Precision Measurement of Neutrino Mixing at JUNO

Jiajie Ling
Sun Yat-Sen University
for the JUNO Collaboration

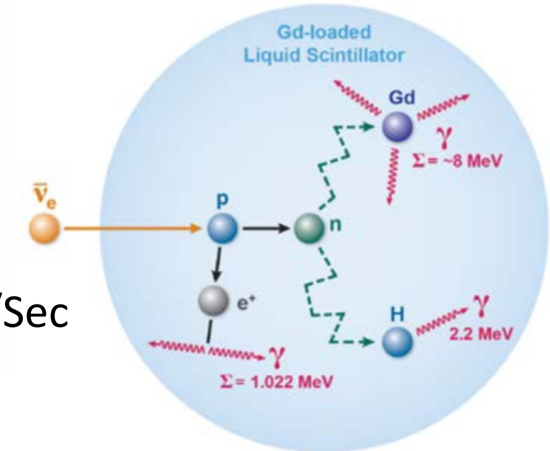
Reactor $\bar{\nu}_e$ Production and Detection

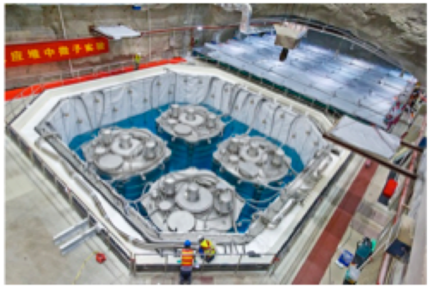
Source: Pure $\bar{\nu}_e$

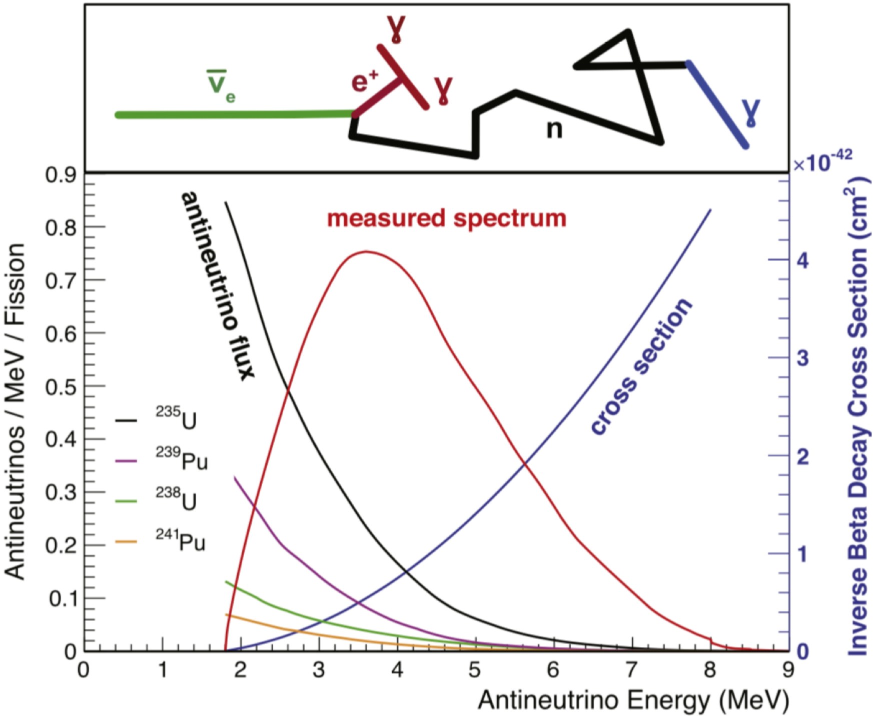
~ 200 MeV / fission

~ 6 $\bar{\nu}_e$ / fission

~ 2 x 10^{20} $\bar{\nu}_e$/GW_{th}/Sec







$$S(E_\nu) \approx c \cdot \sum_i f_i \cdot S_i(E_\nu) \cdot \sigma(E_\nu)$$

Observed $\bar{\nu}_e$ spectrum	Isotope fission fraction	Isotope neutrino spectra	IBD Xsec

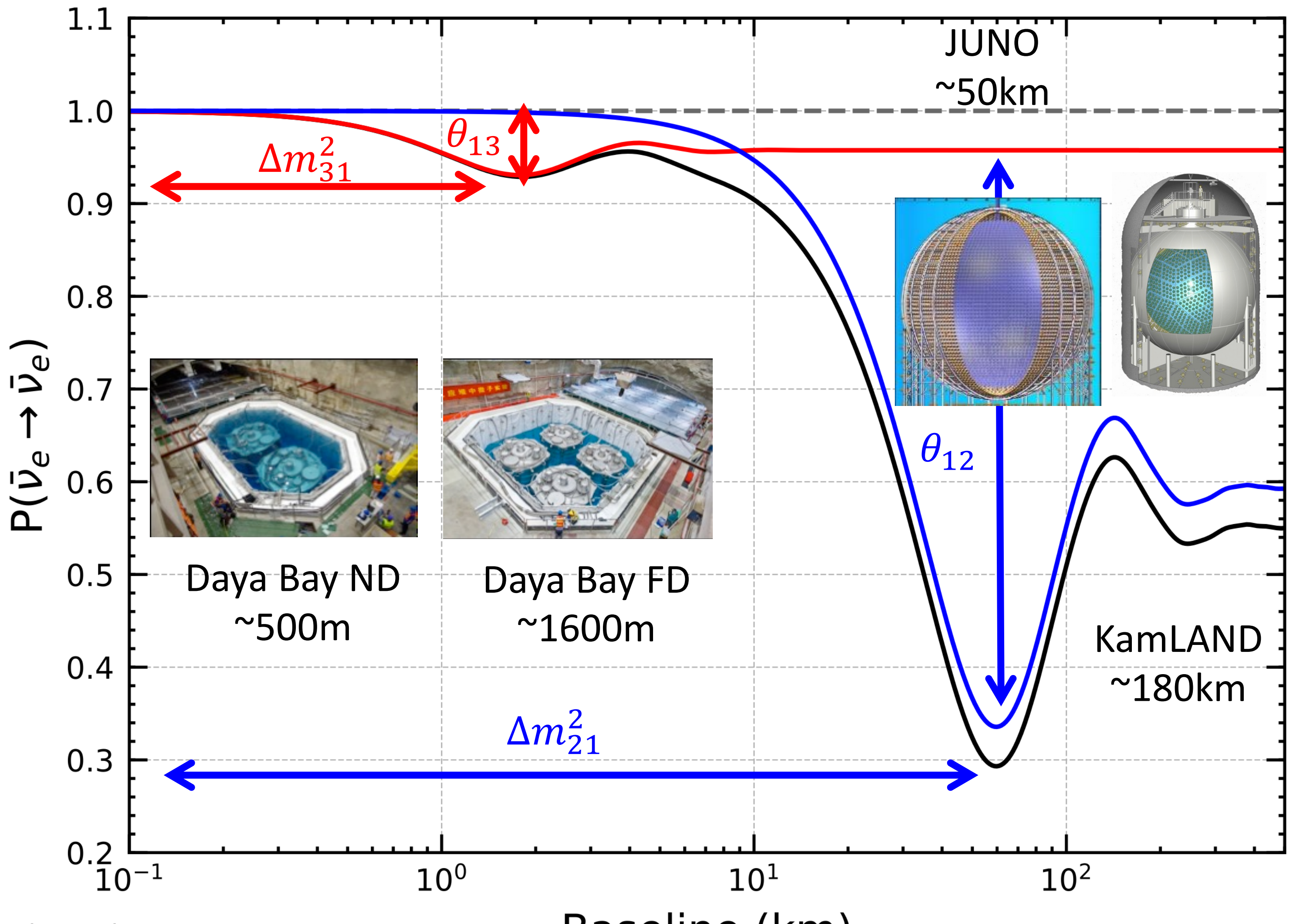
Detection: Inverse β decay (IBD)

