Status and prospects of the JUNO experiment

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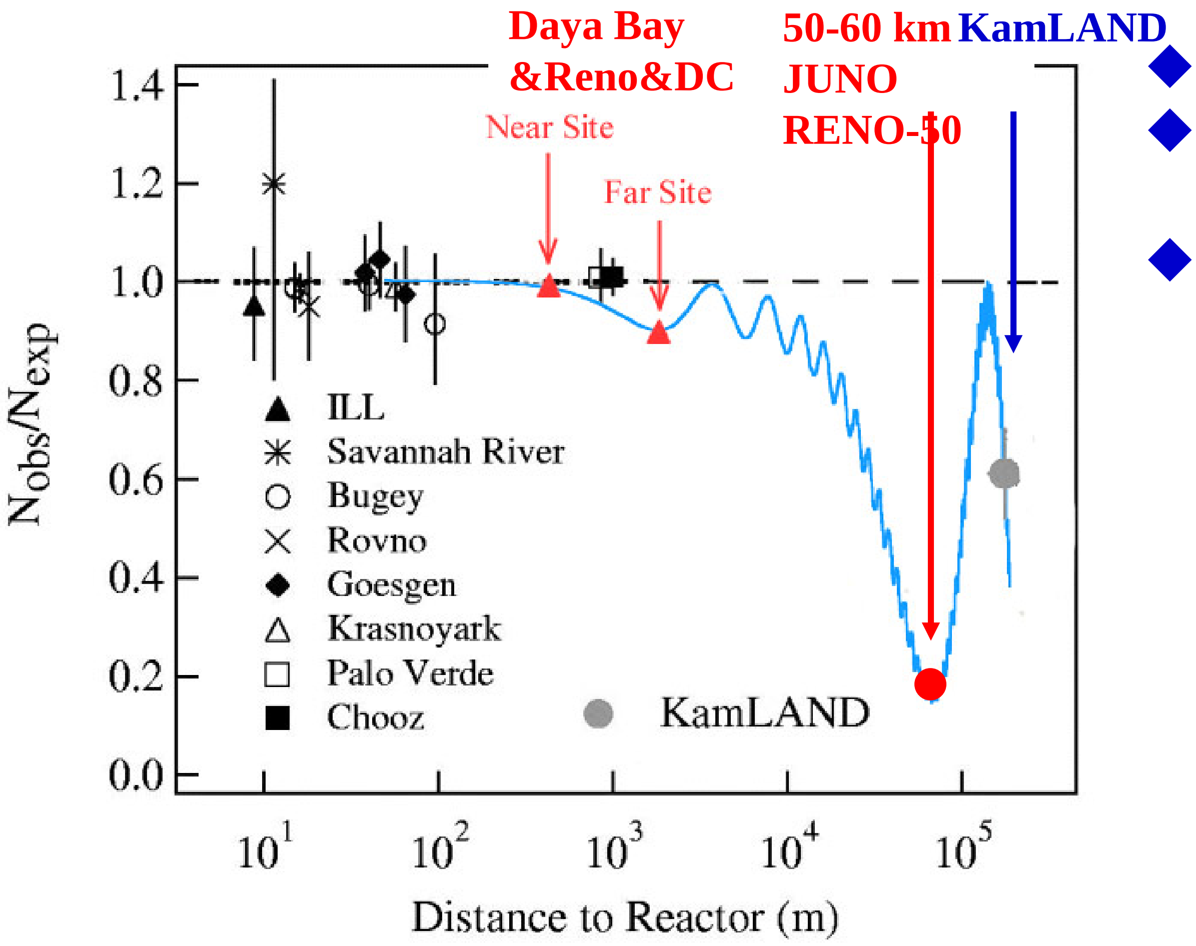
6th Roma International Confrence
on AstroParticle physics

Frascati - June 22, 2016

- 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 Experiment – physics summary



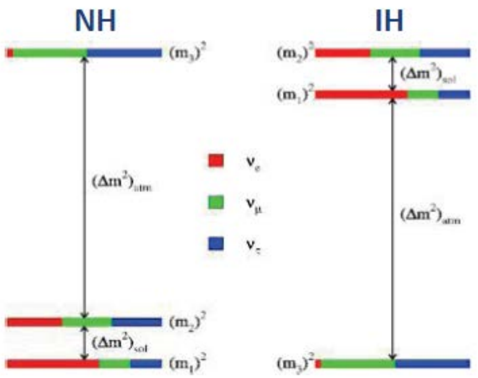
Daya Bay &Reno&DC

50-60 km JUNO RENO-50

KamLAND

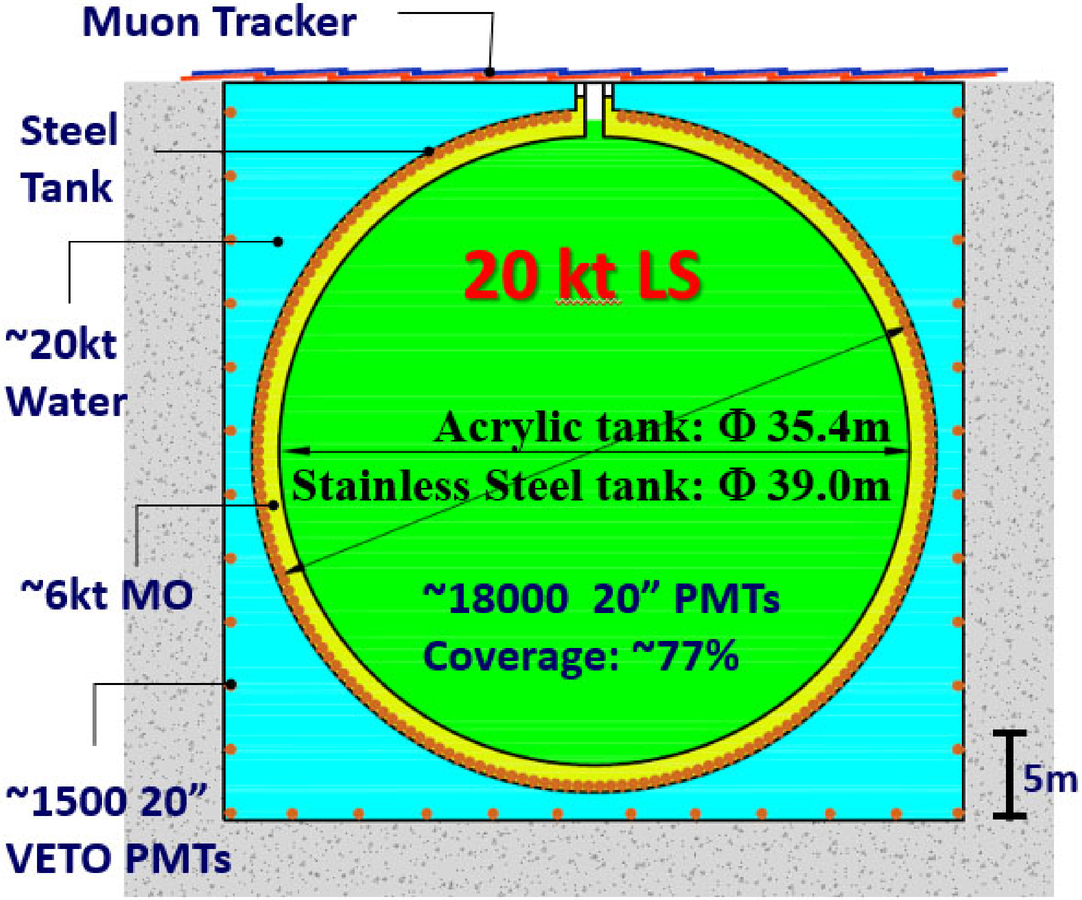
- **20 kton LS detector**
- **~3 % energy resolution-the greatest challenge**
- Rich physics possibilities
  - ⇨ **Mass hierarchy**
  - ⇨ **Precision measurement of 3 mixing parameters**
  - ⇨ **Supernovae neutrino**
  - ⇨ **Geoneutrino**
  - ⇨ **Sterile neutrino**
  - ⇨ **Atmospheric neutrinos**
  -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

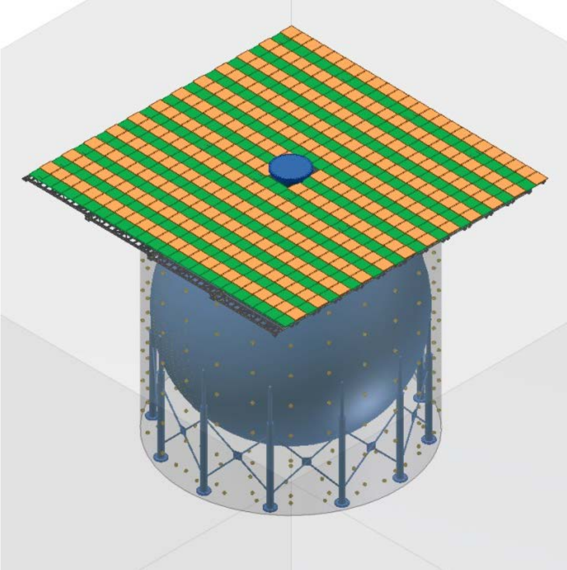
Neutrino Physics with JUNO, J. Phys. G 43, 030401 (2016)



A large LS detector

- LS large volume: ➔ for statistics
- High Light(PE) ➔ for energy resolution





JUNO has been approved in China in Feb. 2013. ~ 300 M$

Later approval of funding from several European Countries:

- **Italy**
- **Germany**
- **France**
- **Russia**
- **Belgium**
- **Czechia**

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

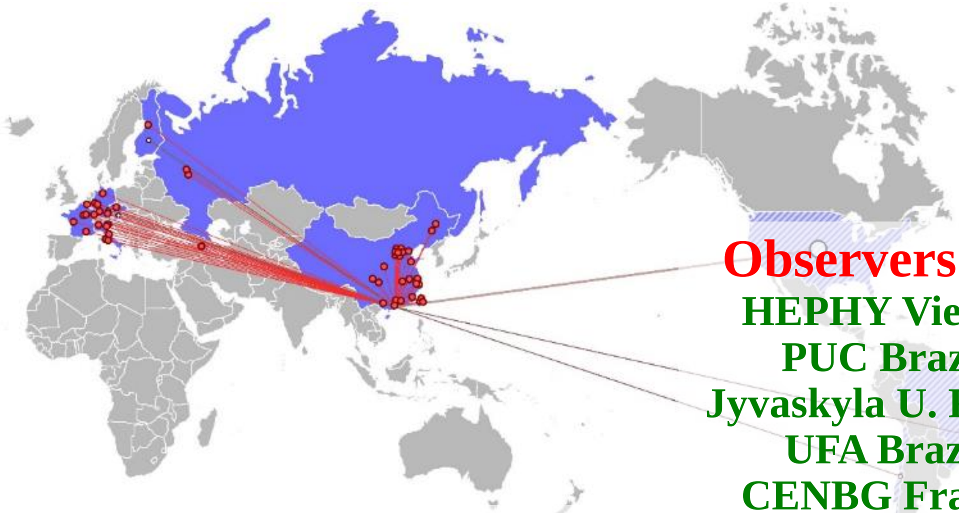
by 2020: 26.6 GW

Overburden ~ 700 m

Kaiping,
Jiang Men city,
Guangdong Province

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

JUNO Collaboration



Asia (31)

BNU
CAGS
CQ U
CIAE
DGUT
ECUST
Guangxi U
HIT
IHEP
Jilin U
Jinan U.

