InAs/GaAs Quantum Dot Scintillator for 4D Tracking Applications

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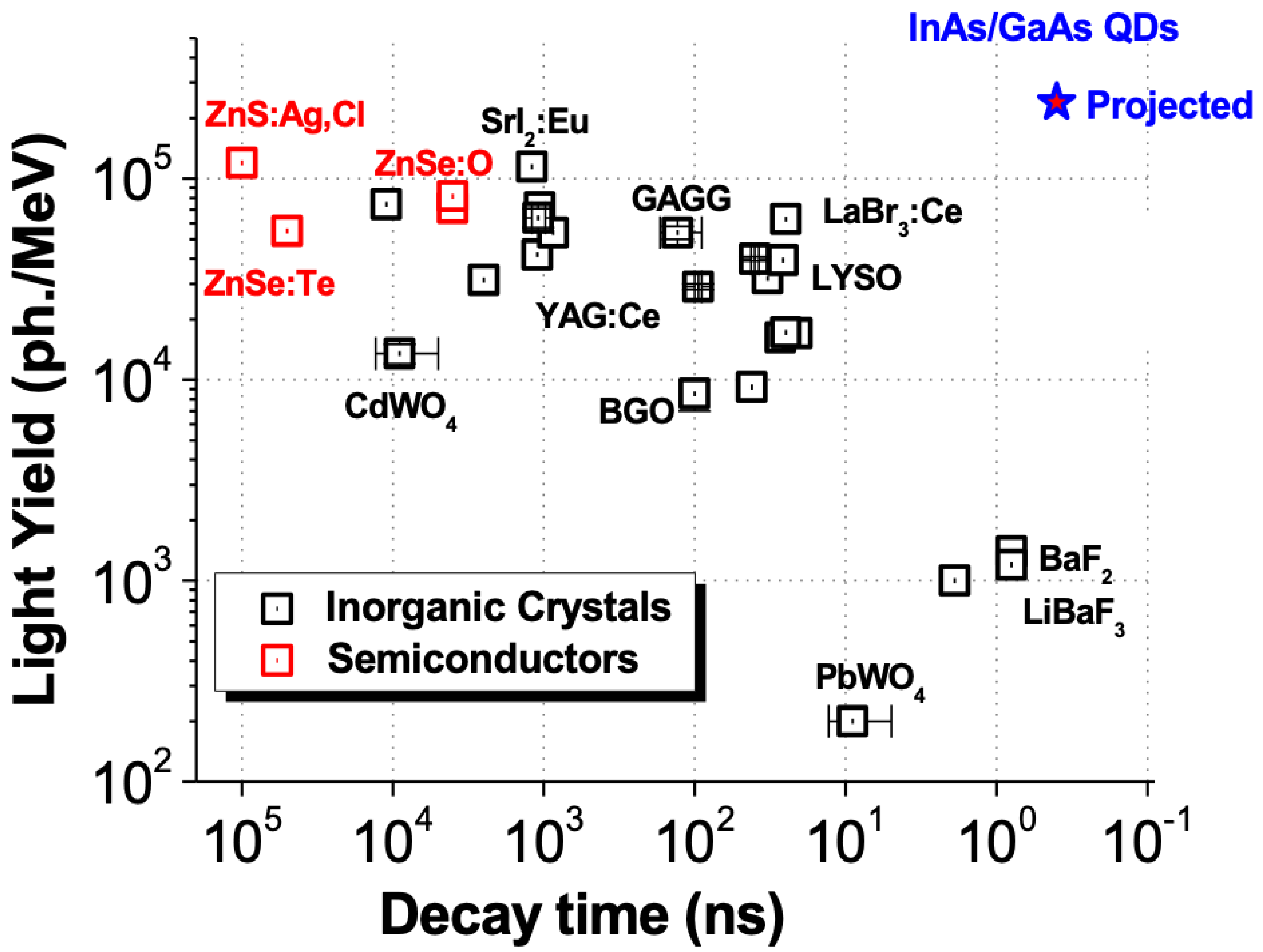
Nanomaterial Based Scintillator with Unique Properties

Very Promising Material – InAs/GaAs Quantum Dot Scintillator

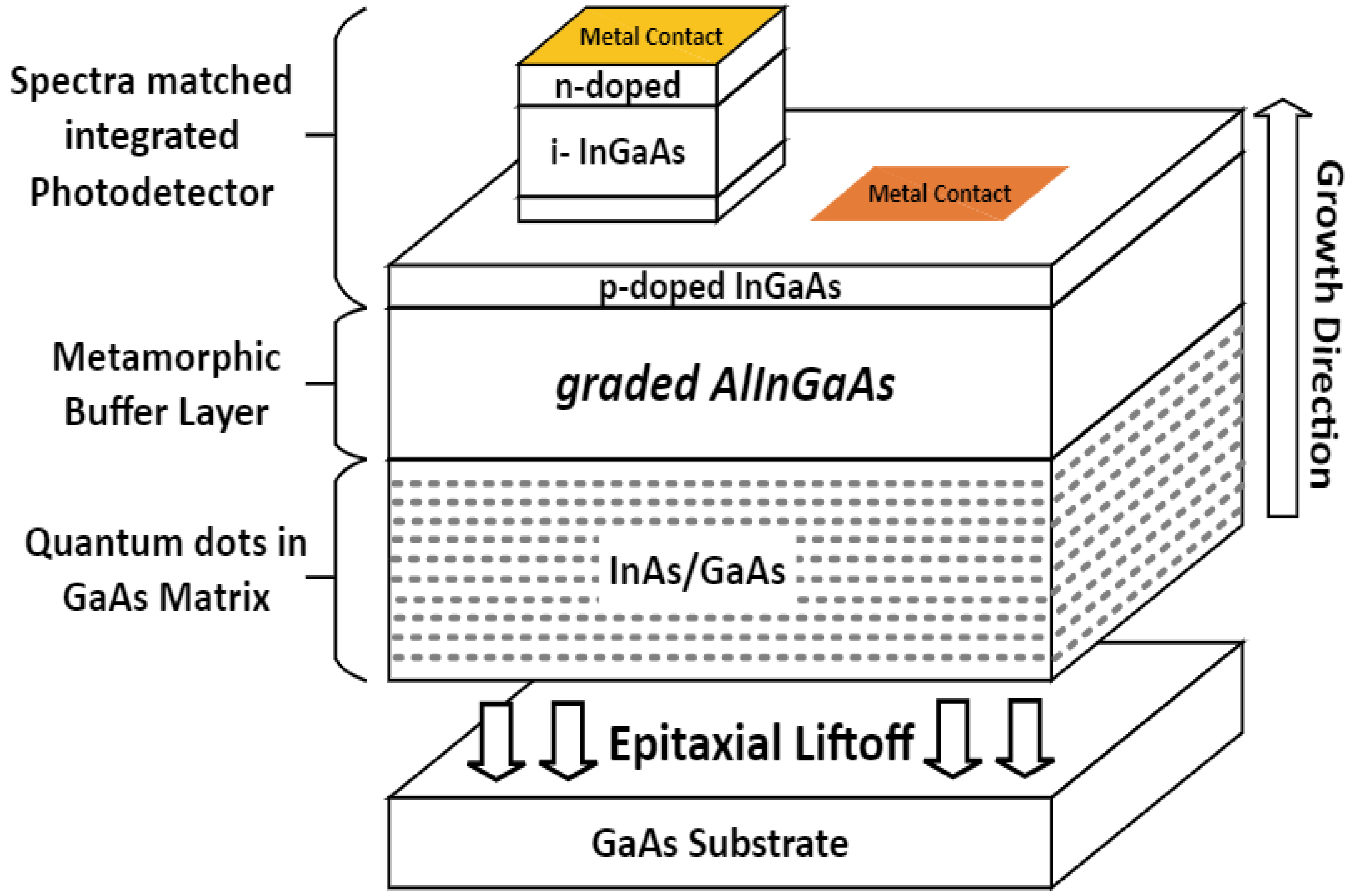
- **High Light Yield (240,000 Photons/Mev)**
- **Fast Luminescence Time (<1ns)**
- **Integrated Photodetector**
- **Radiation Hard**
- **Room Temperature Operation**
- **Low Power**



