Strategies for improved light detection in noble element radiation detectors

André Cortez
Visiting Scientist at AstroCeNT
Nicolaus Copernicus Astronomical Center
Polish Academy of Sciences
acortez@camk.edu.pl

ASTROCENT

NICOLAUS COPERNICUS ASTRONOMICAL CENTER
OF THE POLISH ACADEMY OF SCIENCES

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 952480

Dark Wave

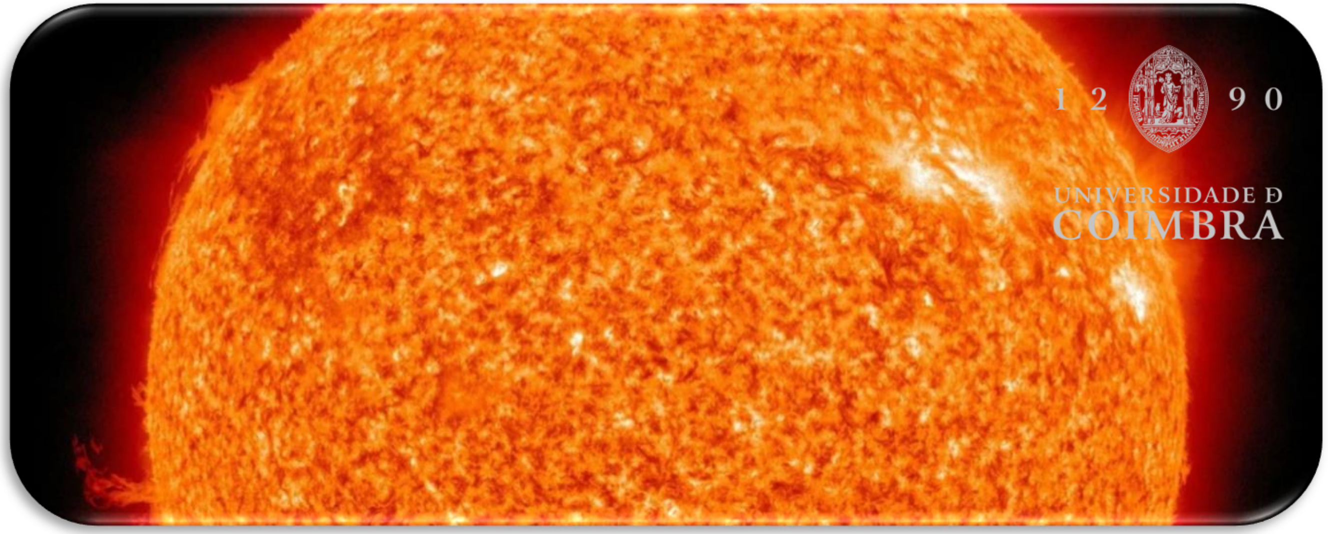
European Funds

Republic of Poland

FNP Foundation for Polish Science

European Union

Outline



- Electroluminescence
- Historical Roadmap
- How to improve light detection?
- Recent developments in optical amplification structures
- Future perspectives in light detection
- Conclusions

NICOLAUS COPERNICUS ASTRONOMICAL CENTER OF THE POLISH ACADEMY OF SCIENCES
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 952480
Dark Wave
European Funds
Republic of Poland
FNP Foundation for Polish Science
European Union

Electroluminescence

- **Carlos Conde** and **Armando Policarpo** focused their research on studying direct interaction processes leading to the discovery of the electroluminescence phenomenon. (Conde, Policarpo, 1967)

Although the first known observations of the phenomenon were made by **Harold Edgerton (1903-1990).**

What is electroluminescence?

Following excitation and ionization of the gas atoms by radiactive particle , scintillation photons are emitted – **the Primary Scintillation**:

Excitation and Ionization of gas atoms → Deexcitation → Scintillation photons are emitted

Excitation luminescence

$e^- + X \rightarrow X^* + e^-$ Excited atoms

$X^* + 2X \rightarrow X_2^* + \mathrm{X}$ Excited dimers/excimers

$X^* \rightarrow X + h\nu$ atomic lines (<50 Torr)

$X_2^* \rightarrow X + X + h\nu'$ continuum (>50 Torr)

Recombination luminescence

$e^- + X \rightarrow X^+ + 2e^-$ Atomic Ions

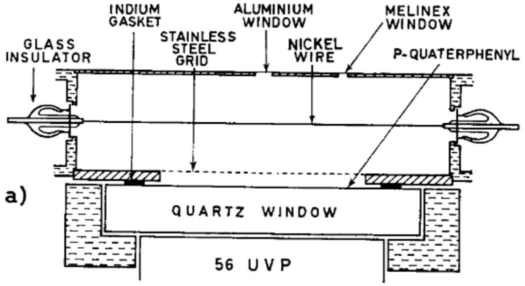
$X^+ + 2X \rightarrow X_2^+ + X$ Diatomic Ions

$e^- + X^+ \rightarrow X^* \rightarrow X + h\nu$

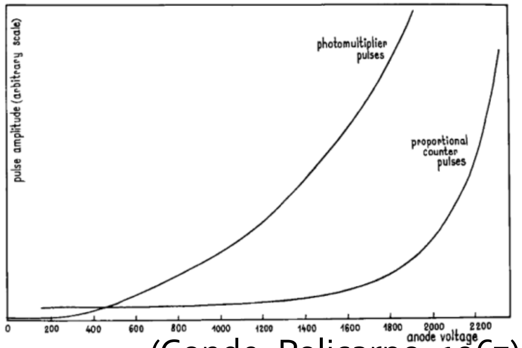
$X_2^+ + e^- \rightarrow X_2^* \rightarrow X + X + h\nu'$

Electroluminescence

First works adapted a proportional counter to study electroluminescence, while an uniform field gas proportional chamber was used to study the effect of E/p.



(Policarpo et al, 1970)



(Conde, Policarpo, 1967)

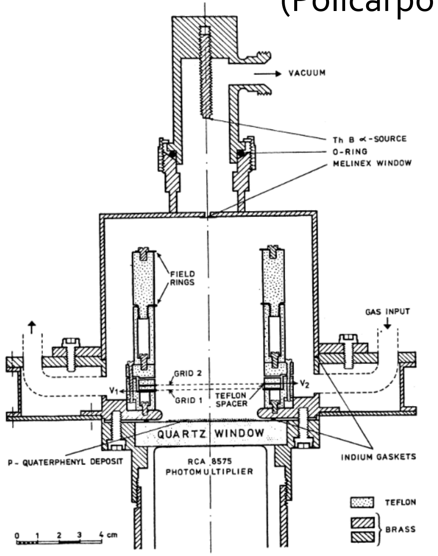
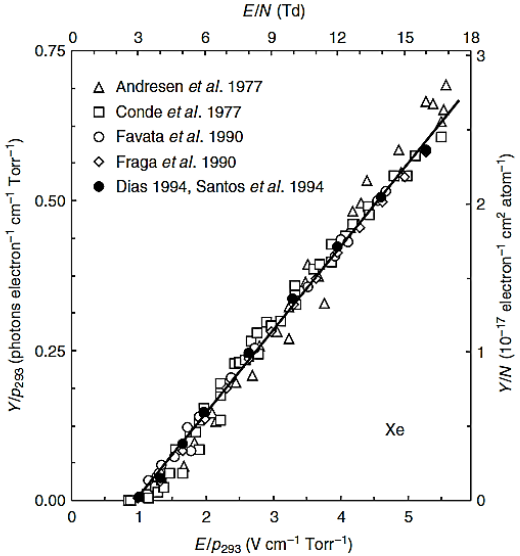
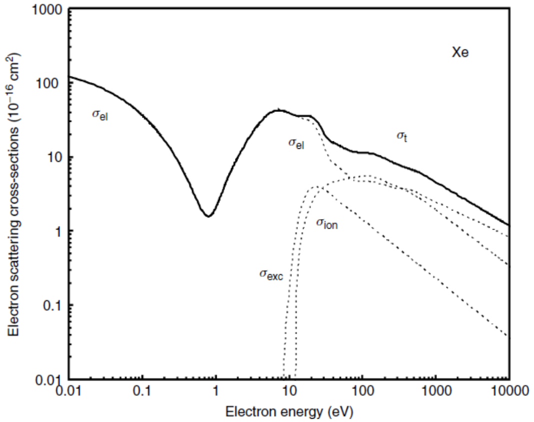
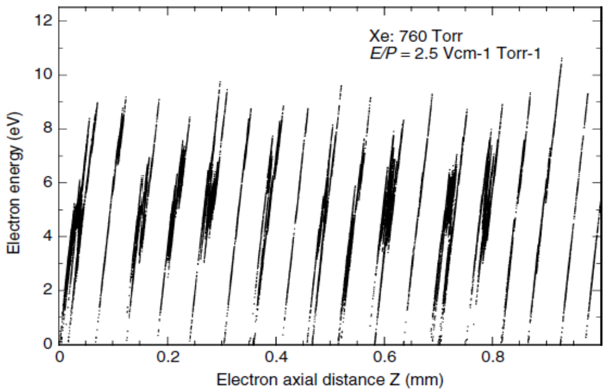


Fig. 2 - Cross section of the uniform field gas proportional scintillation counter.

