Development of the calibration sources for the JUNO experiment

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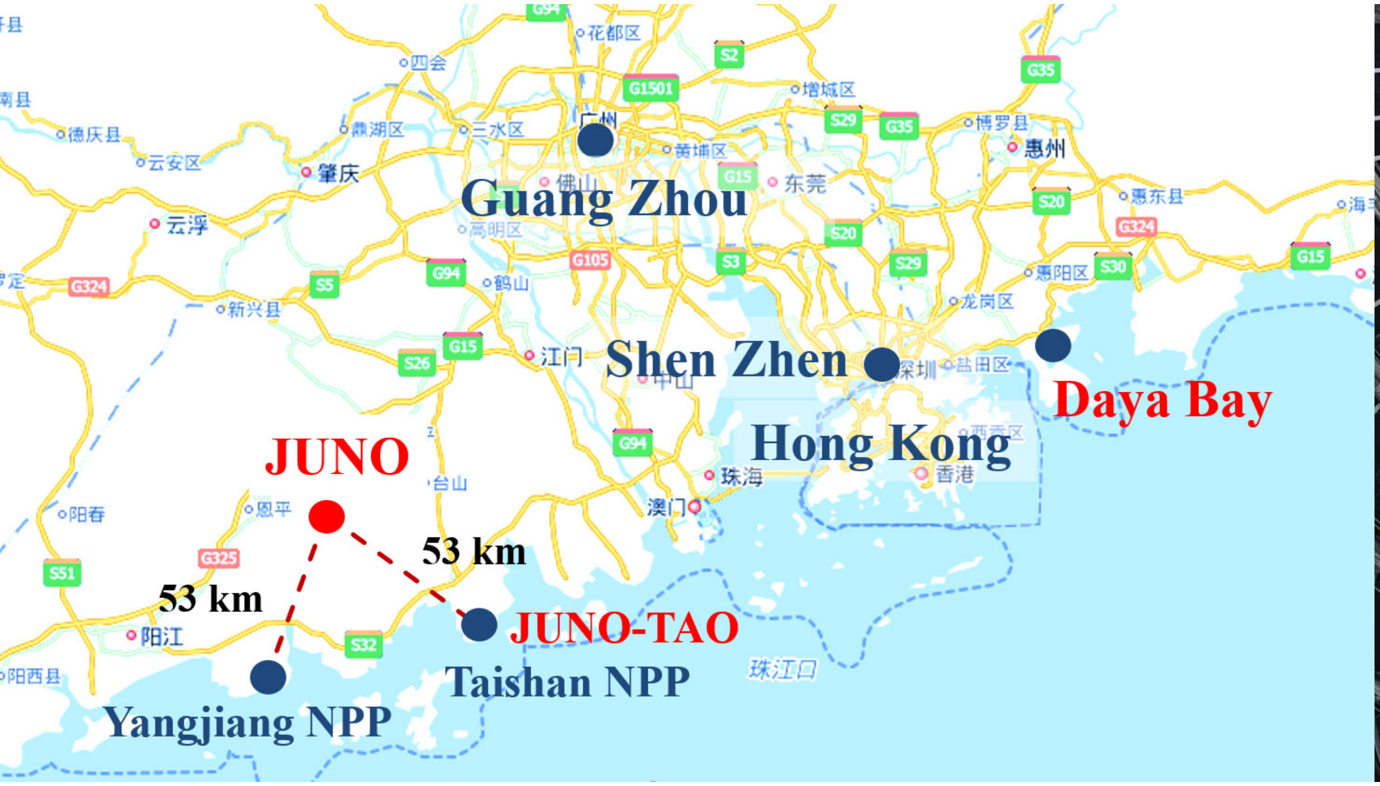
TAUP Conference in Xichang

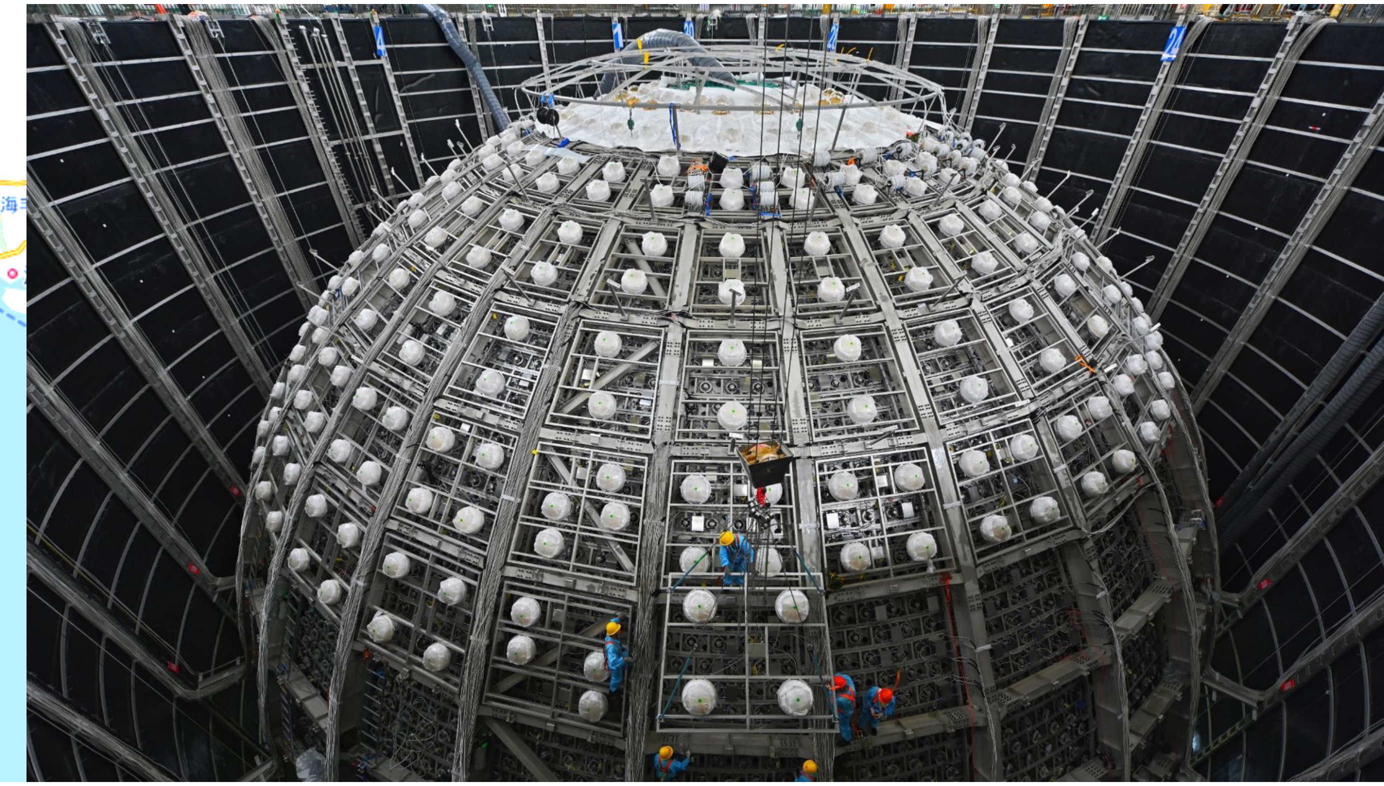
28th/Aug./2025

The work presented below was performed during my time at Shanghai Jiao Tong University

JUNO Experiment

PPNP 123, 103927 (2022)

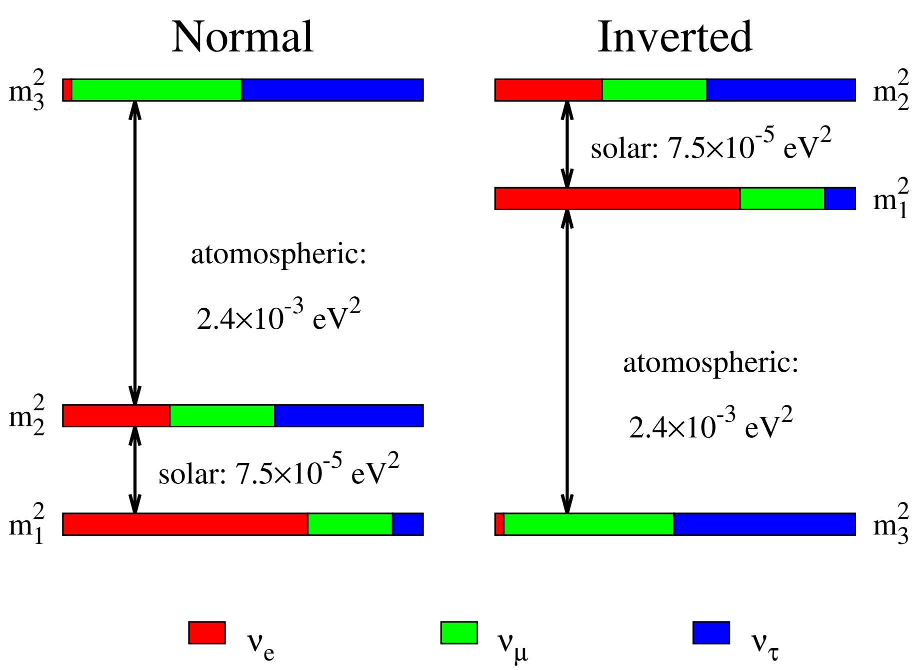




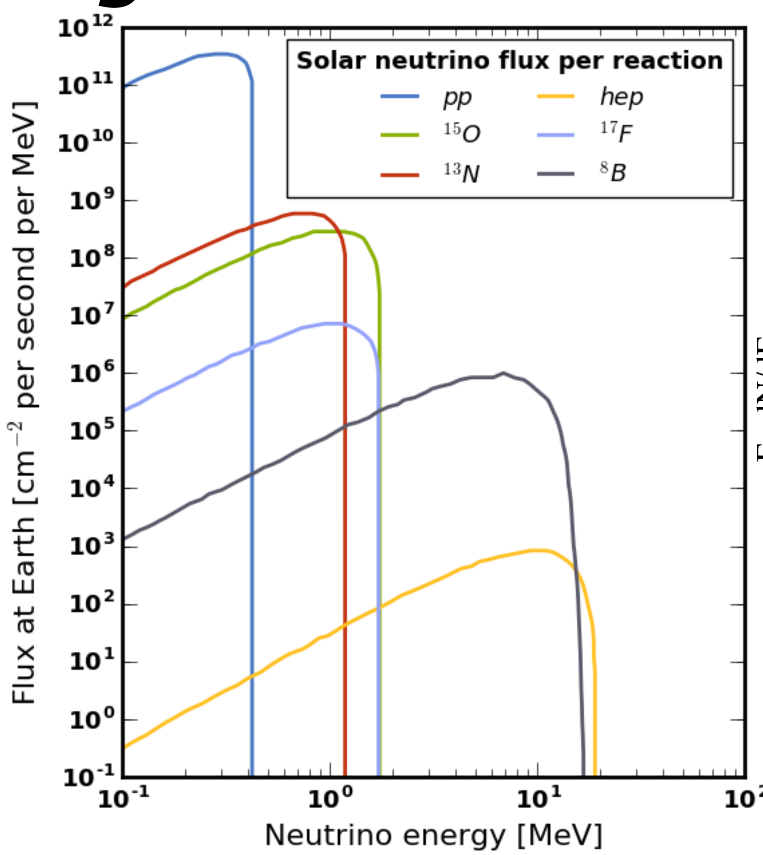
- JUNO is the world's largest underground (~650 m overburden) liquid scintillator experiment, located in Jiangmen, China.
- The detector construction, including the liquid scintillator filling, was completed several days ago.
- The collaboration consists of 74 institutions and over 700 members.

