NANOPARTICLE-ENHANCED READOUT FOR BaF_2 CRYSTALS

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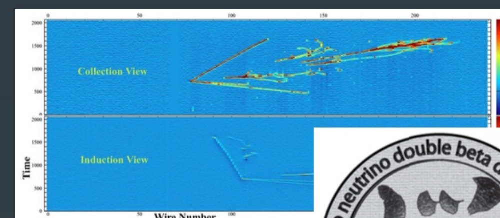
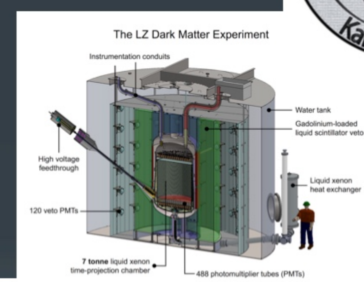
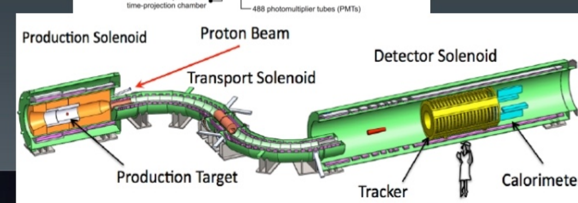
Motivation

- Liquid Argon Neutrino detectors –> SBN (Short Baseline Neutrinos), DUNE (Deep Underground Neutrino Experiment – Homestake Mine, South Dakota) *(128 nm scintillation light)*
- Liquid, Gaseous Xenon Neutrinoless Double Beta Decay -> EXO, NEXT, KamLAND-Zen *(178 nm scintillation light)*
- Liquid, Gaseous Xenon Dark Matter detectors -> Lux/LZ, Xenon, High Pressure Gaseous Xenon
- Crystal detectors -> Muon g-2 *(PbF2 Cerenkov light)*, Mu2e Direct Conversion *(BaF2 220 nm scintillation light)*, Dual-Readout Crystal Calorimeter *(Cerenkov light at a future e+e- collider, EIC ep collider)*

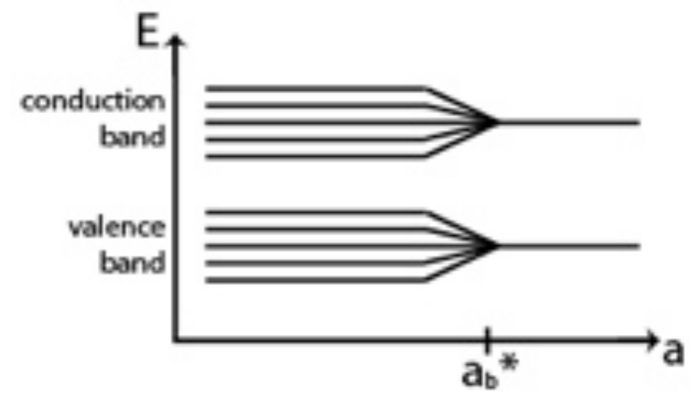






Nanoparticles - Quantum Confinement

- If the size of the nanoparticle is smaller than the electron wavelength :
  - -> Quantum Confinement condition
    - ✓ Larger energy gap
    - ✓ Splitting of energy levels
    - ✓ Strong transitions
  - -> Tunable electronic and optical properties if nanoparticle size typically < 10 nm
- Occurs on atomic/molecular level –> higher intensity, efficiency than in bulk material

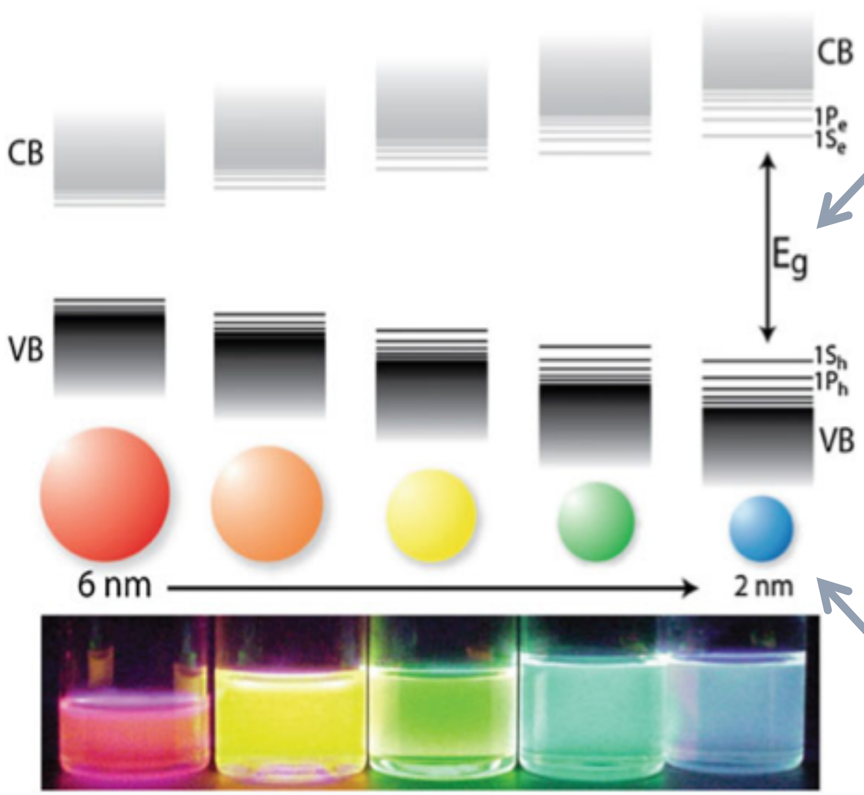


Energy level splitting vs size (a); a_b* is exciton Bohr radius

Happens in the Sun - quantum confinement dominates -> many energy level splittings -> ~continuous to make white light

