JUNO Detector Response

in the First Physics Data-Taking Phase

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on behalf JUNO Collaboration

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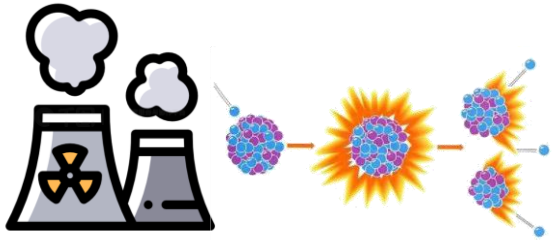
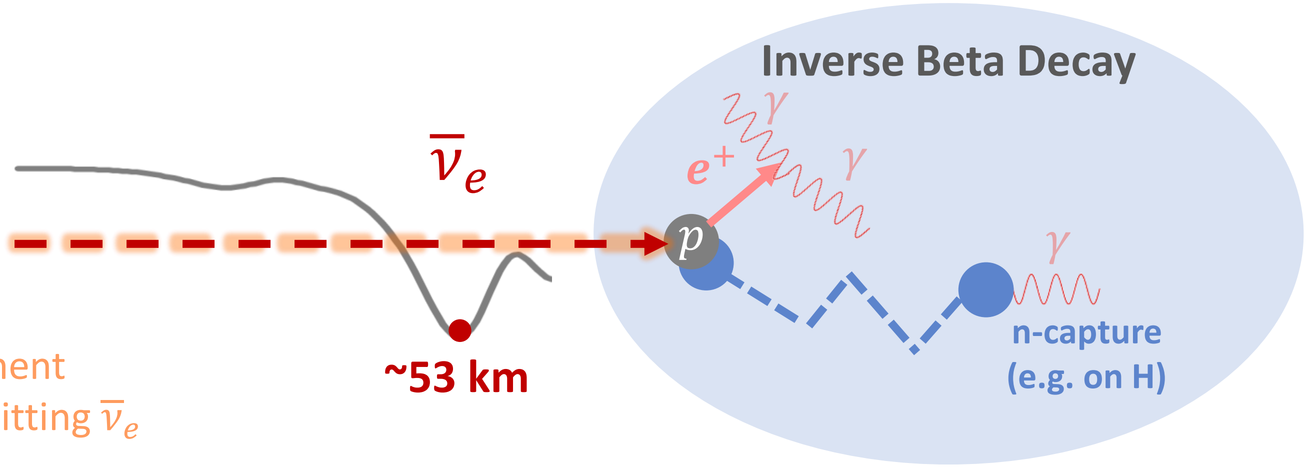
Antineutrino Detection

Reactor Neutrinos



- ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu fragment
- Daughter nuclei beta-decay emitting $\bar{\nu}_e$



Prompt signal

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Delay signal

Distinct coincident event pair correlated in time and space

What is the detector response function in JUNO?

E_{prompt} → E_{Qedep} → E_{rec}

E_{prompt} Positron spectrum

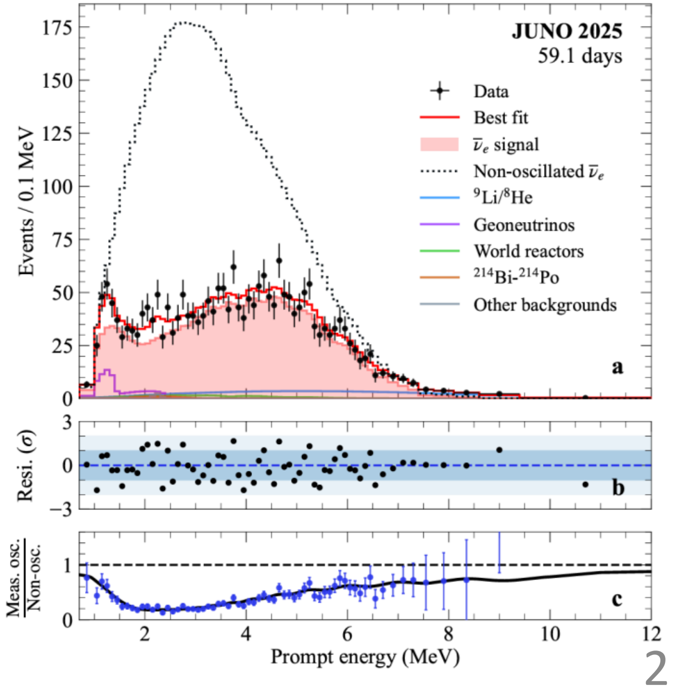
- $E_{\bar{\nu}_e} \approx E_{e^+} + 0.78$ MeV
- Predicted with the reactor power and neutrino flux models.
- $P_{sur}(E_{\bar{\nu}_e})$ from oscillation theory

