Jiangmen Underground Neutrino Observatory

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- *JUNO and a brief review on MH via reactors*
- *The JUNO design, R&D and current status*
- *Expected JUNO detector performance and physics potential*

Jiangmen Underground Neutrino Observatory

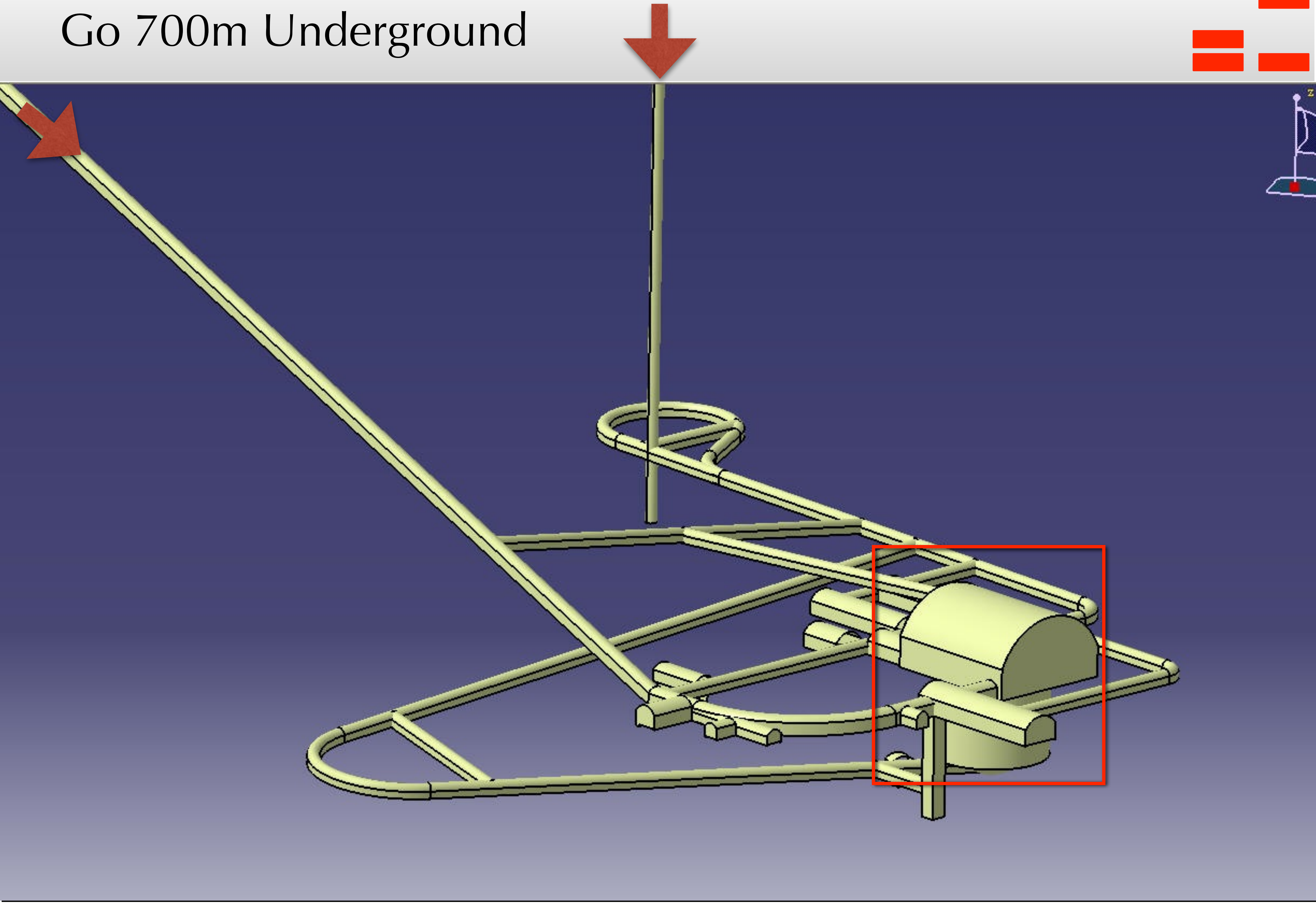
China to build a huge underground neutrino experiment

Mar 24, 2014 5 comments

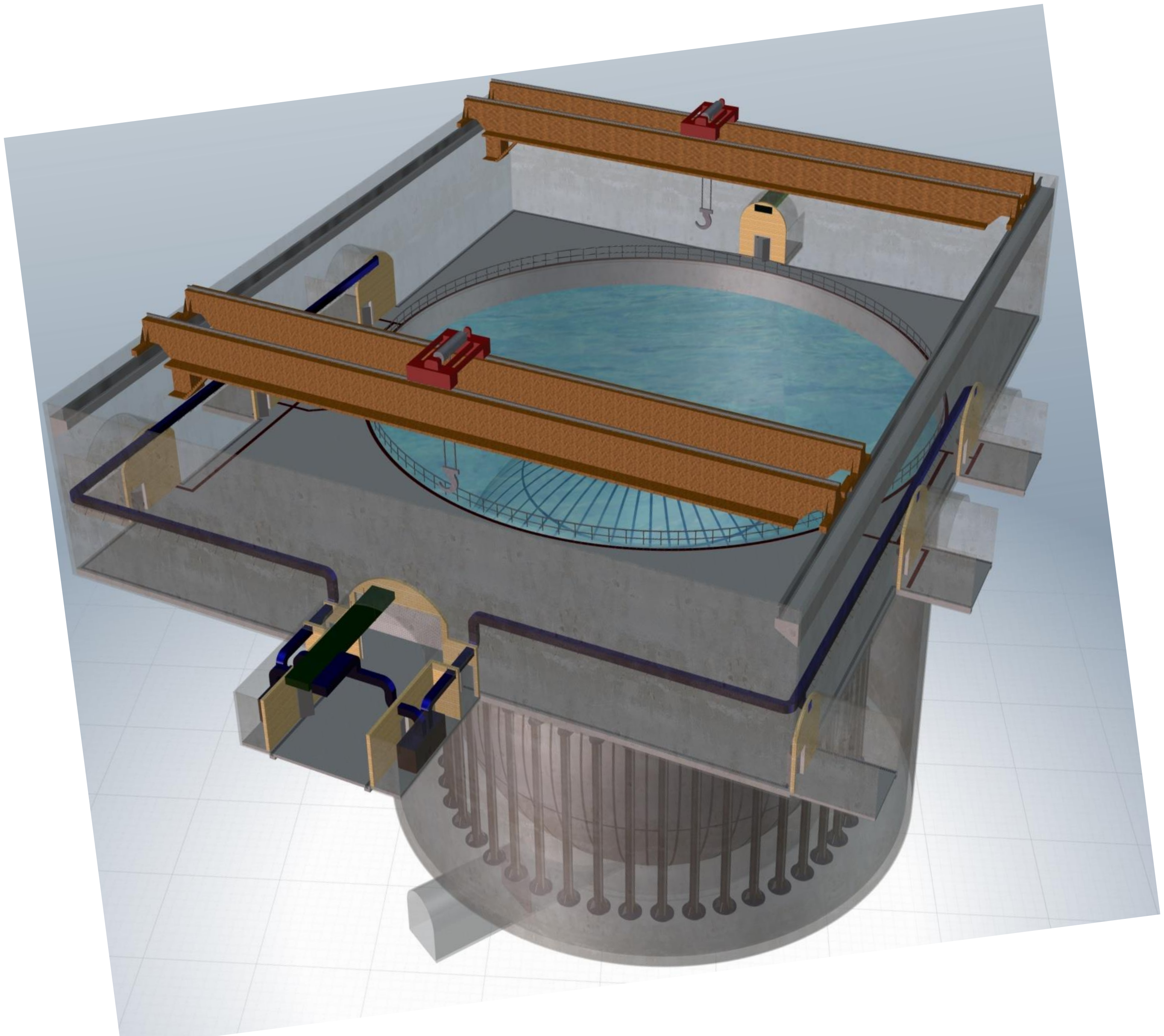
Test site for the Jiangmen Underground Neutrino Observatory

"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."

Go 700m Underground



The Underground Detector System of JUNO

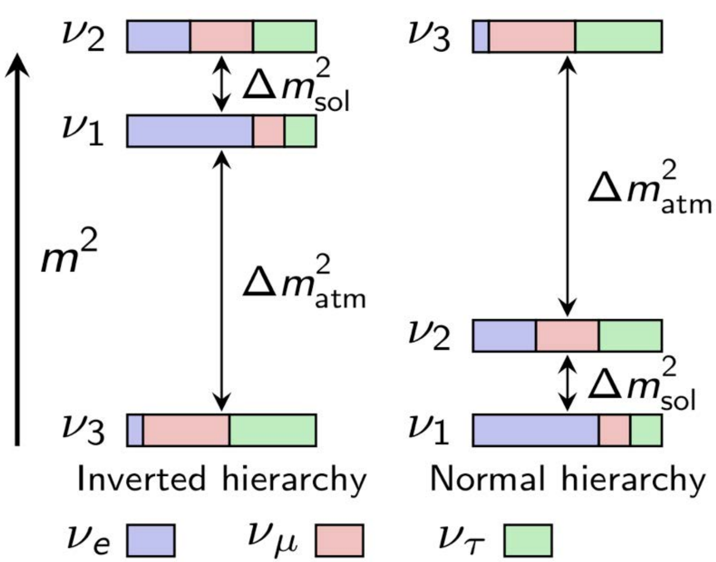


- A 20kt spherical liquid scintillator detector
- The muon veto system combines a cylindrical water Cherenkov detector and other types of detectors on the top to provide more information

A Medium-Baseline Reactor Neutrino Experiment

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

The Gate to Mass Hierarchy is Open



How to resolve neutrino mass hierarchy using reactor neutrinos

- KamLAND (long-baseline) measures the solar mass-squared splitting
- Short-baseline reactor neutrino experiments observe the oscillation of atmospheric scale
- Both scales presented in the survival spectrum of reactor neutrino flux → mass-squared ordering?

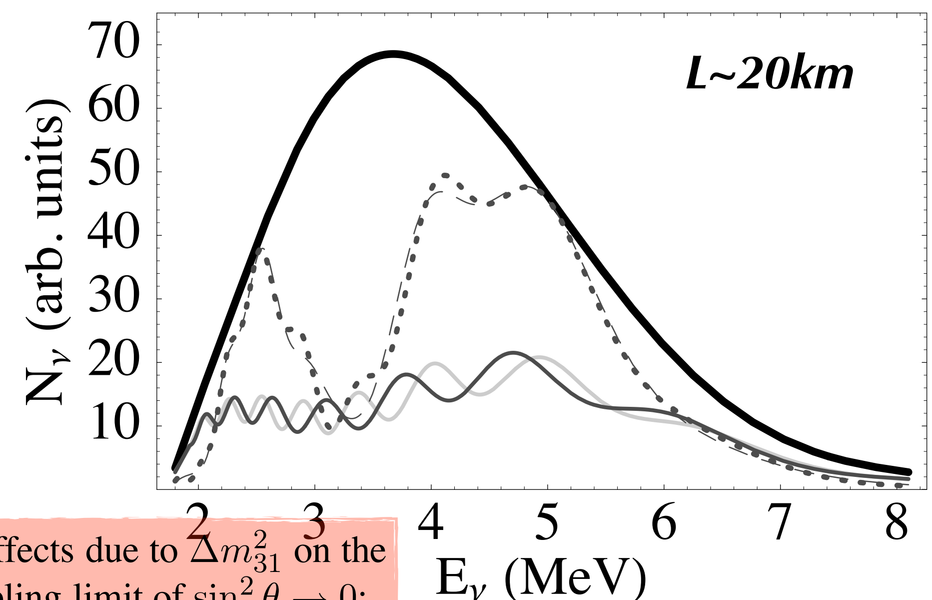
$$P_{\bar{\nu}_e\to\bar{\nu}_e} = 1 - \boxed{\cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}}$$

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

✓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; and DYB/RENO

Fourier Transformation to Extract Mass Hierarchy

- Treating L/E as the time domain, the frequency domain simply corresponds to Δm^2

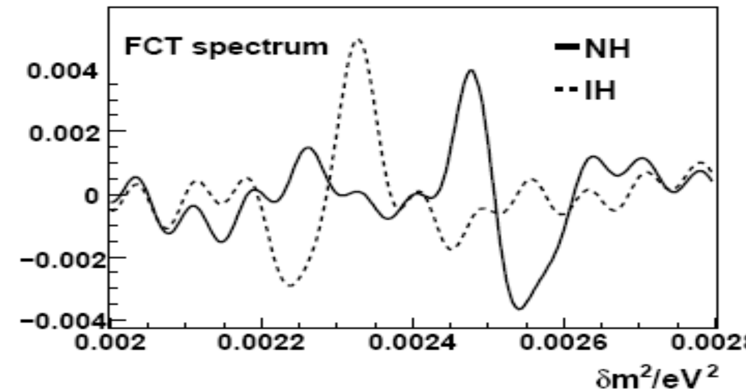
$$FST(\omega) = \int_{t_{min}}^{t_{max}} F(t)\sin(\omega t)dt$$

