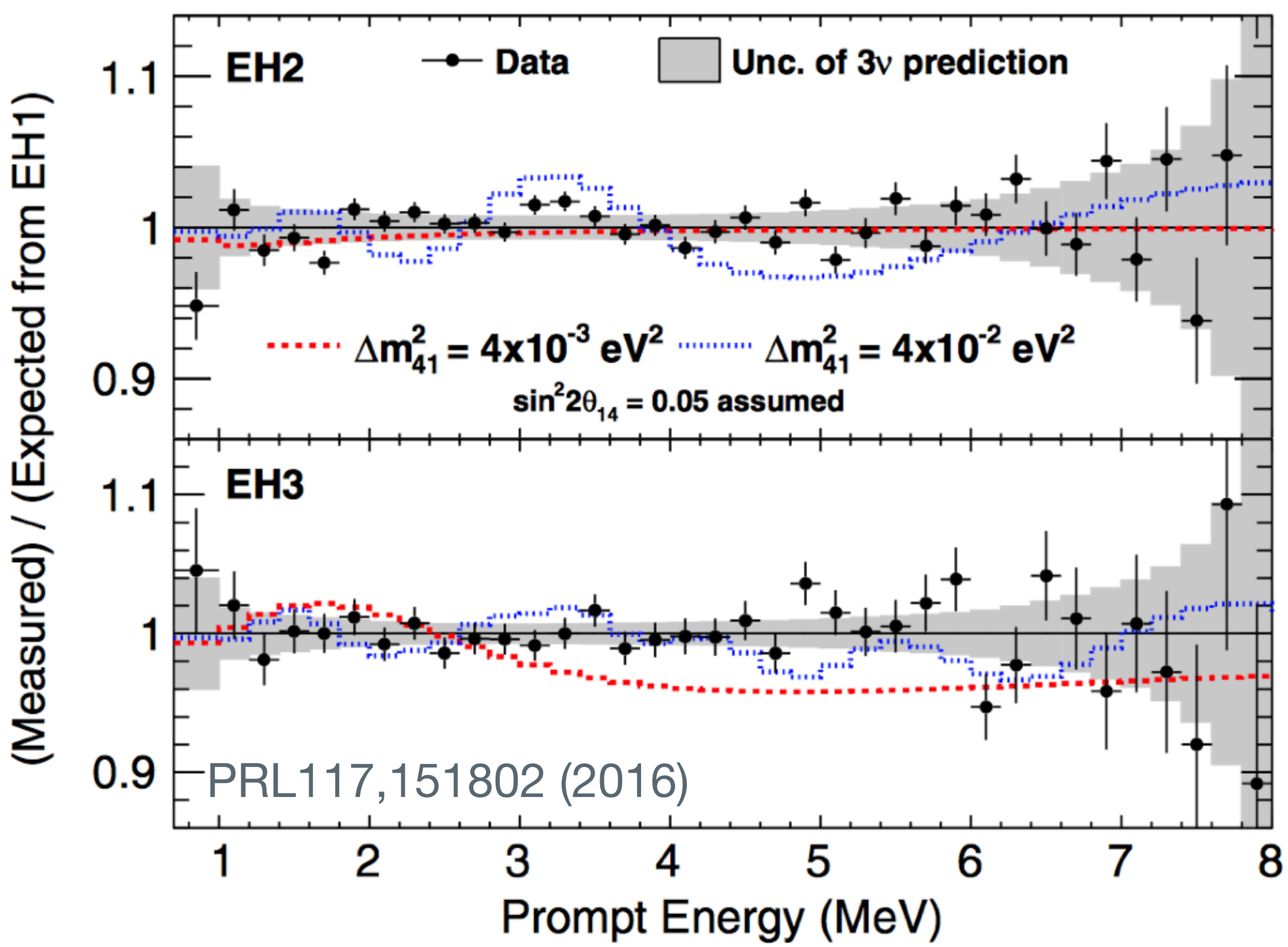
PRL121,221801 (2018)



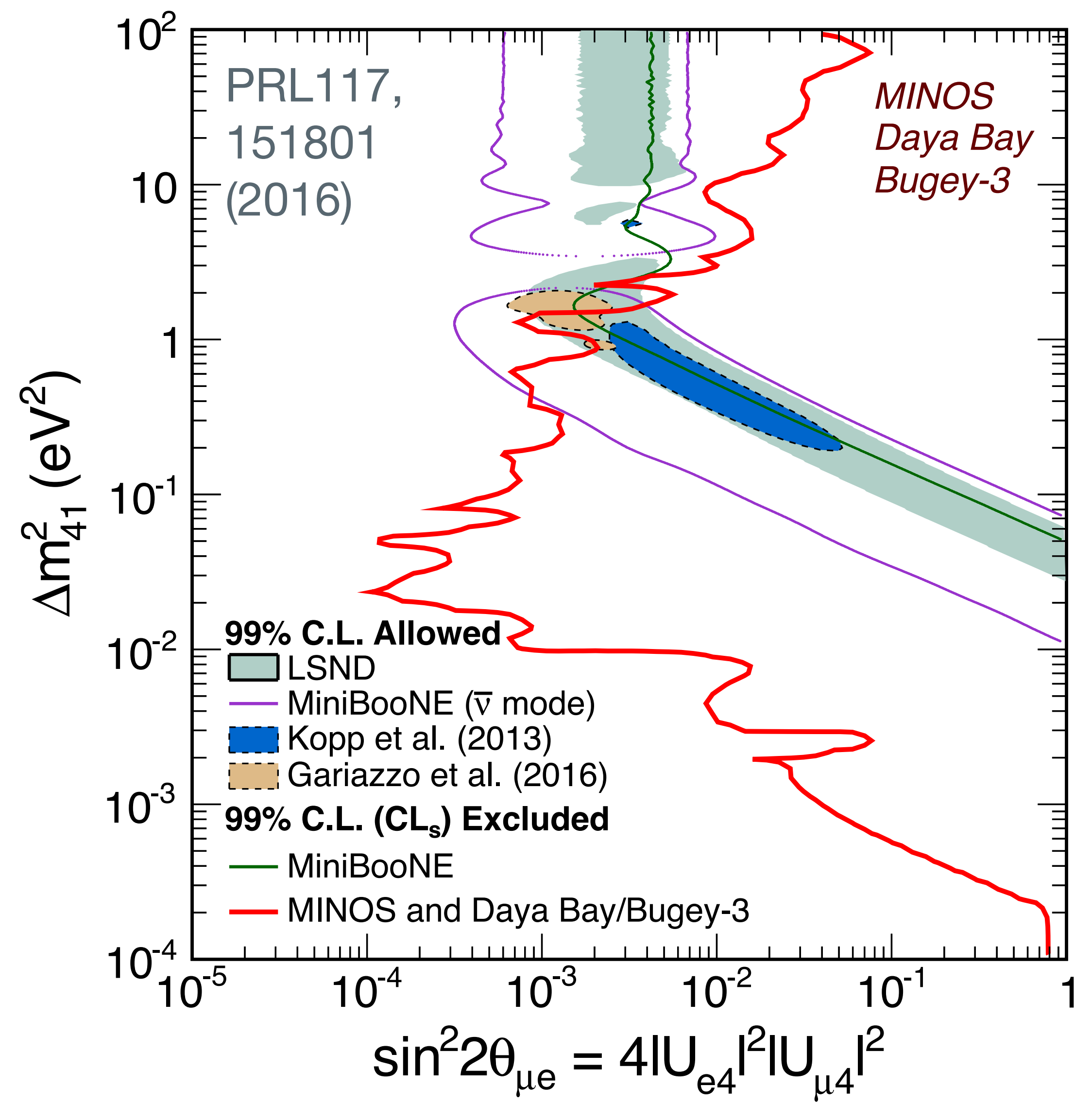
Search for Sterile Neutrinos

- The existence of sterile neutrinos could be detected via their modification to the 3 active neutrinos' oscillatory behavior if they mix with them
- Accelerator (MINOS) and reactor (Daya Bay + Bugey-3) results have been recently combined to yield stringent exclusion limits:

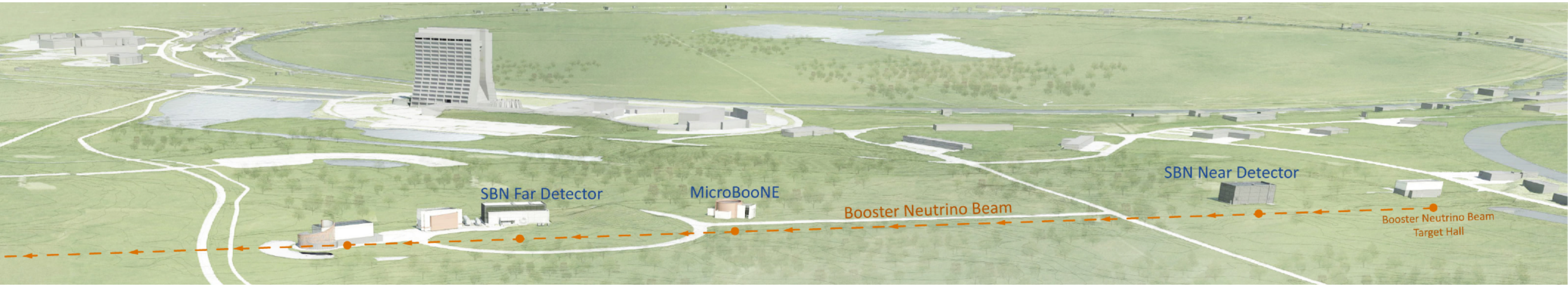
In region covered by Daya Bay, signal would appear as an additional spectral distortion with a frequency different from standard 3-neutrino oscillations



LSND + MiniBooNE's allowed parameter space excluded < 0.8 eV² @ 90% C.L.

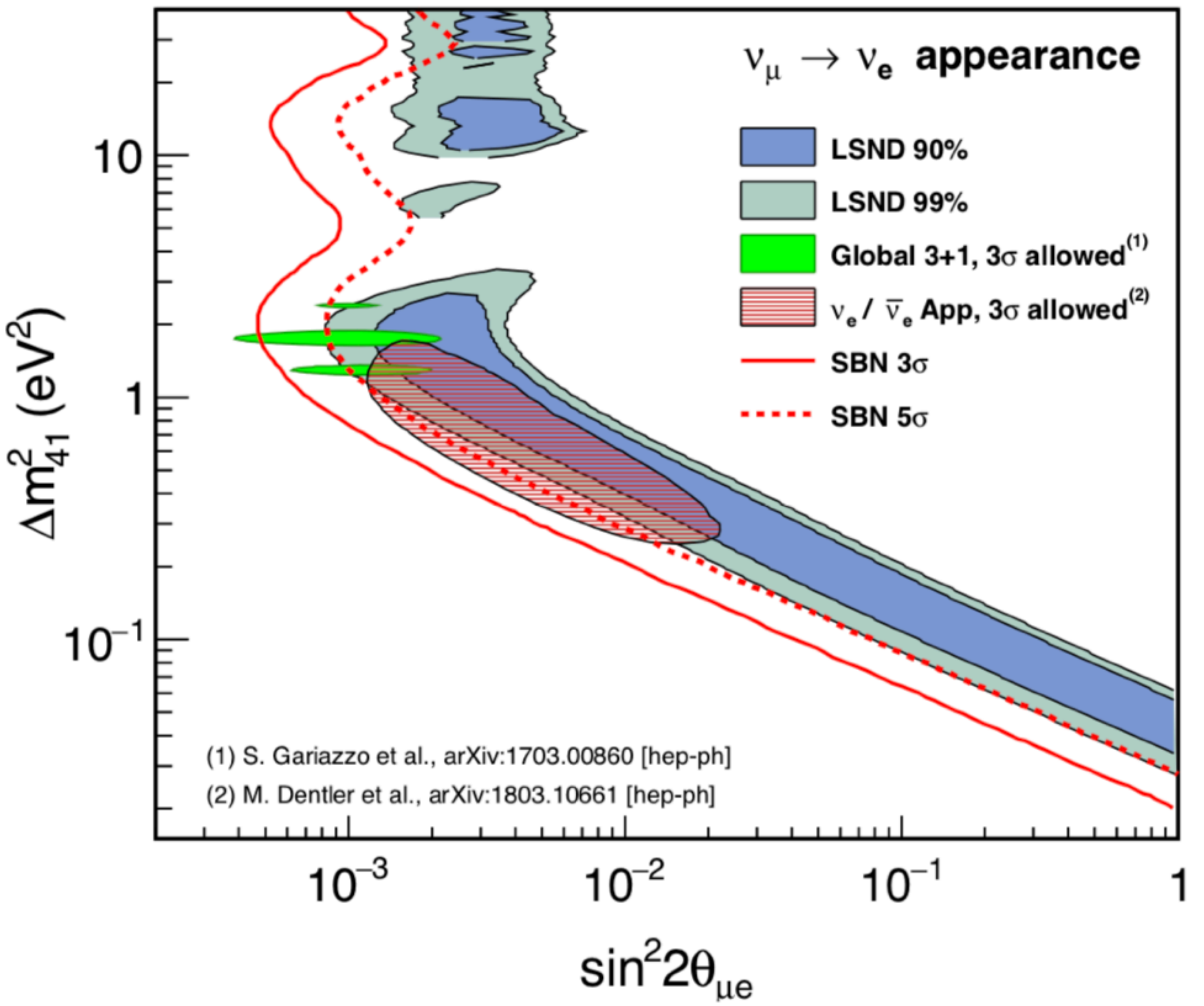


Fermilab's SB Neutrino Program



- Fermilab's SB neutrino program will also tackle this question
  - Three detectors (MicroBooNE, ICARUS and SBND) sampling the same beam at 3 different baselines
  - Will be able to make a **definite test** of all the currently allowed parameter space
  - All 3 experiments expected to be online by 2020

