Wavelength shifters for optically read out MPGDs

F.M. Brunbauer, K.J. Flöthner, D. Janssens, M. Lisowska, Pedro Sviatopolk Mirsky, H. Muller, E. Oliveri, G. Orlandini, L. Ropelewski, L. Scharenberg, M. Van Stenis, R. Veenhof (CERN)

A. Cools, E. Ferrer-Ribas, T. Papaevangelou, E. Pollacco (IRFU, CEA, Université Paris-Saclay),

M. Cortesi (FRIB, MSU)

F. Garcia, J. Nummi (HIP)

D. Pfeiffer, J. Samarati (European Spallation Source ERIC (ESS)

MPGD2024, USTC Hefei, October 15, 2024

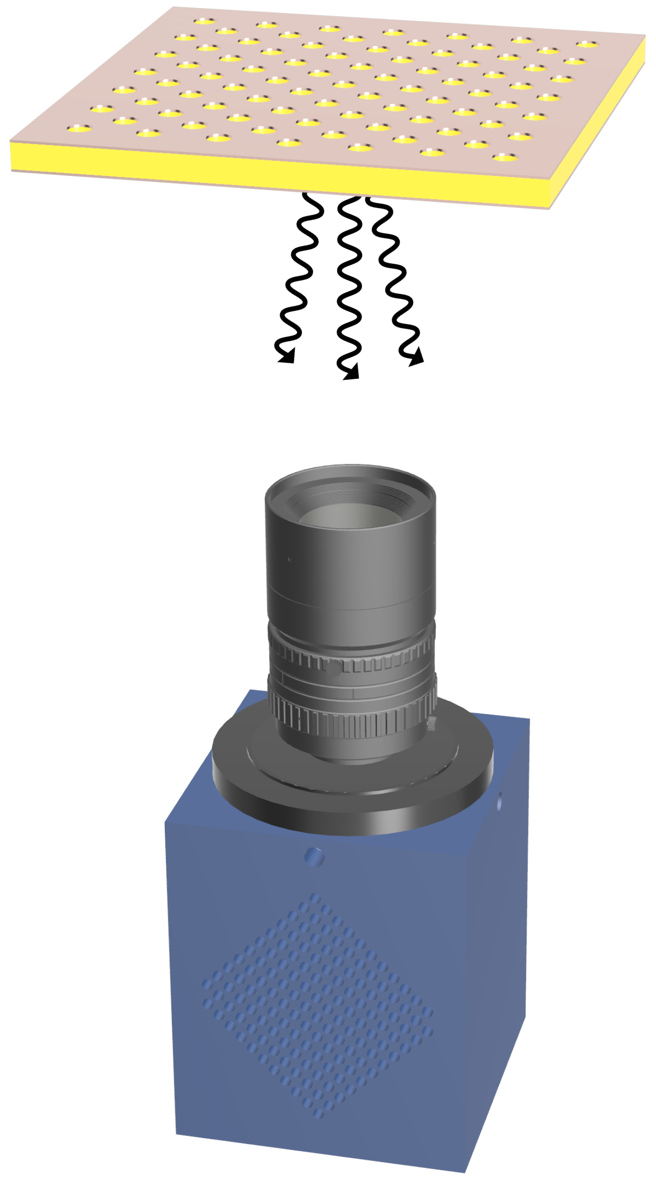
Optical readout

Pixellated readout (integrated / event-by-event) with **high spatial resolution**

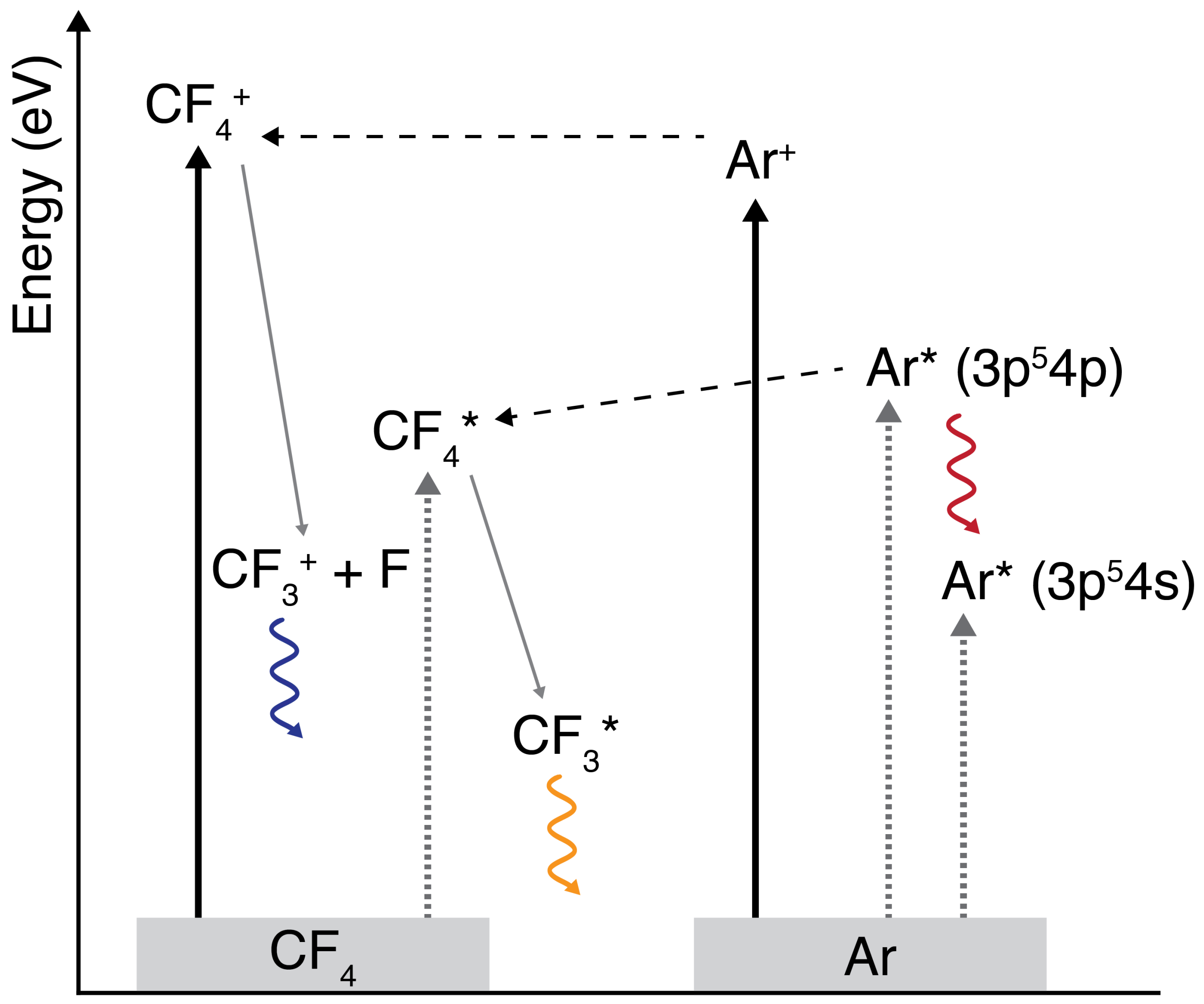
Adjustable magnification with optics (lenses, mirrors, …)

Limited **frame rate**

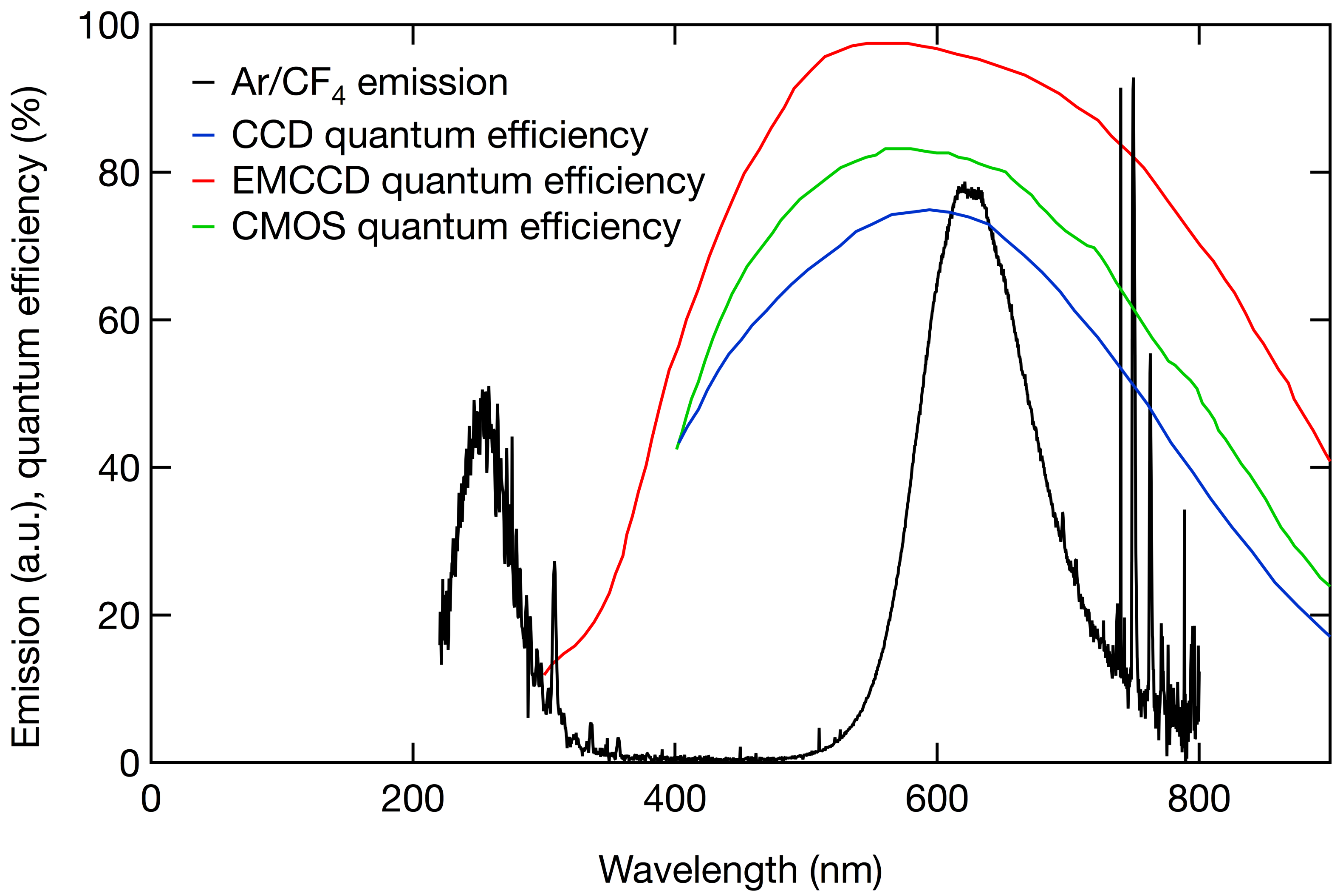
Requires good matching of **emission spectrum** to image sensor QE



Ar/CF_4 scintillation mechanism



CF_4 emission matches sensitive wavelength range of many conventional imaging sensors

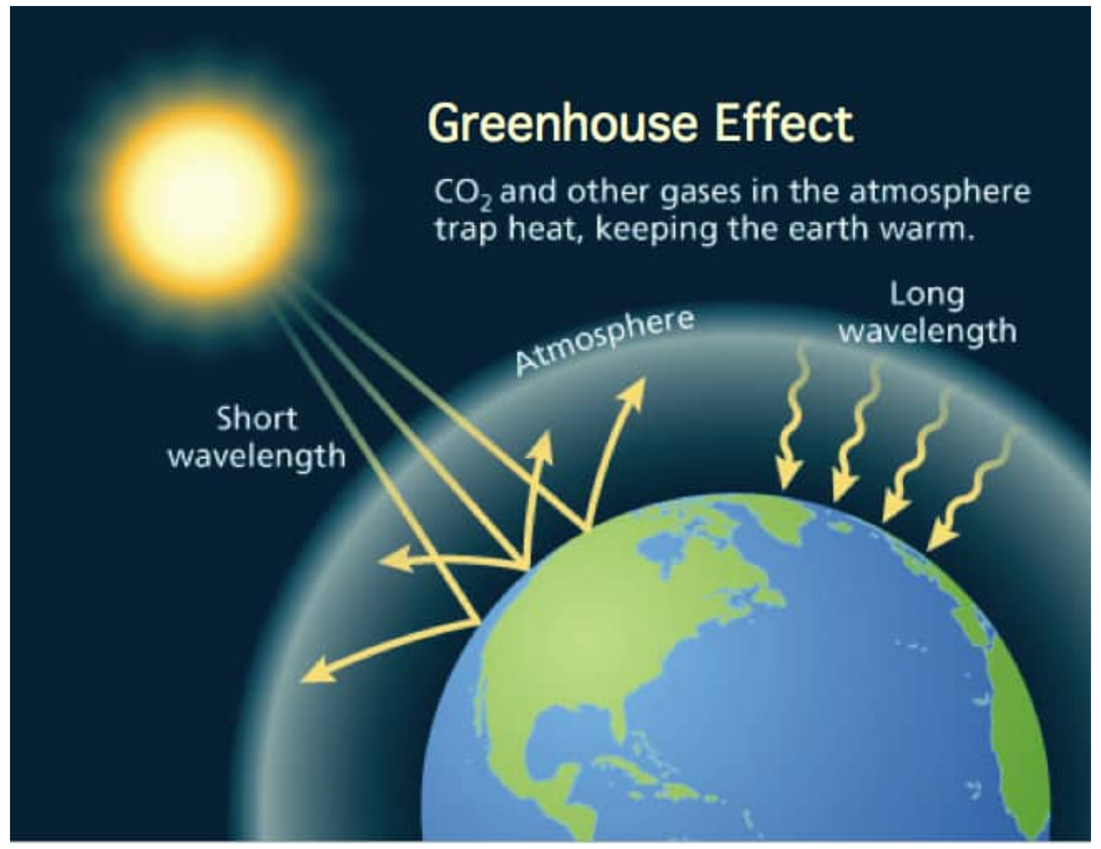


Schematics not drawn to scale

CF_4 limitations

CF_4 is a **strong greenhouse** gas with GWP ≈ 7000.

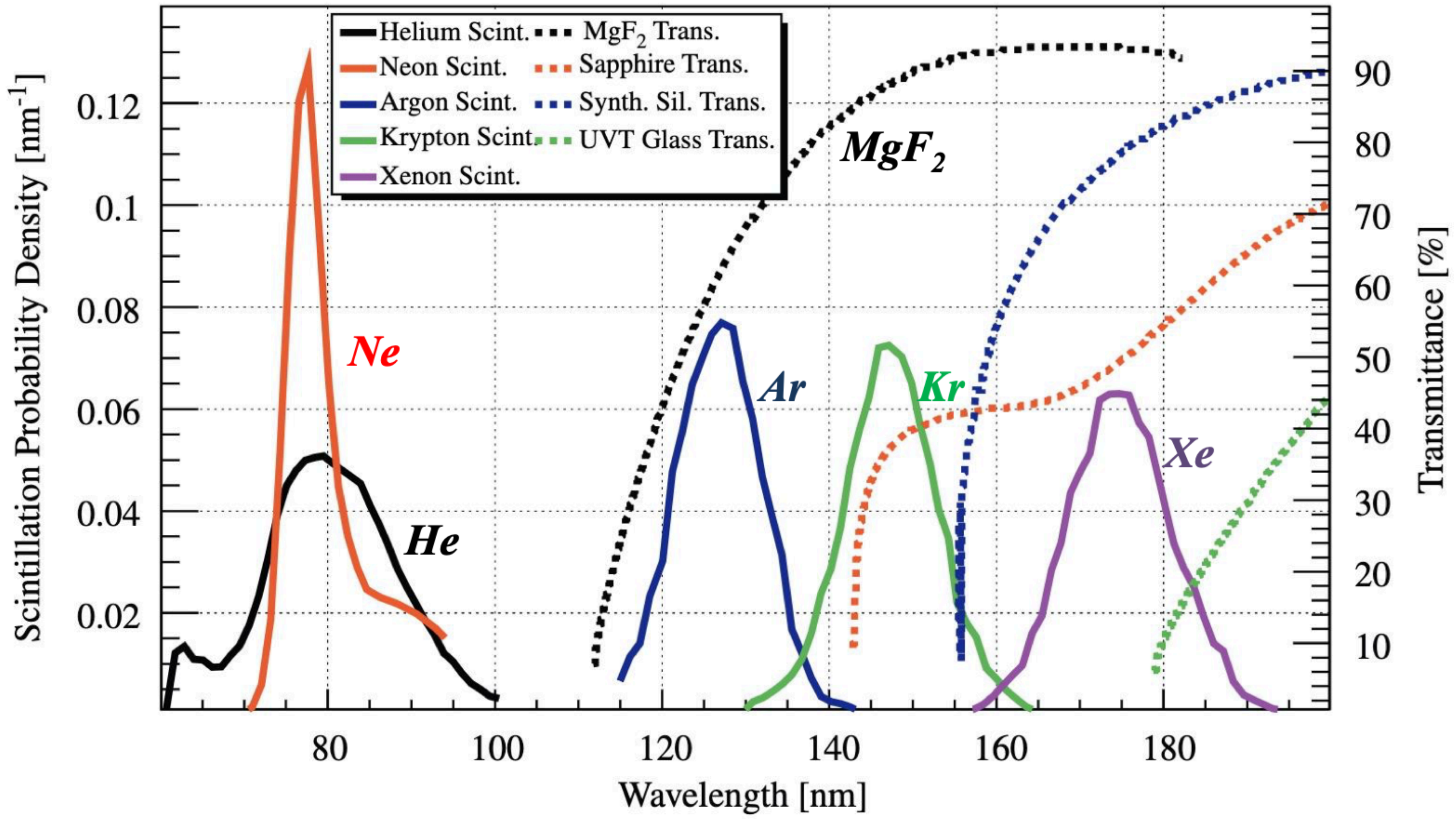
In addition, **decreasing availability** and **increase cost** of CF_4 pose issues for using it in future detectors with optical readout.



https://facts.net/global-warming-facts/

While CF_4 may be a good gas for some **active target TPCs** (high density, high F number), other applications may require other target gases such as pure noble gases.

Vacuum-UV emission of noble gases poses challenges for using this scintillation for optical readout.

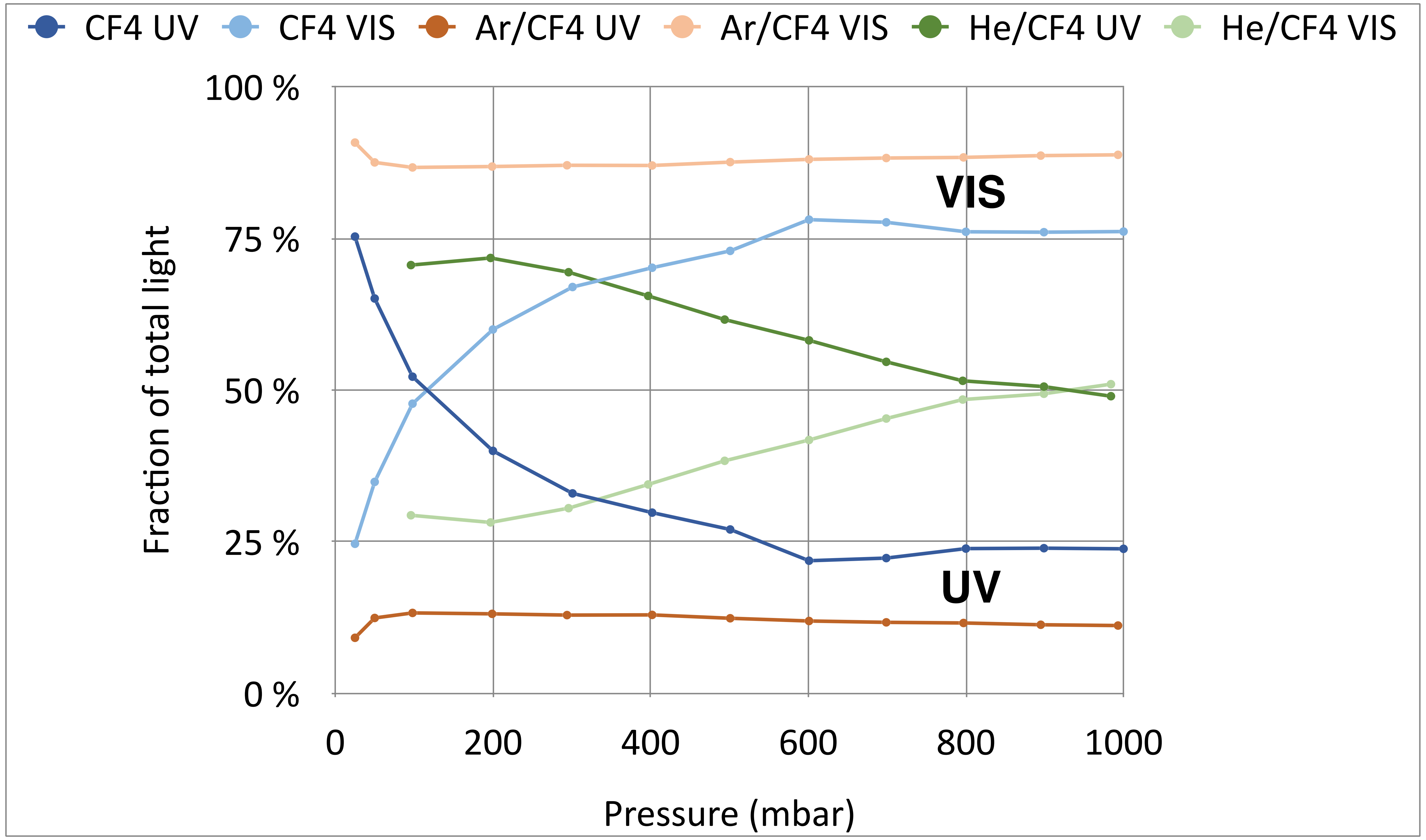


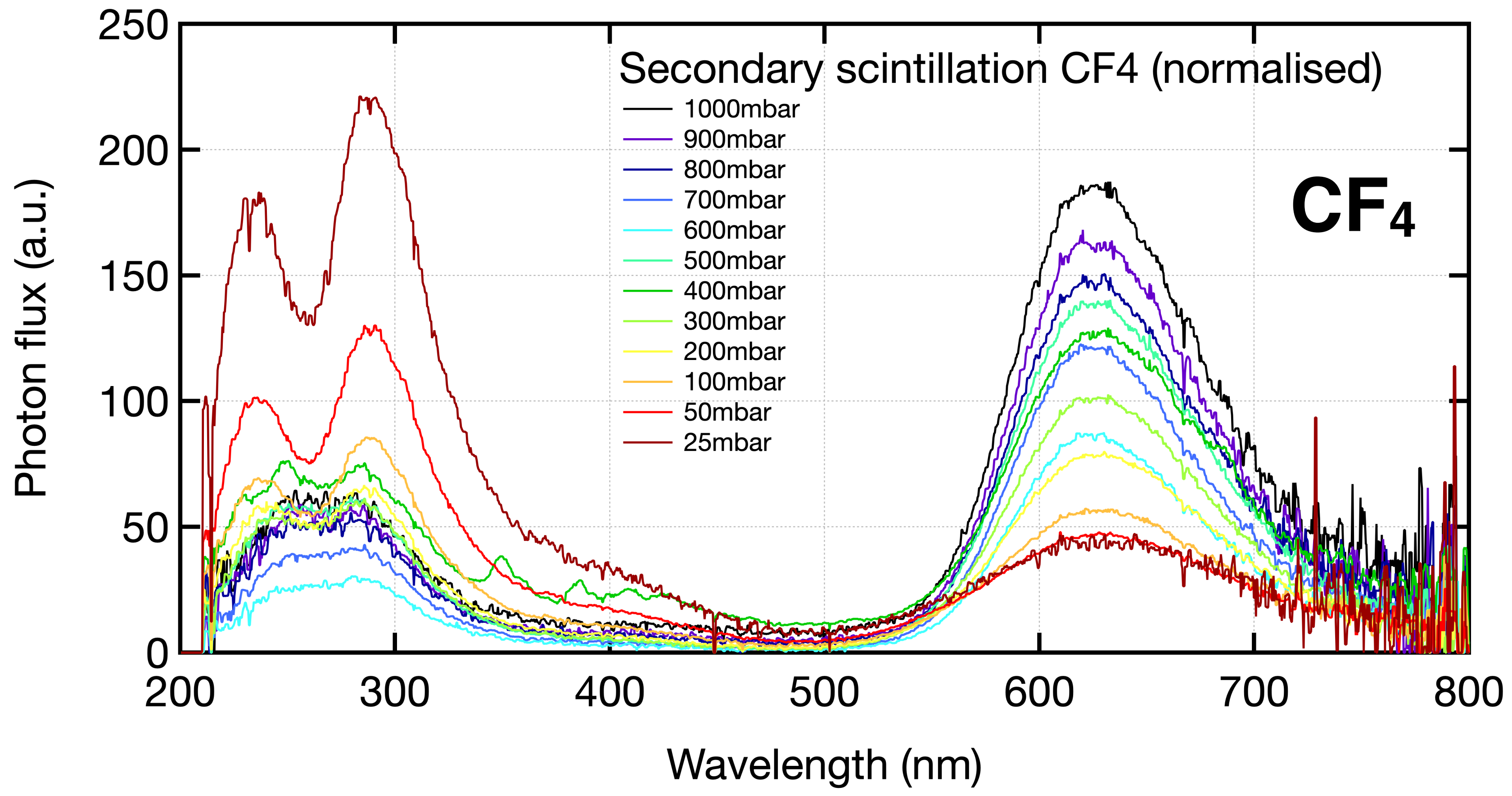
C. Benson et al, Eur Phys J C 78(2018)120