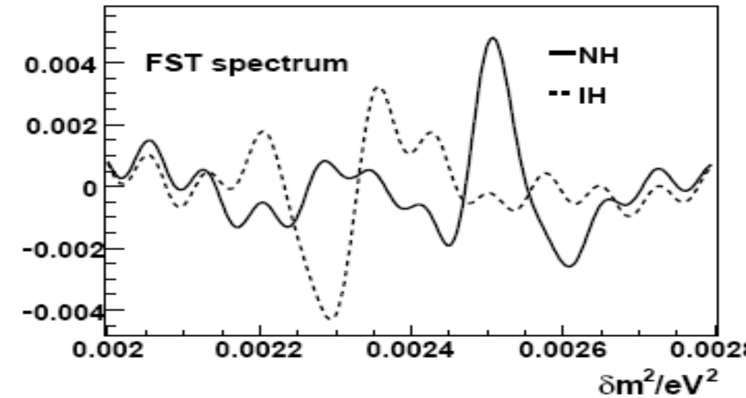
$$FCT(\omega) = \int_{t_{min}}^{t_{max}} F(t)\cos(\omega t)dt$$

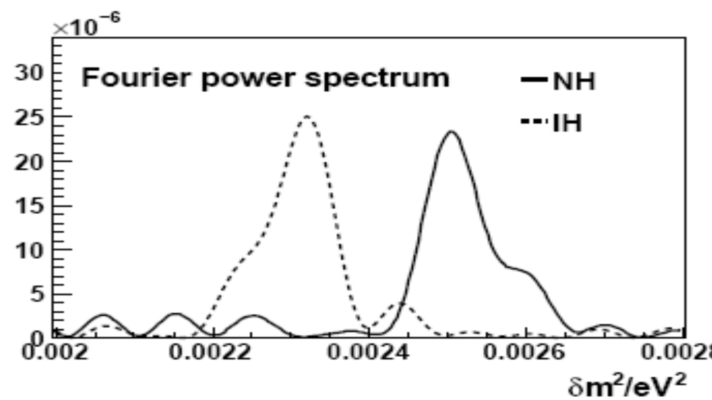
- In the Δm^2 domain, take Δm^2_{32} as the reference point,
  - NH: take "+" sign, the effective Δm^2 peaks on the right of Δm^2_{32}, then a valley
  - IH: take "-" sign, the effective Δm^2 peaks on the left of Δm^2_{32}, right to a valley
- Δm^2 spectra have very distinctive features for different hierarchies

L. Zhan et al., PRD78(2008)111103

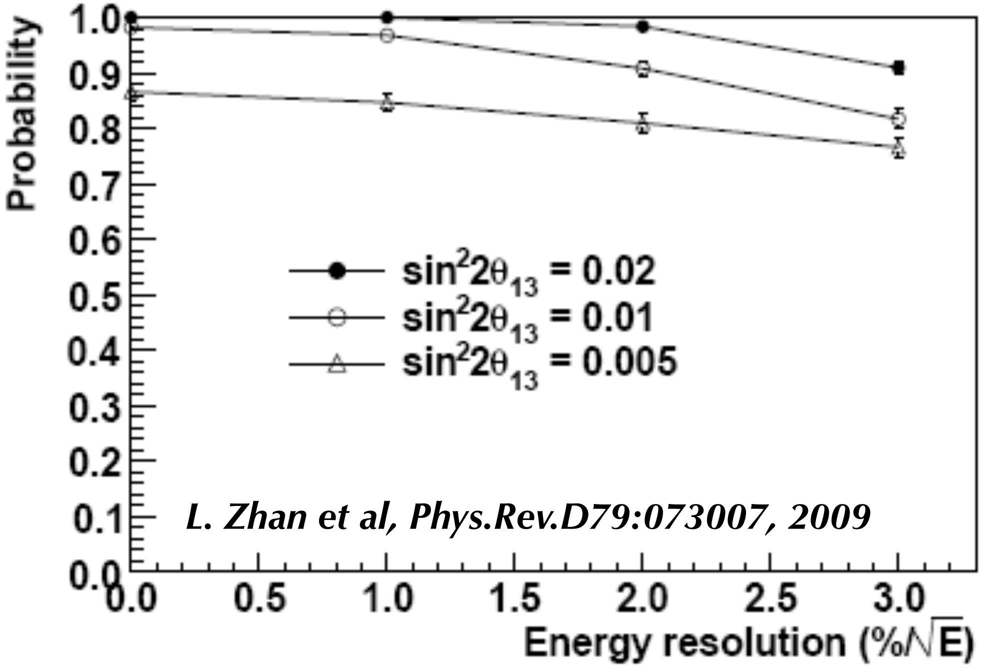
J. Learned et al proposed the FT power spectrum method 2006

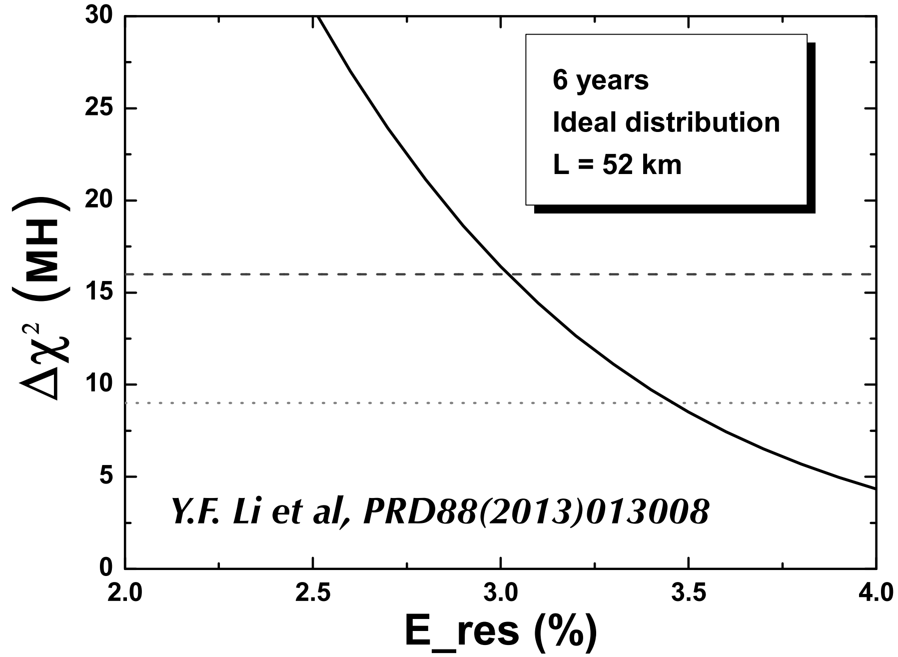




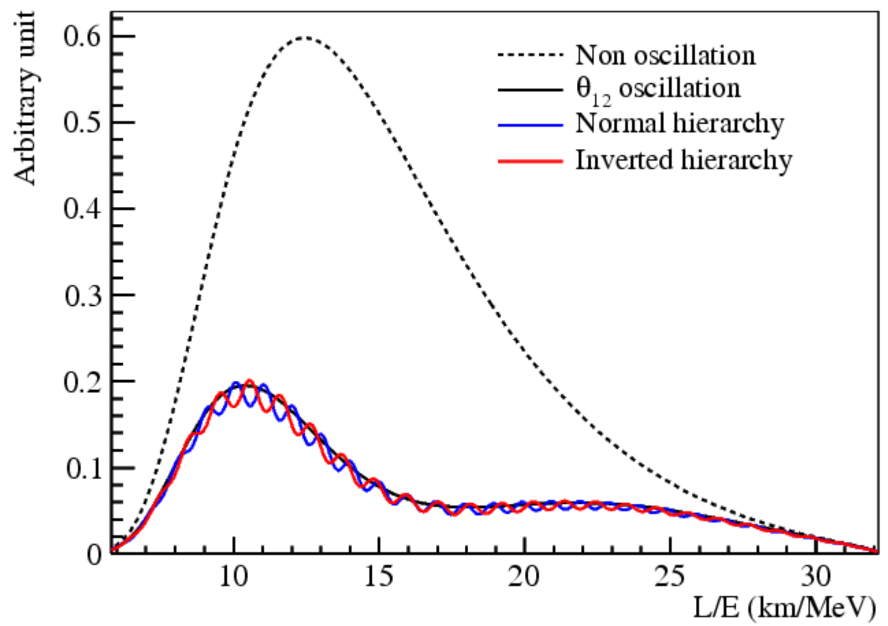


Demand on Energy Resolution of JUNO Detector





- We need the energy resolution better than ~ 3%/√E
- This is simply due to the ratio between solar and atmospheric mass-squared splittings



Demand on the Energy Scale Accuracy

S.J. Parke et al, Nucl.Phys.Proc.Suppl. 188 (2009)

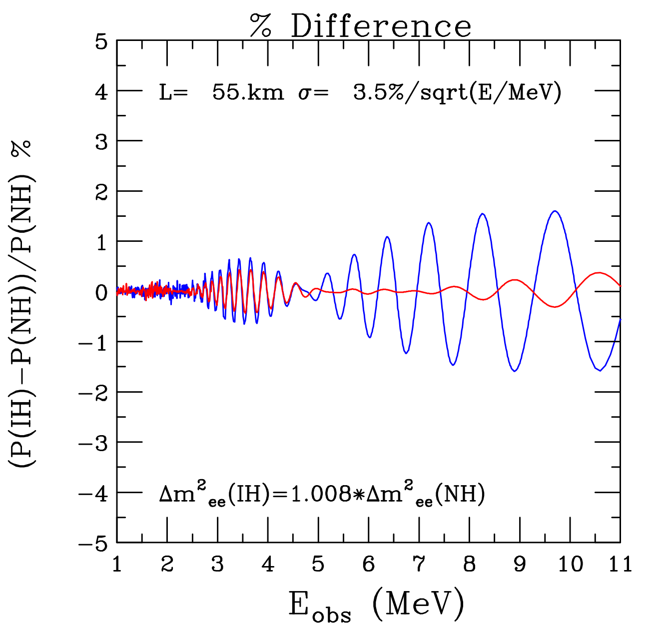
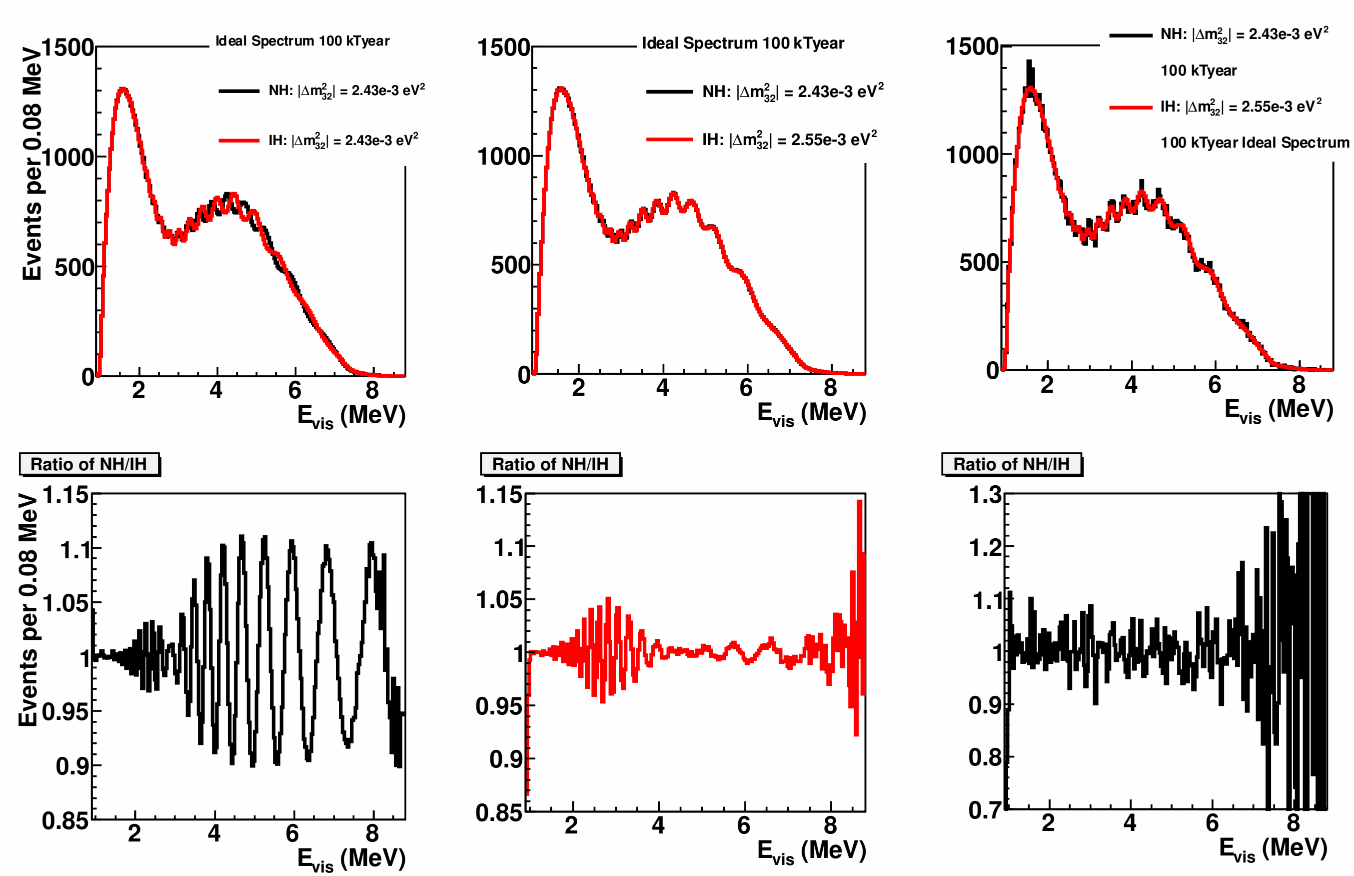


Figure 4. The percentage difference between the inverted hierarchy and the normal hierarchy. The blue curve is assuming $E_{obs} = E_{true}$ and maximum difference is less than 2%. Whereas for the red curve we have assumed that $E_{obs} = 1.015E_{true} - 0.07$ MeV for the IH, so as to represent a relative calibration uncertainty in the neutrino energy. Here the maximum percentage difference is less than 0.5%.