E_{Qedep} Deposited Energy

- Liquid scintillator nonlinearity: Scintillation quenching (Birks law) + Cherenkov light
- Instrumental linearity

E_{rec} Reconstructed Energy

- Energy resolution
  - Photoelectron stats.,
  - PMT charge smear
  - …
- Energy scale
  - Residual non-uniformity
  - Energy scale stability

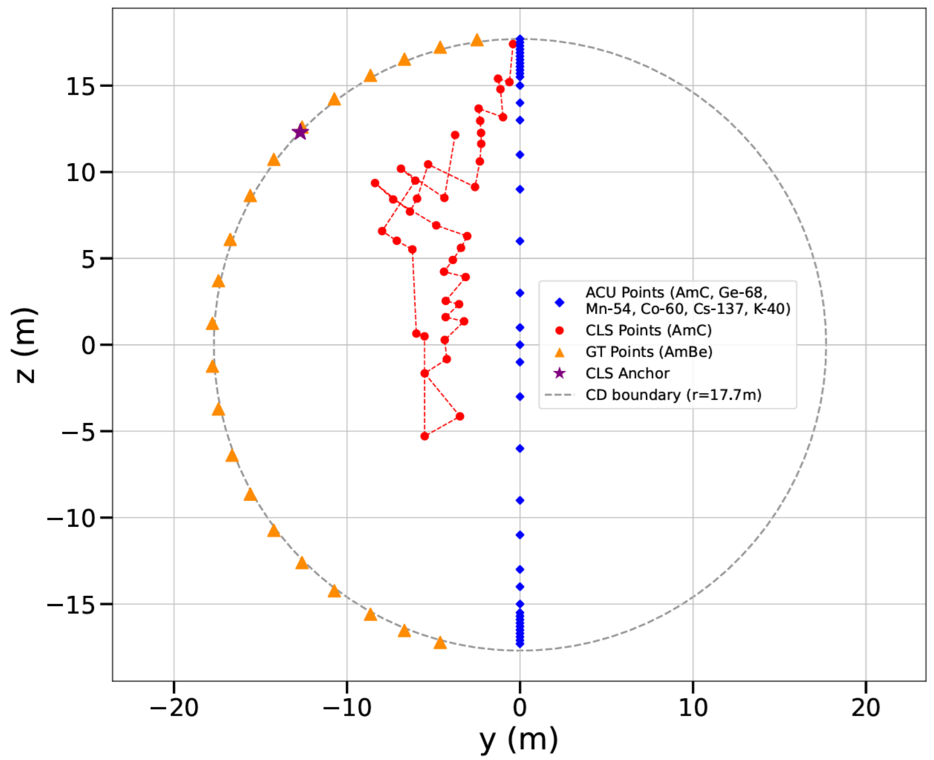


Calibration System & Strategy

- **Three complementary calibration systems deployed in JUNO**
  1. **Automatic Calibration Unit (ACU 1D):** deploys sources along the Z-axis
  2. **Cable Loop System (CLS 2D):** Moves source in z-y vertical plane
  3. **Guide Tube (GT 2D):** Deploys source along acrylic vessel surface

