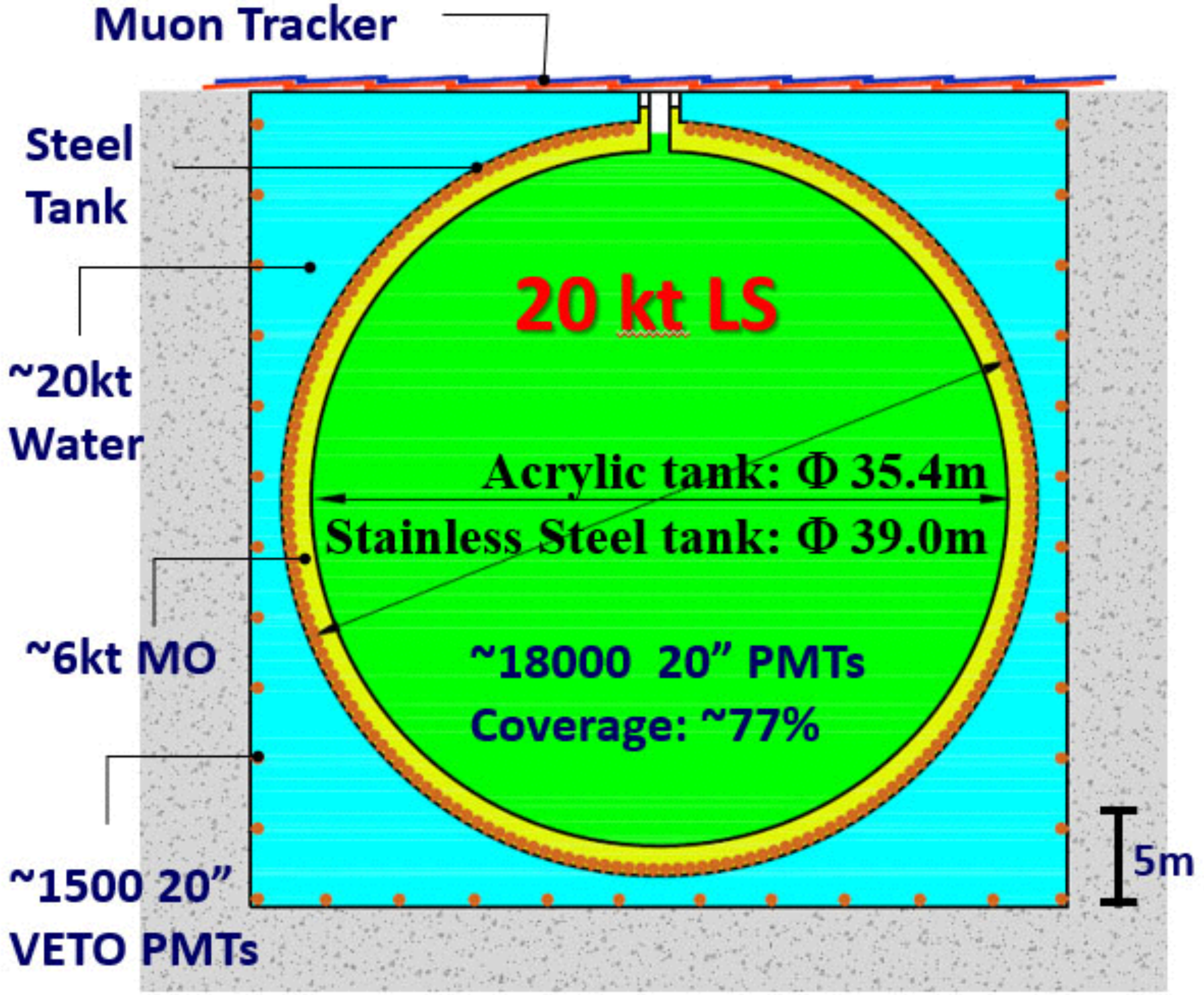
Jiangmen Underground Neutrino Observatory

Xiang Zhou, Wuhan University
on behalf of the JUNO collaboration
Hadron 2016, Aug. 10, 2016, Wuhan

Where is JUNO?

Where is JUNO?

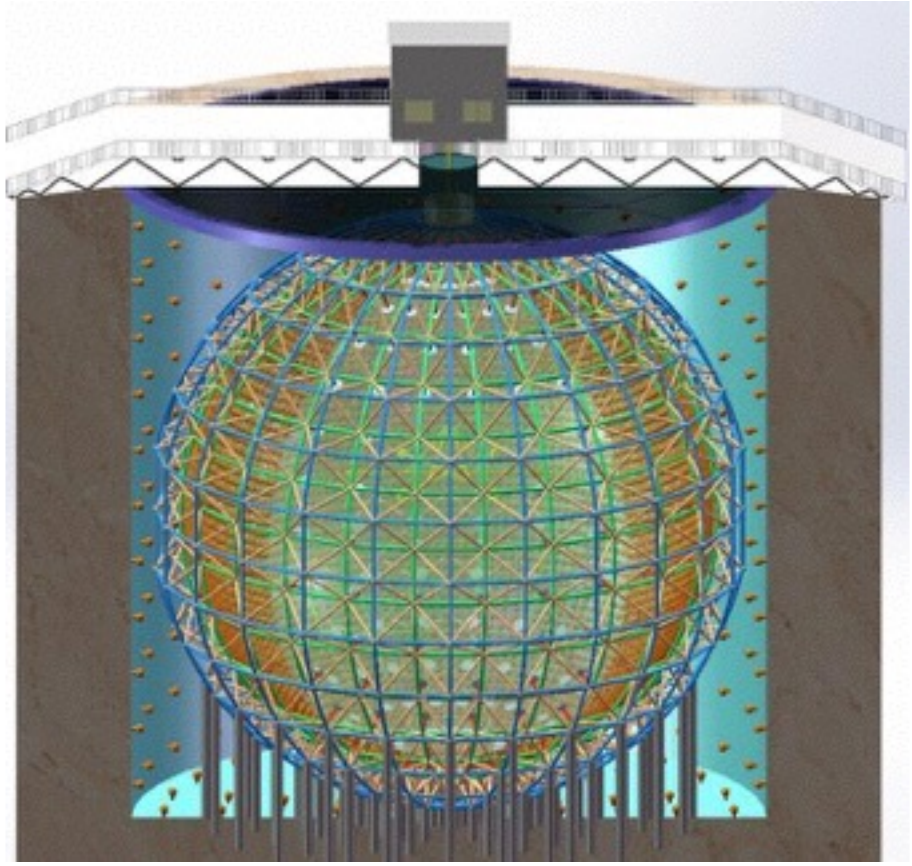
High-precision, Giant LS detector



	KamLAND	BOREXINO	JUNO
LS mass	1 kton	0.5 kton	20 kton
Energy resolution	6%/√E(MeV)	5%/√E(MeV)	3%/√E(MeV)
Light yield	250 p.e./MeV	511 p.e./MeV	1200 p.e./MeV

Rich Physics Program

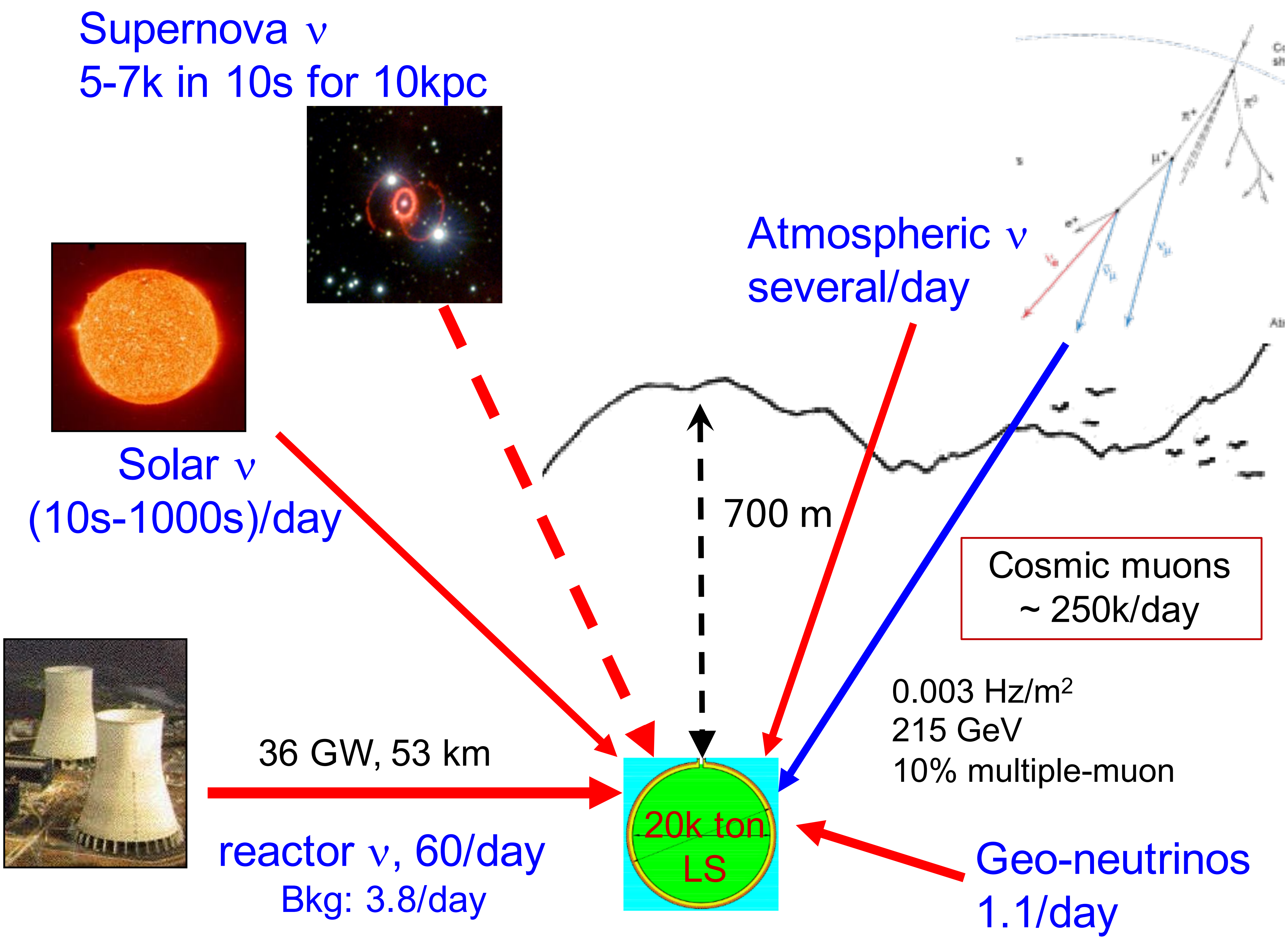
JUNO has been approved in Feb. 2013. ~300M$



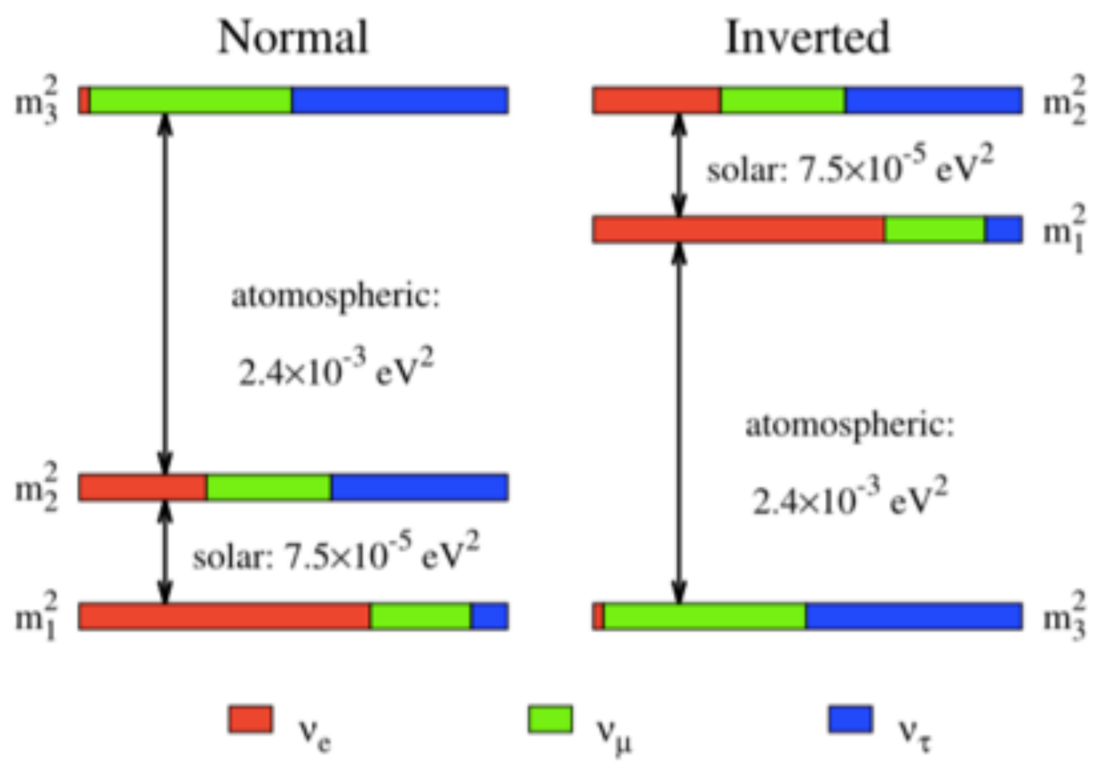
Neutrino Physics with JUNO
J. Phys. G **43**, 030401(2016)

- **20 kton LS detector**
- **3% energy resolution**
- 700 m underground
- Rich physics possibilities
  - **Mass hierarchy**
  - **Precision measurements**
  - Supernovae neutrino
  - Geo-neutrino
  - Solar neutrino
  - Atmospheric neutrino
  - Proton decay
  - Dark mater

JUNO Event Rates



Neutrino Mass Hierarchy



mass eigenstates

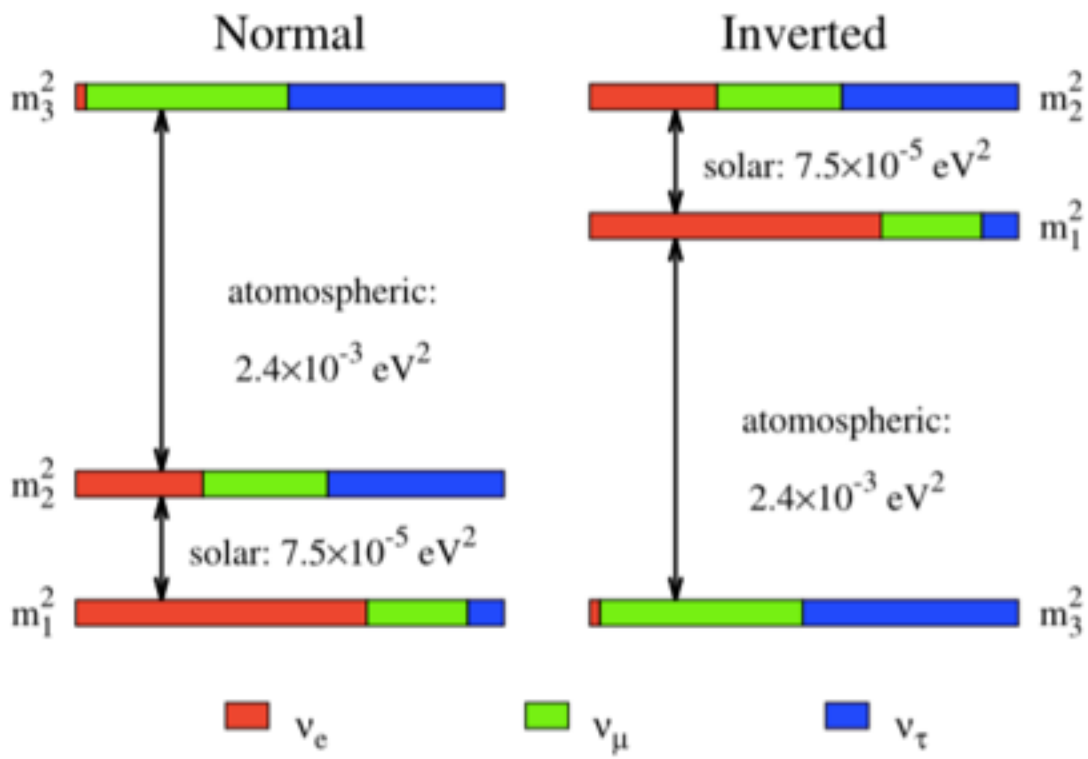
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} P_\nu$$

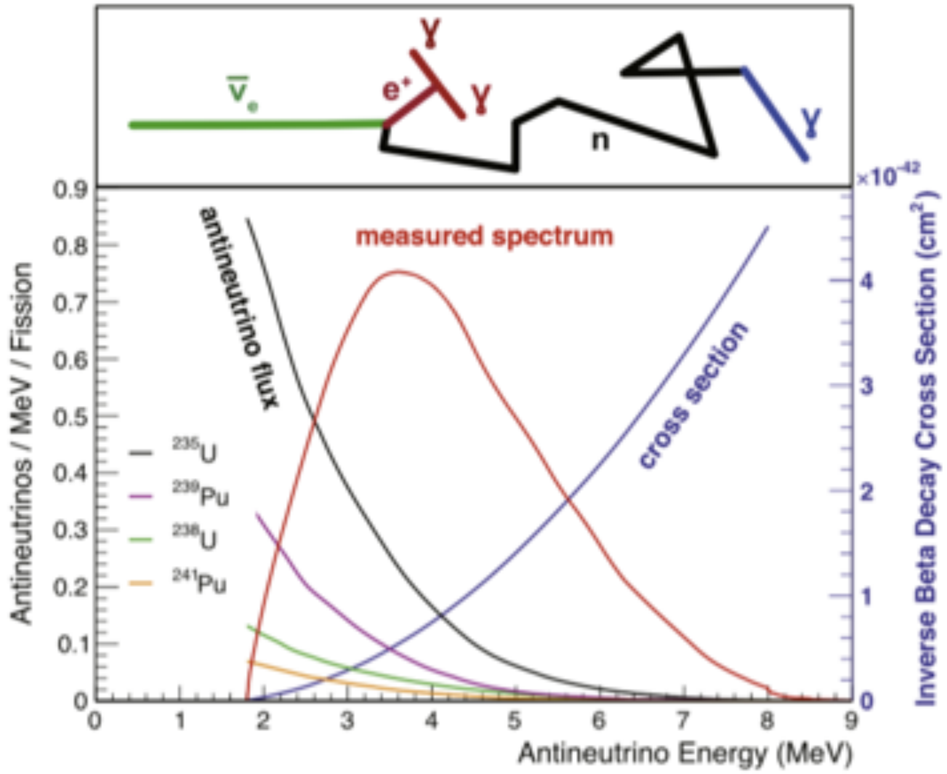
flavor eigenstates

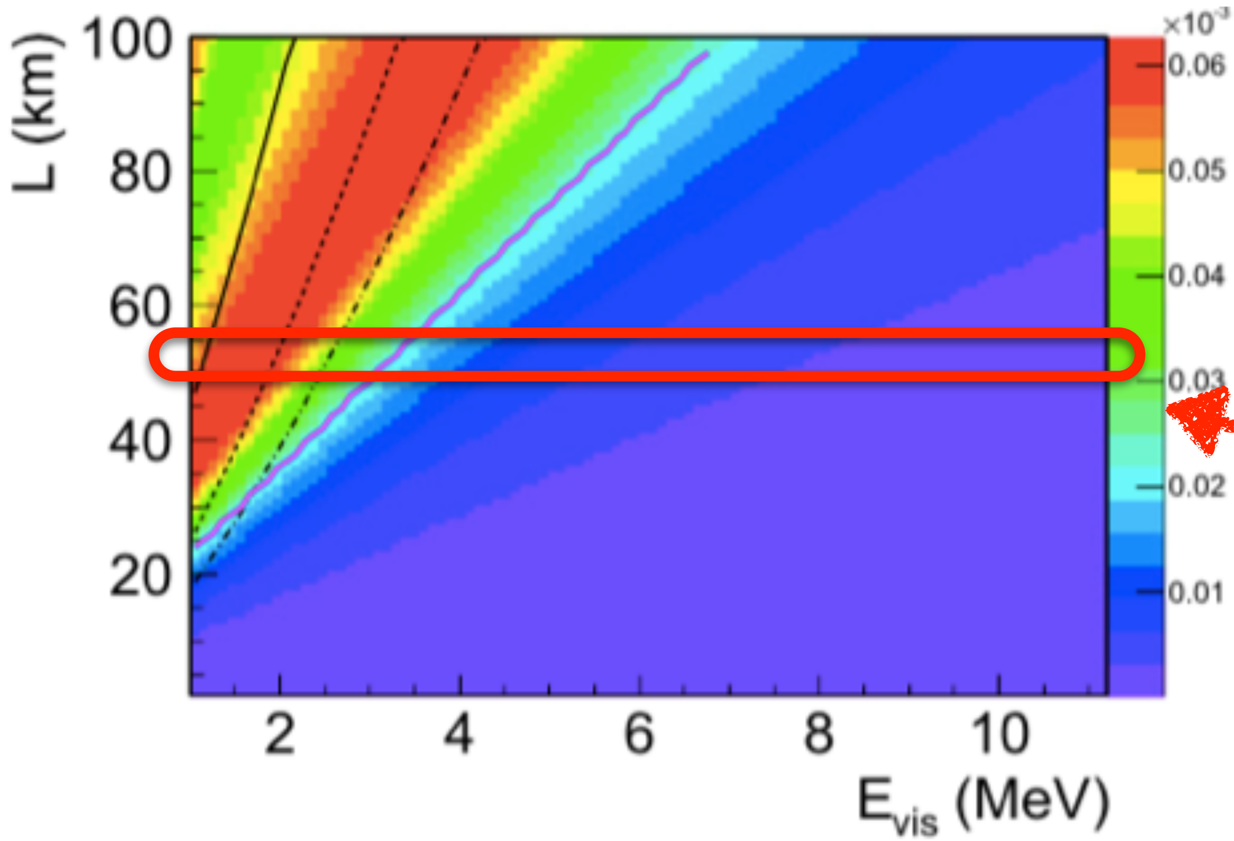
$$P(\overline{\nu}_e \to \overline{\nu}_e) = 1 - \sin^2 2\theta_{12} c_{13}^4 \sin^2 \frac{\Delta m_{21}^2 L}{4E} - \sin^2 2\theta_{13} \left[c_{12}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} + s_{12}^2 \sin^2 \frac{\Delta m_{32}^2 L}{4E} \right]$$