X. Qian et al, PRD87(2013)3, 033005

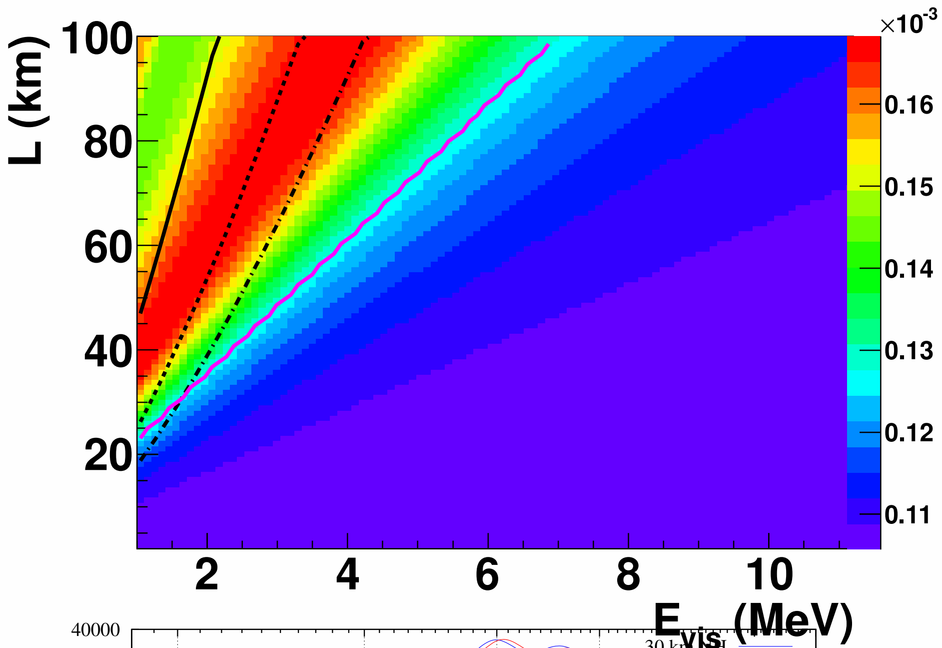


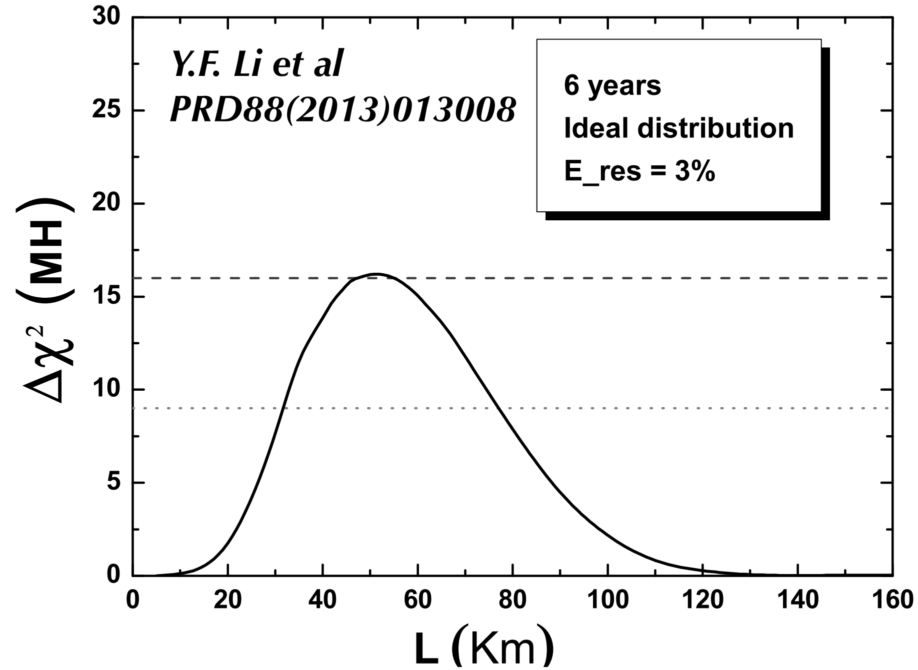
- Oscillation is governed by ~$\Delta m^2_{32}/E$, if energy reconstruction introduces in shifts, or worse, non-linearity residuals, signals might disappear or wrong
- Various studies show ~1% uncertainty is needed

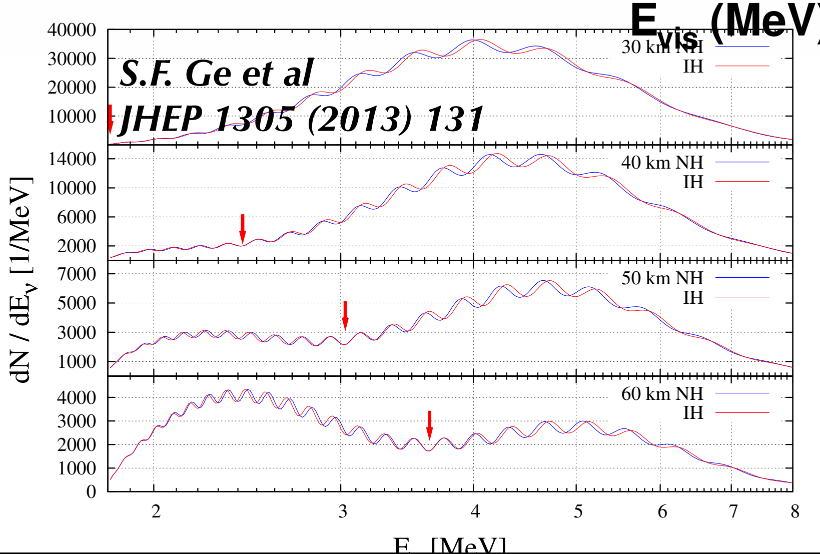
Where to Place the Detector?

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

X. Qian et al, PRD87(2013)3, 033005



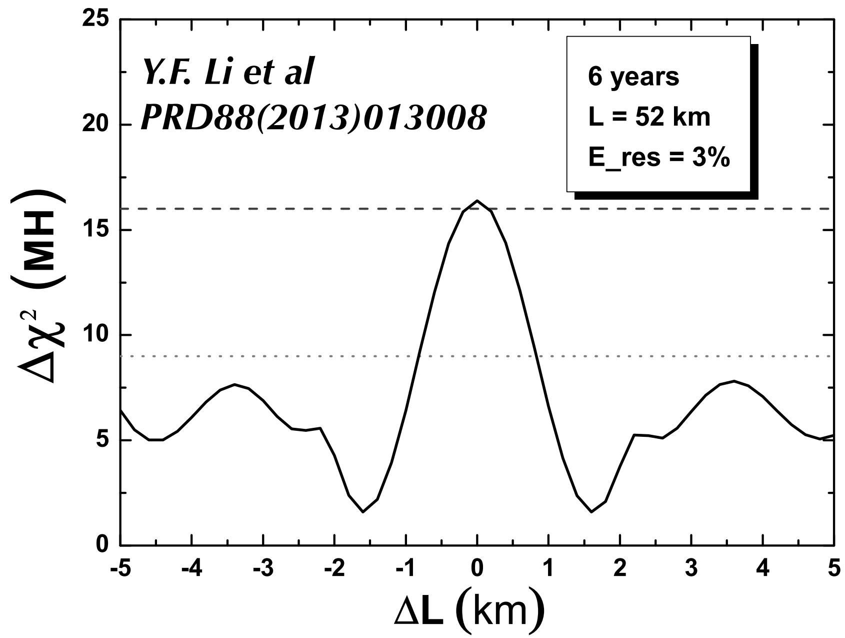


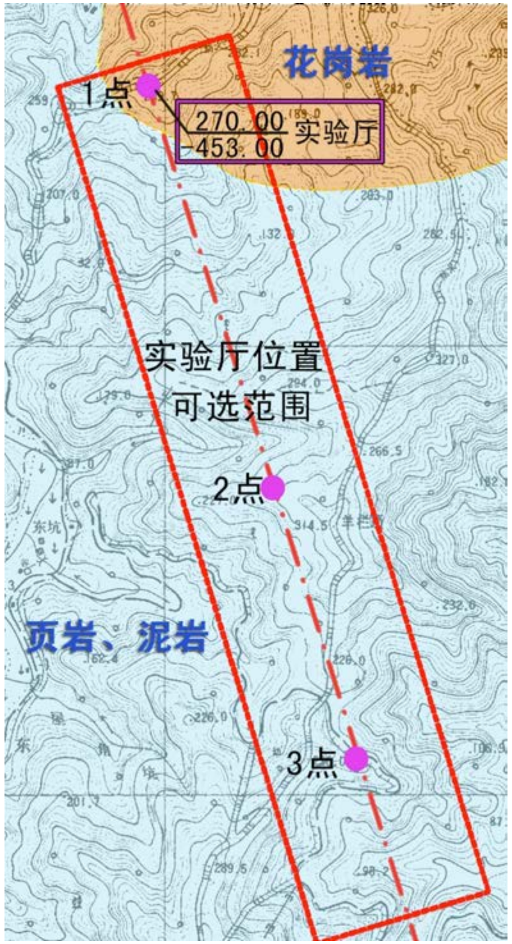


- The power lies in the contrast between the lower part and the higher part of the inverse beta decay spectrum
- The baseline needs to be 50km - 60km

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



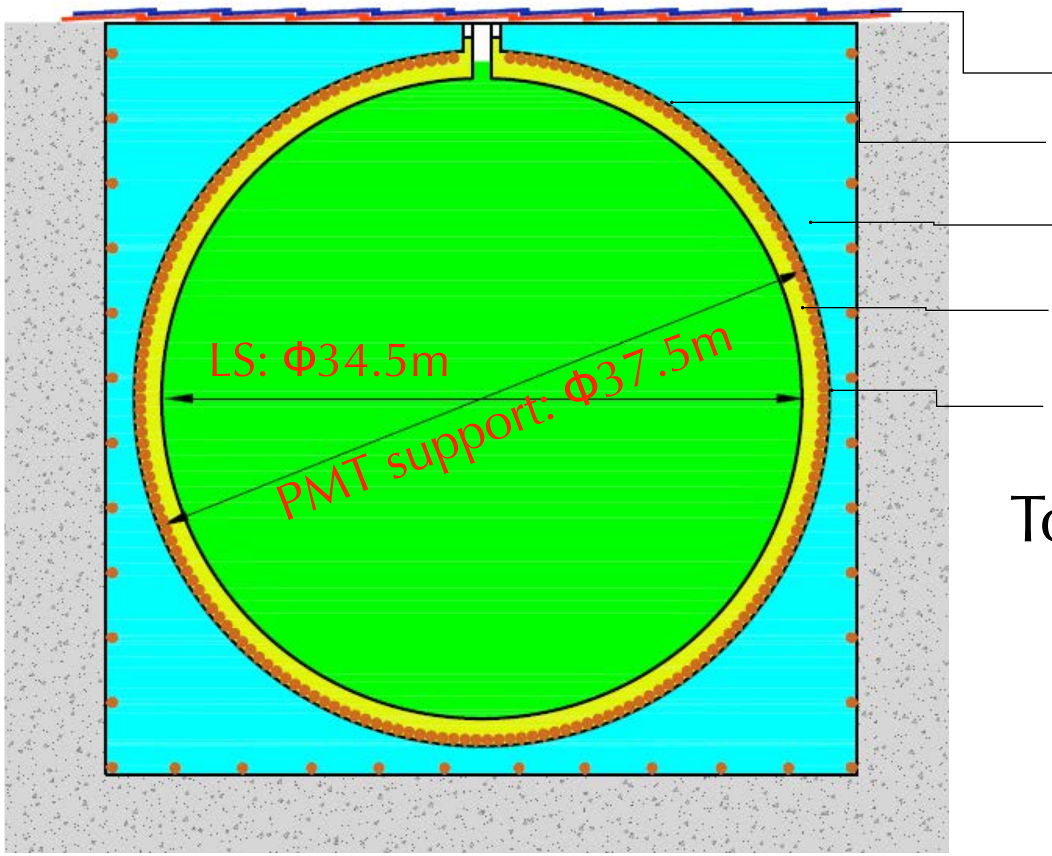


- Reactor cores at the same power plant like to be ~km apart. If baselines are shifted by half oscillation length, they cancel each other's signals.

