Jiangmen Underground Neutrino Observatory

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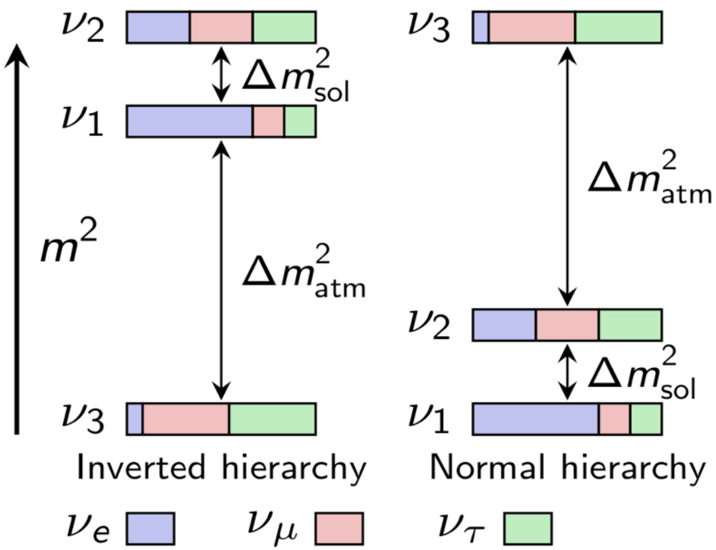
Sun Yat-Sen University
EPS-HEP 2015, Vienna, July 24, 2014

- *Reactor antineutrino sources capable of resolving MH*
- *JUNO designs address multiple challenges*
- *Expected performance of the JUNO detector system*
- *Summary and conclusion*

The Known θ_{13} Enables Neutrino Mass Hierarchy at Reactors



- How to resolve neutrino mass hierarchy using reactor neutrinos
  - KamLAND (long-baseline) measures the solar sector parameters
  - Short-baseline reactor neutrino experiments designed to utilize the oscillation of atmospheric scale
  - ✓ Both scales can be studied by observing the spectrum of reactor neutrino flux

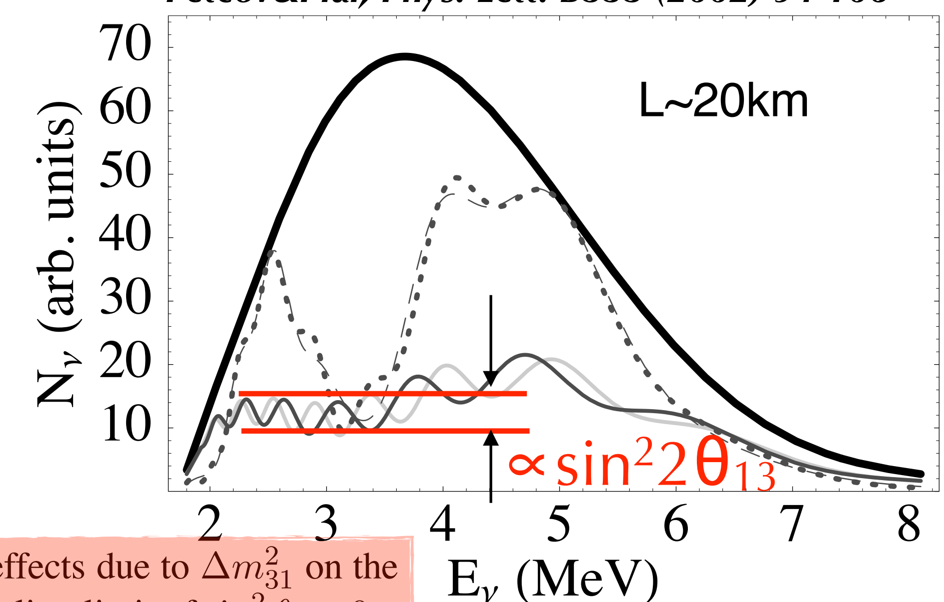
$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

$$-\sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})$$

✓ Mass hierarchy is reflected in the spectrum

✓ Signal independent of the unknown CP phase

Petcov&Piai, Phys. Lett. B533 (2002) 94-106

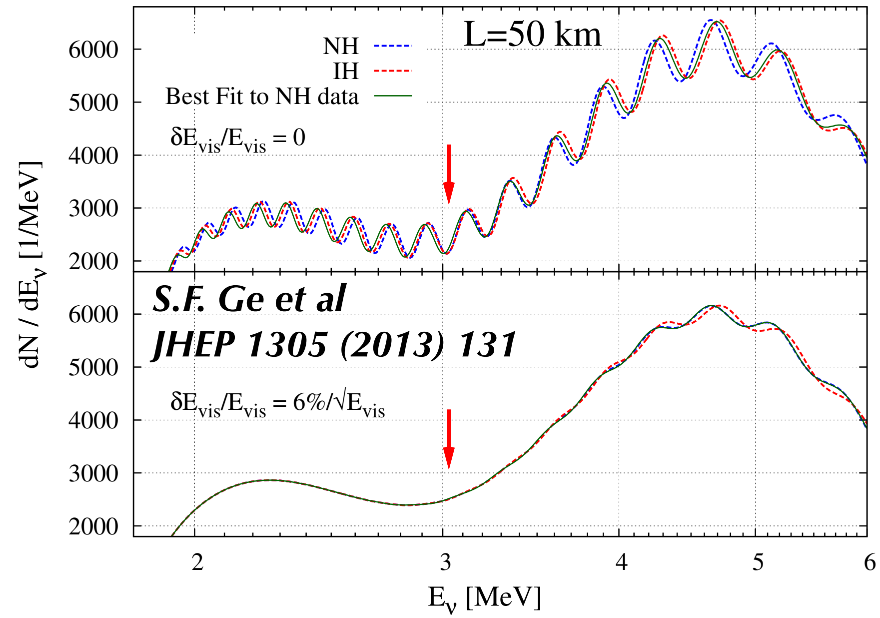


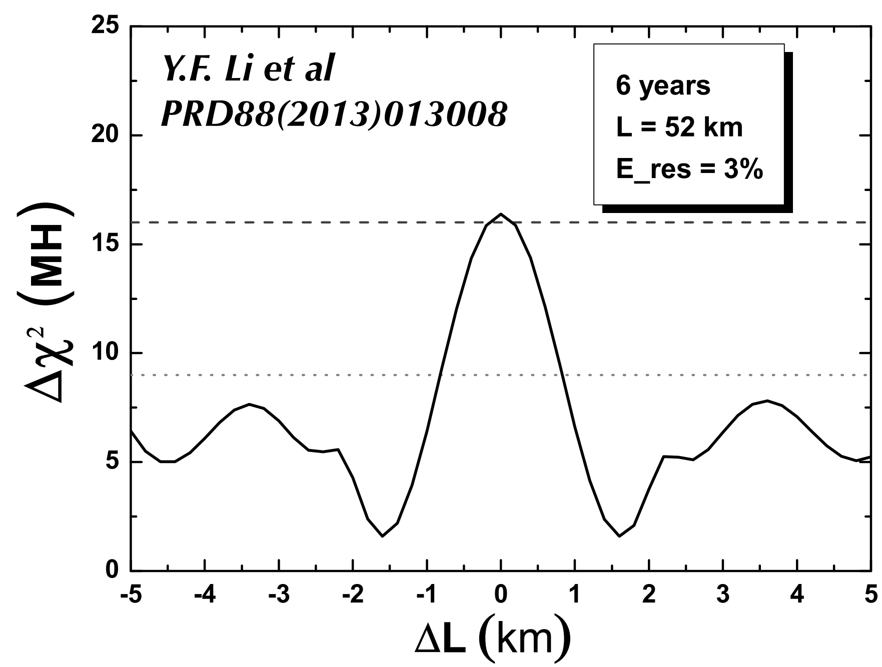
- the value of $\sin^2\theta$, which controls the magnitude of the sub-leading effects due to Δm^2_{31} on the $\Delta m^2_{\odot}$−driven oscillations: the effect of interest vanishes in the decoupling limit of $\sin^2\theta \to 0$;

Realization&Plausibility: L. Zhan et al, PRD.78.111103; J. Learned et al PRD.78.071302

Challenges in Resolving MH using Reactor Sources

- Energy resolution: ~3%/sqrt(E)
  - Bad resolution leads to smeared spectrum and the MH signal practically disappears
- Energy scale uncertainty: <1%
  - Bad control of energy scale could lead to a wrong result
- Statistics (who doesn't need more?)
  - ~36GW thermal power, a 20kt detector plus precise muon tracking to get the best statistics
- Reactor distribution: <~0.5km
  - If too diversified, the signal could go away due to cancellation of different baselines
  - JUNO baseline differences are within half kilometer.





Jiangmen Underground Neutrino Observatory

China to build a huge underground neutrino experiment

Mar 24, 2014 5 comments

Test site for the Jiangmen Underground Neutrino Observatory

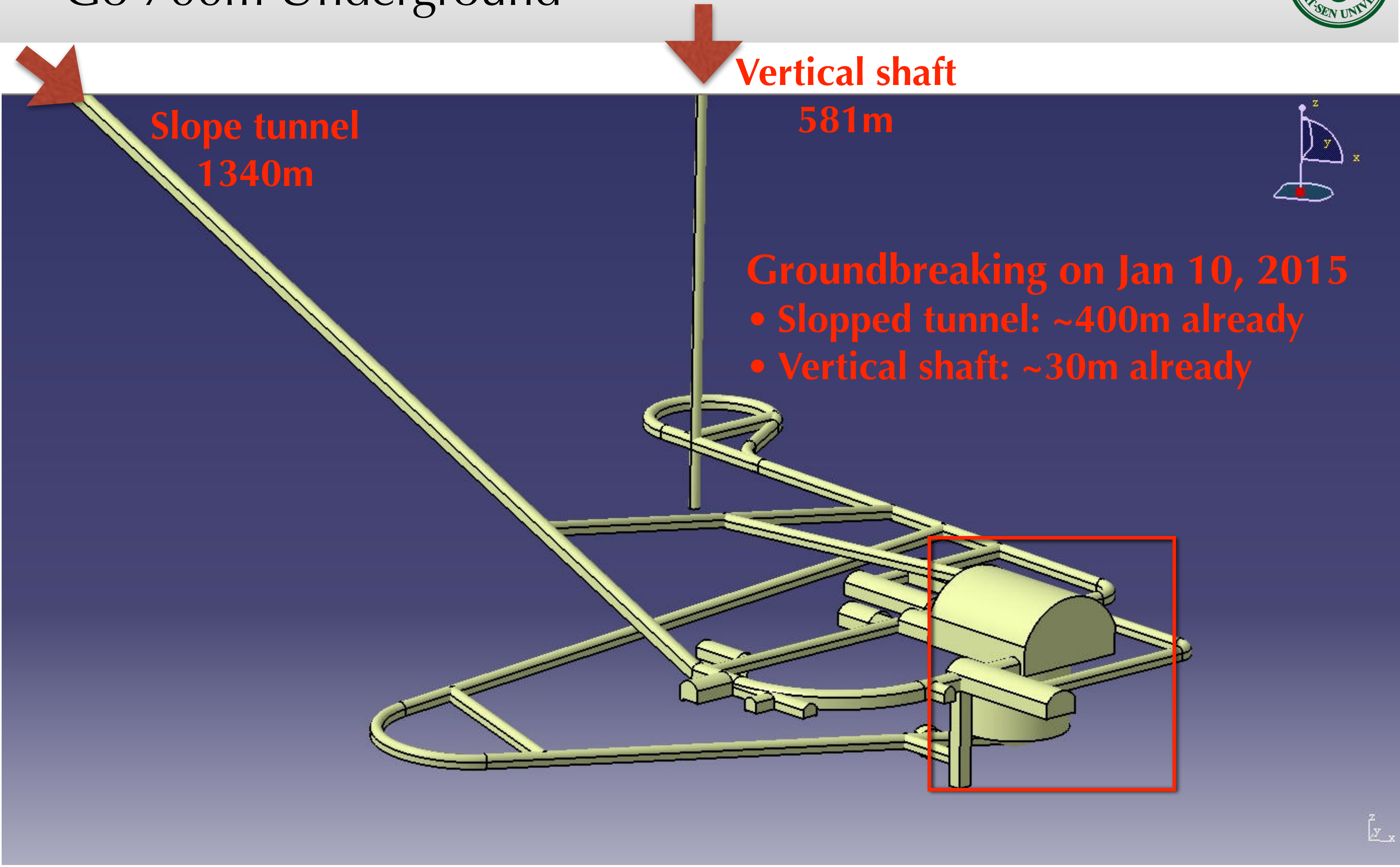
"Work has started on a huge underground neutrino lab in China. The $330m Jiangmen Underground Neutrino Observatory (JUNO) is being built in Kaiping City, Guangdong Province, in the south of the country around 150 km west of Hong Kong. When complete in 2020, JUNO is expected to run for more than 20 years, studying the relationship between the three types of neutrino: electron, muon and tau."

