Reactor Neutrino Experiments

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Vietnam School on Neutrinos

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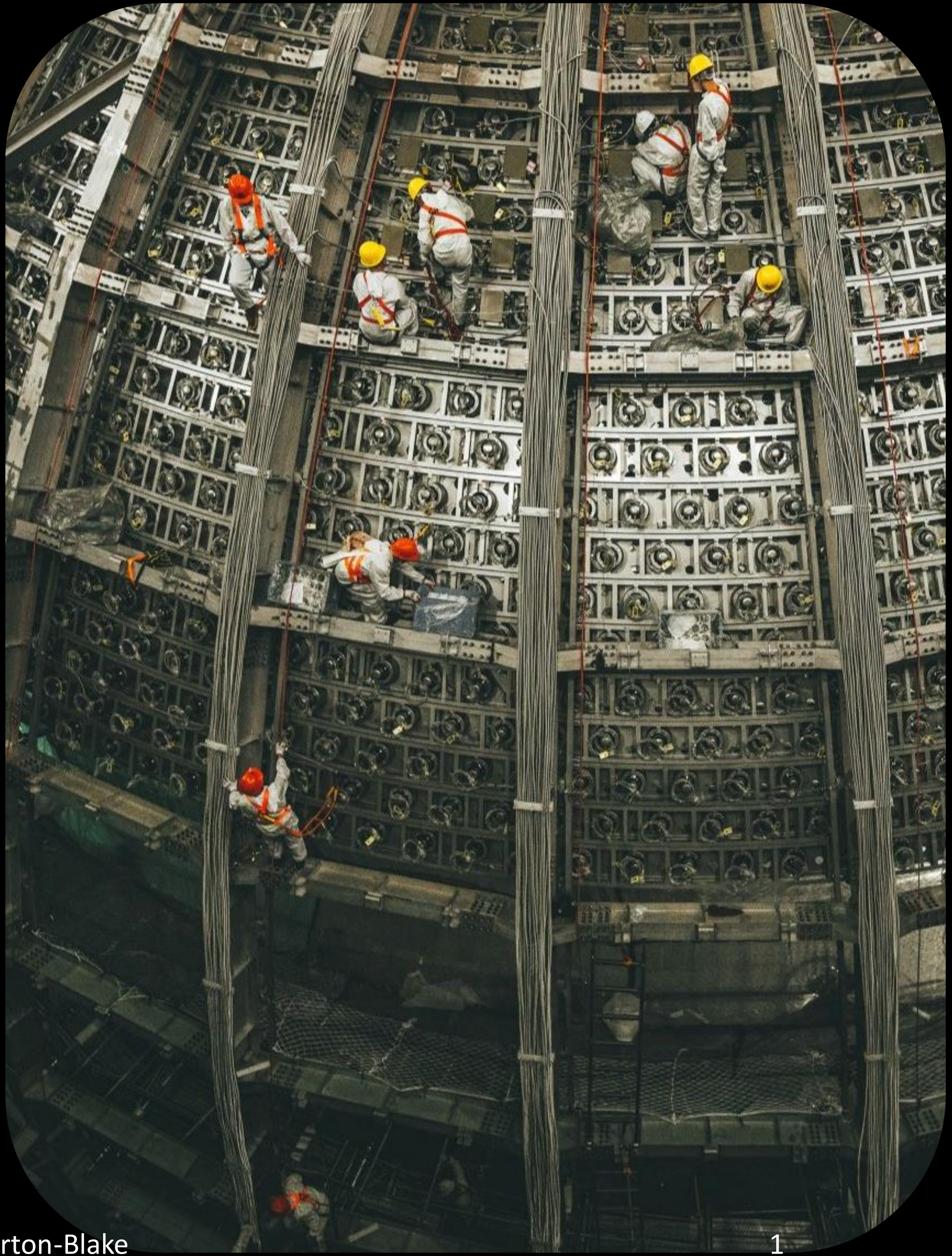
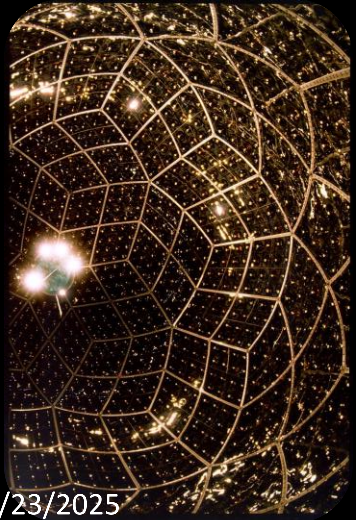


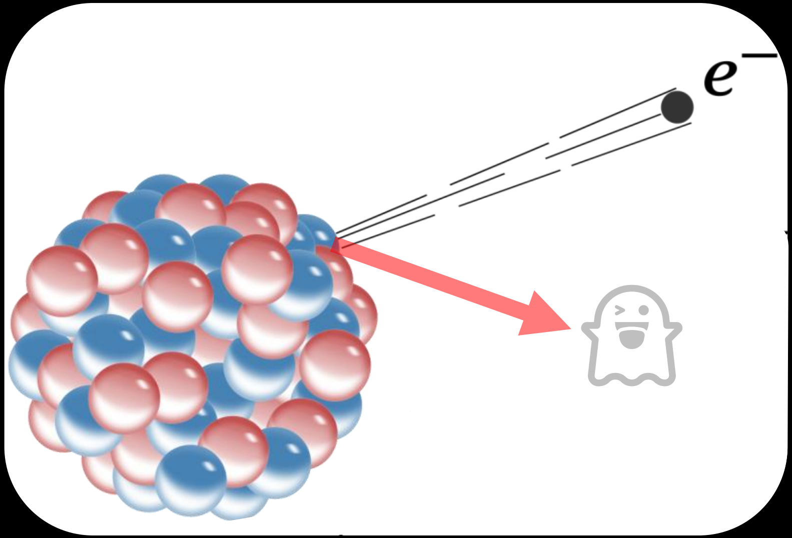


Contents

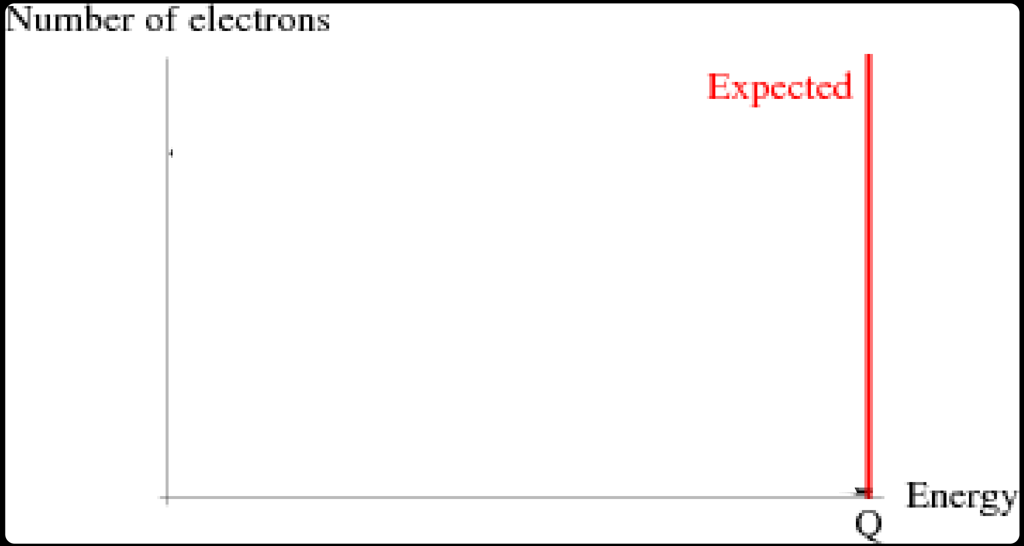
Up quark
Down quark
Strange quark
Bottom quark
Tau neutrino
Muon neutrino
Electron neutrino
Electron
Muon
Tau
Top quark
Charm quark
Photon
Gluon
Higgs boson
W boson
Z boson

Beta decay

Q-value : the change in nucleus binding energy following decay



Energy of electrons emitted in beta decay



Momentum taken away by an undetected particle

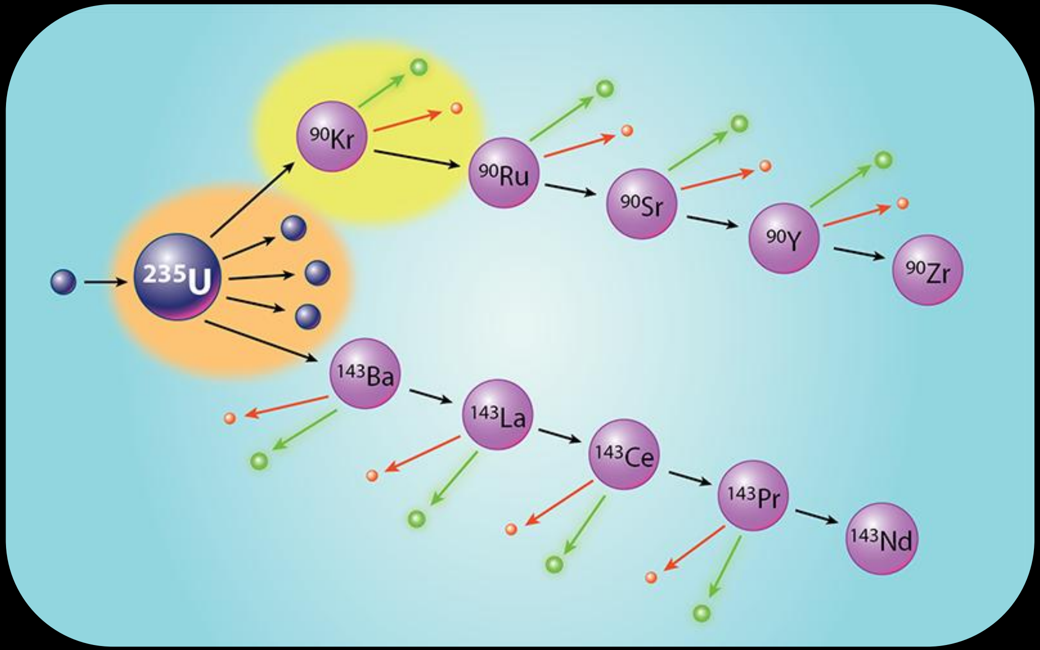
- 1930 – Wolfgang Pauli: proposed ½ spin, neutral, weakly interacting particle
- 1932 – James Chadwick: experimental discovery of neutron
- 1934 – Enrico Fermi: "little neutral one" – neutrino $\mathrm{n} \rightarrow p + e^- + \bar{\nu}_e$
- 1942 – Wang Ganchang proposed inverse beta decay ($\bar{\nu}_e + p \rightarrow n + e^+$) for their detection

Proposed an undetectable particle, "something a theorist should never do"

A huge neutrino source

- Neutron-rich heavy radioisotopes may fragment into neutron-rich daughter nuclei.
- Daughter nuclei subsequently beta-decay (to achieve stable nuclear configurations) emitting $\bar{\nu}_e$ in the process.
- The four primary contributing radioisotopes used to fuel reactors are ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu.
- ~6 neutrons on average are converted to protons per fission of radioactive nucleii fueling most nuclear reactors. This then corresponds to the emission of 6 $\bar{\nu}_e$ per fission.
- ~2×10^{20} $\bar{\nu}_e$ per second per GigaWatt e.g. Daya Bay nuclear reactor ~17.5GW

Carefully controlled fission of heavy isotopes → boil water → generate electricity



Proposed detection : Inverse Beta decay (IBD)

- Inverse Beta Decay (IBD) : interaction of $\bar{\nu}_e$ on a proton:

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

- Positron is charged → detectable!
- Neutron can be captured/absorbed on a nucleus → detectable!
- Minimum energy for IBDs:
  - ~Mass difference of proton and neutron:

$$E_{\bar{\nu},\mathrm{min}}^{\mathrm{IBD}} = \frac{(m_n + m_e)^2 - m_p^2}{2m_p} = 1.806\mathrm{MeV}$$

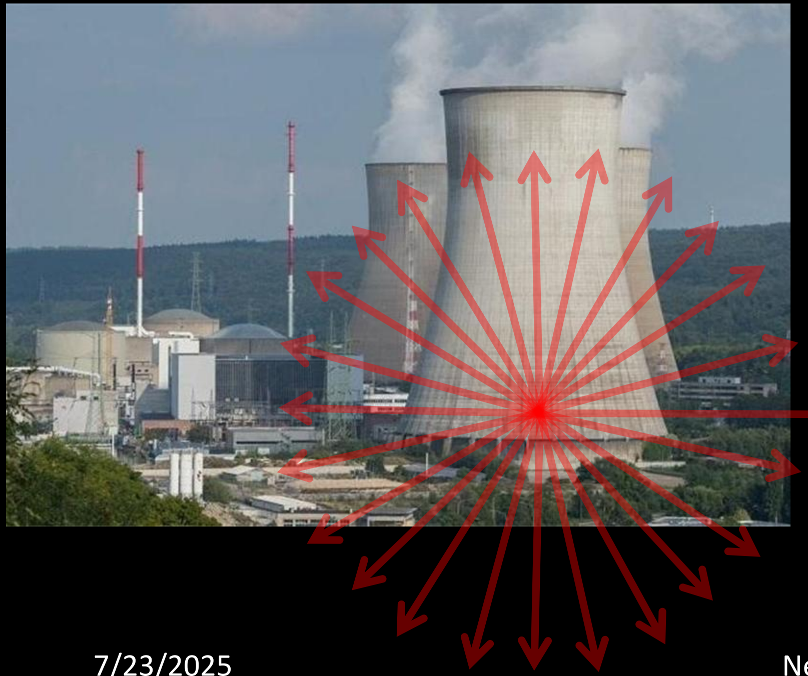
- Reactor $\bar{\nu}_e$ range from 0 to ~10 MeV
  - Let's try!

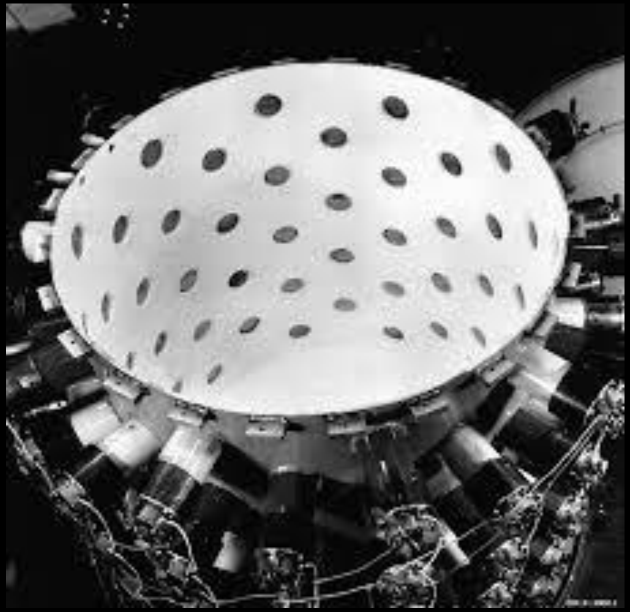
First neutrino detection

<u>Reines and Cowan first attempted in 1953</u>

Used 300 Litres of liquid scintillator (will come back to this later) to detect IBD

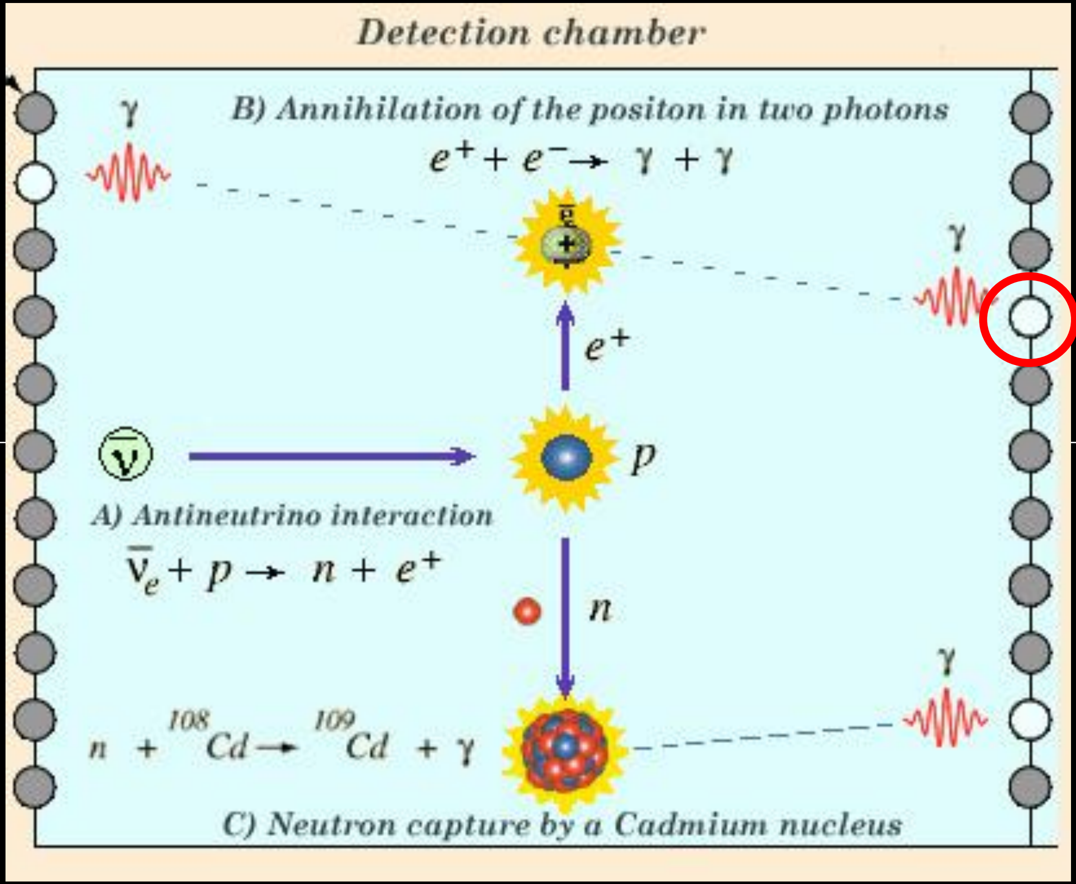
90 photomultiplier tubes (PMTs) to detect the faint light from e^+ and neutron

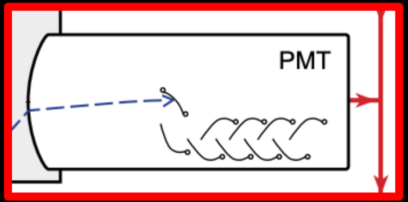




First neutrino detection

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



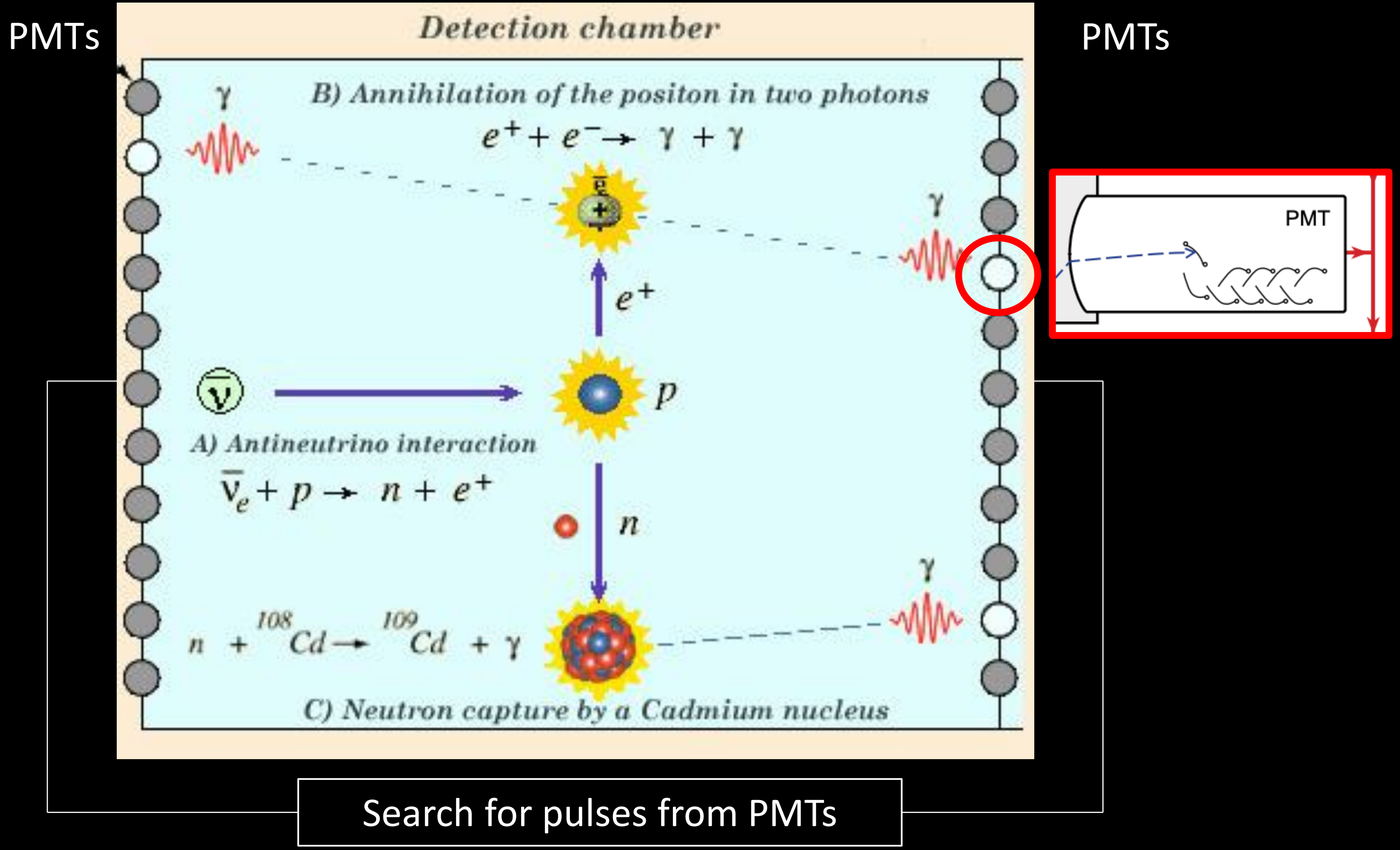


Search for pulses from PMTs

- e^+ and e^- annihilate into 2 gammas
- Shower of charged particles deposit energy in scintillator → emits light
- PMTs amplify the single photon signals
- Neutron takes 100s of nanoseconds to capture on Cd then emit a gamma:
  → **Search for prompt – late pair**

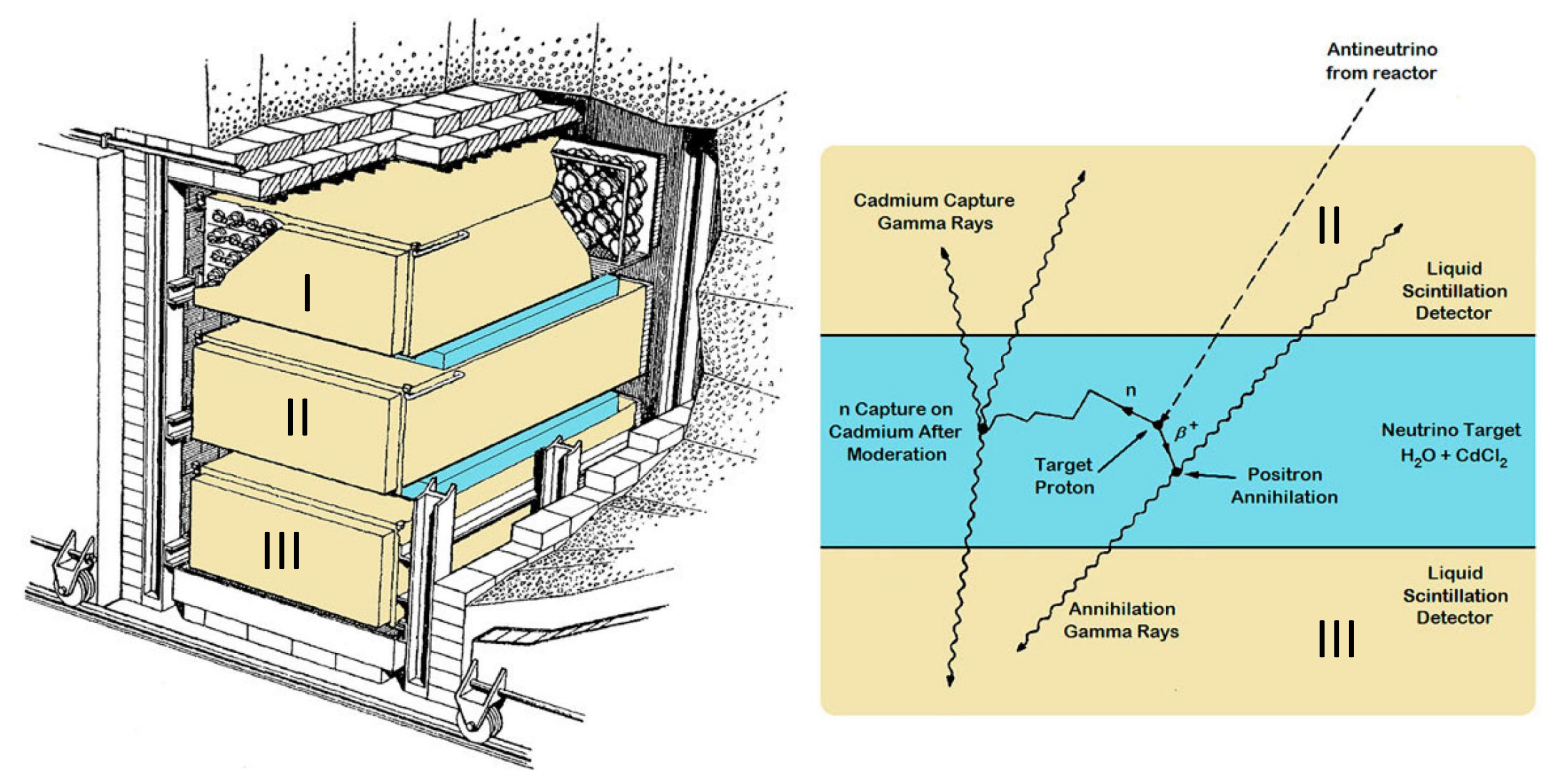
First neutrino detection

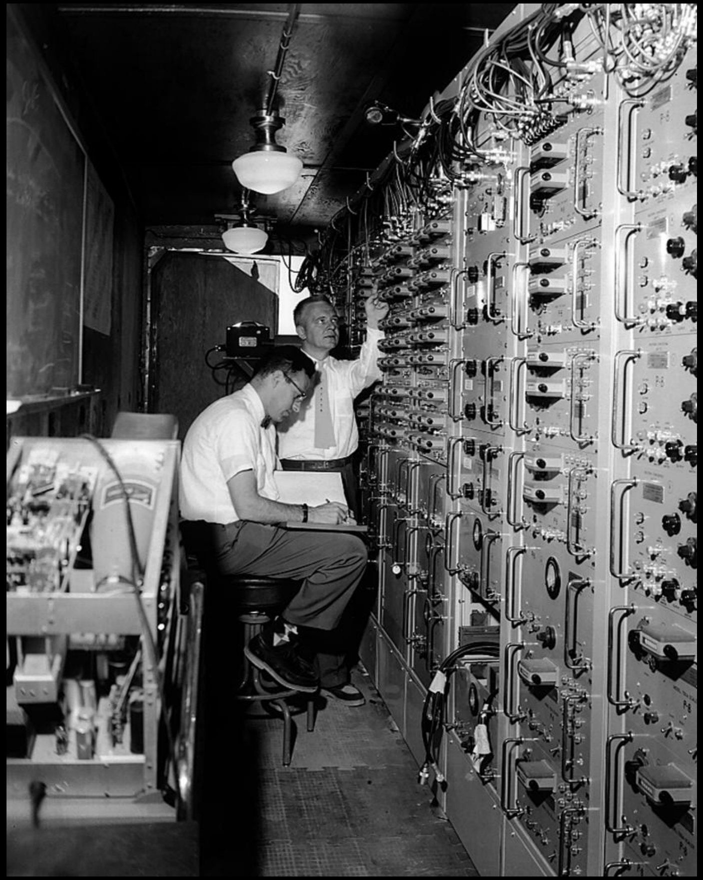
$$\bar{\nu}_e + p \rightarrow e^+ + n$$



- Indications of signals found – but a larger detector with lower backgrounds were needed
- Reines and Cowan planned an upgraded experimental setup

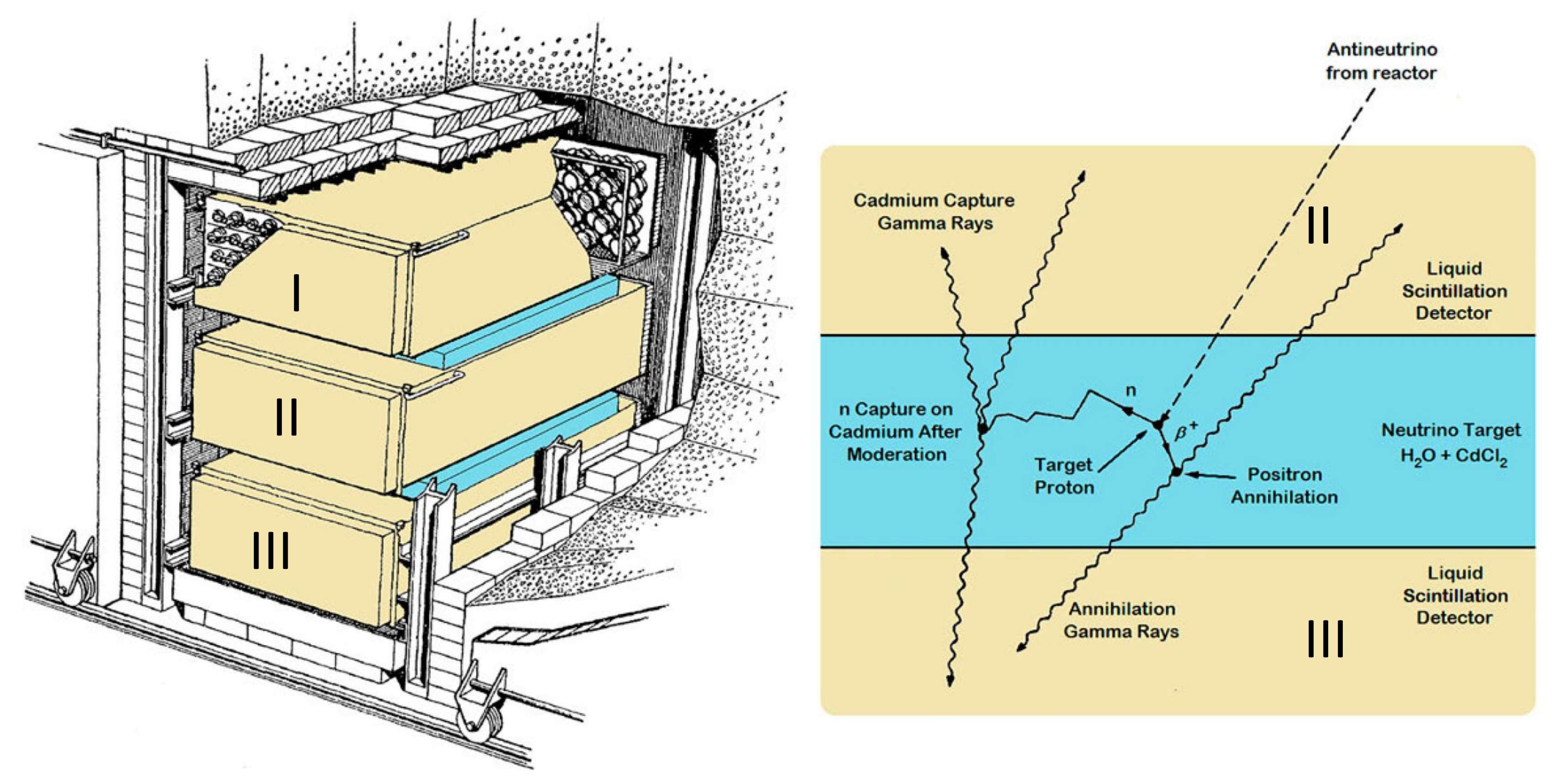
First neutrino detection





1956 – Savannah River Detector

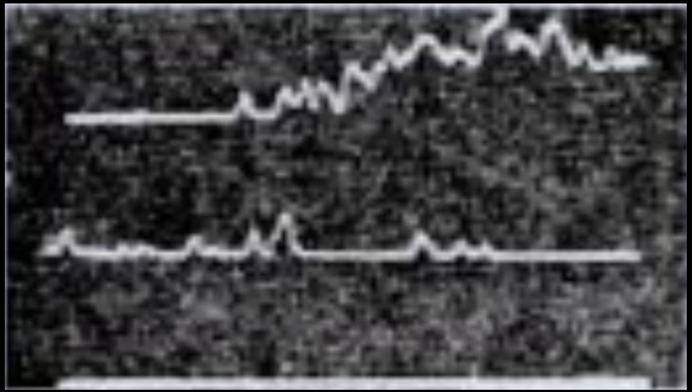
First neutrino detection



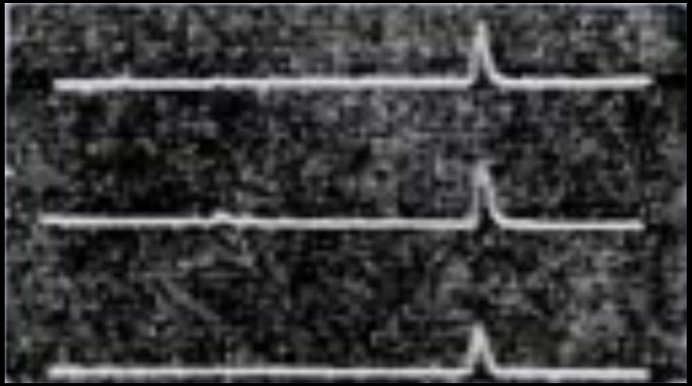
1956 – Savannah River Detector

Backgrounds:

