Supernova Neutrino Observation at JUNO

Yu-Feng LI

Institute of High Energy Physics, Beijing

On behalf of the JUNO collaboration

Workshop on Supernova at Hyper-Kamiokande

@University of Tokyo (Japan)

Supernova Neutrinos: SN 1987A

Kamiokande-II (Japan):

- Water Cherenkov (2,140 ton)
- Clock Uncertainty ± 1 min

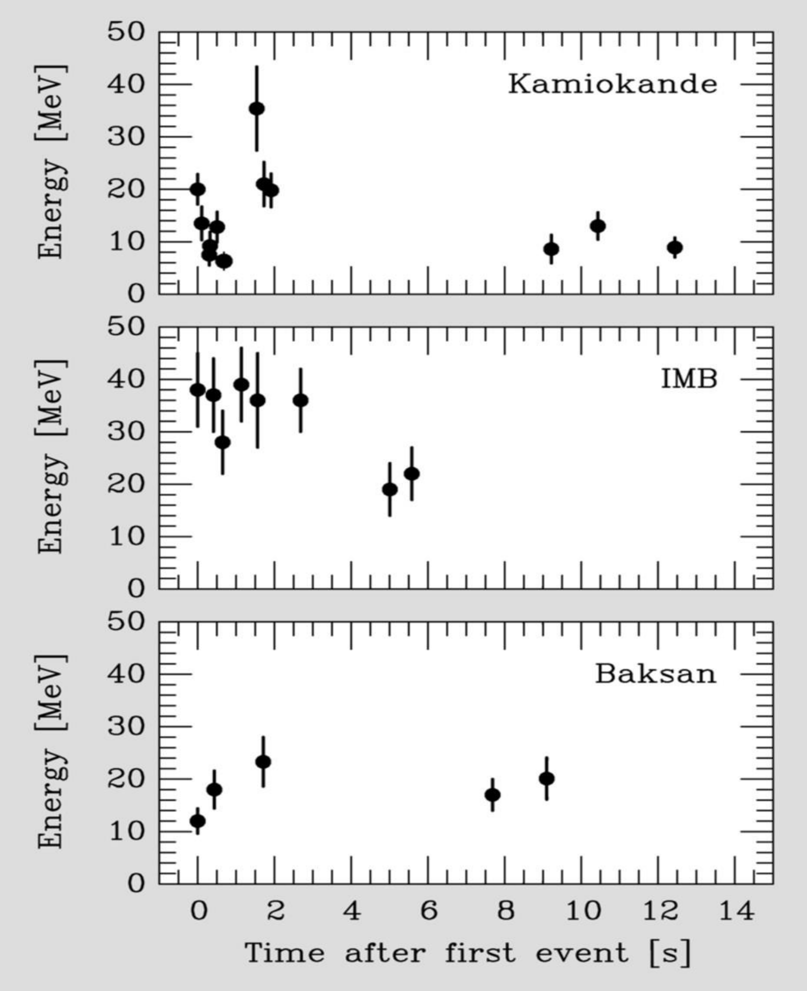
Irvine-Michigan-Brookhaven (US):

- Water Cherenkov (6,800 ton)
- Clock Uncertainty ±50 ms

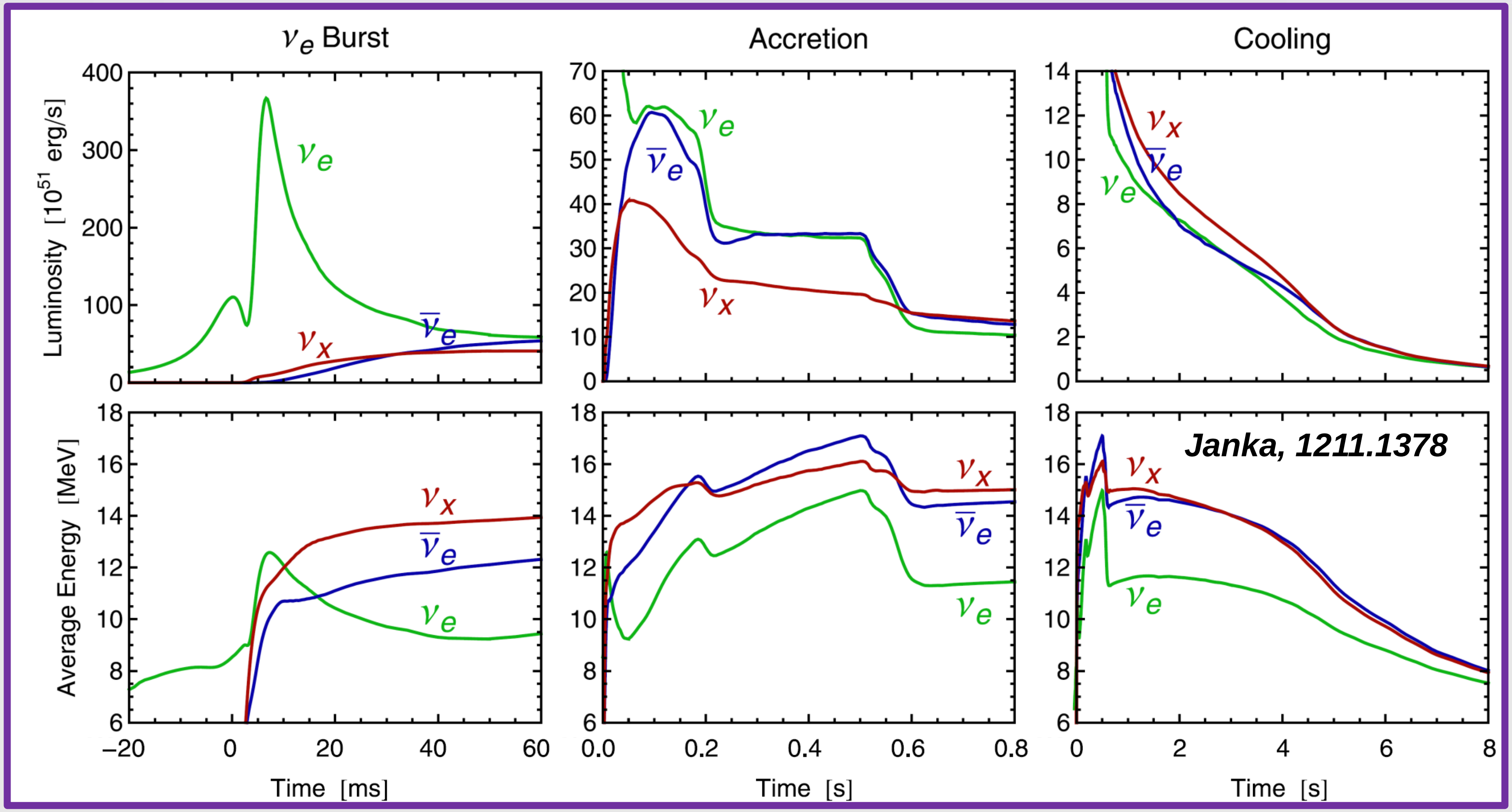
Baksan LST (Soviet Union):

- Liquid Scintillator (200 ton)
- Clock Uncertainty +2/-54 s

Mont Blanc: 5 events, 5 h earlier



SN neutrino bursts from simulation



Shock breakout

$$e^- + p \rightarrow n + \nu_e$$

Shock stalls ~150 km
Neutrinos powered by infalling matter

Cooling on the neutrino diffusion time scale

Future Supernova Neutrino Detection

(1) Water Cherenkov Detector

Hyper Kamiokande (also SuperK-Gd):

1 Mt, mostly nu_e_bar, largest statistics

(2) Liquid Scintillator Detector

JUNO (also RENO50 or LENA):

20 kt, nu_e_bar dominates, different flavors, best energy resolution

(3) Liquid Argon Detector

DUNE: 10-40 kt, nu_edominates

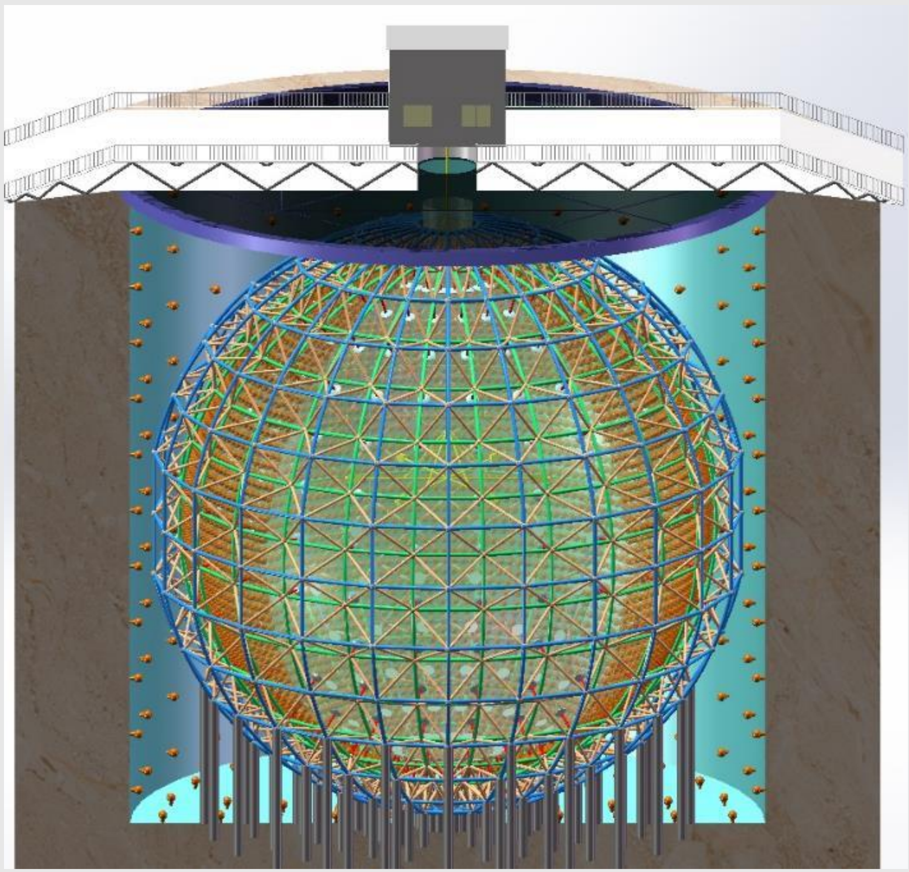
(4) Ice Cherenkov Detector

Good time profile, no event-by event observation

Jiangmen Underground Neutrino Observatory

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

A multiple-purpose neutrino experiment



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

- **20 kton LS detector**
- **3% energy resolution**
- **700 m underground**
- **Rich physics possibilities**
  - **Reactor neutrino for Mass hierarchy and precision measurement of oscillation parameters**
  - **Supernova neutrinos**
  - **Geo-neutrinos**
  - **Solar neutrinos**
  - **Atmospheric neutrinos**
  - **Exotic searches including proton decay, dark matter**

Neutrino mass hierarchy measurement

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{12} \cos^4\theta_{13} \sin^2 F_{21} - \frac{1}{2}\sin^2 2\theta_{13}(1 - \cos F_* \cos F_{21} + \cos 2\theta_{12} \sin F_* \sin F_{21})$$