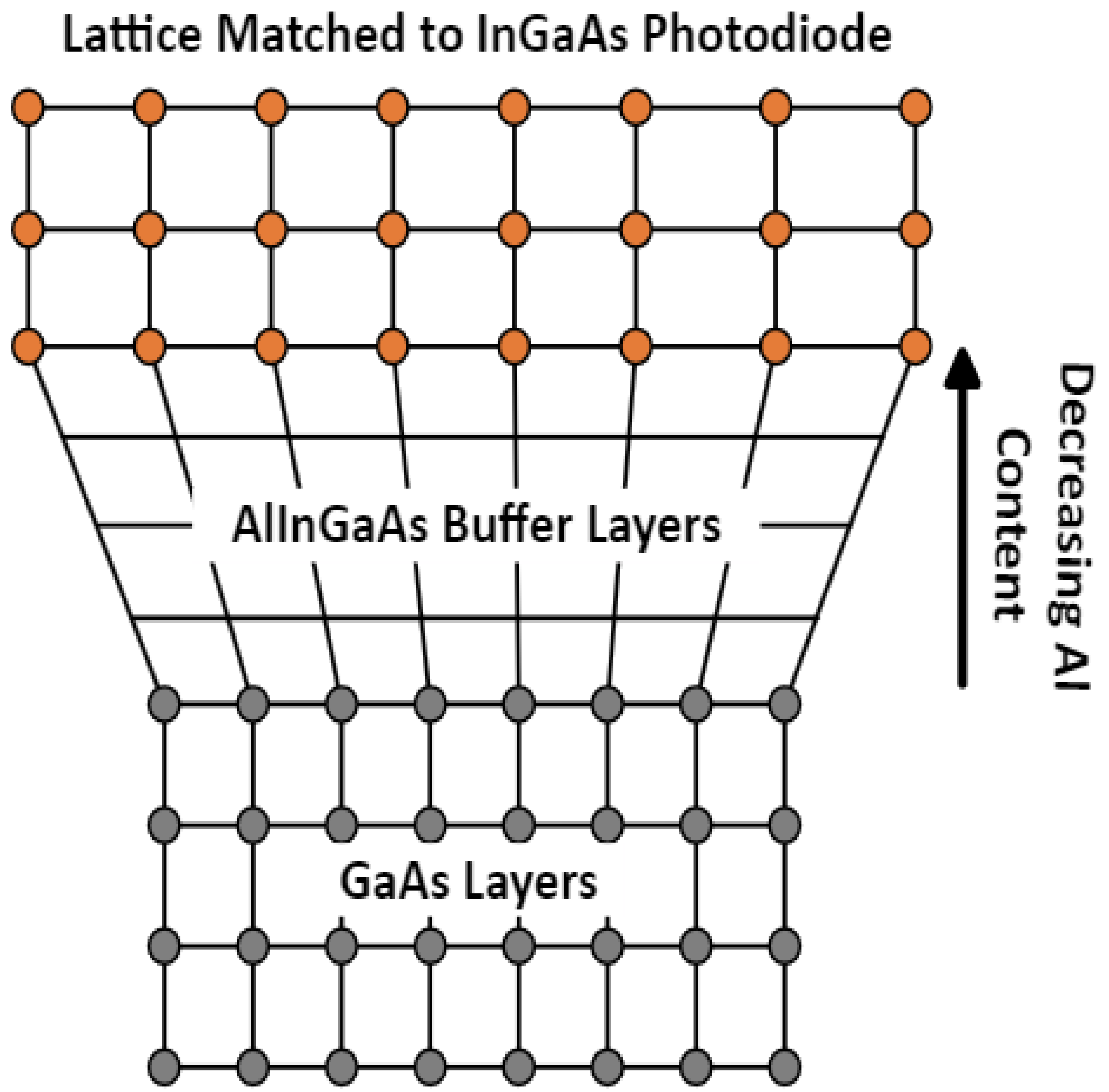
	GaAs	Si
e^- Mobility, μ	8500 $cm^2\ V^{-1}s^{-1}$	1400 $cm^2\ V^{-1}s^{-1}$
# e^--h pair generated by MIP	*163 pairs/μm*	*80 pairs/μm*