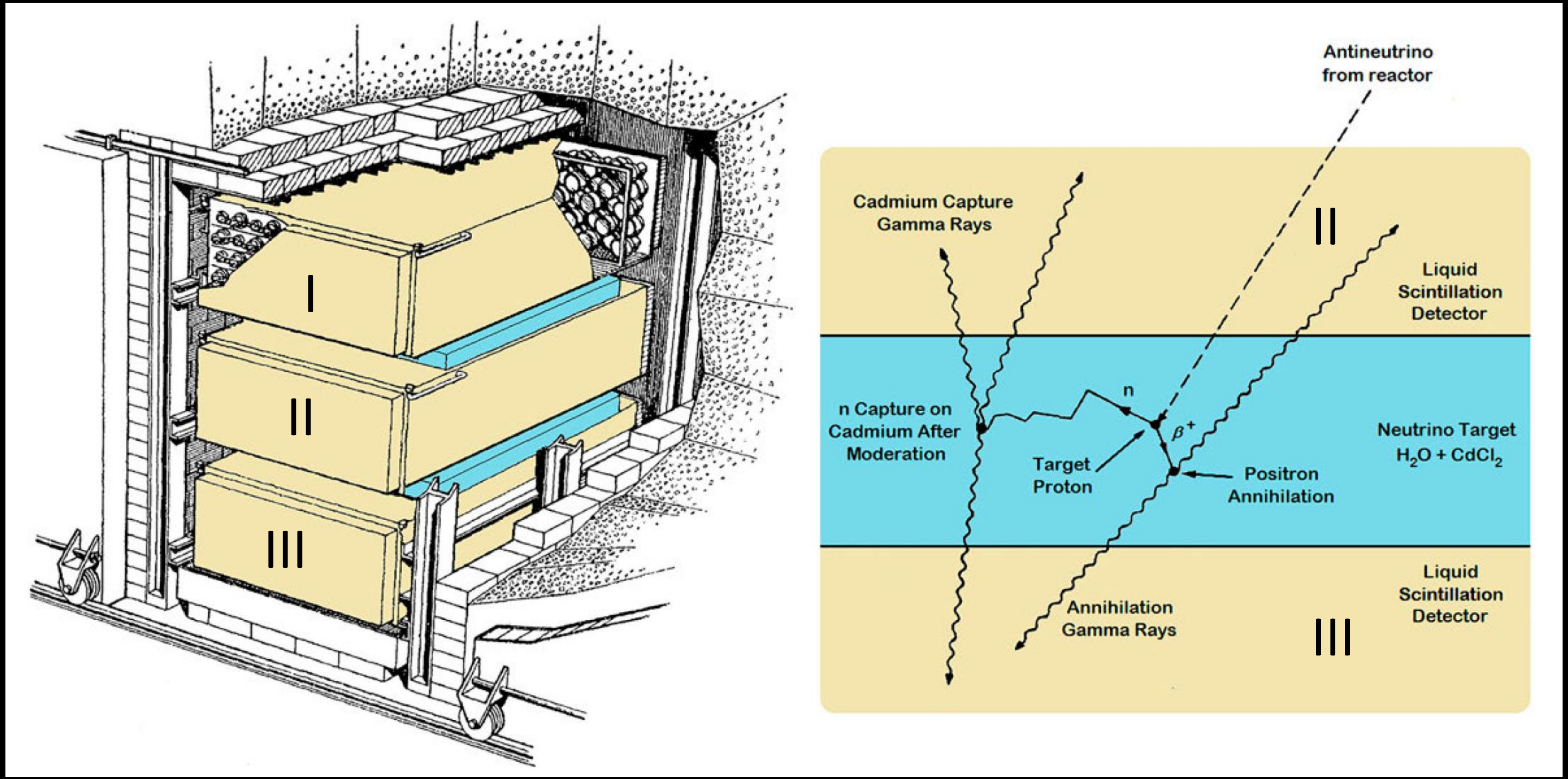
- Radioactivity → beta-decay / gammas can produce signals



- E.g. Muons can pass through all 3 layers



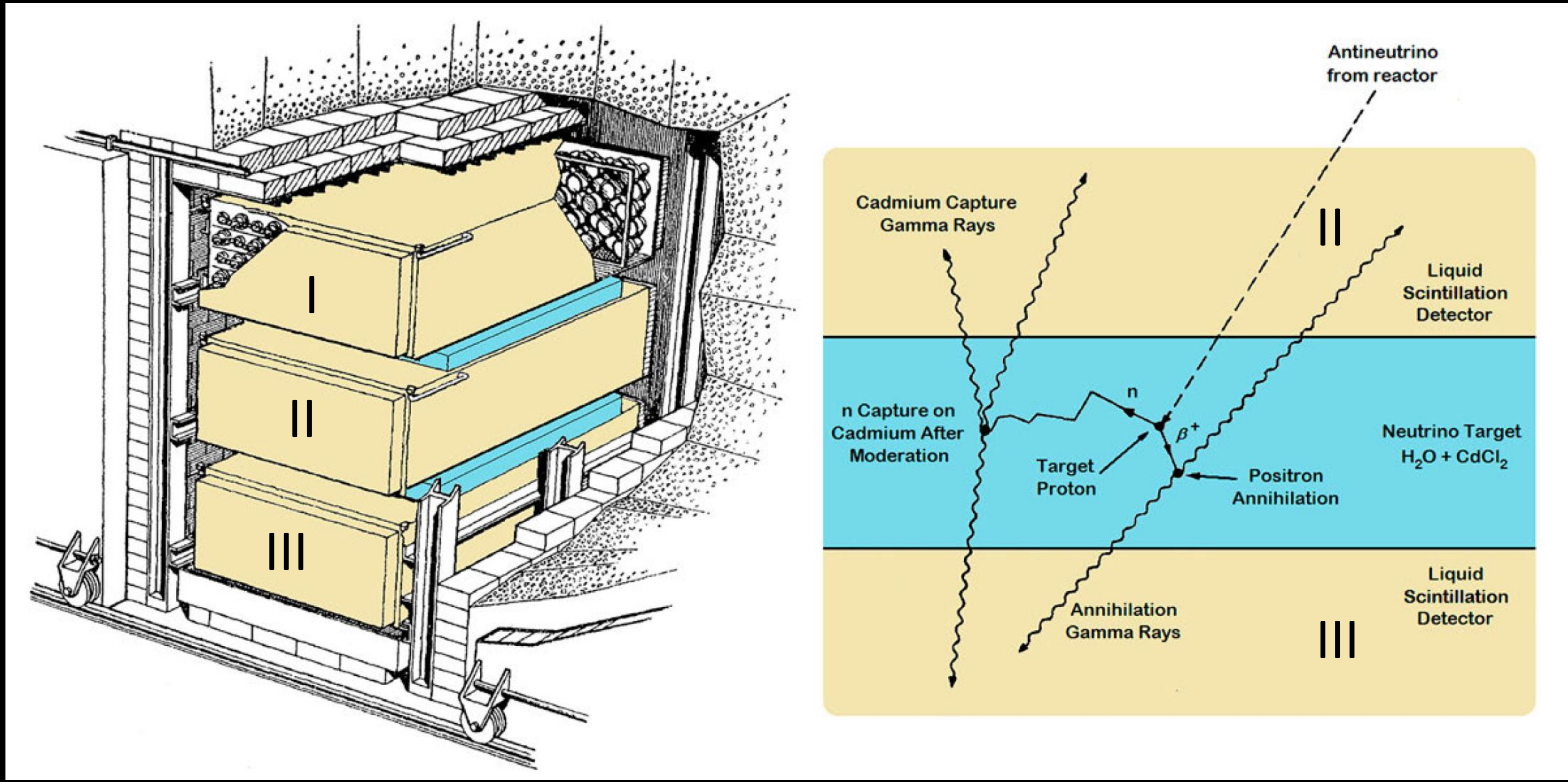
First neutrino detection

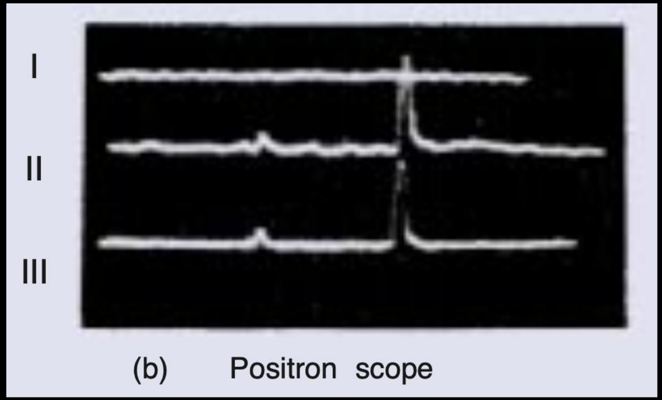


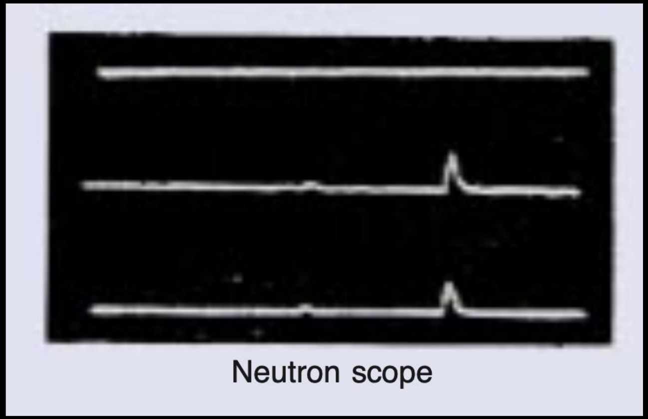
1956 – Savannah River Detector

Calibration:
- Want to detect positrons and neutrons
- Place well-known radioactive sources:
- Positron source + neutron source to verify the expected signals

First neutrino detection







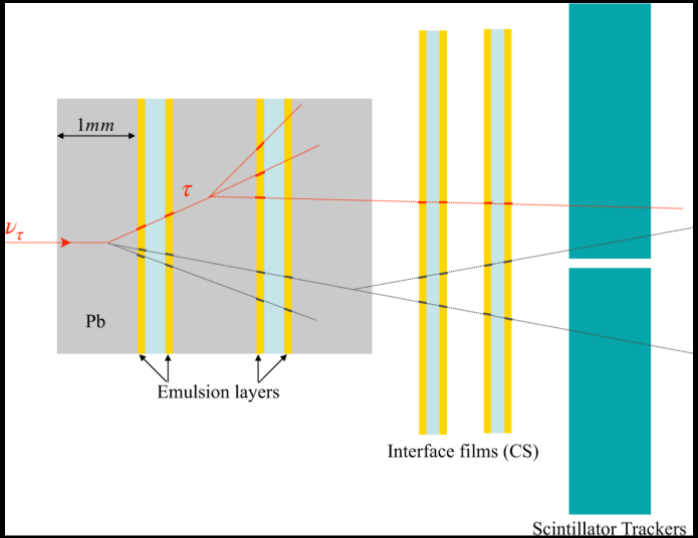
1956 – Clyde Cowan and Fred Reines experimental discovery of $\bar{\nu}_e$

<u>Clear signals found</u>:
2 gammas from positron
2 gammas from neutron capture
Triple coincidence clearly seen!

Neutrino Flavours ν_e ν_μ ν_τ

1962 – First experimental measurement of ν_μ by Lederman, Schwartz and Steinberger.

2000 – Tau neutrino ν_τ by the DONUT experiment



- After 1957, Bruno Pontecorvo presented a theory of oscillation between ν and $\bar{\nu}$, inspired by the first measurement of kaon particle-antiparticle oscillation.
- After the measurement of ν_μ, Pontecorvo completed his theory, allowing for oscillation between <u>two neutrino flavours.</u>

Contents

1) Neutrinos and their Discovery

2) Neutrino oscillation measurements

3) Reactor neutrino experiments

4) Ahead

"How to make a neutrino beam"

By Jessica Orwig, Symmetry Magazine 11/13/12

Solar neutrino problem

- First hint of neutrino oscillation was in 1970 in the Homestake solar neutrino experiment, by Ray Davis and John Bahcall
- Bahcall predicted the solar neutrino flux
- Davis used ^{37}Cl as the detection medium deep in the Homestake mine to avoid atmospheric backgrounds
- Experiment saw approximately 1/3 the theoretical model
- Known as the ‘solar neutrino problem’

Homestake solar neutrino experiment

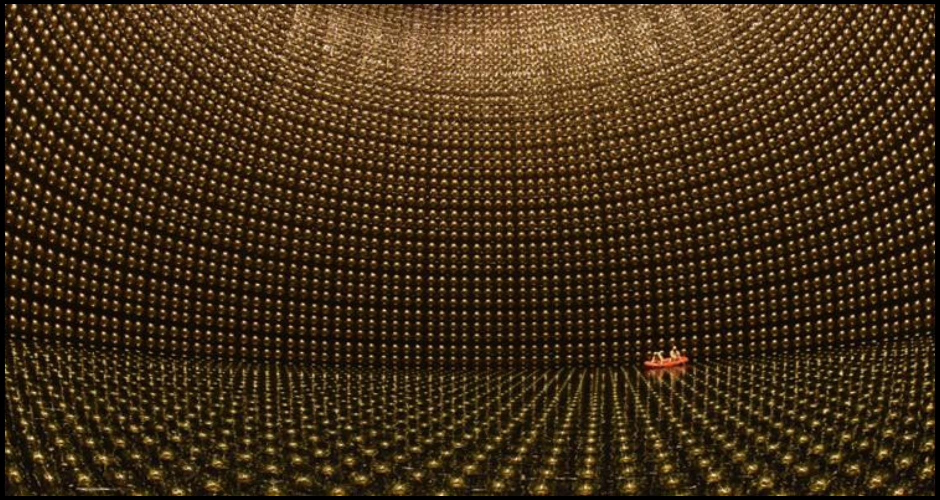
Solar neutrino problem

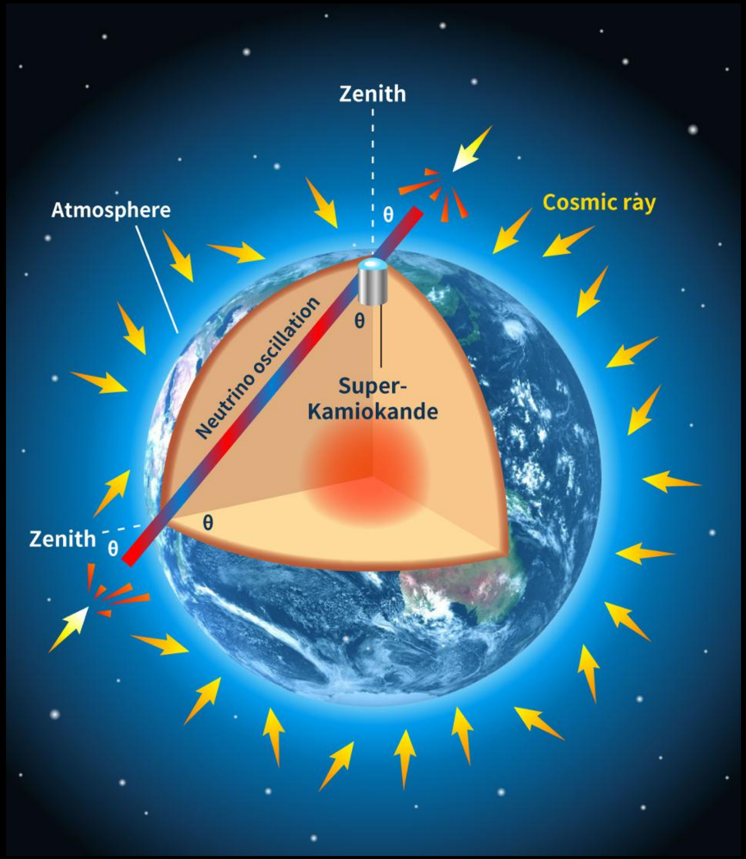
- Anomalies also seen later for atmospheric neutrinos in 1980's. Kamiokande-II and IMB both measured significant deficits in the expected ratio of ν_μ to ν_e

Homestake solar neutrino experiment

Neutrino Oscillation Measurement (1/2)

- Super Kamiokande – 50,000 ton Cherenkov detector
- 1996 measured clear asymmetry in ν_μ above and below the detector
- Oscillation of $\nu_\mu \rightarrow \nu_\tau$ was inferred





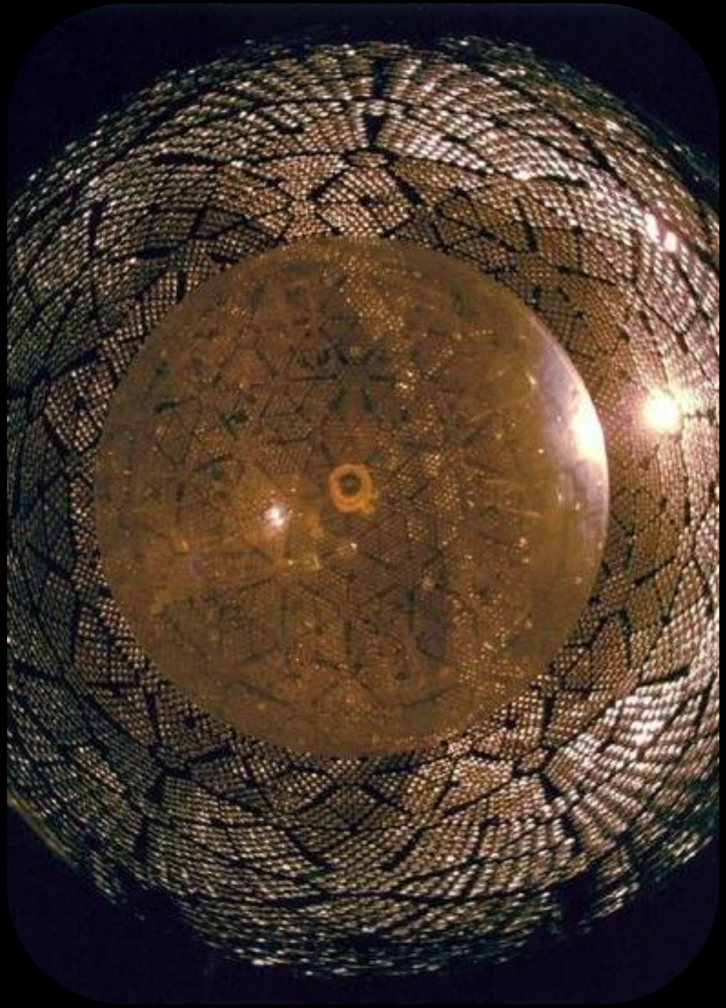
Neutrino Oscillation Measurement (2/2)

- In 2002 SNO, 1000 tons of heavy water definitively demonstrated oscillation in solar neutrinos.
- Heavy water, deuterium (p+n) allowed for the measurement of ν_e through the charged-current (CC) process, and the total ν_X through the neutral current (NC) interaction.

$$\nu_e + d \rightarrow p + p + e^-$$

$$\nu_x + d \rightarrow p + n + \nu_x,$$

- The SNO result confirmed the standard solar model and the observable mixing between ν_e, ν_μ and ν_τ

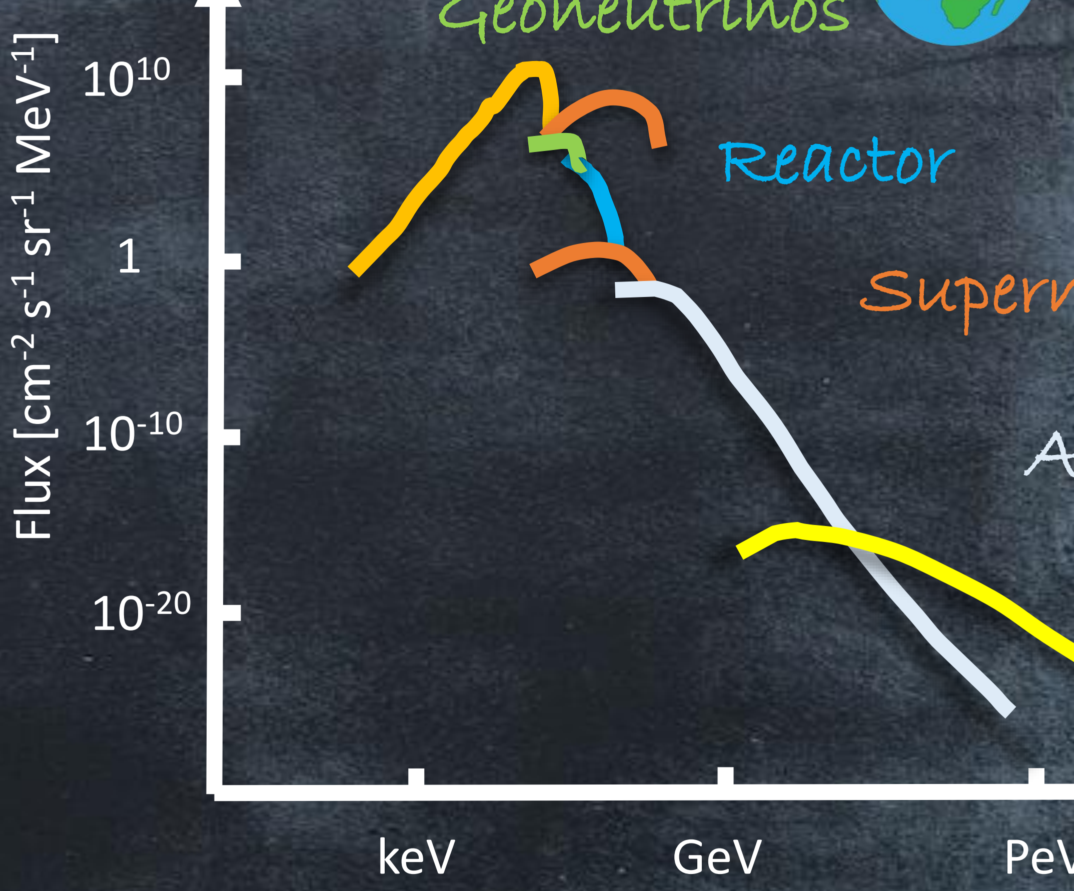


Neutrino Sources

~100 billion ν pass through your thumbnail per second!

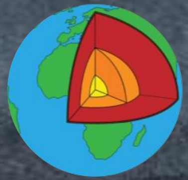
Nuclear fusion within the sun produces ν_e

Solar



Decay of radionuclides (U/Th/K) within the Earth

Geoneutrinos



Fission of U/Th → huge flux of neutrinos

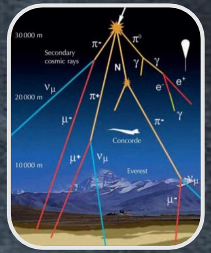
Reactor

99% of energy released in (anti)neutrinos of all flavours

Supernova

Cosmic rays colliding with atmosphere

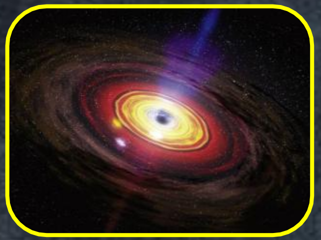
Atmospheric



Many GUTs require baryon number violation and predict nucleon decay

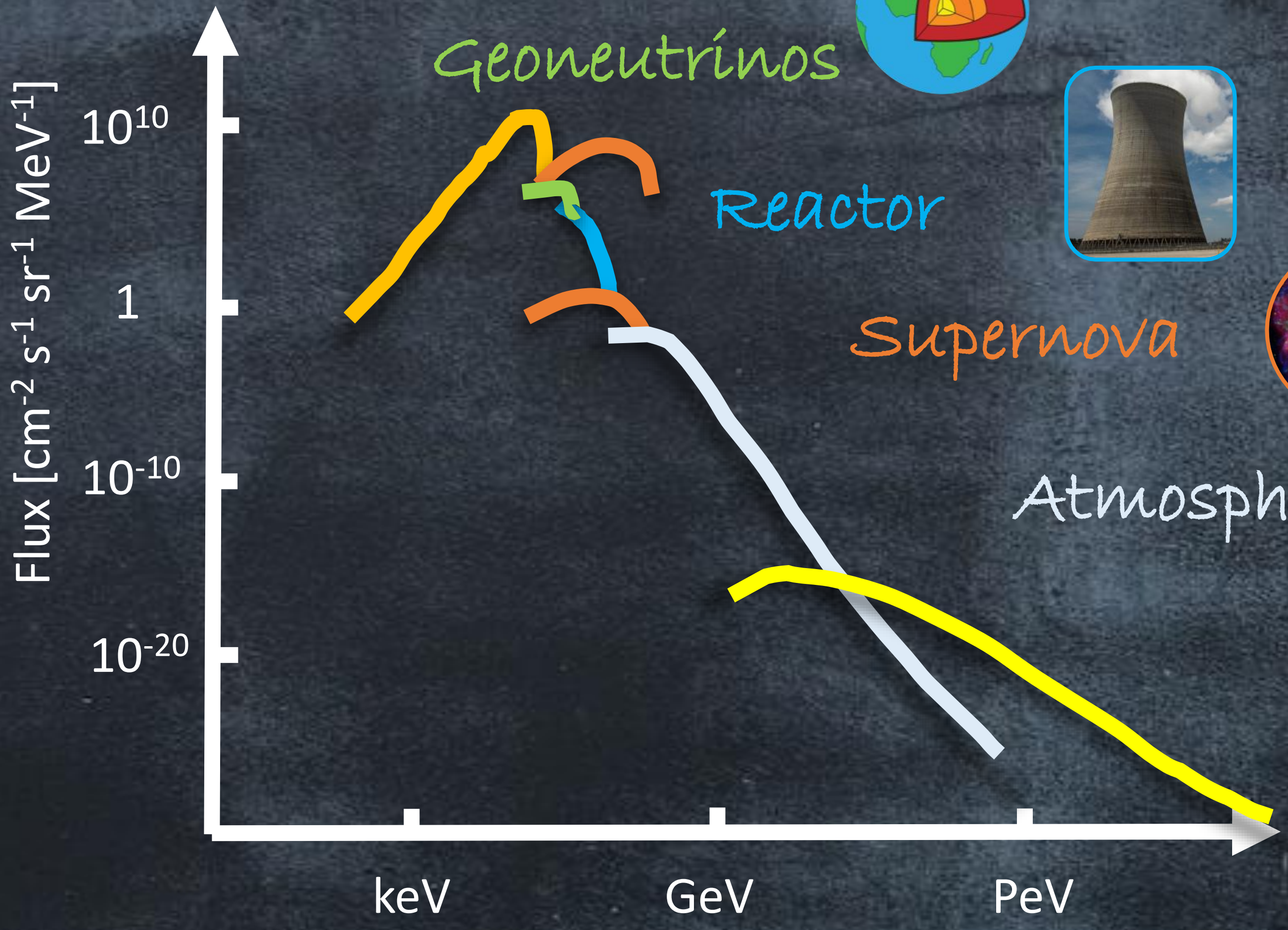
Exotic Searches

Active galactic nucleus, cosmological sources



Neutrino Sources

~70 years experience in neutrino measurement!



