Development of wavelength-shifting PEN foils for next generation experiments

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ASTROCENT

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Dark Wave

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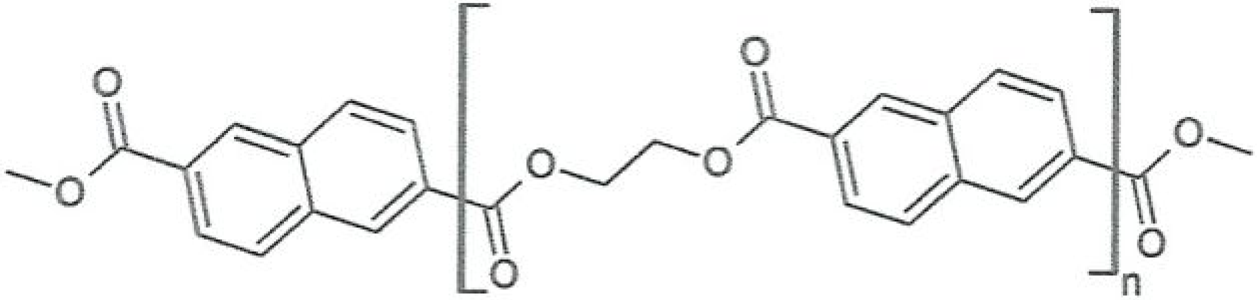
Wavelength shifter

- Tetraphenyl butadiene (TPB) works fine*, but production of up to 1000m^2 using vacuum evaporation technique would be a challenge
  - Large vacuum chamber needed
  - Pumpdown and production cycle take much time and labour.

- Alternatives:
  - Solvent based methods
    - Efficiency between 0.33 and 0.5 of evaporated TPB
    - Much easier, but mass production still complicated
  - PEN



* except, not stable in LXe and evidence for ‘emanation’ in LAr

PEN as a scintillator

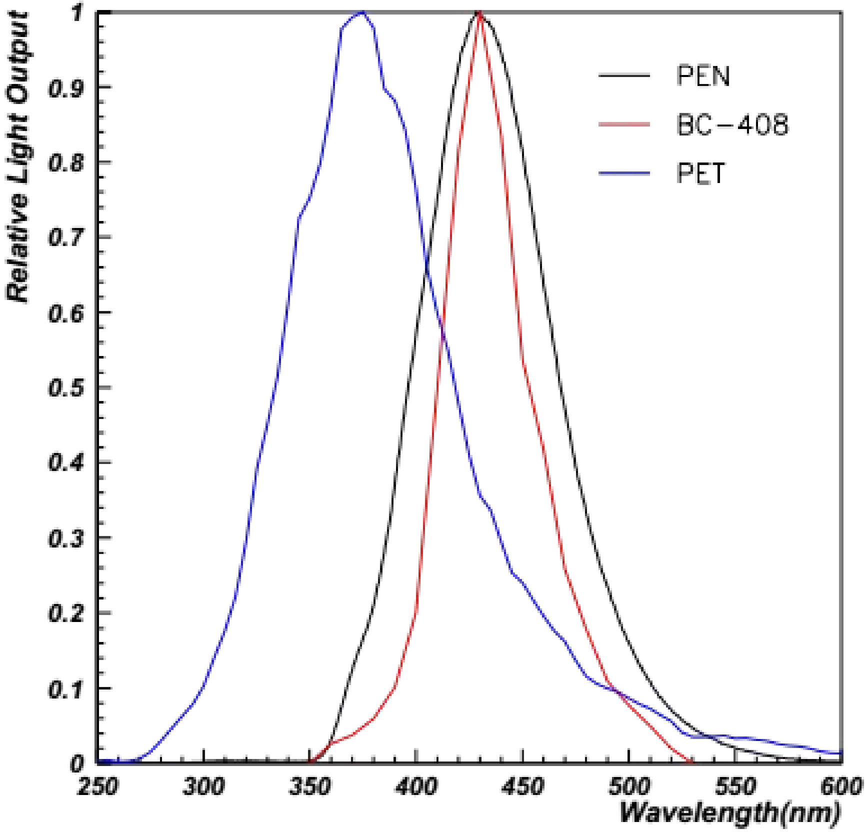
epl A Letters Journal Exploring the Frontiers of Physics

EPL, **95** (2011) 22001
doi: 10.1209/0295-5075/95/22001

Evidence of deep-blue photon emission at high efficiency by common plastic

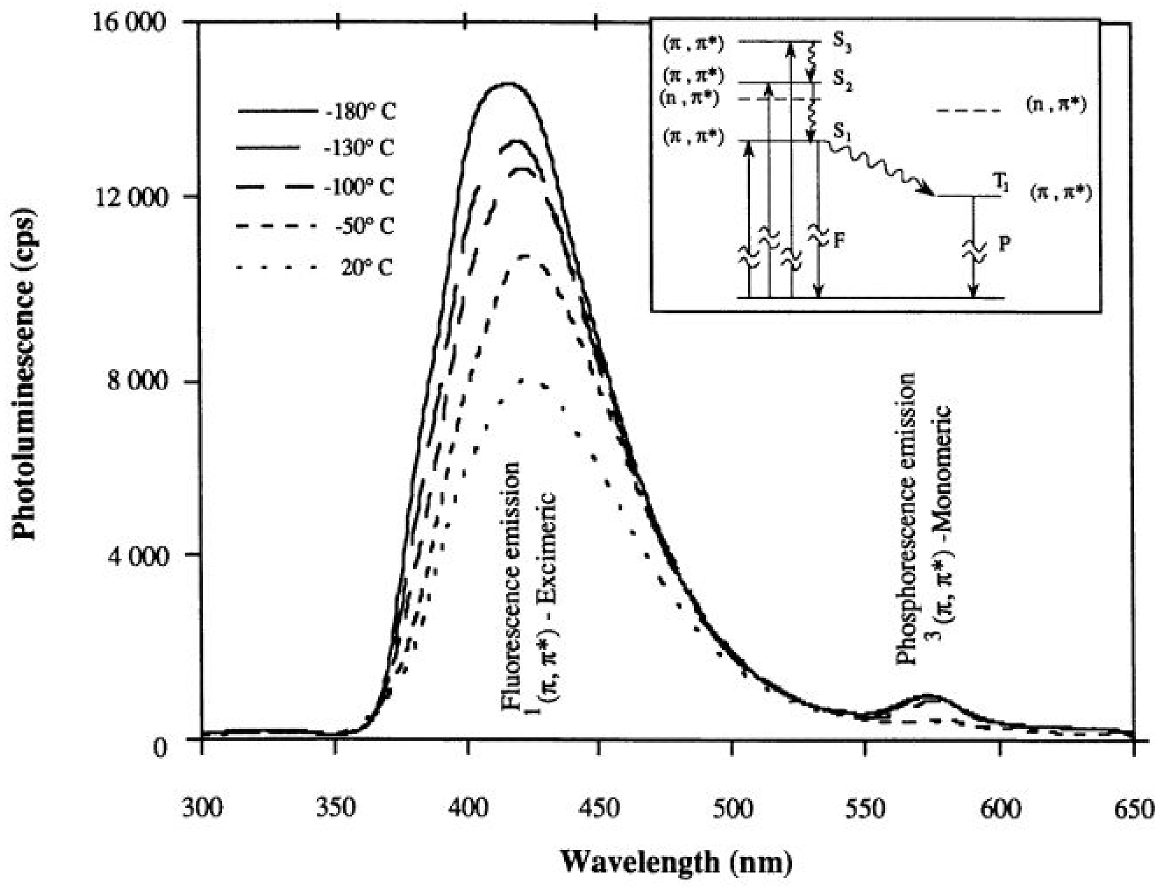
H. Nakamura[1,2(a)], Y. Shirakawa[2], S. Takahashi[1] and H. Shimizu[3]

Fig. 1: Photograph of a dinner set composed of polyethylene naphthalate.