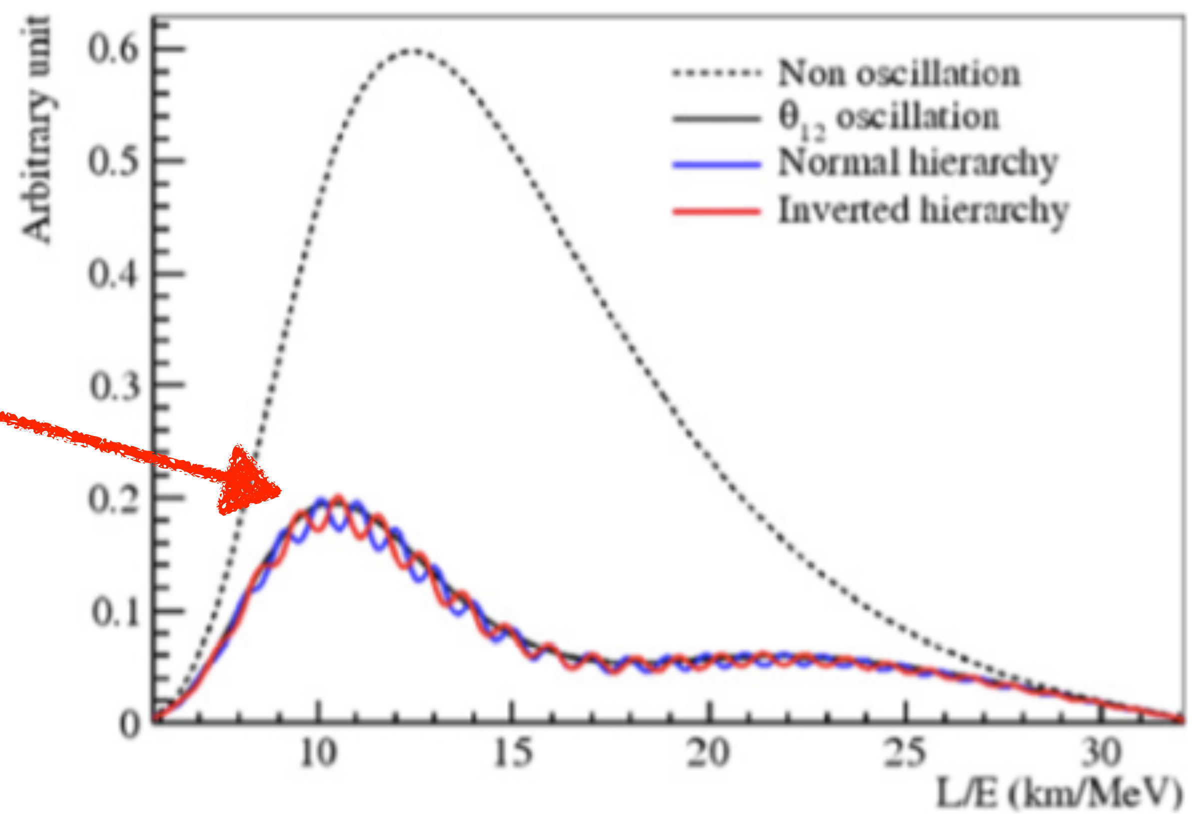
$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

Neutrino Mass Hierarchy



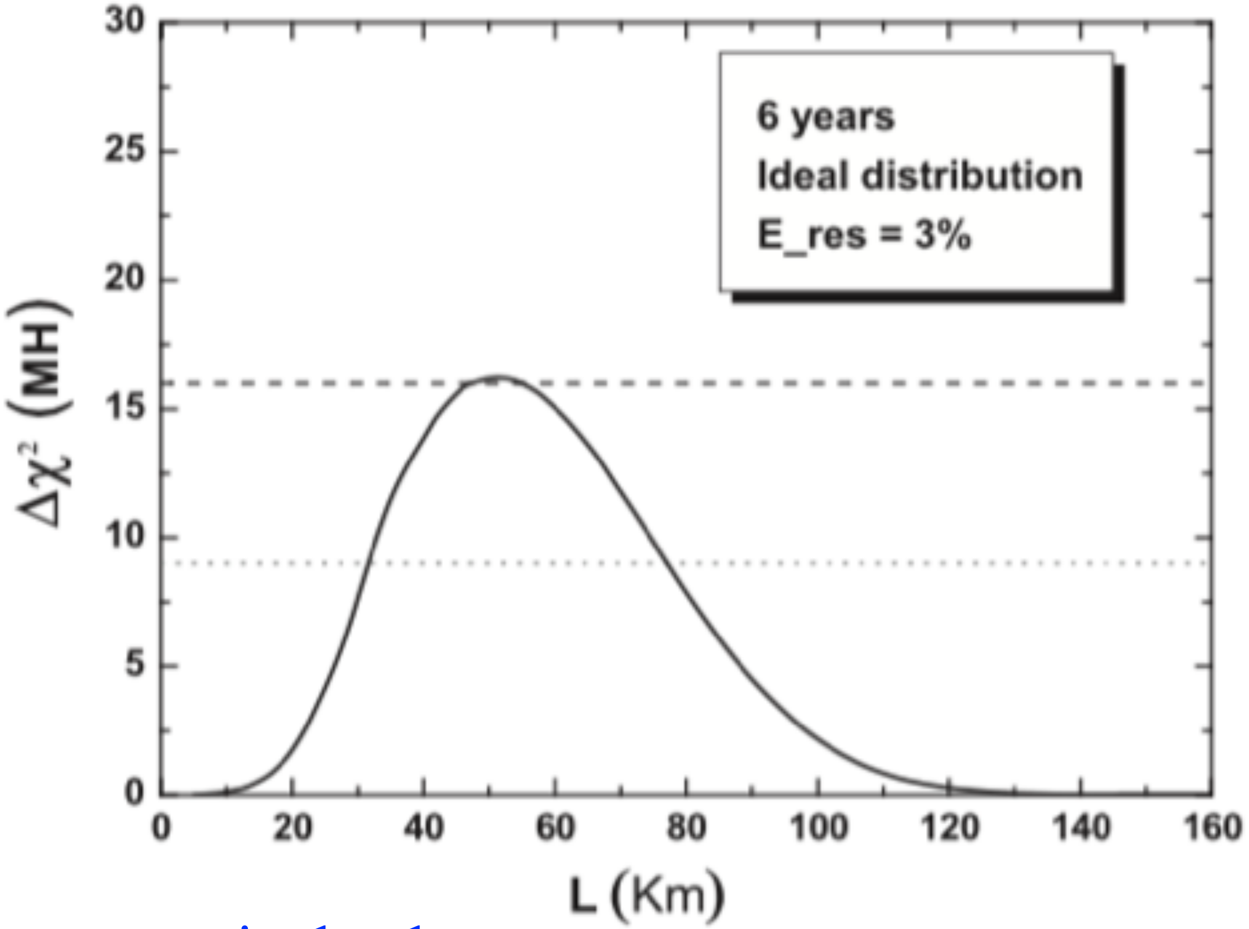


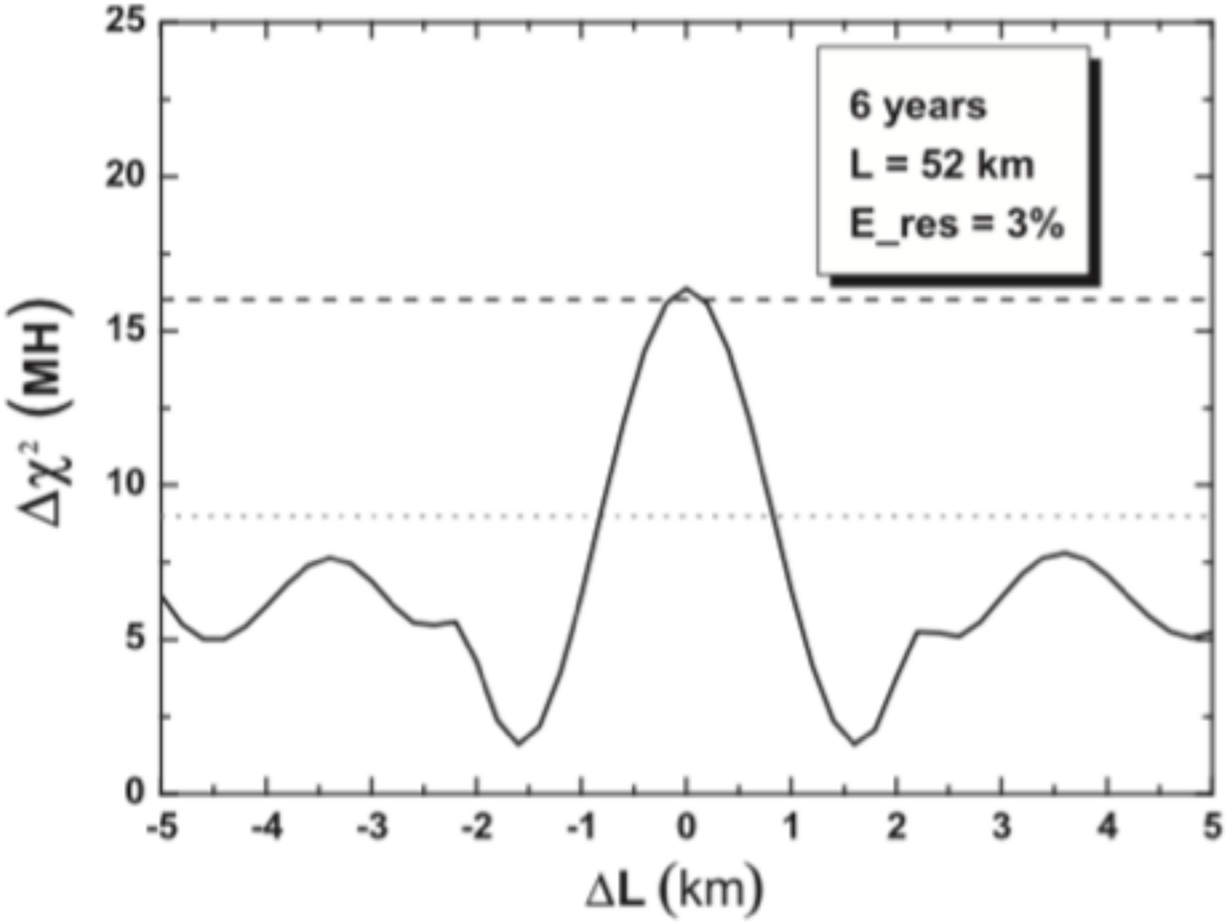




MH sensitivity in JUNO

$$\Delta\chi^2_{MH} = |\chi^2_{min}(N) - \chi^2_{min}(I)|$$





nominal value (Stat. only)

nearby NPPs

BG uncertainties statistical & shape

	Stat.	Core dist.	DYB and HZ	Shape	B/S (stat.)	B/S (shape)	$\lvert\Delta m^2_{\mu\mu}\rvert$
Size	52.5 km	Table 2	Table 2%	1%	6.3%	0.4%	1%
$\Delta\chi^2_{MH}$	+16	−3	−1.7	−1	−0.6	−0.1	+(4 − 12)