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

A Conceptual Design is Formed



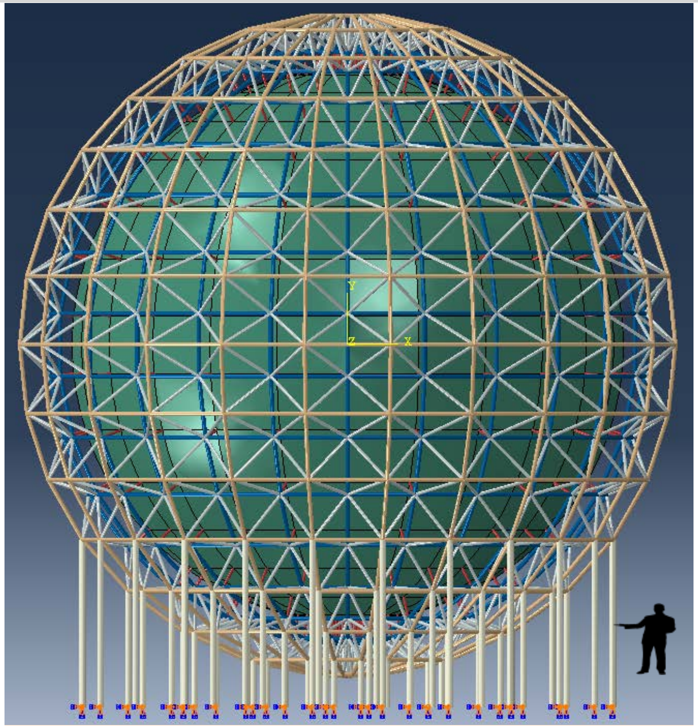
$$\frac{\Delta E}{E} = \sqrt{a^2 + \frac{b^2}{E} + \frac{c^2}{E^2}}$$

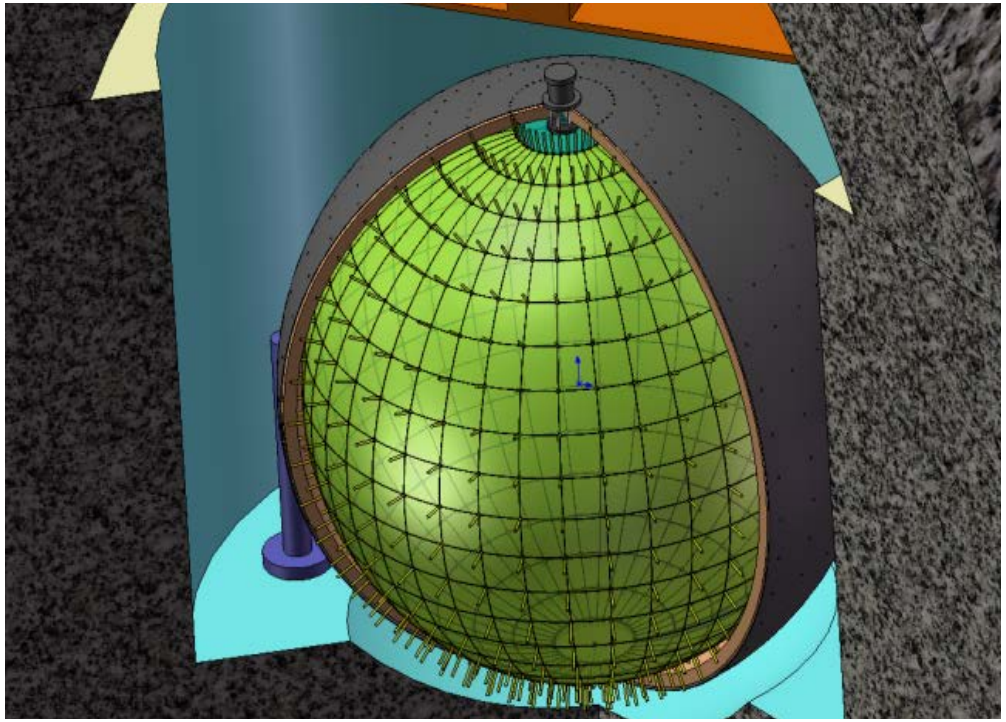
- a: Energy leakage & non-uniformity
- b: Photon statistics
- c: Noise (~background)

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

Two JUNO Detector Designs





- **Primary design**: a 35m diameter acrylic sphere holds the LS
- Stainless truss provides mechanical supports to the acrylic sphere and the PMTs
- Designing/Improving details and interfaces with other components
- Independent FEA calculations

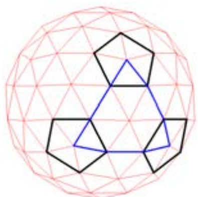
- **Backup option**: A balloon holds the LS
- Acrylic panels (not welded together like the sphere) + stainless steel sphere support the balloon and PMTs
- The buffer liquid can be oil or LAB while the acrylic ball+truss design is water
- Leakage and dusts are the serious concerns

PMT Arrangement and Photocathode Coverage

Polyhedral module layout method

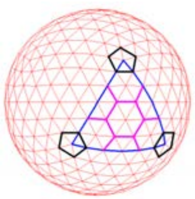
others

module

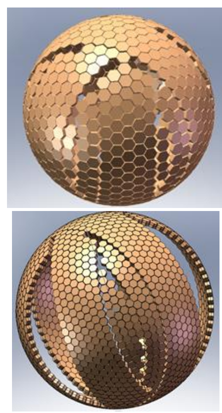


3 layers: 180 Triangles(or 12 Pentagons and 20 hexagons)

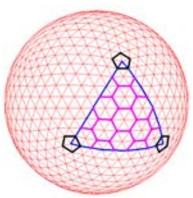
Football



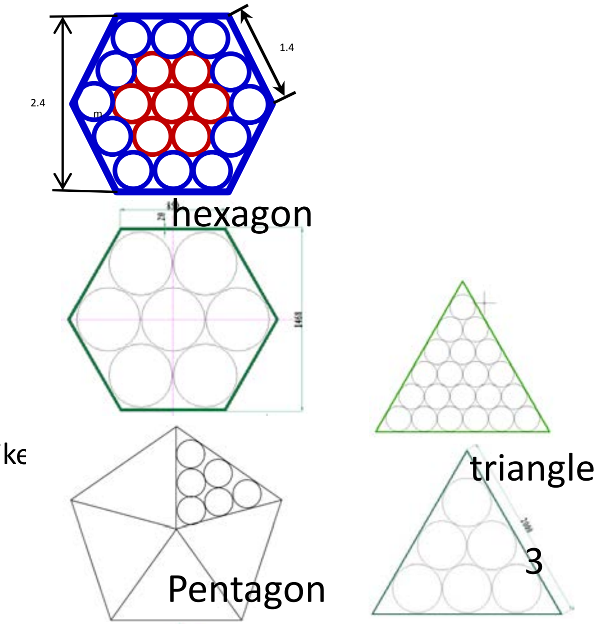
6 layers: 720 Triangles(or 12 Pentagons and 110 hexagons)

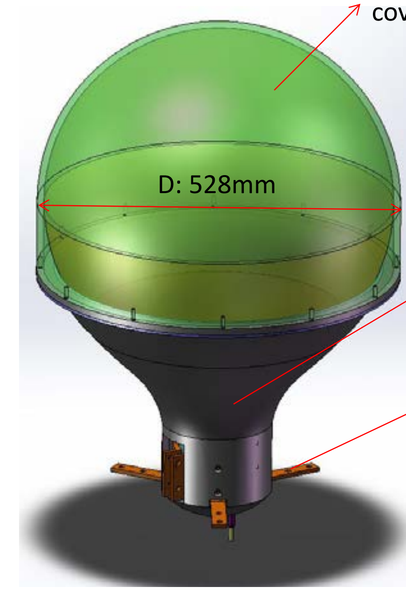


Volleyball-like



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



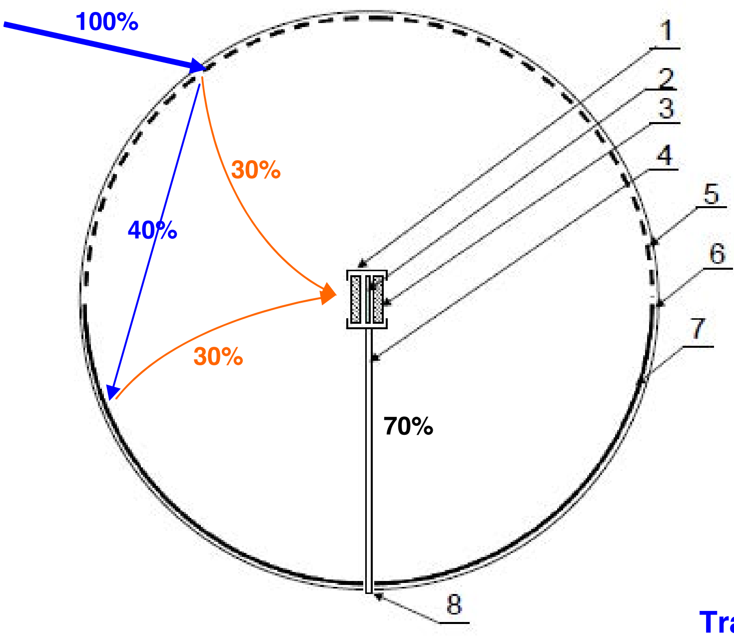


Conceptual explosion proof Structure of PMT

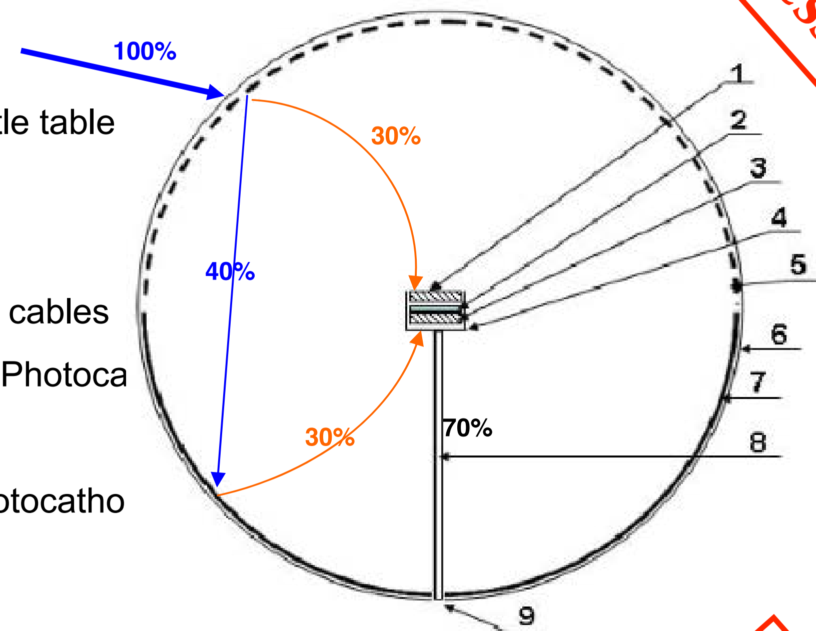
Scheme	Acrylic vessel+steel space truss	stainless-steel tank + balloon with acrylic support
Arrangement method	Layer-by-layer layout method: arrange PMT optimally then deleted PMT where bars occupied	9-layers' module layout method: 272 modules or 1620 installed cells
Radius & PMT No.	Radius has no influence 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%**

A New Type of PMT: MCP Replacing Dynode

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



JUNO PMT Plan A progressing well

Transmission rate of the glass: 40%

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

Collection Efficiency (CE) of MCP : 70%;

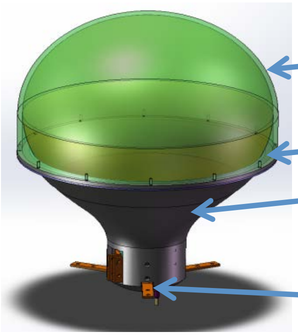
If nothing else changes, the detection efficiency (QE*CE) is nearly doubled by "saving" the ~40% transmitted photons.

