Prospects with Reactor Neutrinos

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Remote conference

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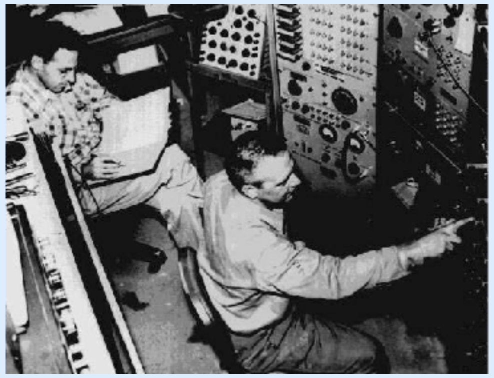
Overview

- Introduction
- Measurement of θ_{13} mixing angle
- JUNO
  - JUNO-TAO
- Very short baseline neutrino experiments
- Conclusions

Spoiler alert: **Future is bright!** Unfortunately, all cannot be covered.

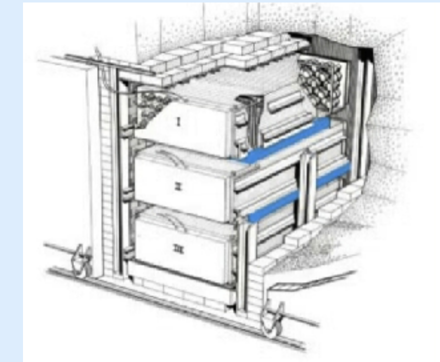
I focus mainly on fundamental neutrino properties
(from reactor neutrino oscillation measurement)

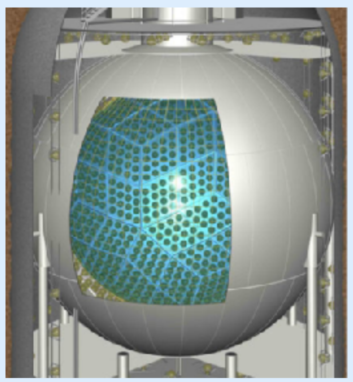
Workhorse of Fundamental ν Physics



1950s: Savannah River

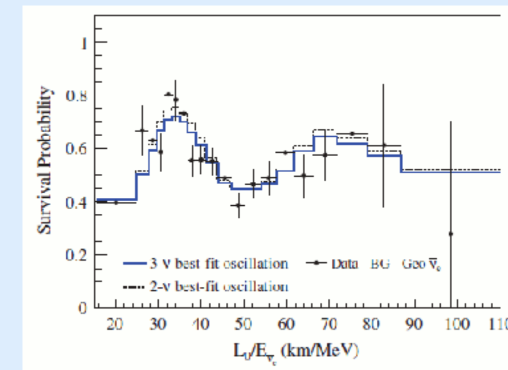
Discovery of (anti)neutrinos

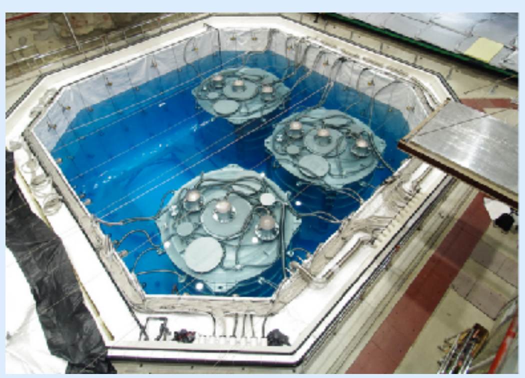




2000s: KamLAND

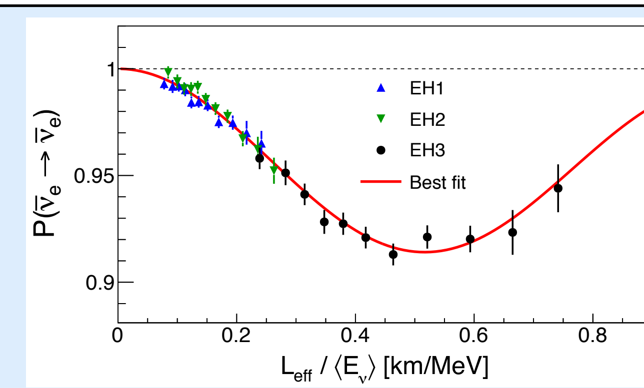
First evidence for Δm^2_{21}-driven oscillations

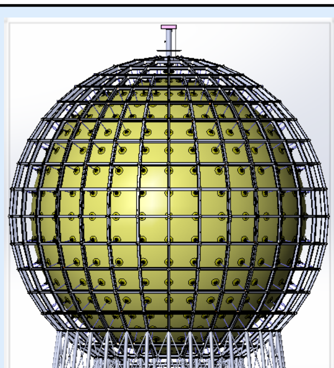




2012: Daya Bay, RENO, Double CHOOZ

Non-zero θ_{13} mixing angle



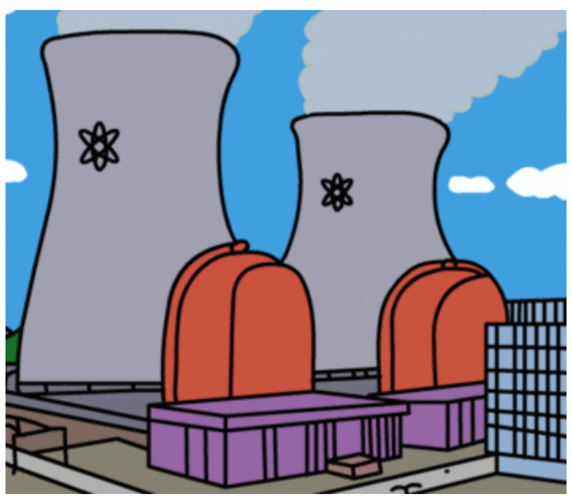


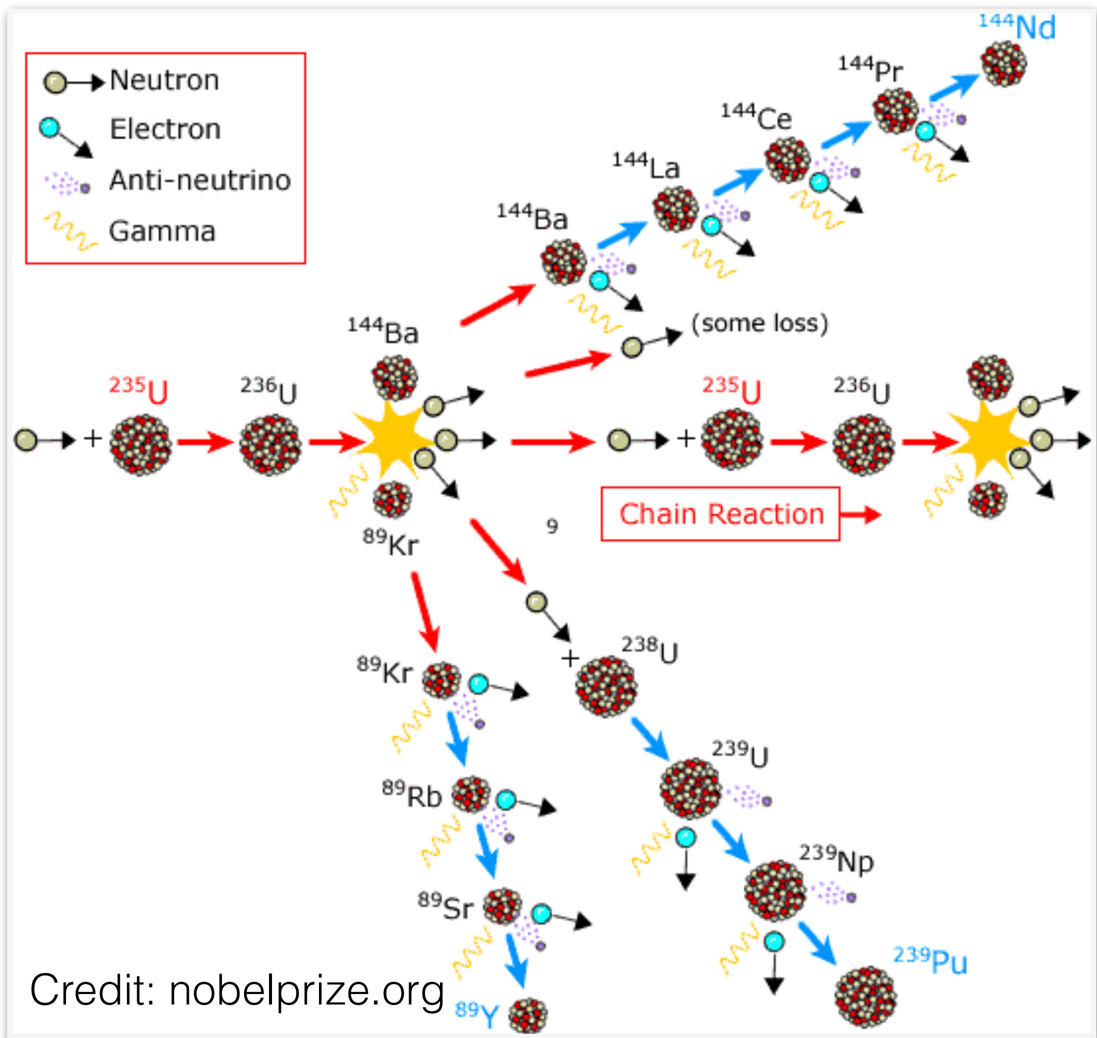
2020+: JUNO, Various short baseline experiments

Keep on ploughing

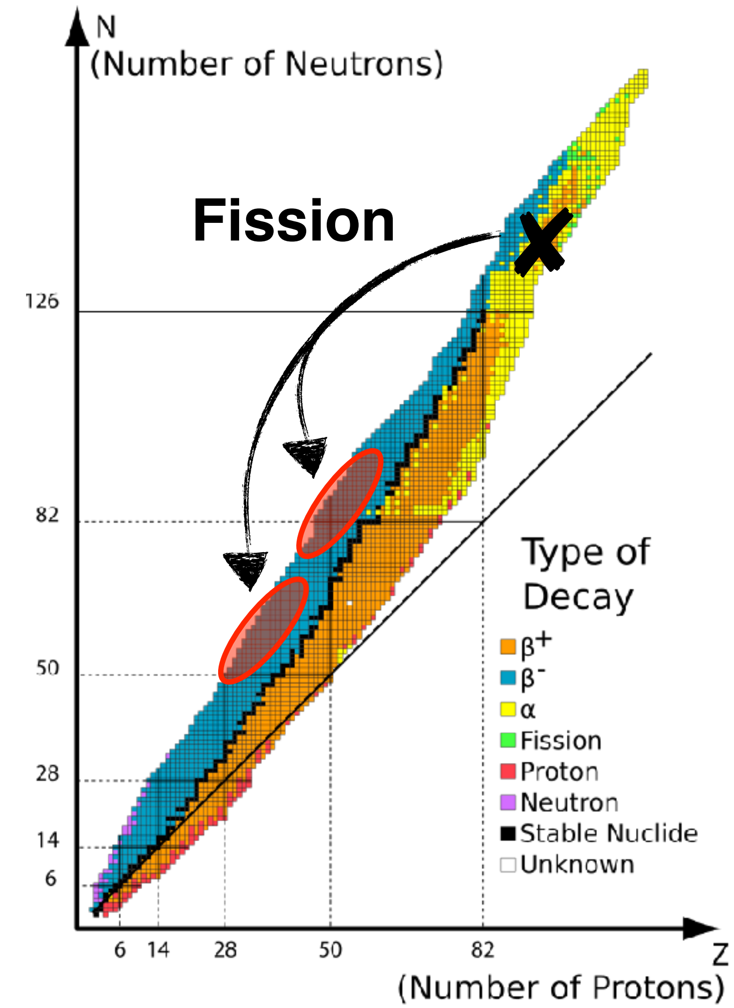
Source of Reactor Antineutrinos

- Commercial nuclear reactors: Fission of primarily 4 isotopes: ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu
- Produce neutron-rich fission daughters

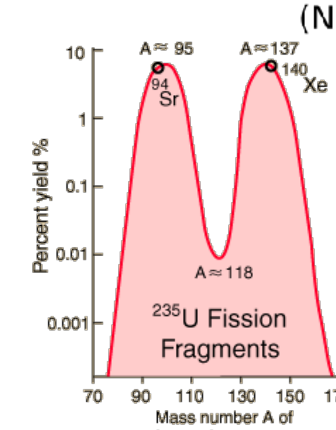




Credit: nobelprize.org



Credit: wikipedia



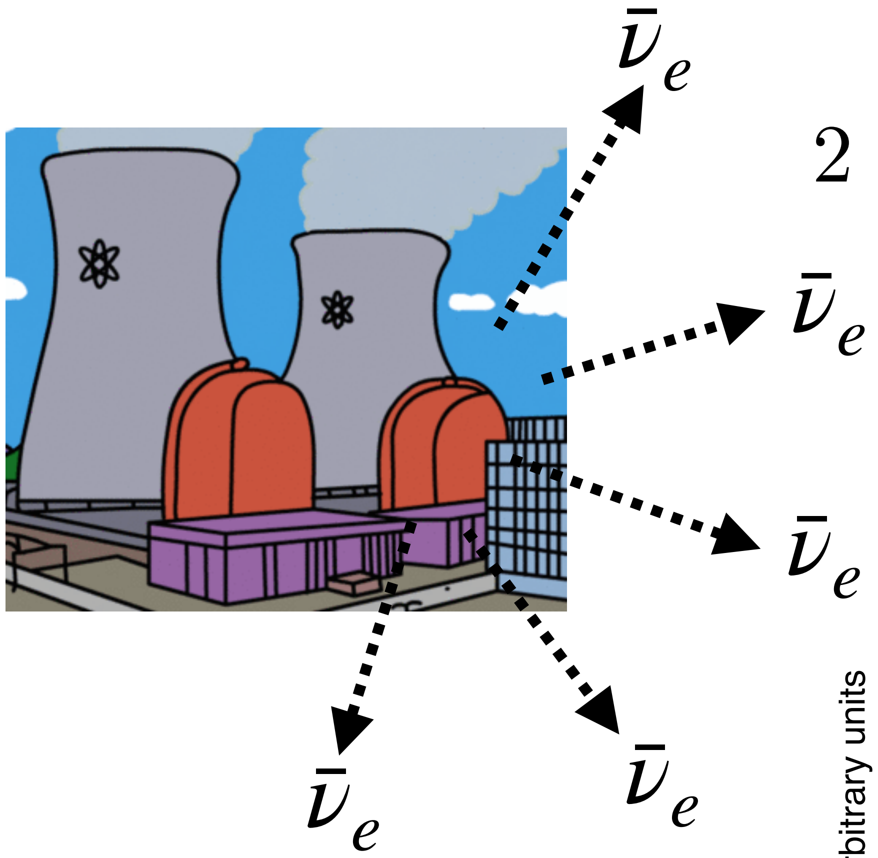
Credit: HyperPhysics

Source of Reactor Antineutrinos

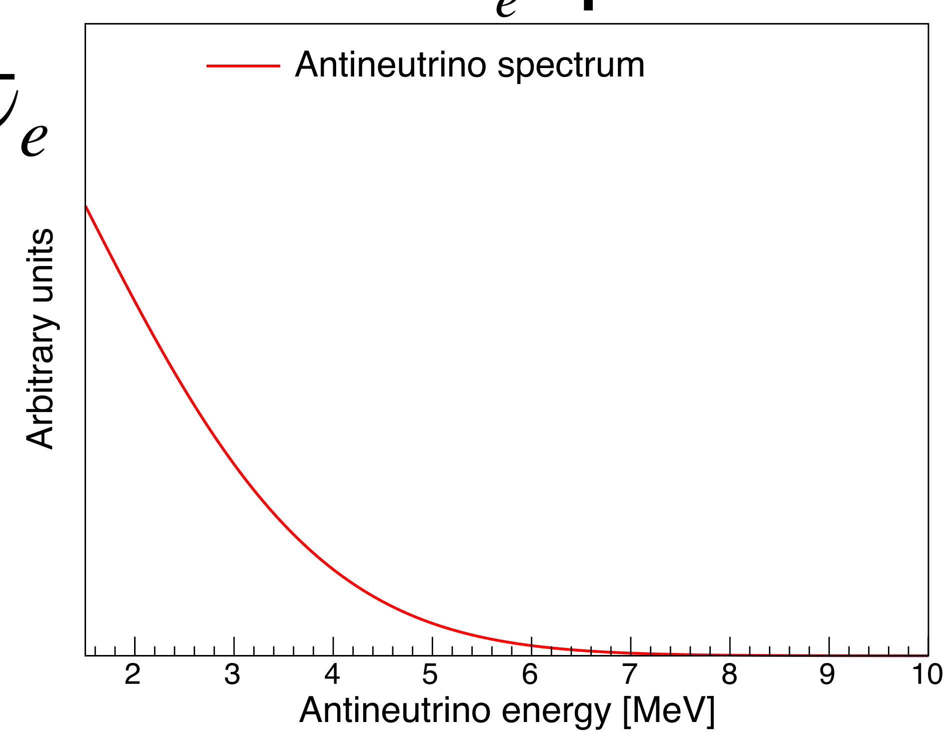
- Neutron-rich fission daughters undergo β decays
- Reactor: a powerful source of pure $\bar{\nu}_e$'s

