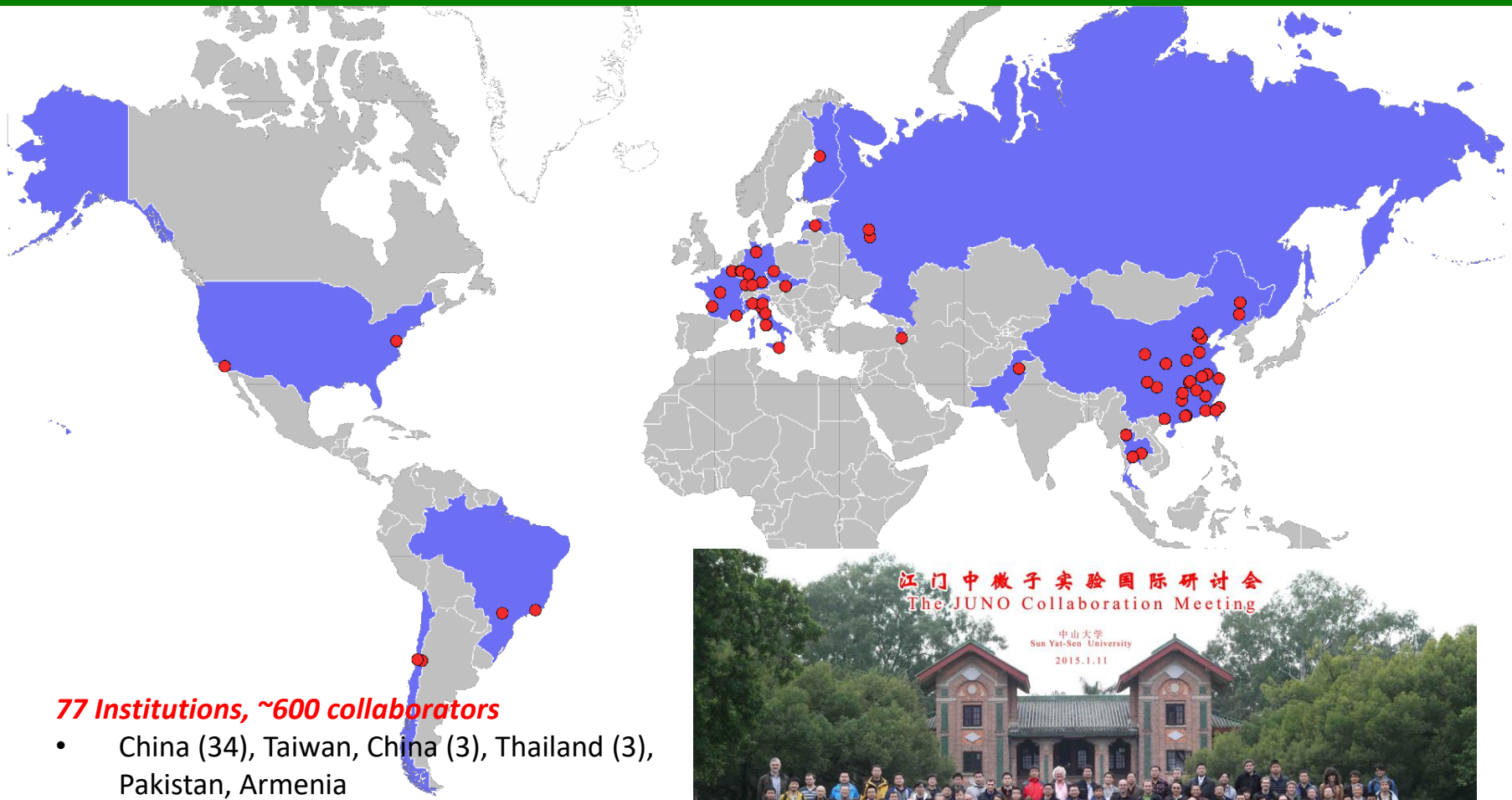
Status of JUNO

Jiajie Ling
Sun Yat-Sen University
for the JUNO Collaboration

Module of Opportunity for DUNE
BNL, Nov 12, 2019

The JUNO Collaboration



77 Institutions, ~600 collaborators

- China (34), Taiwan, China (3), Thailand (3), Pakistan, Armenia
- Italy (8), Germany (7), France (5), Russia (3), Belgium, Czech, Finland, Slovakia, Latvia
- Brazil (2), Chile (2), USA (3)

The JUNO Site

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

by 2020: 26.6 GW

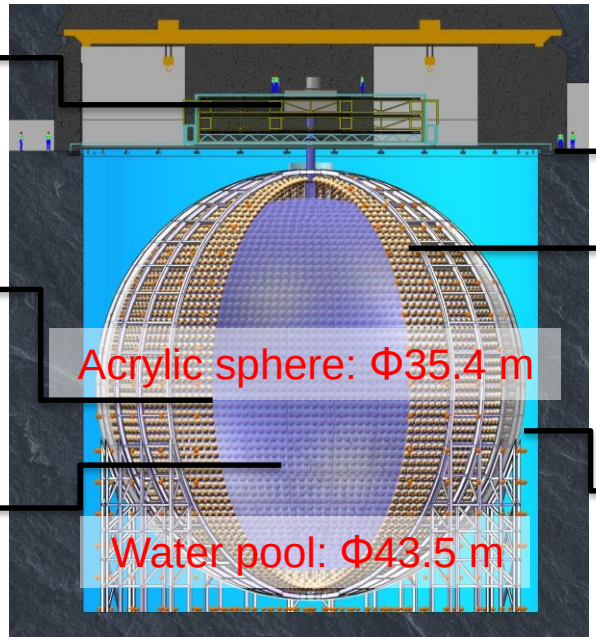
JUNO Detector Design

	KamLAND	Borexino	Daya Bay	JUNO
LS Mass [kton]	1	0.278	~0.04 x 8	20
E resolution@ 1 MeV	6%	5%	8%	3%
Photo-coverage	34%	30%	12%	77%
E calibration	1.4%	1%	0.5%	1%

Calibration room

Central detector
SS latticed shell
Acrylic sphere

Liquid scintillator
20 kton



Top Tracker

PMTs
17,600 20" PMTs +
25,000 3" PMTs:
coverage 77.5%

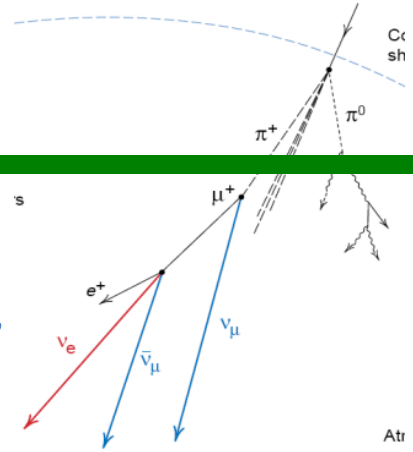
Water Cherenkov
35 kton pure water
2,000 20" veto PMTs

