Micro-structured multiplier concepts for single-phase detectors

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- **Goal** - combined high-sensitivity S1 & S2 detection
- **Aims** - overcome physical/technical 2-phase issues; lowering detection thresholds.
- **Potential applications -** large-volume DM experiments & more.

A.B. 2022 https://doi.org/10.1088/1748-0221/17/08/P08002
Martinez Lema 2023 https://arxiv.org/abs/2308.08314
Martinez-Lema 2023 https://doi.org/10.1088/1748-0221/19/01/P01030

Single-phase detectors

- **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 S2-only energy resolution
  - Radial TPC
  - Symmetric central cathode TPC → lower voltages needed
  - Horizontal & vertical

Challenges

- High EL and CM thresholds in LXe → amplification requires extreme electric fields
- Techniques & Technologies

Single phase with thin wires

Wire array: Talk by MULLER
Single wire: Talk by QI & NI

- ~50 years of Wires in LXe:

  Derenzo PRA 1974

  Masuda NIM 1979

  Aprile JINST 2014

  Brown JINST 2022

- So far no "practical" success
- Potential problems (for large detectors):

  High fields →

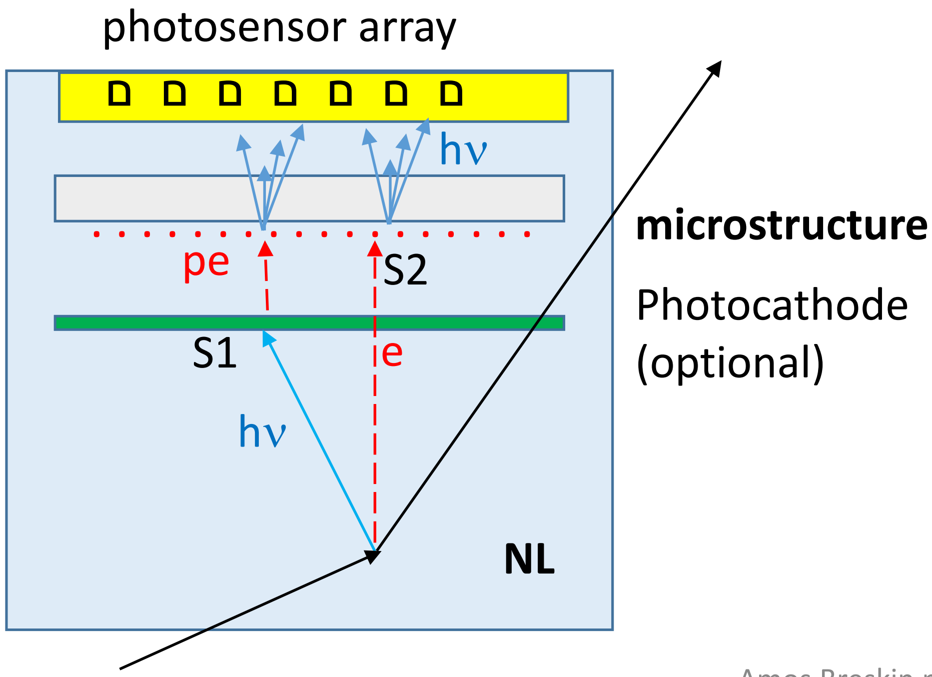
  ➔Few μm Φ wires or very high voltage

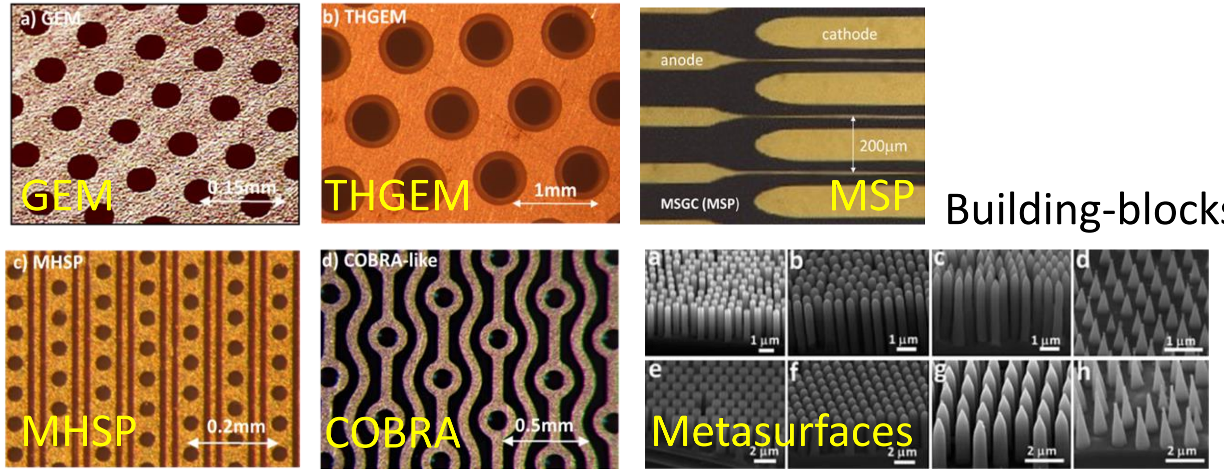
  ➔ wires sagging, staggering

APRILE JINST 2014
Threshold fields:
EL: ~ 412 kV/cm
CM: ~ 725 kV/cm

Single-phase liquid multiplying microstructures

- **S2 e** (& **S1 pe** from a photocathode in NL) collected onto micro-structured electrodes: MSP, MHSP, COBRA, Metasurfaces…
- Charge multiplication (CM) & electroluminescence (EL), at high fields.
- EL & CM photons detected by near-by photosensors.
- Various configurations discussed for **e** & combined **e/pe** detection.



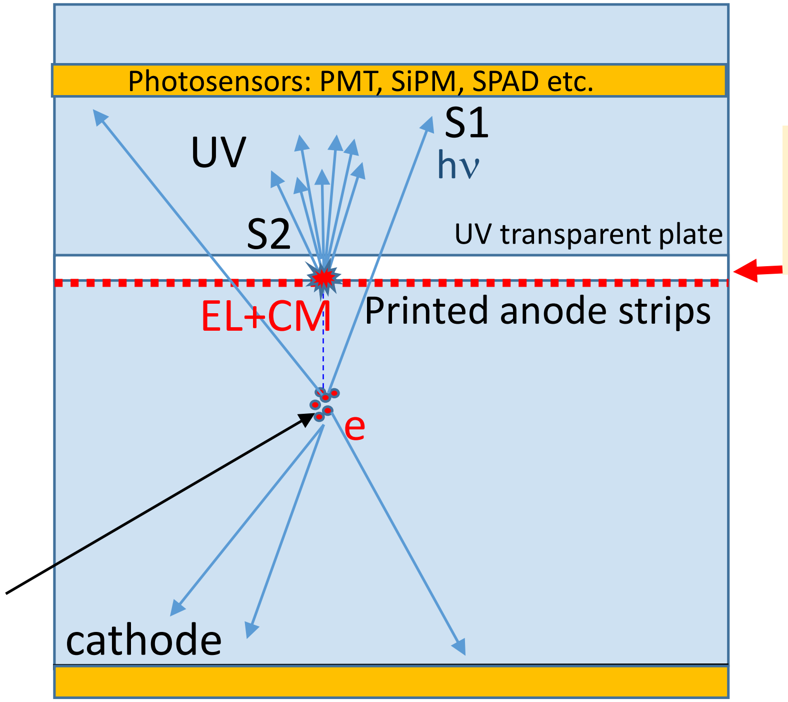


Building-blocks

S2 Only
“reality”

Charge multiplication with microstructures

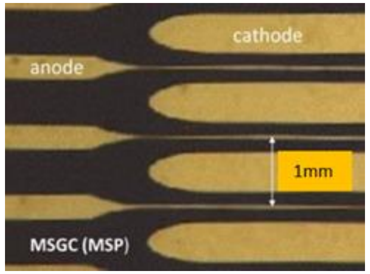
S2 detection

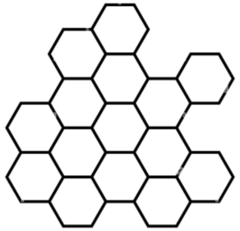


PMT, SiPM, SPAD etc.
or **reflective cathode**.

