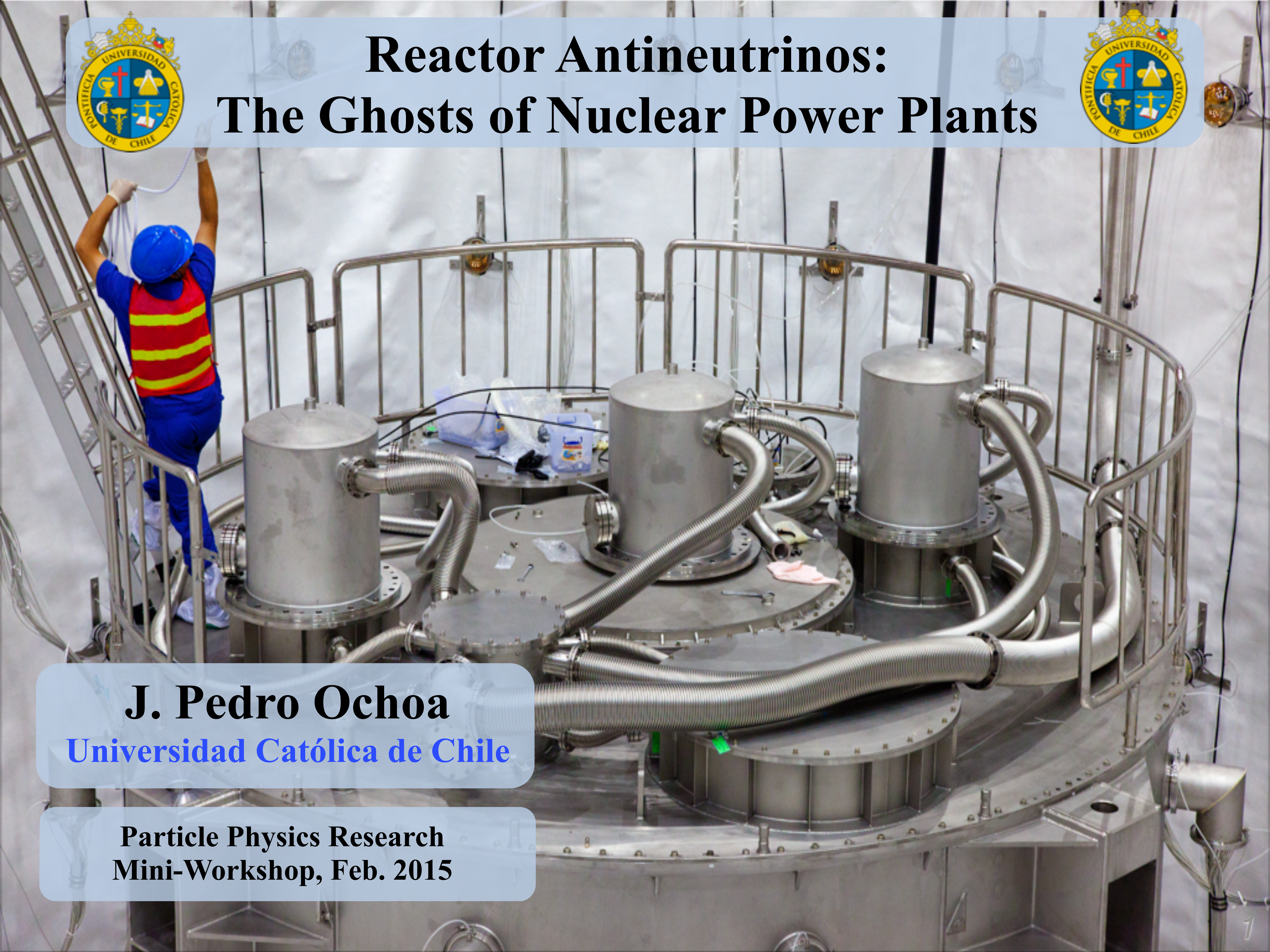
Reactor Antineutrinos:
The Ghosts of Nuclear Power Plants

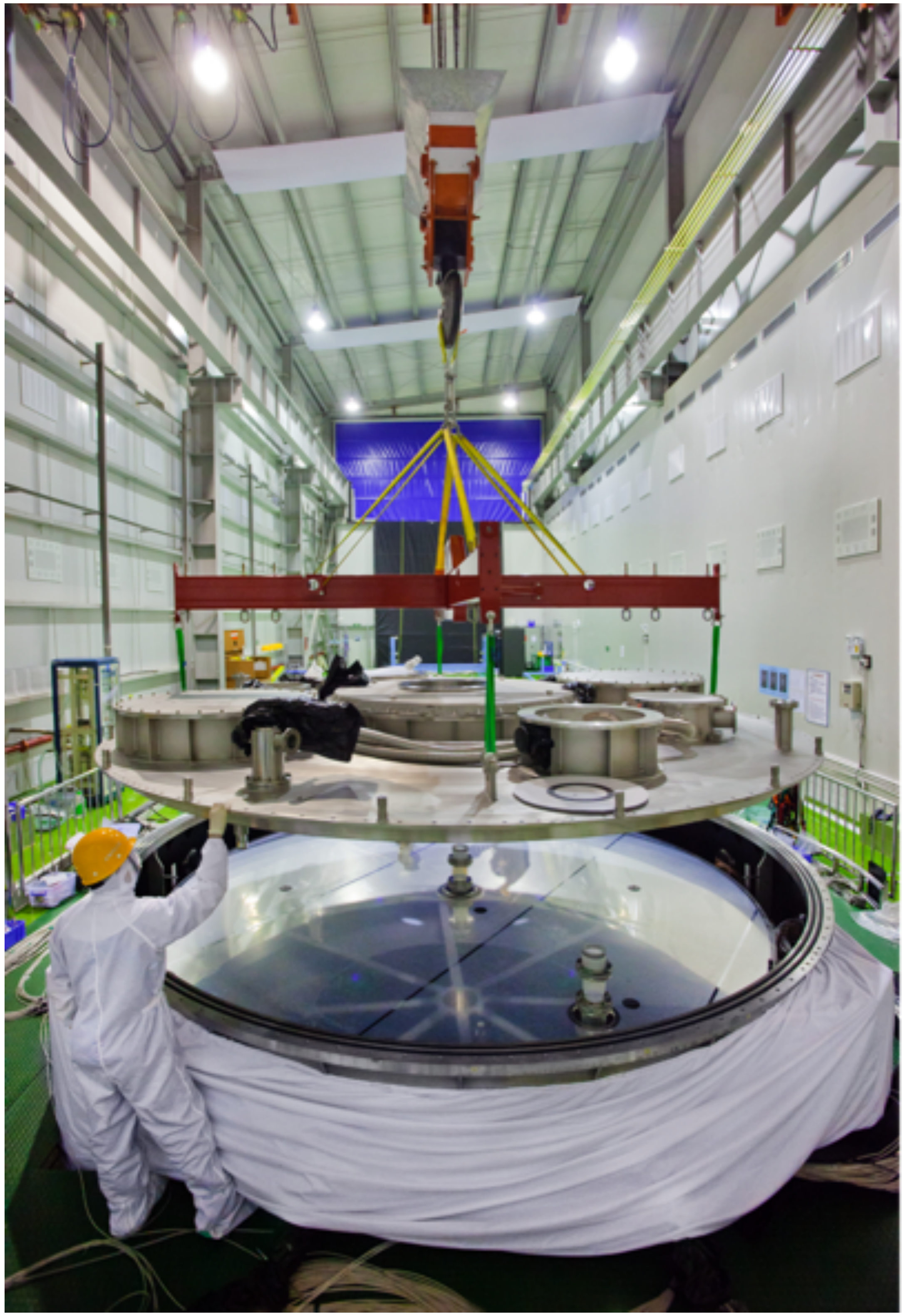


J. Pedro Ochoa
Universidad Católica de Chile

Particle Physics Research
Mini-Workshop, Feb. 2015

Topics to Cover

- Why Neutrinos?
- Present: Daya Bay
- Future: JUNO
- Summary & Conclusions



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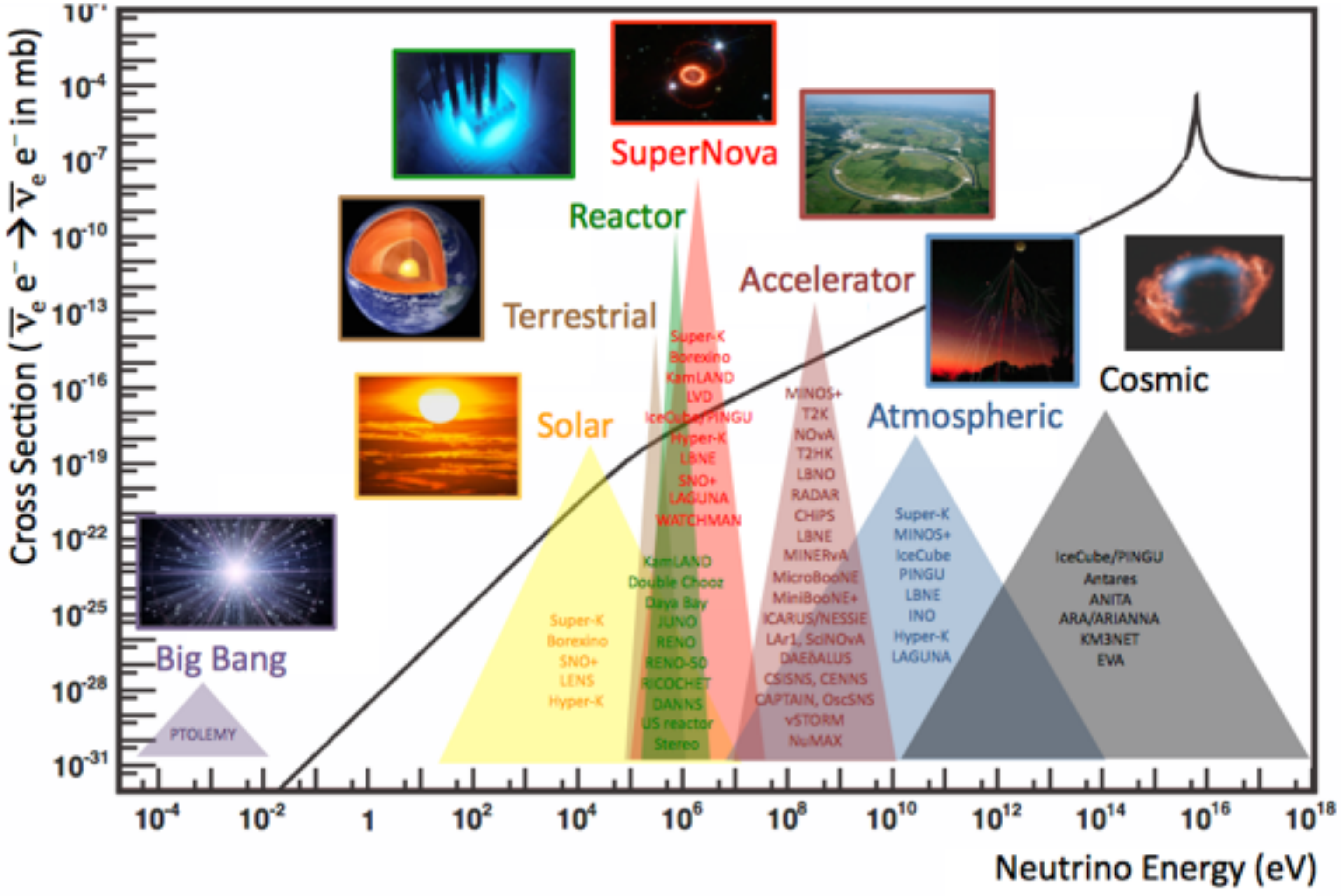
Why Neutrinos?

