# Neutrino Oscillation Physics at JUNO

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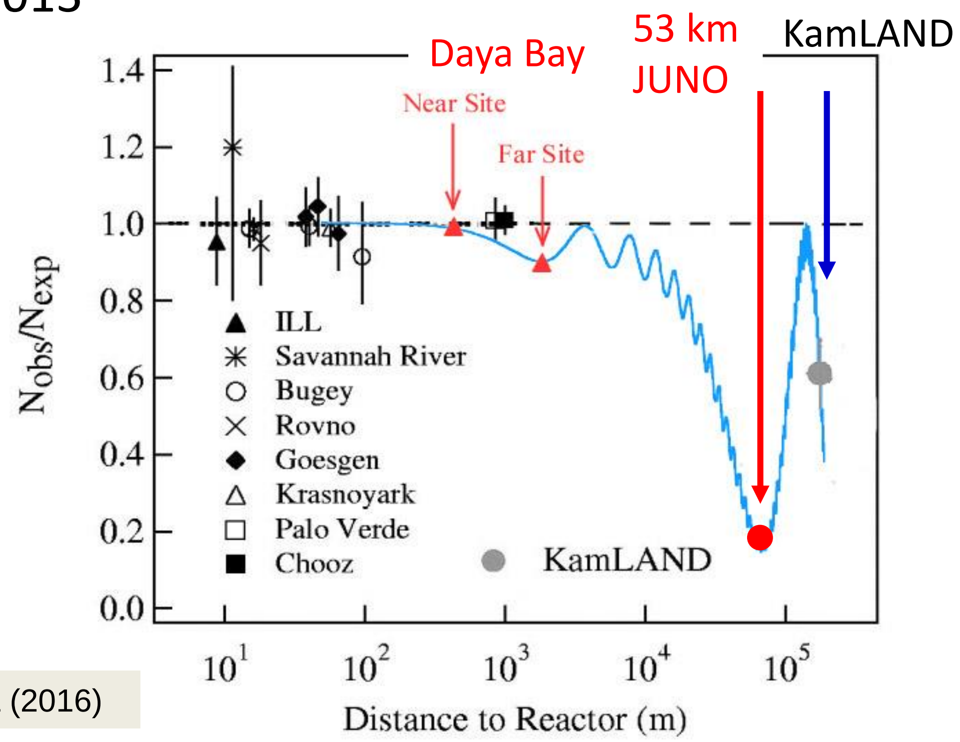
*On behalf of the JUNO Collaboration*

# Neutrino Physics at JUNO

- Jiangmen Underground Neutrino Observatory
- 27-36 GW reactor power, 20 kton LS detector, 3%/√E energy resolution
- Proposed in 2008, approved in 2013
- Rich physics possibilities
  - Mass hierarchy
  - Precision measurement of 3 mixing parameters
  - Supernovae neutrino
  - Geoneutrino
  - Solar neutrino
  - Atmospheric neutrino
  - Exotic searches including nucleon decay, dark matter

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




- This talk will focus on the mass hierarchy and precision measurement, and two posters will cover other aspects.

# Neutrino Mass Hierarchy

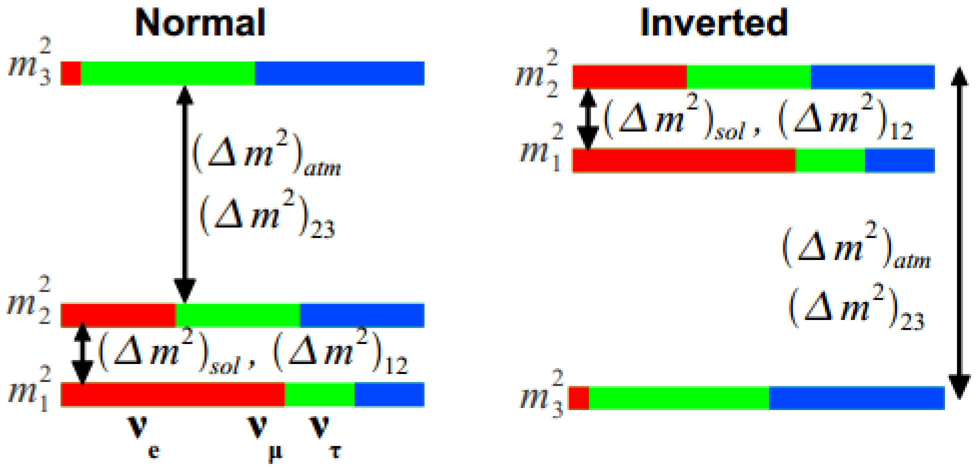
- Large $\theta_{13}$ opens a door to neutrino MH and CP violating phase, as the focus of next generation neutrino experiments.
- MH can be determined utilizing
  - Matter effects of accelerator (DUNE, T2K, Nova) and atmospheric (PINGU, HK, INO) neutrinos
  - Oscillation interference effects of reactor neutrinos driven by $\Delta m^2_{32}$ and $\Delta m^2_{31}$

