TIPP2026 | Technology in Instrumentation & Particle Physics Conference

Characterization of Quantum Dot (QD) Properties for Enhanced Calorimetry in High Energy Physics

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Outline

- **Application of Quantum Dots in nuclear and particle physics**
- **Characterization of Lab grown QDs and Nanocrystals**
- **Characterization of commercially purchased QDs and Nanocrystals**
- **Summary and future directions**

Application of Quantum Dots for low and high energy physics

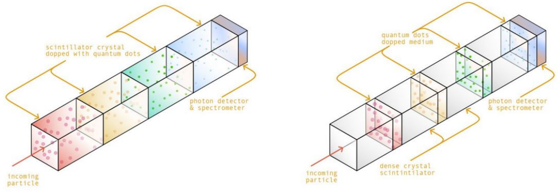
In a chromatic calorimeter

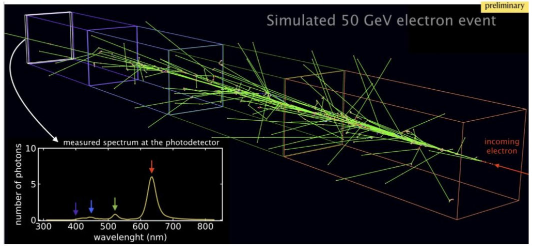
- In a homogeneous calorimeter, we benefit from an excellent stochastic term, but lose information on the depth of interaction.
- The concept of a **chromatic calorimeter** has been proposed (*Y. Haddad et al.**) to recover this information without explicit electronic readout at different depths.
- **Core 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.

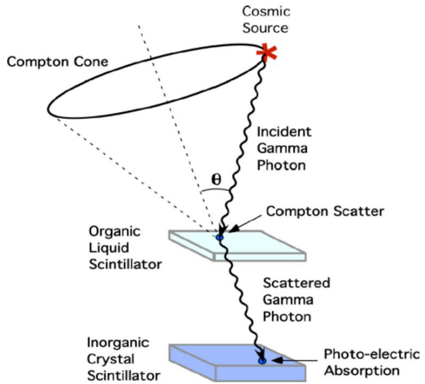
Potential application in a Compton telescope

- 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).







Color Calorimetry & Spectral Ordering

Spectral ordering in the correct configuration

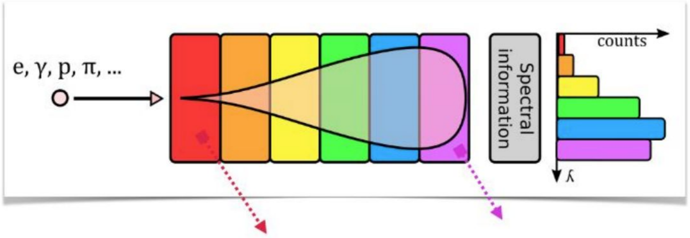
- To uniquely assign an emission band to a depth in the calorimeter, **downstream layers must not absorb light emitted by upstream layers**.

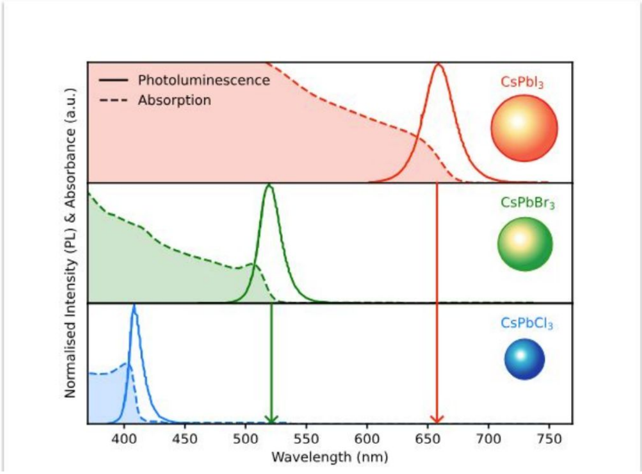
Working example:

- **Leftmost block:** absorbs wavelengths < 650 nm, emits at > 680 nm
- **Next block:** absorbs wavelengths < 520 nm, emits at > 540 nm
- **Rightmost block:** absorbs wavelengths < 410 nm, emits at > 420 nm

Material requirements:

- Narrow emission spectrum (to prevent overlaps)
- Stokes-shifted absorption
- Fast response
- Radiation tolerance and long-term stability

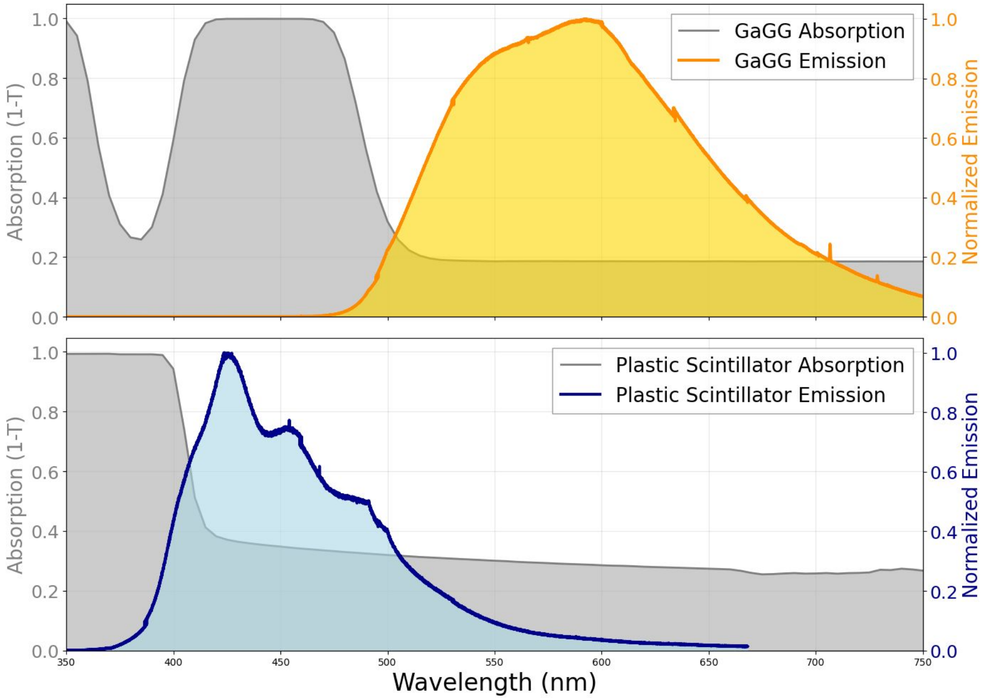




Y. Haddad et al., Quantum Dot–Based Chromatic Calorimetry: A Proposal, arXiv:2501.12738 (2025).

Can we use scintillators for spectral encoding?

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



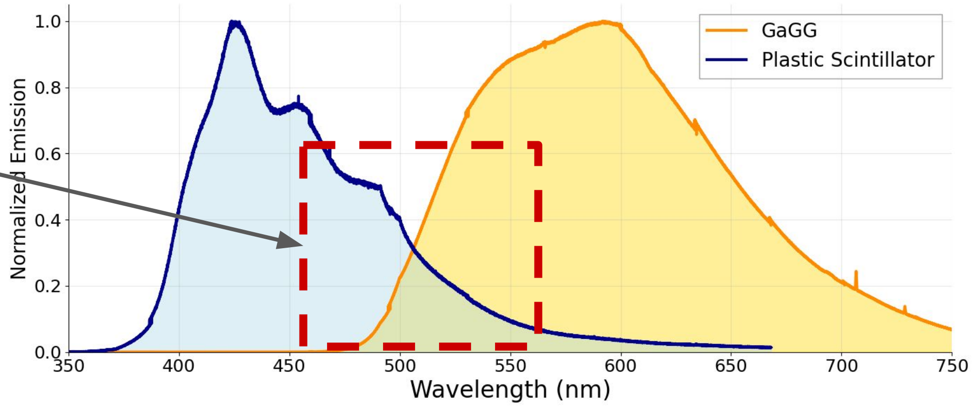
Can we use scintillators for spectral encoding?