Why neutrinos?

- We need to understand neutrinos if we want to understand our universe!
  - Unlike light, neutrinos travel without interference, which makes them **invaluable astronomical messengers**
  - They are the **second most abundant particle in the universe**, and as such they are important players in cosmological processes

Neutrinos teach us volumes about a great variety of processes, inside and outside our planet



  - Some of their properties lie **outside the realm of our current best theory of particle physics** (see next slide)

Neutrinos have mass!

- Neutrino oscillation can be understood through a simple principle:

How they interact

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

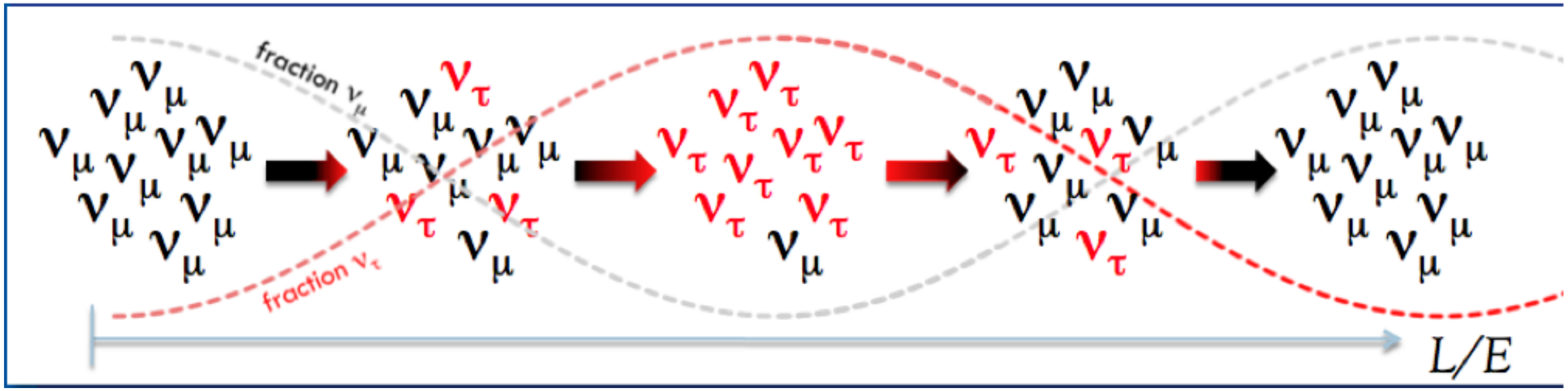
How they propagate

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

amplitude **frequency**

For example, as an approximation: $P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$

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

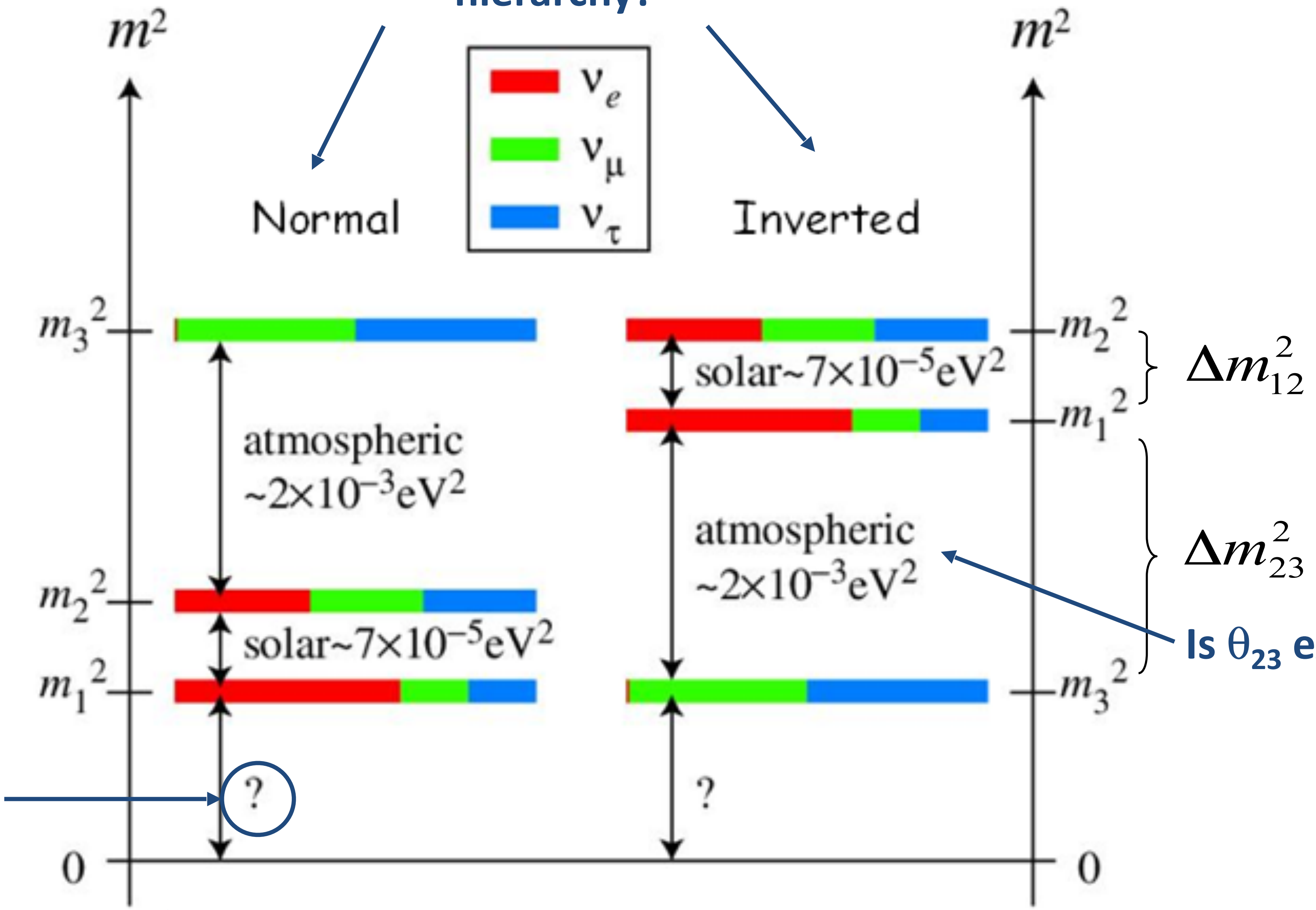


– Huge implication: neutrinos are massive (in contradiction with SM)!

Our knowledge of neutrinos remains incomplete

- Amazing progress has occurred in the last decade!
- Nonetheless, many open questions remain:

Which is the right mass hierarchy?



Is θ_{23} exactly $\pi/4$?

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

And also:

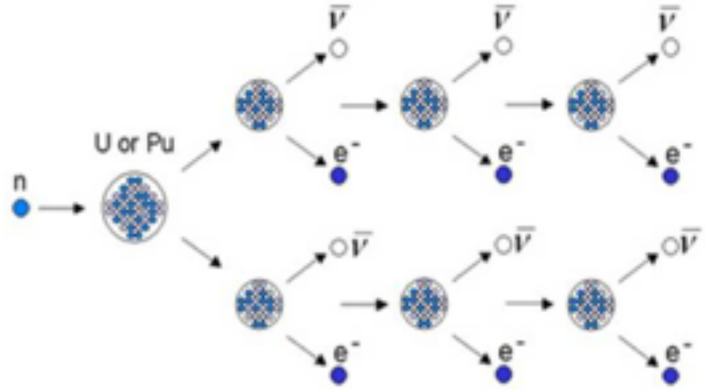
Do neutrinos obey CP, CPT?
Are neutrinos their own antiparticles?
Are there more than 3 neutrinos (sterile, heavier than Z)?
Others…

Reactor Antineutrinos

- Field of experimental neutrino physics is very wide:
  - Can study neutrinos from astrophysical sources, the atmosphere, accelerators, radioactive isotopes … etc.
- This talk focuses on **antineutrinos from nuclear reactors:**
  - Nuclear reactors are excellent sources of electron antineutrinos

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

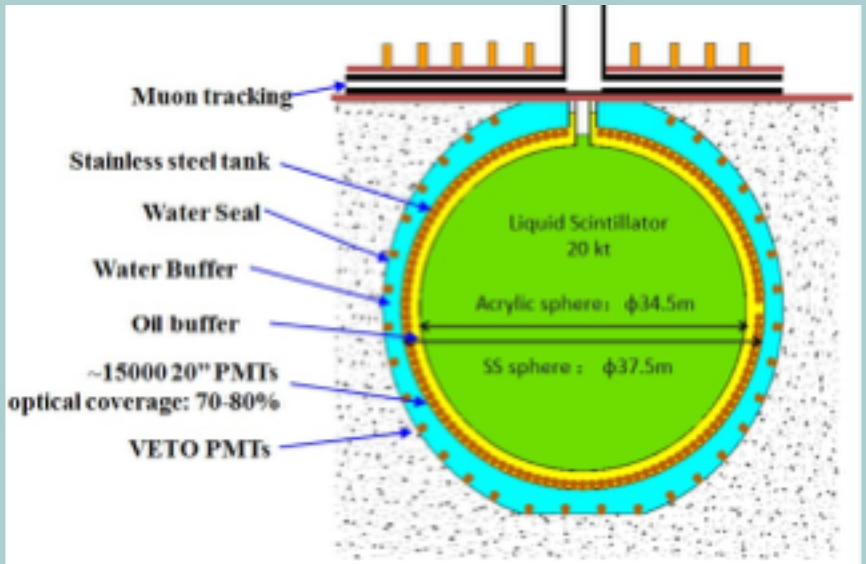
β^- decay of neutron-rich fission products



  - We are involved in two experiments:

