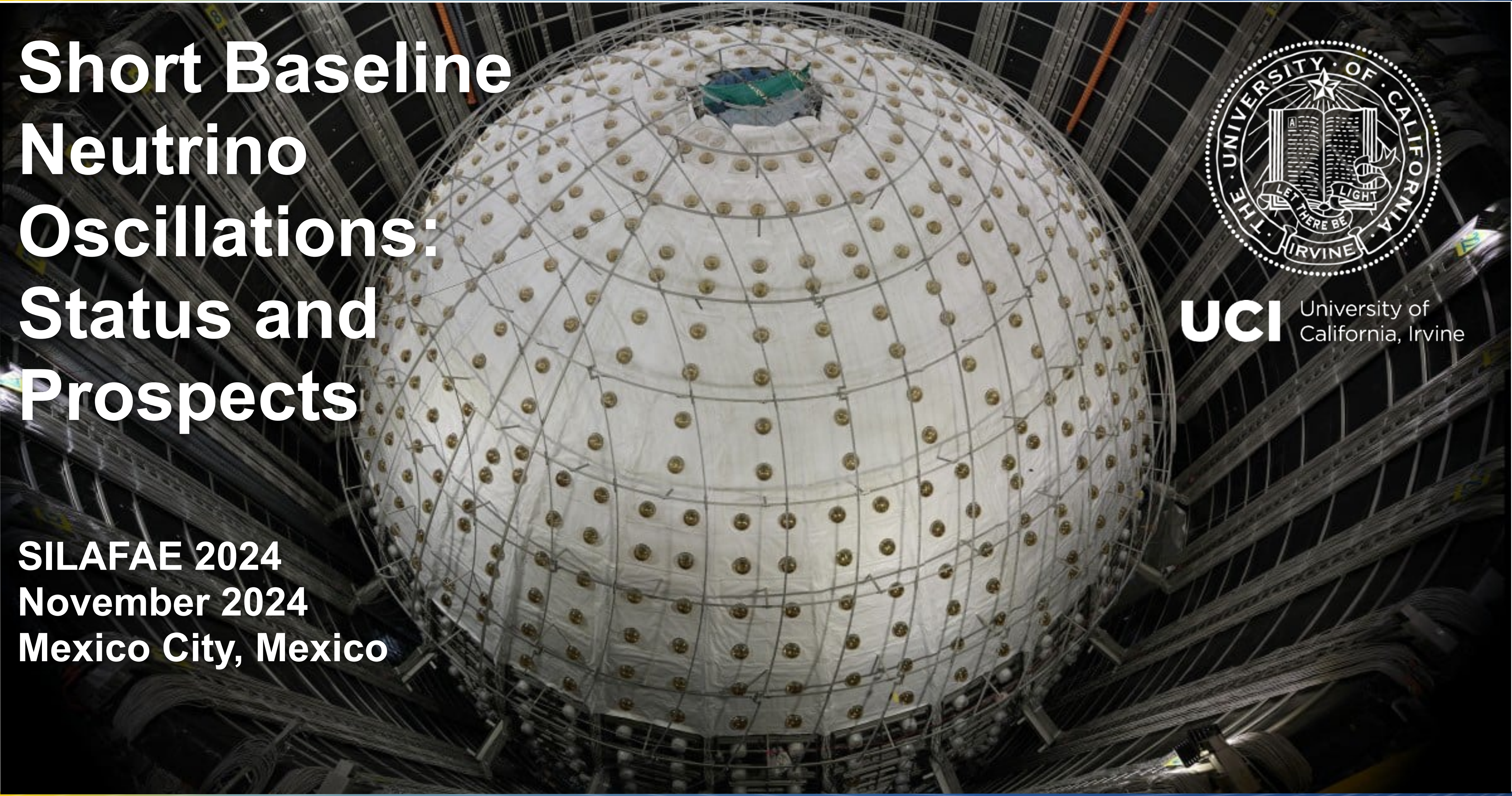
Short Baseline Neutrino Oscillations: Status and Prospects



SILAFAE 2024
November 2024
Mexico City, Mexico

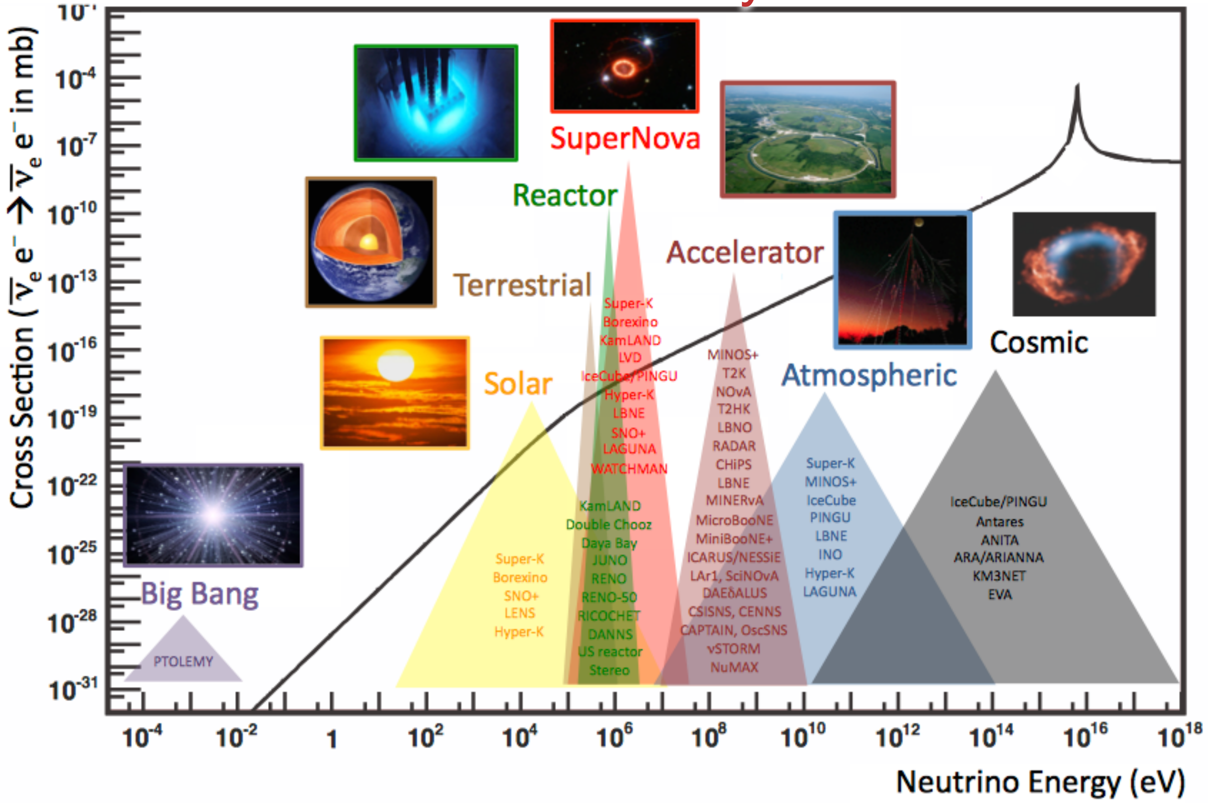
Brief Introduction

to Neutrino Oscillations

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
  - Their behavior is **beyond the Standard Model**

Neutrinos are everywhere!



Neutrino Oscillation Refresher

- The principle behind neutrino oscillations: **neutrino mixing**

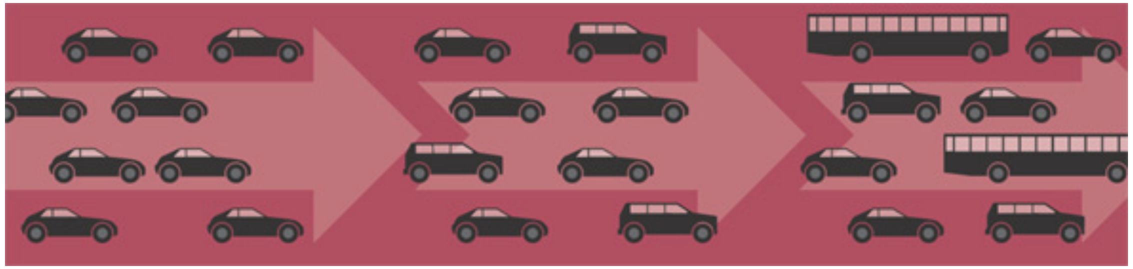
$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$

How they interact (ν_e, ν_μ, ν_τ)

How they propagate (ν_1, ν_2, ν_3)

where the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix U is parameterized in terms of three mixing angles (θ_{12}, θ_{23}, θ_{13}) and one CP-violating phase δ_{CP}

Illustration of neutrino oscillation:



For example, as a <u>rough</u> approximation at short baselines, the $\bar{\nu}_e$ "survival" probability is:

amplitude

frequency

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

(where the $\Delta m^2_{ij} = m^2_i - m^2_j$ are the so-called "mass splittings")

Open Questions

- Neutrino oscillation implies that neutrinos are massive
- Have many open questions:
  - What are the values of the oscillation parameters?

$$\sin^2\theta_{12},\ \Delta m^2_{21}\ \ \sin^2\theta_{23},\ \Delta m^2_{32},\ \ \sin^2\theta_{13}$$

Note: Δm^2_{31} can be determined from the other two mass splittings if the mass ordering is known

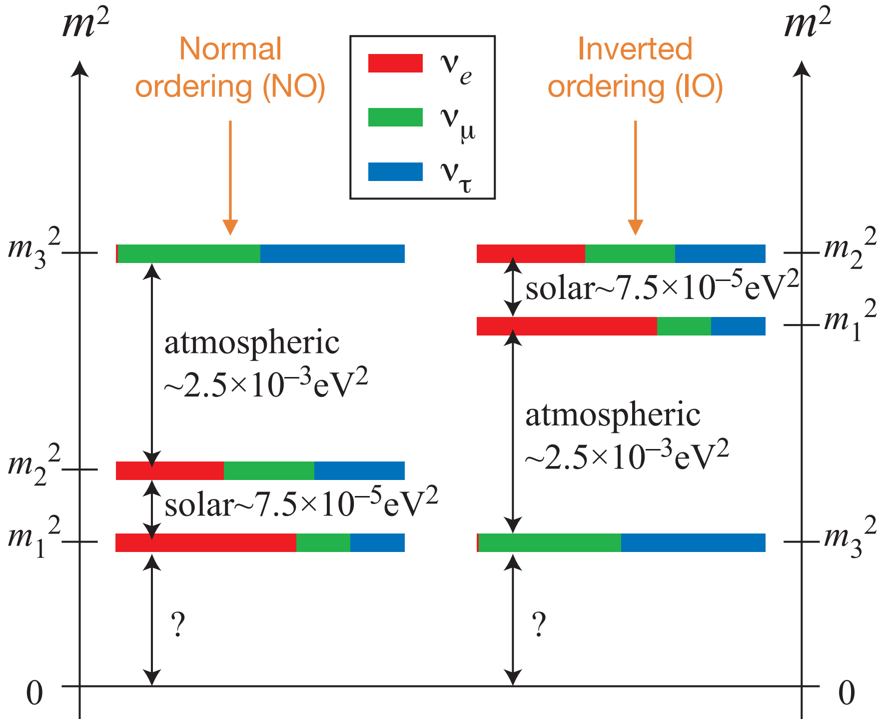
  - Do neutrinos obey the CP symmetry (is $\delta_{CP} = 0$)?
  - What is the ordering of the neutrino masses (i.e. sign of Δm^2_{32})?
  - Are there additional neutrino states?