FERMILAB-PUB-19-079-ND-T

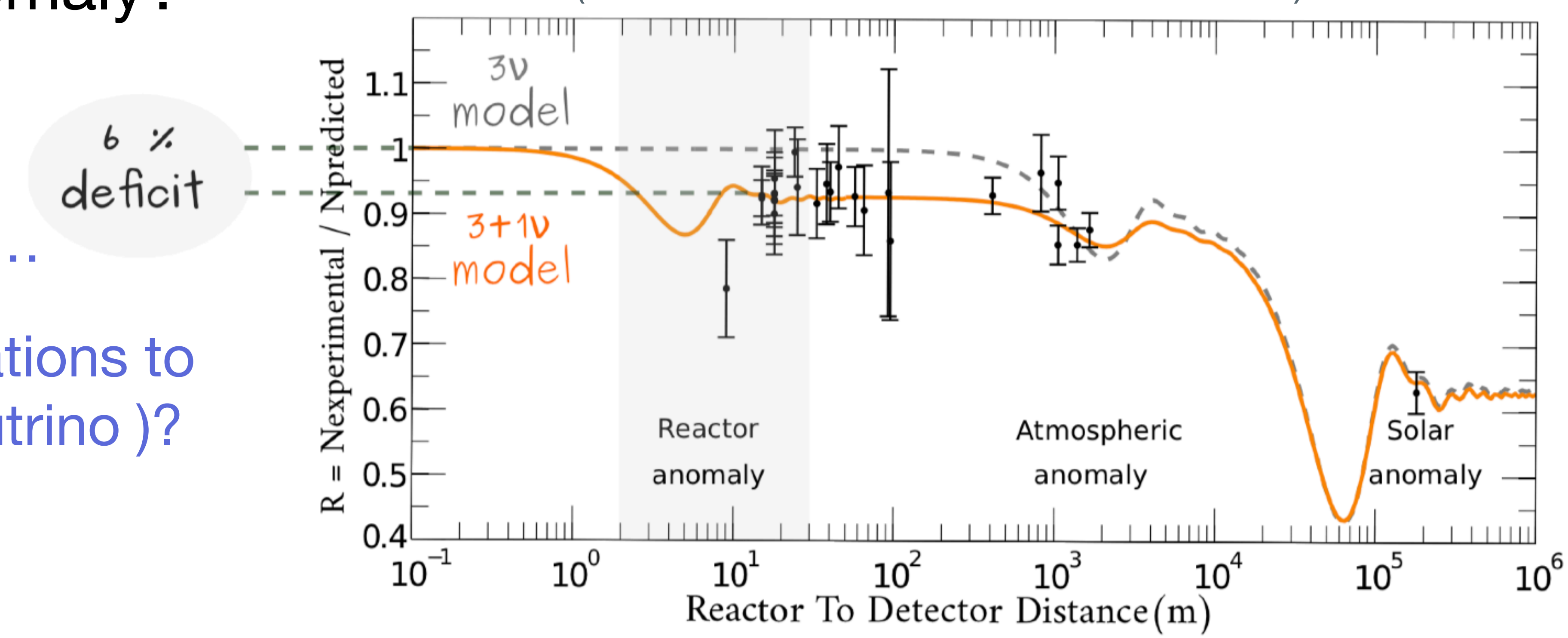


Reactor Antineutrino Anomaly

- Ongoing reactor experiments have also shed light on yet another anomaly:
  - The reactor antineutrino anomaly (RAA): data from short baseline reactor experiments show a ~2.5σ deficit with respect to the most recent flux prediction models

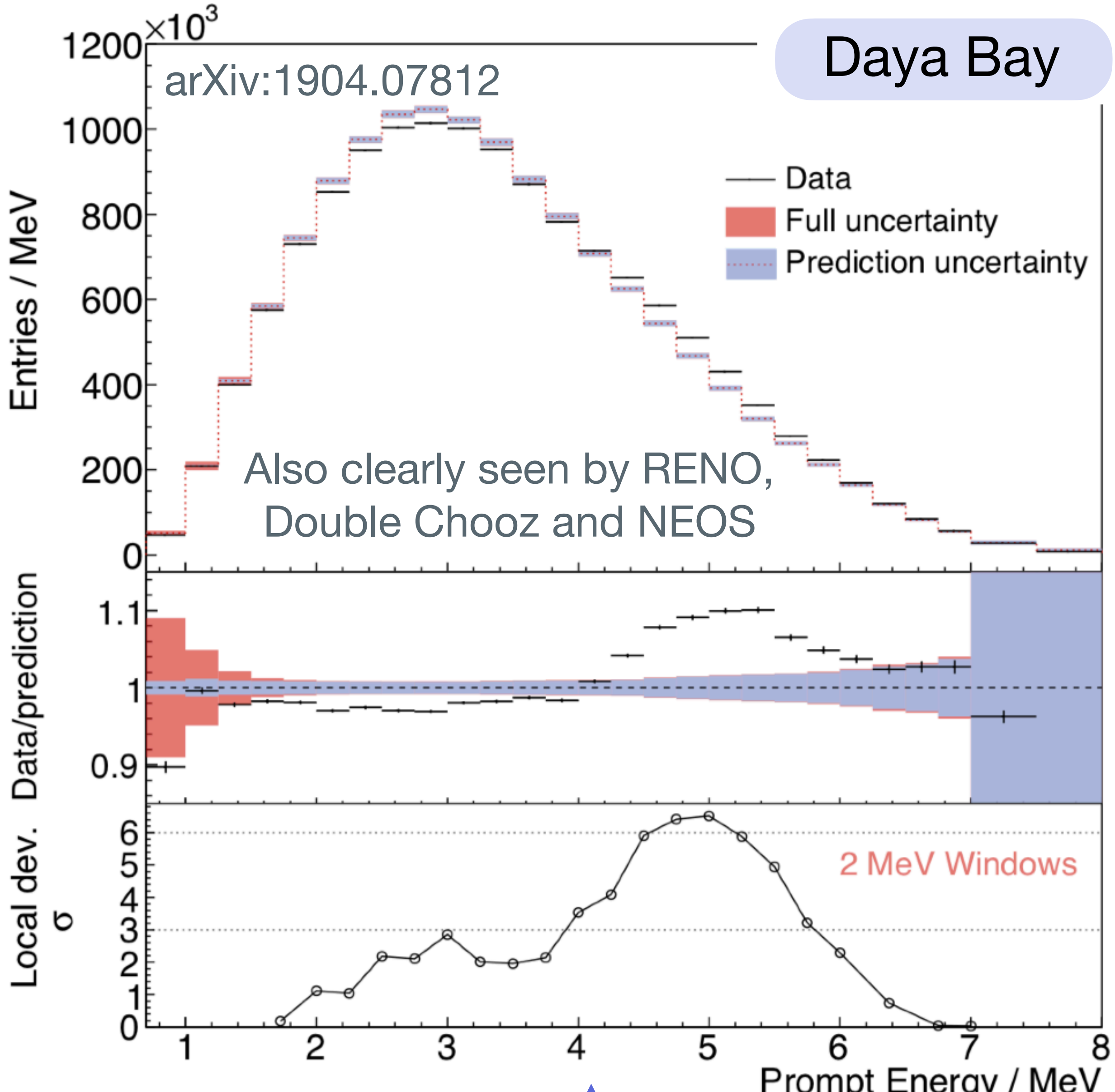
- Causes of the anomaly?
  - Experimental systematics? **Extremely unlikely**…
  - New Physics (oscillations to a 4th ~eV sterile neutrino)? **Maybe**….
  - Problems with the prediction? **Likely (see next slides)**

(from L. Bernard's talk at Moriond 2019)