Growth and Fabrication of InAs/GaAs Scintillator

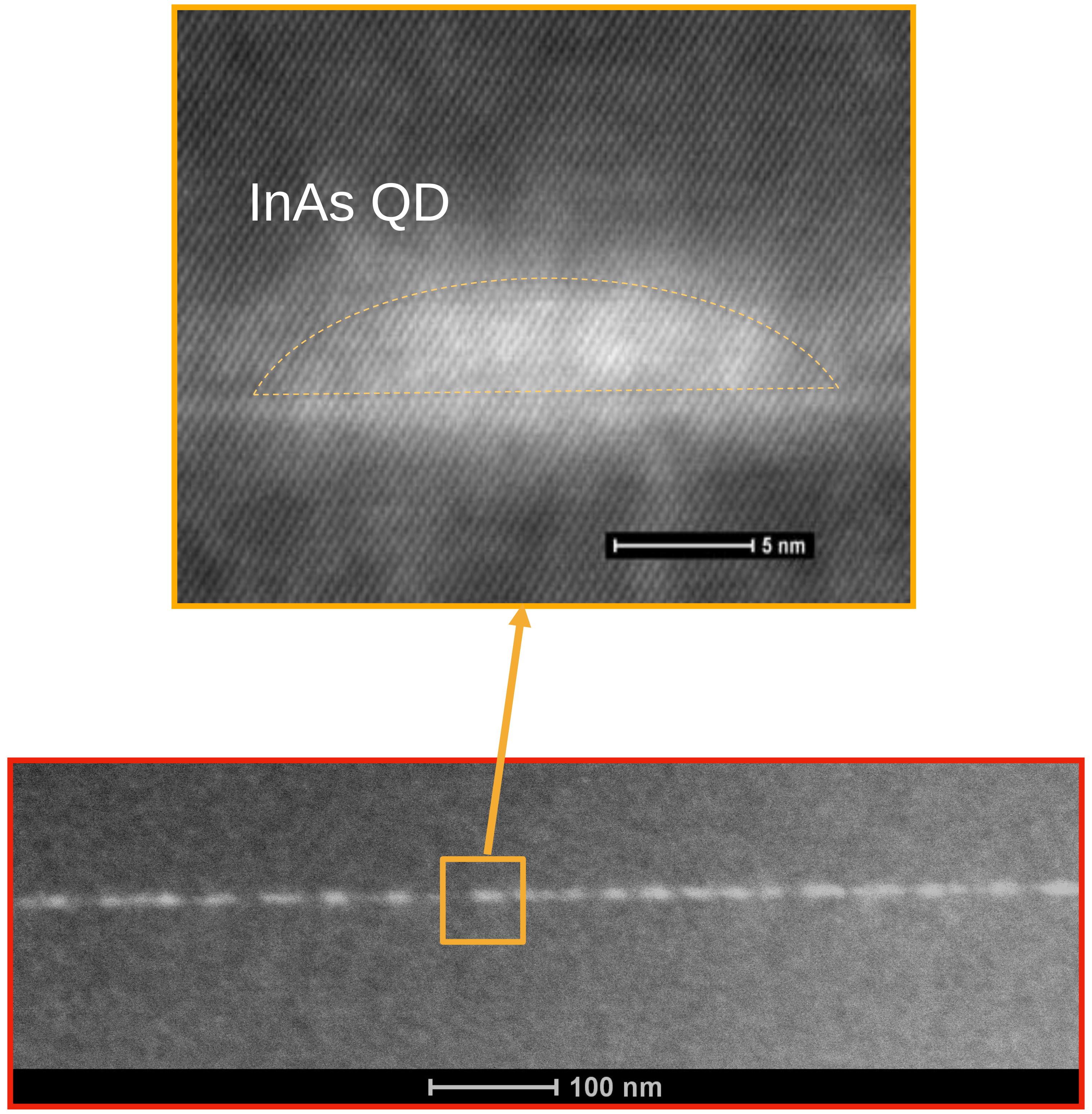
- **Medium is grown as thin film heterostructure using molecular beam epitaxy**
- **Photodetector is monolithically integrated in same epitaxy growth**
- **Compatible with full-wafer processing similar to Si technologies**