Nanjing U
Nankai U
Natl. CT U
Natl. Taiwan U
Natl. United U
NCEPU
Pekin U
Shandong U
Shanghai JTU
Sichuan U
SUT

SYSU
Tsinghua
UCAS
USTC
U. of S. China
Wuhan U
Wuyi U
Xiamen U
Xi'an JTU

Observers (7):

HEPHY Vienna
PUC Brazil
Jyvaskyla U. Finlan
UFA Brazil
CENBG France
UTFSM Chile
IMP CAS China

Europe (27)

France (5)
APC Paris
CPPM Marseille
IPHC Strasbourg
LLR Paris
Subatech Nantes
Finland (1)
U Oulu
Czech (1)
Charles U

Italy (8)
INFN Catania
INFN-Frascati
INFN-Ferrara
INFN-Milano
INFN-Bicocca
INFN-Padova
INFN-Perugia
INFN-Roma 3
Russia (3)
JINR
INR Moscow
MSU

Germany (7)
FZ Julich
RWTH Aachen
TUM
U Hamburg
IKP FZI Jülich
U Mainz
U Tuebingen
Belgium (1)
ULB
Amenia (1)
YPI

America (4)

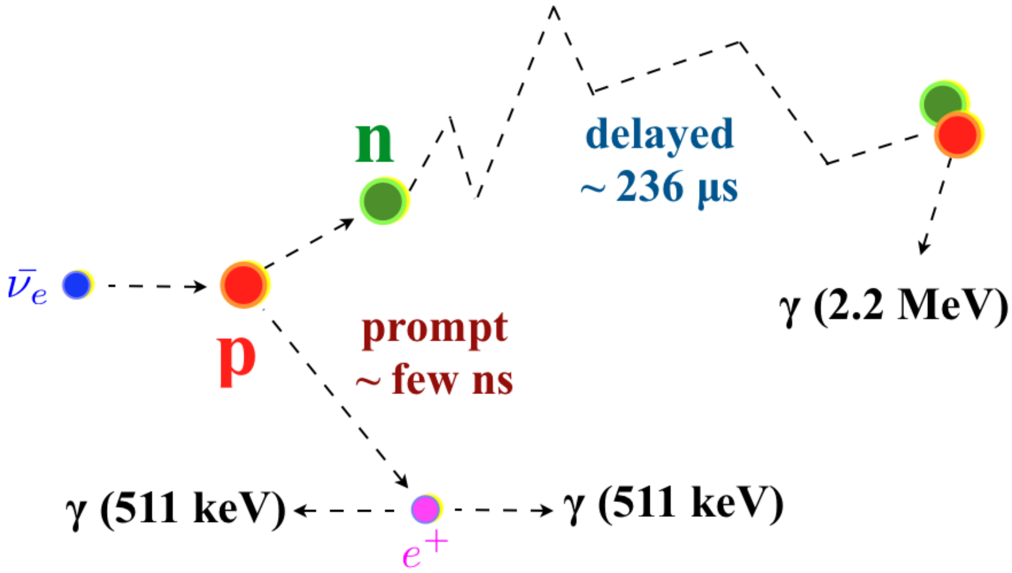
PCUC – BISEE Chile
Maryland U.- 2 groups

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 (we use it in Borexino for the geo-neutrinos)

$\bar{\nu} + p \rightarrow n + e^+$ E_ν>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 $E_{vis}(e^+) = E(\bar{\nu}) - 0.8$ MeV

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

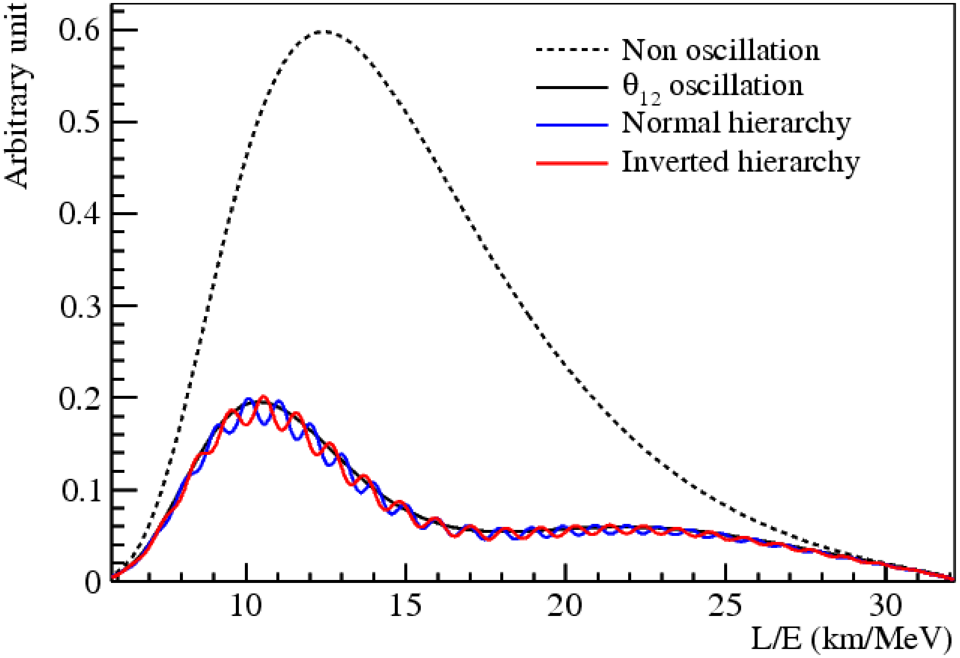
MH and Survival probability

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 $\Delta m^2_{32} \approx \Delta m^2_{31}$:

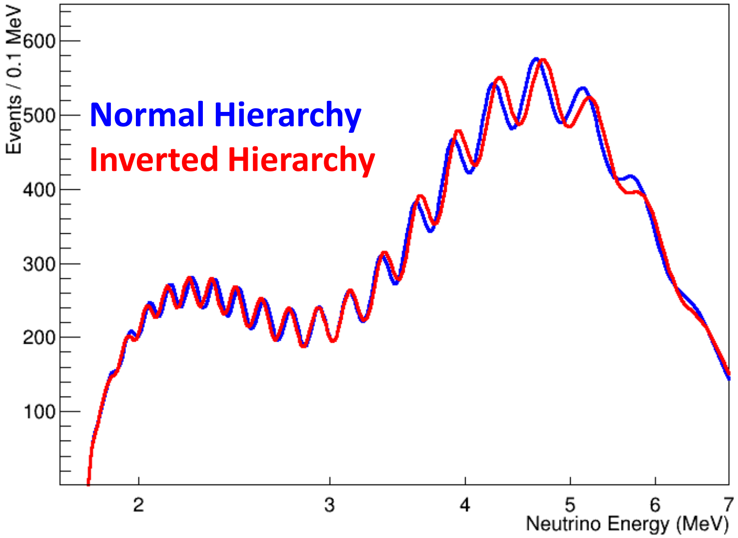


$$P_{ee} = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2(\Delta_{21})$$
$$- \sin^2 2\theta_{13}\sin^2(|\Delta_{31}|)$$
$$- \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2(\Delta_{21})\cos(2|\Delta_{31}|)$$
$$\pm \frac{\sin^2\theta_{12}}{2}\sin^2 2\theta_{13}\sin(2\Delta_{21})\sin(2|\Delta_{31}|),$$

+ NH
- IH

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

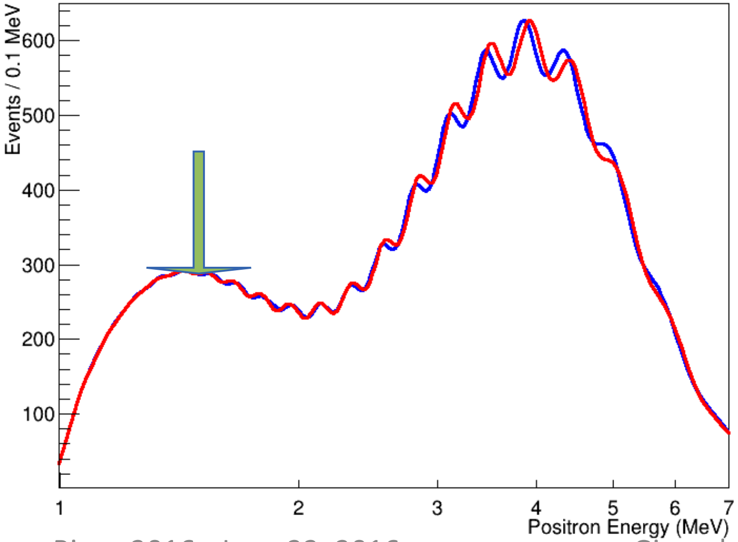
Neutrino & Positron Spectra



Spectrum in term of neutrino energy – no energy resolution

Replicating sensitivity study in arXiv 1210.8141

- 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 JUNO values ▶ used to be in sync with paper



Visible energy due to inverse beta decay

- 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 – with energy resolution : **the challenge of the experiment**

Example of χ^2 comparison – NH true

Numerical values as before
Scan of penalized (i.e. marginalized over the other minimization parameters) χ^2 vs. $|\Delta m^2_{31}|$

Case NH true- average spectrum

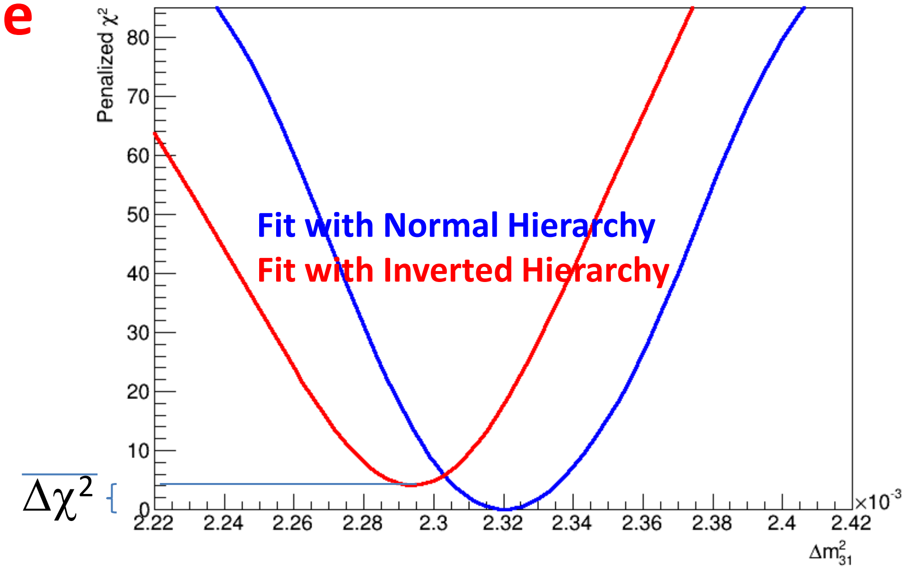
(no fluctuation –**Asimov data set**)

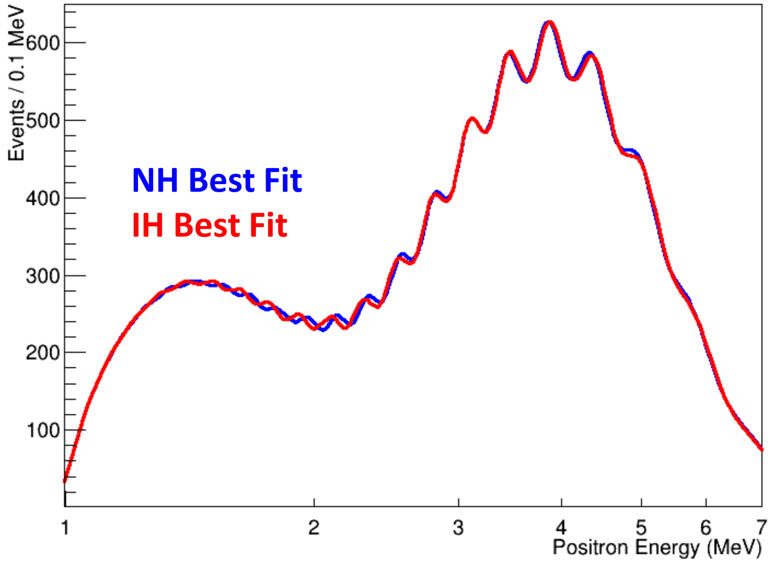
Test statistics → $\Delta\chi^2=\chi^2_{min}(NH) - \chi^2_{min}(IH)$

