Novel Detector Concepts for Future Dark Matter experiments

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Outline

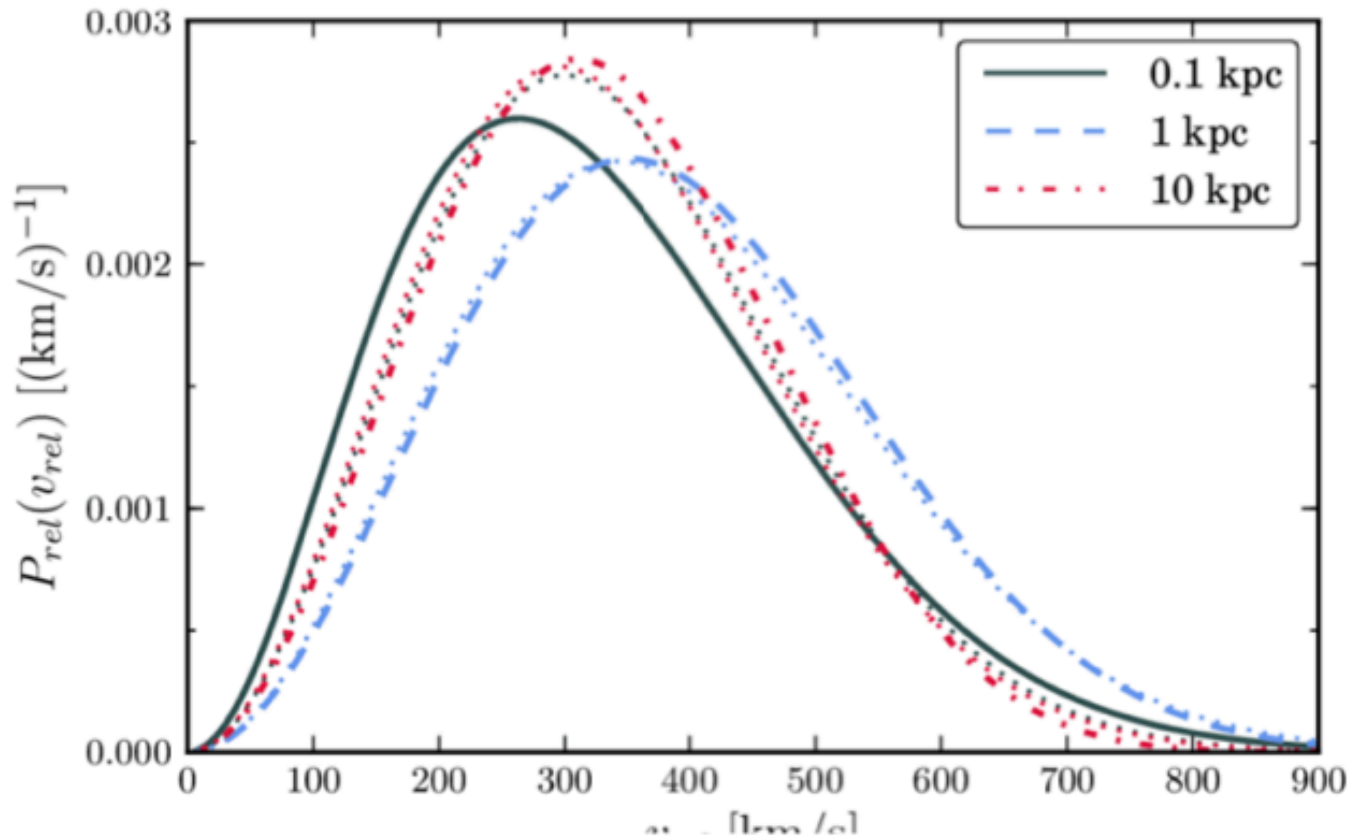
- Dark matter and WIMPs
- How can we explore Dark Matter?
- Challenges in Dark Matter-LowMass (sub-GeV) quest
- Novel Detector concepts for future Dark Matter searches
- Conclusions

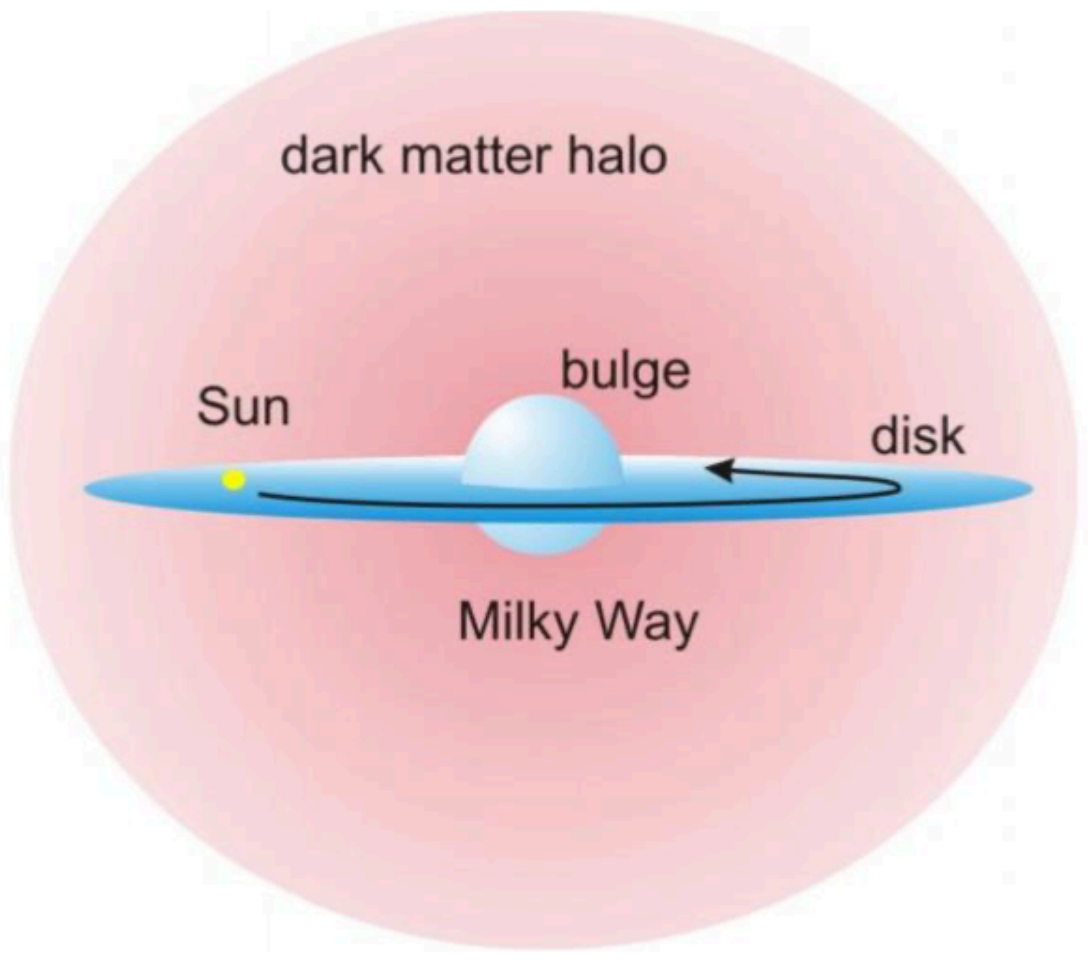
Dark matter and WIMPs

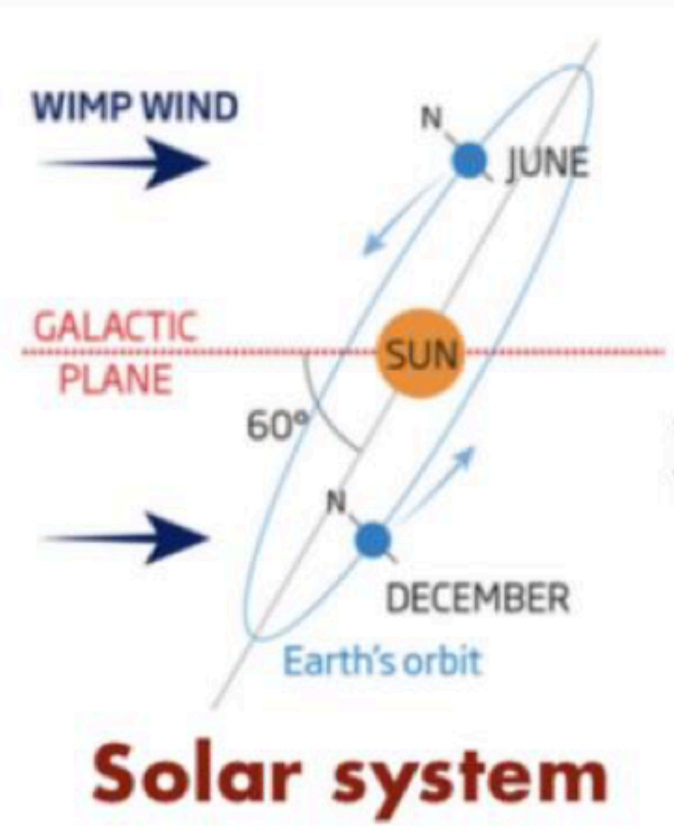
- One of the possible constituents of Dark Matter are the Weakly Interacting Massive Particles: neutral particles with a very low interaction probability with ordinary matter.

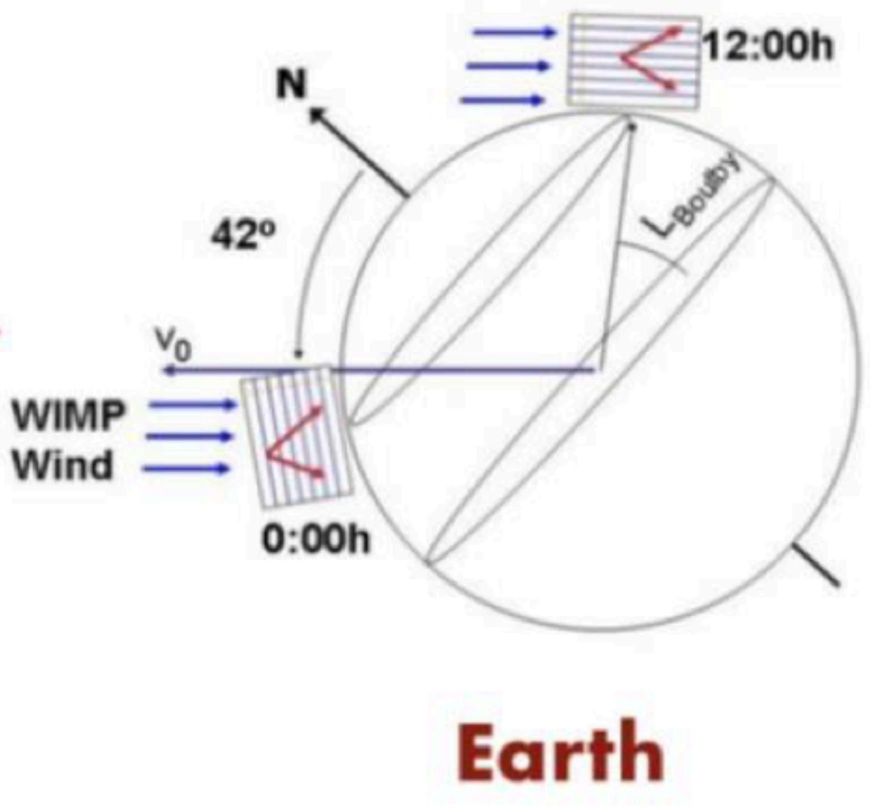
- Our Milky Way, like most galaxies, is surrounded by an approximately spherical halo of WIPMs. The Sun and the planets move through this halo towards the Cygnus constellation intercepting a WIMP wind originating from it.

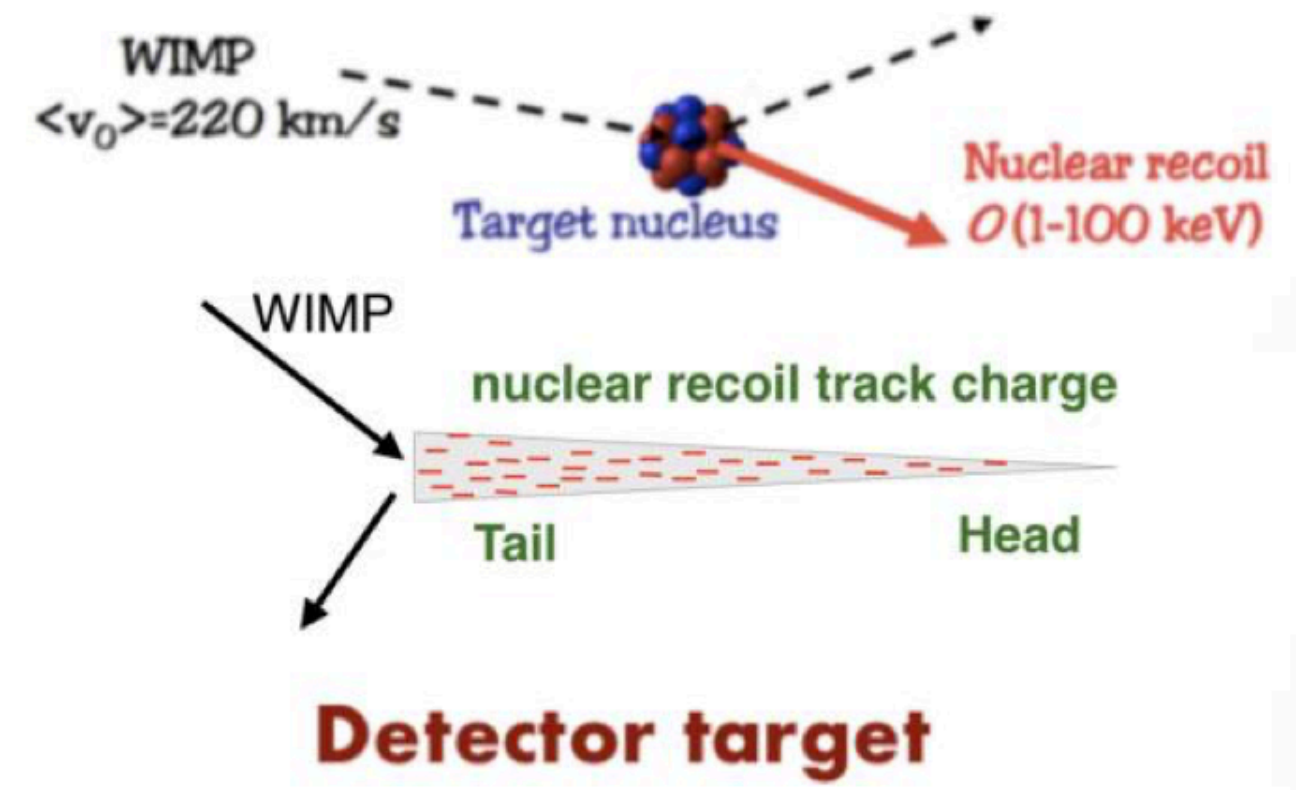
- Events from Dark Matter interactions have a preferential direction in space because of the Earth's motion with respect to the Dark Matter halo.





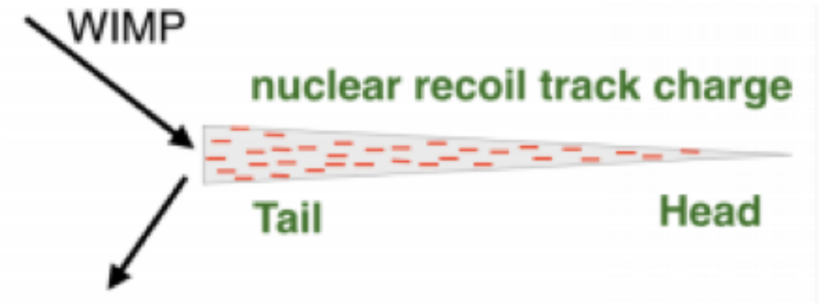




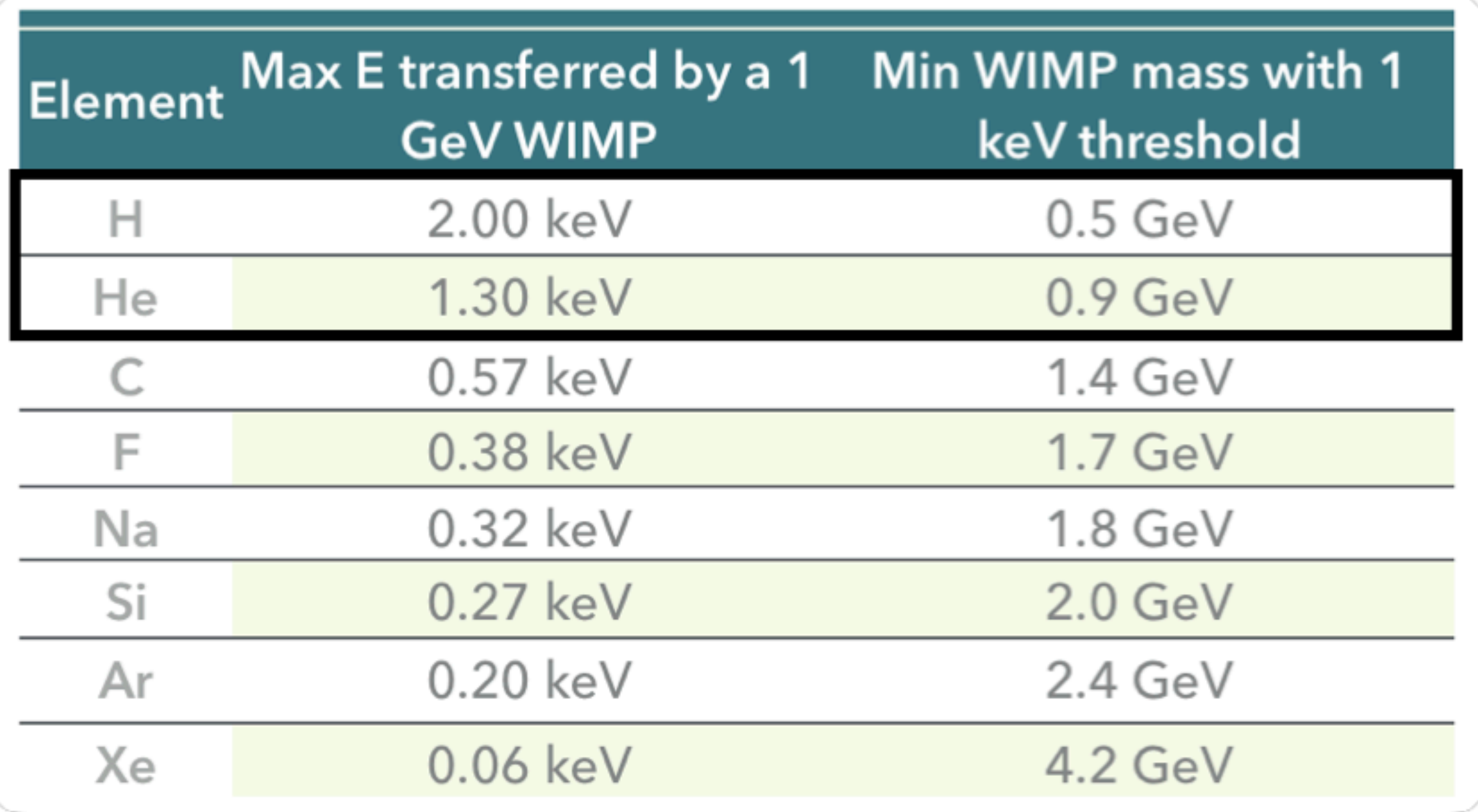


How can we explore Dark Matter?

