Scintillating quantum dots for ultrafast charged particle detection

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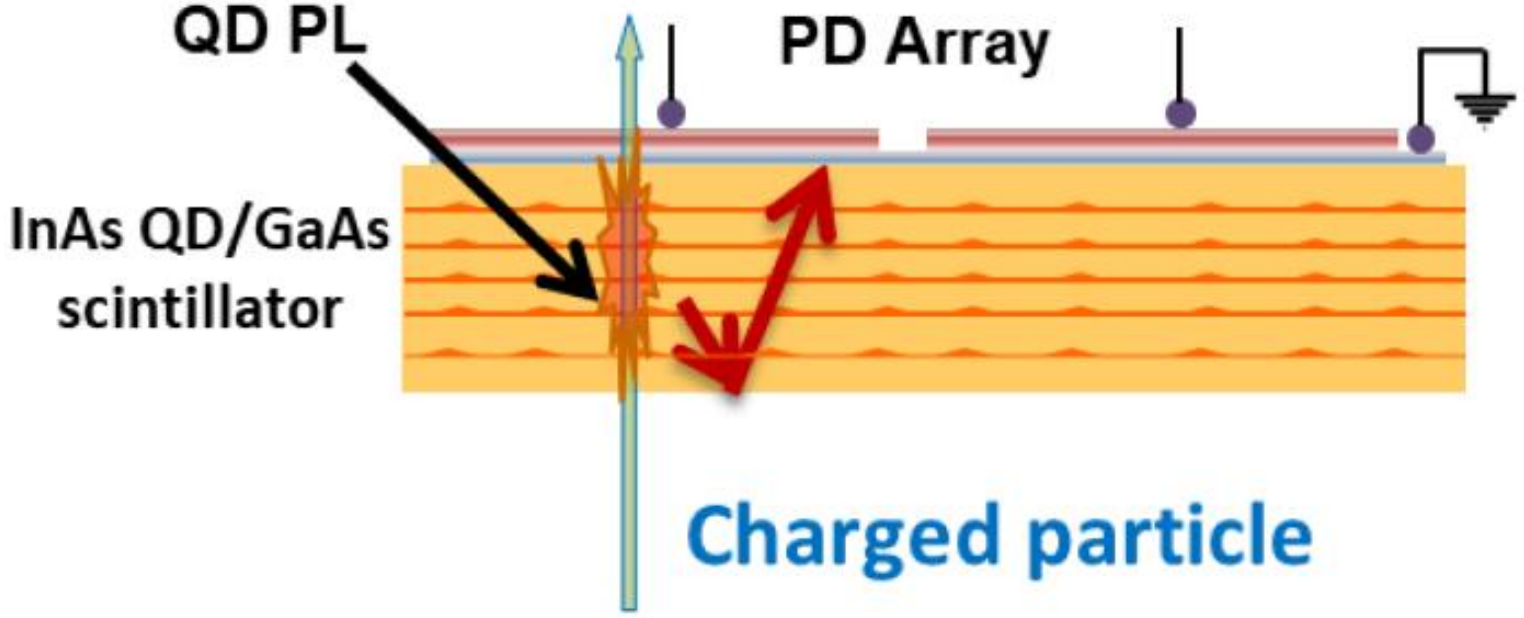
Fermilab