Coincidence signals to suppress background:

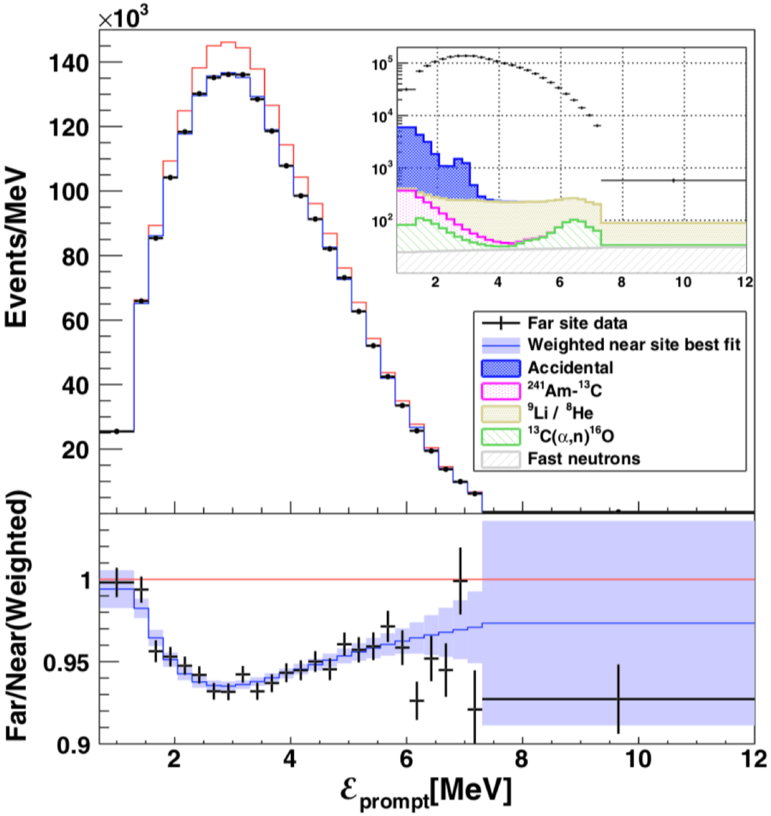
- Prompt: e+ $E_p \approx E_\nu - 0.8\ MeV$
- Delayed: nH (2.2 MeV) or nGd (~8 MeV)

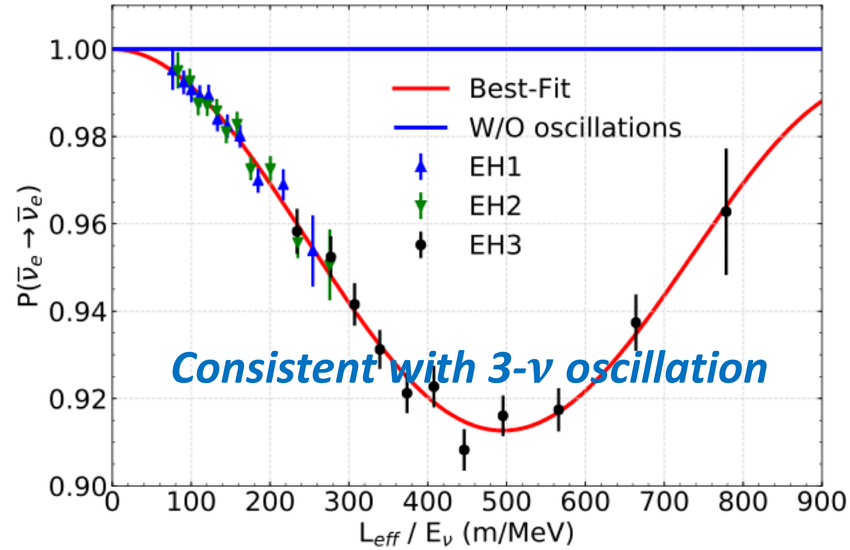
Reactor Neutrinos Oscillation

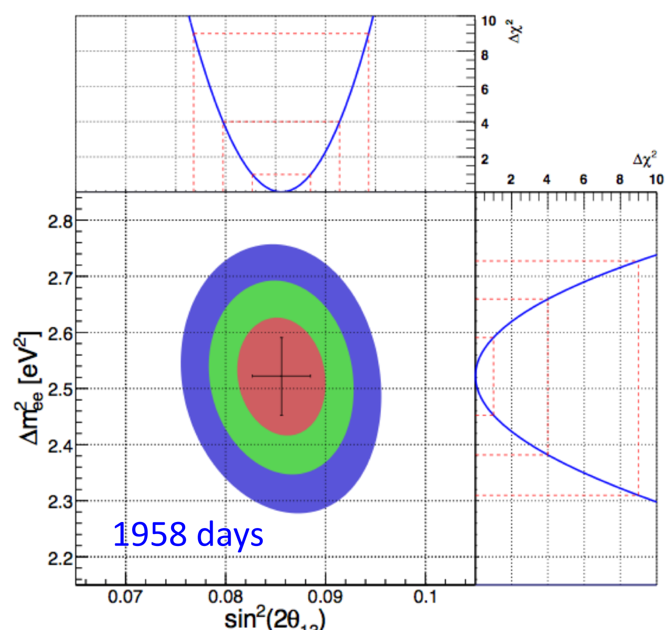
$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13}\left(\cos^2\theta_{12}\sin^2\frac{\Delta m^2_{31}L}{4E} + \sin^2\theta_{12}\sin^2\frac{\Delta m^2_{32}L}{4E}\right) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\frac{\Delta m^2_{21}L}{4E}$$



Daya Bay Recent Result







Phys. Rev. Letts 121, 241805 (2018)

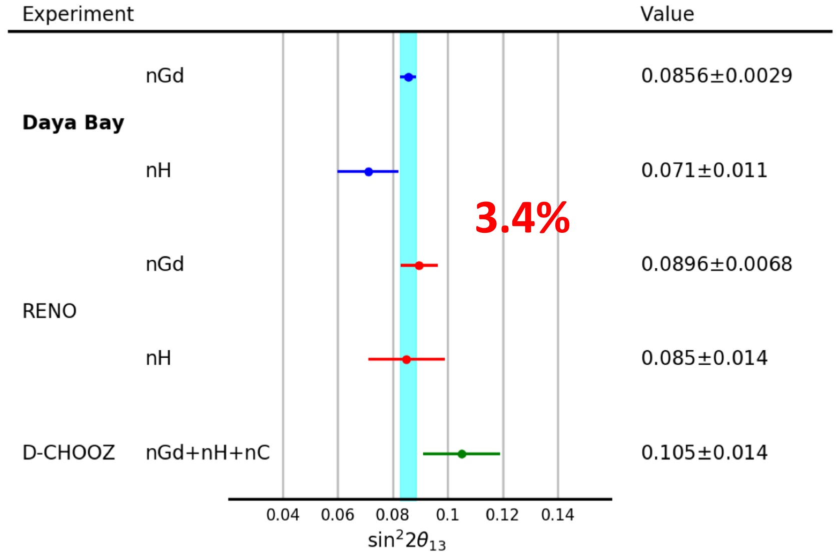
$$\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$$