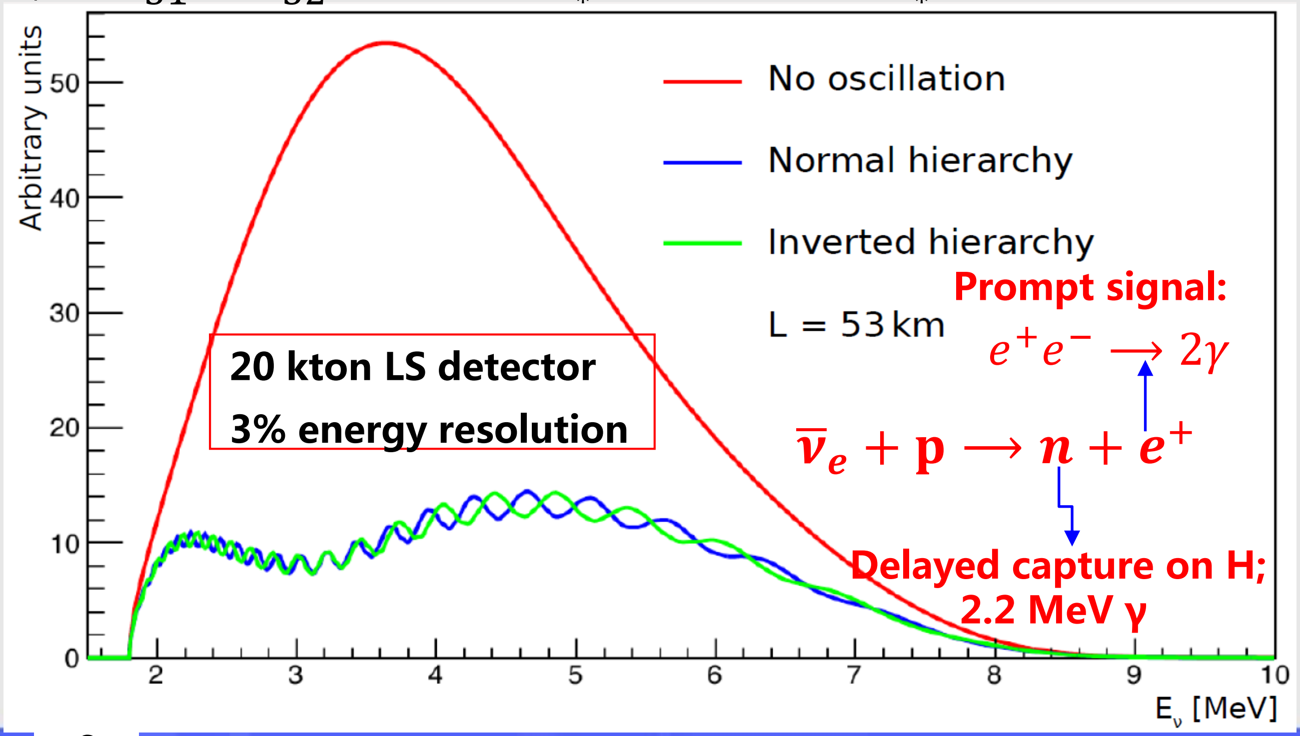
$$F_{ji} = \frac{\Delta m^2_{ji} L}{4E}$$

Li et al., PRD, 13

Neutrino Physics with JUNO, JUNO Collaboration, JPG, 16

JUNO:
3~4σ (MH) for 6-year running (from 2020)

$F_* = F_{31} + F_{32}$ NH: $F_* > 0$ IH: $F_* < 0$



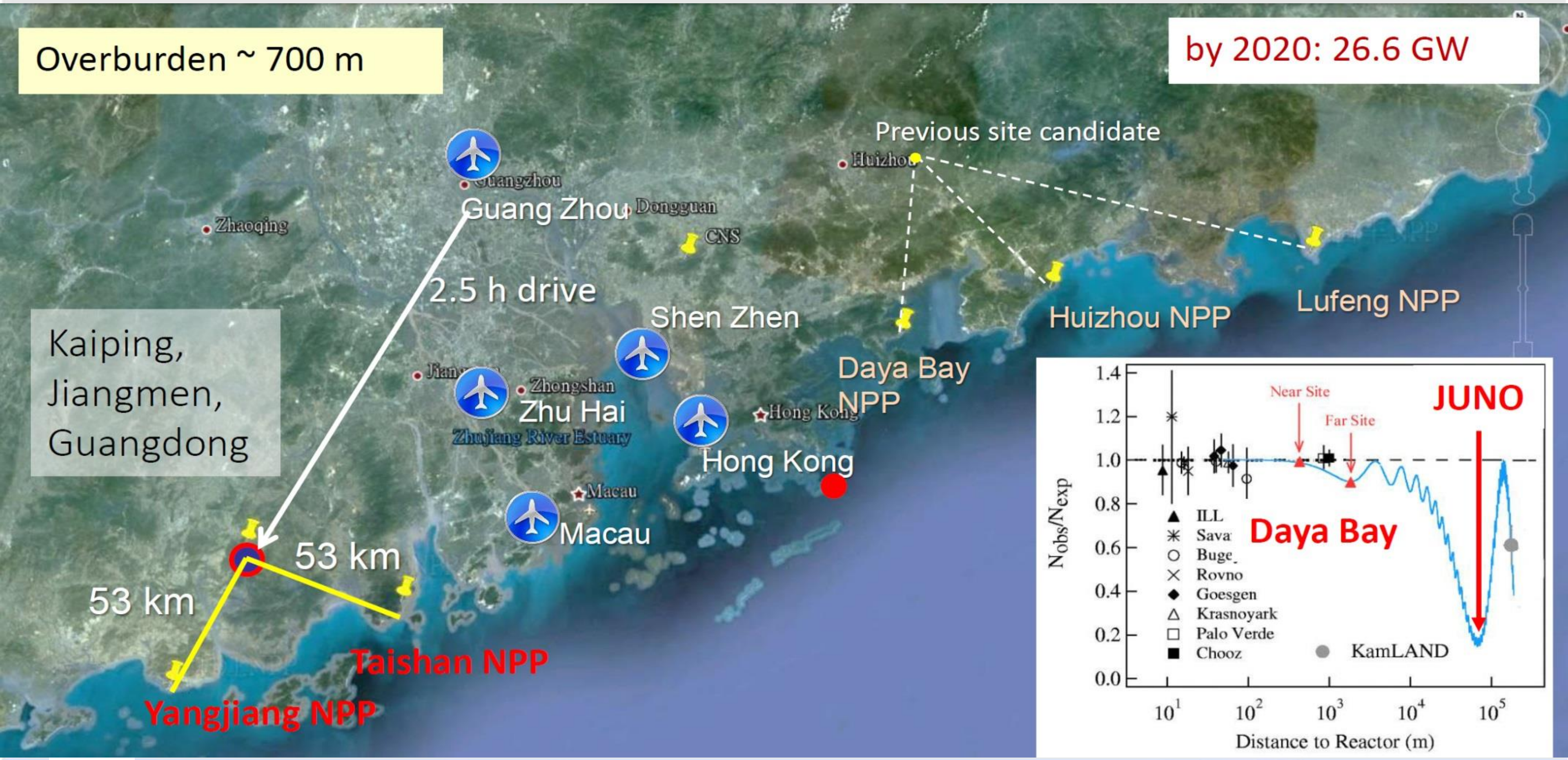
Parameters	Precision
$\sin^2 2\theta_{12}$	0.54%
Δm^2_{21}	0.24%
$\lvert\Delta m^2_{ee}\rvert$	0.27%

Precision Era (< 1%)

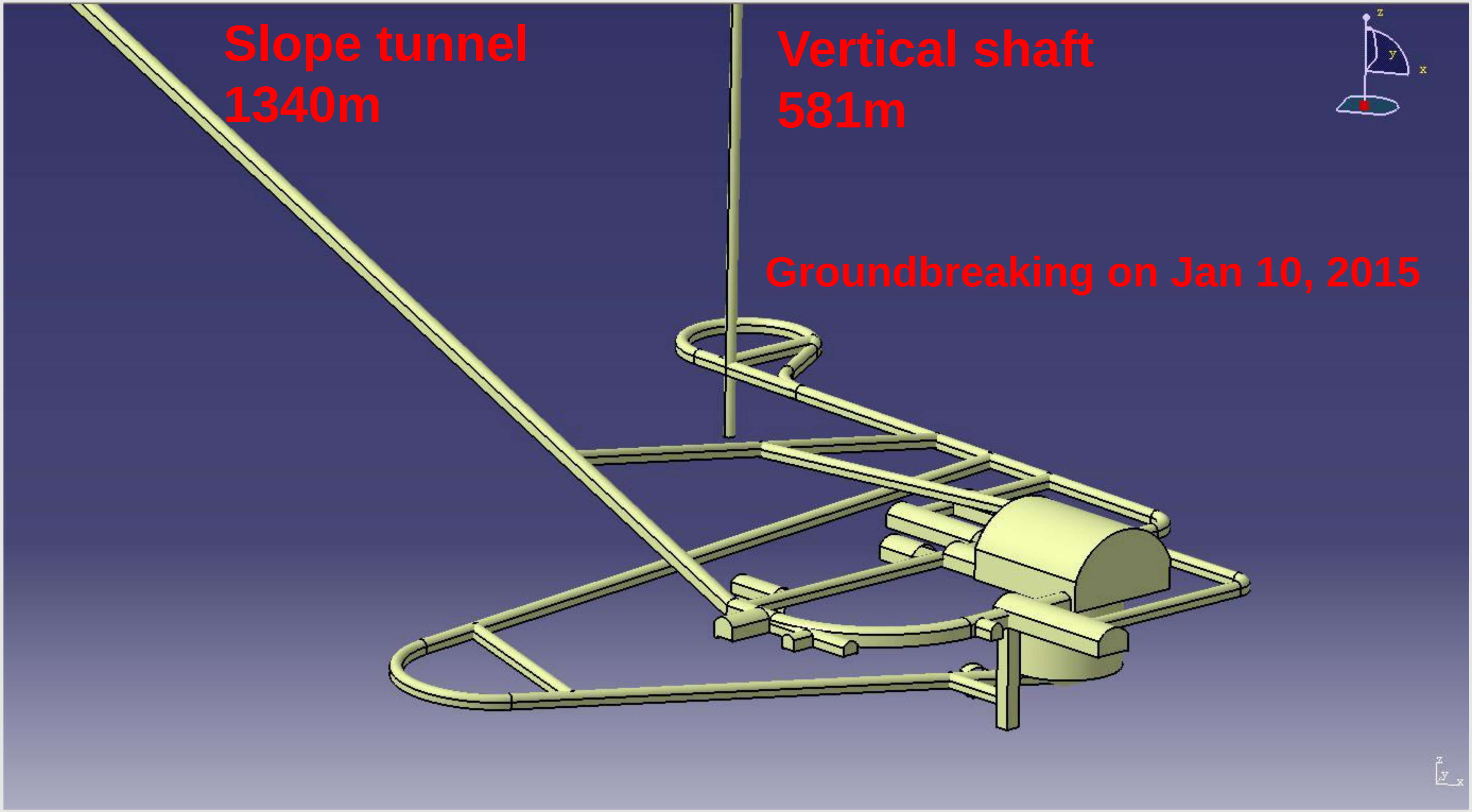
- **Test of 3-ν oscillations and Leptonic unitarity violation**