Solar

Homestake (1970)

SNO (2002)

Geoneutrinos

KamLAND (2005)

Borexino (2010)

Reactor

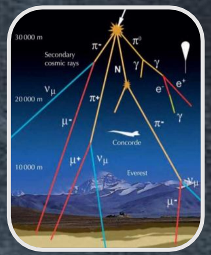
Reines & Cowan (1957)

Daya Bay (2012), KamLAND +…

Supernova

Kamiokande (1987)

Atmospheric

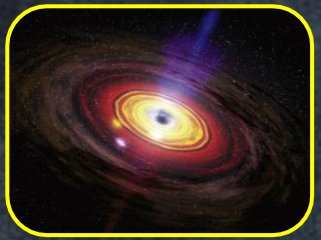


Super-Kamiokande (1998)

Exotic Searches

KamLAND-Zen (2011) (0νββ)

Active galactic nucleus, cosmological sources



Neutrino Oscillation

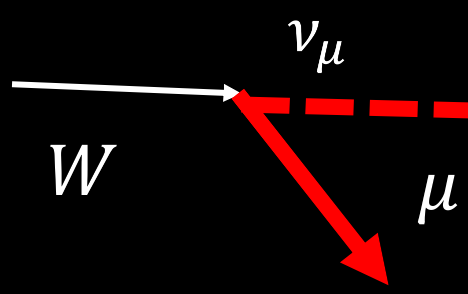
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \cdot \\ \cdot \end{pmatrix} \neq \begin{pmatrix} \nu_1 \\ \nu_2 \\ \cdot \\ \cdot \end{pmatrix}$$

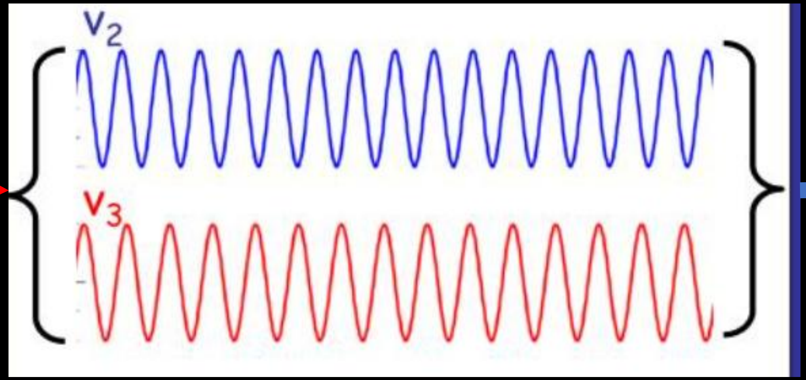
- Neutrinos produced with fixed flavour
- Flavour eigenstates orthogonal to mass states
- Flavour can be written as superposition of mass states

$$|\nu_\alpha\rangle = U_{\alpha 1}|\nu_1\rangle + U_{\alpha 2}|\nu_2\rangle + U_{\alpha 3}|\nu_3\rangle$$

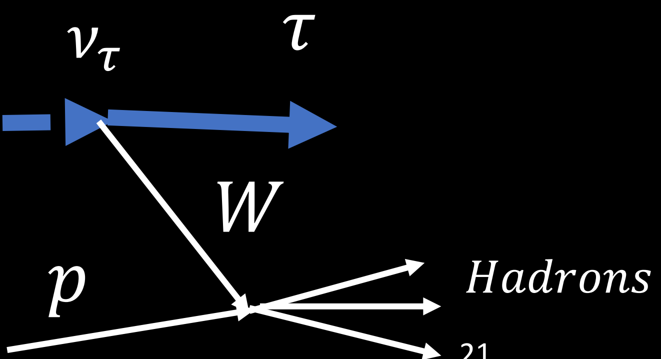
- Mass states dictate the propagation of neutrinos

Neutrino production:





Neutrino detection:



Neutrino Oscillation

- Schrodinger equation → neutrino mass m_j, as a plane wave

$$|\nu_j(t, L)\rangle = \mathcal{H}\ |\nu_j\rangle = \exp[-iE_jt + ip_jL]\ |\nu_j\rangle$$

- Mass states, j, can be written as superposition of flavour states ,α

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\nu_{j,L} = \sum_\alpha U^*_{\alpha j} \nu_{\alpha, L}$$

→ $$|\nu_\alpha(t, L)\rangle = \sum_j U^*_{\alpha j} \exp[-iE_jt + ip_jL]\ |\nu_j\rangle$$

Neutrino Oscillation

- Evolution of flavour state:

$$|\nu_\alpha(t, L)\rangle = \sum_j U^*_{\alpha j} \exp[-iE_j t + ip_j L] \; |\nu_j\rangle$$

- Want to know the probability of flavour transition $\alpha \to \beta$, after time t, propagation distance L

$$\langle \nu_\beta| = \sum_j U_{\beta j} \langle \nu_j|$$

$$\begin{aligned}\langle \nu_\beta|\nu_\alpha(t, L)\rangle &= \sum_{j,k} U^*_{\alpha j} U_{\beta k} \exp[-iE_j t + ip_j L] \; \langle \nu_k|\nu_j\rangle \\ &= \sum_j U^*_{\alpha j} U_{\beta j} \exp[-iE_j t + ip_j L],\end{aligned}$$

Neutrino Oscillation

- Previous expression can be written as:

$$P_{\alpha\beta}(L,E) \approx \left| U \begin{pmatrix} 1 & 0 & 0 \\ 0 & \exp[-i\frac{\Delta m_{21}^2 L}{2E}] & 0 \\ 0 & 0 & \exp[-i\frac{\Delta m_{31}^2 L}{2E}] \end{pmatrix} U^\dagger \right|^2$$

$$\nu_{j,L} = \sum_\alpha U_{\alpha j}^* \nu_{\alpha,L}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

U matrix transforms between mass and flavour

Neutrino Oscillation

- General 3x3 complex matrix → 18 real, independent parameters
- Unitary matrix 18 → 9
- 9 = 3 real + 6 complex phases
- 5 complex phases can be removed via field rephasing (leaves Lagrangian unchanged)

$$\nu_\alpha \rightarrow e^{i\phi_j}\nu_\alpha$$

- 4 independent physical parameters

Neutrino Oscillation

- Pontecorvo-Maki- Nakagawa-Sakata (PMNS) matrix, with 3 real parameters in the form of mixing angles θ_{12}, θ_{13}, θ_{23} and 1 complex phase δ_{CP} that allows for CP violation

$$c_{ij} \equiv \cos\theta_{ij} \text{ and } s_{ij} \equiv \sin\theta_{ij}$$

$$U_D = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{-i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{-i\delta_{CP}} & s_{23}c_{13} \\ s_{12}c_{23} - c_{12}c_{23}s_{13}e^{-i\delta_{CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{-i\delta_{CP}} & c_{23}c_{13} \end{pmatrix}$$

Neutrino Oscillation

- 6 parameters:
  - 2 mass differences
  - 4 angles (3 real + 1 complex)

$$P_{\alpha\beta}(L,E) \approx \left| U \begin{pmatrix} 1 & 0 & 0 \\ 0 & \exp[-i\frac{\Delta m^2_{21}L}{2E}] & 0 \\ 0 & 0 & \exp[-i\frac{\Delta m^2_{31}L}{2E}] \end{pmatrix} U^\dagger \right|^2$$

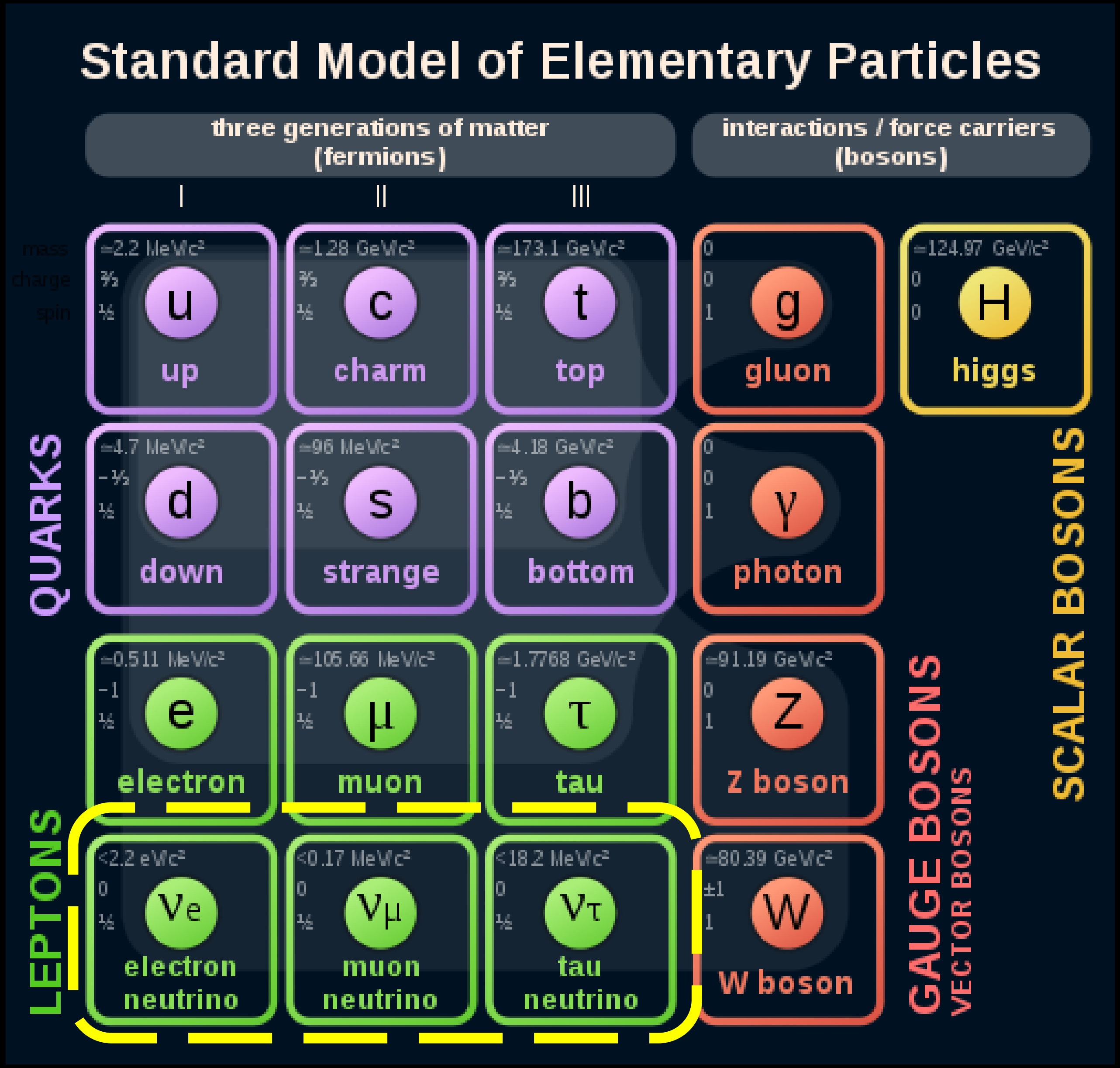
$$\begin{aligned} U_D &= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \\ &= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{-i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{-i\delta_{CP}} & s_{23}c_{13} \\ s_{12}c_{23} - c_{12}c_{23}s_{13}e^{-i\delta_{CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{-i\delta_{CP}} & c_{23}c_{13} \end{pmatrix} \end{aligned}$$

Neutrinos

What we know (so far)

- Neutral fundamental particles
- Very small masses
- 3 masses / flavours
  - Oscillation : described by

    6 parameters

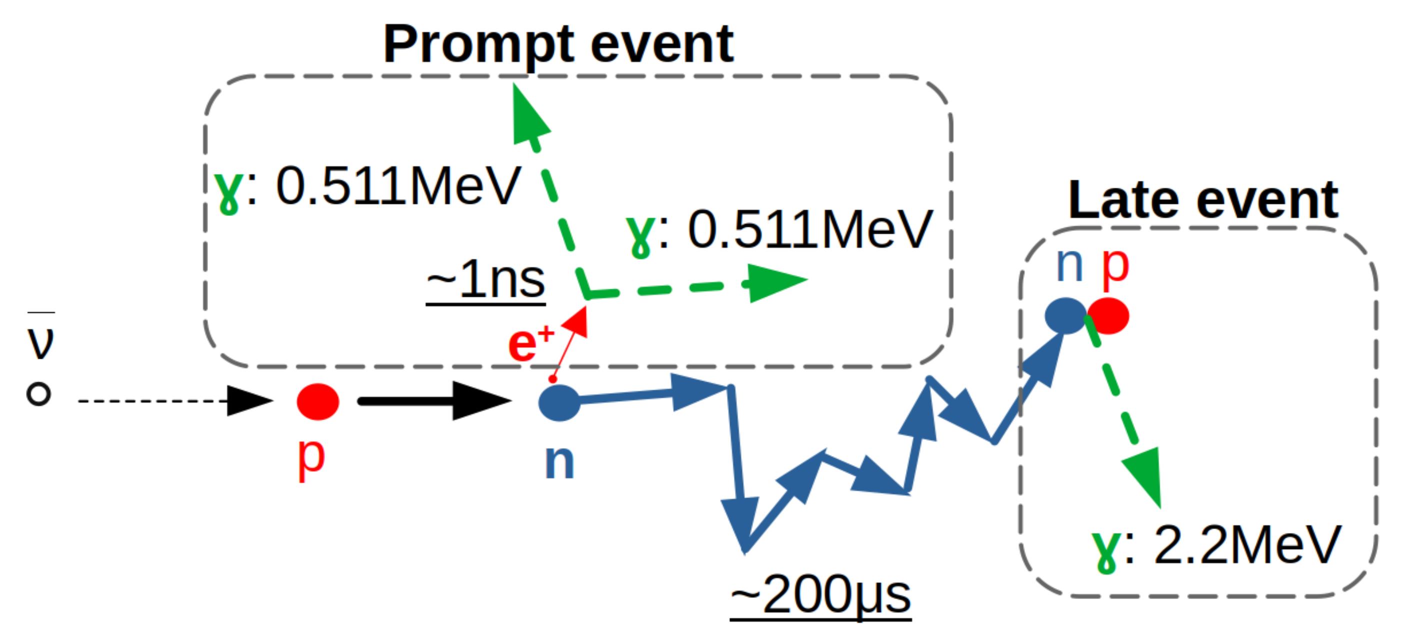


Returning to neutrino detection

- Detect neutrinos by detecting the energetic charged particles produced

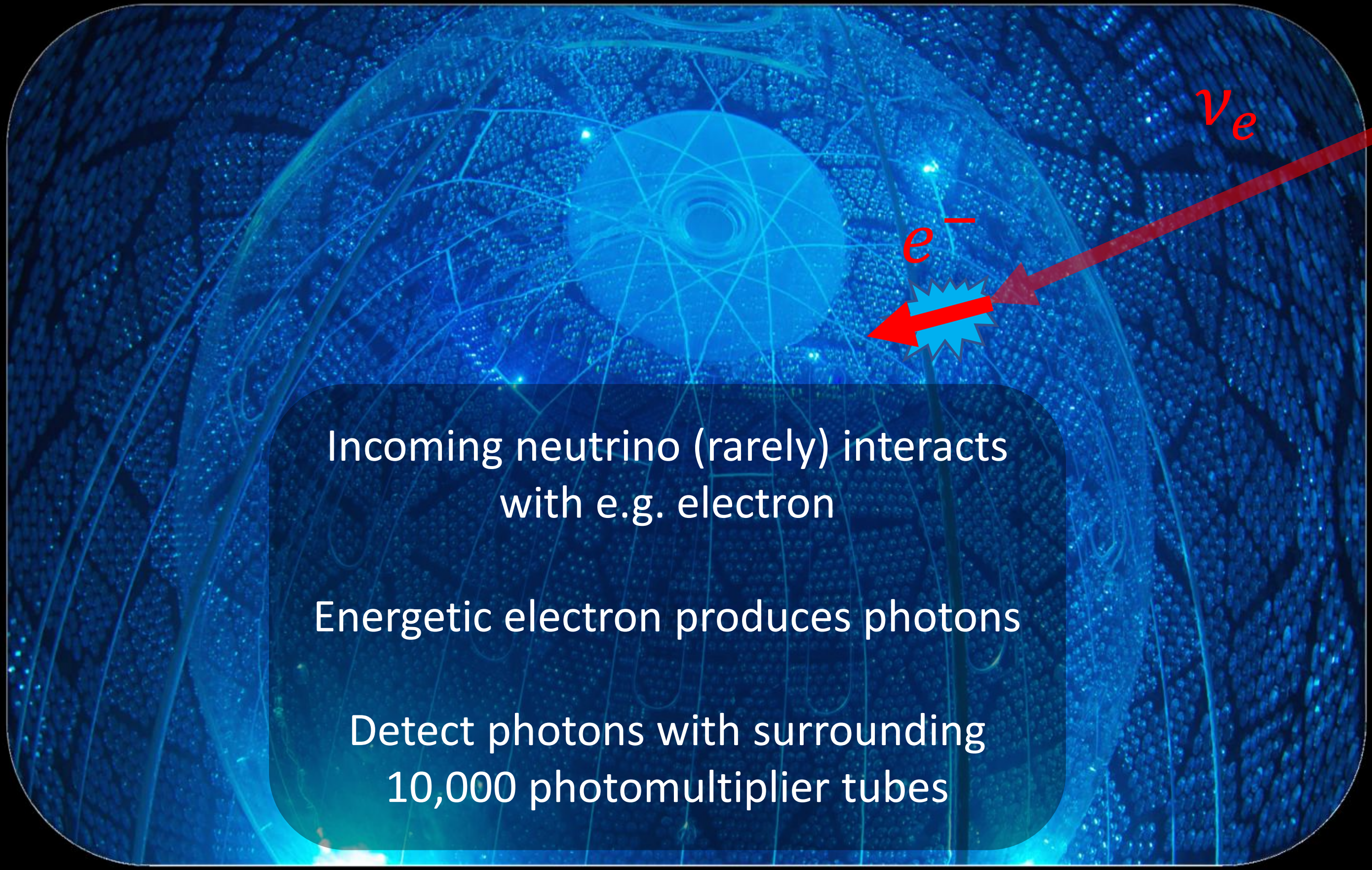
Generally done through:

- Liquid scintillator → chemical which absorbs energy from charged particles, remits scintillation photons
- Fast moving charged particles emit Cherenkov photons



Antineutrino detection (e.g. reactor)

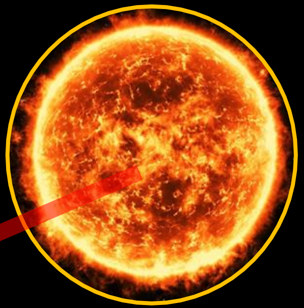
Neutrino Detector Example



Incoming neutrino (rarely) interacts with e.g. electron

Energetic electron produces photons

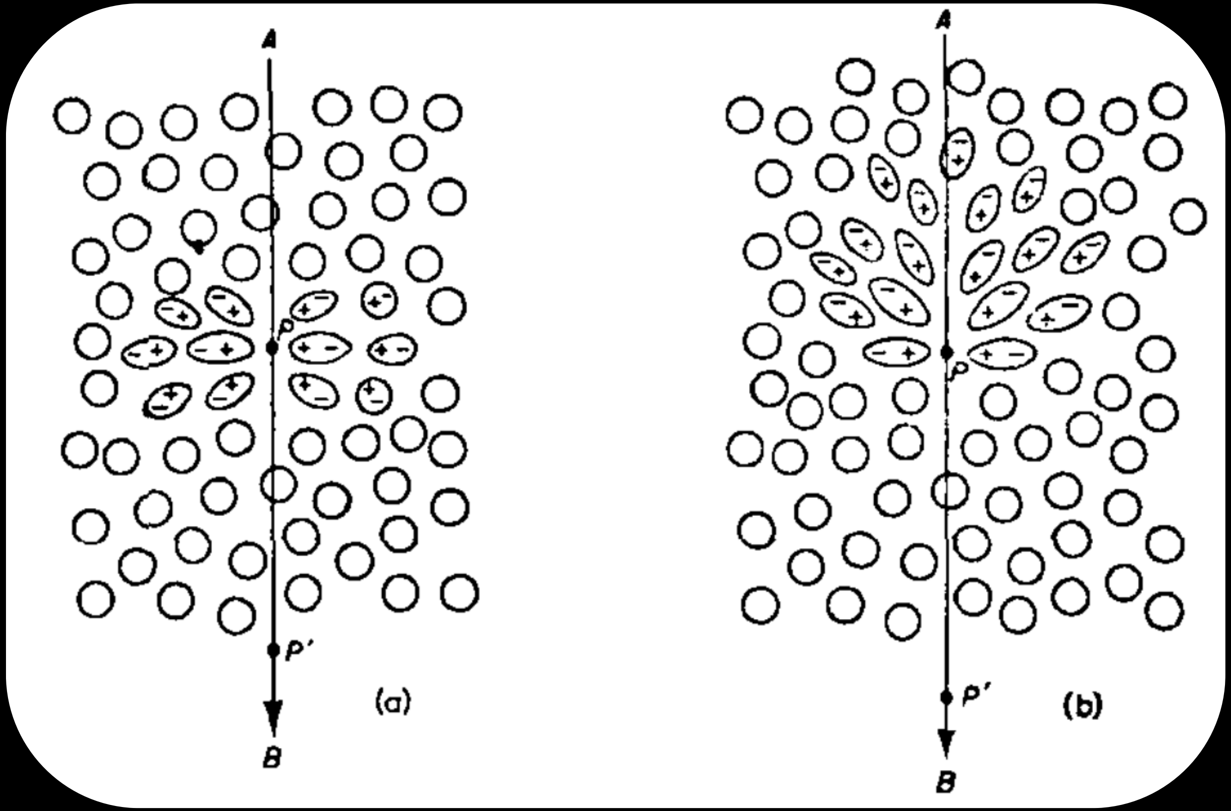
Detect photons with surrounding 10,000 photomultiplier tubes



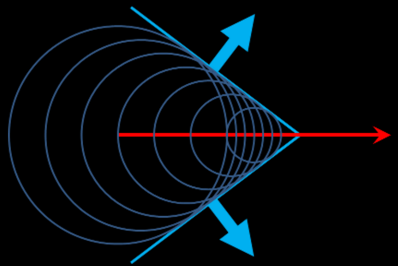
Neutrinos are <u>difficult</u> to detect
For reference: SNO: 1000 tons of ultra-pure water

ν_e : Probability to interact ~10^{-44} cm^2
SNO sees ~10 solar neutrinos per day

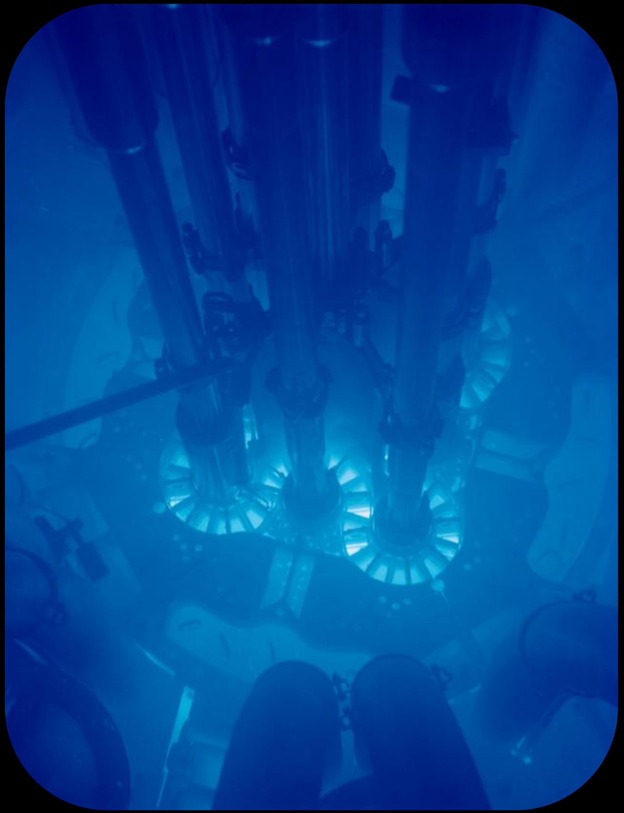
Cherenkov light → Detecting energetic particles



Polarisation of a molar medium for:
(a) slow (b) fast charged particle

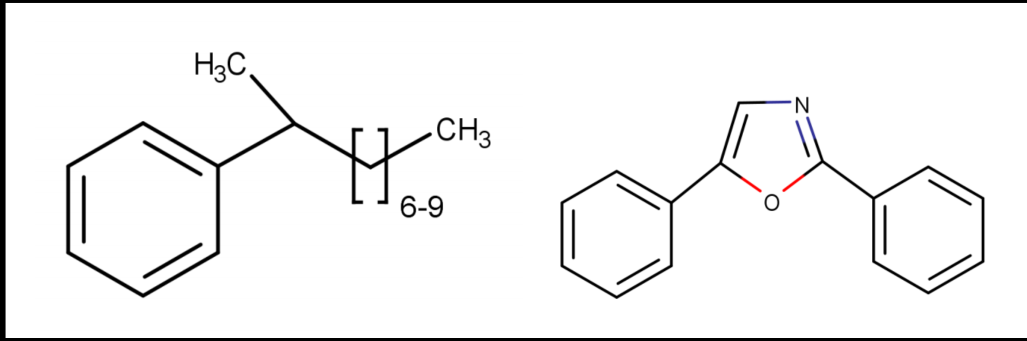


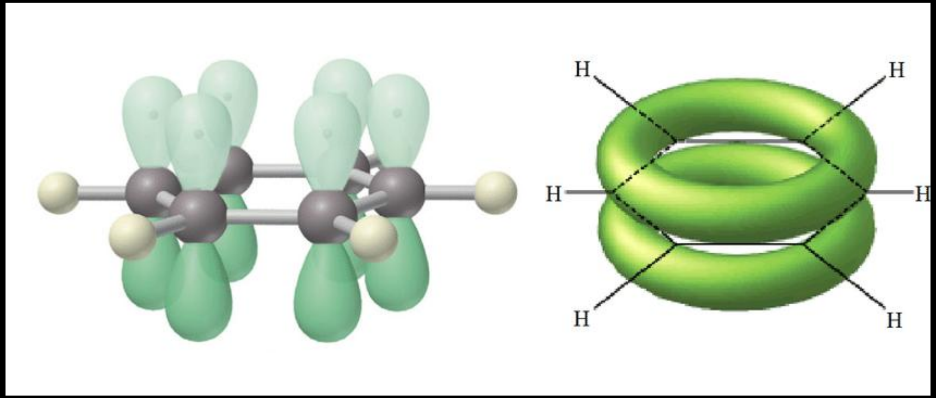
Cherenkov light emitted at fixed angle from particle → can get the direction



Characteristic blue glow in water in nuclear reactor core

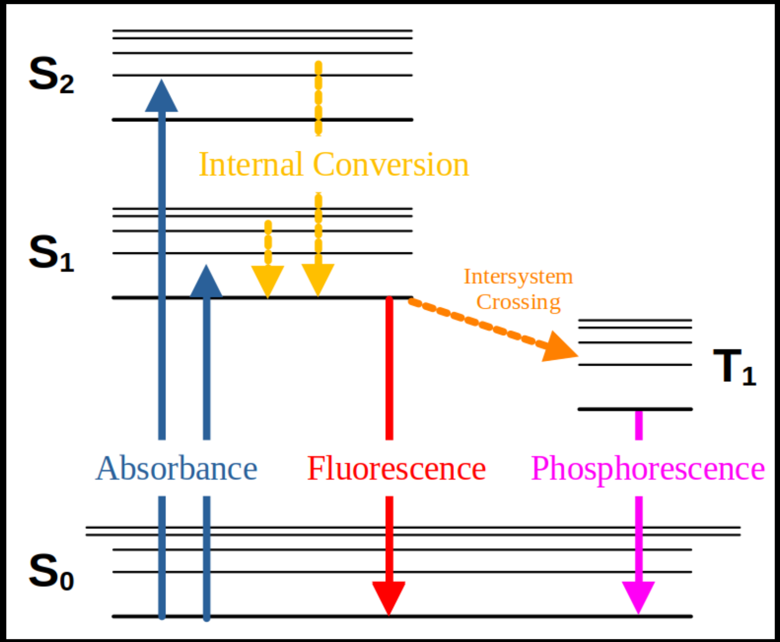
Liquid Scintillator → Detecting energetic particles





Long chain scintillator molecule with benzene ring
Electrons in benzene ring can get excited by charged particles

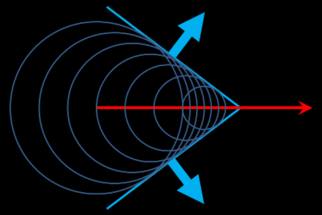
Dexcitation of electrons emits scintillation light



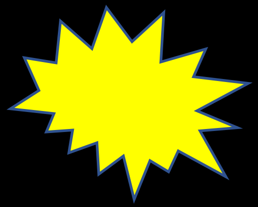
- ~ 100x the light compared to Cherenkov!
- But, light emitted in all directions

Water Cherenkov vs Liquid Scintillator

Water



Scintillator



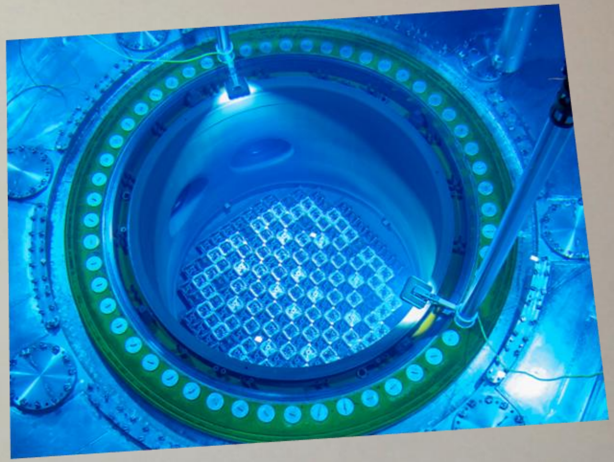
Scintillator:

- ~100x Light Yield
- Loss of Direction
- Much Higher Purity

Reactor neutrinos, we know where the reactor is, direction is not absolutely needed!

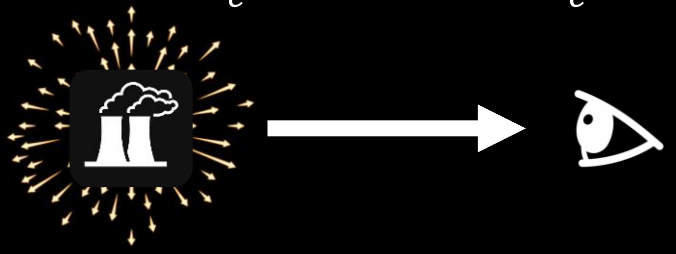
Fine energy resolution needed → need more light → liquid scintillator

Contents



Returning to reactor neutrinos

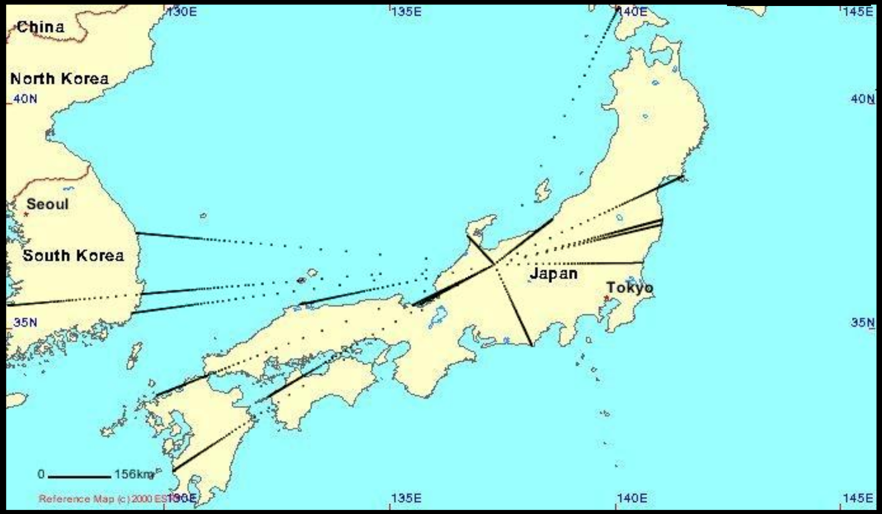
- What was known:
- Oscillations seen in atmospheric and solar neutrinos
- How about reactor neutrinos over long baselines
- For reactor experiments, measure the survival of $\bar{\nu}_e$
- $\bar{\nu}_e$ produced in reactors, detectors only detect $\bar{\nu}_e$: $P_{surv} = \frac{N_{observed}}{N_{expected}}$



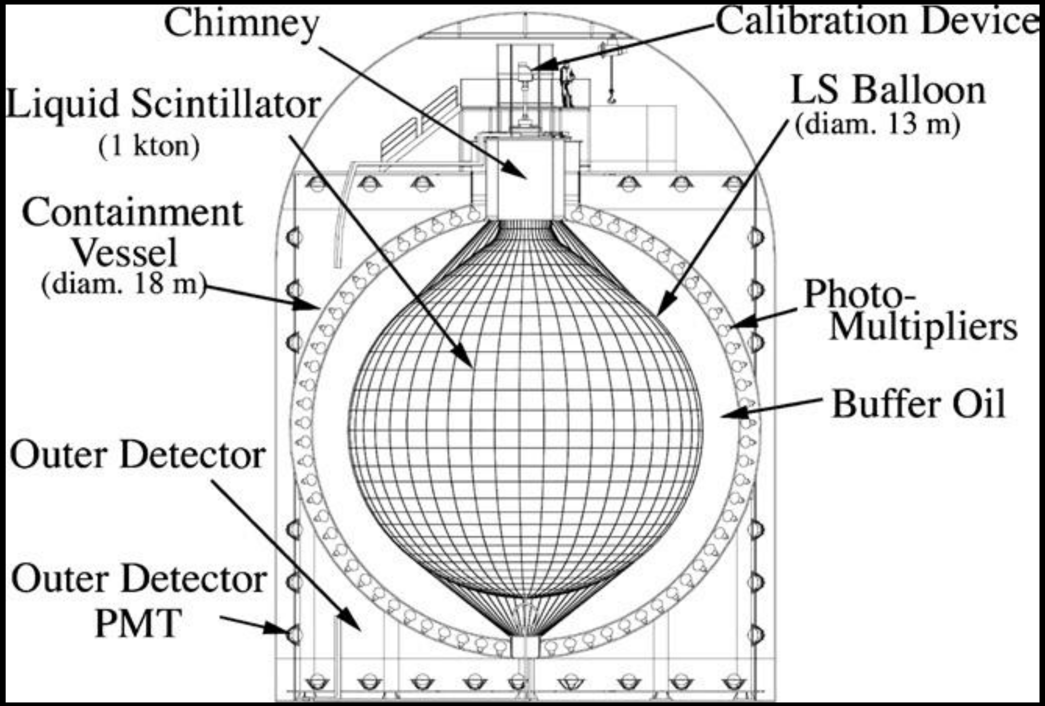
$$P_{\bar{\nu}_e \to \bar{\nu}_e}(L, E) = 1 - \cos^4 \sin^2(2\theta_{12}) \sin^2(\frac{\Delta m^2_{21} L}{4E}) - \sin^2(2\theta_{13})[\sin^2(\theta_{12}) \sin^2(\frac{\Delta m^2_{32} L}{4E}) + \cos^2(\theta_{12}) \sin^2(\frac{\Delta m^2_{31} L}{4E})]$$

KamLAND 2002

Average reactor-detector baseline of 180 km



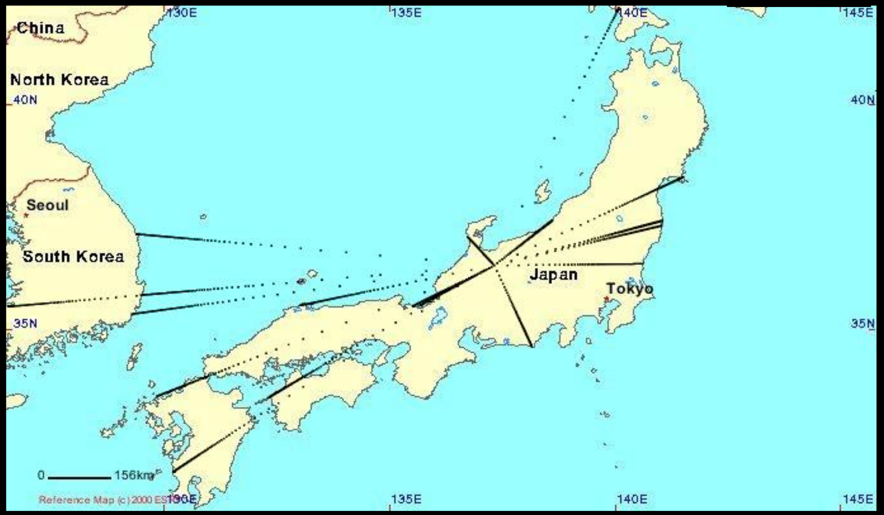
Proposed in 1994, started taking data in 2002
Goal: Confirm $\bar{\nu}_e$ oscillation over long baselines