InAs QD Detector Schematic

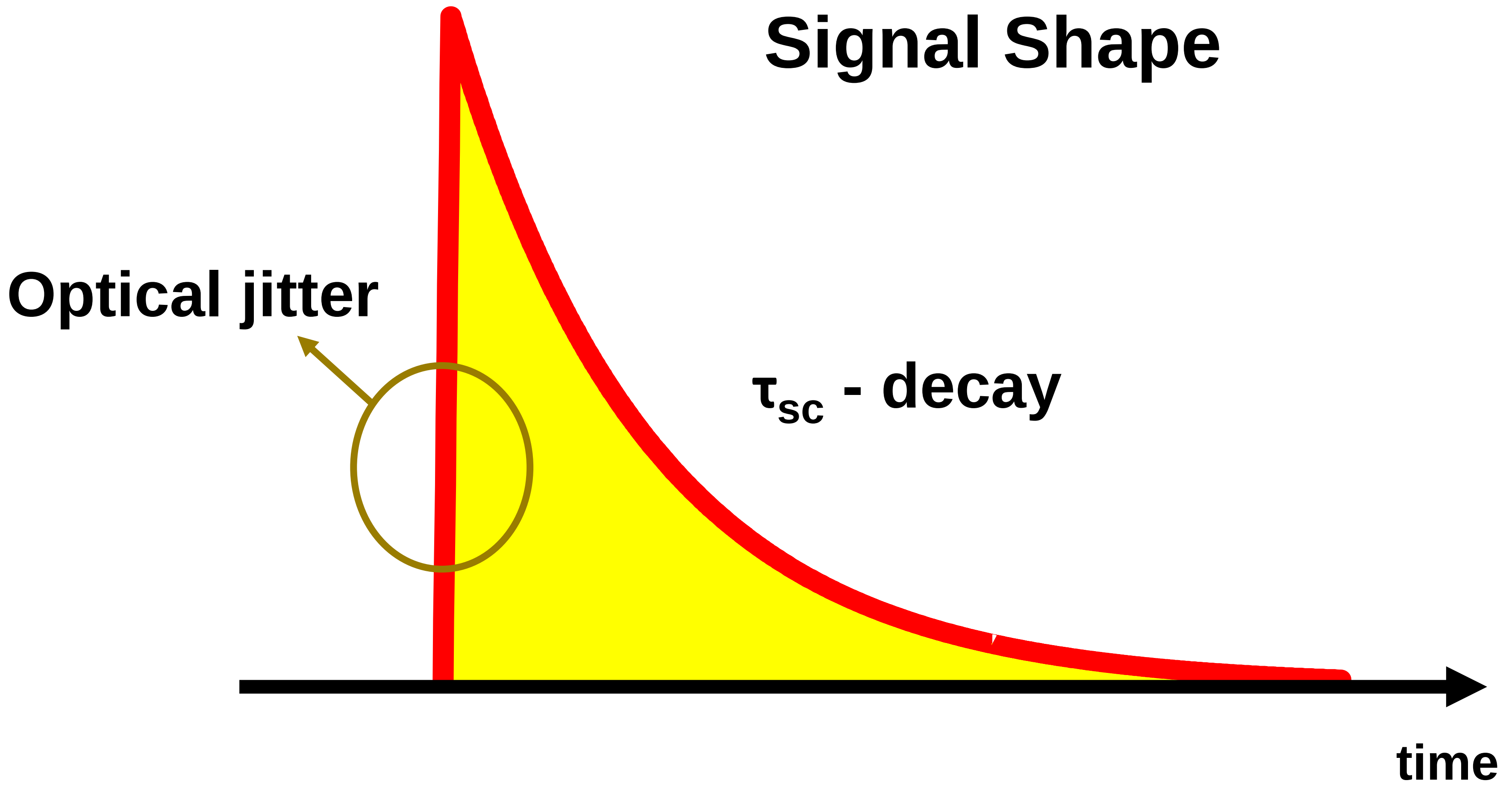


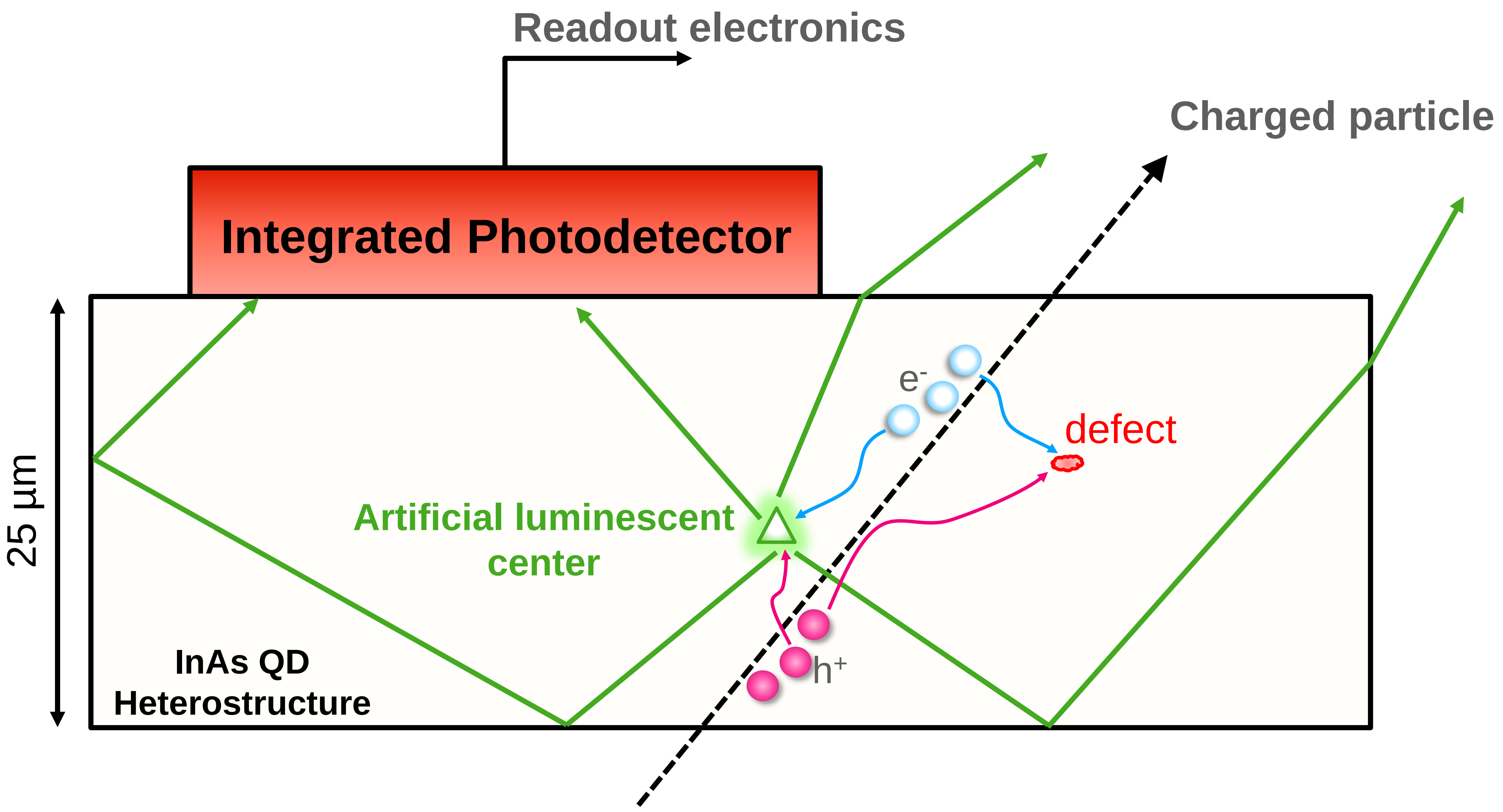
Monolithic Photodetector Integration Scheme



The detector is grown, fabricated and tested in CNSE's Clean room and further testing is being done in FNAL

Moving from Charge Drift to Light Collection





Collects photons not carriers

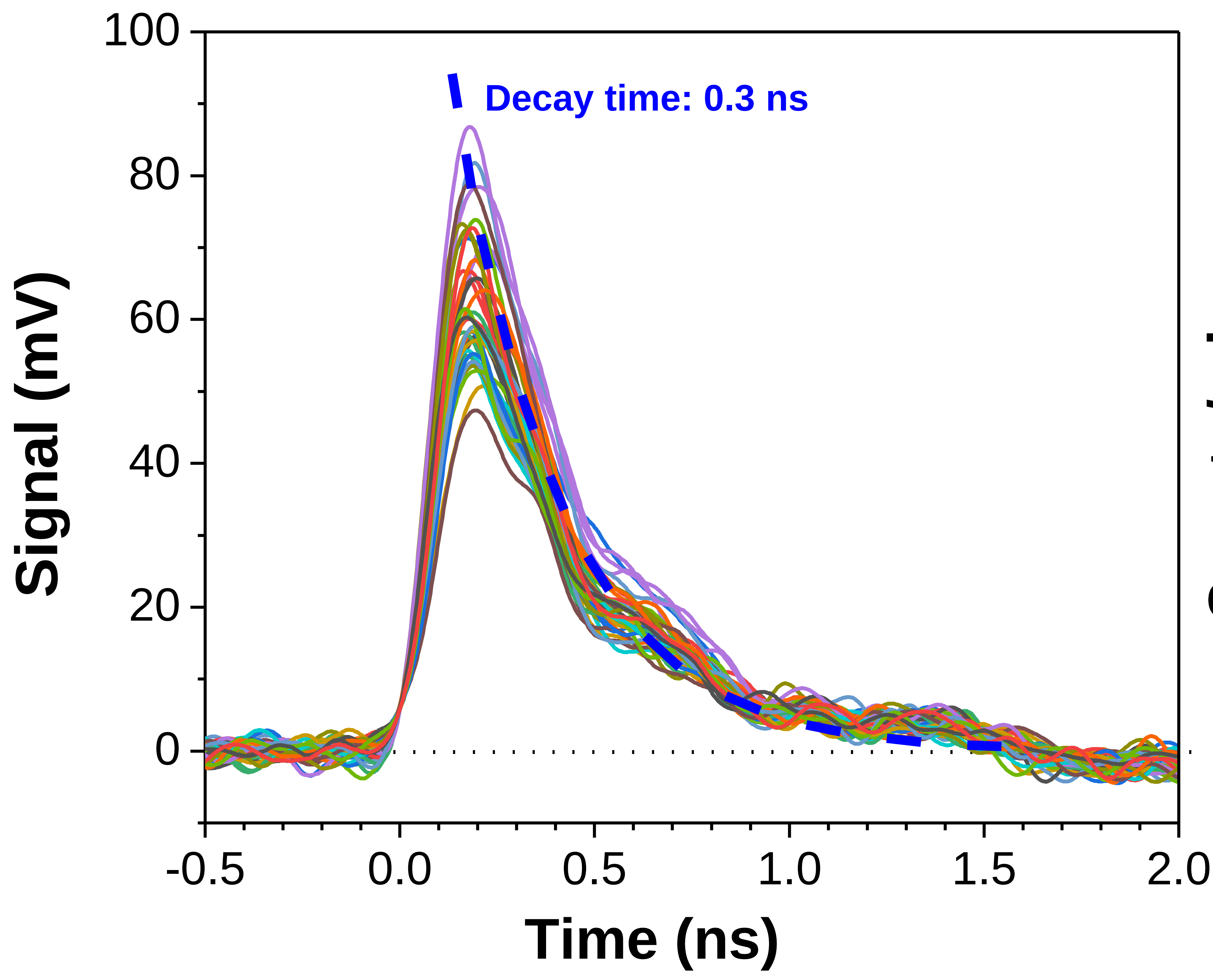
The detector consists of three integrated systems:

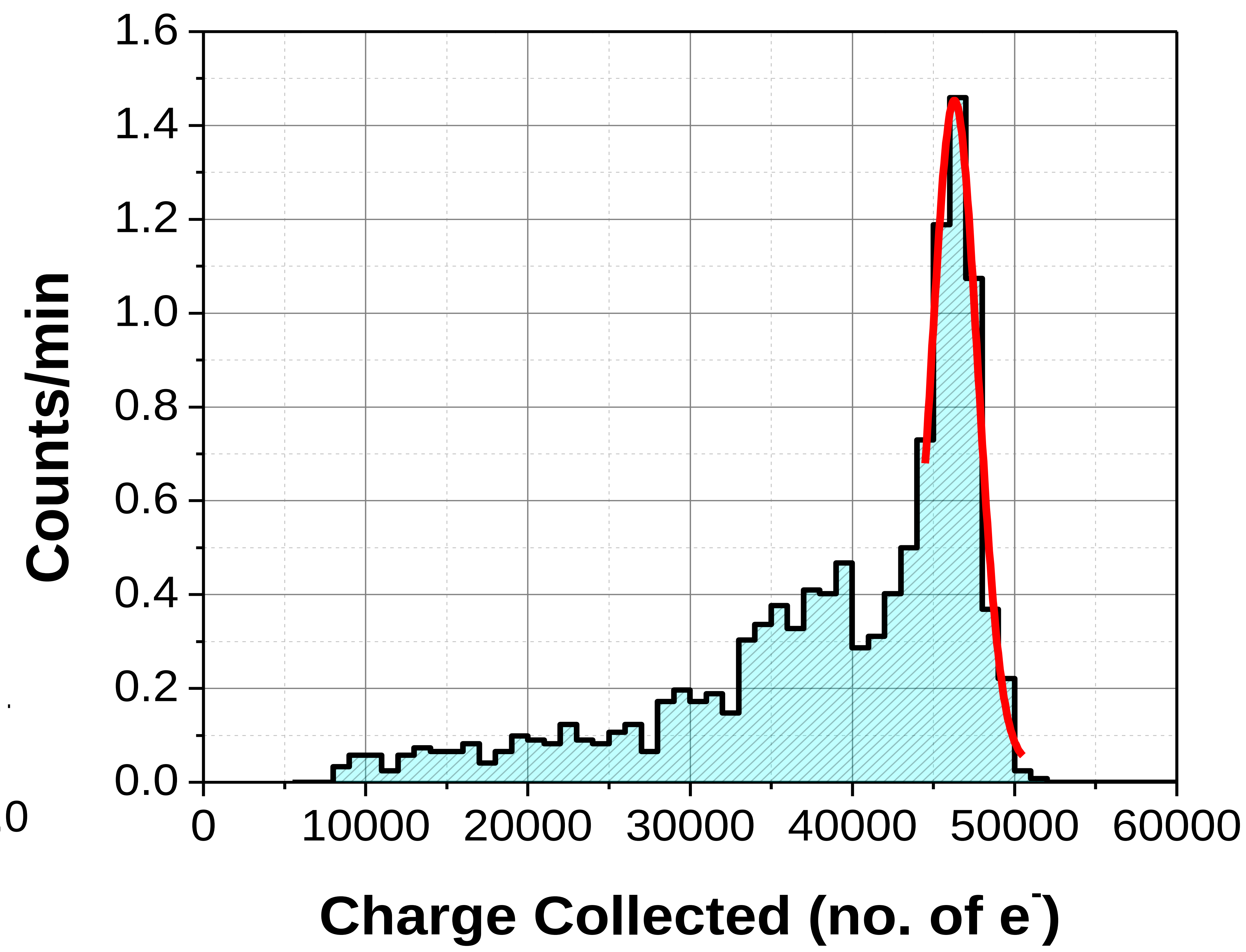
- QD/semiconductor as a radiation stopping material
- Waveguide for QD emission
- Photodiode for optoelectronic conversion

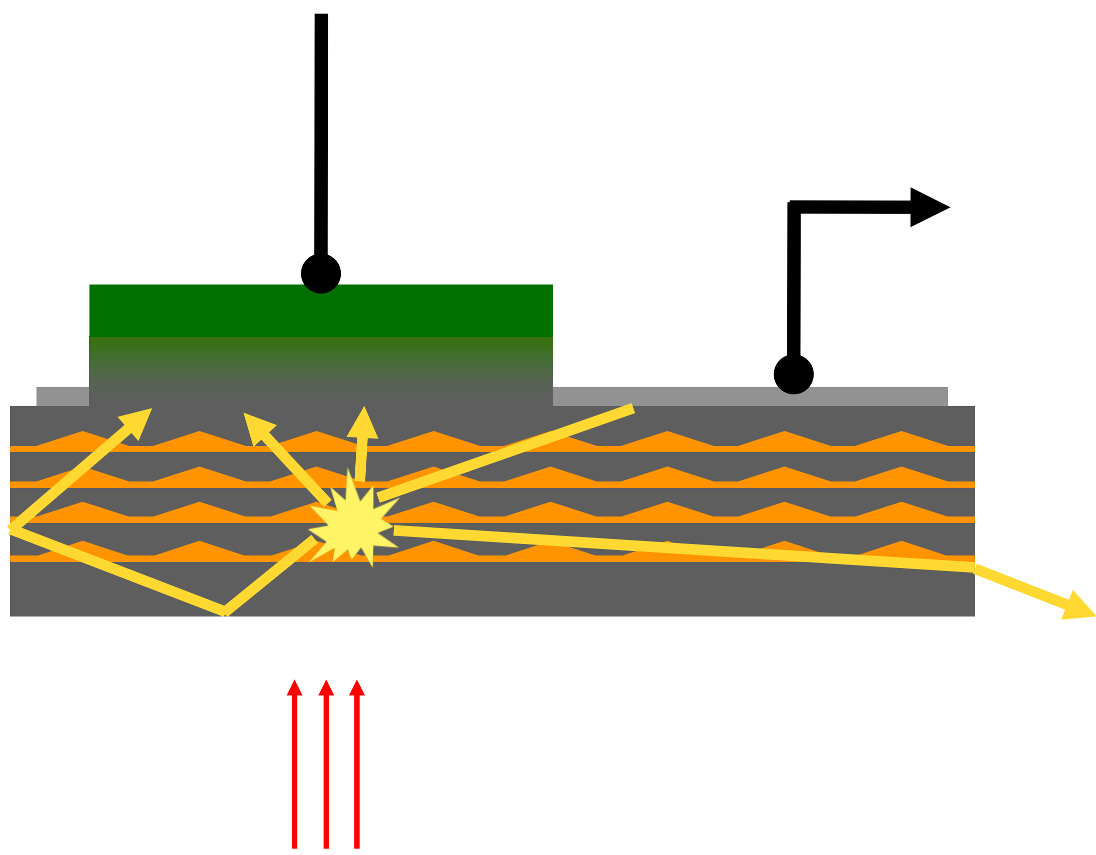
Signal Formation in InAs QD Scintillator:

- QD does not start emitting light until electrons reach QDs and start recombining
- Total jitter time including drift and capture process is **10 ps**
- As the capture is complete generated light output peaks and undergoes exponential decay
- Luminescence decay is dictated either radiative or non-radiative recombination

