# Novel noble-liquid detector concepts

**Amos Breskin**

*Dept. of Astrophysics & Particle Physics*

WEIZMANN INSTITUTE OF SCIENCE

# Main NL-detector "users": DM & ν physics

also 0νββ decay, HEP calorimetry, medical imaging, homeland security, …

DM: mostly liquid XENON LXe (Darkside LAr)

Neutrino: liquid ARGON LAr

## **DM:** WIMPS (GeV-TeV)

WIMP elastic scattering off atomic target nuclei

➔ low deposited energy (**keV**) by nuclear recoils ➔ **few – to few tens e-'s**

requires low detection thresholds!

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

➔ **background-radiation discrimination**

## Neutrino physics:

High **MIP** charge deposits (**~ $10^4$ e-/mm**)

➔ Can operate **without charge multiplication**

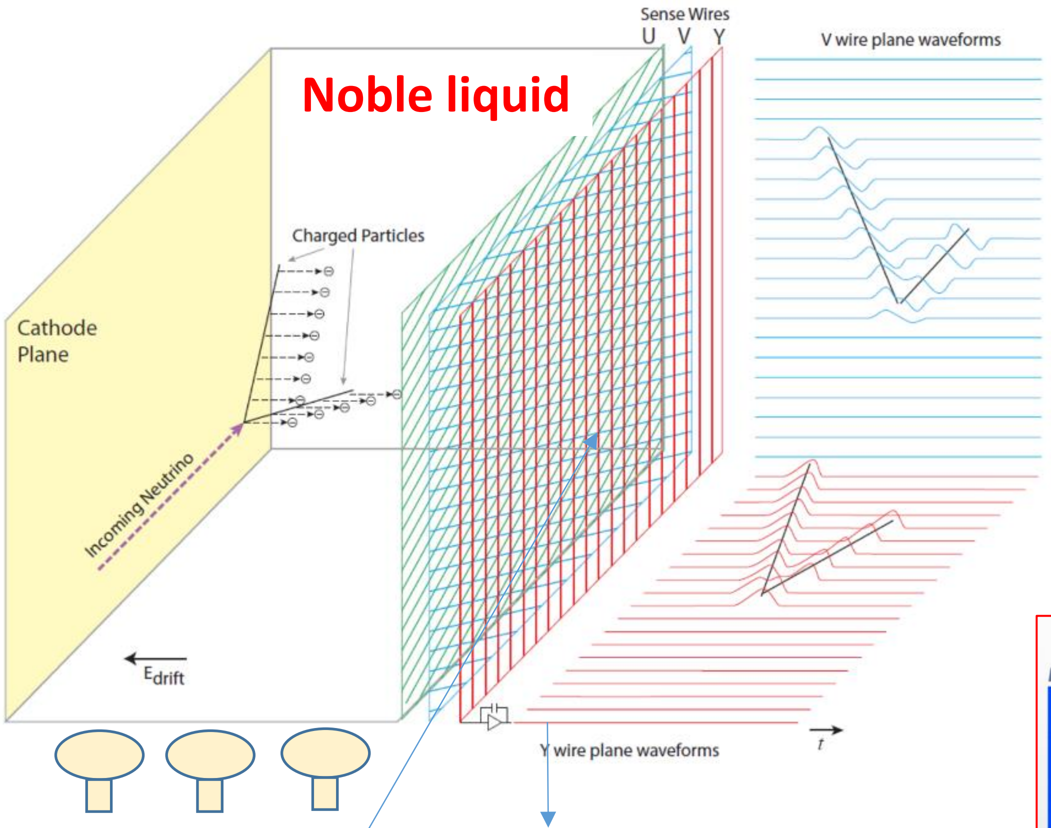
★ multiplication would ease electronics; lower detection thresholds

➔ other physics goals? (e.g. *lower-energy phenomena*)

# Single-phase TPC concept - Neutrinos

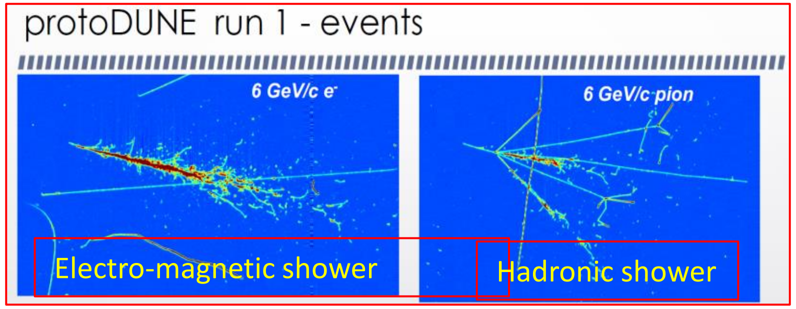
**Single-phase**
***Charge collection***

**Noble liquid**




**PMTs ➔ $t_0$** $t_1$

- ν - induced charged particles ionize the noble liquid;
- ~ few $10^4$ $e^-$/mm in LAr (MIPs)
- 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 (760t), DUNE (68.000t)...**



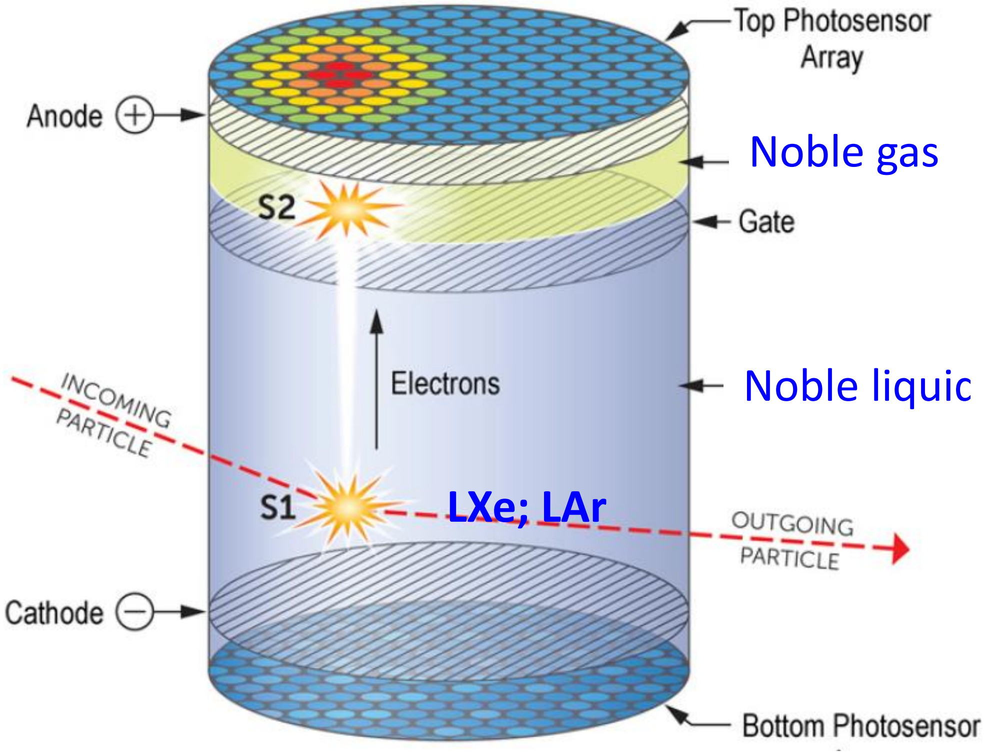

***single*** *proto-DUNE module...*

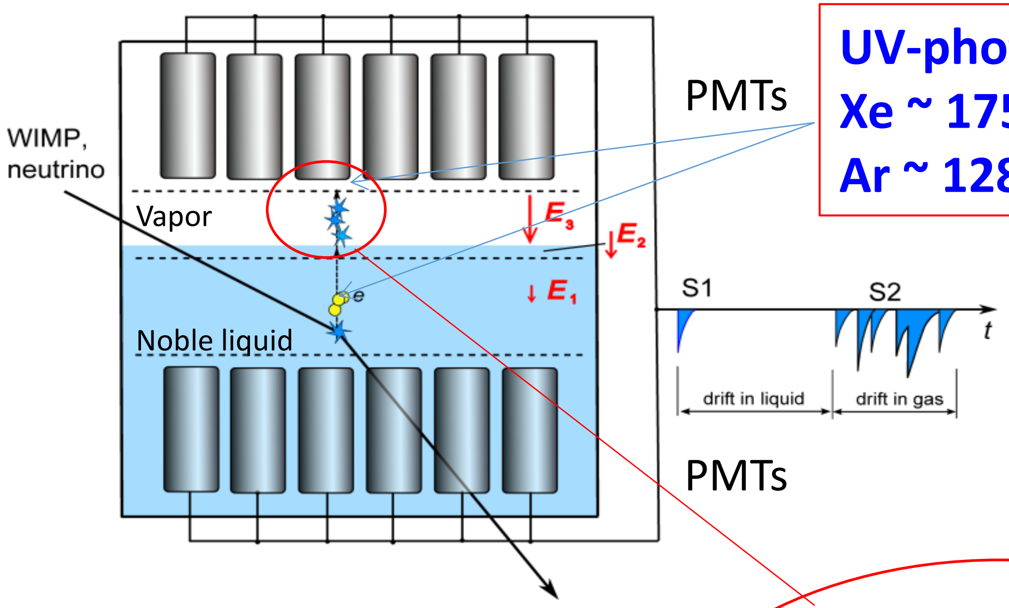
- **3 wire planes or**
- **Multilayer perforated PCB** In 2 DUNE "vertical drift" modules

# Dual-phase TPC concept - WIMPs

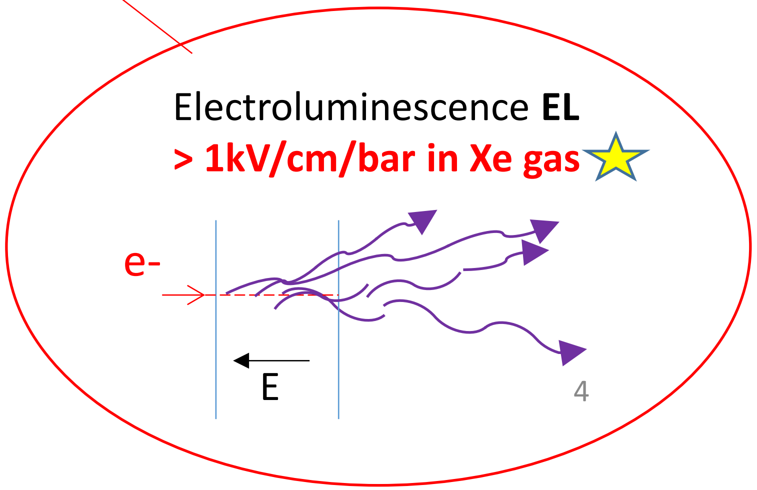
Direct detection of rare **WIMP** elastic scattering off atomic target nuclei

**EL-photon** readout




**UV-photons:**
**Xe ~ 175nm**
**Ar ~ 128nm**




**S1 light signal:**
- prompt scintillation photons

**S2 charge signal:**
- secondary scintillation photons from electroluminescence in GXe due to drifted electrons

**3D event position reconstruction:**
- X,Y: S2 hit pattern
- Z: drift time S2-S1

## e.g. LXe 2-phase:

| XENONnt, | LUX-ZEPLIN (LZ), | PNDA X, | DARWIN/G3 |
|---|---|---|---|
| 8.5t | 10t | 4t | 50t |

# Rare events: fighting background

**WIMP signals:**

Extremely small WIMP interaction cross sections **<$10^{-48}$cm$^2$**

➔ VERY LARGE VOLUMES & HIGH SENSITIVITY

- Very rare:

  **1 event/ton** x **Y in LXe**

- Buried in huge background:

  > $10^6$-fold higher rates

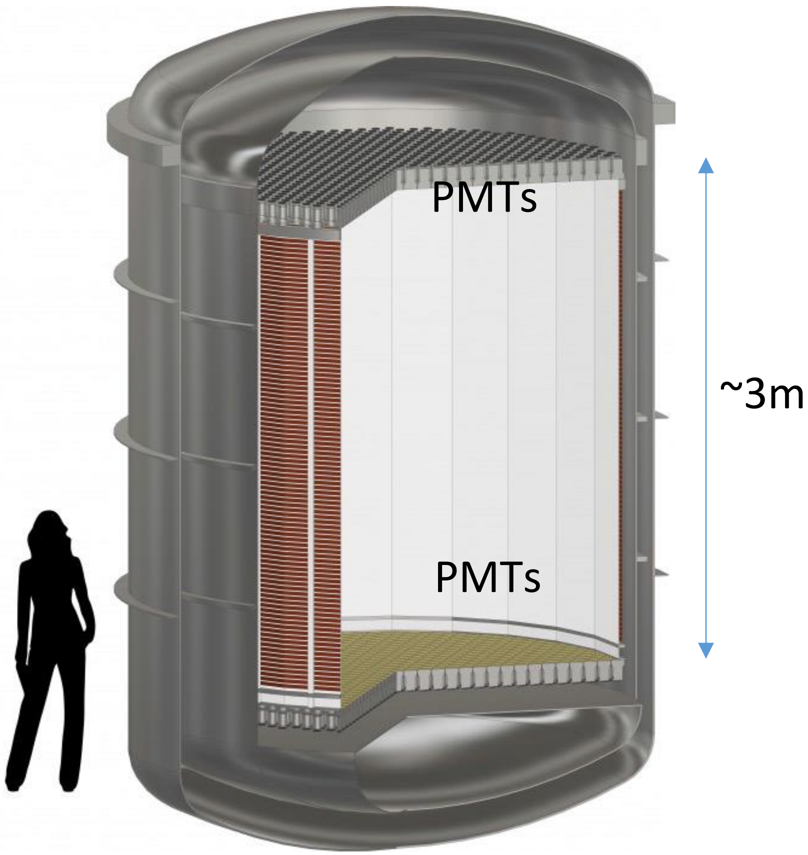
- Very small: low-E recoils eV-KeV

  ➔ **few-to-tens electrons** in noble-liquid

$10^{-49}$ cm$^2$ ➔
DARWIN **LXe**: 50t x 20Y
ARGO **LAr**: 300t x 10Y

➔ **Underground**
➔ **Low-radioactivity materials/gas**
➔ **Cosmics VETO**
➔ **ER background rejection**

➔ **Motivation for: novel detector concepts**




**Future** **50-ton LXe**

**DARWIN/G3** Dark-matter observatory

**XENON-LZ-DARWIN (XLZD consortium)**

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

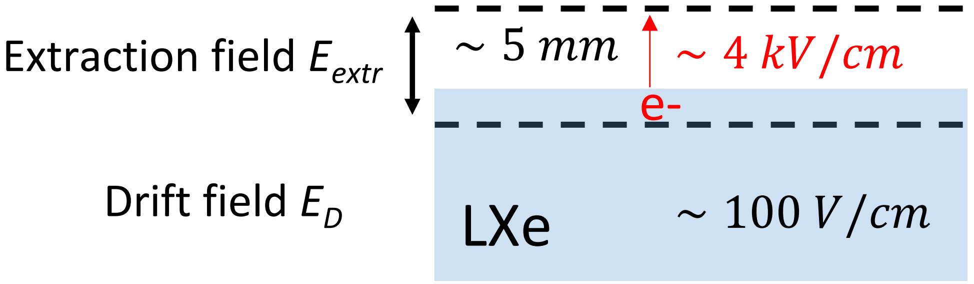
DARWIN/G3 Baseline: Dual-phase/PMTs
Ongoing extensive R&D on
detector & photo-sensors

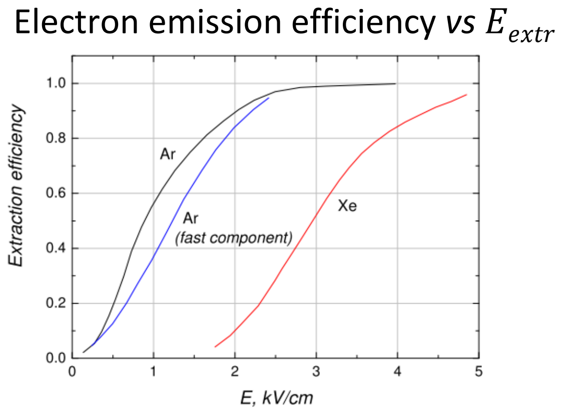
# Why new concepts?

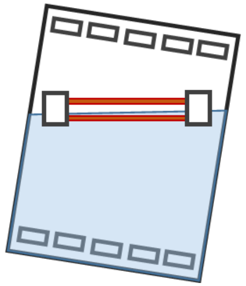
- **Dual-phase detectors: Problems**

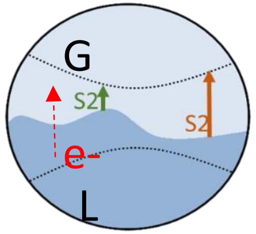
  Current expected problems affecting resolution & efficiency:

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






**Low energy deposits** ➔ need multiplication & efficient photon detection

Limited avalanche gain in noble gases ➔ electroluminescence multiplication

- **Single-phase detectors:**

  Current limit: No multiplication in liquid.

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

Stable primary-charges multiplication & efficient detection in both configurations

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

# Single-phase TPCs

**Ultimate goal:**

Combined efficient detection of both ionization electrons and VUV photons

- **Advantages**
  - No liquid-gas interface
    - Reduced instabilities (interface ripples)
    - No delayed $e^-$ emission or $e^-$ transfer efficiency through interface
    - No gate-interface-anode alignment problems
    - Horizontal drift → sporadic bubbling not a concern
    - Potential improvement to the ionization $e^-$s energy resolution
  - Different geometries possible
    - Radial TPC
    - Symmetric central cathode TPC → lower voltages needed
- **Challenges**
  - High EL and CM thresholds → amplification requires high electric fields

# Single-phase - from wires to microstructures

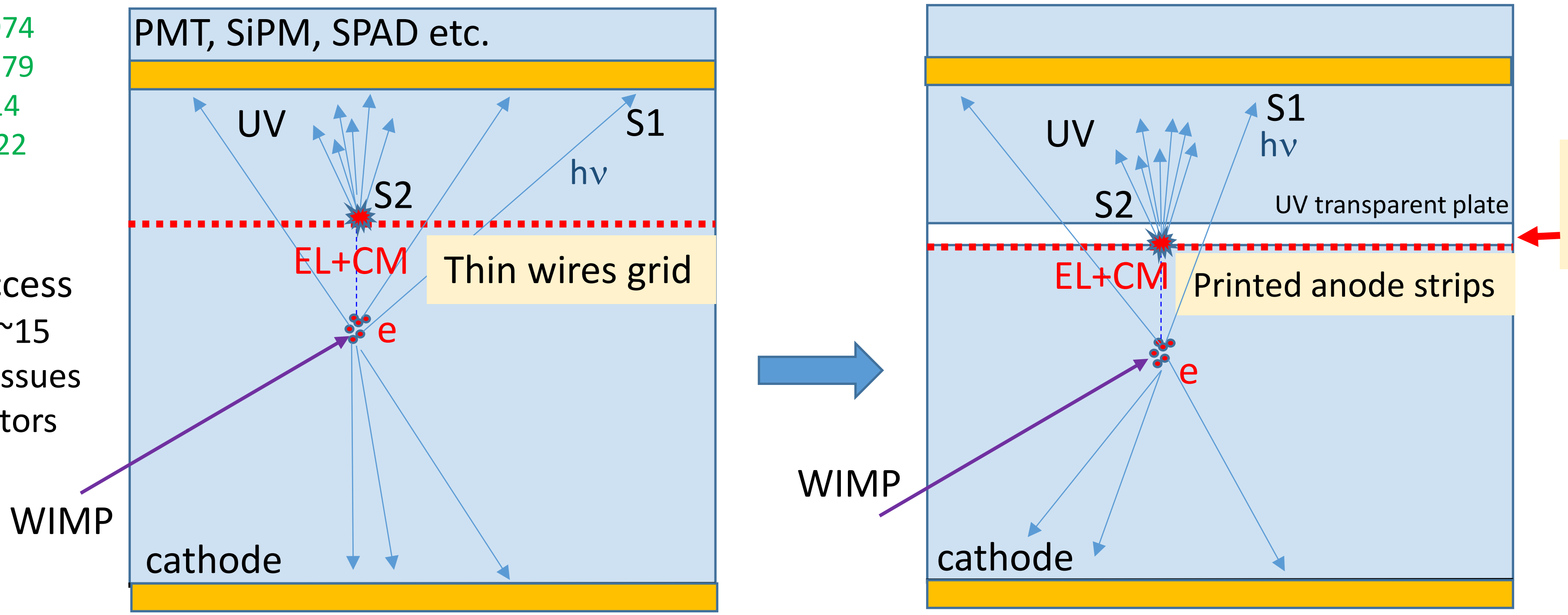
Examples: here multipliers sense **S2-e⁻ ONLY**
Scintillation **S1-photons** recorded by photosensors

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

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

**So far:**
- No real success
- Charge gain ~15
- Mechanical issues @ large detectors

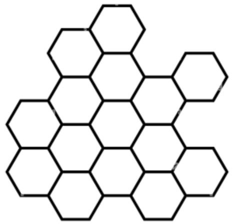
**Wires** | **Microstructures**




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

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

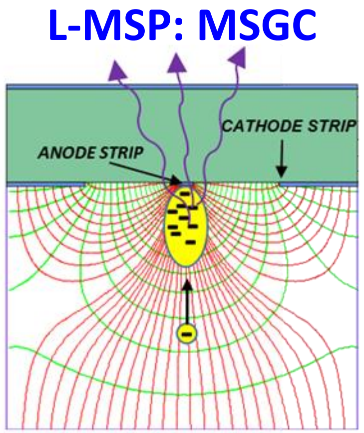
**Micro Strip Plates & more!**

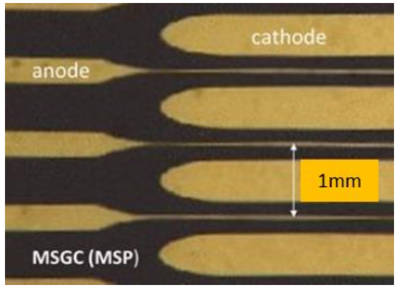


**Robust**
**Modular**

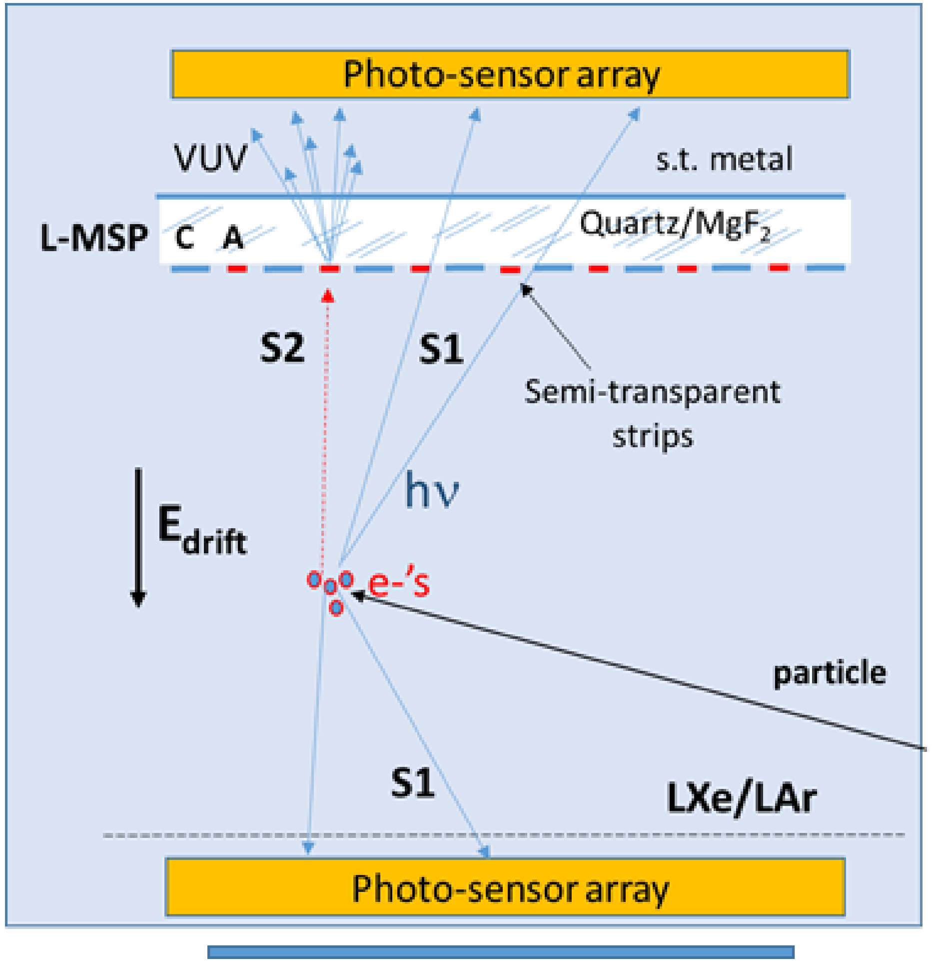
**Goals**: Devise other robust high-gain solutions for detecting both S2-e⁻ & S1-photons