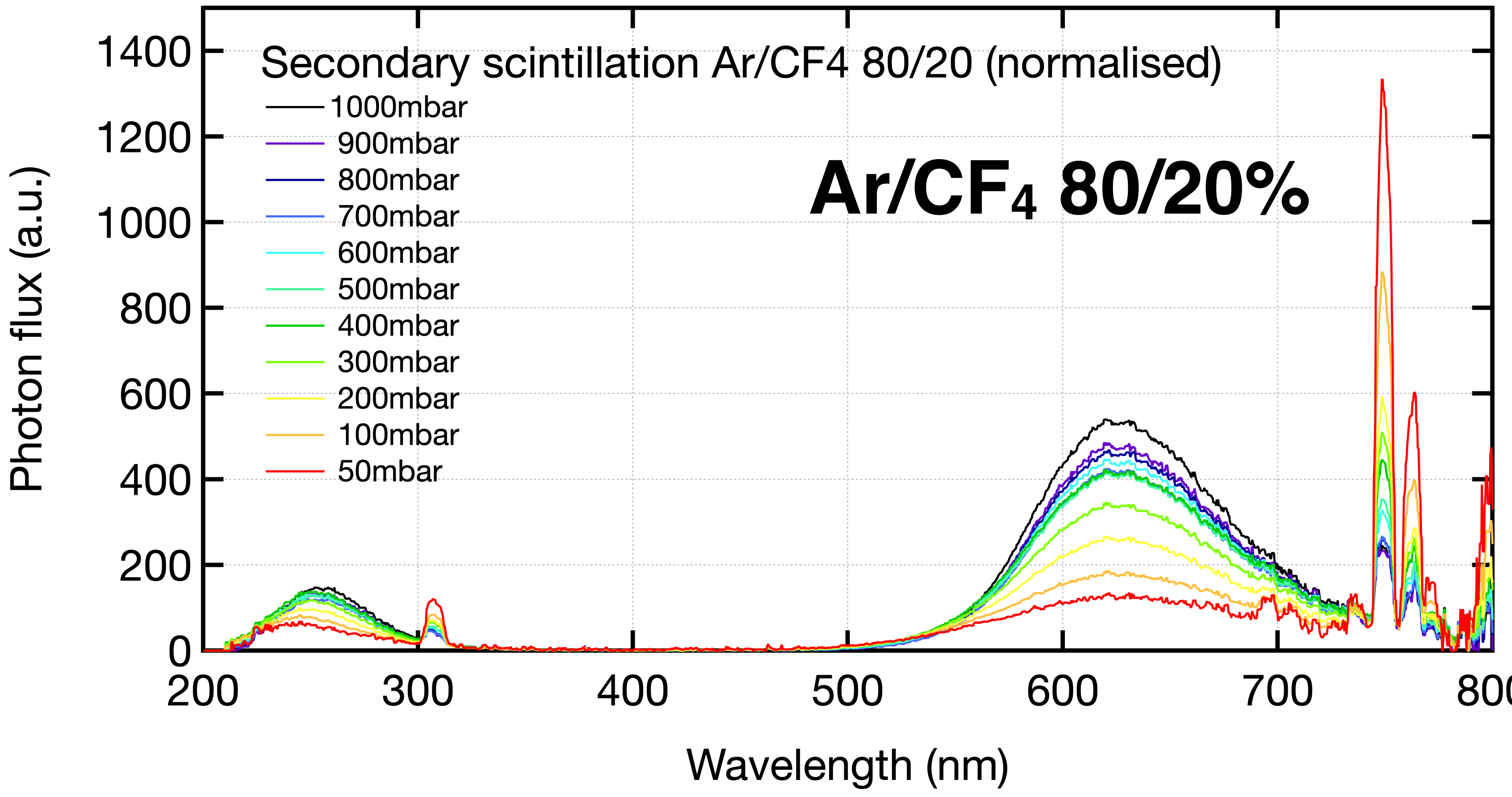
Secondary scintillation spectra

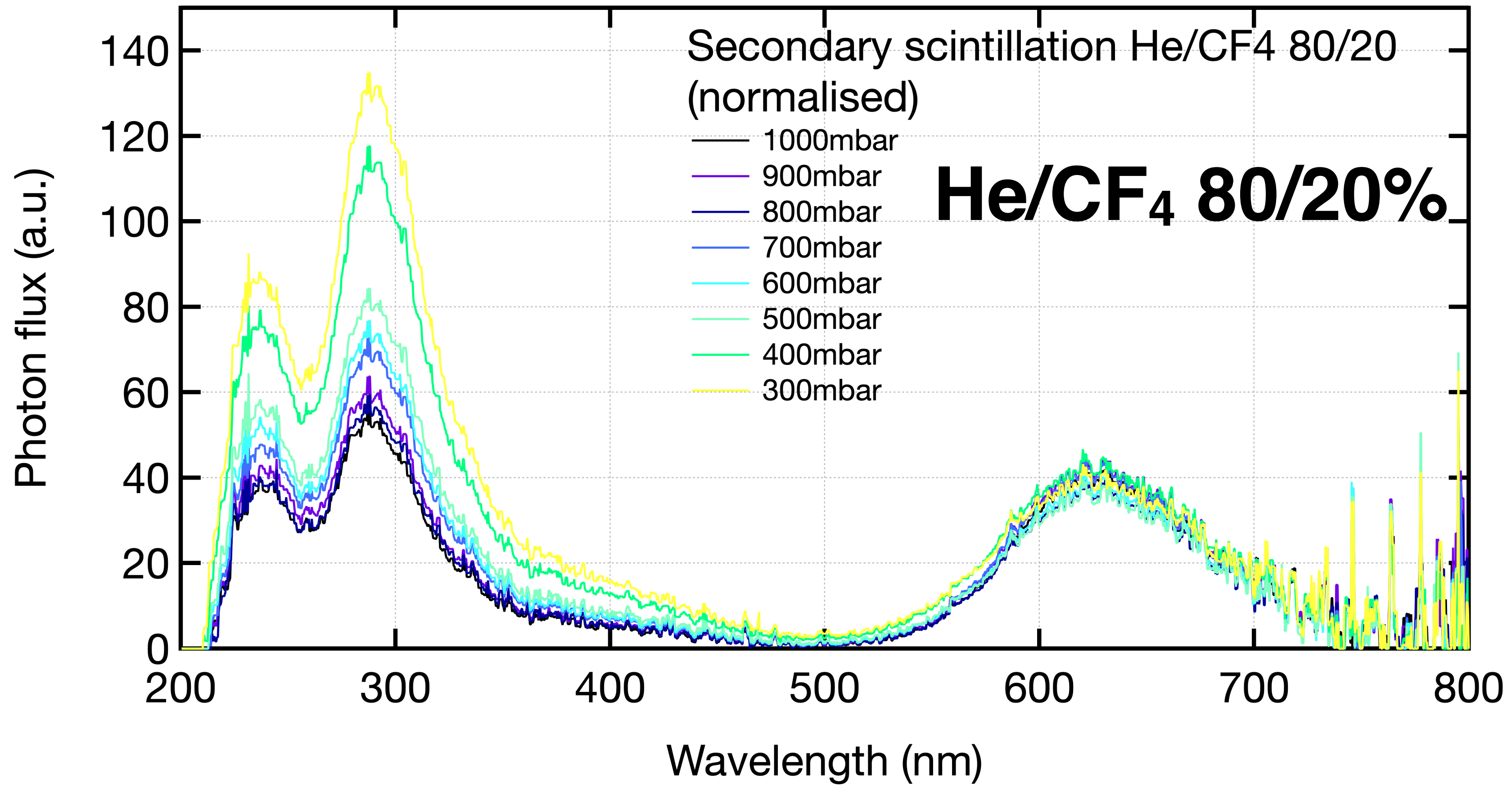
Ratio of UV and VIS components change with pressure with enhancement of UV component for CF4 and He/CF_4 with lower pressure

Ar/CF_4 scintillation intensity decreases with ≈ equal ratio between UV and VIS





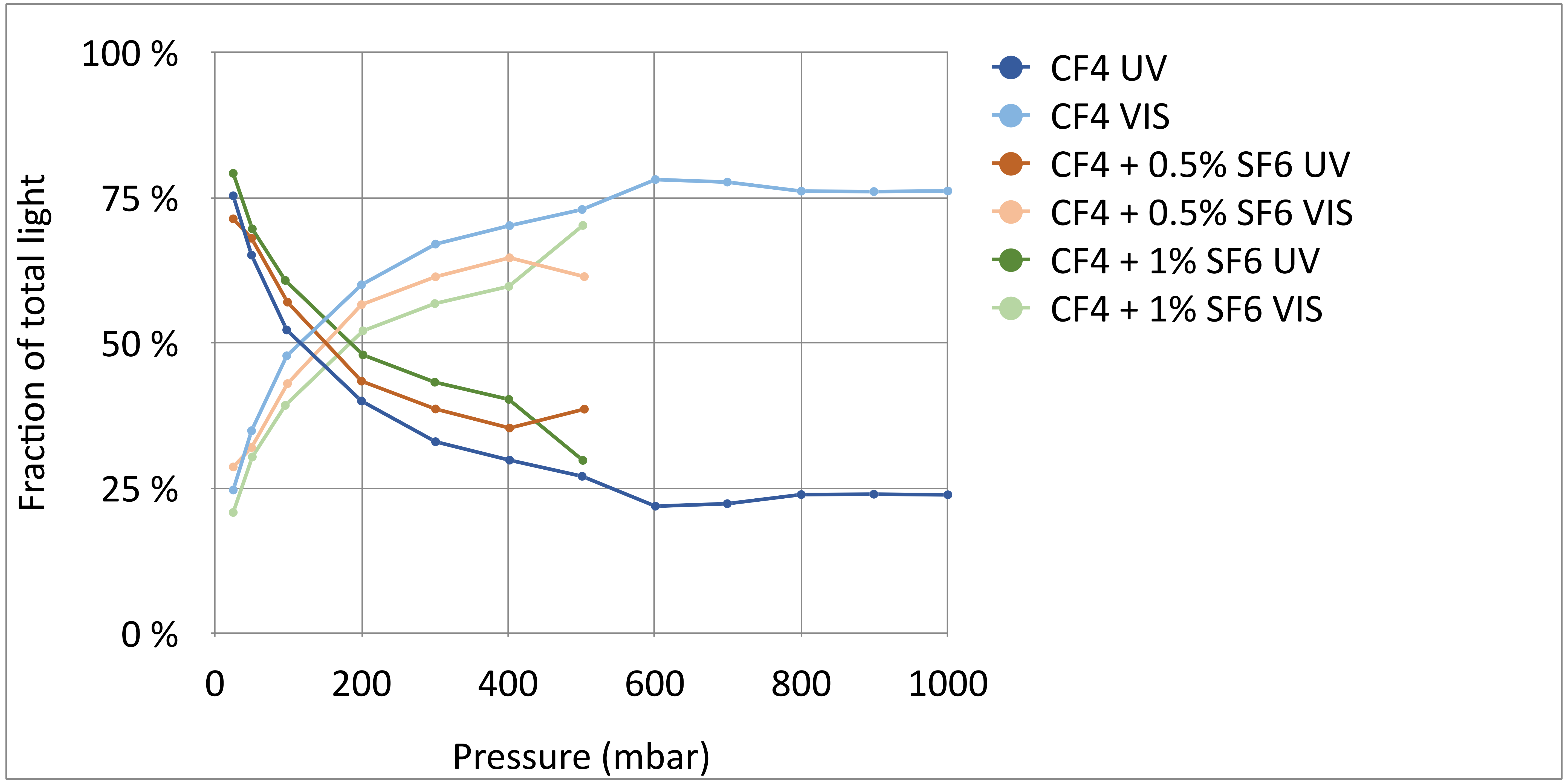


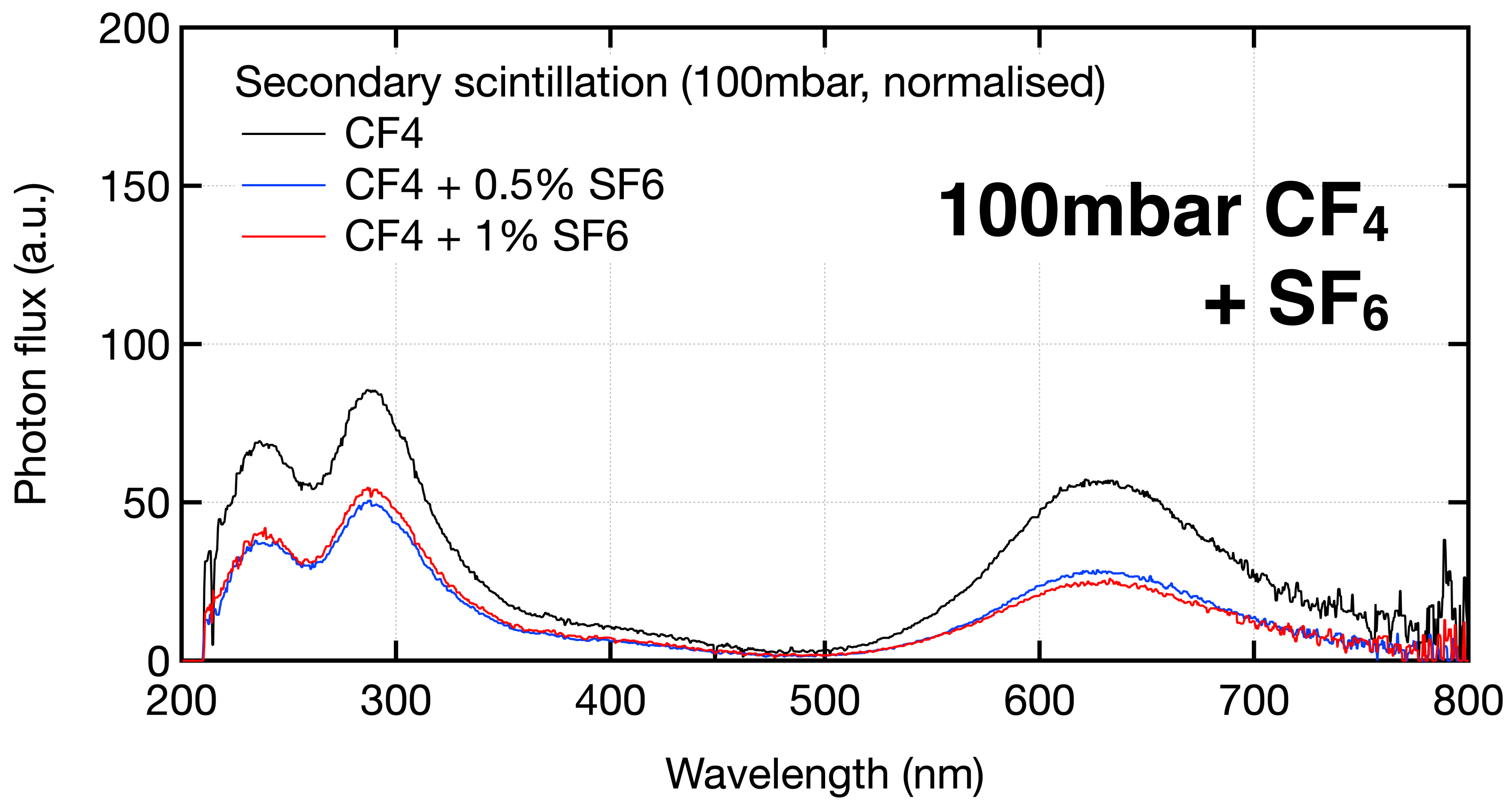


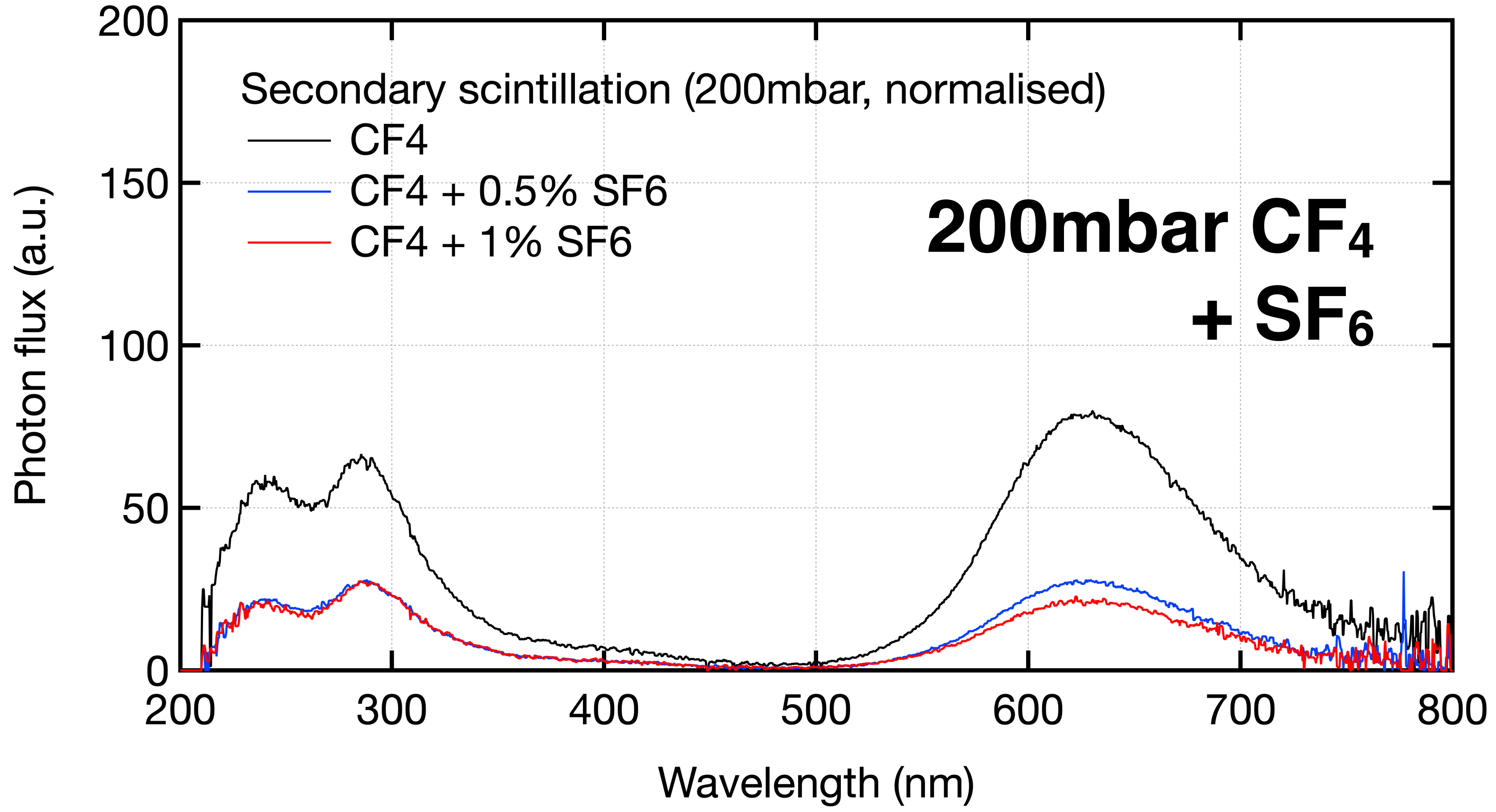
Scintillation spectra with SF_6

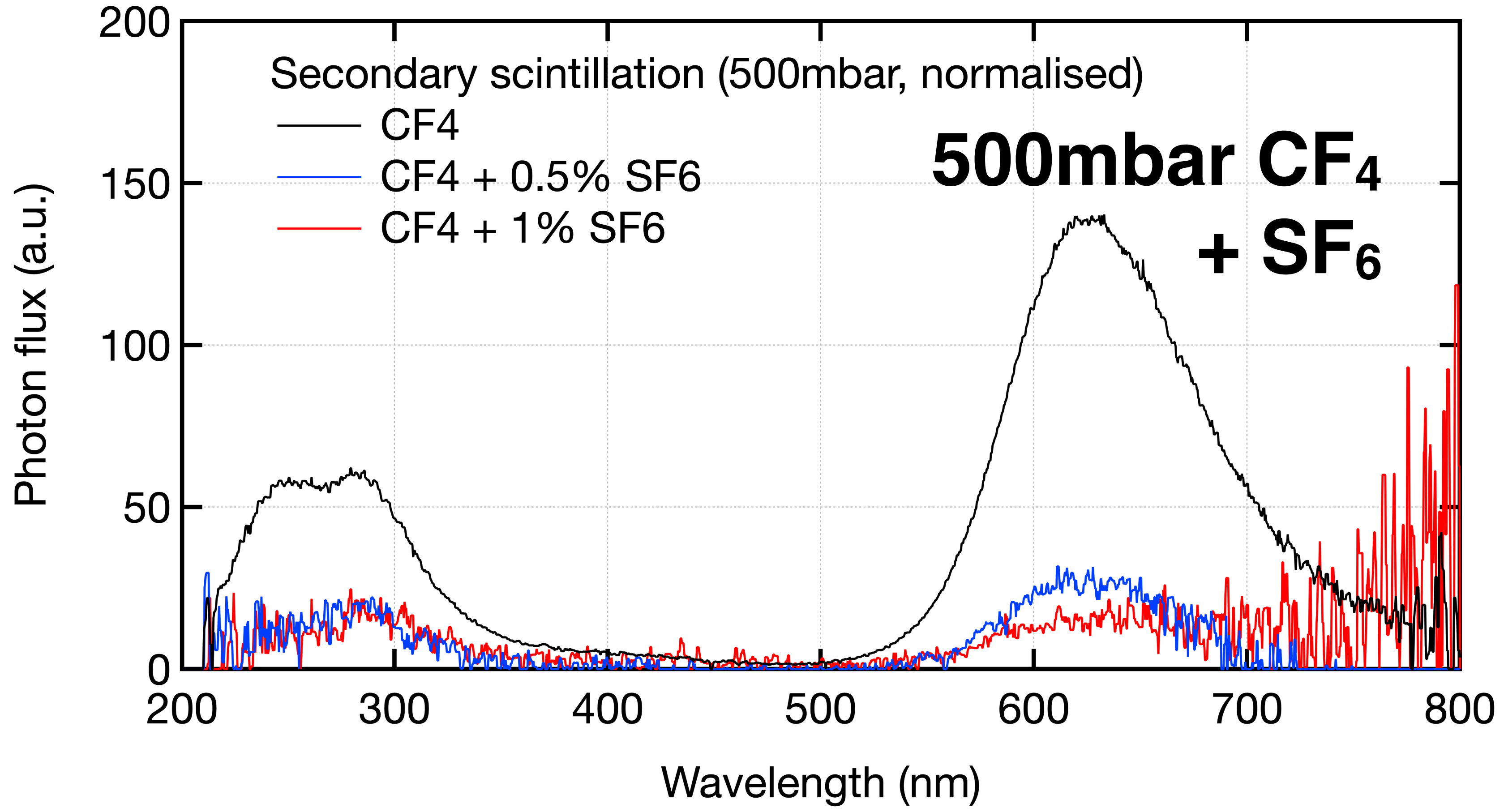
Addition of SF_6 suppressed scintillation output across all wavelengths

SF_6 percentage seems to influence the VIS emission band more significantly than the UV emission





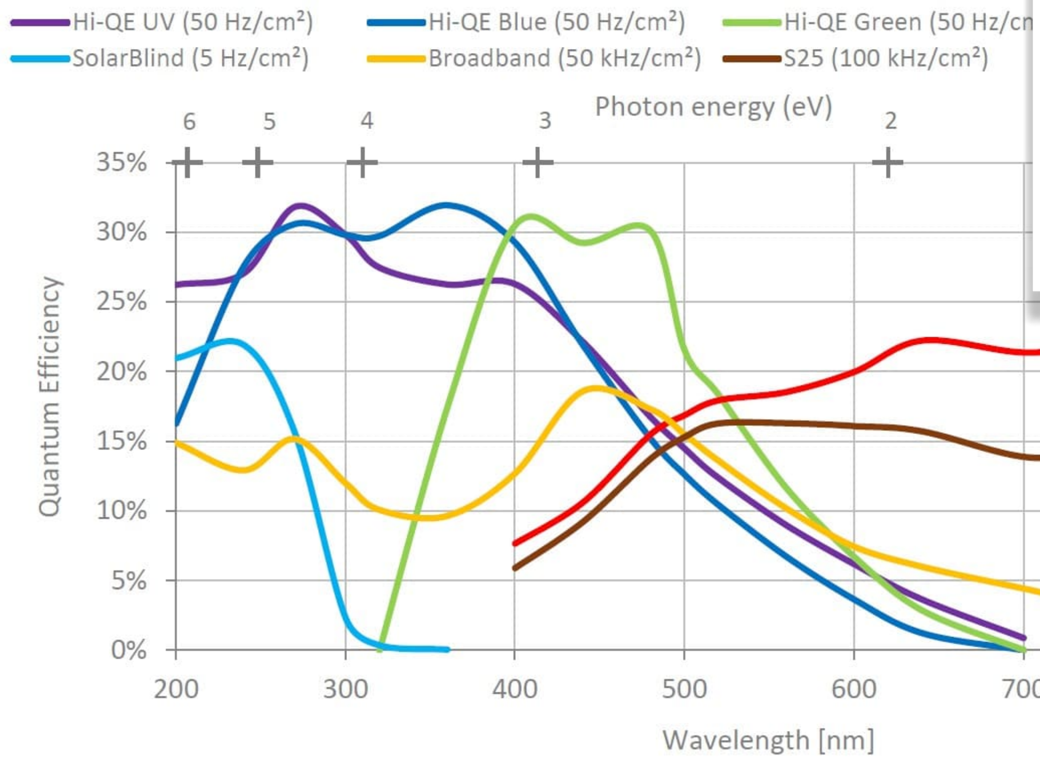




UV light readout

Using cameras / converters with UV sensitivity

https://www.photonfocus.com/products/uv-cmos-camera-with-global-shutter/

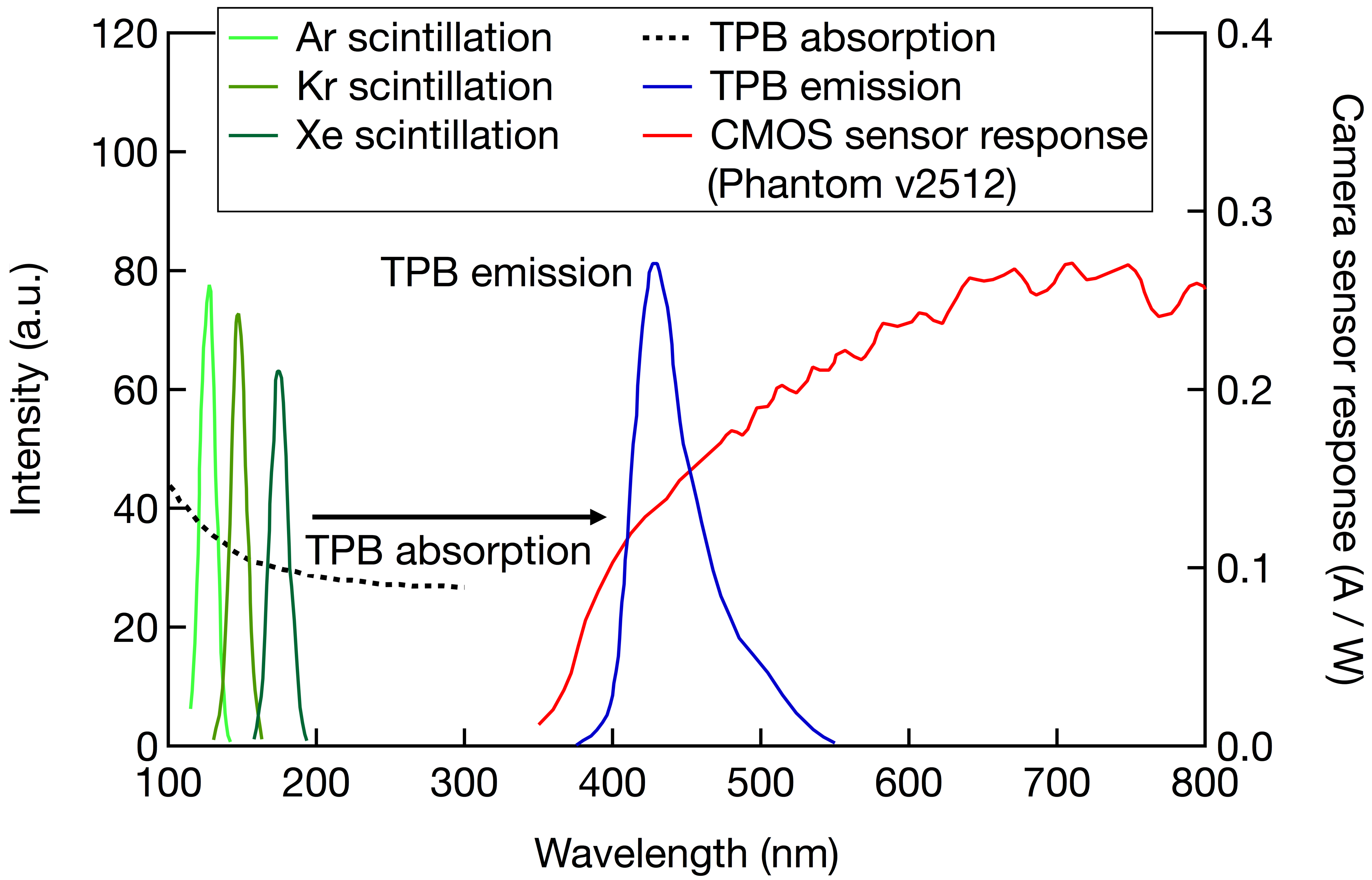


https://www.axiomoptics.com/products/cricket-image-intensifier/

Specialised image sensors for **UV sensitivity** may be used to directly record scintillation from gas mixtures or pure gases.