- **The Calibration Source covers the energy region from ~0.5 to 8 MeV**

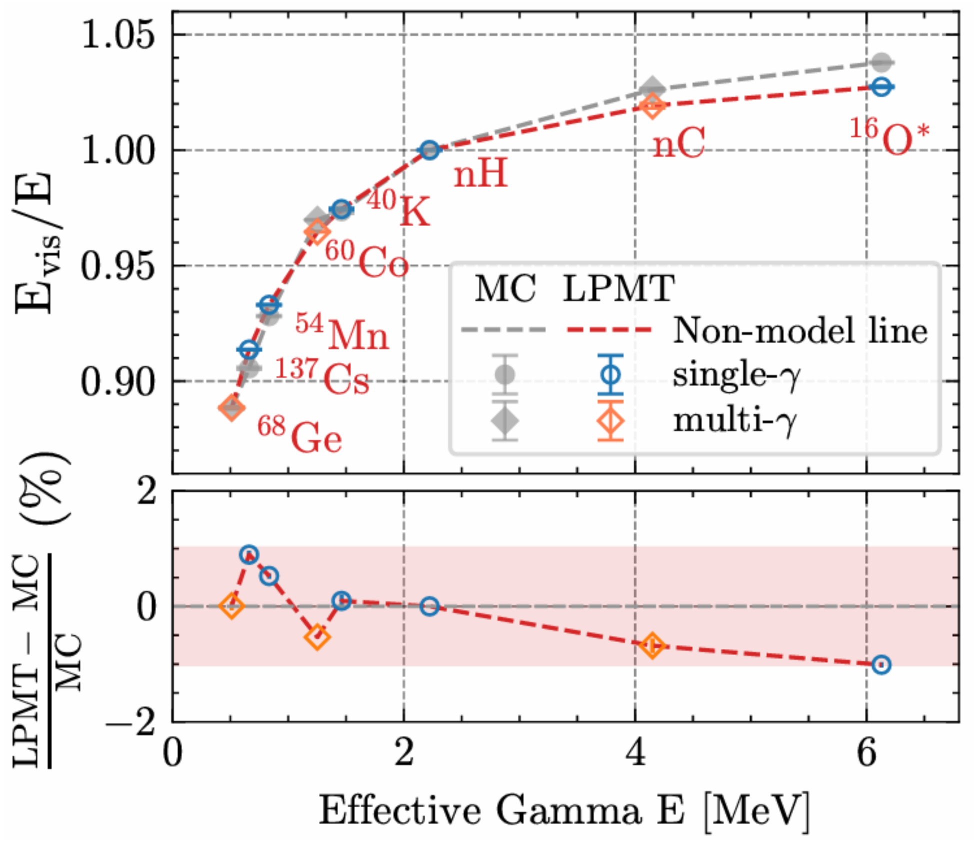
Sources/Processes	Type	Radiation
^{137}Cs	γ	0.662 MeV
^{54}Mn	γ	0.835 MeV
^{60}Co	γ	1.173 + 1.333 MeV
^{40}K	γ	1.461 MeV
^{68}Ge	e^+	annihilation 0.511 + 0.511 MeV
^{241}Am-Be	n, γ	neutron + 4.43 MeV (^{12}C*)
^{241}Am-^{13}C	n, γ	neutron + 6.13 MeV (^{16}O*)
(n,γ)p	γ	2.22 MeV
(n,γ)^{12}C	γ	4.94 MeV or 3.68 + 1.26 MeV

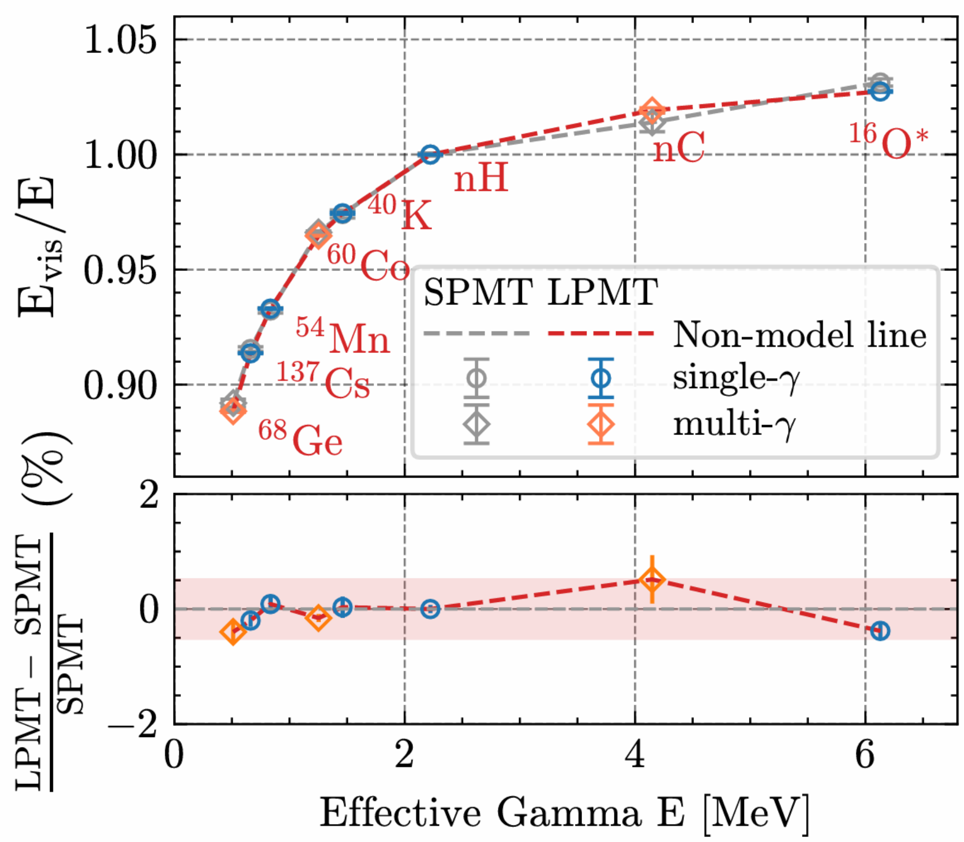


- **The Calibration Strategy keeps monitor the PMT and detector response:**
  - After LS filling completed: intensive calibration campaign for detector response analysis
  - Weekly calibration: Am-C neutron source (energy scale monitor)+ laser via ACU (PMT gain monitor and timing response)

Energy Non-linearity

- ✓ Good optical parameter estimation (e.g., k_B, k_C for $e^{\pm}$, raw light yield, Cherenkov yield, etc.)
  - The response understood to be < 1% accuracy
- ✓ Consistent results at a level of ±0.5% were confirmed with the small PMT system.