MSP LXe: gain 10
Policarpo et al. NIMA 1995

Microstructure:
e.g. Micro Strip Plates



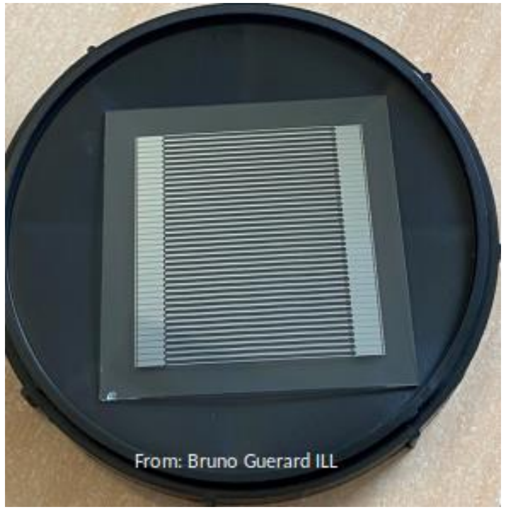


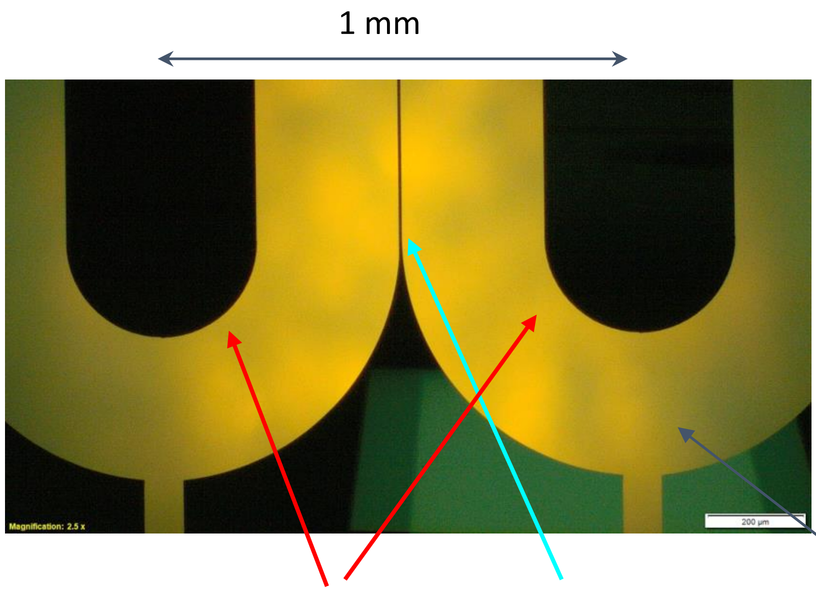
Robust
Modular

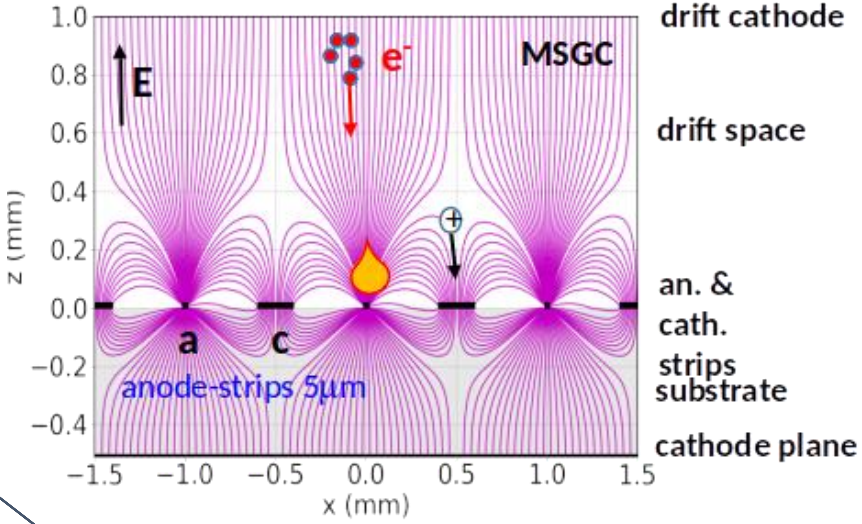
- Microstructure (e.g. MSP) formed on VUV-transparent substrate, with semi-transparent Ni or Cr electrodes.
- Deposited charges drift in liquid; undergo **EL & small charge multiplication (CM)** near thin (μm) anode strips (structures).
- The resulting photo-yield depends on type & configuration.
- EL+CM S2 Photons recorded above.
- S1 scintillation photons: with top & bottom photo-sensors (or reflective cathode)