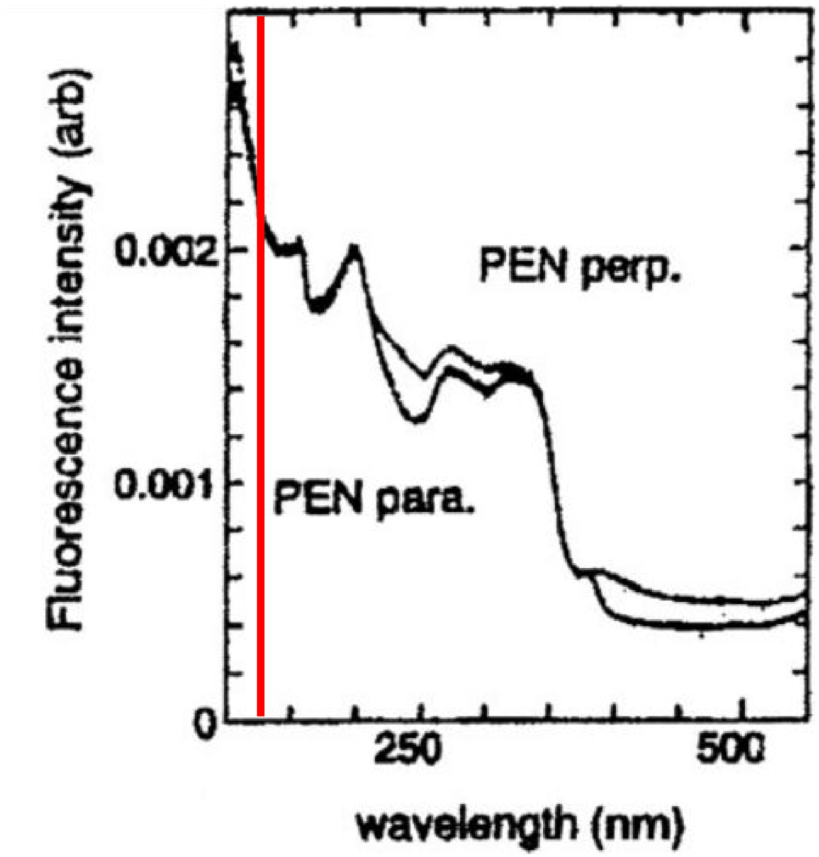


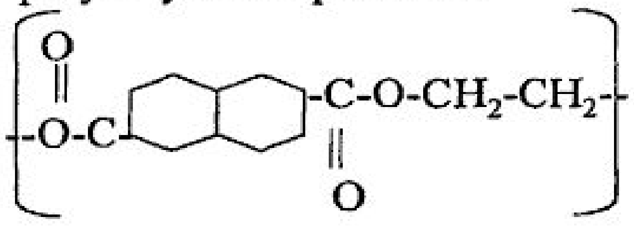
PEN evidence for fluorescence

D. Mary et al., J. Phys. D: Appl. Phys. 30 (1997)



Ouchi et al., 10.1002/app.26085 (2006)

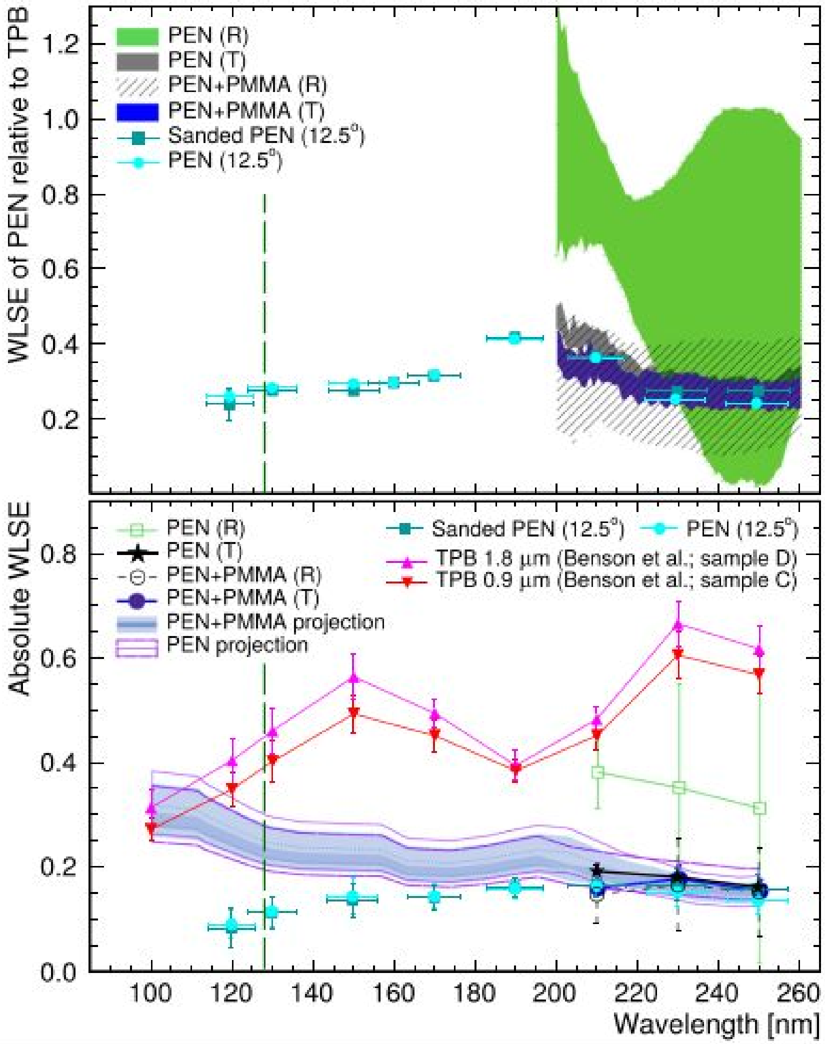




- Significant enhancement at low temperatures and at VUV excitation wavelengths
- Excimer emission

LIDINE 2019: PEN as wavelength shifter

MK et al, Eur. Phys. J. C (2019) 79:291

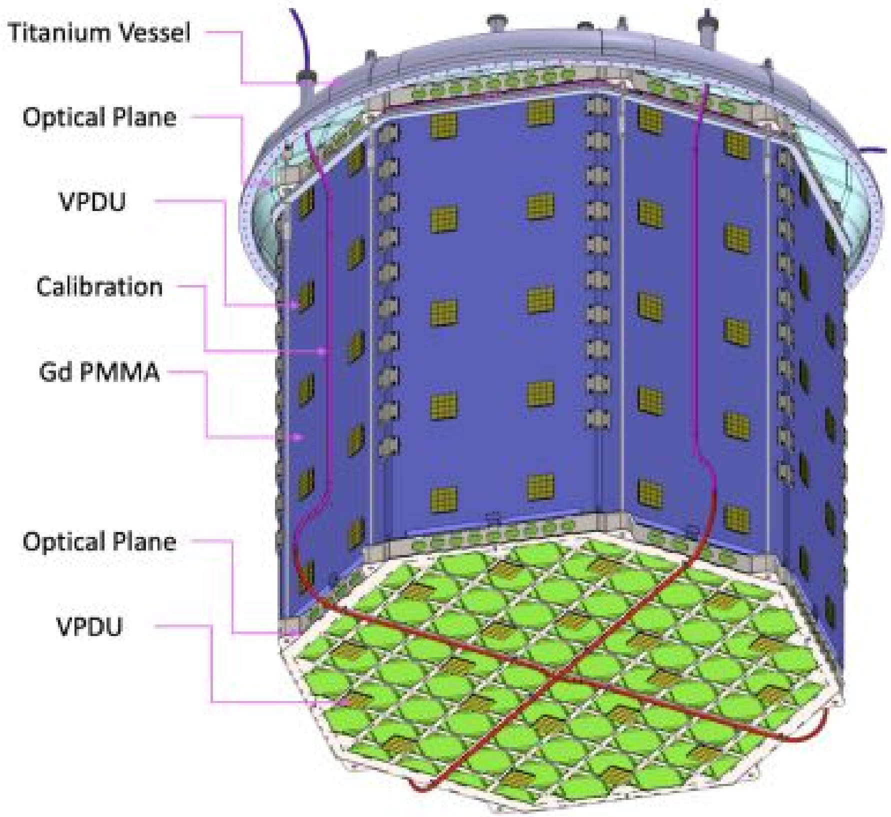


Sample	293 K 250 nm	293 K 128 nm	87–93 K 128 nm
TPB+PMMA	0.59(7)	0.43(7)	0.52(10)
PEN+PMMA	0.15(2)	0.24(4)	0.40(7)
PEN	0.16(4)	0.25(5)	0.42(8)
PEN (glass)	0.15(3)	0.12(3)	0.20(6)
$\frac{\text{PEN+PMMA}}{\text{TPB+PMMA}}$	0.25(5)*	0.56(13)	**0.77(20)**
$\frac{\text{PEN}}{\text{TPB+PMMA}}$	0.27(8)*	0.58(15)	**0.80(23)**
$\frac{\text{PEN(glass)}}{\text{TPB+glass}}$	0.26(4)*	0.28(4)*	**0.38(7)**
$\frac{\text{VM2000}}{\text{TPB+TTX}}$	0.09		0.317(16)

