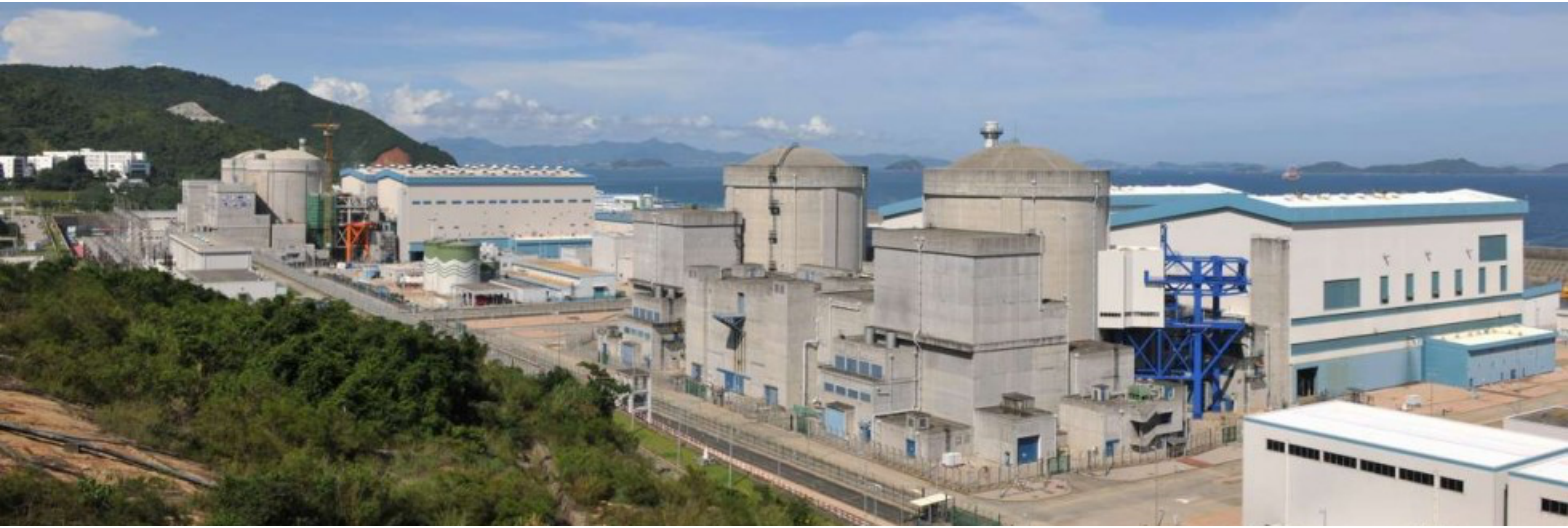
Design and Status of the JUNO Experiment



(Photo: Yangjiang NPP)

J. Pedro Ochoa Ricoux*
Pontificia Universidad Católica de Chile
**on behalf of the JUNO Collaboration*

NuFact
Uppsala, September 2017

Outline

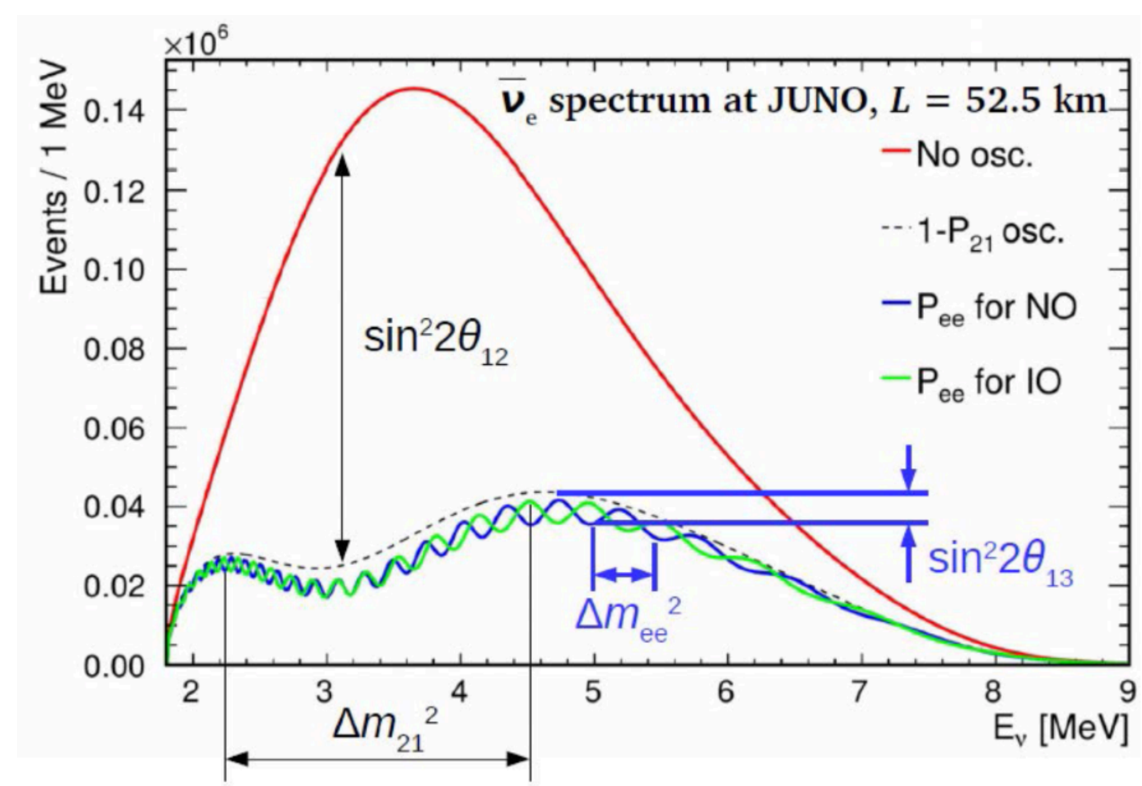
- Introduction
- Main features of JUNO
  - Location, concept and resolution
- Subsystems of JUNO
  - Large PMT system
  - Liquid scintillator
  - Calibration system
  - Small PMT system
  - Muon veto system
  - Civil construction
- Timeline
- Summary & Conclusions

Introduction

- The **J**iangmen **U**nderground **N**eutrino **O**bservatory (JUNO) is a multipurpose experiment under construction in China:
  - Rich physics program: neutrino mass hierarchy, sub-% measurement of oscillation parameters, astrophysical neutrinos, geo-neutrinos, atmospheric neutrinos, search for exotic physics… etc.

(See previous talk from B. Clervaux talk for details on JUNO's physics goals)

- Main keys to accomplishing the physics goals:
  - **Optimal baseline**
  - **High statistics**
  - **Superb energy resolution (3% @ 1 MeV)**
  - **Excellent control of energy response systematics**
  - **Background reduction**

