Experimental Validation of a Gamma–Tweedie Charge Response Model for High-Efficiency MCP-PMTs in Liquid Neutrino Detectors

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Motivation

The Jinping Neutrino Experiment (JNE) is a **500 m^3** slow liquid-scintillator detector for MeV solar, geo, and supernova neutrinos and $0\nu\beta\beta$, read out by 8-inch high-efficiency MCP-PMTs (NNVT GDB-6082) and staged now on a 60-channel one-tonne prototype. Their single-PE charge response carries a **jumbo tail** [1] that biases the energy scale.

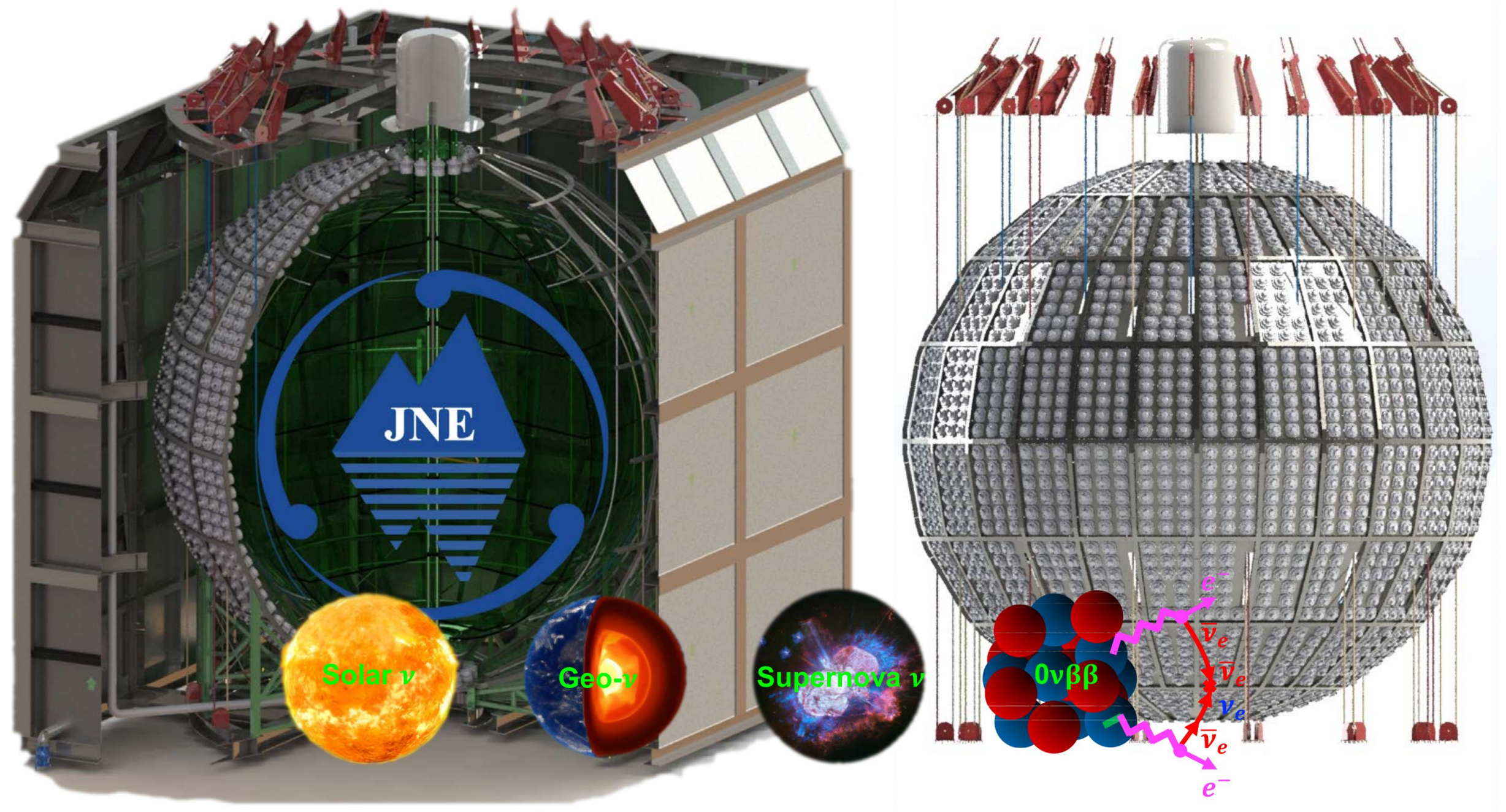

Fig. 1: JNE 500 m^3 detector and its MeV-ν reach.