- One possibility is trying to detect the products of its interactions with ordinary matter, through charged particles that we know how to detect;

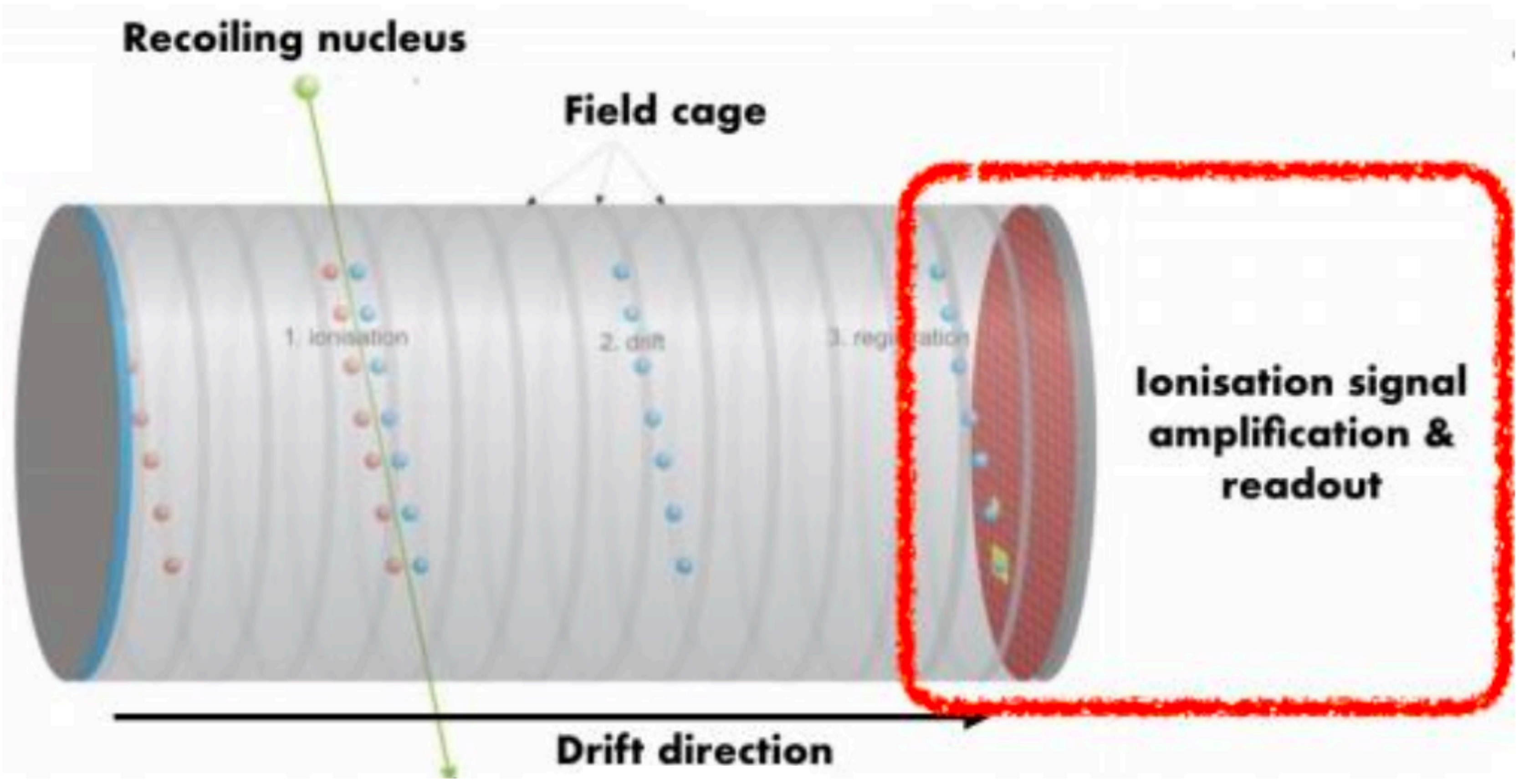


- In order to maximize the fraction of transferred energy we can always play with the target mass;
  Depending on the mass we can target at different WIMP masses (with lighter target masses, lower WIMP masses can be explored - see table)



Element	Max E transferred by a 1 GeV WIMP	Min WIMP mass with 1 keV threshold
H	2.00 keV	0.5 GeV
He	1.30 keV	0.9 GeV
C	0.57 keV	1.4 GeV
F	0.38 keV	1.7 GeV
Na	0.32 keV	1.8 GeV
Si	0.27 keV	2.0 GeV
Ar	0.20 keV	2.4 GeV
Xe	0.06 keV	4.2 GeV

How to detect?

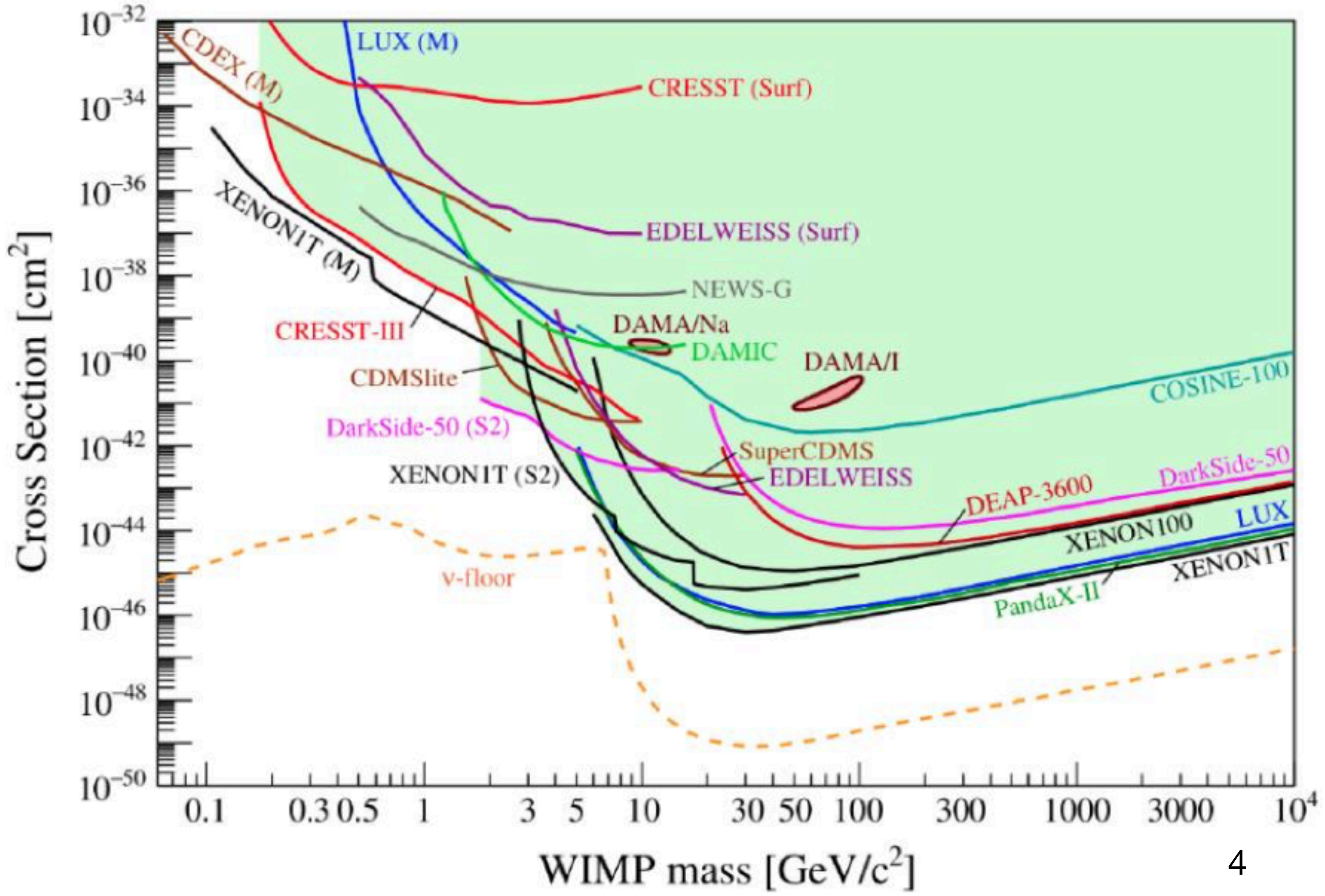


What can get?

- 3D tracking (position and direction)
- Particle ID (dE/dx)
- Axial directionality
- Head/tail
- Background rejection
- 3D fiducialization

Historical marks:

- Time Projection Chamber (TPC) introduced in 1977 by David Nygren.



How can we explore Dark Matter?

Energy information

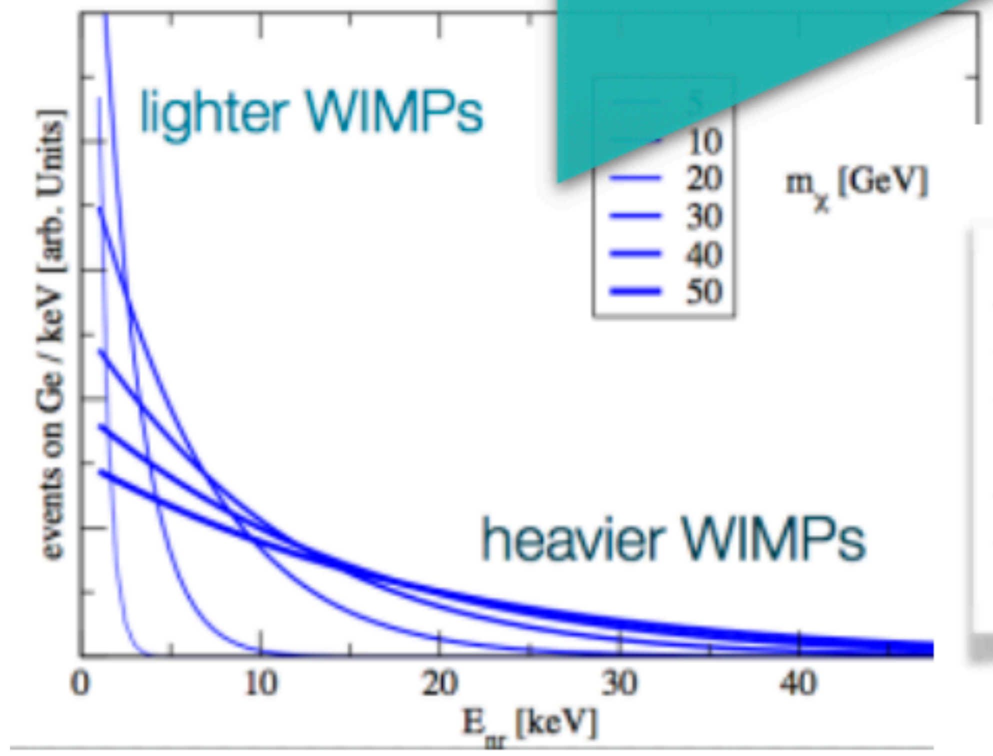
- Falling exponential with no peculiar features

Temporal information

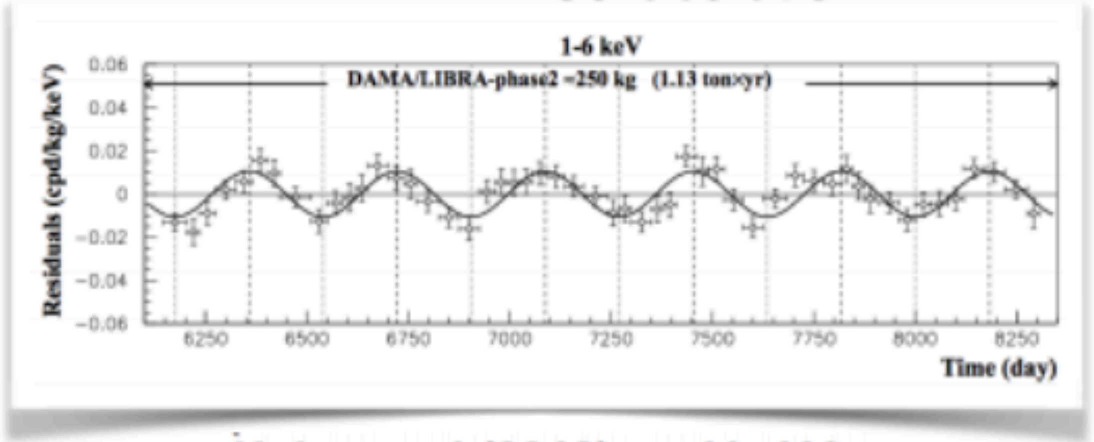
- A few percent (%) annual modulation

Directional information

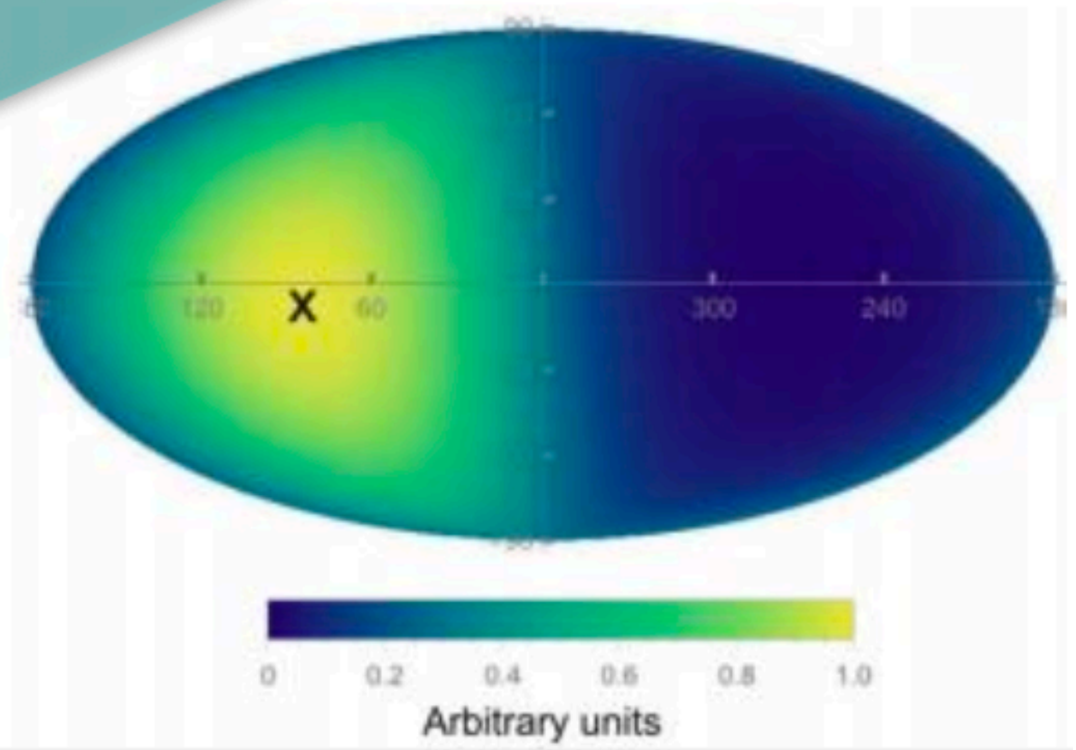
- Allows unequivocally the identification of the event



DAMA/LIBRA Collaboration



Universe 4 (2018) no.11, 116

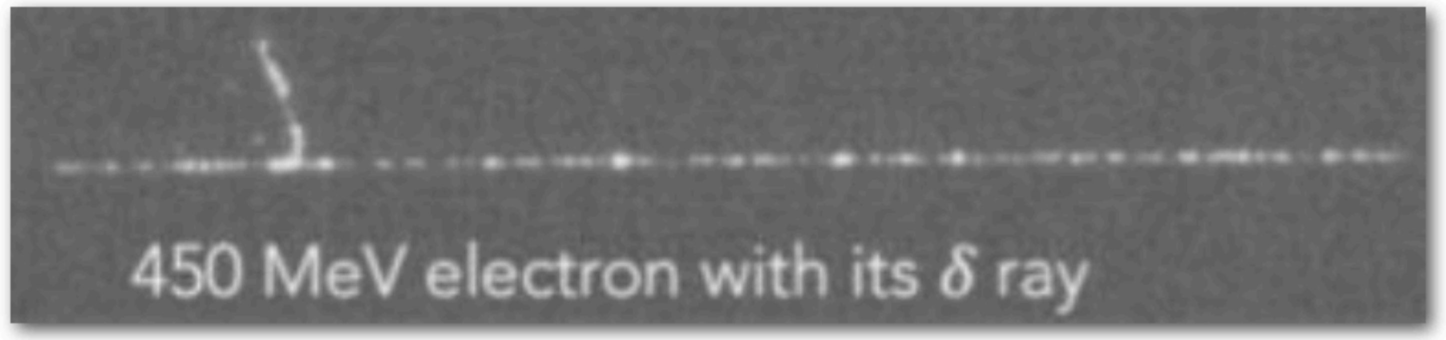


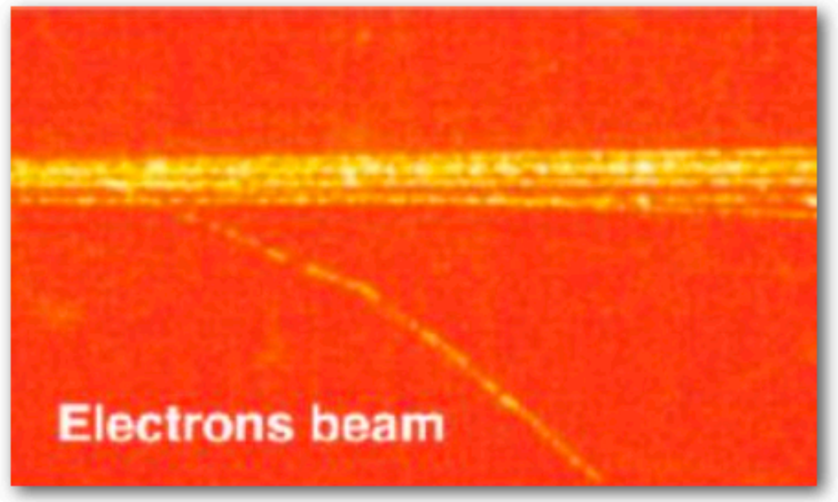
What can we explore?