Microstrips

- First proposed by Oed in 1988 for the MicroStrip Gas Chamber (MSGC)
- Thin strips deposited on a substrate (ideally VUV-transparent)
- Original design: cathode and anode strips interleaved

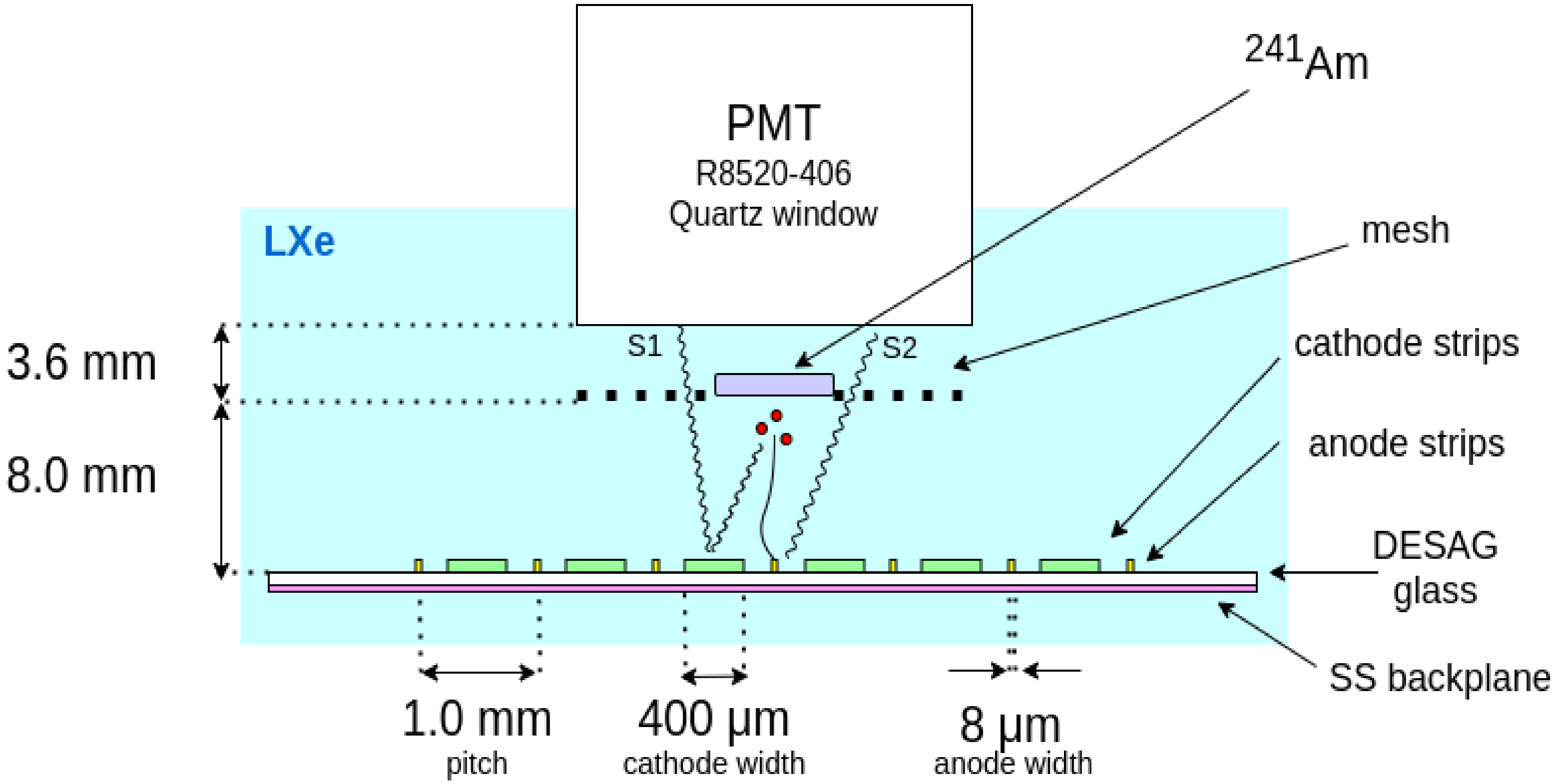


