Hyper-K PMTs Charge and Time Reconstruction with HKROC ASIC

Antoine Beauchêne - *July 12th, 2023*

GDR - **D**étecteurs et **I**nstrumentation pour les **2 I**nfinis

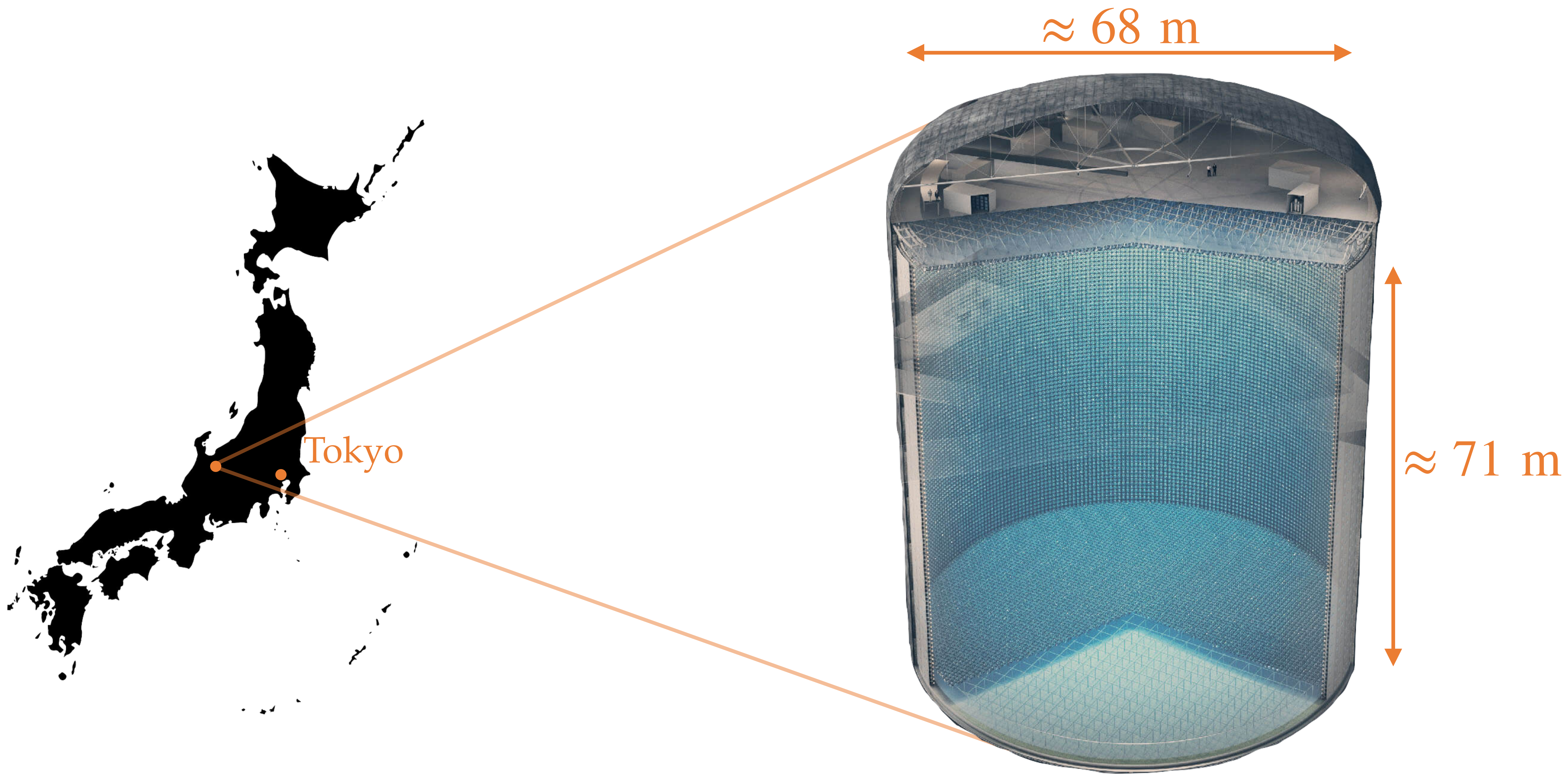
Hyper-Kamiokande

Water Cherenkov detector

- Construction: 2020 → 2027 (on-time)
- Beginning of data taking: 2027
- Water mass (Fiducial mass): 258 kton (186 kton)

$\times \approx 8$

Super-Kamiokande: 50 kton (22.5 kton)



Courtesy of Hyper-Kamiokande collaboration

Hyper-Kamiokande

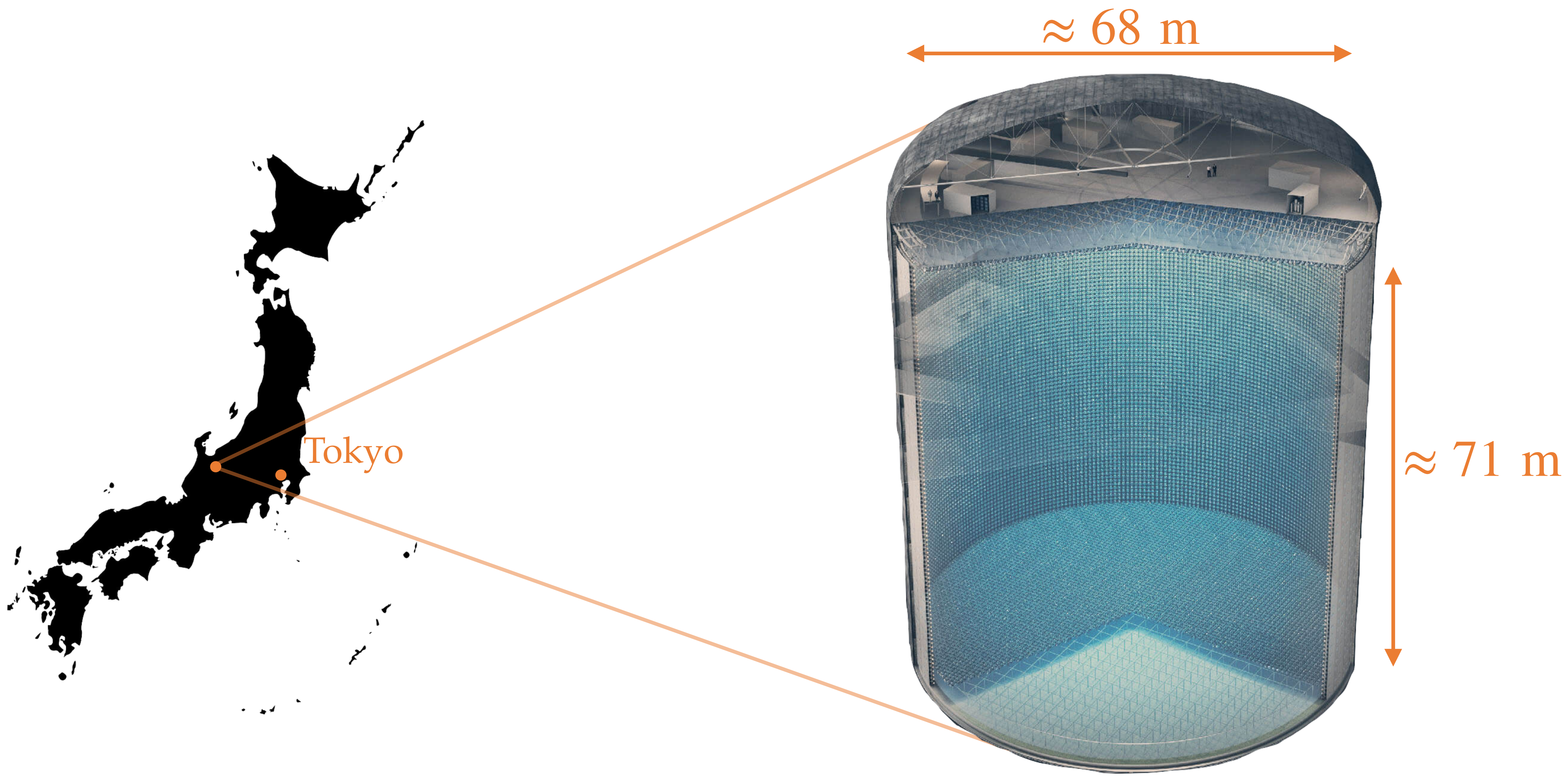
Water Cherenkov detector

- Construction: 2020 → 2027 (on-time)
- Beginning of data taking: 2027
- Water mass (Fiducial mass): 258 kton (186 kton)
- 20 000 PMTs in the **I**nner **D**etector
  - Diameter: 50 cm
  - Photocathode coverage: 20%
- Located 650 m under Mt. Nijugoyama
  - Shield from cosmic muons

$\times \approx 8$

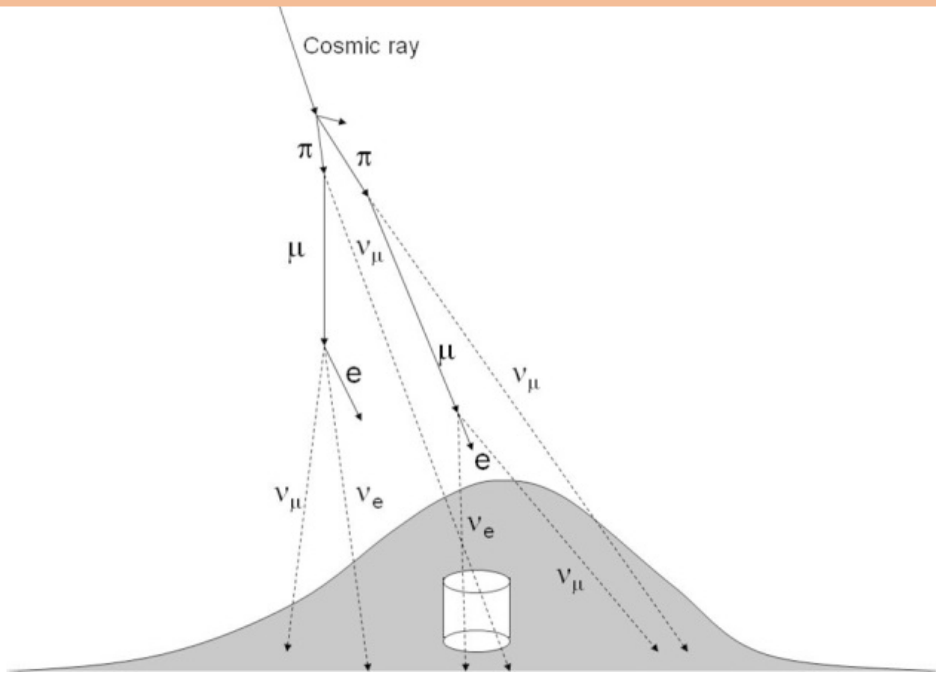
Super-Kamiokande: 50 kton (22.5 kton)

10 km from Super-K

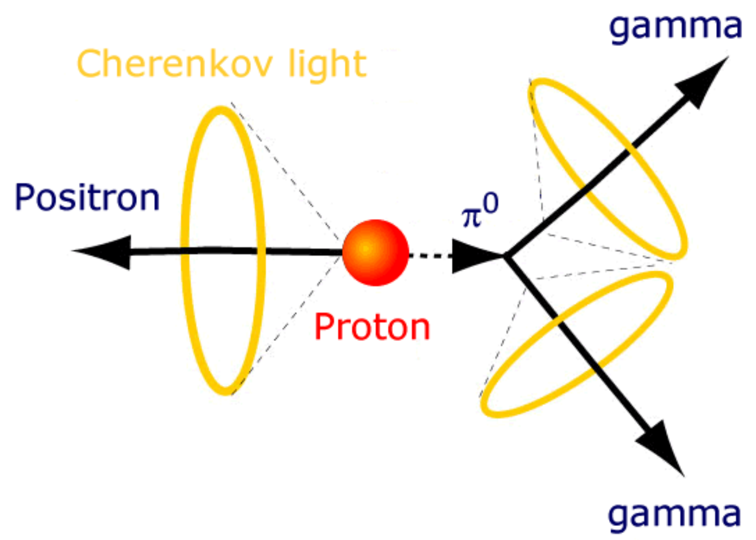


Hyper-Kamiokande

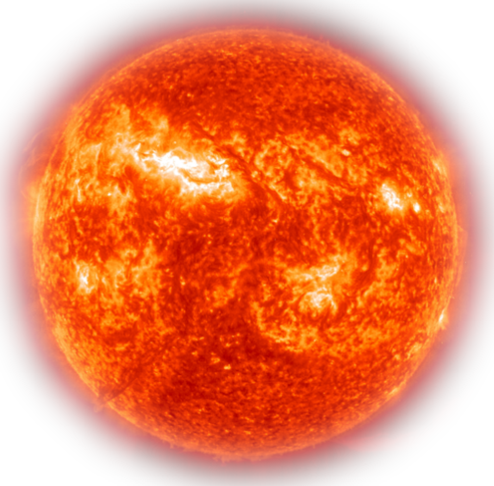
Physics program



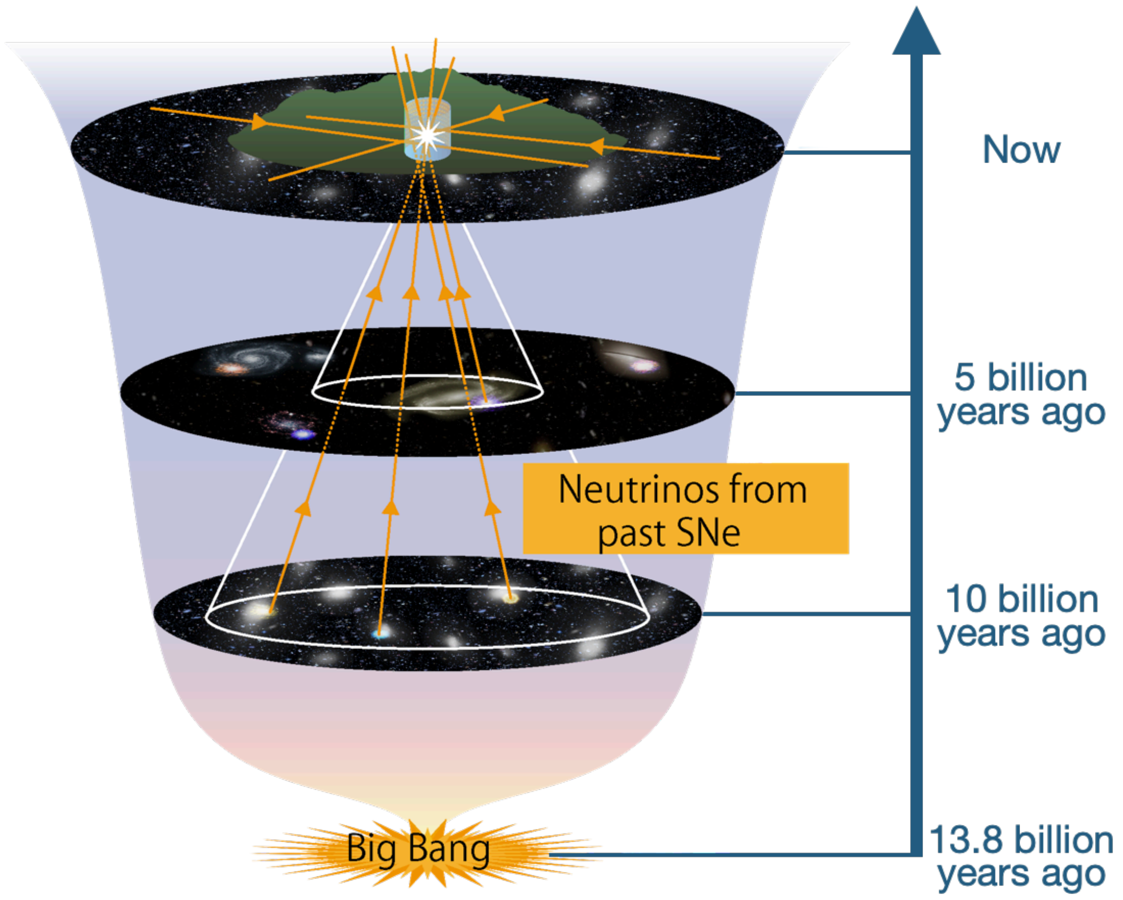
- Accelerator & Atmospheric ν
  - CP violation for leptons; Measurement of δ_{CP}; Leptogenesis; Mass hierarchy
- Proton decay
  - **G**rand **U**nified **T**heories through p decay