Experimental site

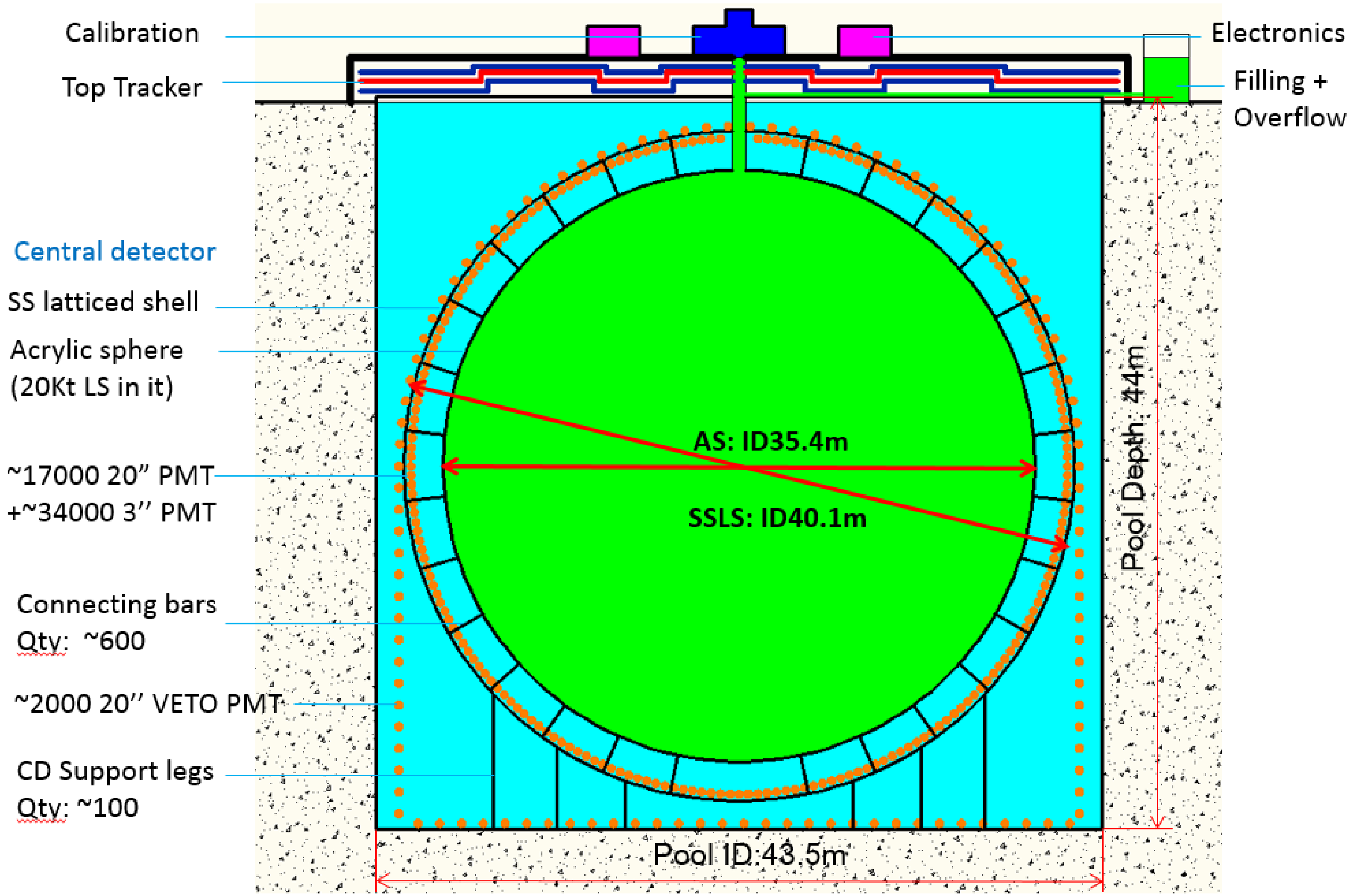
NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW



Go 700 m Underground



Large and precision Liquid Scintillator detector



AS: Acrylic sphere; SSLS: stainless steel latticed shell

Multi-channels of SN neutrino detection

For 20 kt LS@JUNO

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
$\nu + e \to \nu + e$	ES	3.6×10^2	3.6×10^2	3.6×10^2
$\nu + {}^{12}\text{C} \to \nu + {}^{12}\text{C}^*$	NC	1.7×10^2	3.2×10^2	5.2×10^2
$\nu_e + {}^{12}\text{C} \to e^- + {}^{12}\text{N}$	CC	4.7×10^1	9.4×10^1	1.6×10^2
$\overline{\nu}_e + {}^{12}\text{C} \to e^+ + {}^{12}\text{B}$	CC	6.0×10^1	1.1×10^2	1.6×10^2

Detect $\overline{\nu}_e, \nu_e, \nu_x$ from a galactic SN @ 10 kpc

JUNO Collaboration, JPG 2016

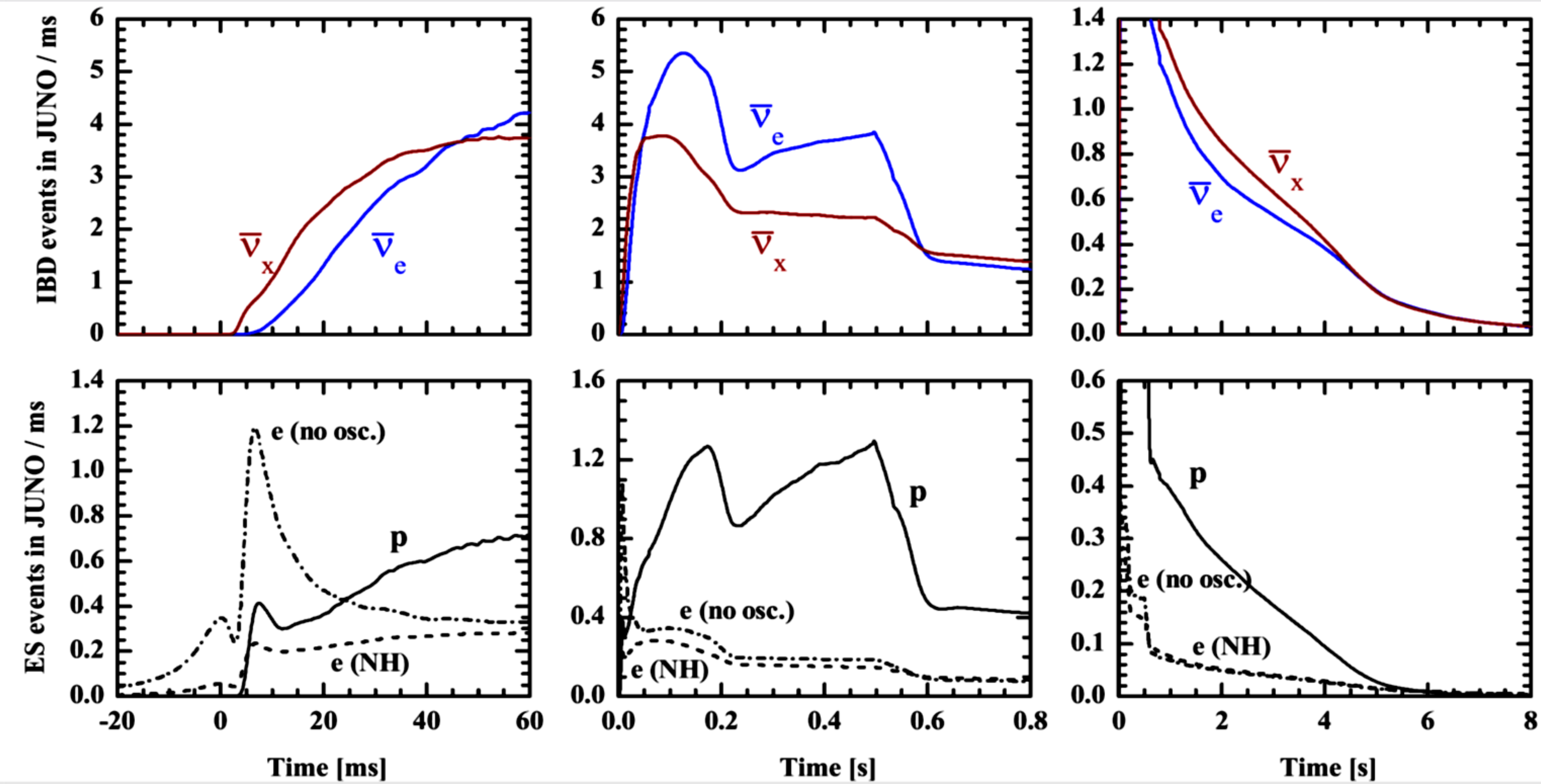
- **real-time measurement of three-phase ν signals**
- **distinguish between different ν flavors**
- **reconstruct ν energies and luminosities**
- **almost background free due to time information**