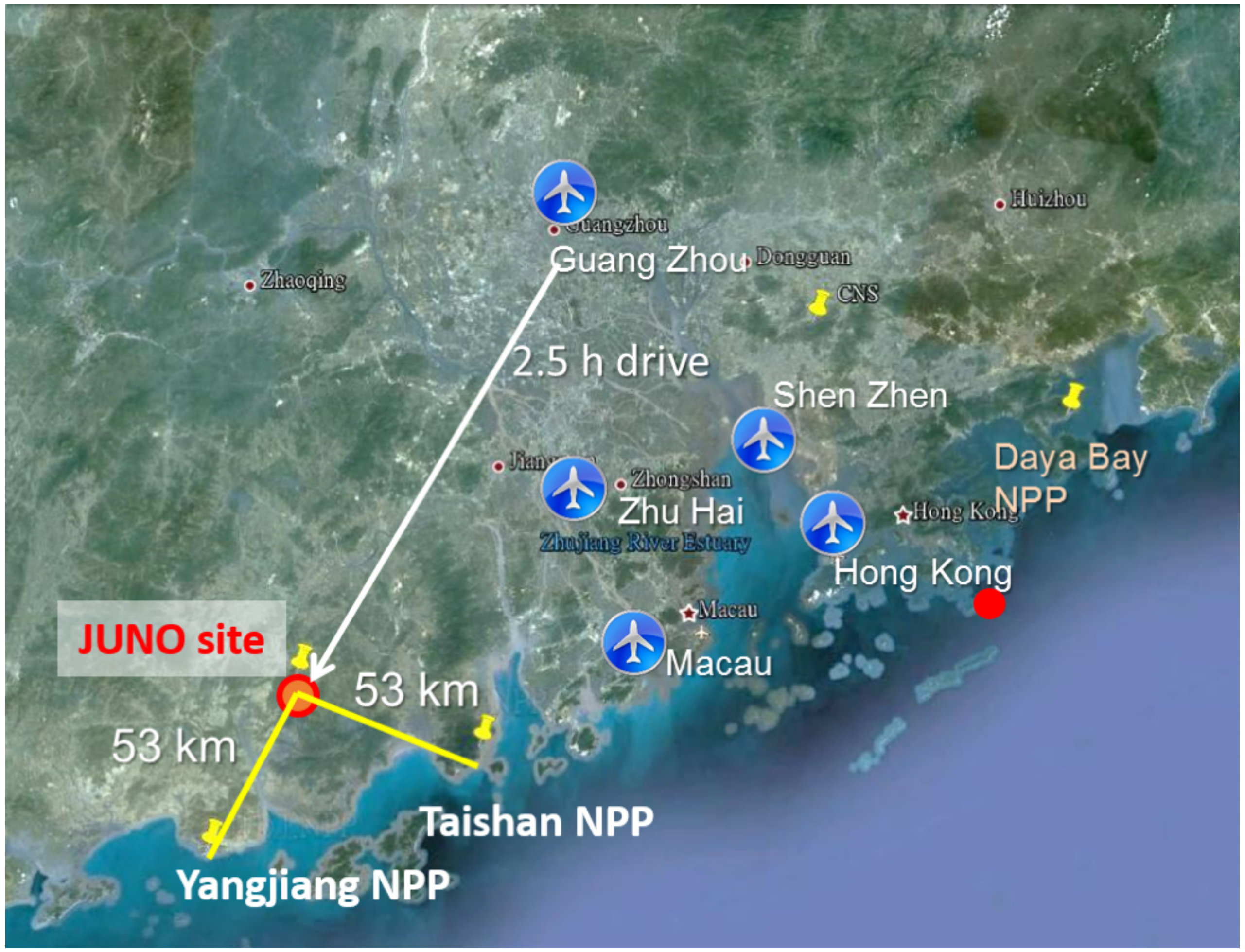


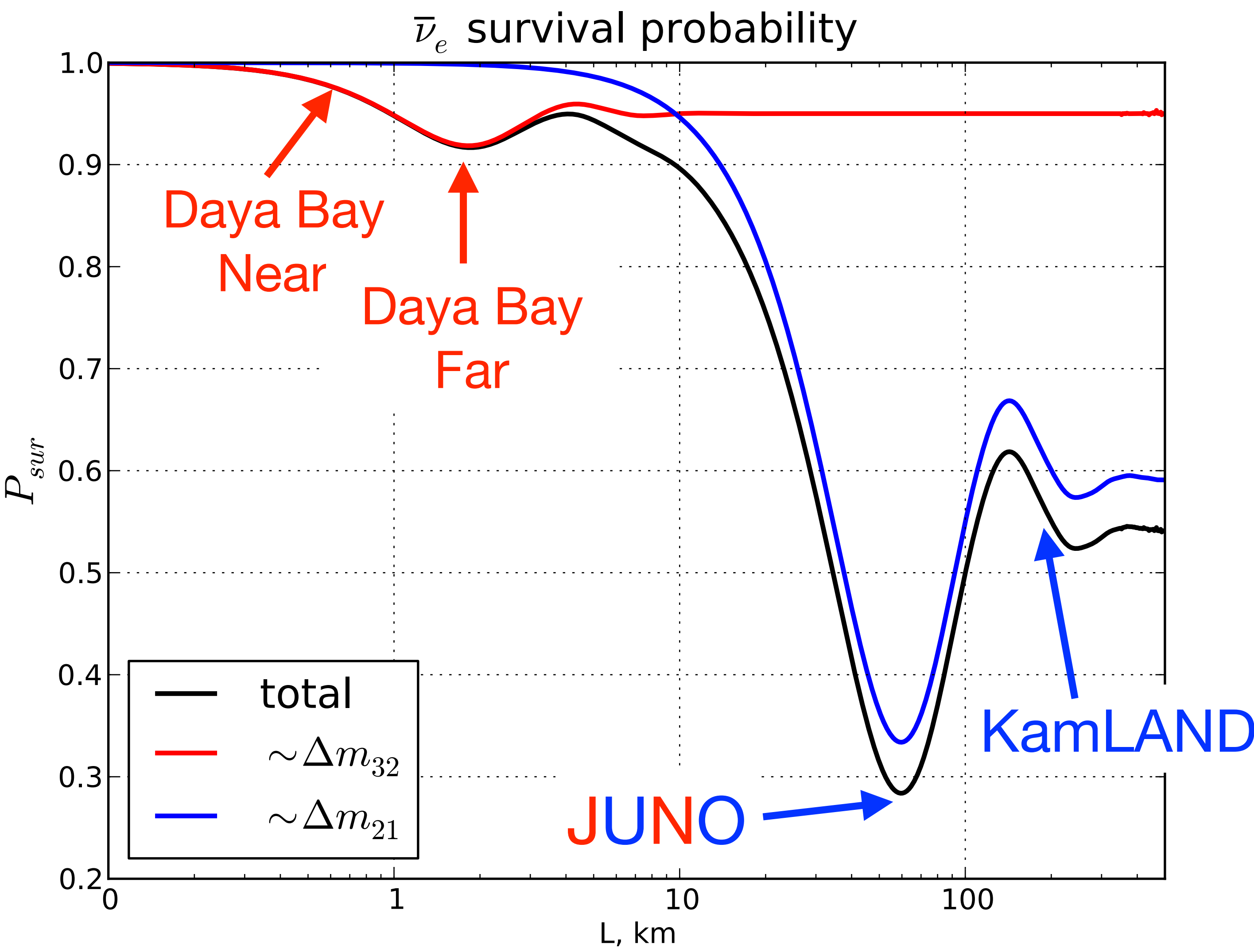
This talk describes how all these are addressed in JUNO's design, as well as the status

A strategic location

- JUNO will be located very near the optimal position for distinguishing between the mass hierarchies: the solar oscillation maximum (~53 km)