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




A. Oed 1988




Or a reflective cathode

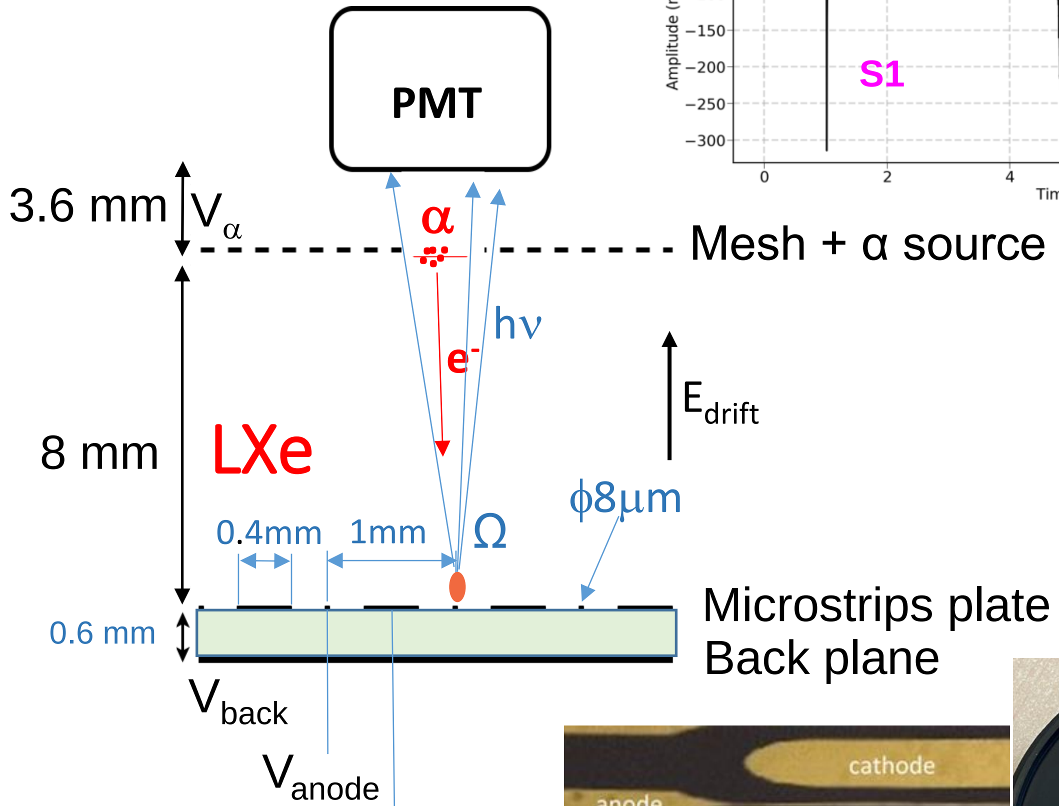
- MSP formed on VUV-transparent substrate, with semi-transparent Ni or Cr electrodes.
- Deposited charges drift in liquid; undergo **EL & small charge multiplication (CM)** near anode strips.
- The EL photo-yield depends on MSP type.
- EL Photons recorded above.
- S1 scintillation photons: with top & bottom photo-sensors (or reflective cathode)

**Policarpo, Chepel 1995**
**x10 electron multiplication**
**in LXe with MSGC;**
**No EL photons recorded**

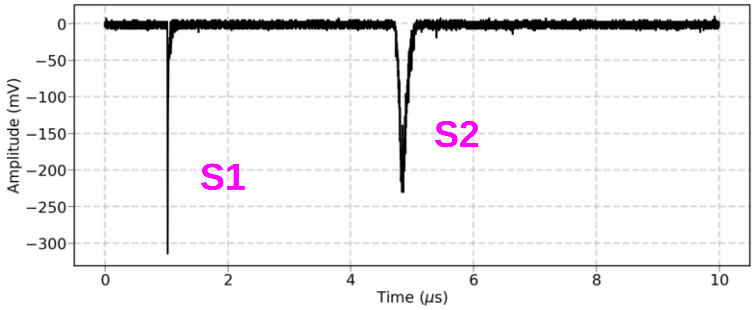
# Microstrip Plate - Preliminary results in LXe

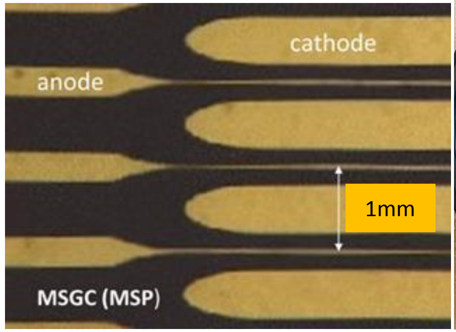
**Paper underway**

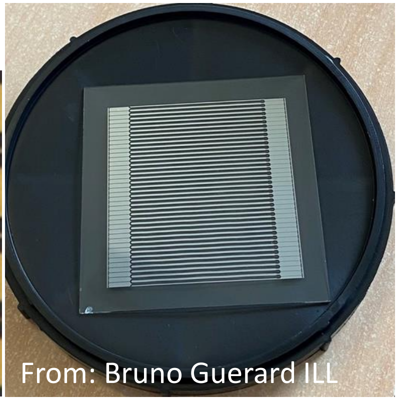
## Setup



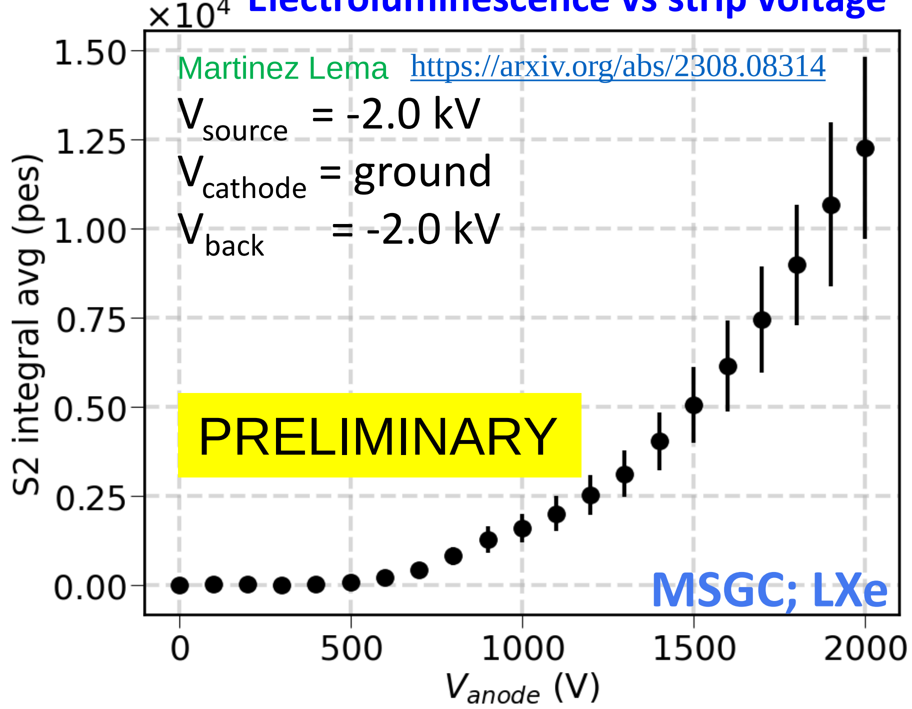

**Single event**




**Electroluminescence vs strip voltage**

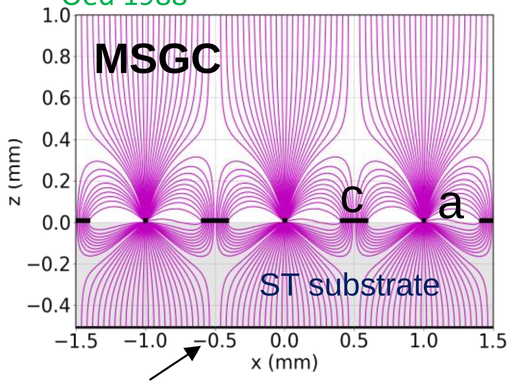



At present discharge-limited **HV=2kV**:
Charge gain **~3**
Photo-yield **~ 33 photons/e-**

**Much higher Q-gains/photoyields expected with other multipliers @ higher $V_{anode}$**

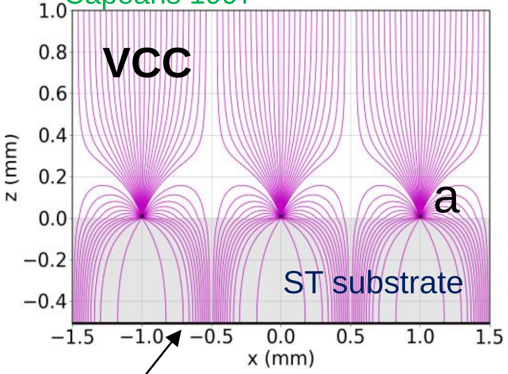
# Prospects: MSGC vs COCA-COLA vs VCC

Oed 1988



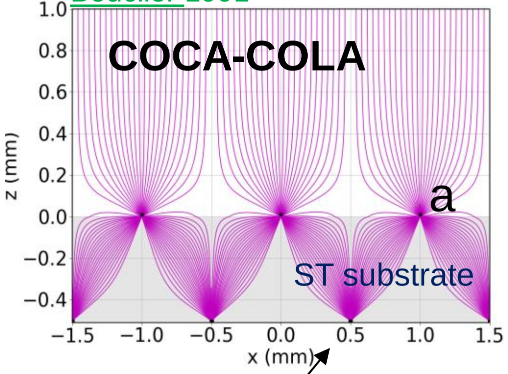

Conductive surface/grid

Capeans 1997




Conductive surface/grid

Bouclier 1991




Cathode strips

**MSGC** has the best field configuration

- But operation is limited to ~2 kV a-to-c (~33photons/ie)

**COCA-COLA & VCC** can operate at higher V without discharges

higher e⁻ multiplication and light yields

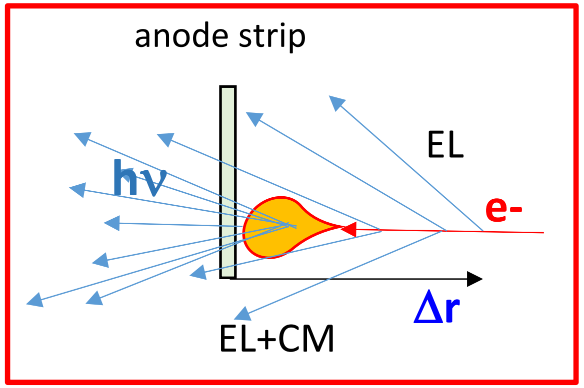
**COCA-COLA** COated CAthode - COnductive LAyer potential