JUNO Commissioning Talk: 28th 2:40 PM (Iwan Morton-Blake), JUNO Plenary Talk: 29th 0:20 PM (Alberto Garfagnini)

JUNO Physics Programs

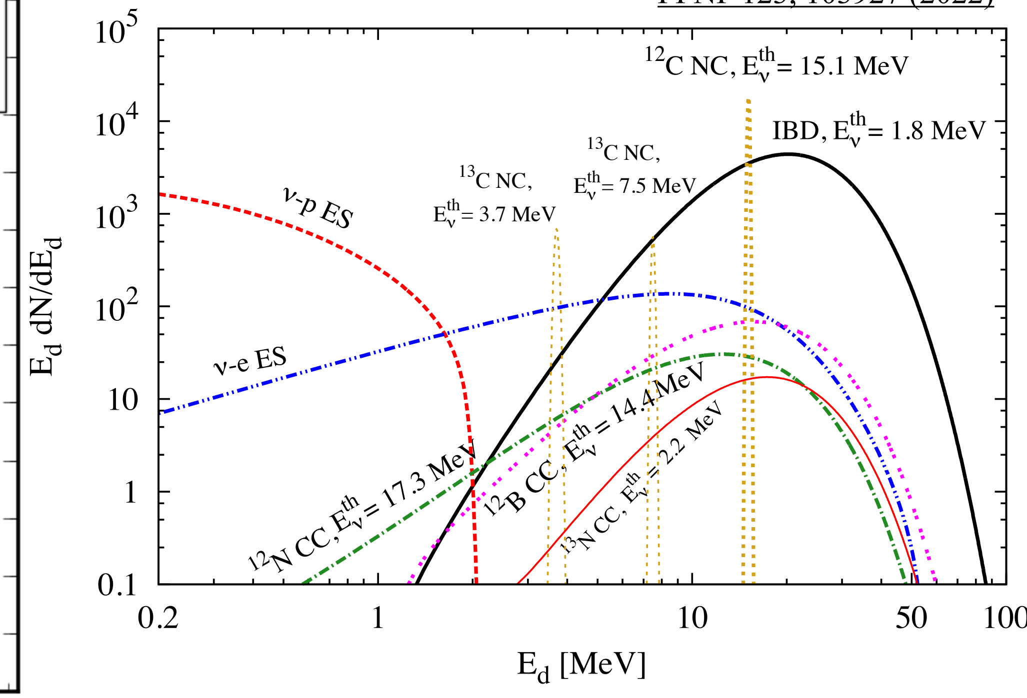


Neutrino mass ordering



Solar neutrino spectra

PPNP 123, 103927 (2022)

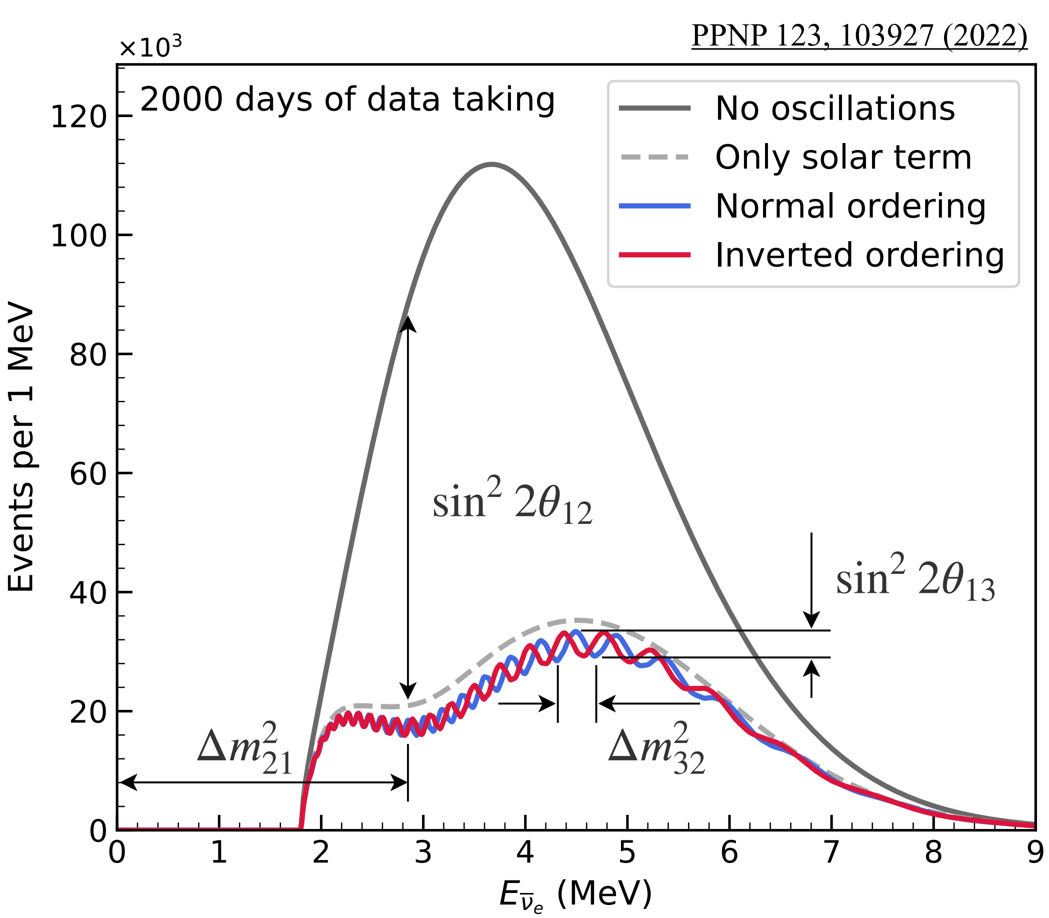


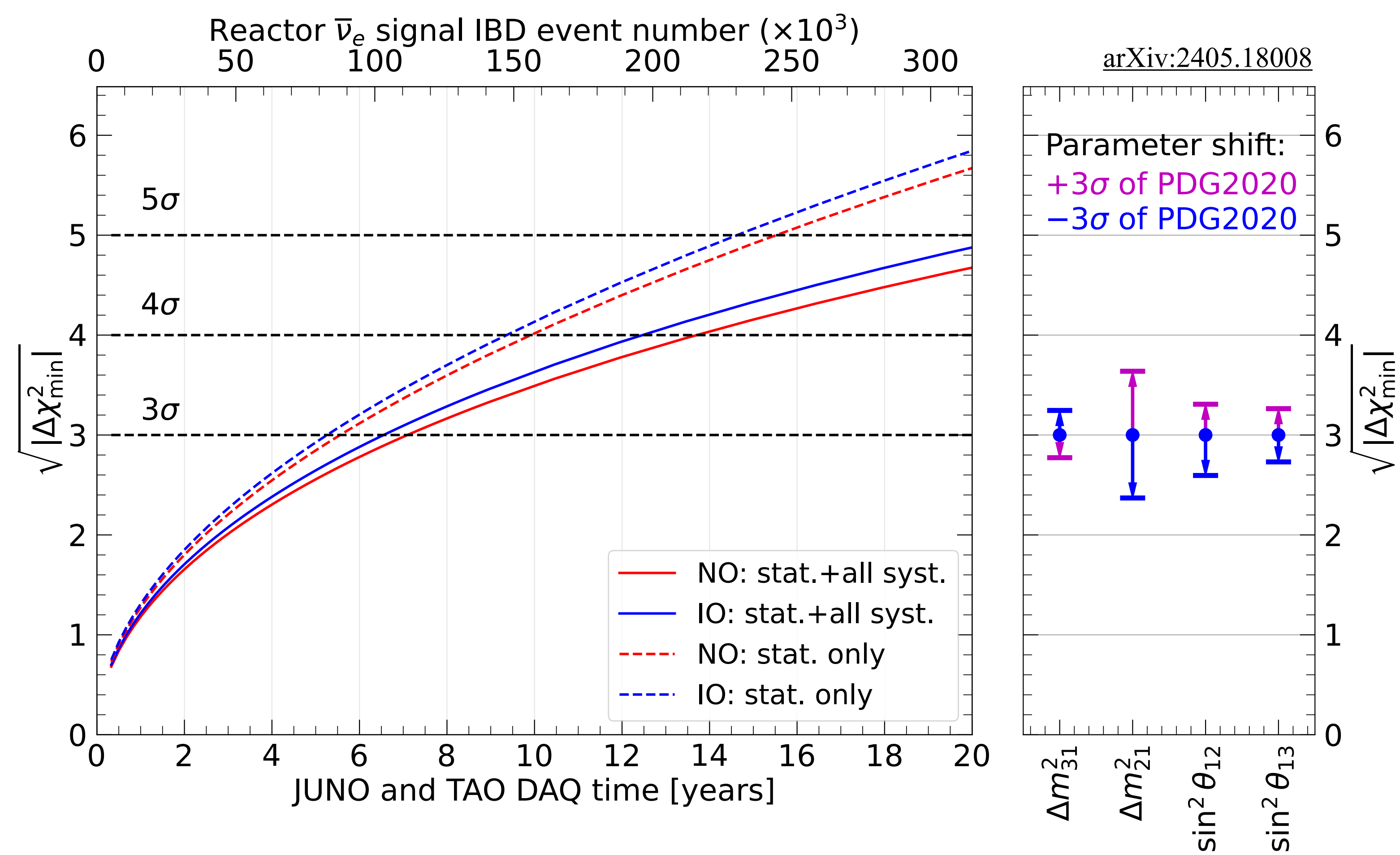
Expected spectra from SN

- JUNO is going to address a variety of physics topics:
  - Reactor, atmospheric, solar, geo, and supernova neutrino observations,
  - Nucleon decay searches,
  - Other new physics searches, etc.