Energy Non-linearity

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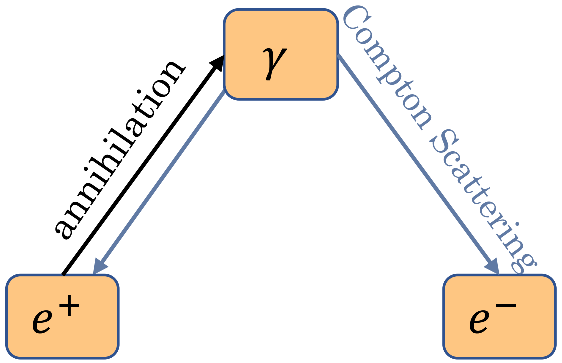
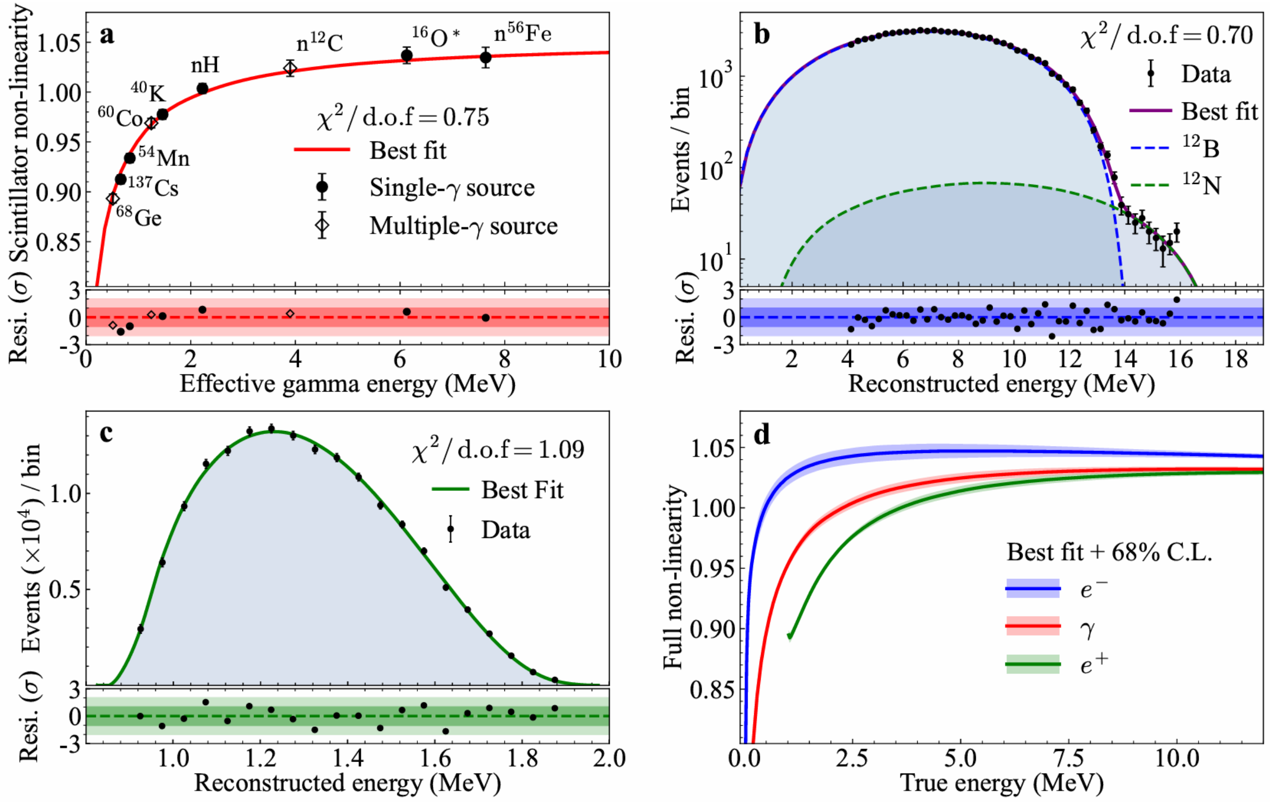
  - The response understood to be < 1% accuracy
- ✓ Consistent results at a level of ±0.5% were confirmed with the small PMT system.
- ✓ Calibration sources(γ) + cosmogenic ^{12}B (β^-)+ ^{11}C (β^+) spectra are used to characterize the particle-dependent non-linearity response
  - non-linearity uncertainty of 1% is achieved for e^+
  - Three independent analyses agree within 0.5%