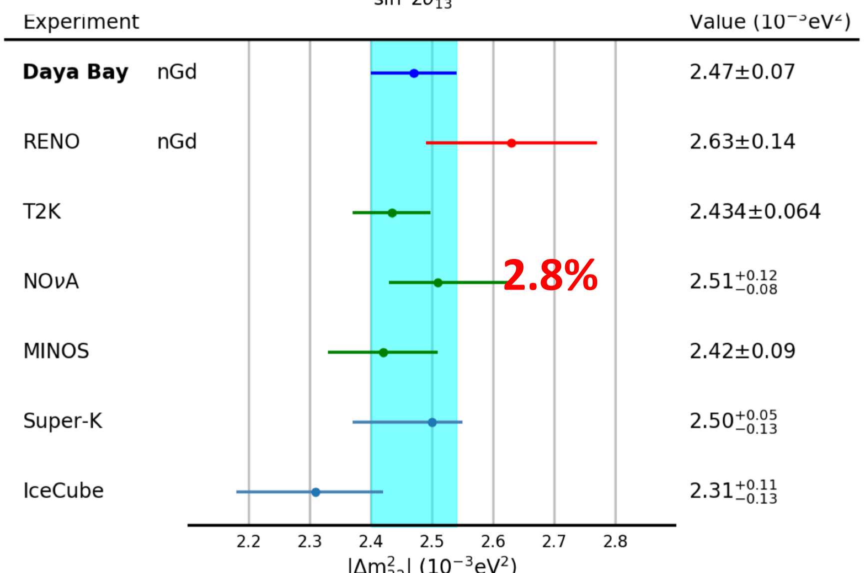
$$|\Delta m^2_{ee}| = (2.52 \pm 0.07)\times 10^{-3}\,\mathrm{eV}^2$$

$$\Delta m^2_{32} = (2.471^{+0.068}_{-0.070})\times 10^{-3}\,\mathrm{eV}^2 \text{ (NO)}$$

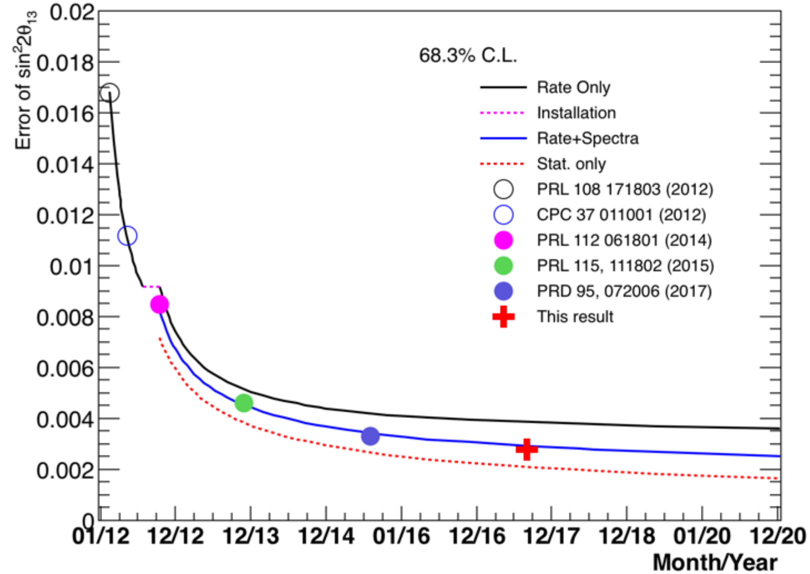
$$\Delta m^2_{32} = -(2.575^{+0.068}_{-0.070})\times 10^{-3}\,\mathrm{eV}^2 \text{ (IO)}$$

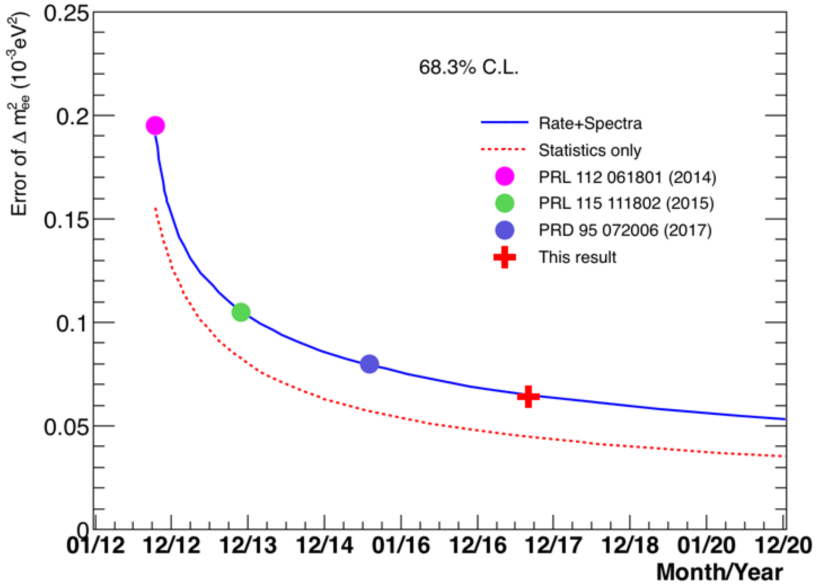
Precision Measurement from Daya Bay





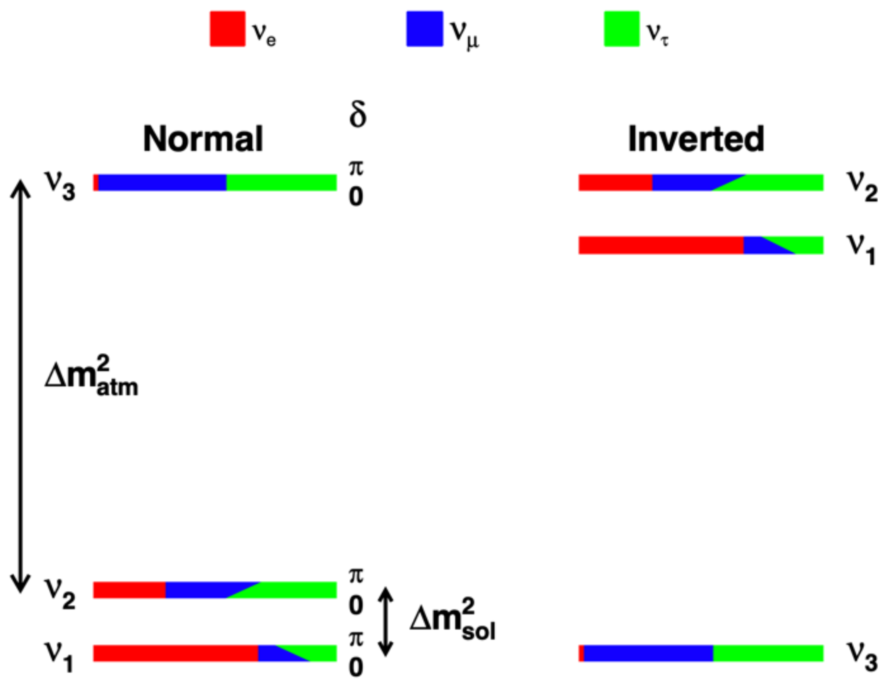
Normal





Open Questions of Massive Neutrinos

- Are neutrinos responsible for the matter anti-matter asymmetry?
- What's the neutrino mass ordering?
- Are neutrinos Dirac or Majorana particles?
- What is the neutrino mass?
- Do sterile neutrinos exist?
- Why neutrino mass is so tiny?
- ……



