Stokes-shift engineered colloidal quantum dots as wavelength shifter for detection of VUV light in LAr and LXe detectors

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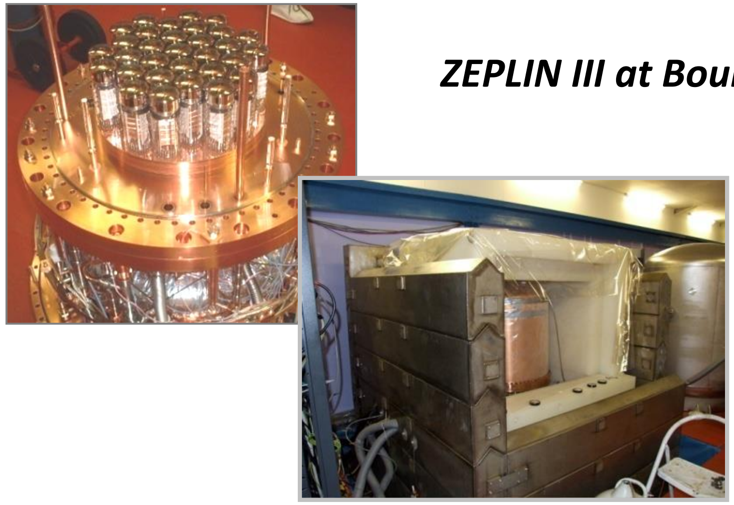
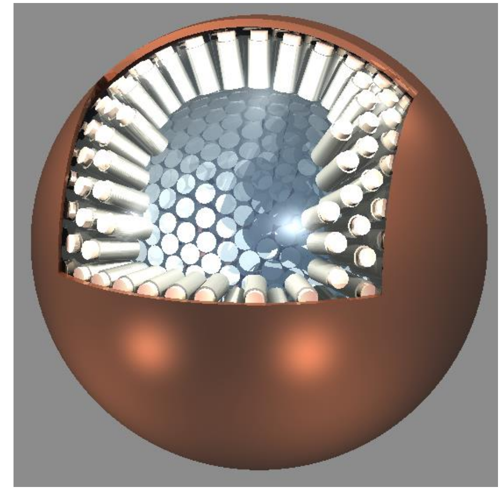
Noble ``gas'' detectors: some examples

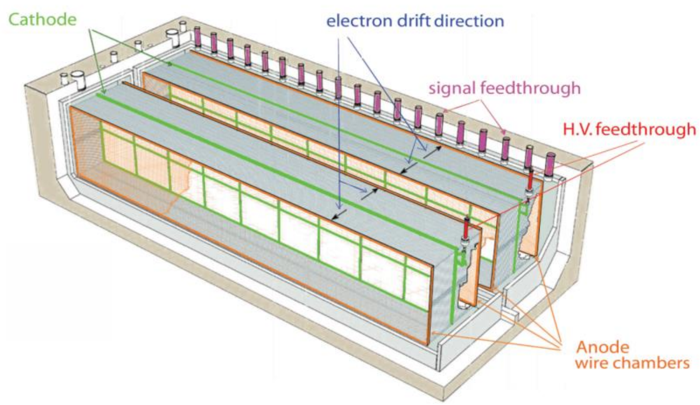
Xenon 100



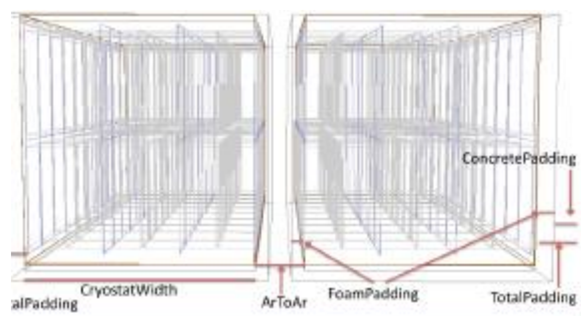
ZEPLIN III at Boulby mine



XMASS at Kamioka



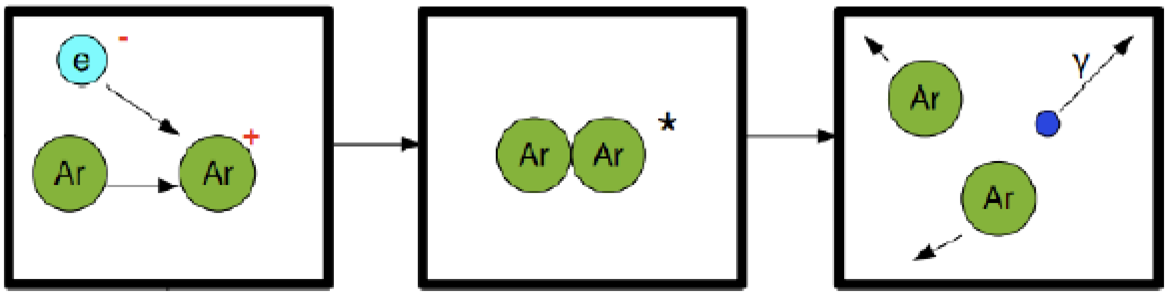
Icarus T 600



LBNE ⟶ Dune

Many examples for neutrino physics and dark matter searches

Noble gas scintillation



2 processes production scintillation light in LAr

$$\mathrm{Ar}^* + \mathrm{Ar} \rightarrow \mathrm{Ar}_2^* \rightarrow 2\mathrm{Ar} + \gamma$$

