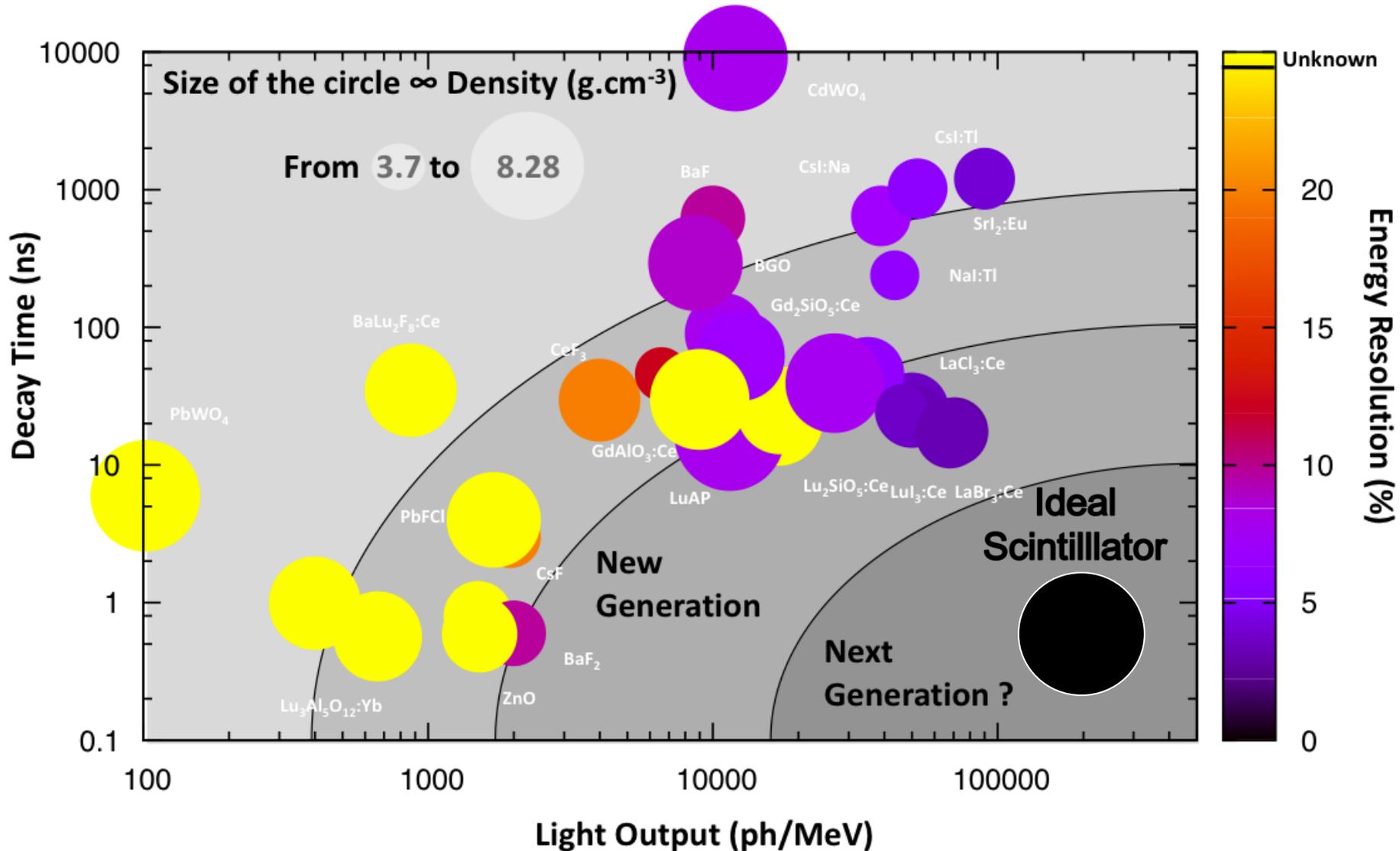# Towards the development of multichannel scintillator detector system

- **Introduction to the interaction of photon**

- **What is the ultimate time resolution**

- **Characteristics of SiPM**

- **Studies with**

  - **Inorganic scintillator with SiPM**

  - **Organic scintillator with SiPM/PMT**

  - **Quantum dots**

- **Conclusion**

Scintillator materials for the Measurement of Energy

- What scintillator material to be used ?
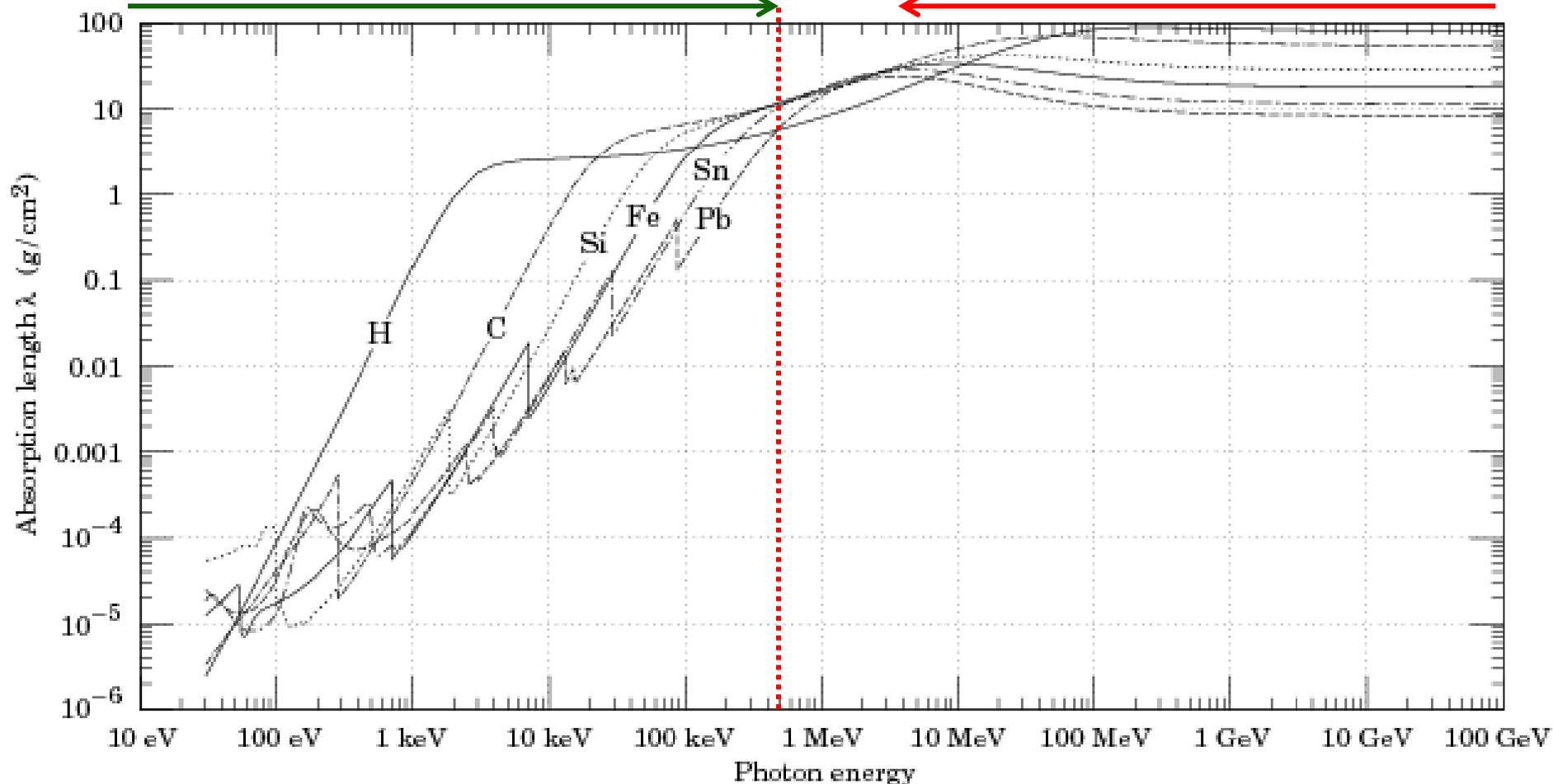 - Organic or Inorganic or quantum dots?

Absorption length of photon in different materials

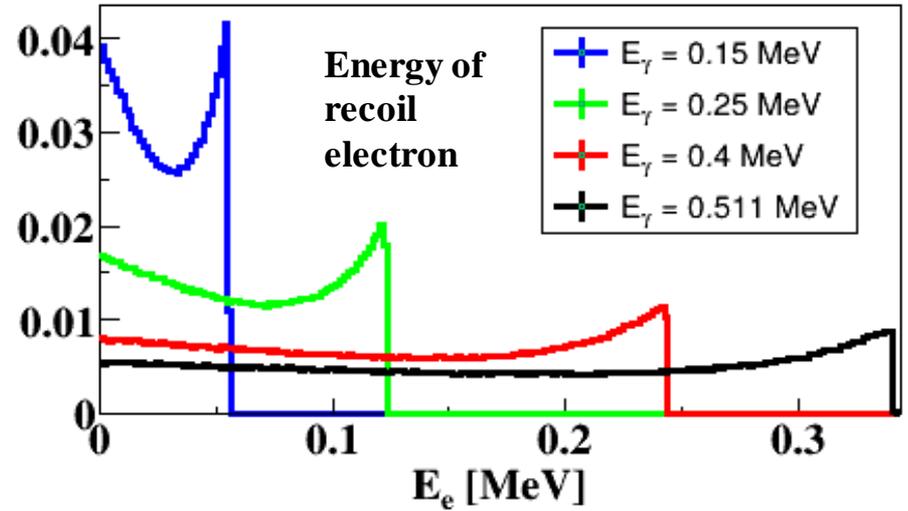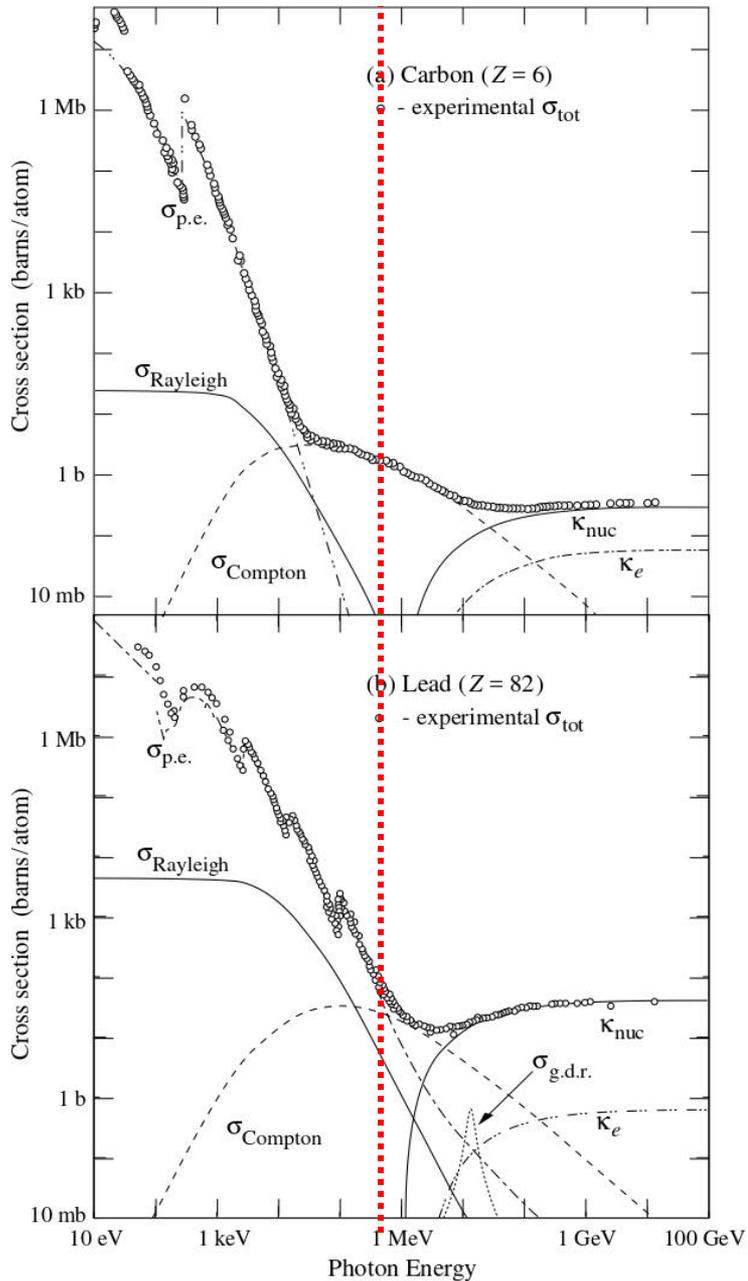**Mass absorption coefficient, $\lambda = 1/(\mu/\rho)$ [gm-cm^{-2}] with $\mu = N_A \cdot \sigma/A$**

$$\sigma_{ph} \propto \frac{Z^5}{E^{3.5}}$$
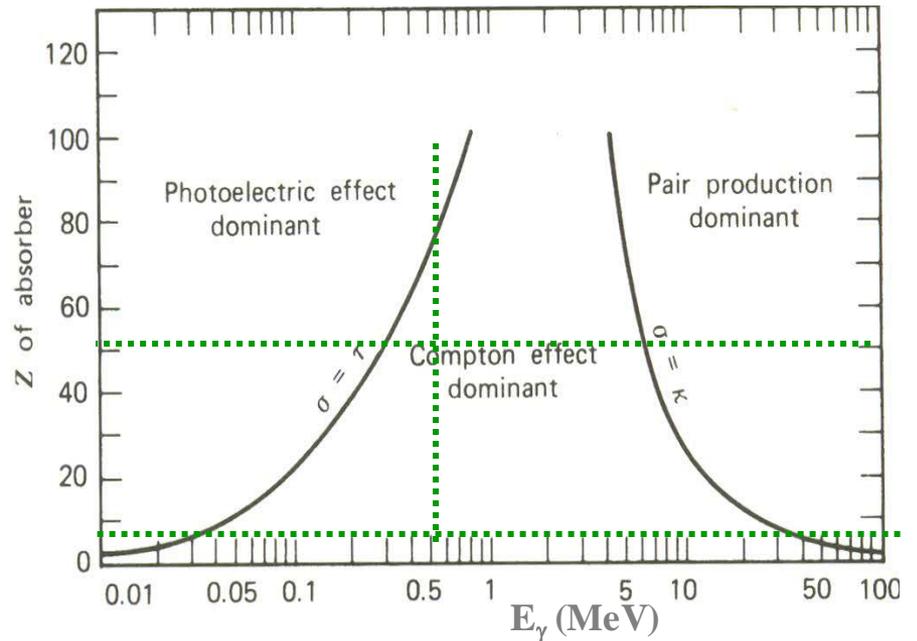
$$\sigma_{compton} \propto \frac{lnE}{E} \cdot Z$$

$$\sigma_{pair} \propto Z^2 lnE$$

Photoelectric vs Compton

(a) Carbon (Z = 6)
  - experimental σ_tot

σ_p.e.