Physics model:

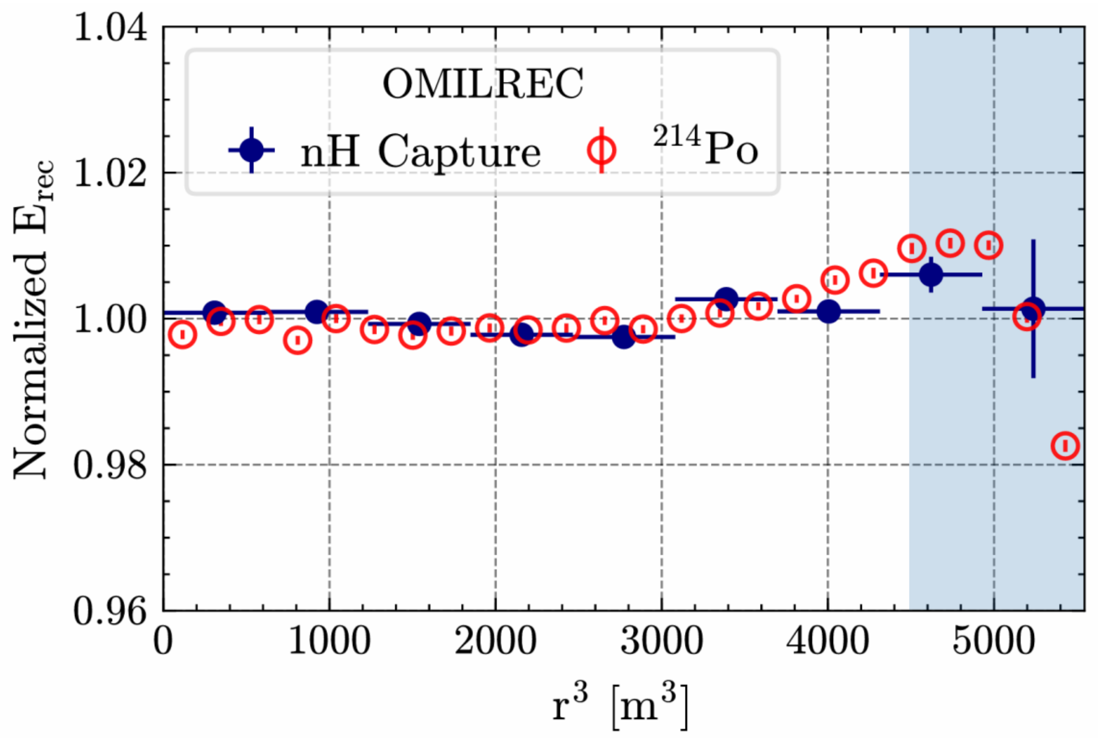
- LS Non-linearity are contributed by quenched scintillation (Birks' law) and Cherenkov contribution
- Instrumental non-linearity are also considered

