UV-enhanced Photodetection with Nanoparticles

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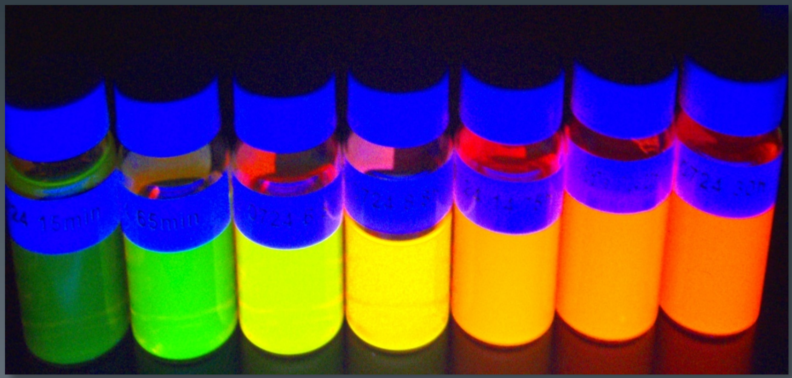
Motivation

- Need for a ***thin*** UV photosensor to read out Cerenkov light from a clear, dense crystal in a dual-readout homogeneous hadron calorimeter (proposed for future e+e- collider)(3-year DOE Advanced Collider Detector R&D grant)
- Observation (M. Nayfeh, et al. at U of Illinois) that Si nanoparticles are sensitive to UV light and also act as waveshifters, absorbing light in the UV range and re-emitting it as visible light

CdTe nanoparticles under UV light

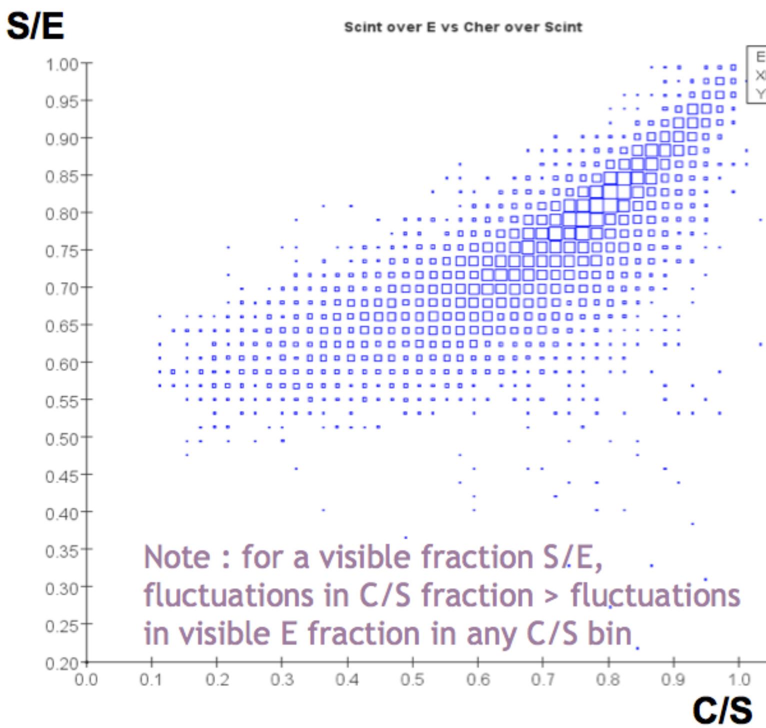


Dual-Readout Crystal Calorimeter

- Development of clear, dense crystals (BGO, PWO, . . .)
  - -> Total-absorption calorimeter ~same volume as current detectors
    - 7-9 g/cc densities -> 5-6 λ_I in, e.g., CDF calorimeter volume
  - -> Readout 2 sources of photons from 1 detector material
- Cerenkov from fast, light particles -> e± from EM showers
  - Fast, UV light
    - -> Few photons -> sensors with high collection efficiency, large area, directionality?
- Scintillation from all charged particles -> EM and Hadronic showers
  - Slower response, longer wavelength
    - -> Plentiful in current crystals -> small sensors? -> SiPM
- Dual-Readout advantage
  - -> C/S ratio is dependent on the em fraction of the visible energy
    - Large fluctuations in em fraction -> poor E resolution

Use C/S to correct total E response -> much improved E resolution

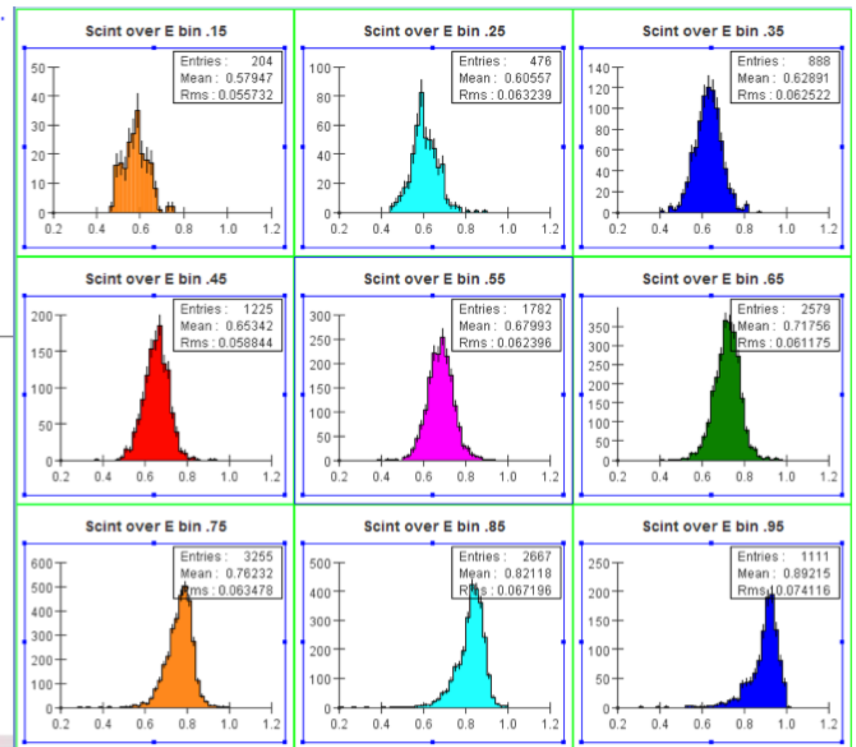
Cerenkov, Scintillation Response



Note : for a visible fraction S/E, fluctuations in C/S fraction > fluctuations in visible E fraction in any C/S bin