JUNO Solar Neutrino Talk: 26th 4:20 PM (Marco Beretta)

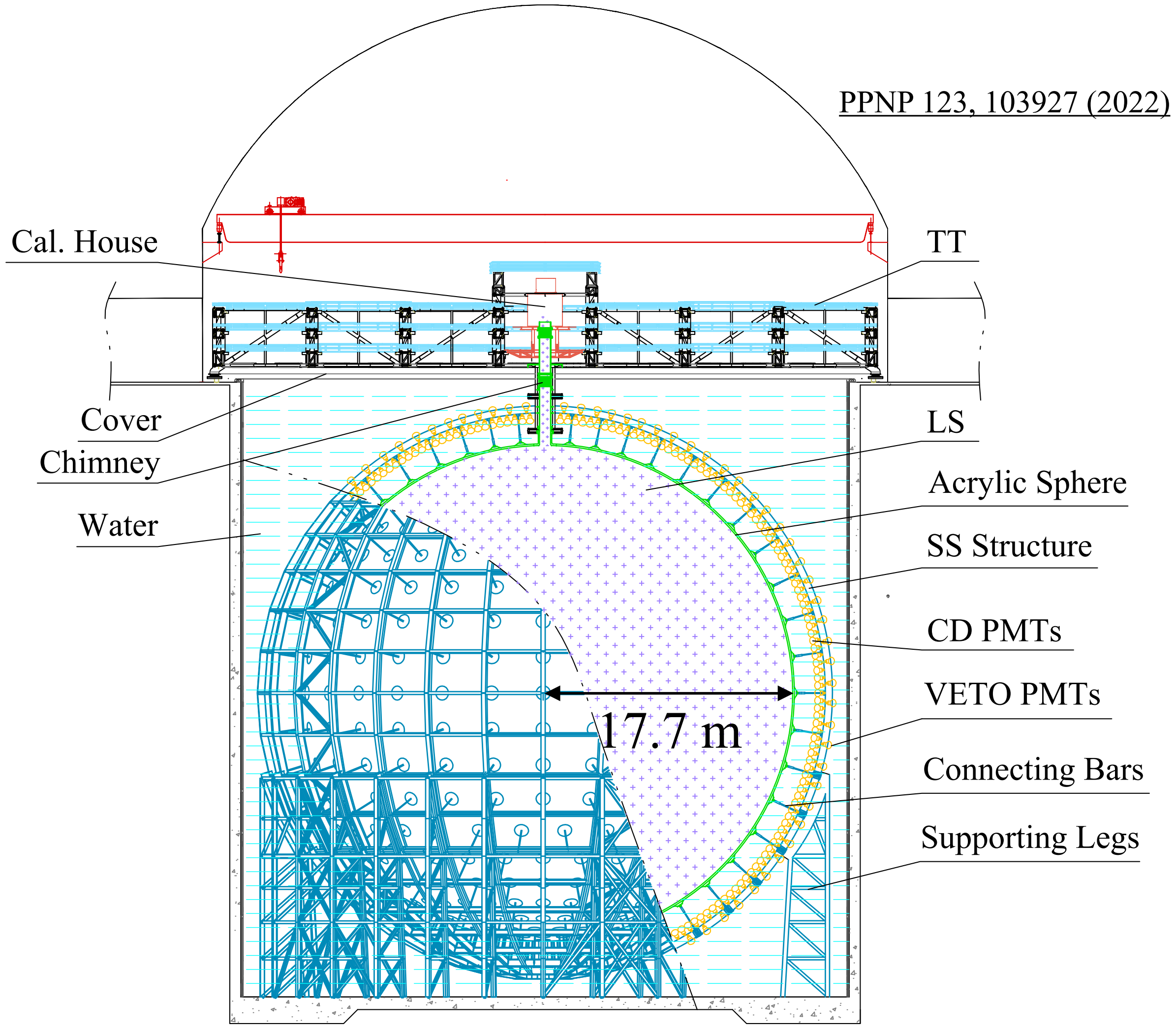
Neutrino Mass Ordering





- The primary goal is to determine the neutrino mass ordering from the energy spectrum of reactor neutrinos.
  - The sign of the mass ordering manifests as a phase shift.
- The sensitivity will reach 3 σ after ~6 years of operation, assuming:
  - An optimized energy resolution of 3% at 1 MeV.
  - The energy scale uncertainty remains below 1%.

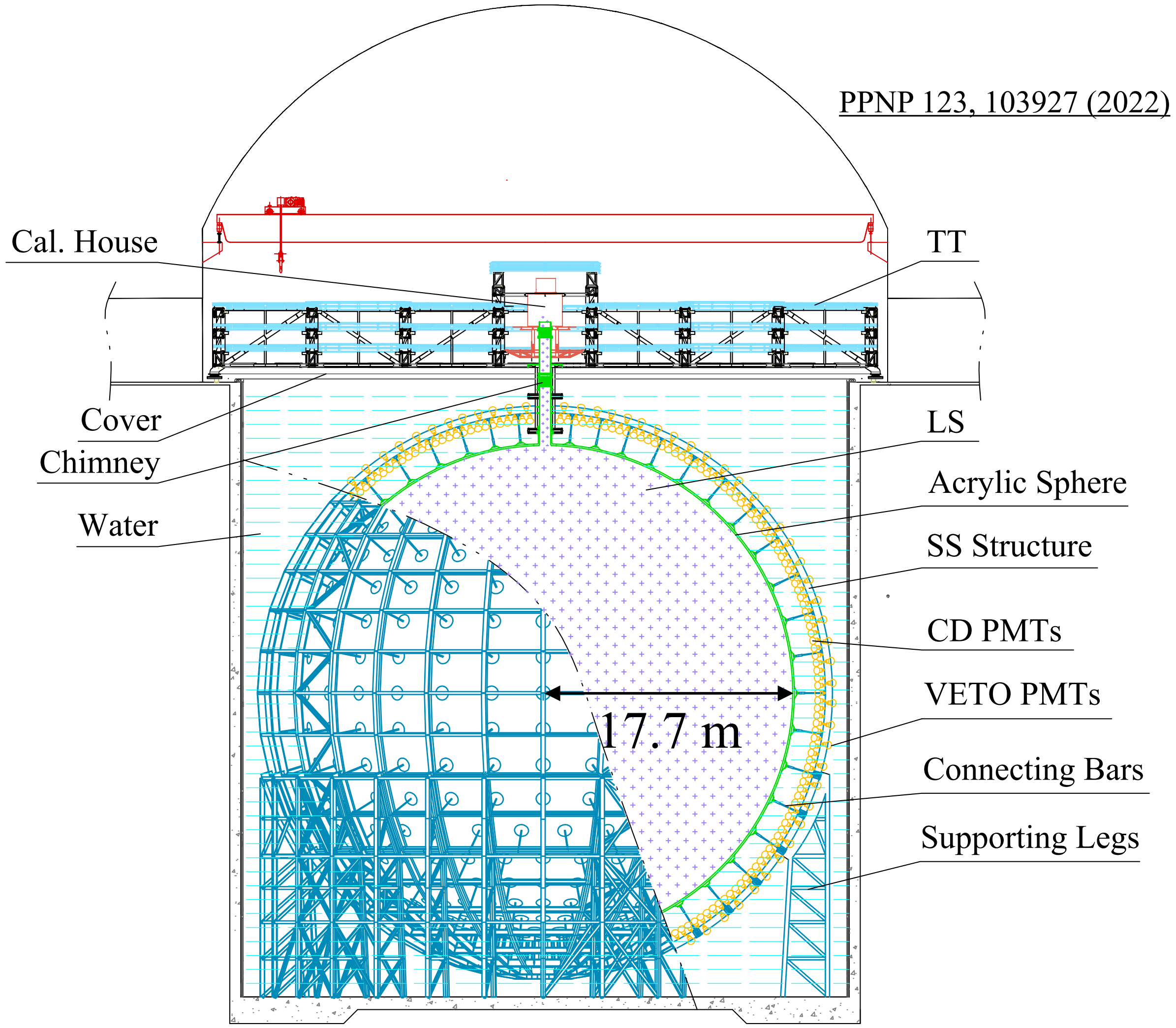
JUNO Detector (1)



- The 20-kton liquid scintillator (LS) is housed in an acrylic sphere, sustained by a stainless steel structure, submerged in pure water.
  - The composition of the fluor and wavelength shifter in the LS has been optimized to maximize its light yield. NIMA 988, 164823 (2021)

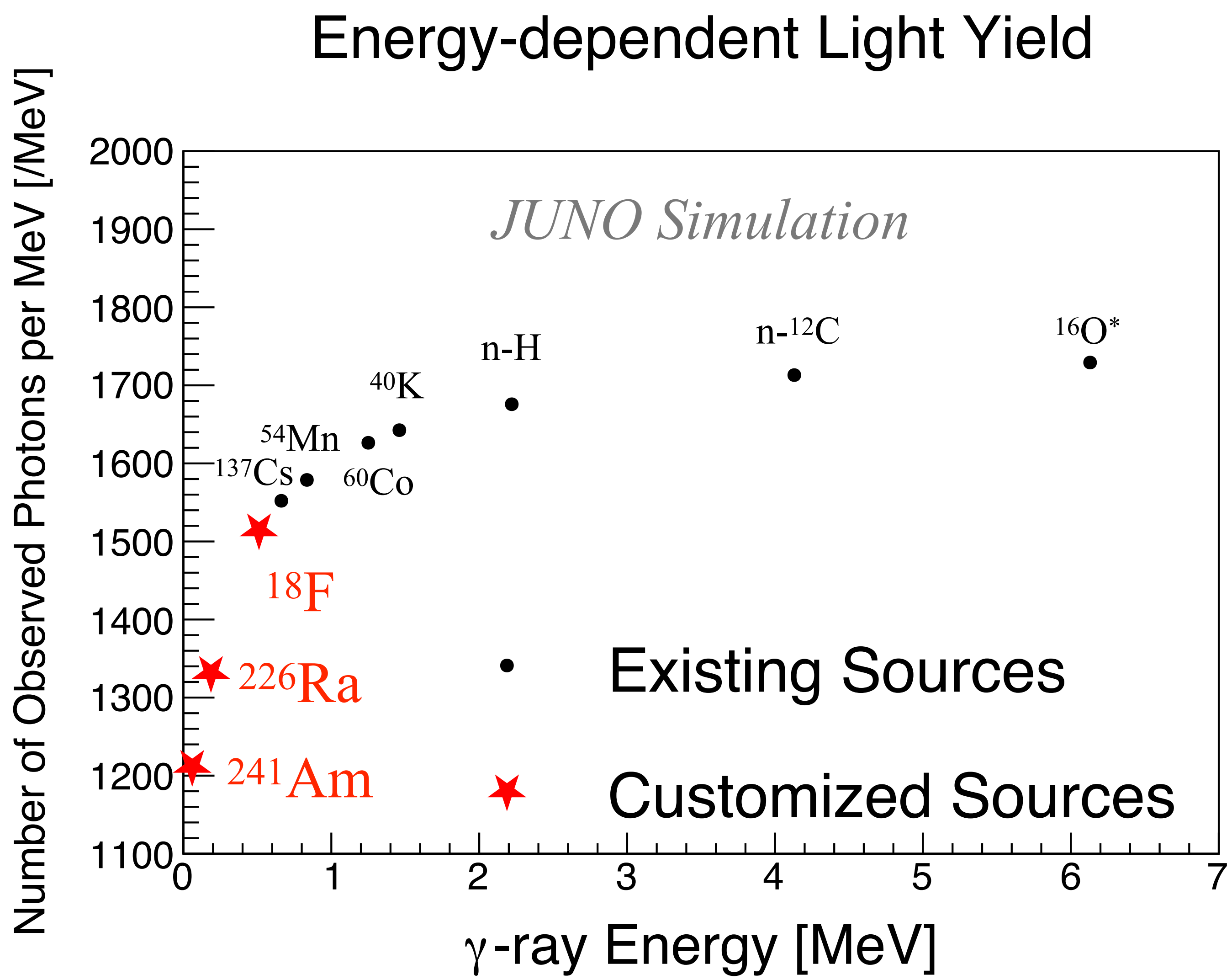
JUNO Liquid Scintillator Talk: 28th 5:00 PM (Ulrike Fahrendholz)

JUNO Detector (2)



- A large number of photomultiplier tubes (PMTs) were installed in the stainless steel structure:
  - 17,596 20-inch PMTs, and 25,600 3-inch PMTs.
- The expected number of observed photoelectrons (p.e.) per MeV for events at the detector center is ~1650 p.e.

