Systematics, calibration and analysis techniques in JUNO

Jian Tang

Sun Yat-Sen University, Guangzhou, China

On behalf of the JUNO collaboration

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Email: tangjian5@mail.sysu.edu.cn

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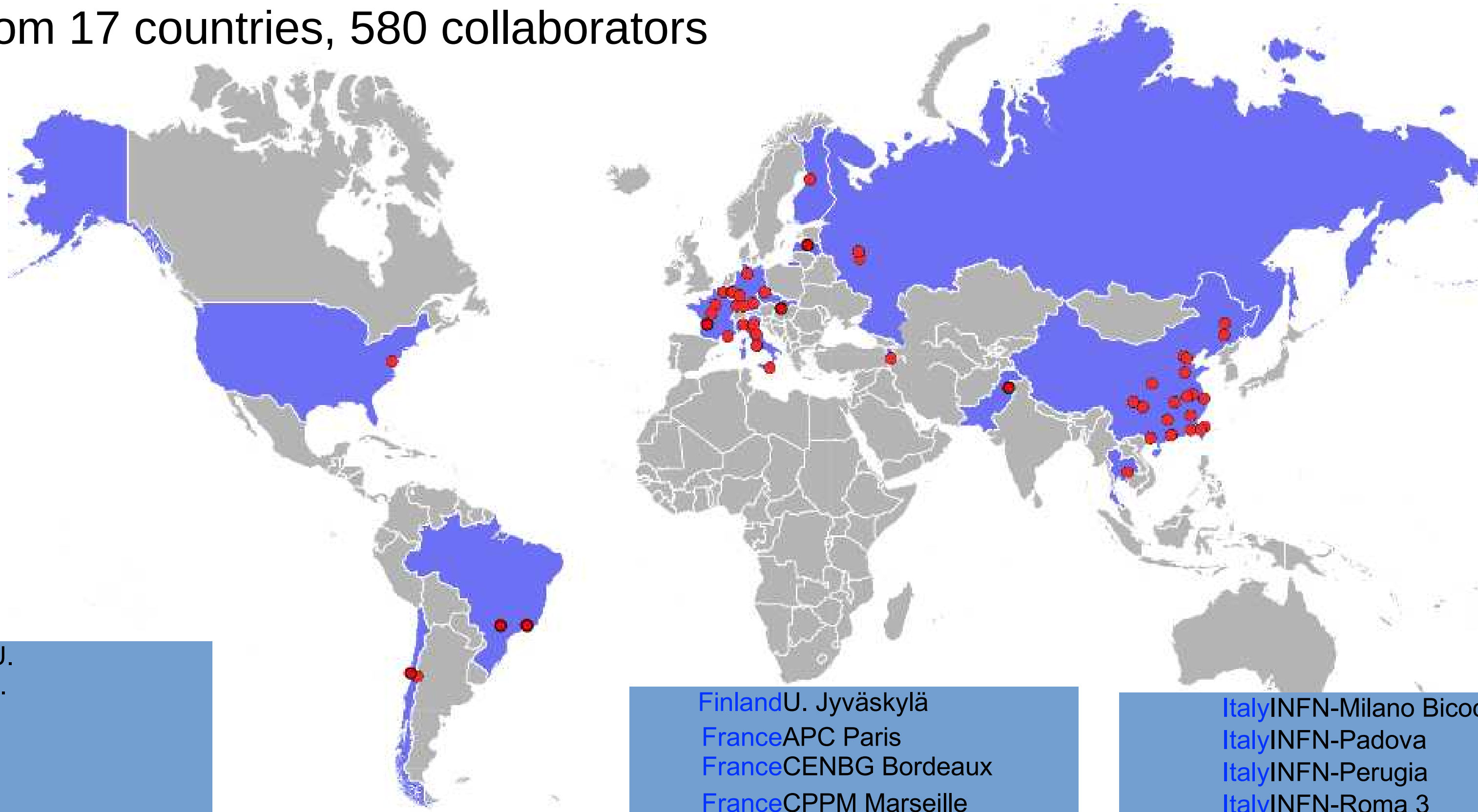
JUNO: Jiangmen Underground Neutrino Observatory

72 institutes from 17 countries, 580 collaborators



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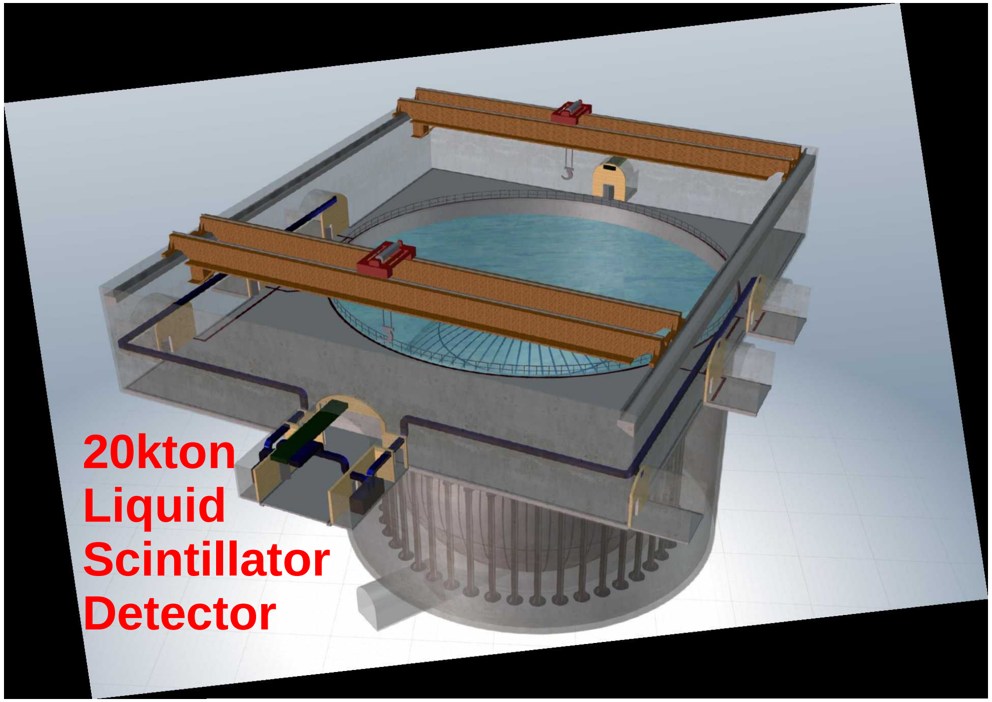
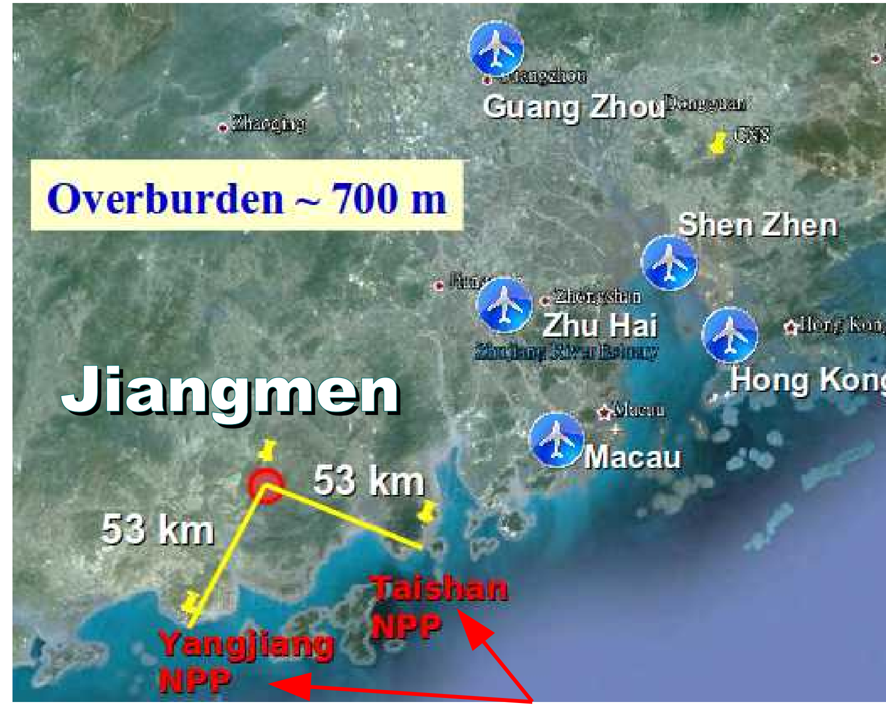
ChinaSYSU
ChinaTsinghua U.
ChinaUCAS
ChinaUSTC
ChinaU. of South China
ChinaWu Yi U.
ChinaWuhan U.
ChinaXi'an JT U.
ChinaXiamen University
ChinaZhengzhou U.
CzechR. Charles U. Prague