Daya Bay results from Neutrino 2016

$\sin^2 2\theta_{13} = [8.41 \pm 0.33] \times 10^{-2}$

$|\Delta m^2_{ee}| = [2.50 \pm 0.08] \times 10^{-3} \mathrm{eV}^2$

Precision of **$\sin^2 2\theta_{13}$** will reach 3%

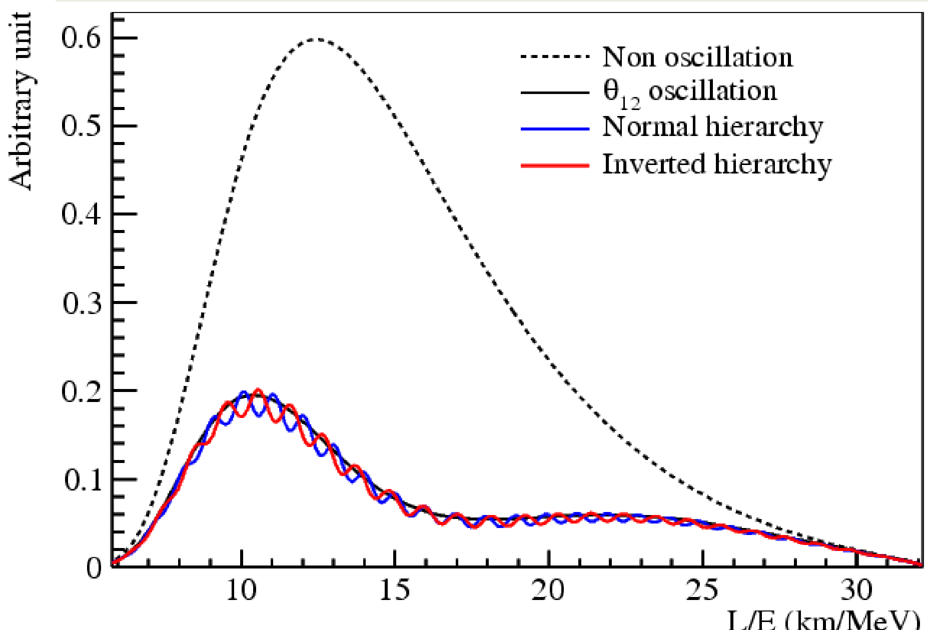


# Reactor Antineutrinos to Determine Mass Hierarchy

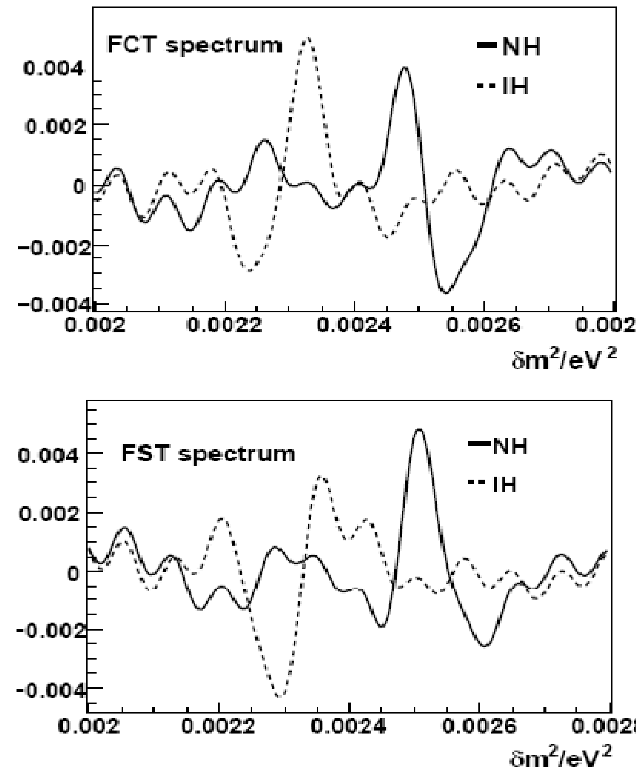
Oscillation probability independent of CP phase and $\theta_{23}$

$$P_{ee}(L/E) = 1 - P_{21} - P_{31} - P_{32}$$
$$P_{21} = \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21})$$
$$P_{31} = \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31})$$
$$P_{32} = \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})$$

Effects of $P_{31}$ and $P_{32}$ interference are proportional to $\sin^2 2\theta_{13}$



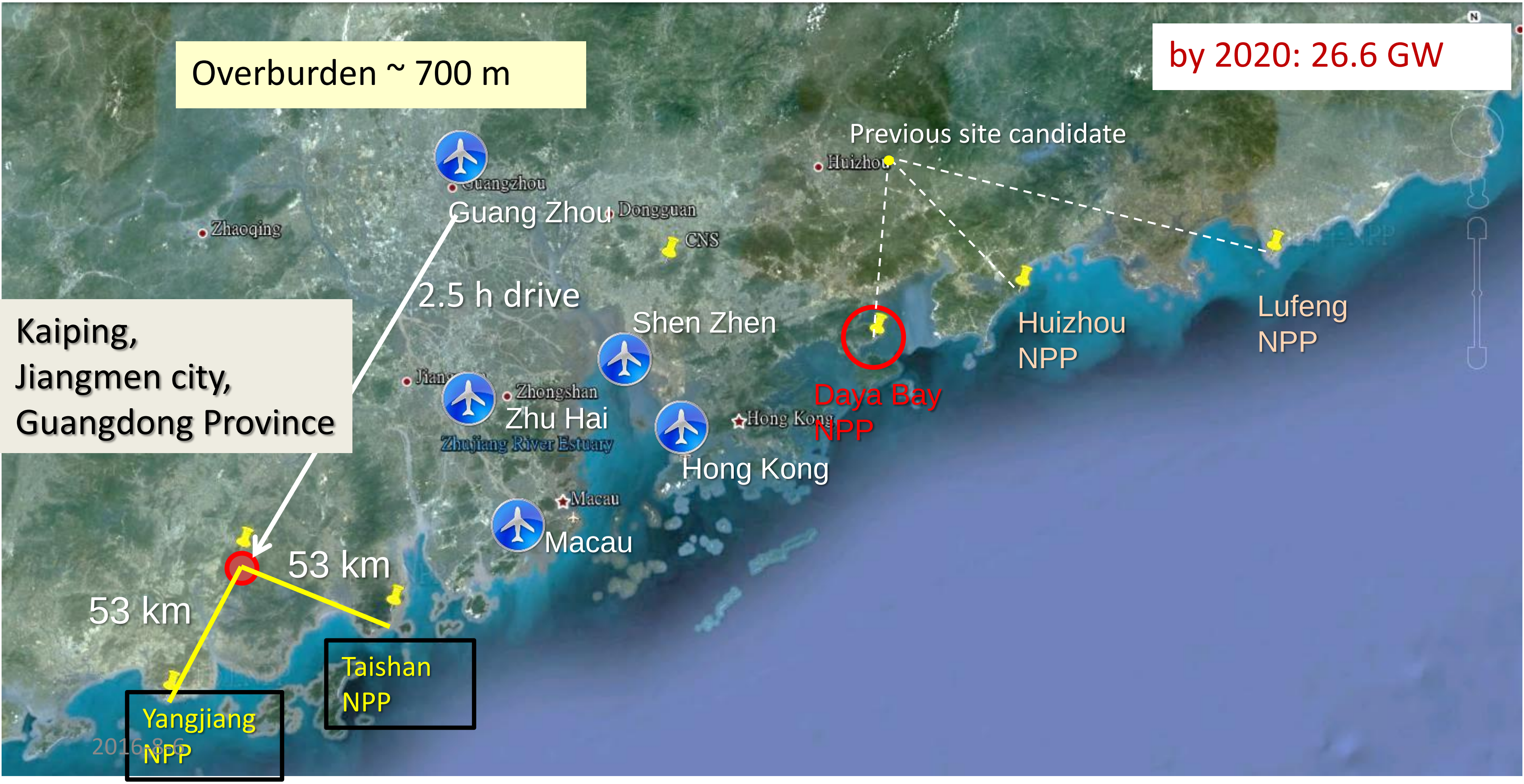

Fourier transform to show the interference




S.T. Petcov et al., PLB533(2002)94
S.Choubey et al., PRD68(2003)113006
J. Learned et al., Phys.Rev. D78 (2008) 071302
Zhan, Y. Wang, J. Cao, L. Wen, PRD78:111103, 2008
PRD79:073007, 2009