Alternatively, converters such as image intensifiers with **UV-sensitive photocathodes** and VIS re-emission may be used to record UV light with visible-sensitive imaging sensors.

Using wavelength shifters (WLS)



Data from: Ignarra, C.M. Physics Procedia 37 (2012): 1217–1222.
Scintillation data from: V. M. Gehman et al. NIM A 654 (2011) 1.

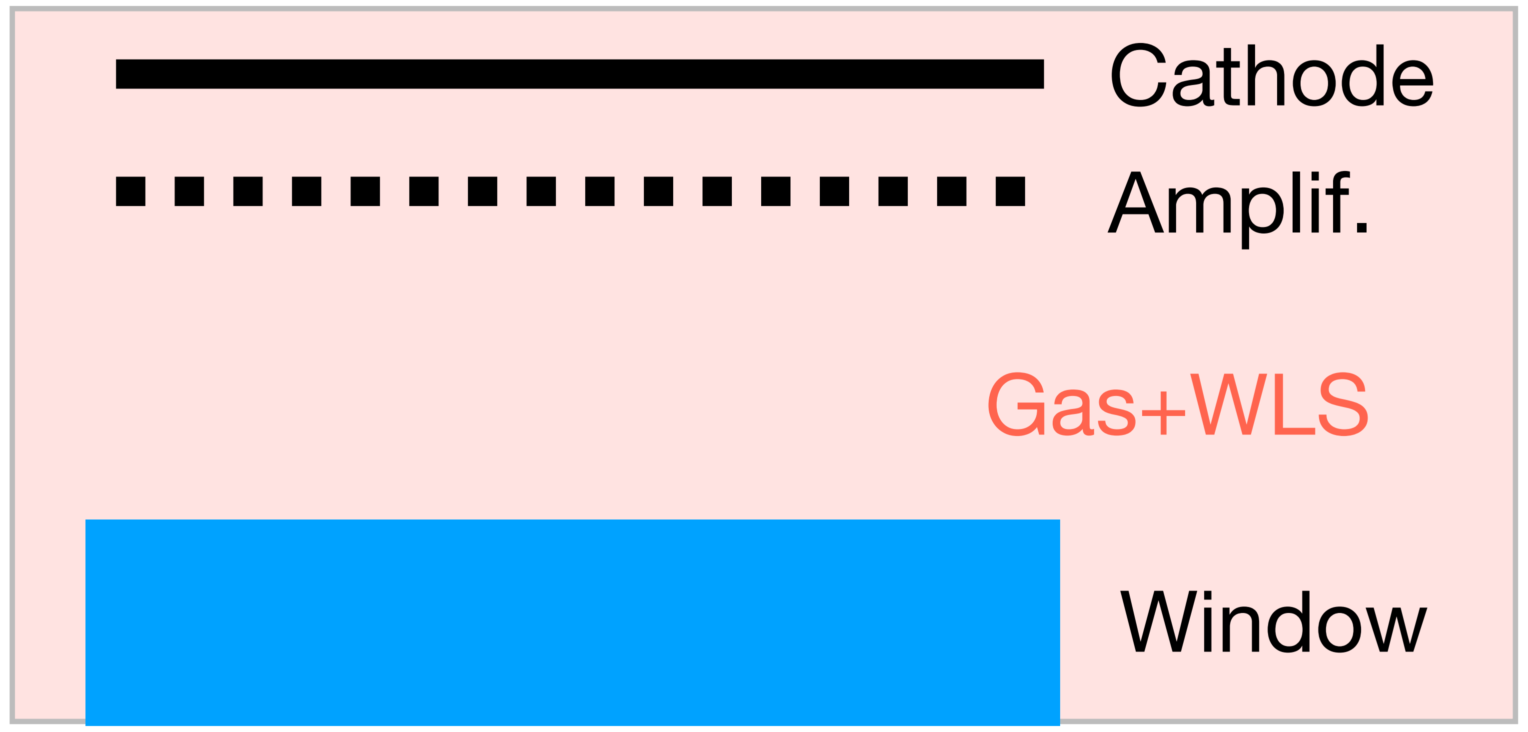
Wavelength shifters such as tetraphenyl butadiene (**TPB**) can be used to shift scintillation light spectrum to the visible wavelength range with a peak around **425 nm.**

Wavelength shifter configurations

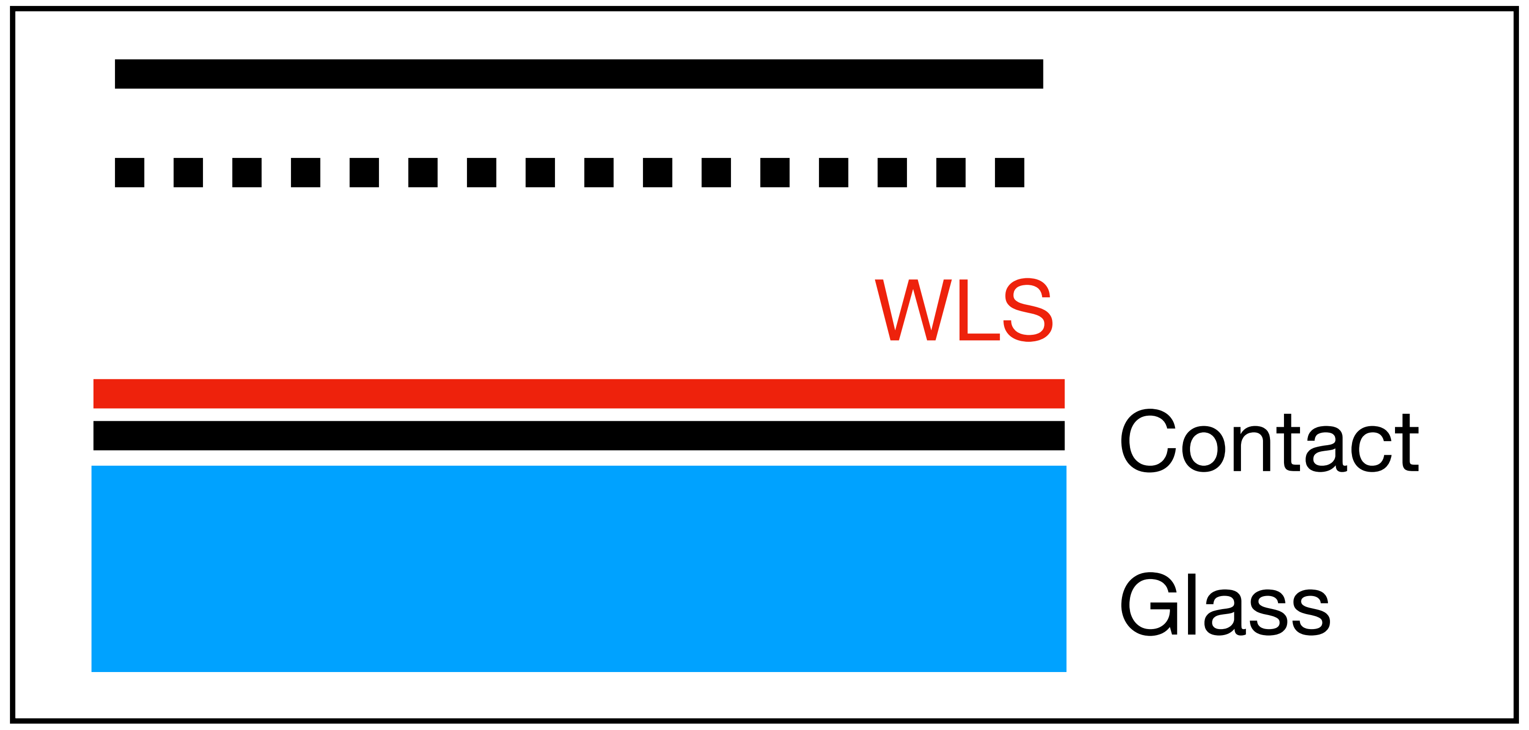
Wavelength shifters (WLS) may be in **gaseous or solid form**. Typical WLSs absorb in a wide wavelength range covering the UV range and re-emit in the visible range at ≈400-500nm.

Structure and location of WLS determines their **suitability for high resolution readout** and their robustness.

Gaseous WLS
Added to gas mixtures, continuous wavelength shifting, possible loss of resolution



Solid WLS - thin film coating
Coated on window with thin film deposition techniques, e.g. TPB, ≈hundreds of nm thickness, localised WLS



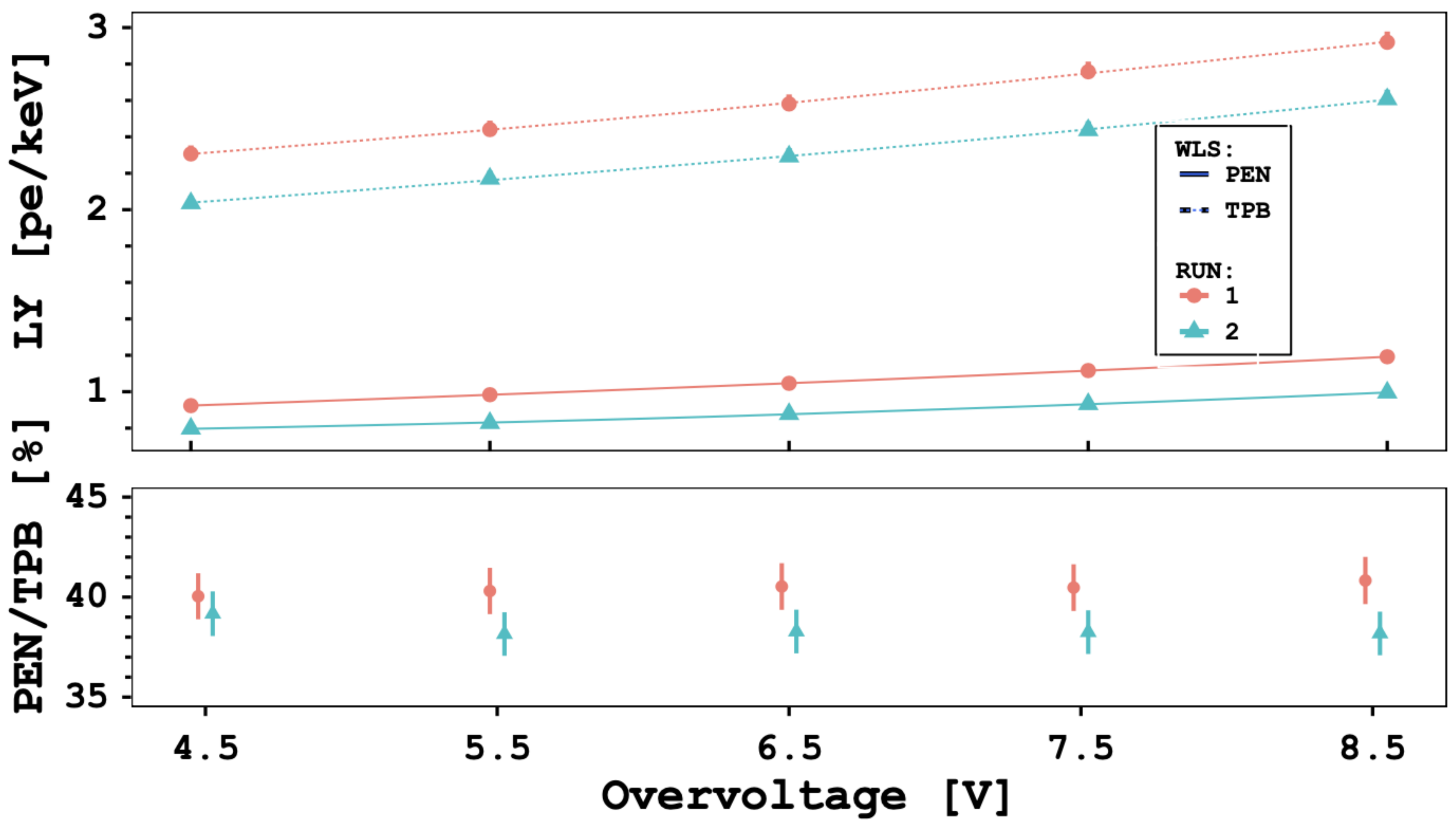
Solid WLS - bulk material
E.g. PEN, ≈μm thickness, potentially more robust than thin film coatings

Schematics not drawn to scale

Comparison of solid WLS materials

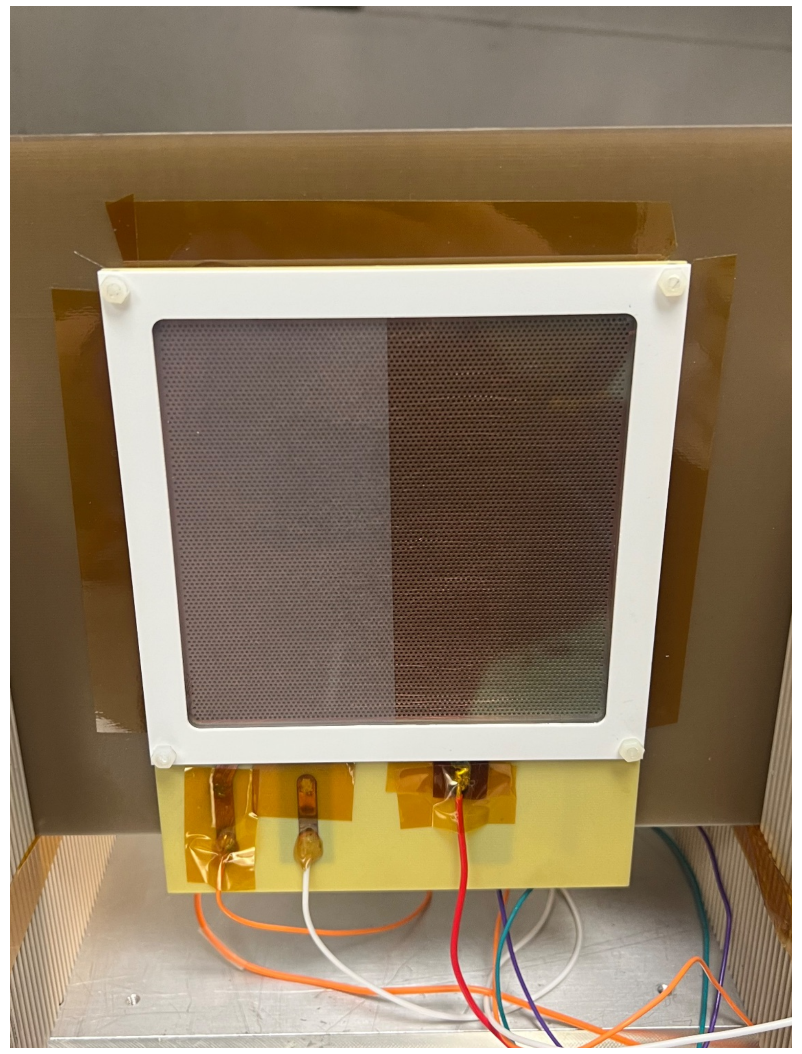
Comparison of 3 different solid wavelength shifters in pure Ar with M-THGEM and same voltage settings
Ageing of TPB partially explains difference between thin/thick layers, PEN less efficient

PEN efficiency is about 45% of the one of TPB



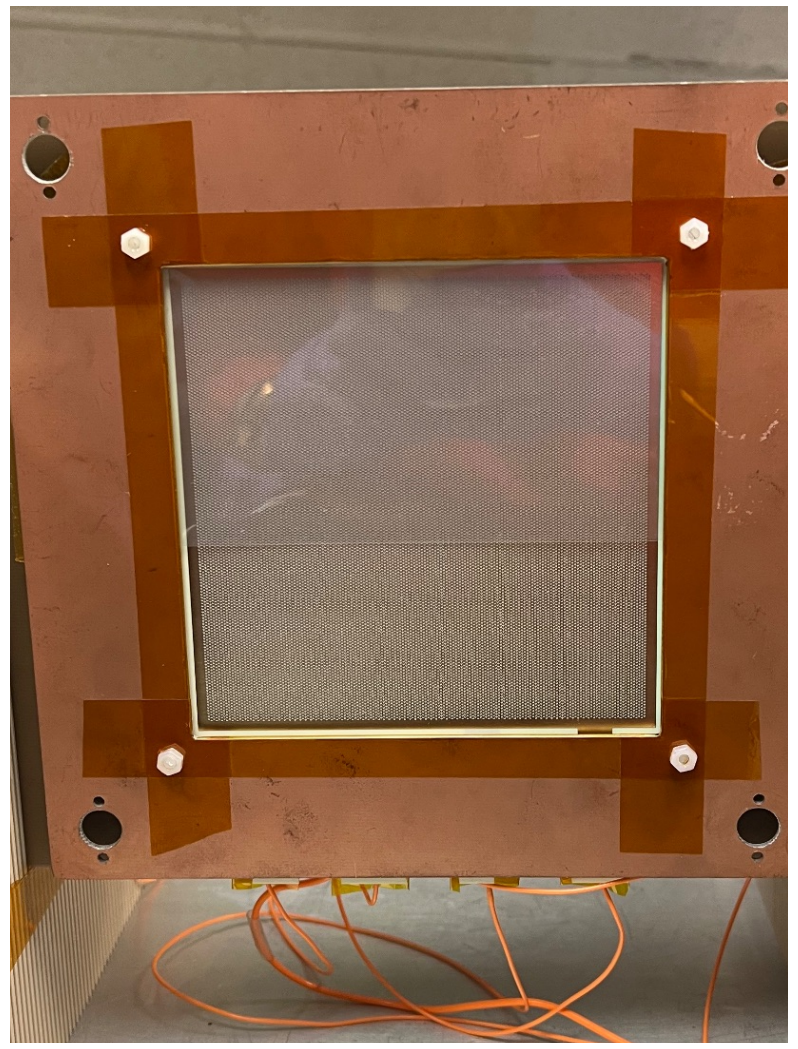
https://doi.org/10.1140/epjc/s10052-021-09870-7

Thin TPB - half coated
0.1 mg/cm^2 ≈ 860nm



Thick TPB - fully coated
0.2 mg/cm^2 ≈ 1720nm

PEN foil - half covered - 25µm thick



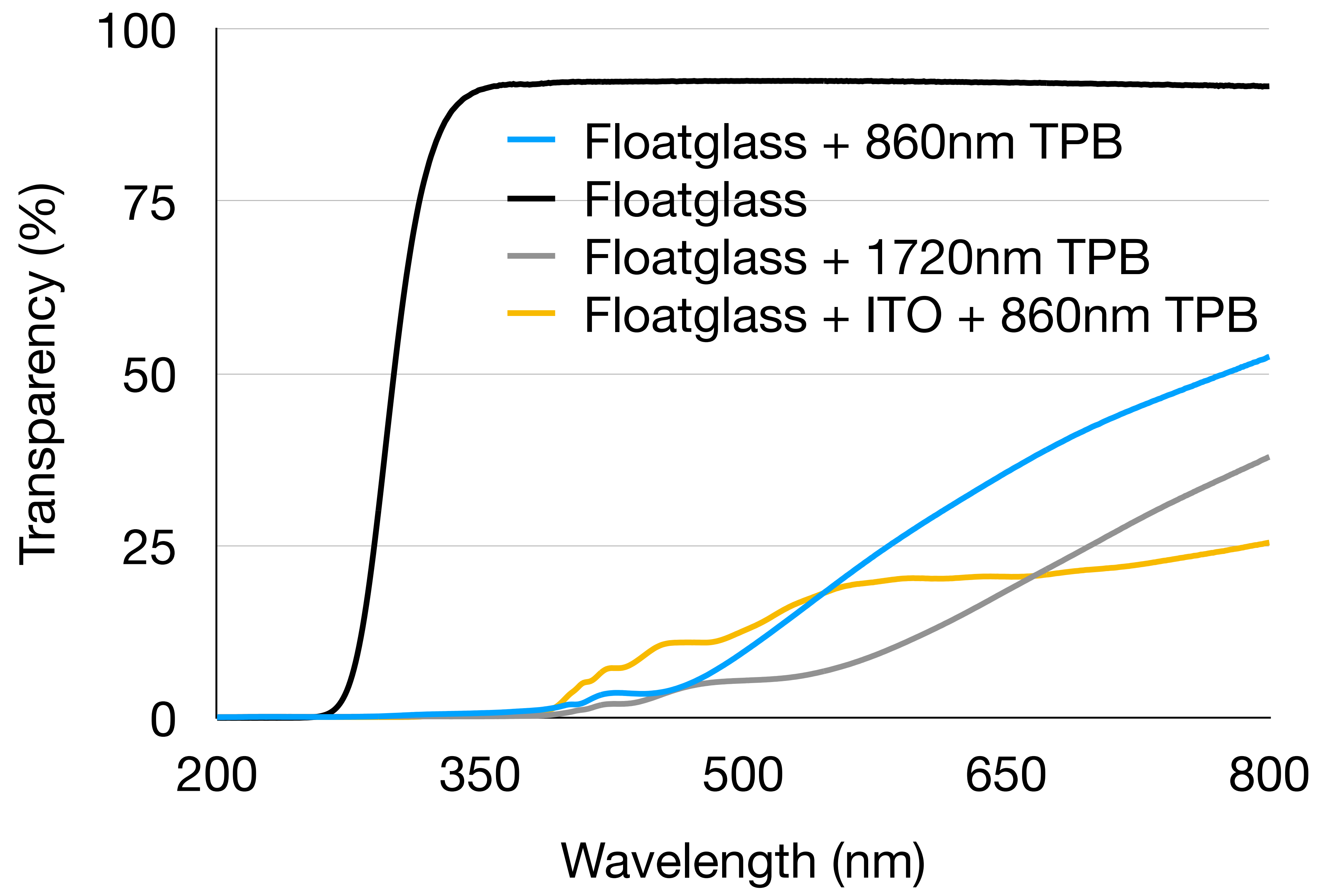
WLS materials	Relative intensity
Thin TPB - 860nm	0.95
Thick TPB - 1720nm	1.99
PEN foil - 25µm	0.52

TPB transmission

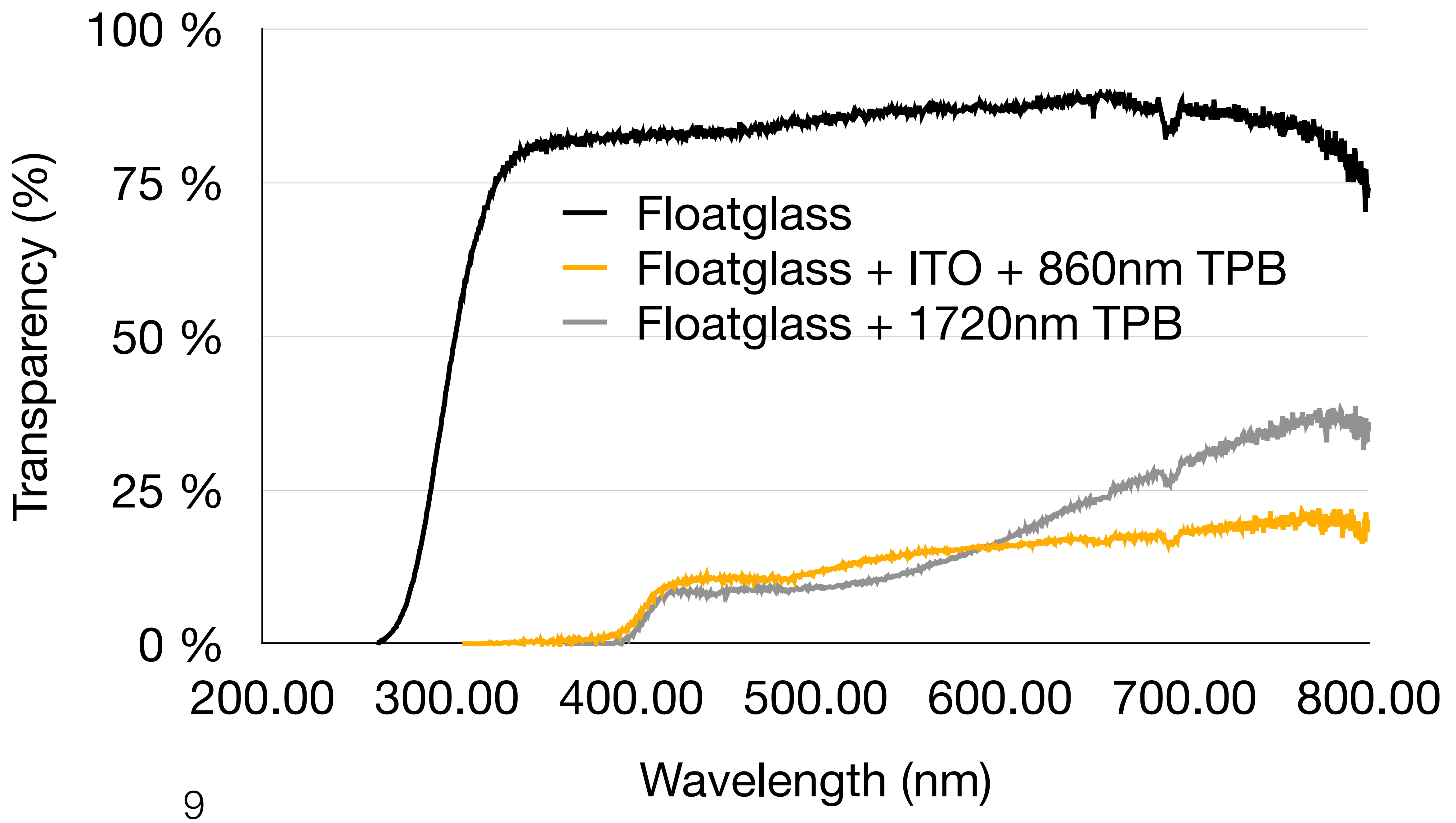
Examined TPB layers were **semi-transparent**, i.e. some scintillation light was absorbed, some fraction was transmitted through the WLS layers.

Measurements of transparency were conducted with scanning monochromator (irradiation only at measured wavelength) and with a full-spectrum deuterium-halogen lamp and a CCD spectrometer. Similar transmission characteristics were observed.