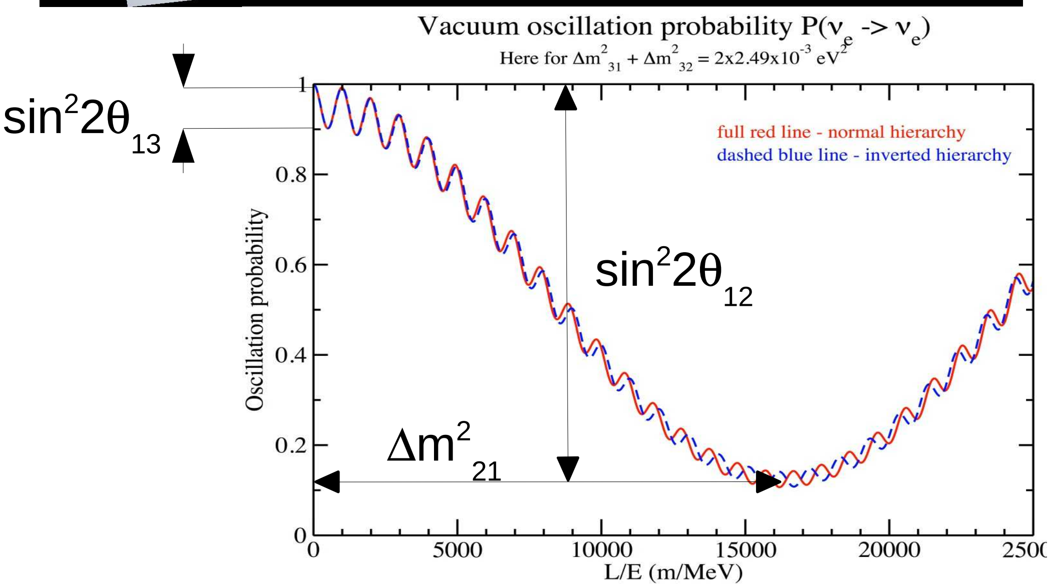
FinlandU. Jyväskylä
FranceAPC Paris
FranceCENBG Bordeaux
FranceCPPM Marseille
FranceIPHC Strasbourg
FranceSubatech Nantes
GermanyZEA FZ Julich
GermanyRWTH Aachen U.
GermanyTUM
GermanyU. Hamburg
GermanyIKP-2 FZ Jülich
GermanyU. Mainz
GermanyU. Tuebingen
ItalyINFN Catania
ItalyINFN di Frascati
ItalyINFN-Ferrara
ItalyINFN-Milano

ItalyINFN-Milano Bicocca
ItalyINFN-Padova
ItalyINFN-Perugia
ItalyINFN-Roma 3
LatviaIECS Riga
PakistanPINSTECH Islamabad
RussiaINR Moscow
RussiaJINR
RussiaMSU
SlovakiaU. Bratislava FMPICU
TaiwanNational Chiao-Tung U.
TaiwanNational Taiwan U.
TaiwanNational United U.
ThailandNARIT
ThailandPPRLCU Bangkok
ThailandSUT
USAUMD1
USAUMD2

JUNO: Jiangmen Underground Neutrino Observatory







High power nuclear power plants (26.6 GW total power)

- Decode the tiny difference in reactor neutrino oscillation spectra.
- Determine the neutrino mass hierarchy as a main task.
- Precision measurements of solar mixing parameters: Δm^2_{21} and $\sin^2 2\theta_{12}$
- SNe neutrinos, atmospheric neutrinos, geoneutrinos......

Overview of the JUNO detector

- **Central detector**

  - Acrylic sphere with 20kt liquid scintillator

  - 2000×20'' PMTs in water buffer

  - HQE PMT with ～78% coverage: 18000×20'' + 25000×3''

- **Liquid scintillator:**
  - **High light-yield: 10^4 photons/MeV**
  - **High transparency:**