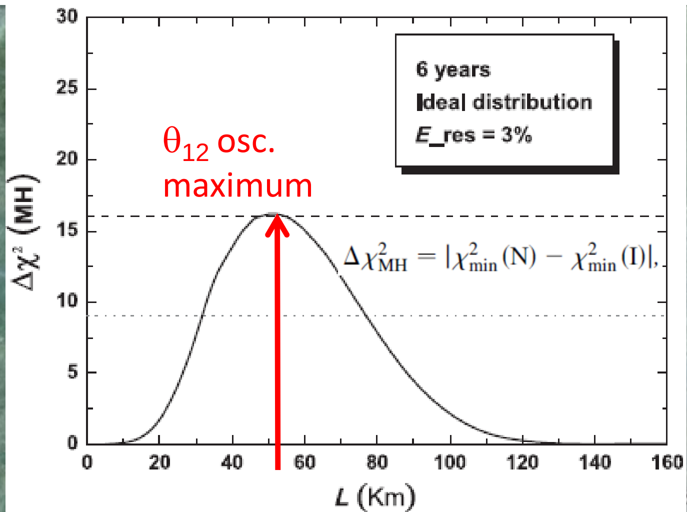
# Location of JUNO

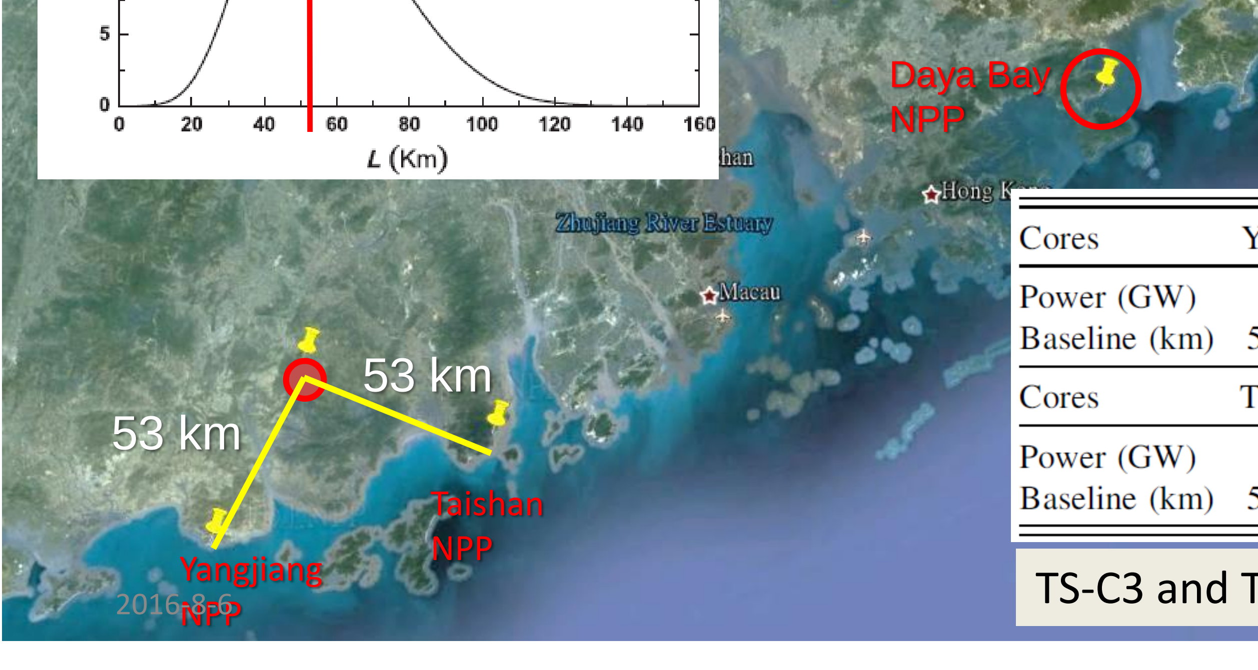
| NPP | Daya Bay | Huizhou | Lufeng | Yangjiang | Taishan |
|---|---|---|---|---|---|
| Status | Operational | Planned | Planned | Under construction | Under construction |
| Power | 17.4 GW | 17.4 GW | 17.4 GW | 17.4 GW | 18.4 GW |

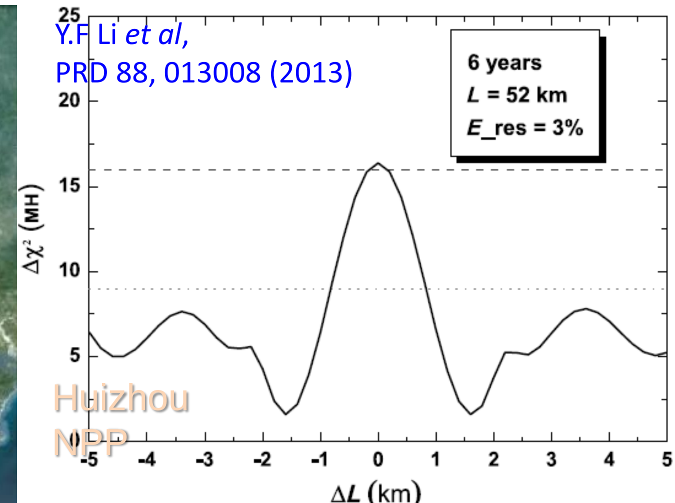


# Optimum Baseline for MH

- Optimum at the oscillation maximum of $\theta_{12}$
- Multiple reactors may cancel the oscillation structure
  - Baseline difference cannot be more than 500 m