(A): Probes of all three neutrino flavors

Lu, YFL, Zhou, PRD 2016

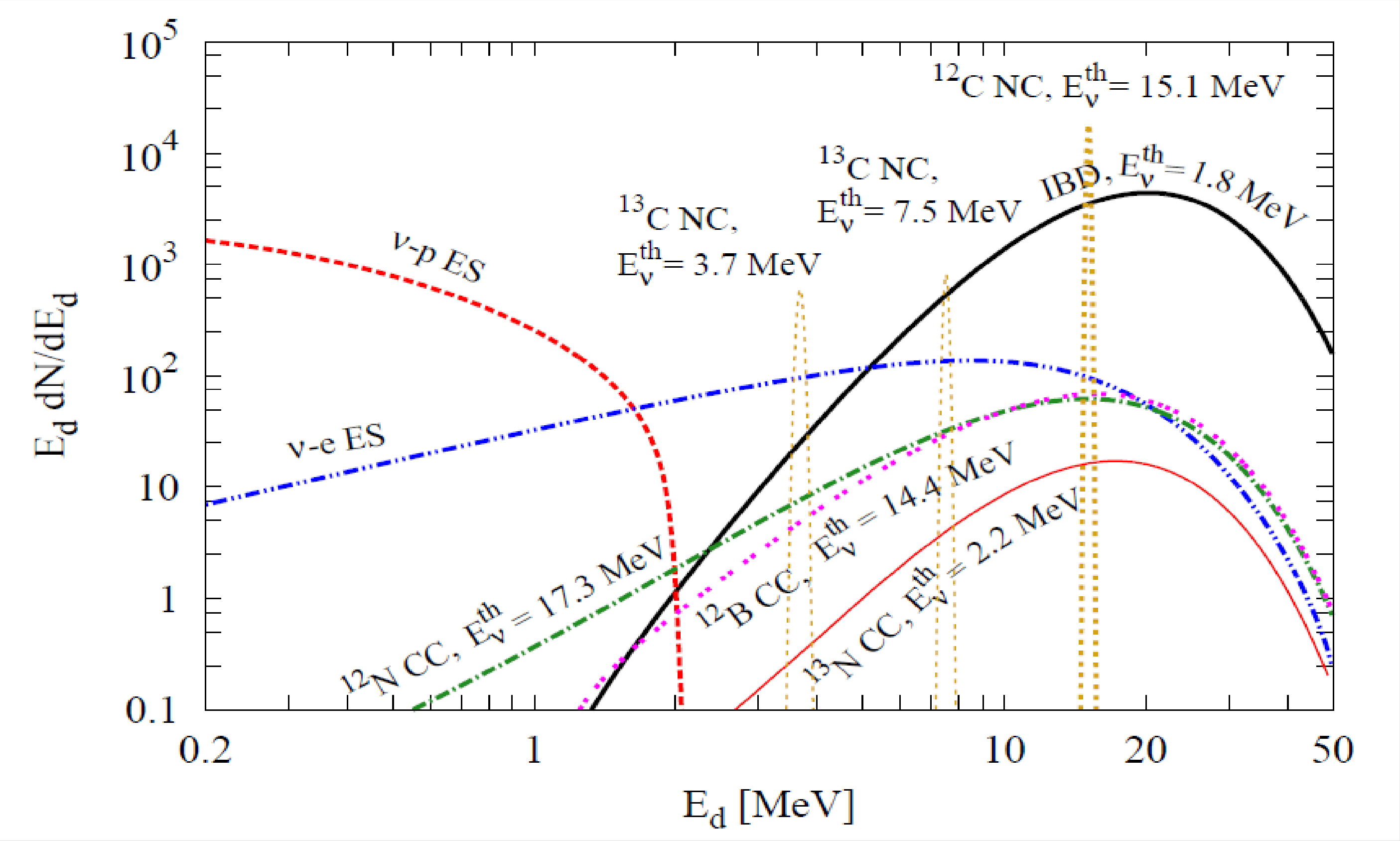
Channel	Type		Number of SN Neutrino Events at JUNO: No Oscillations	Normal Ordering	Inverted Ordering
$\overline{\nu}_e + p \to e^+ + n$	CC		4573	4775	5185
$\nu + p \to \nu + p$	ES		1578	1578	1578
		ν_e	107	354	278
		$\overline{\nu}_e$	179	214	292
		ν_x	1292	1010	1008
$\nu_e + e \to \nu_e + e$	ES		314	316	316
		ν_e	157	159	158
		$\overline{\nu}_e$	61	61	62
		ν_x	96	96	96
$\nu_e + {}^{12}\mathrm{C} \to e^- + {}^{12}\mathrm{N}$	CC		43	134	106
$\overline{\nu}_e + {}^{12}\mathrm{C} \to e^+ + {}^{12}\mathrm{B}$	CC		86	98	126
$\nu + {}^{12}\mathrm{C} \to \nu + {}^{12}\mathrm{C}^*$	NC		352	352	352
		ν_e	27	76	61
		$\overline{\nu}_e$	43	50	65
		ν_x	282	226	226

(B): Time distribution (IBD & ES events)



w/o oscillation or **with largest transition** between ν_e($\bar{\nu}_e$) and ν_x

(C): Neutrino energy distribution



Lu, YFL, Zhou, PRD 2016

See also Lujan-Peschard, Pagliaroli, Vissani, 2014

1) IBD events dominate at the high energy range
2) nu-p ES channel dominates at low energies
3) coincidence events vs. singles events
4) e. vs. p discrimination: Pulse shape discrimination

(D): Detection of SN $\bar{\nu}_e$

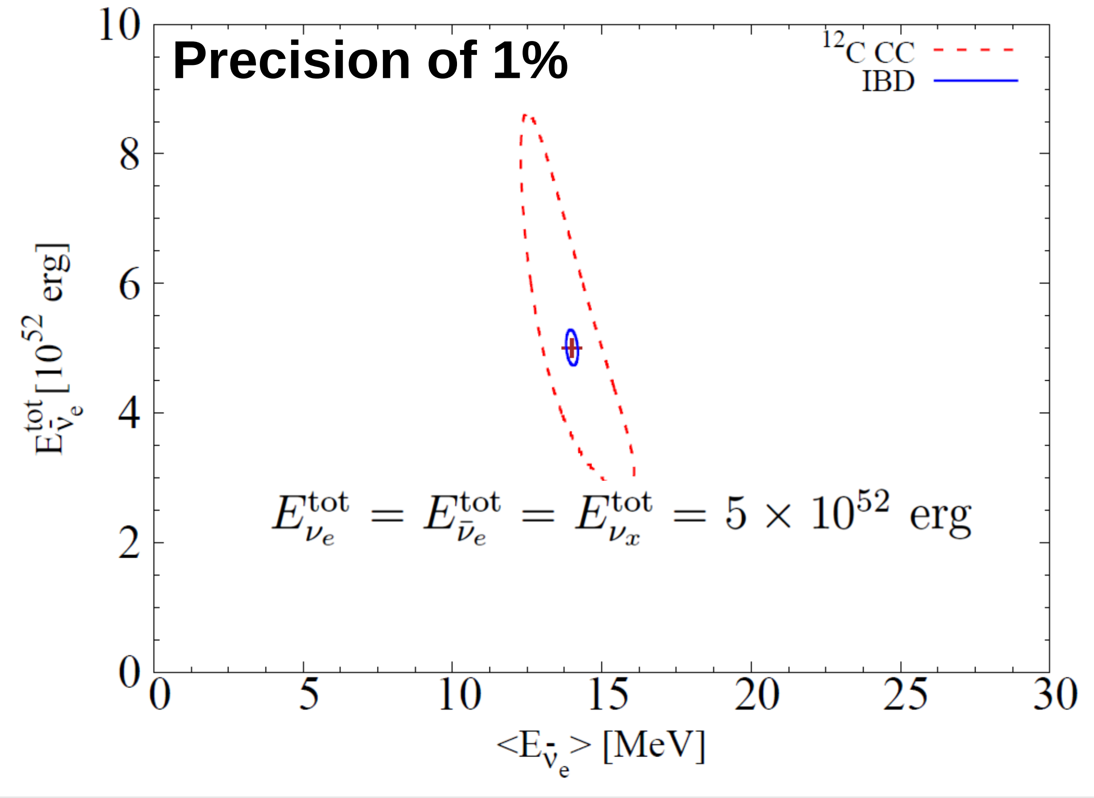
Mostly Inverse beta decay (IBD) $\bar{\nu}_e + \mathrm{p} \longrightarrow n + e^+$

Spectra $$F^0_\alpha(E) = \frac{1}{4\pi D^2}\frac{E^{\rm tot}_\alpha}{\langle E_\alpha\rangle}\frac{(1+\gamma_\alpha)^{1+\gamma_\alpha}}{\Gamma(1+\gamma_\alpha)}\left(\frac{E}{\langle E_\alpha\rangle}\right)^{\gamma_\alpha}\exp\left[-(1+\gamma_\alpha)\frac{E}{\langle E_\alpha\rangle}\right]$$

(1) ~5000 IBD events, golden channel for SN neutrino observations

(2) Coincidence of prompt and delayed signals: least background

(3) good reconstruction of the neutrino energy

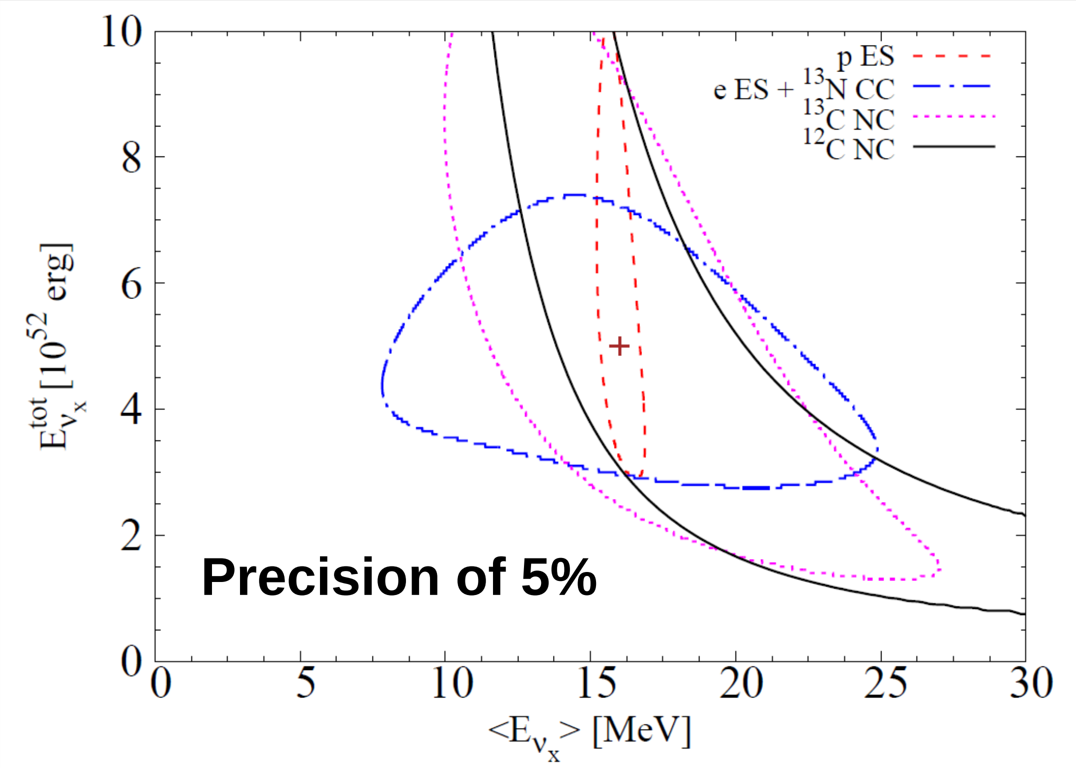


Lu, YFL, Zhou, PRD 2016

(E): Detection of SN ν_x

(1) nu-p scattering (pES) events: quenched proton
(2) nu-^{12}C NC events: 15.11 MeV γ
(3) nu-electron scattering (eES) events: recoiled electron

- ~2000 pES events
- Low threshold **(0.2 MeV)**
- reconstruction of neutrino energy spectrum: **high-energy tail**