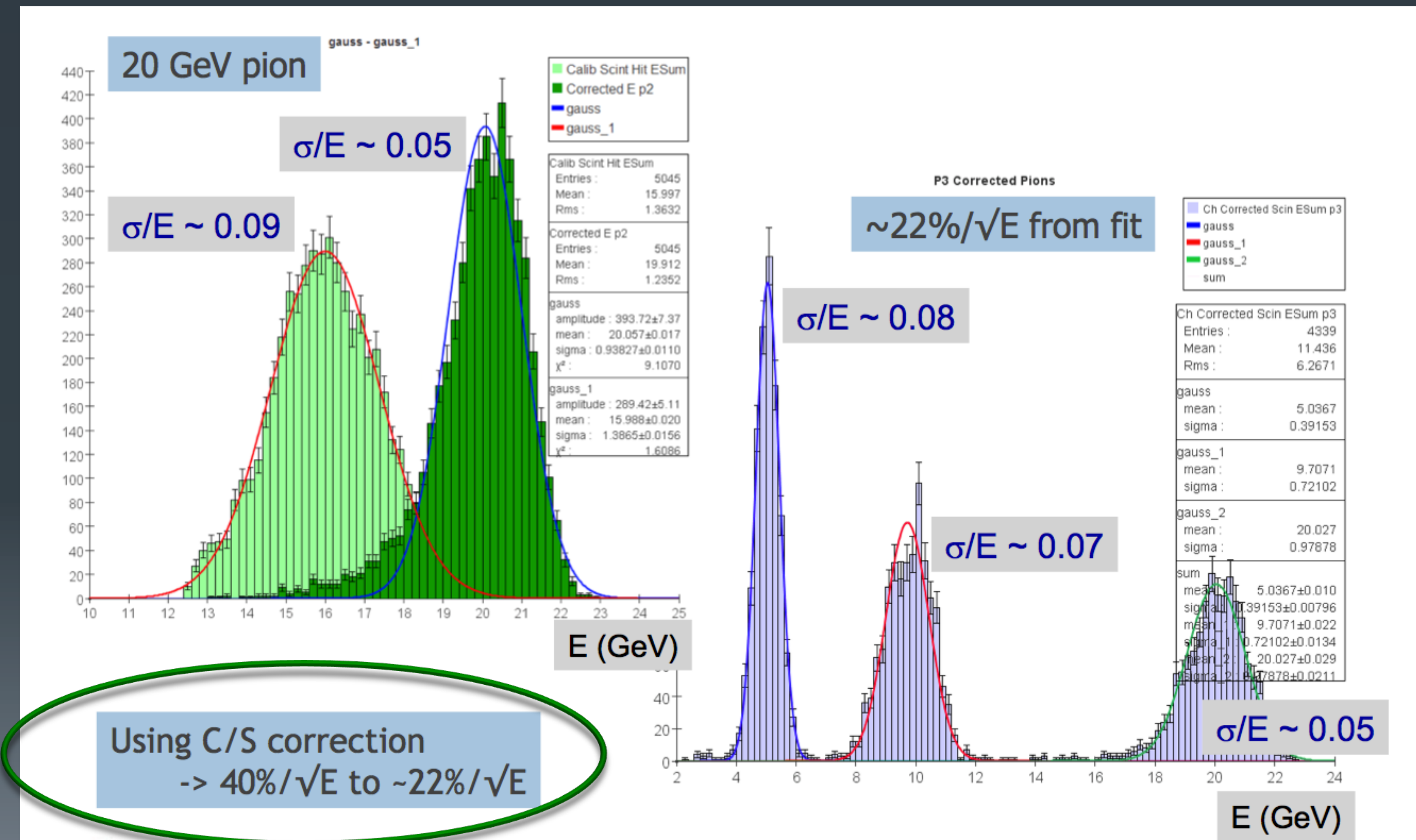
5, 10, 20, 50, 100 GeV pions

S/E slices in C/S bins

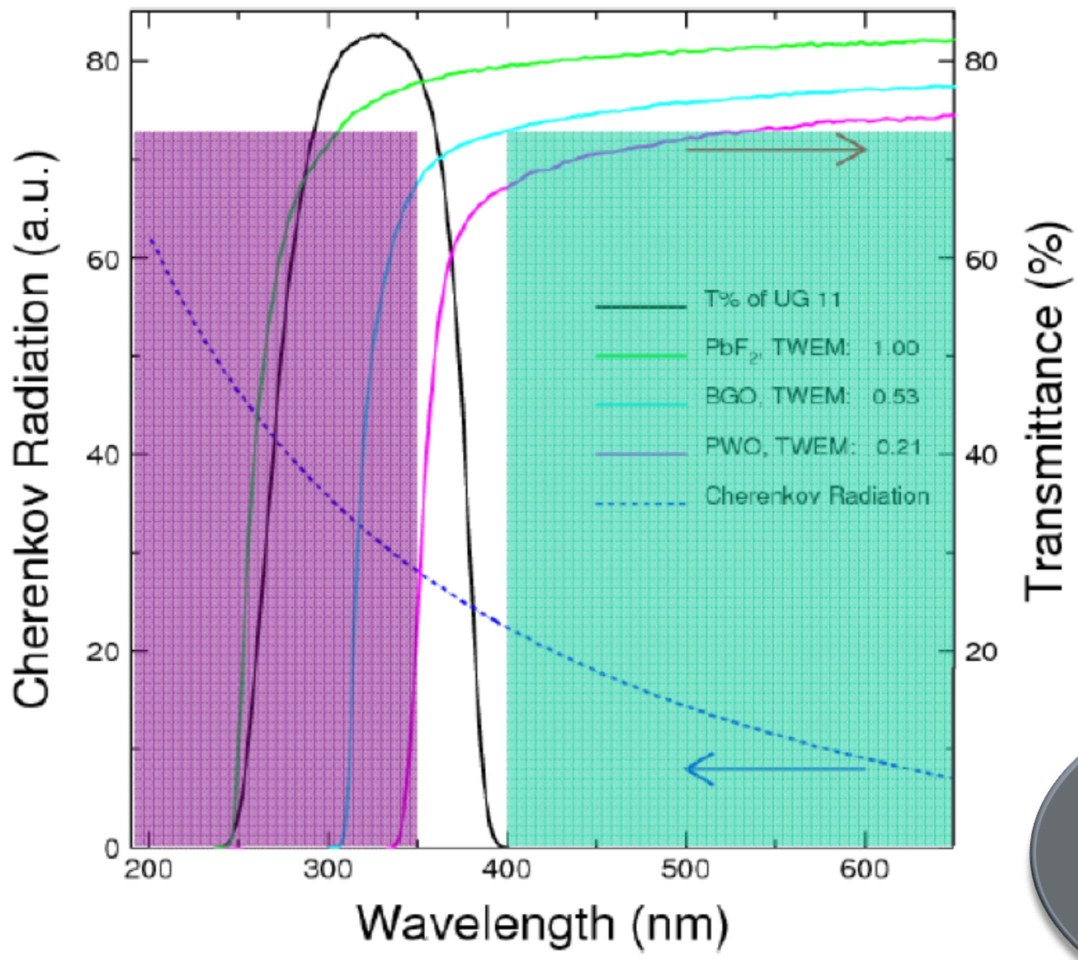


S (e calibrated scintillator response)
-> em and had visible energy
C (e calibrated cerenkov response)
-> ~em part of shower
C/S ~ em fraction of visible energy
S/E = total fraction of energy seen

C/S Corrected Pion Energies



Separate detection of C, S

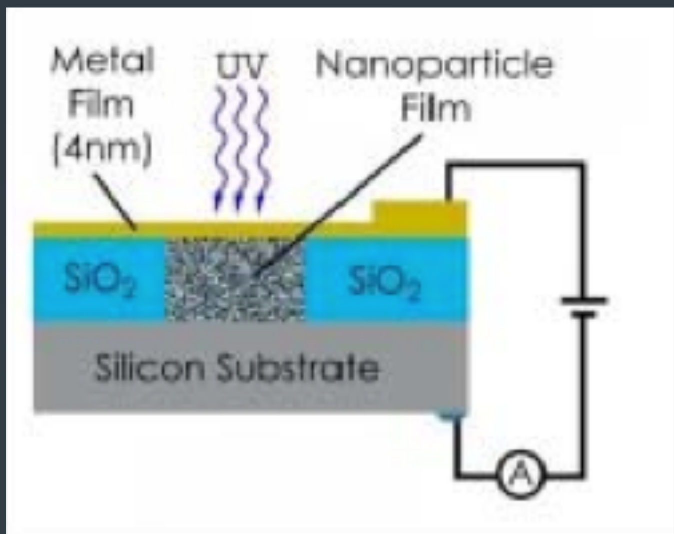


Separate, independent measurements of the Cerenkov and Scintillator signals by wavelength-sensitive detectors

