Neutrino Mass hierarchy at JUNO and related statistical issues:

Jiangmen Underground Neutrino Observatory

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On behalf of the JUNO collaboration

PhyStat-ν Workshop on Statistical Issues in Experimental Neutrino Physics

Kavli IPMU, The University of Tokyo

Current status of neutrino oscillations

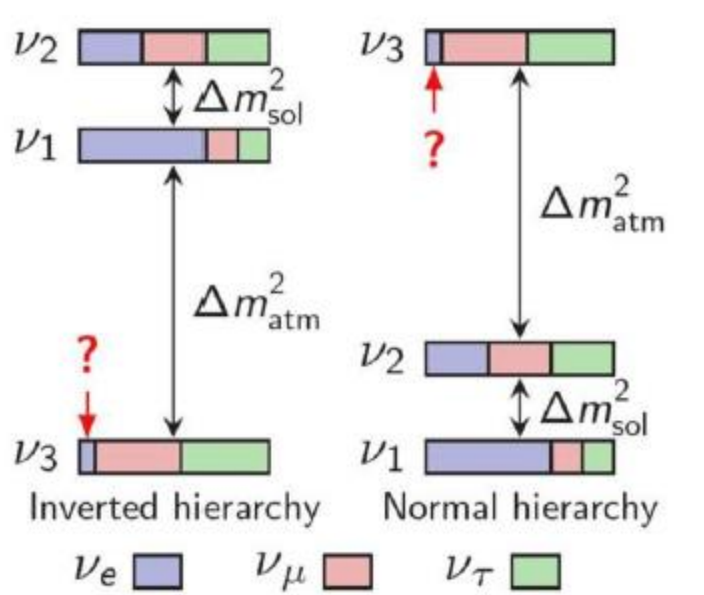
$$\mathbf{U_{3\times3}} = \mathbf{U}_{\mathrm{PMNS}}$$

See Talk by Prof. Petcov

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

flavor eigenstates | atmospheric mixing | reactor mixing & CP violation | solar mixing | mass eigenstates

$\theta_{23} \approx (45\pm9)^\circ$ | $\theta_{13} \approx (8.9\pm1.4)^\circ$, $\delta_{CP}=?$ | $\theta_{12} \approx (34\pm3)^\circ$



Unresolved issues:

Mass hierarchy

CP-violating phase

Theta(23) octant

Are there additional sterile neutrino species?

Mass hierarchy

Matter effect: Accelerator, atmospheric, supernova neutrinos

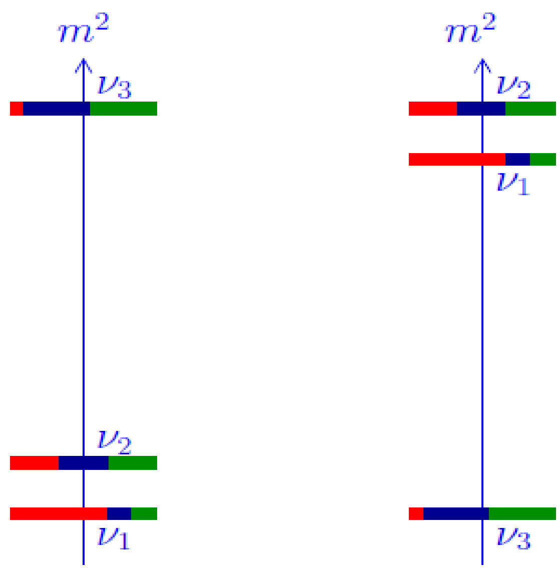
- $\nu_e \leftrightarrows \nu_\mu$ MSW resonance: $V = \frac{\Delta m^2_{13} \cos 2\vartheta_{13}}{2E} \Leftrightarrow \Delta m^2_{13} > 0$ NH
- $\bar{\nu}_e \leftrightarrows \bar{\nu}_\mu$ MSW resonance: $V = -\frac{\Delta m^2_{13} \cos 2\vartheta_{13}}{2E} \Leftrightarrow \Delta m^2_{13} < 0$ IH

Vacuum oscillation: reactor neutrinos S. T. Petcov *et al.*, PLB 533, 94 (2002)

Normal Hierarchy

$|\Delta m^2_{31}|$ = $|\Delta m^2_{32}| + |\Delta m^2_{21}|$

$|\Delta m^2_{31}| > |\Delta m^2_{32}|$



Inverted Hierarchy

$|\Delta m^2_{31}|$ = $|\Delta m^2_{32}| - |\Delta m^2_{21}|$

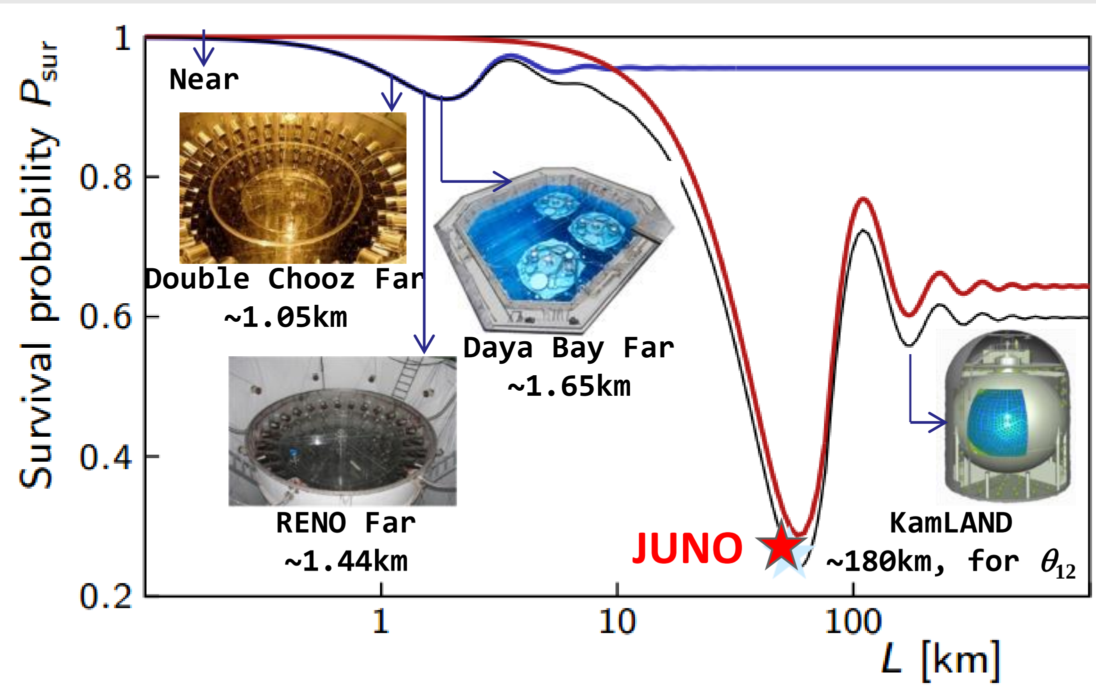
$|\Delta m^2_{31}| < |\Delta m^2_{32}|$

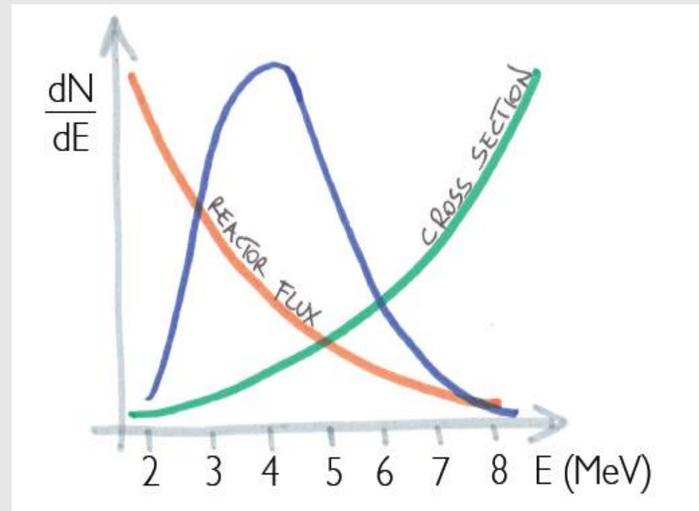
Reactor neutrinos

Survival Probability

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\vartheta_{13} \left(\cos^2\vartheta_{12} \sin^2\Delta_{31} + \sin^2\vartheta_{12} \sin^2\Delta_{32}\right) \quad \text{FAST} \quad \Delta m^2_{ATM}$$

$$- \sin^2 2\vartheta_{12} \cos^4\vartheta_{13} \sin^2\Delta_{21} \quad \text{SLOW} \quad \Delta m^2_{SOL}$$