σ_Rayleigh

σ_Compton

κ_nuc

κ_e

(b) Lead (Z = 82)
  - experimental σ_tot

σ_p.e.

σ_Rayleigh

σ_Compton

σ_g.d.r.

κ_nuc

κ̄_e

Cross section (barns/atom)

Photon Energy

Energy of recoil electron

$E_\gamma = 0.15$ MeV
$E_\gamma = 0.25$ MeV
$E_\gamma = 0.4$ MeV
$E_\gamma = 0.511$ MeV

E_e [MeV]

Plastic scintillator : Dominant effect is Compton scattering, no direct measurement of energy

Z of absorber

Photoelectric effect dominant

Pair production dominant

Compton effect dominant

$\sigma = \tau$
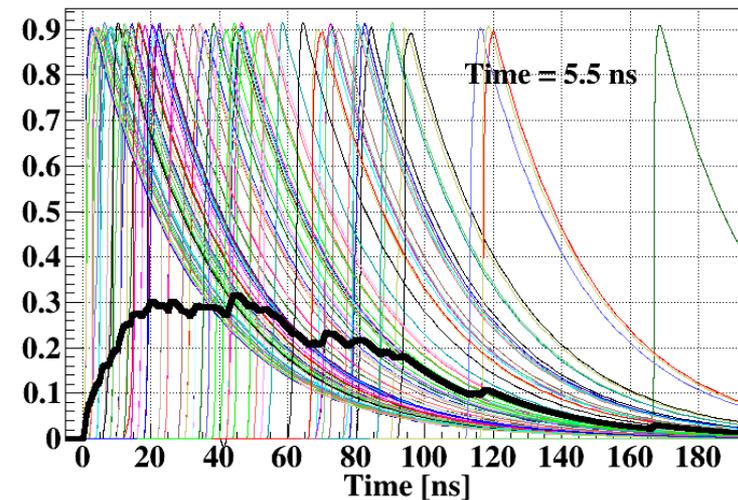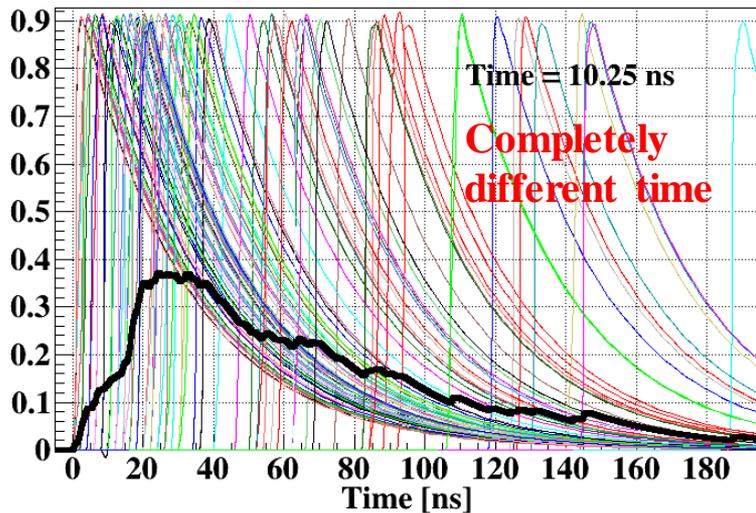
$\sigma = \kappa$

E_γ (MeV)

Shape of scintillator signal and time resolution

- **Neither linearity, not the shape is maintained**
- **Depends on scintillator/WLS decay constant**
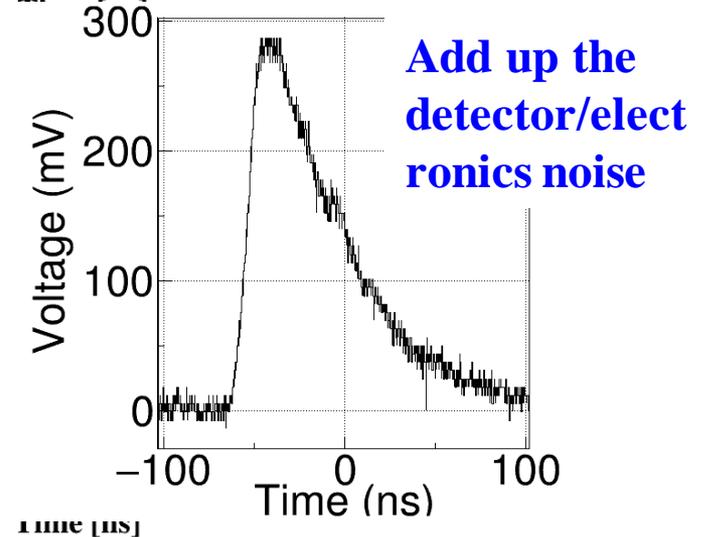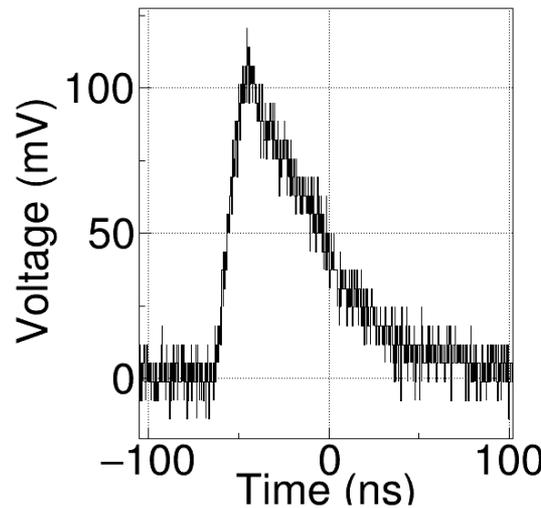- **Poor performance of timing, though no effect on Q**

$$[exp(-t/\tau_F) - exp(-t/\tau_R)]$$
$$\tau_F = 30ns, \tau_R = 0.6ns$$

Time = 8.35 ns
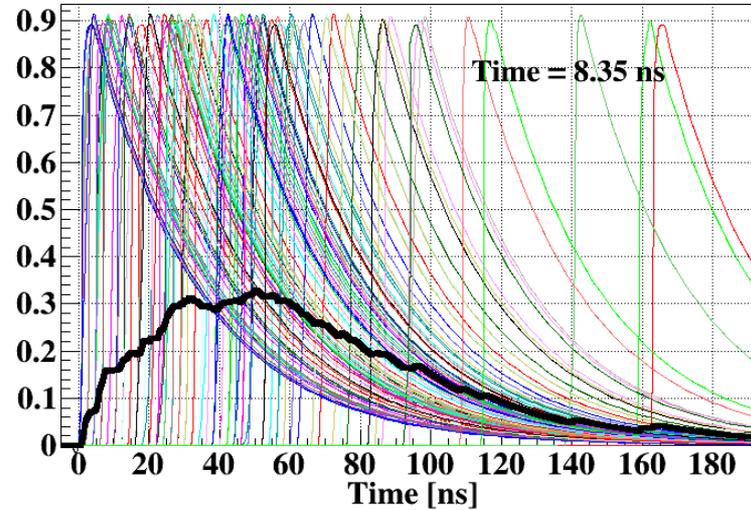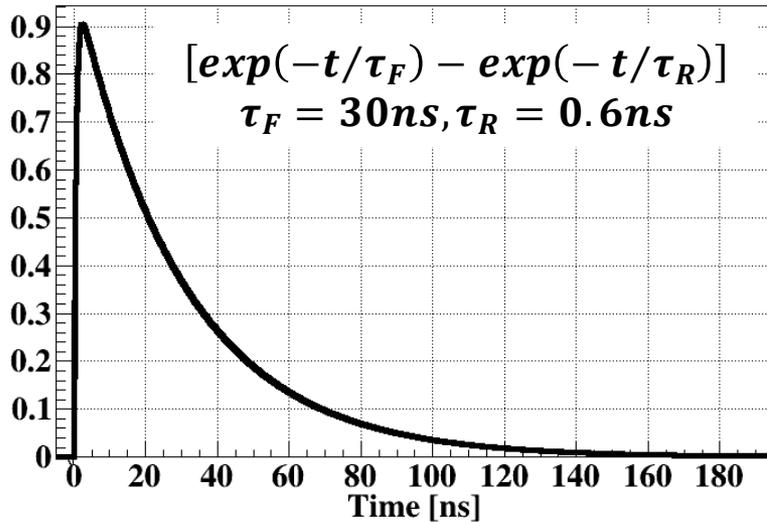
$N_{ava} = 100$
Scintillator decay time,
$\tau_{sc} = 40ns$

Time = 10.25 ns

Completely different time

Time = 5.5 ns

Shape of scintillator signal and time resolution in experiment

- **Neither linearity, not the shape is maintained**
- **Depends on scintillator/WLS decay constant**
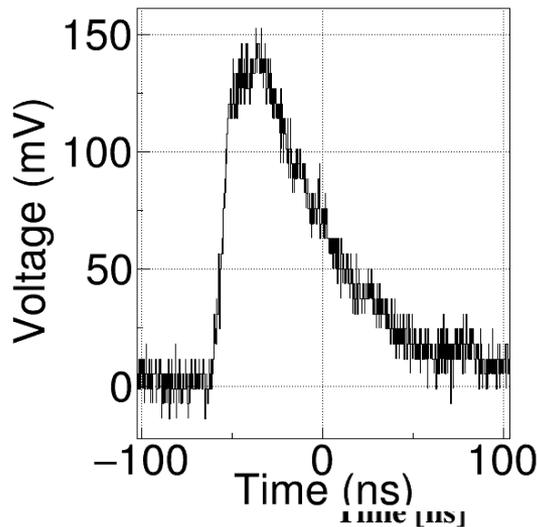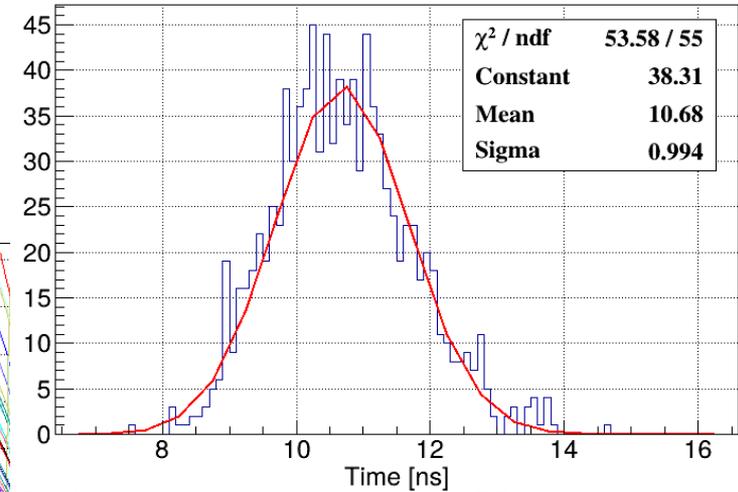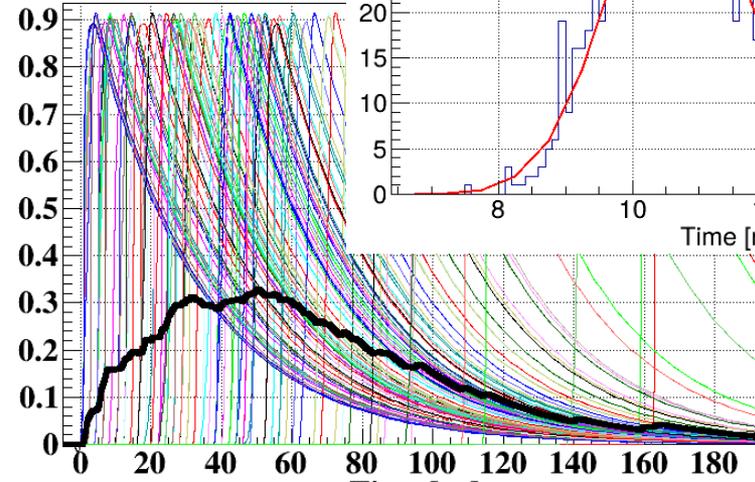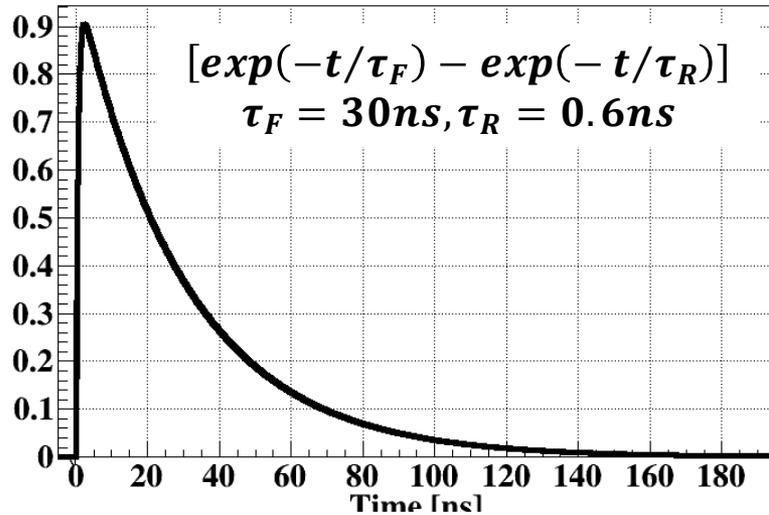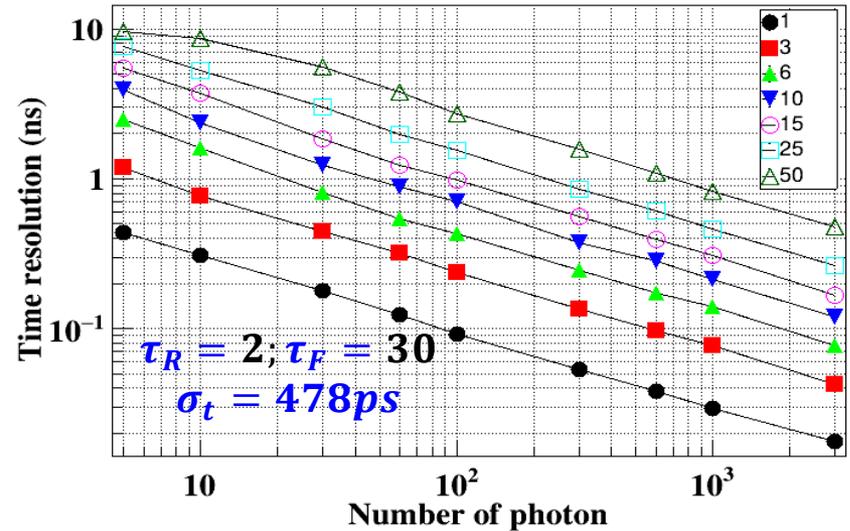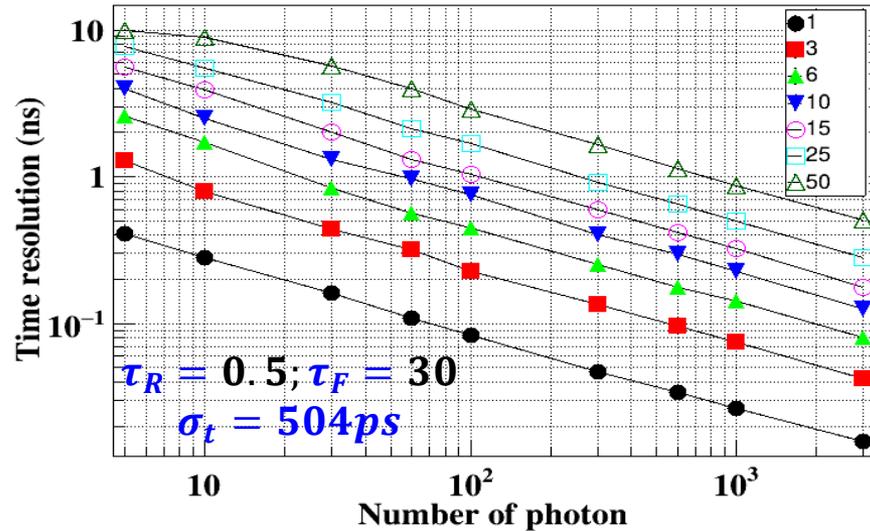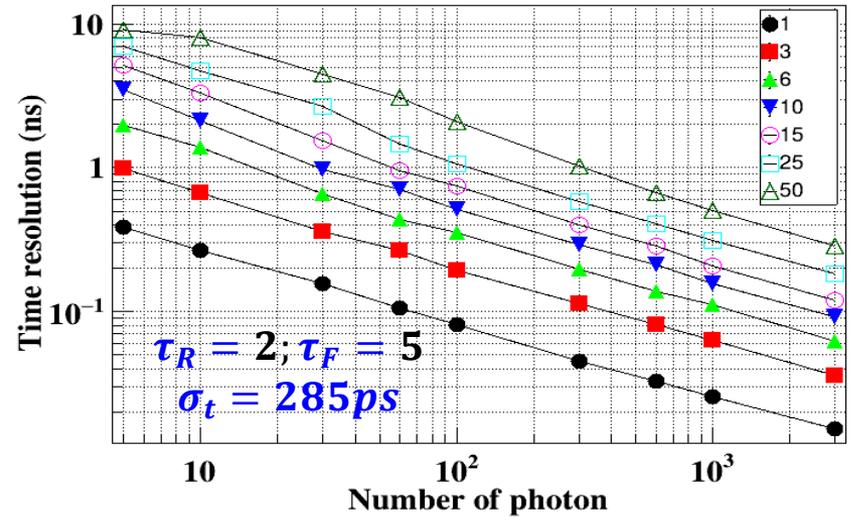- **Poor performance of timing, though no effect on Q**