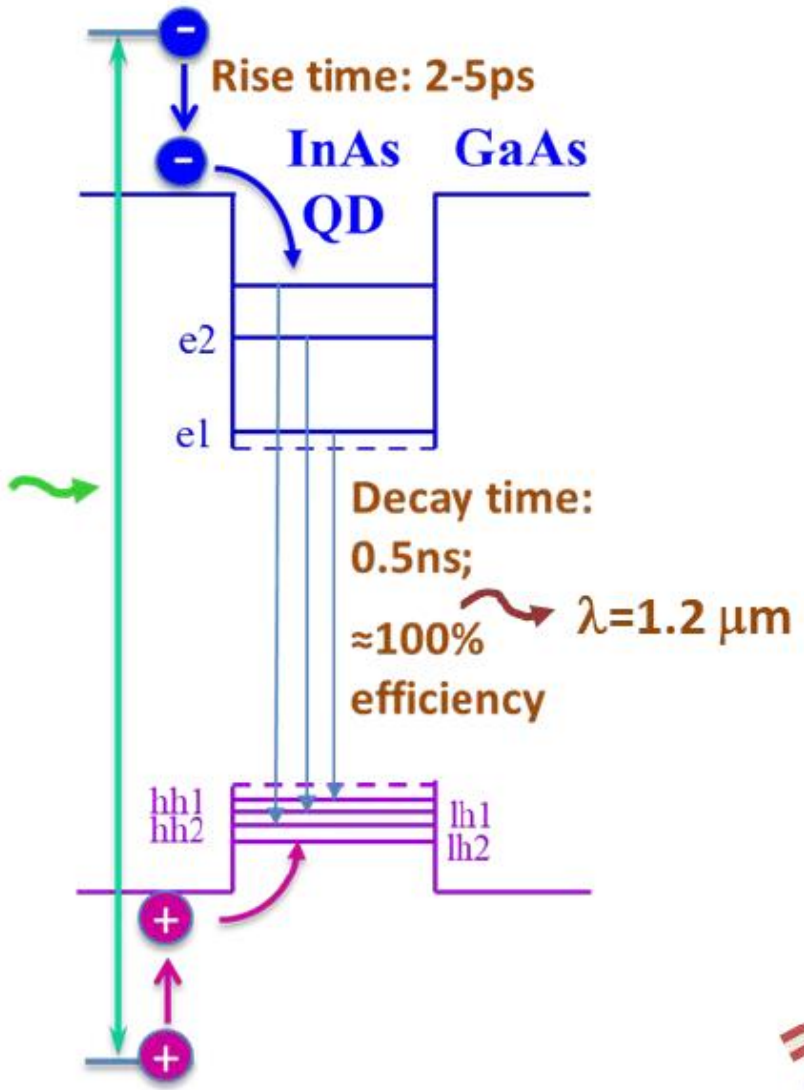
Blue skies question

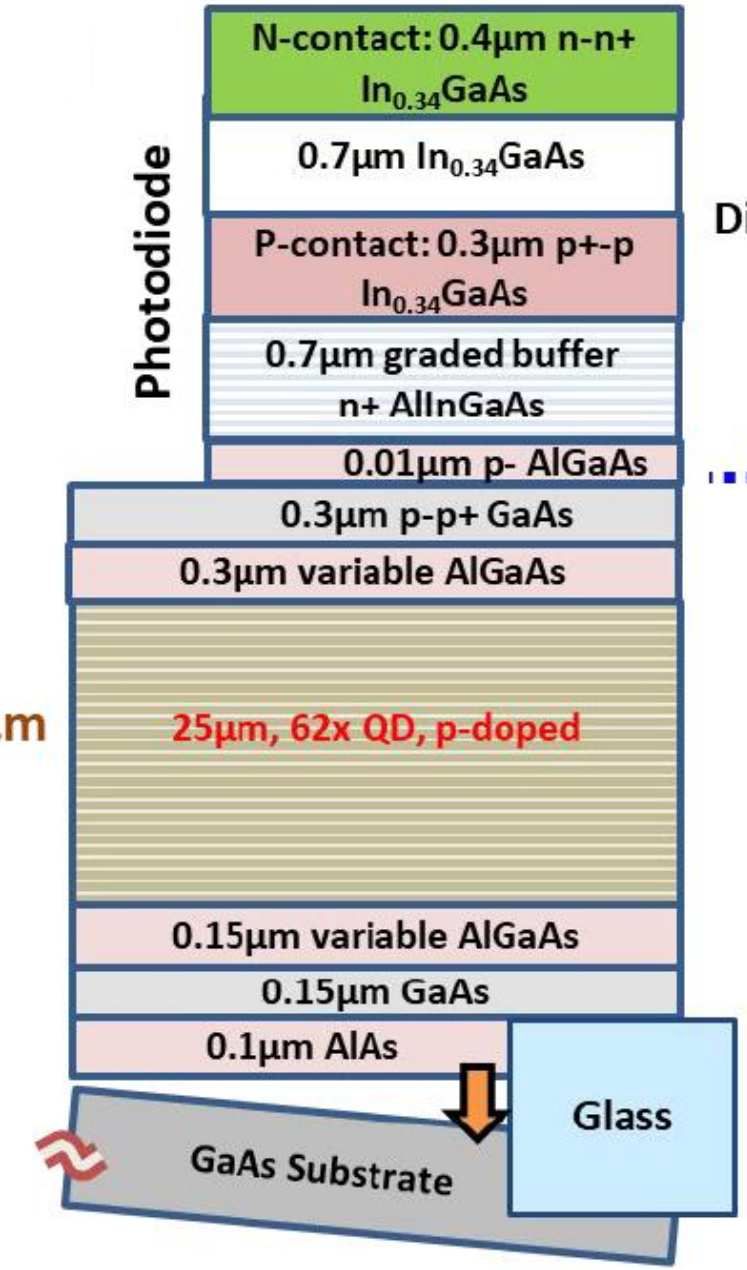
Can we replace slow charge drift with fast optical signals in low mass detectors with high carrier mobility?