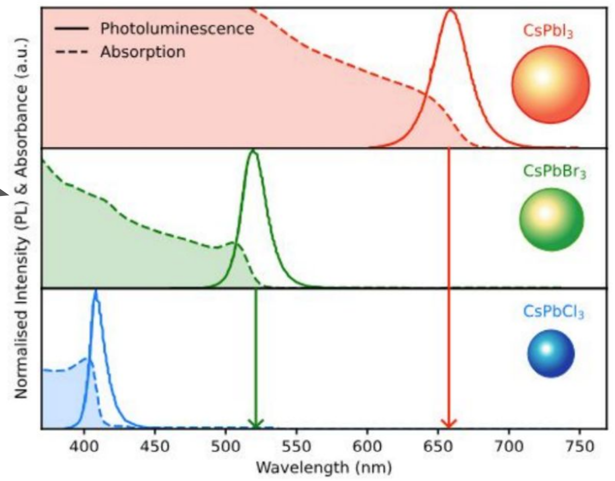
Conventional scintillators exhibit broad emission spectra, leading to **significant spectral overlap** when multiple scintillators are used.

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 color calibration and detection.

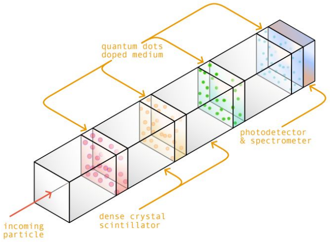
- **Narrow Emission lines**: Quantum dots have very sharp emission lines(FWHM ~20 nm) as compared to eg. scintillators (FWHM)

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

But are quantum dots / nanocrystals stable or radiation hard?

The Materials and the measurements

- **Loading Quantum Dots (QDs) in a Polymethyl methacrylate (PMMA) matrix**
- 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)



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.

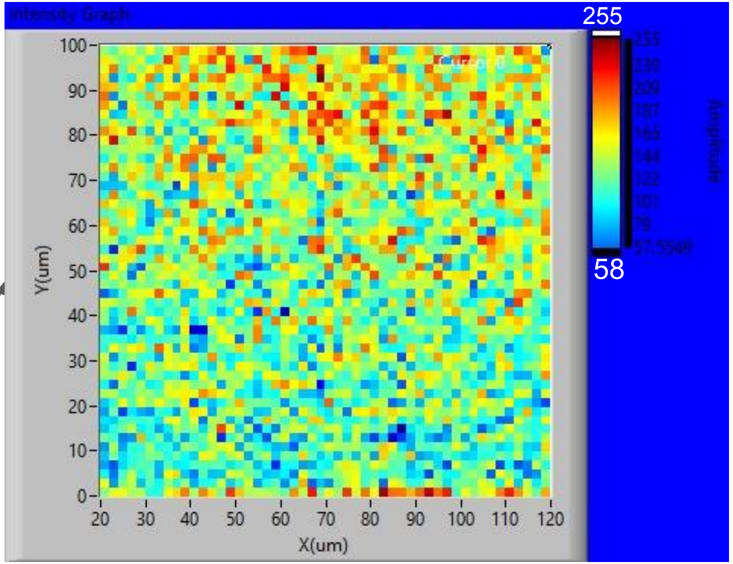
Mixing: Stir the solution for 15 min, until uniform mixture

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.

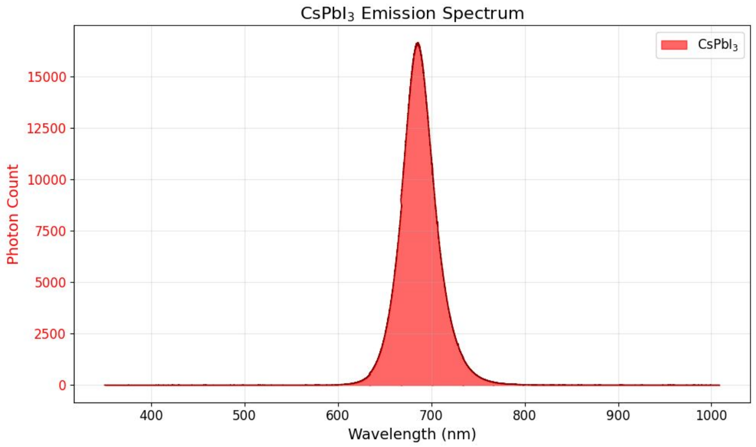
Photoluminescence scan (100µm*80µm) of CdSe-PMMA matrix

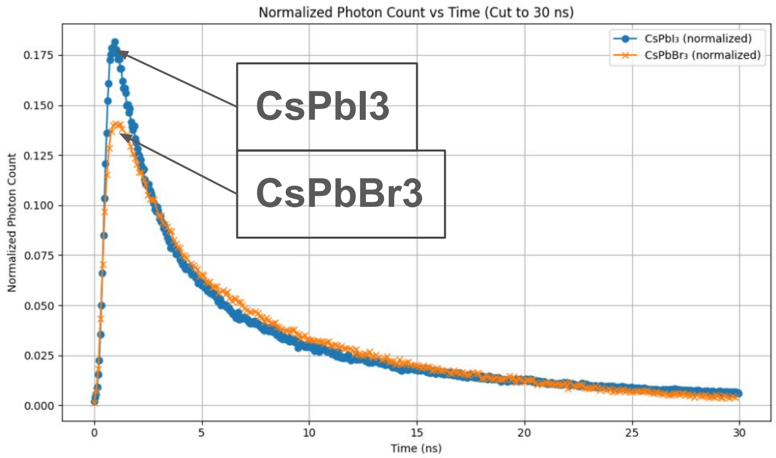


Photoluminescence confirms successful fabrication of QD in PMMA matrix.

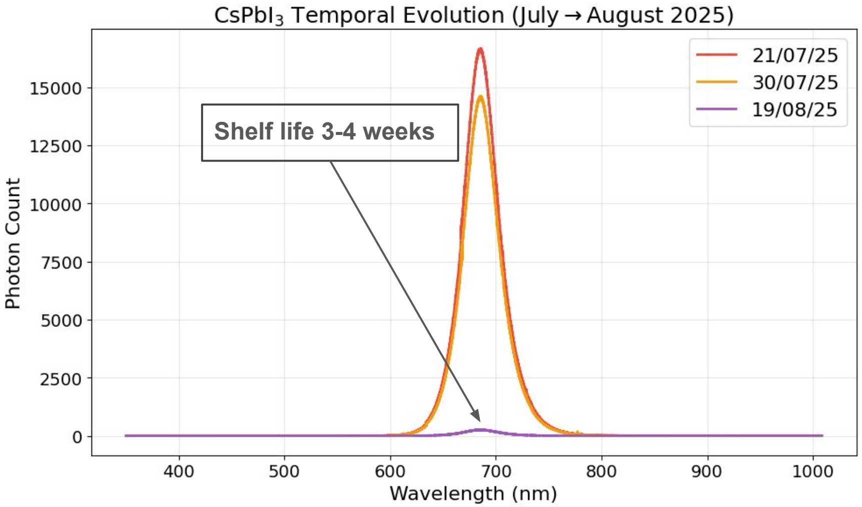
Characterisation: Lab grown Quantum Dots
$CsPbI_3$(690 nm), $CsPbBr_3$ (560 nm), CdSe (560 nm)