There are other questions but those require more than oscillation experiments to be answered

From PDG 2024

		Precision
$\sin^2(\theta_{12})$	0.307 ± 0.013	4.2 %
Δm^2_{21}	$(7.53 \pm 0.18) \times 10^{-5}\ \mathrm{eV}^2$	2.4 %
$\sin^2(\theta_{23})$	$0.558^{+0.015}_{-0.021}$	3.2 %
Δm^2_{32}	$(2.455 \pm 0.028) \times 10^{-3}\ \mathrm{eV}^2$	1.1 %
$\sin^2(\theta_{13})$	0.0219 ± 0.0007	3.2 %

Parameters are currently known to a few **percent**, but need more precision. Also, octant of θ_{23} is unknown



Credit: H. Murayama

Rest of This Talk

- Short baseline experiments are at the forefront in helping us address some of these questions
- Some types of experiments have traditionally been more effective at probing certain sectors of the PMNS matrix

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta_{CP}} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Atmospheric (+Accelerator) | **Reactor (+Accelerator)** | **Solar (+Reactor)**

Rough values of L/E ideal for observing three-flavor neutrino oscillations:

- 15 km / MeV for Δm^2_{21}
- 500 m / MeV for Δm^2_{32}

  – The only way to probe three-neutrino (standard) oscillations at “short” baselines is with reactor experiments

First part of this talk

We’ll call reactor baselines “short” for the purposes of this talk

	Neutrino Energy	Baseline
Reactor	1-10 MeV	few m to ~200 km
Accelerator	sub-GeV to a few GeV	< 1,300 km
Atmospheric	sub-GeV to a few GeV	< 12,000 km
Solar	1-15 MeV	10^6 - 10^8 km

But anomalous ($\Delta m^2 \gtrsim 1\ \mathrm{eV}^2$) oscillation signatures can also be probed at short baselines with reactor, accelerator and source experiments

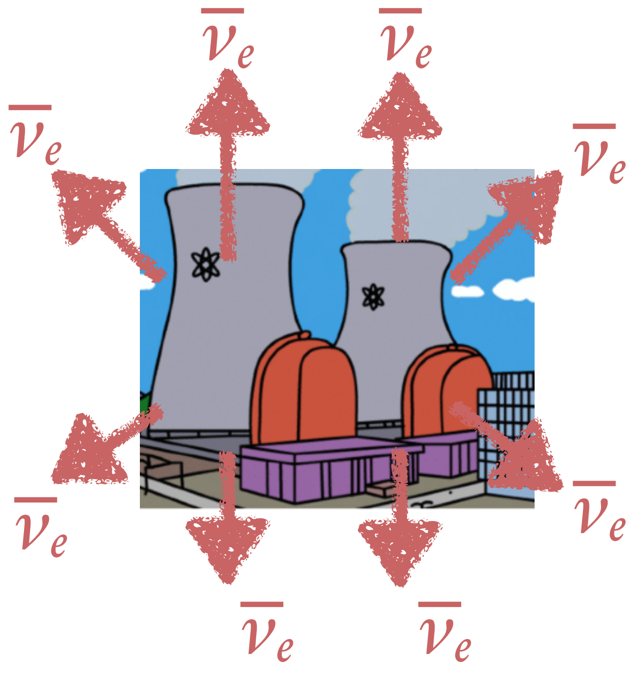
Second part of this talk

Three-Neutrino Oscillations

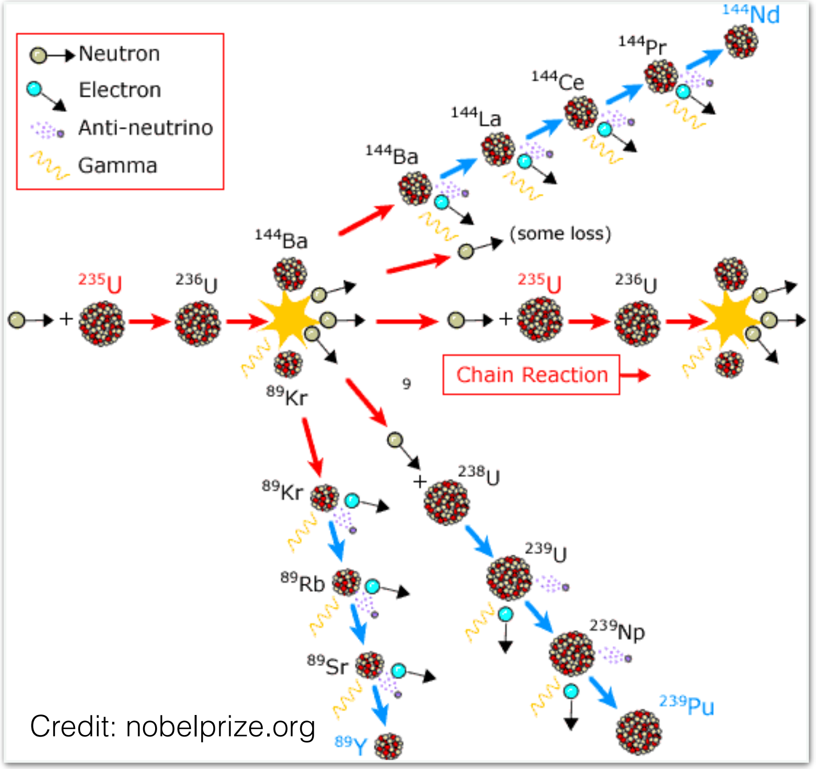
with Reactor Experiments

Reactor Antineutrinos

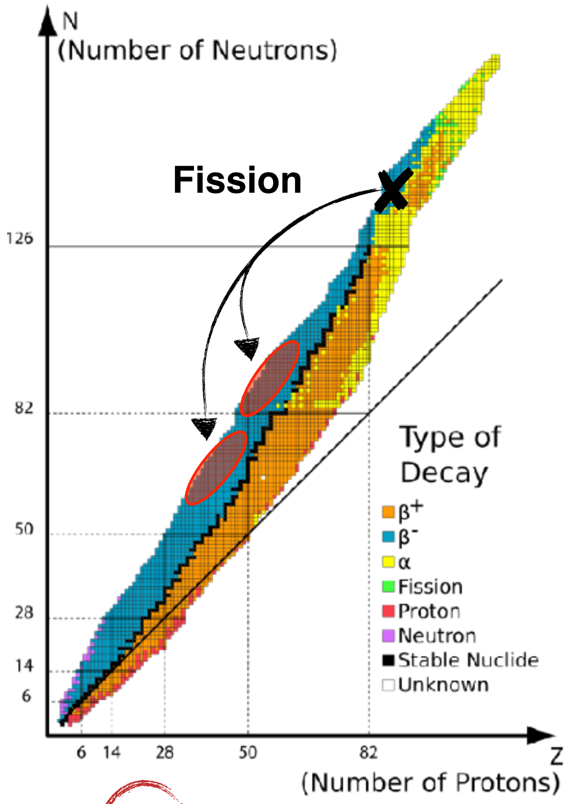
- Nuclear reactors are a flavor-pure, widely available, cost-effective, **extremely intense** and well-understood source of electron antineutrinos:



$\sim 10^{20}\ \bar{\nu}_e/\mathrm{s}/\mathrm{GW}_{\mathrm{th}}$



Credit: nobelprize.org



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

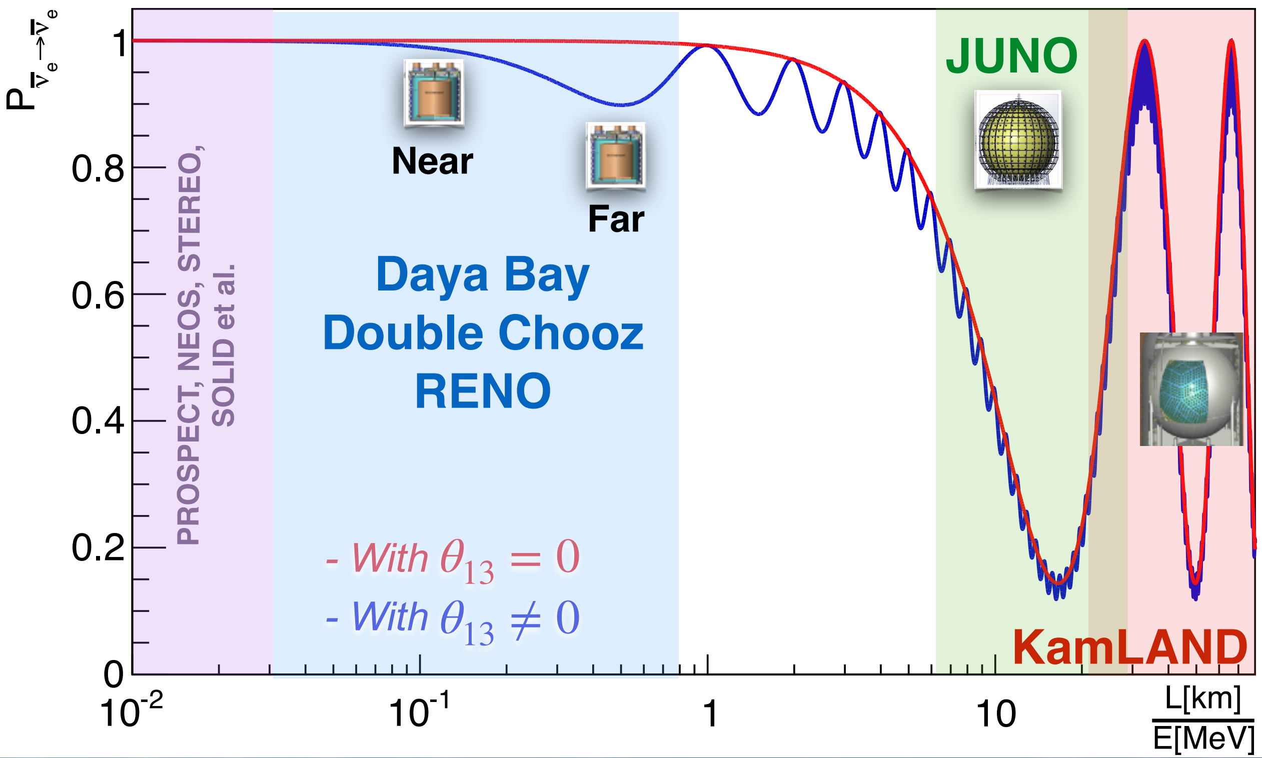
– A 1 $\mathrm{GW}_{\mathrm{th}}$ core produces in one minute more neutrinos than the NuMI and BNB beams produce in a year

Oscillation Probability

- Muon and tau neutrinos from reactor electron antineutrino oscillations lack sufficient energy for charged-current interactions
- Therefore, reactor experiments focus on electron antineutrino disappearance:

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

  - Access to 4/6 oscillation parameters: θ_{12}, θ_{13}, Δm^2_{21}, and Δm^2_{31} (Δm^2_{32})
  - Independent of θ_{23} and δ_{CP}
  - Physics goals drive choice of baseline



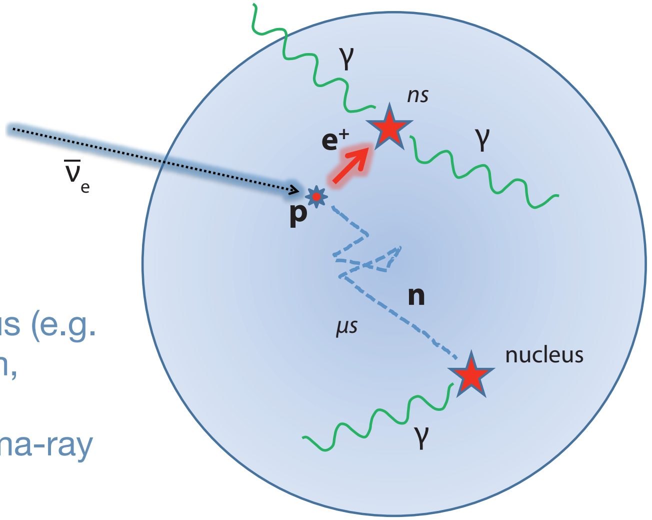
Antineutrino Detection

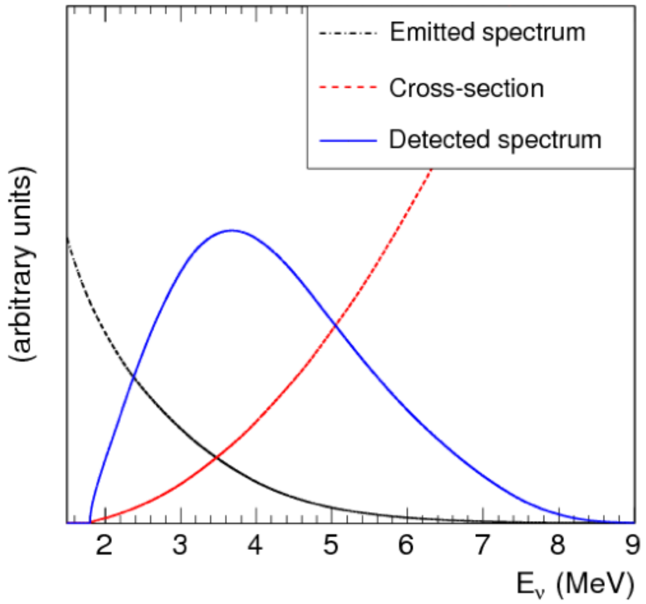
- The medium of choice for most reactor neutrino experiments has been scintillator (plastic or liquid)
- The primary detection channel is the Inverse Beta Decay (IBD) reaction:

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

Prompt signal: e^+ kinetic energy loss + annihilation

Delayed signal: n capture on nucleus (e.g. Hydrogen, Lithium, Gadolinium) and subsequent gamma-ray emission