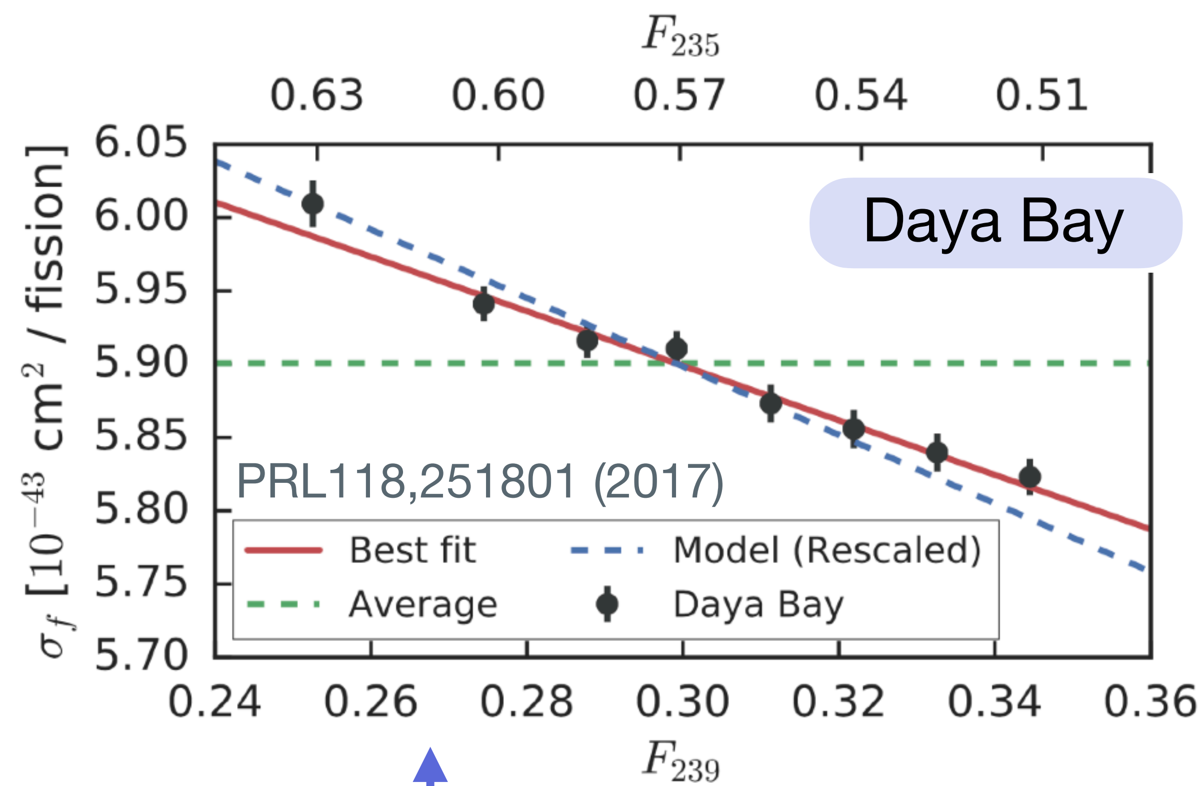


More "Anomalies"

- Additional discrepancies between data and prediction have come to light in the last few years



Discrepancy between predicted and observed spectral shape (a.k.a. 4-6 MeV "bump").



Discrepancy between observed and predicted flux evolution with effective ^{239}Pu fission fraction (suggests ^{235}U is primary contributor to RAA)

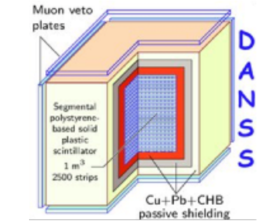
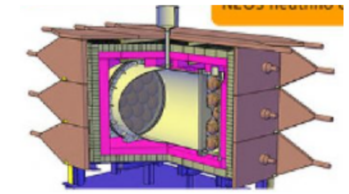
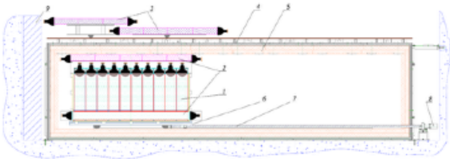
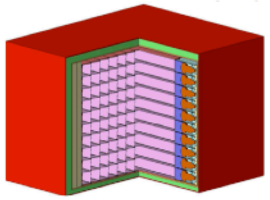
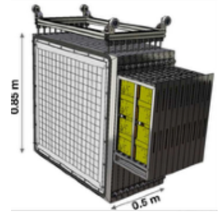
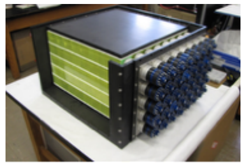
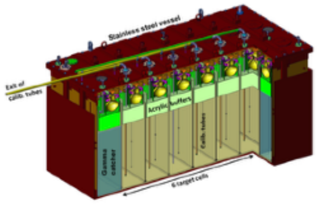
There is still room for sterile neutrinos, but prediction issues are definitely at play

Short Baseline Reactor Experiments

- These findings spurred an aggressive program of very short baseline (~10-30m) reactor experiments
- Main goals:
  - Search for oscillations to a ~eV scale sterile neutrino

    + directly measure ^{235}U yield and spectrum (in some cases)

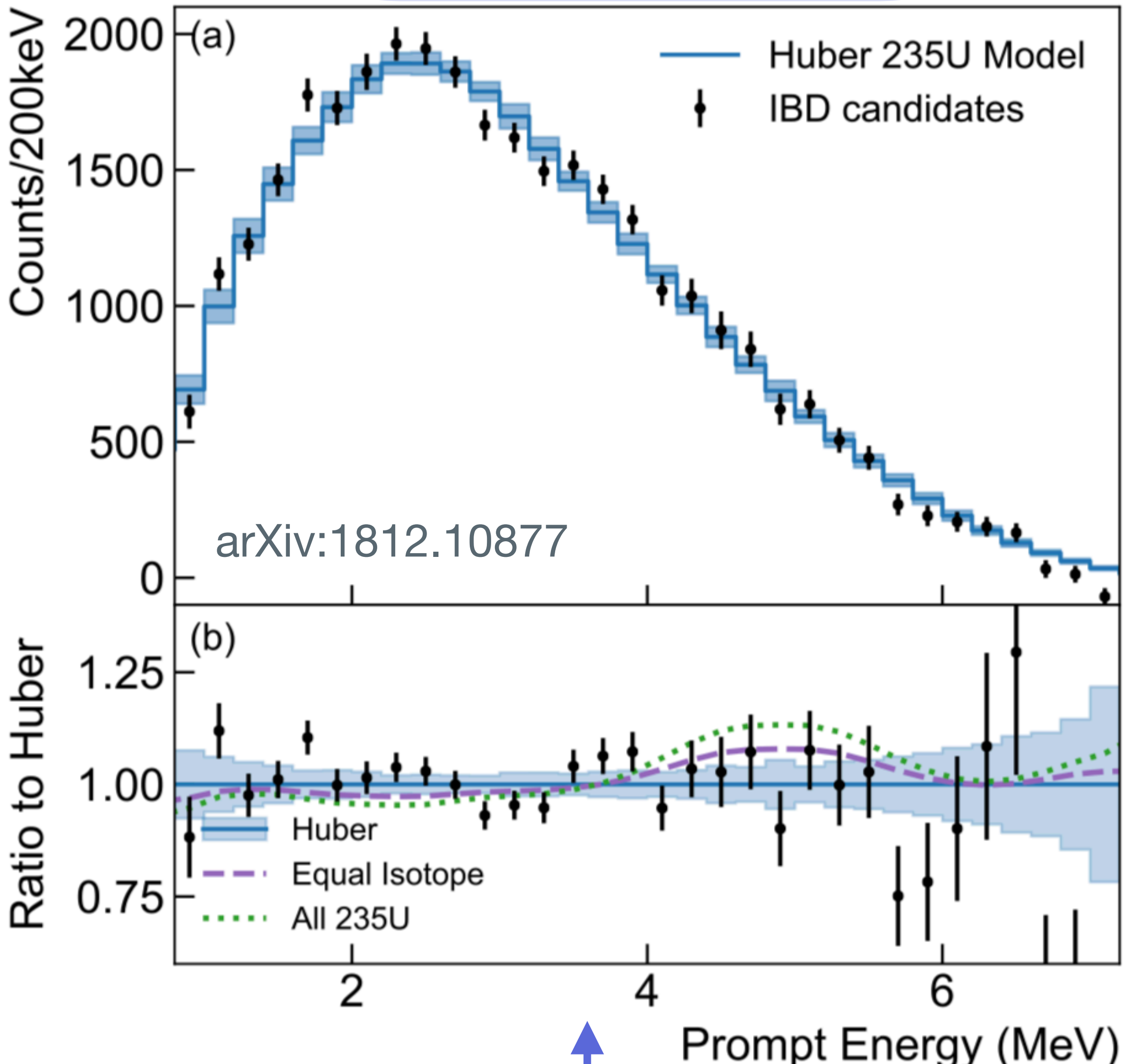
    + reactor monitoring and nonproliferation (in some cases)
- Use a variety of approaches (reactor type, segmentation, … etc)