Extrapolation based on literature data at 128 nm

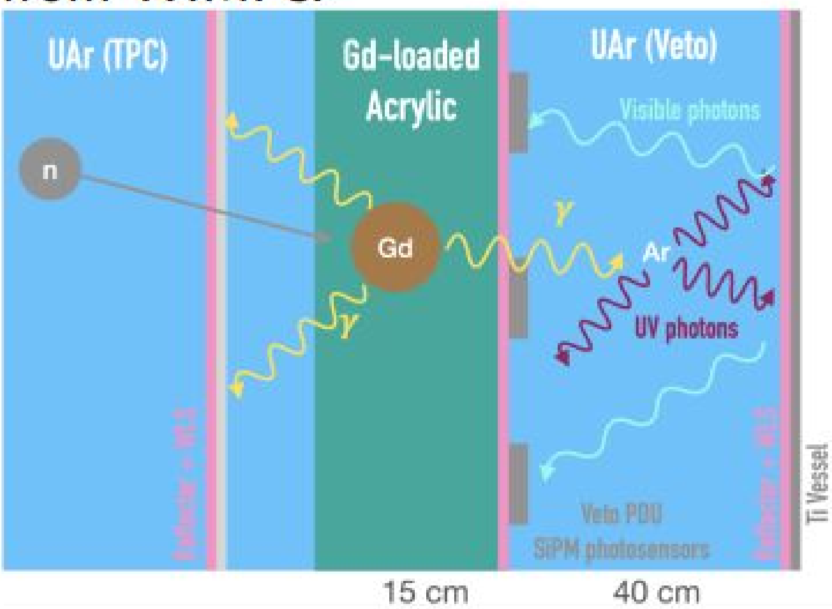
Extrapolation based on our sample measured at 128 nm.

Application: DarkSide-20k neutron veto



- 40 cm thick space between the Ti vessel and Gd-PMMA
- 8 walls made from 15 cm thick Gd-PMMA
- ESR reflector with PEN WLS foils on all the surfaces (174 m^2)

Neutrons elastically scattering from argon nuclei are indistinguishable from WIMPs.

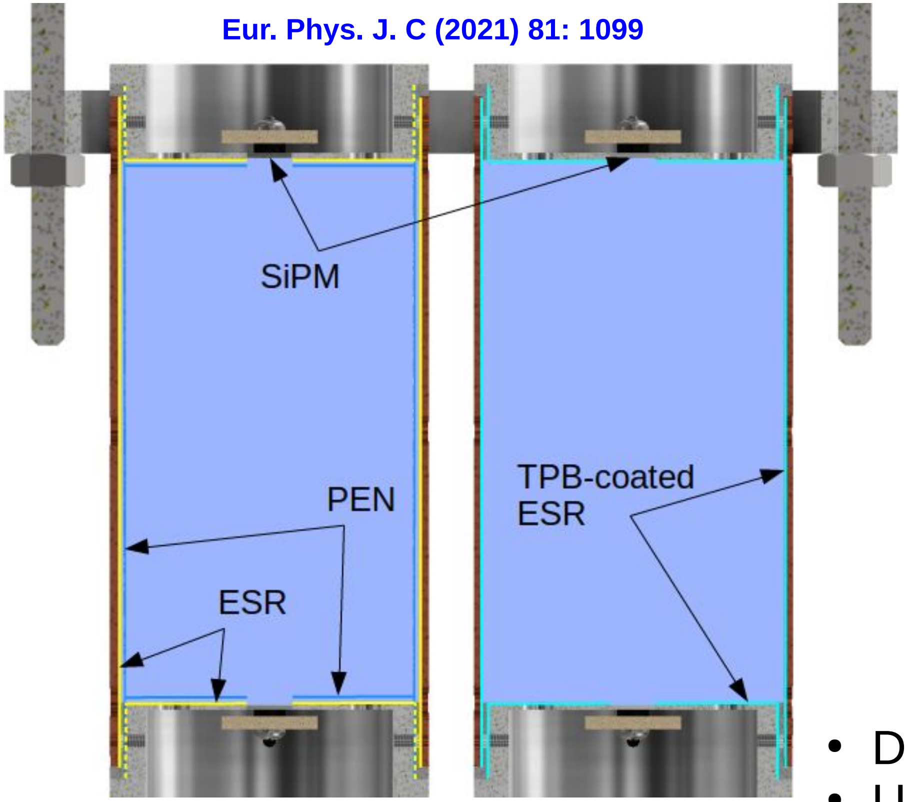


- Neutrons are moderated in the PMMA and captured by Gd,
- Gd emits multiple γs with energy up to 8 MeV,
- UAr scintillation light is shifted and detected by vPDUs.

Slide courtesy: M. Walczak (APS 2022)

LIDINE 2021: confirmed performance in LAr

Eur. Phys. J. C (2021) 81: 1099



Approx. 5 cm diameter each

- Dual-chamber system immersed in a LAr bath at LNGS
- Using Teonex Q51, 25 micron thick (identified as the most promising in ex-situ measurements).

- Light yield of the PEN chamber to be **39.4 +/- 0.4(stat) +/- 1.9(syst)%** of the yield of the TPB chamber

- Using a Monte Carlo simulation wavelength shifting efficiency of PEN is extracted: **47.2 +/- 5.7%**

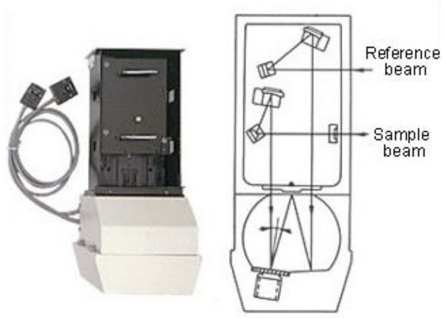
- Satisfactory for DarkSide-20k – supported the collaboration decision to use PEN as WLS in the veto detector

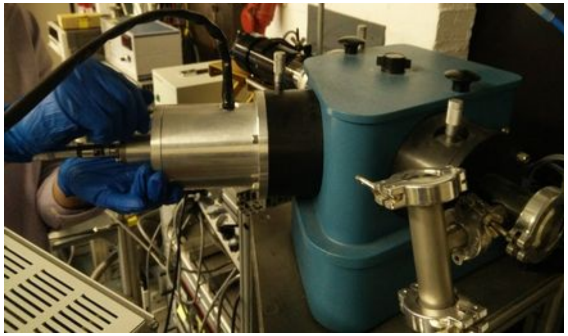
What remains to be done?

