

## JUNO Detector & Motivation

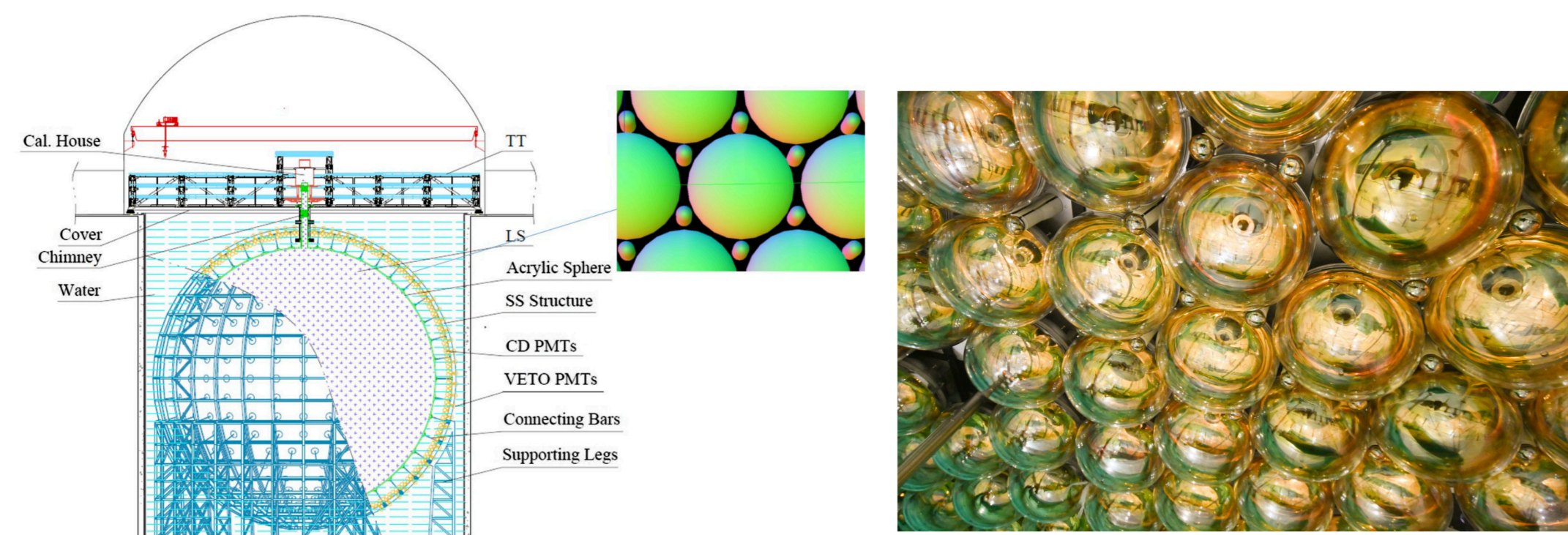


Fig 1. JUNO central detector and PMT layout. Adapted from Ref. [1] & [2]

JUNO is a 20-kton liquid-scintillator detector for precision measurements of reactor antineutrino oscillations.

- **20-inch Large PMTs (LPMTs):** primary light detection system, dominate energy reconstruction, but they can have a non-linear energy response.
- **3-inch Small PMTs (SPMTs):** installed between LPMTs and provide an independent low-occupancy light measurement.
- **Goal:** use stable and linear SPMT response to monitor LPMT charge non-linearity.

## LPMT Charge Non-Linearity

The LPMT charge for JUNO's oscillation analyses is reconstructed with the Continuous Over-Threshold Integral (COTI) algorithm, which integrates waveform pulses above a threshold. The COTI-reconstructed LPMT charge is compared to the occupancy-based sPMT reference. The contribution of PMT dark noise and the impact of threshold effects have been considered and corrected.

### Key observations:

- The LPMT response is approximately linear in the low-charge region.
- Over a larger charge range, the relative response deviates by several percent.
- The trend differs between Hamamatsu (Dynode) and NNVT (MCP) LPMTs and changes with HV stages, which correspond to different periods of data taking with distinct PMT high-voltage settings.