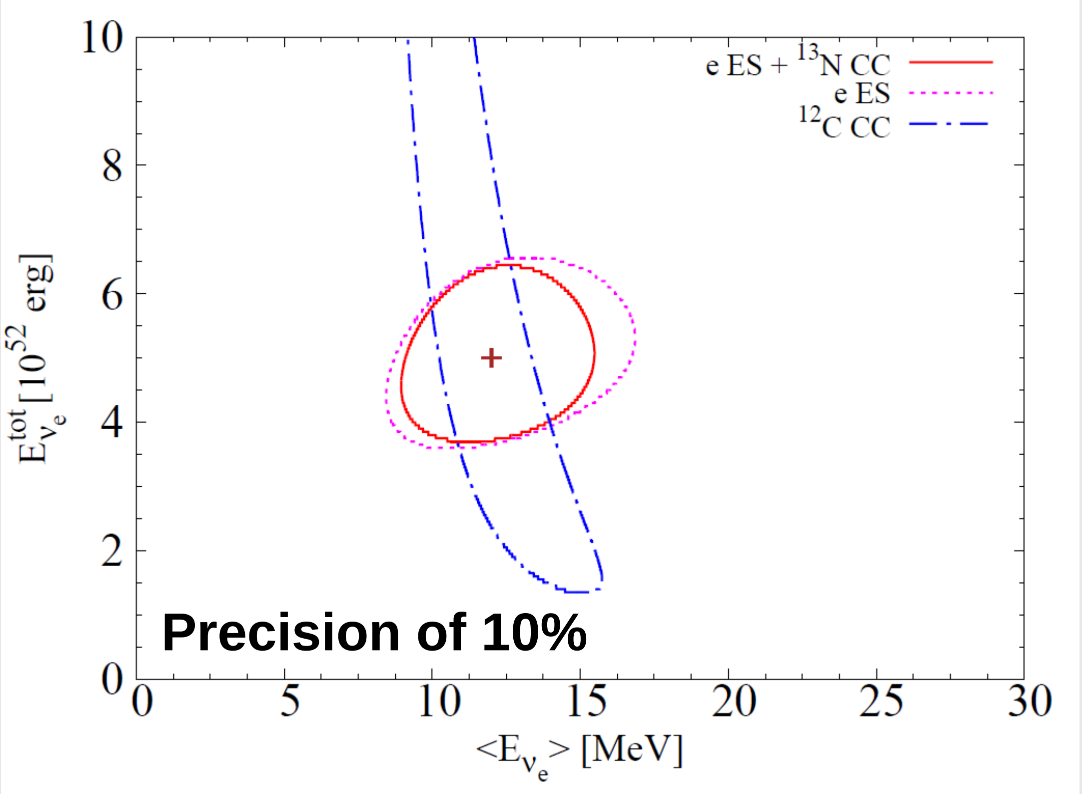
Lu, YFL, Zhou, PRD 2016

(F): Detection of SN ν_e at JUNO

(1) nu-electron scattering events: recoiled electrons

(2) nu-^{12}C CC events: coincidence with decayed ^{12}N

- ~300 eES events
- ~300 ^{12}C CC events
- Background events: from IBD in-efficiency
- electron v.s. proton: pulse shape discrimination (PSD)

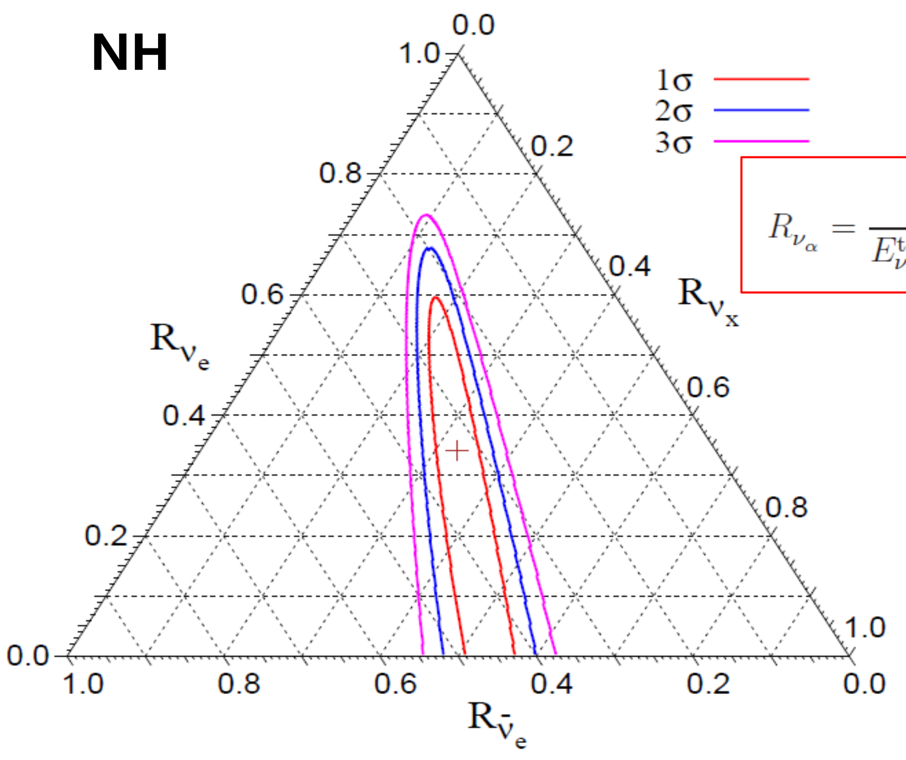


Lu, YFL, Zhou, PRD 2016

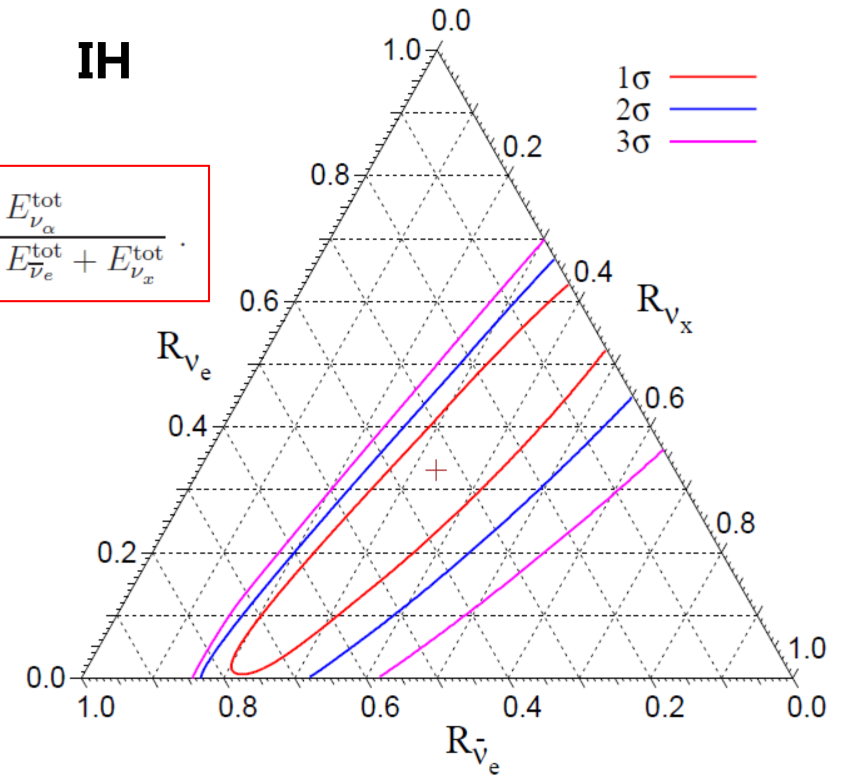
(G): Test of the energy equipartition

A fundamental assumption in SN physics
Not guaranteed in simulation

Lu, YFL, Zhou, PRD 2016



$$R_{\nu_\alpha} = \frac{E^{\rm tot}_{\nu_\alpha}}{E^{\rm tot}_{\nu_e} + E^{\rm tot}_{\overline{\nu}_e} + E^{\rm tot}_{\nu_x}} \ .$$



(1) Assuming standard MSW effects
(2) marginalization of three average energies and E_tot.

Neutrino mass scale with SN neutrinos

SN1987A limits of neutrino mass scale: 5.8 eV@ 95 C.L.

Beta decay experiments:

Current: 2 eV@ 95 C.L., KATRIN: 0.2 eV @ 95 C.L.

Cosmology probes:

Total mass smaller than 0.23 @ 95C.L.

Double beta decay:

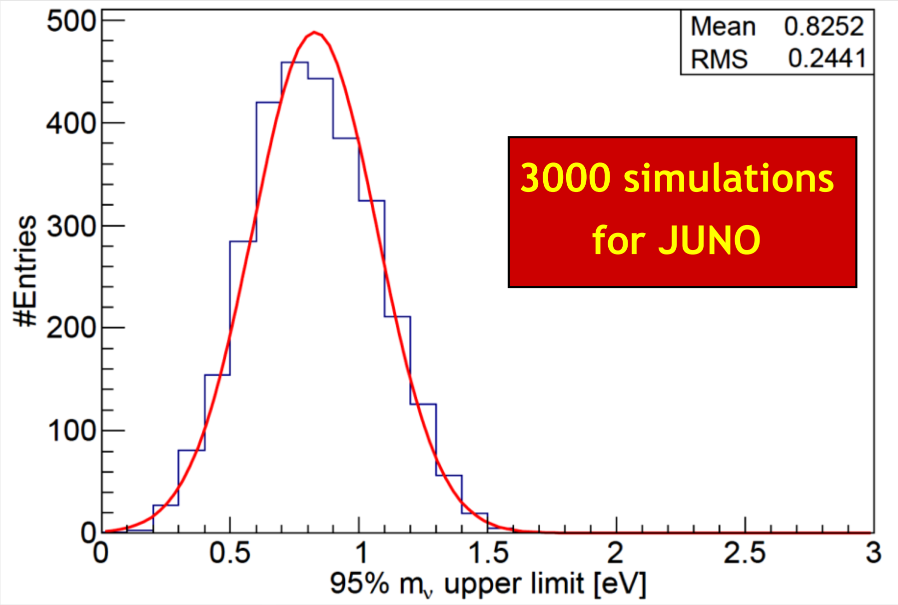
Depending on matrix elements and Majorana phases

We need elaborate what can we do best from SN neutrinos

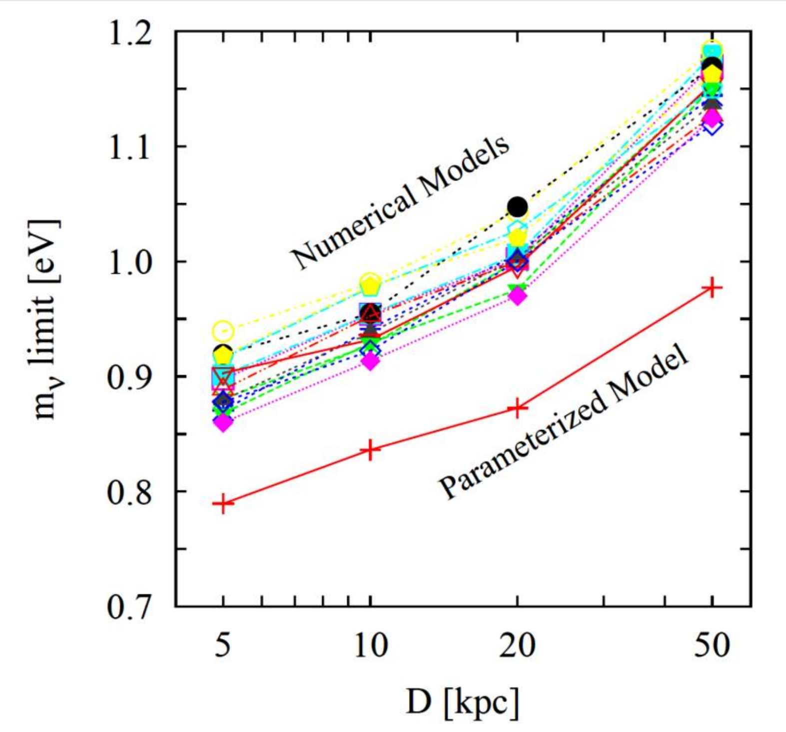
(H): Neutrino mass bound

Time delay of massive neutrinos

$$\Delta t(m_\nu, E_\nu) = 5.14 \text{ ms} \left(\frac{m_\nu}{\text{eV}}\right)^2 \left(\frac{10 \text{ MeV}}{E_\nu}\right)^2 \frac{D}{10 \text{ kpc}}$$