Measurements by scanning wavelength



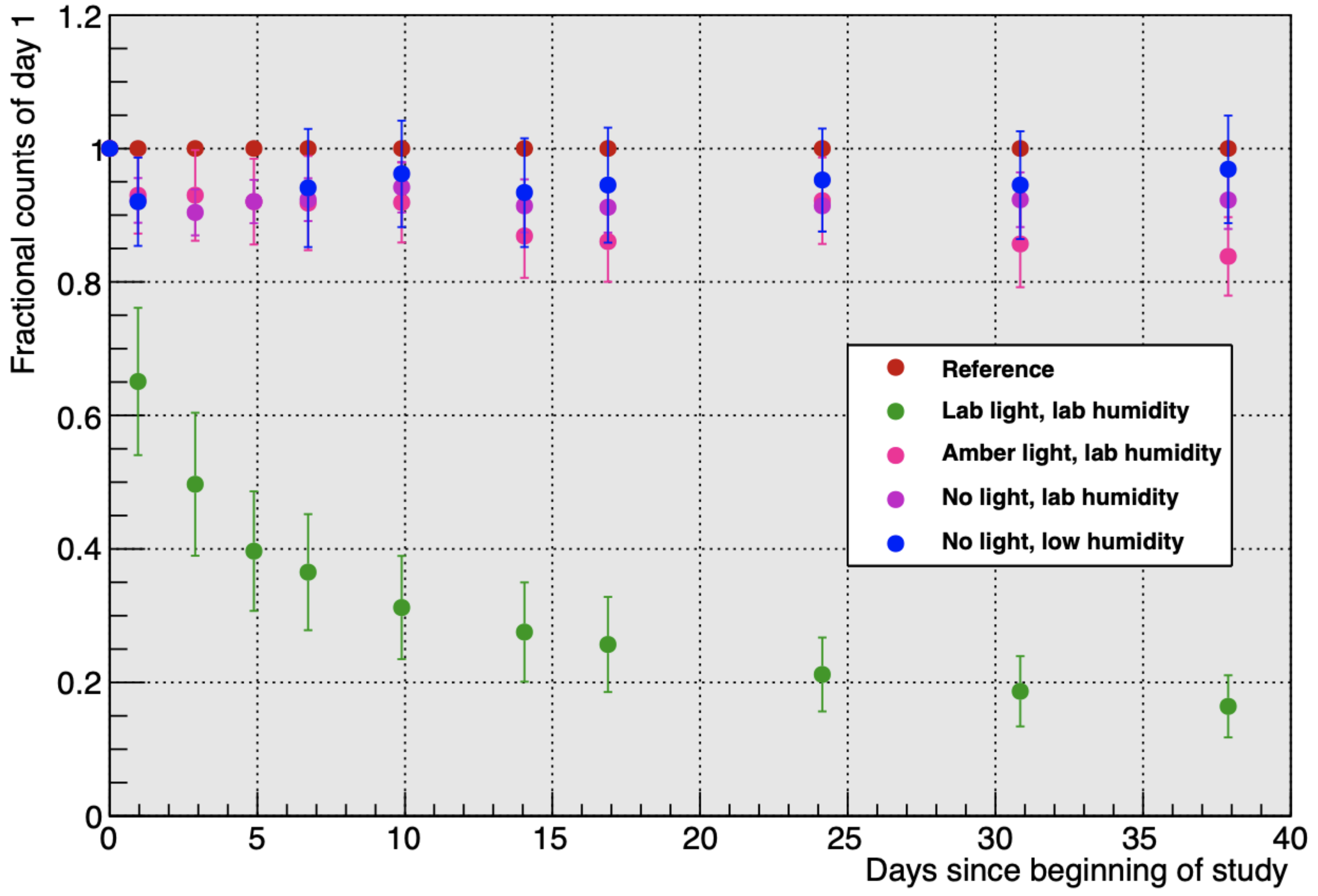
Measurements Lamp+Spectrometer - Full spectrum



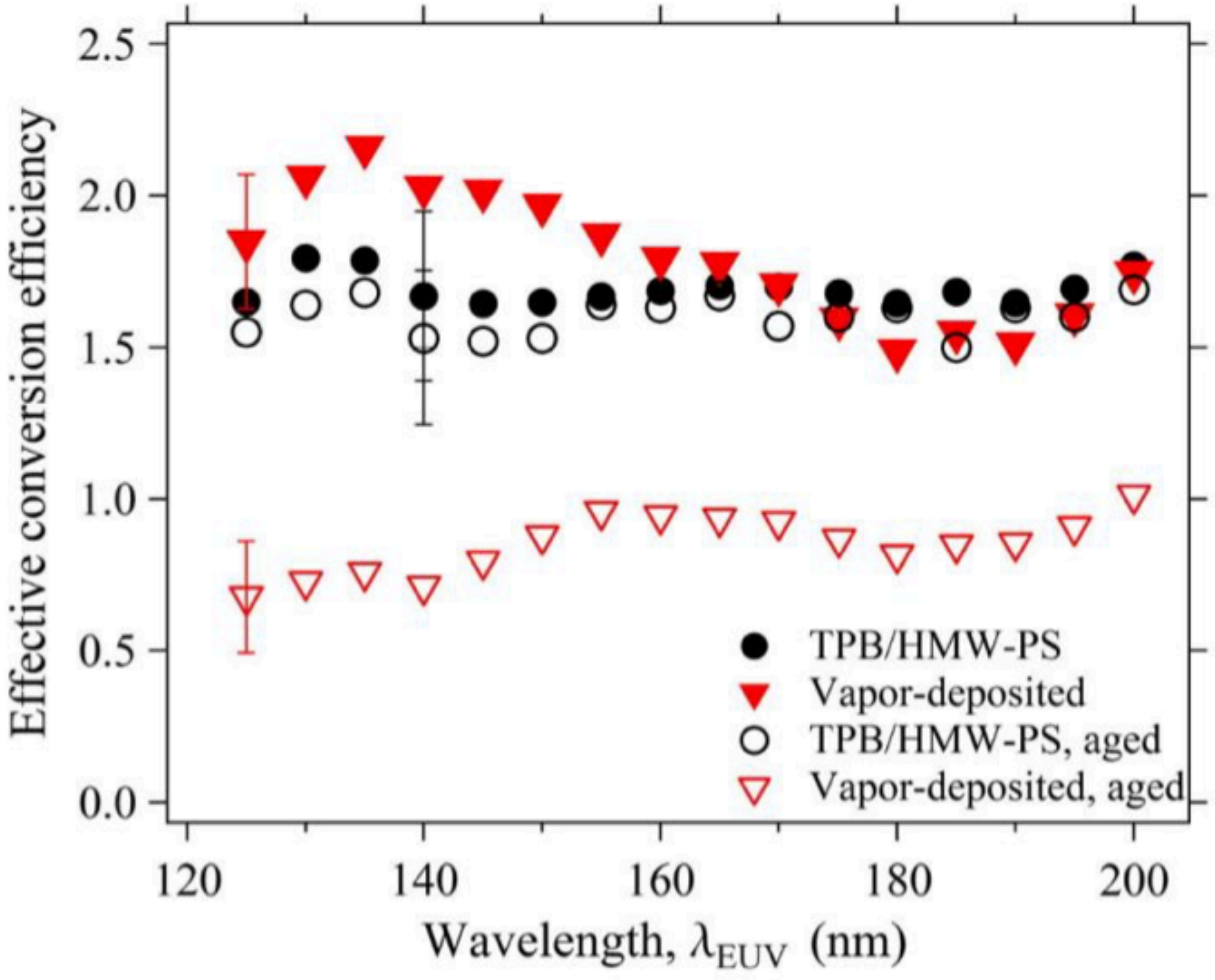
TPB degradation

TPB efficiency is degraded by humidity exposure (minor) and under light irradiation (significantly) - light exposure can degrade TPB response down to tens of % of initial efficiency.

WLS for studies shown in following measurements were stored in dark but in ambient atmosphere for weeks before study - possible degradation may be present.



C S Chiu et al 2012 JINST 7 P07007 https://arxiv.org/pdf/1204.5762.pdf

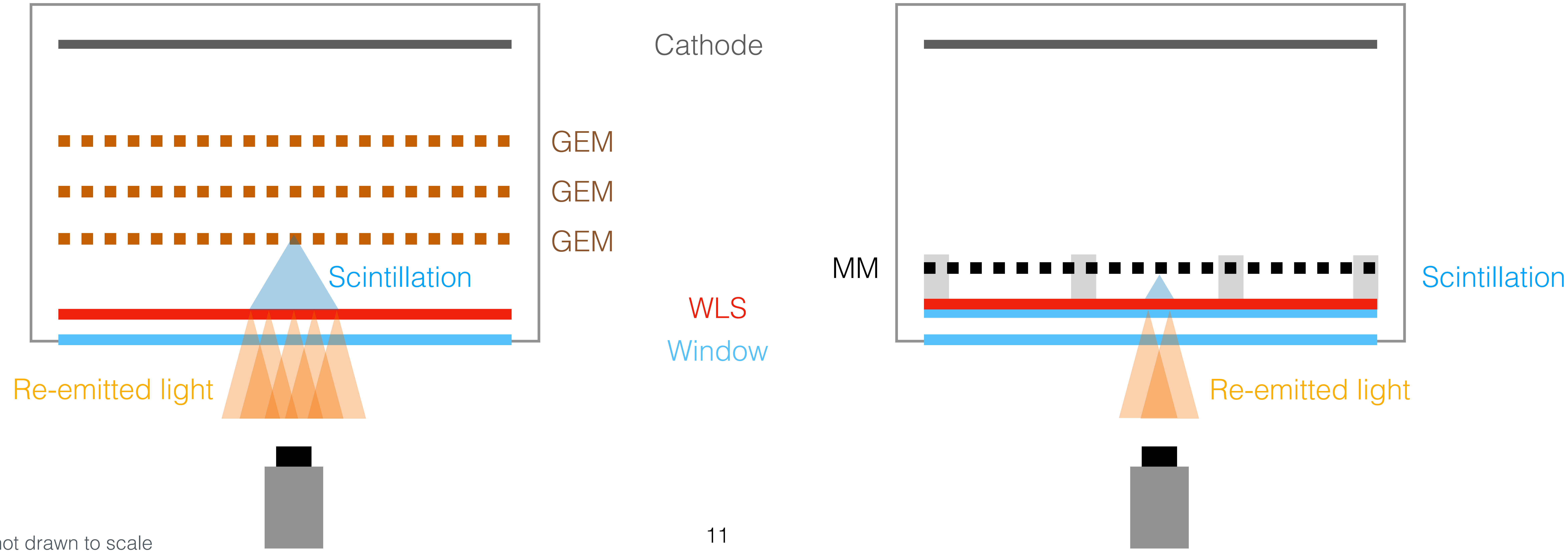


J. Graybill, Applied Optics Vol. 59, Issue 4, pp. 1217-1224 (2020)

Placement of solid WLS

Solid WLS can provide **superior spatial resolution** due to localisation of light conversion.

Placement of WLS at a distance from initial **light production site** (avalanche location) leads to additional image blurring → optimal placement of WLS as **close** to avalanche site as possible.



Schematics not drawn to scale

TPB integration

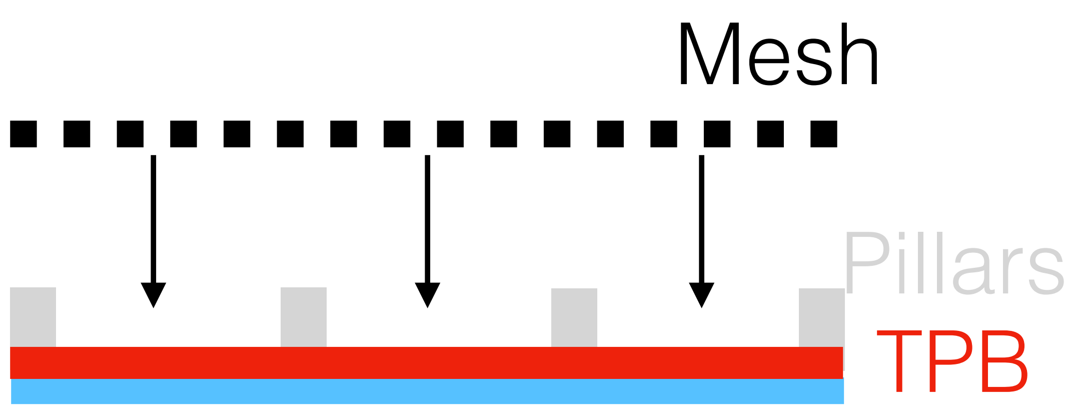
Evaporation of TPB can be done on glass substrate and Micromegas can then be formed by placing mesh on pillars.

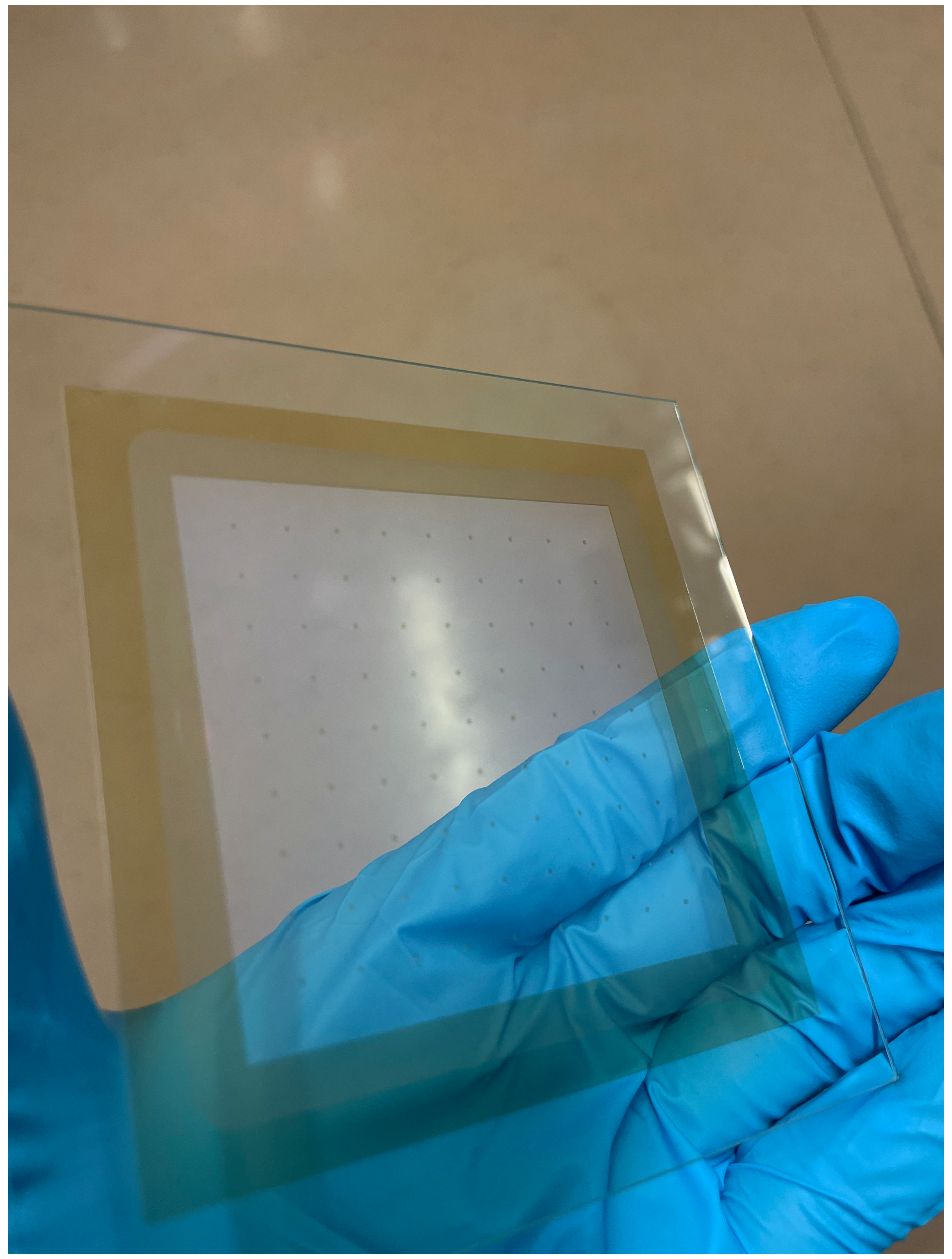
Alternatively, **bulk Micromegas** on glass substrate can be evaporated with TPB directly.

TPB is **insulating** and does not create issues of electrical shorts or instability. Contacts must be kept free to contact anode and mesh of Micromegas after evaporation.

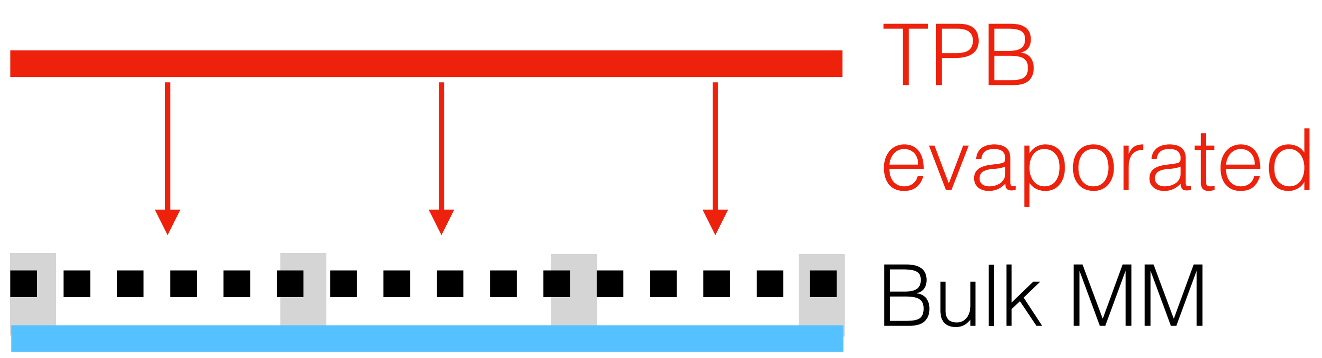
Typical TPB thickness deposited by evaporation is on the order of **1μm**.

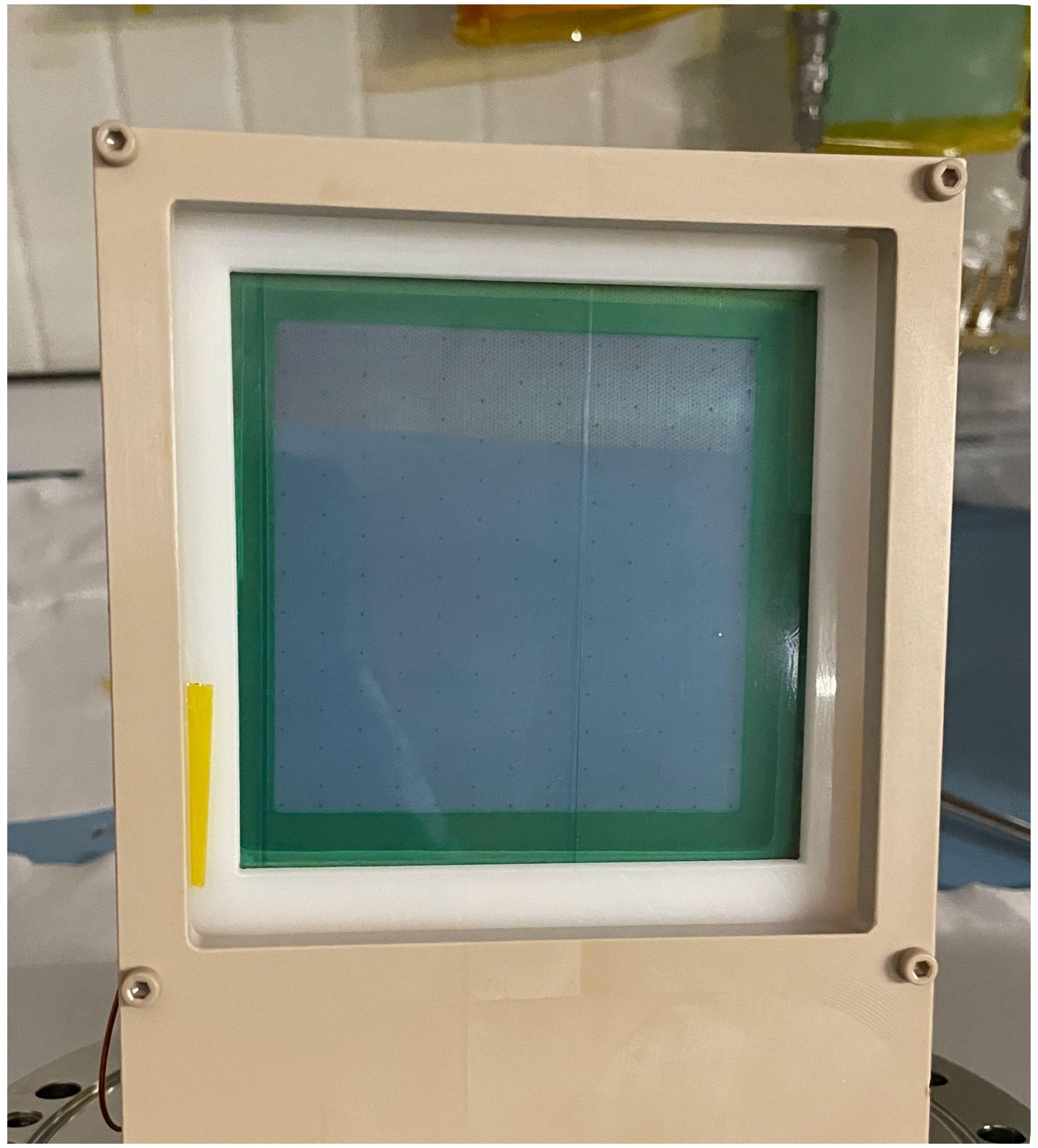
1. Evaporation of TPB
2. Placement of mesh





1. Bulking of MM
2. Evaporation of TPB





Schematics not drawn to scale

X-ray imaging setup

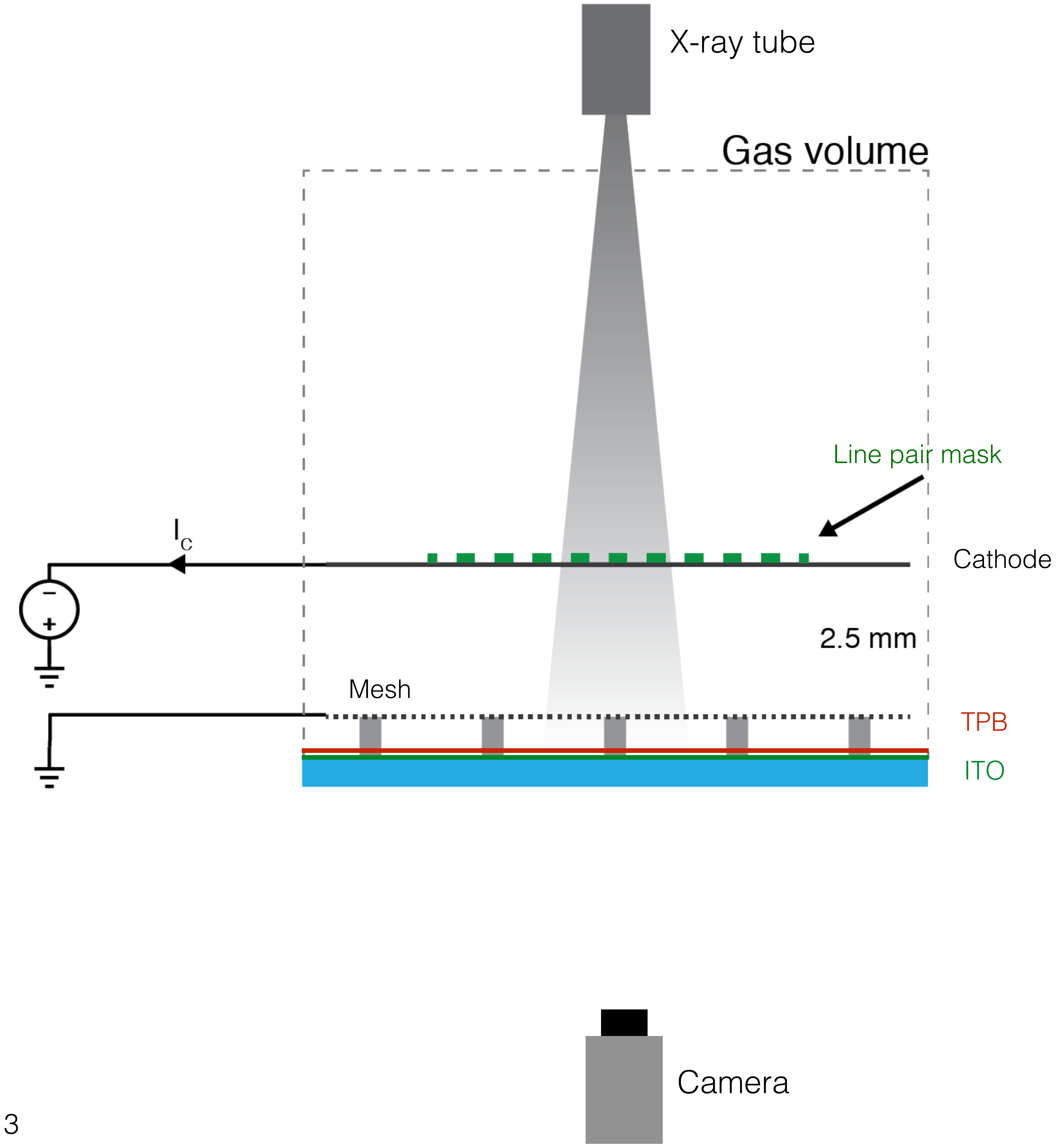
Achievable **spatial resolution** with different WLS configurations was quantified with an X-ray radiography setup.

Detector under test (triple-GEM or MM) was assembled with a cathode at 2-3mm from amplification structure.

A **line pair mask** (50μm Pb) with increasing spatial frequency line patterns was placed directly on the cathode to minimise parallax blurring.
The detector was irradiated with a Cu X-ray tube placed at ≈1m from the cathode.

Images were recorded with a 6MP **CCD camera** with a 25mm f/0.95 lens (+1mm spacer, +3 diopter) placed at ≈25cm from the anode.

Multiple 10-30s exposure images were recorded, averaged and subtracted by averaged background image.