Present: Daya Bay

Near Future: JUNO

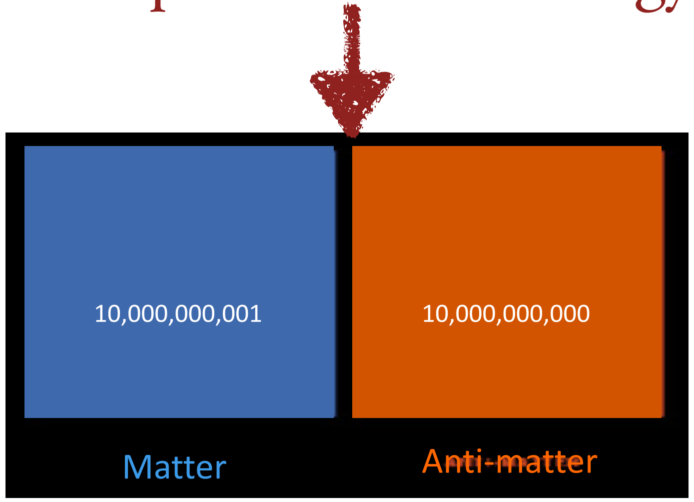


Present: Daya Bay

Motivation: The Search for θ_{13}

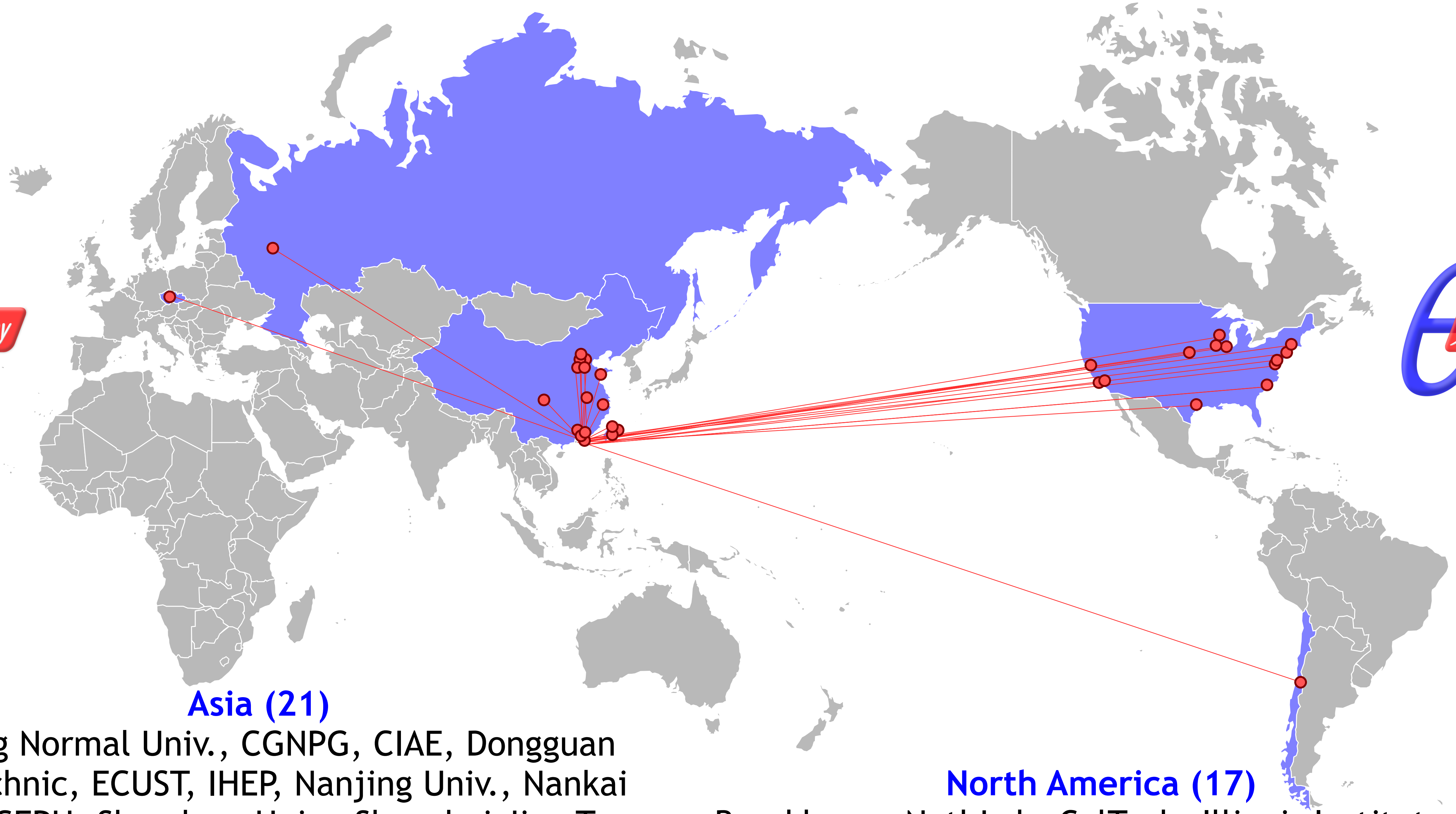
- The Daya Bay Experiment was designed with one goal in mind: making a precision measurement of the **θ_{13} mixing angle**:
- Why do we care about θ_{13}?
  - θ_{13} was the last missing piece in the neutrino oscillation puzzle (i.e. input to SM)
  - θ_{13} is inextricably linked to the possibility of observing CP violation in the leptonic sector
  - It is through θ_{13} - driven oscillations that other experiments hope to determine the neutrino mass hierarchy

possible important consequences in cosmology!



- There are currently three reactor experiments that can measure θ_{13}: Daya Bay, Double Chooz and Reno:
  - I will focus uniquely on Daya Bay, which made the first unambiguous determination of a non-zero θ_{13} in 2012

The Daya Bay Collaboration



Asia (21)

Beijing Normal Univ., CGNPG, CIAE, Dongguan Polytechnic, ECUST, IHEP, Nanjing Univ., Nankai Univ., NCEPU, Shandong Univ., Shanghai Jiao Tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Xian Jiaotong Univ., Zhongshan Univ.,
Chinese Univ. of Hong Kong, Univ. of Hong Kong, National Chiao Tung Univ., National Taiwan Univ., National United Univ.

North America (17)

Brookhaven Natl Lab, CalTech, Illinois Institute of Technology, Iowa State, Lawrence Berkeley Natl Lab, Princeton, Rensselaer Polytechnic, Siena College, UC Berkeley, UCLA, Univ. of Cincinnati, Univ. of Houston, UIUC, Univ. of Wisconsin, Virginia Tech, William & Mary, Yale

Europe (2)

Charles University, JINR Dubna

~230 Collaborators

South America (1)

Catholic University of Chile

Daya Bay

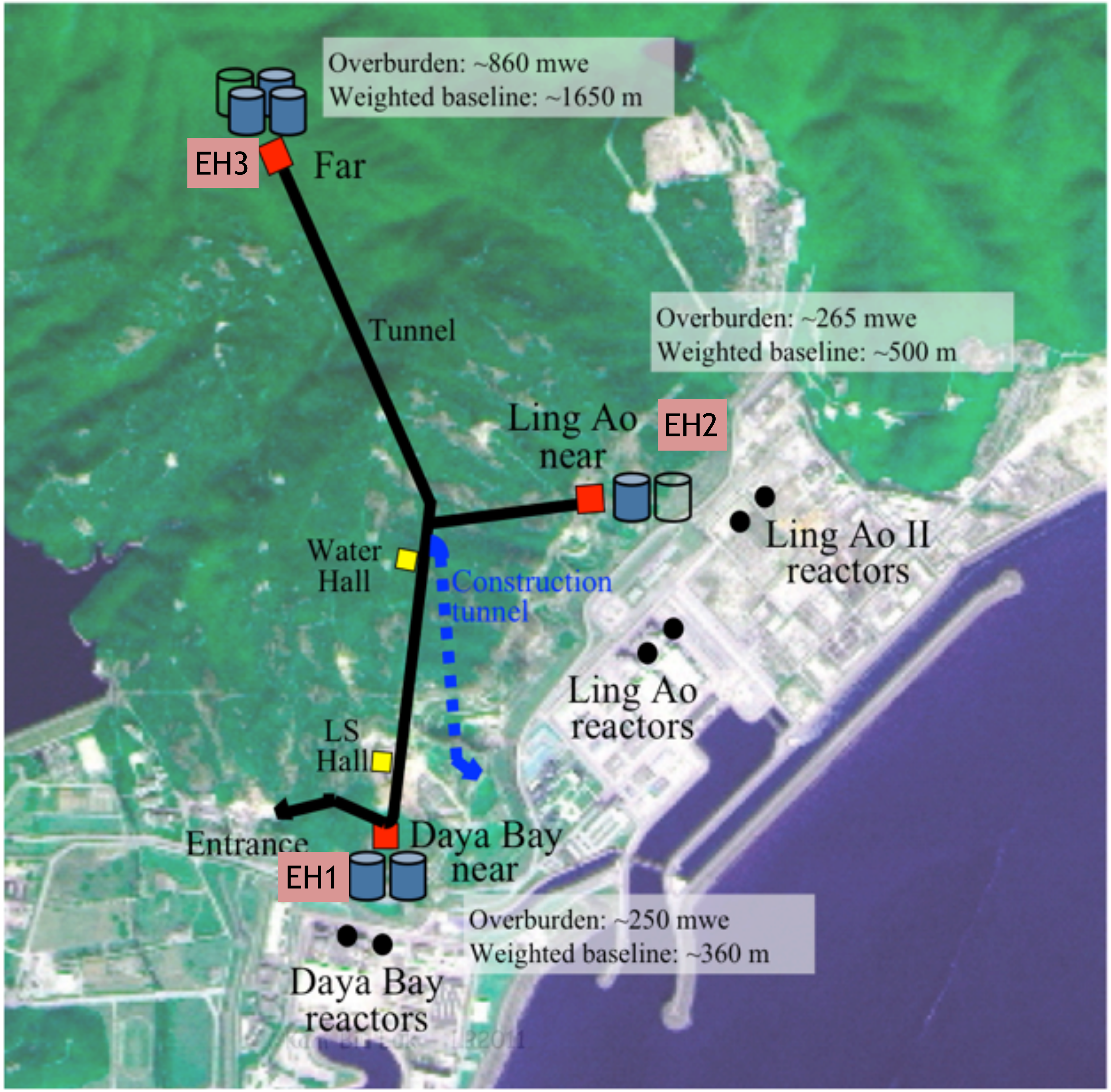
- 8 identical detectors (represented by the cylinders in the plot) positioned around the Daya Bay Power Plant in China

- **Main Principle:**

  (i) sample the reactor antineutrino flux in the near and far locations, and

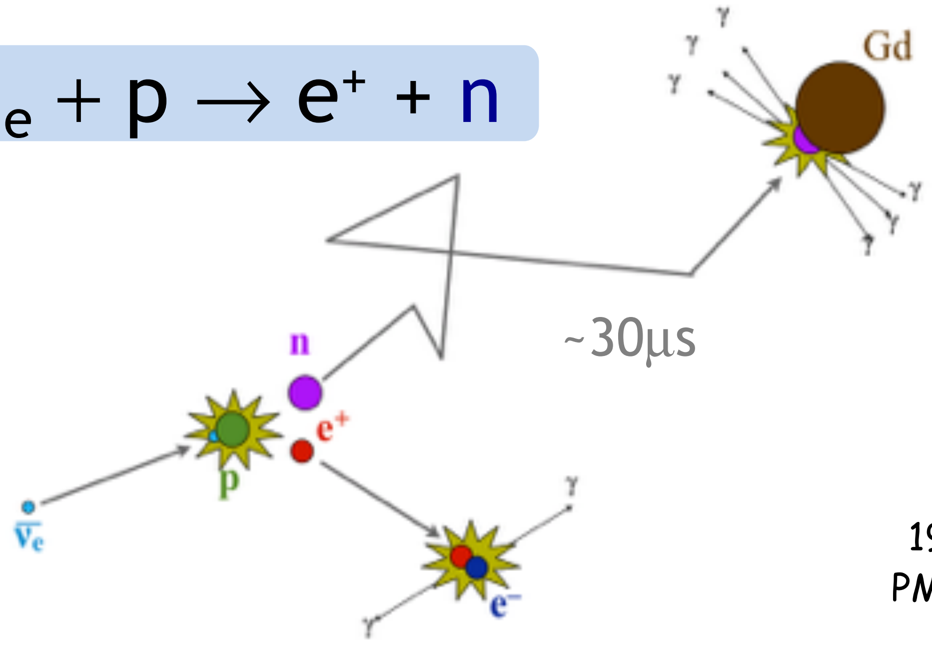
  (ii) look for evidence of disappearance

