JUNO:
Status and Prospects

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on behalf of the JUNO collaboration

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Outline

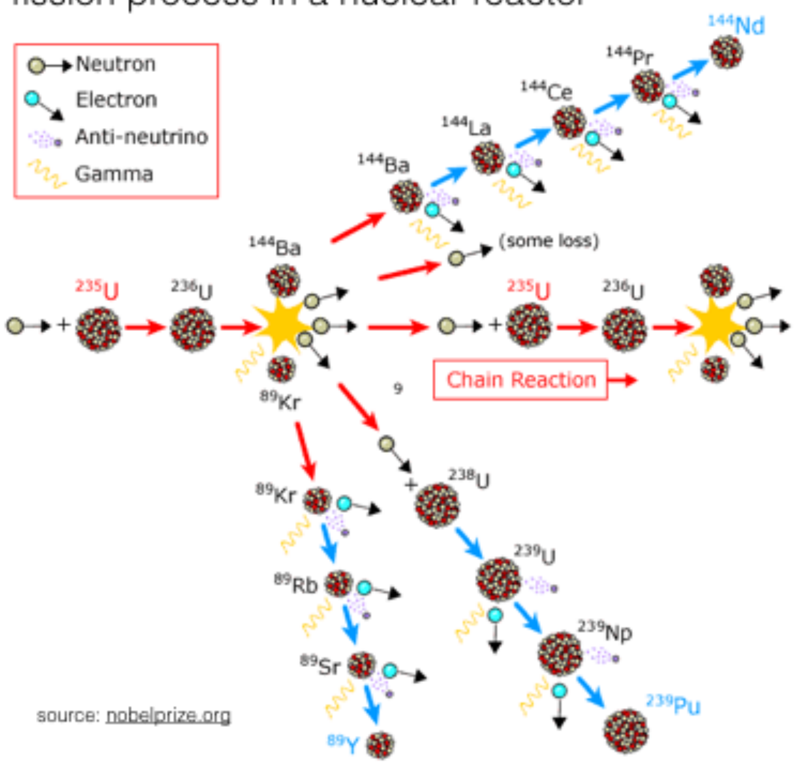
- Basics
- Physics Goals
- Detector Design & Status
- Timeline
- Summary & Conclusions

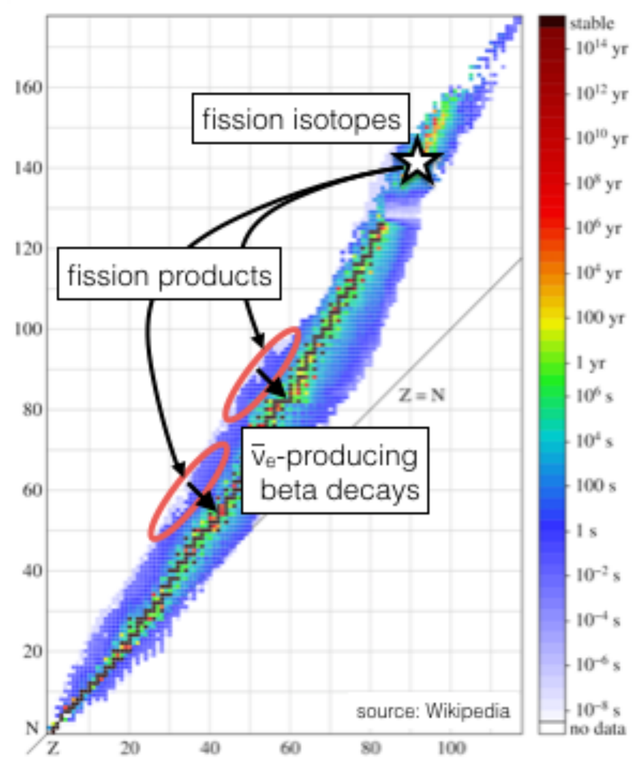
Reactor Neutrino Refresher

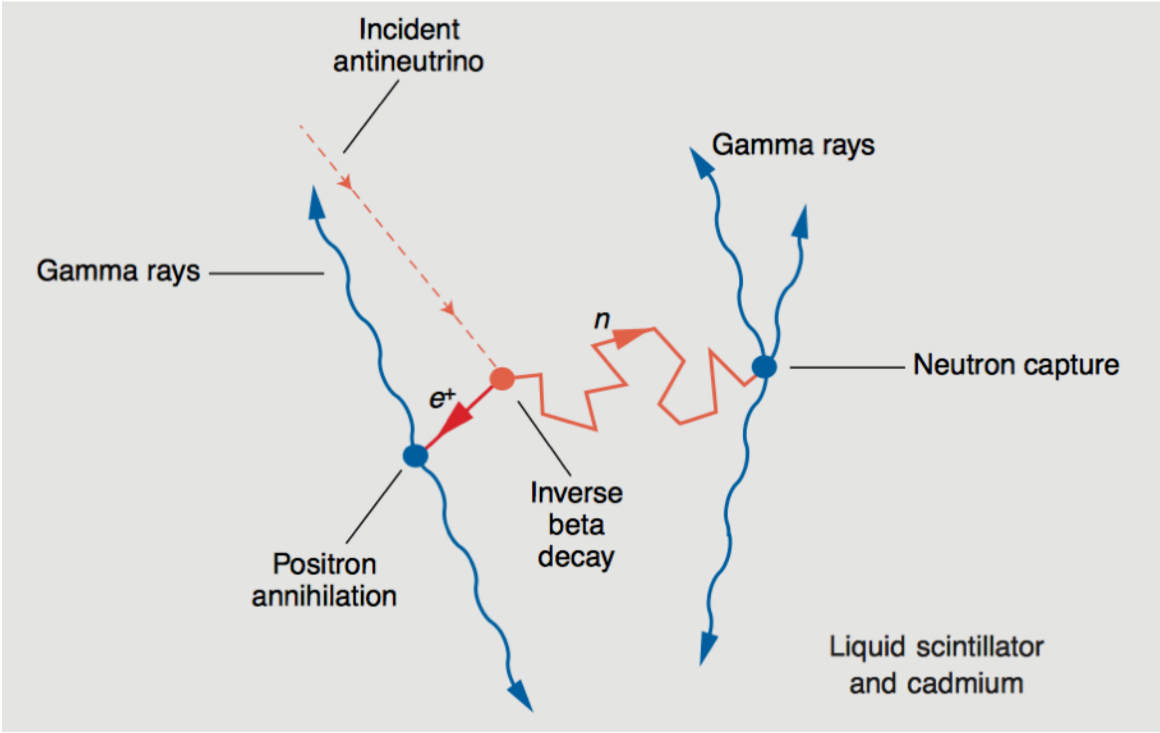
Nuclear reactors are a bountiful and well-understood source of electron antineutrinos