(Conde et al, 1975)







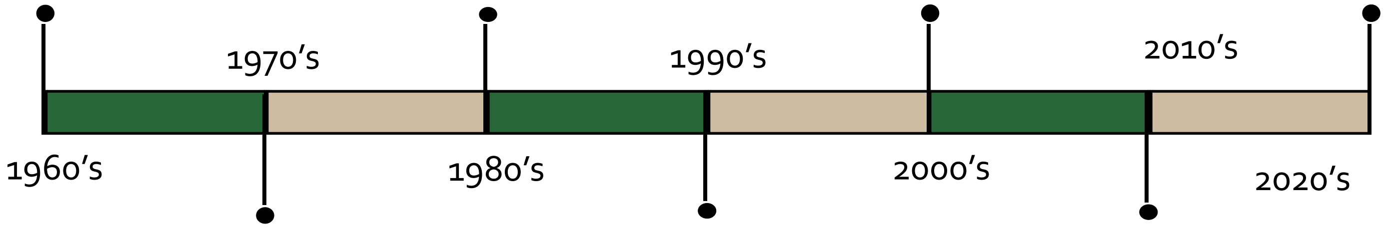
Good energy resolution (close to intrinsic)

From these studies they were able to obtain the empirical expression that allows to estimate the scintillation yield (Y).

$$\frac{Y}{p}(293\ K) = A\frac{E}{p} - B_{(photons\ electron^{-1} cm^{-1} Torr^{-1})}$$

Note: A and B are constants that depend on the gas.

Roadmap



First studies:
- Identification of S1 and S2
- S2 appeared above a certain threshold and was independent of the charge
- Signals proportional to the incident radiation.

Detector R&D:
- New design configurations (uniform field, cylindrical and spherical proportional scintillation counters)
- Characterization of electroluminescence in noble elements (Xe, Ar)
- First WLS studies using Penning Effect (Ar-Xe mixtures).

Simulation
- Secondary scintillation;
- Efficiency for light production;
- Electron drift time, average number of collisions, induced charge pulse amplitude are also calculated
- Model the fundamental processes taking place in these detectors.

Experimental Studies
- Avalanche based electroluminescence.

Alternative Readouts and MPGD integration
- Introduction of APVs
- MSP use with electroluminescence

Solid angle compensation
- Curved grid (varying the electric field)
- Masking the optical readout
- Electrostatic lensing techniques

New readout technologies
- Development of the Micro-Hole and Strip Plate.
- Gas Electron Multiplier (GEM)
- Thick-GEM development

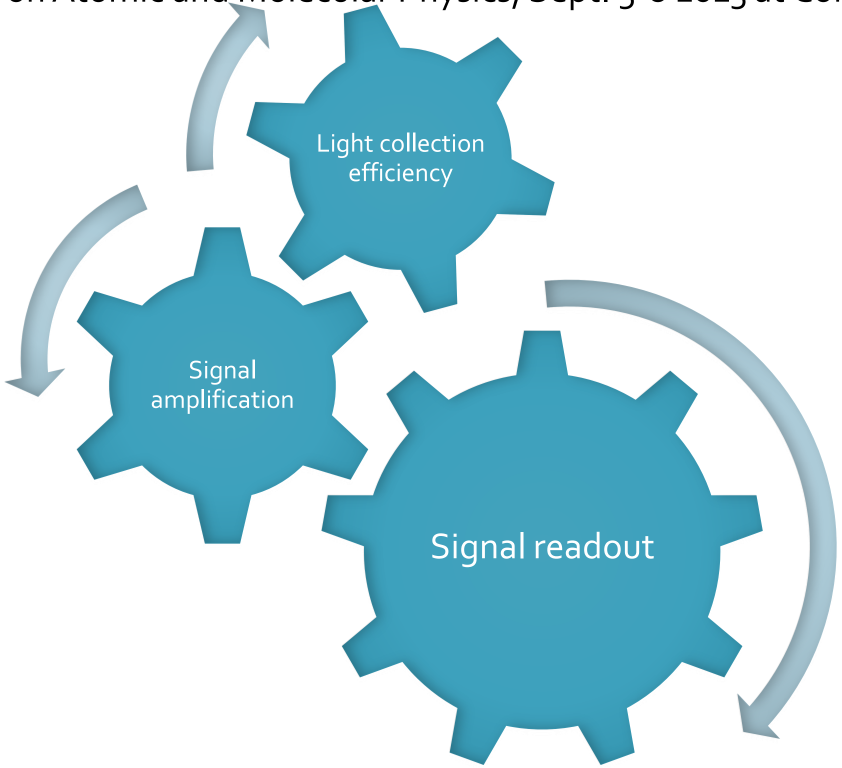
New MPGDs and Ion Backflow suppresion
- Thick- Cobra/Cobra-125
- PACEM (Photo Assisted Cascaded Electron Multipliers)
- Zero-IBF
- Readout with CCD cameras
- Readout with sCMOS cameras
- SiPM readout

Optical amplification structures
- M-THGEM
- G-THGEM
- FAT-GEM
- WLS FAT-GEM
- Floating THGEM

With essential contributions from **Prof. Carlos Conde**, **Prof. Armando Policarpo**, **Prof. Joaquim dos Santos**, **Prof. Francisco Fraga, Prof. Vitaly Chepel** and **Prof. João Veloso (from the UC)**.

For more details please check "Coimbra Gas Radiation Detectors Heritage", SXSDG 2019
Presentation_Coimbra_2019_-_Andre_Cortez.pdf (lip.pt)

How to improve light detection?



Improving light collection efficiency is critical for the performance of detectors as it affects:

- Event triggering
- Position and energy reconstruction
- Particle ID

What strategy to follow?

Improving light detection

Common strategies: light collection efficiency (solid angle, WLS strategies (passive/active), reflective materials), amplification structures and new photosensors.

Problem: lack of dedicated, scalable light amplification structures.

State-of-the-Art

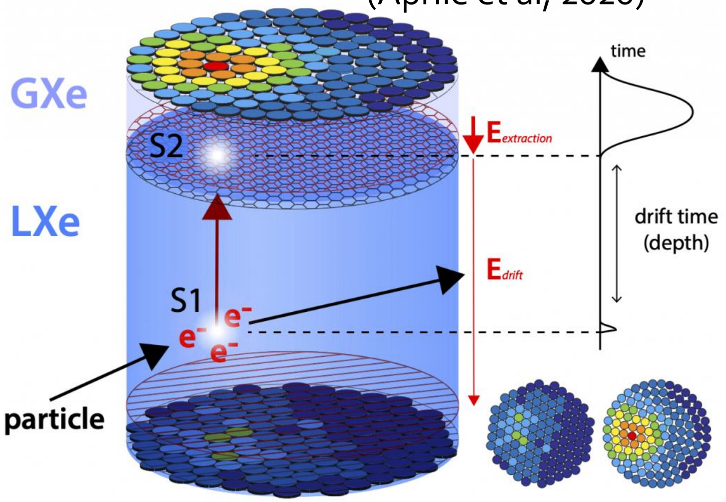
- Meshes are widely used (in rare event searches)
  - Excellent energy resolution and ability to detect single-electrons
    - Difficult scalability

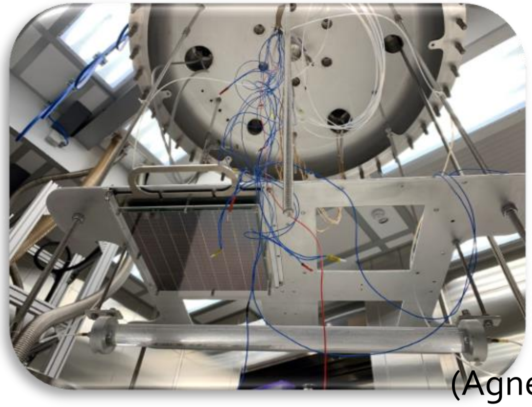
- Loss of tension
- Mesh stretching over large areas is complicated
- Vulnerability to weak points
- Lack of modularity (plus issues with the liquid-gas interface in dual-phase TPCs)

NEXT
(Monrabal et al, 2018)

What solutions are there?

XENON
(Aprile et al, 2020)

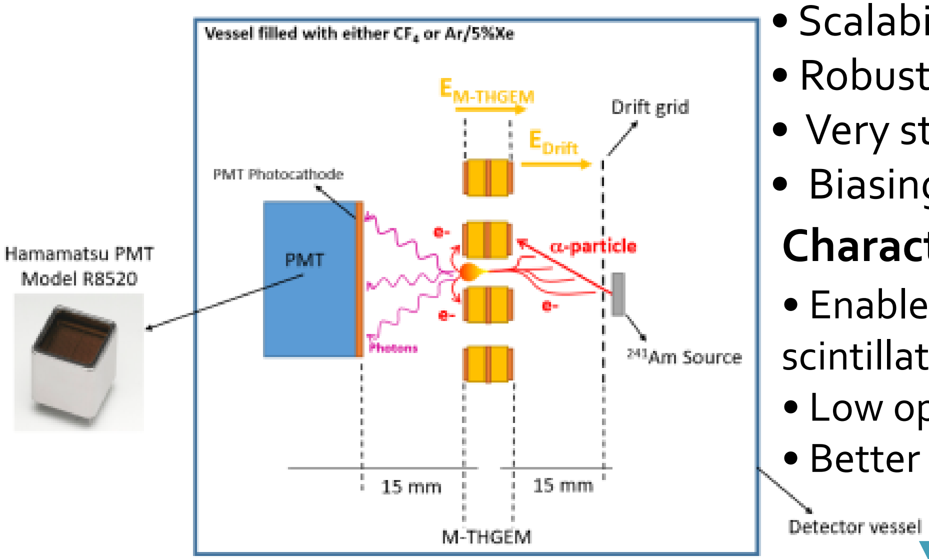




DarkSide
(Agnes el al, 2023)

Recent developments in optical amplification structures

Multi-Layer Thick Gas Electron Multipliers (M-THGEM) (Cortesi et al, 2023)