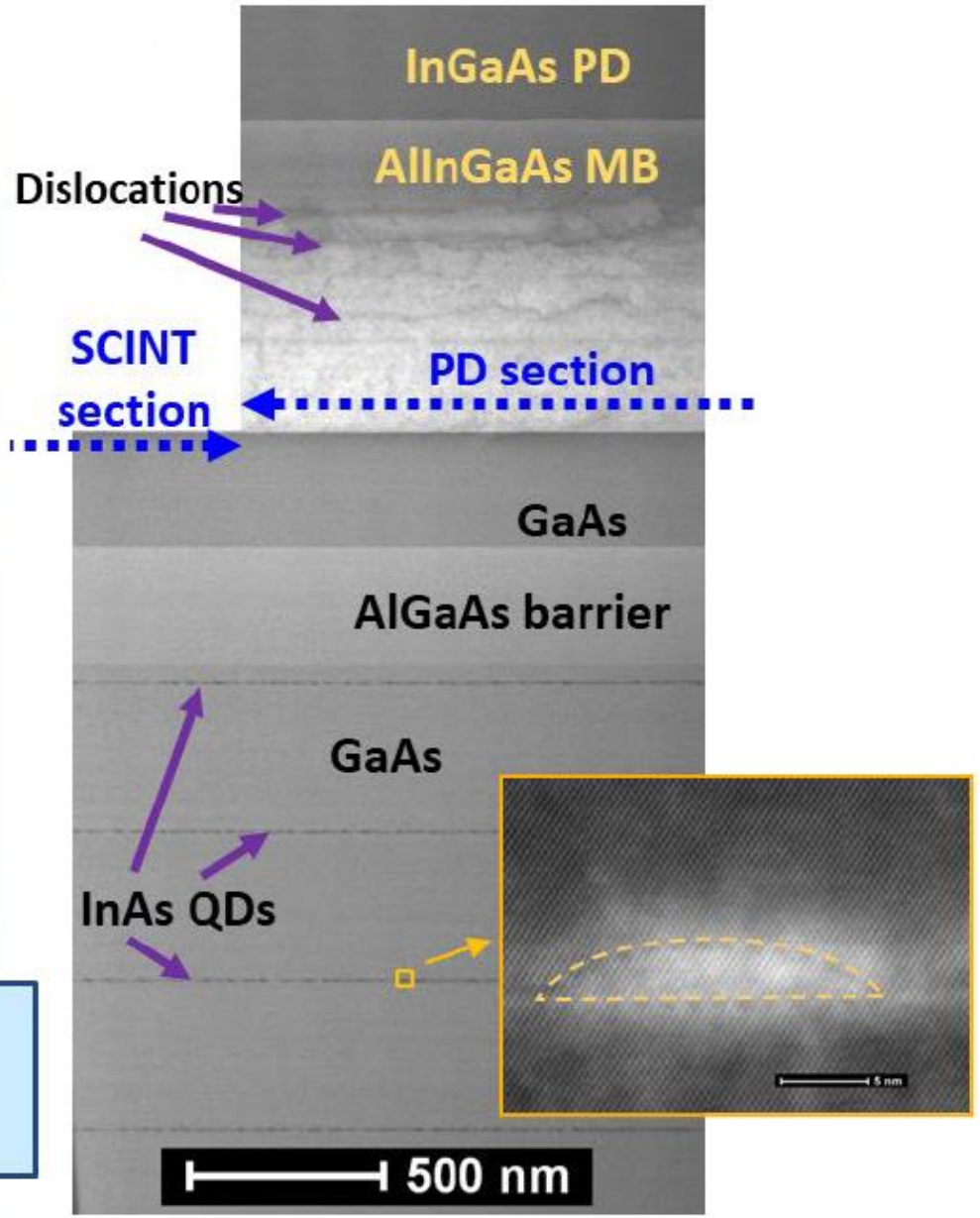
Detector Concept

- Thin layers of InAs quantum dots (QDs) sandwiched between layers of GaAs
- Ionization electrons in GaAs fast captured by QDs
- QDs scintillate via de-excitation (<500 ps), light collected by integrated InGaAs photodiode
- Grown via molecular beam epitaxy at U. Albany