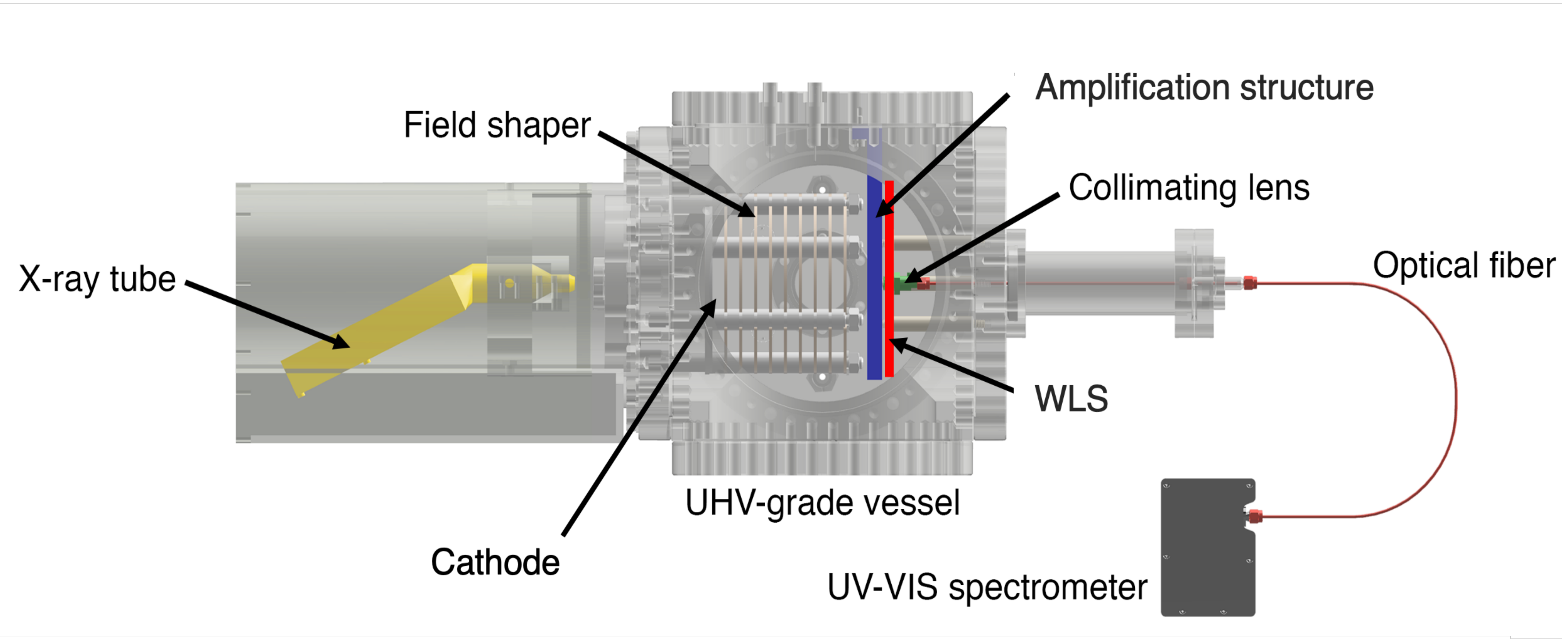
Schematics not drawn to scale

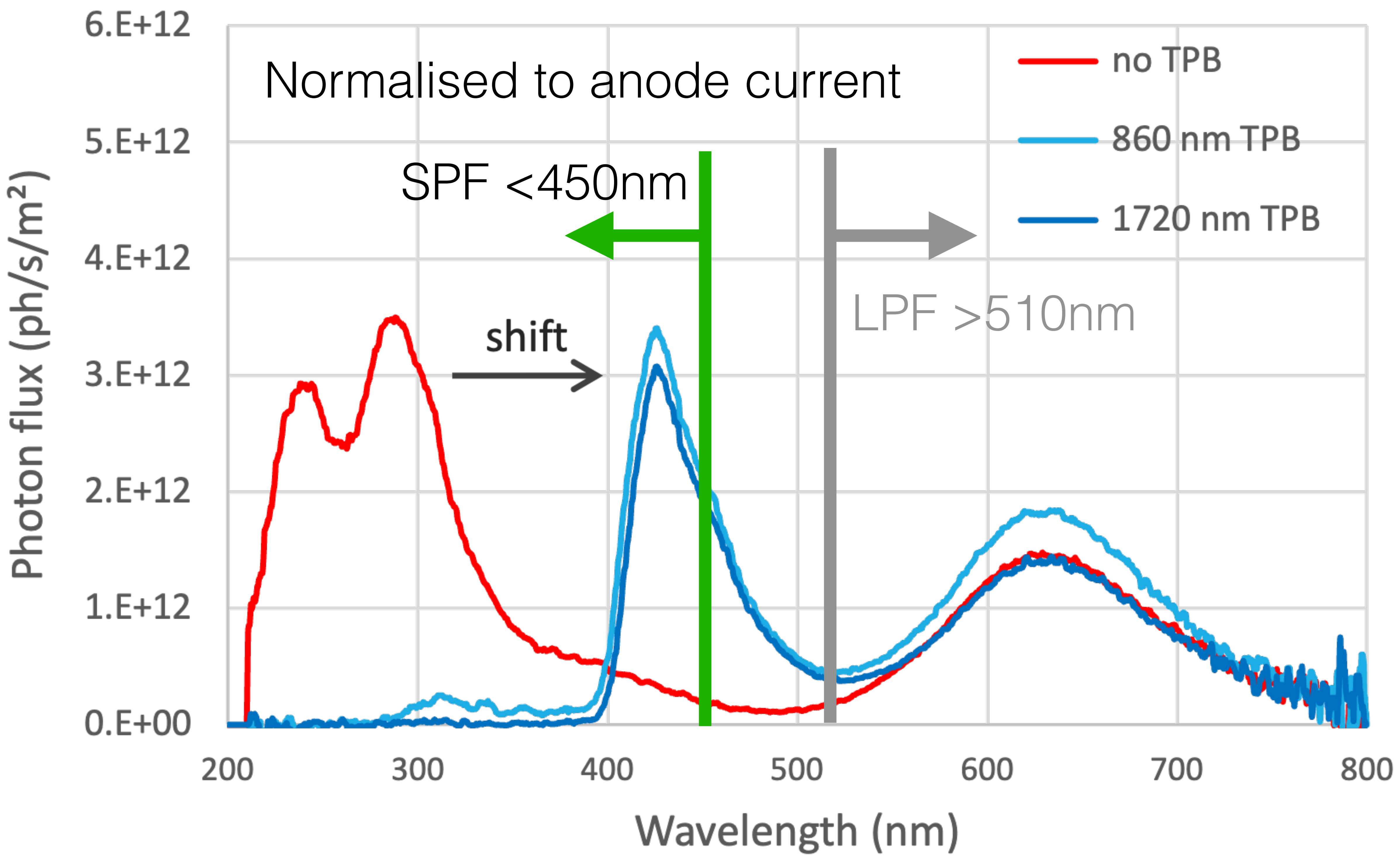
Conversion efficiency

Measurement of **light output** from **TPB layers** on glass substrates with two different thicknesses in detector filled with pure CF_4

Separation of light spectra by **450nm shortpass filter** (SPF) and **510nm longpass filter** (LPF)

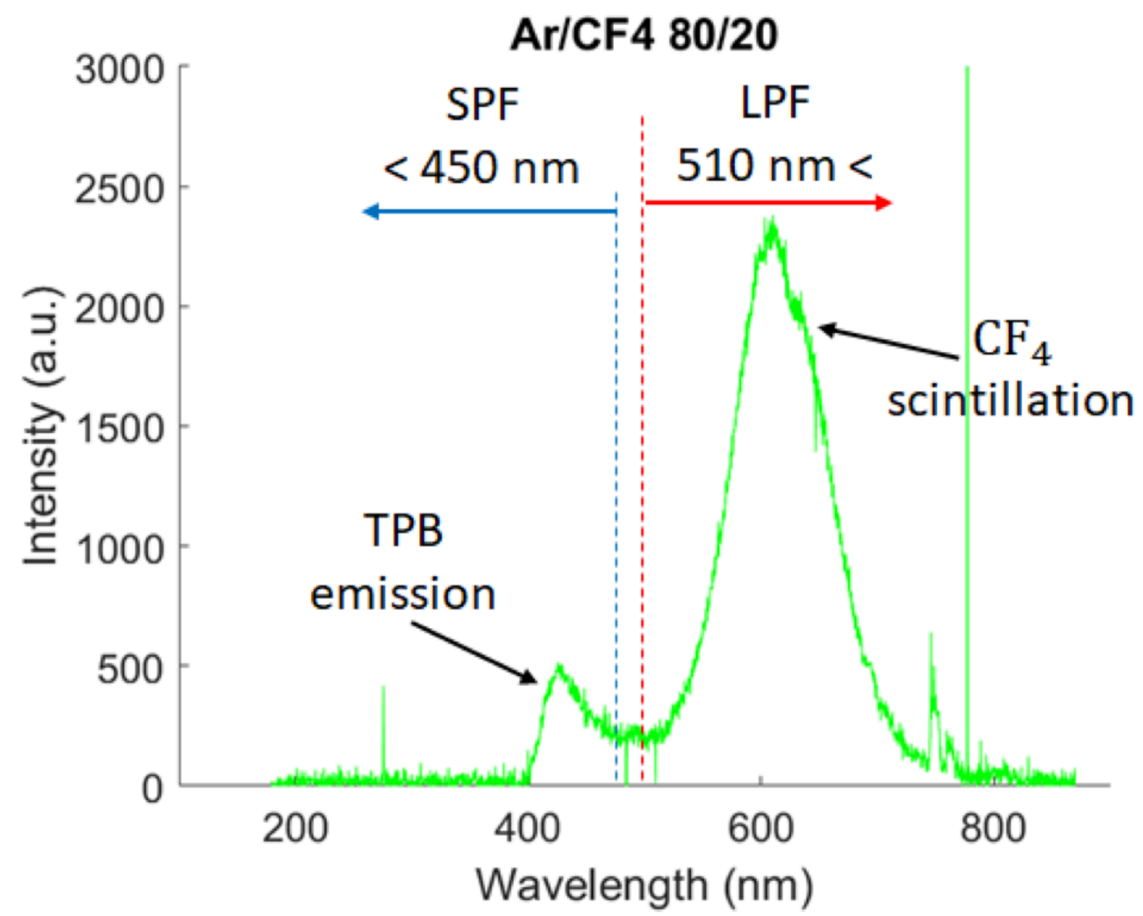
Spectroscopic measurement to quantify light re-emission from TPB layer located below amplification structure.





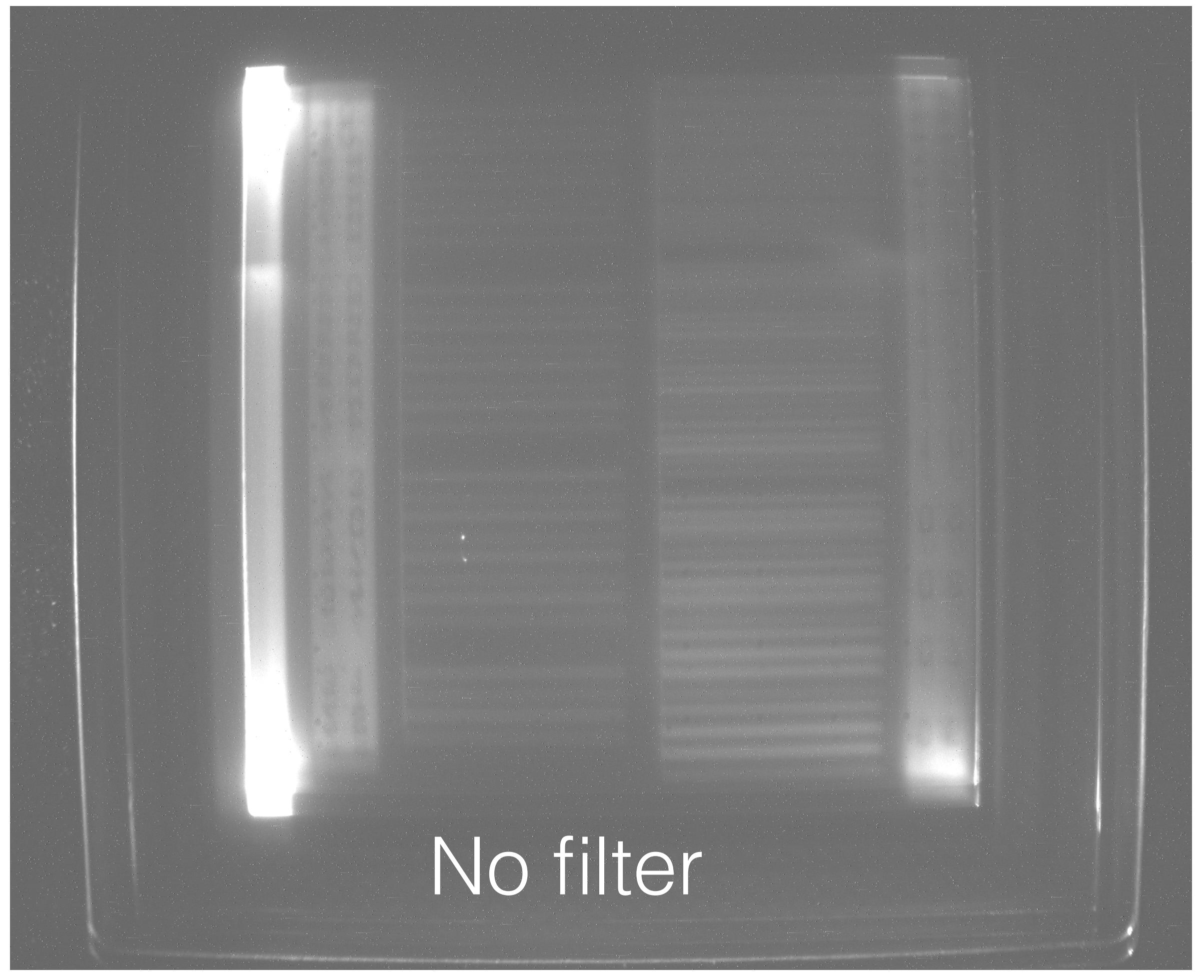
Schematics not drawn to scale

Extraction of edge profile

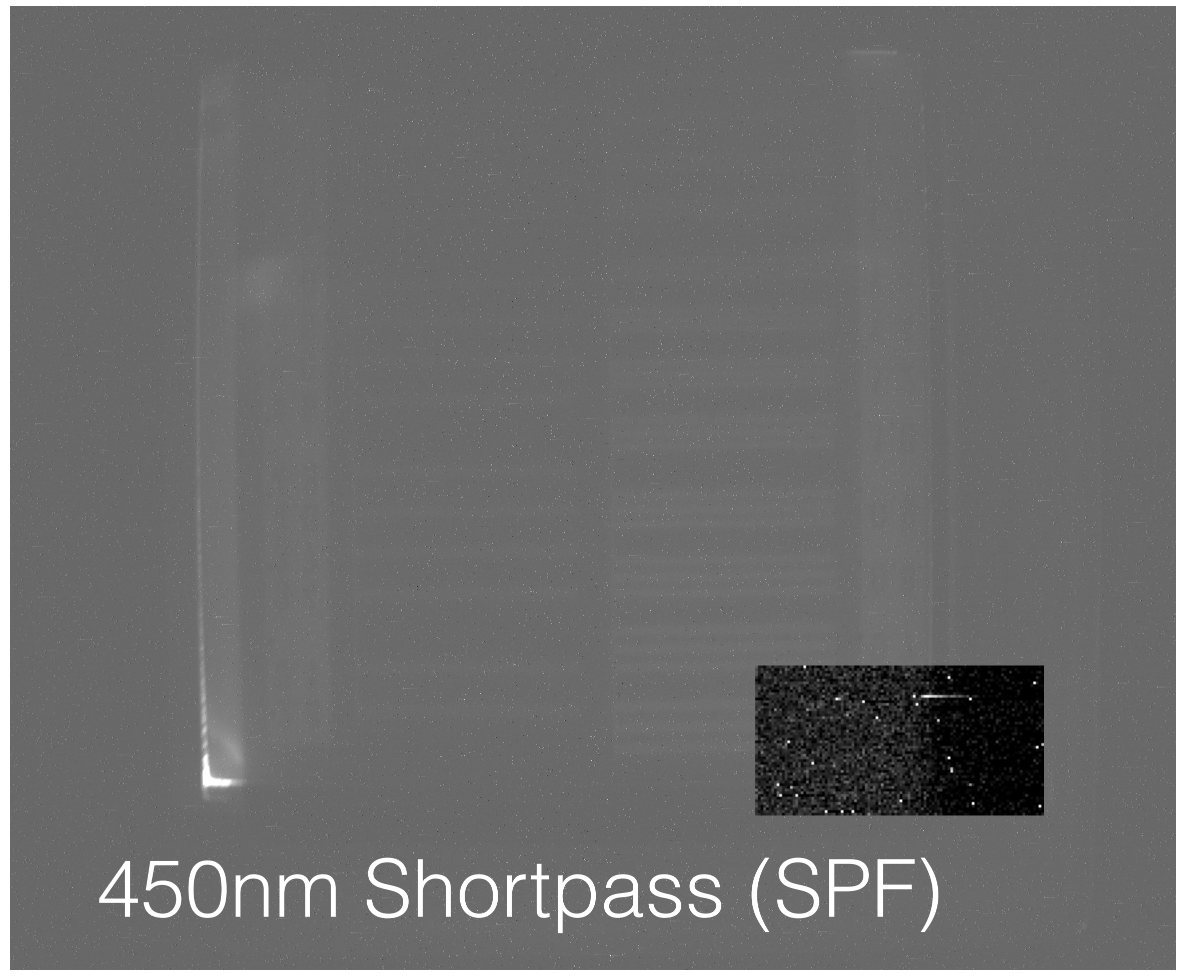


Edge-spread-function (width of edge) used to quantify image sharpness.

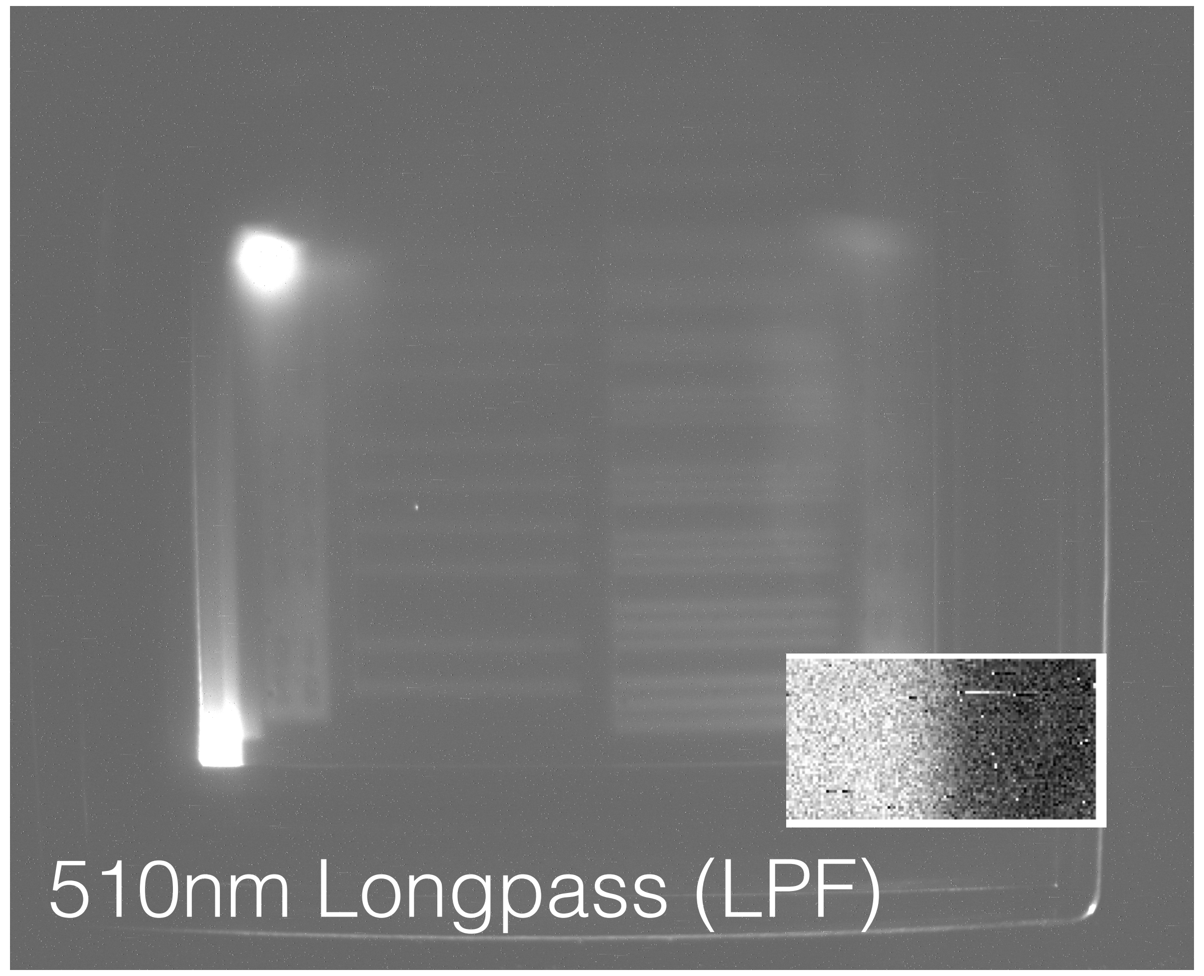
Imaging was performed in Ar/CF_4 and a **450nm shortpass filter** and a **510nm longpass filter** were used to separate re-emitted and transmitted light components, respectively.



