# Detectors & Physics

Physics **with** Detectors

Detectors **for** Physics

Physics **of** Detectors

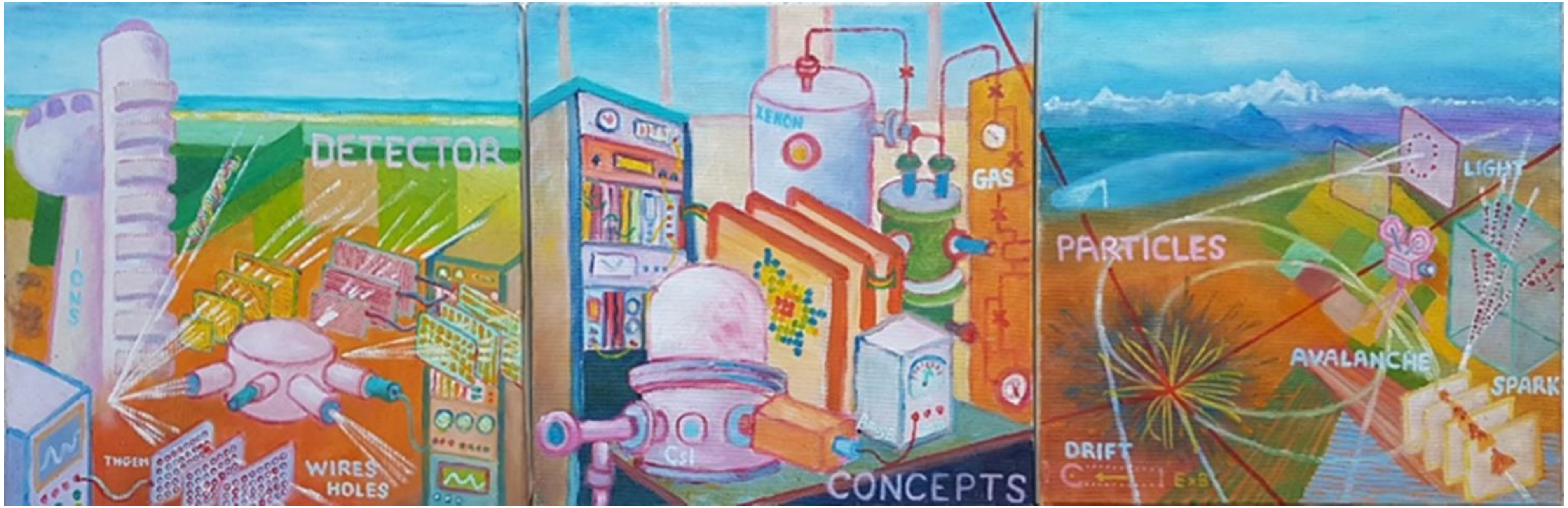
## A disclaimer: Today's talk:

# Physics of Detectors ONLY

~~Detectors for Physics~~

~~Physics with Detectors~~

**50 YEARS**

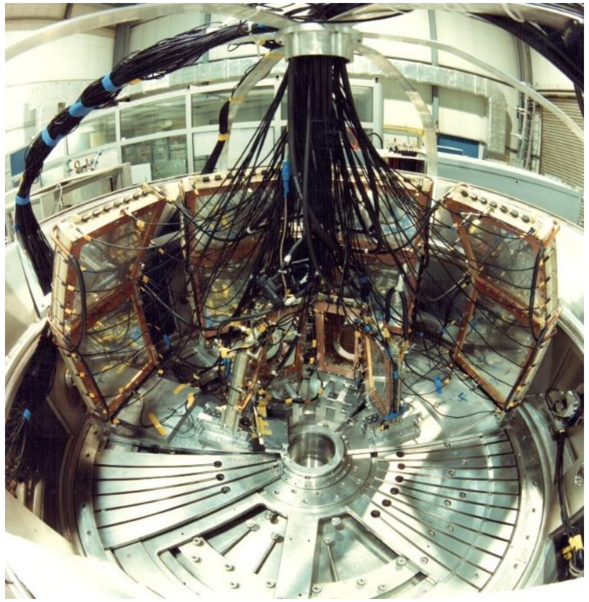



*Amos 2017*

# Radiation Detection Physics @ Weizmann

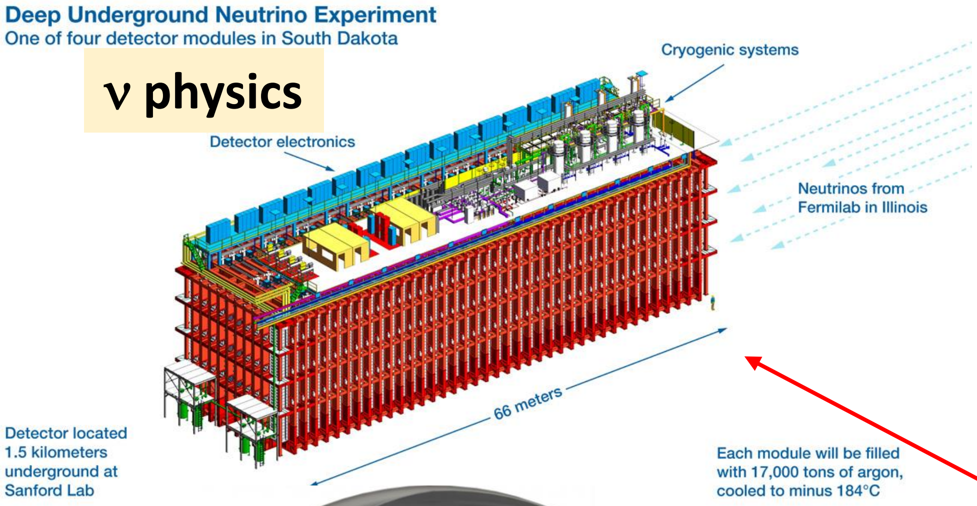
## From mbar of gas – to – noble liquids

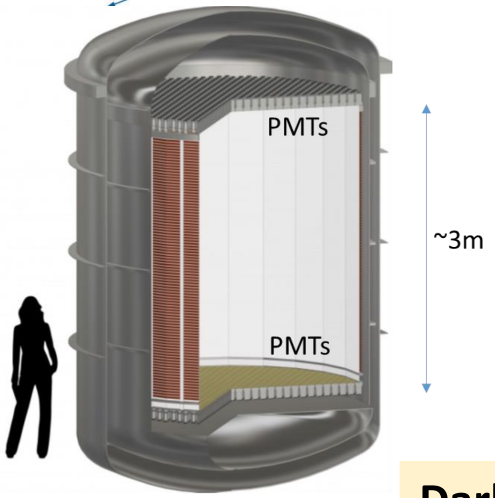
Very low pressure (mbar) ultra-fast MWPC Heavy-Ion imaging detectors



Brugger et al. Nature 1989
Search for Strange Matter

ν physics

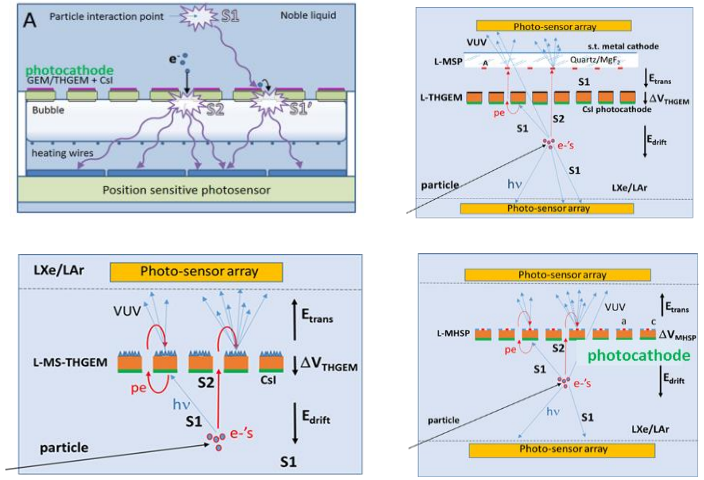


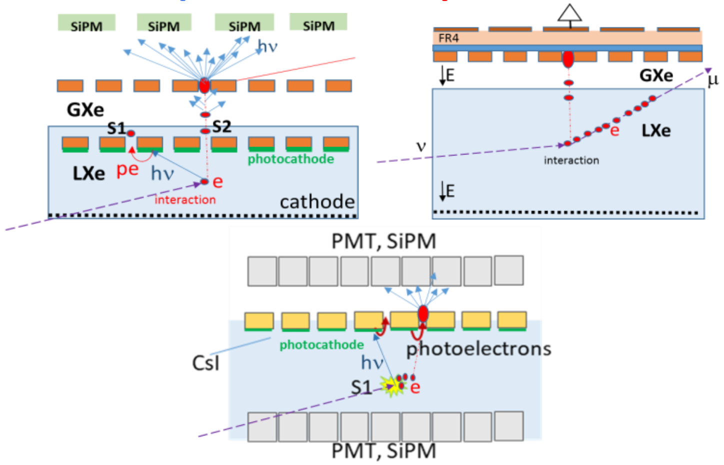

Dark Matter

**Future 50-ton LXe**
**DARWIN Collaboration**
**(XLZD* consortium)**
Dark-matter observatory
*XENON-LZ-DARWIN

### Single-phase noble-liquid detectors




### Dual-phase noble-liquid detectors



# Novel noble-liquid detector concepts*

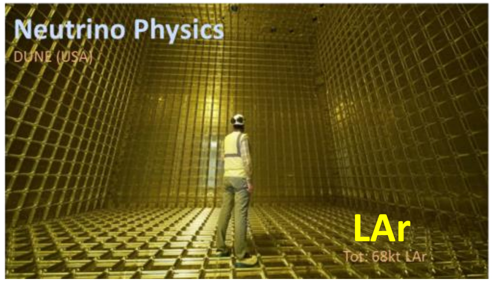
**Amos Breskin**

WEIZMANN INSTITUTE OF SCIENCE

* for more details:
http://arxiv.org/abs/2203.01774
https://doi.org/10.1088/1748-0221/17/08/P08002

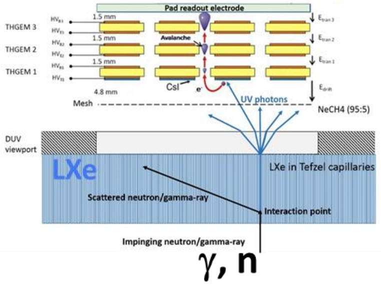
# Why noble-liquid detectors?

- ***Why noble-liquid detectors?***
  - High density ➔ higher interaction probability;
  - High scintillation and ionization yields ➔ VUV photons & Ionization-electrons
  - Scalability (**Xe** cost >>> **Ar**)
- ***What are the challenges ?***
  - Rare events ➔ large volumes, high radiopurity & background discrimination, very high sensitivity
- ***How?***
  - **Charge readout** (with/without multiplication)
  - **Light readout** (primary scintillation & electroluminescence)  with PMTs, SiPMs etc.



Homeland security




- HEP
  Calorimetry
- Nucl Phys

# DM & ν physics

**DM:**

low deposited energy (**keV**) by nuclear recoils ➔ low detection thresholds

➔ **charge multiplication & efficient scintillation-photon recording**

➔ **background-radiation discrimination**

**Neutrino physics:**

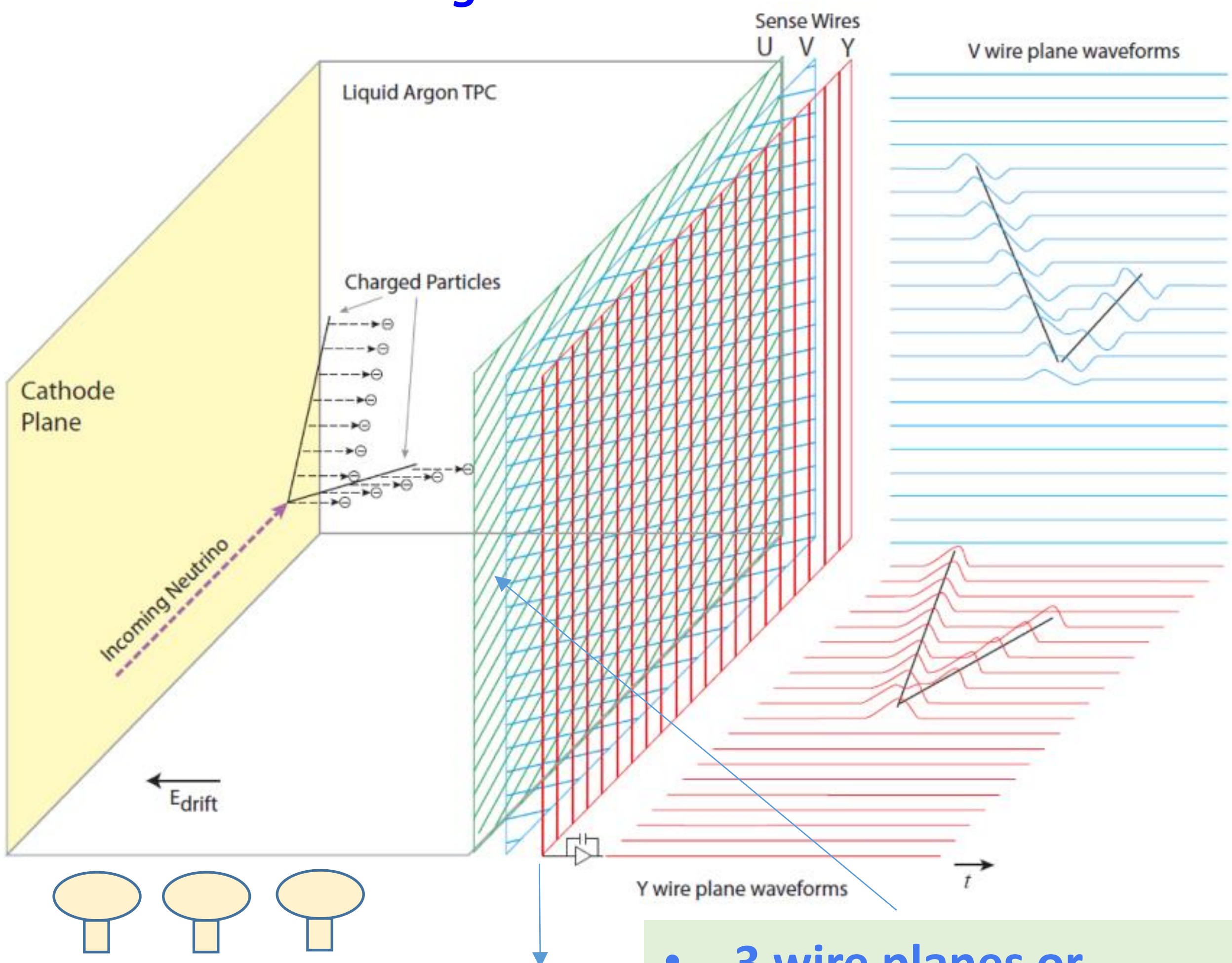
High μ charge deposits (**few $10^4$ e/mm**)

➔ Can operate **without charge multiplication**

multiplication would ease electronics & lower thresholds

# Single-phase TPC concept

**Single-phase**
***Charge collection***




**PMTs ➔ $t_0$**

$t_1$

- **3 wire planes or**
- **Multilayer perforated PCB**

(➔ In 2 DUNE modules)

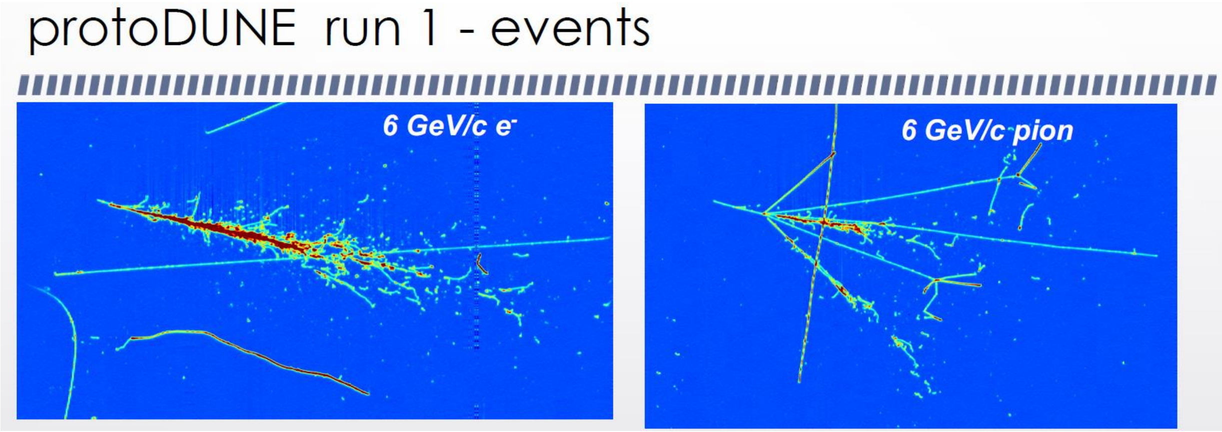
- Charged particles ionize the noble liquid;
- ~ few $10^4$ $e^-$/mm in LAr
- Electrons drift to, and induce charge on anode wires (2D);
- Primary-scintillation light provides the $e^-$ drift time
  ➔ third coordinate; $(t_1 - t_0)\ v_e$
  ➔ 3D spatial reconstruction from wire planes;
- Charge collection with **no multiplication**
  ➔ good only for **large deposited charge** (e.g. neutrino physics)
- **Largest: ICARUS, DUNE...**

# Fermilab Neutrino Experiments

| Experiment | Goal | Techniques |
|---|---|---|
| ArgoNeut | R&D | LArTPC |
| MiniBooNE | oscillation | Scintillation |
| LArIAT | R&D | LArTPC |
| MicroBoone | Anomaly | LArTPC **170t** |
| MINERvA | $\nu$ reaction with 5 different nuclei | Plastic scintillators |
| MINOS | $\nu$ **oscillations** | Plastic scintillators |
| NOvA | $\nu_\mu \rightarrow \nu_e$ | Plastic filled with liquid scintillator |
| DUNE | CP Violation – SN - p+ decay | LArTPC **68,000t** |
| SBND | Anomaly | LArTPC **270t** |
| ICARUS | Anomaly | LArTPC **760t** |

Ana Amelia B. Machado - LIDINE 2022 21/09/22

# Single-phase: neutrino physics




Electro-magnetic shower

Hadronic shower

**DUNE: Future 68-Kton LAr**
**Fermilab Long Baseline Neutrino Experiment**
*Photo: Inside a **single** module…*

# Dual-phase TPC concept - DM

**EL-photon** readout

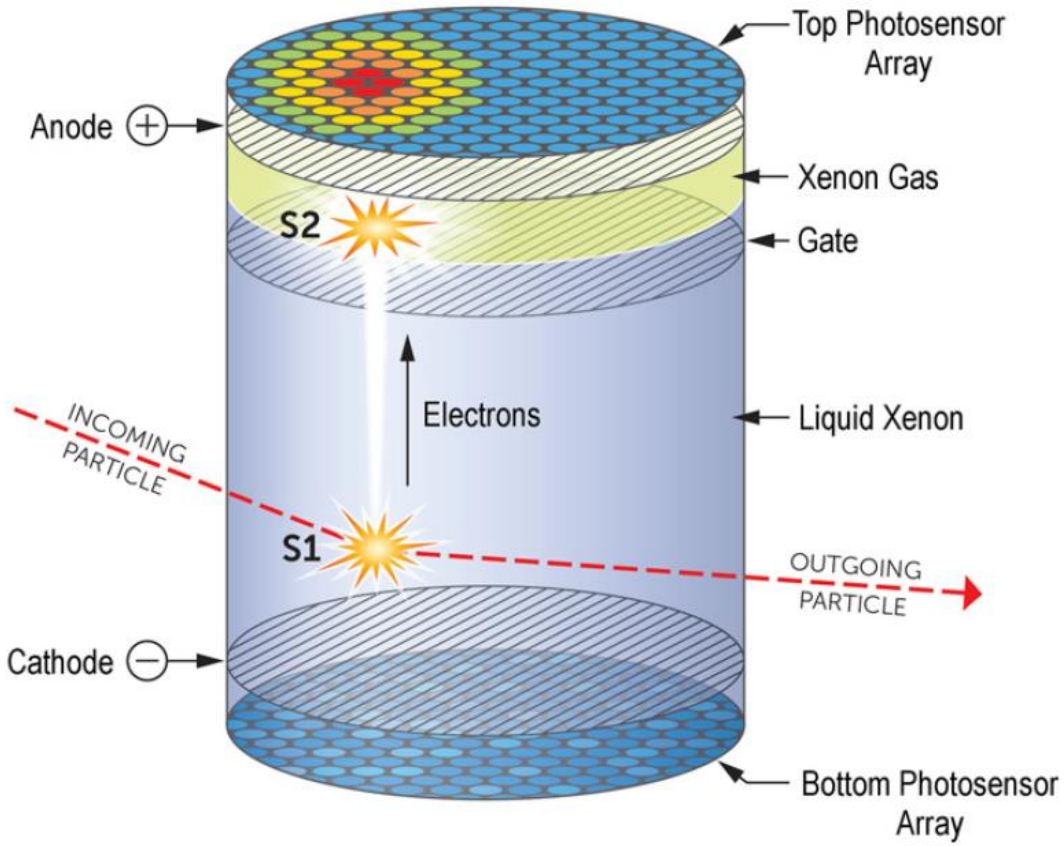
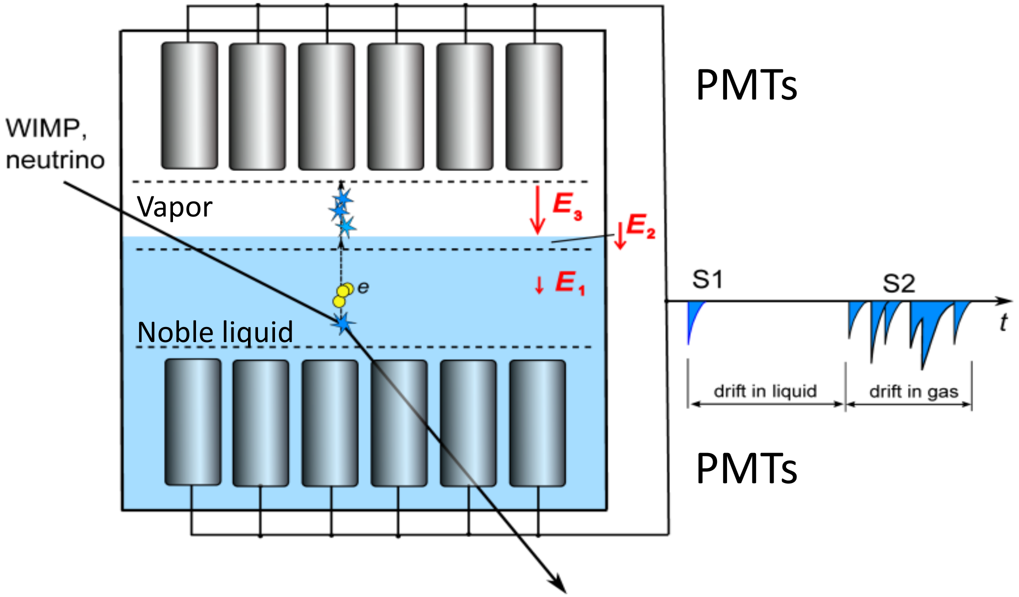
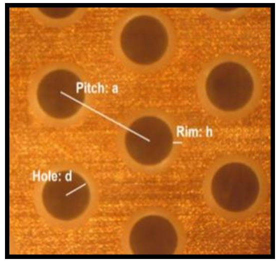



**Figure 4.** Principle of a dual-phase liquid xenon TPC. Energy from a particle interaction within the active liquid xenon volume produces prompt scintillation light (S1) and a delayed signal (S2) from electroluminescence (proportional scintillation) in the gaseous xenon layer. The localization of the S2 signal and the time difference between S1 and S2 allows for determination of the original vertex location.