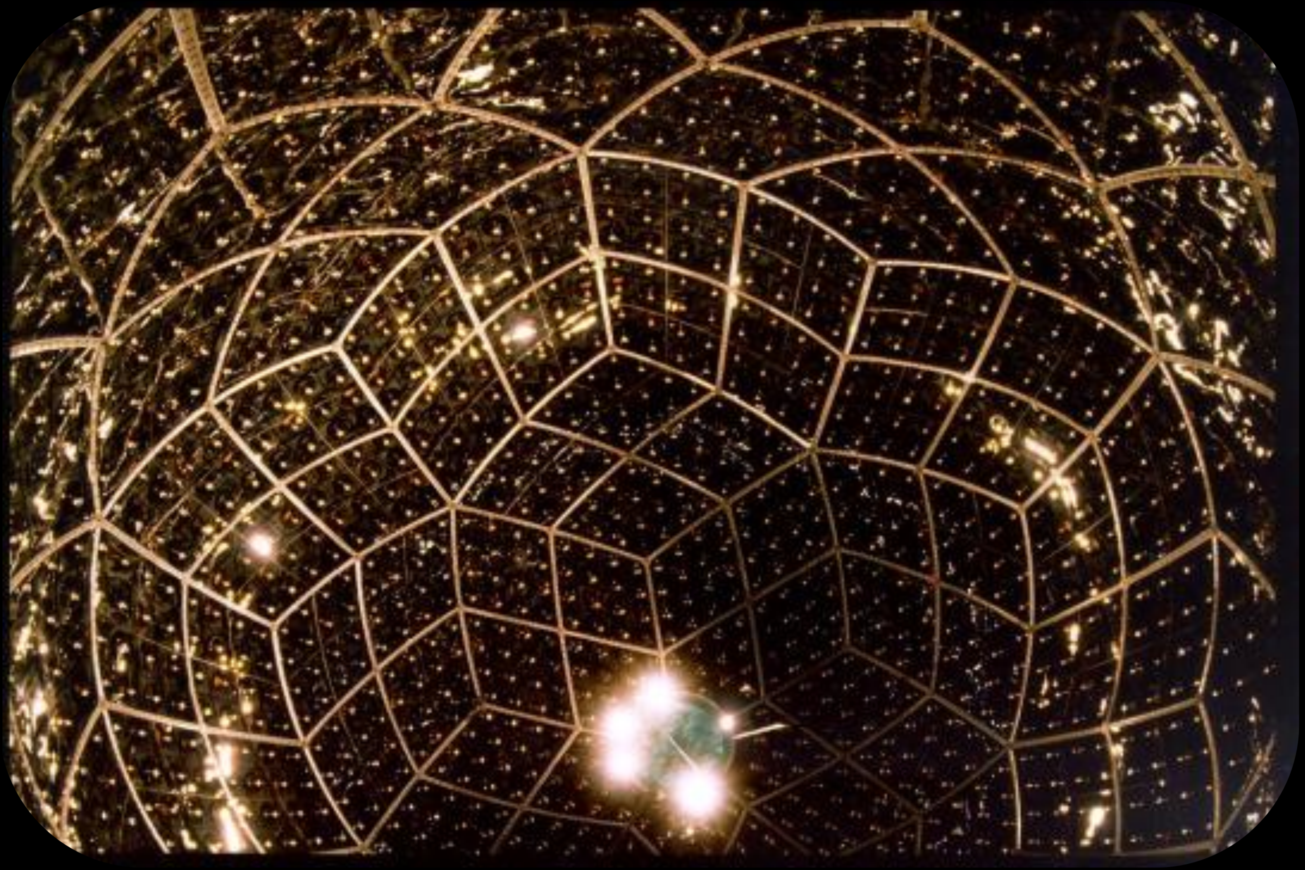


- 1000 tons of Liquid scintillator
- 2000 PMTs

KamLAND 2002

Average reactor-detector baseline of 180 km





- 1000 tons of Liquid scintillator
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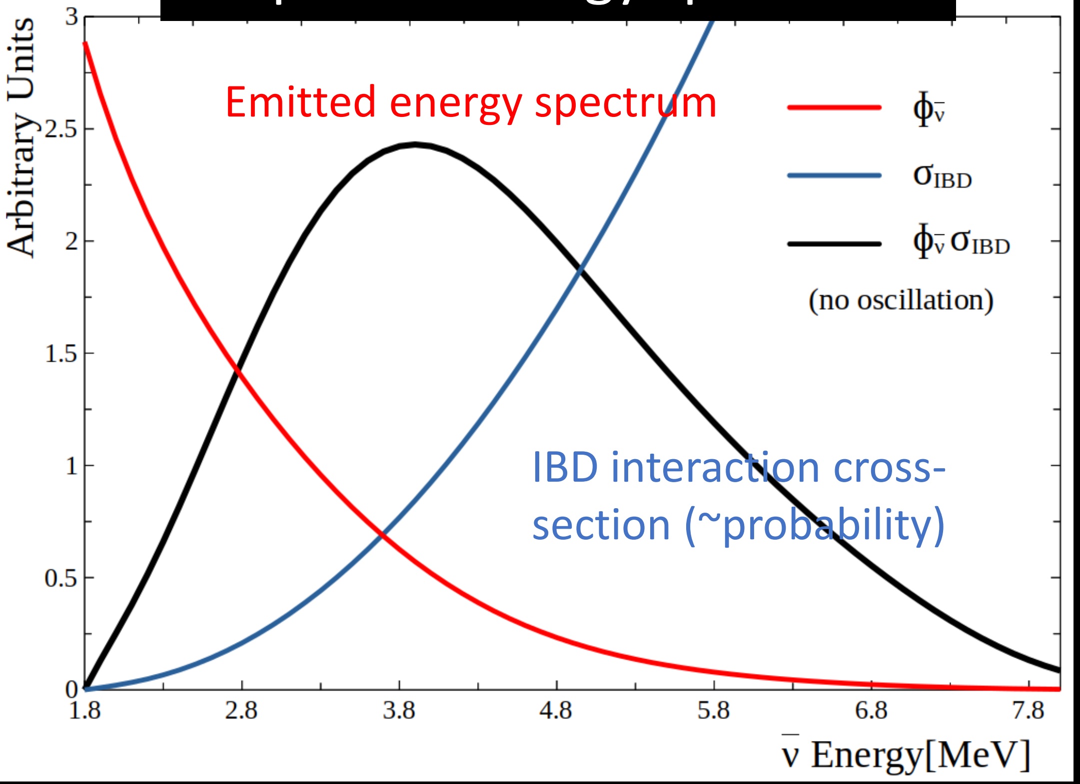
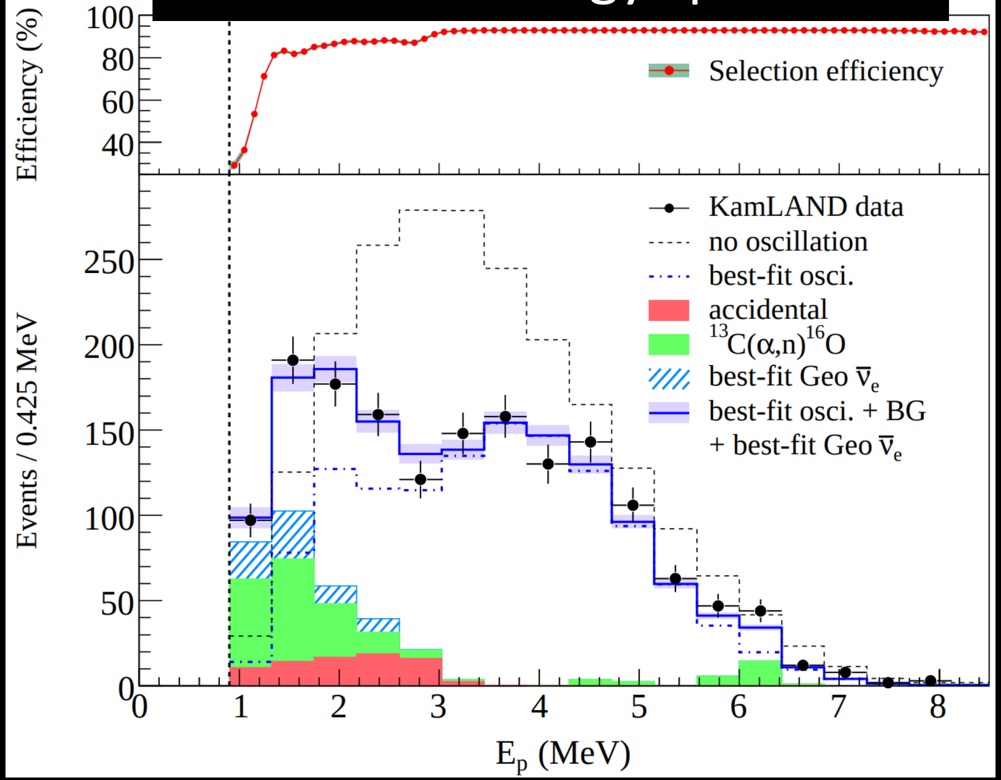
KamLAND 2002

Average reactor-detector baseline of 180 km

Expected Energy spectrum

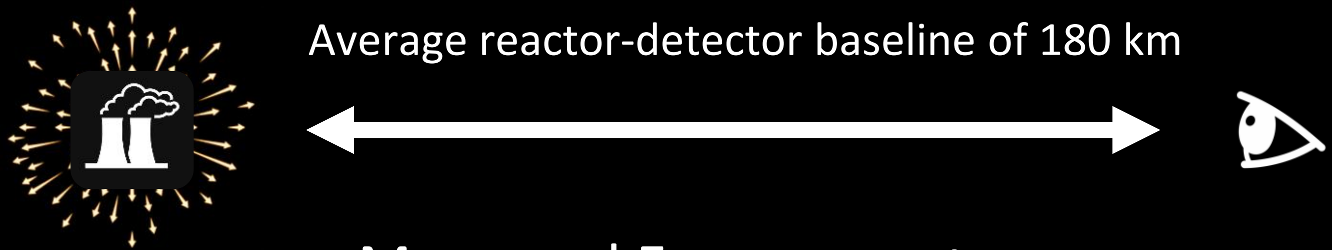


Measured Energy spectrum



$$P_{\bar{\nu}_e \to \bar{\nu}_e}(L, E) \approx 1 - \frac{1}{2}\sin^2(2\theta_{13}) - \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right)$$

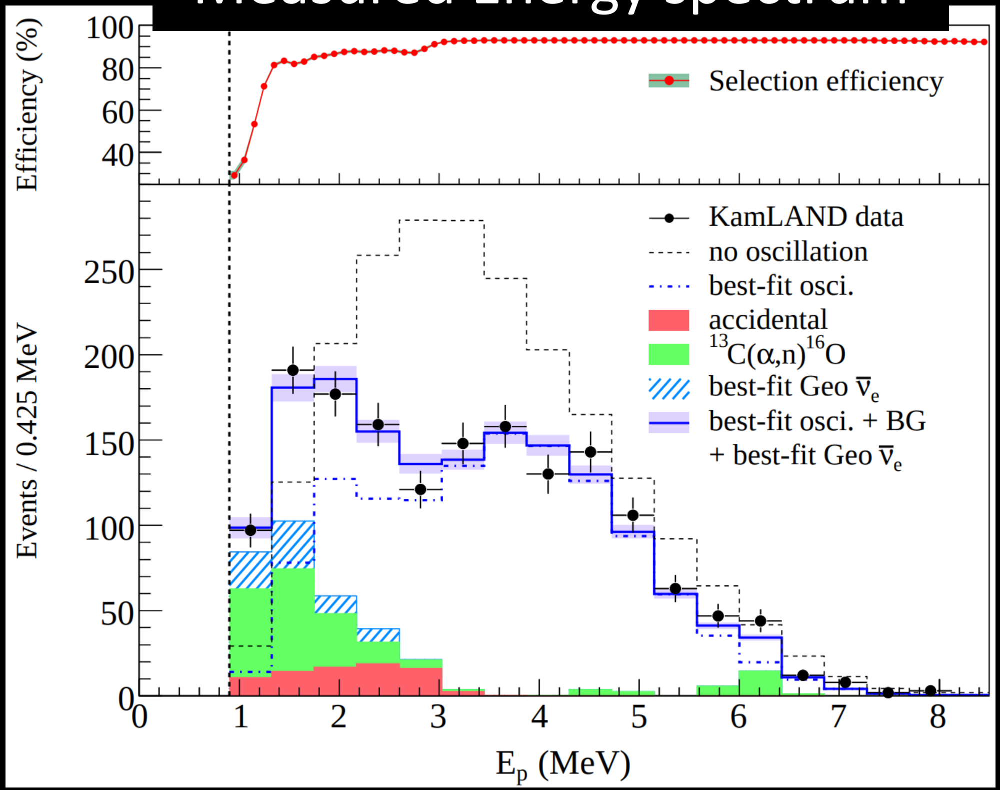
KamLAND 2002



Compare to theoretical no-oscillation spectrum to the measured spectrum

Can measure oscillation parameters from the shape and size of the spectrum.

Measured Energy spectrum

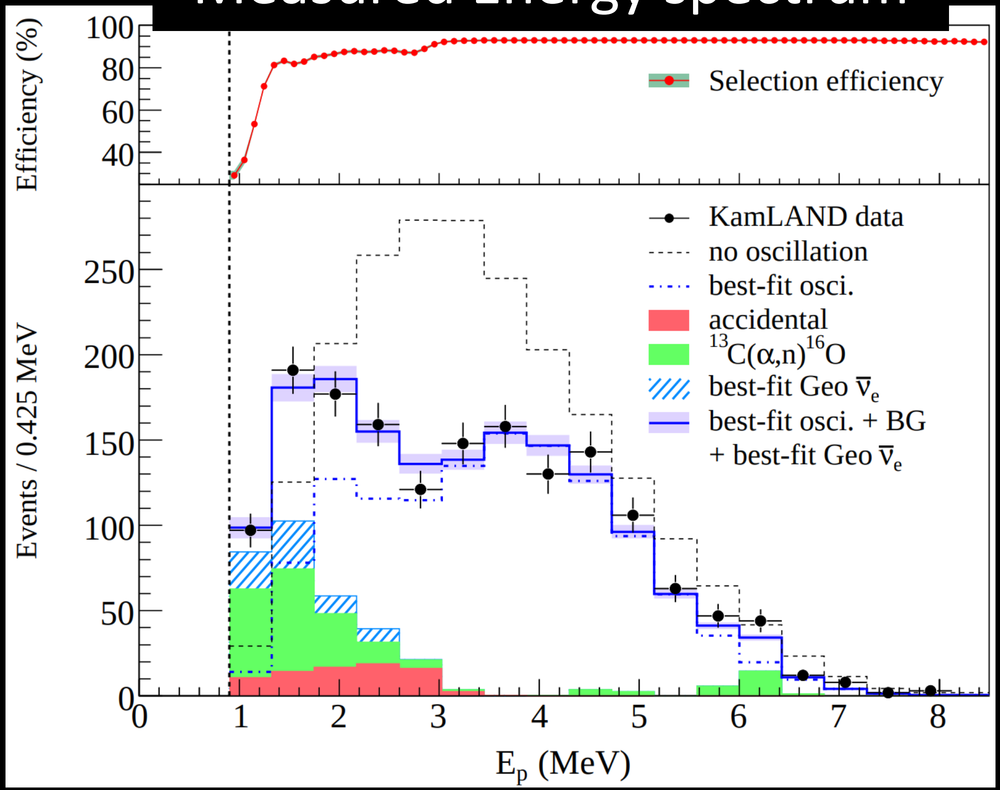


$$P_{\bar{\nu}_e \to \bar{\nu}_e}(L,E) \approx 1 - \frac{1}{2}\sin^2(2\theta_{13}) - \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$

KamLAND 2002

Average reactor-detector baseline of 180 km

Measured Energy spectrum



$$\Delta m^2_{21} = 7.58^{+0.14}_{-0.13}(\mathrm{stat})^{+0.15}_{-0.15}(\mathrm{sys})$$

$$\tan^2\theta_{12} = 0.56^{+0.10}_{-0.07}(\mathrm{stat})^{+0.10}_{-0.06}(\mathrm{sys})$$

- Precise measurements of two oscillation parameters using reactor neutrinos
- Confirmed long-baseline neutrino oscillation

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

θ_{13}?

Remembering there's 6 oscillation parameters, have measured to this point:

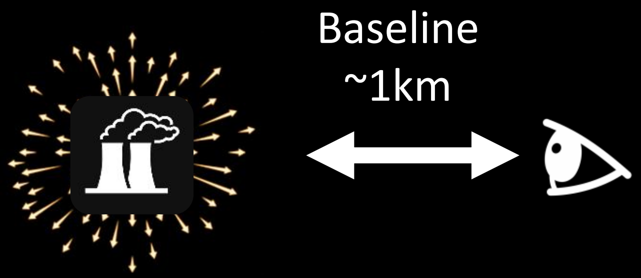
$\theta_{23}, \Delta m^2_{32}$: Atmospheric neutrinos
$\theta_{12}, \Delta m^2_{21}$: Solar, reactors
θ_{13} ?
δ_{CP} ?

δ_{CP} → may explain matter-antimatter asymmetry of the universe
Measurable if θ_{13} is non-zero

Man-made neutrino beam experiments, T2K + MINOS, saw hints of non-zero θ_{13}

$$U = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & -s_{13}e^{i\delta_{CP}} \\ & 1 & \\ -s_{13}e^{i\delta_{CP}} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}$$

θ_{13}?



Short baseline reactor experiment: Chooz also placed limits

$$P_{surv} = \frac{N_{observed}}{N_{expected}}$$

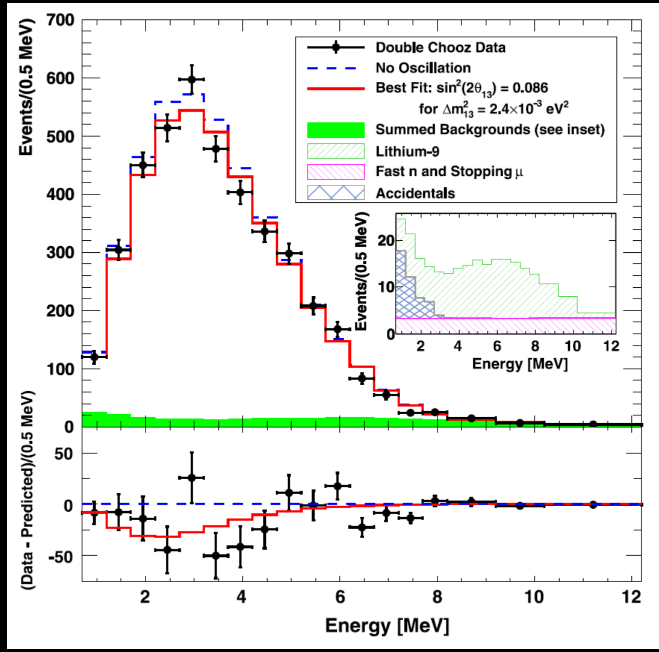
Counting total IBDs

Nuclear emission
Theoretical prediction

Placed detector ~1km from a reactor

Compared the expected and measured energy spectrum

→ No conclusive disagreement with <u>no-oscillation</u>



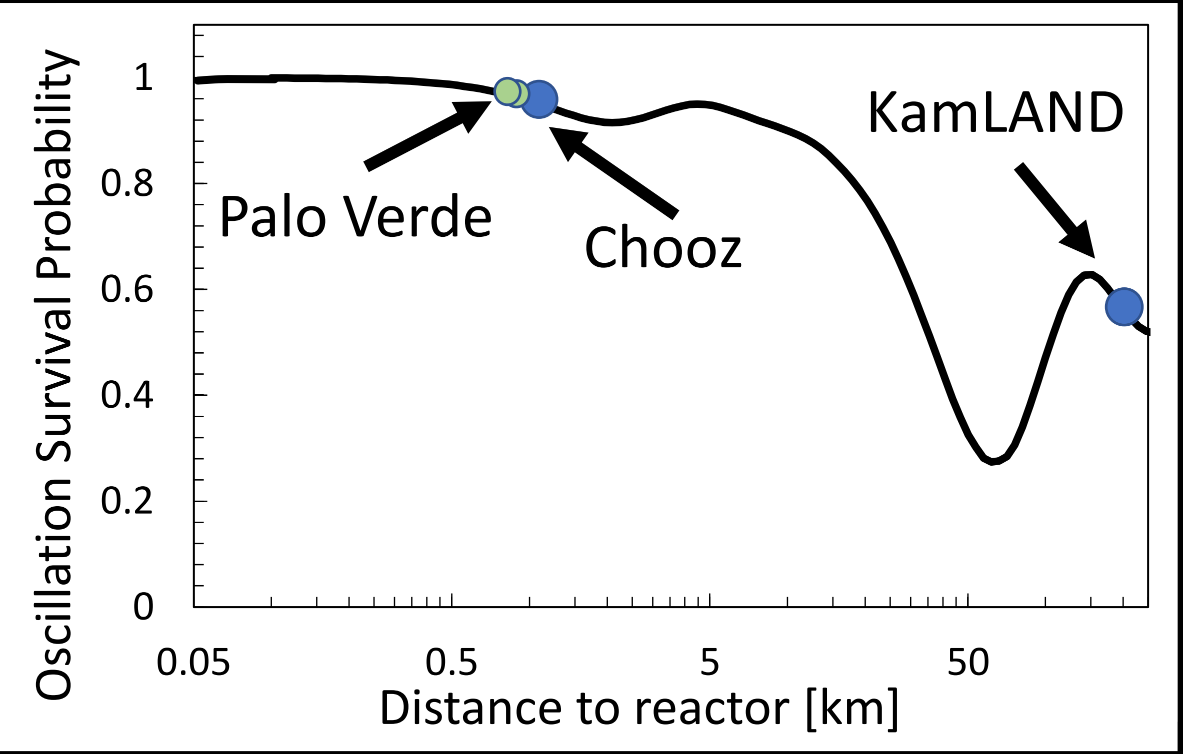
θ_{13}?

Difficult to compare measured spectrum with theoretical no-oscillation spectrum (+ difficult detector uncertainties)

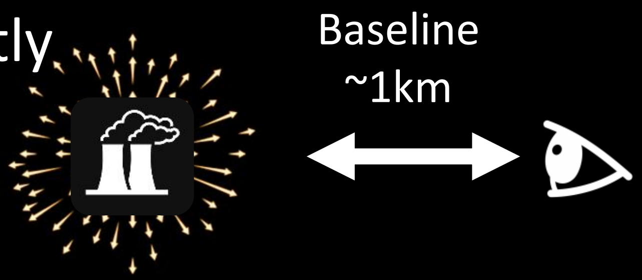
How to progress?

- <u>Larger detectors</u>
- <u>Place 2 detectors, near and far</u>
  → Compare their spectra directly

The Daya Bay experiment



($\bar{\nu}_e$ survival averaged over reactor energy spectrum)



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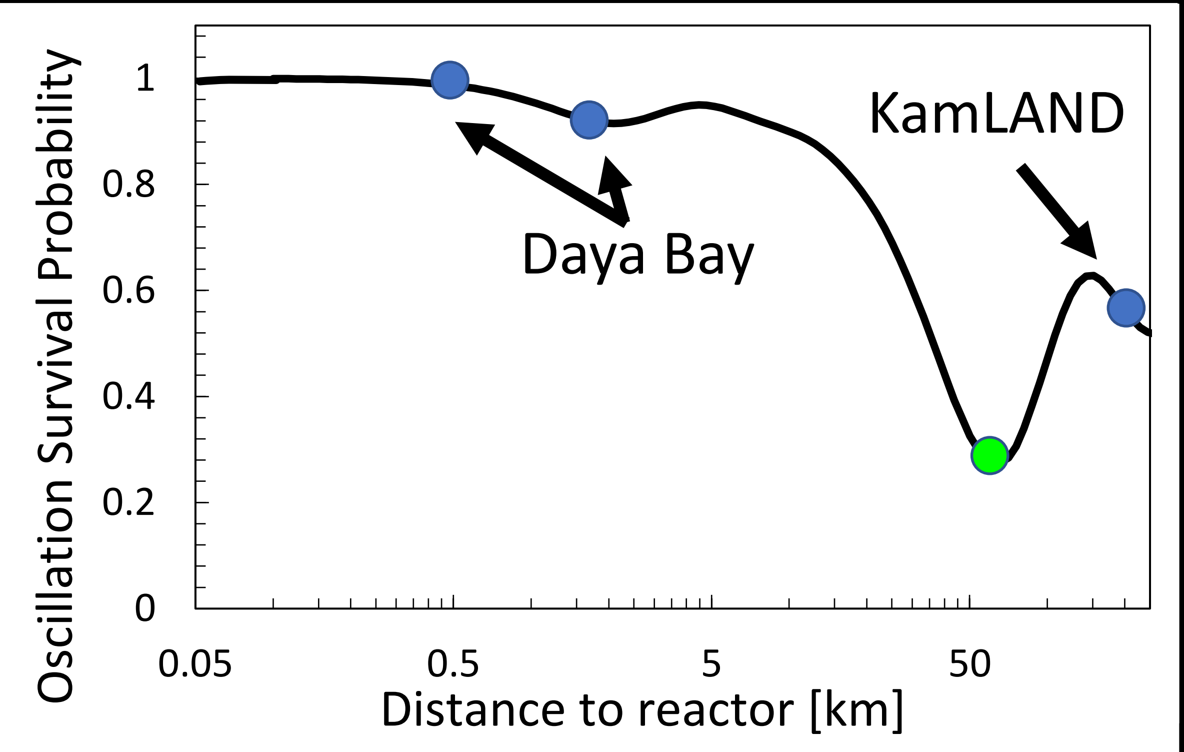

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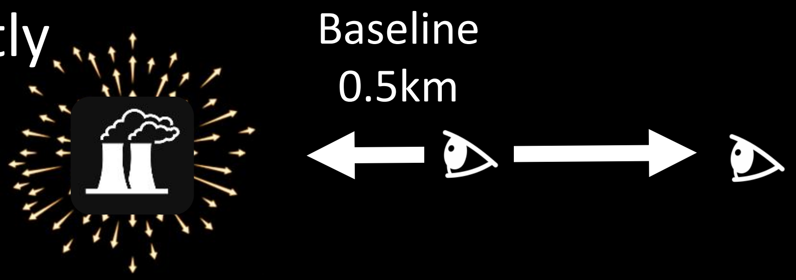
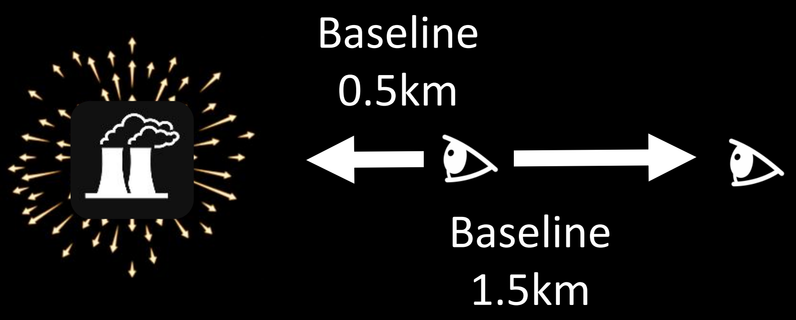
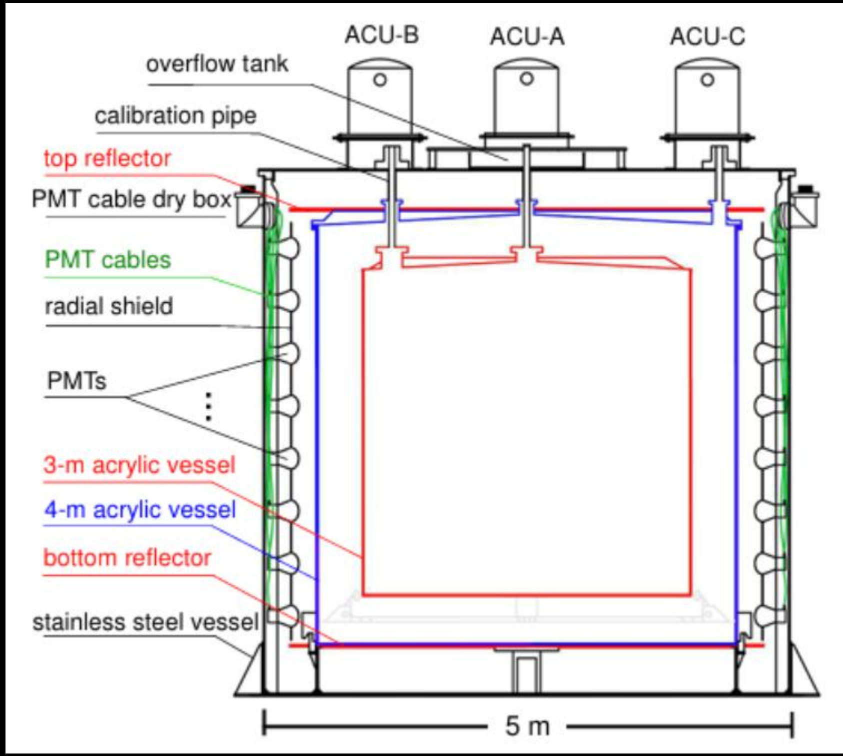
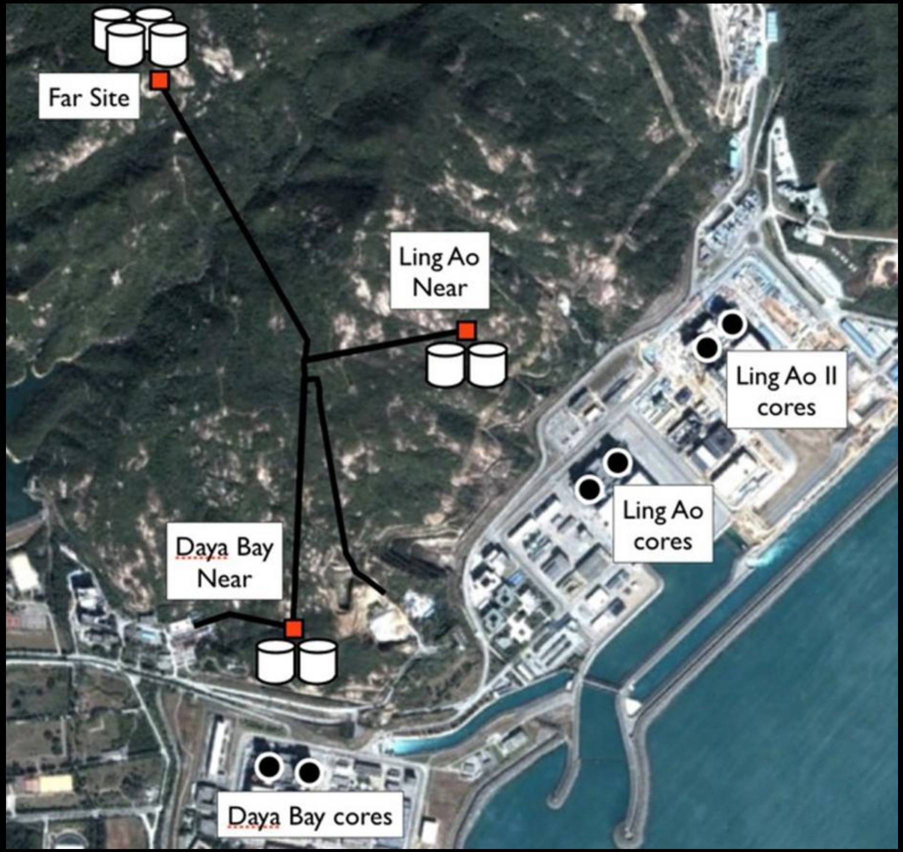


$$P_{surv} \sim \frac{n_{observed,far}}{n_{observed,near}} * \frac{d_{far}^2}{d_{near}^2}$$