The primary detection channel is the inverse beta decay (IBD) reaction

fission process in a nuclear reactor





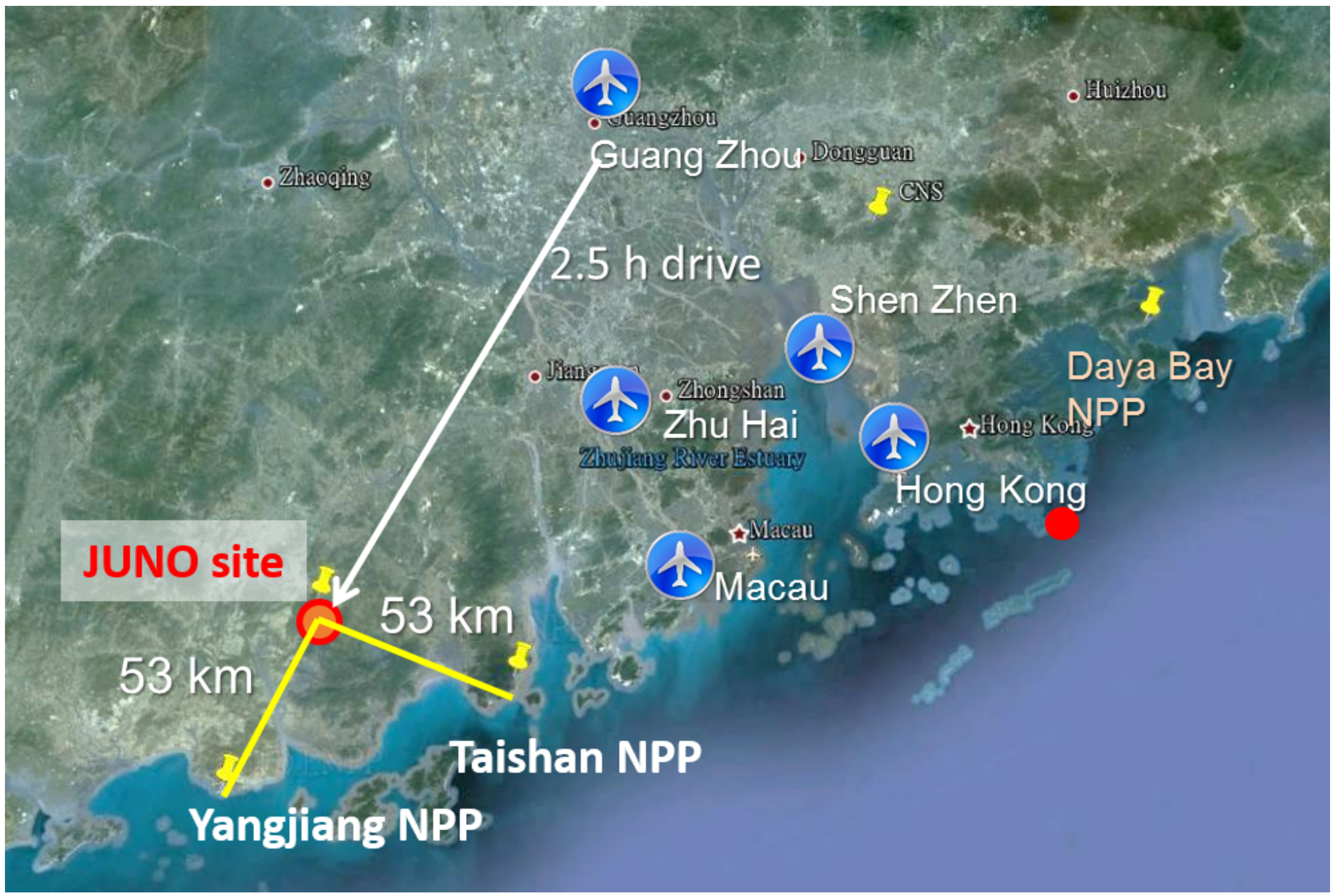


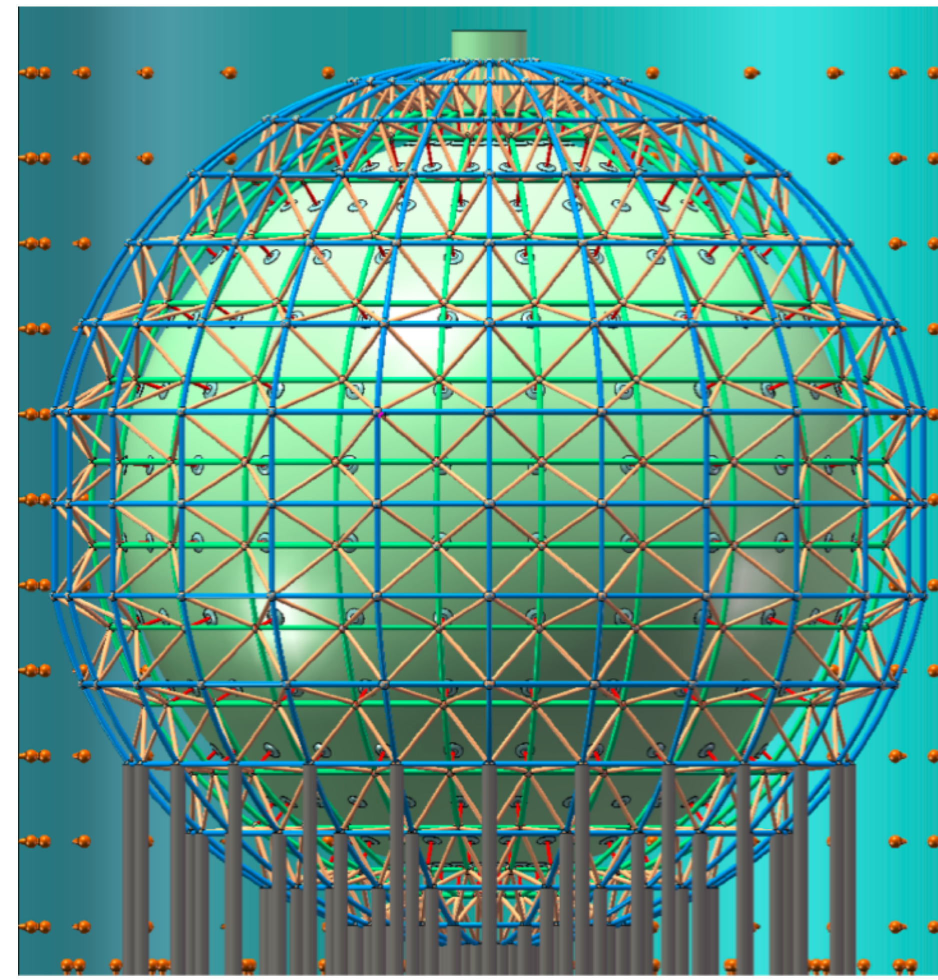
Beta decay: $n \rightarrow p + e^- + \bar{\nu}_e$

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

JUNO Basics

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

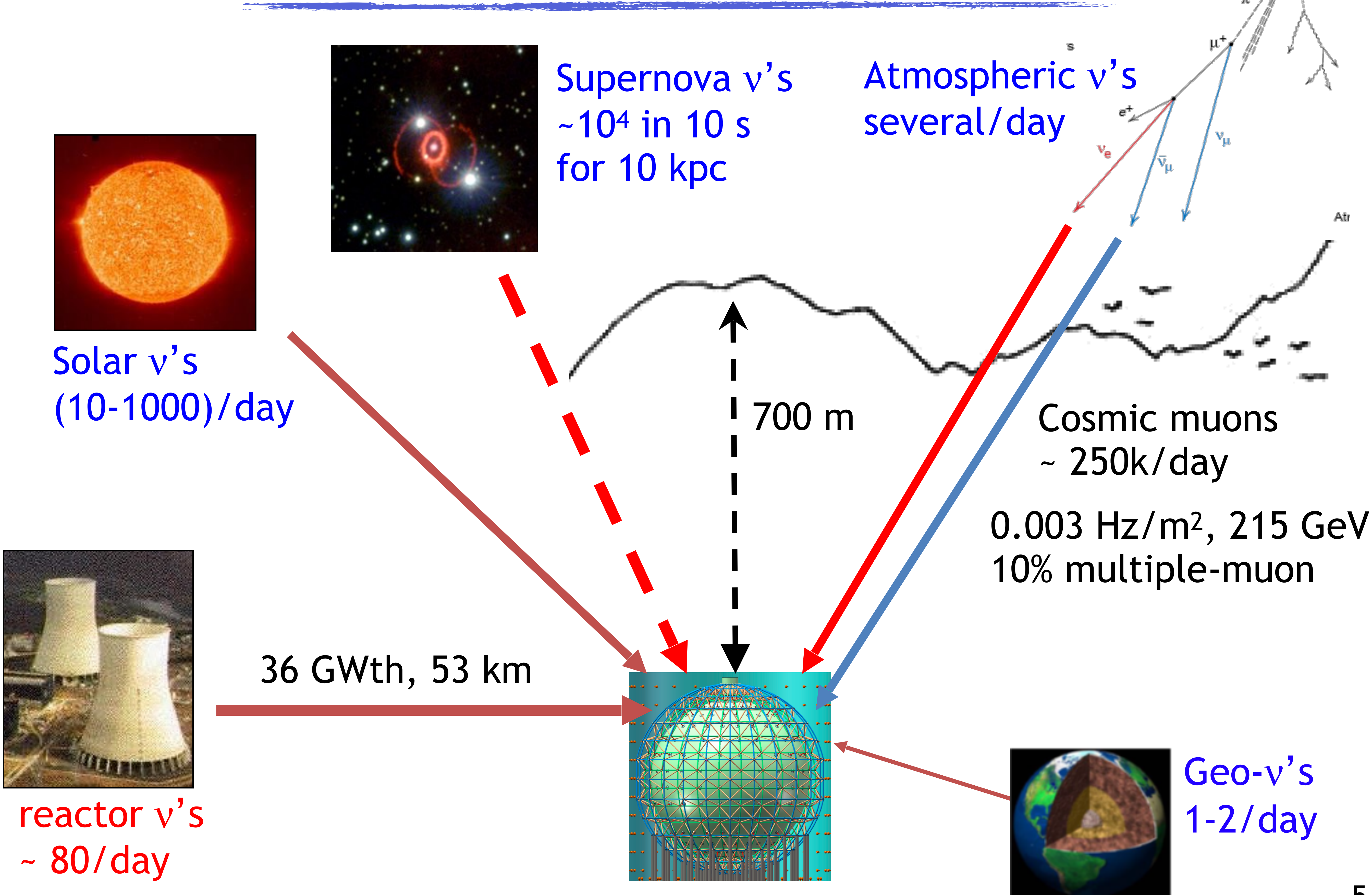




- 53 km from two major nuclear power plants (10 reactors)
- 35 m diameter sphere with 20 ktons of liquid scintillator

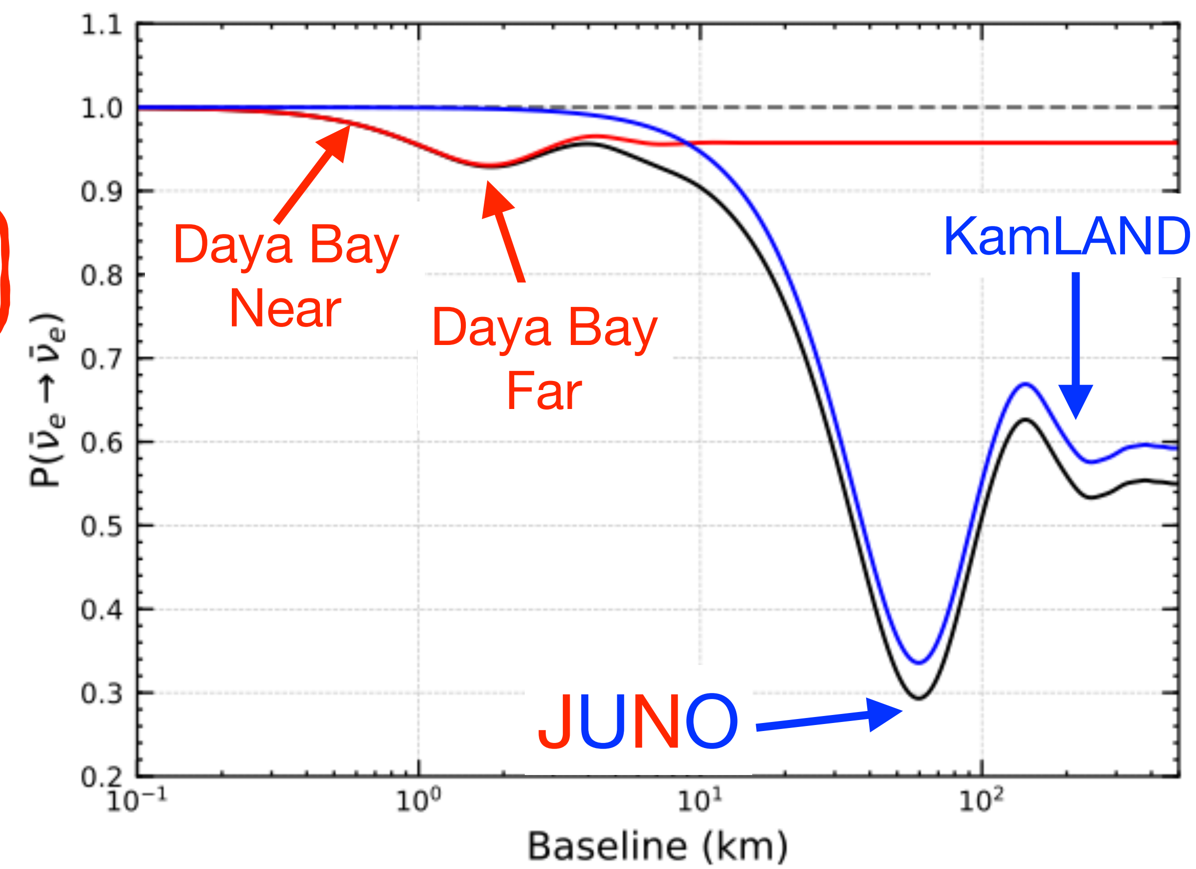
LS Detectors	Daya Bay	Borexino	KamLAND	JUNO
Target Mass	**20 t x 8**	**300 t**	**1 kt**	**20 kt**

A Multipurpose Neutrino Observatory

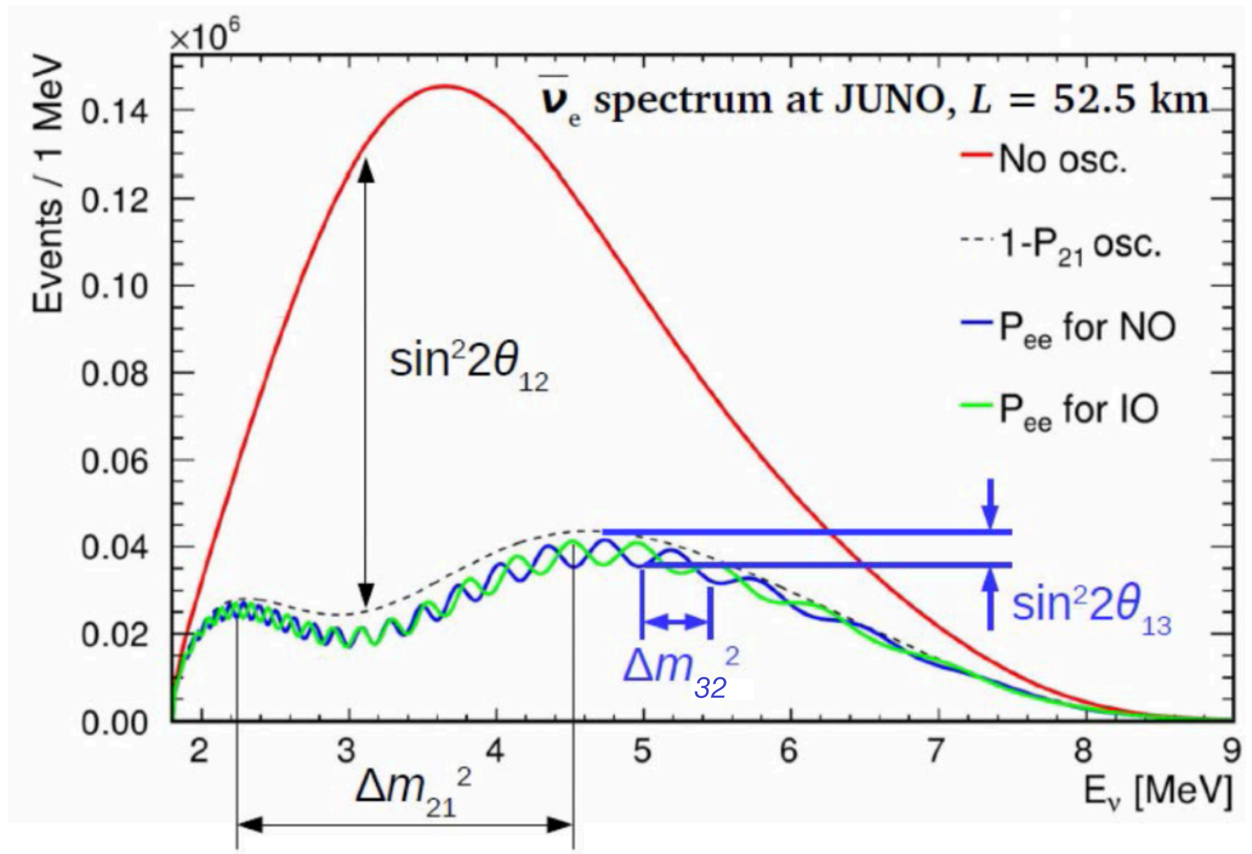


Oscillation Physics with Reactor $\bar{\nu}_e$'s

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



- Determination of the neutrino mass ordering (NMO)
  - Exploit interference effects in the fine structure of the oscillated spectrum
  - > 3σ sensitivity within 6 years

