The JUNO Experiment: *Jiangmen Underground Neutrino Observatory (JUNO)*

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On behalf of the JUNO collaboration

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2nd International Workshop on Particle Physics and Cosmology after Higgs and Planck

Outline

(1) Physics motivations

a) Neutrino mass hierarchy

b) Precision measurement of parameters

c) Search for New Physics

d) Observatory of astrophysical neutrino sources

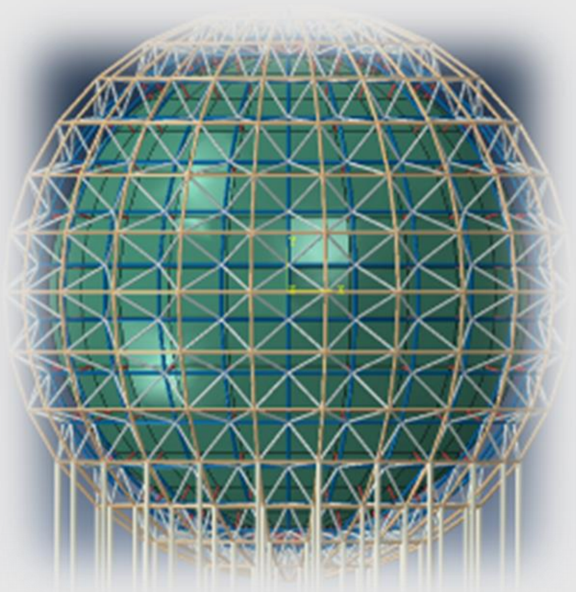
(2) Project status

a) Experimental site

b) R&D program

c) Collaboration

d) Schedule



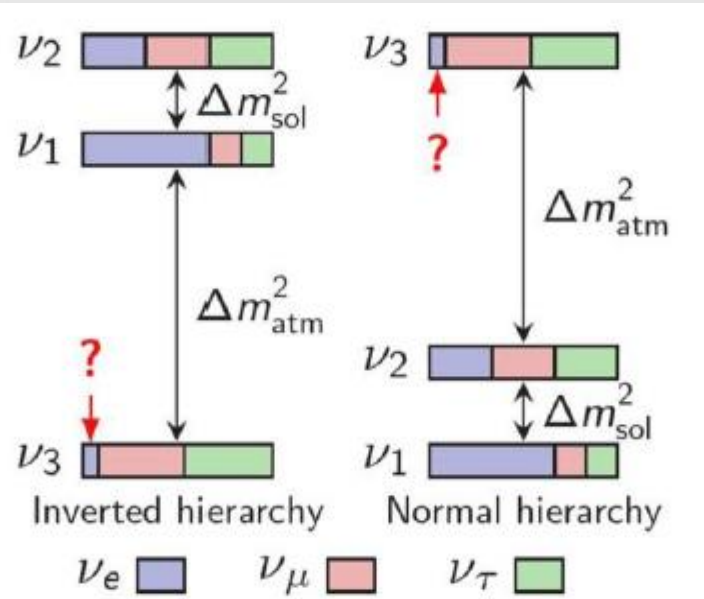
Current status

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

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

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

$\theta_{23} \approx (45\pm9)^\circ$ $\theta_{13} \approx (8.9\pm1.4)^\circ$, δ_{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

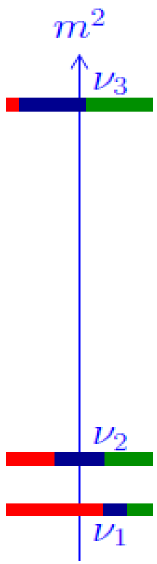
- $\nu_e \leftrightarrows \nu_\mu$ MSW resonance: $V = \dfrac{\Delta m^2_{13} \cos 2\vartheta_{13}}{2E} \Leftrightarrow \Delta m^2_{13} > 0$ NH
- $\bar{\nu}_e \leftrightarrows \bar{\nu}_\mu$ MSW resonance: $V = -\dfrac{\Delta m^2_{13} \cos 2\vartheta_{13}}{2E} \Leftrightarrow \Delta m^2_{13} < 0$ IH

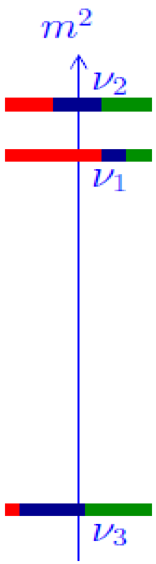
Vacuum oscillation: reactor neutrinos S. T. Petcov *et al.*, PLB 533, 94 (2002)