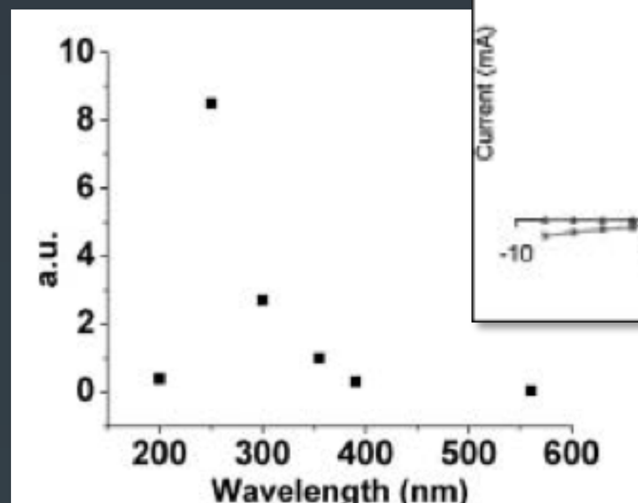
More detector area required for Cerenkov signal

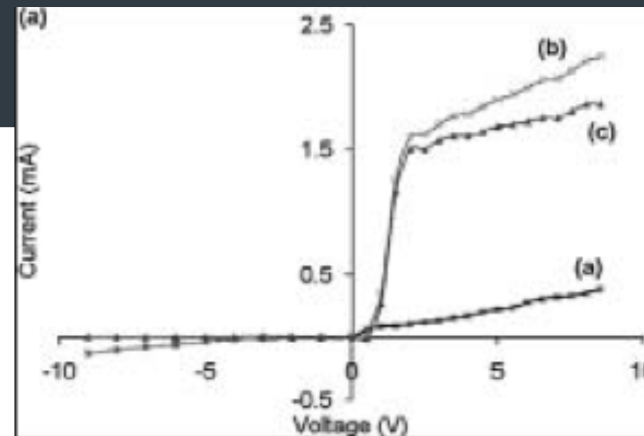
- ✓ Large area
- ✓ ***Thin profile***

Si Nanoparticle UV Sensor

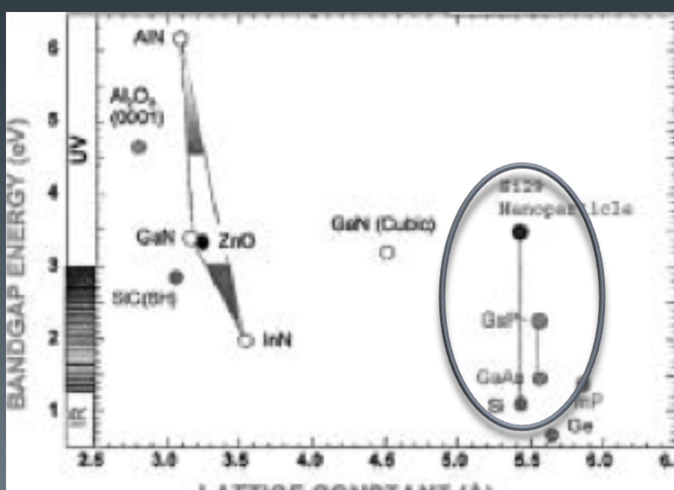


Nanoparticle photodiode





a) Dark response vs bias
b) 365 nm light response
c) Difference b-a



Bulk Si has a Band Gap of 1.1 eV
Si nanoparticle Band Gap is increased to ~3.4 eV
-> wavelength sensitivity into UV range (~250 nm)

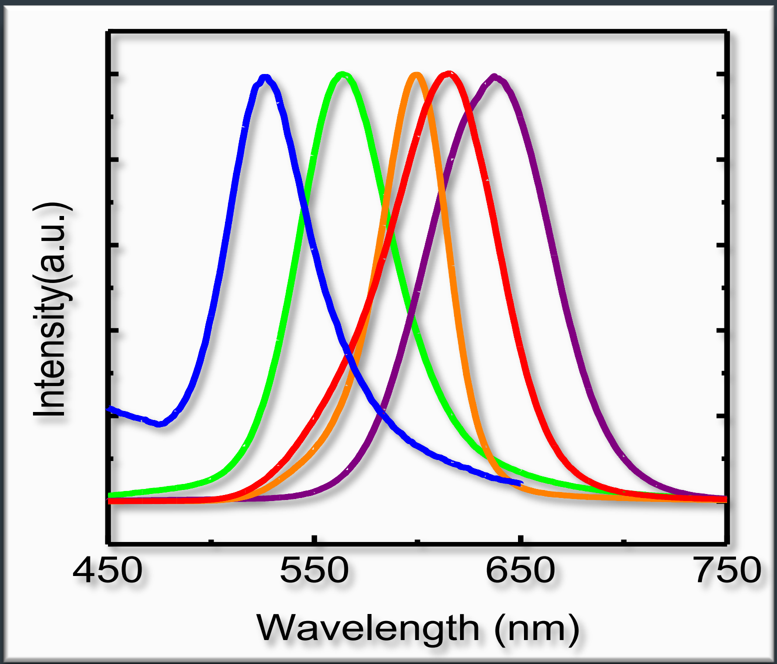
Also, detected UV light shifted to
~650 nm (3 nm particles)
~450 nm (1 nm particles)

O.M. Nayfeh, et al, IEEE Photonics Technology Letters, Vol. 16, No. 8, August 2004

Nanoparticle luminescence studies

Nanoparticle samples under study:
Si nanoparticles (Munir Nayfeh, UI)
Rare earth luminescent nanoparticles
Nanoscale semiconductors
Scintillating nanocrystals (Wei Chen, UTA)

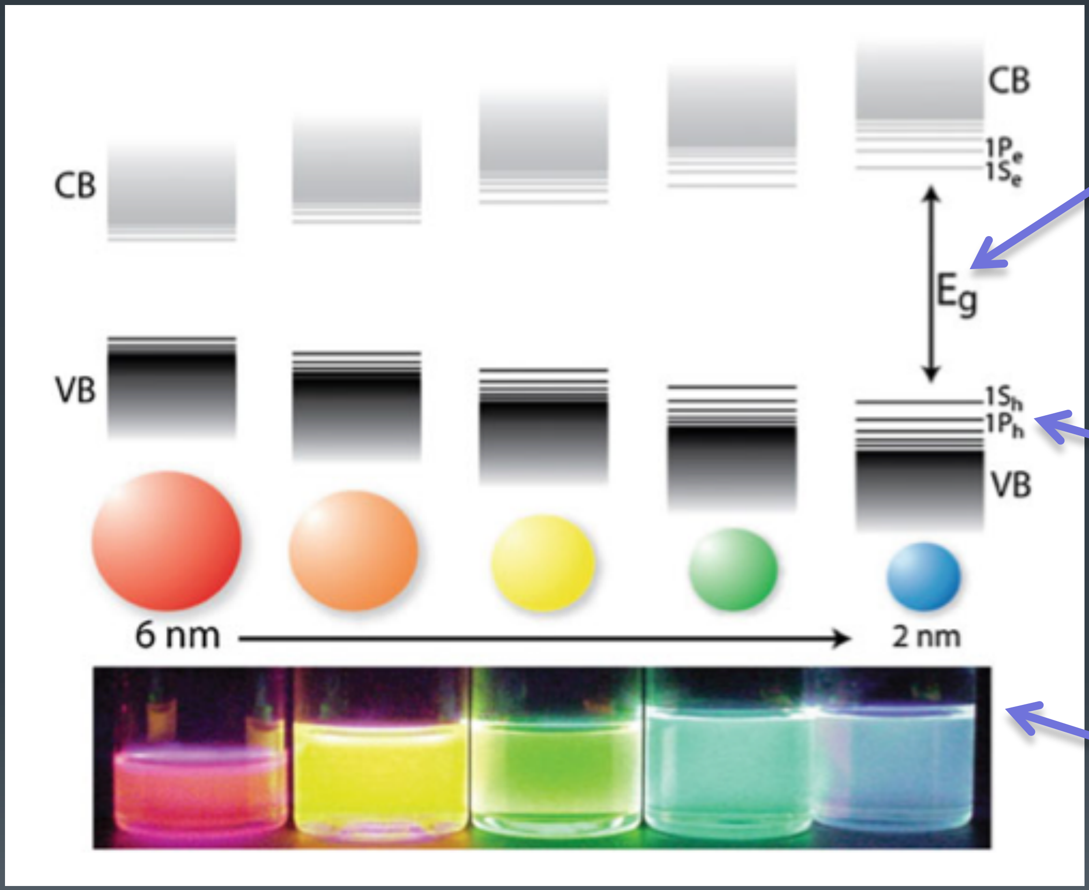
-> ~non-reactive – material compatibility
-> wavelength-shifting properties
-> emission wavelength depends on nanoparticle size
-> higher efficiency, intensity of emitted light
-> fast response (~10 nsec emission time)
-> good energy resolution
-> tunable sensitivity