The **EL-photon** readout can be substituted by **charge** readout: electron avalanche multiplication. e.g. in: LEM (THGEM). So far low gain.

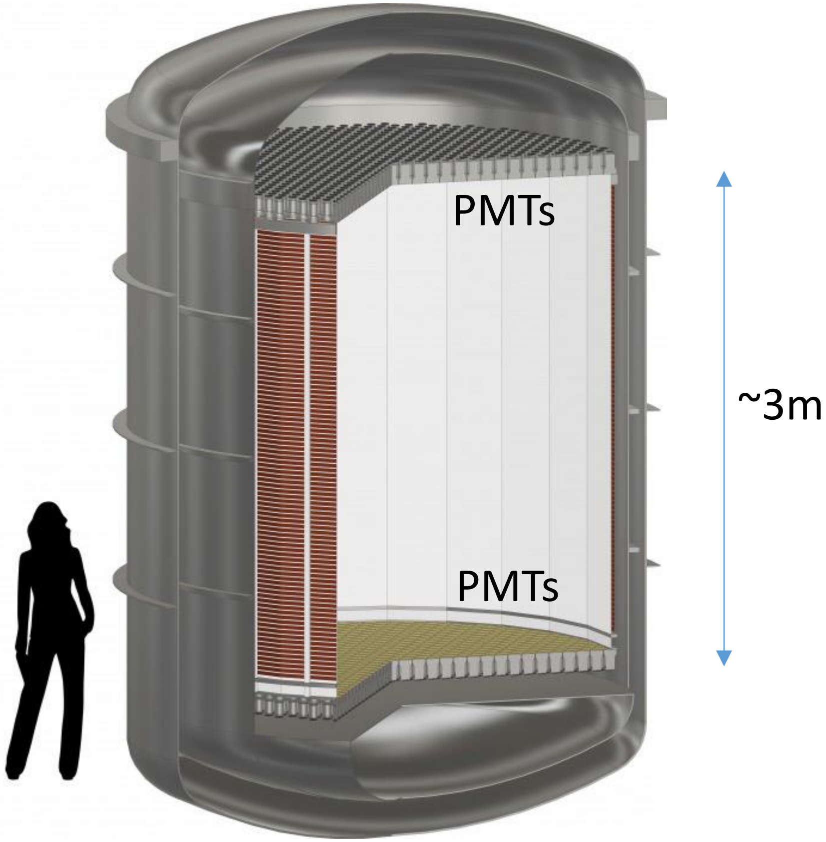


# Dual-phase: Dark Matter searches

XENONnt, LUX-ZEPLIN (LZ), PNDA X, DARWIN/G3

8.5t 10t 4t 50t


**XENONnt**
**@ Grand Sasso**



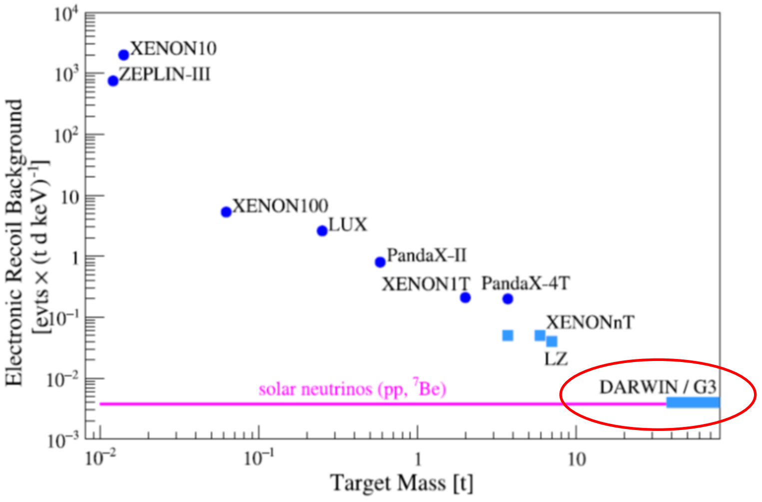

**Future** 50-ton LXe

**DARWIN/G3**

Dark-matter observatory

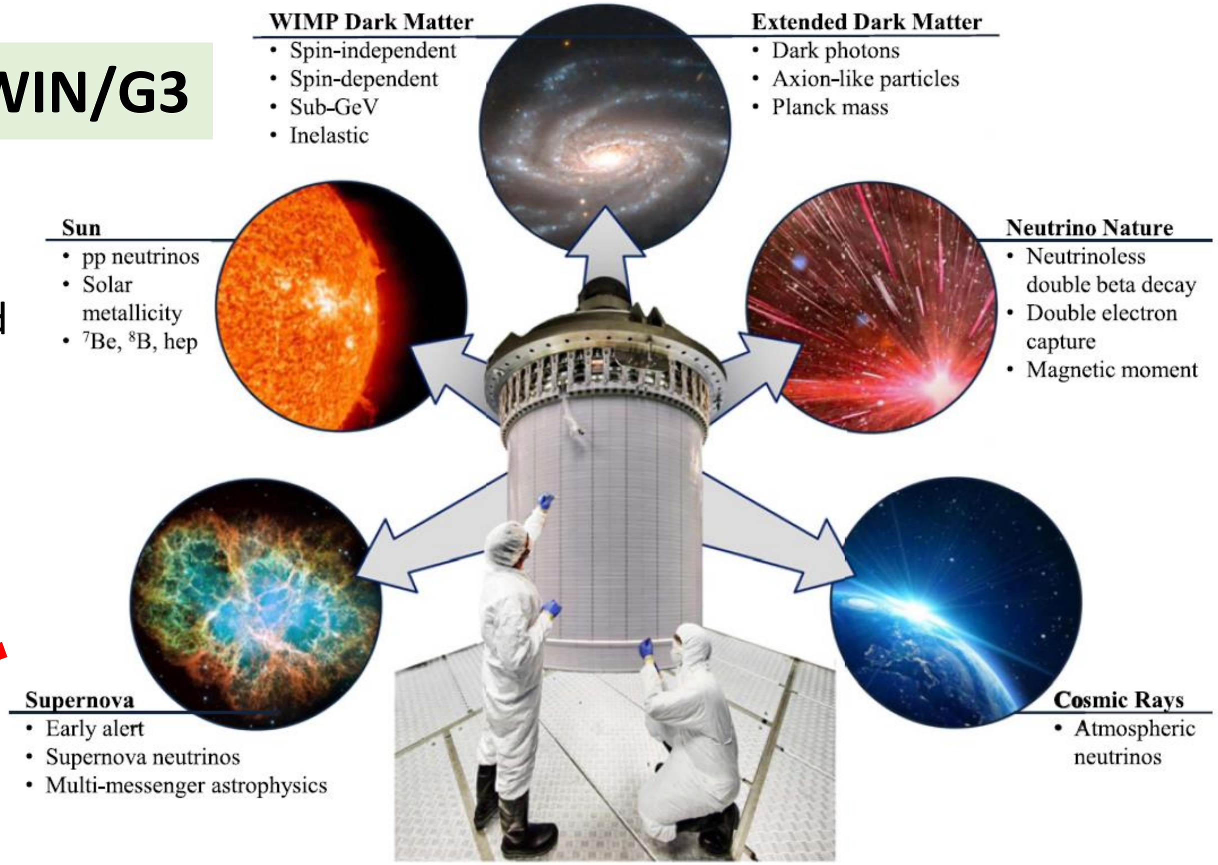
XENON-LZ-DARWIN (XLZD consortium)

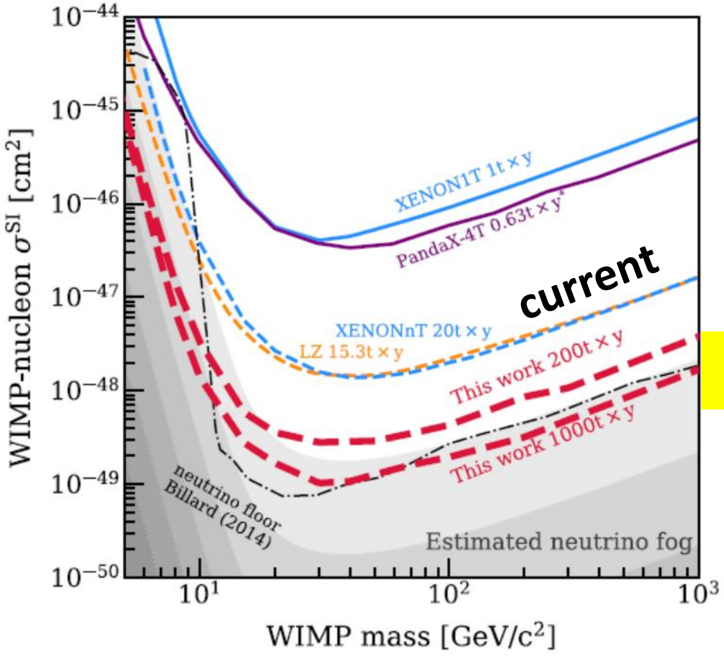
# DARWIN/G3 50t LXe observatory for DM & neutrino physics




Low background

DARWIN/G3




← 50t x 20Y

**Figure 2.** The science channels of a next-generation liquid xenon observatory for rare events spans many areas and is of interest to particle physics, nuclear physics, astrophysics, solar physics, and cosmology.

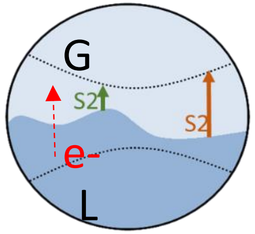
Aalbers et al 2023 J. Phys. G: Nucl. Part. Phys. 50 013001
DAWIN/G3

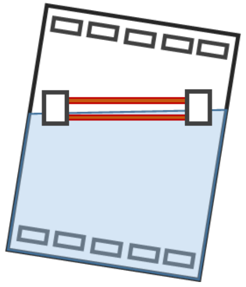
# Why new concepts?

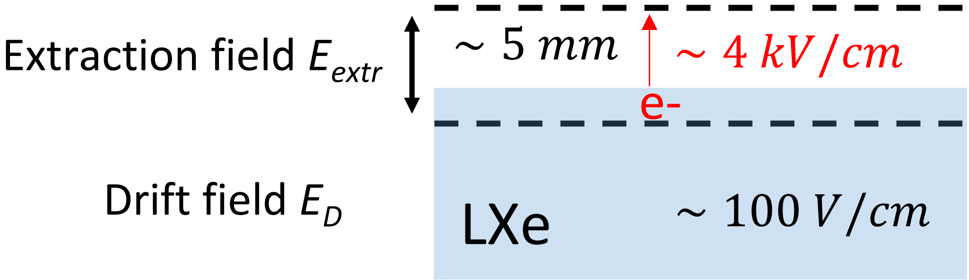
- **Dual-phase detectors: Problems**

Current expected problems with large-volume detectors, affecting resolution & efficiency:

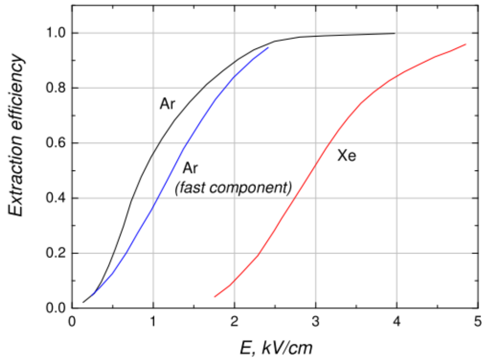
➔ liquid-gas interface instabilities - spontaneous electron emission, gas gap variations (tilt), electron extraction efficiency into liquid.






Electron emission efficiency vs $E_{extr}$




**Low energy deposits** ➔ need multiplication

Limited avalanche gain in noble gases ➔ <u>electroluminescence multiplication</u>

- **Single-phase detectors:**

Current limit: <u>No multiplication</u> in liquid.

➔ OK only for **large energy deposits**.

Stable primary-charges multiplication & efficient detection in both configurations

➔ **lowering detection thresholds (& cost?)**

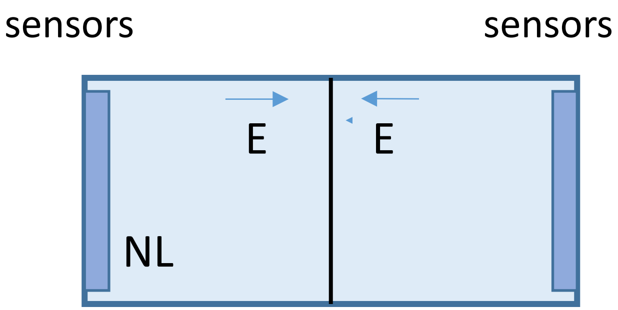
# Single-phase TPC:
# novel concepts

# Why single phase?

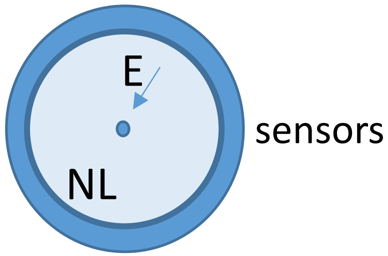
- To overcome liquid-gas **interface problems** in large dual-phase detectors:

- Only single-phase can be **"face-to-face"** and **"horizontal":**

  ➔ Half of HV for equal field; avoids effects of sporadic bubbles



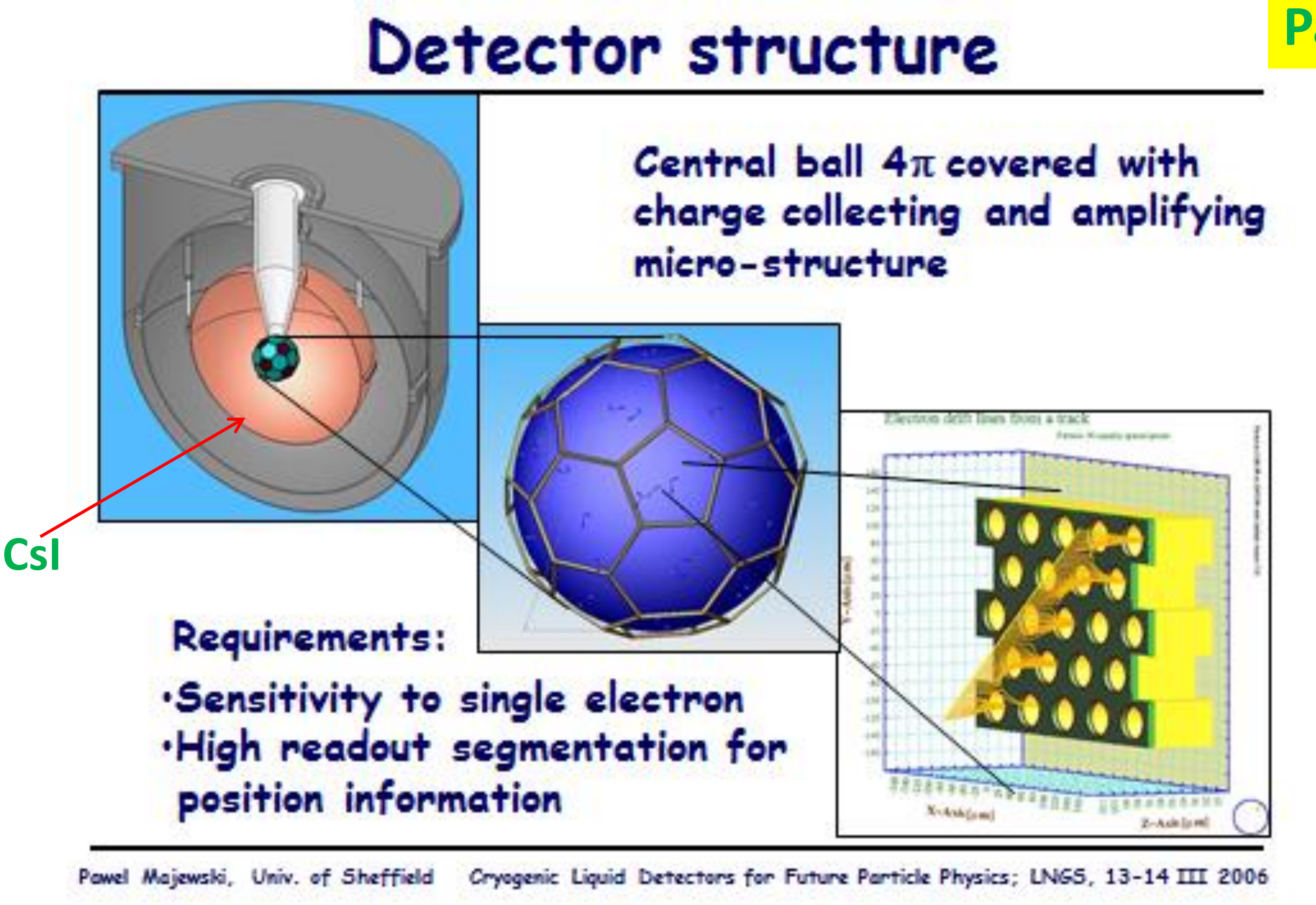

- "**Radial** geometry" possible



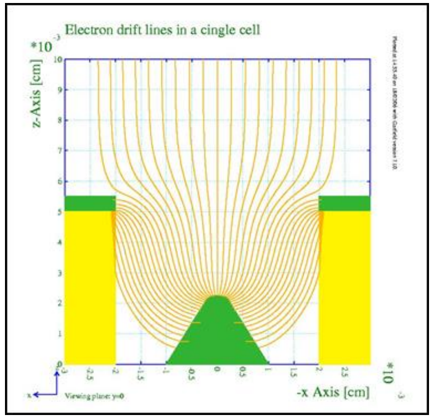

- New concepts: potentially lower detection thresholds

# Idea: A spherical Single-Phase LXe DM detector

**Pawel Majewski 2006**




- WIMP interaction ➔ scintillation photons@ electrons;
- Photons + CsI ➔ pe;
- e + pe drift to & multiplied on sphere covered with micro-structure charge multipliers.