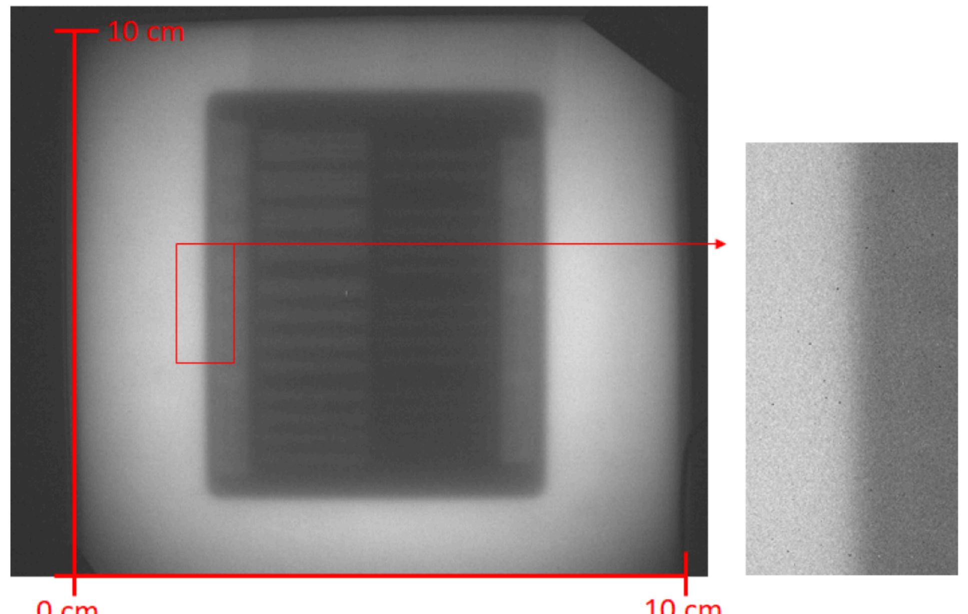
≈

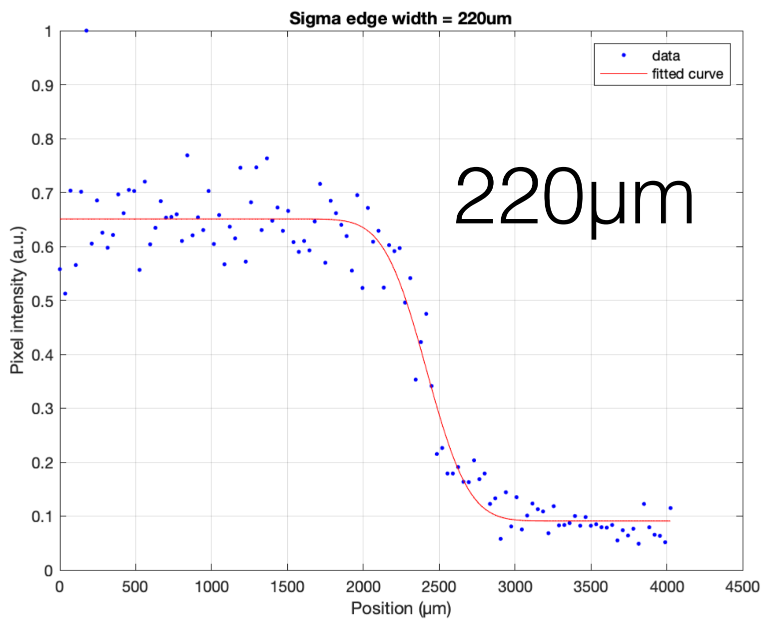


+

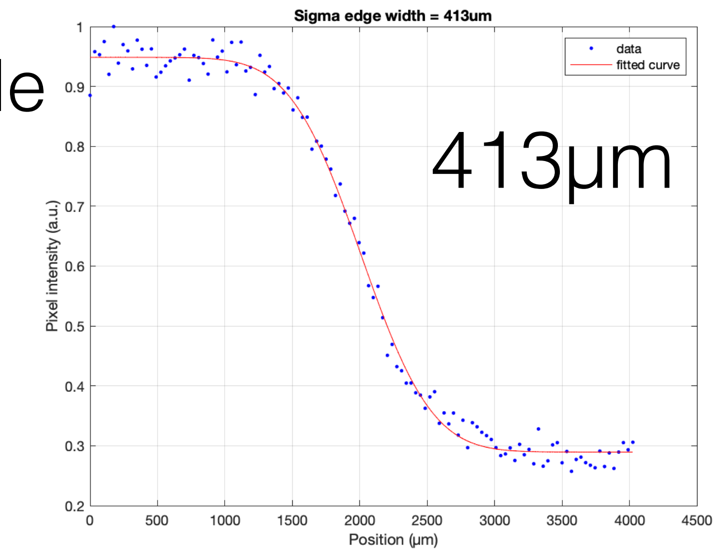


Extraction of edge profile at edge with vertical 1D projection

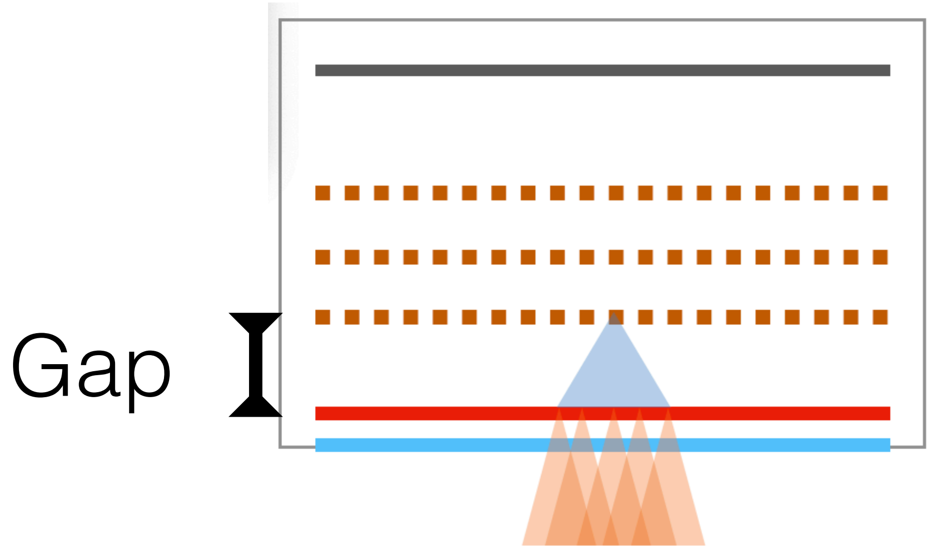




Edge profile



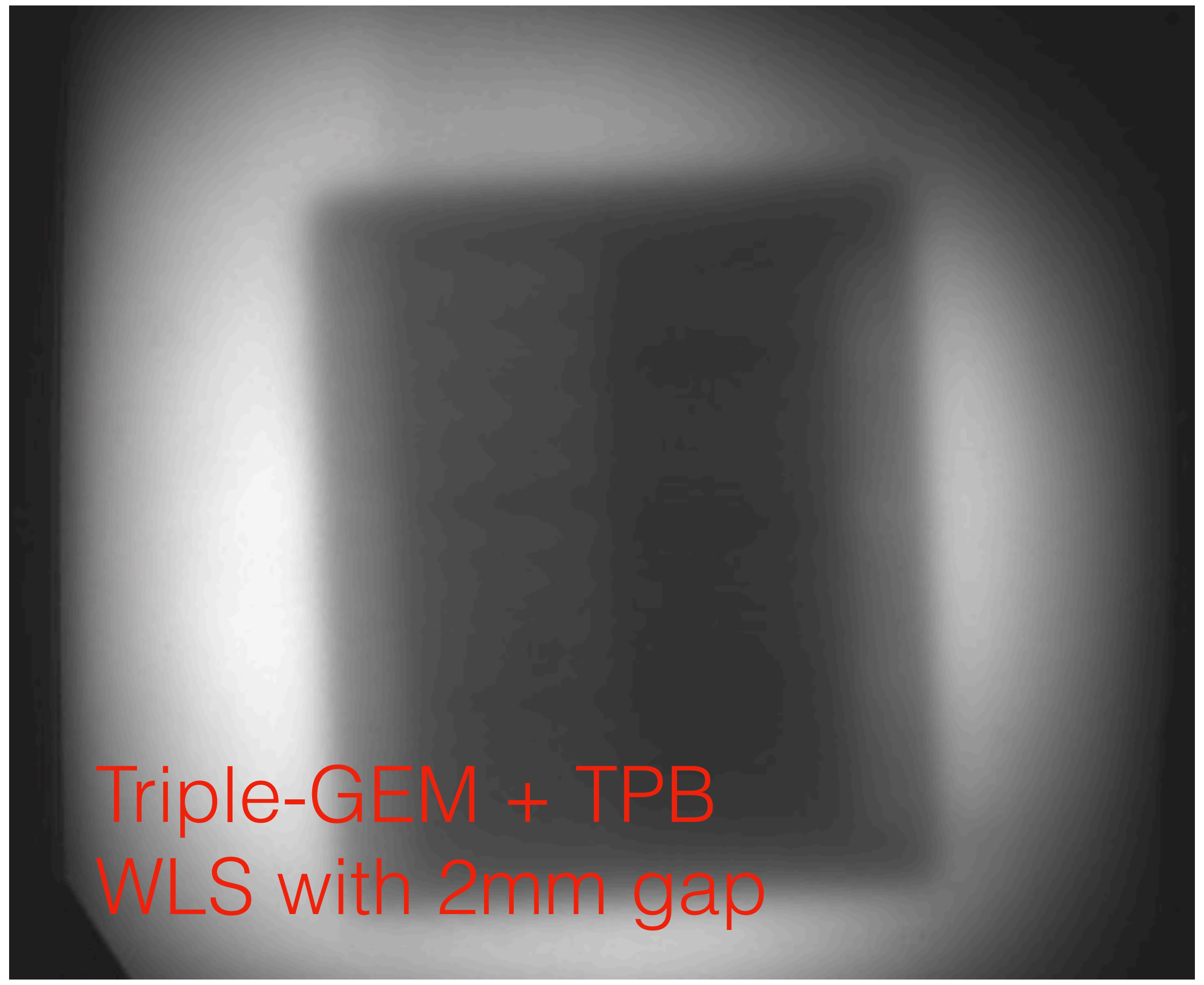
Effect of WLS on spatial resolution

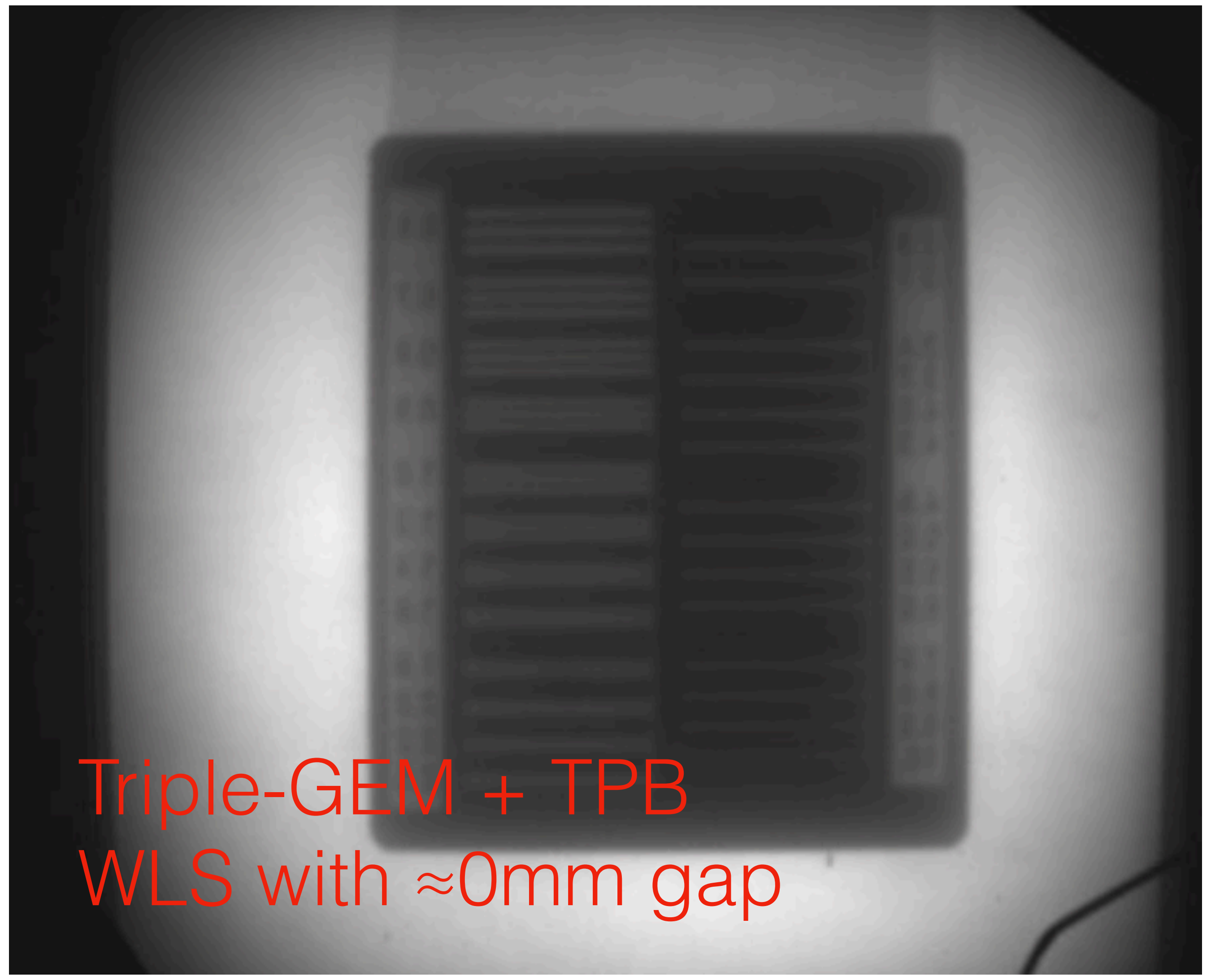


Placing a **solid WLS** on a glass plate at a significant distance from the gain stage results in **image blurring**.

Edge-spread-function (ESF, width of edge) was evaluated for a triple GEM with 0 to 2mm gap between the bottom GEM and the WLS as well as for a **glass Micromegas** which achieved minimal image blurring with an ESF of ≈220µm.

	Gap (mm)	ESF (mm)
Triple GEM	2	2.09
	1	1.43
	0.5	0.80
	0	0.46
Micromegas	0	0.22





J. Nummi, CERN Summer Student Report, https://cds.cern.ch/record/2887384/files/SummerProjectReport_Nummi.pdf

Ar/CF_4 80/20% with 450nm shortpass filter

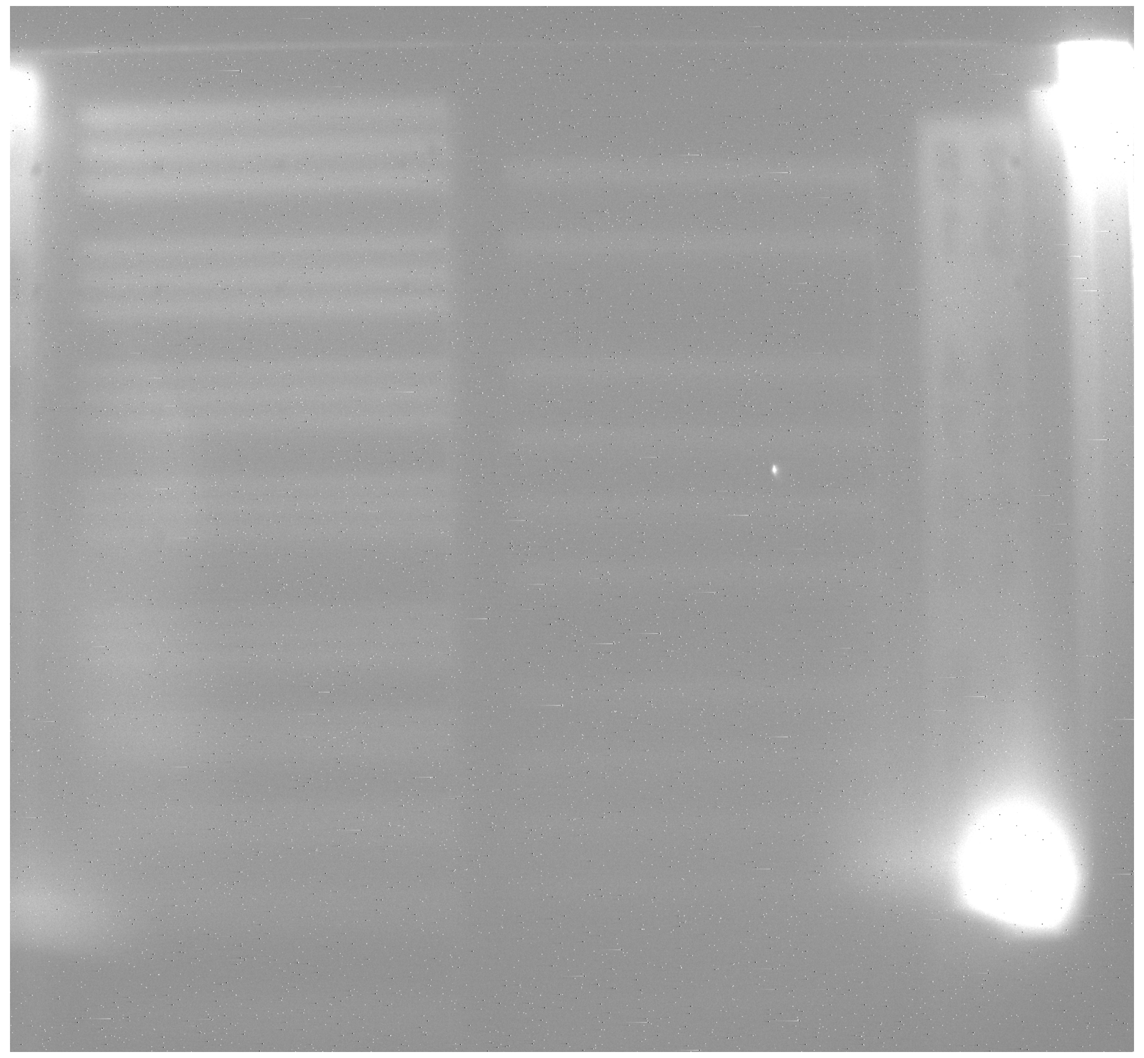
Schematics not drawn to scale

Charging up of TPB on ITO

TPB exhibits long term **charging up** behaviour and preserves a **negative image** of a previously placed line-pair mask even when the mask is removed.

Within minutes of flat field irradiation, intensity of retained image fades and eventually disappears.

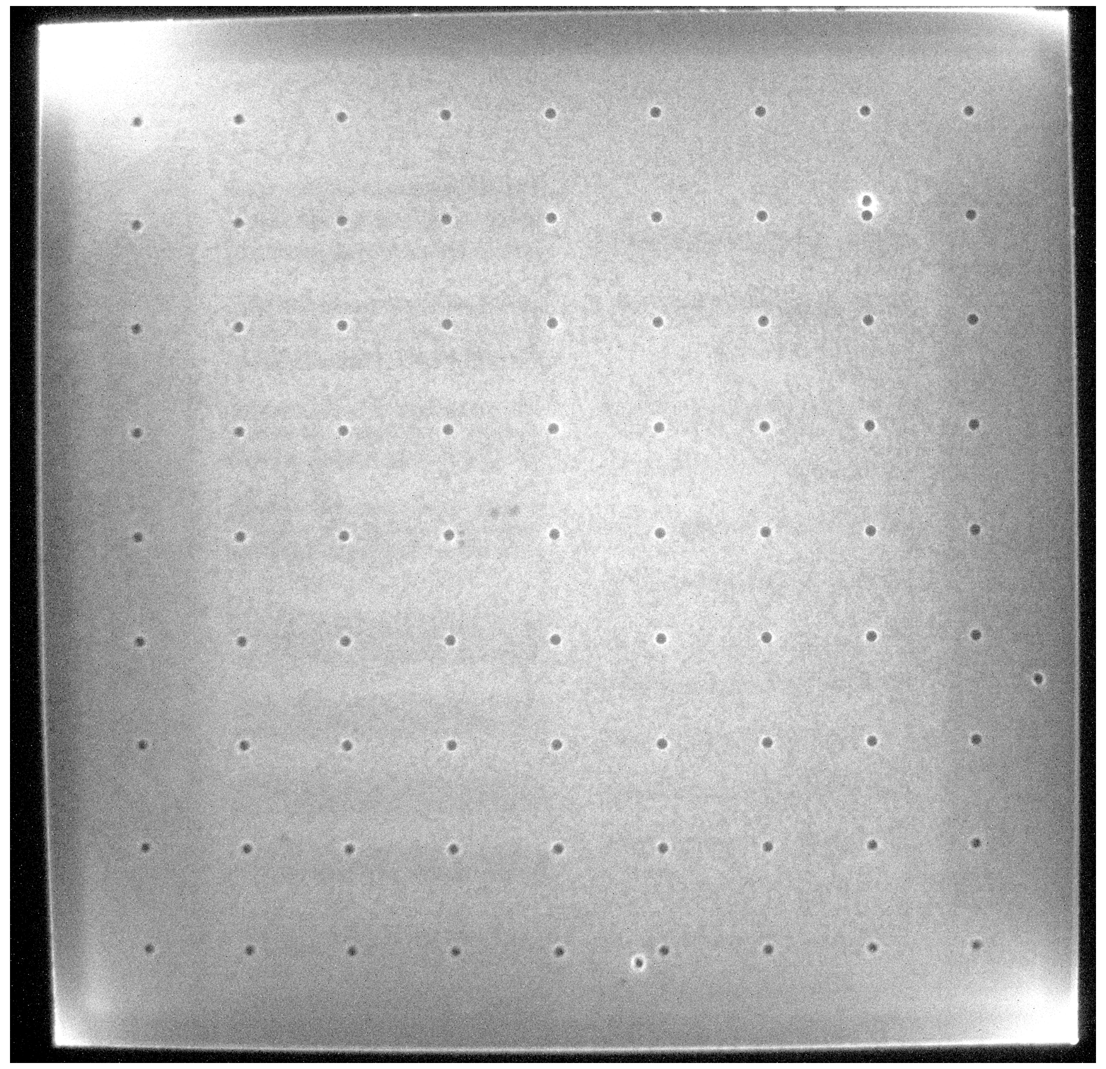
Image recorded with mask



Detector off for 2 days

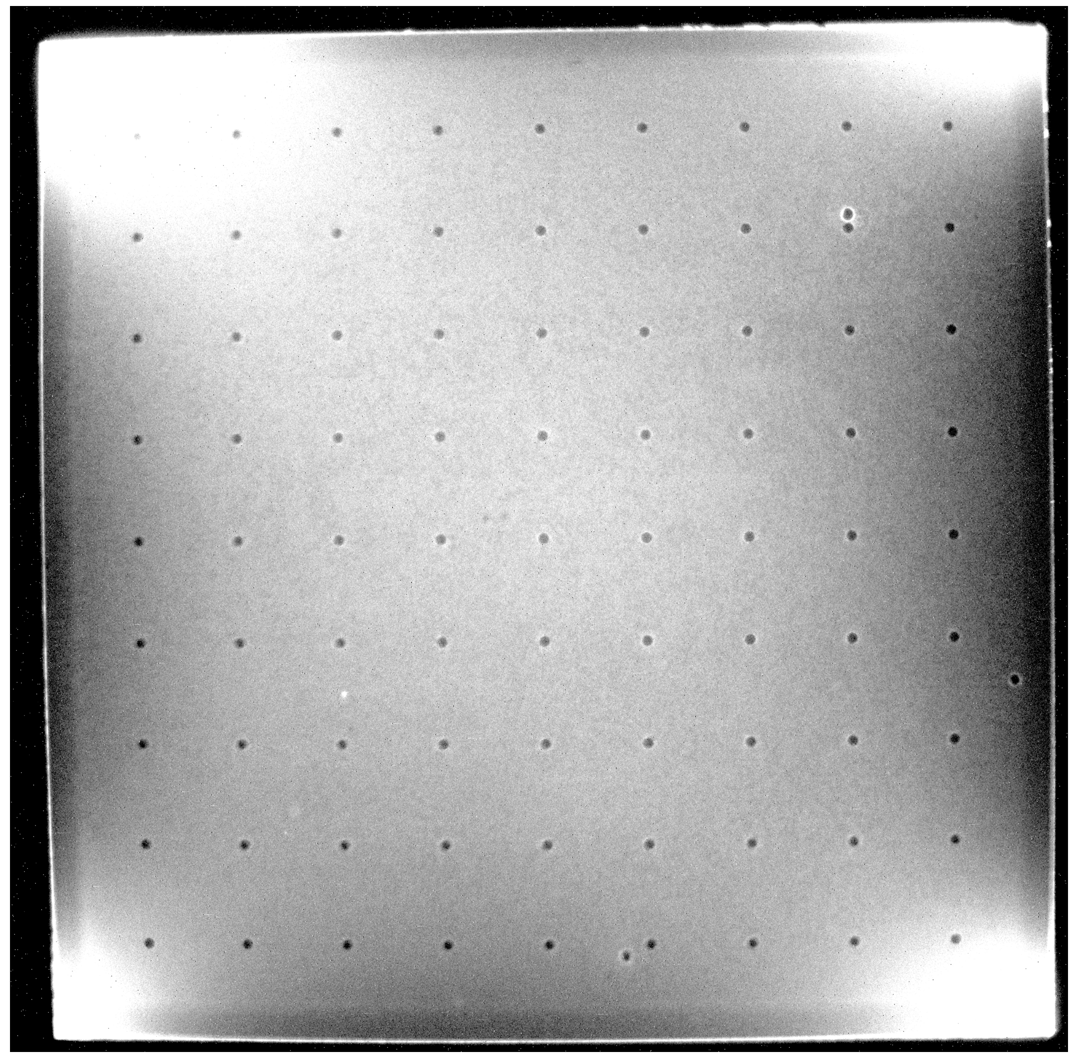
Mask removed

Detector off for 2 days
No mask placed → negative image retained



5min
X-ray

After irradiation
for ≈5min



2 days off

5min irradiated

Ar/CO_2 80/20%
TPB on ITO glass with pillars

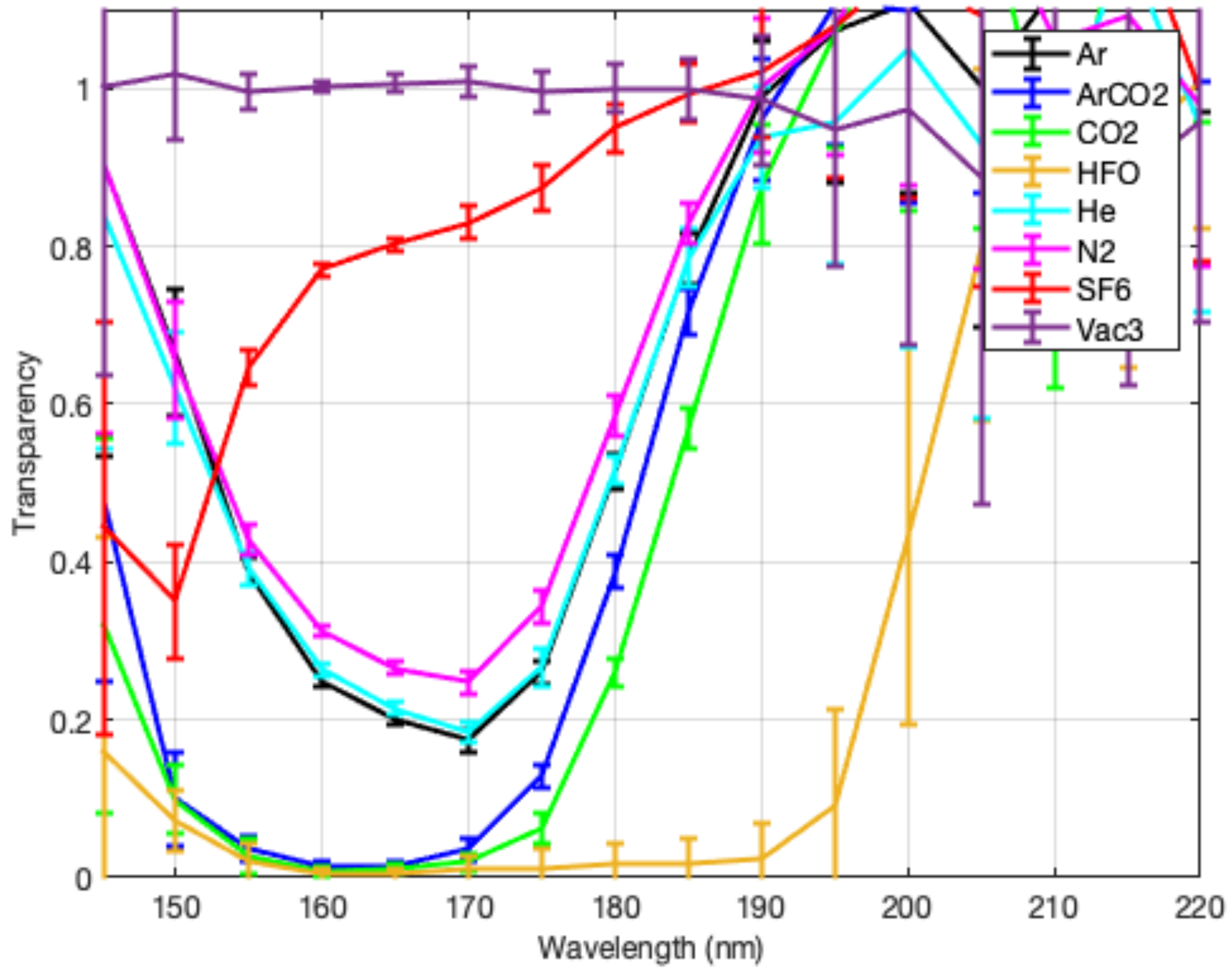
Gas transparency

Transparency of gases to light emitted during avalanche multiplication determines their efficiency as quencher.

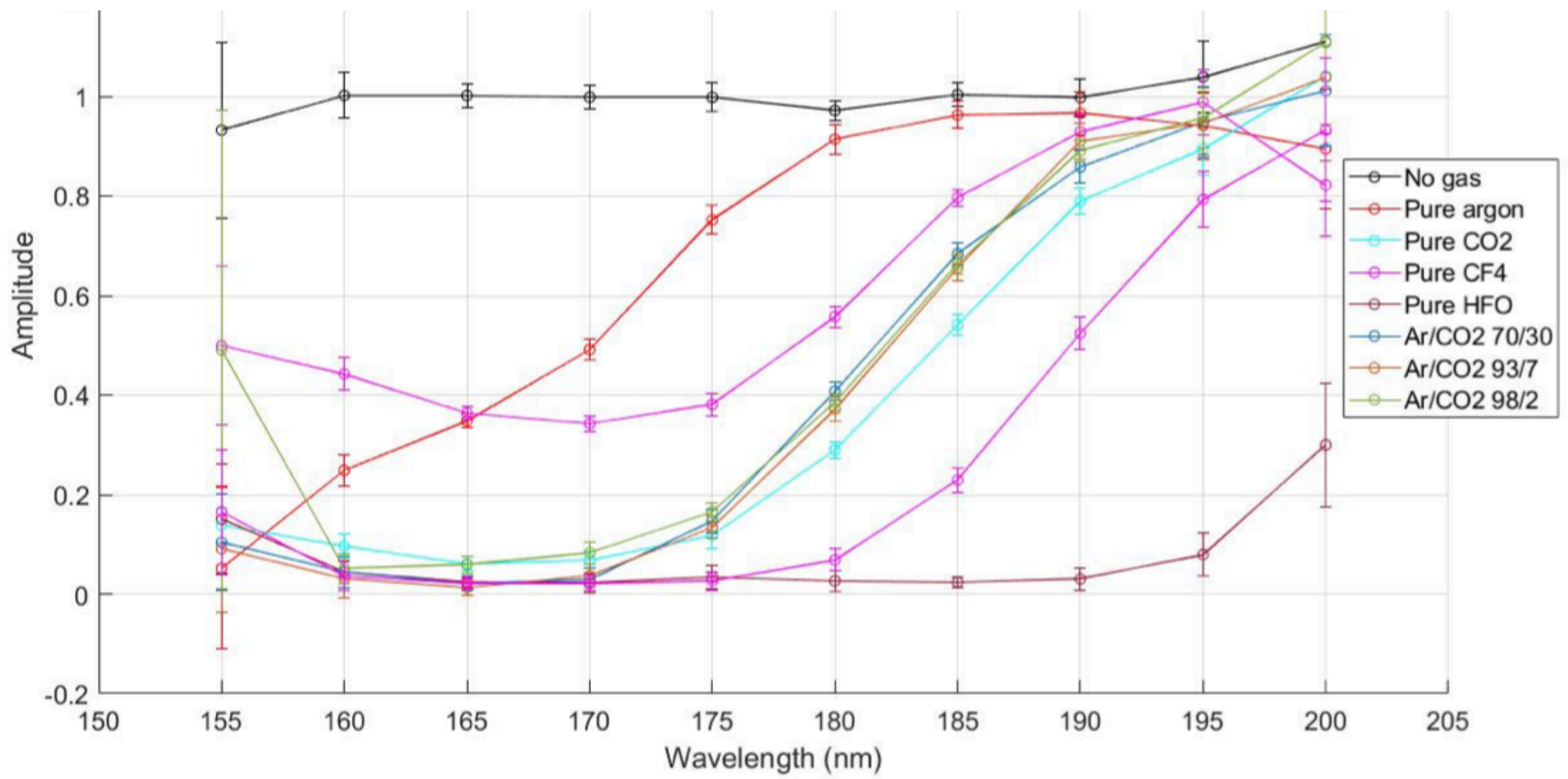
While strong **UV absorption** is advantageous for strong quenching properties, it may absorb scintillation light thus making optical readout impossible.