Daya Bay



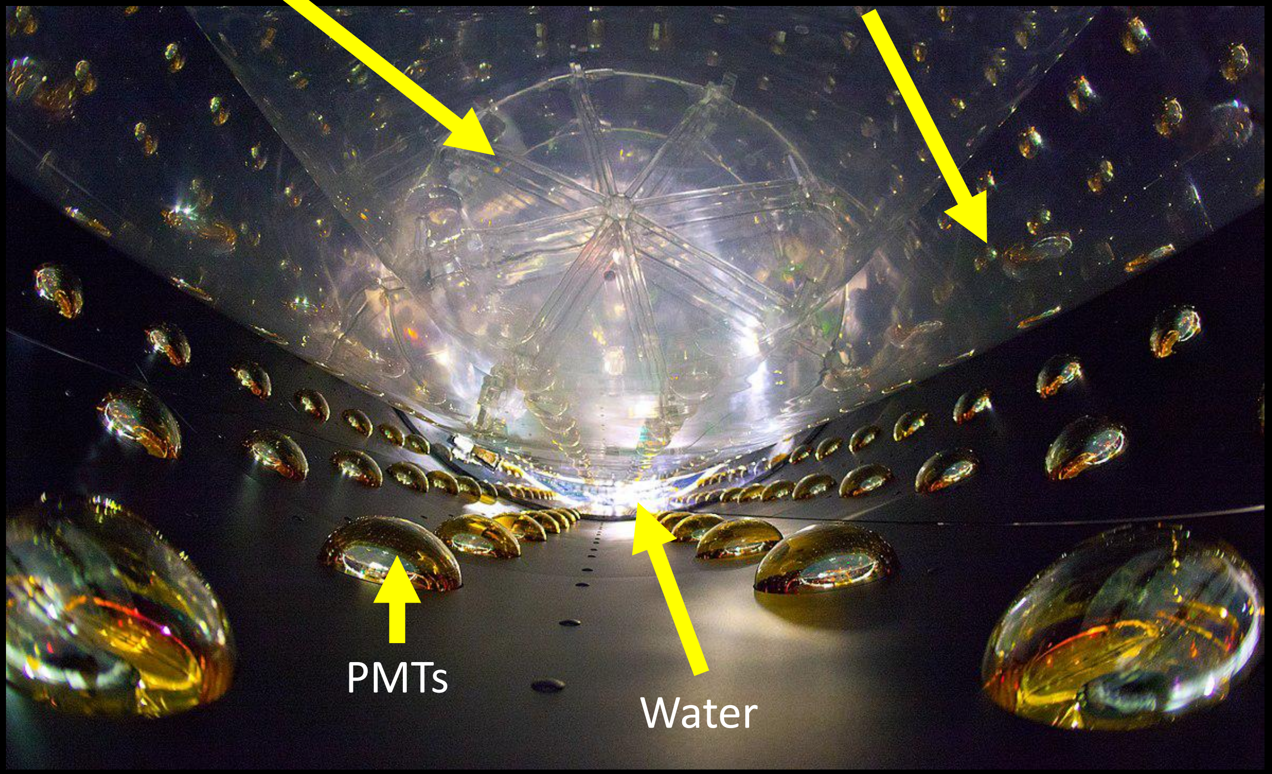


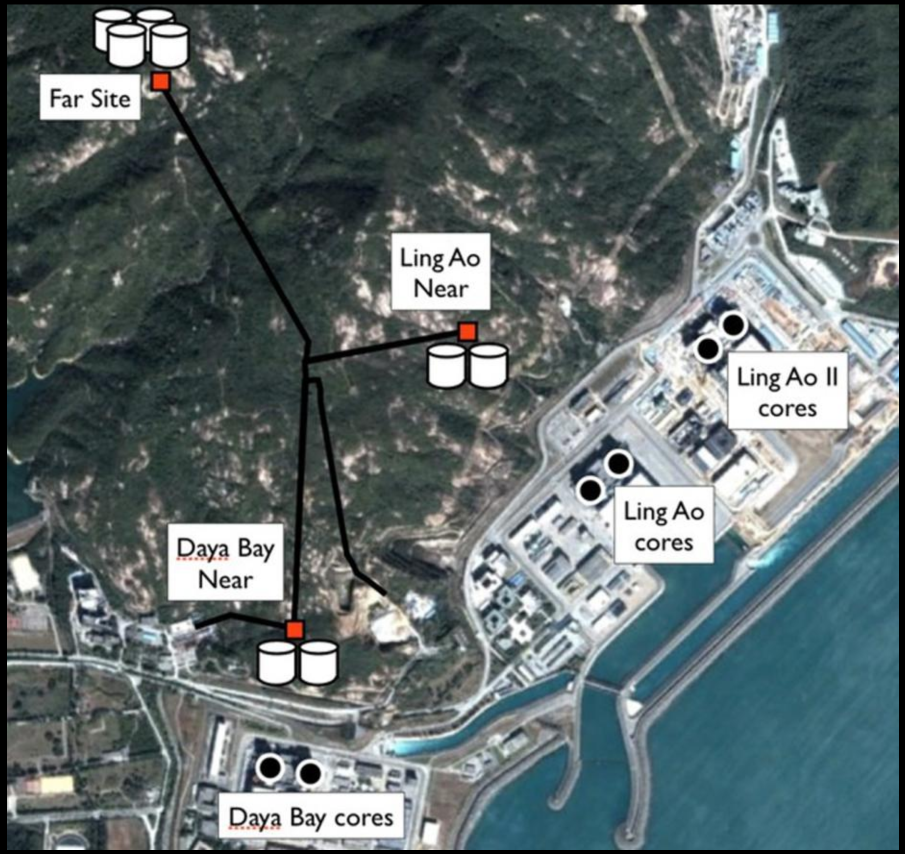


<u>Multiple</u> 20 ton liquid scintillator detectors

Added Gd → boost neutron signal from IBD

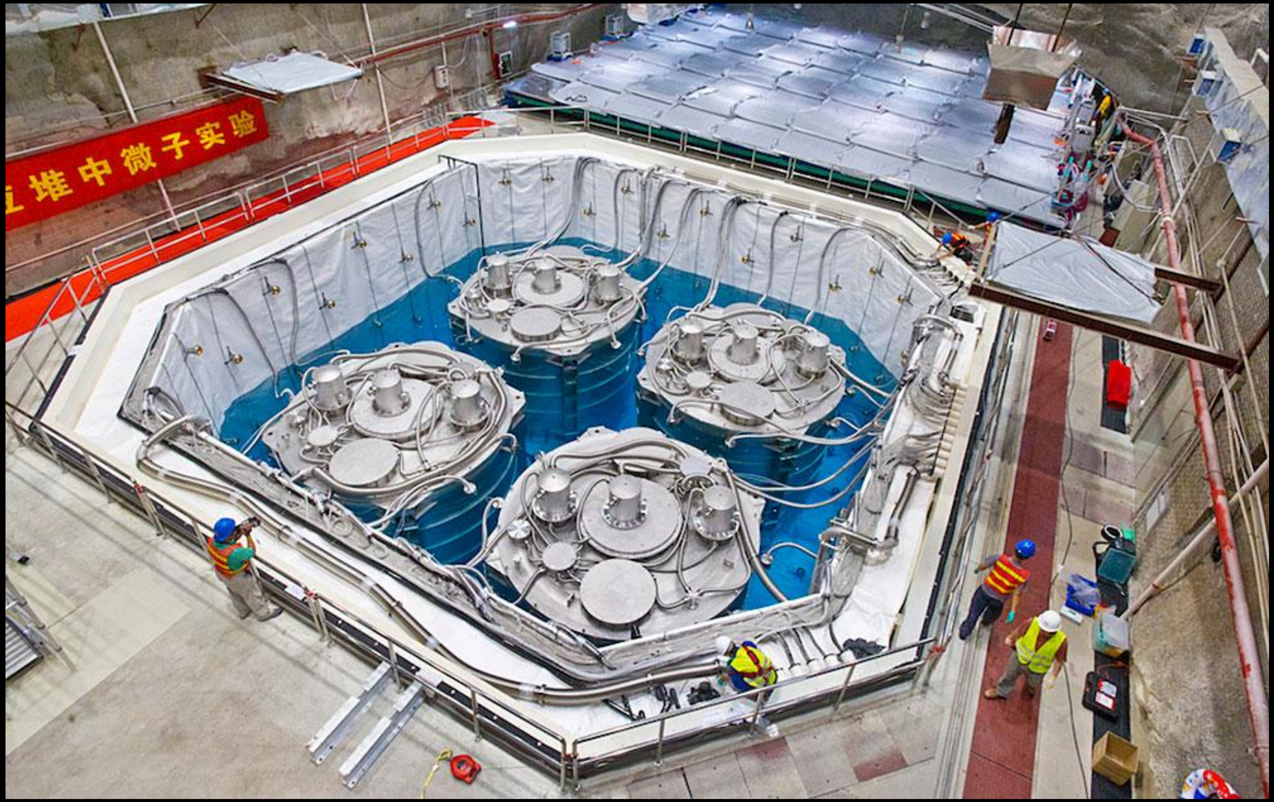
Daya Bay



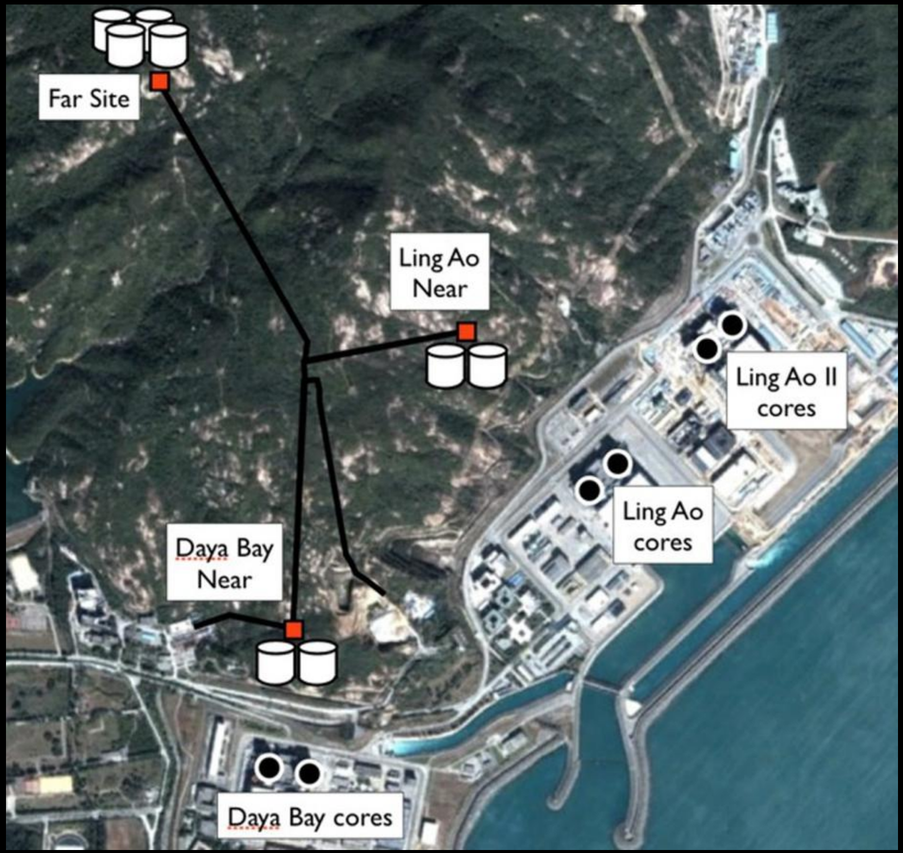


Multiple 20 ton liquid scintillator detectors

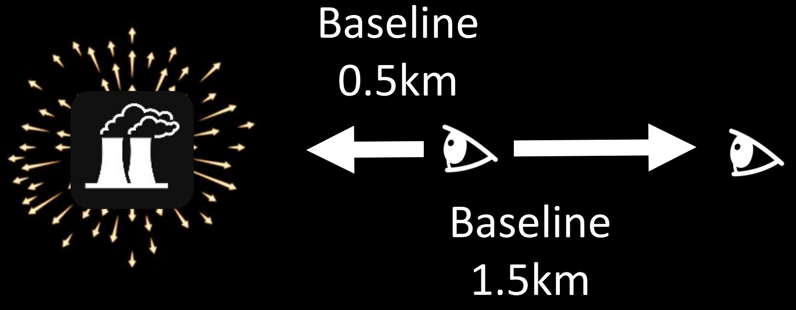
Daya Bay



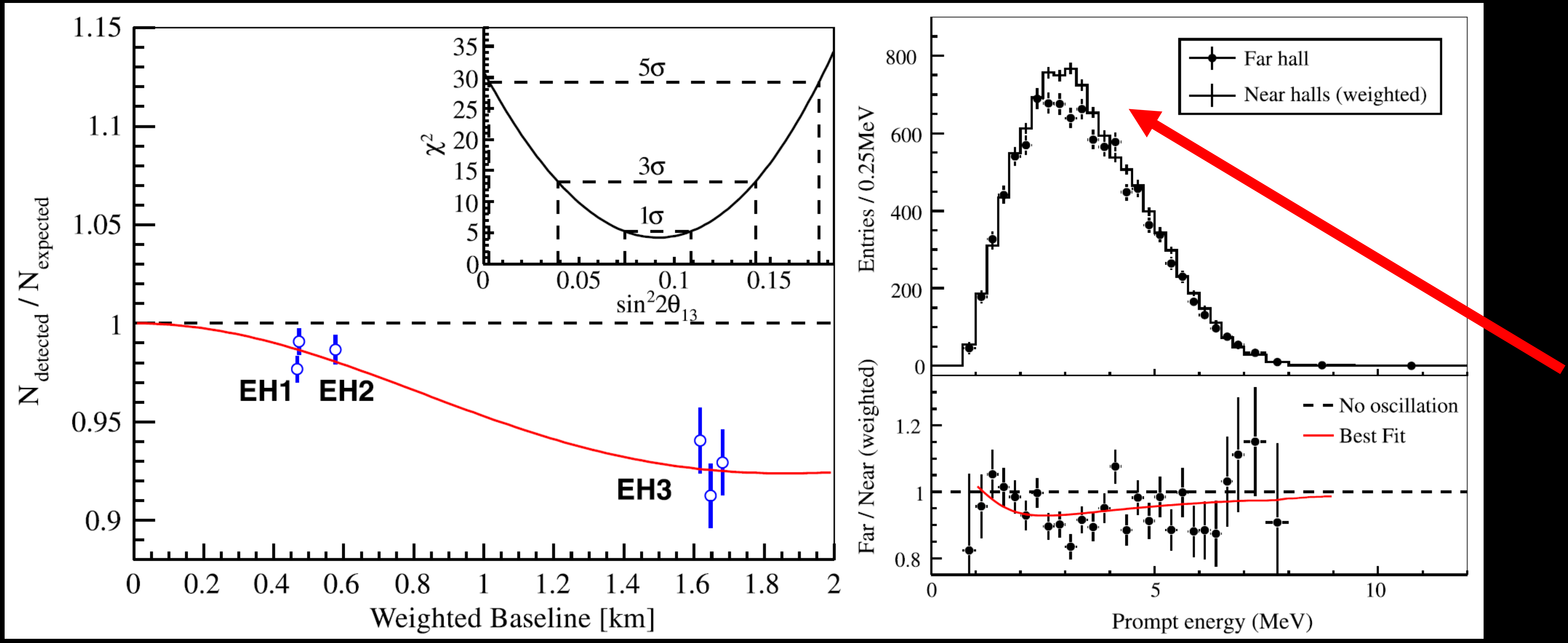
Multiple 20 ton liquid scintillator detectors



Daya Bay



$$P_{surv} \sim \frac{n_{observed,far}}{n_{observed,near}} * \frac{d_{far}^2}{d_{near}^2}$$

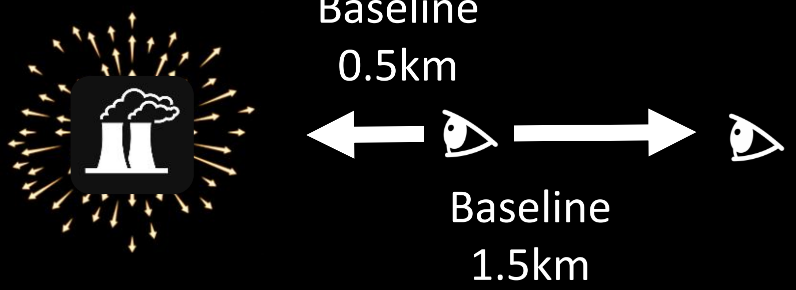


Early DayaBay experimental results

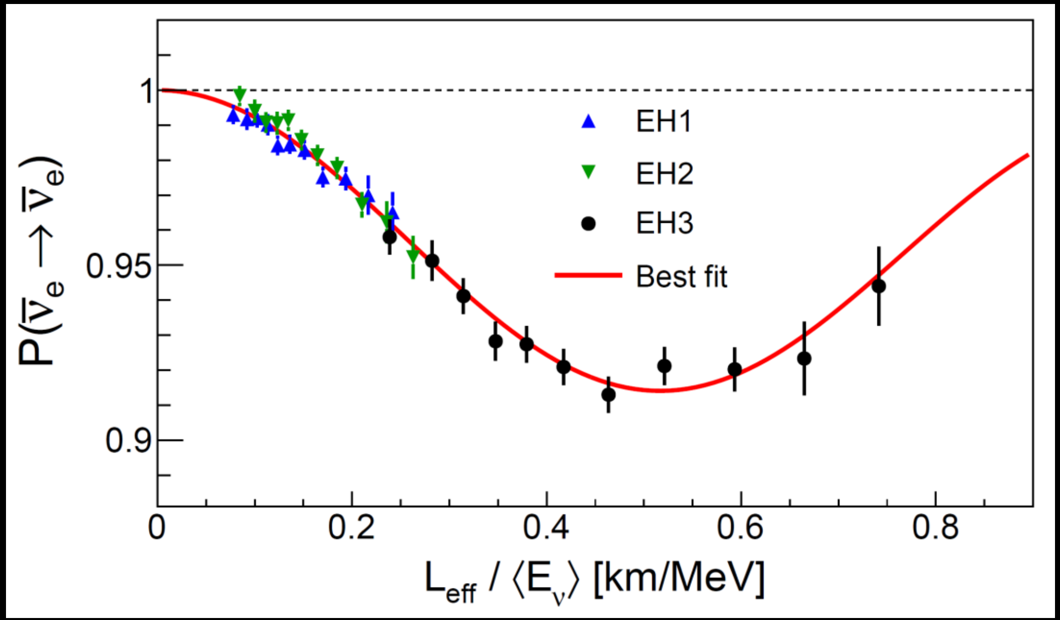
Clear deviation between near and far detectors

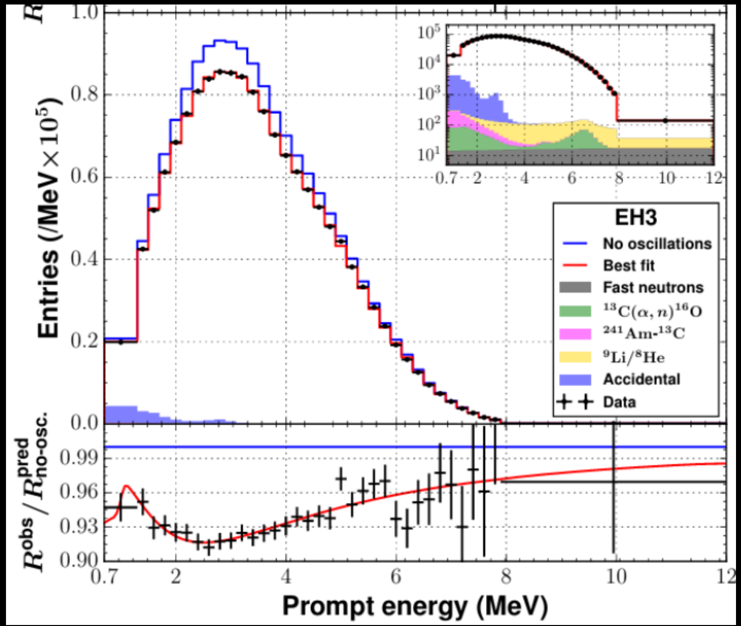
Result: $\theta_{13} \approx 9°$, surprisingly large

Daya Bay



$$P_{surv} \sim \frac{n_{observed,far}}{n_{observed,near}} * \frac{d_{far}^2}{d_{near}^2}$$





Final result
with 1230 days
of data

$\sin^2(2\theta_{13}) = 0.0841$
±00027(stat) ± 00019(syst)

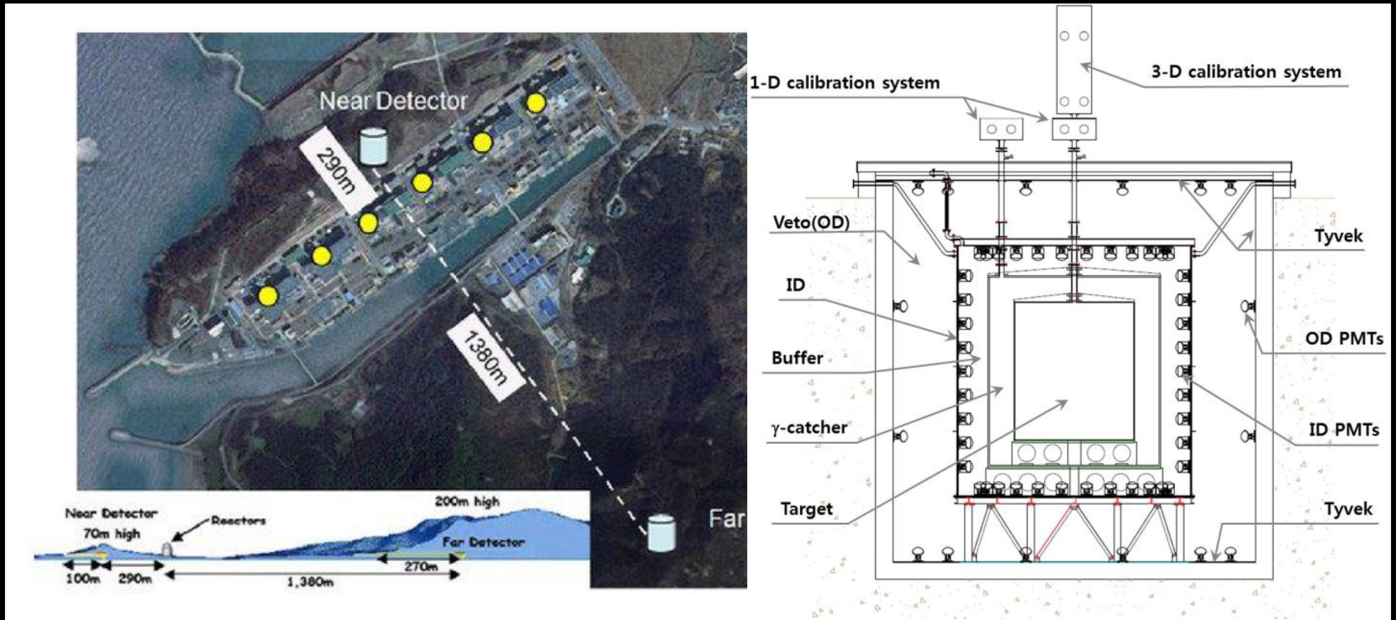
$$U = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & -s_{13}e^{i\delta_{CP}} \\ & 1 & \\ -s_{13}e^{i\delta_{CP}} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}$$

θ_{13} relatively large
→ hope to probe
δ_{CP}

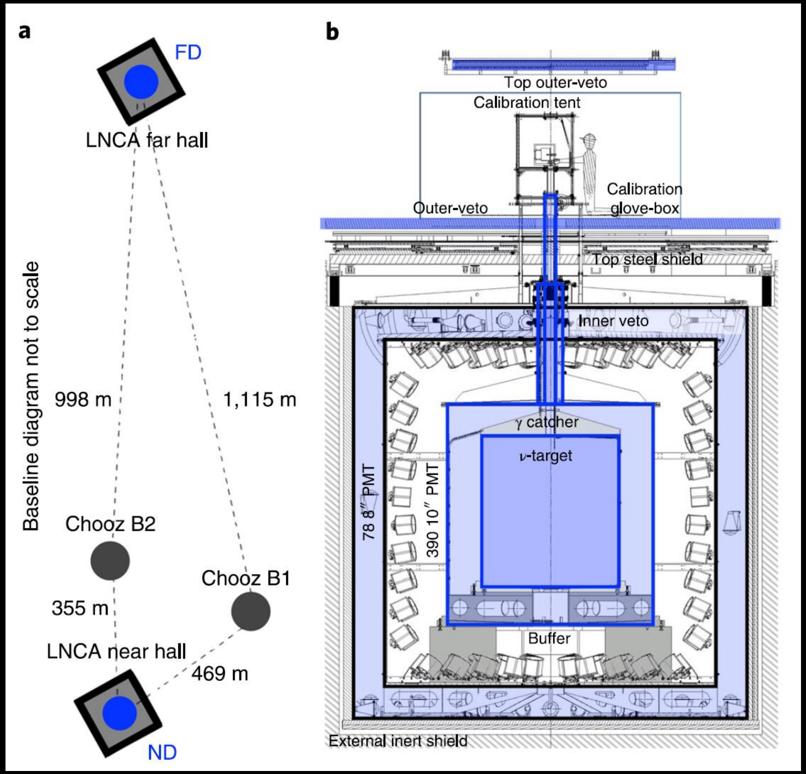
Combined efforts

Have focused on Daya Bay, but as always → independent efforts allow for validation

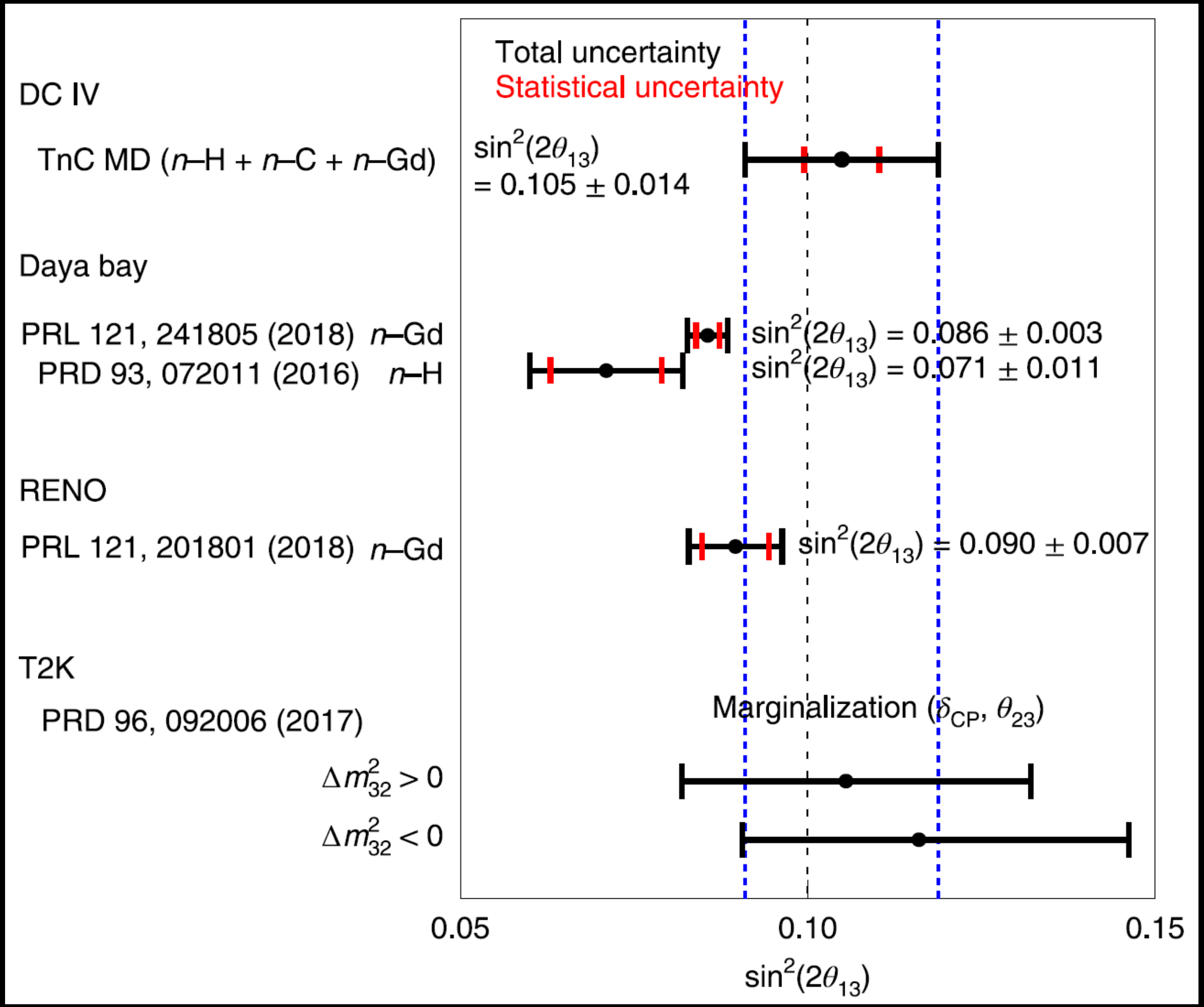
RENO:



Double CHOOZ:



Combined efforts



A comparison on θ_{13} measurements in 2020. Double CHOOZ 2021 and Daya Bay 2023 results not included.

Contents

(Some) Outstanding Questions

- θ_{12}
- θ_{13}
- θ_{23}
- Δm^2_{21}
- Δm^2_{32}
- <u>Mass Ordering?</u>
- <u>δ_{CP}?</u>

Have measured neutrino mass differences, what about their order?

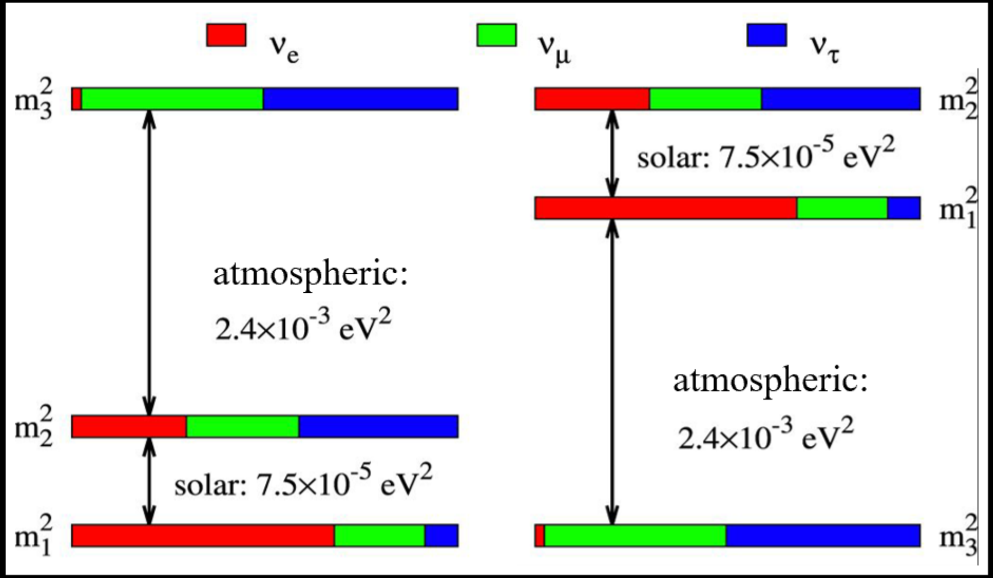
θ_{13} is relatively large, measuring δ_{CP} gives insight into matter-antimatter asymmetry

Are neutrinos Majorana particles?

$$\psi_R \equiv (\psi_L)^c$$

What is the mechanism for neutrino mass?

Are there more than 3 neutrinos – sterile neutrinos → dark matter?