Emission spectra of CdTe nanoparticles excited at 400 nm

Quantum Confinement condition
–> higher energy gap, discrete spectral features, strong transitions
Leads to size dependence of emission

Quantum Confinement, Nanoparticle Size



Bandgap E increases with decreasing size

Discrete energy levels form at the band-edges

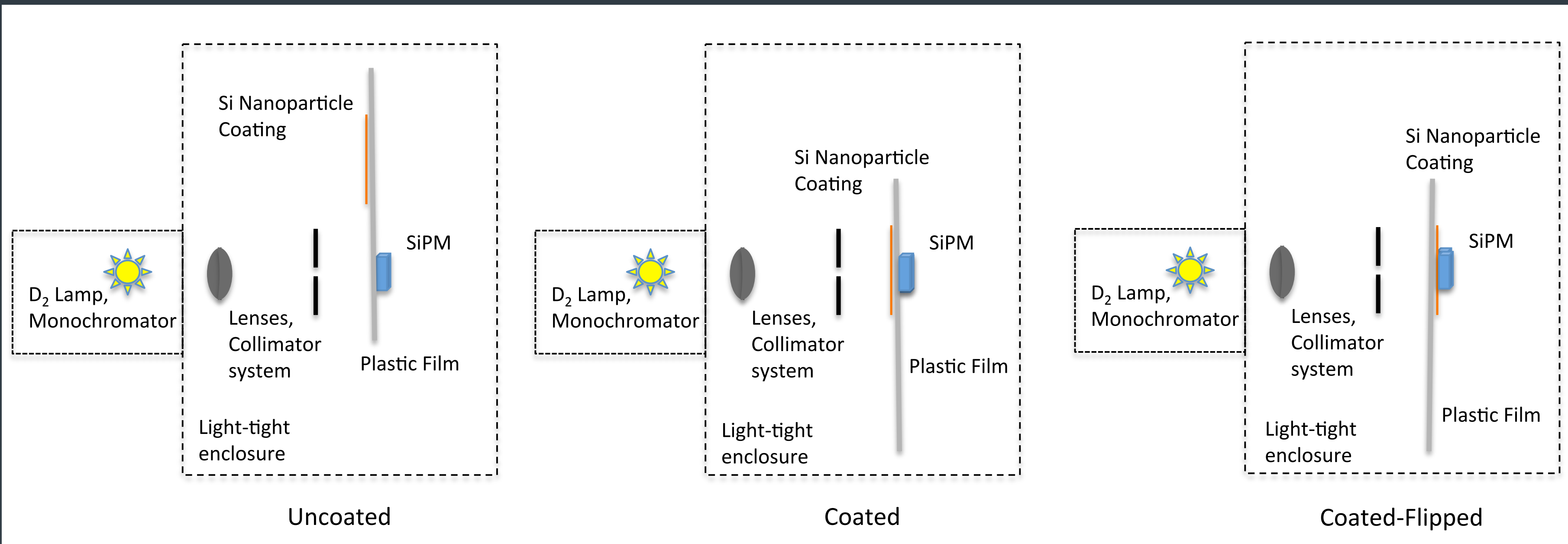
- Energy difference between band-edge levels increases with decreasing size

Luminescence wavelength decreases with decreasing size

Quantum Confinement – condition when nanoparticle size is less than the electron-hole distance (*exciton Bohr radius*) in semiconductor nanoparticles

- Few nm typically
- For metals, when density of states is sufficiently large ~ 2 nm for Au