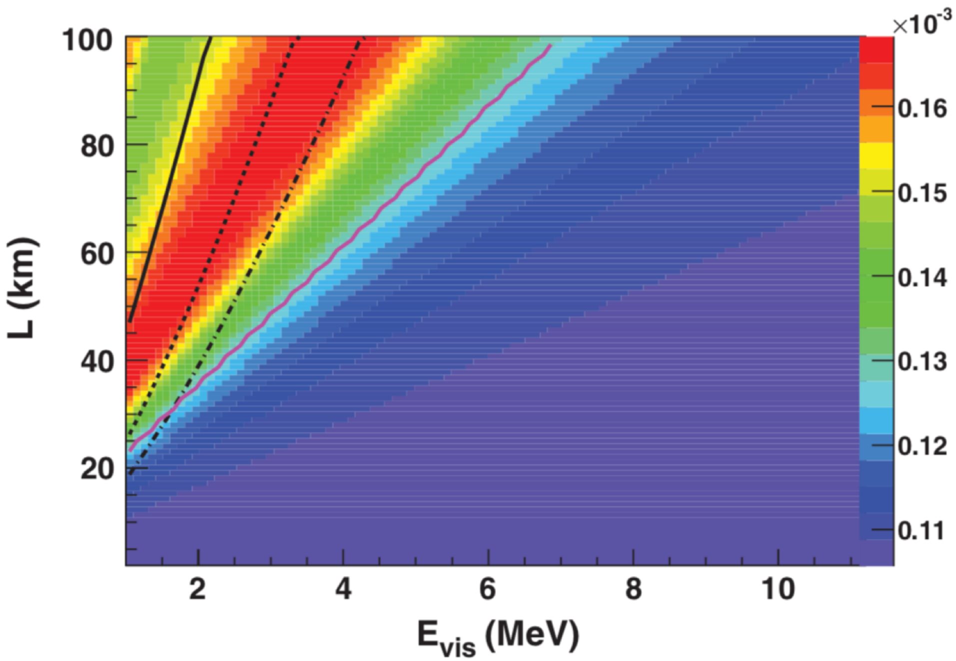
NO : $|\Delta m^2_{31}| = |\Delta m^2_{32}| + \Delta m^2_{21}$

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

Neutrino Mass Ordering (NMO)

*X.Qian et al. Phys. Rev.D.**87**, 033005 (2013)*

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$$
$$= 1 - cos^4\theta_{13} sin^2 2\theta_{12} sin^2\Delta_{21} - sin^2 2\theta_{13}(cos^2\theta_{12} sin^2\Delta_{31} + sin^2\theta_{12} sin^2\Delta_{32})$$
$$= 1 - cos^4\theta_{13} sin^2 2\theta_{12} sin^2\Delta_{21} - 2sin^2\theta_{13} cos^2\theta_{13}$$
$$+2sin^2\theta_{13} cos^2\theta_{13}\sqrt{1 - 4sin^2\theta_{12} cos^2\theta_{12} sin^2\Delta_{21}}\cos(2\Delta_{32} \pm \phi_{ee})$$



$$\Delta_{ij} = 1.27\frac{\Delta m^2_{ij}\, L(\mathrm{m})}{E\ (\mathrm{MeV})}$$

$$tan\phi = \frac{cos^2\theta_{12} sin 2\Delta_{21}}{cos^2\theta_{12} cos 2\Delta_{21} + sin^2\theta_{12}}$$

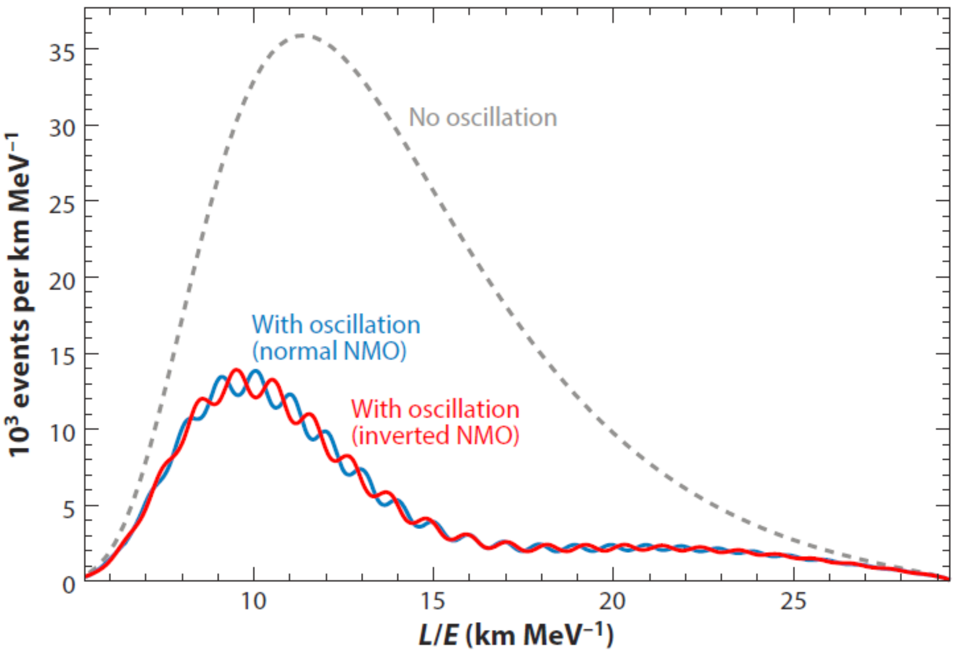
$$\Delta m^2_{\phi_{ee}}(\mathrm{eV}^2) = \frac{\phi}{1.27}\cdot\frac{E(\mathrm{m})}{L(\mathrm{MeV})}$$

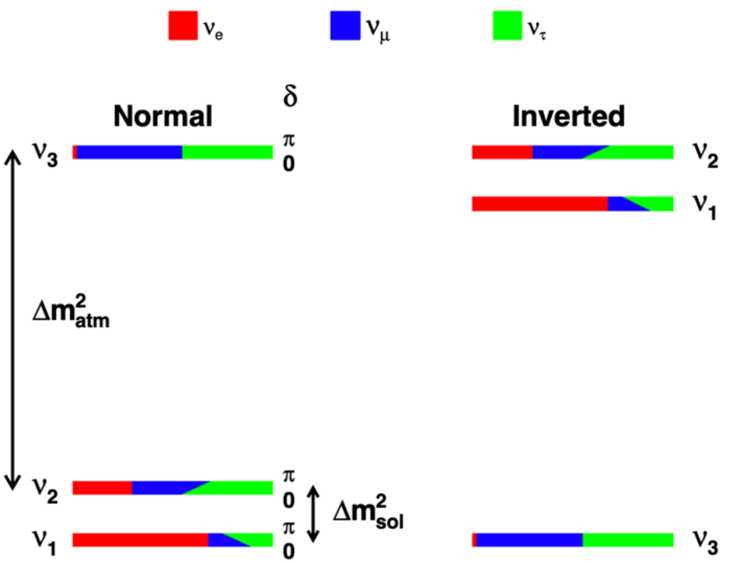
Neutrino oscillation can cause different oscillation frequencies at different L and E

The JUNO 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

Neutrino Oscillation at Jiangmen Underground Neutrino Observatory (JUNO)