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



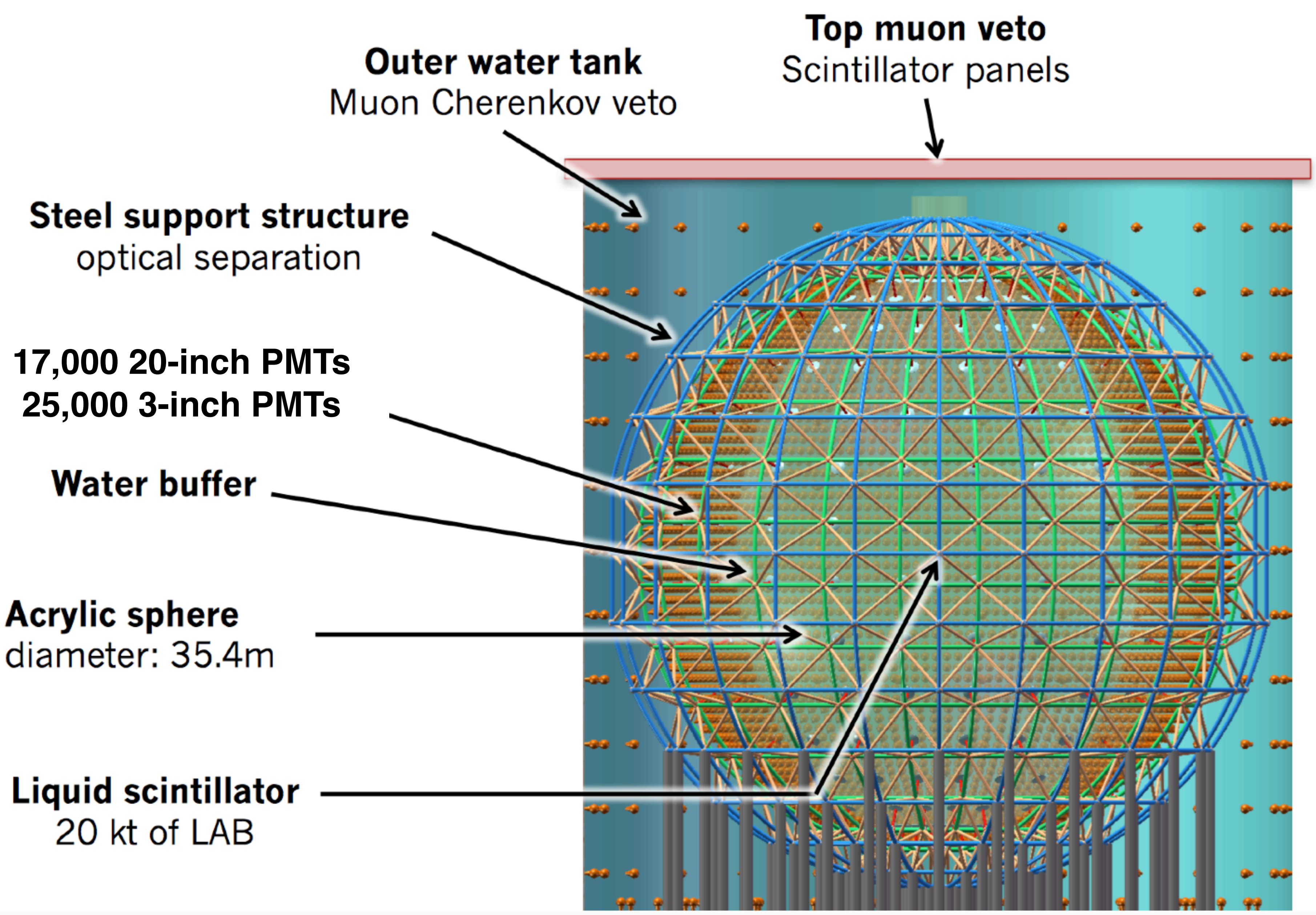


- The chosen location is equidistant from two major nuclear power plants (10 reactors) that provide a high flux of antineutrinos

Size and Concept

- Given these constraints (the larger baseline and the physics goals) the detector will have to be extremely large:

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



Similar in concept to previous LS experiments, but much LARGER

In fact, JUNO will be the largest liquid scintillator (LS) detector so far in history!

Energy resolution

- With 3% @ 1 MeV, JUNO will also be the LS detector with the best energy resolution in history

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

stochastic term: depends on photostatistics

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

- 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 / R	15/16 m	25/35 m	~0.8
PMT QE×CE	20%×60% ~ 12%	~30%	~2

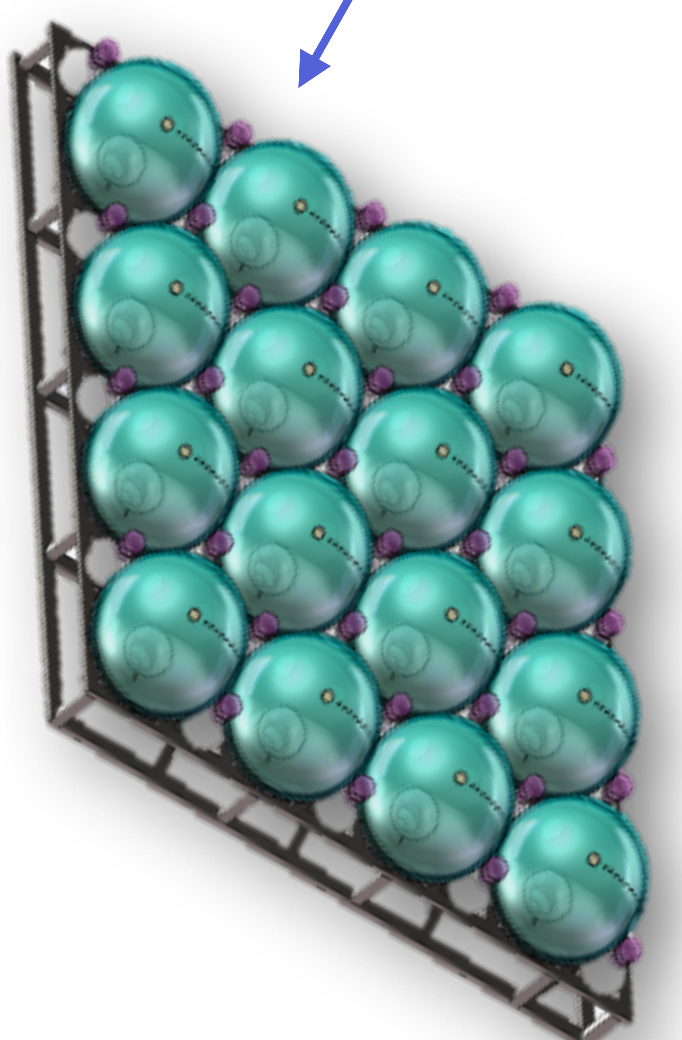
use KamLAND as reference

goal

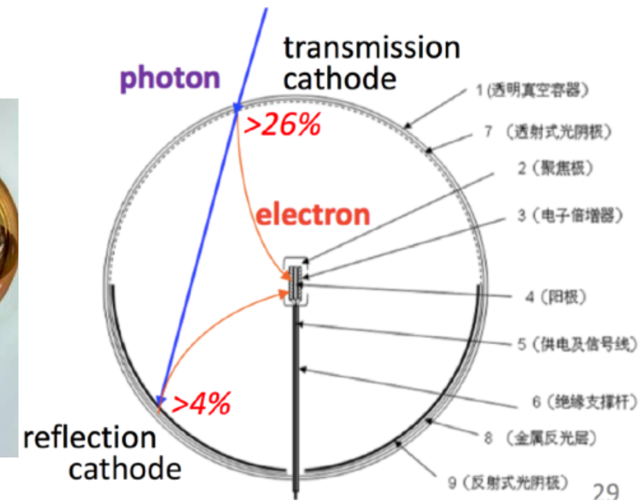
Large PMT system

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

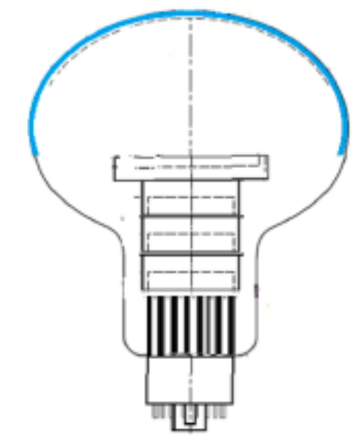
Arranged as tightly as possible, with a photocathode coverage of ~75%



2 complementary (and new!) technologies:



Microchannel plate (MCP)-PMTs



Dynode-PMTs

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

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

Both reach QE x CE ~ 30%!

JUNO has already signed a contract for 15,000 MCP-PMTs and 5,000 Dynode-PMTs

Large PMT system

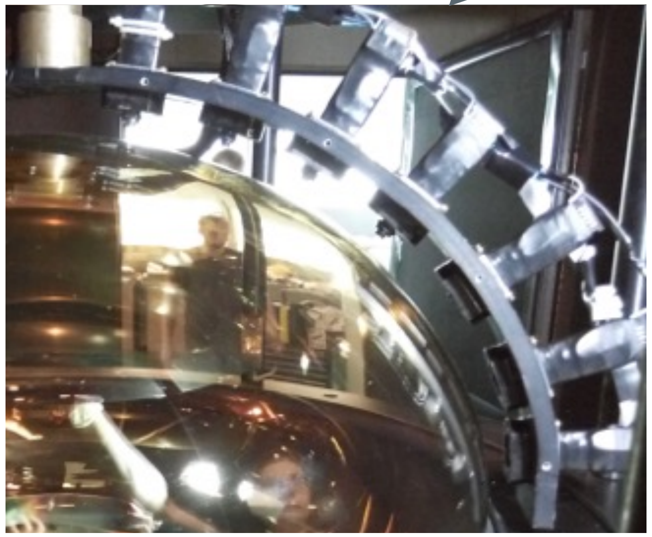
- We have already received > 3,000 PMTs:

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

Almost ready to begin acceptance & characterization tests in full production mode

