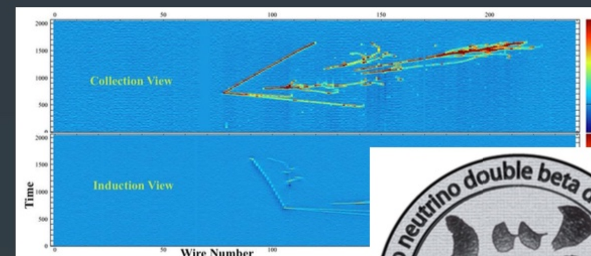
Nanoparticle-enhanced photosensors for UV light detection

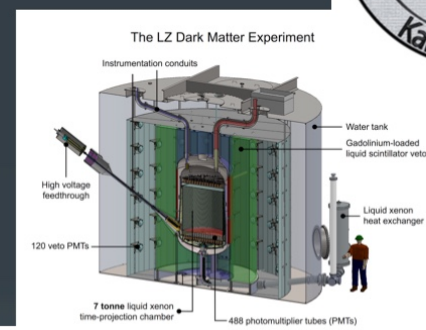
Steve Magill
Argonne National Laboratory

Motivation

- Liquid Argon Neutrino detectors –> SBN (Short Baseline Neutrinos), DUNE (Deep Underground Neutrino Experiment – Homestake Mine, South Dakota) *(128 nm scintillation light)*

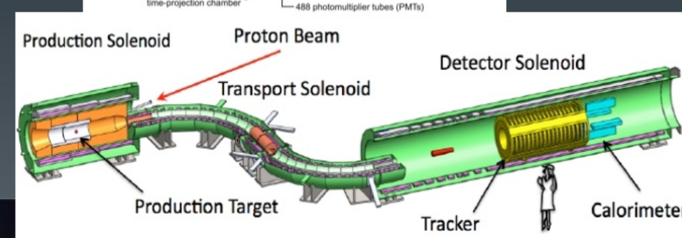


- Liquid, Gaseous Xenon Neutrinoless Double Beta Decay -> EXO, NEXT, KamLAND-Zen *(178 nm scintillation light)*



- 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)*



Quantum Confinement

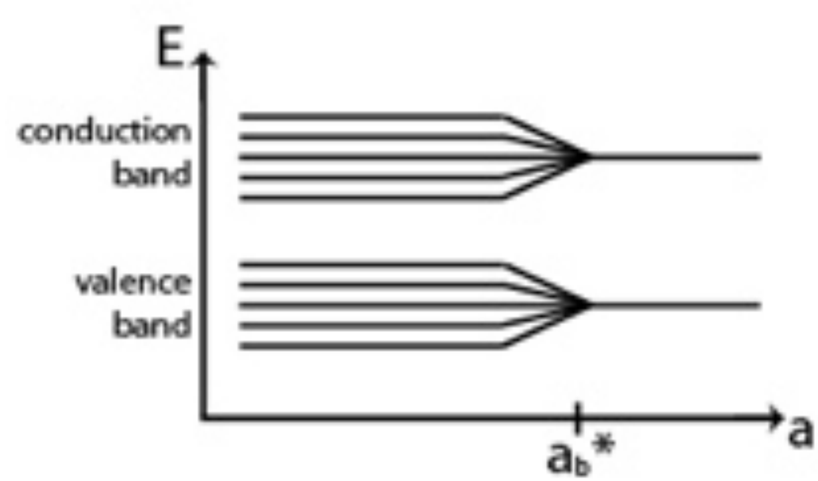
- If the size of a particle is smaller than the electron wavelength :

  -> Quantum Confinement condition

  - ✓ Larger energy gap
  - ✓ Splitting of energy levels
  - ✓ Strong transitions

  -> Tunable electronic and visible optical properties if particle size typically <10 nm (Nanoparticle)

- Occurs on atomic/molecular level –> *higher intensity, efficiency* than bulk material

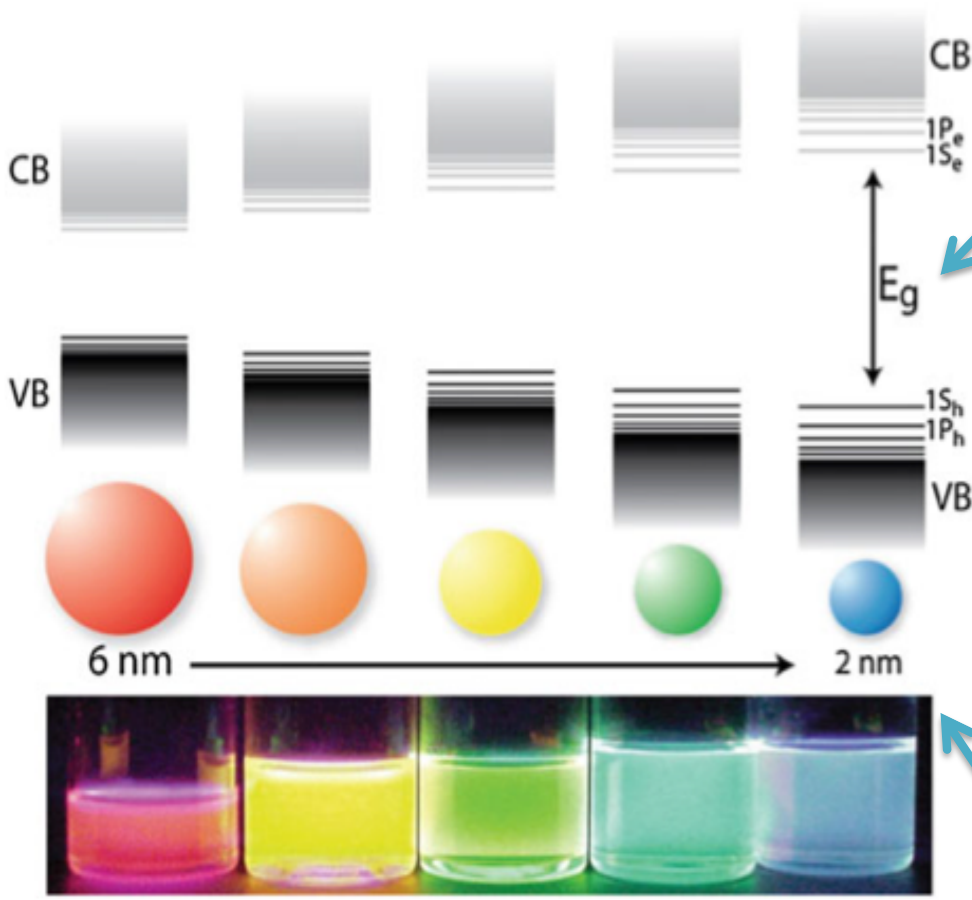


Energy level splitting vs size (a); a_b^* is exciton Bohr radius

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

Optical properties - Quantum Confinement

Quantum Confinement changes material properties when particle size < electron wavelength



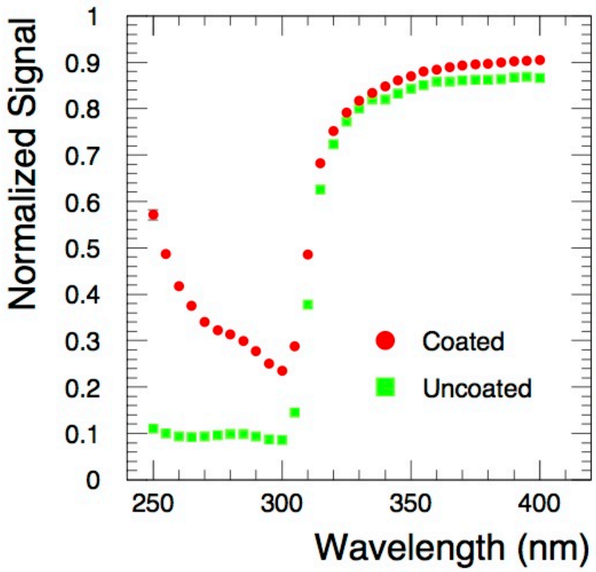
Eg increases with decreasing particle size -> ***UV photon absorption***