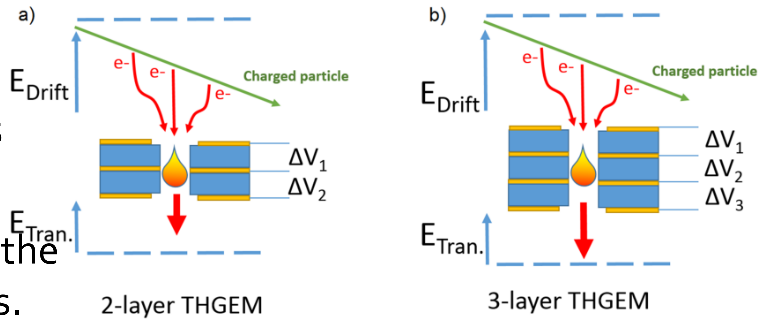


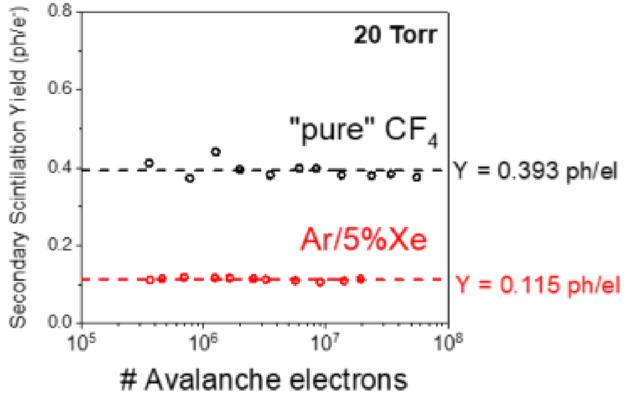
- Scalability
- Robust and easy to produce
- Very stable at high gains
- Biasing is independent for all electrodes

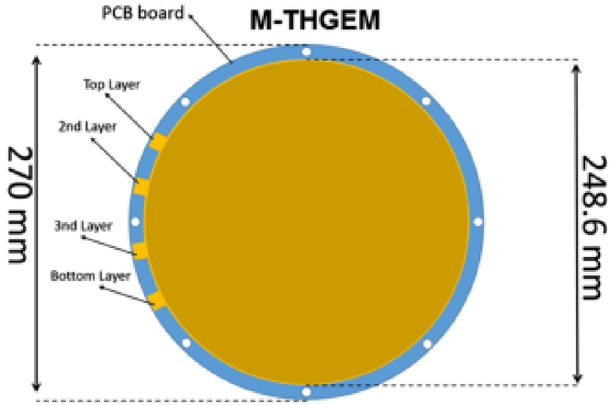
Characteristics:

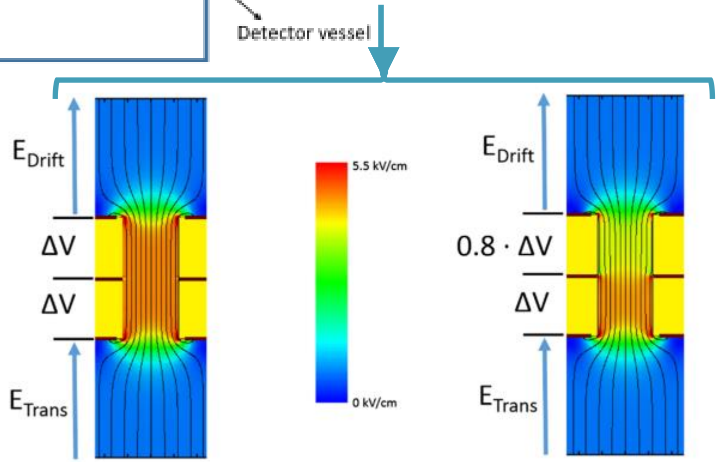
- Enables to constrain and define the E/p of the scintillation region inside the GEM-like holes.
- Low optical gain.
- Better contrast (due to light collimation).

Enables multiple designs/configurations:









Light yield

$$Y = \frac{\text{Avalanche Photons}}{\text{Avalanche Electrons}} = \frac{\text{ADC}_{\text{light}} \cdot \text{Cal}_{\text{light}}}{\text{ADC}_{\text{charge}} \cdot \text{Cal}_{\text{charge}}} \cdot \frac{4\pi}{\Omega} \cdot \frac{1}{\text{GAIN}_{\text{PMT}} \cdot \text{PDE}}$$

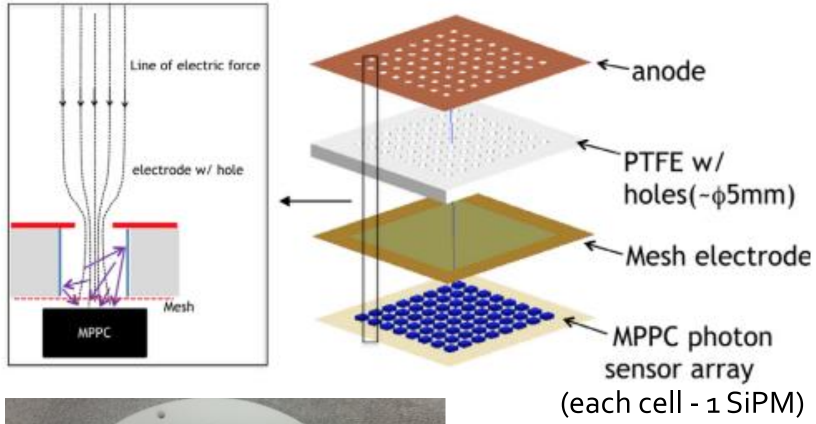
Main limitations:

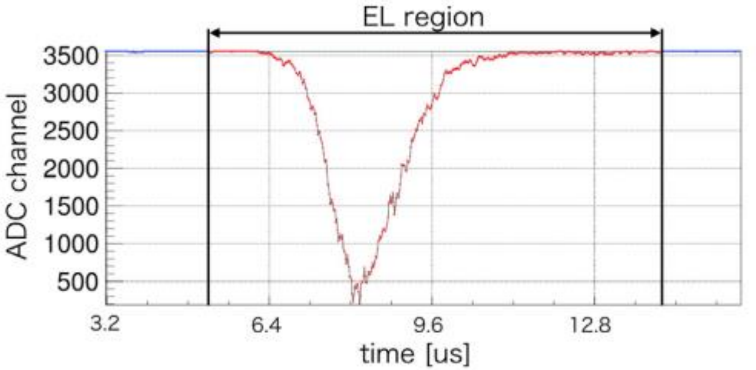
- Needs optimization in terms of radiopurity materials
- Limited to avalanched originated scintillation (so far)
- Use in Argon based detectors limited (due to the wavelength of Ar scintillation).
- Only tested at low pressure (up to 100 Torr)

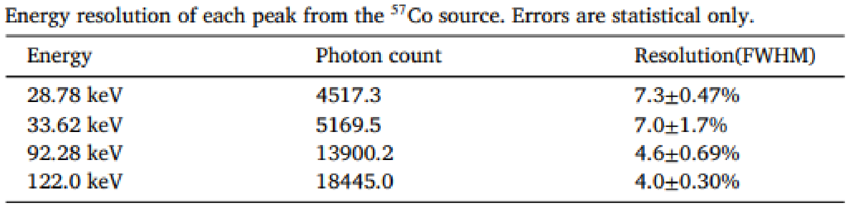
Recent developments in optical amplification structures

ELectroluminescence Collection Cell (ELCC) of the AXEL detector (Ban et al, 2017)

- Scalability
- Robust and easy to produce
- Very stable at high gains
- Pixelized solution

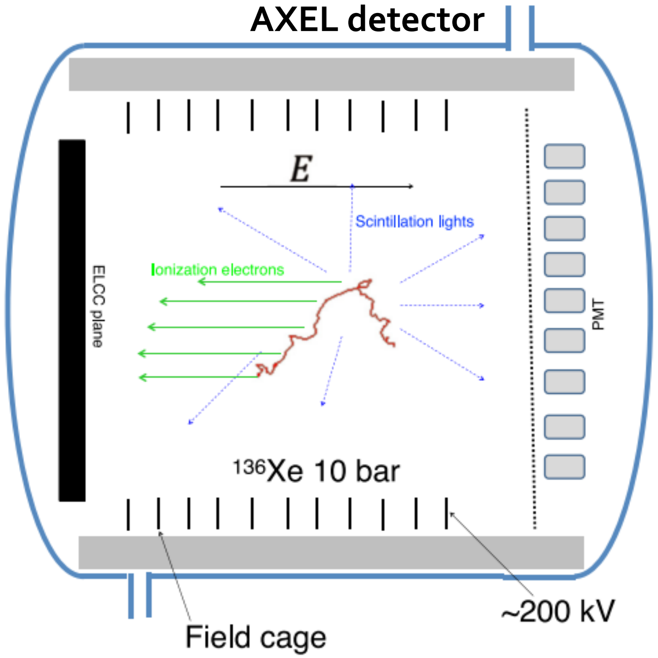


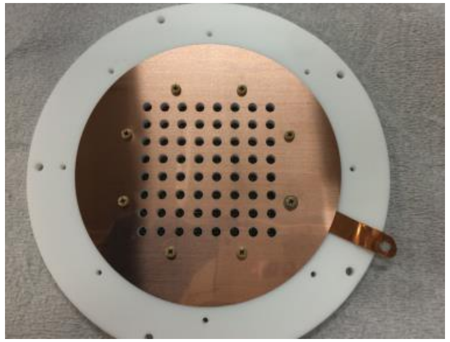




Energy resolution of each peak from the ^{57}Co source. Errors are statistical only.

Energy	Photon count	Resolution(FWHM)
28.78 keV	4517.3	7.3±0.47%
33.62 keV	5169.5	7.0±1.7%
92.28 keV	13900.2	4.6±0.69%
122.0 keV	18445.0	4.0±0.30%





Characteristics:

- Enables energy deposition and event topology reconstruction.
- Good energy resolution.
- Good contrast (due to light collection scheme).