Fit NH minimum: $1.6\ 10^{-2}$ (practically 0)

FIT IH minimum: 4.0

$\overline{\Delta\chi^2}$ ~4.0





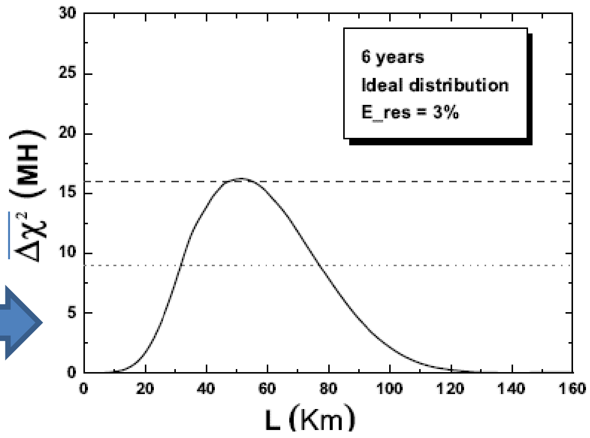
Comparison between IH/NH best fits

The best fit $|\Delta m_{31}|$ is different in the two cases

Fit almost succeeds in accommodating IH spectrum to NH data

The two solutions are fully degenerate but in a limited range of distances

Optimum distance to maximize $\overline{\Delta\chi^2}$

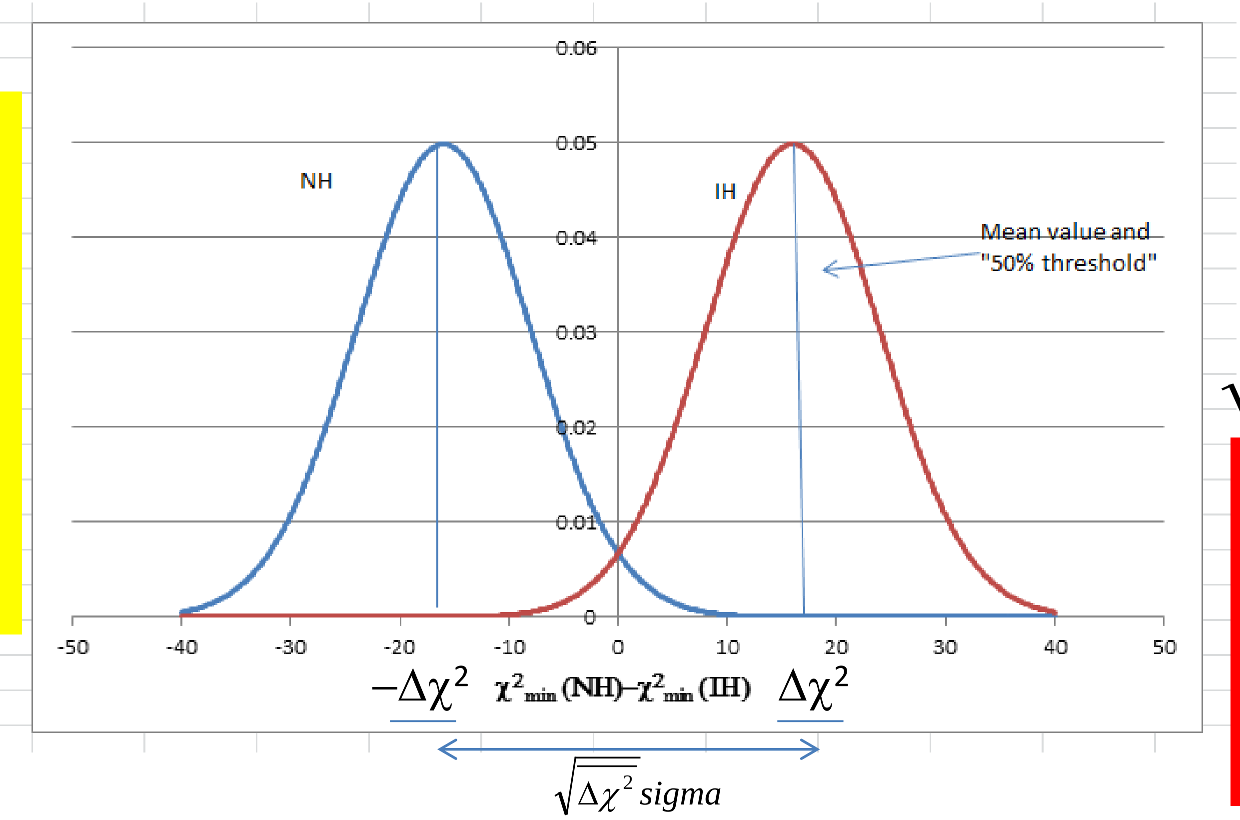


From arXiv:1303.6733v1 [hep-ex] JUNO
$\overline{\Delta\chi^2}$ can be as high as **16** @ 52 km

Distribution of test statistics and number of sigmas for discovery

- **Not unique answer**
- It depends upon the assumed framework (**frequentist or Bayesian**)
- However the actual information is fully encoded in the amount of overlap of the two Gaussian independently from how it is summarized as number of σ
- General result: sigma of each Gaussian = $2\sqrt{\Delta\chi^2}$ **arXiv: 1210.8141v2**

The mean value of the Gaussian curves is taken as representative of the **JUNO** capability at 52 Km arXiv:1303.673



The mean values of the two curves are displaced of exactly

$$\sqrt{\Delta\chi^2}\ sigmas$$

Assumed in a frequentist framework as quantification of discovery capability

arXiv:1311.4076

Frequentist considerations for the number of σ

The special relation between sigma and mean value of the two distributions implies that the median sensitivity according to the frequentist framework is automatically equal to

$$\sqrt{\Delta\chi^2}\,\sigma$$

This means that if the actual outcome of the experiment is more extreme than the expected mean value one get a positive indication for one of the two hierarchies (IH if the outcome is positive or NH if the outcome is negative) with a CL better than $\sqrt{\Delta\chi^2}\,\sigma$ i.e. with a probability of making a mistake (type I error according to the statistical terminology) equal to the corresponding one tailed p-value on the Gaussian curve

3 σ → p-value (1-0.9973)/2 instead of the standard 1-0.9973

In summary for JUNO

- If the outcome is as typically expected, the MH will be determined rather unambiguously
- Even better if there will be an upward fluctuation
- A downward fluctuation will produce an ambiguous result

With these characteristics JUNO declare a 4 σ sensitivity with the above meaning (spectrum with about 100000 events)

Baseline: 52 km

Fiducial Volume: 20 kt

Thermal Power: 36 GW

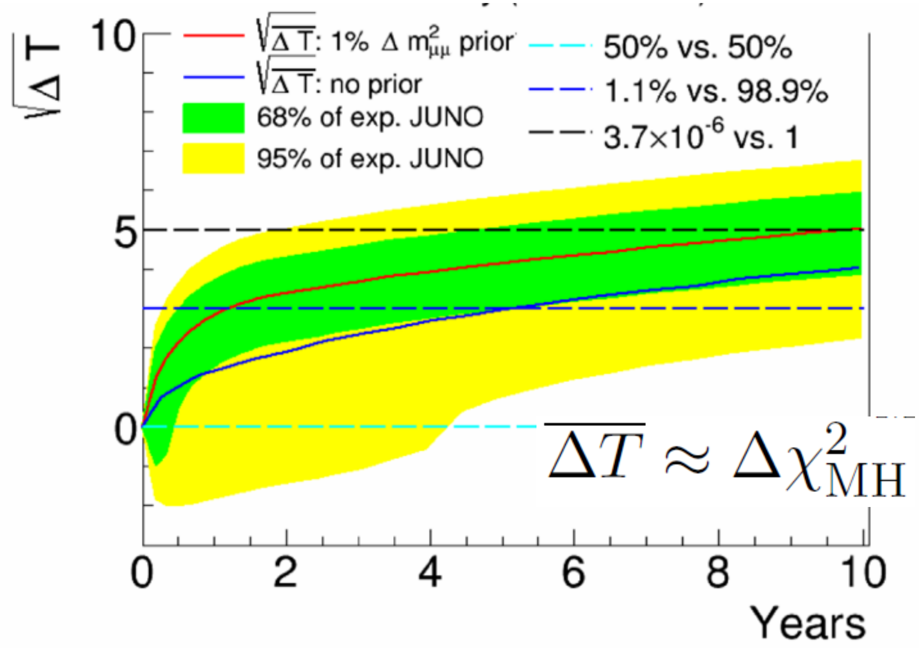
Exposure Time: 6 years

Proton content 12% in mass , en. res. 3%

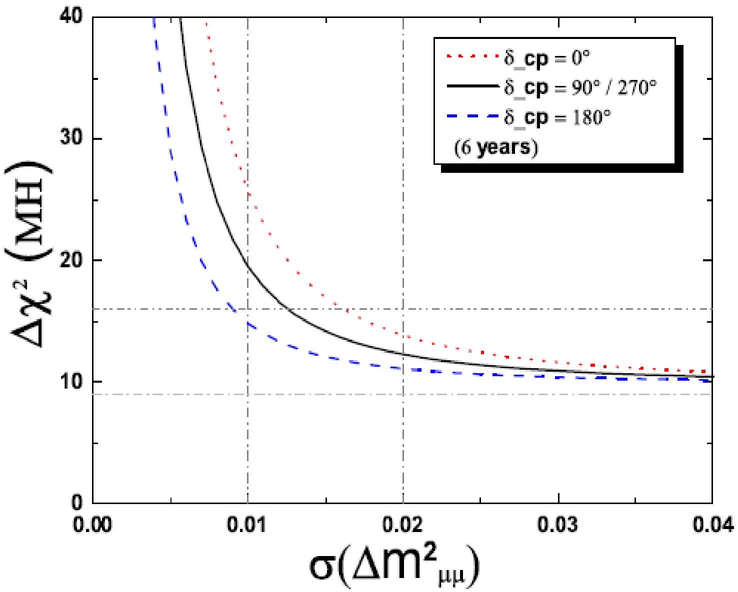
Summary of MH Sensitivity

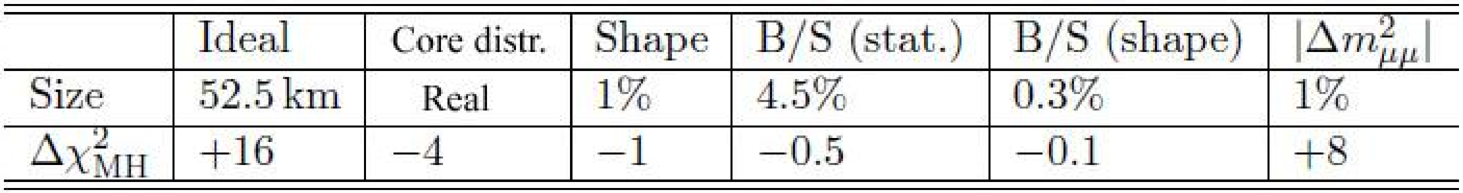
PRD 88, 013008 (2013)	Relative Meas.	Use absolute Δm^2
Statistics only	4σ	5σ
Realistic case	3σ	4σ

