Neutrino Physics with Nuclear Reactors

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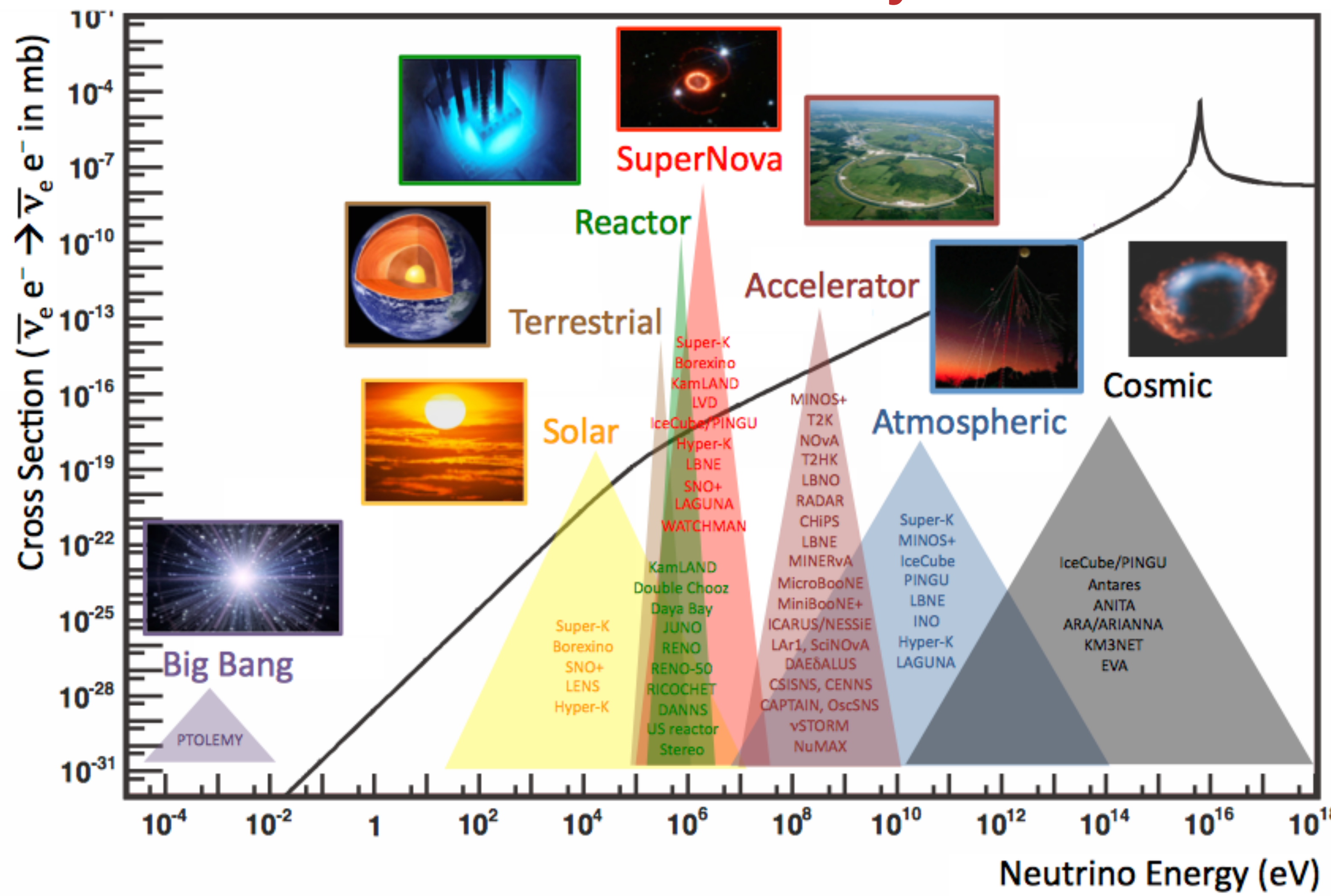
Why Neutrinos?

Neutrinos Matter!

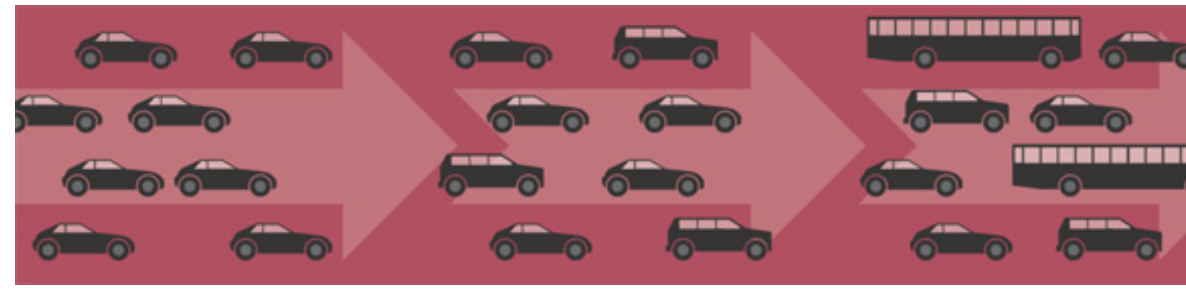
- We need to understand neutrinos if we want to understand our universe!
  - They are **invaluable astronomical (and terrestrial) messengers**
  - They are the **second most abundant particle in the universe**
  - **They can guide the way to new theories**

Neutrinos are everywhere!



Neutrinos have mass!

- The observation that neutrinos oscillate implies that they are massive:



$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle$$

How they interact

How they propagate

where U is parameterized in terms of three mixing angles (θ_{12},θ_{13},θ_{23}) and one phase δ

For example, as a <u>rough</u> approximation at short baselines:

frequency

amplitude

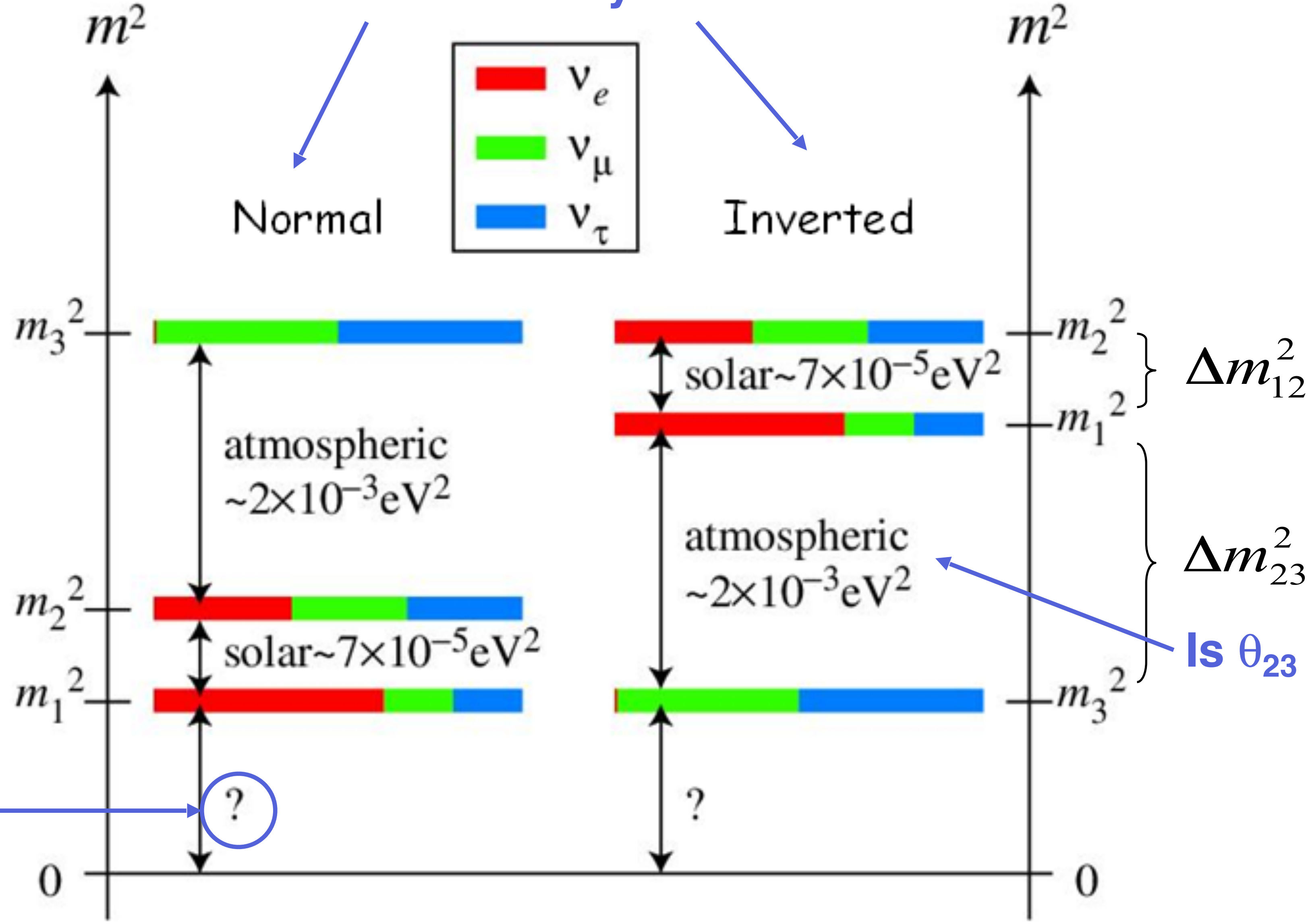
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \cong 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{32} L}{4E}$$

(where $\Delta m^2_{ij} \equiv m^2_i - m^2_j$ is the so-called "mass splitting")

Open Questions

- Despite the great progress over the past two decades, many questions still don't have an answer:

Which is the right mass hierarchy?



Is θ_{23} exactly $\pi/4$?

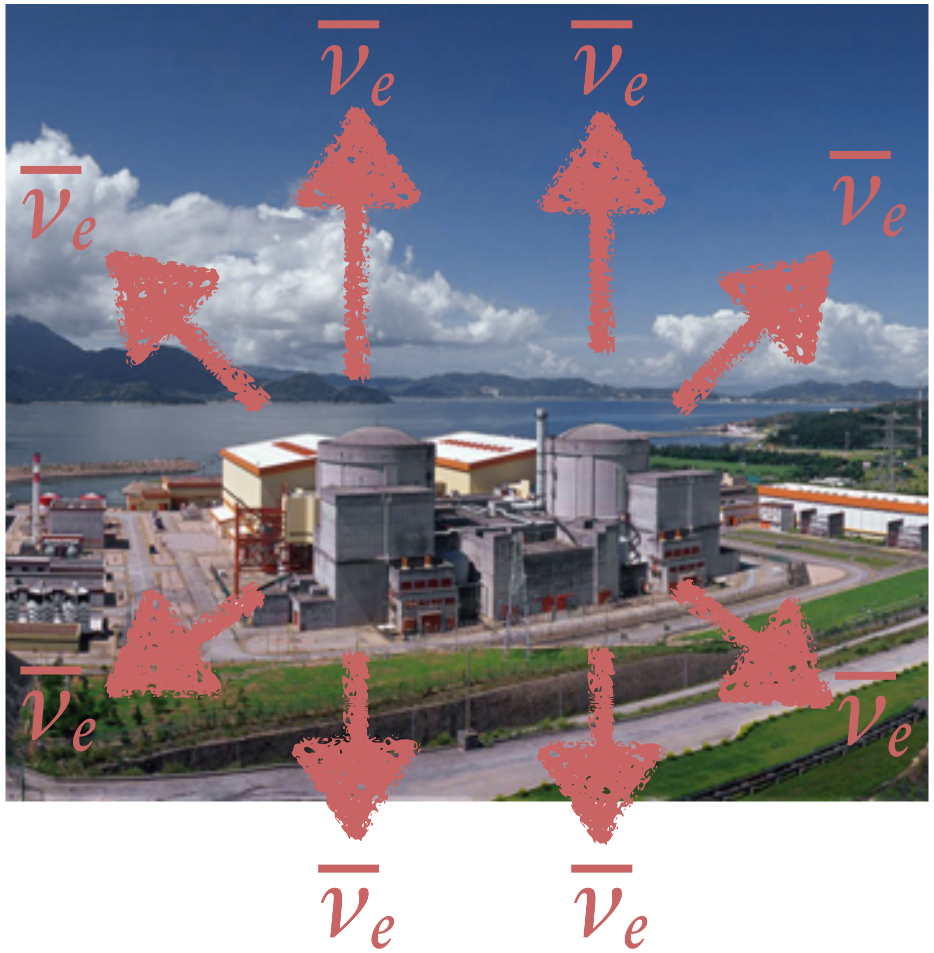
What is the rest mass of neutrinos (and what is their origin)?

And also:
- **Do neutrinos obey CP & CPT symmetries?**
- **Are neutrinos their own antiparticles?**
- **Are there more than 3 neutrinos (sterile, heavier than Z)?**
- **Others…**

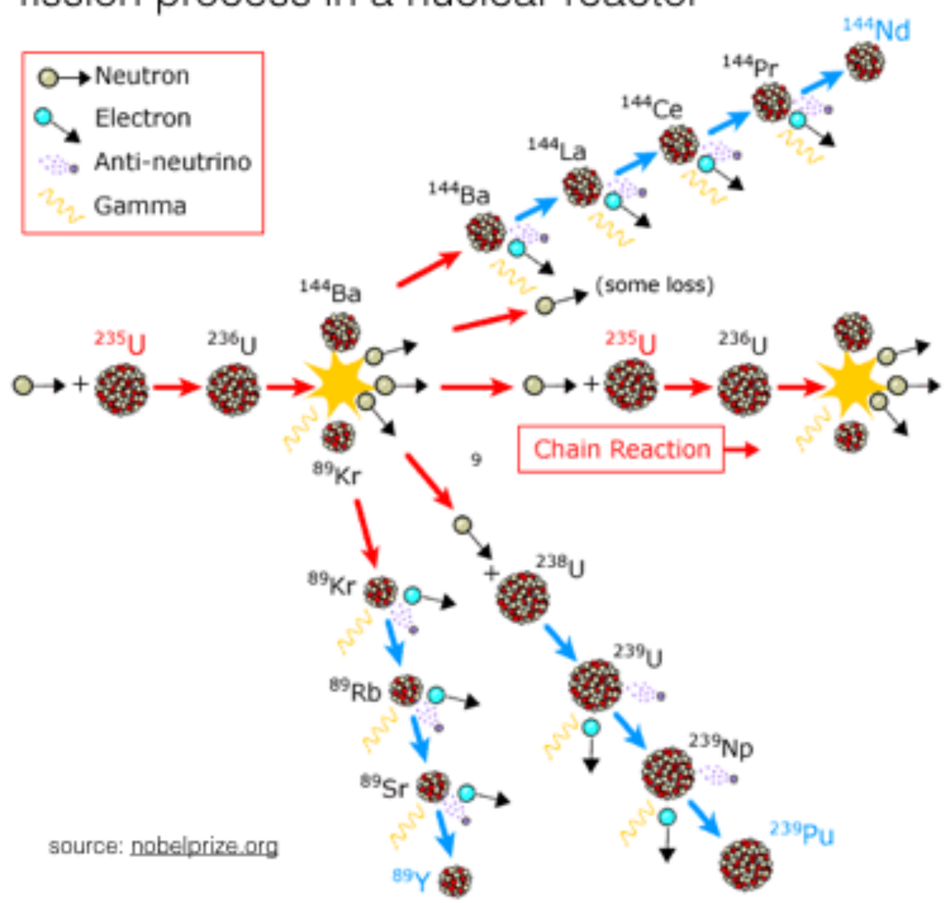
Basic Principles of Reactor Neutrino Experiments