A Medium-Baseline Reactor Neutrino Experiment

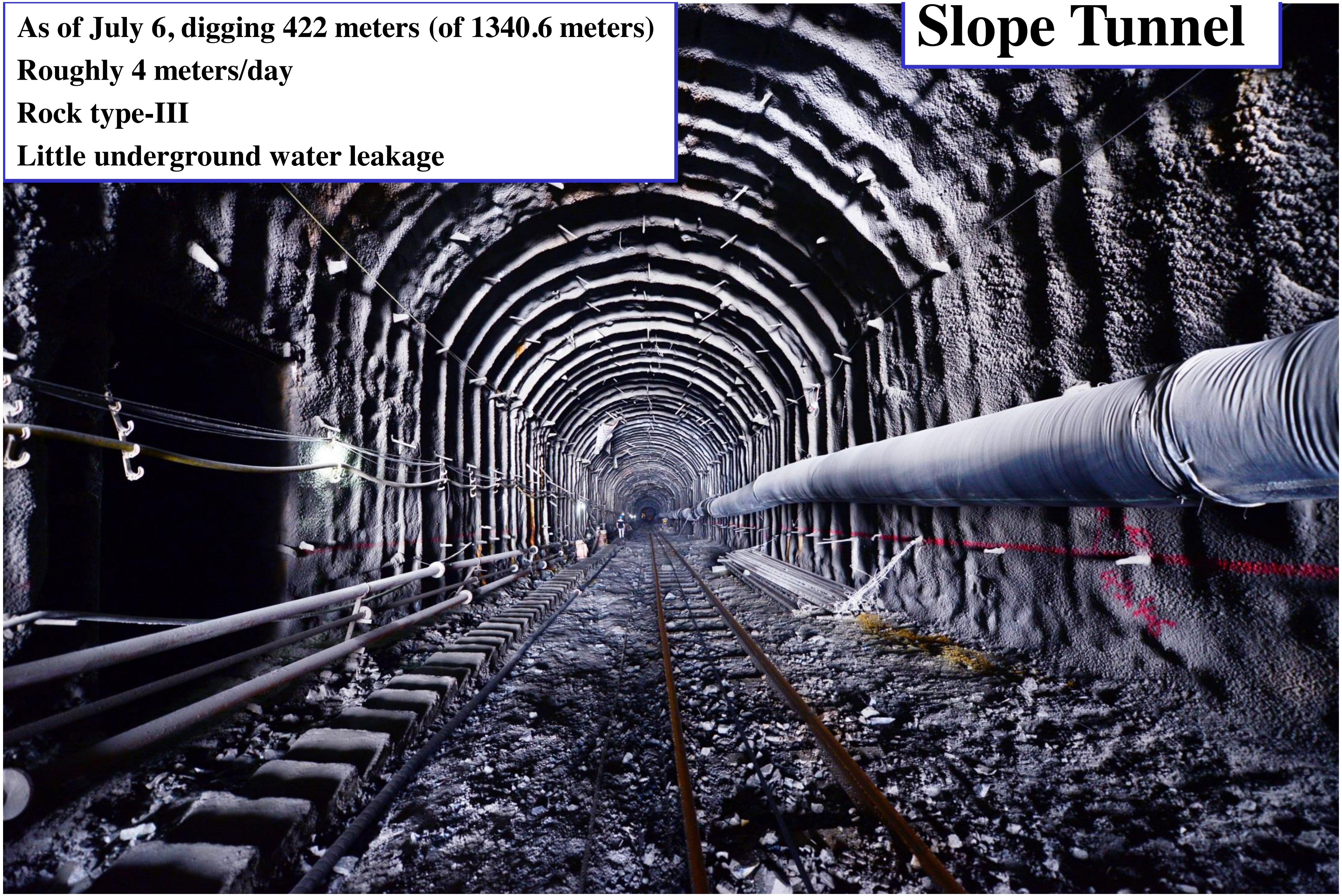
	Yangjiang	Taishan
Status	under construction	under construction
Power/GW	17.4	18.4

Surface Facilities: Look into the Near Future……

Go 700m Underground

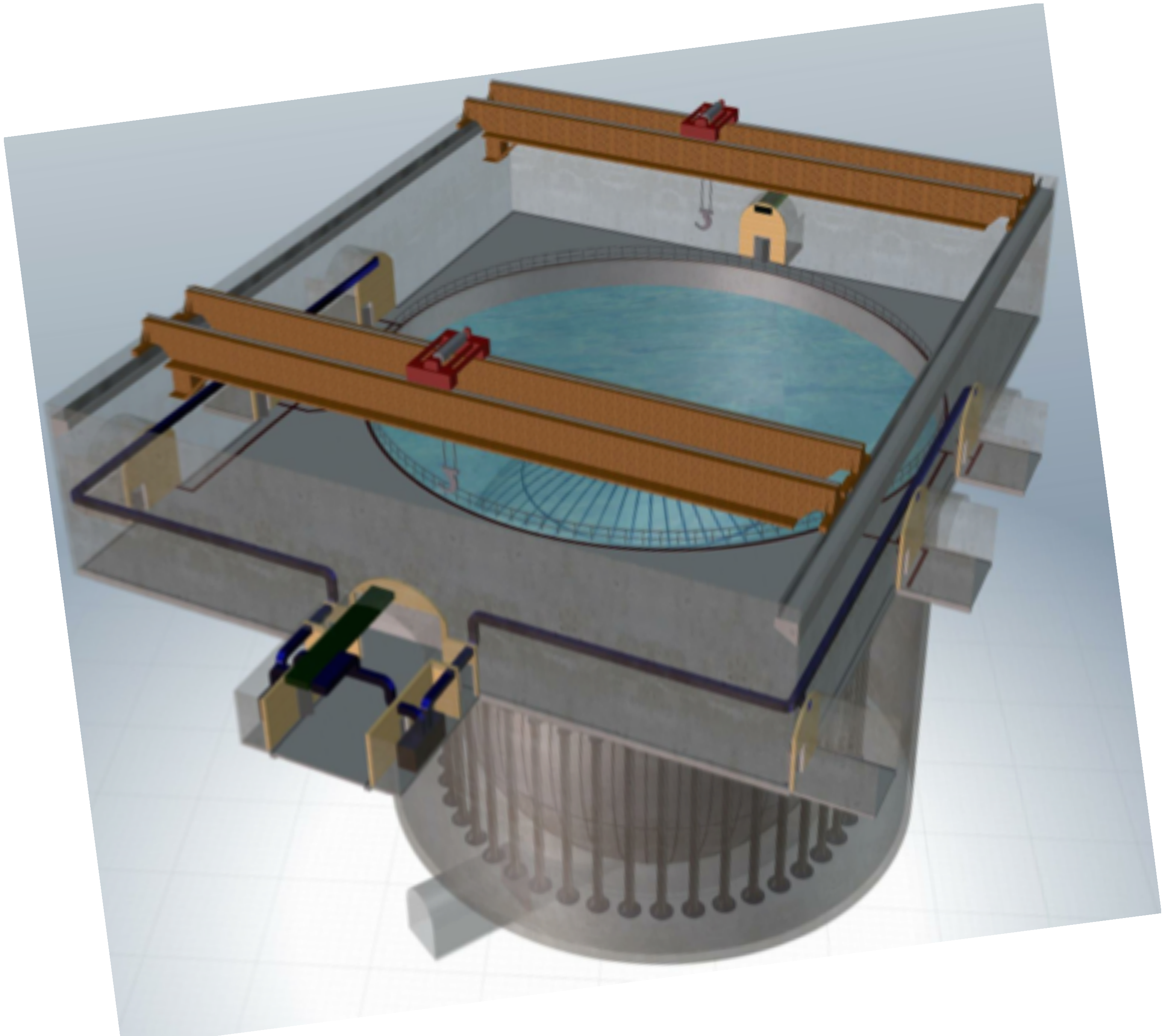


Slope Tunnel Progress (July 13, 2015)



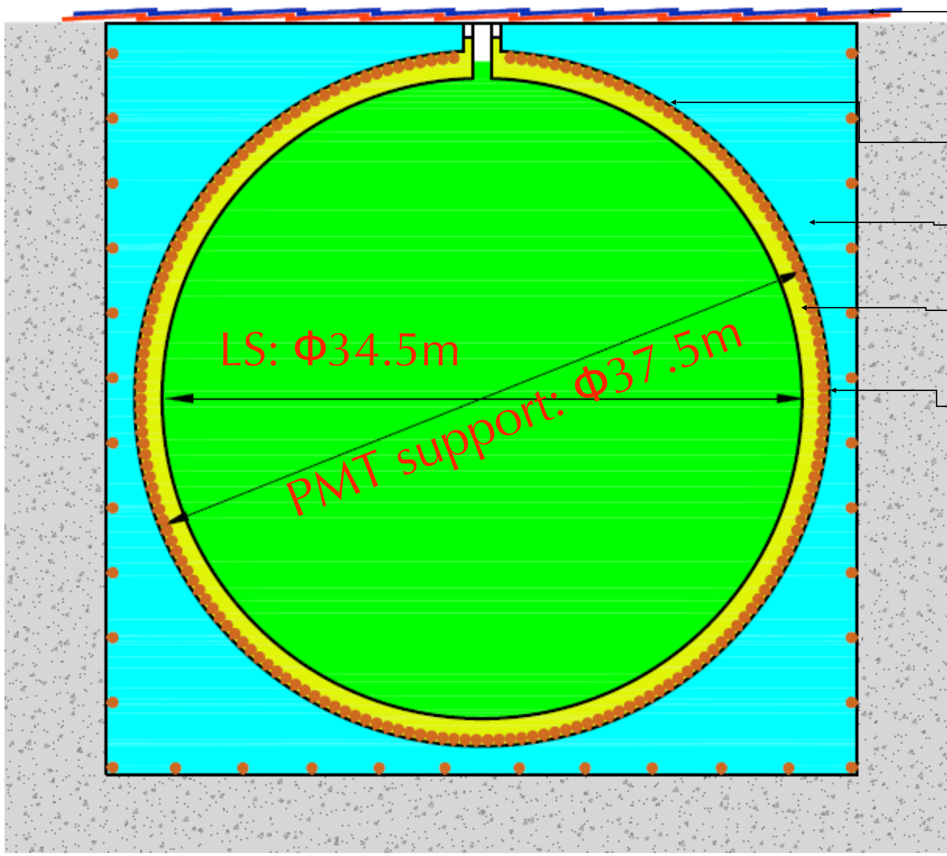
Vertical Shaft Groundbreaking and Progress (Jul 13, 2015)

The Underground Detector System of JUNO



- A 55x48x27 m^3 main experimental hall and other halls&tunnels for electronics, LS, water, power, refuge and other facility rooms.
- A 20kt spherical liquid scintillator detector
- The muon veto system combines a cylindrical water Cherenkov detector (~42.5m in diameter and depth) and the OPERA calorimeters on the top to provide tracking information