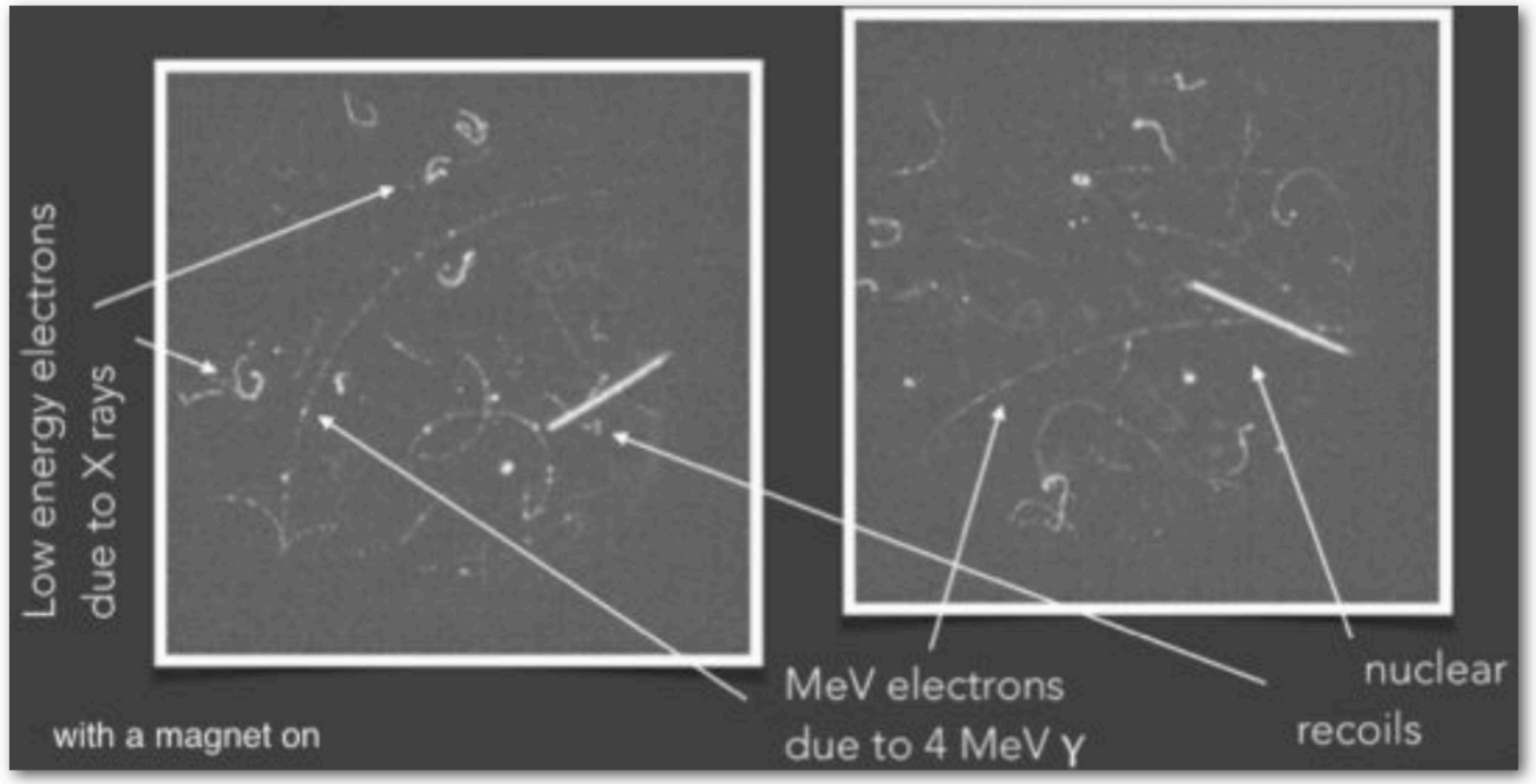
- Capability to reject isotropy;
- Capability to discriminate WIPMS from neutrinos;
- Capability to probe Dark Matter nature;

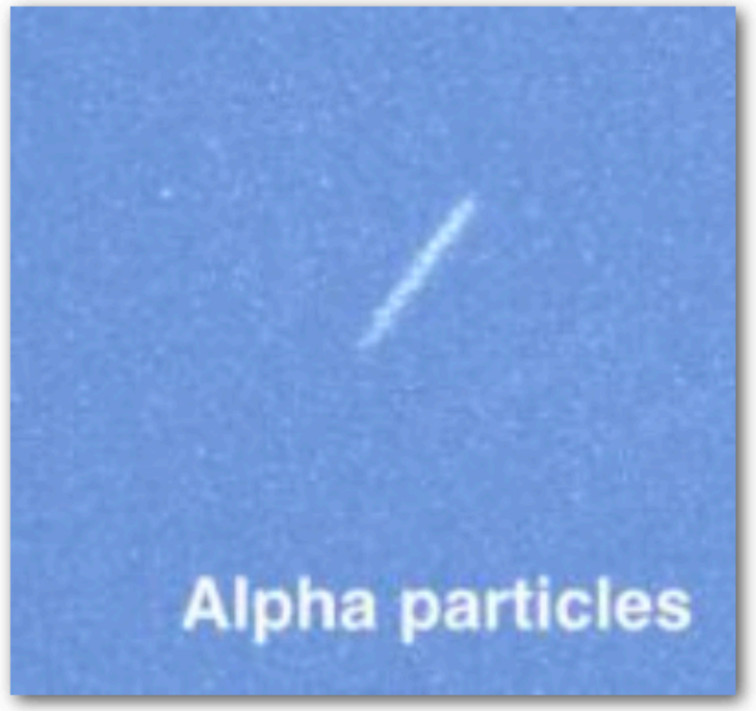
How do particles look like when interacting in a detector?

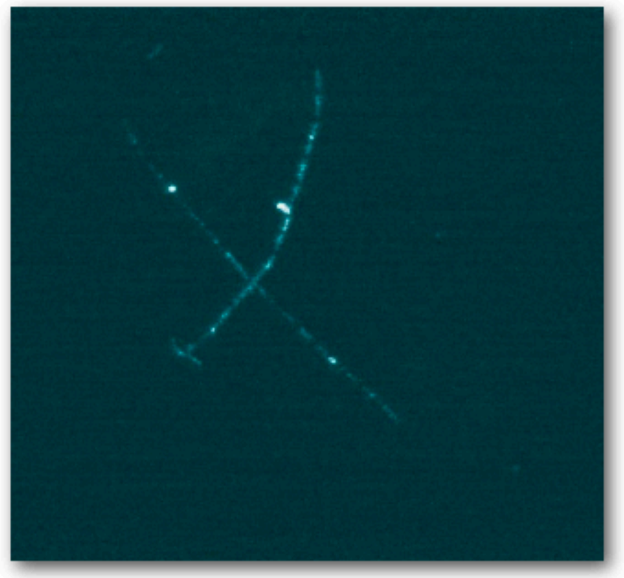
Different particles will look differently..

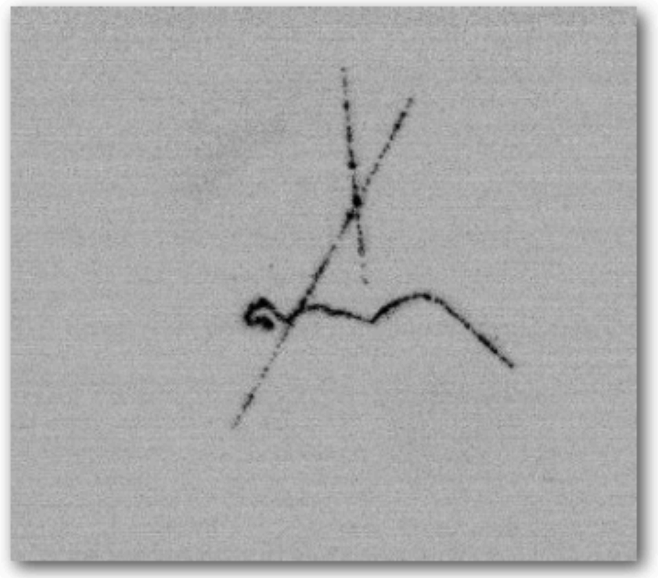


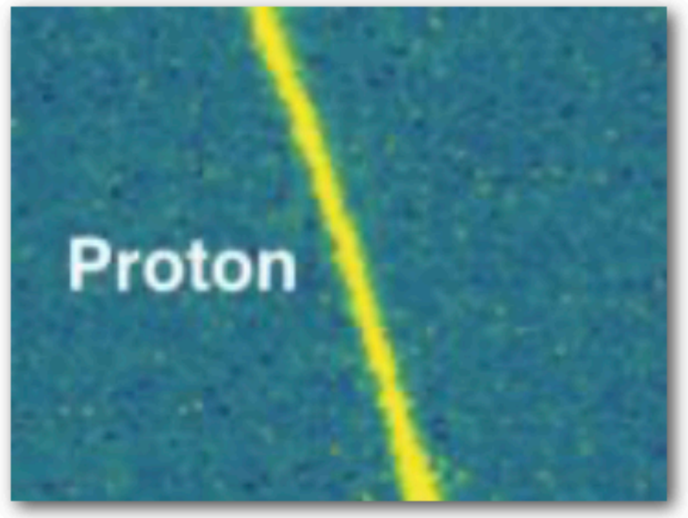




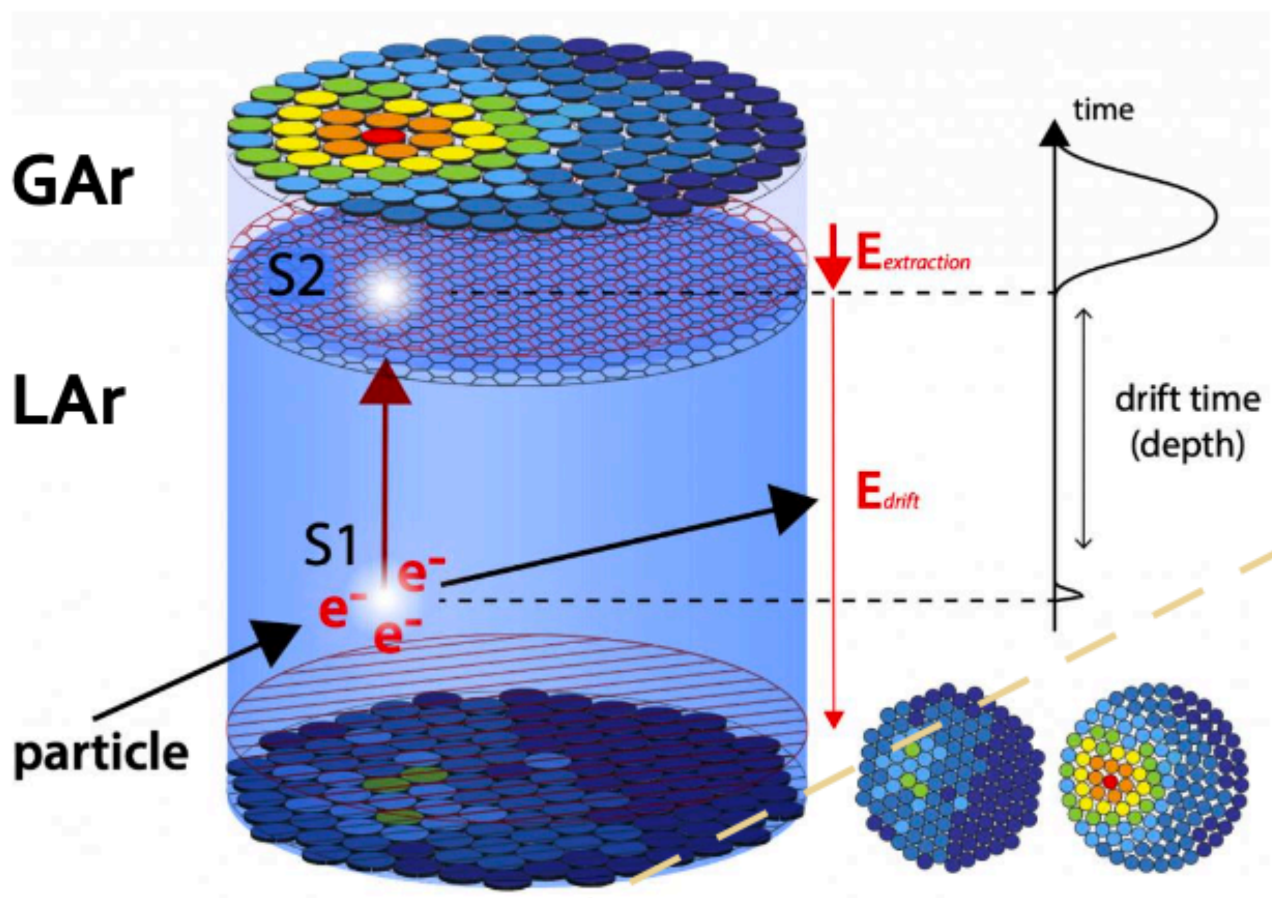


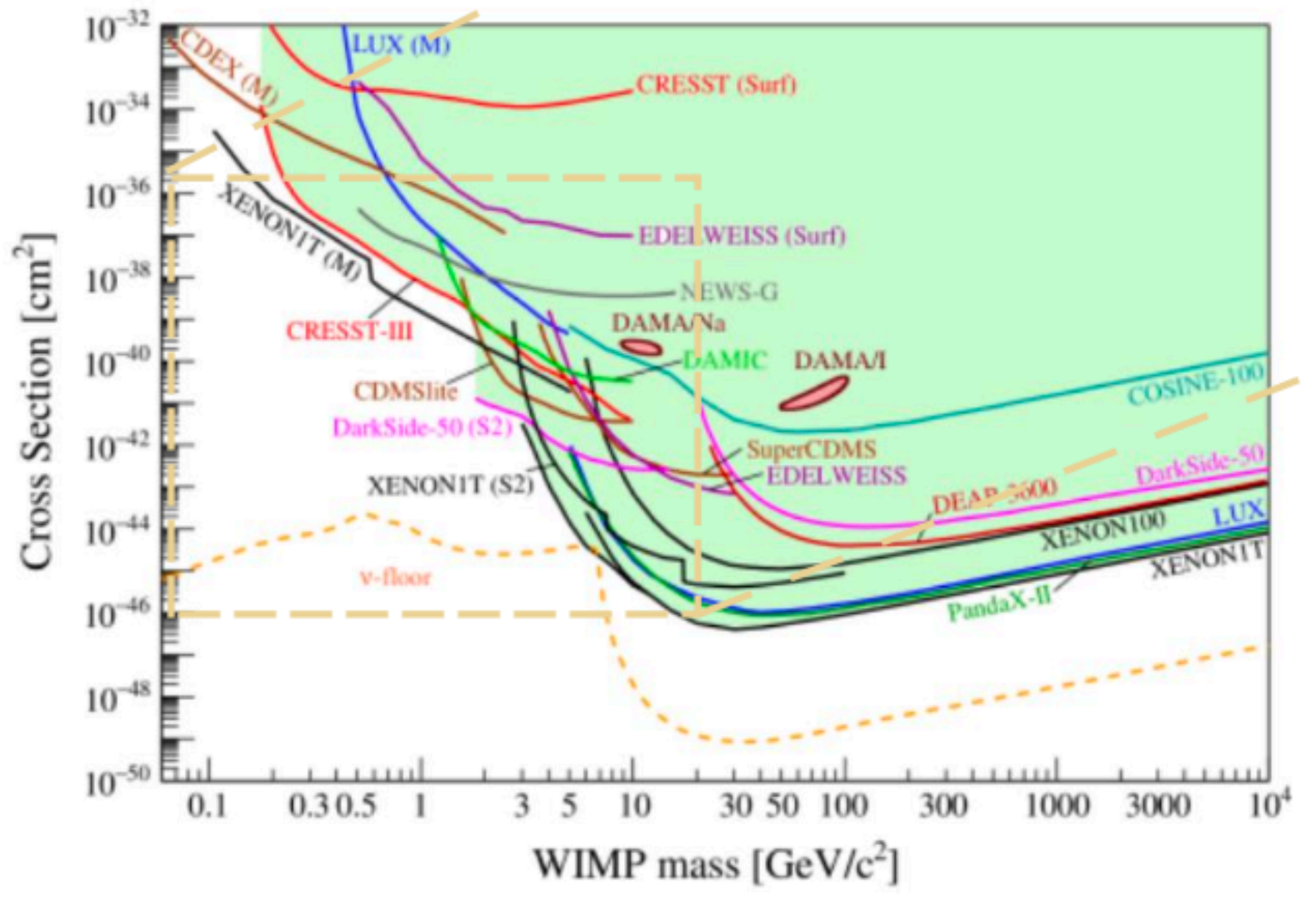






Challenges in Dark Matter-LowMass quest





How to explore low mass Dark Matter?

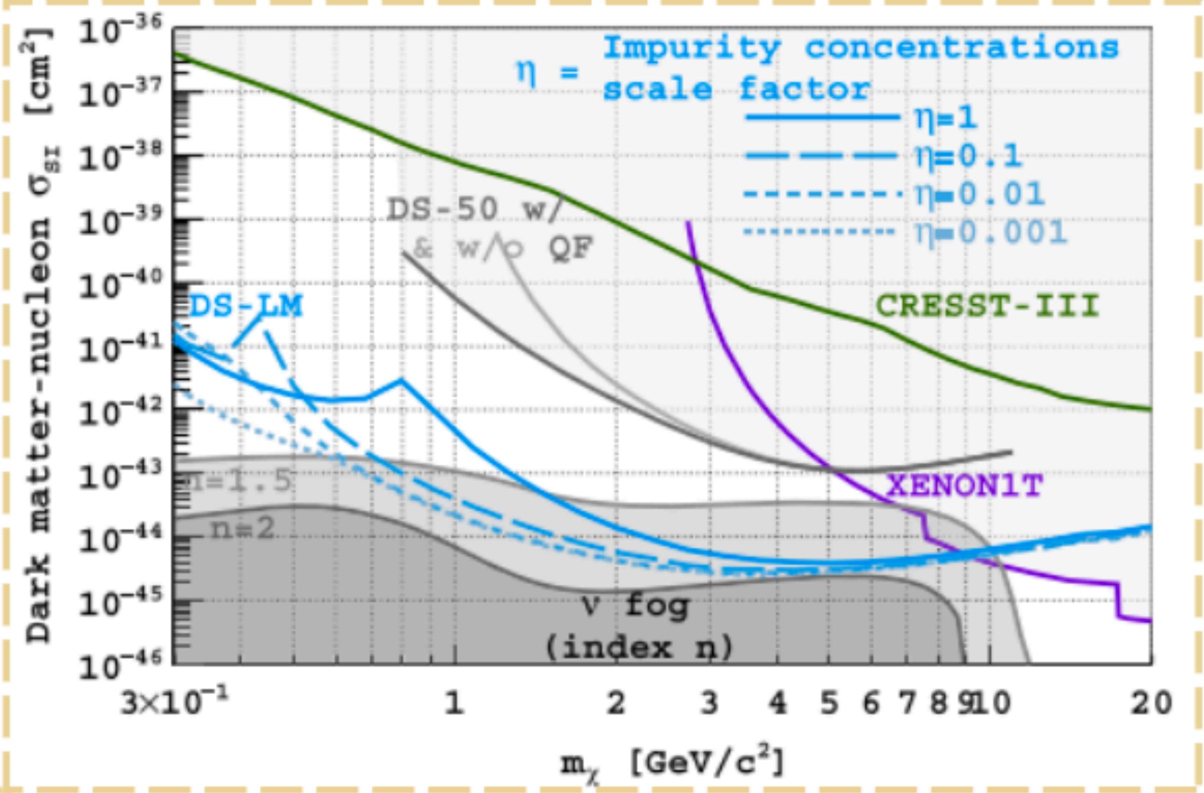
- Exposure (time and target mass) ➡ Typical approach low atomic mass target materials (CYGNO Experiment)
- Reduce/control background
- Improve energy threshold