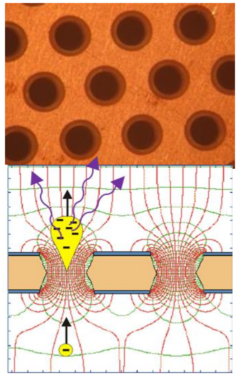

Multiplication in liquid difficult

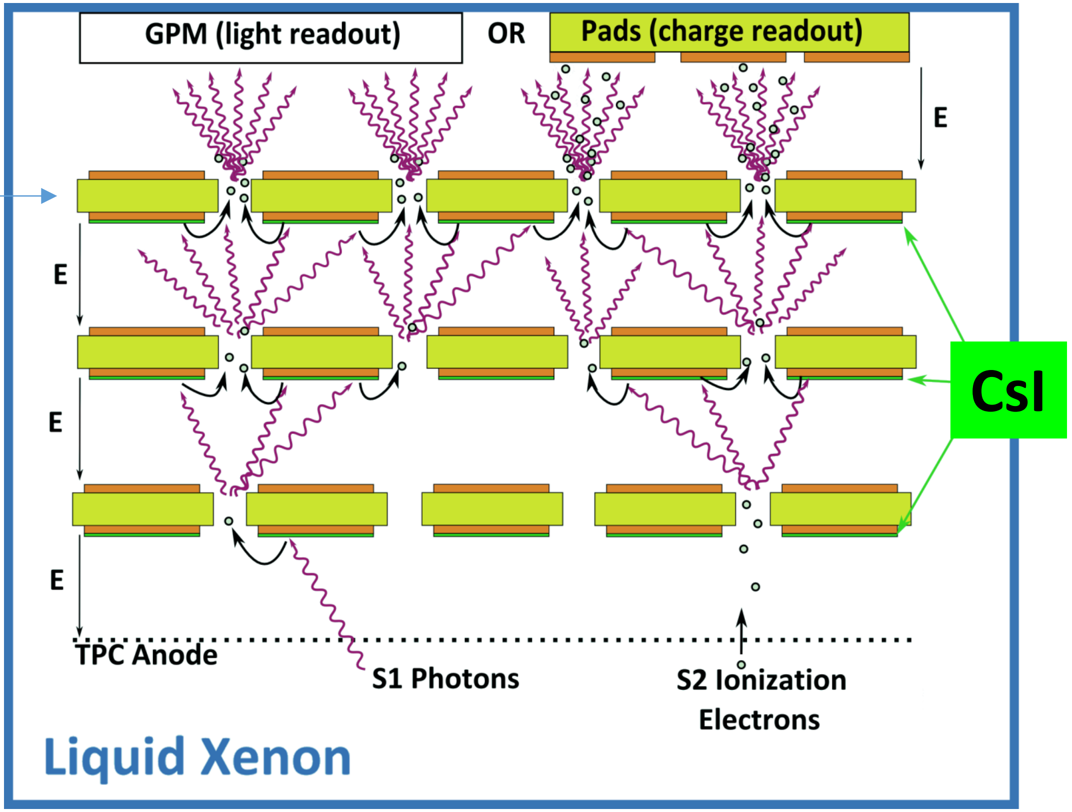
# Originally proposed: Liquid Hole-Multipliers **LHM** in single-phase LXe

A.B. *J. Phys. Conf. Ser.* **460** (2013) 012020

THGEM*

*Thick Gas Electron Multiplier






- Simultaneous detection of **S1** scintillation UV-photons & **S2** ionization electrons by a cascade of CsI-coated perforated electrodes.
- Electron multiplication via electroluminescence, EL (+ maybe little charge gain) in the holes.
- Optical readout (or maybe charge readout)

## Observed large signals!

Arazi 2013 JINST 8 C12004

But: LXe prior art:

- Electroluminescence (EL) threshold:

  ~400 kV/cm - on wires

- e-avalanche threshold :

  ~700 kV/cm on wires Aprile 2014

Conclusion:

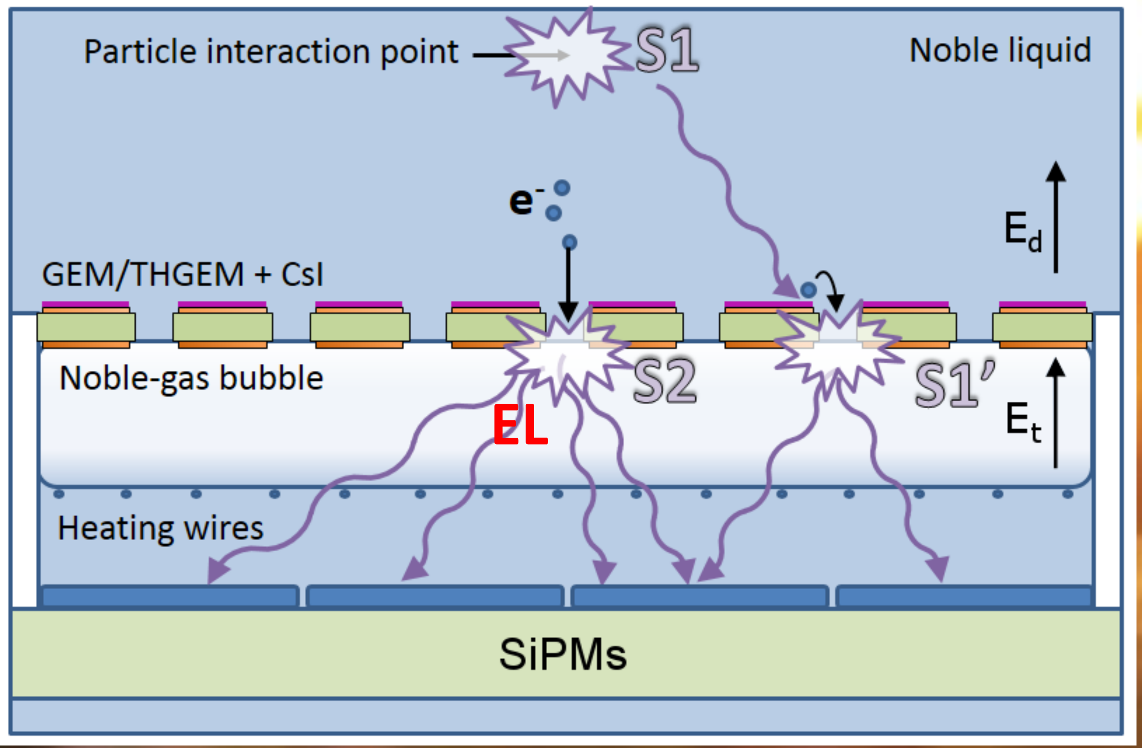
**EL in gas sporadic bubbles** Arazi 2015 JINST 10 P08015

Similar conclusion by Lightfoot 2009

Electroluminescence from THGEM holes / SiPM in LAr

# EXOTICS: A “local dual phase” TPC

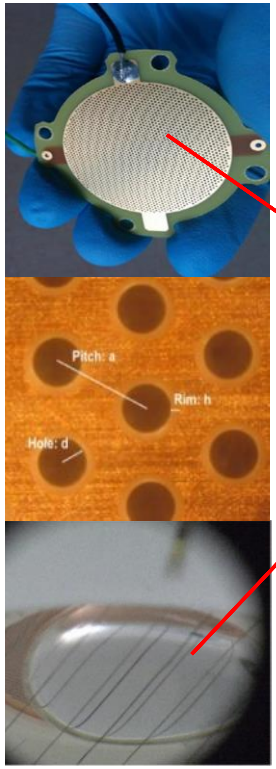
## The bubble-assisted Liquid Hole Multiplier (LHM)

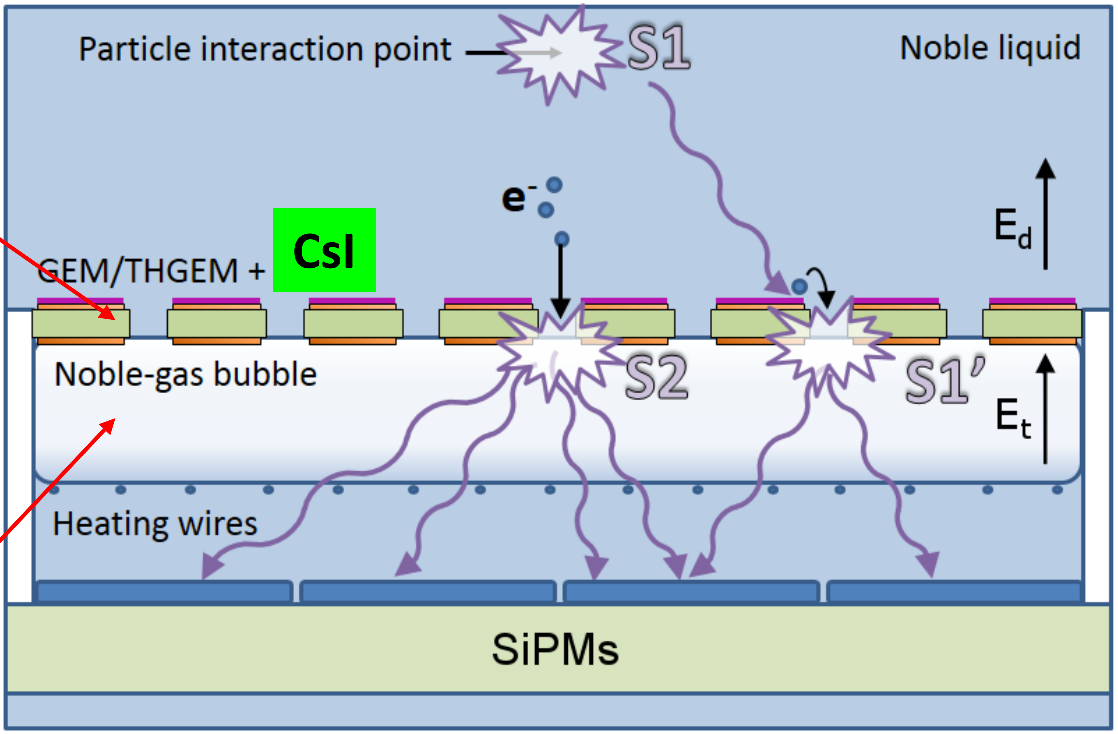



e- & scintillation-photon induced electroluminescence in a bubble, trapped in liquid under a photocathode-coated perforated electrode

# Bubble-assisted Liquid Hole Multiplier LHM

## Principle: Radiation-induced electroluminescence from a bubble trapped in noble liquid




- Creating a local "vapor bubble" underneath a "GEM-like" perforated electrode, immersed within a large noble-liquid volume.
- The electrode is coated by CsI photocathode.
- **BOTH: S2** Electrons and **S1**-induced **S1'** photoelectrons drift from the liquid into the bubble.
- ELECTROLUMINESCENCE within the bubble ➔ **Energy, 2D localization.**
- **Demonstrated in both LXe & LAr.**

Bubble LHM LXe.mp4

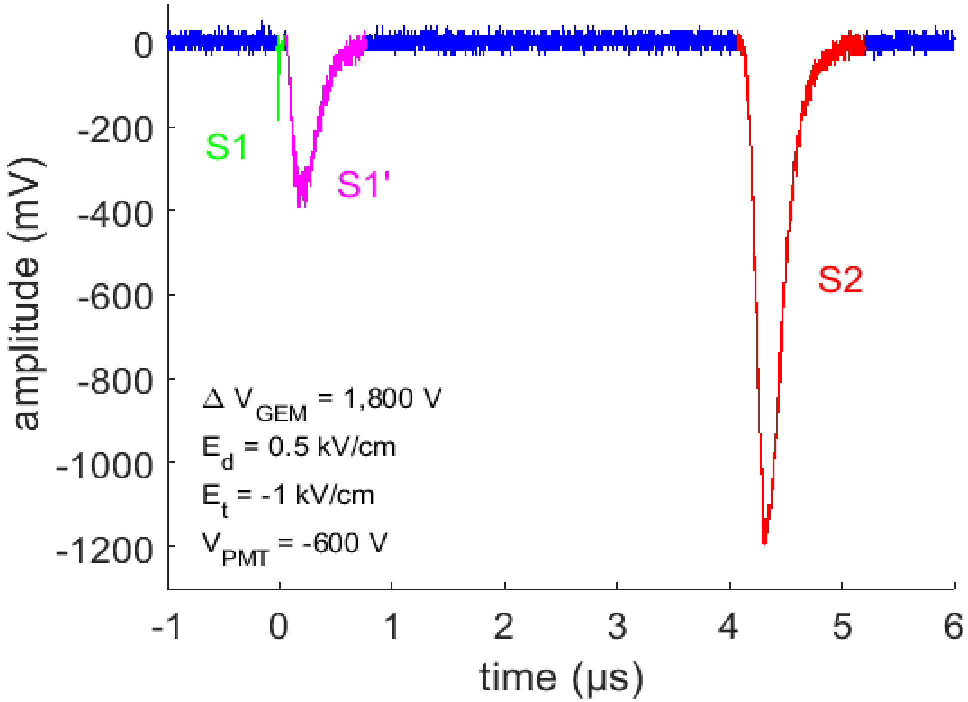
Precise control of the liquid-gas interface, expected:

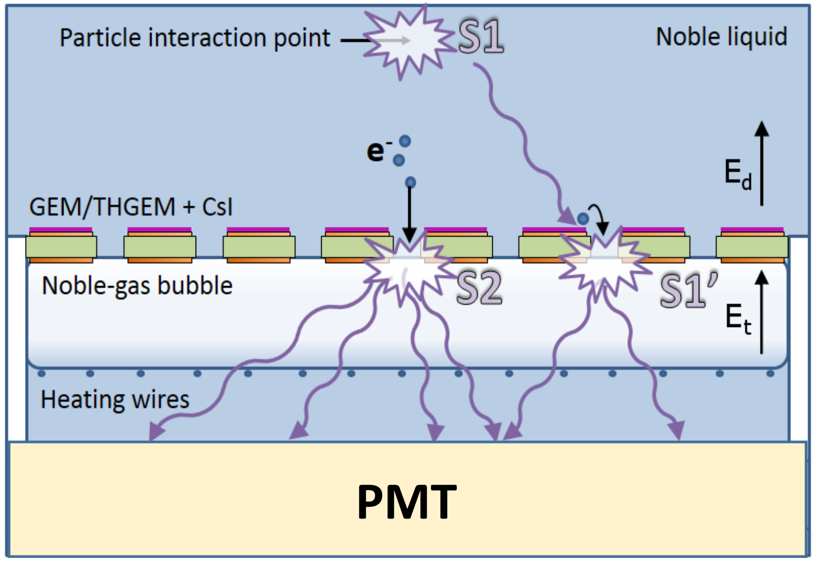
➔ better S2 resolution

➔ potentially better S2/S1-based background discrimination


Arazi et al., 2015_JINST 10 P08015
Arazi et al., NIM A 845 (2017) 218
Erdal et al., 2019 JINST 14, P01028
Erdal et al., 2018 JINST 13 P12008
Erdal et al., 2019 JINST 14 P11021

# Waveform structure




Typical waveform of an alpha-particle event, recorded by a **PMT** below the bubble

**S1**: primary light passing through holes

**S1'**: EL light from bubble, by photoelectrons emitted from the CsI photocathode

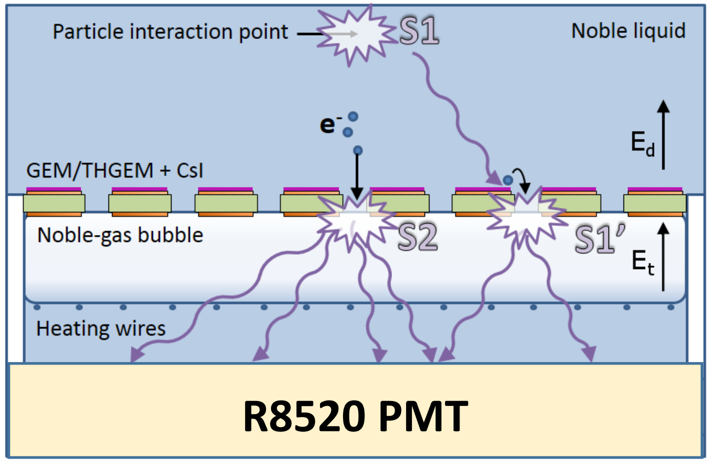
**S2**: EL light from bubble, by ionization electrons from track

Erdal, NIMA 845 (2017) 218

Light yield, resolution & PDE ➔ hole-electrode geometry

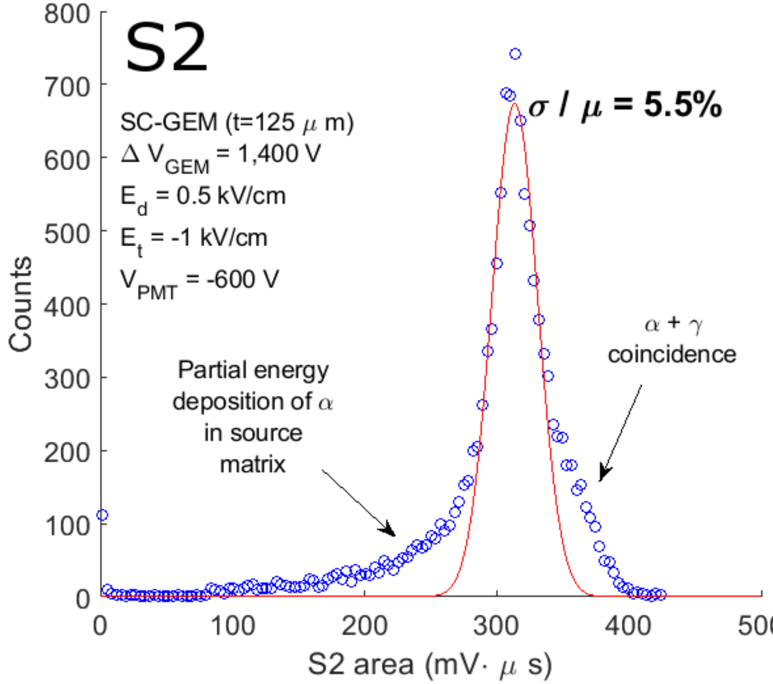
Best reached: ~**400 photons /e-/4π**

# Energy resolution



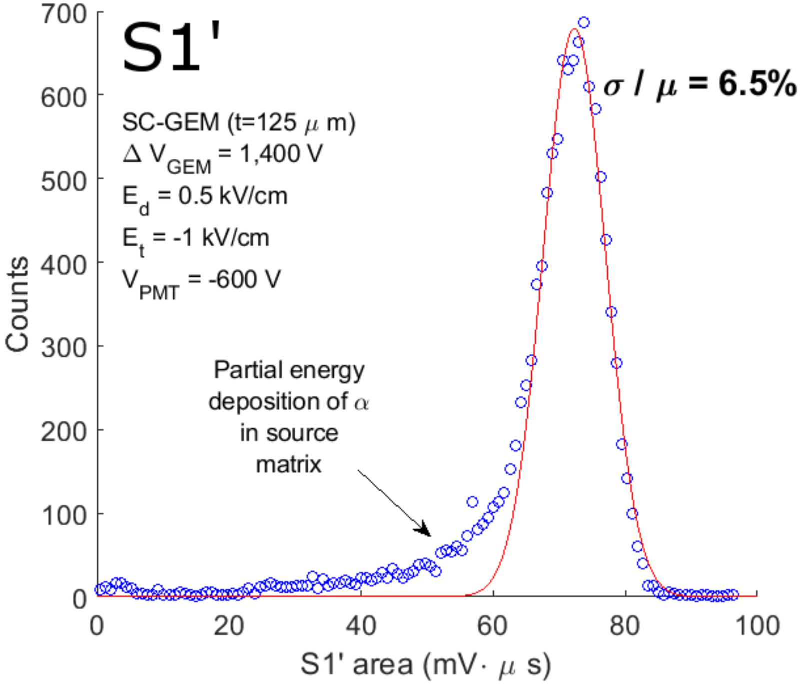

Erdal, 2018 *JINST* **13** P12008

**Ionization electrons → EL**




S2 ~7,000 ionization electrons/event

**Scintillation-induced photons → CsI → EL**

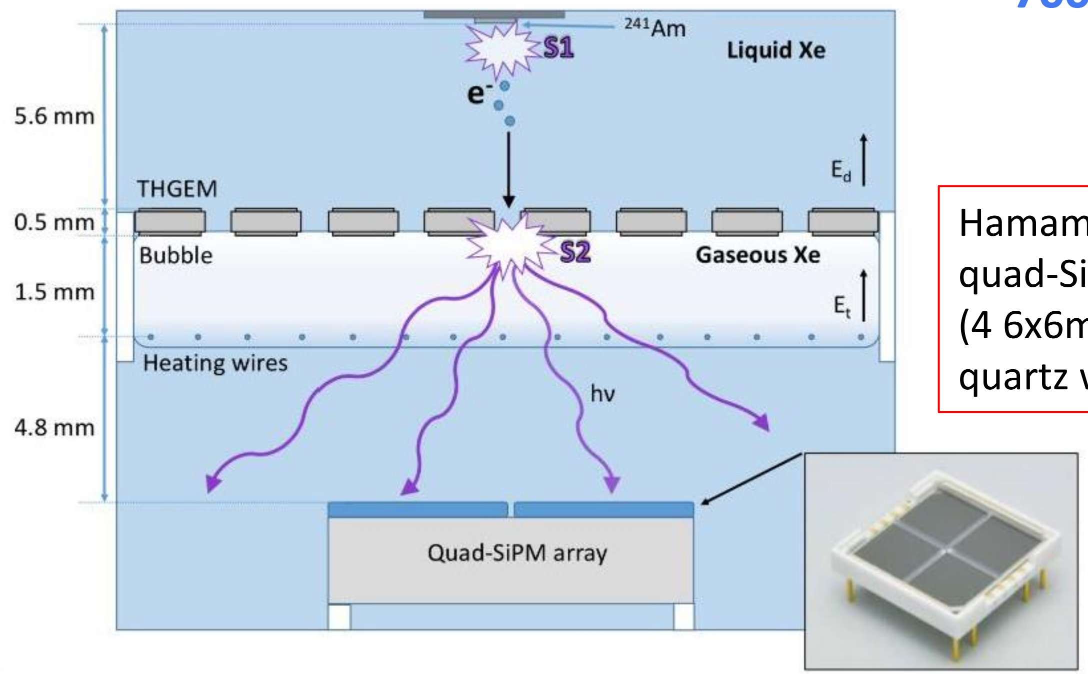



S1 ~1,700 photoelectrons/event

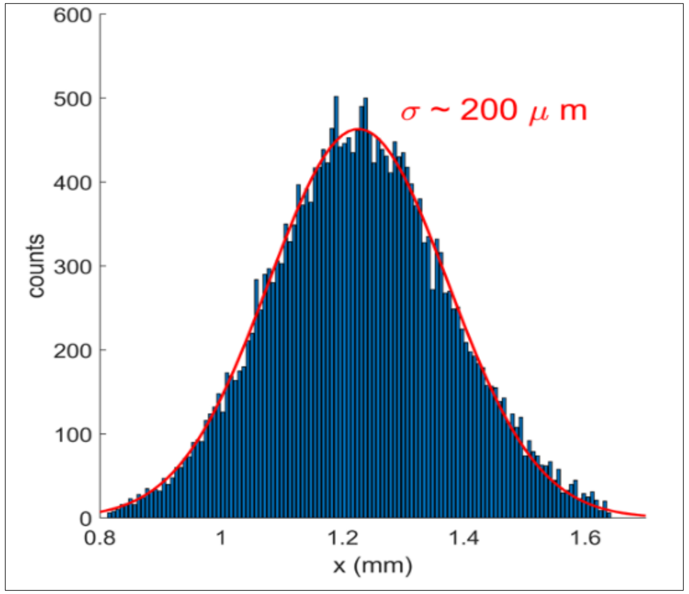
**BUT**: Better resolutions expected → **possible e- losses @ interface!**
**Preliminary studies with micro-CT → interface shape varies with E**