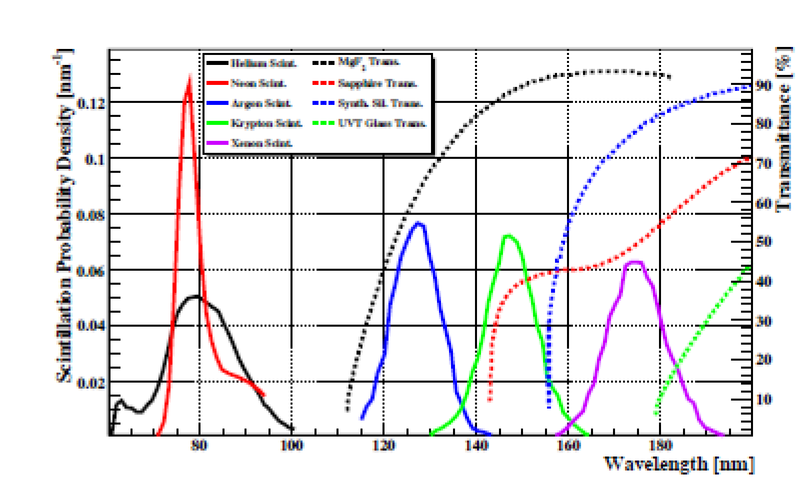
$$\mathrm{Ar}^+ + \mathrm{Ar} \rightarrow \mathrm{Ar}_2^+ + e \rightarrow \mathrm{Ar}_2^* \rightarrow 2\mathrm{Ar} + \gamma$$

prompt light at 6 ns (23%) and late light at 1.6 µs (77%)

Absolute event timing enables:

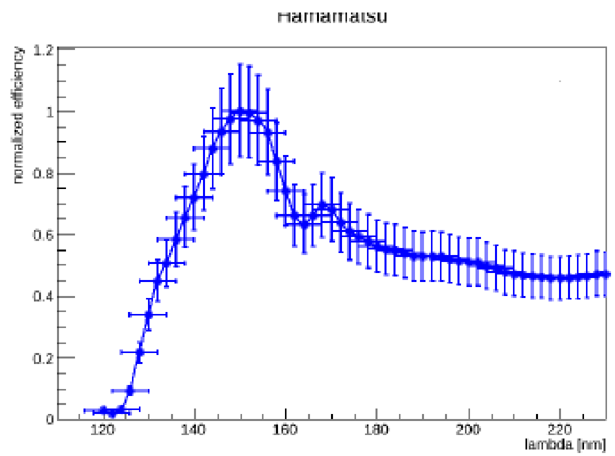
- *Mitigation of cosmic ray backgrounds for surface detectors*
- *Gives t_0 to detector*
- *…..*

- *Light is created through bonding and separation of Ar dimers*
- *High scintillation light yield (20-40 photons/keV)*
- *Light created at very short wavelengths (VUV)*
- *Noble gas transparent to their scintillation light*
- *useful for particle PID*
- *Problem: VUV light difficult to detect*

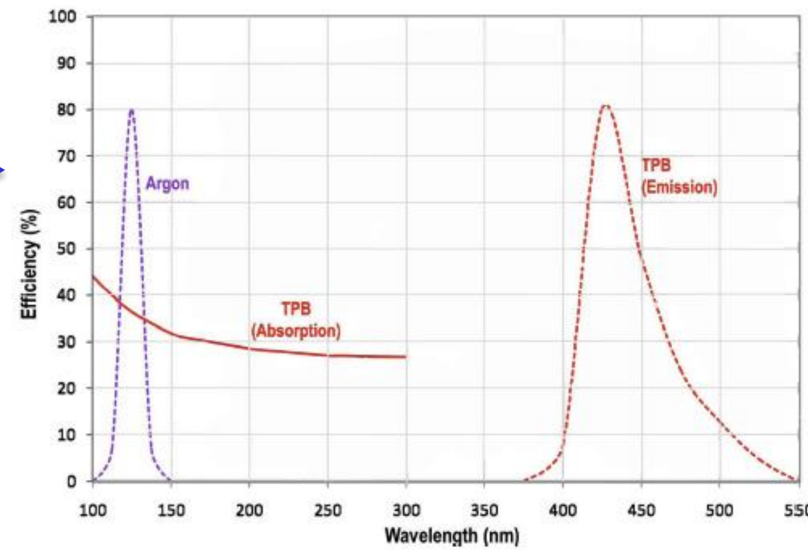


What to do with this ``troublesome'' photons

- *Some devices are directly sensitive to them*
- *Solid state devices can be sensitive to below 100nm . Small area, expensive, often slow*
- *Some PMTs sensitive down to 160 nm, UV-transmitting window limits sensitive area*
- *Usually you need a suitable WLS from VUV to VIS light (solution implemented in Icarus T600)*

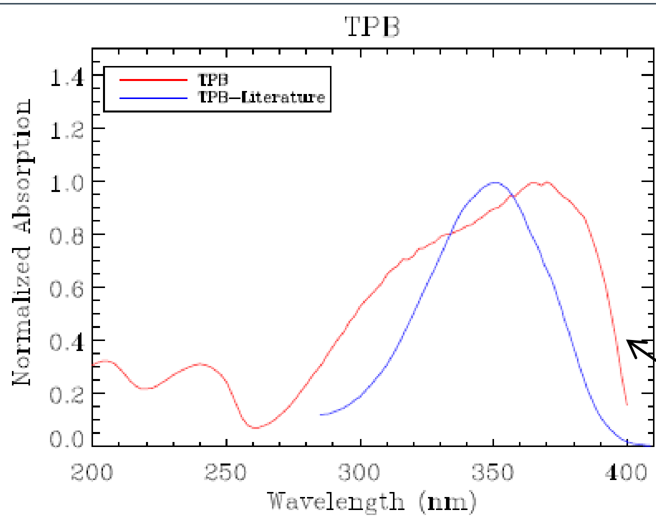


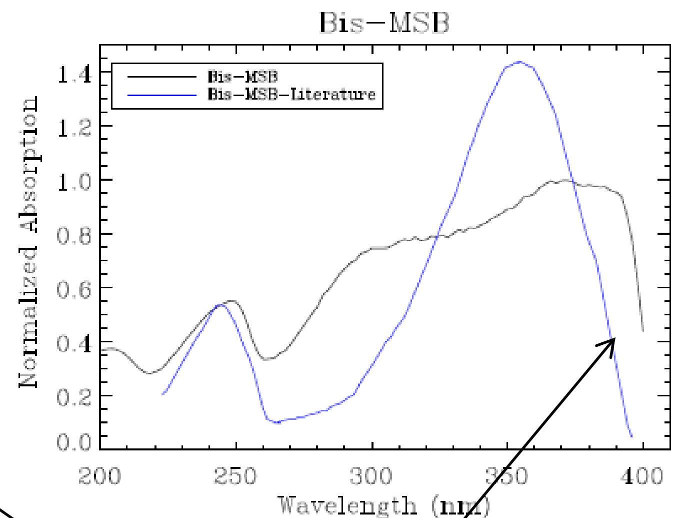
Response of Hamamatsu 3x3MM-50UM VUV2 SiPMT (A.Falcone et al., NIM A787 (2015) 216)



