Status of JUNO

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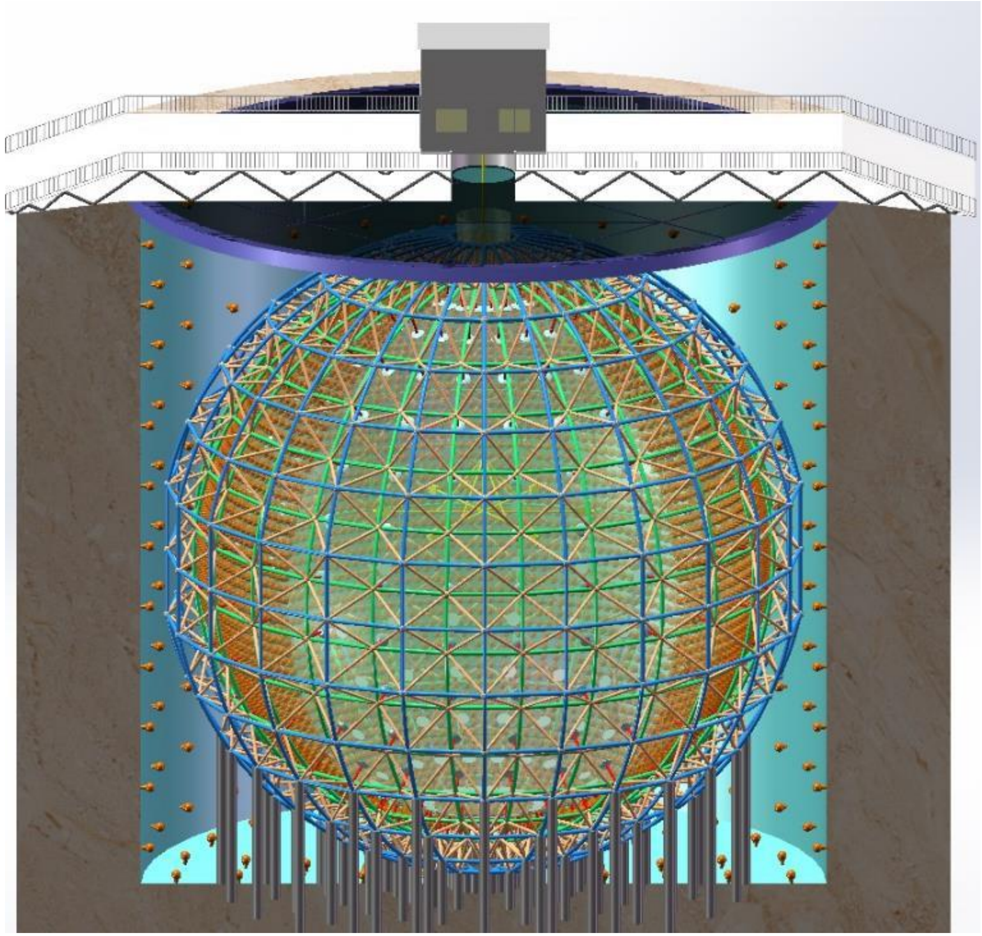
The JUNO Experiment

Jiangmen Underground Neutrino Observatory
Approved at Feb. 2013, ~330M$.



- 20kt liquid scintillator detector
  - In an acrylic ball, diameter ~35m
- 700m underground
- 3% energy resolution
  - 77% photocathode coverage
    - About 17000 20'' PMTs
  - PMT maximum QE ~ 35%
  - LS attenuation length > 22m @ 430nm
- Rich physics possibilities

Talk by Y.F. Wang at ICFA seminar 2008, NeuTel 2011; by J. Cao at NuTel 2009, NuTurn 2012;
Paper by L. Zhan, Y.F. Wang, J. Cao, L.J. Wen, PRD78:111103, 2008; PRD79:073007, 2009.

Yellow Book

Neutrino Physics with JUNO

The Jiangmen Underground Neutrino Observatory (JUNO), a 20 kton multi-purpose underground liquid scintillator detector, was recently proposed with the determination of the neutrino mass hierarchy as a primary physics goal. The excellent energy resolution and the large fiducial volume anticipated for the JUNO detector offer exciting opportunities for addressing many important topics in neutrino and astro-particle physics. In this document, we present the physics motivations and the anticipated performance of the JUNO detector for various proposed measurements.

arXiv: 1507.05613

- Reactor neutrino physics
  - Mass hierarchy, precision measurements, (geo-neutrino),…
- Astro-particle physics
  - Supernova neutrino, diffused supernova neutrino background, solar neutrino
- High energy events
  - Atmospheric neutrino, nucleon decays, …