Industrial container mass testing system

Photocathode uniformity scanning system

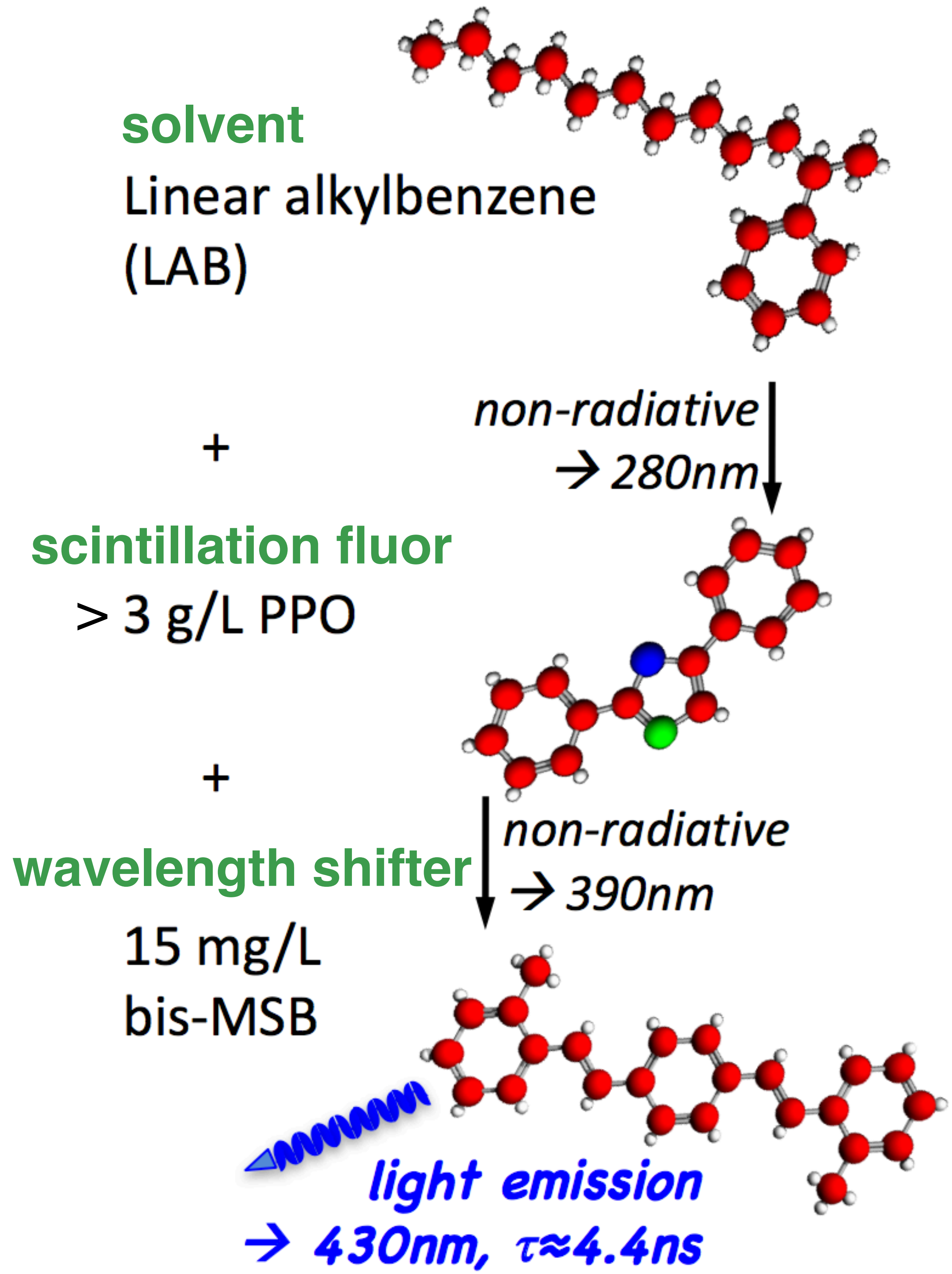


Scanning stations

An industrial process!

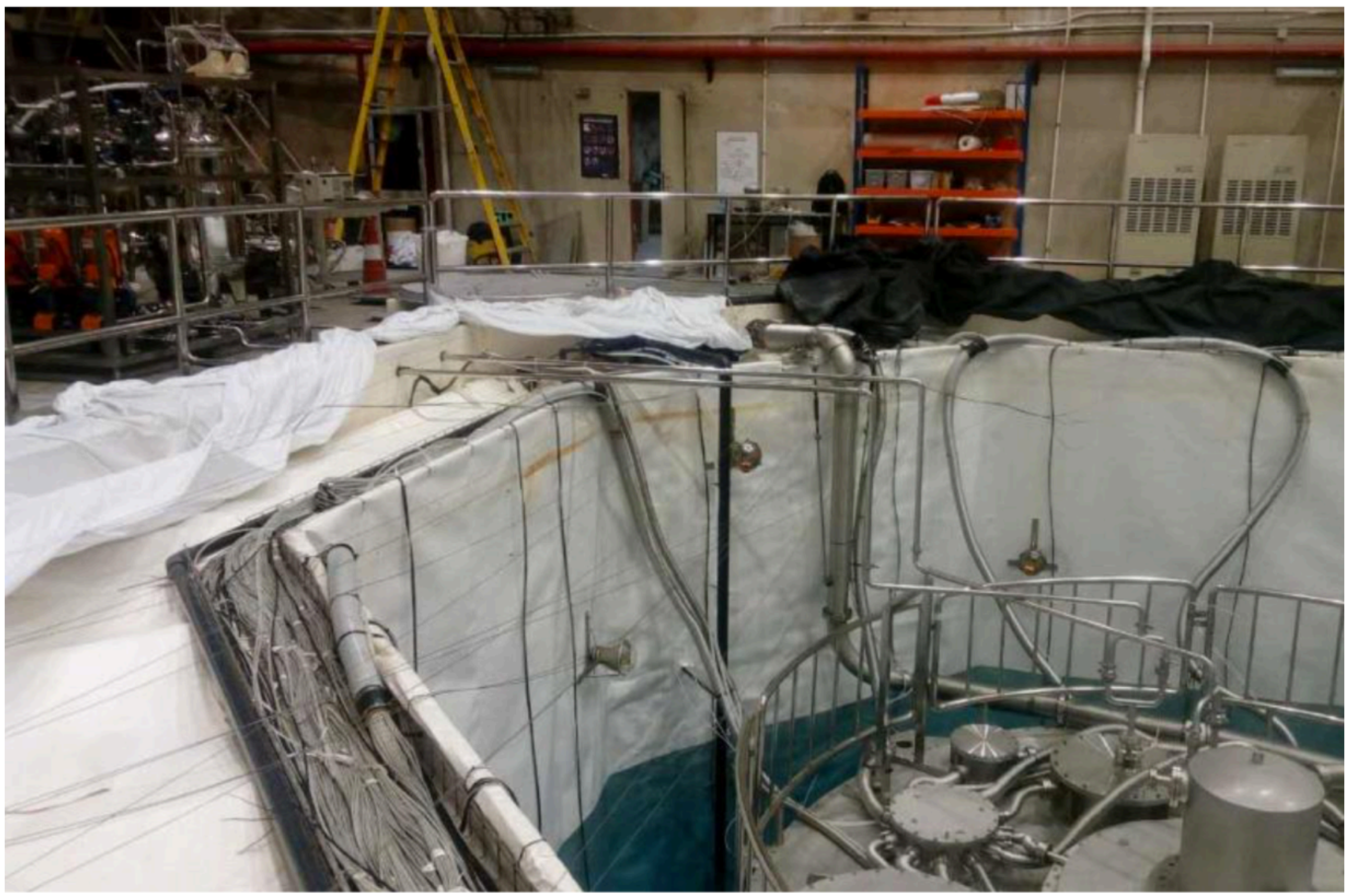
Liquid Scintillator

- Using a recipe inspired from Daya Bay's experience
- Requirements:
  - Light transport over 20 m:
    - LAB is very transparent
    - No doping
    - Al_2O_3 column purification
  - High light-yield:
    - Pure LAB, no addition of paraffins
    - Large fluor (PPO) concentration
  - Good radiopurity:
    - $< 10^{-15}$ g/g in U/Th
    - $< 10^{-16}$ g/g in K
    - Vacuum distillation