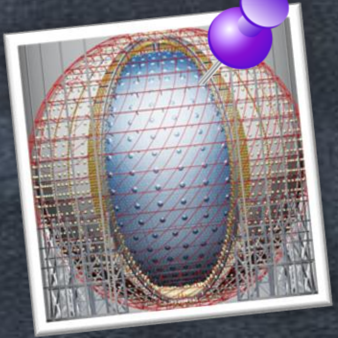


Normal Ordering
$m_1 < m_2 < m_3$

Inverted Ordering
$m_3 < m_1 < m_2$

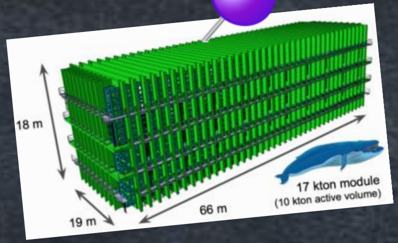
The next generation of experiments are beginning now

Massive detectors are here

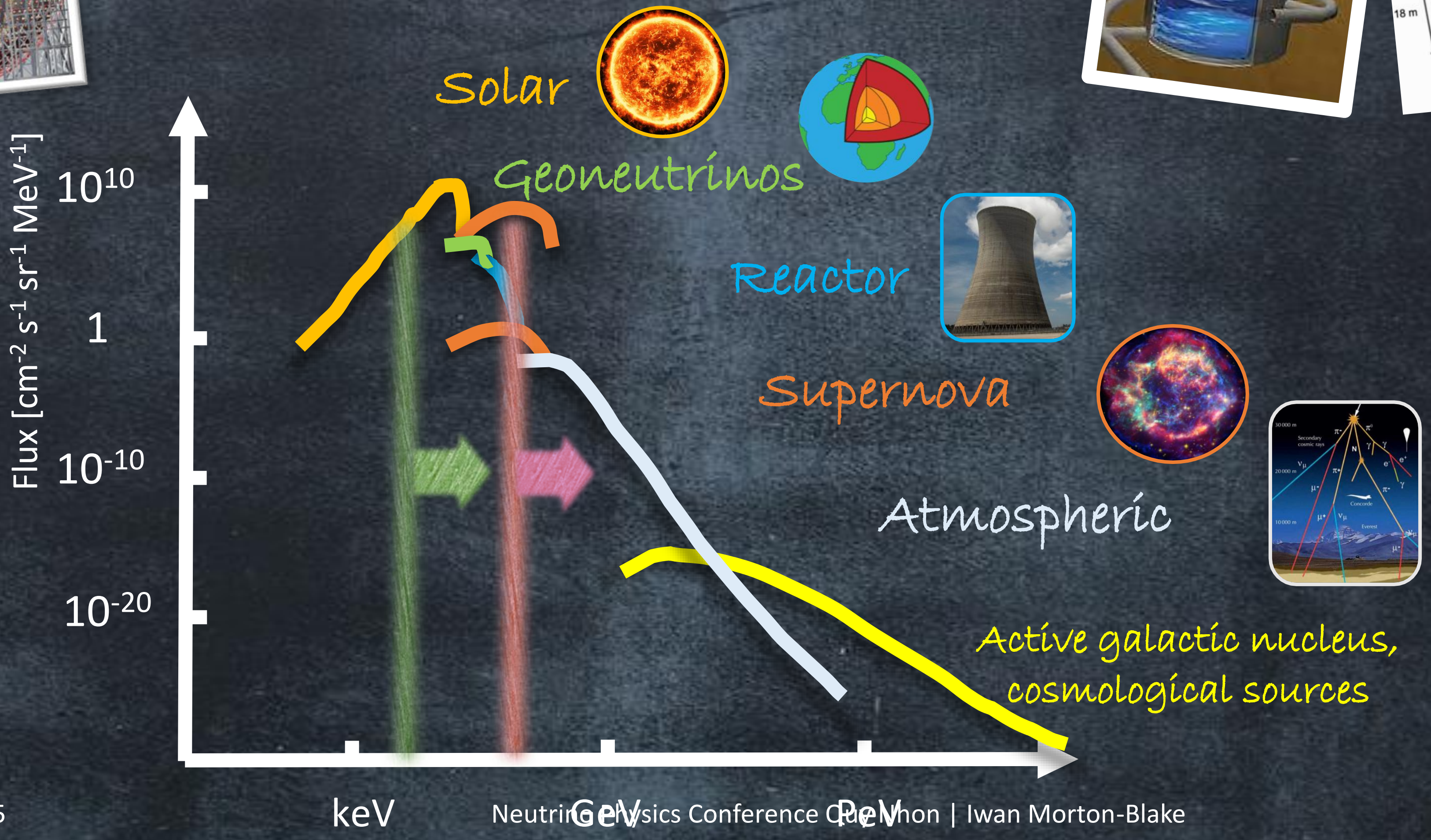


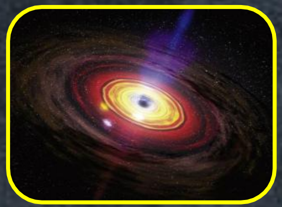
JUNO
~20 kilotons

Hyper-K
~200 kT



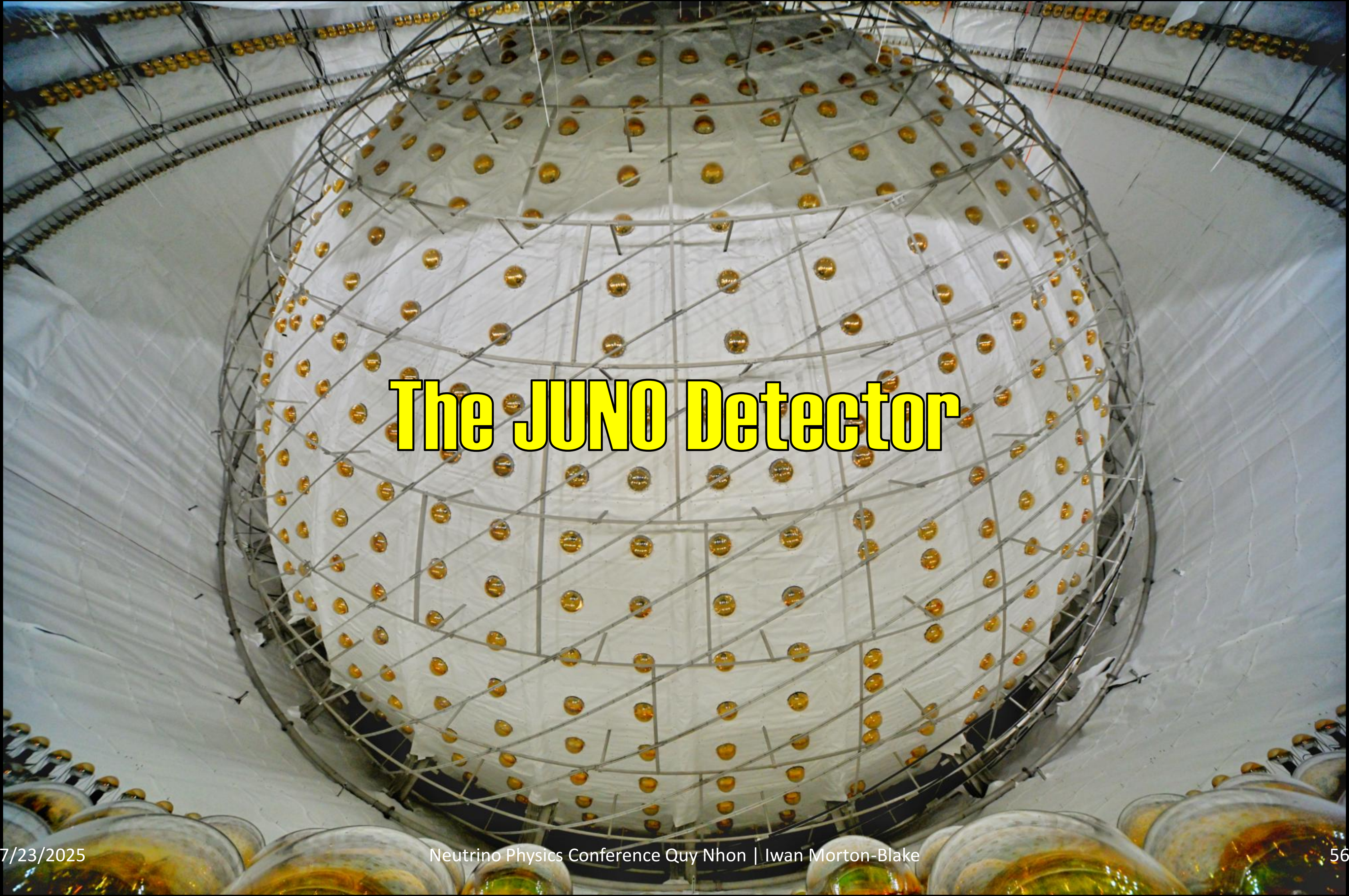
DUNE
~70 kT



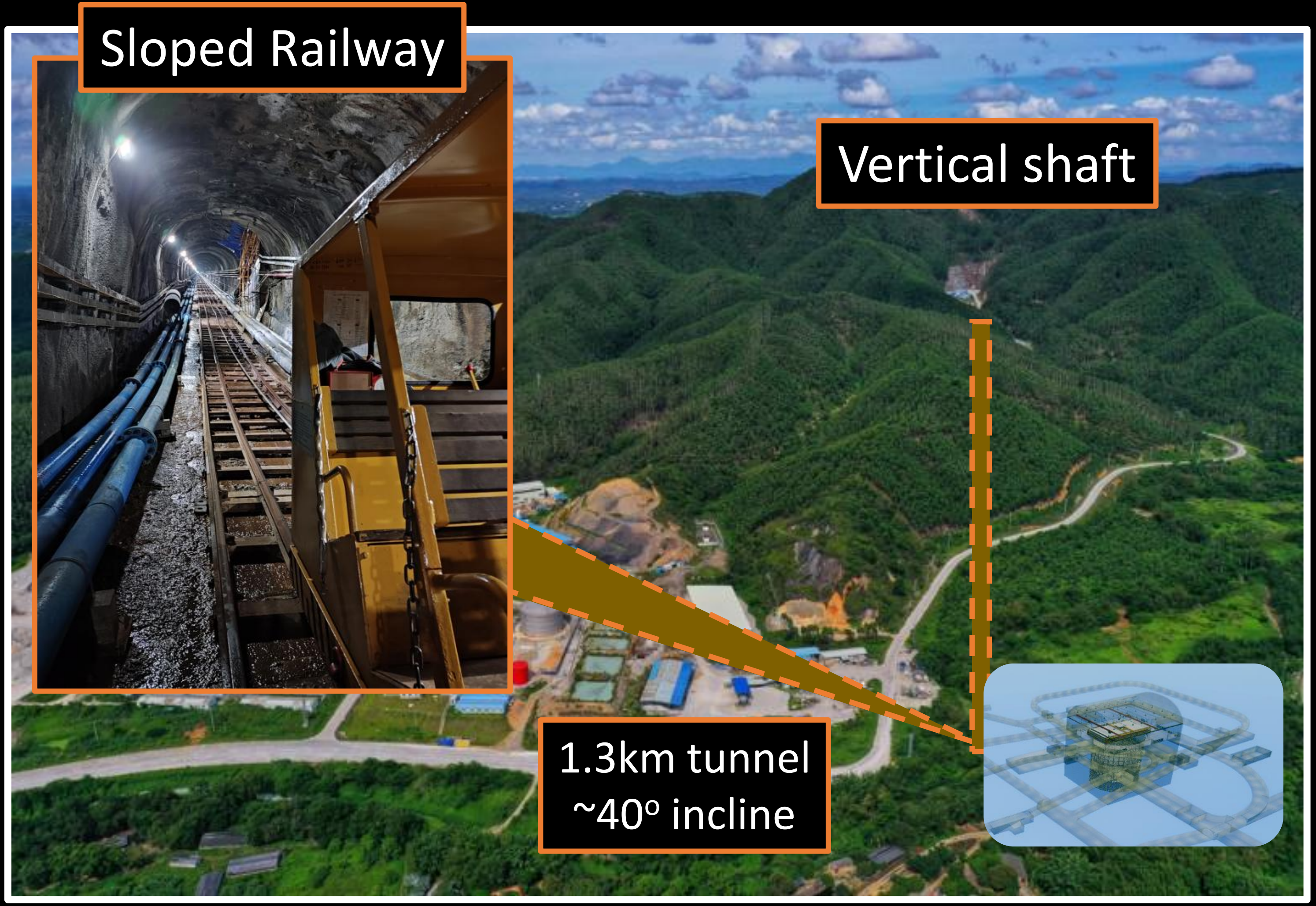


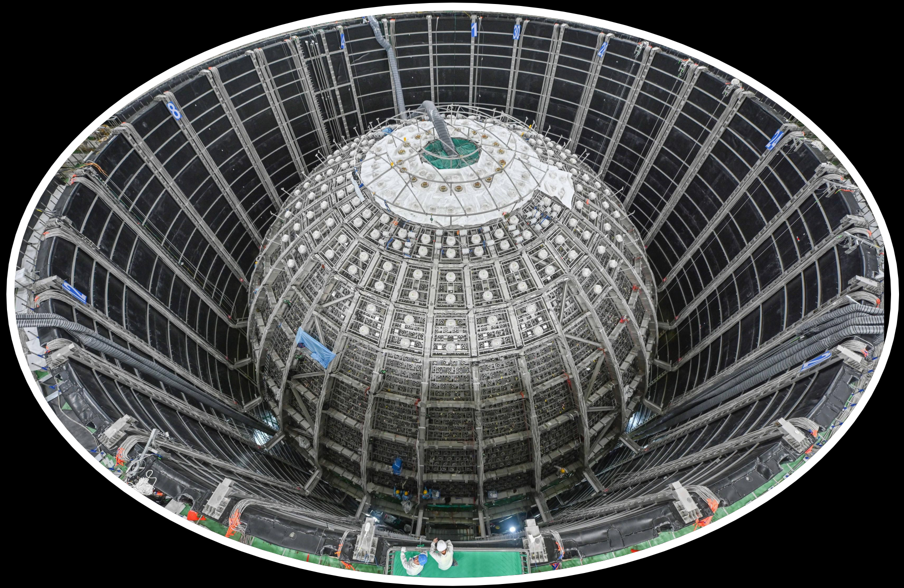
Massive detectors are here

The JUNO Detector



Jiangmen Underground Neutrino Observatory





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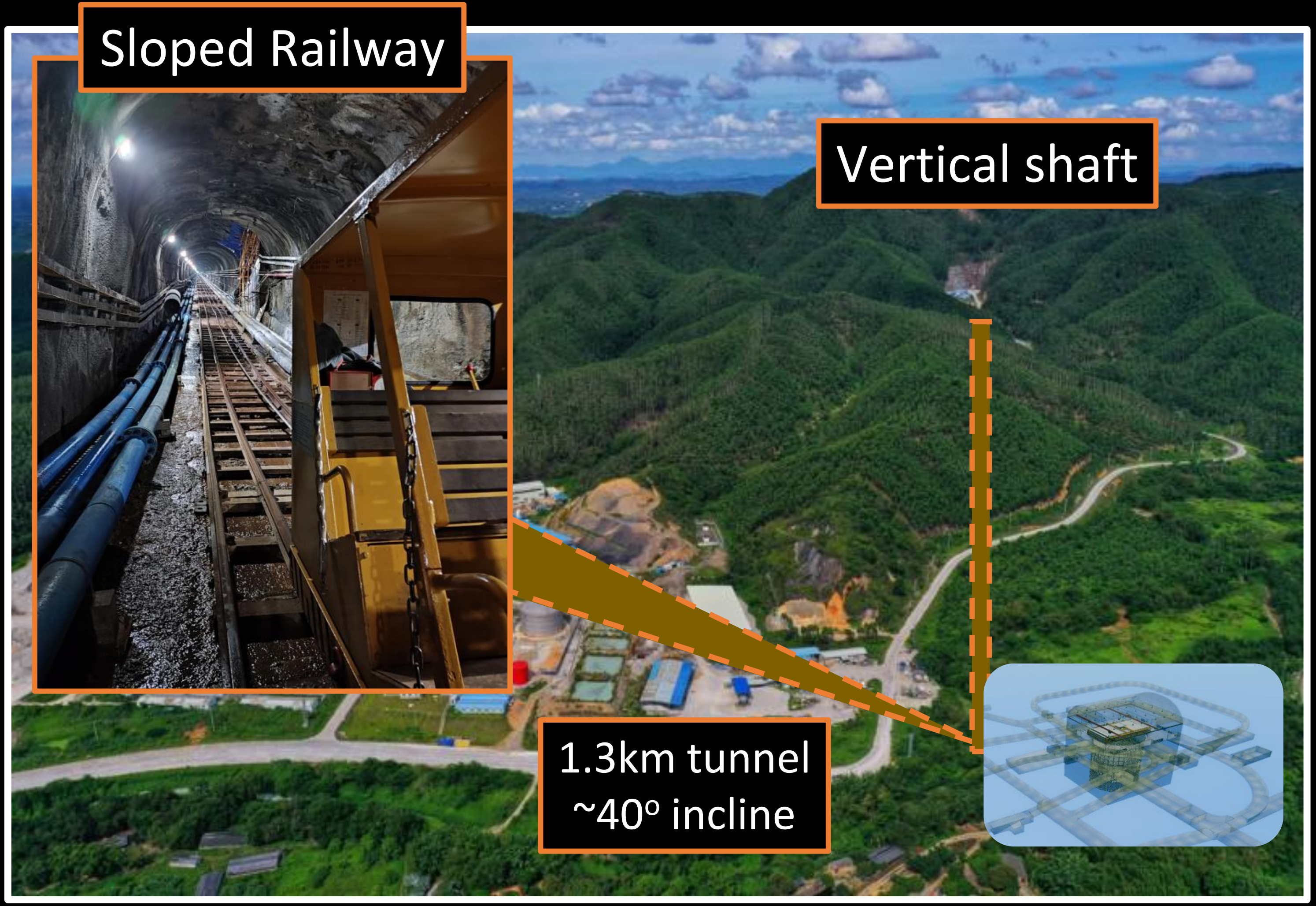
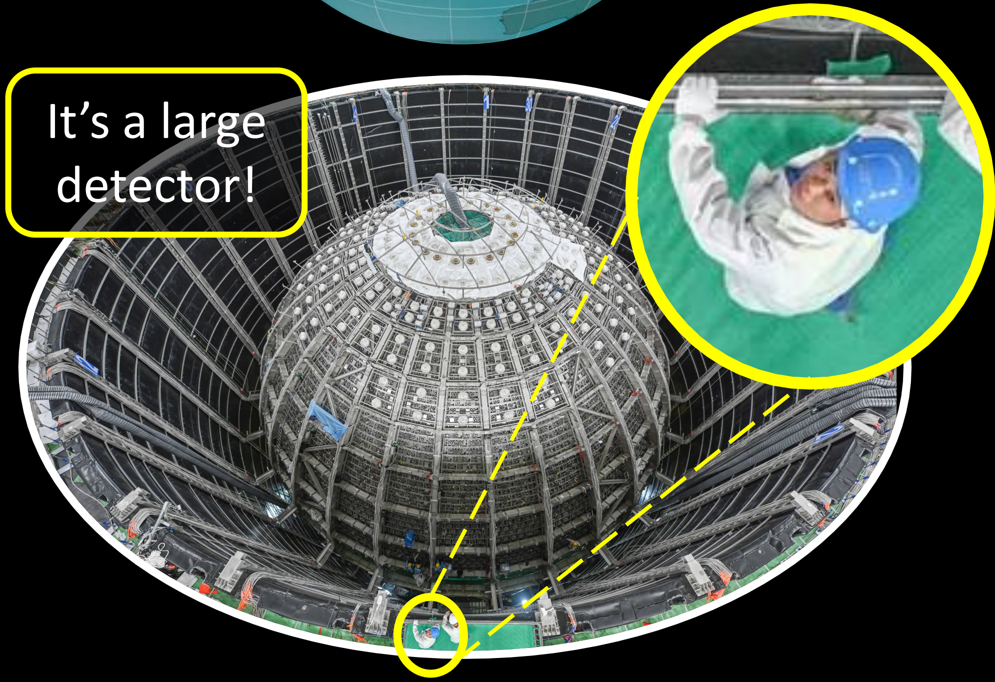
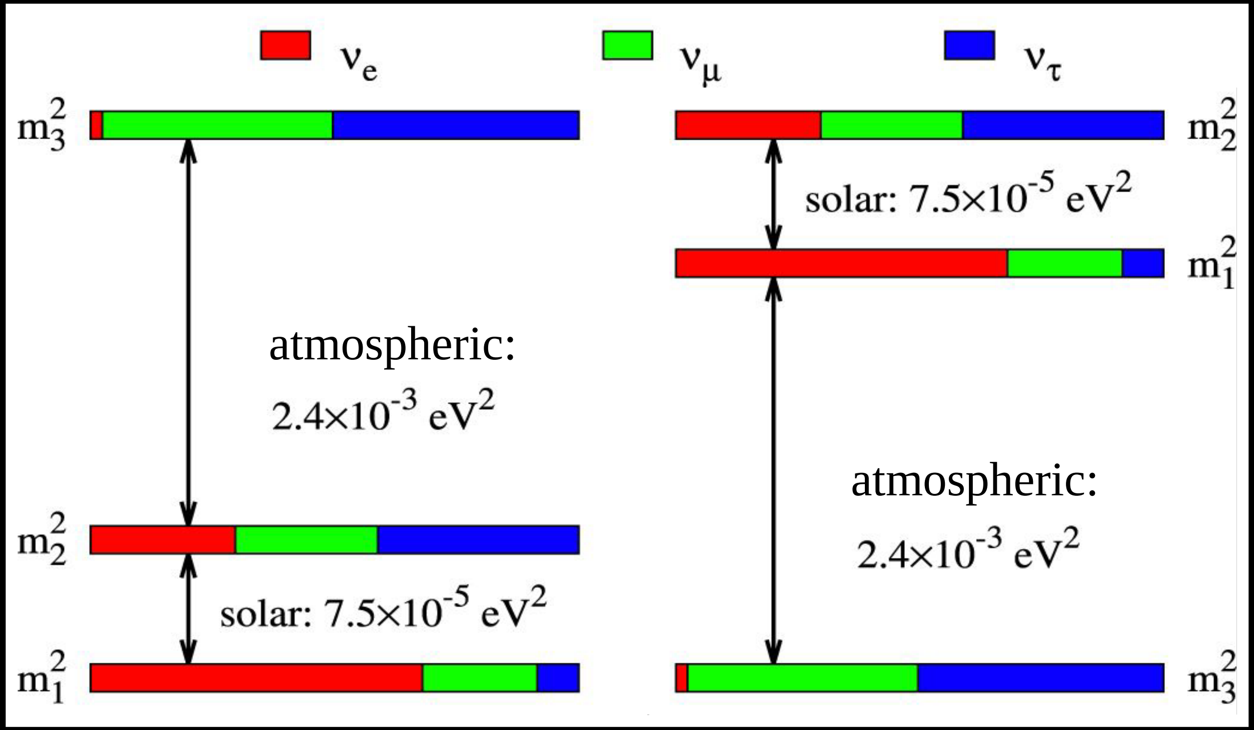




JUNO Physics Goals



Normal Ordering
$m_1 < m_2 < m_3$

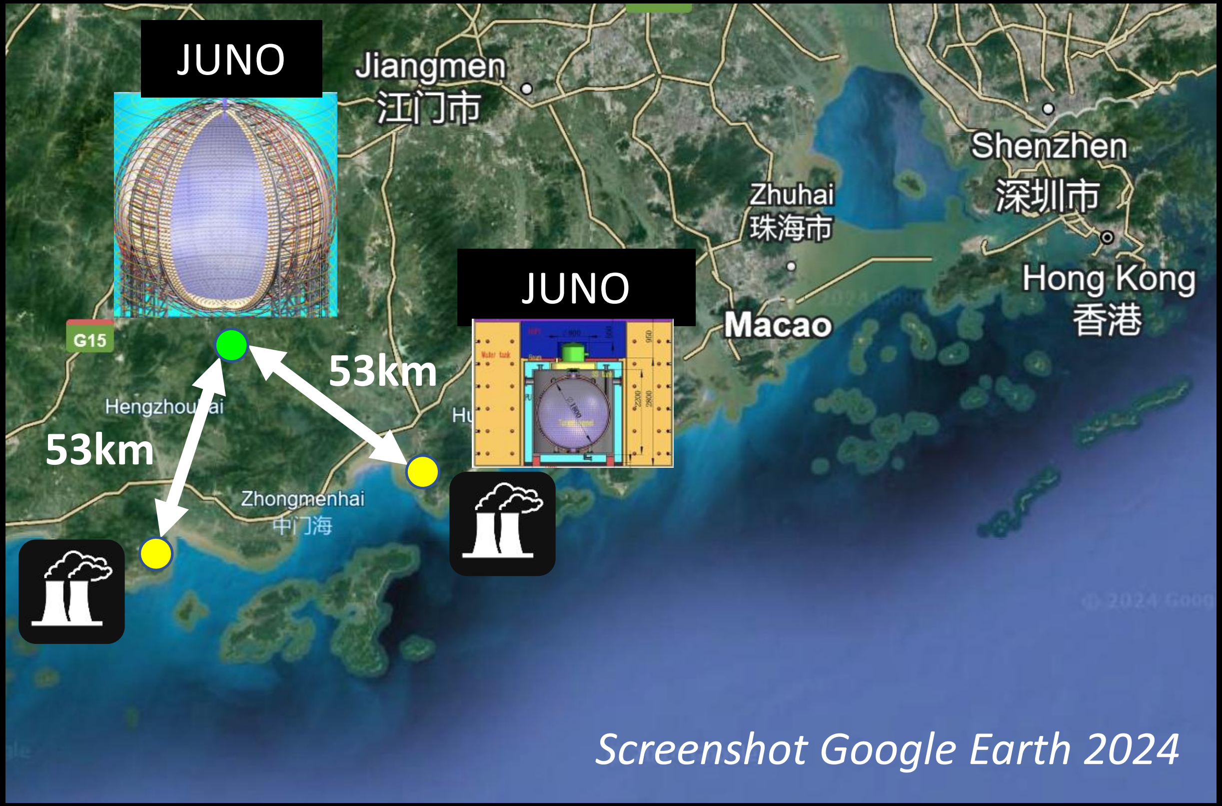
Inverted Ordering
$m_3 < m_1 < m_2$

1) Determine Neutrino Mass Ordering (NMO)

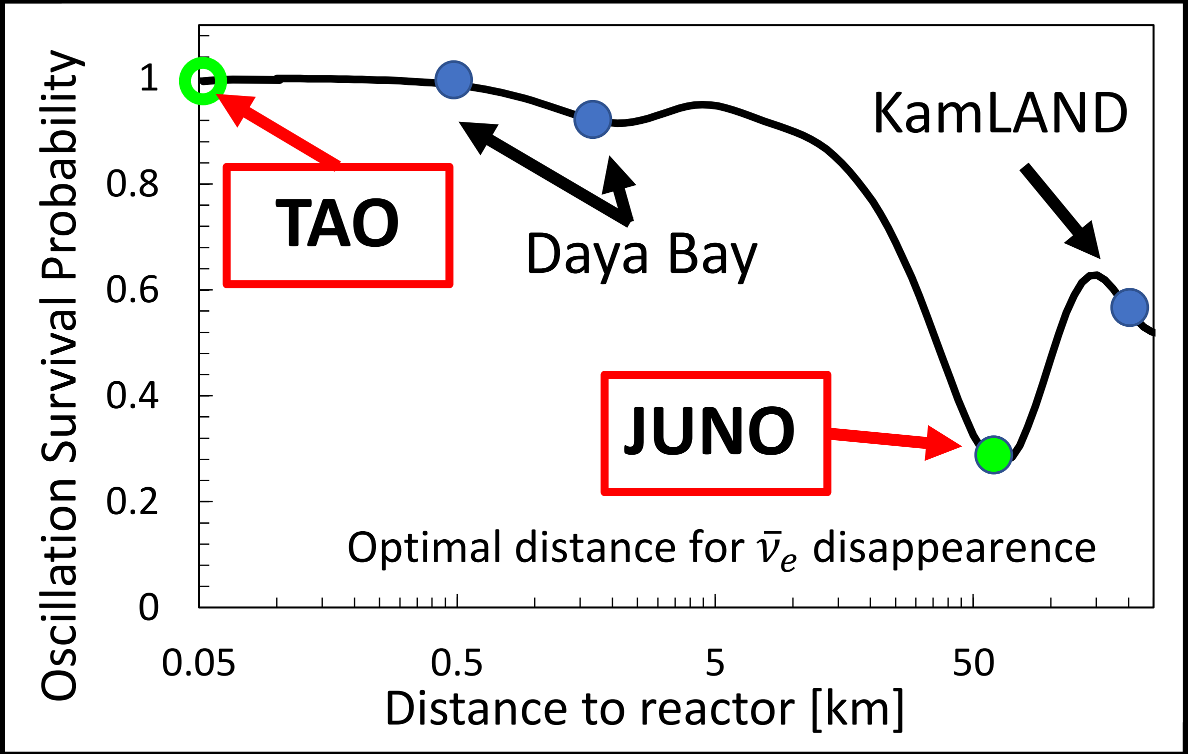
2) Precisely determine oscillation parameters $\Delta m^2_{31}, \Delta m^2_{21}$ and $\sin^2\theta_{12}$

JUNO : Reactor Neutrinos

JUNO's nearest nuclear reactors



Reactor - detector baselines



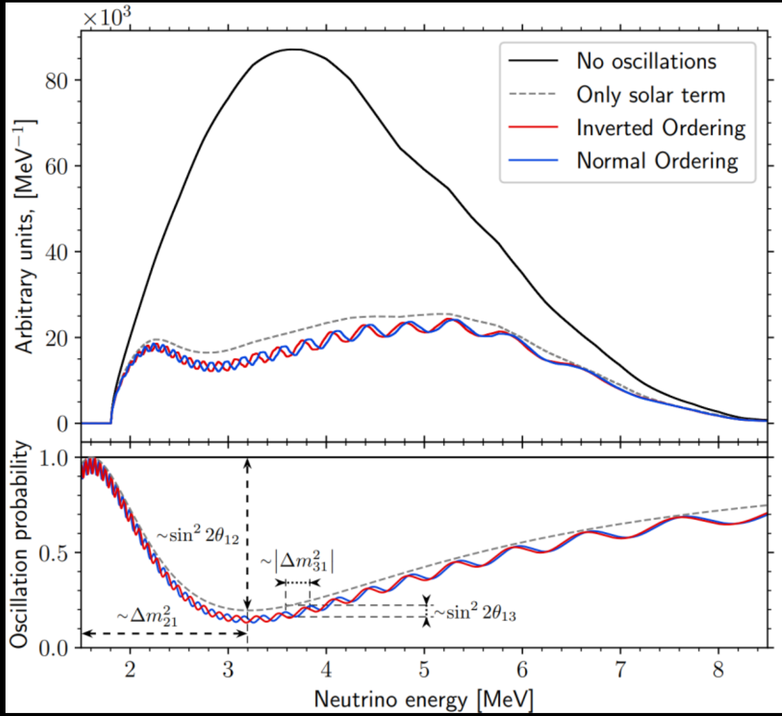
($\bar{\nu}_e$ survival averaged over reactor energy spectrum)

[“Potential to Identify the Neutrino Mass Ordering with Reactor Antineutrinos in JUNO,” arXiv:2405.18008 (2024)]

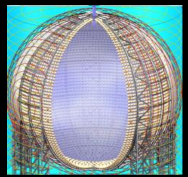
[“Sub-percent precision measurement of neutrino oscillation parameters with JUNO,” Chin. Phys. C **46** (2022)]

JUNO : Reactor Neutrinos

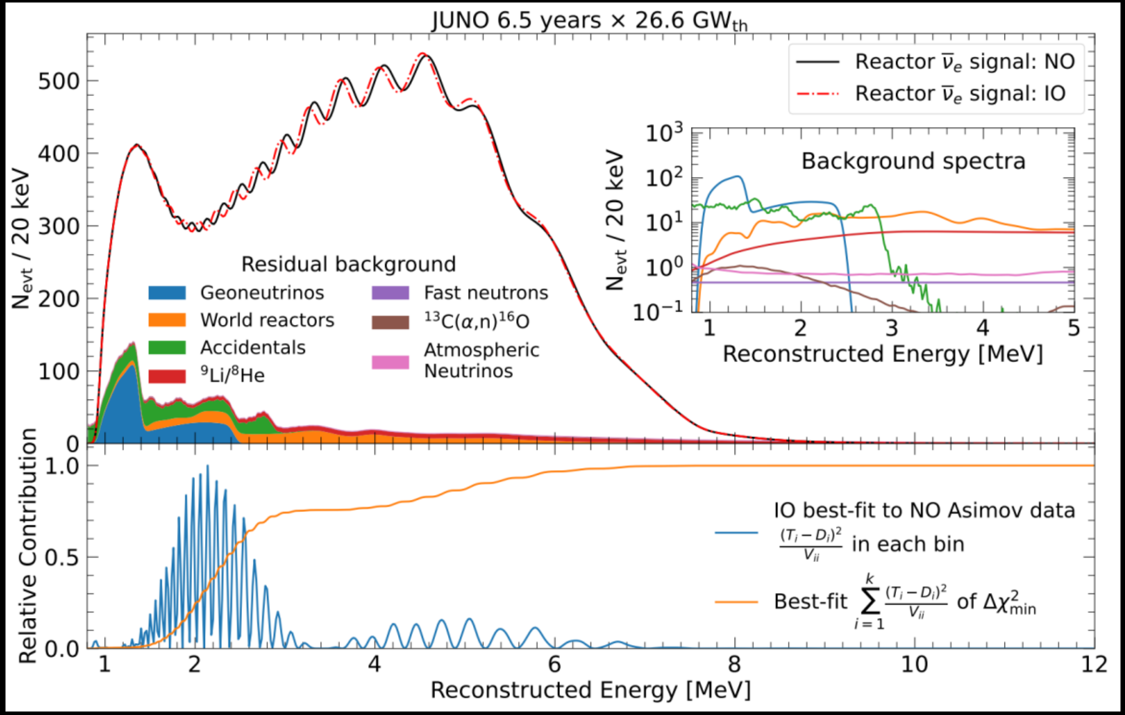
Reactor $\bar{\nu}_e$ Energy Spectrum



Detector Response



Expected Reconstructed Energy Spectrum



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

No δ_{CP}, θ_{23} dependency

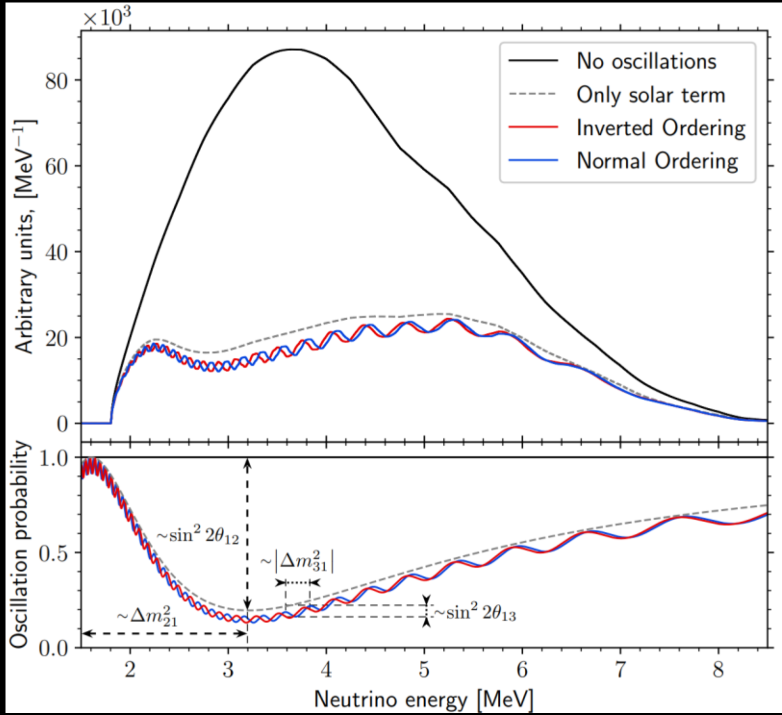
$$\Delta_{\mathrm{ij}} = \frac{\Delta m^2_{ij} L}{4E}$$