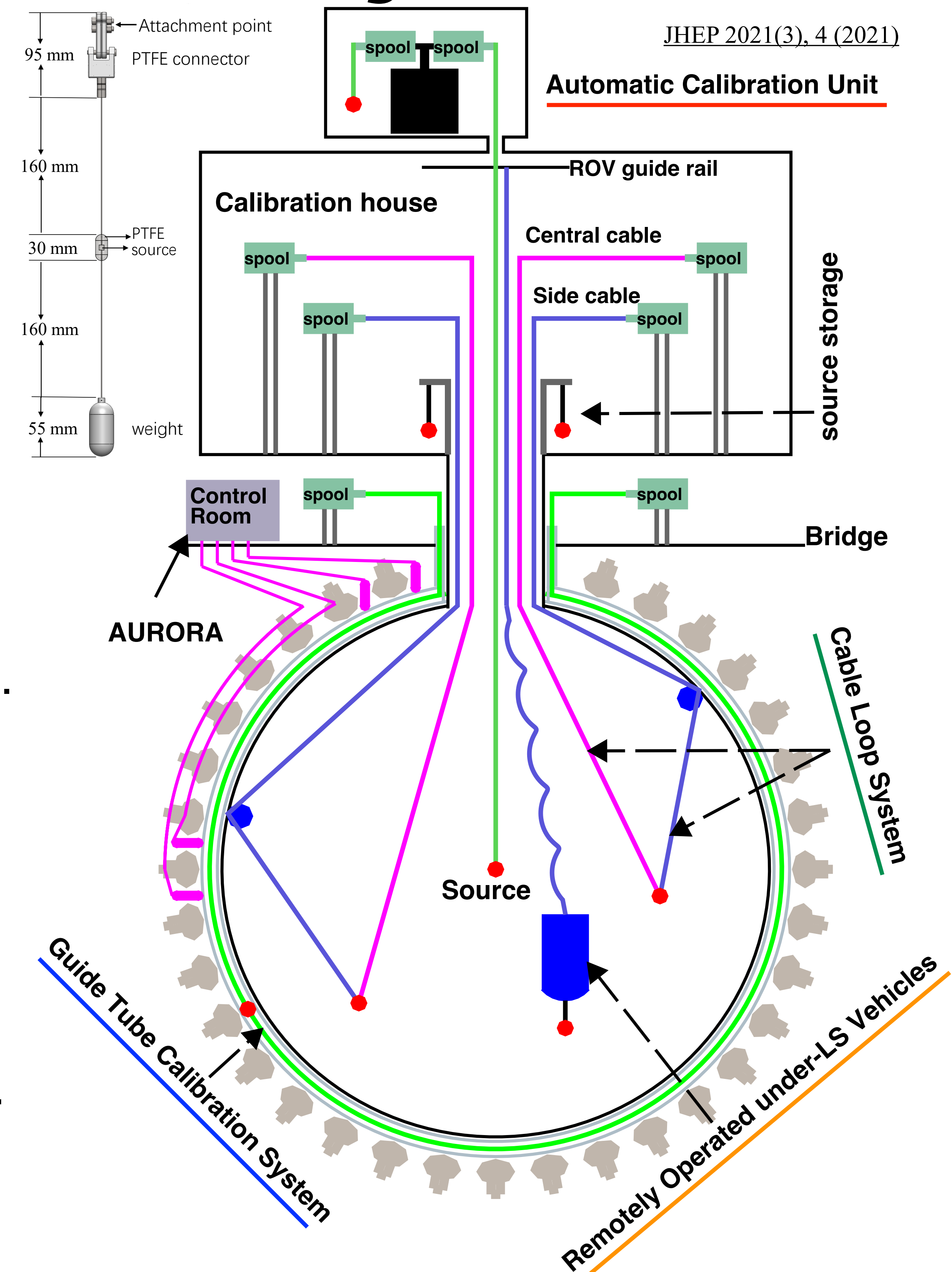
Liquid Scintillator Non-linearity



- The light yield of the LS is non-linear to the deposited energy of the particle due to the LS quenching and Cherenkov light contribution.
- Several γ-ray sources are deployed in the detector to understand this non-linearity and establish an energy response model.
- In addition to the commercial sources, we have developed multiple more radioactive sources (^{18}F, ^{226}Ra, and ^{241}Am).

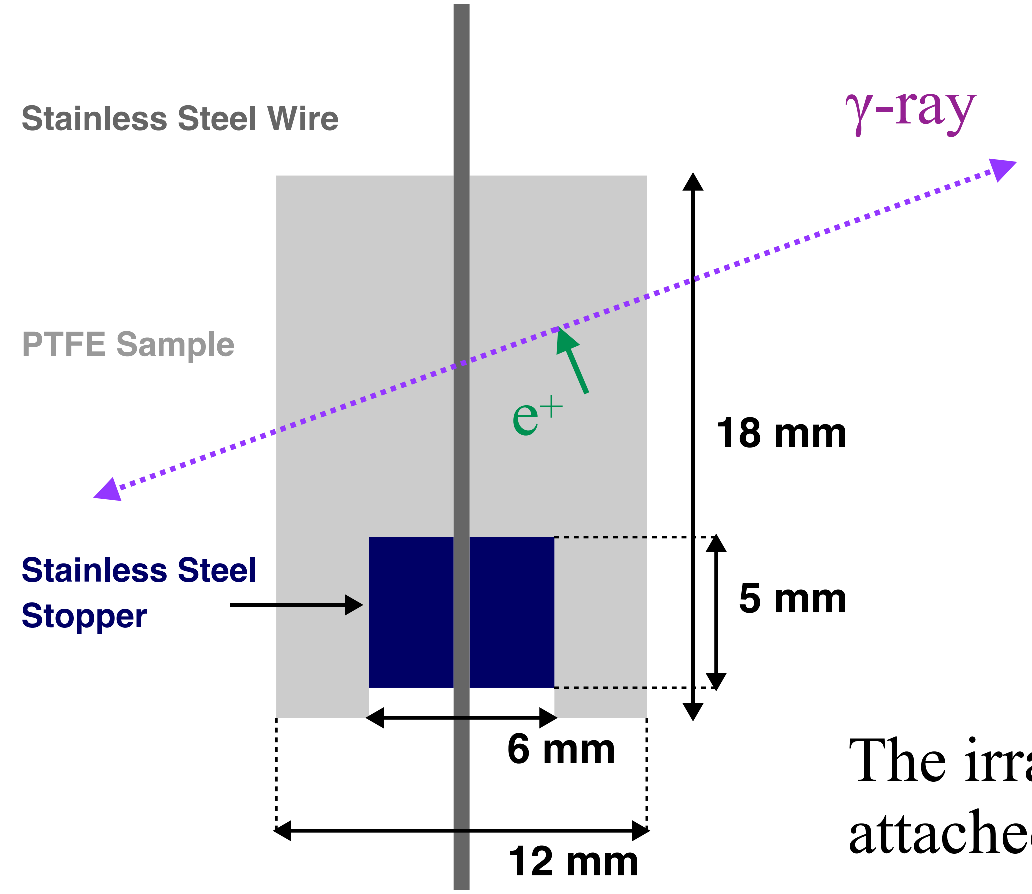
JUNO Calibration System

- Multiple calibration source deployment devices are installed, placing a calibration source at different positions:
  - Automatic Calibration Unit (ACU) covers the central axis.
  - Cable Loop System (CLS) can cover the off-axis region in a two-dimensional plane.
  - Guide Tube Calibration System (GTCS) deploys the source on the outer surface of the acrylic sphere.
  - Remotely Operated Vehicle (ROV) can access any position inside the LS volume.



JUNO Calibration Posters: Rui Li (Calibration system), Yaoguang Wang (PMT gain calibration)

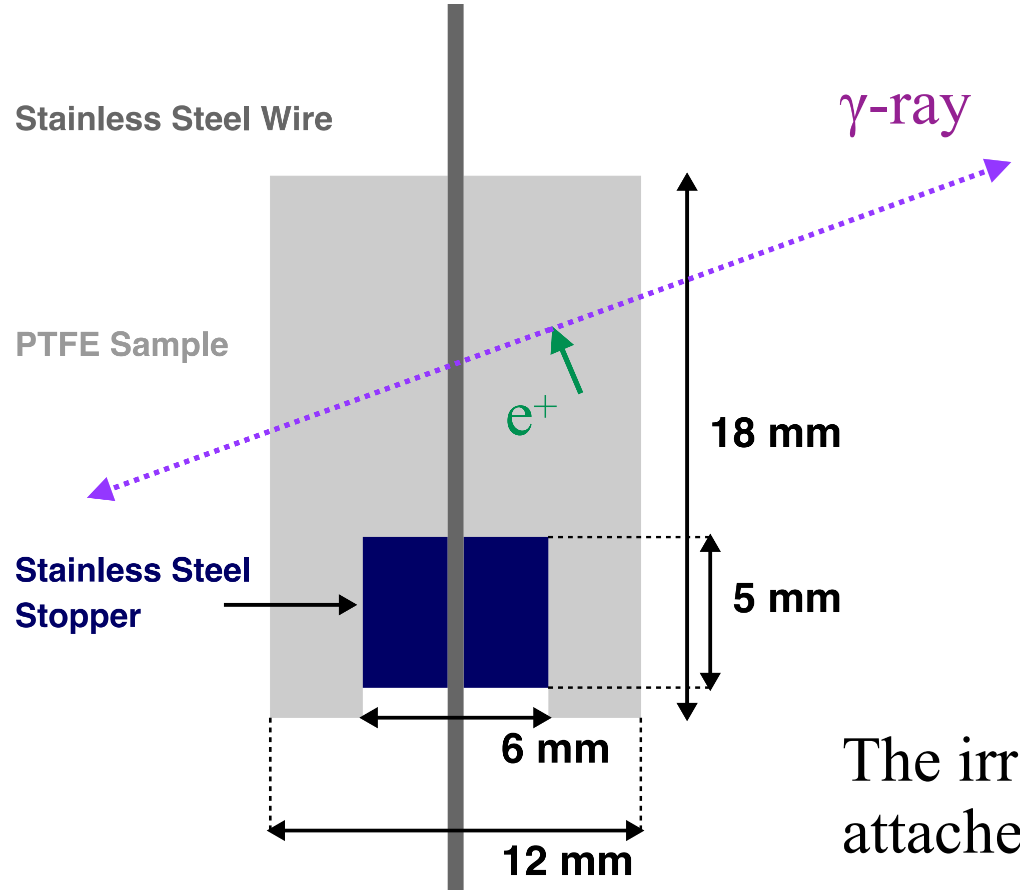
Radioactive ^{18}F Source (1)



The irradiated PTFE source can be attached to the stainless steel wire

- Florine-18 (^{18}F) is a β^+-decay isotope with a reasonably short lifetime ($\tau_{1/2}$~110 minutes).
- It can be produced by irradiating fast neutrons into fluoride, such as PTFE (C_2F_4), $^{19}F(n, 2n)^{18}F$.
- Two 511 keV γ-rays from the e^+ annihilation within the source volume serve as a useful calibration source.