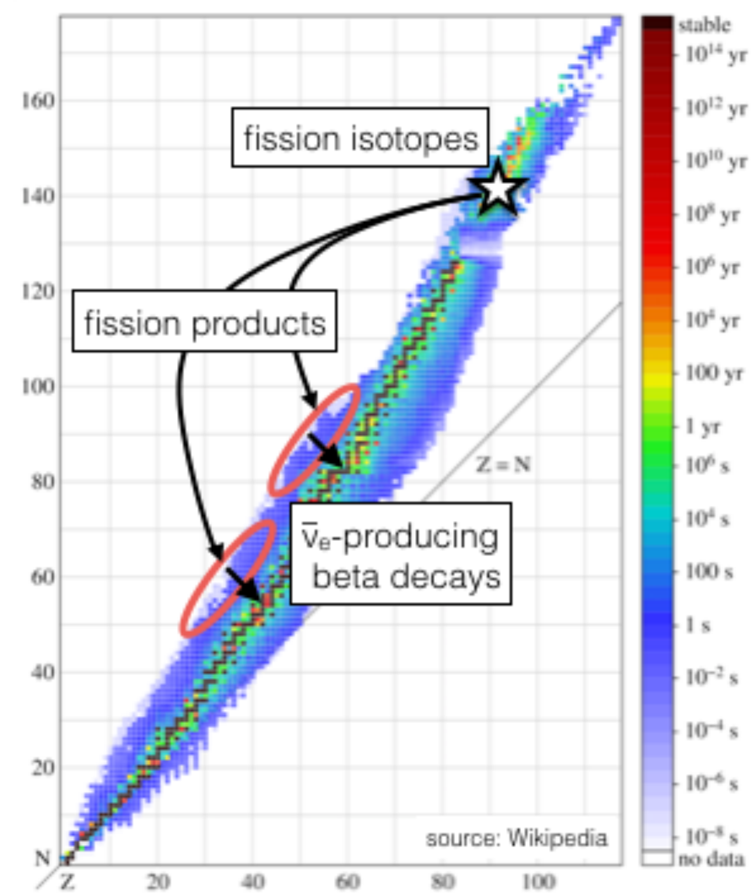
Reactor Antineutrinos

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



fission process in a nuclear reactor





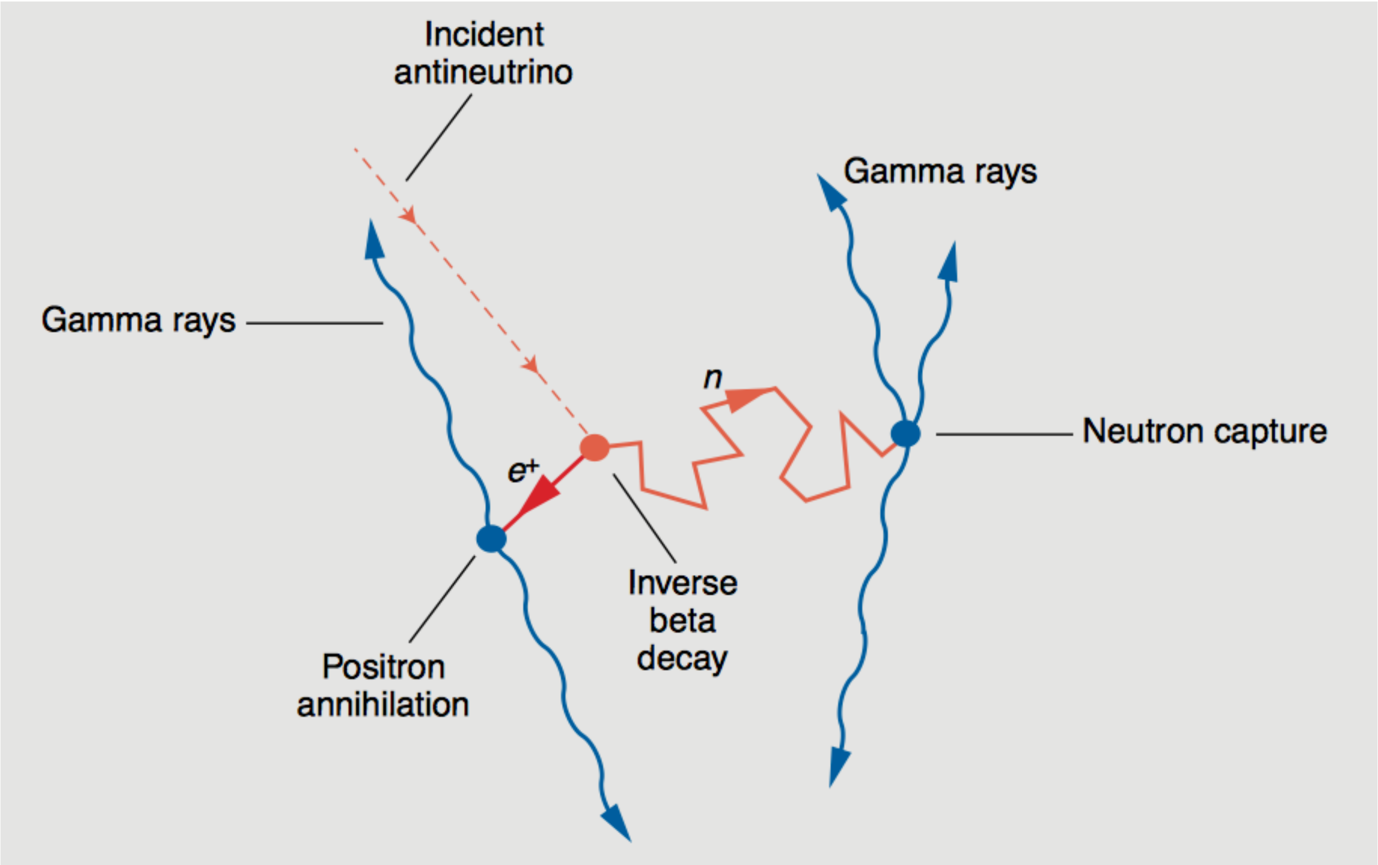
$$n \longrightarrow p + e^- + \bar{\nu}_e$$

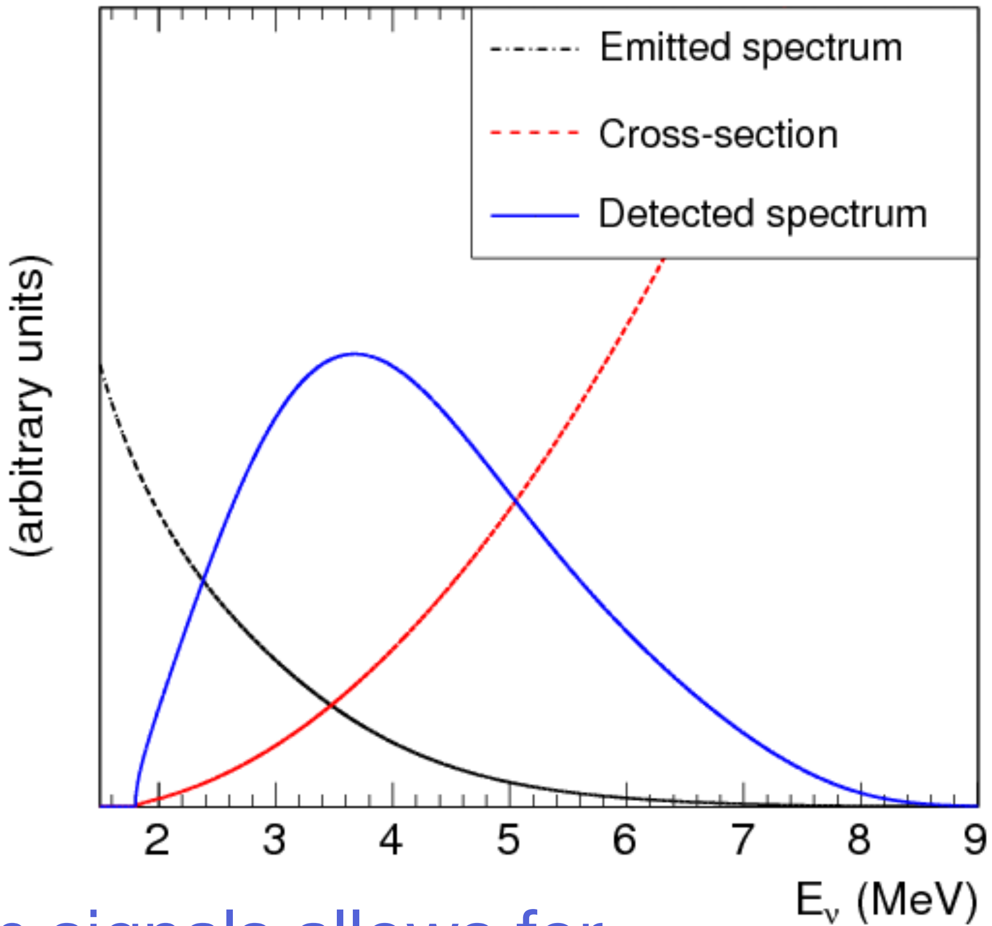
– Knowing the fractions of isotopes that are fissioning at a given time and the total power it is possible to predict the expected antineutrino flux

Detection Essentials

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

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





- 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
- **Energy of positron preserves information about energy of incoming $\overline{\nu}_e$**

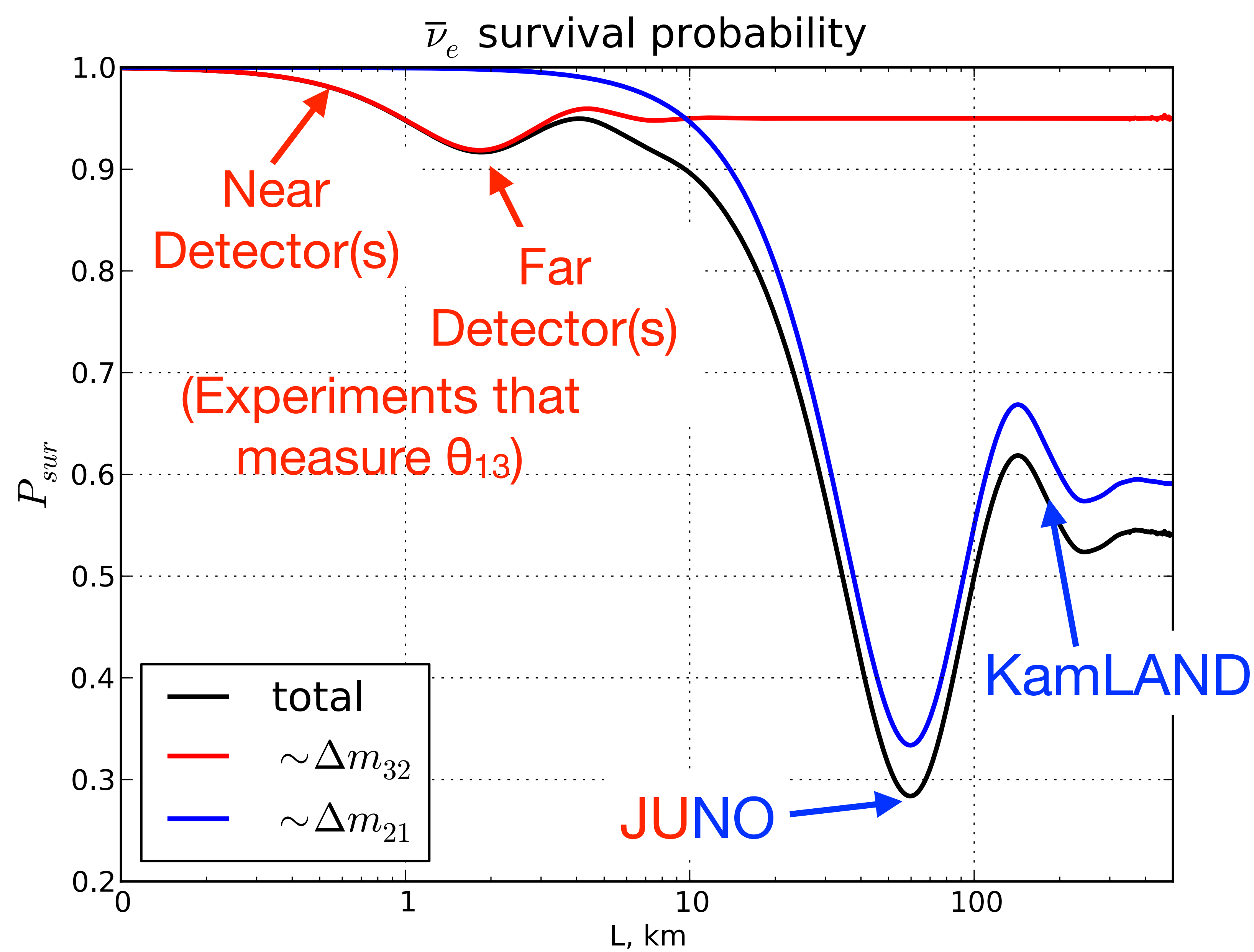
Electron Antineutrino Disappearance

- The disappearance of electron antineutrinos is given by:

$$P_{\bar{\nu}_e \to \bar{\nu}_e} \approx 1 - \boxed{\sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{32} L}{4E}} + \boxed{\cos^4 \theta_{13} \sin 2\theta_{12} \sin^2 \frac{\Delta m^2_{21} L}{4E}}$$

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.

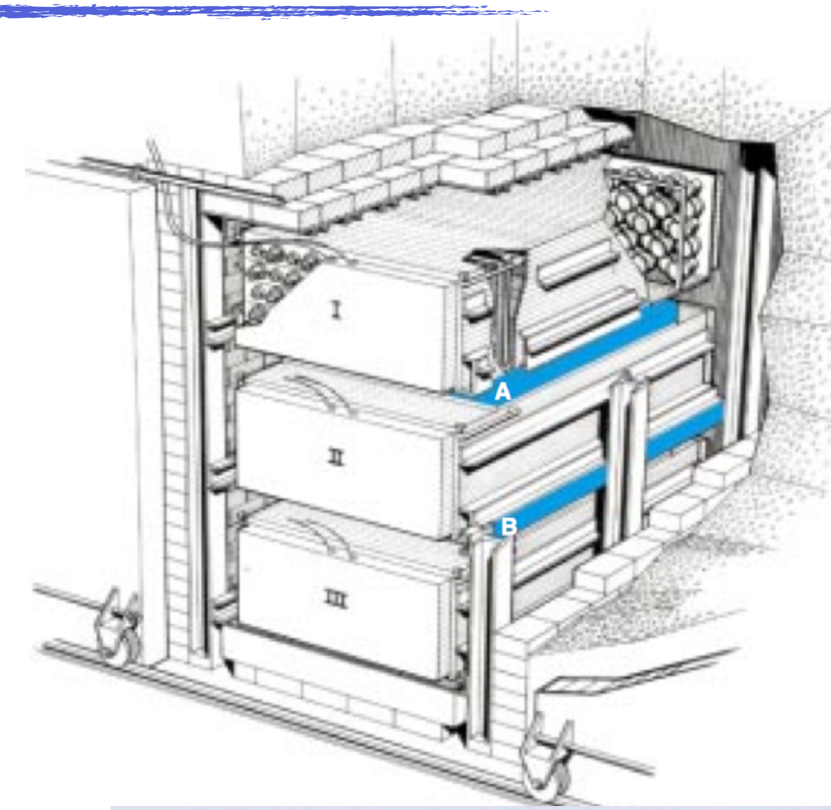
Physics goals drive choice of baseline

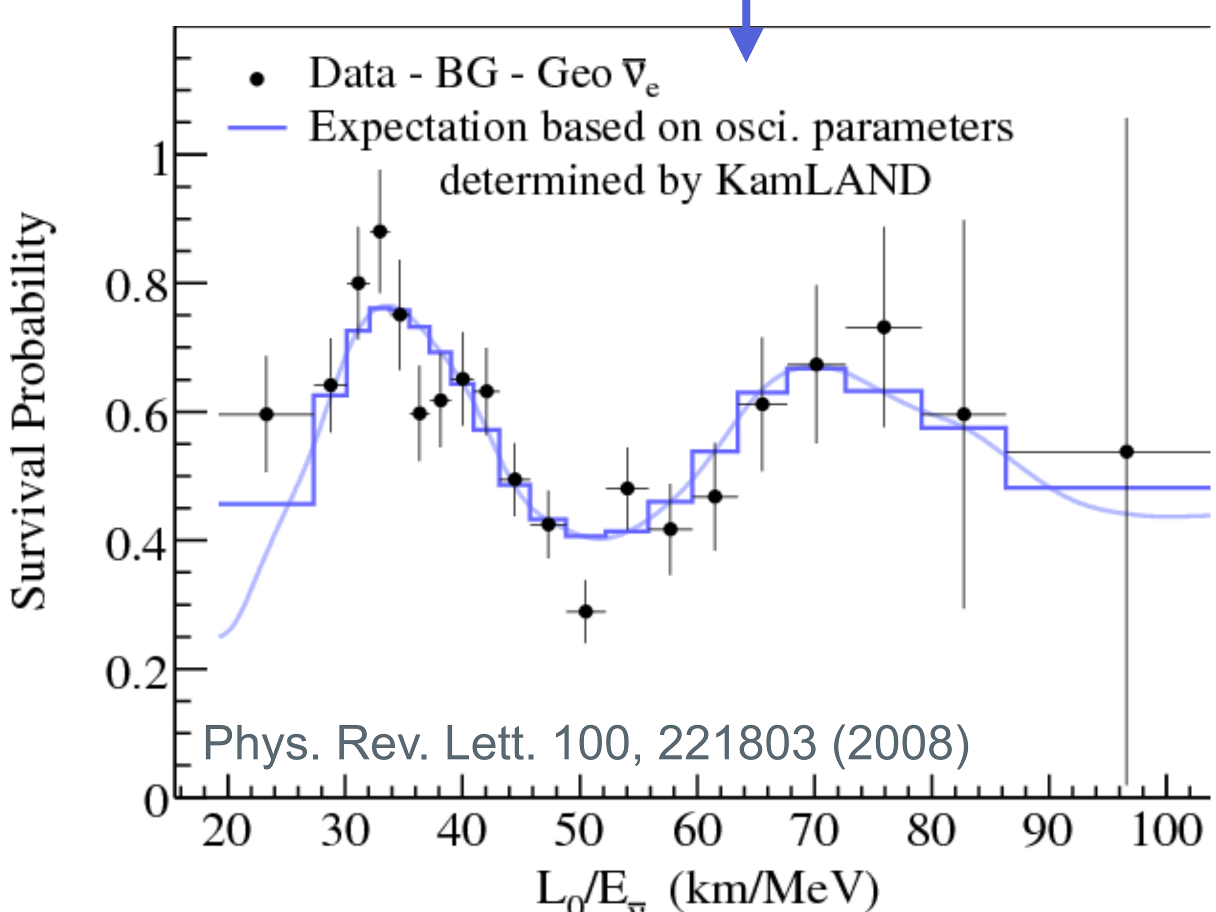


(disclaimer: only including a subset of reactor experiments in this graph)