$CsPbI_3$
Emission Spectra & Time Response



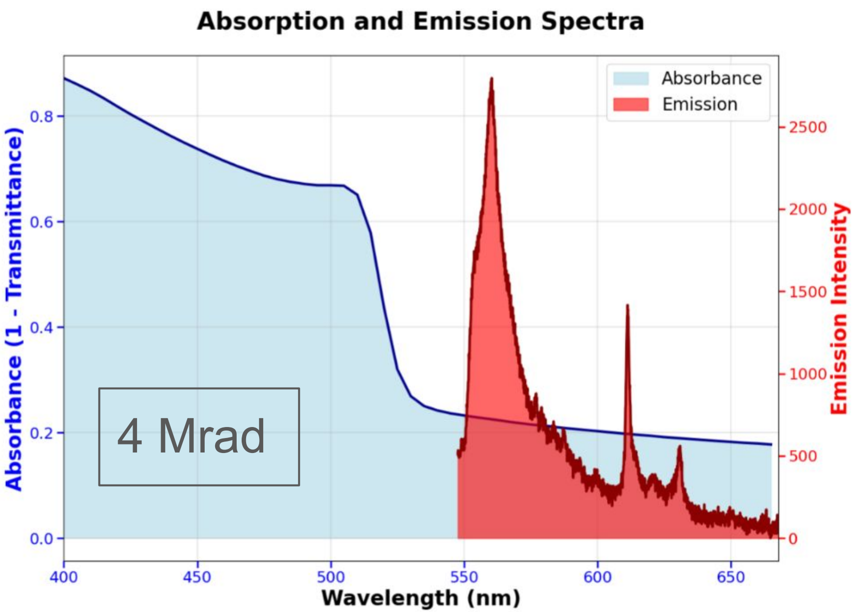


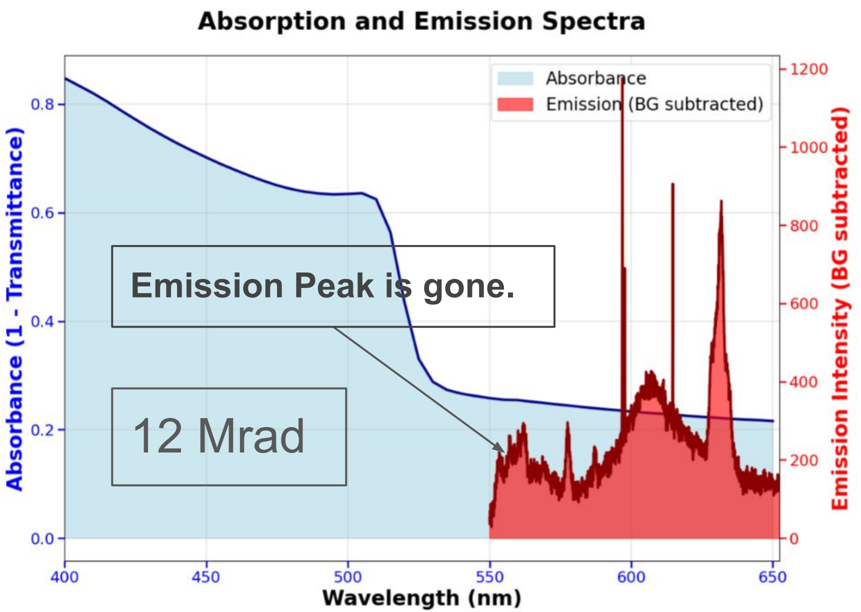
- Sharp emission peak ~690 nm
- $CsPbI_3$ is faster than $CsPbBr_3$
- Current shelf-life 3-4 weeks



- Working on stabilising the Quantum Dot.

$CsPbBr_3$ Emission Spectra



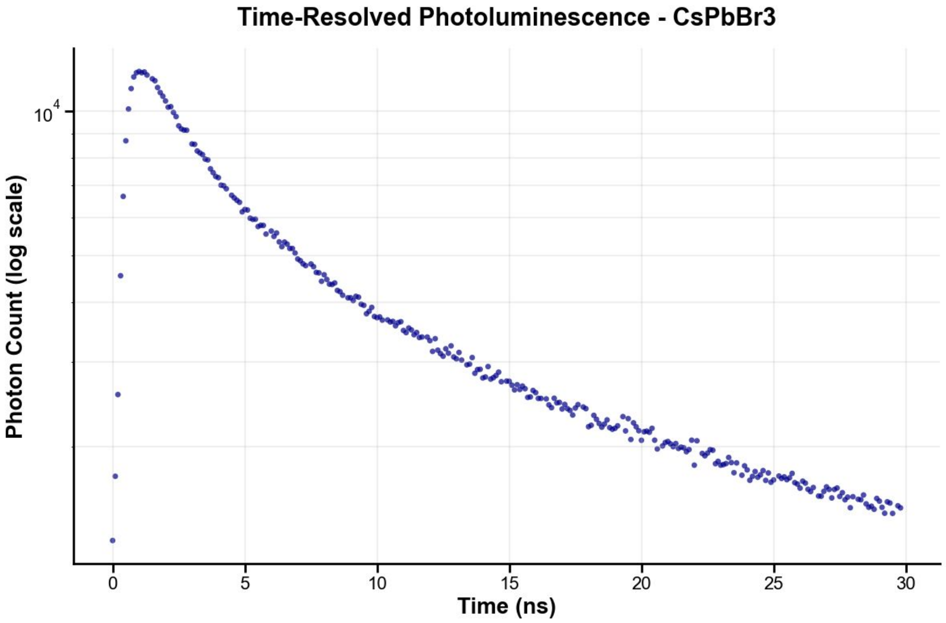


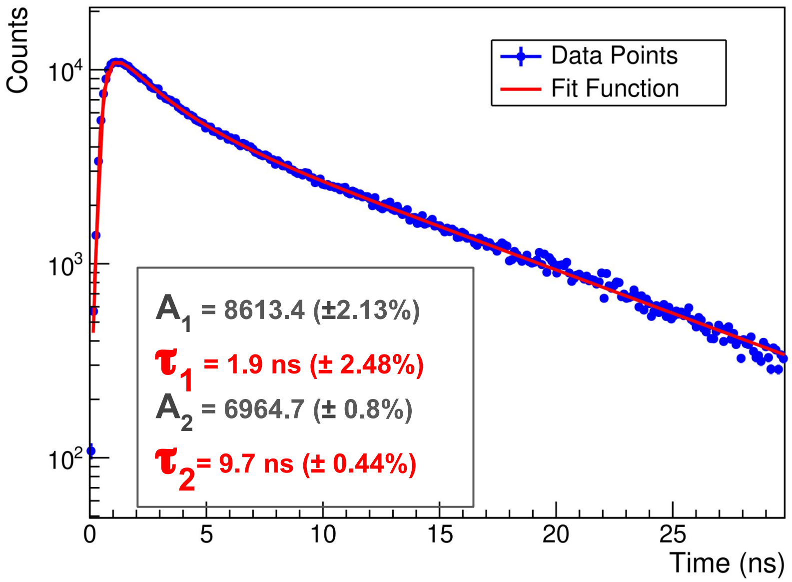
$CsPbBr_3$ (560 nm) Emission Spectra (Excitation: 532 nm)

$CsPbBr_3$ (560 nm) is stable for 6 month without any irradiation, and survives at least 4 Mrad of irradiation.

$CsPbBr_3$ Time Response Measurements

Fit function = $f(t) = \frac{1}{\sqrt{2\pi}\sigma}\int_{-\infty}^{\infty} \exp\left(-\frac{(t-t')^2}{2\sigma^2}\right)\left[A_{\mathrm{decay1}}e^{-t'/\tau_{\mathrm{decay1}}} + A_{\mathrm{decay2}}e^{-t'/\tau_{\mathrm{decay2}}} - A_{\mathrm{rise}}e^{-t'/\tau_{\mathrm{rise}}}\right]dt' + bkg$