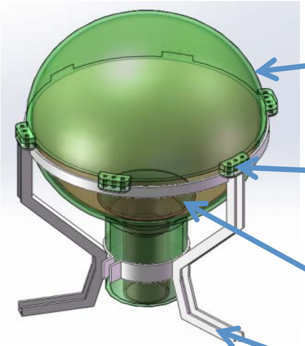
- **JUNO PMT plan B: Photonis China PMTs**
- **JUNO PMT plan C: new 20" Hamamatsu SBA high QE PMTs**

3 Plans in Parallel by Collaborators

PMT Protection

Possible Implosion-proof structure

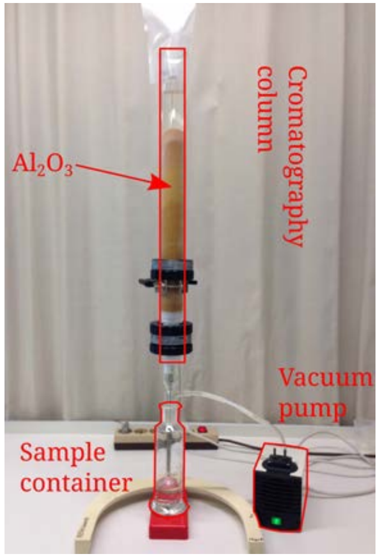


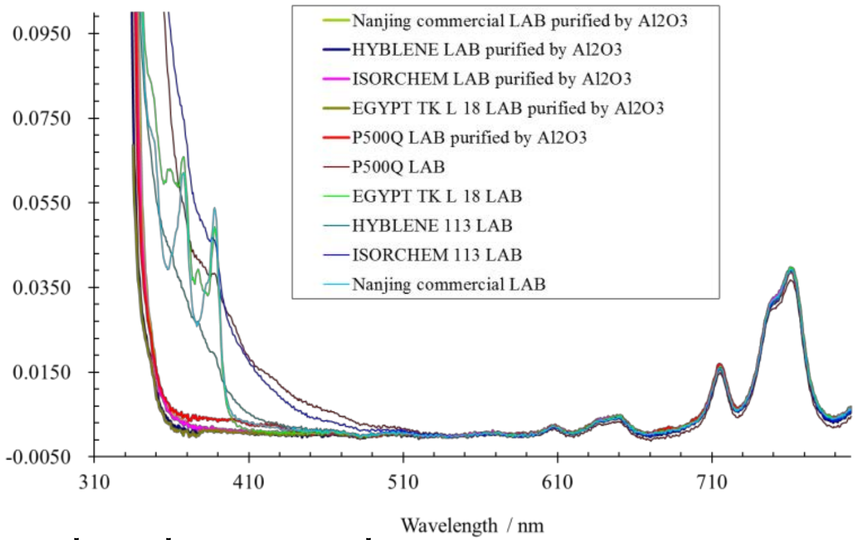


- Two groups are working on the implosion prevention design, calculation and experimentation, one navy lab and another a university lab
- This year: finishing the shock wave calculation and comparing with experimental data
- Next year: chain reaction experimentation and iteration between designs and experiments

Liquid Scintillator Purification

- 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
  - Column purification
    - Various packing materials
  - Vacuum Distillation (V.D.)
    - Single stage V.D. in the lab at IHEP
    - Multi-stage V.D. in the lab at IHEP
    - Molecular distillation (commercially available)
    - Real boiling point distillation (commercially available)

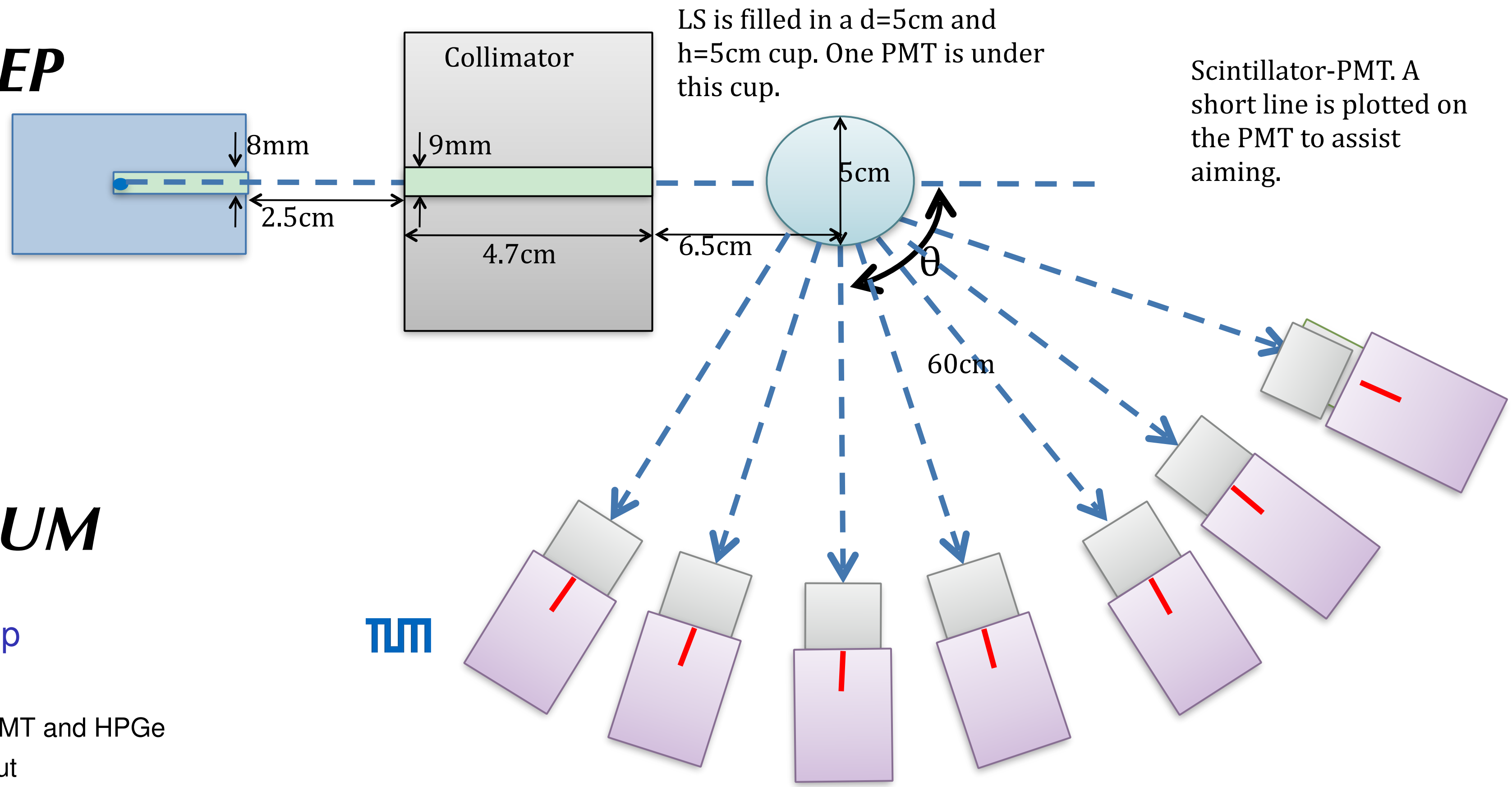




– Our Italian, Russian and German collaborators are also doing studies in parallel. We all see space for improvements and R&D activities are ongoing