Main limitations:

- Expensive materials (teflon+copper)
- Mechanical characteristics far from ideal for high-pressure (expansion due to gas absorption)
- Teflon surface reflections not ideal (diffuse reflectivity)
- Misses the opportunity to explore S1 scintillation (triggering and absolute 3D track reconstruction)
- Spatial resolution (due to 7.5 mm pitch holes)

Light yield

$$dN_{\mathrm{EL}}/dx = 70(E/p - 1.0)p,$$

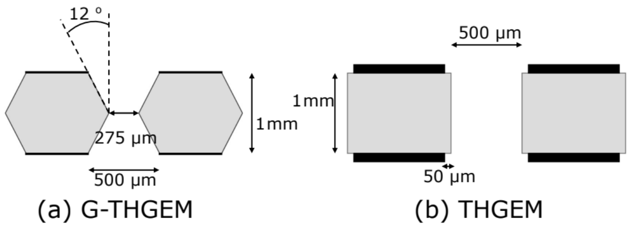
Recent developments in optical amplification structures

Glass Thick Gas Electron Multipliers (G-THGEM) (Mavrokoridis, Roberts et al, 2021)

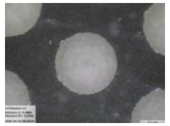
- Scalability
- Robust and easy to produce (improved stiffness - better than FR4/PCB THGEMs)
- Stable at high gains
- Radiopure materials

Characteristics:

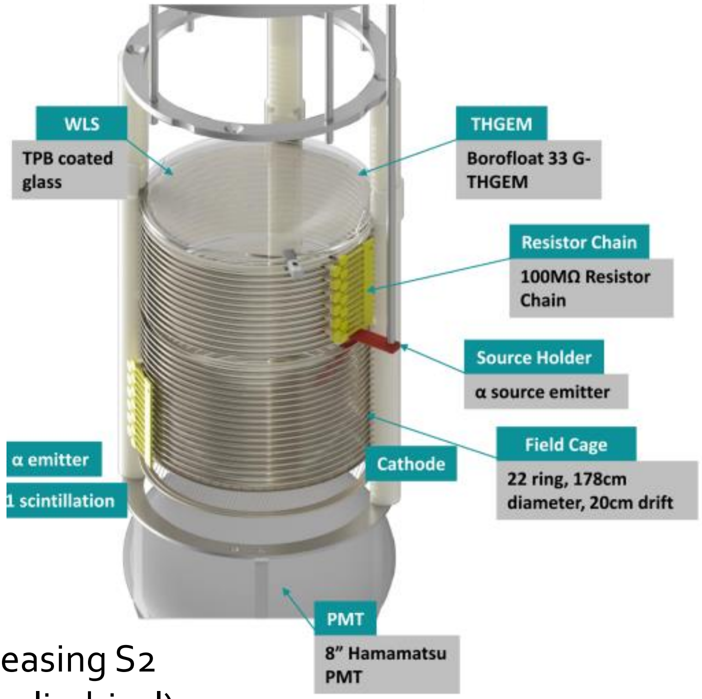
- Abrasive machining process allows for unprecedented customisation (substrate, electrode, hole shape, size and pattern)
- Increased S2 light production (when compared with THGEMs)

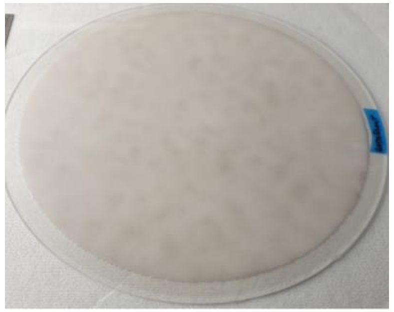


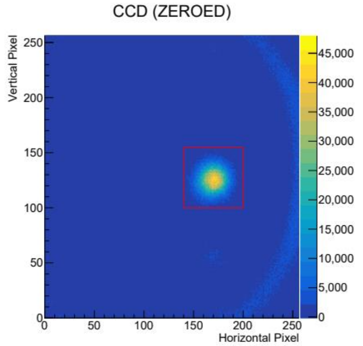
(a) G-THGEM (b) THGEM

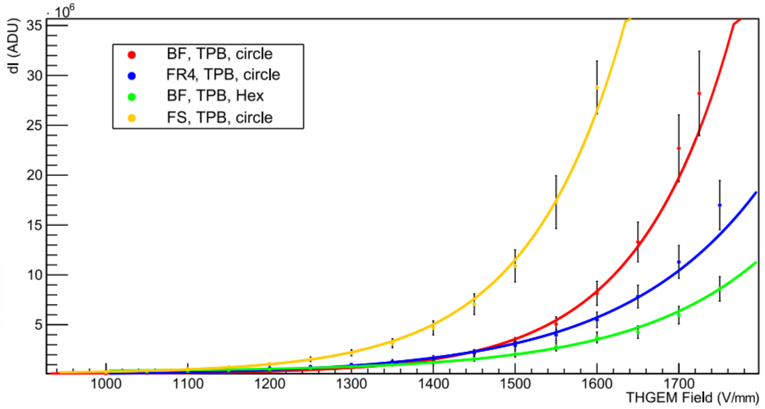


Bi-conical holes -> Increasing S2 (when compared with cylindrical)









THGEM Type	Substrate	Electrode	Hole Shape	Hole Size (µm)	Hole Pitch (µm)	Rim Size (µm)
FR4 circ	FR4	Cu	Circle	500	800	50
FS circ	FS	ITO	Circle	500	800	None
BF circ	BF	ITO	Circle	500	800	None
BF hex	BF	ITO	Hexagonal	870	1100	None

Main limitation:

- Charging up effects observed in terms of scintillation.
- Limited to VUV – additional structures needed to perform wavelength-shifting.

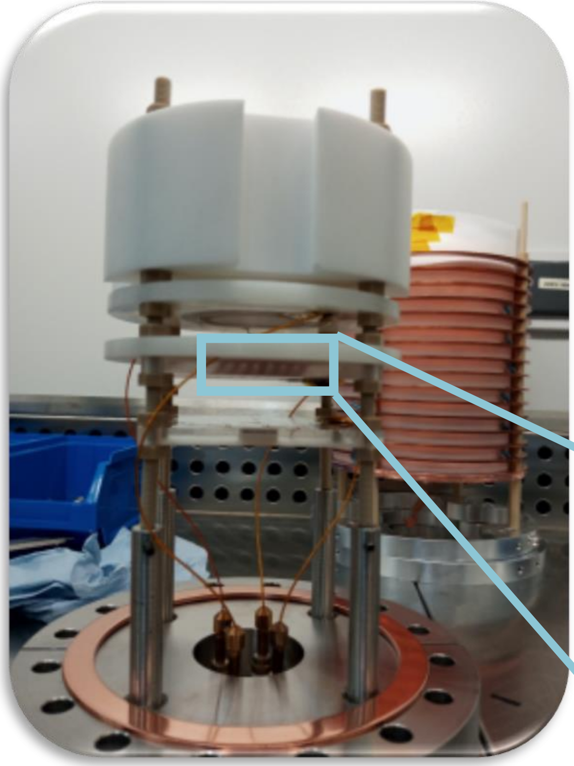
Recent developments in optical amplification structures

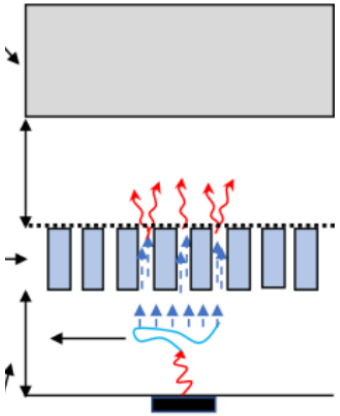
Field-Assisted Gas Electroluminescence Multiplier (FAT-GEM) (Gonzalez-Diaz et al, 2020)

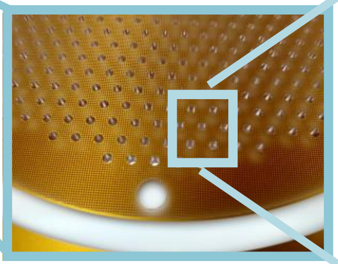
- Scalability
- Radiopurity
- Transparent to scintillation

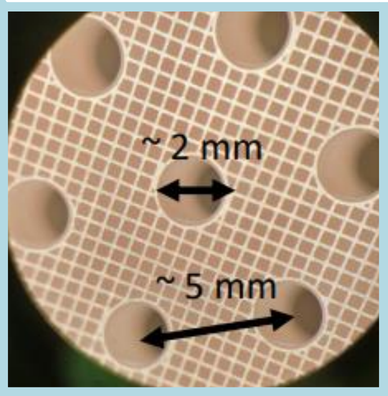
Characteristics:

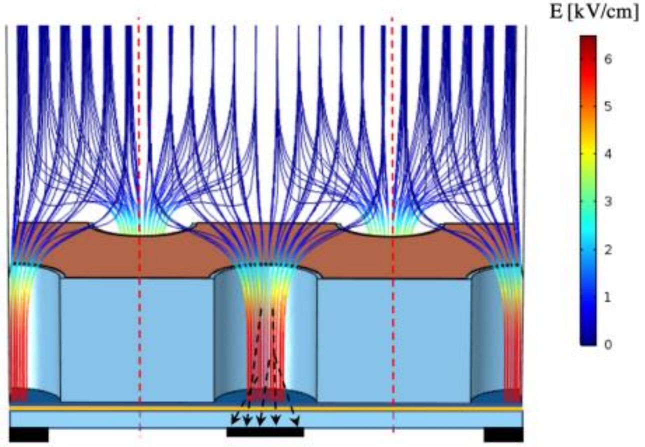
- Bulk made of PMMA (Polymethyl methacrylate)
- Copper mesh, PEDOT:PSS or ITO coating
- Area up to 50 cm x 50 cm at least (easily tiled)
- Thickness = 5 mm (!) (important for high electroluminescence yields)