A Conceptual Design of the Detector is Formed



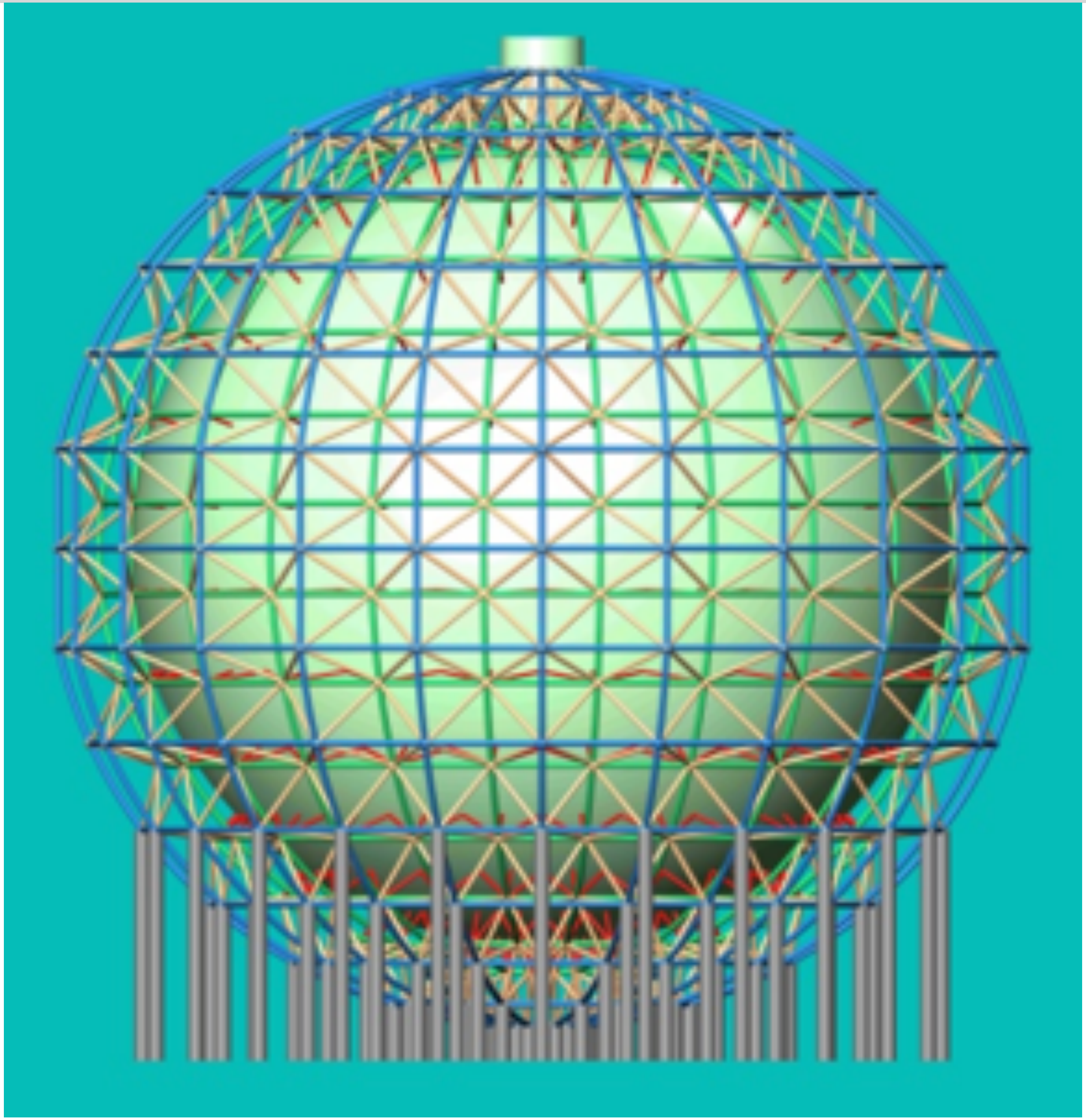
$$\frac{\Delta E}{E} = \sqrt{a^2 + \frac{b^2}{E} + \frac{c^2}{E^2}}$$

Energy leakage & non-uniformity → a; Photon statistics → b; Noise (~background) → c

To reach ~3%/√E energy resolution,

- Keep the detector as uniform as possible → a spherical detector
- Keep the noise as low as possible → clean materials and quiet PMTs
- Obtain as many photons as possible → high light yield scintillator, high photocathode coverage, and high detection efficiency PMTs

More Light: the JUNO Detector Design



- JUNO central detector design: a 35m diameter acrylic sphere holds the LS
- Stainless truss provides mechanical supports to the acrylic sphere and the PMTs
- Water Cherenkov detector with top tracker functions as the muon veto and reconstruction system
- Underwater electronics is the current baseline

The Detector Performance Goals

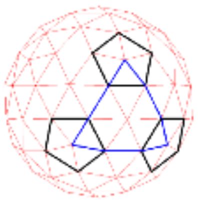
	Daya Bay	BOREXINO	KamLAND	RENO-50	JUNO
Target Mass	20t	~300t	**~1kt**	**~18kt**	**~20kt**
PE Collection	~160 PE/MeV	**~500 PE/MeV**	~250 PE/MeV	**>1000 PE/MeV**	**~1200 PE/MeV**
Photocathode Coverage	~12%	**~34%**	**~34%**	**~67%**	**~80%**
Energy Resolution	~7.5%/√E	**~5%/√E**	~6%/√E	**3%/√E**	**3%/√E**
Energy Calibration	~1.5%	**~1%**	~2%	**?**	**<1%**

➡ **An unprecedented LS detector is under development for the JUNO project —> a great step in detector technology**

More Light: Photocathode Coverage

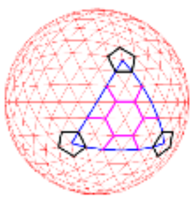
Polyhedral module layout method

others

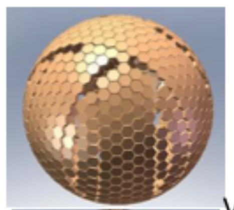


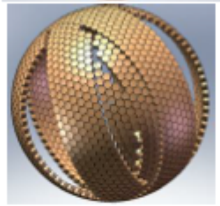
3 layers: 180 Triangles(or 12 Pentagons and 20 hexagons)

Football



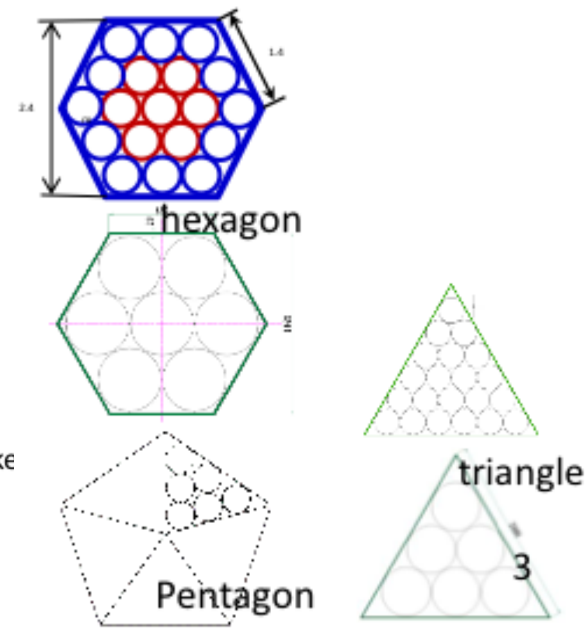
6 layers: 720 Triangles(or 12 Pentagons and 110 hexagons)

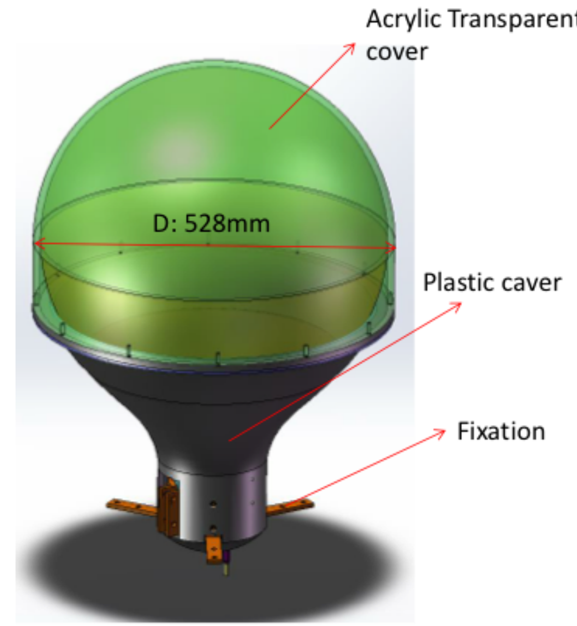




9 layers: 1620 Triangles(or 12 Pentagons and 260 hexagons)

Volleyball-like



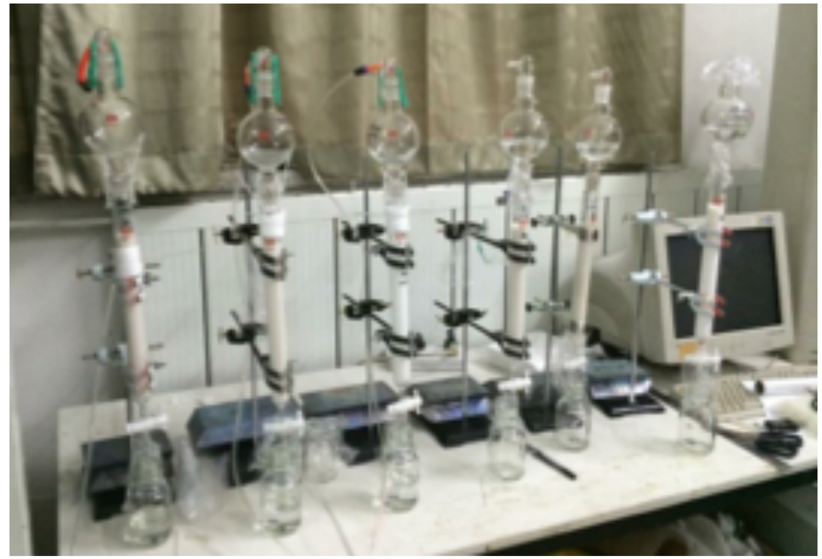


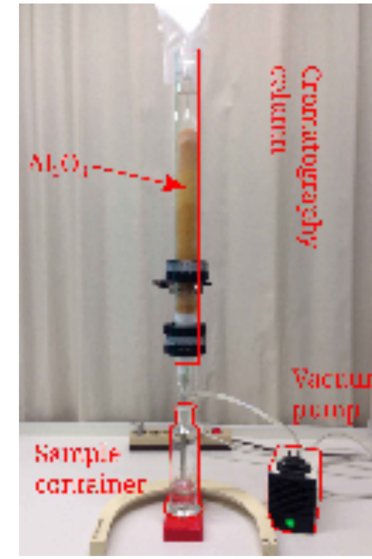
Conceptual explosion proof Structure of PMT

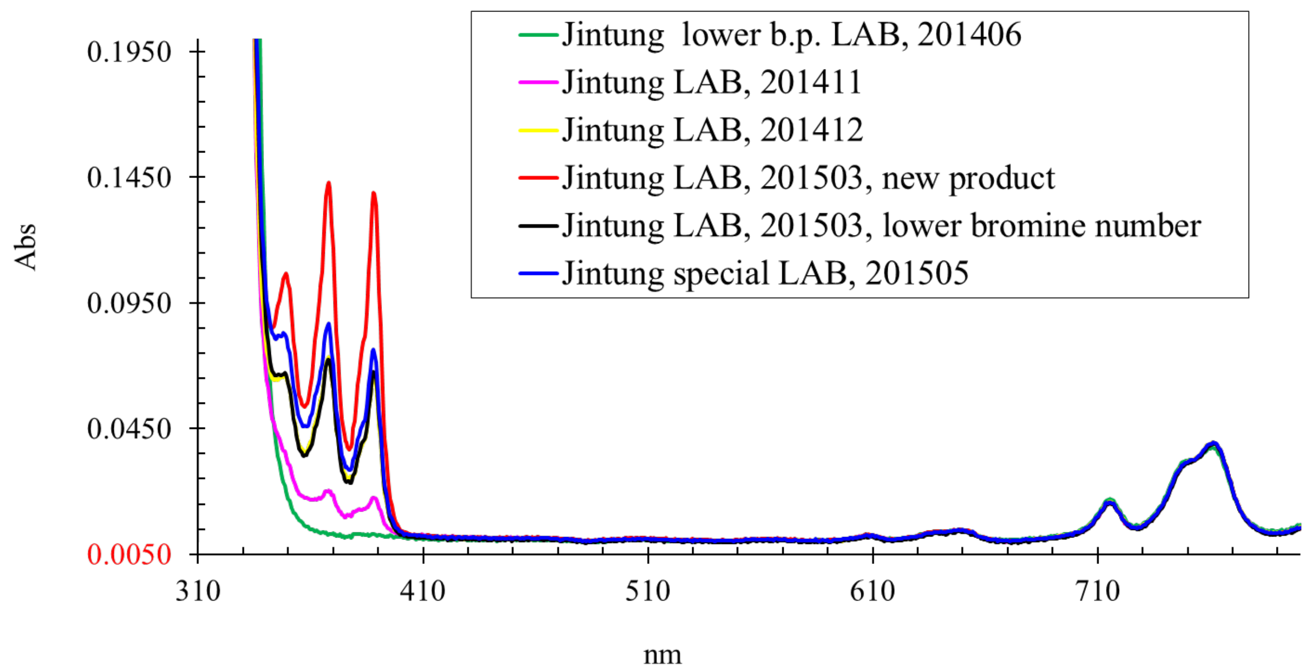
Scheme	Acrylic vessel+steel space truss	stainless-steel tank + balloon with acrylic support
Arrangement method	Layer-by-layer layout method: arrange PMT optimally then deleted PMT where bars occupied	9-layers' module layout method: 272 modules or 1620 installed cells
Radius & PMT No.	Radius has no influence to coverage R1: 18.7m PMT No. : 16918-616 coverage: 77.7 R2: 19.9m PMT No. : 19214-616 coverage: 77.9	Optimal radius: 18.7m PMT No. : 16520
Maximum coverage	~77.9%-2.5%≈75.4%	~76.8%