Scintillator Energy Response Evaluations

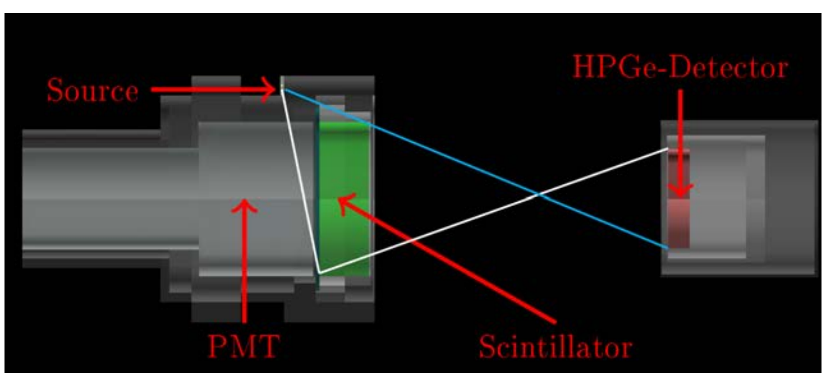
Setup I: IHEP



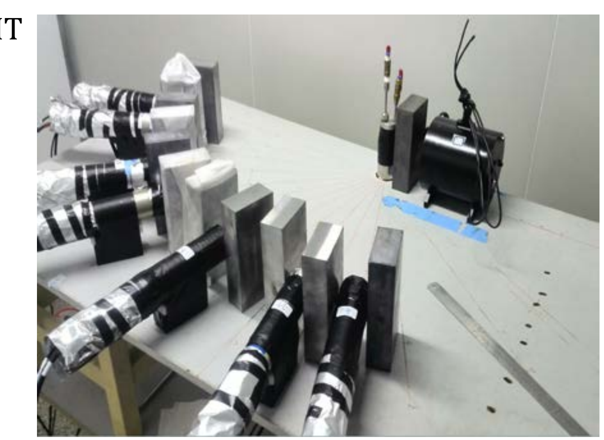
Setup II: TUM

Electron quenching: set-up

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



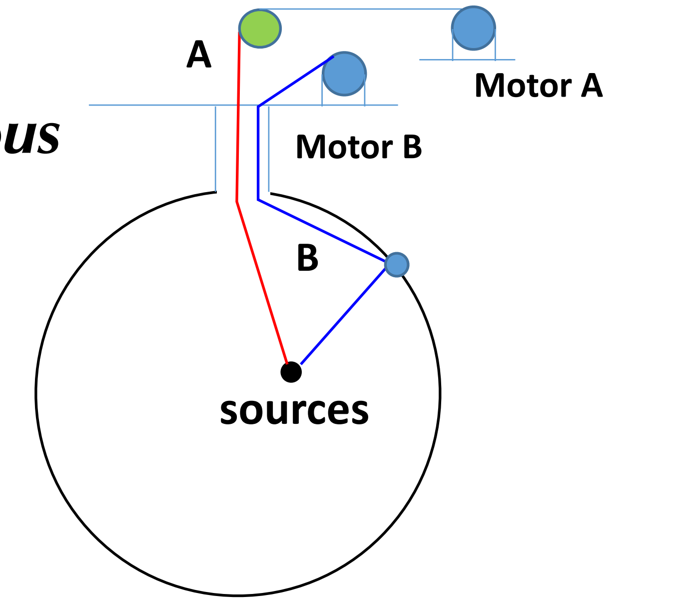
7 LaBr-PMT



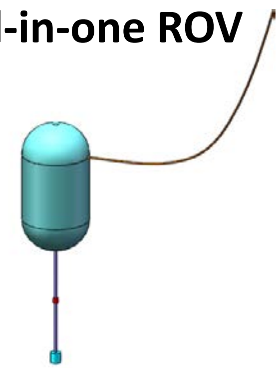
Calibration System Conceptual Designs

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

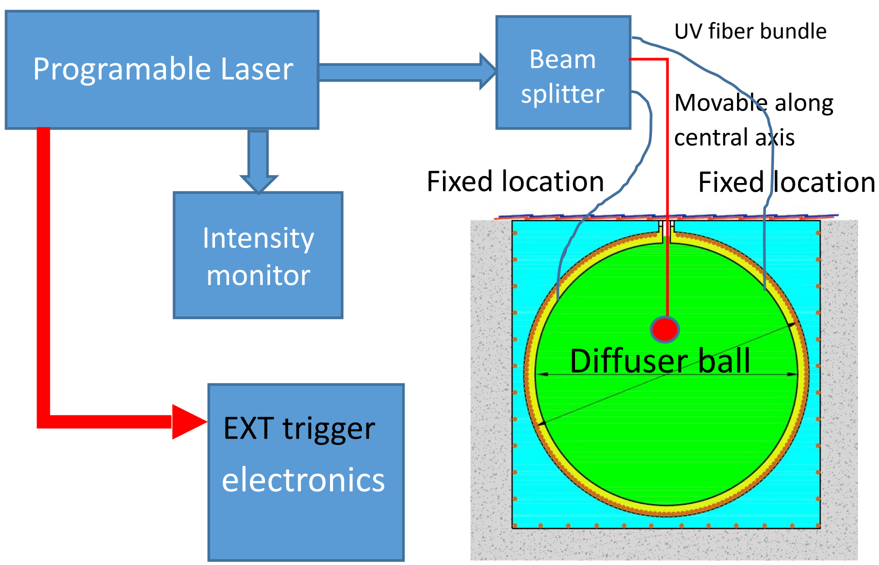
A-B rope synchronous motion



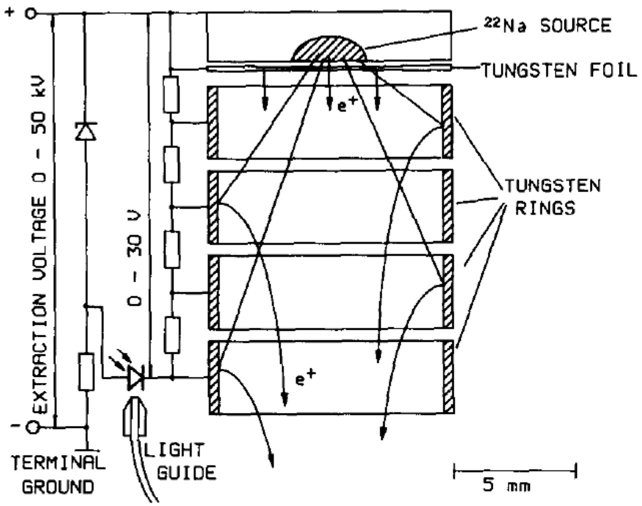
All-in-one ROV



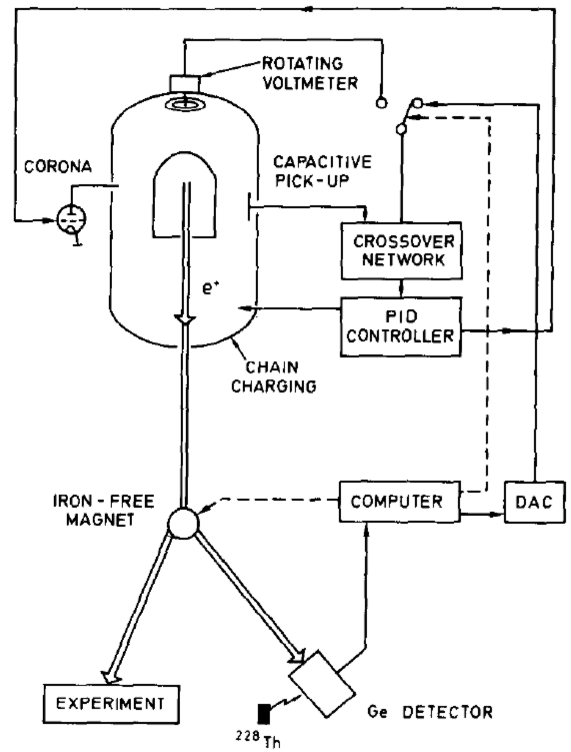
sources

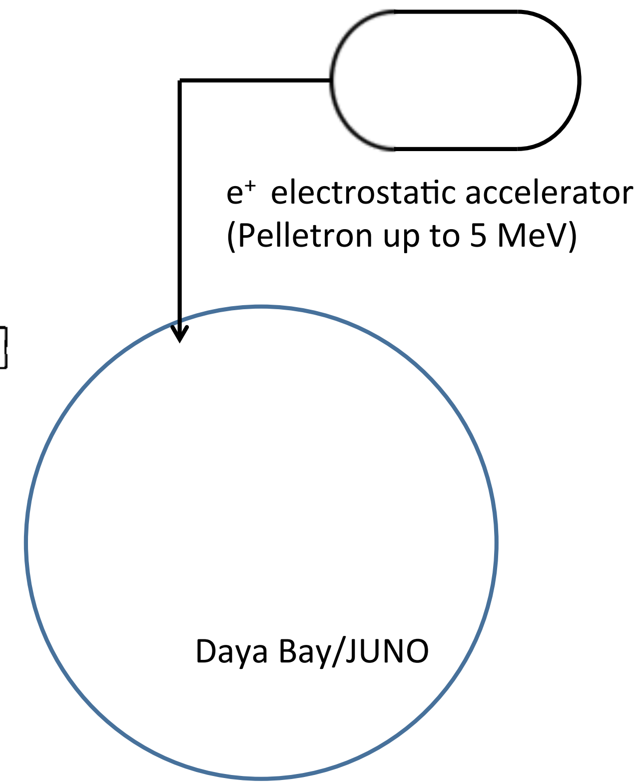


Pelletron Provides Direct Positron Controls



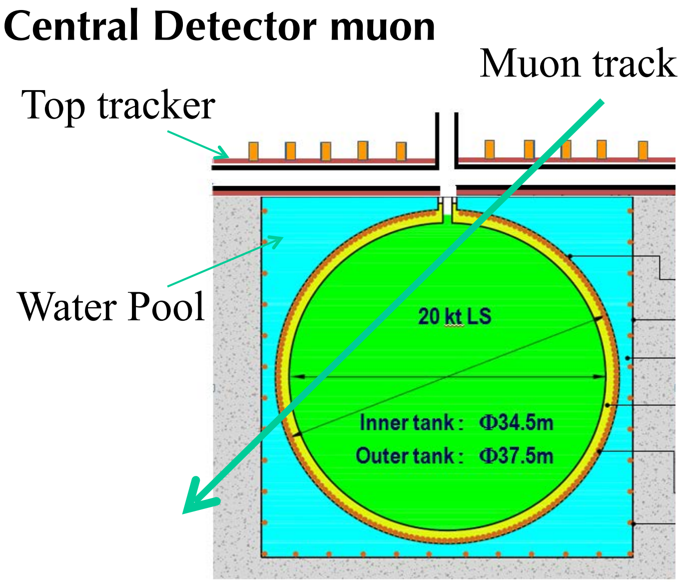
Bauer et al, The Stuttgart positron beam, its performance and recent experiments, NIM B50, 300 (1990)

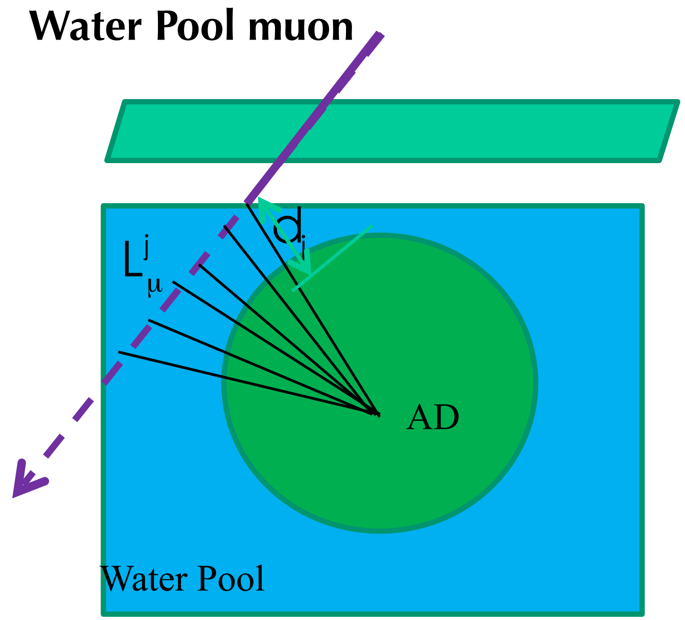


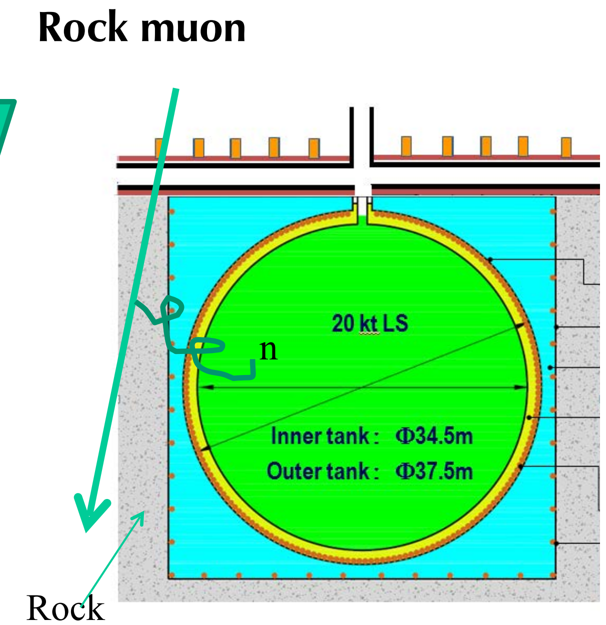


- Mature technology and commercially available. Energy coverage 0.5-6.5MeV and energy precision $<10^{-4}$; Coverage is sufficient if reach 5MeV; Below 5MeV, pelletron is more economical than LINAC
- Super-K LINAC e beam calibration reached 0.6% absolute energy scale uncertainty

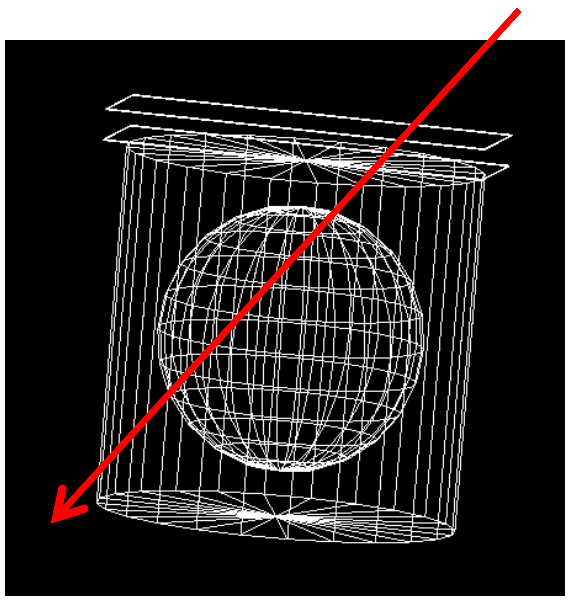
Veto System Considerations and Designs





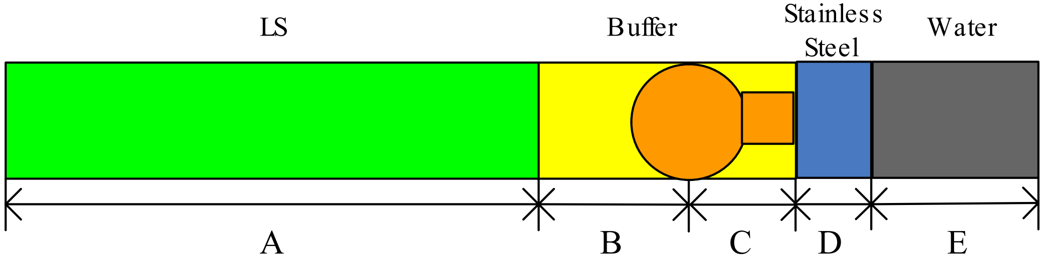


- Veto is not just a veto. We need tracking information to better understand and remove cosmogenic backgrounds
- Various designs and options for the Top Tracker (TT)
  - OPERA scintillator calorimeters will be moved to JUNO
  - RPCs are being considered
  - Ar gas TPCs are being considered
  - NOvA like LS tubes are being considered
- Simulation and design are going through iteration
- Earth magnetic field shielding is being designed together with the veto system design

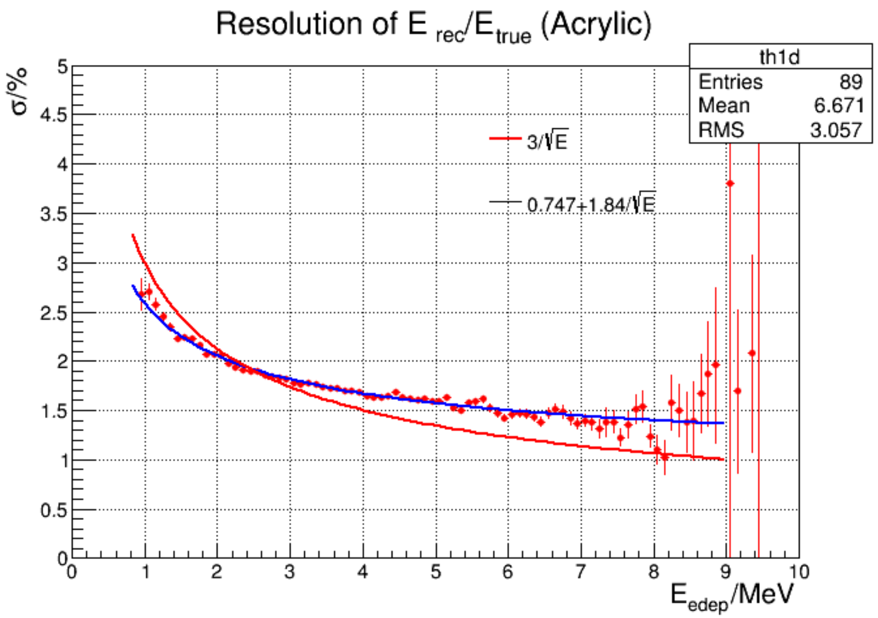


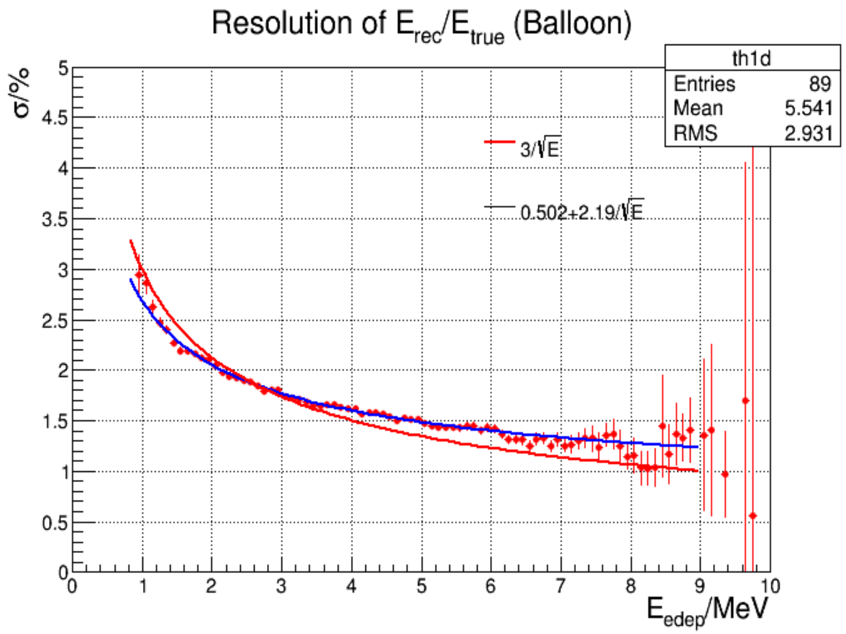
Putting Everything together (Simulation)