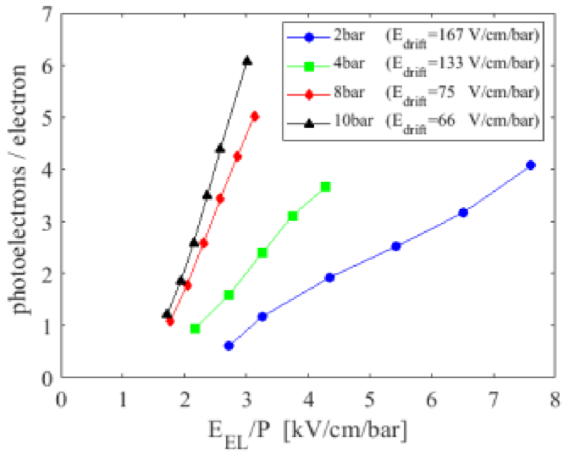


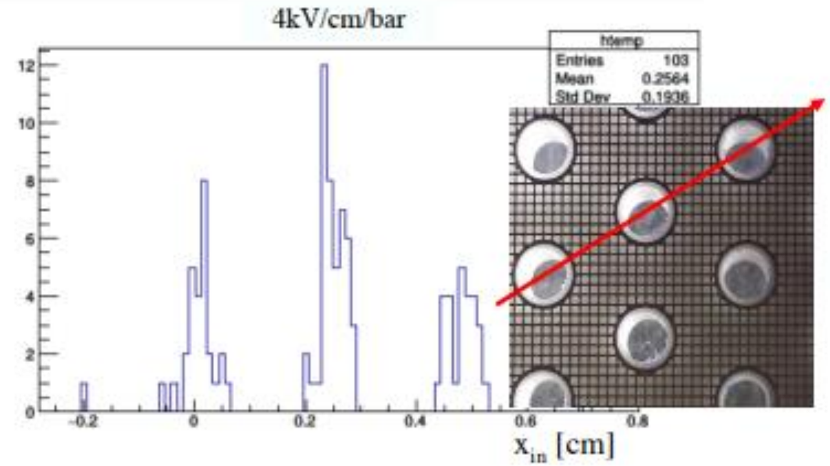
	Acrylic (mBq/kg)	FAT GEM (mBq/cm^2)
U-238/Pa-234m	<340	<0.741
U-238/Pb-214	<2.8	<0.006
U-238/Bi-214	<2.3	<0.007
Th-232/Ac-228	<8.8	<0.021
Th-232/Pb-212	<2.9	<0.007
Th-232/Tl-208	<6.3	<0.014
U-235/U-235	<1.9	<0.006
K-40	<17	<0.036
Co-60	<0.74	<0.002
Cs-137	<1.1	<0.002

Note: Radiopurity of FAT-GEM studied at Canfranc Underground Laboratory.

Recent developments in optical amplification structures

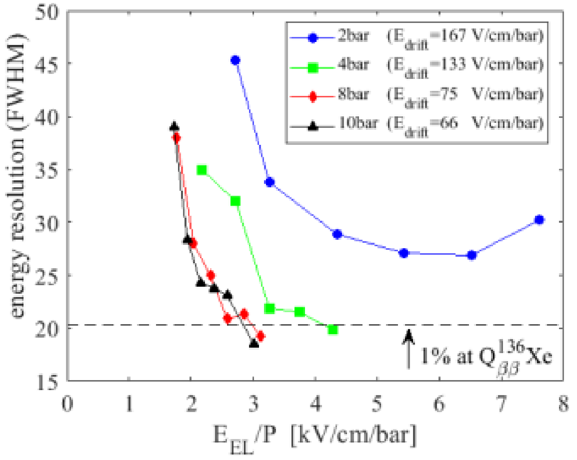
Field-Assisted Gas Electroluminescence Multiplier (FAT-GEM) (Gonzalez-Diaz et al, 2020)

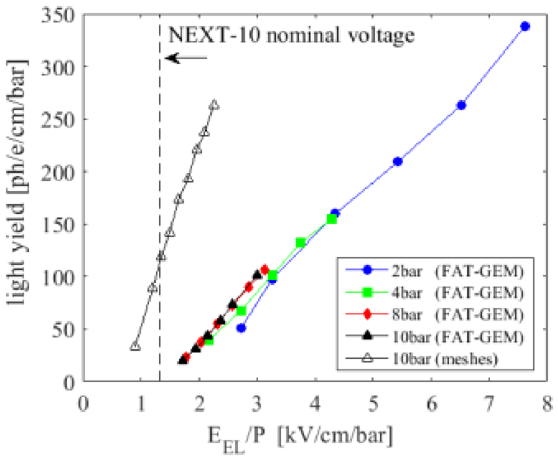


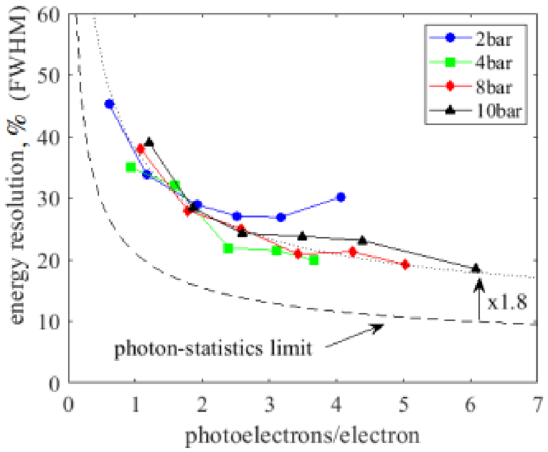


First results were promising:

- Optical gain: 500 ph/e-
- Stable operation (high pressure, cryogenic and high E/p)
- Competitive with best performing MPGDs:
  - Micromegas in Xe-TMA (9.6% (22.1keV), P=10bar
  - Teflon-based hole structures (7.3% (28.8keV), P=4bar







Main limitation:

PMMA itself not transparent to VUV

How to further improve light production?

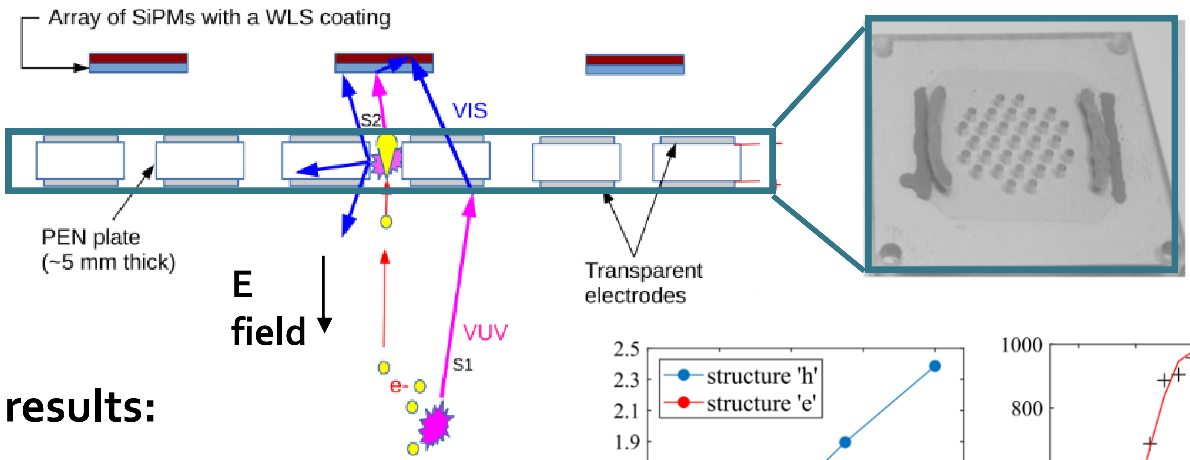
Implement wavelength-shifting.

Recent developments in optical amplification structures

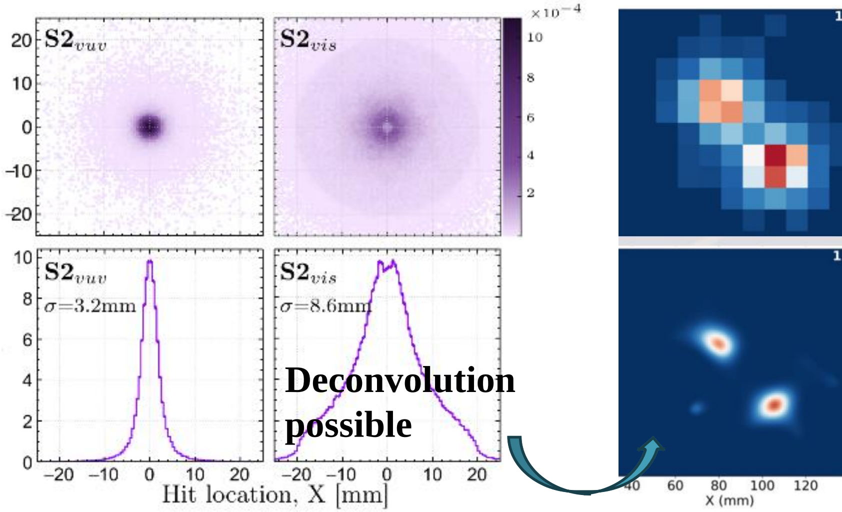
Wavelength-Shifting Field-Assisted Gas Electroluminescence Multiplier (WLS FAT-GEM) (Kuzniak et al, 2021)

New structure developed at ASTROCENT and IGFAE Instituto Galego de Física de Altas Enerxías

- Scalable solution (tileable)
- Increase both EL yield and light collection efficiency
- Wavelength-Shift VUV to Vis (S1 and S2)



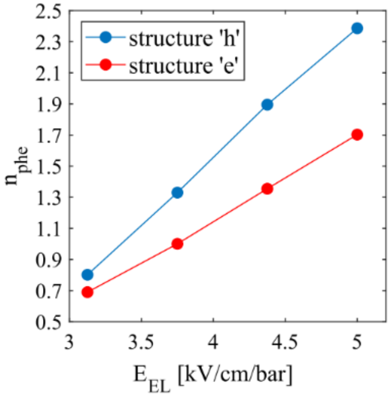
Simulation:

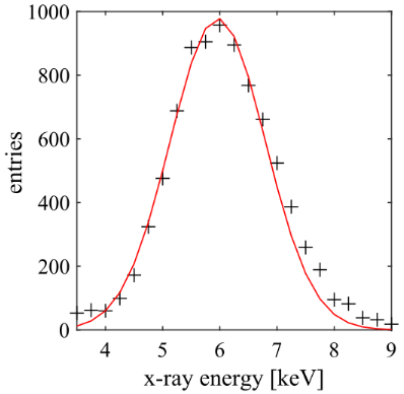


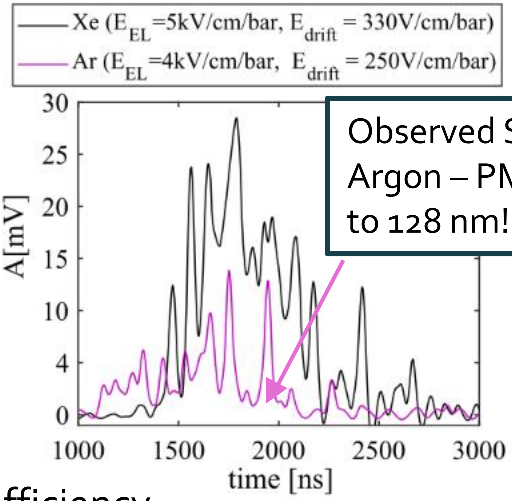
PSF of 10-mm possible
(Simon et al 2022)

Preliminary results:

Comparison with a TPC supplied with wire mesh electrodes, shows:
- similar S1-light collection yield (up to 75%)
- up to 2–3 times higher for S2,







Observed S2 waveform in Argon – PMT not sensitive to 128 nm! -> hints of WLS

What to do?

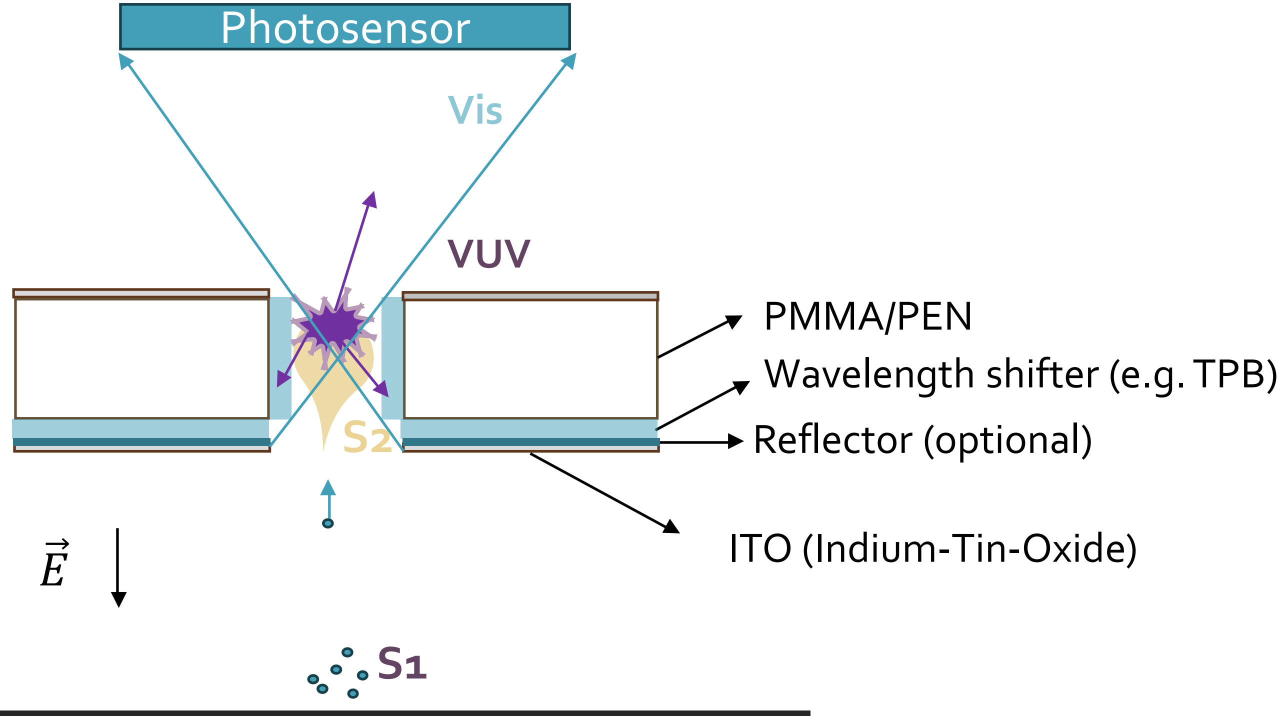
For information on WLS materials and production:
(Kuzniak et al, 2021) and (Kuzniak, Szelc, 2021)

Main limitation: PEN has low wavelength shifting efficiency.

Recent developments in optical amplification structures

How to further improve light detection?

- **FAT-GEM holes with TPB coating** -> light collection **x1.8** with respect to mesh configuration
- **Reflector layer** -> improves light collection **x2.9** with respect to mesh configuration (according to Geant4 simulations) (Kuzniak et al, 2021)

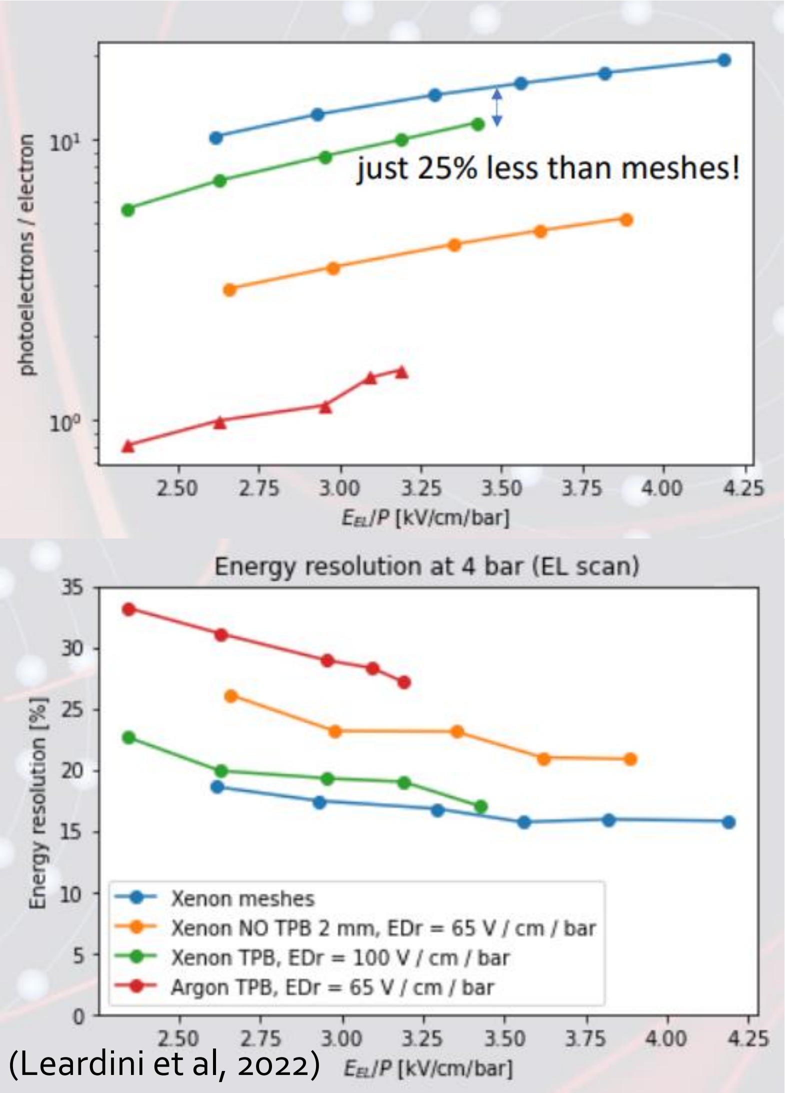


PMMA/PEN

Wavelength shifter (e.g. TPB)

Reflector (optional)

ITO (Indium-Tin-Oxide)



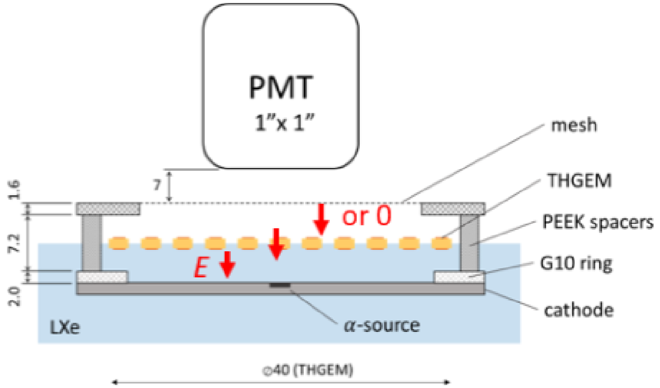
(Leardini et al, 2022)

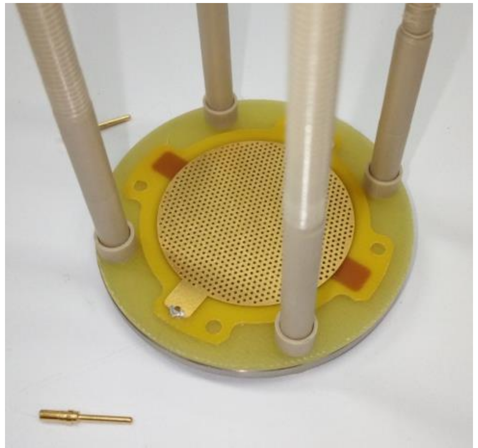
Recent developments in optical amplification structures