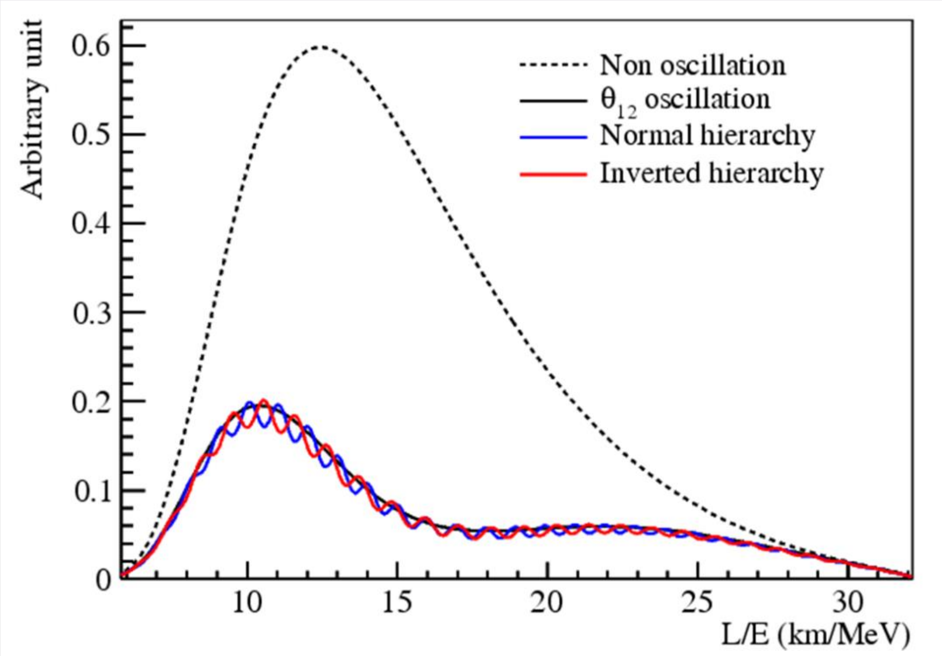
Prompt signal

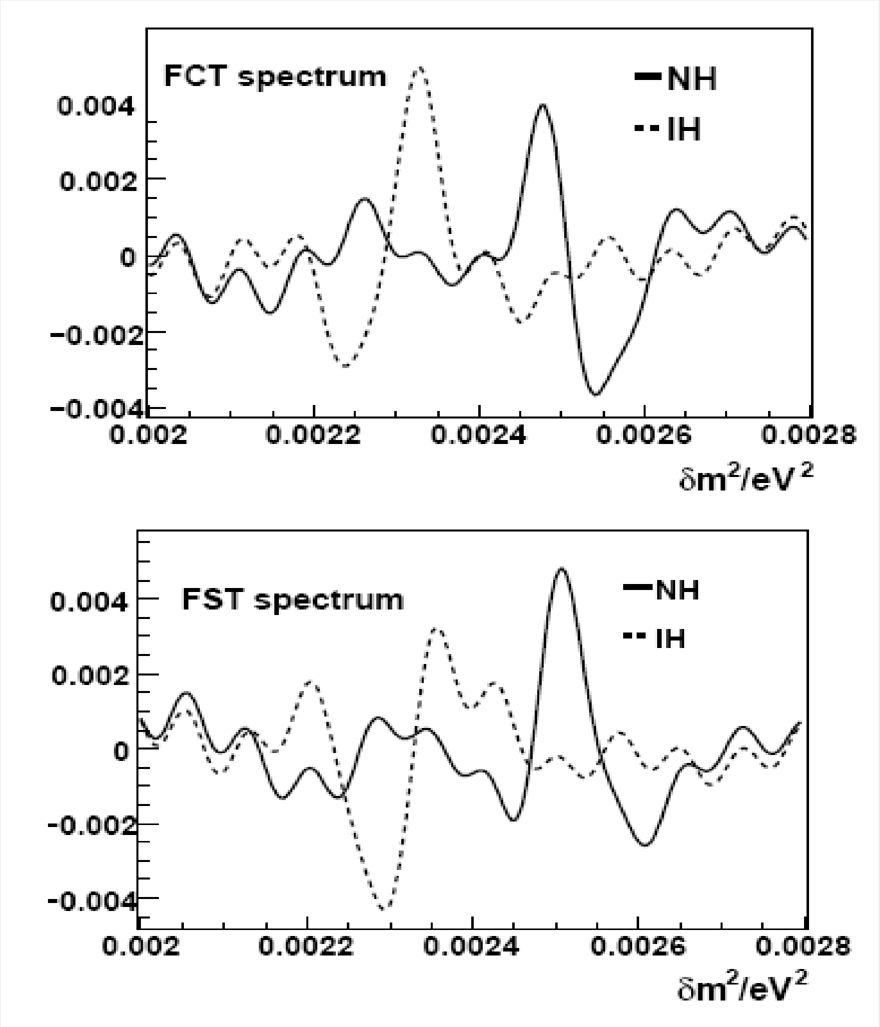
$$e^+ + e^- \to 2\gamma$$

$$\bar{\nu}_e + p \to e^+ + n$$

Capture on H or Gd, Delayed signal, 2.2 or 8 MeV

Spectral information





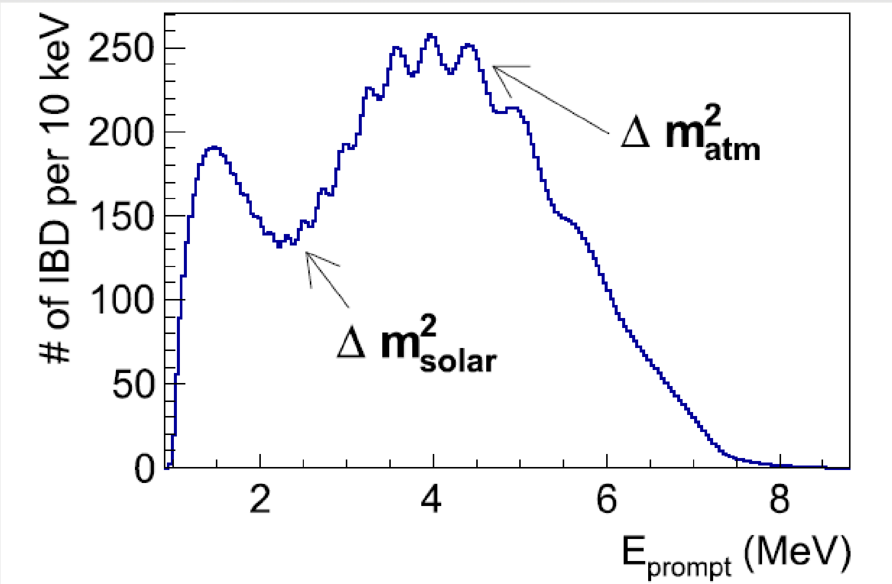
How the interference happens?

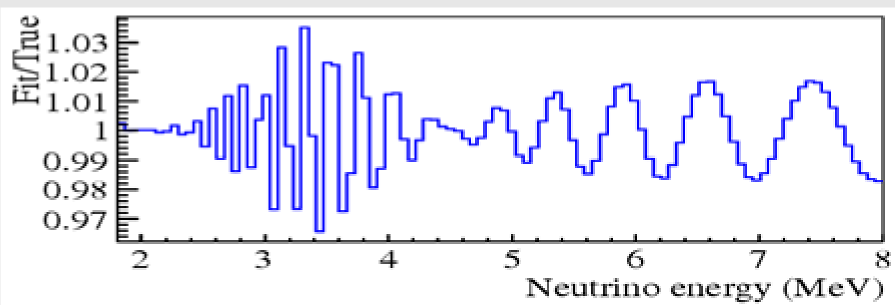
Fourier transform to L/E spectrum:

L/E spectrum←→Δm^2 spectrum(oscillation frequency)

J. Learned *et. al.* hep-ex/0612022
L. Zhan *et. al*. 0807.3203

$\Delta\chi^2$ as the standard statistics





$$\chi^2_{\rm REA} = \sum_{i=1}^{N_{\rm bin}} \frac{\left[M_i - T_i\left(1 + \sum_k \alpha_{ik}\,\epsilon_k\right)\right]^2}{M_i} + \sum_k \frac{\epsilon_k^2}{\sigma_k^2},$$

First, we have the observed spectrum of measurements.

Second, fit the (pseudo-)data with both hypotheses (normal and inverted hierarchies).

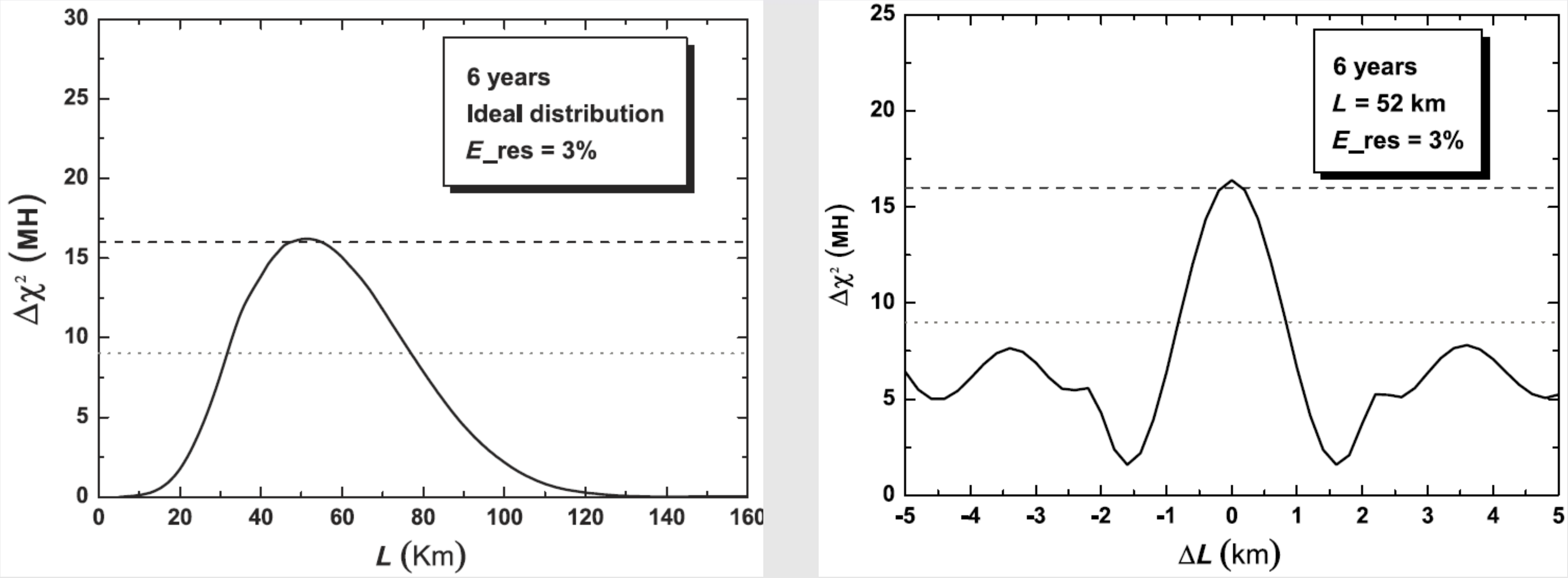
Third, define $\Delta\chi^2$ as our standard statistics.

Finally, use $\Delta\chi^2$ as the discriminator for experimental design and optimization.

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

F. An *et al.* [JUNO Collaboration] JPG 43, 030401 (2016)

Baseline optimization

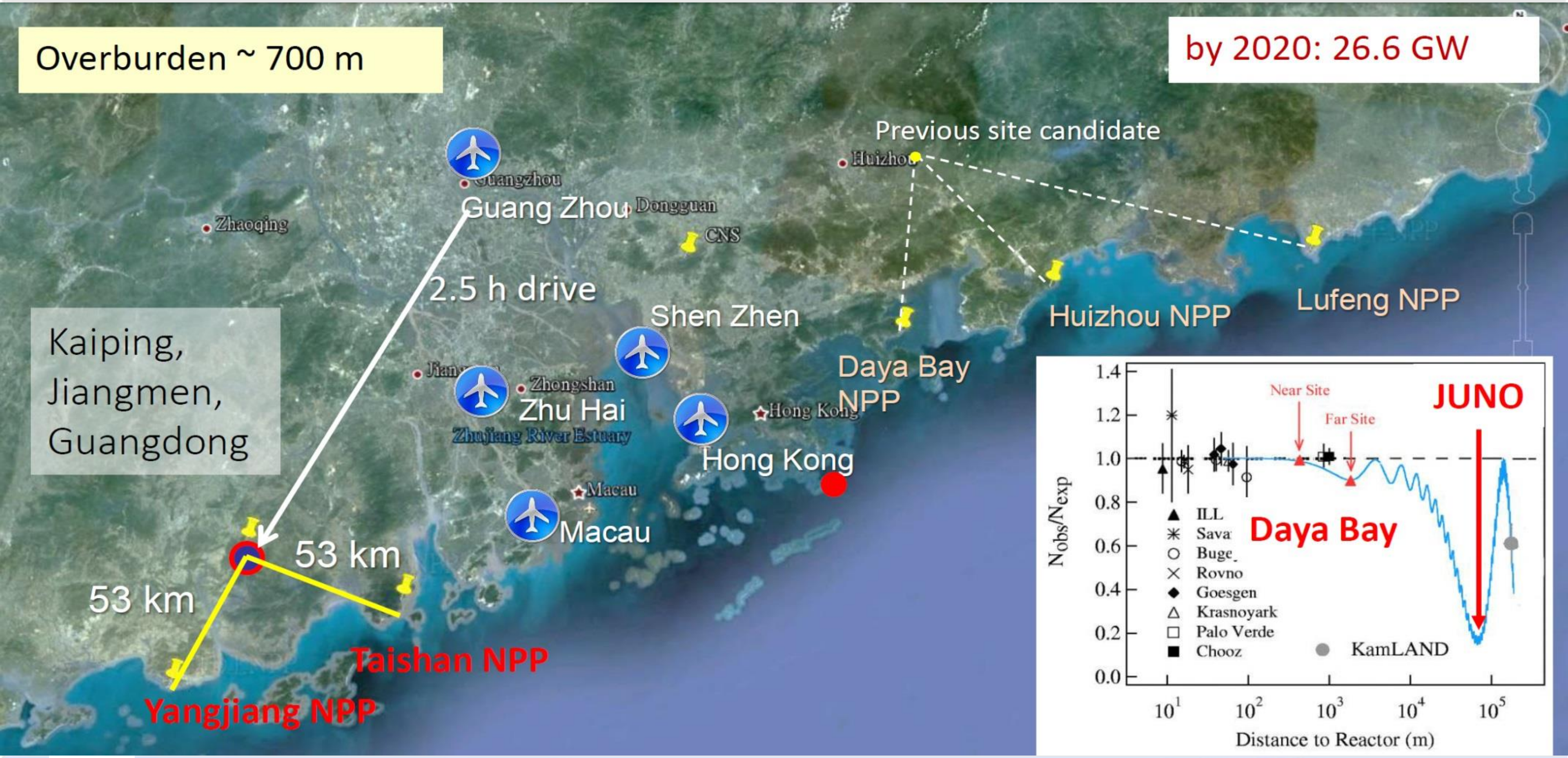


- The optimum baseline is required to be at the oscillation maximum of Δm^2_{21} .
- The control of baseline difference is important to maximize the sensitivity.