    Attenuation Length (A.L.) > 20m @430nm

- **Water Cherenkov muon veto**

  - 35 ktons ultra-pure water

  - Efficiency > 95%

  - Radon control → less than 0.2 Bq/m3

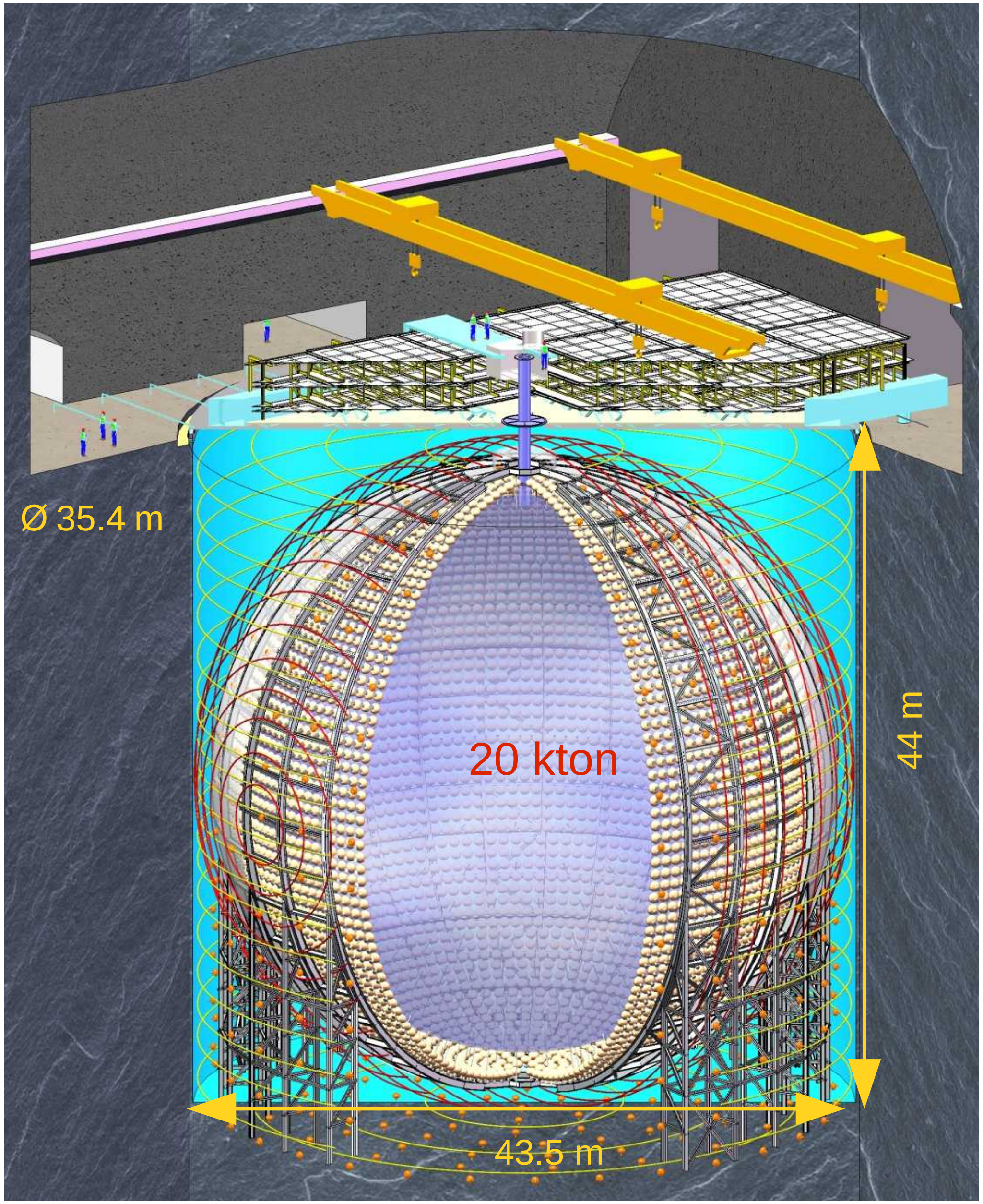
- **Compensation coils: Earth magnetic field suppressed to <10%**

- **Top tracker inherited from OPERA**

  - Precise muon tracking

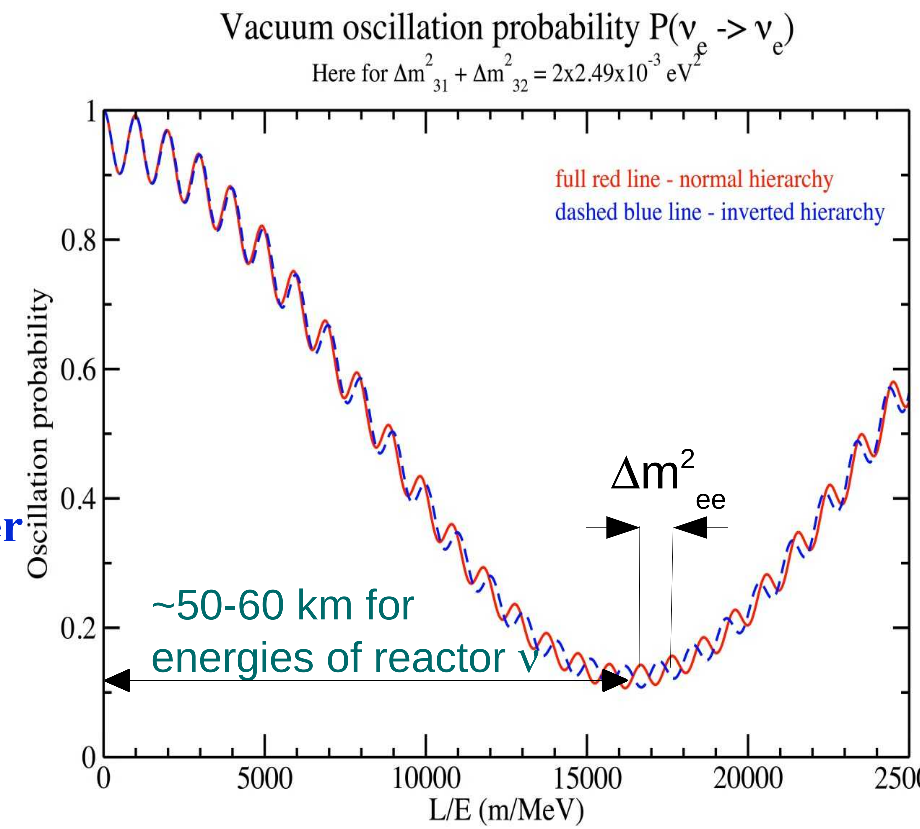
  - 3 plastic scintillator layers

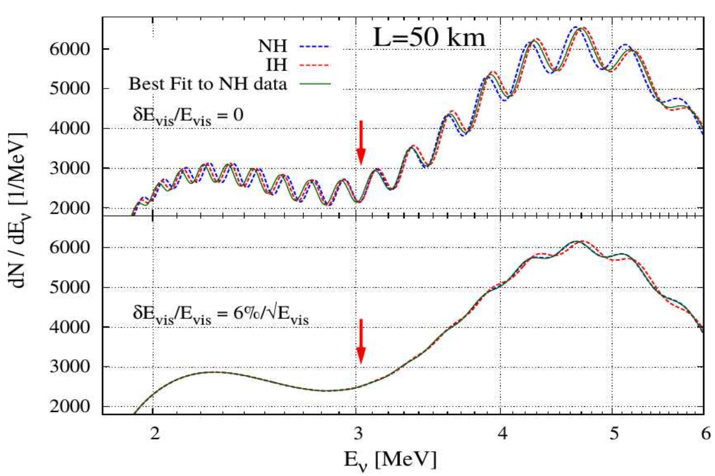
  - Covering half of the top area



Challenges in the MH determination

- **Reactor baseline variation: < 0.5 km**
  - **- JUNO site meets this requirement**
- **Energy resolution: ~ 3%/√E**
  $$\sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + \left(\frac{1.6b}{\sqrt{E}}\right)^2} \le 3\%$$
  - **- The crucial parameter**
- **Energy scale uncertainty: < 1%**
  - **- Large uncertainties could lead to a wrong answer**
- **Statistics: 100k events in 6 yrs**
  - **- 26.6 GW reactor power**
  - **- 20 kton detector (→ ~60 evts/day)**
  - **- Precision muon tracking to maximize exposure (minimize vetoed volume)**