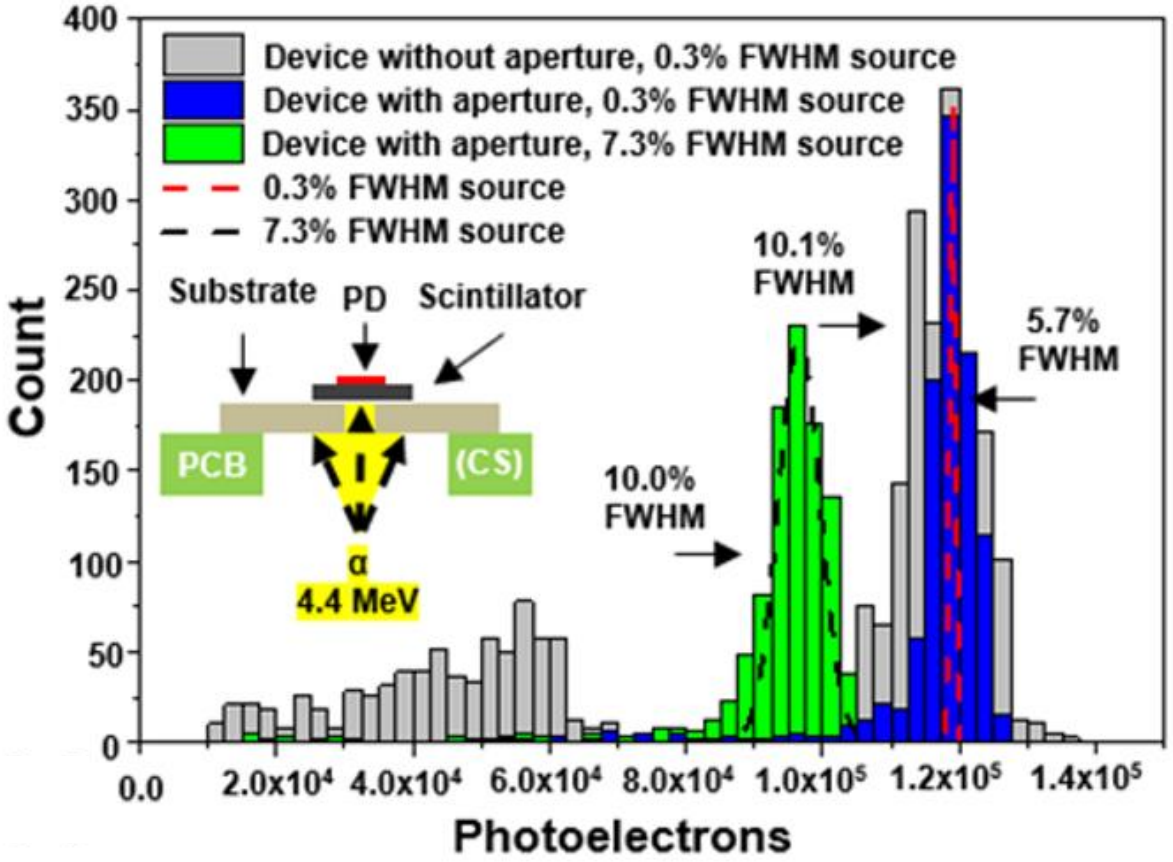


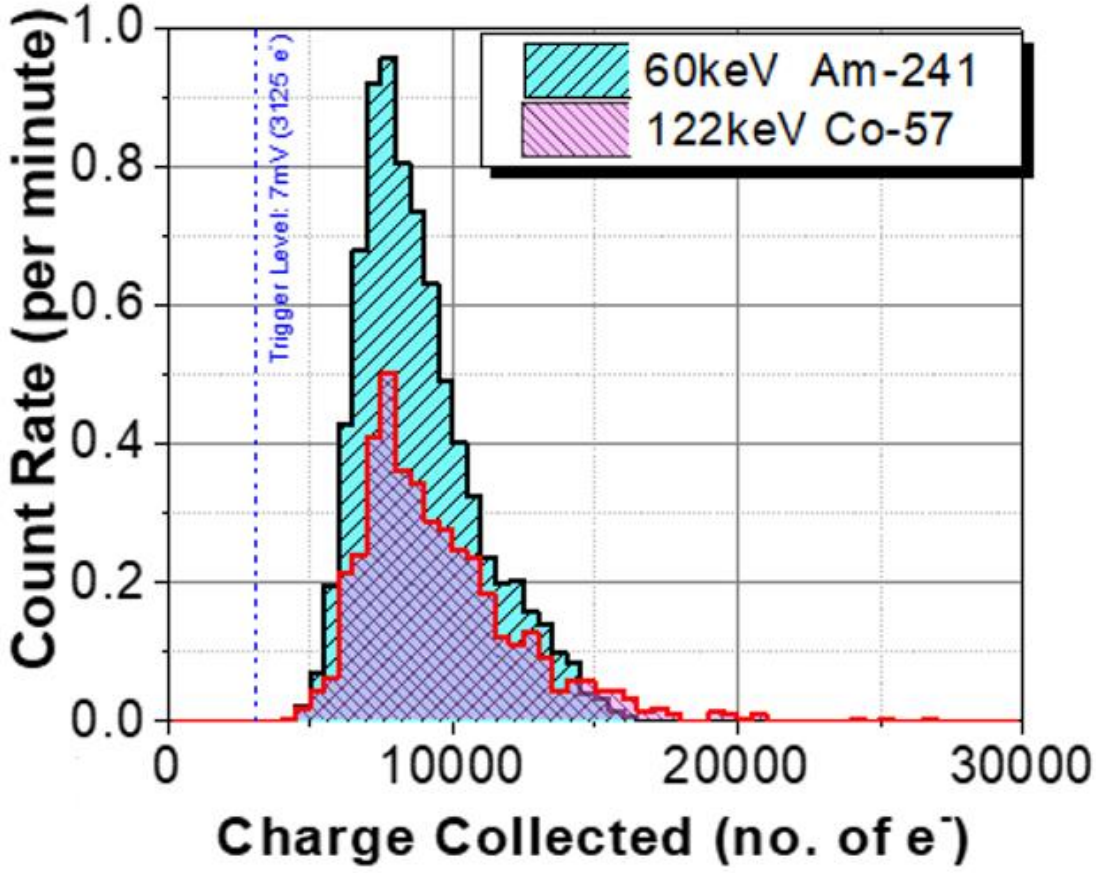

Rise time: 2-5ps
InAs
GaAs
QD
e2
e1
Decay time:
0.5ns;
≈100%
efficiency
λ=1.2 μm
hh1
hh2
lh1
lh2