$$[exp(-t/\tau_F) - exp(-t/\tau_R)]$$
$$\tau_F = 30ns, \tau_R = 0.6ns$$

χ^2 / ndf	53.58 / 55
Constant	38.31
Mean	10.68
Sigma	0.994

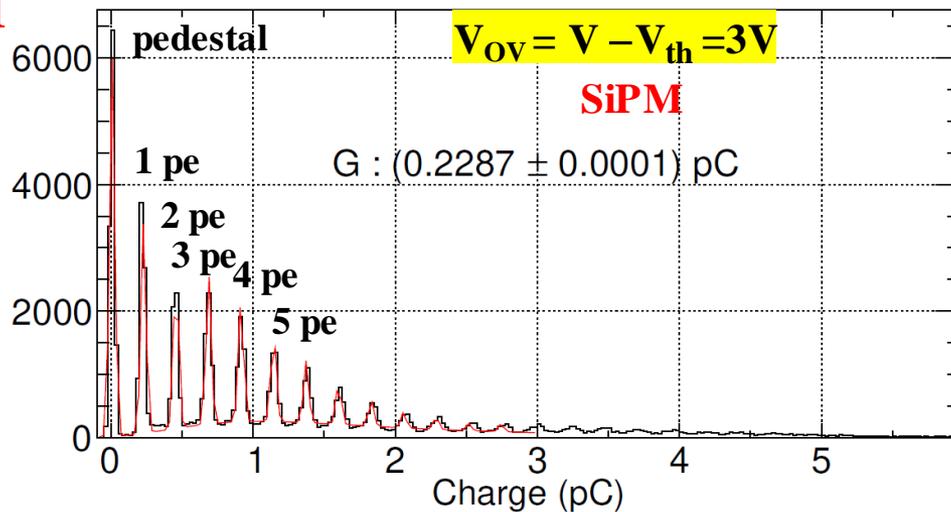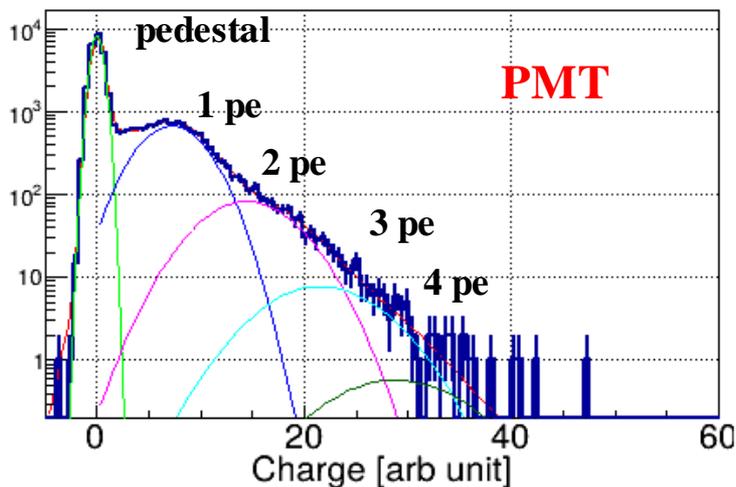**Add up the detector/elect ronics noise**

Limits on time resolution
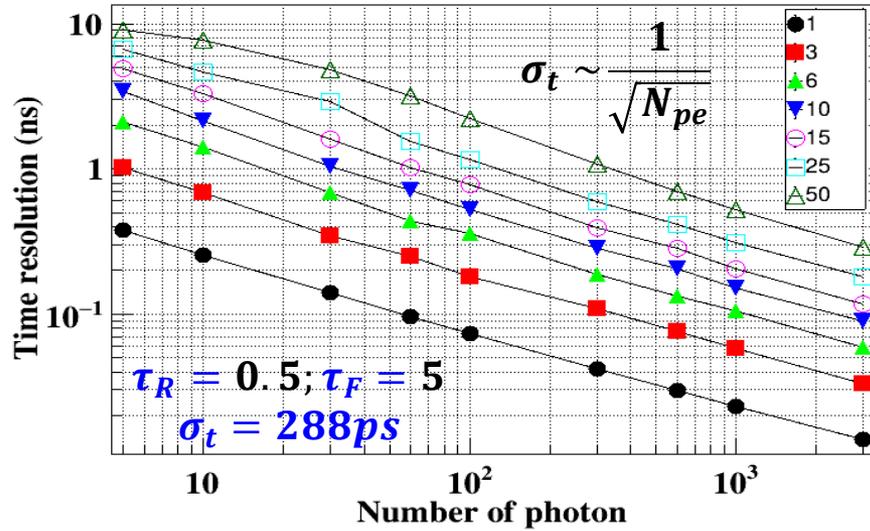
- **Backend electronics can not improve these factors**
- **What photo-transducer is suitable for us ? PMT vs SiPM**

Energy resolution of scintillator detector using

- **Photomultipliers (PMT) and SiPM**

$$f(x) = \sum_{n=0}^{\infty} \frac{(N_{pe})^n e^{-N_{pe}}}{n! \sqrt{2n\pi}\,\sigma} \, e^{-\frac{(x - nQ_1)^2}{2n\sigma^2}}$$

* Diff level of σ for pedestal

- **This simple Poisson statistics is not valid in SiPM signal due to large cross talk and Geiger signal in pixel**
- **Also impossible to combine a few independent Gaussians due to afterpulse effect.**

- **Resolution of single p.e. is much better in SiPM than PMT**
- **But no experiment in nuclear/particle physics uses SiPM for precise energy measurement.**

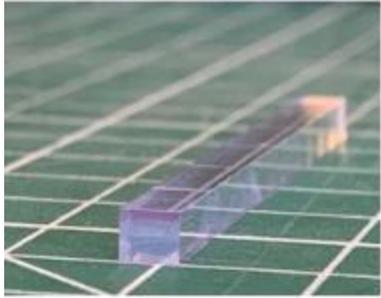# Yet to use SiPM for a precise energy measurement
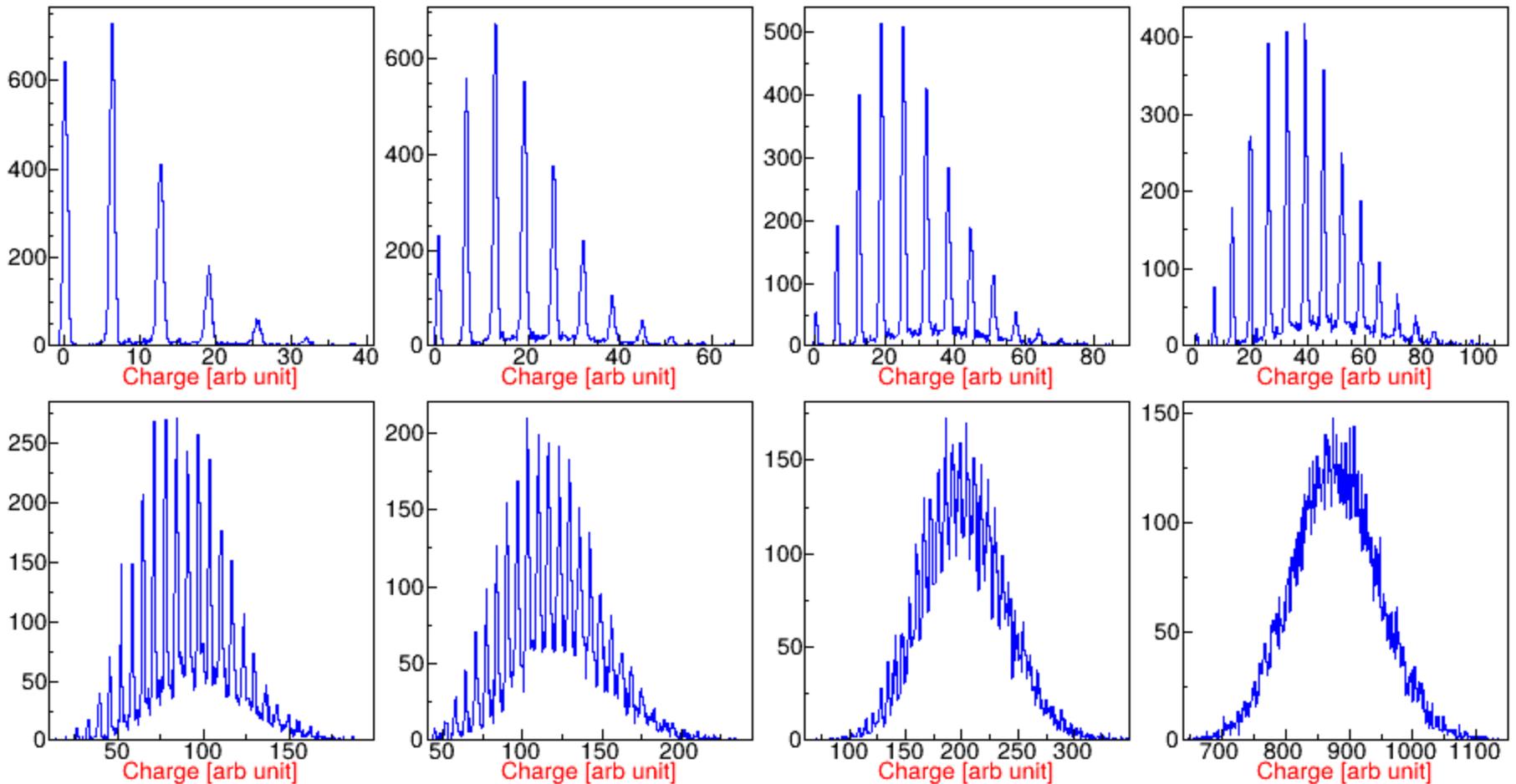
- **Fluctuation on the number of observed photons dominates the energy resolution in the region of MeV energy in the scintillator.**

- **Dark noise in SiPM is much larger, and more importantly large correlated noise in SiPM**

Inorganic Scintillator

LYSO crystal - $[Lu_{(1-x)}Y_x]2\ SiO_5 : Ce$

ρ = **7.1g/cc;**   **LY = 33,000γ/MeV;**   **Z=71,39,58;** τ **(fast) ~36ns**

LYSO Crystal
(3mm×3mm×56 mm)