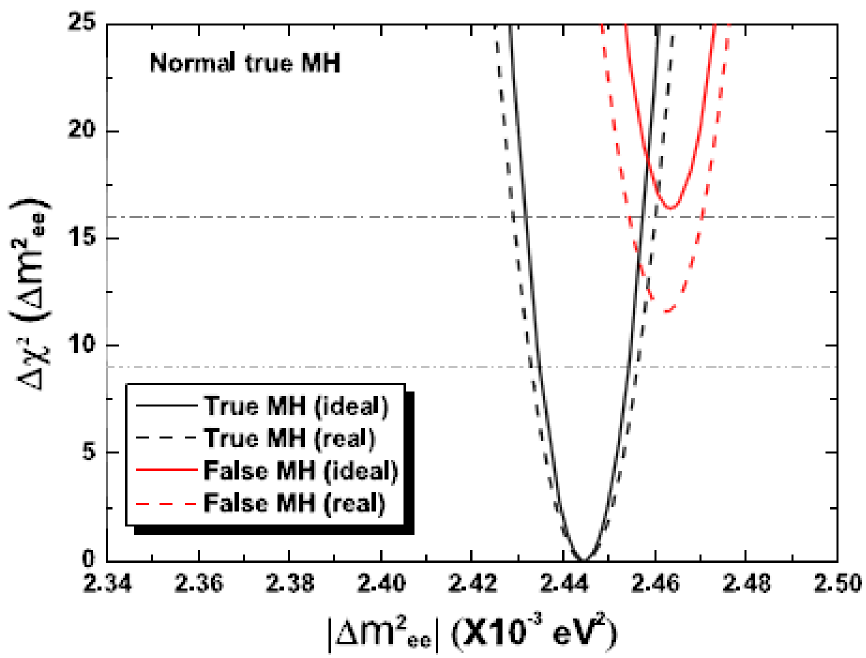

| Cores | YJ-C1 | YJ-C2 | YJ-C3 | YJ-C4 | YJ-C5 | YJ-C6 |
|---|---|---|---|---|---|---|
| Power (GW) | 2.9 | 2.9 | 2.9 | 2.9 | 2.9 | 2.9 |
| Baseline (km) | 52.75 | 52.84 | 52.42 | 52.51 | 52.12 | 52.21 |
| Cores | TS-C1 | TS-C2 | TS-C3 | TS-C4 | DYB | HZ |
| Power (GW) | 4.6 | 4.6 | 4.6 | 4.6 | 17.4 | 17.4 |
| Baseline (km) | 52.76 | 52.63 | 52.32 | 52.20 | 215 | 265 |

TS-C3 and TS-C4 will not be running in 2020

# Sensitivity of MH Determination

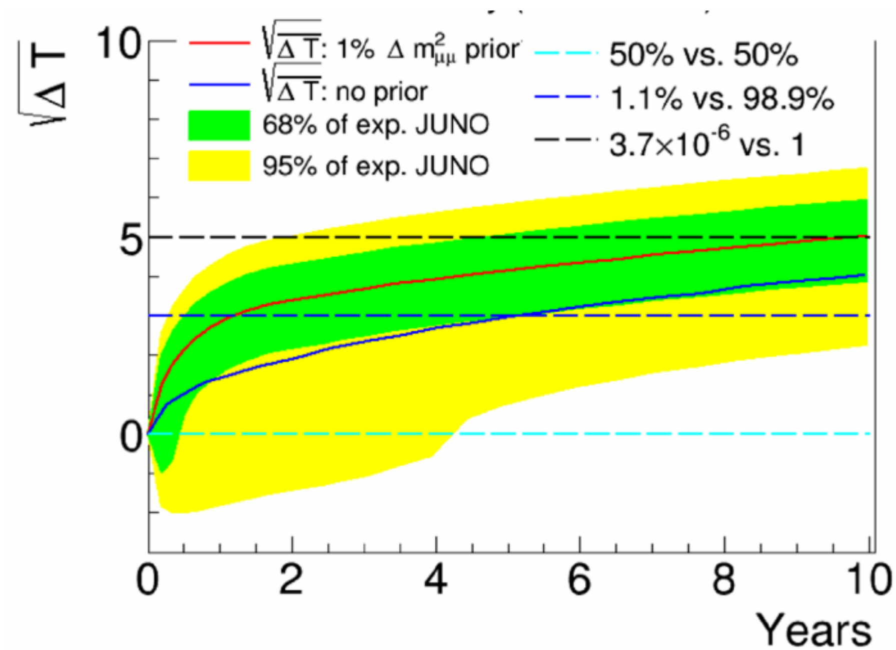
Assume NH as true MH, and fit the spectrum with false and true MH cases respectively, and we get
$\Delta\chi^2 = \chi^2(\text{false}) - \chi^2(\text{true})$

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




Nominal experimental setup
- Detector size: 20kt
- Energy resolution: 3%/√E
- Thermal power: 36 GW
- Running time: 6 years