# Image of α-particles of ring-shaped $^{241}$Am source

~7000 electrons/event

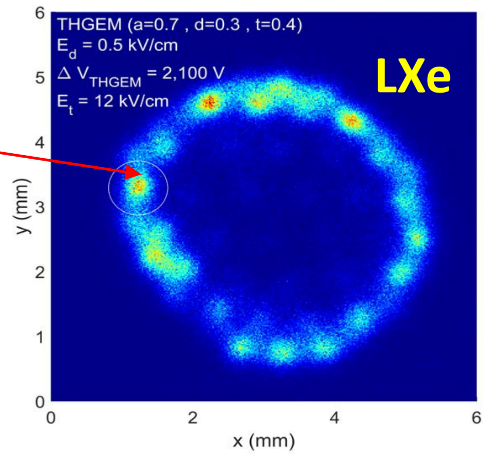



Hamamatsu VUV4 quad-SiPM array (4 6x6mm$^2$ elements); quartz window

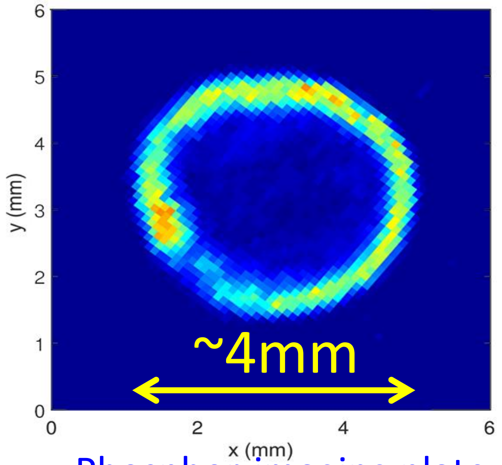



Reconstruction resolution of THGEM holes:
**~ 200μm RMS**

THGEM holes:
Φ 0.3 holes,
0.7 spaced




LHM reconstruction




Phosphor-imaging plate

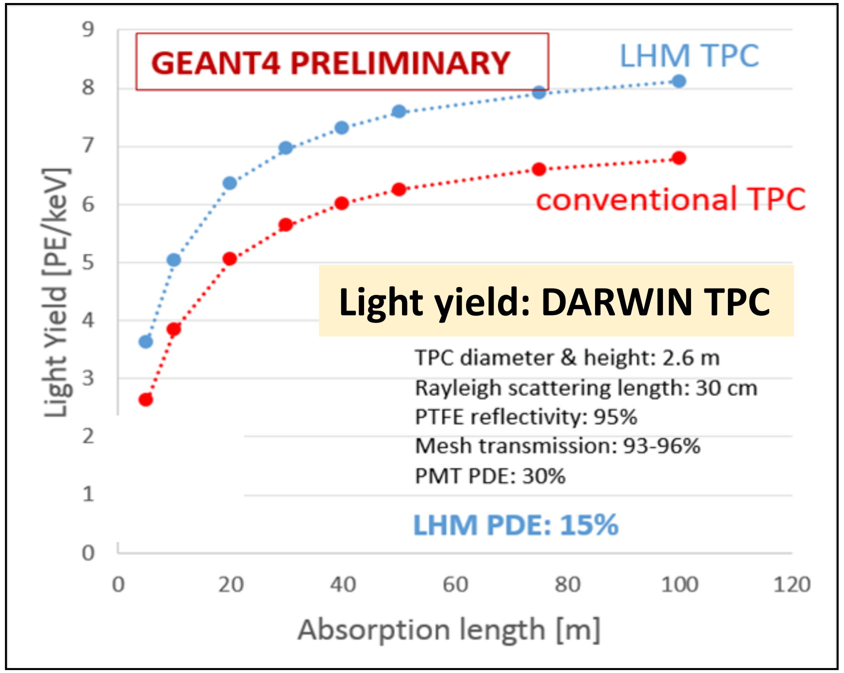
Erdal 2019 JINST 14 P01028

# LHM highlights

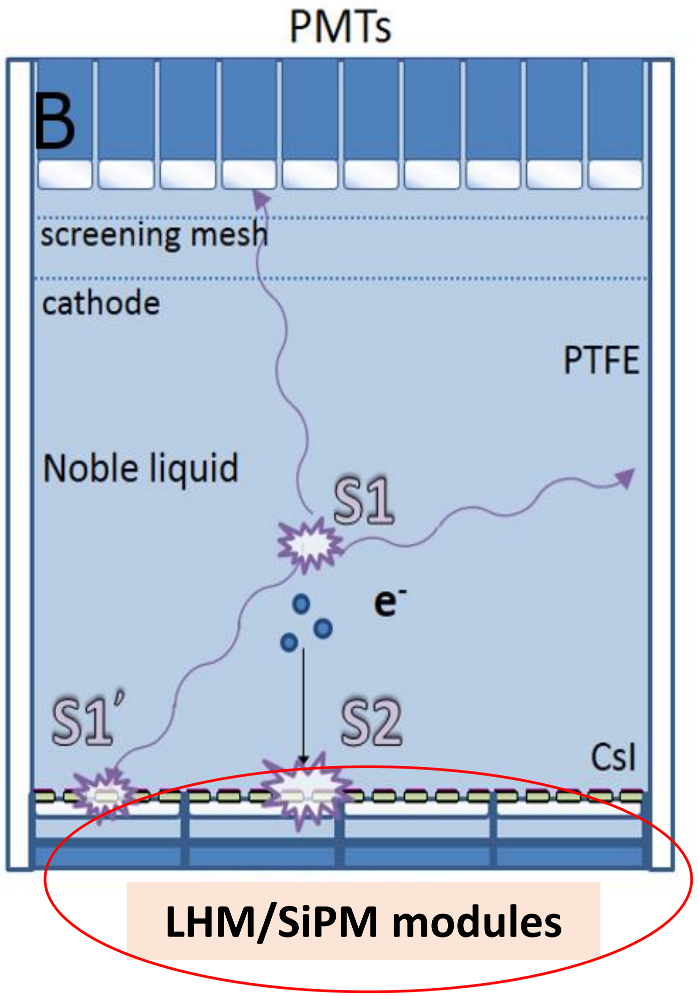
**RESULTS in LXe:**

- Controlled bubble formation & long-term stability S2 E-resolution: **6% RMS** for ~3000 electrons
- Light yield: ~**400 photons /e-/4π**
- PDE: **<5%** ; expecting 15% ➔ potentially higher light yield in a DARWIN LHM-TPC
- Localization resolution: reconstruction: **~ 200μm RMS**

**LHM demonstrated also in LAr.**
**worse resolutions**
**(lower photon yields)**




**Potential DARWIN LHM-TPC**



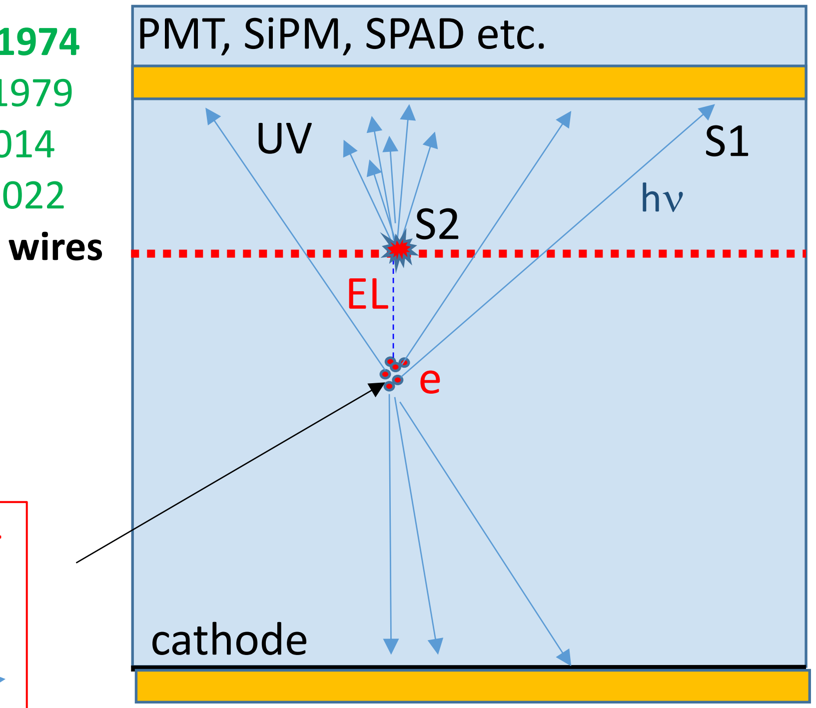
# NEW: Single-phase - from wires to microstructures

Examples: here multipliers sense **S2-e$^-$ ONLY**
Scintillation **S1-photons** recorded by photosensors

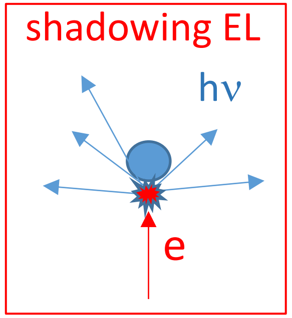
**~50 years of Wires in LXe:**

**Derenzo PRA 1974**
Masuda NIM 1979
Aprile JINST 2014
Brown JINST 2022

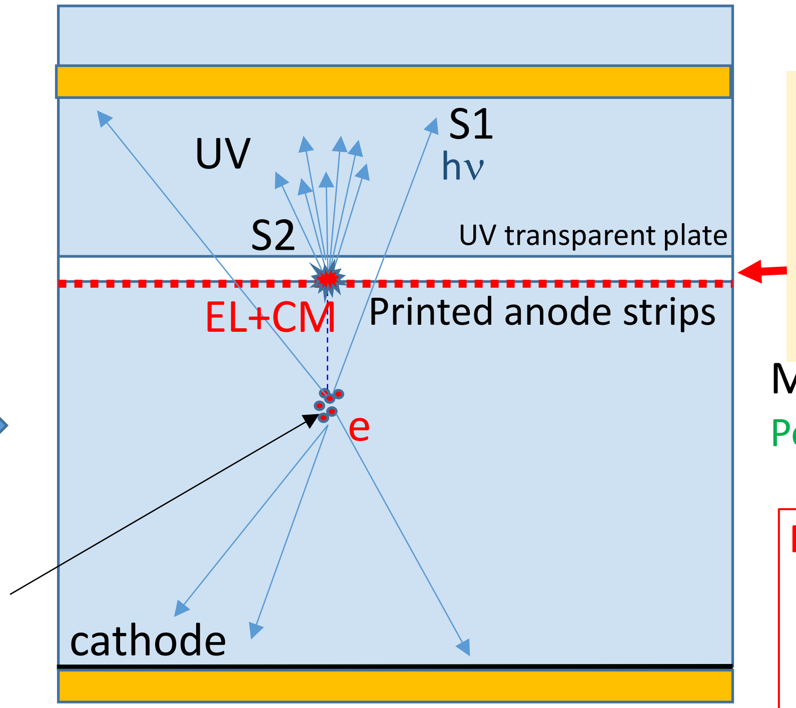
**Wires**




Few μm wires or very high voltage
➔**wires sagging, staggering**



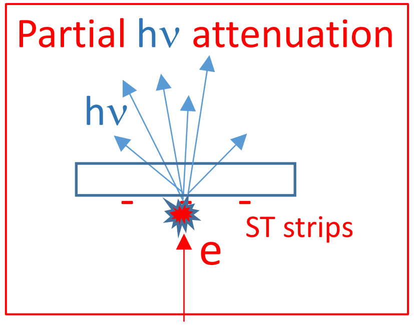

**Microstructures**




PMT, SiPM, SPAD etc.
or **reflective cathode**.

**Robust**
**Modular**
**Micro Strip Plates**
**& more!**

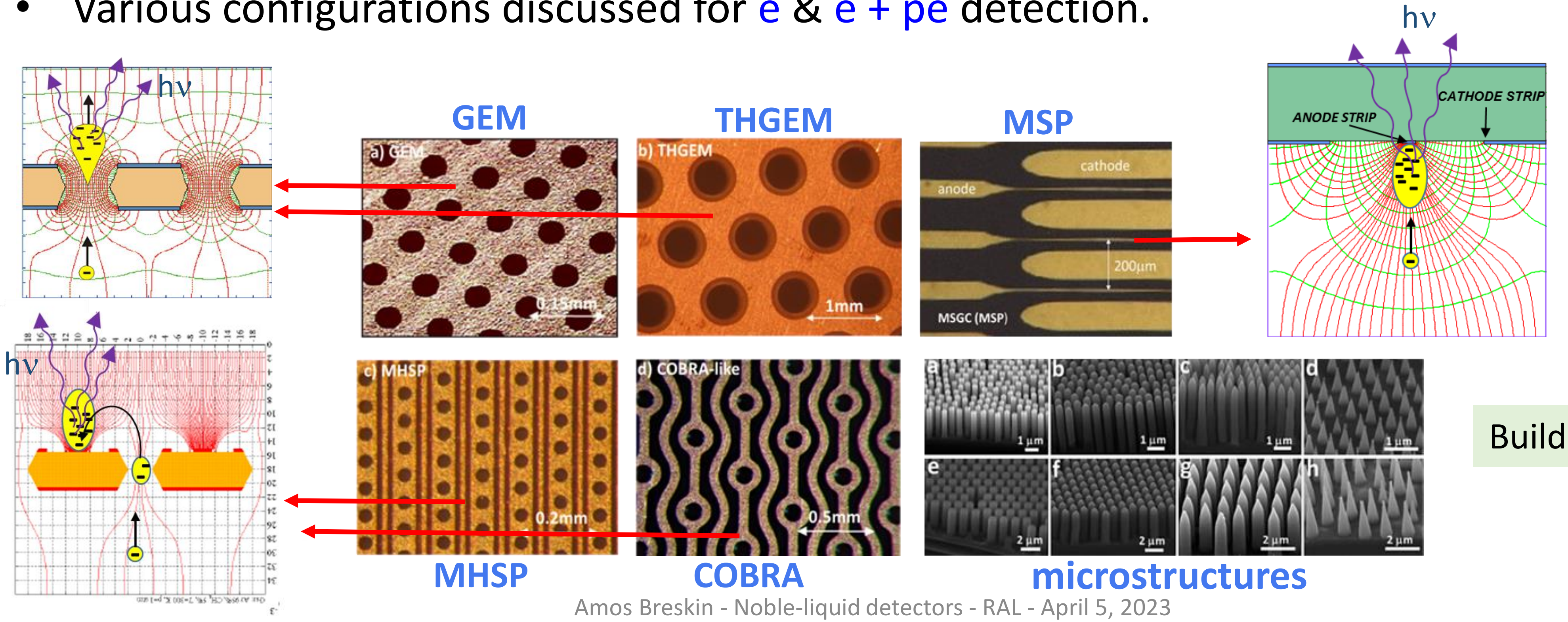
MSP LXe: gain 10
Policarpo et al. NIMA 1995




**Goals**: Devise other robust high-gain solutions for detecting both **S2-e$^-$ & S1-photons**

# SINGLE-PHASE LIQUID-MPGD TPC CONCEPTS

- Particle interaction in liquid ➔ *ionizing electrons* & *single-photoelectrons* (from a photocathode).
- pe & e collected onto fine strip anodes (**MSP, MHSP, COBRA**...).
- Charge multiplication (**CM**) and electroluminescence (**EL**), occur at high fields on the thin strips.
- EL & CM photons detected by nearby photosensors.
- Various configurations discussed for e & e + pe detection.