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

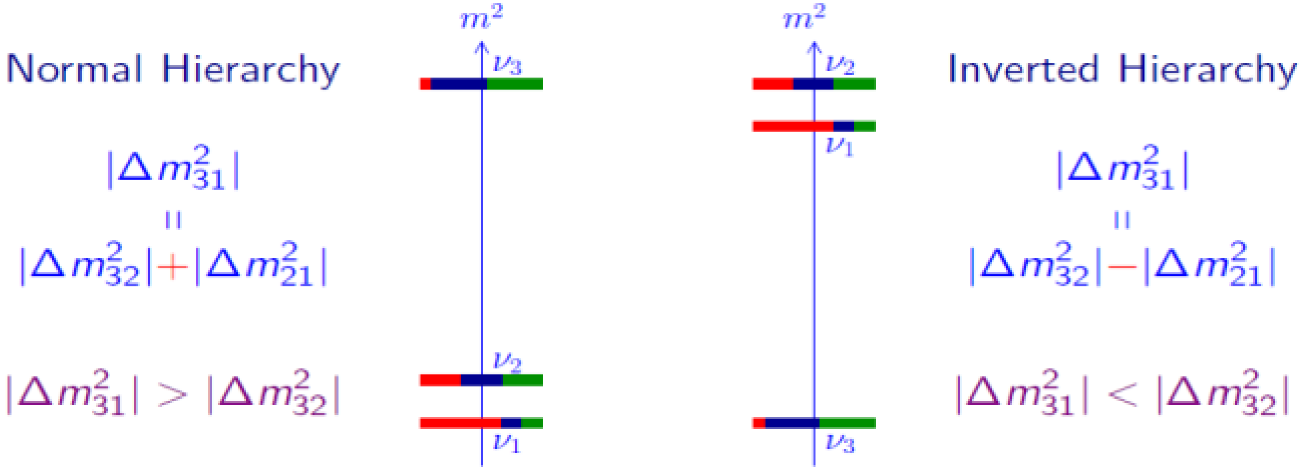
by 2020: 26.6 GW

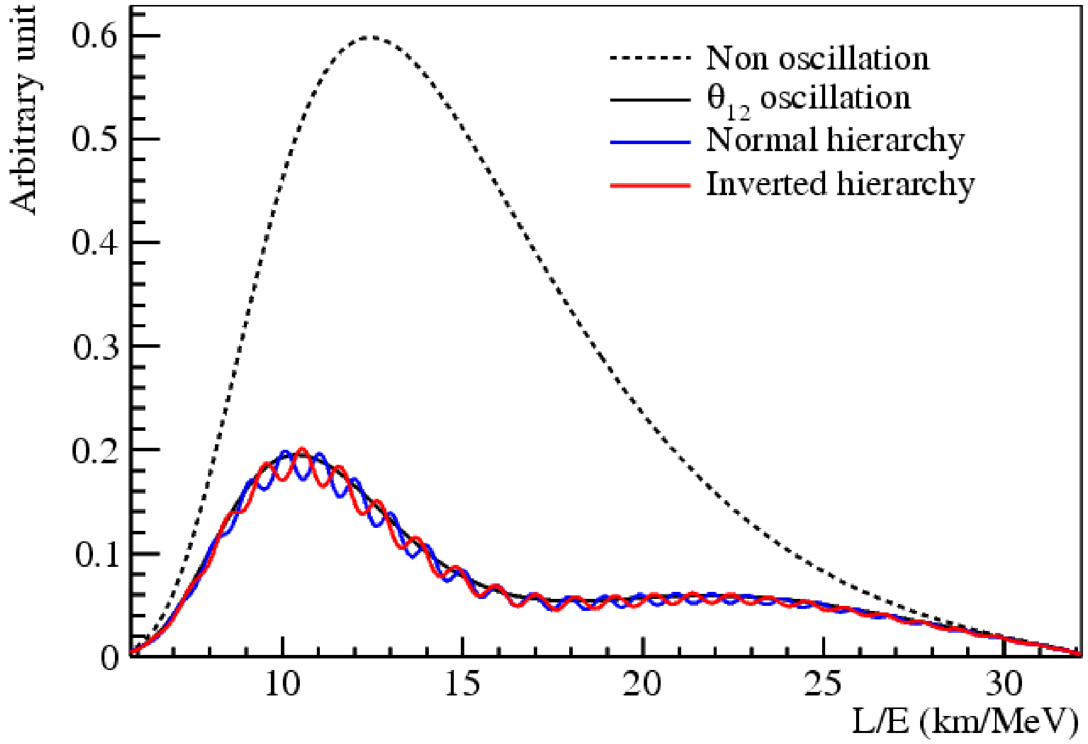
Cores	YJ-C1	YJ-C2	YJ-C3	YJ-C4	YJ-C5	YJ-C6
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9
Baseline (km)	52.75	52.84	52.42	52.51	52.12	52.21
Cores	TS-C1	TS-C2	TS-C3	TS-C4	DYB	HZ
Power (GW)	4.6	4.6	4.6	4.6	17.4	17.4
Baseline (km)	52.76	52.63	52.32	52.20	215	265

Determine MH w/ reactor neutrinos

$\bar{\nu}_e$ disappearance experiments

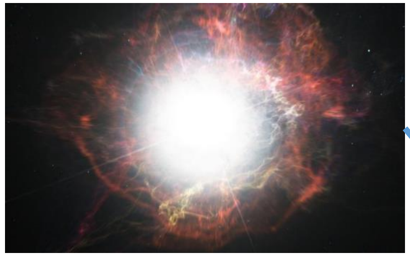
$$
\begin{aligned}
P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\
P_{21} &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \\
P_{31} &= \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) \\
P_{32} &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})
\end{aligned}
$$



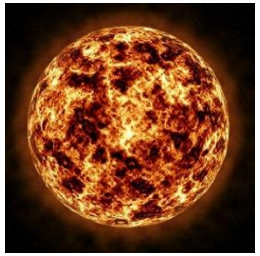


- Precision energy spectrum measurement for the interface of P_{31} and P_{32}
- Further improvements with precise $\Delta M^2_{\mu\mu}$ from accelerator experiments

Neutrino rates

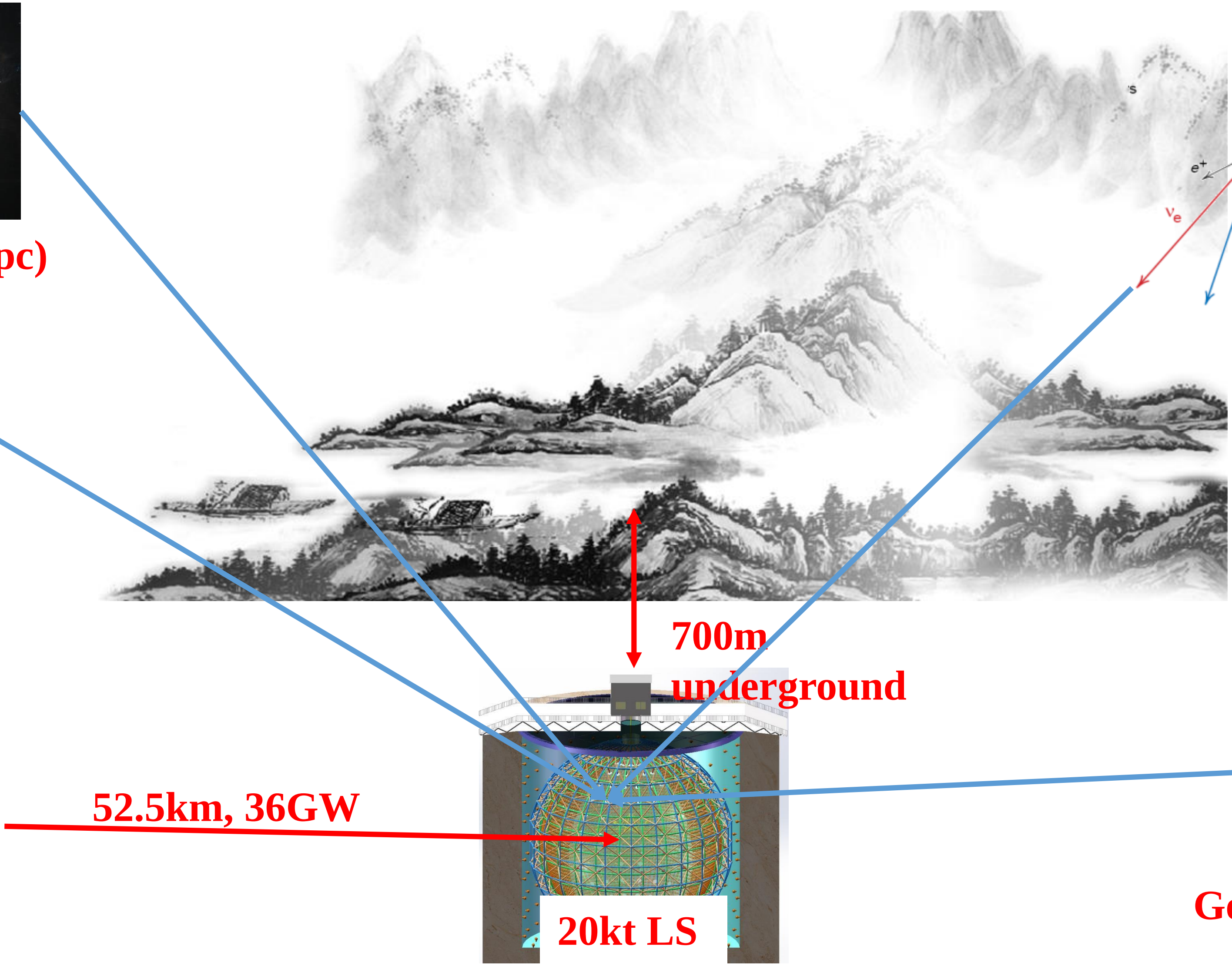


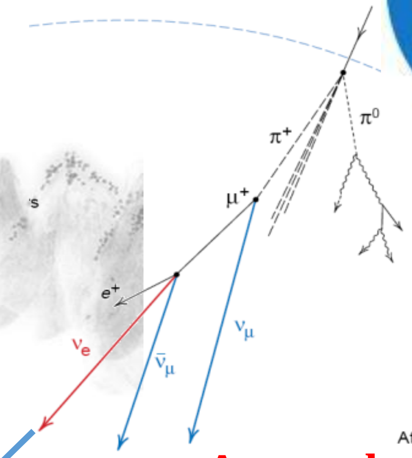
SN ν 5000/10s (10kpc)