SiPM
Mounting
PCB
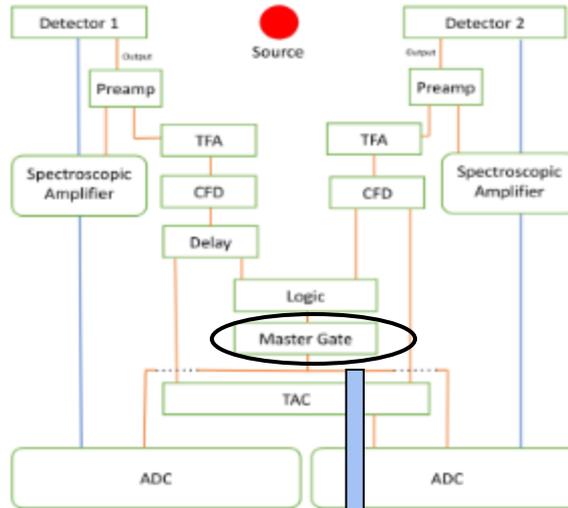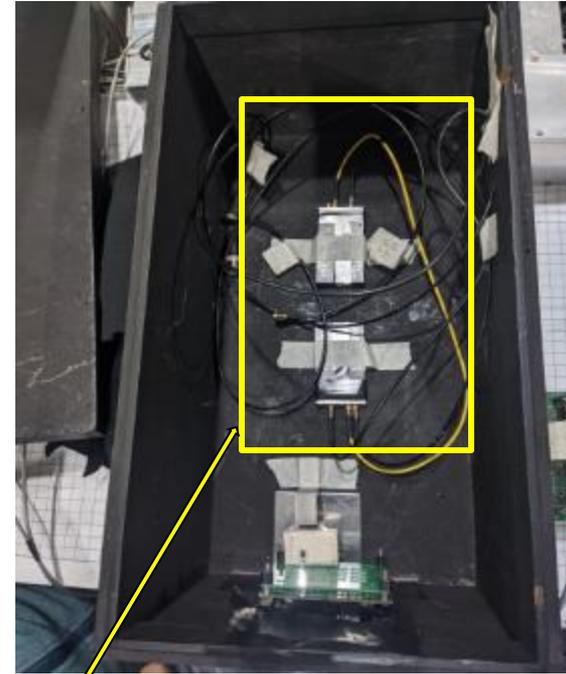
Transimpedance
Amplifier (TIA)

Diagram courtesy: Mr. Sho___ik Pal

The master gate ensures the events are recorded only when two detectors got signals within a certain time window.


LYSO + SiPM coupled (air coupling); V_{OV} = 2.0V

# Estimation of timing using Analogue Electronics

γ-rays of known energies are used to calibrate the detectors.

Putting a gate on energy using AND condition. (The master gate ensures the events are recorded only when two detectors got signal within a certain time window. This is later used for gating.)

LYSO + SiPM coupled (air coupling)
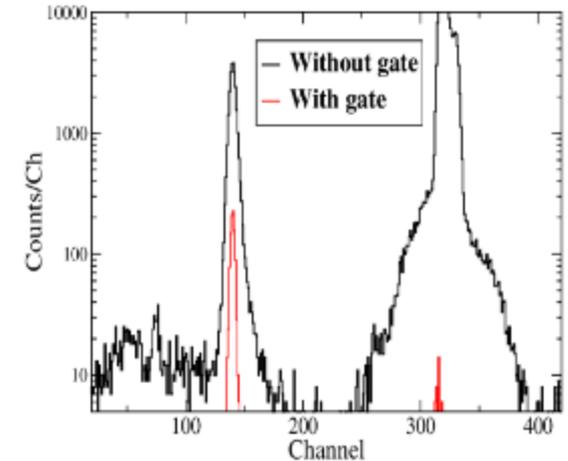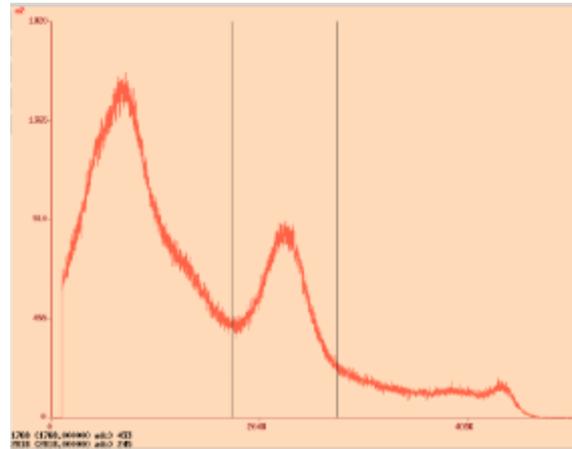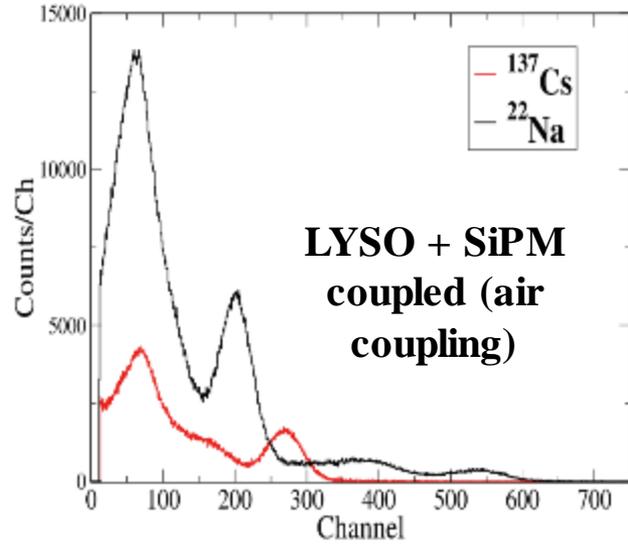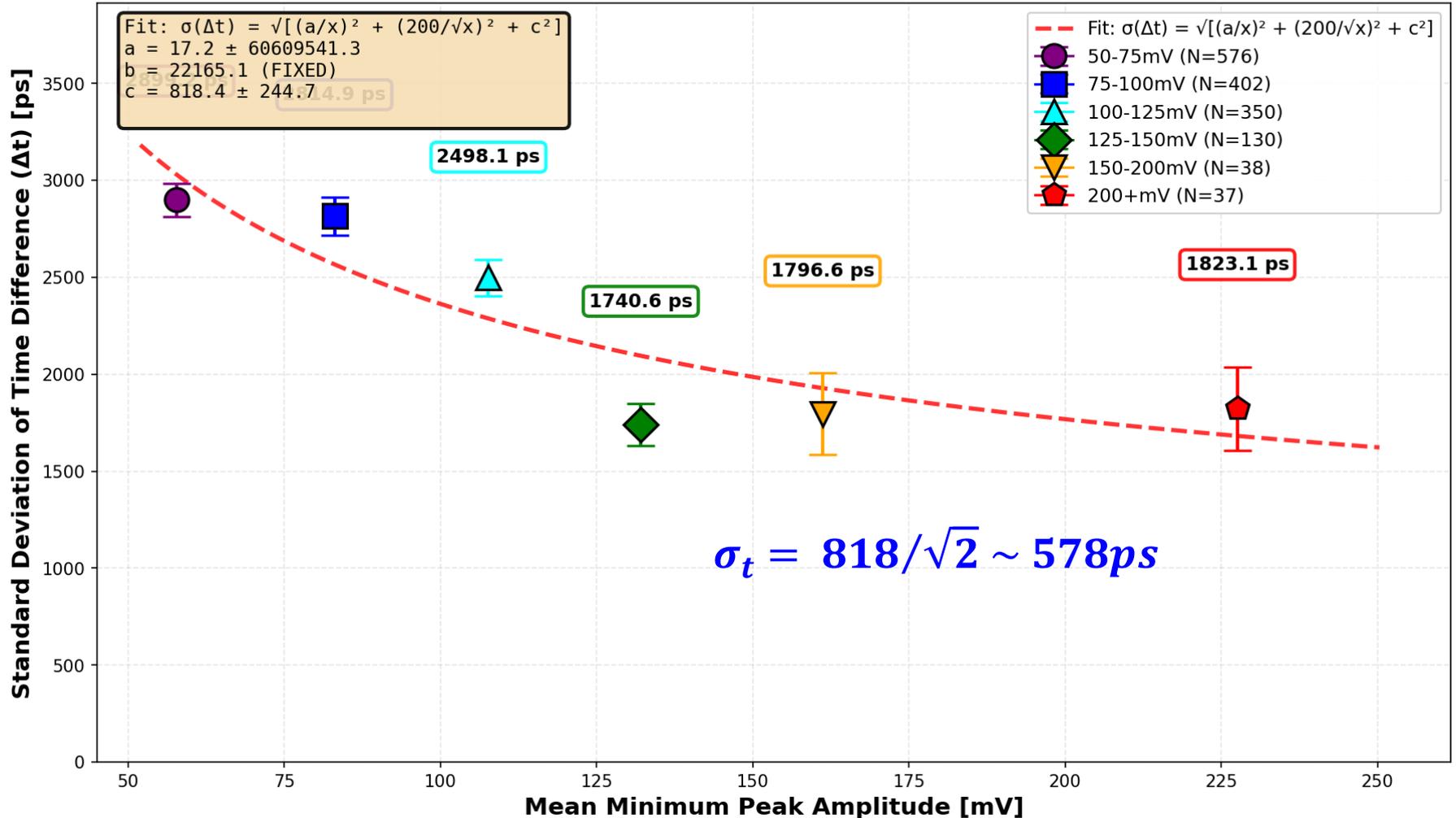
Also need to improve the energy measurement
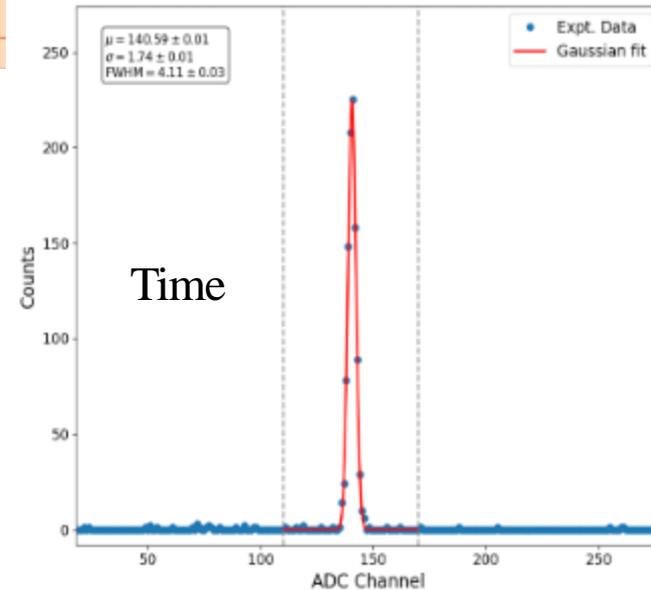
Timing with Digital Electronics (DRS4)

Timing Resolution vs Minimum Peak Amplitude (6 Bins)
Standard Deviation of Δt for Different Amplitude Bins
Classification: min(peak_CH1, peak_CH2)
Fit: $\sigma(\Delta t) = \sqrt{[(a/x)^2 + (b/\sqrt{x})^2 + c^2]}$

$$\sigma_t = 818/\sqrt{2} \sim 578ps$$

Plastic Scintillator

Plastic scintillator : Experimental Components

$\rho = 1g/cc; \quad LY = 10,000\gamma/MeV; \quad Z=1,6; \quad \tau \sim 1.5ns$

- **Photodetectors:**
  - **PMT: ET 9807B, 51 mm (2") diameter.**
  - **Hamamatsu S13360-2050VE (2mm×2mm, 1584 pixel, 50 μm pitch, $V_{bd} \sim$51 V)**
  - **Onsemi MICROFJ-X0035 (3mm×3mm, 5676 pixel, 35 μm pitch, $V_{bd} \sim$24 V)**
  - **Onsemi MICROFJ-X0065 (6mm×6mm, ~22k pixel, 35 μm pitch, $V_{bd} \sim$24 V)**

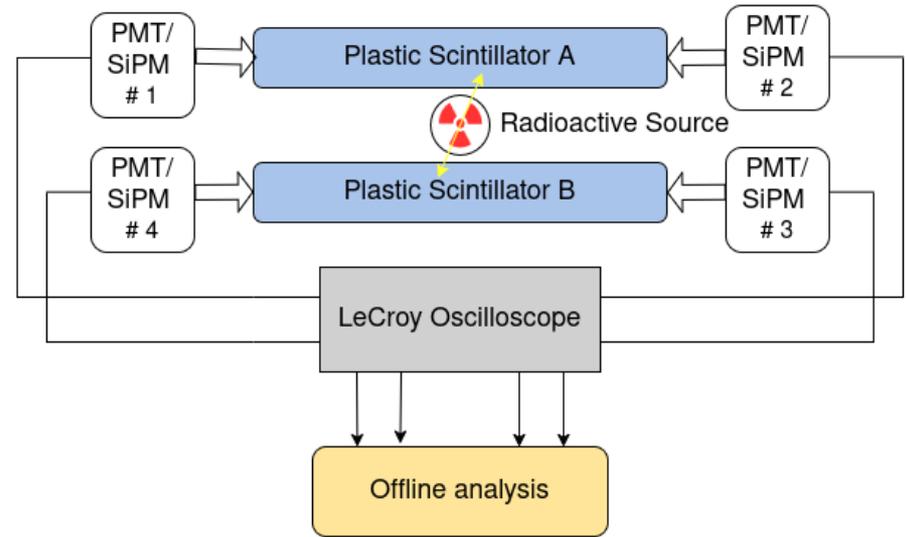- **Plastic scintillators** *(Multiple lengths and cross-sections)***:**
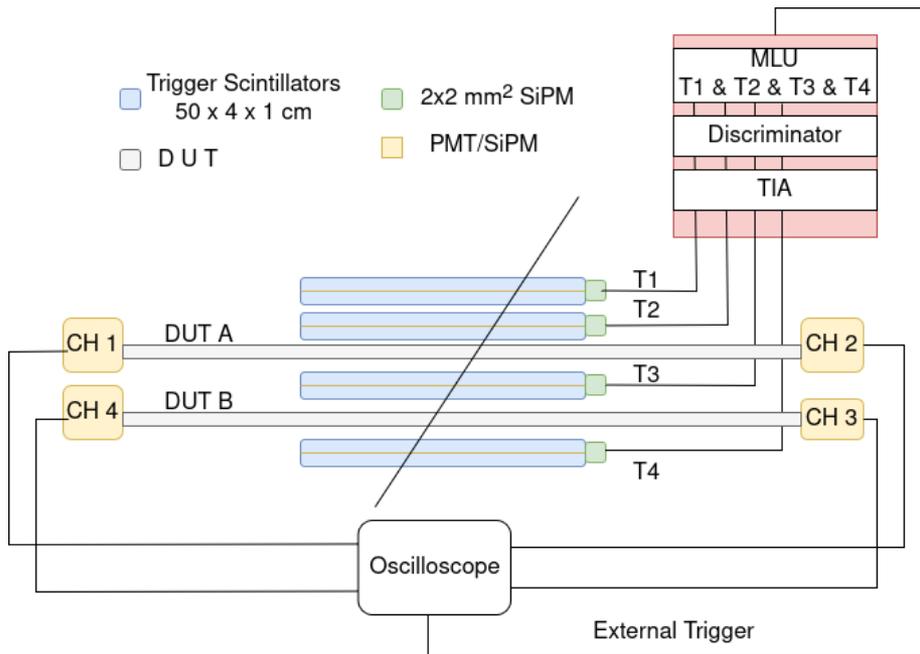 - **Type-1: BC-404 (PVT based)**
  - **Type-2: locally fabricated (PS based, CRL, Ooty)**