JUNO **MH sensitivity with 6 years' data:**



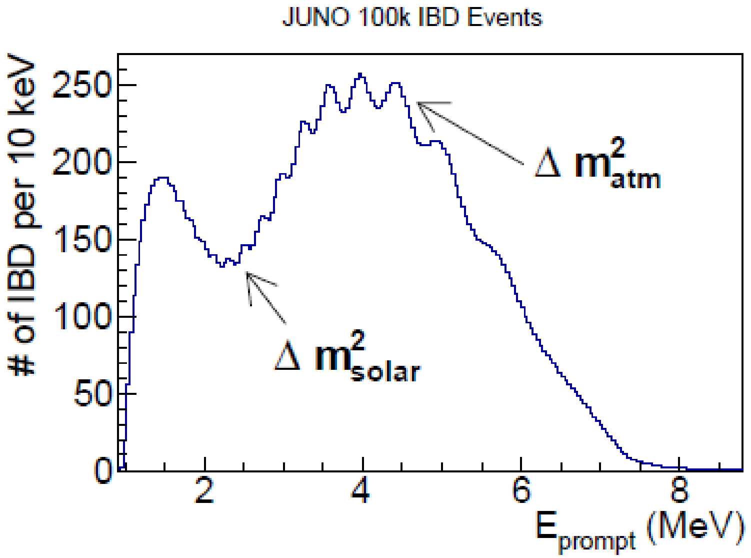
$$\overline{\Delta T} \approx \Delta\chi^2_{\rm MH}$$





	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%
$\Delta\chi^2_{\rm MH}$	$+16$	-4	-1	-0.5	-0.1	$+8$

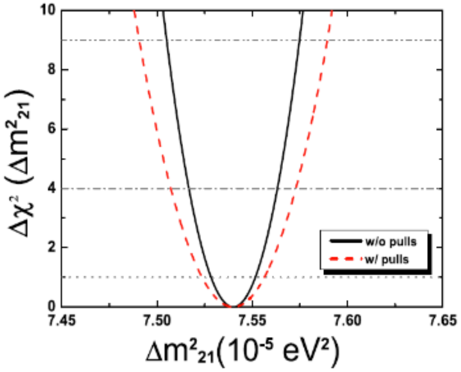
Precision Measurements



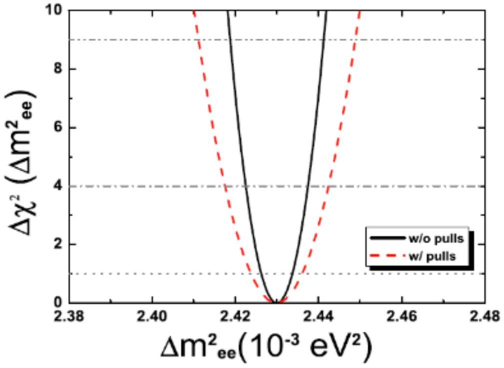
Probing the unitarity of U_{PMNS} to ~1%

more precise than CKM matrix elements !

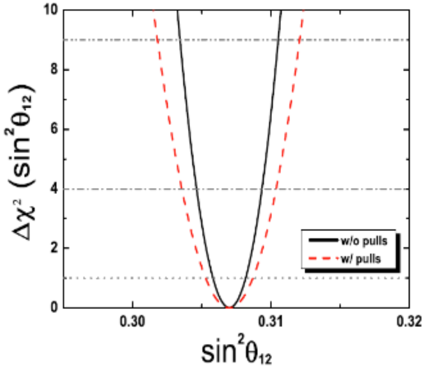
	Statistics	**+BG** **+1% b2b** **+1% EScale** **+1% EnonL**
$\sin^2\theta_{12}$	0.54%	0.67%
Δm^2_{21}	0.24%	0.59%
Δm^2_{ee}	0.27%	0.44%



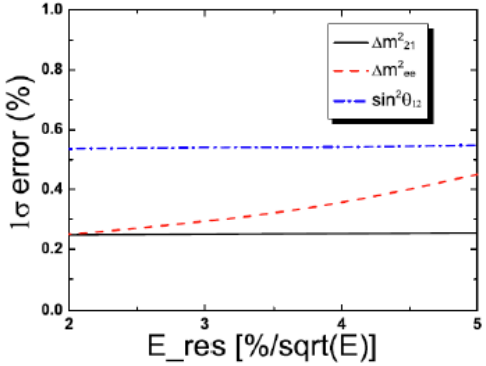
0.16%→0.24%



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**

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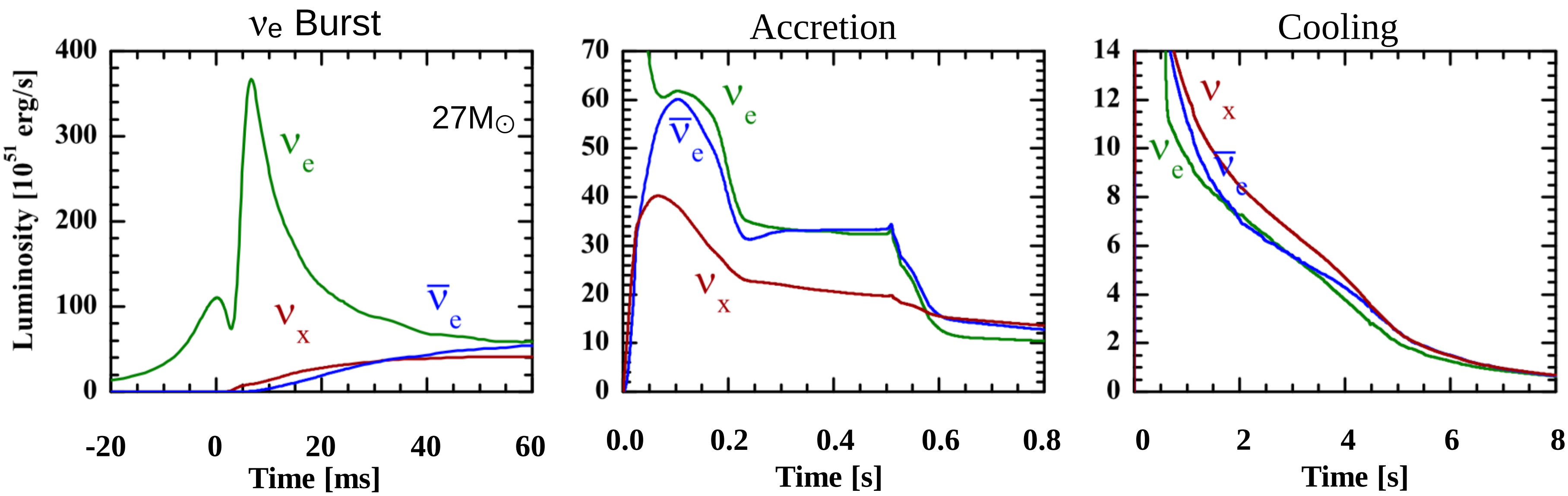
Supernova Neutrinos



- Typical case :huge amount of energy (3×10^{53}erg) emitted in neutrinos at 10Kpc
- 3 phases equally important ▸ 3 "experiments" teaching us about astro- and particle-physic

Process	Type	Events ⟨E_ν⟩=14MeV
$\bar{\nu}_e + p \rightarrow e^+ + n$	CC	5.0×10^3
$\nu + p \rightarrow \nu + p$	NC	1.2×10^3
$\nu + e \rightarrow \nu + e$	ES	3.6×10^2
$\nu + {}^{12}C \rightarrow \nu + {}^{12}C^*$	NC	3.2×10^2
$\nu_e + {}^{12}C \rightarrow e^- + {}^{12}N$	CC	0.9×10^2
$\bar{\nu}_e + {}^{12}C \rightarrow e^+ + {}^{12}B$	CC	1.1×10^2

NB Other ⟨E_ν⟩ values need to be considered to get complete picture.

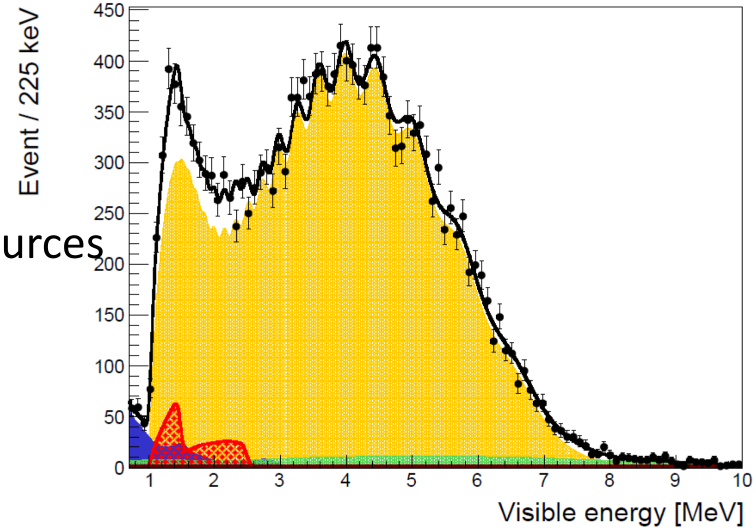
Bound on neutrino masses
Imprinting of the mass ordering
Collective neutrino oscillations
Constraining new physics

Expected events in JUNO for a typical SN distance of 10kpc

We need to be able to handle Betelgeuse (d~0.2kpc) resulting in ~10MHz trigger rate

Geo-neutrinos

- **Geo-neutrinos**
  - Current results
    KamLAND: 30±7 TNU *(PRD 88 (2013) 033001)*
    Borexino: 38.8±12.2 TNU *(PLB 722 (2013) 295)*
    Statistically dominated errors
  - More precise measurements for multiple geological insights
    Fraction of heat flow from radioactive sources
    nature of mantle convection
    energy needed to drive plate tectonics
  - JUNO ×20 statistics
    - Huge reactor neutrino backgrounds
    - Need accurate reactor spectra



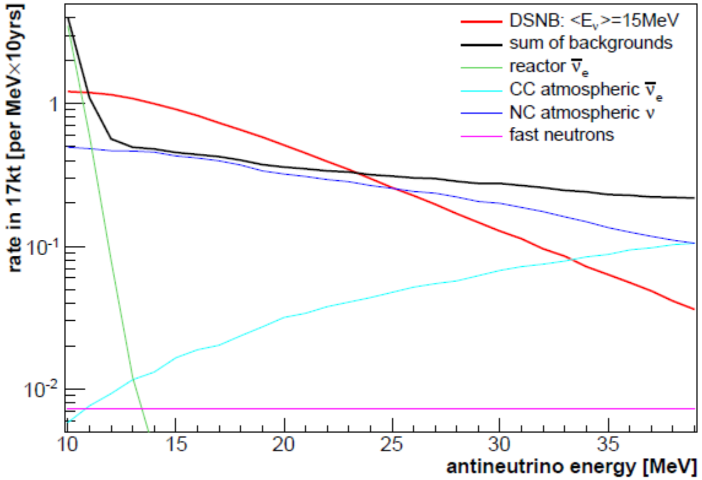
Source	Events/year
Geoneutrinos	408 ± 60
U chain	311 ± 55
Th chain	92 ± 37
Reactors	16100 ± 900
Fast neutrons	3.65 ± 3.65
^{9}Li - ^{8}He	657 ± 130
$^{13}C(\alpha,n)^{16}O$	18.2 ± 9.1
Accidental coincidences	401 ± 4

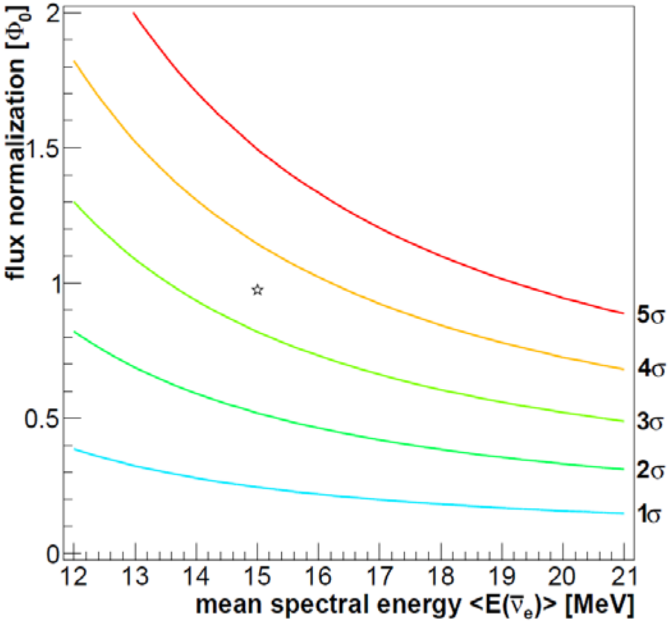
Chondritic ratio Th/U=3.9

Combined shape fit of geo-ν and reactor-ν

	Best fit	1 y	3 y	5 y	10 y
U+Th Fix ratio	0.96	17%	10%	8%	6%
U (free)	1.03	32%	19%	15%	11%
Th (free)	0.80	66%	37%	30%	21%