Building-blocks

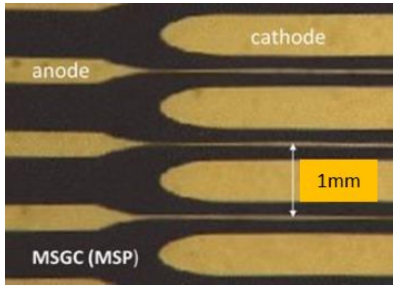
# Single-phase with Micro Strip Plates (MSP): S2 e⁻ only

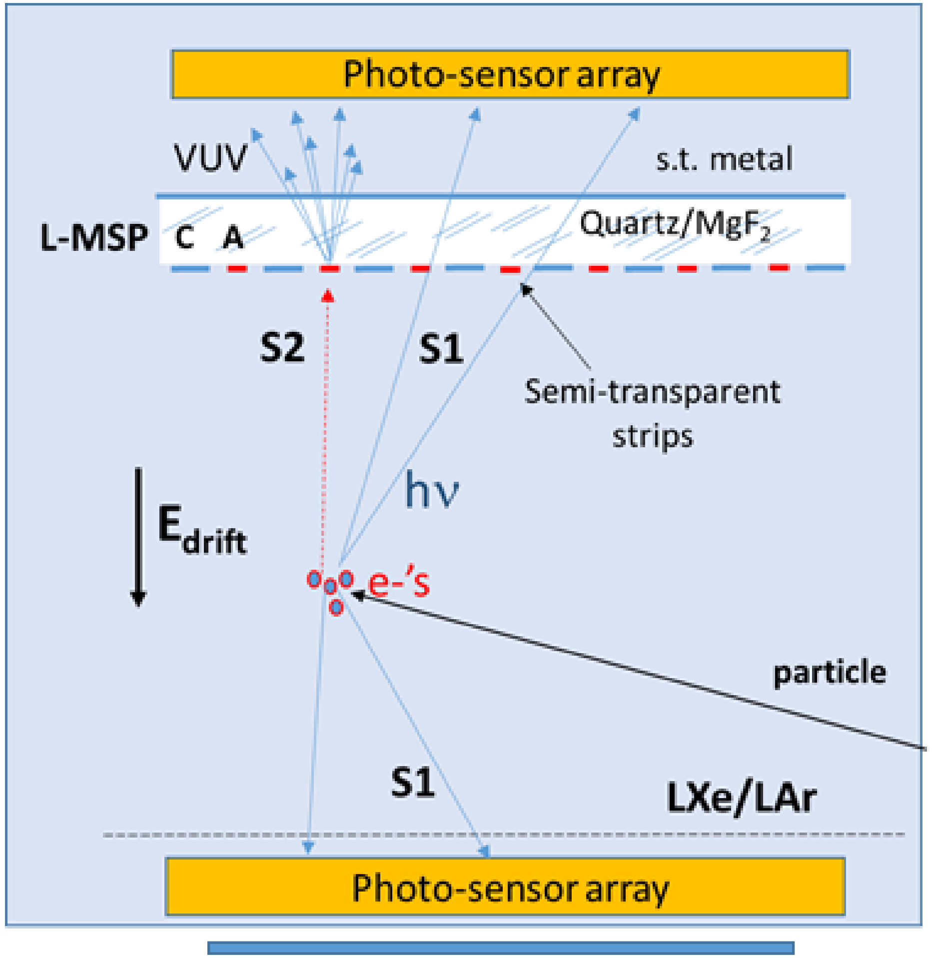
**S2**: **EL+avalanche** on strips. S2 Photons detected through VUV-transparent substrate
**S1**: photons detected (no amplification) by top and bottom photo-sensors (bottom can be replaced by a reflector)

**MSGC**

Policarpo, Chepel 1995

**x10 electron multiplication in LXe with MSGC; No EL photons recorded**



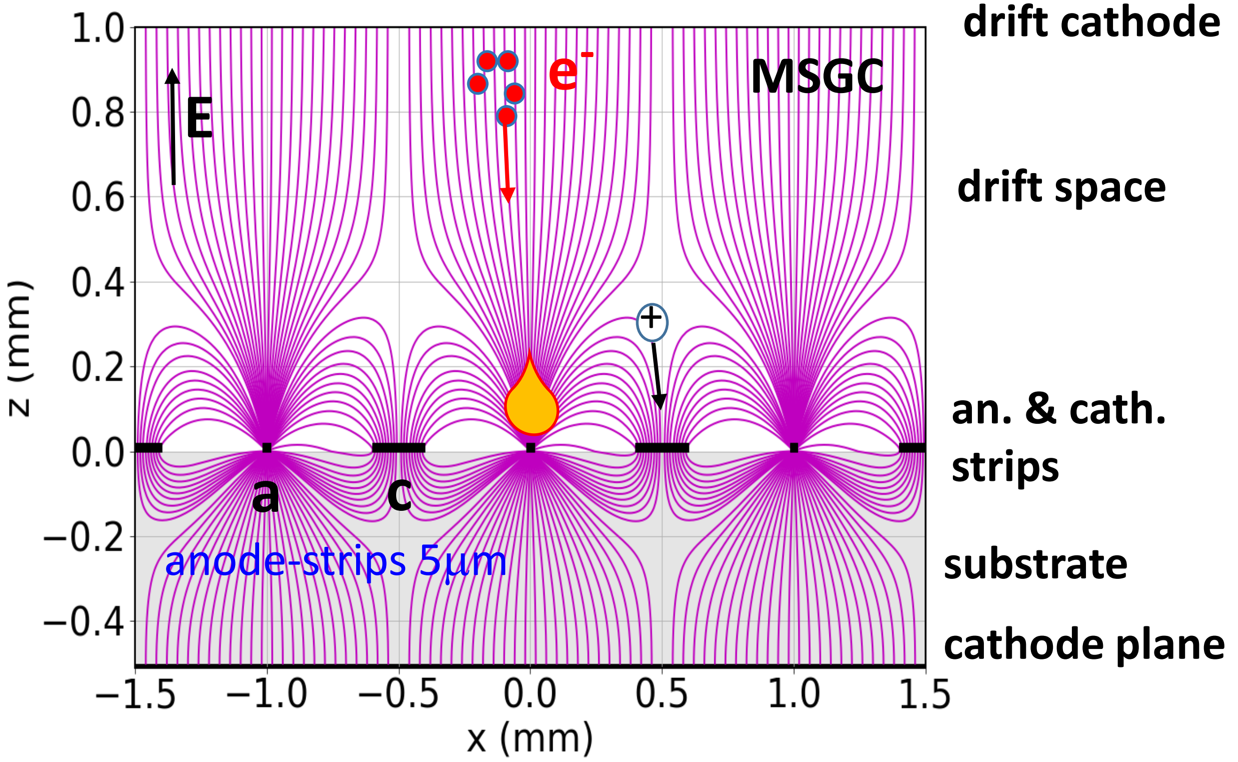




Or a reflective cathode

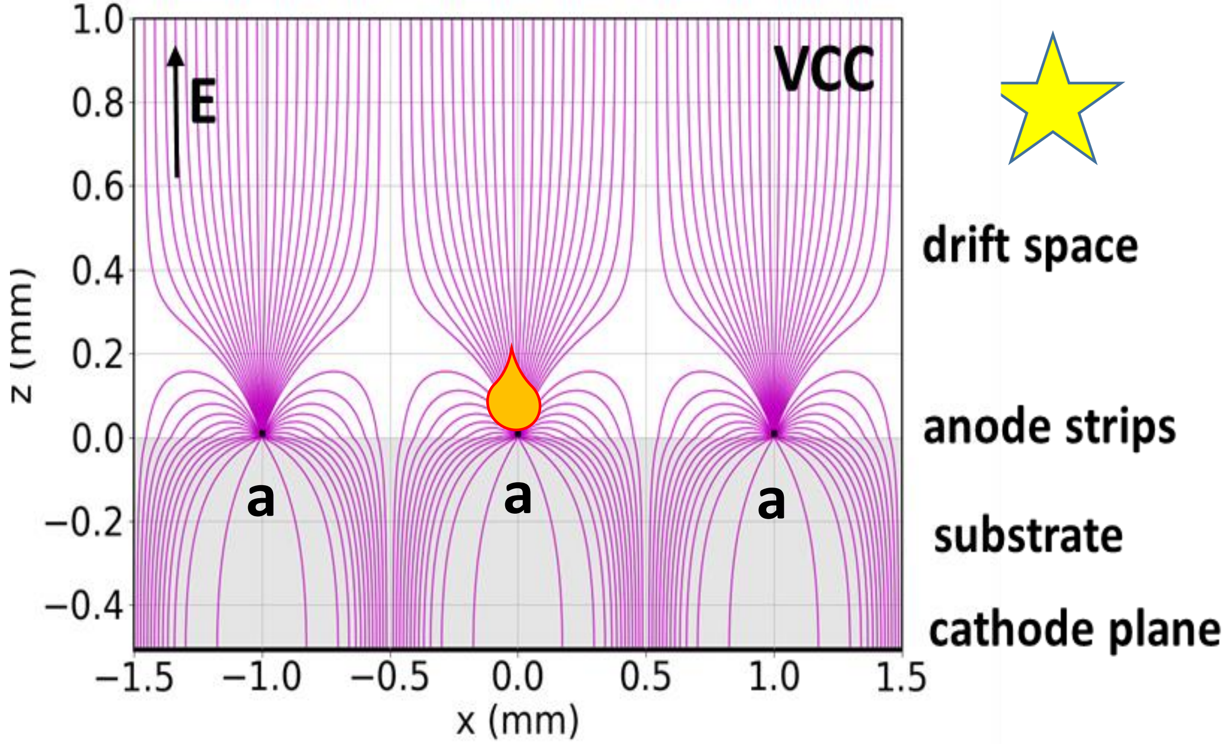
- MSP formed on VUV-transparent substrate, with few-nm thin Ni or Cr electrodes. (>50% transmission@175nm) ➔ small "shadowing"
- **L-MSP**: MSGC, VCC …
- Charges deposited in liquid, undergo **EL & small avalanche multiplication** at high field, near **anode strips**.
- Photons recorded with nearby photo-sensors
- The effective light-emission region depends on the MSP type, & potentials applied to the anode & cathode strips, cathode-backplane, and drift field.

# MSPs: MSGC & VCC – field simulations

**Microstrip Gas Chamber** Oed 1988




**Virtual Cathode Chamber** Capeans 1997

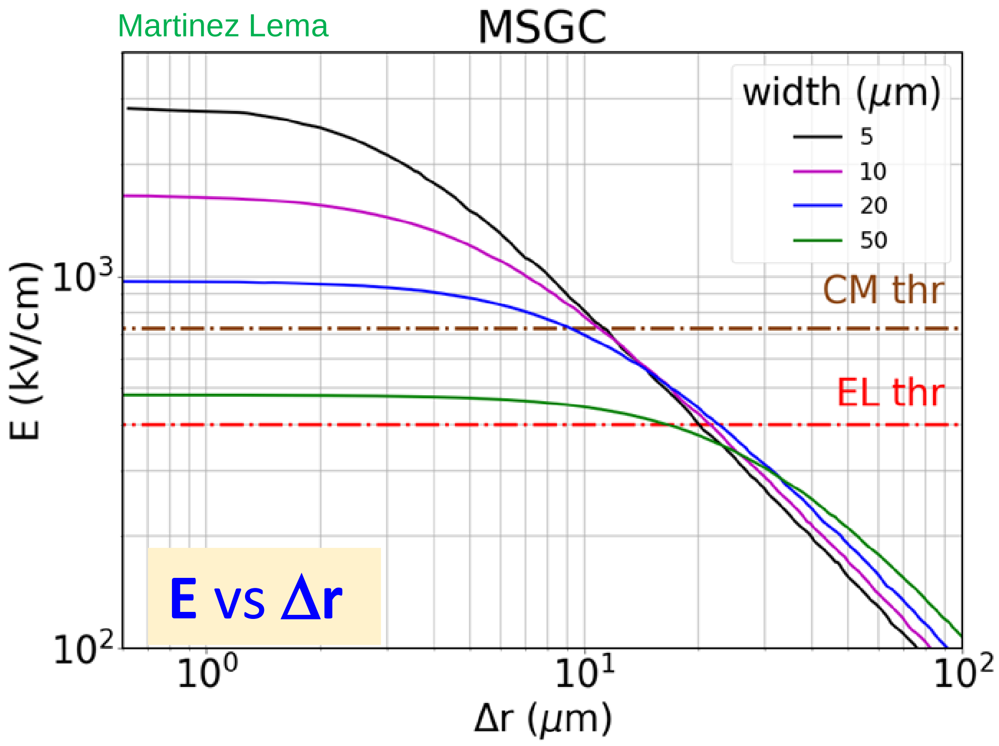


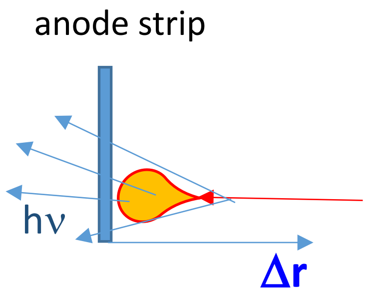

Weakness: discharges a-c limit HV

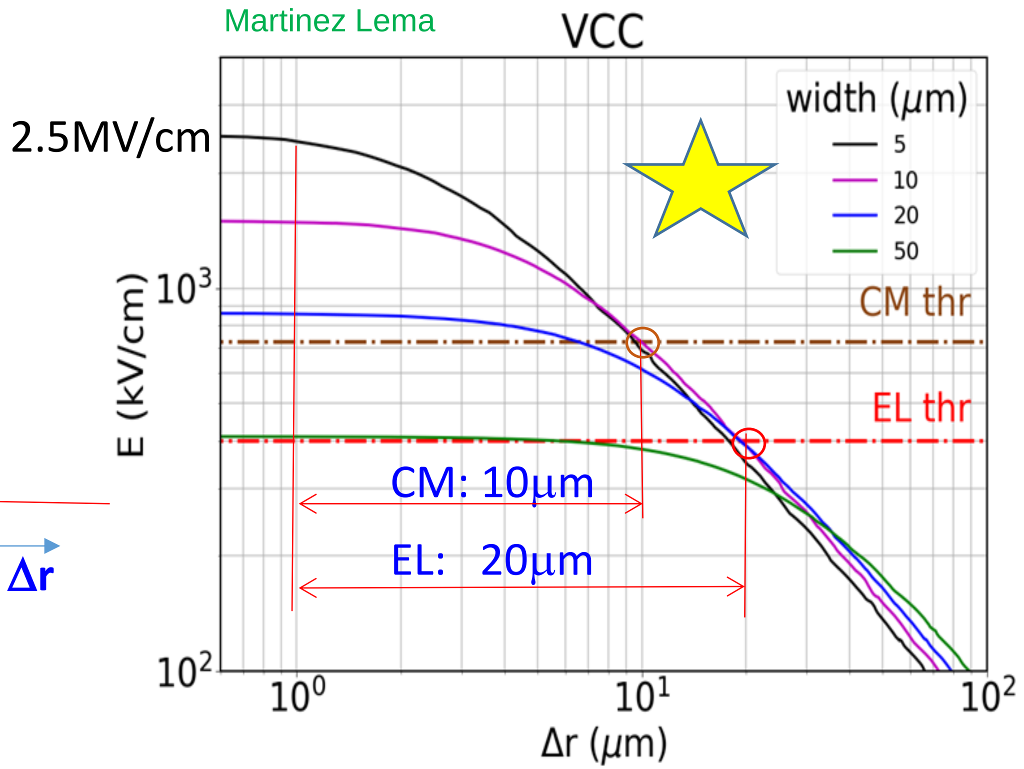
Benefit: **discharge-less**.
The substrate separates strips from cathode plane

**Field-line simulations:** substrate 0.5mm; anode-strips 5µm; cathode-strips 200µm; drift-gap=1.9mm; strip pitch=1mm. Potentials: $V_a$=5KV; $V_c$=0; backplane: $V_b$=0; drift: $V_d$=-300V.

# Simulated E vs distance from anode strip: MSGC vs VCC



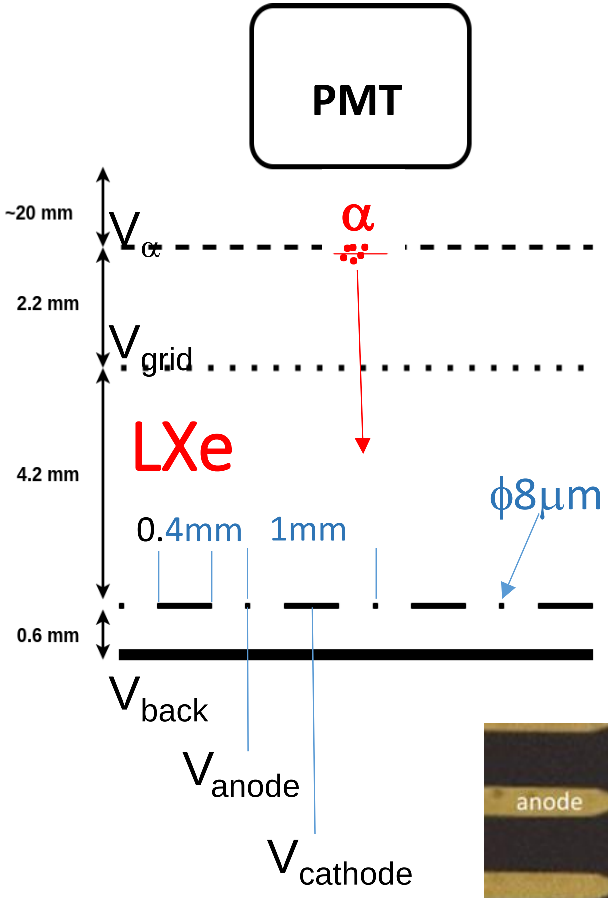

Substrate 0.5mm; anode-strips 5-50μm; cathode-strips 200μm; drift-gap=1.9mm; strip pitch=1mm. Potentials: $V_a$=5KV; $V_c$=0; backplane: $V_b$=0; drift: $V_d$=-300V.

crossing EL threshold **~ 20μm from strip surface.** Avalanche threshold **~10μm from surface.** (thresholds: **Aprile 2014**)

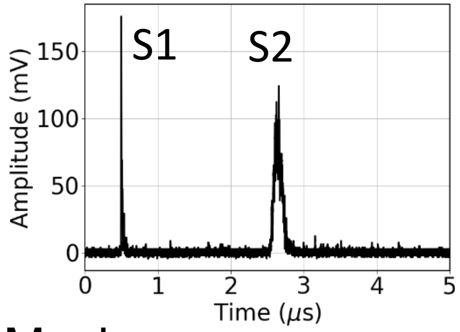
**MSGC & VCC: similar results @ $V_a$= 5kV**
**But: in practice, not applicable to MSGC**

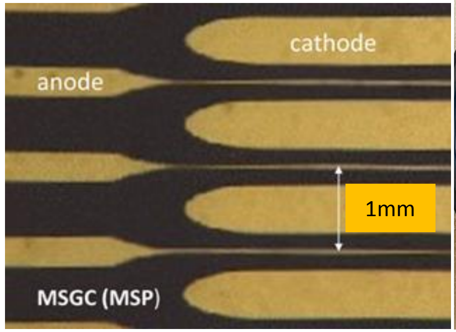
# Microstrip Plate - Preliminary results in LXe

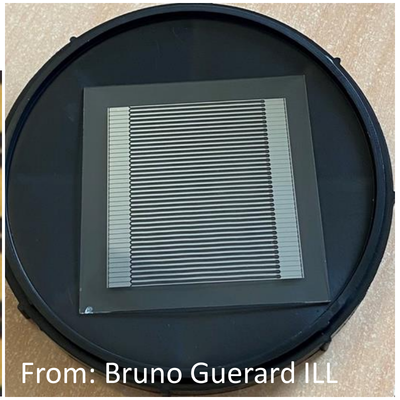
## Setup



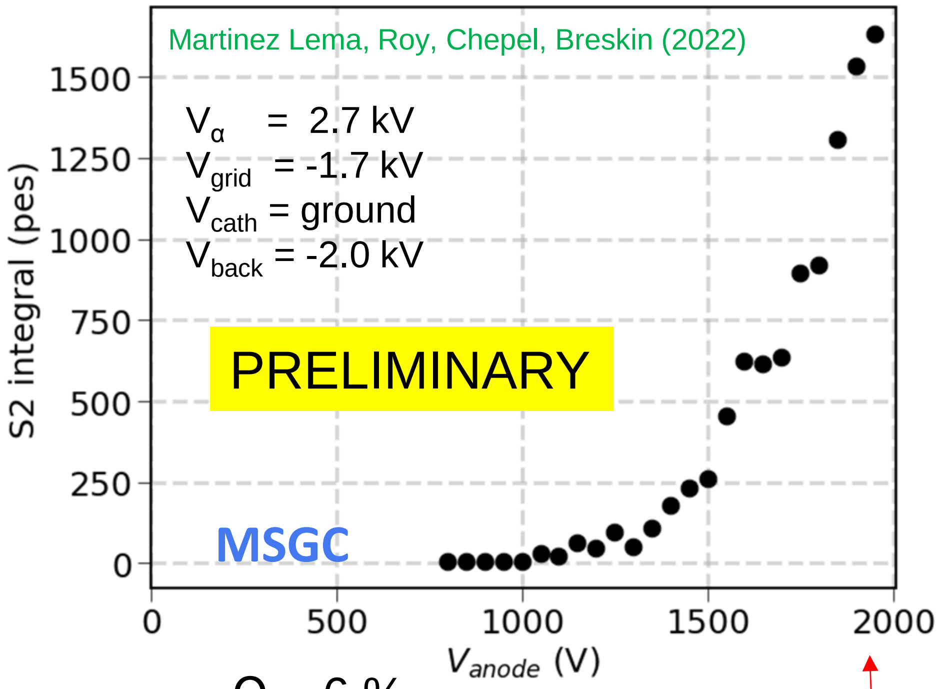

## Single event




## Average of S2 spectrum vs $V_{anode}$

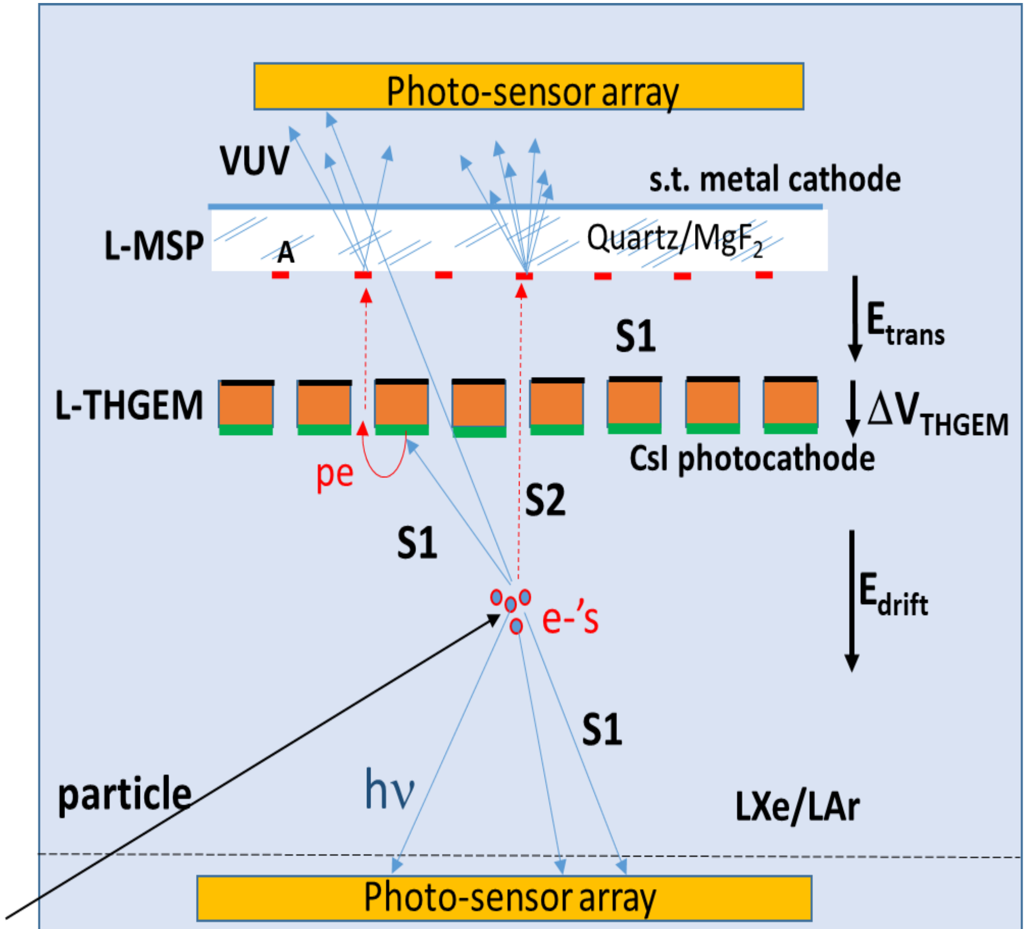



Ω ~ 6 %
T ~ 90%
QE ~ 40%
$Q_{total}$ (α) ~ 1 fC
**Y ~ 10 photons/e @ 2.0 kV**
(discharge limit)