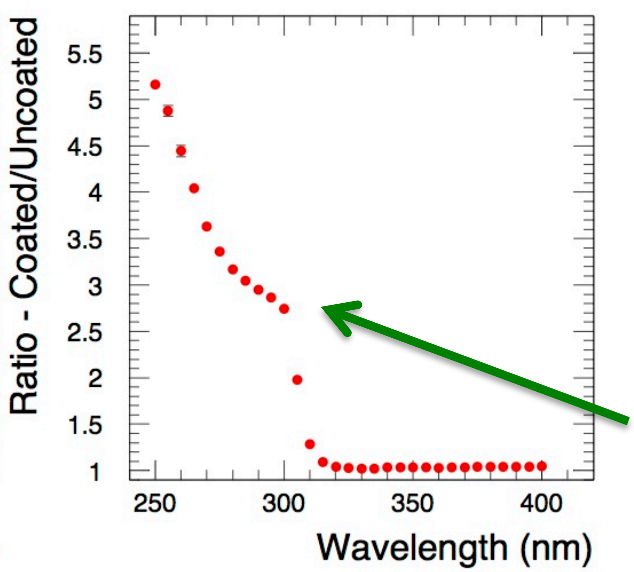
Discrete energy levels form at the band-edges

Stokes Shift is difference between absorption and emission wavelength

Emission wavelength decreases with decreasing size -> ***tunability***

Initial Nanoparticle sample tests





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

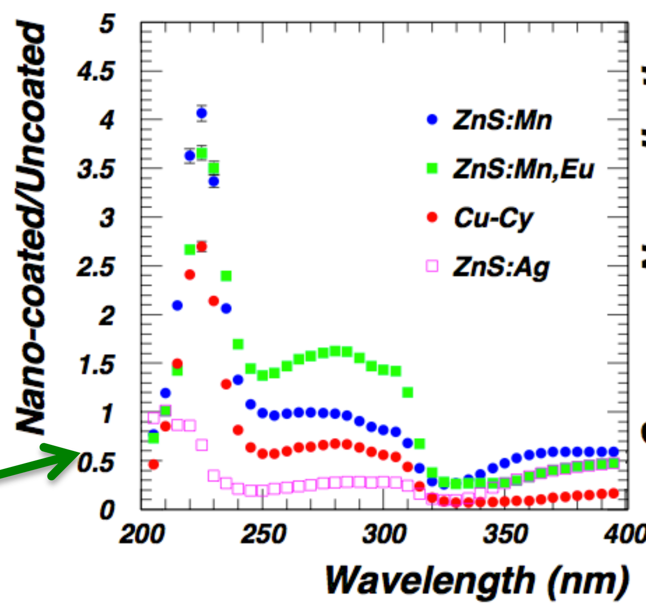
Published result:
JINST 10 05008 (2015)

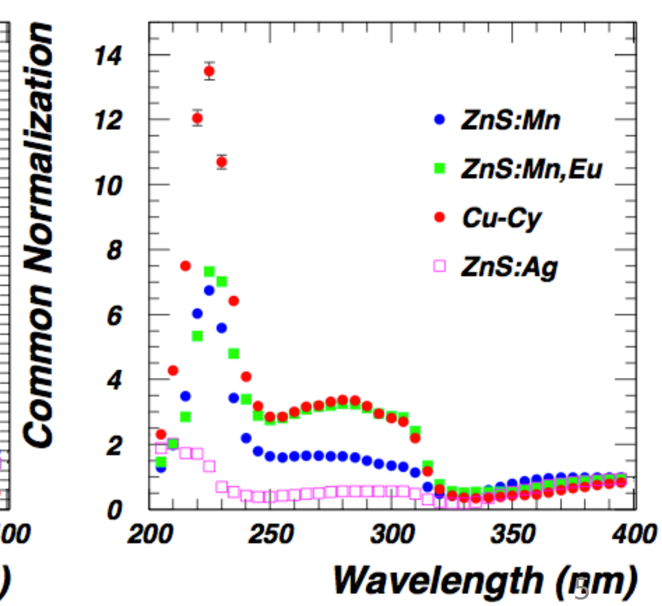
Enhanced response:
250 nm < λ < 300 nm

Nanoparticles deposited on clear plastic tape (UTA partner)

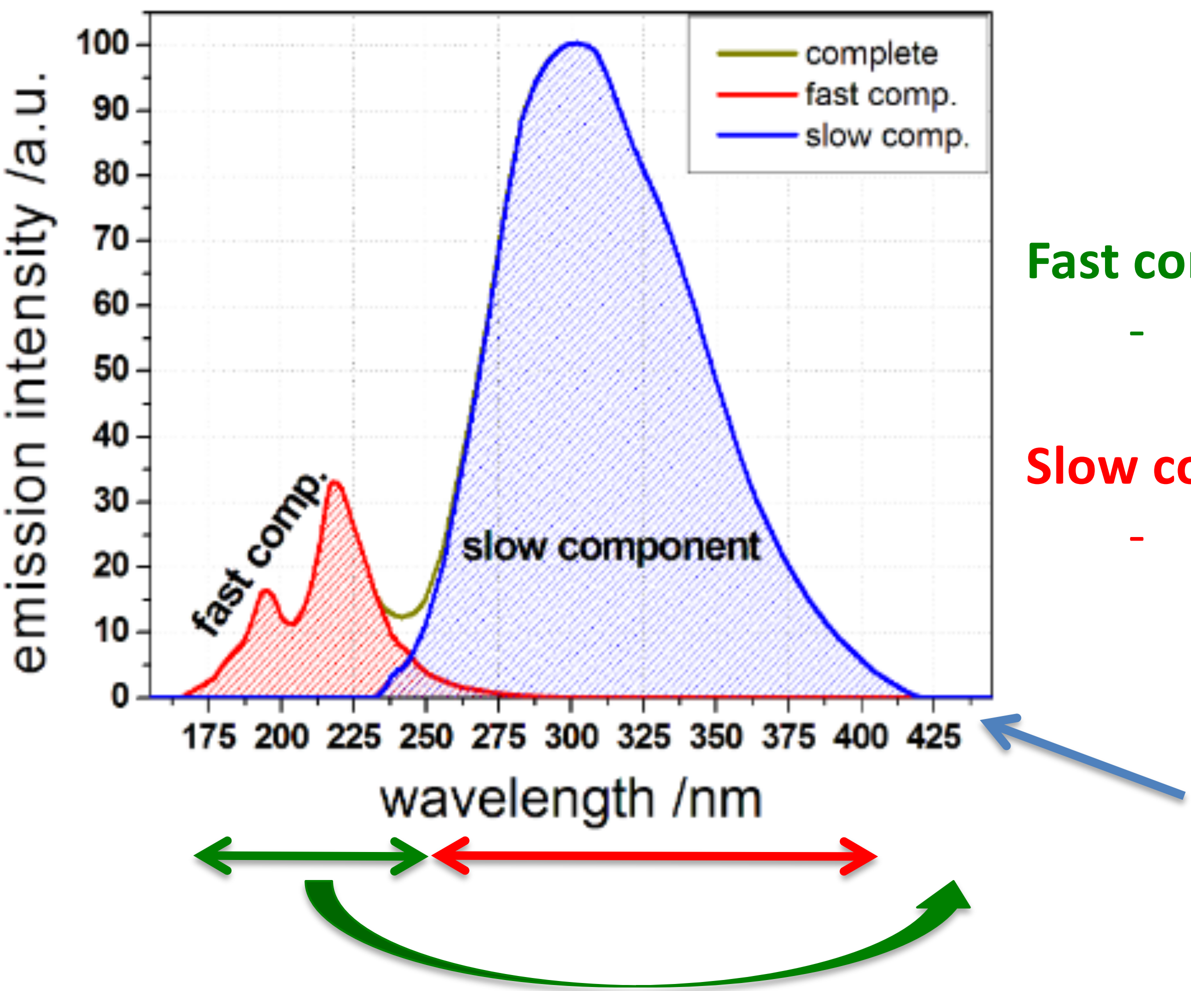
Published result:
SR 8:10515 (2018)