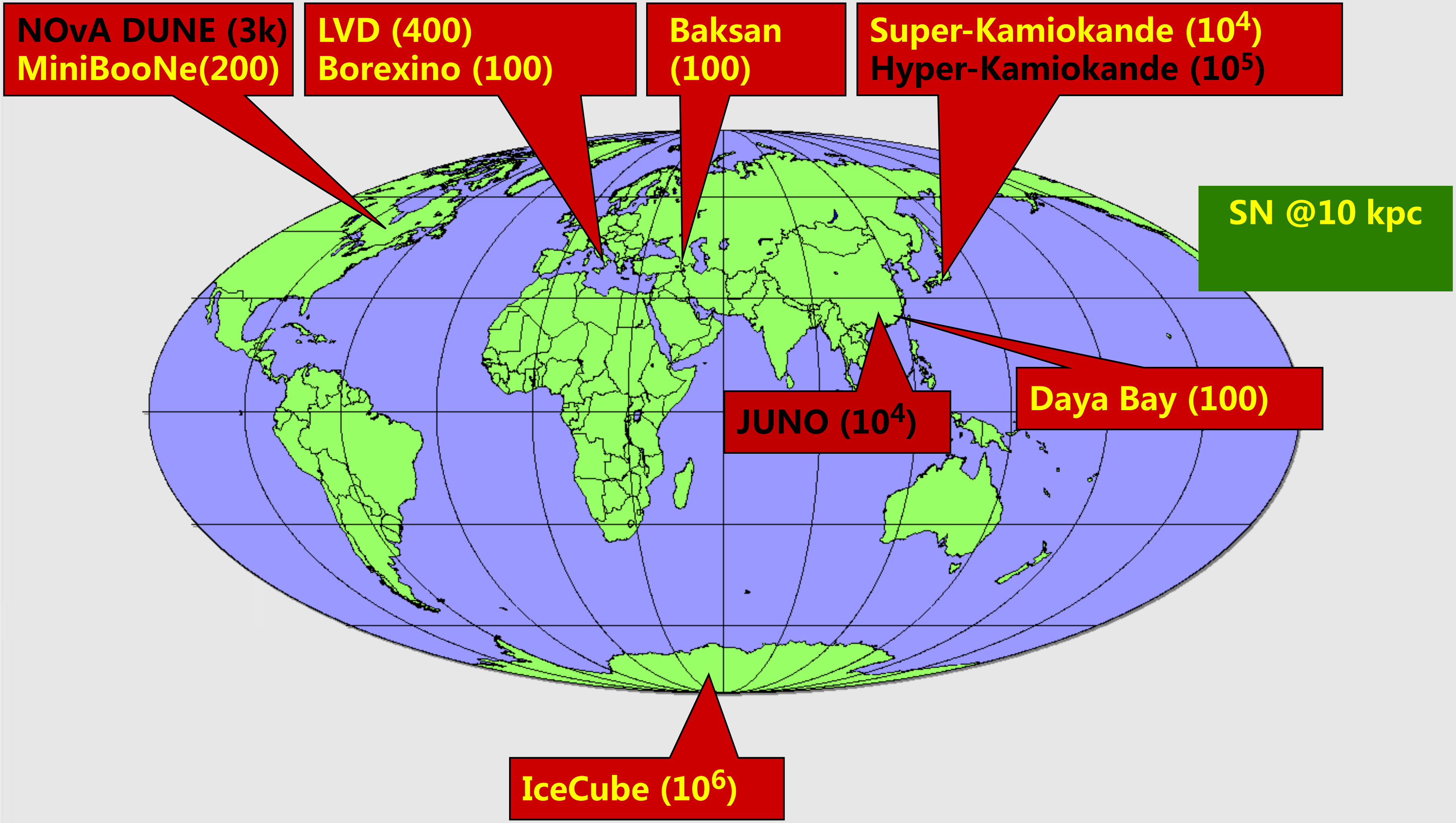
J.S. Lu et al., JCAP, 2015



(1) SK limit: **(0.94 ± 0.28) eV**

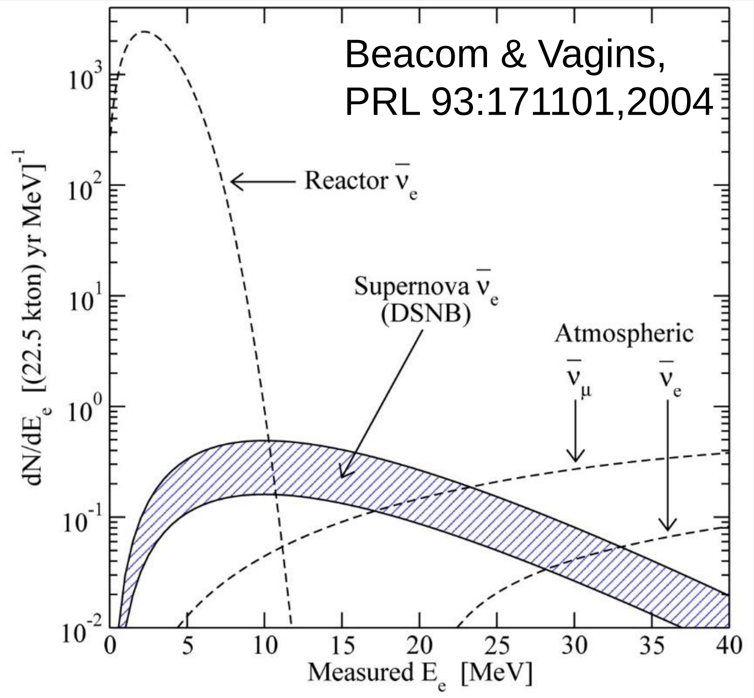
(2) 5 or 10 times of JUNO: **(0.52±0.15) eV, (0.42±0.13) eV**

JUNO in the Future SN ν Detection Network



Diffuse SN Background (DSNB)

- **Approx. 1-10 core collapses/sec in the visible universe**
- **Detectable $\overline{\nu}_e$ flux at Earth ~ 10 cm^{-2} s^{-1} mostly from redshift $z \sim 1$**



Neutrinos from all the SNe in our Universe

# of SNe per yr per Mpc³(un. SFR, IMF)

$$\frac{dF_{\bar{\nu}_e}}{dE_{\bar{\nu}_e}} = \frac{c}{H_0} \int_0^{z_{\max}} dz \, \frac{R_{\rm SN}(z)}{\sqrt{\Omega_{\rm m}(1+z)^3 + \Omega_\Lambda}} \, \frac{dN_{\bar{\nu}_e}(E'_{\bar{\nu}_e})}{dE'_{\bar{\nu}_e}}$$