Solar ν 10-1k/day

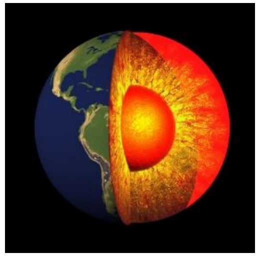
Reactor $\bar{\nu}_e$ ~ 60/day





Atmospheric ν
several/day

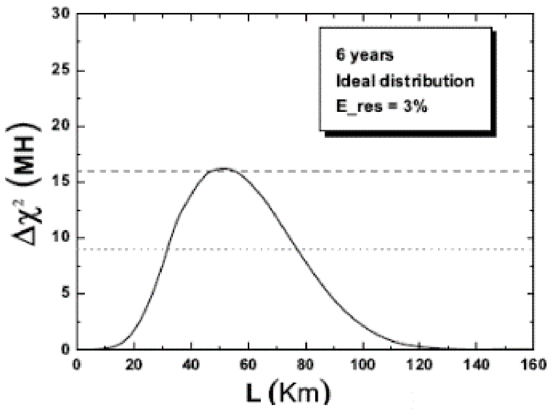
Muon ~ 250k/day
215GeV
10% multi-muon



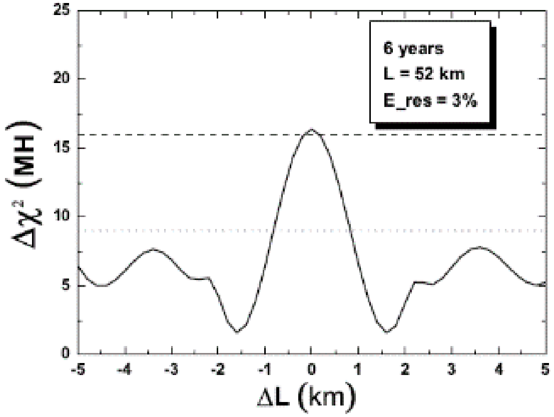
Geo-$\bar{\nu}_e$ 1~2/day

Mass hierarchy sensitivity

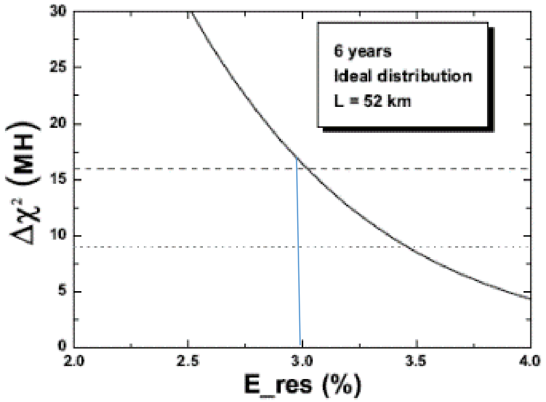
JUNO MH sensitivity with six years running: 100k reactor $\bar{\nu}_e$ events



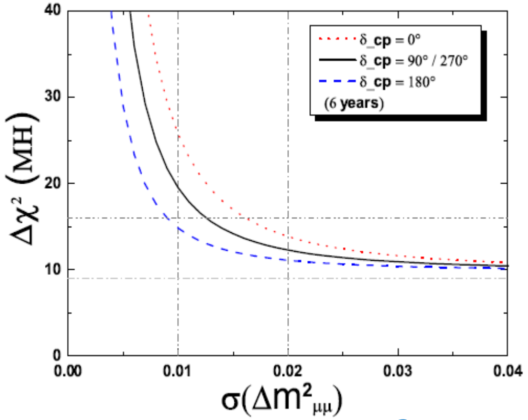
Baseline: JUNO 52.5km



Equal baselines



3% energy resolution



Inputs of $|\Delta M^2_{\mu\mu}|$

- 3σ with the spectrum measurement
- 4σ with external input of $|\Delta M^2_{\mu\mu}|$

	Ideal	Core distr.	Shape	B/S(stats.)	B/S(shape)	$\lvert\Delta M^2_{\mu\mu}\rvert$
Size	52.5km	Real	1%	4.5%	0.3%	1%
$\Delta\chi^2_{MH}$	+16	-4.7	-1	-0.5	-0.1	+8

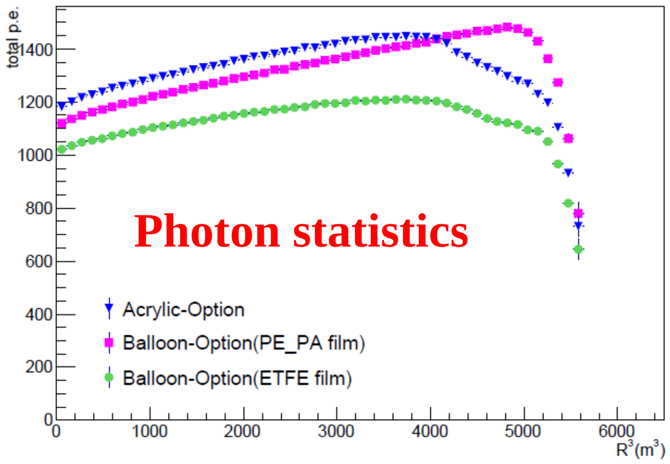
Energy resolution

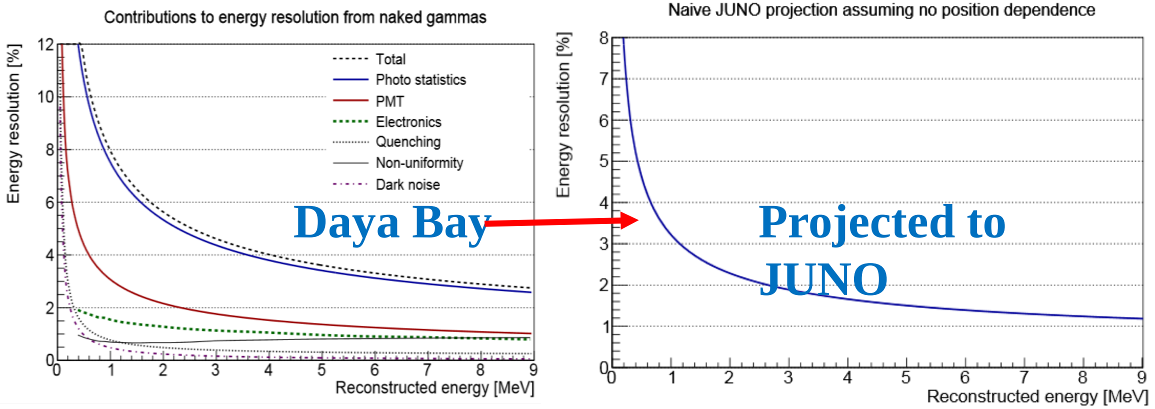
$$\frac{\sigma_E}{E} = \sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + b^2 + \left(\frac{c}{E}\right)^2}$$

Impact to MH sensitivity

$$\simeq \sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + \left(\frac{1.6\,b}{\sqrt{E}}\right)^2 + \left(\frac{c}{1.6\,\sqrt{E}}\right)^2}$$

- **a: statistical term**
  - MC simulation based Daya Bay MC w/
    - JUNO geometry and 77% PMT coverage
    - Maximum PMT QE 35% and 20m LS ATTL
    - 1200 p.e. /MeV @ center, 2.89%/sqrt(E)
    - 1400 p.e. /MeV @ edge,   2.67%/sqrt(E)
- **b: constant term, c: noise term**
  - Residual non-uniformity, electronics flaw, ..
  - Estimated with data validated full MC (Daya Bay and Double Chooz)
- **No JUNO show stopper found**