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





BaF2 Crystal Readout – Mu2e Upgrade



Fast components (195, 224 nm)

- **Decay time ~1 ns**

Slow component (250 -> 400 nm)

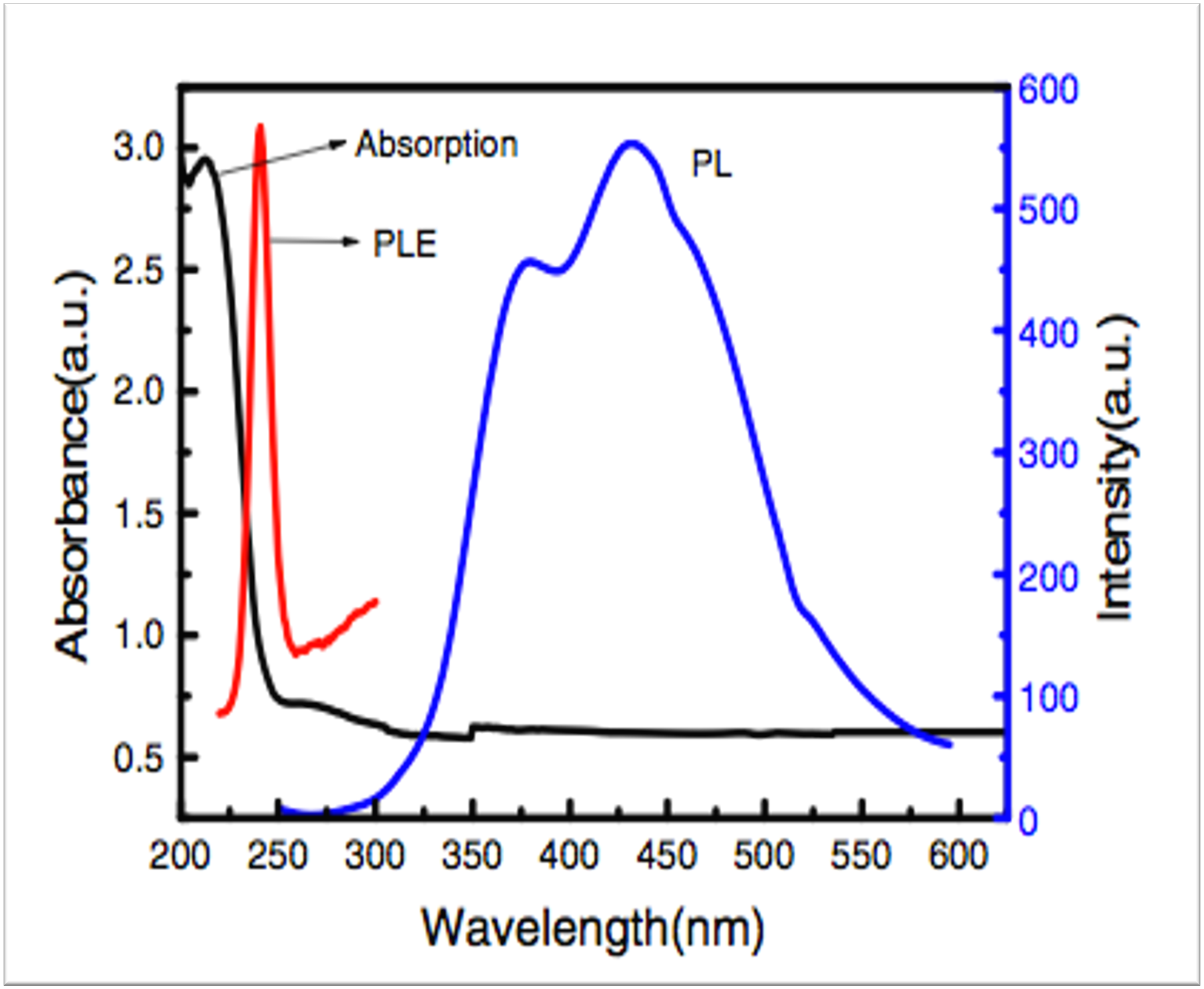
- **Decay time ~650 ns**

SiPM peak sensitivity (425 nm)

Absorption, then Stokes shift over slow component to sensor

no sensitivity for slow component!