- 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



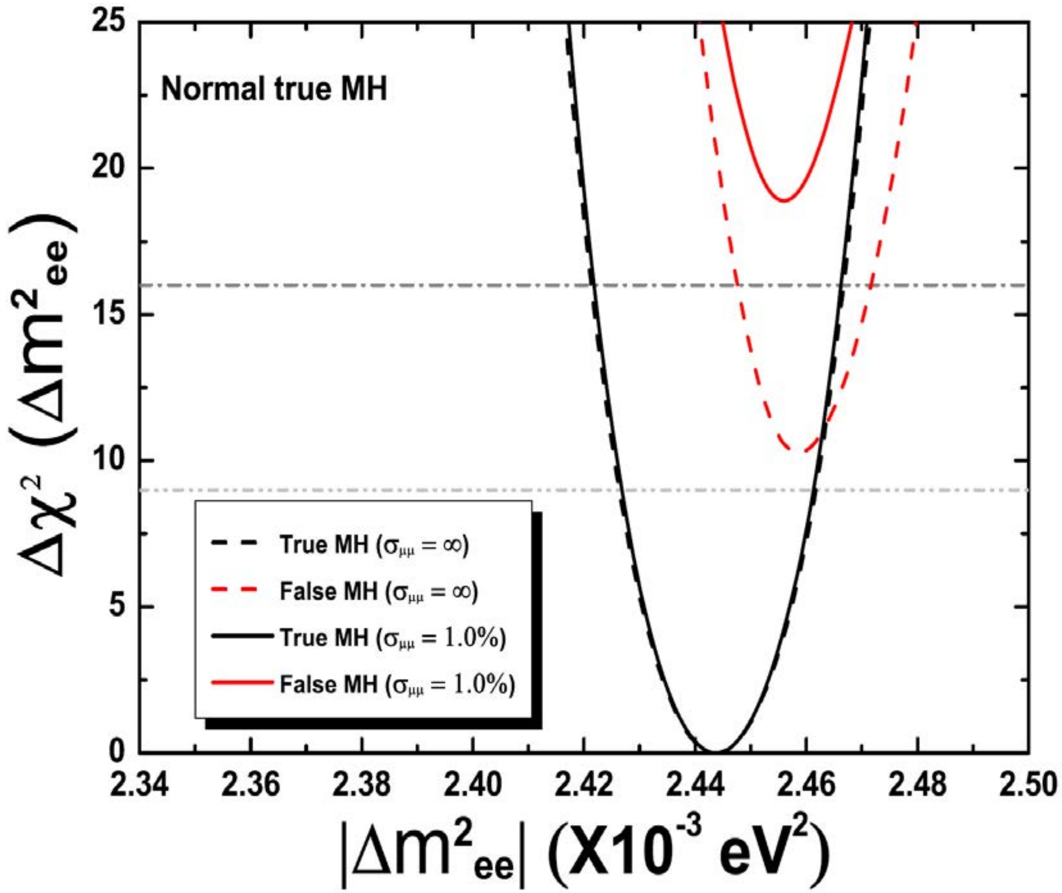
A=17.7m (LS)
B=(0.12+1.426+0.254)m=1.8m
C=0.45m
A+B=19.5m (position of PMT sphere center)
A+B+C=19.95m





- Simulation tells that effective photocathode coverage can reach ~75% in both designs after considering the (current) support structures. A 3% energy resolution is plausible

Expected Significance to Mass Hierarchy



- ~3-sigma if only a relative spectral measurement without external atmospheric mass-squared splitting inputs
- ~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

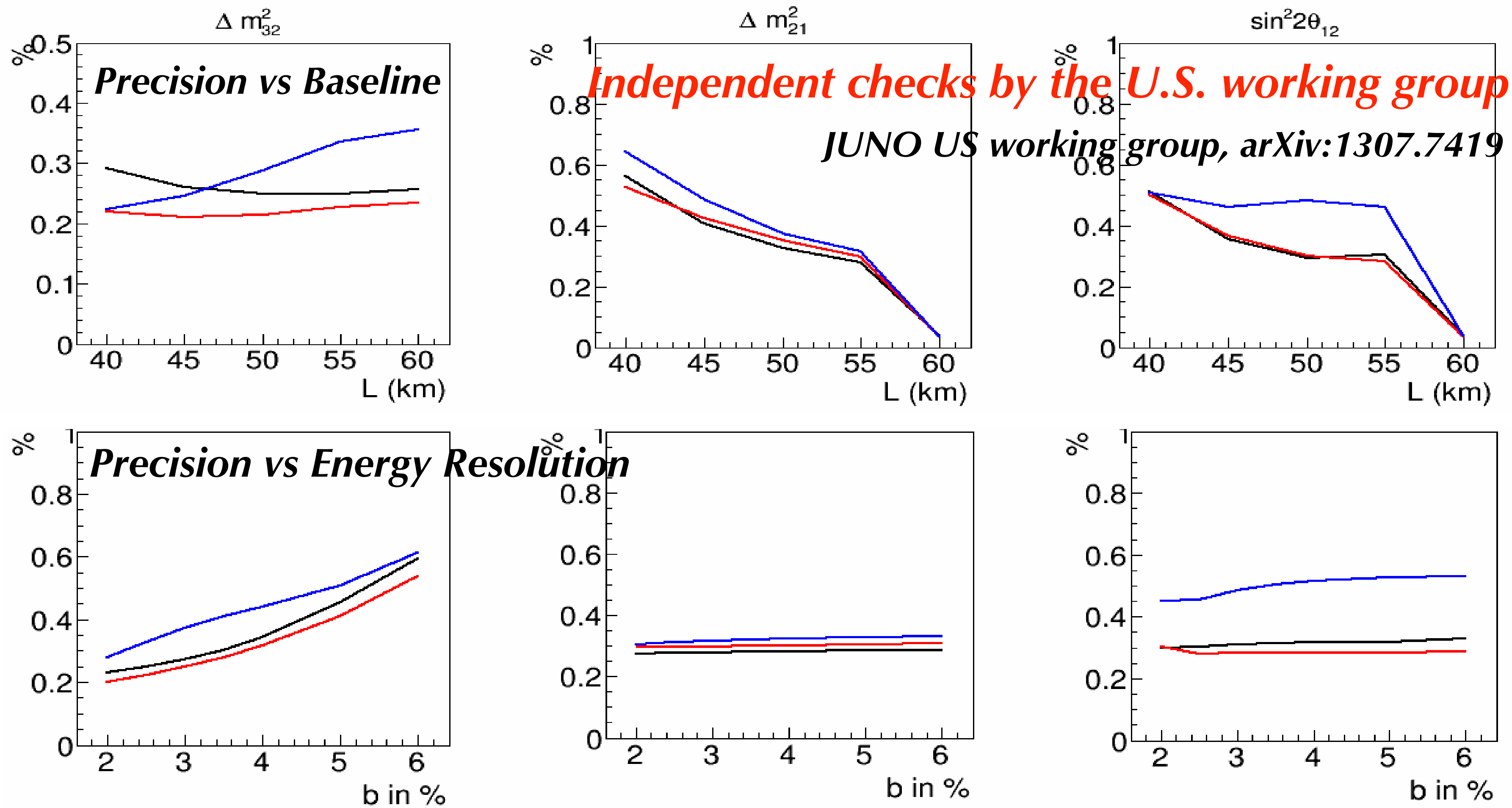
✓Realistic reactor distributions considered

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

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

Expected Precisions on Oscillation Parameters

	Nominal	+ B2B (1%)	+ BG	+ EL (1%)	+ NL (1%)
$\sin^2\theta_{12}$	0.54%	0.60%	0.62%	0.64%	0.67%
Δm^2_{21}	0.24%	0.27%	0.29%	0.44%	0.59%
$\lvert\Delta m^2_{ee}\rvert$	0.27%	0.31%	0.31%	0.35%	0.44%