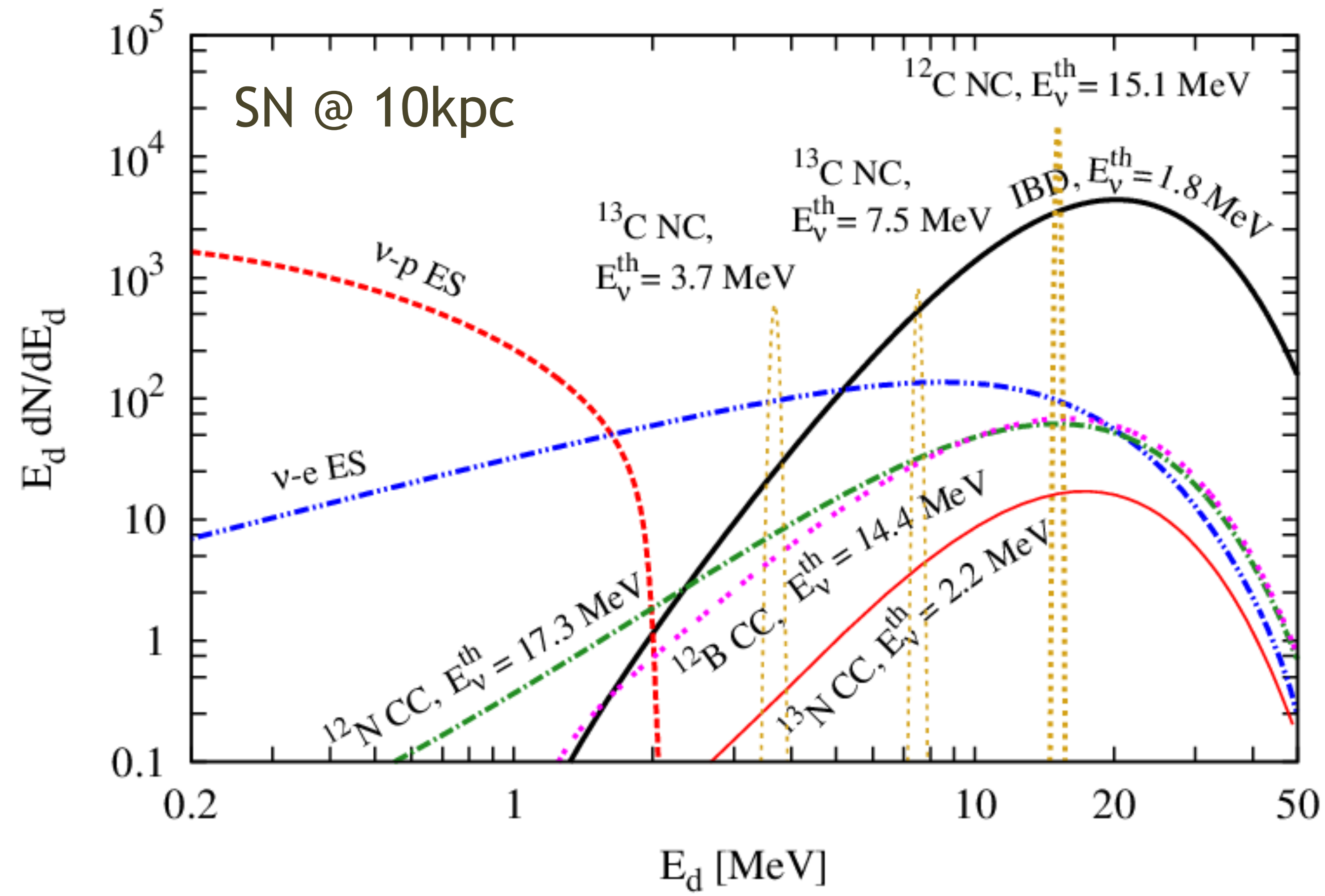


- Measurement of $\sin^2 2\theta_{12}$, Δm^2_{21} and Δm^2_{31} to better than 0.7%
  - New era of precision for model building and U_{PMNS} unitarity tests (~1%)

J. Phys. G43:030401 (2016)

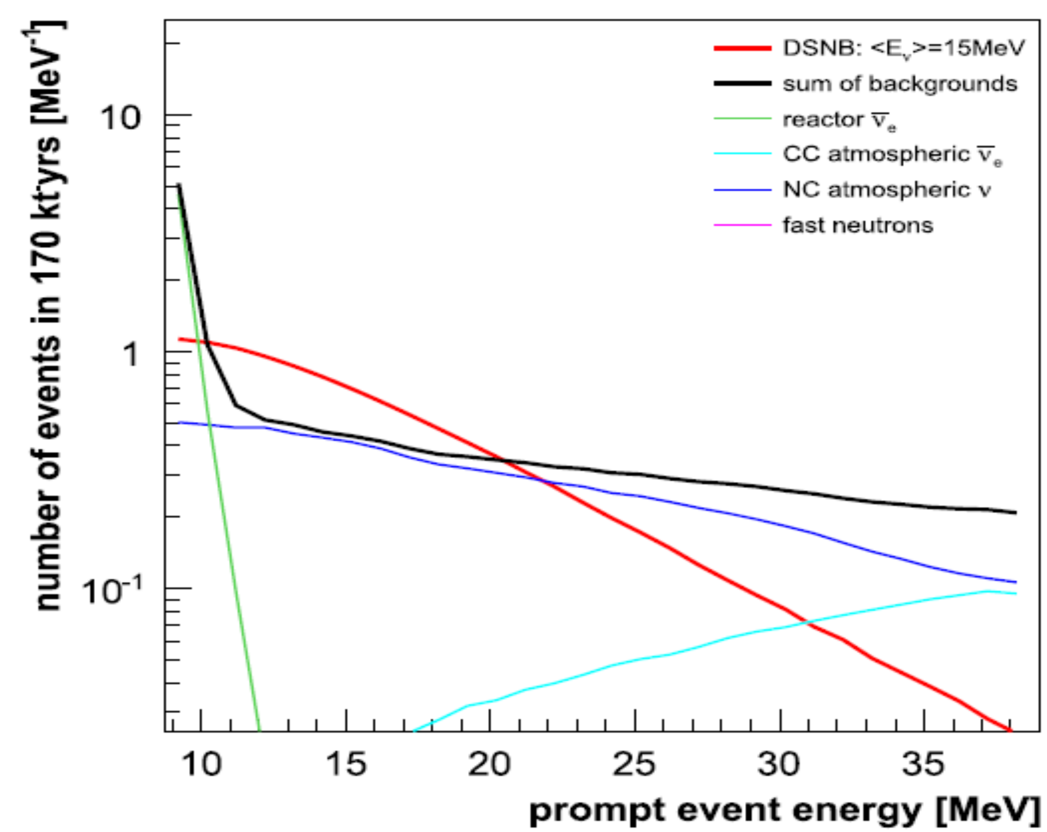
Supernova Neutrinos

- Able to determine flavor content, energy spectrum and time evolution of SN burst neutrinos
  - 10^4 detected events (5000 IBDs) for SN@10kpc
  - Low threshold ~0.2 MeV
  - Complementary to other detectors and with unique contributions (e.g. ν_x from ν-p ES channel)



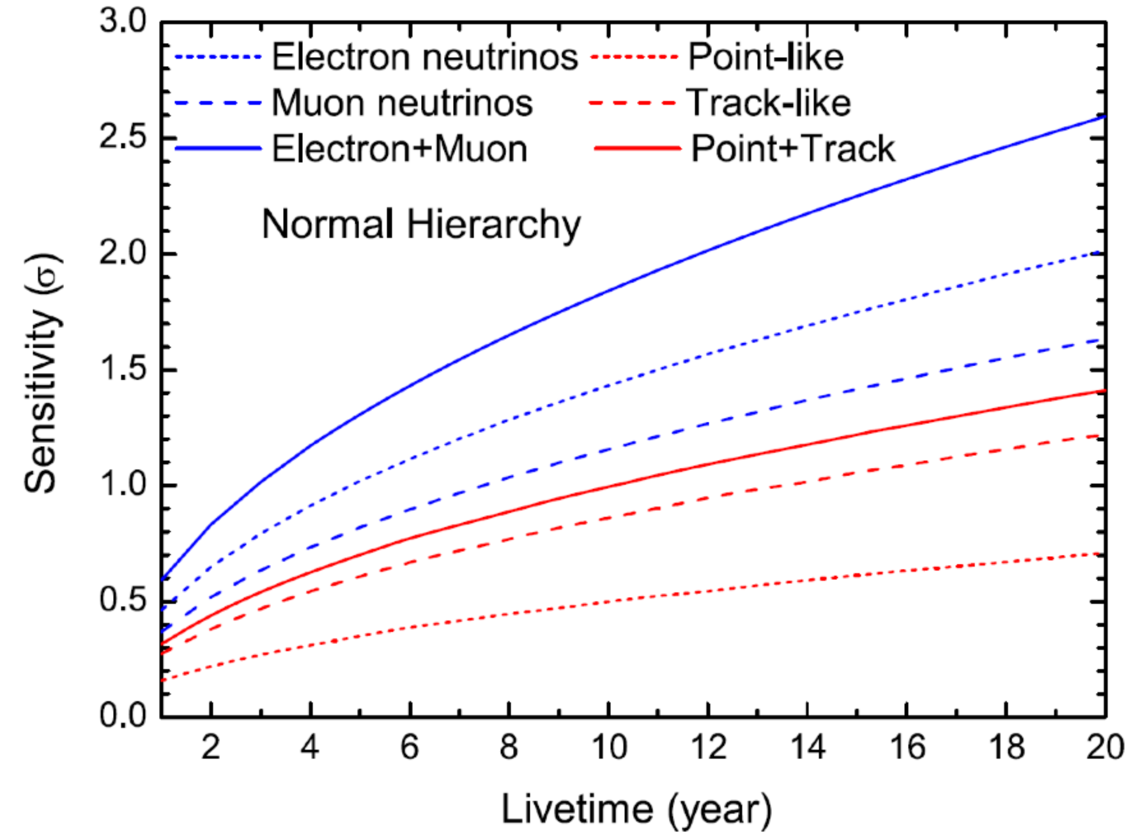
- Also sensitive to diffuse SN neutrino background (DSNB)
  - Expected detection significance of ~3σ after 10 years of data
  - Provide leading constraint if DSNB is not observed