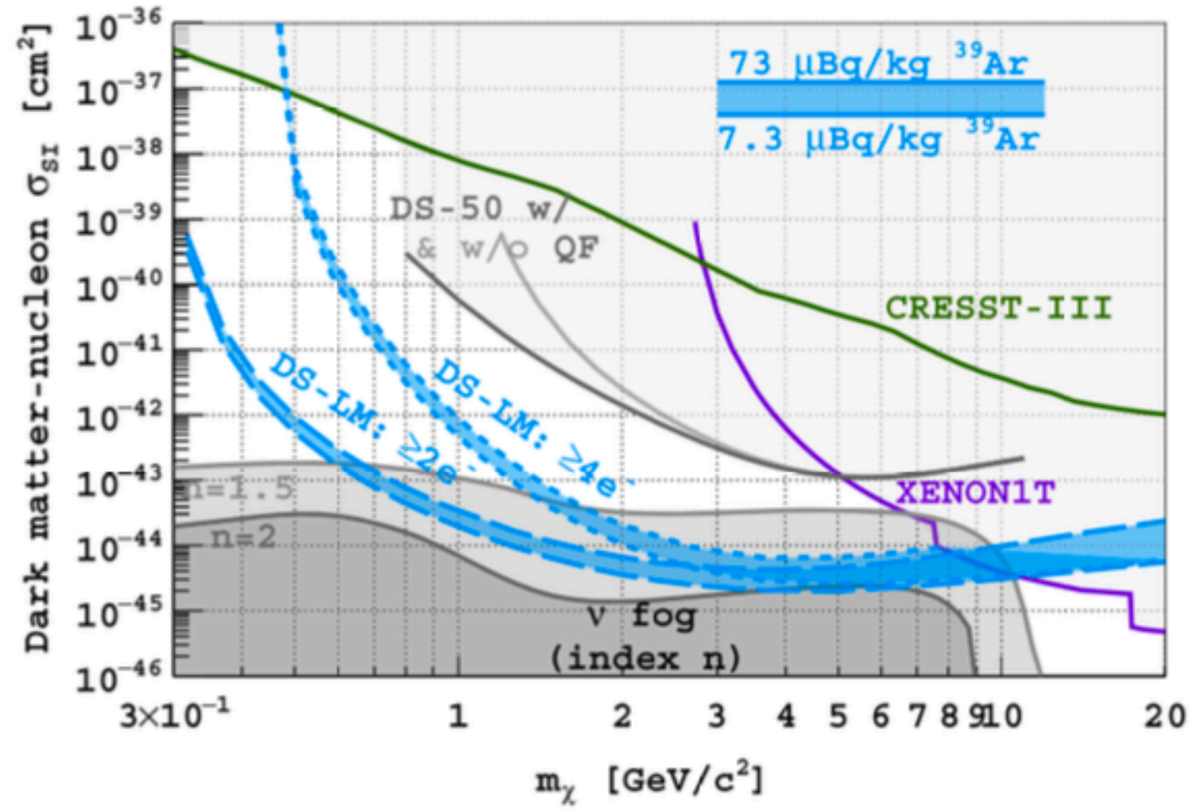
S2-only analyses allowing an increase in the sensitivity for low mass candidates

- particle discrimination
- z-coordinate information

(S1 fall under energy threshold)

Lost



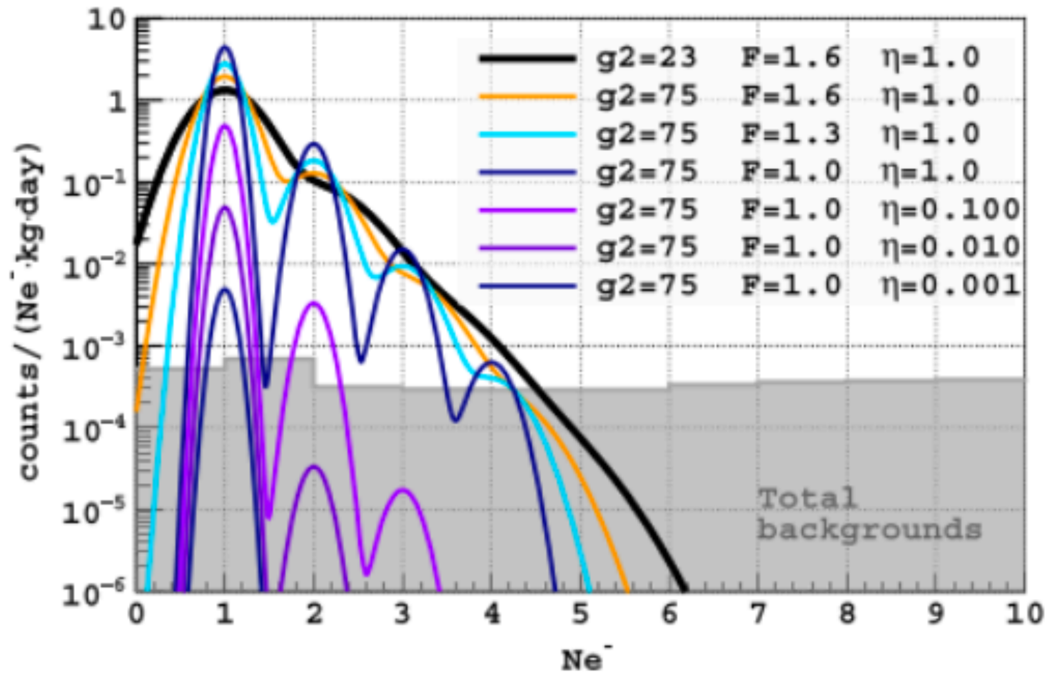


Historical marks:

- Time Projection Chamber (TPC) introduced in 1977 by David Nygren.

Low-energy sensitivity improves, many detectors start to see a large number of not-well-identified low-energy events (excess of events).

SEs dominate signals below 4 e−.

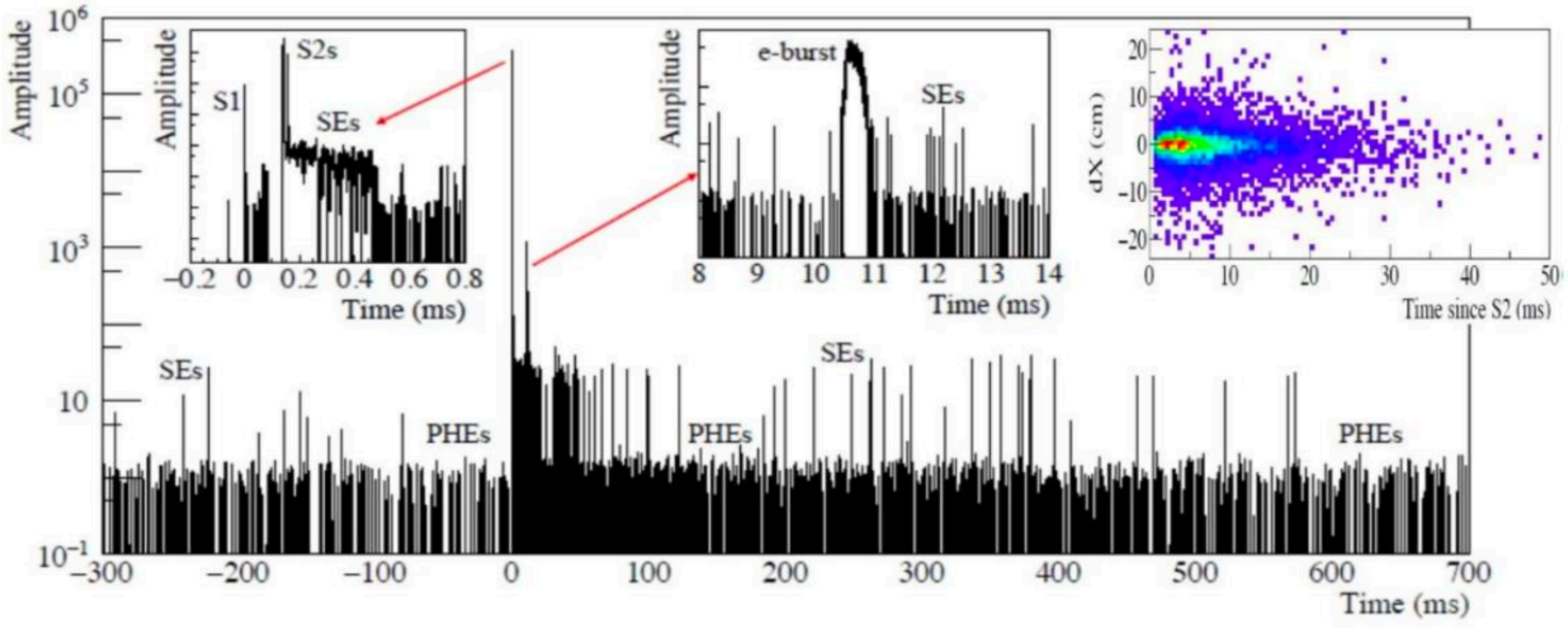


Problem: Poor background understanding at these energies.

How to improve background?

Challenges in Dark Matter-LowMass (sub-GeV) quest

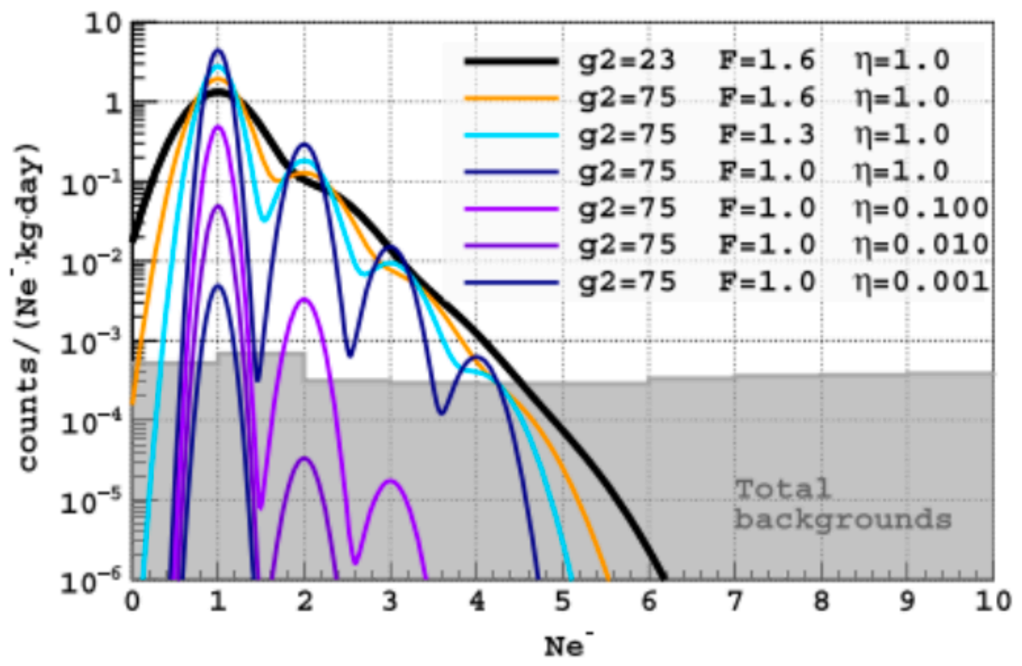
As mentioned SEs dominate signals below 4e-.

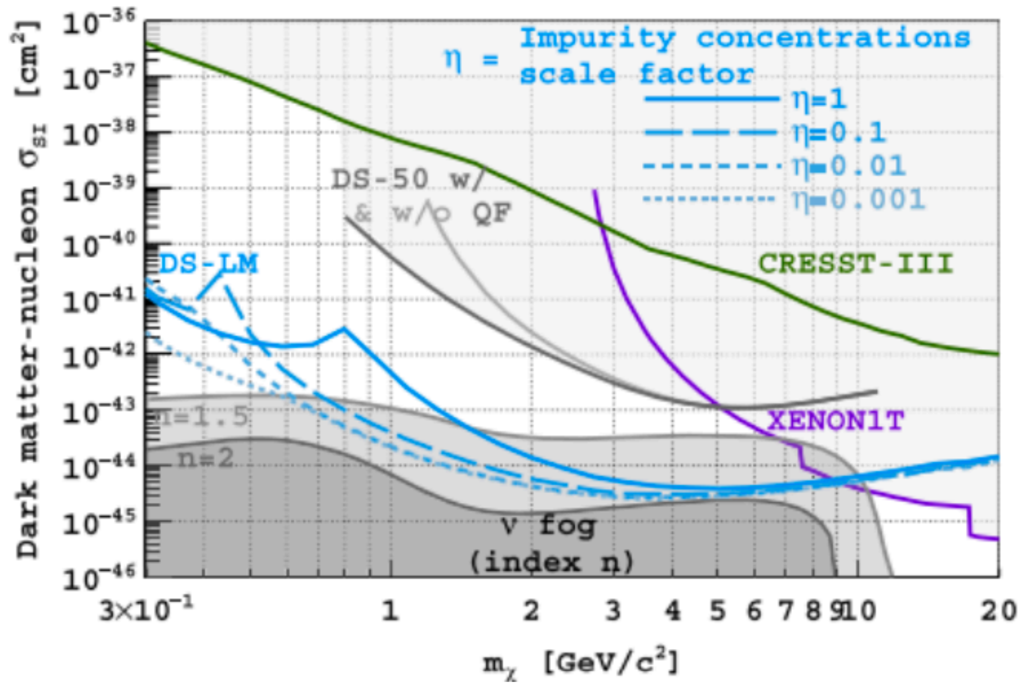


What is the origin of these spurious events?

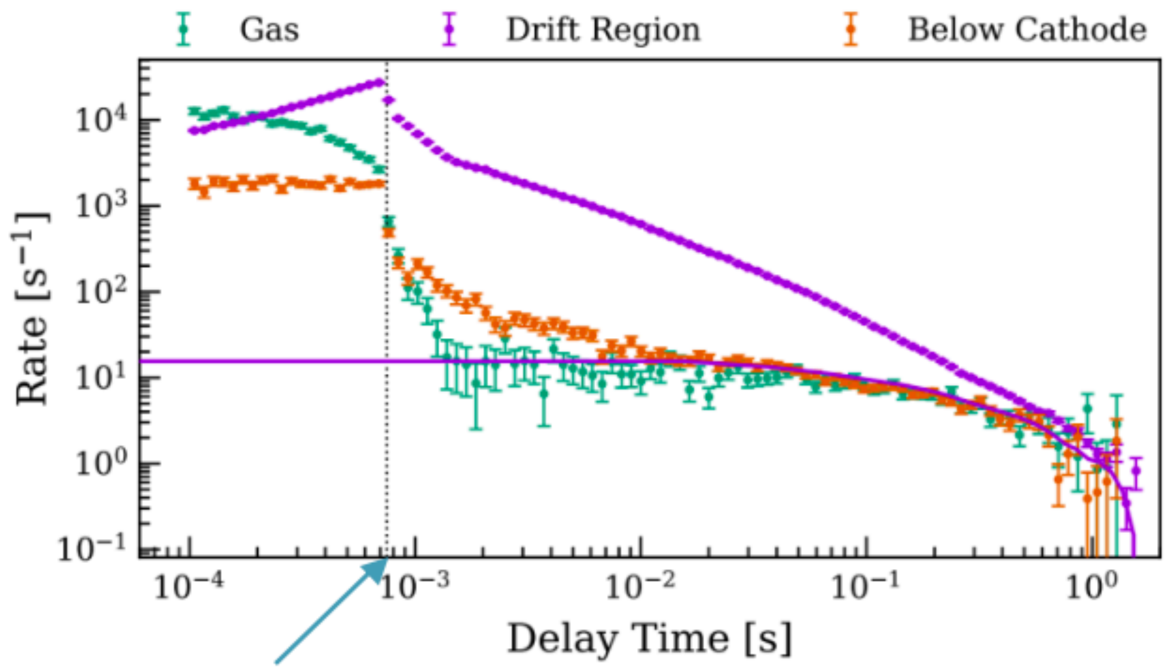
Origin of the emission:

1. Spontaneous emission of electrons accumulated under the interface;
2. Photoemission of electrons from negative ions under the interface;
3. Photoemission of electrons from the cathode by very intense electroluminescence;



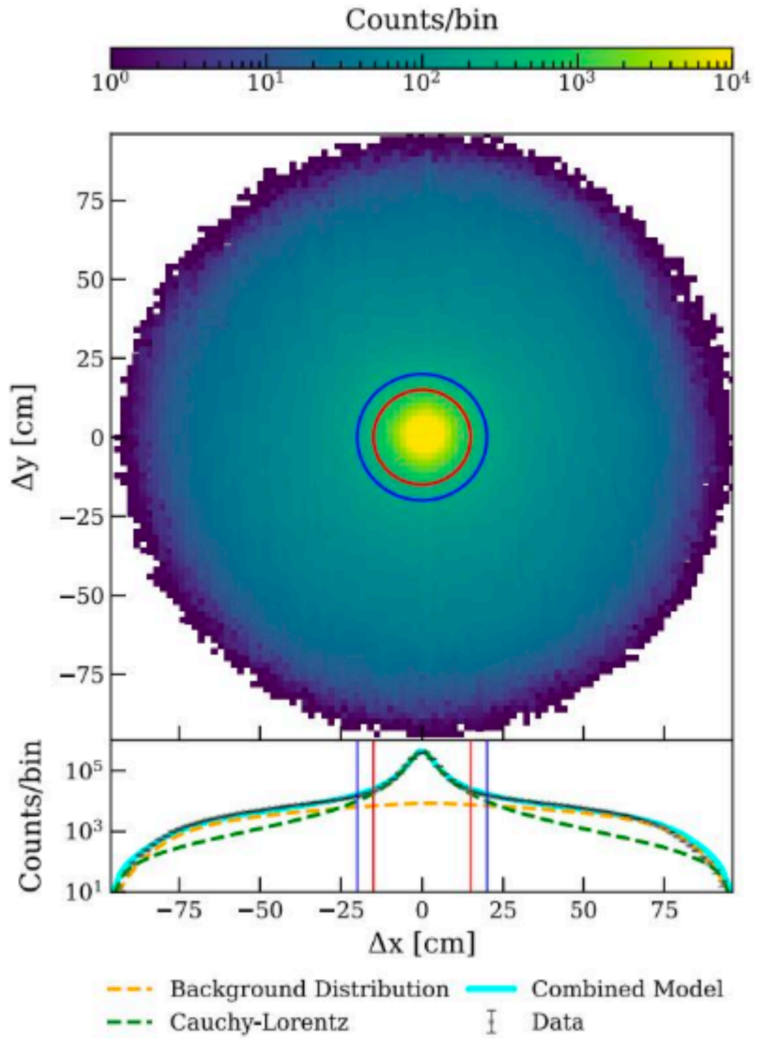


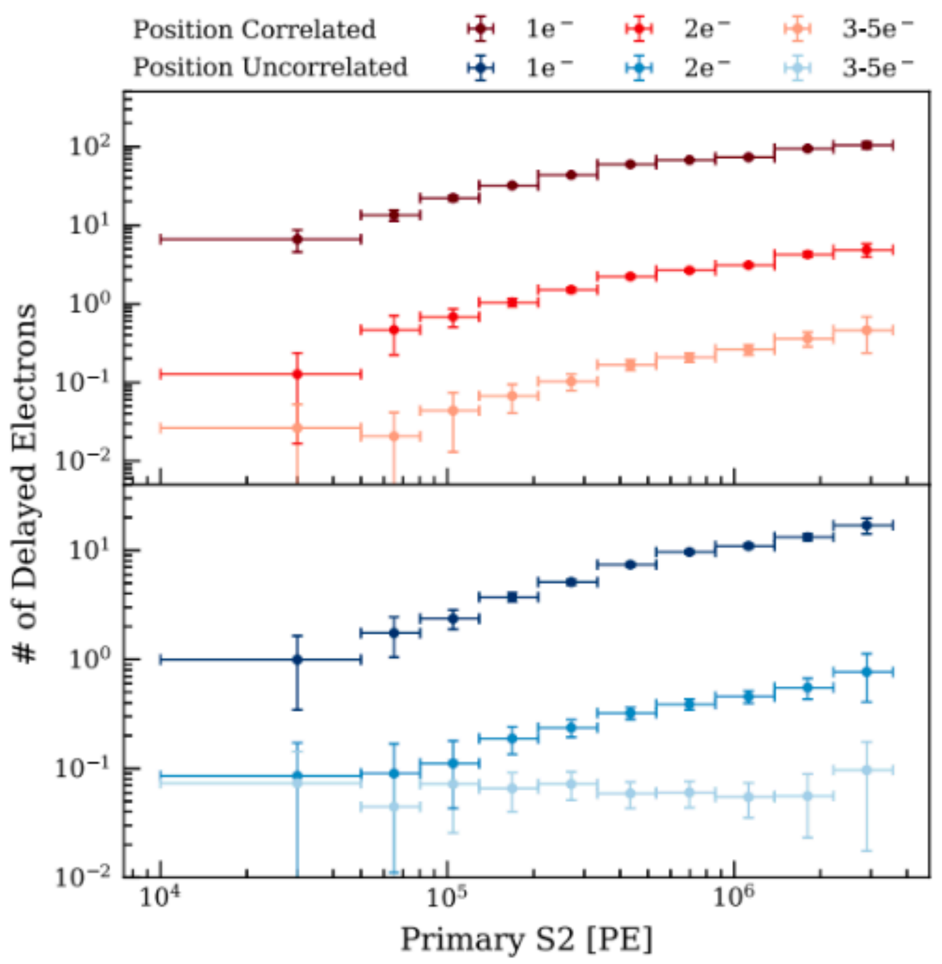
(i) Detector region



Maximum drift time (XENON TPC)