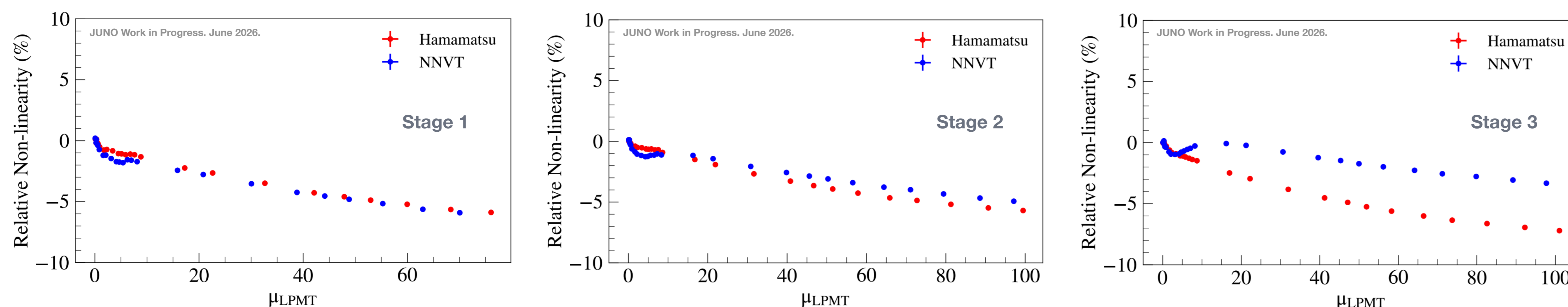


Fig 6. Relative COTI-reconstructed LPMT charge non-linearity under three HV stages

## SPMT Gain/DCR Method & Stability

Before using SPMTs as a reference, we validate that their gain, resolution, and dark count rate (DCR) are stable.

- SPE spectra from periodic trigger events
- Simultaneous fit to two readout buffers, ping and pong, with shared gain and resolution

$$f(x) = A \exp \left[ -\frac{1}{2} \left( \frac{x - \text{ped} - GP_1}{\text{res} \cdot GP_1} \right)^2 \right]$$

- DCR measured from periodic trigger and pre-trigger windows

**Result:** After quality selection, run-averaged gain and resolution remain stable over the analyzed physics runs.

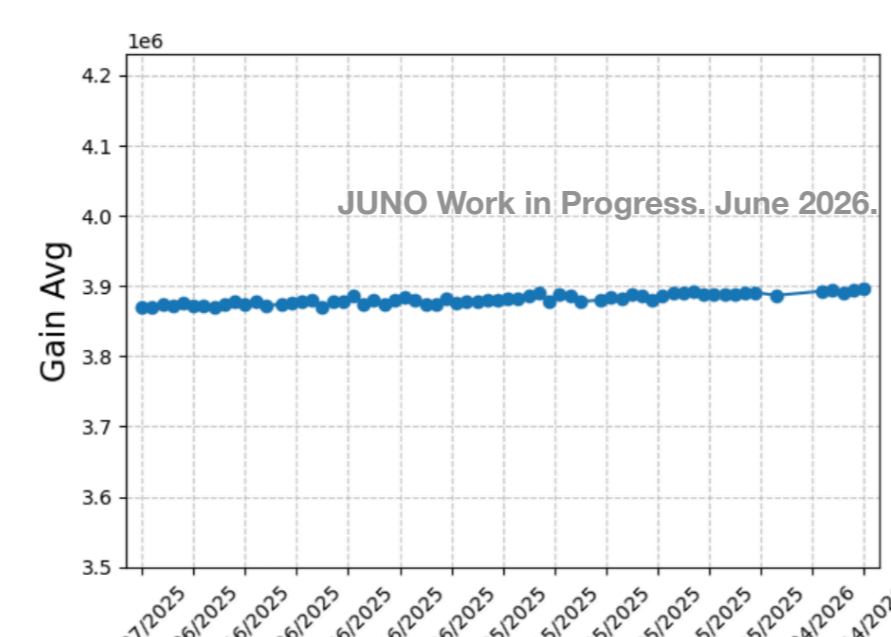


Fig 2. Run-averaged SPMT gain stability.