~x14 e⁻ multiplication @5kV

~525 photons / ie

**VCC** Virtual Cathode Chamber potential

- ~x40 e⁻ multiplication
- ~1670 photons / ie @5kV (8μm strips)

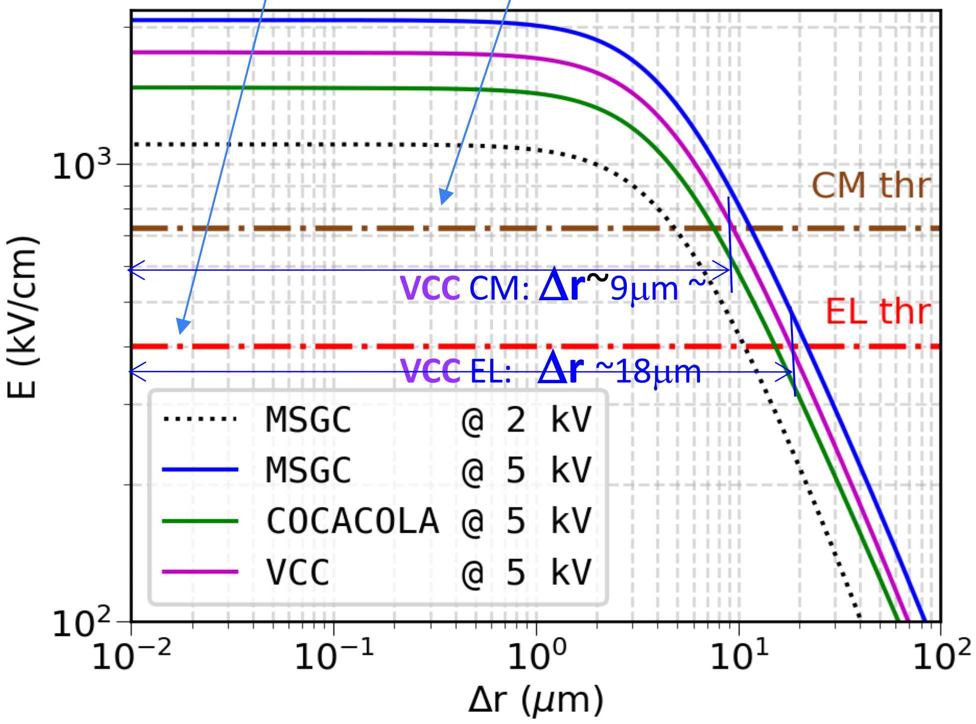



Δr increases at lower strip widths

**For comparison:**

**wires in LXe:**
Aprile 2014
10μm wires / 6.75 kV
~ charge gain x14
~ **290** photons/e-

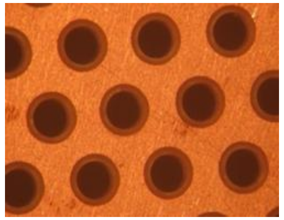
**THRESHOLDS**: Aprile JINST 2014
EL, ~400KV/cm; CM, ~700KV/cm

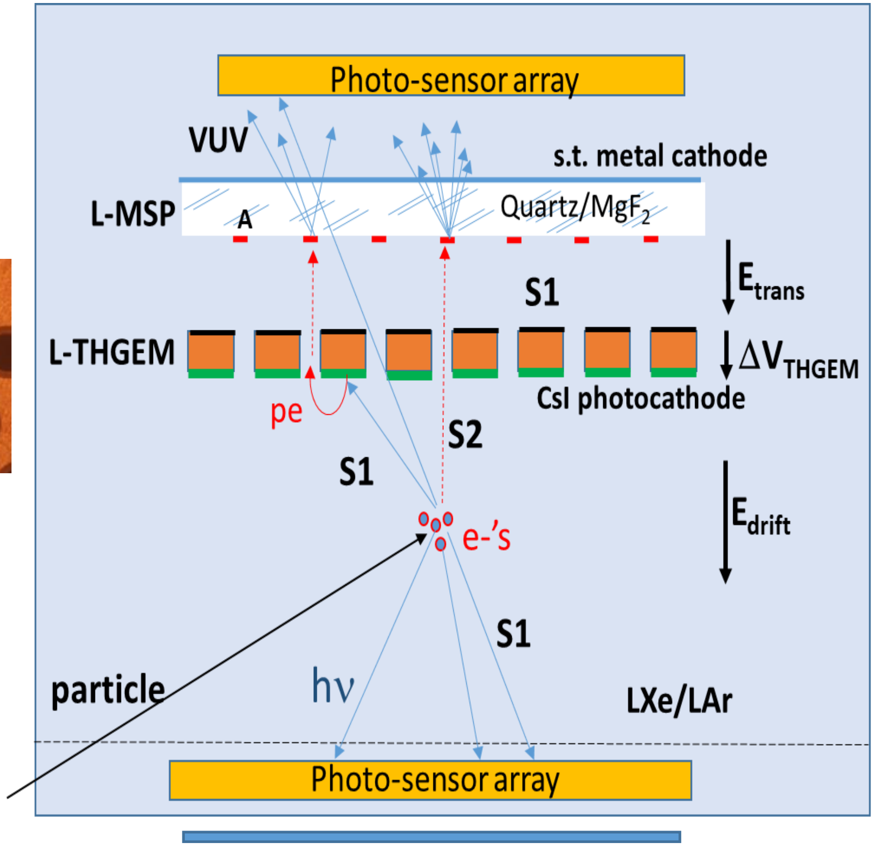



- 1-10 nm thick, **8μm wide anode strips**
- COCACOLA cathode 200 μm wide
- MSGC cathode 400 μm wide

# Single-phase with cascaded THGEM* + MSP ➔ S1 hν & S2 e⁻

THGEM






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-MSP.
- 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).

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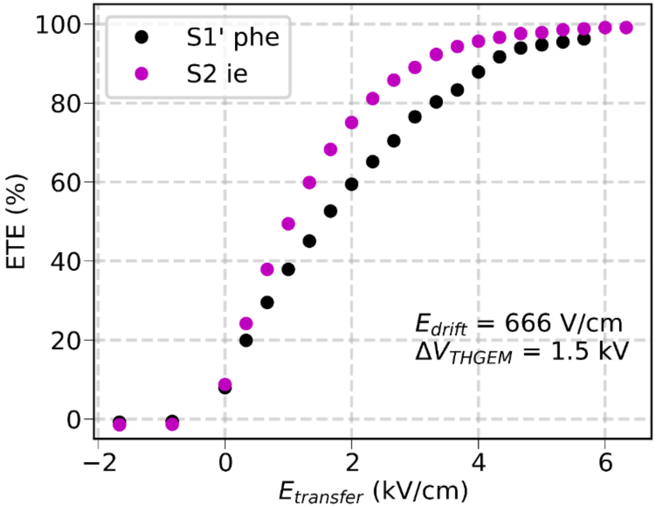
*THGEM: Thick Gas Electron Multiplier

**Martinez-Lema** https://arxiv.org/abs/2308.08314

Experimental Transfer Efficiency of e⁻ and pe⁻ through THGEM holes in LXe.