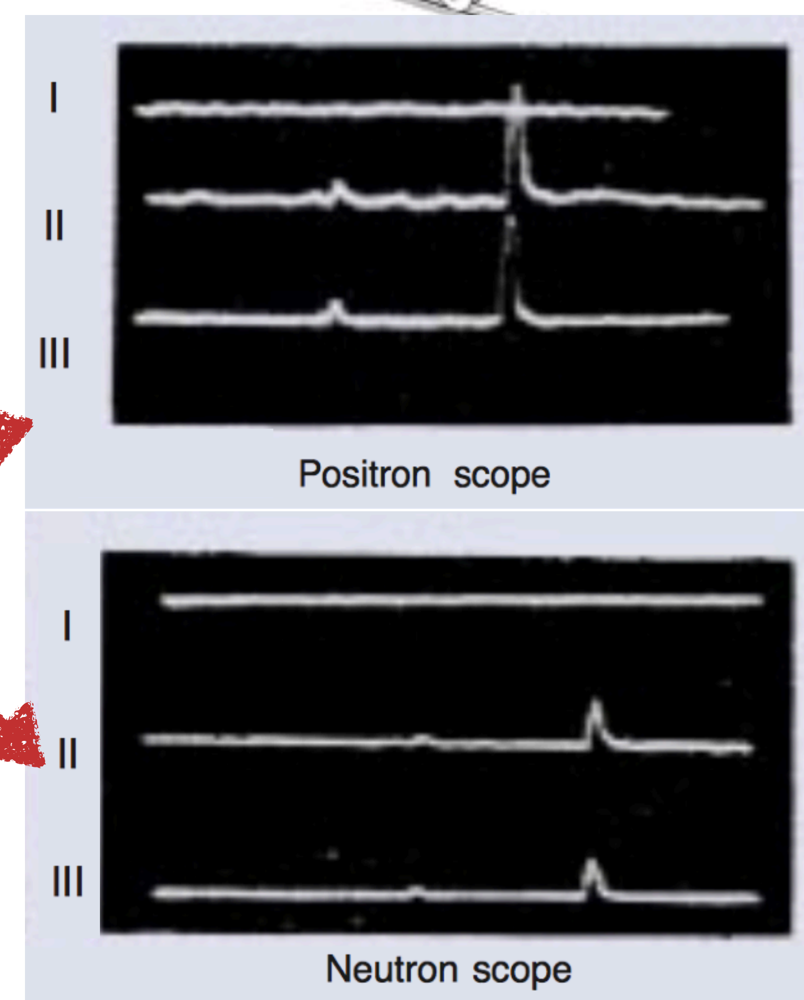
A Rich History

- Reactor antineutrino experiments have a very rich history:
  - Discovery of the neutrino (1953-1956, “Project Poltergeist”)
  - KamLAND experiment: first very clear demostration of L/E dependence (2002)





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



Ongoing Experiments

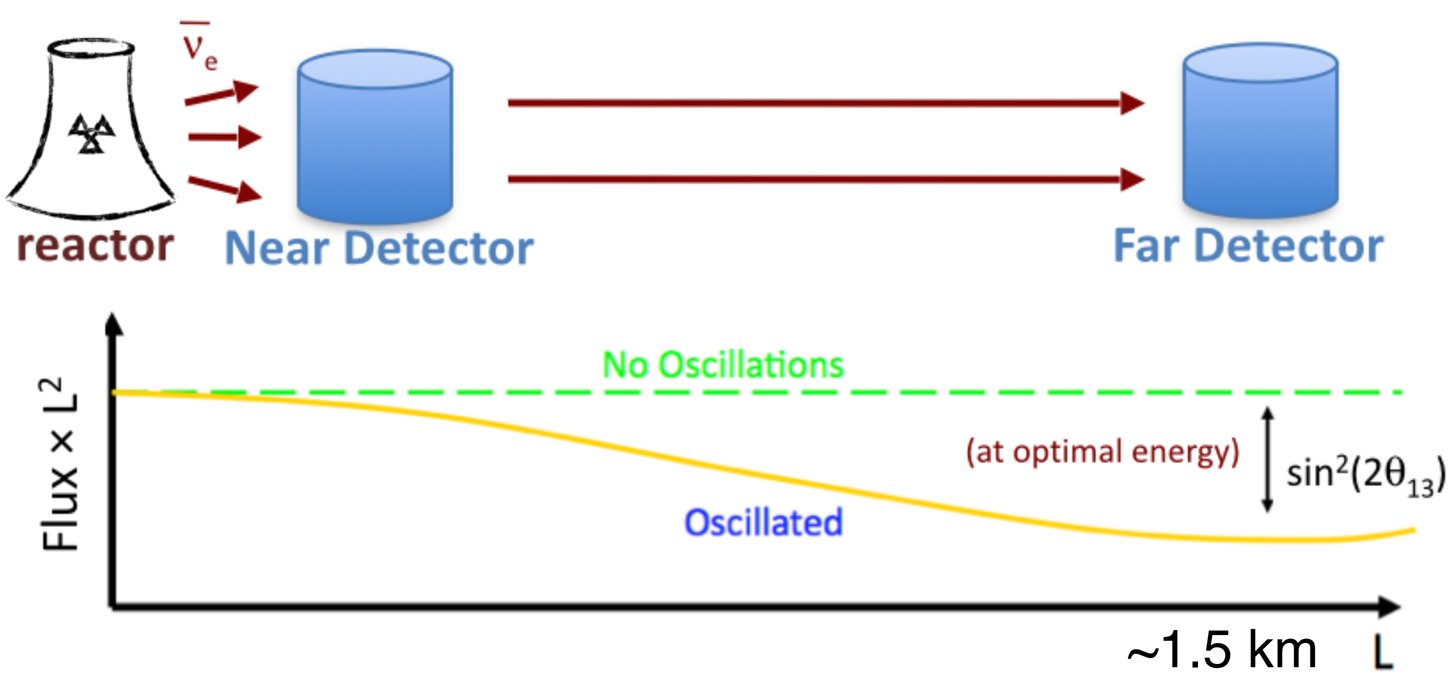
Current Generation of Experiments

- Current experiments (Daya Bay, RENO and Double CHOOZ) were designed to make a **precision measurement of the θ_{13} mixing angle**:
  - Last unknown mixing angle in the PMNS matrix
  - θ_{13} is inextricably linked to the possibility of observing CP violation in the leptonic sector

possible important consequences in cosmology!

  - θ_{13} - driven oscillations provide a way to measure the mass hierarchy

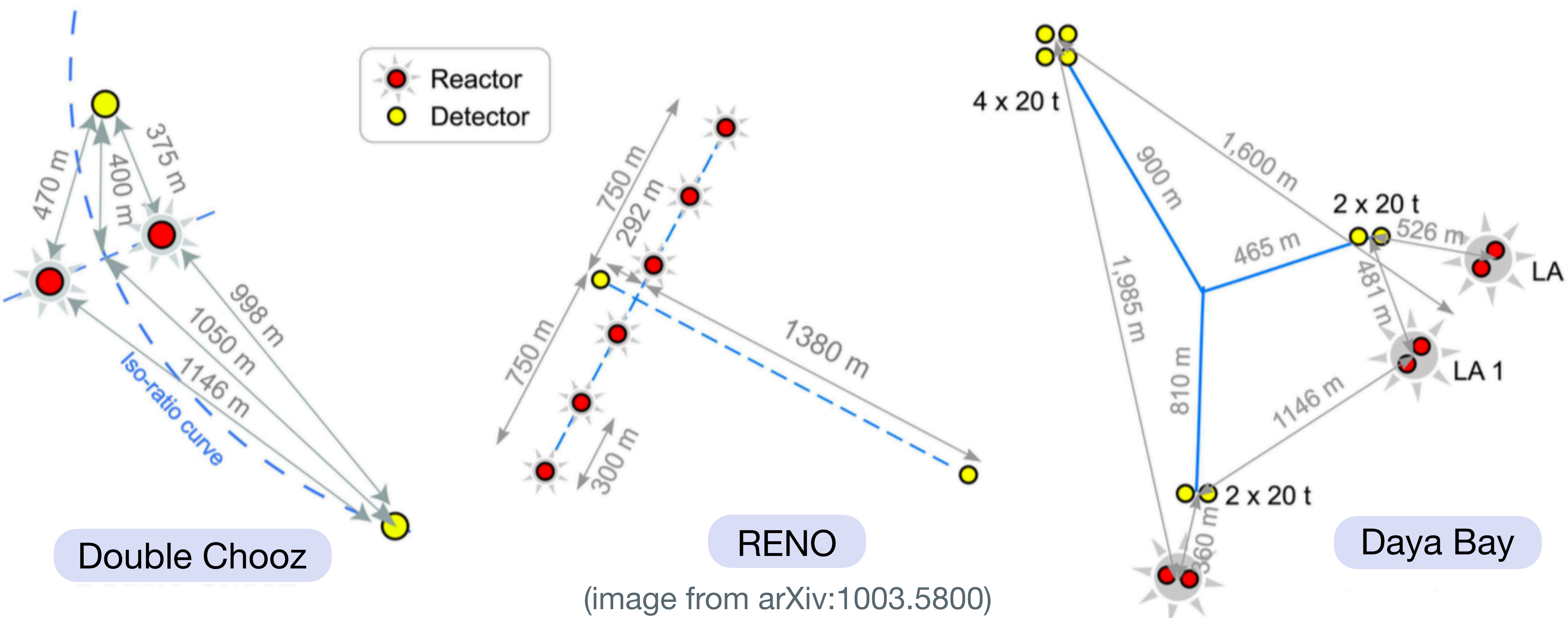
- Strategy: look for disappearance at **short (~1-2 km) baselines:**



  - Need "small" (hundreds of tons) detectors
  - Looking for a small effect, so **key is keeping systematics under control**

Experimental Layouts

- Main principle: sample flux in near and far locations, and compare

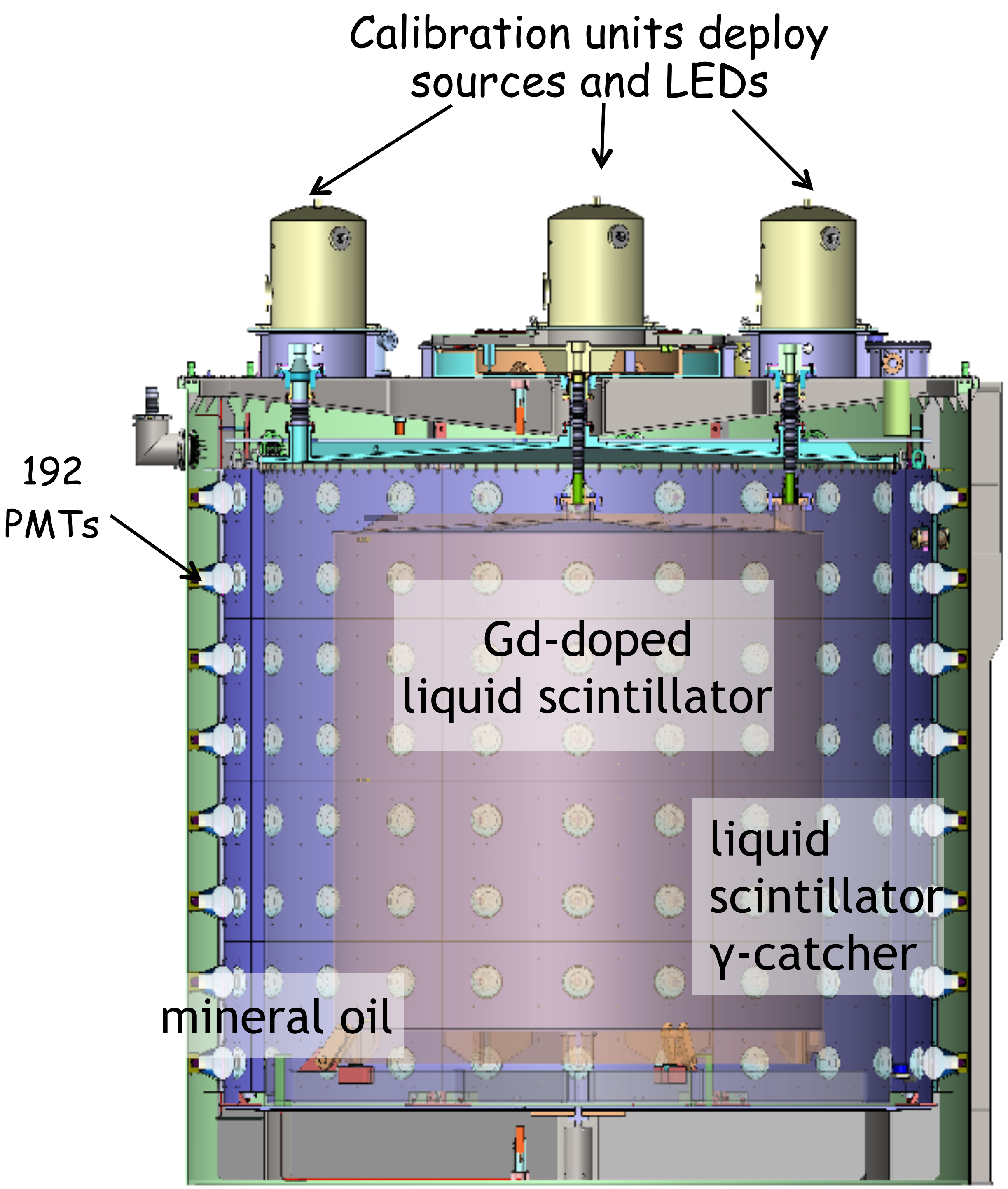


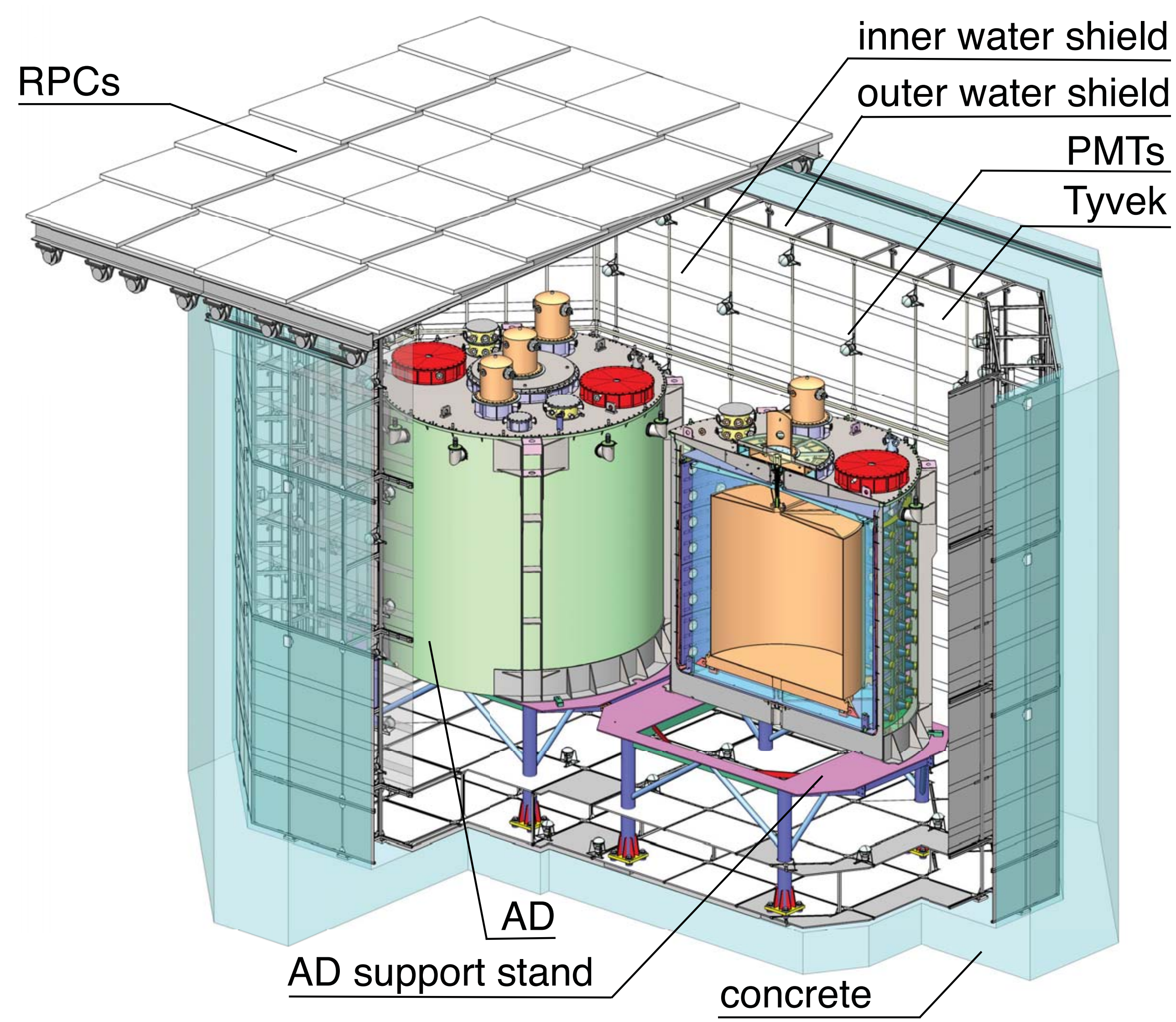
(image from arXiv:1003.5800)