Nanoparticle Wavelength Shifting

Quantum Confinement changes material properties when particle size < electron wavelength



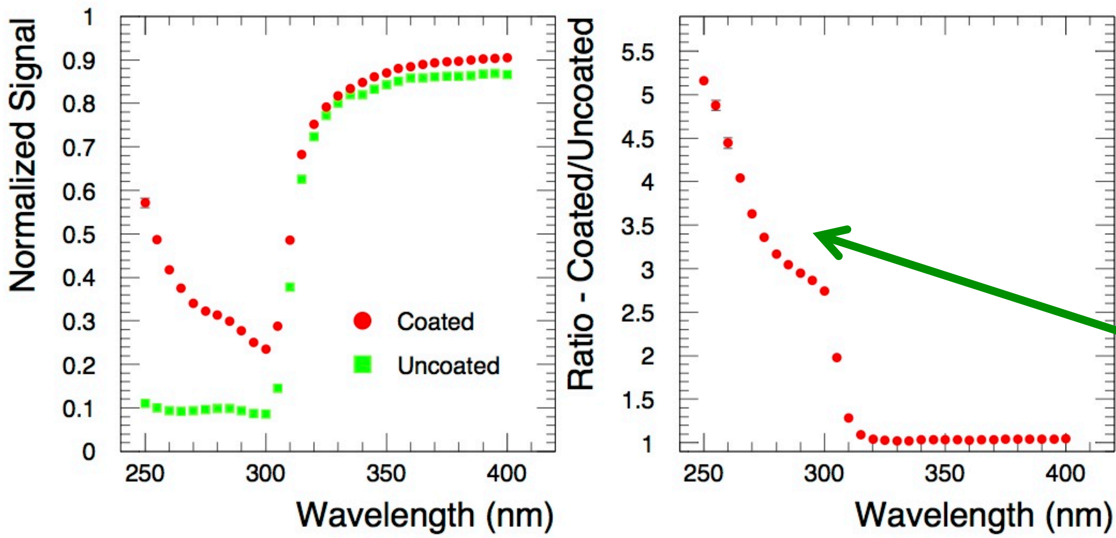
E_g increases with decreasing particle size -> ***UV photon absorption***

Discrete energy levels form at the band-edges

Stokes Shift is difference between absorption and emission wavelength

Emission wavelength decreases with decreasing size

Initial Nanoparticle Sample Tests



Si nanoparticle coating on plastic film (U of Illinois partner)

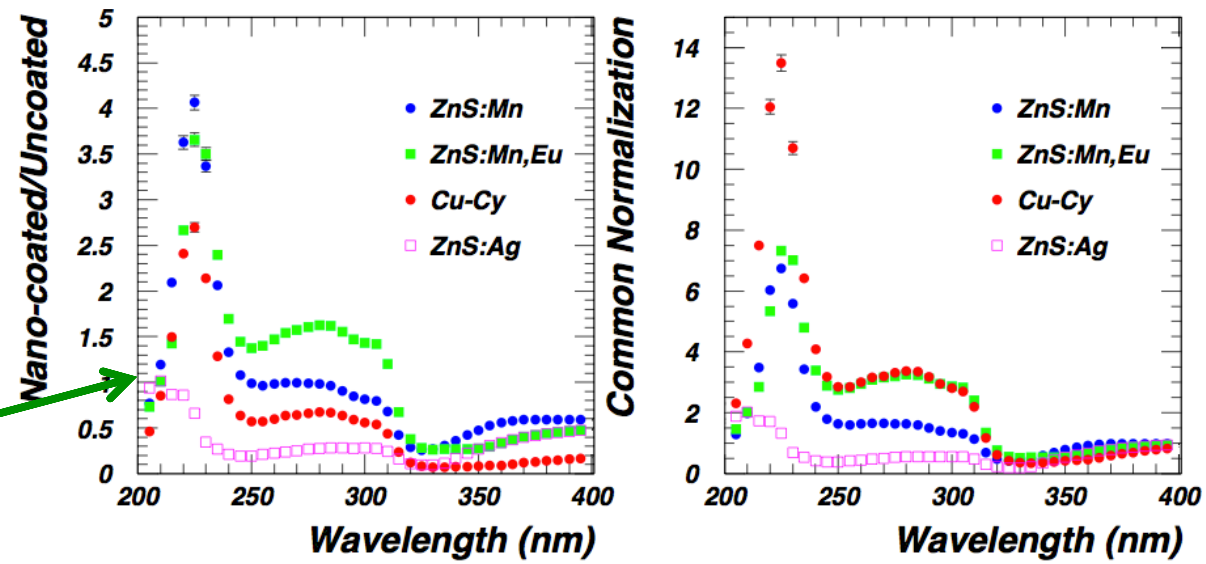
Published result:
JINST 10 05008 (2015)