Diffuse Supernova Neutrino





- DSNB: Past core-collapse events
  - Cosmic star-formation rate
  - Core-collapse neutrino spectrum
  - Rate of failed SNe

Item		Rate (no PSD)	PSD efficiency	Rate (PSD)
Signal	$\langle E_{\bar{\nu}_e}\rangle = 12\,\mathrm{MeV}$	12.2	$\varepsilon_\nu = 50\,\%$	6.1
	$\langle E_{\bar{\nu}_e}\rangle = 15\,\mathrm{MeV}$	25.4		12.7
	$\langle E_{\bar{\nu}_e}\rangle = 18\,\mathrm{MeV}$	42.4		21.2
	$\langle E_{\bar{\nu}_e}\rangle = 21\,\mathrm{MeV}$	61.2		30.8
Background	reactor $\bar{\nu}_e$	1.6	$\varepsilon_\nu = 50\,\%$	0.8
	atm. CC	1.5	$\varepsilon_\nu = 50\,\%$	0.8
	atm. NC	716	$\varepsilon_{\mathrm{NC}} = 1.1\,\%$	7.5
	fast neutrons	12	$\varepsilon_{\mathrm{FN}} = 1.3\,\%$	0.15
	Σ			9.2

10 Years' sensitivity

Syst. uncertainty BG	5 %		20 %	
$\langle E_{\bar{\nu}_e}\rangle$	rate only	spectral fit	rate only	spectral fit
12 MeV	$1.7\,\sigma$	$1.9\,\sigma$	$1.5\,\sigma$	$1.7\,\sigma$
15 MeV	$3.3\,\sigma$	$3.5\,\sigma$	$3.0\,\sigma$	$3.2\,\sigma$
18 MeV	$5.1\,\sigma$	$5.4\,\sigma$	$4.6\,\sigma$	$4.7\,\sigma$
21 MeV	$6.9\,\sigma$	$7.3\,\sigma$	$6.2\,\sigma$	$6.4\,\sigma$

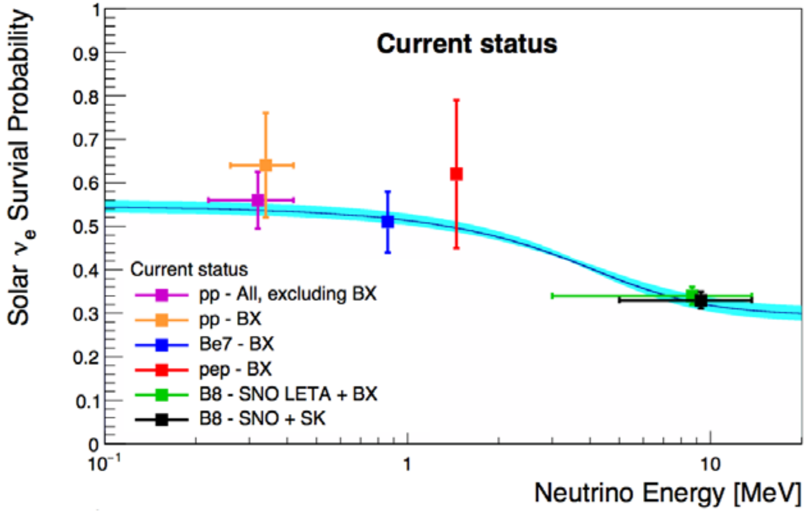
Solar Neutrinos

Fusion reactions in solar core: powerful source of electron neutrinos O(1 MeV)

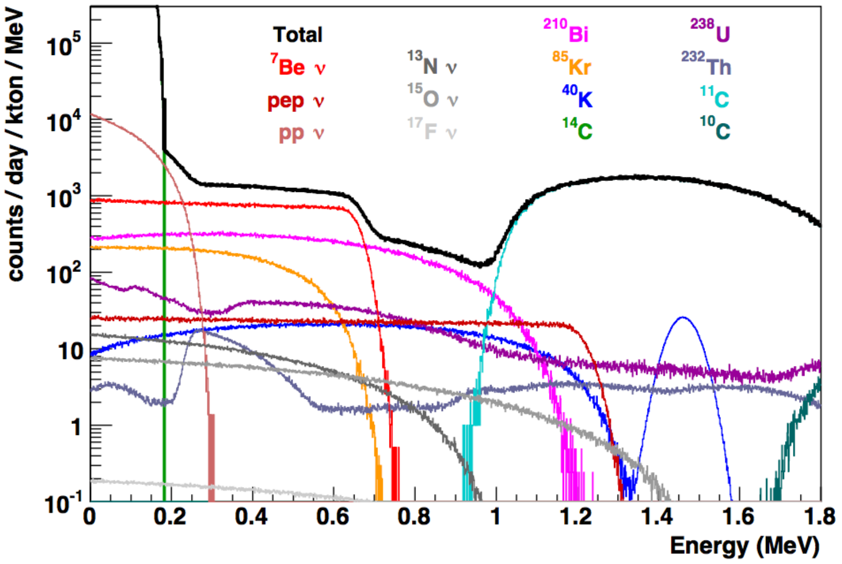
JUNO: neutrinos from ^{7}Be and ^{8}B chains

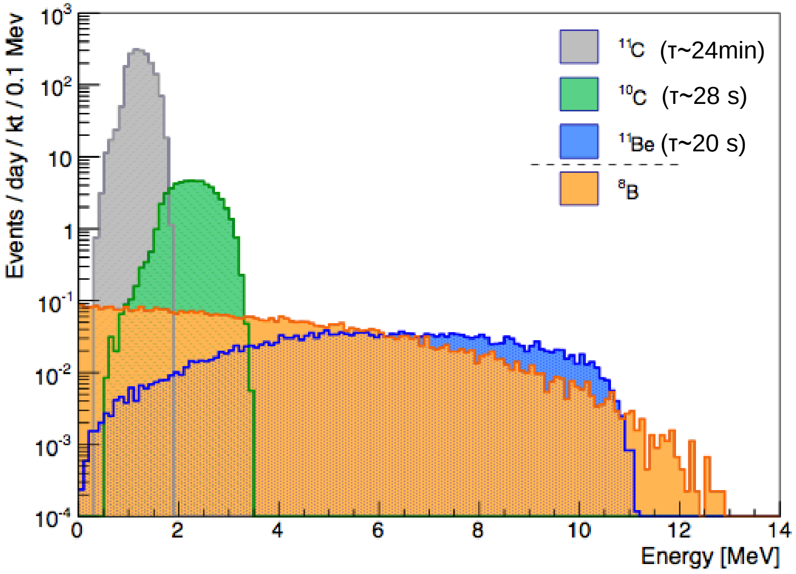
Investigate MSW effect: Transition between vacuum and matter dominated regimes

Constrain Solar Metallicity Problem: Neutrinos as proxy for Sun composition



arXiv 1602.01733





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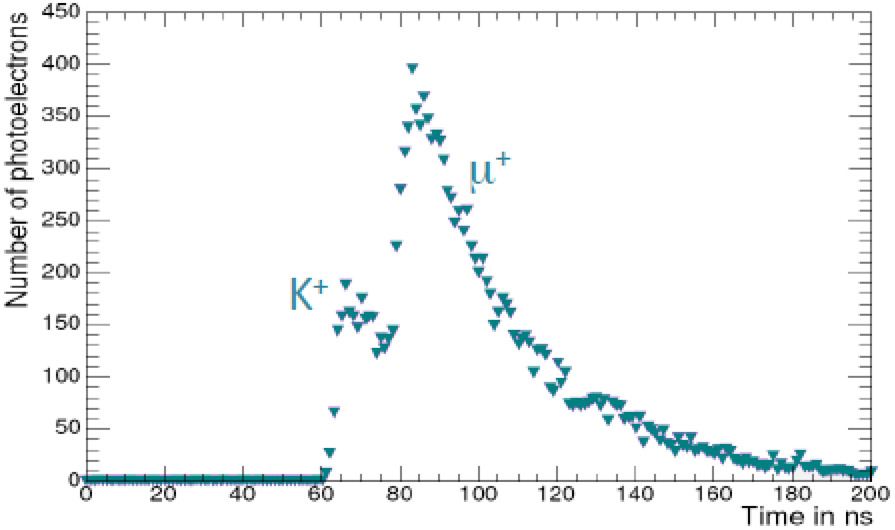
Proton decay into $K^+\bar{\nu}$



SUSY-favored decay mode

Signature $p \to K^+\bar{\nu}$

$\hookrightarrow \mu^+\nu_\mu / \pi^0\pi^+$

→ kaon visible in liquid scintillator!

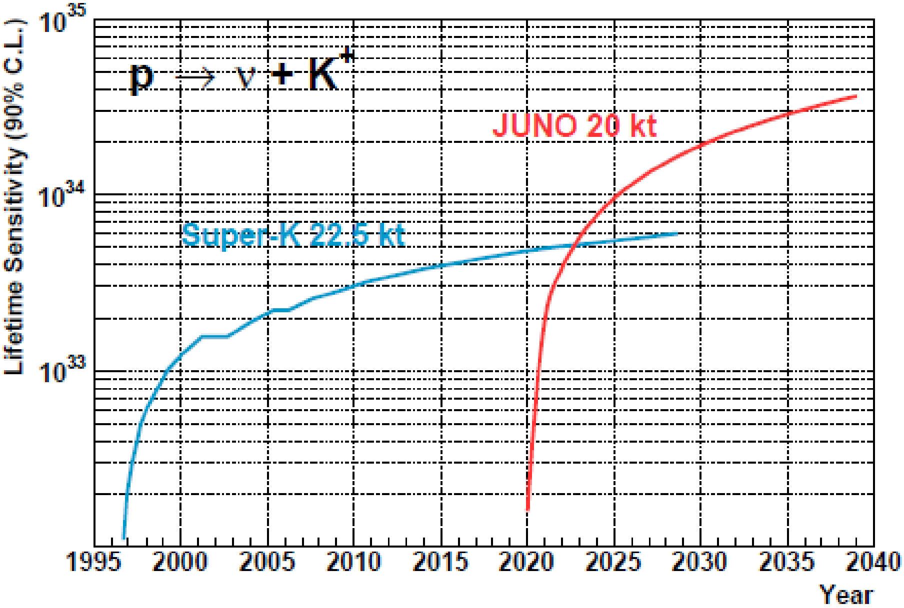
→ fast coincidence signature (τ_K = 13 ns)

→ signal efficiency: ~65% (atm. ν bg)

→ remaining background: <0.1 ev/yr

Limit for LENA if no event is observed in 10yrs (0.5 Mt·yrs):

$\tau_p > 4x10^{34}$ yrs (90%C.L.)