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Challenges in JUNO

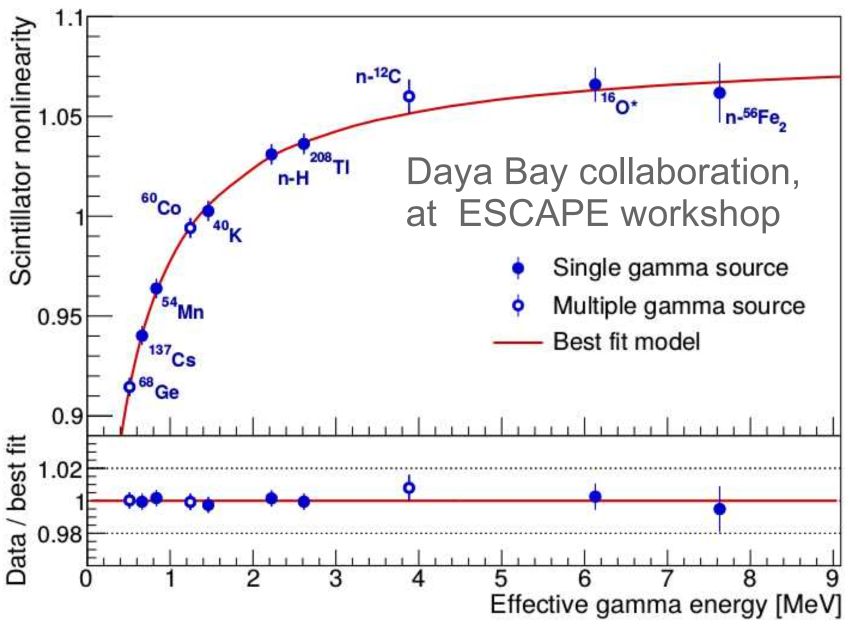
- **Answer: Meticulous calibration**

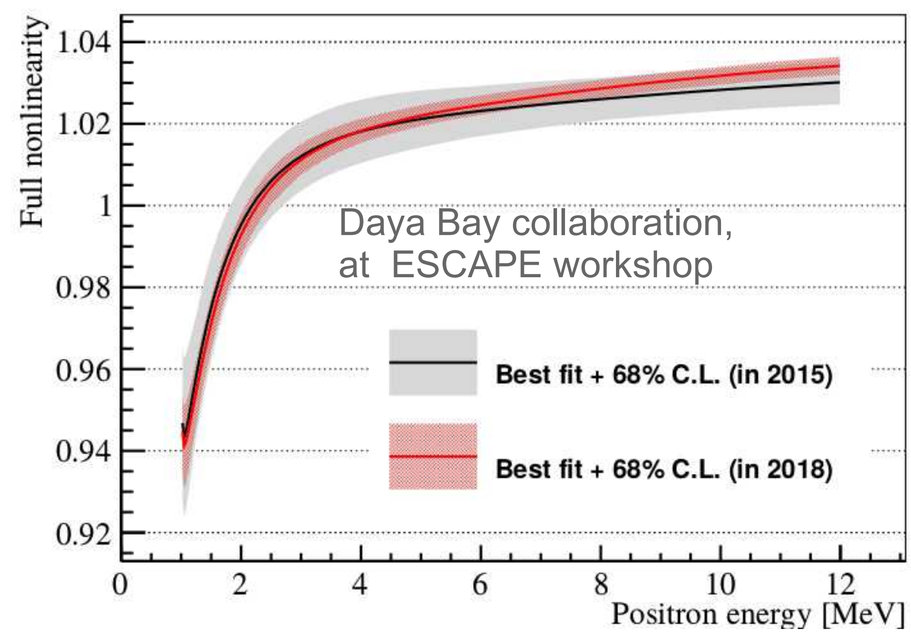
  (Different sources, over whole energy range, continuously, ...)

- **Other experiments already achieved 0.5% accuracy**

  (Daya Bay ~0.5%, Double Chooz 0.74%, Borexino <1% (at low energies), KamLAND 1.4%)

New results from ESCAPE workshop



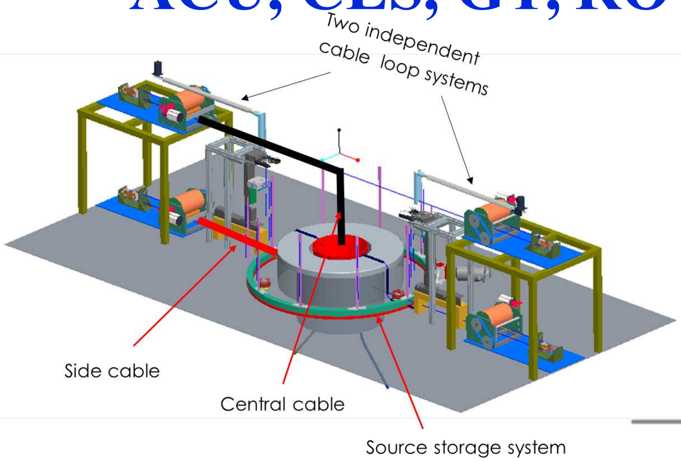


For more information see: Daya Bay collaboration, Phys. Rev. D 95, 072006 (2017)