LS Replacement in Daya Bay

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

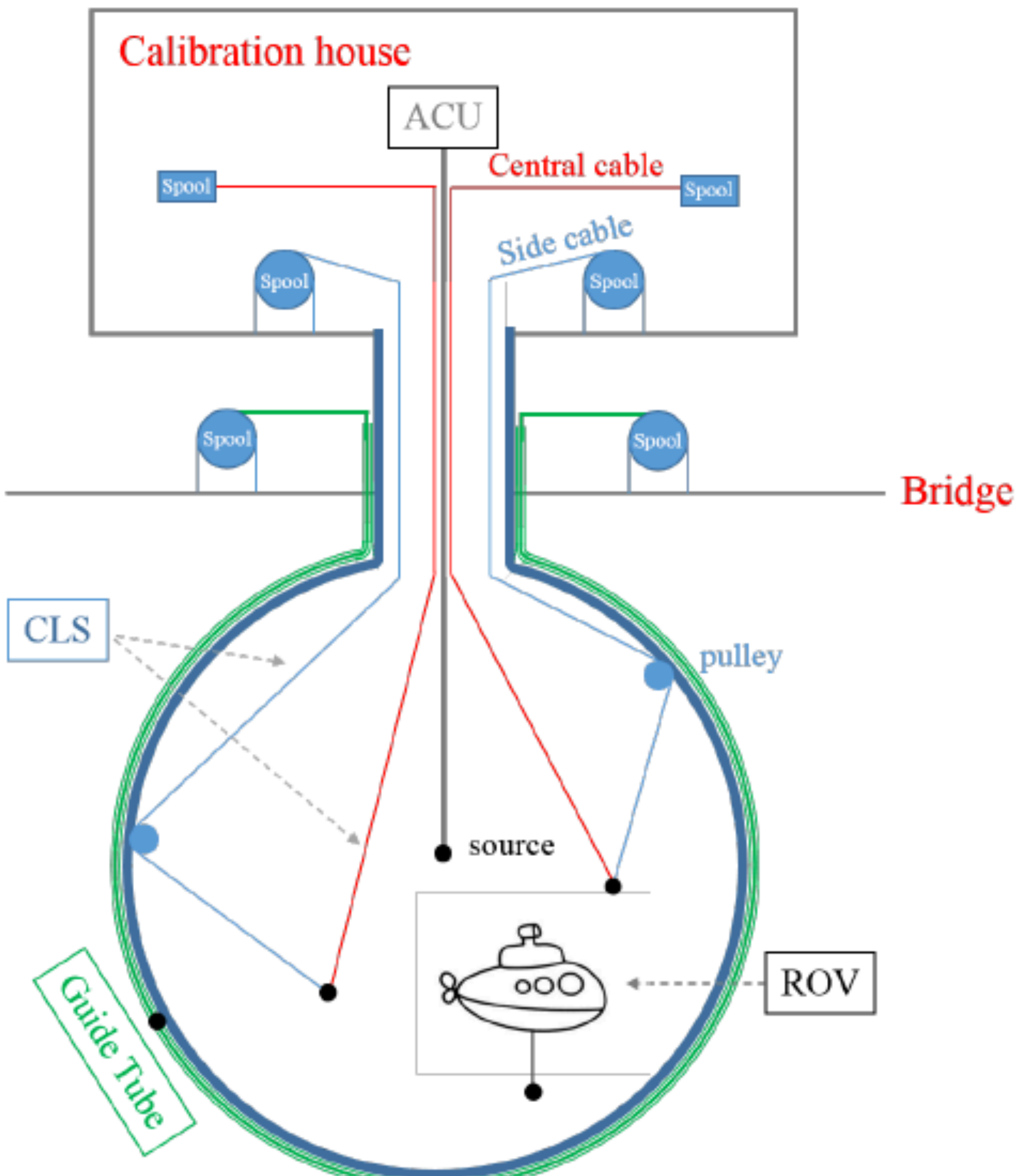


- This has been an **invaluable experience**:
  - Studied properties of LS for different recipes (different concentrations of PPO and bis-MSB) and benchmarked simulation
  - Evaluated performance of purification methods
  - Gained much practical experience (air leakage, radon in water)
  - Tested complementary calibration techniques, such as dissolving ^{40}K

Studies are still ongoing, and a **publication is expected in the near future**

Calibration

- Needless to say, 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 sources along the central axis
  - **2D**: Cable Loop System (CLS) to scan vertical planes
  - **2D**: Guide Tube Calibration System (GTCS) 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

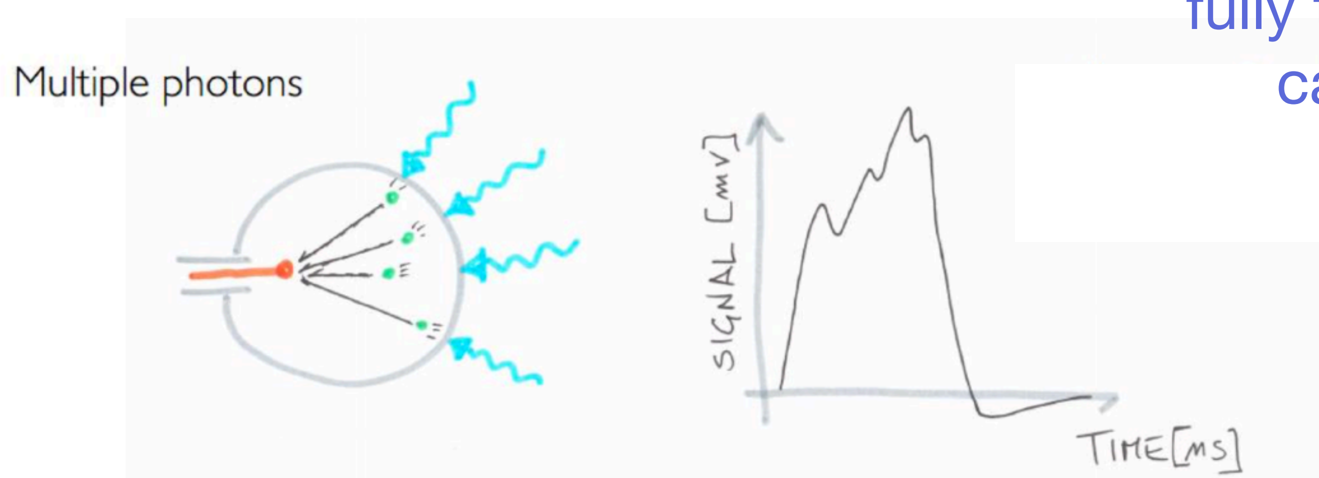
- JUNO will also have to control the non-stochastic term of the resolution at an unprecedented level (≲1%)

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

< 1% never achieved before!

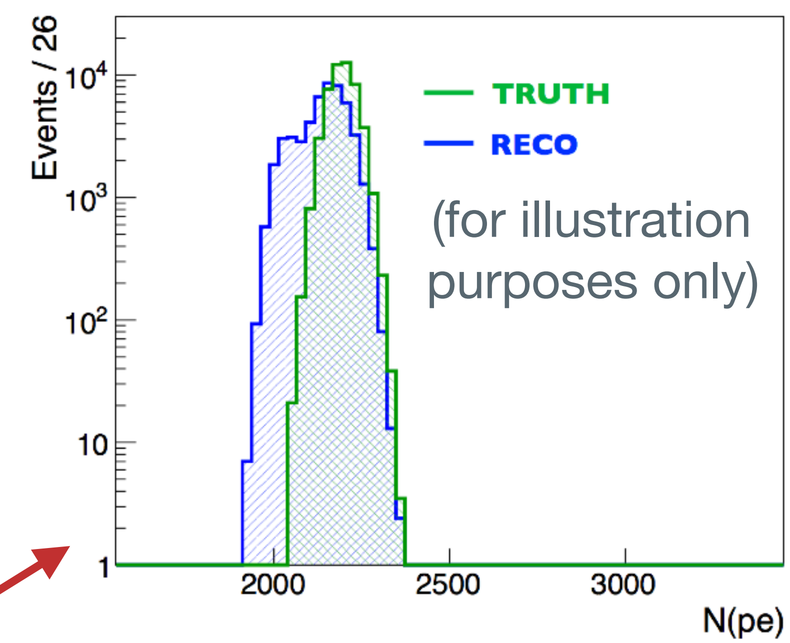
Example of how residual systematics could affect JUNO:

1) Charge extraction with the large PMTs is non-trivial and can lead to systematics (e.g. non-linearity)



2) The non-linearities in the charge reconstruction can introduce an artificial non-uniformity

3) This effect is energy dependent and thus cannot be fully taken out with calibrations.