(ii) X-Y correlation to previous S2 event (drift region only)





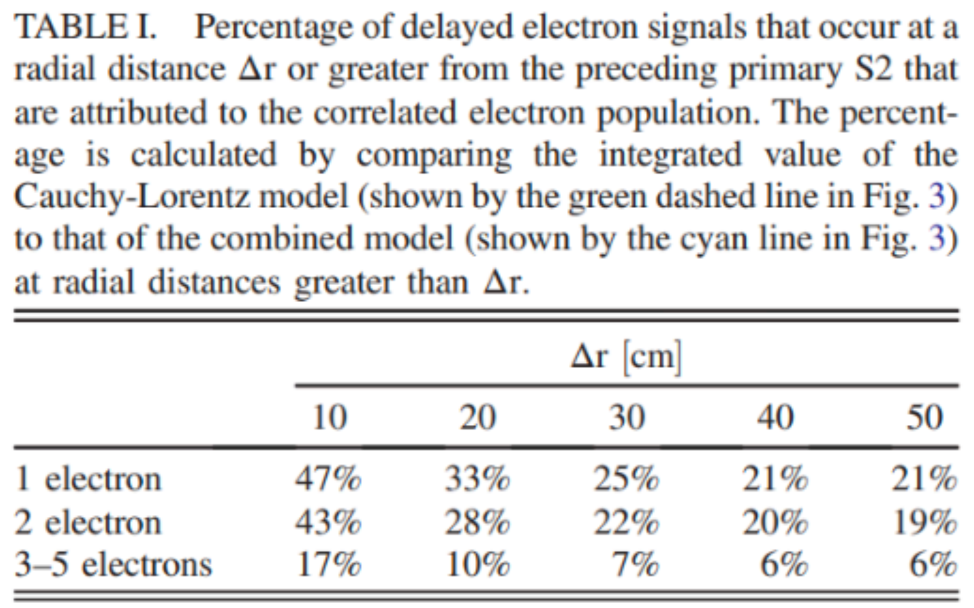


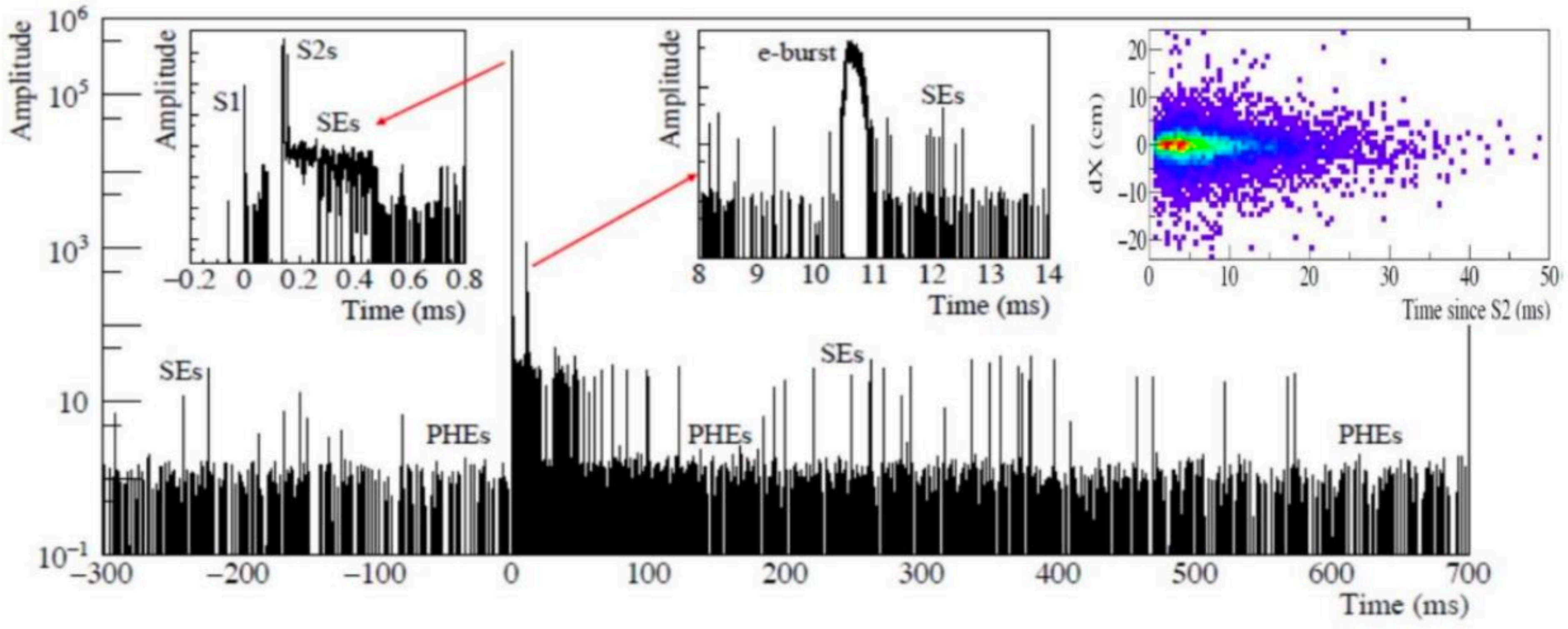
TABLE I. Percentage of delayed electron signals that occur at a radial distance Δr or greater from the preceding primary S2 that are attributed to the correlated electron population. The percentage is calculated by comparing the integrated value of the Cauchy-Lorentz model (shown by the green dashed line in Fig. 3) to that of the combined model (shown by the cyan line in Fig. 3) at radial distances greater than Δr.

	Δr [cm]				
	10	20	30	40	50
1 electron	47%	33%	25%	21%	21%
2 electron	43%	28%	22%	20%	19%
3–5 electrons	17%	10%	7%	6%	6%

Note: Position uncorrelated was defined for interaction positions greater than 20 cm.

XENON Collaboration results
(Aprile et al, Phys. Rev. D 106 (2022), 022001)

Challenges in Dark Matter-LowMass (sub-GeV) quest



Considerations on electron transport through the interface between liquid and gas phase.

- Potential energy of electrons near the interface depends on its original position (z coordinate);

Two things can happen:
- If pz (momentum along z axis) > p0, the electron is transmitted to the gas-phase
- If pz < p0, the elec

However

The electrons localized under the surface can nevertheless escape from the condensed dielectric owing to thermal electron emission process, although this process may require a significant time.

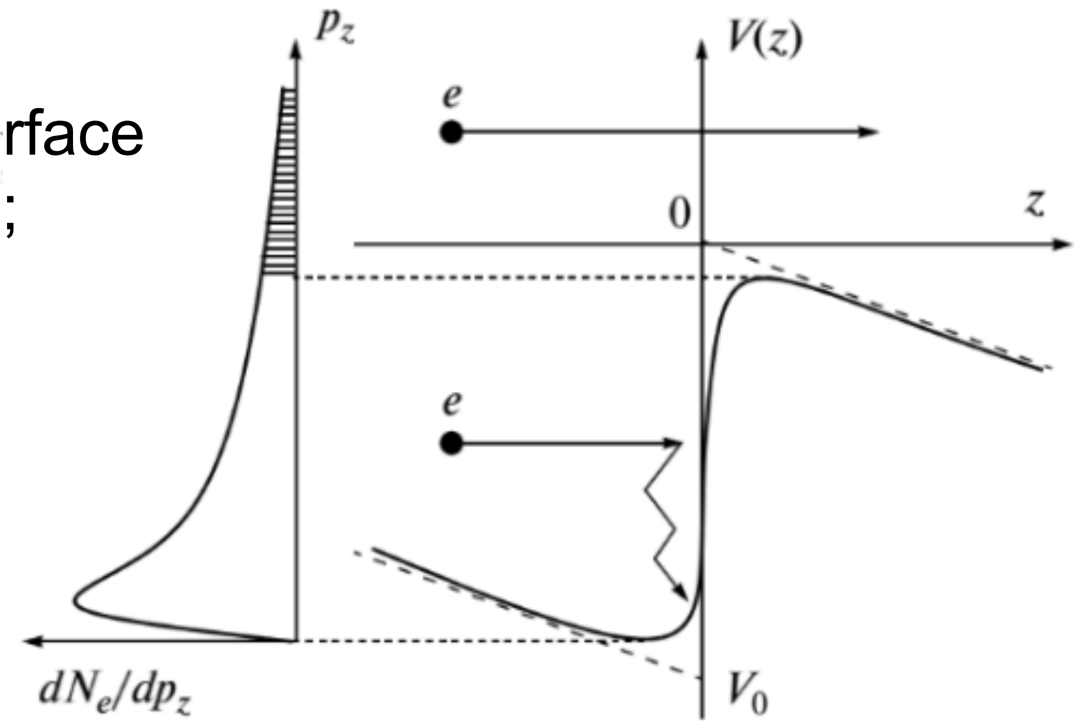


Fig. 1. Emission of hot electrons from a nonpolar dielectric with a negative energy of the ground state of quasi-free electrons V_0 into the rarefied phase ($z > 0$).

The **charge carriers** move towards the interface and **accumulate** at a depth **zo** that **corresponds** to the **minimum potential** (at the interface).

$$z_0 = -\left[\frac{e}{4E_1}\,\frac{\varepsilon_1-\varepsilon_2}{\varepsilon_1(\varepsilon_1+\varepsilon_2)}\right]^{1,}$$

Under certain favourable conditions, these charge carriers may be extracted from the condensed phase. The **emission is characterised by the emission time *te*** (vz drift velocity).

$t_e = l/v_z$ where $l = 3kT/(2eE_1)$

(linear space distribution of the electrons)

The total number of electrons emitted within the time t could be calculated by integration of the emission rate dN(t)/dt multiplied by the emission probability or coefficient (Ke)– non unity.

$$N(t) = N_0\exp(-t/t_e)$$

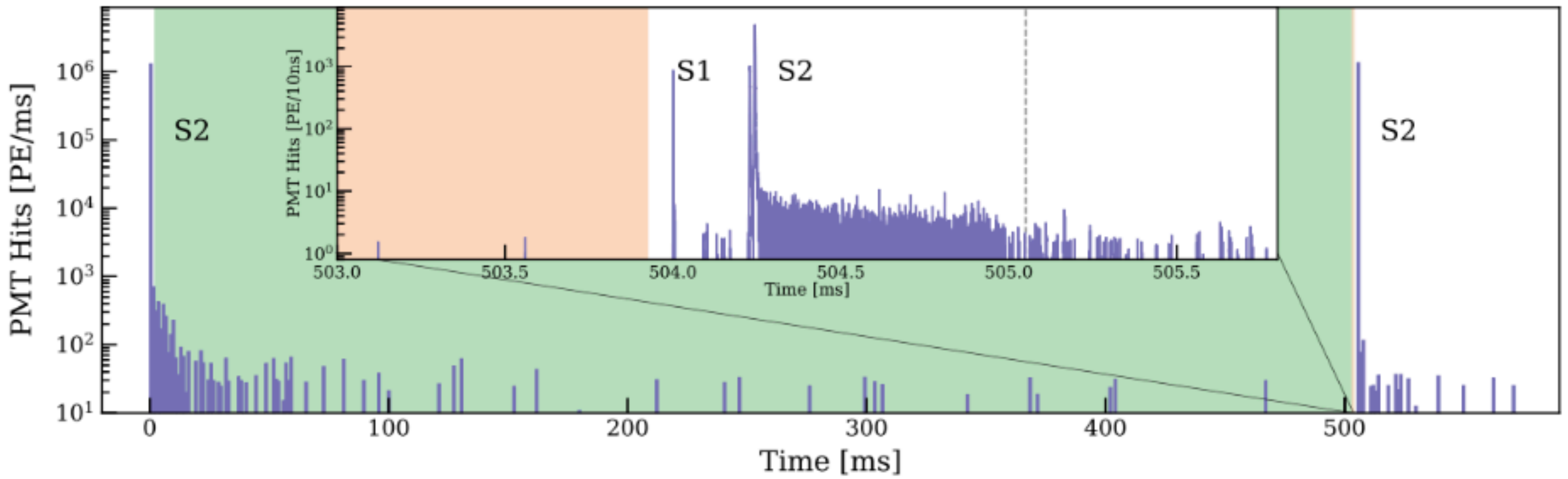
Note: Lifetime of quasi-free electrons is limited by impurity level and consequently the time tc till the moment of their trapping by an electronegative impurity.

$$K_e = N_e(\infty)/N_0 = (1 + t_e/t_c)^{-1}$$

(Akimov et al, Instruments and Experimental Techniques, 2012, Vol. 55, No. 4, pp. 423–428)

Challenges in Dark Matter-LowMass (sub-GeV) quest

Typical PMT signal (XENON Experiment)



So far we've seen that this emission can be either prompt or delayed, depending on the electric field that influences the potential barrier width.

Looking at the energy distribution we can see:

- Height of the potential barrier is comparable to the kinetic energy (quasi-free electrons);
- Penetration through the potential barrier may occur at the expense of thermal energy (for example);

Mechanisms that can contribute to this emission whose influence is not completely understood...

Internal

- long-term exposure to ionizing radiation,
- temperature and pressure variation,
- electric and magnetic fields,
- surface instabilities (ripples, waves, microexplosions)

External

- exposure to light (including near-UV and IR),
- changes in the microwave or RF backgrounds,
- mechanical stress or vibrations

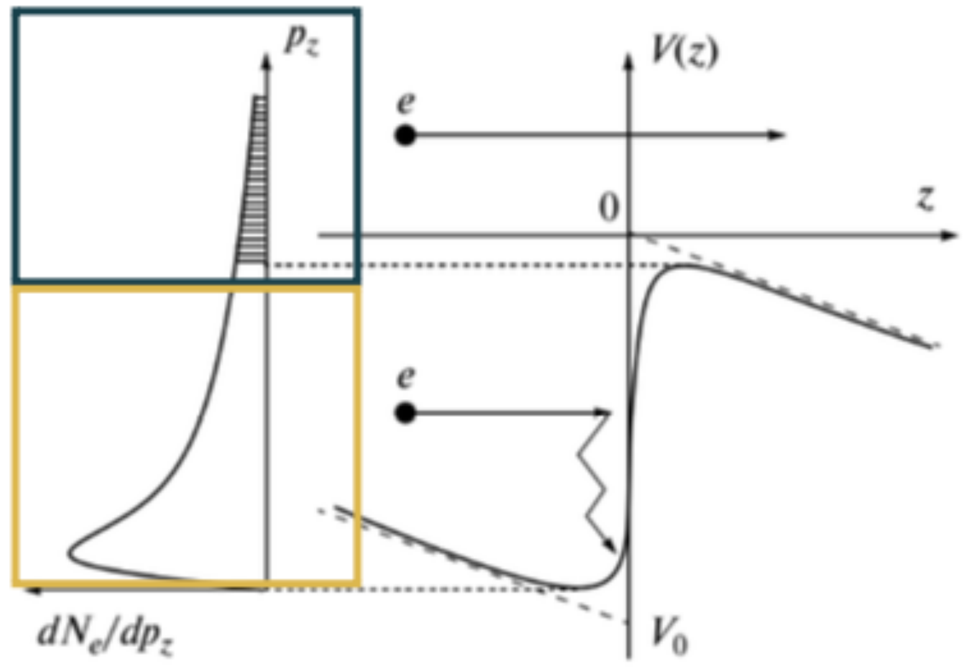


Fig. 1. Emission of hot electrons from a nonpolar dielectric with a negative energy of the ground state of quasi-free electrons V_0 into the rarefied phase ($z > 0$).

Unextracted electrons at the gas-liquid interface contributes to:

- change E/p in both liquid and gas-phase (energy resolution)
- increased electron diffusion under the surface (position resolution)
- spurious emission of electrons to the gas-phase (background)
- reduction of electron extraction by surface charges (thermalization and recombination with ions)

(Pereverzev, Journal of Instrumentation 18, 2023, C07011)

Challenges in Dark Matter-LowMass (sub-GeV) quest

How to increase the exposure?

Common strategies:
- Increase the target mass (mass, density, volume);
- Increase the exposure time;

How to improve the detection threshold?
The solution might reside in improving light detection

Common strategies:
- Enhanced light collection efficiency
- Novel amplification structures (improving the charge/light gain);
- New photosensors (improved sensitivity and gain)

Problem: lack of dedicated, scalable light amplification structures

State of the art solution:
- 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)

Challenges in Dark Matter-LowMass (sub-GeV) quest

How can we address these challenges?