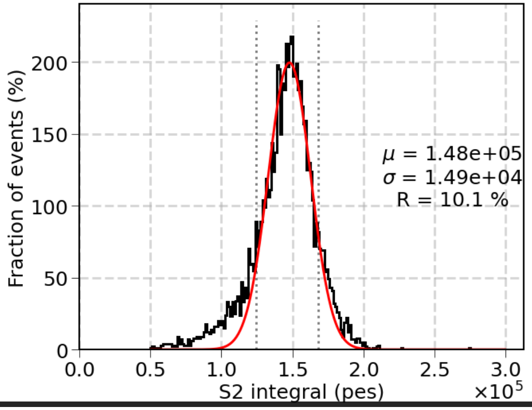
Floating optical amplification structures

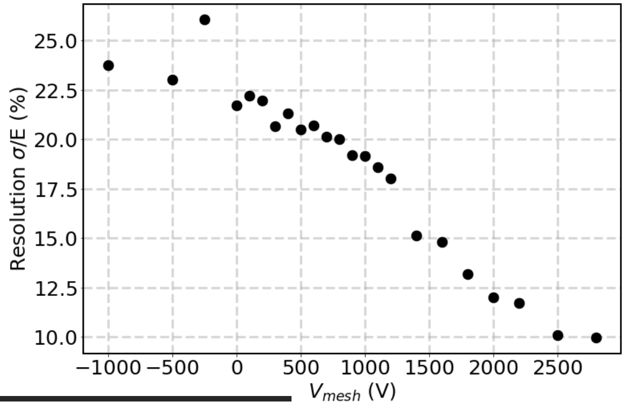
A floating Thick-GEM was already successfully tested in LXe…

(Chepel et al, 2022)









Main advantages:

- Reduced probability of any kind of surface instabilities (ripples, waves, microexplosions, etc.) – limited to hole surface
- Electron drift/diffusion under the surface minimized (within the hole pitch)
- High electron extraction probability thanks to high field at the interface (unreachable in uniform field)
- Positive ion feedback (if any) – likely to end up at the floating electrode
- Reduced single electron noise

Challenges:

- Optical transmission for VUV (S1 problem)
- Physics – meniscus profile, wettability, field effects, electron transmission efficiency
- Structure optimization – thick structures? Bigger holes?
- Possibility of working in LAr (1.4 g/cm^3)?

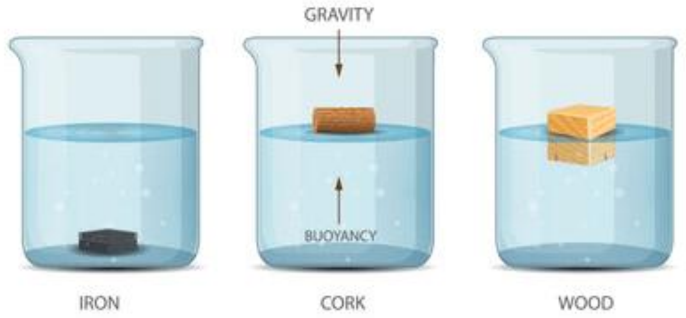
Future perspectives in light detection

Floating Wavelength-Shifting Field-Assisted Gas Electroluminescence Multiplier (FWLS FAT-GEM)

ongoing effort with Kuzniak (Astrocent)

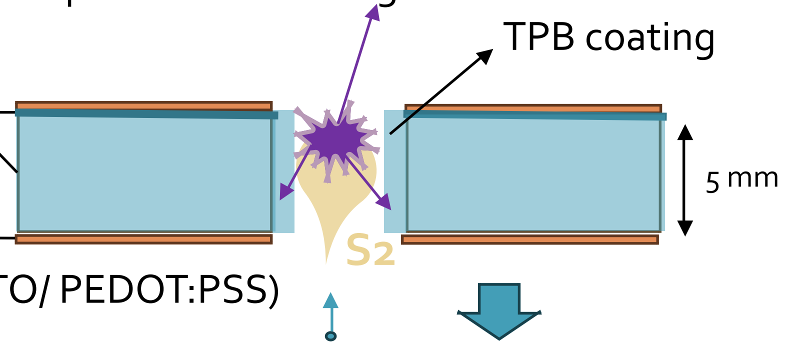
How to design?

Archimedes principle



polyethylene naphthalate (PEN) (bulk material) ρ_{PEN} = 1.36 g/cm^3 → Wavelength-shifting + Transparent to visible light

Enable detection of S1 and S2



TPB coating

Reflective coating (plus TPB)

Semi-transparent electrode (copper mesh, or transparent coating of ITO/ PEDOT:PSS)

Optimizes the collection of S1 and S2

Producing a floating PEN-based WLS FAT-GEM requires that the structure density to be lower than LAr density → $\rho_{WLS} \cdot V_{total} = \rho_{LAr} \cdot V_{sub}$

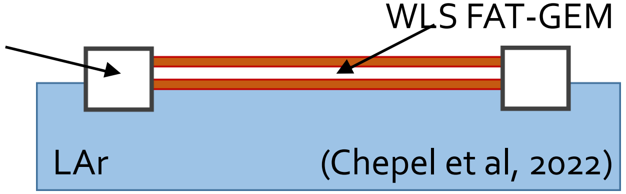
ρ_{LAr} = 1.40 g/cm^3

For **PEN-based WLS:** V_{sub}/V_{Total} is equal to **0.97**

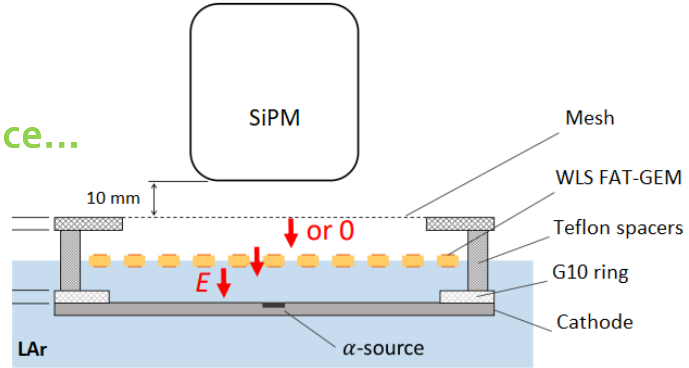
Close but no there yet..solutions may be rely on using a floating device…

Possible materials (floater):

polyethylene (PE) 0.941 and 0.965 g/cm^3 (HDPE)



(Chepel et al, 2022)



Note:

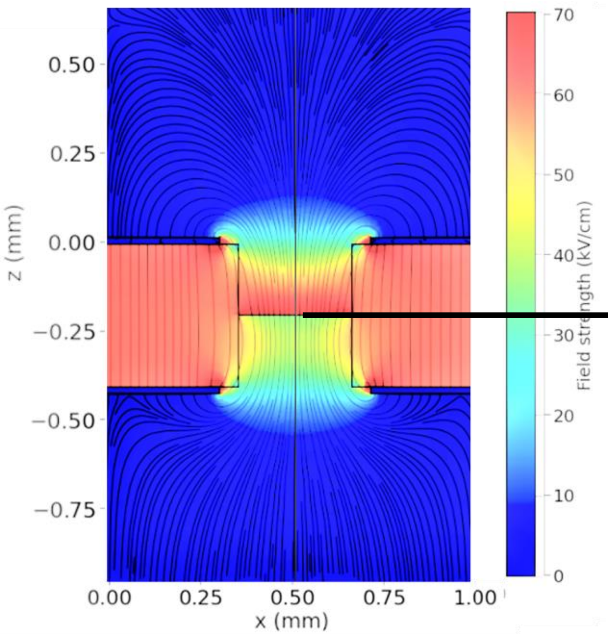
Alternative configuration may consist of bulk PMMA (instead of PEN) with TPB coating plus na evaporated mesh.

Future perspectives in light detection

Floating Wavelength-Shifting Field-Assisted Gas Electroluminescence Multiplier (FWLS FAT-GEM)

How to test?

From simulations we know..



Fields near the interface:

$$E_{gas} \sim 70\,\frac{kV}{cm}$$

Liquid-gas interface

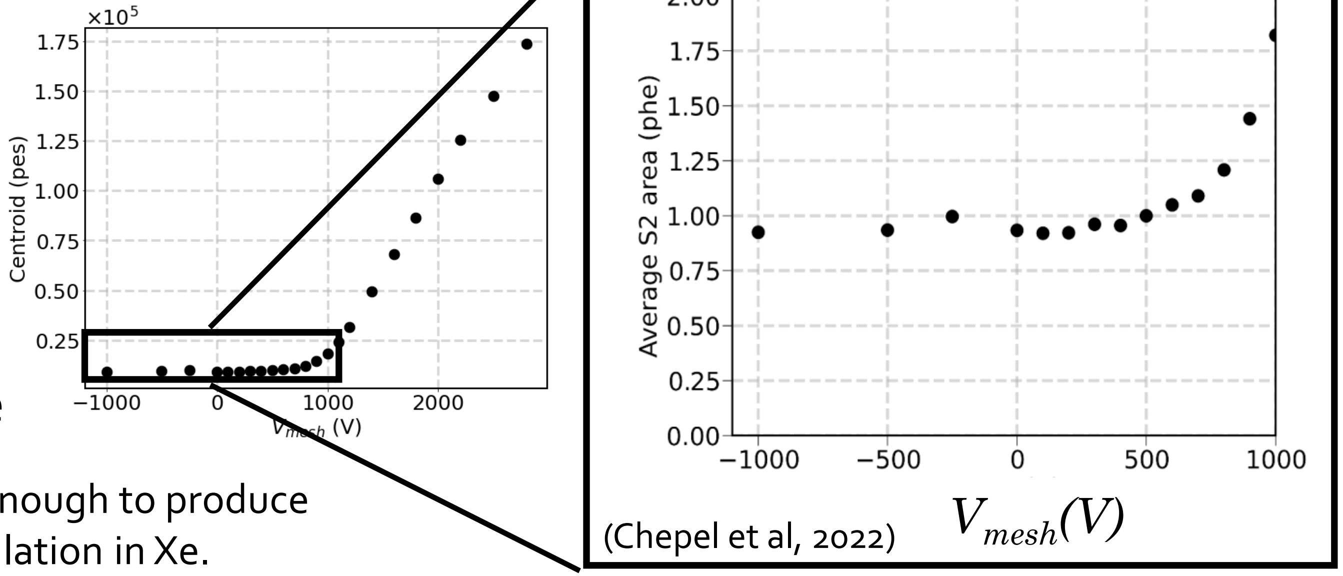
$$E_{liq} \sim 40\,\frac{kV}{cm}$$ → Not enough to produce scintillation in Xe.