Used wls materials

- Conventional: TPB, bis-MSB, p=therfenil, …
- New ones: quantum dots
- What is the problem ? Absorption spectrum may be superimposed with emission spectrum and there may be some uncertainty on measurements
- If there is a wide gap between absorption spectrum and emission spectrum, problem is minimized

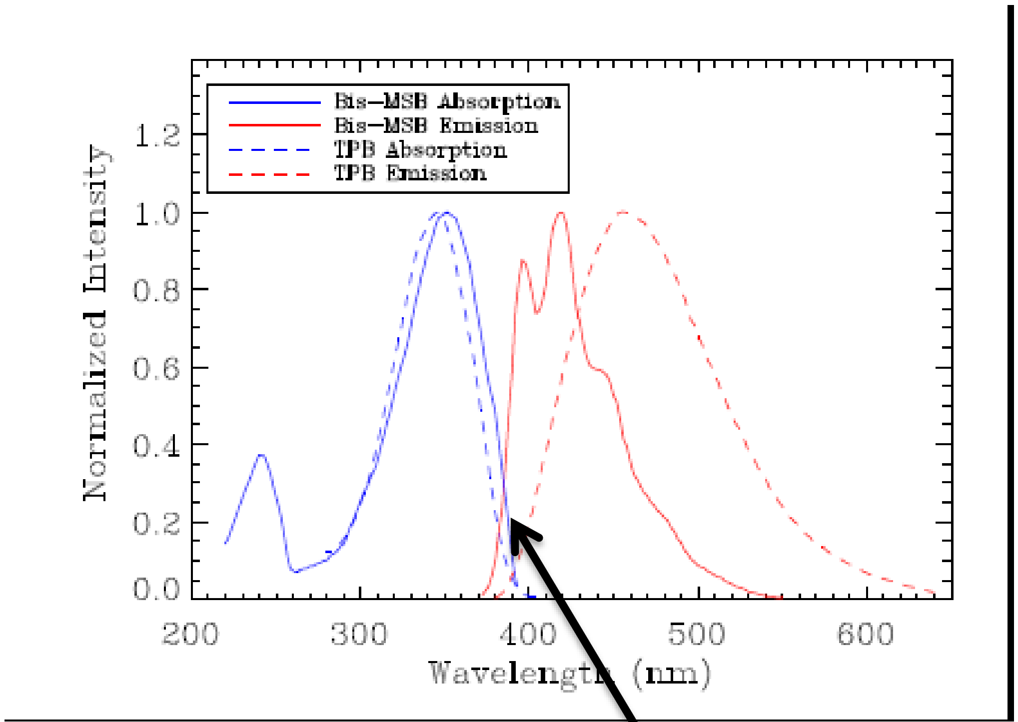


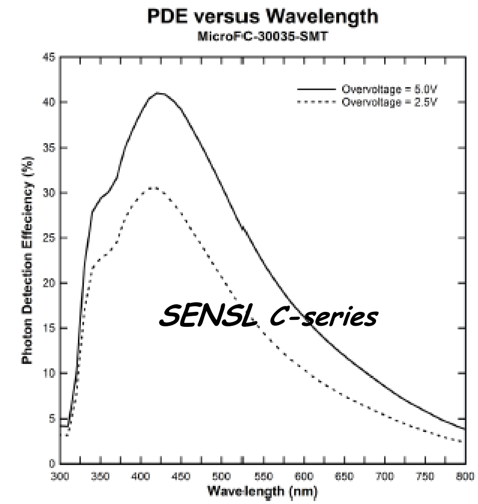


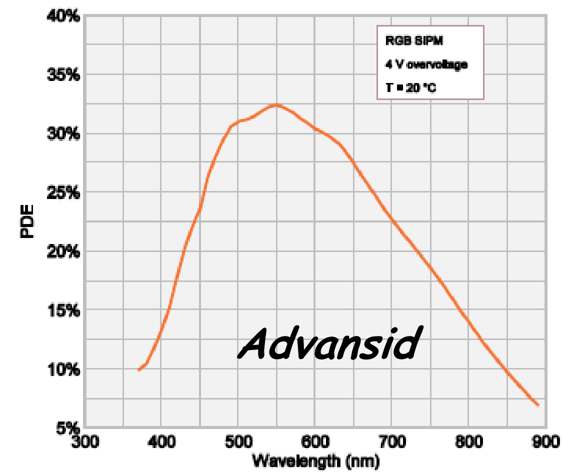
Near UV TPB absorption spectrum

From B. Baptista, LiDiNE meeting FNAl 2013

Emission and absorption spectrum TPB, bis-MSB







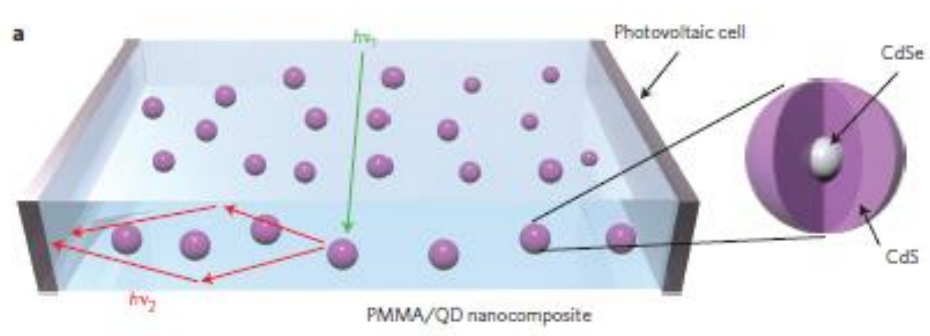
Critical region, in addition low cost photon detectors are better suited to RGB than NUV