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

NO : $|\Delta m^2_{31}| = |\Delta m^2_{32}| + \Delta m^2_{21}$

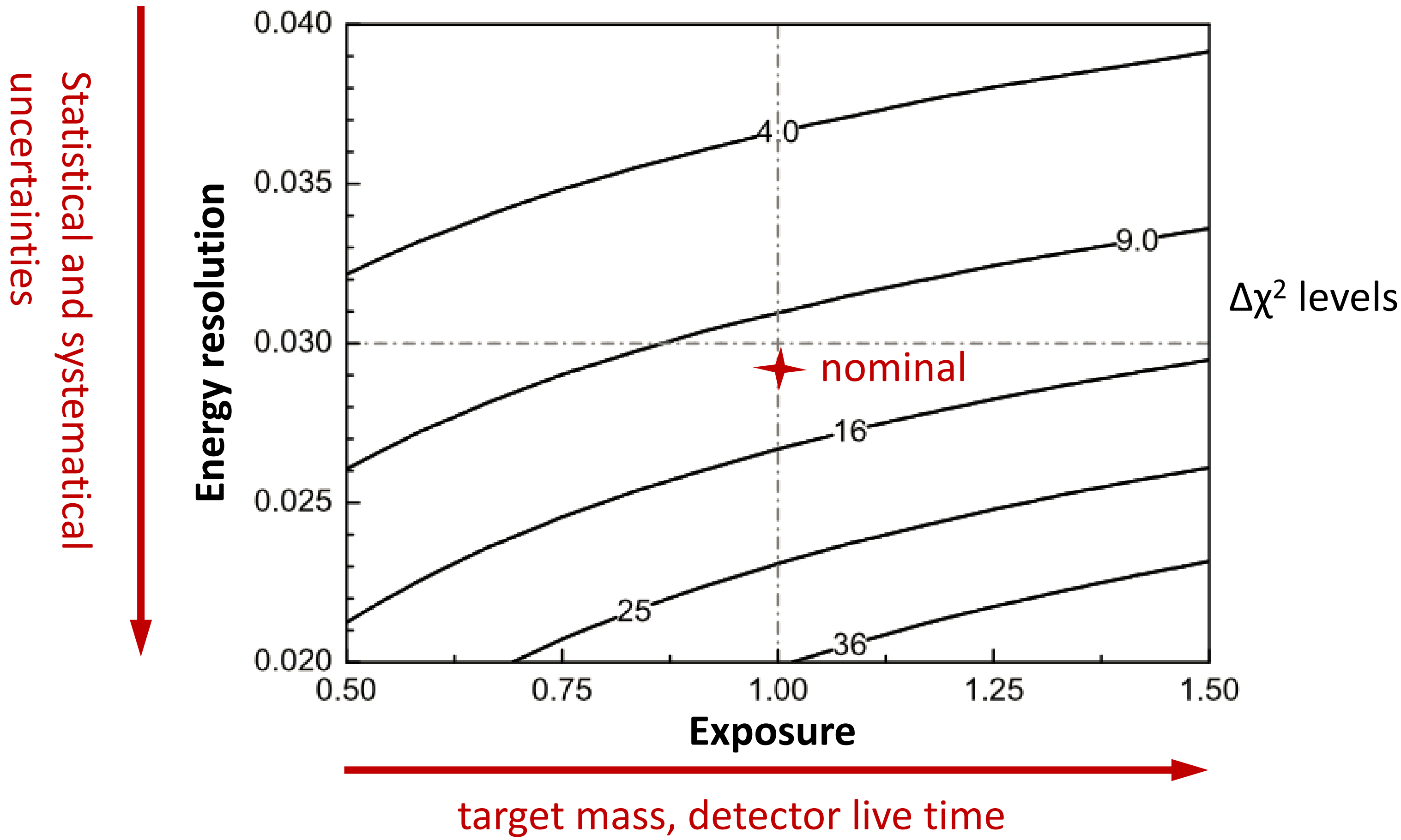
IO: $|\Delta m^2_{31}| = |\Delta m^2_{32}| - \Delta m^2_{21}$

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 NMO Determination

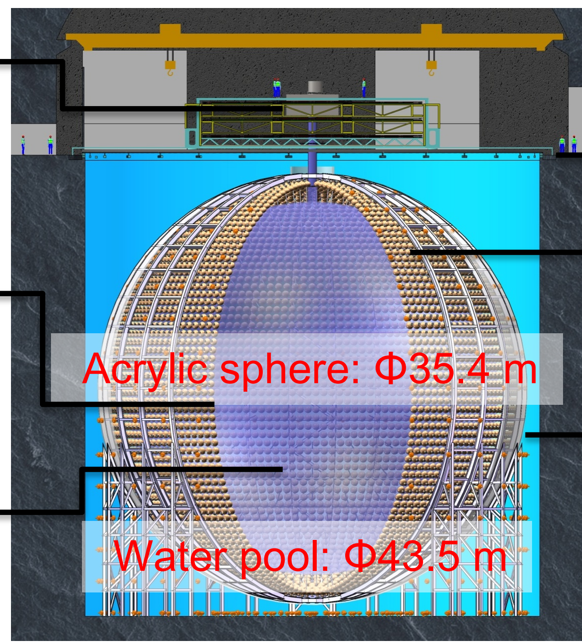
J. Phys. G43:030401 (2016)

Assume NO as true MO, and fit the spectrum with false and true MO cases respectively, and we get $\Delta\chi^2 = \chi^2(\text{false}) - \chi^2(\text{true})$



JUNO Detector Design

	KamLAND	Borexino	Daya Bay	JUNO
LS Mass [kt]	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

Top Tracker

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

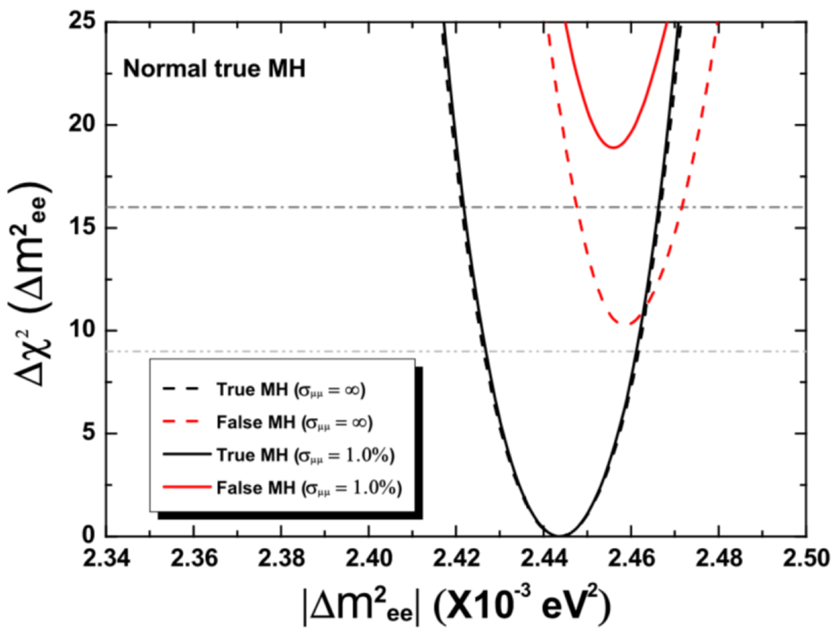
Central detector
SS latticed shell
Acrylic sphere

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

Liquid scintillator
20 kton

Sensitivity of NMO Determination

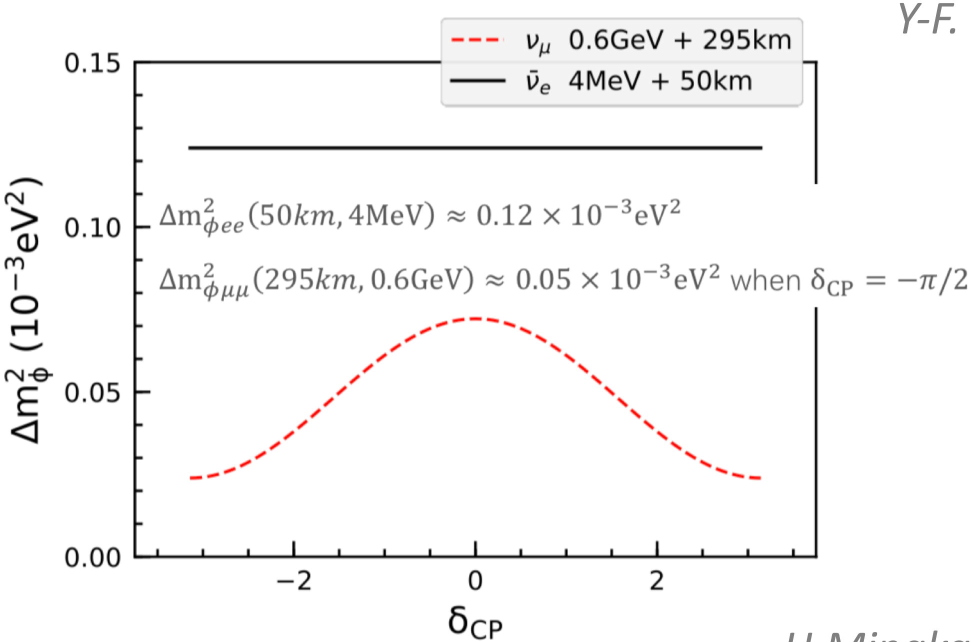
Event type	Rate (per day)	Rate uncertainty (relative)	Shape uncertainty
IBD candidates	60	—	—
Geo-νs	1.1	30%	5%
Accidental signals	0.9	1%	negligible
Fast-n	0.1	100%	20%
^{9}Li–^{8}He	1.6	20%	10%
^{13}C $(\alpha, n)^{16}$O	0.05	50%	50%