Setup for Tests

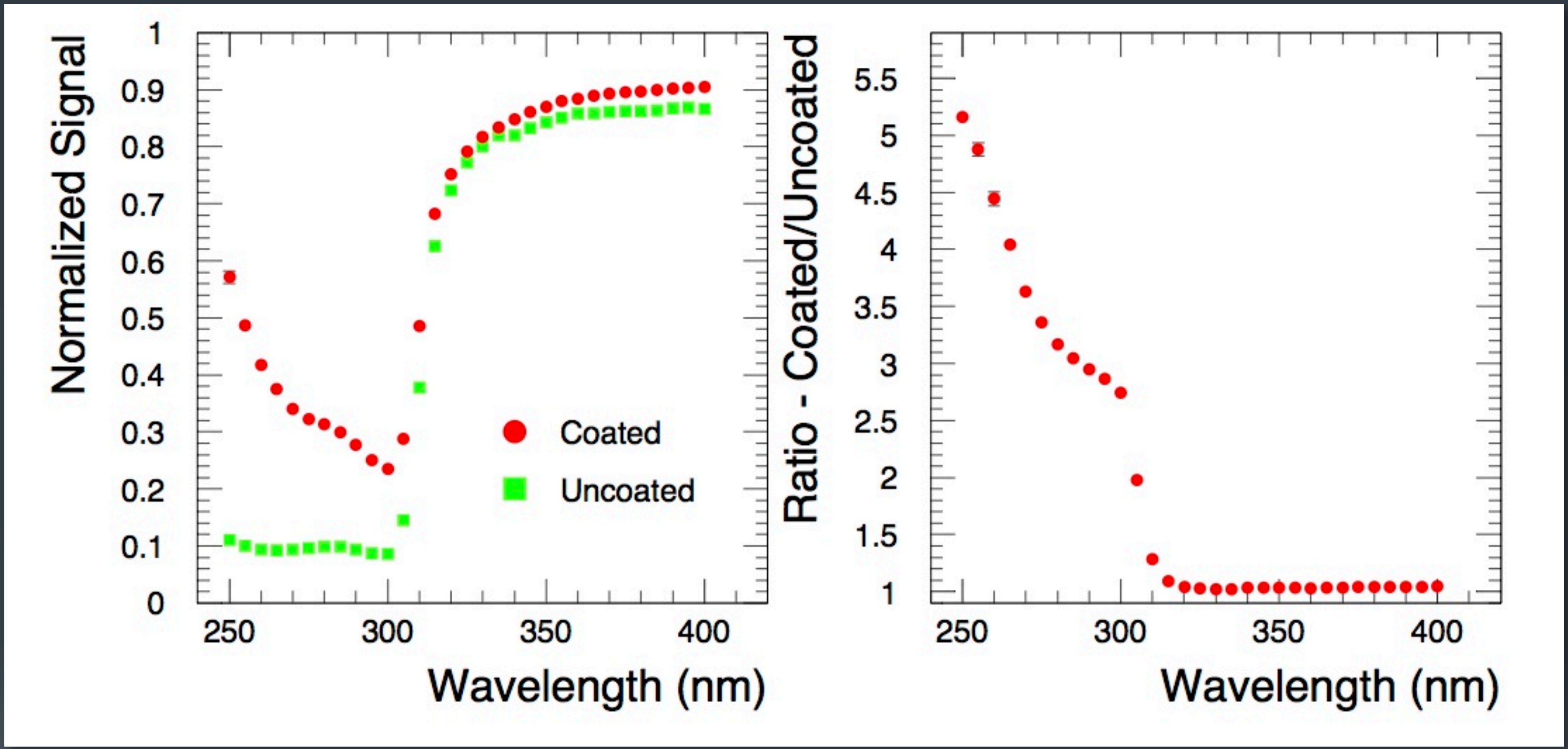


Uncoated – light through plastic film to SiPM

Coated – light through nanoparticle coating, then through plastic film to SiPM

Coated-Flipped – light through plastic film, then nanoparticle coating to SiPM

Test of Si Nanoparticle Coating



First test of Si nanoparticles – 5 nm steps from 250 nm -> 400 nm

Left – Coated and Uncoated normalized to lamp response

Right – ratio of Coated to Uncoated response

Increase in Coated response for wavelengths < 320 nm

-> note 3 nm nanoparticles emit at ~650 nm, not optimal for this SiPM

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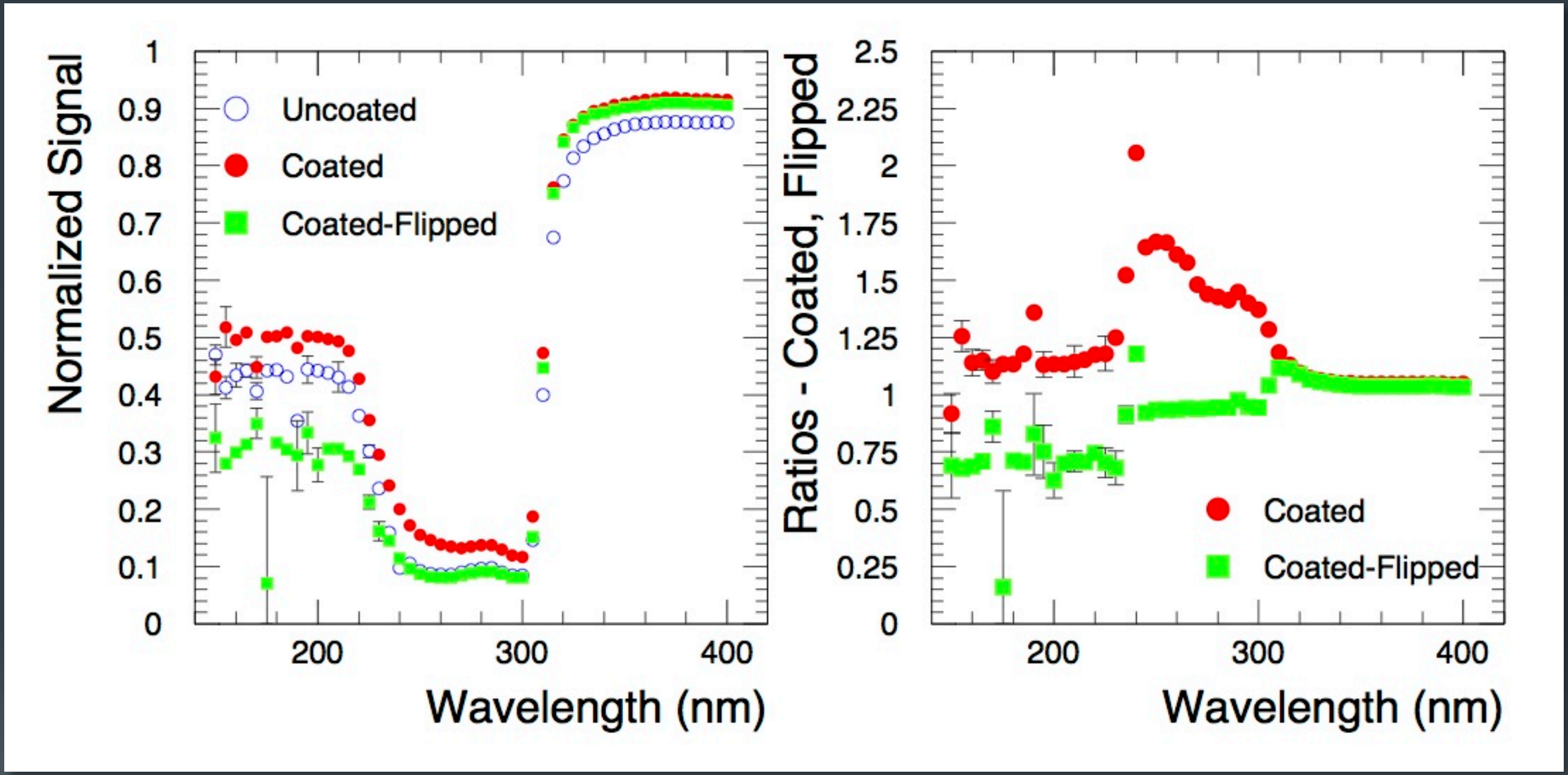
More Si Nanoparticle Results



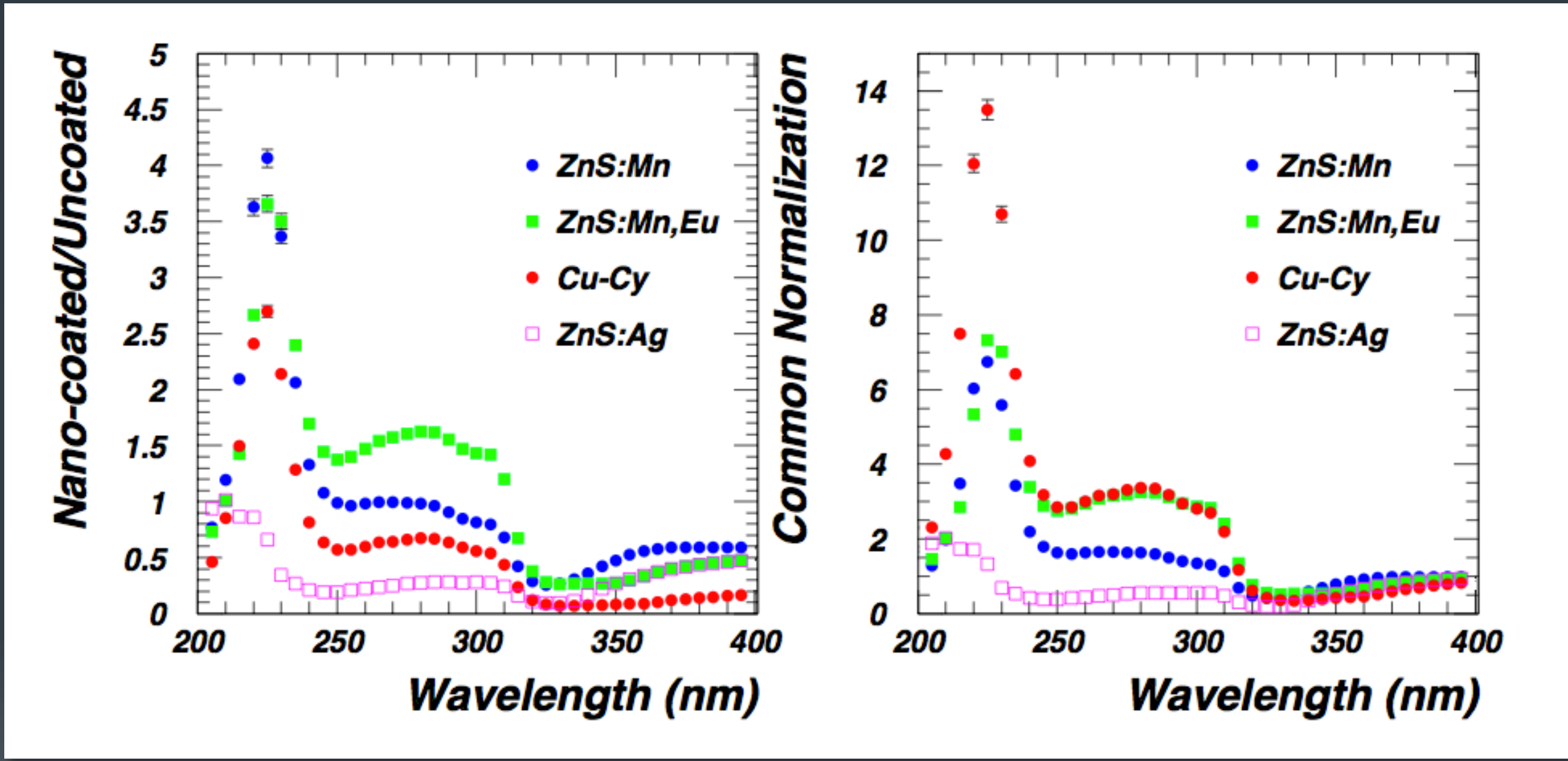
Second test of Si nanoparticles – 5 nm steps from 150 nm -> 400 nm