DANSS* (Russia)	3000 MW LEU fuel	
NEOS* (S Korea)	2800 MW LEU fuel	
nuLAT (USA)	40 MW ^{235}U	
Neutrino-4* (Russia)	100 MW ^{235}U	
PROSPECT* (USA)	85 MW ^{235}U	
SoLid (UK Fr Bel US)	72 MW ^{235}U	
Chandler (USA)	72 MW ^{235}U	
Stereo* (France)	57 MW ^{235}U	

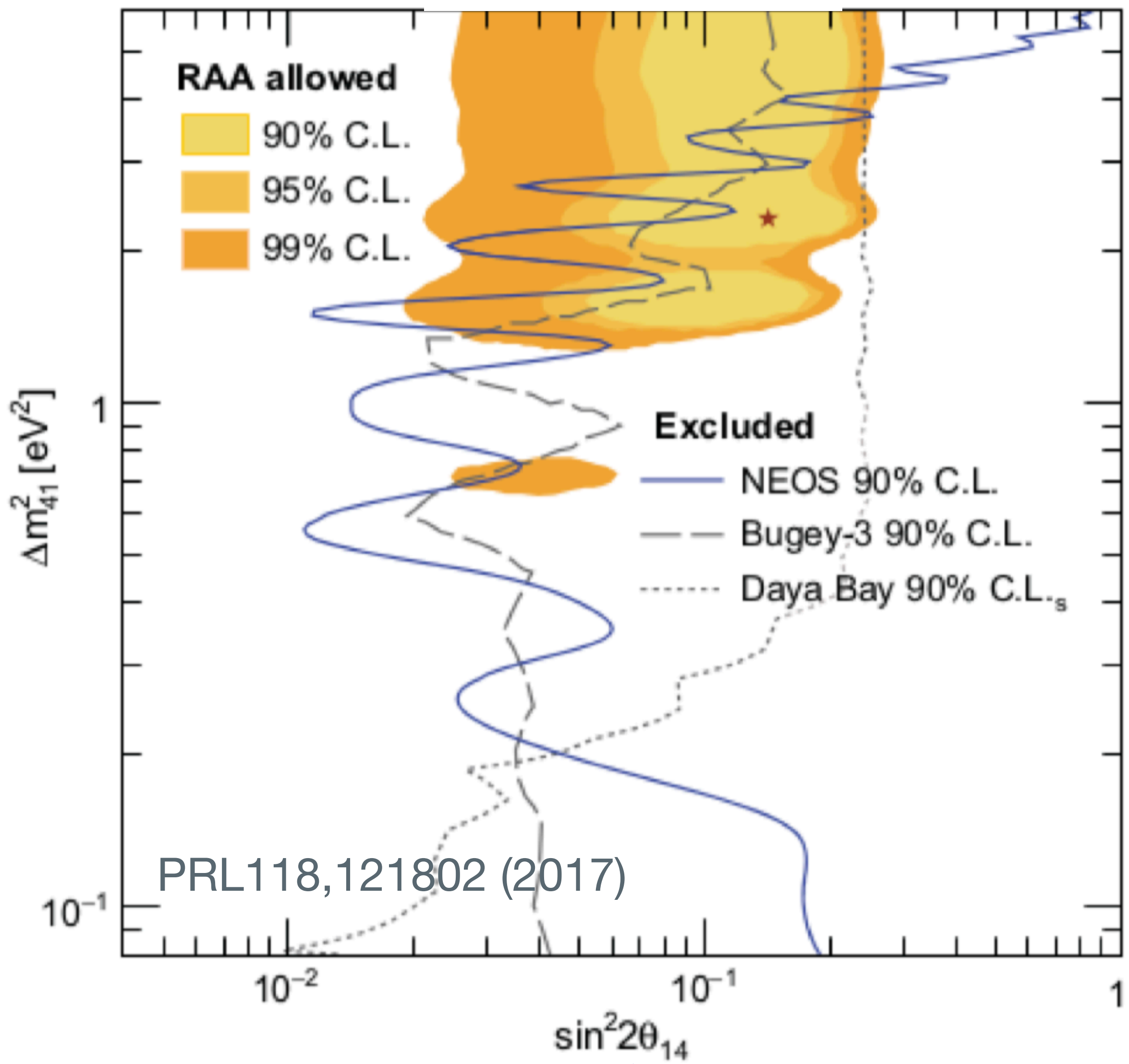
(*= have released results)

Some Highlights

PROSPECT
(segmented detector)



NEOS
(unsegmented detector)