Neutrinos at JUNO

Solar ν
(10s-1000s) /day

Supernova ν 5-7k in 10 s for 10 kpc

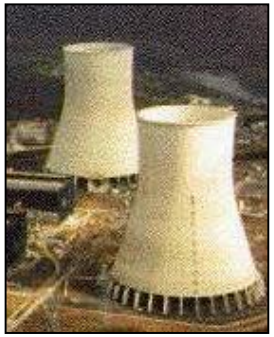
Atmospheric ν
several/day



700 m

Cosmic-ray
~ 250k /day

0.0037 Hz/m^2
215 GeV
10% muon bundles



36 GW$_{th}$, 53 km

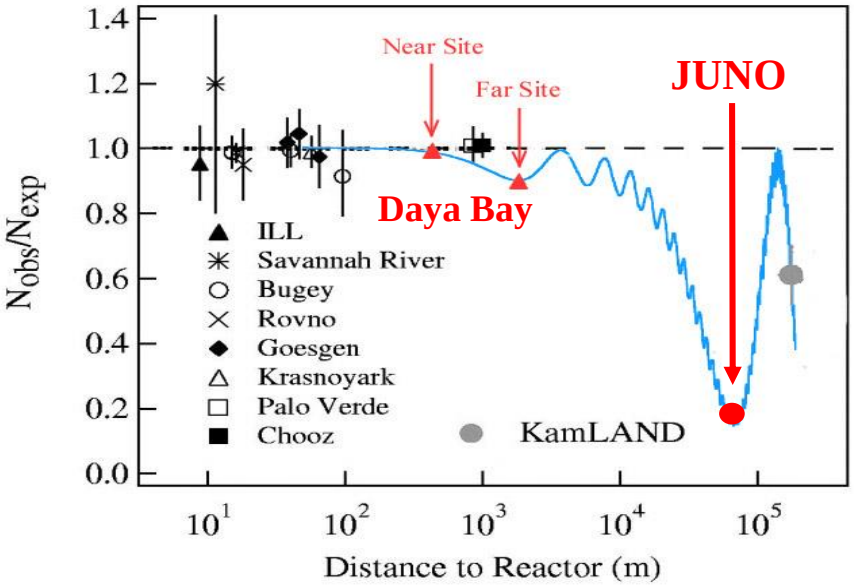
Reactor ν, 60 /day

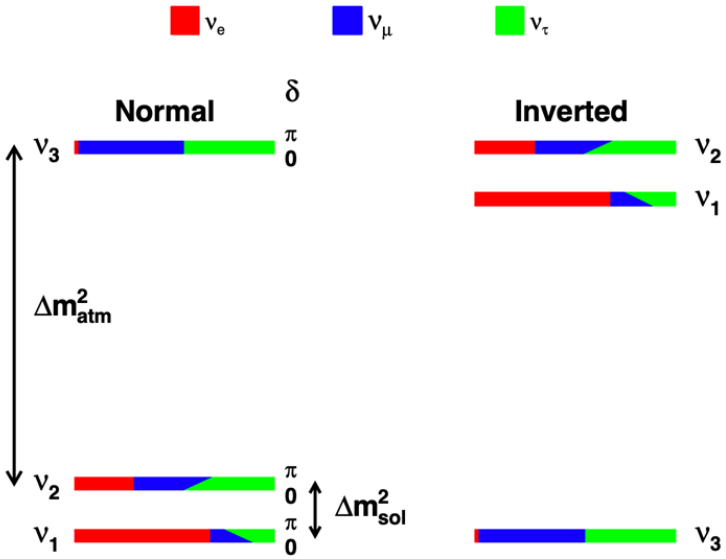
20k ton
LS

Geo ν
1.1 /day

Proton decay

Neutrino Oscillation at Jiangmen Underground Neutrino Observatory (JUNO)





$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - cos^4\theta_{13} sin^2 2\theta_{12} sin^2\Delta_{21} - sin^2 2\theta_{13}\left(cos^2\theta_{12} sin^2\Delta_{31} + sin^2\theta_{12} sin^2\Delta_{32}\right)$$

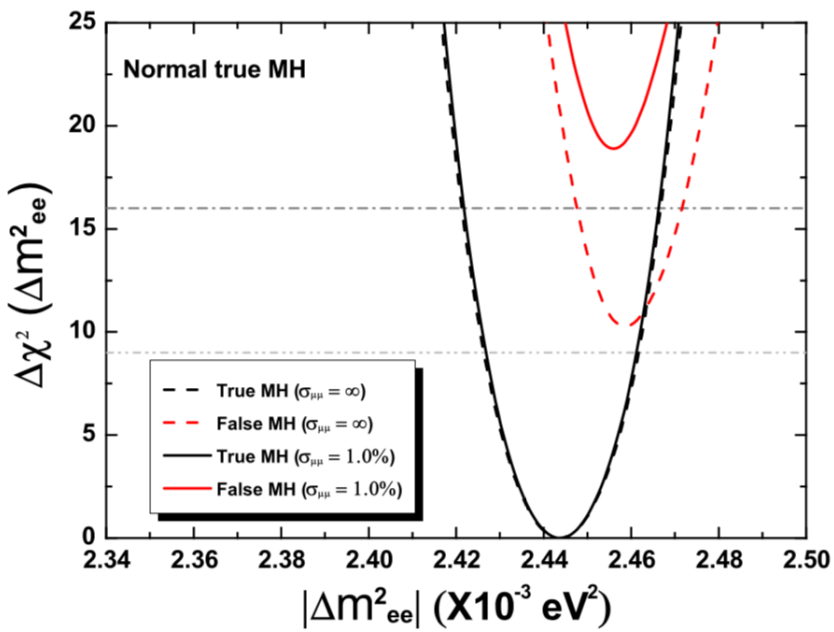
NH : $|\Delta m^2_{31}| = |\Delta m^2_{32}| + \Delta m^2_{21}$

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

S.T. Petcov et al., PLB533(2002)94
S.Choubey et al., PRD68(2003)113006
J. Learned et al., PRD78, 071302 (2008)
L. Zhan, Y. Wang, J. Cao, L. Wen, PRD78:111103, 2008, PRD79:073007, 2009
J. Learned et al., arXiv:0810.2580
Y.F Li et al, PRD 88, 013008 (2013)
…

Sensitivity of NMH Determination

Event type	Rate (per day)	Rate uncertainty (relative)	Shape uncertainty
IBD candidates	60	—	—
Geo-νs	1.1	30%	5%
Accidental signals	0.9	1%	negligible
Fast-n	0.1	100%	20%
^{9}Li–^{8}He	1.6	20%	10%
^{13}C $(\alpha, n)^{16}$O	0.05	50%	50%