- Left – Coated, Uncoated and Coated-Flipped normalized to lamp response
- Right – ratio of Coated and Coated-Flipped to Uncoated response

Increase in Coated response for wavelengths < 320 nm

- -> peak in Coated response similar to photodiode response

Luminescent Nanoparticles



Test of UTA luminescent nanoparticles – 5 nm steps, 200 nm -> 400 nm

- Left – Coated/Uncoated (different thicknesses of samples)
- Right – Coated/Uncoated (common normalization at 400 nm)

Increase in 3 out of 4 samples for wavelengths < 320 nm

- -> peaks at ~225 nm

Fast scintillators

	LSO/LYSO	GSO [1]	YSO [1]	CsI	BaF_2	CeF_3	$CeBr_3$ [2]	$LaCl_3$	$LaBr_3$	Plastic scintillator (BC 404) [3]
Density (g/cm³)	7.40	6.71	4.54	4.51	4.89	6.16	5.23	3.86	5.29	1.03
Melting point (°C)	2050	1950	1980	621	1280	1460	722	858	783	70[#]
Radiation Length (cm)	1.14	1.38	3.04	1.86	2.03	1.70	1.96	2.81	1.88	42.54
Molière Radius (cm)	2.07	2.23	2.87	3.57	3.10	2.41	2.97	3.71	2.85	9.59
Interaction Length (cm)	20.9	22.2	27.3	39.3	30.7	23.2	31.5	37.6	30.4	78.8
Z value	64.8	57.9	33.3	54.0	51.6	50.8	45.6	47.3	45.6	-
dE/dX (MeV/cm)	9.55	8.88	6.70	5.56	6.52	8.42	6.65	5.27	6.90	2.02
Emission Peak[a] (nm)	420	430	420	420 310	300 220	340 300	371	335	356	408
Refractive Index[b]	1.82	1.85	1.80	1.95	1.50	1.62	1.9	1.9	1.9	1.58
Relative Light Yield[a,c]	100	35	40	4.2 1.3	42 4.8	8.6	141	15 49	153	35
Decay Time[a] (ns)	40	65	70	30 6	650 0.9	30	17	570 24	20	1.8
d(LY)/dT[d] (%/°C)	-0.2	-0.7	-0.3	-1.4	-1.9 0.1	~0	-0.1	0.1	0.2	~0

From Ren-yuan Zhu, Caltech

Many crystals have a fast, UV component of light output

-> If fast response is required, need a way to detect UV light from crystals

Nanoparticle-enhanced crystal response

- Find a binder (glue, grease) with refractive index matching that of the desired wavelength from a crystal *(Dow Corning PMX-200)*
- Find a nanoparticle additive that can be mixed with the binder to form a coating on the crystal face that absorbs the desired wavelength light *(Cu-Cy nanoparticles)*
- The matched refractive index allows the desired wavelength photons to exit the crystal, the infused nanoparticles absorb the UV light, wavelength-shifting it to an optimal visible wavelength (10 ns time?) for detection by *existing photosensors*
- *Have developed a fast, UV-sensitive photodetector for crystal scintillators without changing the photosensor itself!*

  - Visible photon filtering as well?

Plans for Future Development

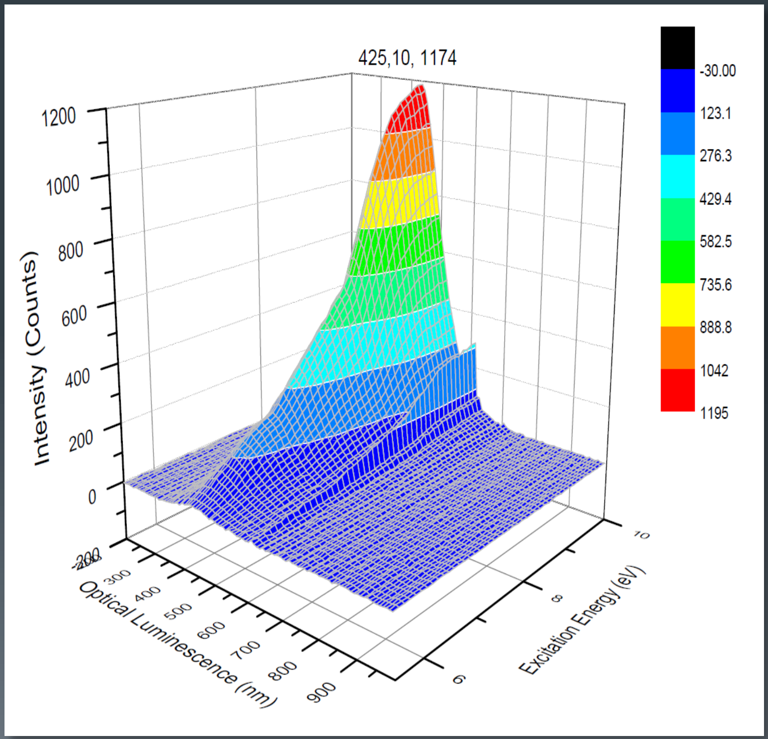
- 3-pronged approach:
  1) Identify nanoparticle candidates for UV absorption and wavelength-shifting emission
  2) Design nanoparticle coatings for direct application to scintillators in order to extract and wavelength-shift UV light
  3) Construct tunable UV-sensitive photodiodes using thin nanoparticle layers

- Testing Activities
  - ➢ Identification of nanoparticle candidates
  - ➢ Characterization of nanoparticle coatings
    - ✓ Absorption, emission spectrums
    - ✓ Optimal coating thickness, refractive index
    - ✓ Light detection efficiency