Photodiode
N-contact: 0.4μm n-n+ $In_{0.34}GaAs$
0.7μm $In_{0.34}GaAs$
P-contact: 0.3μm p+-p $In_{0.34}GaAs$
0.7μm graded buffer n+ AlInGaAs
0.01μm p- AlGaAs
0.3μm p-p+ GaAs
0.3μm variable AlGaAs
25μm, 62x QD, p-doped
0.15μm variable AlGaAs
0.15μm GaAs
0.1μm AlAs
GaAs Substrate
Glass

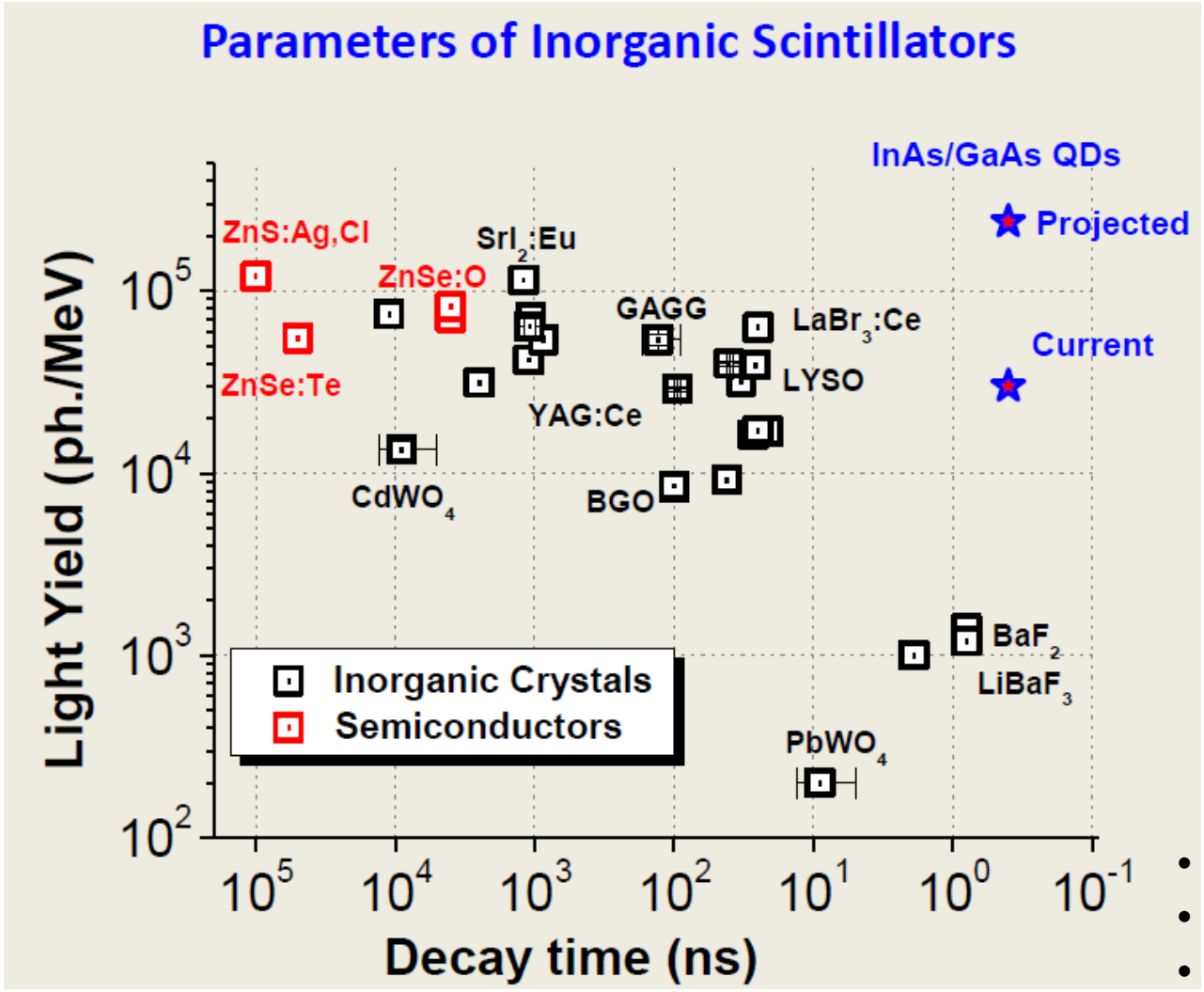

InGaAs PD
AlInGaAs MB
Dislocations
SCINT section
PD section
GaAs
AlGaAs barrier
GaAs
InAs QDs
500 nm