- **Sources of photons**
  - **Cosmic-ray muons (μ's)**
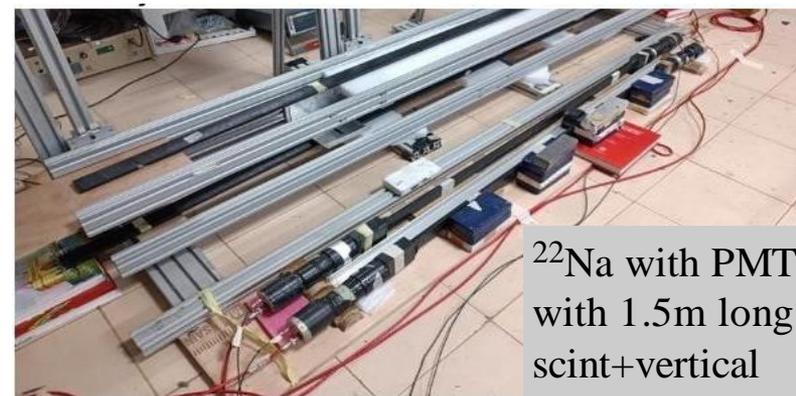 - **^{22}Na radionuclide**
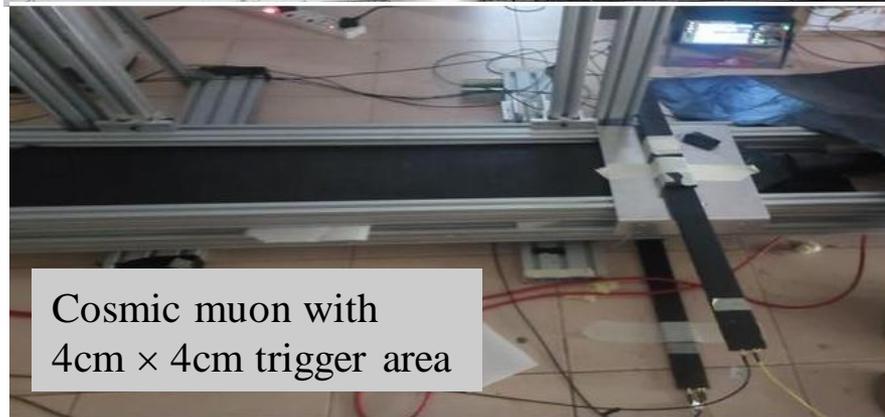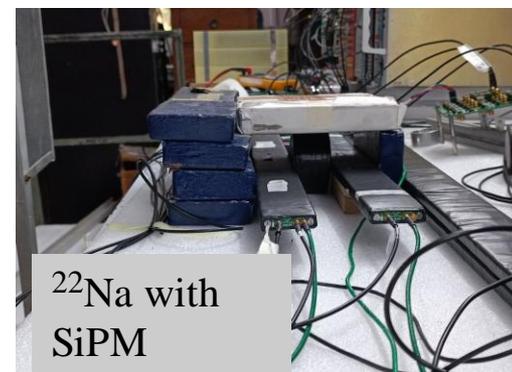 - **Pulsed LED source (CAEN SP5601 LED).**
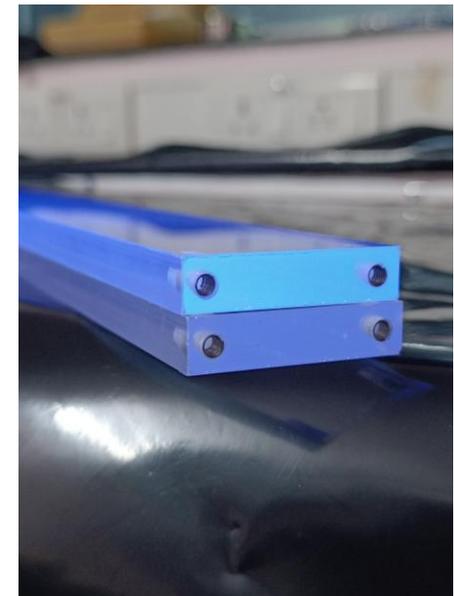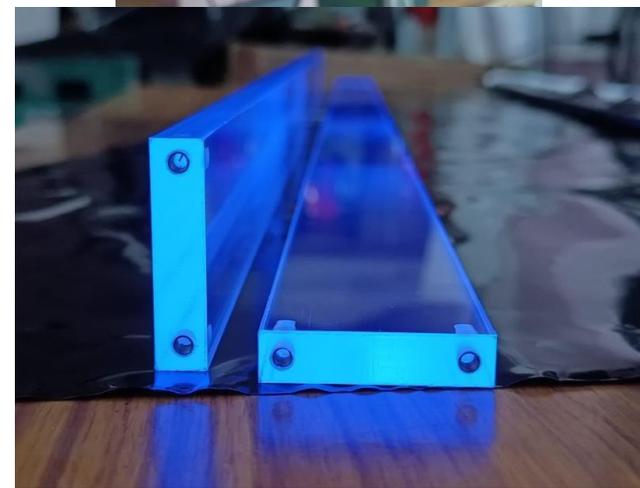
Experimental Methodology

$(T_1 + T_2) - (T_3 + T_4)$ **is independent of position and angle of incident.**

Different configurations

- Length of scintillators 50, 100, 150, 200cm
- For ^{22}Na, orientations are horizontal (4cm depth)/vertical (1cm depth)
- Cosmic trigger scintillator, full length, only 4cm
- ………………………..

^{22}Na with PMT

Cosmic with 50cm scint+ SiPM

^{22}Na with SiPM

Cosmic muon with 4cm × 4cm trigger area

^{22}Na with PMT with 1.5m long scint+vertical
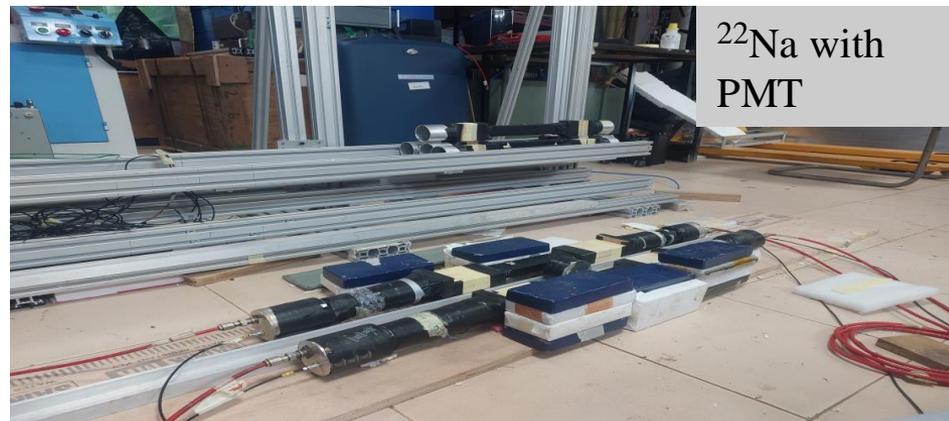
Timing Analysis Methodology : PMT

Raw waveform processing

- Binary → waveform conversion

- Baseline subtraction

- Trigger-based event selection

Type-2 scintillator (4 cm × 2 cm × 50 cm), cosmic run
Type-2 scintillator (2 cm × 1 cm × 50 cm), cosmic run
Type-2 scintillator (2 cm × 1 cm × 50 cm), ^{22}Na run
Type-1 scintillator (50 cm length), ^{22}Na run
Type-1 scintillator (50 cm length), cosmic muon run

Poorer resolution with SiPM readout

Timing Observable

Cosmic muons

χ^2 / ndf	43.1 / 42
Constant	247.4 ± 5.4
Mean	2.677 ± 0.006
Sigma	0.3326 ± 0.0045

Plastic scintillator (4 cm × 2 cm × 50 cm)

$t_1 + t_2 - t_3 - t_4$ (ns)

Time Resolution Comparison

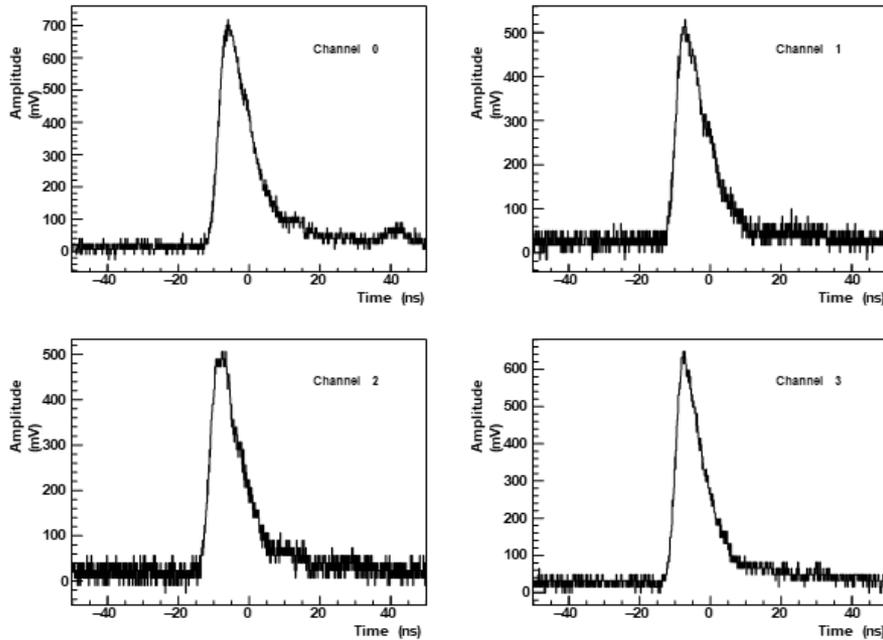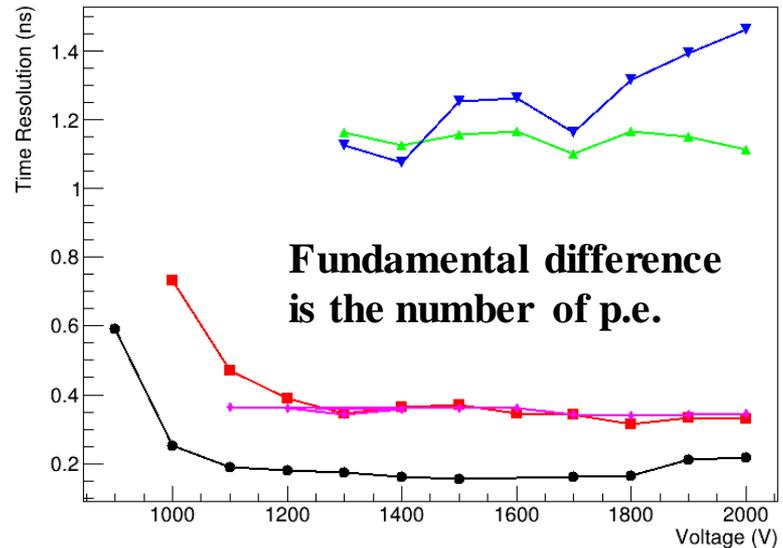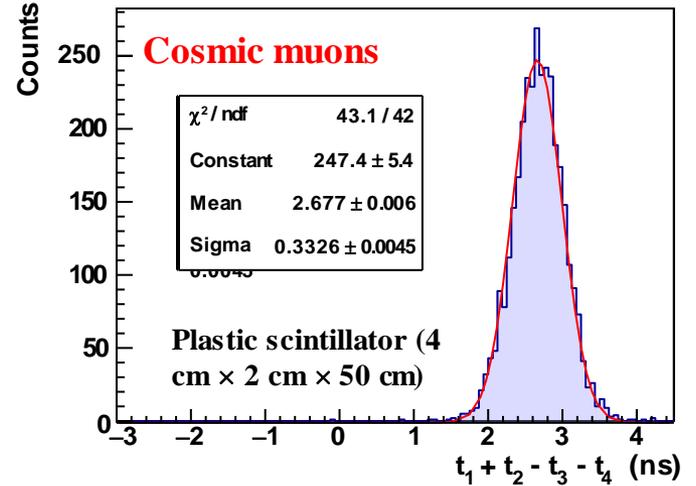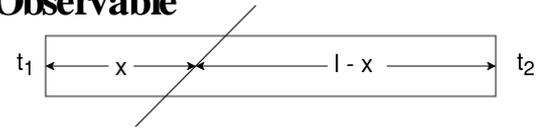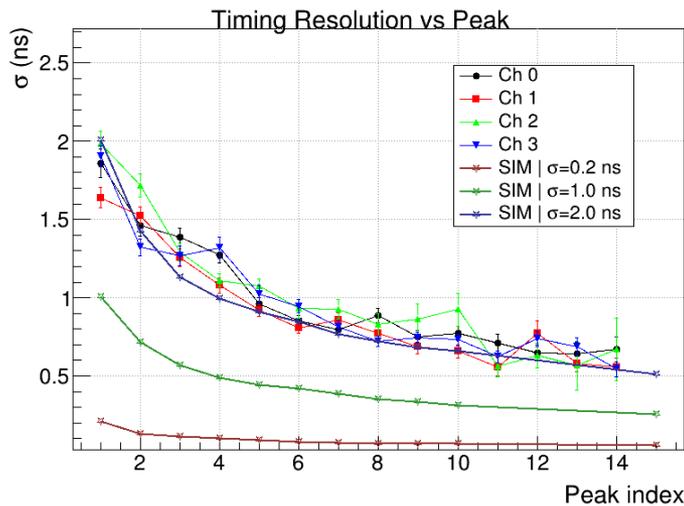**Fundamental difference is the number of p.e.**