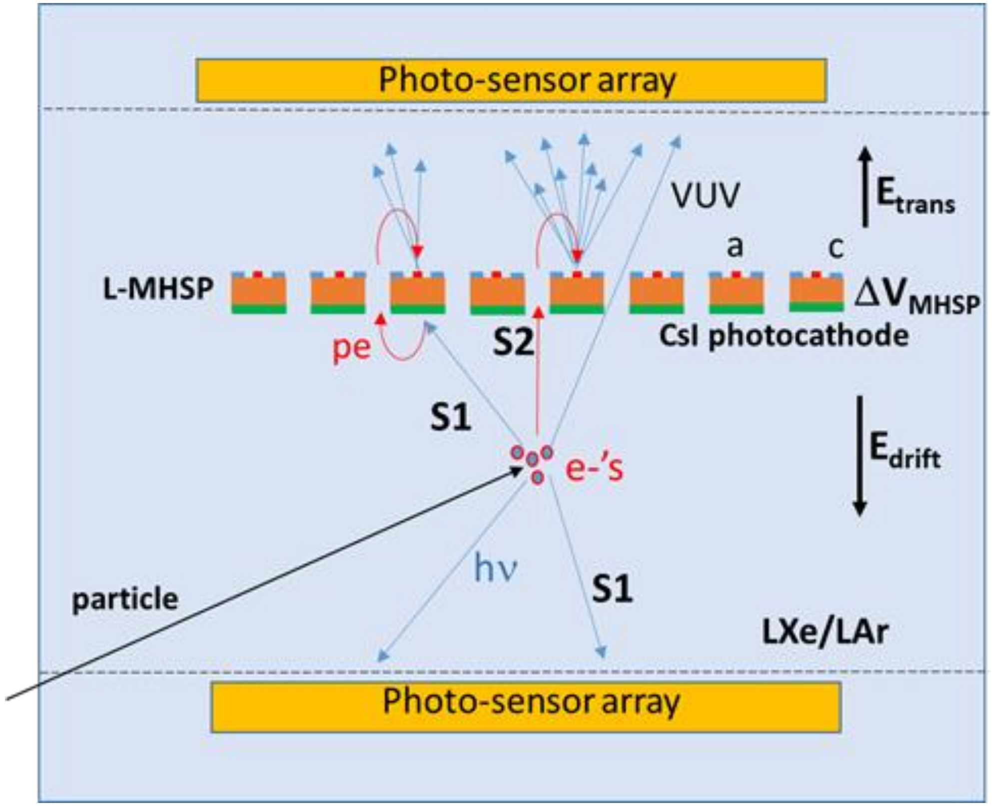


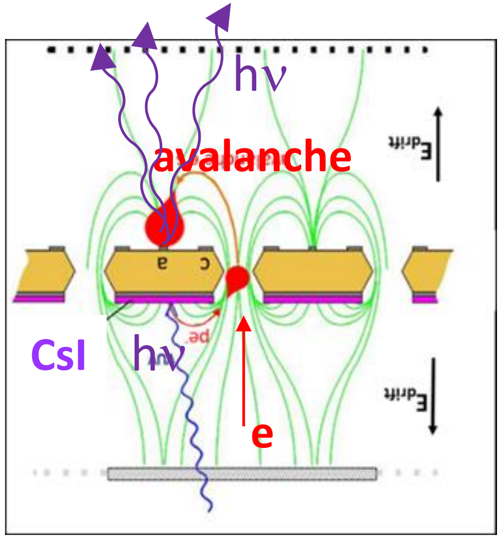

**$QE_{eff}$ of CsI in LXe @ E> 5kV/cm: 25%**

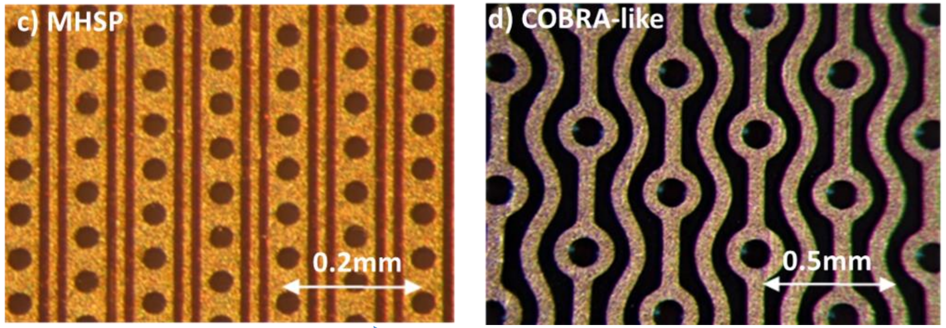
**Erdal 2021**

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

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



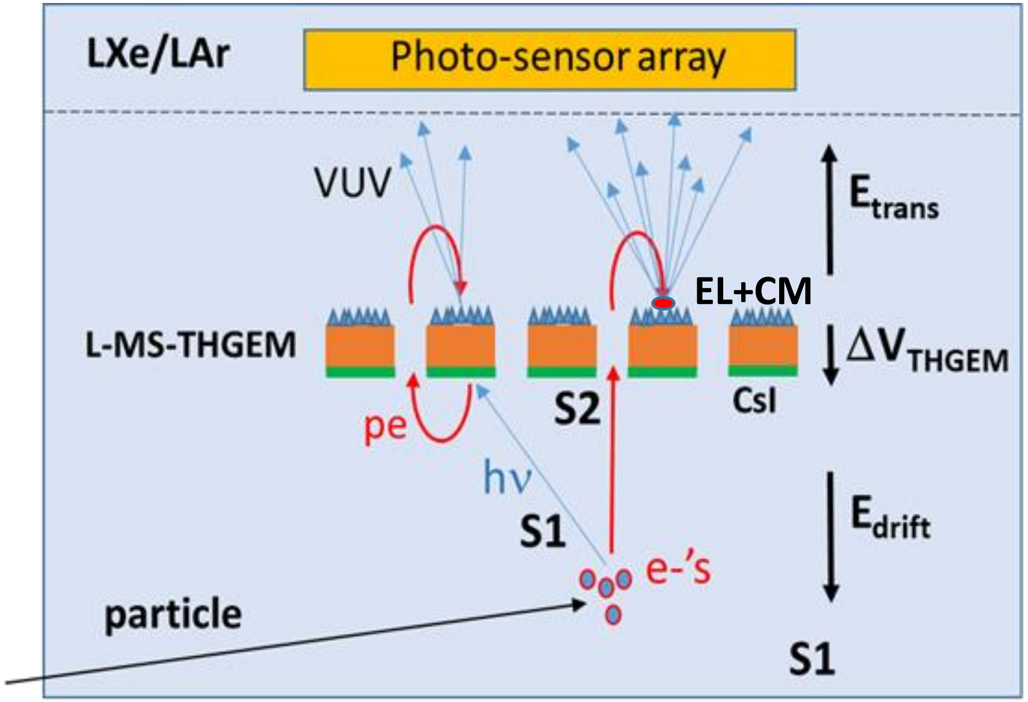



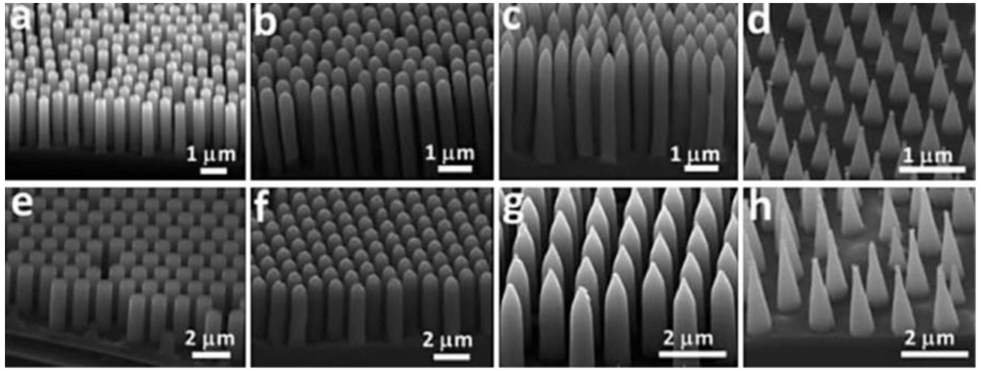

**MHSP**: Veloso, Rev Sci. Instr. 71, 2371 (2000)
https://doi.org/10.1063/1.1150623

Current technologies➔ few-μm strips possible

- A single-phase TPC with CsI-coated **L-MHSP**.
- Both S2 e- & VUV photoelectrons collected into the L-MHSP holes & collected by MHSP anode strips.
- **ALL** VUV photons (EL + CM): detected by the top photo-sensors.
- Other fraction of S1 photons - detected by bottom photo-sensors.

# Single-phase with Micro-structured electrode



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

- Single-phase TPC with micro-structured THGEM top surface (**L-MS-THGEM**), under-coated with CsI.
- Both S2 e- & S1 VUV pe- are collected into the holes towards the micro-structured top surface
- VUV photons emitted by EL + CM at the "anode tips", under high E, are detected by top photo-sensors.
- Other fraction of S1 photons are detected by bottom photo-sensors (not shown).

# Novel Dual-Phase TPC Concepts

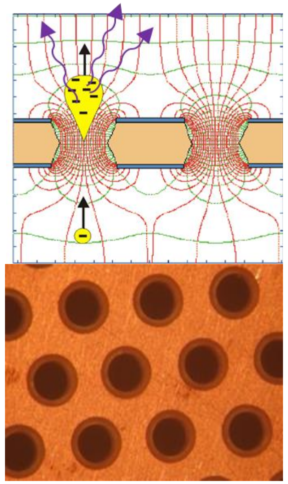
## with reduced interface instabilities

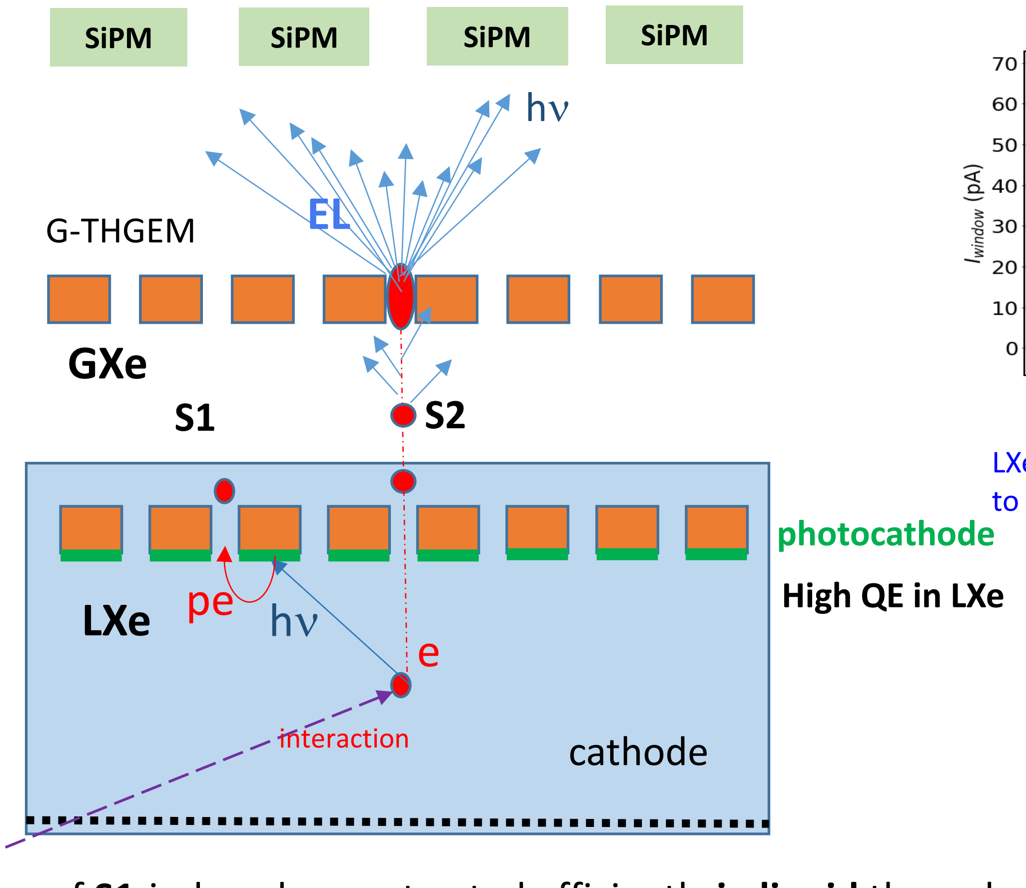
*In case Single-Phase ones remain a dream…*

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

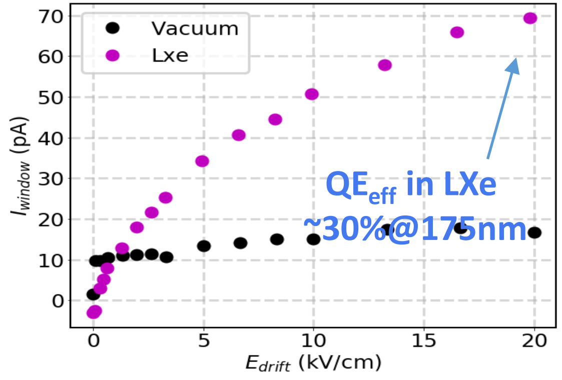
Martinez Lema 2022

## The multiplier: Perforated electrode with thin strips

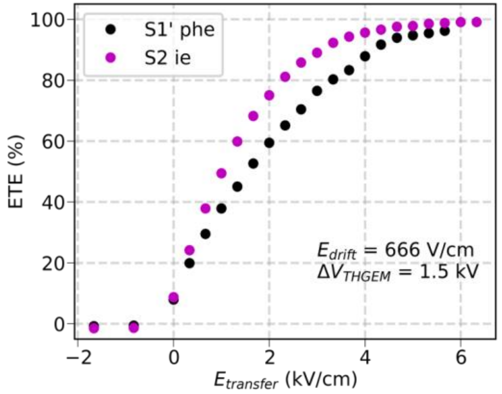




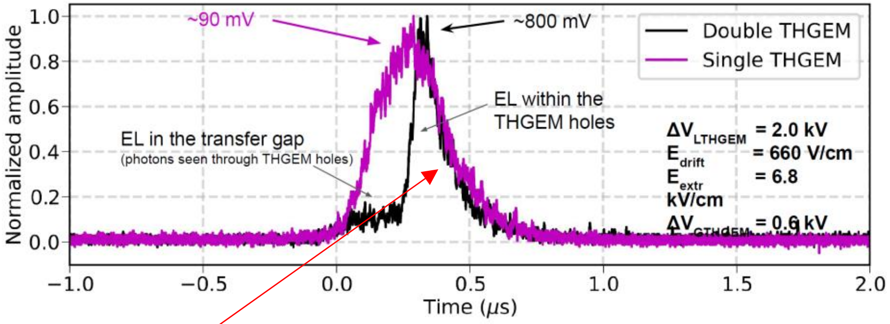

Martinez-Lema https://arxiv.org/abs/2308.08314




LXe: increased $QE_{eff}$ by ~x3.5 compared to vacuum! (Work function)




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




EL in holes is faster & does not depend on interface-gap variations

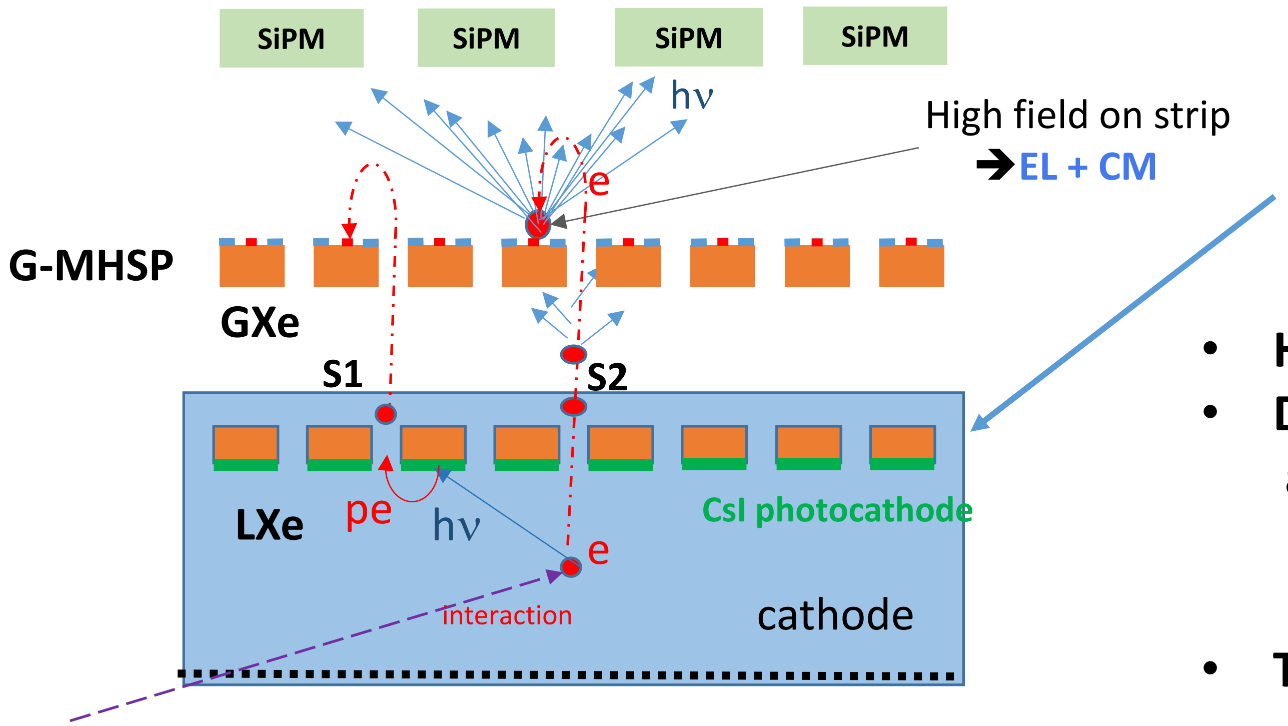
**PRELIMINARY photoyield: ~350 photons\e\4π**