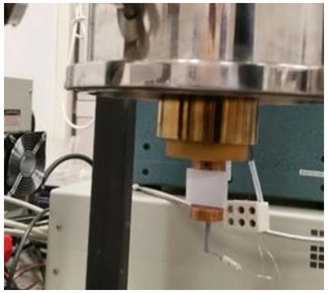
- Means for quality control of large number of PEN samples in representative conditions
- Better understanding of aging (also UV induced) and stability
- Getting the maximum achievable WLSE out of PEN
- Production scale-up to O(100 kg) scale

PEN WLSE efficiency survey

- Integrating sphere spectrophotometer measurements
  - Only possible at near UV and RT
  - Best control of the systematics: excellent stability, insensitive to different TPB and PEN scattering properties
  - For quick pre-screening and selection of most promising candidates (~50 measurements per day)
- Vacuum monochromator measurements @ RT (TUM)
  - Relative measurement at 128 nm
  - Light collected from a fraction of a solid angle
  - Up to 5 samples per day
- Vacuum monochromator with sample @ 80 K (INTiBS PAN)
  - For confirmation of desired performance in LAr conditions
  - Up to 1 sample per day
- Measurements in LAr
  - Final representative application, including SiPMs and reflection optics
  - Up to 1 sample per week

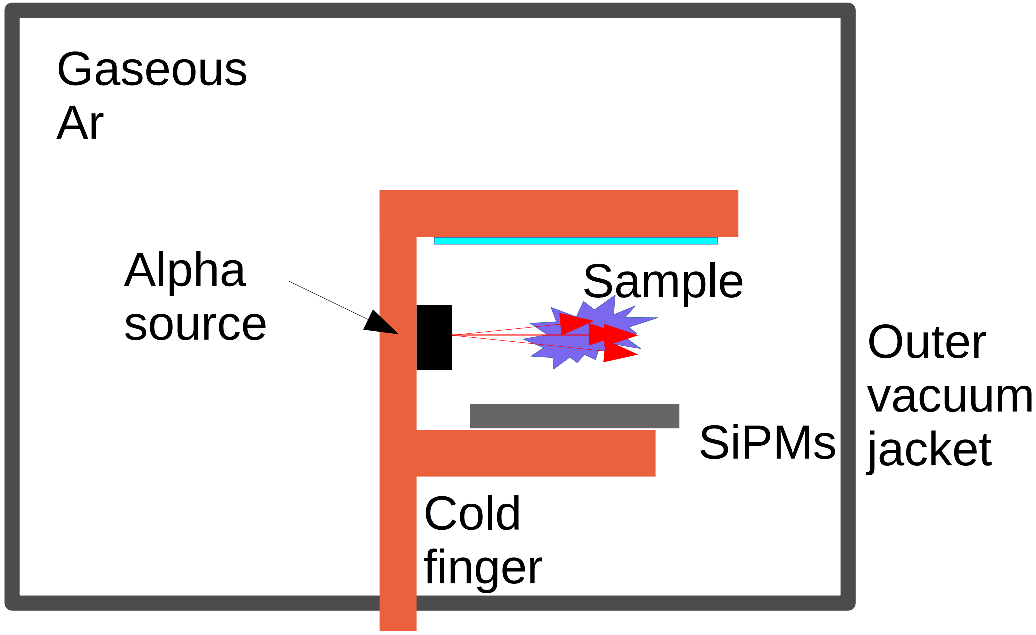


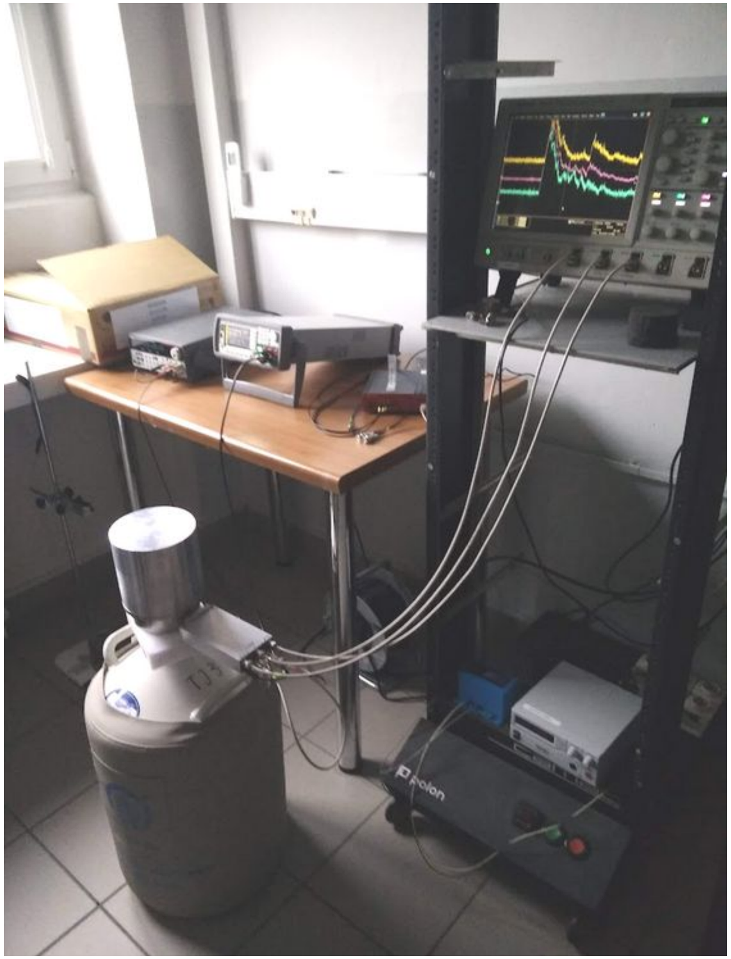


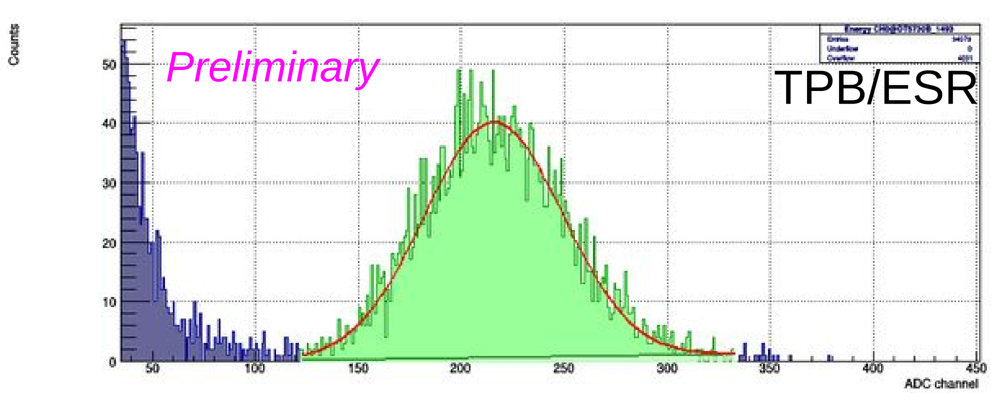


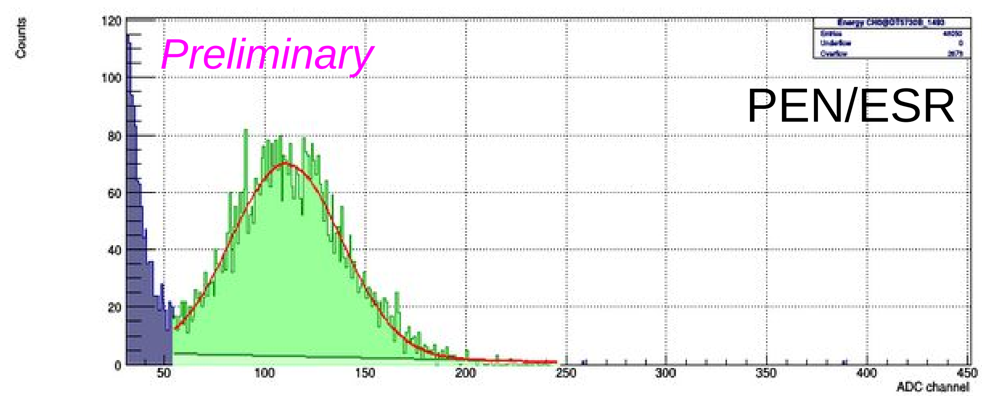
Test stand @ AstroCeNT for quality control

- WLSE of various PEN grades, including samples of the same grade varies
- WLSE depends on the excitation wavelength AND temperature
- Developed an alpha-excited gaseous Ar cell with a cryogenic stage
- Recently successfully commissioned
- For details, see poster by Andre Cortez!