Enhanced response:
250 nm < λ < 300 nm

Nanoparticles deposited on clear plastic tape (U of Texas at Arlington partner)

Published result:
Sci. Rep. 8 (2018), 10515

Enhanced response for ¾ samples:
200 nm < λ < 250 nm



Electron λ vs Nanoparticle Size

Nanoparticle	E_{fermi} (eV)	E_{gap} (eV)	λ_e (nm)	NP size (nm)
Si	12.6	1.1	12.4	1 - 3
CdS	7.5	2.5	15.6	4
CdTe	5.6	1.4	23.2	2
CdSe	7.1	1.7	20.4	-
LaYO	2.8	5.6	24.6	?

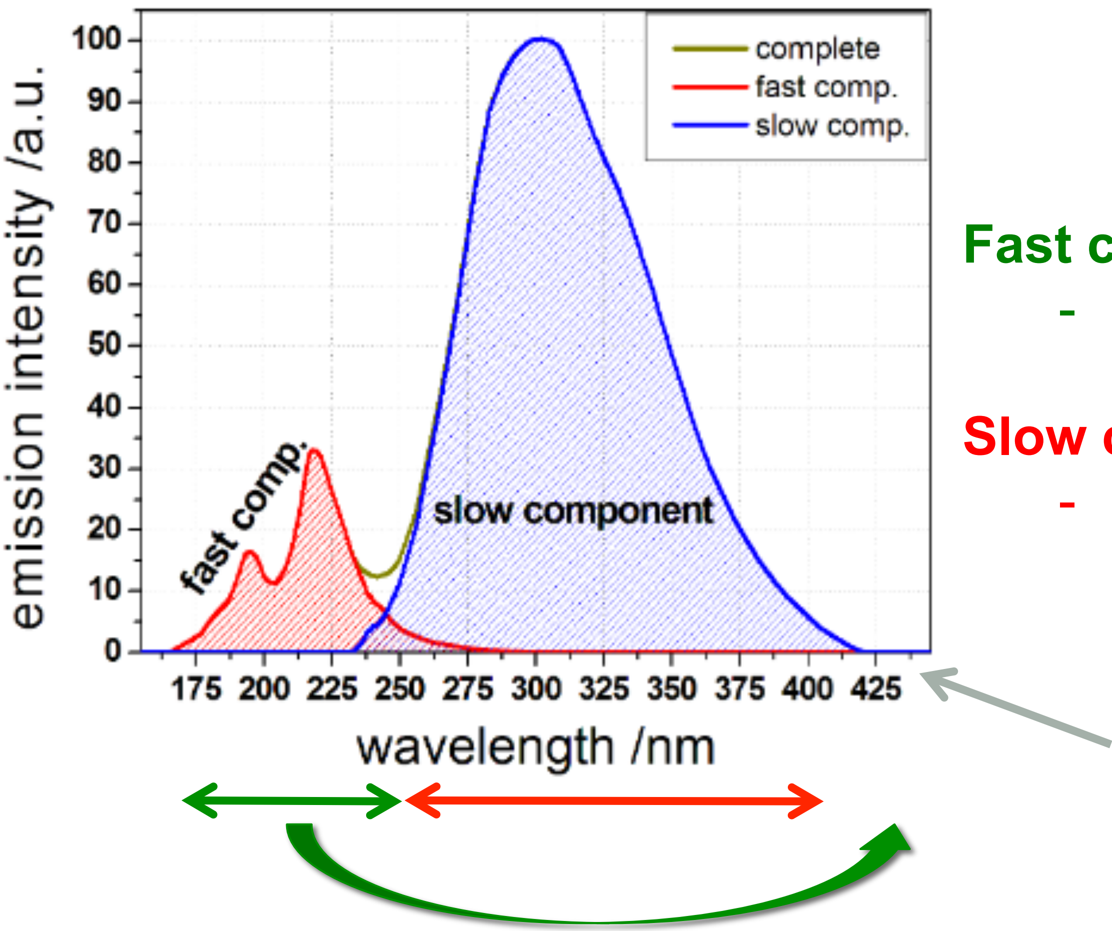
Quantum confinement effects
-> present when a dimension of the material is smaller than the electron wavelength (λ_e) in that material
Table shows calculations of λ_e in several of the nanoparticles that have been tested so far. Where it is known, the NP size of the tested candidates has been smaller than λ_e
-> enhancement of UV response in all but 1 case*

* No enhancement seen in a test of CdS nanoparticles deposited directly on the surface of a SiPM – the deposit was very thick and opaque to visible light – possibly no wavelength shifted light could get through the deposit

Nano-enhanced BaF_2 Readout

- Detection of 220 nm (UV) fast component of BaF_2 scintillation
  - Nanoparticle type that absorbs 220 nm emission
  - Preferably little absorption >250 nm
  - Large Stokes shift to visible wavelength range for detection
- Non-detection and/or filtering of 300 nm slow component
  - Filtering before 220 nm absorption an option
  - Large enough Stokes shift to jump over slow component
    - Nanoparticle type property?
    - Nanoparticle size effect?