More Light: More Transparent LAB-based Liquid Scintillator

- There are a few key points about liquid scintillator: light yield, optical transparency and radioactive purity
  - To improve optical transparency and reduce radioactive impurity, purification is needed
  - Various vendors' samples are being tested, >20m (at 430nm) attenuation lengths achievable in lab with PPO and bis-MSB.
  - Various groups are doing studies in parallel. We all see space for improvements and R&D activities are ongoing

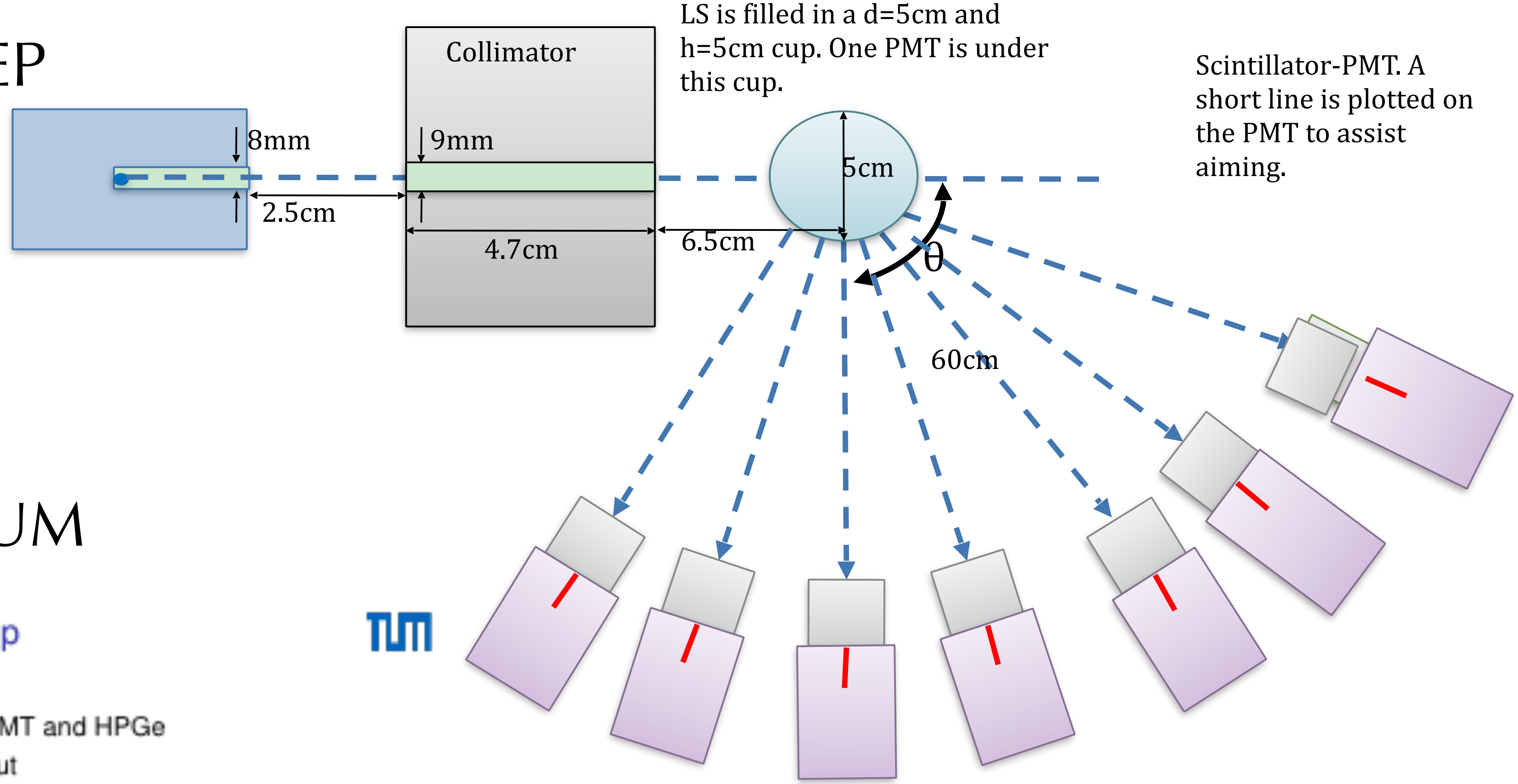






Better Precision: Scintillator Energy Response Understanding

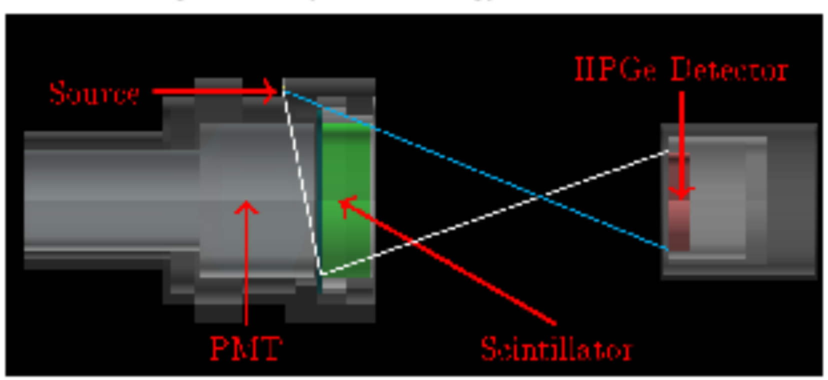
Setup I: IHEP



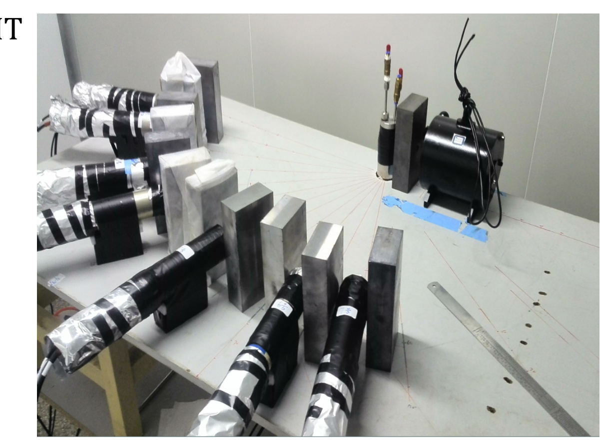
Setup II: TUM

Electron quenching: set-up

- Conincidence between PMT and HPGe
- PMT signal ⇒ Light output
- HPGe signal ⇒ Deposited energy



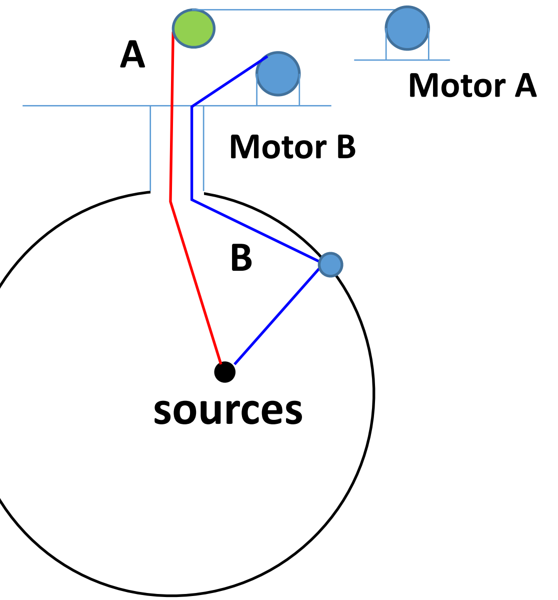
7 LaBr-PMT



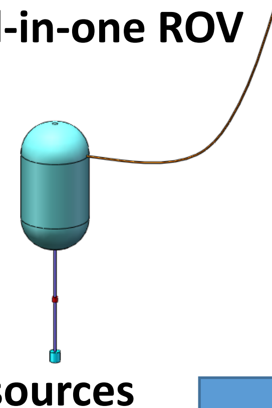
Better Precision: Calibration System Conceptual Designs

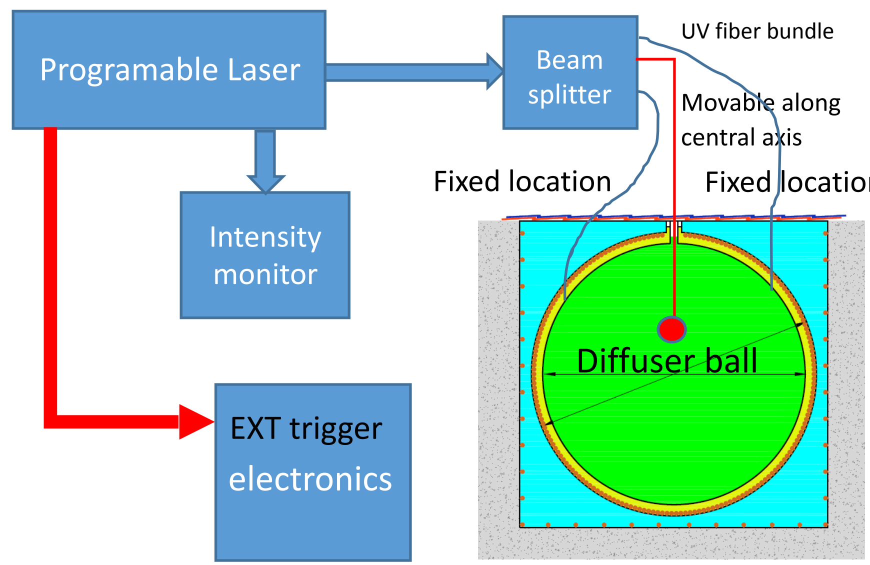
- Point radioactive source calibration systems
  - An automatic rope system is the most primary source delivery system
  - A ROV to be more versatile
  - A guide tube system to cover the boundaries and near boundary regions
- A UV laser system being design to calibrate the LS properties in situ
- Also considering short-lived diffusive radioactive sources to calibrate the detector response