Example: trying to reconstruct 2.2 MeV events with a non-uniformity map derived with 1 MeV events [assuming 1% charge non-linearity]

(For more details see M. Grassi's talk on double-calorimetry at WIN 2017)

- Solution: place 25,000 small 3-inch PMTs placed in the space between the large ones (double-calorimetry)

Small PMT System

- The small PMTs operate predominantly in photon-counting mode and thus serve as a reference against which to calibrate the large ones.

Basic principle: look at the same events with another set of "eyes" having different systematics.

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

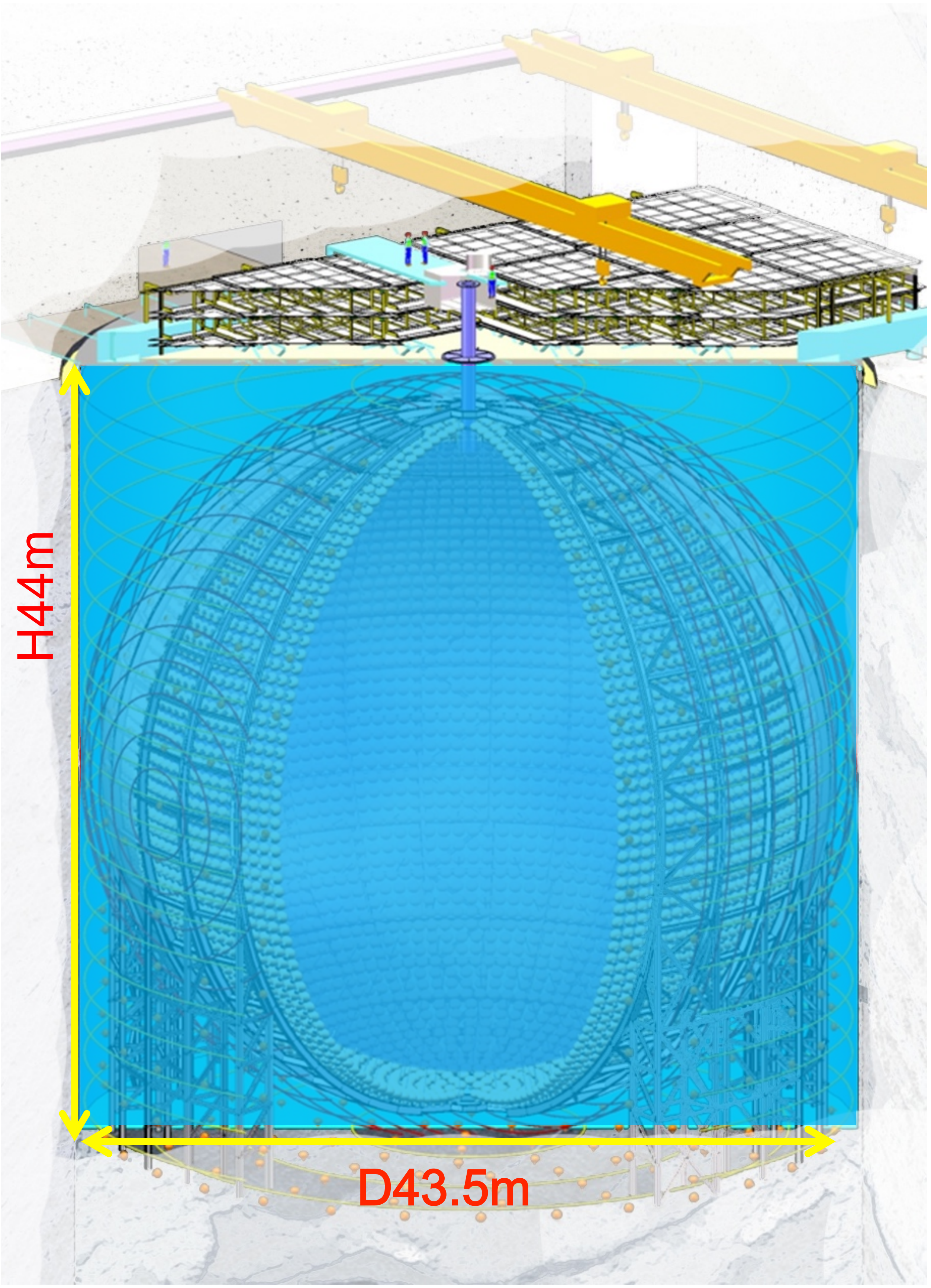
HZC PHOTONICS

XP72B22

A custom design for JUNO!

- A contract has been signed with the HZC-Photonics for the production of 25,000 small PMTs.
  - Production is expected to start early 2018

Muon Veto System

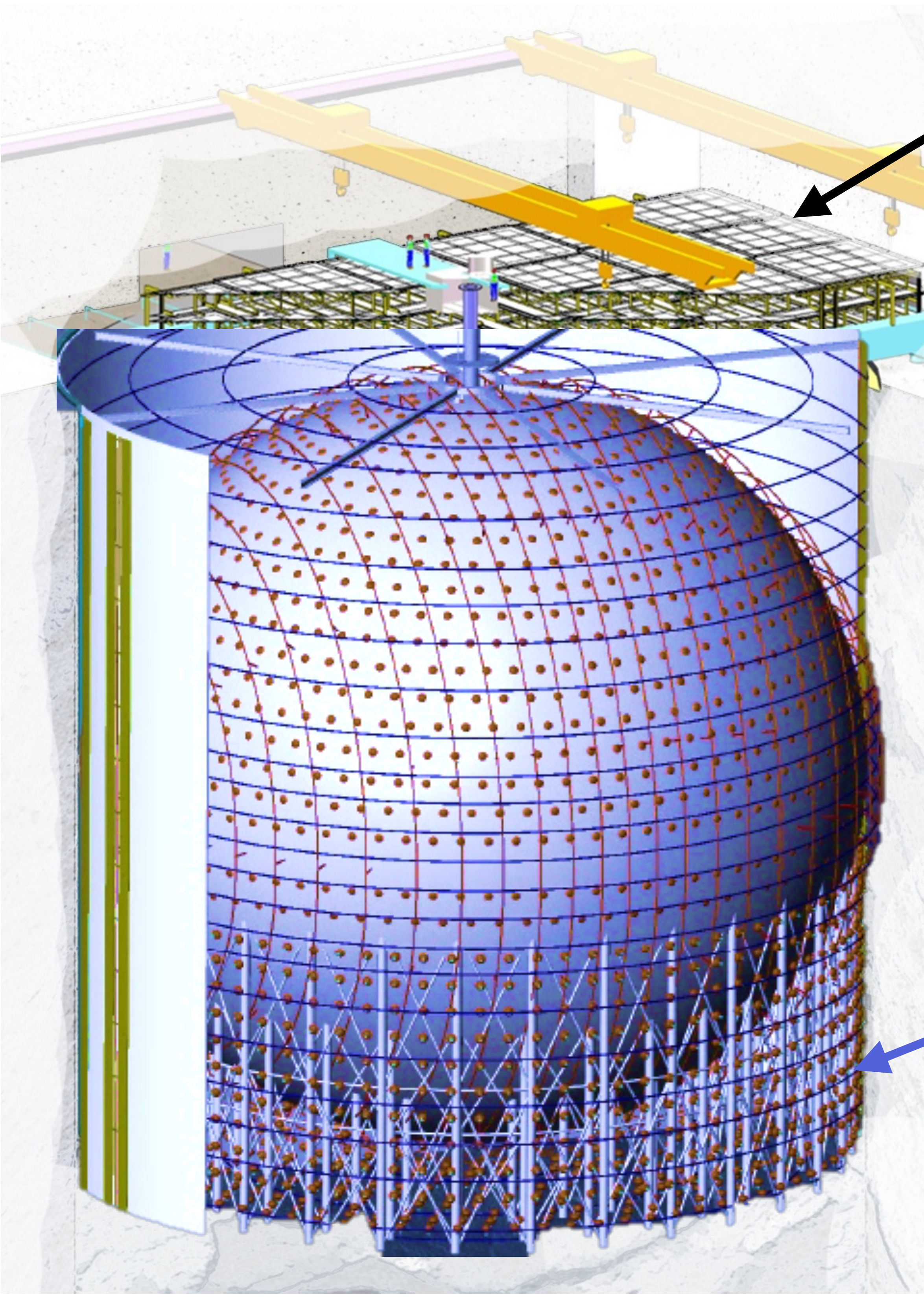


- It is also important to reduce the backgrounds as much as possible.
- The 35 m diameter LS acrylic sphere will be immersed in a cylindrical instrumented water pool:
  - 35 kton ultrapure water with a circulation system