UV ageing

- UV exposure from sunlight or fluorescent lighting can lead to
  - up to an order of magnitude reduction in intensity
  - broadening and shift of the emission peak towards higher wavelengths

D. Mary et al., 2001 Annual Report Conference on Electrical Insulation and Dielectric Phenomena, p. 165 (2001). https://doi.org/10.1109/CEIDP.2001.963512

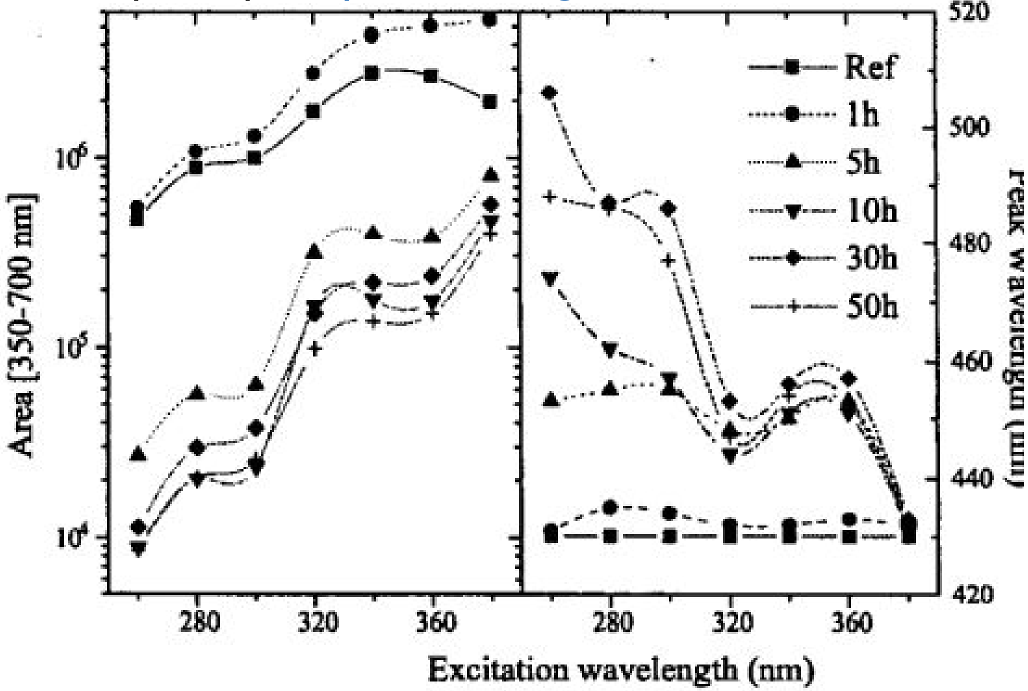


Figure 3: Area (left) and peak wavelength (right) of photoluminescence spectrum as a function of excitation wavelen for different irradiation times. The area is given in counts for an integration time of 10s of the CCD camera.

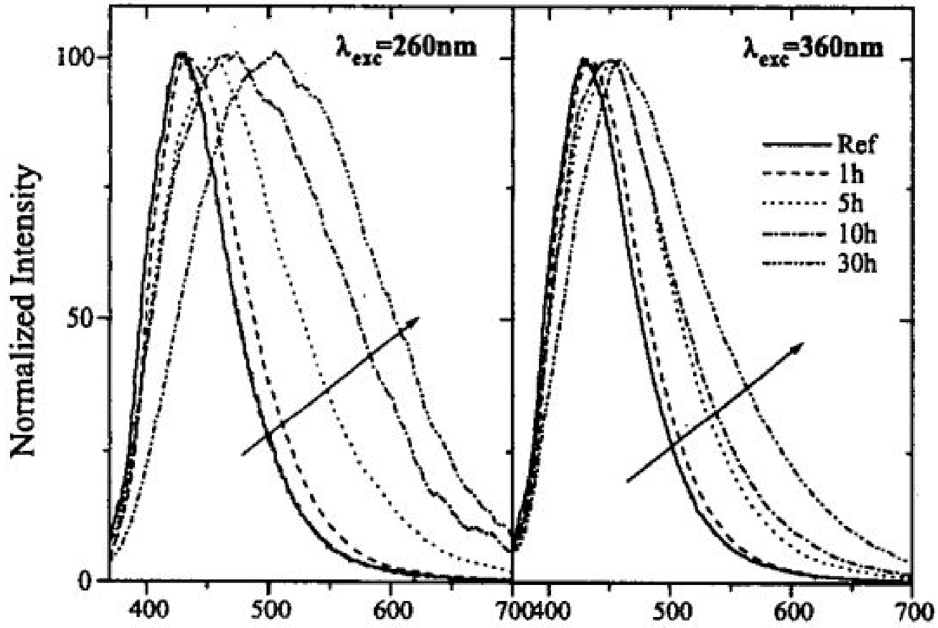
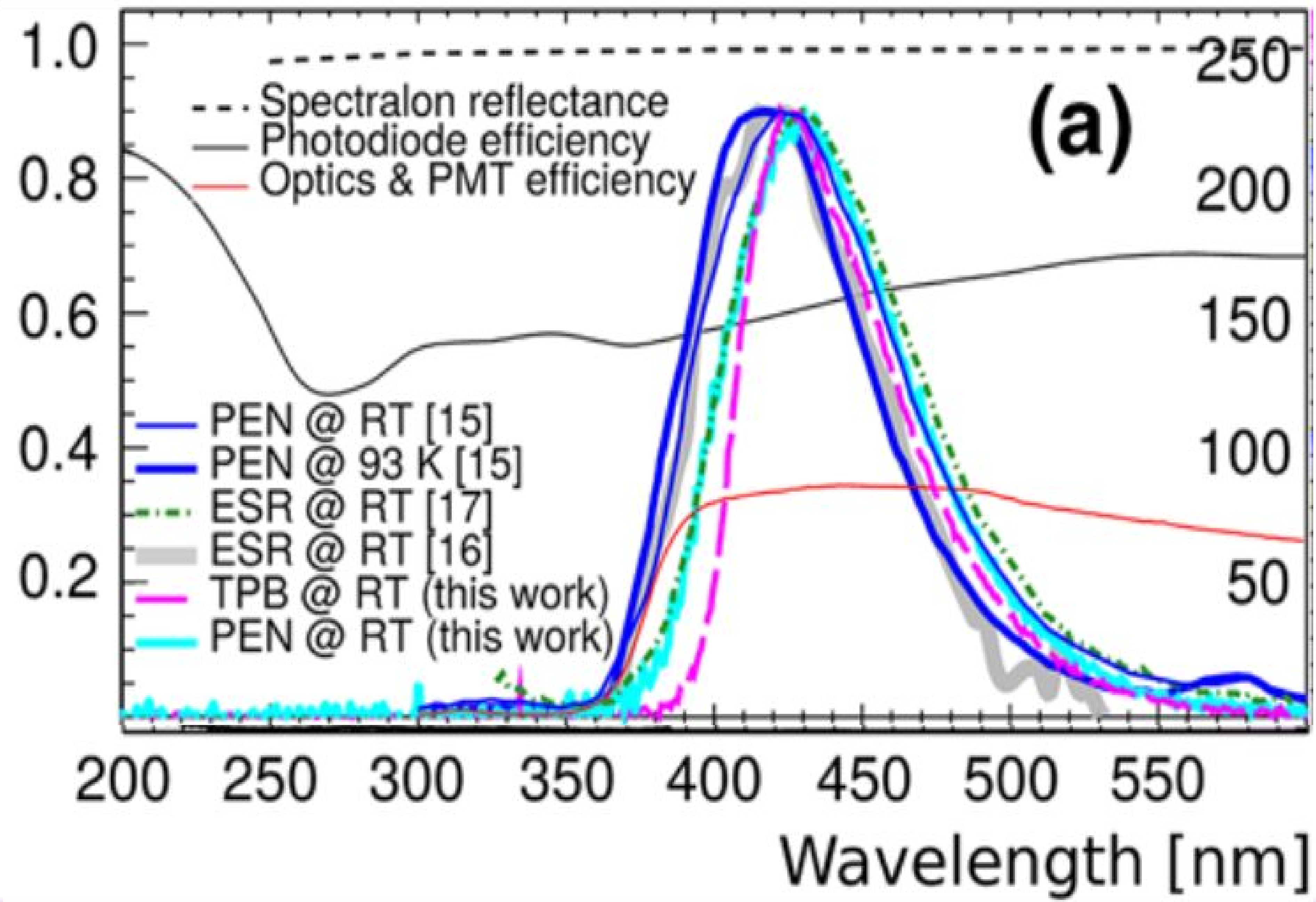