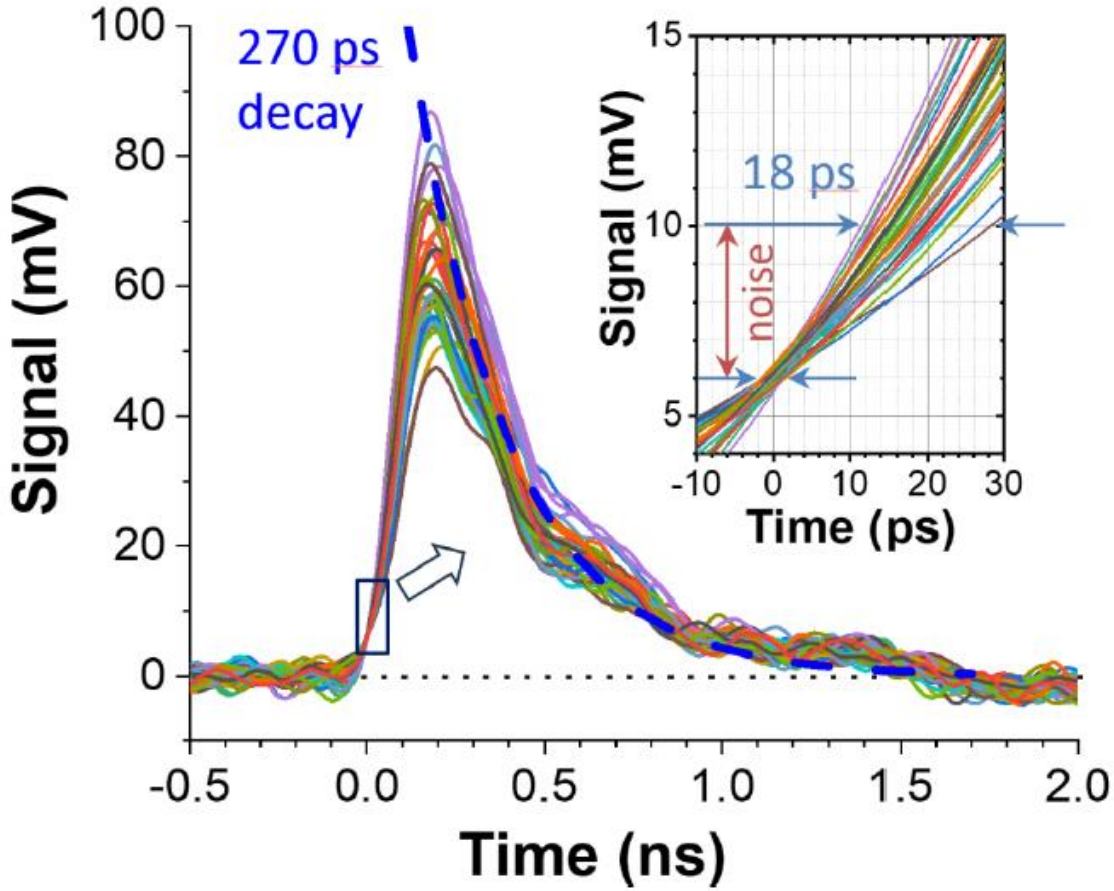
Measured Performance





Measured Performance

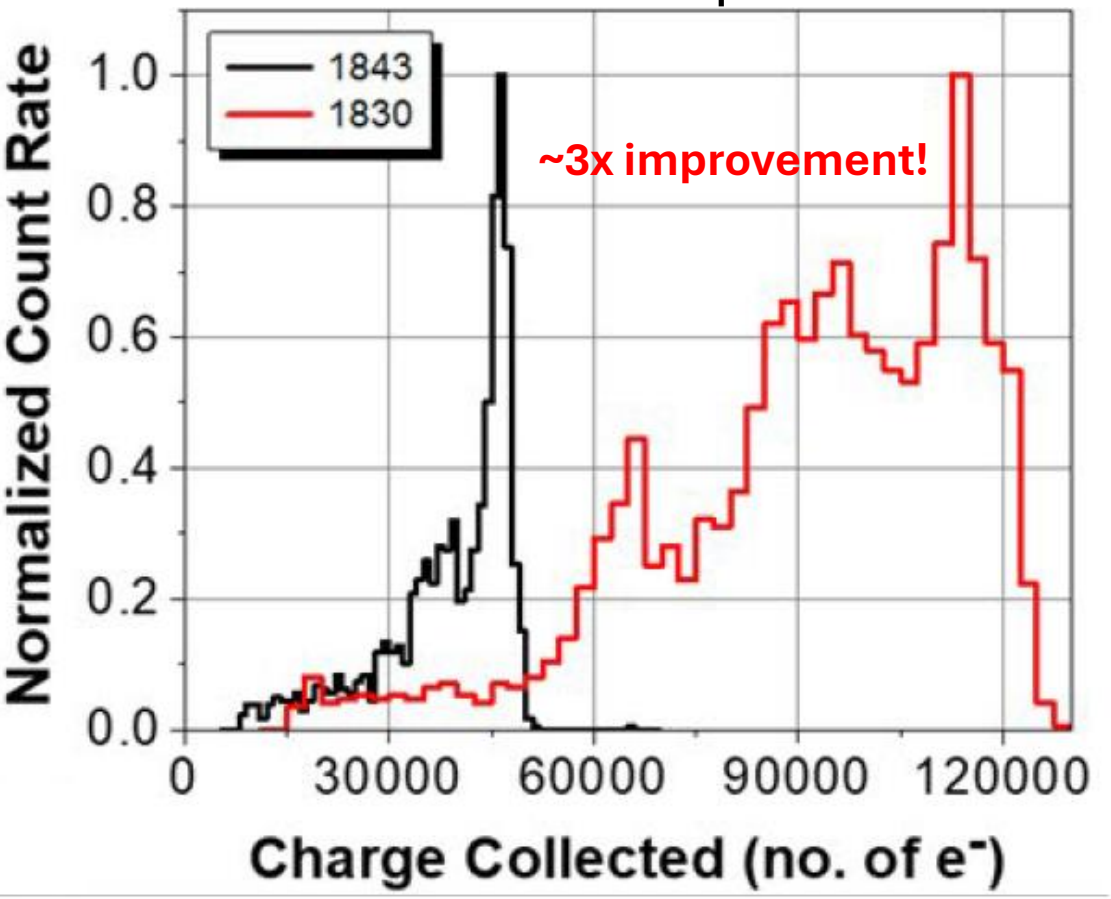


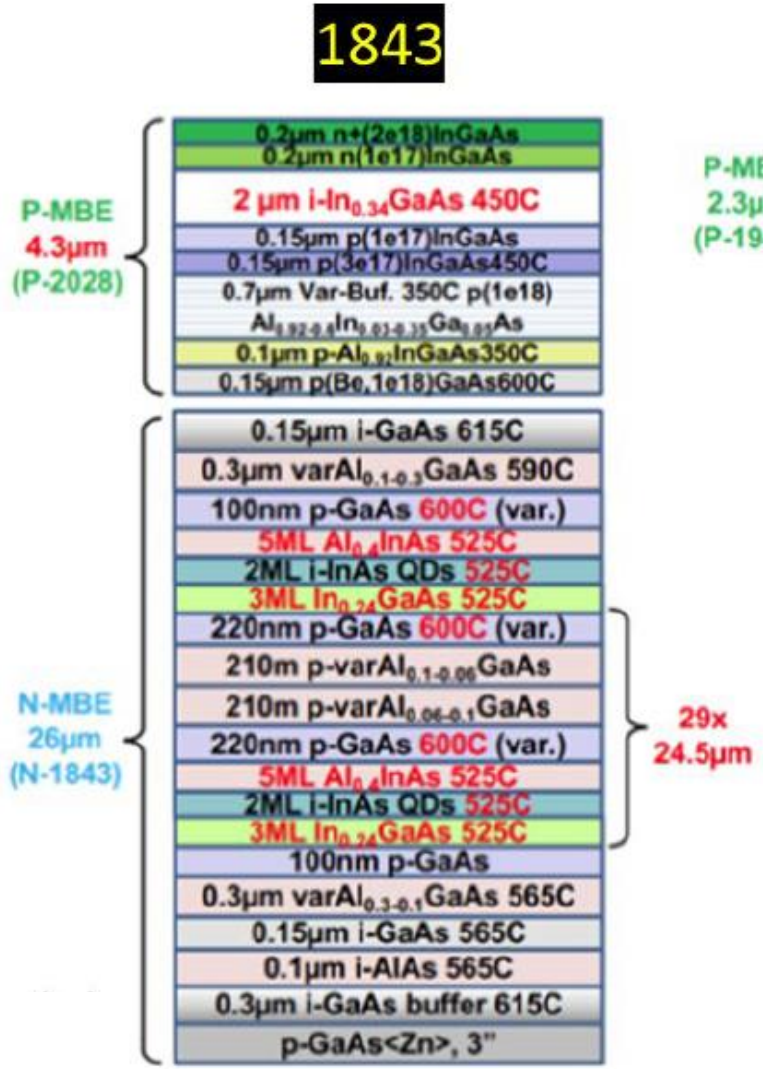


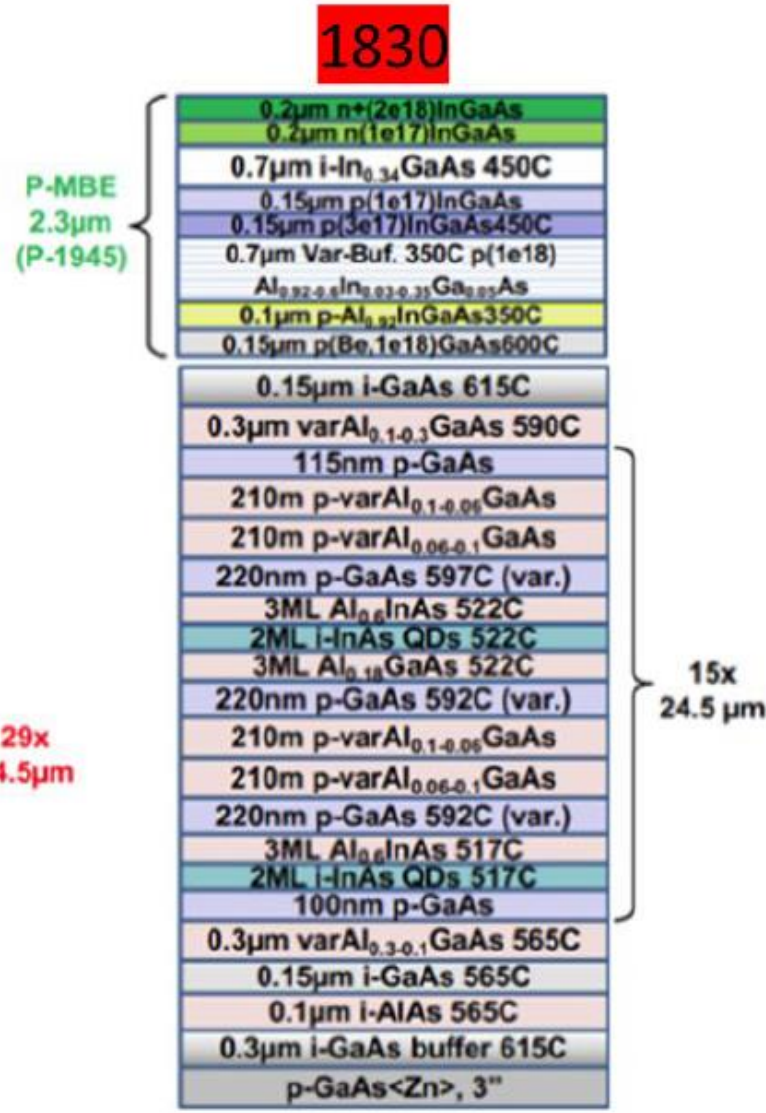
- < 100 ps rise time
- 270 ps QD decay time
- Expect ~20 ps time resolution at average avg 1.5e5 electrons

A surprise

Am-241 alphas







The new plan (FY25 FOA)

WP1: Demonstrate close to 100% charge collection efficiency starting at low LN2 to about (-40 -- -80)°C for α, β, and γ sources.

- Have already started!

WP2: Refine the internal detector structure, including wide-bandgap AlGaAs barriers, increasing the spacing between QD layers in the matrix to reduce the effect of structural defects and effectively suppress non-radiative recombination while speeding up the electron drift and/or diffusion in the barriers towards the QDs.

The new plan (FY25 FOA)