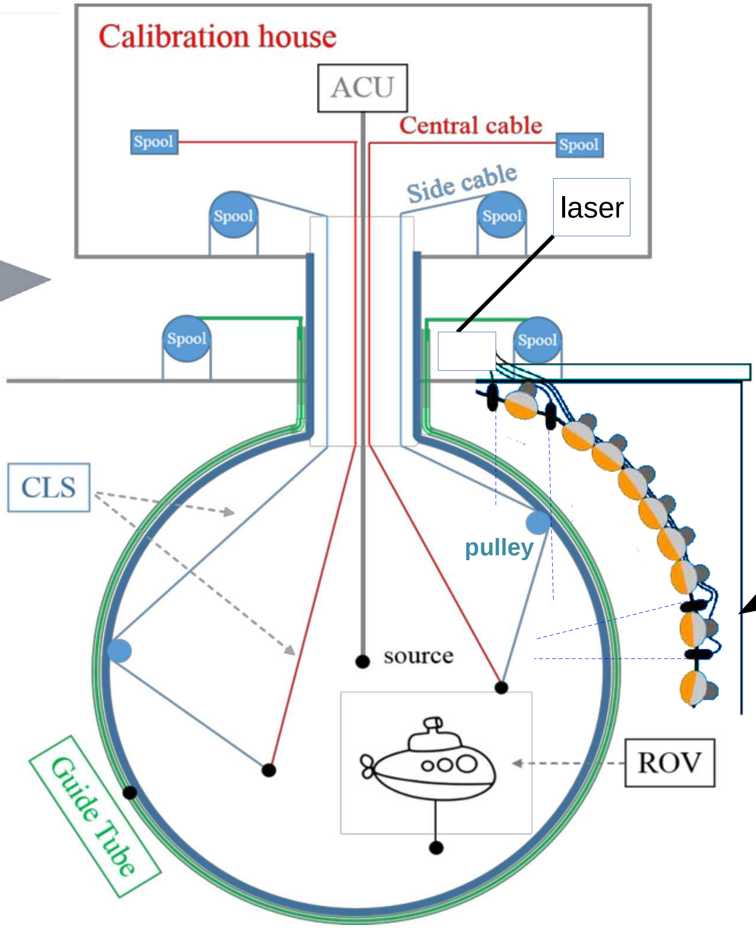
Calibrations in JUNO

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

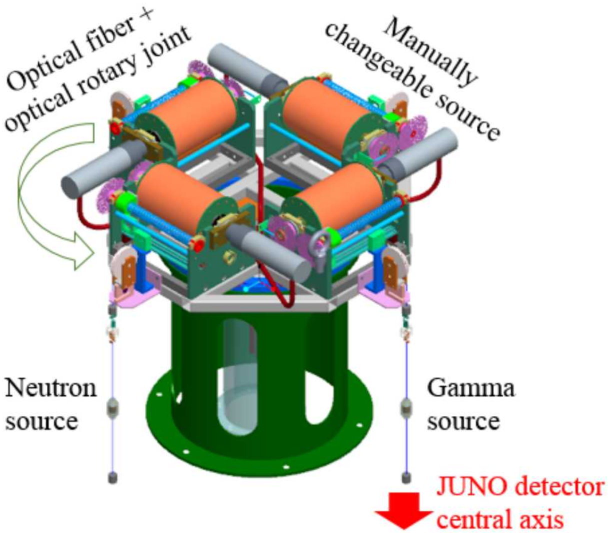
ACU, CLS, GT, ROV, LFS



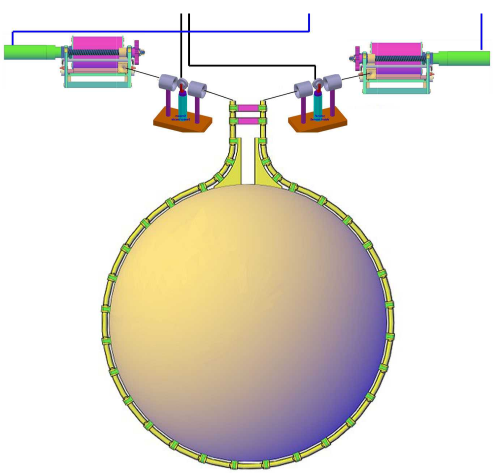
Cable Loop System (CLS)



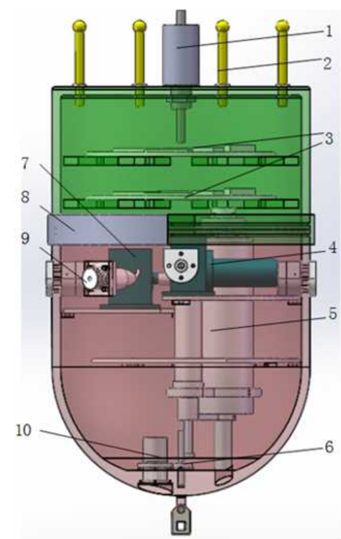
Laser fiber system



Automatic Calibration Unit (ACU)



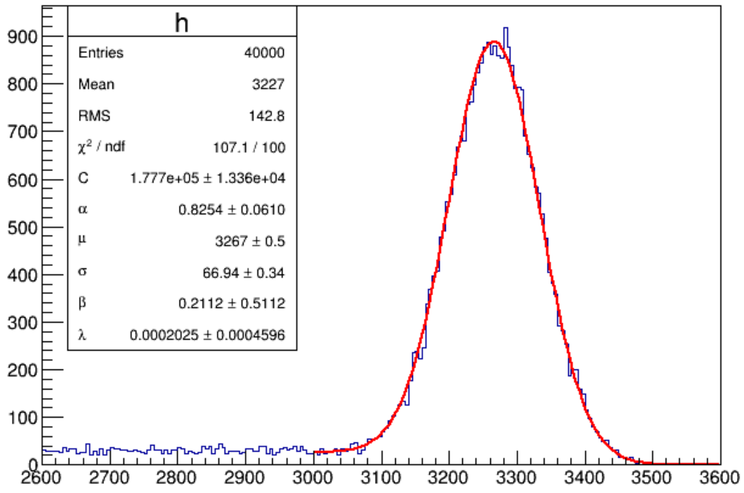
Guide tube system



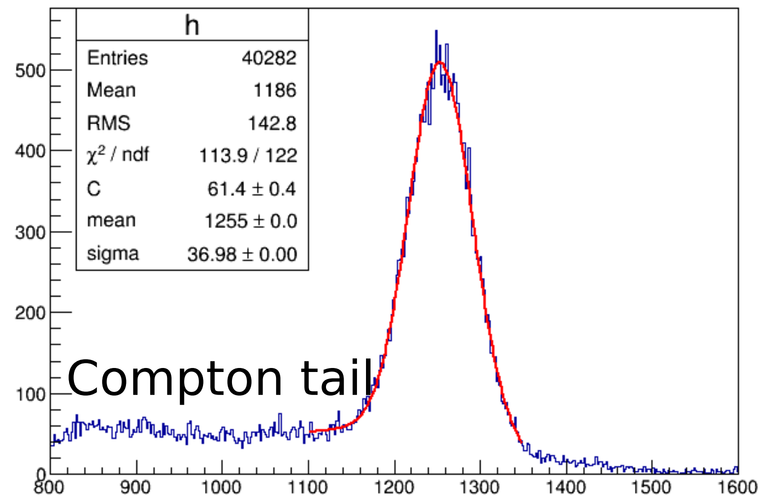
Remotely Operated Vehicle (ROV)