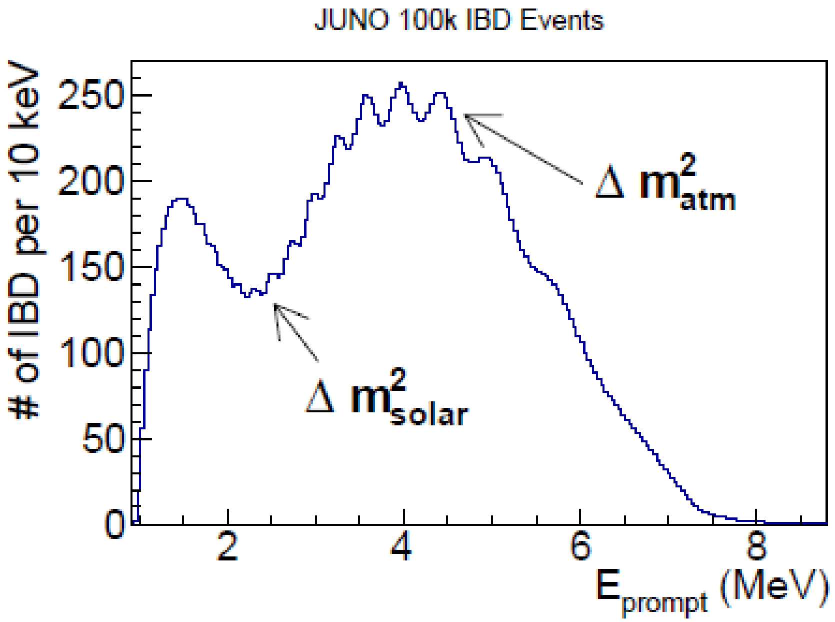




Constant/noise term projected from Daya Bay

Precision measurements

Current status	ΔM^2_{21}	$\|\Delta M^2_{31}\|$	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$
Dominant Exp.	KamLAND	MINOS	SNO	Daya Bay	SK/T2k
Individual 1σ	2.7%	4.1%	6.7%	6%	14%
Global 1σ	2.6%	2.7%	4.1%	5%	11%



JUNO	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%
$\|\Delta M^2_{ee}\|$	0.27%	0.31%	0.31%	0.35%	0.44%

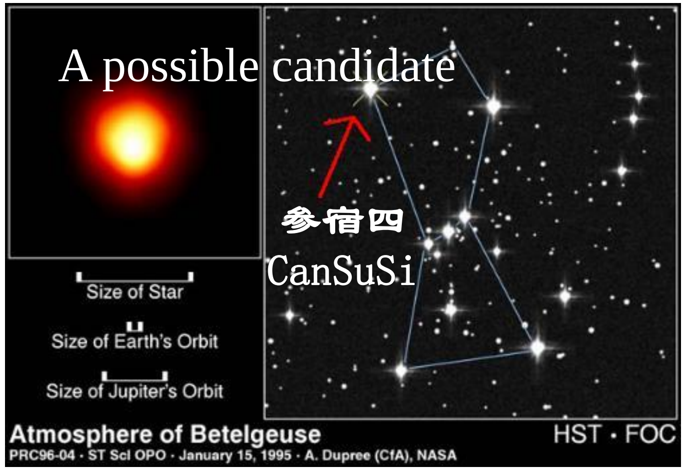
$$|U_{e1}|^2 + |U_{e2}|^2 + |U_{e3}|^2 \stackrel{?}{=} 1\,.$$

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

More precise than CKM matrix elements !

Supernova neutrinos

- **Less than 20 events observed so far**
- **Assume a supernova**
  - Distance: 10 kpc
  - Energy: 10^{53} erg
  - Lν same for all types



Estimated events

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

- **Much better detection to correlated events versus water Cherenkov detector**
- **Could measure energy and flux for all types of neutrinos**

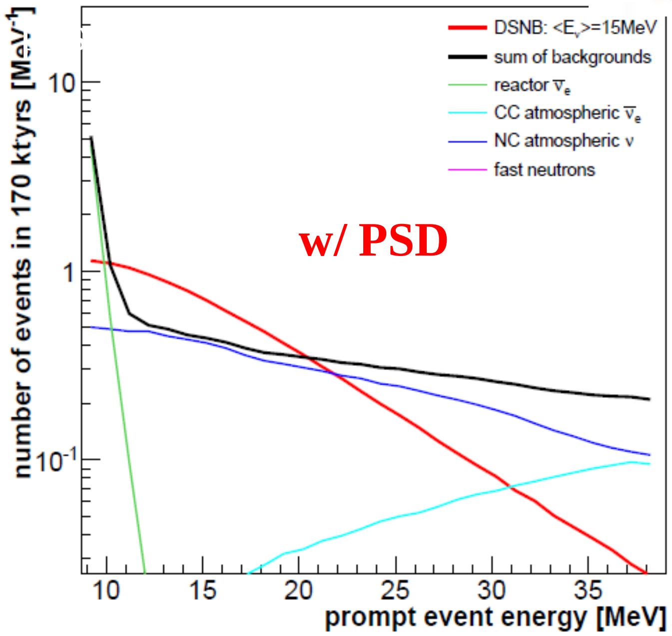
Physics

1. ν mass less than < 0.83±0.24 eV at 95% CL (arXiv:1412.7418) ;
2. Locating SN ~ 9^{o} ;
3. Pre-supernova: ~ 1 day;
4. Collective ν oscillation;
5. Mass hierarchy;

Not the end ……….

Diffused supernova neutrinos

- **Neutrinos from past core-collapse stars**
  - Cosmic star-formation rate
  - Core-collapse neutrino spectrum
  - Rate of failed Sne
  - Several events per year in JUNO
- **Dominated background: atm. NC**
  - Pulse Shape Discriminator could reduce bkg. to 1.1%
- **Expected sensitivity ~3σ to observe DSNB**



10 year's counts

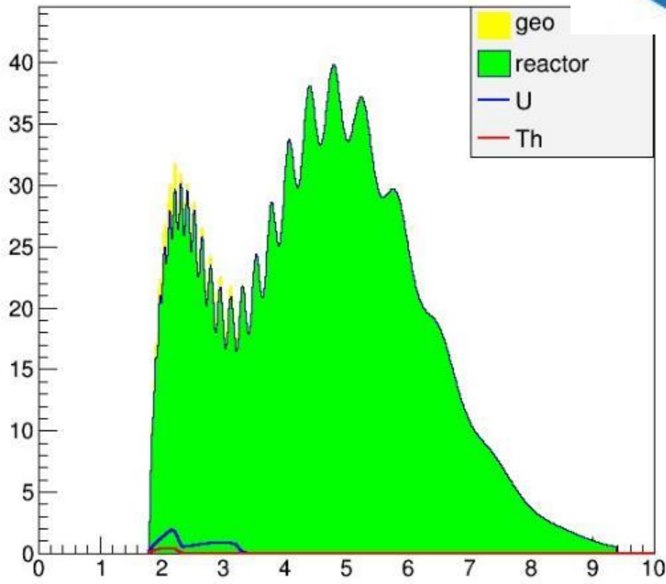
Item		Rate (no PSD)	PSD efficiency	Rate (PSD)
Signal	$\langle E_{\bar{\nu}_e} \rangle = 12\,\mathrm{MeV}$	13	$\varepsilon_\nu = 50\,\%$	7
	$\langle E_{\bar{\nu}_e} \rangle = 15\,\mathrm{MeV}$	23		12
	$\langle E_{\bar{\nu}_e} \rangle = 18\,\mathrm{MeV}$	33		16
	$\langle E_{\bar{\nu}_e} \rangle = 21\,\mathrm{MeV}$	39		19
Background	reactor $\bar{\nu}_e$	0.3	$\varepsilon_\nu = 50\,\%$	0.13
	atm. CC	1.3	$\varepsilon_\nu = 50\,\%$	0.7
	atm. NC	$6 \cdot 10^2$	$\varepsilon_{\mathrm{NC}} = 1.1\,\%$	6.2
	fast neutrons	11	$\varepsilon_{\mathrm{FN}} = 1.3\,\%$	0.14
	Σ			7.1