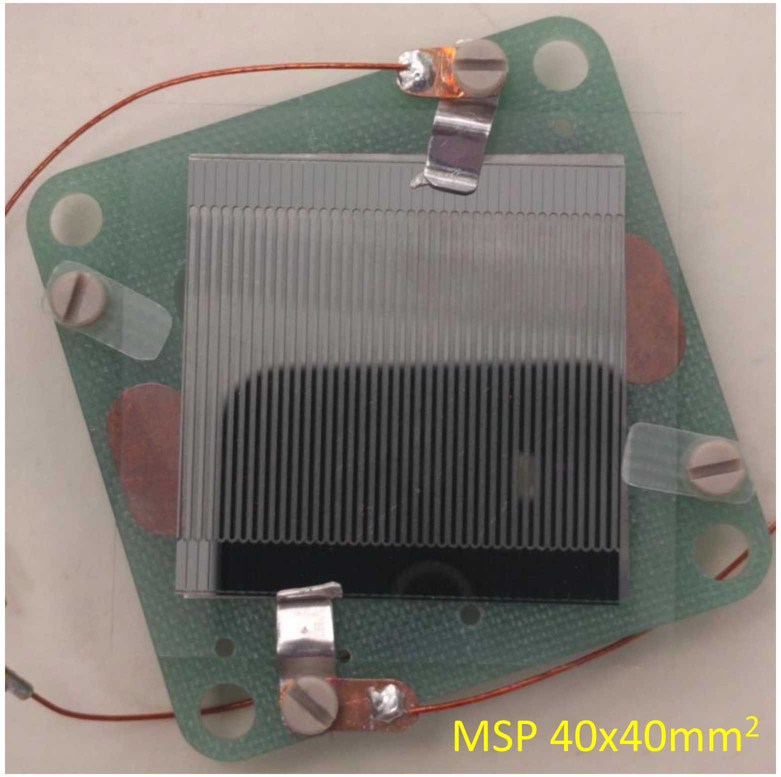




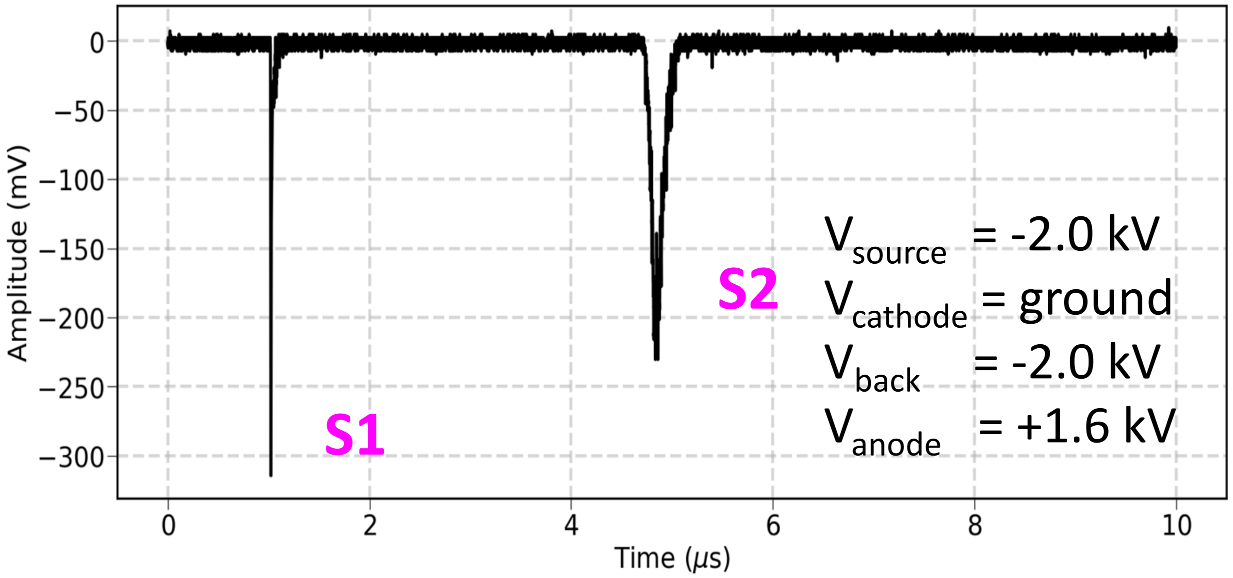
Microstrip multiplier setup

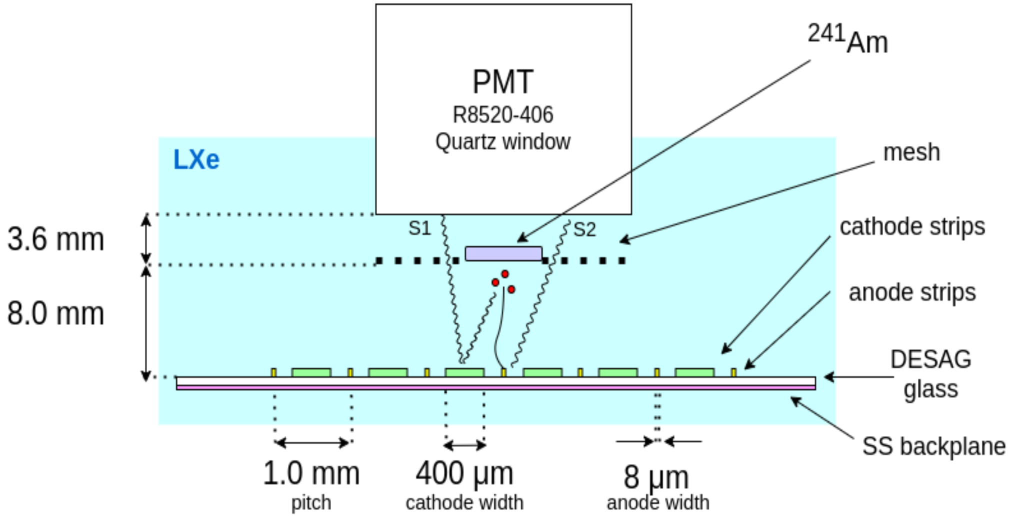
Martinez-Lema 2023 https://arxiv.org/abs/2308.08314