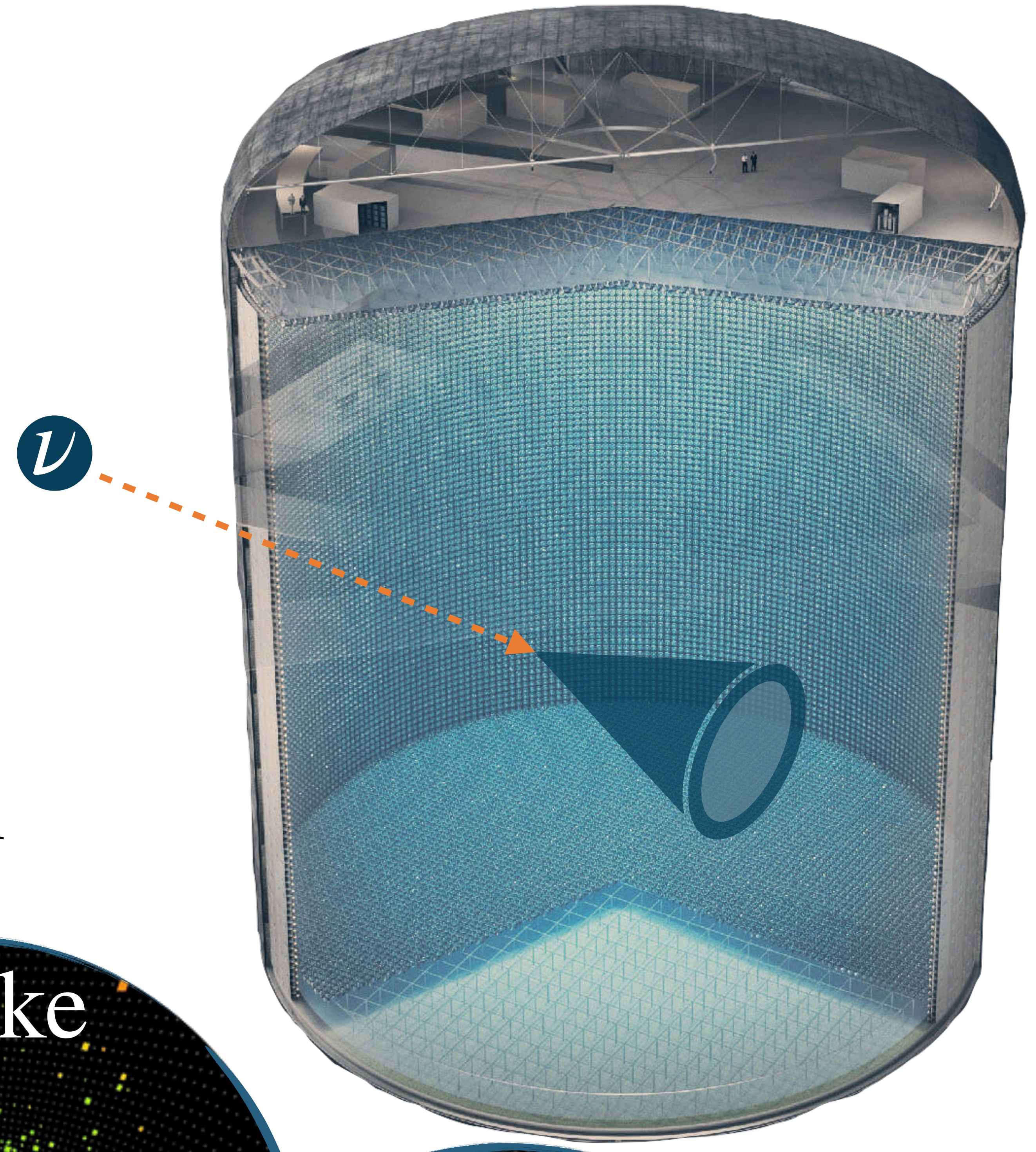
- Solar ν
  - MSW effect; Non-standard interactions



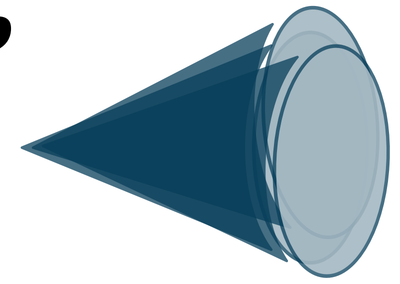
- Supernova ν
  - Direct: Supernova models
  - **D**iffuse **S**upernova **N**eutrino **B**ackground: Star formation rate; Black hole fraction; History of the Universe; Non-standard interactions



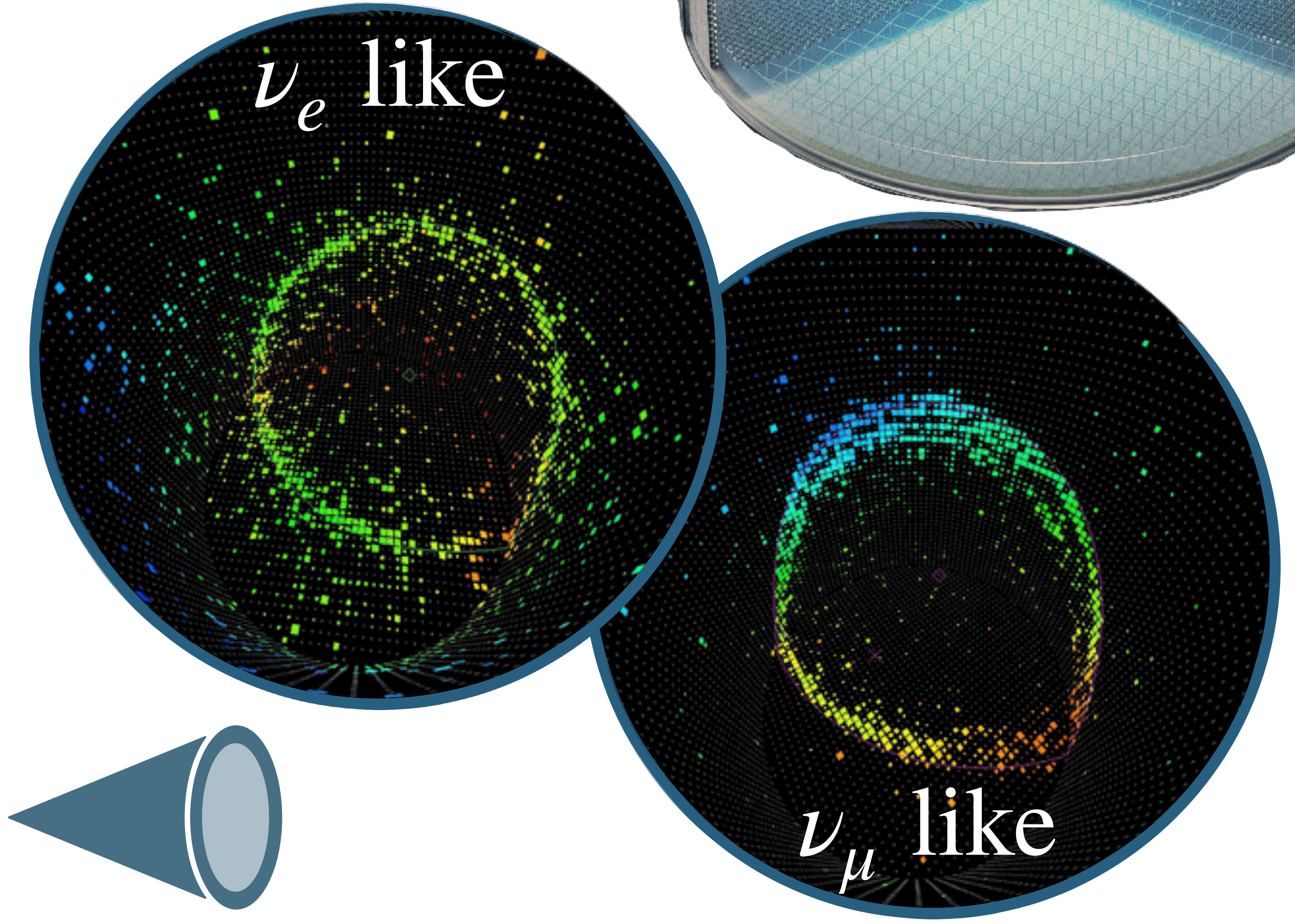
Cherenkov effect



- Need charged particles!
  - $\nu_e \rightarrow e^- \mid \bar{\nu}_e \rightarrow e^+$
  - $\nu_\mu \rightarrow \mu^- \mid \bar{\nu}_\mu \rightarrow \mu^+$
- In a medium: If $v_{\text{charged particle}} > c/n \Rightarrow$ above the Cherenkov threshold
- For SK & HK: $n_{\text{water}} = 1.333 \Rightarrow c/n_{\text{water}} \approx 3c/4$
- Particle identification based on the ring pattern
  - $e^{-/+}$: m_e small → Often scatter → **Fuzzy ring**



  - $\mu^{-/+}$: $m_\mu \approx 200 \times m_e$ → Straight trajectory → **Sharp ring**



Photomultiplier tubes

3 700 delivered up to now

- 20 000 PMTs of 50 cm: Hamamatsu R12860-HQE (↔ **H**igh **Q**uantum **E**fficiency)
- Constant quality inspection: Visual and measurements

Courtesy of Hyper-Kamiokande collaboration

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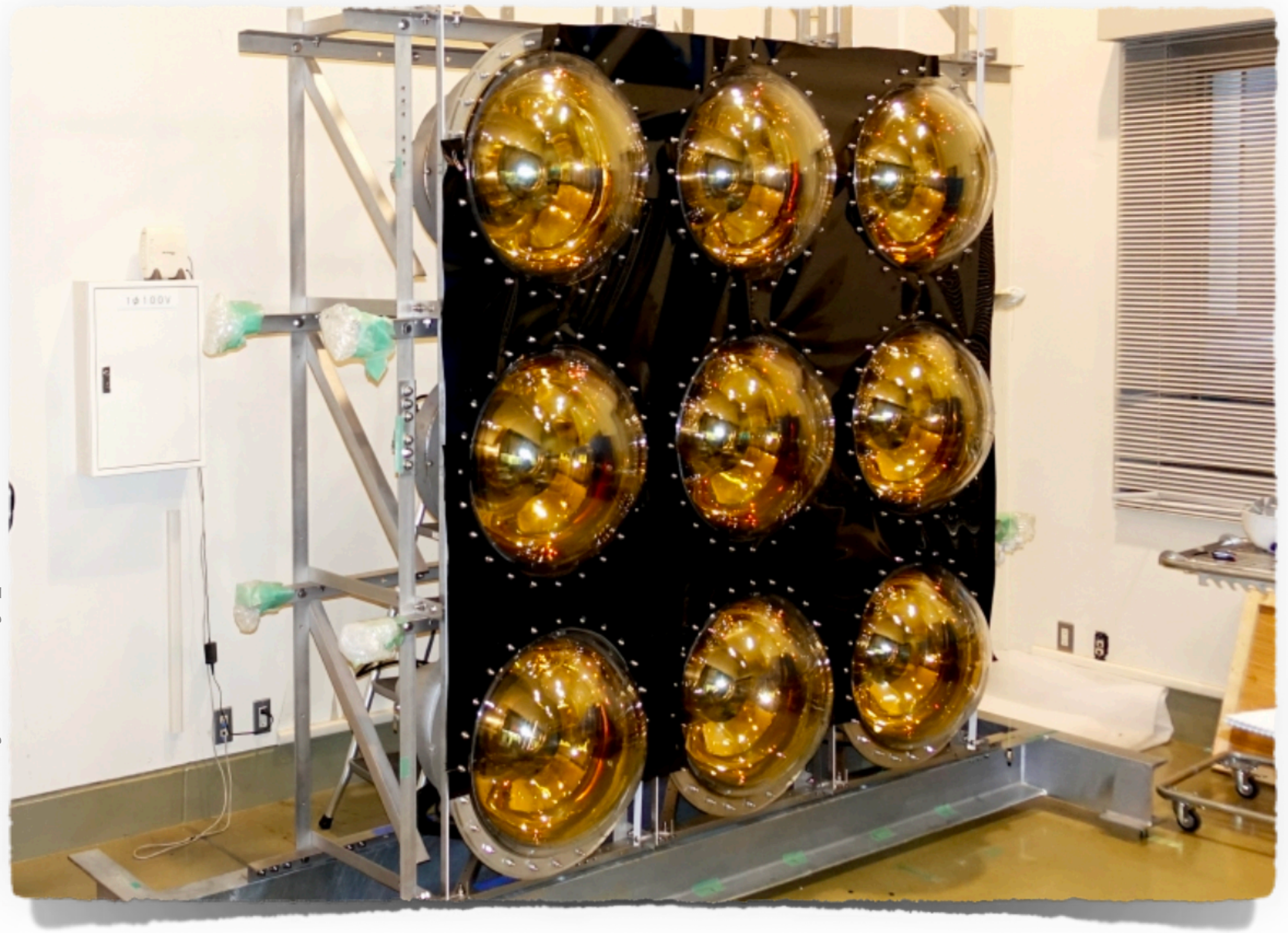
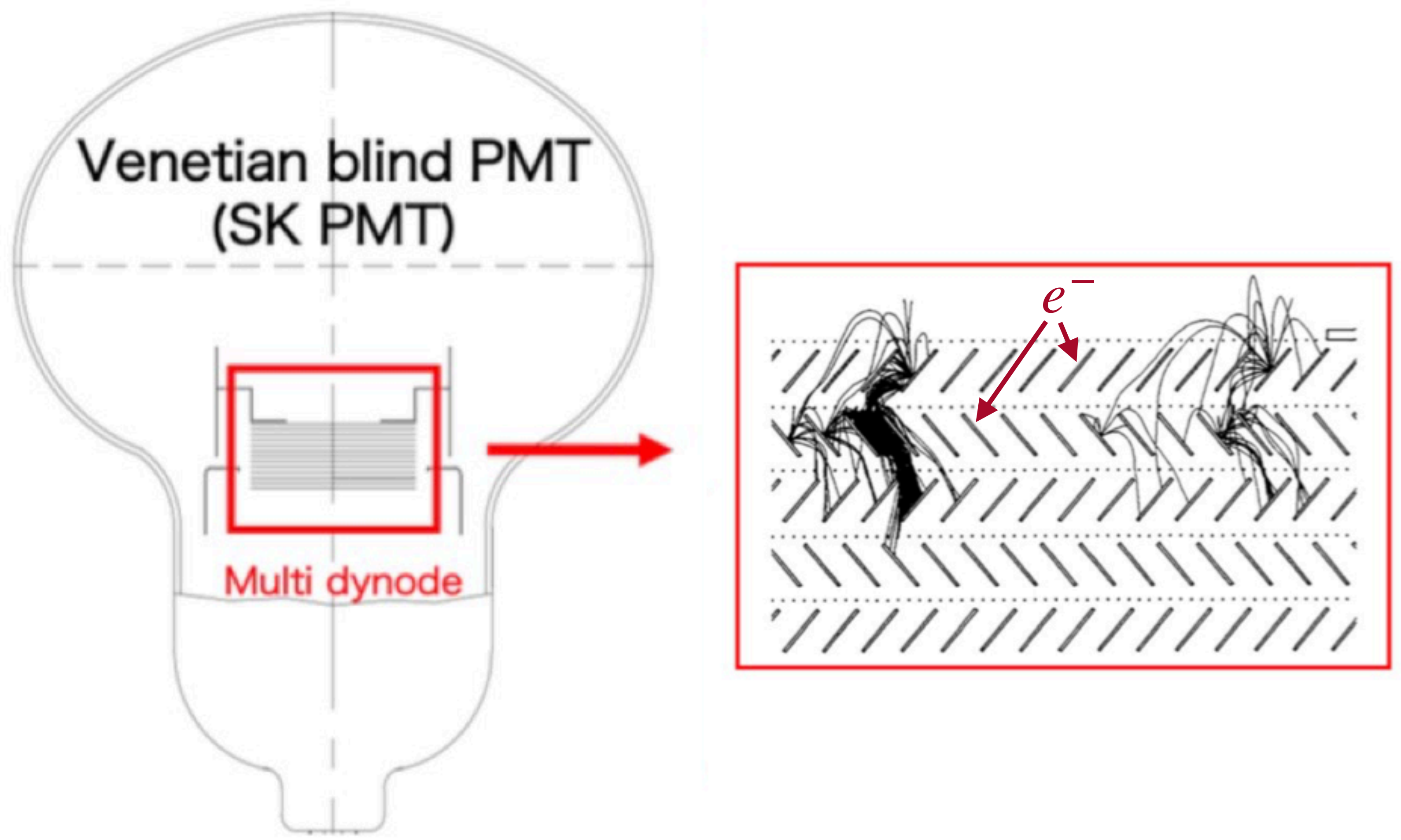
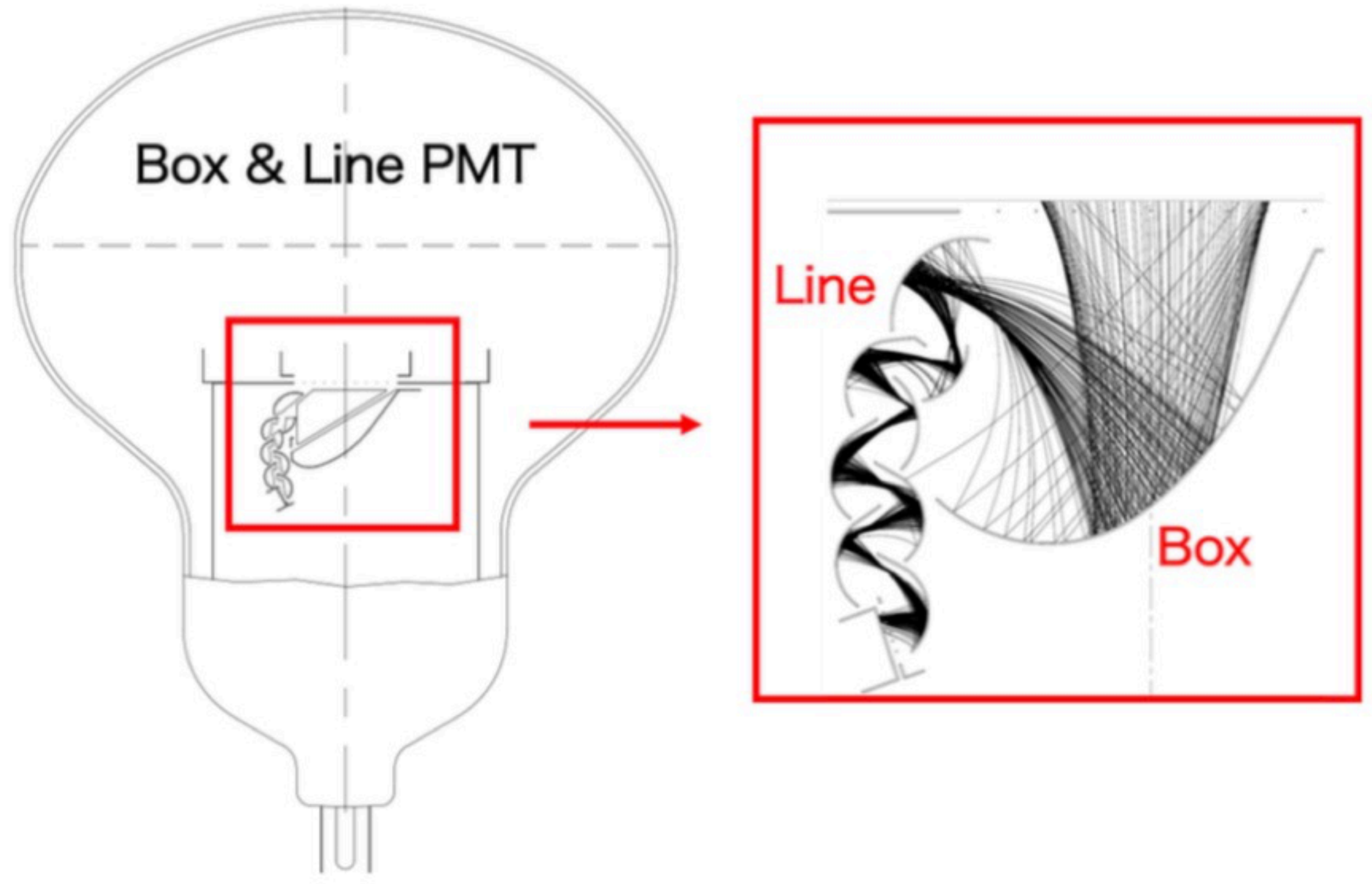