Absorption/emission of nanoparticle candidate

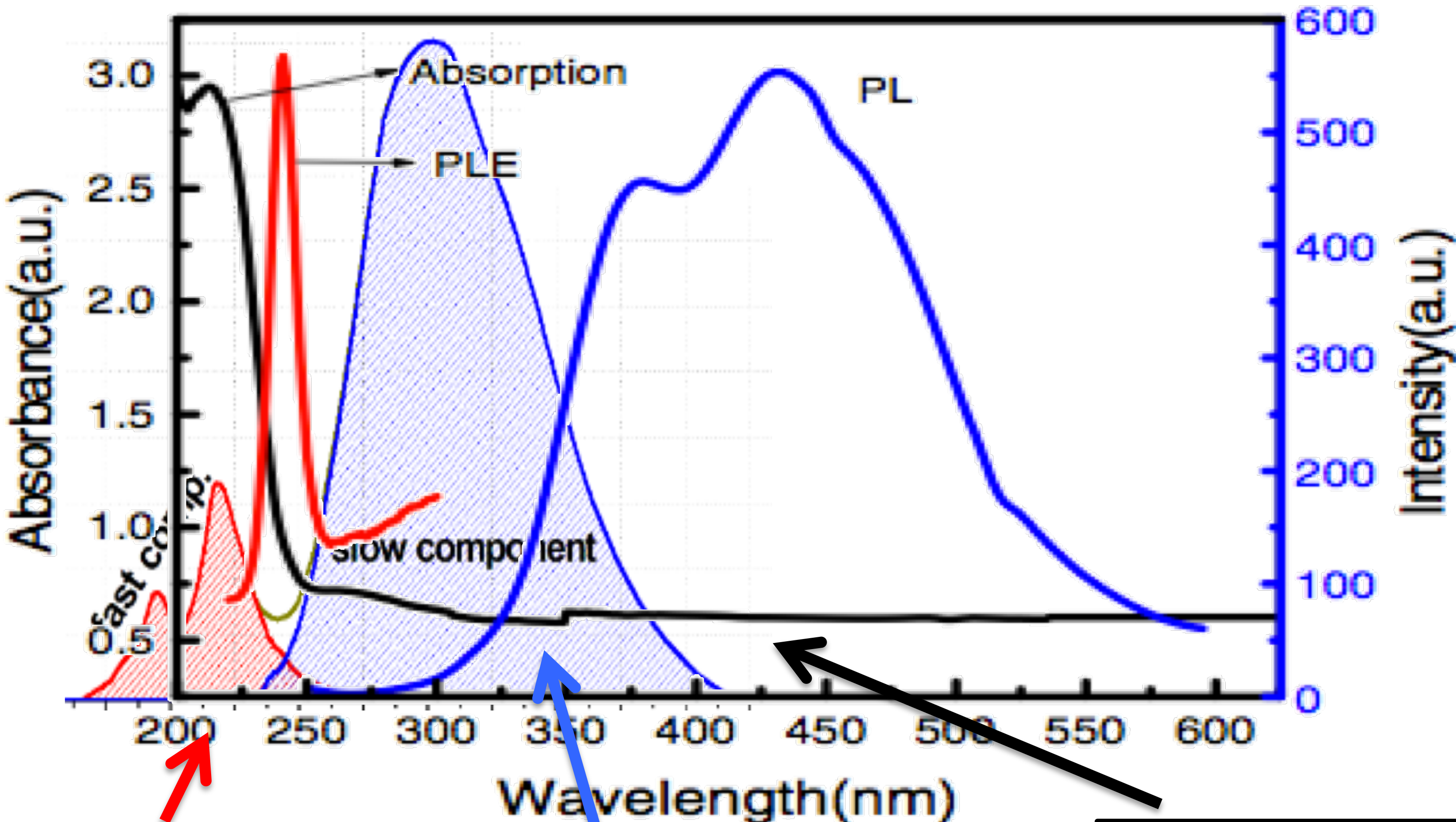


Absorption:
strong < 250 nm
weak > 250 nm

Emission:
300 nm < λ < 600 nm

Stokes Shift:
~200 nm peak-to-peak

Nanoparticle candidate for BaF2 Readout



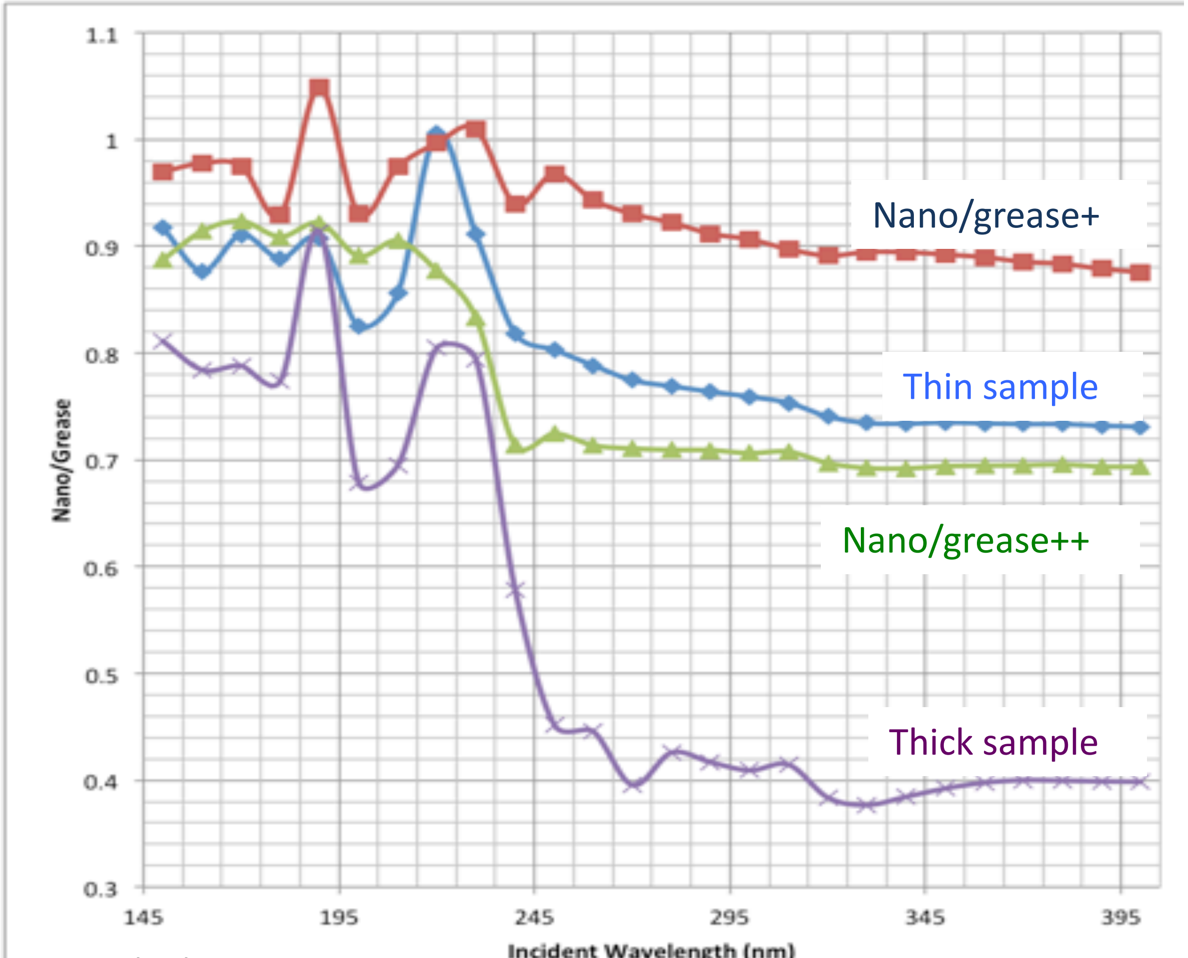
195, 224 nm emission of BaF2
absorption peak of nanoparticle

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

Nanoparticle Response

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

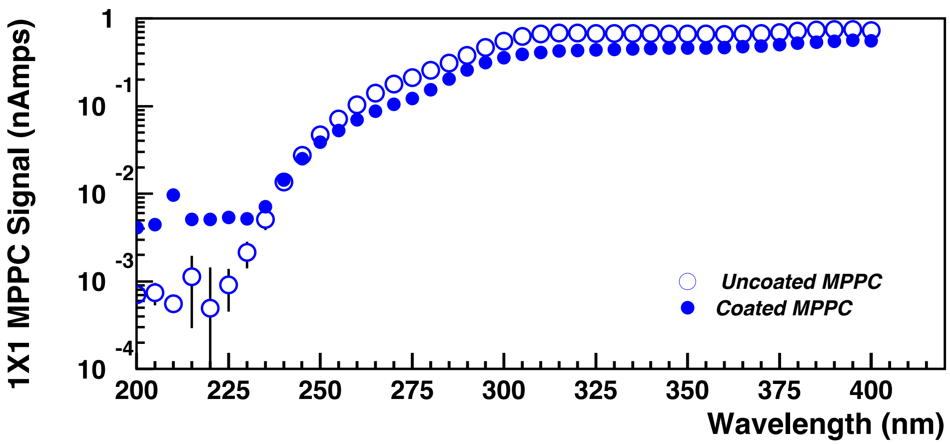


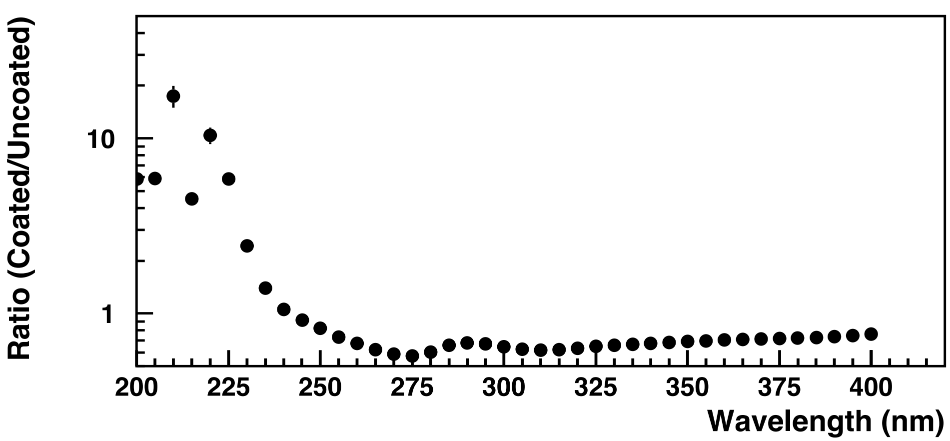
Compare blue, purple – it appears that passing through more nanoparticles helps – small reduction in the peak at 220 nm and a larger reduction in the signal > 245 nm.