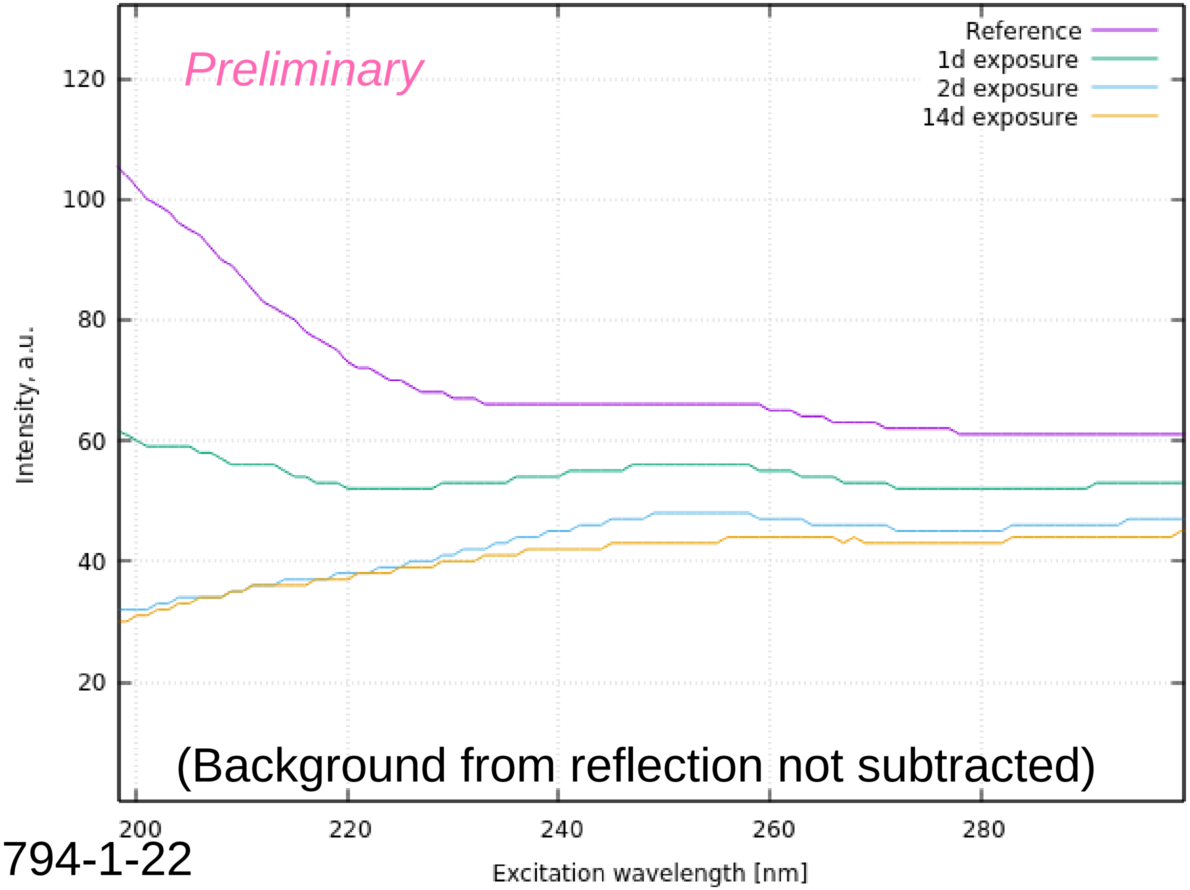
Figure 2: Normalized photoluminescence emission, spectra of PEN as a function of UV exposure time, for two excitation wavelengths.

Illumination with a 30 W broadband UVA lamp

UV ageing

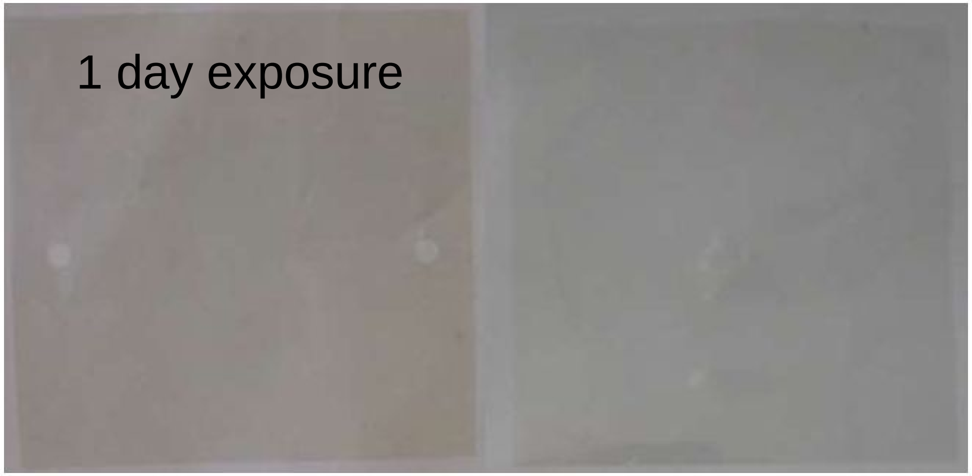

1.0
0.8
0.6
0.4
0.2
250
200
150
100
50
(a)
Spectralon reflectance
Photodiode efficiency
Optics & PMT efficiency
PEN @ RT [15]
PEN @ 93 K [15]
ESR @ RT [17]
ESR @ RT [16]
TPB @ RT (this work)
PEN @ RT (this work)
200 250 300 350 400 450 500 550
Wavelength [nm]

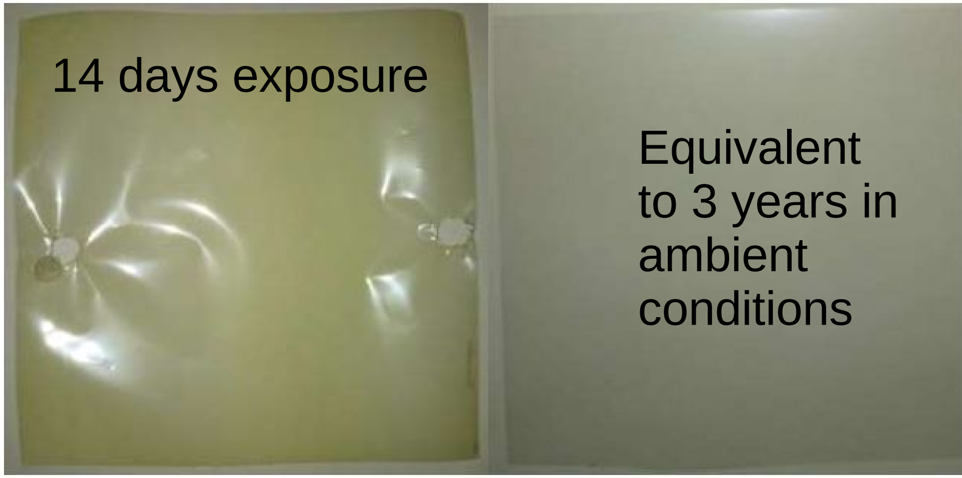
UV aging



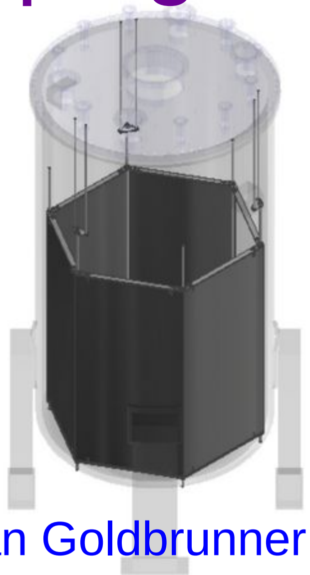
Equivalent to 2 months in ambient conditions