Energy scale and calibration data by MC

^{60}Co at CD center with source enclosure



^{68}Ge at CD center with source enclosure



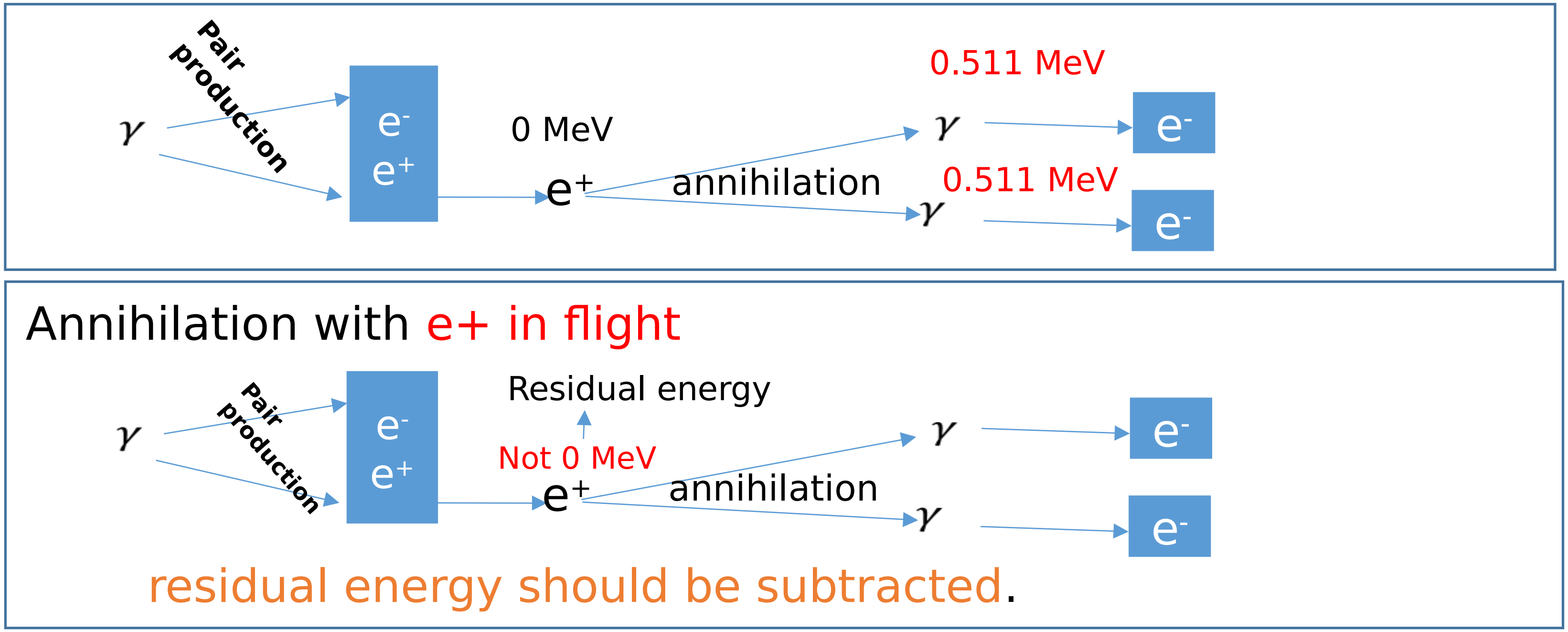
- Full absorption peak as measure.
- **^{60}Co as energy scale**: =1304 PE/MeV
- Reconstructed energy for ^{68}Ge: =0.96 MeV
- Non-linearity: E_{rec}/E_{true} =0.96/1.022 = 0.94

- Reconstruct energy for ^{54}Mn, ^{137}Cs, ^{40}K, n-H, n-C, Am-C with same energy scale.

Credit: Fei-Yang Zhang

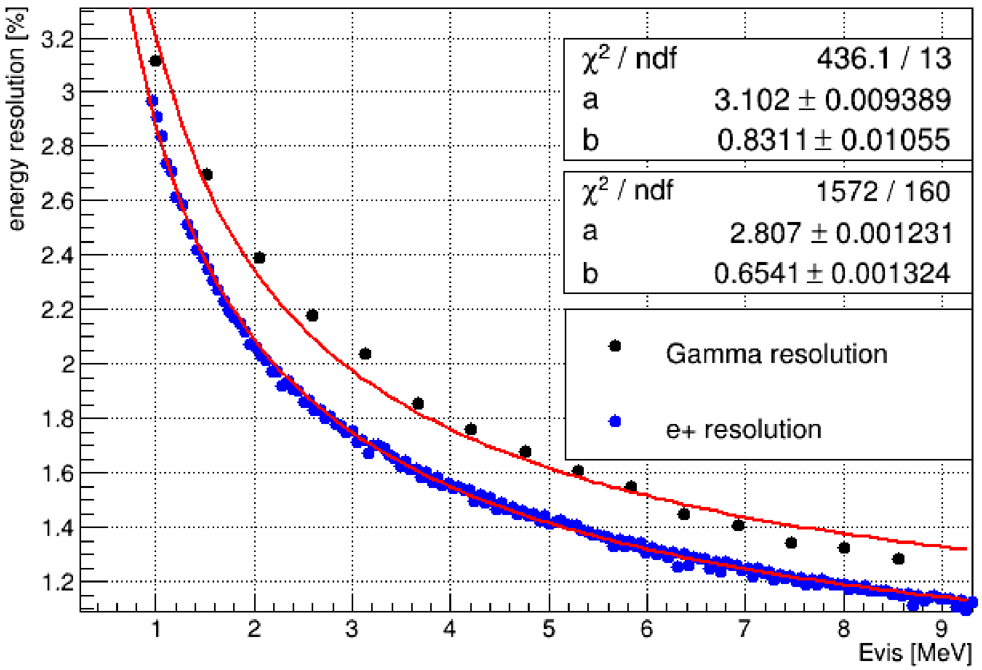
Gamma to e-/e+ conversion

- Gamma convert to e-/e+:
  - Pair production
  - Compton scattering
  - Photoelectric
- Gamma energy non-linearity can be deduced from non-linearity of primary e-/e+
- The electron from annihilation gamma should also be considered.



Construct a energy reconstruction model?

Energy resolution of gamma and e+



- Obviously difference between gamma and e+.
- Necessary to develop e+ energy resolution model.
- Resolution of gamma can be obtained from calibration data.
- Derive e+ energy resolution from gamma.

Credit: Fei-Yang Zhang

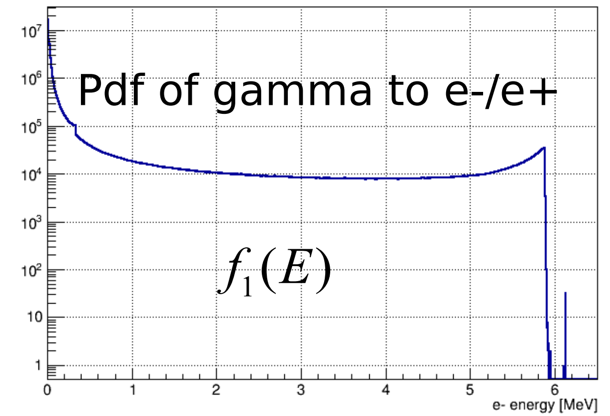
Model of gamma energy non-linearity

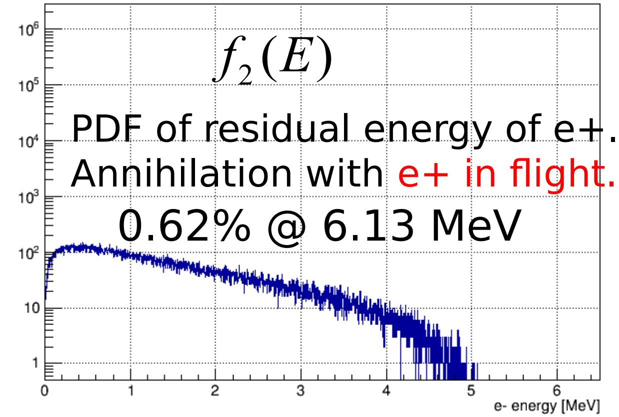
Empirical formula to describe electron non-linearity:

$$f_{nonl}(\mathrm{E}) = \frac{E_{rec}}{E_{true}} = \frac{p_0 + p_1 \times E + \frac{p_2}{E}}{1 + p_3 \times e^{-p_4 \times E}}$$