Measurement of 5.5 MeV Alpha Particle



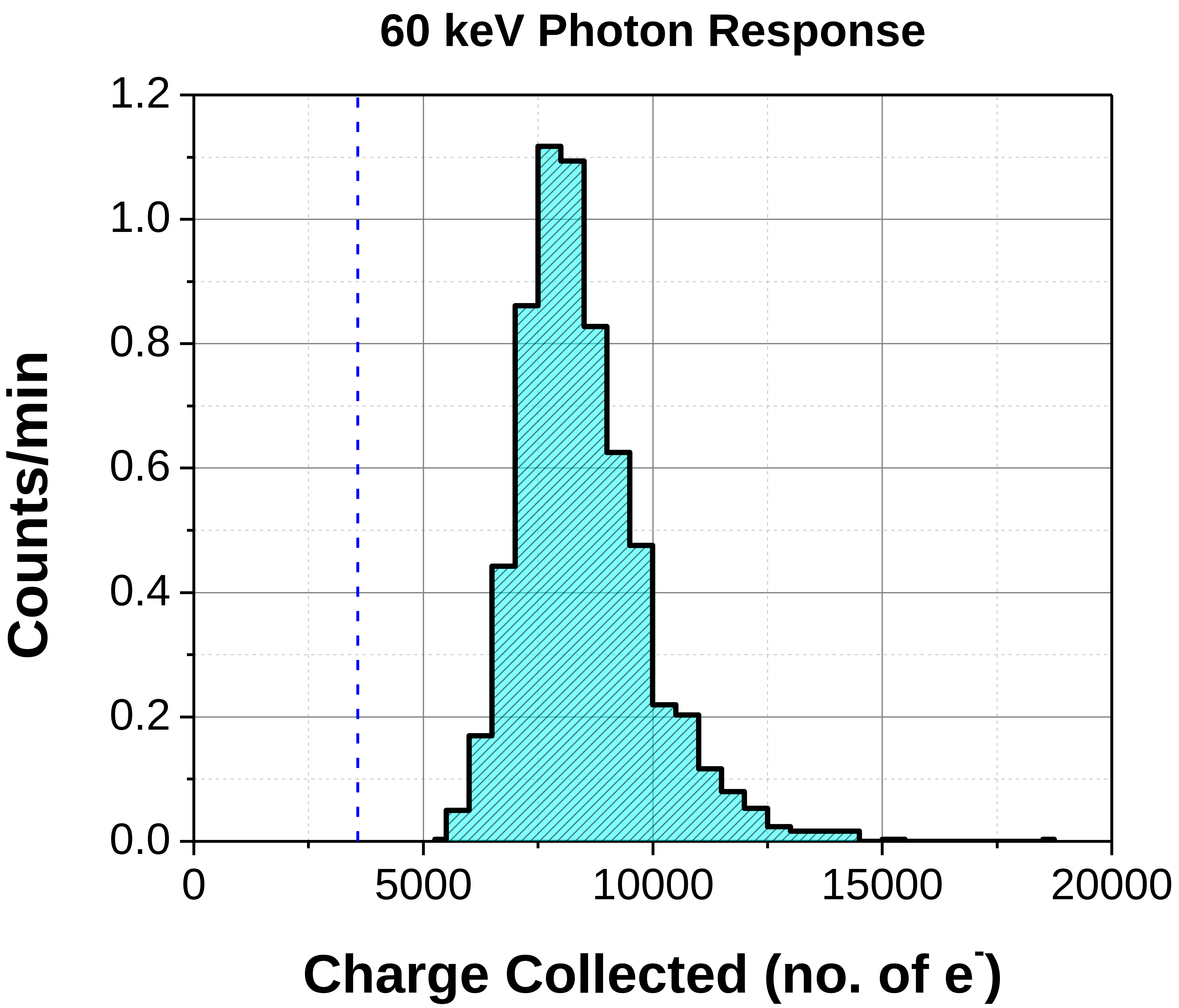




No direct ionization in photodetector

- The response of detector is dictated by **light collection efficiency and geometry**
- Light collection is limited by losses due to **surface scattering** and **self-absorption**
- **Sub 0.1 ns scintillation risetime**
- Energy resolution, **ΔE/E = 7.2%**

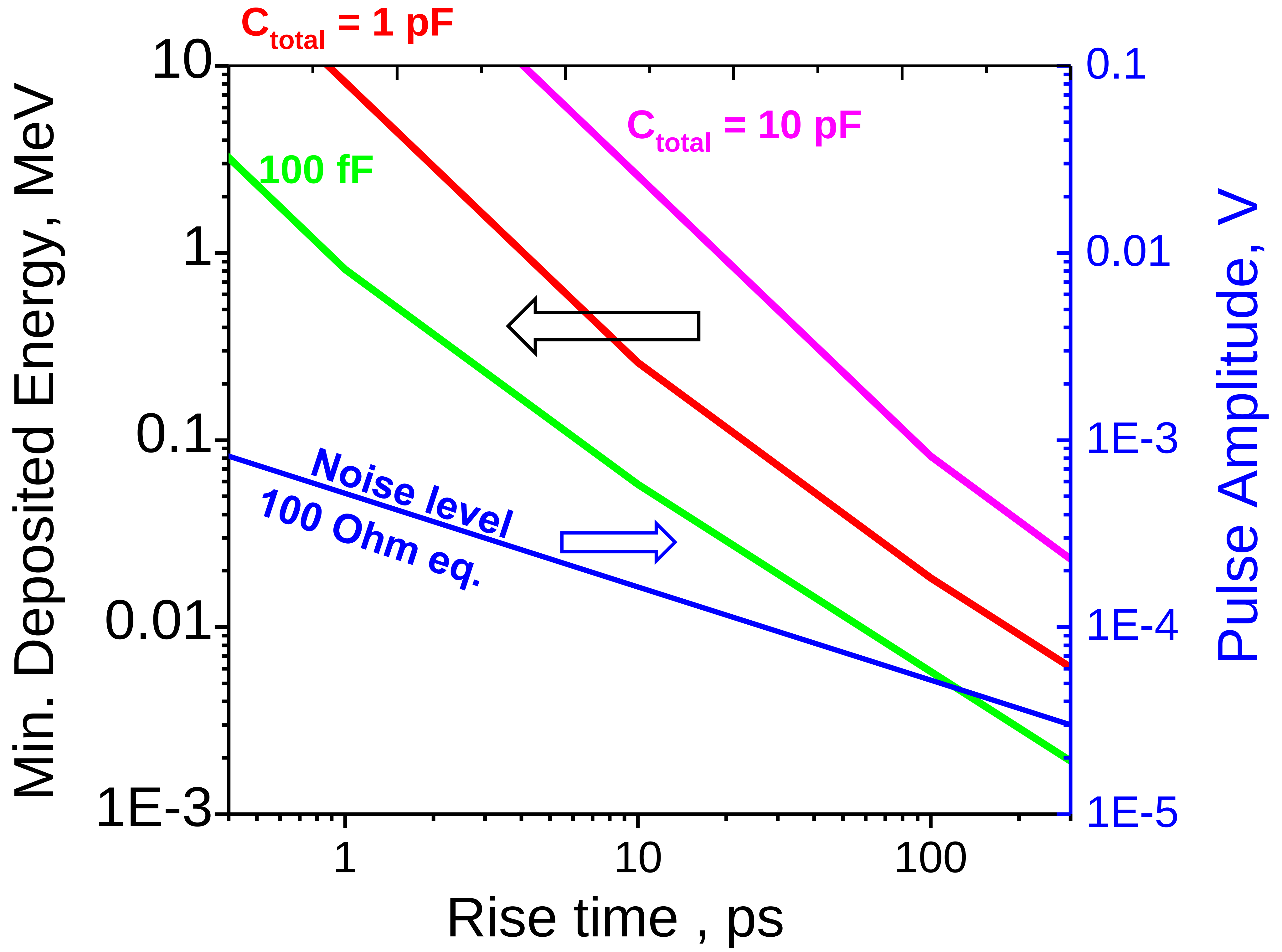
Low Energy Photon Measurement with InAs QD Detector