**Charge gain ~ 4**

**Much higher gains/yields expected with VCC @ higher $V_{anode}$**

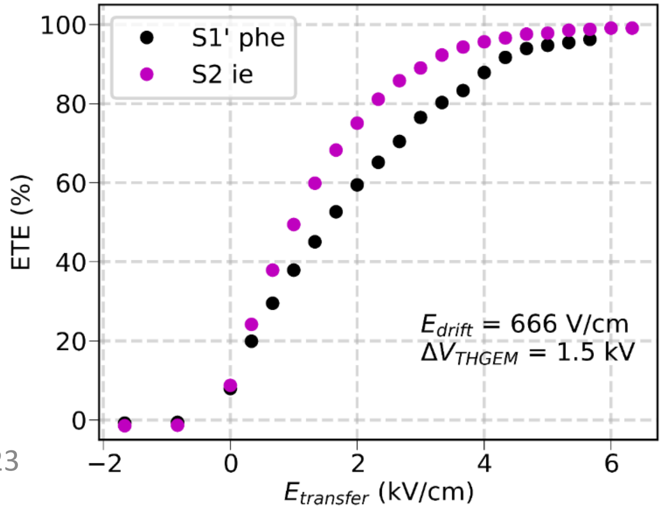
# Single-phase with cascaded THGEM + MSP ➔ S1 & S2




Or a reflective cathode

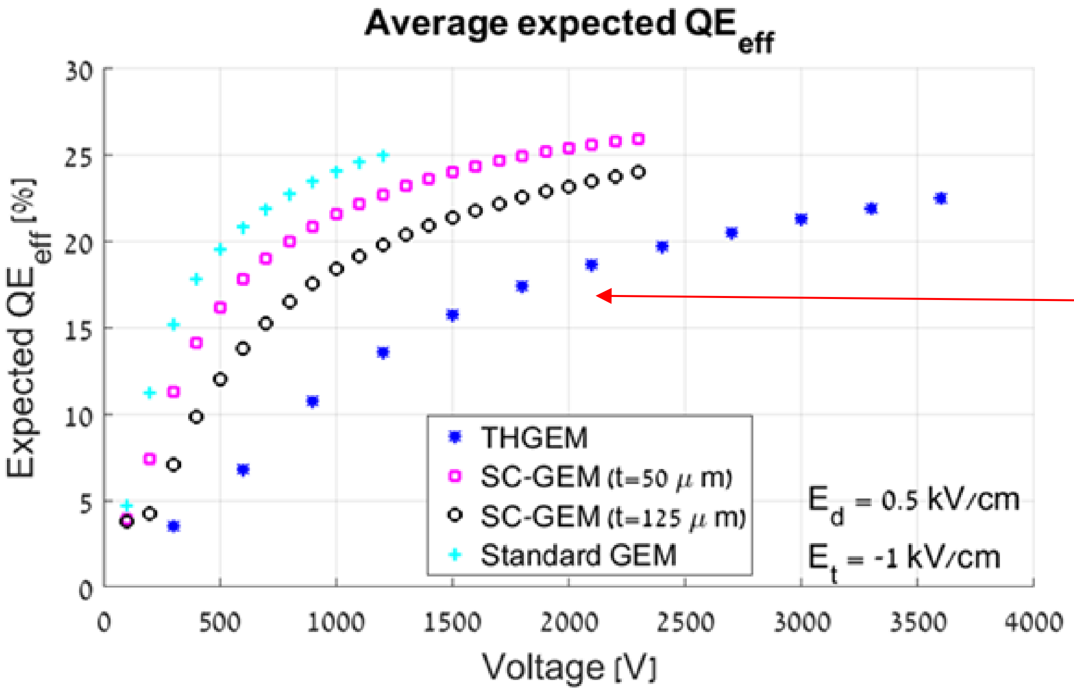
- 2-stage TPC with CsI-coated **L-THEM + L-MSP;** (here **L-VCC** with S.T. Cr\Ni strips on VUV- substrate)
- **S2** $e^-$ & **S1 UV-pe**$^-$ collected into L-THGEM holes & efficiently* transferred to the L-VCC.
- VUV photons emitted by **EL + small avalanche** near strips, detected through the substrate, by top photo-sensors.
- A fraction of S1 photons – detected by bottom photo-sensors or reflected by a reflective-cathode to the CsI.
- Option: top L-THGEM surface can be reflective or WLS-coated (➔ visible-range photo-sensors, glass substrate).

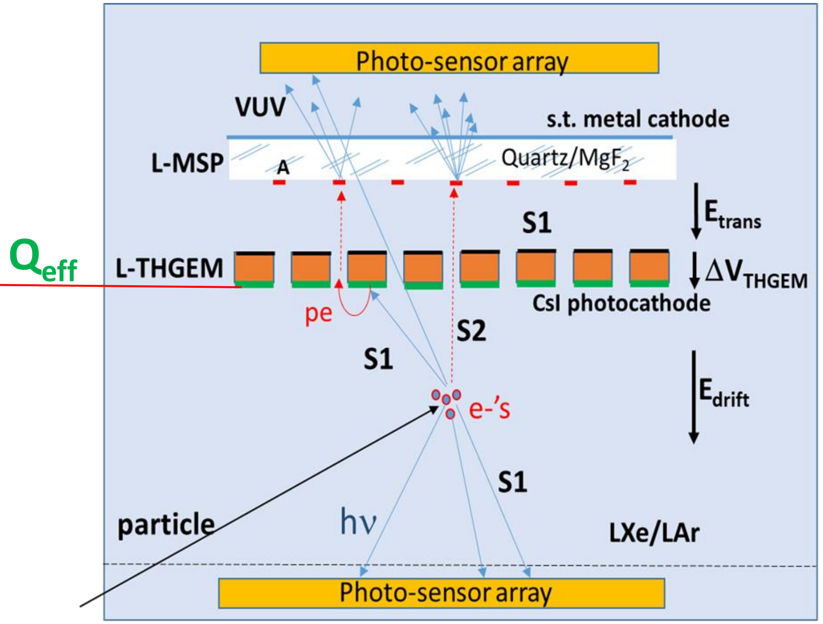
* Experimental Transfer Efficiency of $e^-$ and $pe^-$ through THGEM holes in LXe.



# Effective quantum efficiency $Q_{eff}$ of CsI in LXe

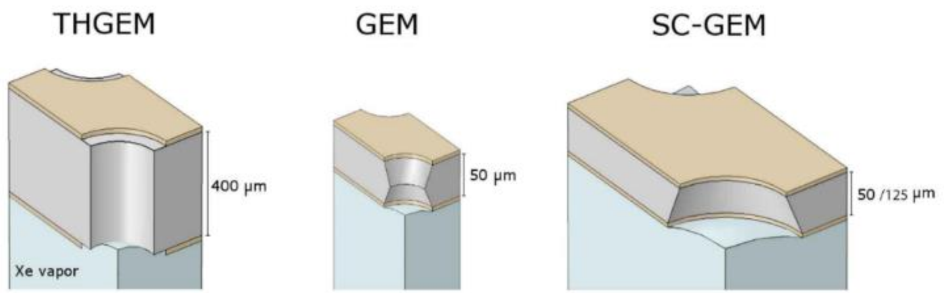
**GEM, SC-GEM, THGEM**



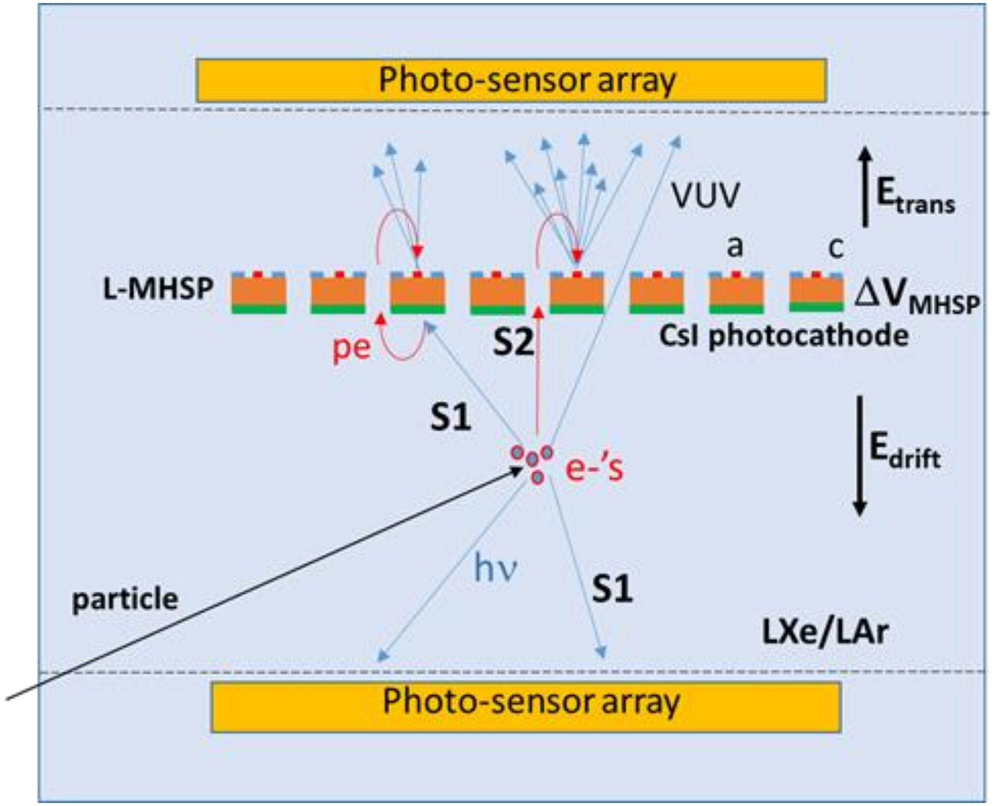



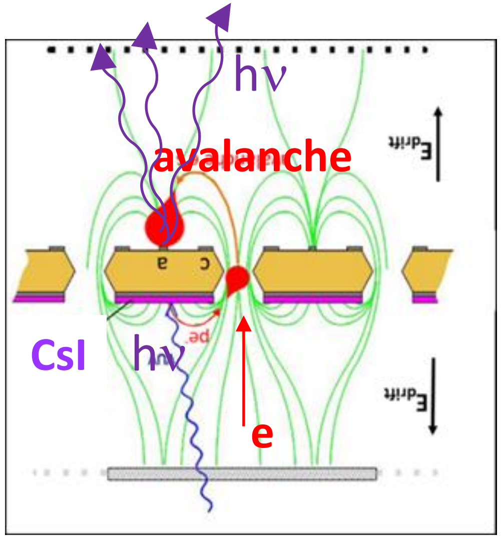

**Erdal 2021** https://jinst.sissa.it/jinst/theses/2021_JINST_TH_002.jsp

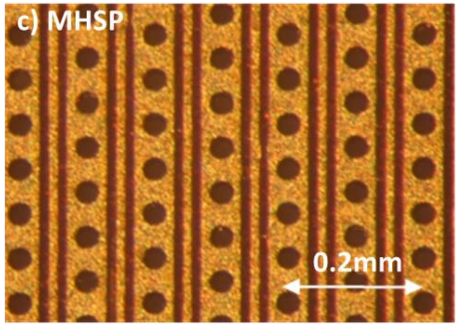
*Expected average $QE_{eff}$ in LXe across the entire surface of an electrode, as a function of voltage across the electrode. They were computed (using COMSOL®) for different perforated electrodes; electric field values: $E_d$=0.5 kV/cm and $E_t$=-1 kV/cm.*

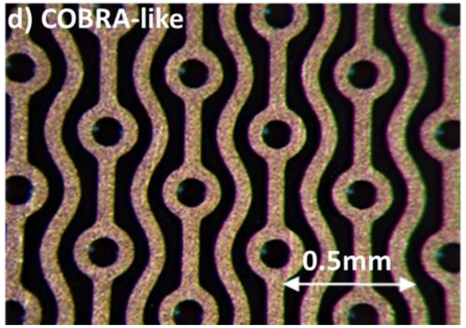


# Single-phase with single Micro Hole & Strip Plate (MHSP)



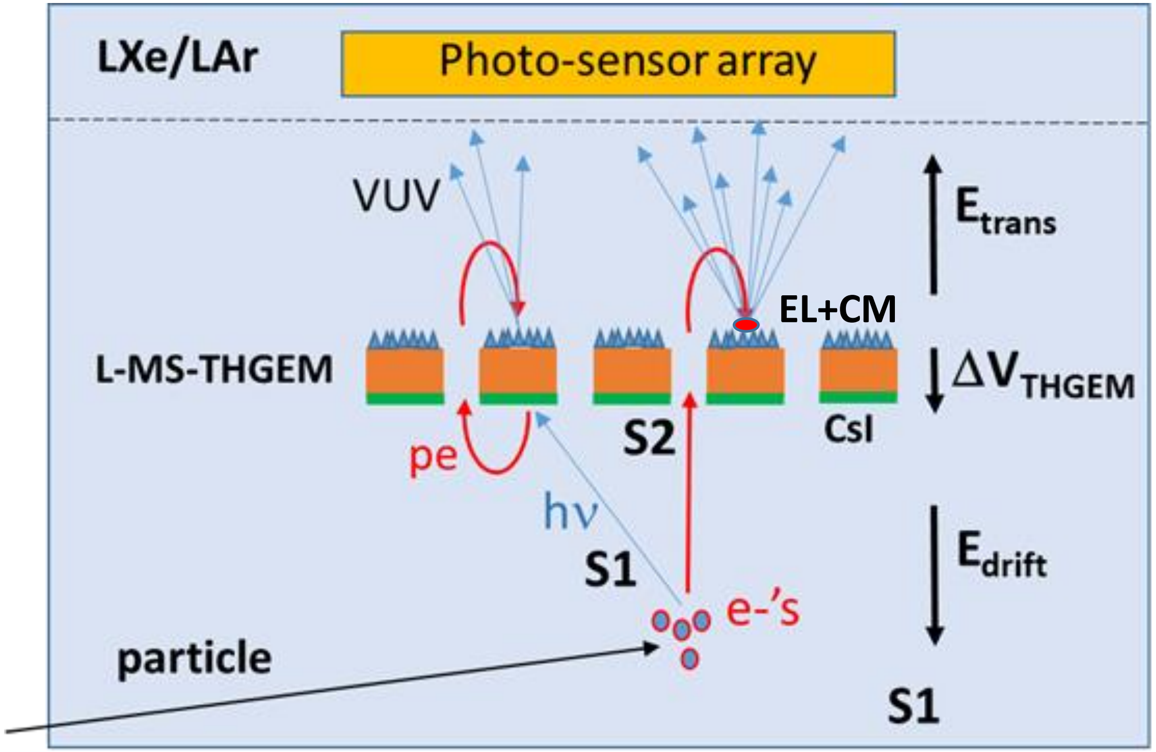



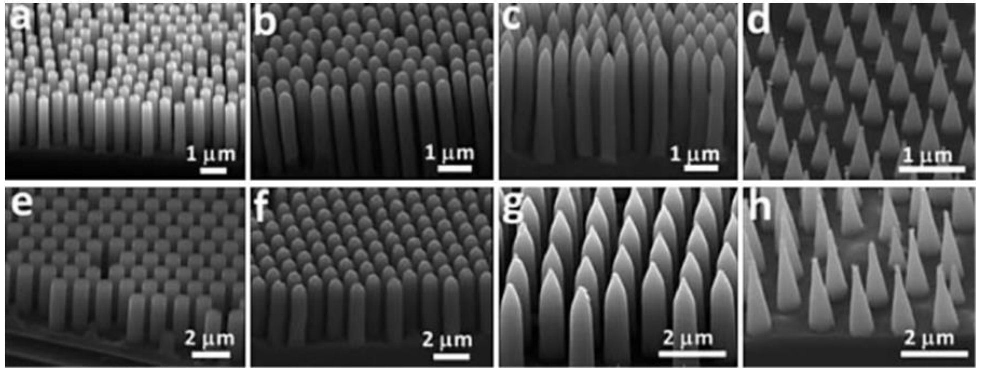

**MHSP**: Veloso, Rev Sci. Instr. 71, 2371 (2000)
https://doi.org/10.1063/1.1150623

Current technologies ➔ few-μm strips possible

- A single-phase TPC with (here) a CsI-coated **L-MHSP**.
- Both S2 e- & VUV photoelectrons are collected into the L-MHSP holes, drift to MHSP anode strips.
- VUV photons by EL + small avalanche near strips, are detected by the top photo-sensors.
- Other fraction of S1 photons - detected by bottom photo-sensors (or reflected.