Normal Hierarchy

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

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



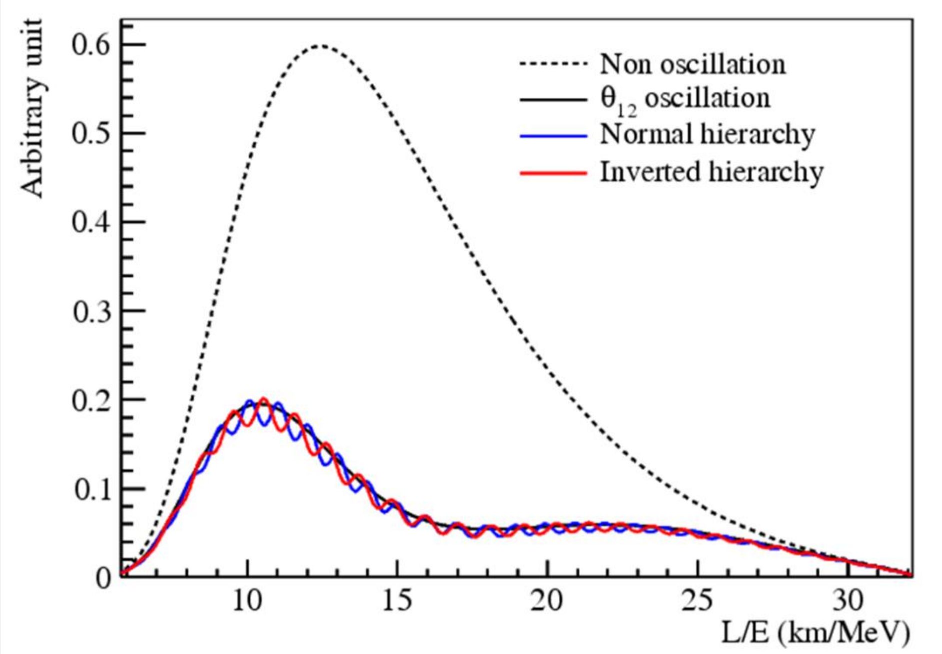


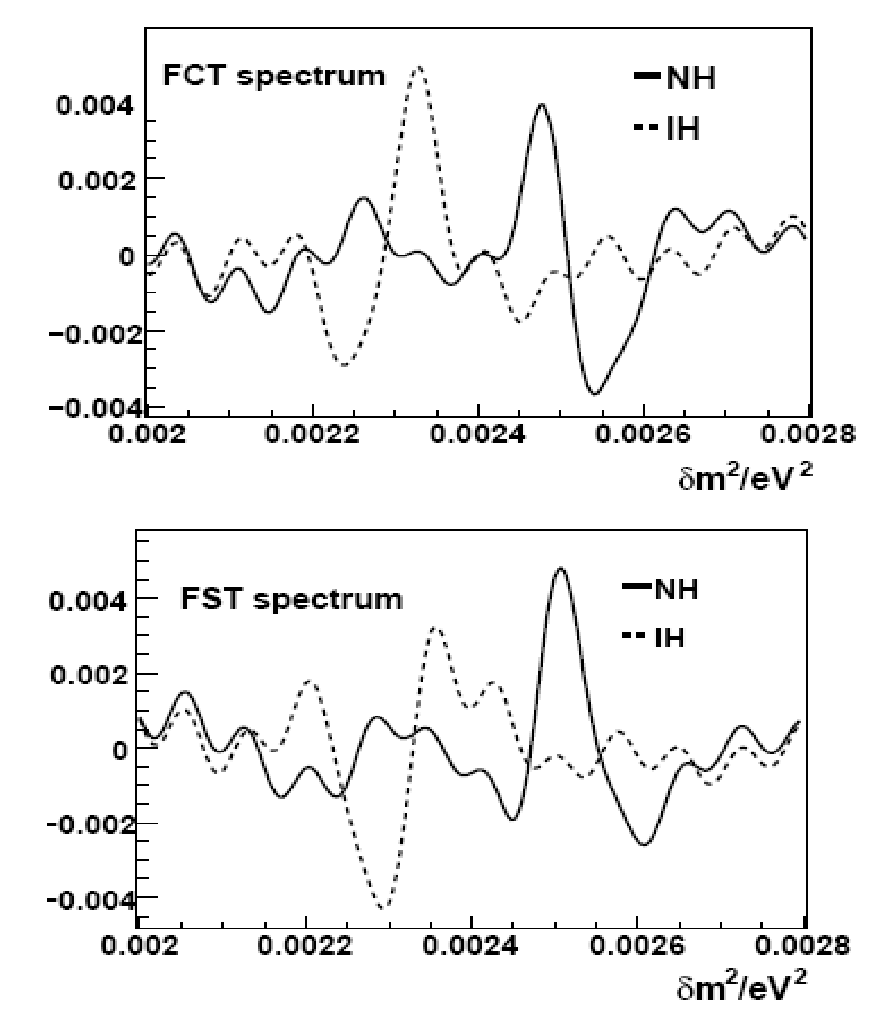
Inverted Hierarchy

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

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

Spectral information





How the interference happens?

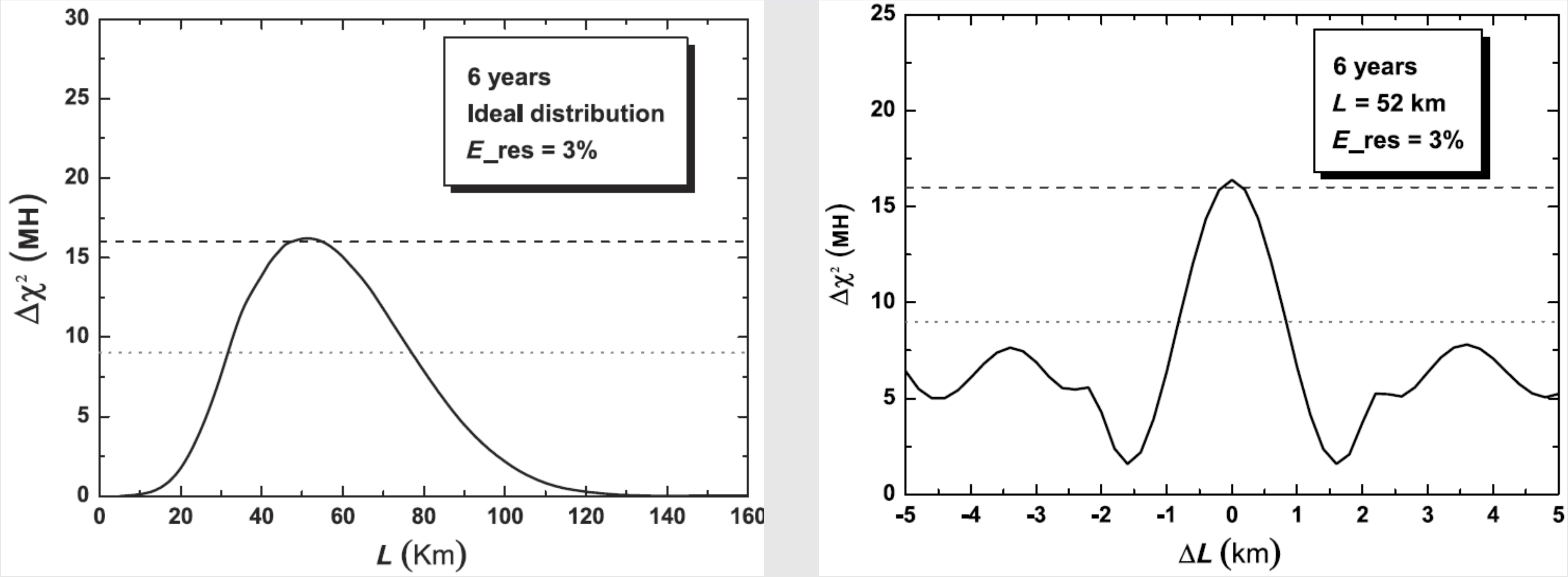
Fourier transform to L/E spectrum:

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

J. Learned *et. al.* hep-ex/0612022

L. Zhan *et. al*. 0807.3203

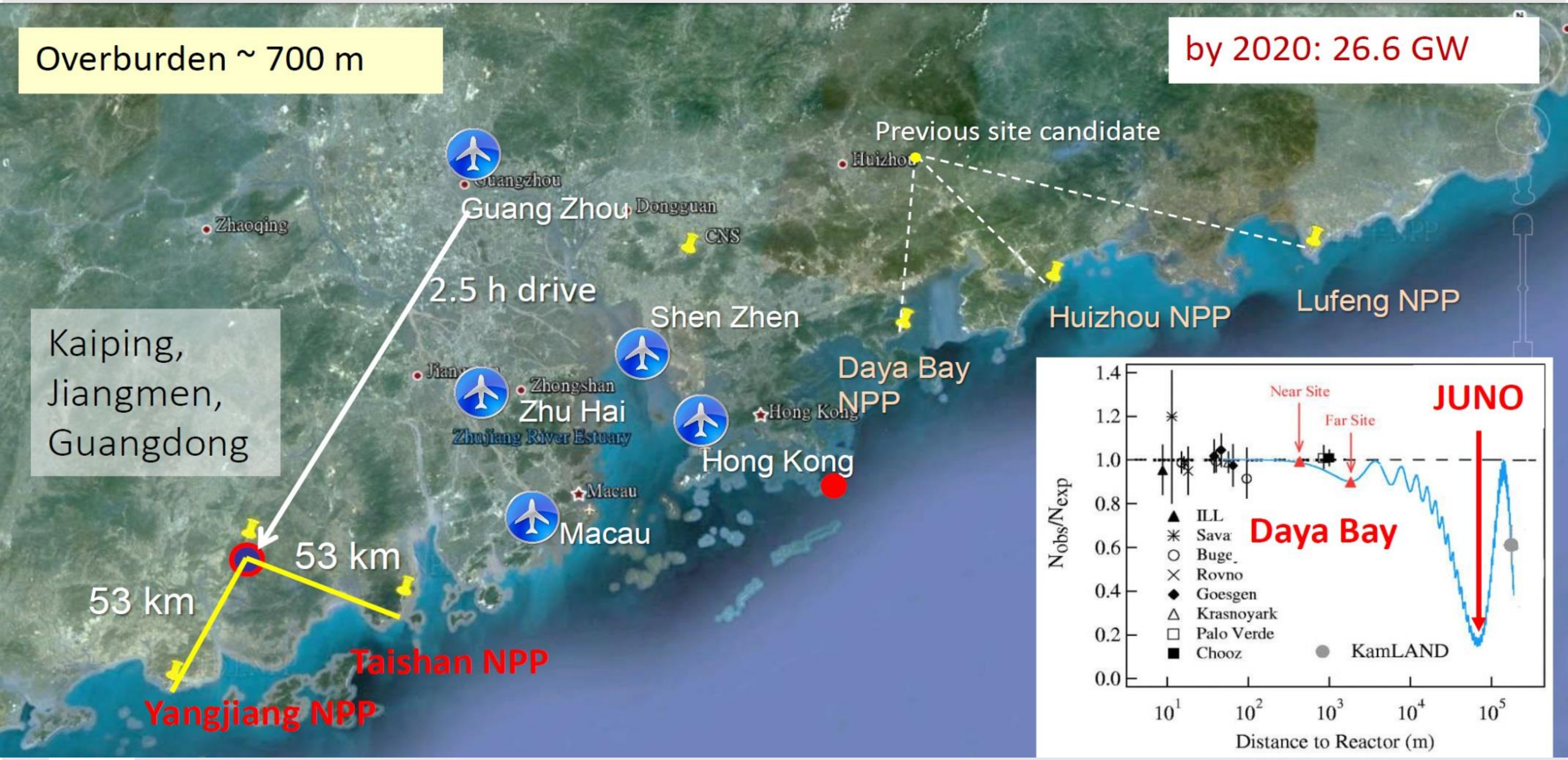
Baseline optimization



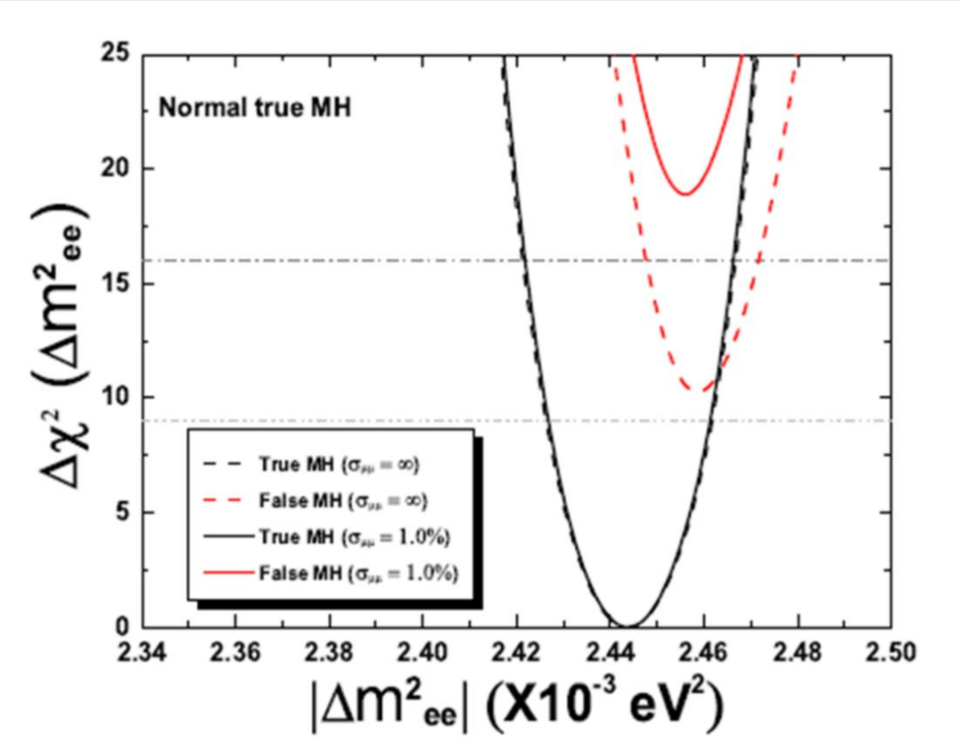
- The optimum baseline is required to be at the oscillation maximum of Δm^2_{21} .
- The control of baseline difference is important to maximize the sensitivity. Y.F Li *et al*, PRD 88, 013008 (2013)