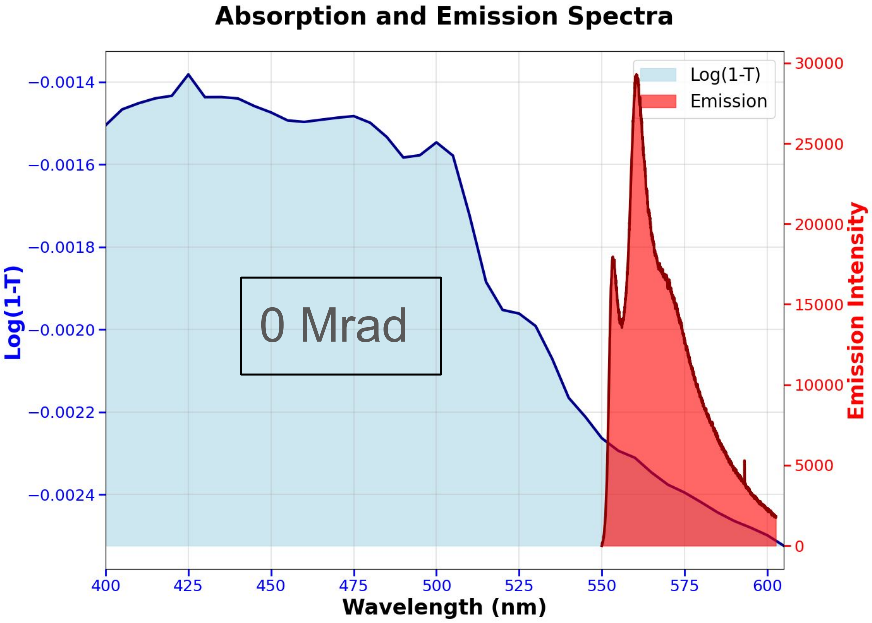


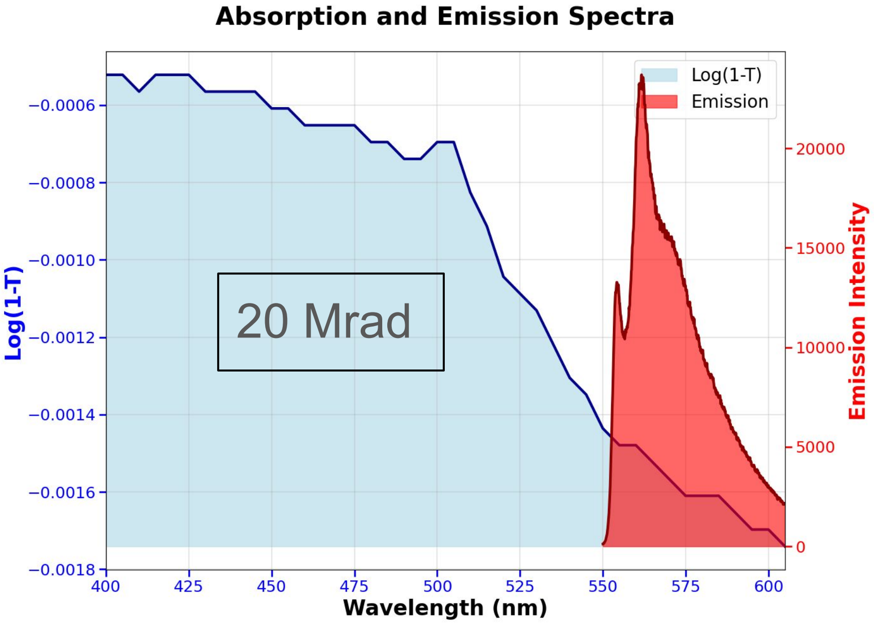


$CsPbBr_3$ Time Response Measurements (Time Correlated Single Photon Counting, TCSPC)

CdSe Emission & Absorption

Emission Peak remains.

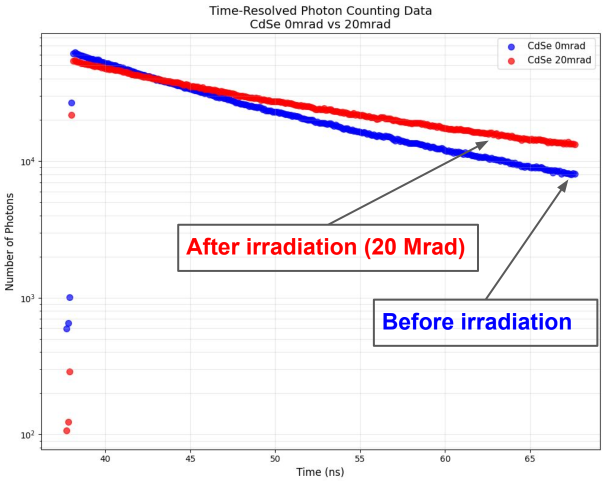




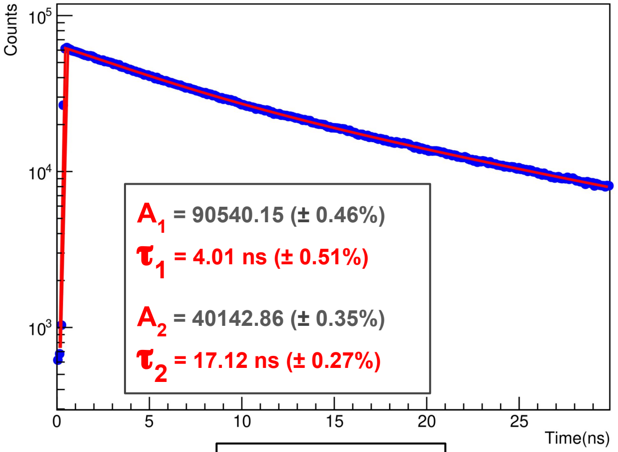
CdSe (560 nm) Emission Spectra (Excitation: 532 nm)

CdSe Quantum Dot Time Response

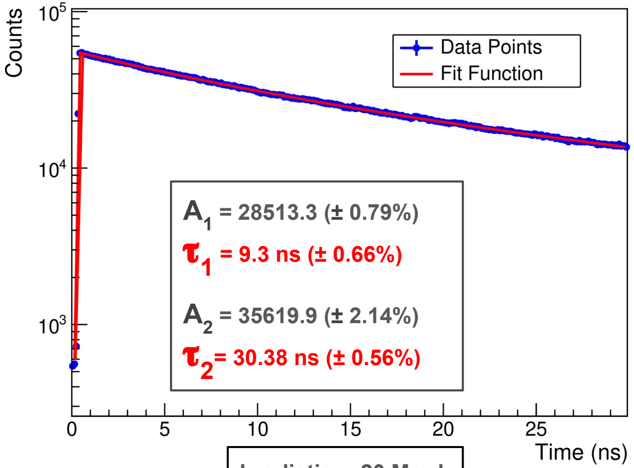
$$f(t) = \frac{1}{\sqrt{2\pi}\sigma}\int_{-\infty}^{\infty} \exp\left(-\frac{(t-t')^2}{2\sigma^2}\right)\left[A_{\text{decay1}}e^{-t'/\tau_{\text{decay1}}} + A_{\text{decay2}}e^{-t'/\tau_{\text{decay2}}} - A_{\text{rise}}e^{-t'/\tau_{\text{rise}}}\right]dt' + bkg$$



Before and after irradiation



Irradiation: 0 Mrad



Irradiation: 20 Mrad

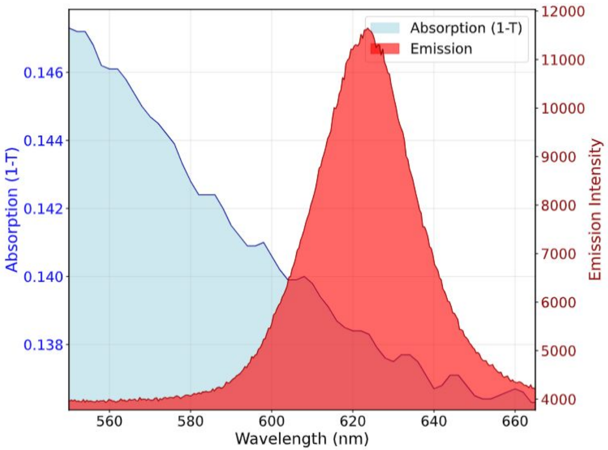
CdSe Time Response Measurements (Time Correlated Single Photon Counting, TCSPC)

Characterisation: Commercially purchased Quantum Dots $CsPbBr_3$ (510 nm), CdSe (470 nm, 620 nm)

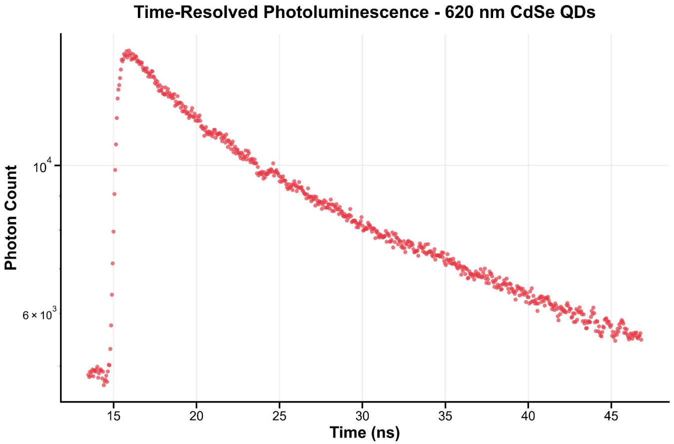
CD Bioparticles

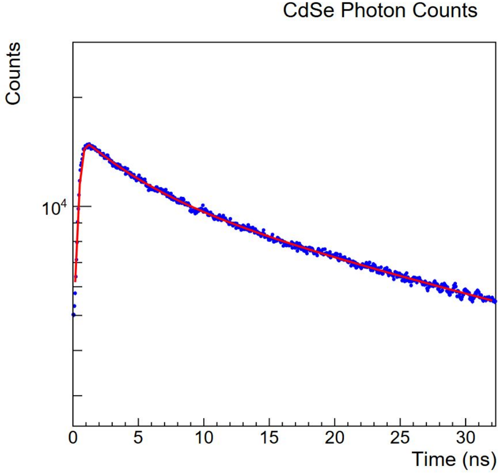
CdSe (620 nm)