	P_{Th} [GW]	nGd target mass @ far site [tons]	Overburden (near/far) [mwe]	Start-End data-taking
Double Chooz	8.6	8.3	80/300	2011-2017
RENO	16.4	15.4	90/440	2011-2021(?)
Daya Bay	17.4	80	270/950	2011-2020

Detector Technology

- Similar detection technologies:
  - Three-zone detectors
  - Surrounded by instrumented water shields that also serve to veto muons





(using Daya Bay as an illustration)

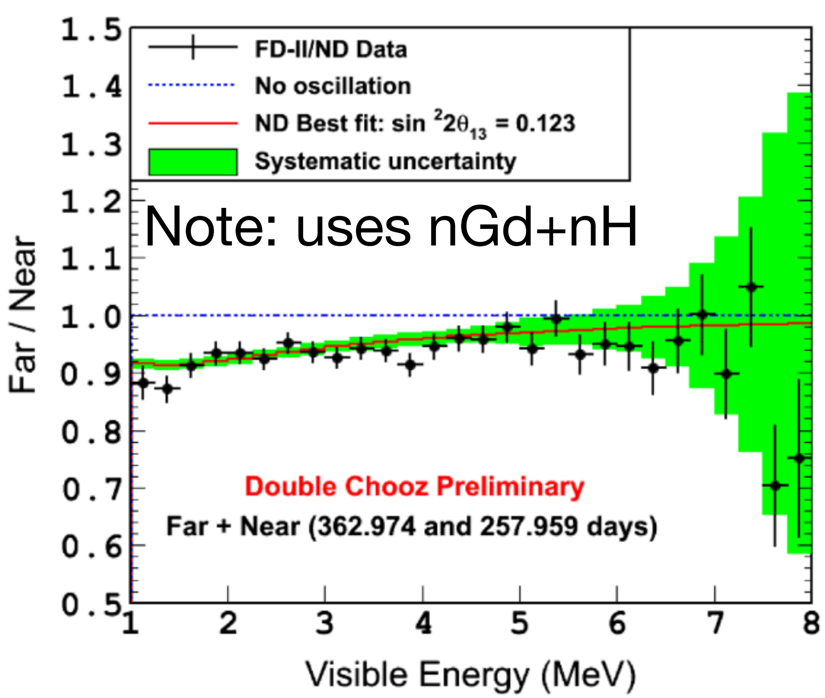
Determination of θ_{13}

- Timeline for the discovery of a non-zero θ_{13}:

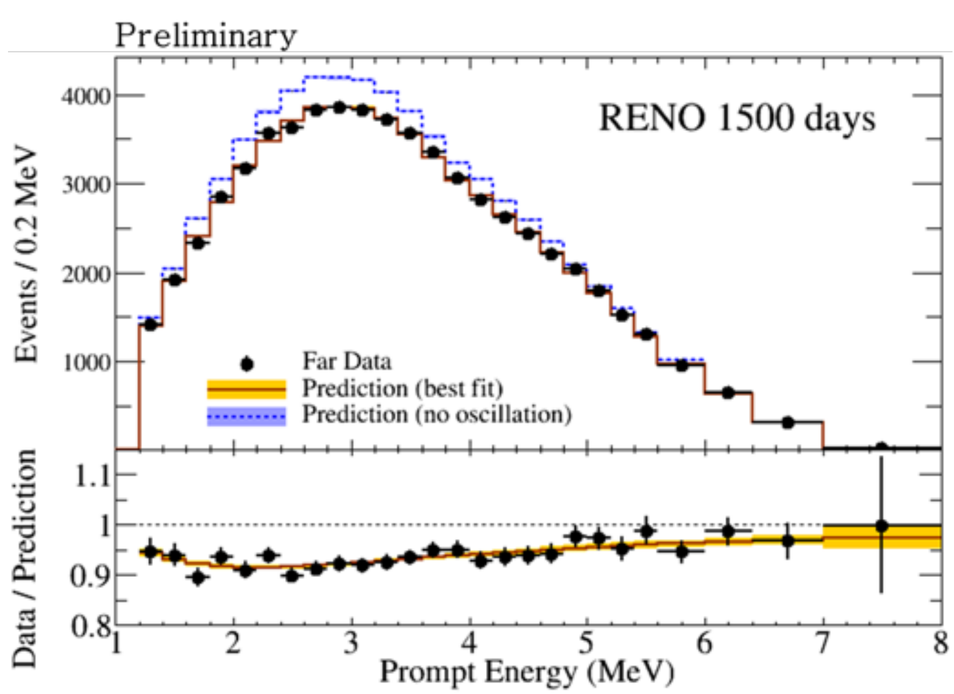
2003	2011	2012
Chooz and Palo Verde: $\sin^2(2\theta_{13})$ < 0.17 @ 90 C.L.	T2K, MINOS and Double Chooz see indications of non-zero θ_{13} ($\lesssim 3\sigma$)	Daya Bay obtains unambiguous (> 5σ) evidence of non-zero θ_{13}. RENO experiment confirms shortly after.

- Now this angle is the best known in the PMNS matrix:

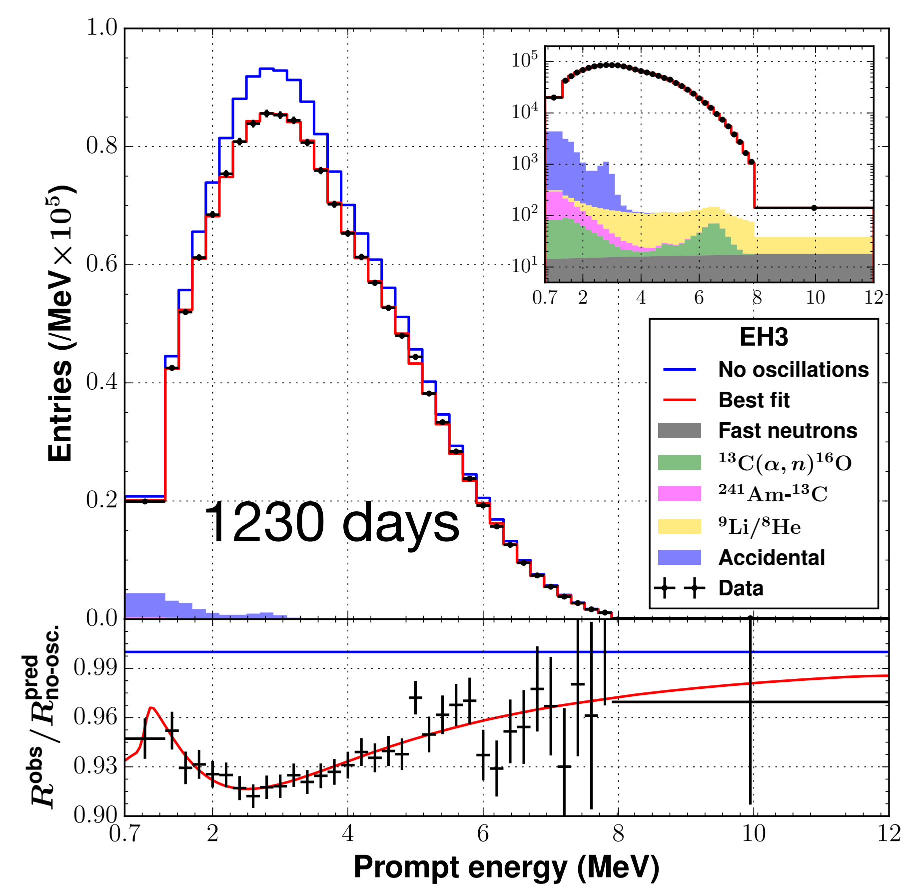
Double Chooz



RENO



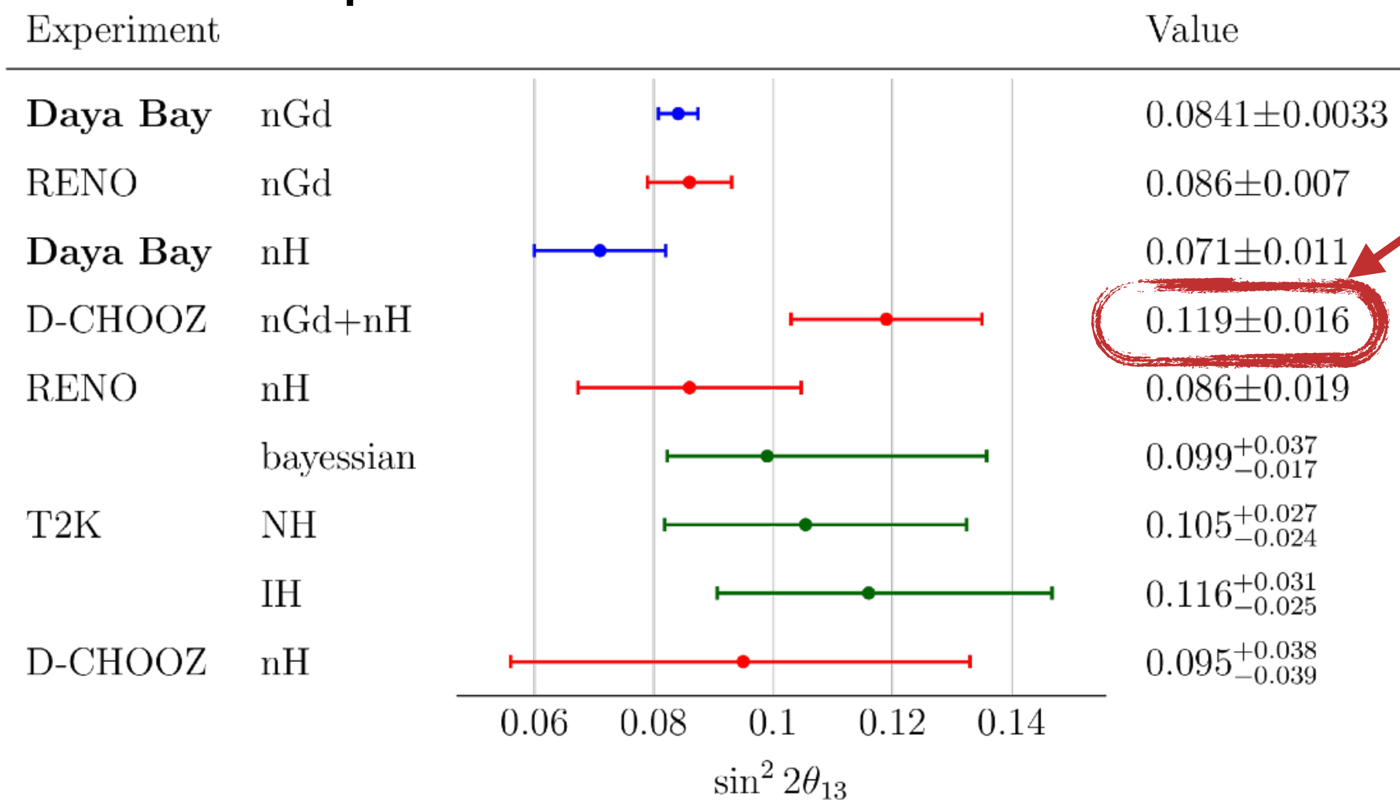
Daya Bay



– All experiments see a very clear disappearance signature consistent with three-flavor oscillations

Global Landscape

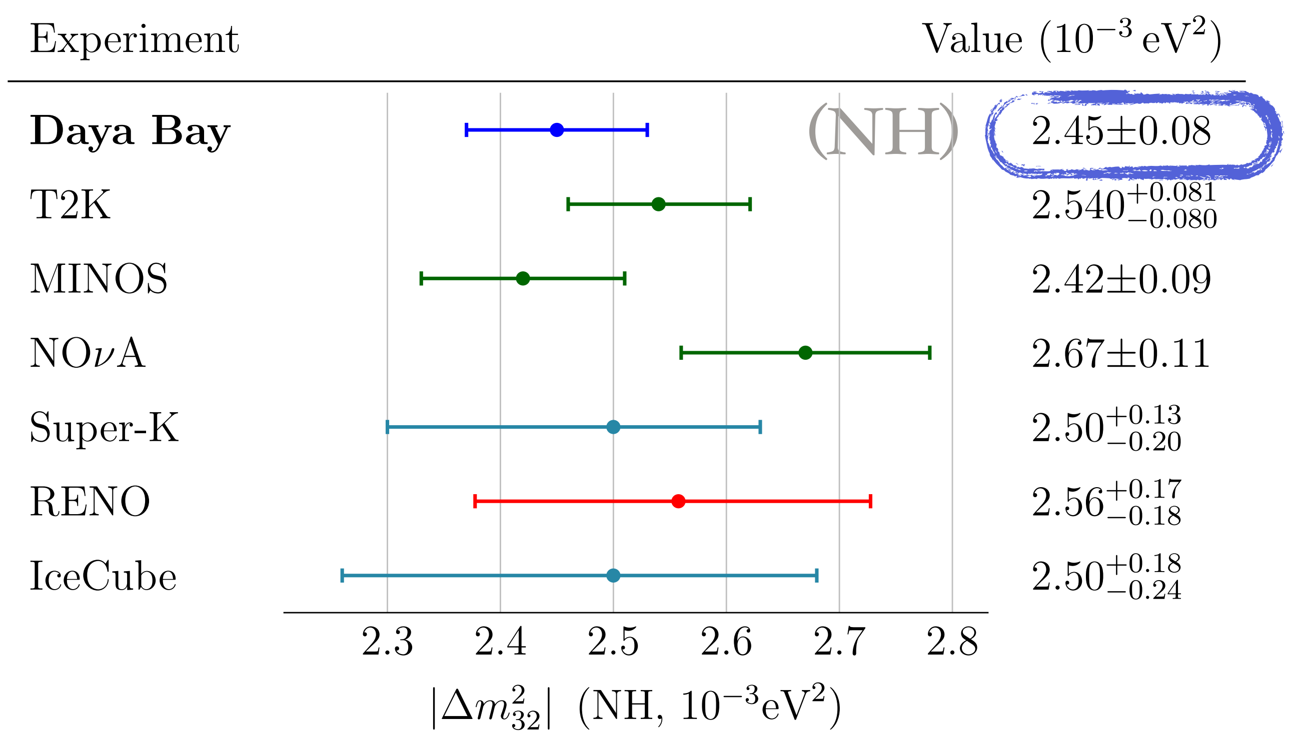
- The most precise measurements of θ_{13} come from reactor experiments:



Some tension (~2.2σ) with latest preliminary results by Double Chooz.

Daya Bay, RENO and Double CHOOZ are considering making a joint analysis of cosmogenic backgrounds.

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



Similar precision to that in accelerator experiments

(figures courtesy of M. Gonchar)

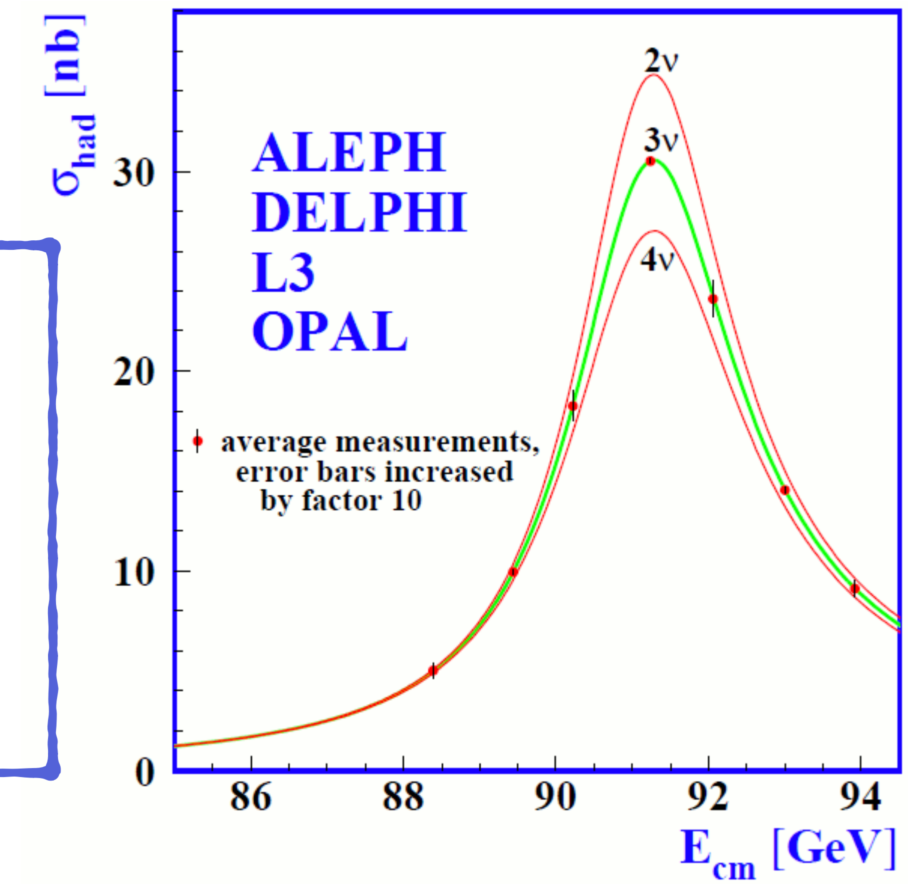
Sterile Neutrinos

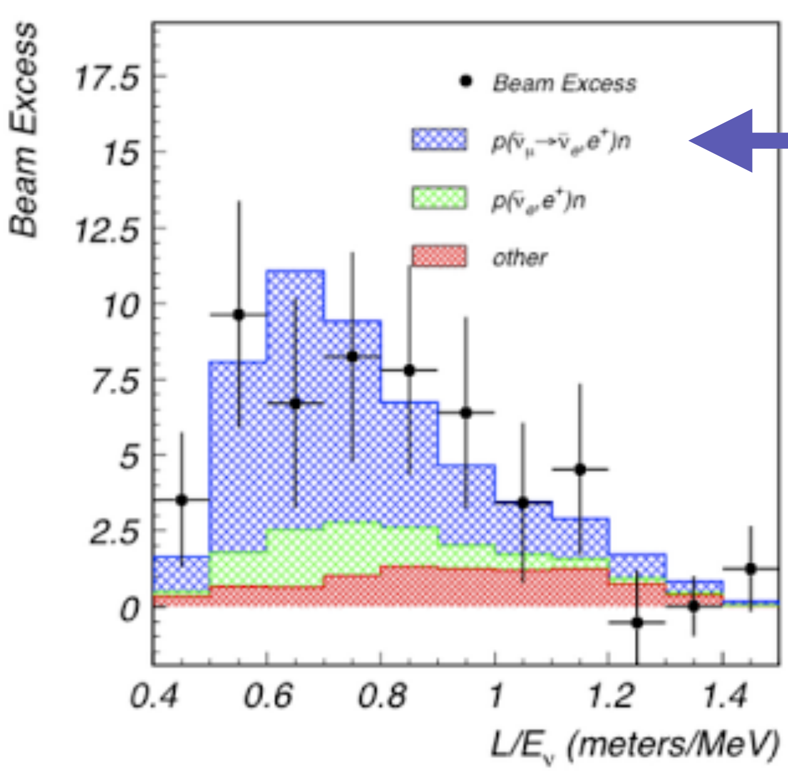
- Reactor experiments are also an ideal ground to search for sterile neutrinos:

✔ Well-motivated from the theoretical standpoint

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

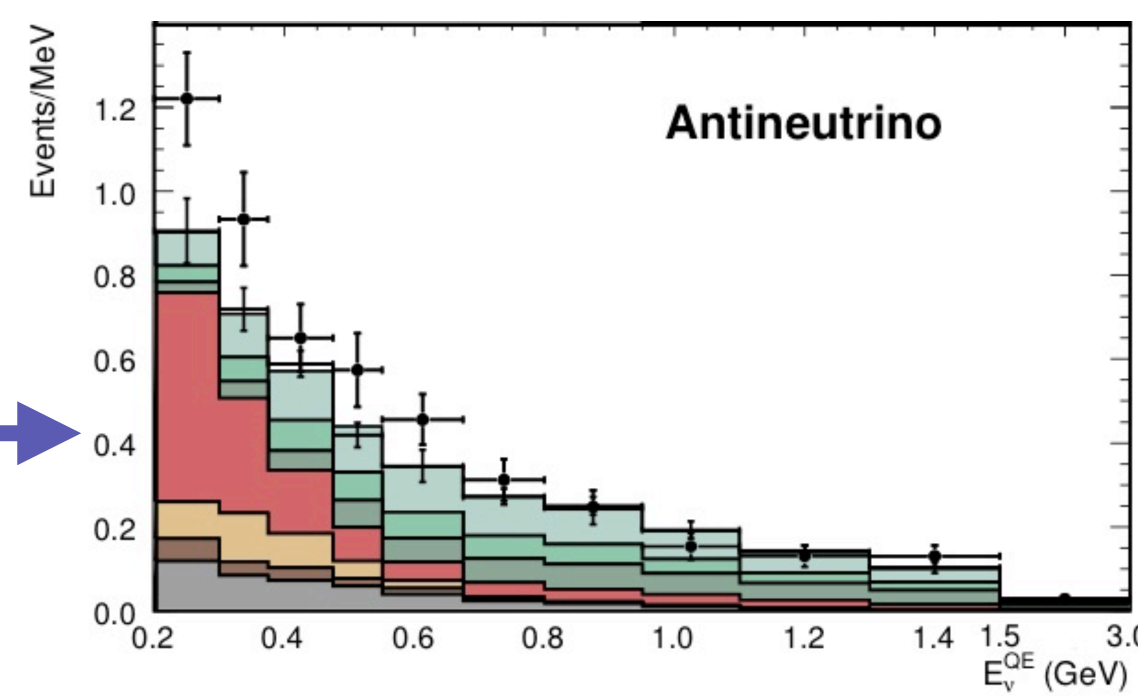
✔ Could explain some of the anomalies seen in neutrino physics





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

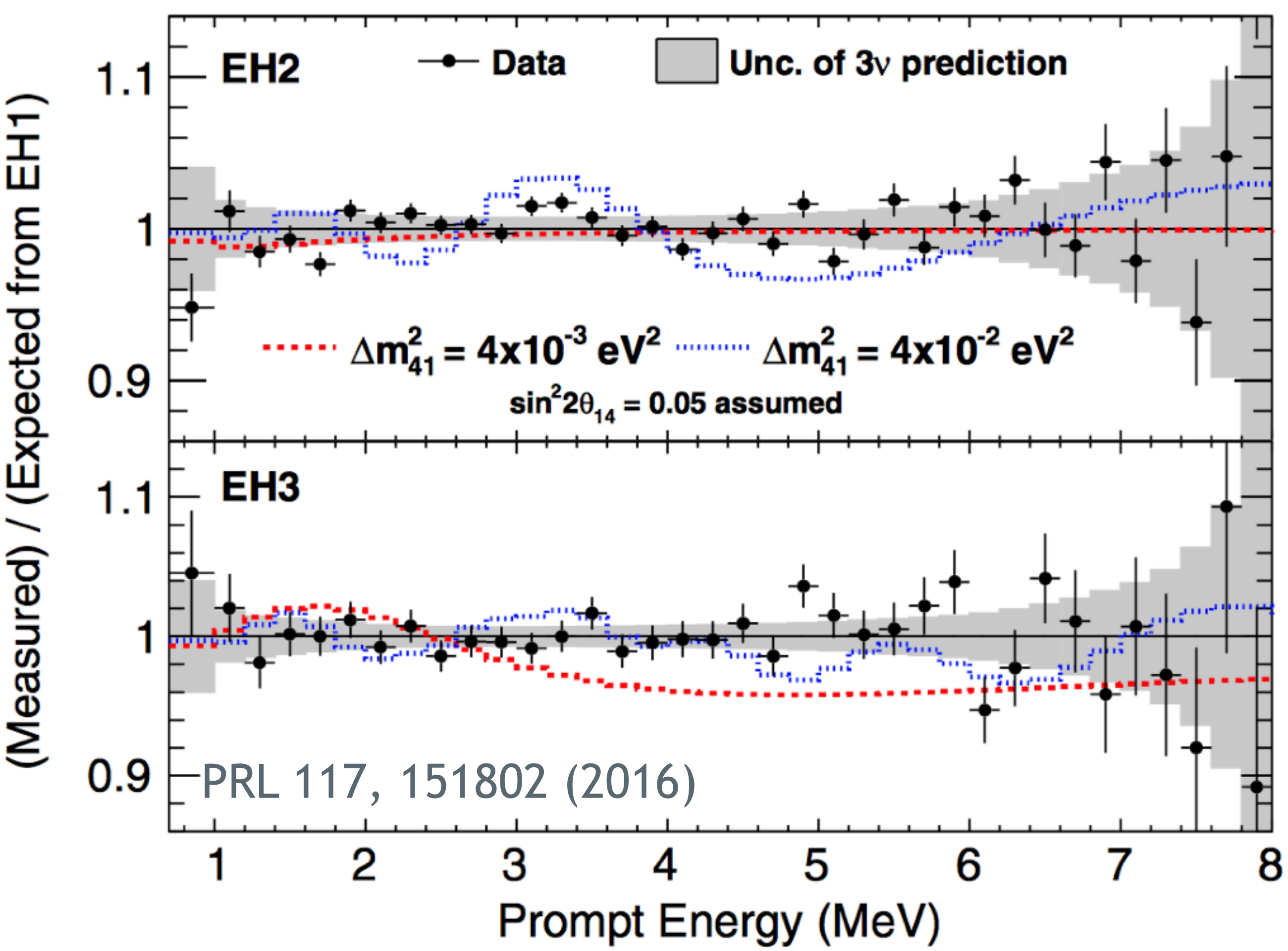
MiniBooNE antineutrino anomaly: 2.8σ excess of $\bar{\nu}_e$ in a $\bar{\nu}_\mu$ beam (2013)



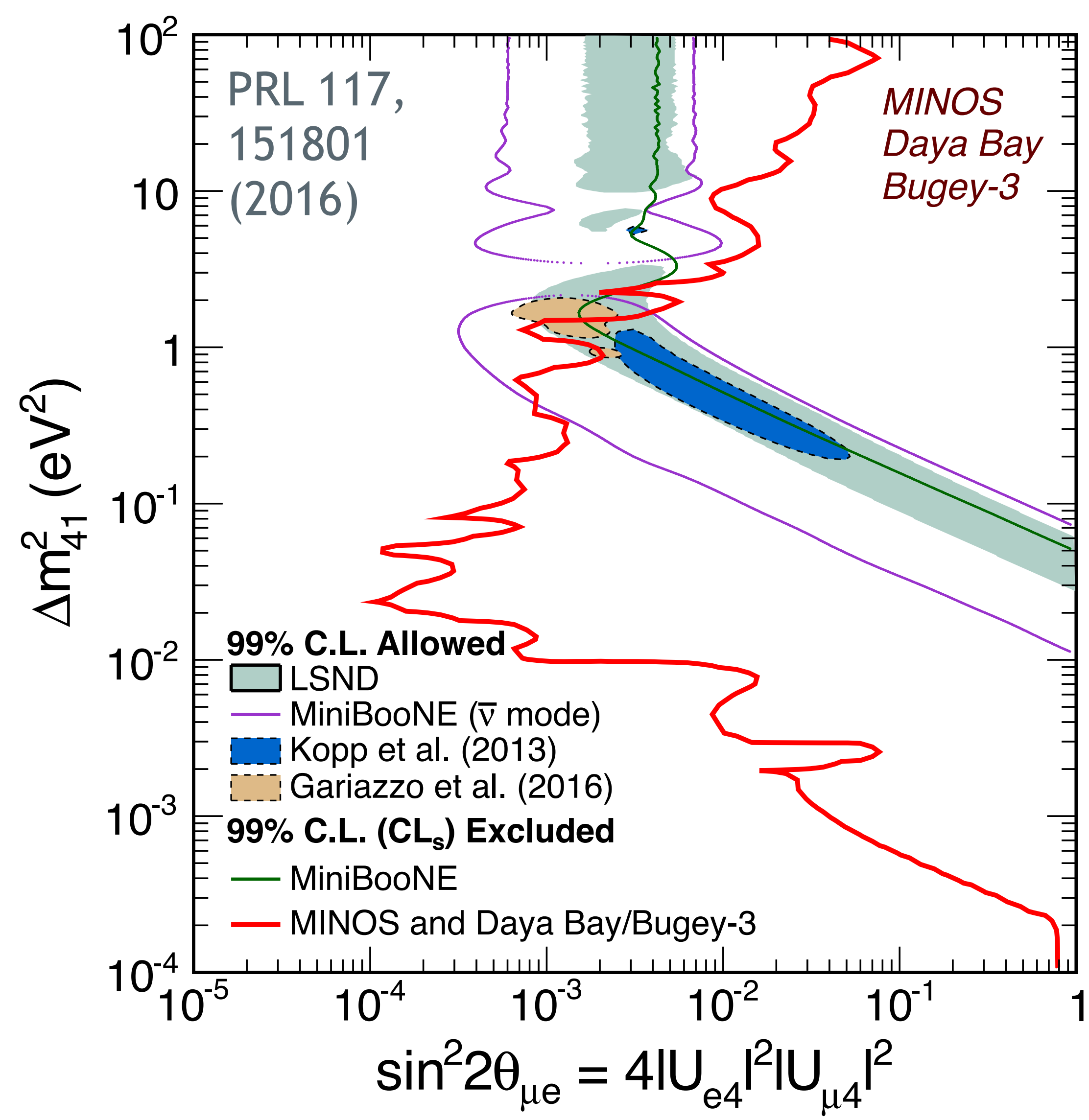
Search for Sterile Neutrinos

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



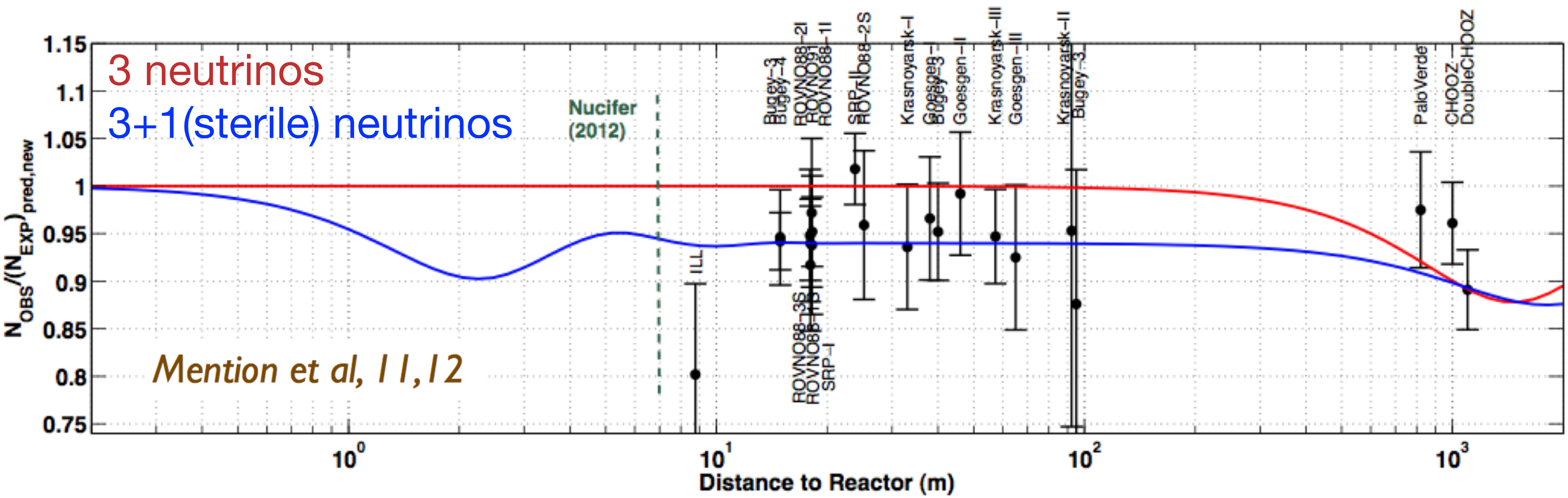
LSND + MiniBooNE's allowed parameter space excluded < 0.8 eV2 @ 90% C.L.