A typical PMT waveform





Ω ~ 10.5 %

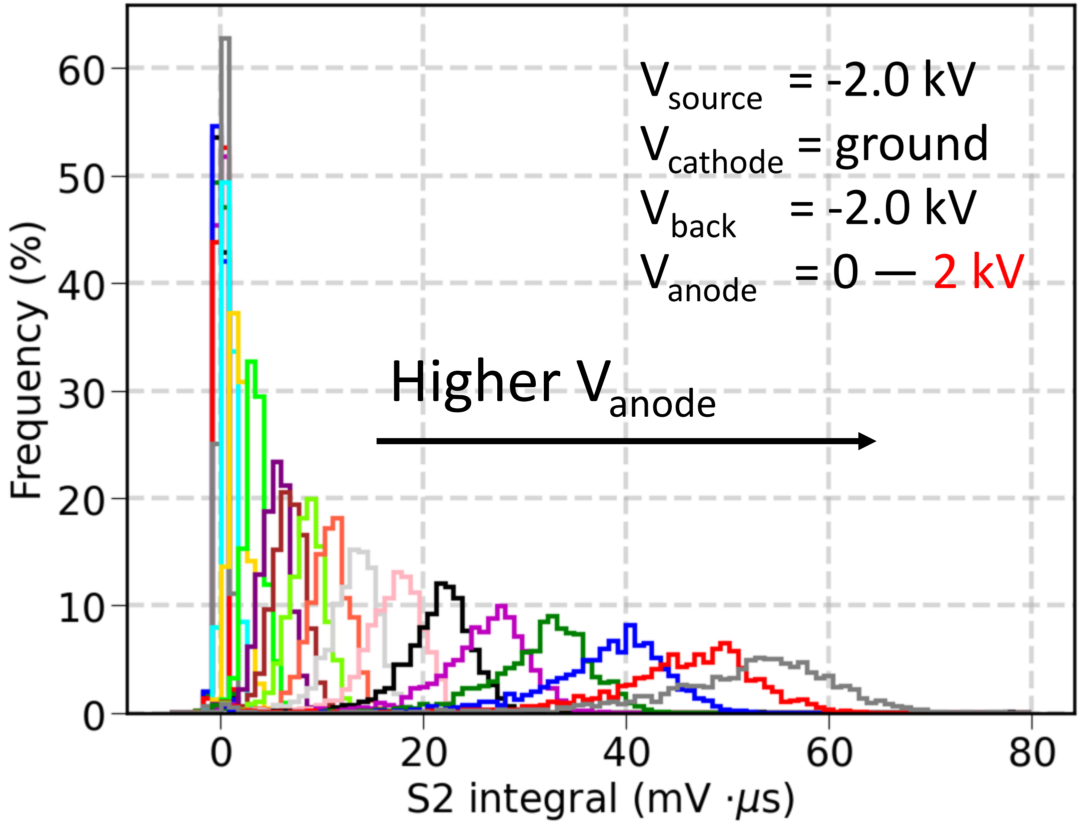
T ~ 81%

QE ~ 28%

N_{ie} ~ 15500 ~ 2.5 fC

Integrated S2 signal

- PMT waveform integrated on fixed S2 window
- Integral of S2 increases with V_{anode}
- Max V_{anode} = 2 kV due to anode-to-cathode discharges