JUNO MH sensitivity with 6 years' data assuming full reactor power

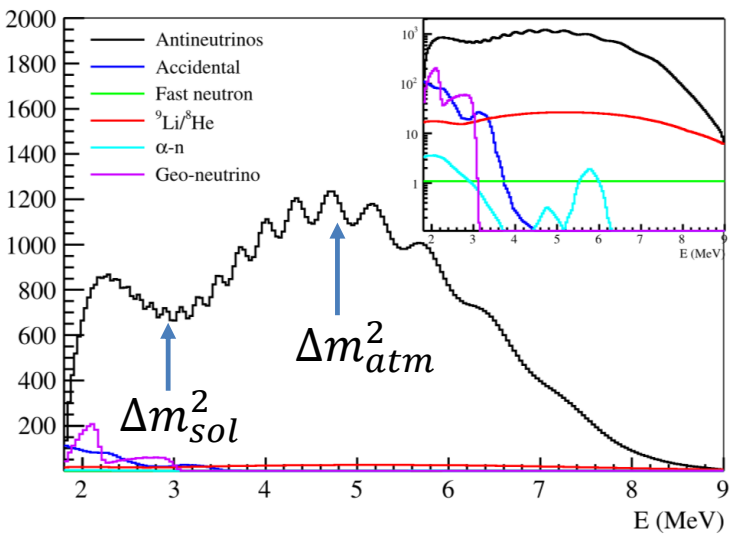
	Size	$\Delta\chi^2_{MO}$
Ideal	52.5 km	+16
Core distr.	Real	-3
DYB & HZ	Real	-1.7
Spectral Shape	1%	-1
B/S (rate)	6.3%	-0.6
B/S (shape)	0.4%	-0.1

Precision Measurement

Current precision

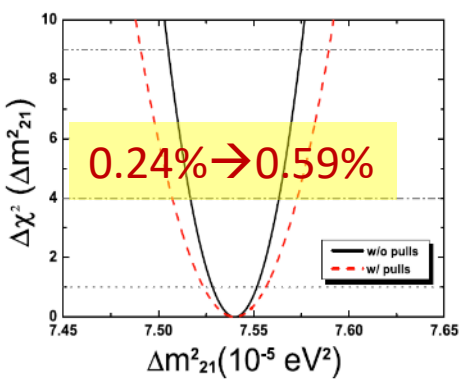
	Δm^2_{21}	$\lvert\Delta m^2_{31}\rvert$	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$	δ
Dominant Exps.	KamLAND	T2K	SNO+SK	Daya Bay	NOνA	T2K
Individual 1σ	2.4%	2.6%	4.5%	3.4%	5.2%	70%
Nu-FIT 4.0	2.4%	1.3%	4.0%	2.9%	3.8%	16%

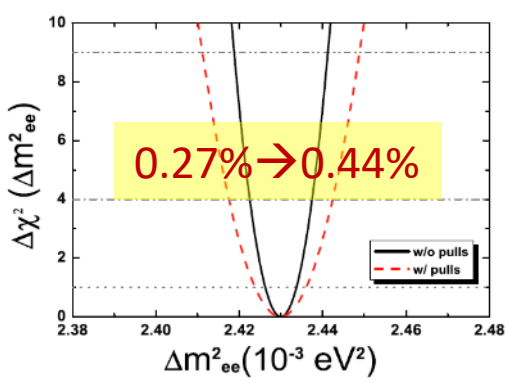
Probing the unitarity of U_{PMNS} to ~1%, more precise than CKM matrix elements!

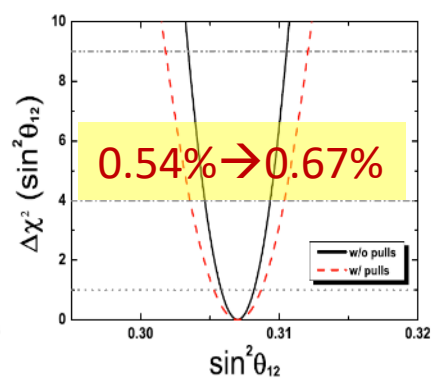


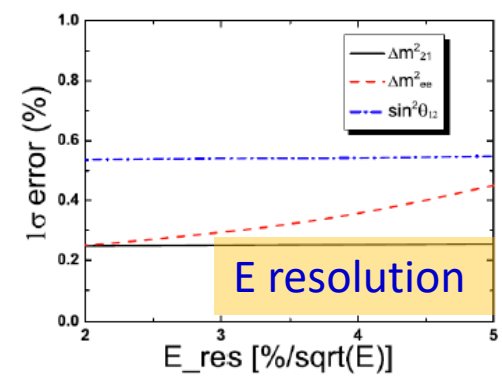
	Statistics	+BG, +1% b2b +1% EScale , +1% EnonL
$\sin^2\theta_{12}$	0.54%	**0.67%**
Δm^2_{21}	0.24%	**0.59%**
Δm^2_{32}	0.27%	**0.44%**