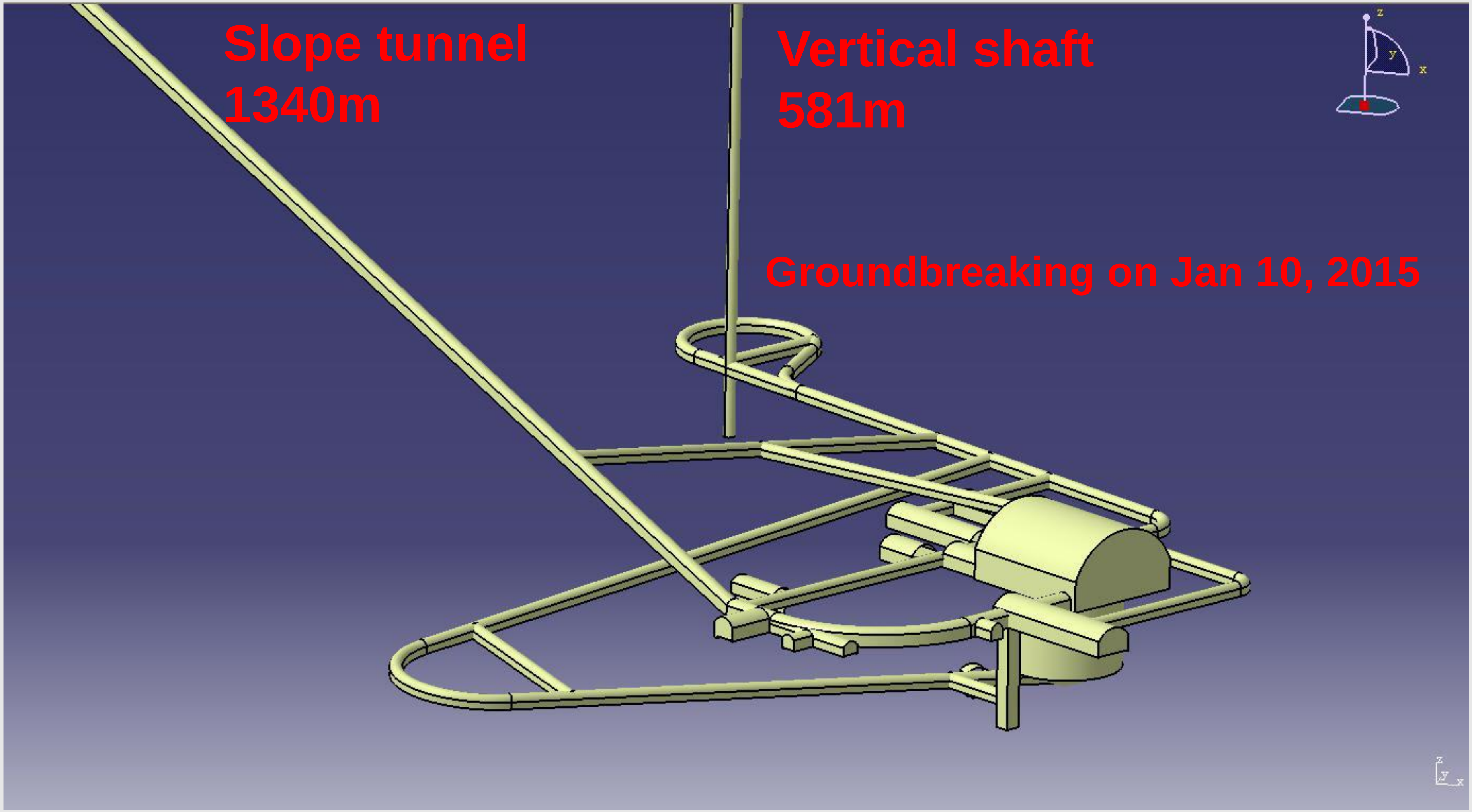
Y.F Li *et al*, PRD 88, 013008 (2013)

Experimental site

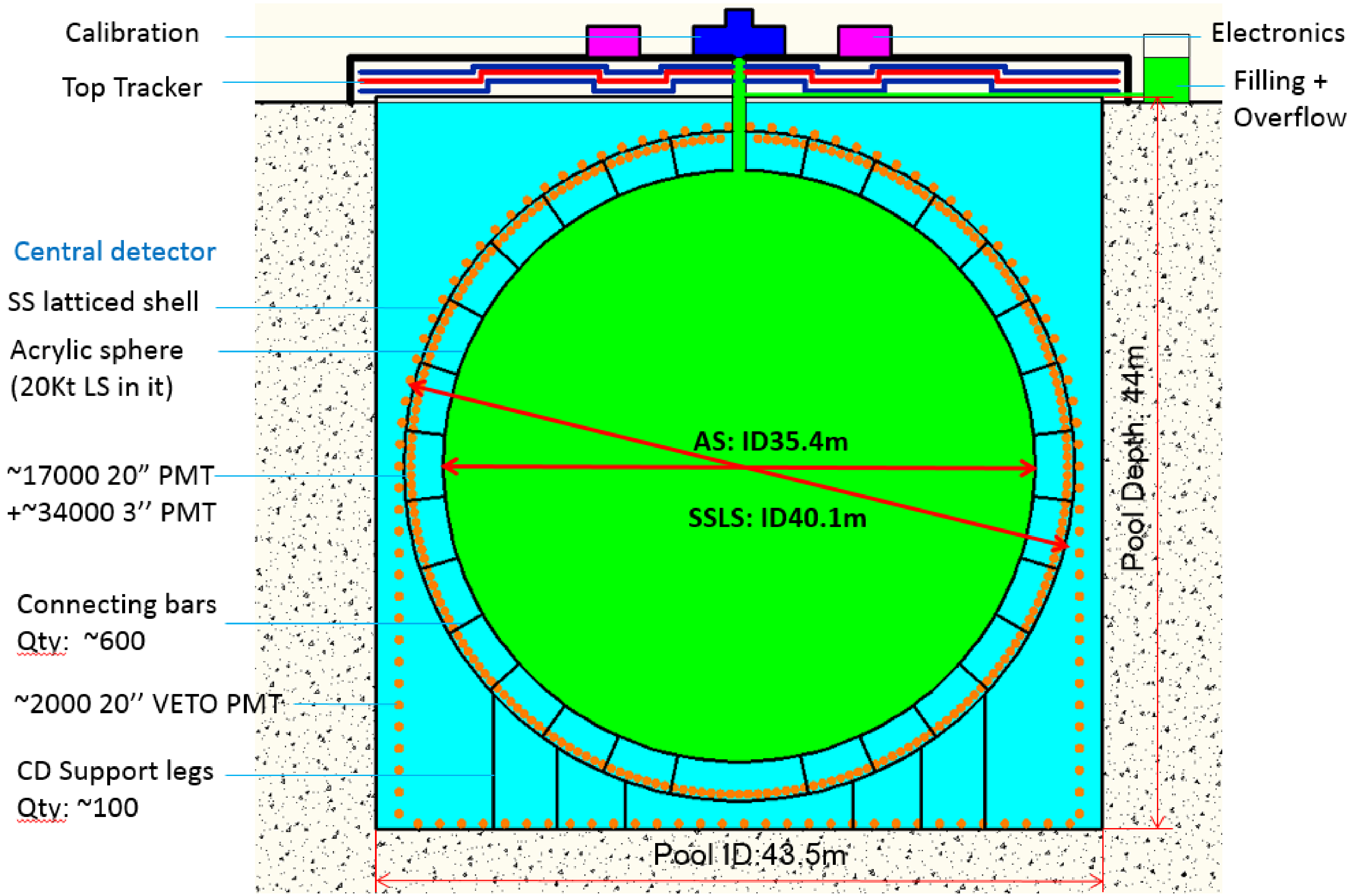
NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW



Go 700 m Underground

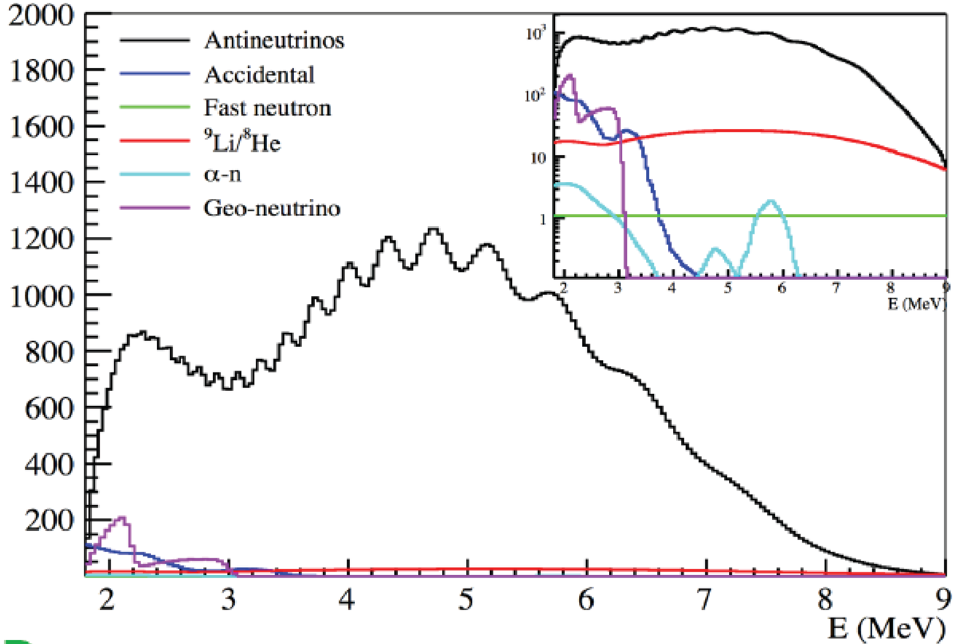


Large and precision Liquid Scintillator detector



AS: Acrylic sphere; SSLS: stainless steel latticed shell

Reactor Signal and backgrounds

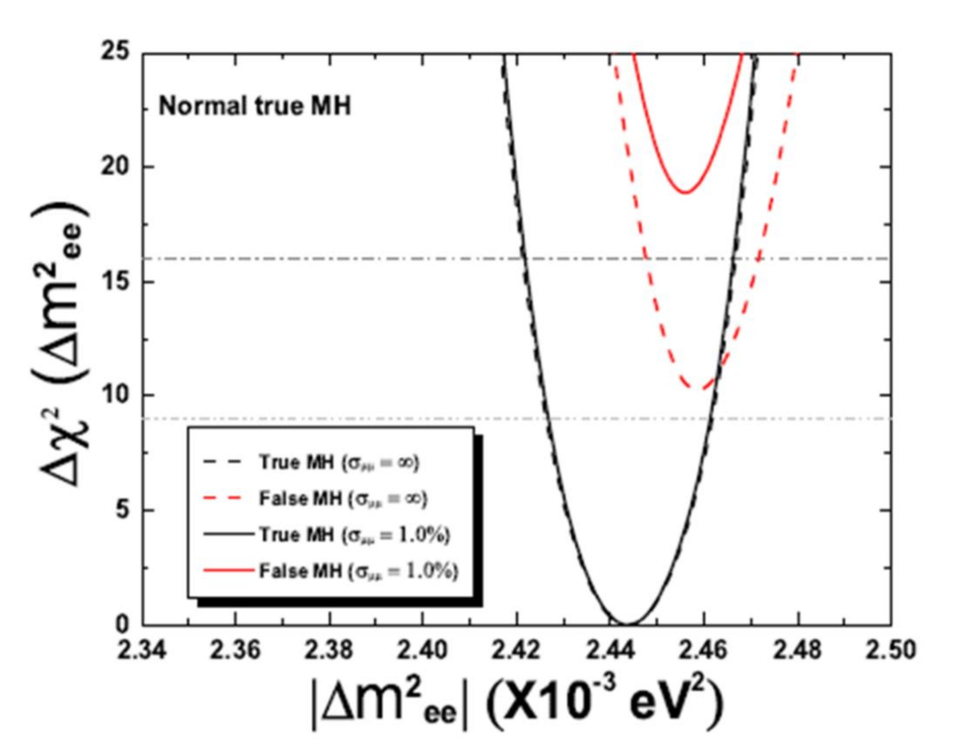


Event Rate per Day

Selection	IBD efficiency	IBD	Geo-νs	Accidental	^{9}Li/^{8}He	Fast n	(α, n)
-	-	83	1.5	$\sim 5.7 \times 10^4$	84	-	-
Fiducial volume	91.8%	76	1.4	410	77	0.1	0.05
Energy cut	97.8%	73	1.3		71		
Time cut	99.1%						
Vertex cut	98.7%			1.1			
Muon veto	83%	60	1.1	0.9	1.6		
Combined	73%	60	3.8				

F. An *et al.* [JUNO Collaboration] JPG 43, 030401 (2016)

Physics Potential



Nominal assumption:

20 kton Liquid Scintillator (LS) detector

3%/sqrt(E) energy resolution

Realistic reactor spreads

36 GW and 6 years

Y.F Li *et al*, PRD 88, 013008 (2013)

Using Asimov data, the MH potential:

$\Delta\chi^2$>10 with the spectral measurement

$\Delta\chi^2$~16 if including an external Δm^2(*atm*) measurement

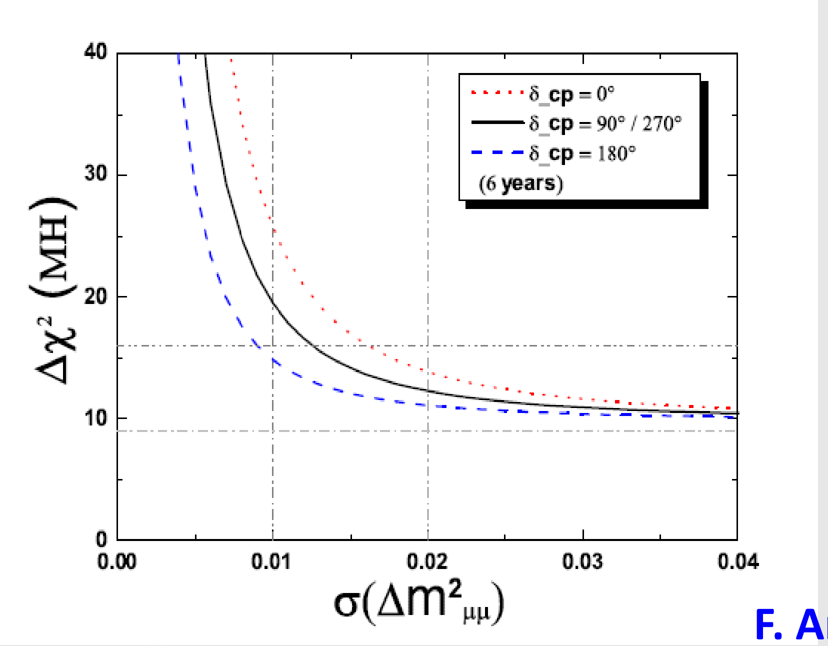
reactor core spreads; reactor flux uncertainty; energy scale uncertainty

Systematics decomposition

	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%
$\Delta\chi^2_{\rm MH}$	+16	−3	−1.7	−1	−0.6	−0.1	+(4 − 12)

Reactor spectrum and detector energy scale uncertainties are crucial.

$$|\Delta m^2_{ee}| - |\Delta m^2_{\mu\mu}| = \pm\Delta m^2_{21}\left(\cos 2\theta_{12} - \sin 2\theta_{12}\sin\theta_{13}\tan\theta_{23}\cos\delta\right)$$



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

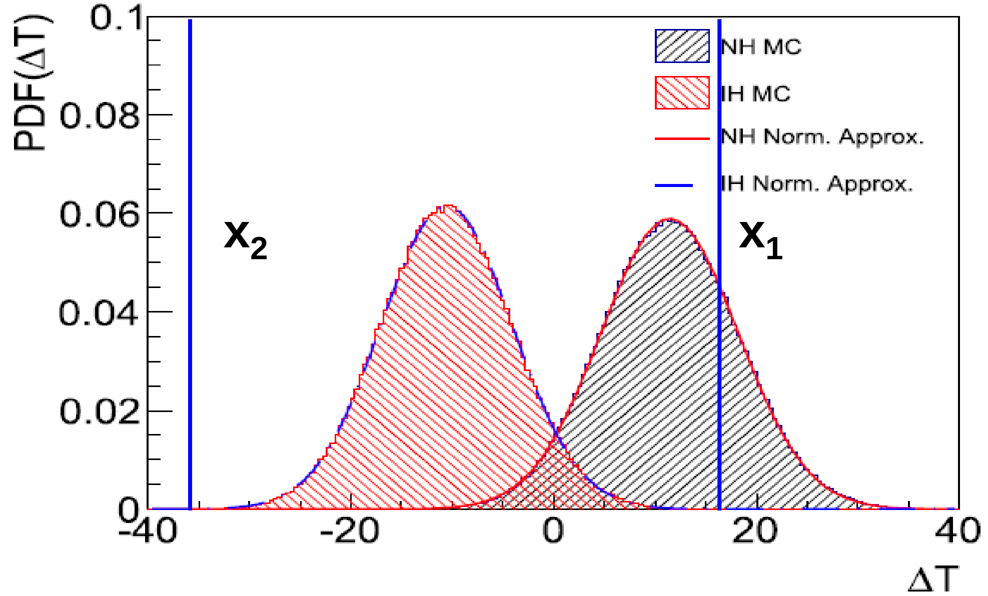
$$\chi^2_{\rm pull}\left(\left|\Delta m^2_{\mu\mu}\right|\right) = \frac{\left(\left|\Delta m^2_{\mu\mu}\right| - \left|\overline{\Delta m^2_{\mu\mu}}\right|\right)^2}{\sigma^2\left(\Delta m^2_{\mu\mu}\right)},$$

Depending on the CP-violating phase, the gain would range from 4 to 12.

F. An *et al.* [JUNO Collaboration] JPG 43, 030401 (2016)

From $\Delta\chi^2$ to the sensitivity

For the MH measurement, there are two different but related questions:
i) given the data from an experiment, how to quantify the finding regarding MH?
ii) when designing an experiment, how to evaluate its sensitivity to MH?



$$\chi^2_{\min}(\mathrm{I}) - \chi^2_{\min}(\mathrm{N}).$$

$$\mathcal{N}\left(\pm\Delta\chi^2_{\mathrm{MH}},\ 2\sqrt{\Delta\chi^2_{\mathrm{MH}}}\right),$$

From JPG 43, 030401 (2016)
See also in:
Qian *et al.* 1210.3651
Ge *et al.* 1210.8141
Ciuffoli *et al.* 1305.5150
Blennow *et al.* 1311.1822

Figure 14. The T distribution function for the JUNO nominal setup of six year running.

Regarding the hypothesis test from PDG:
One has type-I error rate α: probability of rejecting null hypothesis H_0 if H_0 is true.
and type-II error rate β: probability of accepting the null hypothesis H_0 if H_1 is true.

Using α at a fixed β (Frequentist)

One can use α at a fixed β to define the sensitivity of a future experiment:

(1) α(β=0.5): median sensitivity: commonly used in the neutrino MH community, denotes averaged performance of a designed experiment:

50% probability of not reaching it and 50 % probability of doing better, not 50 % probability of "being wrong".

(2) The "standard" sensitivity of taking square root of $\Delta\chi^2$ is very close to the medium sensitivity.

(3) α(β=α): crossing sensitivity

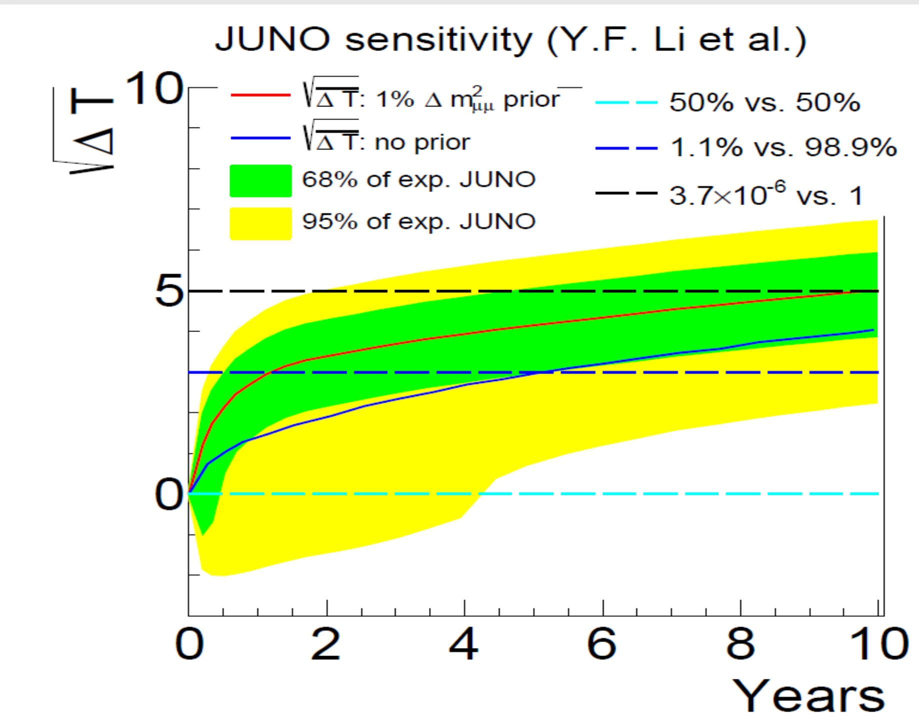
Table 4. The MH sensitivity with the JUNO nominal setup of six year running.