Cosmological evolution

ν spectrum

Prospective of a DSNB measurement

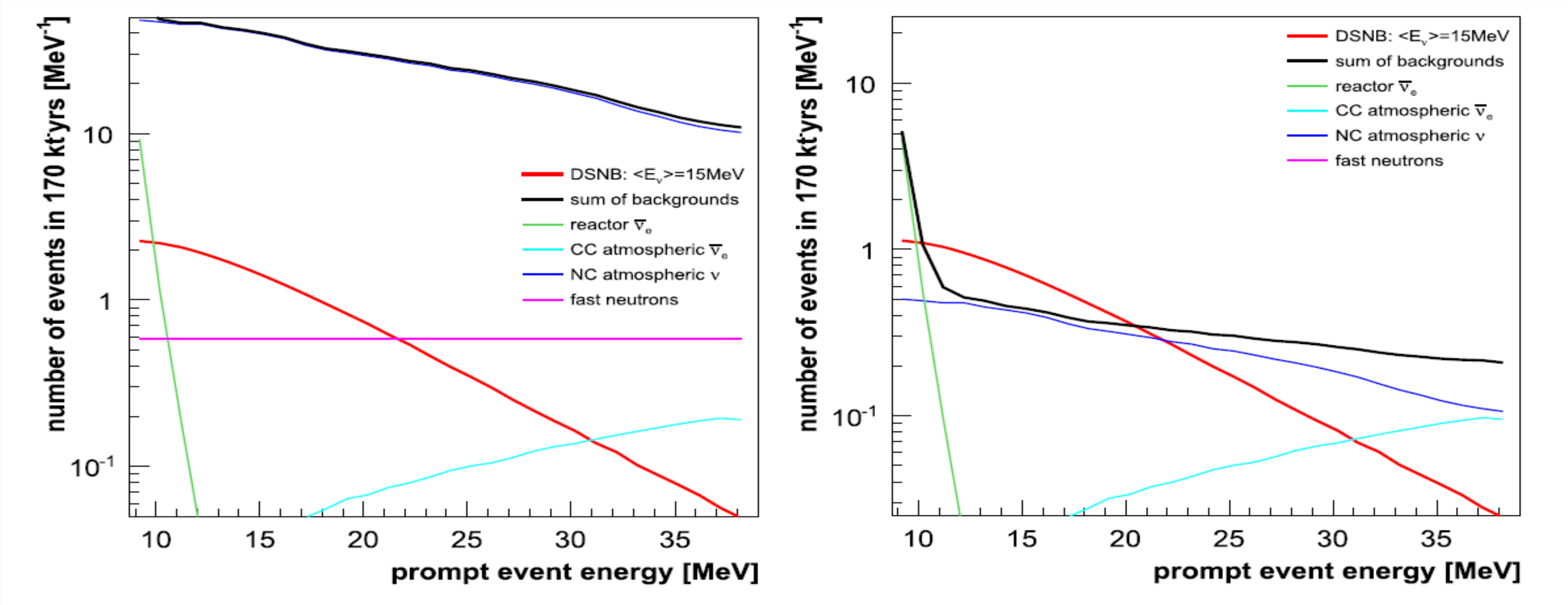
(1) first of all: discovery

(2) averaged supernova ν spectrum

(3) red shift-dependent SN rate

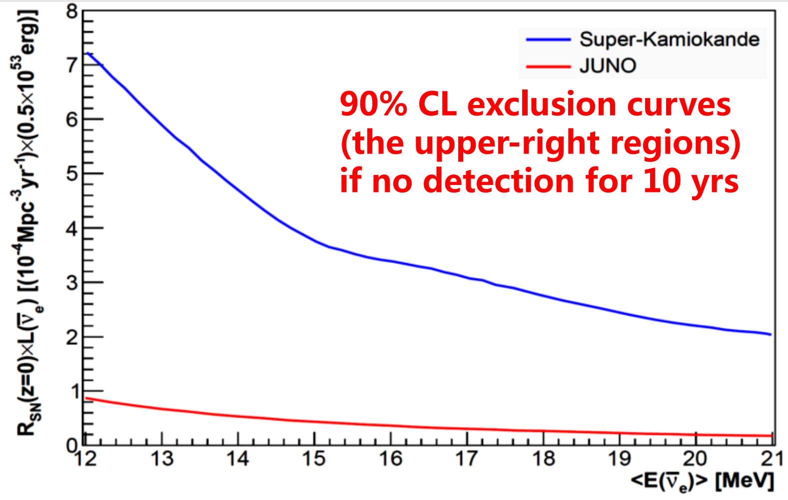
(4) fraction of hidden/failed SNe

DSNB at JUNO



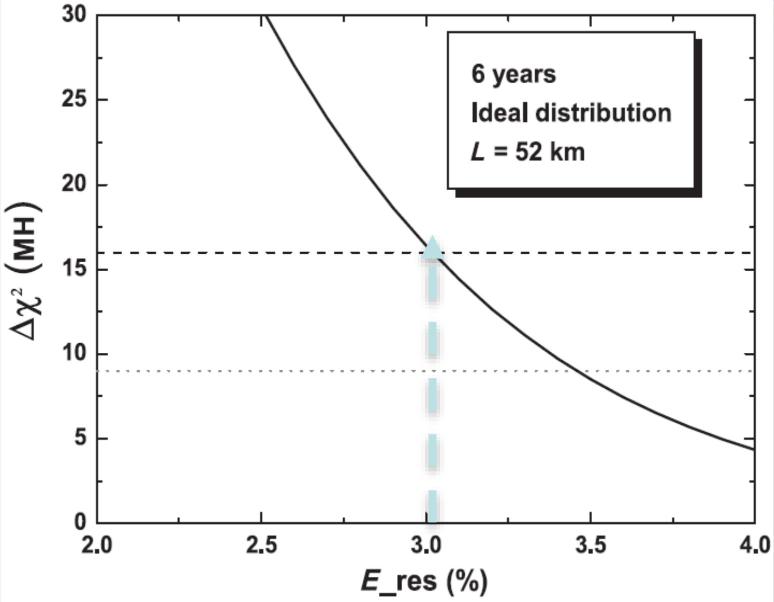
- Observation window: 11 MeV < E_ν < 30 MeV
- PSD techniques for NC atmospheric ν
- Fast neutrons: r < 16.8 m (equiv. 17 kt mass)

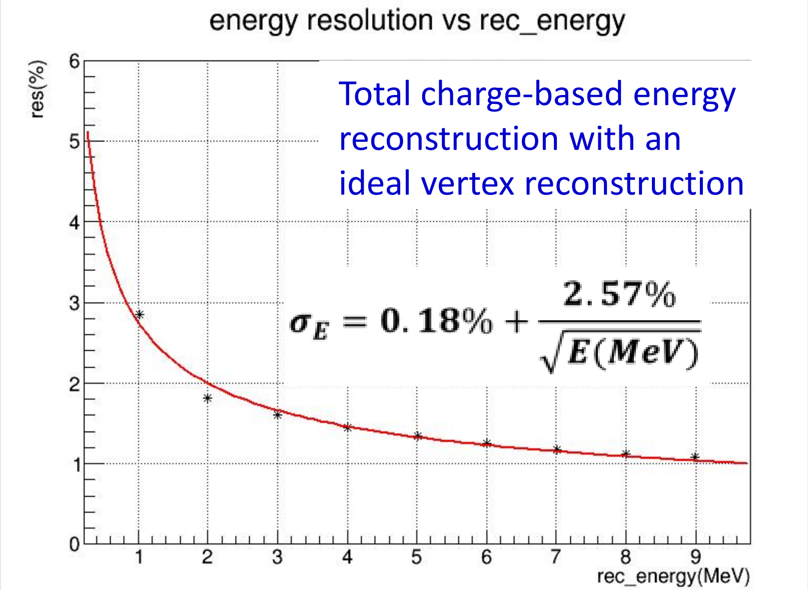
Syst. uncertainty BG	5 %		20 %	
$\langle E_{\bar{\nu}_e} \rangle$	rate only	spectral fit	rate only	spectral fit
12 MeV	$1.7\,\sigma$	$1.9\,\sigma$	$1.5\,\sigma$	$1.7\,\sigma$
15 MeV	$3.3\,\sigma$	$3.5\,\sigma$	$3.0\,\sigma$	$3.2\,\sigma$
18 MeV	$5.1\,\sigma$	$5.4\,\sigma$	$4.6\,\sigma$	$4.7\,\sigma$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



Project status

Mass hierarchy sensitivity vs energy resolution





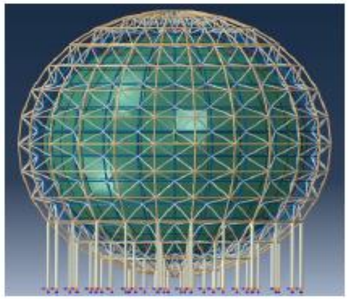
- **Energy resolution**:

  3%@1MeV energy resolution for 4 sigma sensitivity at ideal distribution.

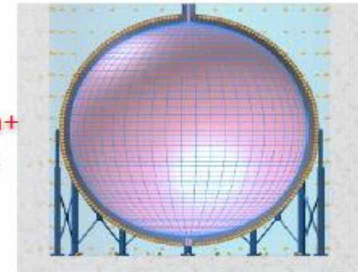
- **Experiment requirements to achieve such an unprecedented energy resolution**
  - PMT coverage: 75%
  - High QE PMT: 35%
  - Liquid scintillator attenuation length >20 m@430nm

CD Option Selection

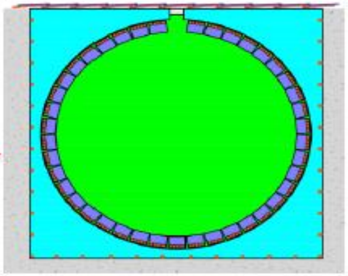
Acrylic sphere+ SS truss



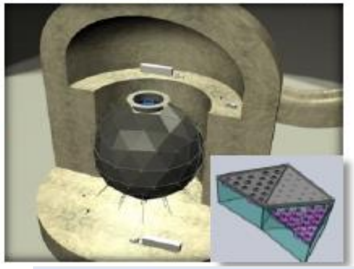
Balloon+ SS tank



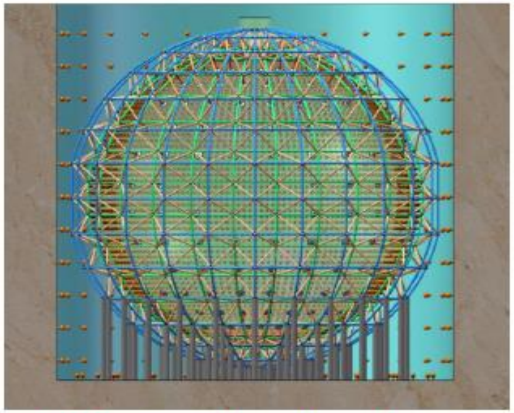
Acrylic module+ SS tank



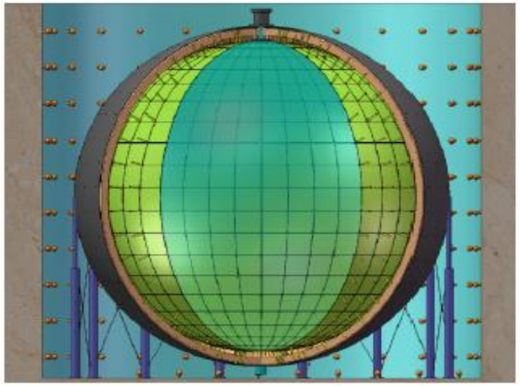
Acrylic sphere+ SS tank



March, 2014



SS truss+ Acrylic sphere



Balloon + Acrylic support+ SS tank

July, 2015

Final decision:
Acrylic sphere + SS truss

20-inch high QE PMTs

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

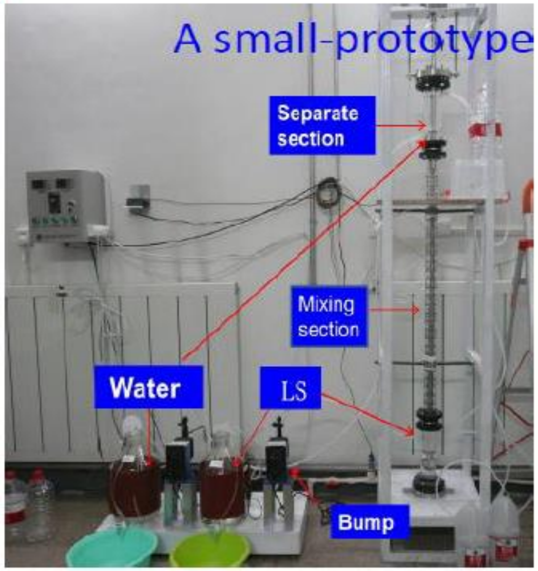
Meant for Calorimetry

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

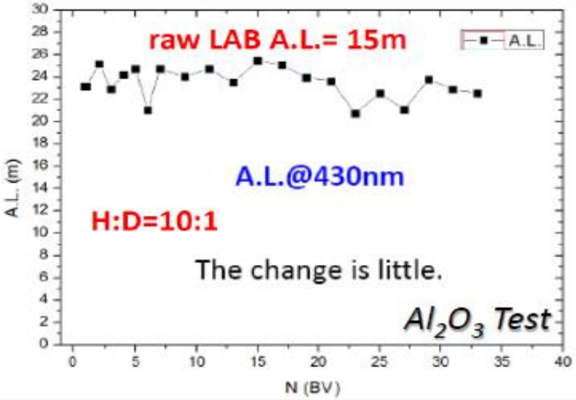
Liquid Scintillator

- *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

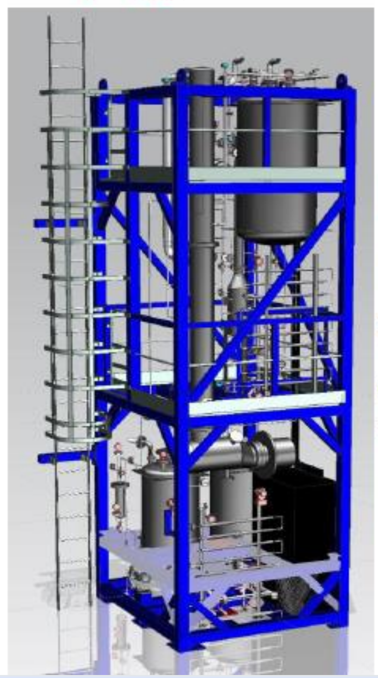
JUNO-LS Pilot plant

- 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

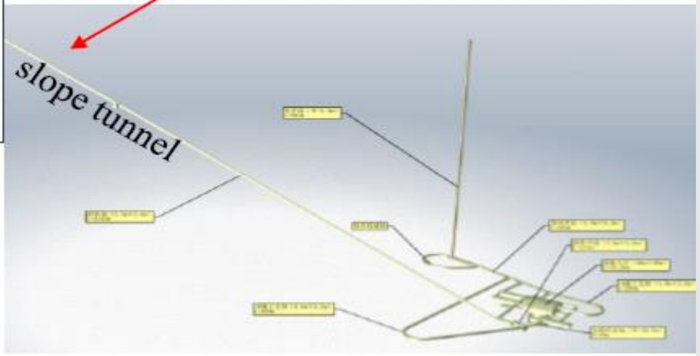
Al_2O_3 column pilot plant installed in Daya Bay LS hall

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



Summary and Outlook

(a) Neutrinos from next nearby supernova cannot be missed (a once-in-a-lifetime opportunity!).