Starting point: the LSCs problem

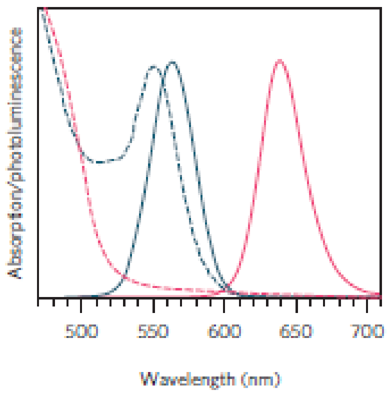
Starting point was the development of large area solar concentrators (F. Meinardi et al., Nature Photonics 8 (2014) 392

- ***Typical LSCs consist of plastic optical waveguides doped with fluorophores or glass slabs coated with active layes of emissive materials***
- ***Sunlight is absorbed by fluors and re-emitted at longer λ***
- ***The luminescence is guided by total internal reflection to a photovoltaic cell placed at the edge, where it is converted to electricity***

Quantum dots

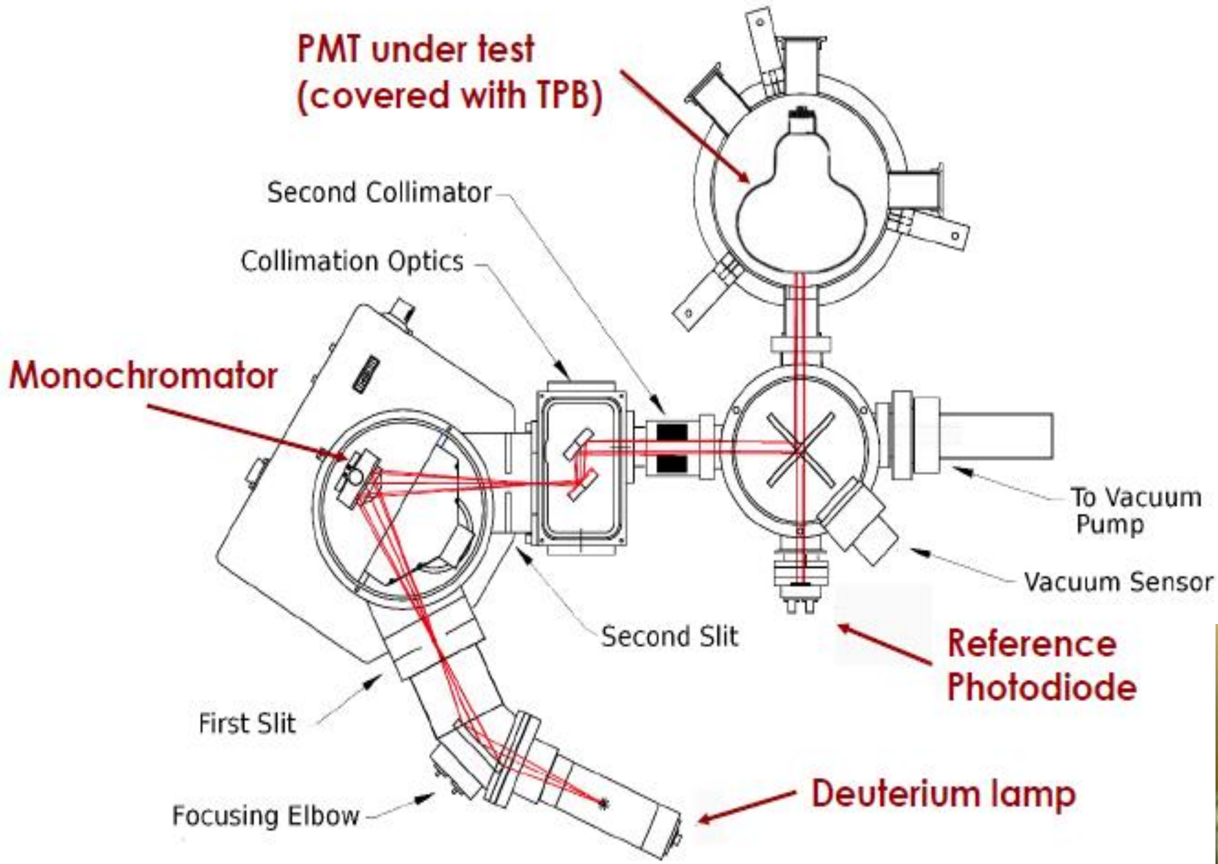


- Use suitable colloidal Qdots immersed in PMMA support (giant CdSe/CdS)
- Large Stokes-shift (self-absorption of emitted light) that may be tuned to application



- Emission (depending on QD size) may be engineered to the RED region, well suited to some type of photodetectors