	Median sens.	Standard sens.	Crossing sens.
Normal MH	3.4 σ	3.3 σ	1.9 σ
Inverted MH	3.5 σ	3.4 σ	1.9 σ

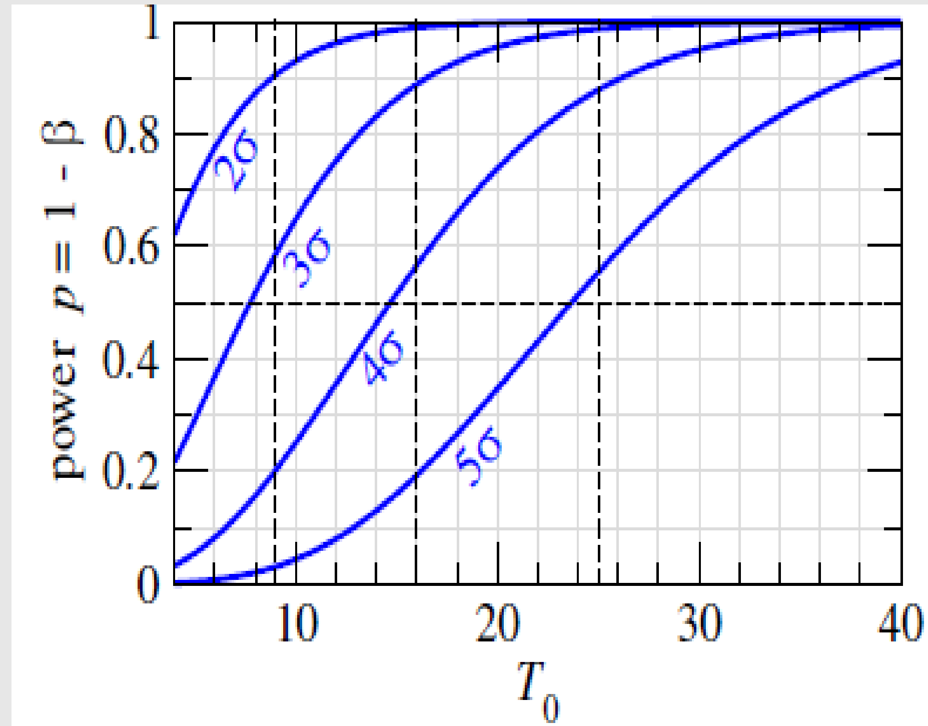
From JPG 43, 030401 (2016)

Beyond the median sensitivity

Instead of quoting a single number at β=0.5, one can
(1) produce a range of possible experimental outcomes;
or
(2) calculate power of the test β as a function T_0 at fixed α.



From JPG 43, 030401 (2016)



Blennow *et al. 1311.1822*

JUNO: A Multi-purpose Observatory

J. Phys. G: Nucl. Part. Phys. 43 030401 (2016) (188pp)

Neutrino Physics with JUNO

arXiv:1507.05613v1

Abstract

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.

a) Reactor antineutrino physics:

Mass hierarchy, precision measurement, search for new physics

b) Astrophysical neutrinos:

supernova burst neutrinos, DSNB, solar neutrinos, geo-neutrinos

c) Search for High energy events:

atmospheric neutrinos, nucleon decays, indirect dark matter search

Reactor antineutrino probes

	Δm^2_{21}	$\lvert\Delta m^2_{31}\rvert$	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$
Dominant Exps.	KamLAND	MINOS	SNO	Daya Bay	SK/T2K
Individual 1σ	2.7% [20]	4.1% [25]	6.7% [6]	10% [21]	14% [23, 24]
Global 1σ	2.6%	2.7%	4.1%	8.6%	11%

	Nominal	+shape(1%)	+BG	+1.0% (EL)	+1.0% NL
$\sin^2\theta_{12}$	0.54%	0.60%	0.62%	0.64%	0.67%
Δm^2_{21}	0.24%	0.27%	0.29%	0.44%	0.59%
$\lvert\Delta m^2_{31}\rvert$	0.27%	0.31%	0.31%	0.35%	0.44%

From JPG 43, 030401 (2016)

New Physics test in low-energy oscillation phenomena:

light sterile neutrinos 1405.6540

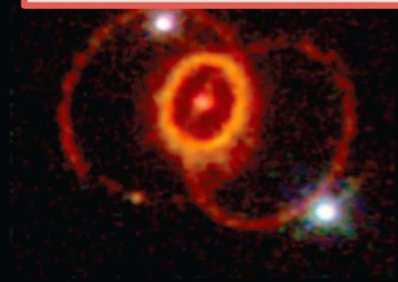
nonstandard neutrino interactions 1310.5917, 1408.6301

Lorentz and CPT violation 1409.6970

Observatory of astrophysical neutrinos

Indirect DM search
→ discover DM or extend excluded parameter space

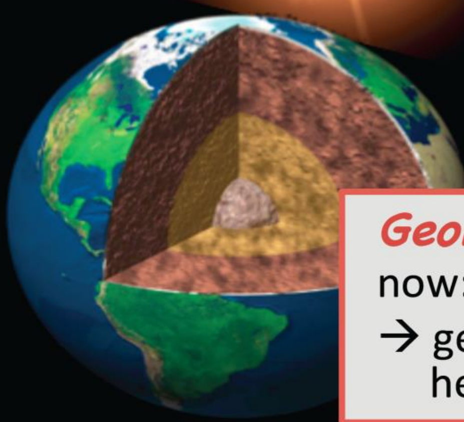
Supernova neutrinos
ν burst established
→ extract information on core-collapse and neutron star formation



galactic
cosmic

Solar neutrinos
pp-chain measured
→ CNO neutrino flux
→ study solar interior

Observation Range
<1 to 50 MeV

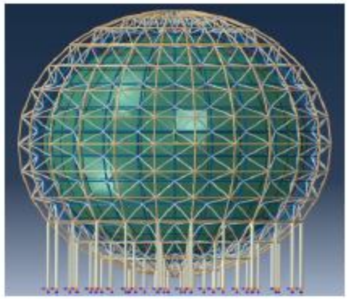


Diffuse SN neutrinos
still unobserved
→ discovery, z-dep. SN rate and average spectrum

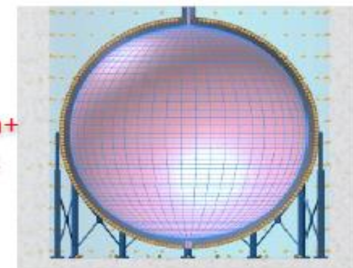
Geoneutrinos
now: 4σ observation
→ geology: radiogenic heat, U/Th conc.

CD Option Selection

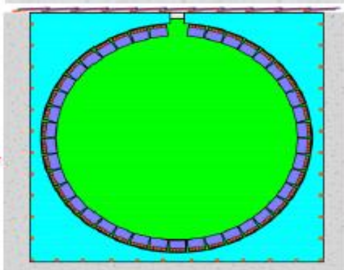
Acrylic sphere+ SS truss



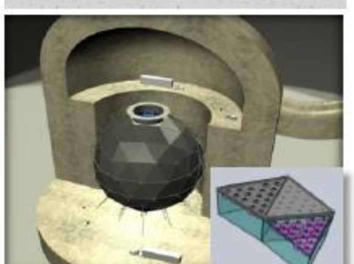
Balloon+ SS tank



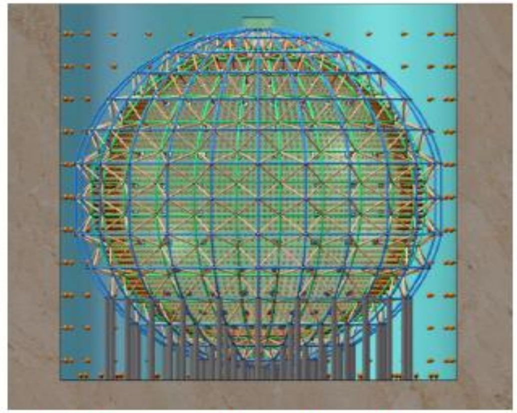
Acrylic module+ SS tank



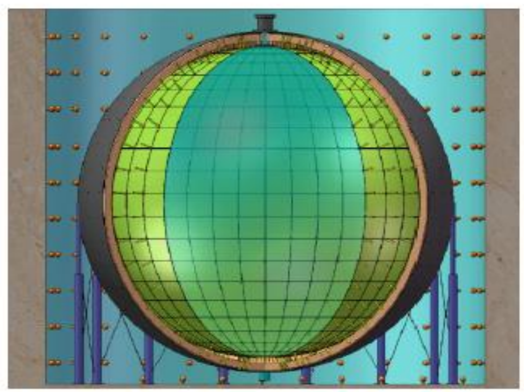
Acrylic sphere+ SS tank



March, 2014 →



SS truss+ Acrylic sphere



Balloon + Acrylic support+ SS tank

July, 2015 →

Final decision:
Acrylic sphere + SS truss

20-inch MCP-PMT

Large PMTs: 20", 78% coverage - 30% quantum efficiency at 420 nm

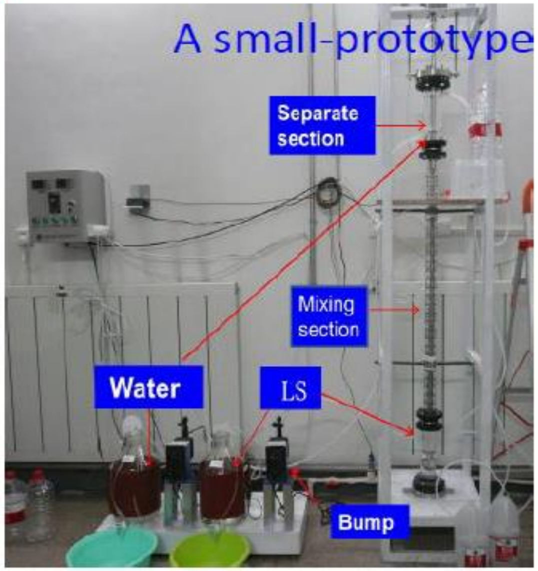
Meant for Calorimetry

2 different producers: NNVC (China) 15000 units & Hamamatsu (Japan) 5000 units

Characteristics	unit	MCP PMT (NNCV - IHEP)	R12860 (Hamamatsu)	Note
Electron Multiplier		Micro Channel Plate	Dynode	
Photocathode Mode		Reflection + Transmission	Transmission	
Quantum Efficiency (400nm)	%	26(T), 30 (T+R)	30 (T)	En Resolution
Relative Detection Efficiency	%	110	100	En Resolution
Single Photo-electron P/V		3+	3+	Reconstruction
Transient Time Spread	ns	12	3	Vertex
Rise Time / Fall Time	ns	R~2, F~10	R~7, F~17	
Anode Dark Count	Hz	~30 k	~30 k	Trigger
After Pulse Time Distribution	µs	4.5	4, 17	
After Pulse Rate	%	3	10	
Glass		Low-Potassium Glass	Hario-32	Background