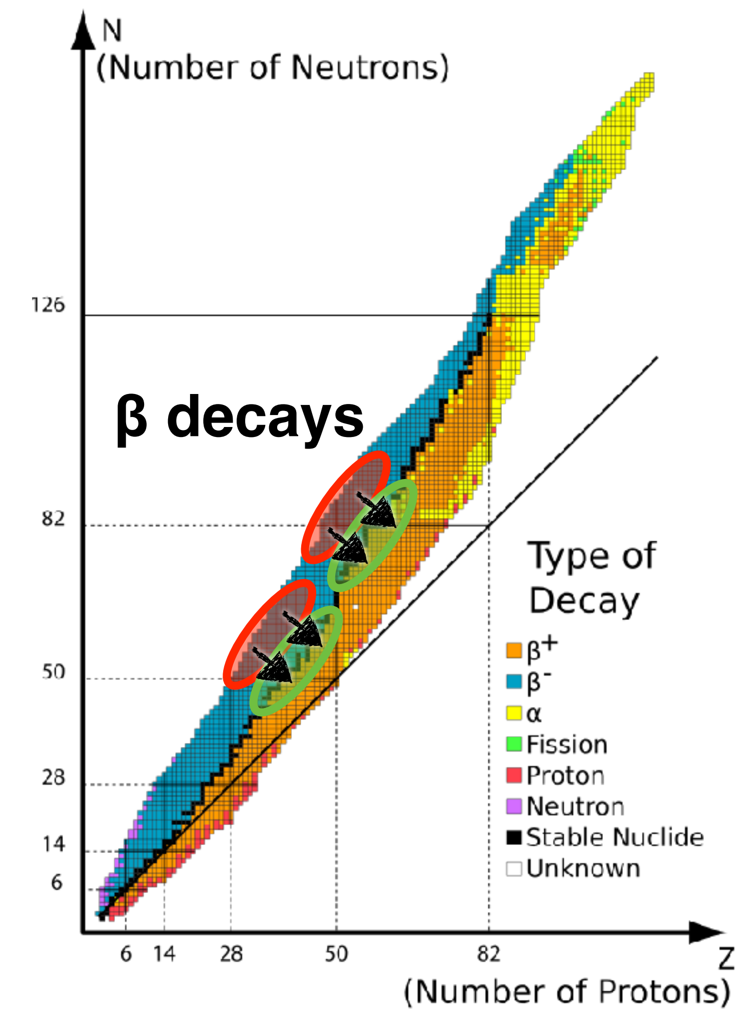
$$\sim 6\ \bar{\nu}_e \text{ per fission}$$

$$2 \times 10^{20}\ \bar{\nu}_e/\text{second}/\text{GW}_{th}$$



Emitted $\bar{\nu}_e$ Spectrum



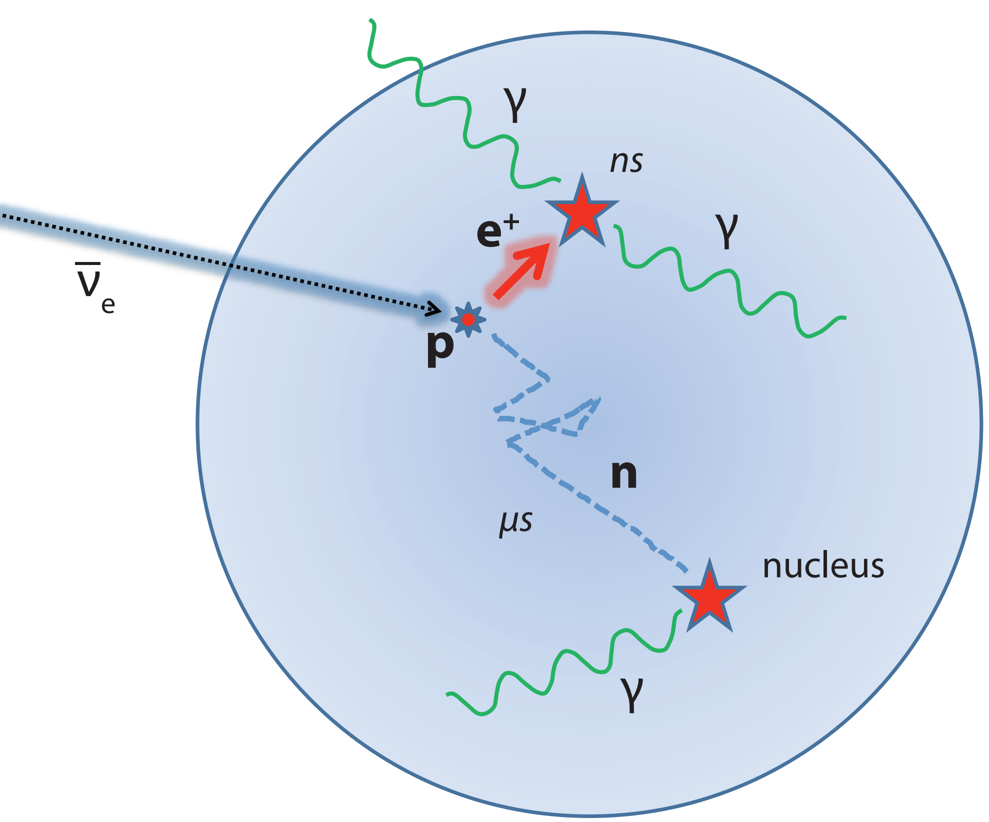


Credit: wikipedia

$$^{A}_{Z}X \rightarrow {}^{A}_{Z+1}X' + e^{-} + \bar{\nu}_e$$

Reactor Antineutrino Detection

- Primary detection method - Inverse beta decay (IBD)
- Powerful background rejection with positron-neutron coincidence
  - Very often, protons (atoms of hydrogen) are naturally present in active detector volume



Coincidence in time

prompt signal — delayed signal

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

$$E_{\bar{\nu}_e} \simeq E_{prompt} + 0.78\ \mathrm{MeV}$$

$$\rightsquigarrow n + H \rightarrow D + \gamma\ (2.22\ \mathrm{MeV})$$

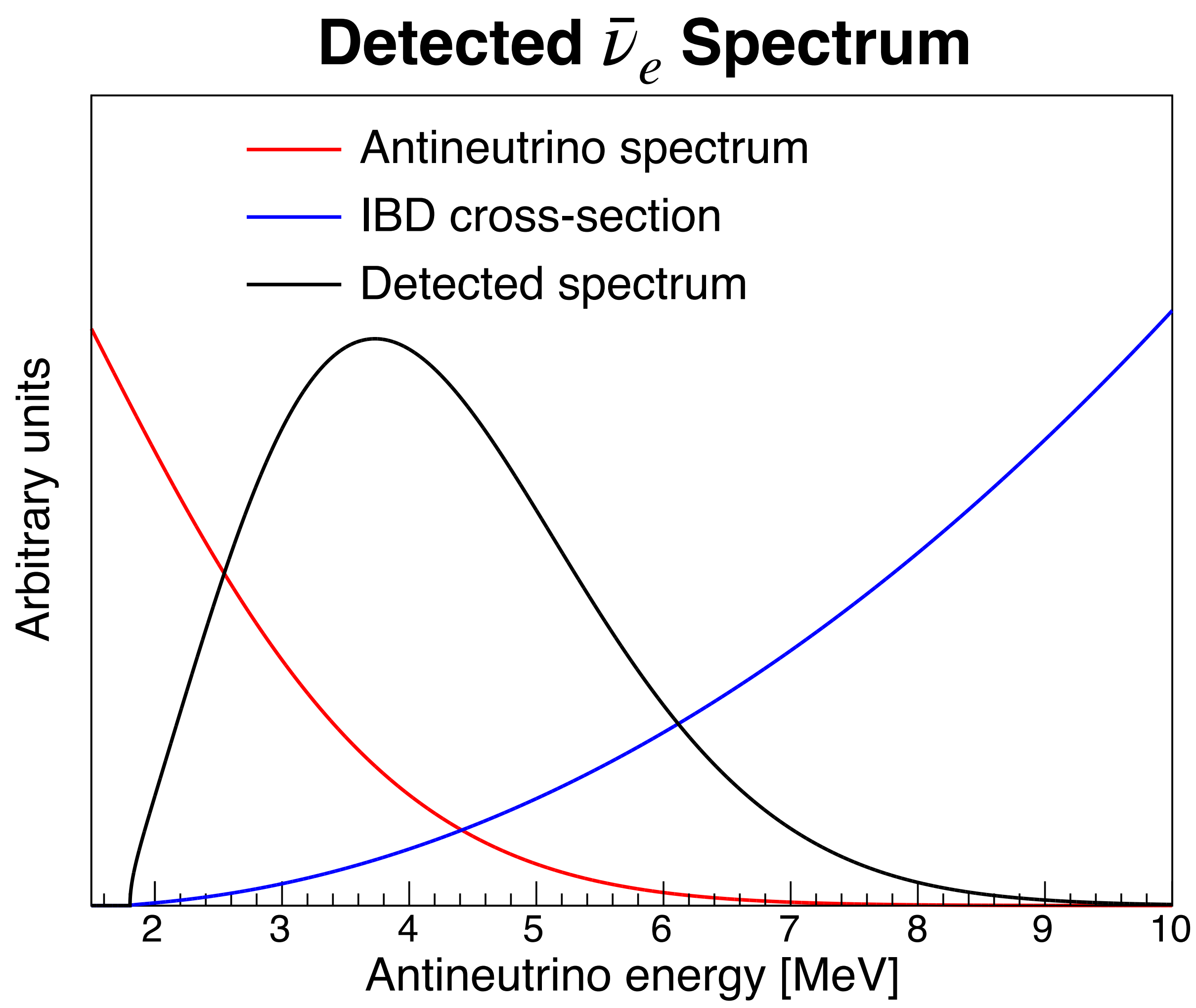
$$\rightsquigarrow n + Gd \rightarrow Gd^* \rightarrow Gd + \gamma\text{'s}\ (8\ \mathrm{MeV})$$

$$\rightsquigarrow n + Cd \rightarrow Cd^* \rightarrow Cd + \gamma\text{'s}\ (9\ \mathrm{MeV})$$

$$\rightsquigarrow n + Li \rightarrow Li \rightarrow \alpha + T\ (4.78/\sim 0.5\ \mathrm{MeV})$$

Reactor Neutrino Detection

- Primary detection method - Inverse beta decay (IBD)
- Powerful background rejection with positron-neutron coincidence
  - Very often, protons (atoms of hydrogen) are naturally present in active detector volume



Neutrino Mixing and Oscillations (3ν's)

Three-neutrino mixing: ***see talk by Iván Esteban***

Atmospheric, accelerator ν — Solar, reactor L~60 km ν

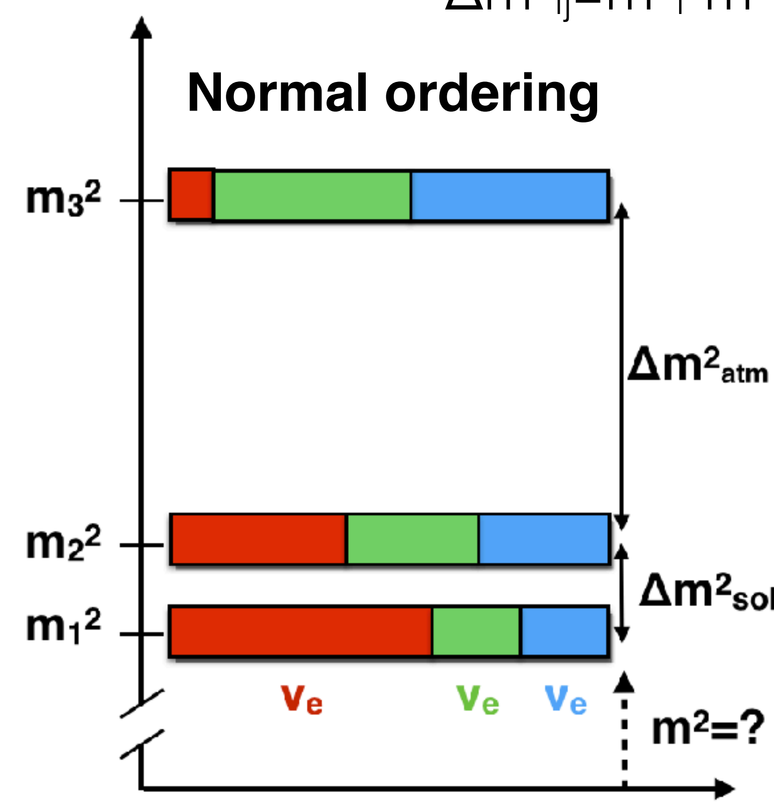
$$\text{Flavor states} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \text{Mass states}$$

Reactor L~2 km, accelerator ν

$c_{ij}=\cos\theta_{ij}$
$s_{ij}=\sin\theta_{ij}$
$\Delta m^2_{ij} \equiv m^2_i - m^2_j$

Oscillation parameters:

Parameter	Value	Open questions
Δm_{21}^2*	7.5×10^{-5} eV²	—
$\lvert\Delta m_{31}^2\rvert \simeq \lvert\Delta m_{32}^2\rvert$*	2.5×10^{-3} eV²	Ordering?* ⇔ $\Delta m_{31}^2 \lesseqgtr 0$
θ_{12}*	33°	—
θ_{23}	45°?	Maximal? ⇔ $\theta_{23} \gtreqless 45°$
θ_{13}*	9°	—
δ_{CP}†	?°	Value?



*Can be measured by reactor neutrino experiments

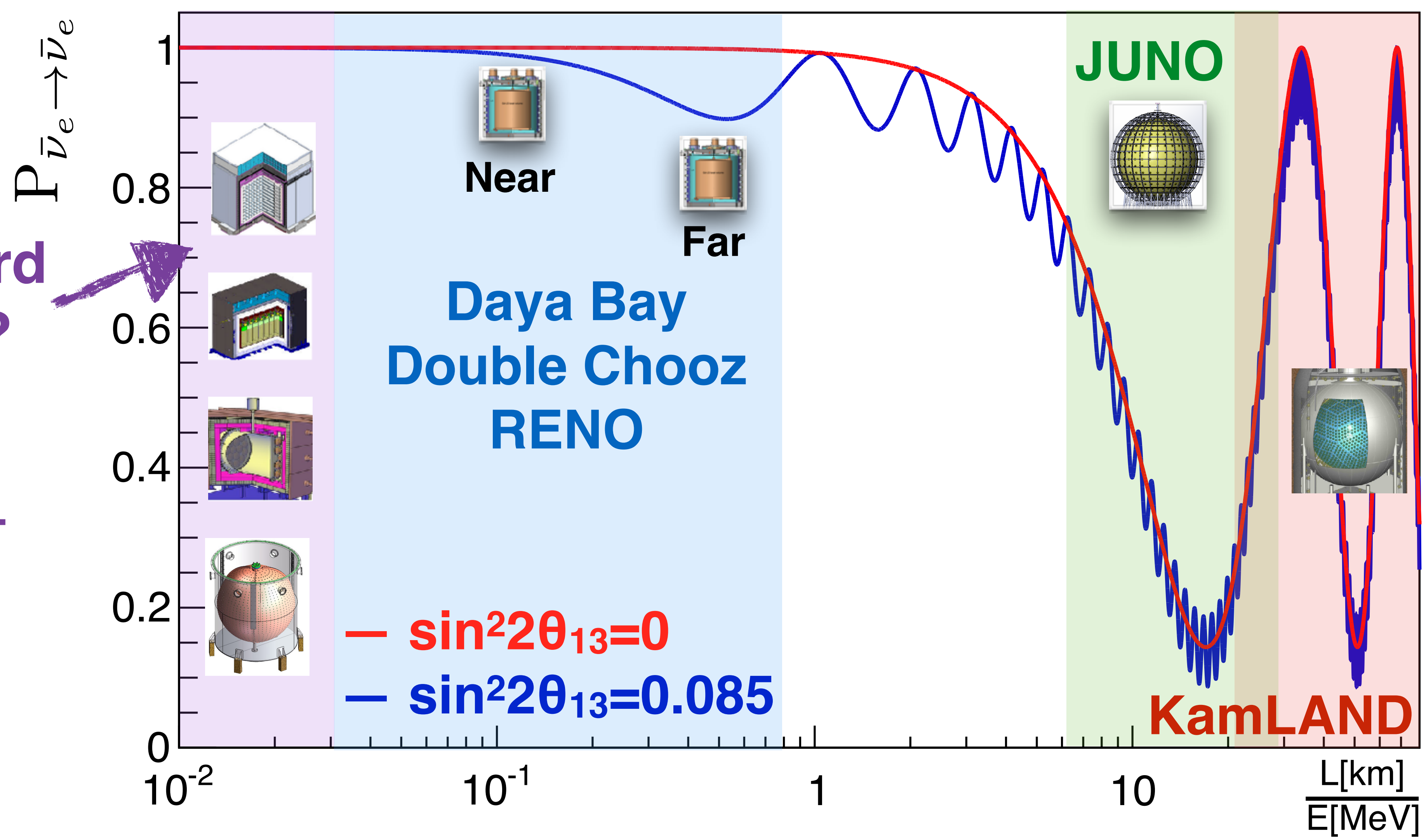
†Highly constrained thanks to precise measurement of θ_{13} in reactor ν experiments

Reactor Neutrino Oscillations

Two modes of oscillations: Directly depends on θ_{12}, θ_{13}, Δm^2_{21}, Δm^2_{31} & Δm^2_{32} (or mass ordering) | Fully Independent on θ_{23} and δ_{CP}

Medium baseline | **Short baseline**

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

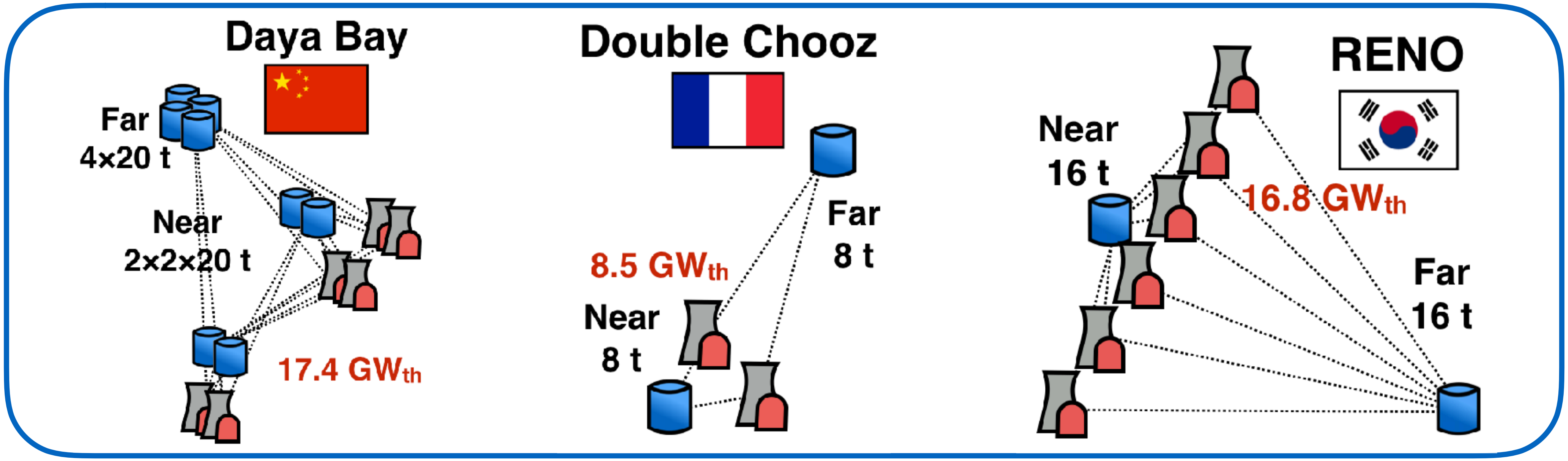


Is there 3rd mode?!?

DANSS
NEOS
PROSPECT
STEREO
SoLid
JUNO-TAO
...