Note: first started taking data with 6 detectors, and then installed all 8



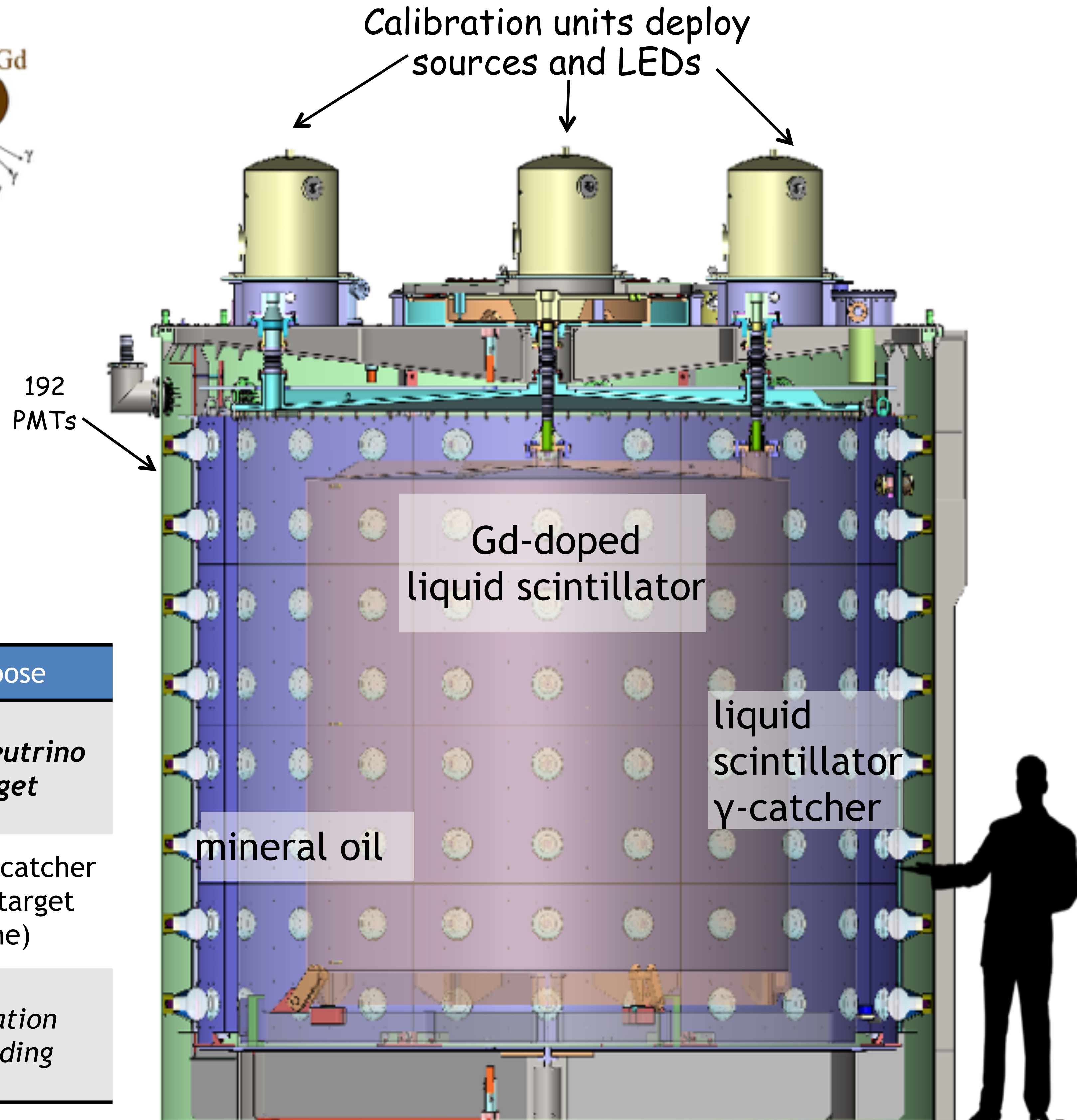
Daya Bay Antineutrino Detectors (ADs)

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



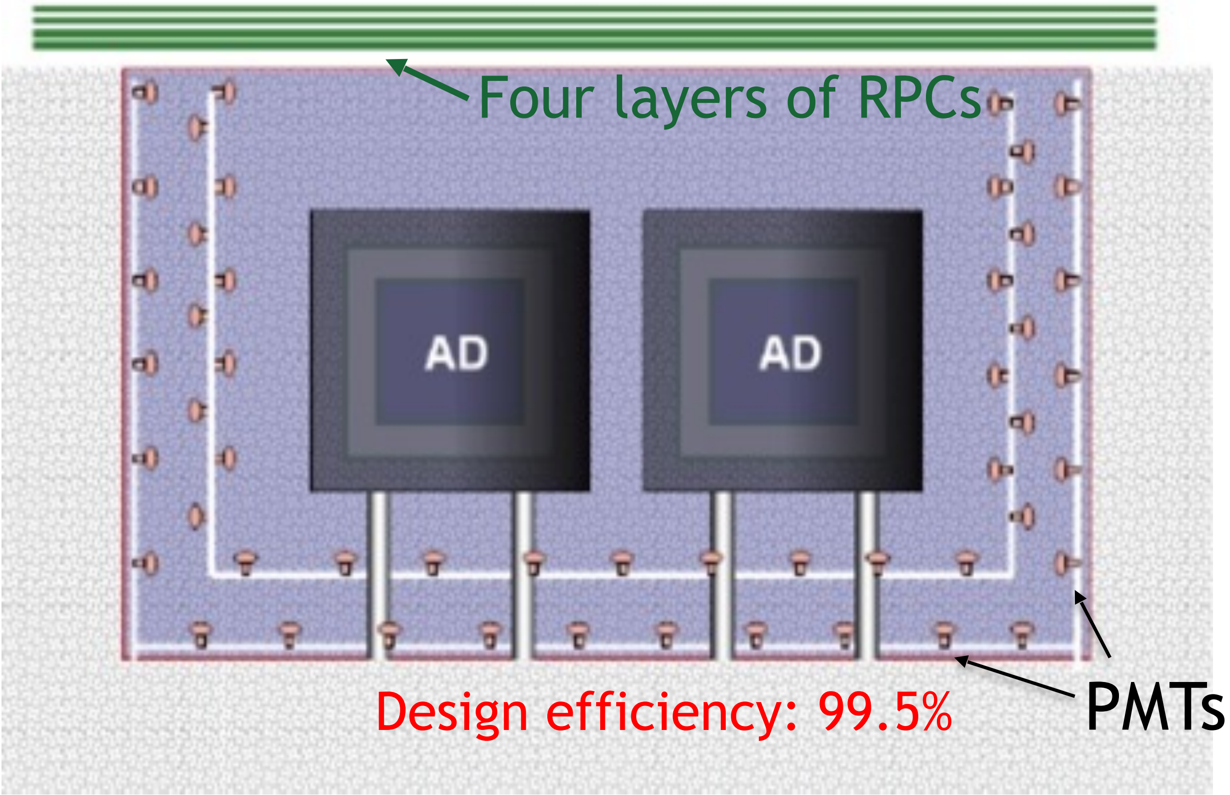
The detectors are ~100ton three-zone cylindrical modules:

Zone	Mass	Liquid	Purpose
Inner acrylic vessel	*20 t*	*Gd-doped liquid scintillator*	***Anti-neutrino target***
Outer acrylic vessel	20 t	Liquid scintillator	Gamma catcher (from target zone)
Stainless steel vessel	*40 t*	*Mineral Oil*	*Radiation shielding*



Daya Bay Antineutrino Detectors

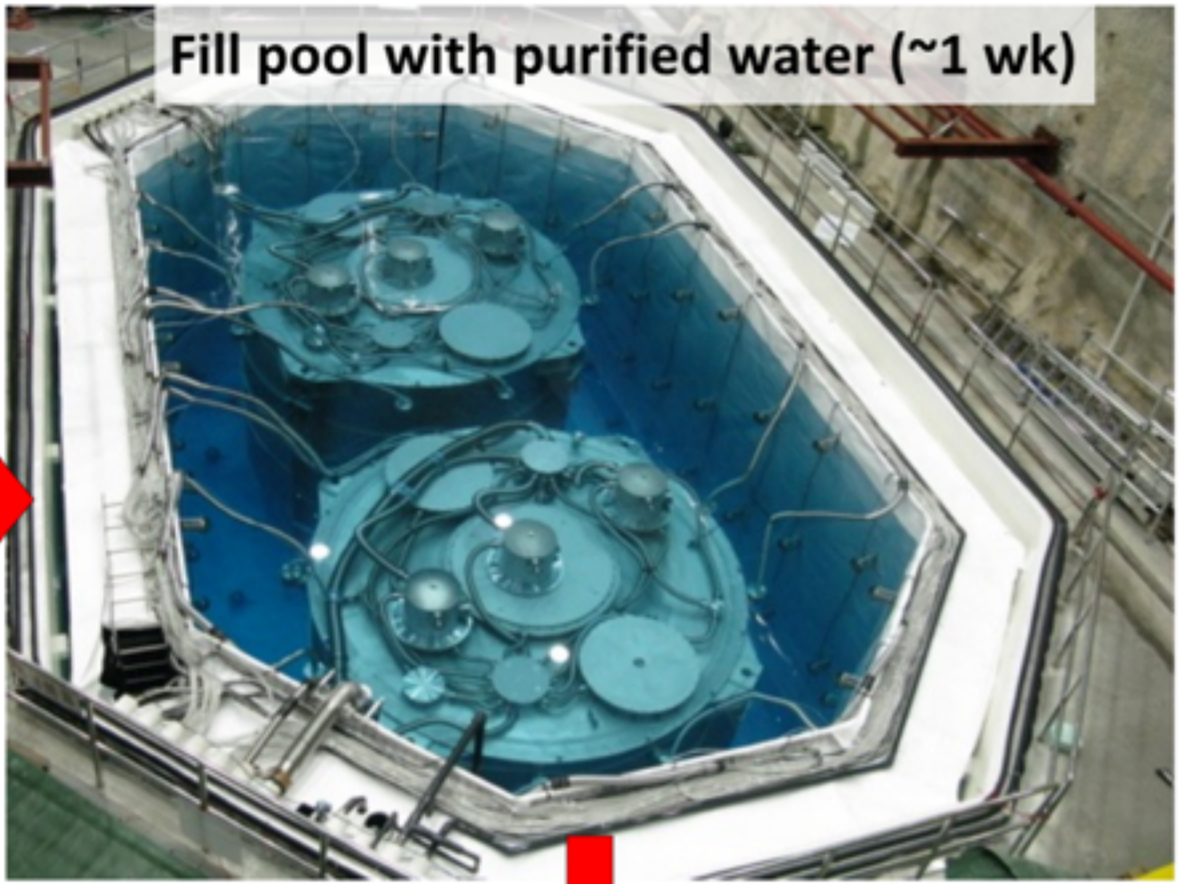
- The detectors are immersed in instrumented water pools:
  - ✓ Shields against gammas from ambient radioactivity and neutrons produced by cosmic rays
  - ✓ Serves as a Cerenkov detector to tag cosmic ray muons (thus reducing backgrounds)
- The water pools are divided into two optically-decoupled detectors:
  - ✓ Allows for increased redundancy and efficiency
- The pools are covered with a retractable RPC roof for further cosmic-ray tagging