A_1 = 4575.8 (± ~1%) A_2 = 10285.5 (± ~1%)
τ_1 = 5.03 ns (± ~2%) τ_2= 38.2 ns (± ~1%)



Emission and Absorption Spectra



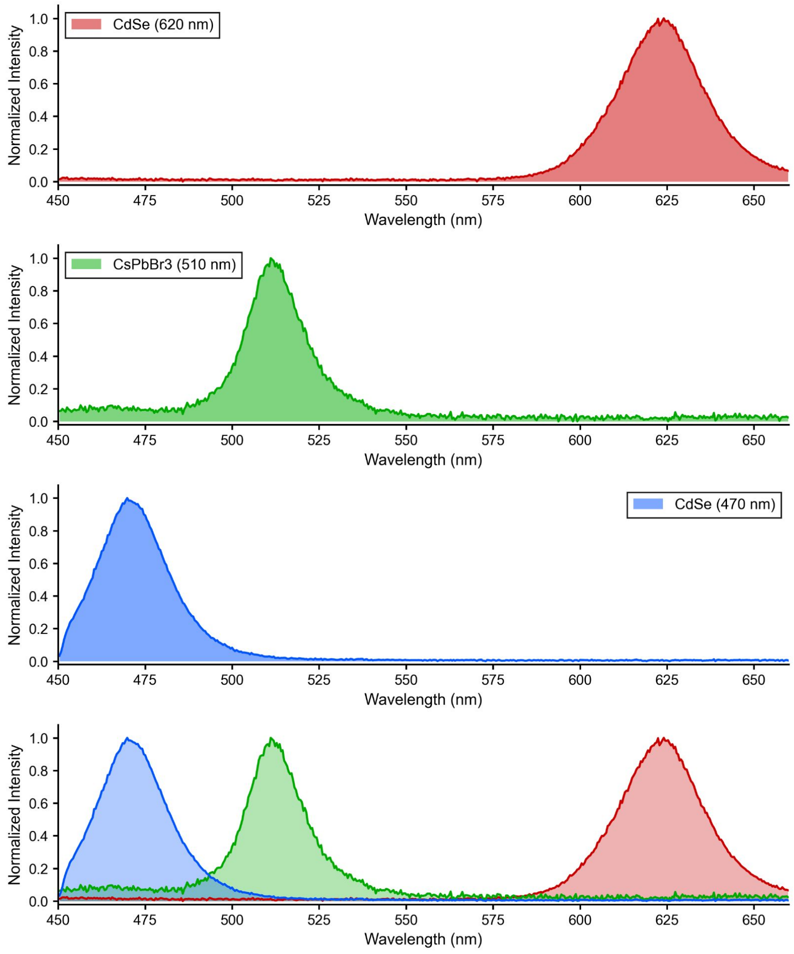


Time Correlated Single Photon Counting (TCSPC)

Emissions of $CsPbBr_3$ & CdSe

Conclusions

- Quantum dots were successfully **fabricated and embedded in a polymer 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 colorimetric readout.
- Overall, **QD–polymer composites are promising candidates for colour (chromatic) calorimetry**.



Summary and futures plans

Over the past ~year, **we have established a comprehensive measurement and fabrication pipeline** to characterise different species of quantum dots (QDs), including studies of their performance after irradiation (so far limited to electromagnetic radiation).

From the measurements, our initial conclusions are:

- **$CsPbBr_3$**(560 nm) retains its performance up to at least **4 MRad**, while **CdSe**(560 nm) remains functional beyond **20 MRad**.
- In terms of timing performance, **$CsPbI_3$** is the fastest, whereas **CdSe** is significantly slower.
- **$CsPbI_3$** currently suffers from stability issues; work is underway to improve its longevity.

Going forward, we will **repeat the measurements with proton and neutron irradiation**, and extend the studies to **additional QD materials and emission wavelengths**.

Acknowledgement

Core expertise on the active materials lies within **materials science**, while **HEP** provides strengths in sensor architecture and readout design.

Consequently, the development of **quantum sensors for HEP-scale experiments** is inherently an **interdisciplinary effort**. The materials studied were developed by **T. Choudhury (IEM, Kolkata)** and **P. Mandal (IISER, Kolkata)**.

The measurements presented in the following slides were enabled by direct laboratory support at **TIFR** from:

A. Venugopal, S. Ghosh, S. Prabhu, G. Remesh, R. Vij (Department of Condensed Matter Physics and Materials Science)

D. Khushalani, K. Nagarajan, J. Singh, B. Chandanshive, G. Kothapalli (Department of Chemical Sciences)

Irradiation studies were carried out at **BARC**.

Backup

Irradiation facilities (with varied levels of access)

The irradiation facilities that are available include those present in the TIFR, Mumbai campus as well as those from sister institutes of our parent organization.

EM irradiation :

– Co-60 source with a “strength” of ~ 4-5 kGray/hour

All irradiated results shown today are with this source

– 5-10 MeV electron beam can deliver a comparable doses as the Co-60 source

Neutron irradiation :

A neutron irradiation facility from the Apsara-U reactor at BARC. This is a swimming pool type reactor with a total power of 2 MW.

→ Dose depends on distance from the core.

Irradiation with 1 MeV neutron equivalents to ~10^{16} n/cm^2 per day is possible.

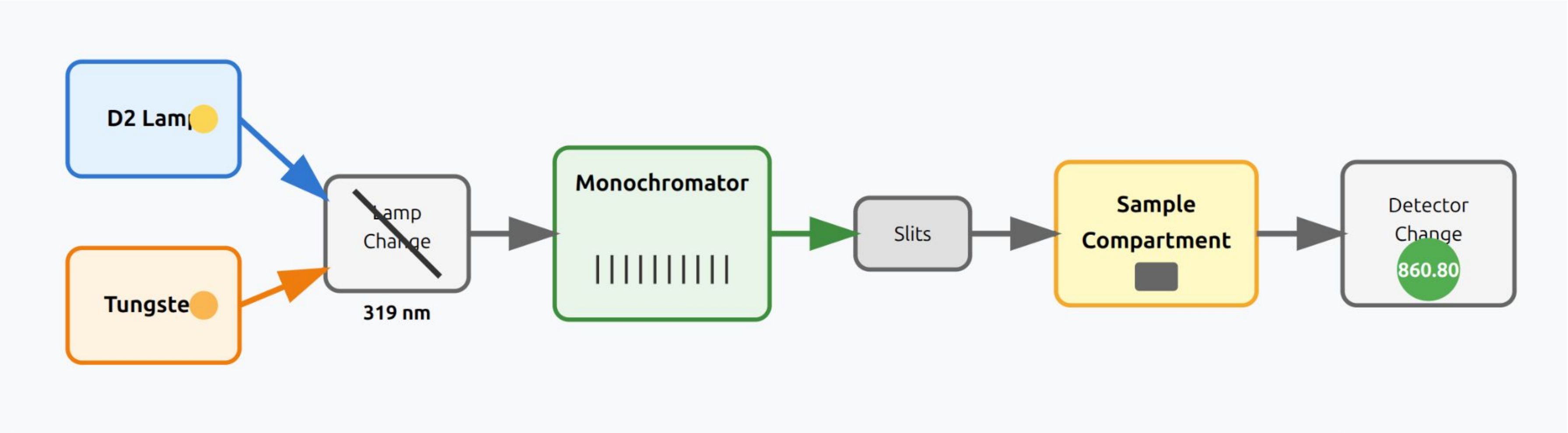
TIFR pelletron facility :