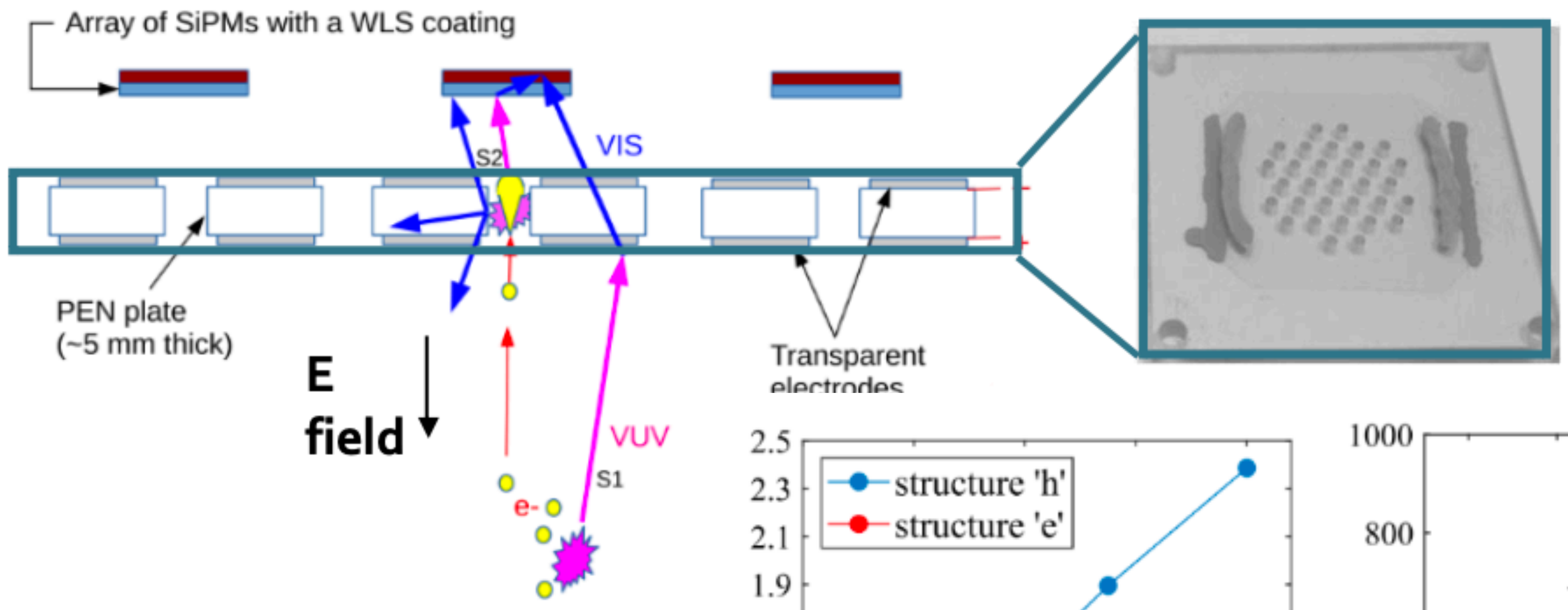
Novel Detector concepts for Future Dark Matter searches

R&D on novel amplification structures

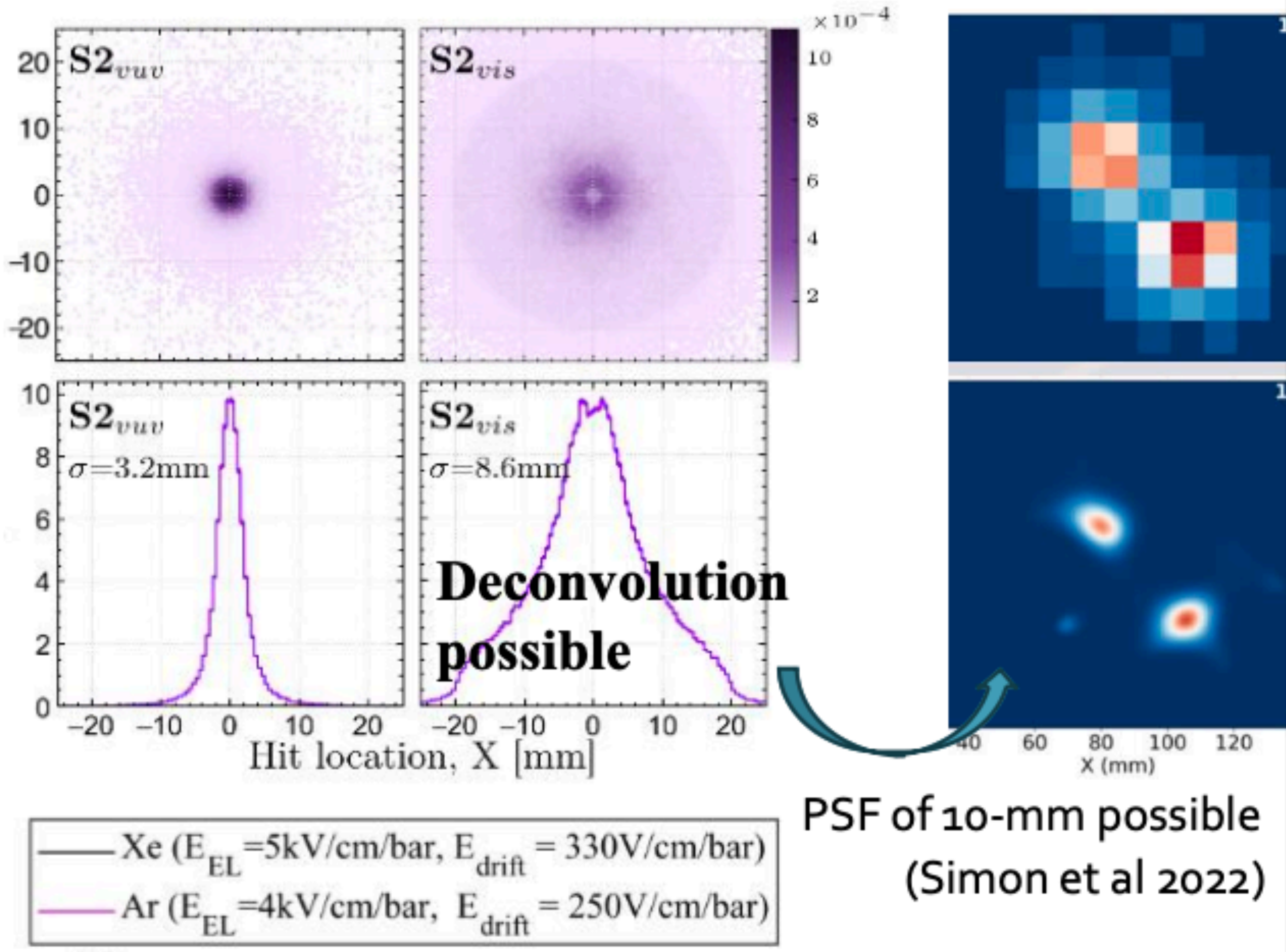
Wavelength-Shifting Field-Assisted Gas Electroluminescence Multiplier (WLS FAT-GEM)

New structure developed at ASTROCENT and IGFAE

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



Simulation:

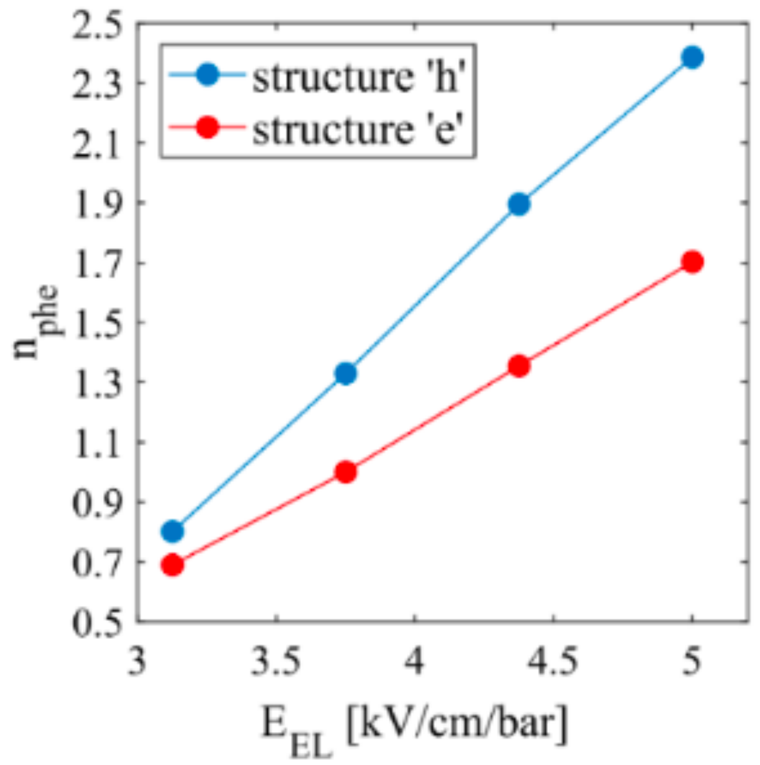


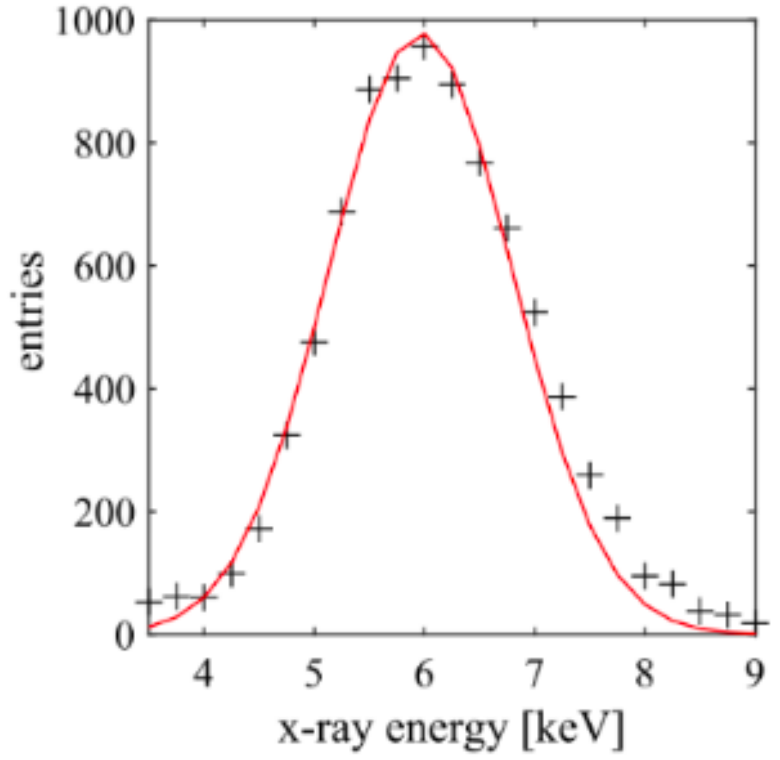
PSF of 10-mm possible (Simon et al 2022)

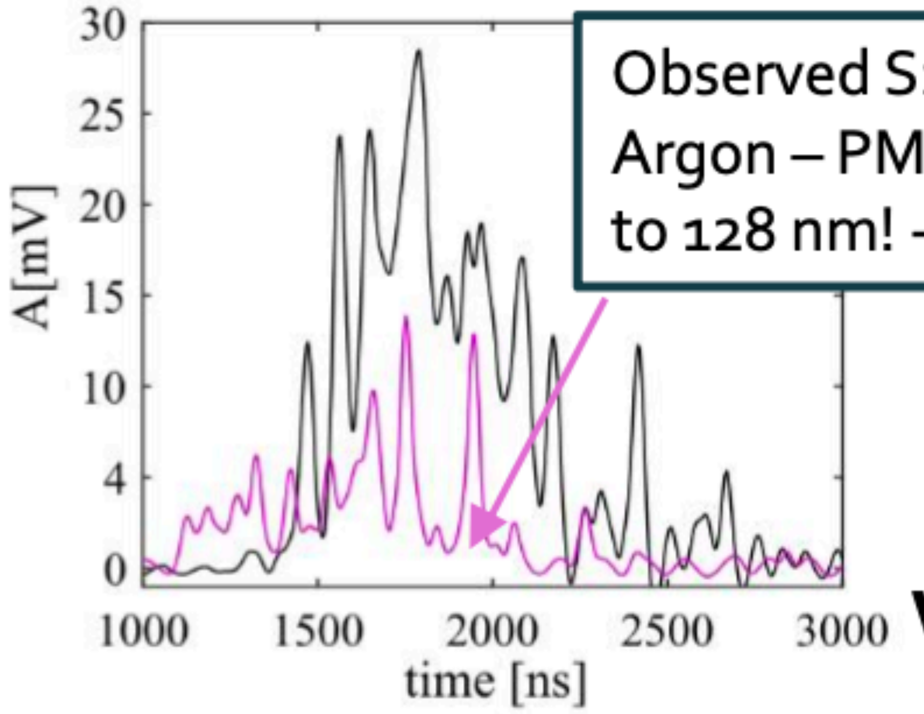
Preliminary results:

Comparison with a TPC supplied with wire mesh electrodes, shows:

- Similar S1 light collection yield (up to 75%);
- Up to 2-3 times higher S2;







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

What to do?

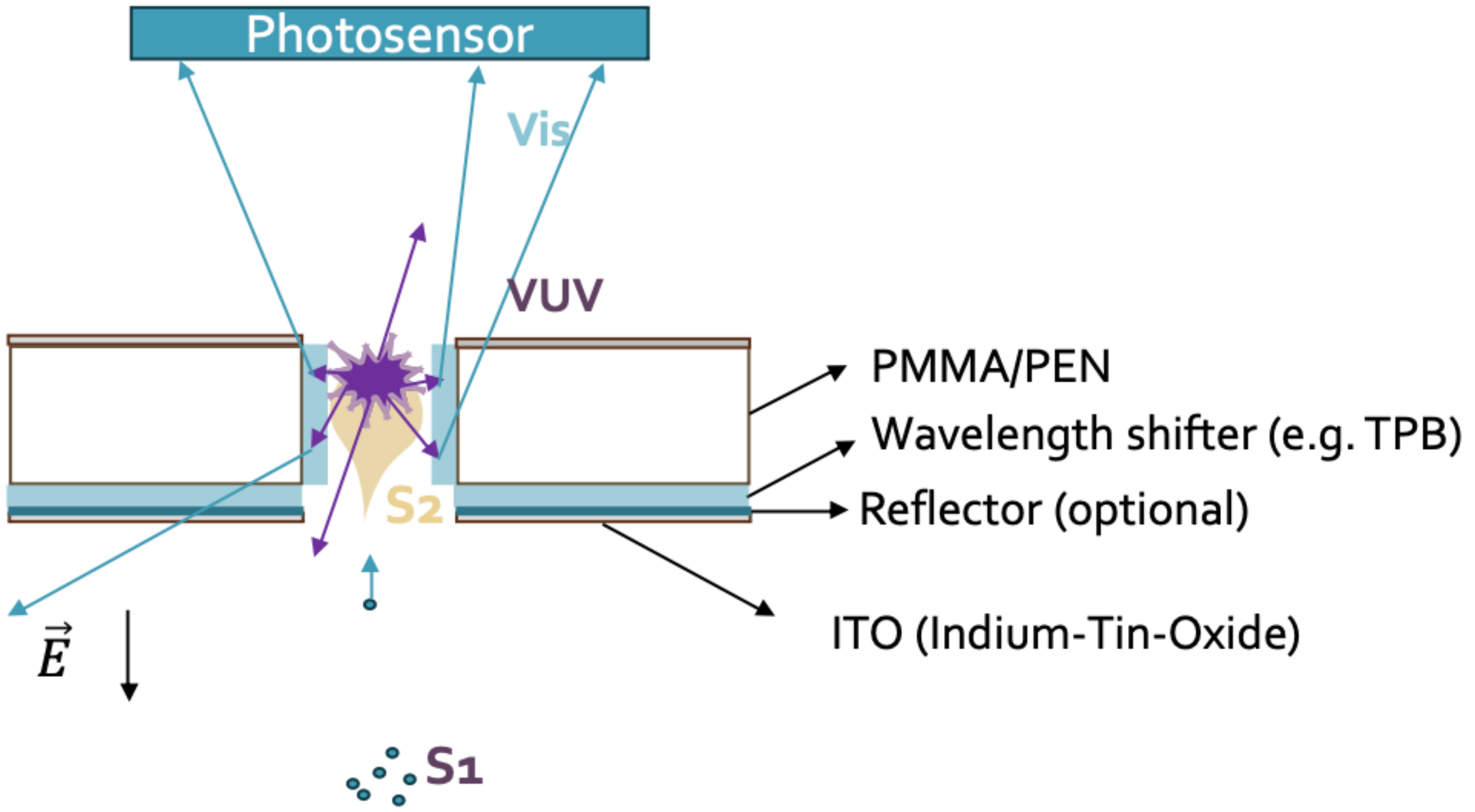
Main limitation: PEN has low wavelength shifting efficiency.

Novel Detector concepts for Future Dark Matter searches

R&D on novel 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)

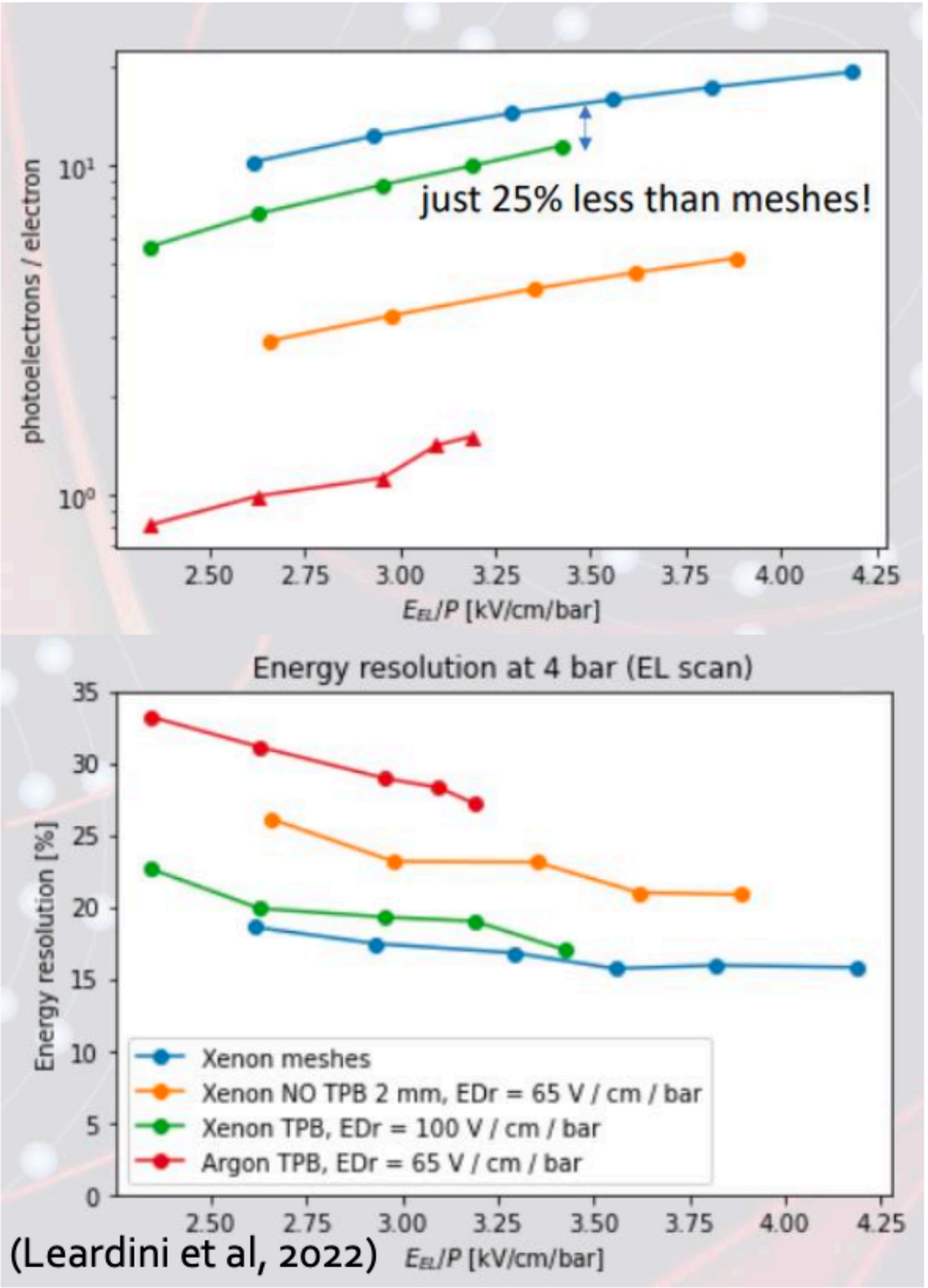


PMMA/PEN

Wavelength shifter (e.g. TPB)

Reflector (optional)

ITO (Indium-Tin-Oxide)



just 25% less than meshes!