Photomultiplier tubes

PMT Properties	Super-K	Hyper-K
Dynode structure	Venetian blind	Box & Line





Hamamatsu R12860-HQE

- e^- might miss first dynode (↘ **CE**)
- Drift path can vary (↘ **T & Q res.**)

- e^- almost never miss box-shape dynode (↗ **CE**)
- Uniform drift path (↗ **T & Q res.**)

Photomultiplier tubes

PMT Properties	Super-K	Hyper-K
Dynode structure	Venetian blind	Box & Line
Quantum Efficiency (at 390 nm)	≈ 22%	≈ 30%

Hamamatsu R12860-HQE

$$\mathrm{QE}_\lambda = \frac{N_{\text{p.e.}}}{N_\gamma} = (1 - R) \cdot \frac{P_\lambda}{k} \cdot \left(\frac{1}{1 + 1/(kL)} \right) \cdot P_S$$

Reflection Loss · Excitation Efficiency · Photocathode Loss · Escape Probability

*p.e. ↔ photoelectron

- Layers:
  - Input window (*borosilicate glass*)
  - Anti-reflection layer
  - Photocathode (*bialkali*)

- Optimized **thickness of anti-reflection layer** and **photocathode deposition**

Photomultiplier tubes

PMT Properties	Super-K	Hyper-K
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Quantum Efficiency (at 390 nm)	≈ 22%	≈ 30%
Collection Efficiency (at 10^7 gain)	≈ 73%	≈ 95%
Hit Efficiency (at 1/4 p.e. threshold)	≈ 72%	≈ 86%
Detection Efficiency (QE × CE × HE)	≈ 12%	≈ 25%
Time resolution (TTS for 1 p.e.)	≈ 6.7 ns (σ ≈ 3.4 ns)	≈ 2.6 ns (σ ≈ 1.3 ns)
Charge resolution	≈ 60%	≈ 31%
Dark rate	≈ 4 kHz	≈ 4 kHz

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Hamamatsu R12860-HQE

Better vertex reconstruction

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$\times \approx 2.1$

Hamamatsu R12860-HQE

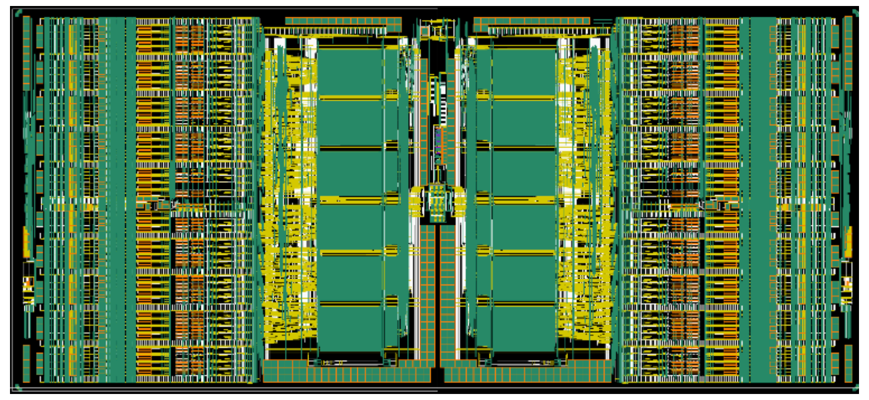
Better vertex reconstruction

Better energy reconstruction

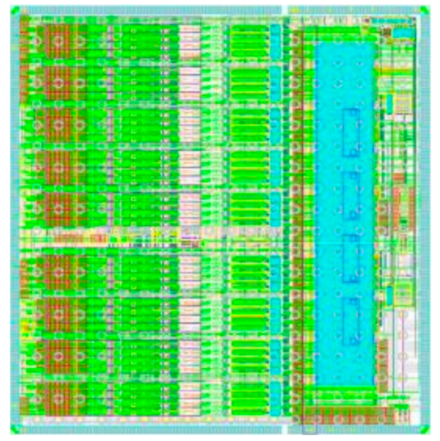
Origins

- Stands for **<u>H</u>**yper-**<u>K</u>**amiokande **<u>R</u>**ead**<u>O</u>**ut **<u>C</u>**hip
- ASIC designed as a proposition for the readout of the PMTs of HK

- Based on **HGCROC** chip developed for the CMS **<u>H</u>**igh-**<u>G</u>**ranularity **<u>C</u>**alorimeter
  - Same ADC, TDC, PLL and readout
  - Small changes in analog and digital parts



HGCROC



HKROC

- Originally created for HK → **Could be adapted/optimized** for different type of PMTs and therefore different experiments

Requirements

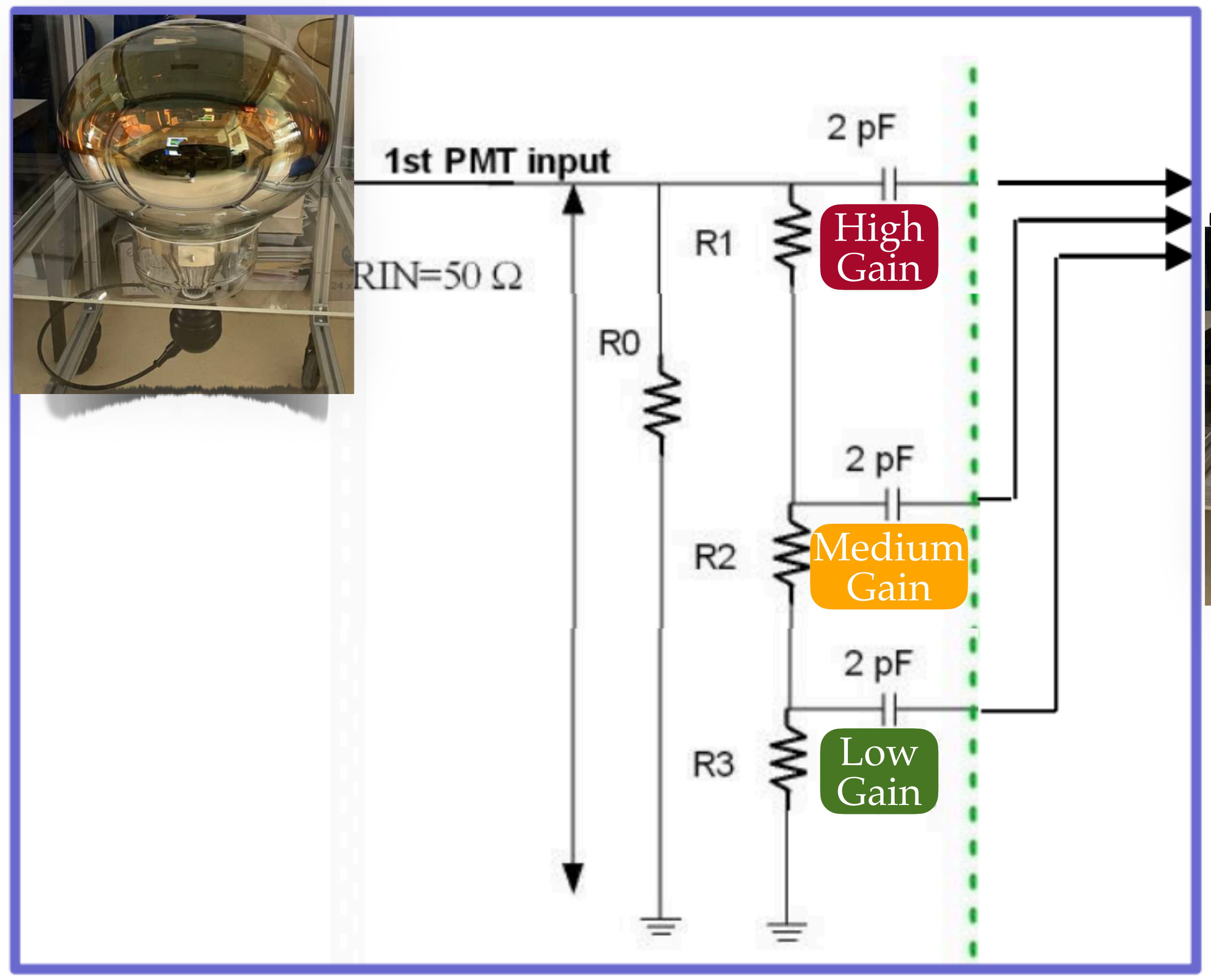
- Electronic box under water: Less cable and signal degradation

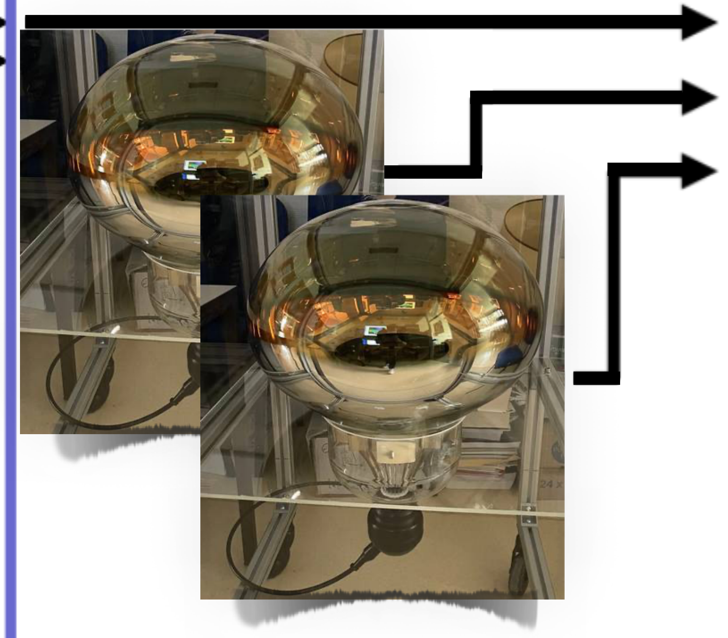
*1 p.e. ↔ 2 pC

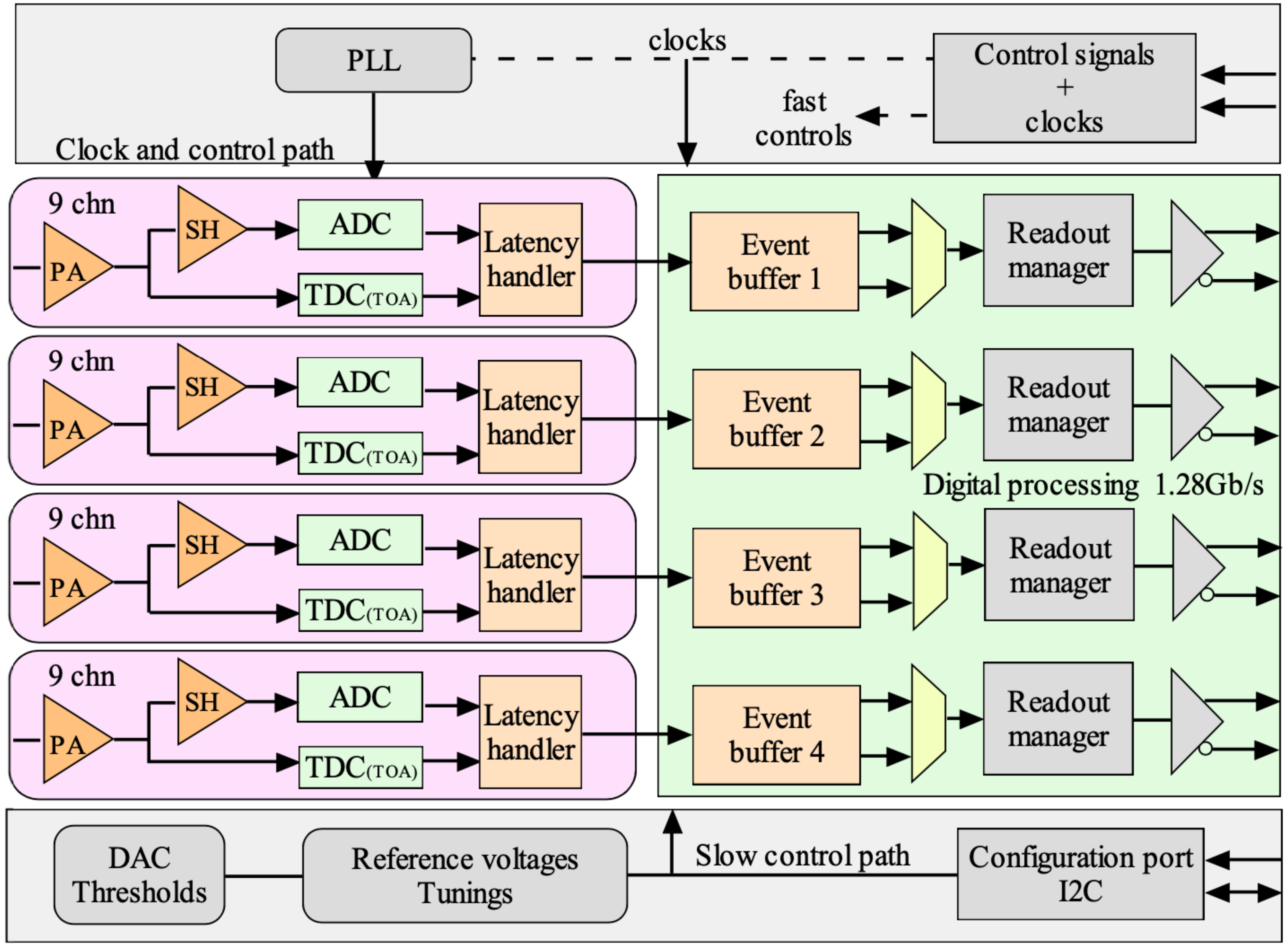
Physics constraint	Electronics requirement
Detect synchronous & asynchronous events (accelerator & atmospheric, solar, supernova and p decay)	Self-triggering for each channel
Detect close supernova without event loss (e.g. Betelgeuse)	Channel dead time ($< 1\ \mu s$)
Low energy events detection (e.g. SN or atmospheric neutrinos)	Low charge threshold ($< 1/6$ p.e.)
Detection of events from low to high energy	Large dynamic charge range (from 1 to 1 250 p.e.)
Excellent charge (i.e. energy) reconstruction performances	Charge linearity and resolution ($< 1\%$)
Electronics time resolution < PMT time resolution (1.3 ns)	Time resolution ($<$ 0.3 ns for 1 p.e.)
Low power consumption	< 1 W/channel