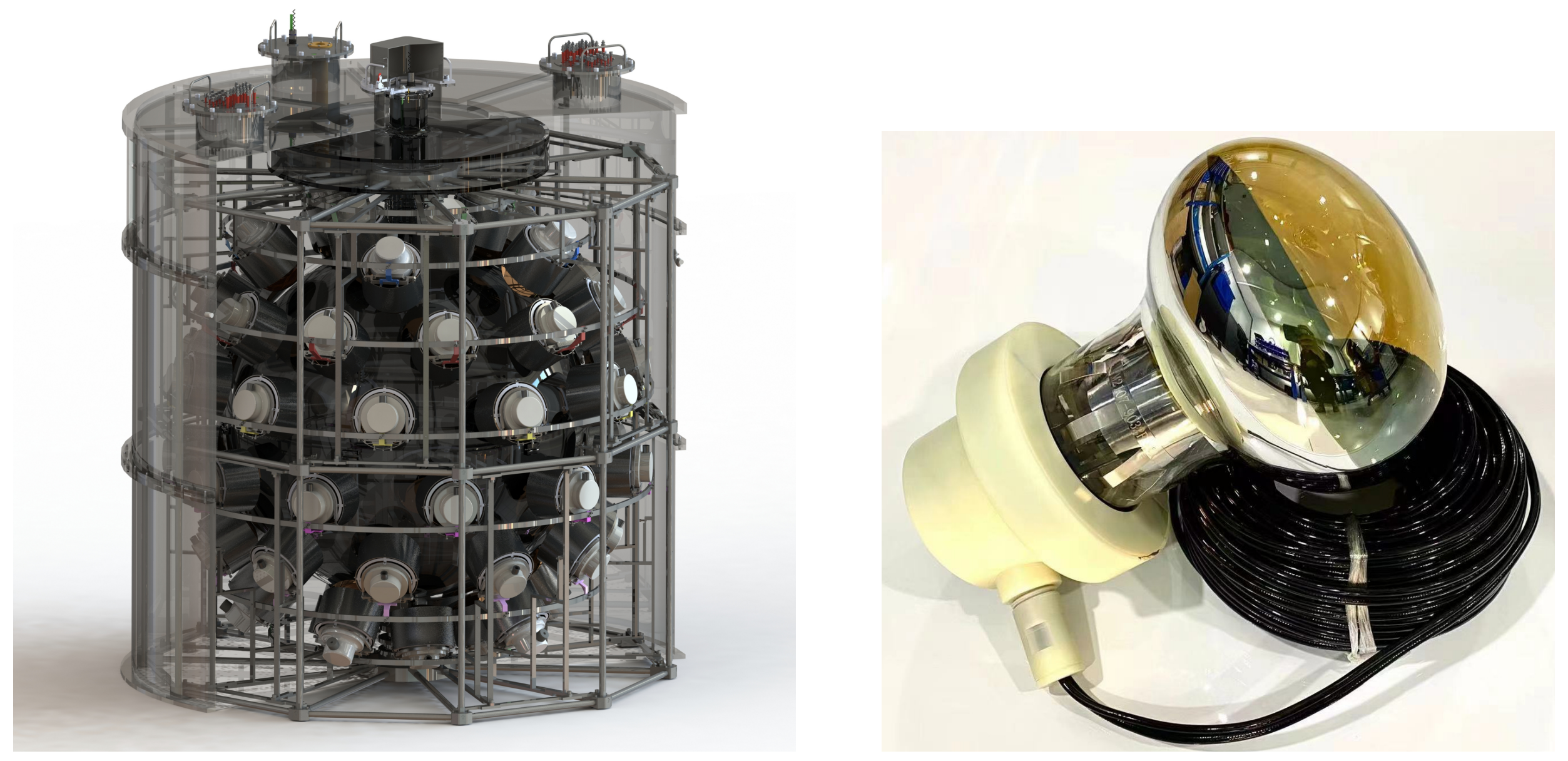

Fig. 2: the 60-channel one-tonne prototype (left) and an 8-inch MCP-PMT (right).