Radioactive ^{18}F Source (2)

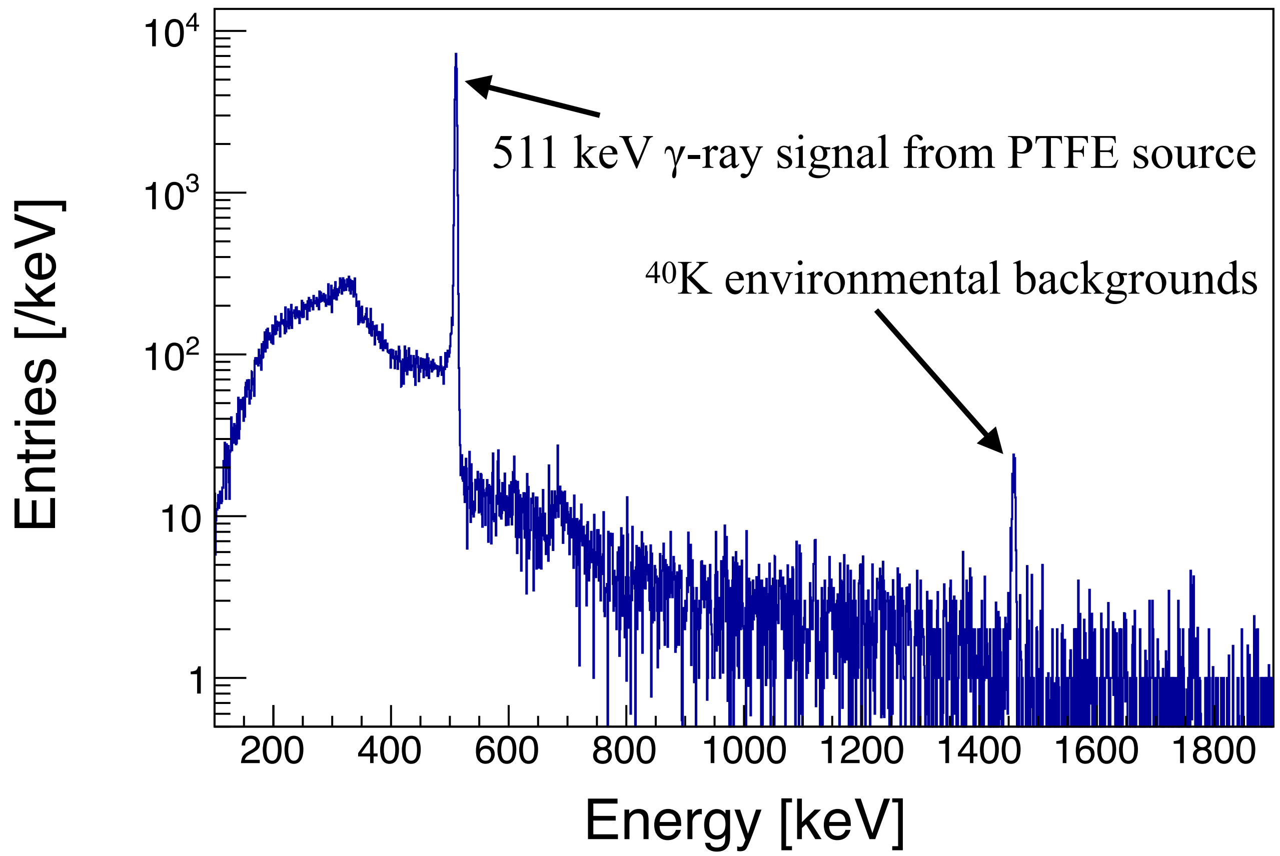


The irradiated PTFE source can be attached to the stainless steel wire

- We have a commercial ^{68}Ge (^{68}Ga) source as a β^+-decay source, but the lifetime is rather short (less than a year) and also expensive…
- This source design allows us to repeatedly regenerate the ^{18}F source by irradiating fast neutrons to the PTFE product every time the calibration is conducted.

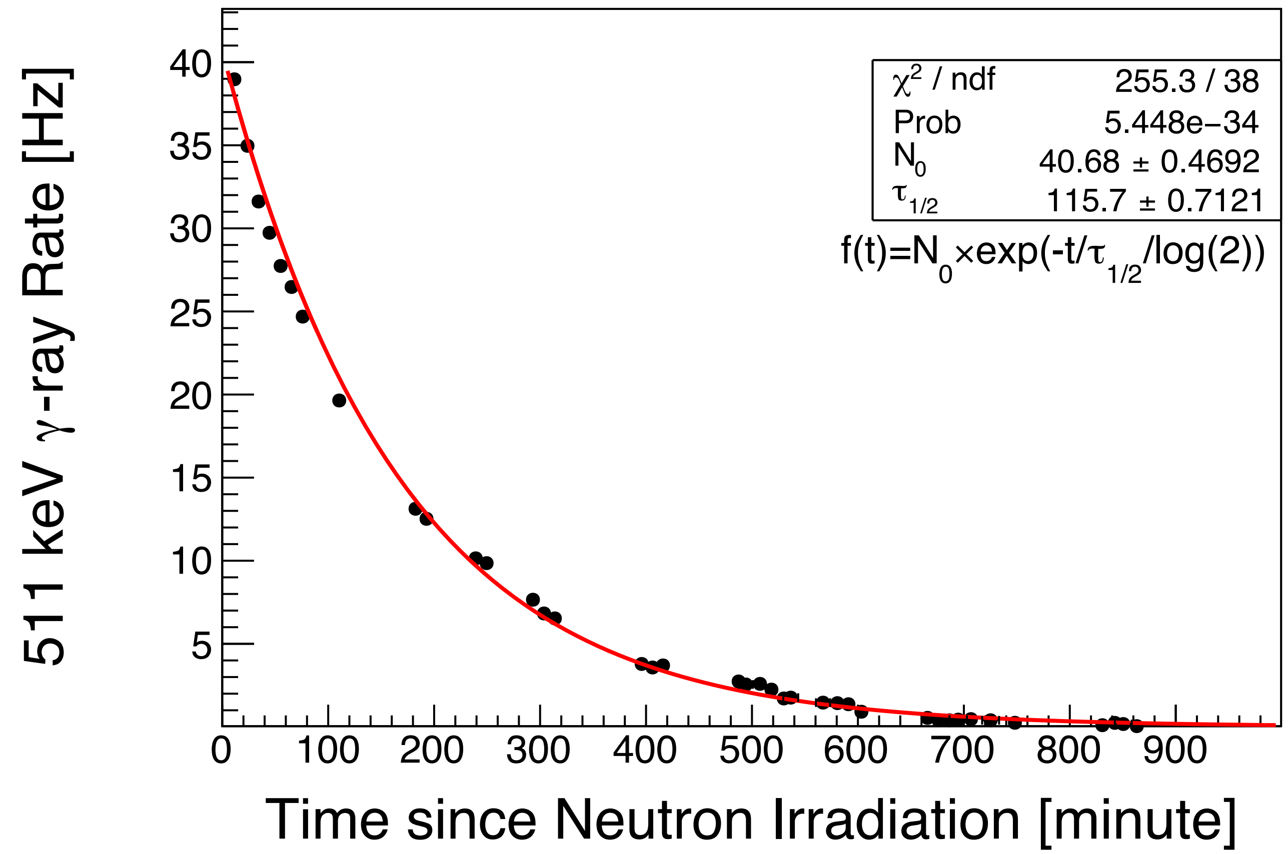
Radioactive ^{18}F Source (3)

Energy Distribution



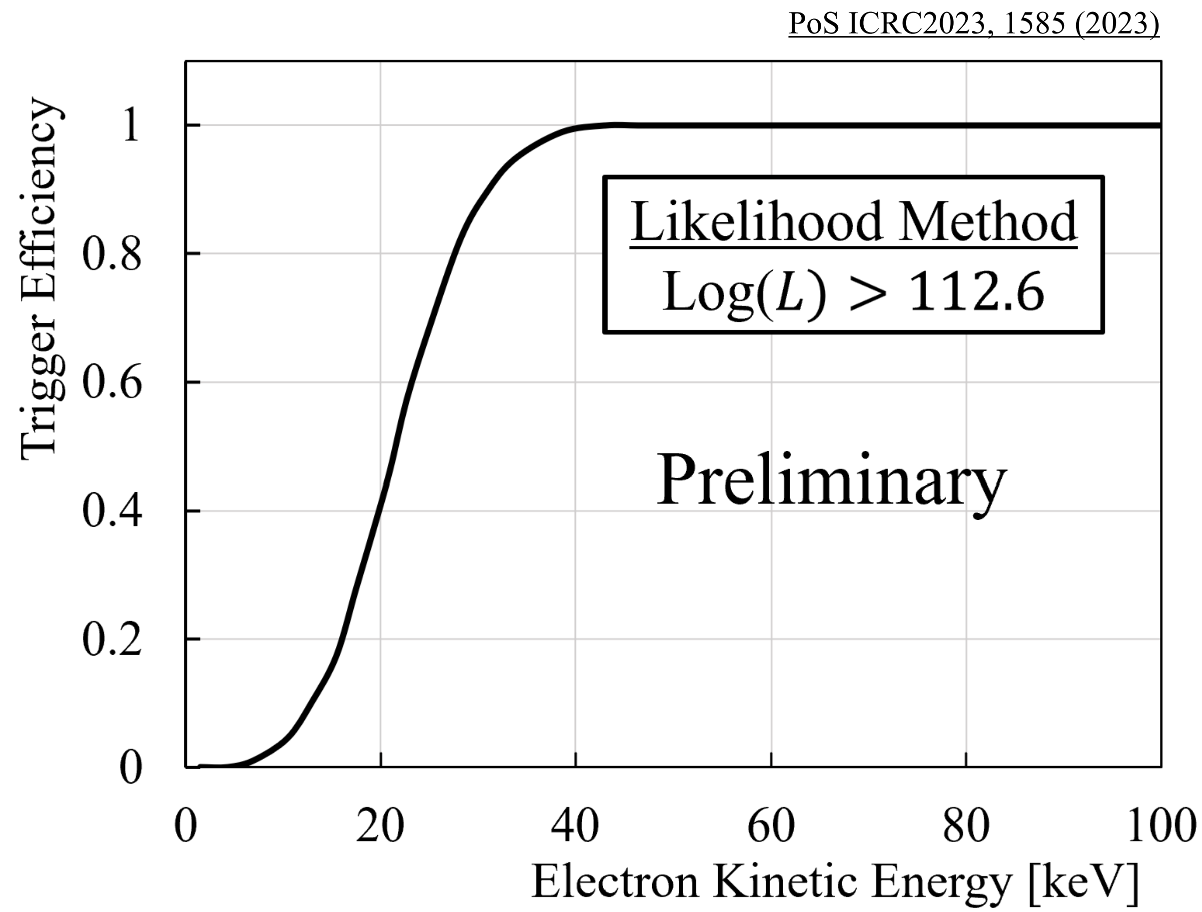
Rate vs. Time

JINST 19 P12019



- A laboratory test was performed with a deuterium–tritium neutron generator (provided by Shiwei Jing at Northeast Normal University).
- The 511 keV γ-rays produced by the e^+ annihilation were clearly observed using a Ge detector at Shanghai Jiao Tong University.
  - Their rate decreased with an expected time constant (~110 minutes).