– Coincidence between prompt positron and delayed neutron signals allows for **powerful background rejection**

– Energy of positron preserves information about energy of incoming $\bar{\nu}_e$:

$$E_{\bar{\nu}_e} \approx E_{\text{prompt}} + 0.78\ \text{MeV}$$

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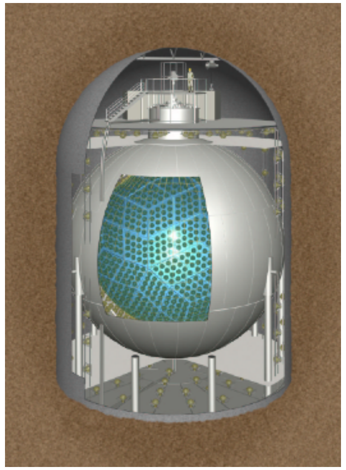
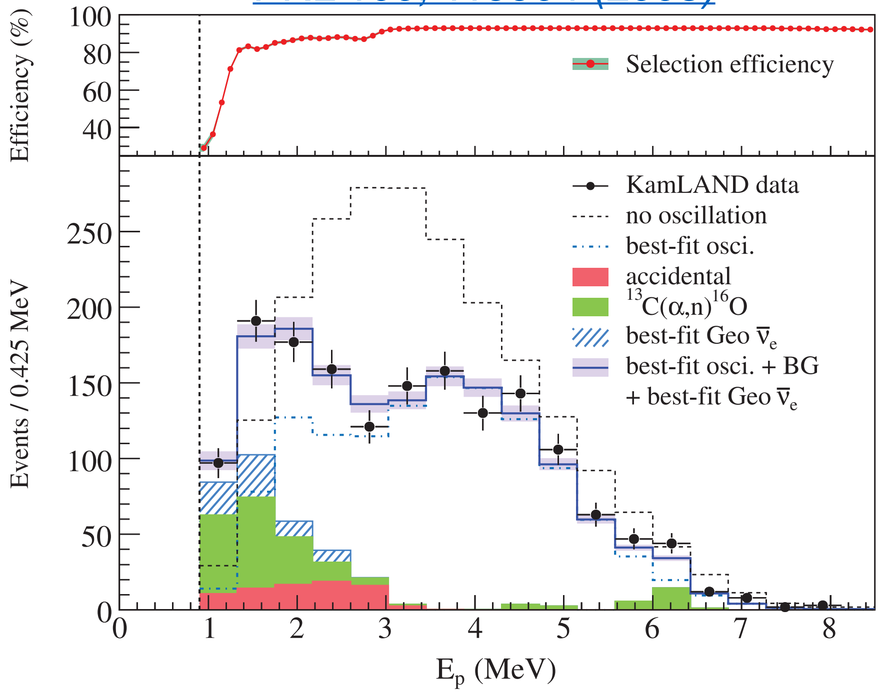
KamLAND

- The KamLAND experiment still provides us with the most precise estimate of Δm^2_{21} to date

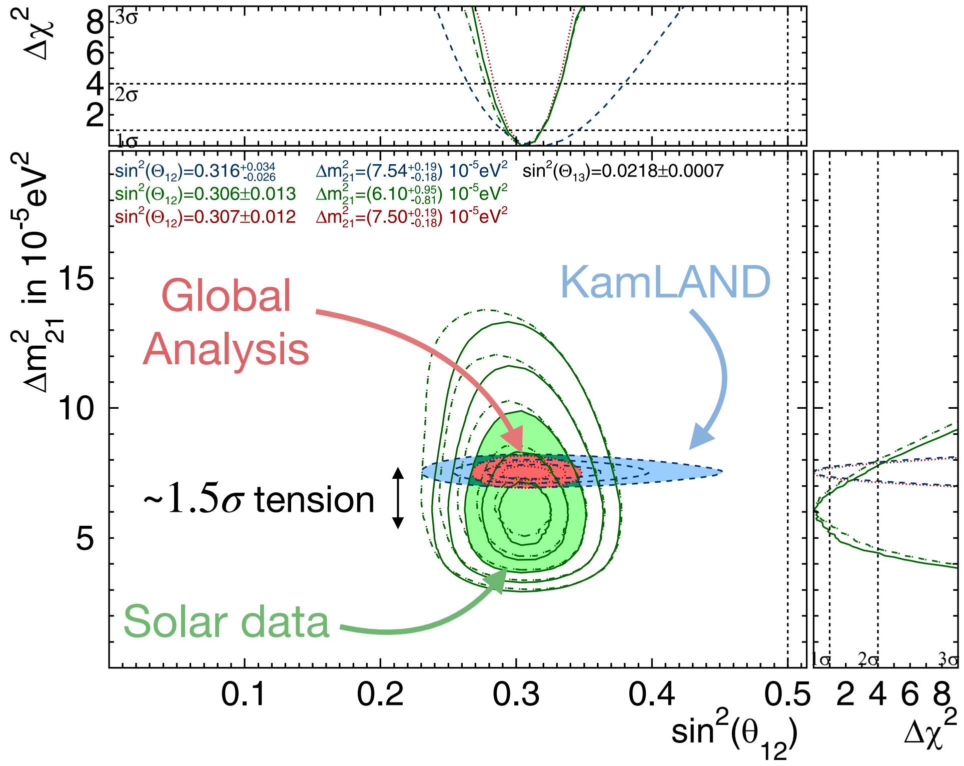
KamLAND:
- 1 kton liquid scintillator (LS) detector
- Surrounded by ~50 nuclear reactors at an average baseline of ~180 km



PRL 100, 119904 (2008)

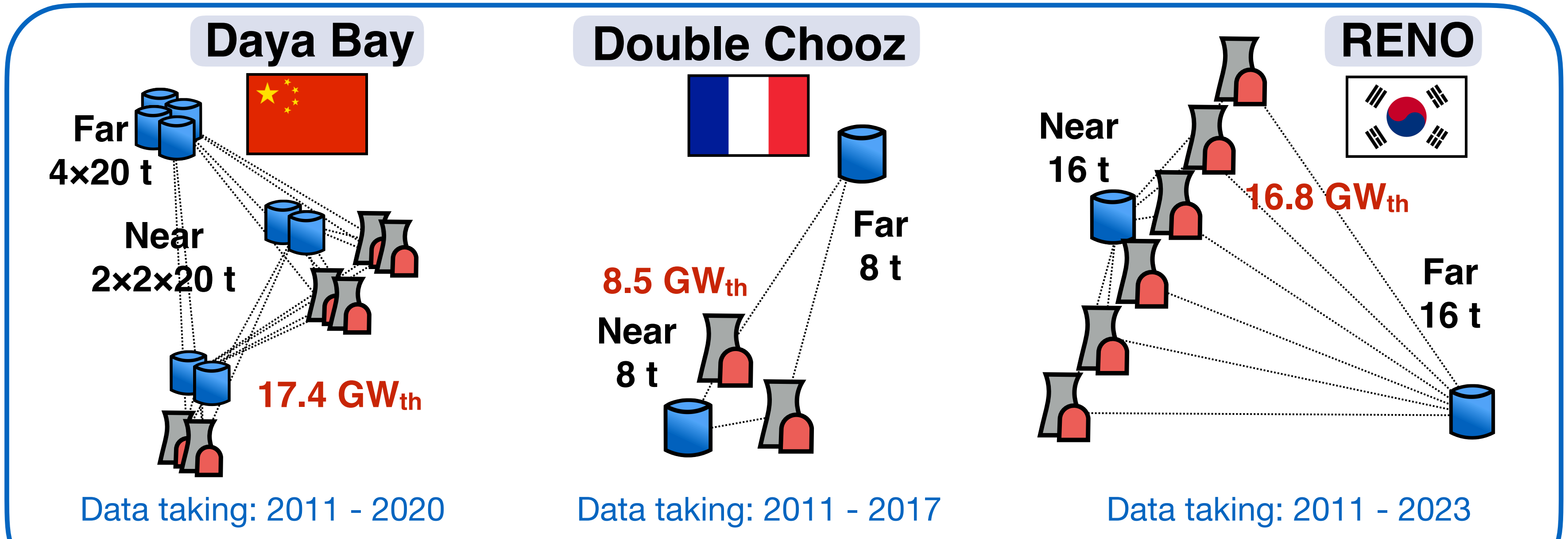


PRD 109, 092001 (2024)



θ_{13} Experiments

- A generation of three experiments designed to precisely measure θ_{13} recently finished collecting data

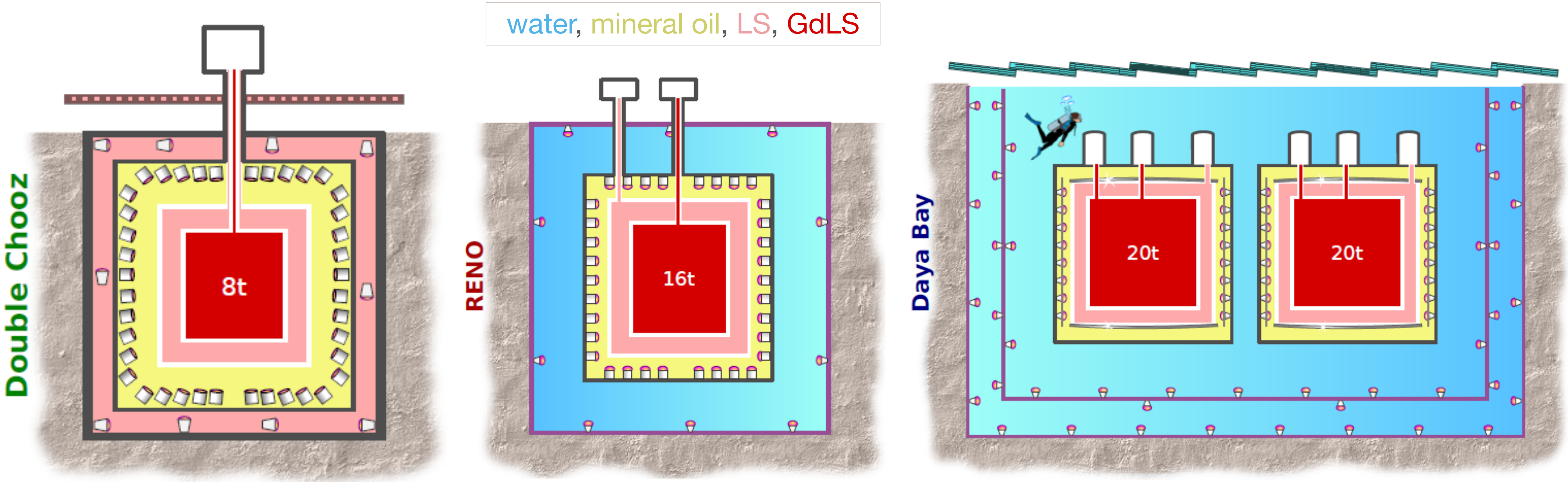


Notes: flags indicate location of experiment, not composition of collaboration

  - < 2 km baseline, so only need "small" detectors (tens or hundreds of tons)
  - Looking for small (<10%) disappearance, so **key is keeping systematics under control**
  - Near/far **relative** comparison allows to essentially cancel uncertainties in flux prediction and correlated detection efficiencies

θ_{13} Experiments

- The three experiments use similar detection technologies:



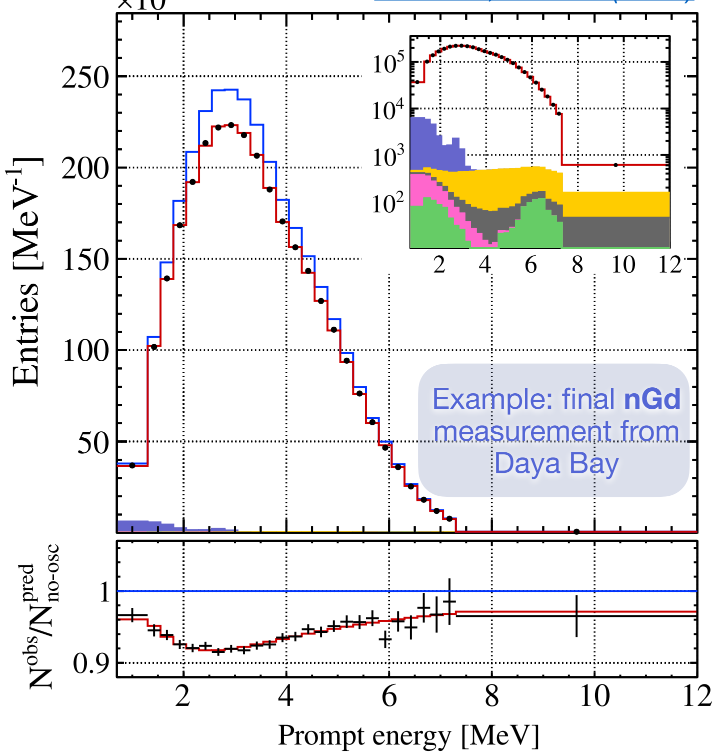
(diagrams courtesy of S. Jetter)