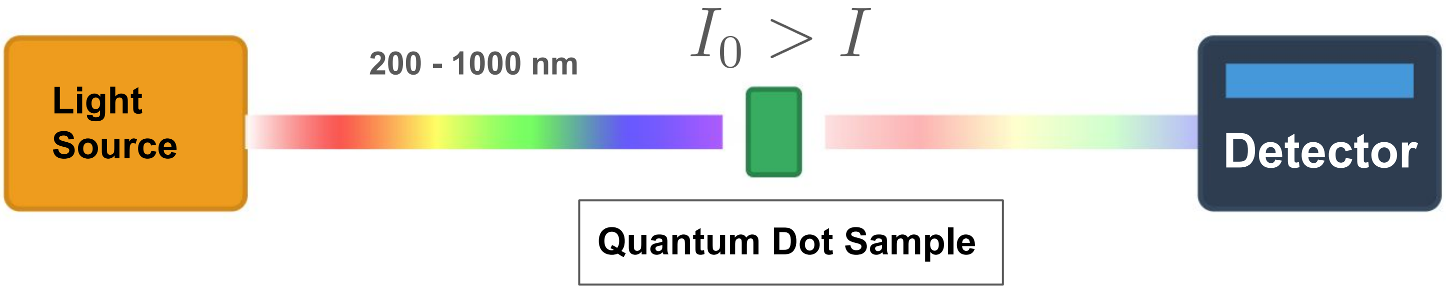
20 MeV proton beam with a flux of 10^10 particles /s/cm2

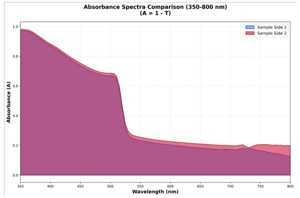
Sample Information: CsPbBr3 & CdSe (Lab grown)

Sample Name	Total Dose (Mrad)	Duration	Notes
Phase 1			
$CsPbBr_3$ in PMMA Sr. 01	4	~12 hrs 25 min	Initial irradiation
$CsPbBr_3$ in PMMA Sr. 02	4	~24 hrs 25 min	Initial irradiation
Er Doped MZP	4	~24 hrs 25 min	Initial irradiation
CdSe in PMMA	12	~36 hrs 51 min	Higher dose irradiation
Phase 2 (Additional Exposure)			
$CsPbBr_3$ in PMMA Sr. 01	12	25 hrs 11 min	4 Mrad + 8 Mrad additional
$CsPbBr_3$ in PMMA Sr. 02	12	25 hrs 11 min	4 Mrad + 8 Mrad additional
Er Doped MZP	12	25 hrs 11 min	4 Mrad + 8 Mrad additional
CdSe in PMMA	20	25 hrs 11 min	12 Mrad + 8 Mrad additional