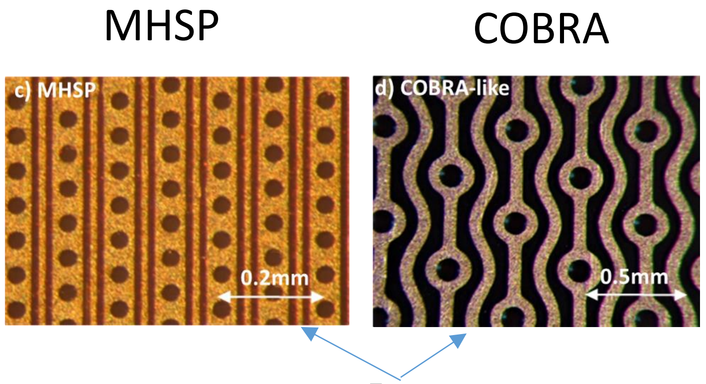
- **S2** e- and fraction of **S1**-induced pe- extracted efficiently **in liquid** through holes of a **CsI-coated** immersed L-THGEM electrode.
- They traverse the liquid-gas interface inducing EL **in gas phase**, mostly in G-THGEM holes.
- Readout by nearby photo-sensors. Bottom cathode: reflective,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

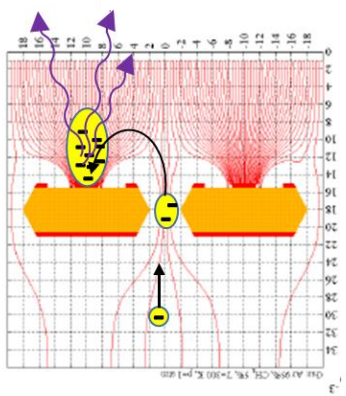
# Dual-Phase: Cascaded Liquid Hole Multiplier (LHM) - S1 & S2

**The multiplier: Perforated electrode with thin strips**

Similar operation as with G-THGEM, but EL photons emitted from strips



Current technologies➔ few-µm strips possible

- **High CsI QE ➔** expected high PDE
- **Detection of gas-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

**EXPECTED: higher field @strips ➔ larger photon yield & faster signals**

# Dual-Phase: The Floating Hole Multiplier FHM

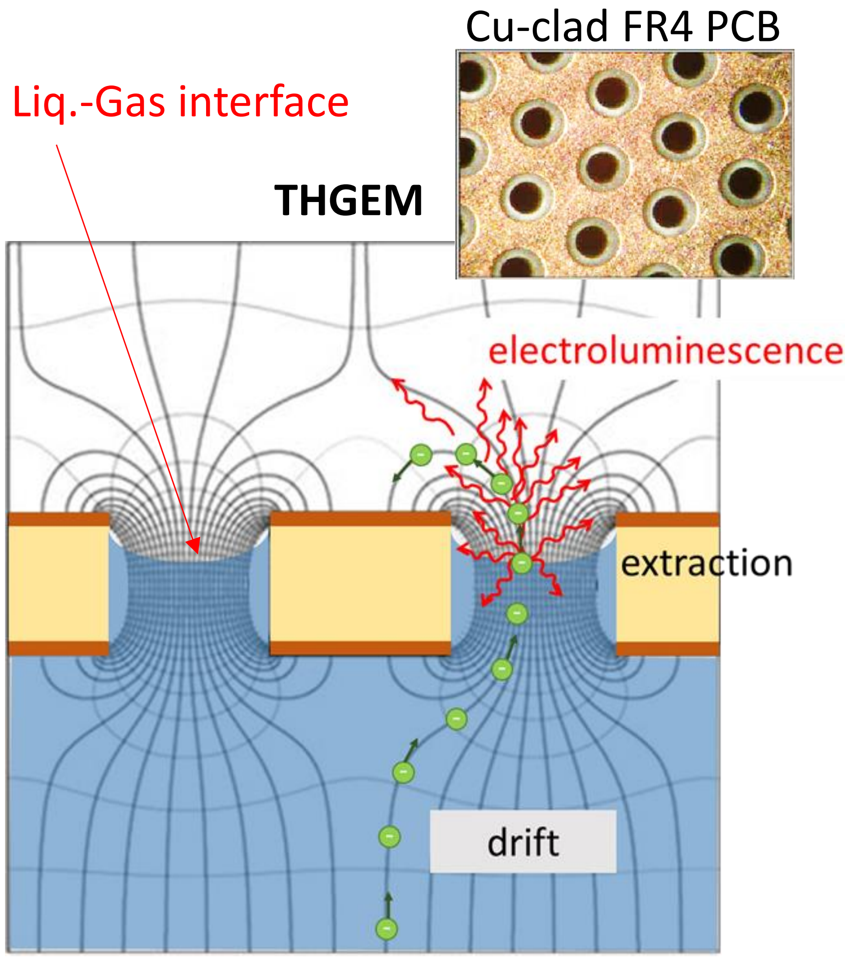
- Better surface-effects control by separation of the two phases;
- A “rubust” interface: perforated electrode FLOATING on the liquid surface ➔ e.g. **GEM, THGEM, COBRA**, etc
- Significantly smaller free liquid surface ➔ reduced surface instabilities
- High E @ interface ➔ High electron extraction probability

  ➔ **Result – reduced single-electron noise**
- No need for fine detector levelling and liquid level control

LXe density **2.9** g/cm3

FR4 density **2.0±0.2** g/cm3

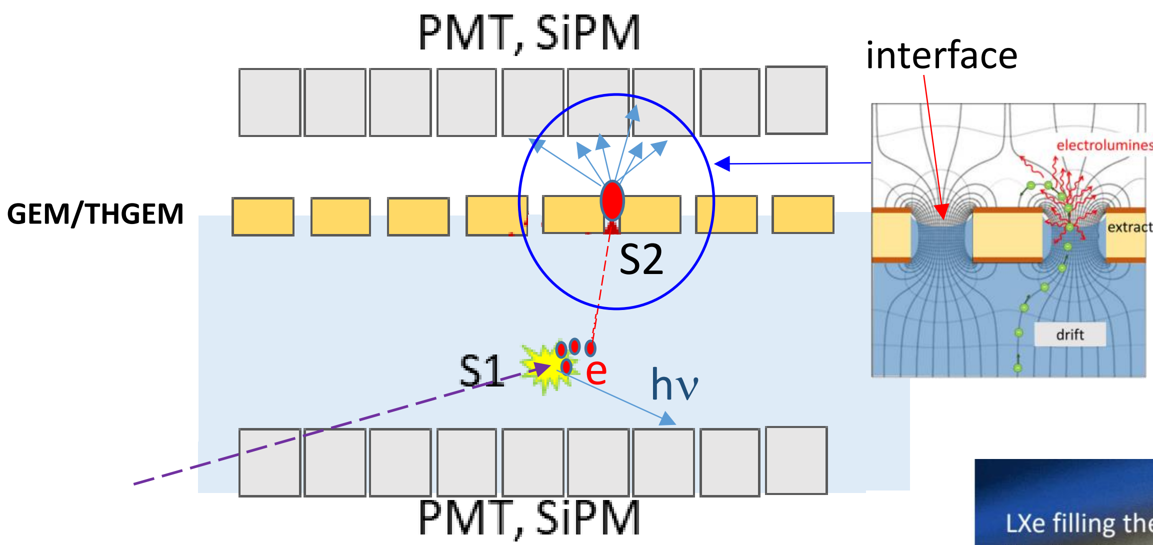
If copper cladding is not too heavy → THGEM **should float** on the surface of LXe

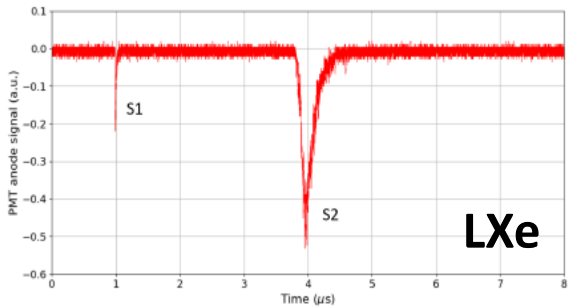




Idea V. Chepel

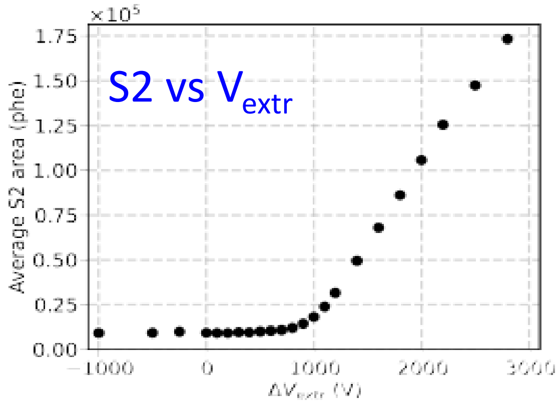
# FHM – S2 $e^-$ only

**proof of FHM principle in LXe:**
**Chepel 2023** http://arxiv.org/abs/2301.12990



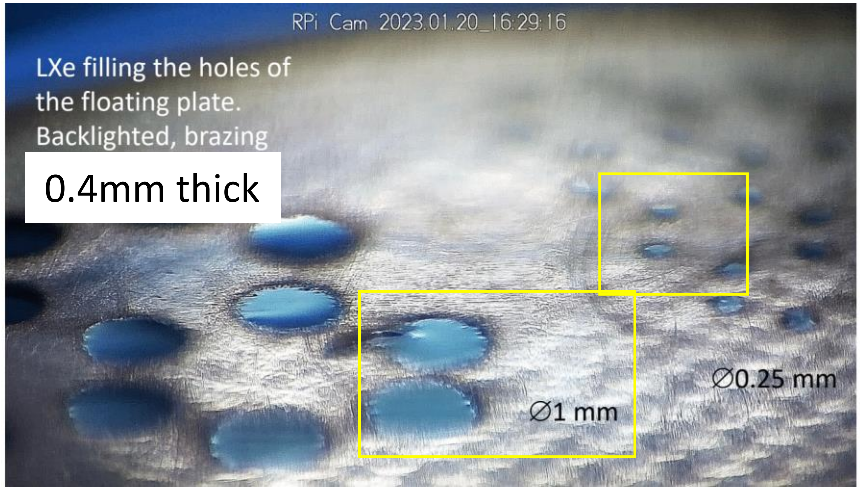




α-induced S1 & S2



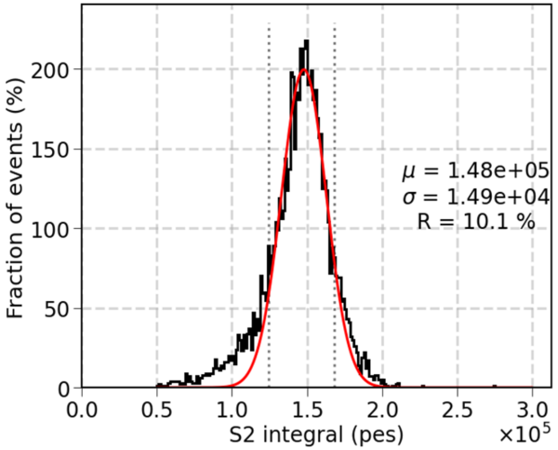

- S2 electrons extracted efficiently through the interface within holes of a perforated electrode, **floating on the liquid**.
- They traverse the interface (under high fields) inducing EL **in gas**.
- Readout by nearby photo-sensors.