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



Physics Potential



Nominal assumption:

20 kton Liquid Scintillator (LS) detector

3%/sqrt(E) energy resolution

52-53 km baselines

36 GW and 6 years

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

MH sensitivity for JUNO:

3σ ($\Delta\chi^2$>10) with the spectral measurement

4σ if including an external Δm^2(atm) measurement

spread of reactor cores; uncertainties from reactor antineutrino flux; the energy scale and non-linearity.

Other oscillation 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%

New Physics test in low-energy oscillation phenomena:

light sterile neutrinos 1405.6540

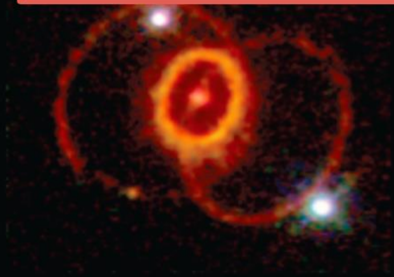
nonstandard neutrino interactions 1310.5917, 1408.6301

Lorentz and CPT violation 1409.6970

Observatory of astrophysical sources

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

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

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

Supernova neutrinos

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

- **For a SN at 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: 0.7 eV@95% C.L. [10 kpc]
- **astrophysics:**

  b) pre-SN neutrinos: ~ 1000 events/day [0.2 kpc]

Many other physics and astro-physics potentials

A physics yellow book will be released by end of this year.

Detector concept

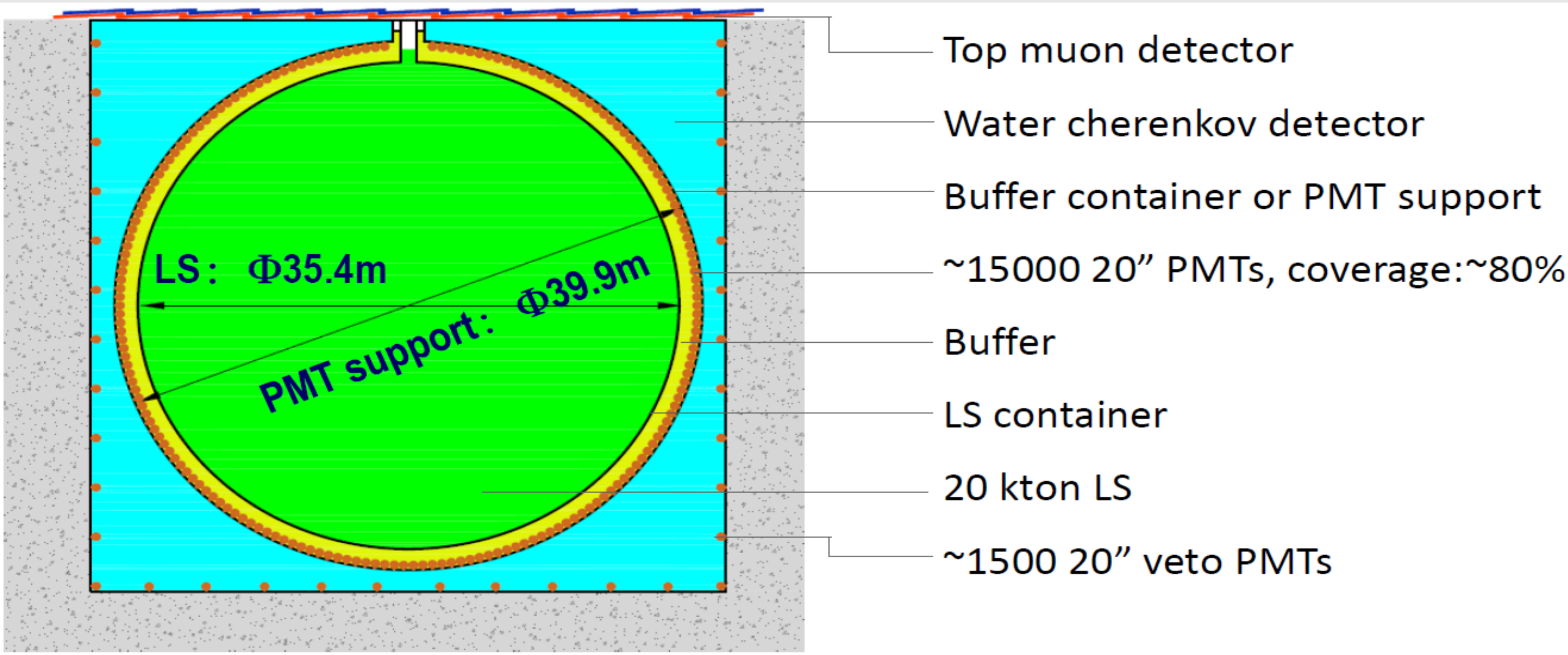
Requirements:

Large detector: **20 kt LS**

Energy resolution:

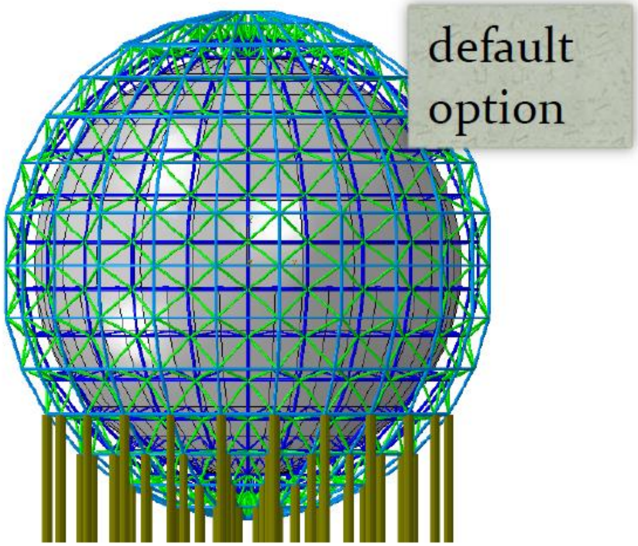
3%/√E → 1200 p.e./MeV

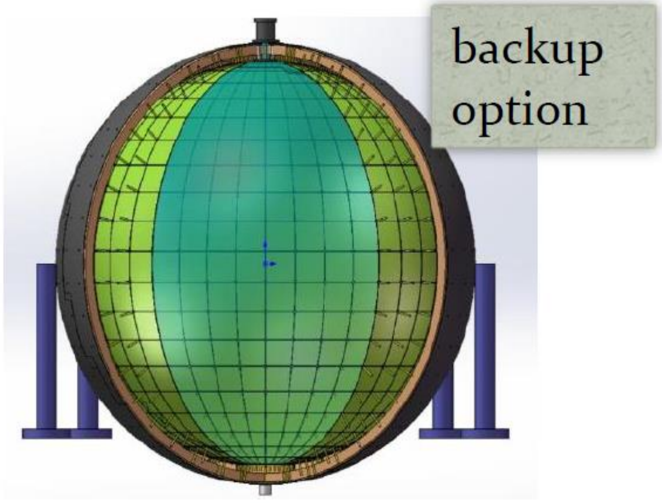
	KamLAND	JUNO
LS mass	**~1 kt**	**20 kt**
Energy Resolution	**6%/√E**	**3%/√E**
Light yield	**250 p.e./MeV**	**1200 p.e./MeV**



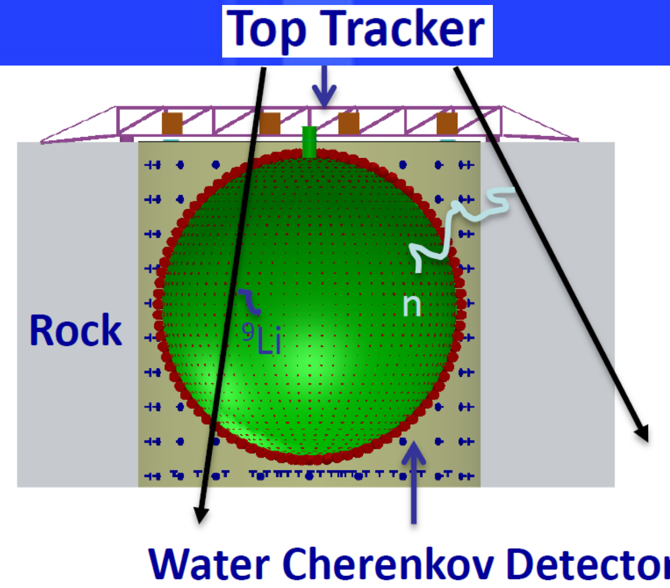
Central detector

- A giant detector in a water pool
  - Default option: acrylic tank(D~35m) + stainless steel (SS) structure
  - Backup option: balloon + acrylic structure + SS tank(D~38m)
- Considerations:
  - Engineering: mechanics, lifetime, safety...
  - Physics: cleanness, light collection, materials compatibility...
  - Assembly & installation
- R&D and prototypes are in progress





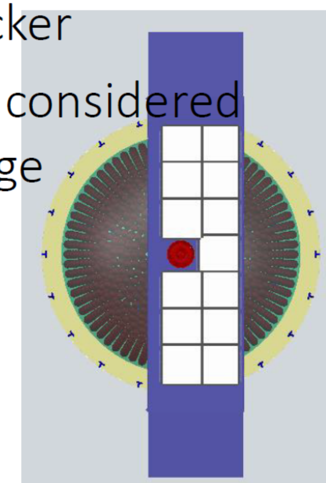
Veto system



- Goals of veto
  - Cosmogenic isotopes rejection
  - Neutron background rejection
  - Gamma background passive shielding
  - …

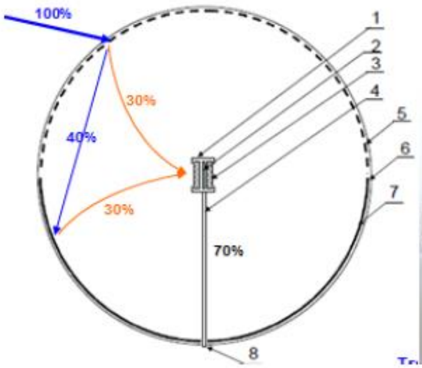
- Water cherenkov detector
  - ~1500 20” PMT
  - 20~30 kton ultrapure water with a circulation system
  - Earth magnetic field shielding
  - Tyvek reflector film
  - PMT support frame
  - Water pool sealing

- Top tracker
  - Use OPERA Target Tracker
  - Additional options are considered to increase the coverage