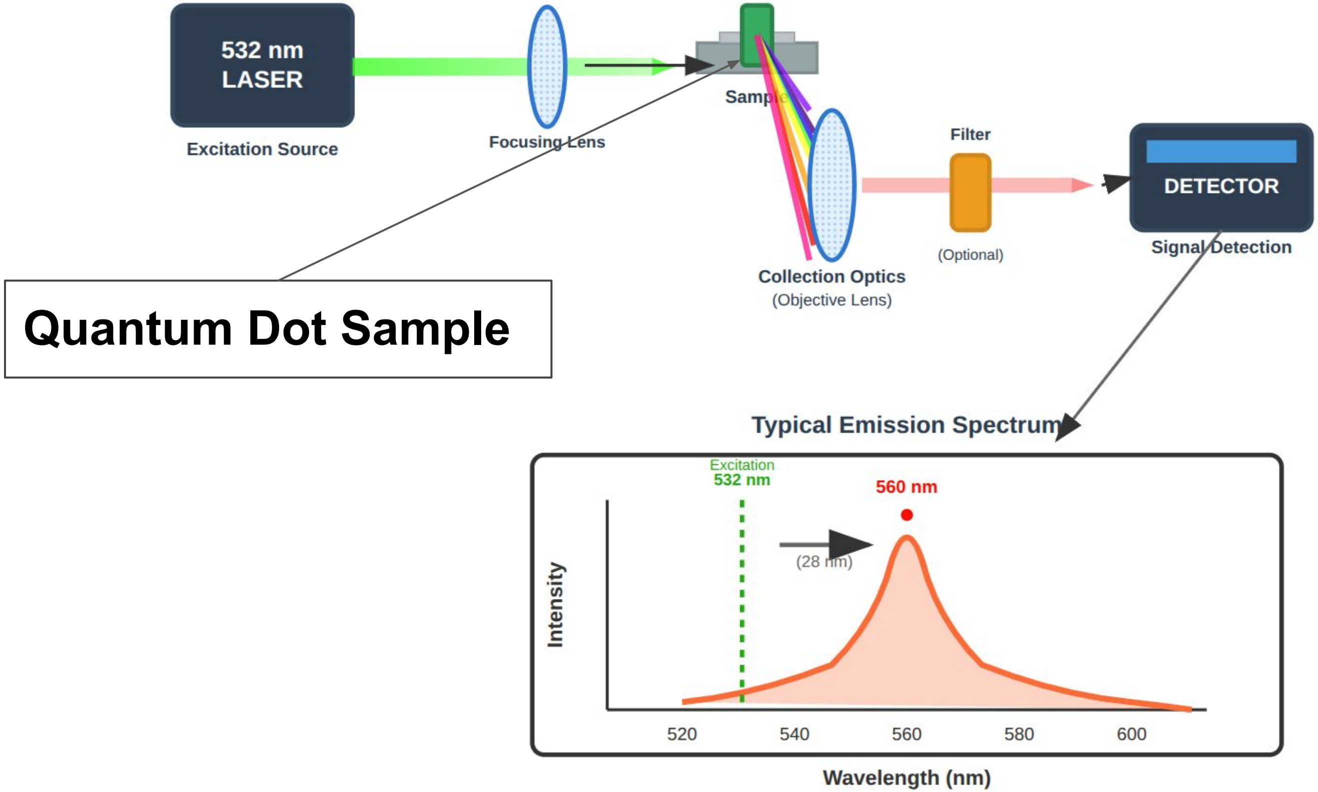
Absorbance Measurement



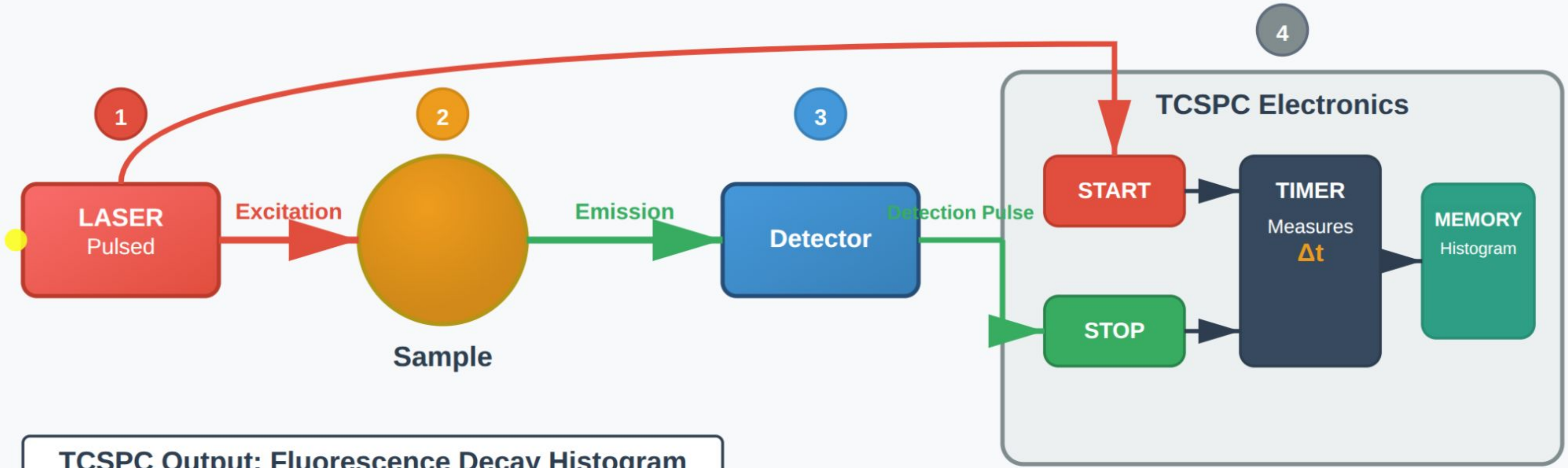




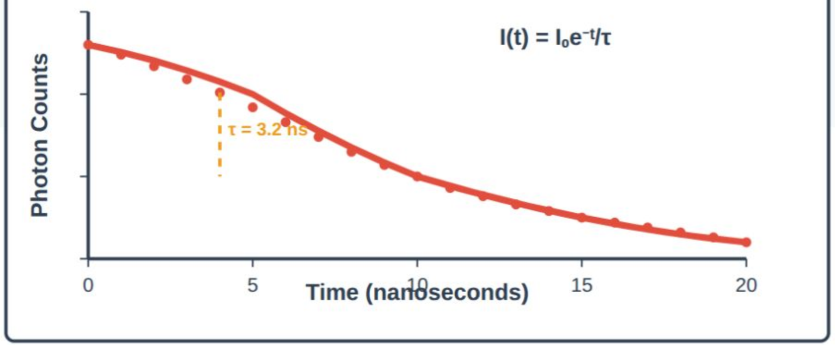
Emission Spectra Measurement



Time-Correlated Single Photon Counting (TCSPC)



TCSPC Output: Fluorescence Decay Histogram

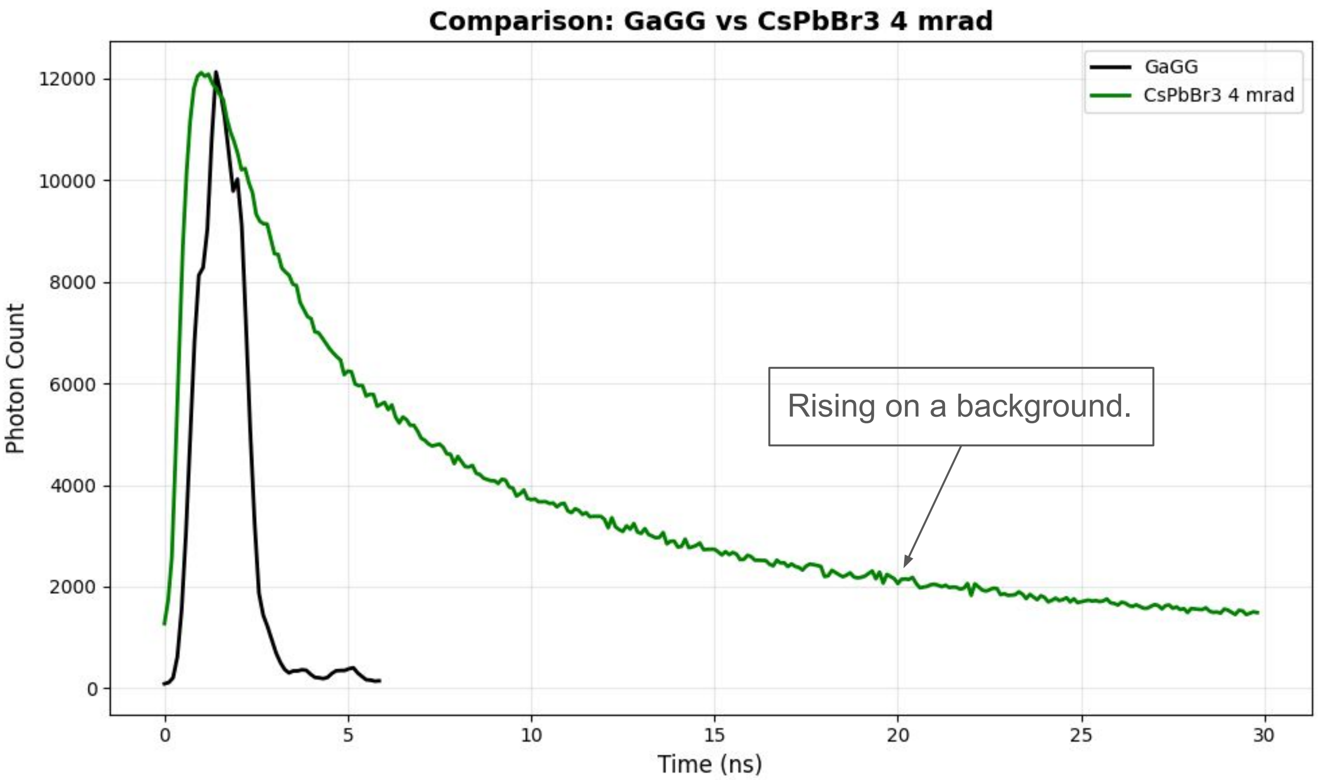


Process Flow:

1. Pulsed laser excites sample → START signal to timer
2. Sample fluorescence → photon emission
3. Detector captures single photon → STOP signal to timer
4. Timer measures Δt → builds lifetime histogram

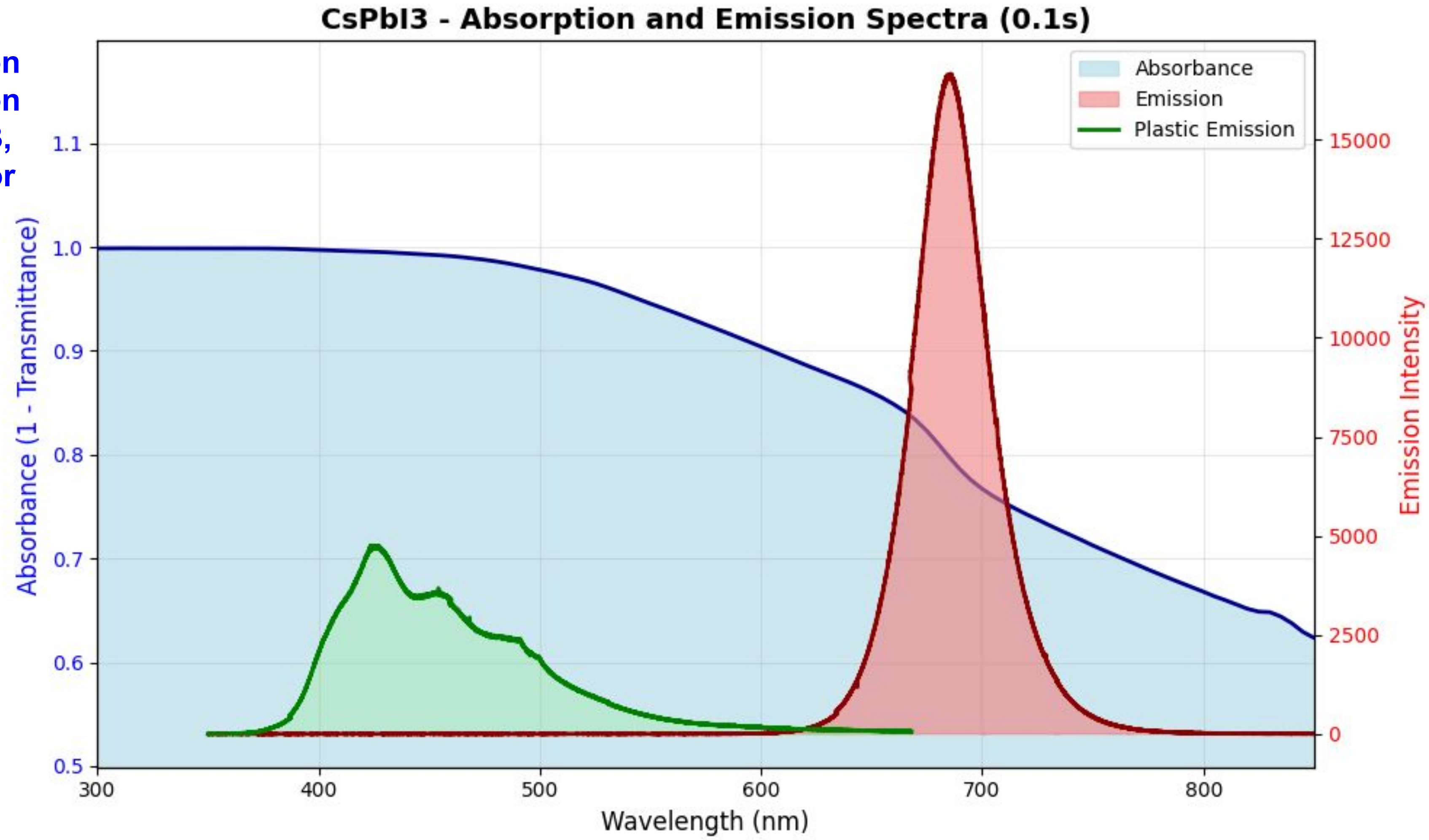
GaGG Scintillator: Time Response

- GaGG Rise component is slower than $CsPbBr_3$ (4 Mrad)
- Infact its slower than all QDs we have characterised ($CsPbBr_3$, CdSe).