J. Phys. G43:030401 (2016)



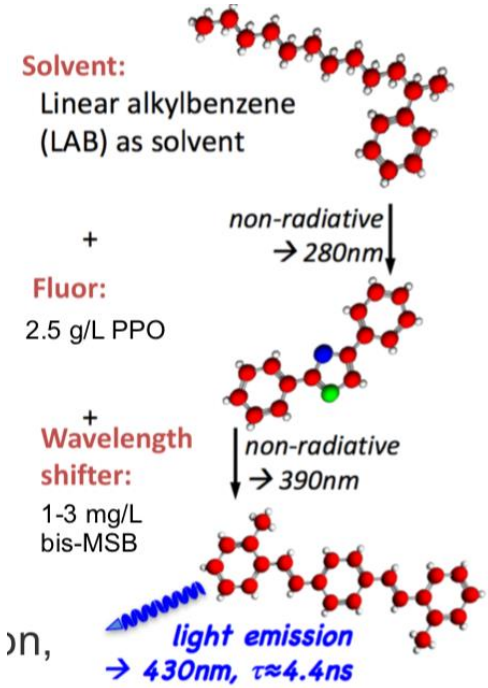






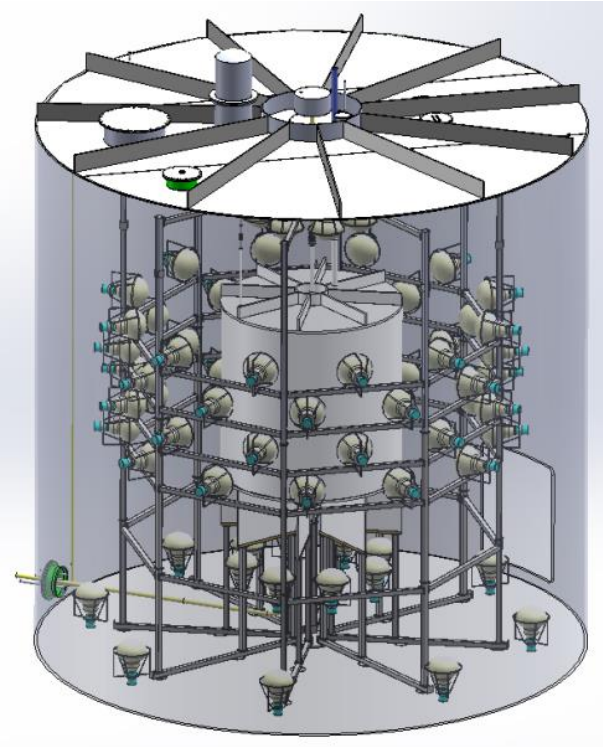
Liquid scintillator

- Requirements for JUNO LS
  - Low background: $^{238}U < 10^{-15}$ g/g, $^{232}Th < 10^{-15}$ g/g, $^{40}K < 10^{-17}$ g/g
  - High light yield: 10^4 PE/MeV
  - High transparency: Attenuation length > 20m@430nm
- Purification pilot plant
  - Distillation: Remove heavy metal and improve transparency
  - Al_2O_3 column purification: Remove impurity
  - Water extraction: Remove U/Th/K
  - Gas stripping: Remove Ar/Kr/Rn
  - Use one DayaBay AD for R&D
  - 222Rn suppression > 94%
  - Attenuation length > 20m @ 430nm

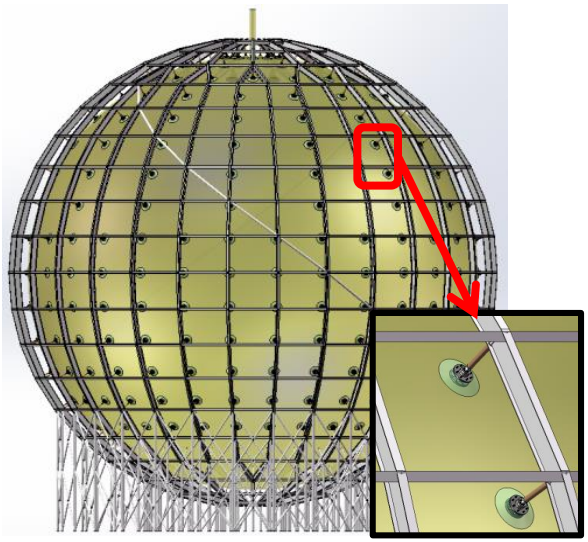


OSIRIS

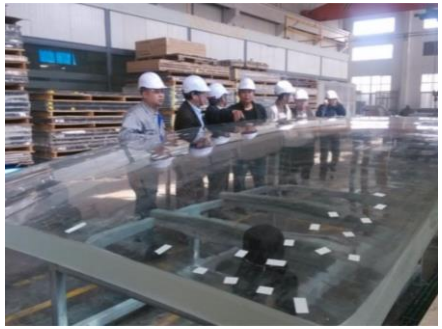
- Online Scintillator Internal Radioactivity Investigation System (OSIRIS);
- Measure the radioactive contamination of LS before filling into JUNO detector;
- Sensitivity: 10^{-16}g/g for U/Th within 24h measurement;
- Measure ~19t LS per day;
- Detector:
  - Φ3m*H3m Acrylic tank;
  - 2.5m water shielding;
  - 81 PMTs for photon detection;



Central detector

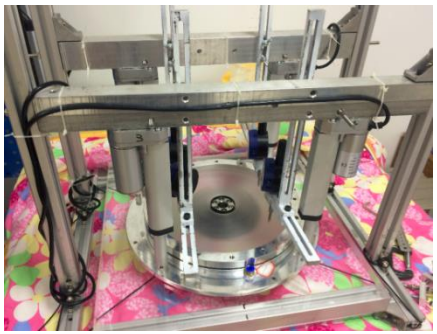


- Acrylic sphere: ID 35.4m, thickness: 120 mm
  - 265 pieces of 3 m×8 m panels
- Stainless steel: ID 40.1 m, OD 41.1 m
  - 30 longitudes and 23 layers
- Transparency > 96% in pure water
- 1ppt level of U/Th/K in acrylic sample
- Production company: Donchamp acrylic

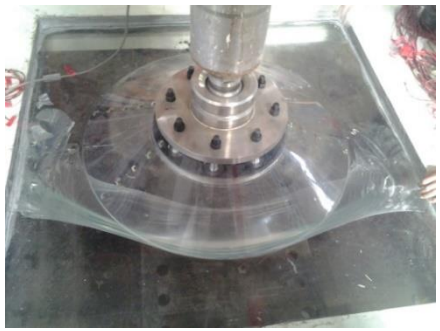


Acrylic panel

Onsite assembly



Bonding machine



Node test

Double calorimetry

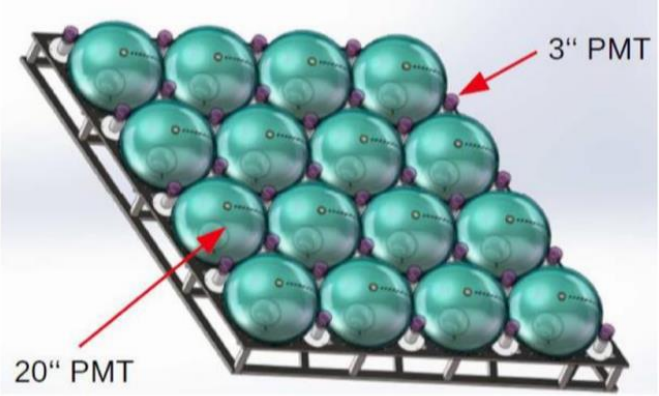
- 20” PMTs (75% photon-coverage)
  - 15,000 MCP-PMTs from NNVT
  - 5,000 dynode PMTs from Hamamatsu
- 3” PMTs (2% photon-coverage)
  - 25,000 PMTs from HZC
  - Photon counting
  - Extend dynamic range of muon measurements

20” MCP-PMT

20” Dynode-PMT

3.1” PMT

Characteristics	unit	MCP-PMT (NNVC)	R12860 (Hamamatsu)
Detection Efficiency (QE*CE*area)	%	28.3%	28.1%
P/V of SPE		3.5, > 2.8	3, > 2.5
TTS on the top point	ns	~12, < 15	2.7, < 3.5
Rise time/ Fall time	ns	2/12	5/9
Anode Dark Count	Hz	20K, < 30K	10K, < 50K
After Pulse Rate	%	1, <2	10, < 15
Radioactivity of glass	ppb	238U:50 232Th:50 40K: 20	238U:400 232Th:400 40K: 40