real distribution of reactor cores

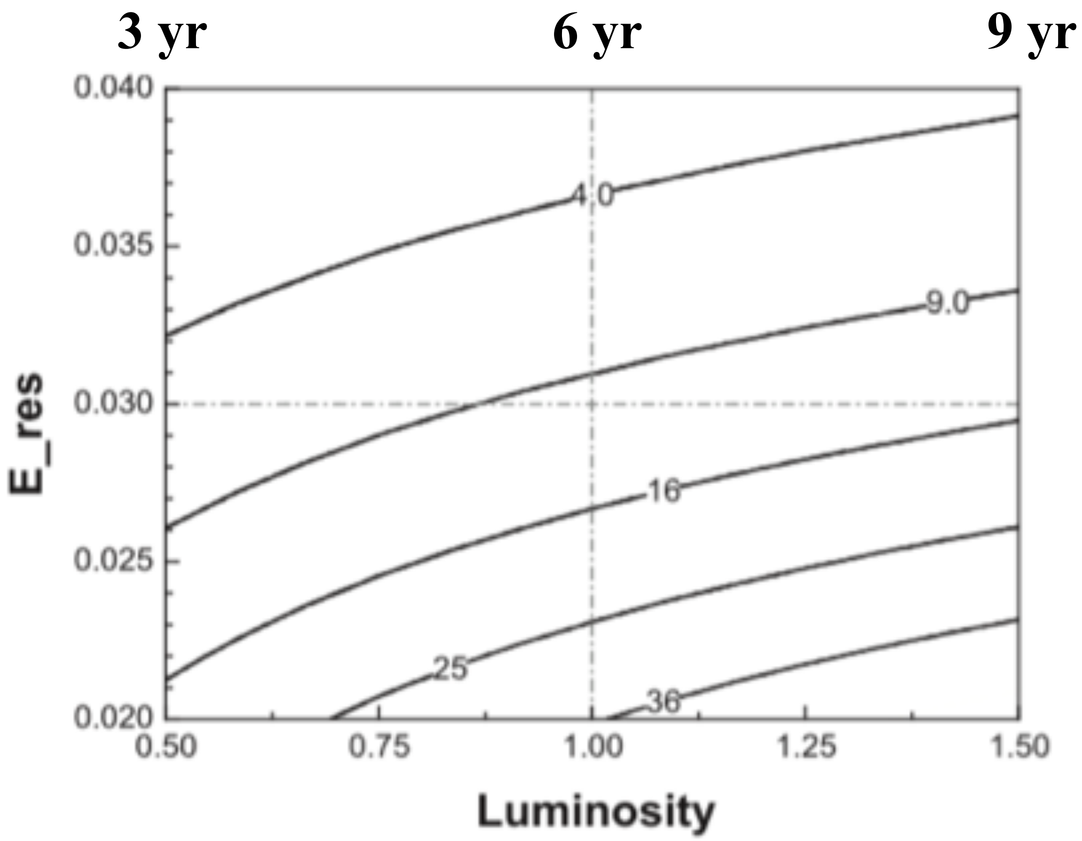
reactor shape uncertainty

ν_μ oscillations precision measurement

MH sensitivity in JUNO

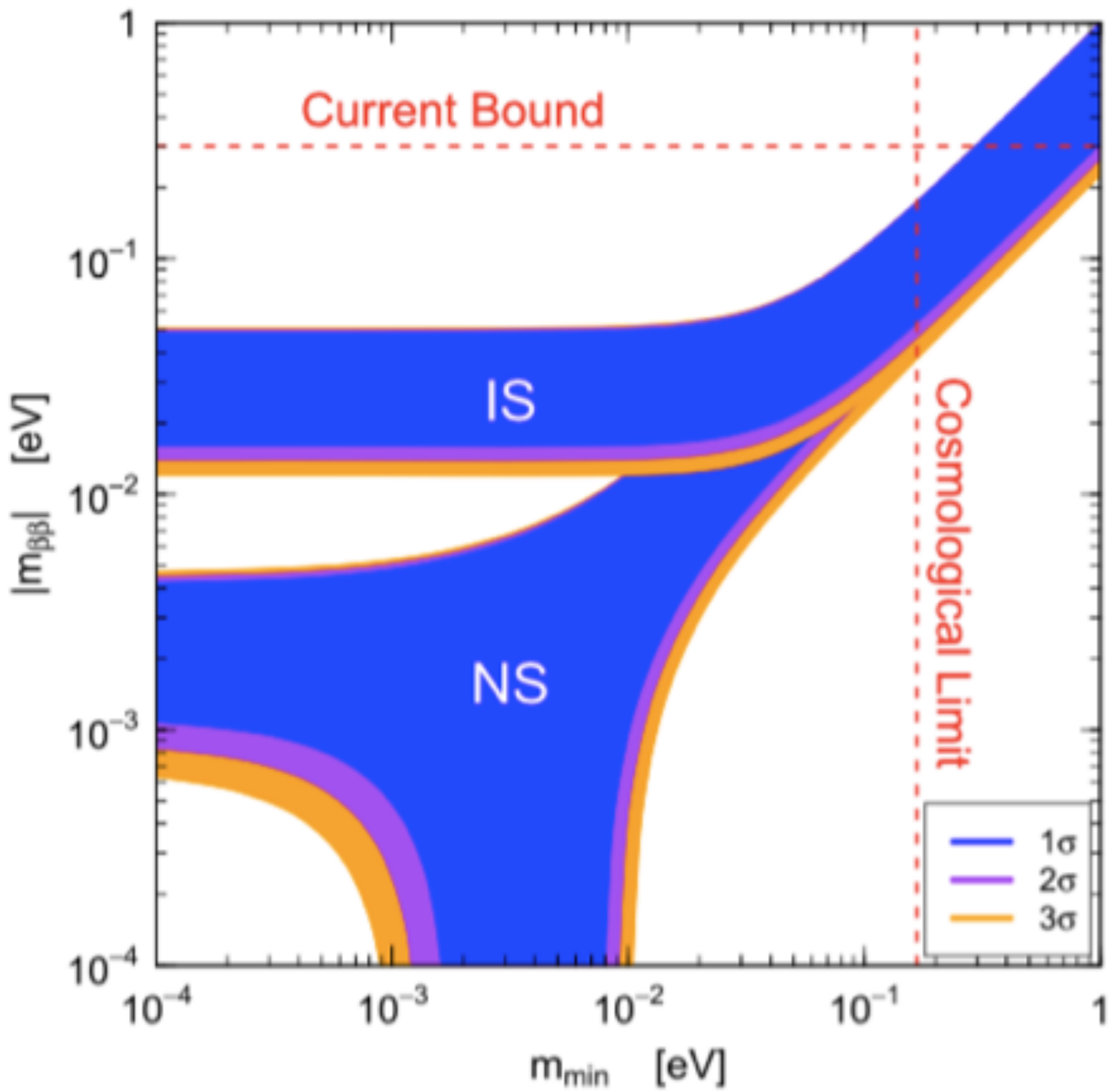
JUNO MH sensitivity with 6 years' data

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

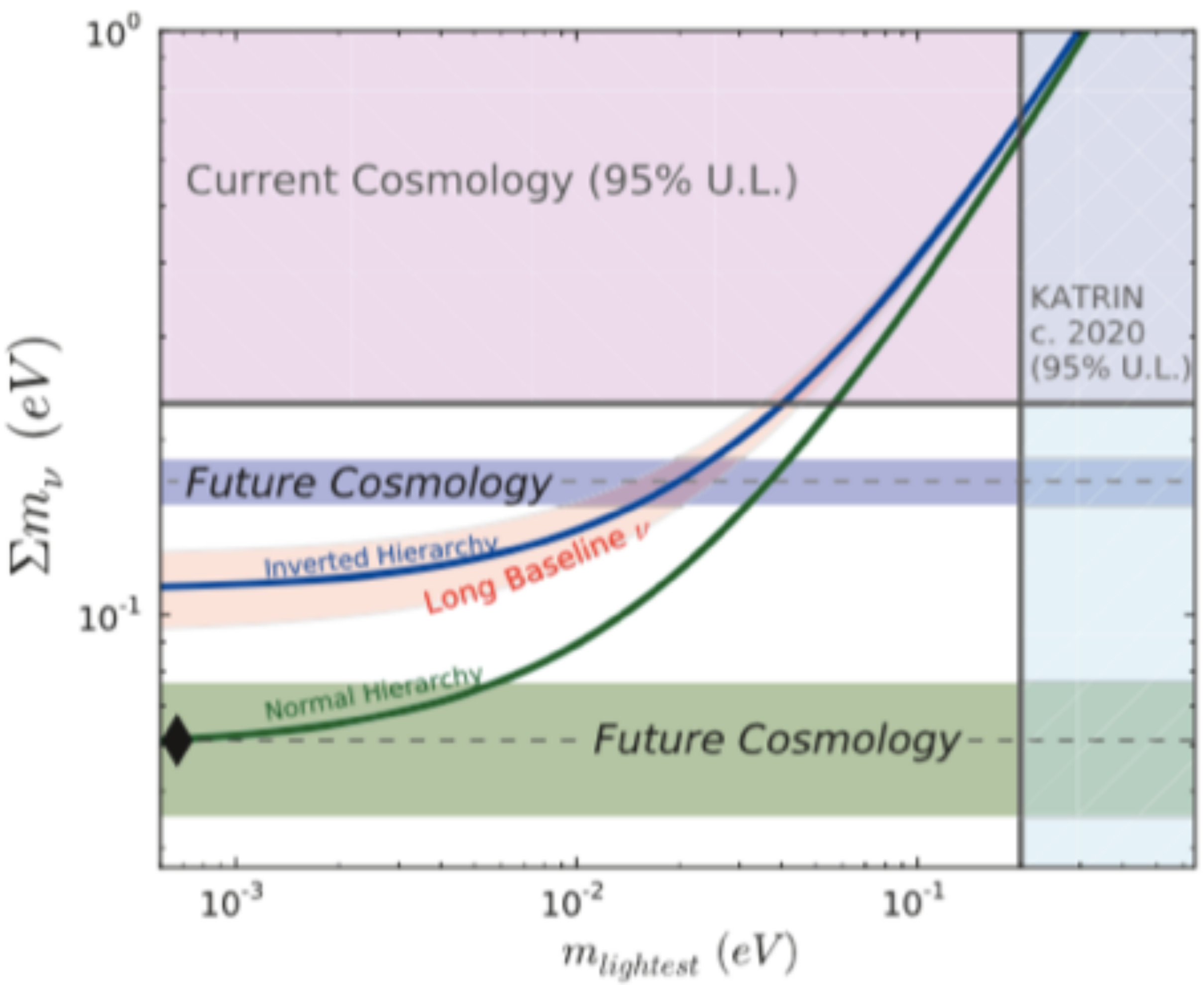


- Big Challenge: 3% Energy resolution
- 77% photocathode coverage
- PMT peak QE: 35%
- Attenuation length: 20 m
  - abs. 60 m + Rayleigh scatt. 30 m

MH sensitivity in JUNO

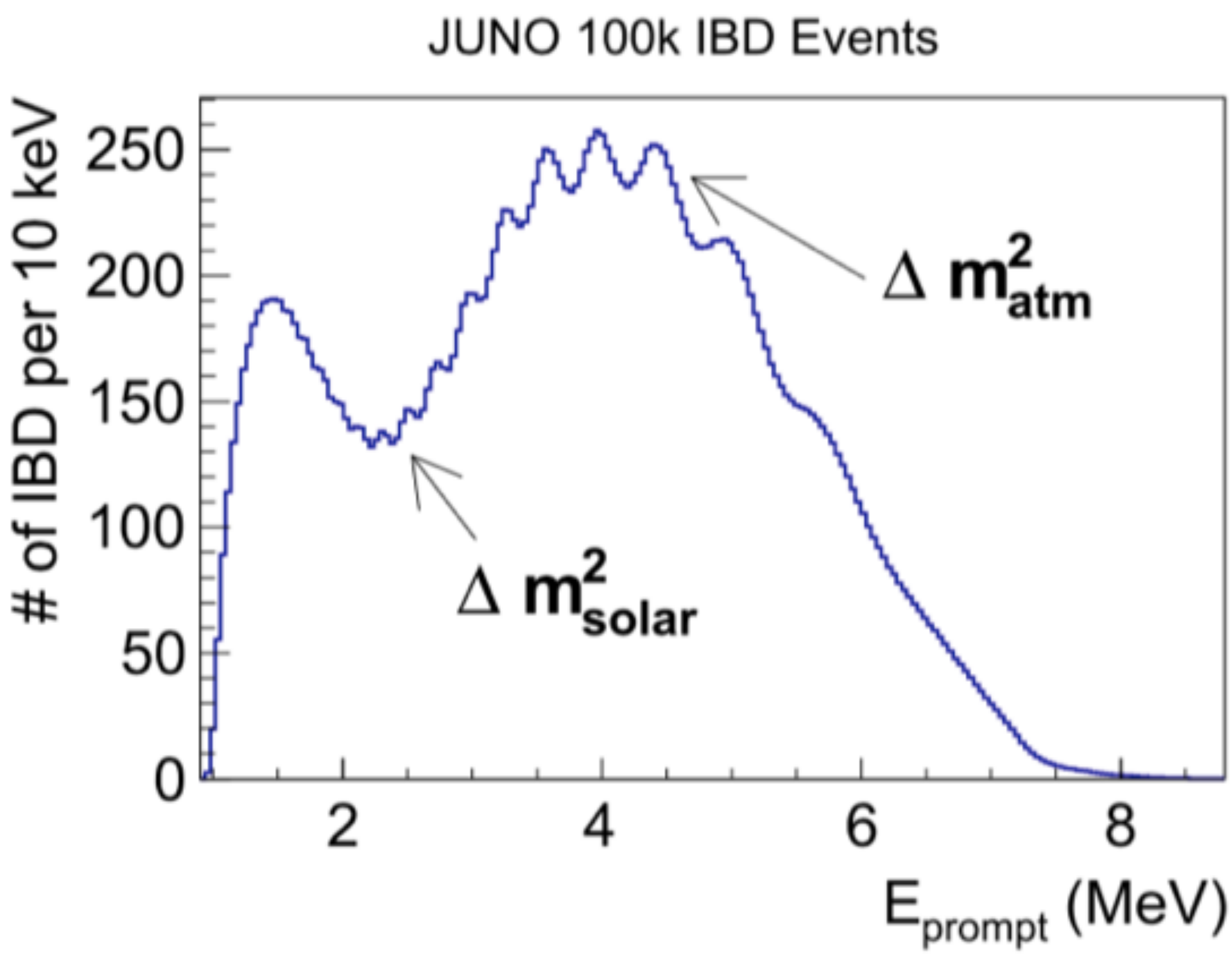


The chance to observe $0\nu\beta\beta$ in the next-generation double beta decay experiments is greatly enhanced for an inverted MH and the Majorana nature of massive neutrinos.



IM: future combined cosmological constraints would have a very high-precision detection of Σm_ν, with 1σ error.
MH: future cosmology would detect the lowest Σm_ν at a level of ~4σ.

Precision Measurements



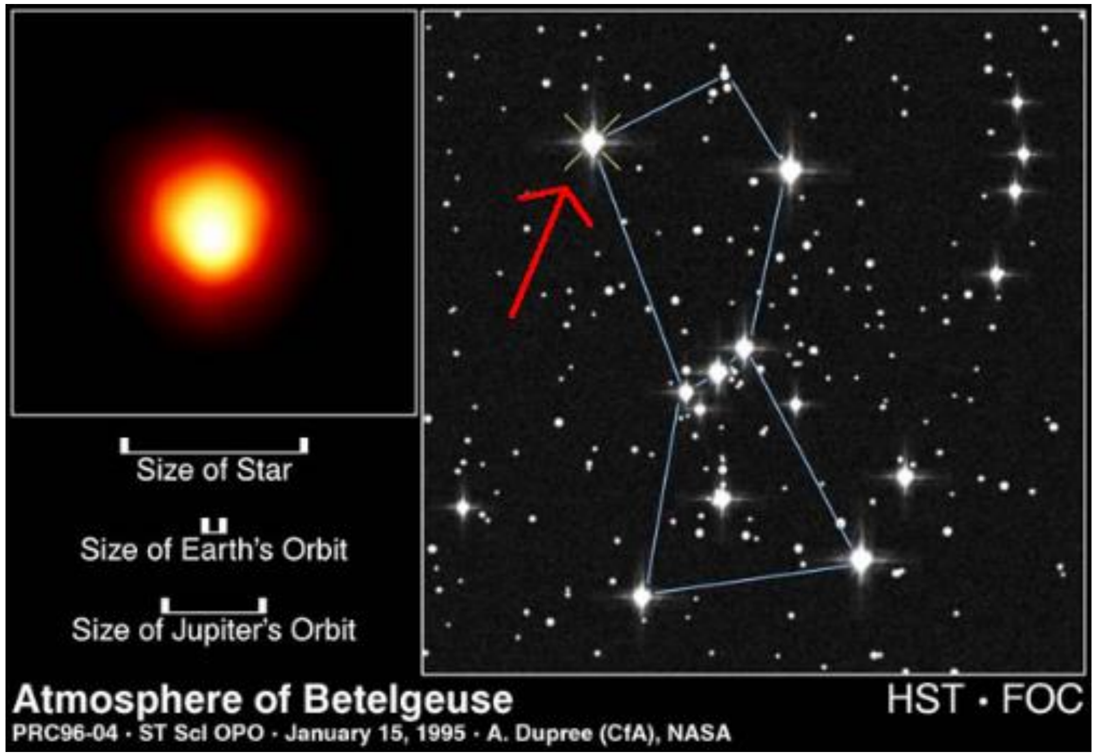
Probing the unitarity of U_{PMNS} to ~1%
more precise than CKM matrix elements !

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

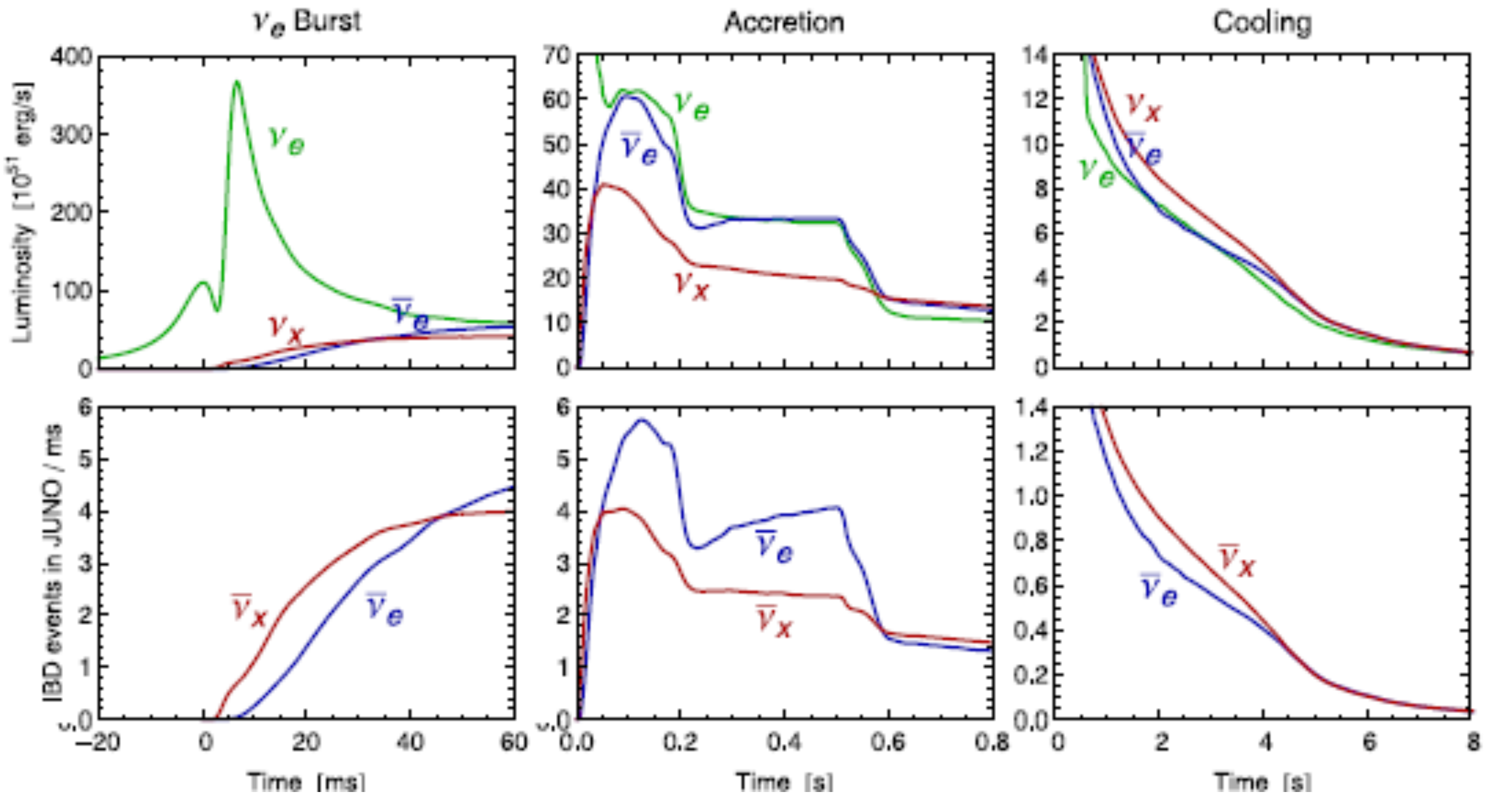
$$\Delta m^2_{ee} = \cos^2\theta_{12}\Delta m^2_{31} + \sin^2\theta_{12}\Delta m^2_{32}$$

Supernova burst Neutrinos

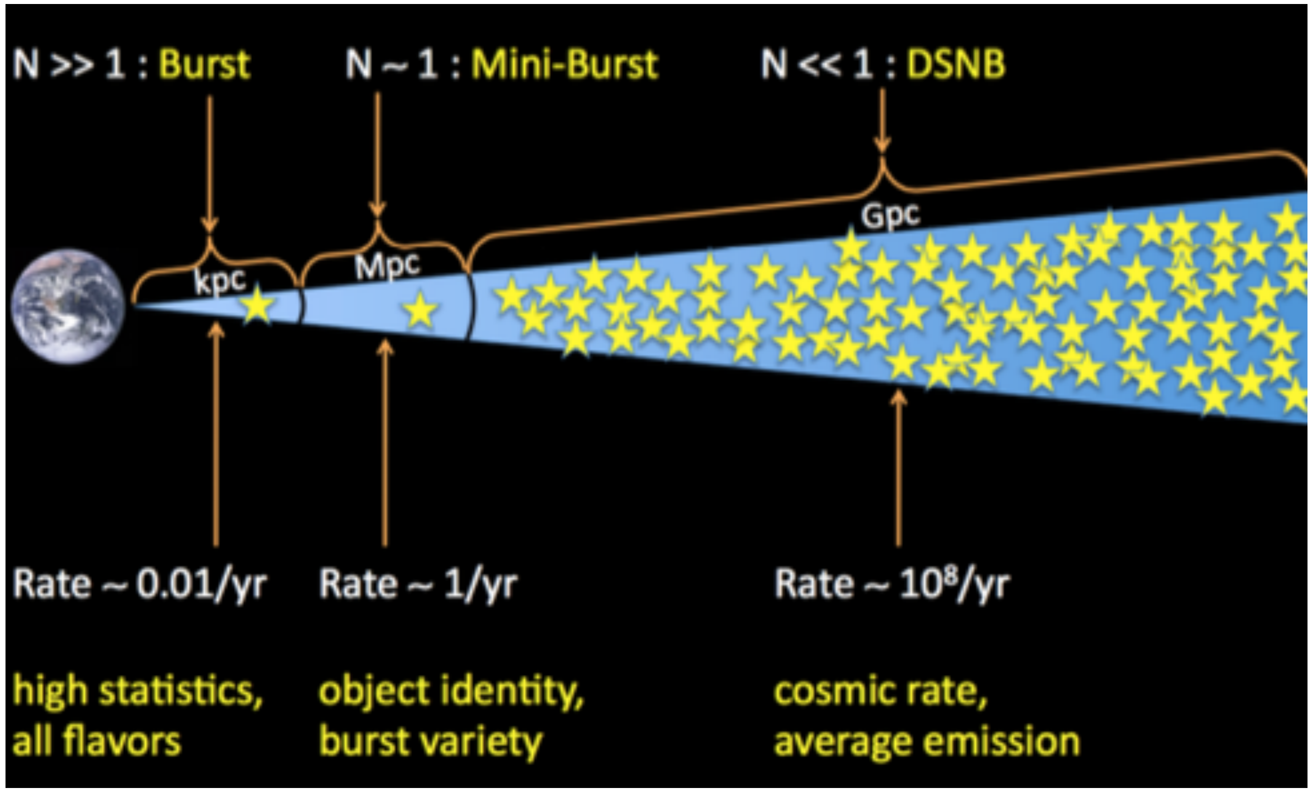
- **Less than 20 events observed for 1987A**
- Assumptions:
  - Distance: 10 kpc (1pc = 3.26156 ly)
  - Energy: 3×10^{53} erg (1 erg = 10^{-7} J)
  - L_ν: the same for all types
- **5000 IBD events**
- **2000 all flavor events**

