Status and perspectives of the JUNO experiment

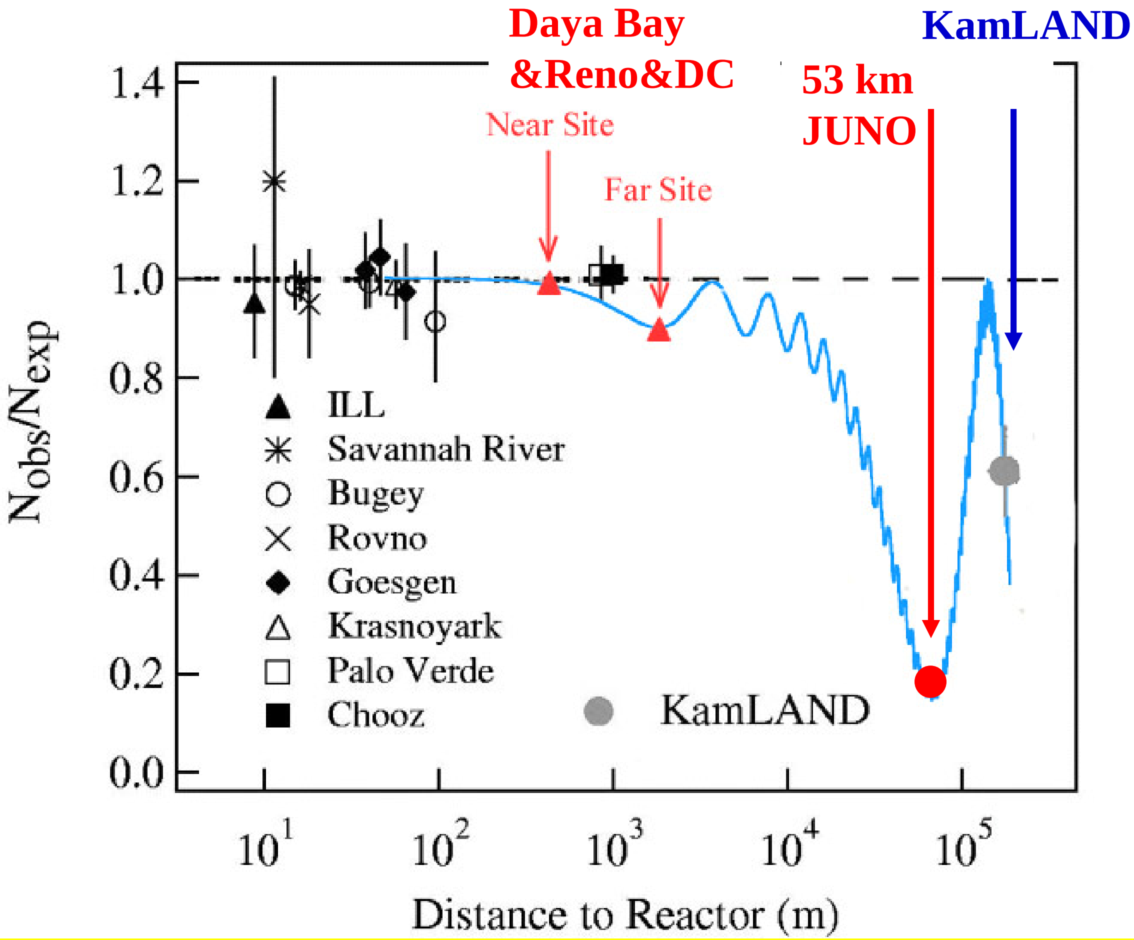
Gioacchino Ranucci
INFN – Milano

On behalf of the JUNO Collaboration

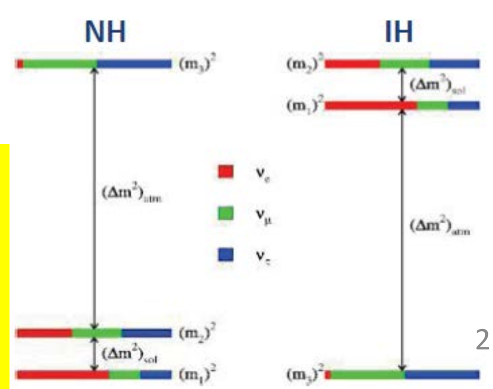
Catania
Conference on Neutrino and Nuclear Physics
October 17, 2017

- Determination of the neutrino mass hierarchy with a large mass liquid scintillation detector located at medium distance – few tens of km – from a set of high power nuclear reactors
- Precise measurements of oscillation parameters
- Additional astroparticle program
- Requirements, technical features and status of the experiment

JUNO physics summary



- **20 kton LS detector**
- **~3 % energy resolution-the greatest challenge**
- Rich physics possibilities
  - ⇨ **Mass hierarchy**
  - ⇨ **Precision measurement of 3 mixing parameters**
  - ⇨ **Supernovae neutrino**
  - ⇨ **Geoneutrino**
  - ⇨ **Sterile neutrino**
  - ⇨ **Atmospheric neutrinos**
  - ⇨ **Nucleon Decay**
  - ⇨ **Exotic searches**



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

The tension between the solar and KamLAND Δm^2 has further boosted the importance of the precision Δm^2_{21} measurement

A large LS spherical detector

– LS large volume: ➔ for statistics

– High Light(PE) ➔ for energy resolution 1200 pe/MeV

Steel Truss

Holding PMTs

~20000 x 20”

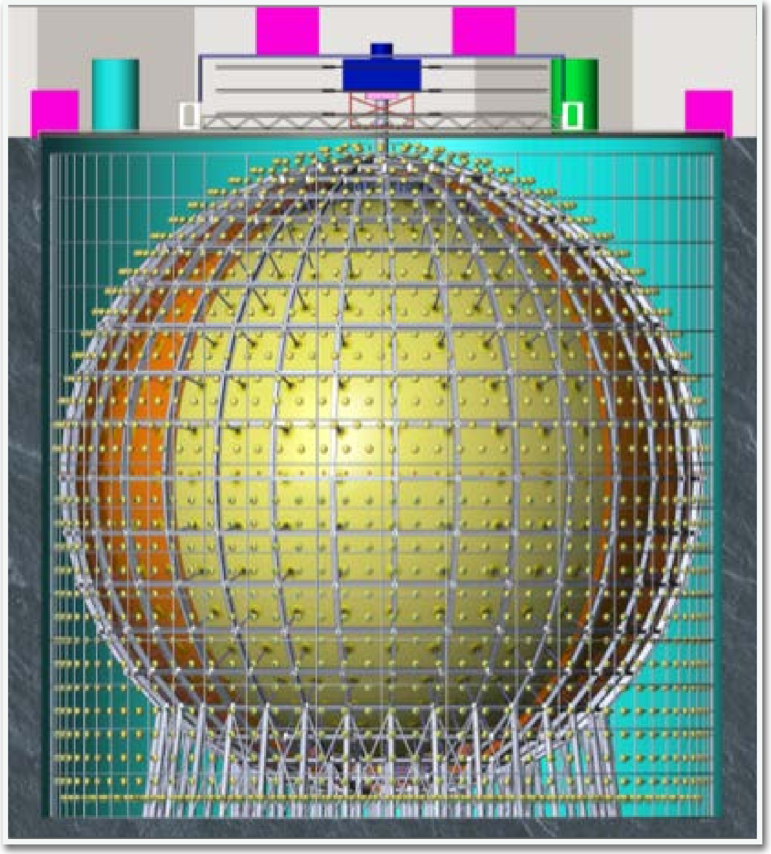
18000 Inner

2000 veto

~25000 x 3”

Acrylic Sphere

filled with 20 kt LS



JUNO has been approved in China in Feb. 2013

Prospective and approved funding from several other countries:

- **Belgium**
- **Czechia**
- **Finland**
- **France**
- **Germany**
- **Italy**
- **Russia**
- **Taiwan**
- **Chile**
- **Brasil**
- **Thailandia**
- **Pakistan**

Updated list of JUNO members

Country	Institute	Country	Institute	Country	Institute
Armenia	Yerevan Physics Institute	China	IMP-CAS	Germany	U. Mainz
Belgium	Universite libre de Bruxelles	China	SYSU	Germany	U. Tuebingen
Brazil	PUC	China	Tsinghua U.	Italy	INFN Catania
Brazil	UEL	China	UCAS	Italy	INFN di Frascati
Chile	PCUC	China	USTC	Italy	INFN-Ferrara
Chile	UTFSM	China	U. of South China	Italy	INFN-Milano
China	BISEE	China	Wu Yi U.	Italy	INFN-Milano Bicocca
China	Beijing Normal U.	China	Wuhan U.	Italy	INFN-Padova
China	CAGS	China	Xi'an JT U.	Italy	INFN-Perugia
China	ChongQing University	China	Xiamen University	Italy	INFN-Roma 3
China	CIAE	China	NUDT	Latvia	IECS
China	DGUT	Czech Rep.	Charles U.	Pakistan	PINSTECH (PAEC)
China	ECUST	Finland	University of Oulu	Russia	INR Moscow
China	Guangxi U.	France	APC Paris	Russia	JINR
China	Harbin Institute of Technology	France	CENBG	Russia	MSU
China	IHEP	France	CPPM Marseille	Slovakia	FMPICU
China	Jilin U.	France	IPHC Strasbourg	Taiwan	National Chiao-Tung U.
China	Jinan U.	France	Subatech Nantes	Taiwan	National Taiwan U.
China	Nanjing U.	Germany	Forschungszentrum Julich ZEA2	Taiwan	National United U.
China	Nankai U.	Germany	RWTH Aachen U.	Thailand	NARIT
China	NCEPU	Germany	TUM	Thailand	PPRLCU
China	Pekin U.	Germany	U. Hamburg	Thailand	SUT
China	Shandong U.	Germany	IKP FZJ	USA	UMD1
China	Shanghai JT U.			USA	UMD2