Characterization Using LED Source: SiPM

- CAEN SP5601 LED as pulsed light source (20 Hz)

- SiPM sizes: 2mm×2mm, 3mm×3mm, 6mm×6 mm

- Measurements at multiple *Vov* and intensities
  Signal chain: TIA → 10 GSa DSO/2.5GHz

CAEN LED Driver

$\lambda_{peak} = 400nm$

FWHM=1.03ns

Charge [arb unit]

Charge [arb unit]

2 × 2 SiPM

3 ×3 SiPM

CAEN LED Driver

6 × 6 SiPM's

Timing Resolution vs Peak

- Ch 0
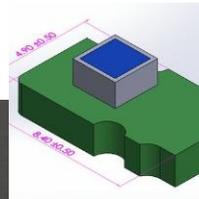- Ch 1
- Ch 2
- Ch 3
- SIM | σ=0.2 ns
- SIM | σ=1.0 ns
- SIM | σ=2.0 ns

σ (ns)

Peak index
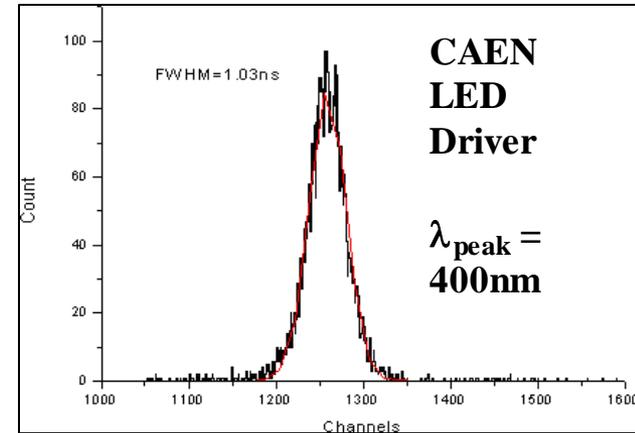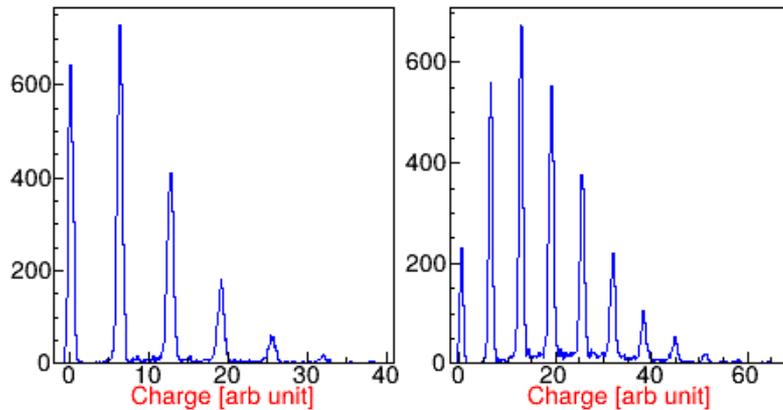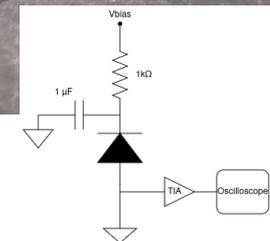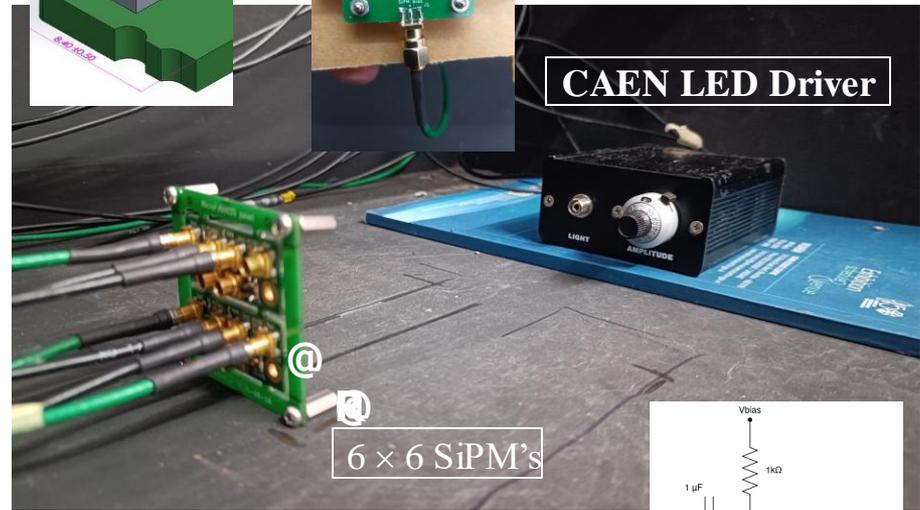
Characterization Using LED Source: SiPM
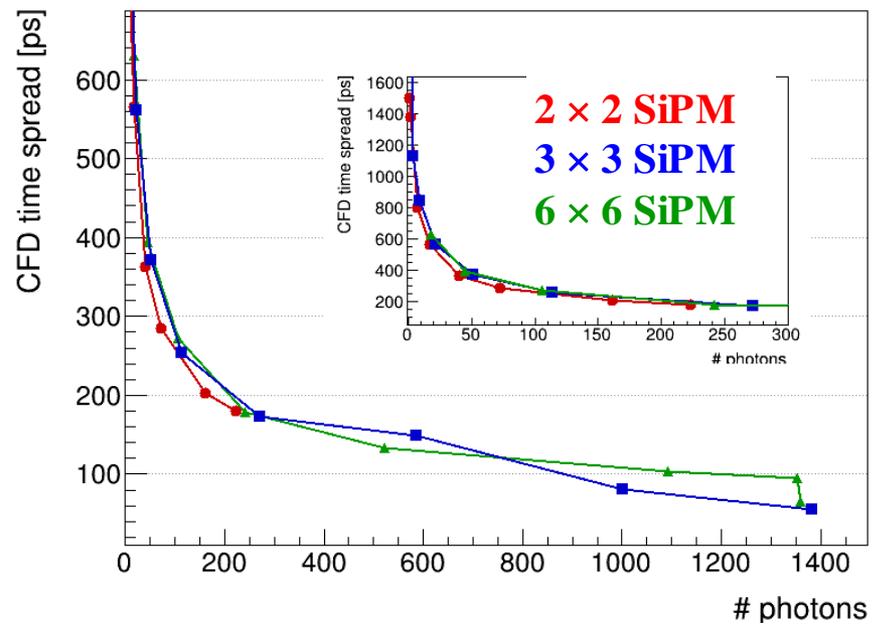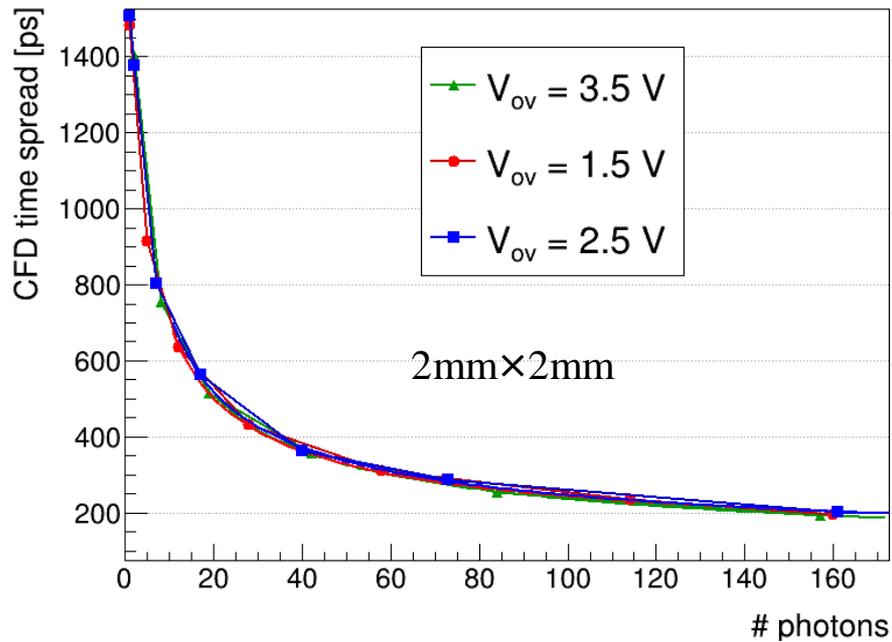
- **Time resolution depends only on the total number of photon**
- **No dependency on size or overvoltage**

Time spread of light source ~1ns

Comparison of PMT and SiPM

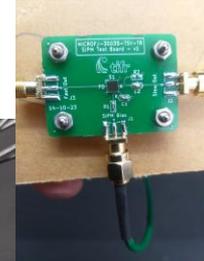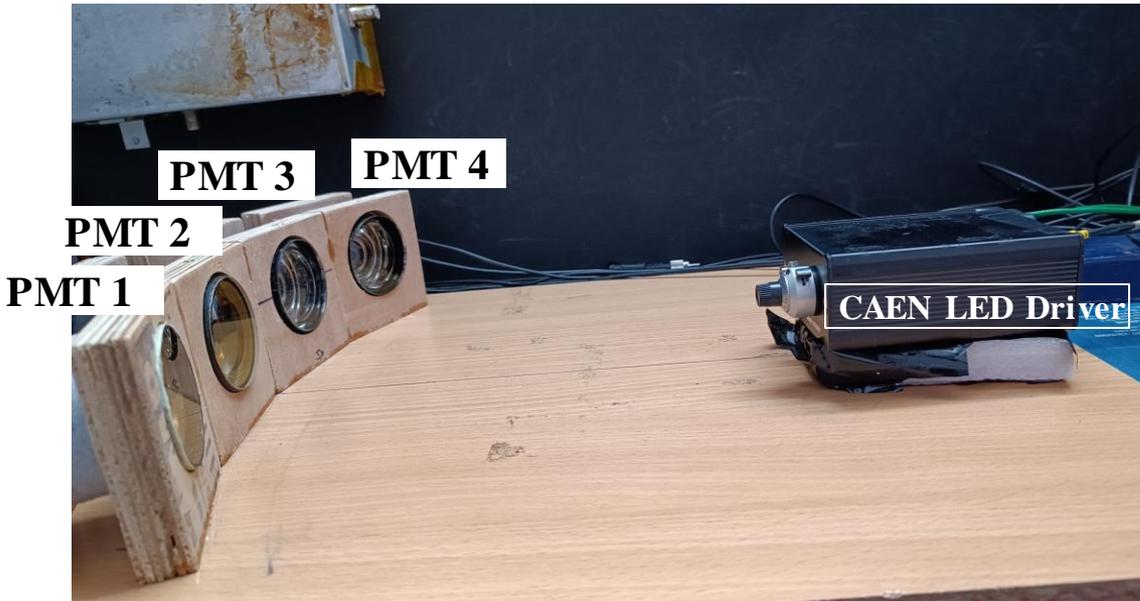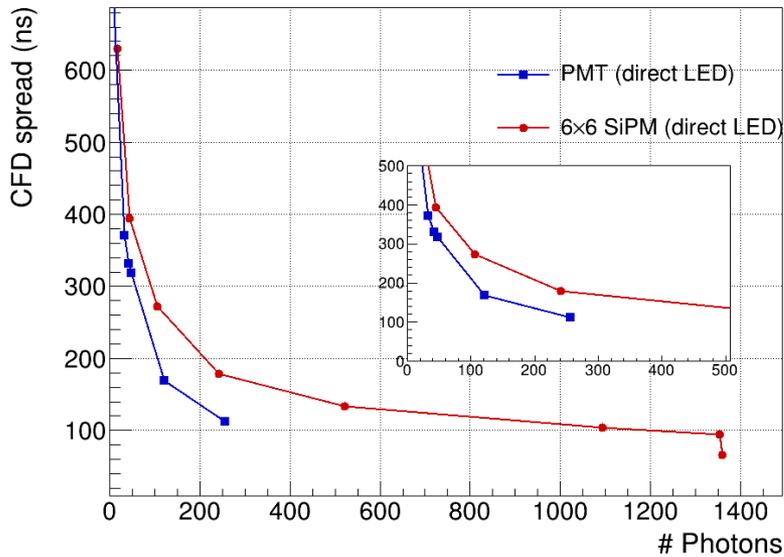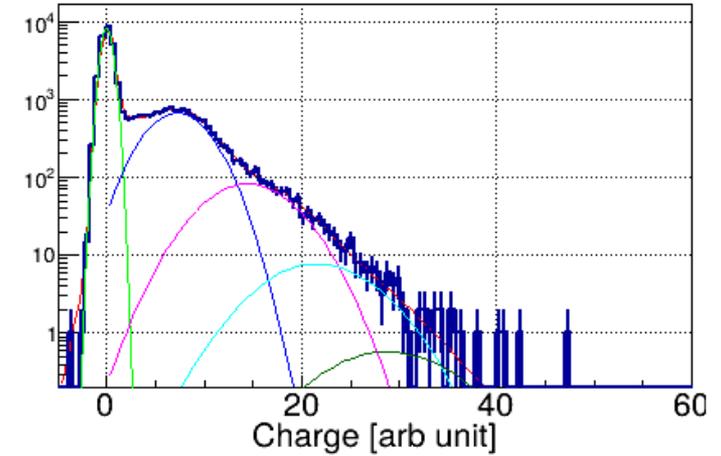PMT 1, PMT 2, PMT 3, PMT 4

CAEN LED Driver

Calibration of PMT

Quantum sensor

Application of Quantum Dots for low and high energy physics

Chromatic calorimeter

- In a homogeneous calorimeter, we benefit from an excellent stochastic term, but lose information on the depth of interaction.