[“Potential to Identify the Neutrino Mass Ordering with Reactor Antineutrinos in JUNO,” arXiv:2405.18008](https://arxiv.org/abs/2405.18008) (2024)

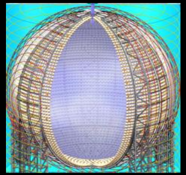
[“Sub-percent precision measurement of neutrino oscillation parameters with JUNO,” Chin. Phys. C **46** (2022)]()

JUNO : Reactor Neutrinos

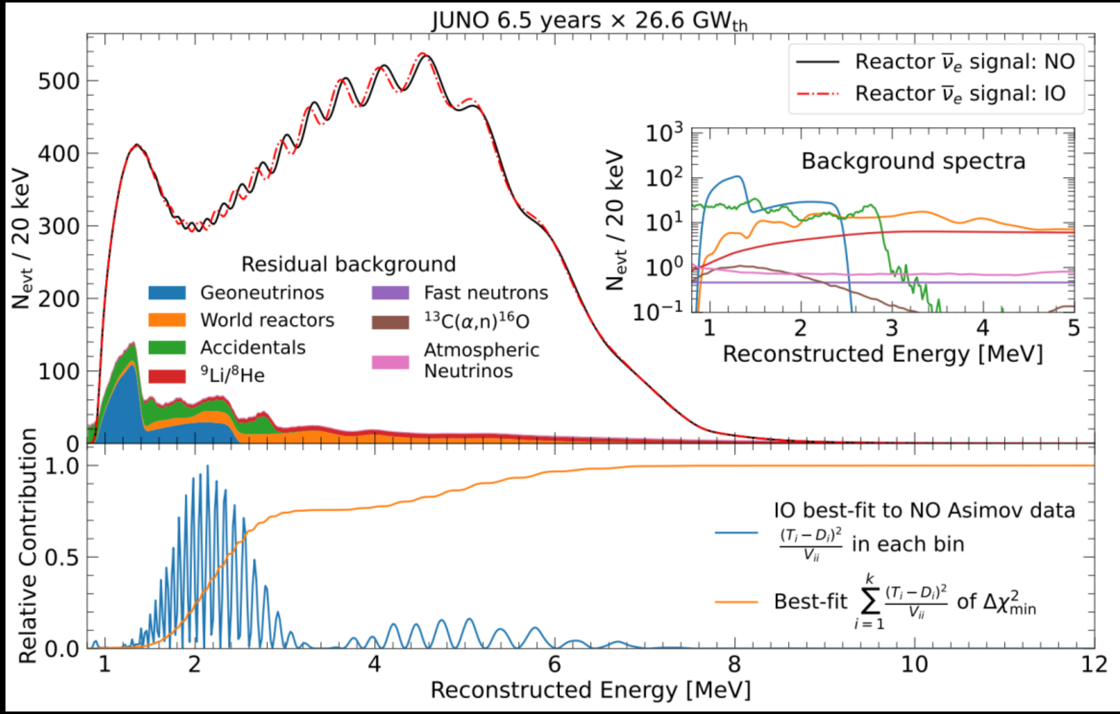
Reactor $\bar{\nu}_e$ Energy Spectrum



Detector Response



Expected Reconstructed Energy Spectrum



JUNO Goals:

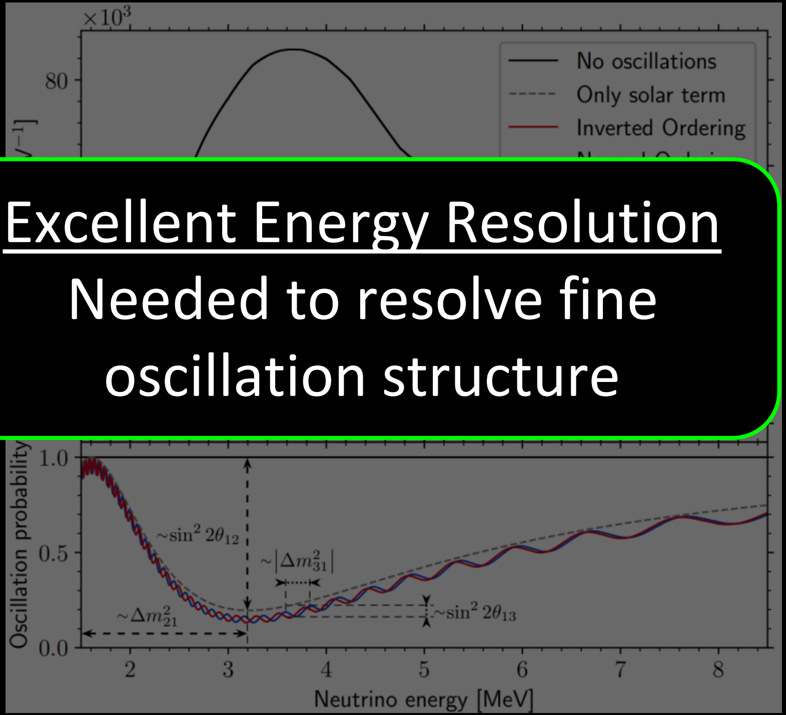
- ➢ Separate NO vs IO
- ➢ Precisely measure Δm^2_{31}, Δm^2_{21} and $\sin^2\theta_{12}$

[“Potential to Identify the Neutrino Mass Ordering with Reactor Antineutrinos in JUNO,” arXiv:2405.18008](https://arxiv.org/abs/2405.18008) (2024)

[“Sub-percent precision measurement of neutrino oscillation parameters with JUNO,” Chin. Phys. C **46** (2022)]()

JUNO : Reactor Neutrinos

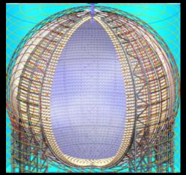
Reactor $\bar{\nu}_e$ Energy Spectrum



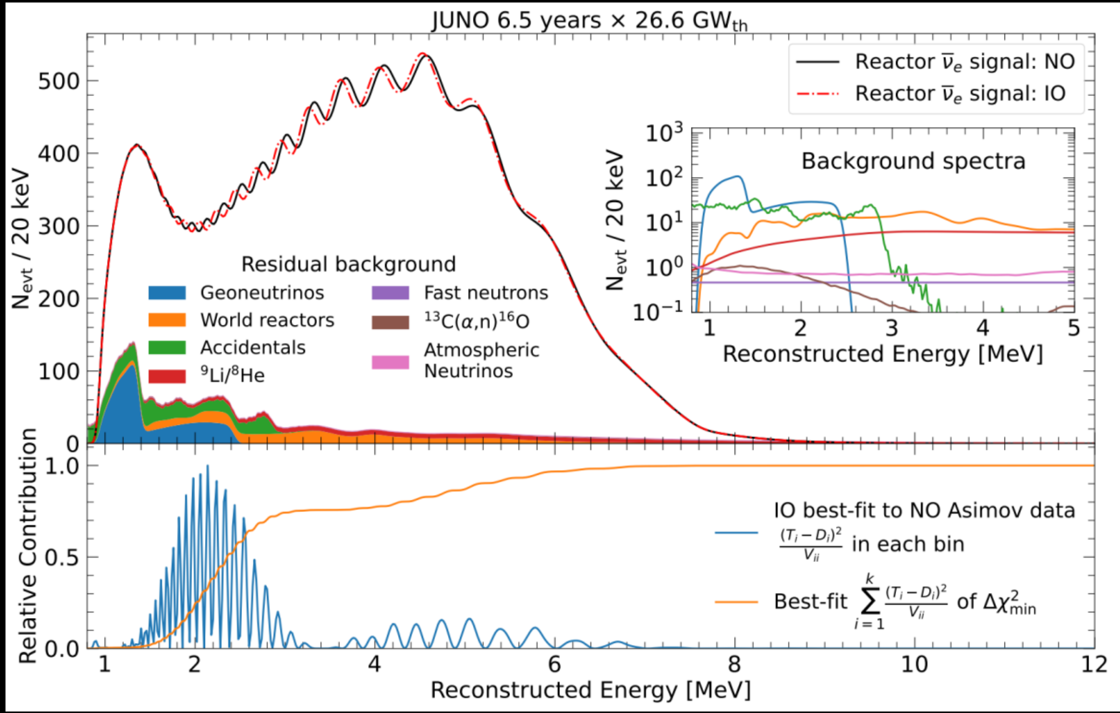
Excellent Energy Resolution

Needed to resolve fine oscillation structure

Detector Response



Expected Reconstructed Energy Spectrum



JUNO Goals:

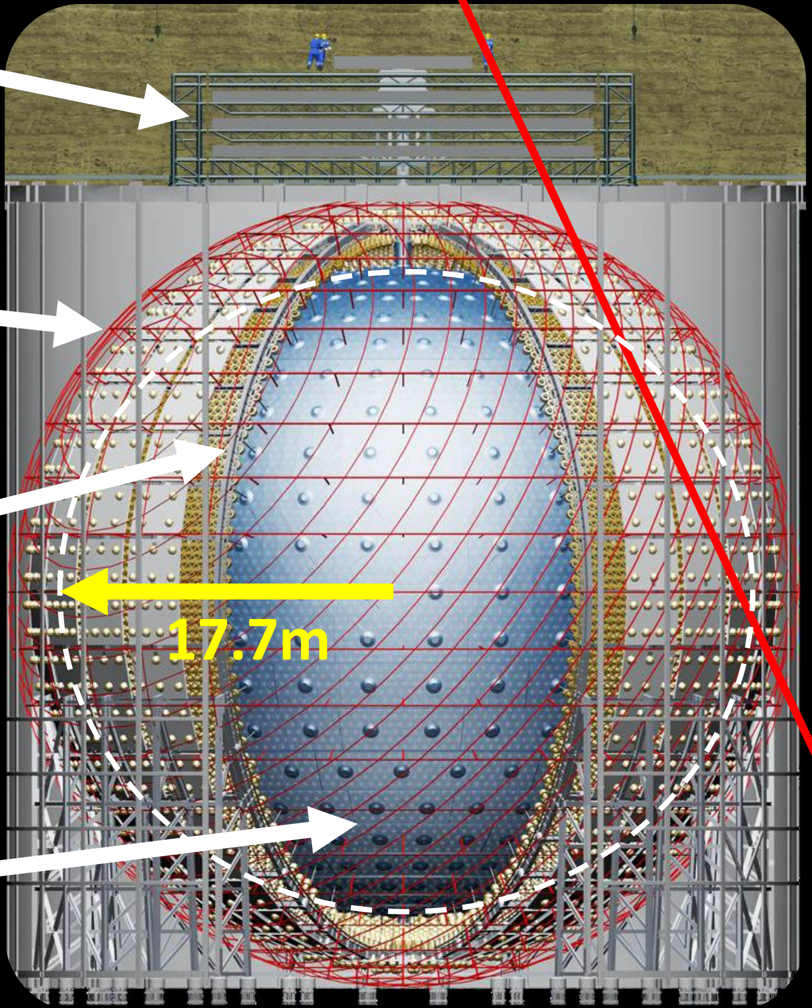
- Separate NO vs IO
- Precisely measure $\Delta m^2_{31}, \Delta m^2_{21}$ and $\sin^2\theta_{12}$

The JUNO Detector

Cosmic muons thru CD ~4Hz
Muon Veto > 99.5%

μ

~650m overburden



Top Tracker
Plastic scintillator layers

Outer Cherenkov Detector
35 kilotons ultrapure water
>2500 20” PMTs

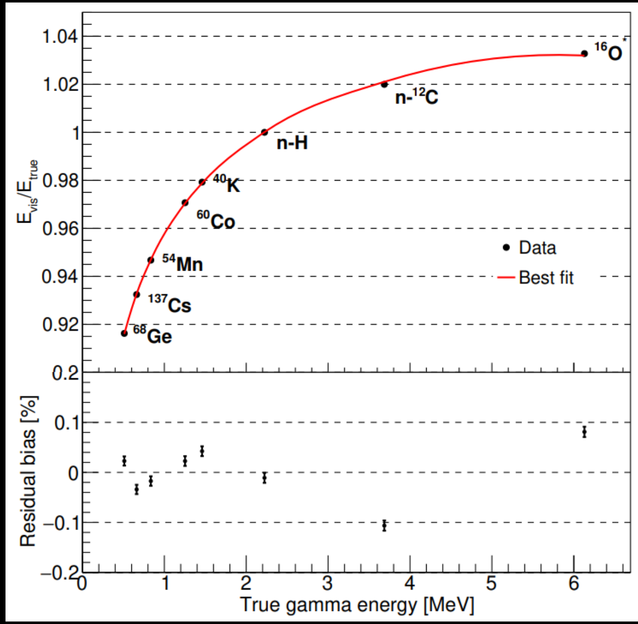
PMTs
17,596 20” + 25,600 3”

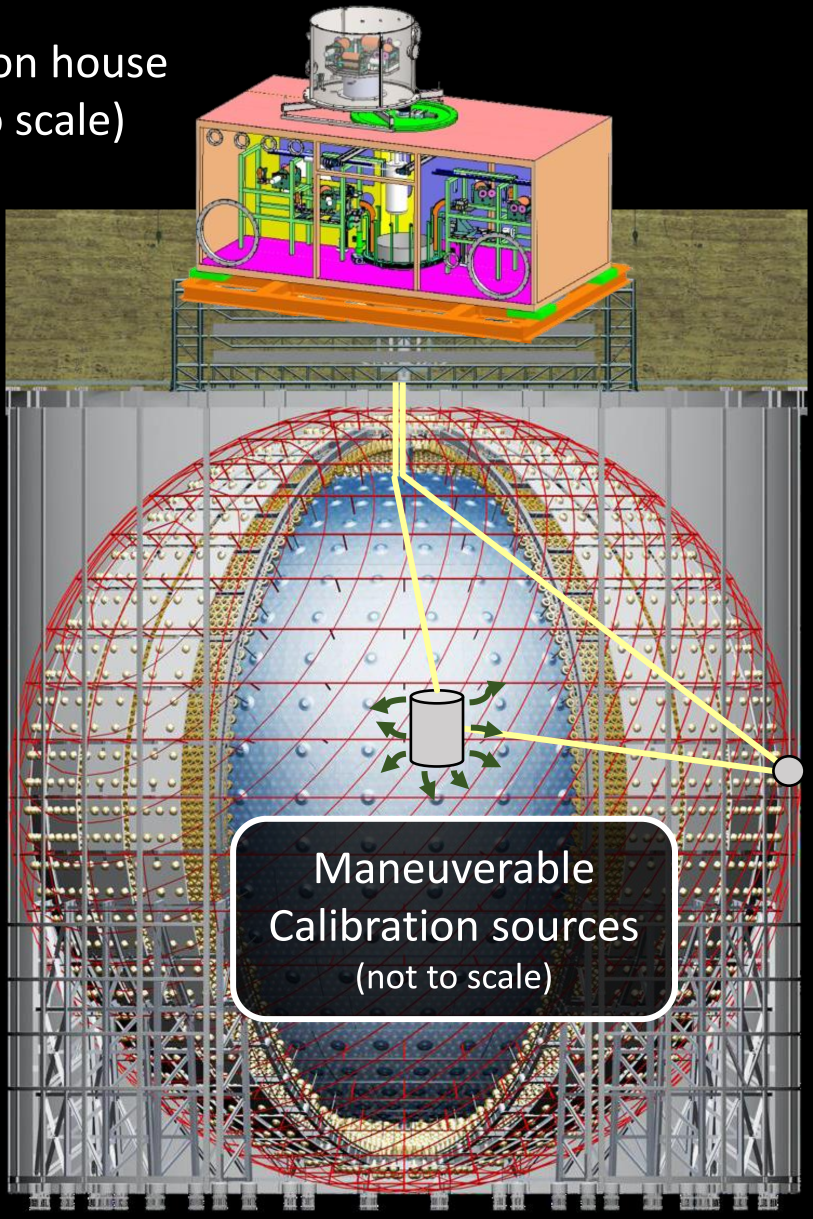
Acrylic Vessel
17.7 m in radius
20 kilotons of liquid scintillator
LAB + 2.5 g/L PPO + 3 mg/L bis-MSB

Calibration in JUNO

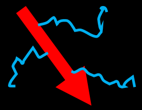
Deployable calibration sources in JUNO

Sources/Processes	Type	Radiation
^{137}Cs	γ	0.662 MeV
^{54}Mn	γ	0.835 MeV
^{60}Co	γ	1.173 + 1.333 MeV
^{40}K	γ	1.461 MeV
^{68}Ge	e^+	annihilation 0.511 + 0.511 MeV
^{241}Am-Be	n, γ	neutron + 4.43 MeV (^{12}C*)
^{241}Am-^{13}C	n, γ	neutron + 6.13 MeV (^{16}O*)
(n,γ)p	γ	2.22 MeV
(n,γ)^{12}C	γ	4.94 MeV or 3.68 + 1.26 MeV





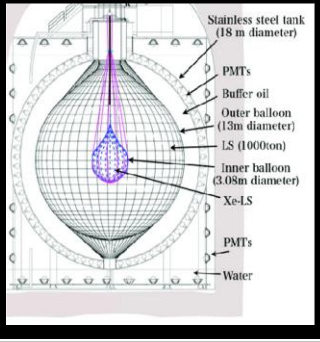
Can also use naturally present interactions in the detector

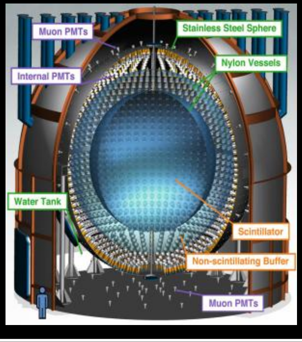
- Cosmic-ray muon spallation neutrons [5] 
- Radioactivity e.g. BiPo214 decays [6] 

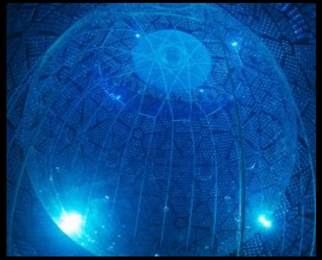
JUNO : Detector Comparison

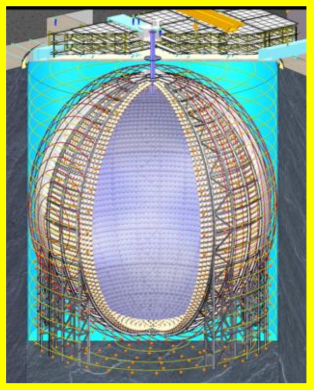
[“Prediction of Energy Resolution in the JUNO Experiment”, arXiv:2405.17860 (2024)]

JUNO:
Energy Resolution
< 3% @ 1MeV









	KamLAND [1]	Borexino [2]	SNO+ [3]	JUNO
Target Mass [kilotons]	1.0	0.3	0.78	**20**
Number of PMTs	1900	2200	10,000	**17,596 + 25,600**
PMT Coverage	~34%	~30%	~50%	**78%**
Light Collection [photoelectrons/MeV]	~250	~450	~520	**~1600**

High-precision Short Baseline Measurement

- Making next-generation precision oscillation measurements
  - → Again must understand the emitted reactor spectrum
  - → Use a next-generation short-baseline detector

- Sterile neutrinos
  - Hypothetical particle which doesn't interact via weak force
  - Heavier sterile neutrinos could be dark matter candidate?
  - Arises in a number of Beyond the Standard Model theories
  - → Can it be seen in 3 → 3+1 flavour oscillation?
  - → Precision spectrum measurement

Some recent/ on-going very short baseline experiments:

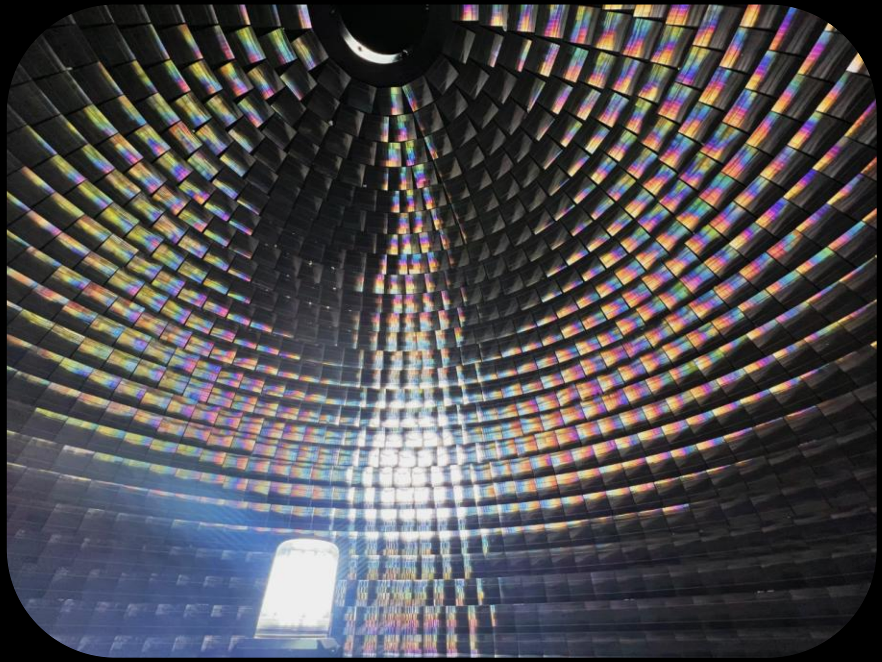
- Neutrino-4
- DANSS
- NEOS
- PROSPECT
- STEREO
- SoLid

No conclusive evidence for steriles seen to date

Taishan Antineutrino Observatory (TAO)

[“Overview of the JUNO-TAO detector”, NIM-A Vol. 1048 (2023)]

Construction of TAO detector – connecting SiPMs

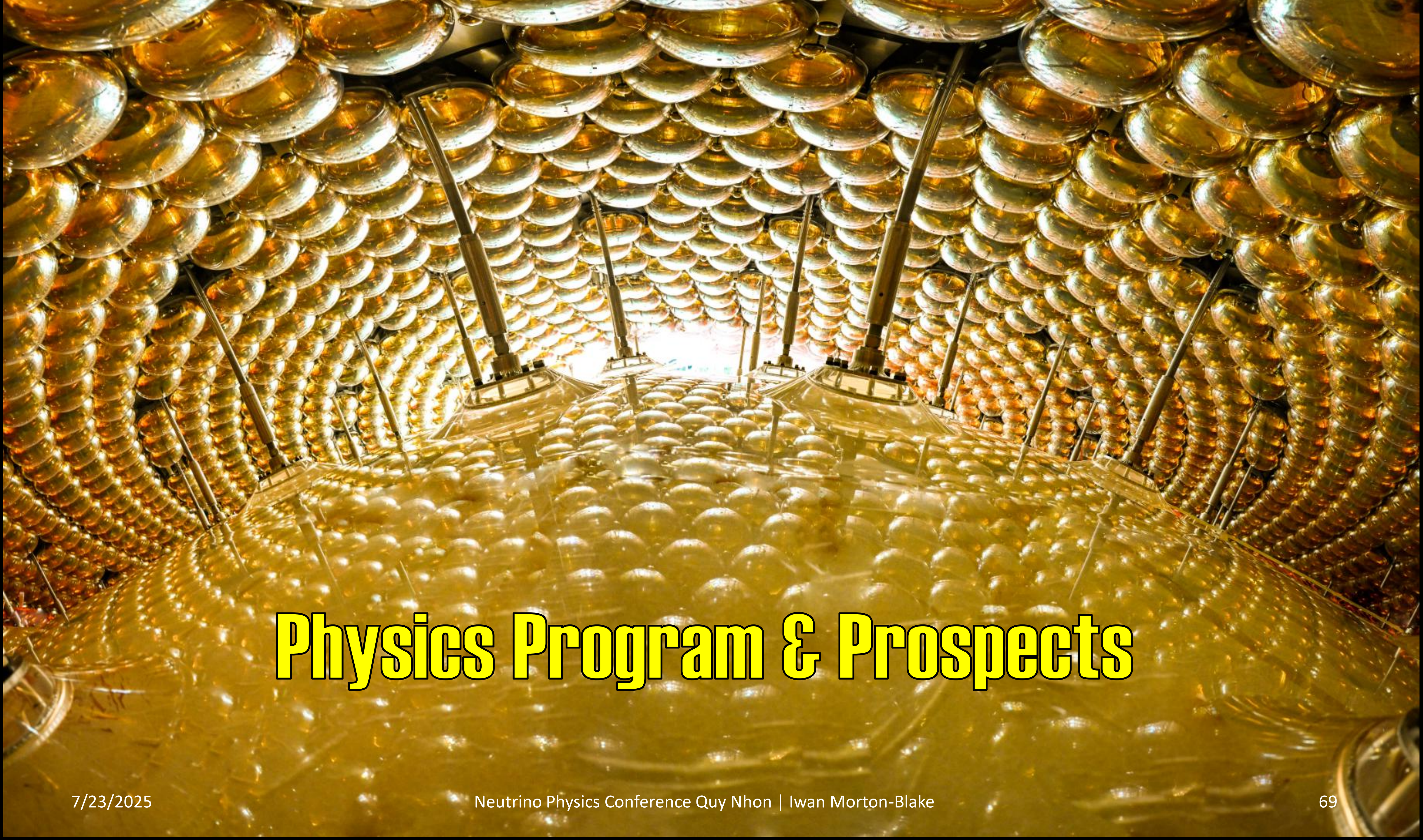


Internal view of TAO and SiPMs

- ~40m baseline from Taishan NPP
- 2.8 t Gd-loaded LS
- Operating temperature: -50 ℃
- SiPM coverage: 94%
- Energy resolution <2% @ 1 MeV
- 1000 IBDs / day

➢ Model-Independent measurement of reactor energy spectrum

➢ Sterile neutrino search

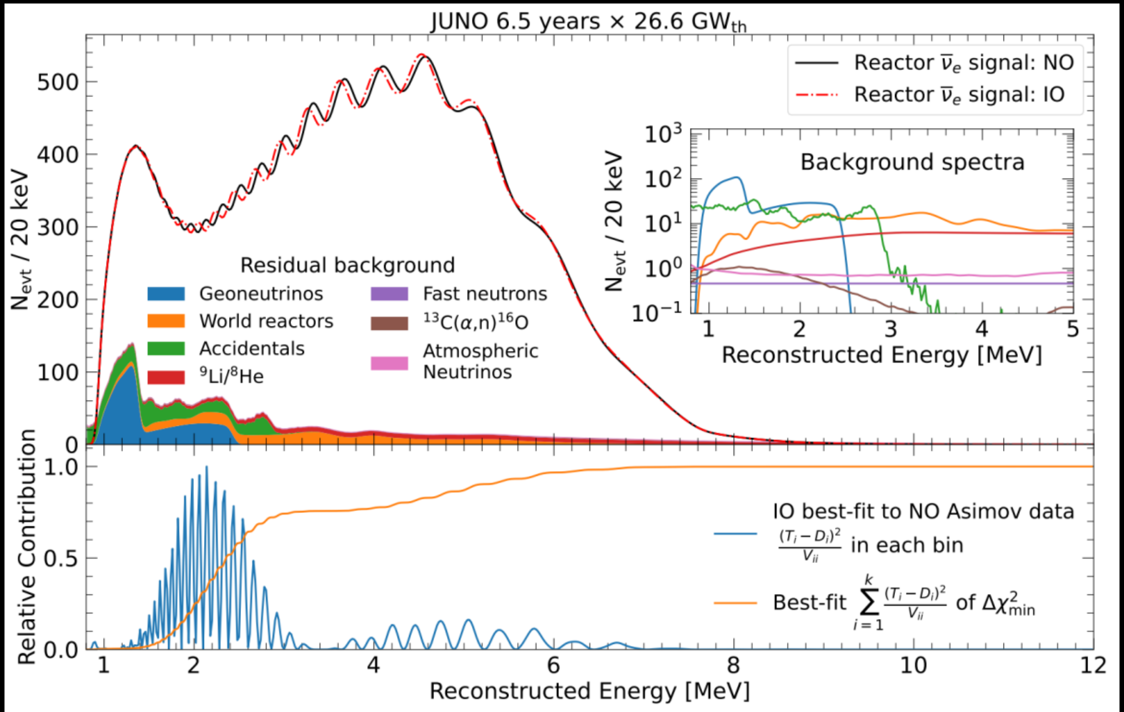


Physics Program & Prospects

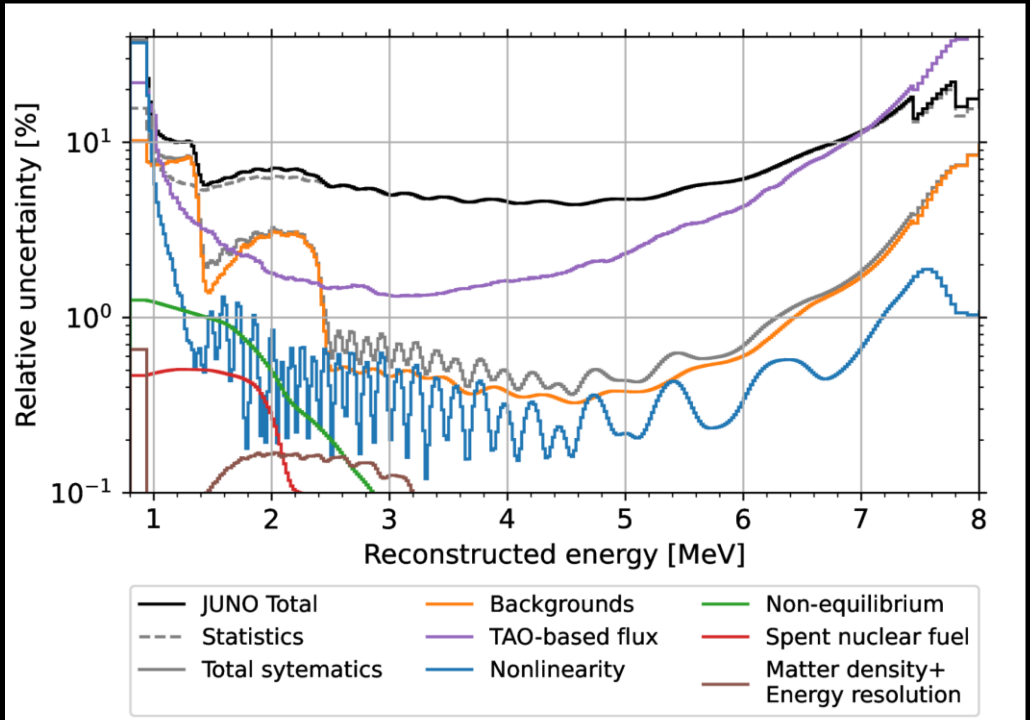
NMO with reactor neutrinos

[“Potential to Identify the Neutrino Mass Ordering with Reactor Antineutrinos in JUNO,” arXiv:2405.18008 (2024)]

Expected reconstructed energy spectrum NO vs IO



Expected uncertainties in predicted spectrum



(assuming 3σ NMO sensitivity livetime)