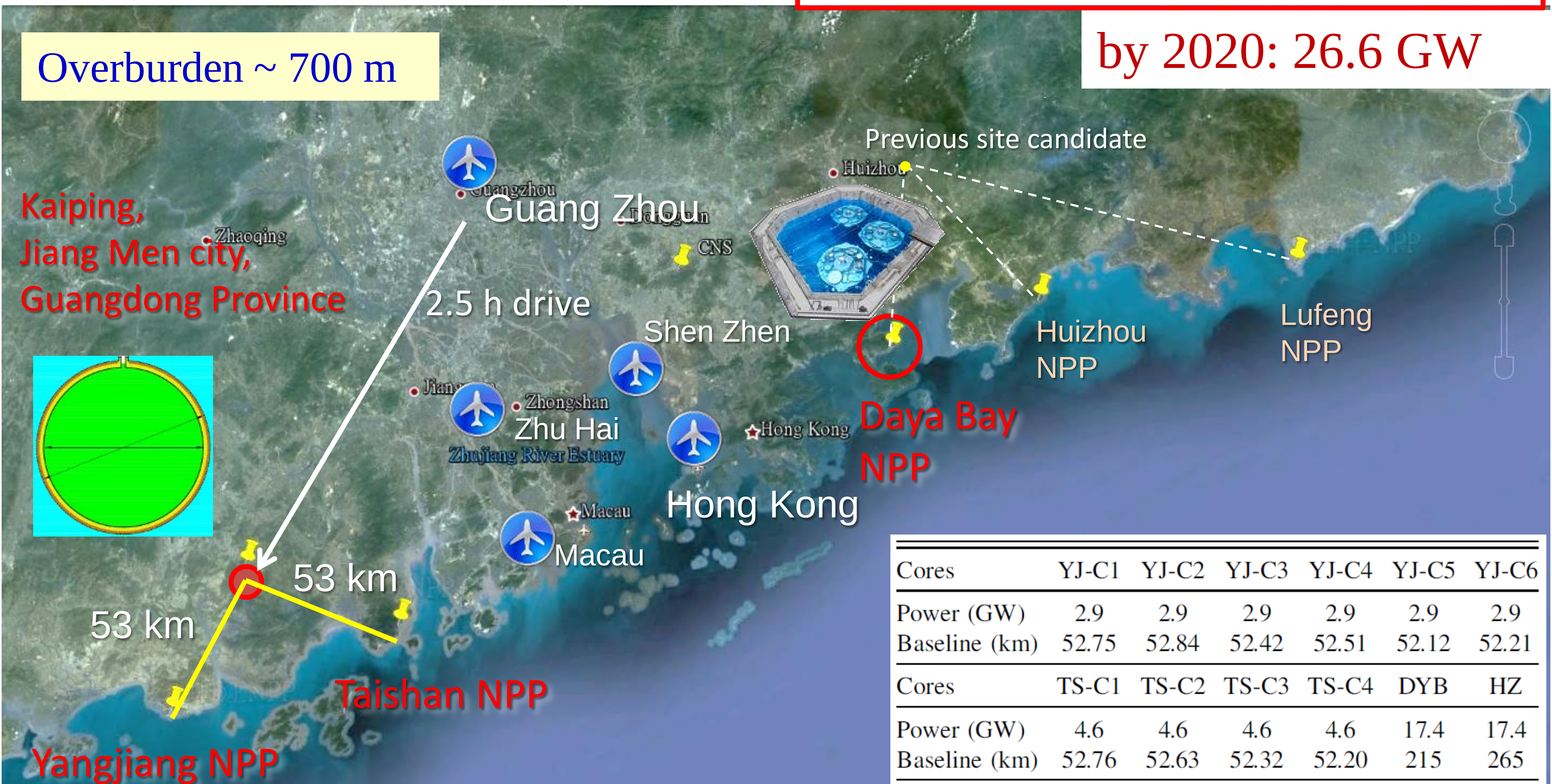
= 71 member Institutions

Observers:

1. Department of Physics, Jyvaskyla University, (Finland)
2. Department of Physics, University of Malaya (Kuala Lumpur)

Location of JUNO

NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW



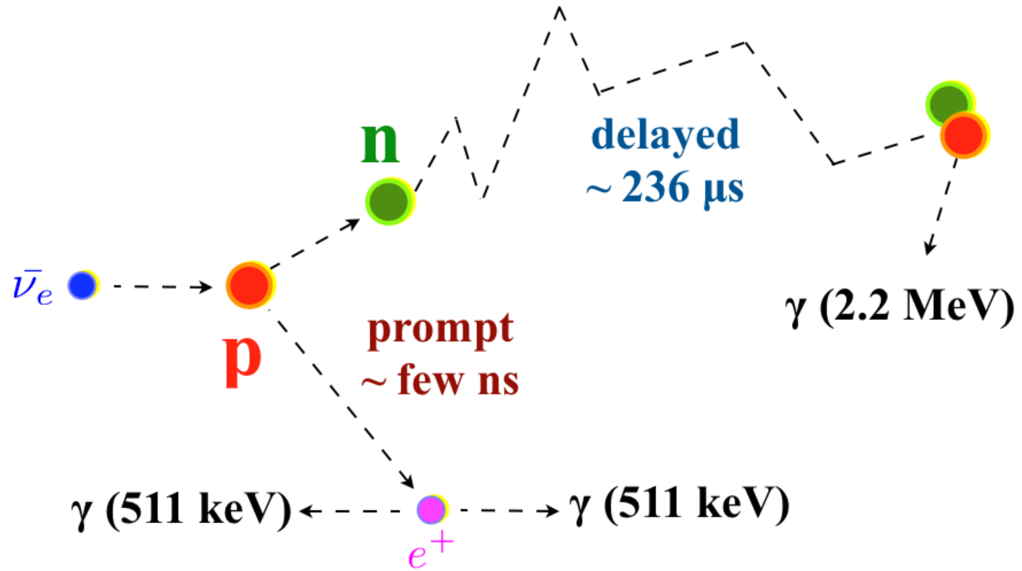
Cores	YJ-C1	YJ-C2	YJ-C3	YJ-C4	YJ-C5	YJ-C6
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9
Baseline (km)	52.75	52.84	52.42	52.51	52.12	52.21
Cores	TS-C1	TS-C2	TS-C3	TS-C4	DYB	HZ
Power (GW)	4.6	4.6	4.6	4.6	17.4	17.4
Baseline (km)	52.76	52.63	52.32	52.20	215	265

Approach to infer the Mass Hierarchy

The determination of the mass hierarchy relies on the identification on the positron spectrum of the "imprinting" of the anti-ν_e survival probability

Detection through the classical inverse beta decay reaction

$$\bar{\nu} + p \rightarrow n + e^{+}$$ $E_\nu > 1.8$ MeV



The time coincidence between the positron and the γ from the capture rejects the uncorrelated background

The "observable" for the mass hierarchy determination is the positron spectrum
It results that $E_{vis}(e^+) = E(\nu) - 0.8$ MeV

Method from Petcov and Piai, Physics Letters B 553, 94-106 (2002)

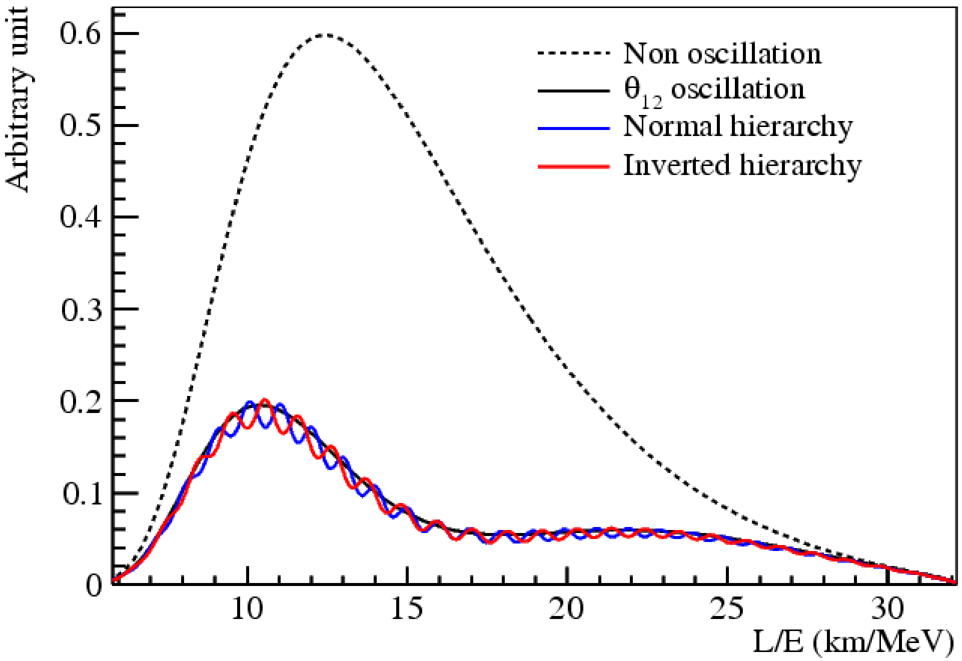
MH and Survival probability

arXiv 1210.8141

$$P_{ee} = \left| \sum_{i=1}^{3} U_{ei} \exp\left(-i\frac{m_i^2}{2E_i}\right) U_{ei}^* \right|^2$$
$$= 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2(\Delta_{21})$$
$$- \cos^2\theta_{12}\sin^2 2\theta_{13}\sin^2(\Delta_{31})$$
$$- \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2(\Delta_{32})$$