Main features

- 1 HKROC chip: 12 PMTs ↔ 36 channels (High, Medium & Low gain)





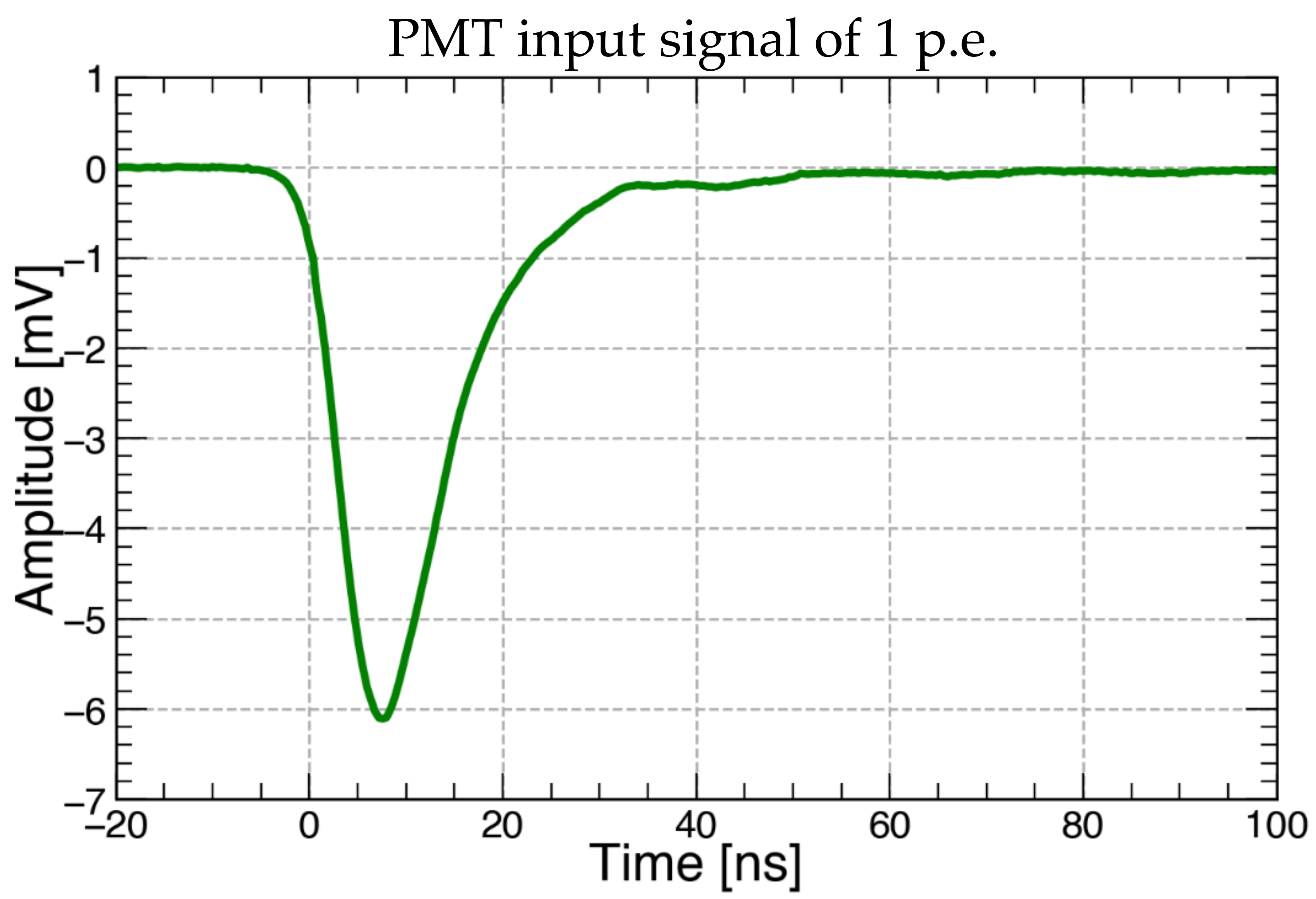


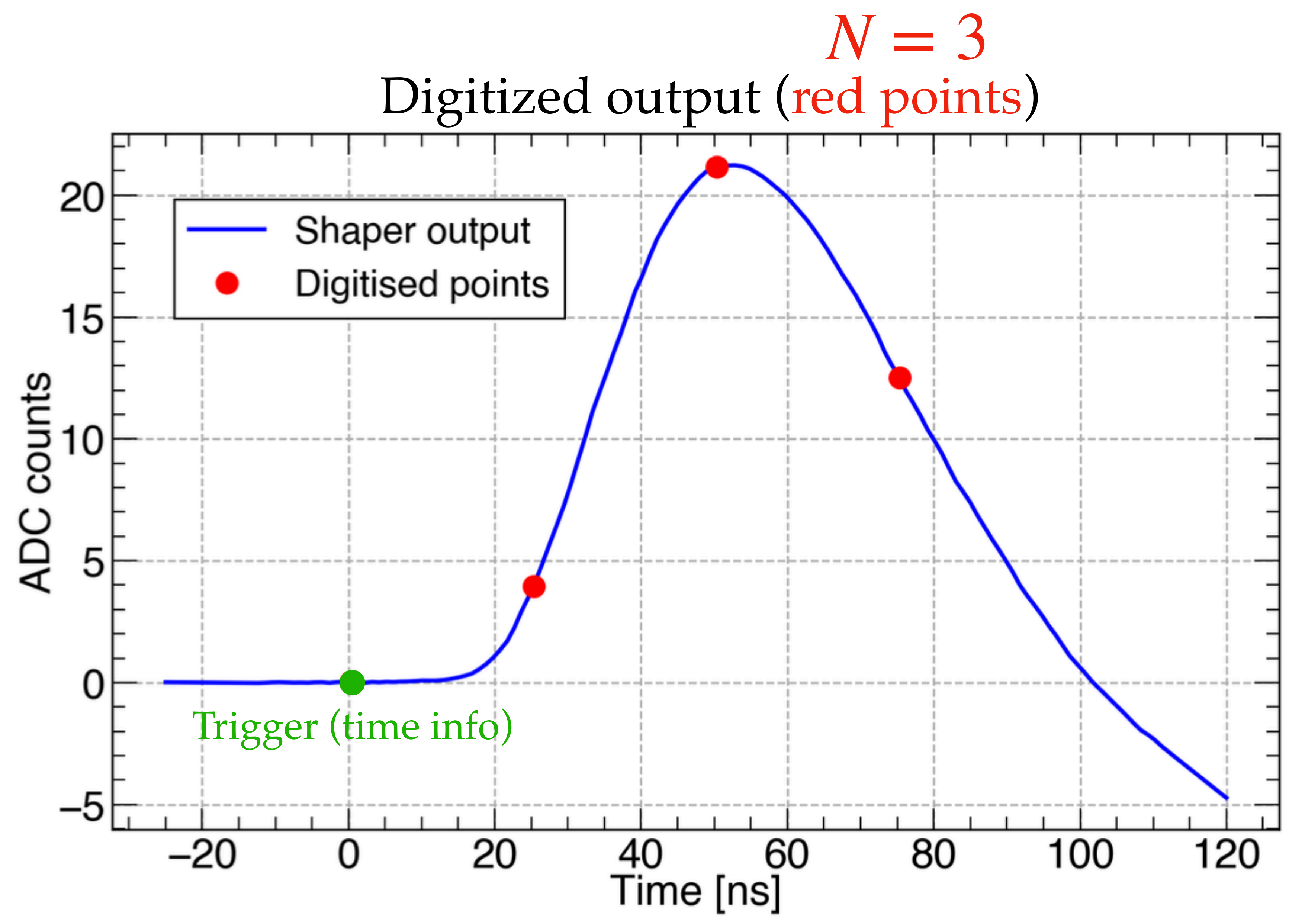
- ASIC in TSMC 130 nm node
- Low power: 10 mW/channel
- Large dynamic range: From 1 to 1 250 p.e.
- 4 readouts/ASIC @ 1.28 Gb/s: 1 readout ↔ 3 PMTs

Principle

Digitizer: Front-end board for charge and time reconstruction
2 HKROC chip/digitizer

- **40 MHz waveform digitizer with auto-trigger**:
  - Full shape of the signal waveform is reconstructed
  - Extremely precise timing measurement (1 point/25 ns)
- Charge digitized by $N = 1 \rightarrow 7$ points (tunable)





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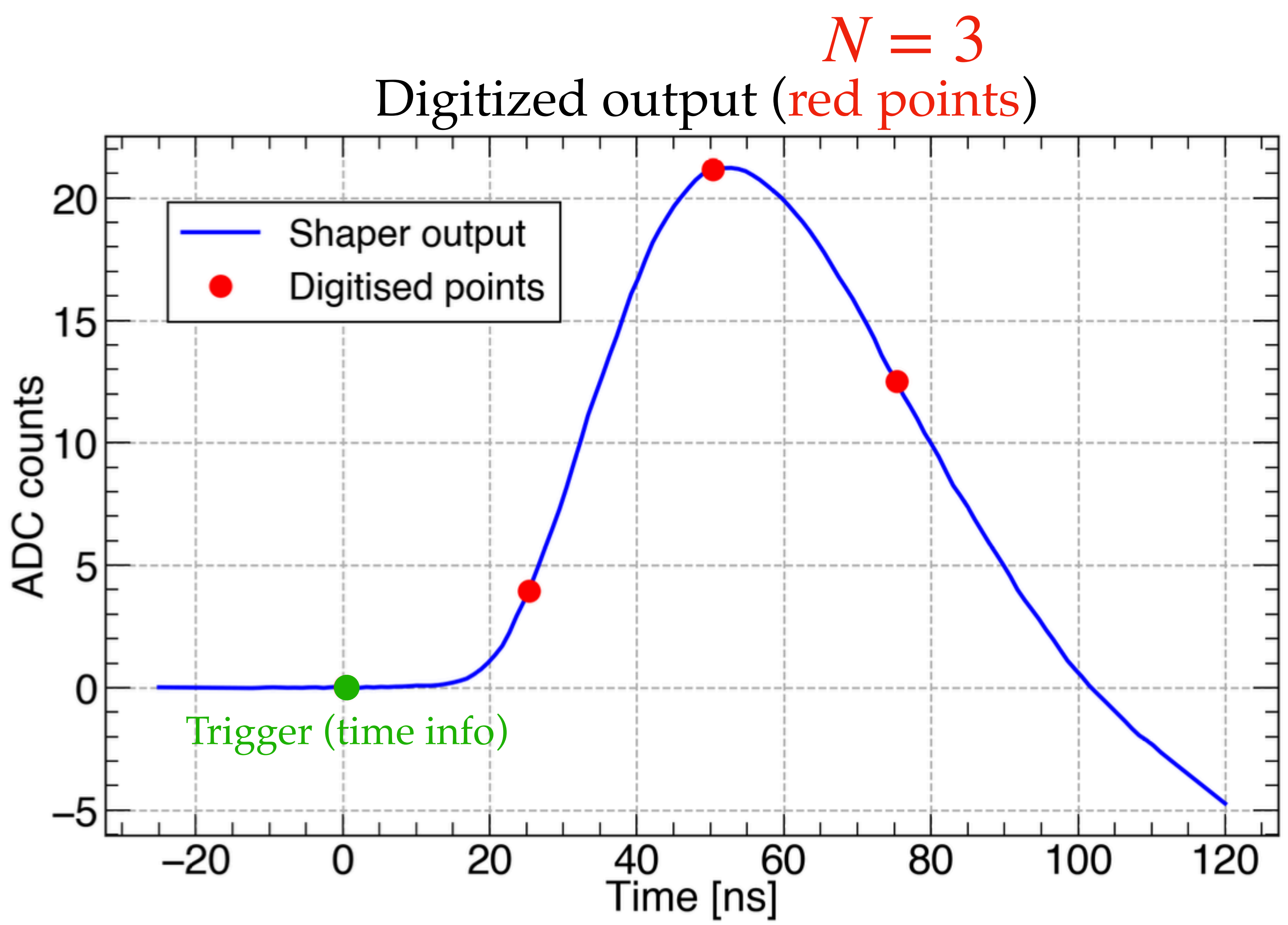
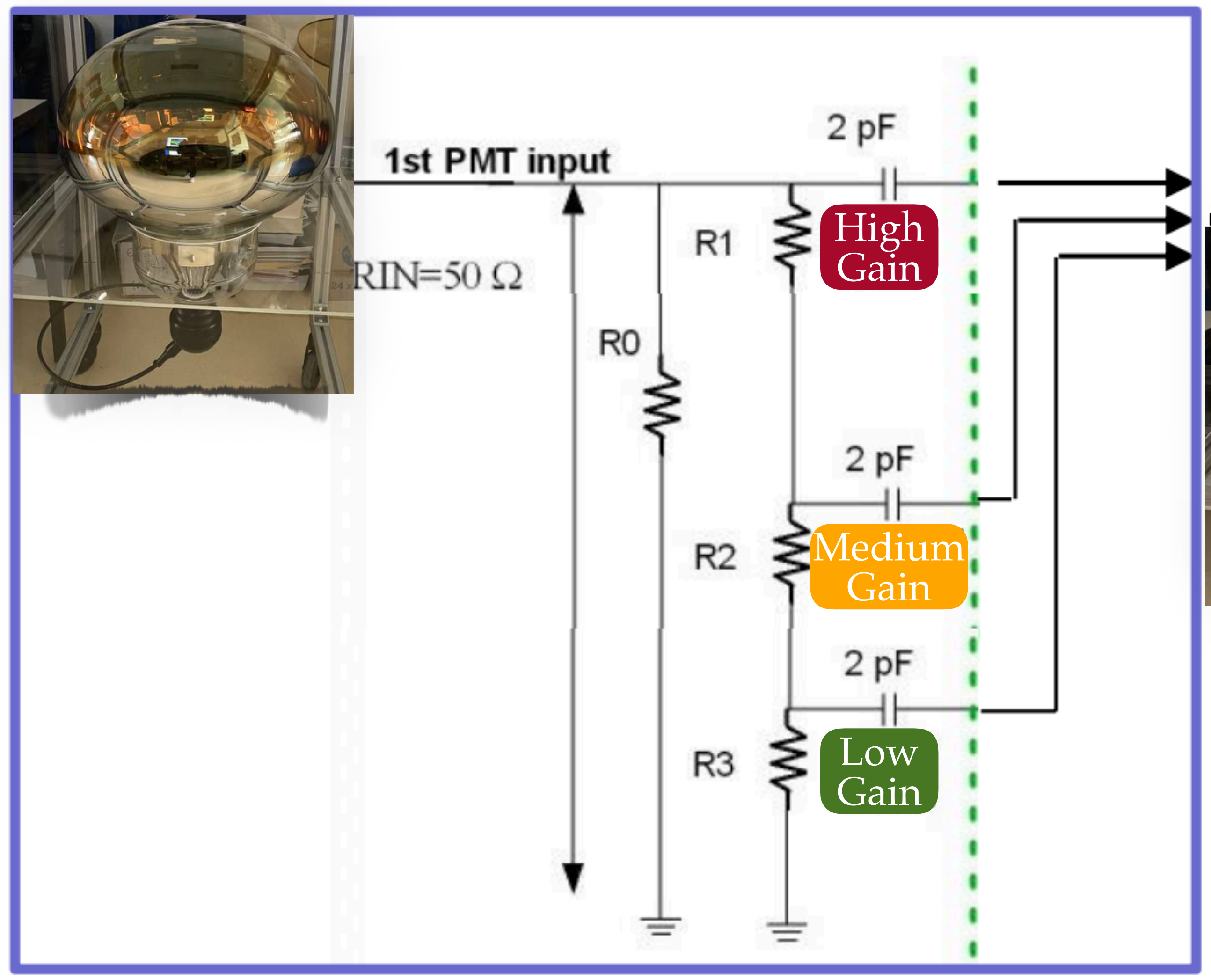
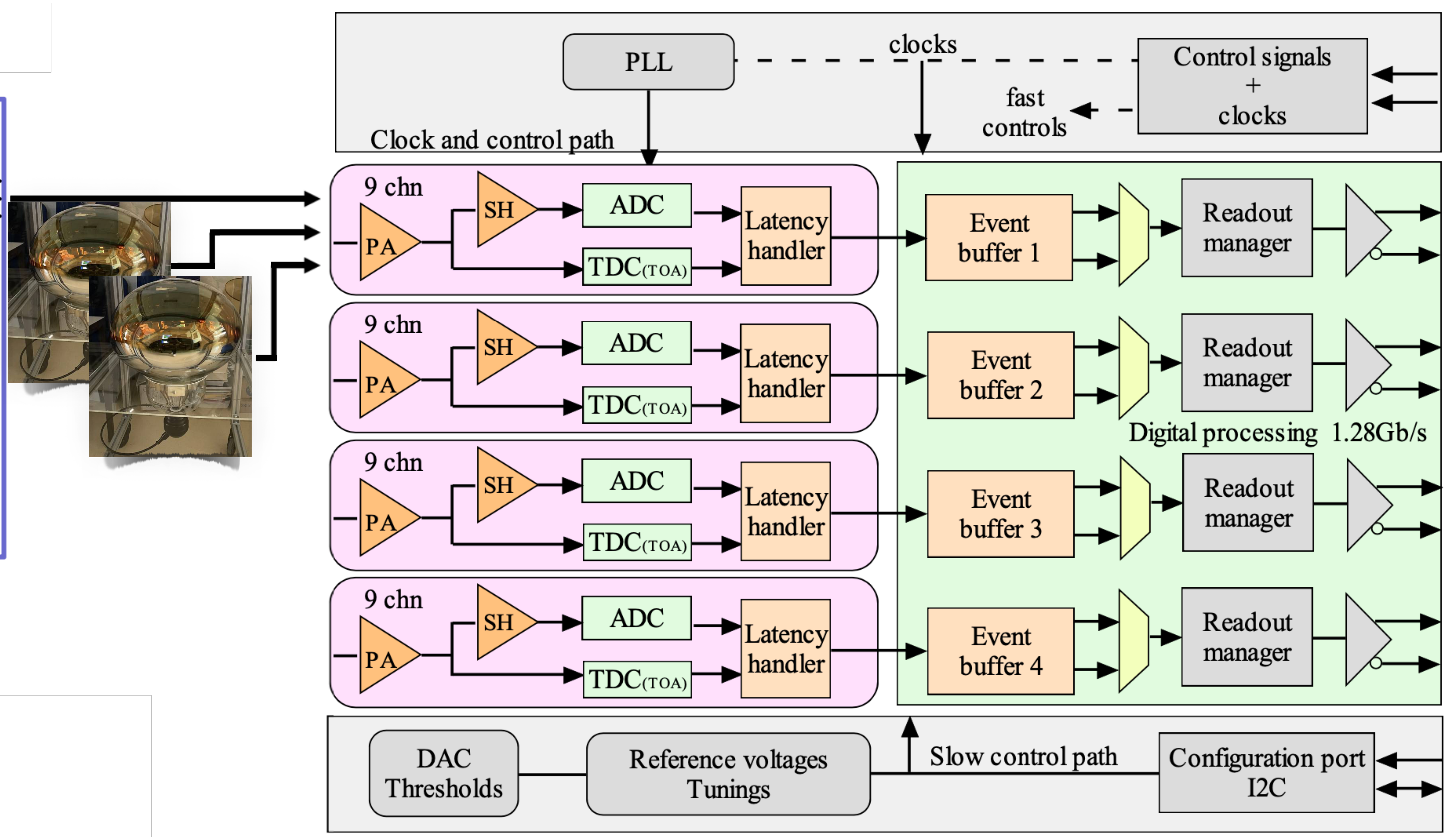
- Charge digitized by $N = 1 \rightarrow 7$ points (tunable)
- Charge reconstruction algorithm in FPGA