J. Phys. G43:030401 (2016)



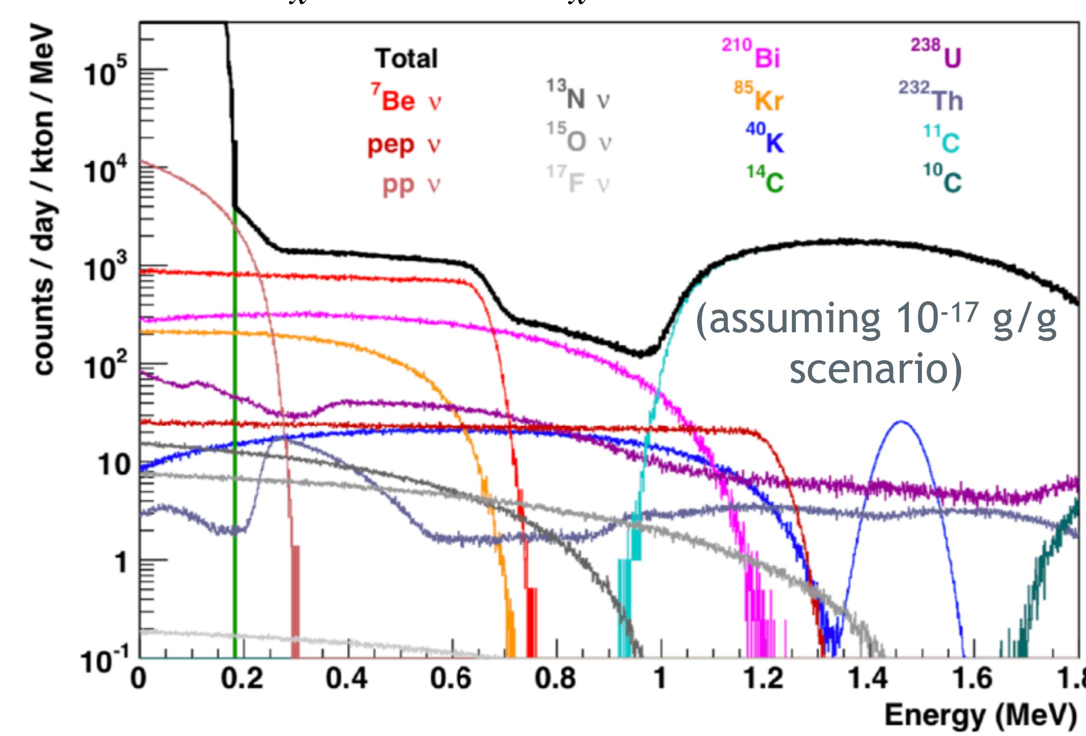
Solar and Atmospheric Neutrinos

- Atmospheric neutrinos:
  - Independent measurement of NMO via matter effect →
    - Complementary information to that from other experiments (e.g. IceCube)
  - Also sensitive to θ_{23} (precision ~6°)



- Solar neutrinos:
  - Measure ^{7}Be & ^{8}B fluxes
    - Challenge: cosmogenic & radiogenic backgrounds
    - Planning solar phase with 10^{-17} g/g
  - Explore current tension in Δm^2_{21} between solar and reactor measurements with same detector
  - Shed light on metallicity problem (low vs. high Z versions of the solar model)

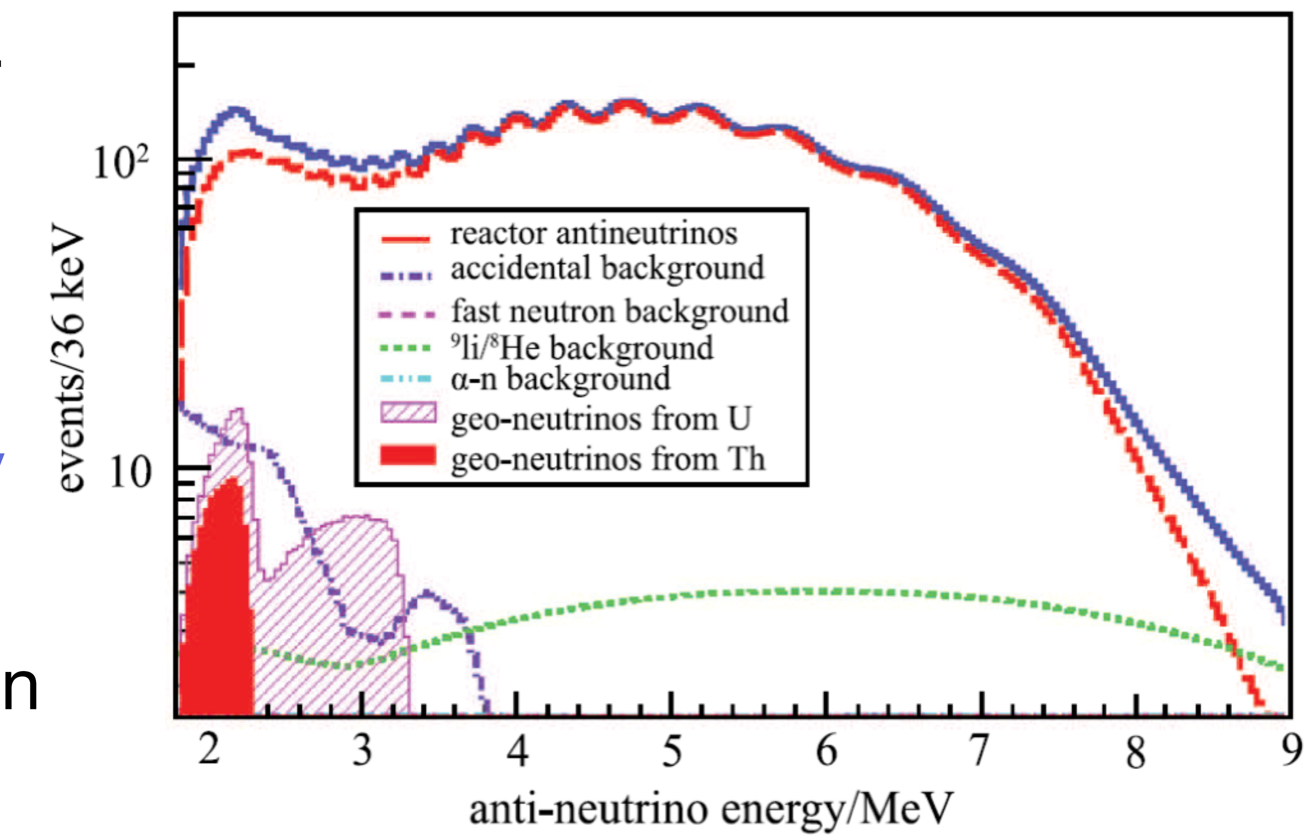
$$\nu_x + e^- \rightarrow \nu_x + e^- \text{ channel}$$



J. Phys. G43:030401 (2016)

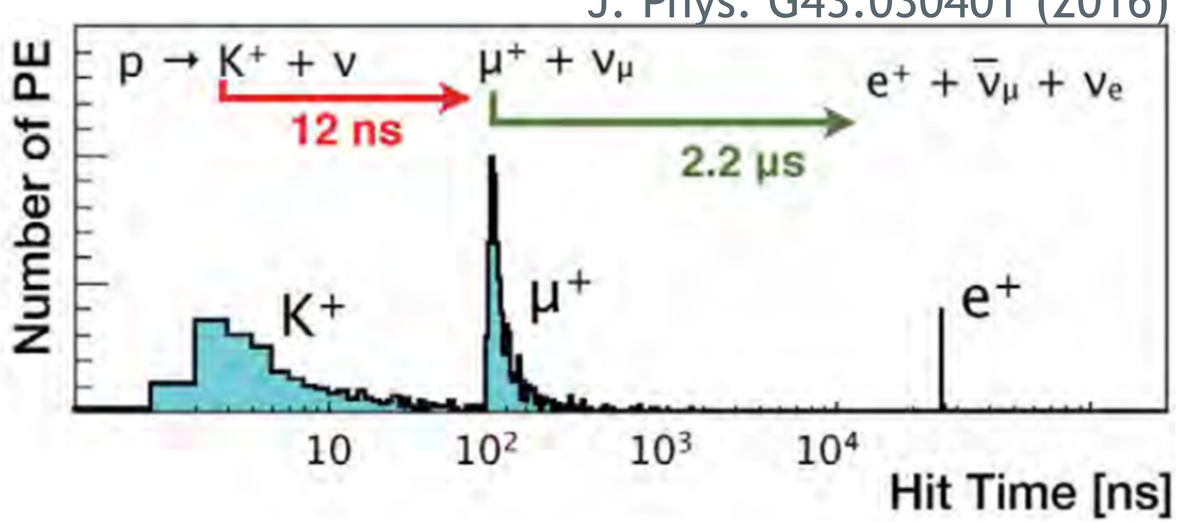
Geoneutrinos and Nucleon Decay

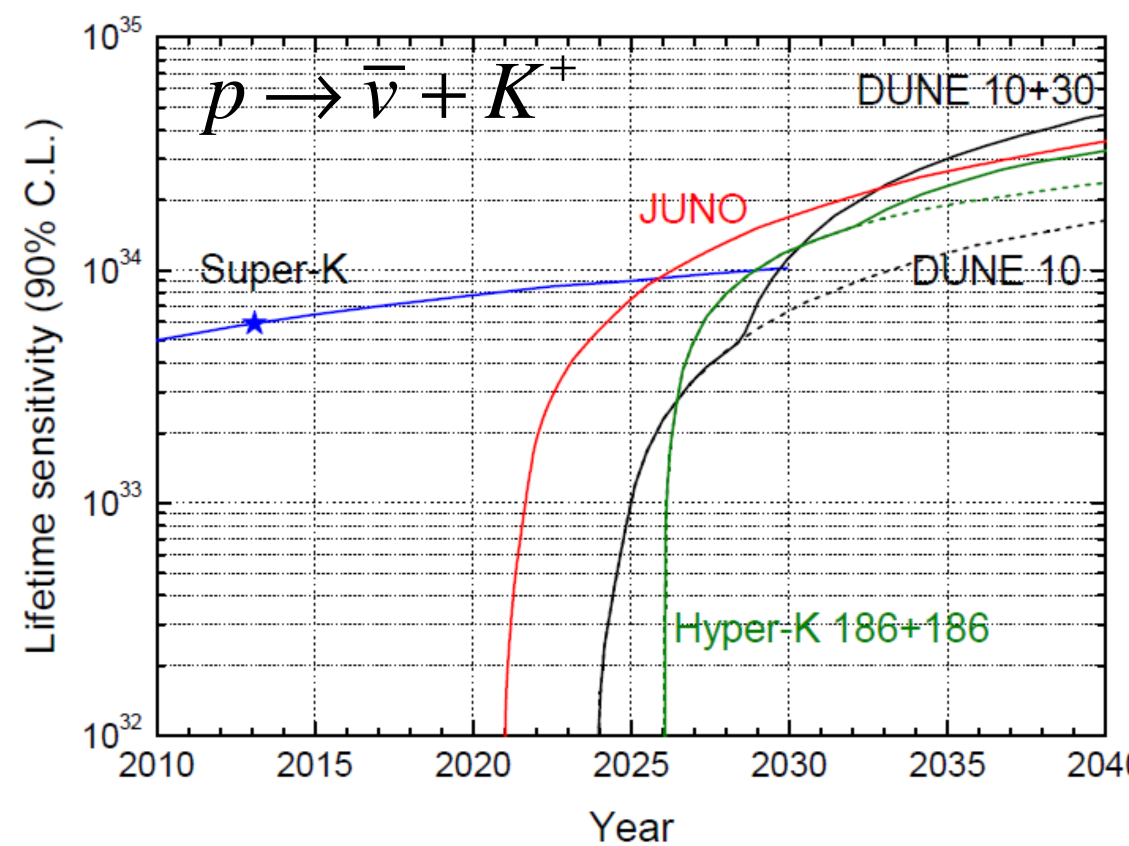
- 400-500 geoneutrinos per year
  - Precision of ~13% in 1 year and ~5% in 10 years
  - Local crust model under development by interdisciplinary team