# Single-phase with Micro-structured electrode



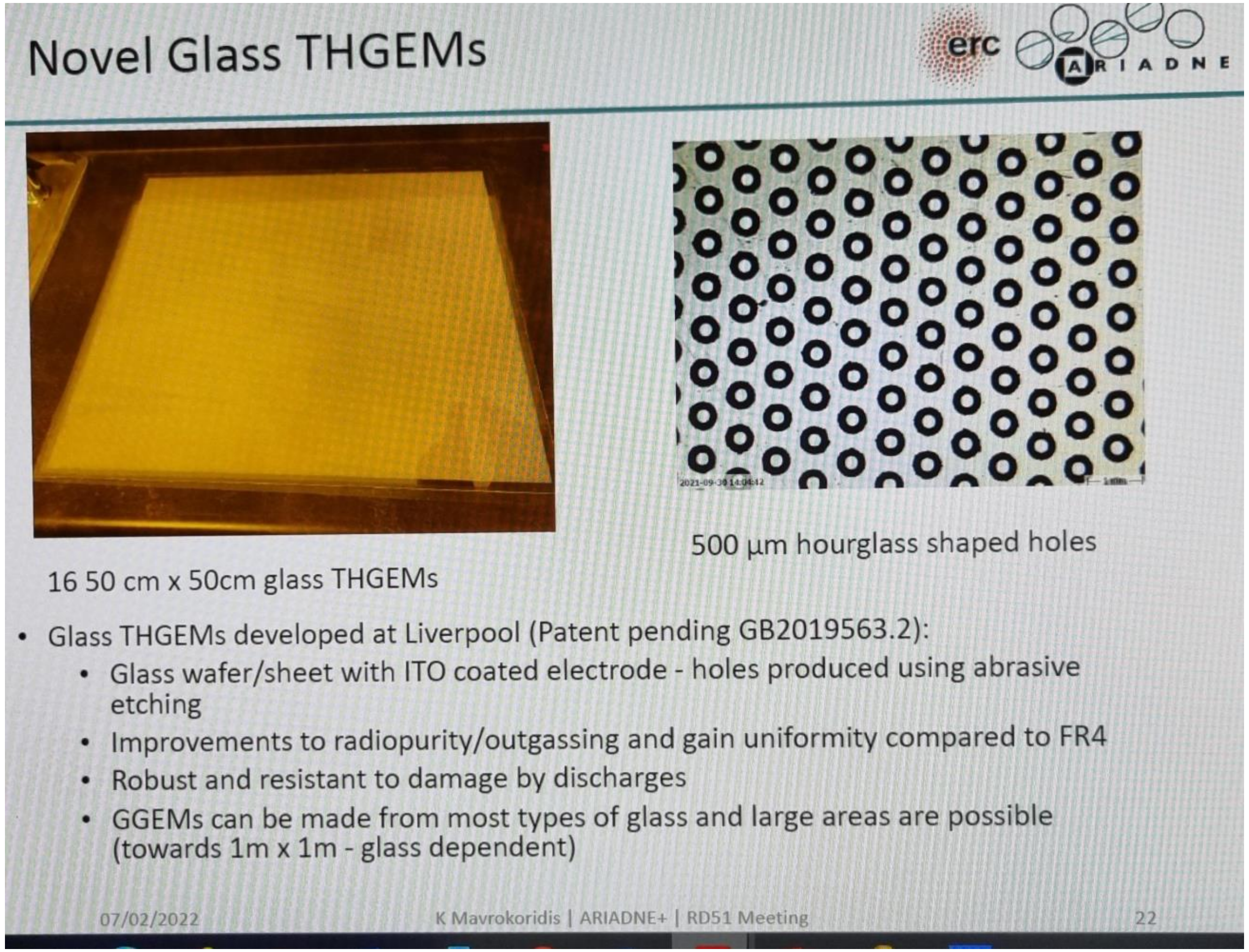




Hao Lin https://doi.org/10.1039/C3TA11889D

- A single-phase TPC with a Liquid micro-structured THGEM multiplier (**L-MS-THGEM**) coated with CsI. Both S2 ionization electrons and S1 VUV photoelectrons are collected into the holes, drift through the THGEM, towards the micro-structured top surface.
- VUV photons emitted by EL + small avalanche at the vicinity of the "anode tips", are detected by the top photo-sensors.
- Other fraction of S1 photons are detected by bottom photo-sensors (or reflected to CsI)

# Can we form large-size patterned electrodes?

**ARIADNE** LAr TPC with optical readout. **50x50cm$^2$ glass THGEM (GTHGEM)**



## Novel Glass THGEMs

16 50 cm x 50cm glass THGEMs

500 µm hourglass shaped holes

- Glass THGEMs developed at Liverpool (Patent pending GB2019563.2):
  - Glass wafer/sheet with ITO coated electrode - holes produced using abrasive etching
  - Improvements to radiopurity/outgassing and gain uniformity compared to FR4
  - Robust and resistant to damage by discharges
  - GEMs can be made from most types of glass and large areas are possible (towards 1m x 1m - glass dependent)

07/02/2022 K Mavrokoridis | ARIADNE+ | RD51 Meeting 22

Lowe et al. Appl. Sci. **2021**, 11(20), 9450;
https://doi.org/10.3390/app11209450

- So far, borofloat 33 glass and fused silica glass electrodes (the latter of *higher radio purity*) produced by abrasive formation of sub-mm holes.
- Electrode surfaces coated by resistive ITO film;
- Can be patterned, by laser techniques – e.g. to form **COBRA-like patterns**.
- Thin anode strips and other metallic patterns currently formed in industry: inkjet & photolithographic techniques. (few-micron thin strips on relatively large areas (up to 24"x 24") already formed on a variety of substrate materials.

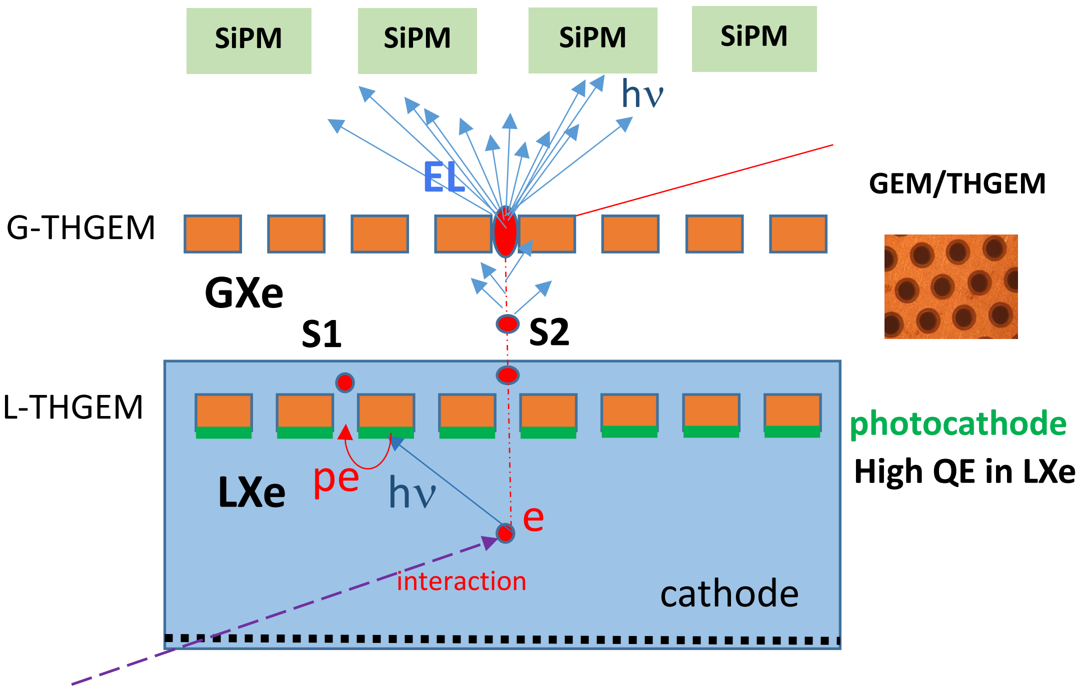
See refs in https://doi.org/10.1088/1748-0221/17/08/P08002

# Novel Dual-Phase TPC Concepts

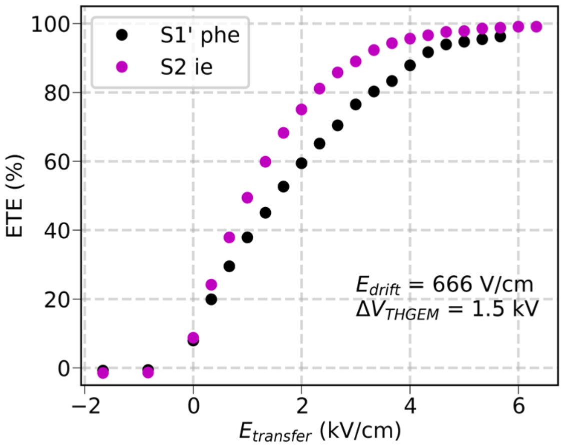
## In case Single-Phase ones remain a dream…

# Dual-Phase: Cascaded Liquid Hole Multiplier (LHM) – S1 & S2

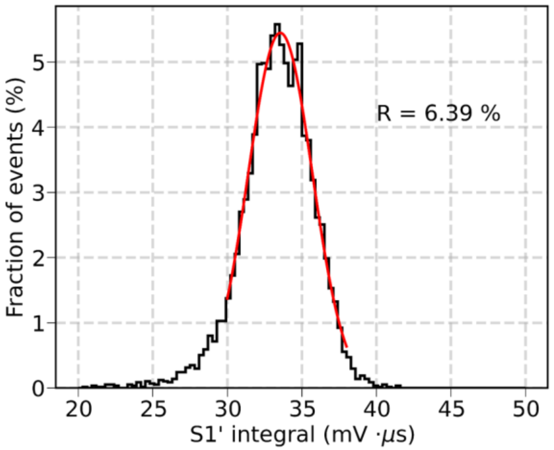
Martinez Lema et al. https://events.camk.edu.pl/event/47/contributions/377/attachments/126/281/LIDINE-2022%20The%20Bubble-Free%20Liquid%20Hole-Multiplier-v2.pdf



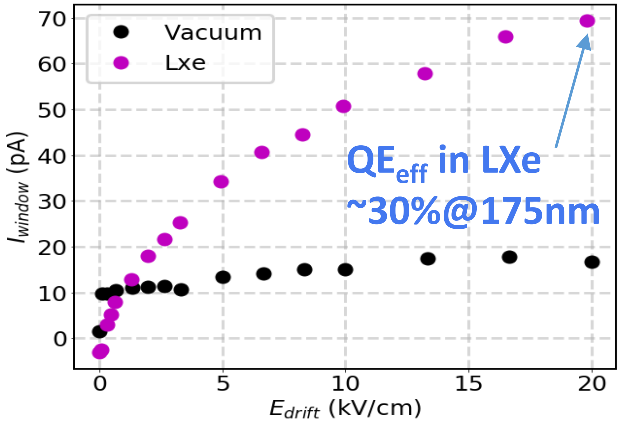

**S2** electrons and fraction of **S1**-induced photoelectrons extracted efficiently **in liquid** through the holes of a **CsI-coated** immersed L-THGEM electrode. They traverse the interface inducing electroluminescence (EL) **in gas phase**, mostly in holes of a second perforated G-THGEM electrode. Readout by nearby photo-sensors. Bottom cathode: reflective, or photosensors underneath.




e- & pe- transfer efficiency through THGEM immersed in LXe




α-induced S1 energy resolution



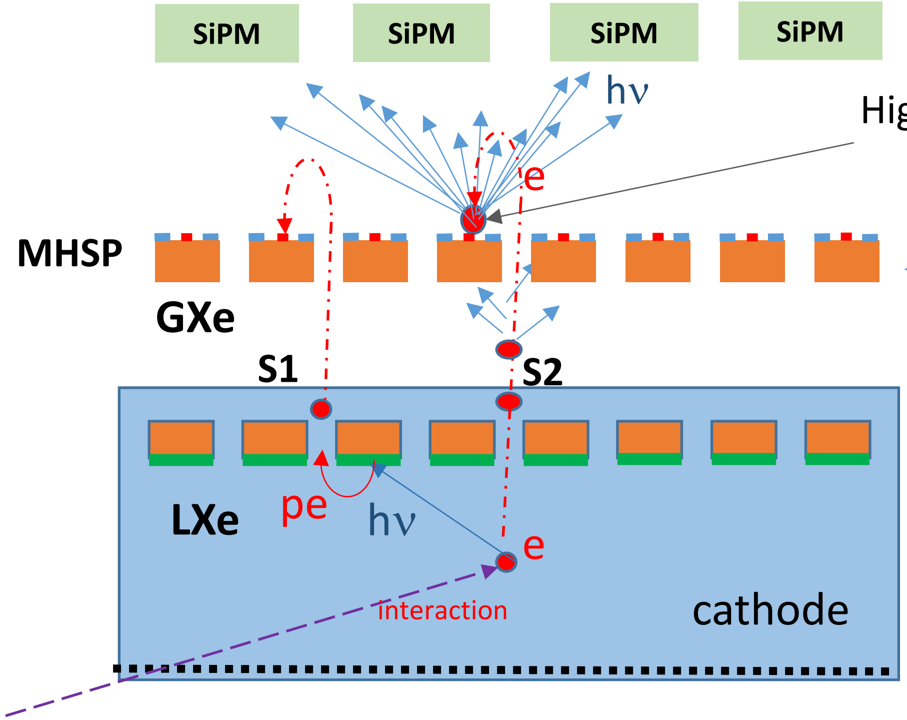

**PRELIMINARY:**
**~350 photons\e\4π**

**LXe: increased $QE_{eff}$ by ~x3.5 compared to vacuum!**

**EL in holes does not depend on interface-gap variations**

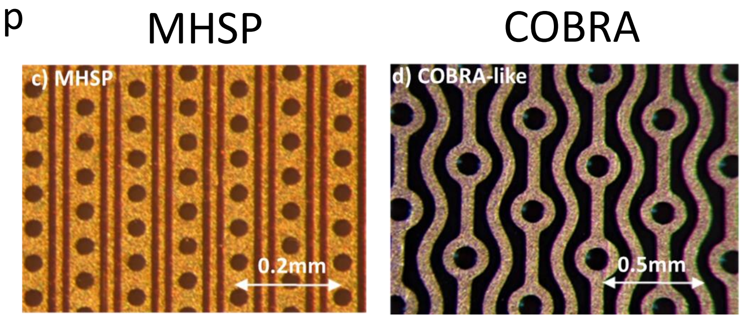
# Dual-Phase: Cascaded Liquid Hole Multiplier (LHM) R&D - S1 & S2

## The multiplier: Perforated electrode with thin strips




High field on strip
➔ EL + CM

photocathode
High QE in LXe

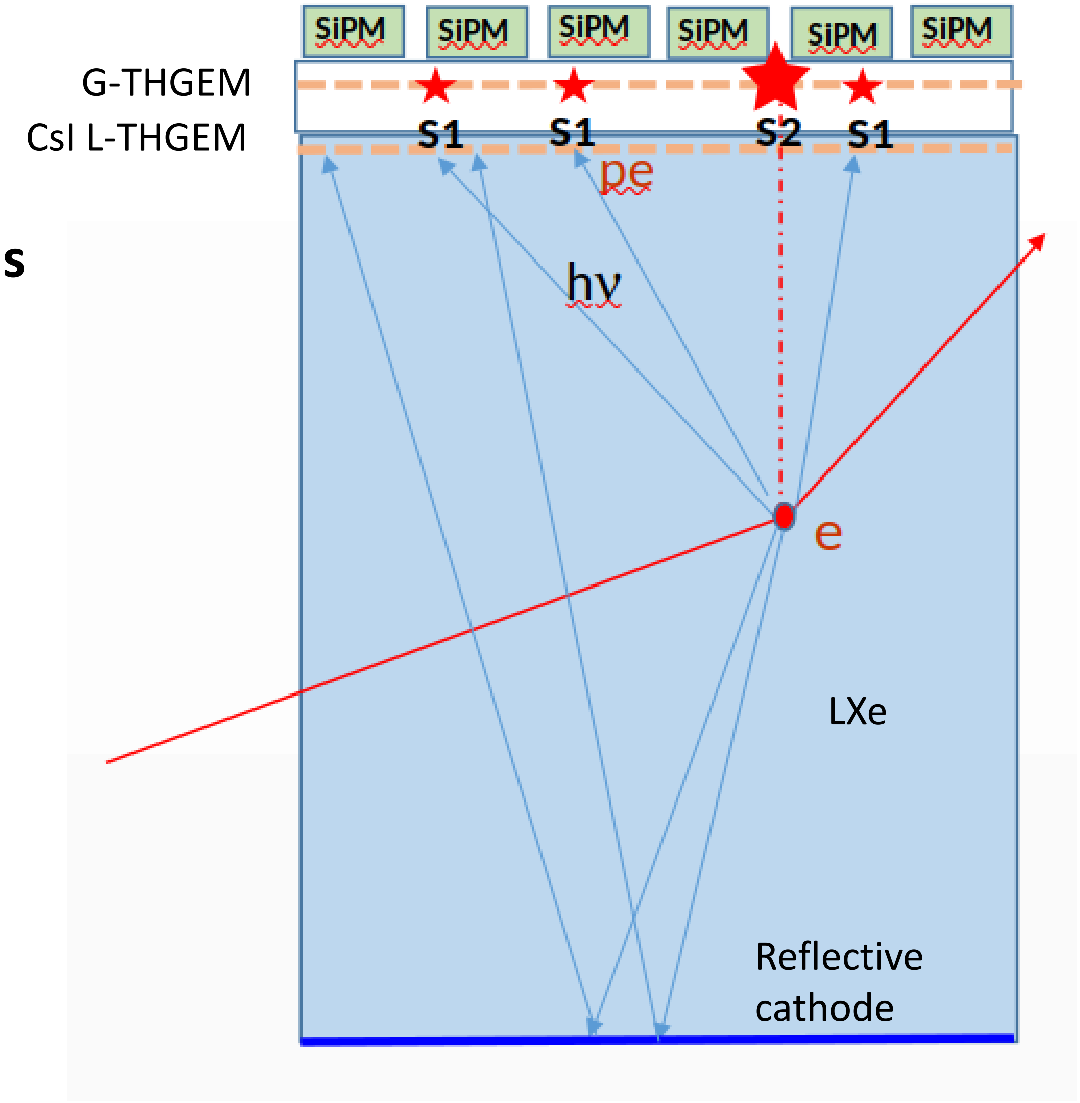



Current technologies➔ few-µm strips possible

EXPECTED: higher field➔ larger photon yield & faster signals

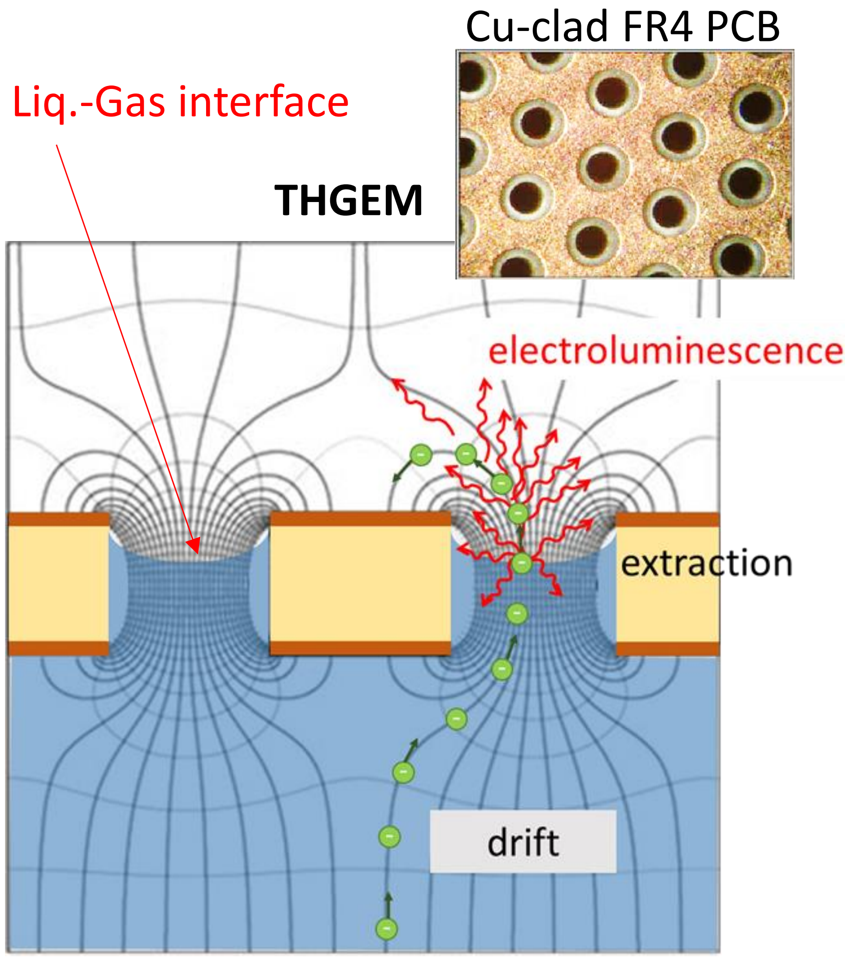
# A potential cascaded LHM DM TPC

- **High CsI QE**
  ➔ expected high PDE
- **Unambiguous detection of amplified single photons**
  Above dark current
  Possible to use SiPM, CMOS-SPAD etc.
  ➔Lower detection threshold
- **Transmitted charges detected in G-THGEM holes:**
  Interface fluctuations not critical
  Faster EL signals
- **No PMTs**
  Economic
  Radio-purity?
  No wasted LXe in buffer region



# Dual-Phase: The Floating Hole Multiplier FHM

- Better surface-effects control by separation of the two phases;
- The liquid phase and the gas should be in thermal equilibrium (at the interface)
- Use "rubust" interface: a perforated electrode FLOATING on the liquid surface ➔ e.g. **GEM, THGEM, COBRA**, etc
- Must control the liquid level precisely to have liquid below and gas above.