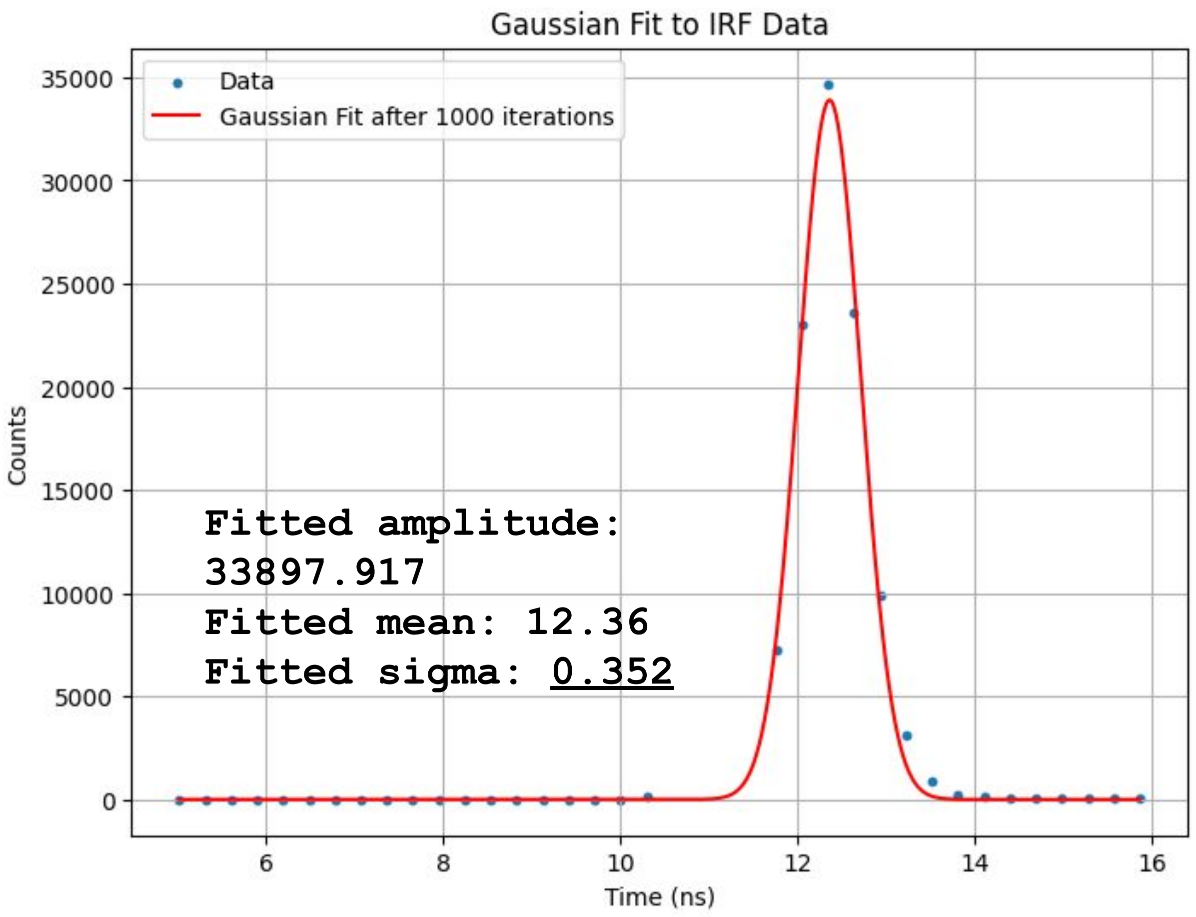


Laser: 532 pulse laser (5ps)
Laser Power: ~7 microW (GaGG)
~70 microW ($CsPbBr_3$) (The shape remains same)
(The set up changed and we had
to accommodate that)
Rep rate: 15.6 MHz (GaGG),
26 MHz ($CsPbBr_3$) (does not matter given the same range. Shorter repetition gives longer tail)

Absorption & emission Of CsPbI3, Scintillator Emission



Instrument Response Function for TCSPC

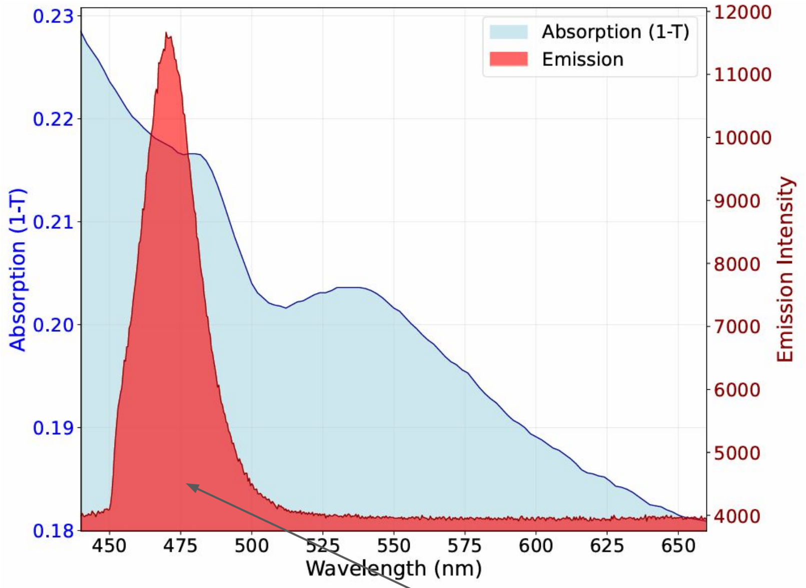


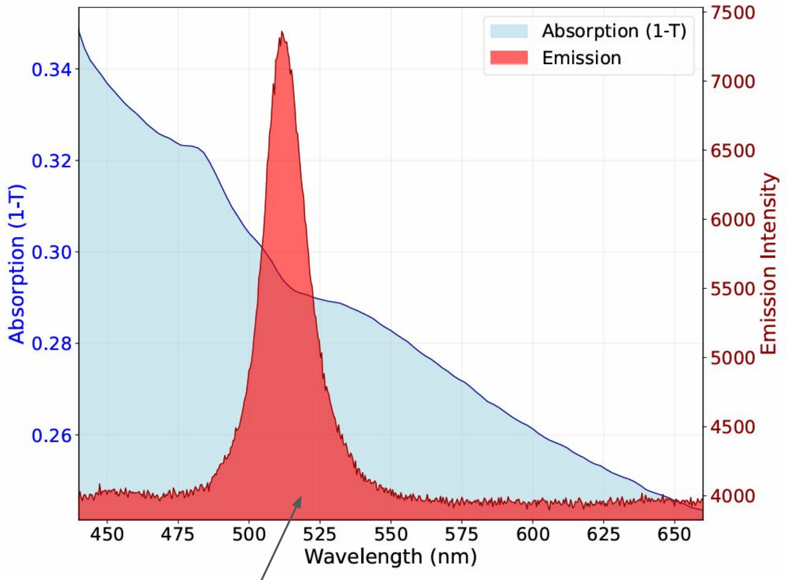
IRF for Time Response Measurement

Laser:
532 nm pulse laser with pulse width of 5ps

Spurious points deleted and IRF shifted

CdSe (470 nm) & $CsPbBr_3$ (510 nm)





CdSe (470 nm)

Sharp emission peaks

$CsPbBr_3$ (510 nm)