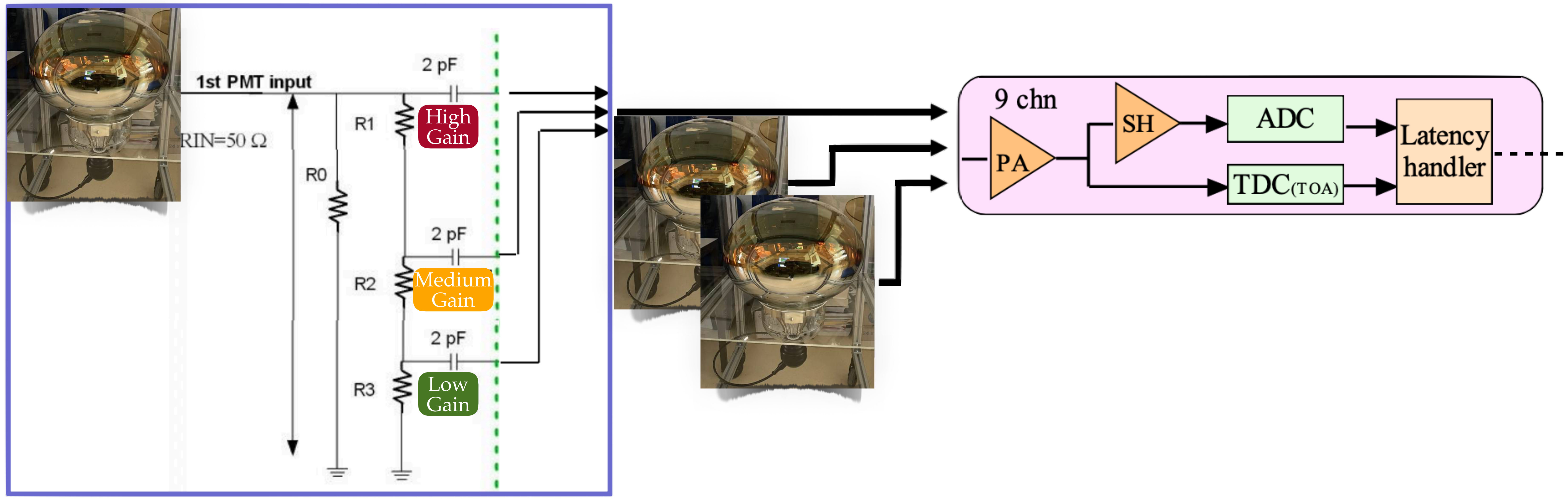
- Two modes:
  - Normal mode: Hit rate capability up to 400 kHz/PMT (High, Medium & Low)
  - Supernova mode: Increased up to 950 kHz by focusing on High gain

Principle… with more details

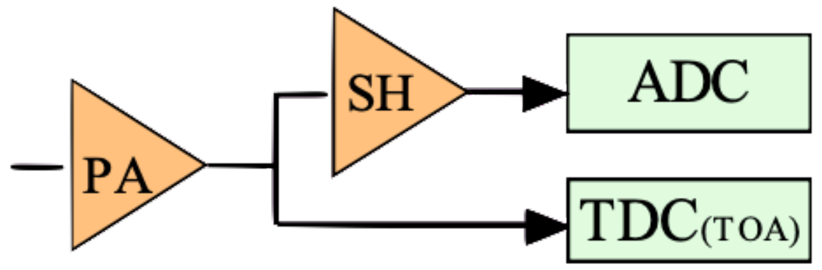




Principle… with more details

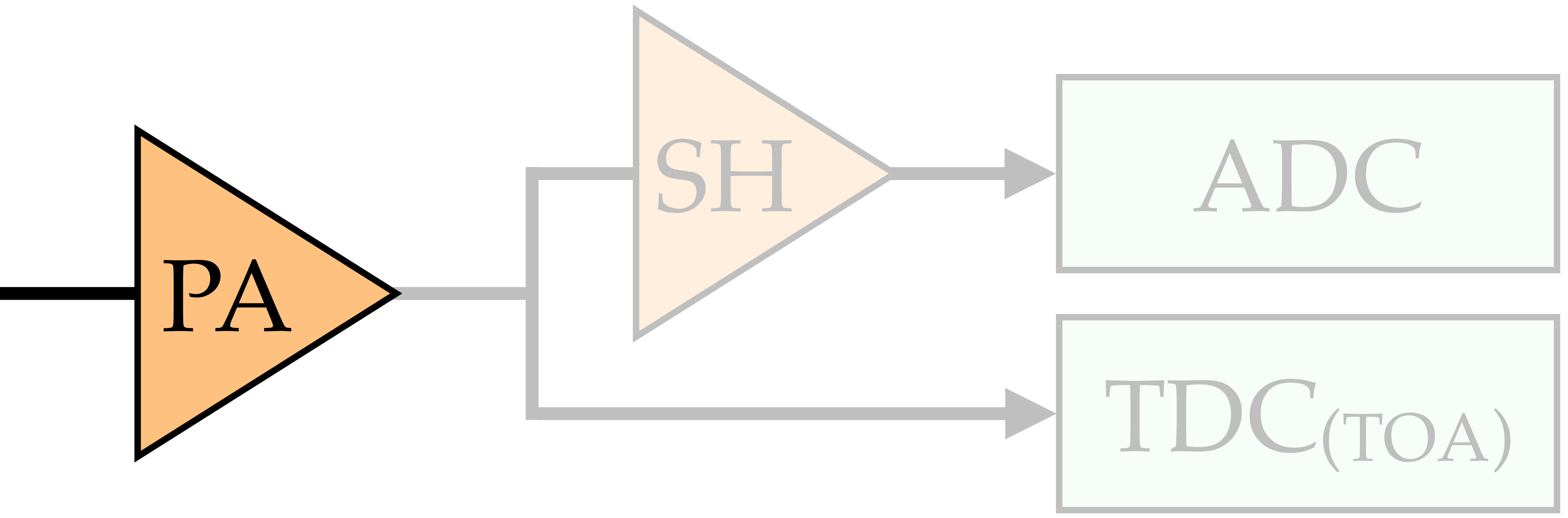


Principle… with more details



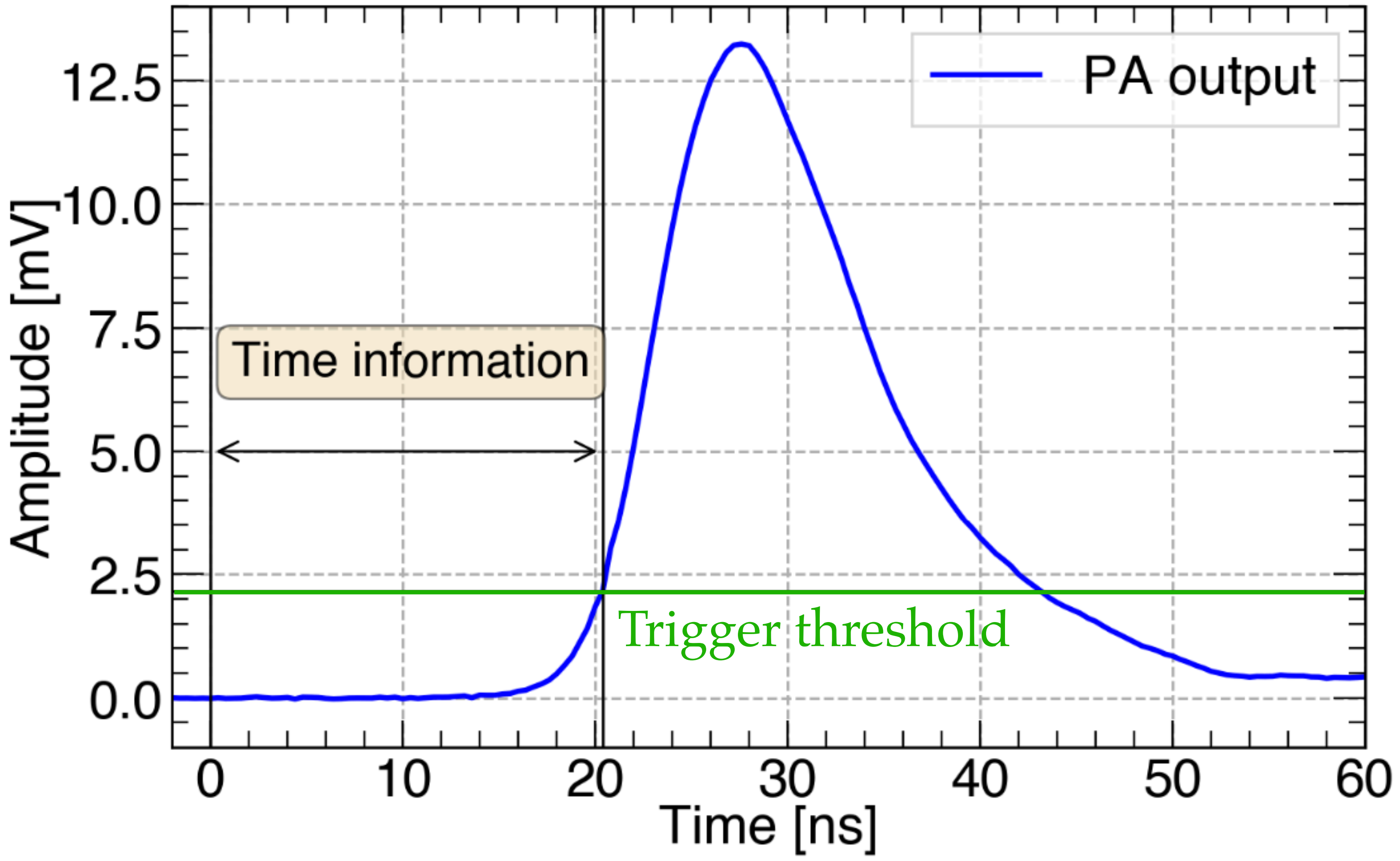
Principle… with more details

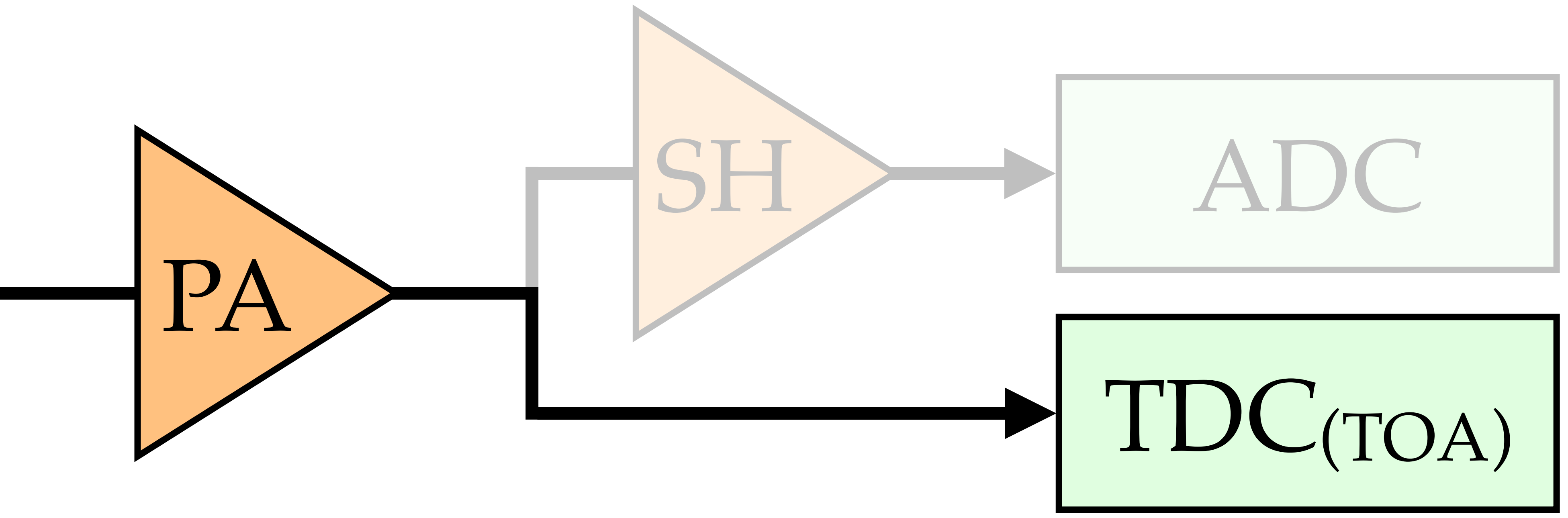
- After preamplification, signal follows two paths:



Principle… with more details

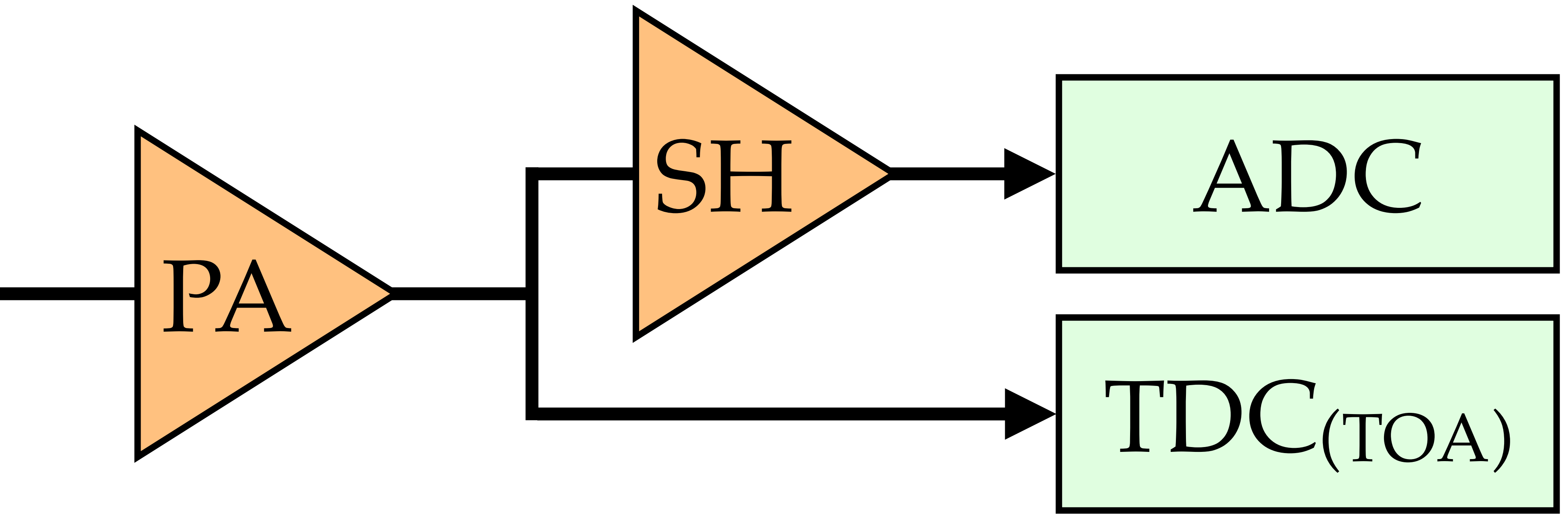
- After preamplification, signal follows two paths:
  - Fast path with discriminator connected to the TDC for **time measurement**:
    - Dead time: 30 ns

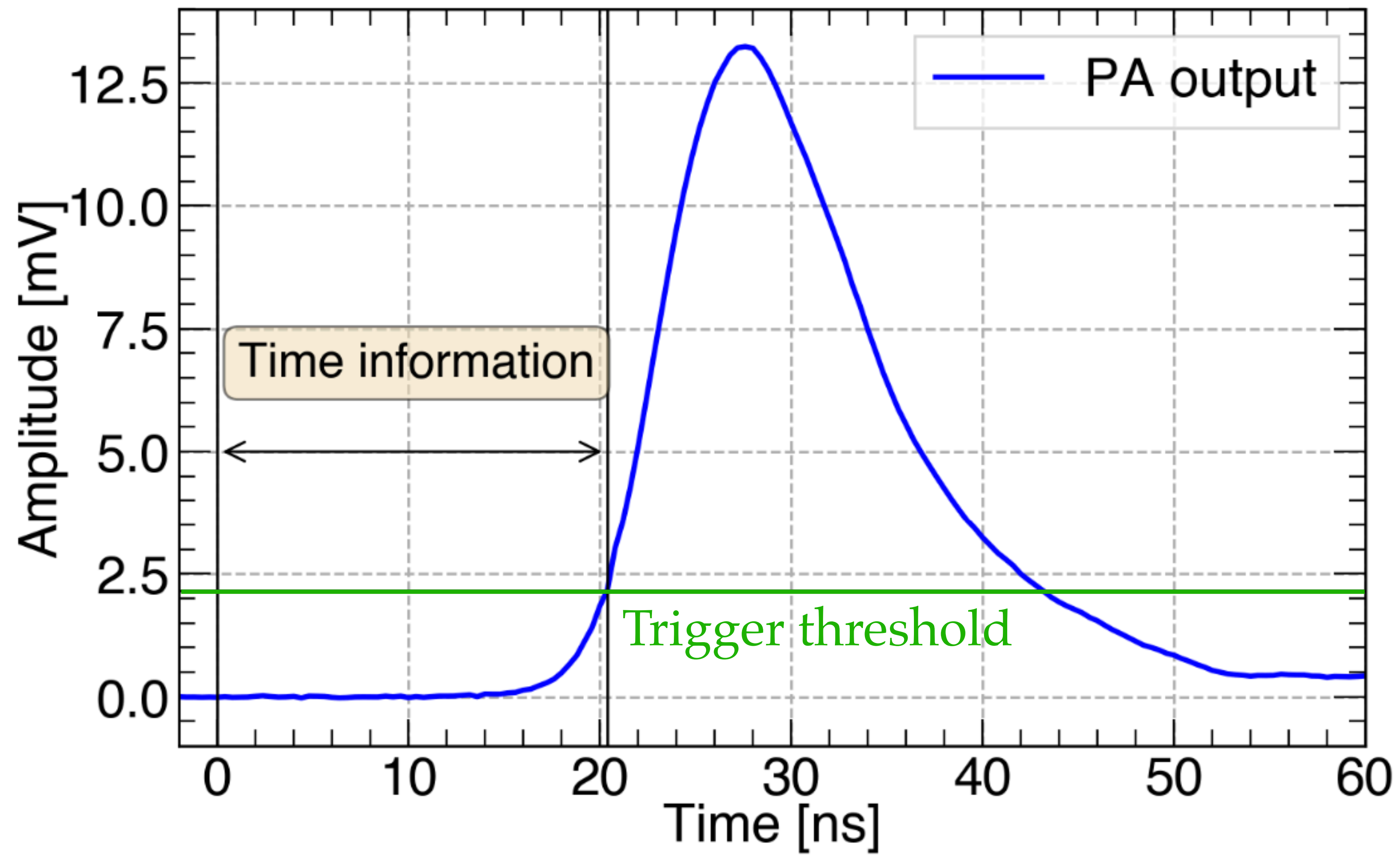


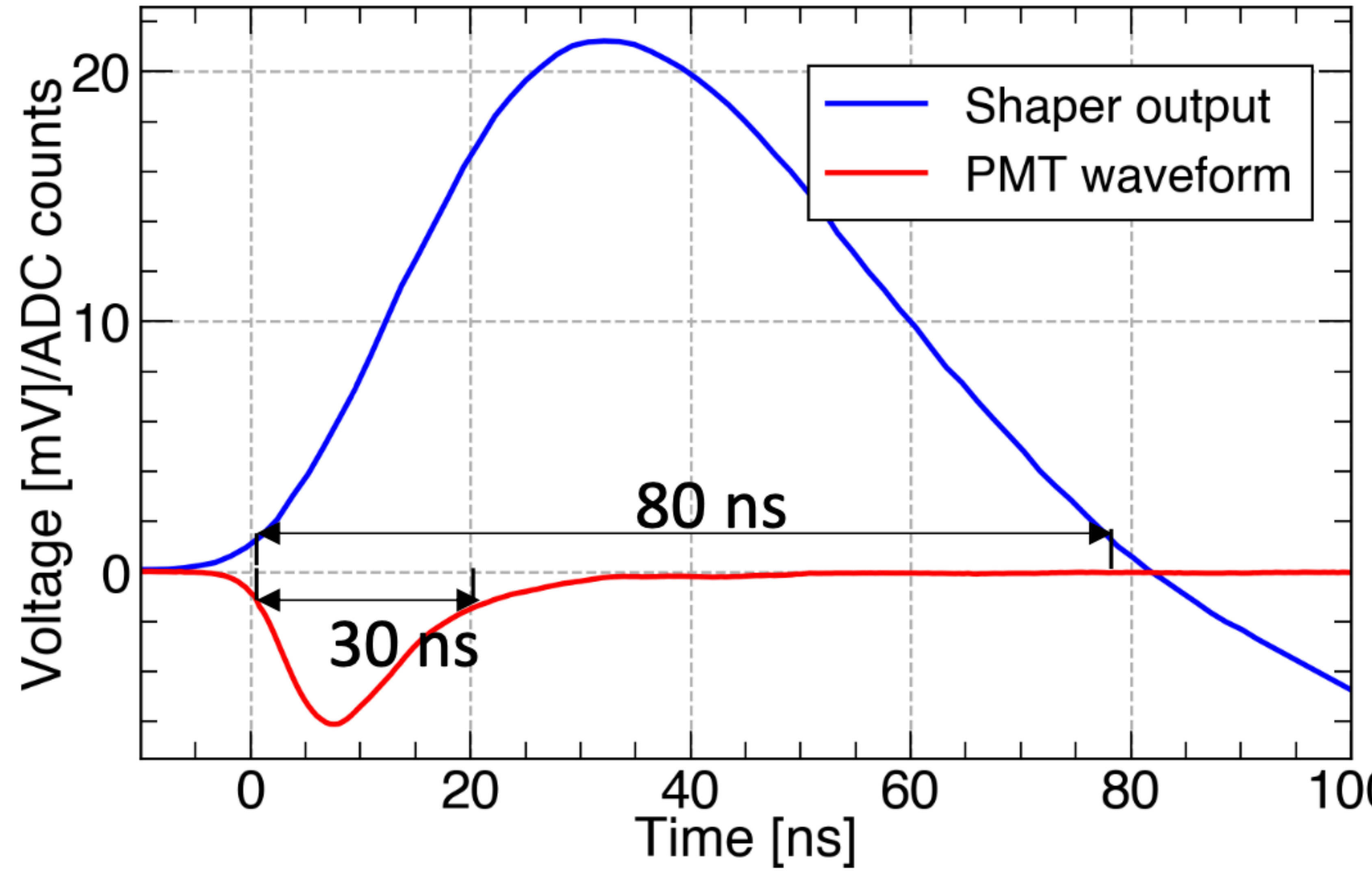


Principle… with more details

- After preamplification, signal follows two paths:
  - Fast path with discriminator connected to the TDC for **time measurement**:
    - Dead time: 30 ns
  - Slow path with shaper connected to the ADC for **charge measurement**:
    - Use the full available dynamic range (1.2 V)