- The concept of a chromatic calorimeter has been proposed (*Y. Haddad et al.* *) to recover this information without explicit electronic readout at different depths.

- Core idea: assign a unique emission band to each depth using wavelength shifting material.

- By "reading" the colour of the emitted light (spectral intensity), the interaction depth can be inferred.
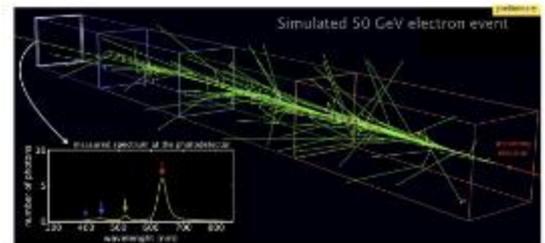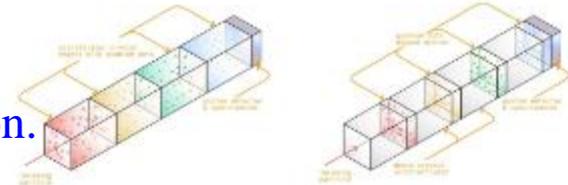
Potential application in a Compton telescope

- A similar concept can be applied to a Compton telescope with a scatterer–absorber configuration.

- A key requirement is to minimize dead material after the scatterer.

- By spectrally encoding the emission at the scatterer and absorber, this can be achieved without additional readout layers.
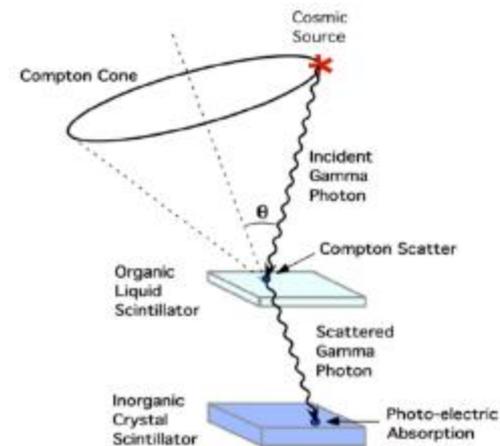
*Y. Haddad et al., Quantum Dot–Based Chromatic Calorimetry: A Proposal, arXiv:2501.12738 (2025).

Can we use scintillators for spectral encoding?

Conventional scintillators exhibit broad emission spectra, leading to significant spectral overlap when multiple scintillators are used.

This spectral overlap limits the ability to extract depth information using chromatic readout techniques, making scintillators a sub-optimal choice for this application.

Materials with narrow emission spectra are required to minimise spectral overlap and enable a clean, unambiguous readout.

Quantum Dots (QDs), with their tunable and intrinsically narrow emission bandwidths, are well suited for depth-resolved chromatic readout.
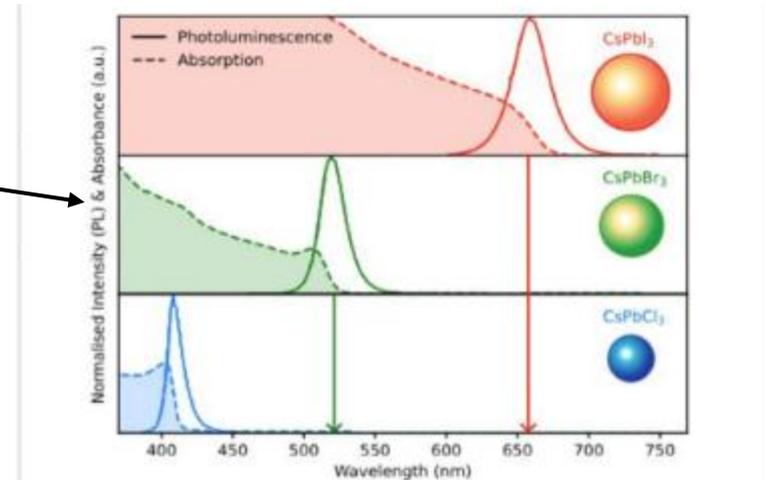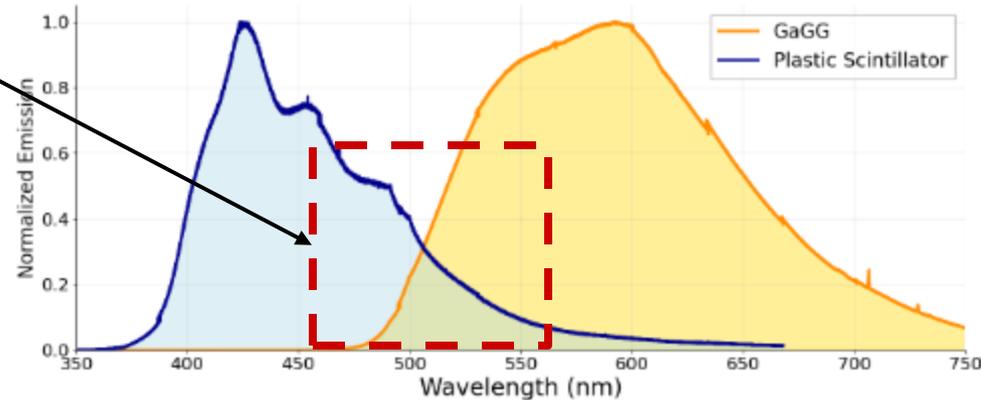
Can we use Quantum Dots/Nanocrystals to achieve this?

- **Tunable Emission Spectra:** **By adjusting the size of quantum dots, one can get specific emission wavelengths across the whole visible spectrum. This enables precise colour calibration and detection.**

- **Narrow Emission lines:** **Quantum dots have very sharp emission lines(FWHM ~20 nm) as compared to eg. scintillators (FWHM)**

- **Fast Time Response:** **The response time of Quantum Dots are faster (FWHM ~ 10 ns) compared to inorganic scintillators.**
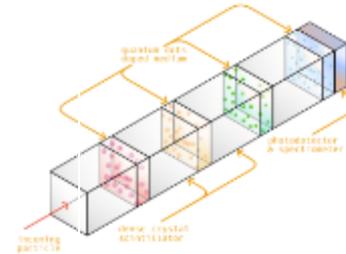

In TIFR we have been working with both lab grown and commercially made quantum dots
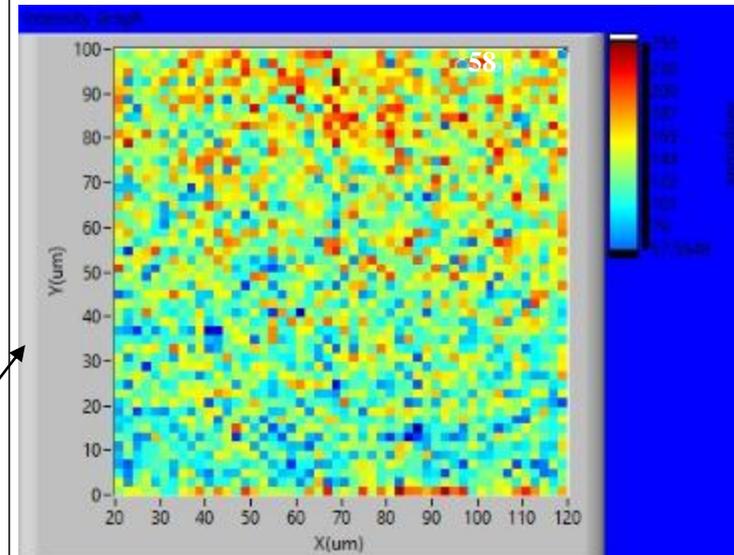**But are quantum dots / nanocrystals stable or radiation hard?**

The Materials and the measurements

- Loading Quantum Dots (QDs) in a Poly(methyl methacrylate), PMMA matrix for characterisation

- Study of two material classes: lab-synthesised and commercially sourced QDs

- Characterisation via laser-induced photoluminescence, absorption, time response and radiation hardness (EM irradiation,Cobalt-60 Source, upto 20 Mrad)

Photoluminescence scan (100µm×80µm) of CdSe-PMMA matrix

- Loading Quantum Dots in polymer matrix (PMMA): CsPbBr3, CdSe

- Preparing the solutions: Sol_1: X mg/mL QD in toluene, Sol_2: Y mg/mL Poly-methyl methacrylate (PMMA) in toluene. Different ratios from QD:PMMA (in toluene) w:w = 1:1, 1:3, 1:5 was prepared by mixing Sol 1 & 2.

- Mixing: Stir the solution for 15 min, until uniform mixture

- Spin coating: Small amount of solution is dropped in 1cm*1cm perspex, then spin coat for 15 sec for 1000 rpm

- Drying/storing: Left in vacuum at room temperature

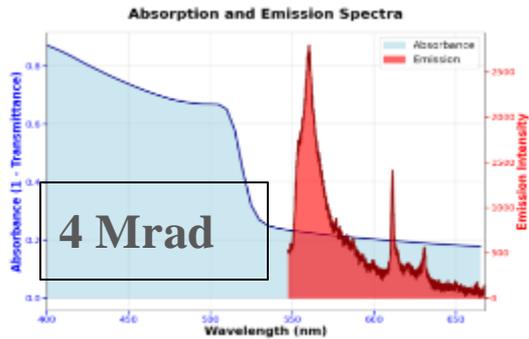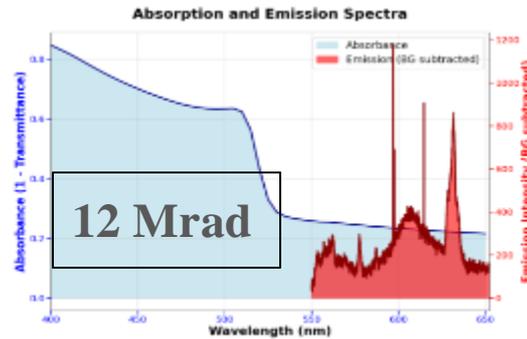- Results: Almost uniform distribution of QD over the PMMA matrix.

Uniform Photoluminescence confirms successful fabrication of QD in PMMA matrix.

Lab grown perovskite nano crystals

Unirradiated CsPbBr₃ shelf life > 6 months. Sustains 4 MRad EM irradiation
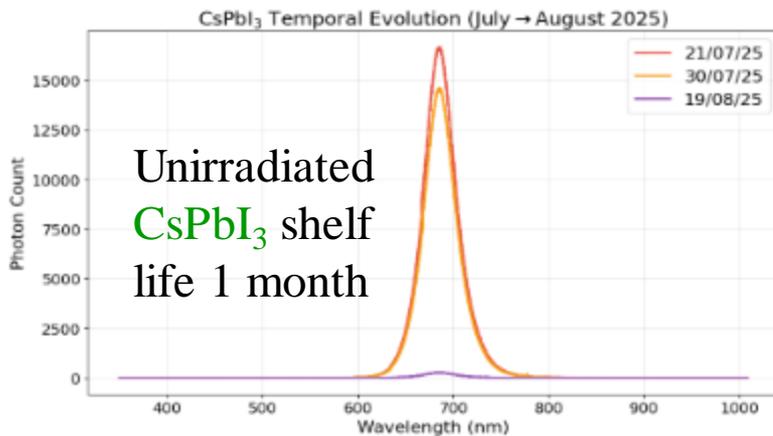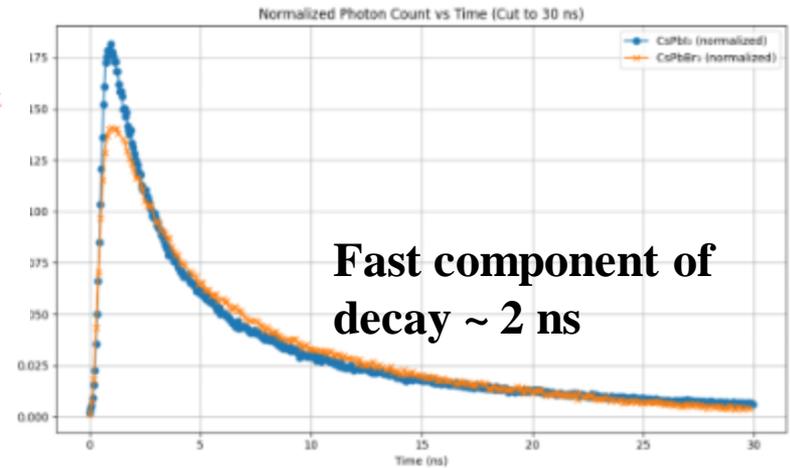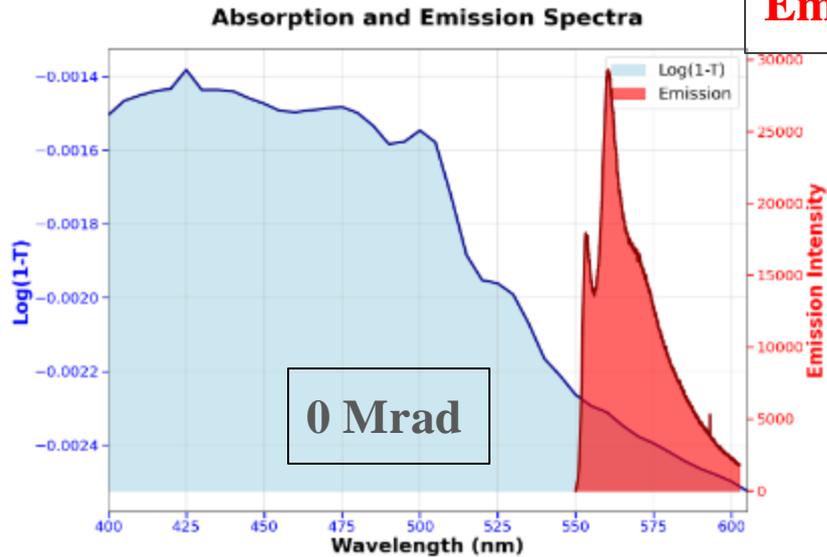
Time response