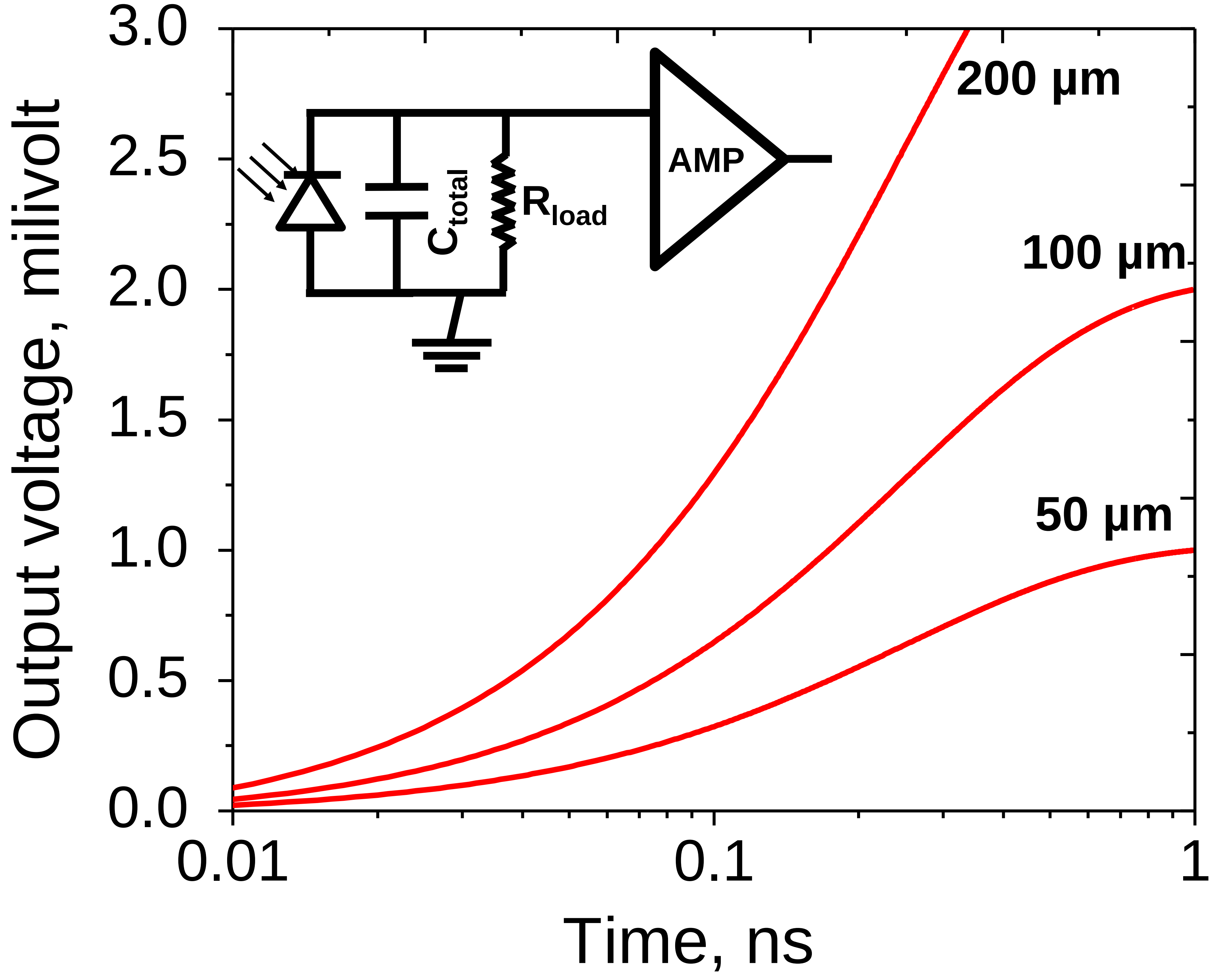
- Alpha particles (Am-241) were screened by 150 µm polymer sheet
- Tail of charge distribution is observed
- The response is currently limited by system noise
- Charge collection greater than **166 ph. e/keV**
- Possible Birks quenching in scintillator