$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E_\nu}, \quad (\Delta m_{ij}^2 \equiv m_i^2 - m_j^2)$$

Or to make the effect of the mass hierarchy explicit, exploiting the approximation $\Delta m^2_{32} \approx \Delta m^2_{31}$:

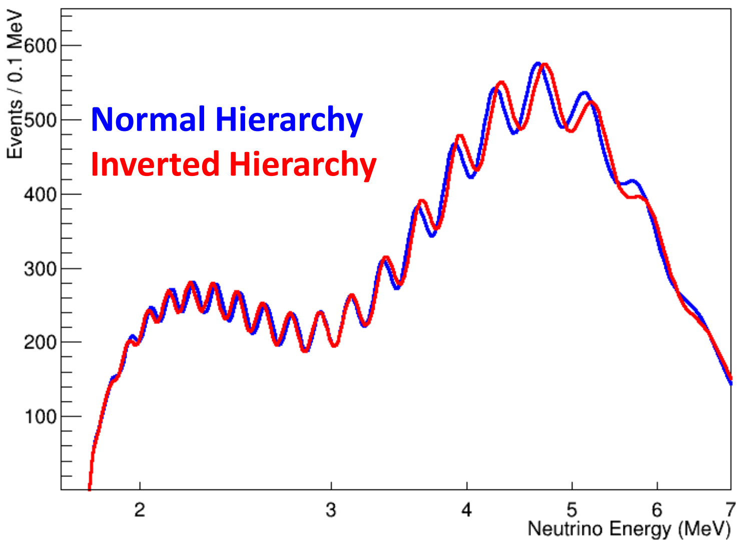


$$P_{ee} = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2(\Delta_{21})$$
$$- \sin^2 2\theta_{13}\sin^2(|\Delta_{31}|)$$
$$- \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2(\Delta_{21})\cos(2|\Delta_{31}|)$$
$$\pm \frac{\sin^2\theta_{12}}{2}\sin^2 2\theta_{13}\sin(2\Delta_{21})\sin(2|\Delta_{31}|),$$

+ NH
- IH

The big suppression is the "solar" oscillation → Δm^2_{21} , $\sin^2\theta_{12}$
The ripple is the "atmospheric" oscillation → $|\Delta m^2_{31}|$ from frequency
MH encoded in the phase
"high" value of θ_{13} crucial

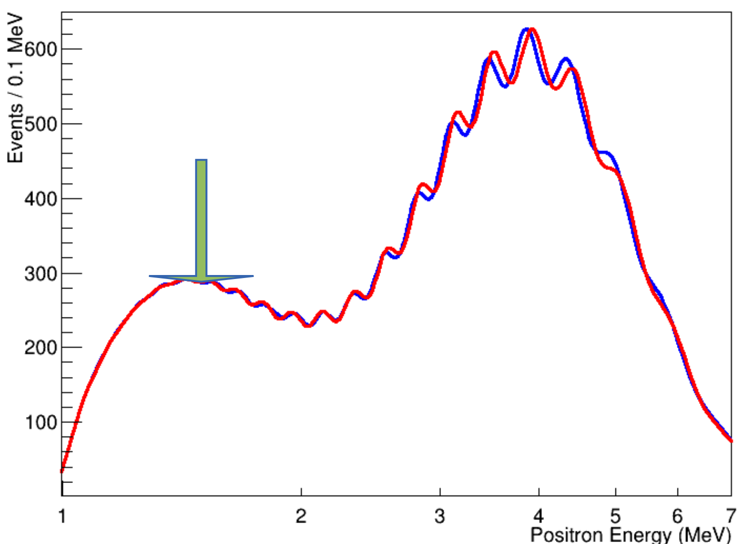
Neutrino & Positron Spectra



Spectrum in term of neutrino energy – no energy resolution

Conditions for the example

- Three neutrino framework (no effective Δmee Δmμμ)
- Baseline: 50 km
- Fiducial Volume: 5 kt
- Thermal Power: 20 GW
- Exposure Time: 5 years
- more pessimistic than the true JUNO values



Positron visible energy

- E(vis) ~ E(ν) – 0.8 MeV
- Assuming 3% / sqrt(E) resolution
- Assuming negligible constant term in resolution

Spectrum in term of positron visible energy – folded with energy resolution
→ **the challenge of the experiment**

Summary of MH Sensitivity

PRD 88, 013008 (2013)	Relative Meas.	$\Delta m^2_{\mu\mu}$ from LBL Expts
Statistics only	4σ	5σ
Realistic case	3σ	4σ