High QE PMT

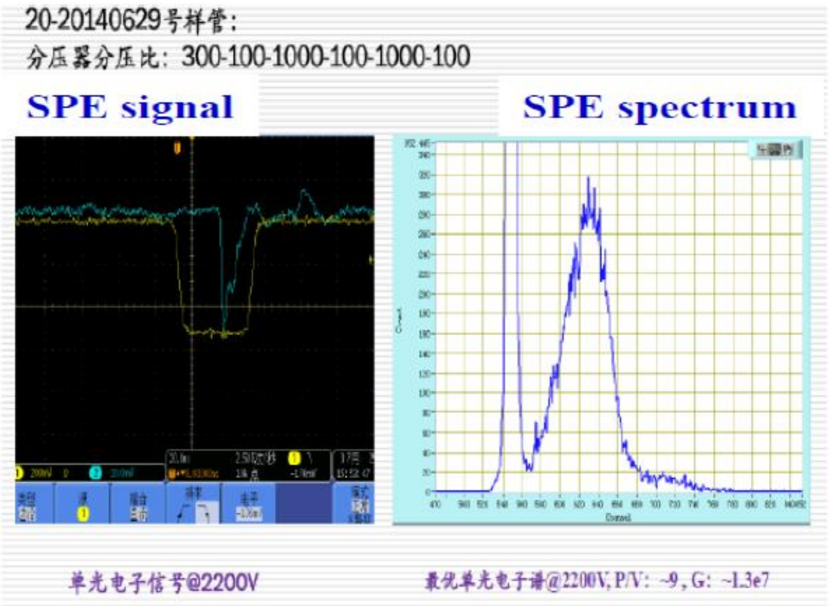
- 20” PMTs under discussion:
  - MCP-PMT with Chinese Industry
  - Photonics-type PMT: 8”→12”→20”
  - Hammamatzu R5912-100 (SBA)
- MCP-PMT development:
  - Technical issues mostly resolved
  - Successful 8” prototypes
  - A few 20” prototypes



Photon detection efficiency: ~30%

20” MCP-PMT

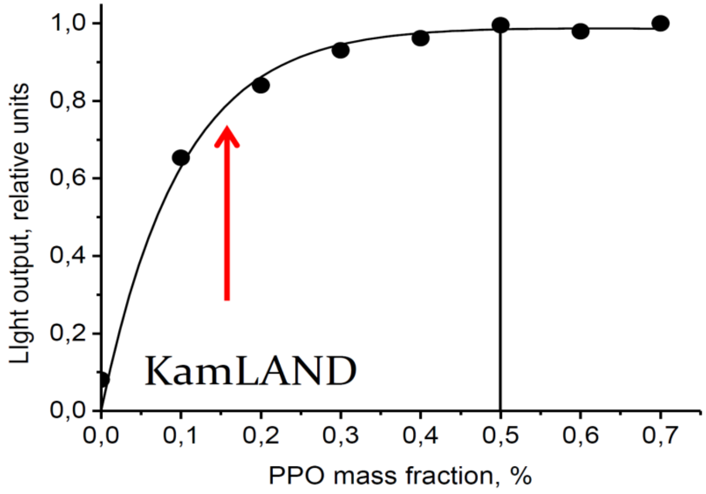
	R5912	R5912-100	MCP-PMT
QE@410nm	25%	35%	25%
Rise time	3 ns	3.4ns	5ns
SPE Amp.	17mV	18mV	17mV
P/V of SPE	>2.5	>2.5	>2.5
TTS	5.5ns	1.5 ns	3.5 ns



Liquid scintillator

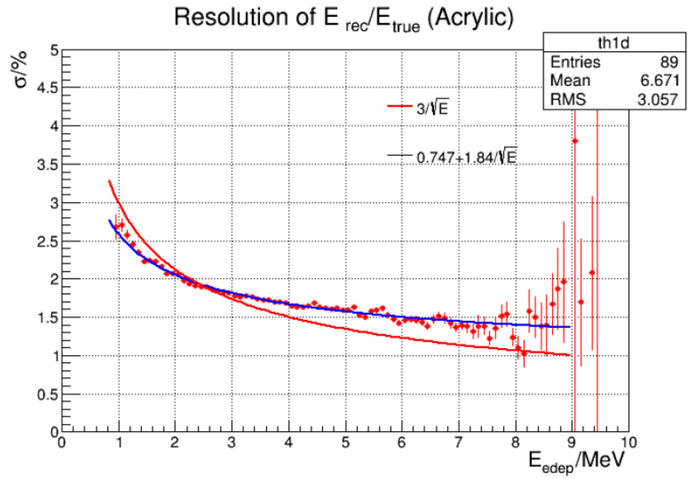
- Recipe: LAB + PPO + bisMSB
  - Attenuation length 15 m → ~30m
  - No Gd-loading for low radioactivity
- R&D efforts:
  - Low background: ➔ No Gd-loading
  - Improve raw materials
  - Improve the production process
  - Purification
    - Distillation, Filtration, Water extraction, Nitrogen stripping…
  - Optimization of fluor concentration
- Other works:
  - Rayleigh scattering length
  - Energy non-linearity
  - Aging
  - Material selection: BKG & purity issues
  - Engineering for 20kt mass production

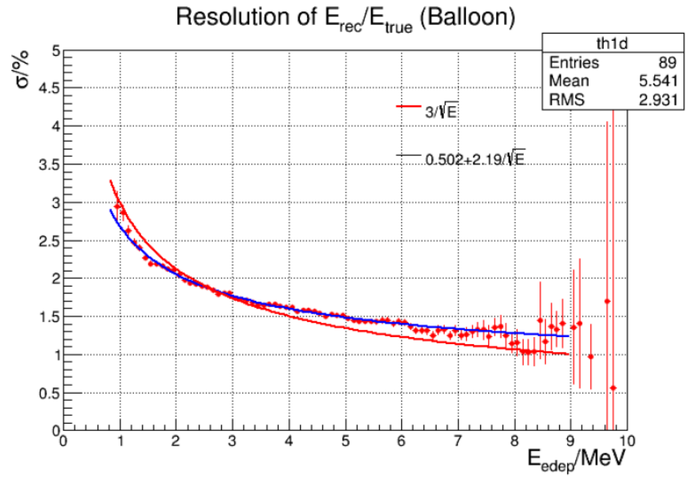
Linear Alky Benzene	Atte. L(m) @ 430 nm
RAW	14.2
Vacuum distillation	19.5
SiO_2 column	18.6
Al_2O_3 column	22.3
LAB from Nanjing, Raw	20
Al_2O_3 column	25