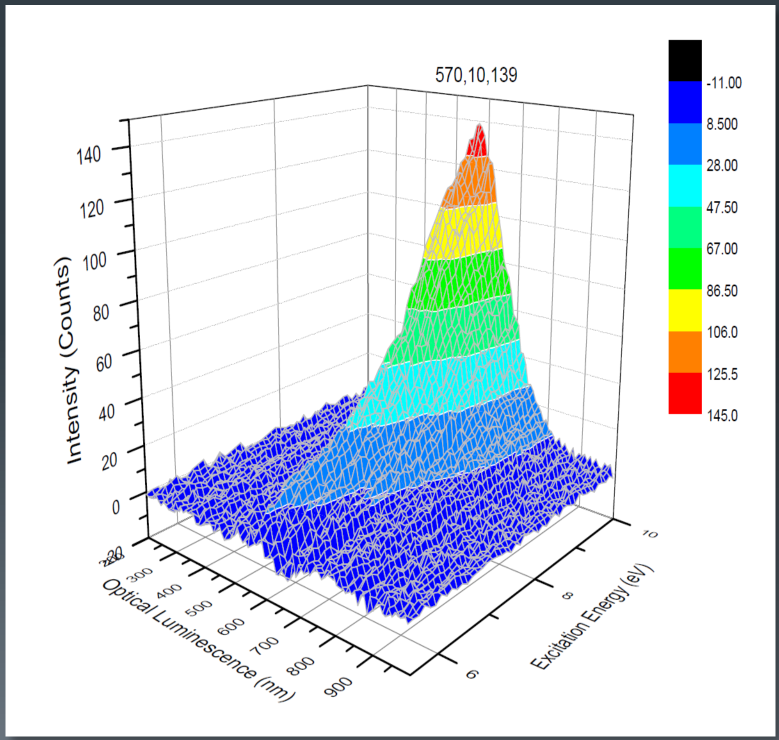
Nanoparticles for Future Tests

Some new nanoparticles for future tests

- Note large emission intensity out to limit of plot – 10 eV -> ~125 nm
  -> Argon emission – LAr detectors DUNE, SBN
- Emission at 425 nm good match for Hamamatsu SiPM