- Three-zone detectors
- Surrounded by instrumented shields (water or liquid scintillator (LS)) that also veto muons
- LS doped with Gadolinium (GdLS) to enhance capture signal

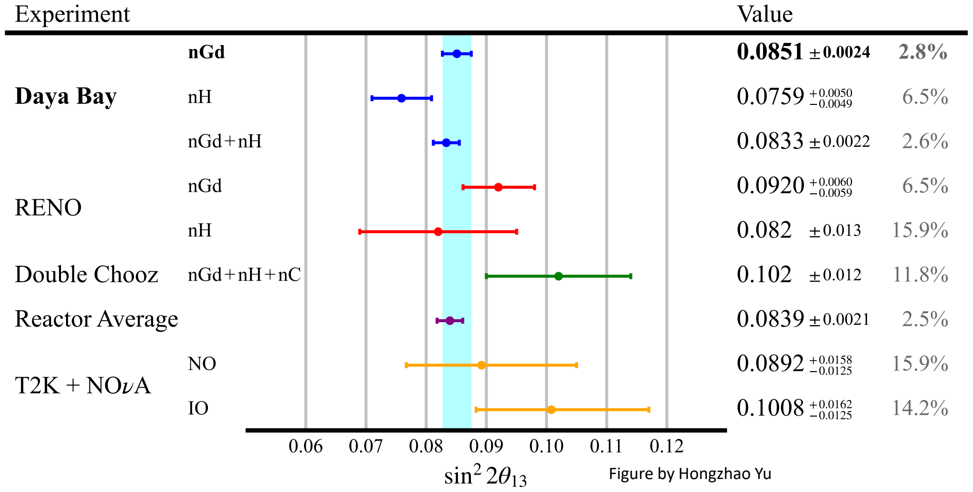
θ_{13} Mixing Angle

- These experiments can use neutron capture on Hydrogen (nH) and/or on Gadolinium (nGd) to identify $\bar{\nu}_e$'s, resulting in essentially independent measurements:

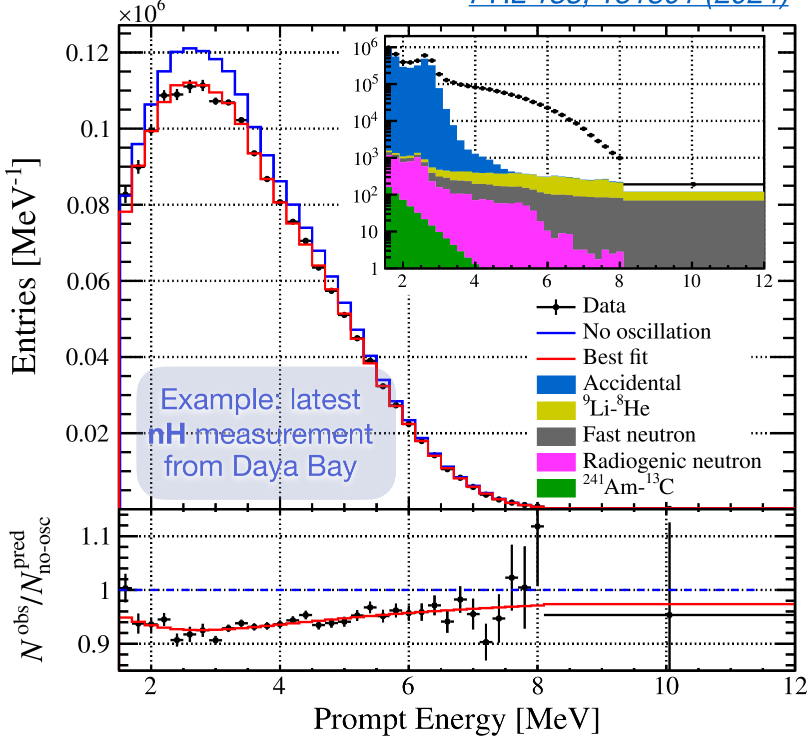
PRL 130, 161802 (2023)



(Plot courtesy of H. Yu, shown in Z. Yu's talk at Neutrino 2024)



PRL 133, 151801 (2024)

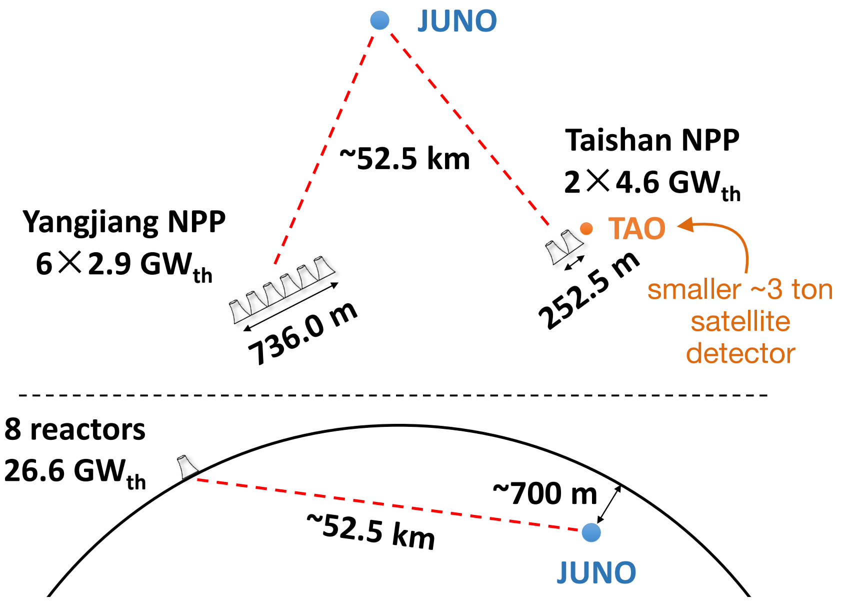


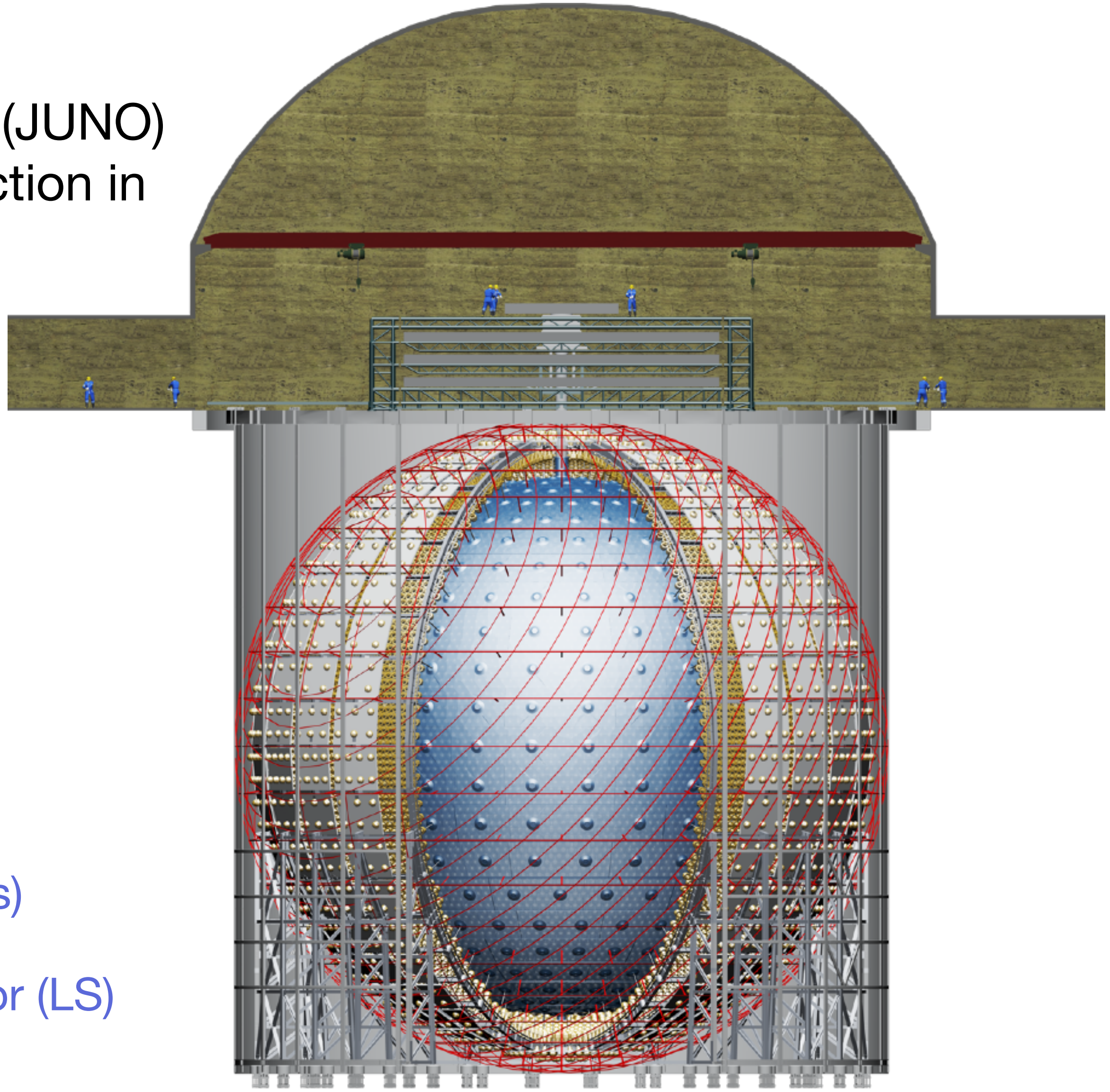
Current reactor measurement of θ_{13} likely to remain the world's most precise for a long time

- Excellent fit to three-neutrino framework
- Excellent agreement with accelerator and atmospheric experiments (also for $|\Delta m^2_{32}|$)

Prospects: JUNO

- The **J**iangmen **U**nderground **N**eutrino **O**bservatory (JUNO) is a large multi-purpose experiment under construction in China:





- 53 km from two major nuclear power plants (8 reactors)
- 35 m diameter sphere with 20 ktons of liquid scintillator (LS) surrounded by 35 kton water Cherenkov detector

Energy Resolution

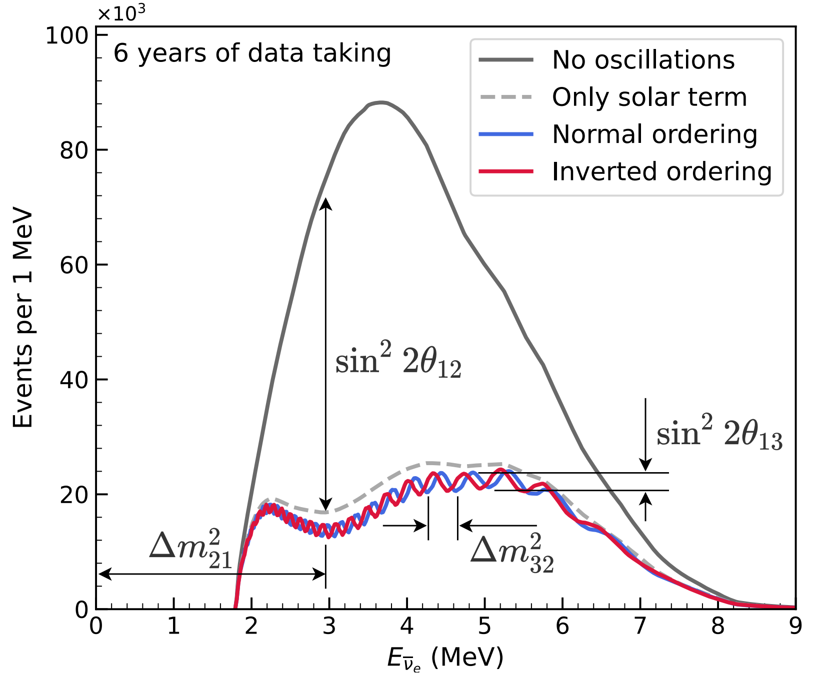
- With 3% @ 1 MeV, JUNO will be the LS detector with the best energy resolution in history
- Most obvious (although not sufficient) requirement for achieving the target energy resolution: **seeing enough photons**.
  - No approach can singlehandedly provide all the light needed. Have to attack the problem from different angles:

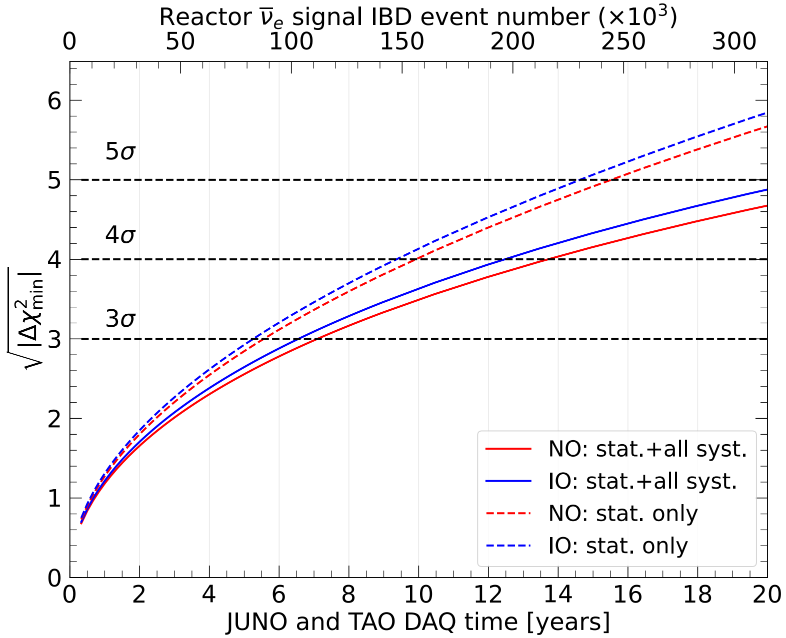
	KamLAND	JUNO	Relative Gain	
				use KamLAND as reference
Total light level	**250 p.e. / MeV**	**>1200 p.e. / MeV**	**5**	**target**
Photocathode coverage	34%	~78%	~2	lots of PMTs
Light yield	1.5 g/l PPO	2.5 g/l PPO	~1.5	optimized LS
Attenuation length / R	15/16 m	20/35 m	~0.8	optimized LS
PMT QE×CE	20%×60% ~ 12%	~30%	~2	more efficient PMTs

JUNO's Oscillation Physics

- The energy resolution allows to extract a wealth of information from the oscillated spectrum
- This includes the neutrino mass ordering
  - Exploit interference effects in the fine structure of the oscillated spectrum
  - **3σ** sensitivity within ~7 years
  - Measurement is independent of θ_{23} and δ_{CP}, and does not rely on matter effects
    - Complementary information to that of other experiments
    - Sensitivity can be boosted in combination with other experiments (e.g. [PRD 101, 032006 (2019)](), [Sci Rep 12, 5393 (2022)]())

Principle: fitting with the wrong ordering yields the wrong Δm^2_{31} value. Therefore, external constraints can help!





[arXiv:2405.18008]() (accepted by CPC)

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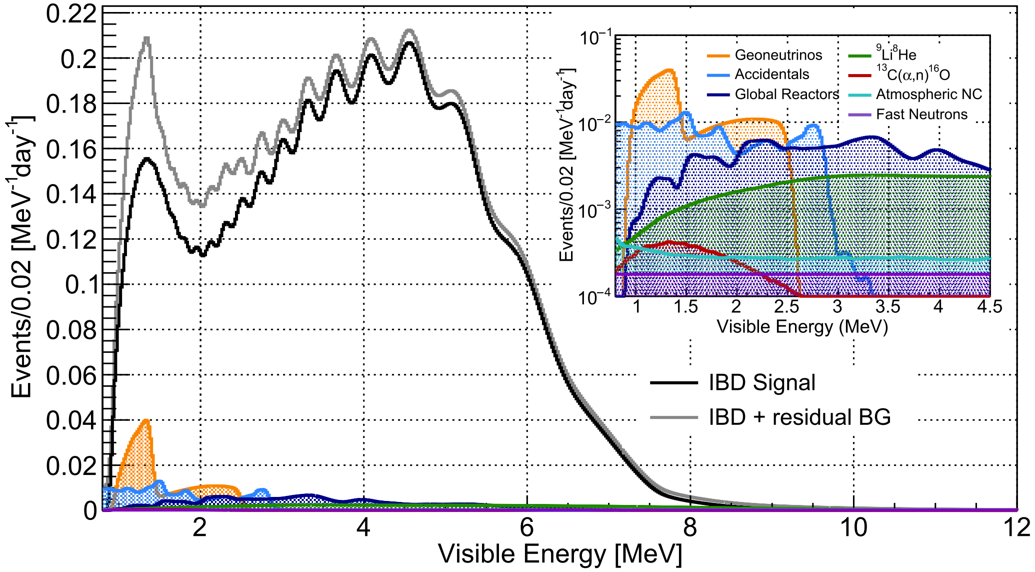
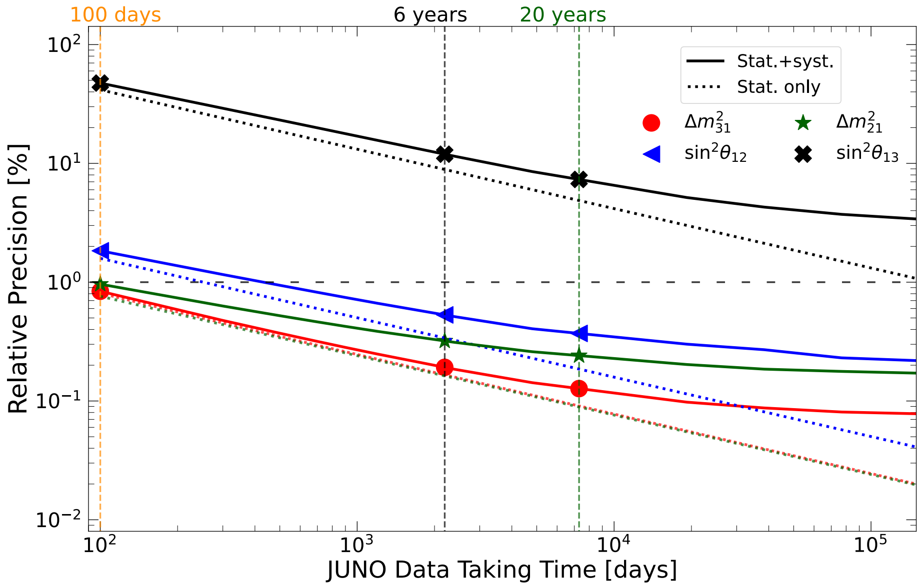
JUNO's Oscillation Physics

- JUNO will also measure $\sin^2\theta_{12}$, Δm^2_{21} and Δm^2_{31} to better than 0.5% in 6 years





Chin. Phys. C 46, 123001 (2022)

- Important input for the neutrino community:
  - New era of precision for neutrino mass & mixing models
  - Model independent tests of the three-neutrino oscillation framework (U_{PMNS} unitarity tests)
  - Narrow down parameter space for $0\nu\beta\beta$ searches

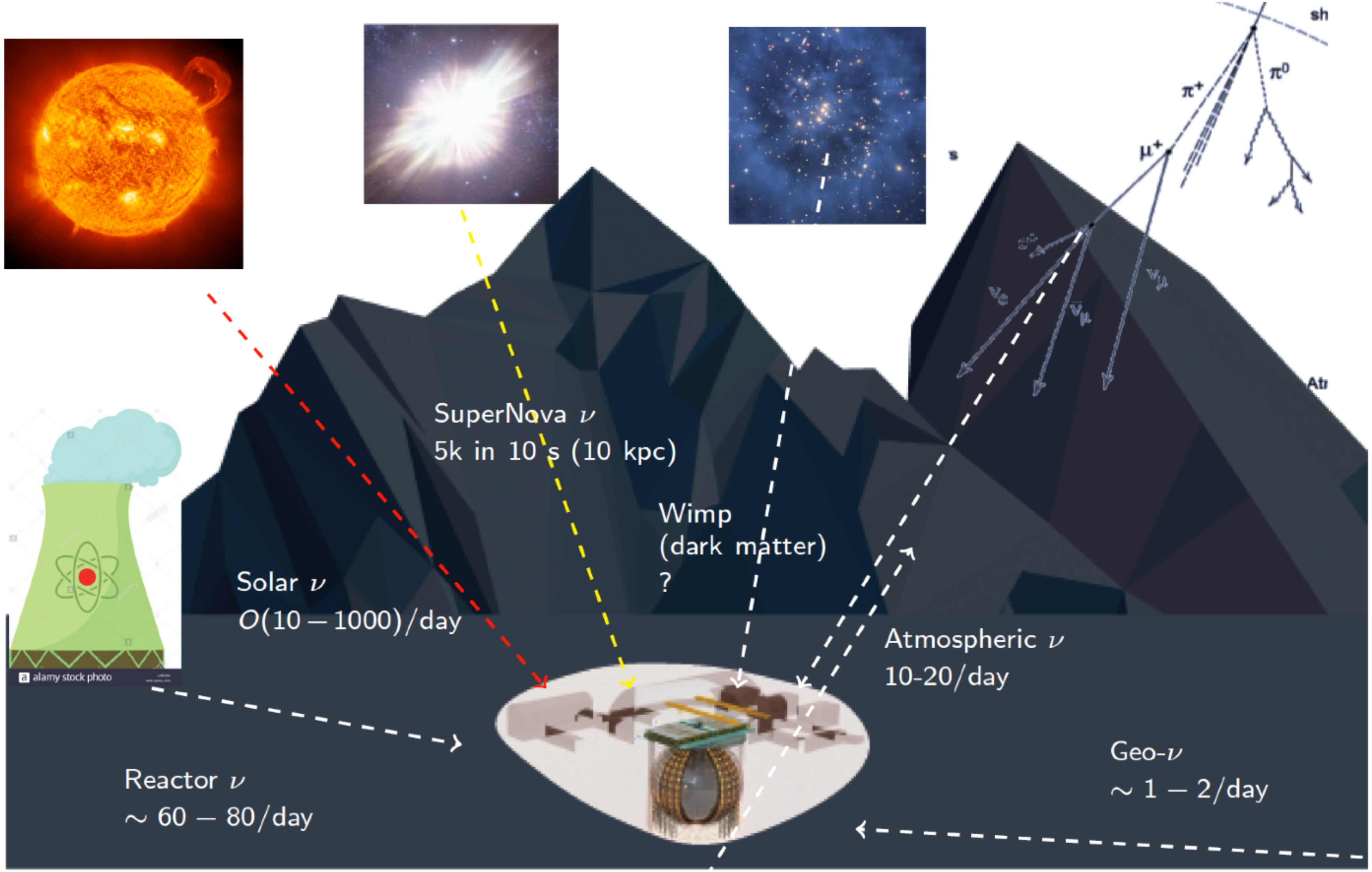
Parameter	$\sin^2\theta_{12}$	Δm^2_{21}	Δm^2_{32}	$\sin^2\theta_{13}$
Current Precision*	4.2%	2.4%	1.1%	3.2%
JUNO 6 years	0.5%	0.3%	0.2%	12.1%

* from PDG 2024

Roughly one order of magnitude improvement over existing precision for 3 parameters!