Gamma–Tweedie model

A photoelectron enters a channel directly (**channel mode**) or strikes the ALD-coated electrode and ejects **secondary electrons** that enter channels later (**surface mode**) [2]. The coating lifts the detection efficiency to **1.71×** a dynode tube, but also feeds the tail. The single-channel gain rises with primary energy and the ALD coating boosts it, as the electron paths and voltage divider on the right show.

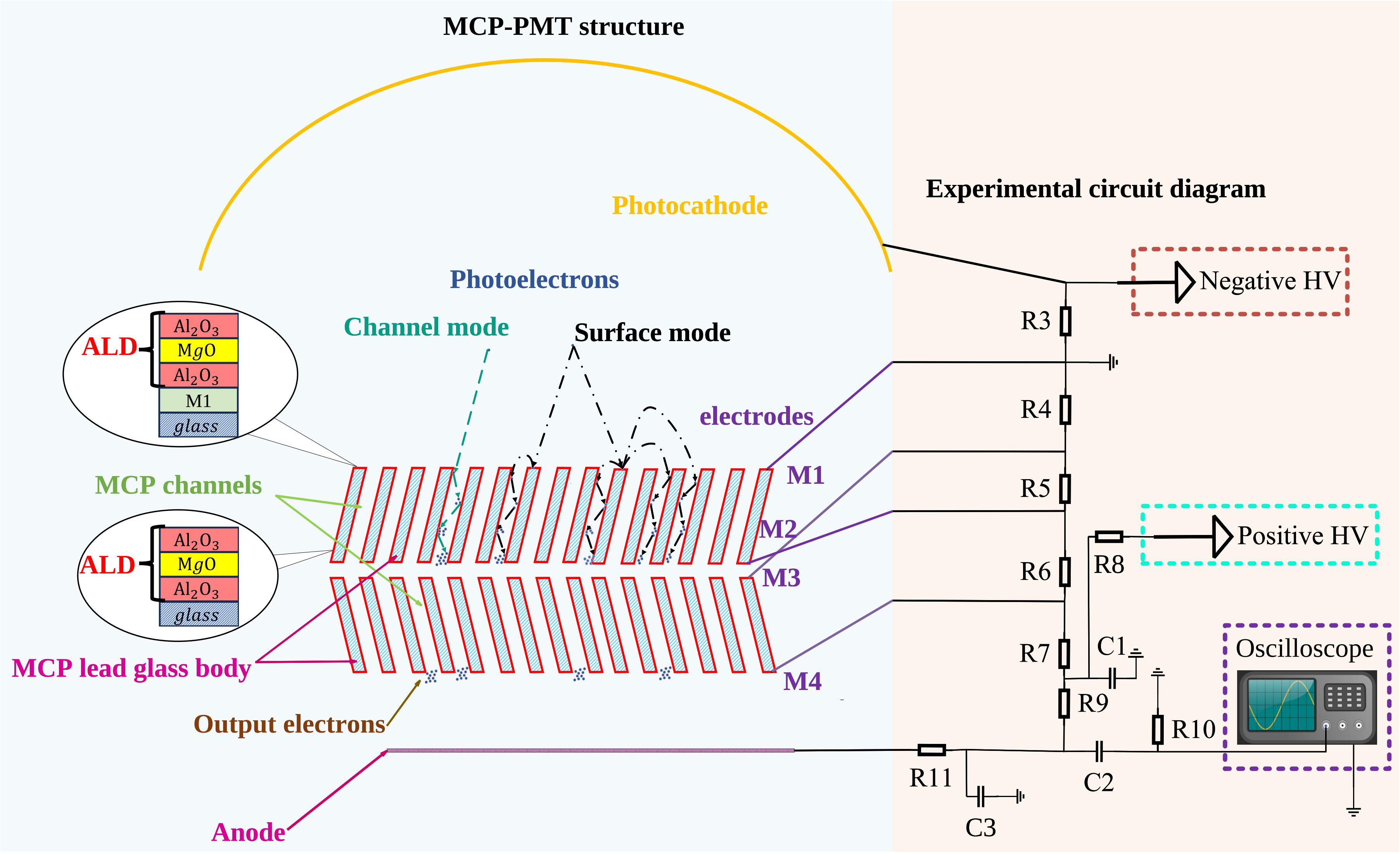

Fig. 3: electron paths and voltage divider of the MCP-PMT: the channel mode and the ALD-driven surface mode [2].