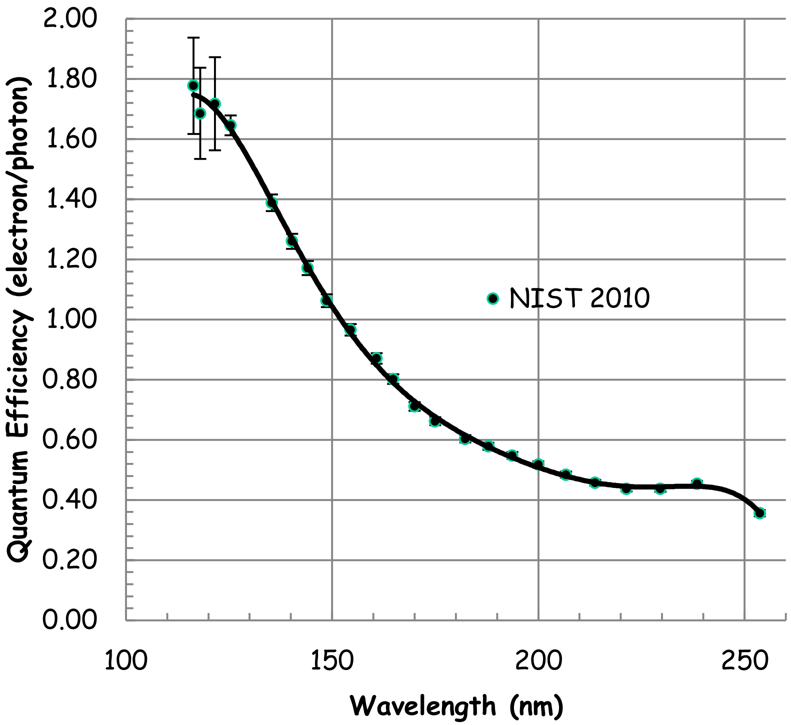
Measurement setup

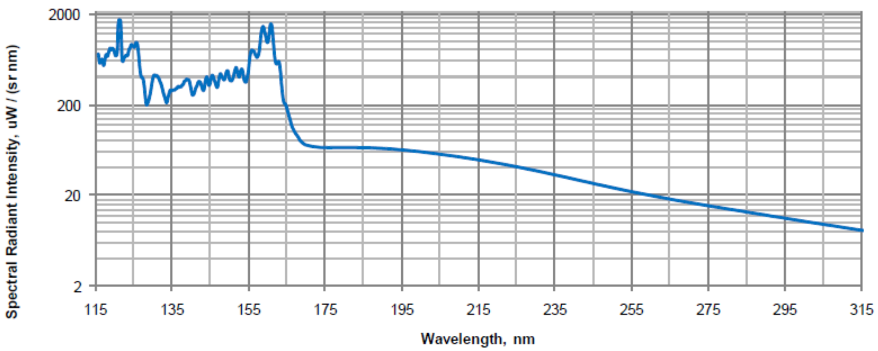


Measurements are done by comparing currents measured with a Keithley 617 electrometer with the device under test and a NIST calibrated photodiode, under VUV illumination

- *Monochromator McPherson 302. 0.1 nm accuracy*
- *Deuterium Lamp McPherson 632 115-380 nm*

Q.E. measurement method



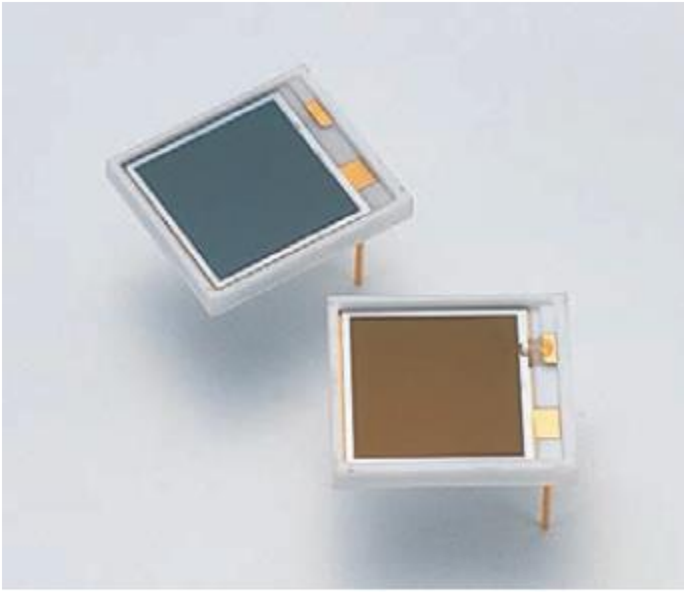


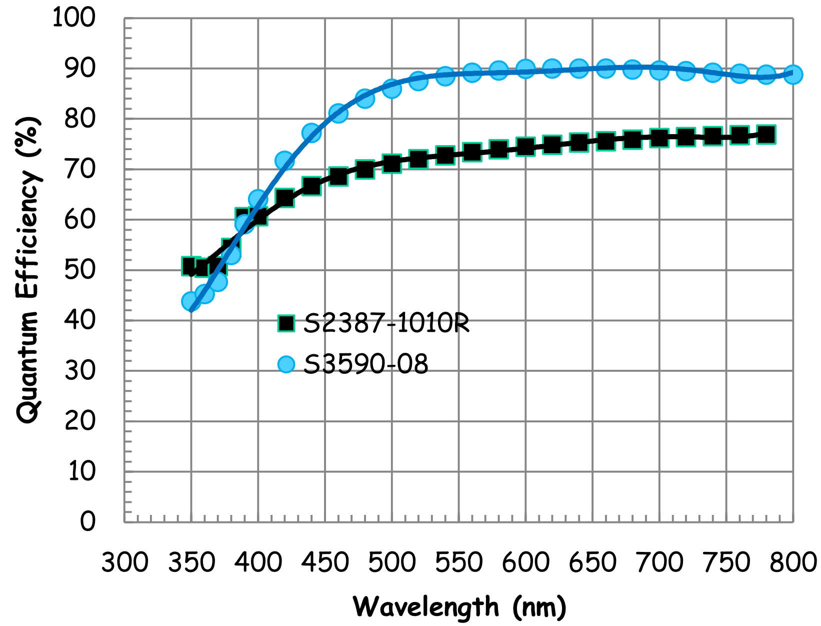
D_2 lamp spectrum

$QE_C(\lambda)$ for the Mc Pherson 632 deuterium lamp in e/γ

$$QE_S(\lambda) = QE_C(\lambda) \times \frac{I_S(\lambda) - I_{Sdark}}{I_C(\lambda) - I_{Cdark}}$$