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)

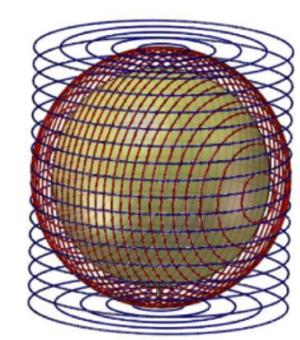
- Some details about the muon veto:
  - About 2,000 20-inch PMTs
  - Detection efficiency expected to be > 95%

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
  - Already have a prototype giving results in agreement with calculations

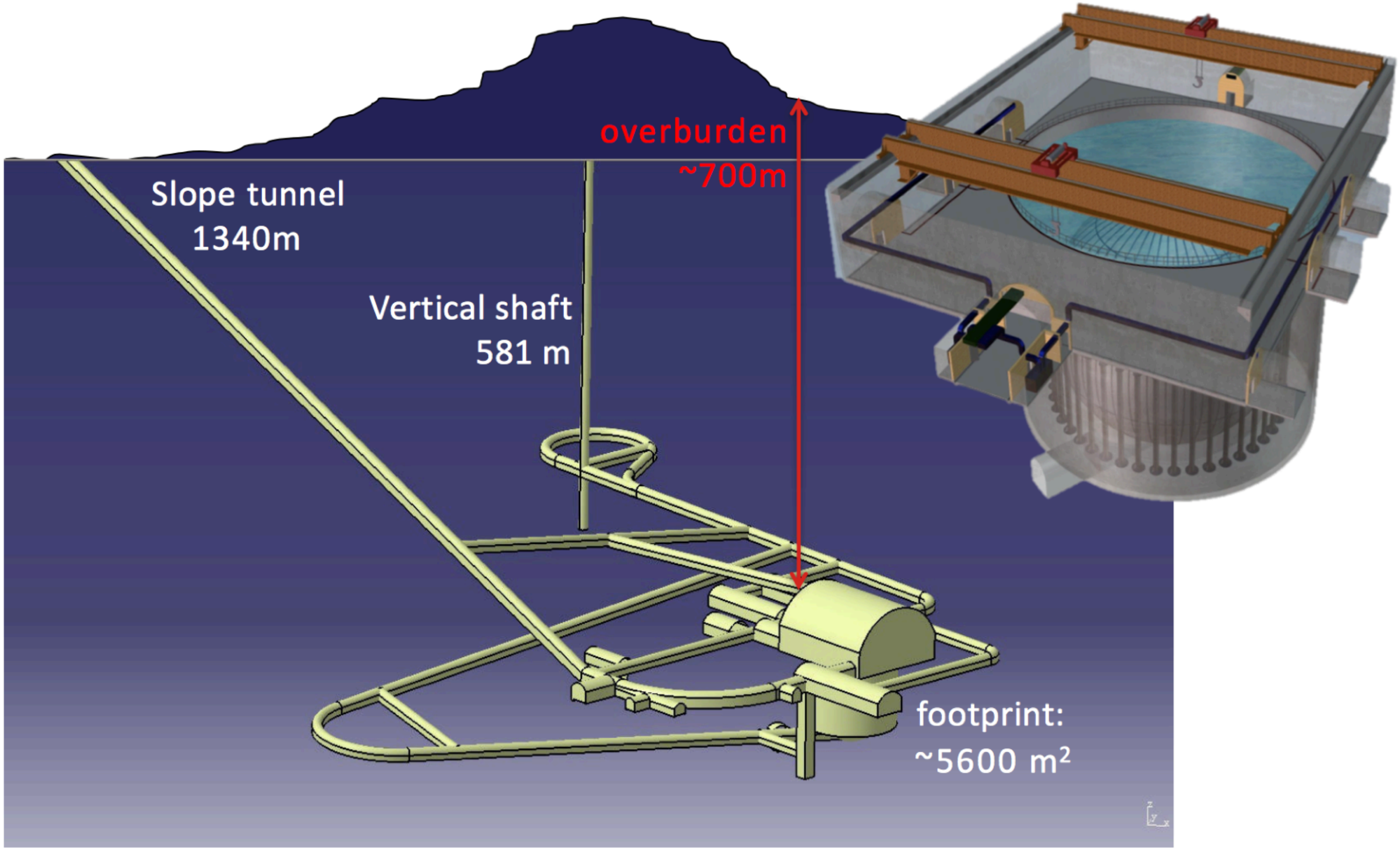


Civil Construction

- A new underground laboratory with a 700 m overburden has to be constructed (with infrastructure at the surface)
- The civil construction started in 2014 and is well underway

Vertical shaft completed!

Slope Tunnel completed!



Timeline

2013: Complete conceptual design. Complete civil design and bidding

2014: Start civil construction. Complete prototyping (PMT & detector). International collaboration established

2015: PMT production line manufacturing

2016: Start PMT production. Start detector production or bidding

2017: Complete civil construction. Start detector construction and assembly

2018: Start LS production

2019: Complete detector assembly, installation and LS filling

2020: Start data taking

Then run for > 2 decades

Summary & Conclusions

- JUNO is a next generation experiment with a rich program in neutrino physics and astrophysics
- JUNO will push the limits in liquid scintillator detection technology
  - Its unprecedented size and energy resolution will require some new solutions in terms of PMT technology, liquid scintillator properties and detector construction
  - JUNO is also developing some unique approaches to calibration and to the reduction of the non-stochastic term of the resolution (double-calorimetry)
- Progress is well underway, and expect to begin running by 2020
- Anticipate some exciting results (and maybe some surprises?)

Stay tuned!