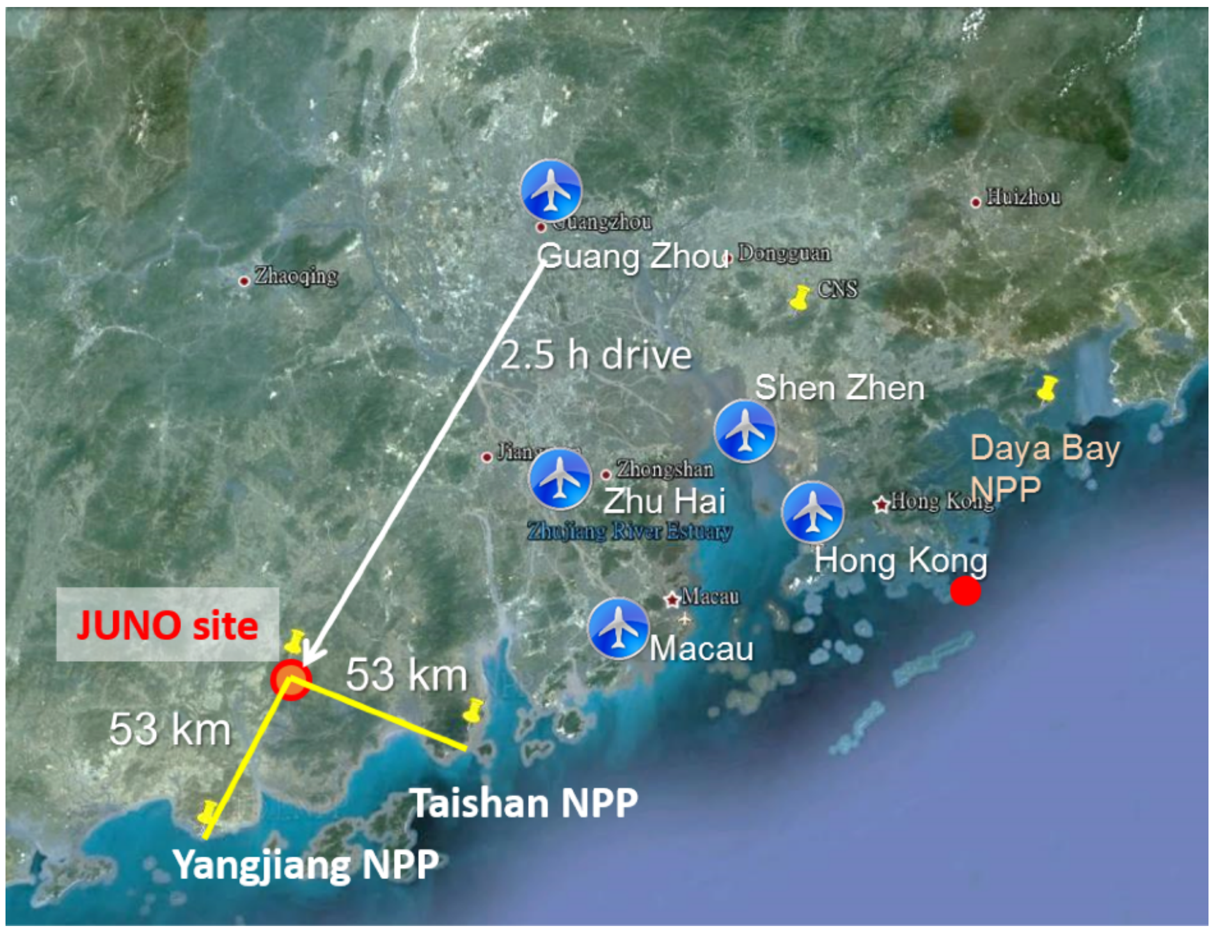
Best measurement of ^{235}U spectrum so far. Disfavor "^{235}U as sole bump contributor" hypothesis at ~2σ

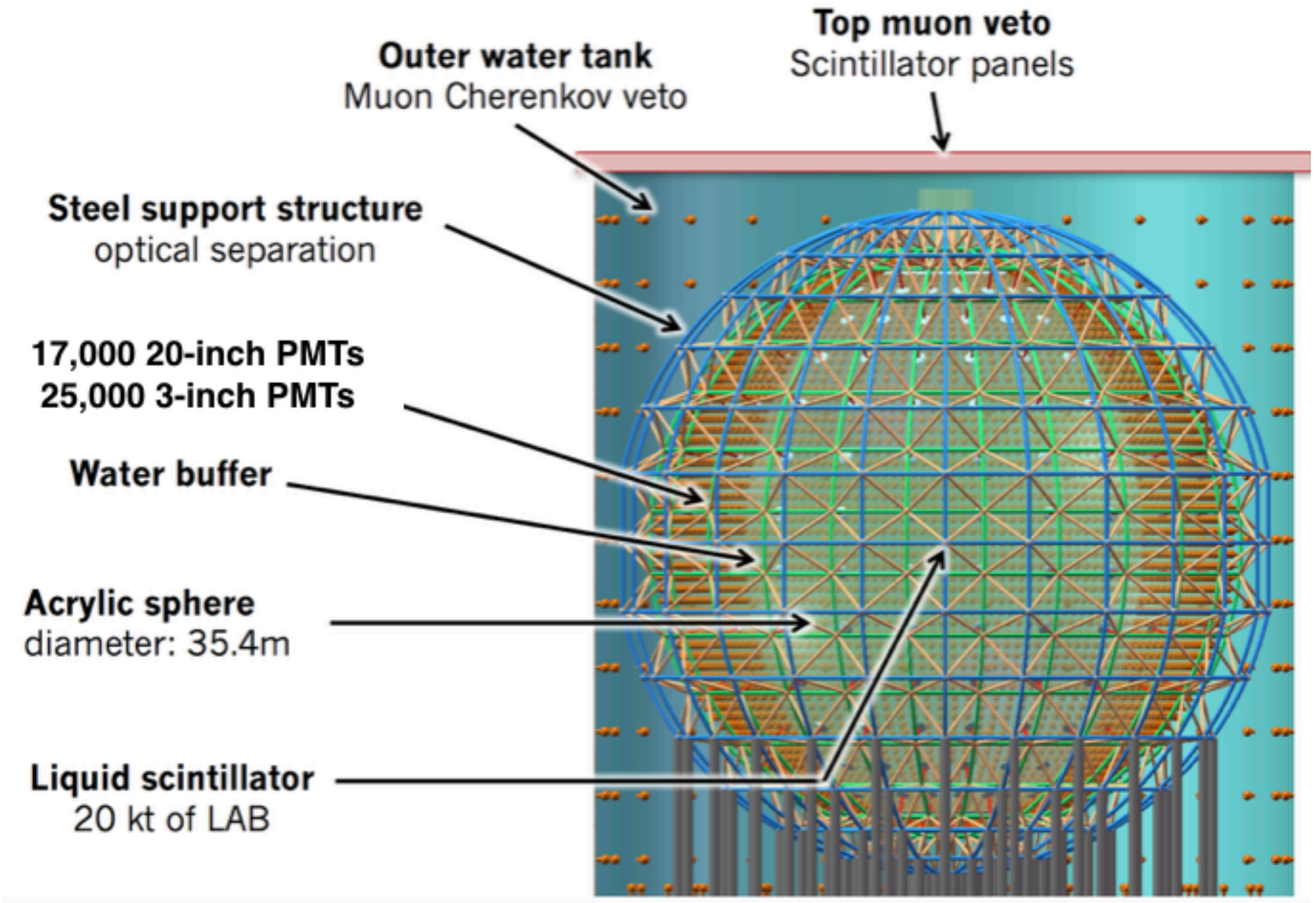
Exclusion limit from Phase I. No sterile neutrino from this or other experiment yet.