Inside of Outer Water Shield

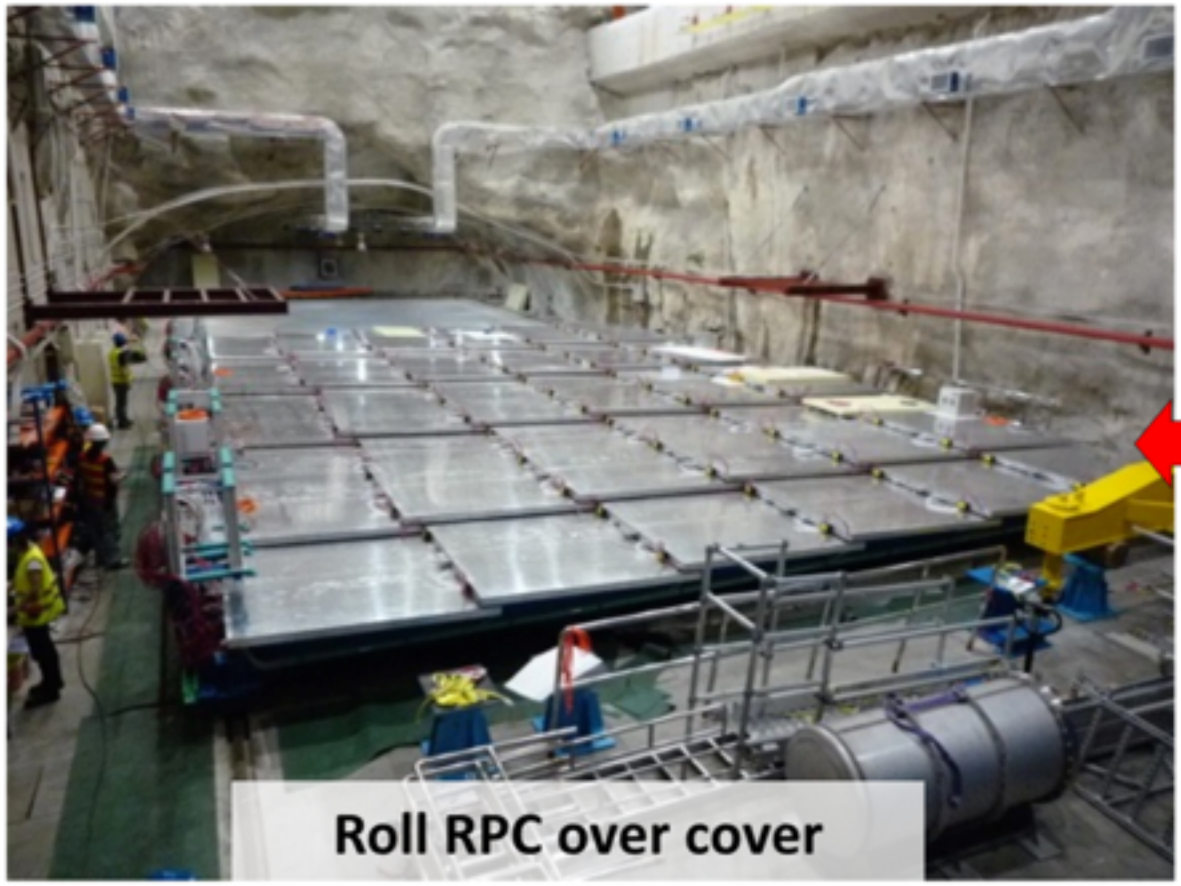
Some Pictures: EH1 installation

Install filled AD1 and AD2 in pool



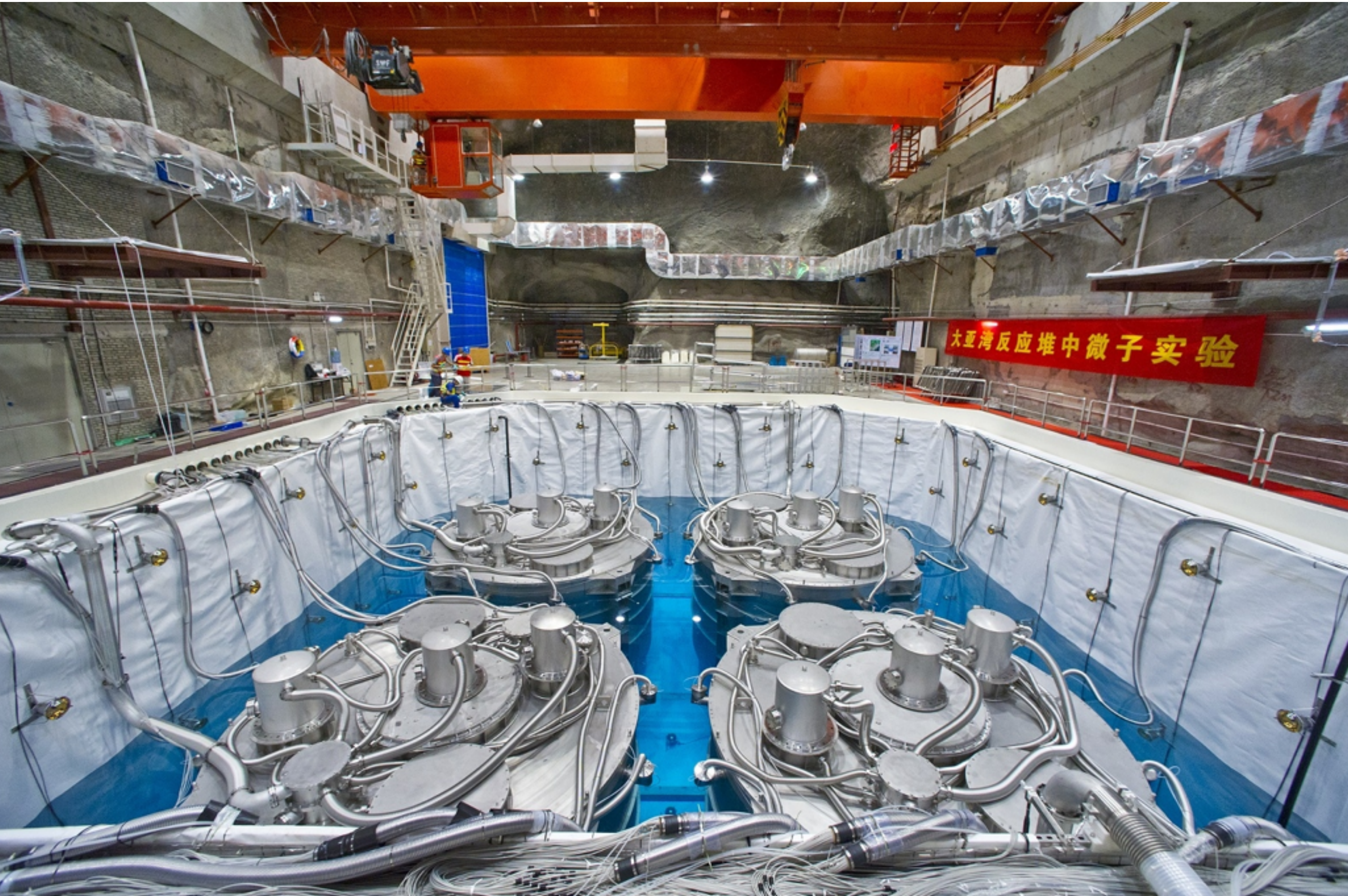
Fill pool with purified water (~1 wk)

Place cover over pool



Roll RPC over cover

Some Pictures: EH3 (Far hall)



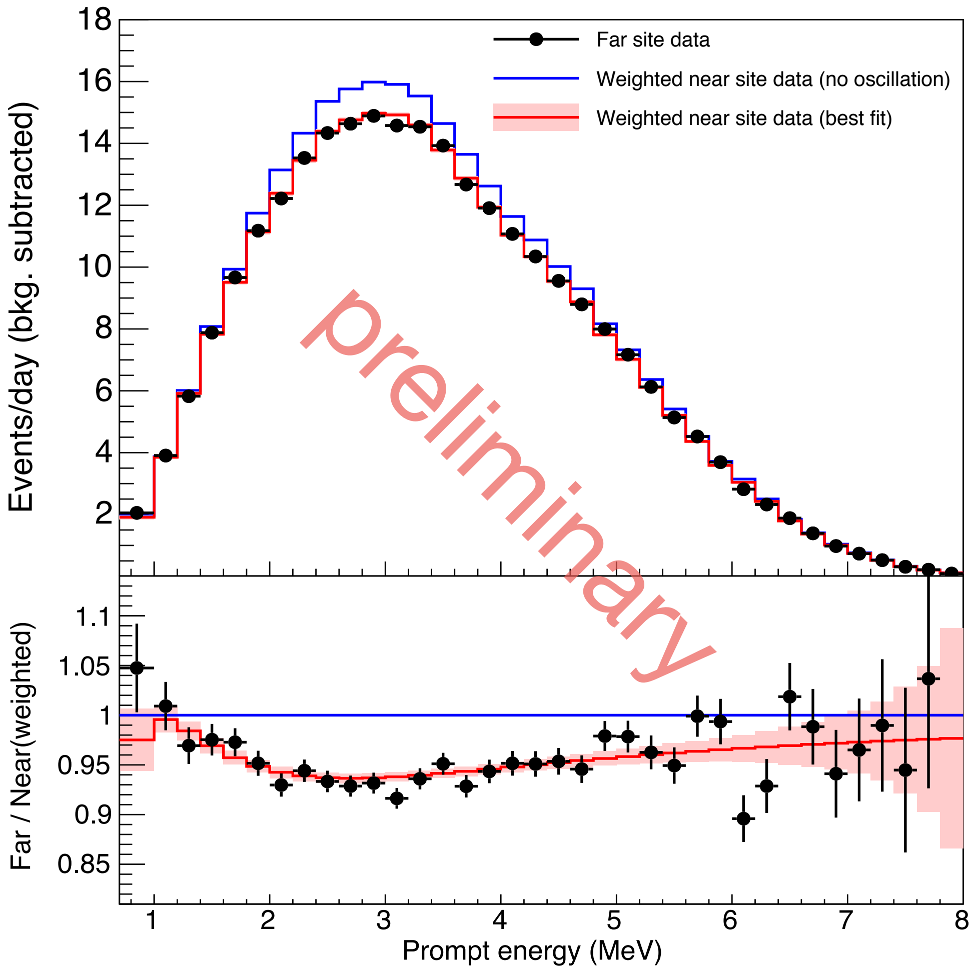
Latest Results on oscillation parameters