10 year's sensitivity

Syst. uncertainty BG	5 %		20 %	
$\langle E_{\bar{\nu}_e} \rangle$	rate only	spectral fit	rate only	spectral fit
12 MeV	$2.3\,\sigma$	$2.5\,\sigma$	$2.0\,\sigma$	$2.3\,\sigma$
15 MeV	$3.5\,\sigma$	$3.7\,\sigma$	$3.2\,\sigma$	$3.3\,\sigma$
18 MeV	$4.6\,\sigma$	$4.8\,\sigma$	$4.1\,\sigma$	$4.3\,\sigma$
21 MeV	$5.5\,\sigma$	$5.8\,\sigma$	$4.9\,\sigma$	$5.1\,\sigma$

Geo-neutrinos

- **The earth is huge "reactor"**
  - **KamLAND**: 30±**7 TNU** *PRD 88 (2013) 033001*
  - **Borexino**: 38.8±**12.2 TNU** *PLB 722 (2013) 295*
  - Statistics dominant
- **JUNO** desires to reach the error of **3 TNU**
  - 20 times more statistics
  - Huge reactor neutrino background
    - Precise reactor spectrum is required
- Precise geo-neutrino measurement would serve the geological community a lot.

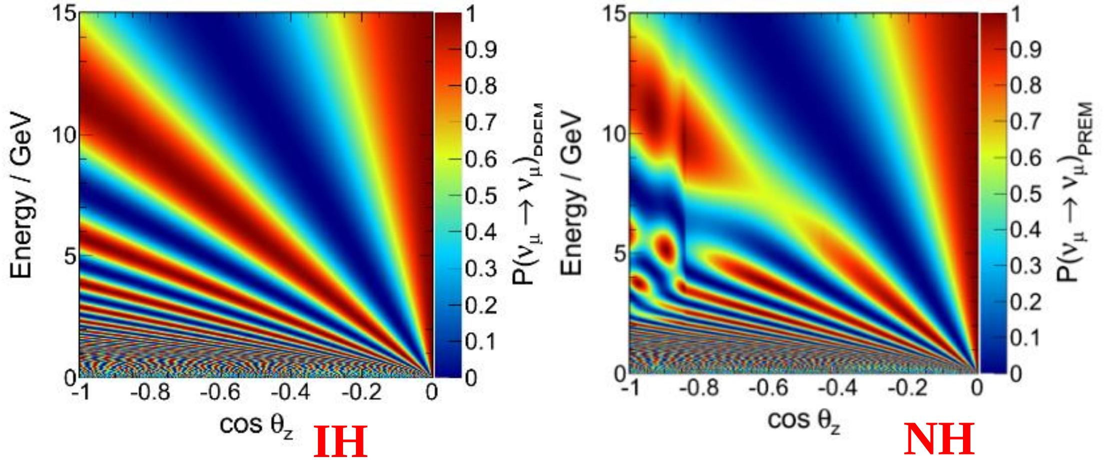


Source	Events/year
Geoneutrinos	408 ± 60
U chain	311 ± 55
Th chain	92 ± 37
Reactors	16100 ± 900
Fast neutrons	36.5 ± 36.5
^{9}Li - ^{8}He	657 ± 130
$^{13}C(\alpha, n)^{16}O$	18.2 ± 9.1
Accidental coincidences	401 ± 4

Atmospheric and Solar neutrino

- **Atmospheric neutrino**
  - Sensitive to MH due to the matter effect
  - 1-2σ sensitivity in JUNO
- **Solar neutrino**
  - ^{7}Be and ^{8}B ν in JUNO
  - Energy threshold and background
    - Possible 0.1MeV w/ rejecting events at the detector center (dark noise) and edge (radioactivity)
- **Sterile neutrino, indirect dark matter search, nucleon decay, etc..**

MH effects in atmospheric ν

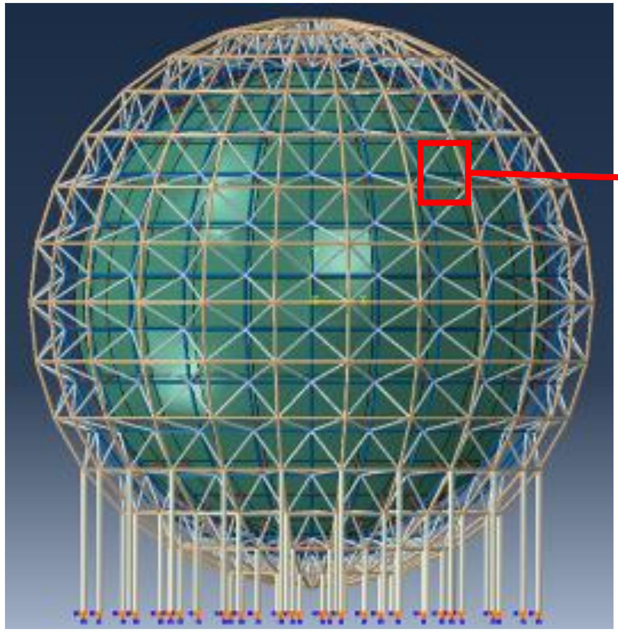


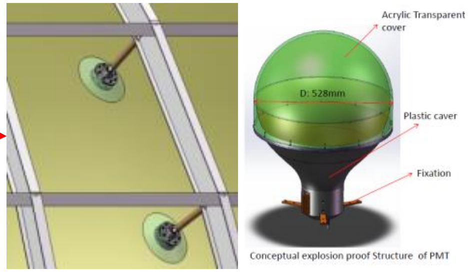
Solar neutrino rate in JUNO

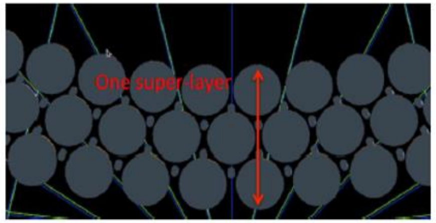
Solar neutrino signal rates [counts/day/kton]	
pp ν	1378
^{7}Be ν	517
pep ν	28
^{8}B ν	4.5
^{13}N/^{15}O/^{17}F ν	7.5/5.4/0.1

Central detector

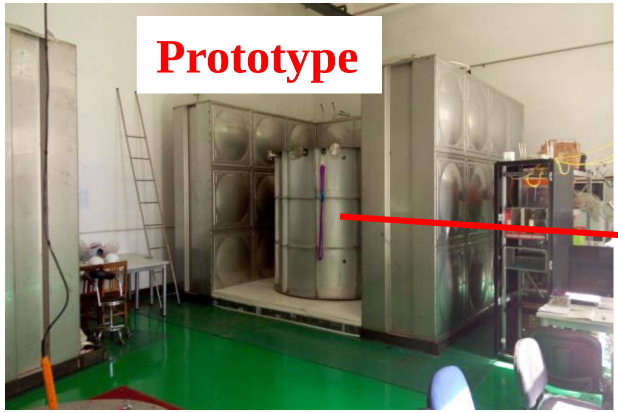
- **A huge LS detector in water**
  - Acrylic tank + SS truss, selected in July, 2015
  - Details in Jie's parallel talk on Oct. 28th
- **Challenges**
  - Engineering: mechanics, safety, lifetime, …
  - LS: high transparency, low background
  - PMT: high QE, high coverage
- **Utilizing 3" PMTs to fill the gaps of 20" PMTs is under consideration**
- A prototype detector is under construction at IHEP, for the test of
  - PMTs of MCP, HZC, Hamamatsu, and potting
  - Electronics
  - Liquid scintillator