-> 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 *<u>deposited directly on the resin (face) of the SiPM</u>*

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

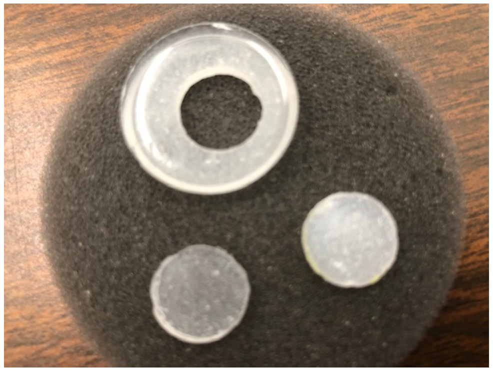
Without any optimization, ratio of coated to uncoated in the 200 – 240 nm range is ~factor of 10 greater than in the region > 250 nm!

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

Plans for BaF_2 220 nm Readout

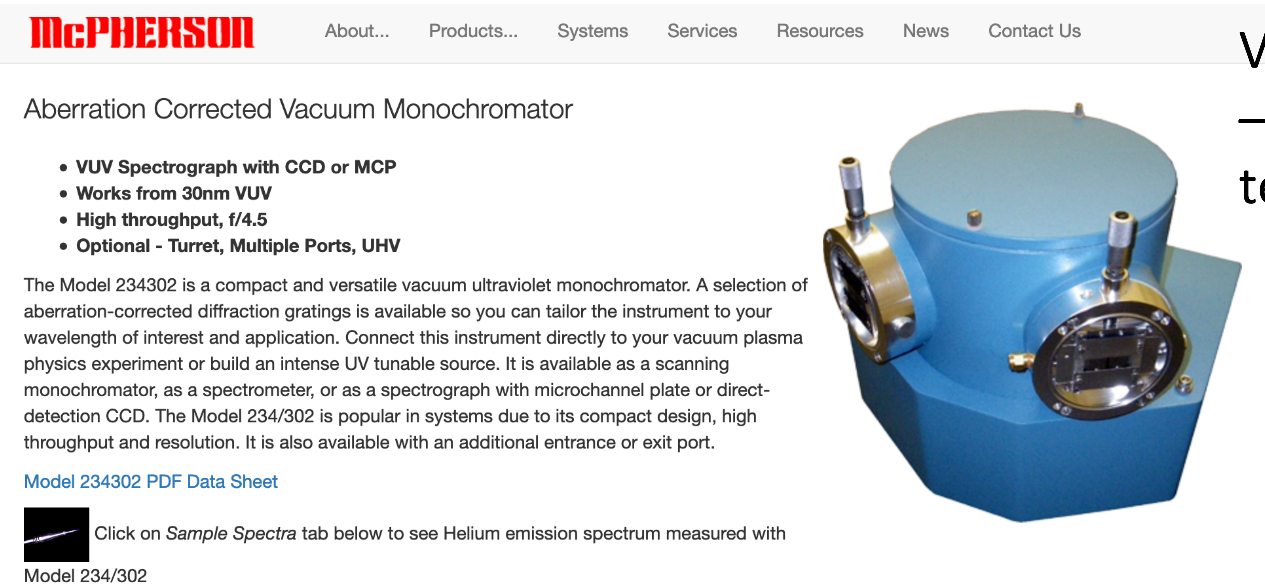
- Optimize thickness, nanoparticle concentration in DOW-Corning grease for best signal to noise (220 nm / 300 nm) ratio using monochromator
- Test this on a BaF_2 crystal with muons
- Binder that contains nanoparticles at the optimal concentration and thickness that makes a *soft cookie for placement between a crystal and a sensor (SiPM)*
  - 3M Siloxane epoxy (same properties as DOW-Corning grease?)
  - *3M hardener + DOW grease + nanoparticles -> soft cookie for crystal face – can produce in sheets then cut*

Two ½" diameter soft cookies w/nanoparticles



- *Or, a hard, permanent coating for a crystal face*
- Produce nanoparticle/sensor combination for Mu2e BaF_2 Calorimeter

UV testing devices at ANL


McPHERSON About... Products... Systems Services Resources News Contact Us

Aberration Corrected Vacuum Monochromator

- **VUV Spectrograph with CCD or MCP**
- **Works from 30nm VUV**
- **High throughput, f/4.5**
- **Optional - Turret, Multiple Ports, UHV**

The Model 234302 is a compact and versatile vacuum ultraviolet monochromator. A selection of aberration-corrected diffraction gratings is available so you can tailor the instrument to your wavelength of interest and application. Connect this instrument directly to your vacuum plasma physics experiment or build an intense UV tunable source. It is available as a scanning monochromator, as a spectrometer, or as a spectrograph with microchannel plate or direct-detection CCD. The Model 234/302 is popular in systems due to its compact design, high throughput and resolution. It is also available with an additional entrance or exit port.

Model 234302 PDF Data Sheet

Click on *Sample Spectra* tab below to see Helium emission spectrum measured with Model 234/302

VUV scanning monochromator – high vacuum for Deep UV testing (30 nm +)