- Competitive sensitivity to proton decay searches, particularly in the $p \rightarrow \overline{\nu} + K^+$ channel
  - Exploit triple coincidence enabled by liquid scintillator

J. Phys. G43:030401 (2016)

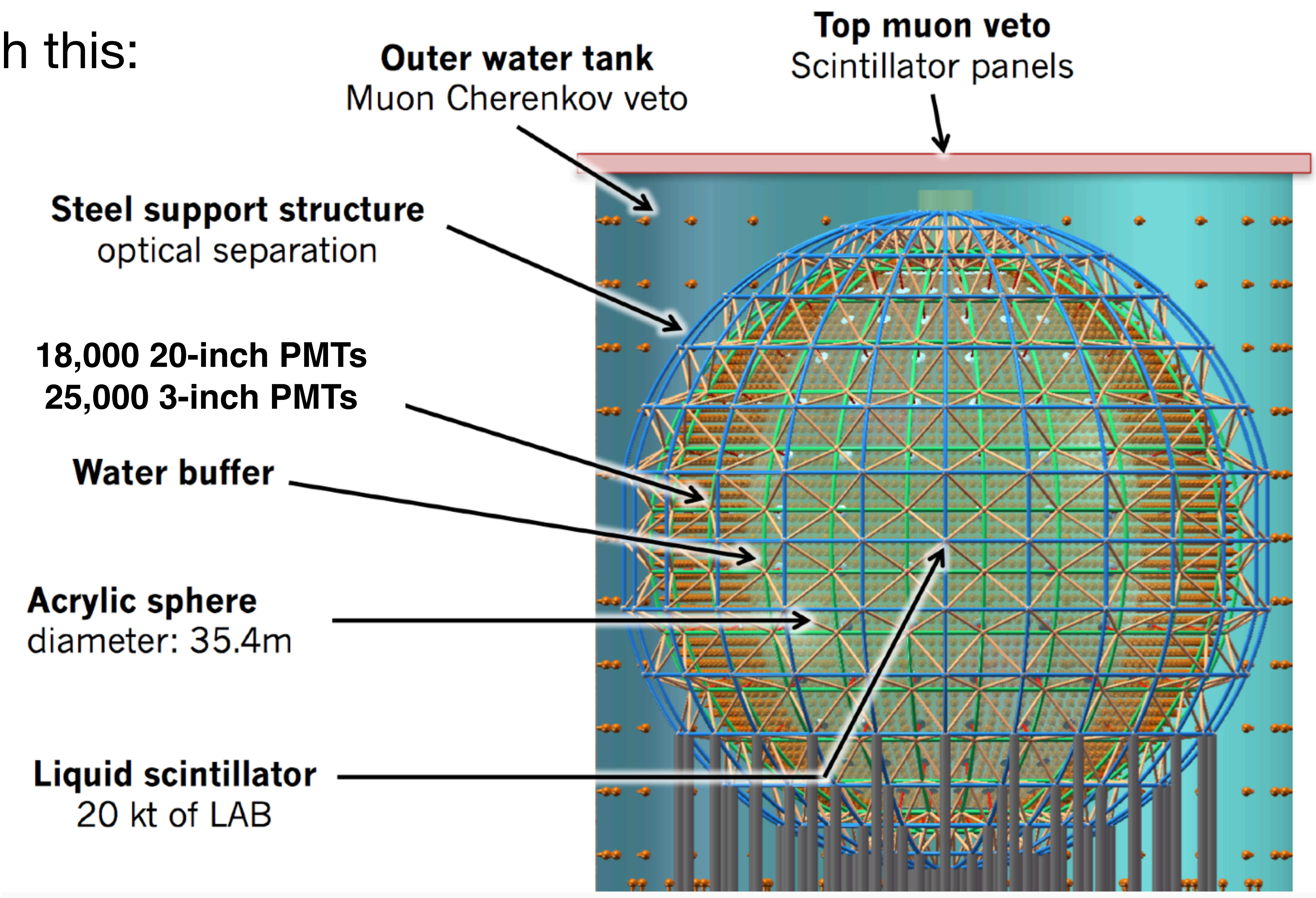




Detector Concept

- Keys to fulfilling the physics goals:
  - **Optimal baseline**
  - **High statistics**
  - **Superb energy resolution**
  - **Excellent control of energy response systematics**
  - **Background reduction**
- How to accomplish this:

Similar concept to previous LS experiments, but much **LARGER** and **MORE PRECISE**



Energy resolution

$$\frac{\sigma(E)}{E} = \sqrt{\frac{\sigma^2_{STOCH}}{E} + \sigma^2_{NON-STOCH}}$$

stochastic term: depends on photostatistics

non-stochastic term: residual issues (stability, uniformity, linearity) after calibration

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

	KamLAND	JUNO	Relative Gain
Total light level	**250 p.e. / MeV**	**1200 p.e. / MeV**	**5**
Photocathode coverage	34%	75%	~2
Light yield	1.5 g/l PPO	3-5 g/l PPO	~1.5
Attenuation length / ⌀	15 m / 16 m	20 m / 35 m	~0.8
PMT QE×CE	20%×60% ~ 12%	~30%	~2

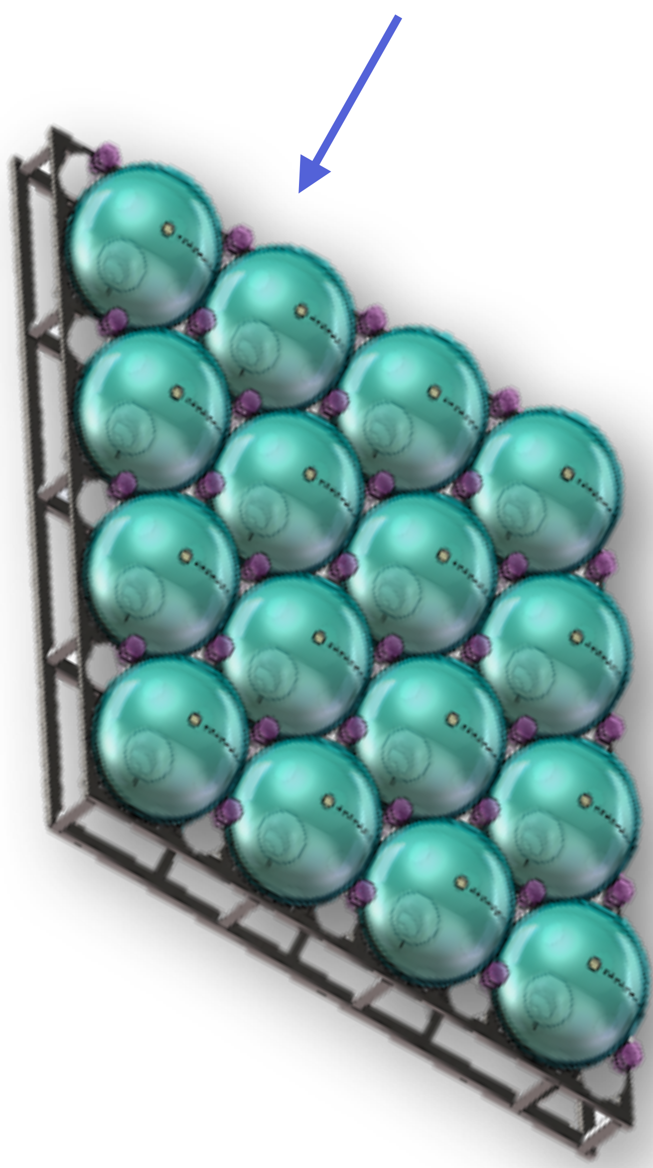
KamLAND used for comparison (→ Relative Gain)

goal (→ 5)

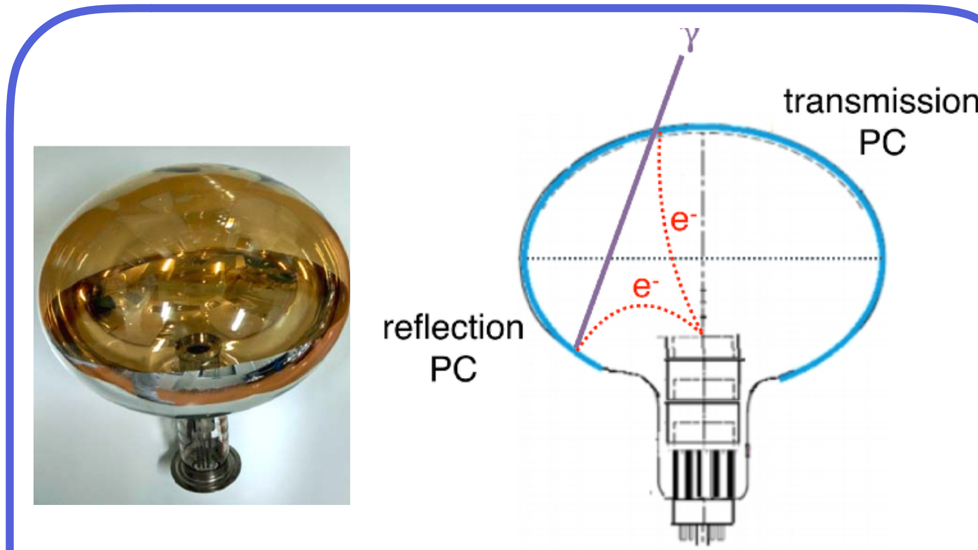
Large PMT system

- JUNO will use large 20-inch PMTs as its main light-detection device

Arranged as tightly as possible, with a photocathode coverage of ~75%

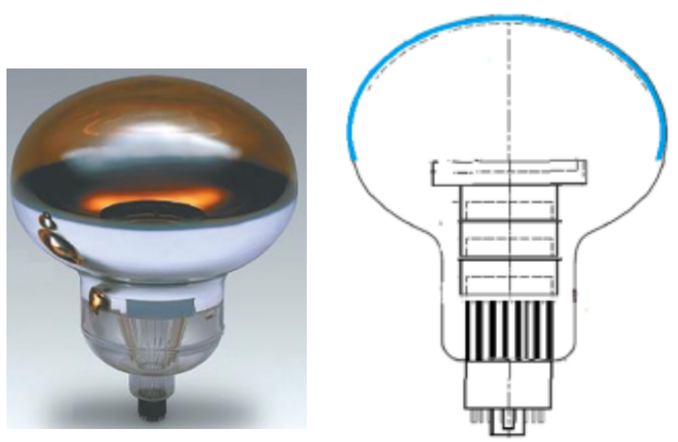


2 complementary (and new!) technologies:



Microchannel plate (MCP)-PMTs

- Developed for/by JUNO
- Use of transmission + reflection cathodes to increase QE
- Good price
- Mass-produced by NNVT (China)



Dynode-PMTs

- R12860 from Hamamatsu
- New type of bialkali photocathode
- Excellent TTS (2.7 ns FWHM)

Both reach QE x CE ~ 30%!