Note: there is a sterile neutrino claim by Neutrino-4 that is in tension with the other data

Looking Ahead: the JUNO Experiment

- There is also a major multipurpose reactor neutrino experiment being constructed in China: the Jiangmen Underground Neutrino Observatory (JUNO)
  - **"Medium" baseline** of 53km from two major power plants (10 reactors)



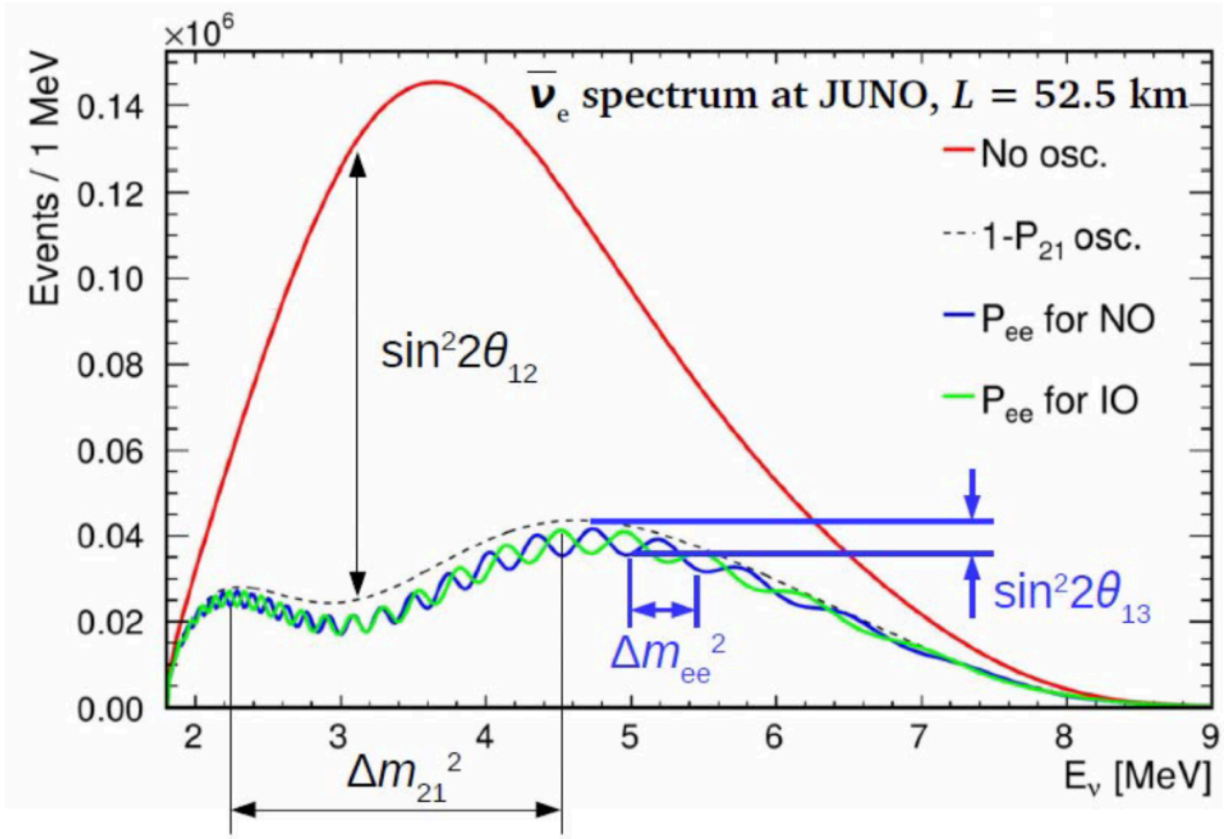


  - Given the larger baseline, the detector will have to be **MASSIVE** (20 ktons)

(Note: a similar proposal in Korea, RENO-50, has now been abandoned)

JUNO Physics

- Physics goals:
  - Determination of the **neutrino mass ordering**
  - **Sub-percent precision** on $\sin^2 2\theta_{12}$, Δm^2_{21} and $|\Delta m^2_{ee}|$
  - Geoneutrinos, supernova neutrinos, solar neutrinos, atmospheric neutrinos
  - Search for new physics and others



- JUNO is pushing limits of liquid scintillator detection technology →
- Will deploy a SB detector called TAO to measure fine structure in unoscillated spectrum
- Data-taking to begin in **2021**

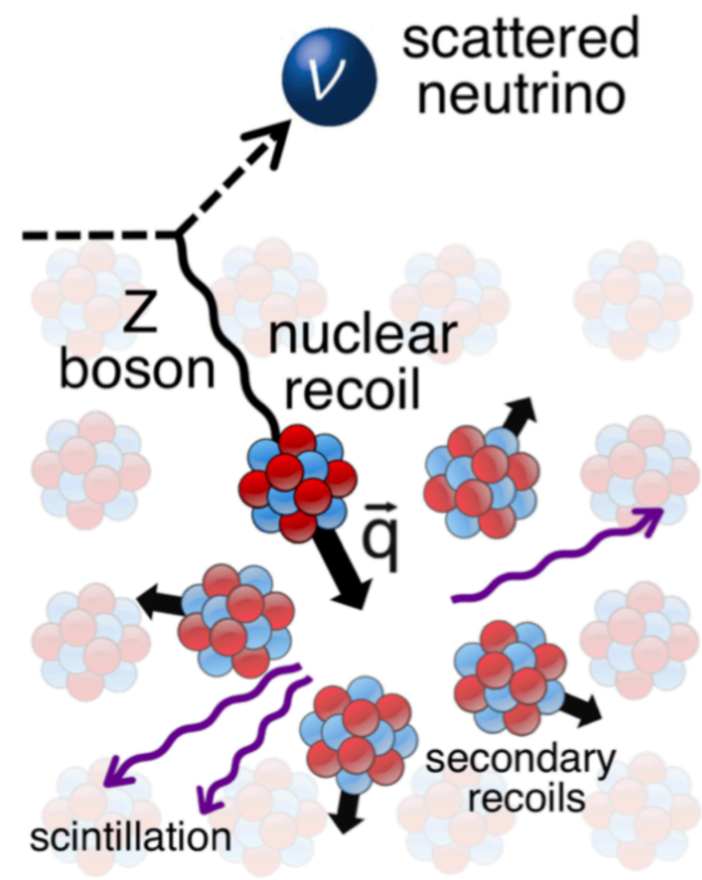
	KamLAND (as reference)	JUNO	Relative Gain
Total light	**250 pe/MeV**	**1200 pe/MeV**	**5**
Photocathode coverage	34%	75%	~2
Light yield	1.5 g/l PPO	3-5 g/l PPO	~1.5
Attenuation	15/16 m	25/35 m	~0.8
PMT QE×CE	~15%	~30%	~2

Coherent Elastic ν Nucleon Scattering

- A new detection channel has just begun to be exploited at short baselines: CEνNS