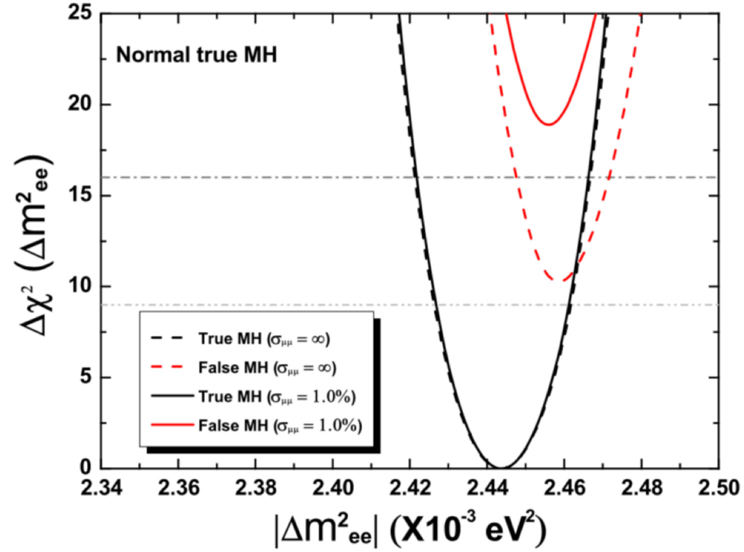
JUNO MO sensitivity with 6 years' data assuming full reactor power

	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

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)*

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

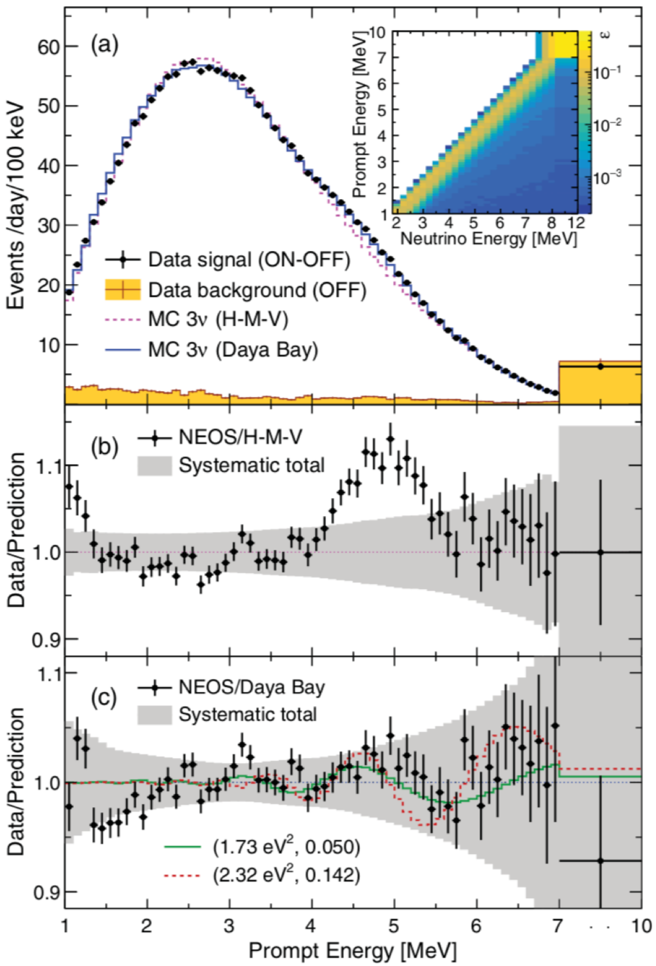
$$\Delta m^2_{\mu\mu} = sin^2\theta_{12}\Delta m^2_{31} + cos^2\theta_{12}\Delta m^2_{32} + cos\delta_{CP} sin\theta_{13} sin2\theta_{12} tan\theta_{23}\Delta m^2_{21}$$

Mass ordering degeneracy at a certain L and E: $|\Delta m^2_{32}(\mathrm{IO})| = |\Delta m^2_{32}(\mathrm{NO})| + \Delta m^2_\phi$

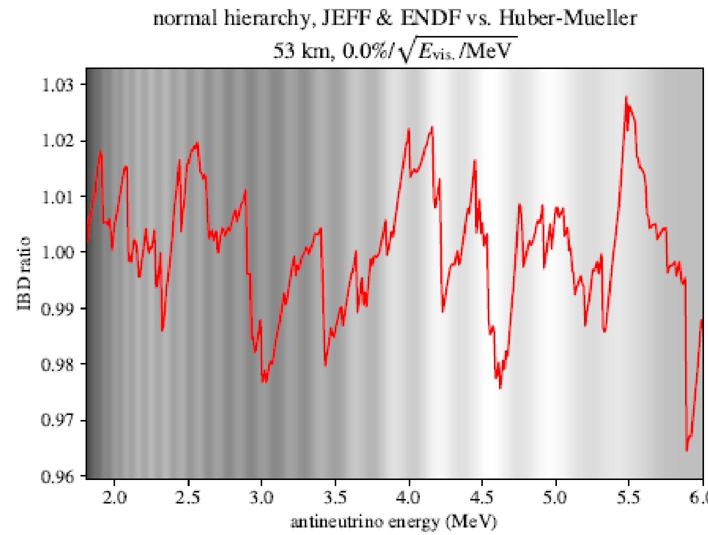
Sensitivity with 100k events (20k ton LS + 6 years with 36GW$_{th}$ reactor power)

- 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)

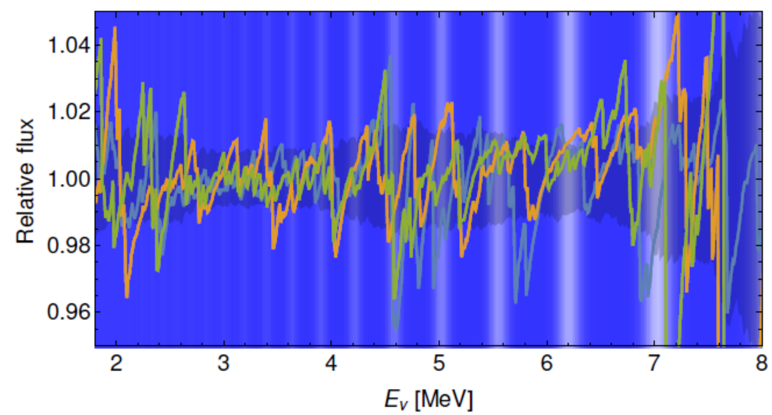
Fine Structure in Reactor Spectrum



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



arXiv:1808.03276



arXiv:1710.07378

Fine structure calculation depends on the ab-initio calculation using nuclear database and can not be precisely determined.