Standard PN-EN 60794-1-22



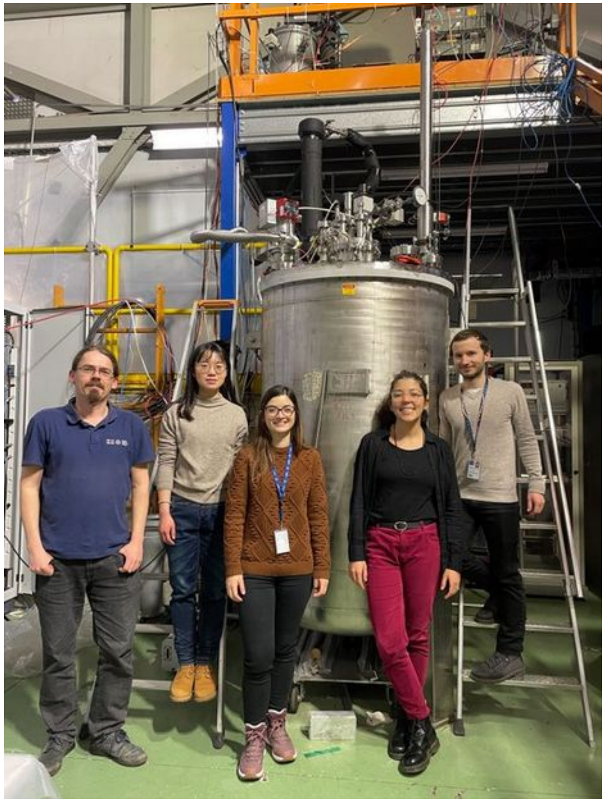


General purpose WLS reflector campaign



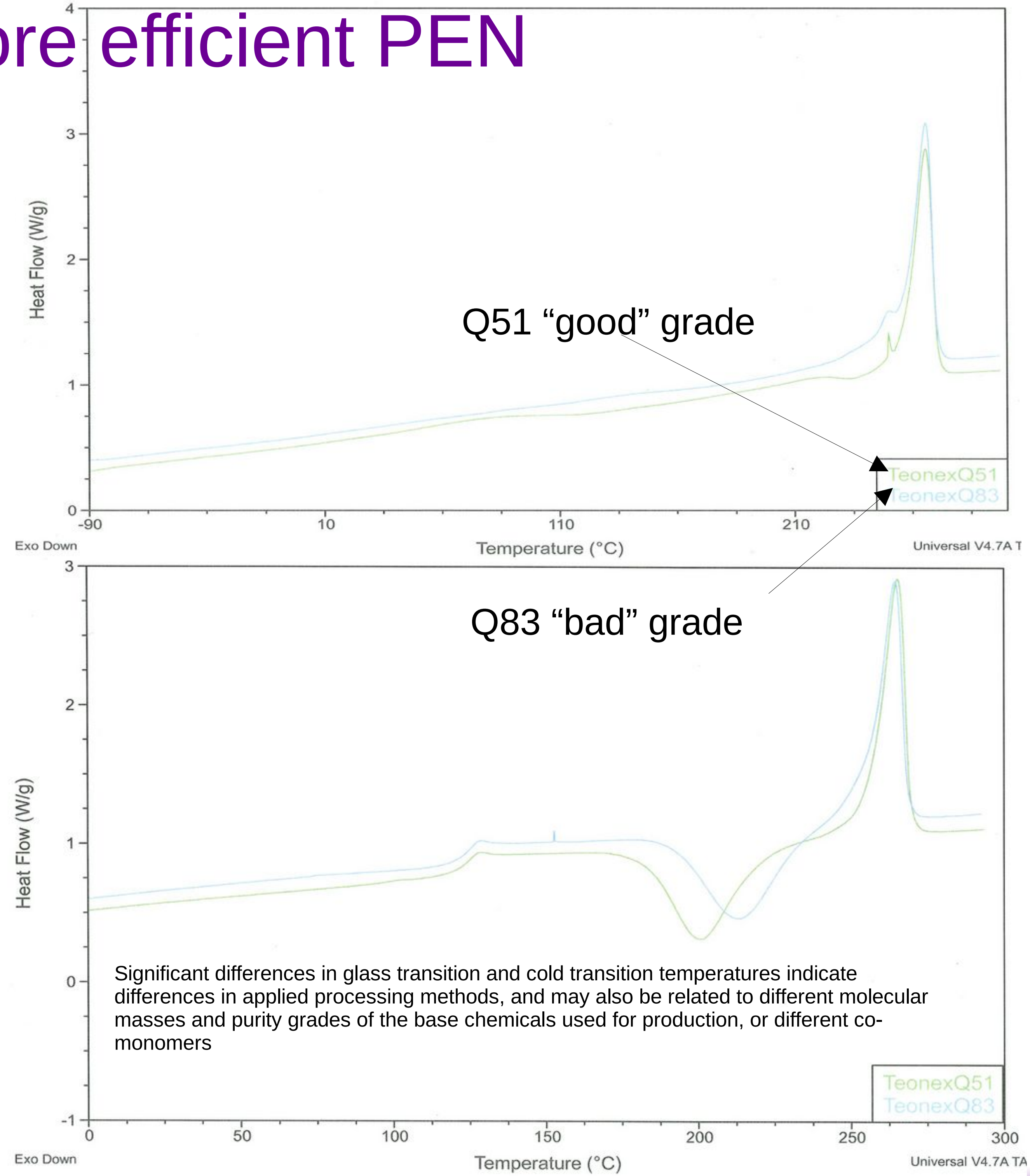
- Jointly with TUM, Uni Zurich, NIKHEF, Uni Edinburgh and CERN
  - Groups from LEGEND, DUNE and DarkSide-20k
- Most promising combination of reflector (ESR) and PEN identified with table-top measurements (Zurich, TUM, Astrocent)
- Large scale LAr test completed at CERN in February to demonstrate light yield and light yield **stability over 2 weeks** long run with an alpha source inside:
  - 1 m tall aluminum cage lined with ESR/PEN (LAr gap inbetween)
  - Viewed by 2 PMTs from the top (Vis and VUV)
  - Analysis currently ongoing

See poster by Maximillian Goldbrunner!