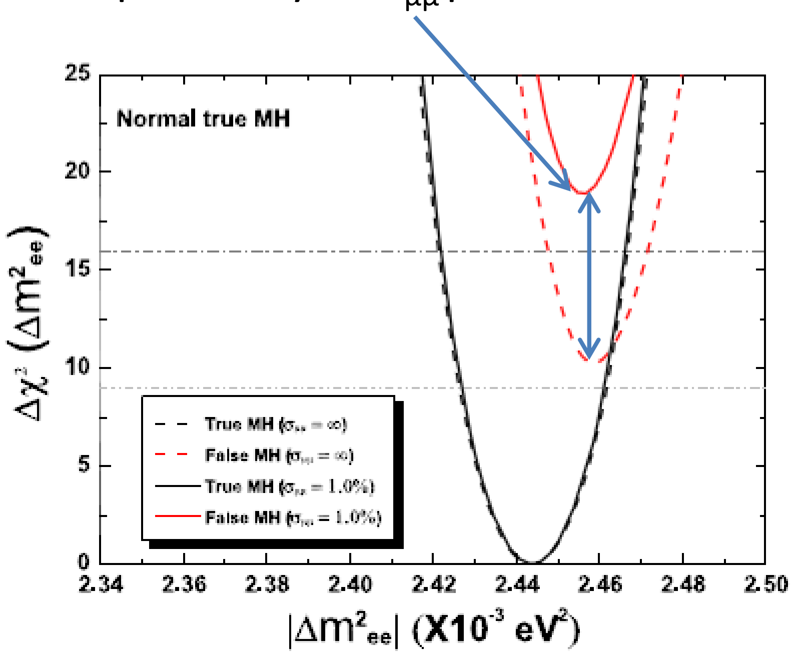
Sensitivity vs. running time



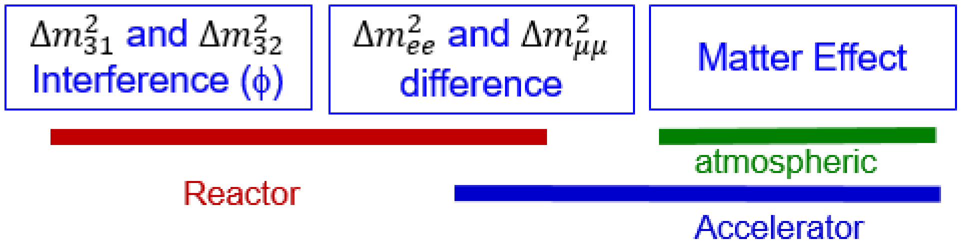
# Taking into account $\Delta m^2_{\mu\mu}$

- MH sensitivity improved by taking into account the $\Delta m^2_{\mu\mu}$ from T2K and Nova in the future

Improved by $\Delta m^2_{\mu\mu}$ precision of 1%

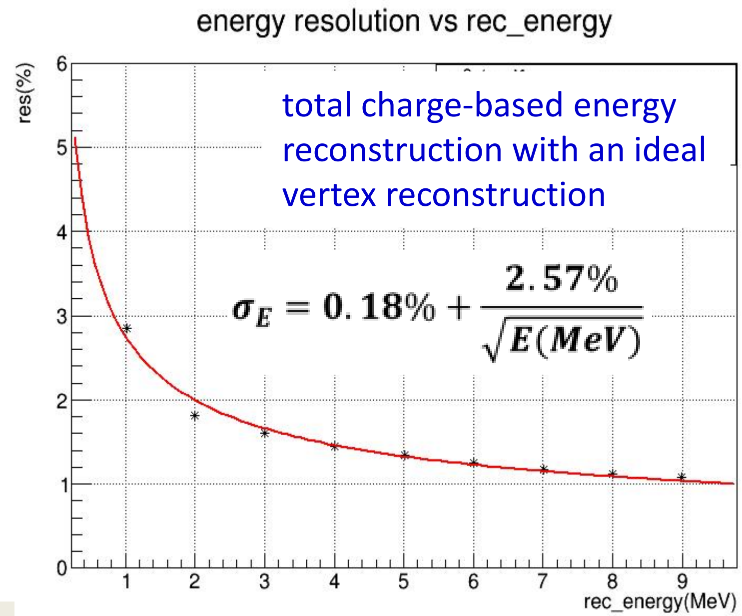



| $\sqrt{\Delta\chi^2}$ | Without $\Delta m^2_{uu}$ input | With $\Delta m^2_{uu}$ input (1%) |
|---|---|---|
| Equal baseline | 4 | 5 |
| Core distribution | 3 | 4 |

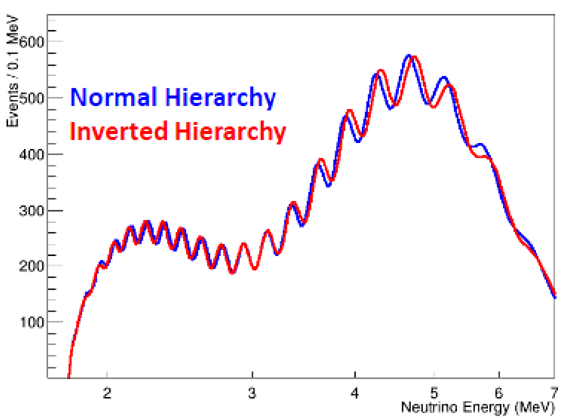


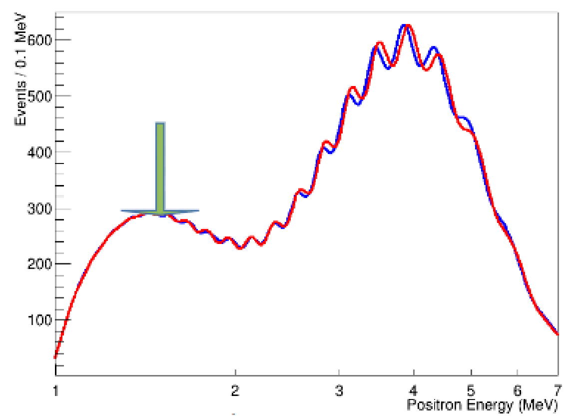
# Requirements on Energy Resolution

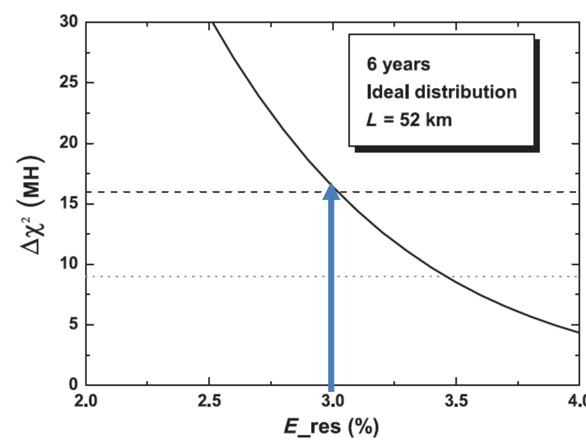
- Energy resolution: 3%/√E is possible based on the JUNO MC simulation.
- Key requirements on detector (1200PE/MeV)
  - PMT coverage: 75%
  - High QE PMT: 35%
  - LS attenuation length: 20 m