The θ_{13} Mixing Angle

- θ_{13} precisely measured by **Daya Bay**, **Double Chooz** and **RENO** rector neutrino experiments designed primarily for this purpose



Key elements for the success:

- **Ideal distance** of 1-2 km from reactors (maximal θ_{13}-dominated osc. effect)
- Use **near-far relative measurement** to mitigate systematic uncertainties
- **Powerful reactor complexes** for huge statistics (millions of $\bar{\nu}_e$'s)
- **Overburden** to reduce cosmic-ray muon flux (source of background)

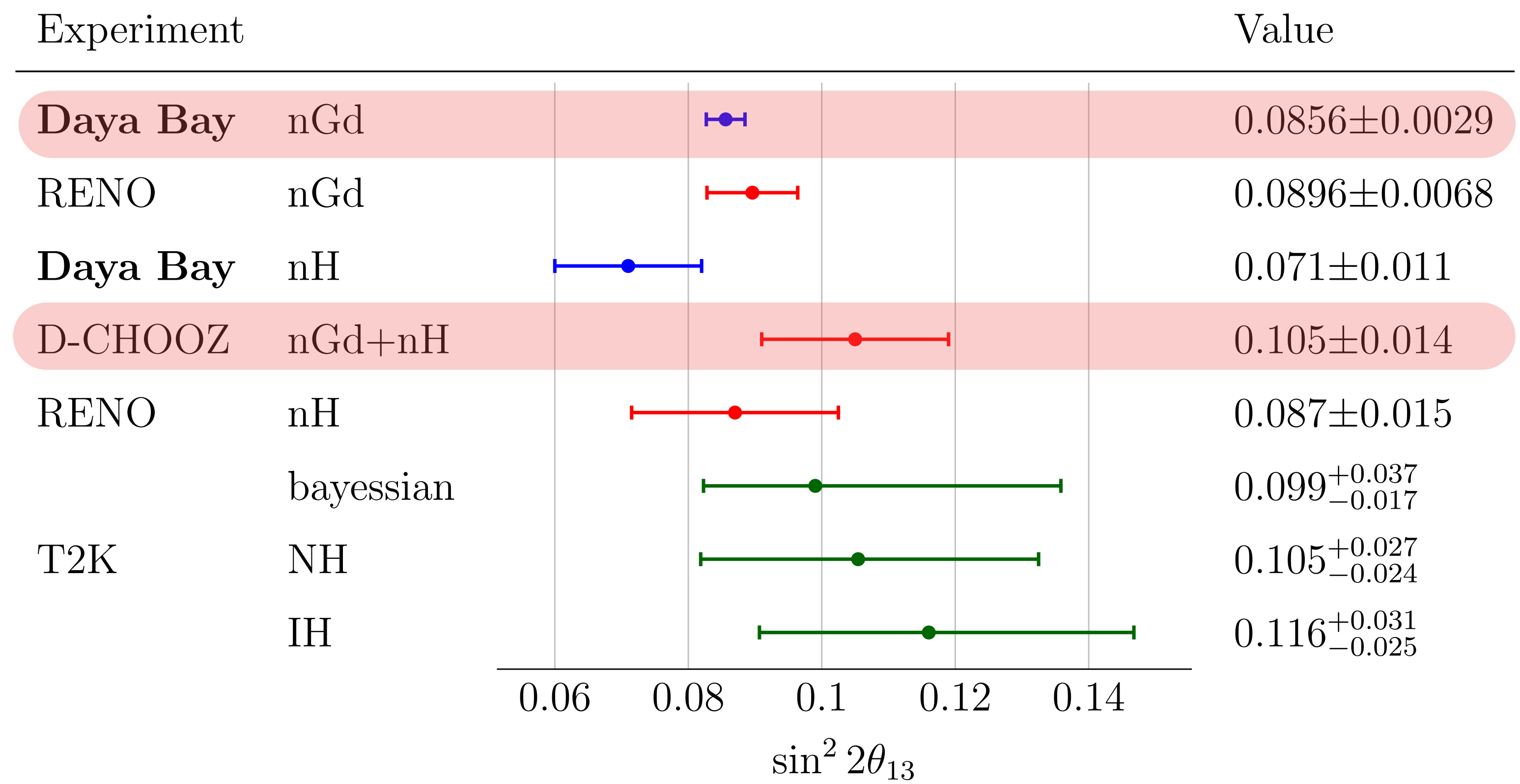
Value of θ_{13} for Foreseeable Future

- θ_{13} - the most precisely known angle in the mixing matrix

Measurements of $\sin^2 2\theta_{13}$:

Daya Bay **precision 3.4%**
➔~3% for the final result

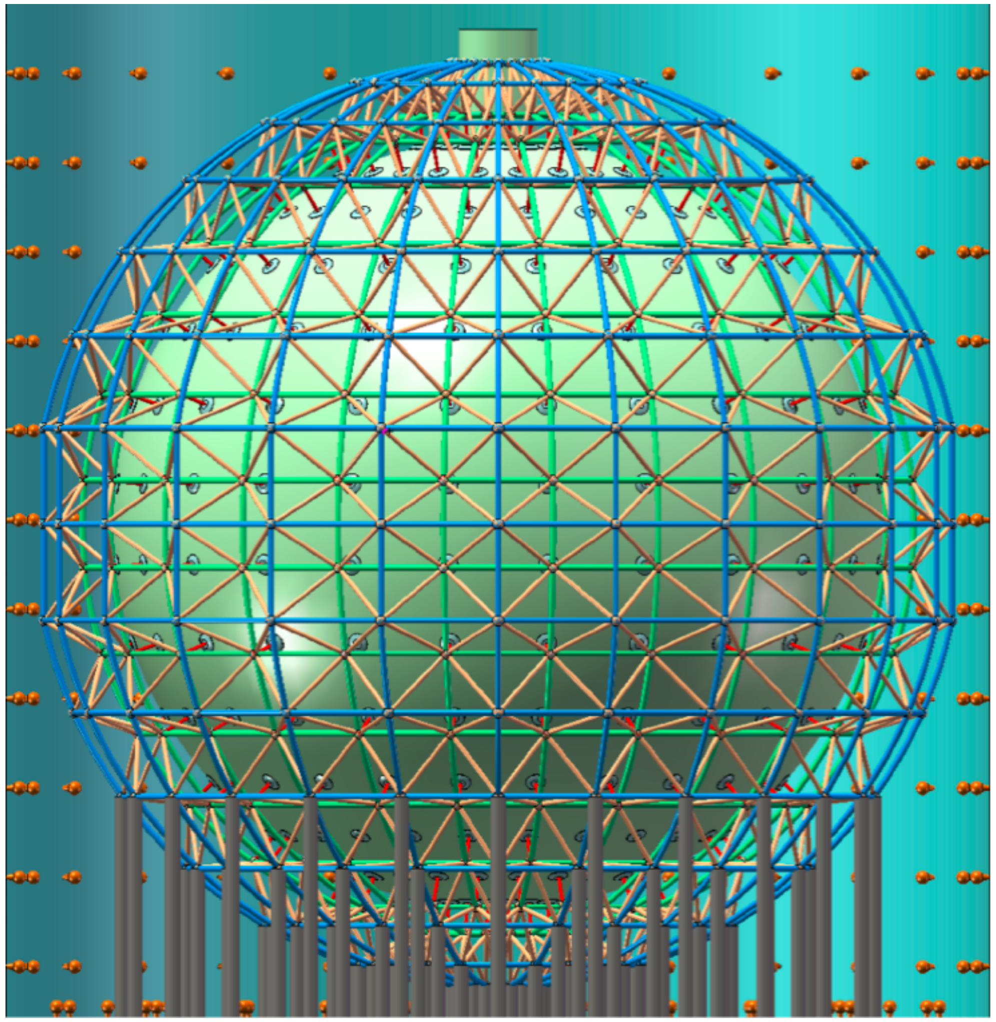
~1σ tension between Daya Bay and Double Chooz



- Double Chooz stopped data taking in Dec 2017 (final result soon)
- Daya Bay will pull the plug in Dec 2020 and RENO might follow
- Final result of Daya Bay will be the **most precise θ_{13} measurement in foreseeable future** - no successor in the pipeline
- Precision in θ_{13} significantly helps constrain δ_{CP} by accelerator neutrino experiments (T2K, NOvA)

JUNO Overview

- **J**iangmen **U**nderground **N**eutrino **O**bservatory (**JUNO**)
- 20 kt liquid scintillator detector
- Superb energy resolution of 3%√E(MeV)
- 700 m overburden
- Use reactor neutrino oscillations
  - To determine neutrino mass ordering at >3σ
  - Measure θ_{12}, Δm^2_{21}, Δm^2_{31} with <0.7% precision
- A lot more… (Multipurpose experiment)
- Ready for data taking in 2022



Experiment	Daya Bay	Borexino	KamLAND	JUNO
LS Mass (t)	8×20	~300	~1,000	20,000
Collected PE/MeV	~160	~500	~250	~1,200
Energy Res. @ 1 MeV	~8%	~5%	~6%	~3%

Largest in the world!

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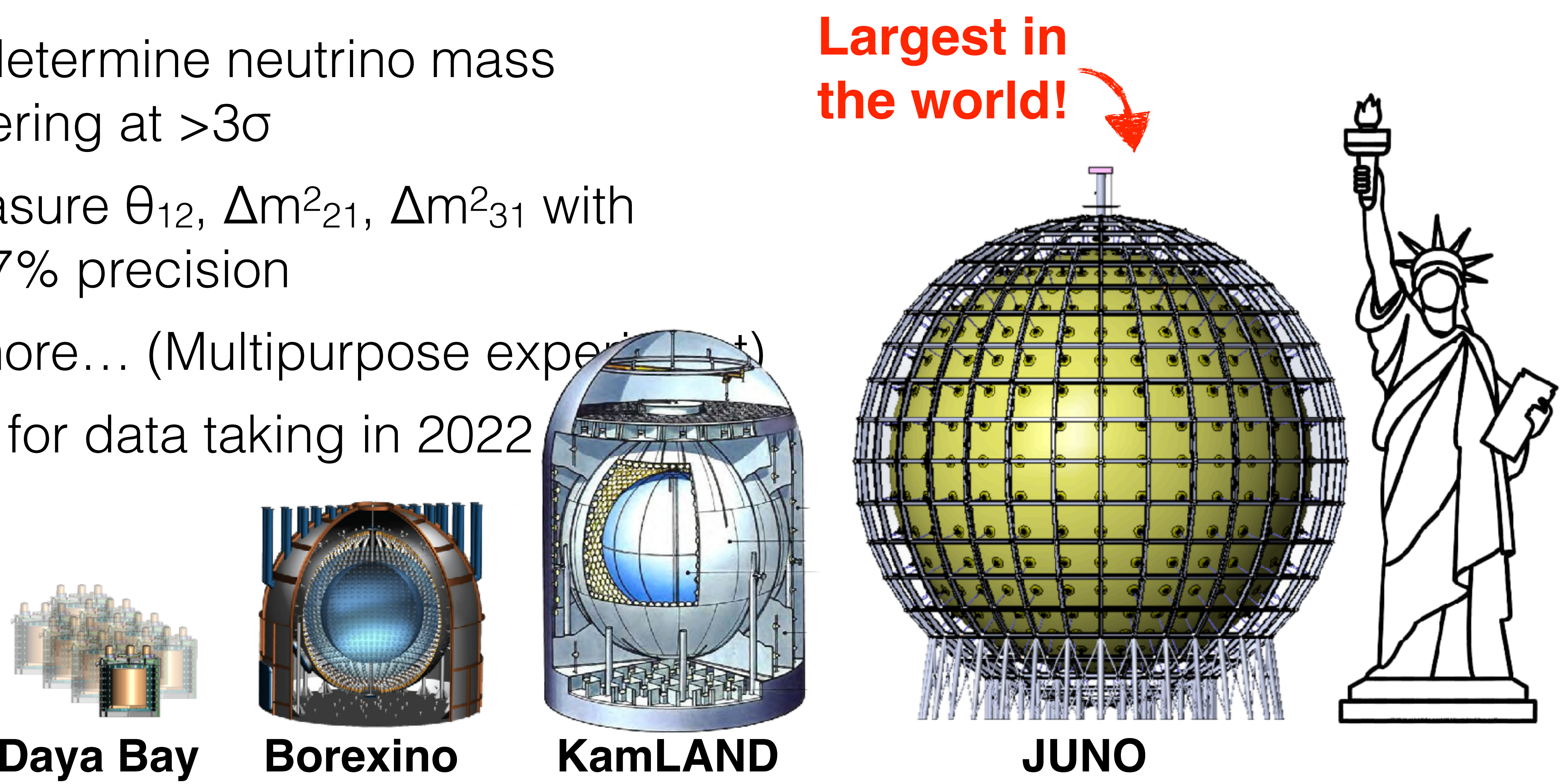
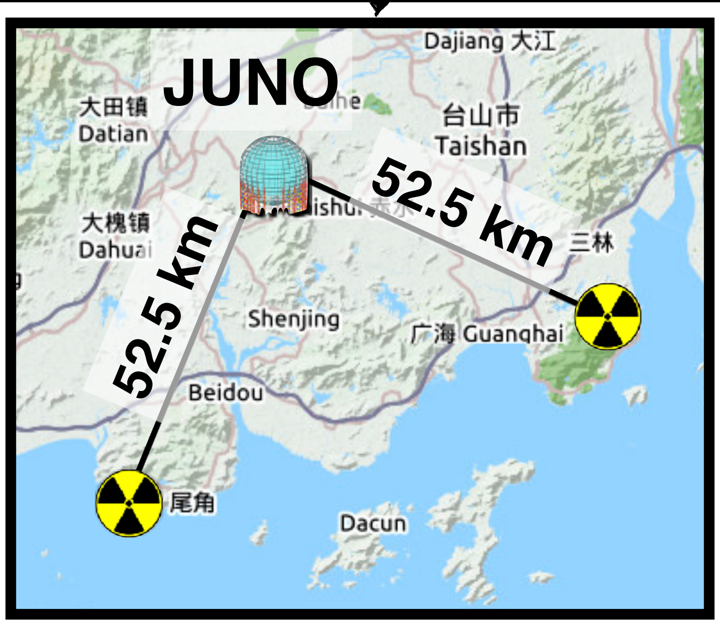
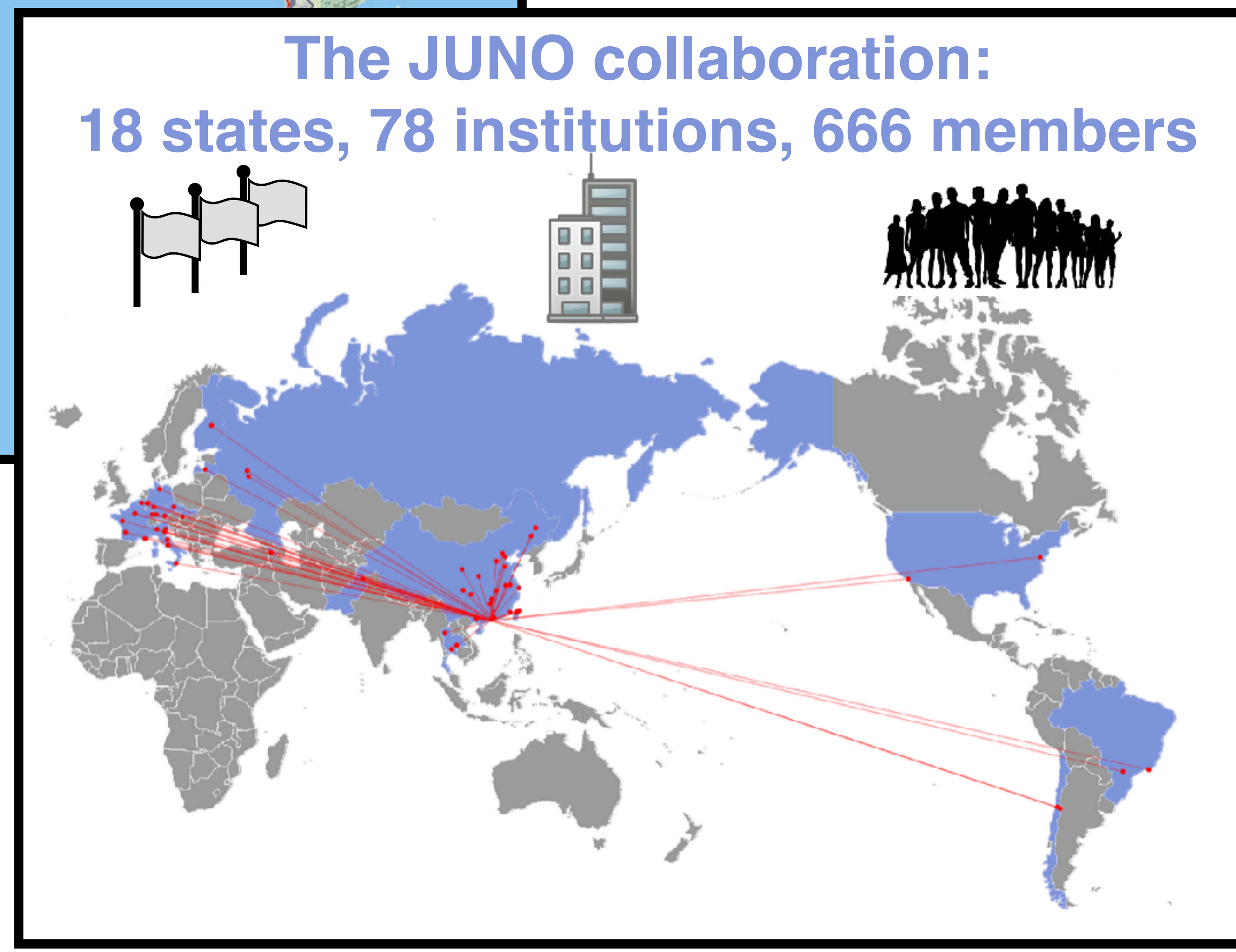
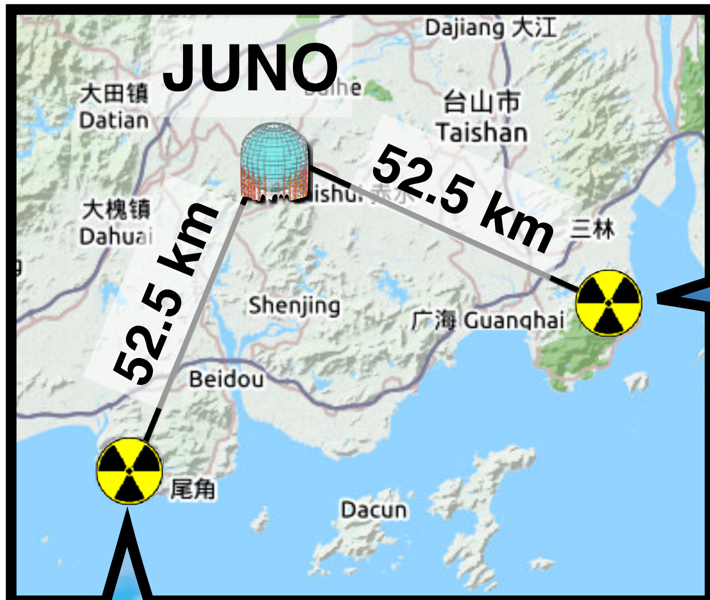