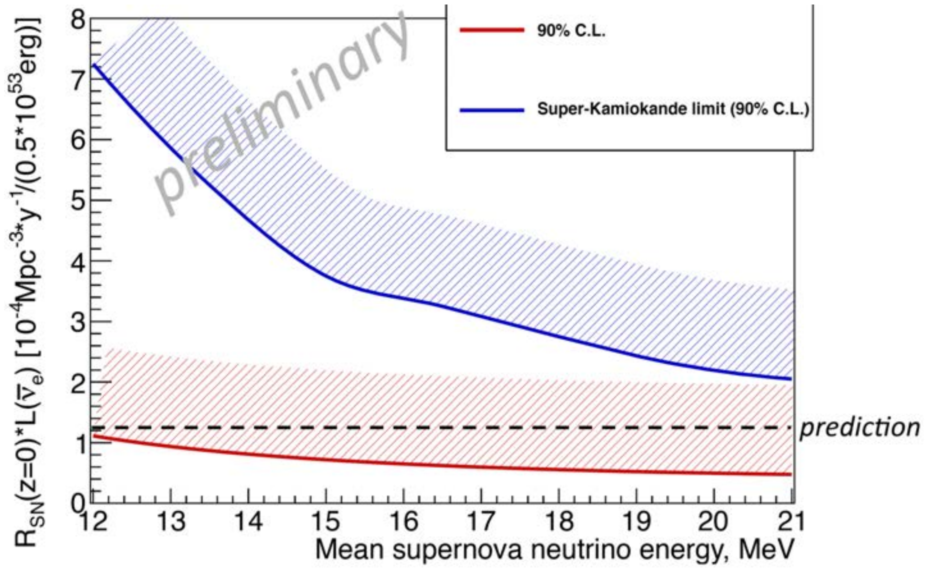


Other Physics Potential of JUNO

- 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)
- ……

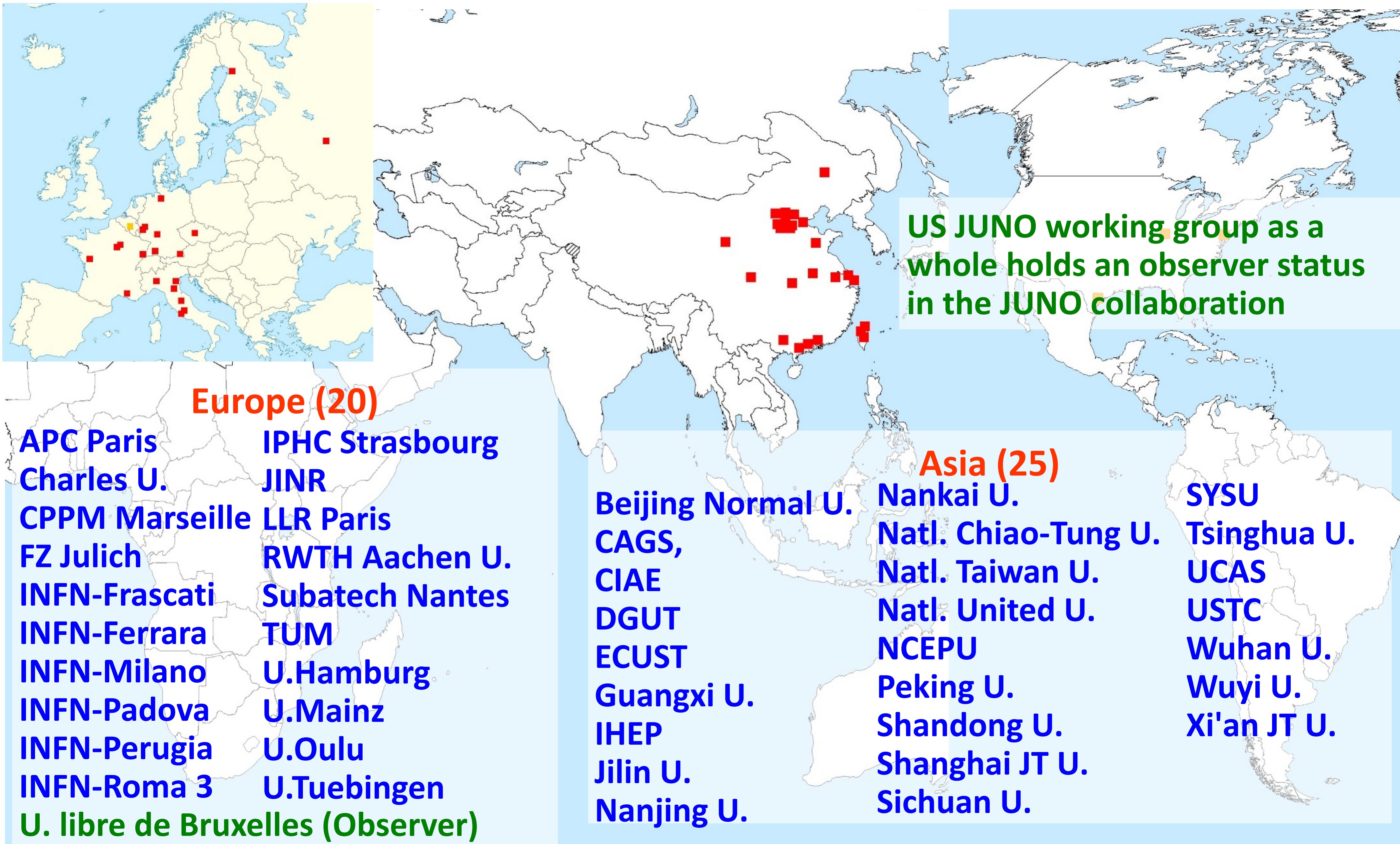
The JUNO Collaboration Formed: Interactions NewsWire #50-14

"Thanks to the great supports by many worldwide funding agencies, the JUNO experiment can kick off in a timely way and we are running to be the first to measure the neutrino mass hierarchy", says Wang.

The JUNO Collaboration consists of more than two hundred scientists from China, Czech, France, Finland, Germany, Italy, Russia, and the US. The collaborating research institutions and universities are more than 50. "This is truly an international collaboration and we are sure that more institutes will join JUNO in the near future", says Marcos Dracos of the IPHC/IN2P3 in Strasbourg, France, the newly-elected Chair of the Institutional Board of the Collaboration.

"We are very excited about this experiment and it's a wonderful and comprehensive physics program", says Gioacchino Ranucci, a Director for Technology at the Istituto Nazionale di Fisica Nucleare of Milan, Italy and a newly-appointed deputy spokesperson of the Collaboration.

JUNO Collaboration



US JUNO working group as a whole holds an observer status in the JUNO collaboration

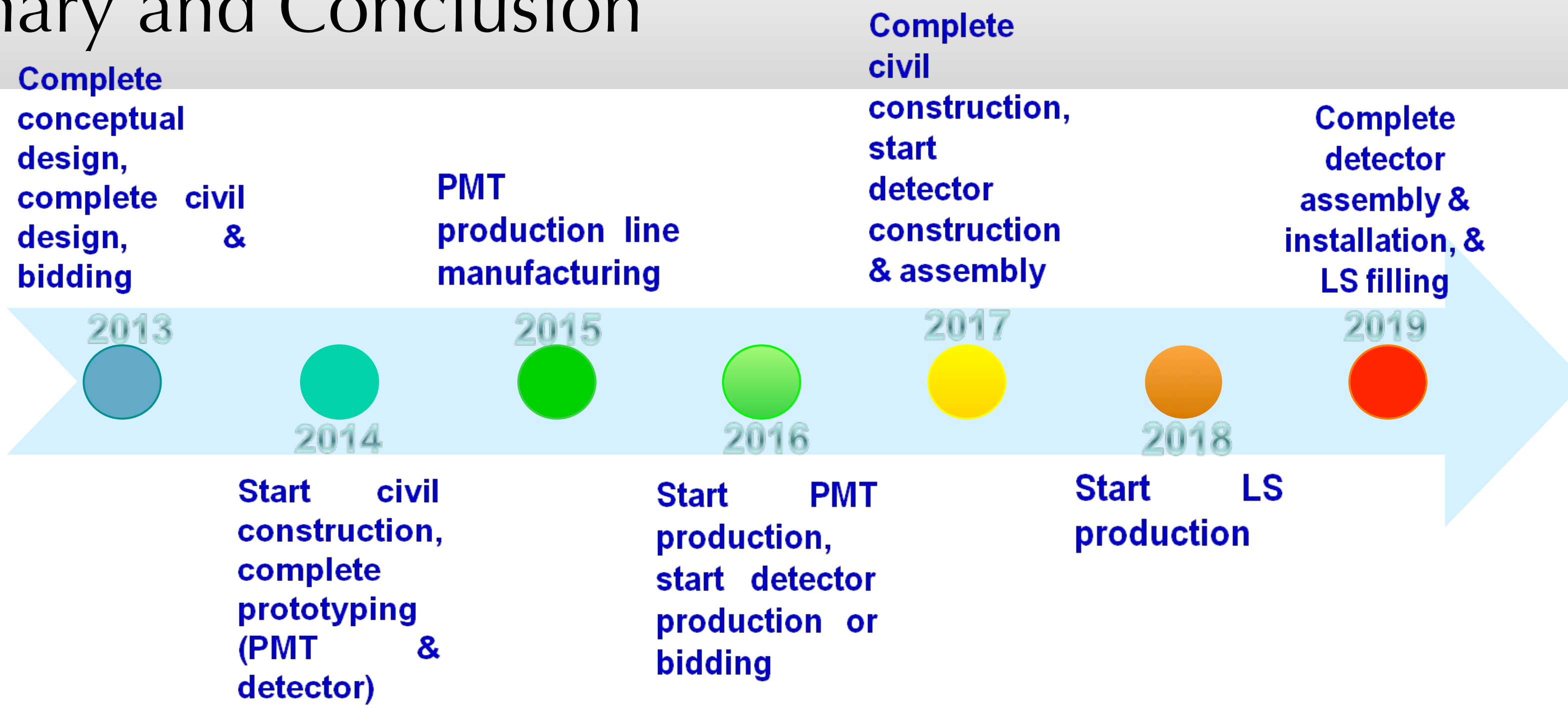
Europe (20)

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

Asia (25)

Beijing Normal U.
CAGS,
CIAE
DGUT
ECUST
Guangxi U.
IHEP
Jilin U.
Nanjing U.
Nankai U.
Natl. Chiao-Tung U.
Natl. Taiwan U.
Natl. United U.
NCEPU
Peking U.
Shandong U.
Shanghai JT U.
Sichuan U.
SYSU
Tsinghua U.
UCAS
USTC
Wuhan U.
Wuyi U.
Xi'an JT U.

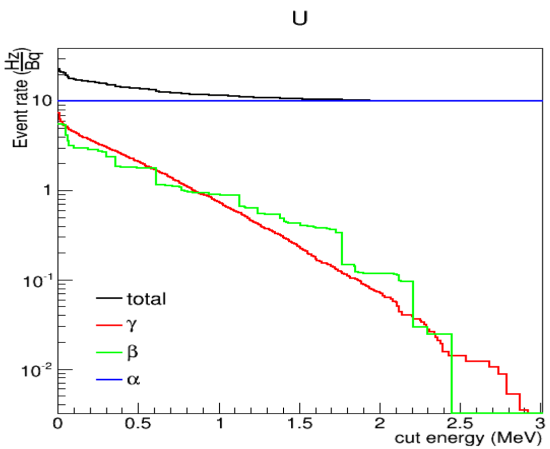
Summary and Conclusion

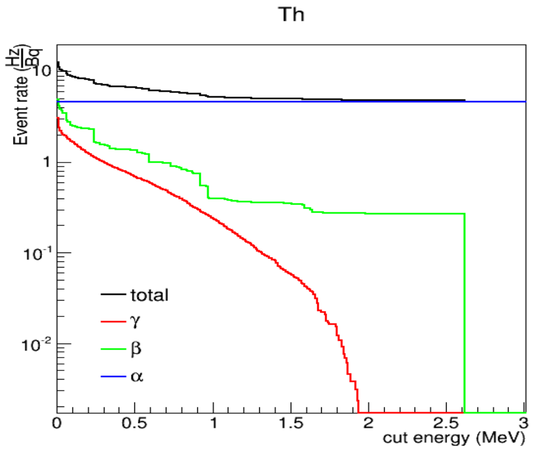


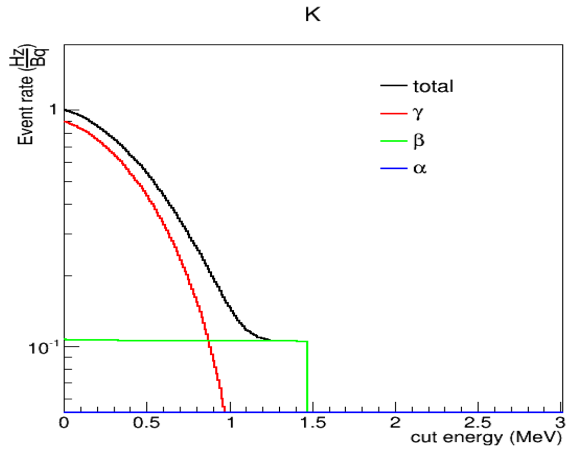
- JUNO is to build an unprecedented massive, accurate and stable liquid scintillator detector, a next-generation medium-baseline reactor neutrino experiment aiming at resolving the neutrino mass hierarchy.
  - It also has warranted precision measurements in solar mixing angle, solar mass-squared splitting and atmospheric mass-square splitting amongst other physics potential
- JUNO is a funded project in China and an international collaboration was formed in July 2014. Its data taking is expected in 2020.
- JUNO R&D's are making great progresses in all participation institutes. We could use more manpower from the international community.

Some Further Details

Background Rate Estimation







20 kton LS	U238 (1e-6 ppb)	Th232 (1e-6 ppb)	K40 (1e-6ppb)	Pb210 (0.1mBq/m	SUM
Event rates	3.5 Hz	0.81 Hz	5.4 Hz	6.9 Hz	16.61Hz
Event rates (cut 0.7MeV)	1.07 Hz	0.44 Hz	2.24 Hz	0.965 Hz	4.73 Hz

Impurity of Different Materials

	U238	Th232	K40	Pb210 (Rn222)	Kr85	Co60	Reference
PMT Glass	22 ppb	20 ppb	3.54 ppb	~	~	~	Schott glass
Acrylic	1ppt	1ppt	1ppt	~	~	~	SNO (C)
Film	2ppt	4ppt	1ppt	~	~	~	Borexino(D)
Dust	30 Bq/Kg (2.4 ppm)	40 Bq/Kg (10 ppm)	600 Bq/Kg (2.3 ppm)	~	~	~	DYB(B) Borexino(E)
Steel	0.0012 Bq/ Kg (0.096 ppb)	0.008 Bq/Kg (1.975 ppb)	0.0134Bq/Kg (0.049 ppb)	~	~	0.002 Bq/Kg	DYB
LS	10	10	10	0.1 mBq/m	0.1 mBq/m	~	KamLAND (A)

Reference:

A: Online monitor system and data management for KamLAND . arXiv:hep-ex/0405074v1. KamLAND-Zen for the Neutrino-less Double Beta Decay of ^{136}Xe .

B: DYB-doc-3366.

C: Measurements of Th & U in Acrylic for SNO ./ Th and U Measurements in Acrylic .

D: Juno-doc-#141.

E: The Borexino Nylon Film and the Third Counting Test Facility.

U^{238} : 1ppb = 12.40 mBq/Kg

Th^{232}: 1ppb = 4.05 mBq/Kg

K^{40} : 1ppb = 271 mBq/Kg

Dusts on Film

For the balloon option ,we should consider the deposited dust on the film.
If made in Cleanroom of Class 10000:
350 particles/L @ 4um size (diameter), 2.5 particles/L @ 10um size (diameter);
if assuming the dust density is 2700kg/m3 →~0.035mg/m^3

Assume the dust accumulation rate to film is ~3e-5m/s ~3e-9m/s along vertical .
1g dust on the film, exposure time is :

1g, 2 sides	Class 1	Class 10	Class 100	Class 1000	Class 10000
JUNO, 3936.9 m Exposure time	336000h	33600h	3360h	336h	**33.6h**