BaF2 Crystal Readout – Mu2e Upgrade



Fast components (195, 224 nm)
- **Decay time ~1 ns**

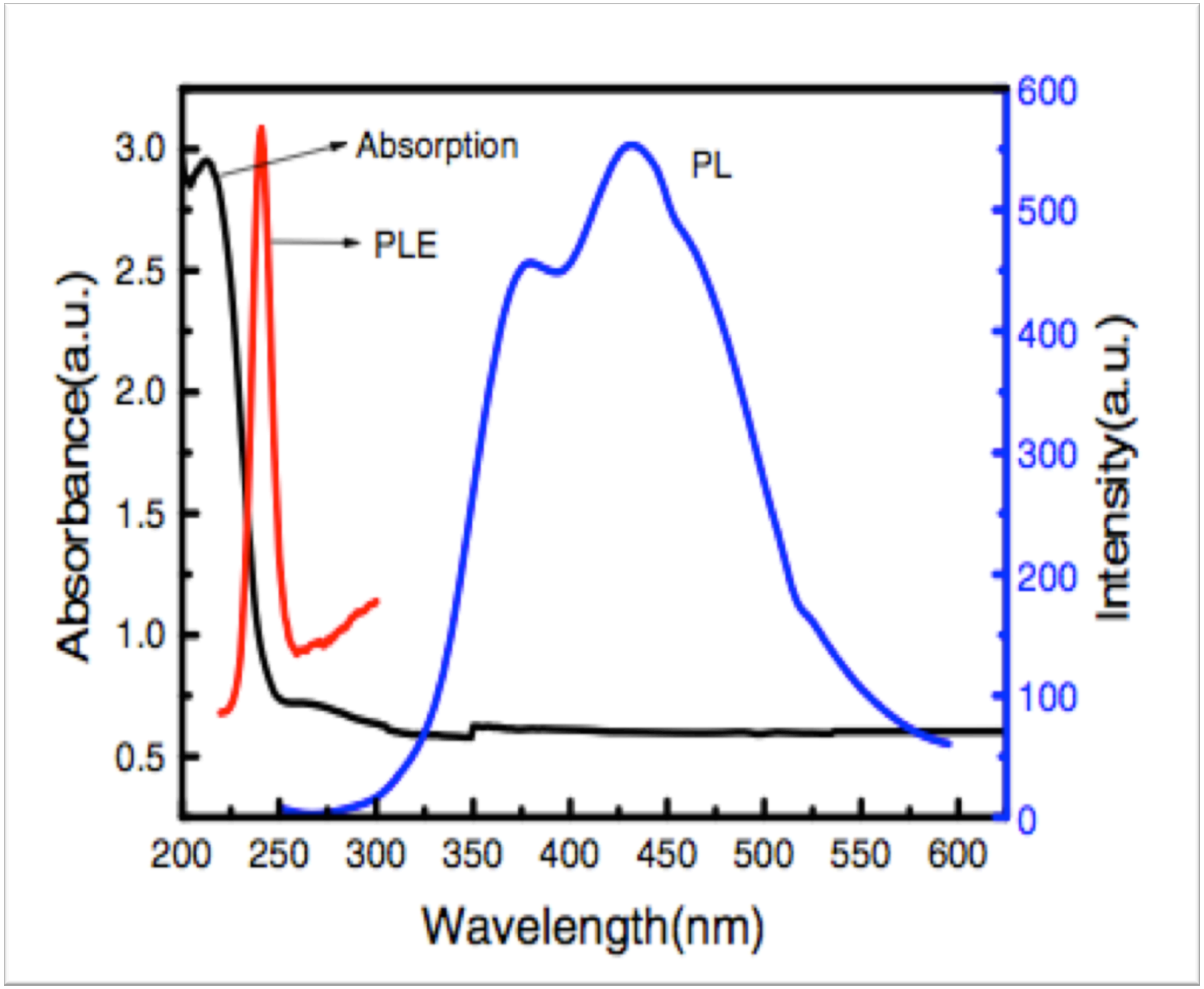
Slow component (250 -> 400 nm)
- **Decay time ~650 ns**

SiPM peak sensitivity (425 nm)

Absorption, then Stokes shift over slow component to sensor

no sensitivity for slow component!