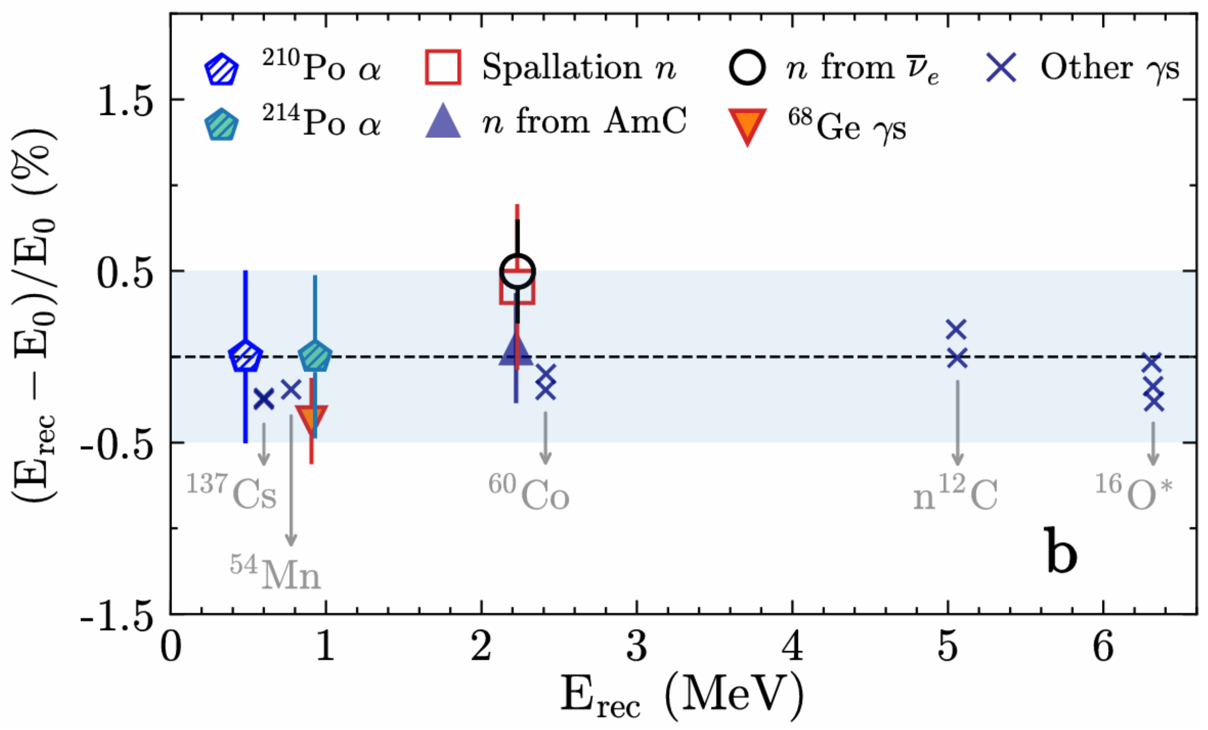




Energy Scale Uncertainty

- Energy scale uncertainty better than ±0.5% for a detector with 35. 4 m diameter
  - Including time & residual spatial variation for R < 16.5 m
  - Evaluated naturally-present alphas (^{214}Po, ^{210}Po), nH captures (spallation-n, AmC-n, IBD-n)
- Will be improved with more calibration campaign in the future





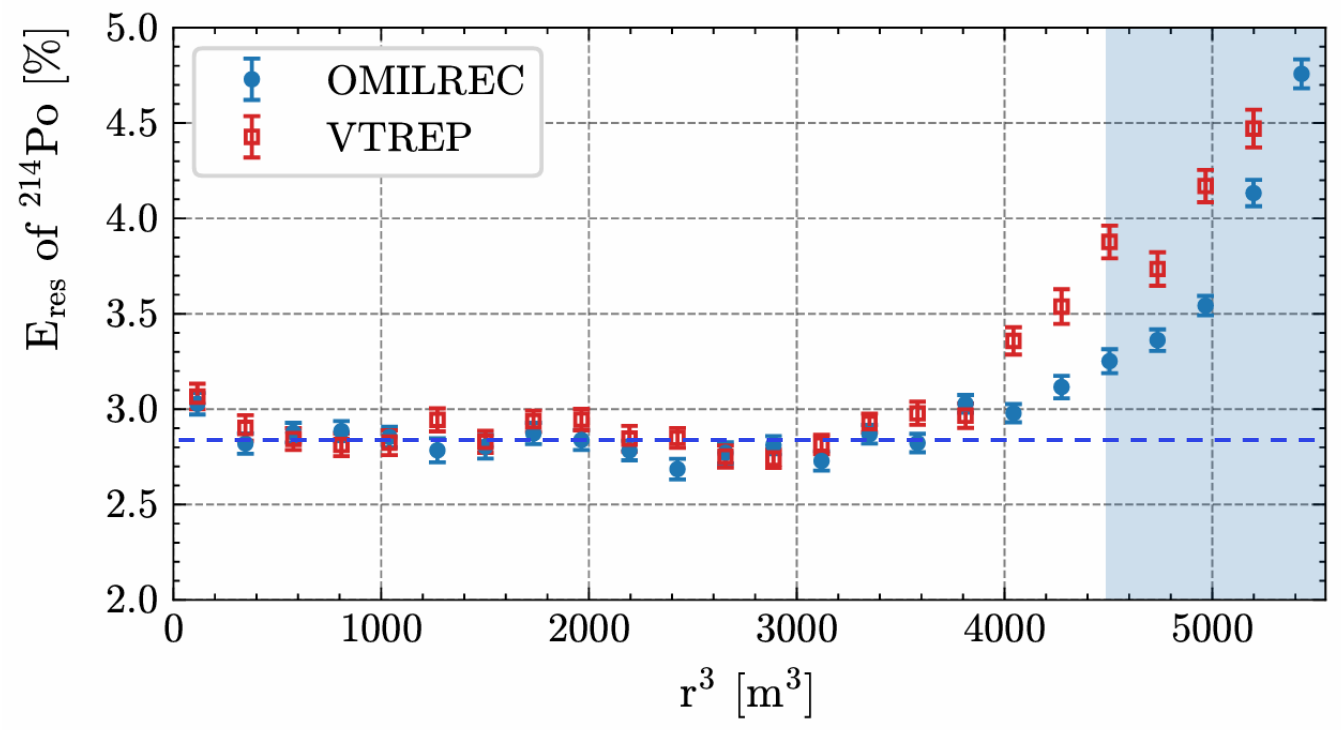
Energy Resolution

- Energy resolution is approaching design goal (~3%@1MeV)
  - <3.0% for ^{214}Po-α (~1 MeV after quench)
  - ~3.4% for ^{68}Ge-e^+ (~1 MeV after annihilation)