- Setup in ~1 month

Low wavelength filter-based vacuum/N2 or inert gas atmosphere testing device

Other Testing Tools at ANL

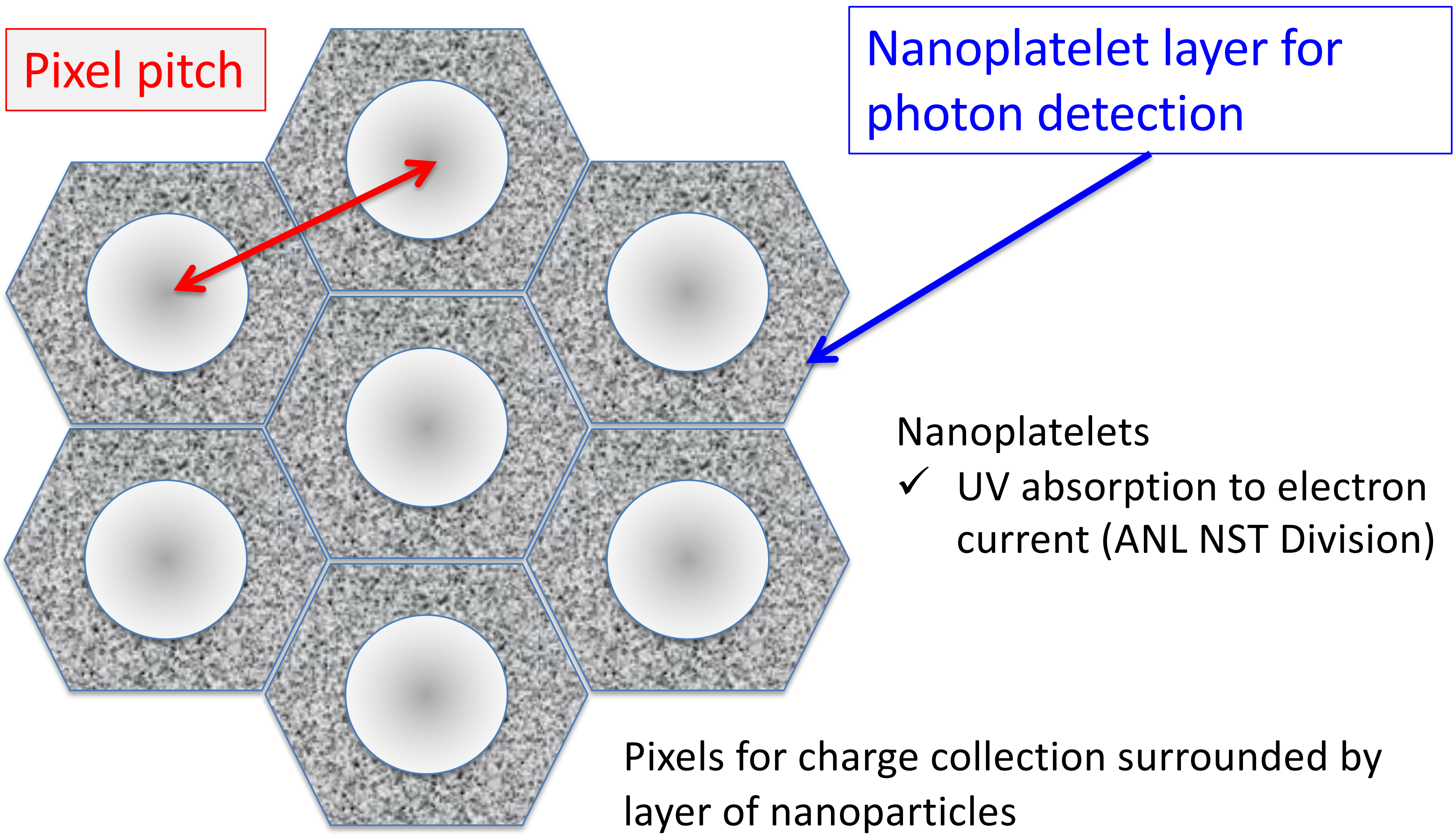
- PYTHON macros to calculate relevant quantities – electron wavelength, fermi energy, band gap enhancement, etc.
  - predict whether a candidate will show QC effects
  - used in our recent SR article to successfully explain observations
- Near UV Scanning monochromator – good down to ~200 nm, LabView software
- Spectrophotometer – Ocean instrument with observation of emitted light from 200 nm+
- ANL NST (NanoScience and Technology Division)
  - measurements of timing of Stokes Shift, other nano diagnostics
  - simulation code to predict nanoparticle properties
  - Direct conversion of UV absorption -> current in nanolayer

Future Pixel APA for DUNE (4^{th} detector)

Nanoparticle idea for photon detection on a pixel APA

- Need plane with 2D pixels (metal charge collector) and photon sensors
- Idea – photon sensors form the plane with charge collection pixels isolated within the photon sensors
- Pixel plane is made of a substrate material with nanoplatelets deposited on the substrate, readout on the back side (outside of TPC)
- Nanoplatelets absorb VUV photons, generate electrons – direct conversion of photons to current (possibly no separate photosensor)
- Identify nano candidates sensitive to 128 nm and 175 nm –> form into nanoplatelets -> direct signal
- *Keep in mind – doping Argon with hundreds of ppm Xenon converts all 128 nm light to 175 nm – may already have suitable candidates to start incorporating into nanoplatelets (to be tested in pDuNE)*

Qpix plane inside Field Cage



Nanoplatelets

✓ UV absorption to electron current (ANL NST Division)

Pixels for charge collection surrounded by layer of nanoparticles

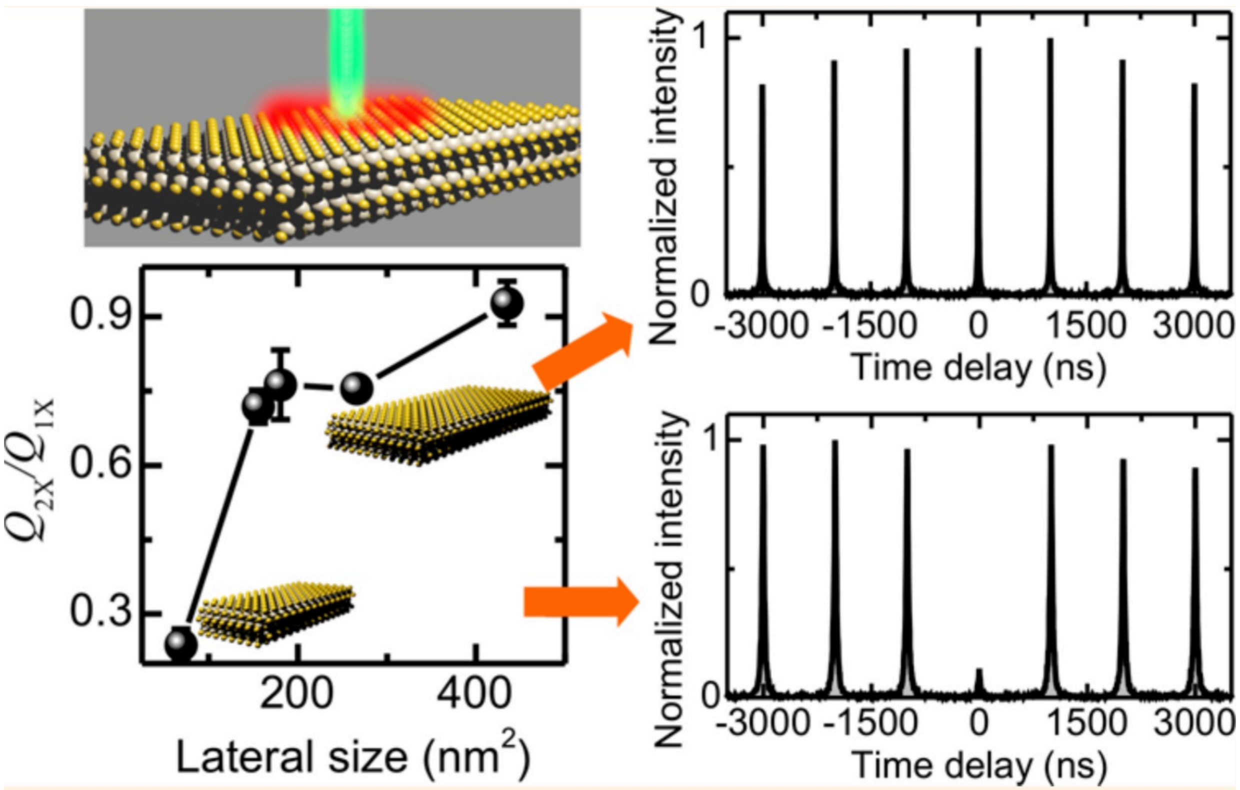
- UV -> Visible -> photosensor -> readout
- Or, possibly UV -> electron current -> readout

ANL NST - 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)



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

Potential Nanosensors, Applications, Customers

Detector	App	Absorbed λ (nm)	Emitted λ (nm)	Nano Candidates	Customers
Argon	Coating	125	425	CdTe	HEP(DUNE, SBN)
Xenon	Coating	178	425	CdTe	HEP, NP(Dark Matter, 0νββ)
Water	Coating	125-300	425	CdTe, LaF3:Ce	HEP(ANNIE)
BaF2 Xstal	Cookie, Surface	220	425	LaYO, CuCy, ZnS:Mn, ZnS:Mn-Eu, CdTe	HEP(Mu2e)
PbF2 Xstal	Cookie, Surface	200-300	425	Si, LaYO, LaF3:Ce, CdTe	HEP, NP(g-2, DRCal)
CsI, CeF3, CeBr3, LaCl3, LaBr3 Xstals	Cookie, Surface	300-371	425	LaF3:Ce	Medical
Plastic Lens	Infusion, Coating	300-400	425-550	LaF3:Ce	Night Vision, Defense
Window Glass	Infusion, Coating	300-400	425-550	LaF3:Ce	Homes, Businesses, Greenhouses