Idea V. Chepel

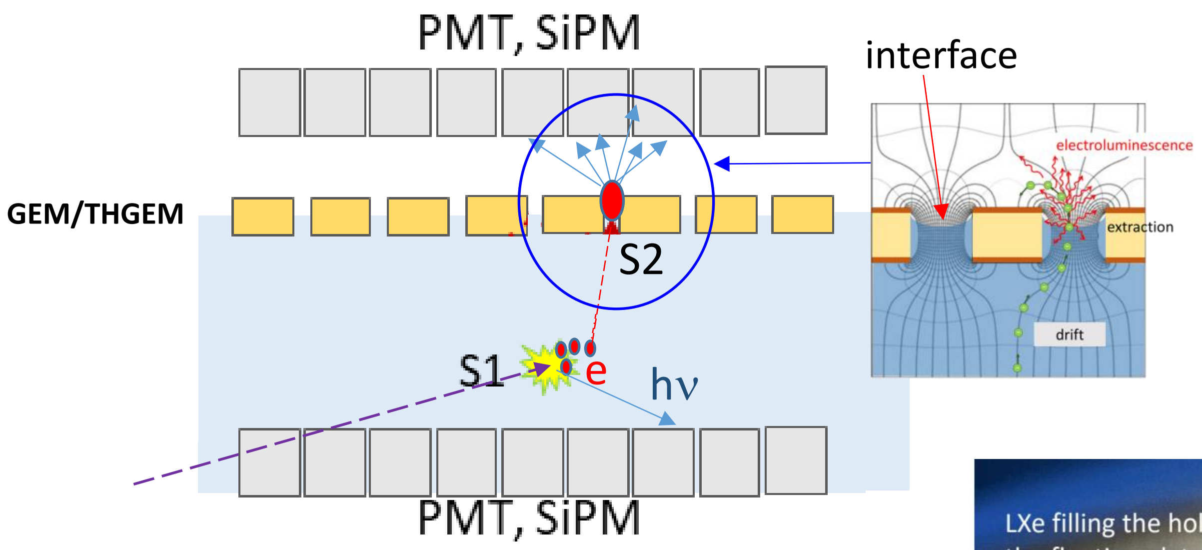
LXe density **2.9** g/cm3

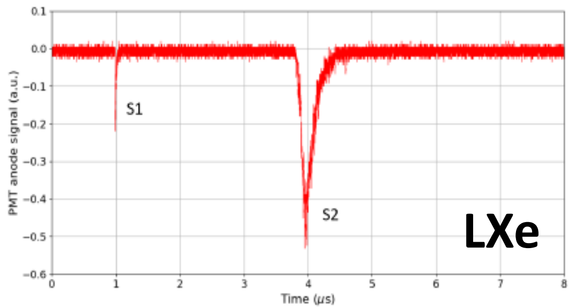
FR4 density **2.0±0.2** g/cm3

If copper cladding is not too heavy → THGEM **should float** on the surface of LXe

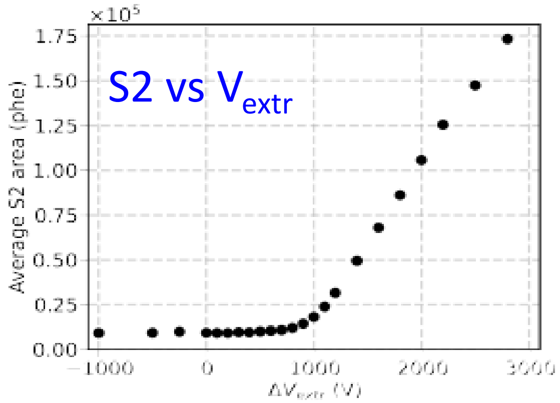
# FHM – S2 e⁻ only

proof of FHM principle in LXe: Chepel et al. http://arxiv.org/abs/2301.12990

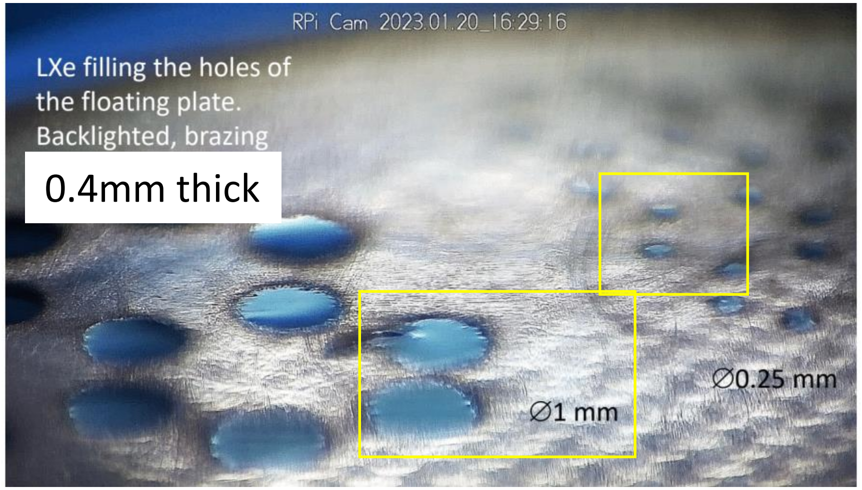



α-induced S1 & S2

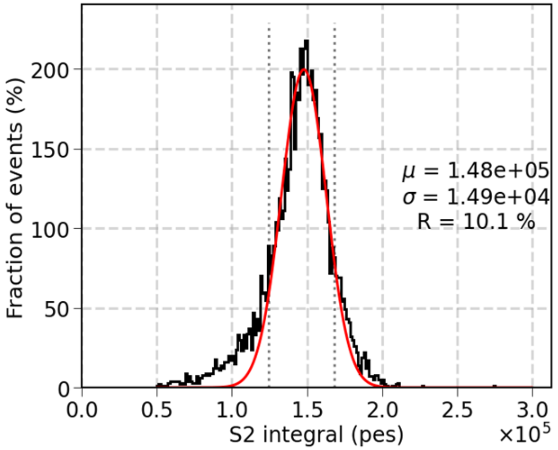



S2 electrons extracted efficiently through the interface within holes of a perforated electrode, **<u>floating on the liquid</u>**. They traverse the interface (under high fields) inducing EL **in gas**. Readout by nearby photo-sensors.




With 0.4mm thick electrode floating on LXe, the holes are rather filled with the liquid.
R&D: Thicker electrode:
➔ expected higher photon yields.

PRELIMINARY:
Y~500 photons\e\4π

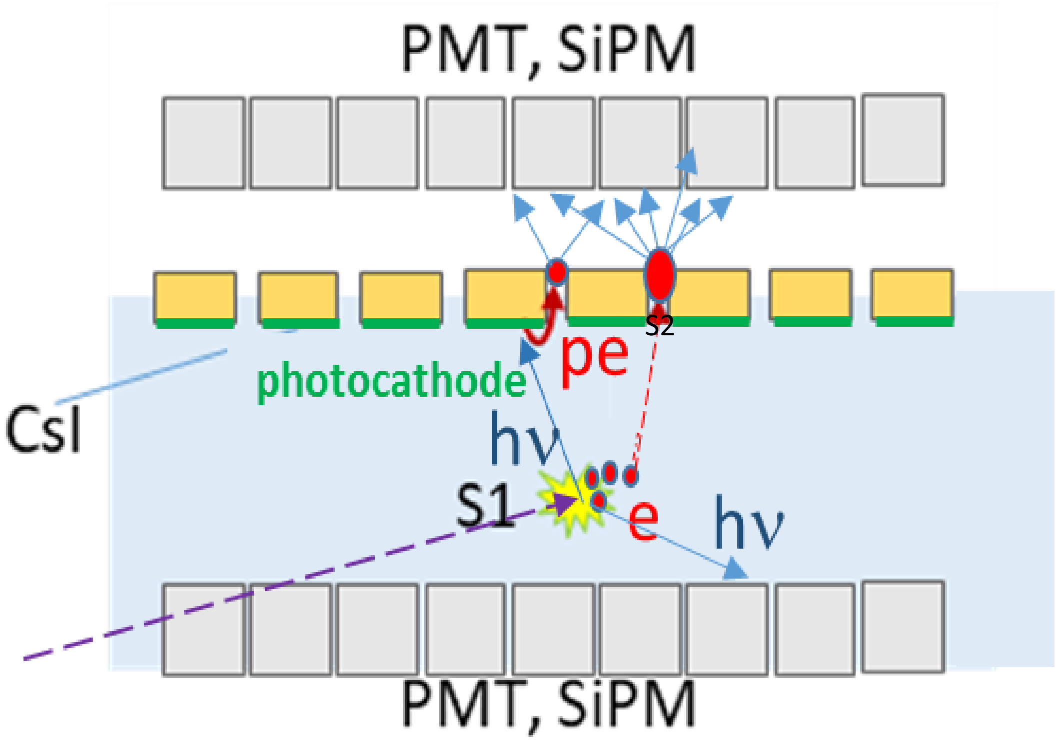



α-induced S2
Energy resolution

Reduced interface effects and instabilities

# FHM – S1 photons & S2 e⁻

## Future R&D




An optional **CsI-coated** perforated floating electrode allows for detecting both, a fraction of **S1 photons** (photoelectrons from CsI) **and S2 electrons.** Both are collected into the holes and traverse the interface (under high fields) inducing EL **in gas**. Readout by nearby photo-sensors. Under R&D.

# FHM – potential benefits

- Significantly smaller free liquid surface – reduced surface instabilities
- High electron extraction probability thanks to high field at the interface

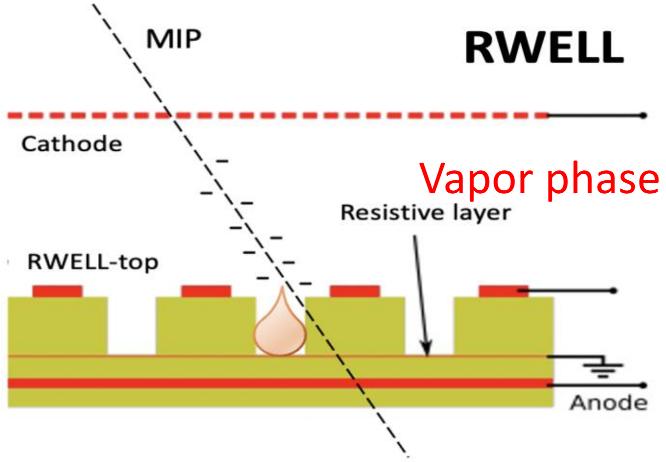
  ➔ **Result – reduced single-electron noise**
- Parallelism between the gate and extraction electrodes
- No sagging
- No need for fine detector levelling and liquid level control

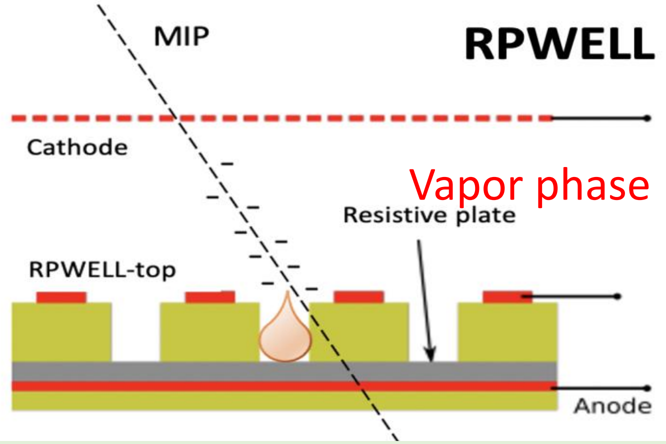
**R&D:**

- Electrode optimization to maximize light emission from holes
- Physics of interface
- Photosensitive (CsI) FHM
- FHM on LAr: need lower density PCB materials

# Cryogenic charge multipliers with resistive electrodes

**Motivation:** Charge multiplication in noble gases limited by discharges due to secondary effects to <10 (DUNE)
**Goal:** Quench harmful discharges by deploying **resistive materials** in the gas-avalanche multiplier




- THGEM electrode, coupled to readout anode via **resistive electrode**,
- Deposited charges are collected into holes, undergoing avalanche multiplication under $\Delta V_{RWELL}$

### Resistive WELL (RWELL)

- **Resistive film**, e.g. Diamond-Like-Carbon (DLC), on an insulator.
- Charges evacuated sideways to ground via resistive layer
- Signals are induced on readout anode by charges movement

### Resistive-Plate WELL (RPWELL)

- **resistive plate**, e.g. a ceramic material Yttria-Stabilized-Zirconia (YSZ) doped with ferrite oxide (Fe2O3), to readout anode.
- Amplified charge travel through the resistive plate to the anode.

challenges: find/develop resistive materials of the "right" surface/bulk resistivity at noble-liquid temperature

# Cryogenic RWELL & RPWELL challenges

## Discharge quenching:

An occasional gas breakdown ➔ very large charge accumulation within holes.
➔ reduction of the local electric field.
➔ quenching of discharge energy.
➔ Prevents damage to electrodes & electronics

## A main challenge:

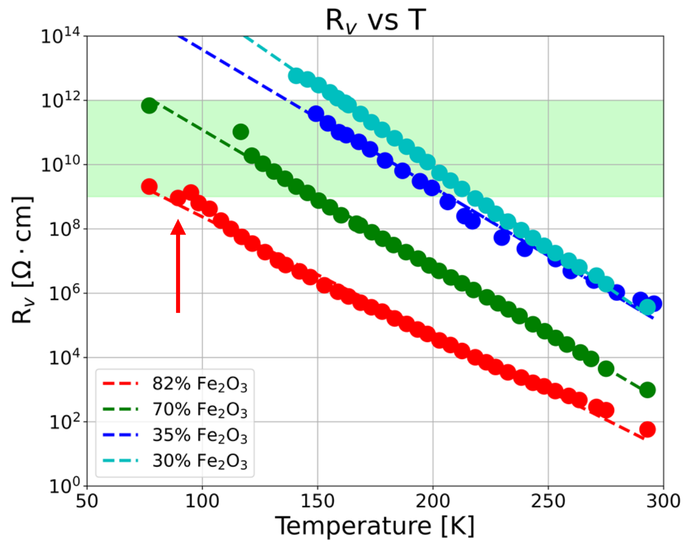
find/develop resistive materials of the "right" surface/bulk resistivity at noble-liquid temperatures (LAr ~87K; LXe ~ 165K).

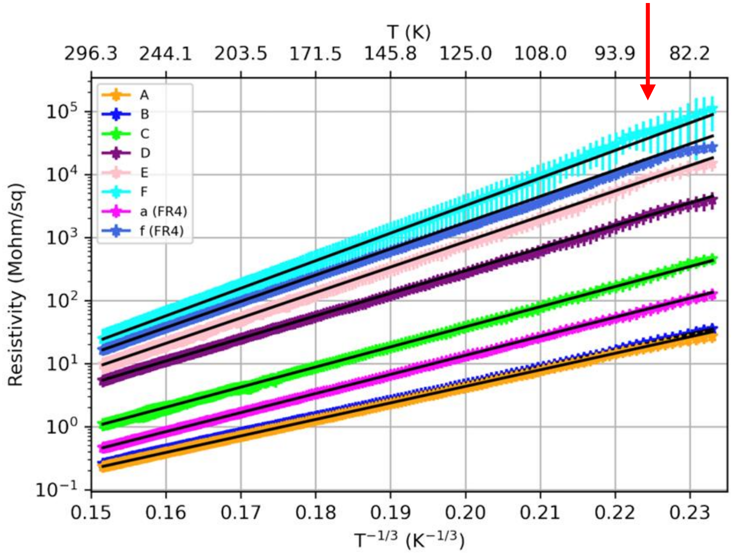
Resistive FILM: ~ 20GΩ/□

Resistive PLATE: ~ $10^9$-$10^{12}$Ω·cm

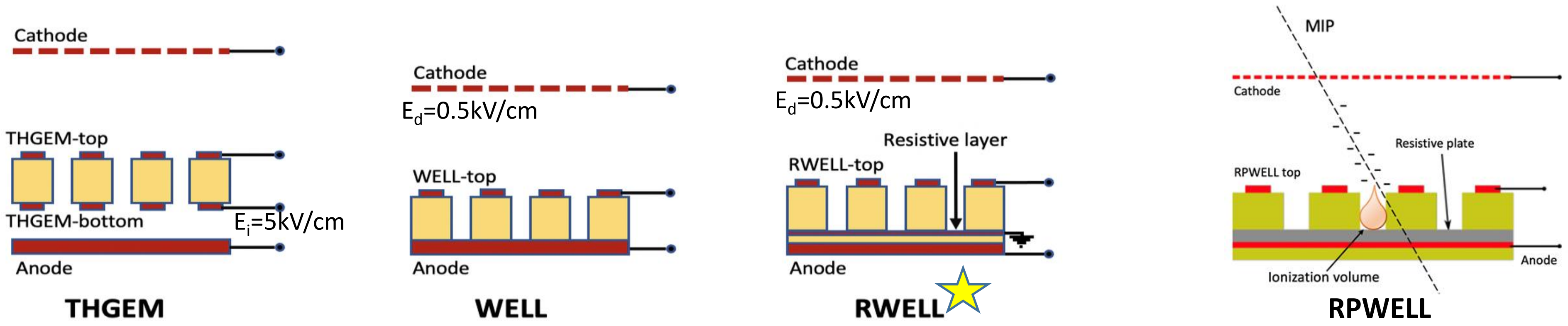
**Tesi, MPGD2022**

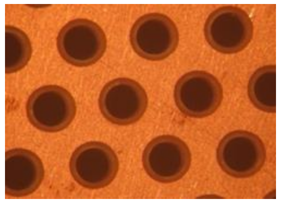
https://indico.cern.ch/event/1219224/contributions/5130754/attachments/2566756/4531430/Tesi_MPGD2022.pdf

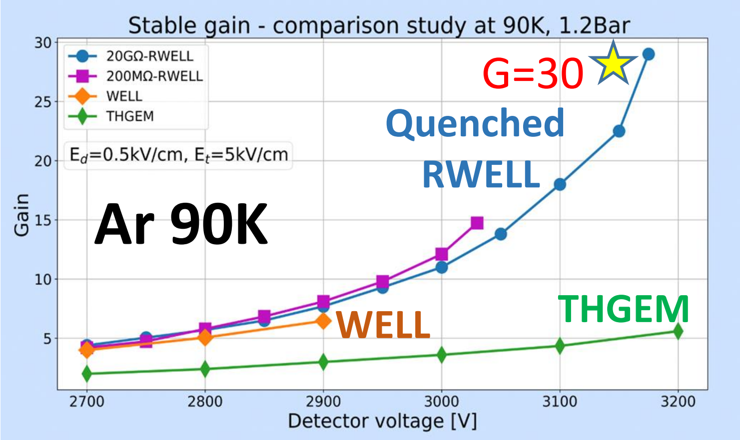


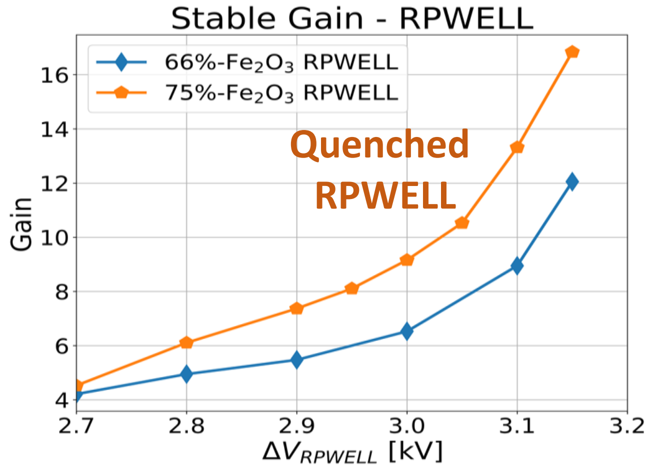



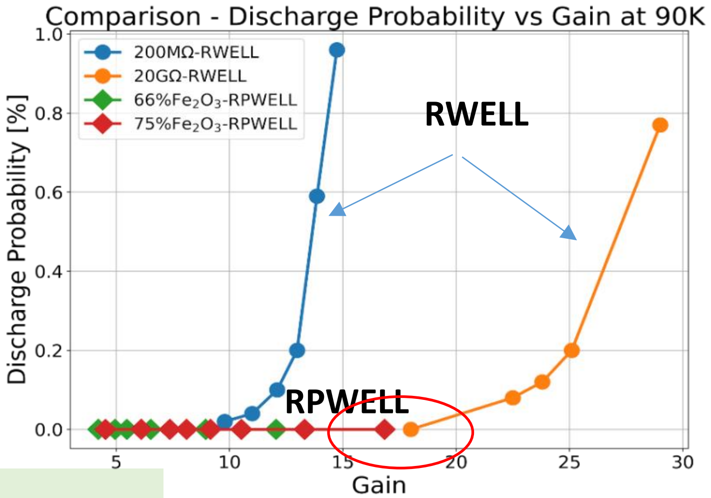
# Gain comparison: unquenched THGEM/WELL & RWELL






So far, with experiments performed under <u>equal conditions:</u>
**RWELL/DLC** gain > THGEM (LEM) gain;
**RWELL** gain > **RPWELL** gain (but higher quenched-discharges rate
Near zero discharges @ gain < 17

# Summary & Outlook

**GENERIC R&D**

- Ideas & concepts for potential improvement of large-volume noble-liquid detectors: DM, neutrino…;
- Goal: Effective detection of both, scintillation photons and/or ionization electrons;
- Single-phase: various **optically-recorded** configurations incorporating micro-structured elements;
- Dual-phase: **Optically-recorded** *Cascaded (liquid/gas) multipliers, Floating Hole Multipliers, Bubble-assisted Liquid Hole Multipliers* – and **electrically-recorded** *Resistive Charge Multipliers;*

## So far:

Investigations in LXe (with only LHM investigated also in LAr);
Lower PDE and worse E-resolution than expected (*electron losses at interface*)

Single phase: - Charge & light amplification investigated on **MSGC** strips in LXe
Preliminary: low due to discharge limits. High amplification expected with **VCC** plates

Dual phase: - proof of principle for all; ~500 photons/e-/4$\pi$
➔ potential to detect single photons above background with simpler photosensors
- Imaging investigated only in LHM (200$\mu$mRMS)

**Potential applications:** DM, $\nu$ physics, n/$\gamma$ detection in Nucl. Physics,* Homeland security**…

*Cortesi 2017; **Israelashvili 2017

***Many open questions*** *requiring Simulations & exp. R&D (LAr, LXe); R&D on nanostructures, on stability of VUV-photocathodes in noble liquids & on technologies*

*Thank you*