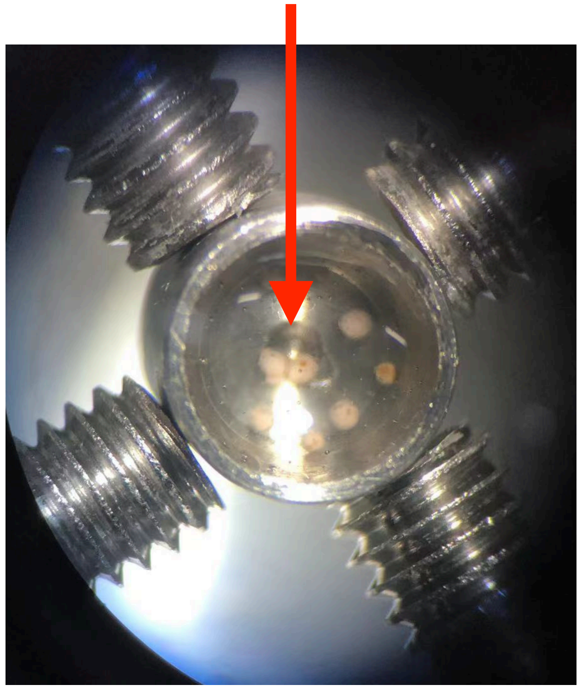
Low-energy Radioactive Sources



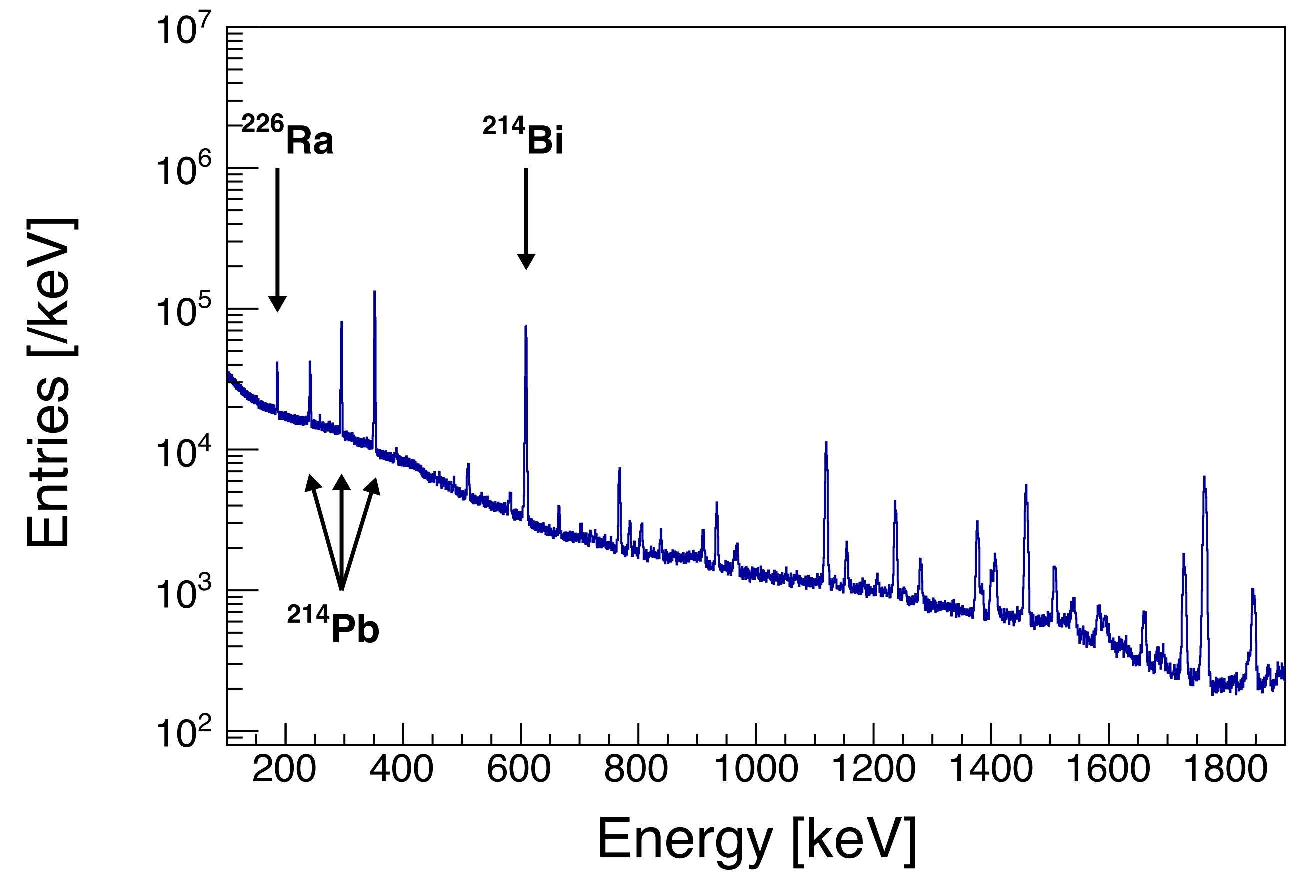
- A new trigger system, capable of lowering the energy threshold to ~20 keV, has been developed to maximize the astrophysics potential.
  - Multi-messenger trigger (Chinese Phys. Lett. 38 111401).
- Following this development, low-energy calibration sources were also prepared to explore the JUNO low-energy range.
  - ^{226}Ra (186 keV γ-ray) and ^{241}Am (59.5 keV γ-ray).

Radioactive ^{226}Ra Source

^{226}**Ra source particulate**

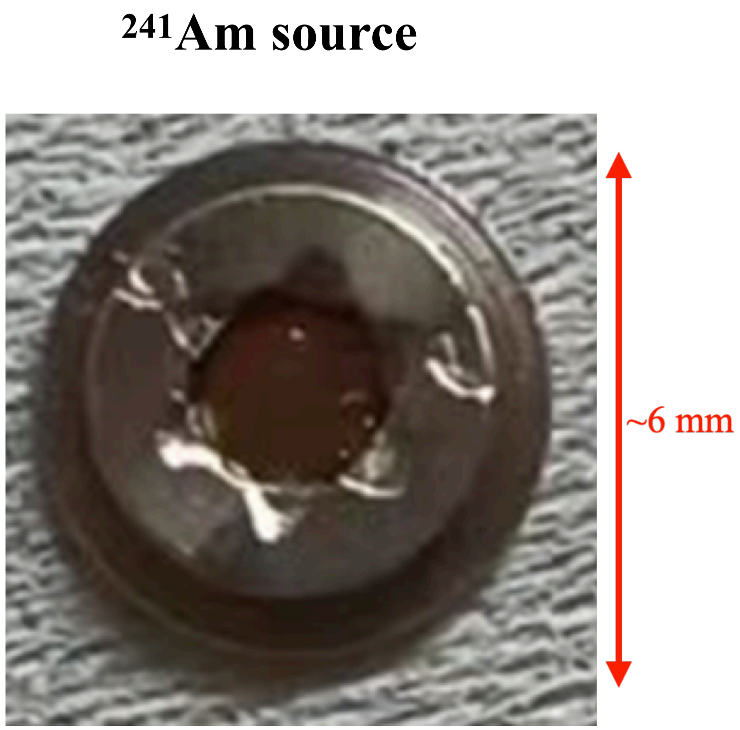


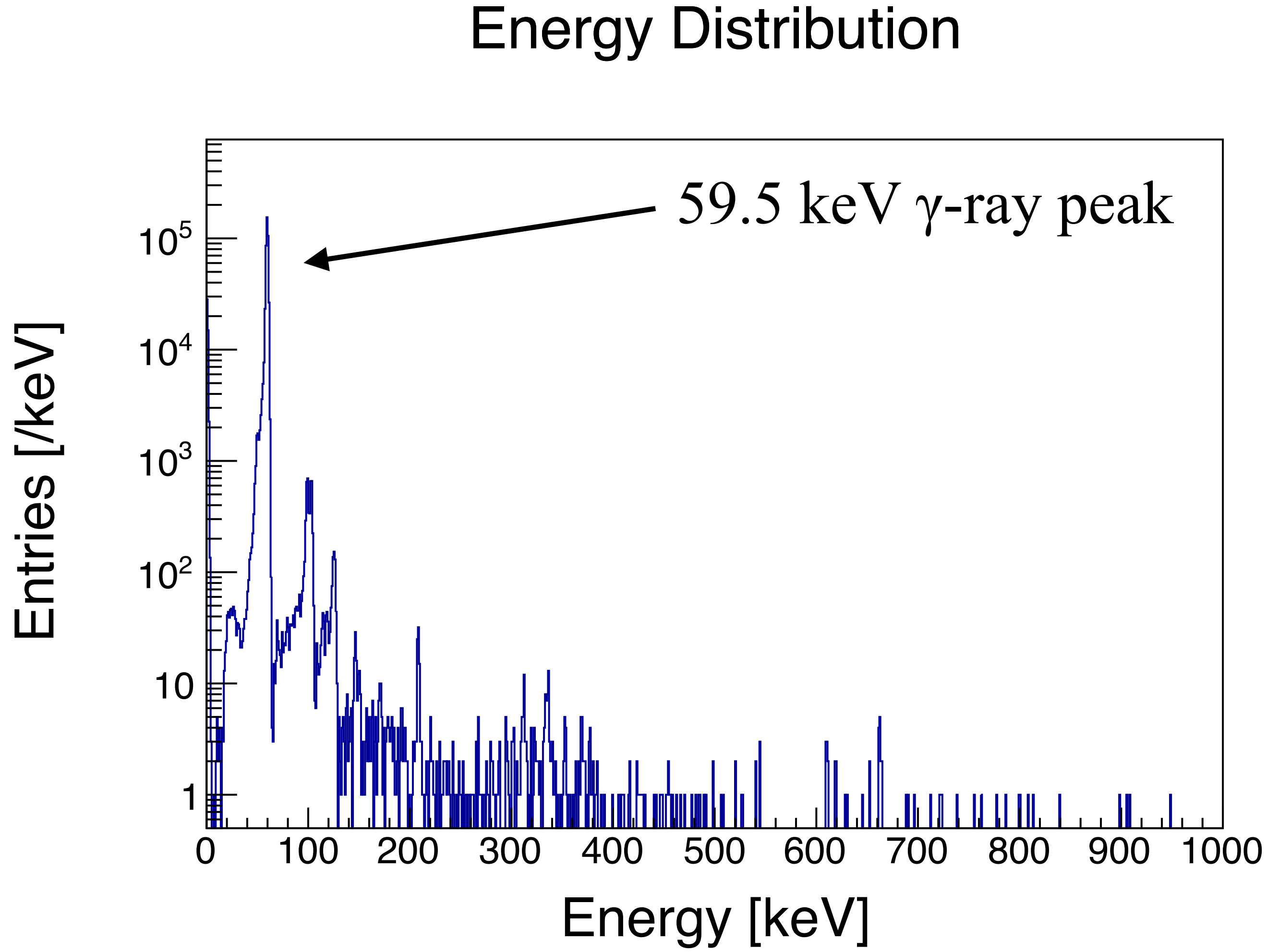
Energy Distribution



- Radium-226 (^{226}Ra) is an α-decay isotope, emitting a 186 keV γ-ray after its decay.
- Porous particulates that absorbed ^{226}Ra were provided by Shoukang Qiu at Nanhua University.
- The particulates were filled in the source container, and γ-rays from ^{226}Ra and its decay products were confirmed with the Ge detector.