JUNO's central detector will use 13,000 MCP-PMTs and 5,000 Dynode-PMTs

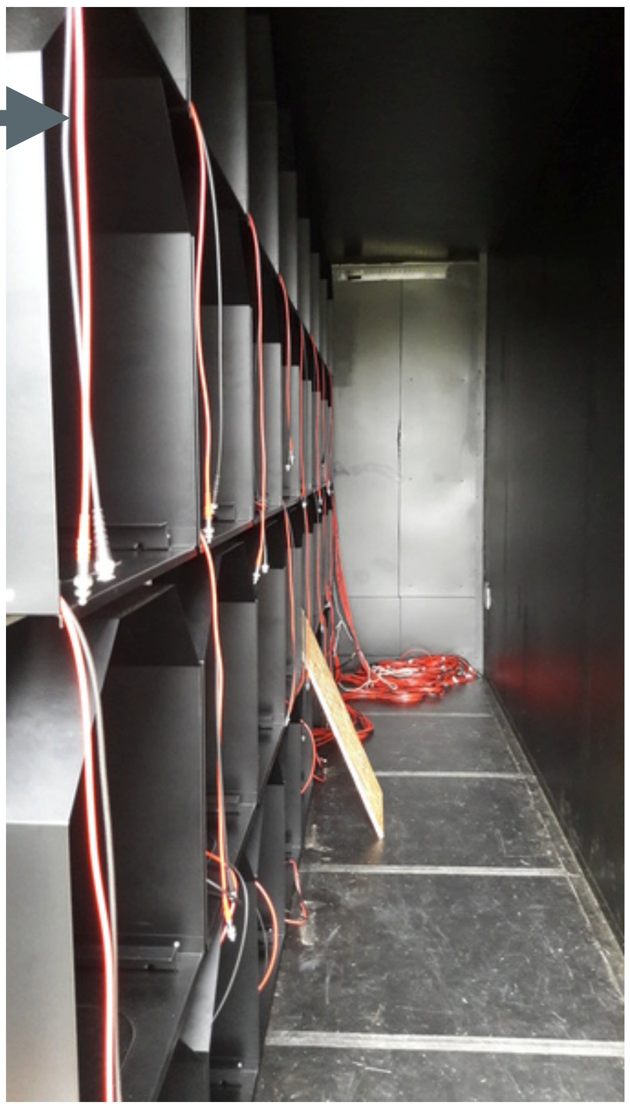
Large PMT system

- We have already received all dynode PMTs and over 10,000 MCP PMTs:

Have a very large storage, testing and potting facility near the JUNO site

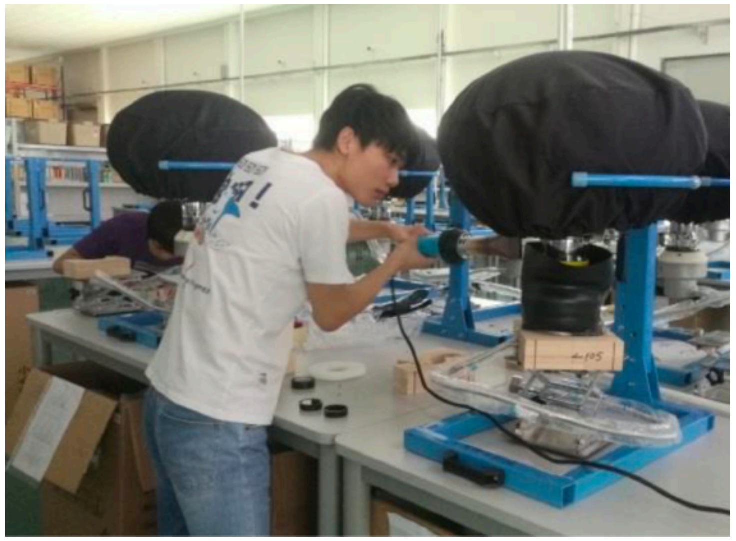
Acceptance & characterization tests ongoing at full speed

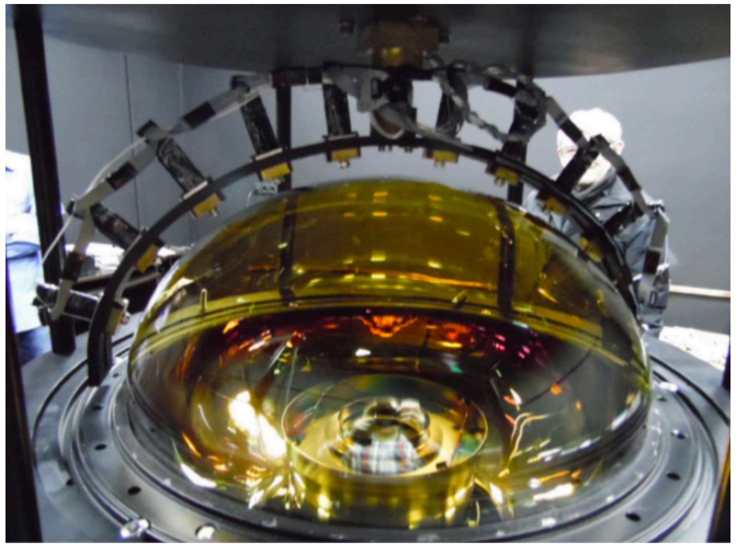
Industrial container mass testing system



Photocathode uniformity scanning system

Potting lab

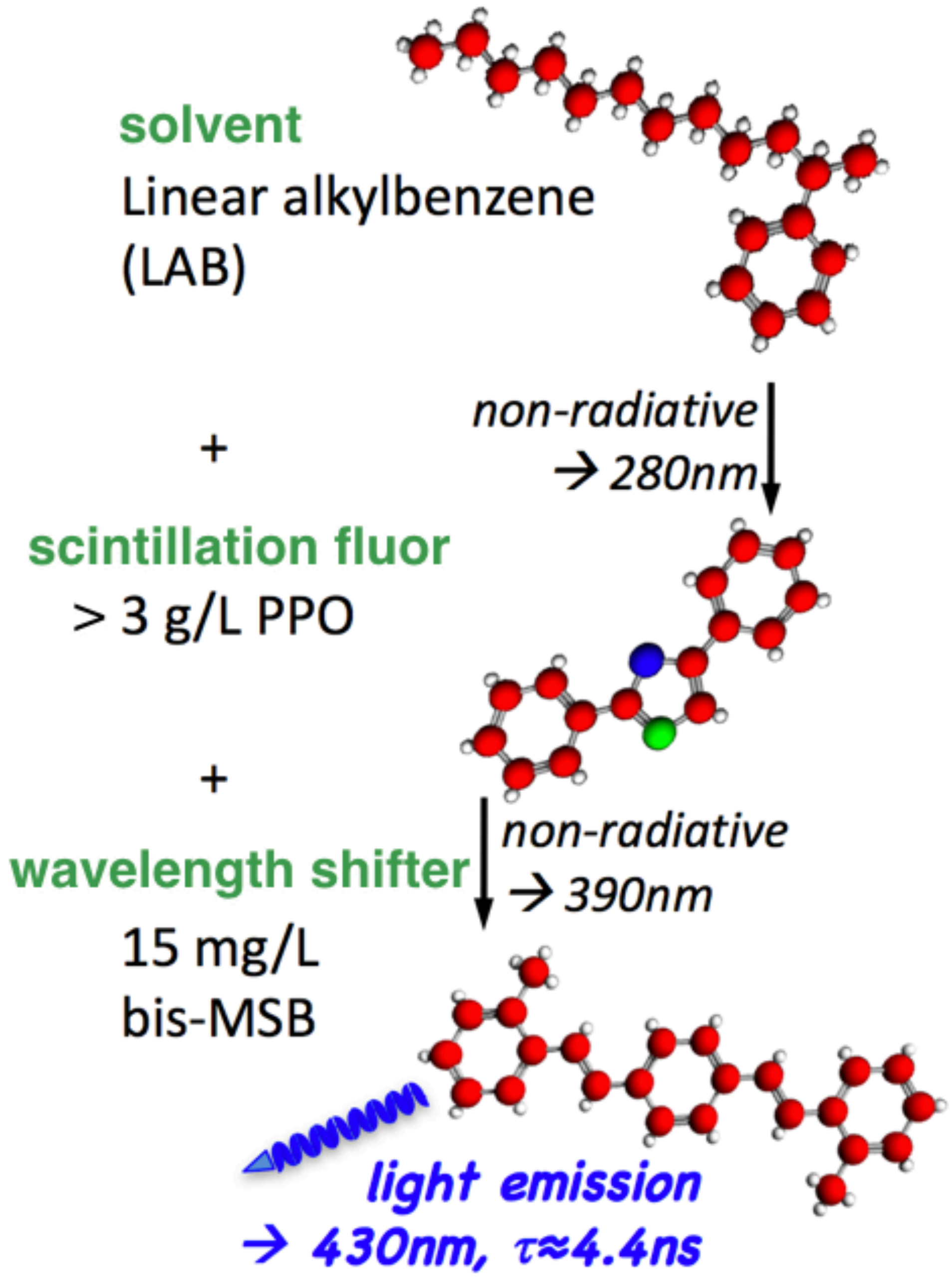




An industrial process!

Liquid Scintillator

- Using a recipe inspired from Daya Bay's experience



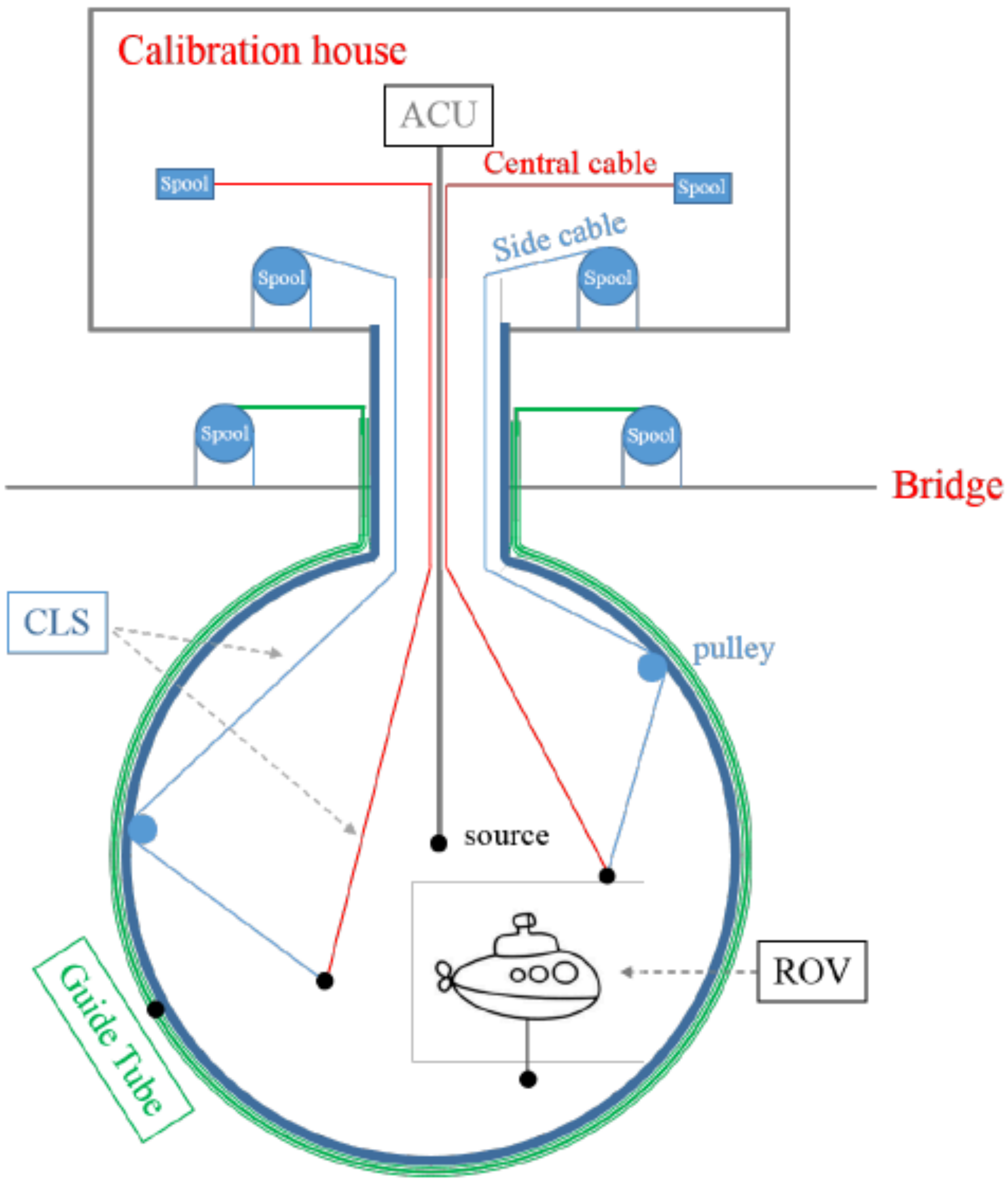
Since early 2017 one of the eight Daya Bay detectors was taken down permanently and its Gd-LS replaced with JUNO LS

Invaluable experience to study different recipes and purification methods

- No doping, large fluor concentration, Al_2O_3 column purification, vacuum distillation.