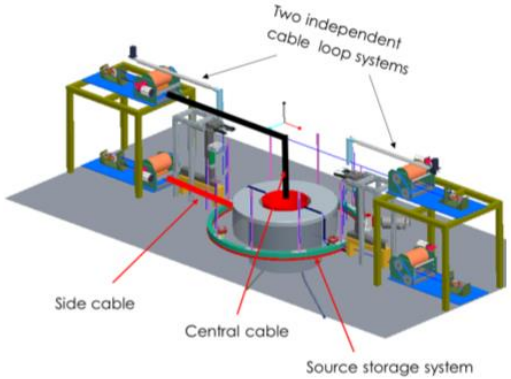
3” HZC-PMT

JUNO custom design: XP72B22

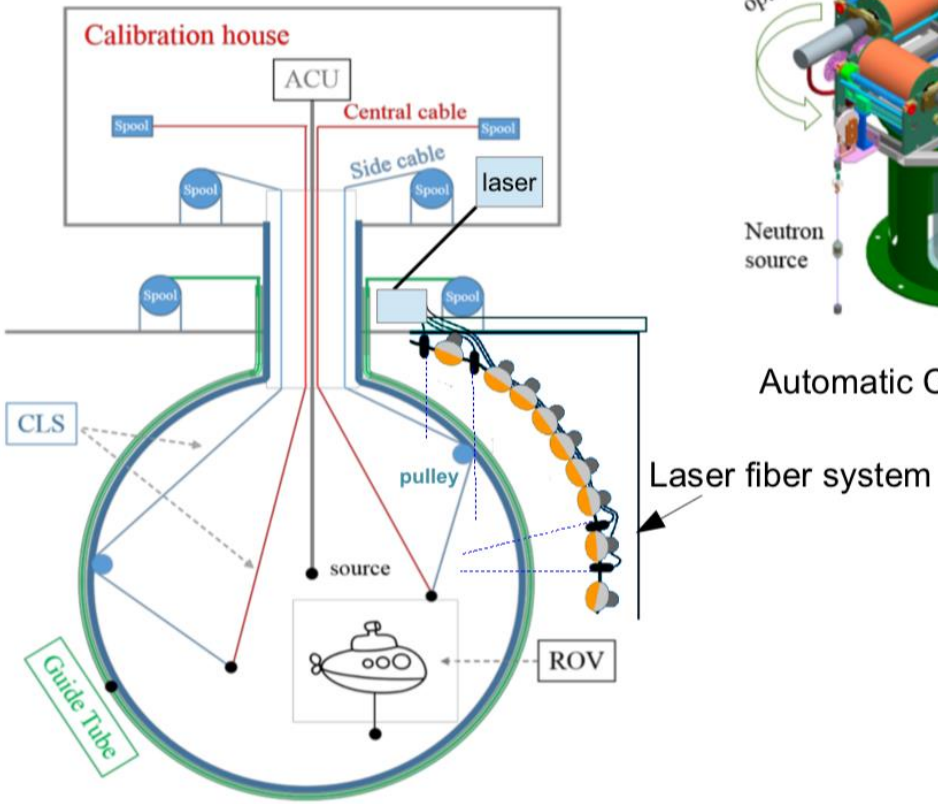
QE*CE 25%, P/V 3.2, SPE resolution 33%, TTS 4.9 ns

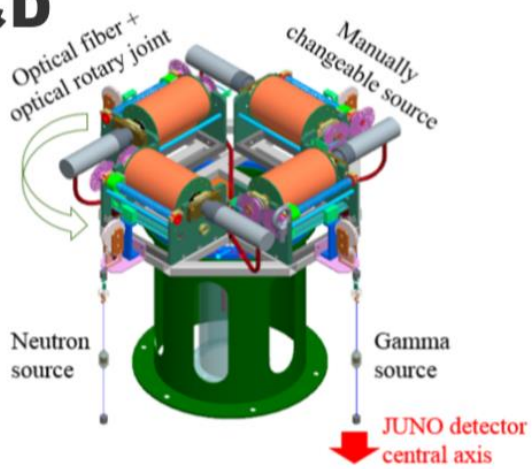
Energy calibration

- **Five complementary systems under R&D**



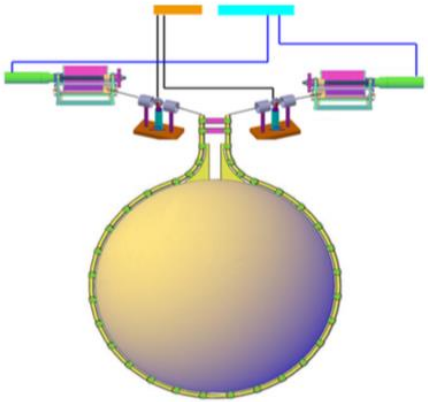
Cable Loop System (CLS)



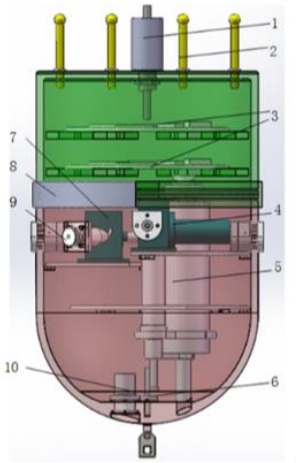


Automatic Calibration Unit (ACU)

Laser fiber system



Guide tube system



Remotely Operated Vehicle (ROV)

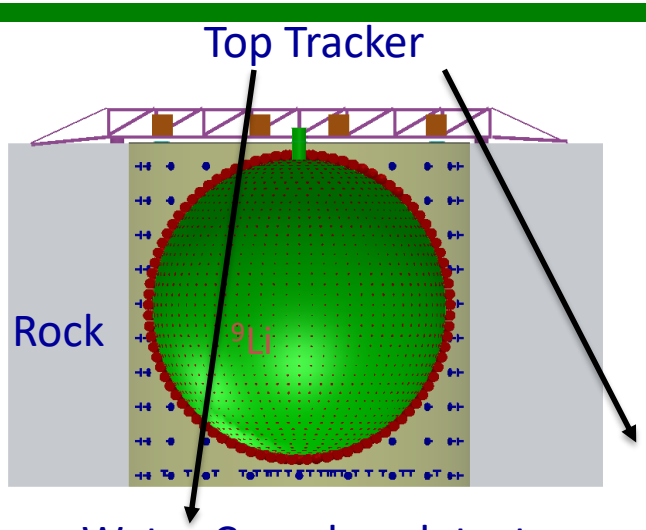
Muon veto

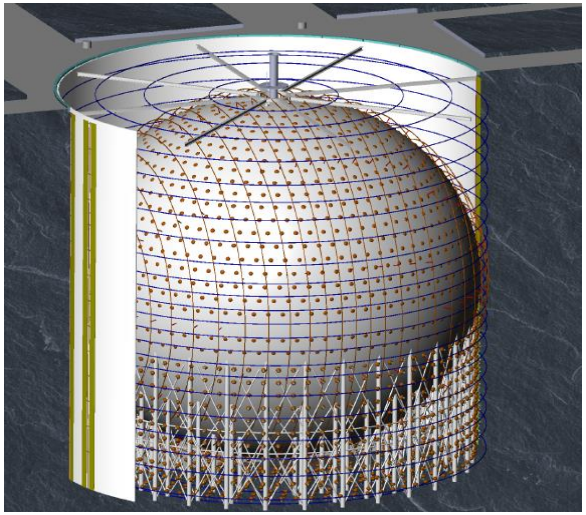
Goal of muon veto

- Active and passive shielding
- Muon tracking and cosmogenic isotope study
- Earth magnetic field shielding for 20” PMTs