Used photodetectors

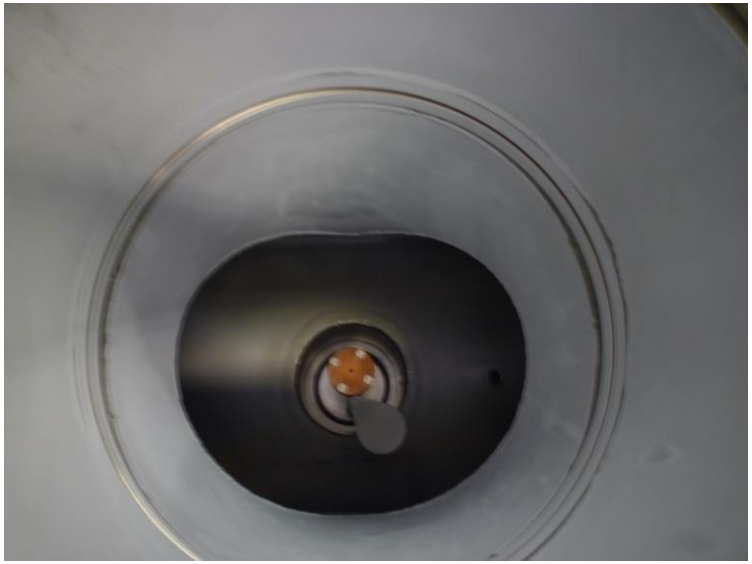




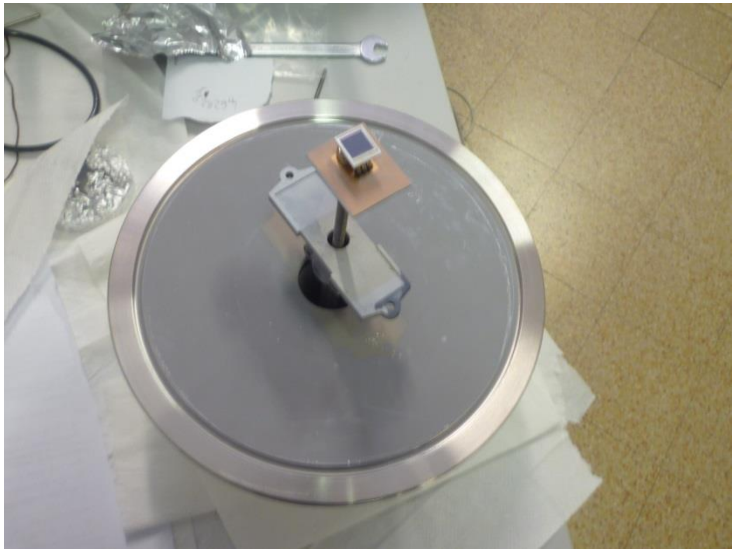
Electrical and optical characteristics (Typ. Ta=25 °C, unless otherwise noted)

Type No.	Spectral response range λ (nm)	Peak sensitivity wavelength λp (nm)	Photo sensitivity S λ=λp (A/W)	Photo sensitivity S LSO 420 nm (A/W)	Photo sensitivity S BGO 480 nm (A/W)	Photo sensitivity S CsI(TI) 540 nm (A/W)	Short circuit current Isc 100 lx (μA)	Dark current ID VR=70 V Typ. (nA)	Dark current ID VR=70 V Max. (nA)	Temp. coefficient of ID TCID VR=70 V (times/°C)	Cut-off Frequency fc VR=70 V (MHz)	Terminal capacitance Ct f=1MHz VR=70 V (pF)	NEP VR=70 V (W/Hz$^{1/2}$)
S3590-08	340 to 1100	960	0.66	0.20	0.30	0.36	100	2	6	1.12	40	40	3.8×10^{-14}
S3590-09				0.22	0.33	0.41	90						
S3590-18			0.65	0.28	0.34	0.38	100	4	10				7.6×10^{-14}
S3590-19			0.58	0.33	0.37	0.4	86						