JUNO Location & Collaboration





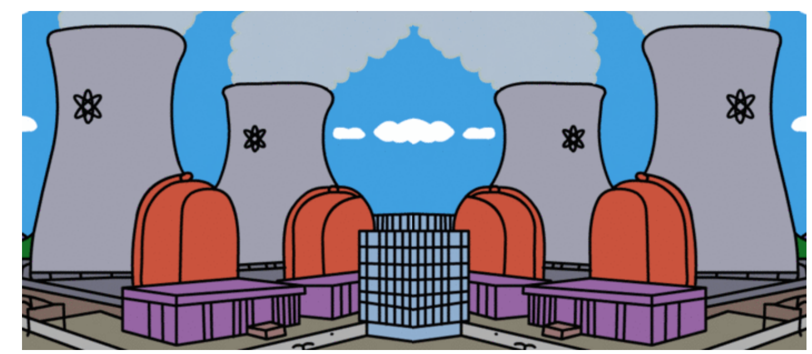
Reactor Neutrino Sources



Taishan nuclear power plant

Yangjiang nuclear power plant

Two other Taishan cores come later



26.6 GW_{th} by 2022:

Cores	YJ-C1	YJ-C2	YJ-C3	YJ-C4	YJ-C5	YJ-C6
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9
Baseline(km)	52.75	52.84	52.42	52.51	52.12	52.21

Cores	TS-C1	TS-C2	TS-C3	TS-C4
Power (GW)	4.6	4.6	4.6	4.6
Baseline(km)	52.76	52.63	52.32	52.20

The JUNO Detector

Design similar to previous LS experiments - JUNO larger and more precise

Top muon tracker
Plastic scintillator panels

Ultra-pure water pool
Water Cherenkov detector

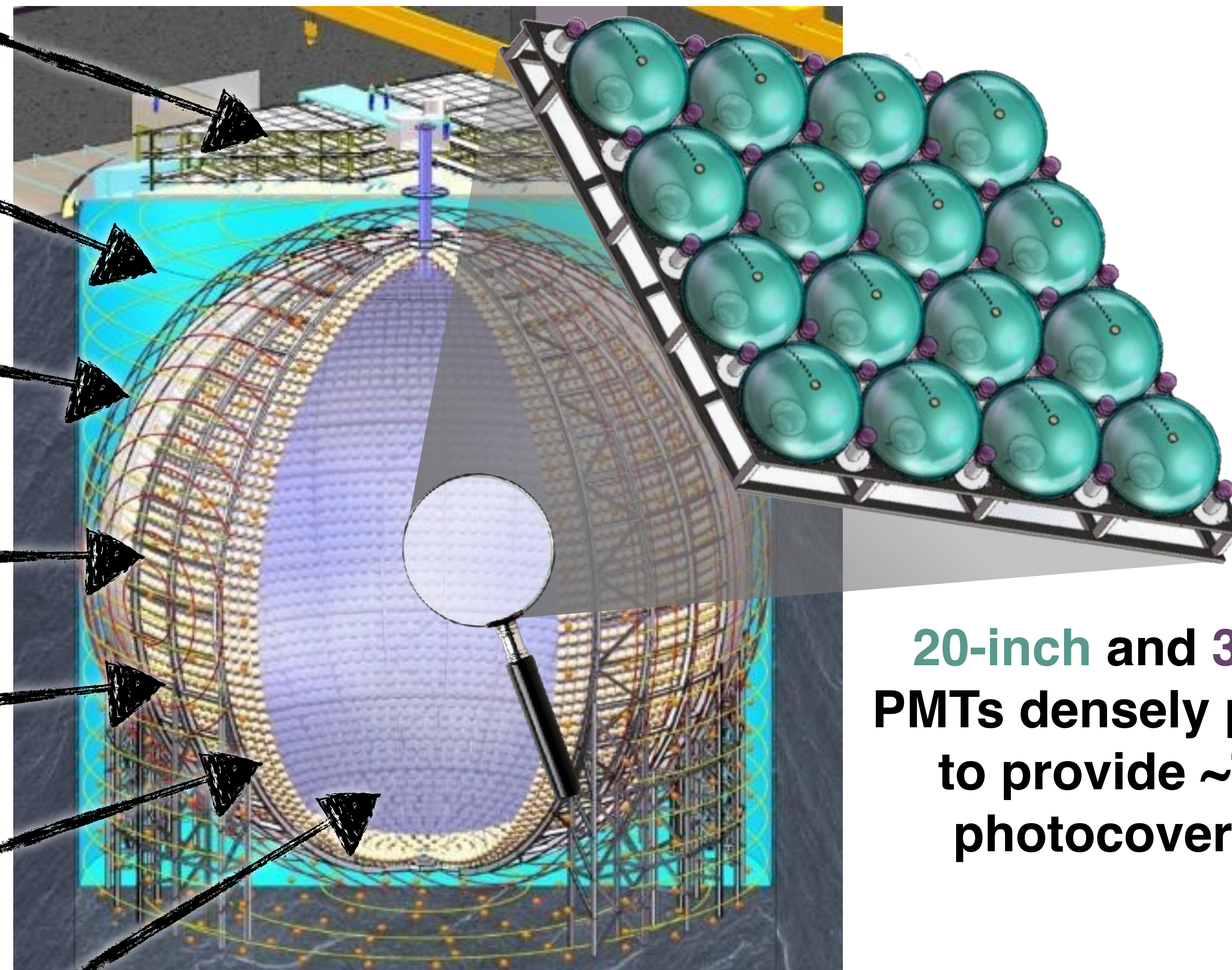
Stainless-steel support
With coils to compensate
Earth magnetic field

18,000 20-inch PMTs
26,000 3-inch PMTs

~1.5 m water buffer

Acrylic sphere
⌀ 35.4 m

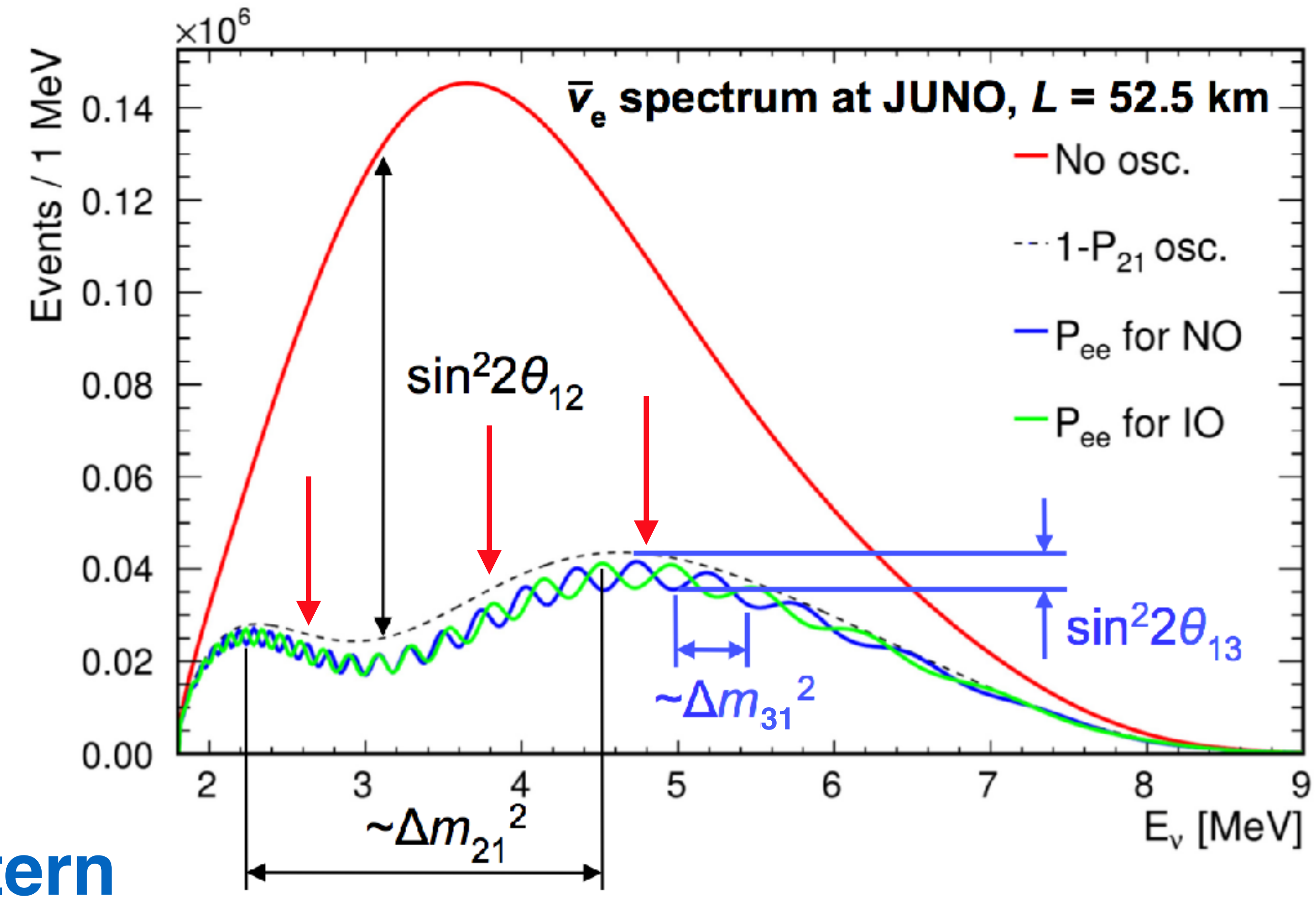
Liquid scintillator
20 kt LAB-based



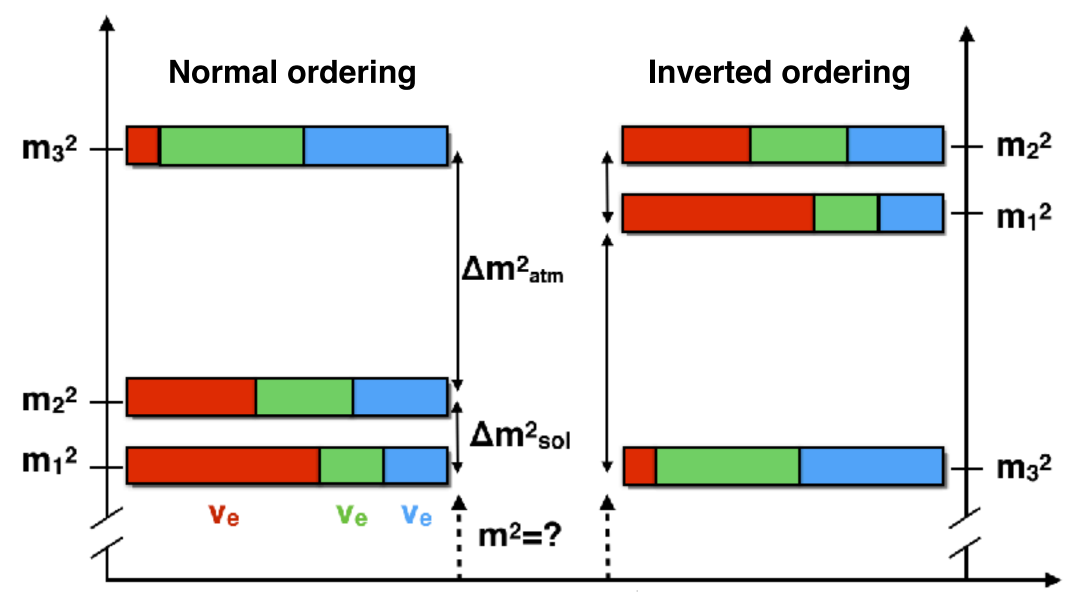
20-inch and 3-inch PMTs densely packed to provide ~78% photocoverage

Neutrino Mass Ordering Determination

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



- Mass ordering determined by exploiting the **fine oscillation pattern** in reactor neutrino spectrum
- Mass ordering measurement independent on δ_{CP} and θ_{23}
- JUNO first experiment to observe solar and atmospheric neutrino oscillation modes simultaneously!



Normal $m_3 > m_2$ (m_1)

Inverted $m_3 < m_1$ (m_2)

Key Aspects of JUNO Success

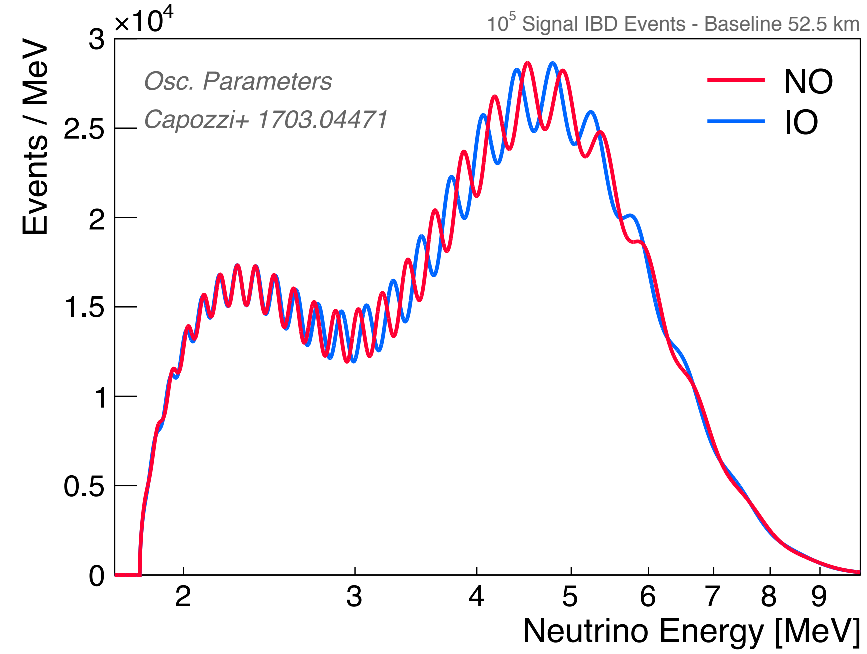
- **Large statistics:** 20 kt × 26.6 GW_{th} × 8 y >100,000 detected $\bar{\nu}_e$'s
- **Optimized baselines:**
  - Ideal baseline ~52.5 km
  - Equal baselines from each reactor
- **Superb energy resolution**:
  - 3% at 1 MeV

$$\frac{\sigma_E}{E} = \sqrt{\frac{\sigma^2_{stoch}}{E} + \sigma^2_{non-stoch}}$$

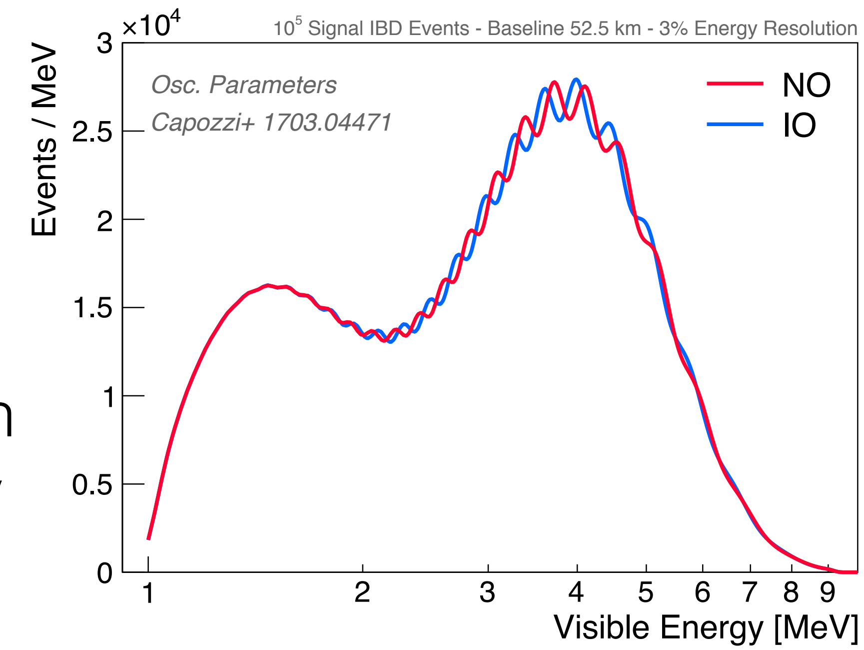
Large photocoverage mainly due to 20-inch PMTs ~78% ⇔ >1200 PE/MeV