- Water Cerenkov detector
  - ~2000 20” PMTs inside EMF veto
  - 35 kton ultrapure water with circulation
  - Muon detection efficiency > 95%
  - Radon control < 0.2 Bq/m^3
  - Fast neutron background ~0.1 /day

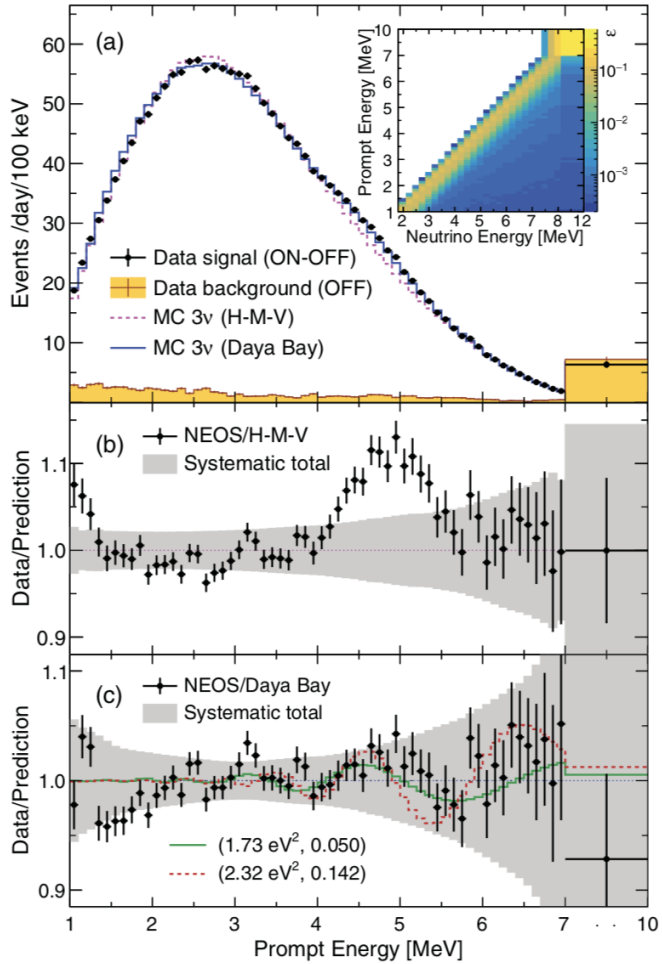
- Top tracker
  - Reuse OPERA’s target tracker
  - Cover half of the top area



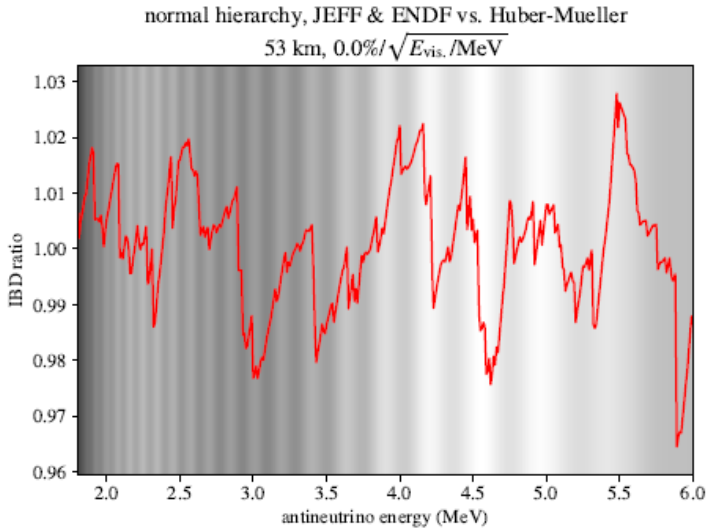


EMF coil shielding

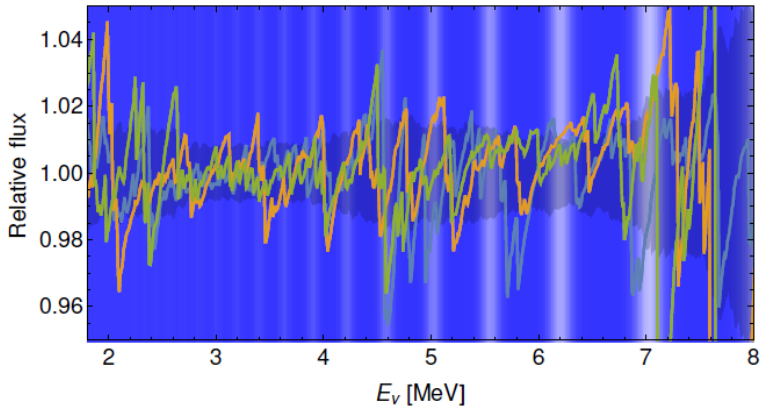
Fine Structure in Reactor Spectrum



Phys.Rev.Lett. 118, 121802 (2017)



arXiv:1808.03276



arXiv:1710.07378

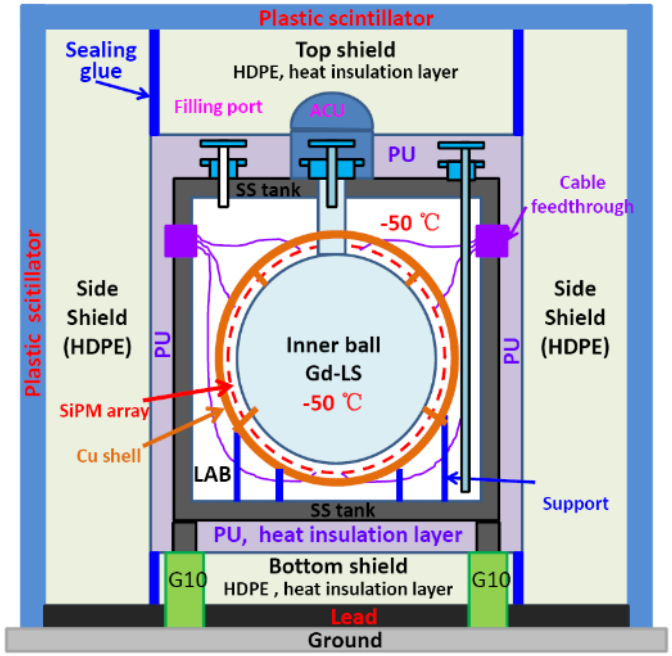
JUNO-TAO

- Taishan Antineutrino Observatory (TAO), a ton-level, high energy resolution LS detector at 30 m from the core, a satellite exp. of JUNO.