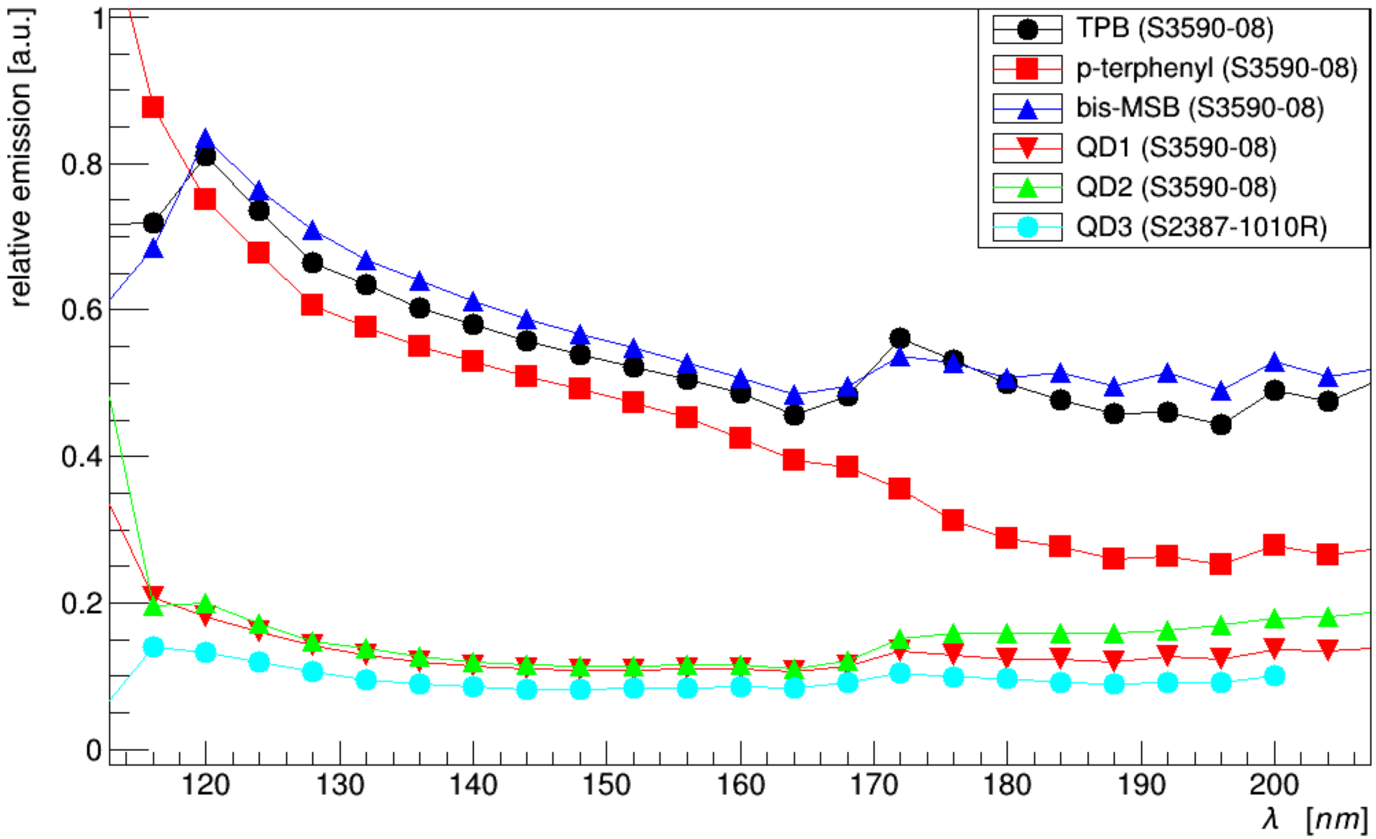
Coating of photodiodes



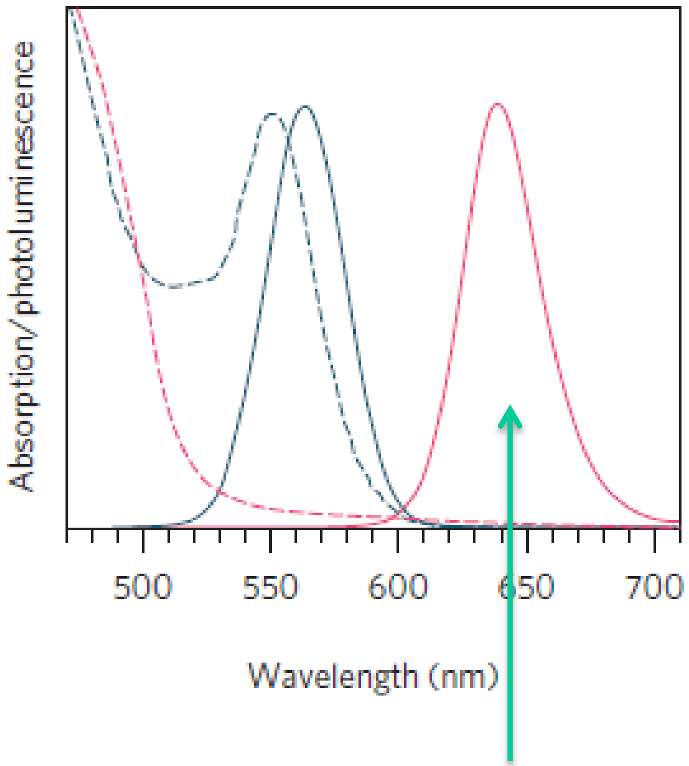
- ❑ ***Coating with TPB, p-therfenil, bis-MSB via a dedicated thermal evaporator***

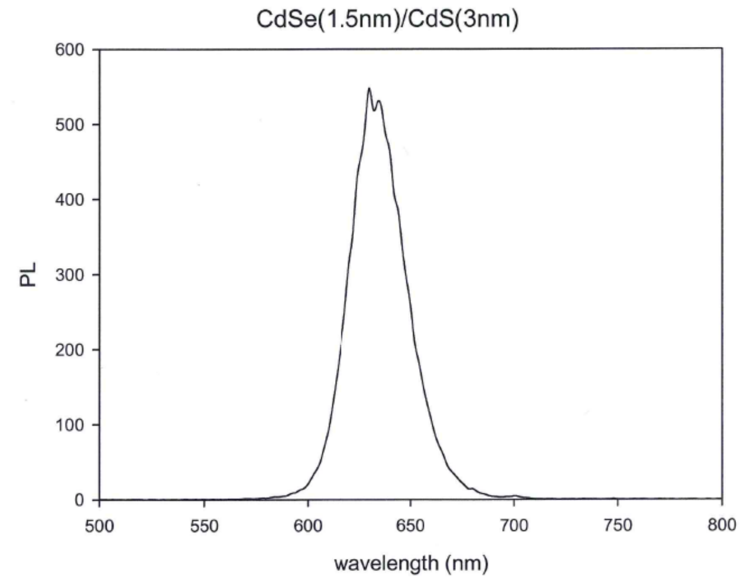


Experimental results



More on CdSe/Cds Qdots





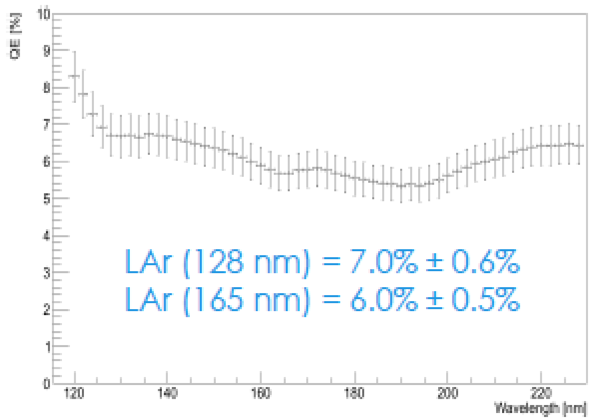
Absorption (dashed lines) /emission (solid line) spectra for optimized CdSe/CdS Qdots