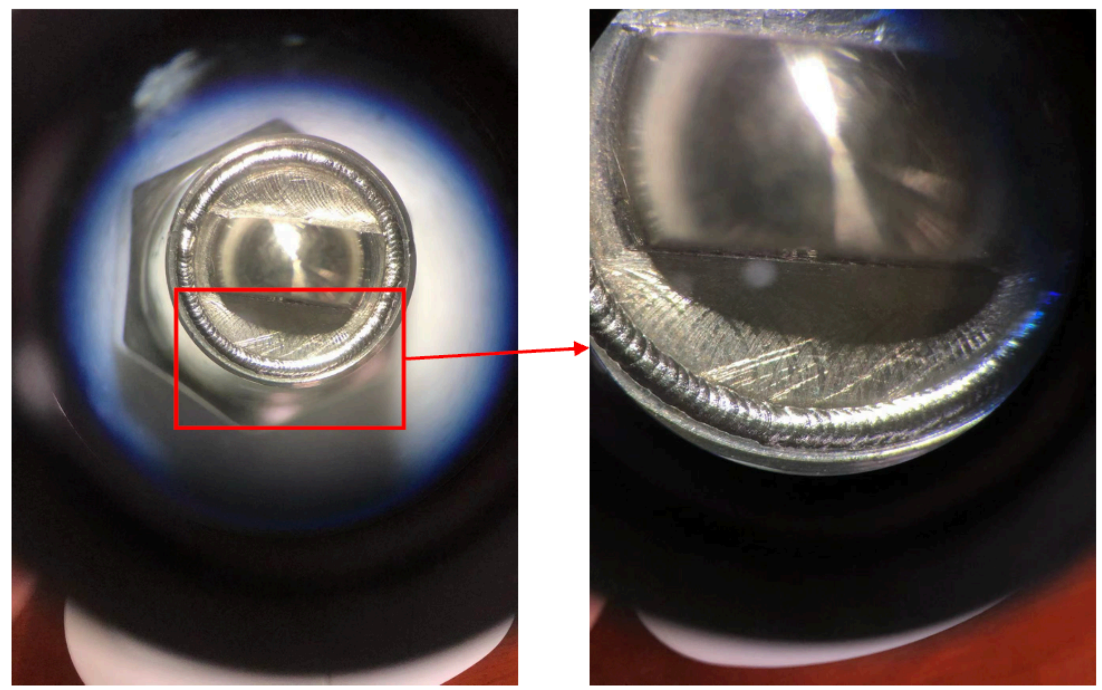
Radioactive ^{241}Am Source





- Americium-241 (^{241}Am) is also an α-decay isotope, emitting a 59.5 keV γ-ray.
- It is often used in a commercial smoke detection device.
- Its radioactivity was measured to be 6 kBq per source using the Ge detector in Jinping and the silicon-based α-detector.

Source Sealing



- The ^{226}Ra and ^{241}Am sources were sealed into titanium containers with laser welding to prevent them from leaking out.
  - The laser welding generates less heat than the arc welding, reducing the risk of the source evaporation.
- No gas leak from the container was confirmed using helium gas.
- No significant radioactivity change from the source inside was also confirmed after welding them.

Summary

- JUNO aims to determine the neutrino mass ordering by achieving:
  - an optimal energy resolution of 3% at 1 MeV, and
  - better than 1% systematic uncertainty on the energy scale.
- Multiple radioactive sources are used to calibrate the non-linear response of the liquid scintillator to the particle energy.
- In addition to the commercial radioactive sources, three new radioactive sources were customized.
  - ^{18}F — β^{+}-emitter, irradiated PTFE source.
  - ^{226}Ra — 186 keV γ-ray.
  - ^{241}Am — 59.5 keV γ-ray.
- Details of the development are published in JINST 19 P12019.
- These new sources are ready and will be deployed into the detector in the near future.

Backup

Energy Calibration

$$f_{\mathrm{non-linear}} = \frac{E^{\mathrm{e}}_{\mathrm{vis}}}{E^{\mathrm{e}}}$$

$$f_{\mathrm{non-linear}} = \frac{p_0 + p_3/E^{\mathrm{e}}}{1 + p_1 \mathrm{e}^{-p_2 E^{\mathrm{e}}}}$$

$$E^{\gamma}_{\mathrm{vis}} = \int_0^{\mathrm{E}^{\gamma}} P(E^{\mathrm{e}}) \times f_{\mathrm{non-linear}}(E^{\mathrm{e}}) \times E^{\mathrm{e}} dE^{\mathrm{e}}$$

E_{e} : Electron/positron kinetic energy.

E_{vis} : Visible energy.

$P(E^{\mathrm{e}})$: Probability density function of electron/positron emission with a kinetic energy of E^{e} from a given γ-ray source.

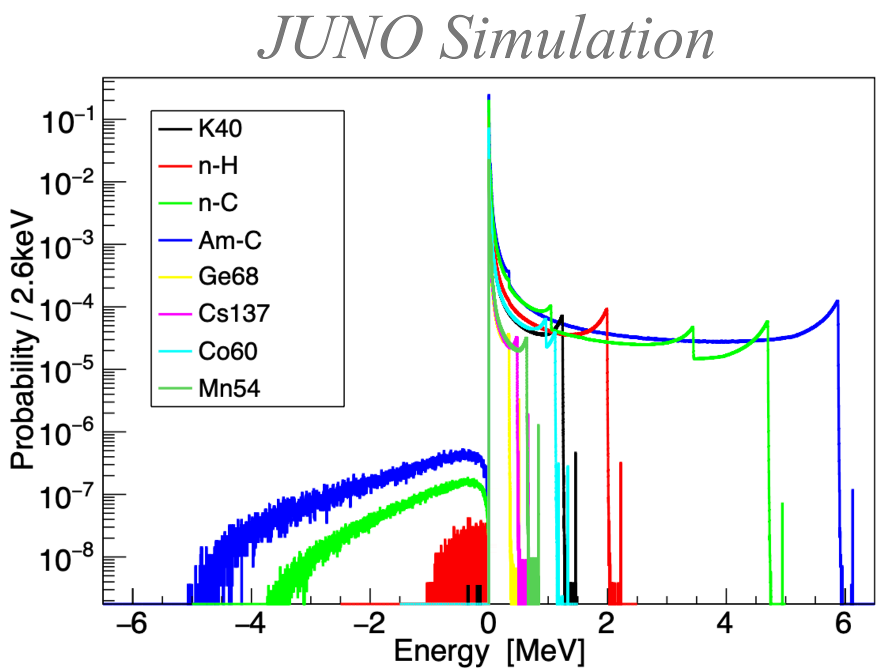
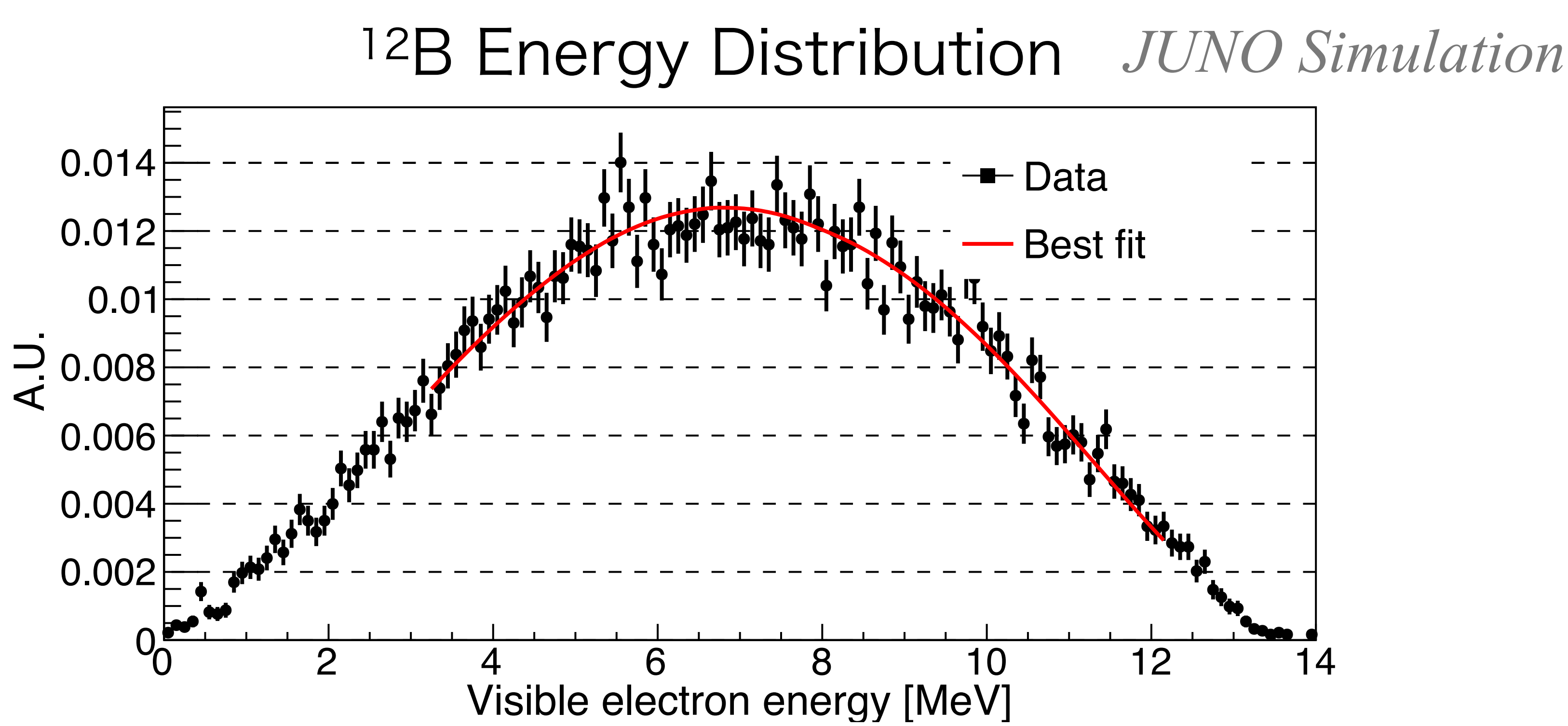
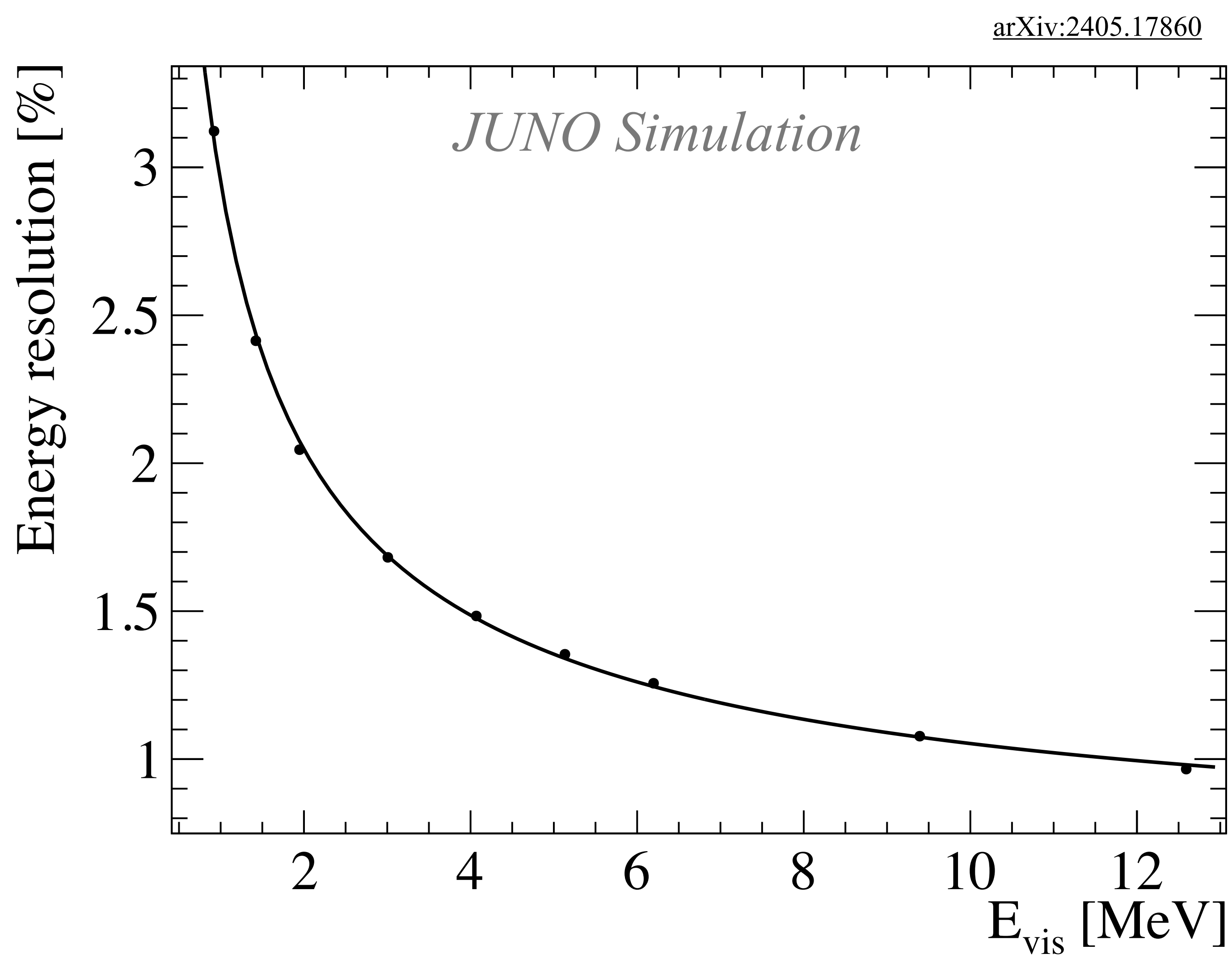


Figure 4–4 The probability density function (PDF) for primary electron of gamma from the calibration source. The parts with energy less than 0 are corresponding to the events with positron annihilation in flight. The annihilation in flight means that not all the kinetic energy of positron converts into the scintillation light, which should be subtracted in the PDF.