Energy resolution 0 → Energy resolution 3%



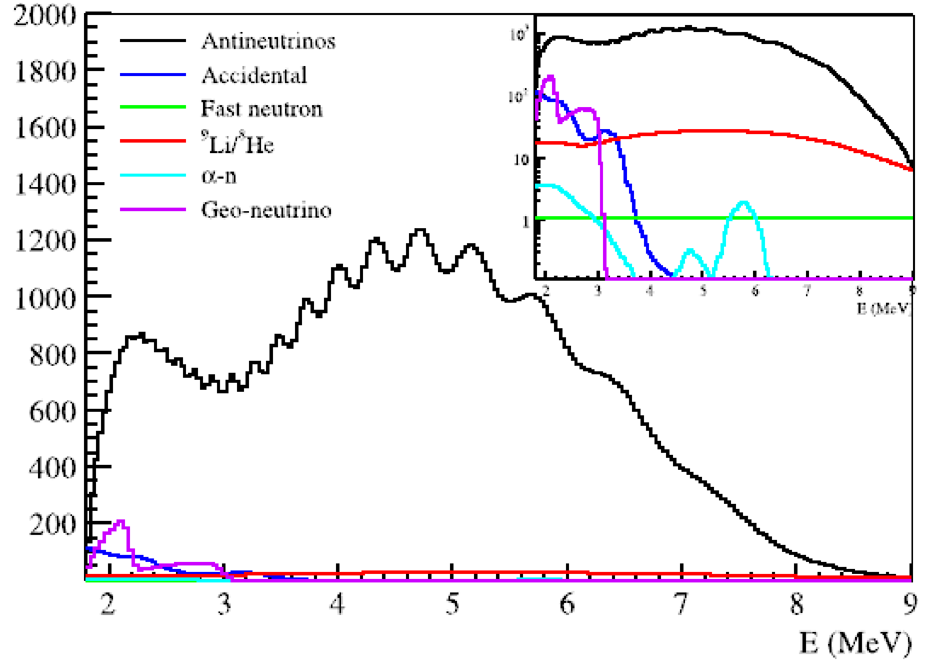



# Systematic decomposition

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

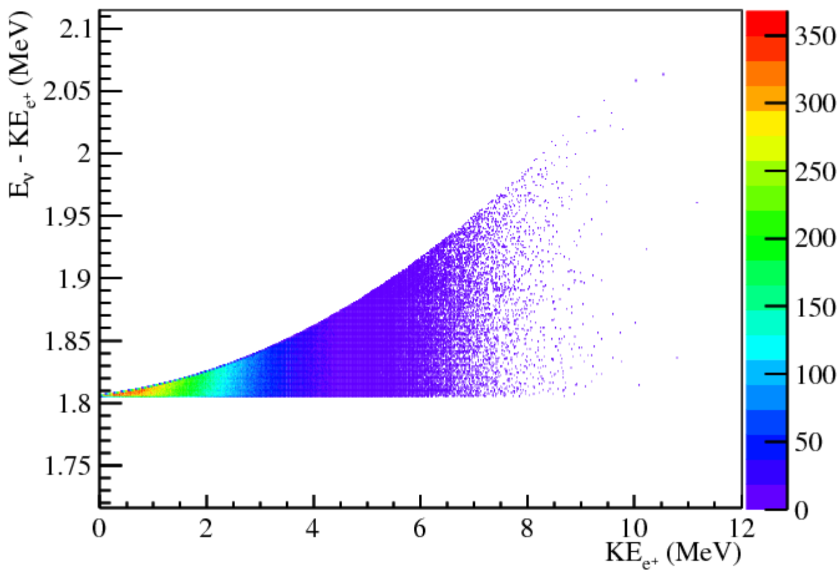
- Backgrounds estimated based on the investigation of material radioactivity and evaluation of neutron and isotope production due to cosmic muon.

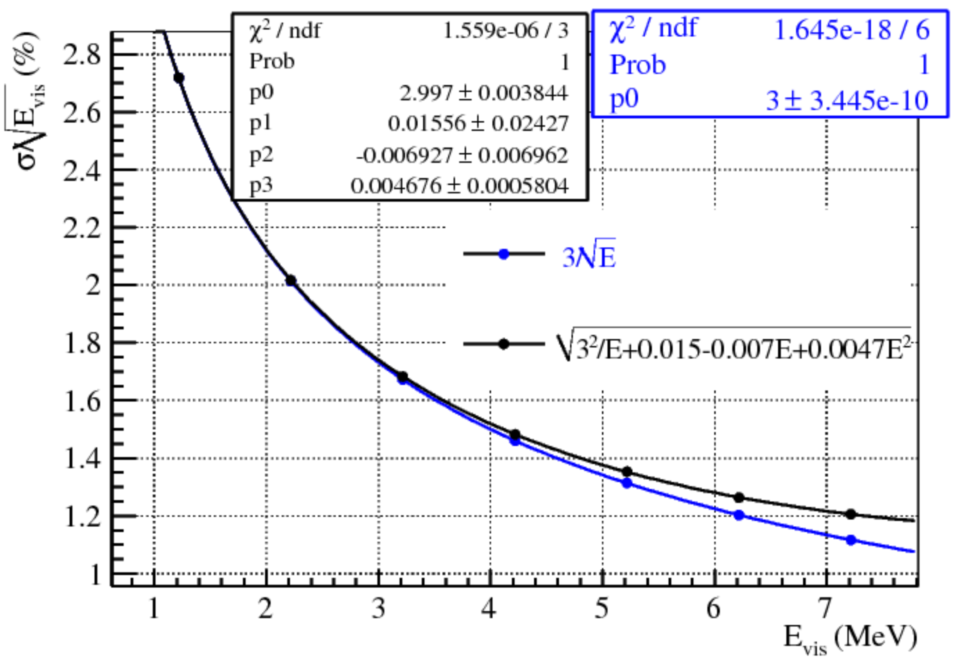


# IBD Neutron recoiling

$$\mathrm{KE}_{e+} = E_{\nu} - (m_n - m_p) - m_e - T_n$$

- Additional smearing in the prompt energy measurement induced by neutron recoiling in the inverse beta decay reaction (IBD)
- Effective energy resolution increased




- Larger smearing when neutrino has larger energy
- The reduction on $\Delta\chi^2$ is 0.2