Absolute Measurements

- Ongoing reactor experiments can also measure the spectral shape of reactor antineutrinos with unprecedented precision

- This allows to investigate yet another anomaly:
  - The reactor antineutrino anomaly: data from short baseline reactor experiments show a consistent deficit with respect to the most recent estimates of the expected flux

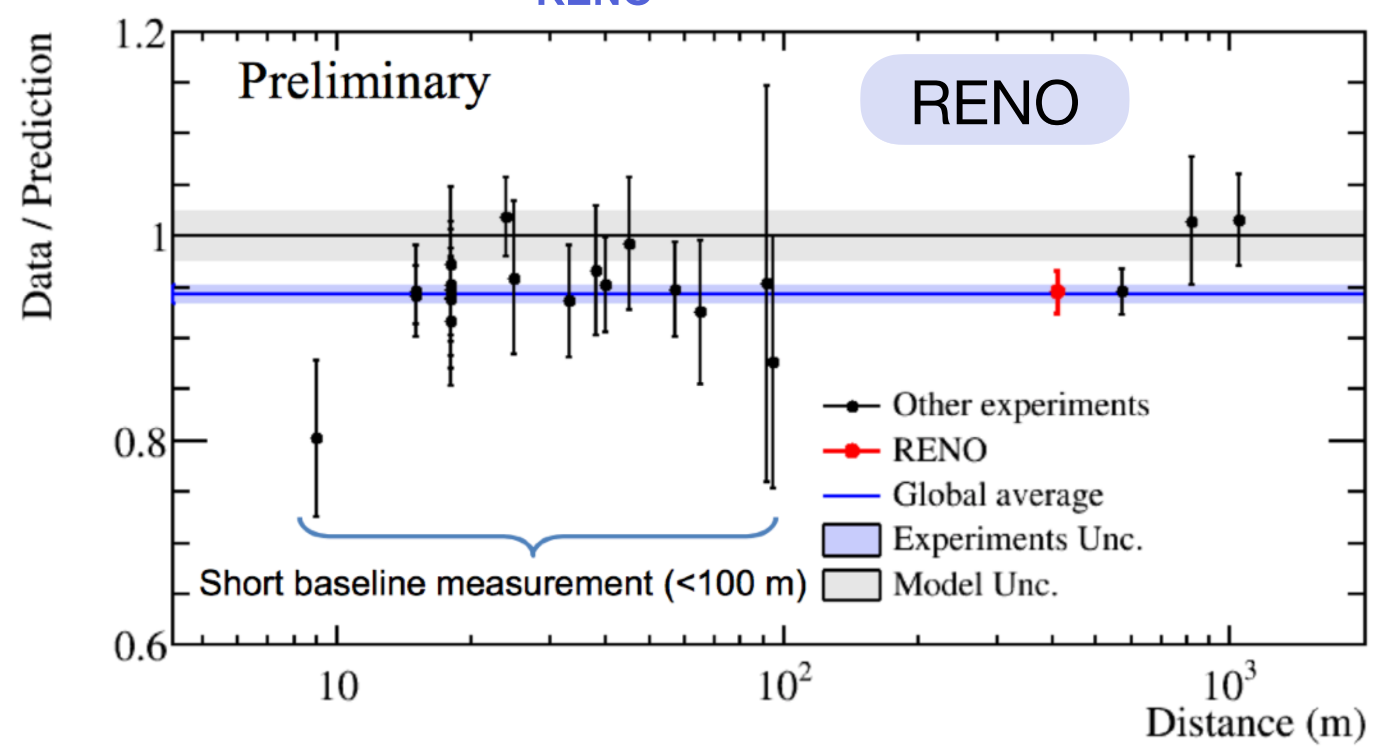


  - With all < 100 m baseline experiments combined, it is a ~5.5% deficit at ~2.5σ [Phys.Rev. D83 073006 (2011)]

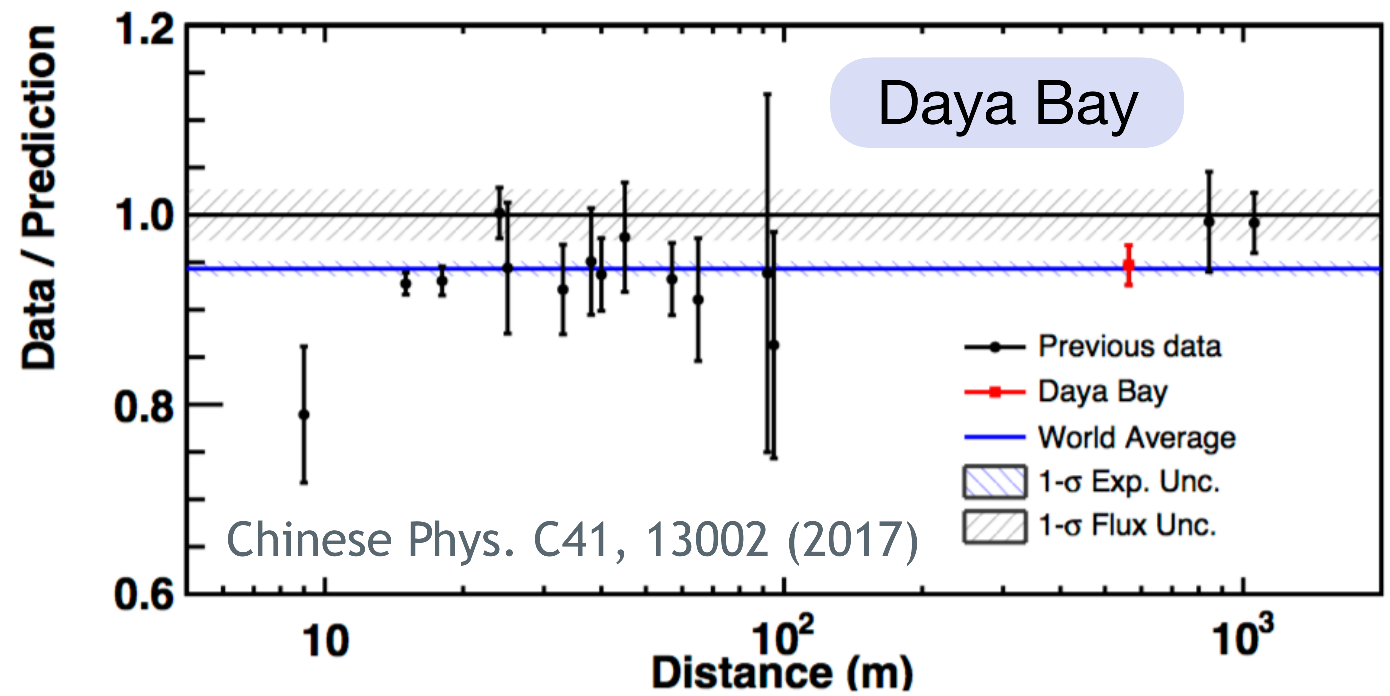
Reactor Antineutrino Flux

- Results from RENO and Daya Bay are consistent with those of previous short baseline experiments
- Causes of the anomaly?
  - Experimental systematics? **Extremely unlikely**…
  - New Physics (oscillations to a 4th ~eV sterile neutrino)? **Maybe**….
  - Unaccounted systematics in the prediction? **Likely**…

R_{RENO}= 0.946 ±0.021

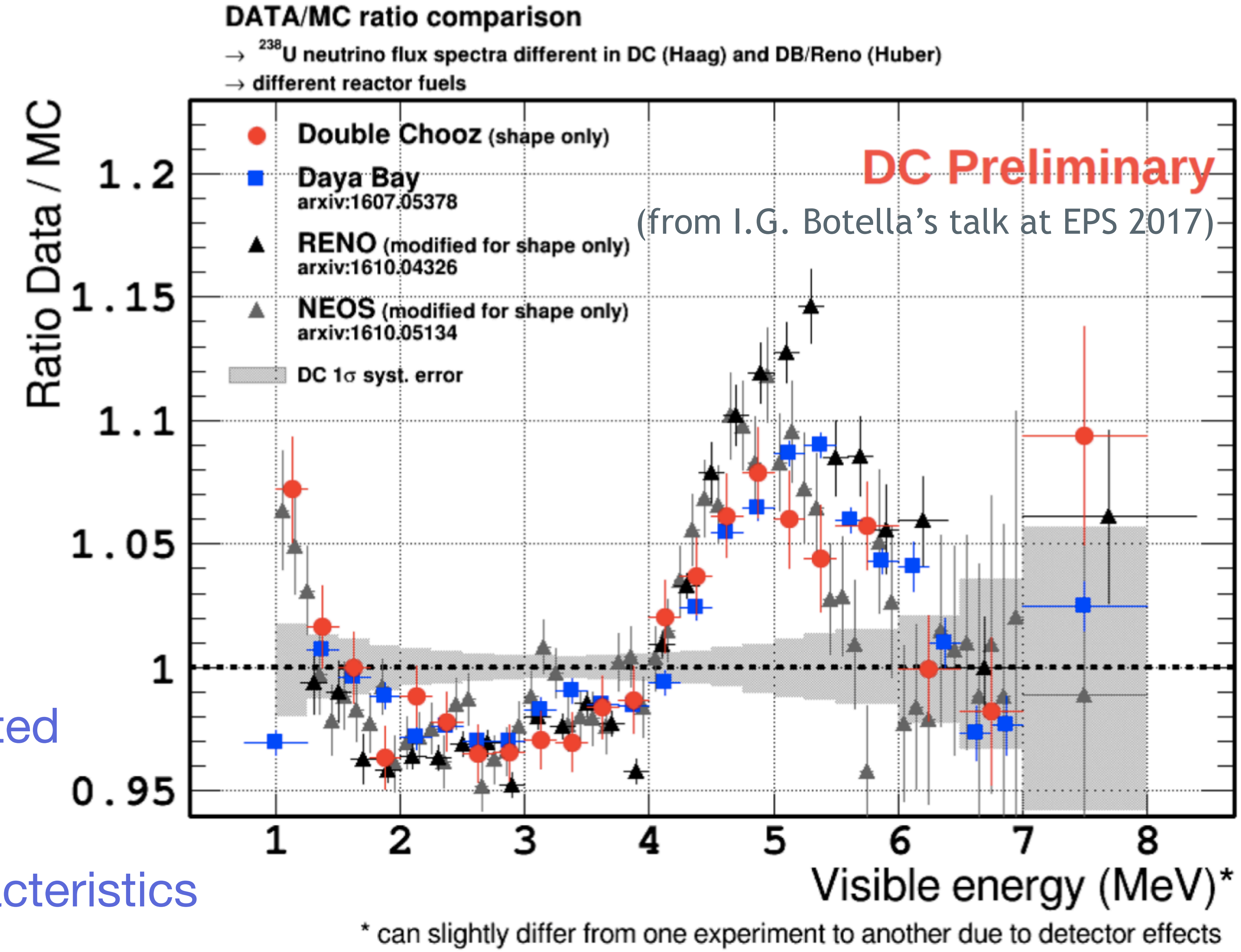


R_{DYB}= 0.946 ±0.020



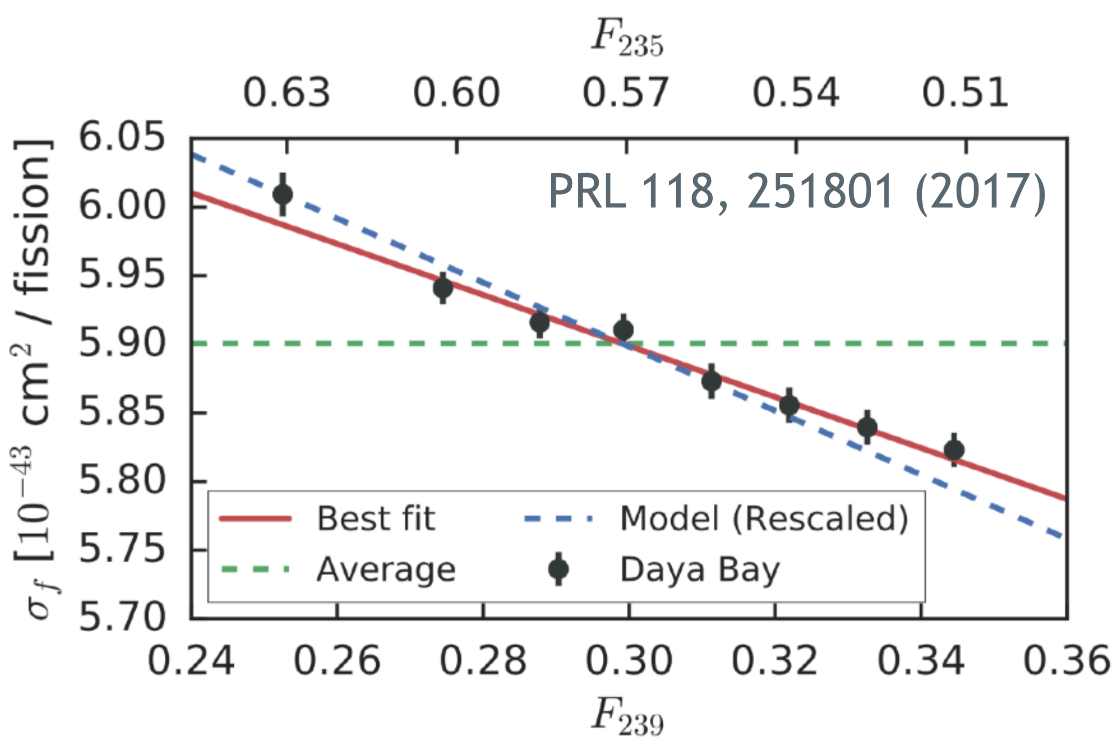
Reactor Antineutrino Spectral Shape

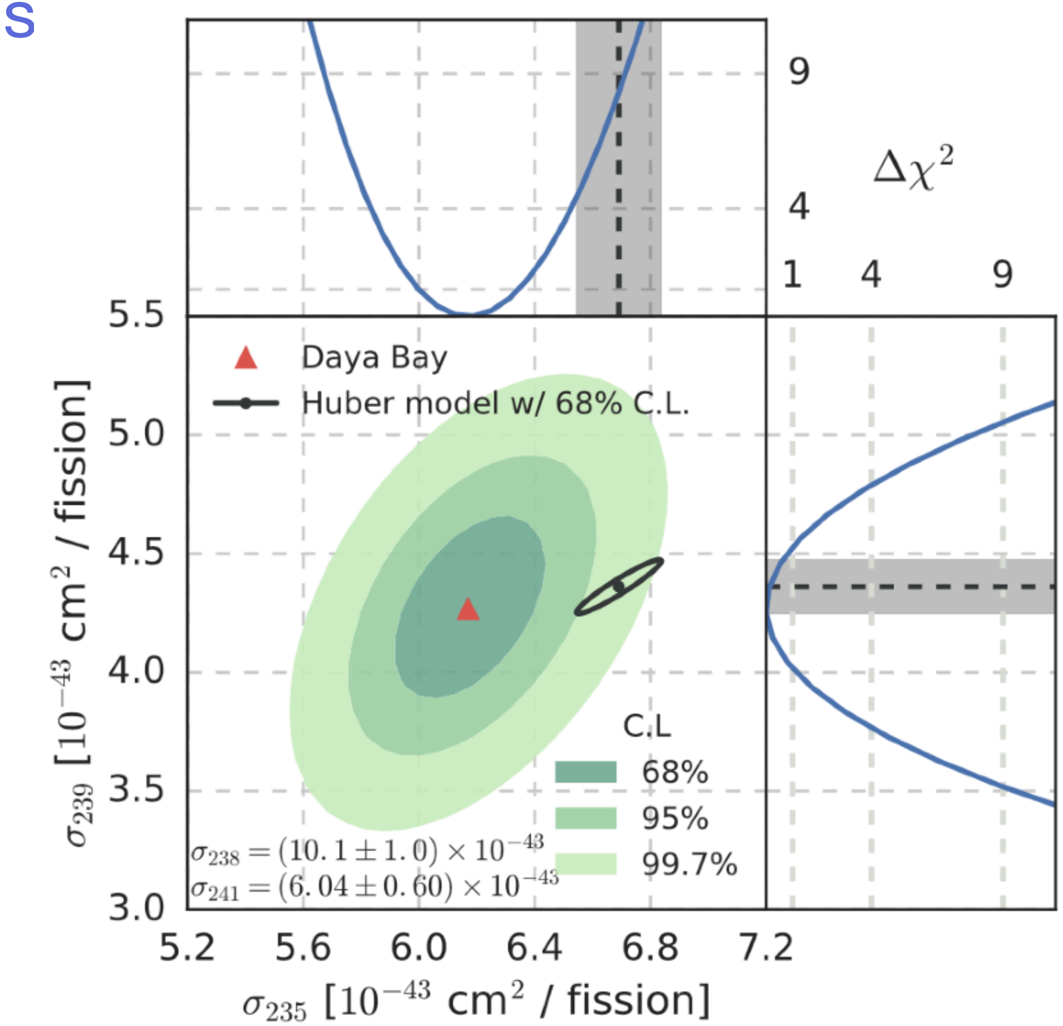
- Ongoing reactor experiments can also do an **absolute shape comparison with unprecedented statistics**
  - All see a clear "bump" from 4-6 MeV
- Observations so far:
  - Events are power correlated and time independent
  - Events have all IBD characteristics
  - Bump not seen in other spectra (e.g. ^{12}B), ruling out electronics and/or energy model
- Implications are clear: if cannot predict shape as accurately as expected, maybe the same is true for the flux



Hints from Study of Fuel Evolution

- Daya Bay has recently released a study of how flux and shape changes with fuel evolution (measured with ^{239}Pu effective fission fraction, F239)
  - See clear changes in flux and shape with reactor fuel evolution, as expected (>10σ and >5σ respectively)
  - Evolution is inconsistent with prediction from Huber + Mueller model at ~3σ
  - Using some conservative constraints on ^{241}Pu and ^{238}U, can use these data to extract individual ^{235}U and ^{239}Pu yields





Equal deficit of all isotopes (as required by sterile neutrino interpretation of anomaly) disfavored at 2.8σ.