- Measure reactor neutrino spectrum with <2% E resolution.
  - model-independent reference spectrum for JUNO
  - a benchmark for investigation of the nuclear database

- Ton-level Liquid Scintillator (Gd-LS)
- Full coverage of SiPM w/ PDE > 50%
- Operate at -50 ℃ (SiPM dark noise)
- 4500 p.e./MeV

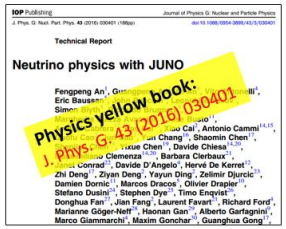
- Taishan Nuclear Power Plant, 30-35 m from a 4.6 GW_th core
- 2000 IBD/day in FV (4000)
- Online in 2021



JUNO Schedule

2014
International collaboration established

2015
- PMT production line setup
- CD parts R&D
- Civil construction start

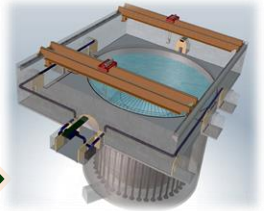


2016
- PMT production start
- CD parts production start
- Yellow book published

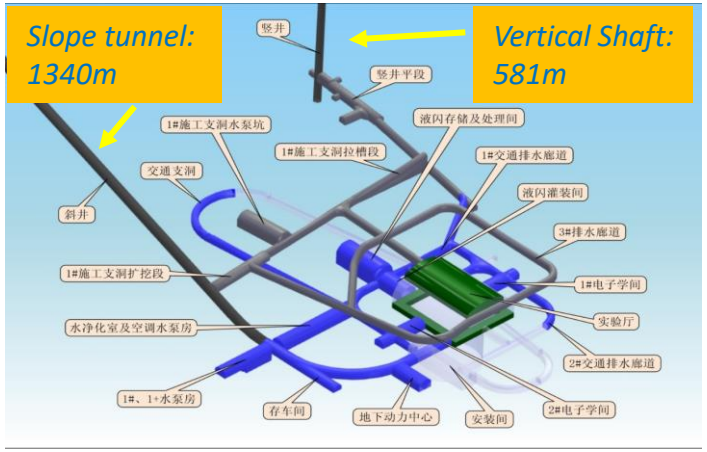
2017
- PMT testing start
- TT arrived

2018
- PMT potting
- Start delivery of surface building
- Start production of acrylic sphere

2019-2020
- Electronics production starts
- Civil construction and lab preparation completed
- Detector construction



2021
- Complete the construction and start data taking



Summary

- JUNO can have independent determination of neutrino mass hierarchy at >3σ.
- JUNO also can have sub-percent measurement on θ_{12}, Δm^2_{21}, Δm^2_{32}
- JUNO will largely advance the reactor neutrino physics and liquid scintillator technology. It will be complementary to the DUNE.

Backup

Δm^2_{ee} Definition

- Reactor ν oscillation

$$P = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})$$

- Daya Bay's 2-ν approximation

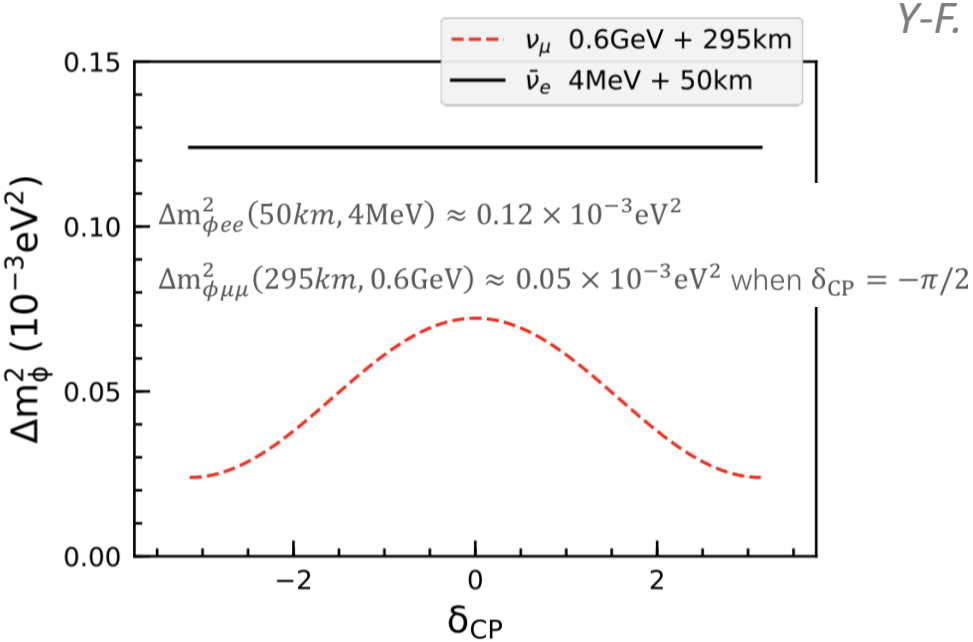
$$P_{\text{sur}} \simeq 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}\sin^2\Delta_{ee}$$

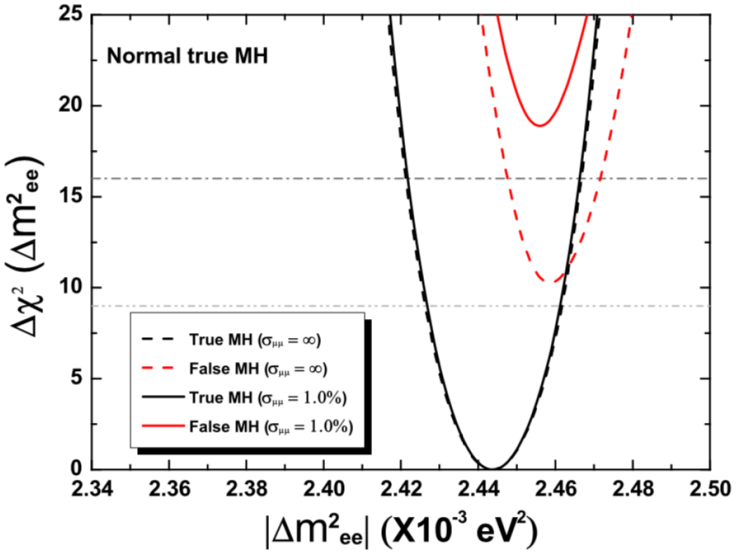
  – In the standard 3-ν framework: $\sin^2\Delta_{ee} \equiv \cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}$

- The Δm^2_{ee} definition is irrelevant to JUNO, since the 2-ν approximation is not valid. Δm^2_{31} and Δm^2_{32} should always be used.
- Detailed information is in *arXiv:1905.03840*

NMO Sensitivity with External ν_μ Constraints

*Y-F. Li, et.al. Phys.Rev.D.**88**, 013008 (2013)*





*H.Minakata, et.al. Phys.Rev.D.**74**, 053008 (2006)*

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

$$\Delta m^2_{\mu\mu} = sin^2\theta_{12}\Delta m^2_{31} + cos^2\theta_{12}\Delta m^2_{32} + cos\delta_{CP}sin\theta_{13}sin2\theta_{12}tan\theta_{23}\Delta m^2_{21}$$