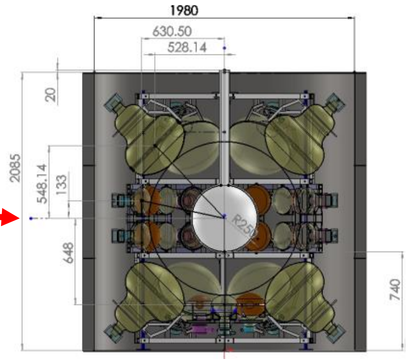






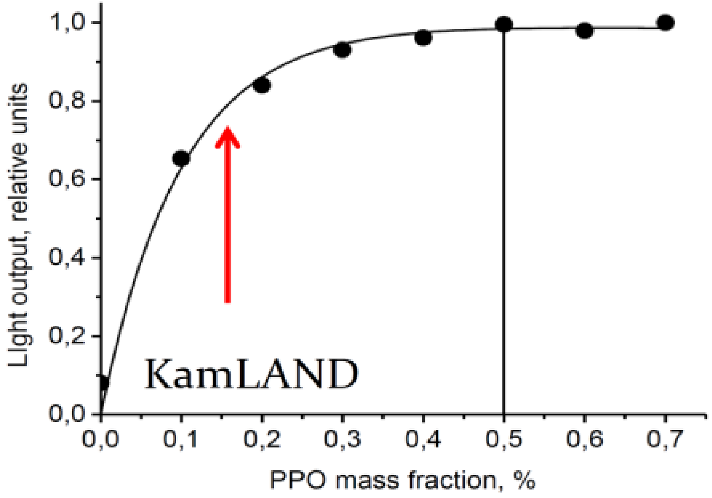
Add 3-inch PMTs in the gaps

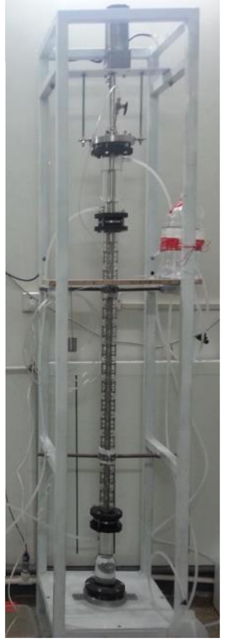




Liquid scintillator in the CD

- **LAB + PPO + bis-MSB, no Gd**
- **Increase light yield**
  - Optimize fluors concentrations
- **Increase transparency**
  - Better quality raw LAB
  - Online handling and purification
    - Distillation, Filtration, Water extraction, Nitrogen stripping, …
- **Reduce radioactivity**
  - Less risk since no Gd loading



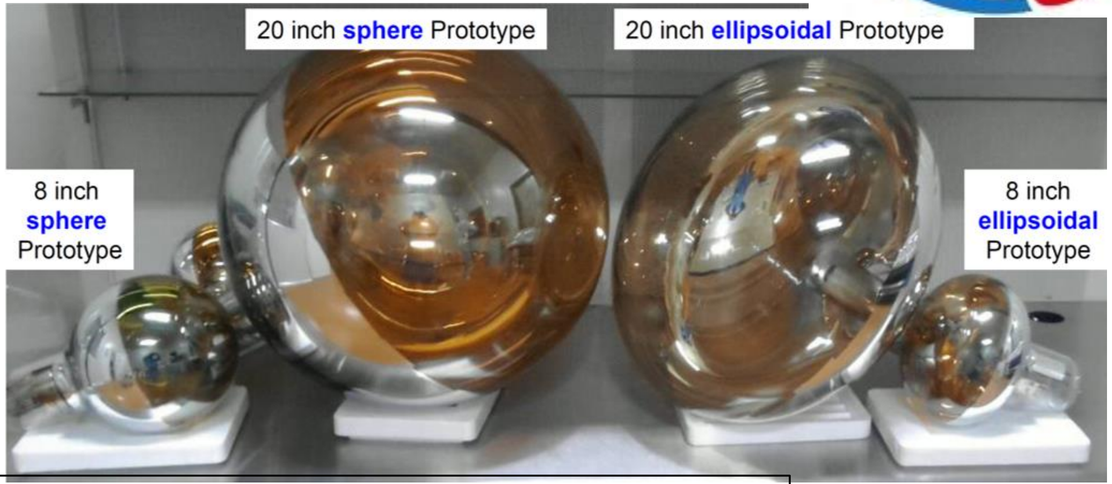


Linear Alky Benzene (LAB)	Atte. Length @ 430 nm
RAW (specially made)	14.2 m
Vacuum distillation	19.5 m
SiO_2 coloum	18.6 m
Al_2O_3 coloum	25 m

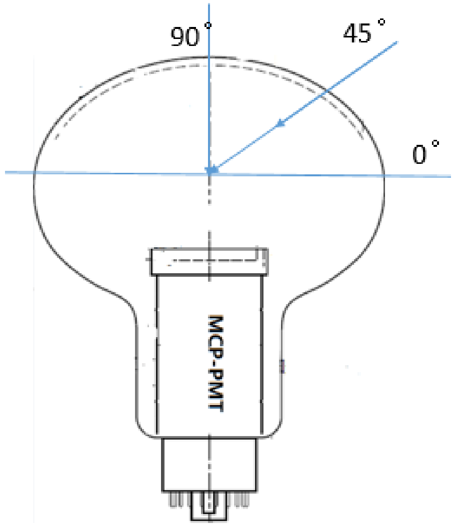
LS radio. g/g	^{238}U	^{232}Th	^{40}K	^{210}Pb	Ref.
No distillation	10^{-15}	10^{-15}	10^{-16}	$1.4*10^{-22}$	Borexino, KamLAND, CTF
After distillation	10^{-17}	10^{-17}	10^{-18}	10^{-24}	

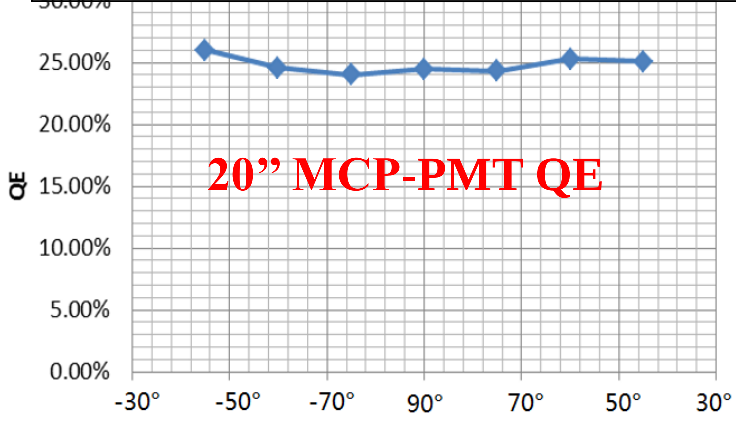
High QE PMT efforts

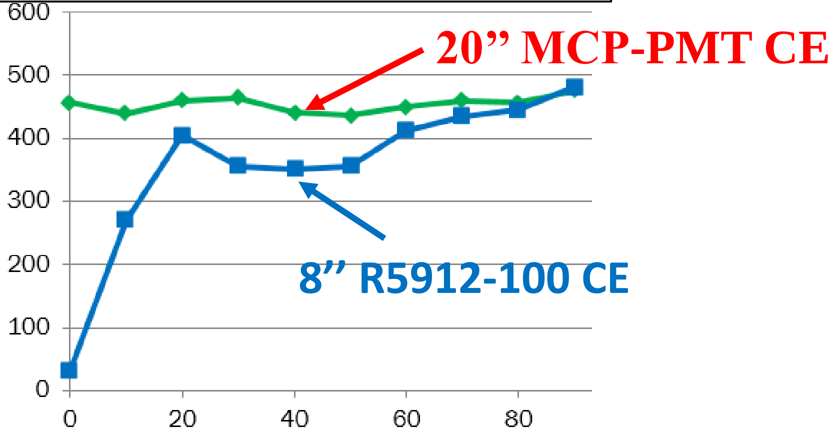
- A new design of using MCP
  - 4π collection, under development
  - Technical issues mostly solved, successful 8” and 20” prototypes.
- Alternative options: Hamamatsu or Photonics
- **News from 20” MCP-PMT:**
  - **Quantum Efficiency ~ 25% @ 410nm**
  - **Collection Efficiency ~ 100%**