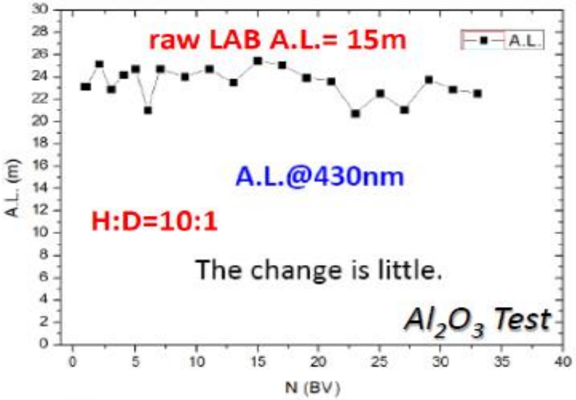
Liquid Scintillator

- ***LAB+PPO+bisMSB (no Gd-loading)***
- **Increase light yield**
  - **Optimization of fluors concentration**
- **Increase transparency**
  - **Good raw solvent LAB**
  - **Online handling/purification**
    - **Distillation, Filtration, Water extraction, Nitrogen stripping, ... To be tested with Daya Bay detector**
- **Reduce radioactivity**
  - **No Gd, Less risk. Singles<~3Hz (>0.7MeV), with U/Th <10^{-15} g/g, ^{40}K< 10^{-16} g/g**



water extraction


Al_2O_3 column



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	24~25 m

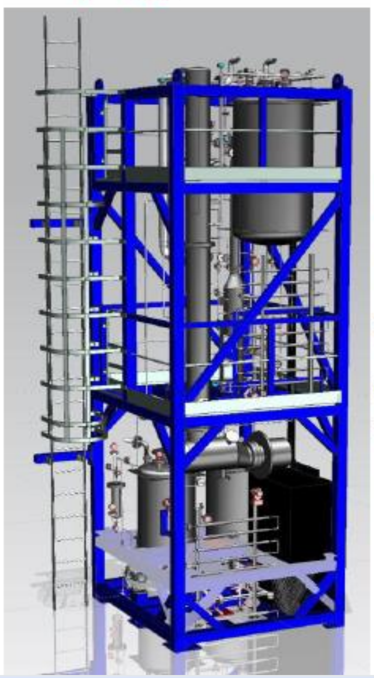
JUNO-LS Pilot plant

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

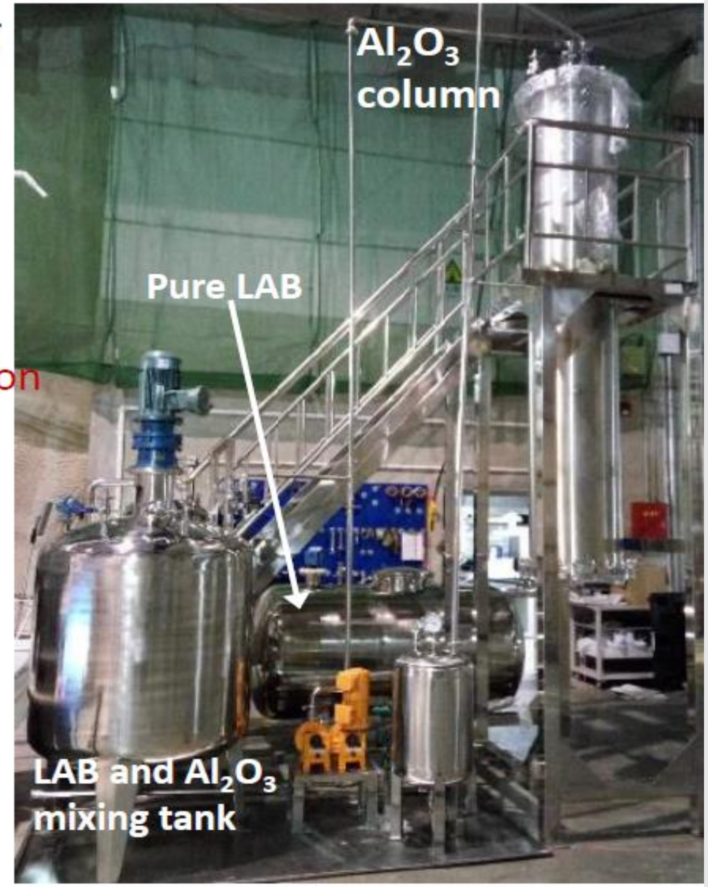
Distillation and steam stripping system (by Italian group).

Be transported to Daya Bay at Apr/May

Distillation system



Steam stripping system



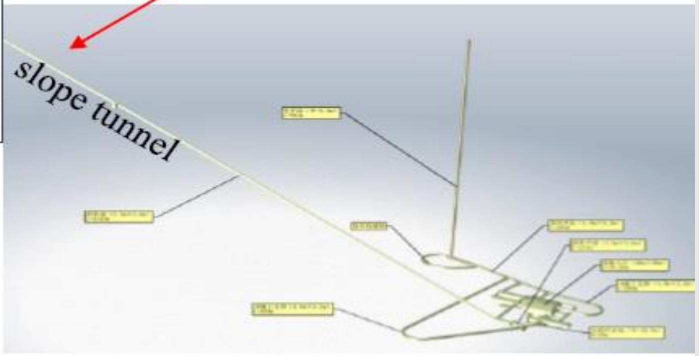
Al_2O_3 column pilot plant installed in Daya Bay LS hall

Progress and Schedule

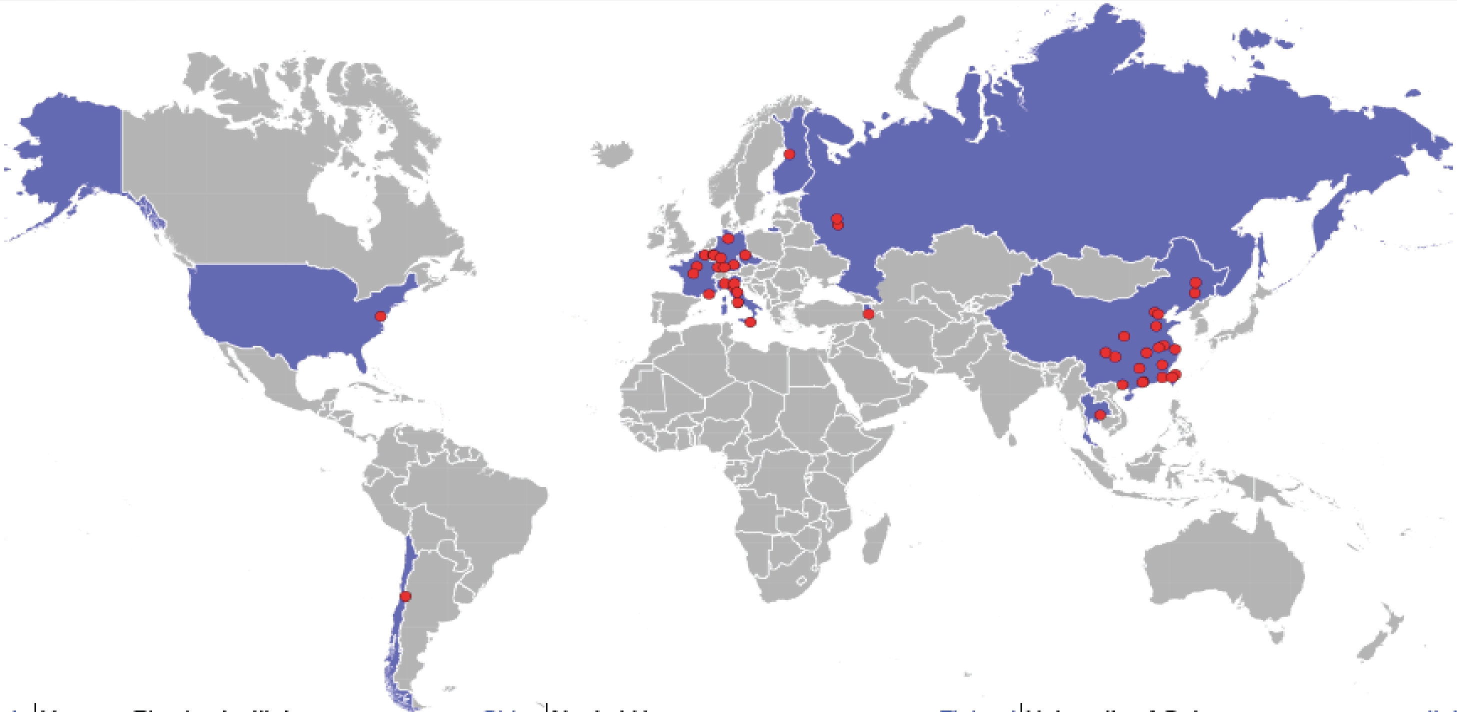
Decided Central Detector Scheme: 2015.07
Finished PMT bidding: 2015.12 (production: 2016-2019)

Finish the engineering design of detector structure: 2016.07
Bidding for acrylic production: end of 2016

Civil construction: 2015-2017
Detector component production: 2016-2017
Build detector onsite: 2018-2019
PMT installation, Veto, cleaning, filling : 2019-2020
Data taking: 2020



Collaboration Established (in 2014.7)



Armenia	Yerevan Physics Institute
Belgium	Université libre de Bruxelles
Chile	PCUC
China	BISEE
China	Beijing Normal U.
China	CAGS
China	ChongQing University
China	CIAE
China	DGUT
China	ECUST
China	Guangxi U.
China	Harbin Institute of Technology
China	IHEP
China	Jilin U.
China	Jinan U.
China	Nanjing U.
China	Nankai U.
China	NCEPU
China	Pekin U.
China	Shandong U.
China	Shanghai JT U.
China	Sichuan U.
China	SYSU
China	Tsinghua U.
China	UCAS
China	USTC
China	U. of South China
China	Wu Yi U.
China	Wuhan U.
China	Xi'an JT U.
China	Xiamen University
Czech	R. Charles U. Prague
Finland	University of Oulu
France	APC Paris
France	CPPM Marseille
France	IPHC Strasbourg
France	LLR Palaiseau
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Germany	IKP FZ Jülich
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Italy	INFN-Milano Bicocca
Italy	INFN-Padova
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Italy	INFN-Roma 3
Russia	INR Moscow
Russia	JINR
Russia	MSU
Taiwan	National Chiao-Tung U.
Taiwan	National Taiwan U.
Taiwan	National United U.
Thailand	SUT
USA	UMD1
USA	UMD2

Summary

- JUNO was approved in Feb. 2013 w/ ~300 M$ budget
- Very rich physics possibilities
- Preparation proceeds very well
  - Detector R&D;
  - Groundbreaking on Jan.10, 2015. Civil construction will be completed in 3 years.
- A strong international collaboration formed

Welcome to JUNO
@Kaiping, Jiangmen

Thanks

Backup

JUNO nominal setup

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

Table 1: Summary of the power and baseline distribution for the Yangjiang (YJ) and Taishan (TS) reactor complexes, as well as the remote reactors of Daya Bay (DYB) and Huizhou (HZ). **Y.F Li *et al*, PRD 88, 013008 (2013)**

- **3%/sqrt(E), 300 effective days times 6 years, 80% efficiency**
- **both old and new evaluations of v_bar flux spectrum.**
- **Oscillation parameters: recent best-fits**
- **Systematics:**