Baseline: 53 km

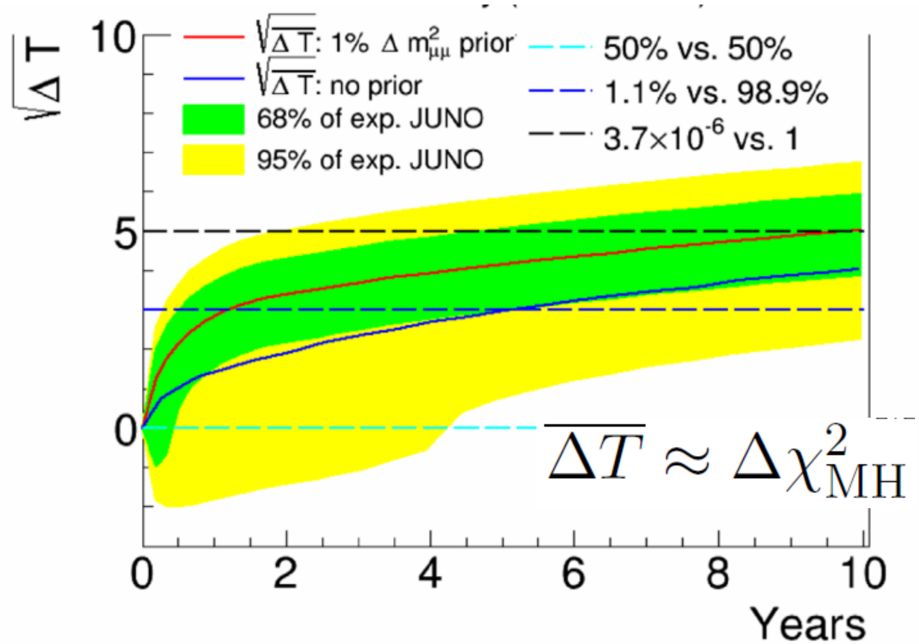
Fiducial Volume: 20 kt

Thermal Power: 36 GW

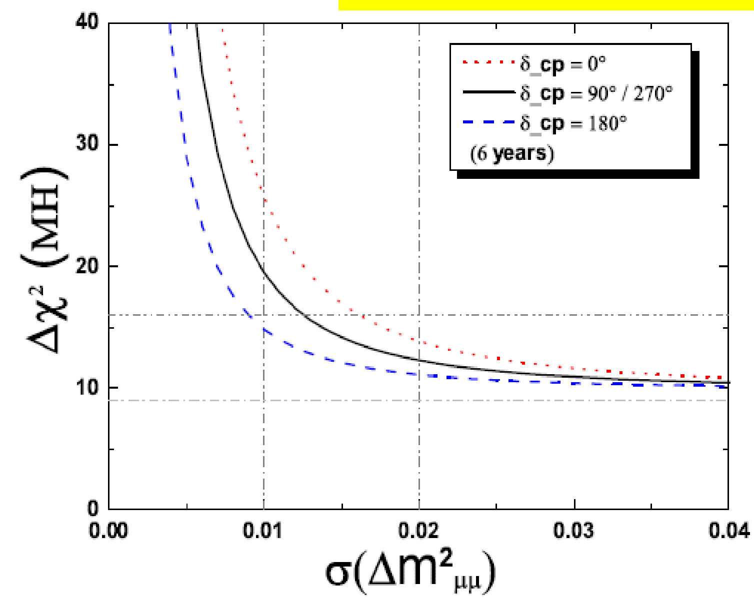
Exposure Time: 6 years

Proton content 12%

en. res. 3%

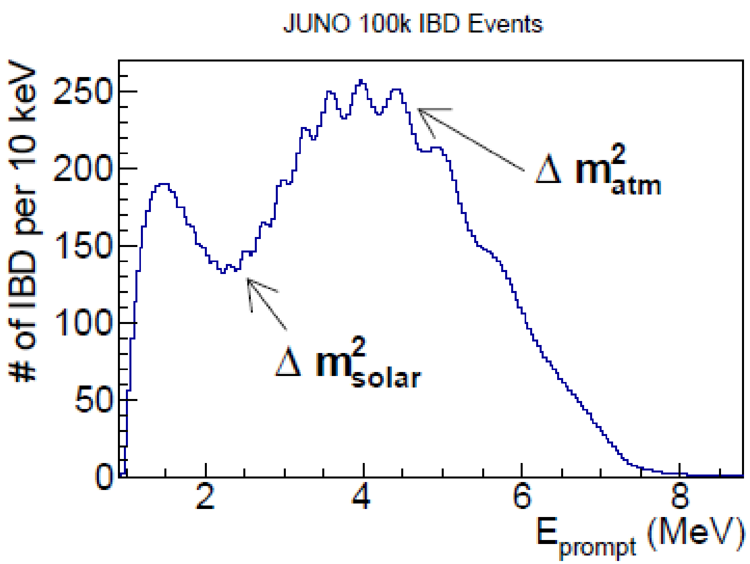


$$\overline{\Delta T} \approx \Delta\chi^2_{\mathrm{MH}}$$



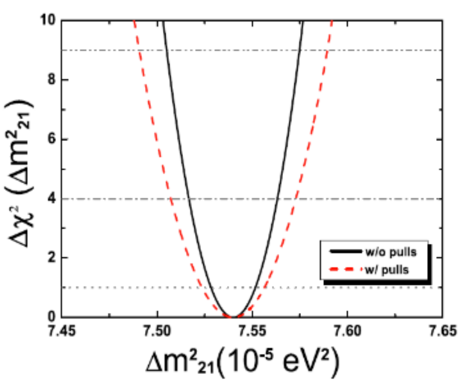
	Ideal	Core distr.	Shape	B/S (stat.)	B/S (shape)	$\lvert\Delta m^2_{\mu\mu}\rvert$
Size	52.5 km	Real	1%	4.5%	0.3%	1%
$\Delta\chi^2_{\mathrm{MH}}$	+16	−4	−1	−0.5	−0.1	+8

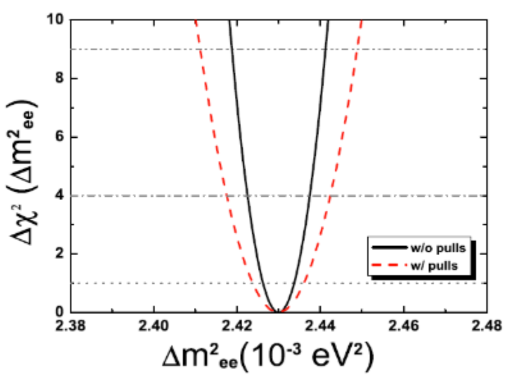
Precision Measurements

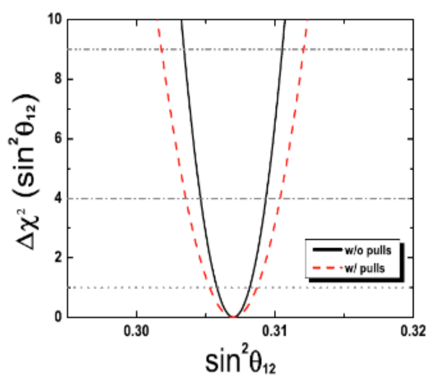


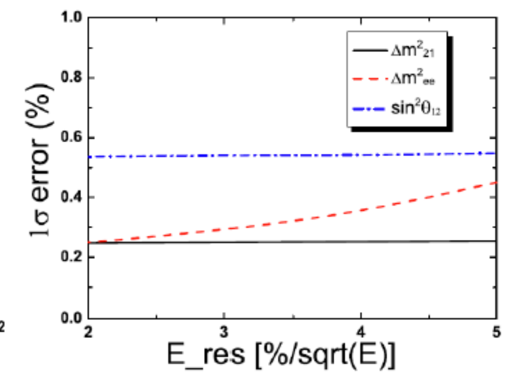
Probing the unitarity of U_{PMNS} to ~1% more precise than CKM matrix elements !

	Statistics	+BG +1% b2b +1% EScale +1% EnonL
$\sin^2\theta_{12}$	0.54%	0.67%
Δm^2_{21}	0.24%	0.59%
Δm^2_{ee}	0.27%	0.44%









0.16%→0.24% 0.16%→0.27% 0.39%→0.54%

E resolution

Correlation among parameters

$$\Delta m^2_{ee} = \cos^2\theta_{12}\Delta m^2_{31} + \sin^2\theta_{12}\Delta m^2_{32}$$

Vast physics reach beyond Reactor Neutrinos

- **Supernova burst neutrinos**
- **Diffuse supernova neutrinos**
- **Solar neutrinos**
- **Atmospheric neutrinos**
- **Geo-neutrinos**
- **Sterile neutrinos**
- **Nucleon decay**
- **Indirect dark matter search**
- **Other exotic searches**

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

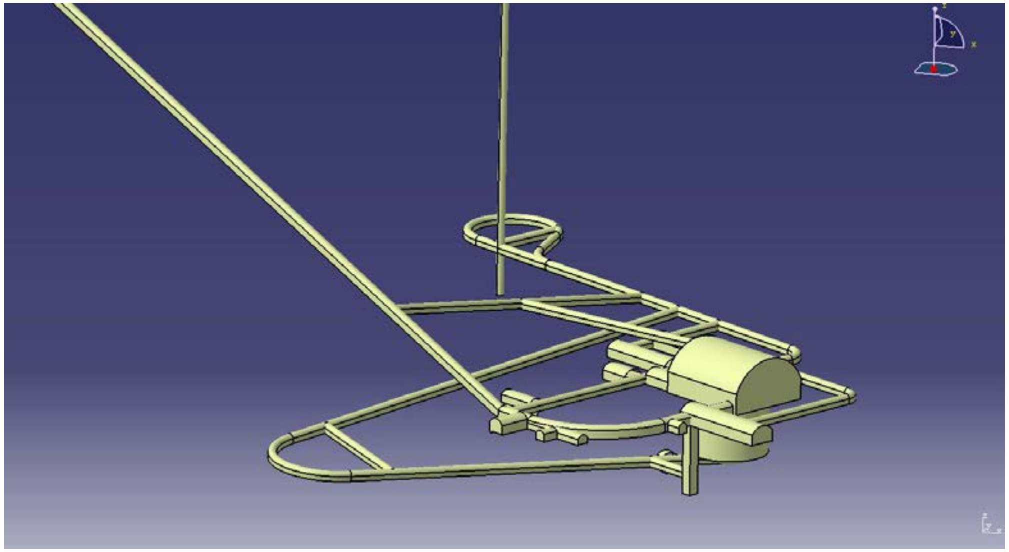
Progress and schedule

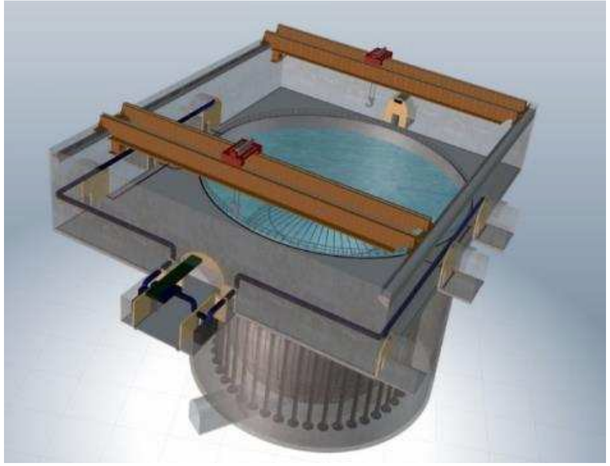
- **Ground breaking in Jan. 2015 – water during excavation**
  - ⇨ 1266 m slope tunnel completed
  - ⇨ 564 m vertical shaft completed
  - ⇨ Overburden between 650-670 m
  - ⇨ New hall location and tunnel arrangement

To avoid water underneath

To avoid falls and cracks

To explore water on top of the hall





Impact of water issue?

original schedule:

Civil preparation：2013-2014

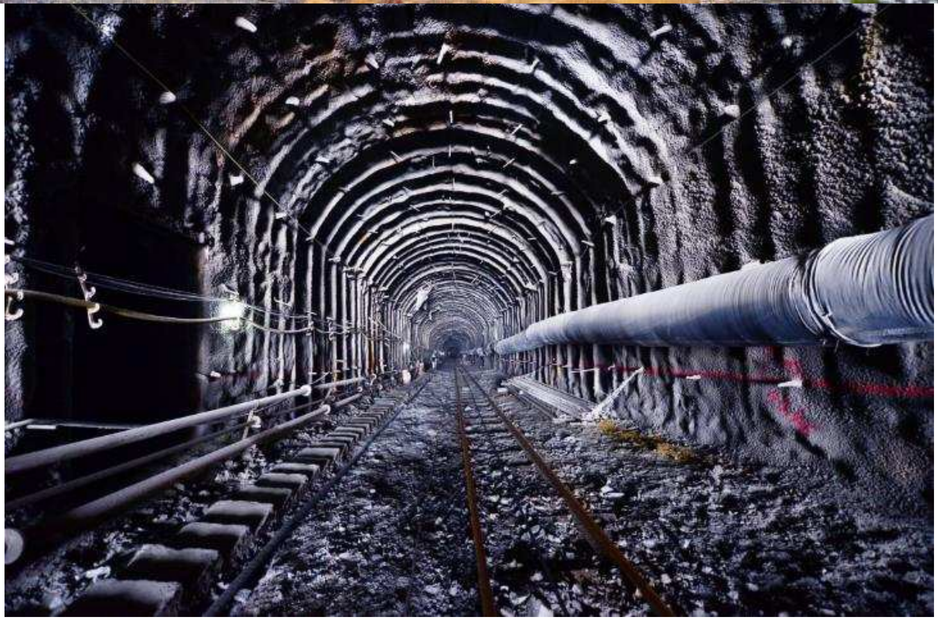
Civil construction：2014-2017

Detector component production：2016-2018

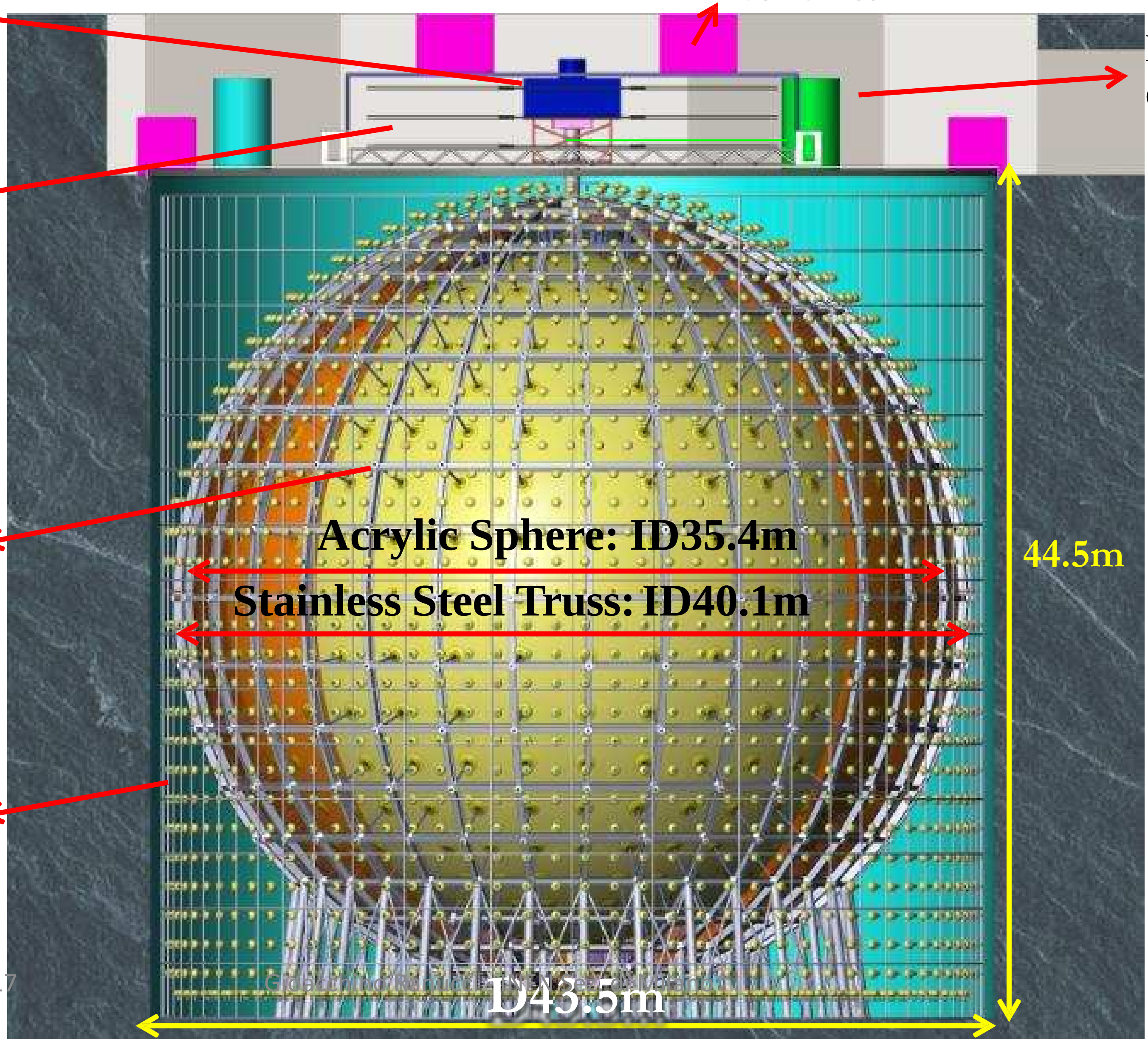
Detector assembly & installation：2018-2020

Filling & data taking：2020

Excavation



Dimensions and layout of the detector

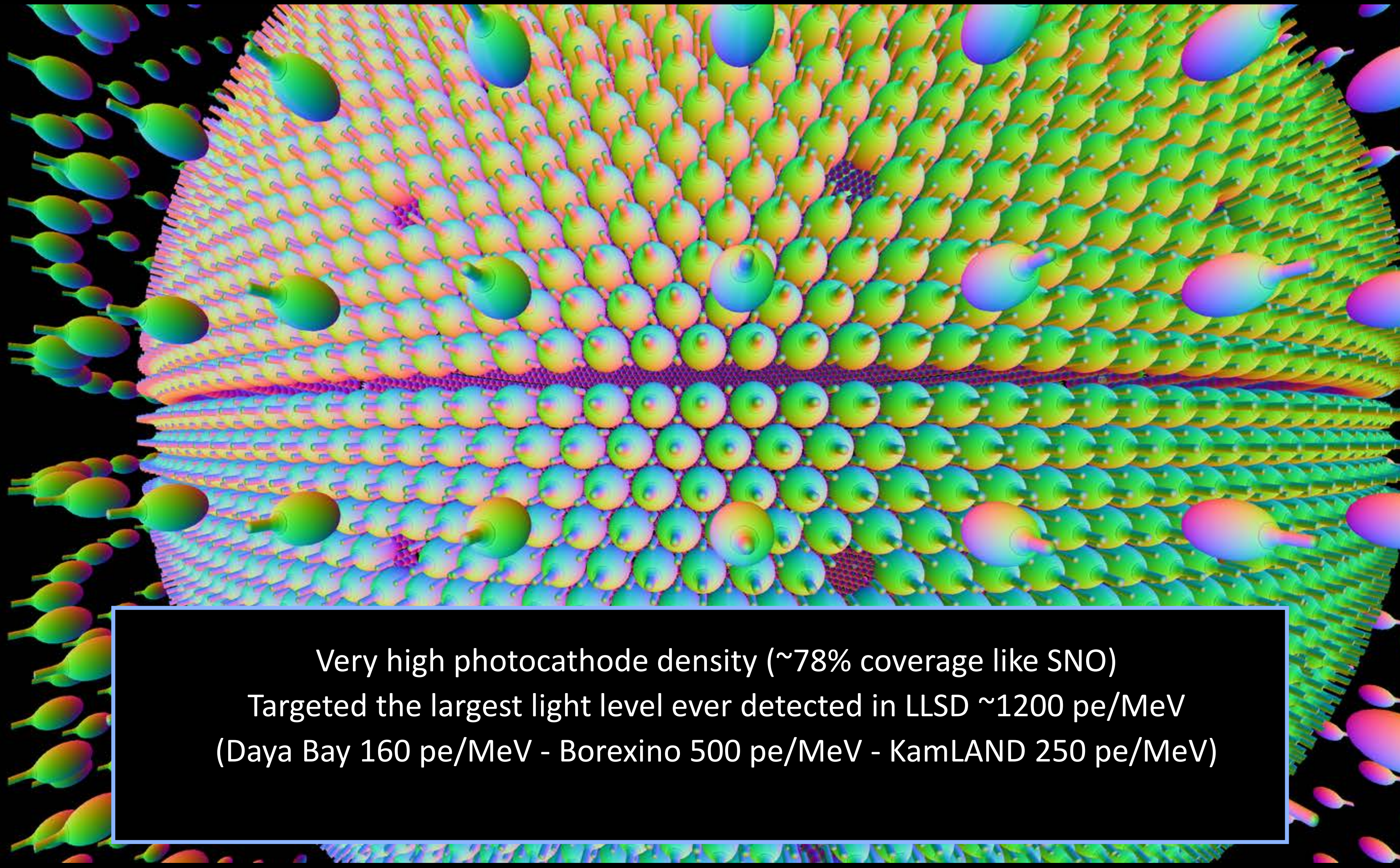


All around coils for Earth's magnetic field compensation

Central detector
Acrylic sphere+
20kt Liquid Scin+
~18000 20" PMT+
~25000 3" PMT

Water Cherenkov
~2000 20" PMT

Central detector distinctive feature: resolution



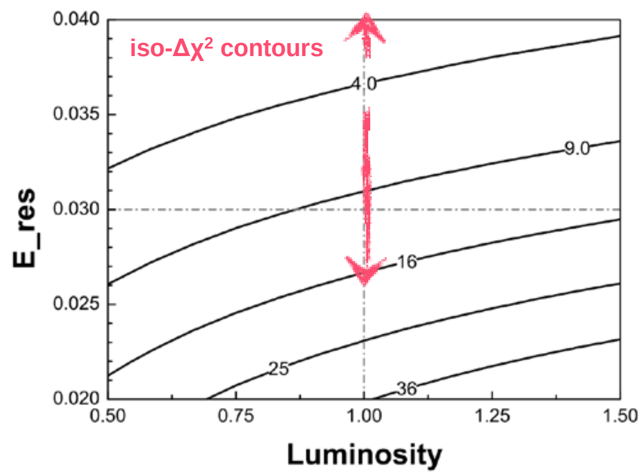
Very high photocathode density (~78% coverage like SNO)
Targeted the largest light level ever detected in LLSD ~1200 pe/MeV
(Daya Bay 160 pe/MeV - Borexino 500 pe/MeV - KamLAND 250 pe/MeV)