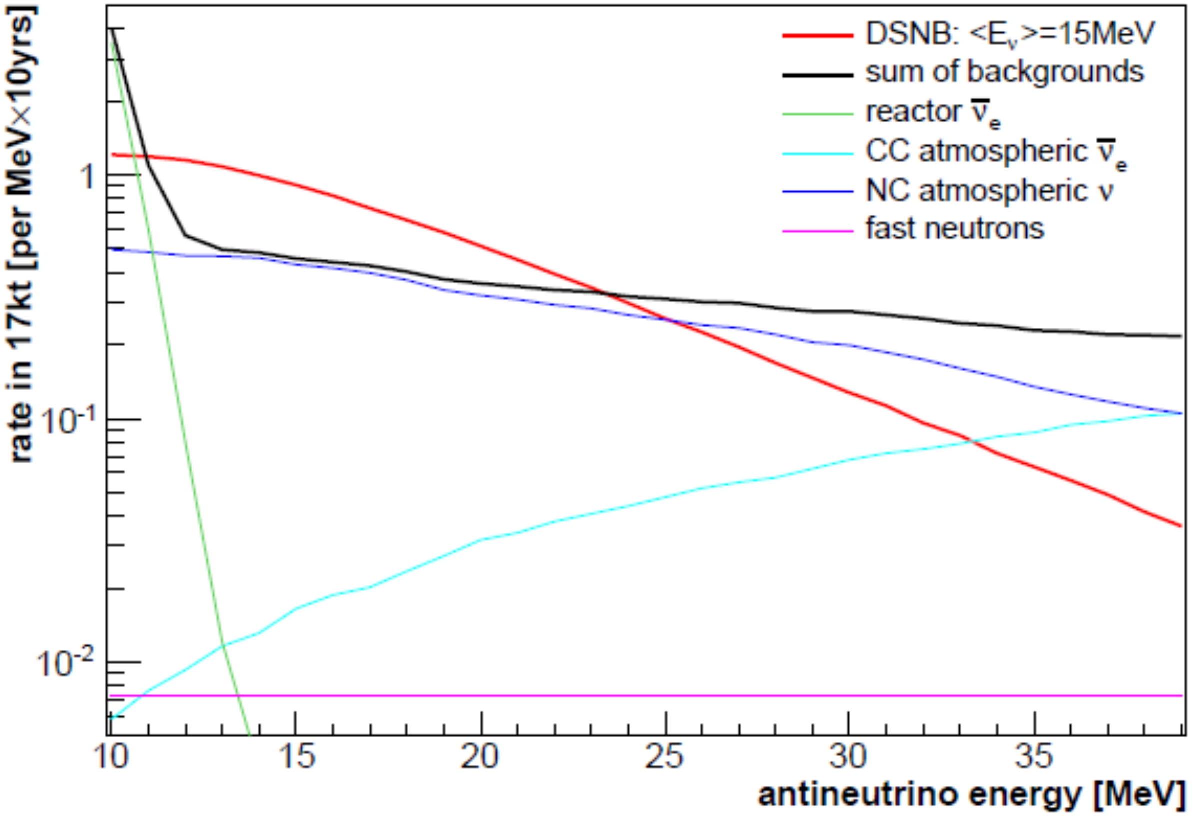


猎户座一等星：参宿四



Diffuse supernova neutrino background





10 years' sensitivity

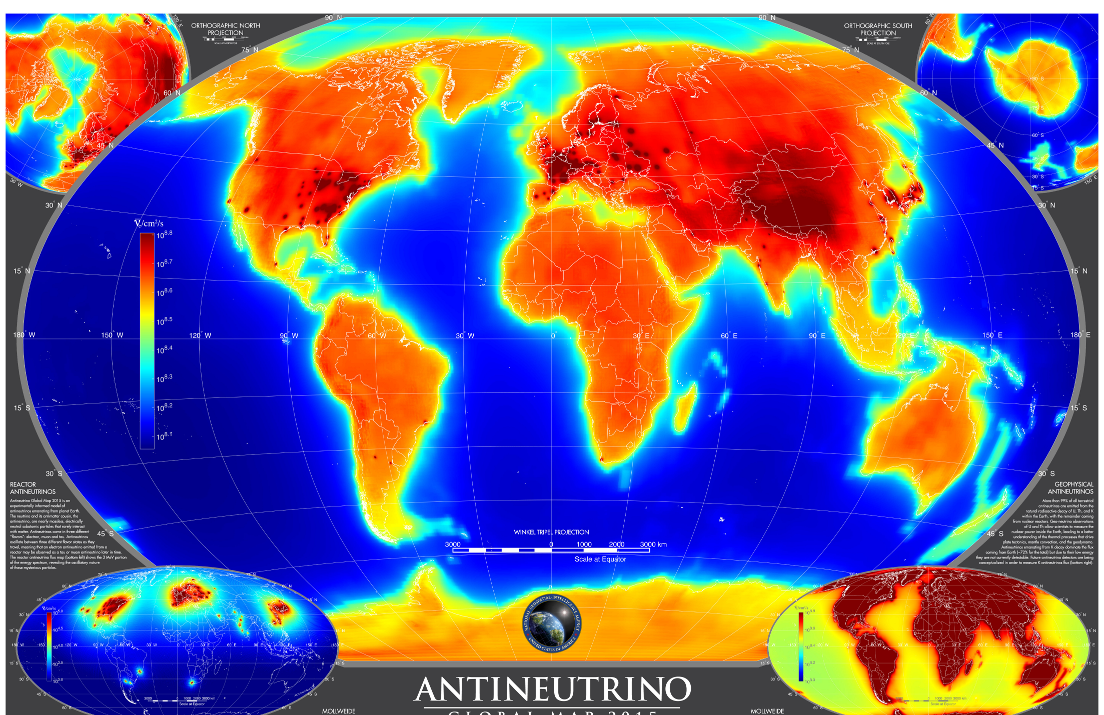
Syst. uncertainty BG	5 %		20 %	
$\langle E_{\bar{\nu}_e} \rangle$	rate only	spectral fit	rate only	spectral fit
12 MeV	$1.7\,\sigma$	$1.9\,\sigma$	$1.5\,\sigma$	$1.7\,\sigma$
15 MeV	$3.3\,\sigma$	$3.5\,\sigma$	$3.0\,\sigma$	$3.2\,\sigma$
18 MeV	$5.1\,\sigma$	$5.4\,\sigma$	$4.6\,\sigma$	$4.7\,\sigma$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

Geo-neutrinos

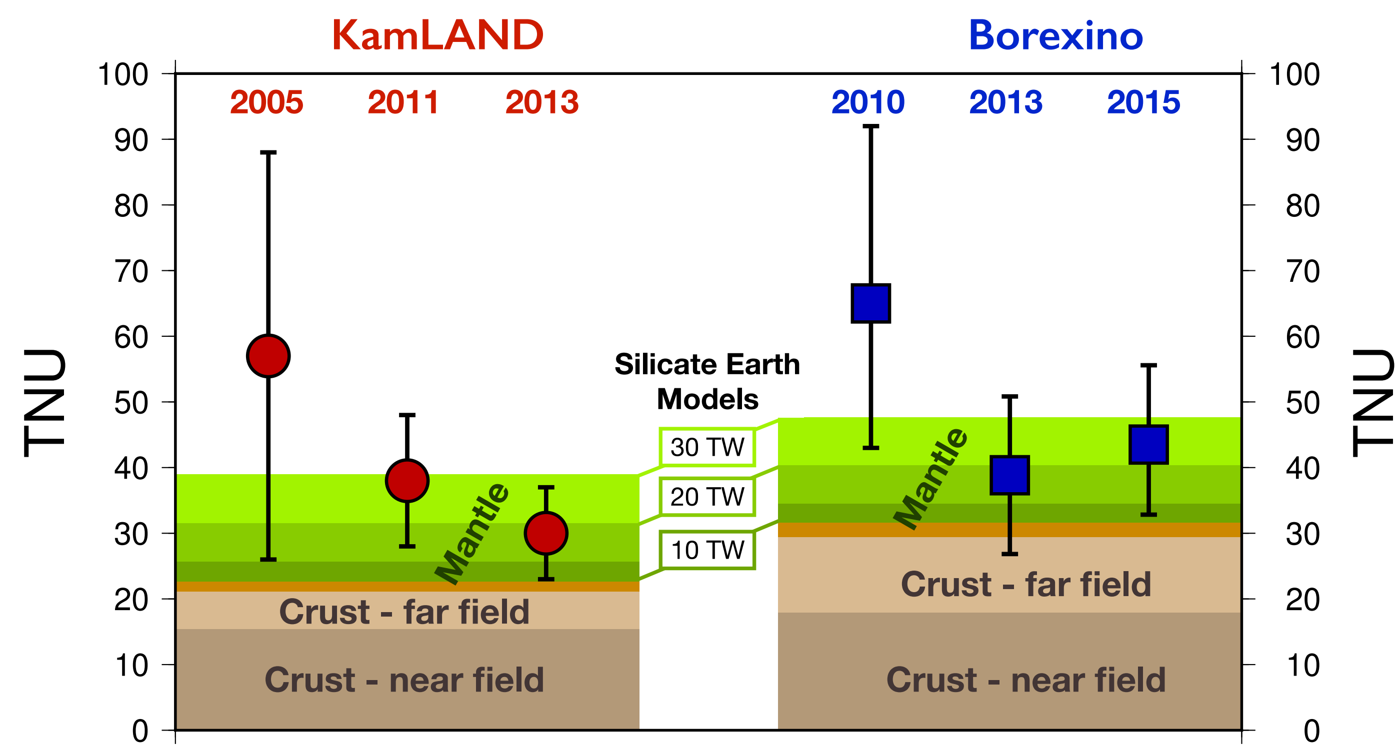
5 Big Questions:

- What is the Planetary K/U ratio?
  planetary volatility curve
- Radiogenic contribution to heat flow?
  secular cooling
- Composition of the deep mantle?
  whole vs layered convection
- Elements in the core?
  Radioactive & light element budgets
- Nature of the Core-Mantle Boundary?
  hidden reservoirs

Antineutrino Map: geoneutrinos + reactor neutrinos



Summary of geoneutrino results



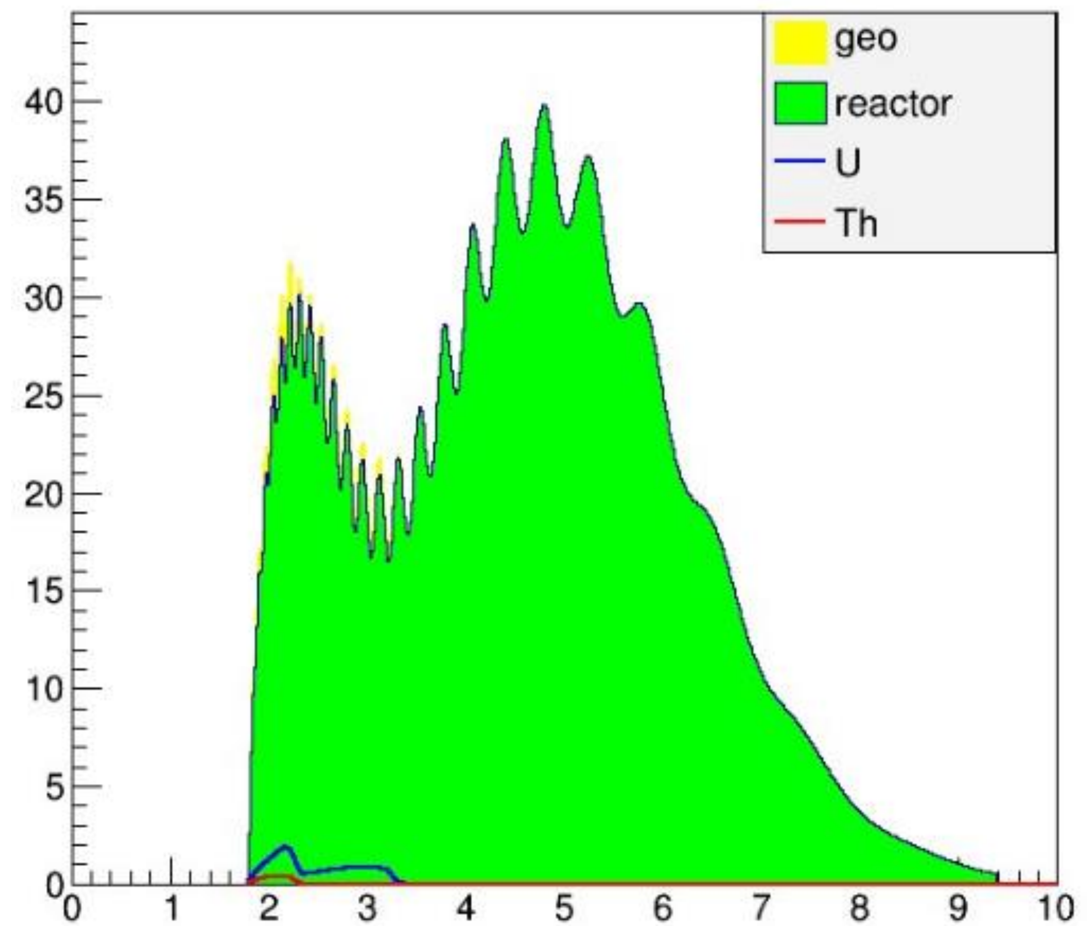
SILICATE EARTH MODELS
<u>Cosmochemical</u>: uses meteorites – 10 TW
<u>Geochemical</u>: uses terrestrial rocks –20 TW
<u>Geodynamical</u>: parameterized convection – 30 TW

TNU: geo-nυ event seen by a kiloton detector in a year

McDonough's slides

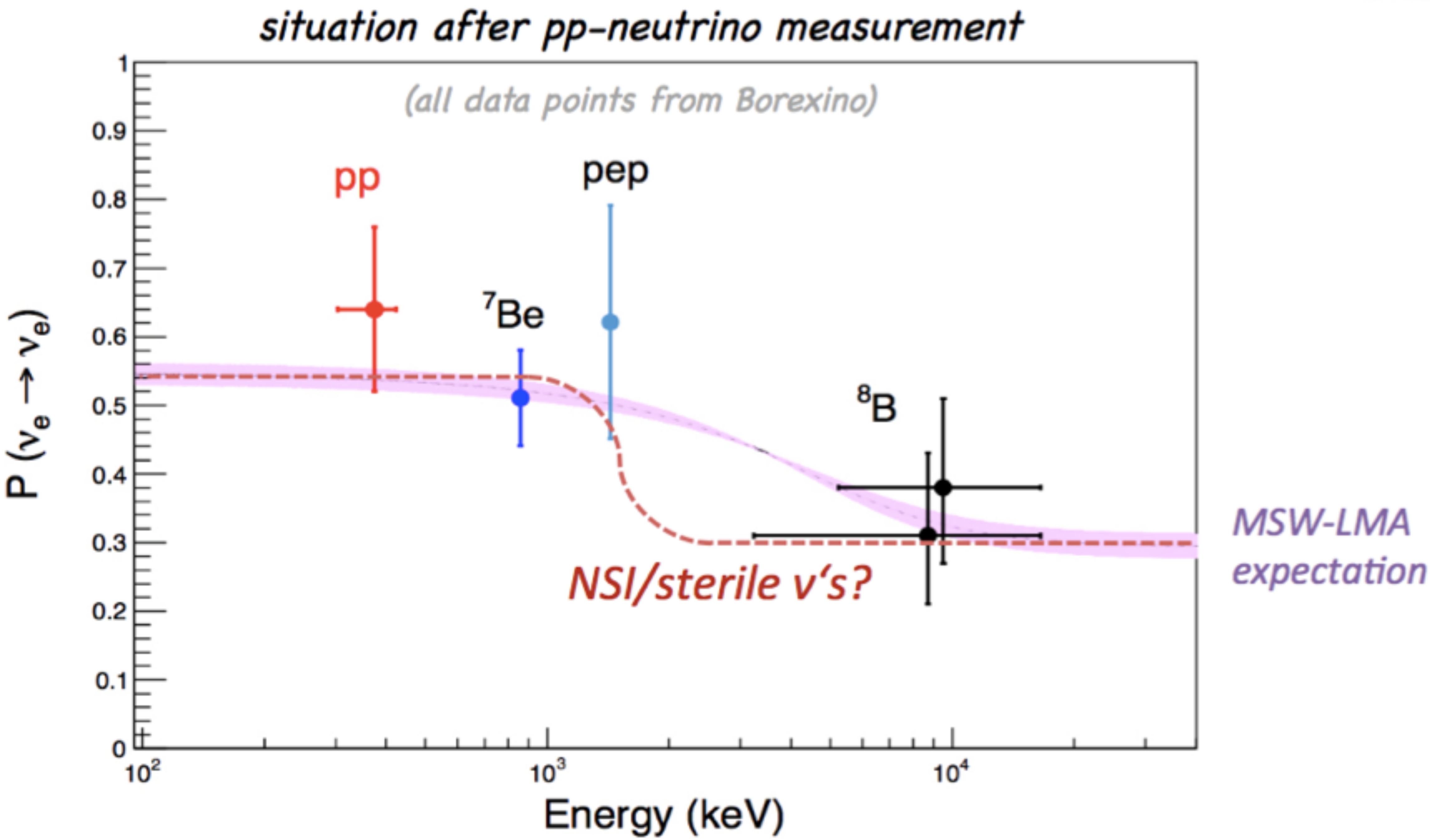
Geo-neutrinos

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



- **JUNO: ×20 statistics**
- Huge reactor neutrino backgrounds
- Need accurate reactor spectra

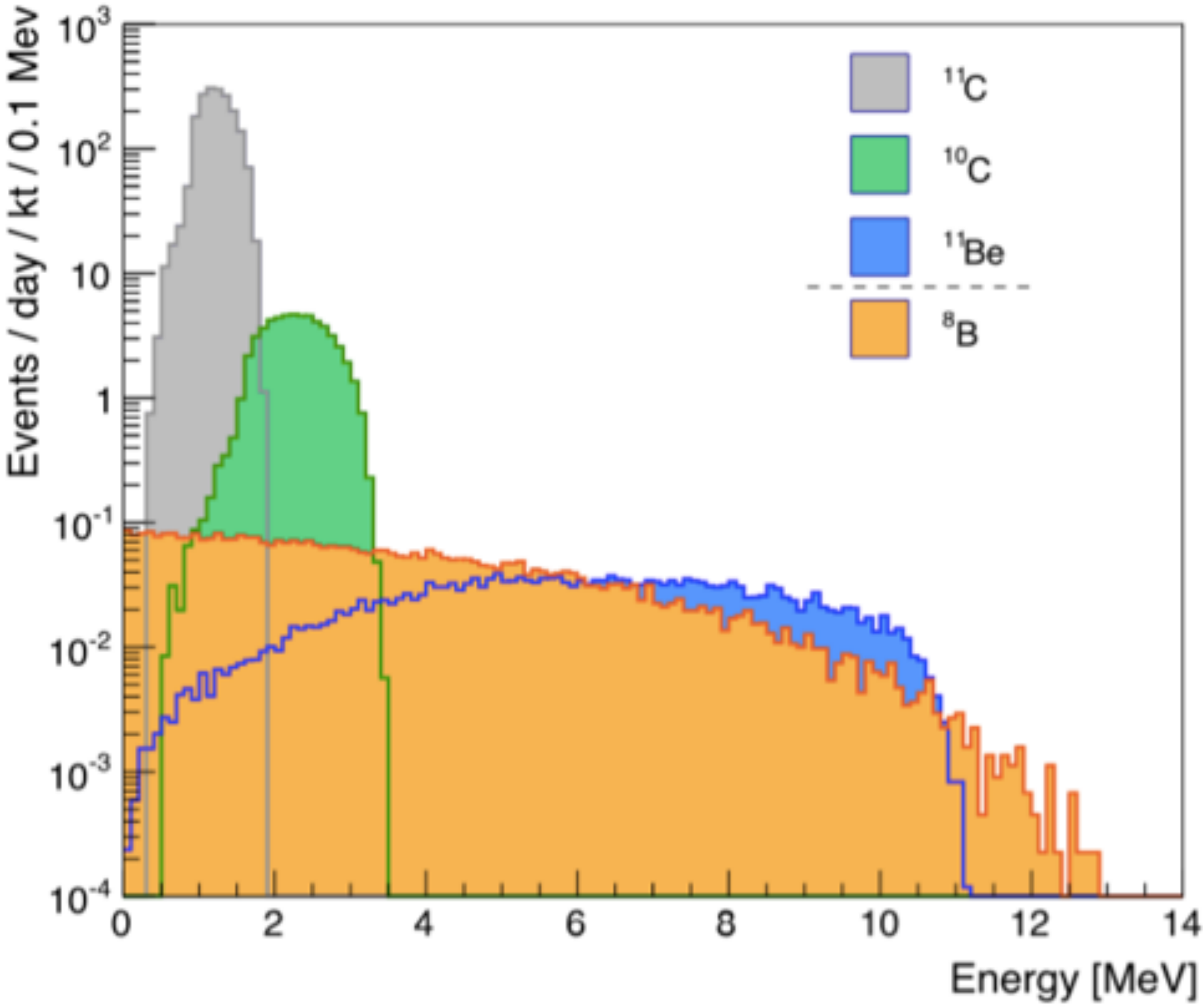
Solar Neutrinos



An improved accuracy of the measurement in the region around 3 MeV would be essential to test the consistency of the MSW-LMA solution and definitely exclude (or confirm) more exotic sub-leading effects