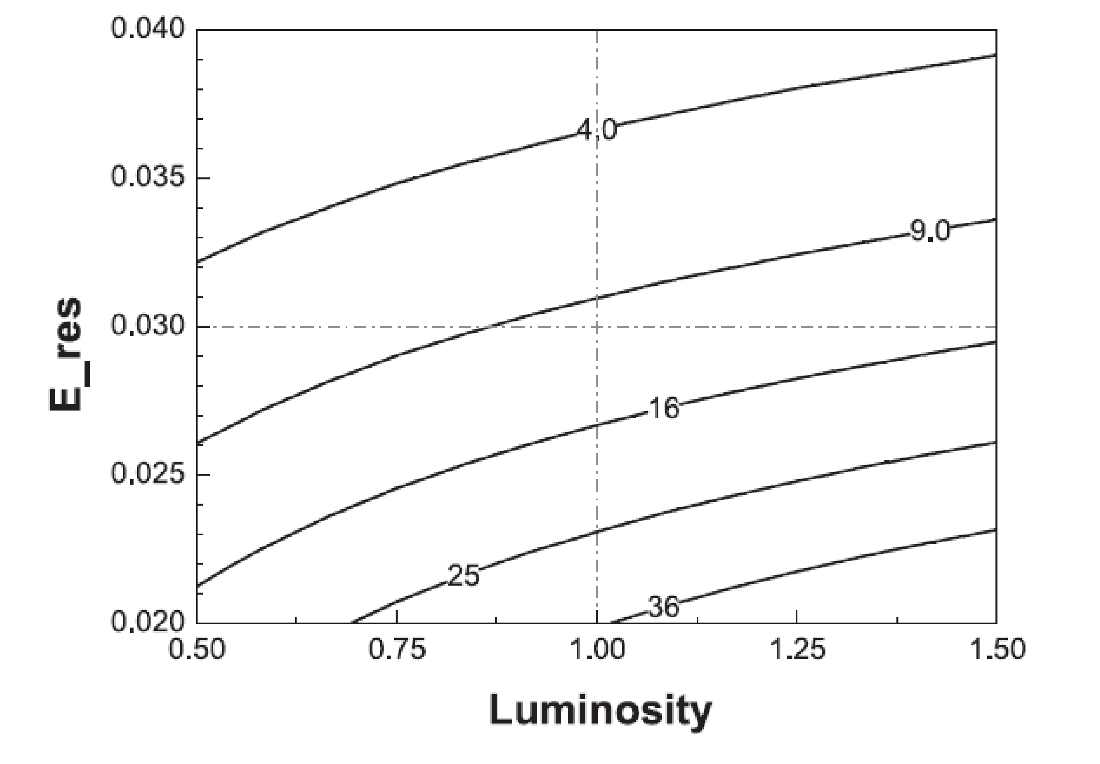
include the correlated (absolute) reactor uncertainty (2%), the uncorrelated (relative) reactor uncertainty (0.8%), the flux spectrum uncertainty (1%) and the detector-related uncertainty (1%). We use 200 equal-size bins for the incoming neutrino energy between 1.8 MeV and 8.0 MeV.

Energy resolution

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

$$\sqrt{(a)^2 + (1.6 \times b)^2 + \left(\frac{c}{1.6}\right)^2} \leqslant 3\%.$$

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



a generic function of the energy resolution

b term is critical.

Iso-$\Delta\chi^2$ curves for the resolution and event statistics (normalized to 6 years of running).

From JPG 43, 030401 (2016)

Bayesian Statistics

Frequenstist method treats two different hypotheses separately.

Bayesian Approach provides a direct comparison of two MHs.

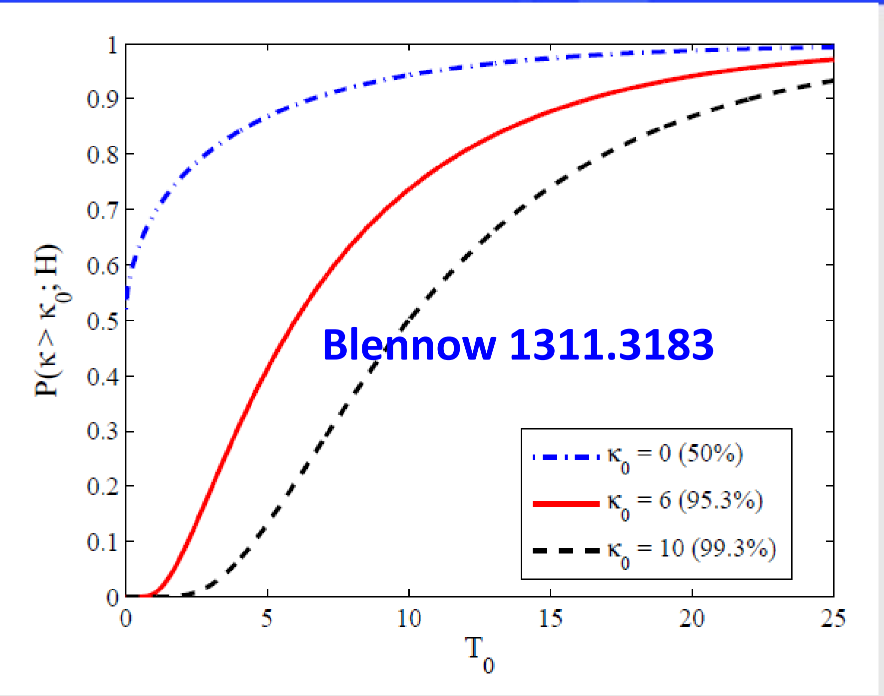


Table 5. Probability ratios with respect to several typical $\Delta\chi^2_{\rm MH}$ values.

$\Delta\tau \approx \Delta\chi^2_{\rm MH}$	1	4	9	16	25
p(IH|D, I) versus p(NH|D, I)	38% versus 62%	12% versus 88%	1.1% versus 98.9%	0.034% versus 99.966%	3.7×10^{-6} versus 100%
p(IH|D, I)/p(NH|D, I)	0.61	0.136	0.011	3.4×10^{-4}	3.7×10^{-6}

From JPG 43, 030401 (2016)

Supernova burst neutrinos

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
$\nu + {}^{12}\mathrm{C} \rightarrow \nu + {}^{12}\mathrm{C}^*$	NC	1.7×10^2	3.2×10^2	5.2×10^2
$\nu_e + {}^{12}\mathrm{C} \rightarrow e^- + {}^{12}\mathrm{N}$	CC	4.7×10^1	9.4×10^1	1.6×10^2
$\overline{\nu}_e + {}^{12}\mathrm{C} \rightarrow e^+ + {}^{12}\mathrm{B}$	CC	6.0×10^1	1.1×10^2	1.6×10^2

- **For a SN@10 kpc, JUNO will register about ~5000 events from inverse beta decay (IBD), ~2000 events from all-flavor elastic neutrino-proton scattering (>0.2 MeV).**

High statistics, different flavors, good energy resolution

- **particle physics:**

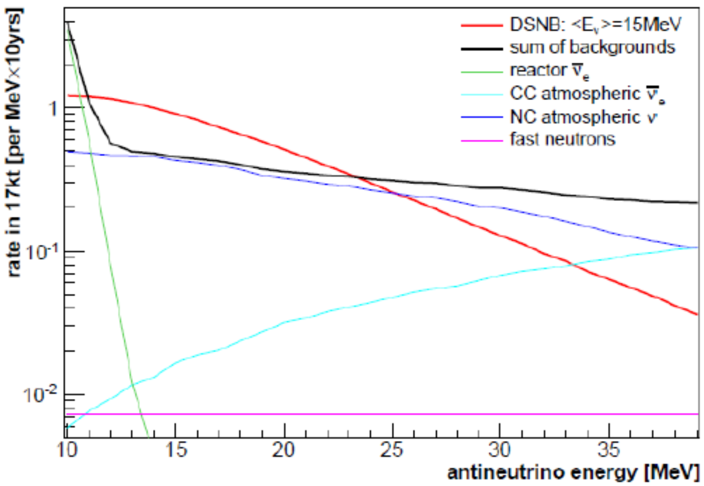
a) neutrino mass scale: 0.8 eV@95% C.L. [10 kpc] ***(arXiv: 1412.7418)***

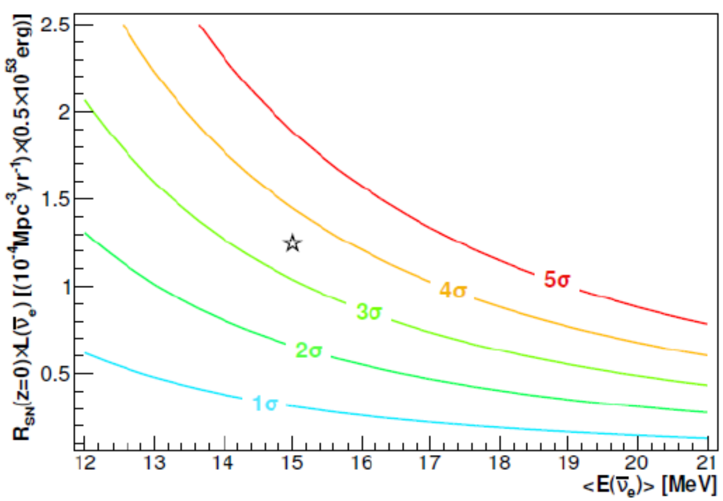
- **astrophysics:**

b) precision of SN parameters (luminosity & ave. energy):

nu_e_bar: 1%, nu_x: 5%, nu_e: 10% ***(arXiv: 1605.07803)***

Diffuse Supernova Neutrino Background





From JPG 43, 030401 (2016)

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

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

10 Years' sensitivity

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

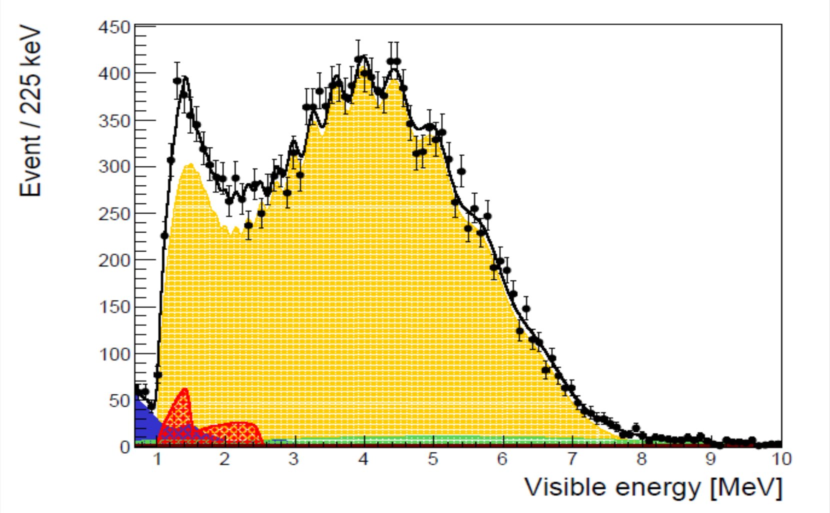
Geo-neutrinos

(1) Current measurements: statistics dominates

KamLAND: 30±7 TNU & Borexino: 38.8±12.2 TNU

(2) JUNO: 40 TNU, with ×20 statistics, but huge reactor backgrounds From JPG 43, 030401 (2016)