LaYO

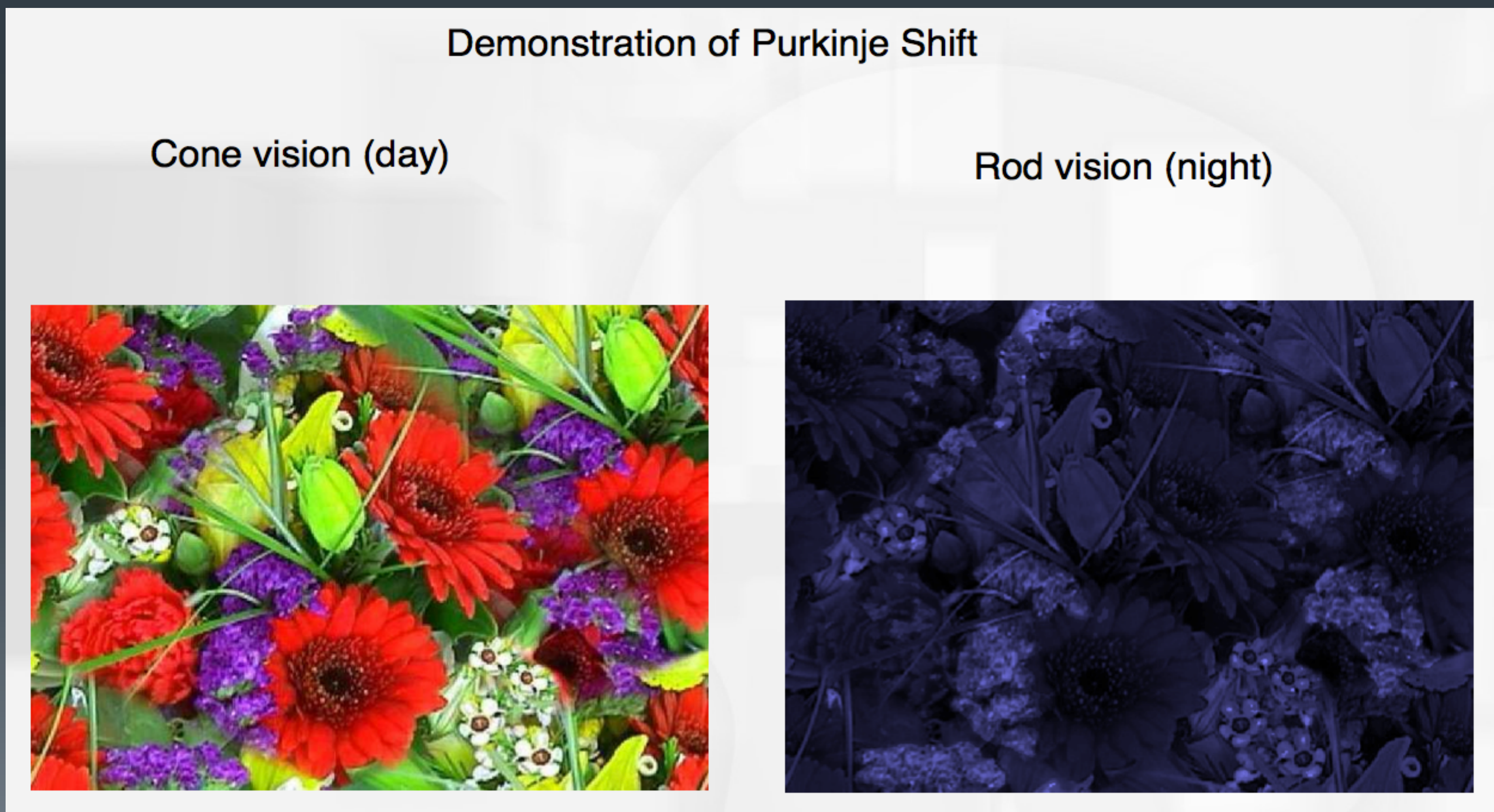


CdS/PVT

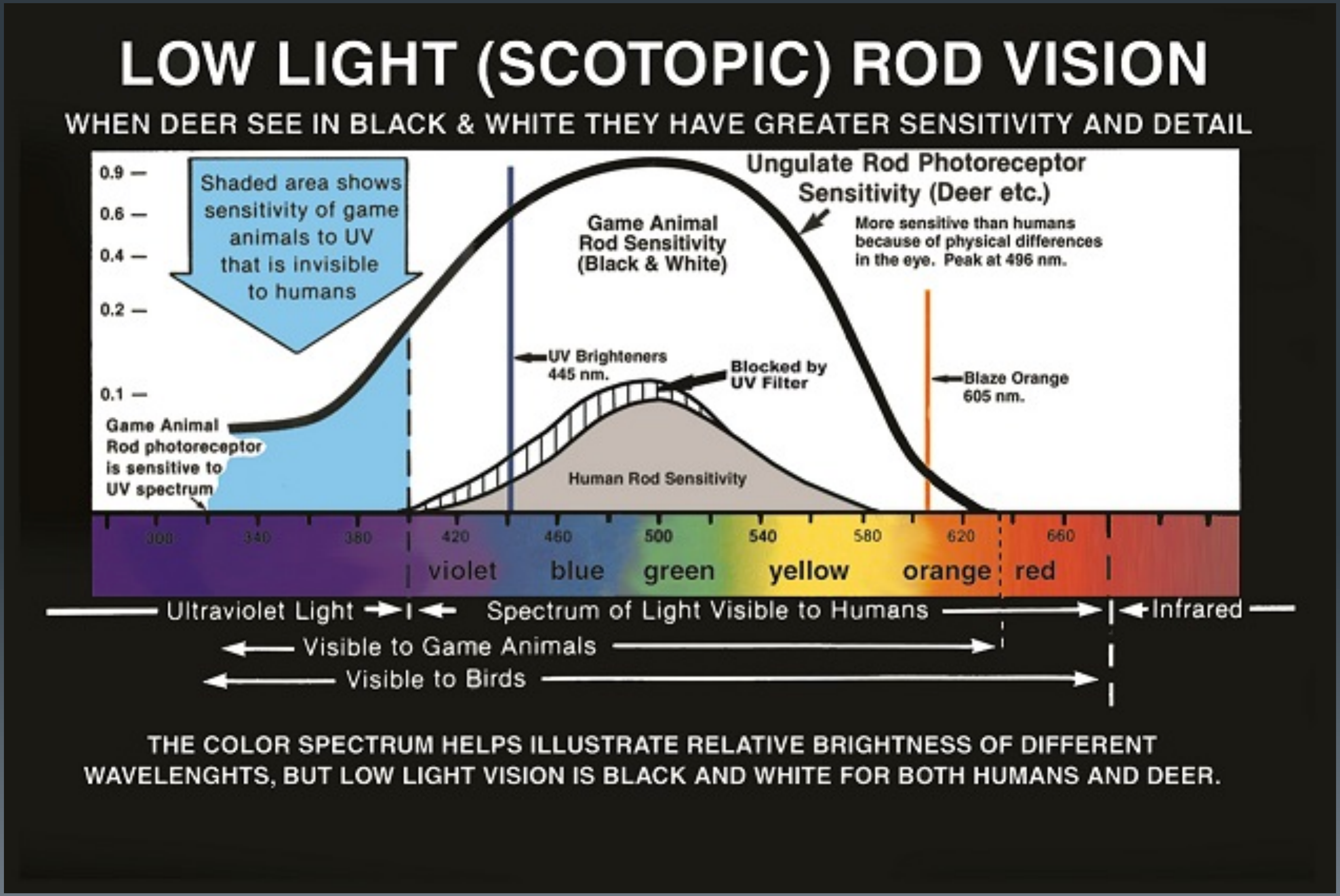
Another App? - UV night vision

At night, ambient light is shifted to shorter wavelengths

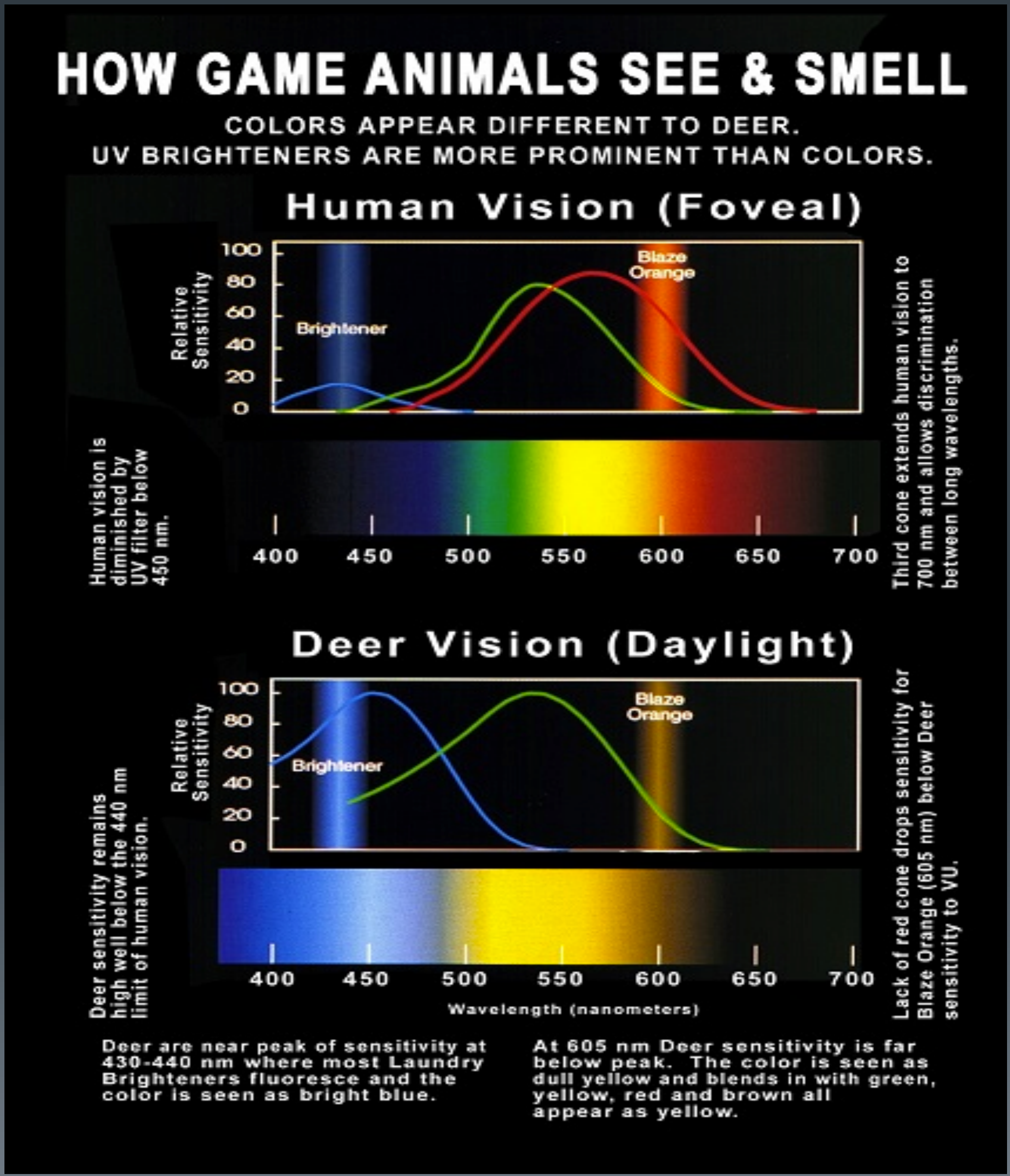
Purkinje shift – enhanced sensitivity to short wavelengths during dark adaptation (cone to rod vision dominance)



UV vision in Deer



Comparison of Human, Deer vision



Humans optimal wavelength – blaze orange color using 3 cones

Deer optimal wavelength in daylight – laundry detergent brighteners!

-> Deer peak sensitivity 430-440 nm

Overall, deer vision peaks at lower wavelengths – near UV cutoff for humans

Nanoparticle-enhanced night vision

- Nanoparticles are sensitive to UV light in a wavelength range where the human eye is blind
- Use nanoparticles to detect UV light in the wavelength range < 400 nm (below cutoff of human detection)
- Then, by optimizing nanoparticle size, can get re-emission at the peak of human (rod) sensitivity (~500 nm)
- Have added light intensity in an unseen wavelength range to the range in which the human eye is sensitive –> *enhancing total night vision*
- Can imagine glasses/contact lenses infused with nanoparticles that can be worn at night aiding in total vision sensitivity

    -> A way to see objects at night that don't radiate heat?

Summary

Program of nanoparticle production and testing – collaboration of University of Texas at Arlington Physics and ANL HEP Division

Planned accomplishments of R&D program :

- Catalog of nanoparticle coatings with performance parameters
- Optimized nanoparticle/base transition coatings for UV light extraction and wavelength-shifting from crystal scintillators and glasses (Cerenkov light)
- Thin, UV-sensitive photodiodes optimized by wavelength

-> Development of new class of UV-sensitive photodetectors using nanoparticles

- ✓ Extends the wavelength response into the UV for existing PMTs
- ✓ Enables efficient extraction of fast, UV light from scintillator (and Cerenkov) detectors
- ✓ Produces thin, UV sensitive photodiodes