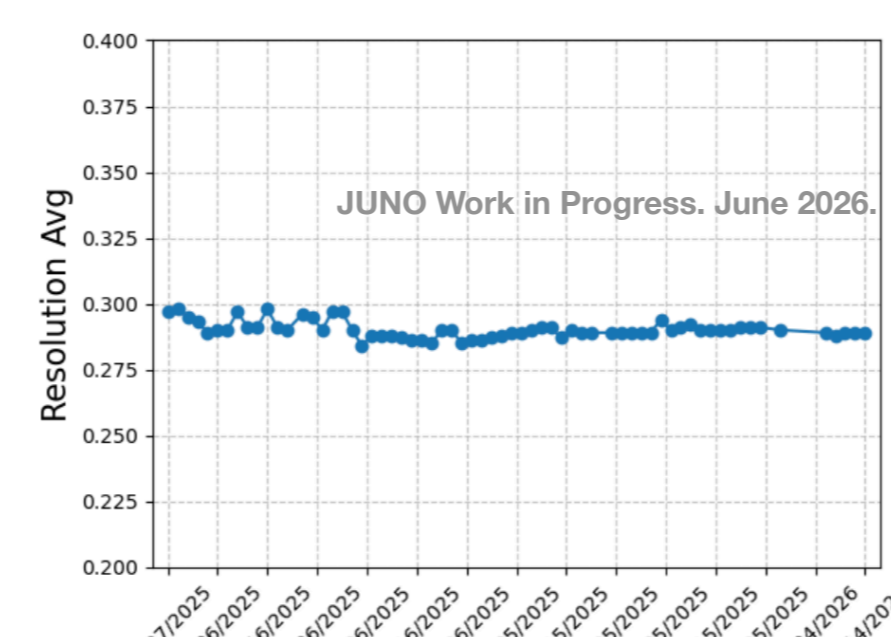


Fig 3. Run-averaged SPE charge-resolution stability

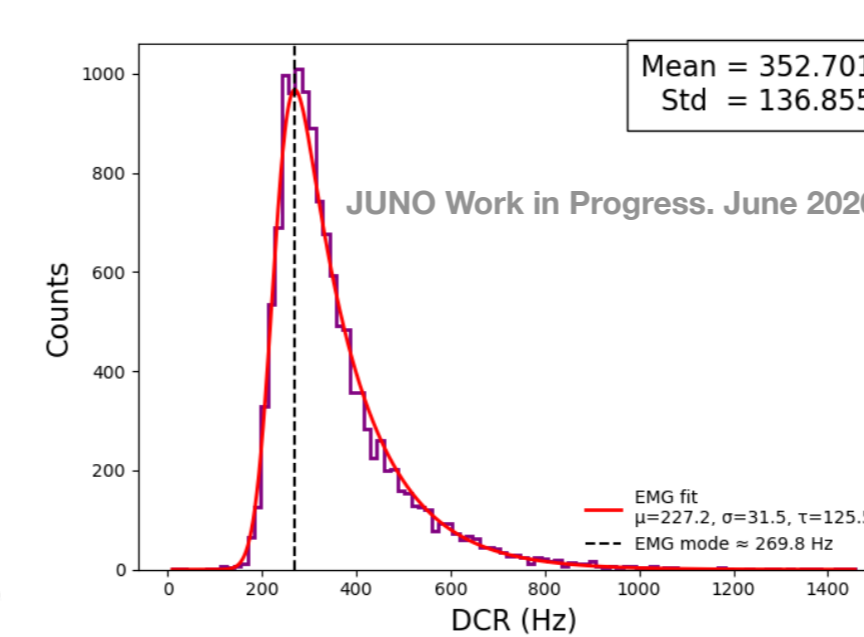


Fig 4. Channel-level DCR distribution

## Occupancy-Based SPMT Reference

### Why occupancy?

- Direct SPMT charge can be biased in multi-hit conditions.
- Instead, use only whether each SPMT channel is fired or unfired.
- For a Poisson mean  $\mu_{\text{SPMT}}$  and a given SPMT channel with  $M$  events and  $M_{\text{fired}}$  fired events, the zero-hit probability is

$$P_{\text{unfired}} = \frac{M - M_{\text{fired}}}{M} = e^{-\mu_{\text{SPMT}}}$$

- Therefore  $\mu_{\text{SPMT}} = -\ln P_{\text{unfired}}$

### Calibration observable:

$$R(\mu_{\text{LPMT}}) = \frac{\mu_{\text{LPMT}}}{\mu_{\text{SPMT}}} \begin{matrix} \curvearrowright \text{mean PE/charge per LPMT} \\ \curvearrowleft \text{mean PE/charge per SPMT} \end{matrix}$$

A constant R indicates linear LPMT response relative to the SPMT reference.