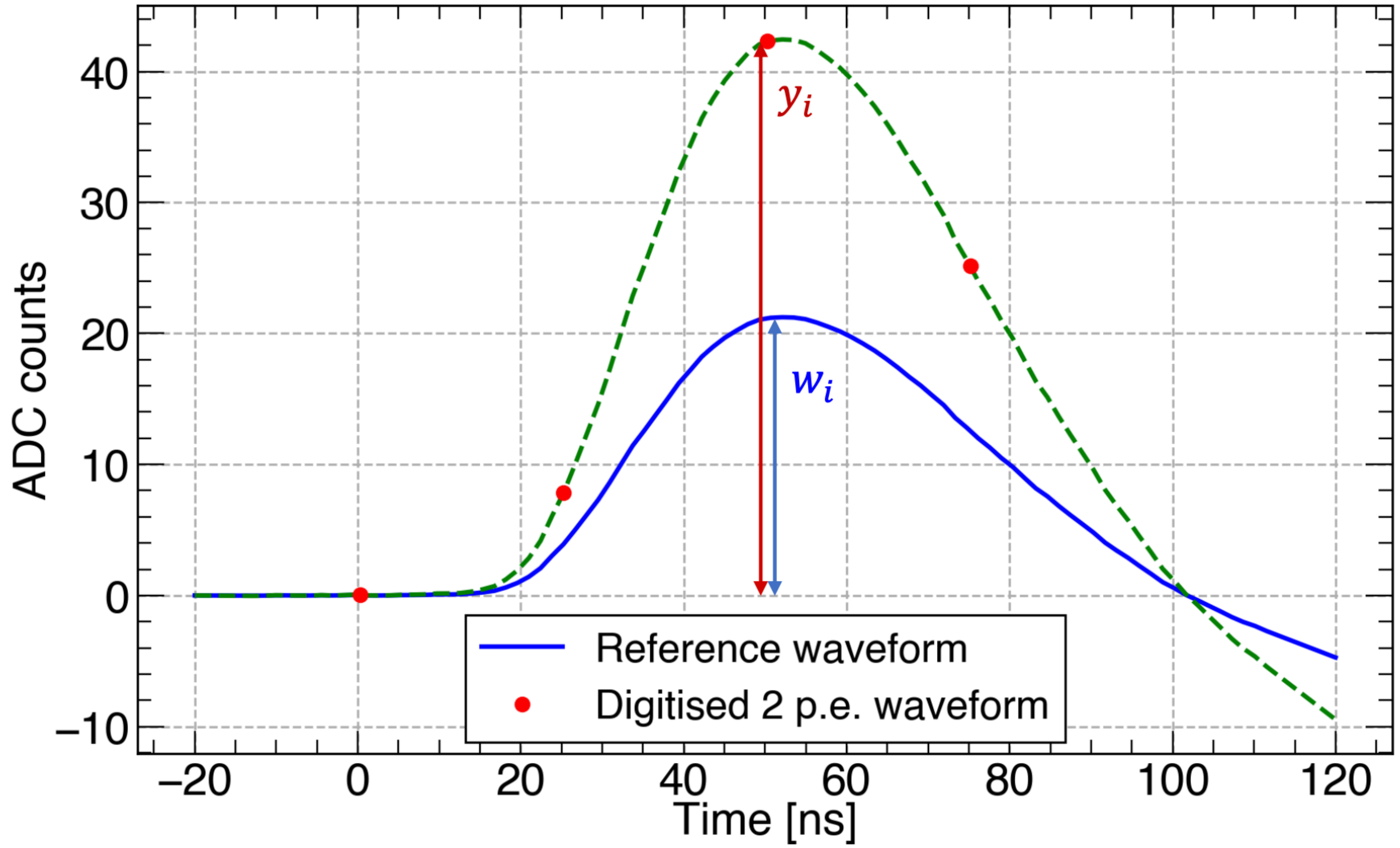




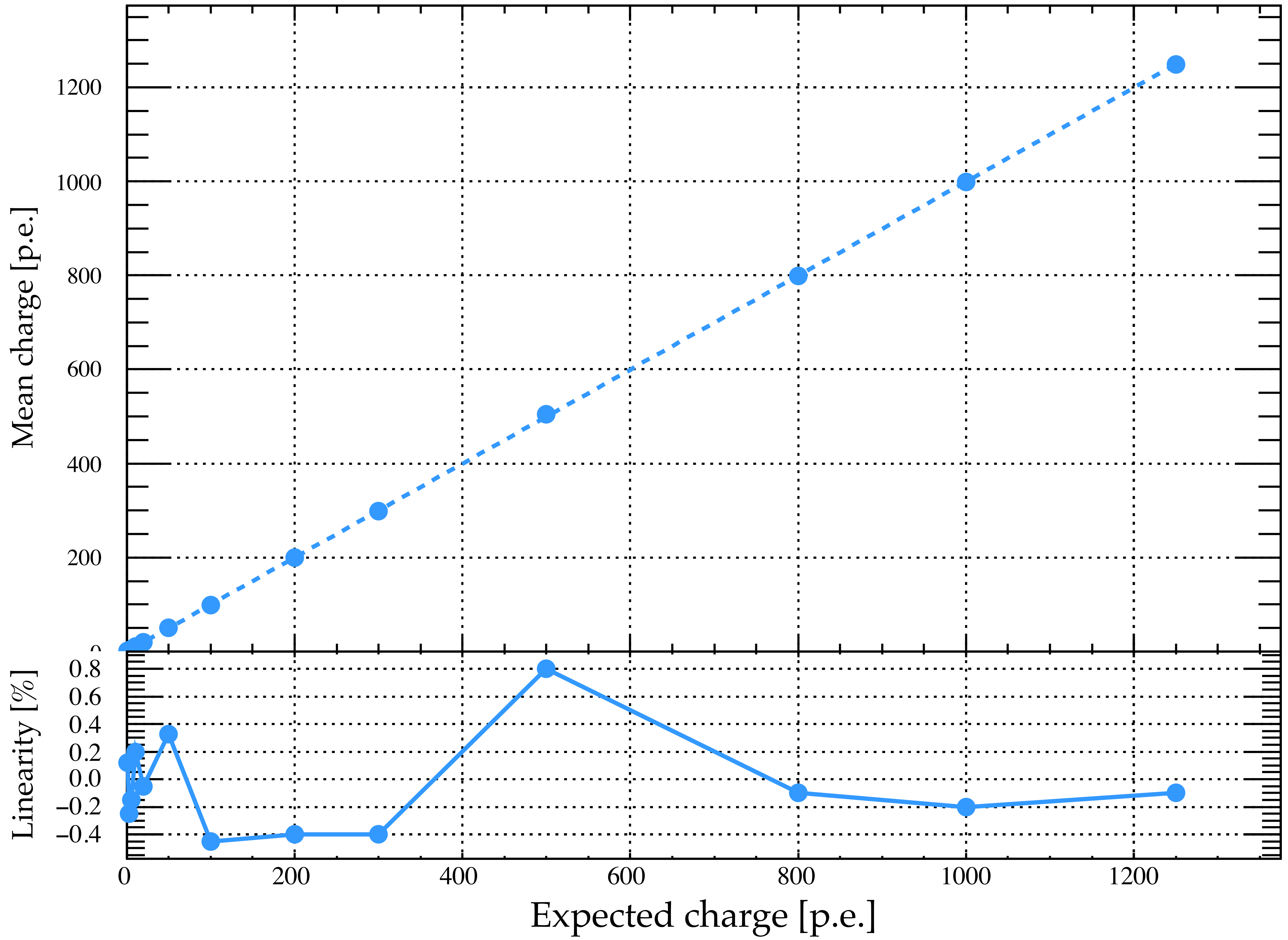


Charge reconstruction

- Build **reference waveforms:**
  - **Calibrate** each channel (gain) with one charge:
    - High gain: $q_{\text{ref.}} = 1$ p.e.
    - Medium gain: $q_{\text{ref.}} = 20$ p.e.
    - Low gain: $q_{\text{ref.}} = 200$ p.e.
- Given a waveform, find associated charge q:
  - $$\chi^2(\alpha) = \sum_{i=1}^{N} \left(\frac{y_i - \alpha\, w_i}{\sigma_i} \right)^2$$
  - $$\frac{d\chi^2}{d\alpha} = 0 \iff \alpha = \frac{\sum_{i=1}^{N} \frac{y_i w_i}{\sigma_i^2}}{\sum_{i=1}^{N} \frac{w_i^2}{\sigma_i^2}} \Rightarrow q = \alpha\, q_{\text{ref.}}$$

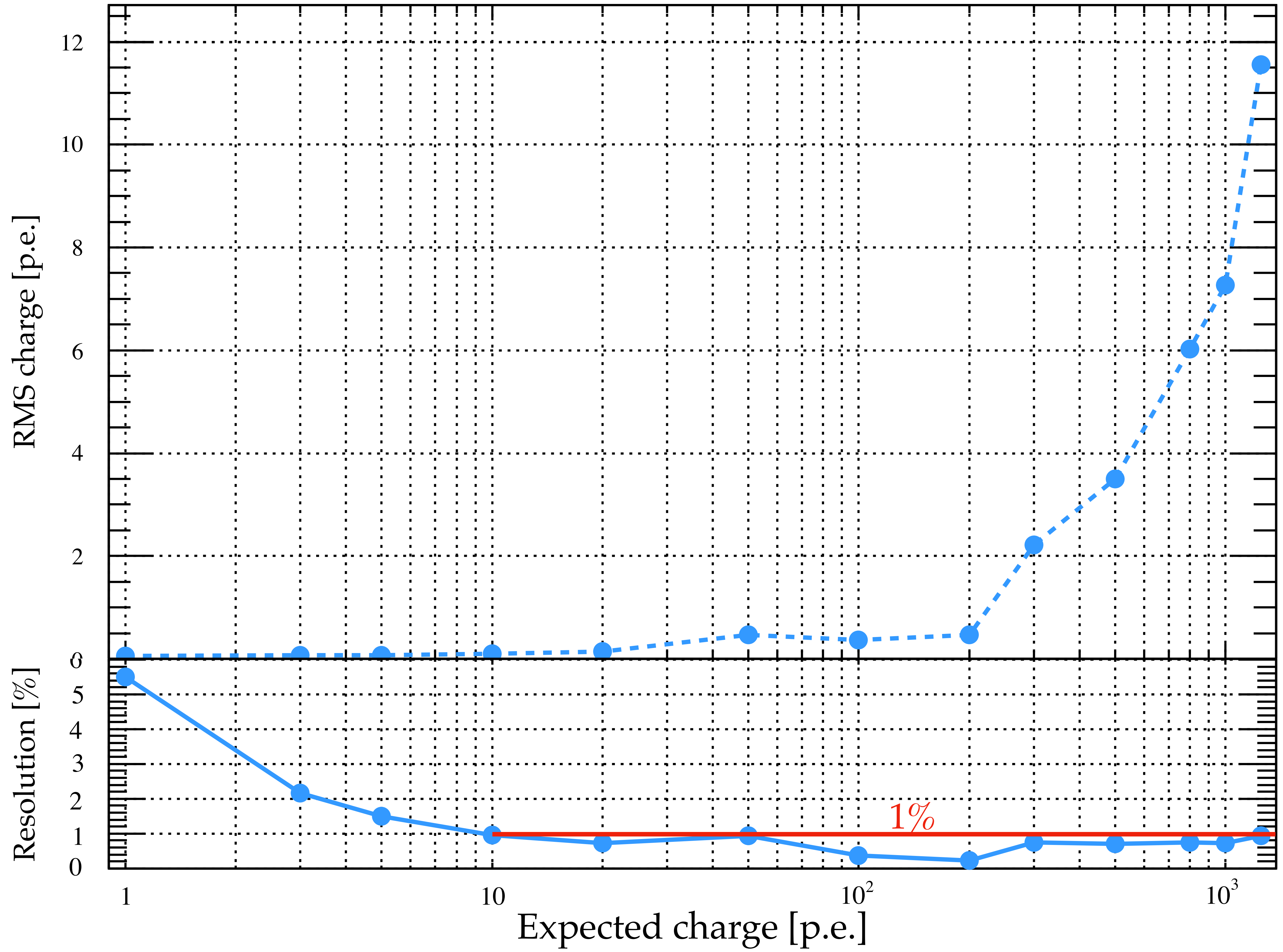


Charge linearity



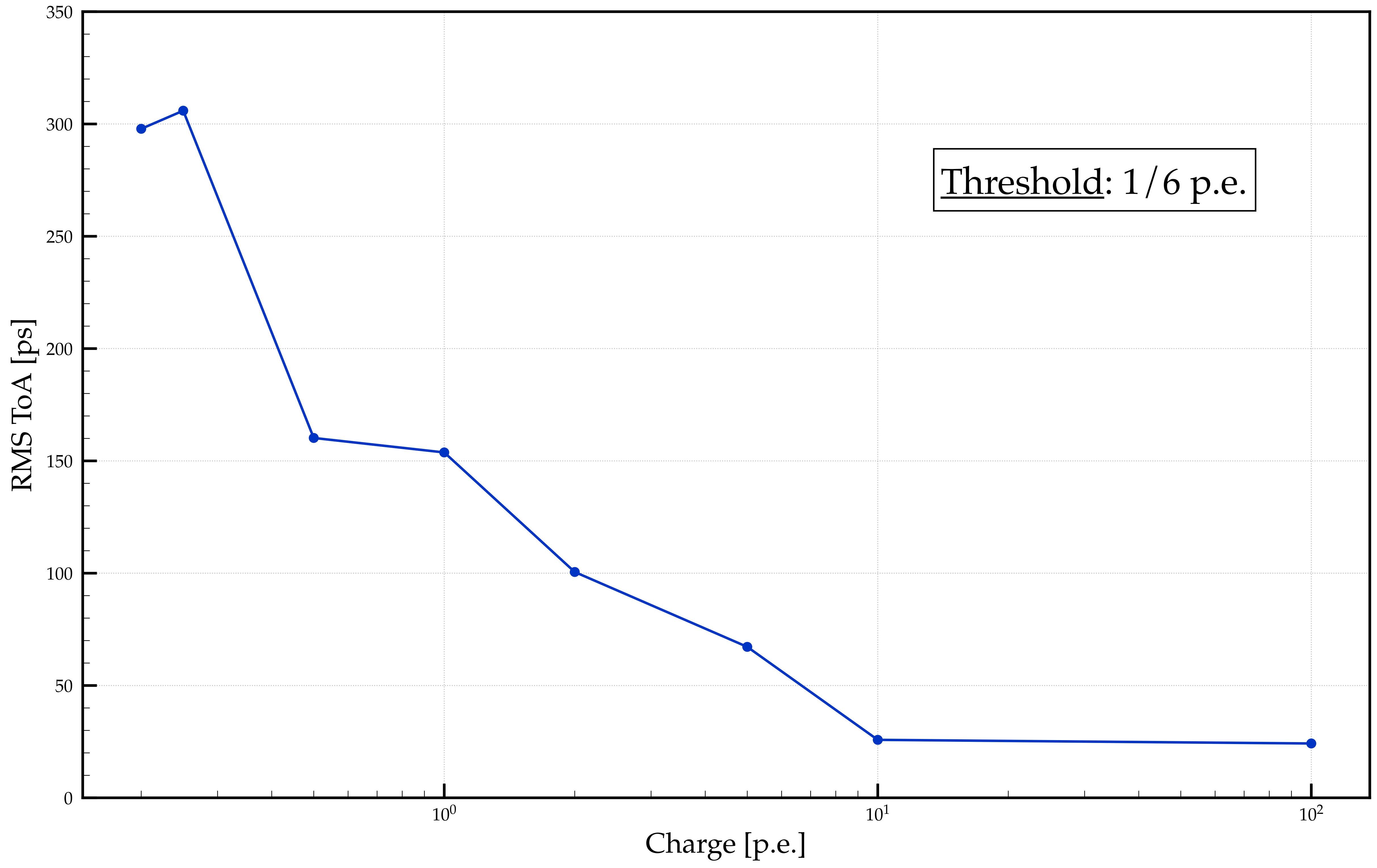
- From 1 to 1 250 p.e.: $< \pm 1\%$

Charge resolution



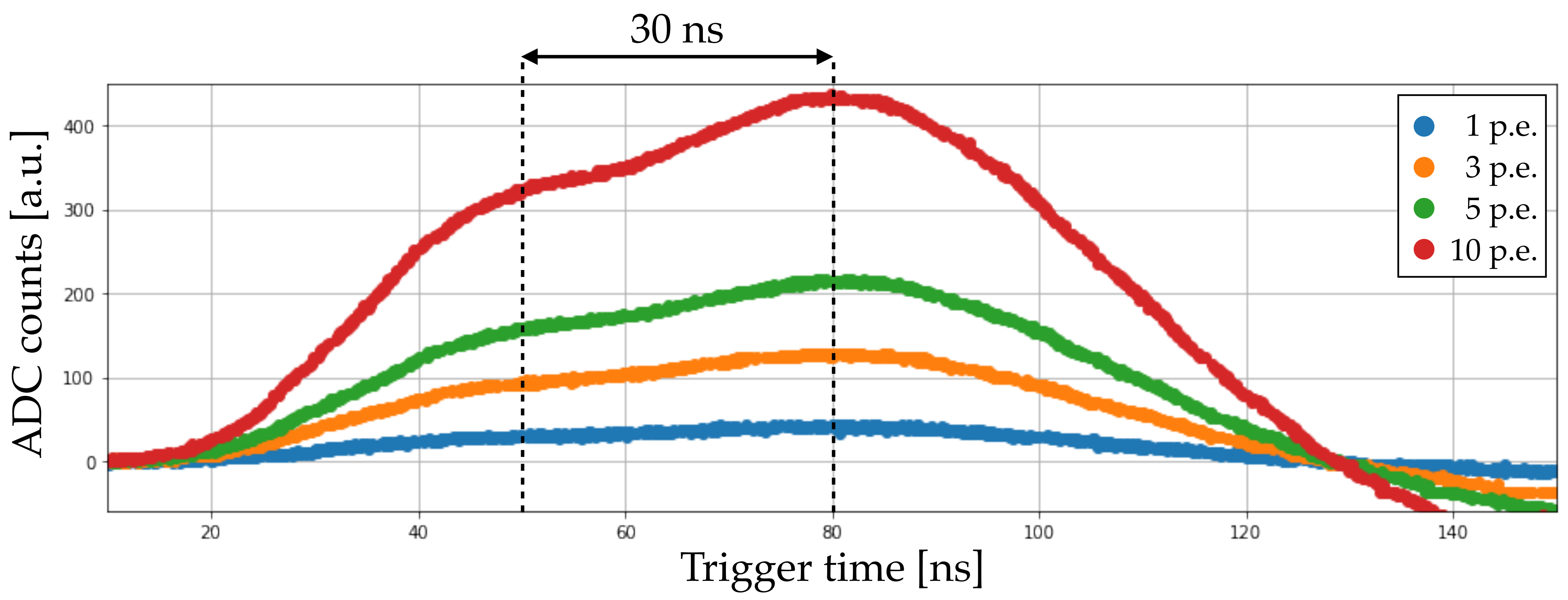
- Below 10 p.e.: < 0.1 p.e.
- Up to 1 250 p.e.: $< 1\%$

Time resolution



- At 1 p.e.: 150 ps
- Above 10 p.e.: 25 ps

Pile-up & Dead time



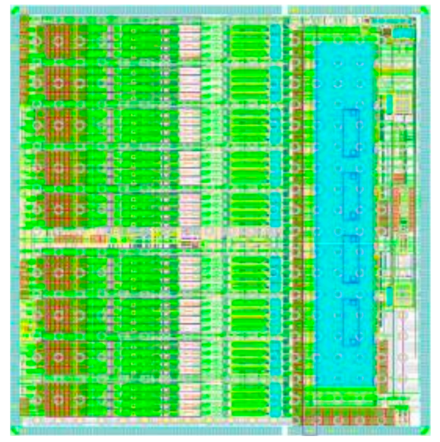
- Charge reconstruction:
  - $\alpha w_i \leftarrow \alpha w_i + \beta w_{i-dt}$
- Dead time: 30 ns

Hyper-Kamiokande PMTs & HKROC

- Hyper-Kamiokande PMTs:
  - 50 cm HQE Box & Line PMTs with twice the detection efficiency of SK PMTs
  - Better vertex and energy reconstruction

Hamamatsu R12860-HQE

- HKROC digitizer:
  - Charge linearity < ± 1% from 1 to 1 250 p.e.
  - Charge resolution < 0.1 p.e. below 10 p.e. and < 1% above
  - Time resolution of 150 ps at 1 p.e. and 25 ps above 10 p.e.
  - Dead time of 30 ns