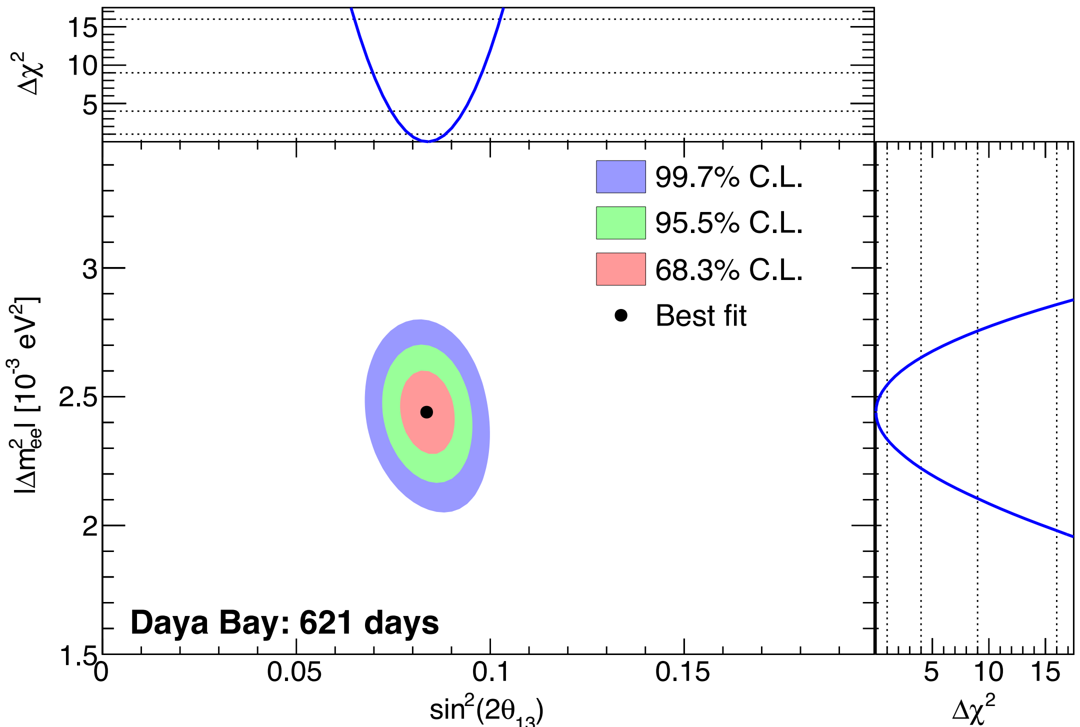
$$\sin^2 2\theta_{13} = 0.084^{+0.005}_{-0.005}$$

$$|\Delta m^2_{ee}| = 2.44^{+0.10}_{-0.11} \times 10^{-3}\mathrm{eV}^2$$

$$\chi^2/NDF = 134.7/146$$

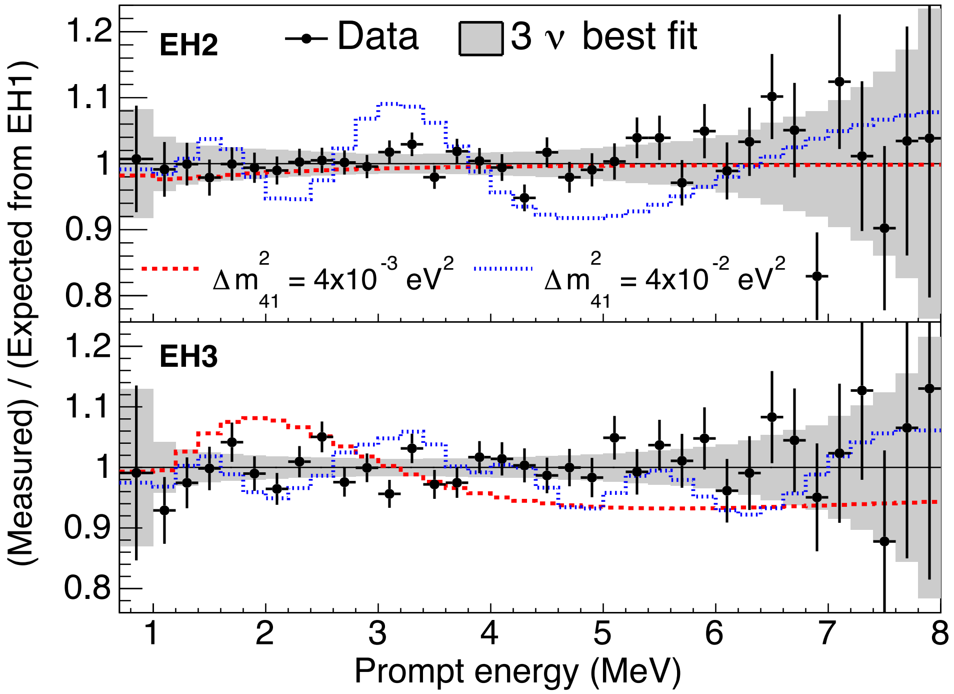
- **World's most precise measurement of $\sin^2 2\theta_{13}$,** (precision < 6%)
- **Most precise measurement of Δm^2_{ee} in the electron neutrino disappearance channel**
  - consistent with the muon neutrino disappearance experiments
  - comparable precision
- Have performed an independent measurement through nH capture (PhysRevD.90.071101)

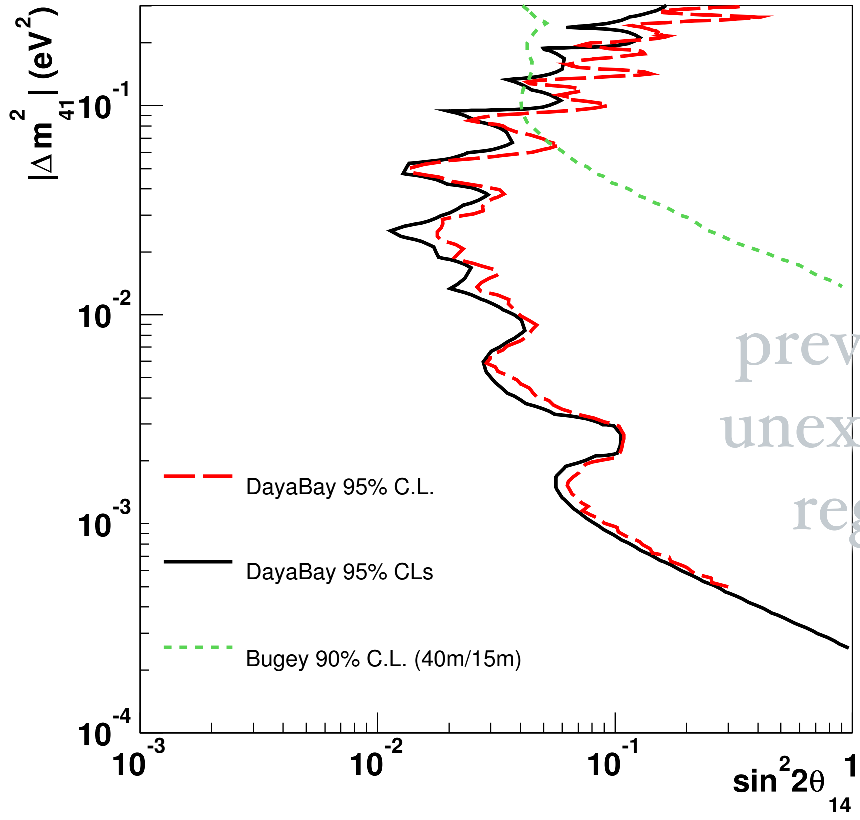




Other results

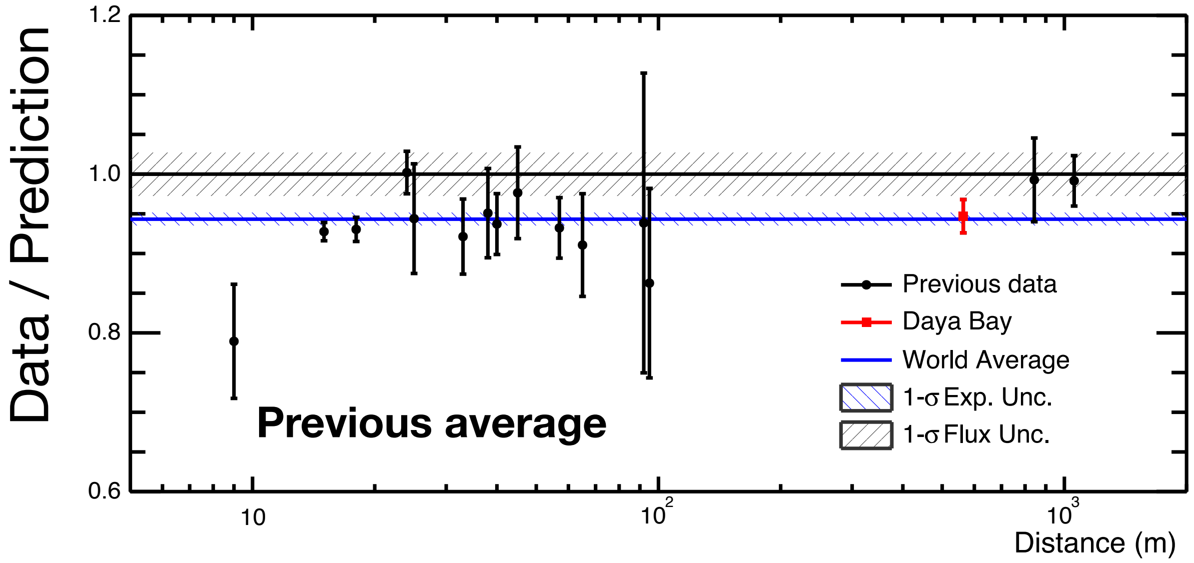
- Daya Bay has also recently released other groundbreaking results:
  - Search for sterile neutrino mixing (PhysRevLett.113.141802)

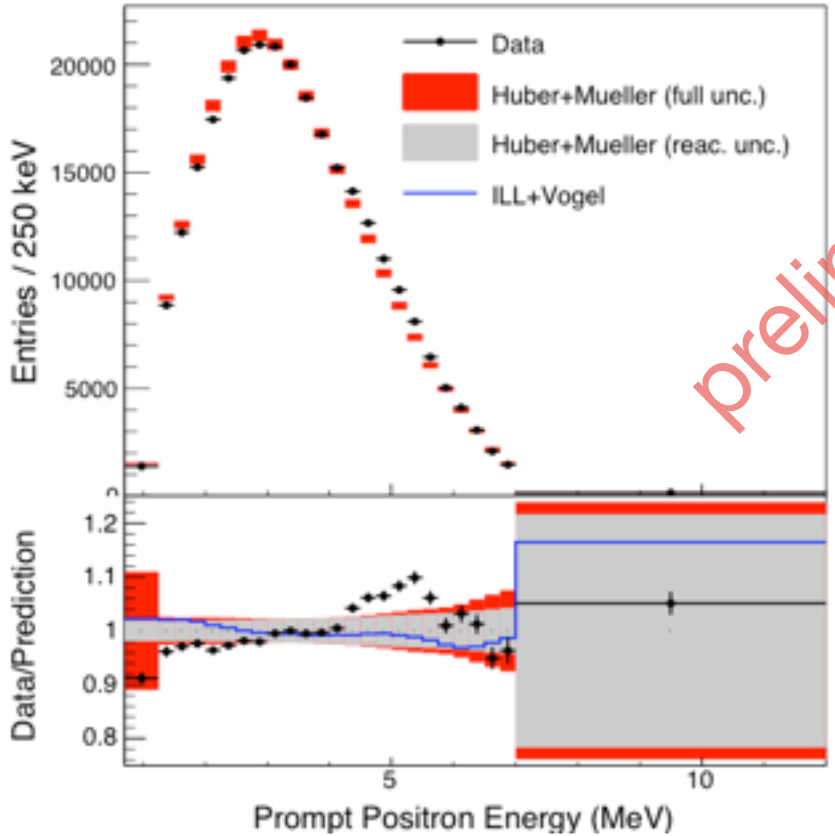




previously unexplored region

  - High-statistics measurement of reactor antineutrino flux and spectral shape:



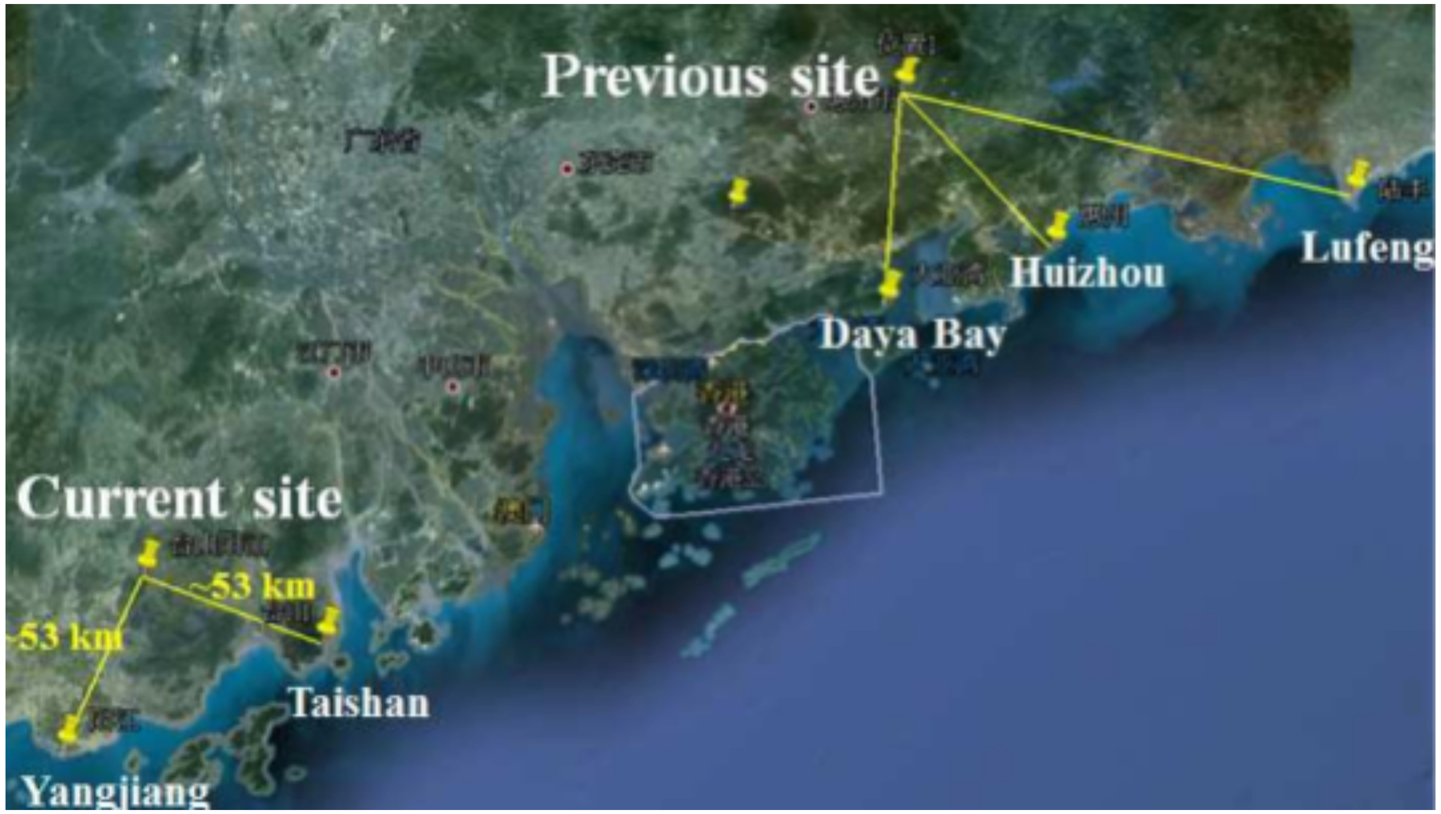


preliminary

Future: JUNO

Future: Going after other questions

- Reactor experiments are also in a great position to answer some of the unanswered questions of our day:
  - For example, the neutrino mass hierarchy:



  - Strategy: put a huge (20kt) liquid scintillator detector at a baseline of ~50-60km from two major power plants in China
  - This experiment is now called **JUNO** (used to be called Daya Bay II)

JUNO Strategy

- Exploit interference between Δm^2_{31} and Δm^2_{32} terms in the oscillation probability:

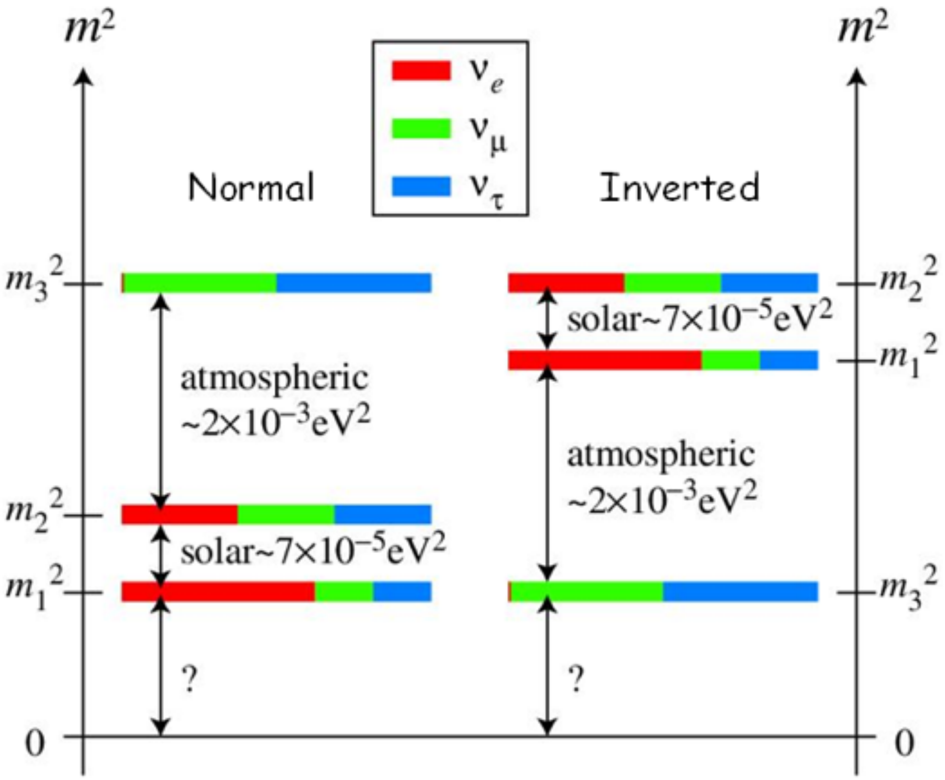
$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \overbrace{\sin^2 2\theta_{13}(\underbrace{\cos^2\theta_{12}}_{\sim 0.7}\sin^2\Delta_{31} + \underbrace{\sin^2\theta_{12}}_{\sim 0.3}\sin^2\Delta_{32})}^{\textit{Daya Bay Oscillation (~km)}} - \overbrace{\cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}}^{\textit{KamLAND Oscillation (~100 km)}}$$

Two oscillation frequencies

$$\Delta_{ji} = 1.267\,\Delta m^2_{ji}(eV^2)\frac{L(m)}{E(MeV)}$$

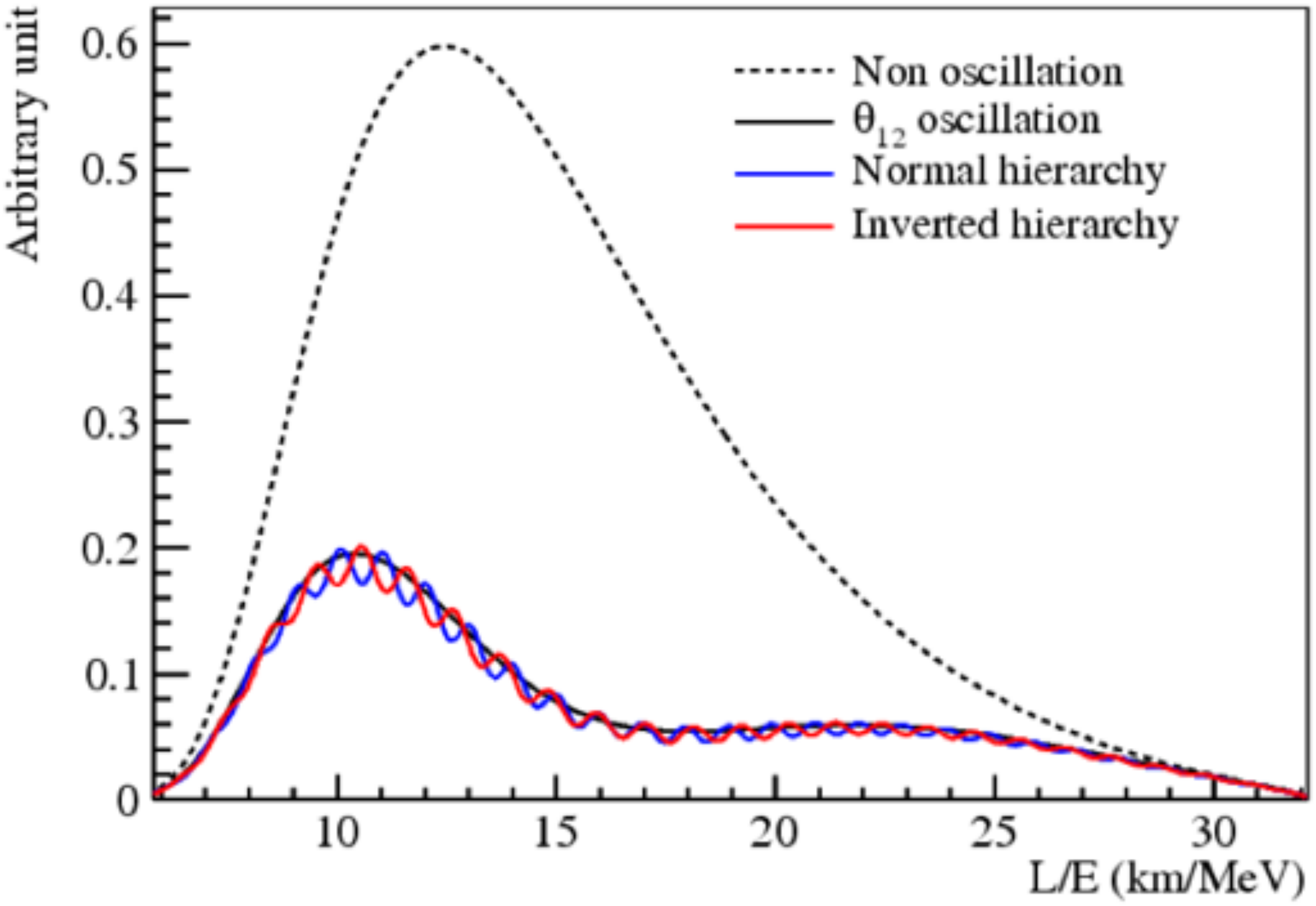
Normal Hierarchy: $|\Delta_{31}| > |\Delta_{32}|$ → *Larger amplitude at higher frequency*