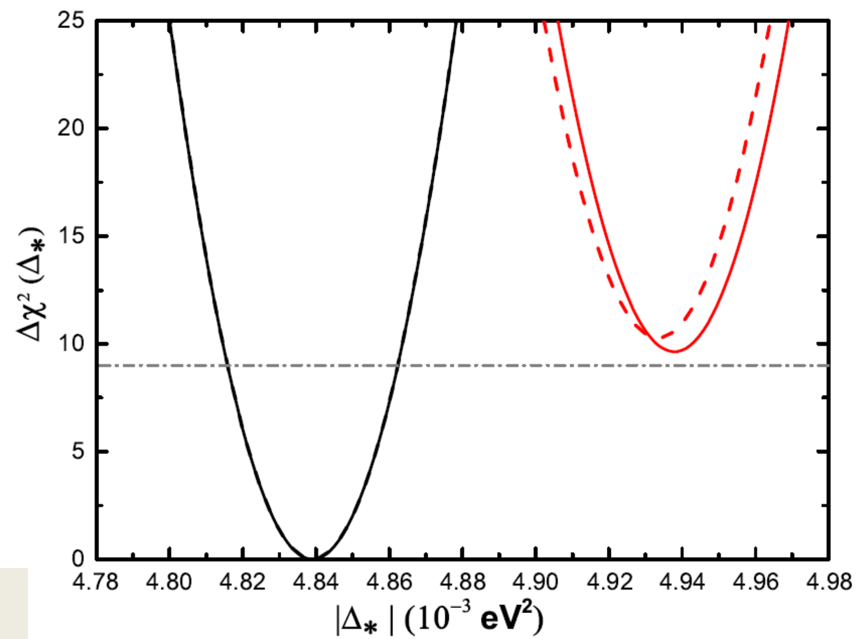
# Matter effects

$$\widetilde{\mathcal{H}}_{\rm eff} = \frac{1}{2E}\left[\widetilde{U}\begin{pmatrix}\widetilde{m}_1^2 & 0 & 0\\ 0 & \widetilde{m}_2^2 & 0\\ 0 & 0 & \widetilde{m}_3^2\end{pmatrix}\widetilde{U}^\dagger\right] = \frac{1}{2E}\left[U\begin{pmatrix}m_1^2 & 0 & 0\\ 0 & m_2^2 & 0\\ 0 & 0 & m_3^2\end{pmatrix}U^\dagger - \begin{pmatrix}A & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{pmatrix}\right]$$

$$\sin^2 2\widetilde{\theta}_{12} \simeq \frac{(\alpha^2-\beta^2)\sin^2 2\theta_{12}}{(\alpha+\beta\cos 2\theta_{12})^2} \simeq \sin^2 2\theta_{12}\left(1 - 2\frac{A}{\Delta_{21}}\cos 2\theta_{12}\right)$$

$$\frac{A}{\Delta_{21}} \simeq 1.05\times 10^{-2} \times \frac{E}{4\ \mathrm{MeV}} \times \frac{7.5\times 10^{-5}\ \mathrm{eV}^2}{\Delta_{21}}$$

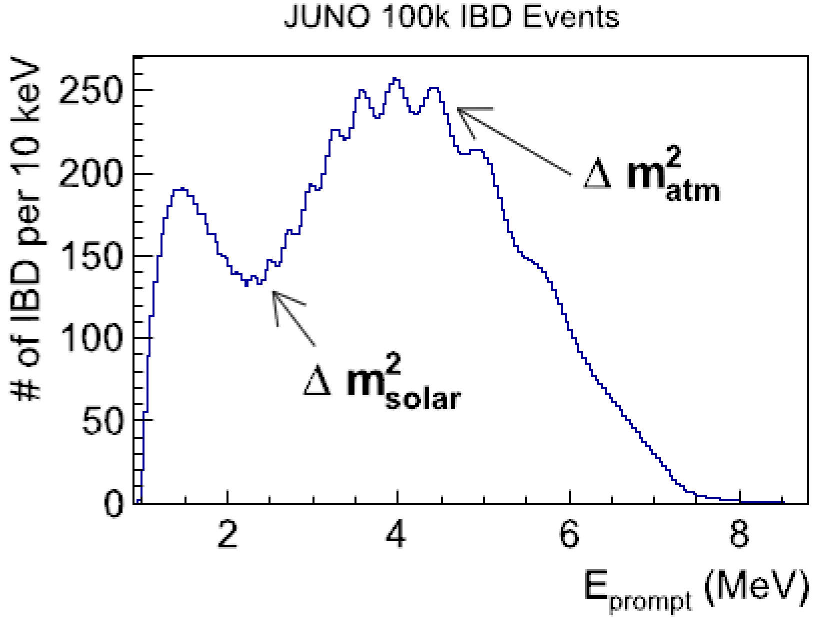
- With six years of running, the $\Delta\chi^2$ of mass ordering measurements will reduce from 10.28 (vacuum) to 9.64 (matter).
- The reduction of $\Delta\chi^2$ is comparable with other systematic error.

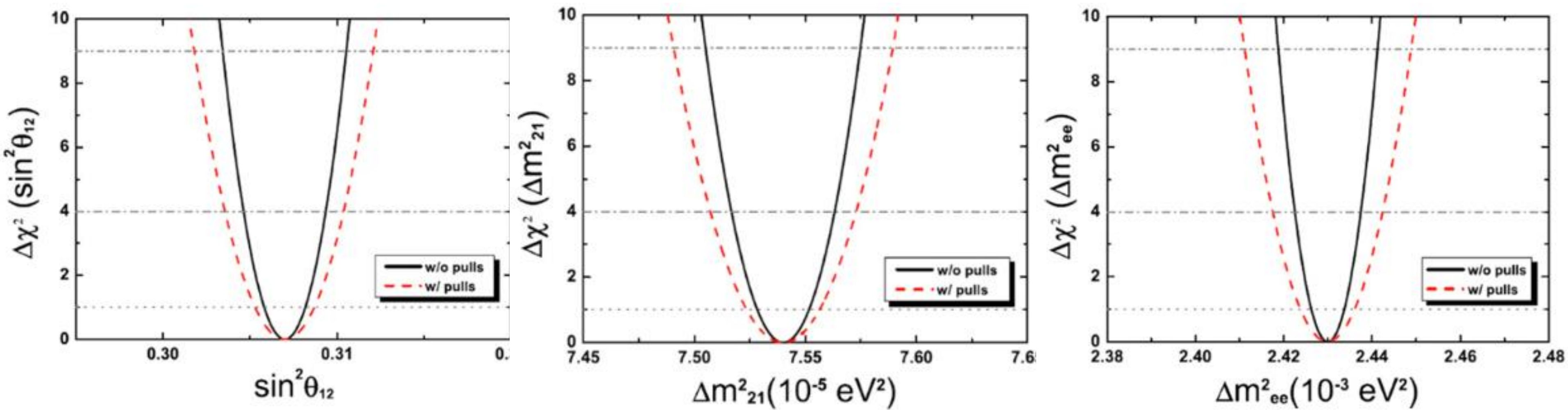



*Chinese Physics C 40(9) (2016) 091001*

# Measurement of Oscillation Parameters

- Good energy resolution and proper baseline help to measure the $\Delta m^2_{21}$ and $\Delta m^2_{32}$ driven oscillations simultaneously.