Reduced interface effects and instabilities



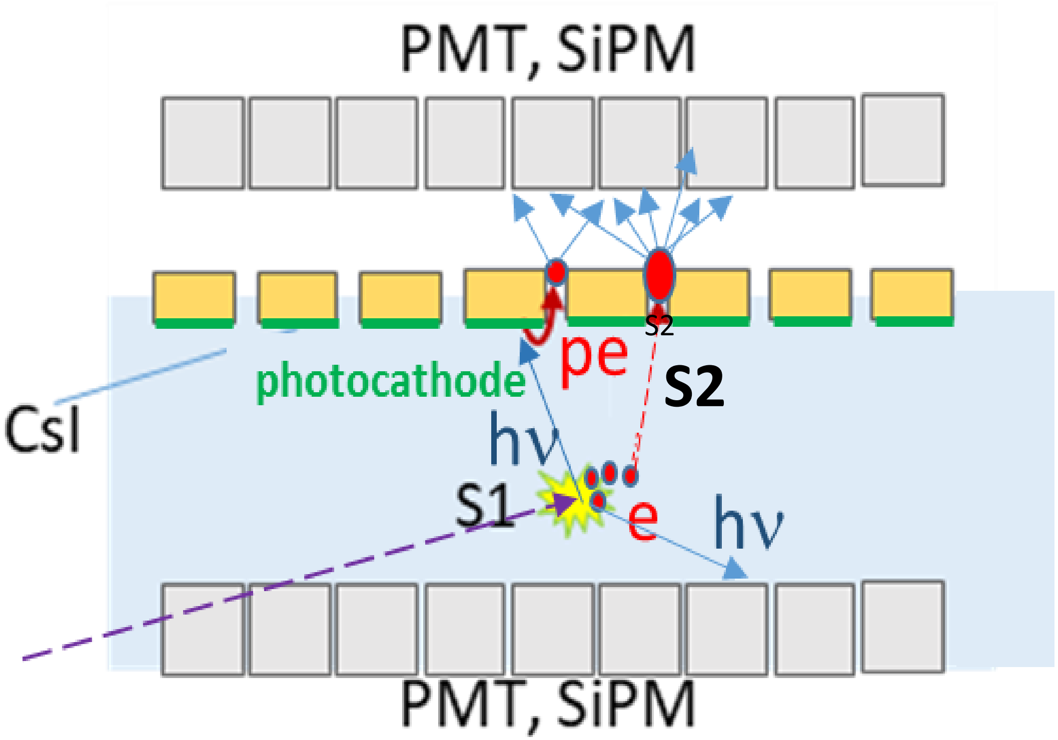

With 0.4mm thick electrode floating on LXe, the holes are rather filled with the liquid.
R&D: Thicker electrode:
➔ expected higher photon yields.

**PRELIMINARY:**
**Y~500 photons\e\4π**




α-induced S2
Energy resolution

# FHM – S1 photons & S2 $e^-$




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.

# Conclusions

- **Generic R&D:** novel methods for future applications.
- Goals - novel sensing concepts for noble-liquid detectors.
- Focus - combined high-sensitivity light & charge detection methods.
- Readout - Optical readout of EL & CM photons
- Preference – **Single-phase TPCs**. (novel 2-phase in case…)
- Aims - solving current physical & technical issues; lowering detection thresholds ➔ potential applications in large-volume experiments.
- Main (but not sole) "users" - future DM experiments and neutrino physics.

Some proofs of principle; others in progress

Many open questions requiring simulations & exp. R&D (LAr, LXe)

*Open to collaborations – seeking for students/postdocs!*

*Thank you!*

# Backup

# Noble liquids

| Element | Z | A | Liquid density (g/cc) | Boiling point (K) | Photon yield ($\gamma$/keV) | Triplet decay time | Emission Wavelength (nm) | Radio activity |
|---|---|---|---|---|---|---|---|---|
| He | 2 | 4.00 | 0.13 | 4.2 | 22 | 13(s) | 80 | None |
| Ne | 10 | 20.18 | 1.2 | 27.1 | 32 | 15($\mu$s) | 78 | None |
| Ar ☆ | 18 | 39.95 | 1.4 | 87.3 | 40 | 1.5($\mu$s) | 128 | $^{39}$Ar 1Bq/kg |
| Kr | 36 | 83.80 | 2.4 | 119.9 | 49 | 85(ns) | 148 | $^{85}$Kr 1MBq/kg |
| Xe ☆ | 54 | 131.30 | 3.1 | 165.0 | 64 | 22(ns) | 175 | $^{136}$Xe < 10uBq/kg |

Nikkel 2012

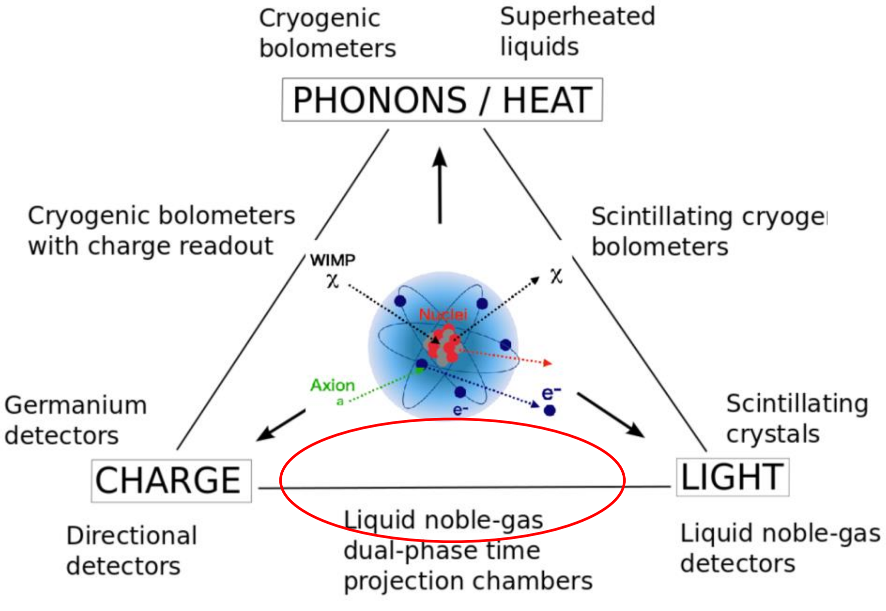
**XENON**: - **higher** density, operation T, photo-yield, emission WL + faster but **HIGH COST**
**- smaller** detector volumes.

**Neutrino**: liquid ARGON **LAr**
**DM:** mostly liquid XENON **LXe**

# Unsolved problems in physics 1 – Dark matter

- Galaxies do not appear to obey current laws of physics.
  Stars' velocity in galaxies > expected by Newtonian mechanics.
- Is there **Dark Matter (DM)**? What is its nature? Is it a **particle**? or:
- Do the phenomena require a **modification of the laws of gravity?**
  MOND? - MOdified Newtonian Dynamics Milgrom 1982

**Several DM detection techniques:**




J. Phys. G43 (2016) 1, 013001& arXiv:1509.08767

**Dark matter candidates:**

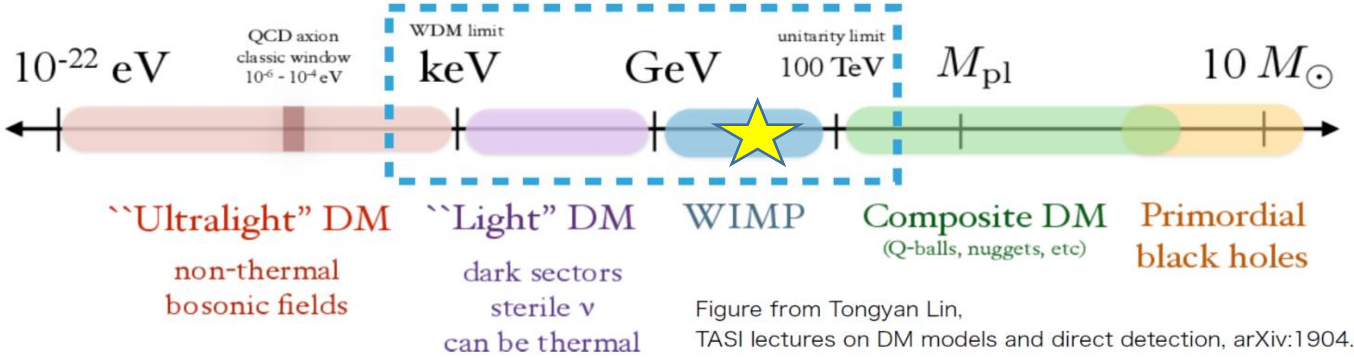



Figure from Tongyan Lin, TASI lectures on DM models and direct detection, arXiv:1904.07915

- **~100 orders of magnitude in mass.**
- A variety of detectors related to mass range.
- Direct-detection of **WIMPs:** with **noble-liquid detectors**:
- Many experiments

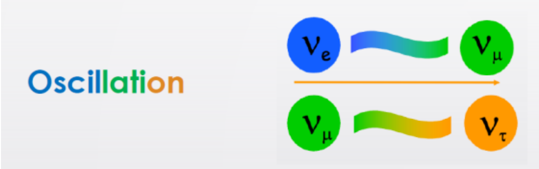
# Unsolved problems in physics 2 - Neutrino

**Neutrinos: Fundamental particles detected >70Y ago.**

Several open questions:

- Do neutrinos and anti-neutrinos oscillate differently (CP violation)?
- Their mass order? (mass hierarchy)

**Long baseline exp.**




- Other neutrino types? Interactions?

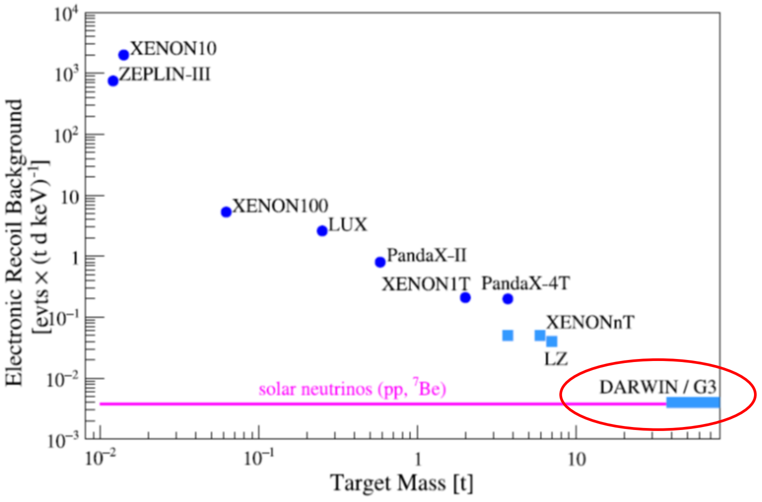
**Short baseline exp.**

- Are neutrinos their own anti-particles? (***Majorna vs Dirac***)
- Neutrino Masses
- ……

**0νββ**

Many experiments!