WP3: Develop the technology for a thicker sensor (50-100μm) to increase the production of scintillating photons and ionization electrons. Demonstrate and analyze the thickness limit for the MBE QD technology. An alternative path towards creating thicker detectors is to bond two or more 25 μm InAs QD scintillator layers together.

- Have already started!

WP4: Design of the detector and development of the integration technology with an existing Fermilab-provided fast-timing ASICs to provide a low-parasitics hybrid integration scheme minimizing the noise of the detector.

The new plan (FY25 FOA)

WP5: Design, demonstration, and monolithic integration of metamorphic avalanche InGaAs photodiodes on the scintillator, thereby providing internal gain to obtain 2-5x improvement in the S/N ratio compared to p-i-n diode.

- Never before demonstrated (to our knowledge)
  - Blue skies within blue skies…?

The new plan (FY25 FOA)

The developed research plan will be implemented over 3 years (12 quarters):

Work Packages	Year 1				Year 2				Year 3			
	1	2	3	4	5	6	7	8	9	10	11	12
WP1. Low temperature detector performance	UA											
			FNAL									
WP2. Epi structure optimization	UAlbany											
					FNAL							
WP3. Technology for a thicker sensor			UAlbany									
							FNAL					
WP4. Integration with ASIC	UA								UAlbany			
	Fermilab											
WP5. Development of AlInAs/InGaAs APD							UAlbany					
											FNAL	

Summary

- We have demonstrated promising performance of novel, blue-skies detector technology using scintillation light from quantum dots in low mass form factor

- We have discovered there could be significant jumps in performance available with targeted R&D
  - Low-temp, optimal growth configuration, avalanching InGaAs PD (!)

- A better optimized detector with Fermilab ASIC would be extremely well suited to broad range of HEP applications

IMAGINE