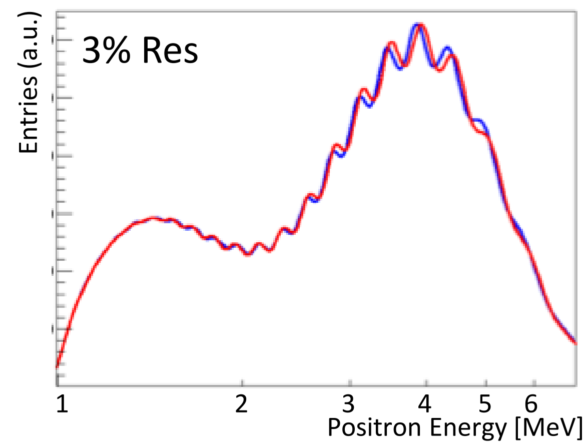
Considerations on resolution

Central Detector design optimised for Mass Hierarchy: “Precise & Large”

Detector Resolution: $$\frac{\sigma_E}{E} = \sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + b^2 + \left(\frac{c}{E}\right)^2}$$

J.Phys. G43 (2016) no.3, 030401





3% resolution at 1MeV is pivotal

a - stochastic term → Maximise detected light → Large photocoverage, Transparent Scintillator, High QE

b,c - non-stochastic terms → Control systematics → Small (3”) PMTs, Calibration

JUNO's Double Calorimetry System…

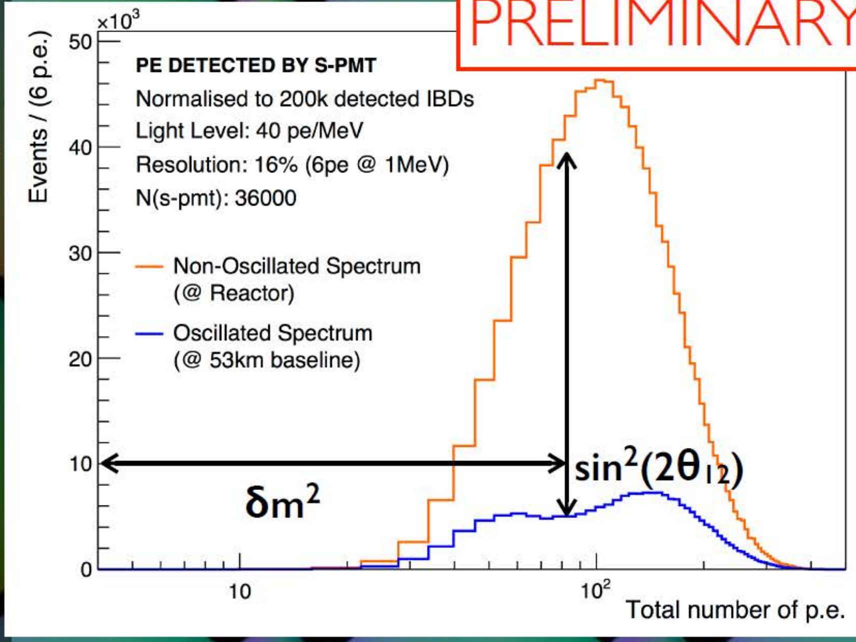
Additional readout system (36000 3" PMTs): 2 independent *readouts embedded within same detector (systematics control)*

- (high precision calorimetry for $\pm\Delta m^2$) response aid to 20" PMTs for non-stochastic systematics ($\lesssim$3% @ 1MeV)
- ($\theta_{12}\oplus\delta m^2$) internal redundancy oscillation parameter measurement: internal cross-check (<1% precision)
- (^{9}Li background) enhanced μ-tracking for cosmogenic ion production tagging/vetoing on C (^{12}B/^{9}Li/^{8}He)
- (supernova readout complementarity) double-readout to ensure unbiassed both energy and rate measurement
- (readout$\oplus$trigger complementarity) complementary time resolution, dynamic range & trigger (position) information → powerful event reconstruction

3" PMT

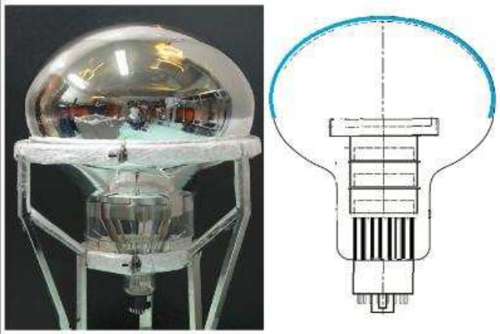
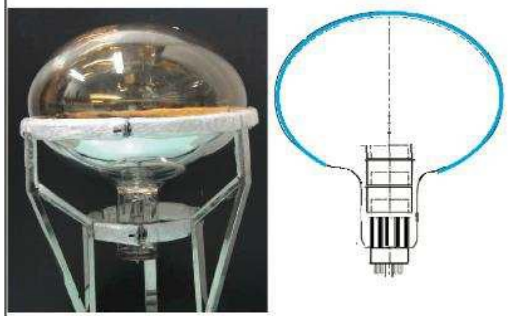
(several options)
- MELZ (RU)
- HZC (CH)
- ETL (UK)
- Hamamatsu(JP)

PRELIMINARY



complementary (θ12,δm^2) measurement

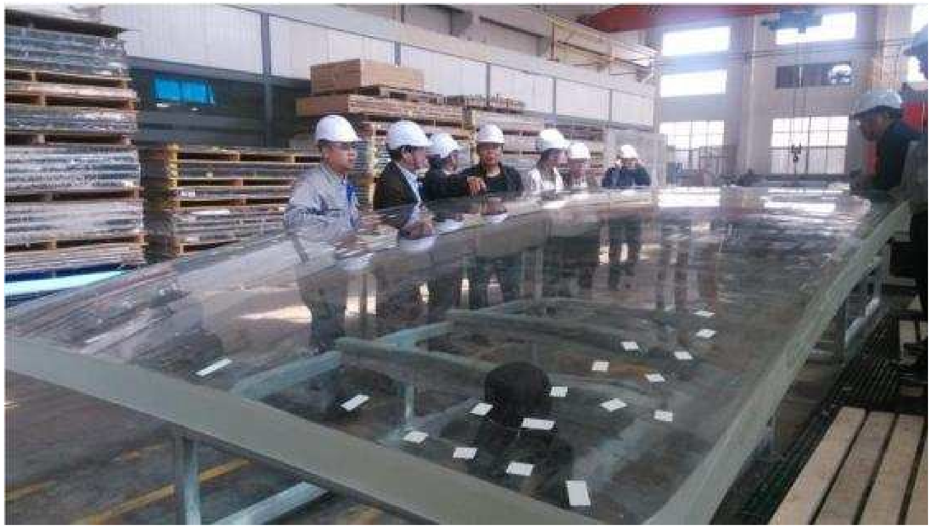
Photomultiplier production

20-inch Hamamatus PMT Dynode Ellipsoidal Glass	20-inch IHEP MCP-PMT Horizontal MCPs Ellipsoidal Glass
	
HQE 1#, 2#, 3#	76#, 77#, 78#, 79#

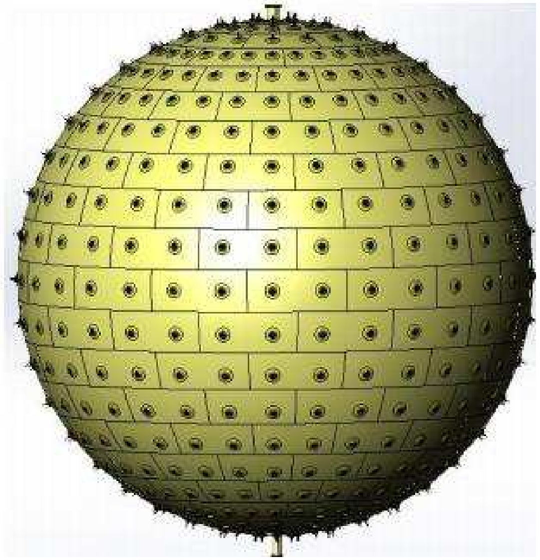
Finished 20” PMT bidding at end of 2015:
-- 15000 MCP-PMT (NNVT)
-- 5000 Dynode-PMT (Hamamatsu)
Bid for 3” PMT done in May this year
Already delivered
1000 Hamamatsu
2000 NNVT
Testing in progress

	unit	MCP-PMT（IHEP）	R12860（Hamamatsu）
Electron Multiplier	--	MCP	Dynode
Photocathode mode	--	reflection+ transmission	transmission
Quantum Efficiency（400nm）	%	26 (T), 30 (T+R)	30(T)
Relativity Detection Efficiency	%	~ 110%	~ 100%
P/V of SPE		> 3	> 3
TTS on the top point	ns	~12	~3
Rise time/ Fall time	ns	R~2 , F~10	R~7 , F~17
Anode Dark Count	Hz	~30K	~30K
After Pulse Time distribution	us	4.5	4, 17
After Pulse Rate	%	3	10
Glass	--	Low-Potassium Glass	HARIO-32