Photon Detection Efficiency = QE*CE, @410nm, 20” MCP-PMT: ~25%, that in MC (slide 8): ~27%





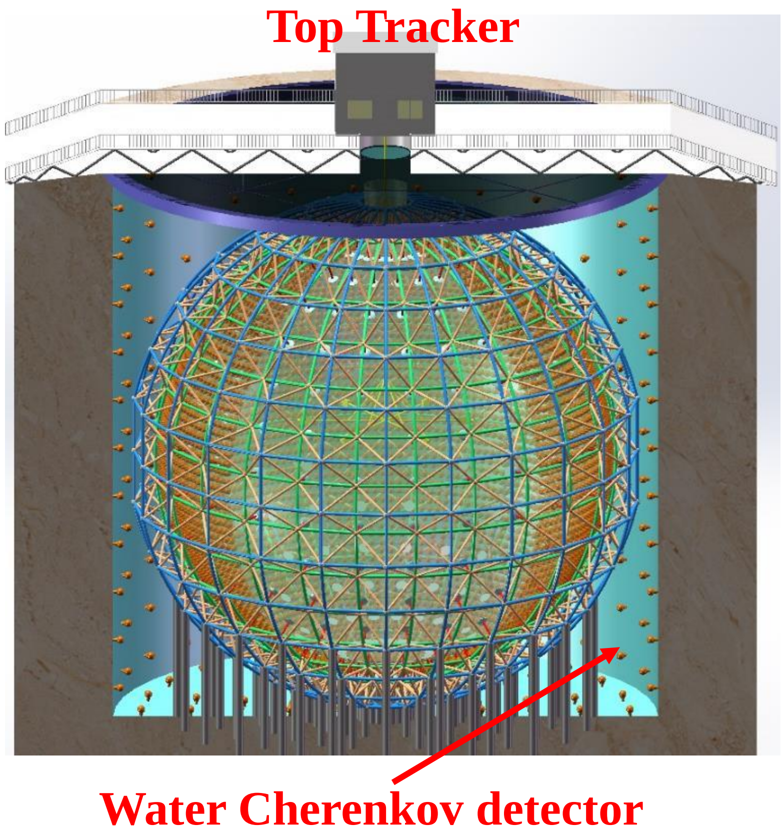


Veto detectors

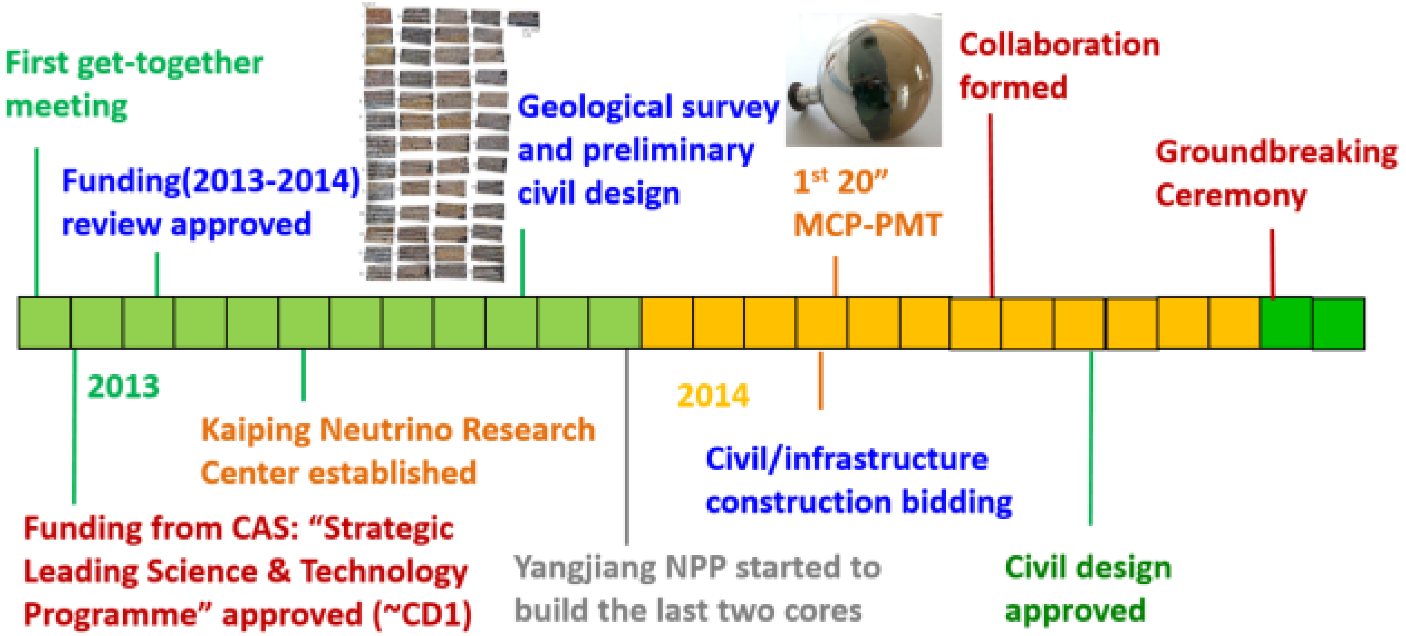
- **Water Cherenkov detector**
  - At least 2 m water shielding
  - ~1500 20"PMTs
  - 20k~30k tons of pure water
  - Earth magnetic field shielding
- **Top muon tracker**
  - Decommissioned OPERA plastic scintillator
- **Cosmic muon rate**
  - 0.0031 Hz/m^2, mean energy 214GeV
  - Muon track will be used for muon-induced background subtraction