Other JUNO Physics

- JUNO also has a rich program in non-oscillation physics, which are outside the scope of this talk
  - Low threshold, excellent energy resolution and large size make it an excellent ground to study neutrinos from the Sun, the Earth, the atmosphere and Supernovae
  - Can also search for new physics, such as nucleon decay



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JUNO construction is well underway

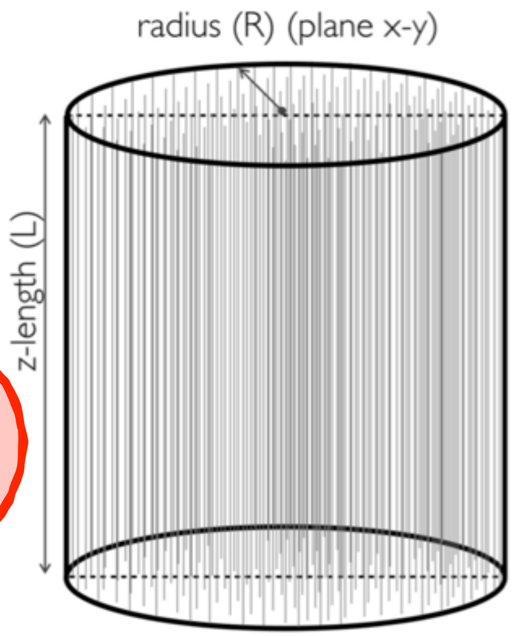
- Acrylic sphere construction was just recently completed
- Hope to begin filling in a few weeks
- Physics data by ~summer 2025

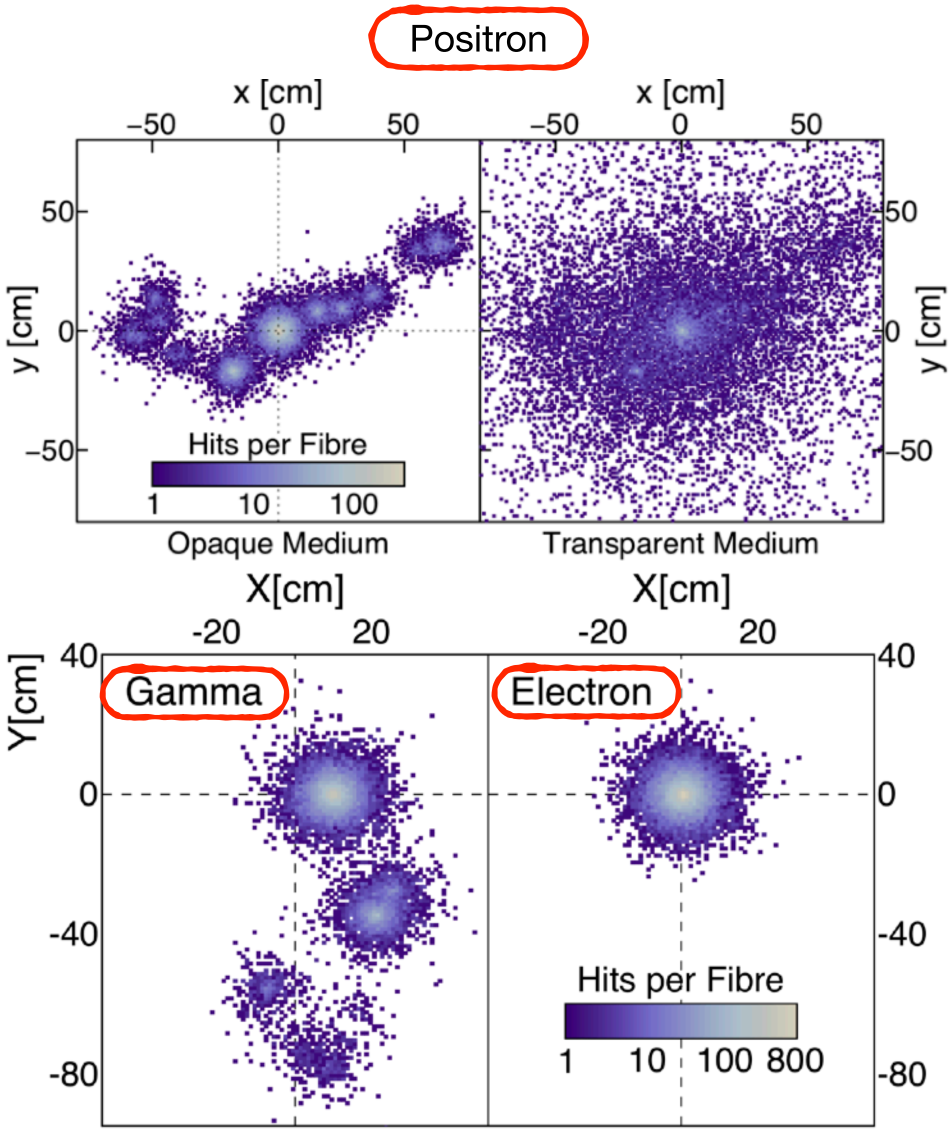
Prospects: SuperChooz

- The θ_{13} mixing angle will soon become the most poorly known
- Proposal for next-generation “SuperChooz” experiment is under active study
  - Would use the LiquidO detection technology

LiquidO detector concept: fill volume with an **opaque** scintillator and collect light with a tight array of fibers

The opacity keeps the light near its creation point, preserving valuable topological information about the event





Each of these panels assumes a 1cm fiber pitch, one pixel per fibre, 2MeV of energy

Enables imaging down to the MeV scale!

Comms. Phys. 4, 273 (2021)

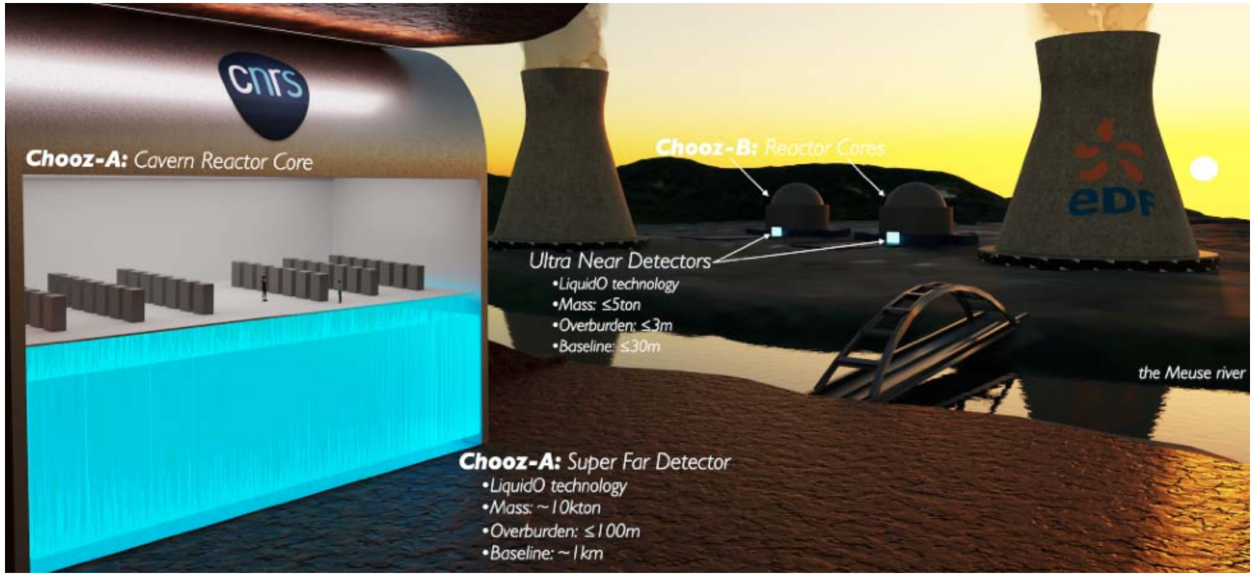
Prospects: SuperChooz

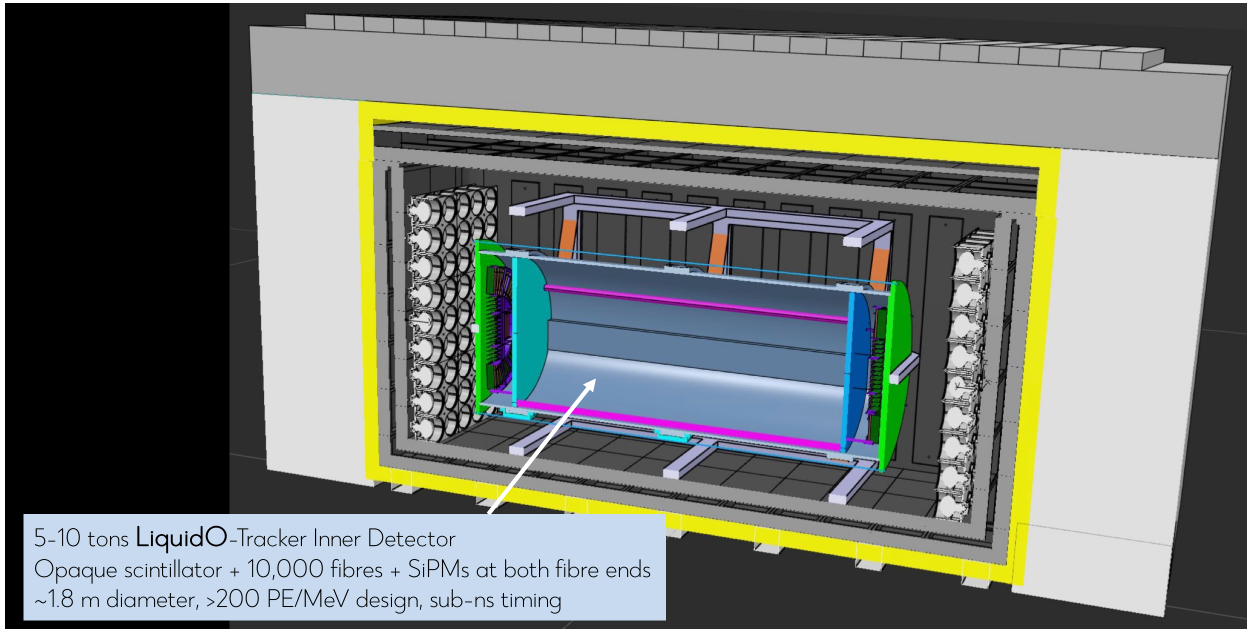
- SuperChooz would have a large, LiquidO-like far detector in cavern of old Chooz-A reactor
- In exploratory phase; demonstrator called “CLOUD” approved and under development

CLOUD:

– Demonstrator of LiquidO technology
– Baseline of about ~35 m from reactor core
– 50-10 tons, 10,000 fibers read out by SiPMs on both ends
– Will operate on three phases focused on detection of reactor antineutrinos, solar neutrinos and geo-neutrinos

For more information, please see for example Diana Navas’ talk at ICHEP 2024





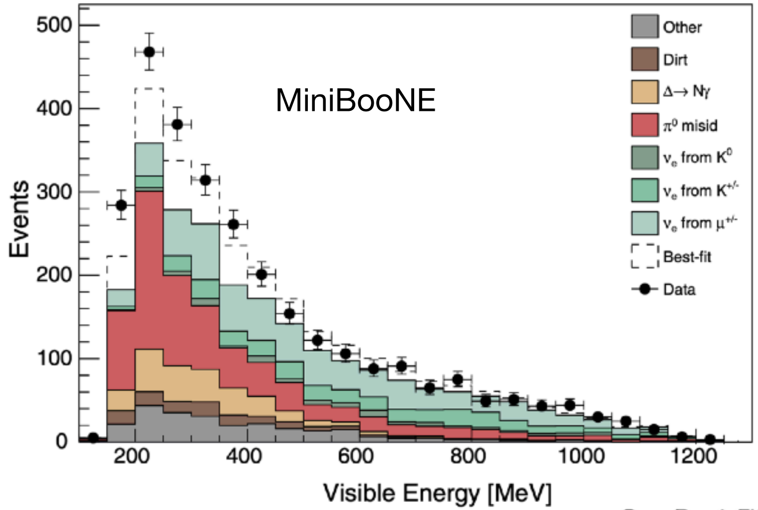
Oscillation Anomalies

with Short Baseline Reactor, Accelerator and Source Experiments

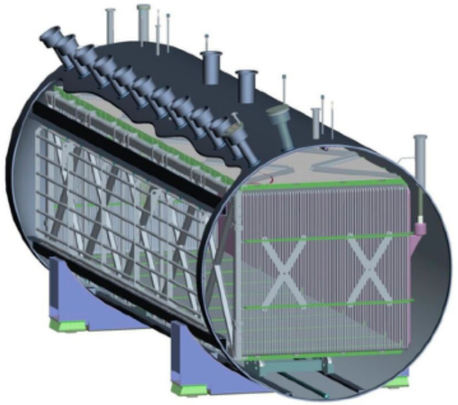
LSND/MiniBooNE

- LSND and MiniBooNE observed a ~6σ excess of electron (anti)neutrinos in a muon (anti)neutrino beam
  - Could be explained via eV-scale sterile neutrino oscillations
- However:

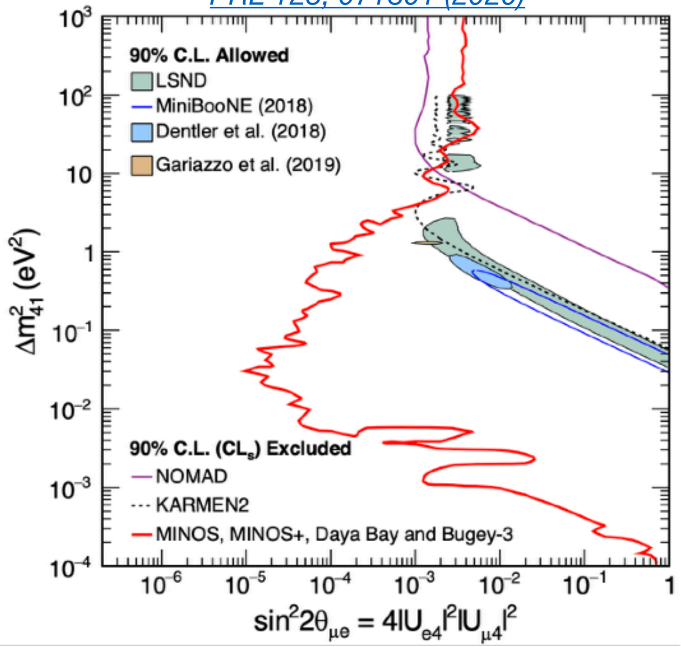
PRD 64,112007 (2001) and PRD 103, 052002 (2021)