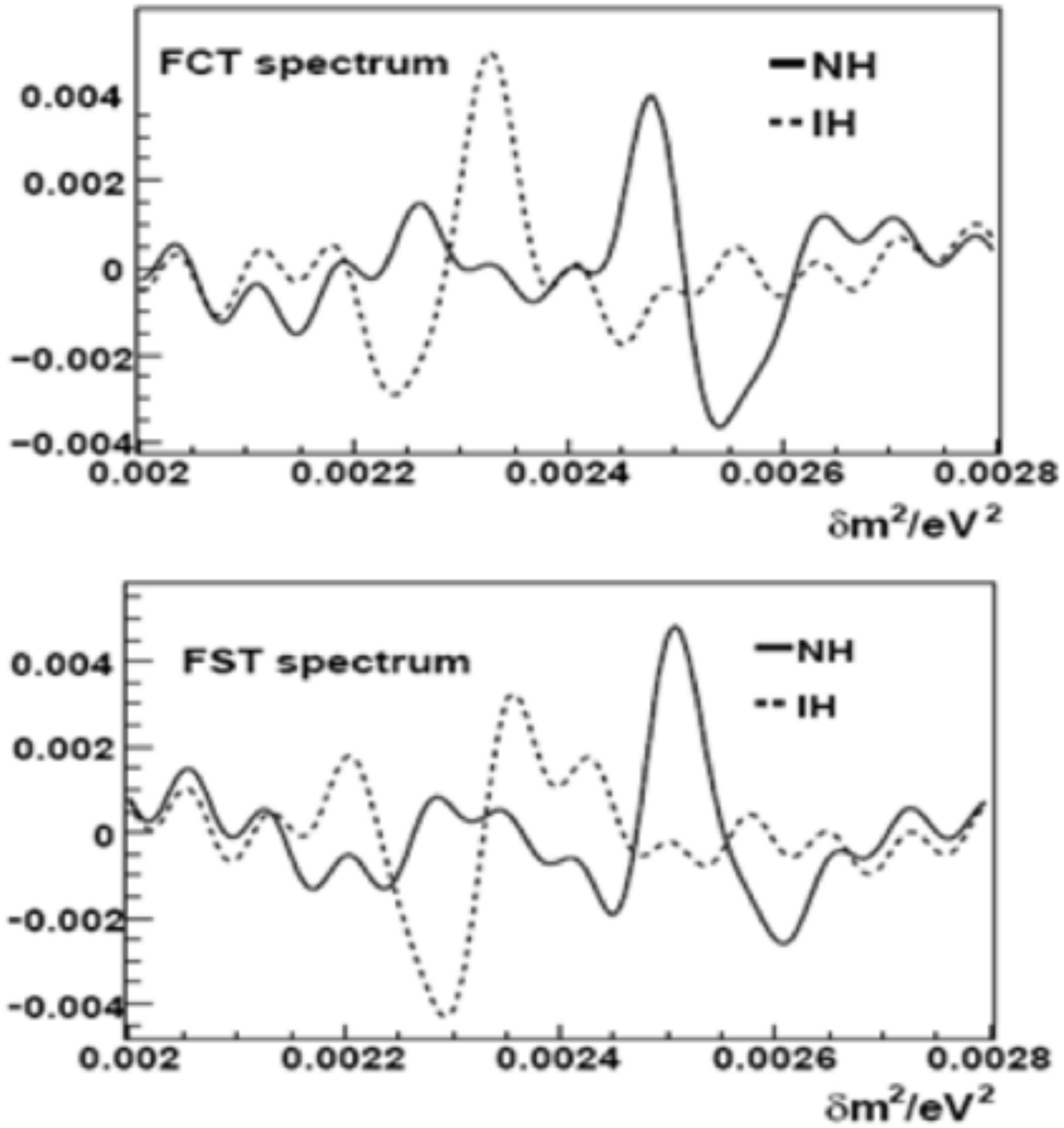
Inverted Hierarchy: $|\Delta_{31}| < |\Delta_{32}|$ → *Larger amplitude at lower frequency*



JUNO Strategy

- Enhance signal through Fourier transform techniques:

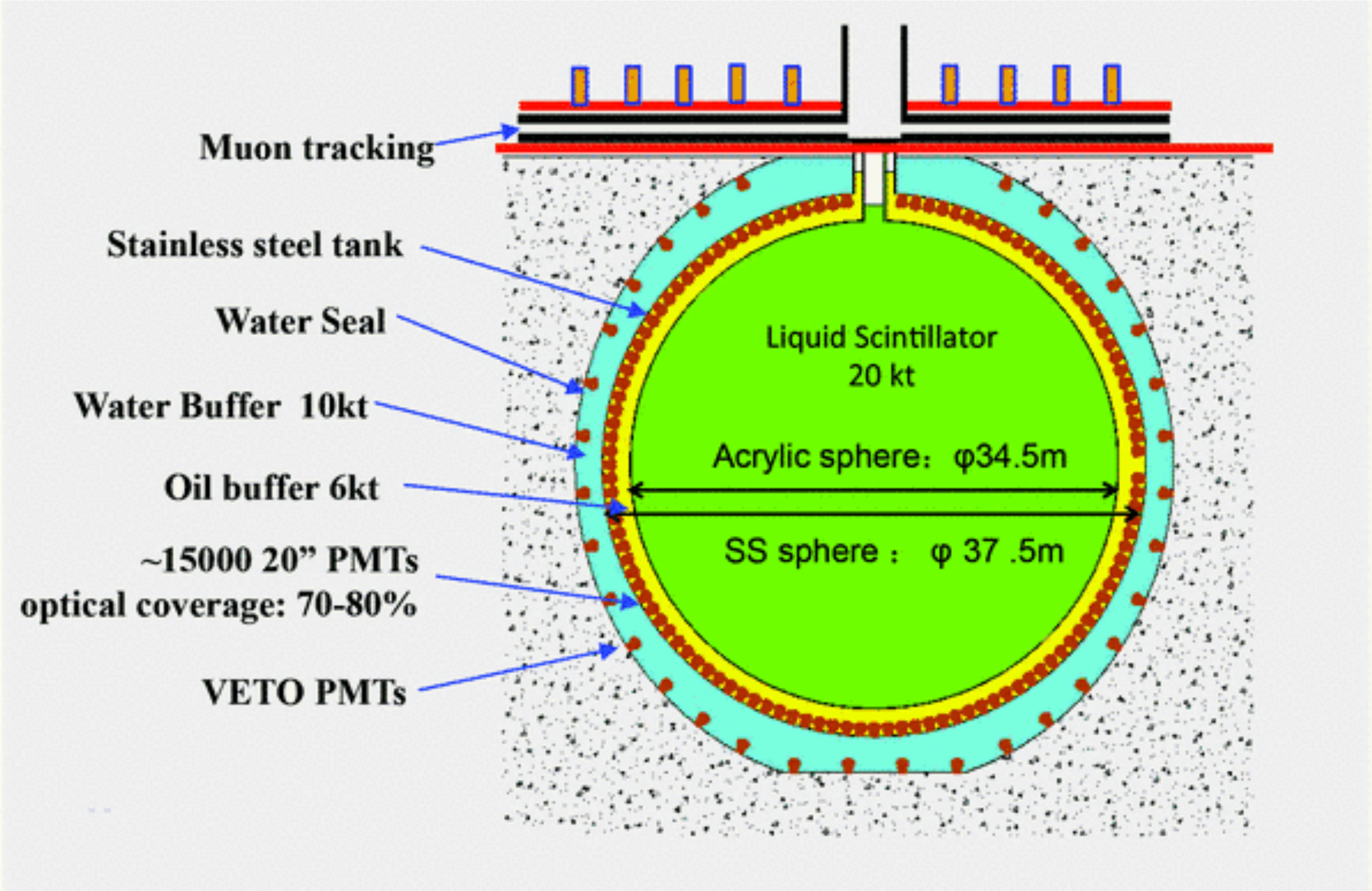




- Expects to achieve a ~3-4σ sensitivity to the mass hierarchy in ~6 years.
  - Will also make the world's most precise measurements of 3 oscillation parameters, as well as precision studies of geoneutrinos, proton-decay…etc.

JUNO expectations

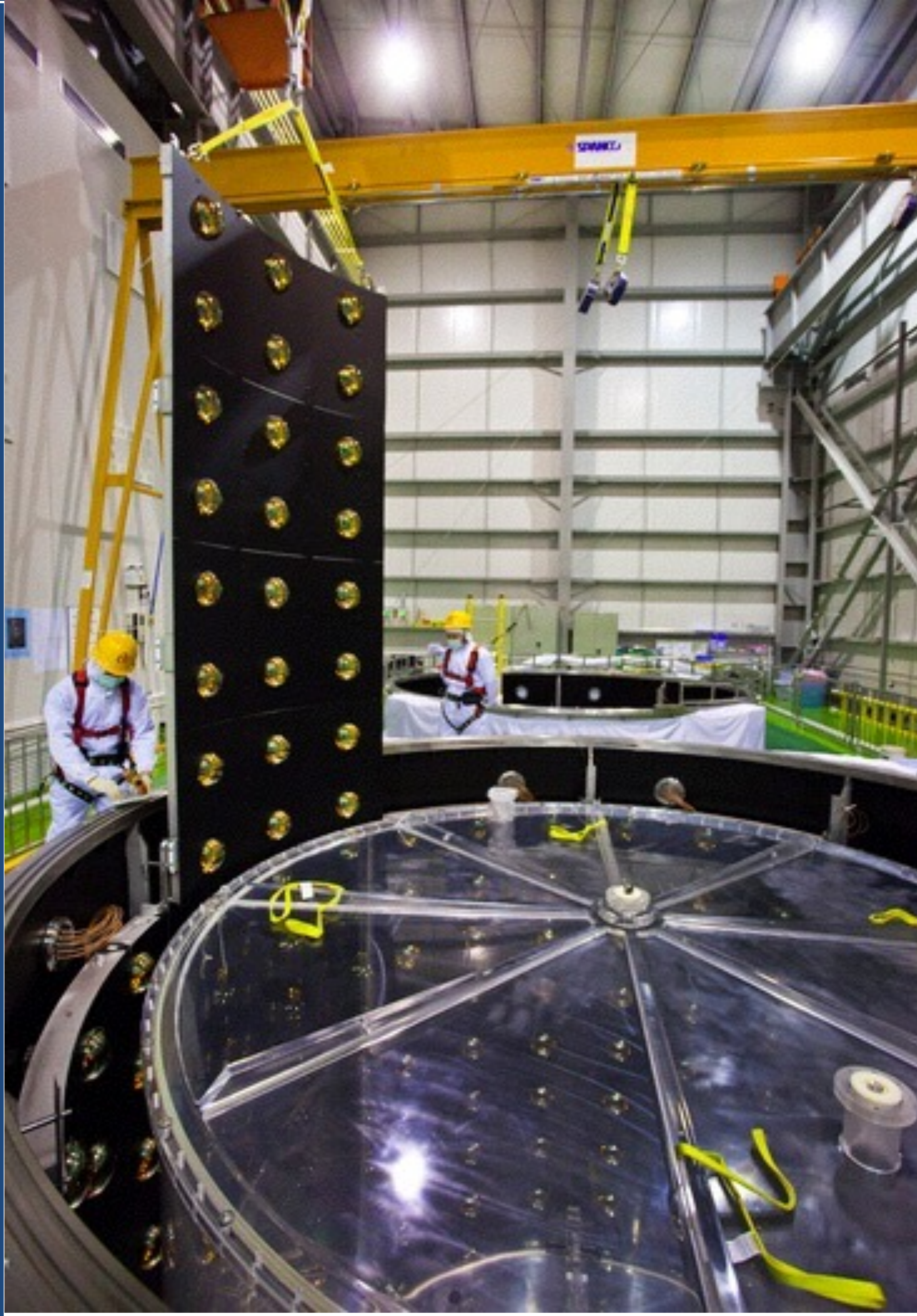
- Funding for R&D is secured
- Total cost is ~300M USD.
- Challenges to address:
  - Building the structure:
    - ✓ Building concentric steel and acrylic spheres is *very* hard
  - Energy resolution:
    - ✓ Need to increase QE of PMTs from ~25% to ~40%
    - ✓ Need highly transparent LS (from ~20m attenuation length to ~30m), with high light-yield
- Could begin data-taking as early as 2020
- Similar proposal in Korea (RENO-50) seems to also be going forward



Summary & Conclusions

Summary & Conclusions

- Neutrinos are fascinating particles that can teach us volumes about our universe
- Reactor Experiments have and will continue to play a major role when it comes to understanding these elusive particles:
  - The Daya Bay and JUNO experiments are at the front line in this field
  - The latest results have already broken new ground in their respective areas, and the same is expected in the near future
- Stay tuned for future results!



Thank you for
your attention!