$$\Delta V_{extr} = 0$$
$$\Delta V_{THGEM} = 2500\ V$$
$$\Delta V_{drift} = 400\ V$$

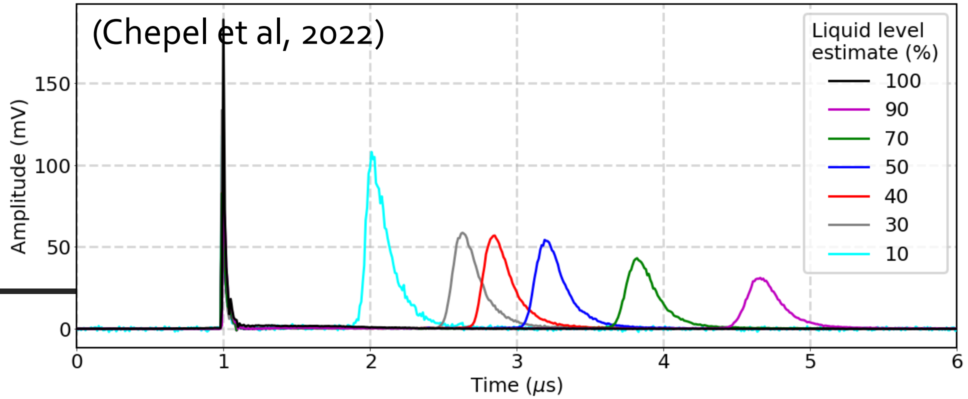
(Chepel et al, 2022)

Light in the GEM-like holes

Light in uniform field (mesh)



(Chepel et al, 2022)



(Chepel et al, 2022)

- Scintillation output is proportional to the gas pocket inside the GEM-like holes
- Time interval between S1 and S2 proportional to the liquid level

The future of floating amplification structures is promising…

Summary

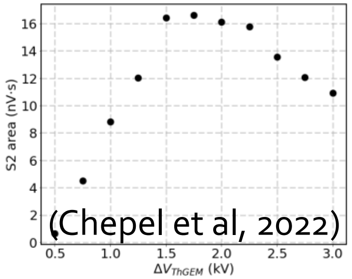
- WLS FAT-GEMs are promising radiopure and scalable structures for electroluminescence – based noble gas detectors
- WLS FAT-GEMs can be used to improve S1 and S2 detection
- Energy resolutions achieved are close to the needs of the NEXT experiment
- Recent success at <u>evaporating the TPB inside the holes</u> at **AstroCeNT**.

The structure shows wavelength-shifiting, making it possible to observe Ar scintillation and enhancing the detection efficiency for Xe at levels already comparable to those of meshes.

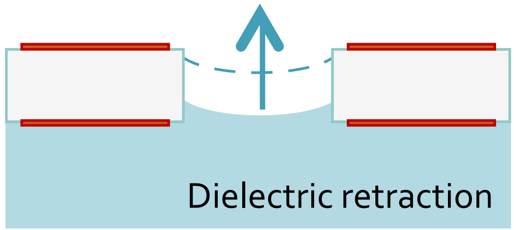
- Floating THGEM in LXe opens the possibility for the development of novel WLS structures.

New developments expected soon..including..the development of a floating WLS FAT-GEM.

..and study of physics and its optimization.



(Chepel et al, 2022)



Stay tunned!

References

- Conde, Policarpo (1967), Nucl. Inst. And Meth. 53, 7
- Policarpo et al (1970), Nucl. Inst. and Meth. NUCLEAR 77, 309
- Conde et al (1975) IEEE Trans. on Nucl. Sci, NS-22, 104
- Aprile et al, (XENON Collaboration) (2020) JCAP11, 031
- Monrabal et al, (NEXT Collaboration) (2018), JINST 13 (12), P12010
- Agnes el al, (Global Argon Dark Matter Collaboration) (2023), Phys. Ver. D 107, 112006
- Cortesi et al (2023), JINST 18, P08005
- Ban et al (2017), Nucl. Instr. Meth. A 875, 185
- Lowe, Majumdar, Mavrokoridis, Philippou, Roberts, Touramanis (2021) Appl. Sci. 11, 9450
- Gonzalez-Diaz et al (2020), J. Phys. Conf. Ser. 1498, 012019
- Leardini et al, (2022), "Rugged and radiopure amplification structures for large-area xenon chambers readout through electroluminescence", oral presentation at LIDINE 2022, Warsar (Poland)
- Kuzniak et al (2021), Eur. Phys. J. C 81, 609
- Kuzniak, Szelc (2021) Instruments 5, 4
- Simón et al (2022) JINST 17, C01014
- Chepel et al, "Floating Hole Multiplier – a novel concept for dual-phase noble liquid detectors", oral presentation at LIDINE 2022, Warsaw (Poland)
- Chepel et al, "A novel concept for dual-phase noble liquid detectors – Floating Hole Multiplier", oral presentation at MPGD 2022, Rehovot (Israel)
- Amaro et al (CYGNO Collaboration) (2022), Instruments 6, 6
- Lopes et al (1997) IEEE Transactions on Nuclear Science, 44(3), 517

NICOLAUS COPERNICUS ASTRONOMICAL CENTER OF THE POLISH ACADEMY OF SCIENCES

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 952480

Dark Wave

European Funds

Republic of Poland

FNP Foundation for Polish Science

European Union

Thank you!

ASTROCENT

NICOLAUS COPERNICUS ASTRONOMICAL CENTER
OF THE POLISH ACADEMY OF SCIENCES

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 952480

Dark Wave

European Funds

Republic of Poland

FNP Foundation for Polish Science

European Union

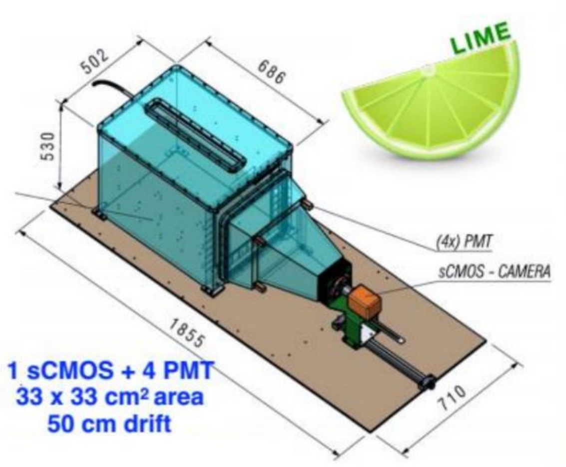
Backup Slides

Improving light collection

Common adopted strategies:

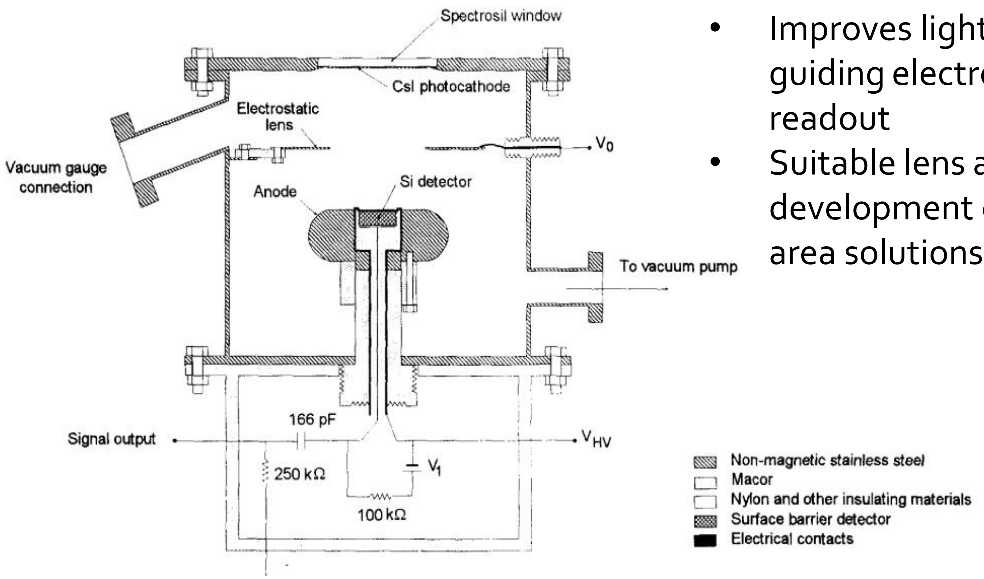
Solid angle ➡ Produce scintillation close to the photosensor

Optical lensing (Amaro el al, 2022)



- Optical sensors provide high sensitivity and granularity, with a fast response with very low noise level.
- Optocoupling enables to keep sensor out of sensitive volume (HV independent and lower gas contamination).
- Suitable lens allow the development of large sensitive area solutions.

Electrostatic lensing (J.A.M. Lopes and C.A.N. Conde 1995)



- Improves light collection by guiding electrons closer to the readout
- Suitable lens allow the development of large sensitive area solutions

Alternatively one could think about diferente geometries..why using uniform field?