Absorption/emission of candidate nanoparticle

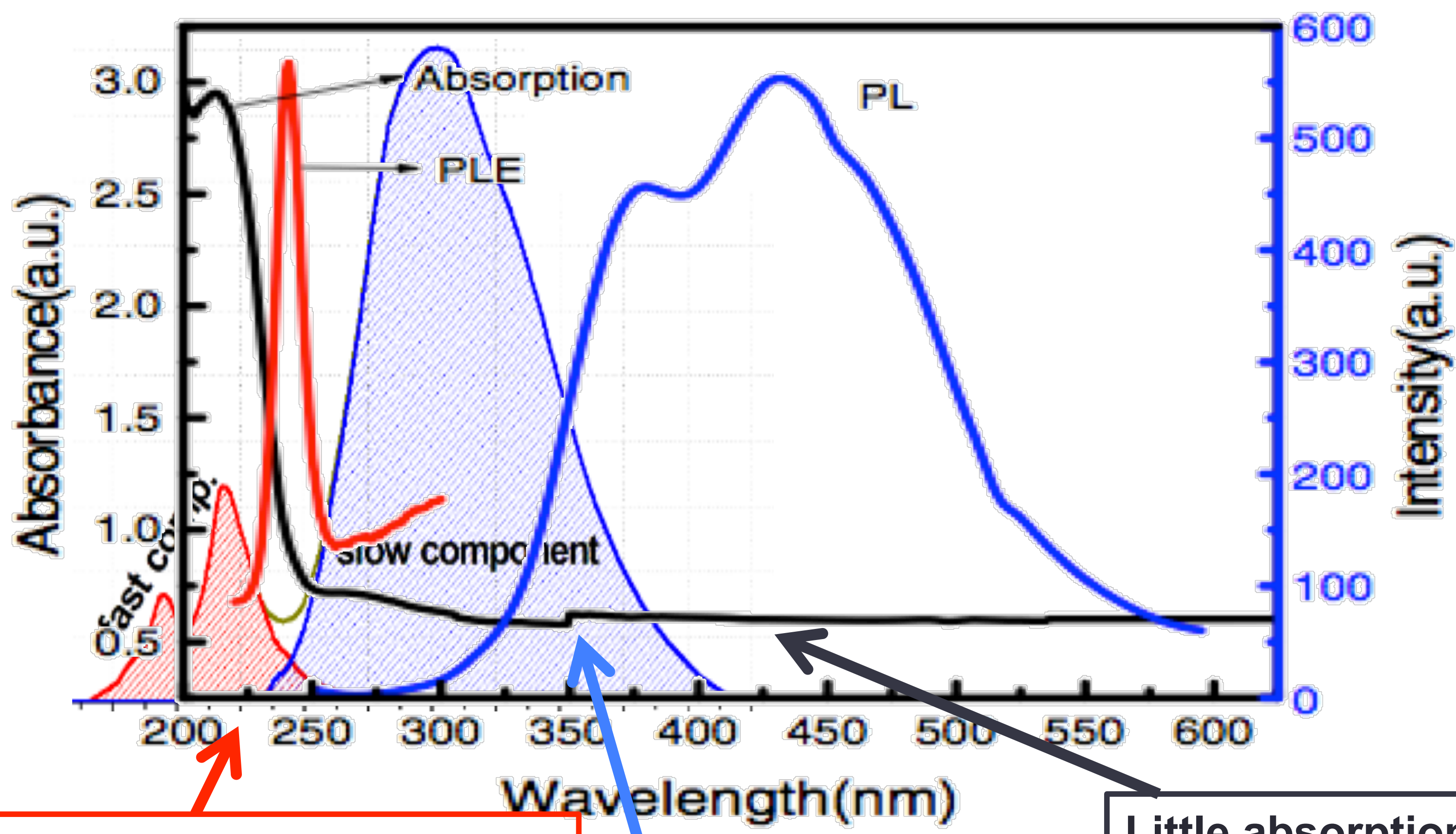


Absorption:
strong < 250 nm
weak > 250 nm

Emission:
300 nm < λ < 600 nm

Stokes Shift:
~200 nm peak-to-peak

Candidate nanoparticle for BaF2 Readout



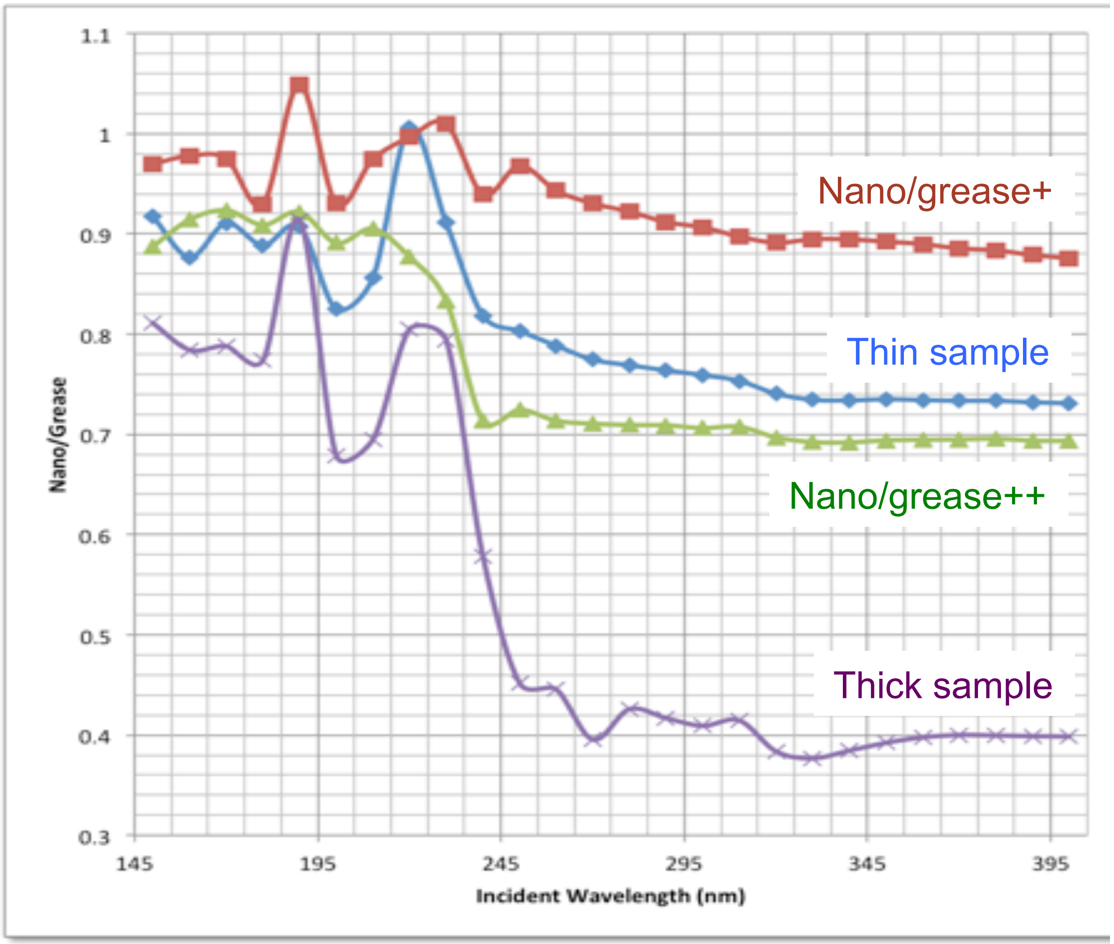
224 nm emission of BaF2
absorption peak of nanoparticle

Little absorption for wavelengths >250 nm

Overlap of slow component and nanoparticle emission:
1) wave-shift to longer wavelength, or 2) resin coating on the SiPM

Tests of selected nanoparticles

Tested a nanoparticle sample made at UTA by *mixing nanoparticles in UV-transparent grease (DOW-Corning)*

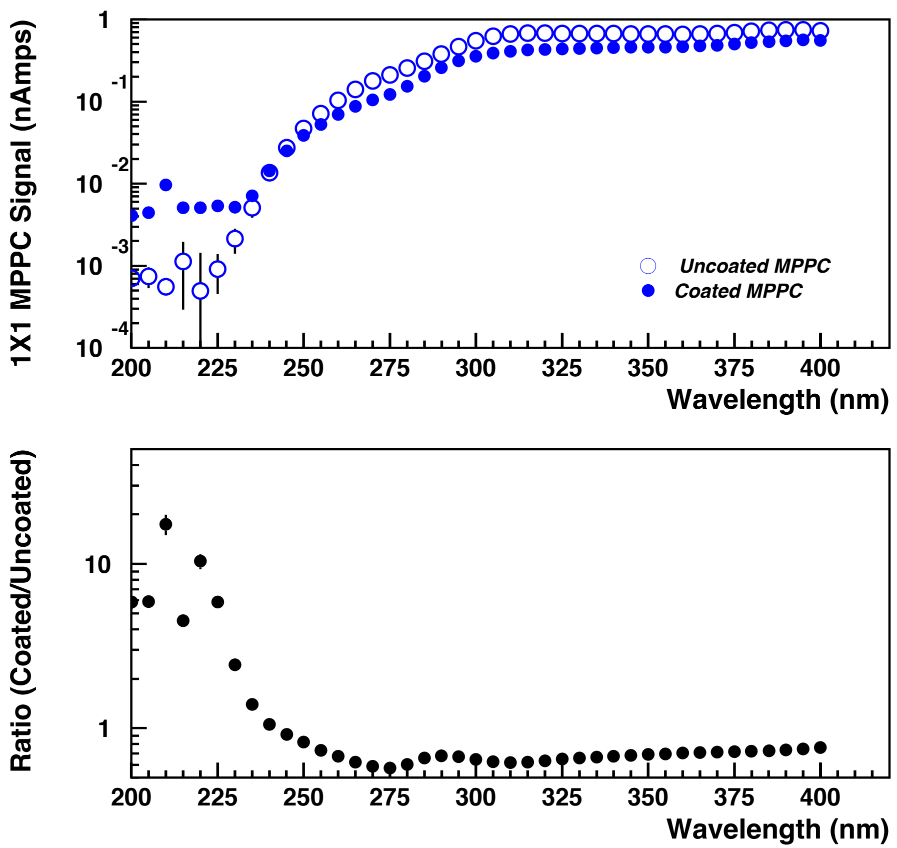


Compare blue, purple – it appears that passing through more nanoparticles helps – small reduction in the peak at 220 nm and a larger reduction in the signal > 245 nm.