MicroBooNE:
- 170 ton LArTPC
- Same L/E and same beam as MiniBooNE

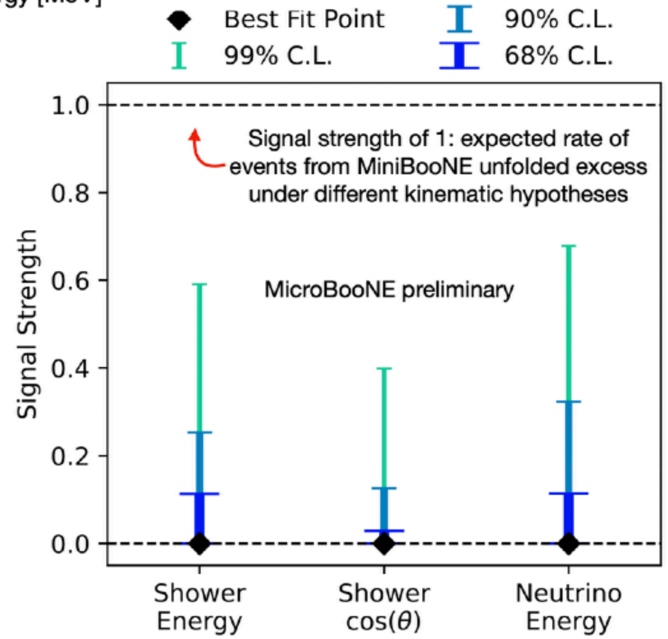


PRL 125, 071801 (2020)



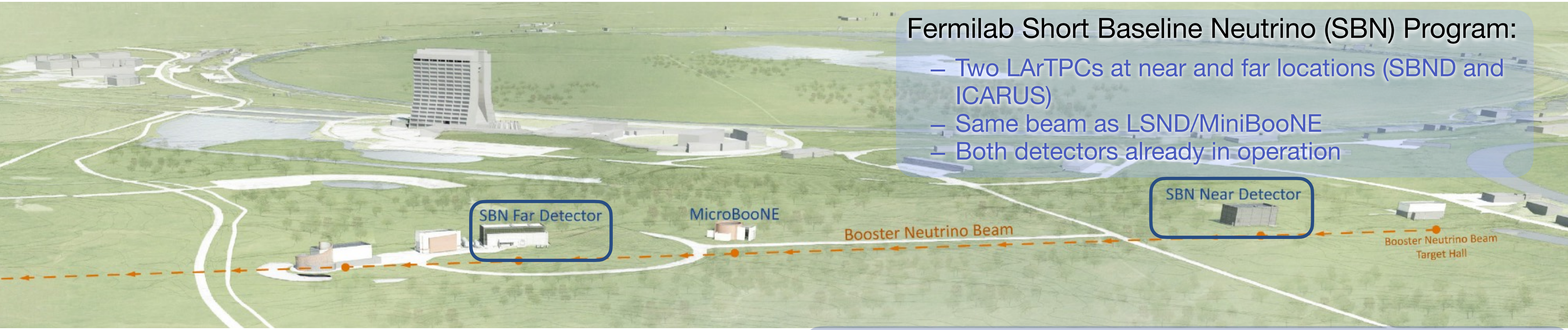
In conflict with accelerator and reactor disappearance measurements

Excess not seen by MicroBooNE experiment as either BSM e^+e^-, single-γ, or ν_e



MicroBooNE public note 1127

Further Tests



Fermilab Short Baseline Neutrino (SBN) Program:

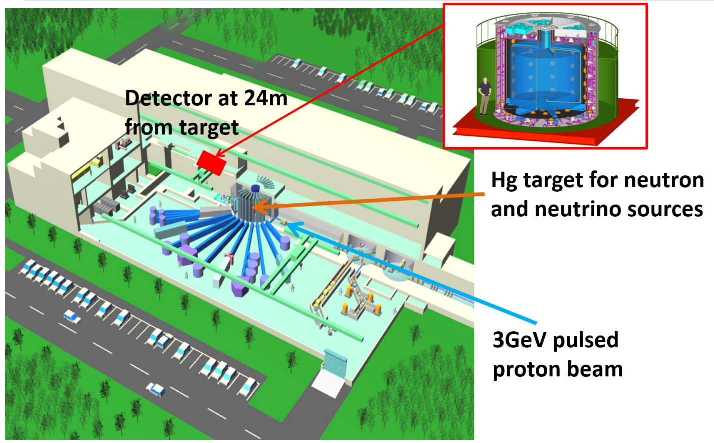
- Two LArTPCs at near and far locations (SBND and ICARUS)
- Same beam as LSND/MiniBooNE
- Both detectors already in operation

- The Fermilab SBN and JSNS[2] experiments will provide definite tests of the oscillation hypothesis:
  - Fermilab SBN: two functionally identical detectors, very robust against flux and cross-section uncertainties
  - JSNS[2]: same type of source (μ decay at rest), neutrino target (proton) and detection principle (inverse beta decay) as LSND, but with better signal-to-noise and two detectors at different baselines

arXiv:2104.13169 and arXiv:2012.10807

JSNS[2]:

- Search for ν_e appearance in ν_μ beam from J-PARC's spallation neutron source
- Pulsed neutrino source from pion, muon and kaon decay at rest



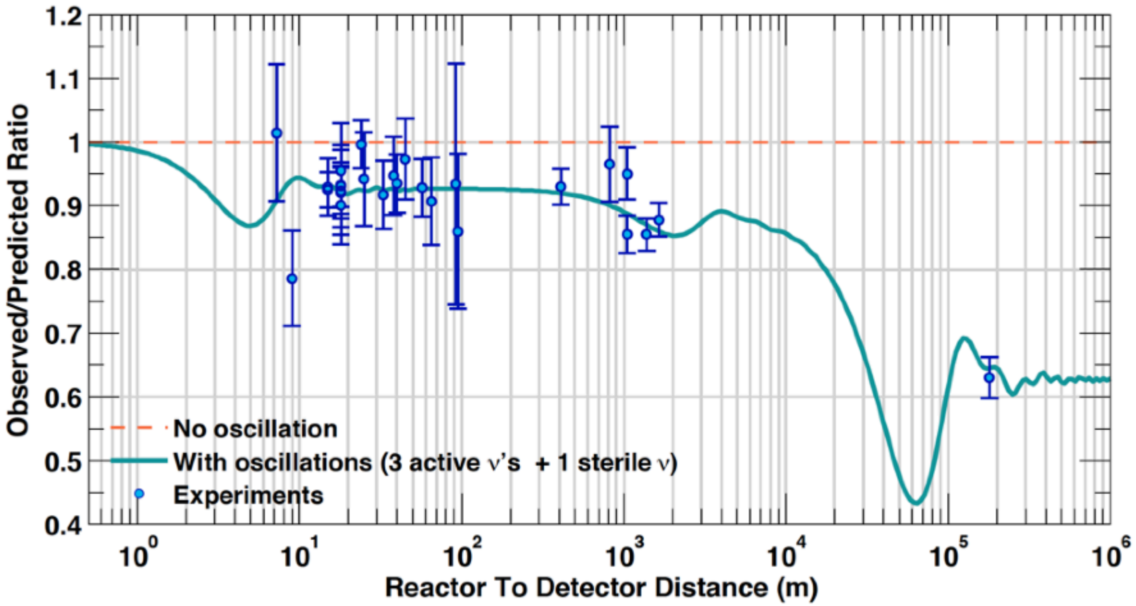
First detector already in operation

Also deploying a second detector at a baseline of 48 m

Reactor Antineutrino Anomaly (RAA)

See arXiv:2203.07214 for a detailed description

- Description: a ~6% deficit with ~3σ significance in the measured total reactor $\bar{\nu}_e$ flux versus the prediction from the Huber+Mueller (HM) model at short baselines
  - Could also be explained by ~eV sterile neutrino oscillations

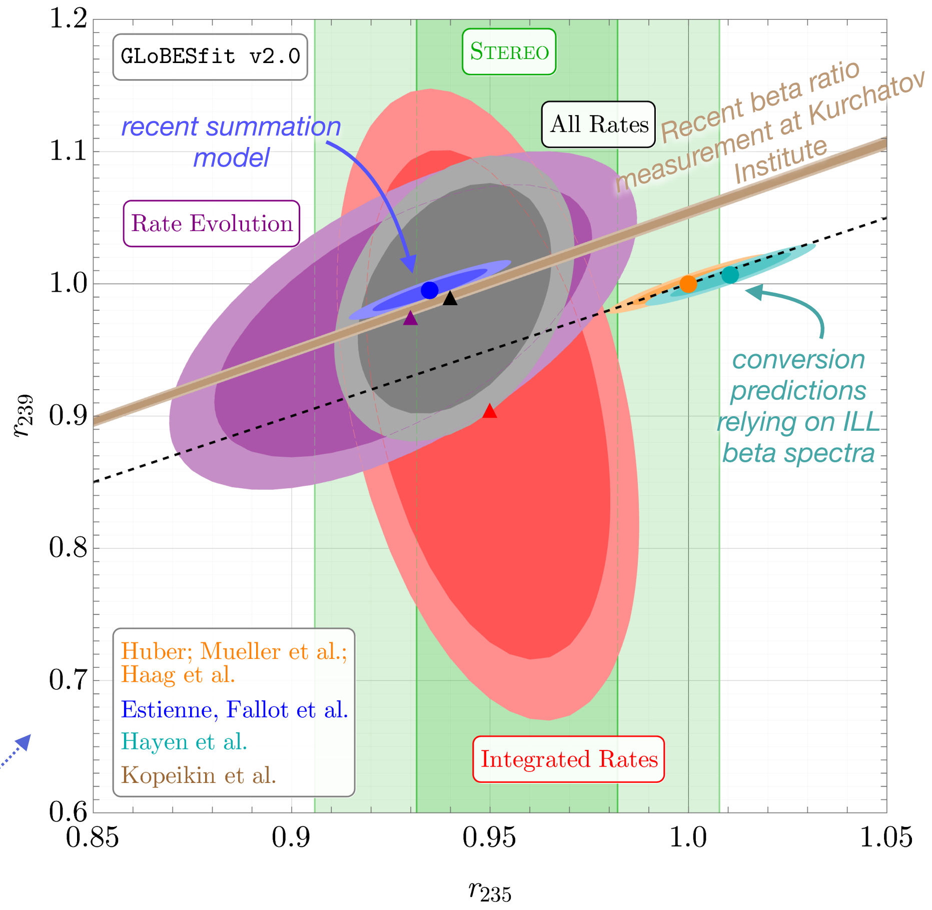


  - However, new data* suggests that the HM model overestimates the $\bar{\nu}_e$ flux from ^{235}U fission

… by about the right amount to explain the anomaly!