Acrylic sphere



Forming panel size: 3m x 8m x 120mm



Acrylic divided into 200+ panels

Prototypes of spherical panels done

The problems of shrinkage and shape variation were resolved. Background evaluated to low acceptable level

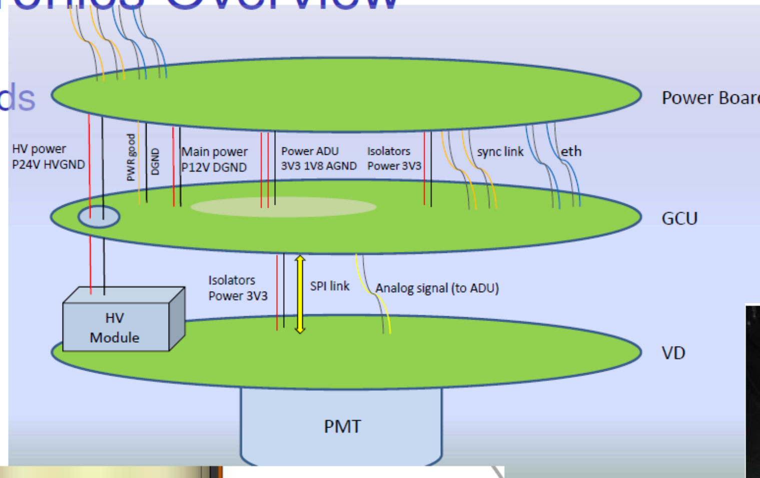
Bid among three companies - producer selected and production started

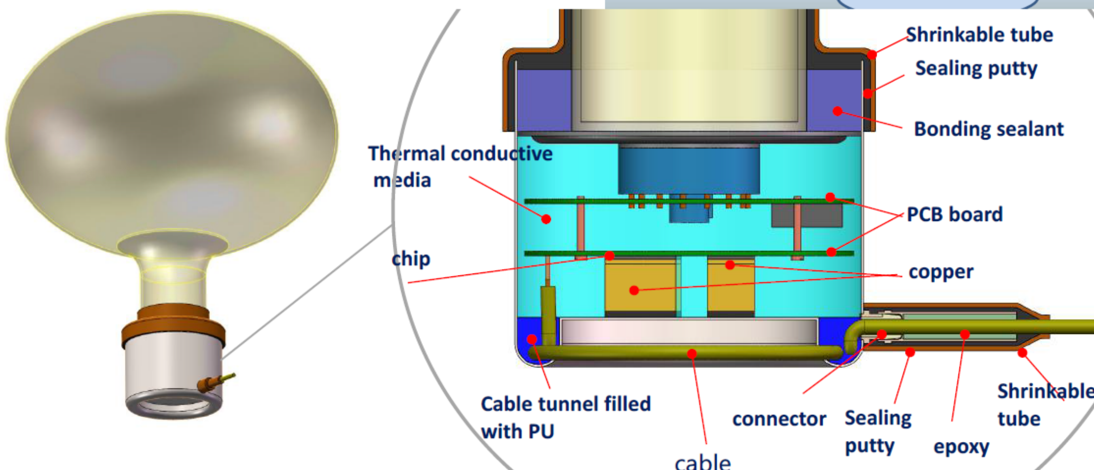
JUNO Electronics Overview

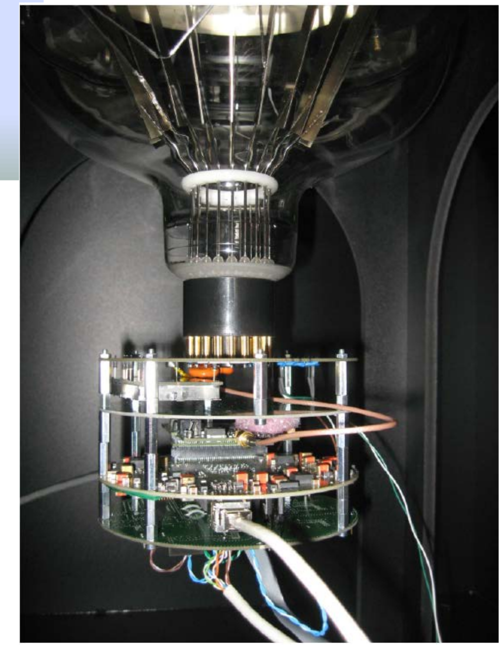
Front-End electronics split into 3 boards

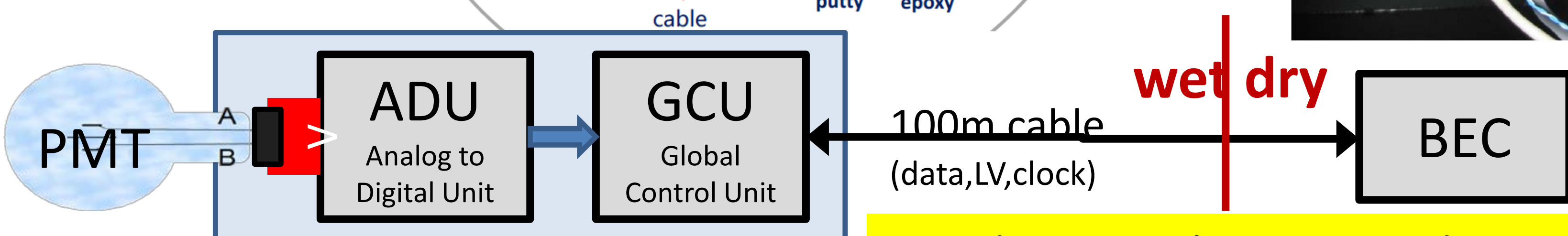
1. Voltage Divider (closer to PMT)
2. Global Control Unit
3. Power Board (further from PMT)

\+ HV module in between









New design → electronics and PMT decoupled (in progress)

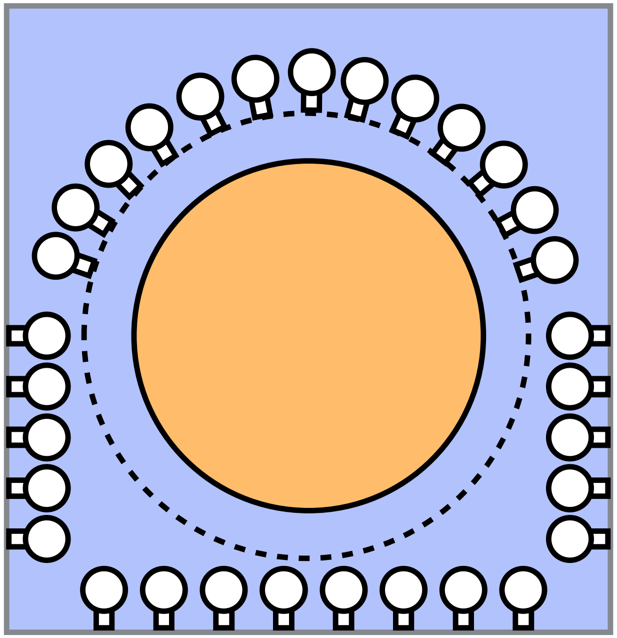
Muon Veto Design

Muon Veto: critical to reduce backgrounds

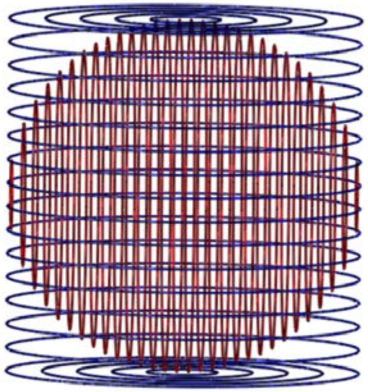
Cosmogenic isotopes rejection:
reconstruction of muon tracks + $\mathcal{O}$(1s) veto surrounding the track

Neutron Rejection:
passive shielding (water) + time coincidence w/ muon + multiple proton recoils

Gamma rejection: passive shielding (water)