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




Low background

DARWIN/G3

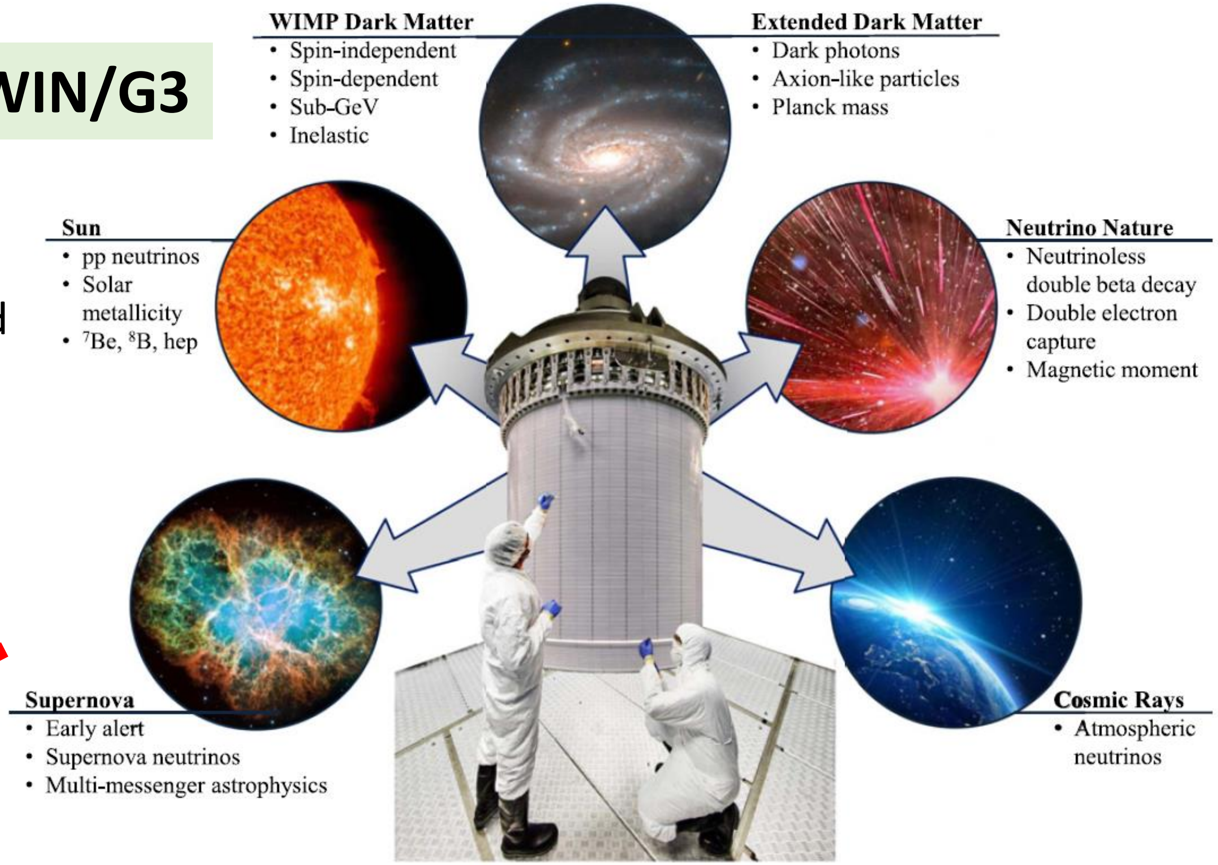
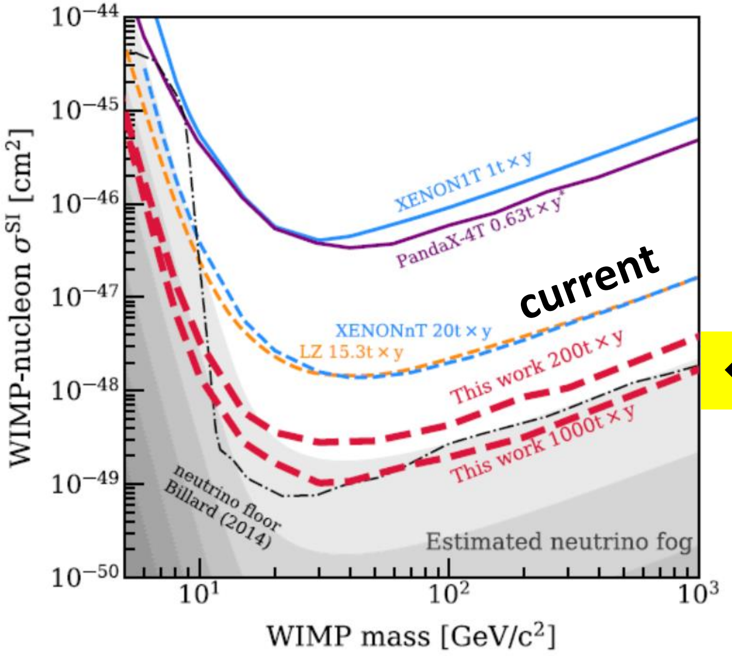



**Figure 2.** The science channels of a next-generation liquid xenon observatory for rare events spans many areas and is of interest to particle physics, nuclear physics, astro-physics, solar physics, and cosmology.

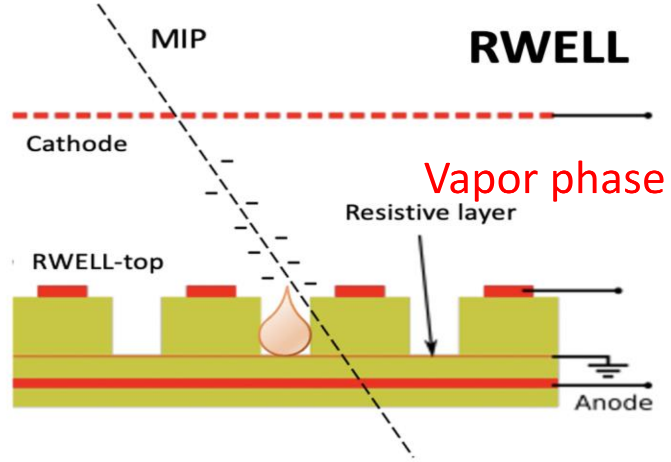
Aalbers et al 2023 J. Phys. G: Nucl. Part. Phys. 50 013001
DAWIN/G3

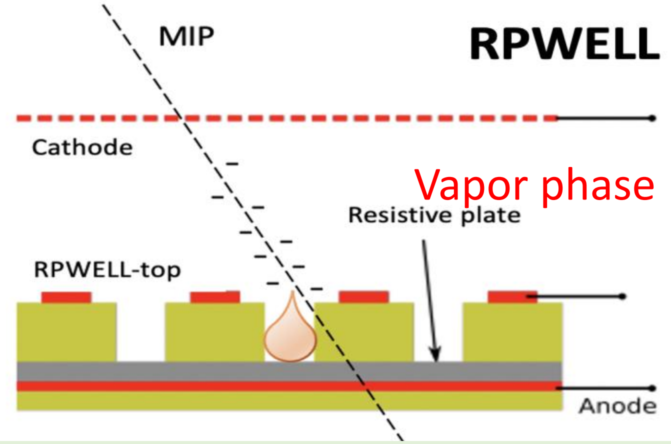



← 50t x 20Y

# 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 collected & undergo avalanche multiplication in the holes.

### Resistive WELL (RWELL)

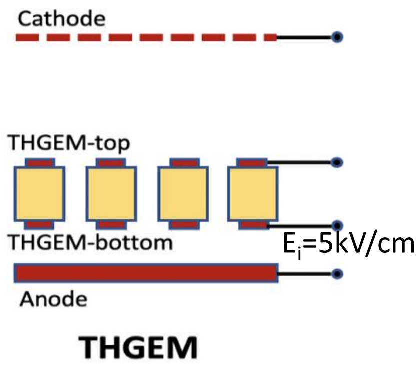
- **Resistive film**, e.g. Diamond-Like-Carbon (DLC), on an insulator.
- Charges evacuated sideways to ground via resistive layer
- Signals are induced on readout anode by charges movement

### Resistive-Plate WELL (RPWELL)

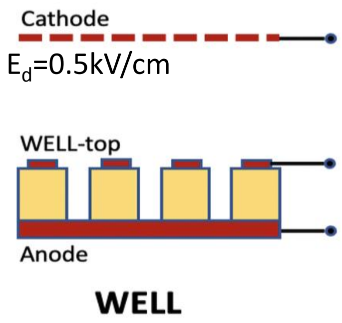
- **resistive plate**, e.g. a ceramic material Yttria-Stabilized-Zirconia (YSZ) doped with ferrite oxide (Fe2O3), to readout anode.
- Amplified charge travel through the resistive plate to the anode.

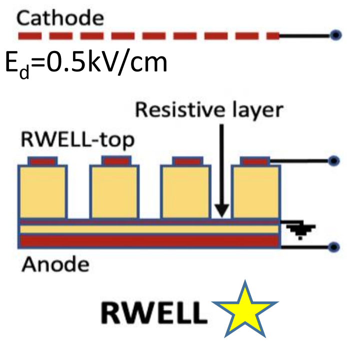
challenges: find/develop resistive materials of the "right" surface/bulk resistivity at noble-liquid temperature

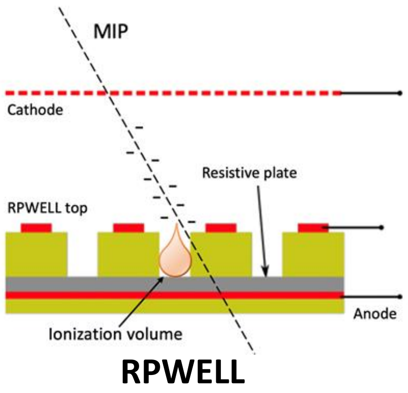
# Comparison: THGEM/WELL & RWELL/RPWELL @ 90K

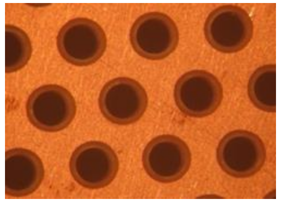


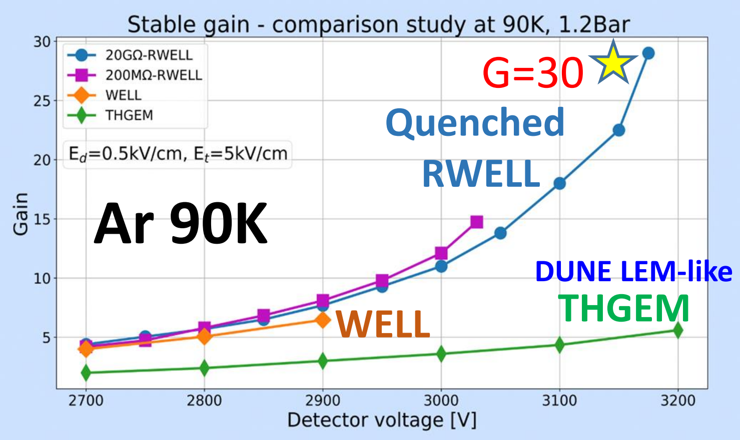

**DUNE LEM-like**

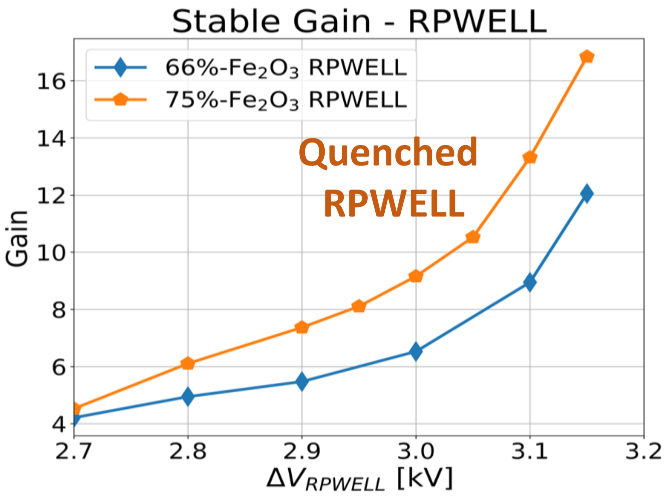





**Optimal resistivities:**

temperatures LAr ~87K

Resistive FILM: ~ 20GΩ/□

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

**Tesi**

https://doi.org/10.1088/1748-0221/18/06/C06017

https://arxiv.org/abs/2307.02343

So far, with experiments performed under <u>equal conditions:</u>

**RWELL/DLC** gain > THGEM (LEM) gain;

**RWELL** gain > **RPWELL** gain (but near zero discharges only @ gain < 17)