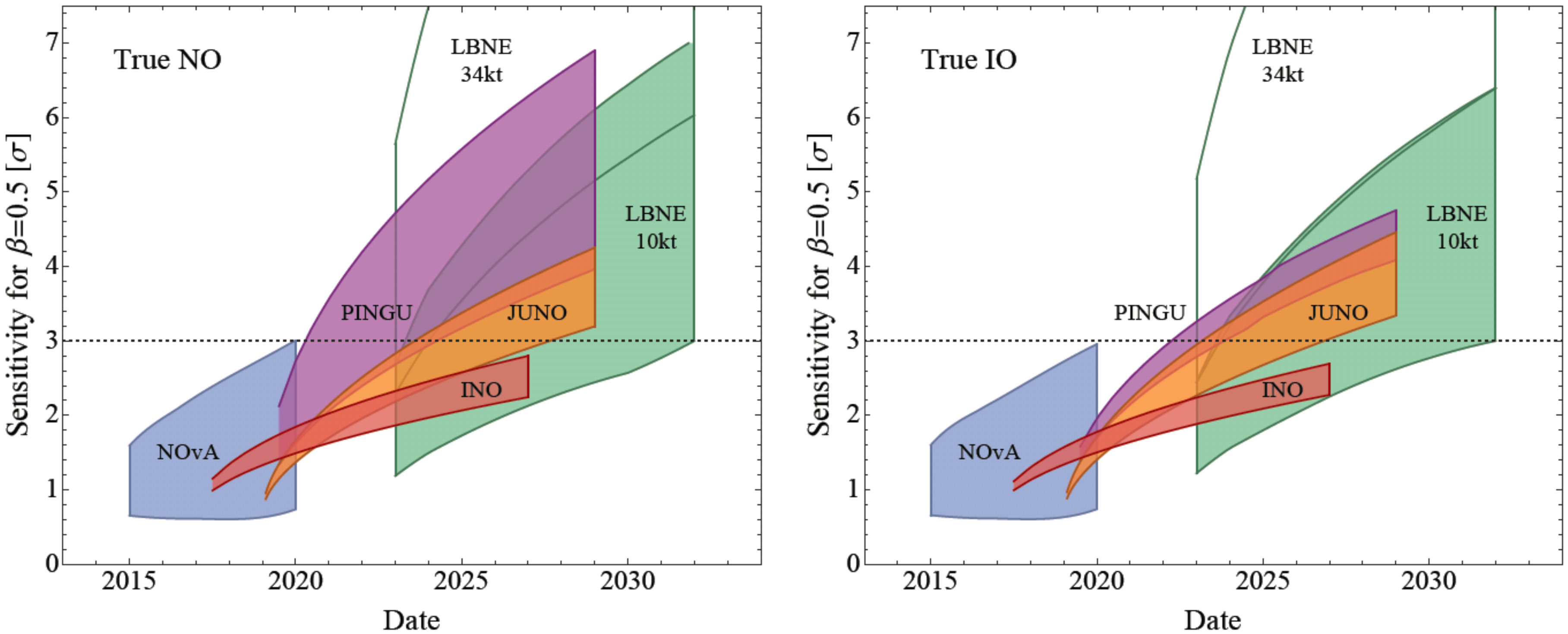
Source	Events/year
Geoneutrinos	408 ± 60
U chain	311 ± 55
Th chain	92 ± 37
Reactors	16100 ± 900
Fast neutrons	36.5 ± 36.5
^{9}Li - ^{8}He	657 ± 130
$^{13}C(\alpha, n)^{16}O$	18.2 ± 9.1
Accidental coincidences	401 ± 4



(3) accurate reactor spectra: a precision of 3 TNU (10 years) to test geophysical models.

(4) accurate local crust geology study: separate the mantle signals

MH global comparison

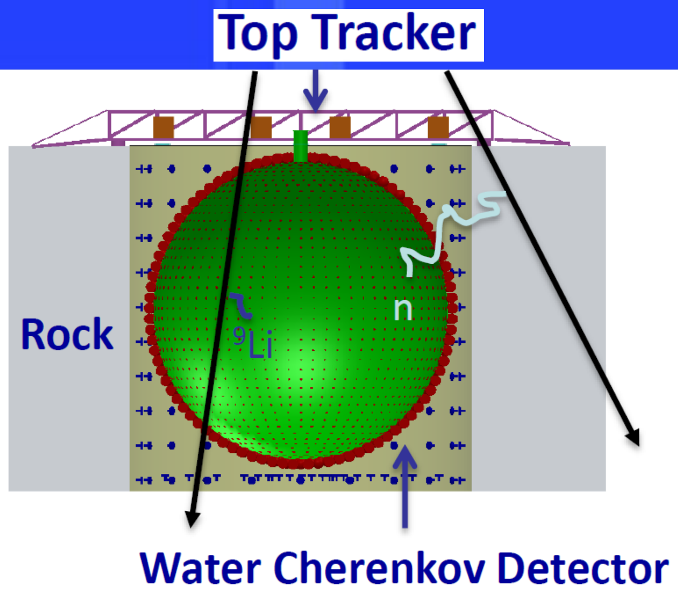


Blennow et al. 1311.1822

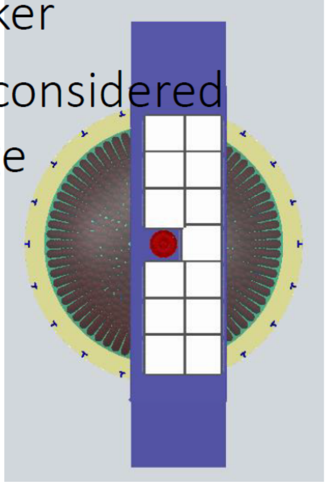
Note: Bands have different meanings:

JUNO: Energy resolution 3%-3.5%, PINGU/INO: theta(23) 40º~50º
LBNE: CP phase (0~2π)

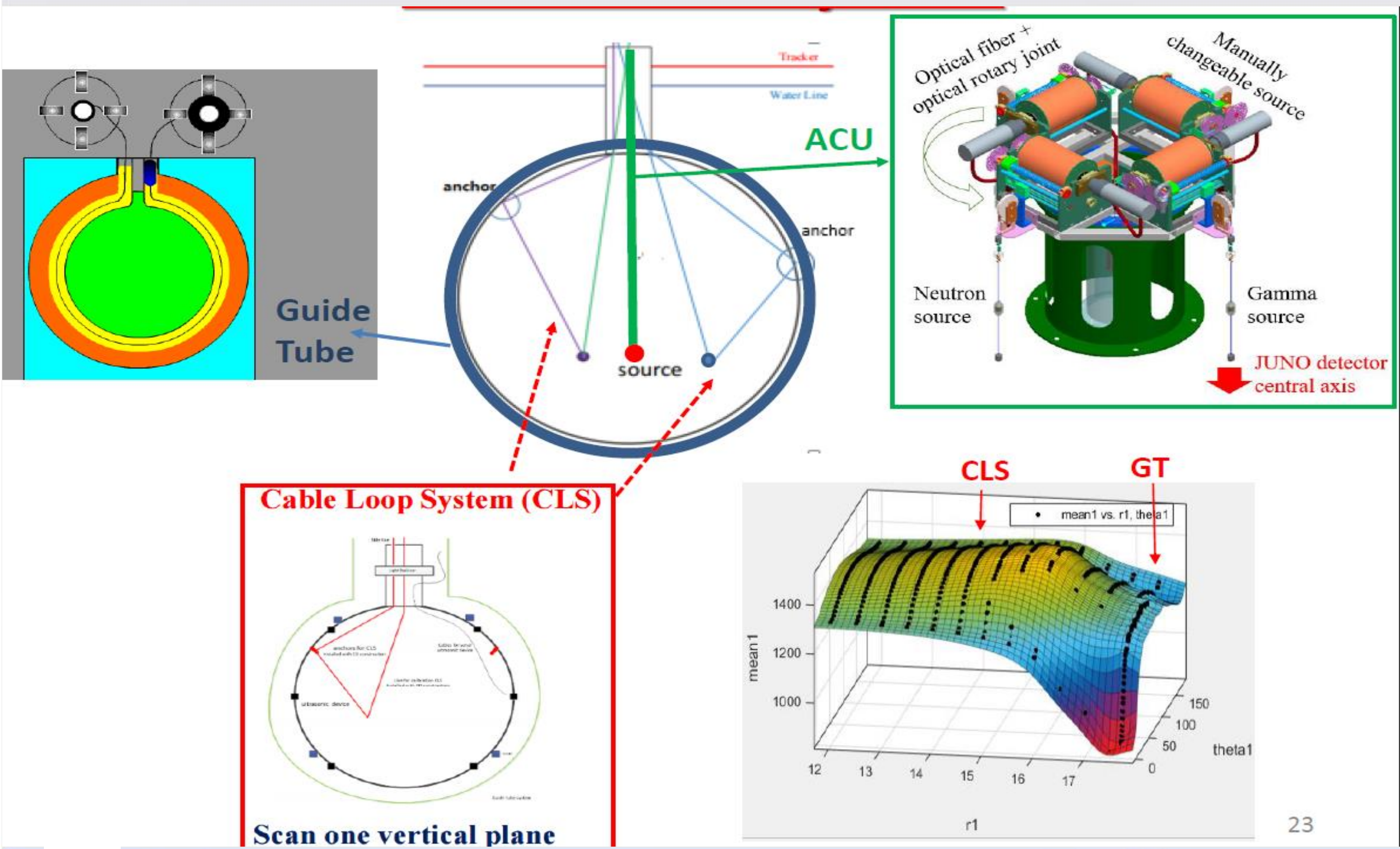
Veto system



- Goals of veto
  - Cosmogenic isotopes rejection
  - Neutron background rejection
  - Gamma background passive shielding
  - …
- Water cherenkov detector
  - ~1500 20” PMT
  - 20~30 kton ultrapure water with a circulation system
  - Earth magnetic field shielding
  - Tyvek reflector film
  - PMT support frame
  - Water pool sealing
- Top tracker
  - Use OPERA Target Tracker
  - Additional options are considered to increase the coverage

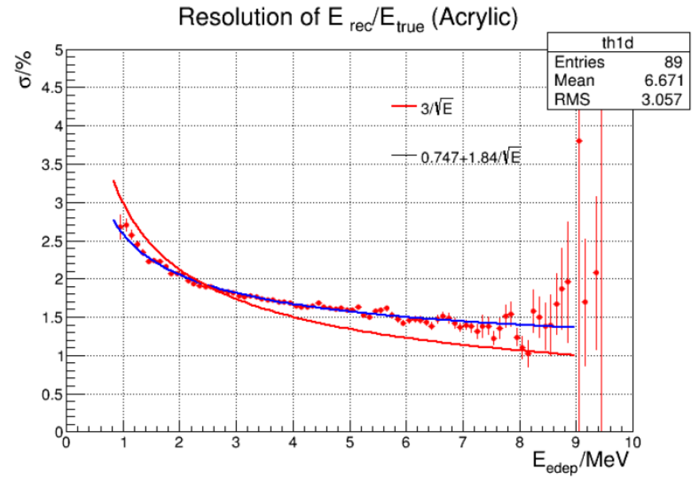


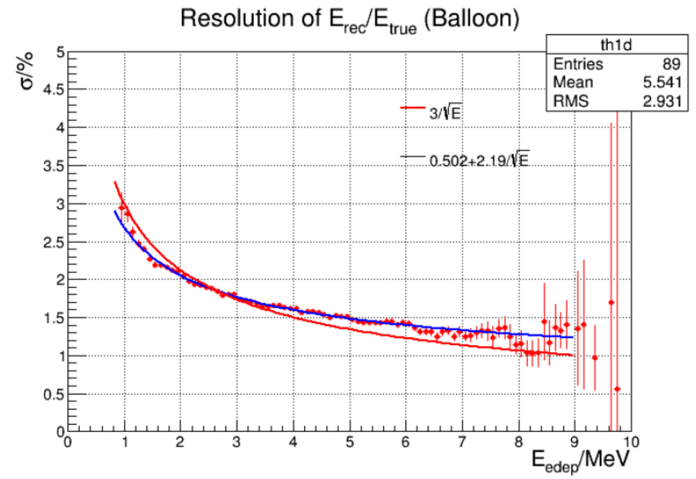
Calibration system



MC studies

- Optical model
  - Based on DYB (tuned to data), except:
  - **PMT QE:** 25%→ 35%
  - **LS light yield:** 10400 photons/MeV
  - **LS attenuation length:** 20 m @430 nm
    - **Absorption** 60m
    - **Rayleigh scattering** 30 m
- Detector performance studies
  - Vertex and energy resolution: σ_E/E~3%@1MeV
  - Effect of steel struts, PMT proof, film transparency, dark noise …
  - Buffer thickness: reduce PMT background
  - Optimize fiducial volume
  - Muon efficiency in water pool: 99.5%





Energy resolution of two detector options: similar performances

Civil construction