Magnetic Field Compensating Coil



Water Cherenkov

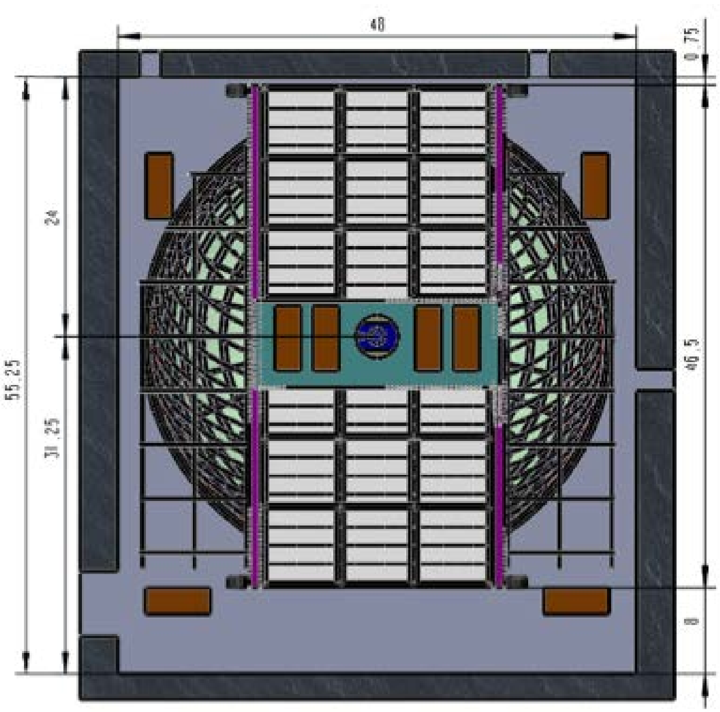
20kt ultra-pure water

Water acting as moderator &
pool instrumented to detect Cherenkov light

2000 20” PMTS located as in the picture

Optimized detection efficiency of Cherenkov light

Muon Veto Design



Top Tracker

Using OPERA plastic scintillator (49m²/module)

Three layers to ensure good muon tracking

Partial coverage due to available modules

- Reject ~50% muons
- Provide tagged muon sample to study reconstruction and background contamination with central detector

Tracker removal at Gran Sasso
Transfer to China completed

TT travel

The traveling by boat takes 45 days (40 foreseen) and customs 21 days delivery 1 day

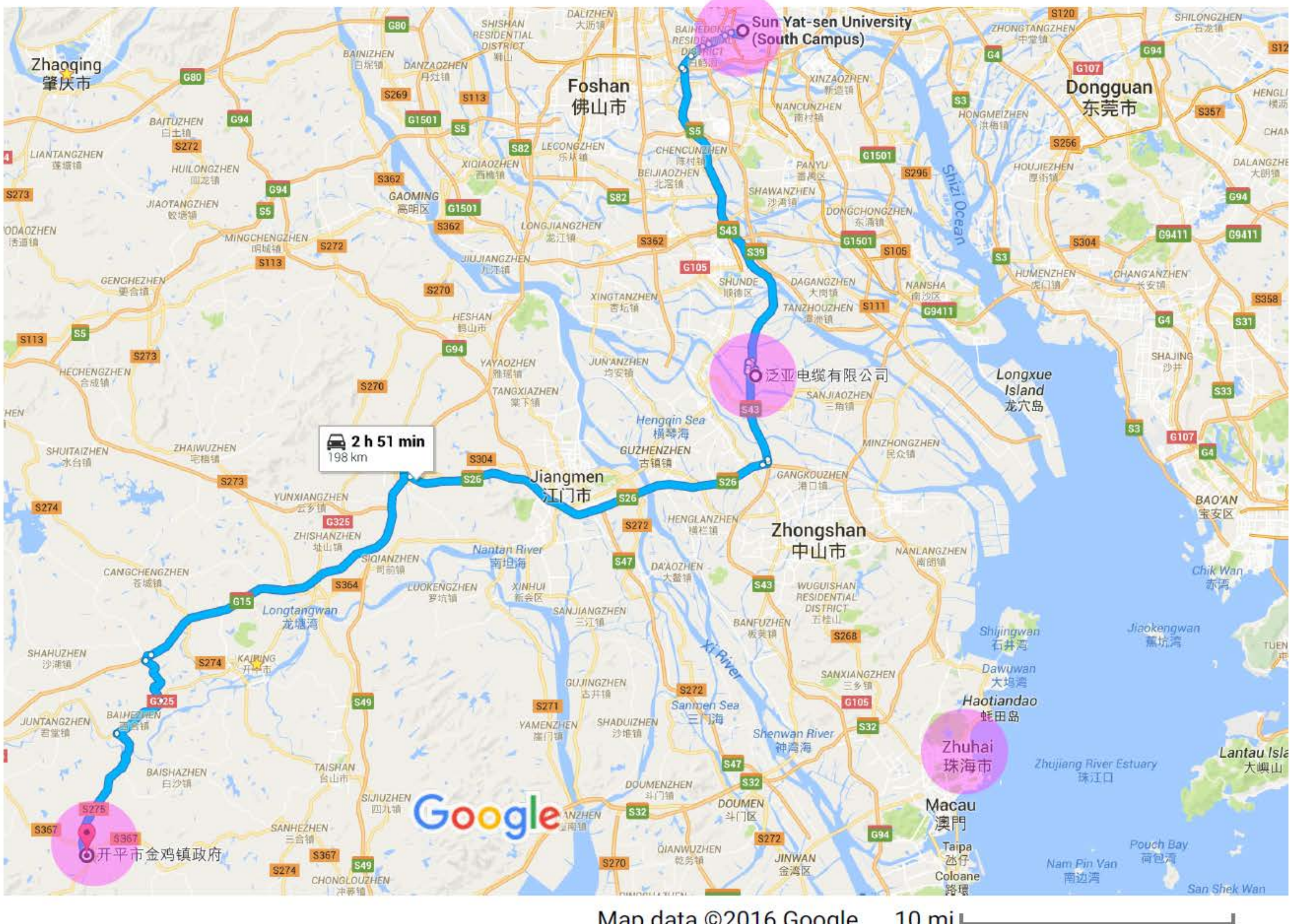
TT travel

July 15 Warehouse

All TT is in the warehouse :
-first visual check next week

Same site of the PMT testing

Storage/Testing Places: Pan-Asia in Zhongshan



Toward the construction of the core infrastructure beyond the acrylic sphere

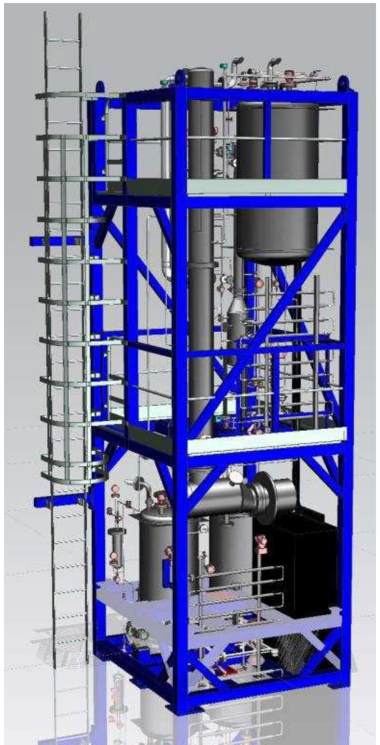
- Detector structure design completed with a number of reviews
  - Earthquake fully understood
  - Interface to civil defined
  - Other technical details
- Assembly & Installation process defined after a lot of discussions with manufacturing & installation companies
- Identified 4 different construction packages
  - Stainless steel structure manufacturing and assembly
  - Supporting platform & lifting structure for Acrylic tank construction
  - VETO structure including the earth magnetic field compensation coil
  - PMT module manufacturing and installation
- Contracts will be signed by the end of the year for each of them

Prototyping at Daya Bay for the liquid scintillator purification plants

- Purify 20 ton LAB to test the overall design of purification system at Daya Bay. Replaced the target LS in one detector
- Quantify the effectivities of subsystems
  - Optical : >20m A.L @430nm?
  - Radio-purity: 10^{-15} g/g (U, Th)?
- Determine the choice of sub-systems
  - Al_2O_3 column, distillation, gas striping, water extraction

Distillation and steam stripping system

Installed at Daya Bay



Al_2O_3 column pilot plant installed in Daya Bay LS hall

Overall LAB5 view at Daya Bay

Achieved better than 25 m of att. length – Design of the full scale plants in progress

Many other ongoing tasks

- PMT potting and anti-implosion shielding
- Calibration:
  - guided source insertion, LED, laser, CCD, …
- Electronics, cable， box,… for the 3” PMT
- LS filling
- Slow control
  - PMT, water, environmental monitoring & control
- DAQ: crates, server, router, software, …
- Offline farm, data storage/data center, software, …
- Radioactivity measurements and material screening
- Development of MC and analysis tools
- …

Key element of the realization strategy → prepare as much as possible the components of the detector in parallel of the excavation so to progress immediately to the final assembly as soon as the site will be ready → mitigation of schedule impact of water issue

Summary

- The collaboration is still increasing with several more collaborators
- A lot of progresses on many hardware fronts
- The civil excavation despite the difficulty of the underground water progresses at reasonable speed
- The design of components and subsystems is well advanced with some already in construction phase (PMTs, acrylic)
- The start up of the preparation and pre-assembly of many subsystems in parallel with the excavation will help mitigate the impact on the schedule