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%

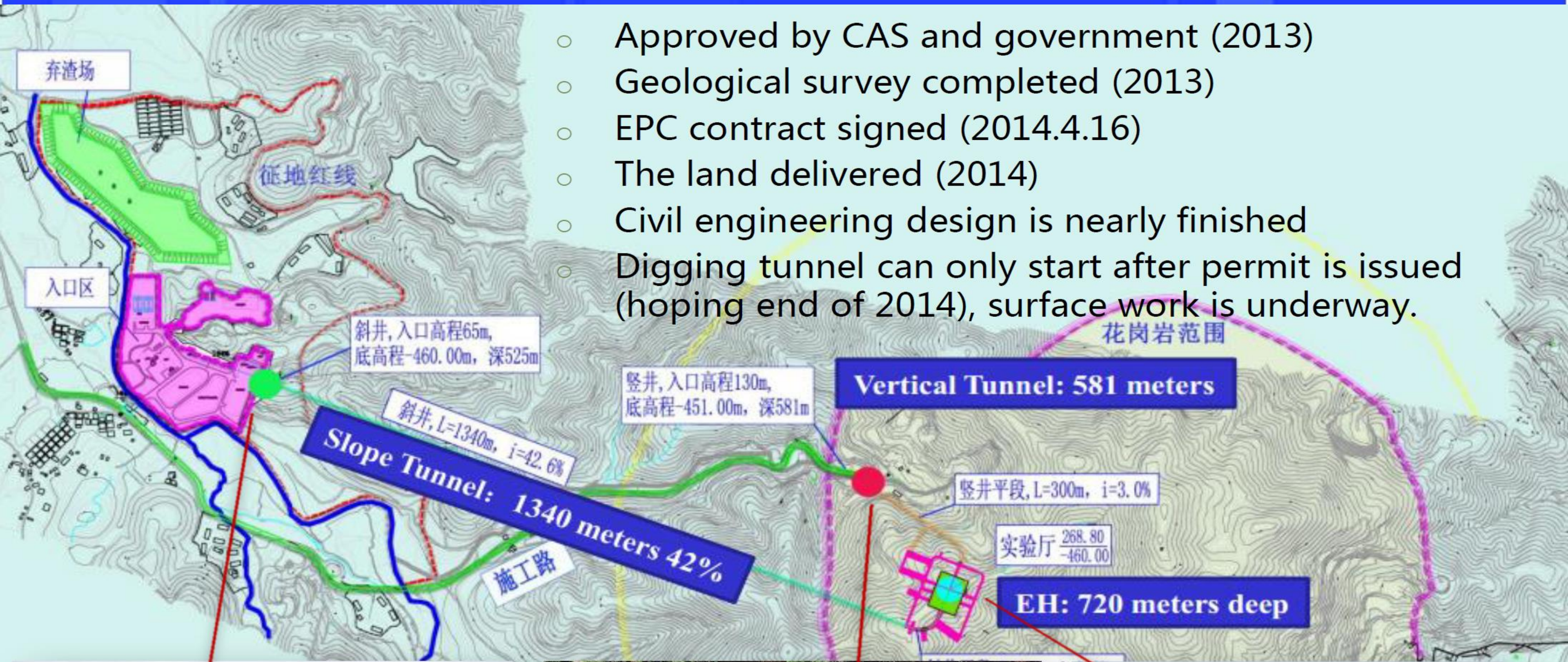


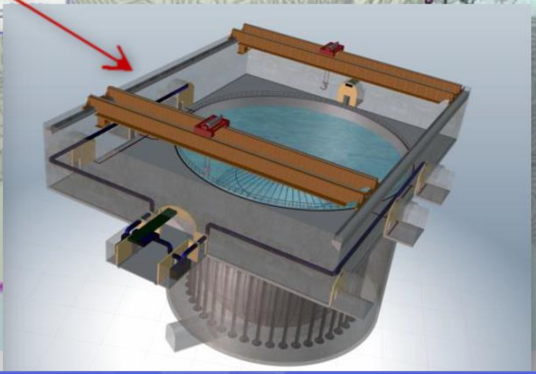


Energy resolution of two detector options: similar performances

Civil construction

- Approved by CAS and government (2013)
- Geological survey completed (2013)
- EPC contract signed (2014.4.16)
- The land delivered (2014)
- Civil engineering design is nearly finished
- Digging tunnel can only start after permit is issued (hoping end of 2014), surface work is underway.





Collaboration Established

Europe (20)*

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

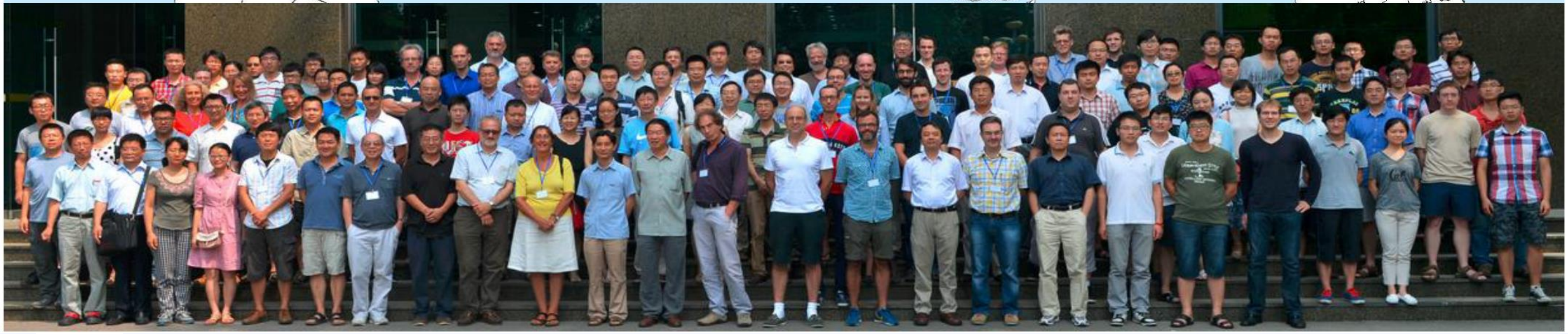
US*

BNL, UIUC, Houston,
Observers on behalf of US institutions

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
Pekin U.
Shandong U.
Shanghai JT U.
Sichuan U.
SYSU
Tsinghua U.
UCAS
USTC
Wuhan U.
Wuyi U.
Xi'an JT U.