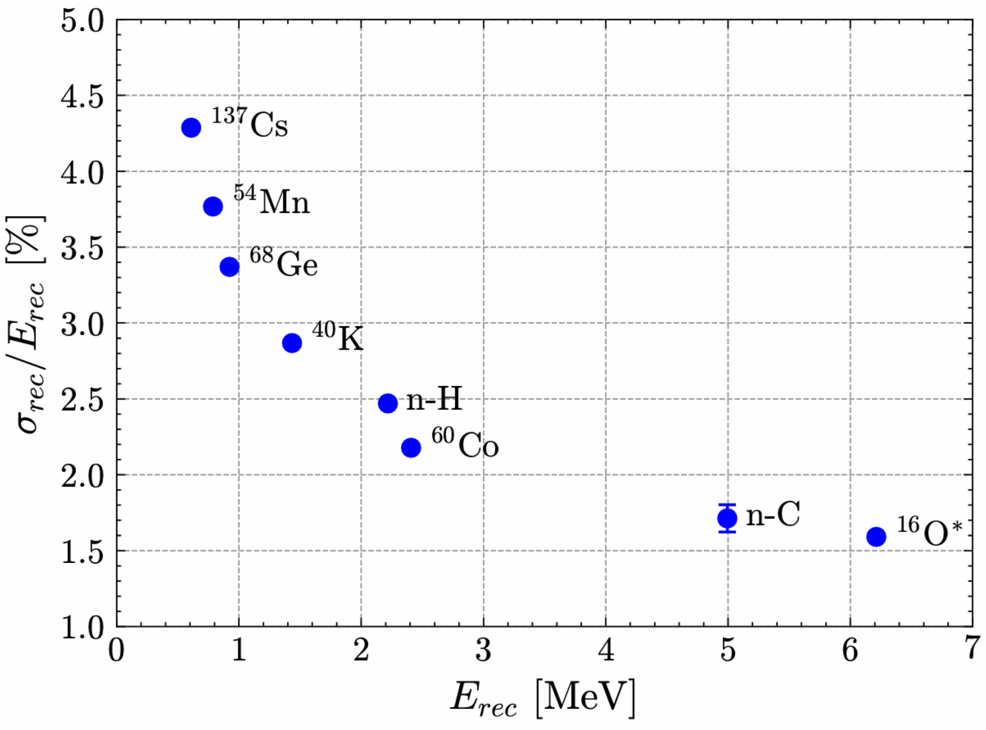
⇨ Particle-dependent resolution observed at similar photoelectron statistics; advanced physics modeling under investigation

- Further improvements are possible by better calibration and reconstruction

Natural radioactivity ^{214}Po



γ source at Detector Center



Conclusion

After almost 12 years efforts by > 700 collaborators and >1000 contractors, JUNO is finally online, and now the largest and most precise LS detector

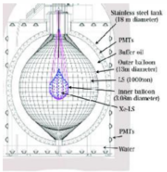
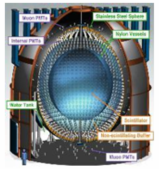
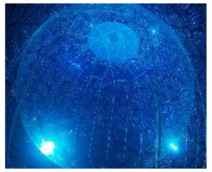
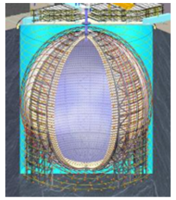
- JUNO has achieved the surpassing performance
  - ~1785 PE/MeV light yield
  - Energy linearity is understood to be < 1% accuracy
  - $\pm$0.5 % energy scale uncertainty achieved in a 35.4 diameter detector
  - Energy resolution is approaching the design goal: <3.0% for ^{214}Po-α AND ~3.4% for ^{68}Ge-γ

With the detector response as the input, JUNO has published the most precision measurement of θ_{12} and Δm^2_{21} with first ~59 days of data