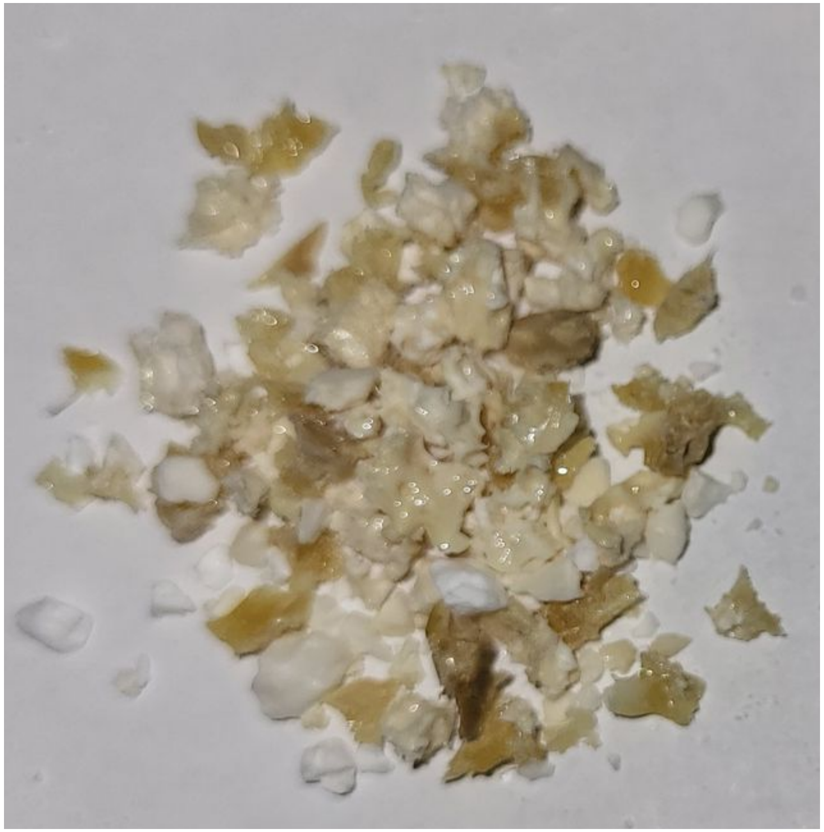
More efficient PEN

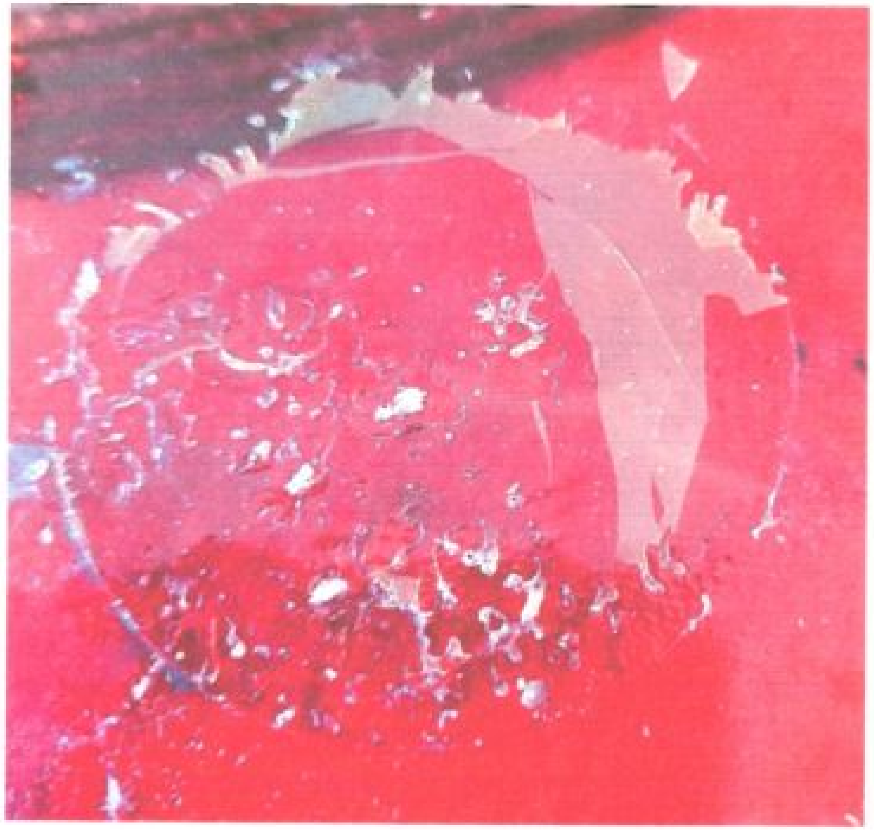
- Industrially available PEN not optimized for WLS
- Old literature data suggests higher efficiencies both for scintillation and WLS than observed in technical PEN
- Why:
  - Coatings or additives (fillers, colorants, plasticizers, stabilizers, catalysts...)
  - Unknown history of samples (storage, integrated UV exposure)
  - Crystalline structure / thermal history



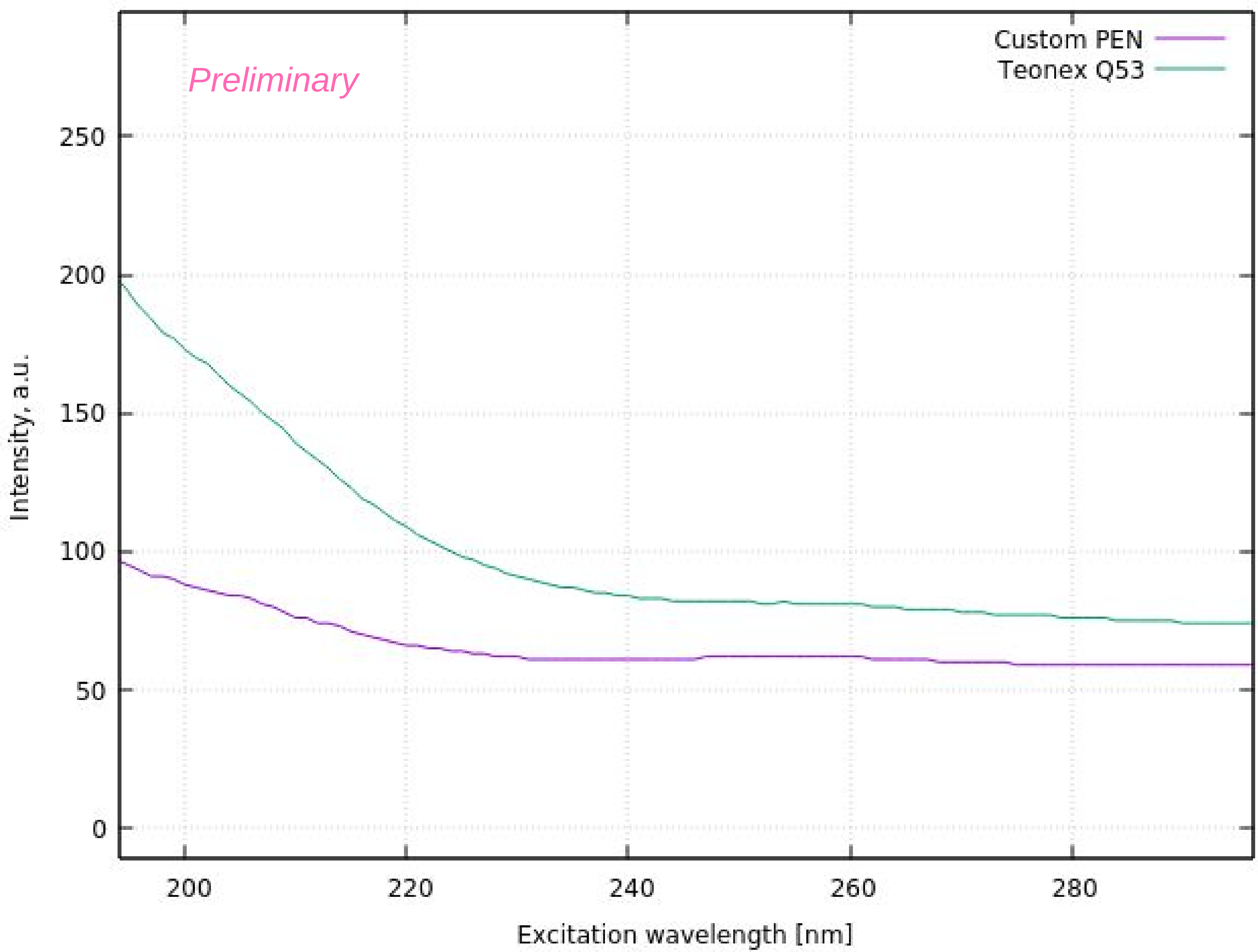
Custom synthesis

- In collaboration with Sławomir Pawłowski (Łukasiewicz Research Network – Institute of Industrial Chemistry in Warsaw)
- Starting from affordable and abundantly available base chemical
- Controlled conditions: no exposure to light, purified base chemicals
- After synthesis pressed into foils (>7kg is the threshold for drawing foils)





At first mixed results and visible yellow tint of the product (effect of temperature and impurities)


Preliminary
Custom PEN
Teonex Q53
Intensity, a.u.
0
50
100
150
200
250
200
220
240
260
280
Excitation wavelength [nm]

Custom synthesis II

- After multiple iterations and improvements, in last weeks finally clean white product!
- High crystallinity results in white color; becomes translucent when heated up and cooled down
- Next step: press into foils and compare with commercial PEN

- Might be useful in the current form as a diffuse WLS reflector
- Synthesis is scalable. Working on acquiring dedicated funds.

Summary

- Efficiency of PEN relative to TPB: 0.5 – 0.7
- Geared up for production and 87K / 128 nm tests for DarkSide-20k
- Suspect UV degradation and additives as the culprit affecting WLSE
- Synthesis optimized to first order. Work in progress.
- Long term stability and UV effects are being quantified

Backup

TPB: the industry standard

- Expensive, requires challenging vacuum evaporation
- “Painted” TPB-doped polymeric coatings yield 3x less light
- Intrinsic QE of TPB: ~60%@128 nm according to a recent paper
- More efficient / easier to use WLS in high demand for large future LAr detectors (Argo, DUNE ...)