CEνNS: a neutrino scatters off a nucleus whose nucleons recoil in phase

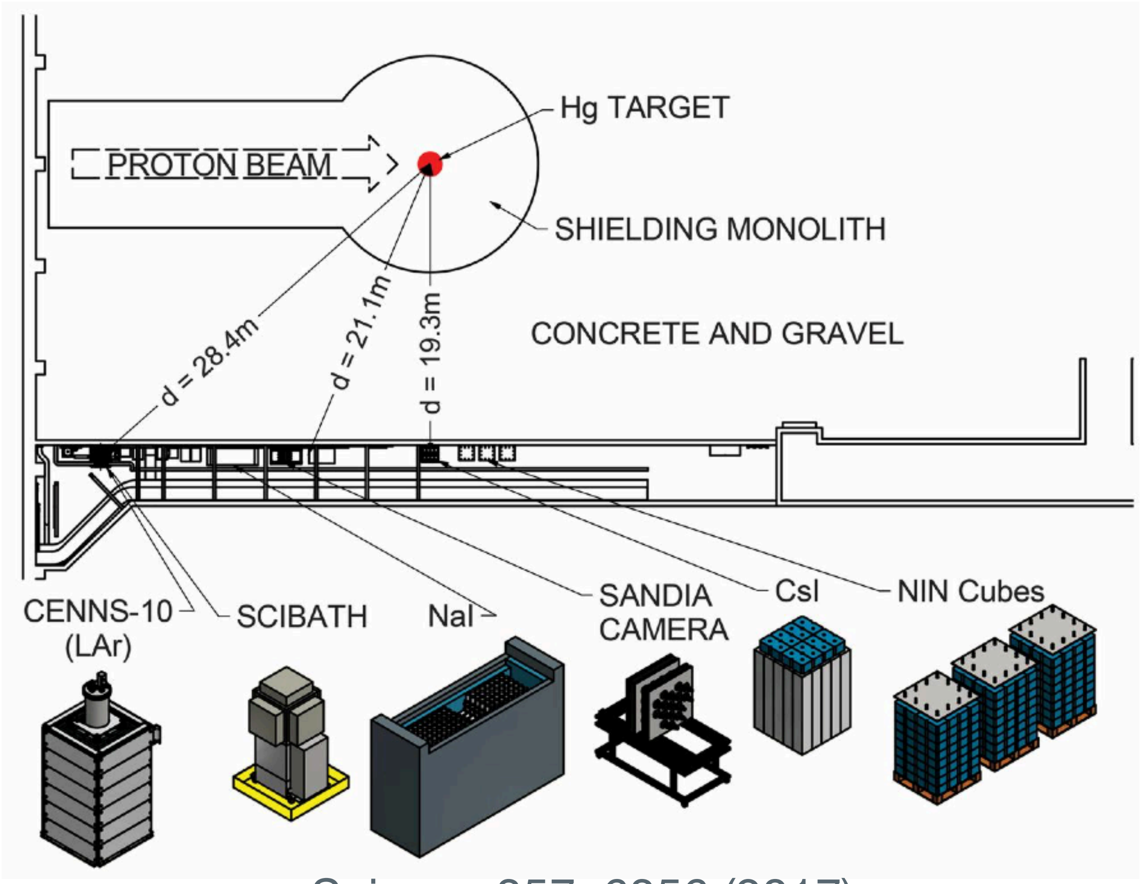
  - Pro: high cross-section (can be orders of magnitude higher than IBD)
  - Con: very challenging to observe (only signal is low-energy recoiling nucleus)



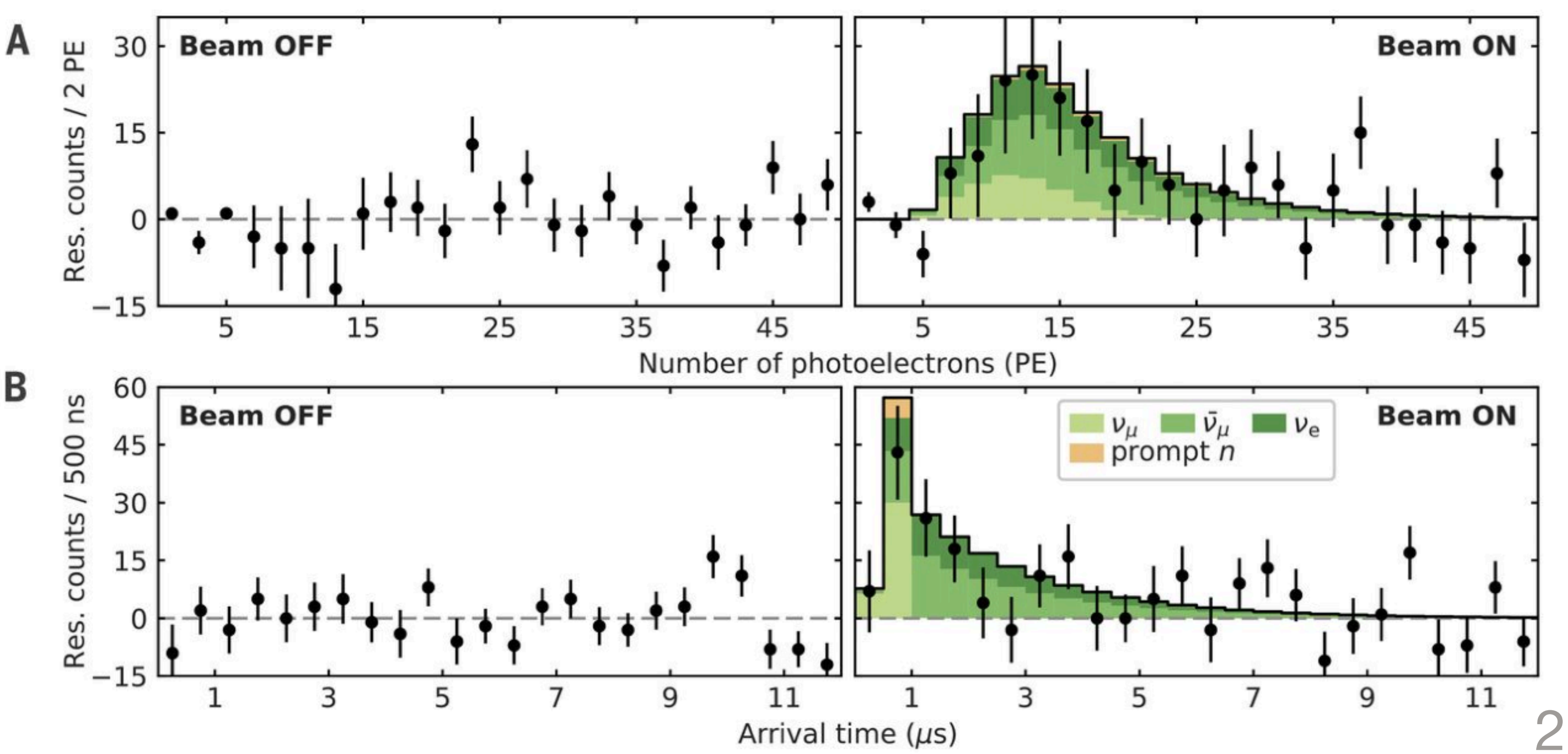
- CEνNES can be used to study a variety of physics topics, including:
  - Complete Standard Model picture of neutrino interactions
  - Search for sterile neutrinos with neutral currents (all flavor disappearance)
  - Neutrinos from core-collapse supernovae (especially for flavors other than ν_e)
  - Search for neutrino magnetic moment and non-standard interactions
  - Probe nuclear structure

Coherent Elastic ν Nucleon Scattering

- CEvNS was first observed by the COHERENT collaboration in 2017
  - Neutrinos from spallation neutron source at Oak Ridge National Lab
  - Using different complementary technologies, but pioneer detector was CsI[Na]
  - 6.7σ significance with 14.6 kg detector!
- Many other experiments ramping up
  - List includes CONUS, Texono, Connie, Red100, Miner, NU-CLEUS, among others



Science 357, 6356 (2017)



Summary & Conclusions

- Cutting edge neutrino physics are being done at short baselines
  - Leading precision in oscillation parameters, searches for sterile neutrinos, high-precision measurements of reactor antineutrino flux and spectral shape, and others.
- A bright future is on the horizon:
  - Experiments at very short baselines from nuclear reactors are starting to shed light on the reactor “anomalies”
  - Large future facilities like JUNO and the Fermilab SB program are well underway and will come online soon
  - Many more experiments will study CEvNS in the near future
- Stay tuned, and be prepared for some surprises!

Thank you for your attention!