A Monte Carlo draws the secondary count and energies from the **Furman** model [2,3] — a Poisson count with Gamma-shaped energies,

$$n \sim \pi(\delta_{\mathrm{ts}}(E_0))\,, \qquad \frac{\mathrm{d}\delta_{\mathrm{ts}}}{\mathrm{d}E} \propto (E/\epsilon)^{p-1}\, e^{-E/\epsilon},$$

each amplified by the gain into a channel peak plus a secondary tail.

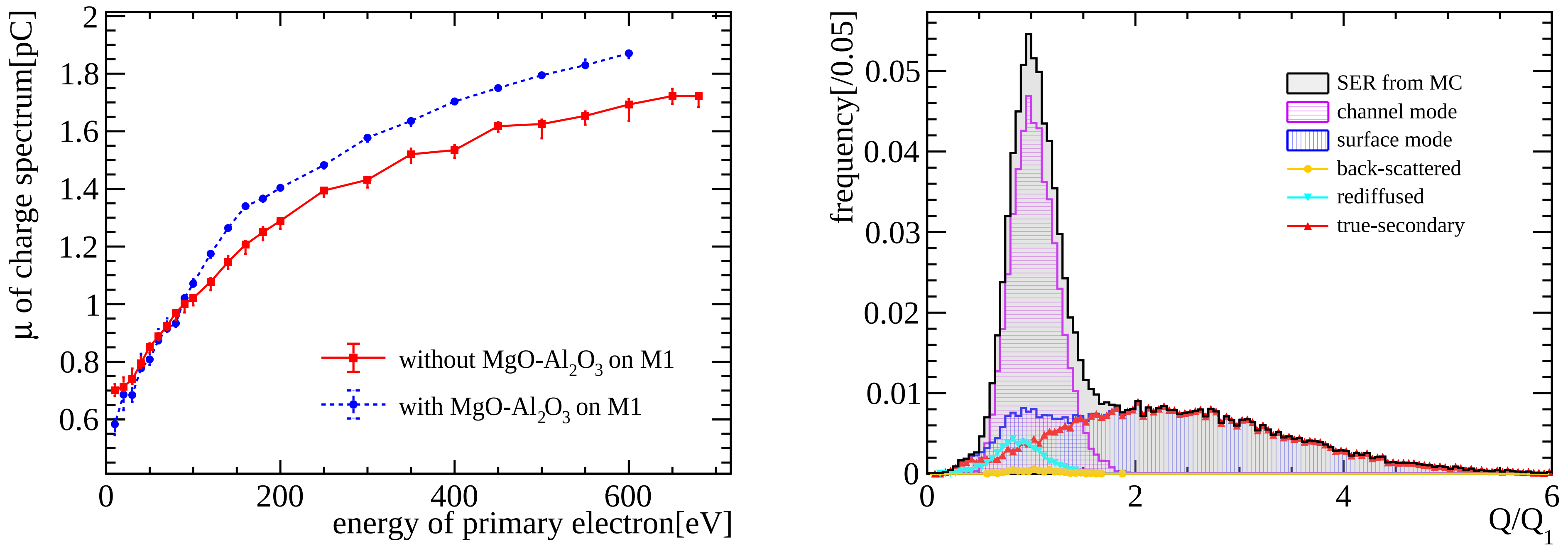

Fig. 4: (left) gain vs primary-electron energy, with/without the ALD coating; (right) Monte Carlo spectrum, channel mode plus secondary modes [2].