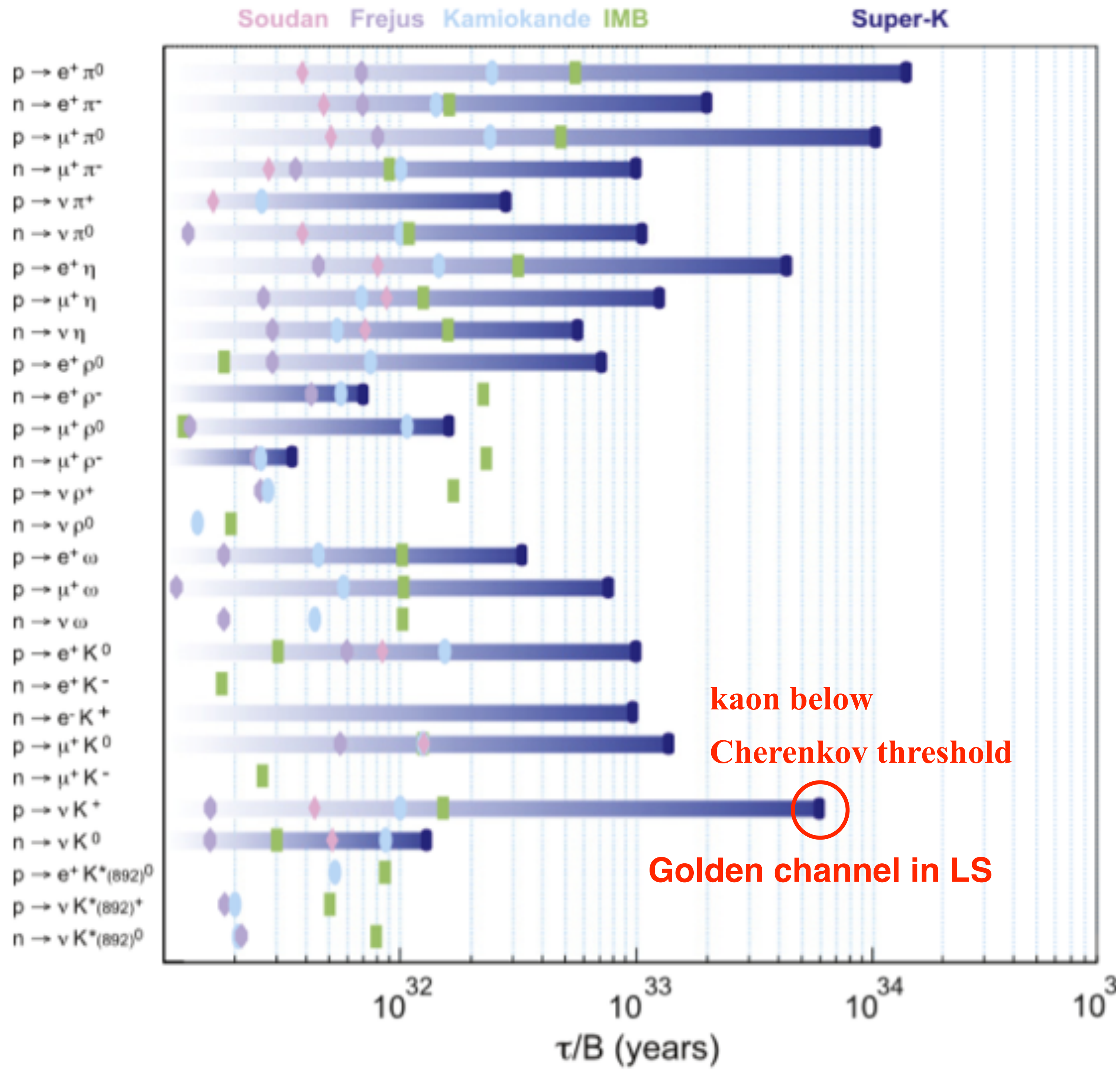
Solar Neutrinos

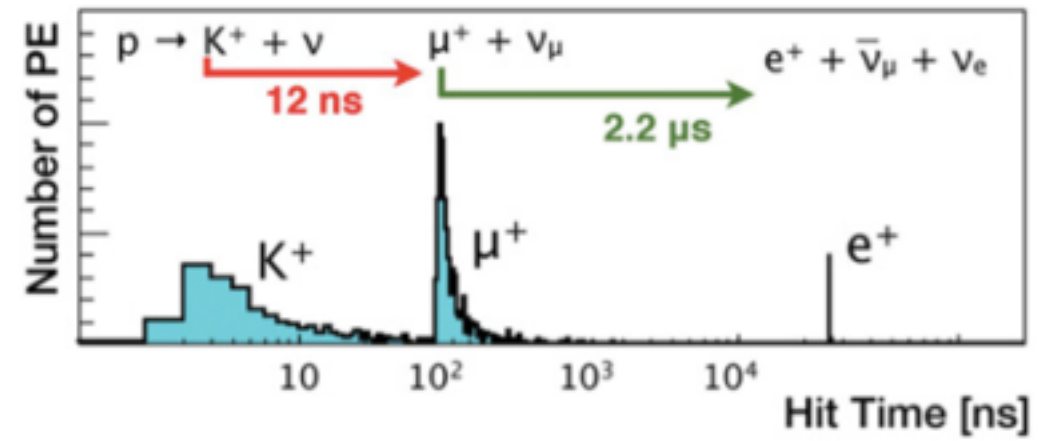
	Internal radiopurity requirements Baseline	Ideal
^{210}Pb	5×10^{-24} (g g^{-1})	1×10^{-24} (g g^{-1})
^{85}Kr	500 (counts/day/kton)	100 (counts/day/kton)
^{238}U	1×10^{-16} (g g^{-1})	1×10^{-17} (g g^{-1})
^{232}Th	1×10^{-16} (g g^{-1})	1×10^{-17} (g g^{-1})
^{40}K	1×10^{-17} (g g^{-1})	1×10^{-18} (g g^{-1})
^{14}C	1×10^{-17} (g g^{-1})	1×10^{-18} (g g^{-1})
Cosmogenic background rates (counts/day/kton)		
^{11}C	1860	
^{10}C	35	
Solar neutrino signal rates (counts/day/kton)		
pp ν	1378	
^{7}Be ν	517	
pep ν	28	
^{8}B ν	4.5	
^{13}N/^{15}O/^{17}F ν	7.5/5.4/0.1	

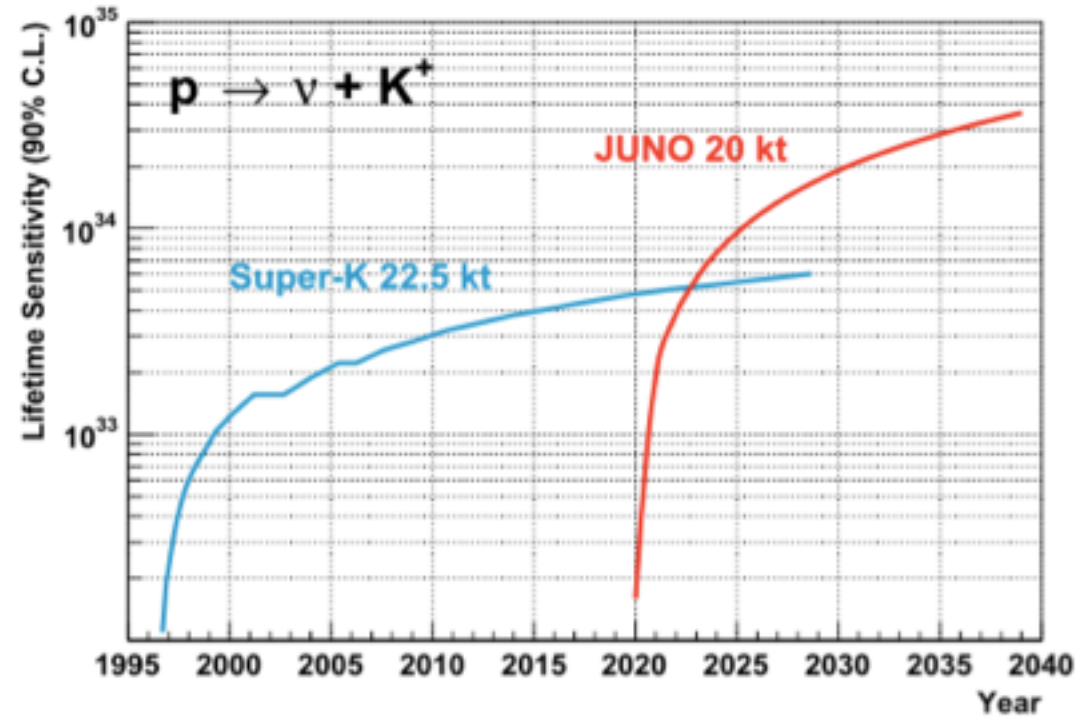


An improved accuracy of the measurement in the region around 3 MeV would be essential to test the consistency of the LMA-MSW solution and definitely exclude (or confirm) more exotic sub-leading effects

Nucleon decays

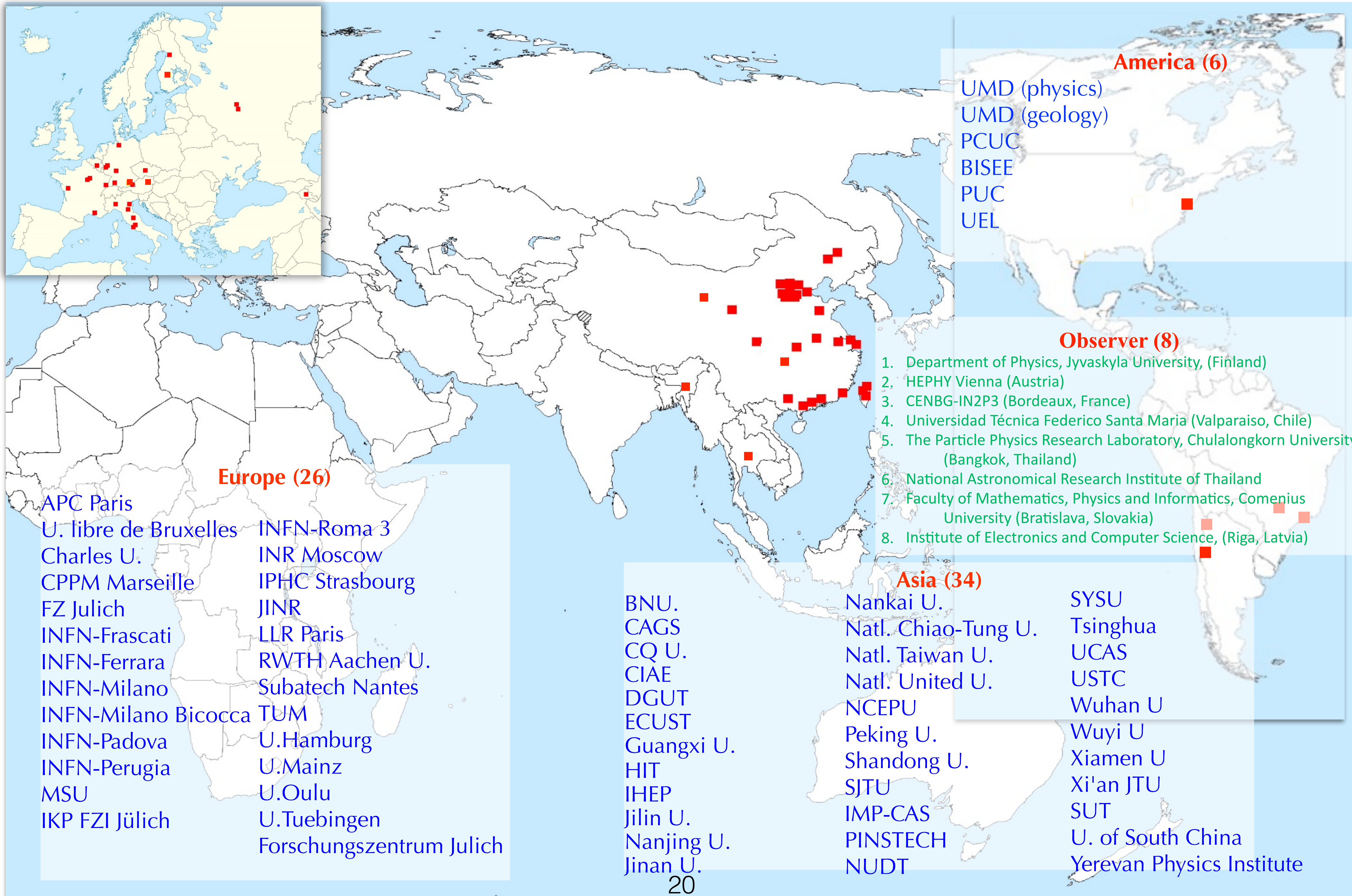






Due to the high efficiency in measuring this mode, JUNO's sensitivity will surpass Super-Kamiokande's in only 3 years since its data taking.

JUNO Collaboration



America (6)

UMD (physics)
UMD (geology)
PCUC
BISEE
PUC
UEL

Observer (8)

1. Department of Physics, Jyvaskyla University, (Finland)
2. HEPHY Vienna (Austria)
3. CENBG-IN2P3 (Bordeaux, France)
4. Universidad Técnica Federico Santa Maria (Valparaiso, Chile)
5. The Particle Physics Research Laboratory, Chulalongkorn University (Bangkok, Thailand)
6. National Astronomical Research Institute of Thailand
7. Faculty of Mathematics, Physics and Informatics, Comenius University (Bratislava, Slovakia)
8. Institute of Electronics and Computer Science, (Riga, Latvia)

Europe (26)

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
MSU
IKP FZI Jülich
INFN-Roma 3
INR Moscow
IPHC Strasbourg
JINR
LLR Paris
RWTH Aachen U.
Subatech Nantes
TUM
U.Hamburg
U.Mainz
U.Oulu
U.Tuebingen
Forschungszentrum Julich

Asia (34)

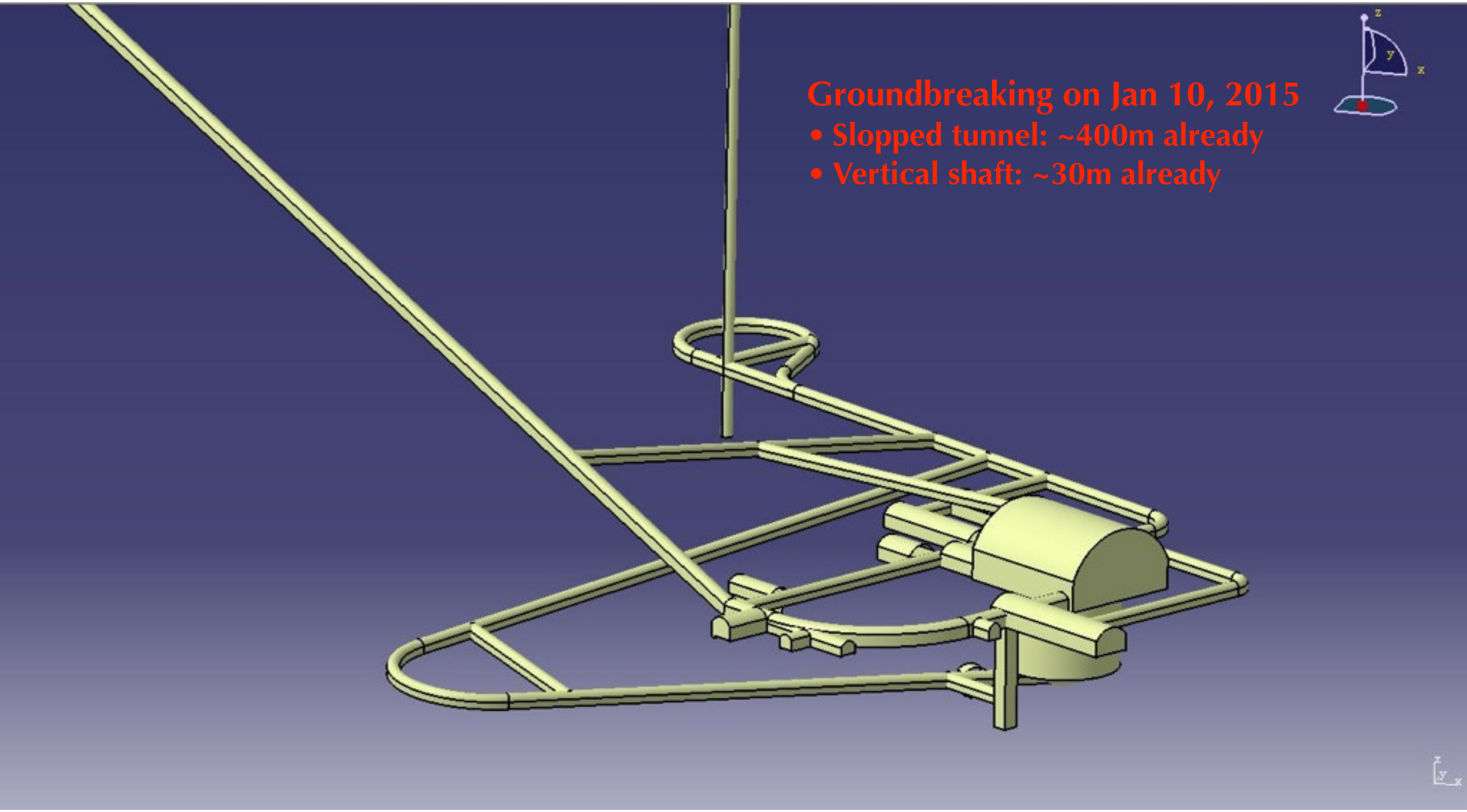
BNU.
CAGS
CQ U.
CIAE
DGUT
ECUST
Guangxi U.
HIT
IHEP
Jilin U.
Nanjing U.
Jinan U.
Nankai U.
Natl. Chiao-Tung U.
Natl. Taiwan U.
Natl. United U.
NCEPU
Peking U.
Shandong U.
SJTU
IMP-CAS
PINSTECH
NUDT
SYSU
Tsinghua
UCAS
USTC
Wuhan U
Wuyi U
Xiamen U
Xi'an JTU
SUT
U. of South China
Yerevan Physics Institute