Moving towards MIP Detection with InAs QD Scintillator

Projected performance of QD scintillator detector

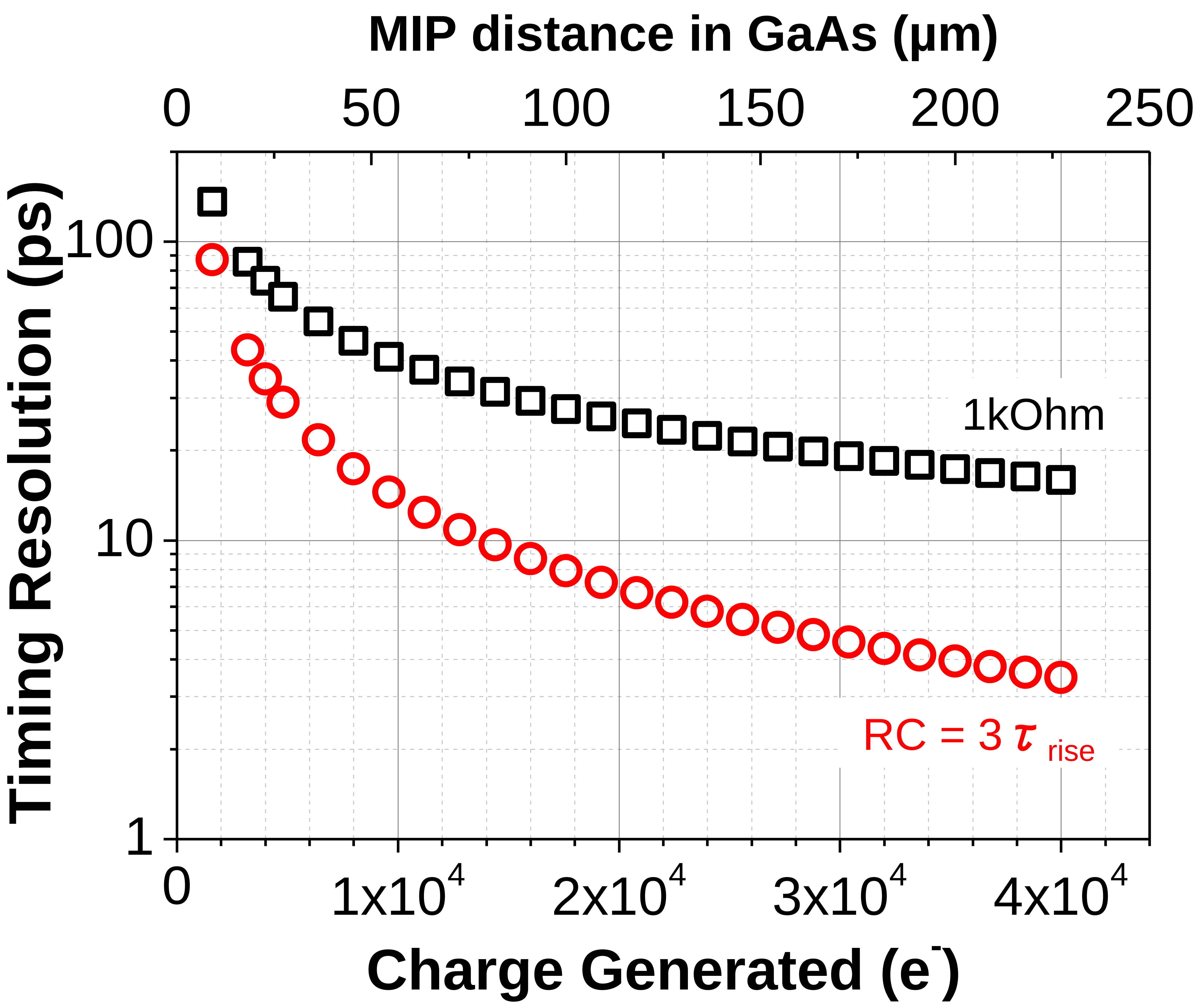


Simulation of MIP signal response of QD scintillation detector



- Fixed scintillator decay time (300ps) → Rise time reduces with deposited energy
- **Lower detector/total capacitance** is needed for fast timing and low noise operation
- Front-end electronics with **optimal resistance load** enables <100 **ps timing resolution**
- Leading edge signal shape of the scintillator/PD device for MIP in thicker device

Moving towards MIP Detection with InAs QD Scintillator



- Timing resolution is improved in thick scintillator (speed of light ~10^3x higher than drift velocity)
- The major source of noise is **resistive load**
- **10 ps timing resolution** is feasible without avalanche multiplication

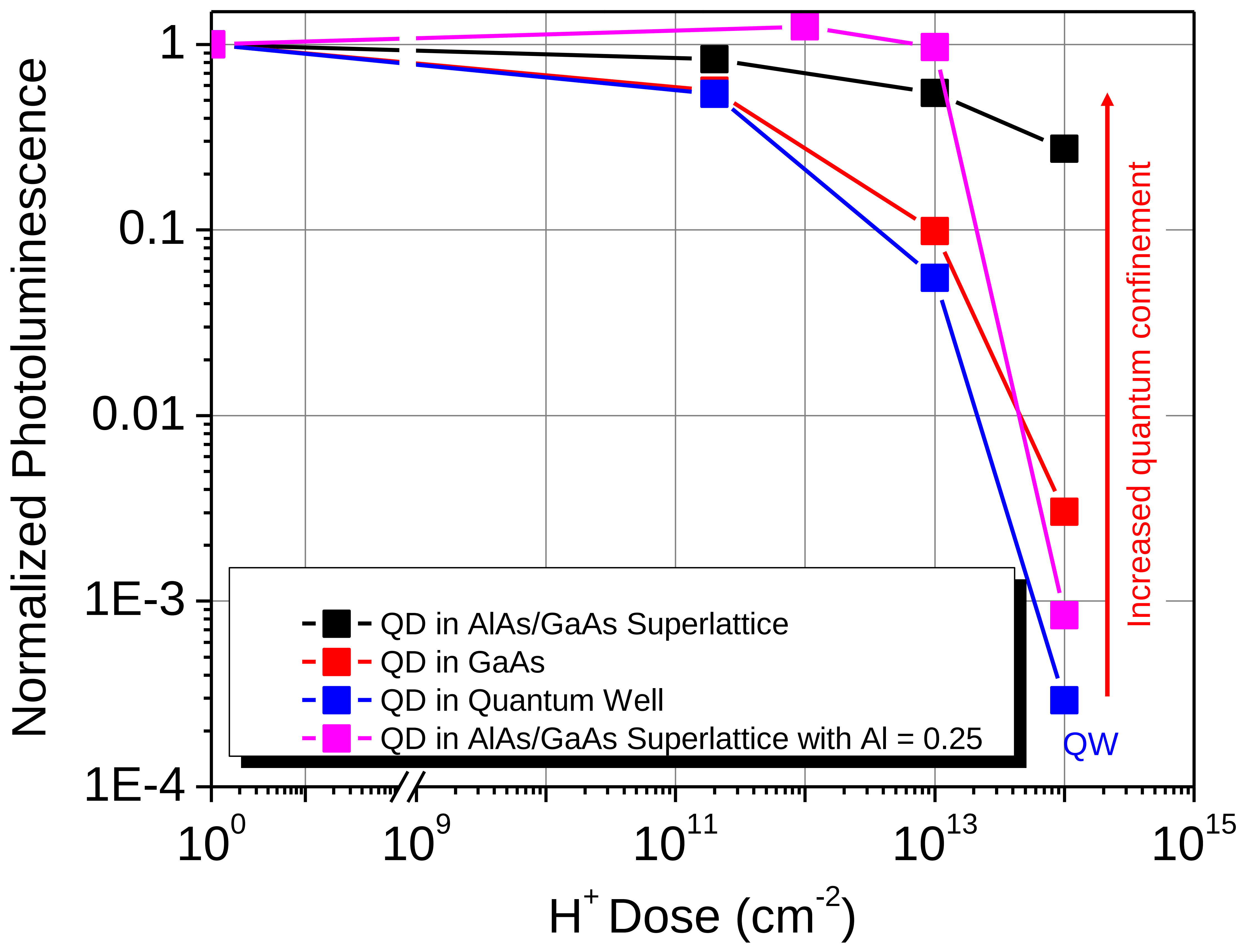
However,

- Challenges associated with growing >50 μm thick scintillator
- Different approaches needed to make thicker scintillator material – epi to bulk

MIP Detection ⟶ ***thick detector*** ⟶ ***improved timing resolution***

Engineering of Radiation Hard InAs Quantum Dots

Effect of 1MeV H^+ irradiation on QD photoluminescence



- Proton generates displacement defects along its path
- Degradation of the PL due to non-radiative recombination on these defects
- The **highest radiation hardness** is observed in QDs embedded in **AlAs/GaAs superlattice** structure, corresponding to $Al_{0.2}Ga_{0.8}As$ alloy
  - **Highly localized states** of carriers in QDs
  - **Lower probability** for carriers to escape the QDs and recombine non-radiatively

InAs Quantum dots can be designed to be radiation hard by hosting it in high barrier matrix

Summary

- We have demonstrated detector technology based on quantum dot embedded in GaAs semiconductor capable of ps timing resolution.
- We have measured **10,000 ph. e /MeV**, **100 ps** rise time with α–particles in **photovoltaic mode** (no bias voltage on PD) at **room temperature**

  - ***fastest and highest light-yield of any known scintillator***

  - still only 10% of expected performance
- Preliminary 60keV photon measurement demonstrated charge collection greater than **150 ph. e/ keV** (theoretical maximum 240 ph.e/keV in GaAs)

  - currently limited by readout noise

  - possible Birk's quenching
- We have assessed radiation hardness with 1MeV H^+ up to 10^{14} cm^{-2} ***only 2x reduction***