A-B rope synchronous motion

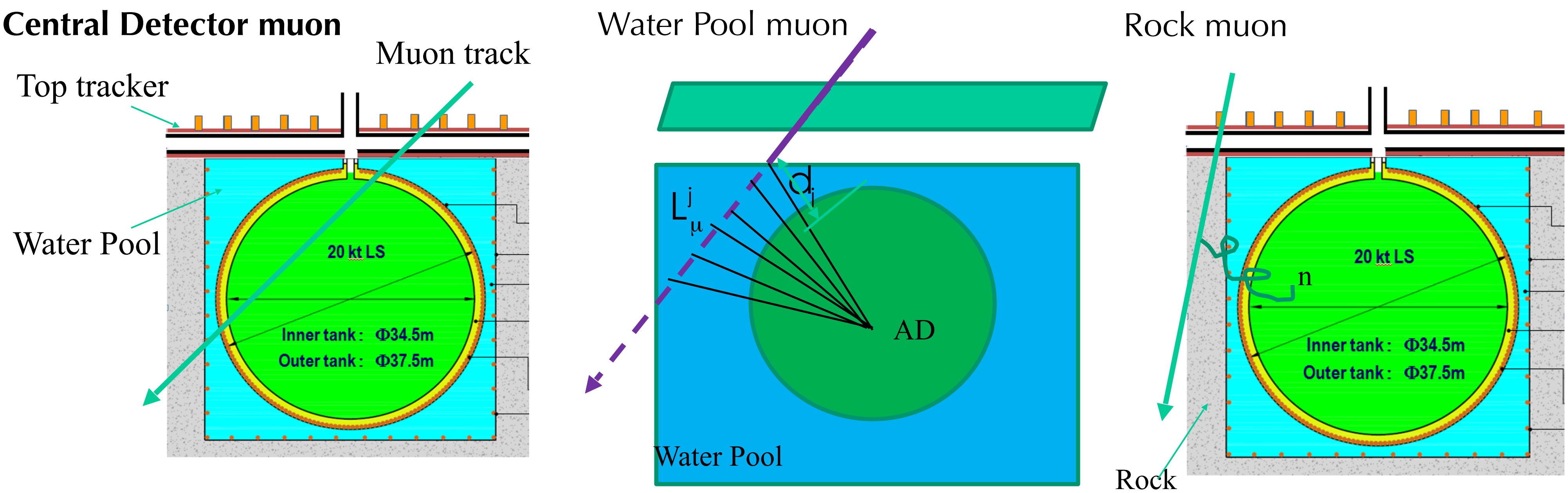


All-in-one ROV

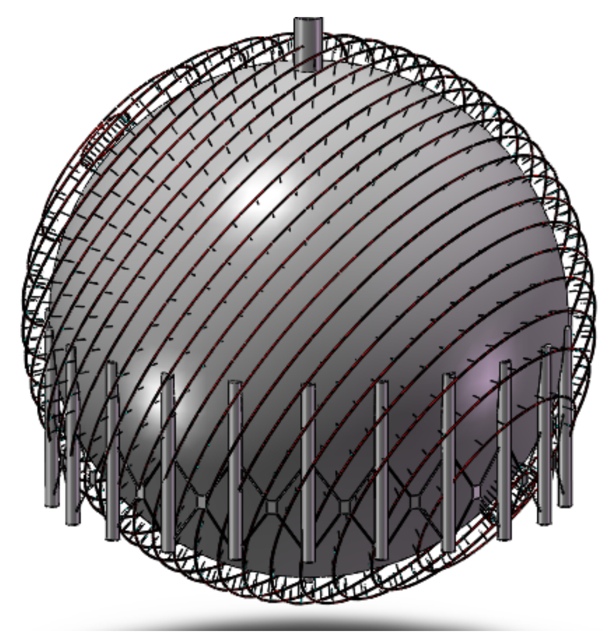




Veto System Considerations and Designs

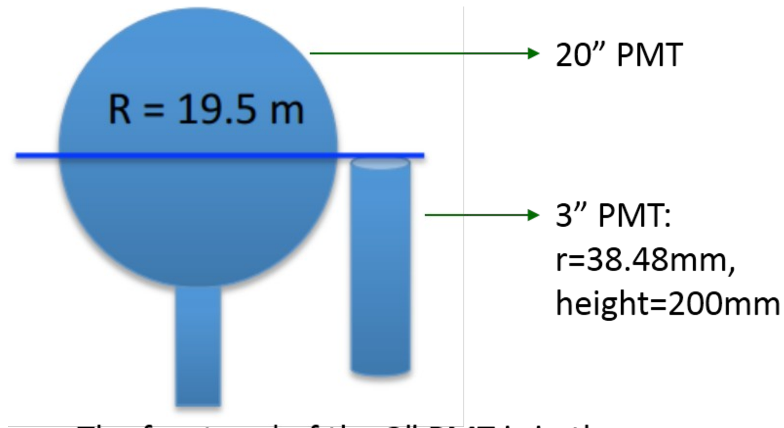


- Veto is not just a veto. Besides radioactive background shielding, we also need tracking information to better understand and remove cosmogenic backgrounds
  - The main body is the water Cherenkov detector
  - OPERA scintillator calorimeters will be moved to JUNO as the Top Tracker (TT)
- Earth magnetic field compensation coils are being designed together with the veto system design
- Radon removal, control and monitoring are under study

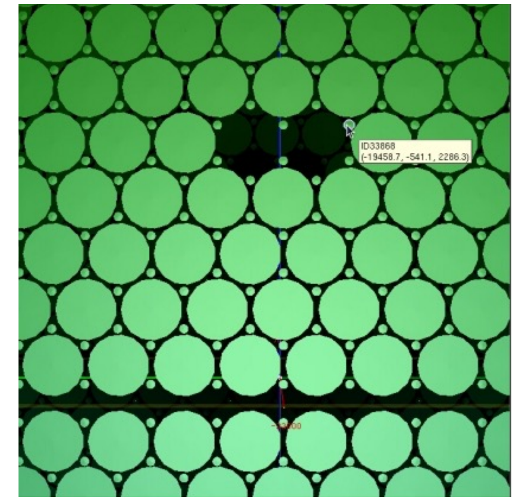


Even Better: A Double Calorimetry Design

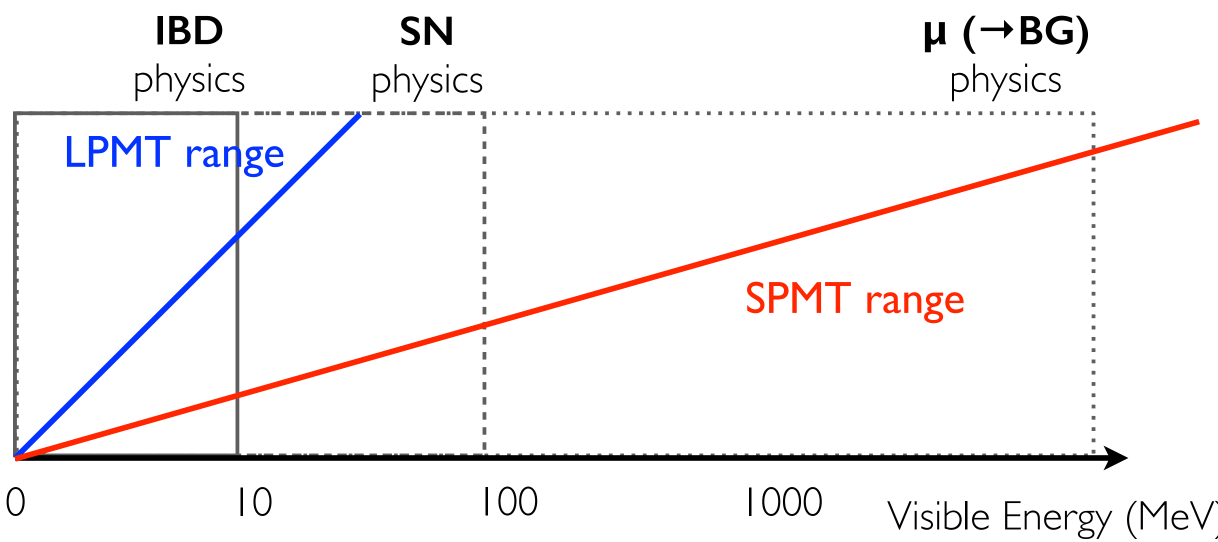
- Small PMTs (SPMT) are cheaper and faster in time response (<1ns), lower noise and higher QExCE
- Adding 3″ PMTs in the gaps: ~2 SPMTs for every large PMT (LPMT)
  - increase the photocathode coverage by ~1%
  - improve the central detector muon reconstruction resolution
  - avoid high rate supernova neutrino pile-up (if very near)
  - increase the dynamic range and global trigger



The front end of the 3” PMT is in the same plane as the equatorial plane of 20” PMT

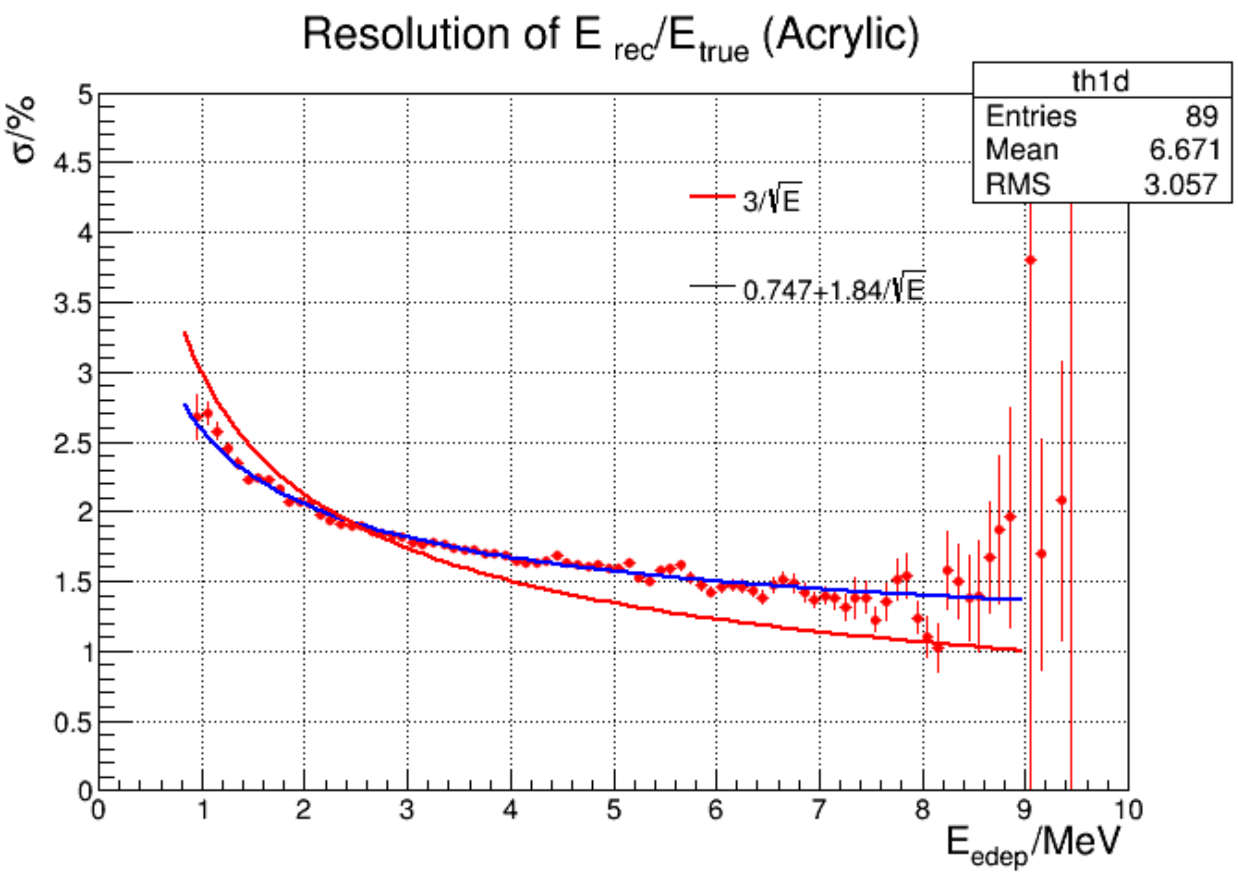


Complementary Roles by sPMTs and LPMTS



Putting Everything Together (Simulation)

- A framework SNiPER is developed at IHEP for the need of non-collider experiments. Major components of the JUNO central detector are implemented
- Assumptions: PMT QE 35%; LS light yield 10.4k photons/MeV and L_{attn} = 20m @430nm



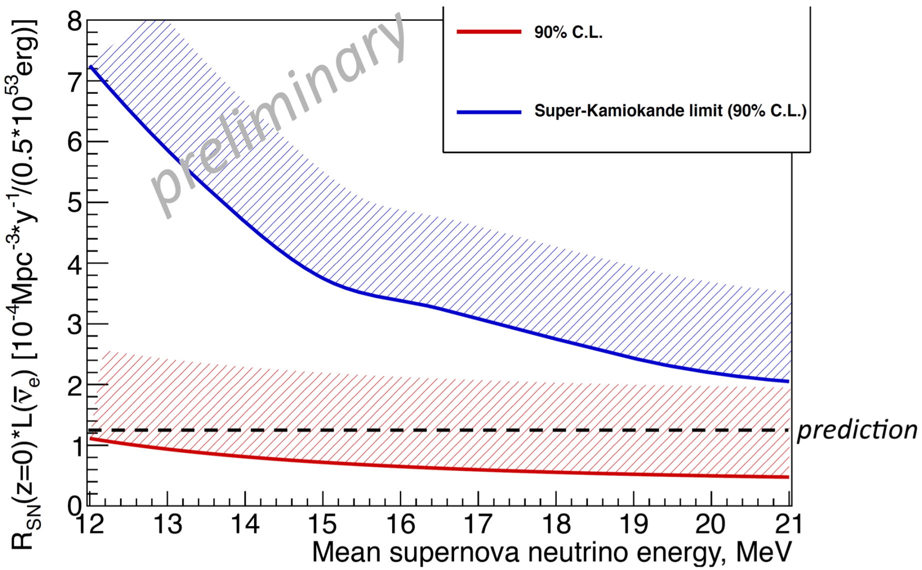
- Simulation suggests that effective photocathode coverage can reach ~75% after considering the (current) support structures.
- A 3% energy resolution is plausible based on the current simulation.