Some other interesting Apps

- UV Night Vision
  - Use reflected UV light in 300-400 nm range to enhance vision in low light conditions
  - UV tag identifiers
- Enhanced plant growth
  - Match light in greenhouses to the dual absorption peaks of chlorophyll
  - Nanoparticle spray for crops in fields!
  - Pending TCF (DOE) proposal
- Window glass lighting
  - Nanoparticle-infused window glass lights interior spaces
  - No power required
  - Planned tests at ANL glass shop

Nanoparticle-enhanced Night Vision

From **Science**Daily

Bats Scan The Rainforest With UV-Eyes

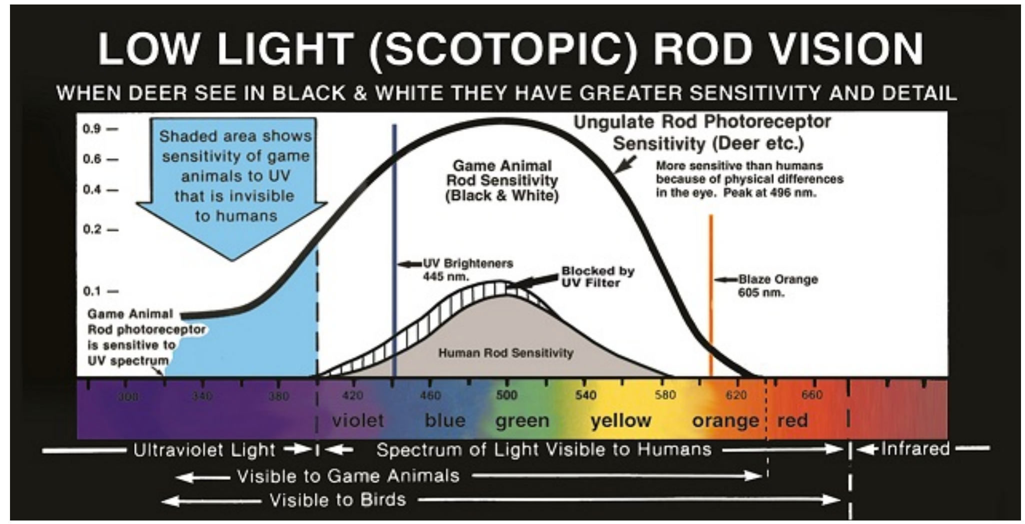
"Bats from Central and South America that live on nectar from flowers can see ultraviolet light (Nature, 9 October 2003)."

"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

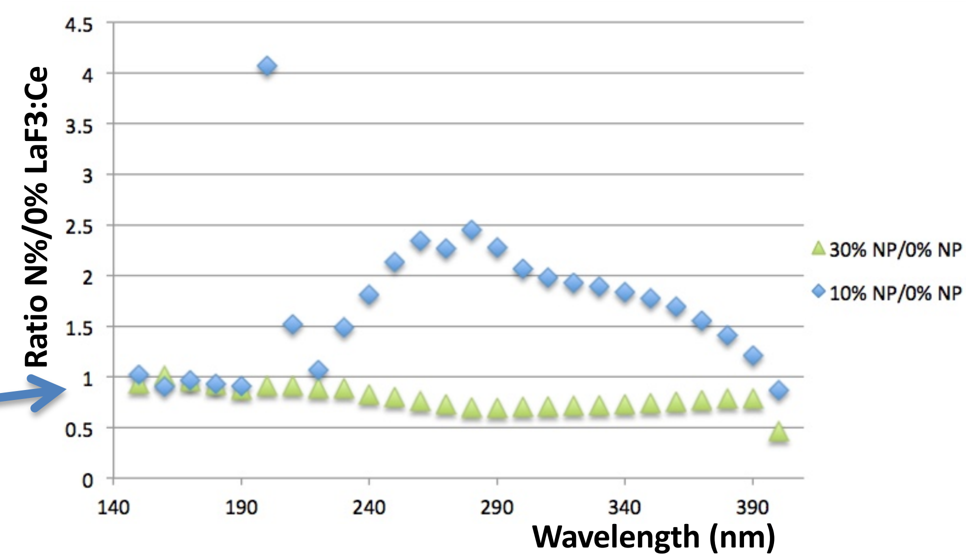


. . . and now Us!

LaF3:Ce nanoparticles in transparent polycarbonate buttons (contacts)

Enhancement for 10% LaF3:Ce:

230 nm < λ < 390 nm



Enhancing Plant Growth

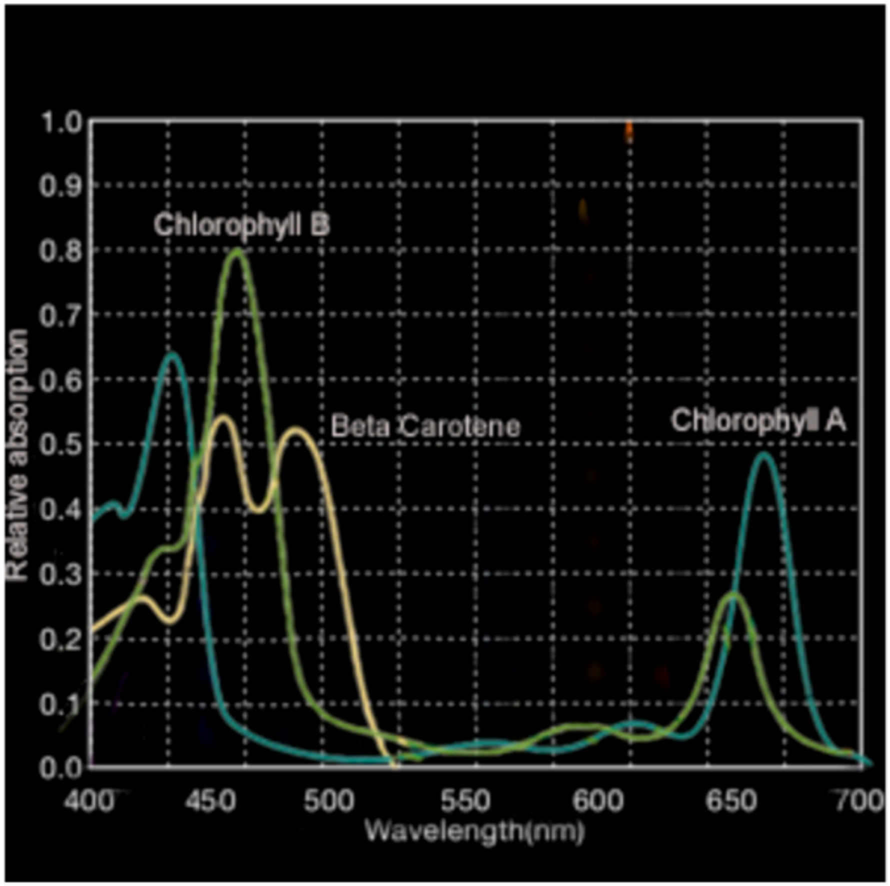


Fig. 1: Absorption Spectrum Chlorophyll A, B and Beta-Carotene

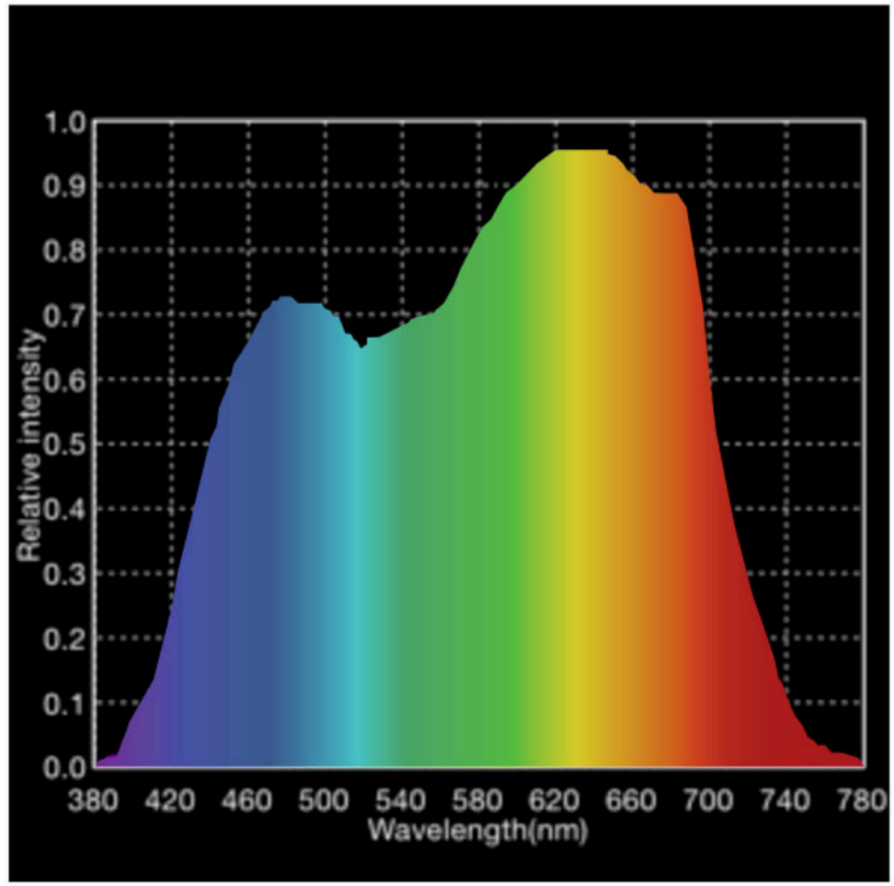
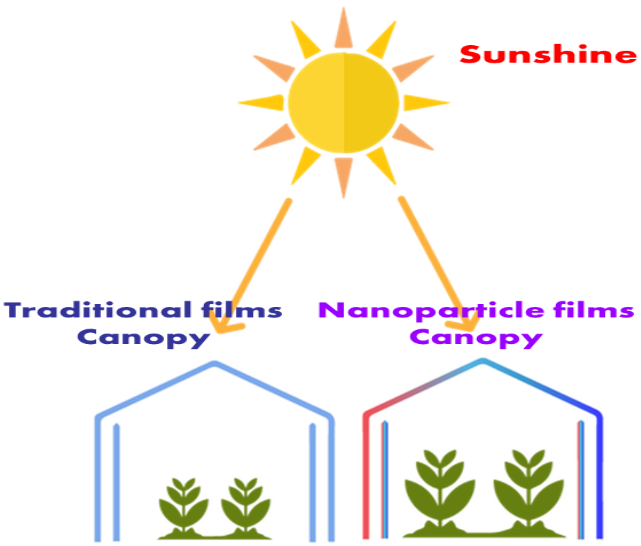


Fig. 2: Action Spectrum

Questions? / Fragen?

Solgro, Inc. Results



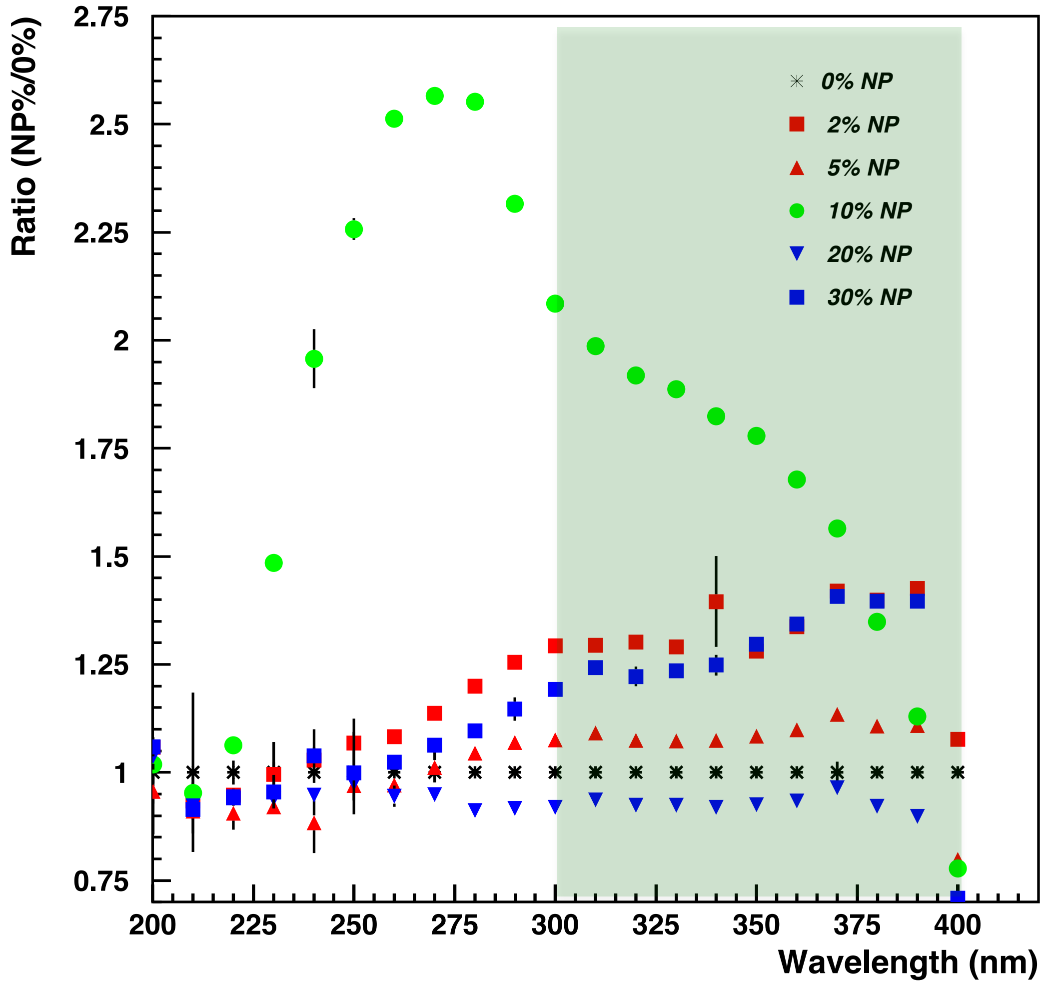
Nanoparticle application:

- Use 2 different nano candidates to convert UV to blue and UV and green to red
- Nano candidates in plastic film
- First results show dramatic increase under nano film section!

Also

- Bioelectricity production from plant-based fuel cells!
- Using other nanoparticle to filter unwanted IR -> lower temp in greenhouse

Nanoparticle candidate for window glass



- Enhanced response for 10% concentration of nanoparticle candidate in range 300 – 400 nm
- Infuse into window glass, chose nanoparticle size so that emitted wavelength is ~470 nm (peak of solar light spectrum)
- At least 10% more usable light! – more in low light conditions