Measiured emission spectrum (PL) for used Qdots

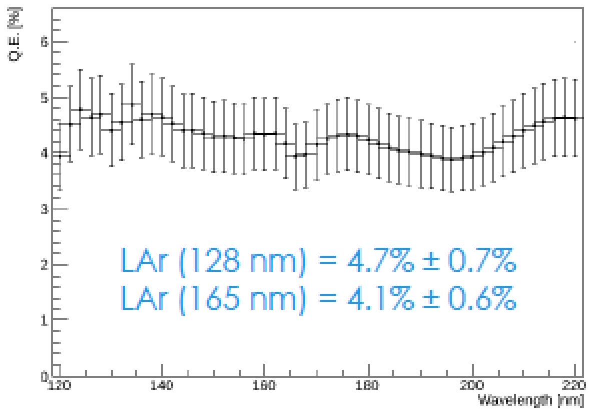
No overlap between absorption spectrum and emission spectrum

More on CdSe/Cds Qdots

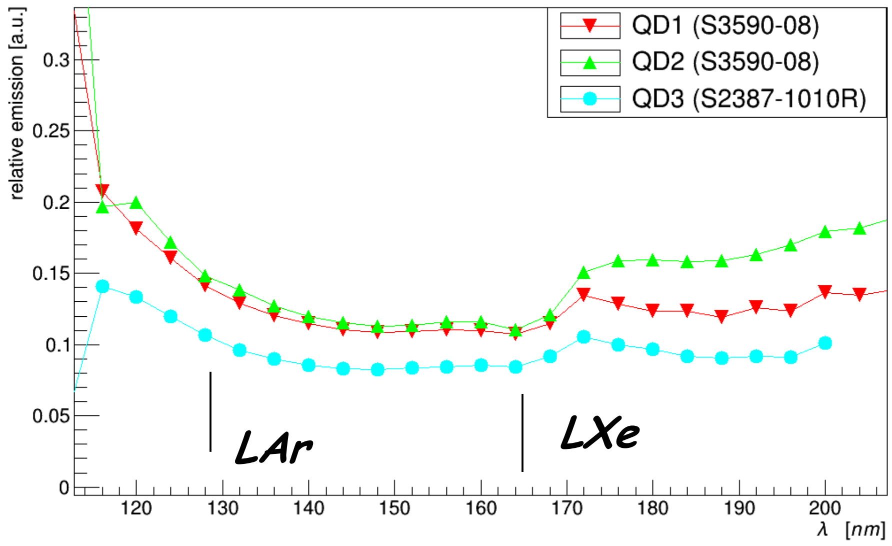
Hamamatsu R5912



ETL 9357 KFLB



Conventional 8” PMTs



Si-pin photodiodes + Qdots

Clearly one has to address cost-issues for Si-pin +QD ….

Other studies

After we started our work we realized that the same idea was put forward by D.Yu. Akimov et al., NIM A695 (2012) 403 in a similar context, but with different QDots engineering

A B S T R A C T

Development study of a wavelength shifter (WLS) to convert a noble gas emission light from the VUV region to the visible range is presented. The shifter is developed for the use with an array of blue-sensitive multipixel avalanche Geiger photodiodes (MRS APD) to detect Xe 175 nm emission. It was found that a polycrystalline p-terphenyl having an absorption peak at 180 nm with a molar extinction coefficient ε of $37500 \pm 5000\ \mathrm{mol}^{-1} \cdot \mathrm{l\,cm}^{-1}$ is well suited for this. To satisfy a requirement of compatibility with an extra pure noble gas detection medium the p-terphenyl layer was coated with an $\sim 1\ \mu\mathrm{m}$ thick poly-para-xylylene protection film.

A new WLS with maximum of emission spectrum at 390 nm and at 420 nm is developed on the basis of a nanostructured organosilicon luminophore.

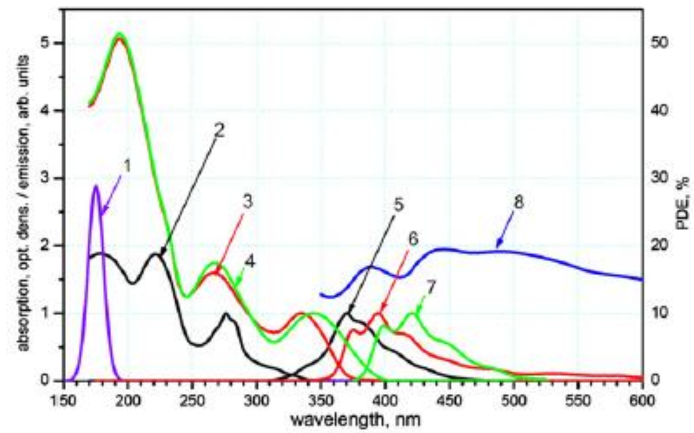


Fig. 2. Emission spectrum of LXe (1), absorption spectrum of *p*-terphenyl (2), absorption spectrum of NSIWLS-I (3), absorption spectrum of NSIWLS-II (4), emission spectrum of *p*-terphenyl (5), emission spectrum of of NSIWLS-I (6), emission spectrum of NSIWLS-II (7), photon detection efficiency (PDE) of the CPTA "blue-sensitive" photodiode (8), right axis. The absorption spectra of WLSs shown in the units of optical density are normalised to the thickness 200 nm. The emission spectra of WLSs are normalised to 1 in arbitrary units.

Conclusions

- ***A lot of WLS known for VUV emission: TPB is just one example***
- ***BUT: emission around 400 nm is slightly overlapped with absorption spectrum and low-cost photon detectors have usually peak responsivity ~600 nm (RED) and not ~400 nm (blue)***
- ***A promising option is the use of quantum dots (QD) with a technology borrowed from solar cells. These may be engineered for optimal usage***
- ***First results are promising, even if work is needed to increase responsivity in VUV region and reduce detectors' costs***