Calibration System

- Achieving a light level of 1200 p.e. / MeV is not enough. Also have to **keep the systematics under control**



- Have an **aggressive calibration program** consisting of 4 complementary systems:
  - **1D**: Automated Calibration Unit (ACU) deploys radioactive and laser (1ns, keV-TeV range) sources along the central axis
  - **2D**: Cable Loop System (CLS) to scan vertical planes
  - **2D**: Guide Tube to scan the outer surface of the central detector (where the CLS cannot reach)
  - **3D**: Remotely Operated Vehicle (ROV) operating inside the LS to scan the full volume

Goal is to keep the energy scale uncertainty < 1%

Small PMT System

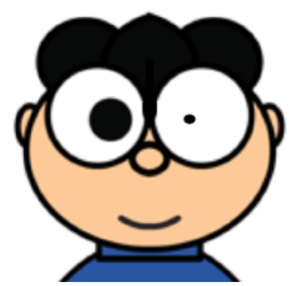
- JUNO will also have to keep the non-stochastic term of the resolution under control (≲1%)

$$\frac{\sigma(E)}{E} = \sqrt{\frac{\sigma^2_{STOCH}}{E} + \sigma^2_{NON-STOCH}}$$

< 1% never achieved before!

- 25,000 3-inch PMTs will operate predominantly in photon-counting mode:

Basic principle: look at the same events with two sets of "eyes" that have different systematics
(e.g. nonlinearity)



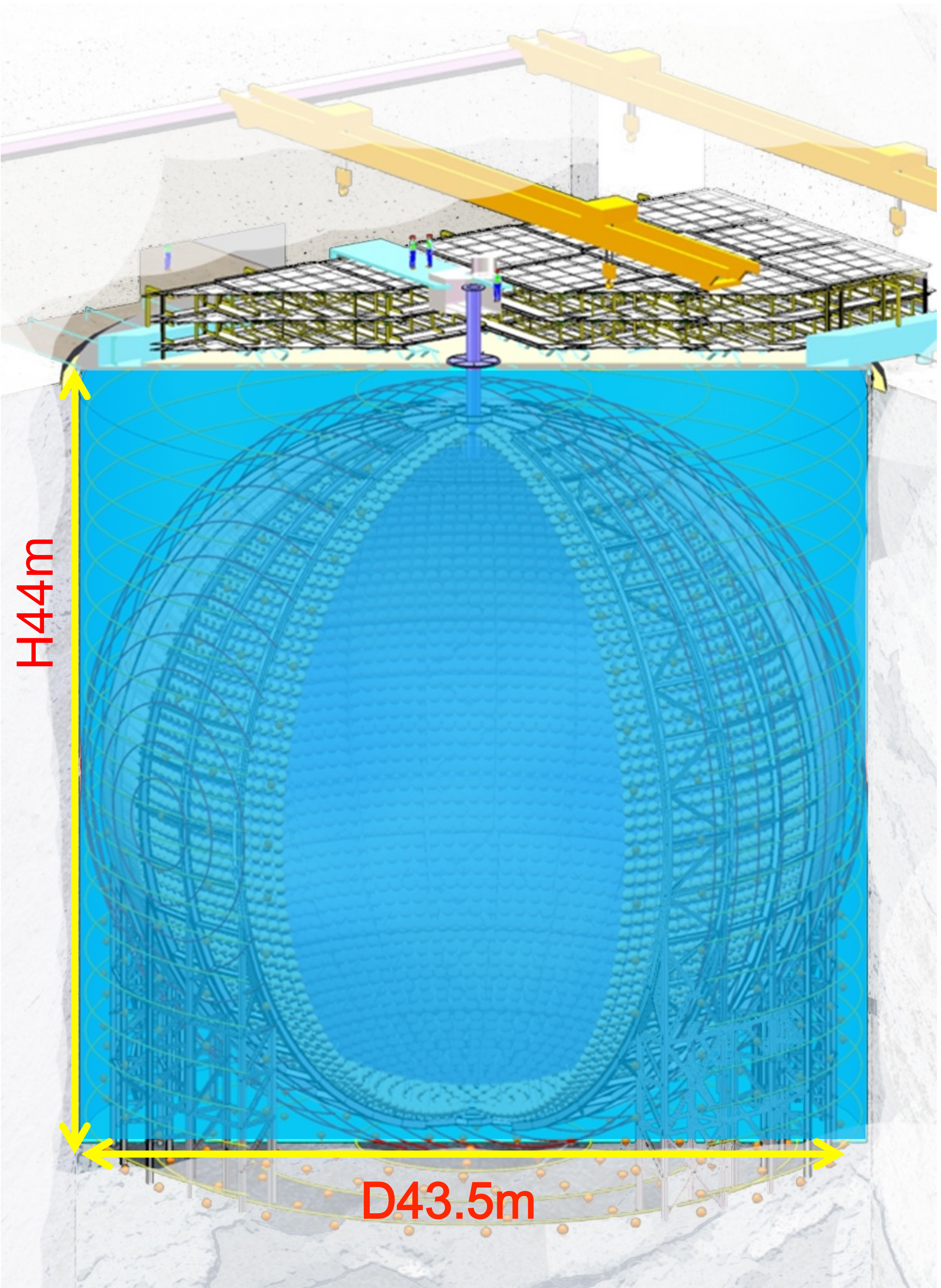
- The small PMTs also bring other nice benefits to the table:
  - Independent physics (e.g. measurement of solar parameters)
  - Aid to position reconstruction and muon track reconstruction
  - Aid to supernova neutrino measurement
  - Others (a little extra light, larger dynamic range… etc).

HZC PHOTONICS

XP72B22

A custom design for JUNO!

Muon Veto System

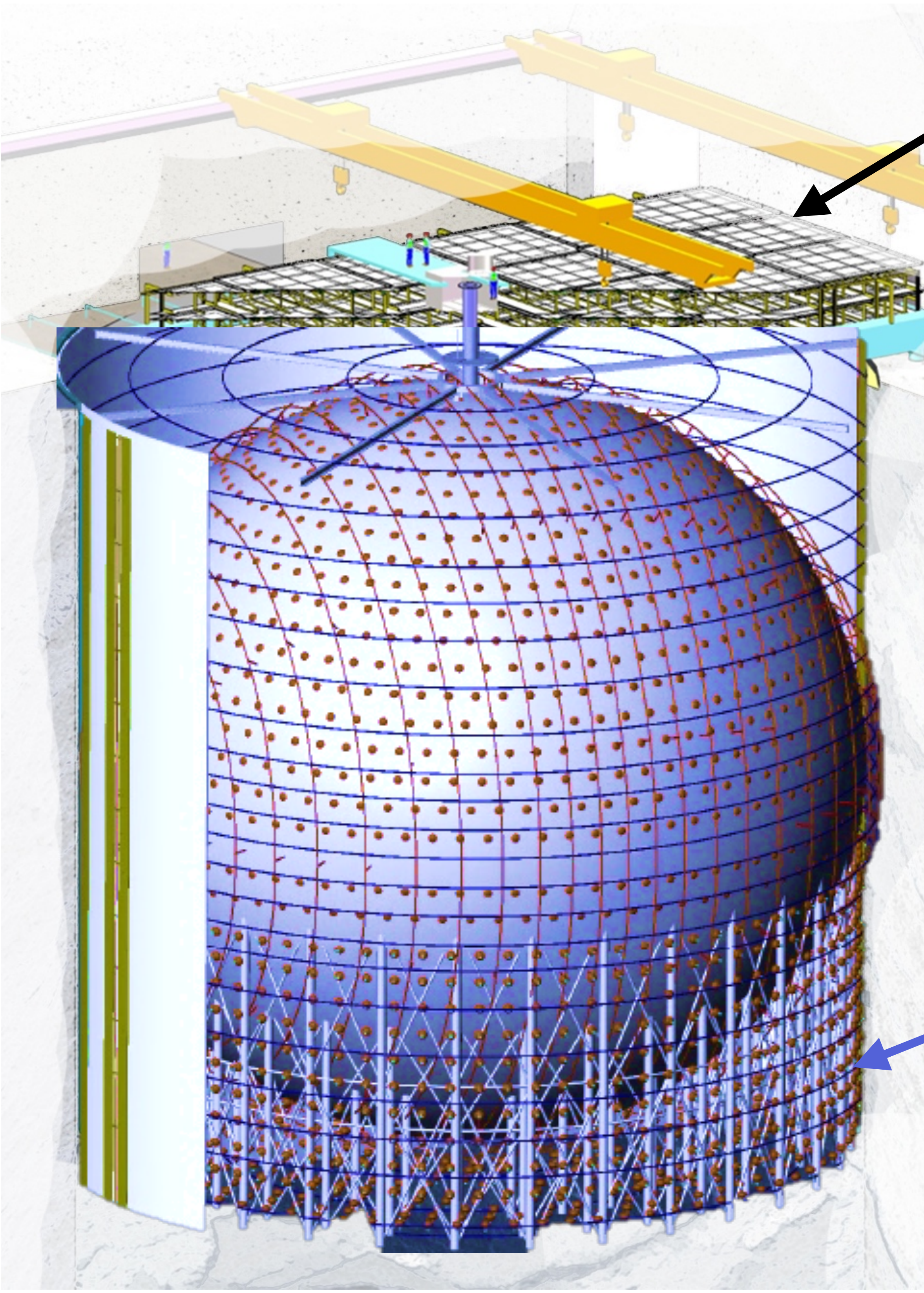


- It is also important to keep the cosmogenic backgrounds under control
- The 35 m diameter LS acrylic sphere will be immersed in a cylindrical instrumented water pool:
  - 35 kton ultrapure water with a circulation system

Double-purpose:
- Shield central detector against radioactivity from rock and neutrons from cosmic rays
- Veto cosmic-ray muons (most backgrounds are of cosmic ray origin)

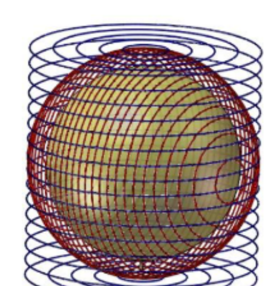
- Some details about the muon veto:
  - About 2,000 20-inch PMTs
  - Detection efficiency expected to be > 95%

Muon Veto System



- The muon veto system will also have a top tracker:
  - 3-layers of plastic scintillators
  - Reuse of OPERA's target tracker

  - Only partial coverage
- There will also be a magnetic field (EMF) shielding system
  - Double coil system