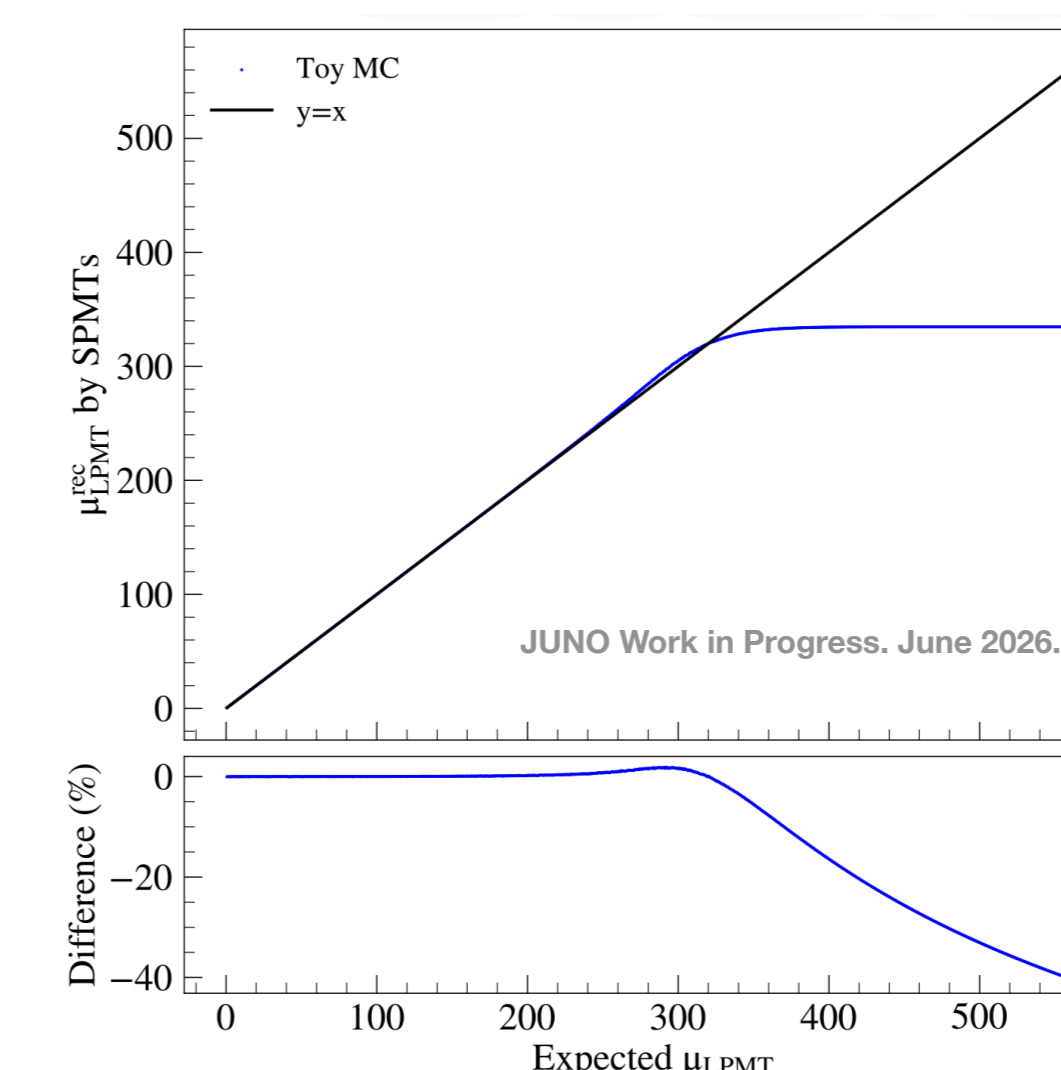


Fig 5. Valid-range study of the SPMT occupancy method

Data are collected with a laser source placed at the detector center and with varying intensity. For off-center events, the formulas would be more complicated.

### Toy-MC validation:

- Black: ideal linear response
- Blue: occupancy estimator
- Saturation appears when  $P_{\text{unfired}}$  becomes too small

## Conclusions

- SPMT gain, resolution, and dark count rate are stable over the analyzed physics runs.
- Controlling LPMT charge non-linearity is essential for maintaining JUNO's energy-scale precision, which directly impacts reactor antineutrino oscillation measurements and mass-ordering sensitivity.
- The occupancy method provides a robust linear SPMT reference without using direct SPMT charge.
- The COTI-reconstructed LPMT response is linear at low charge, but shows several-percent non-linearity over a larger charge range, with dependence on PMT type and HV stage.
- Ongoing work evaluates COTI performance and alternative waveform reconstruction algorithms for improved charge linearity.