(a) 4 Mrad Irradiation

(b) 12 Mrad Irradiation

4 Mrad

12 Mrad

Fast component of decay ~ 2 ns

Unirradiated CsPbI₃ shelf life 1 month

CdSe was found to sustain > 20 MRad EM irradiation dose

Lab grown CdSe quantum dots

Emission Peak remains the same.
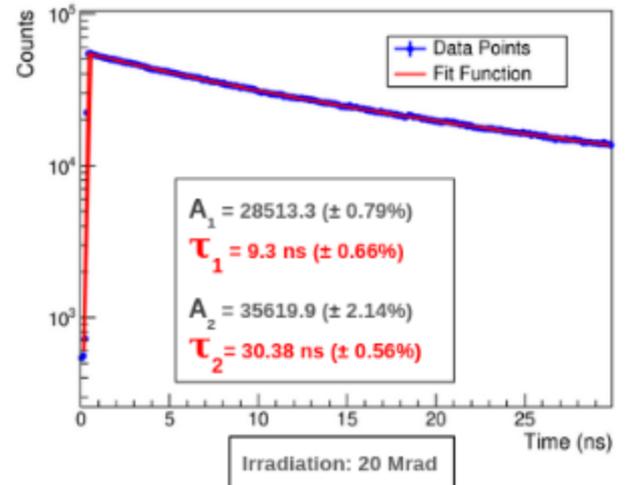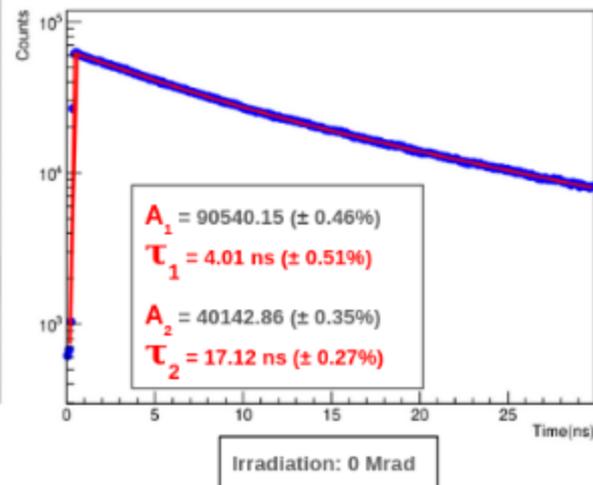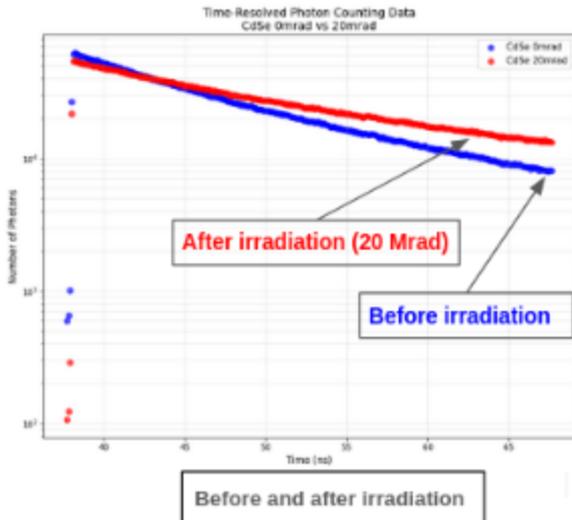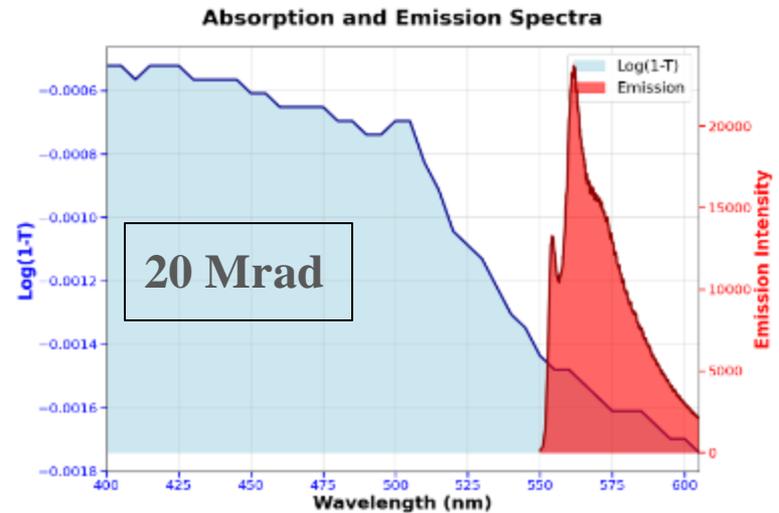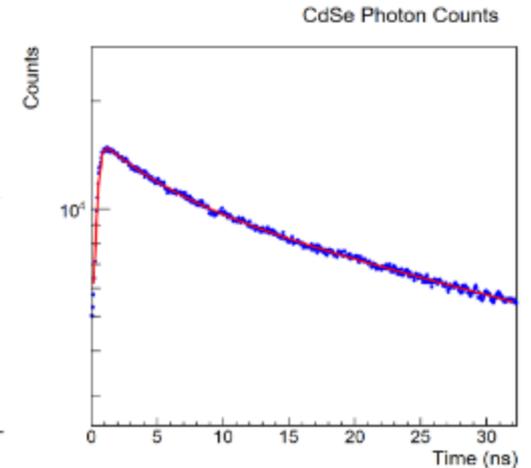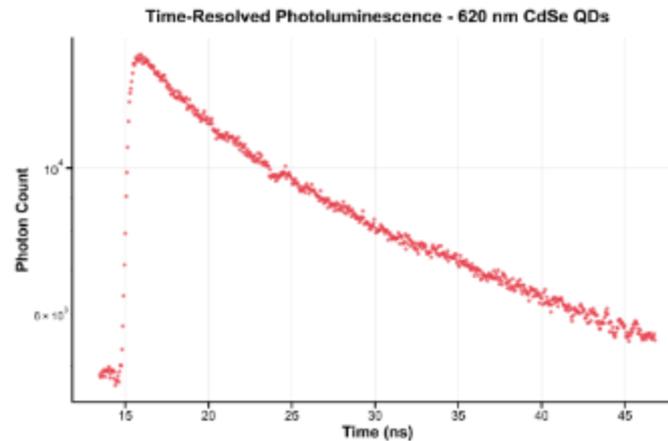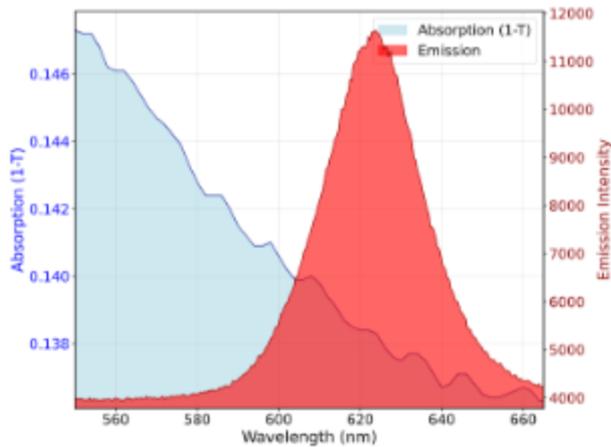
CdSe was found to sustain > 20 MRad EM irradiation dose

Commercial CdSe (620 nm)

$A_1 = 4575.8 \, (\pm \sim 1\%) \quad A_2 = 10285.5 \, (\pm \sim 1\%)$

$\tau_1 = 5.03 \text{ ns} \, (\pm \sim 2\%) \quad \tau_2 = 38.2 \text{ ns} \, (\pm \sim 1\%)$

Emission and Absorption Spectra

Time Correlated Single Photon Counting (TCSPC)

Commercially procured Perovskite and CdSe

- **Quantum dots were successfully fabricated and embedded in a polymer (PMMA) matrix.**

- **All samples exhibit emission at the expected wavelengths, with narrow and well-separated spectra.**

- **CdSe quantum dots are radiation hard up to high doses, preserving their spectral properties.**

- **The materials show a fast time response, compatible with calorimetric readout.**

- **Overall, QD–polymer composites are promising candidates for colour (chromatic) calorimetry.**

- **Working on a full stack with few colours readout with SiPM arrays**
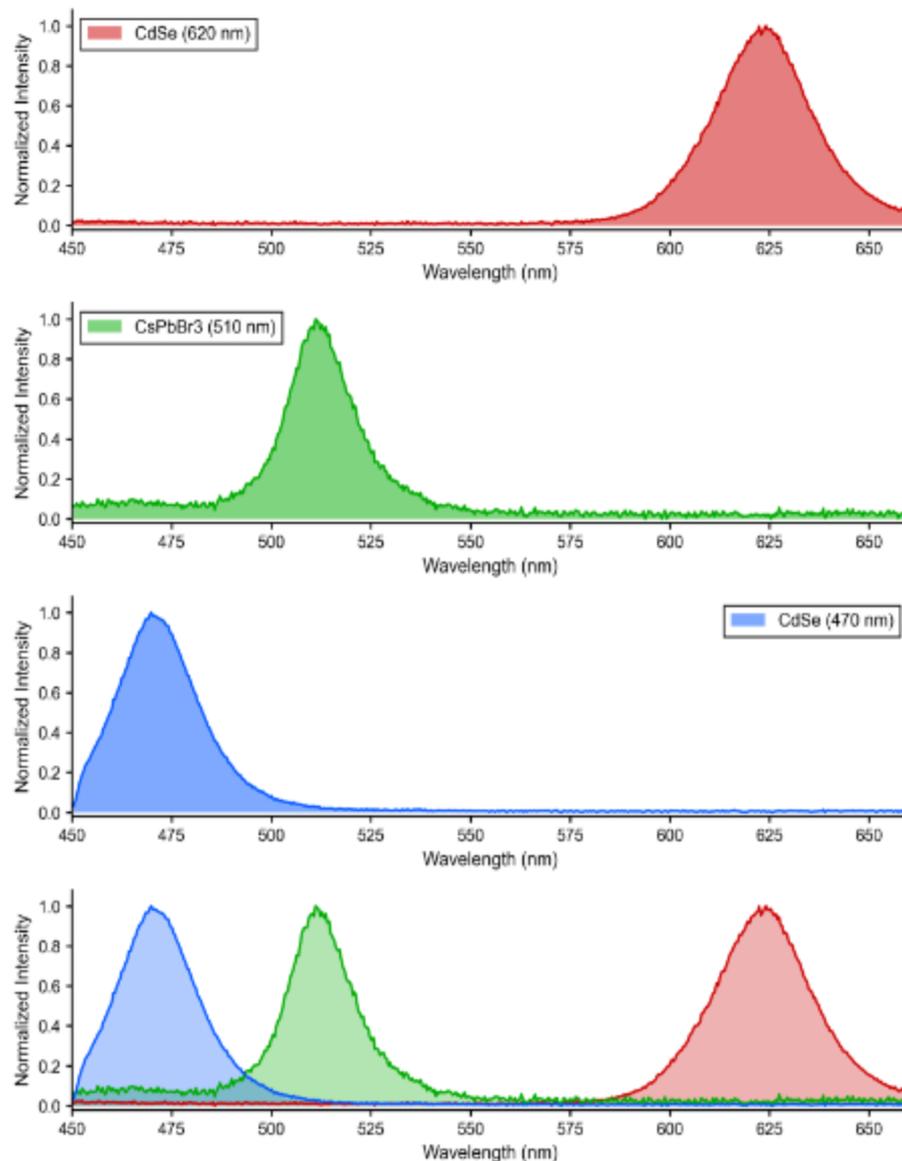
DRS4 for initial 4×4 set of array

- Going to use DRS4 based VME (v1742) digitiser to read out the two 4×4 array of crystals coupled with SiPM.

- It has 32 + 2 (TR0 and TR1) channels that can be used as input.

- It has variable record length: 1024, 512, 256 and 136.

- Sampling rates: 5, 2.5, 1 and 0.75 GS/s software selectable sampling frequencies.

- Transfer speed from crate to the storage is 85 MB/s, but observations are
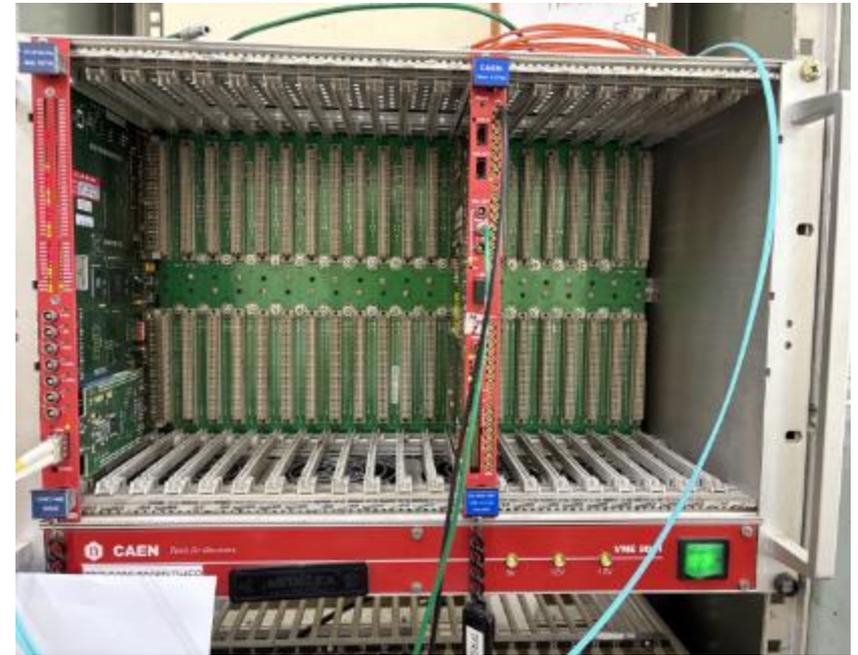
v1742 in VME crate with v2718 master control

Record length	Trigger rate	Cycles	Scalar
1024	250 Hz	10k	10k
520	500 Hz	10k	10k
256	1kHz	10k	10k
136	1.9kHz	10k	10k

- *The theoretical rate that is achievable is ~906 Hz for a record length of 1024*

- *The limitation of 250 Hz arises from the default setting of the wavedump software*

Summary

- **Three different R&D for different projects**

  - **Inorganic scintillators with SiPM & MCP**

  - **Plastics scintillator with SiPM & PMT**

  - **Quantum sensor, stand alone properties**

- **But, will converge soon to one for the positronium project**