Note: there is still a discrepancy in the reactor $\bar{\nu}_e$ spectral shape

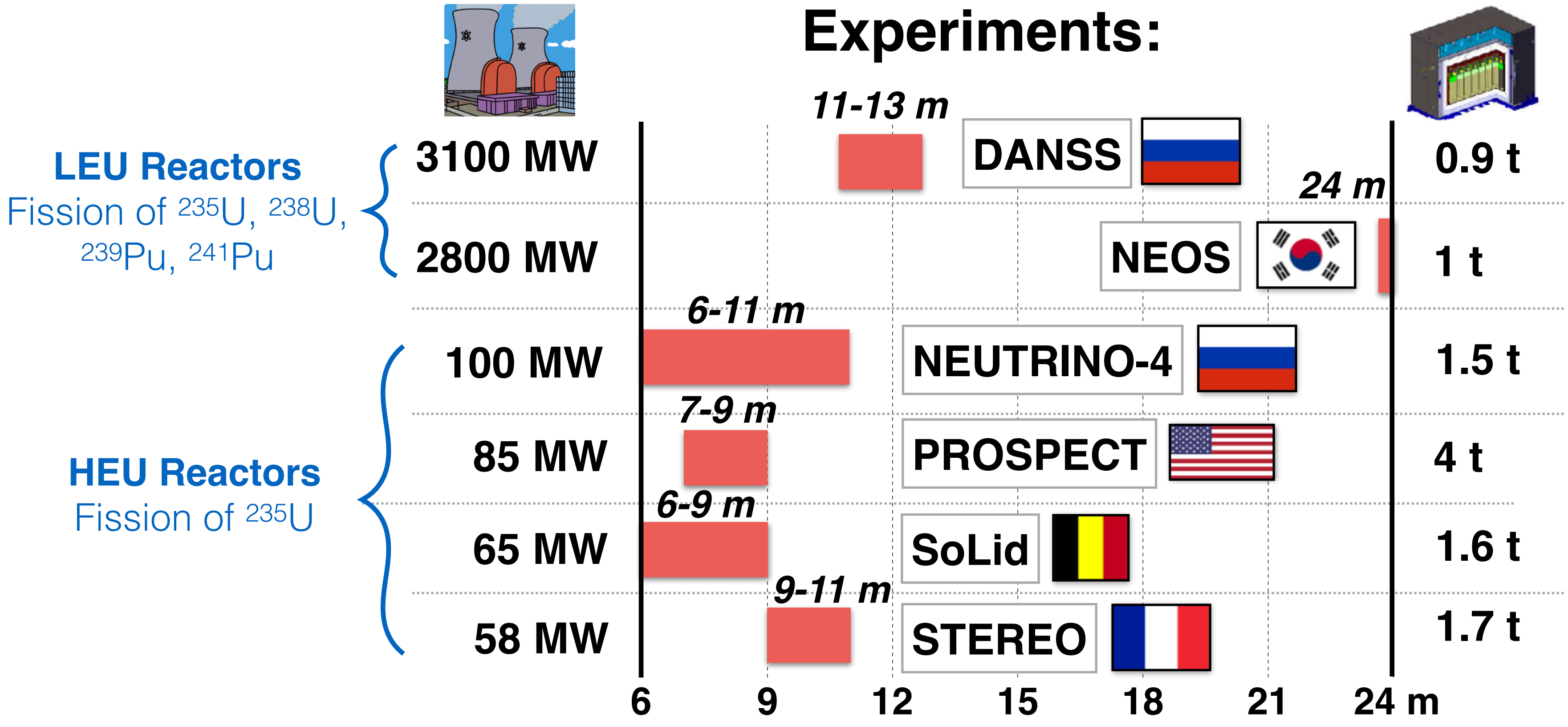
r_X = ratio of measured over predicted rate for isotope X with respect to the HM prediction



**new data = fuel evolution in LEU experiments, measurements in HEU experiments, measurement of ^{235}U/^{239}Pu beta spectra ratio at Kurchatov Institute*

Experimental Exploration of the RAA

- Moreover, searches for sterile neutrino oscillations have been performed at very short baselines:



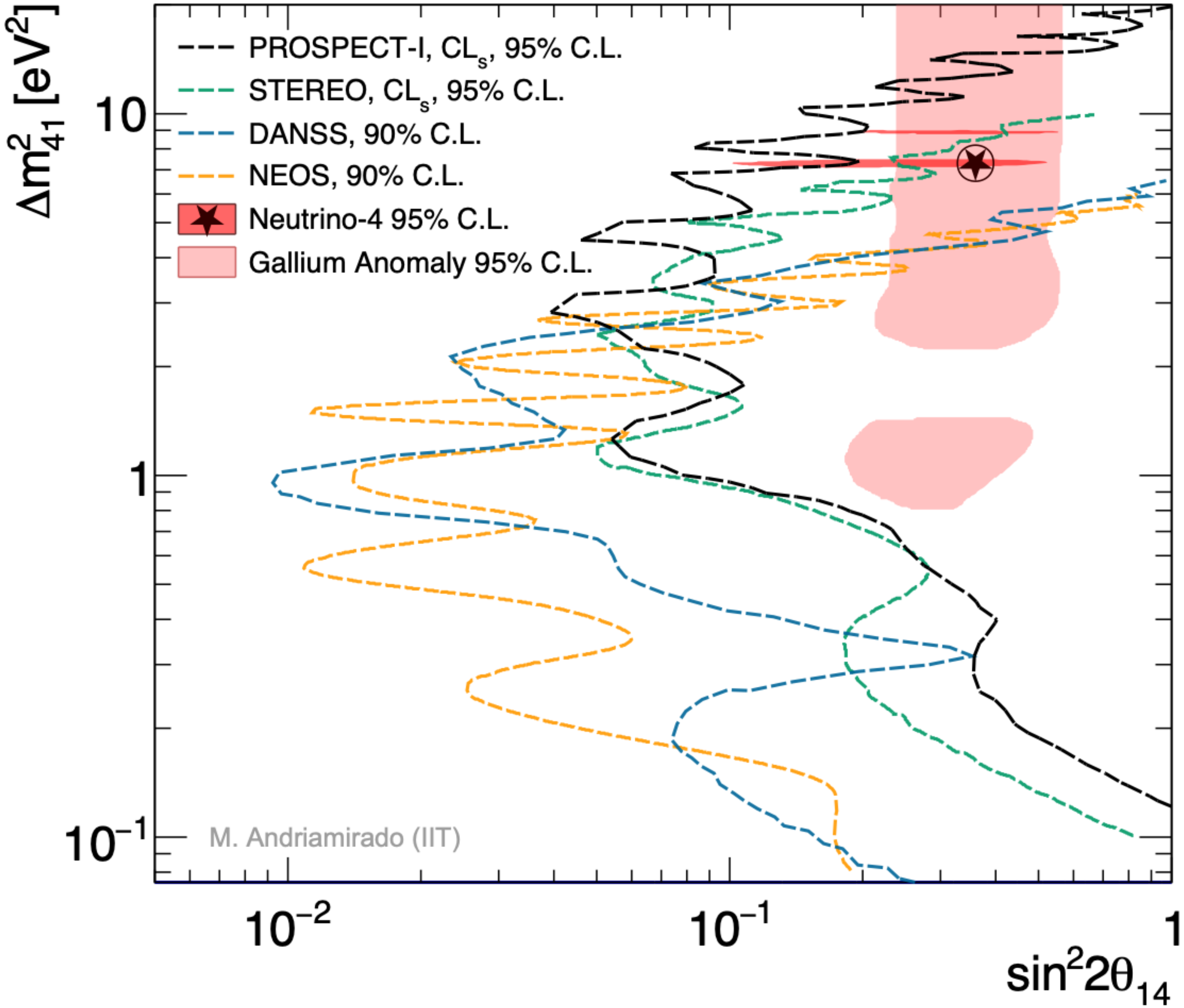
(chart courtesy of B. Roskovec)

+ (mini-)CHANDLER, NuLAT

– Most of these experiments are movable and/or segmented, allowing to search for an unambiguous oscillation signal that is independent of reactor prediction models

RAA Exclusion Contours and Hint

- One of these experiments has claimed an observation: Neutrino-4 ([PRD 104, 032003 (2021)](#))
  - All other experiments so far have set limits
- Comments about Neutrino-4's claim:
  - It is 2.7σ
  - It is controversial (e.g. PLB 816, 136214 (2021) and arXiv:2006.13639)
  - It is in strong tension with null results from other experiments (e.g. right plot)
  - It is roughly consistent with the Gallium Anomaly (next slide)



From D. Lhuillier's talk at Neutrino 2024

UCI University of California, Irvine

The Gallium Anomaly

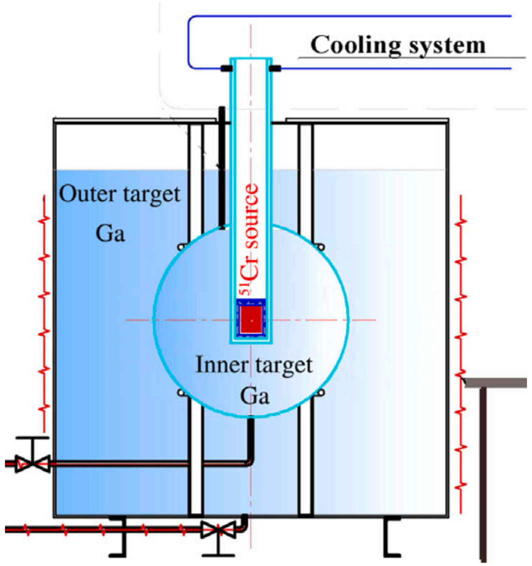
- Description: capture rates of ν_e from calibration sources on ^{71}Ga are below expectation

Gallex and SAGE:

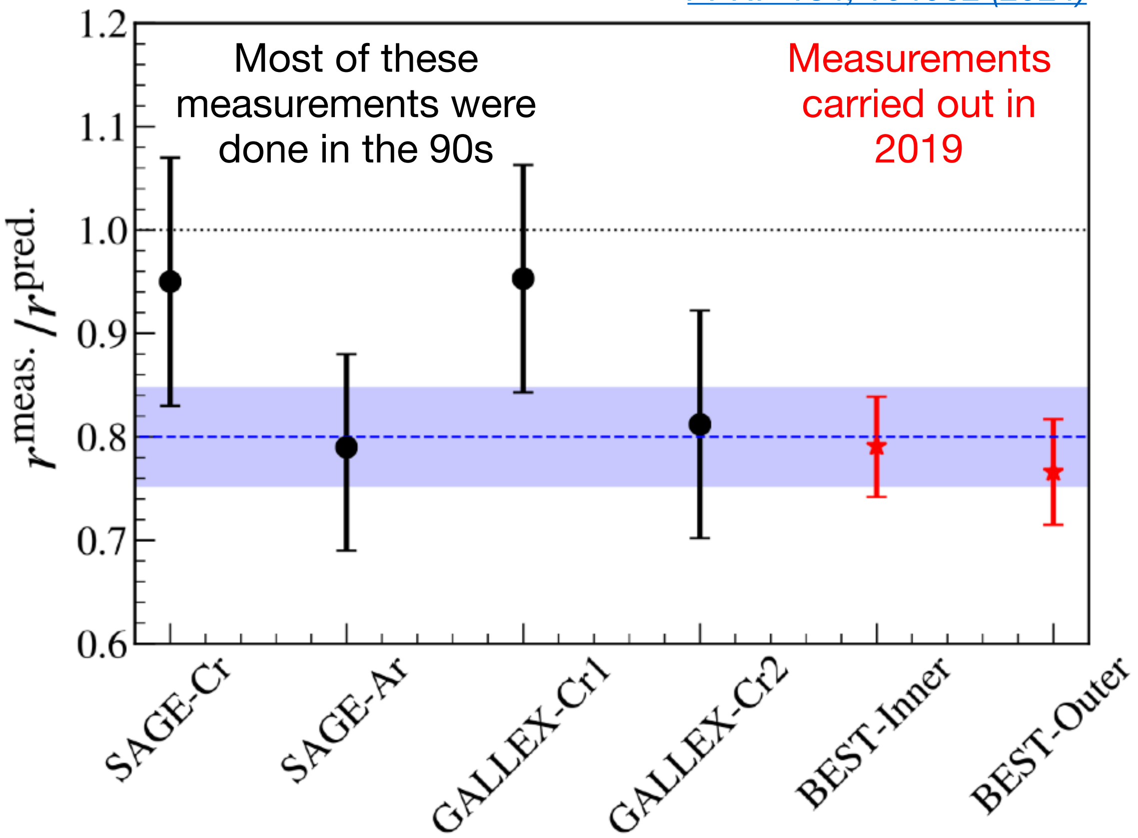
Radiochemical neutrino experiments that detected solar neutrinos via $\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^-$

BEST:

- Independent test of the Gallium Anomaly
- Two-volume design
- High-intensity ^{51}Cr source



PPNP 134, 104082 (2024)



High significance (>5σ), but oscillation interpretation in strong tension with reactor $\bar{\nu}_e$ data and KATRIN exclusion contours

- What next?
  - Several short-baseline reactor $\bar{\nu}_e$ experiments are coming online or working towards an upgrade (DANSS, JUNO-TAO, NEOS, Neutrino-4+ and PROSPECT-II)
  - KATRIN expected to fully cover Neutrino-4 and most of BEST's parameter space
  - Ideas for new tests are under planning & discussion

Summary & Conclusions

Summary & Conclusions

- Neutrino oscillations are a window to physics beyond the Standard Model and an excellent way to measure many properties of these elusive particles
- The field is now in a precision era
  - Measurements at short baselines by reactor experiments have played a critical role in elucidating the neutrino's oscillatory behavior and establishing the three-neutrino framework
  - Future measurements will address some of the most pressing open questions in neutrino physics and probe our knowledge of neutrino oscillations with unprecedented precision
- The majority of the data collected to date can be explained with the three-neutrino framework
  - Several oscillation anomalies have arisen at short baselines
  - Sterile neutrino oscillations not ruled out, but evidence has weakened

Stay tuned for more exciting results and (hopefully) some surprises!

Thank you for your attention!

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