Physics at JUNO

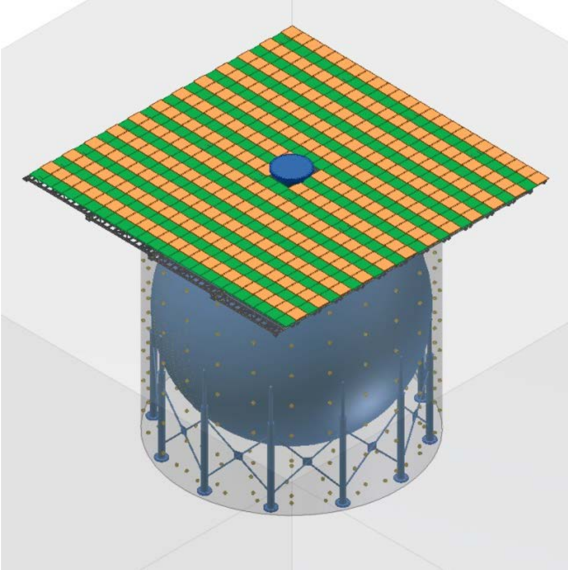
1. **Introduction**
2. **Neutrino Mass Hierarchy**
3. **Precision Measurements of mixing parameters**
4. **Supernova burst neutrinos**
5. **Diffuse supernova neutrinos**
6. **Solar neutrinos**
7. **Atmospheric neutrinos →** some sensitivity to the MH and θ_{23} octant
8. **Geo-neutrinos**
9. **Sterile neutrinos →** Source, IsoDAR ν_e from ^{8}Li decay, superlight sterile based on the reactor spectrum study
10. **Nucleon decay**
11. **Indirect dark matter search →** muon neutrino events from DM annihilation channels
12. **Other exotic searches possible →** sub-leading oscillation effects pointing to new physics
13. **Appendix**

Yellow book

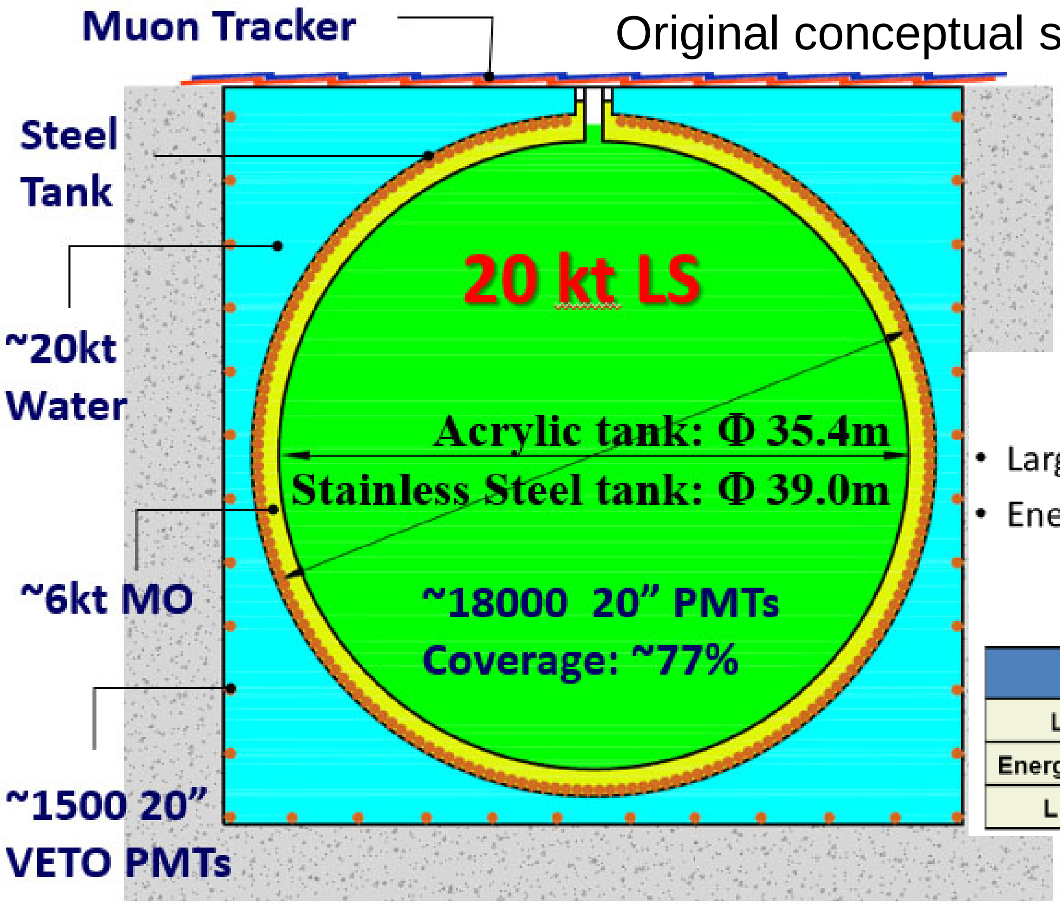
http://arxiv.org/pdf/1507.05613.pdf

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

From the concept to a real detector



- LS large volume: ➔ for statistics
- High Light(PE) ➔ for energy resolution



Original conceptual sketch

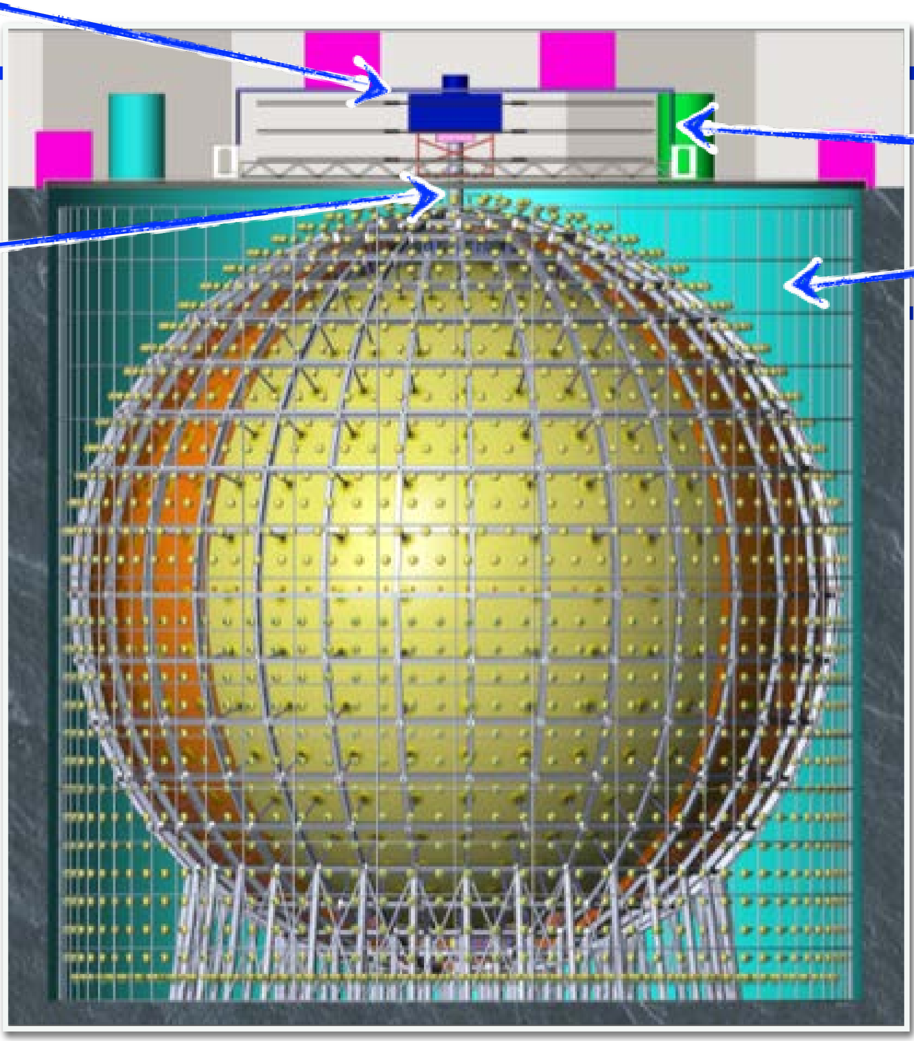
CDR
http://arxiv.org/abs/1508.07166

Challenges

- Large detector: >10 kt LS
- Energy resolution: < 3%/√E ➔ ~1200 p.e./MeV

	Borexino	JUNO
LS mass	~0.3 kt	20 kt
Energy Resolution	5%/√E	3%/√E
Light yield	500 p.e./MeV	~1200 p.e./MeV

Detector Overview



Calibration Room

Muon Veto

Chimney

Top Tracker

Water Pool

Central Detector

Steel Truss

Holding PMTs

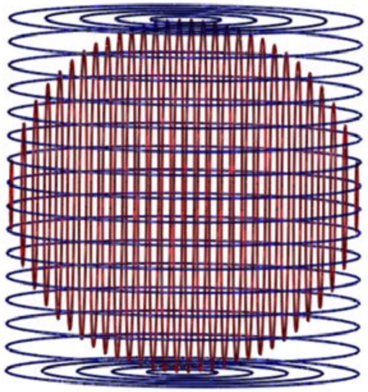
~17000 x 20”

~34000 x 3”

Acrylic Sphere

filled with LS

Magnetic Field
Compensating Coil



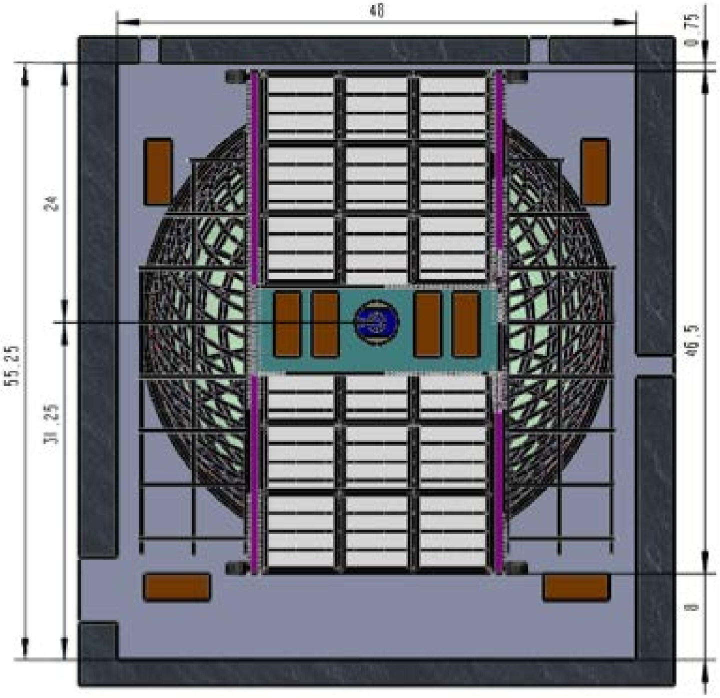
Muon Veto

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)