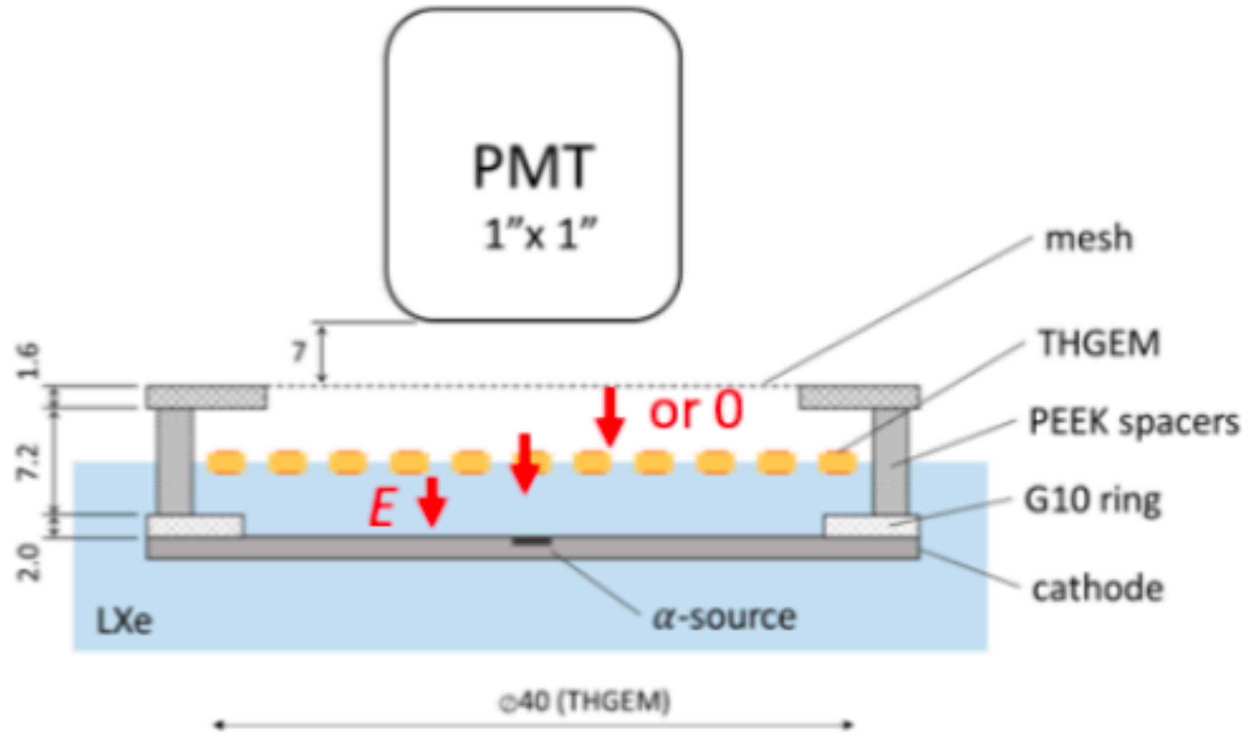
(Leardini et al, 2022)

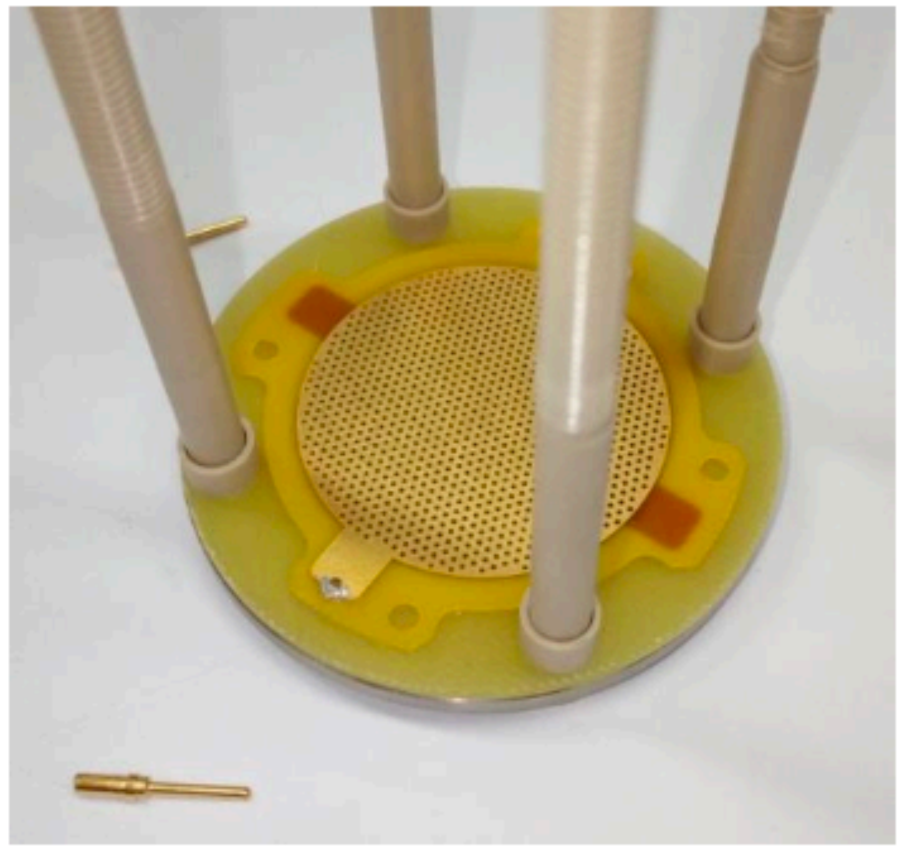
Novel Detector concepts for Future Dark Matter searches

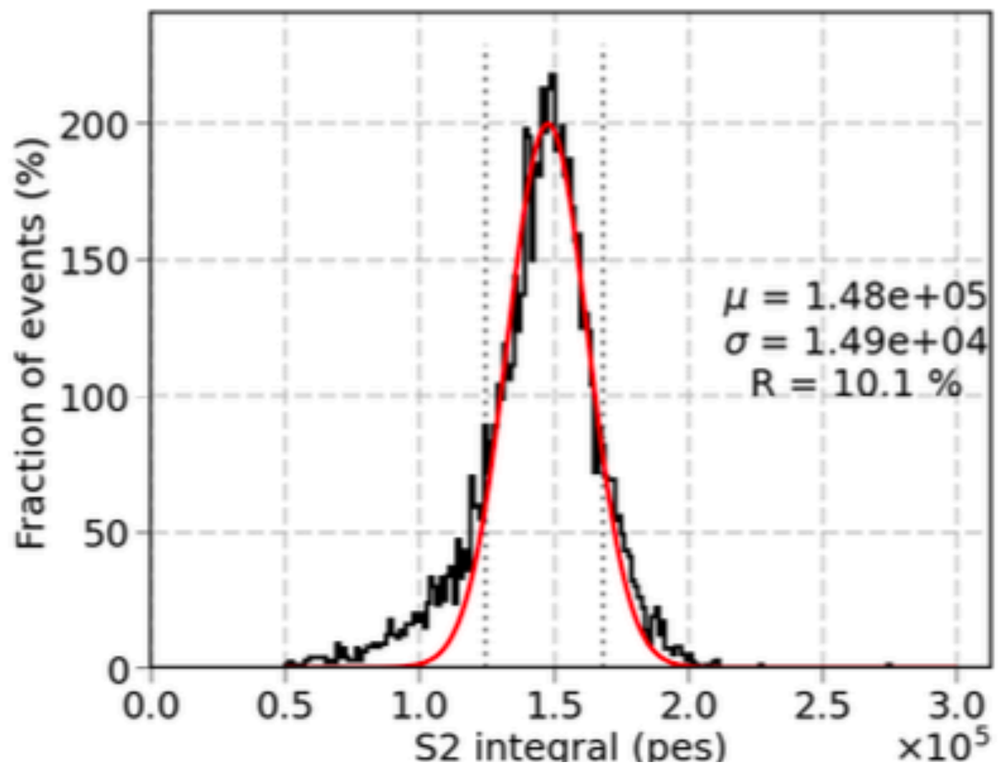
R&D on novel amplification structures

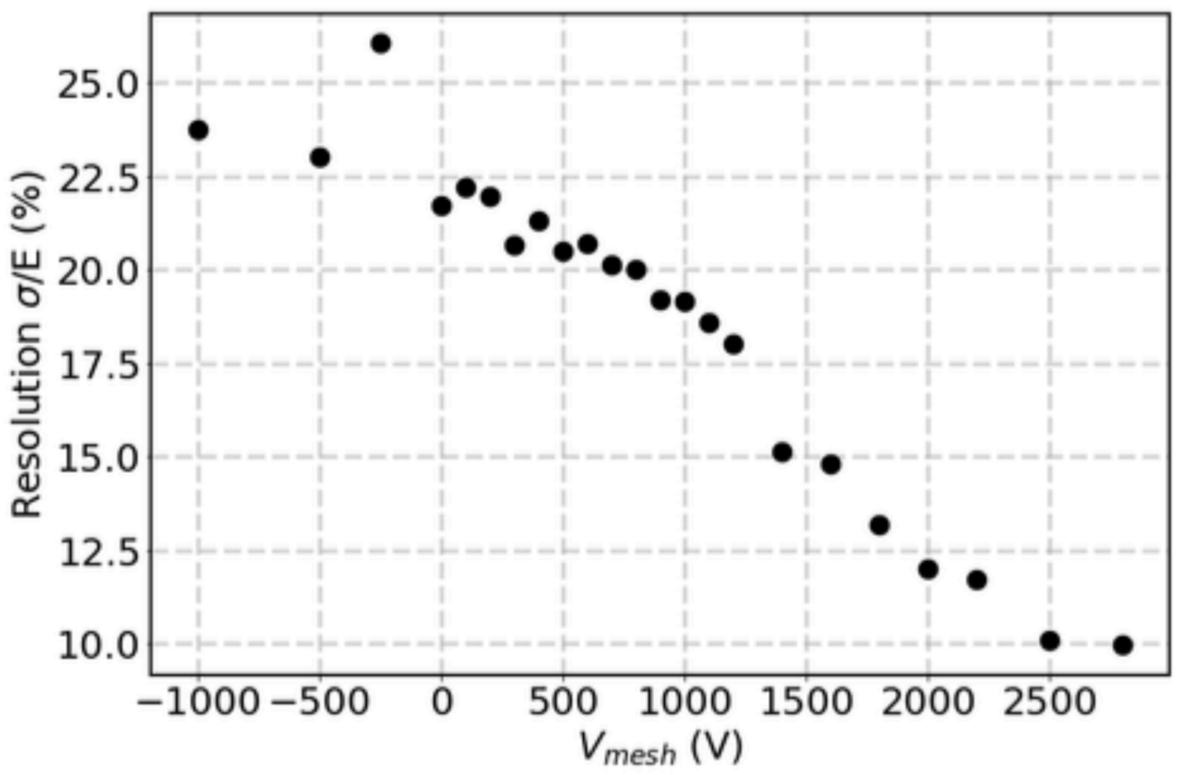
A floating Thick-GEM was already successfully tested in LXe…

(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)?

Novel Detector concepts for Future Dark Matter searches

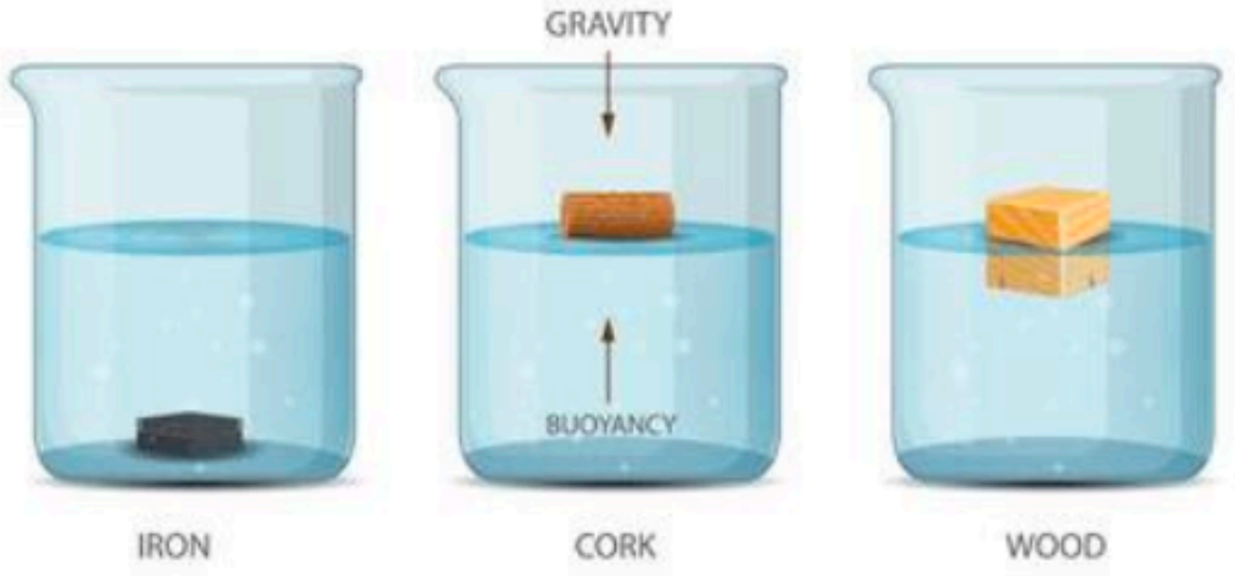
R&D on novel amplification structures

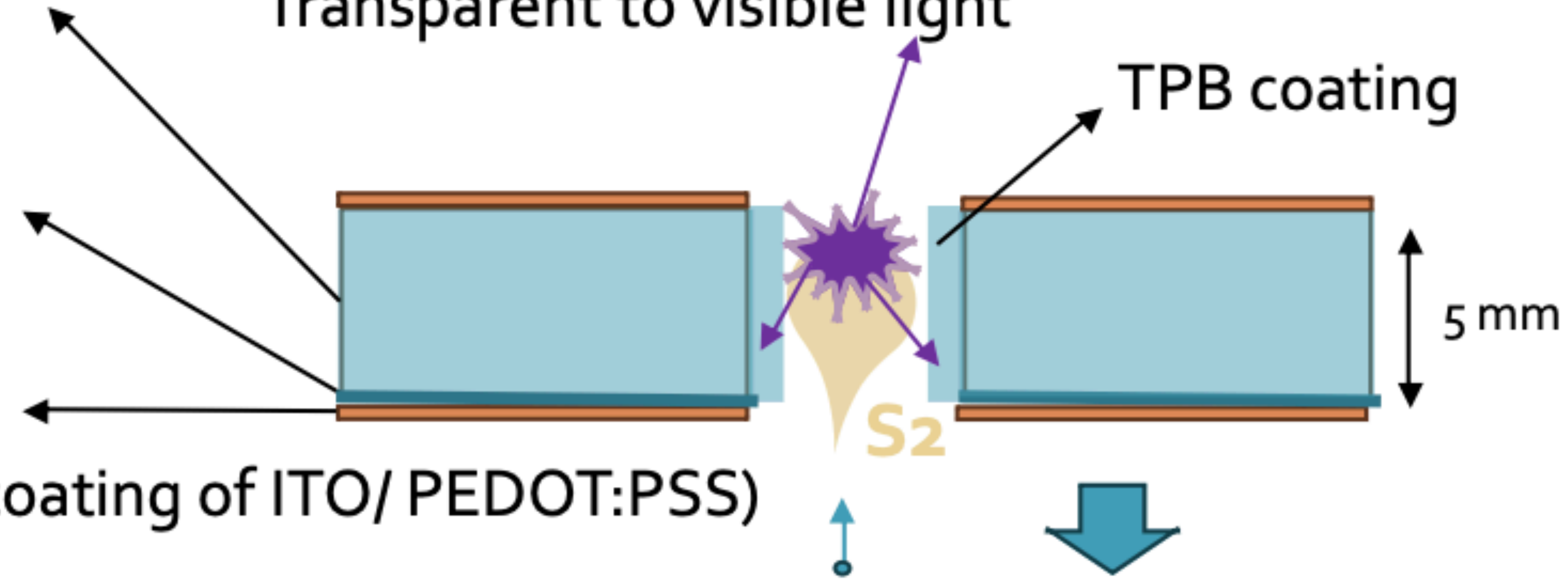
Floating Wavelength-Shifting Field-Assisted Gas Electroluminescence Multiplier (FWLS FAT-GEM)

ongoing effort with Kuzniak (Astrocent)

How to design?