Sensitivity with 100k events (20k ton LS + 6 years with 36GW$_{th}$ reactor power)

- 3% energy resolution@1 MeV, <1% energy calibration
- $\overline{\Delta\chi^2} > 9$ ($\overline{\Delta\chi^2} > 16$ with external 1% $|\Delta m^2_{\mu\mu}|$ constraint)

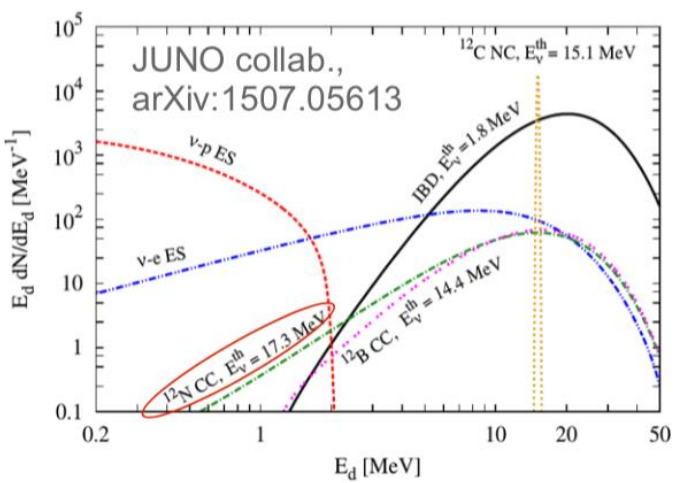
Supernova Neutrinos in JUNO

- **Core-collapse SN at 10kpc**
- **Opens new physics window:**
  - Test SN models
  - Information about MH
  - Multi-messenger astronomy
  - ...

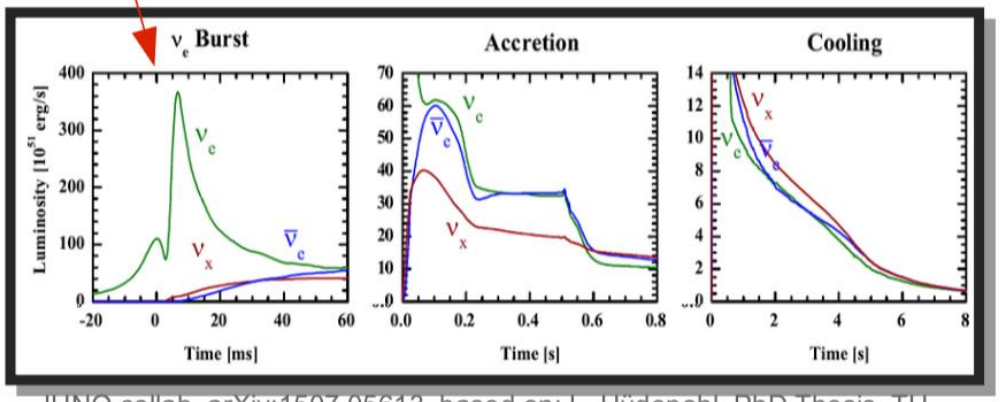
Channel	Type	Events for different $\langle E_\nu \rangle$ values		
		12 MeV	14 MeV	16 MeV
$\overline{\nu}_e + p \rightarrow e^+ + n$	CC	4.3×10^3	5.0×10^3	5.7×10^3
$\nu + p \rightarrow \nu + p$	NC	0.6×10^3	1.2×10^3	2.0×10^3
$\nu + e \rightarrow \nu + e$	ES	3.6×10^2	3.6×10^2	3.6×10^2
$\nu + {}^{12}\mathrm{C} \rightarrow \nu + {}^{12}\mathrm{C}^*$	NC	1.7×10^2	3.2×10^2	5.2×10^2
$\nu_e + {}^{12}\mathrm{C} \rightarrow e^- + {}^{12}\mathrm{N}$	CC	0.5×10^2	0.9×10^2	1.6×10^2
$\overline{\nu}_e + {}^{12}\mathrm{C} \rightarrow e^+ + {}^{12}\mathrm{B}$	CC	0.6×10^2	1.1×10^2	1.6×10^2

JUNO collab., arXiv:1507.05613

Huge statistics + Flavour information



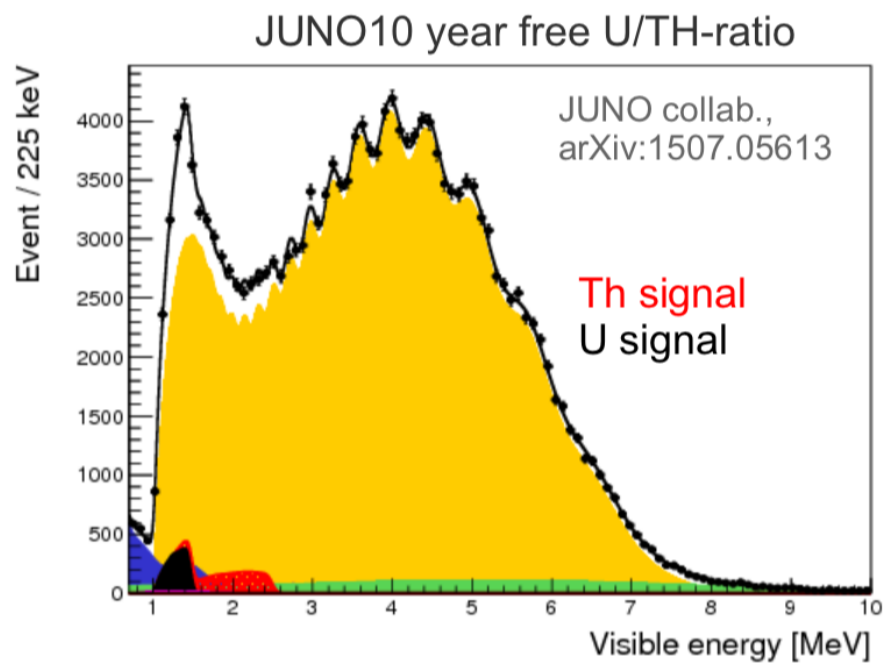
Energy spectrum



JUNO collab.,arXiv:1507.05613, based on: L. Hüdepohl, PhD Thesis, TU Munich (2013), A. Mirizzi et. al., arXiv:1508.00785

Time evolution

Geo-neutrinos

- **Exploring origin and thermal evolution of the Earth**
- **Uncertainty on flux:** 17% (1 yr) / 6% (10 yr) U/TH ratio fixed
- **For comparison:**
  - KamLAND 14.3±4.4 evts PLB 722 (2013) 295
  - Borexino 116+28-27 evts PRD 88 (2013) 033001

- **Uncertainty for U/TH flux:**
  - U: 11% (JUNO 10 yr)
  - Th: 24% (JUNO 10yr)