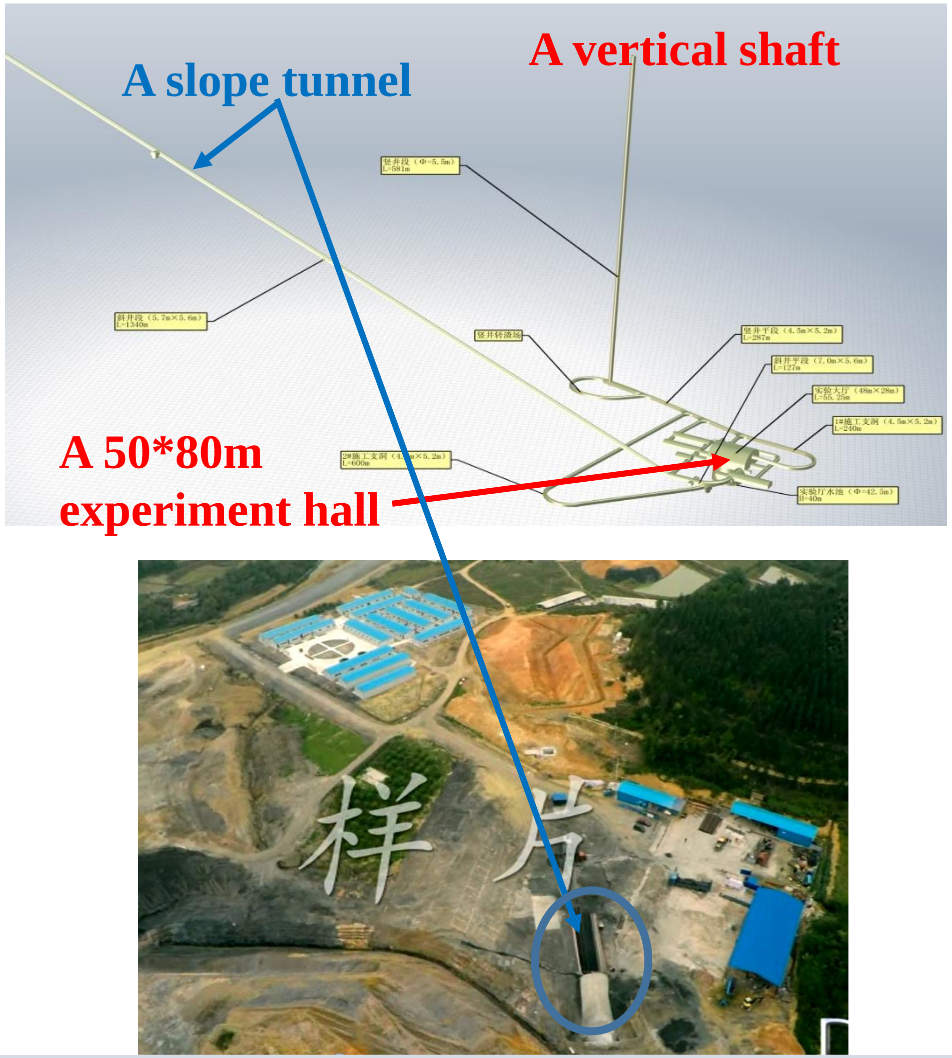
Muon multiplicity

Multiplicity	1	2	3	4	5	6
Fraction	89.6%	7.7%	1.8%	0.6%	0.3%	0.07%



Project plan and progresses

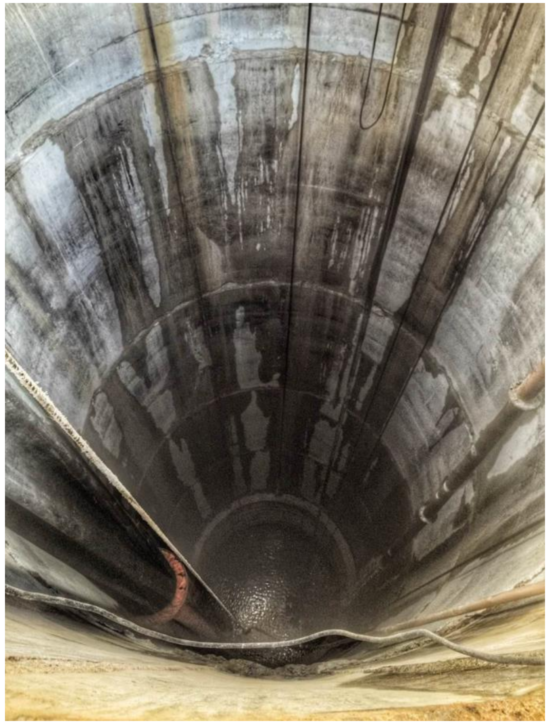




- Civil construction：2015-2017
- Detector component production：2016-2017
- PMT production：2016-2019
- Detector assembly & installation：2018-2019
- Filling & data taking：2020

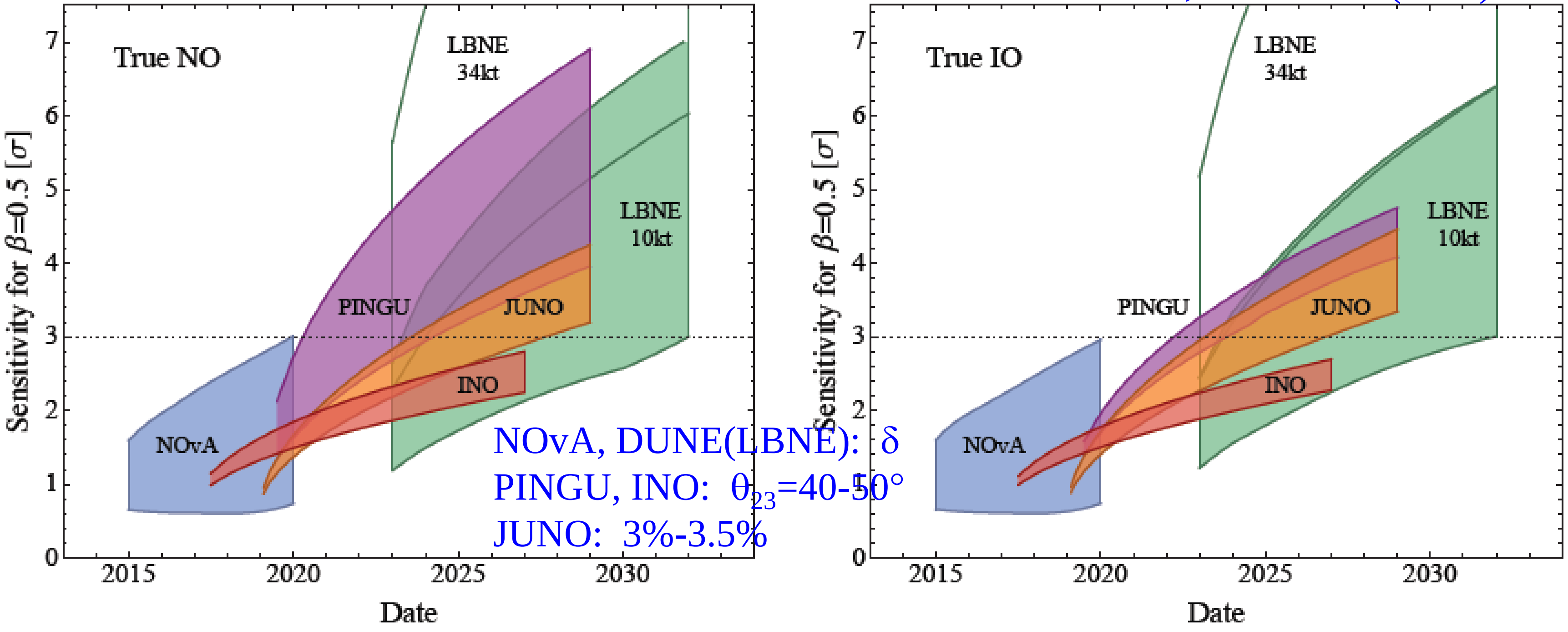
The tunnel

- **By July 26th, the slope tunnel has finished 491.2m of 1340.6m**
  - By the end of 2015, about 900m is expected to be finished
- **The vertical shaft has finished 75m of 611m**
  - To be completed by the end of 2015



Summary

M. Blennow et al., JHEP 1403 (2014) 028



NOvA, DUNE(LBNE): δ
PINGU, INO: θ_{23}=40-50°
JUNO: 3%-3.5%

- JUNO: a multi-purpose LS detector with rich physics possibilities
  - **Competitive in schedule and Complementary in physics**
- R&D activities and civil constructions are smoothly ongoing
- Plan to start data taking in 2020

The collaboration