Comprehensive calibration system & dual calorimetry

Ideal resolution



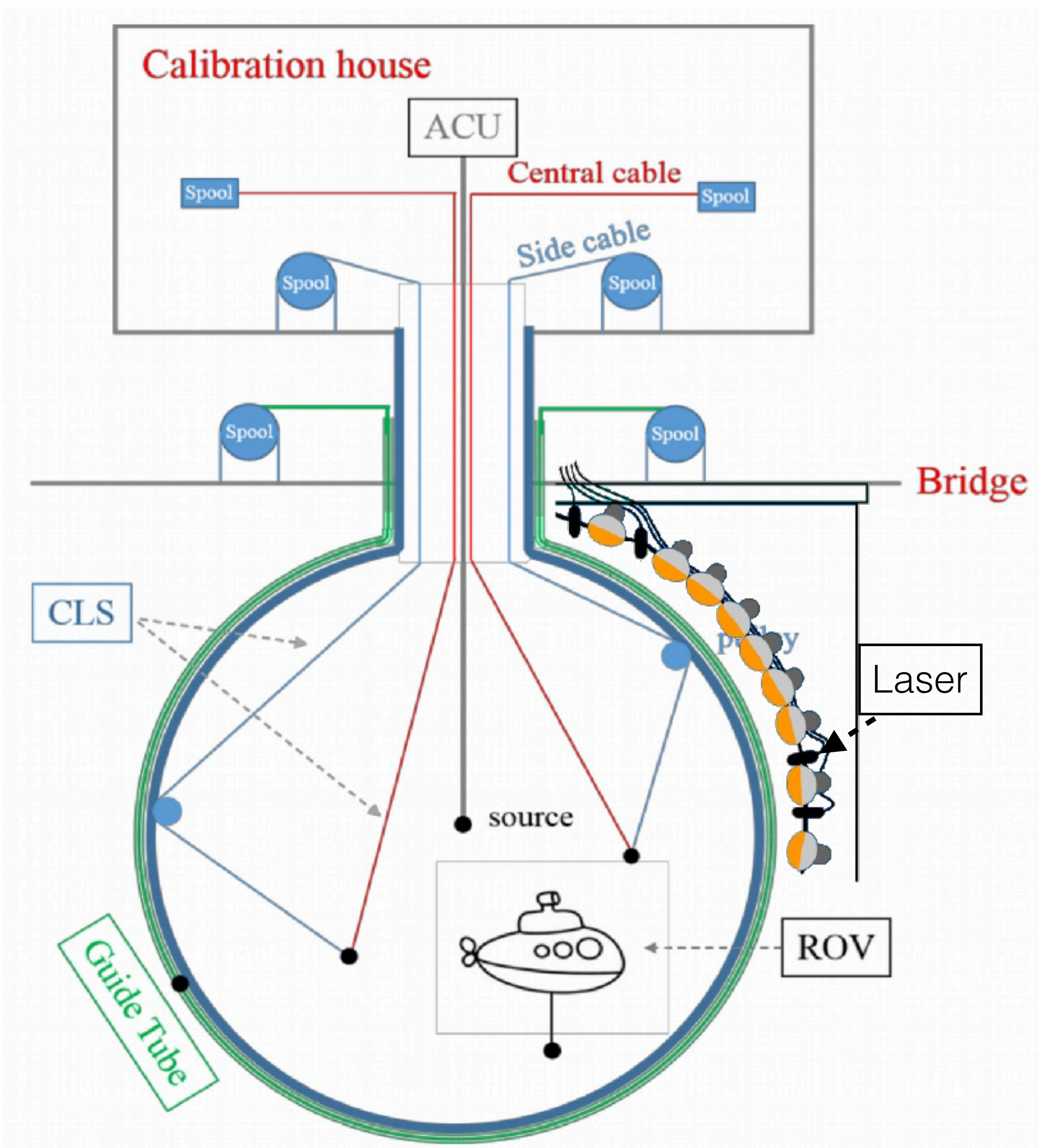
Target resolution

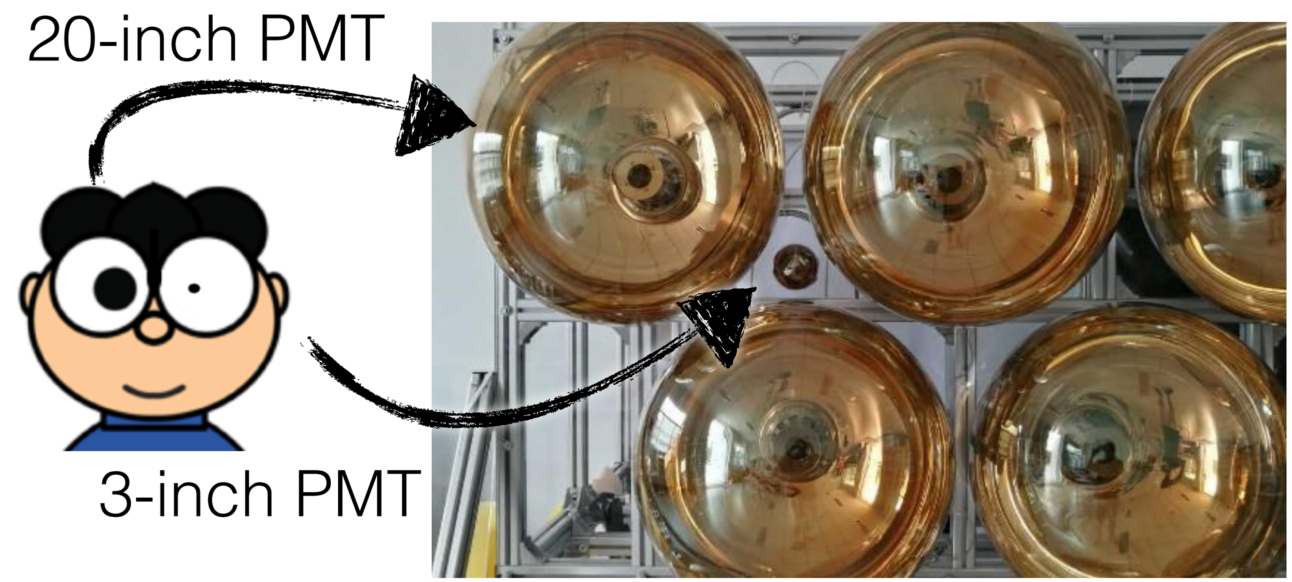


Calibrating the Energy Response

Calibration systems:

- Automated calibration unit (ACU) - Radioactive sources along z axis (1D)
- Cable loop system (CLS) - Radioactive sources in plane (2D)
- Guide Tube - Radioactive sources at edge (2D)
- Remotely operate vehicle (ROV) - Radioactive sources everywhere (3D)
- Laser - Gammas shot into the detector





3-inch PMT system for dual calorimetry:

- 20-inch PMTs deliver photocoverage but has non-linear response (already @ 1-10 MeV)
- Looking at the same events with different eyes
- Photon-counting - linear response @ 1-10 MeV
- Other benefits

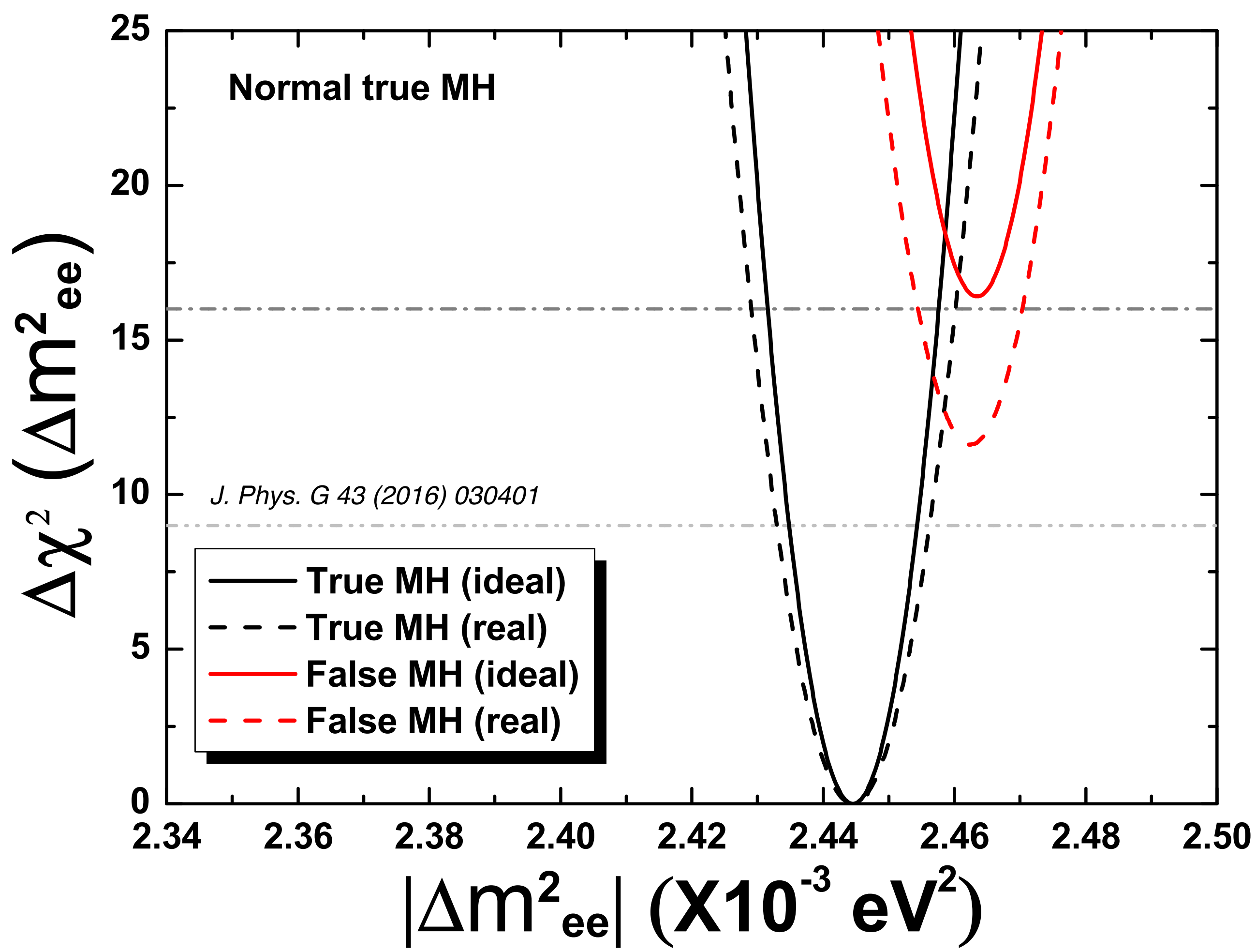
JUNO Prospects with Reactor Neutrinos

- Mass ordering >3σ in <8 years of JUNO data taking
- Combination with other experiments can improve >4σ
- Updated study based on full detector simulation in preparation
- JUNO significantly improve $\sin^2 2\theta_{12}$, Δm^2_{21}, Δm^2_{31} oscillation parameters
- $\sin^2 2\theta_{12}$, Δm^2_{21} <1% with 1 year of data

Parameter	Current precision (1σ)	Improvement by JUNO
$\sin^2 2\theta_{12}$	4.5%	<0.7%
Δm^2_{21}	2.4%	<0.6%
Δm^2_{31}	2.6% sign unknown	<0.5% sign determination

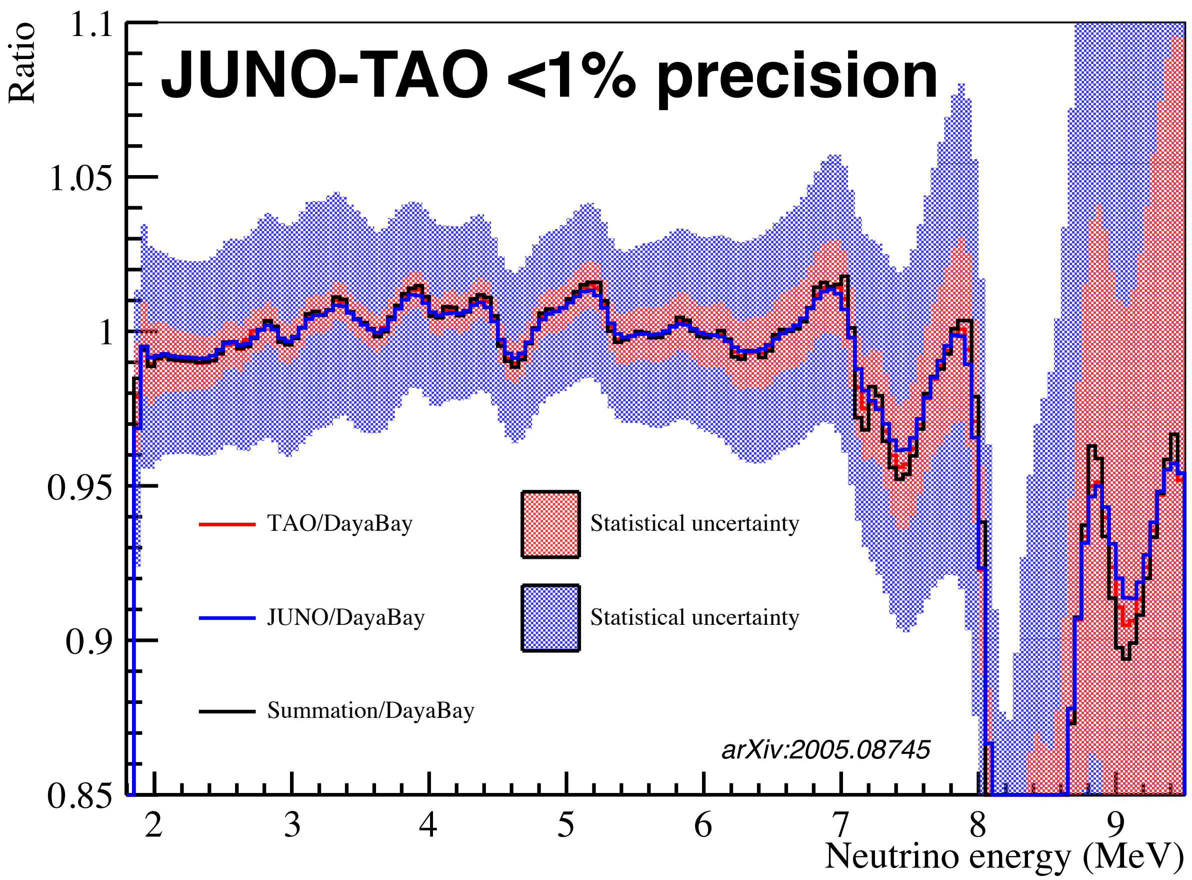
Mass Ordering Sensitivity

Variable	Value	$\Delta\chi^2$
Ideal	L=52.5 km, etc.	16
Core Distances	Real	-3
DYB and HZ Cores	On	-1.7
ν Spectrum Shape	1% uncer.	-1
Background	-	-0.7



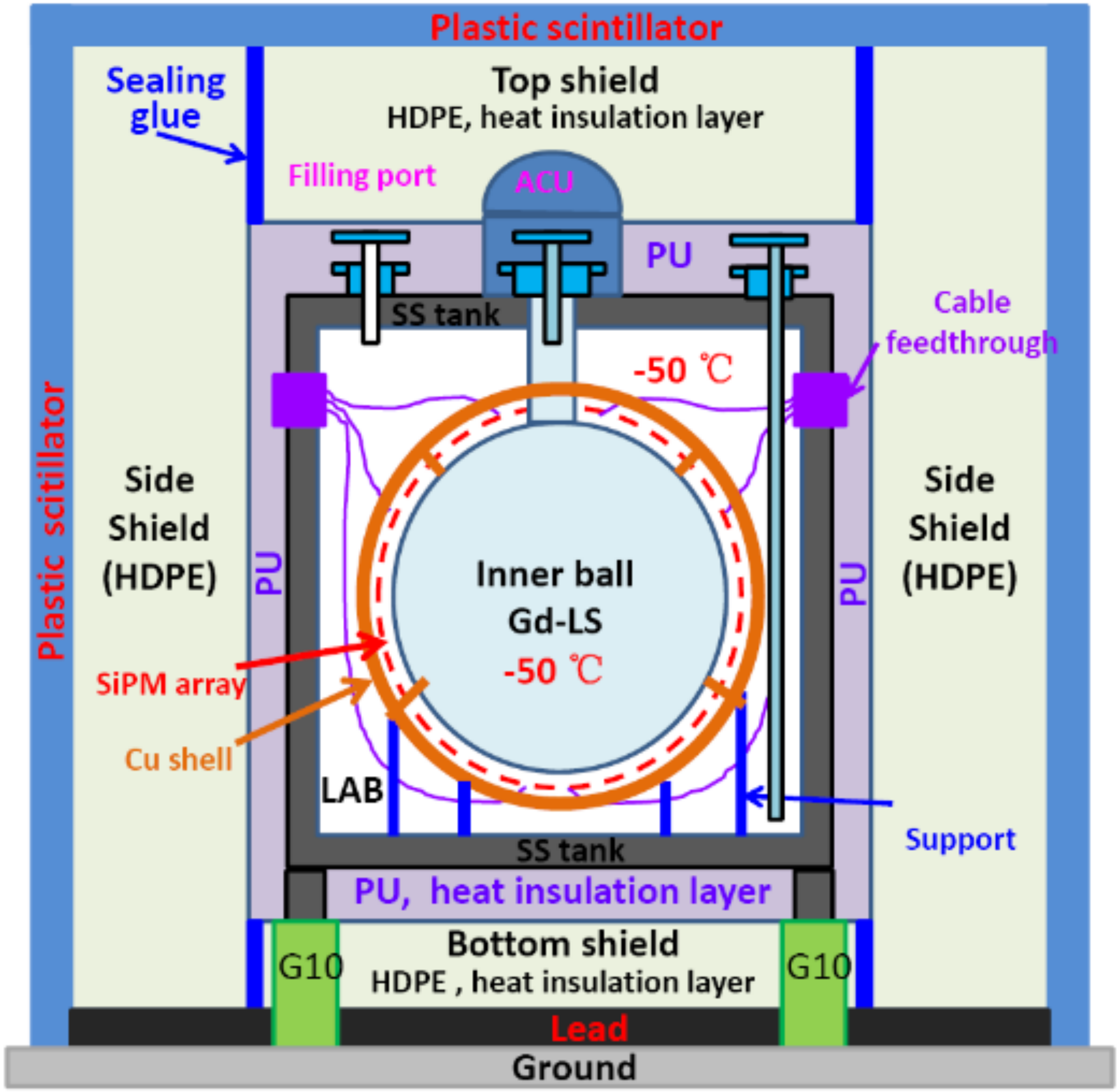
JUNO-TAO Reference Detector

- Ideally, it would be good to know reactor $\bar{\nu}_e$ spectrum with similar resolution as JUNO, i.e. 3%/√E(MeV)
    - Current best from Daya Bay with resolution 8.5%/√E(MeV)
- Neutrino mass ordering determination robust against micro-structures in the spectrum
- **JUNO-TAO, a reference detector** at ~30 m from a Taishan core, with a unprecedented resolution 1.5%/√E(MeV) will:
    - Deliver a reference spectrum for JUNO and other experiments
    - Provide benchmark for nuclear databases
    - Provide isotopic yields and spectra
    - Search for sterile neutrinos
    - Study the possibility of nuclear reactor monitoring



Introducing JUNO-TAO

- **Reference detector for JUNO ➔** Precise measurement of $\bar{\nu}_e$ spectrum
- 30-35 m from one of the Taishan Nuclear Power Plant cores - 4.6 GW_{th}
  10 m underground
- Gd-doped liquid scintillator
  R=0.9 m ⇔ 2.6 t
- Fiducial volume R_{FV}=0.65 m ⇔ 1.0 t
- ~2000 $\bar{\nu}_e$'s per day
- 4500 PE yield ⇔ Resolution
  1.5%/√E(MeV)
- Light detection by ~10 m² of SiPMs (~95% coverage)
  - >50% photon detection efficiency
  - At -50˚C to reduce dark noise
- Data taking in 2022 (along with JUNO)



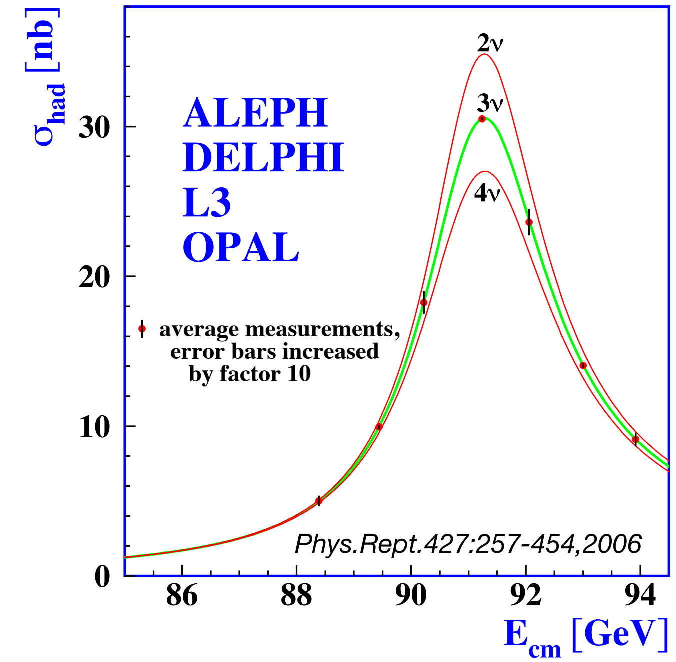
Short Baseline Reactor Experiments

- Several ton-scale very short baseline reactor neutrino experiments (~5-15 m)
- Placed at both commercial and research reactors
- Employ various detector designs and technologies!
- **Main goals:**
  - **Search for light sterile neutrinos** with Δm^2_{new}~0.1-10 eV^2 (ν_s not discussed in this talk - *see talk by Dr. Stefano Gariazzo*)
  - **Measurement of reactor $\bar{\nu}_e$** yields and spectra for individual fission isotopes (mainly ^{235}U and ^{239}Pu)
  - Other goals such as demonstration of **reactor monitoring** capabilities with foreseen use for e.g. nuclear non-proliferation (not discussed in this talk)