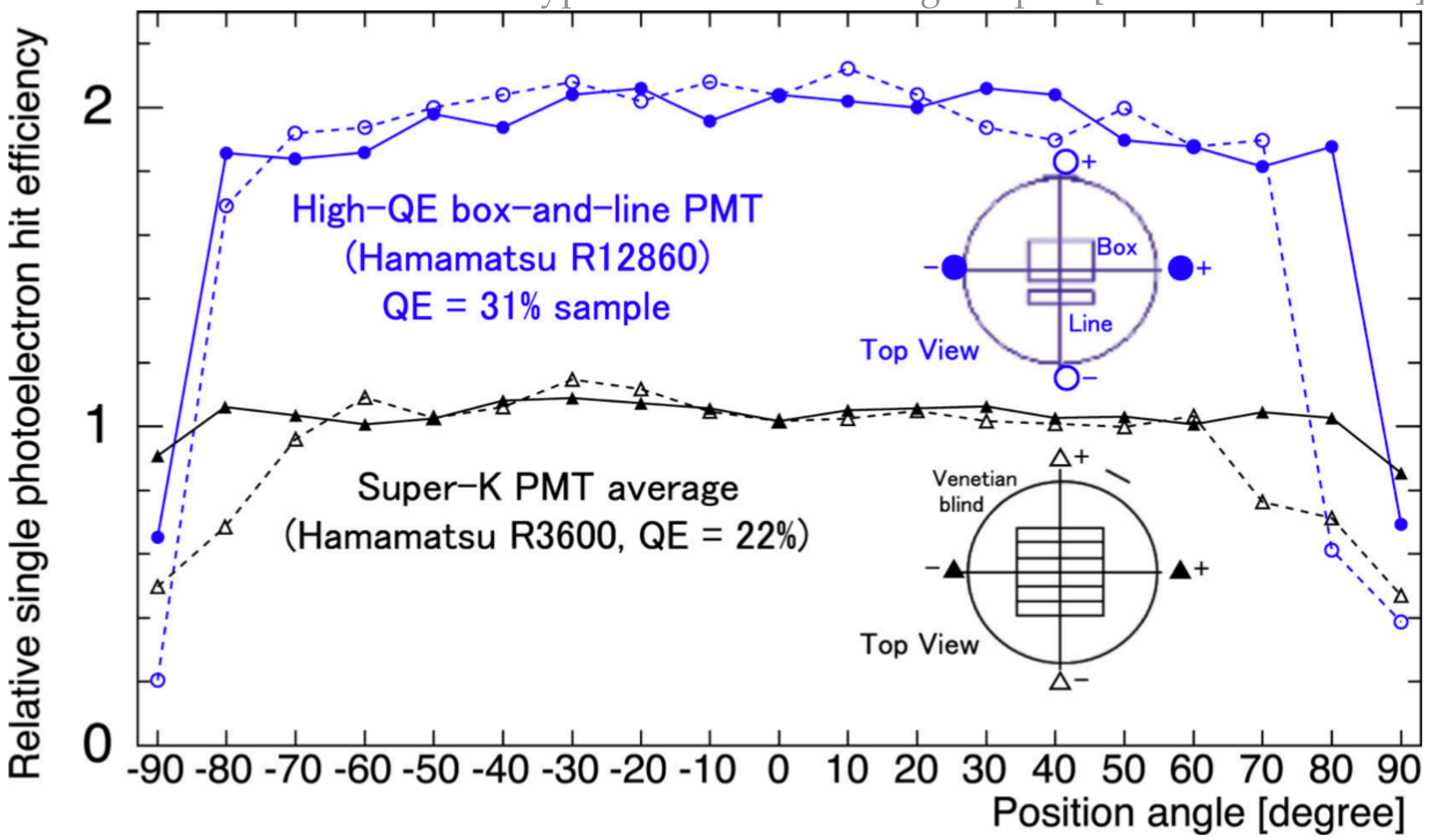


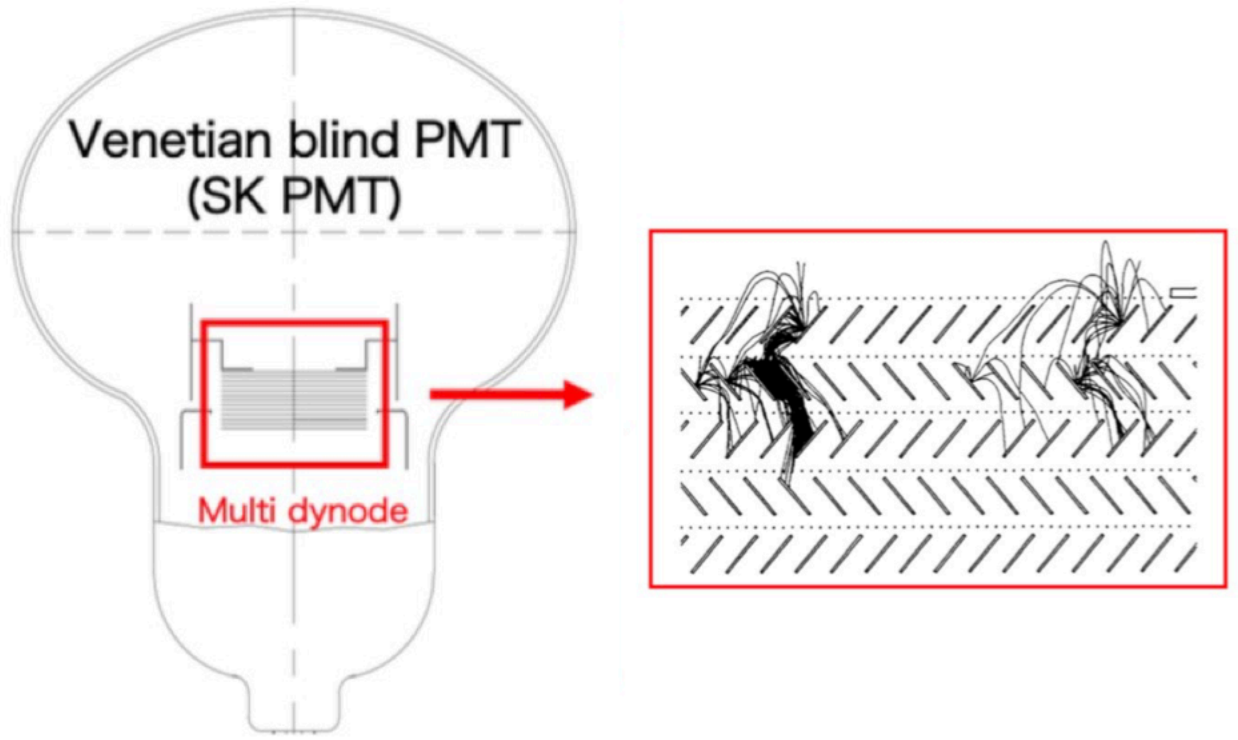
HKROC

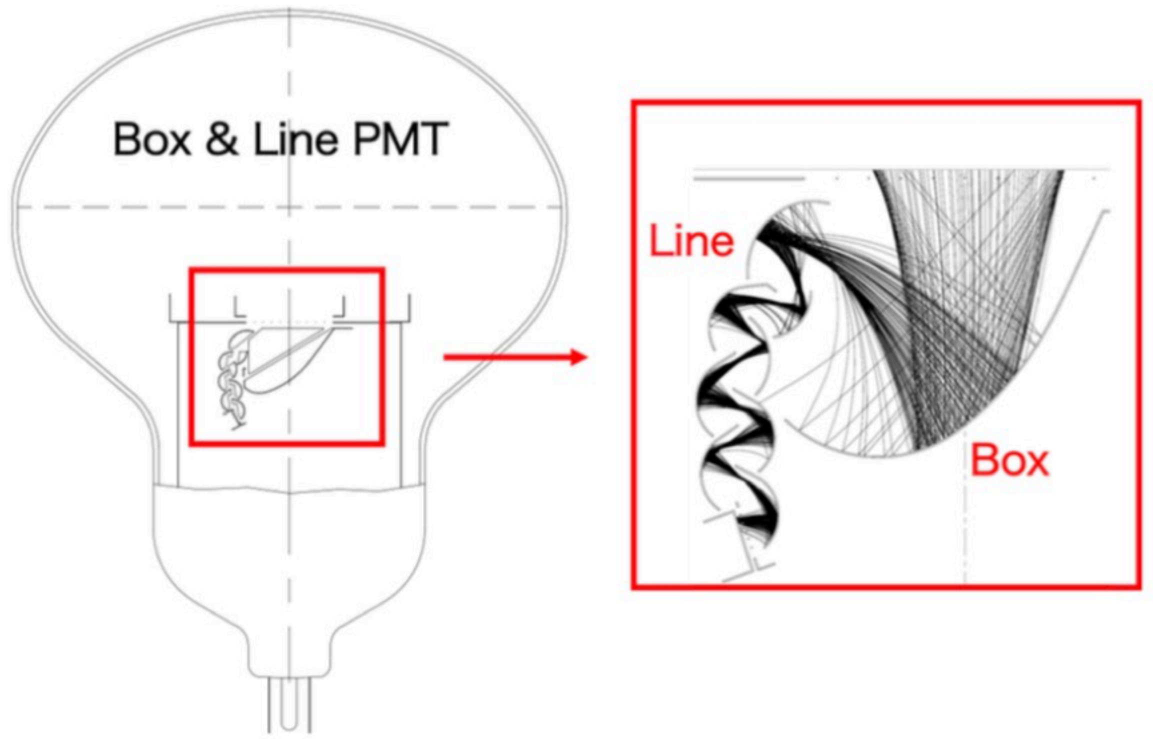
Backup

Photomultiplier tubes

Hyper-Kamiokande Design Report [*arXiv:1805.04163v2*]







$$\mathrm{QE}_\lambda = \frac{N_{\text{p.e.}}}{N_\gamma} = (1-R)\cdot\frac{P_\lambda}{k}\cdot\left(\frac{1}{1+1/(kL)}\right)\cdot P_S$$

Reflection Loss; Excitation Efficiency; Photocathode Loss; Escape Probability

- R: Reflection coefficient
- P_λ: Probability that light absorption excites electrons above the vacuum level
- k: Total photon absorption coefficient
- L: Mean escape length of excited electrons
- P_S: Probability that electrons reaching the photocathode surface will be released into vacuum

Photomultiplier tubes

Time resolution
(TTS for 1 p.e.)
≈ 6.7 ns ($\sigma \approx 3.4$ ns) $\rightarrow \approx 2.6$ ns ($\sigma \approx 1.3$ ns)

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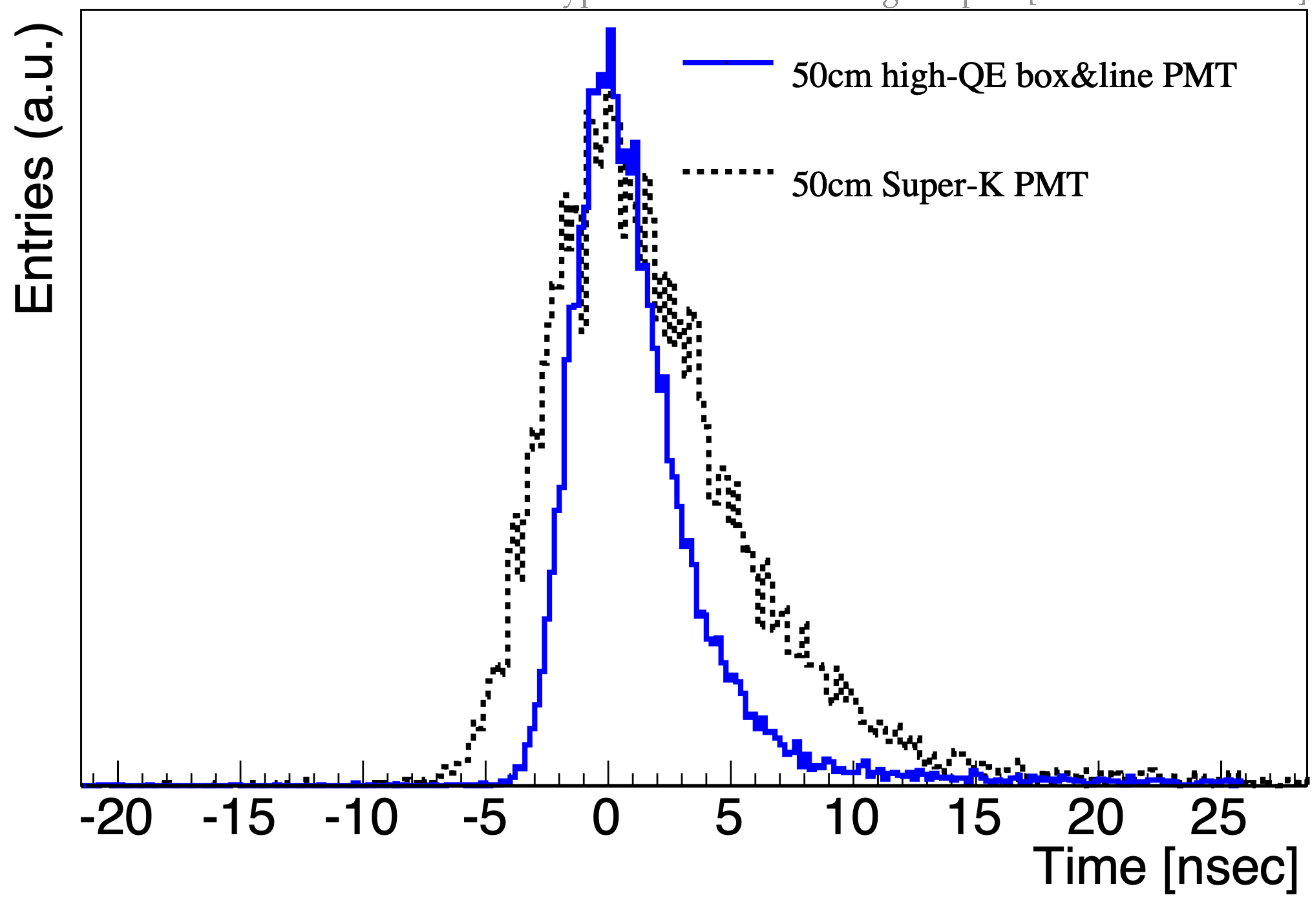

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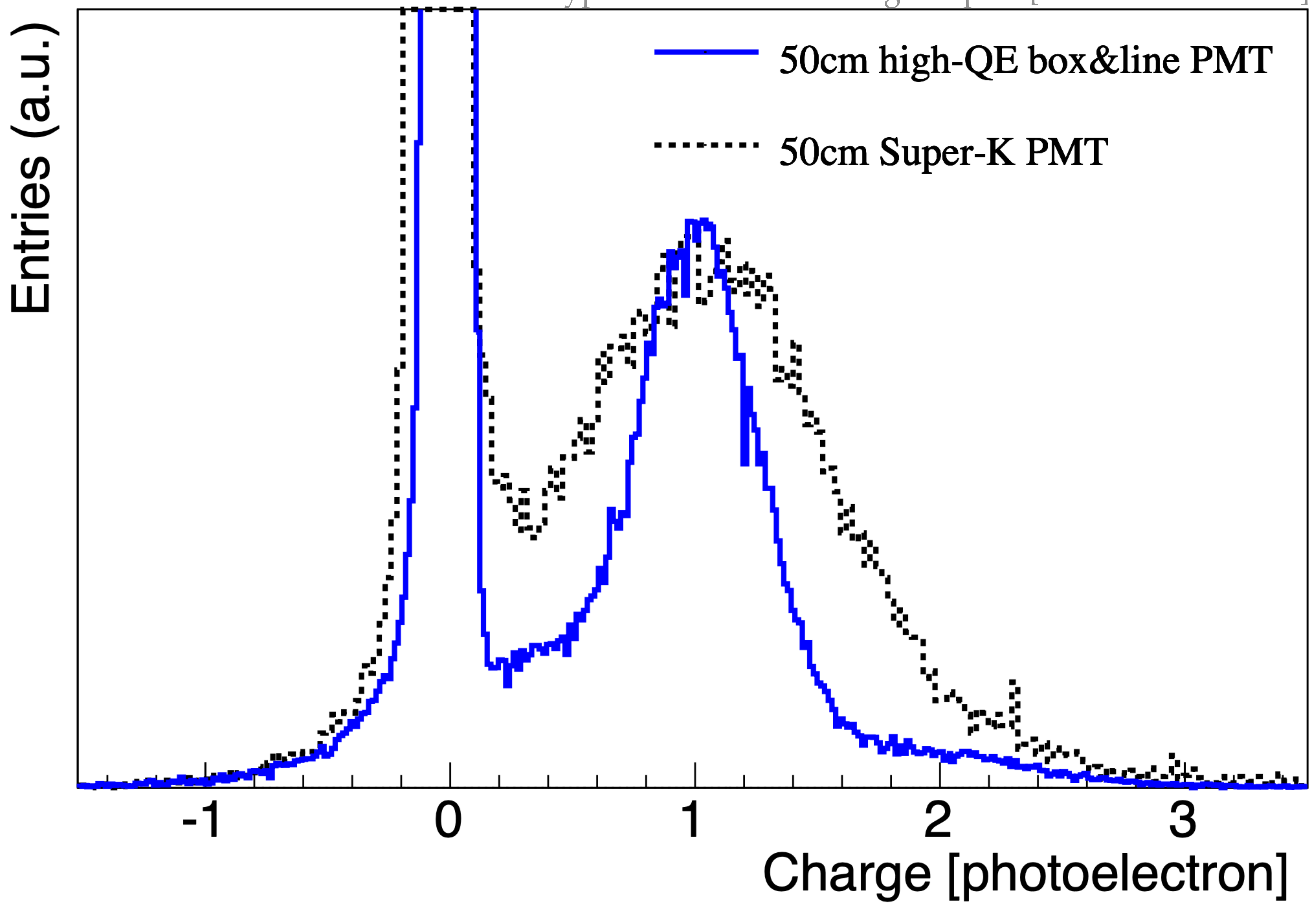

Photomultiplier tubes

- Other improvements:
  - Glass purity: Reduced of residual impurities (source of scintillation) and improved transparency
  - Reduce radon content of cables: 1.4 mBq/m $\rightarrow < 0.1$ mBq/m

Radio isotopes in glass [Bq/kg]	Super-K	Hyper-K
U	5.5	2.5
Th	1.8	0.7
^{40}K	18.2	1.0

Hamamatsu R12860-HQE