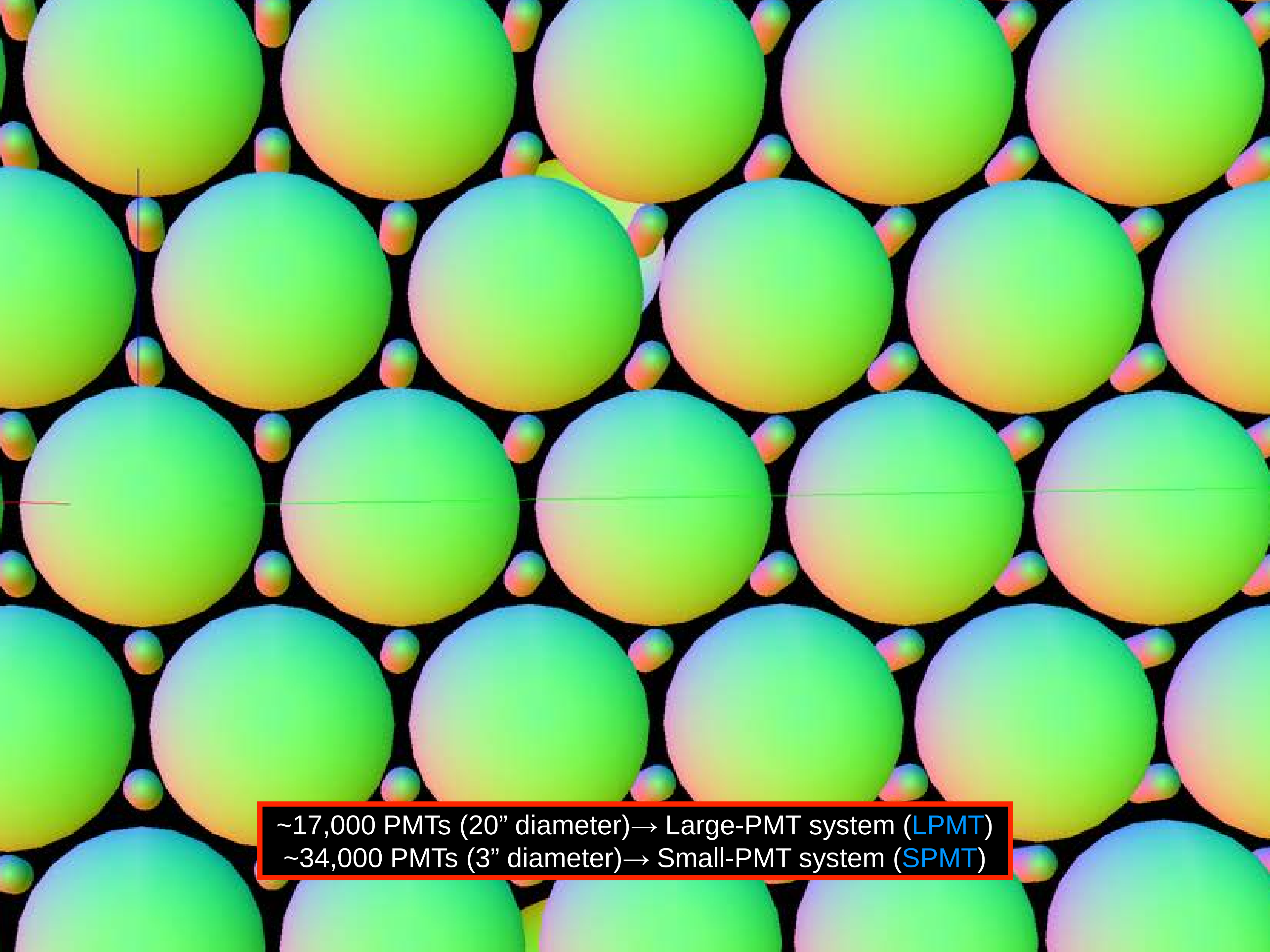
Top Tracker

Using OPERA plastic scintillator (49m^2/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 contaminatio with central detector



~17,000 PMTs (20” diameter)→ Large-PMT system (LPMT)
~34,000 PMTs (3” diameter)→ Small-PMT system (SPMT)

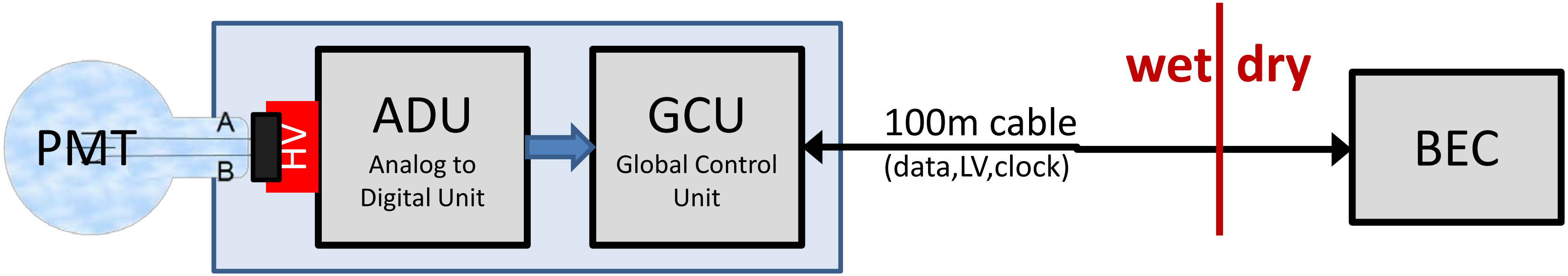
High Quantum Efficiency Photomultipliers

Hamamatsu 20 inches device evolved from the SK type Transmission photocathode

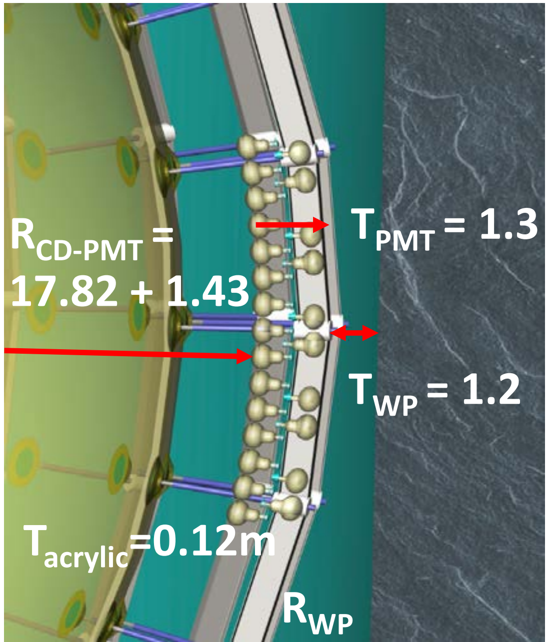
Novel MCP based devices from Chinese producer Transmission + reflective photocathode

Very recent design decision

- Electronics: Underwater option potted with the PMT base


PMT
A
B
HV
ADU
Analog to Digital Unit
GCU
Global Control Unit
100m cable
(data,LV,clock)
wet
dry
BEC

- Pool dimension: diameter - 43.5 m
- 20” PMTs purchasing:
  - 15000 NNVC (MCP based)
  - 5000 Hamamatsu (Dynodes based)



Summary of the strategy to maximize the light yield

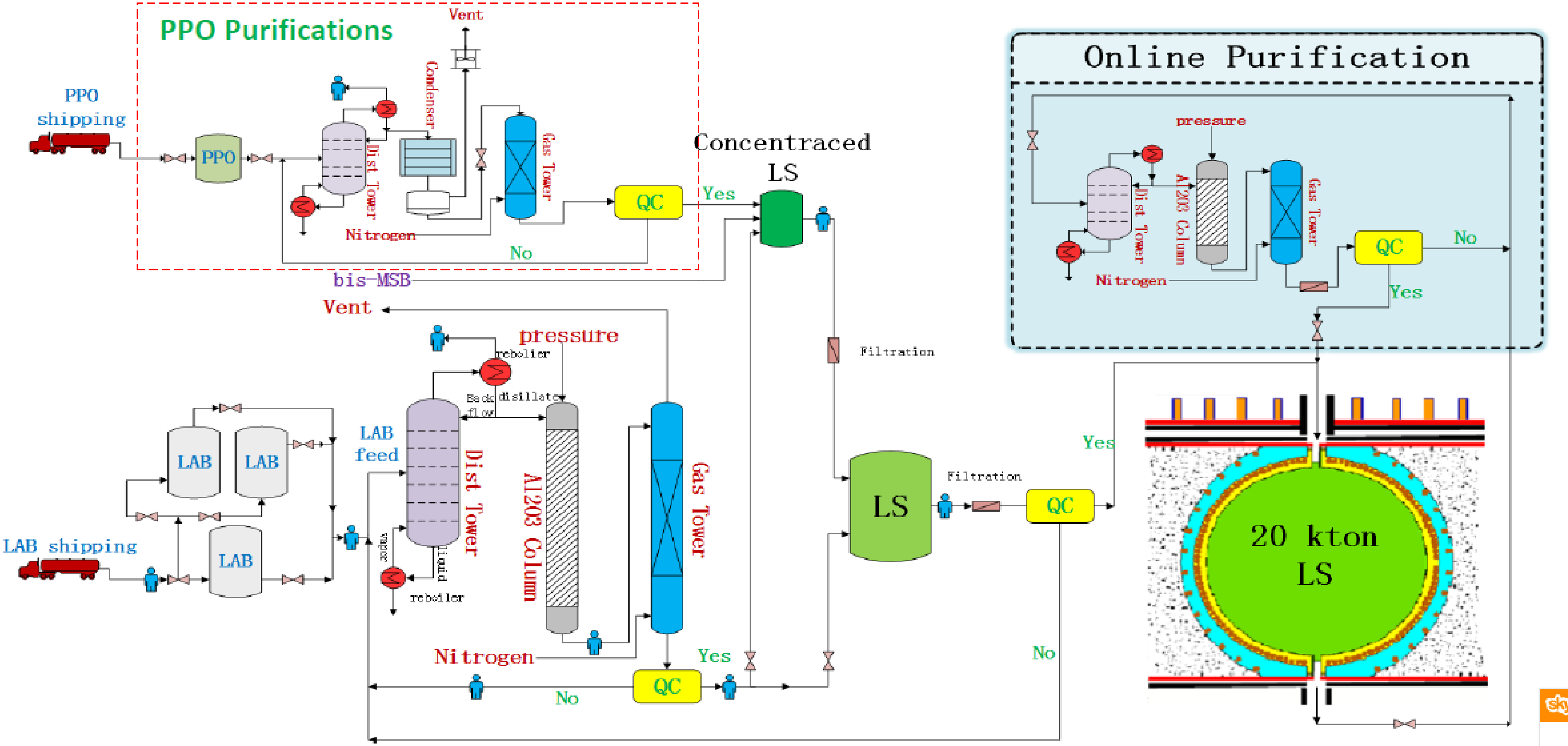
- ✓ Photocathode coverage :
  - **Borexino: 33% → ~ 80%** × **2.3**
- ✓ High QE "PMT":
  - **About 30% both options - better than 90% collection efficiency – In this last respect Chinese option slightly better than (Hamamatsu option)**
- Highly transparent solvent as base of the LS : LAB
  - **Absorption and Rayleigh scattering lengths of several tens of meters**
- High light yield LS:
  - **Borexino: 1.5g/l PPO → 3g/l PPO**

    in addition 4-5 mg/l of bis-MSB (wavelength shifter)

    optimized for increased photon output

Altogether these measures will ensure the desired LY and hence resolution – thorough MC validation

Jiangmen neutrino experiment
LS production-purification flow chart(primary)



To ensure achievement optical and radioactivity requirements → pilot plan installed at Daya Bay

Highlights: LS Pilot plant

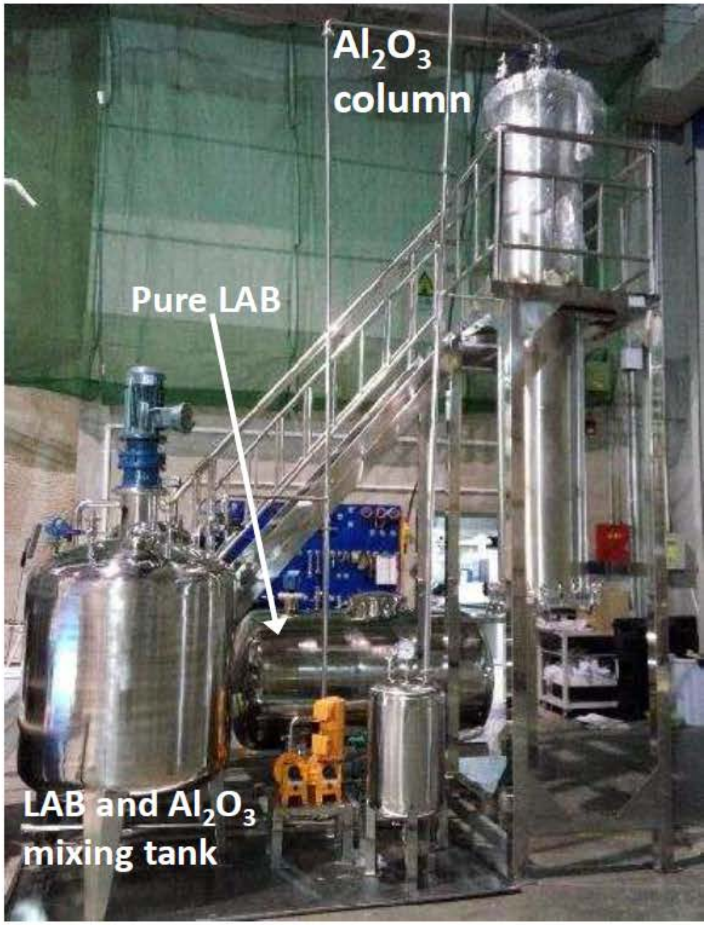
- Purify 20 ton LAB to test the overall design of purification system at Daya Bay. Replace the target LS in one detector
- Quantify the effectivities of subsystems
  - Optical : >20m A.L @430nm?
  - Radio-purity: 10^{-15} g/g (U, Th) ?
- Determine the choice of sub-systems
  - Al_2O_3 column, distillation,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

Distillation and steam stripping system (by Italian group).