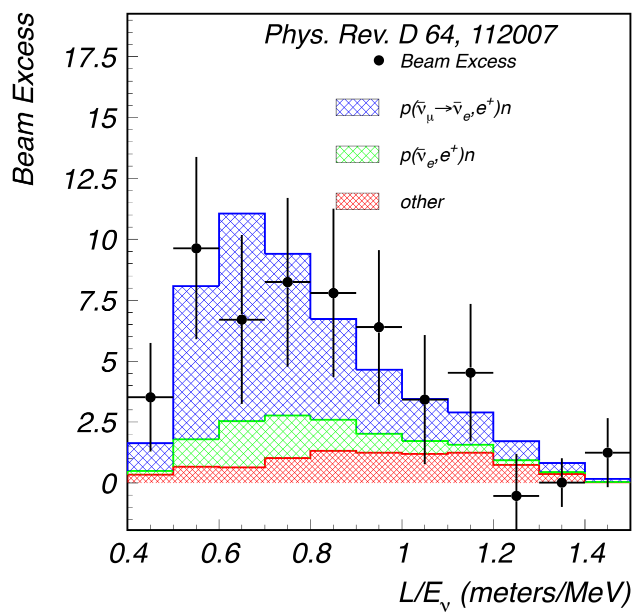
Why There Might be Light Sterile Neutrinos

- Observed **experimental anomalies** which could be explained by light sterile neutrino(s) with $m_\nu \sim 1\ eV^2$
  - LSND and MiniBooNE excesses
  - Gallium anomaly
  - Reactor antineutrino anomaly (RAA)
- Recent developments weaken anomalies

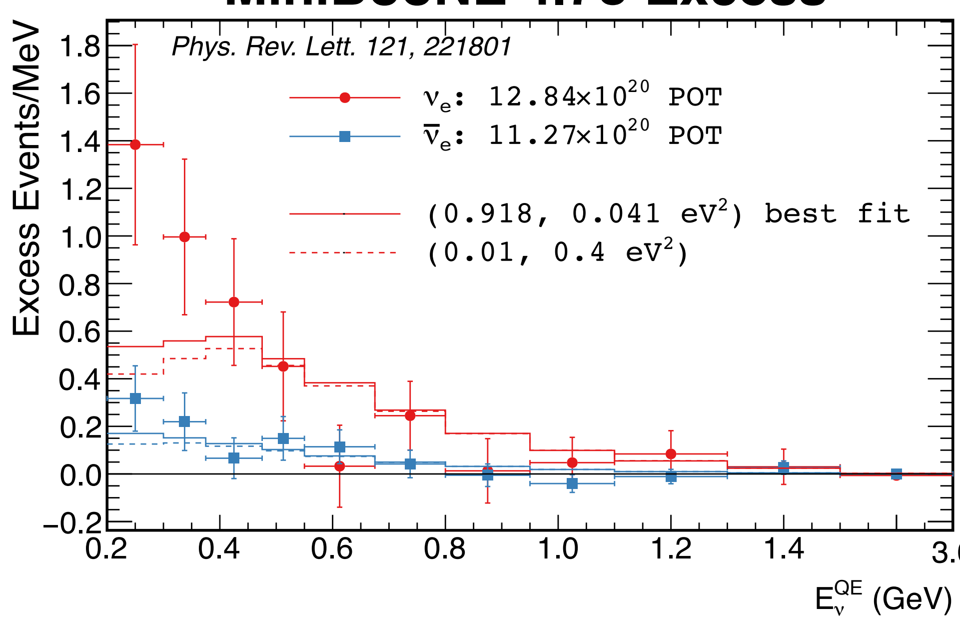
Three Light Active ν's



LSND 3.8σ Excess

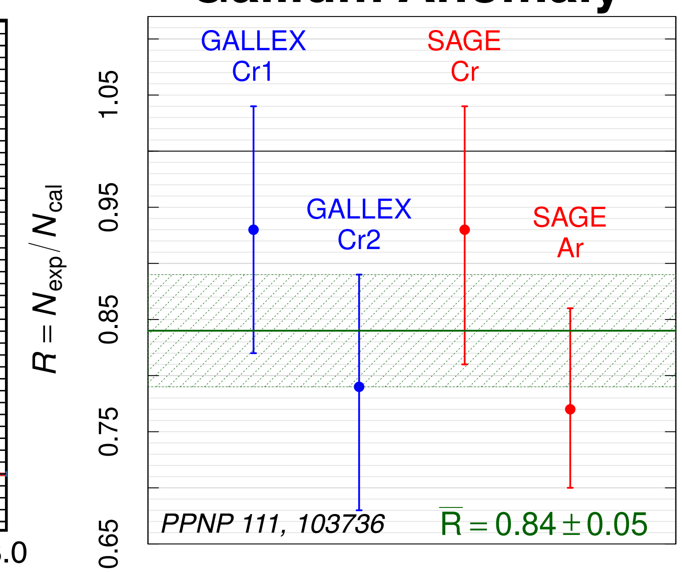


MiniBooNE 4.7σ Excess



ν_e excess not fully compatible with one ν_s

Gallium Anomaly



3.0σ → 2.3σ with recent cross-section

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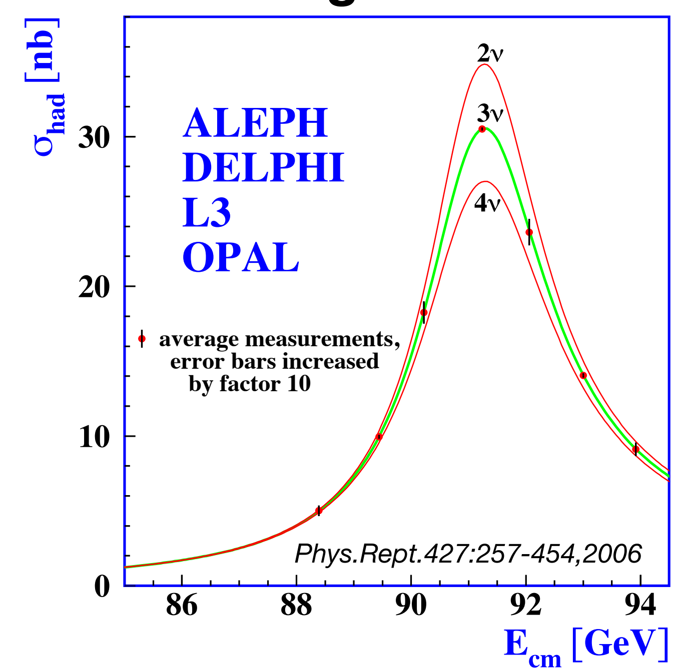
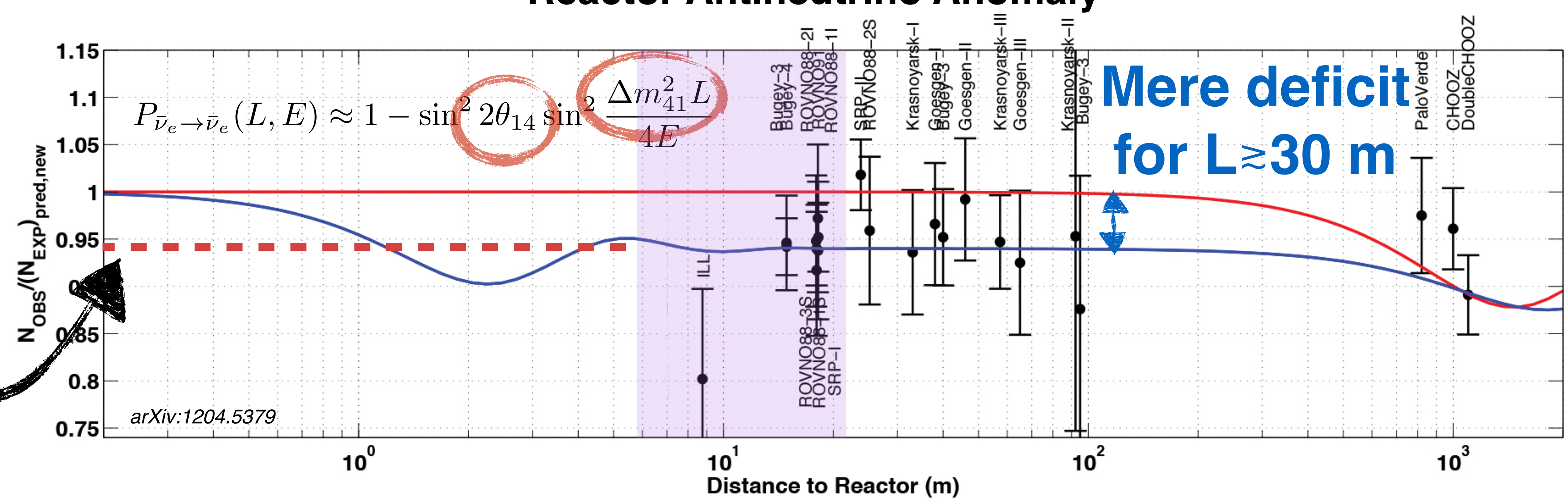
Why There Might be Light Sterile Neutrinos

- Observed **experimental anomalies** which could be explained by light sterile neutrino(s) with $m_\nu \sim 1\ eV^2$
  - LSND and MiniBooNE excesses
  - Gallium anomaly
  - Reactor antineutrino anomaly (RAA)
- Recent developments weaken anomalies

Three Light Active ν's



Reactor Antineutrino Anomaly

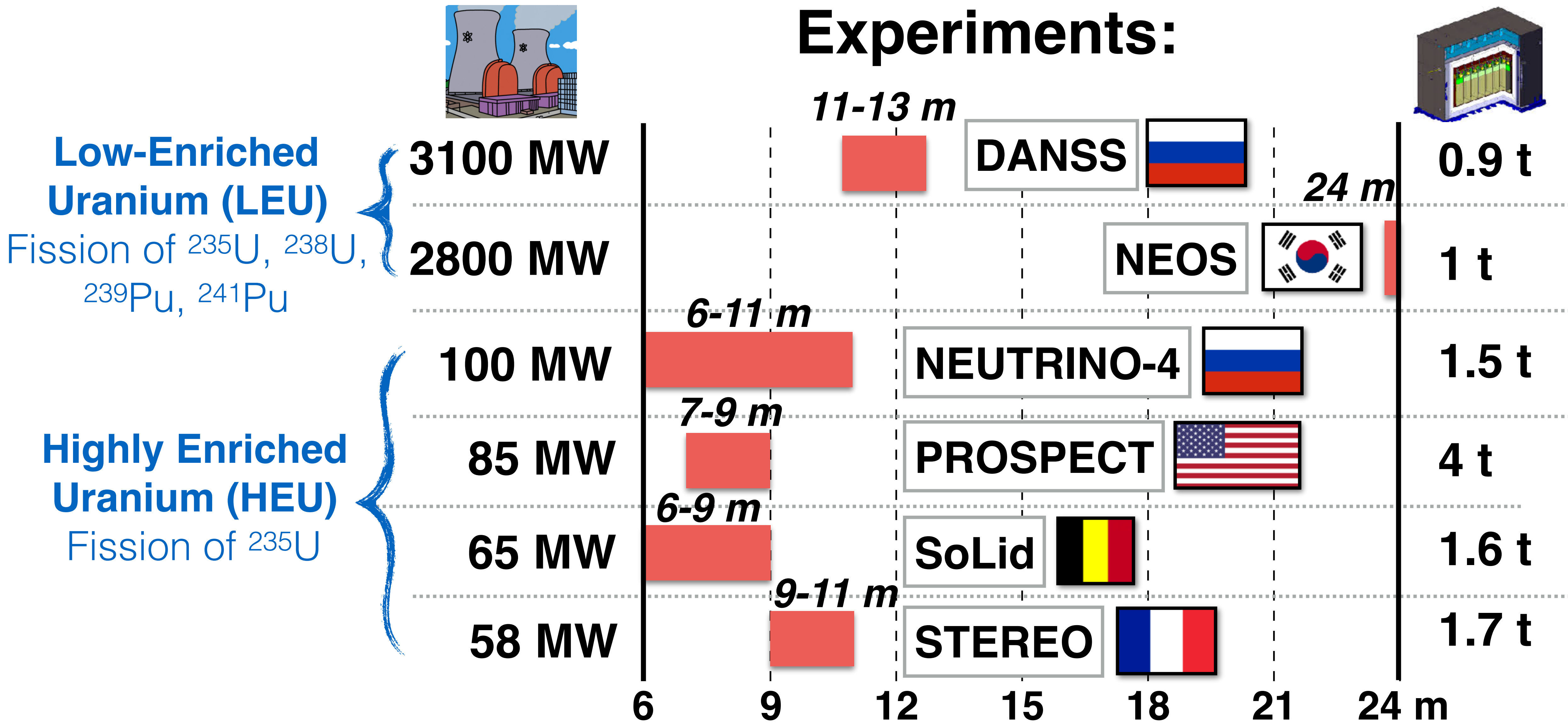


Recent measurements: Prediction might not be completely correct

See more about sterile neutrinos not only in reactor ν experiments in Dr. Gariazzo's talk

Current Short Baseline Reactor Experiments

- Main goals: Sterile neutrinos, reactor $\bar{\nu}_e$ properties, reactor monitoring
- Rich program of ton scale detectors 6-30 m far from LEU&HEU reactors



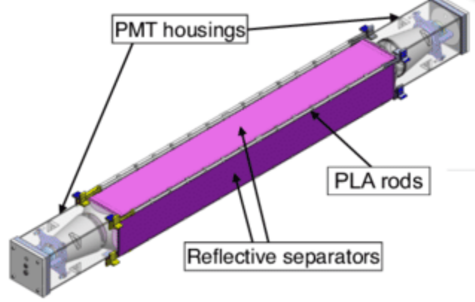
+ (mini-)CHANDLER, JUNO-TAO, NuLAT

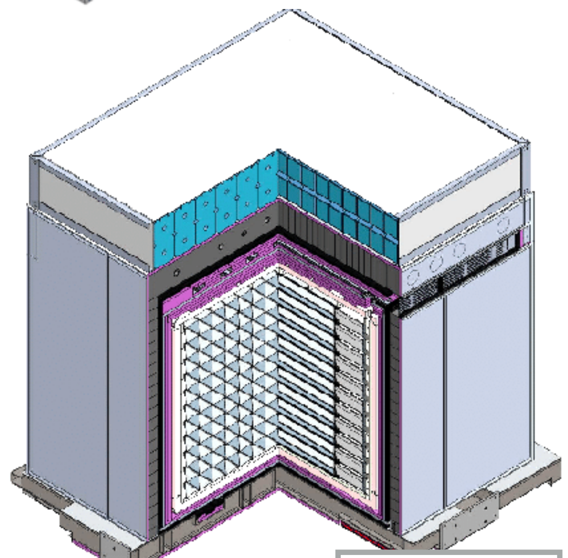
Current Short Baseline Reactor Experiments