Surface Facilities

700 m Underground

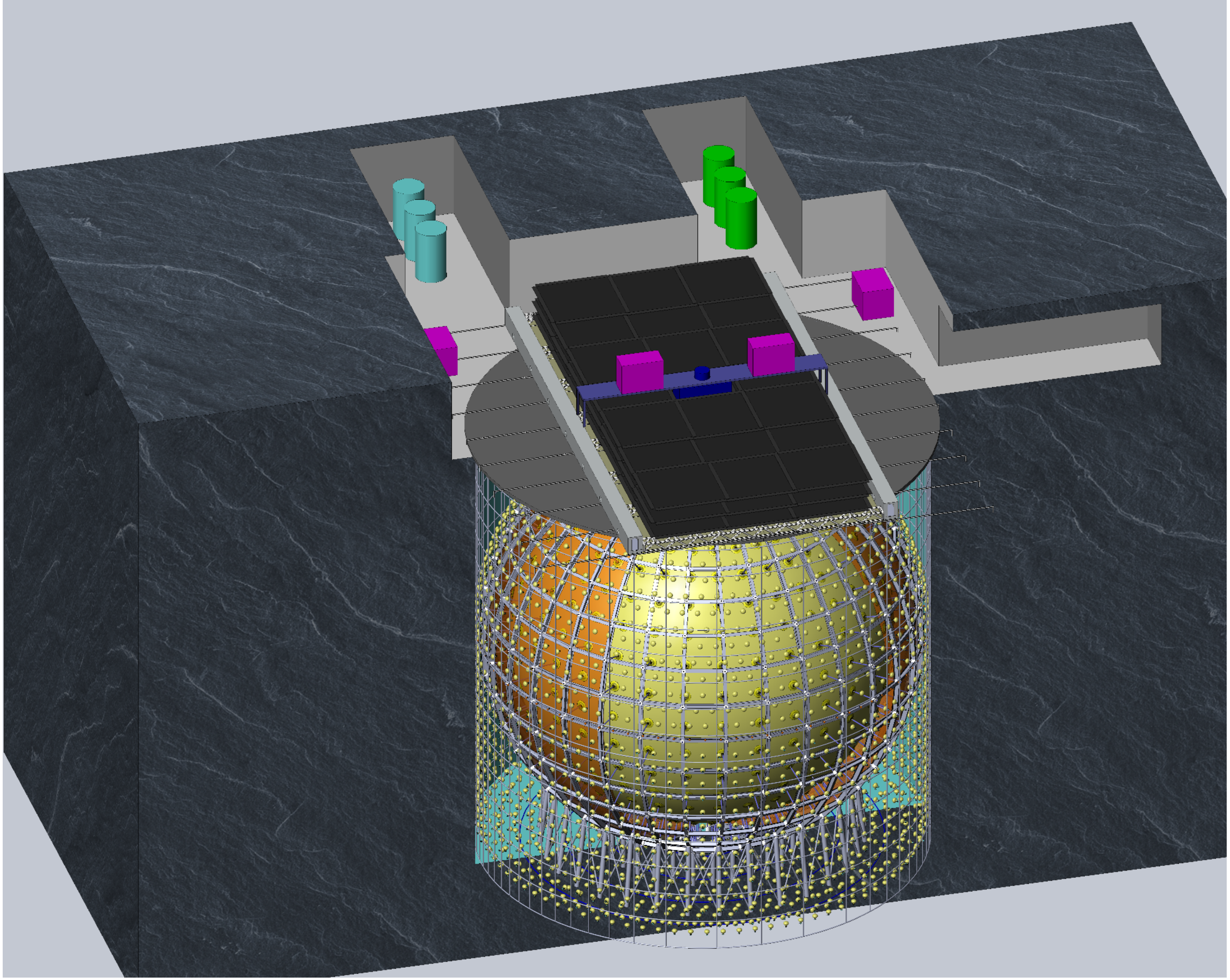
Slope tunnel
1340m

Vertical shaft
581m



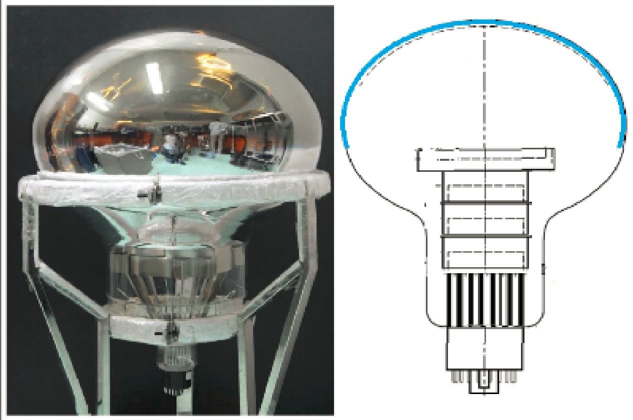
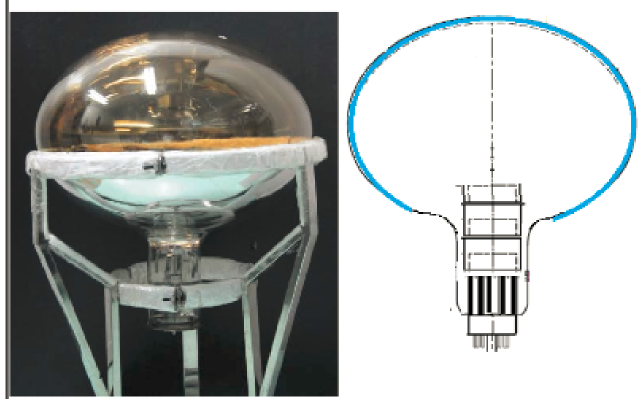
Groundbreaking on Jan 10, 2015
- Slopped tunnel: ~400m already
- Vertical shaft: ~30m already

700 m Underground



Civil Progress

20” PMT bidding

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

Characteristics	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

Finished 20” PMT bidding at end of 2015:

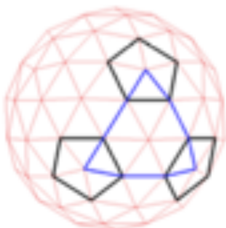
-- 15000 MCP-PMT (North Night Vision Technology, NNVT)

-- 5000 Dynode-PMT (Hamamatsu)

Photocathode Coverage

Polyhedral module layout method

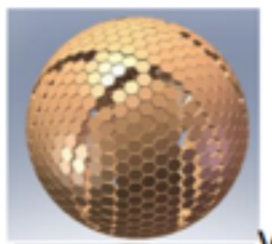
others

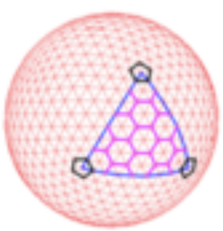


3 layers: 180 Triangles(or 12 Pentagons and 20 hexagons)

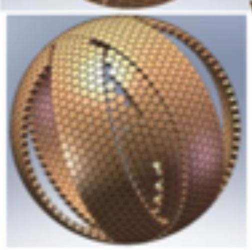
Football

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



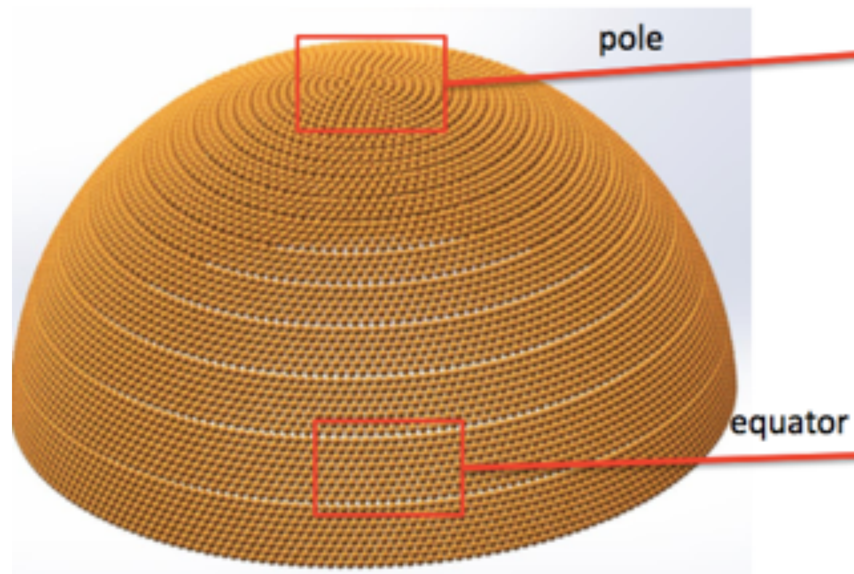


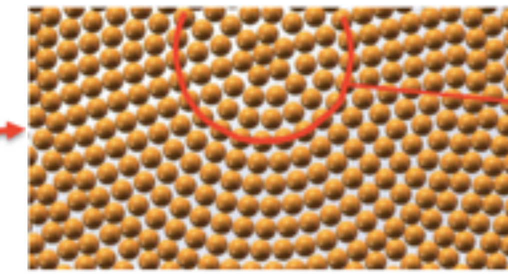
9 layers: 1620 Triangles(or 12 Pentagons and 260 hexagons)



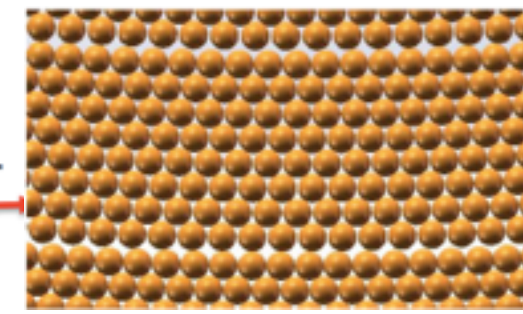
Volleyball-liked

- **Circle and layer**
- A layer contains one or several circles PMTs
- The number of PMT is equal in every circle of the same layer





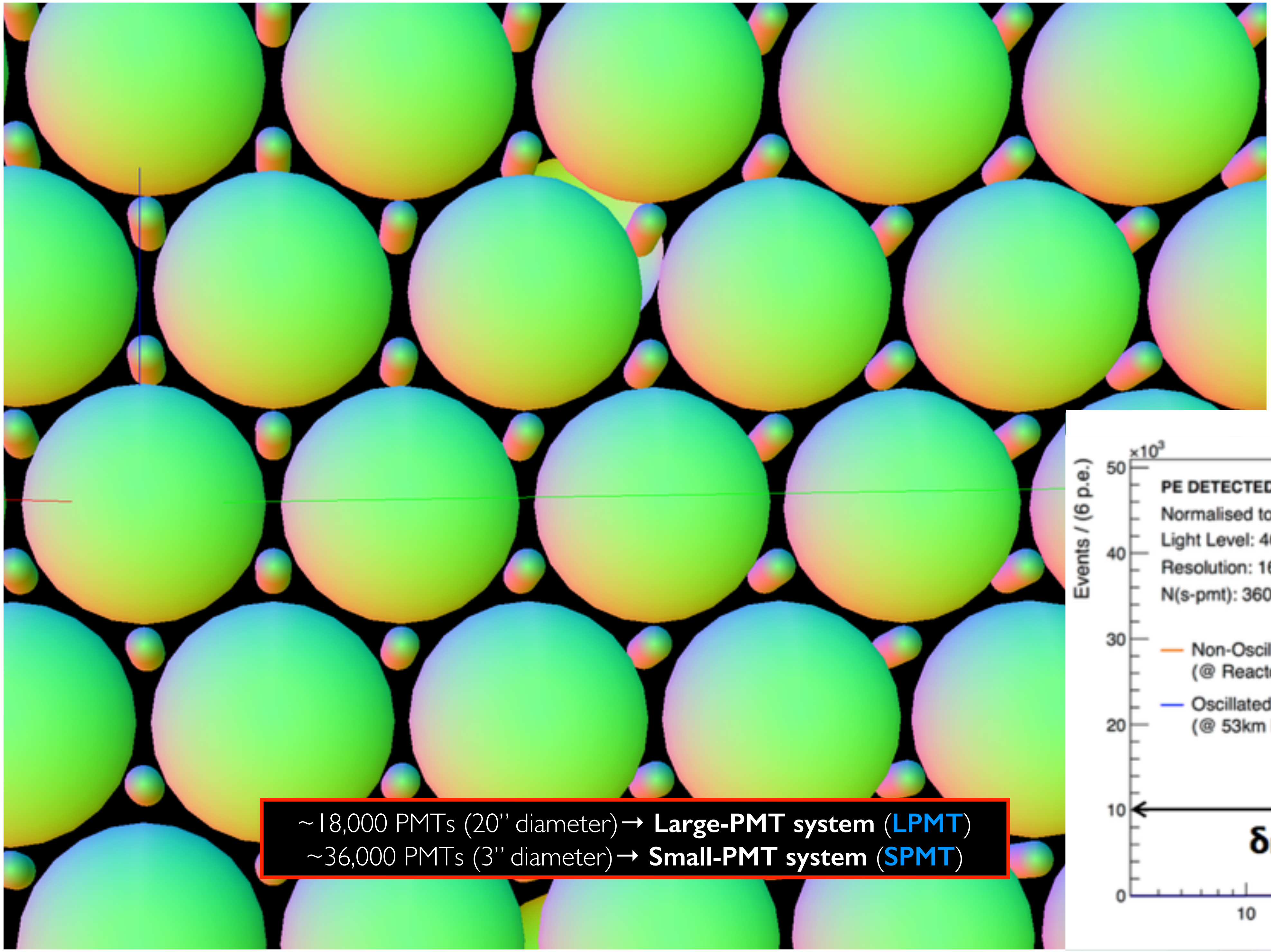
A layer contains only one circle PMT

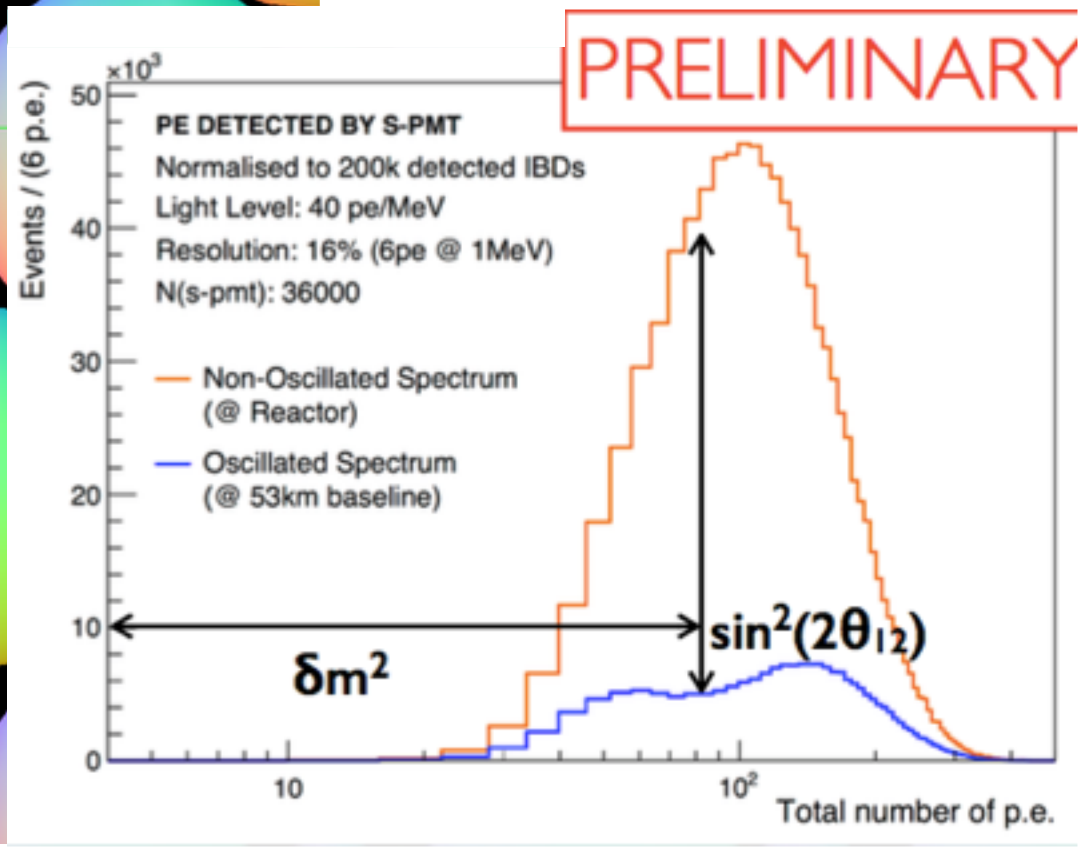


a layer contains several circles PMT (Cross-arranged)

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%

Adding SPMTs





Central Detector Design

Calibration

Top Tracker

Electronics

Filling + Overflow

Central detector

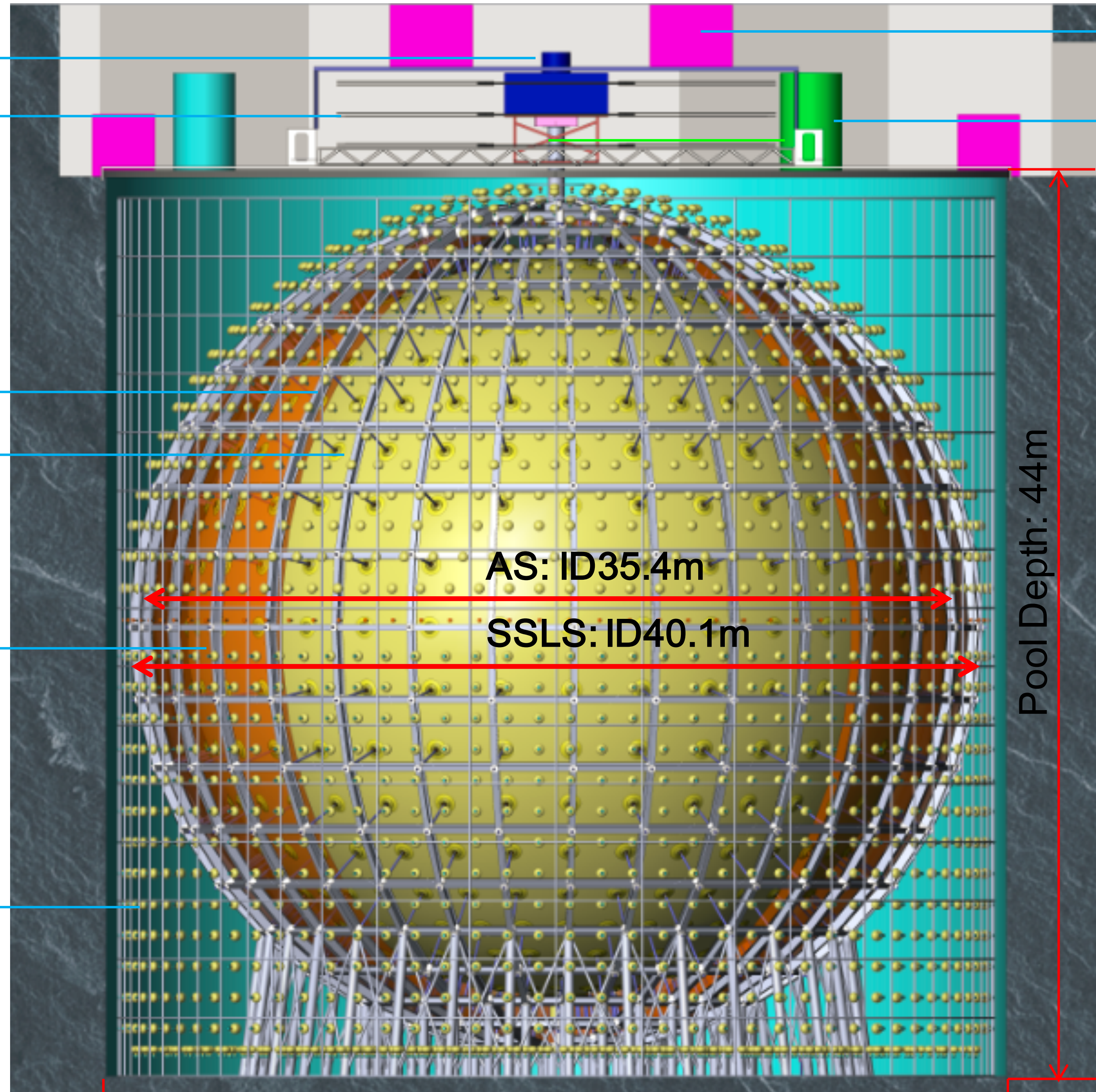
SS latticed shell

Acrylic sphere (20Kt LS in it)

~17000 20” PMT +~34000 3’’ PMT

Water Cherenkov

~2000 20’’ PMT



Pool ID:43.5m

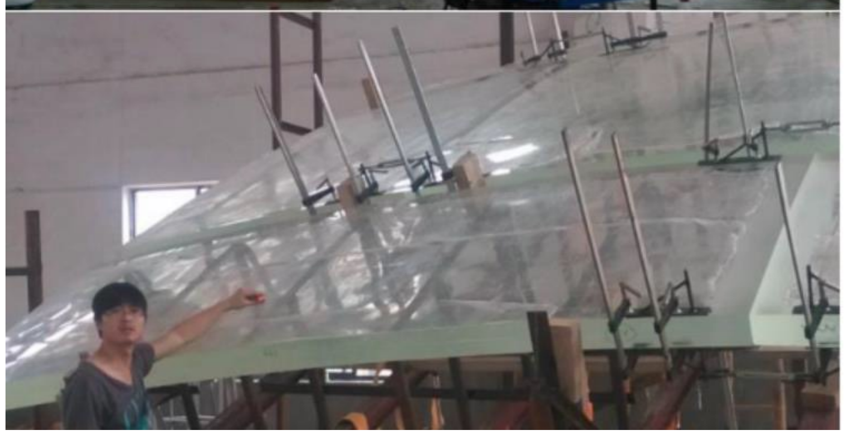
AS: Acrylic sphere; SSLS: stainless steel latticed shell