-> determine the amount of nanoparticles in the grease by optimizing the 220/300 ratio for maximum rejection of light >250 nm.

-> Ratio of 220/300 for purple (thick) sample is ~2/1

A different nanoparticle candidate



UTA nanoparticles *deposited directly on the resin (face) of the SiPM*

Enhanced response of coated SiPM seen in the wavelength range from 200 nm – 240 nm compared to uncoated sensor

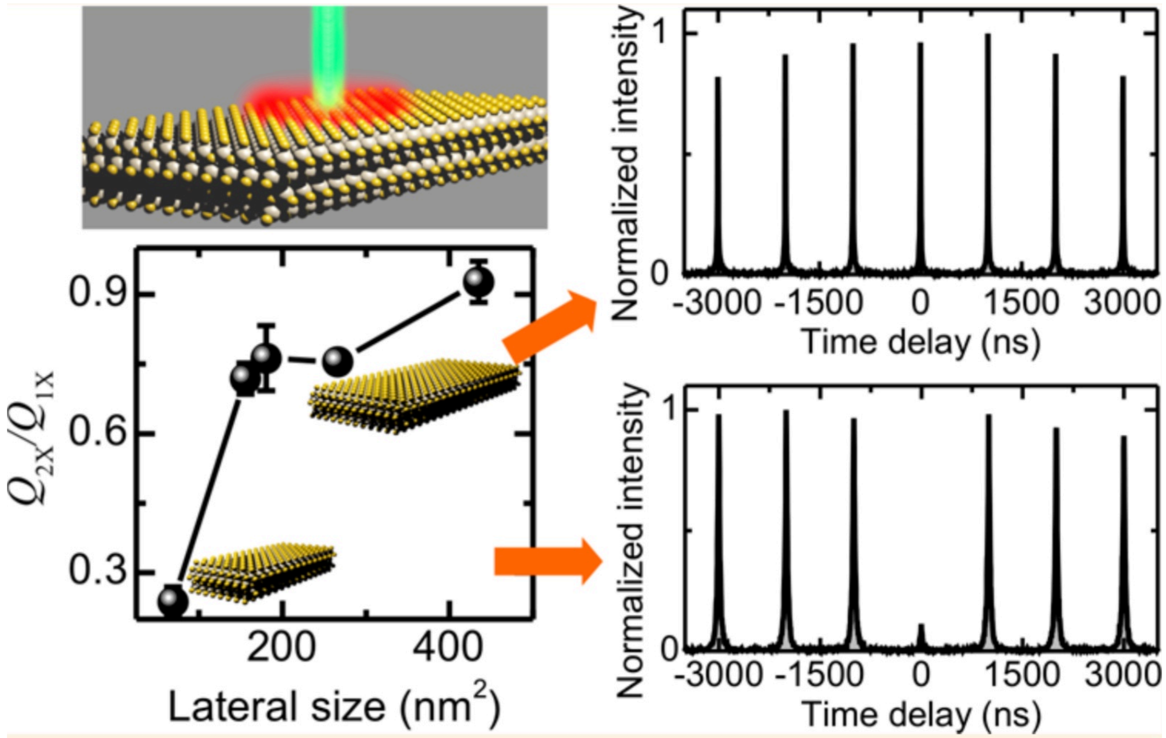
Without any optimization, ratio of coated to uncoated in the 200 – 240 nm range is ~factor of 10 greater than in the region > 250 nm!

-> We have tested at least 2 nanoparticle candidates which show sensitivity in the desired wavelength range and, in addition, much reduced sensitivity without the need for additional filters in the wavelength range > 250 nm

Size-dependent response - nanoplatelets

Alternative form for readout of crystal:

- Nanoplatelet (1-dimension smaller than λ_e) deposited on crystal surface
- Amplification of signal when lateral size increases (multiple signal response shows up at 0 ns time delay)
- Collaboration between CNM and ANLHEP (joint LDRD proposal submitted)



Work at ANL Center for Nanoscale Materials
Published: ACS Nano 2017, 11, 9119-9127

Plans for BaF_2 220 nm Readout

- Optimize thickness, nanoparticle concentration in DOW-Corning grease for best signal to noise (220 nm / 300 nm) ratio using monochromator
- Test this on a BaF_2 crystal with muons
- Find a binder that can contain nanoparticles at the optimal concentration and thickness that makes a *soft cookie for placement between a crystal and a sensor (SiPM)*
  - Siloxane epoxy (same properties as DOW-Corning grease?)
- Test nanoplatelet idea deposited on crystal surface
  - *Direct conversion to electron signal – photosensor unnecessary!*
- Produce nanoparticle/sensor combination for Mu2e BaF_2 Calorimeter