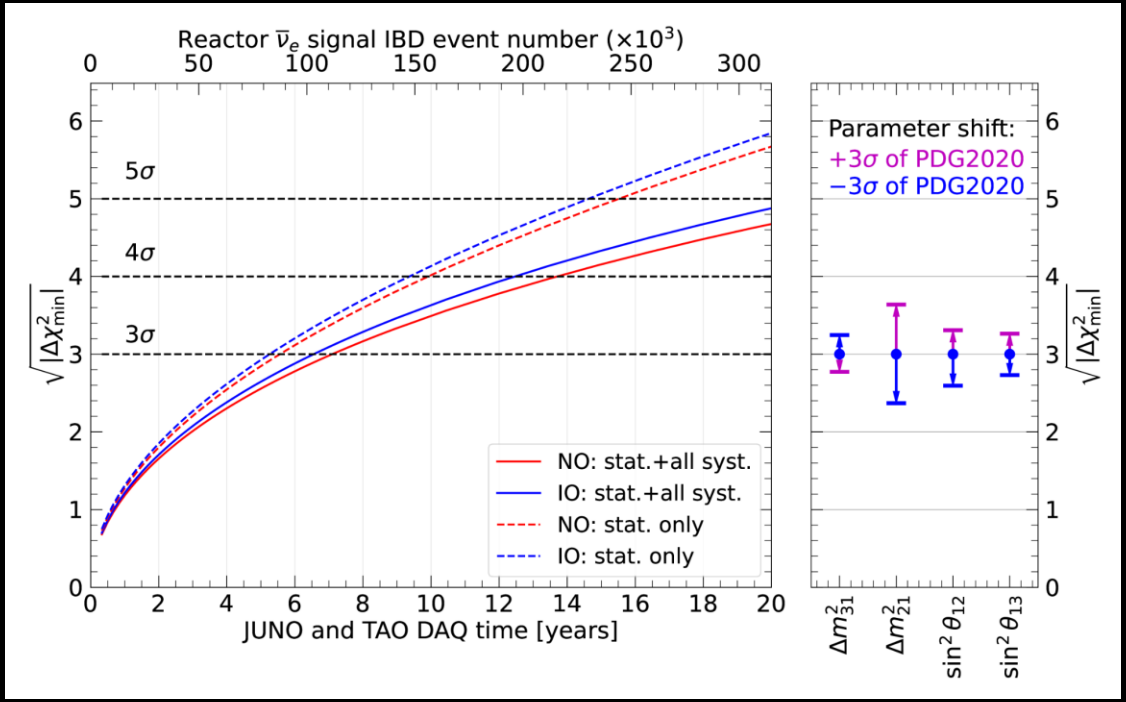
High-statistics reactor $\bar{\nu}_e$ measurement:

→ Important systematics from energy resolution, backgrounds and reactor spectrum

NMO with reactor neutrinos

[“Potential to Identify the Neutrino Mass Ordering with Reactor Antineutrinos in JUNO,” arXiv:2405.18008](https://arxiv.org/abs/2405.18008) (2024)

Expected NMO sensitivity vs livetime



Expected NMO sensitivity vs livetime

Parameter	PDG 2024	JUNO 100 days	JUNO 6 years
Δm^2_{31}	1.2%	0.8%	0.2%
Δm^2_{21}	2.4%	1.0%	0.3%
$\sin^2\theta_{12}$	4.0%	1.9%	0.5%
$\sin^2\theta_{13}$	3.2%	47.9	12.1%

- 3σ expected in 6.5 yrs using reactor neutrinos alone
- World-leading measurements of Δm^2_{21}, Δm^2_{31} and θ_{12} in ~100 days

JUNO Progress and Commissioning

JUNO Timeline

2013 → Project begins

Jan 2015 → Ground breaking

JUNO Timeline

2013 → Project begins

Jan 2015 → Ground breaking

2022 → Detector installation

2024 → Installation complete

Evolution of detector installation (animated gif)

JUNO Timeline

2013 → Project begins

Jan 2015 → Ground breaking

2022 → Detector installation

2024 → Installation complete

Checking the acrylic surface prior to filling

JUNO Timeline

2013 → Project begins

Jan 2015 → Ground breaking

2022 → Detector installation

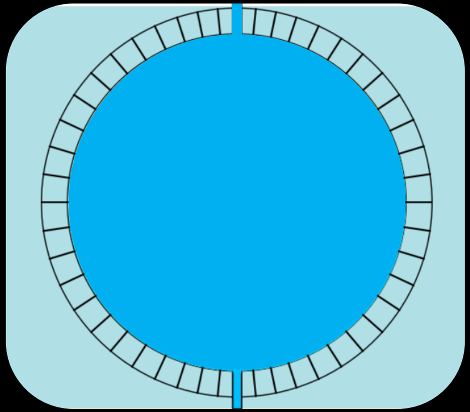
2024 → Installation complete

Dec 18 2024 → Water fill starts

Feb 1 2025 → Water filling complete

Filling of water pool (animated gif)

JUNO Timeline



2013 → Project begins

Jan 2015 → Ground breaking

2022 → Detector installation

2024 → Installation complete

Dec 18 2024 → Water fill starts

Feb 1 2025 → Water filling complete

~7 days of Pure Water Phase

First tests of full detector chain

- Calibration of 20" PMTs with laser
- Deployed gamma and neutron sources to measure the minimum energy threshold
- Observation of muons

JUNO Timeline

2013 → Project begins

Jan 2015 → Ground breaking

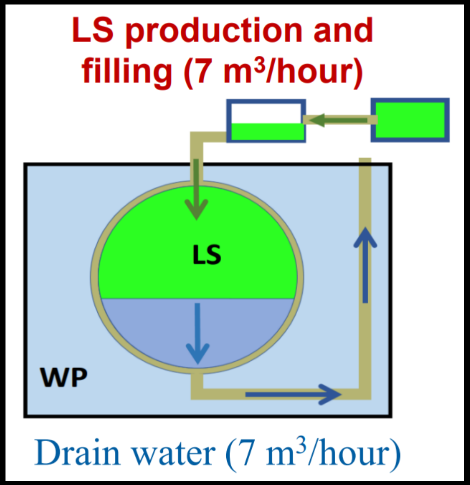
2022 → Detector installation

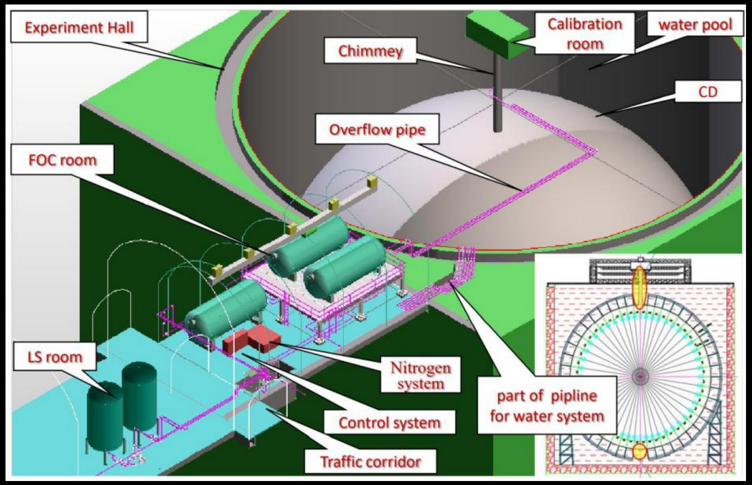
2024 → Installation complete

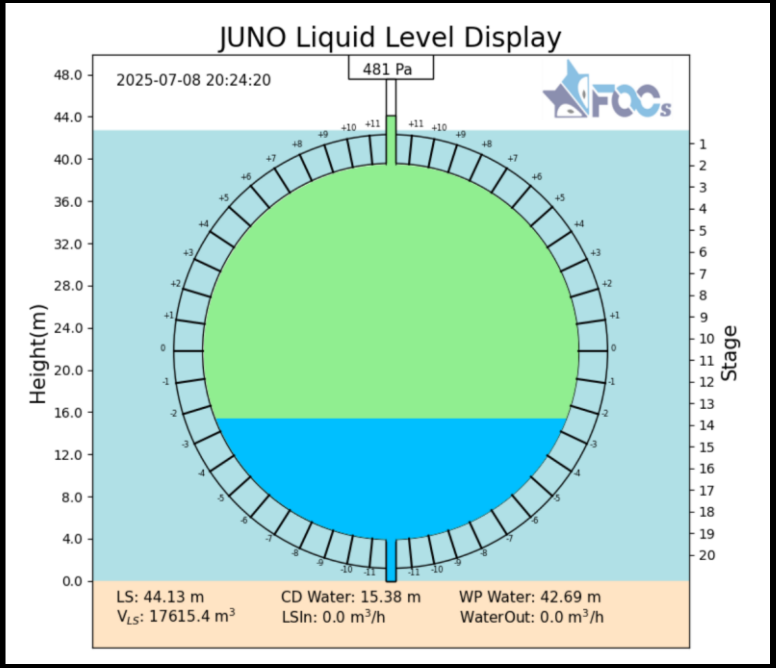
Dec 18 2024 → Water fill starts

Feb 1 2025 → Water filling complete

Feb 8 2025 → LS filling / Water exchange (ongoing)







JUNO Timeline

2013 → Project begins

Jan 2015 → Ground breaking

2022 → Detector installation

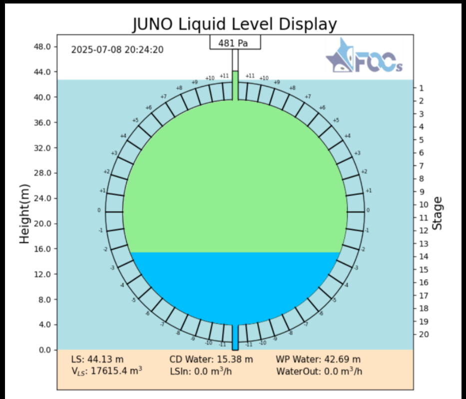
2024 → Installation complete

Dec 18 2024 → Water fill starts

Feb 1 2025 → Water filling complete

Feb 8 2025 → LS filling / Water exchange (ongoing)

Mixed LS phase



- Intense calibration campaign
  - LS optical properties
    - Attenuation length: > 20m
  - Low PMT loss rate during installation 0.1%
  - PMT gain stability < 1%
  - MeV-scale reconstruction development
- LS U/Th background levels: < 10^{-15}g/g
- Muon reconstruction and veto development

Detector performing within expectations!

Conclusion

- Reactor neutrinos: massive source for ν_e
  - Known energy spectrum, fixed distance → great for oscillation
- Detectable through Inverse Beta Decay → can have very pure signal
- Reactors have played invaluable role in neutrino physics
  - Discovery of neutrinos
  - Precise measurement of ½ of oscillation parameters so far
- Sterile neutrinos unclear still (didn't discuss anomaly in reactor spectrum 5MeV bump)
- Mass ordering: JUNO, 3σ after 6 years starting 2025

References

[1] G. Alimonti et al., The Borexino detector at the Laboratori Nazionali del Gran Sasso, Nucl. Instrum. Methods Phys. Res., Sect. A 600, 568 (2009).

[2] A. Gando et al., Measurement of the double-β decay halflife of 136Xe with the KamLAND-Zen experiment, Phys. Rev. C 85, 045504 (2012).

[3] S. Andringa et al., Current status and future prospects of the SNO+ experiment, Adv. High Energy Phys. 2016, 6194250 (2016).

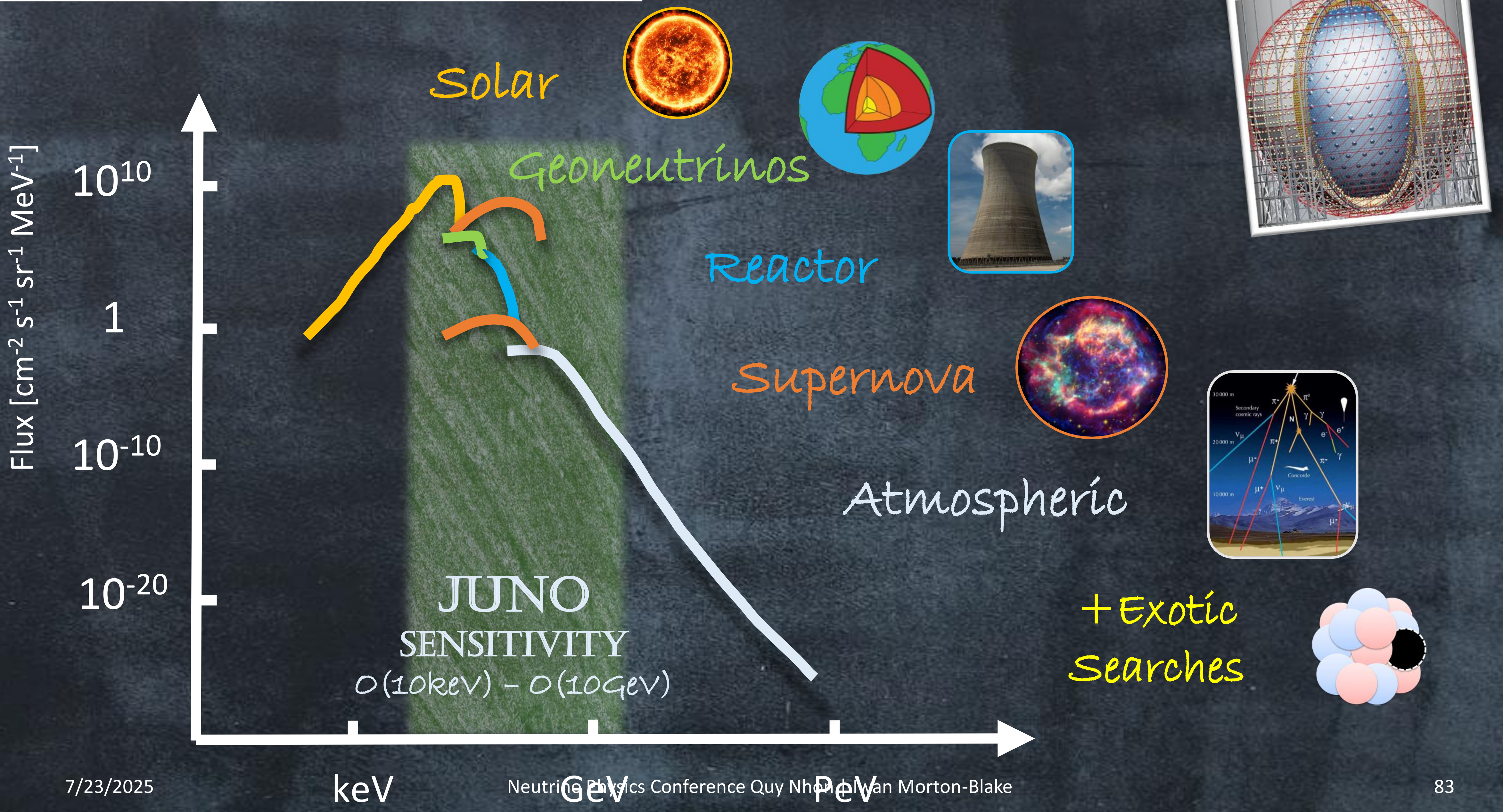
[4] S Al Kharusi et al., SNEWS 2.0: a next-generation supernova early warning system for multi-messenger astronomy, New J. Phys. 23 031201 (2021).

[5] A. Takenaka et al., Neutron source-based event reconstruction algorithm in large liquid scintillator detectors, arXiv:2504.19236

[6] SNO+ Collaboration, Initial measurement of reactor antineutrino oscillation at SNO+, Eur. Phys. J. C 85, 17 (2025)

Backup

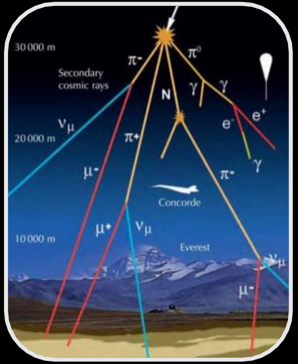
Neutrino Sources



Atmospherics

Neutrino physics with JUNO J. Phys. G 43, 030401 (2016)

"JUNO sensitivity to low energy atmospheric neutrino spectra" The European Physical Journal C volume 81, Article number: 887 (2021)

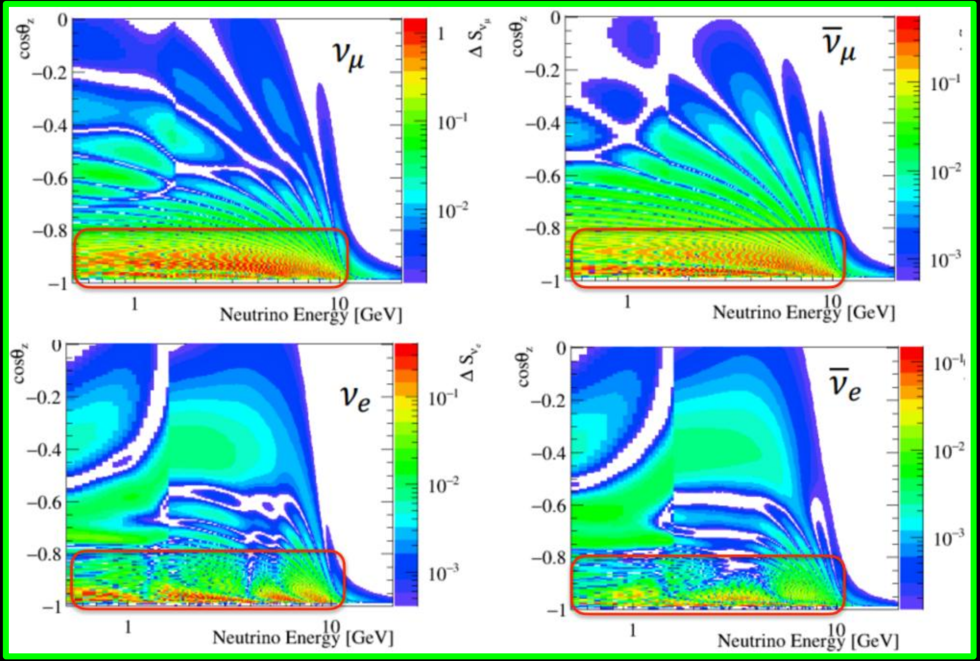


Discriminate ν_e and ν_μ in LS with PMT hit patterns → ~10-25% uncert. in 5 years

Measure differences in direction and energy spectra for $\overset{(-)}{\nu}_e$ and $\overset{(-)}{\nu}_\mu$

Expected direction and energy spectra

Atmos. Flux * Cross-section * Survival prob (NO - IO)



Expected Sensitivity

→ Matter effects over ~3-10GeV provide sensitivity to Neutrino Mass Ordering

→ Would be first measurement of atmospheric neutrino oscillation in liquid scintillator

→ Complementary to the reactor NMO analysis

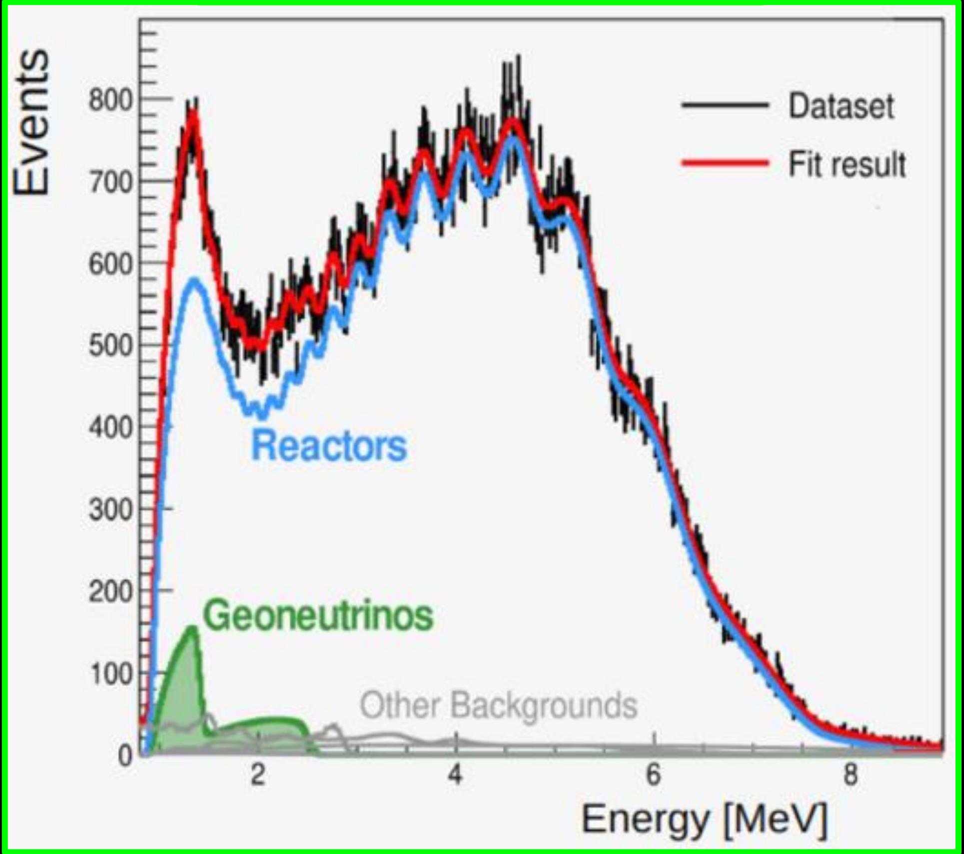
NMO expectation:
0.7-1.4σ in ~6 years exposure

Geoneutrinos : $\bar{\nu}_e$

JUNO physics and detector, Progress in Particle and Nuclear Physics 123 (2022) 103927

Strati et al. Progress in Earth and Planetary Science (2015) 2:5 DOI 10.1186/s40645-015-0037-6

Expected Energy Spectrum



Decay of radionuclides (U/Th/K) within the Earth

- Can measure U and Th abundances.
- Measuring U/Th ratio in crust and mantle probes:
  Earth's formation, mantle convection, plate tectonics, Earth's magnetic field production

JUNO expects ~400 geo-$\bar{\nu}_e$ interactions per year

Fit scenario	Sensitivity (6 years data-taking)	
U/Th ratio fixed	U+Th flux ~10%	
U/Th free	U+Th ~18%	U/Th ratio ~70%

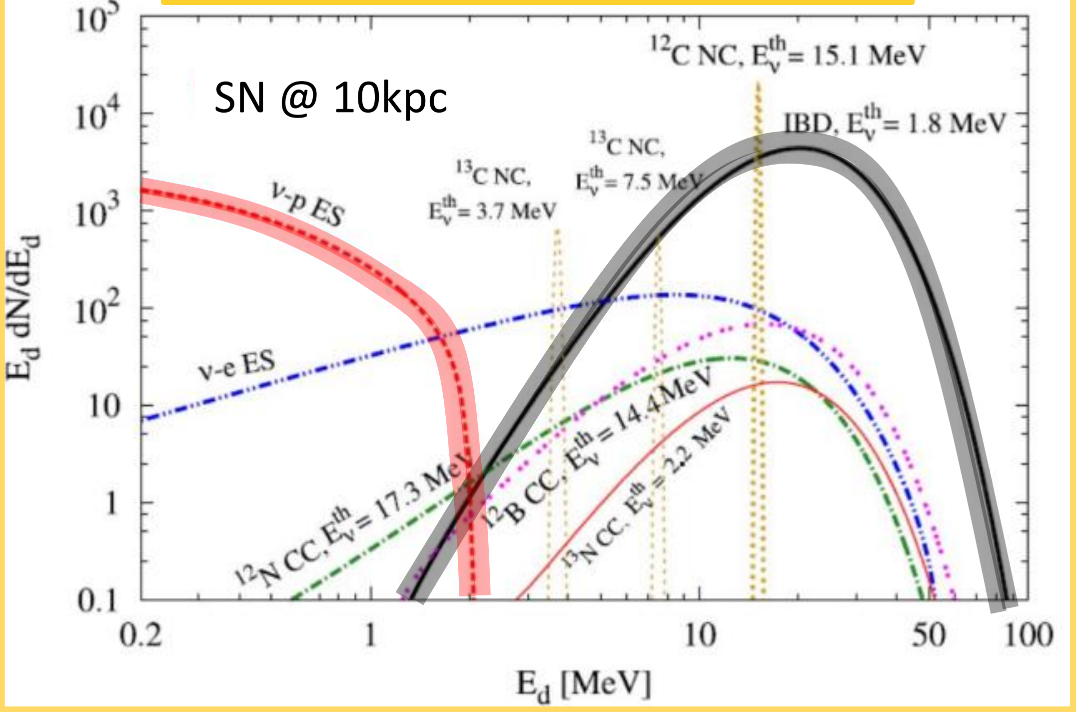
Core-Collapse Supernova Neutrinos

[“Real-time monitoring for the next core-collapse supernova in JUNO”, Journal of Cosmology and Astroparticle Physics (2024)]

$\nu_x + \bar{\nu}_x$

- 99% of energy released in (anti-)neutrinos of all flavours
- ~3 CCSN per century in the Milky Way

Expected Flux vs Visible Energy



Expected Event Rate (@10kpc)

Process	Num. Events (E_{thr} = 0.2MeV)
IBD | $\bar{\nu}_e + p \rightarrow e^+ + n$	~5000
pES | $\nu + p \rightarrow \nu + p$ $(\overset{(-)}{\nu}_{e,\mu,\tau})$	~2000
eES | $\nu + e \rightarrow \nu + e$ $(\overset{(-)}{\nu}_{e,\mu,\tau})$	~400
CC | $\overset{(-)}{\nu}_e + {}^{12}C \rightarrow e^{-(+)} + {}^{12}N({}^{12}B)$	~200
NC | $\nu + {}^{12}C \rightarrow \nu + {}^{12}C^*$ $(\overset{(-)}{\nu}_{e,\mu,\tau})$ $\rightarrow \gamma(15.11\text{MeV})$	~300

Core-Collapse Supernova Neutrinos

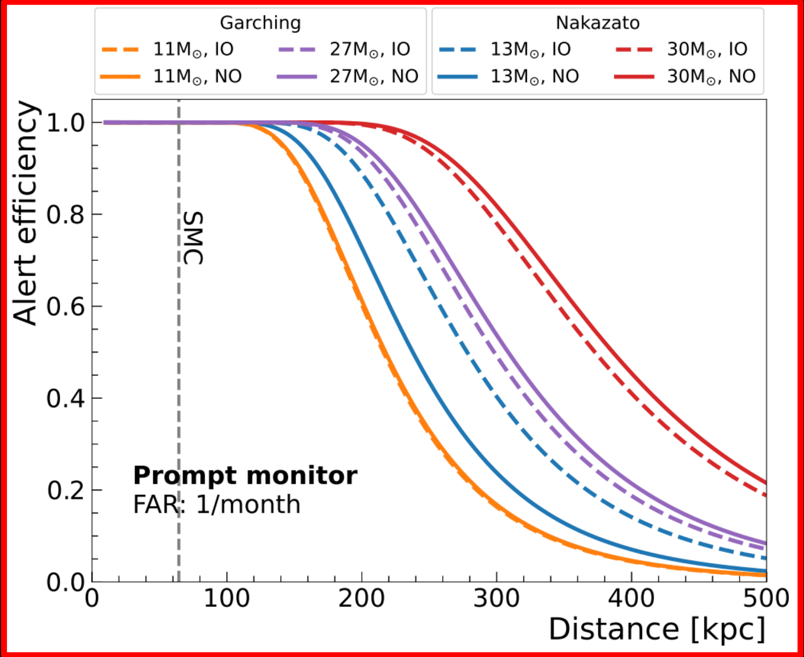
[“Real-time monitoring for the next core-collapse supernova in JUNO”, Journal of Cosmology and Astroparticle Physics (2024)]

$\nu_x + \bar{\nu}_x$

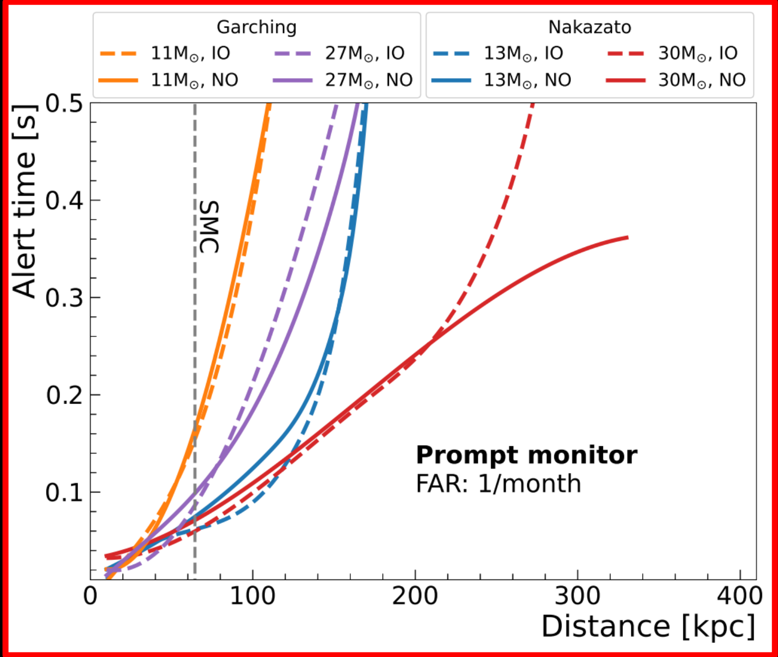
Rapid declarations of transient neutrino signals

Aim to join Supernova Early Warning System (SNEWS) [4]

Alert eff. vs SN distance



Alert time vs SN distance

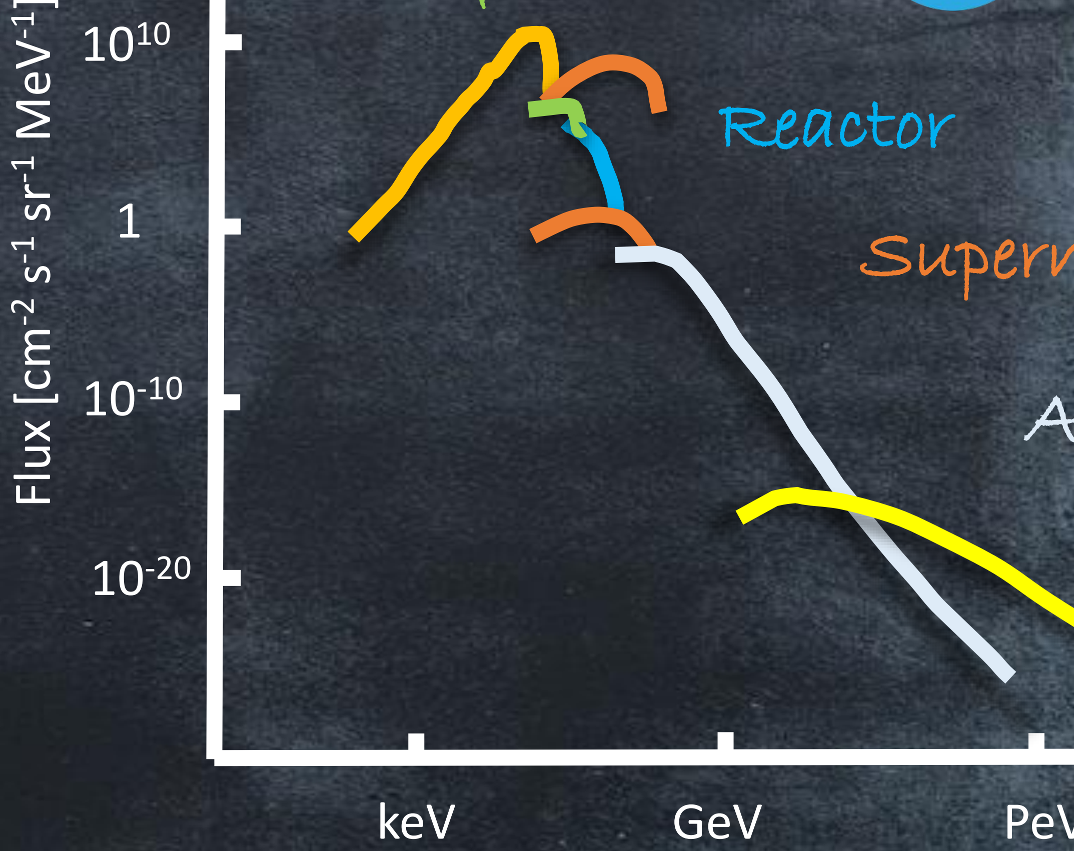


27 $M_\odot$ CCSN:

- ~50% alert efficiency at 300kpc
- Alert Time @ 10kpc ~10-30ms

CCSN Energy spectrum
+ Time evolution
→ Probe mass ordering

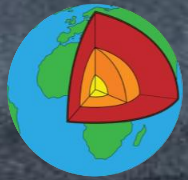
Neutrino Sources



Solar

Nuclear fusion within the sun produces ν_e
probe the solar core – measurement of the solar metallicity

Geoneutrinos



Decay of radionuclides (U/Th/K) within the Earth
Can measure U and Th abundances/ratio → Earth's formation, mantle convection, plate tectonics, magnetic field production

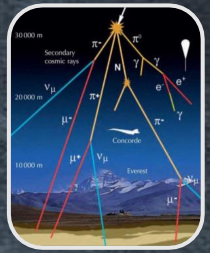
Reactor

Well-understood source, huge flux of neutrinos at a fixed distance → great for oscillation

Supernova

99% of energy released in (anti)neutrinos of all flavours

Atmospheric



High energy oscillations

Exotic Searches

Number of GUTs require baryon number violation and predict nucleon decay

Active galactic nucleus, cosmological sources