Other Physics Potential of JUNO

- Supernova neutrinos
- Diffused supernova neutrinos
- Proton decay $P \rightarrow K^+ + \bar{\nu}$

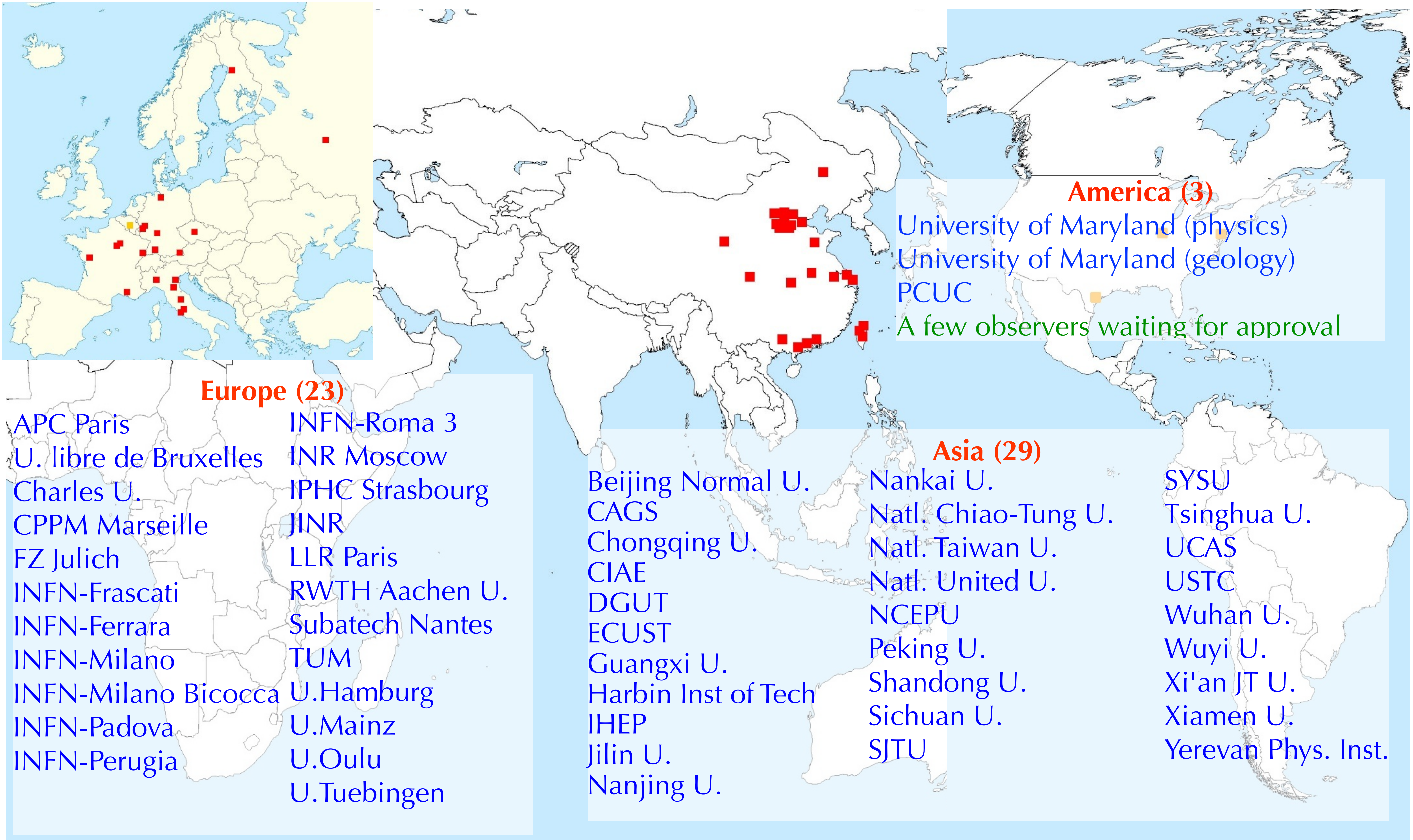
  $\tau > 1.9 \times 10^{34}$ yr (90% C.L.)
- Geoneutrinos
  - KamLAND: 30±7 TNU [PRD 88 (2013) 033001]
  - Borexino: 38.8±12.0 TNU [PLB 722 (2013) 295]
  - JUNO (preliminary): 37±10%(stat)±10%(syst)TNU

Channel	Type	Events for different $\langle E_\nu \rangle$ values		
		12 MeV	14 MeV	16 MeV
$\overline{\nu}_e + p \rightarrow e^+ + n$	CC	4.3×10^3	5.0×10^3	5.7×10^3
$\nu + p \rightarrow \nu + p$	NC	6.0×10^2	1.2×10^3	2.0×10^3
$\nu + e \rightarrow \nu + e$	NC	3.6×10^2	3.6×10^2	3.6×10^2
$\nu + {}^{12}C \rightarrow \nu + {}^{12}C^*$	NC	1.7×10^2	3.2×10^2	5.2×10^2
$\nu_e + {}^{12}C \rightarrow e^- + {}^{12}N$	CC	4.7×10^1	9.4×10^1	1.6×10^2
$\overline{\nu}_e + {}^{12}C \rightarrow e^+ + {}^{12}B$	CC	6.0×10^1	1.1×10^2	1.6×10^2



- Solar neutrinos: high demand on the radioactive background purity. BOREXINO is the standard.
- Atmospheric neutrinos: not much value in redoing what Super-K has done. With JUNO's good energy resolution, atmospheric neutrinos could potentially aid the MH case (PINGU type signal)
- ……

JUNO Collaboration: 55 Groups from 3 Continents



Europe (23)

APC Paris
U. libre de Bruxelles
Charles U.
CPPM Marseille
FZ Julich
INFN-Frascati
INFN-Ferrara
INFN-Milano
INFN-Milano Bicocca
INFN-Padova
INFN-Perugia
INFN-Roma 3
INR Moscow
IPHC Strasbourg
JINR
LLR Paris
RWTH Aachen U.
Subatech Nantes
TUM
U.Hamburg
U.Mainz
U.Oulu
U.Tuebingen

Asia (29)

Beijing Normal U.
CAGS
Chongqing U.
CIAE
DGUT
ECUST
Guangxi U.
Harbin Inst of Tech
IHEP
Jilin U.
Nanjing U.
Nankai U.
Natl. Chiao-Tung U.
Natl. Taiwan U.
Natl. United U.
NCEPU
Peking U.
Shandong U.
Sichuan U.
SJTU
SYSU
Tsinghua U.
UCAS
USTC
Wuhan U.
Wuyi U.
Xi'an JT U.
Xiamen U.
Yerevan Phys. Inst.

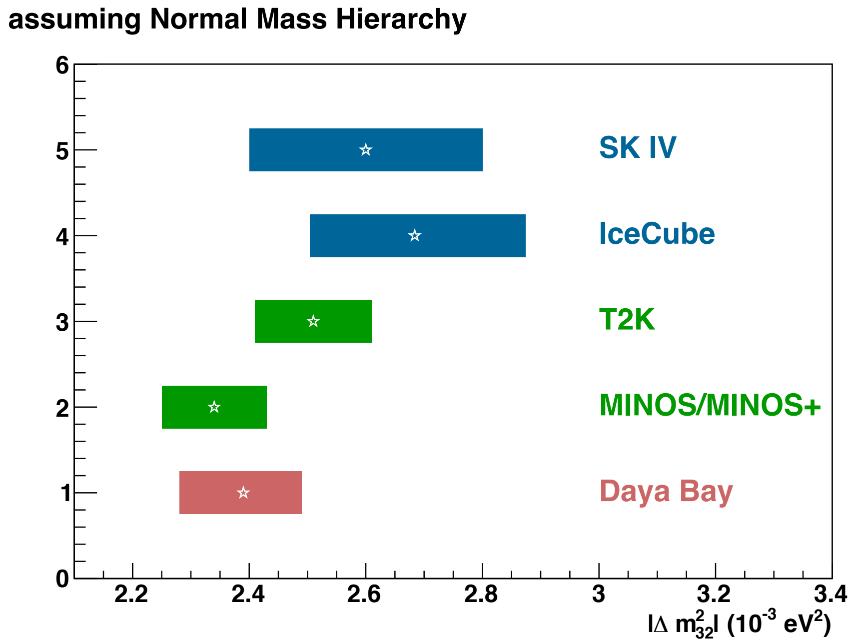
America (3)

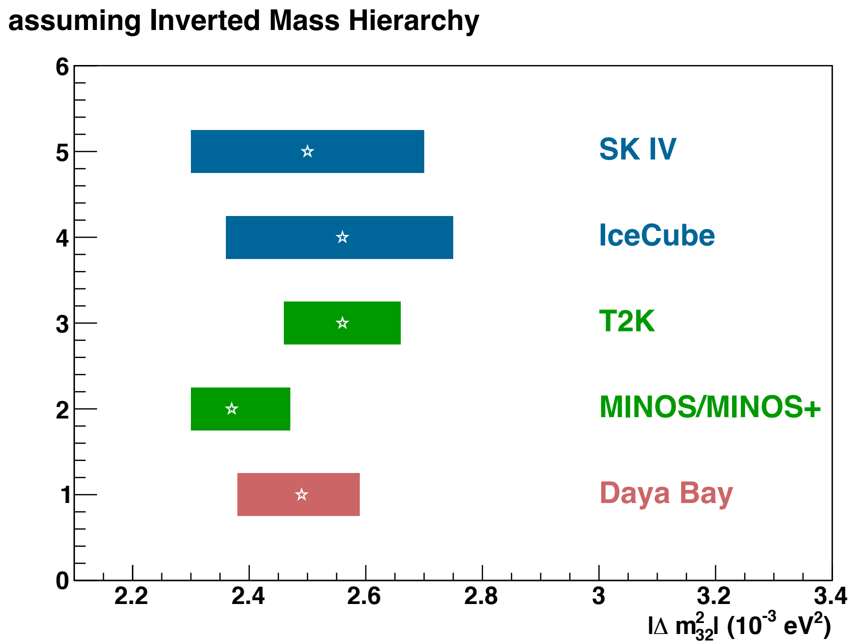
University of Maryland (physics)
University of Maryland (geology)
PCUC
A few observers waiting for approval

Summary and Conclusion

- The current generation reactor neutrino experiments have discovered theta13. Its unexpected large value enables the possibility of resolving neutrino mass hierarchy in medium-baseline reactor neutrino experiments
- **A medium-baseline reactor neutrino project in China, JUNO, has received approval. Ground breaking was on Jan 10, 2015**
  - R&D activities addressing all the challenges have been happening in parallel, at IHEP and among other institutes
  - The civil is progressing well: slope tunnel ~⅓; shaft ~10%
- **JUNO has great potential in resolving neutrino mass hierarchy. In addition, its unprecedented target mass and performance among LS detectors mean great potential on many other topics**
- **JUNO plans to start data taking in 2020**

The Daya Bay Δm^2_{ee} Measurement





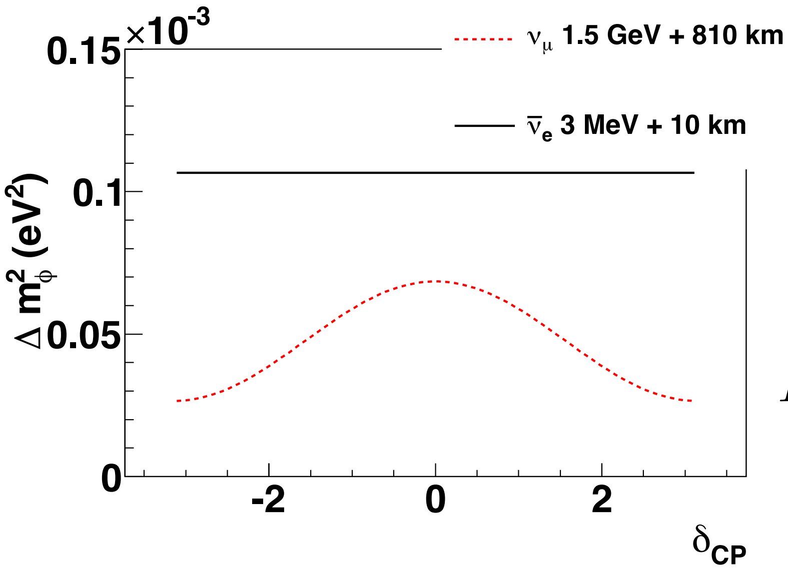
Δm^2_{32} measurements from five experiments

All Results are from Neutrino 2014

- Atmospheric Neutrinos
- Accelerator Neutrinos
- Reactor Neutrinos

(Global Δm^2_{32} measurements slightly favors inverted mass hierarchy)

Why is the e-type Δm^2 Measurement Interesting?