Construct model of gamma energy non-linearity with PDF and electron non-linearity:

$$\frac{E_{rec}}{E_{true}} = \frac{\sum E_i f(E_i) \frac{p_0 + p_1 \times |E_i| + \frac{p_2}{|E_i|}}{1 + p_3 \times e^{-p_4 \times |E_i|}}}{\sum E_i f(E_i)}$$





$$\sum E_i f(E_i) = \sum E_i (f_1(E_i)\text{-}f_2(E_i))$$

=6.128±0.003 MeV

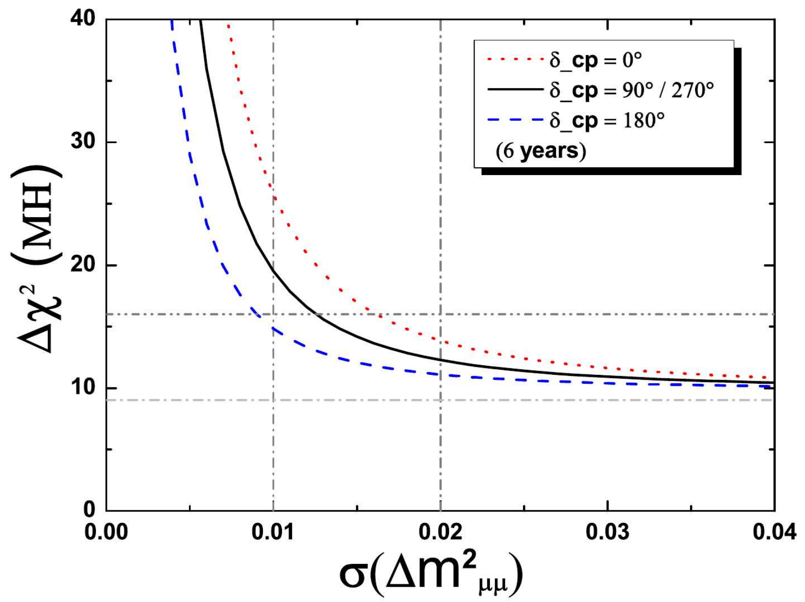
Ref:

- Liangjian Wen, et al., Ref: Daya Bay DocDB 8240-v2
- Fengpeng An, et al (Daya Bay Collaboration): PRL 112, 061801(2014)

Sensitivity in MH measurements

- Measurement with or without constraint on $\Delta m^2_{\mu\mu}$

Y.F. Li et al. Phys.Rev. D88 (2013) 013008, arXiv:1303.6733



- Sensitivity with 100k events (~6 yrs):
  - No constraint: $\Delta\chi^2 > 9$
  - With 1% constraint: $\Delta\chi^2 > 16$

$$|\Delta m^2_{ee}| - |\Delta m^2_{\mu\mu}| = \pm \Delta m^2_{21} \cdot (\cos(2\theta_{12}) - \sin(2\theta_{12})\sin(\theta_{13})\tan(\theta_{23})\cos(\delta))$$

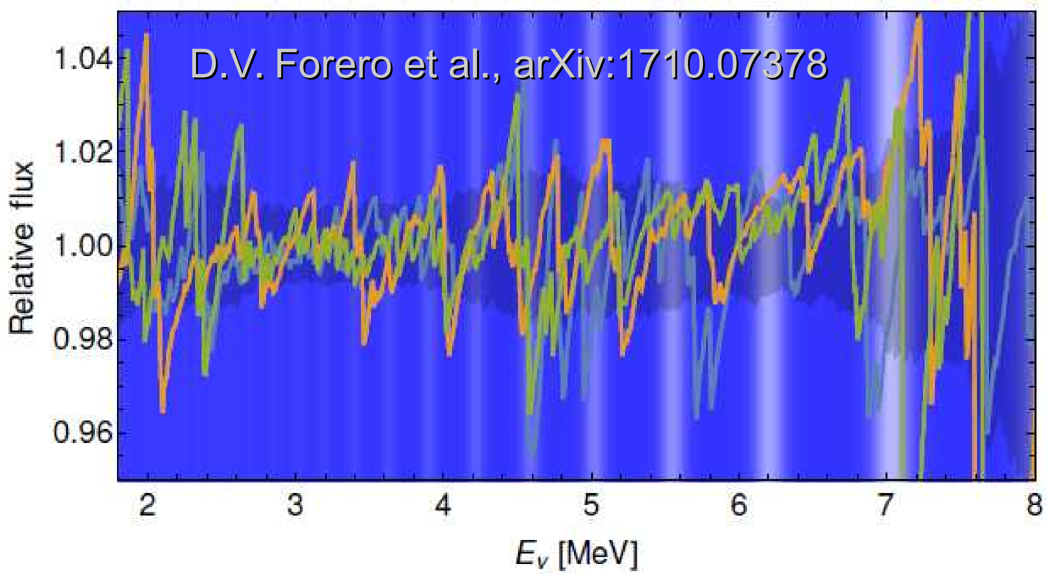
Sign defined by MH

See H. Nunokawa et al, Phys.Rev. D72 (2005) 013009

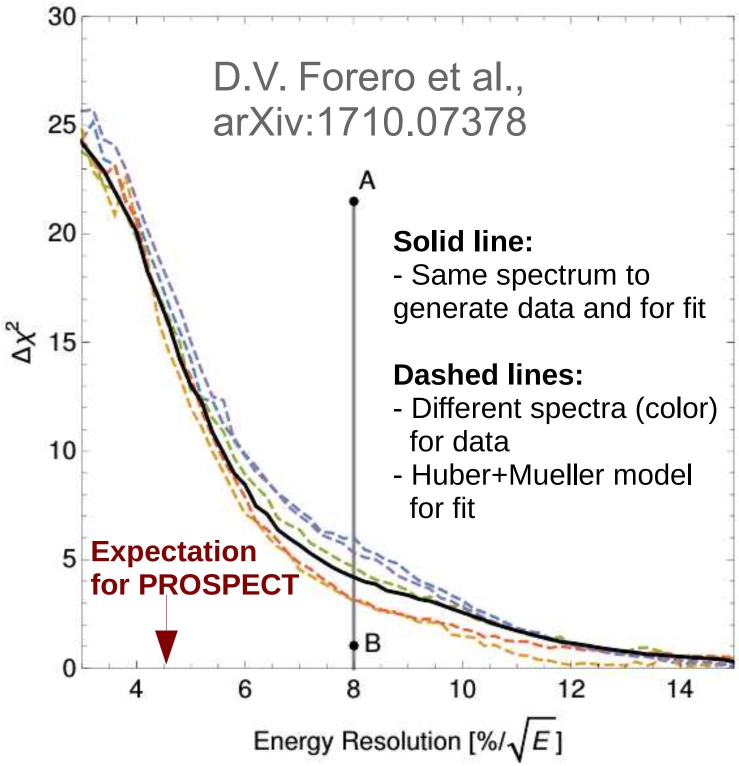
Uncertainties in reactor neutrino spectra

- Reactor spectrum might show micro-structure

  (see e.g. A.A.Sonzogni, et al. arXiv:1710.00092, D. A. Dwyer &T. J. Langford, Phys. Rev. Lett. 114,012502 (2015))
- It might degrade the MH sensitivity by mimicking the periodic oscillation structures