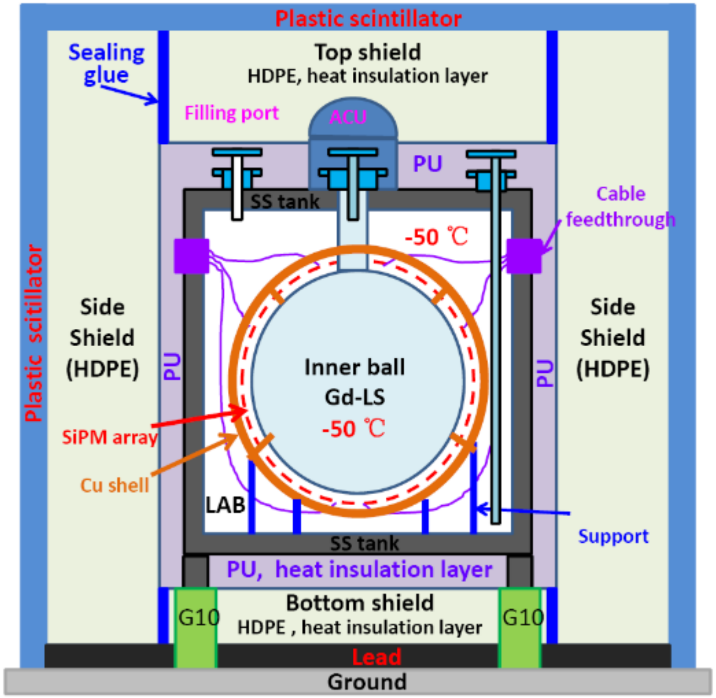
JUNO-TAO

- 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 w/ sub-percent 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 (4000)
- Online in 2021

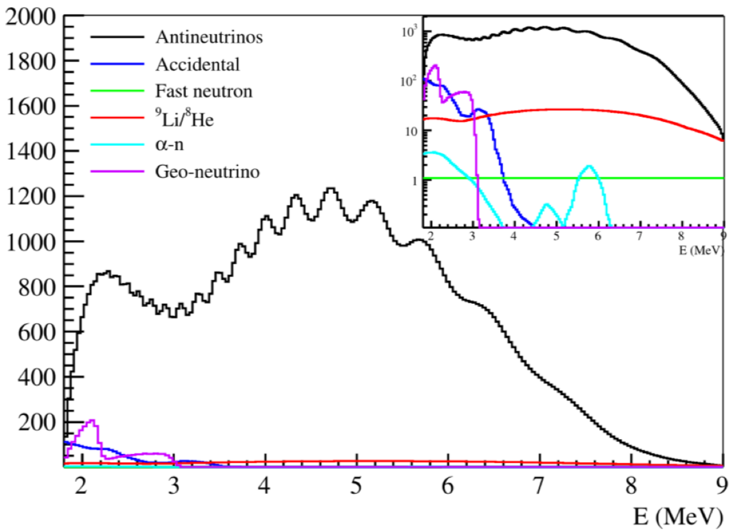


Precision Measurement

Current precision

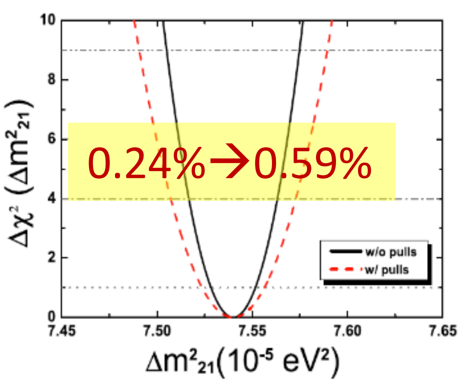
	Δm^2_{21}	$\|\Delta m^2_{31}\|$	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$	δ
Dominant Exps.	KamLAND	T2K	SNO+SK	Daya Bay	NOνA	T2K
Individual 1σ	2.4%	2.6%	4.5%	3.4%	5.2%	70%
Nu-FIT 4.0	2.4%	1.3%	4.0%	2.9%	3.8%	16%

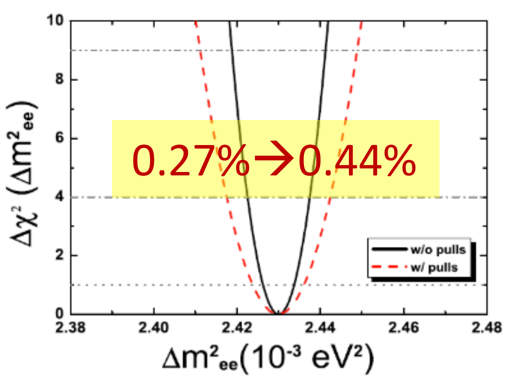
Probing the unitarity of U_{PMNS} to ~1%, more precise than CKM matrix elements!

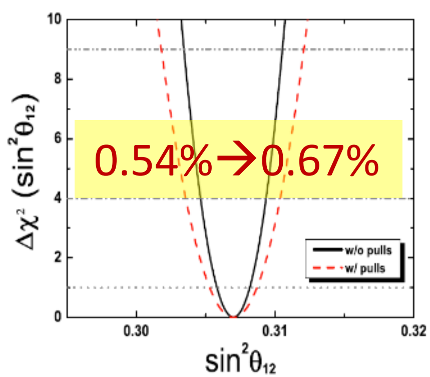


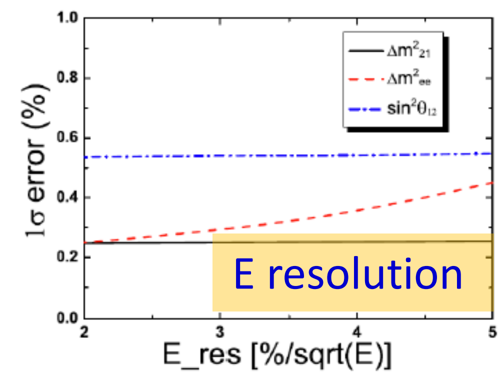
	Statistics	**+BG, +1% b2b +1% EScale , +1% EnonL**
$\sin^2\theta_{12}$	0.54%	**0.67%**
Δm^2_{21}	0.24%	**0.59%**
Δm^2_{32}	0.27%	**0.44%**