- Very similar baseline, yet large diversity in detector design

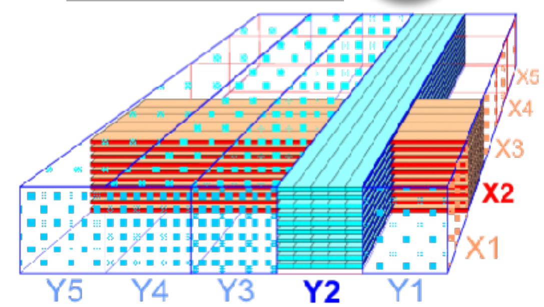
Segmentation:
S Segmented
U Unsegmented

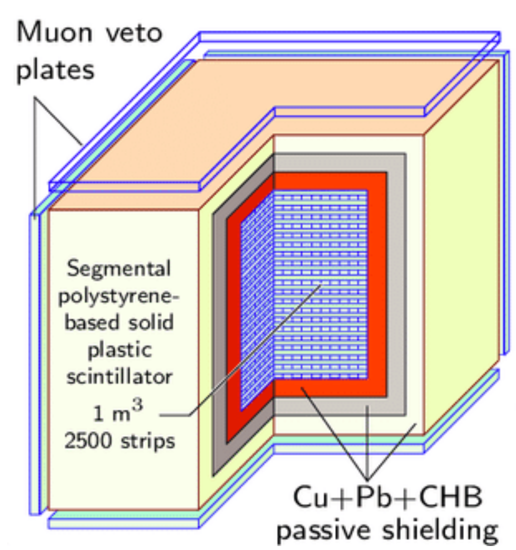
PROSPECT S



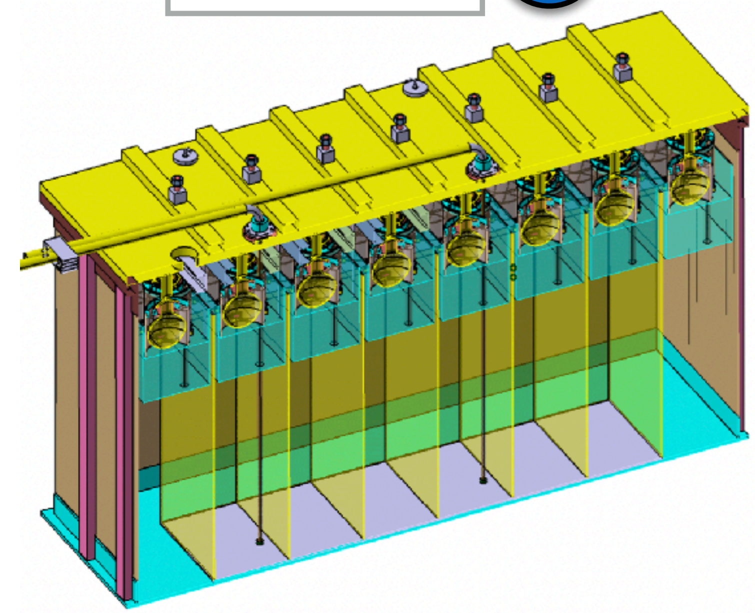


DANSS S

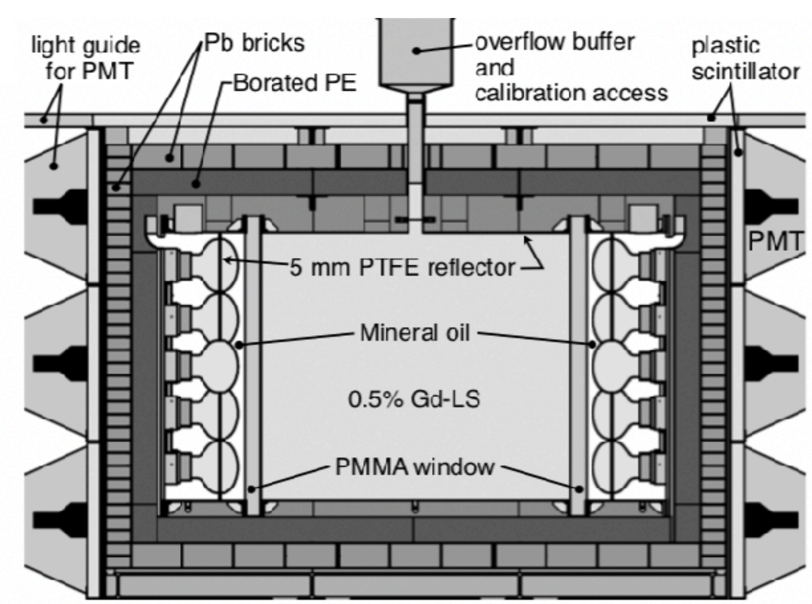




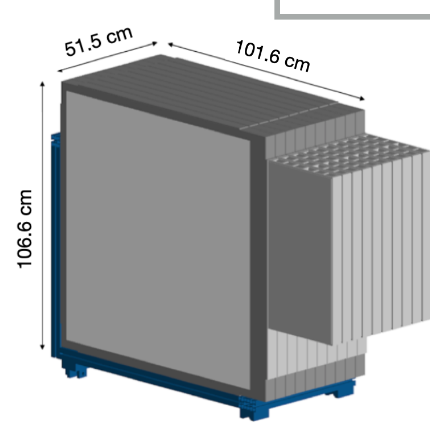
STEREO S

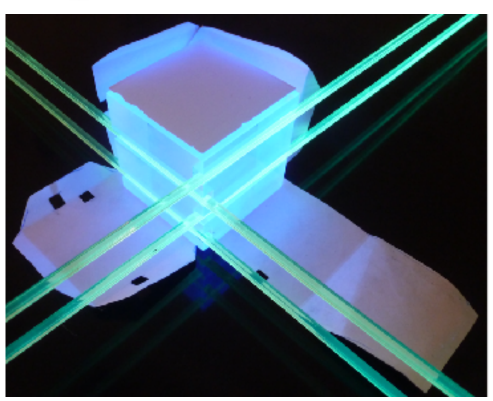


NEOS U



SoLid S





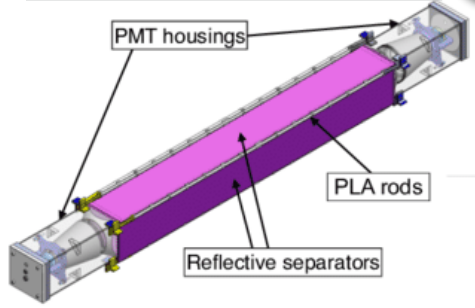
Current Short Baseline Reactor Experiments

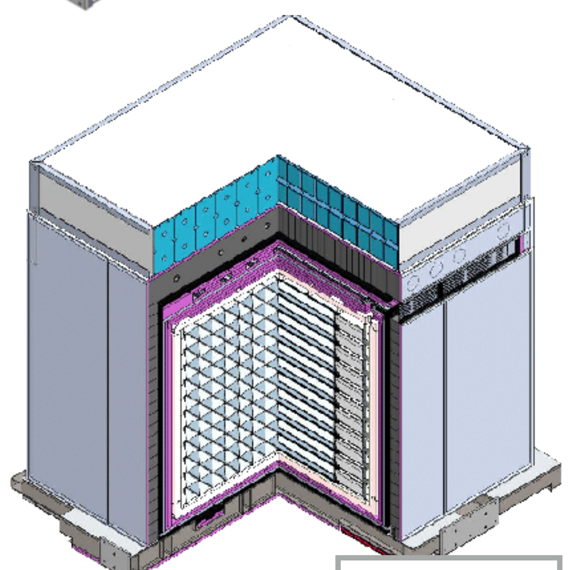
- Very similar baseline, yet large diversity in detector design

Segmentation:
- S Segmented
- U Unsegmented

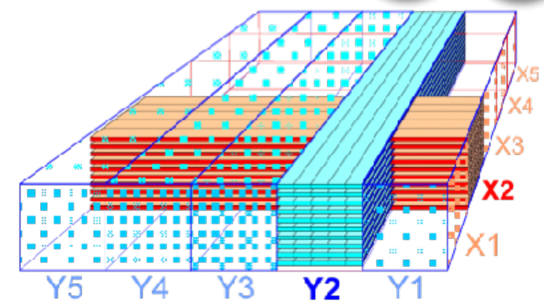
Doping:
- Gd Gadolinium
- Li Lithium

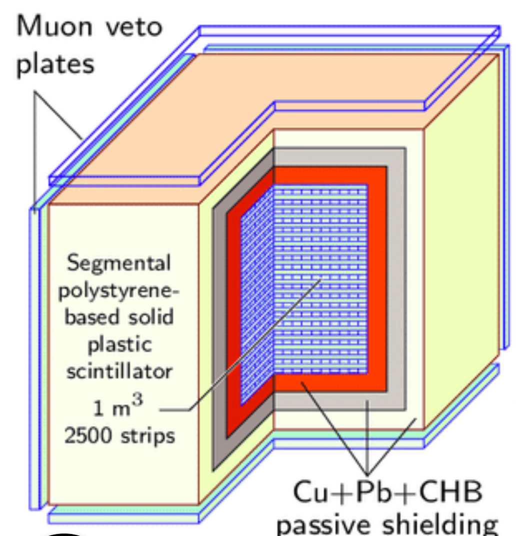
PROSPECT S Li



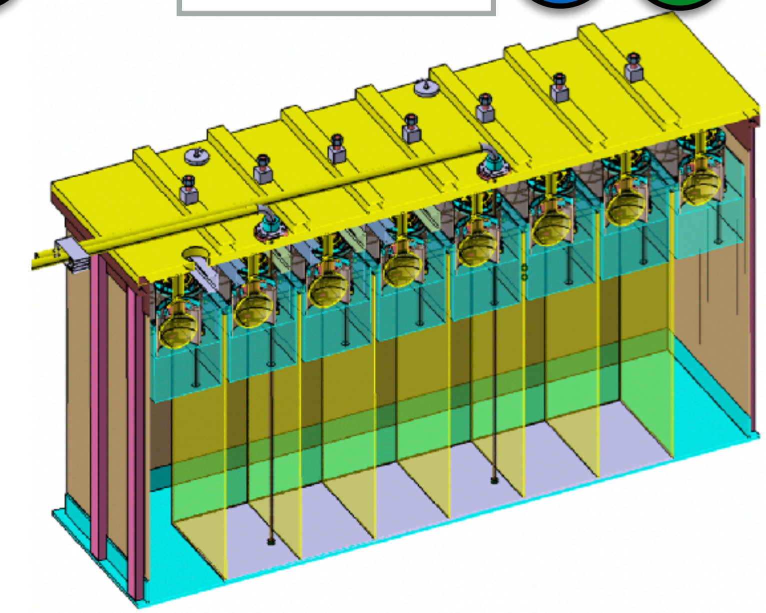


DANSS S Gd

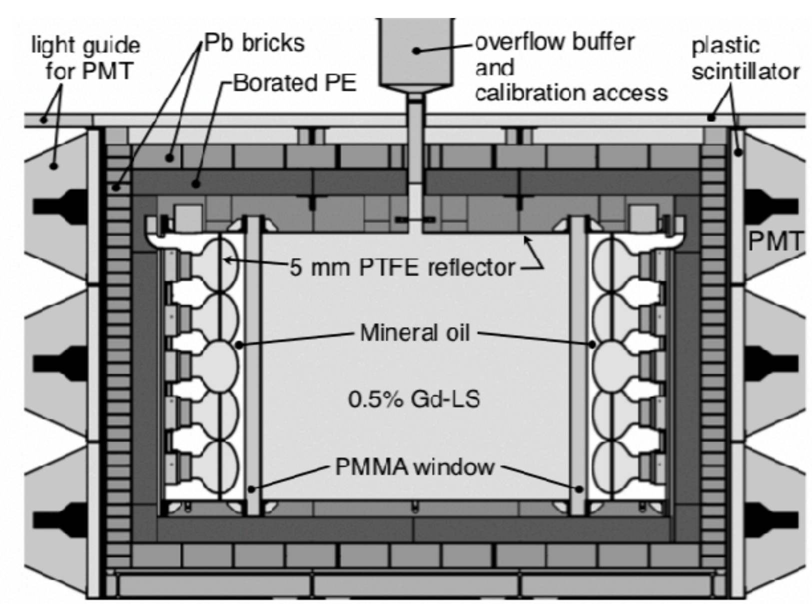




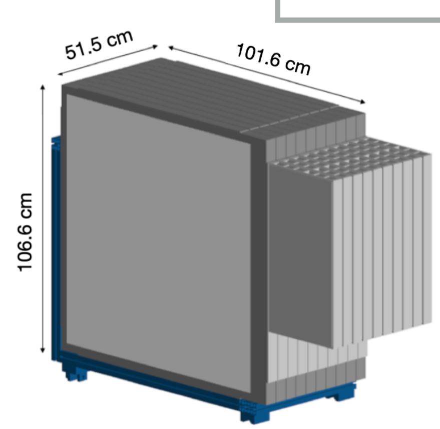
STEREO S Gd

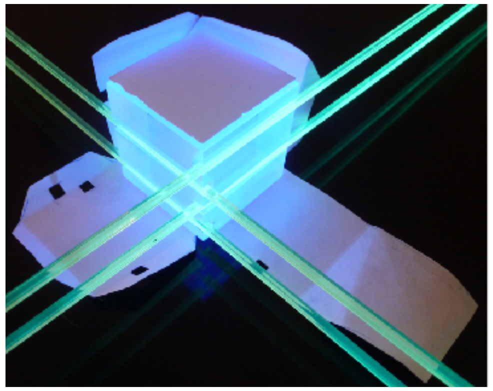


NEOS U Gd



SoLid S Li





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Doping:
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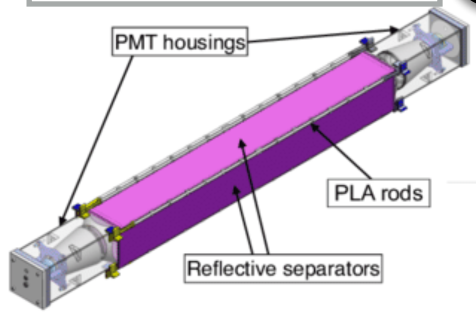
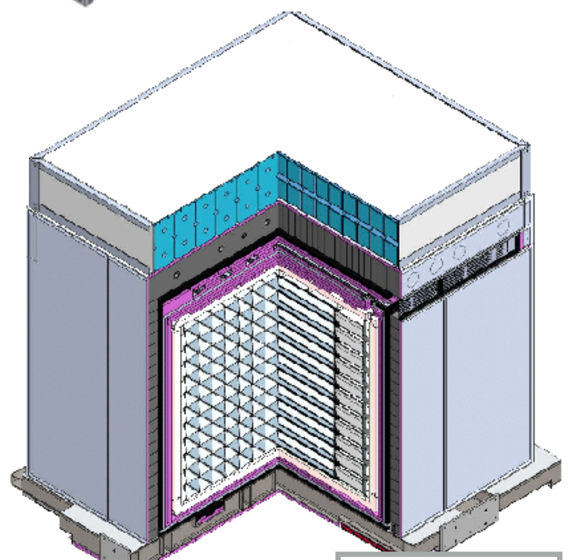
- Li Lithium

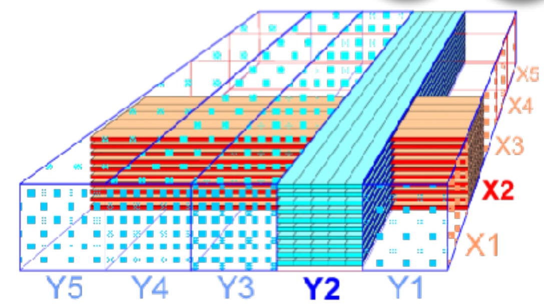
Scintillator:
- LS Liquid
- PS Plastic

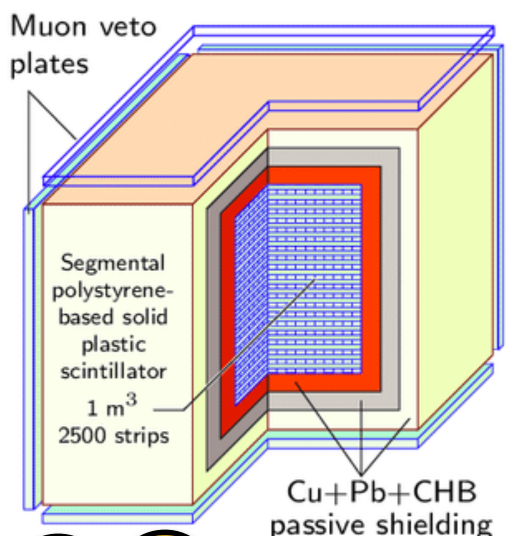
PROSPECT S Li LS



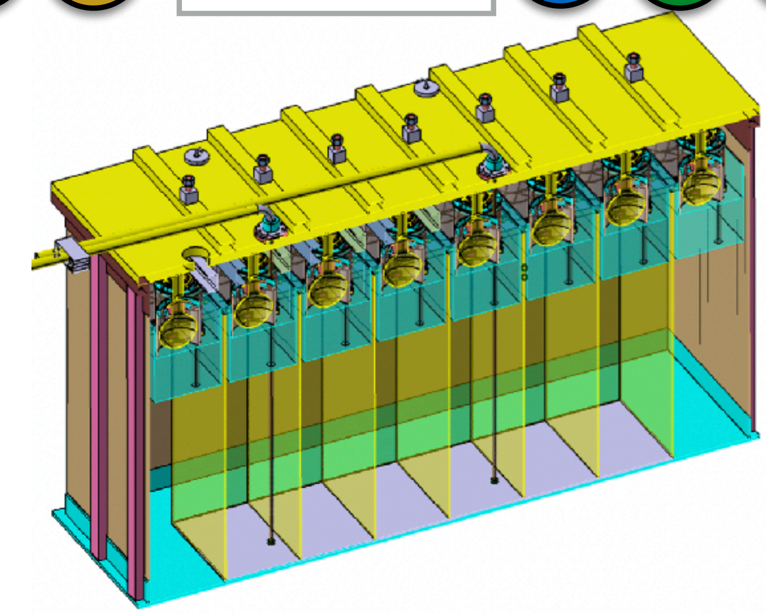


DANSS S Gd PS

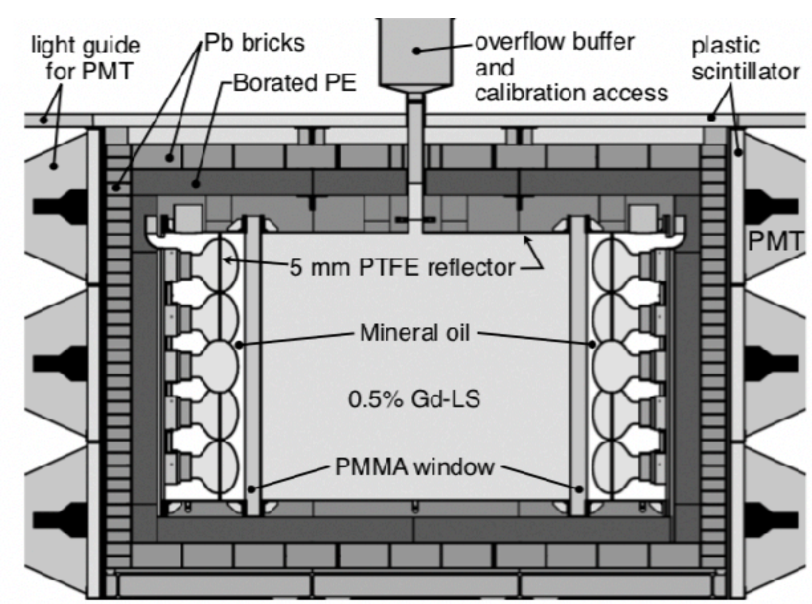




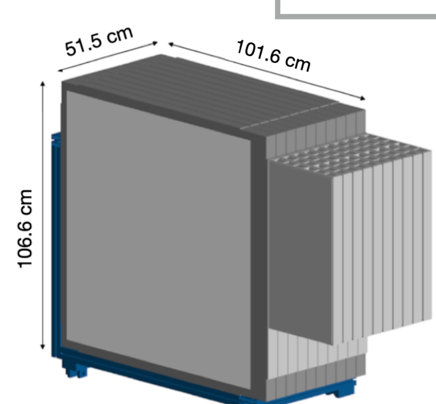
STEREO S Gd LS

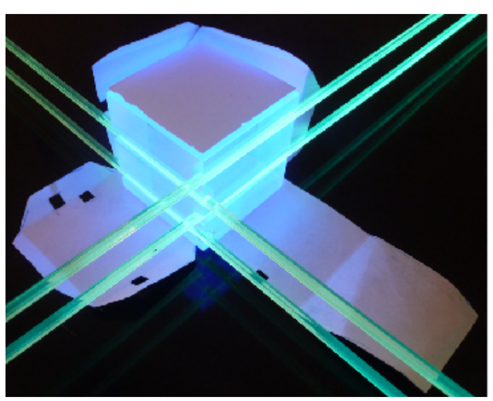


NEOS U Gd LS



SoLid S Li PS





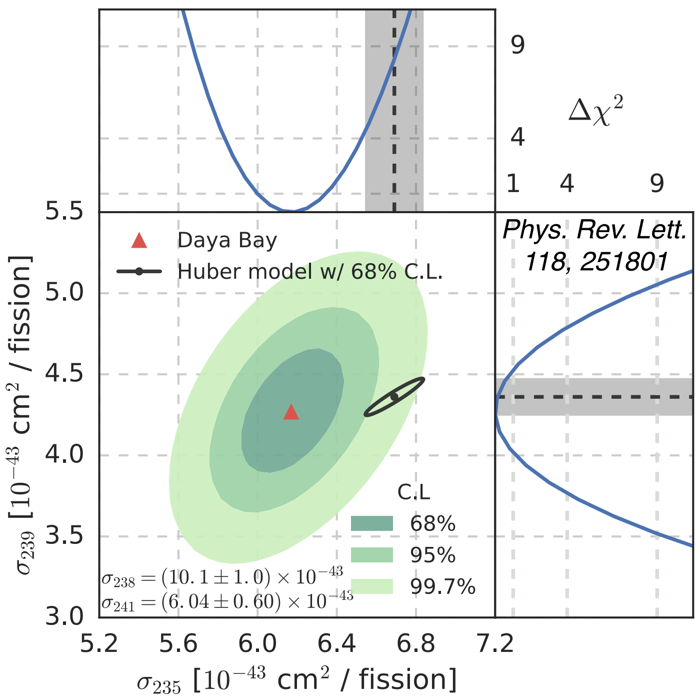
Why Sterile Neutrinos Might Not Be So Hot