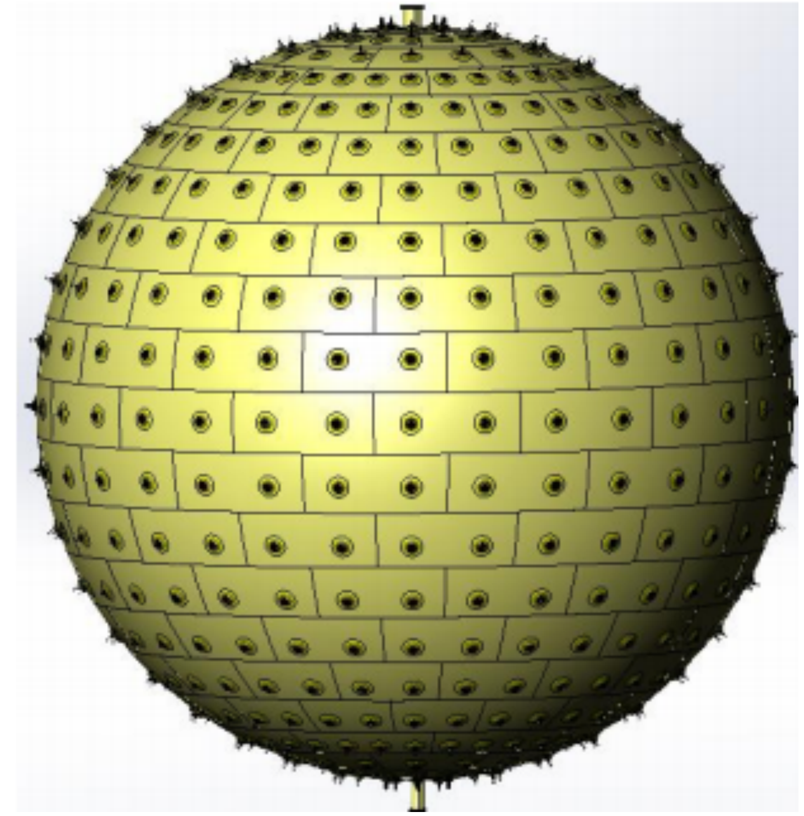
Acrylic Sphere:
ID: 35.4m
Thickness:120mm

SSLS:
ID: 40.1m
OD: 41.1m

Water pool
ID: 43.5m
Height: 44m
Water Depth: 43.5m

Acrylic Sphere R&D





Acrylic divided into 200+ panels

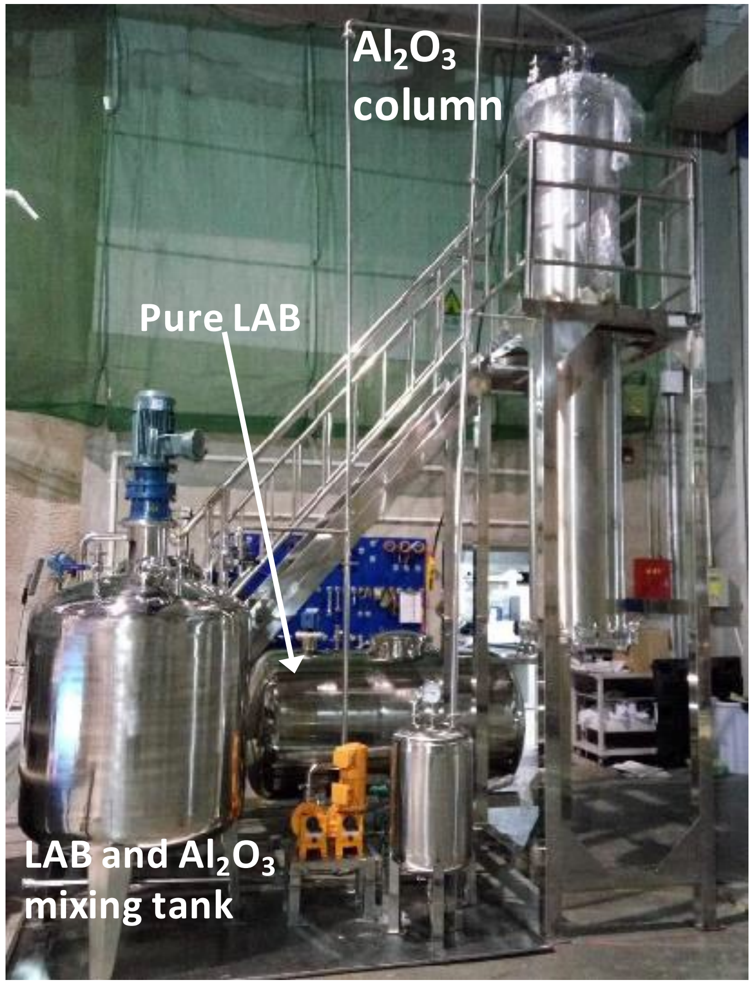
Forming panel size: 3 m x 8 m x 120 mm

Prototype of spherical panel

The problems of shrinkage and shape variation were resolved.

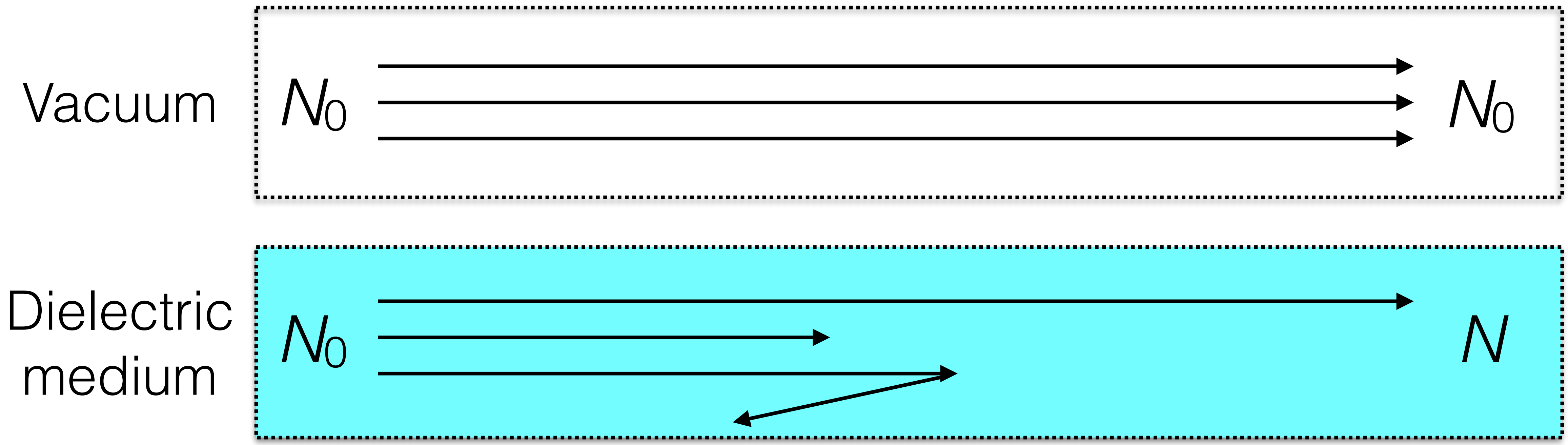
Three companies had good practices.

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

Optical properties of LS



attenuation = **absorption** ⊕ **scattering**

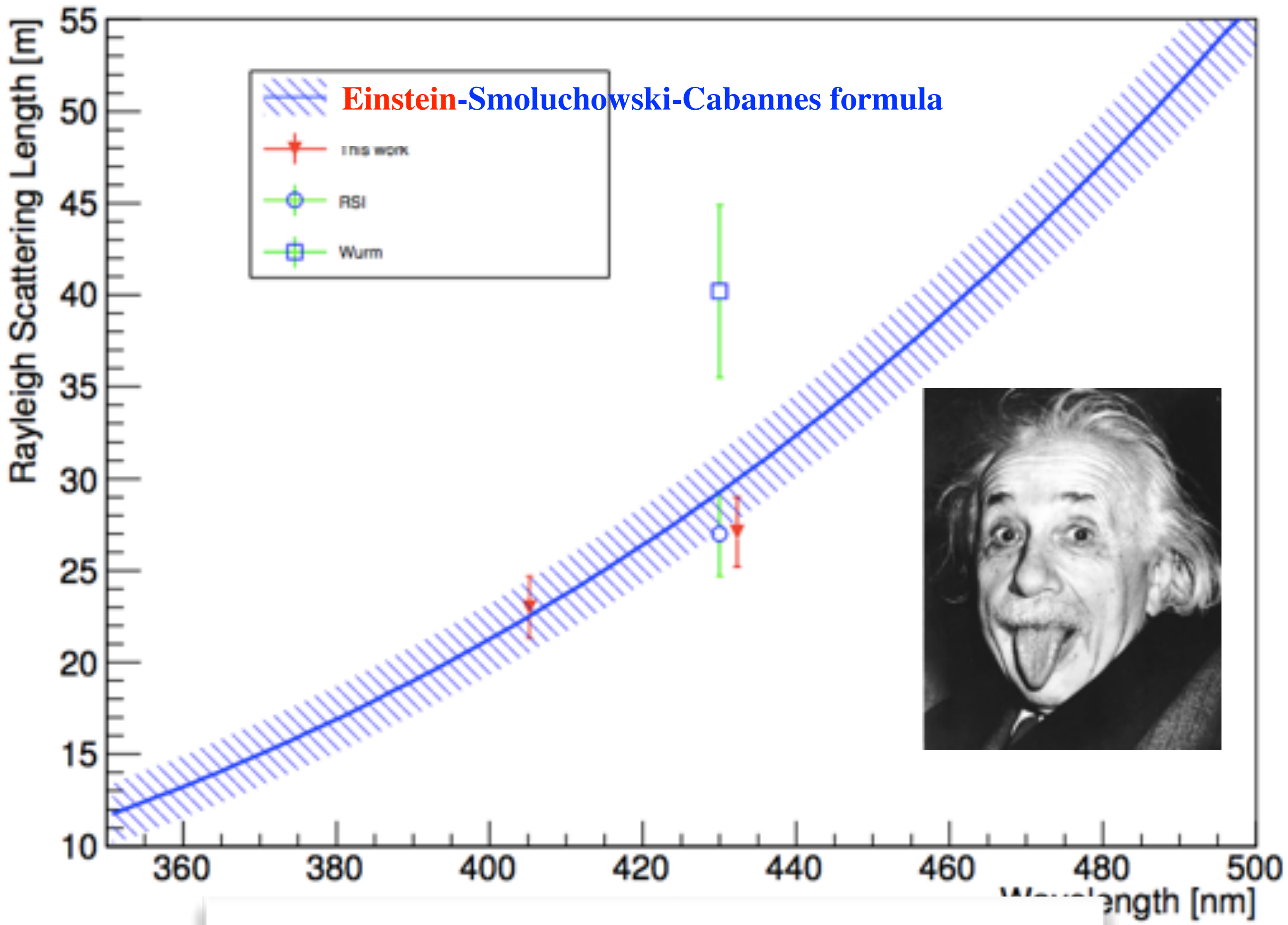
$$\frac{1}{L_{\mathrm{att.}}} = \frac{1}{L_{\mathrm{abs.}}} + \frac{1}{L_{\mathrm{sca.}}}$$

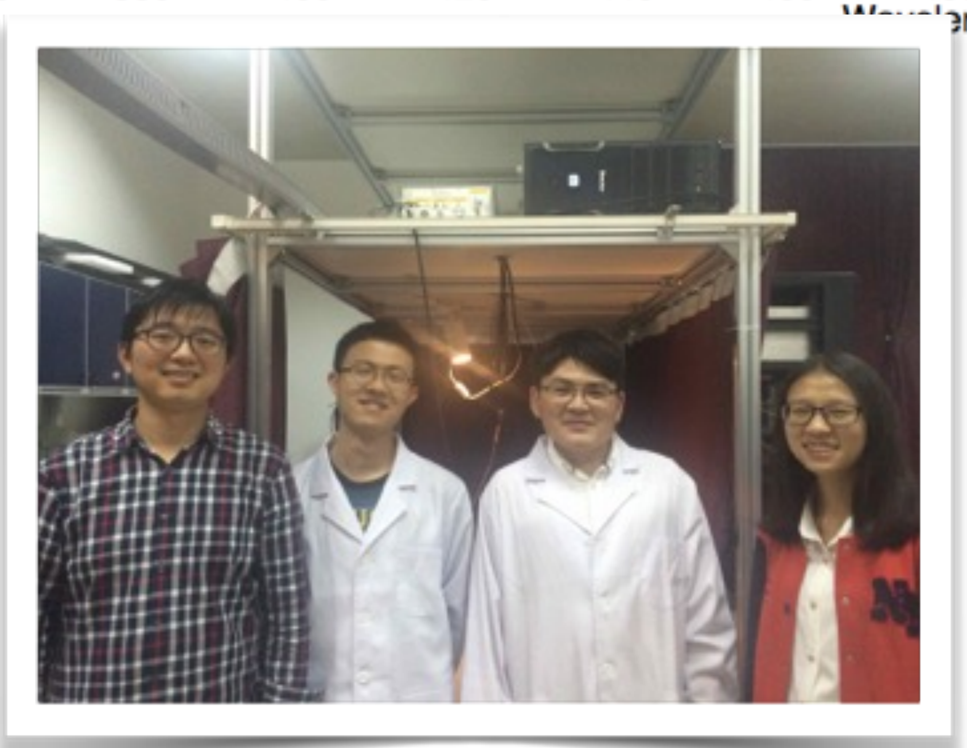
Geant4: **absorption** & **scattering** lengths

Measurements: **attenuation** & **scattering** lengths

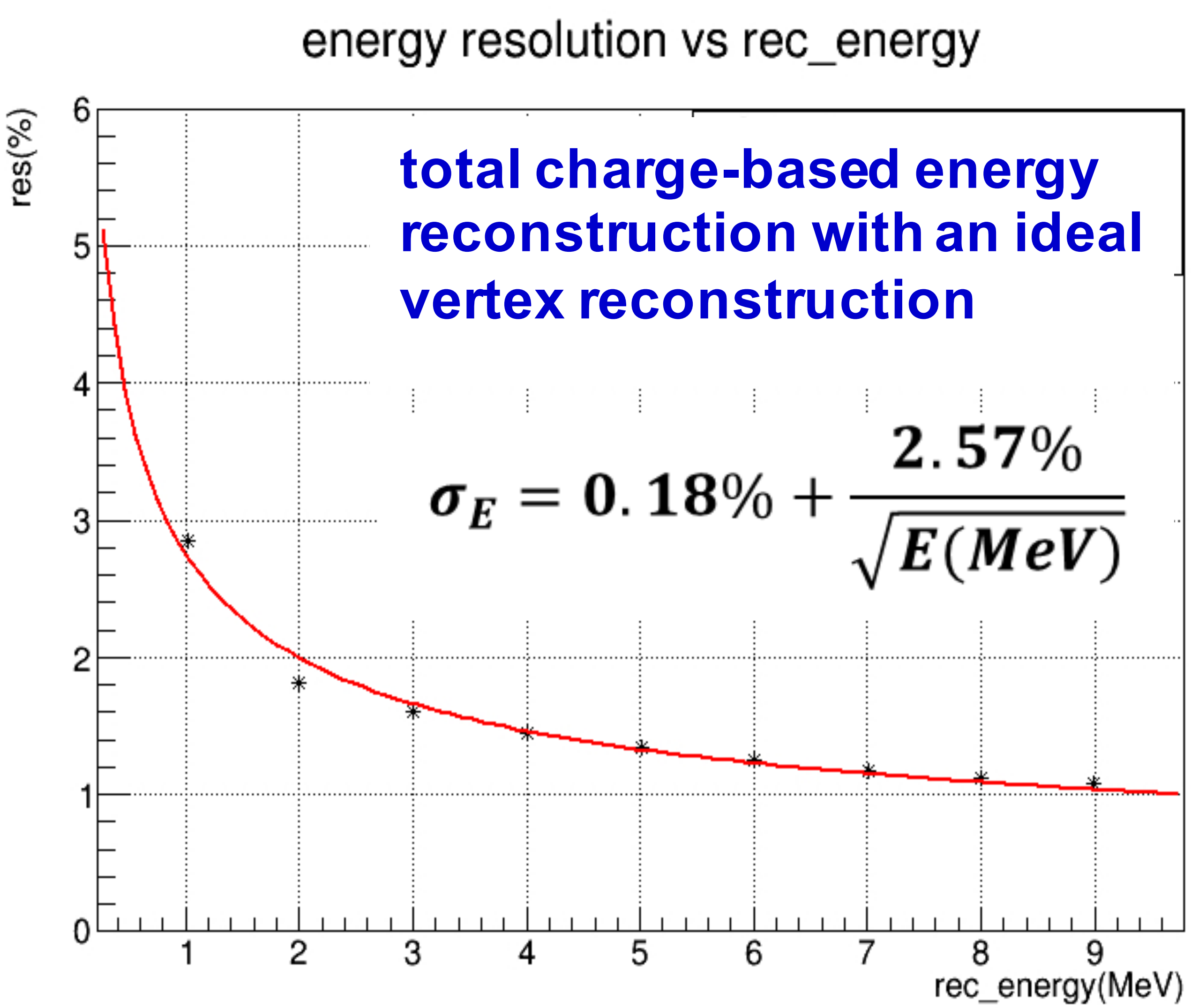
Rayleigh Scattering Measurements

$$l_{\text{Ray}} = 27.1 \pm 1.9\,\text{m@}432.3\,\text{nm}$$





MC study on Energy resolution



$$\sigma_E = 0.18\% + \frac{2.57\%}{\sqrt{E(MeV)}}$$

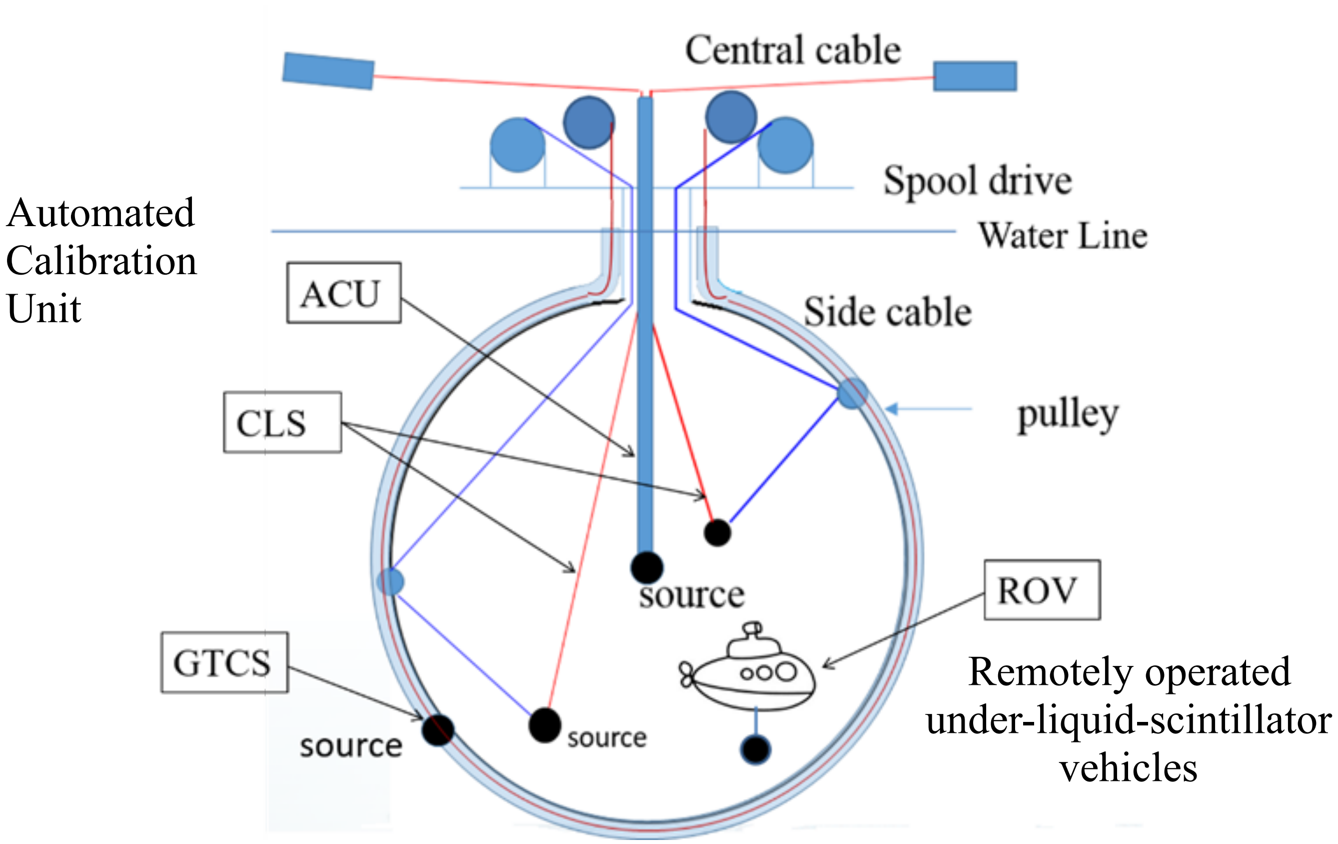
- Based on DYB MC (tuned to data), except
  - JUNO Geometry and 77% photocathode coverage
  - PMT peak QE 35%
  - Attenuation length 20 m@430nm
    - att. 20 m = abs. 60 m + Rayleigh scatt. 30m