As shown in Giunti et al.'s arXiv:1708.01133, significance diminishes if considering global data

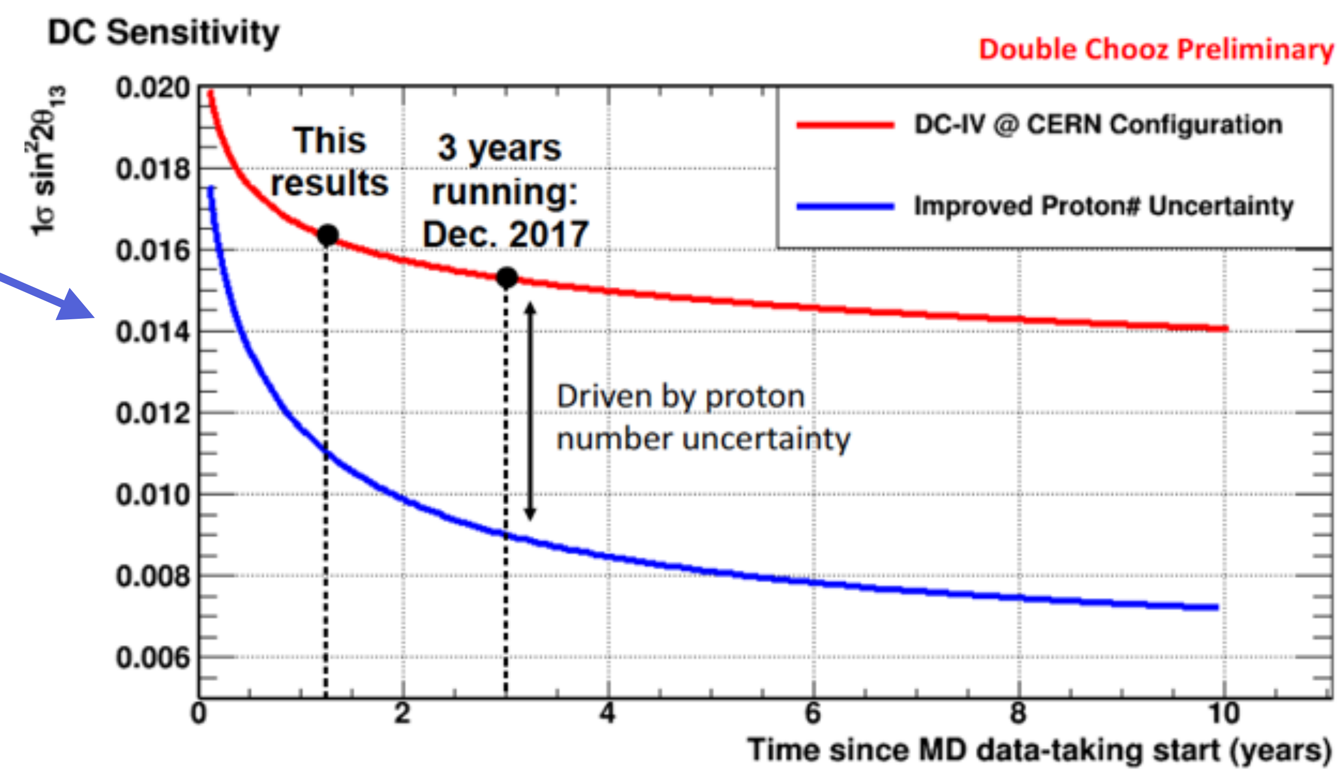
The Future

What's next for running experiments?

- Running experiments still have much to give:

Double Chooz

– End data-taking in 2017 and recount protons (main systematic uncertainty)



RENO

– Run until 2018 (possible extension to 2021)
– Aim for 6% precision in θ_{13} and Δm^2

Daya Bay

– Run until 2020
– Expect < 3% precision in θ_{13} and Δm^2

(see Zeyuan Yu's talk at today's parallel session on "Recent Results from Daya Bay")

+ expect other physics results from these experiments (improved sterile neutrino search, improved absolute flux and shape measurement, searches for new physics, … etc).

- And there are new reactor experiments being constructed (next slides)…

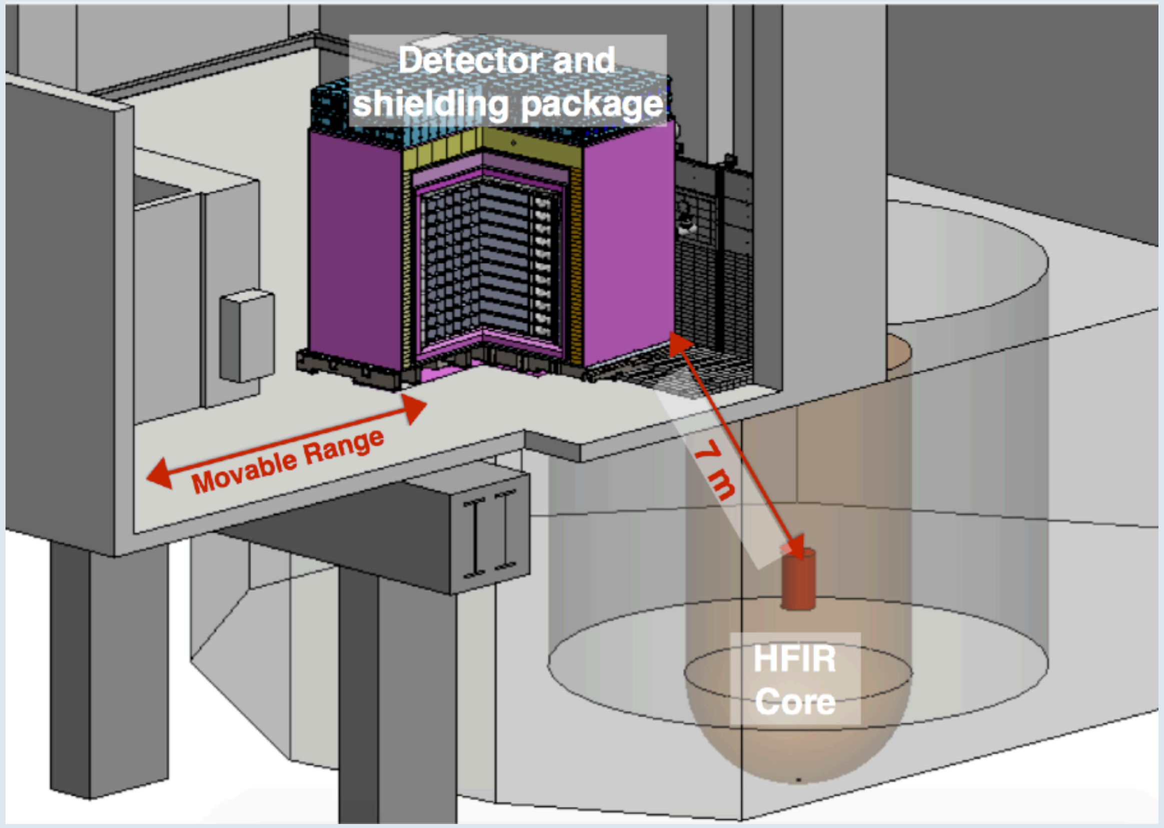
Short Baseline Experiments

- An aggressive program of several very short baseline experiments is underway to address some of the open questions
- Main goals:
  - Search for oscillations to a ~eV scale sterile neutrino

+ shed light on reactor antineutrino anomaly by constraining ^{235}U yield (in some cases)

+ reactor monitoring and nonproliferation (in some cases)

Example: PROSPECT

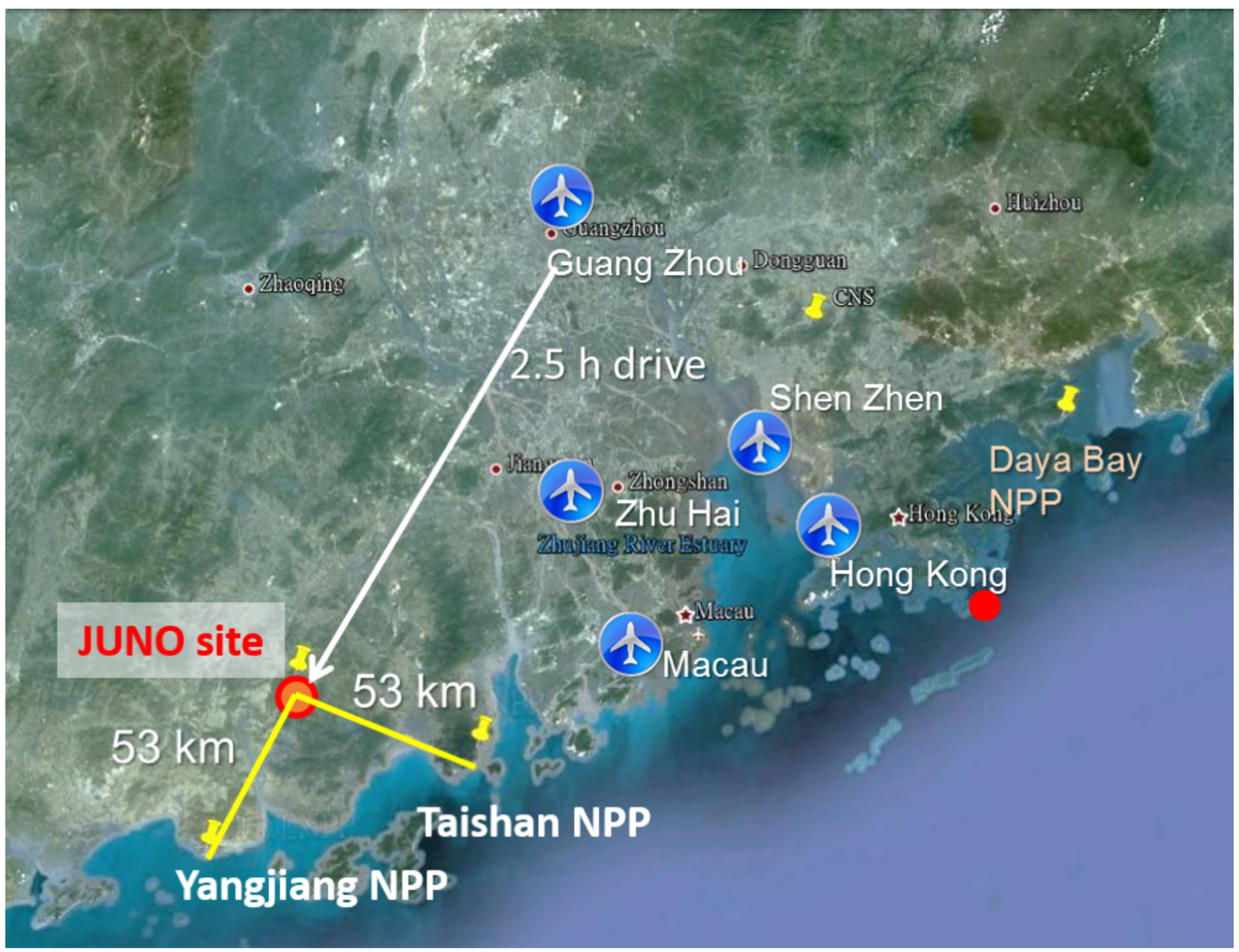


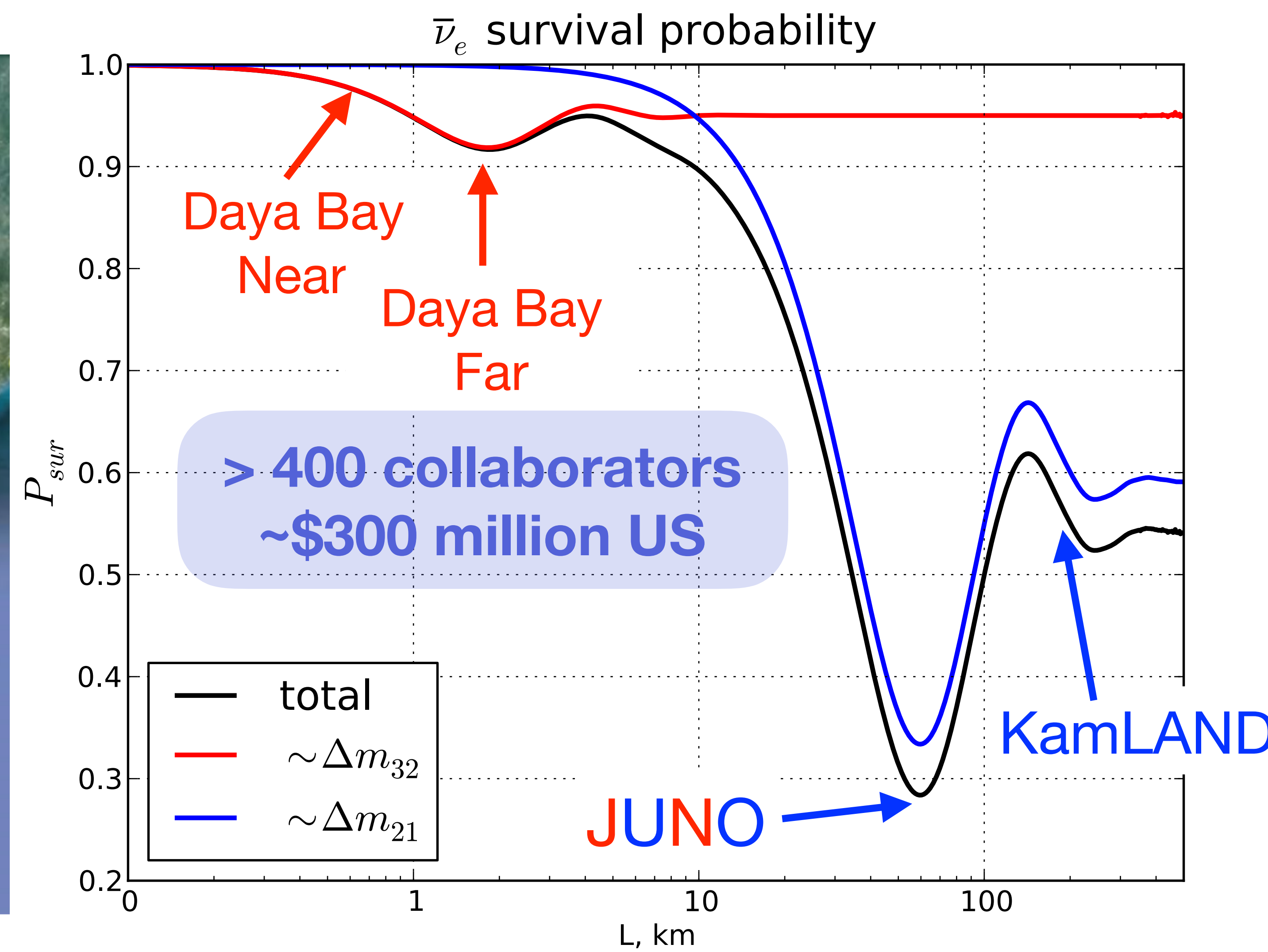
Moveable detector very near a highly enriched uranium (HEU) reactor

- In this conference we will hear about DANSS in Russia, STEREO in France and PROSPECT in the US. The former two are already collecting data.
  - Other experiments include NEOS (South Korea), nuLAT (USA), Neutrino4 (Russia), SoLid (Belgium) and Chandler (France)

The JUNO Experiment

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



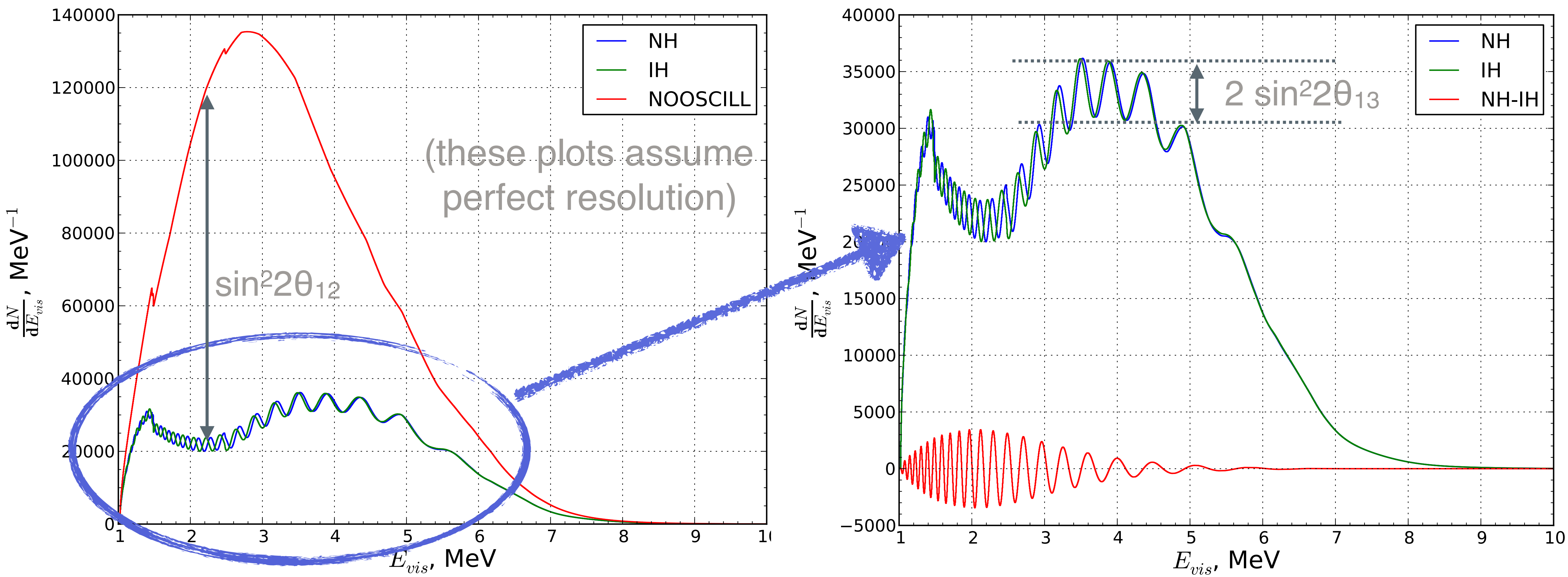


  - Given the larger baseline, the detector will have to be **MUCH** larger than the Daya Bay ones (roughly a factor of 100).