A channel PE follows a **Gamma** law and a scattered PE a **Tweedie** law (a Poisson sum of Gamma jumps, $1 < p < 2$):

$$f(Q) = w\,\mathrm{Gamma}(Q;k,\theta) + (1-w)\ \mathrm{Tw}_p(Q;\mu,\phi).$$

A peak fit captures only the *peak gain* G_p; the mixture recovers the **mean gain $G_m = \langle Q\rangle$**, the true charge per photoelectron, and a faithful energy response.

JNE data

FSMP [4] turns each waveform into single-PE charges; a pre-signal window selects clean single PEs at low occupancy.

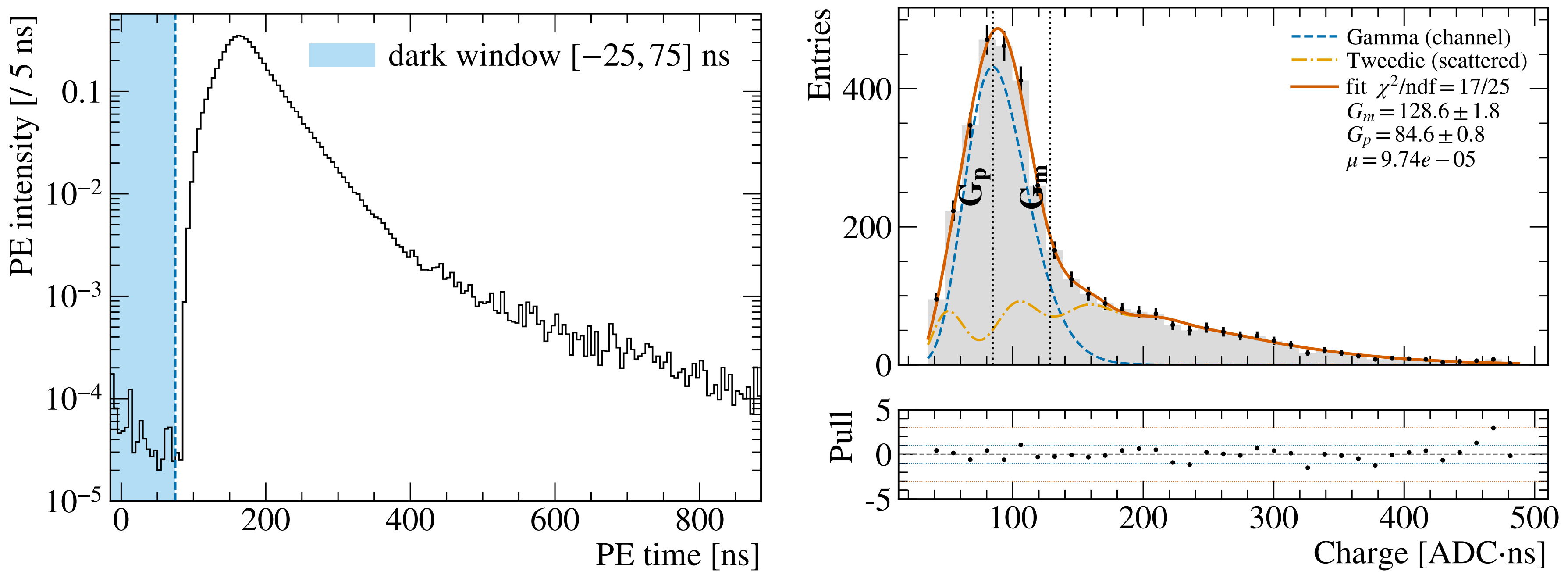

Fig. 5: (left) PE-time light curve with the selection window; (right) Gamma–Tweedie fit on channel 1; the legend lists G_m, G_p, χ^2/ndf (pull below).

Median $\chi^2/\mathrm{ndf} = 1.33$ over all channels; the **peak gain $G_p \approx 83$ understates the mean gain $G_m \approx 122$ ADC·ns by $\sim 32\%$**.