Installed at Daya Bay

Distillation system

Steam stripping system

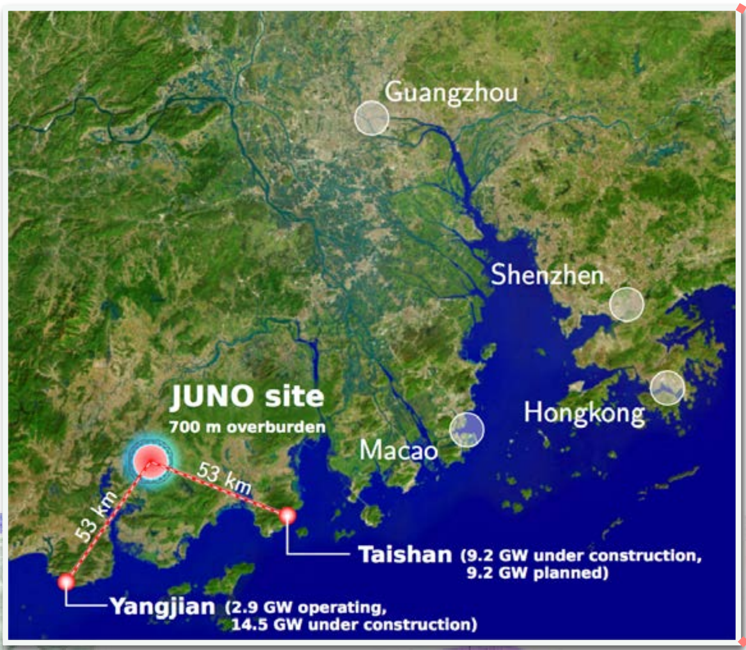


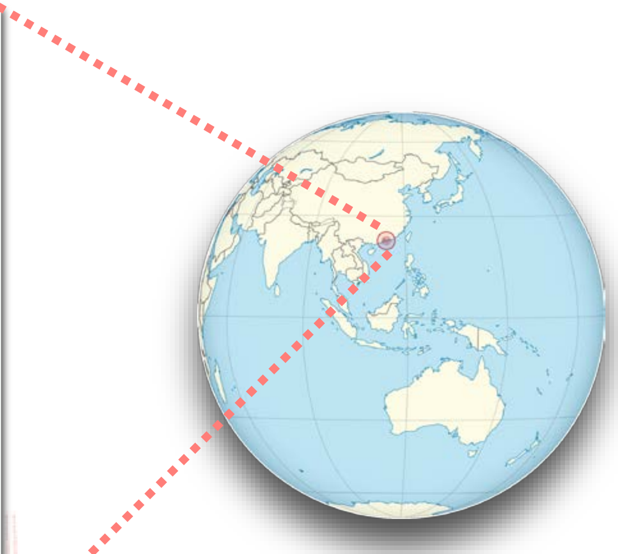
Al_2O_3 column pilot plant installed in Daya Bay LS hall

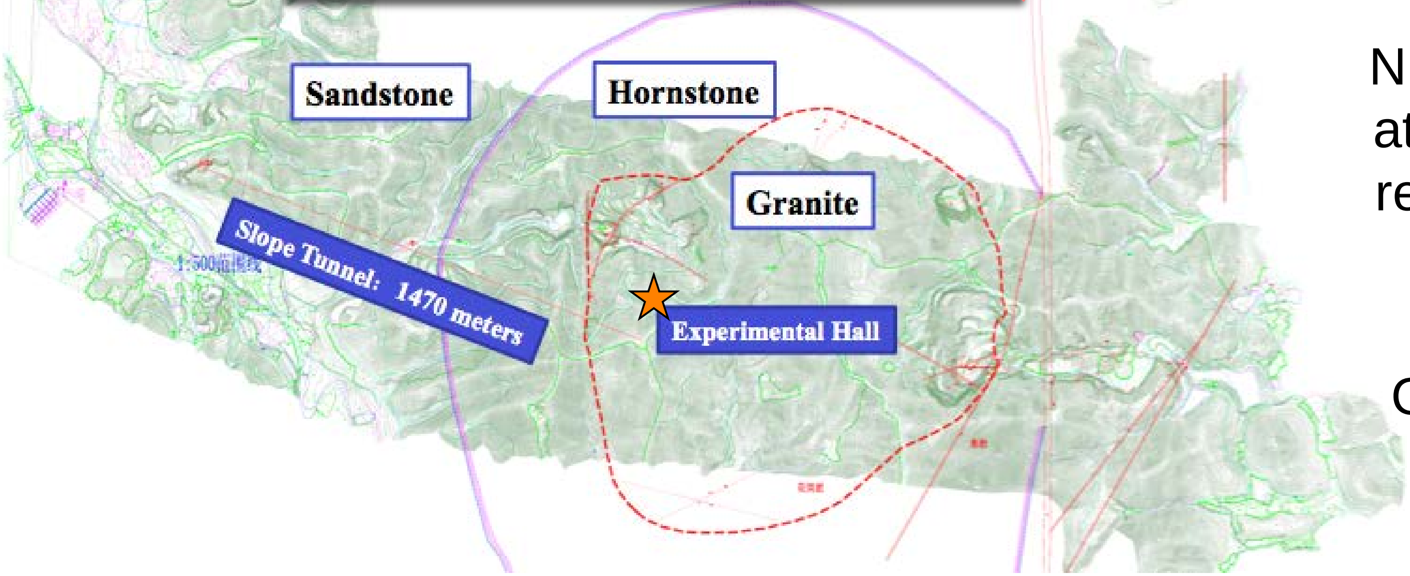
Other ongoing tasks

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

A New Lab in Southern China

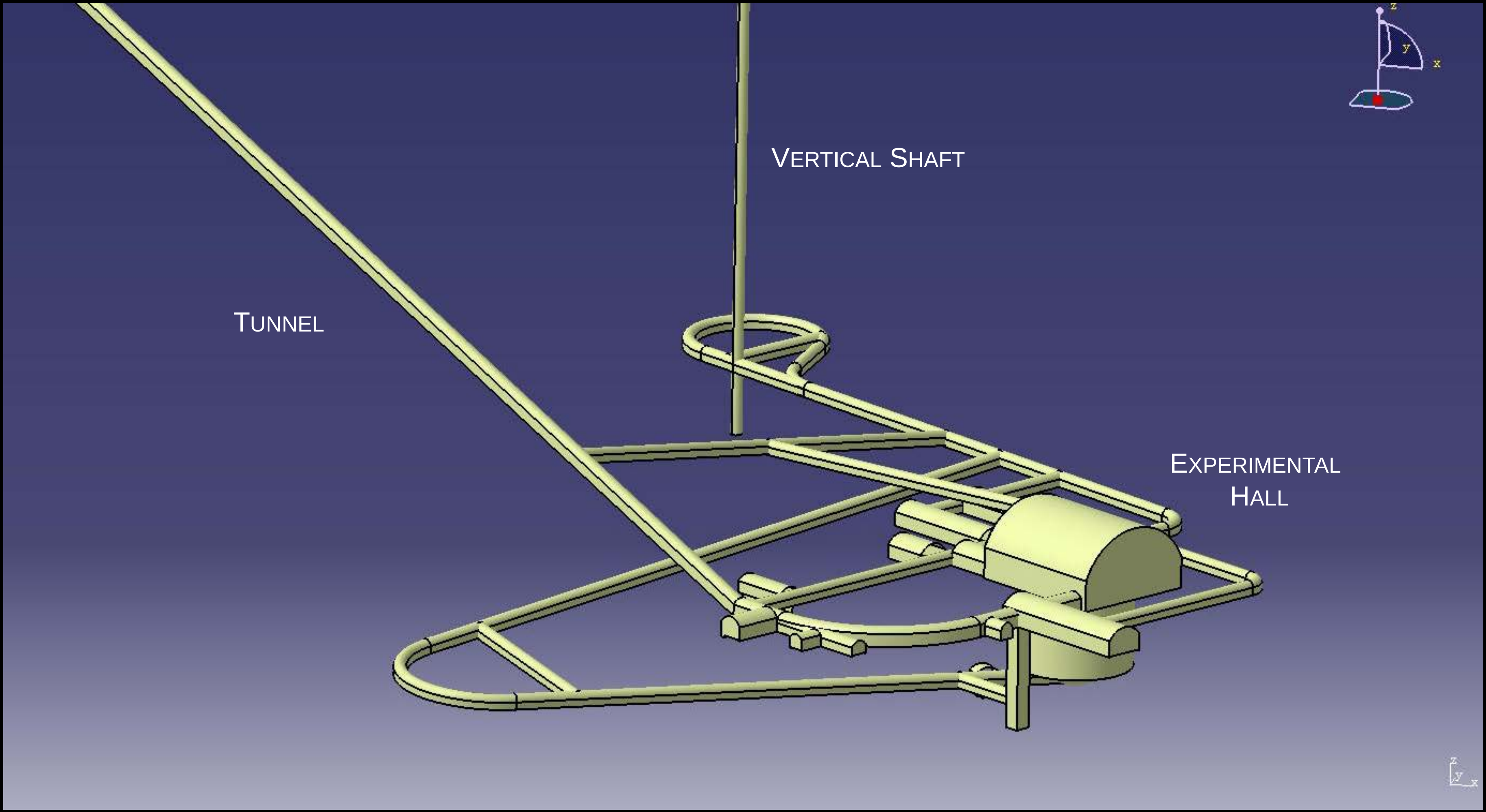






Nice granite structure at right distance from reactors (very lucky!)

Jiangmen City
Guandong province



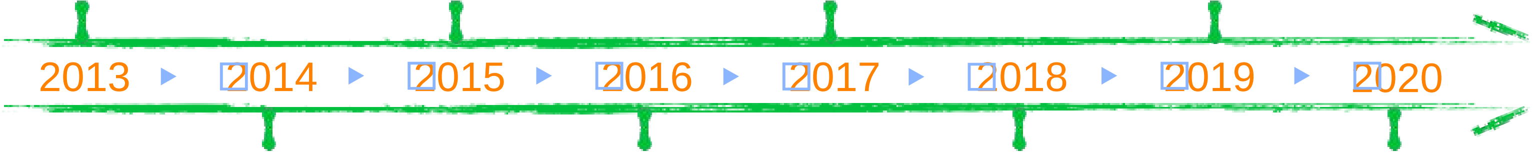
Vertical Shaft

Tunnel

Experimental Hall

Vertical shaft excavation

Schedule



Complete conceptual design. Complete civil design and bidding

PMT production line manufacturing

Complete civil construction. Start detector construction and assembly

Complete detector assembly, installation and LS filling

2013 ▸ 2014 ▸ 2015 ▸ 2016 ▸ 2017 ▸ 2018 ▸ 2019 ▸ 2020

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

Start PMT production. Start detector production or bidding

Start LS production

Start data taking

Conclusion

The vast potential physics reach of very large liquid scintillator detectors - MH determination and beyond – is the foundational motivation of JUNO conceived and planned to mark significant breakthrough for the ultimate quest of the neutrino properties

The Collaboration is rapidly progressing toward the construction of the detector with all the important design decisions already taken and with the excavation advancing “at full steam”

The JUNO exciting science program will start in 2020 when the experiment will be filled

Thank you