(b) LS, WC, LAr detectors are complementary in neutrino flavors, time distributions, energy spectra, etc.

(c)10^4 neutrino events @ JUNO for a typical galactic SN; to reconstruct neutrino spectra, improve neutrino mass bound, probe neutrino mass ordering, directionality etc.

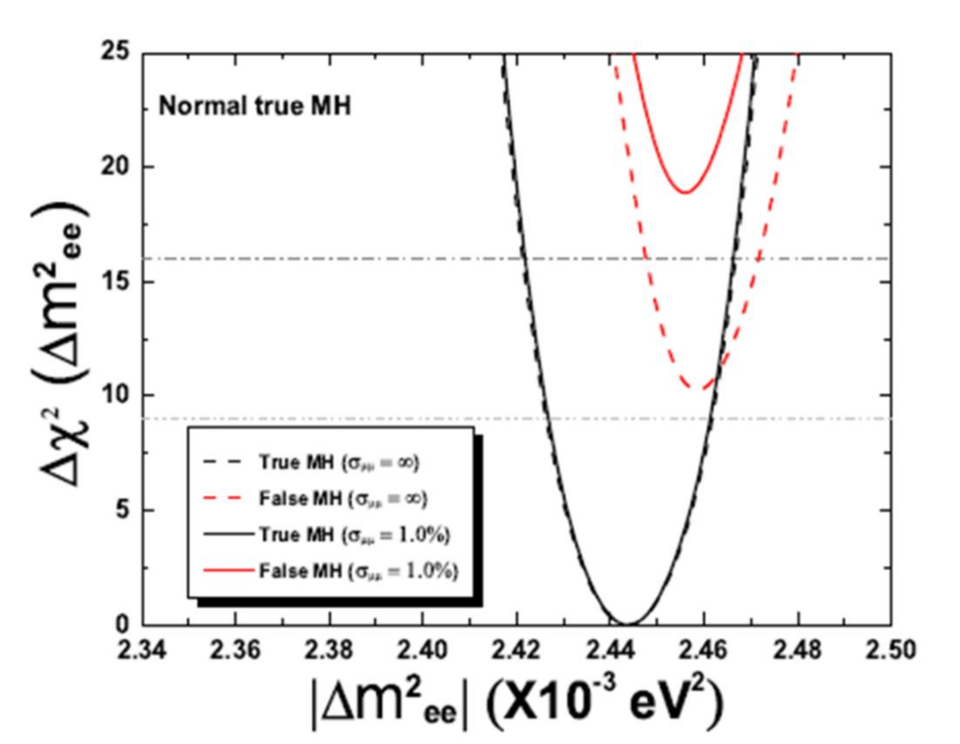
(d) JUNO is also promising in the DSNB observation.

(e) JUNO will be online in 2020.


Welcome to JUNO site
@Kaiping, Jiangmen
Thank you

Backup

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

$\Delta\chi^2\sim16$ if including an external Δm^2(*atm*) measurement

reactor core spreads; reactor flux uncertainty; energy scale uncertainty

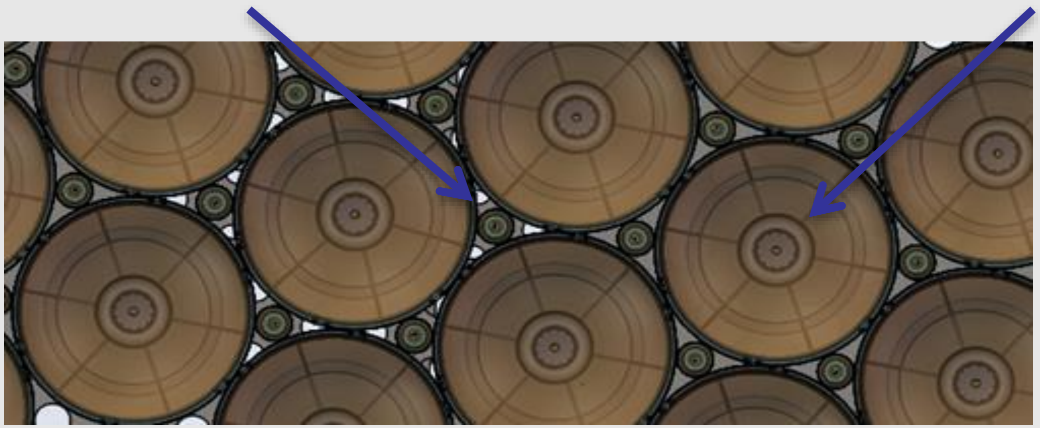
Background budget

Material	Mass (t)	U238	Th232	K40	Co60	Pb210/ Rn222	Singles (Hz) (R<17.7)	Singles (Hz) (R<17.2)
LS	20k	10^{-15}g/g	10^{-15}g/g	10^{-16}g/g		1.4e-13ppb	2.57	2.38
Acrylic	560.97	1ppt	1ppt	1ppt			7.24	0.39
PMT 20”	183.06	129ppb	173ppb	11.8ppb			13.27	1.82
PMT 3”	4.4	145ppb	272ppb	162ppb			0.49	0.06
acrylic node	25.46	0.097ppb	1.97ppb	0.05ppb	2mBq/kg		23.79	2.09
connection bar (SS)	26.46	0.097ppb	1.97ppb	0.05ppb	2mBq/kg		1.07	0.11
Rock		9.7ppm	26.6ppm	5.1ppm			9.13	0.98
PMT glue	62.8	48.4ppb	44.8ppb	4.4ppb			1.24	0.17
Radon	3.5k					0.2Bq/m^3	16.79	1.38
Sum							75.4	9.5

3” PMTs

Double Calorimetry for Central Detector

- ~36000 3” PMT
- 3” PMTs are put into the gap between large 20” PMTs



- An Independent system to cross calibrate the 20” PMT system;
- Extend the energy dynamical range beyond the region where large PMT are no more linear or even saturated;
- Lower TTS of small PMTs with good time resolution for vertex reconstruction improvement;
- Improve muon tracking reconstruction with better timing for better 9Li/8He backgrounds control.

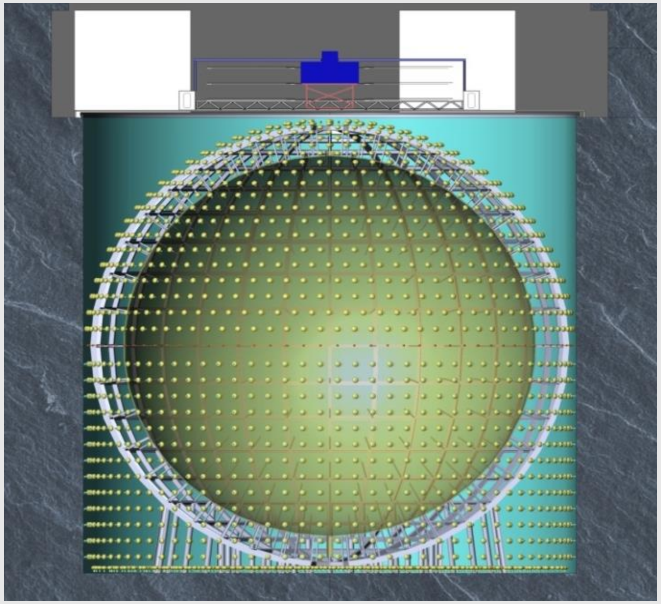
Veto system

Veto system: Water Cherenkov detector+Top tracker system

Cosmogenic isotope reduction (9Li/8He)→ requires a precise muon track reconstruction

Fast neutrons background rejection → passive shielding and possible tagging

Radioactivity from rocks → passive shielding by water



Water Cherenkov detector

- **Detector Characteristics**

  ~2000 20-inch MCP-PMTs used for veto system

  Tyvek reflector film coated on surface to increase light collection efficiency

  Detector efficiency is expected to be > 95%

  Background Estimation: Fast neutron background ~0.1/day

- **Water system:**
  - 20-30 kton ultra pure water in the pool
  - Employ a circulation/polishing water system (~2 weeks for one volume circulation)
  - Keep a good water quality including radon control (<0.2 Bq/m^3)

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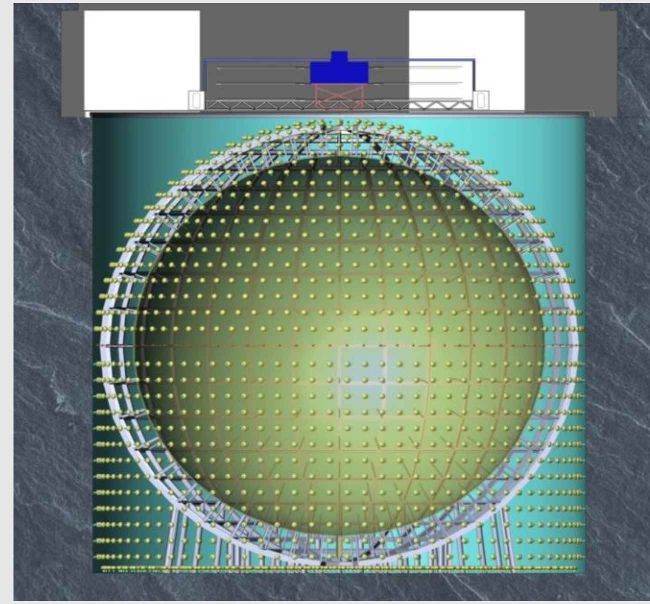

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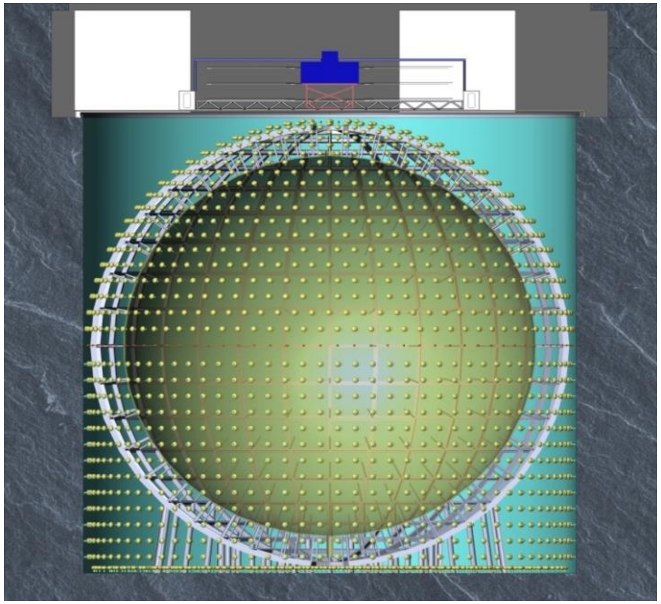

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