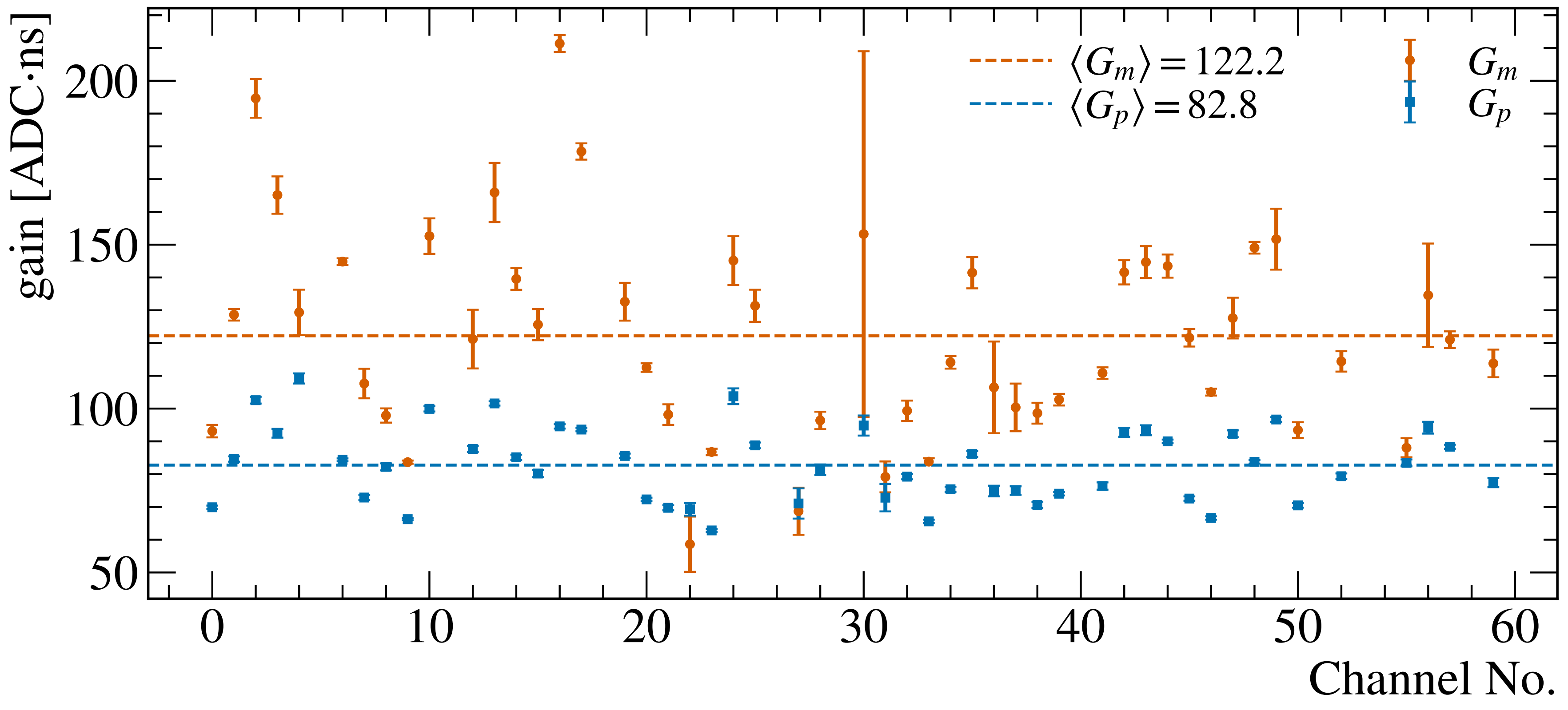

Fig. 6: peak and mean gain across all channels; dashed lines, the means.

Conclusion

The Gamma–Tweedie mixture, validated on JNE, captures the heavy-tailed single-PE spectrum and recovers the $\sim 32\%$ mean-gain bias a peak-only fit misses — analytic, deployable, and ready for JNE energy reconstruction.

References

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