- Reactor antineutrino anomaly: Deficit in the measured antineutrino yield compared to Huber+Mueller at al. prediction

Phys. Rev. C 84, 024617
Phys. Rev. C 83, 054615

- Recent measurements suggest **imprecisions in the prediction**

Daya Bay & RENO Isotopic Yields

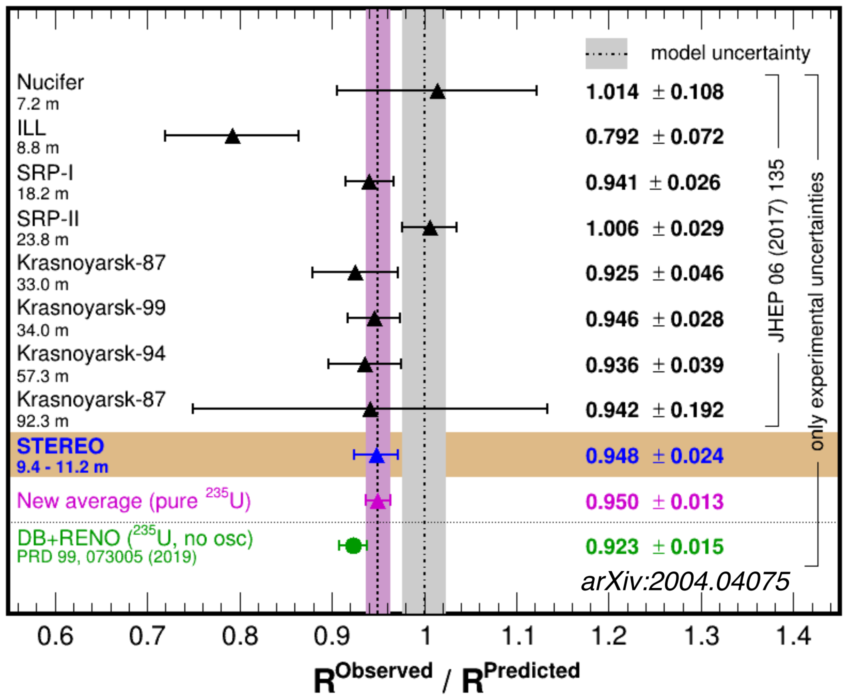


Extraction of U and Pu yields (LEU)

^{239}Pu OK

^{235}U 8% deficit

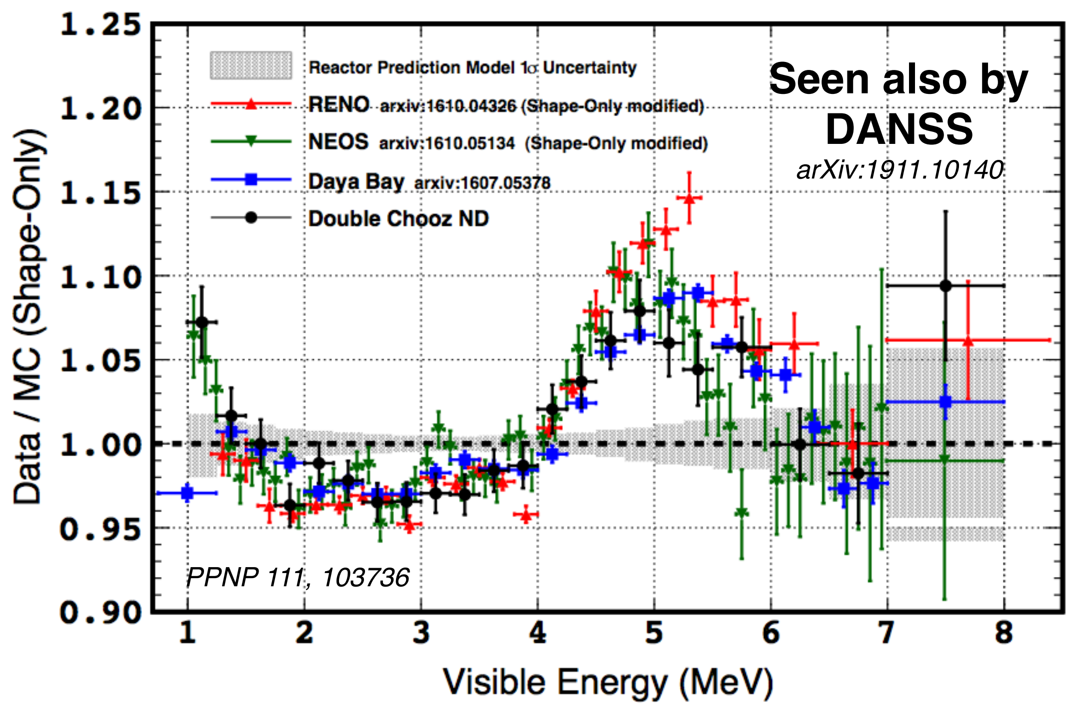
STEREO Isotopic Yield



Mere ^{235}U yield (HEU)

^{235}U 5% deficit

Reactor $\bar{\nu}_e$ spectrum



A 'bump' around ~5 MeV

Isotopic Yields and Spectra

- Piece by piece we are on the way **towards benchmarking the prediction** ➔ revised prediction will match the data

LEU Isotopic
Spectra and **Yields**

- ^{235}U&^{239}Pu yields already from Daya Bay and RENO ✔
- Daya Bay - first extraction of the ^{235}U&^{239}Pu spectra ✔
- JUNO-TAO: Ultimate player here in the future

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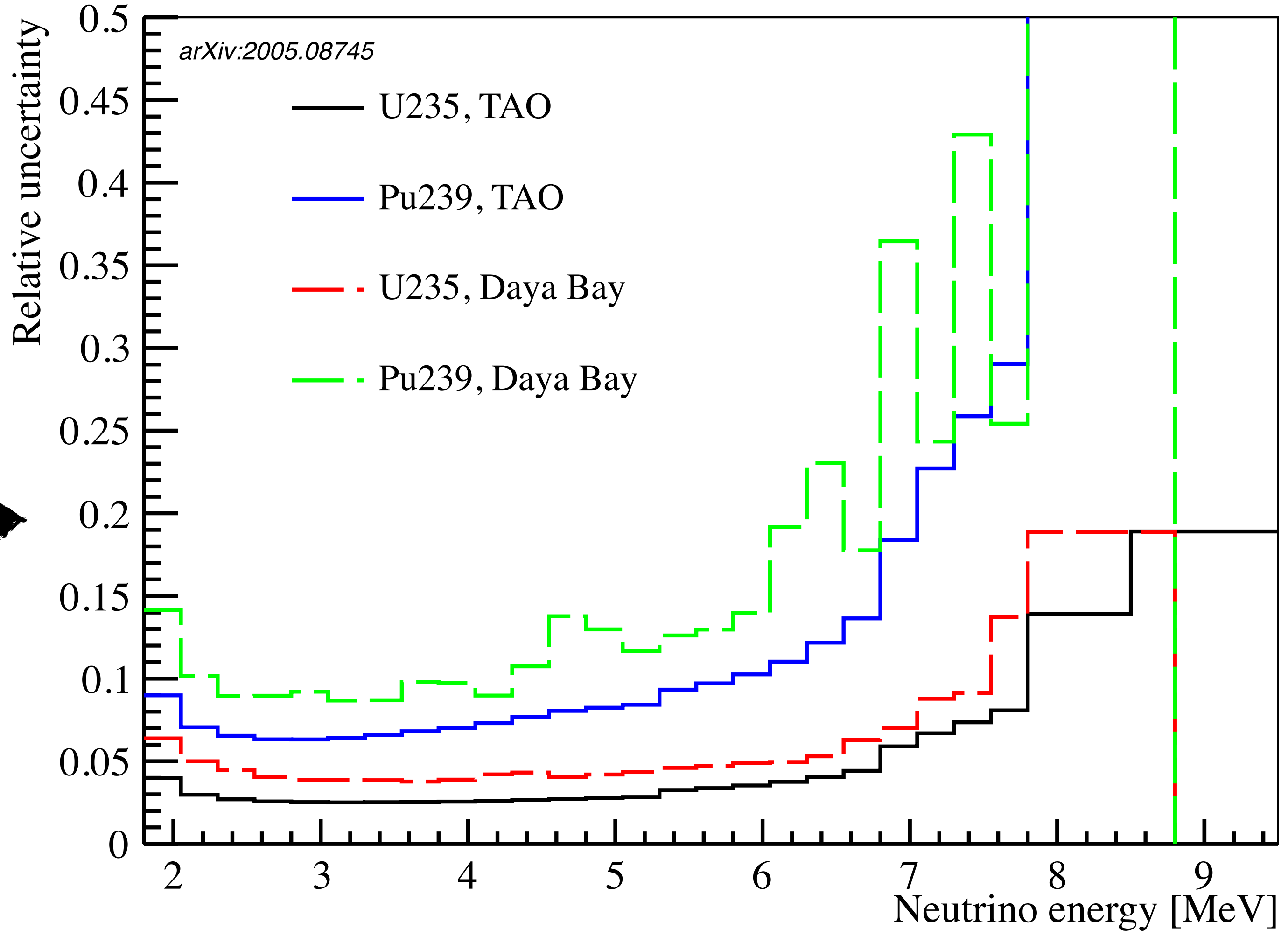

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HEU ^{235}U
Spectrum and **Yield**

- ^{235}U spectrum from PROSPECT ✔
- ^{235}U yield & spectrum from STEREO ✔
- Other HEU experiments will join

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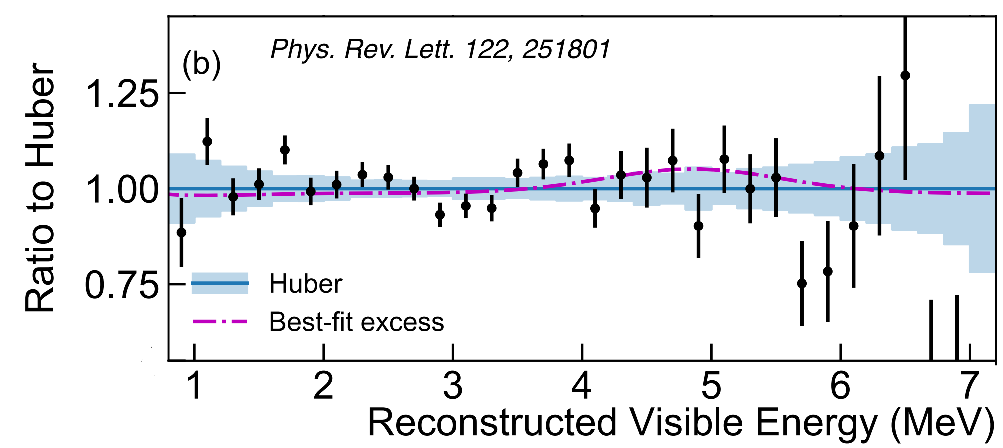
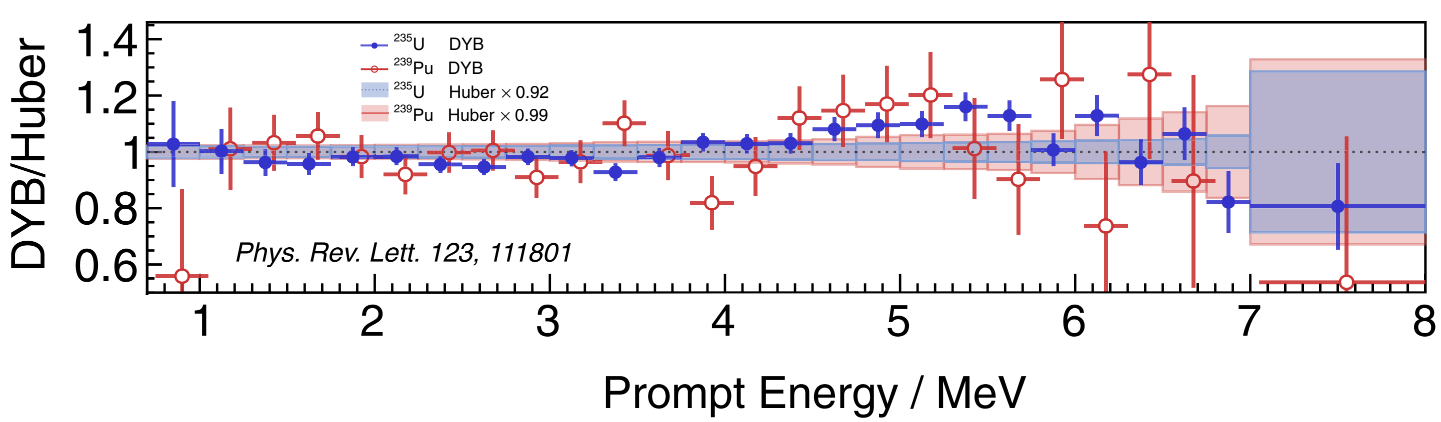
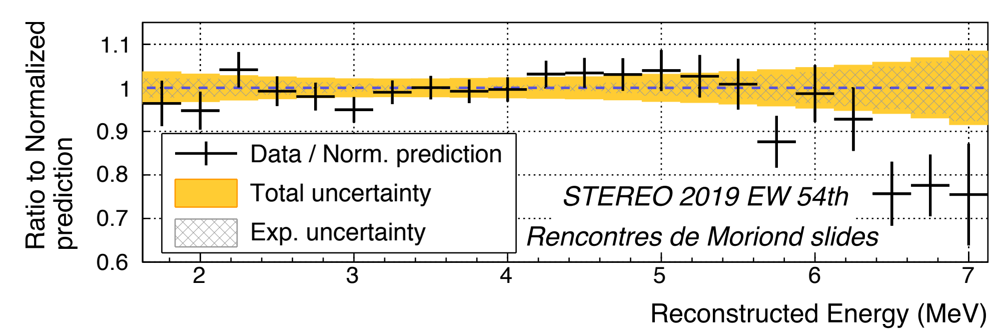
PROSPECT/Prediction for ^{235}U



Daya Bay/Prediction for ^{235}U and ^{239}Pu



STEREO/Prediction for ^{235}U



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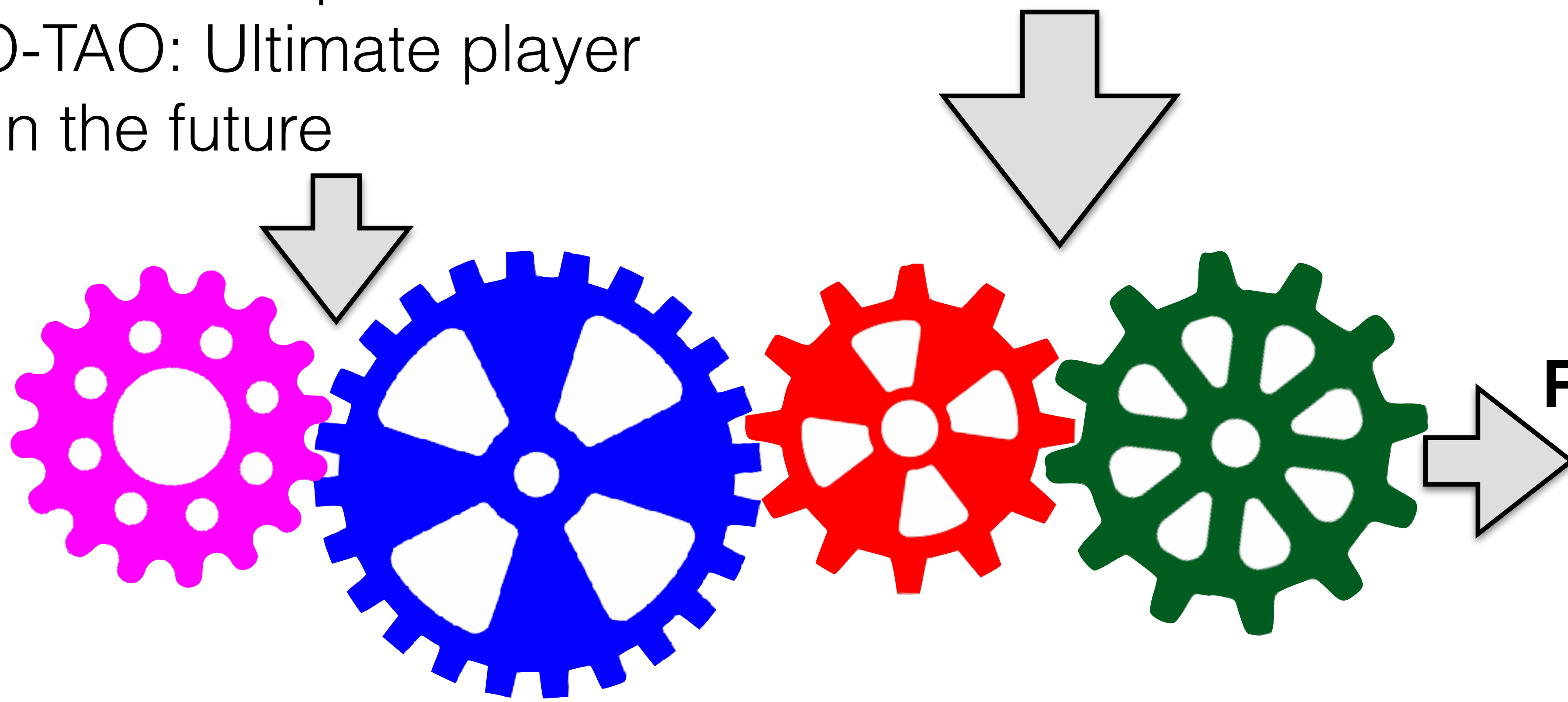

RAA resolution
(whether with steriles or not)

All these measurement should present consistent picture

Conclusions

- **Reactor neutrino experiments:**
  - Providing better understanding of neutrinos for more than 60 years
  - And will keep on doing so…
- **Daya Bay, Double Chooz, RENO:**
  - The value of θ_{13} mixing angle for foreseeable future
- **JUNO:**
  - Neutrino mass ordering at $>3\sigma$
  - $\sin^2 2\theta_{12}$, Δm^2_{31} and Δm^2_{21} with <0.7% precision
- **Short baseline reactor neutrino experiments:**
  - Steriles, or not steriles, that is the question!
  - Benchmarking the prediction to resolve reactor antineutrino anomaly
- **And lot more…**