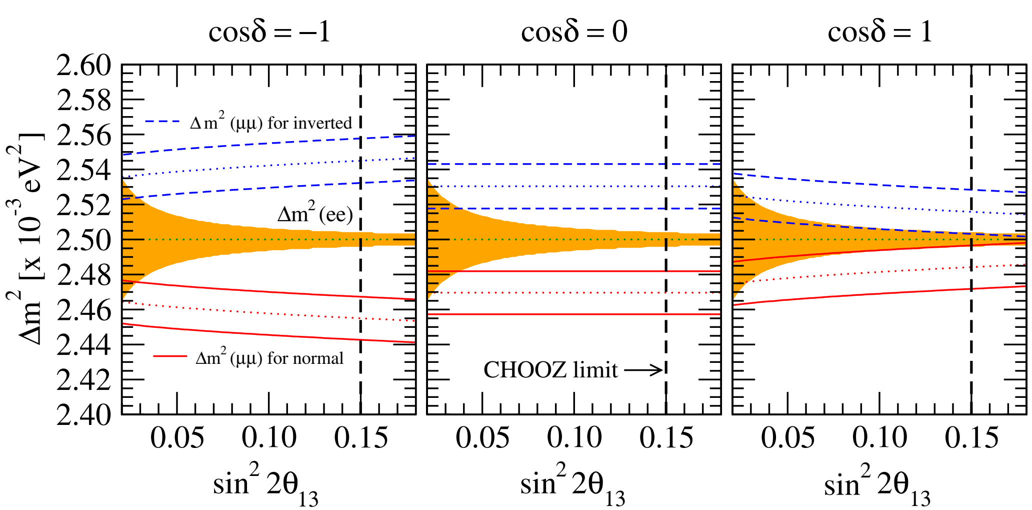
$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$
$$= 1 - 2s_{13}^2c_{13}^2 - 4c_{13}^4s_{12}^2c_{12}^2\sin^2\Delta_{21} + 2s_{13}^2c_{13}^2\sqrt{1 - 4s_{12}^2c_{12}^2\sin^2\Delta_{21}}\cos(2\Delta_{32} \pm \phi)$$

$$P_{\nu_\mu \to \nu_\mu} = 1 - P_{21}^{\mu} - \cos^2\theta_{13}\sin^2 2\theta_{23}\sin^2\frac{(\Delta m_{32}^2 \pm \phi)L}{4E}$$

Qian et al, PRD87(2013)3, 033005

FIG. 6: The dependence of effective mass-squared difference $\Delta m_{ee\phi}^2$ (solid line) and $\Delta m_{\mu\mu\phi}^2$ (dotted line) w.r.t. the value of δ_{CP} for $\bar{\nu}_e$ and ν_μ disappearance measurements, respectively.

Because it could tell MH!



Minakata et al PRD74(2006), 053008

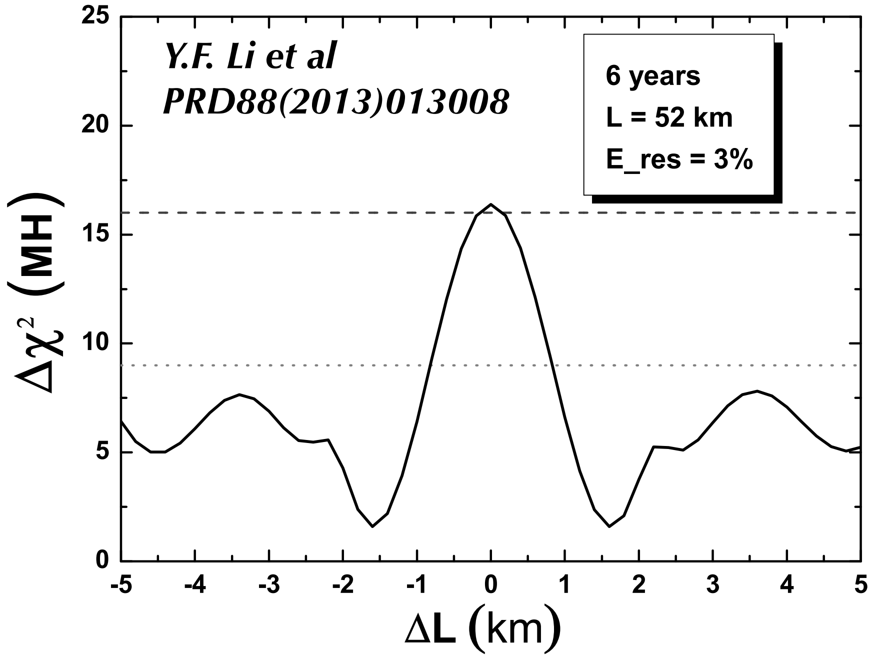
TABLE II: Simple fitting for mass splitting Δm_{32}^2 and Δm_{31}^2 using Eqs. (11), (12), (16), and (19) in NH (or (20) in IH) as constraints. The corresponding 2-tailed p-values increase from that in Table I. Here the slight preference for normal hierarchy remains.

	Fit in normal hierarchy	Fit in inverted hierarchy
Δm_{32}^2	$(2.46 \pm 0.07) \times 10^{-3}$ eV^2	$-(2.51 \pm 0.07) \times 10^{-3}$ eV^2
Δm_{31}^2	$(2.53 \pm 0.07) \times 10^{-3}$ eV^2	$-(2.44 \pm 0.07) \times 10^{-3}$ eV^2
χ^2/DoF	0.96/2	1.21/2
p-value	62%	55%

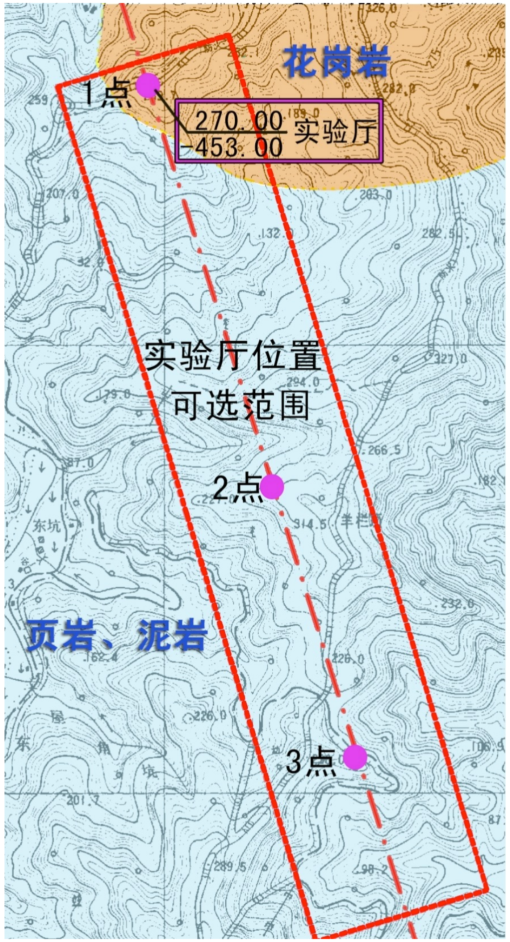
Zhang&Ma, arXiv:1310.4443

A Subtlety in Designing the Baselines

- MH information is in the small oscillation waggles driven by the atmospheric mass-squared splittings whose oscillation length is ~2km for reactor spectrum



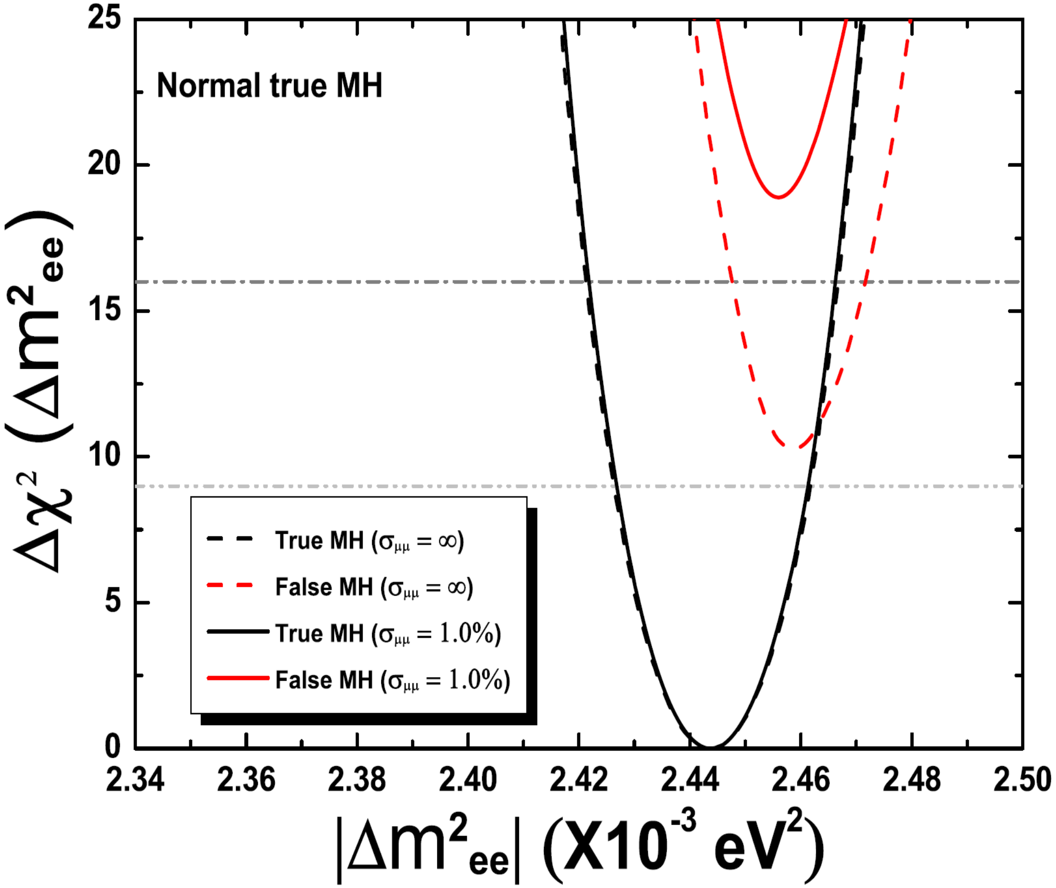
- Reactor cores at the same power plant like to be ~km apart. If baselines are shifted by half oscillation length, they cancel each other's signals.