Archimedes principle





polyethylene naphthalate (PEN) ⇨ Wavelength-shifting + Transparent to visible light

(bulk material)

$\rho_{PEN} = 1.36$ g/cm^3

Reflective coating (plus TPB)

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

TPB coating

Enable detection of S1 and S2

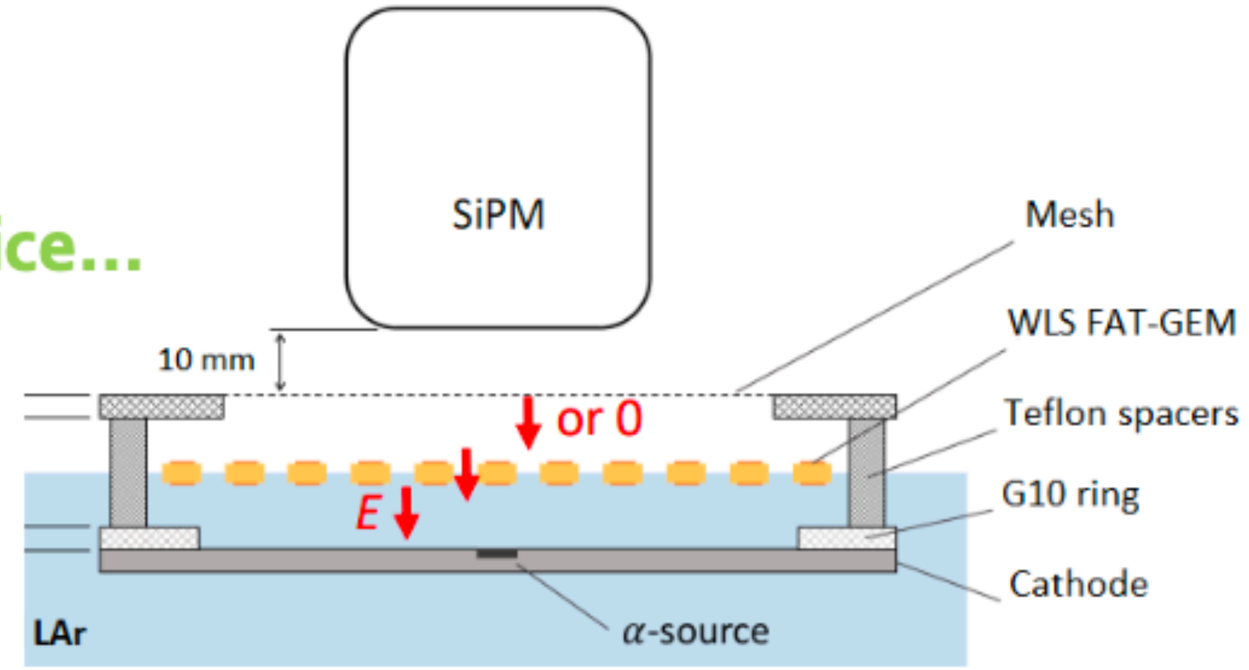
Optimizes the collection of S1 and S2

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

$\rho_{LAr} = 1.40$ g/cm^3

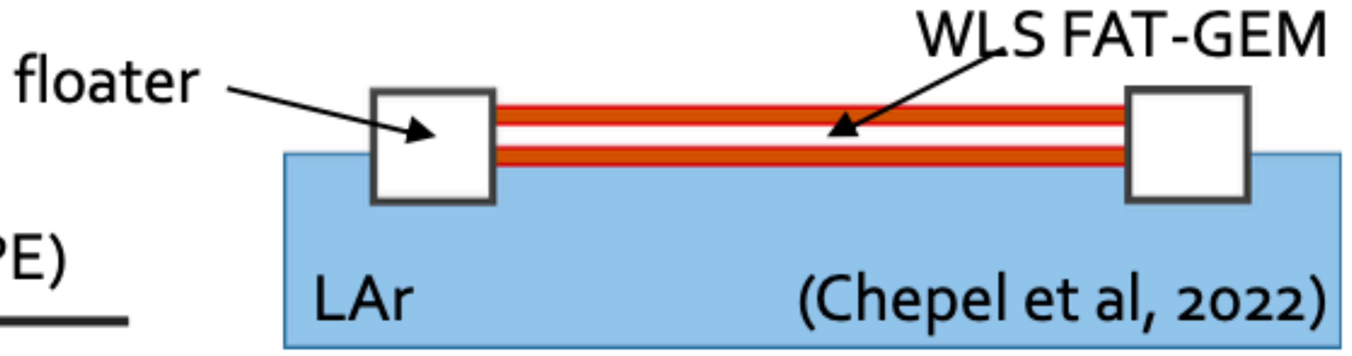
For **PEN-based WLS:** V_{sub}/V_{Total} is equal to **0.97**

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.

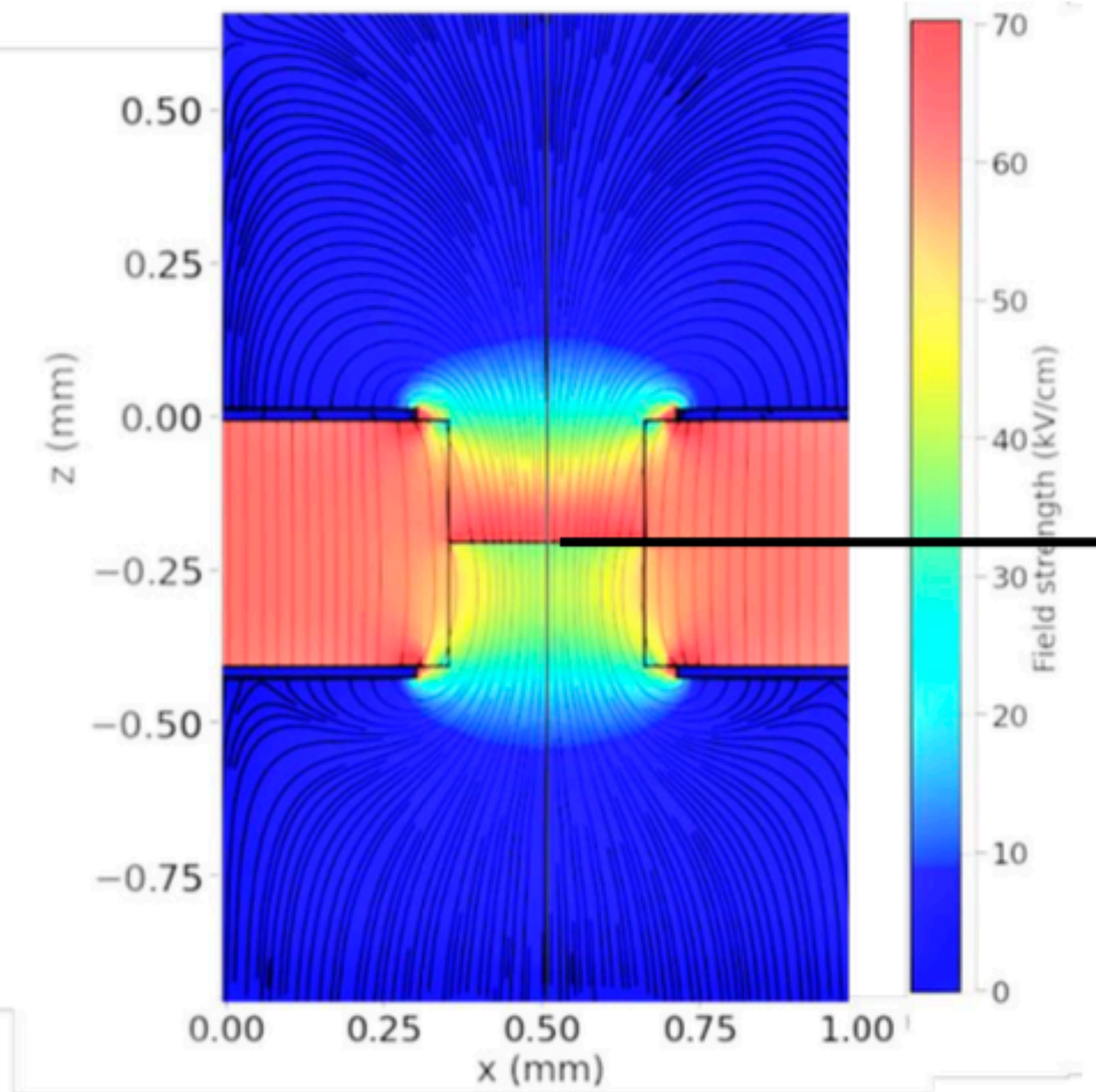
Novel Detector concepts for Future Dark Matter searches

R&D on novel amplification structures

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

How to test?

From simulations we know..



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

(Chepel et al, 2022)

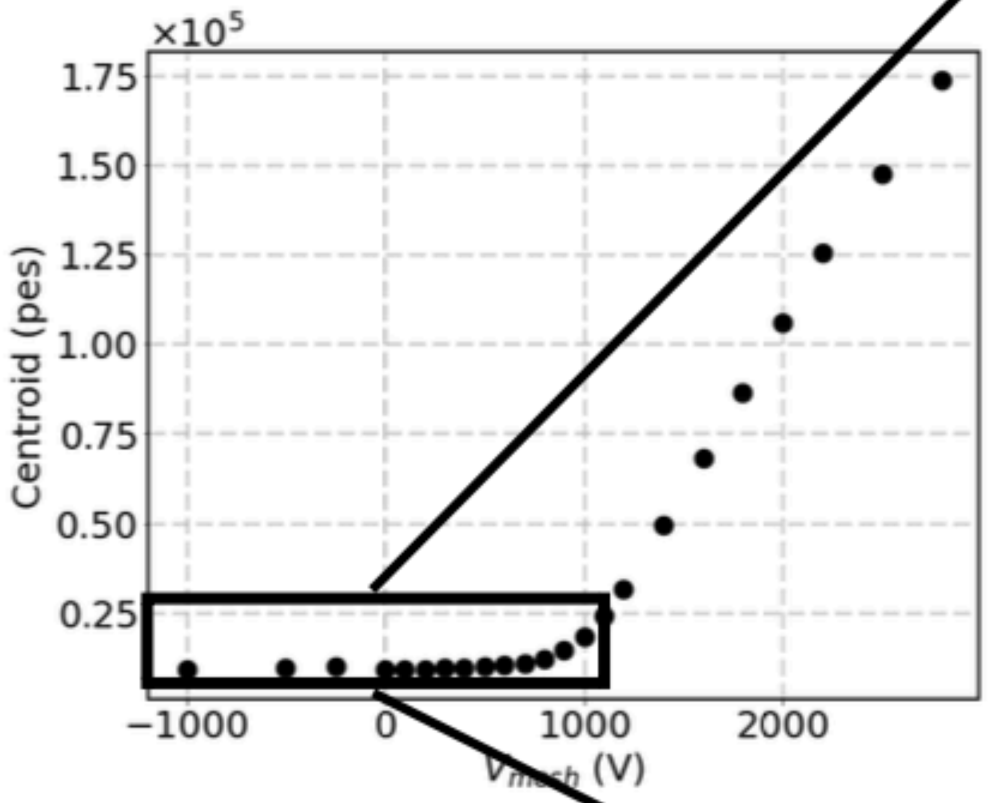
Fields near the interface:

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

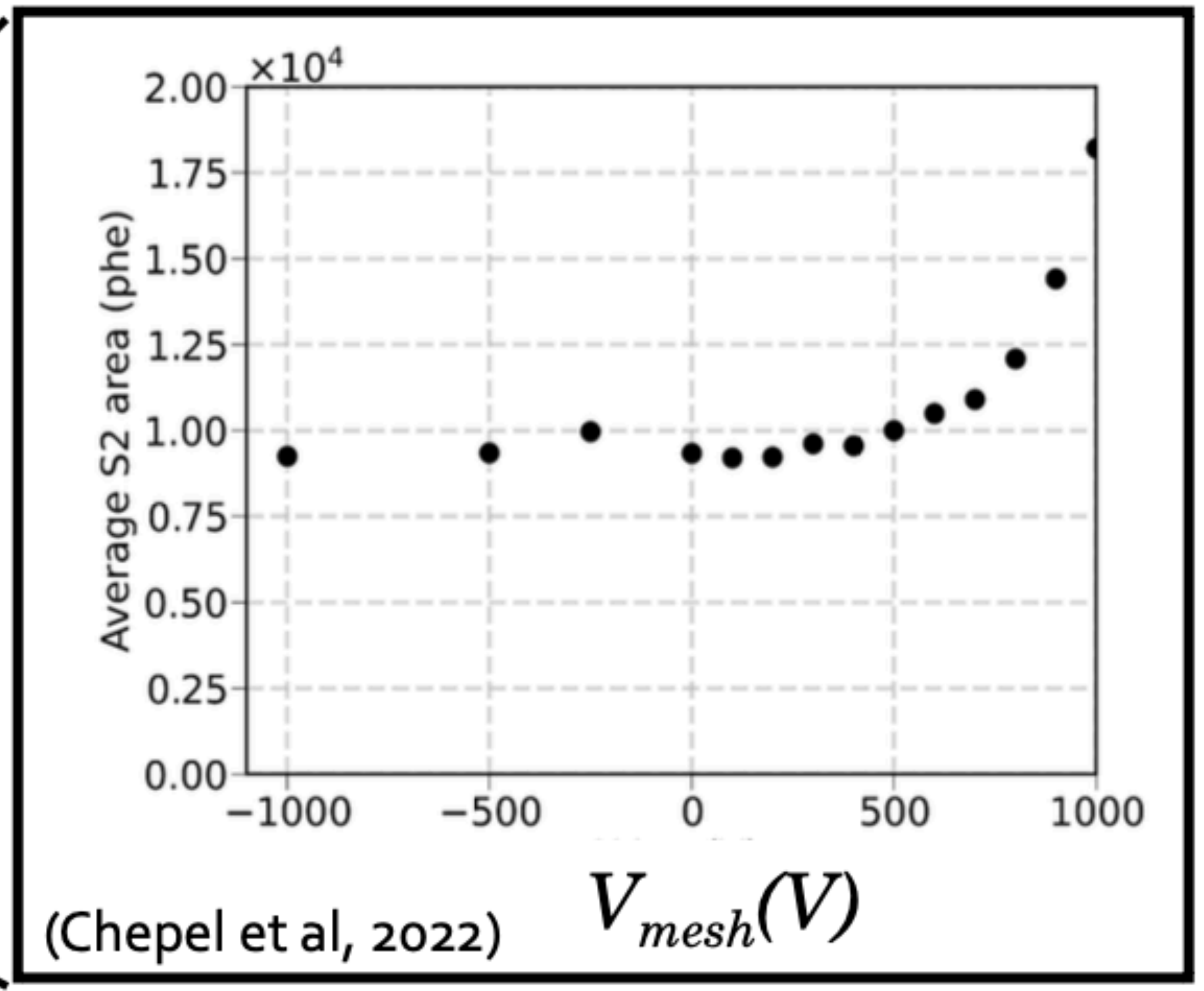
→ Liquid-gas interface

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

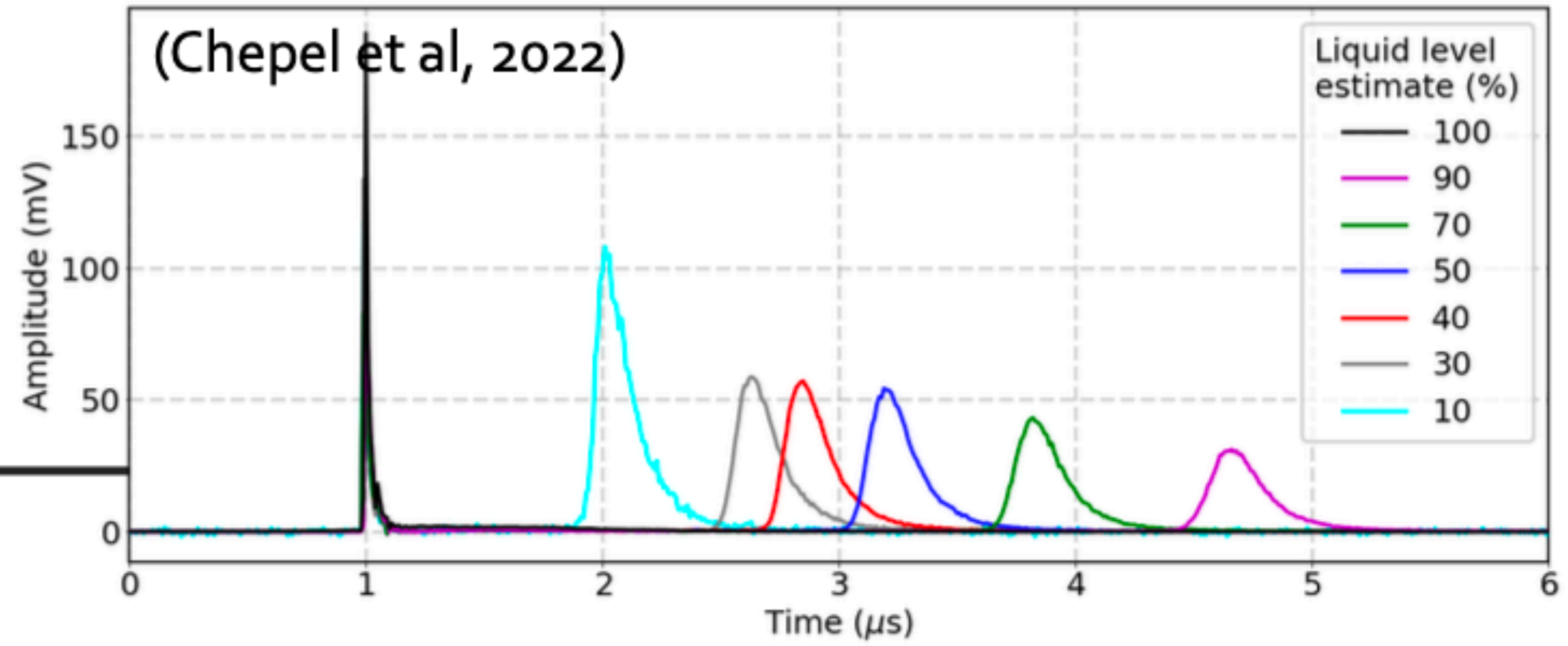
Light in uniform field (mesh)



Light in the GEM-like holes



(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

- Understanding “S2-only” signals opens the possibility to explore Dark Matter LowMass (sub-GeV)
- Complete understanding of background at these energies is the main challenge (excess number of events)

⬇

Understanding the mechanisms behind delayed scintillation emissions will help to solve the puzzle

- Several possible techniques can be used to explore the origin of these spurious events making use of S2 and S3 signals (both energy and position)
- WLS FAT-GEMs are promising radiopure and scalable structures for electroluminescence
- WLS FAT-GEMs can be used to improve S1 and S2 detection and mitigate the occurrence of surface related instabilities
- Energy resolutions achieved are close to the needs of the NEXT experiment
- Recent success at evaporating the TPB inside the holes 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.

The development of such **novel optical amplification structures can open interesting opportunities** for **future Dark Matter LowMass experiments**…

Topic for a PhD thesis to be carried at Astrocent in collaboration with
IGFAE (Spain) and LIP (Portugal)

Stay tuned!

Latest news…

STELLAR (innovative STructures for improvEd Light colLection in ARgon-based TPCs) goal is to boost the advancement of noble gas and liquid optical Time Projection Chamber (TPC) detectors for rare-event searches, with Dark Matter (DM) being one of the most compelling puzzles of todays fundamental physics. STELLAR plans to contribute to the development of novel amplification structures based on Micropattern Gas Detectors (MPGDs) technology incorporating wavelength-shifting materials, capable of providing improved light collection and greater operating stability at higher gains. STELLAR programme can further contribute to the understanding of underlying mechanisms of signal formation in TPCs, opening the possibility of studying the electron extraction efficiency and electroluminescence in electronegative gas mixtures. This is a specially relevant topic considering the recent technological developments observed in DM searches with the use of Negative Ion TPCs, eventually optically readout. It is anticipated that the floating wavelength-shifting Field-Assisted Gas Electron Multipliers (FAT-GEM) mechanical characteristics and performance, can be a valuable alternative to current amplification structures used in noble-element TPCs for DM searches, for instance DarkSide-LowMass, or currently planned for long baseline neutrino experiment DUNE.

Awarded MSCA Fellowship 2023

- Only 5 projects approved in Poland
- 1st MSCA from Astrocent and CAMK

We are waiting for the result of 2 proposals: First Team (4M PLN) and a SONATA 19 (2M PLN)

Topic for a **PhD thesis to be carried at Astrocent** in collaboration with **IGFAE (Spain)**, **LIBPhys (Portugal)**, **LIP (Portugal)** and **LLNL (US)**

Check the PhD recruitment announcement application deadline: April, 7th 2024

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