Relative difference of 3 synthetic spectra to spectrum predicted from ILL data (Huber+Mueller model)



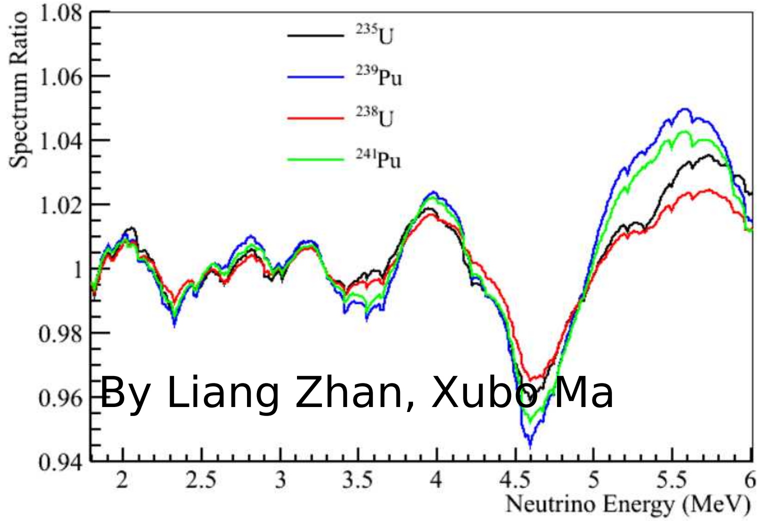
of reactor spectrum measurement

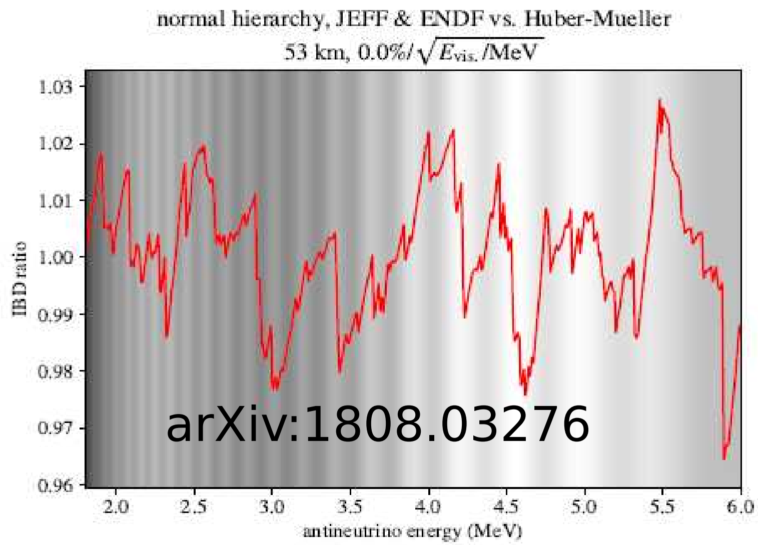
arXiv:1808.0327

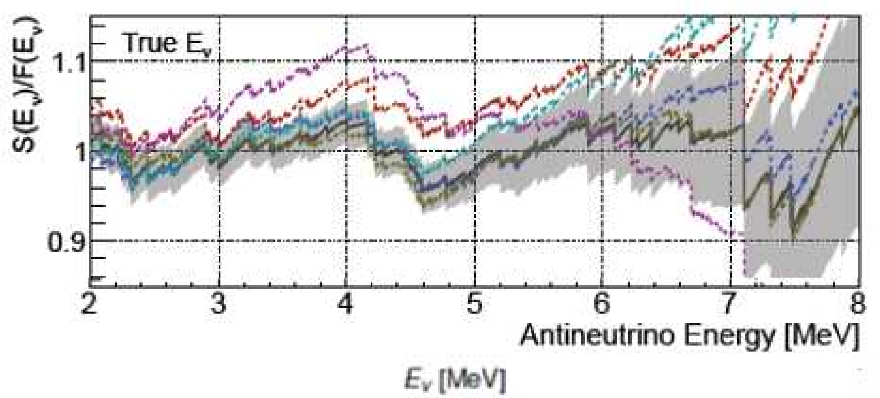
→ Need reactor spectrum with energy resolution similar to JUNO

Uncertainties in reactor neutrino spectra

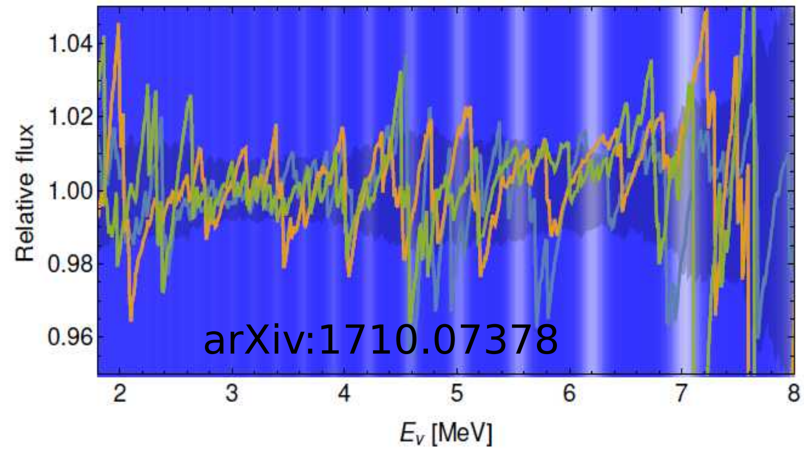
- Fine structure depends on the ab-initio calculation using nuclear database and can not be precisely determined.
- JUNO-TAO provides model independent measurement of fine structure, as inputs for JUNO







Phys.Rev.Lett. 114 (2015) no.1, 012502



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Solution: A Near Detector – JUNO-TAO

- JUNO – Taishan Antineutrino Observatory (JUNO-TAO) acts as a near detector.
- Started R&D

  - 2.9 ton Gd-LS in spherical vessel

  - Outer buffer oil in stainless steel vessel

  → Central detector size ~ 2 m x 2 m x 2 m

  → @35 m to reactor (4.6GW): 10x JUNO statistics (6yr) after 1 year

- Two sensor types under consideration:

  - SiPM → need -50°C → 1.7% energy resolution

  - 2300 3.5” PMTs → 2.5% energy resolution

- Additional motivations:

  - Shed light on reactor spectrum anomaly (5 MeV bump)

  - Serve as benchmark to test nuclear database

Summary

- **JUNO is an unique reactor neutrino experiment to determine the neutrino mass hierarchy with unprecedented energy resolution.**
- **JUNO is doing meticulous calibrations to meet physics requirements.**
- **MH sensitivity: $\Delta\chi^2$>9 ($\Delta\chi^2$>16 with 1% constraint on $\Delta m^2_{\mu\mu}$)**
- **Rich additional physics program. Ref: Yaping's talk at this conference!**
- **Very active R&D program**
- **Data taking will start in 2021**
- **Started near detector R&D： Energy resolution < 3%**

Thanks for your attention!