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

- The JUNO design has considered this issue and made sure baseline differences are less than 0.5km

Expected Significance to Mass Hierarchy



- ~3-sigma if only a relative spectral measurement without external atmospheric mass-squared splitting
- ~4-sigma with an external Δm^2 measured to ~1% level in ν_μ beam oscillation experiments
  - ~1% in Δm^2 is reachable based on the combined T2K +NOvA analysis by S.K. Agarwalla, S. Prakash, WW, arXiv:1312.1477

✓Realistic reactor distributions considered

✓20kt valid target mass, 36GW reactor power, 6-year running

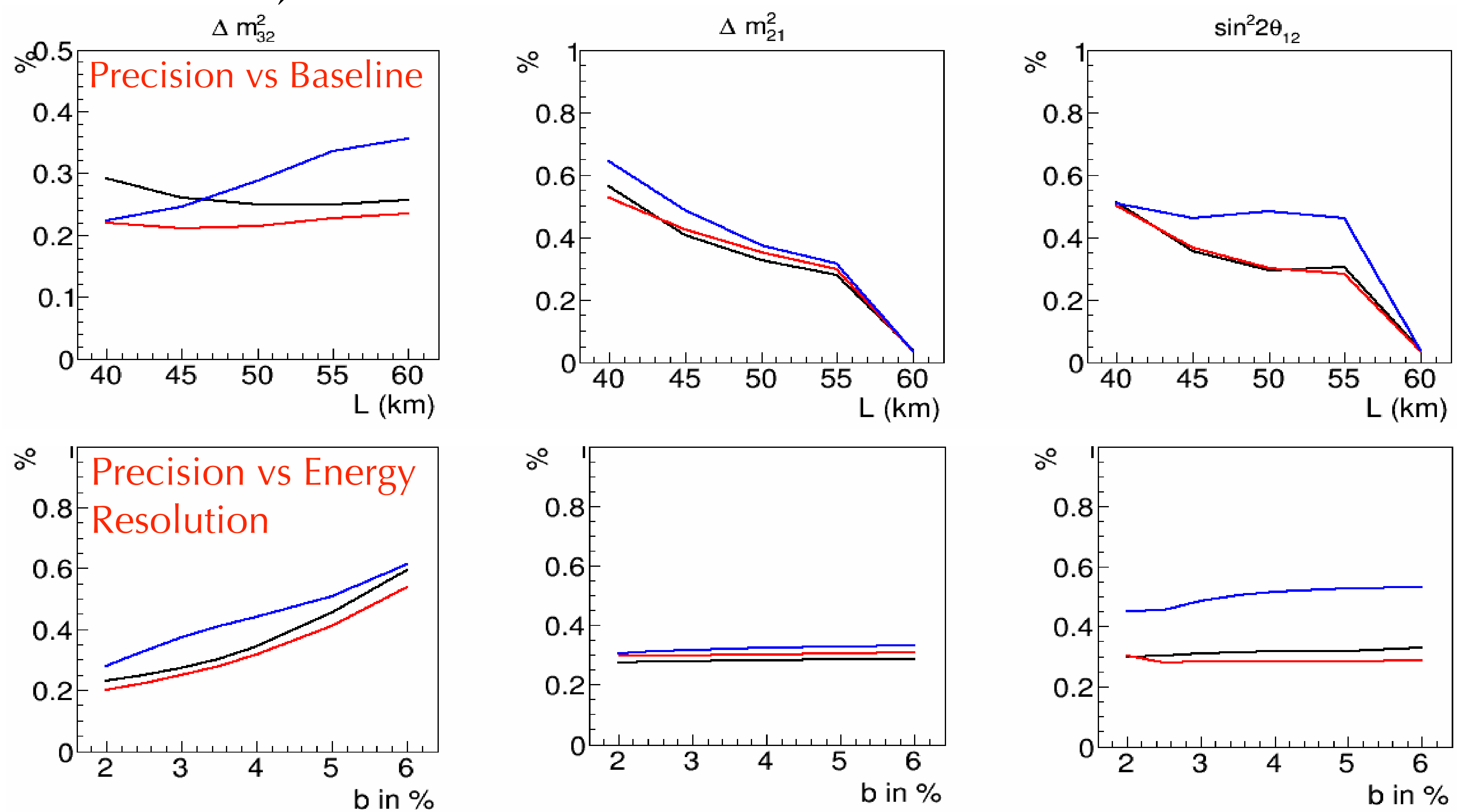
✓3% energy resolution and 1% energy scale uncertainty assumed

JUNO Precision Measurements Warranted

- Precision <1% measurements are warranted in a experiment like JUNO
  - Enable a future ~1% level PMNS unitarity test
  - Neutrinoless double beta decay needs precise θ_{12}

Parameter		best-fit ($\pm 1\sigma$)	
$\Delta m^2_{\odot}$ $[10^{-5}\ \mathrm{eV}^2]$		$7.58^{+0.22}_{-0.26}$	**3.2%**
$\lvert\Delta m^2_A\rvert$ $[10^{-3}\ \mathrm{eV}^2]$		$2.35^{+0.12}_{-0.09}$	**4.5%**
$\sin^2\theta_{12}$	**2.9%**	$0.306\ (0.312)^{+0.018}_{-0.015}$	

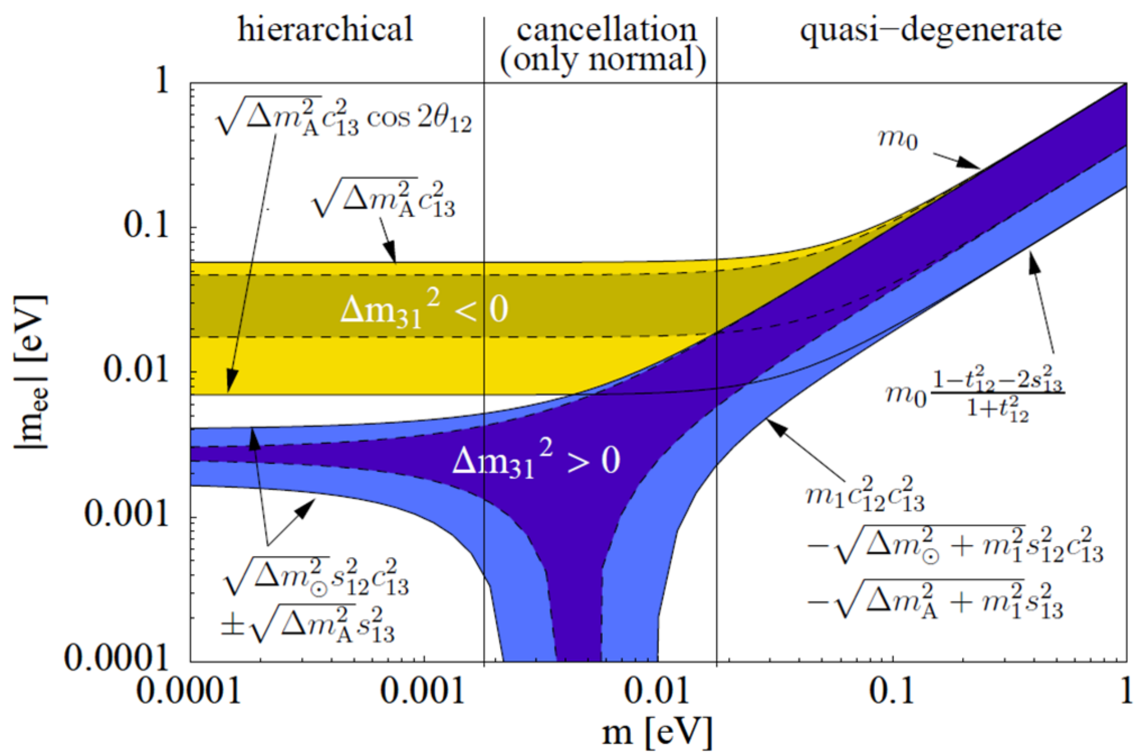
A.B. Balantekin et al, arXiv:1307.7419

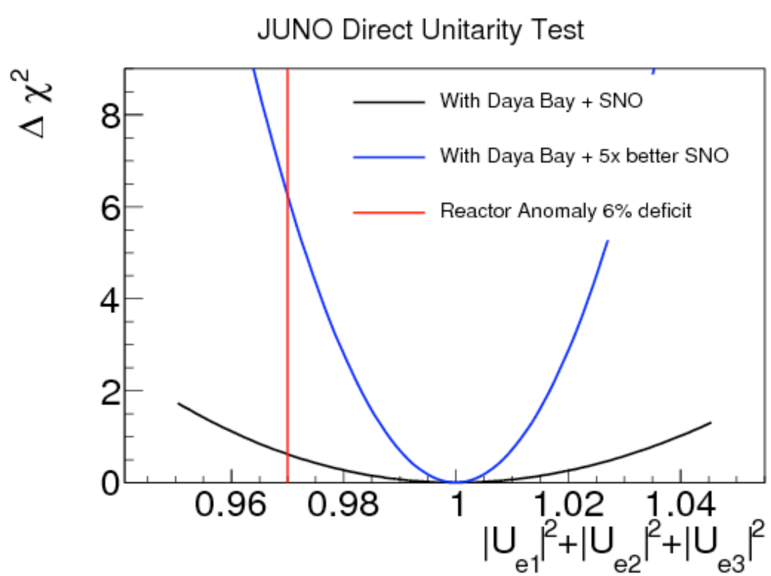


JUNO Impact of Precision Measurements

- Three-neutrino paradigm test
- Valuable input to the neutrinoless double beta decay experiments.

W. Rodejohann, J. Phys. G **39**, 124008 (2012)





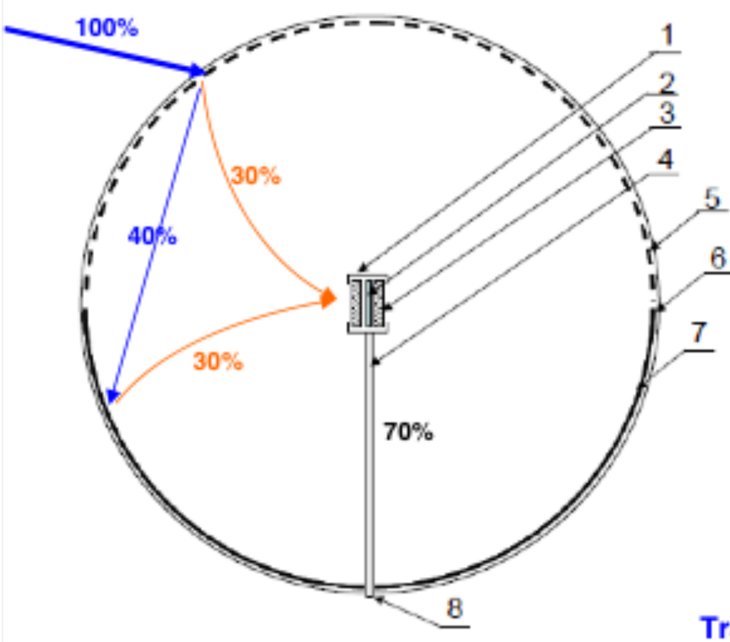
Direct unitarity test of $|U_{e1}|^2+|U_{e2}|^2+|U_{e3}|^2=1$ by combining JUNO, Daya Bay, and solar results. We considered two scenarios i) current SNO constraint and ii) a five times better constraint than SNO.

Qian, X. et al. arXiv:1308.5700

More Light: New Types of PMTs

1) Using two sets of Microchannel plates (MCPs) to replace the dynode chain

2) Using transmission photocathode (front hemisphere) and reflection photocathode (back hemisphere) } Fully active sphere surface



1.Insulated trestle table

2.Anode

3.MCP dodule

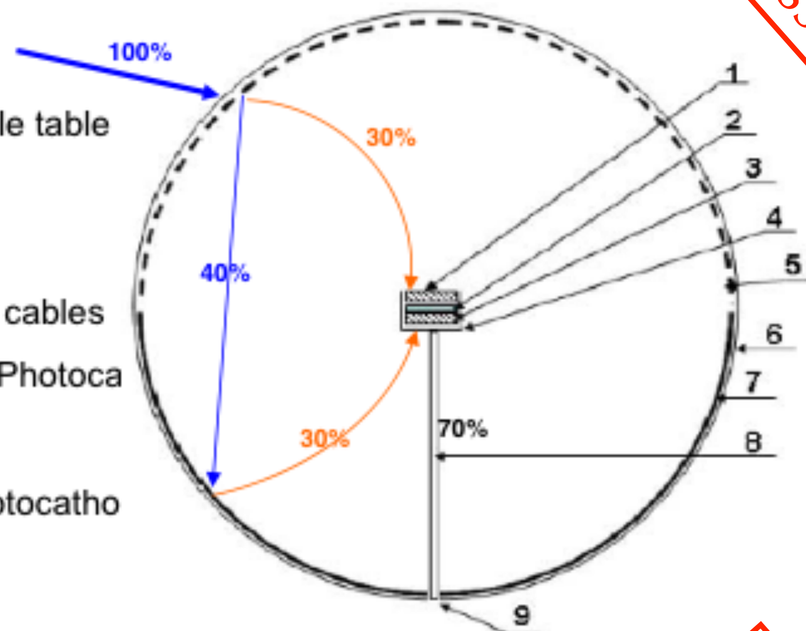
4.Bracket of the cables

5.Transmission Photoca

6.Glass shell

7.Reflection Photocatho

8.Glass joint



Transmission rate of the glass: 40%

Quantum Efficiency (QE) : of Transmission Photocathode 30% ; of Reflection Photocathode 30% ;

Collection Efficiency (CE) of MCP : 70%;

If nothing else changes, the detection efficiency (QE*CE) is nearly doubled by "saving" the ~40% transmitted photons.

JUNO PMT Plan A progressing well

- JUNO PMT plan B: Photonis China PMTs
- JUNO PMT plan C: new 20" Hamamatsu SBA high QE PMTs

3 Plans in Parallel by Collaborators