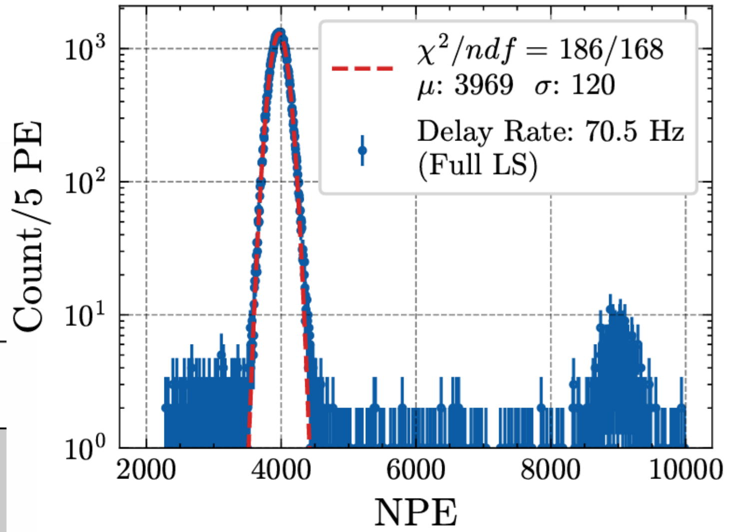
Stay tuned for more exciting oscillation and astrophysical results in the (near) future!

Light Yield

- Compare with LS detector

	KamLAND	Borexino	SNO+	JUNO
Target Mass [tons]	1000	300	780	**20,000**
Number of PMTs	1900	2200	10,000	**17,596 + 25,600**
PMT Coverage	~34%	~30%	~50%	**78%**
Light Collection [PE/MeV]	~250	~450	~520	**>1600**



Performance attribution:

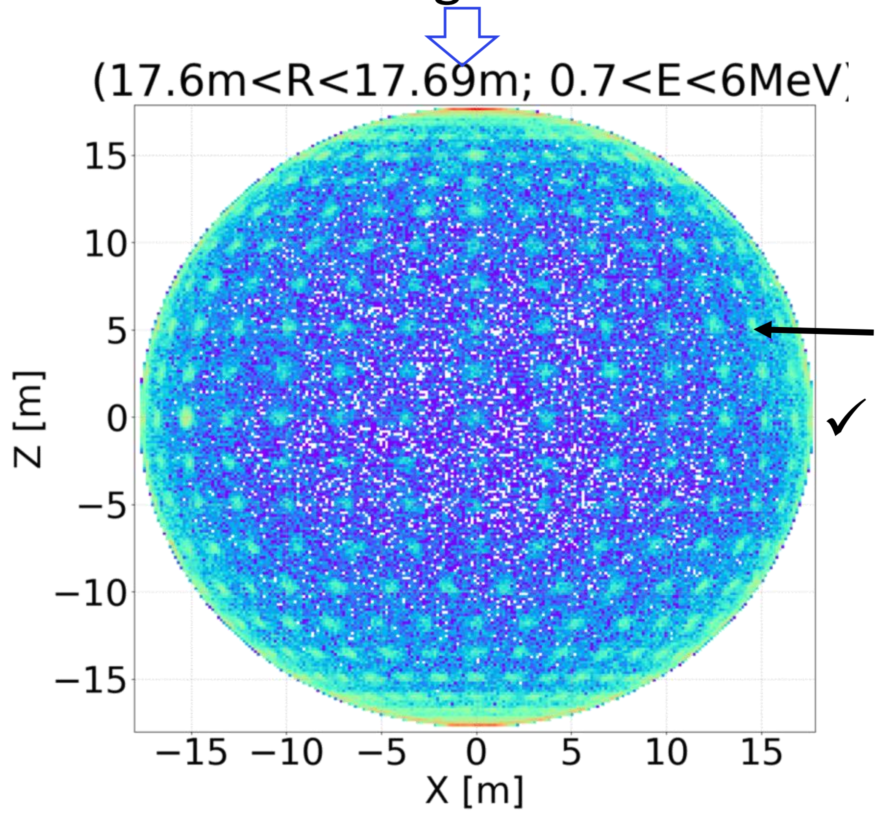
- ✓ LS attenuation: 20.6 m at 430 nm (expectation: 20.0 m)
- ✓ Water attenuation: > 70.0 m (expectation: 40.0 m)

- JUNO: Light Yield ≈ 1785 PE/MeV at CD center exceed expected 1665 PE/MeV
  - Measured using 2.223 MeV γ from neutron capture on hydrogen with Am-C source
- More than x20 increase in the scale **AND** surpassing performance at the same time compared to other LS detector

Vertex reconstruction

- Three independent reconstruction methods
  - ✓ Achieve **vertex bias < 10 cm** across nearly the entire detector
  - ✓ The best **vertex resolution：0.12 m** near detector edge

The Vertex of singles events near the edge in the early stage



Clusters are support joint

✓ Demonstrates excellent vertex resolution