Structures with **minimal distance** between scintillation light emission and a solid wavelength shifting layer may be suitable to shift scintillation light from UV to VIS where gases are highly transparent.

VUV transparency of pure gases at 1bar



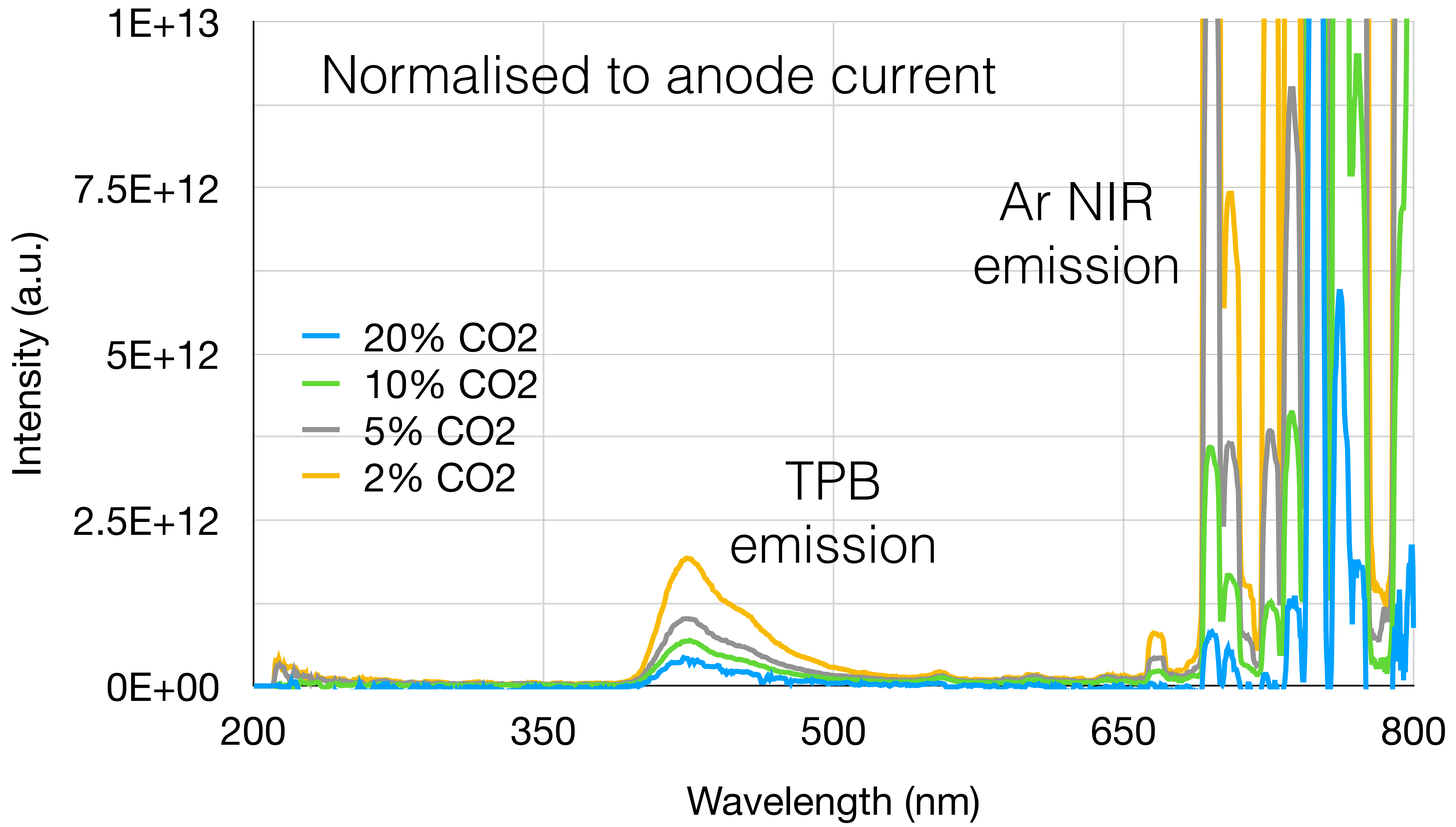
VUV transparency of Ar/CO_2 mixtures

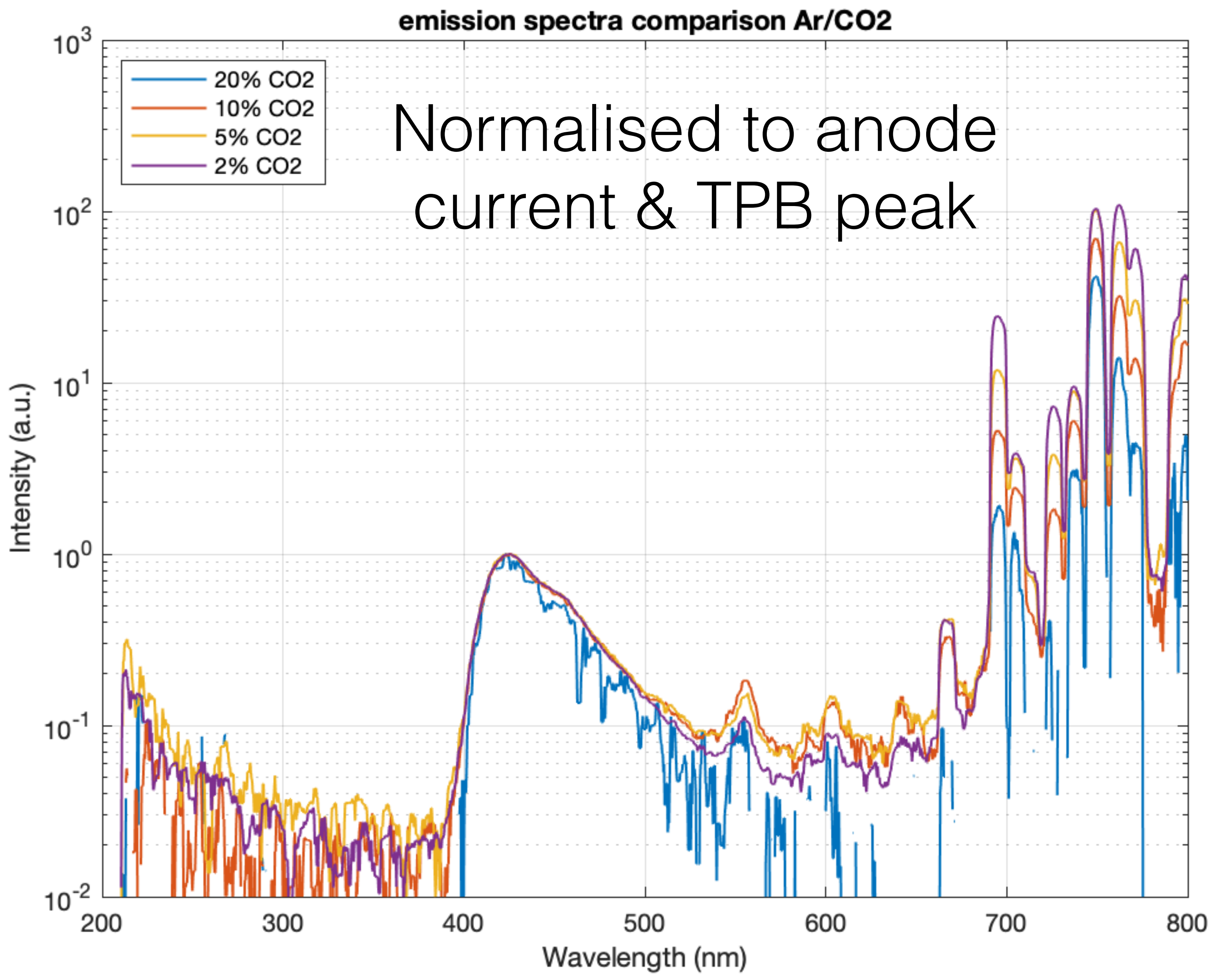


VIS emission from Ar/CO_2 with TPB

Operation in Ar/CO_2 shows UV emission which is absorbed and **re-emitted by TPB** and **strong NIR emission lines** of Ar

With decreasing Ar fraction, relative intensity of NIR lines is observed to decrease.





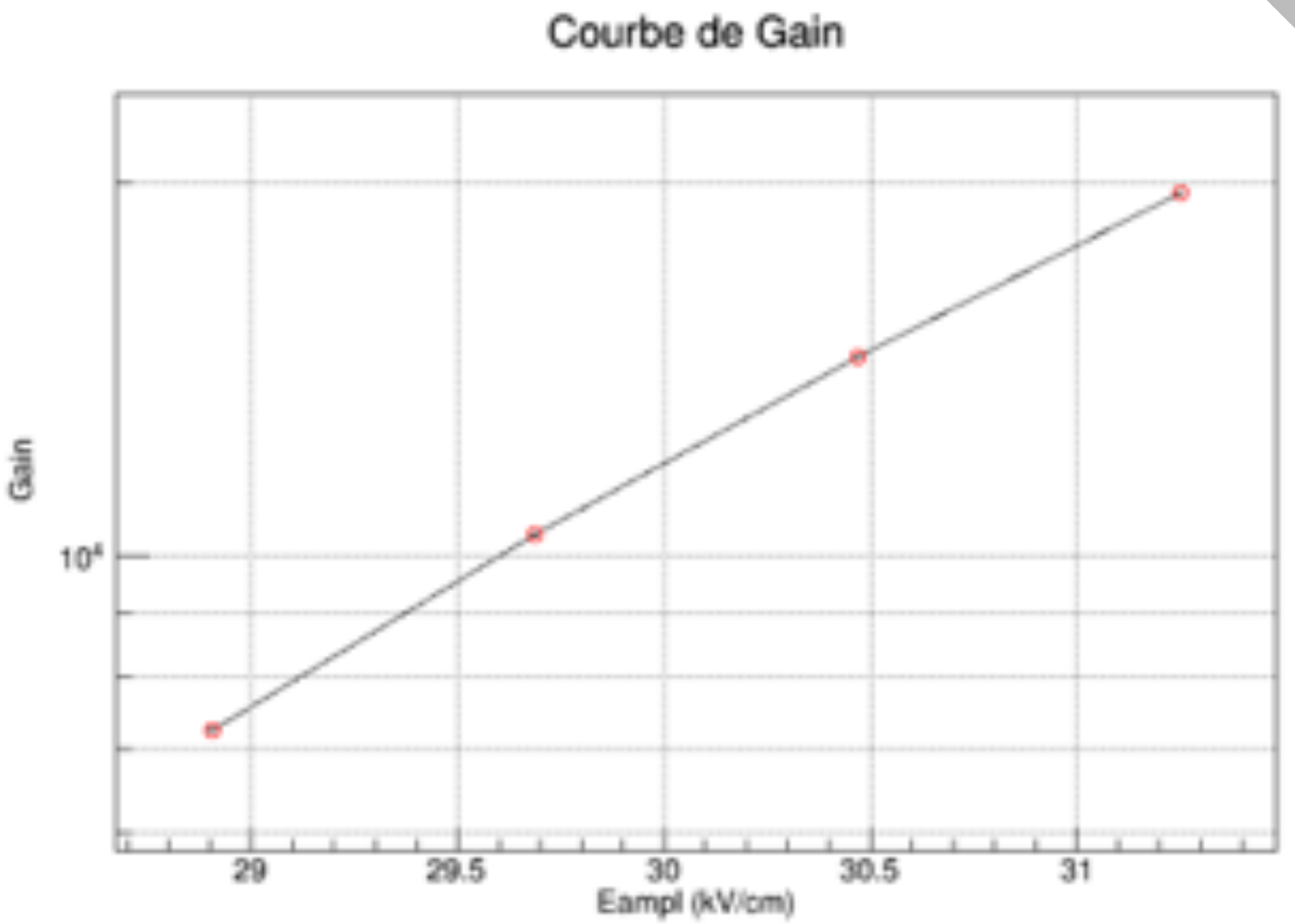
Triple GEM, 2mm drift, 0.5mm gap to TPB, current collected on GEM3B, 1800V on divider, dV=200V drift, ≈260-350V on GEM3B
20kV, 30mA X-ray, 10x 30s exposure, AVG, BG subtracted, calibrated, Varying CO2 content in Ar/CO2, 5l/h flushing

Preliminary

Alternative gas mixtures

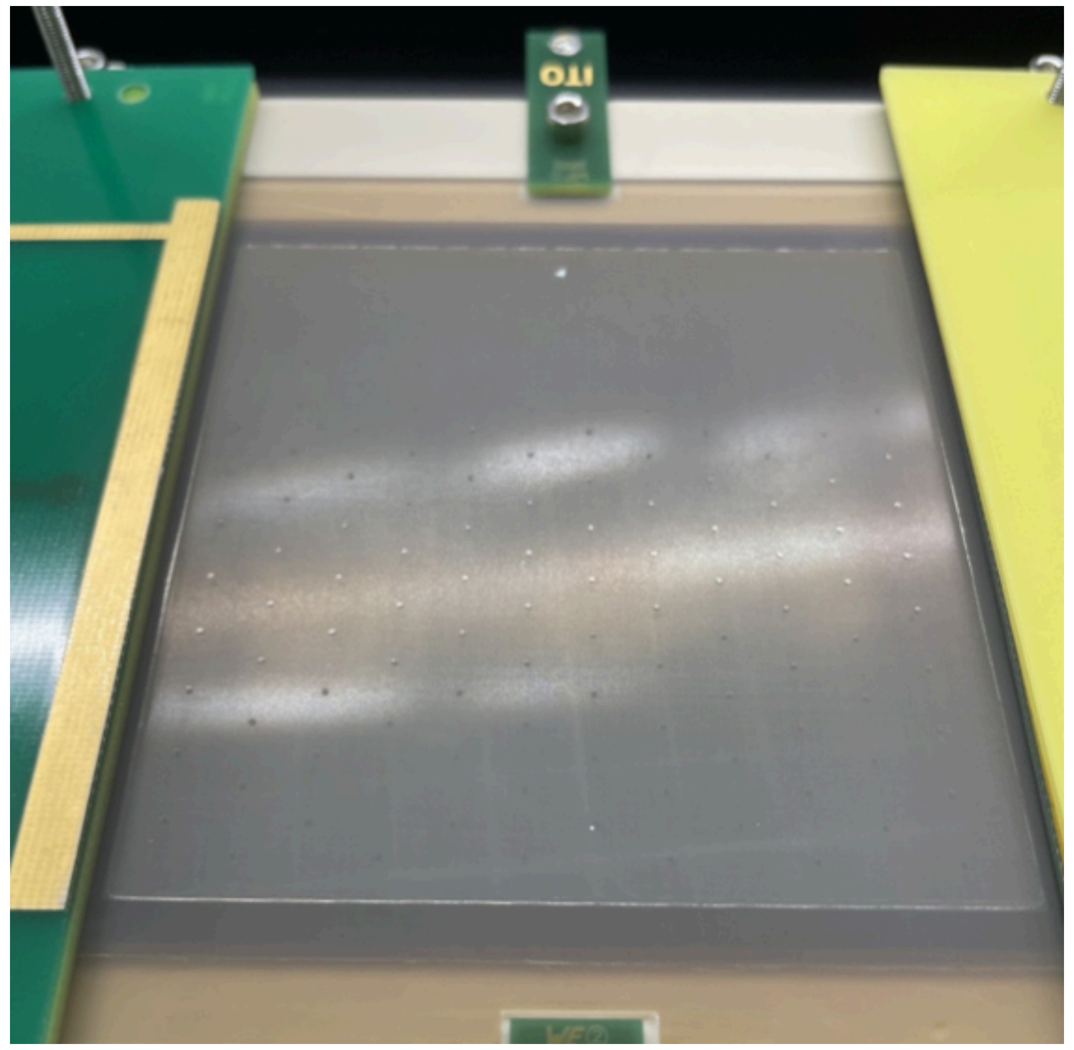
Ar/isobutane (95/5%) mixture achieves **high gain** and light yield of ≈0.2 photons / electron

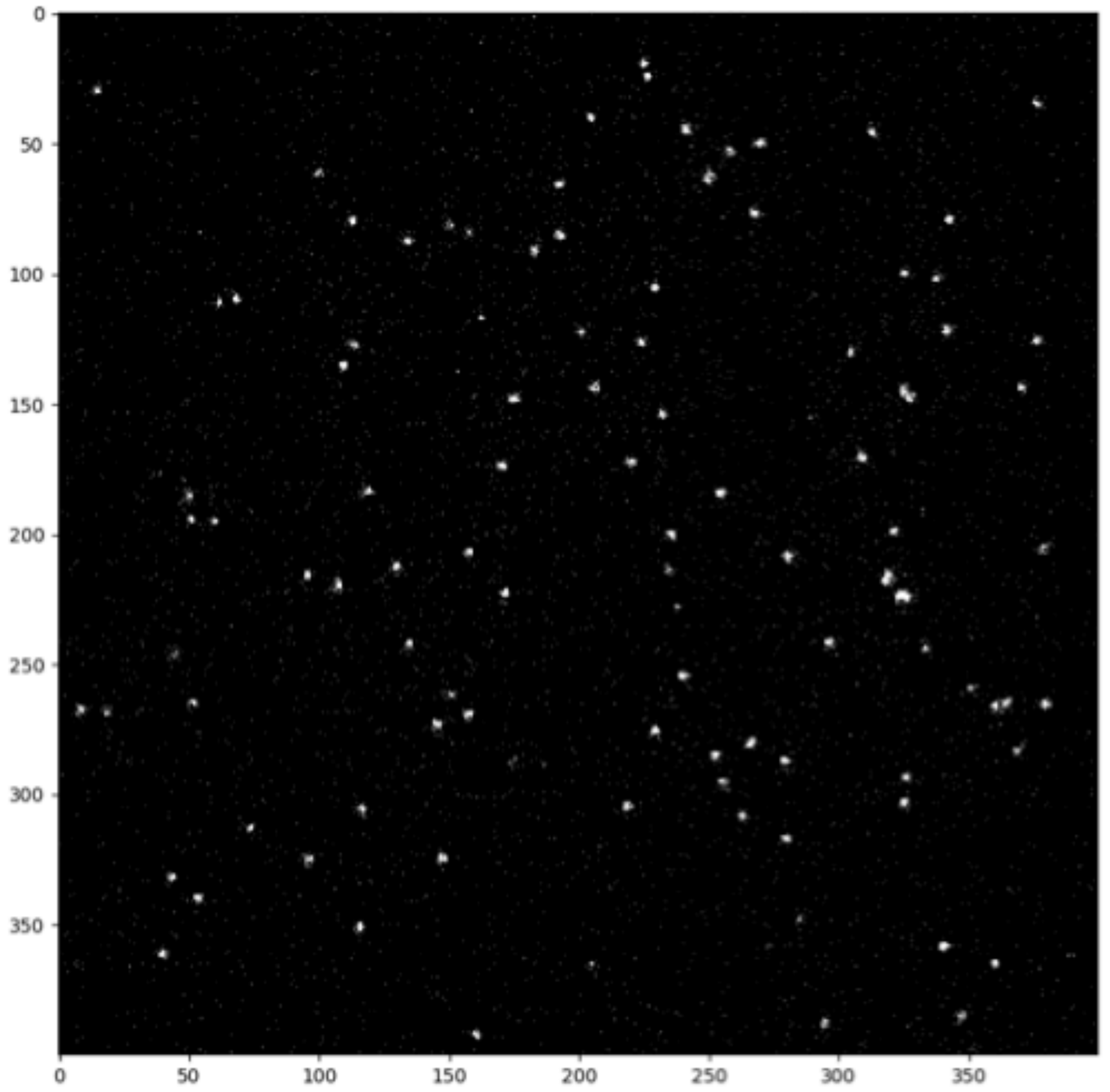
Lower light yield compared to Ar/CF4 but high gain >10^4 achieved allows for higher absolute light amount

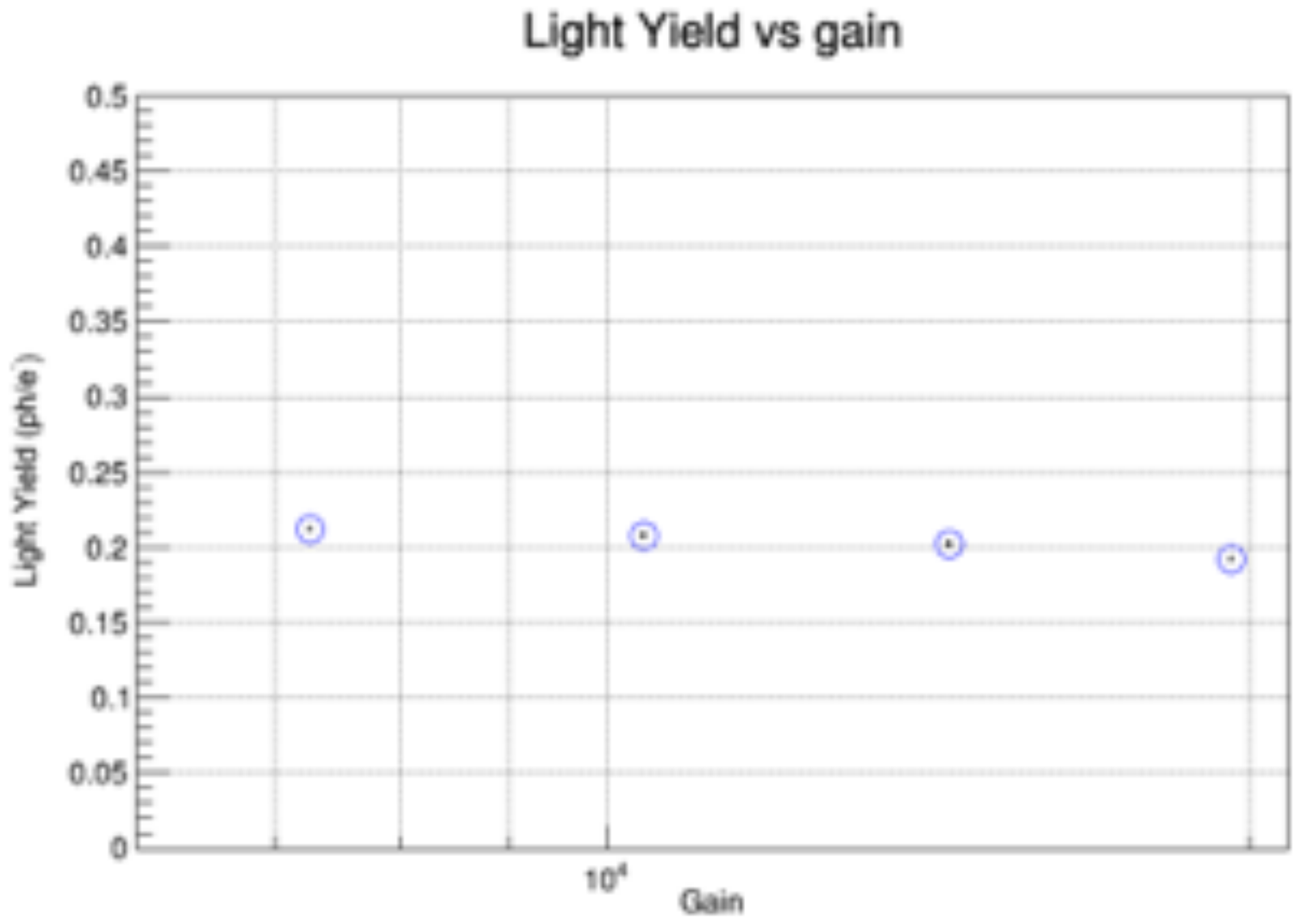


Glass Micromegas with TPB evaporated after bulking

Single **^{55}Fe event sensitivity** achieved which allows for image reconstruction with COG algorithm and spectra imaging.





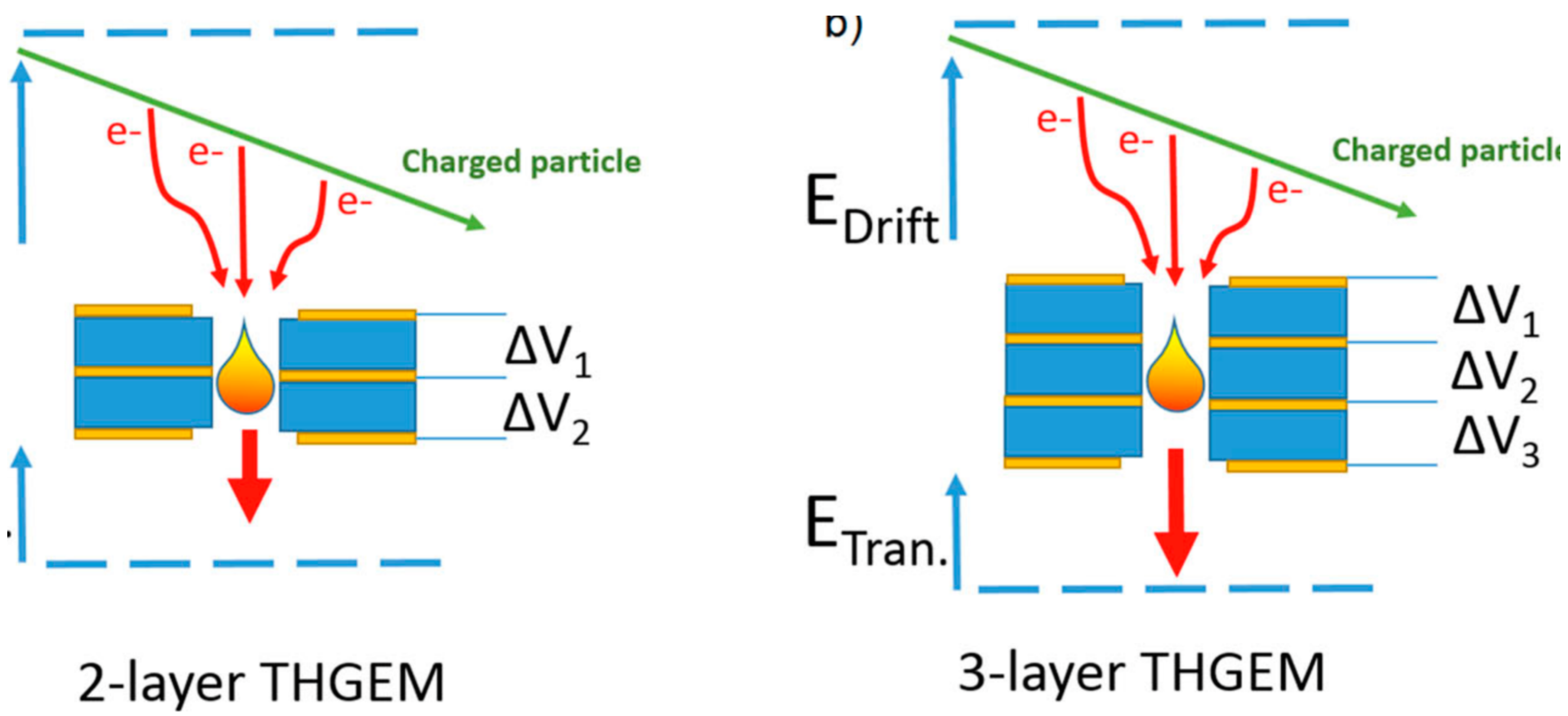


A. Cools, CEA Saclay, PhD thesis, 2024

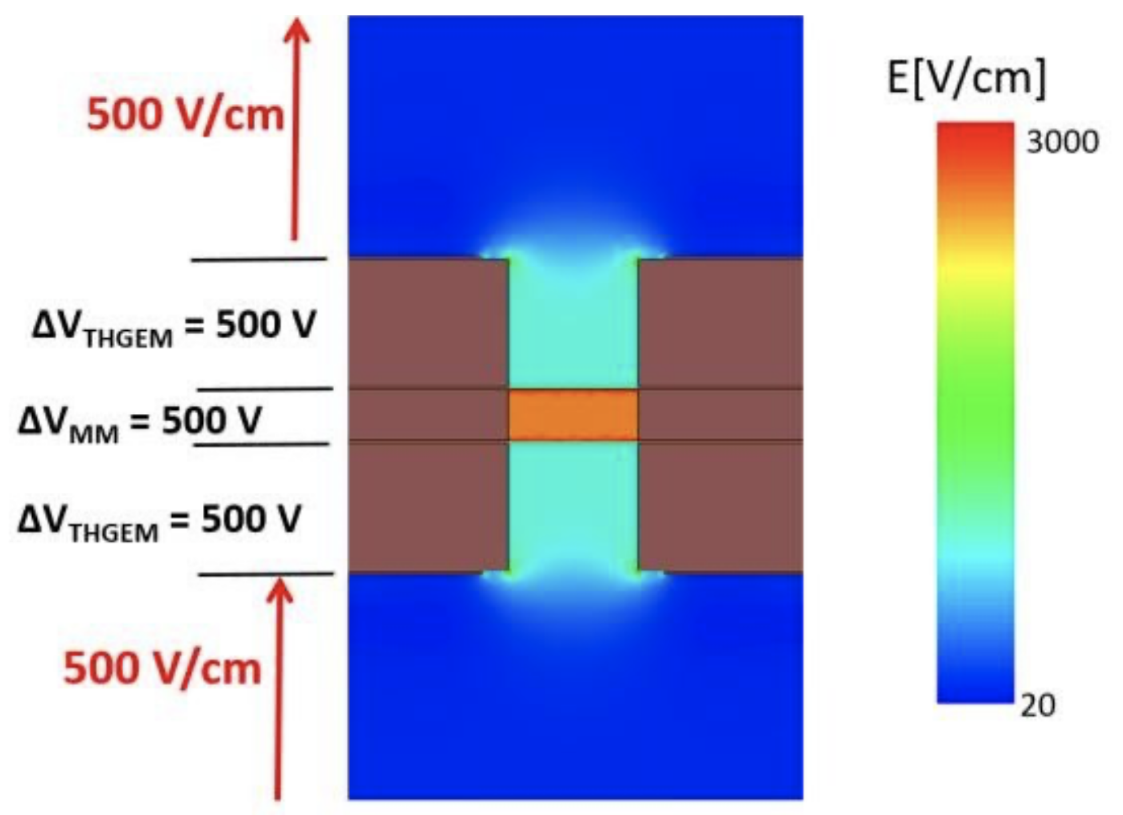
(M)M-THGEMs for pure noble gas operation

Conversion efficiency of solid WLS in pure noble gases can be evaluated with gain structures optimised for minimal feedback. **M-THGEM or MM-THGEM** structures allow for **geometric confinement of avalanches** in long hole-type amplification geometries and can sustain high gain operation even in **low pressure** conditions and **pure noble gases**.