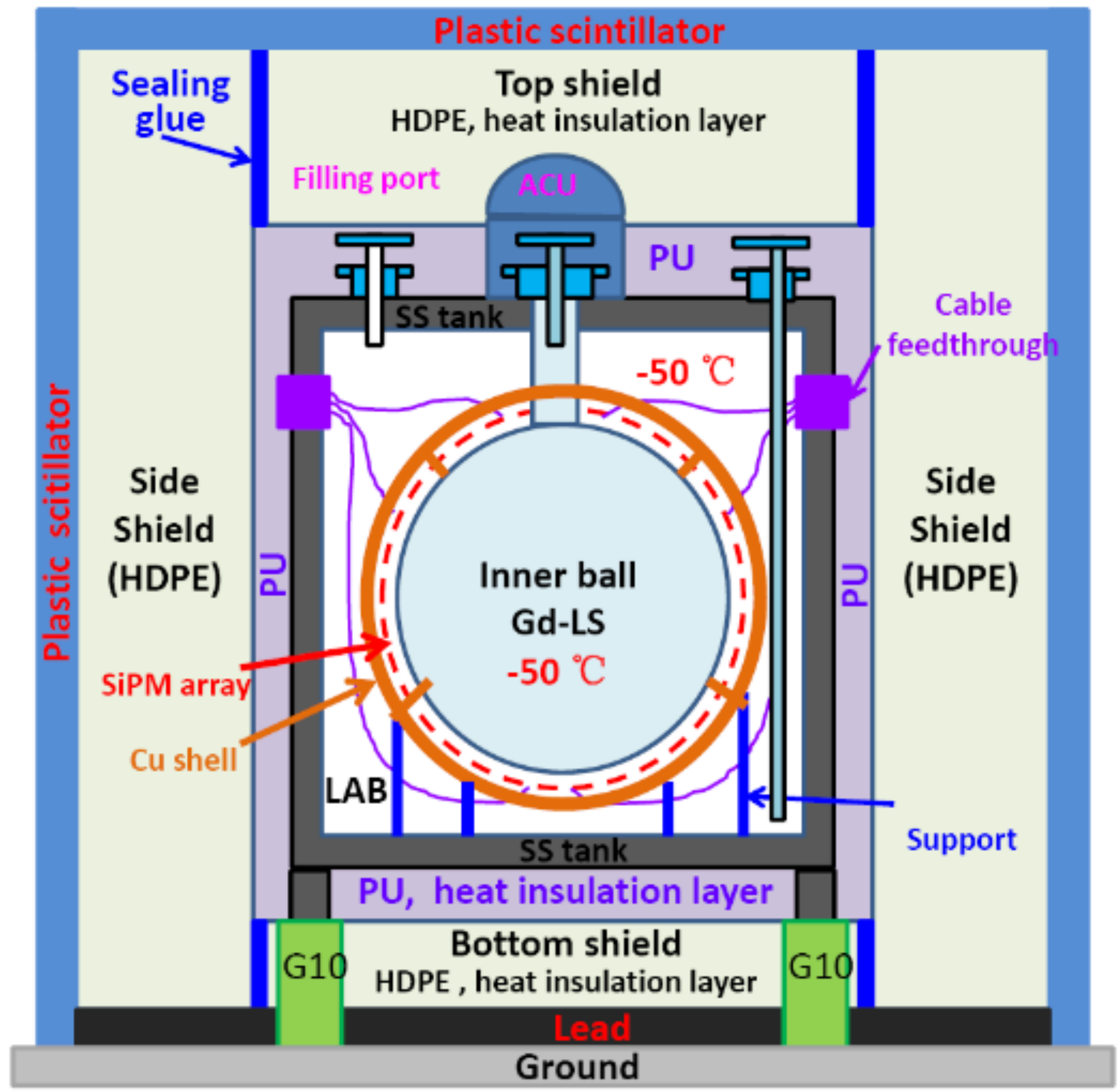


JUNO-TAO

- JUNO will also deploy a satellite detector called TAO (Taishan Antineutrino Observatory)
  - ~35 m from a 4.6 GW_{th} reactor
  - 1 ton fiducial Gd-LS volume
  - SiPM and Gd-LS at -50°C
  - < 2% @ 1 MeV energy resolution

Main goal: measure the reactor antineutrino spectrum with unprecedented resolution

- See fine structure due to Coulomb corrections
- Serve as benchmark for JUNO, other experiments, and nuclear databases
- Search for sterile neutrinos
- Study flux and shape change with fuel evolution & decompose isotope spectra
- Discover something?



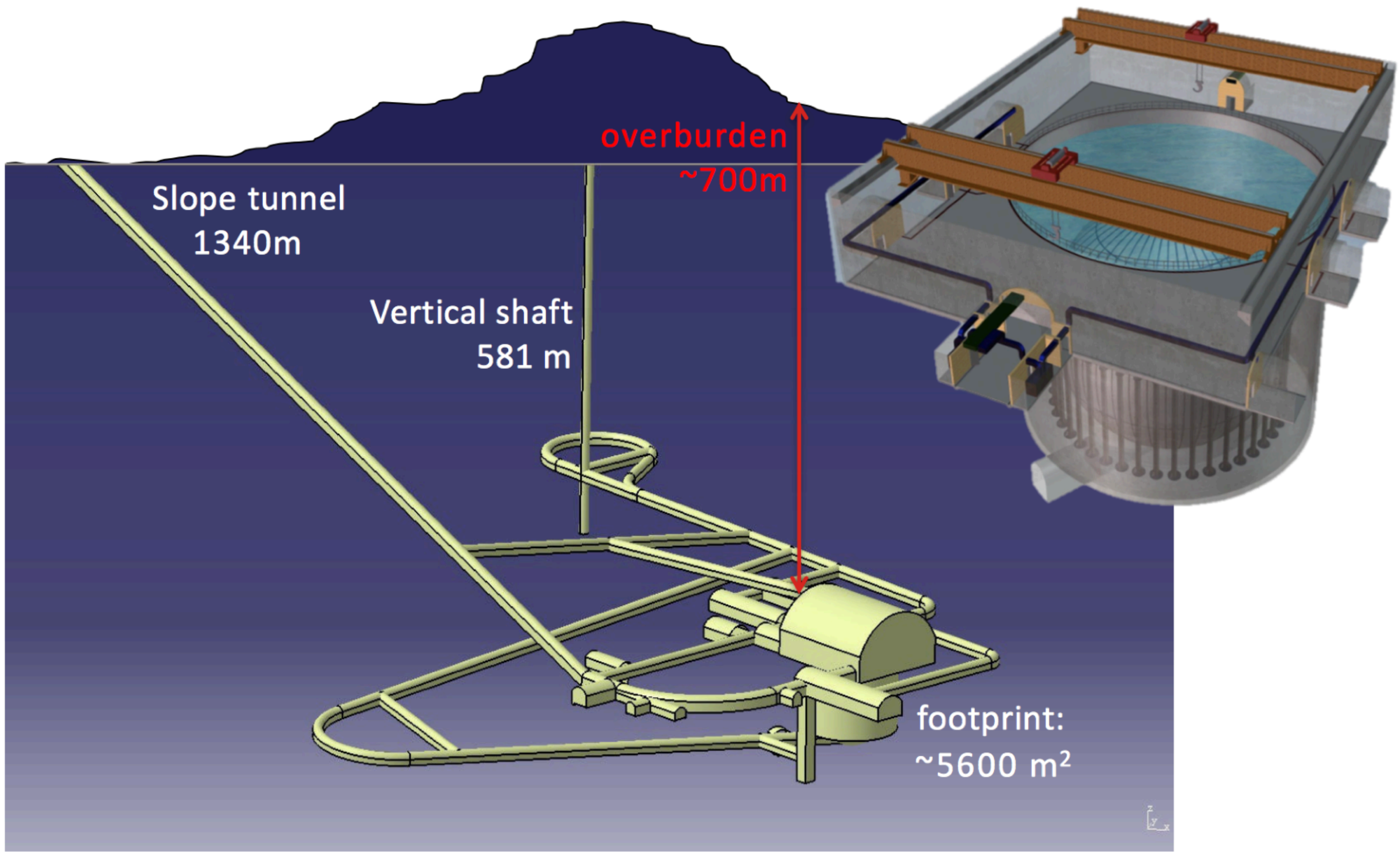
- R&D well underway and prototype under development

Civil Construction

- A new underground laboratory with a 700 m overburden and infrastructure at the surface is under construction since late 2014
- Expect to finish by summer 2020

Vertical shaft

Slope Tunnel



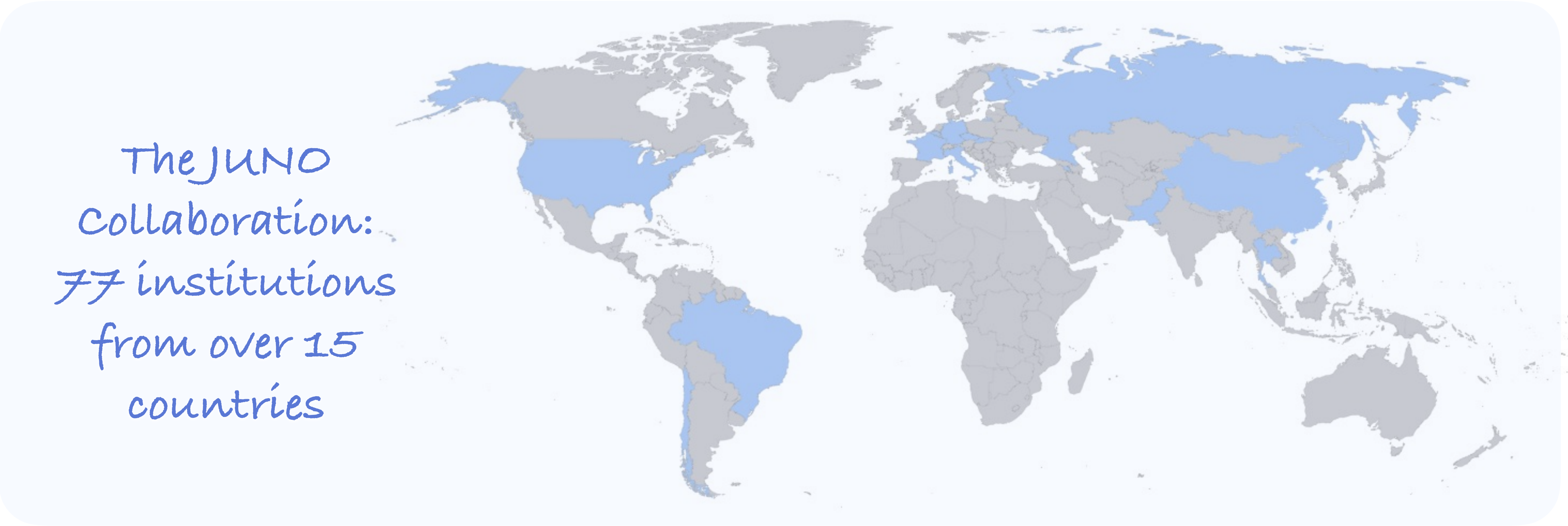
Timeline

- **2014** — Conceptual design completed. International collaboration established
- **2015** — Start of civil construction. Setup of PMT production line
- **2016** — Bidding of detector components
- **2017** — Start PMT mass production. Electronics prototypes delivered
- **2018** — PMT mass production & testing
- **2019** — Start PMT Potting
- **2020** — End of civil construction. Electronics mass production.
- **2021** — PMT Installation in central detector & veto. End of detector construction

Summary & Conclusions

- JUNO is a multipurpose neutrino observatory with a rich program in neutrino physics and astrophysics
  - Neutrino mass ordering, oscillation parameters, supernova ν's, solar ν's, atmospheric ν's, geo-ν's, proton decay, and others.
- JUNO is pushing the limits in liquid scintillator detection technology
  - New solutions in terms of PMT technology, liquid scintillator properties and detector construction
  - Developing some unique approaches to calibration and to the reduction of systematic uncertainties
- Progress is well underway, and expect to complete the construction of the detector by 2021
- Anticipate some exciting results (and maybe some surprises?)

Stay tuned!



Thank you for your attention!