J. Phys. G43:030401 (2016)

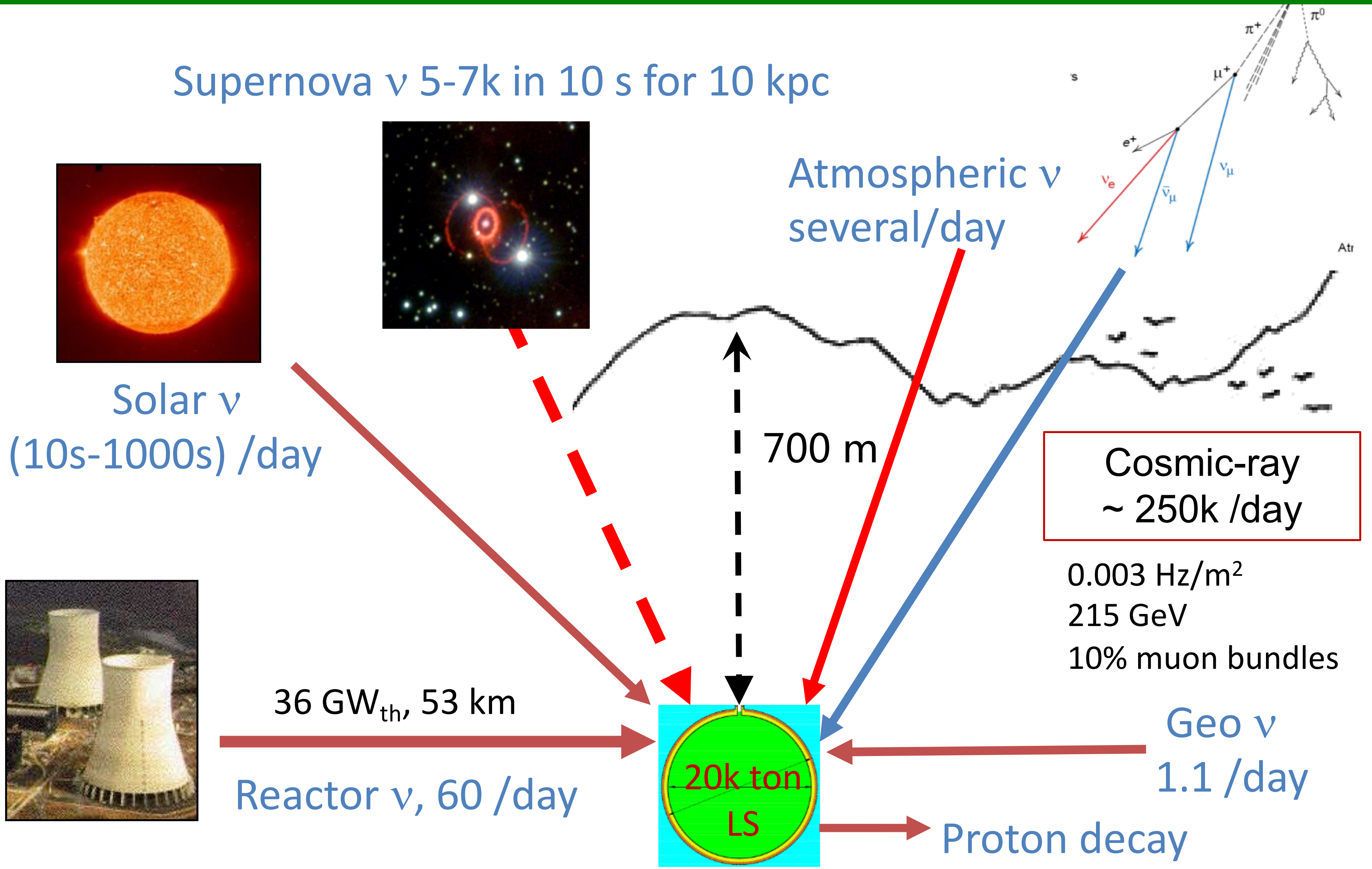




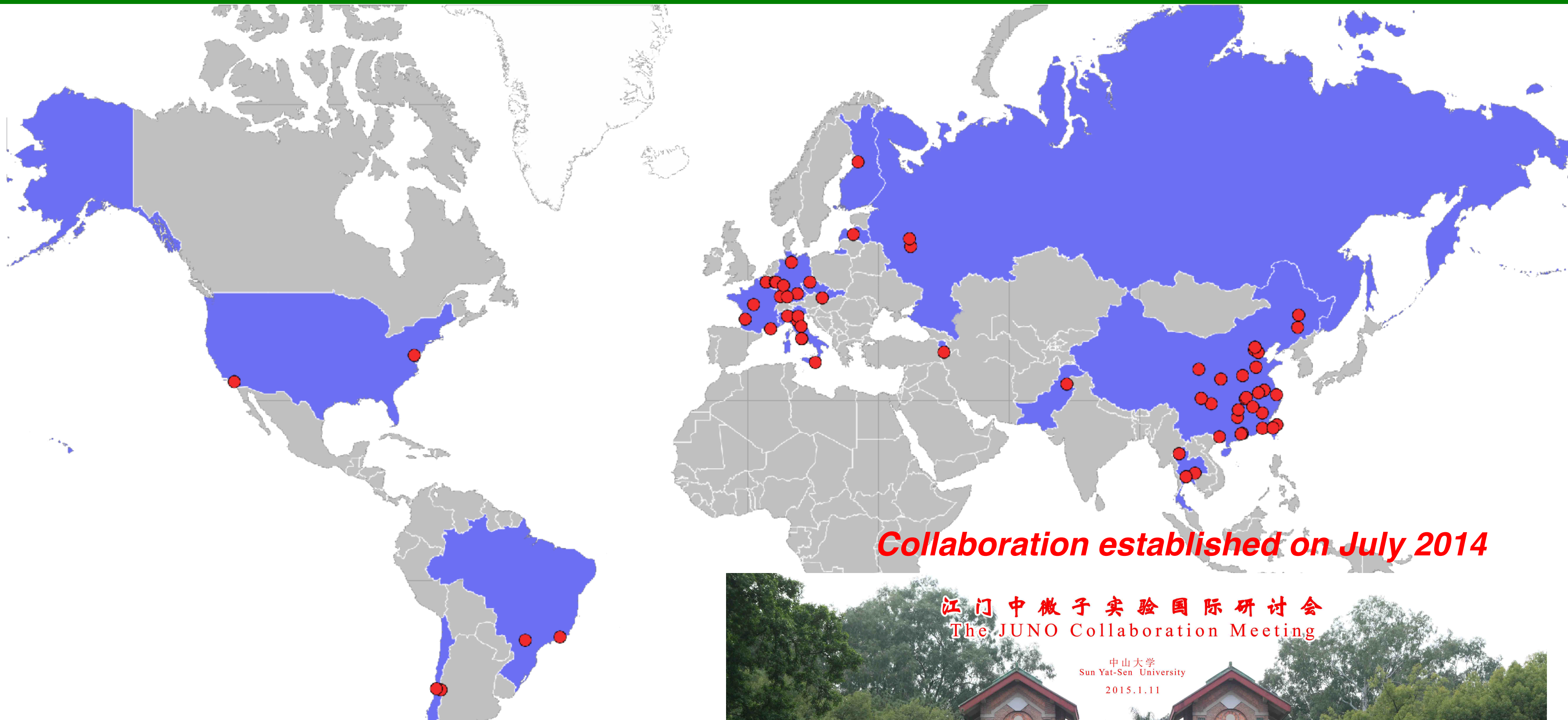




Other Physics for JUNO



The JUNO Collaboration



Collaboration established on July 2014

77 Institutions, ~600 collaborators

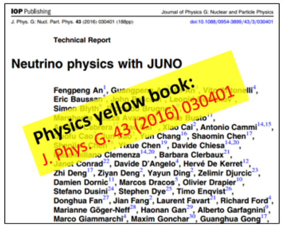
- China (34), Taiwan, China (3), Thailand (3), Pakistan, Armenia
- Italy (8), Germany (7), France (5), Russia (3), Belgium, Czech, Finland, Slovakia, Latvia
- Brazil (2), Chile (2), USA (3)

JUNO Schedule

More details in C. Guo's talk
"Status of the JUNO Detector"

2014
International collaboration established

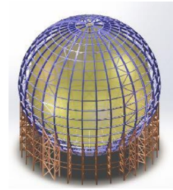
2015
- PMT production line setup
- CD parts R&D
- Civil construction start



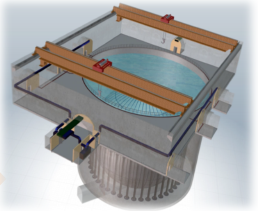
2016
- PMT production start
- CD parts production start
- Yellow book published

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

- Neutrino physics has entered the precision era.
- Daya Bay has the world best measurement on θ_{13}.
- JUNO can have independent determination of neutrino mass hierarchy at >3σ.
- JUNO also can have sub-percent measurement on $\theta_{12}, \Delta m^2_{21}, \Delta m^2_{32}$
- JUNO will largely advance the reactor neutrino physics and liquid scintillator technology.