Backup Slides

Nanoparticle-enhanced Night Vision

From **ScienceDaily**

Bats Scan The Rainforest With UV-Eyes

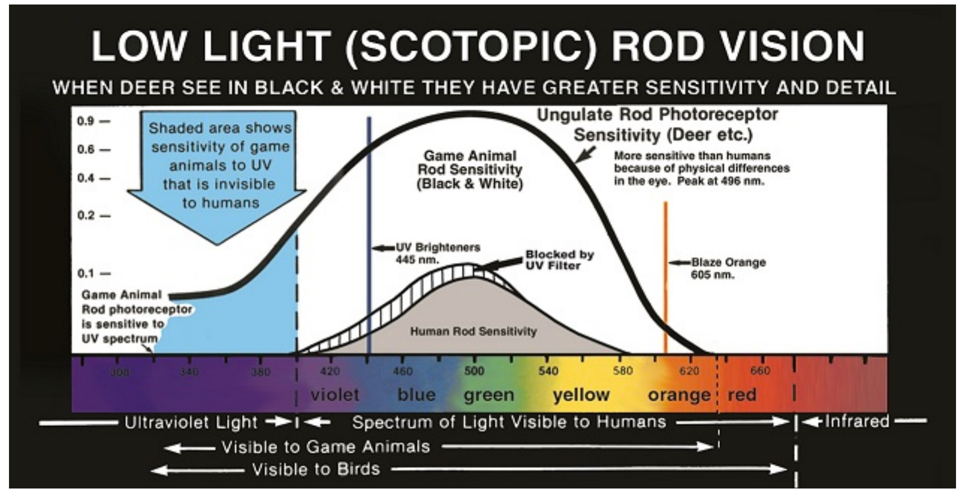
“Bats from Central and South America that live on nectar from flowers can see ultraviolet light (Nature, 9 October 2003).”

“There is little light at night. But compared to daylight, the colour spectrum is shifted towards short, UV-wavelengths.”

“Interestingly, bats achieve an absorption efficiency in the UV bandwidth of nearly 50 percent of their photoreceptors major peak of absorbance (alpha-band). *This is nearly five times the value expected from in-vitro measurements of beta-band absorption in rhodopsin molecules.* Whether this indicates a *novel mechanism for light perception* in the bats eye that is still unkown for mammals remains open.”

-> High efficiency for UV absorption is a characteristic of quantum confinement in nanoparticles – *Bat eye rods are coated with nanoparticles!?*

. . . and Deer

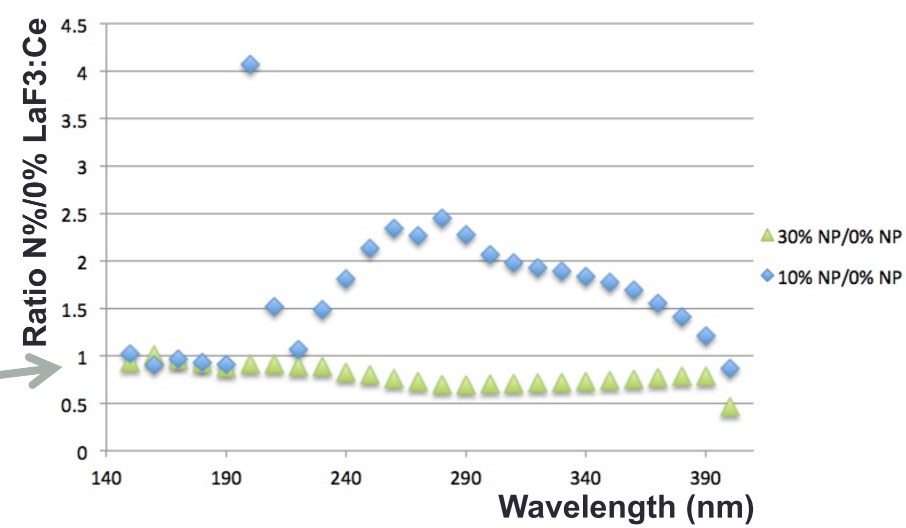


. . . and now Us!

UTA LaF3:Ce nanoparticles in transparent polycarbonate (contacts)

Enhancement for 10% LaF3:Ce:

230 nm < λ < 390 nm



Summary of Possible Applications

Detector	Application	Absorbed λ	Emitted λ	Candidate	Customer
Argon	Coating	128 nm	425 nm	LaYO, CdS	HEP (DUNE, SBN)
Xenon	Coating	178 nm	425 nm	LaYO, ?	HEP, NP (0vBB, Dark Matter)
Water	Coating	125 – 300 nm	425 nm	LaYO	HEP (ANNIE)
BaF2 crystal	Surface	200 – 250 nm	425 nm	ZnS:Mn#, CuCy#, ZnS:Mn,Eu#	HEP (Mu2e)
PbF2 crystal	Surface	200 – 400 nm	425 nm	Si*, LaF3:Ce#	HEP, NP (g-2, DRCal)
Fibers	Coating	300 – 390 nm	425 nm	LaF3:Ce#	Astrophysics (AAO, DES)
Plastic Lens	Infusion	300 – 400 nm	520 nm	LaF3:Ce#	Defense, Night Vision
Other crystals	Surface	Per crystal	425 nm	?	Nat. Sec., HEP, Medicine
Other nobles	Coating	Per element	425 nm	?	HEP

Key: tested results, simulated results, ? (no ID'd candidate yet), * (published), # (pub pending)

Also : high efficiency solar cells, luminescent window glass