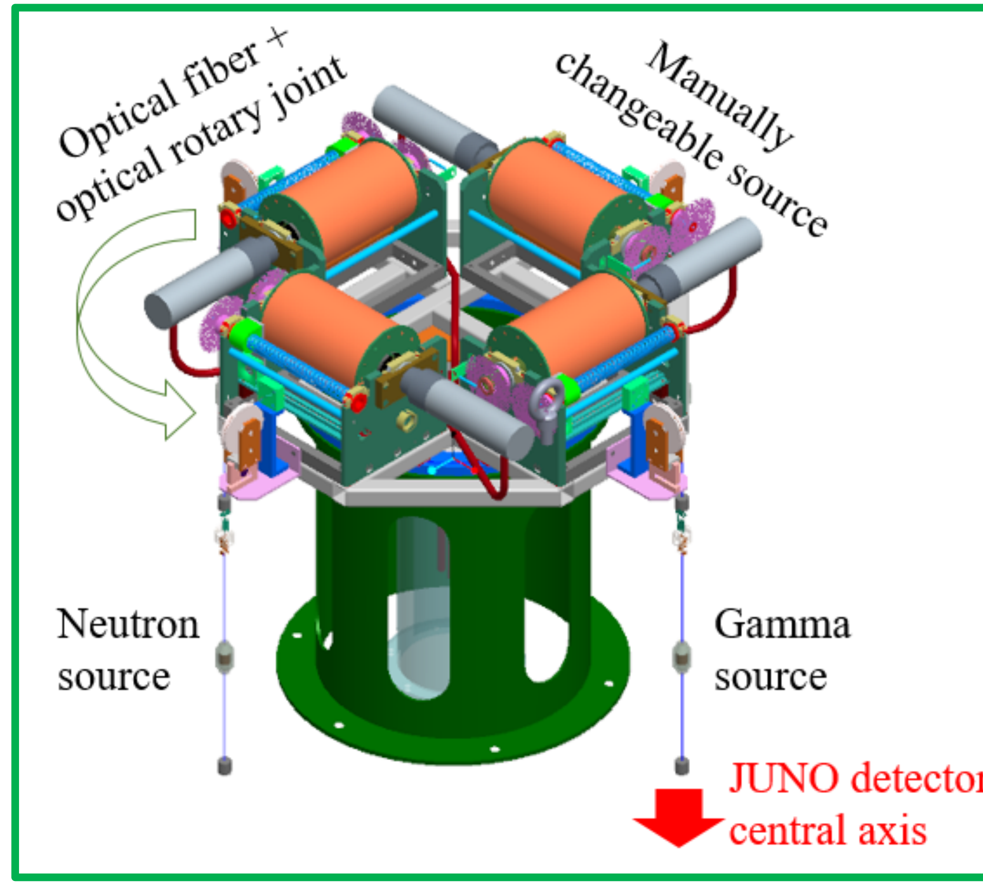
$$\frac{1}{L_{\text{att.}}} = \frac{1}{L_{\text{abs.}}} + \frac{1}{L_{\text{sca.}}}$$

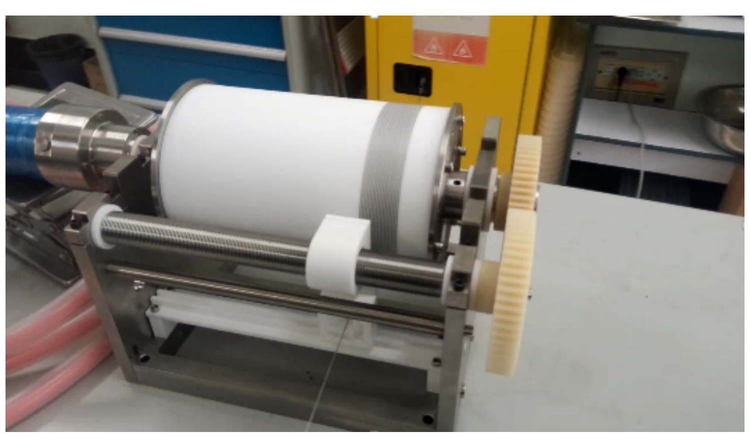
	KamLAND	BOREXINO	JUNO
LS mass	1 kton	0.5 kton	20 kton
Energy resolution	6%/√E(MeV)	5%/√E(MeV)	3%/√E(MeV)
Light yield	250 p.e./MeV	511 p.e./MeV	1200 p.e./MeV

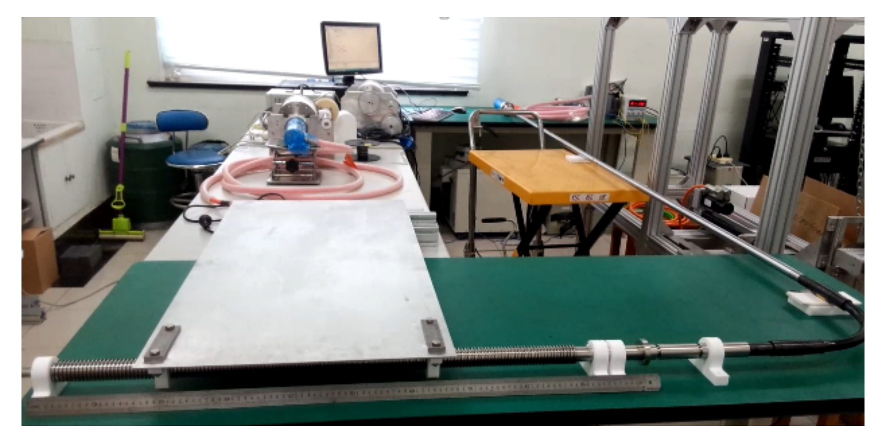
Calibration System Conceptual Designs

Rope Loop System



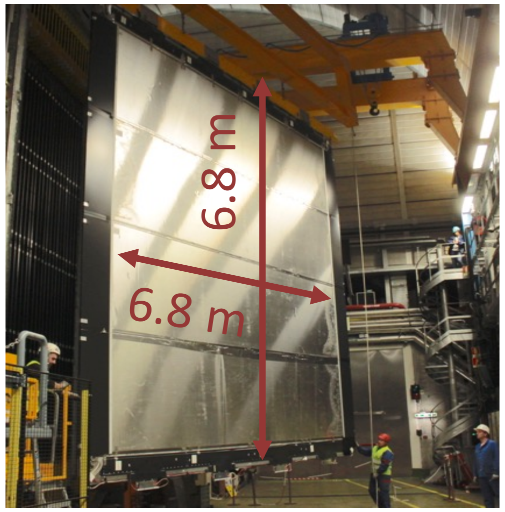


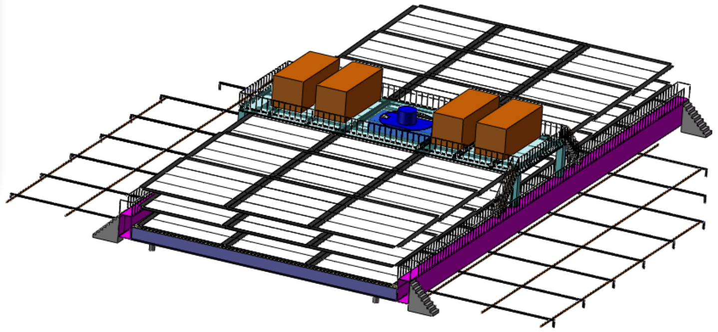




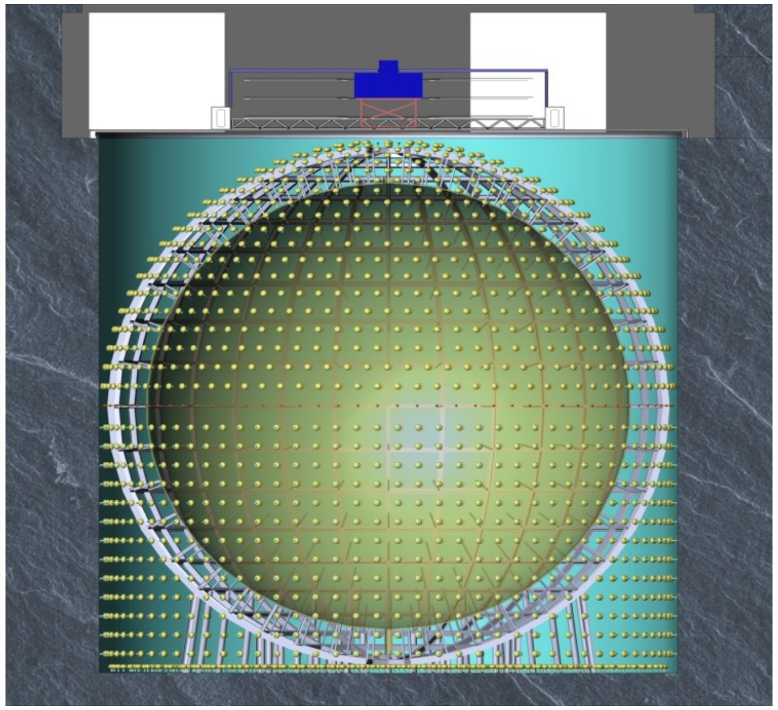
Veto System Considerations and Designs

- Top tracker (TT):
  - Re-using the Target Tracker walls of the OPERA experiment;
  - Total number is 62 and cover half of the top area;
  - 3 TT layers spaced by 1 m ,each layer have x,y readout;
  - A solid bridge support the TT and its mechanical structure;
  - Perform a precise muon tracking and provide valuable information for cosmic muon induced Li9/He8 study.



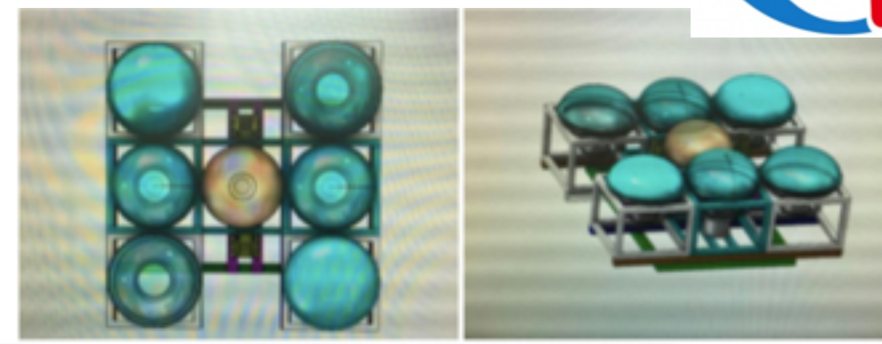


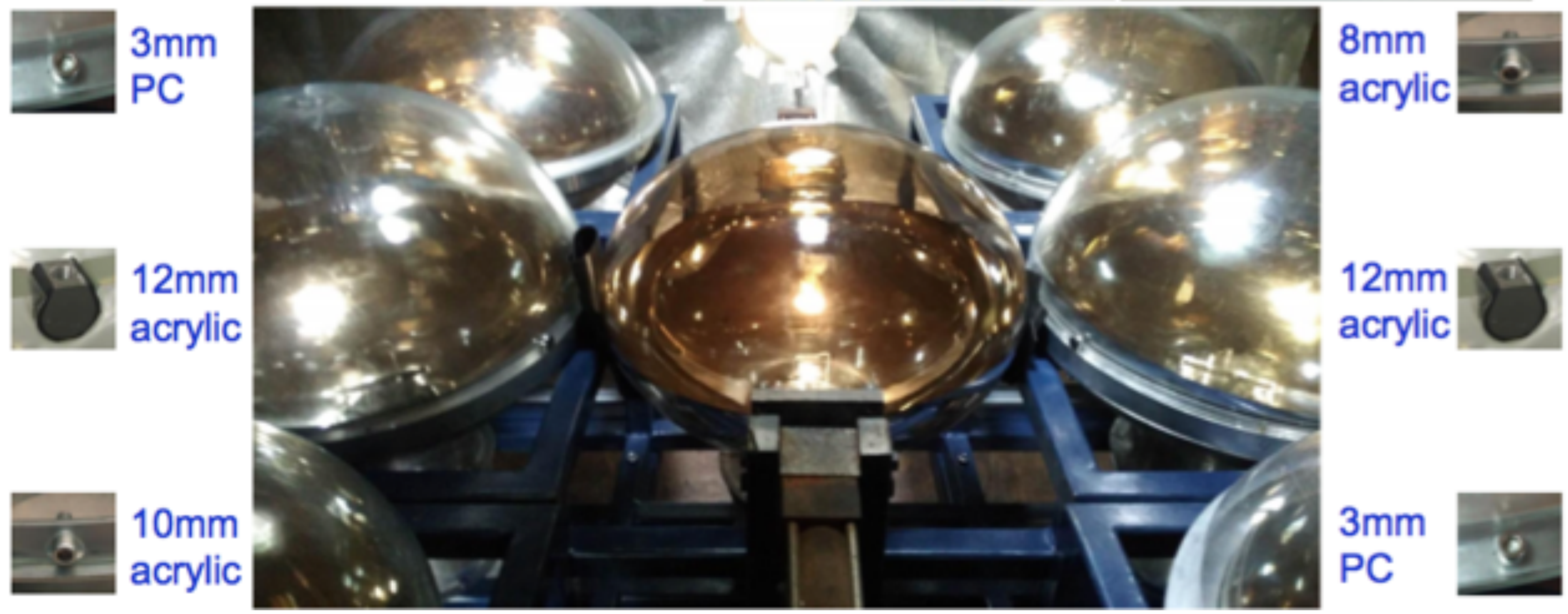
- **Water Cherenkov detector:**
  - 20 inch MCP-PMT used for veto system with number~2000;
  - Detector efficiency requirement is expect to be>95%;
  - Fast neutron background ~0.1/day.
- Compensation coils system used for earth magnet field shielding to keep PMT performance.
- Water system:
  - Employ a circulation/polishing water system;
  - Keep a good water quality -including radon control.



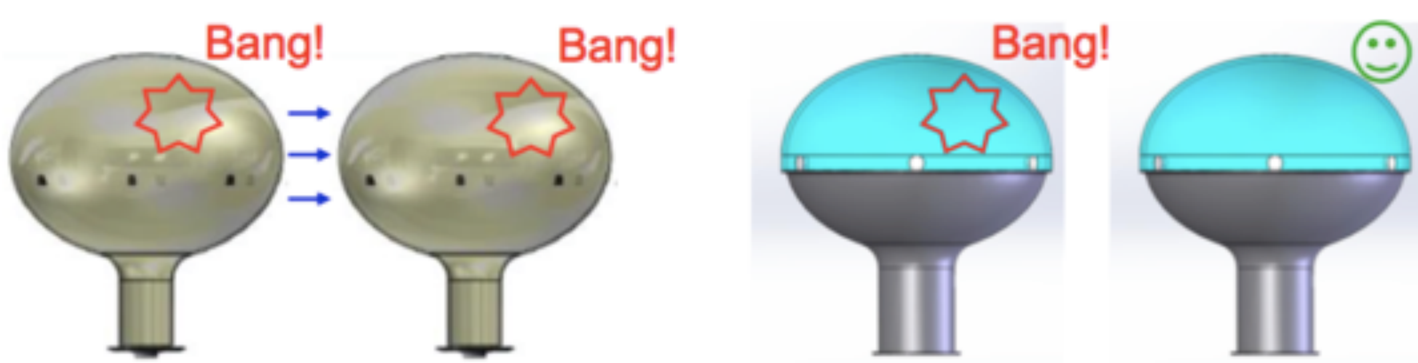
PMT protection

- 1 trigger PMT, 6 PMTs with cover
- Test 4 kinds of top covers with 3 kinds of connection structures





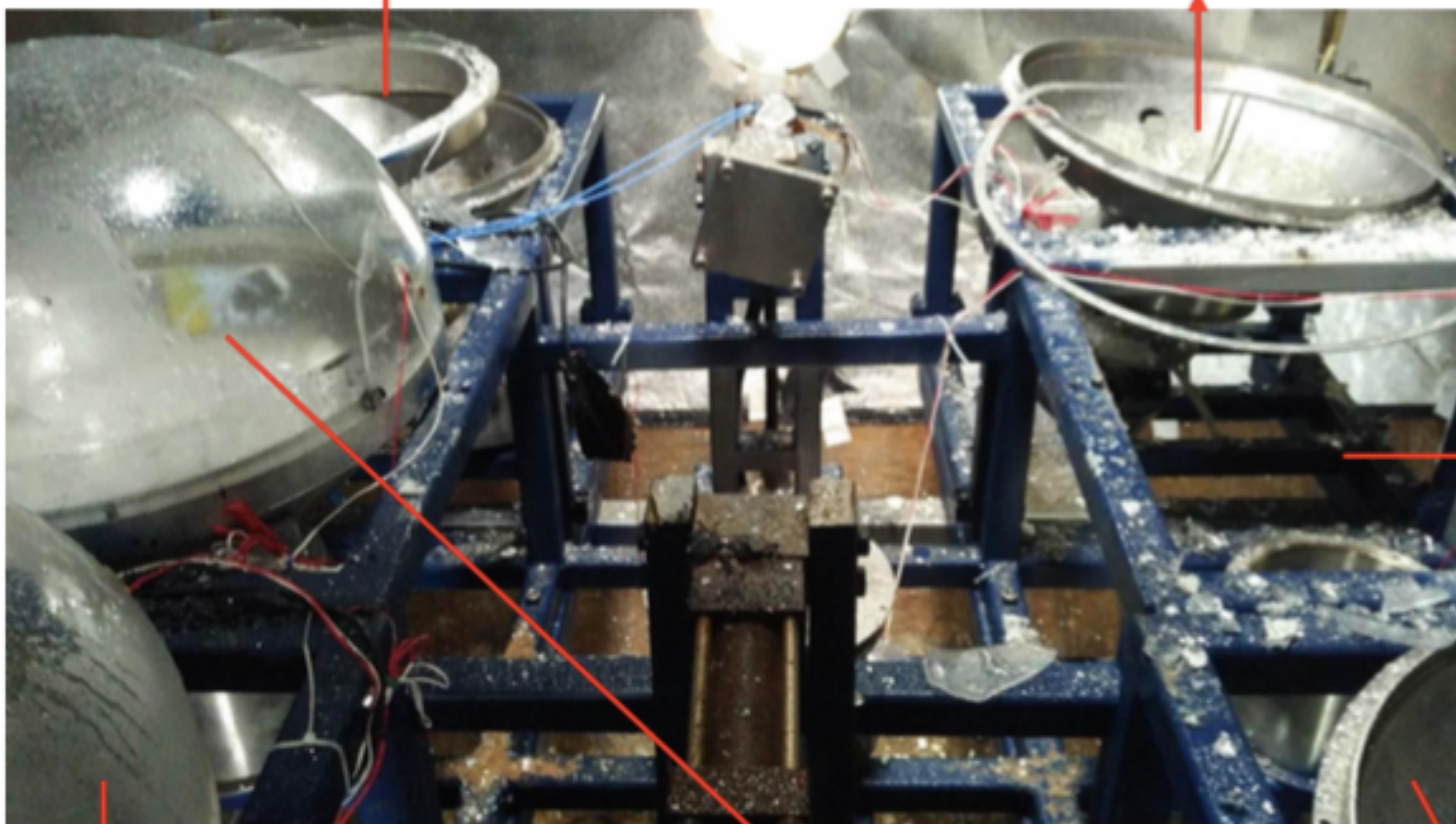
The PMT protection is designed NOT to prevent the PMT implosion but to prevent the generation of shockwave thus to avoid the chain reaction



PMT protection

3mm PC,
broke into pieces

8mm acrylic,
broke into pieces



12mm acrylic,
fell to the floor,
still completed

10mm
acrylic

12mm
acrylic

3mm PC,
broke into pieces

Summary and Conclusion

- A medium-baseline reactor neutrino project in China, JUNO, has received approval.
- JUNO has great potential in resolving neutrino mass hierarchy. JUNO will measure Mass hierarchy (3-4 σ in 2026) and 3 oscillation parameters to <1% level.
- In addition, its unprecedented target mass and performance among LS detectors mean great potential on many other topics.
- JUNO construction and R&D are on schedule, aiming at data taking in 2020.

Thank you!