*Subject to funding agency approval



Schedule

- Civil preparation: 2013-2014
- Civil construction: 2014-2017
- Detector component production: 2016-2017
- PMT production: 2016-2019
- Detector assembly & installation: 2018-2019
- Filling & data taking: 2020


Welcome to Kaiping
Thanks

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.

The median sensitivity

(1) The square root of delta_chi_2 is very close the median sensitivity.

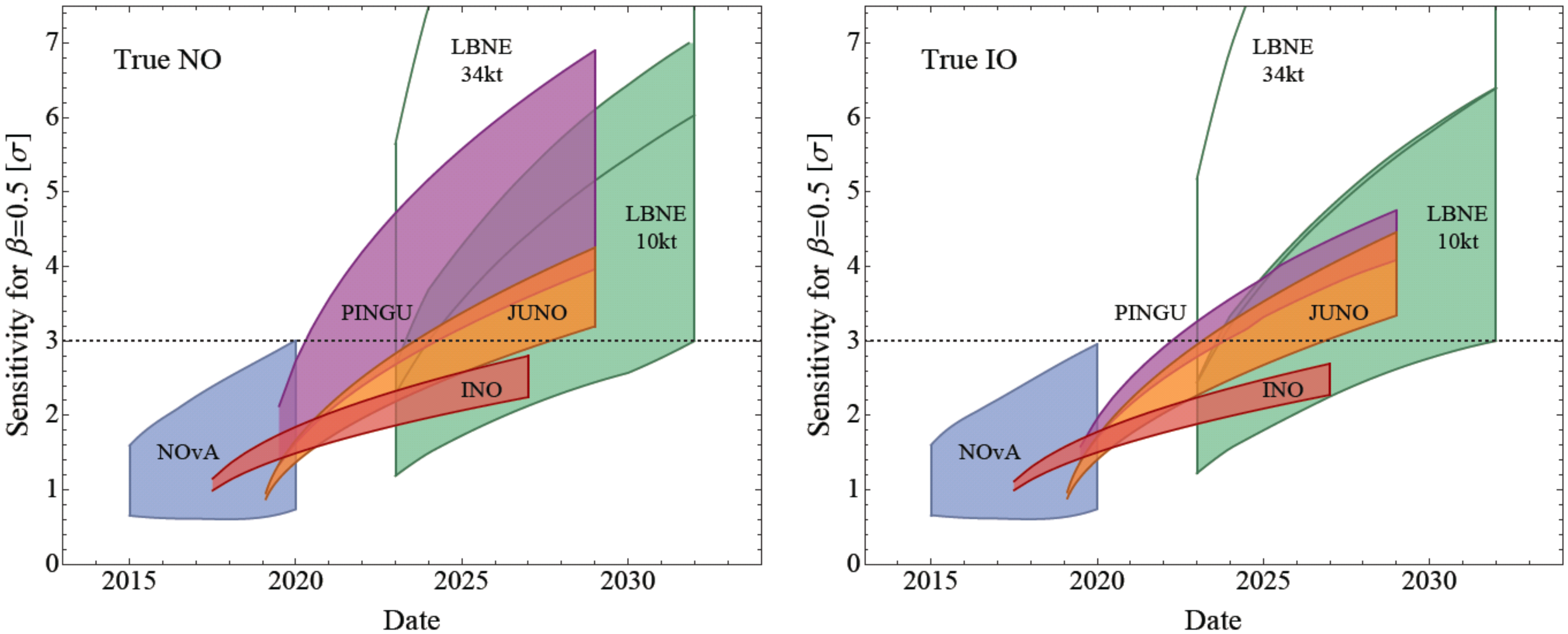
(2) It is representative for how well the experiment will do.

(3) 50 % probability of not reaching it, and 50 % probability of doing better, not 50 % probability of "being wrong ".

	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

Table 2-4: The MH sensitivity with the JUNO nominal setup.

Global comparison



Blennow, Coloma, Huber, Schwetz, JHEP 03, 028 (2014)

Note: Bands have dierent meanings:

JUNO: Energy resolution 3%-3.5%

PINGU/INO: theta(23) 40º~50º

LBNE: CP phase (0~2π)

Signal and background

Signal: $\overline{\nu}_e + p \rightarrow e^+ + n$

$n + p \rightarrow d + \gamma$ (2.2 MeV)

Estimated IBD rate: ~80/day, w/o detection efficiency

Background type	Raw rate	Final number after selection cuts	Relative Uncertainty Rate	Shape
Accidentals	~410/day ($\Delta T < 1.0$ ms)	**1.1/day ($R_{p\text{-}d} < 1.5$m)**	**1%**	**negligible**
*Fast neutron	0.01/day	**0.01 /day**	**100%**	**20%**
$^9Li/^8He$	80/day	**1.8/day (muon veto)**	**20%**	**10%**
$(\alpha$, n)	3.8/day (acrylic opt.) 0.2/day (balloon opt.)	**0.05/day (acrylic), by FV cut negligible (balloon), by FV cut**	**50%**	**50%**

* Fast neutron is being re-evaluated by using real MC

Above table does not take into account the IBD selection efficiency

IBD selection Cuts	Efficiency
0.7 MeV < Ep < 12 MeV, 1.9 MeV < Ed < 2.5 MeV, $\Delta T < 1.0$ ms, $R_{p\text{-}d} < 1.5$ m	**95.6%**
Muon Veto	**83%**

Calibration System Conceptual Designs

- Point radioactive source calibration systems
  - A 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 a short-lived diffusive radioactive sources
- A UV laser system being considered to calibrate the LS responses