# Measurement of Oscillation Parameters

- Precisions of three parameters ($\Delta m^2_{21}$, $\Delta m^2_{ee}$ and $\sin^2\theta_{12}$) reach sub-percent level, several times improvement compared with current precision.
- Probing the unitarity of $U_{PMNS}$ to ~1% level

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

| | Nominal | +B2B (1%) | +BG | +EL (1%) | +NL (1%) |
|---|---|---|---|---|---|
| $\sin^2\theta_{12}$ | 0.54% | 0.60% | 0.62% | 0.64% | 0.67% |
| $\Delta m^2_{21}$ | 0.24% | 0.27% | 0.29% | 0.44% | 0.59% |
| $\lvert\Delta m^2_{ee}\rvert$ | 0.27% | 0.31% | 0.31% | 0.35% | 0.44% |

# JUNO Collaboration

Collaboration established in July 2015
66 institutions, 440 collaborators
Half from China

| | |
|---|---|
| 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 |
| France | Subatech Nantes |
| Germany | ZEA FZ Julich |
| Germany | RWTH Aachen U. |
| Germany | TUM |
| Germany | U. Hamburg |
| Germany | IKP FZ Jülich |
| Germany | U. Mainz |
| Germany | U. Tuebingen |
| Italy | INFN Catania |
| Italy | INFN di Frascati |
| Italy | INFN-Ferrara |
| Italy | INFN-Milano |
| Italy | INFN-Milano Bicocca |
| Italy | INFN-Padova |
| Italy | INFN-Perugia |
| 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 has rich physics possibilities with the main goals to determine mass hierarchy and precisely measure oscillation parameters.

- With 6 years data taking, the sensitivity of mass hierarchy can reach 3 σ ($\Delta\chi^2 = 9$).

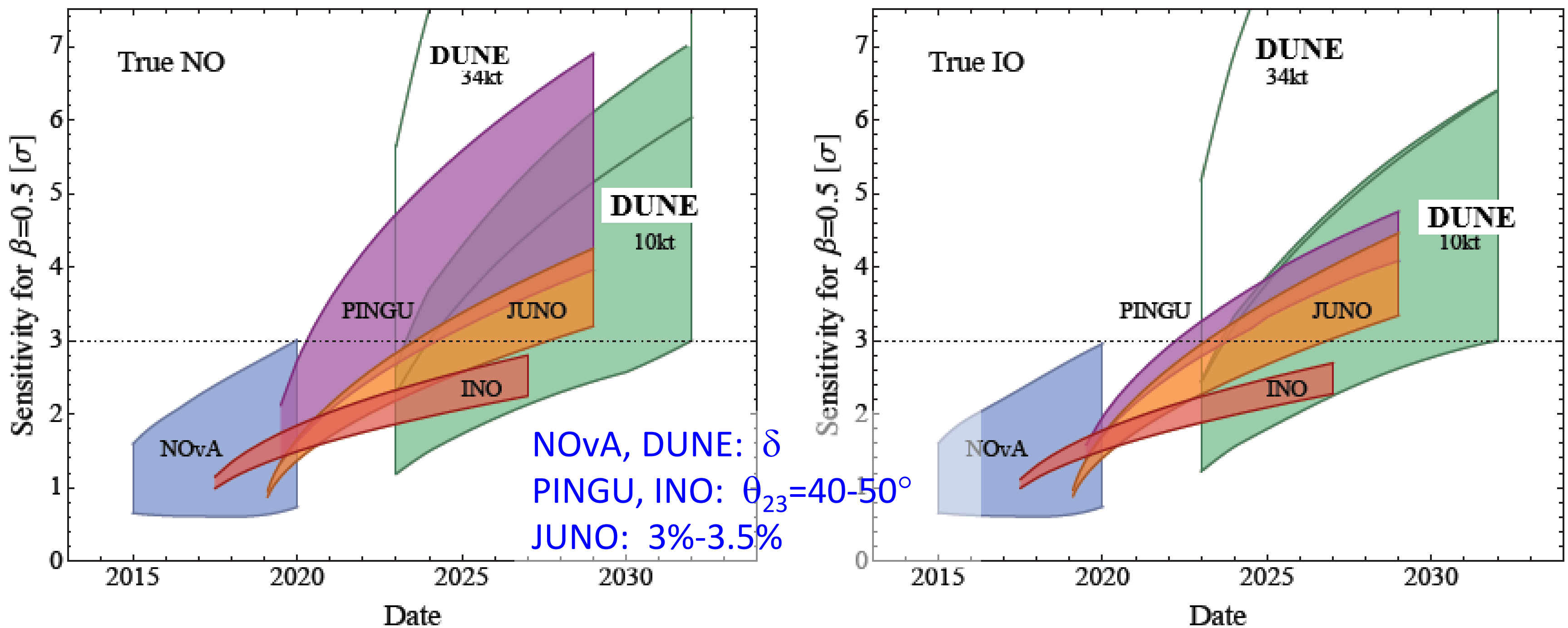
- Three oscillation parameters ($\Delta m^2_{21}$, $\Delta m^2_{ee}$ and $\sin^2\theta_{12}$) can be measured with precision better than 1%.

Thanks!

# Backup

# Comparison with Other Experiments

M. Blennow et al., JHEP 1403 (2014) 028




- JUNO is unique for measuring MH using reactor neutrinos
  - Independent of the CP phase and free from the matter effect: complementary to accelerator-based experiments
  - competitive in time
  - Many other science goals