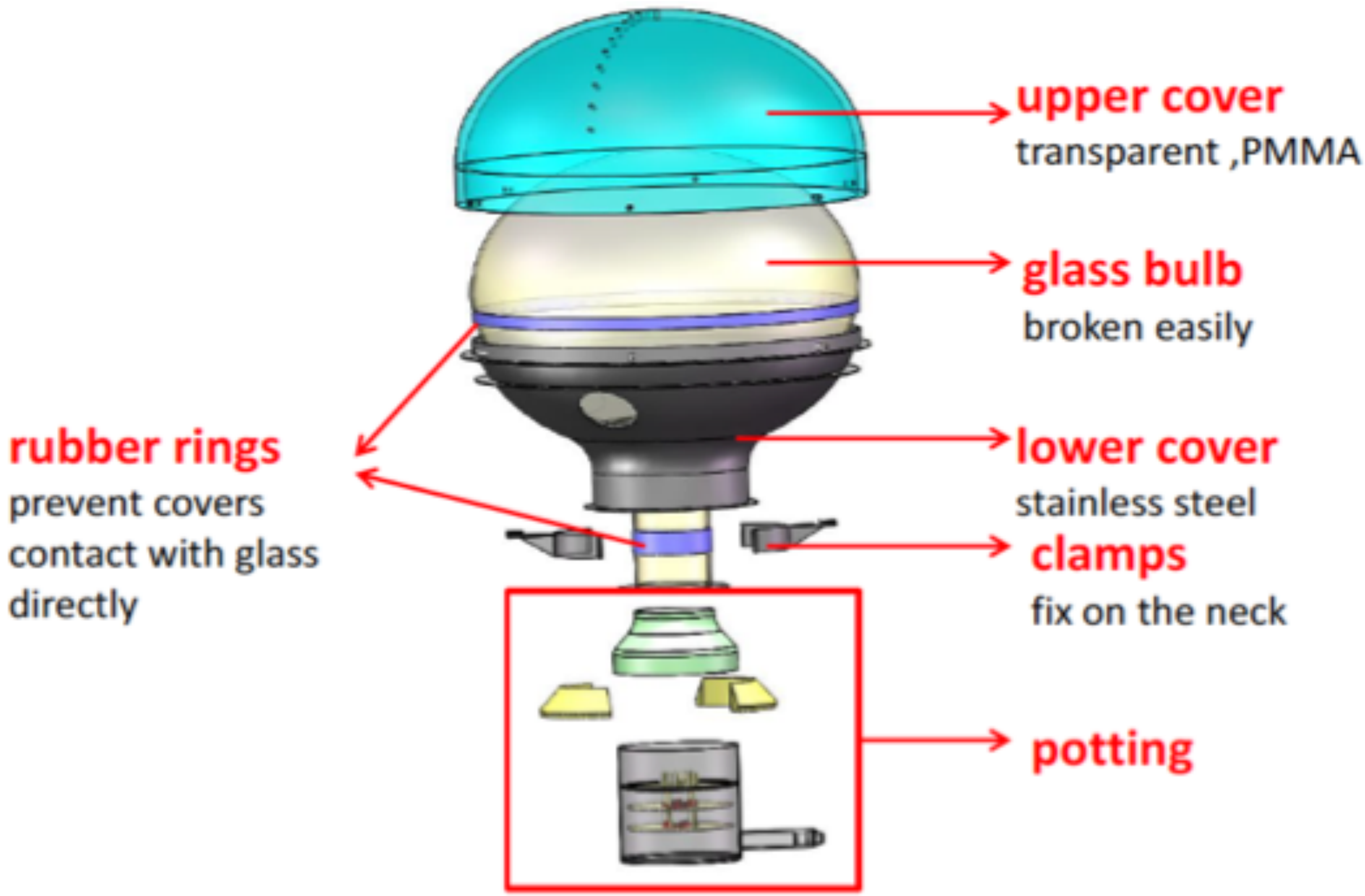
JUNO

(Photo: Taishan NPP)

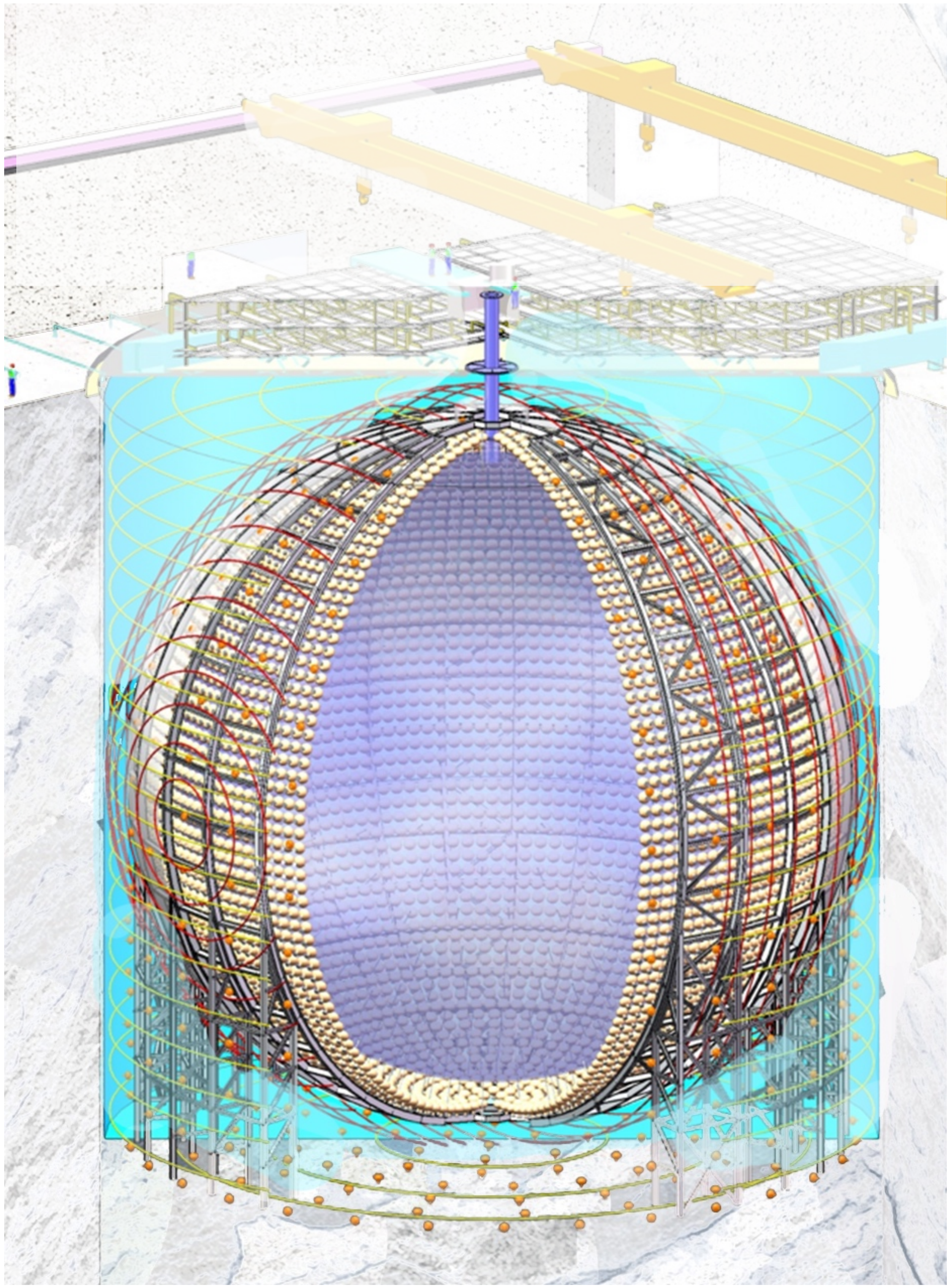
Thank you for your attention!

Backup

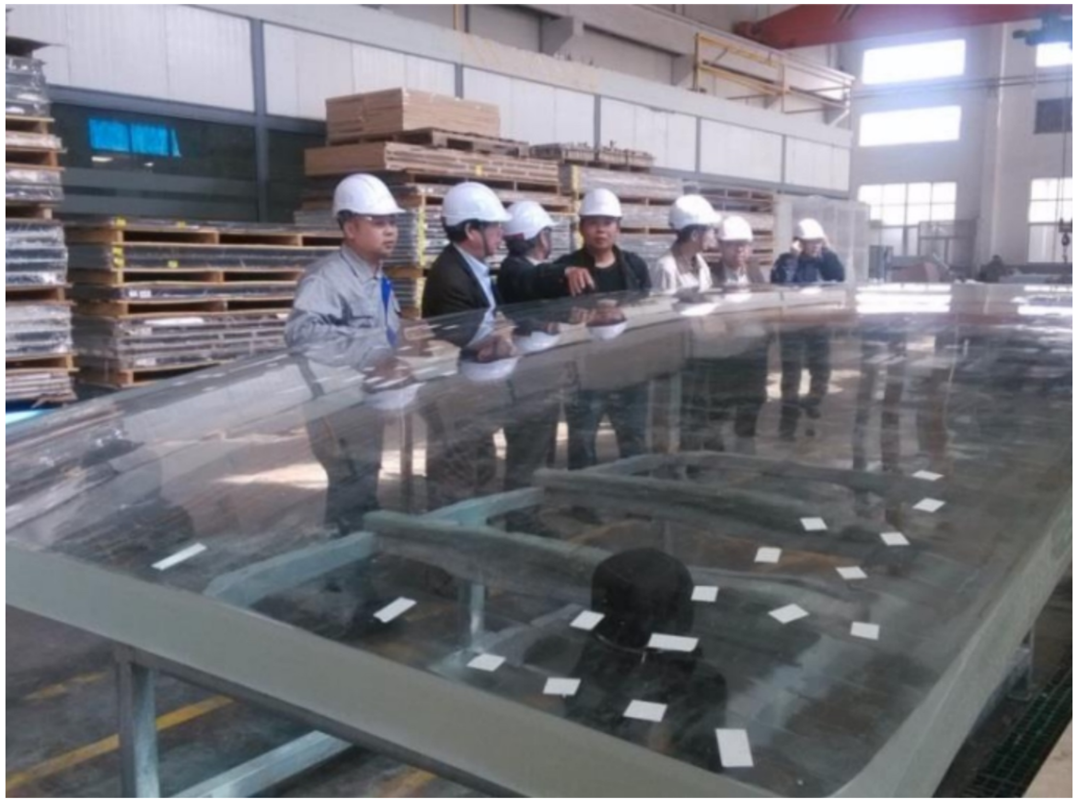
Large PMT Implosion Protection



Central Detector



- The central detector will be built from acrylic panels:
  - Aprox. 260 panels with 12cm thickness



  - Total weight: ~600t of acrylic and ~600t of steel