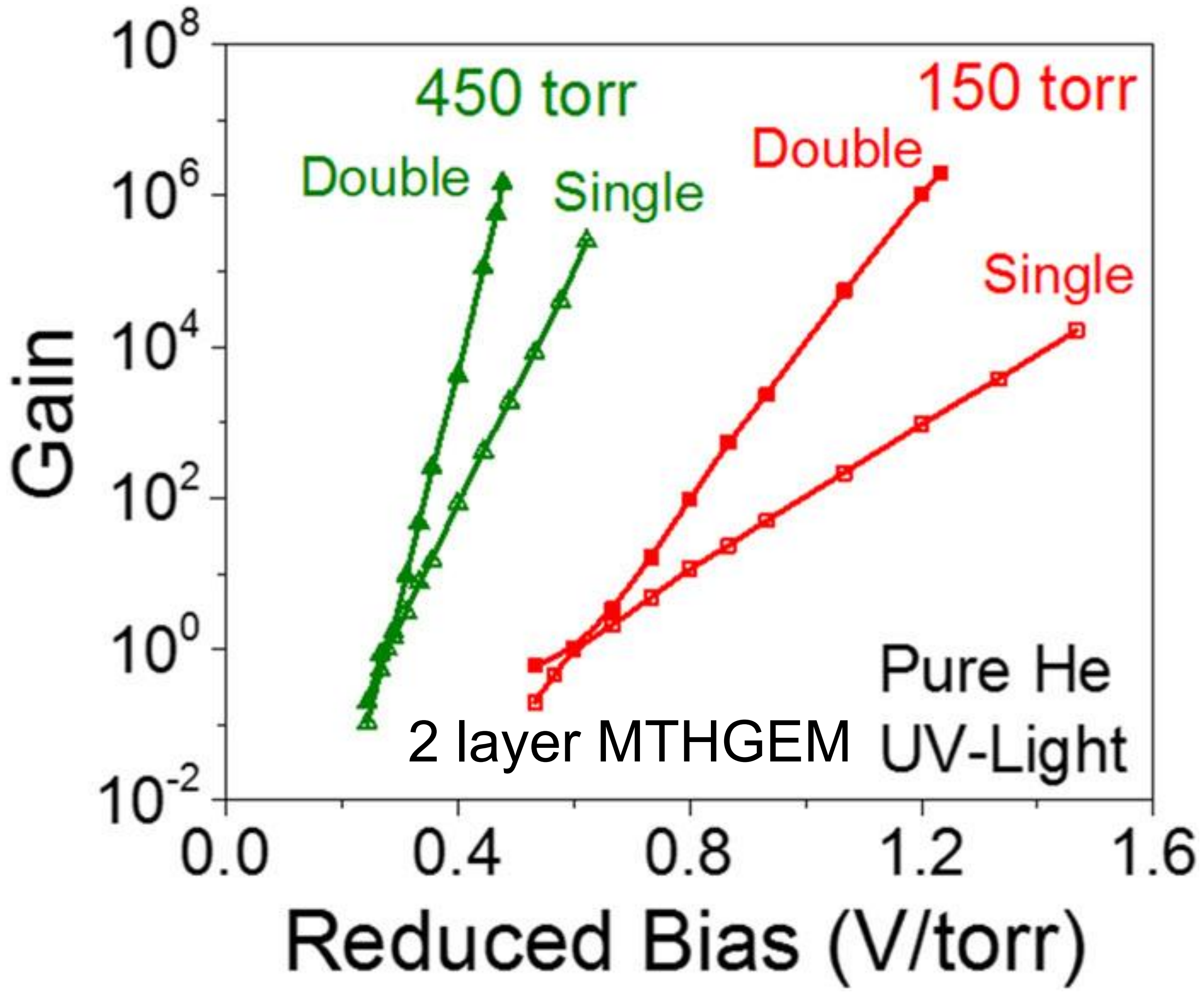
M-THGEM or "Super-GEM"



MM-THGEM with mesh



High gain achievable in pure noble gas



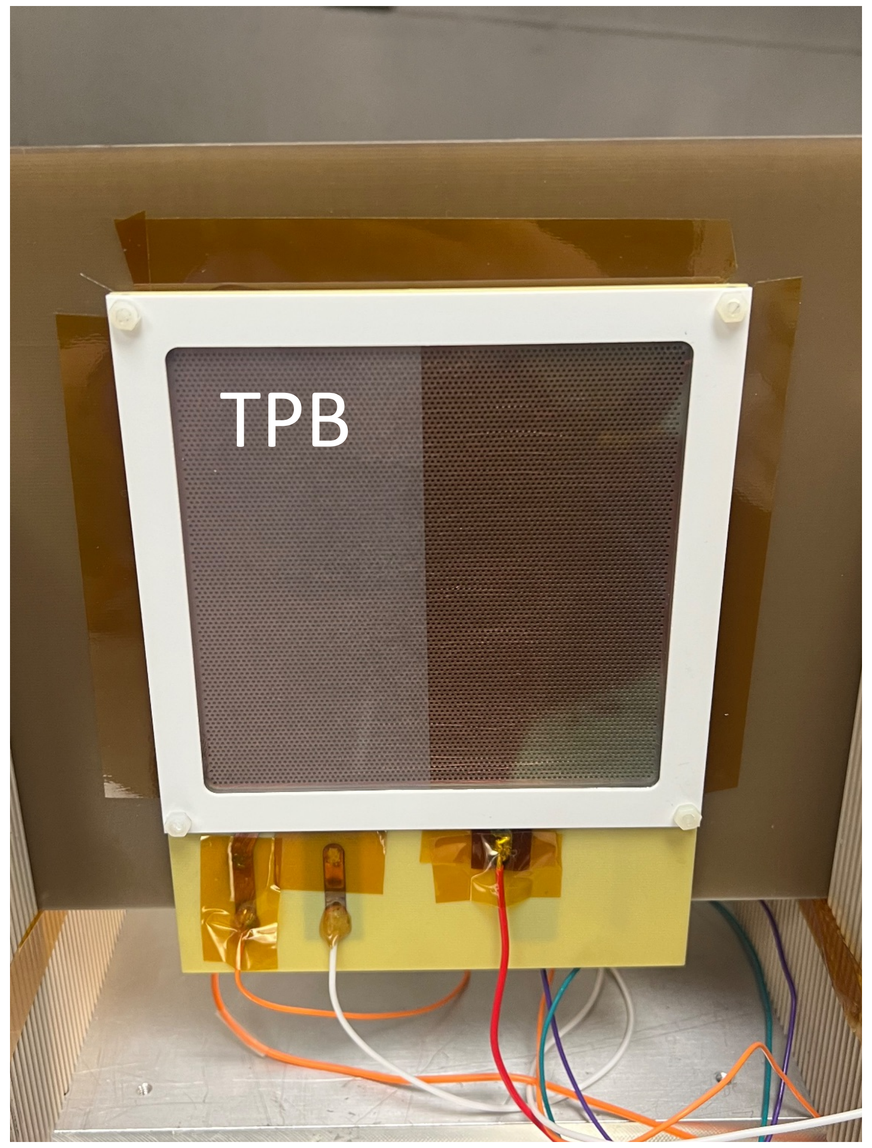
M. Cortesi et al., https://pubs.aip.org/aip/rsi/article/88/1/013303/367603/Multi-layer-thick-gas-electron-multiplier-M-THGEM

Schematics not drawn to scale

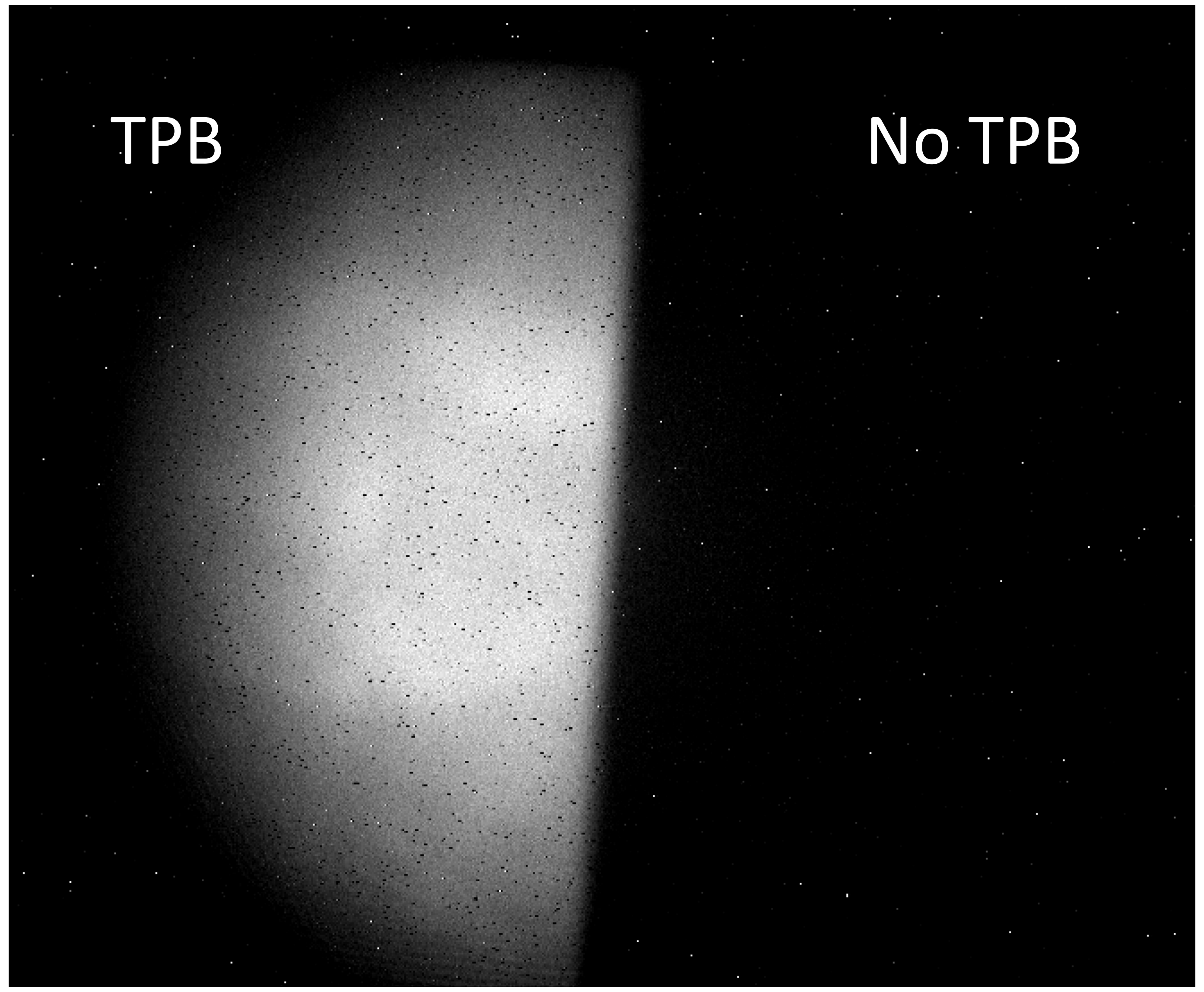
Pure Ar operation of MM-THGEM

Secondary scintillation in **pure Ar** features emission peak around 125nm and NIR emission. Vacuum-UV emission emitted from a **MM-THGEM** in **low pressure pure Ar** was converted with solid TPB layer coated on glass substrate.

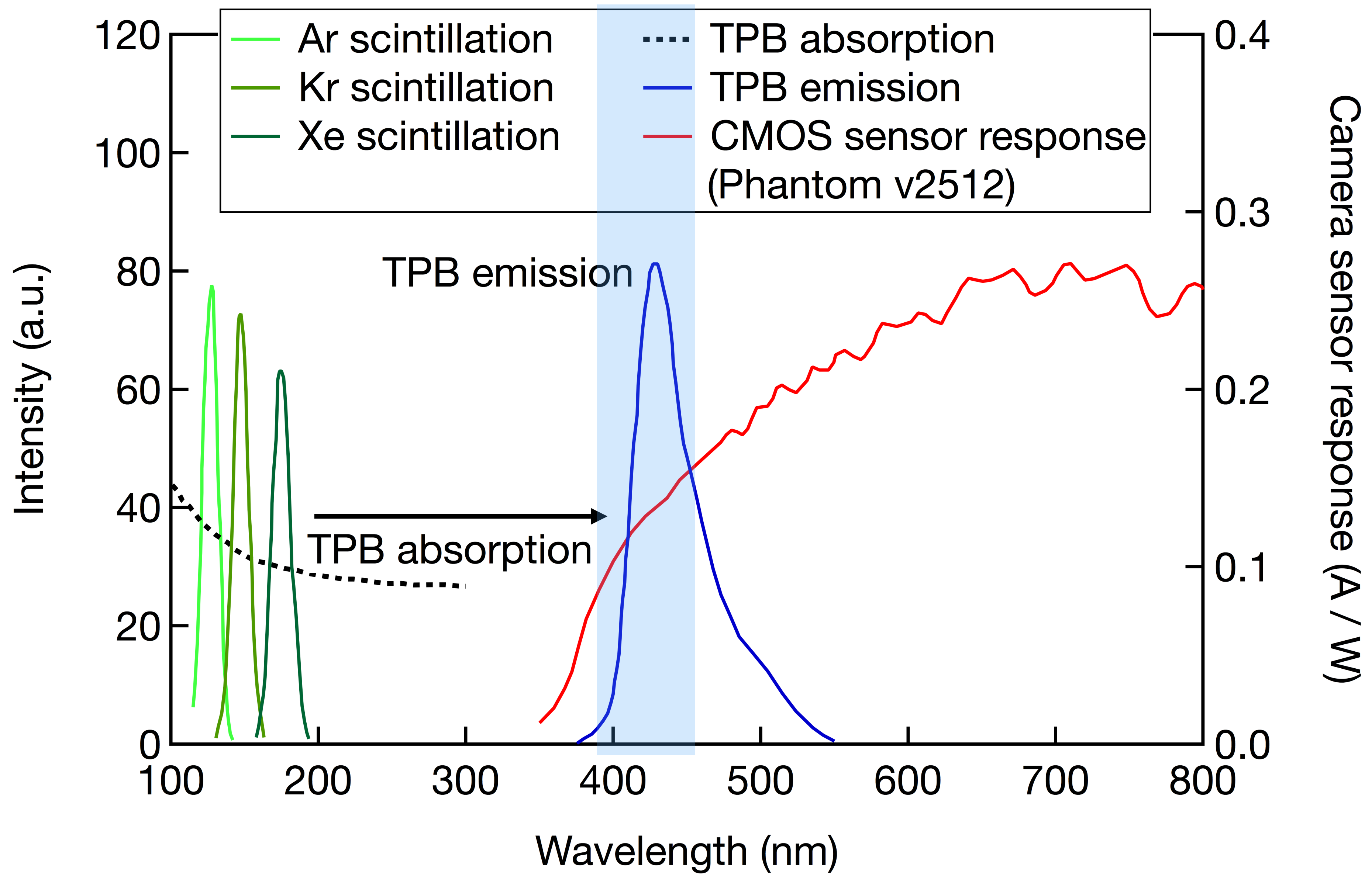
A **450nm shortpass filter** was used to verify that observed light was originating from WLS (higher WL cutoff by SPF, lower WL cutoff by glass substrate).



200 torr Ar
Thin TPB as WLS - half coated MM-THGEM



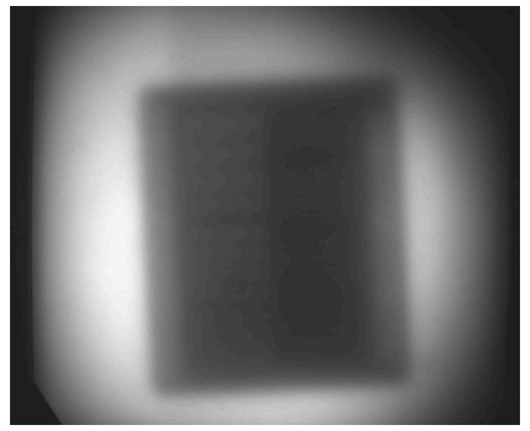
Shortpass filter 450nm

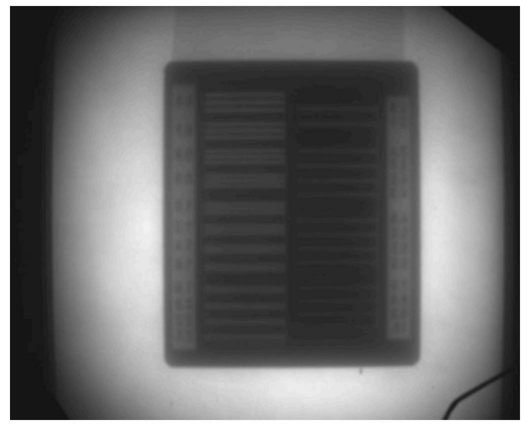


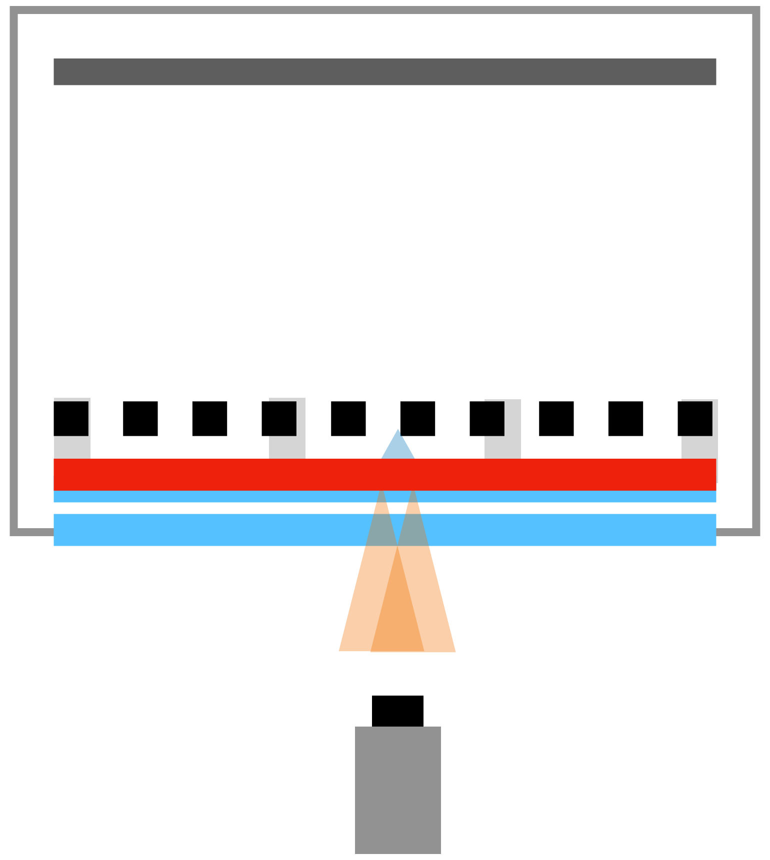
Summary and outlook

Effect of WLS on spatial resolution

Solid WLSs can be used for high resolution optical readout. **Minimal distance** between gain stage and WLS is optimal for spatial resolution → **integration in Micromegas** is advantageous. Evaporation on bulk Micromegas works and achieves <500µm edge width.

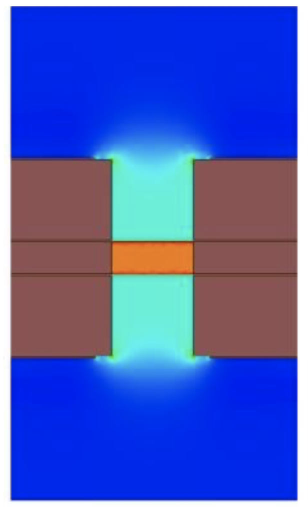


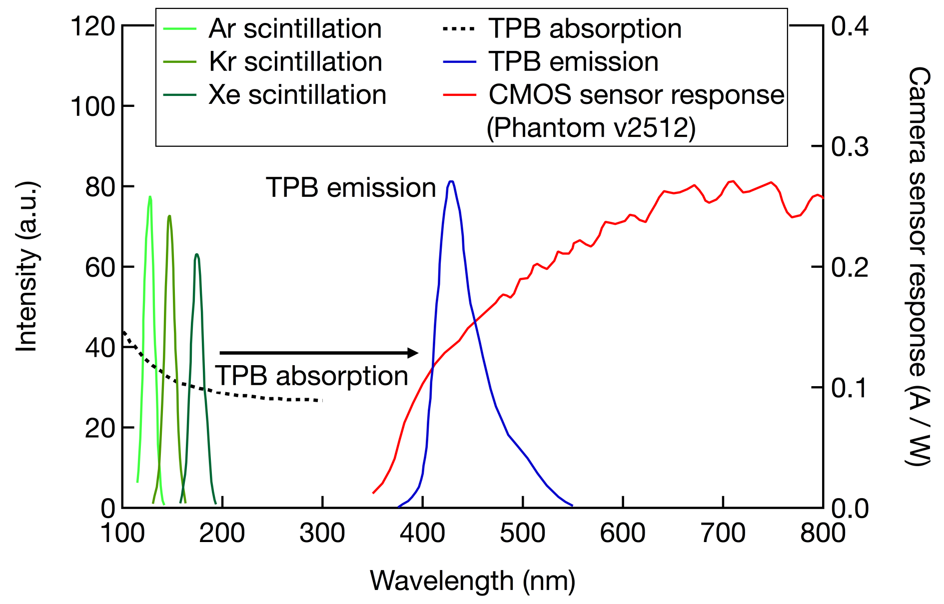


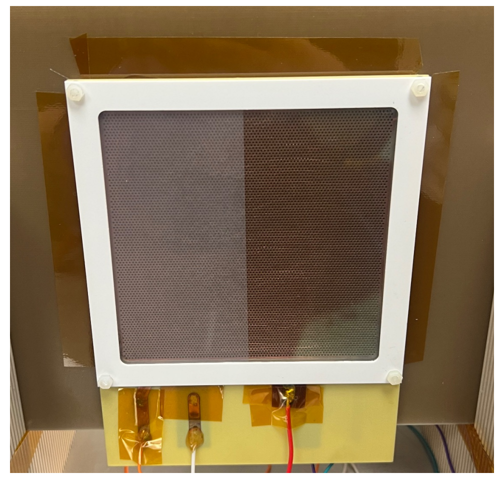


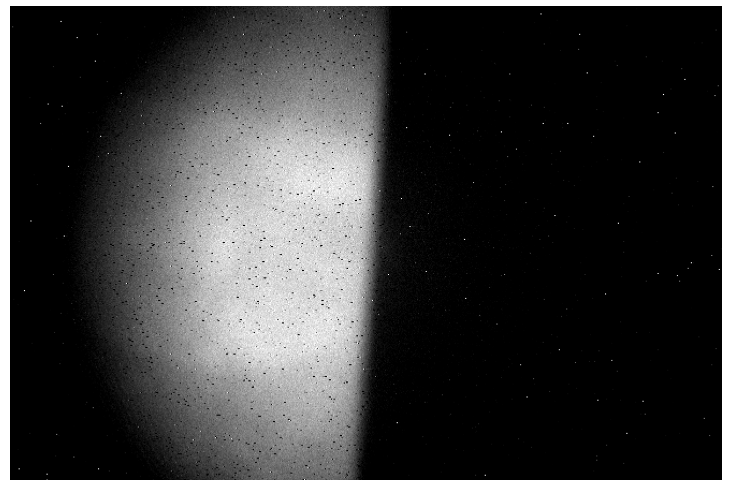
Pure noble gas operation

Long THGEM-like gain structures can achieve **stable high-gain operation** in pure noble gases even at low pressure. Significant light emission in **pure Ar** with **TPB** observed. Strong emission observed also in **NIR** range.









Next steps

Pure gas operation with hole-type multipliers or hybrid THGEM+MM structures for improved spatial resolution.

Operation in environmentally friendly gases and **quantification of achievable light yield**. Spectroscopic verification of direct scintillation light emission and re-emission from WLS of novel gases and mixtures.

Track imaging with WLSs in low-pressure gases.

Evaluation of **conversion efficiency** of alternative wavelength shifters in view of increased robustness and simplified integration with MPGDs.

Schematics not drawn to scale

?