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

JUNO Spectrum

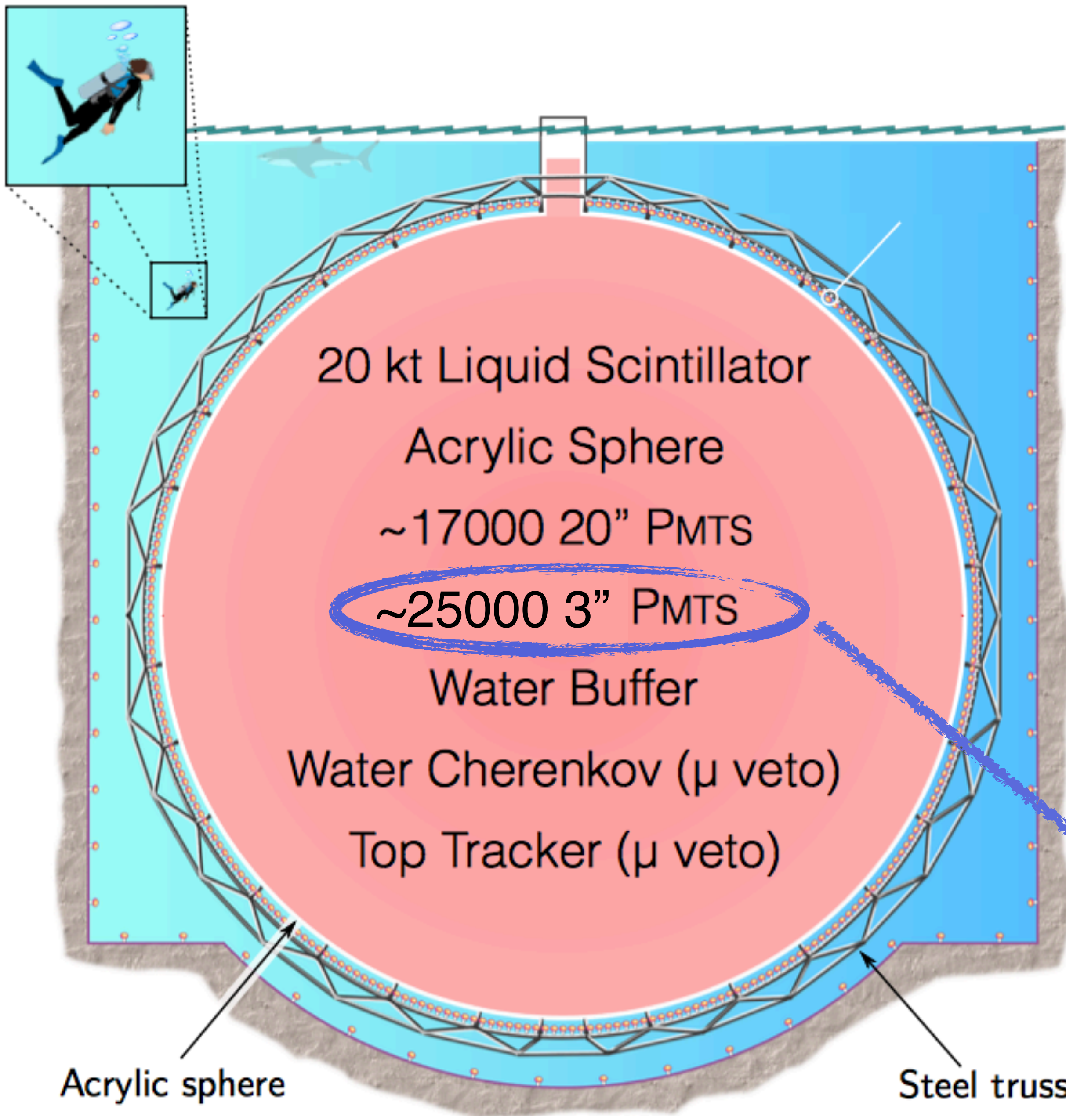
- JUNO's primary purpose is the determination of the neutrino mass ordering through a measurement of the fine structure in the oscillated spectrum:



- JUNO will be the first experiment to make a **combined observation of solar and atmospheric oscillations.**
- For 6 years of running can achieve a sensitivity to the mass hierarchy of ~3σ (or >4σ if <1.5% external constraints on $|\Delta m^2_{\mu\mu}|$ become available)

JUNO Detector

- Need an UNPRECEDENTEDLY LARGE & PRECISE detector:



	DETECTOR TARGET MASS	RESOLUTION
KamLAND	1000 t	$6\%/\sqrt{E}$
Double Chooz	8 t	
RENO	16 t	$8\%/\sqrt{E}$
Daya Bay	20 t	
Borexino	300 t	$5\%/\sqrt{E}$
JUNO	20000 t	$3\%/\sqrt{E}$

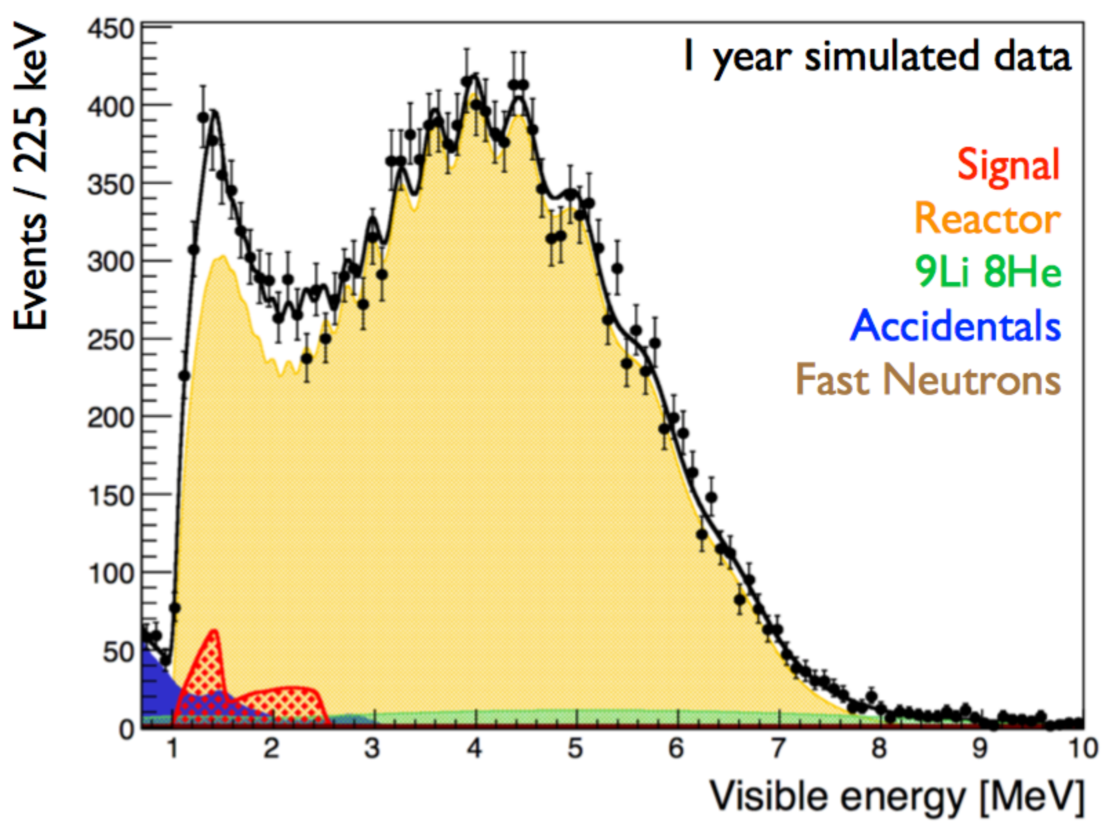
complementary to the large PMTs!

- Will also need highly transparent LS (> 22m attenuation length @ 430nm), photocathode coverage of > 75%, and a PMT quantum efficiency >35%.

Other Physics Topics

- JUNO also has a very rich program in other topics:
  - **Precision measurements of oscillation parameters**: $\sin^2 2\theta_{12}$, Δm^2_{21} and $|\Delta m^2_{ee}|$ will be measured to better than 1%.
  - **Geoneutrinos:** about 300-500 per year (current sample is < 150 events)
  - **Supernova neutrinos:** could measure the time evolution, energy spectra and flavor contents of SN neutrinos
  - **Solar and atmospheric neutrinos**

Expected geoneutrino spectrum



Expected events for SN at 10kpc

Channel	Type	Events for different $\langle E_\nu \rangle$ values		
		12 MeV	14 MeV	16 MeV
$\overline{\nu}_e + p \to e^+ + n$	CC	4.3×10^3	5.0×10^3	5.7×10^3
$\nu + p \to \nu + p$	NC	0.6×10^3	1.2×10^3	2.0×10^3
$\nu + e \to \nu + e$	ES	3.6×10^2	3.6×10^2	3.6×10^2
$\nu + {}^{12}C \to \nu + {}^{12}C^*$	NC	1.7×10^2	3.2×10^2	5.2×10^2
$\nu_e + {}^{12}C \to e^- + {}^{12}N$	CC	0.5×10^2	0.9×10^2	1.6×10^2
$\overline{\nu}_e + {}^{12}C \to e^+ + {}^{12}B$	CC	0.6×10^2	1.1×10^2	1.6×10^2

+ others (sterile neutrinos, proton decay, neutrinos from dark matter… etc)

JUNO Schedule

Complete conceptual design. Complete civil design and bidding

PMT production line manufacturing

Complete civil construction. Start detector construction and assembly

Complete detector assembly, installation and LS filling

2013 ▶ 2014 ▶ 2015 ▶ 2016 ▶ 2017 ▶ 2018 ▶ 2019 ▶ 2020

Start civil construction. Complete prototyping (PMT & detector). International collaboration established

Start PMT production. Start detector production or bidding

Start LS production

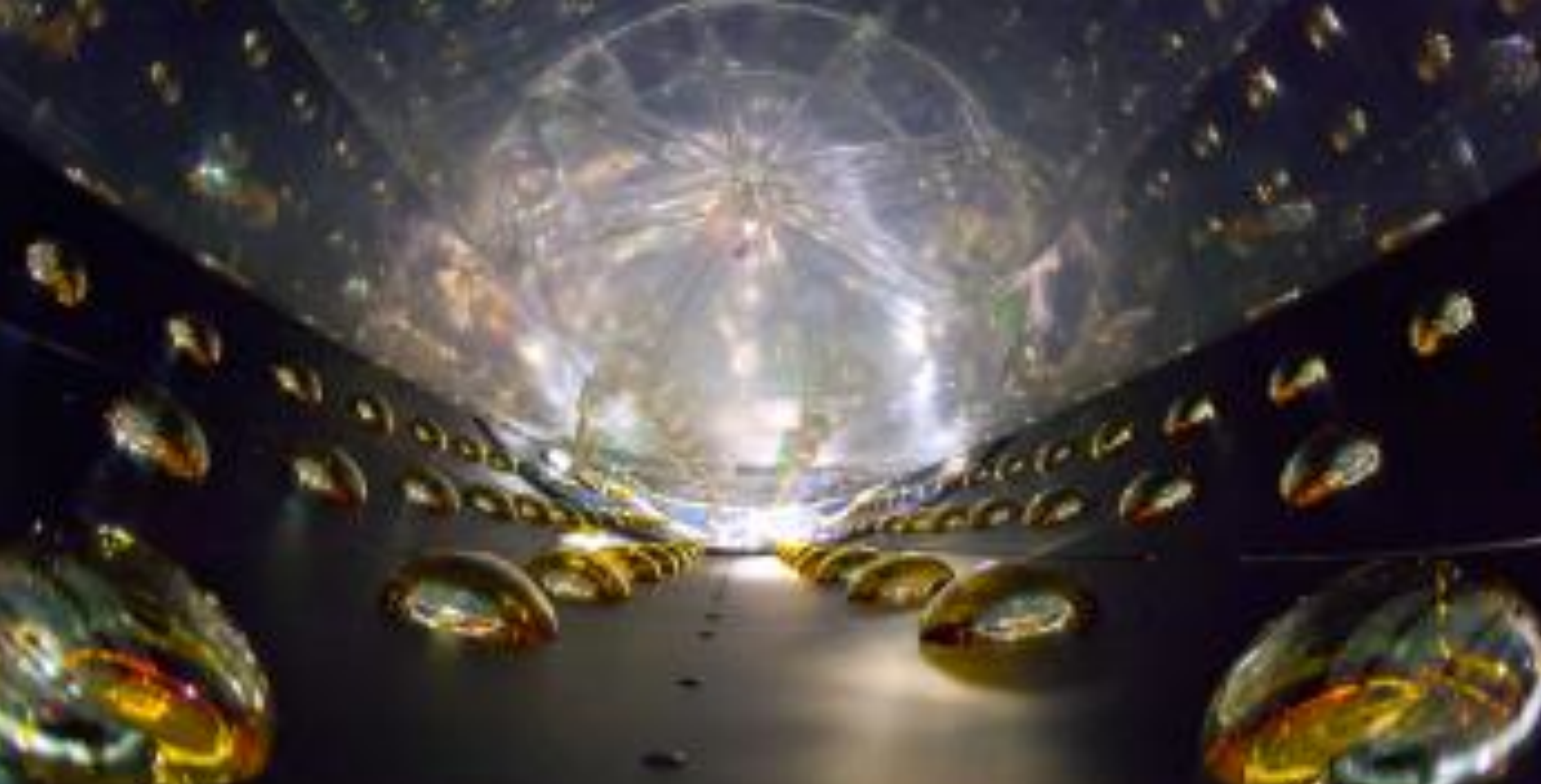
Start data taking

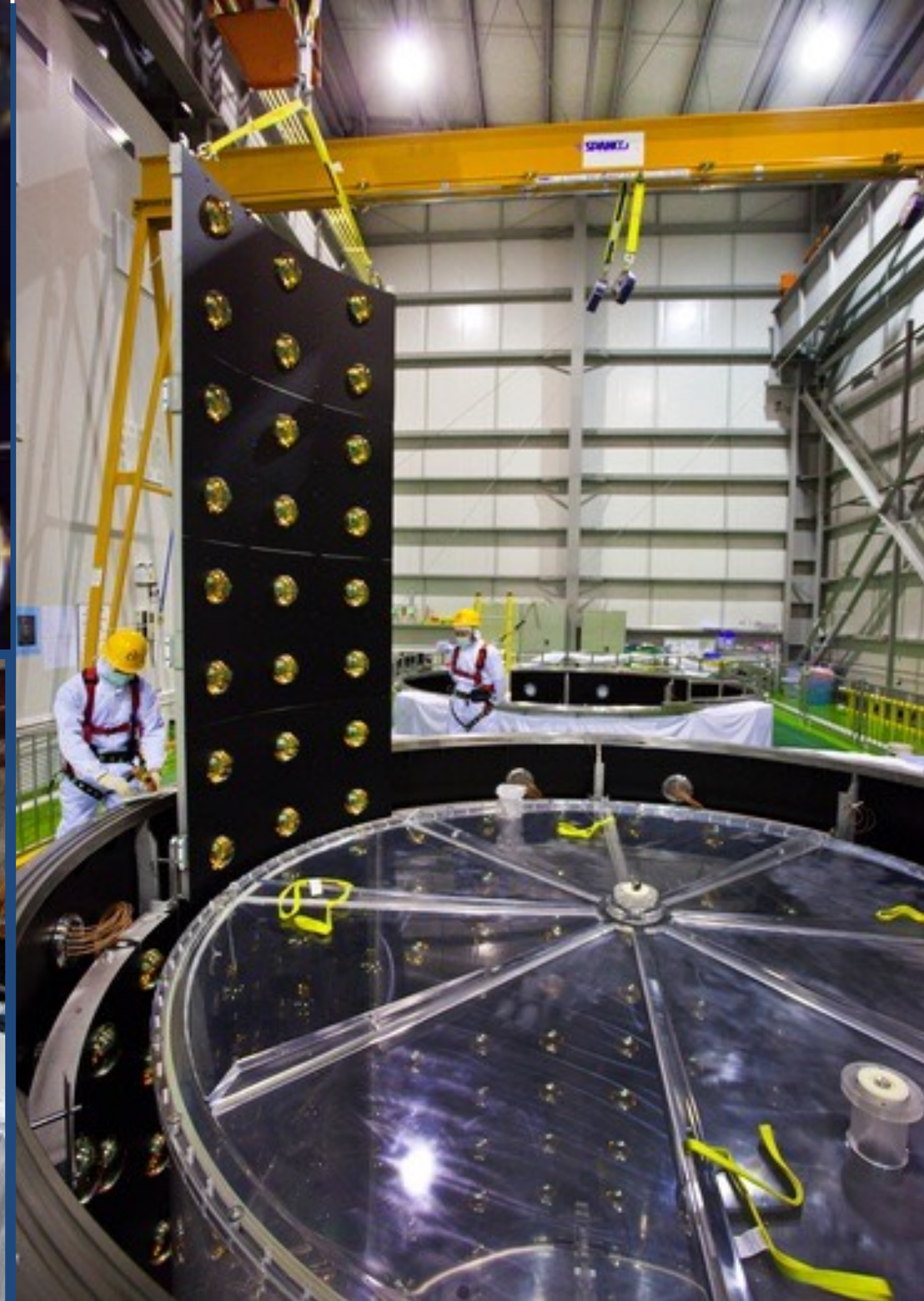
expect to run for over two decades

Summary & Conclusions

Summary & Conclusions

- Reactor Antineutrino Experiments have a long and rich history of contributions to neutrino physics:
  - From the discovery of the neutrino to the determination of the last mixing angle θ_{13}
- A bright future is also on the horizon:
  - Ongoing experiments still have much to give (e.g. exquisite precision in determination of oscillation parameters).
  - Next generation experiments are in the front line to tackle some of the unanswered questions of our day (e.g. what is the neutrino mass hierarchy? are there more than 3 neutrinos?)
- Stay tuned, and be prepared for more possible surprises!





Thank you for your attention!