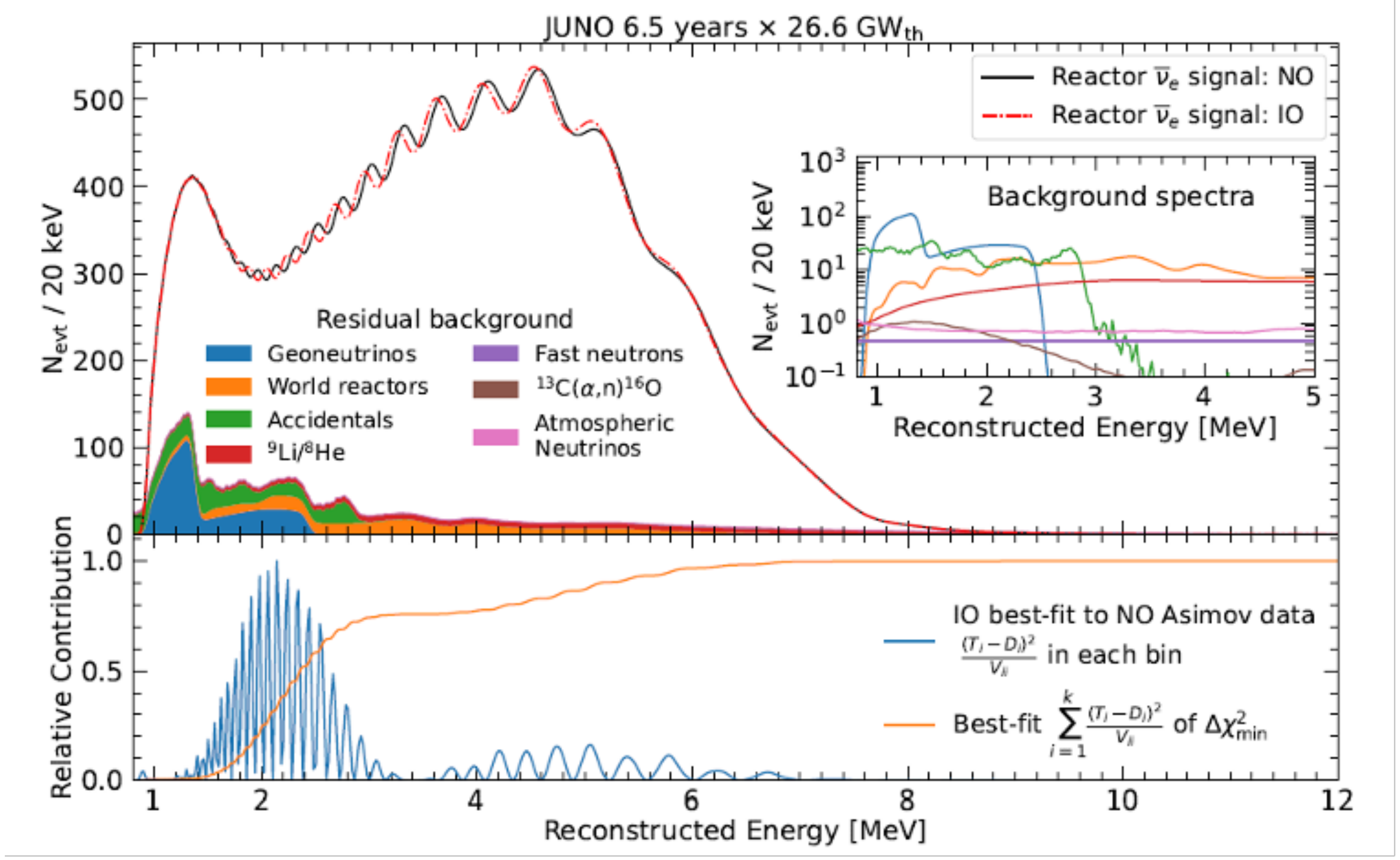
Energy Resolution



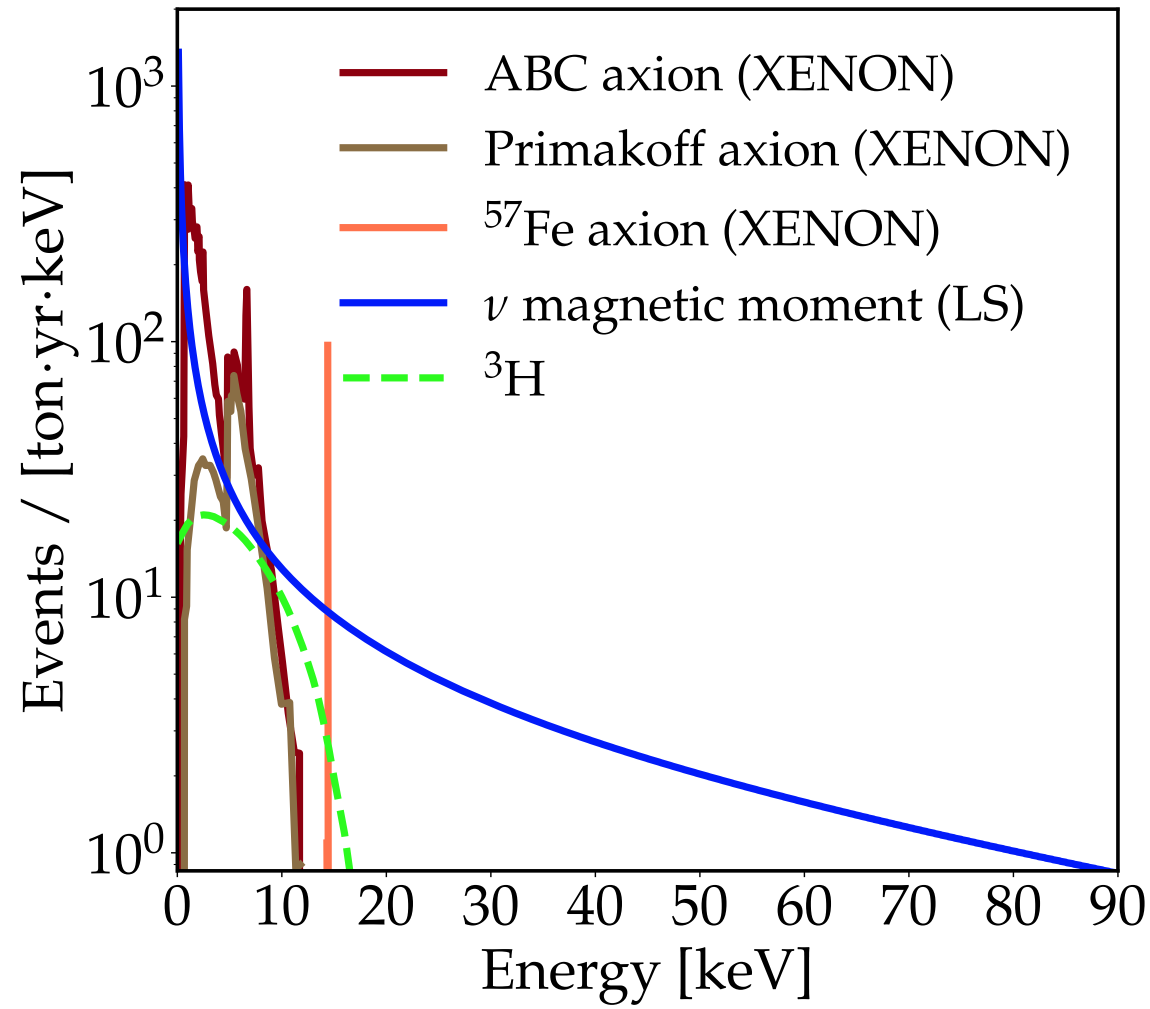
- The energy resolution curve after the event reconstruction.
- The reconstruction removes the detector non-uniformity.
- The energy resolution at E_{vis} = 1 MeV is 2.95%.

Expected Energy Spectrum

JUNO Simulation



MM Trigger



Chinese Phys. Lett. **38** 111401

- Search for neutrino magnetic moment with solar neutrinos.
- Coherent elastic neutrino nucleus scattering on 12C with supernova neutrinos, etc.

Calibration House

Energy Threshold of Isotope Production

Table 1. Nuclear reaction energies Q (in MeV) and products (with their half-lives) of the 14 MeV neutron induced reactions of ^{19}F, $^{12,13}C$ and $^{14,15}N$ isotopes.

Reaction	$^{19}_{9}F$ 100%	$_6C$: $^{12}_{6}C$ 98.89%	$_6C$: $^{13}_{6}C$ 1.11%	$_7N$: $^{14}_{7}N$ 99.64%	$_7N$: $^{15}_{7}N$ 0.36%
(n,2n)	$^{18}_{9}F$ -10.4 109.7 min β^+ 96.9% EC 3.1%	$^{11}_{6}C$ -18.7 20.4 min β^+ 99.76% EC 0.24%	$^{12}_{6}C$ -4.45 stable	$^{13}_{7}N$ -10.6 9.96 min β^+ 100%	$^{14}_{7}N$ -10.8 stable
(n,p)	$^{19}_{8}O$ -4.0 26.9 s β^-	$^{12}_{5}B$ -12.6 0.02 s β^-	$^{13}_{5}B$ -12.7 0.017 s β^-	$^{14}_{6}C$ 0.6 5730 y β^-	$^{15}_{6}C$ -9.0 2.45 s β^-
(n,α)	$^{16}_{7}N$ -1.5 7.1 s β^-, γ	$^{9}_{4}Be$ -5.7 stable	$^{10}_{4}Be$ -3.8 16×106 y β^-	$^{11}_{5}B$ -0.2 stable	$^{12}_{5}B$ -7.5 0.02 s β^-, γ
(n,pn) (n,d)*	$^{18}_{8}O$ -8.0 -5.0 stable	$^{11}_{5}B$ -16.0 -13.8 stable	$^{12}_{5}B$ -17.5 -15.3 0.02 s β^-, γ	$^{13}_{6}C$ -7.6 -5.3 stable	$^{14}_{6}C$ -10.2 -8.0 5730 y β^-

*Q(n,d) = Q(n,np) + 2.22 MeV