- EL threshold @ V_{anode} ~ 500 V



Light yield

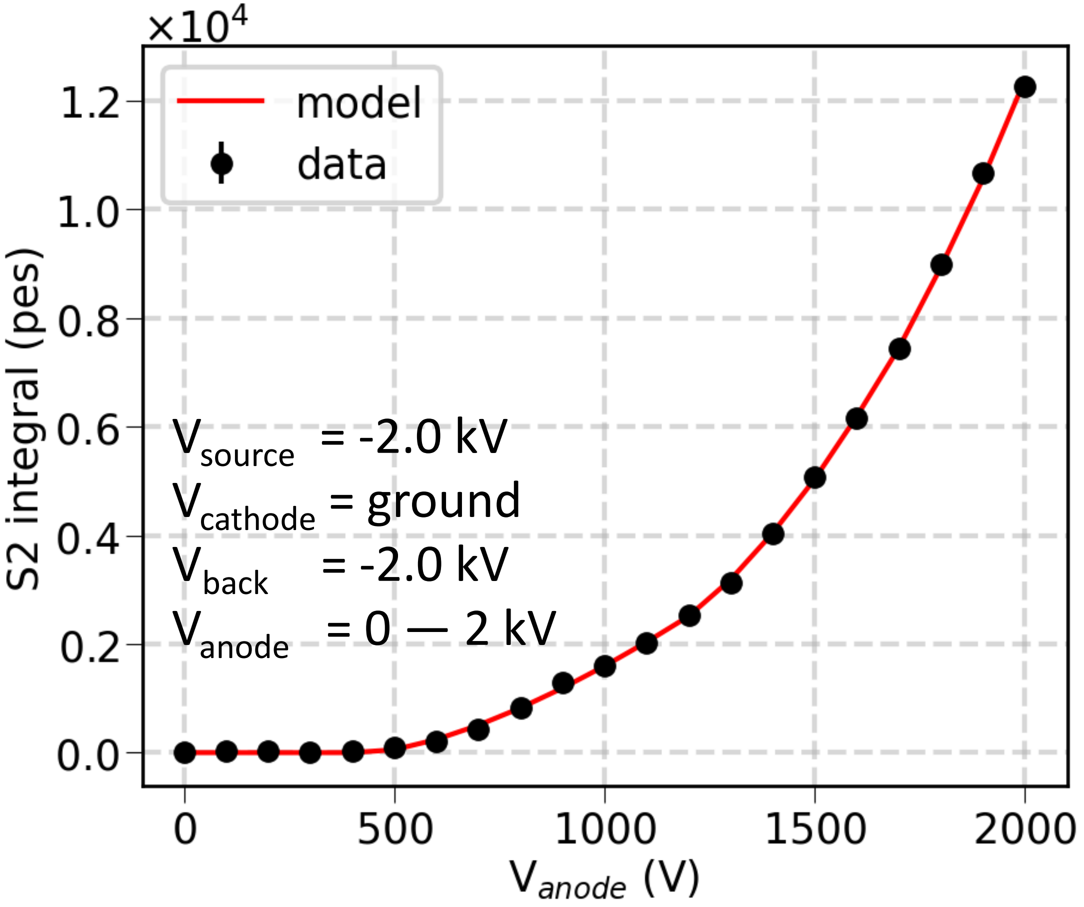
- Conversion to pe's based on in-situ PMT calibration
- Light yield @ V_{anode} = 2 kV

LY = 33 ph/ie

$$LY = \frac{S2}{\frac{\Omega}{4\pi} \cdot T \cdot QE_{PMT} \cdot N_{ie}}$$

mesh transparency (T); from alpha particles (N_{ie})

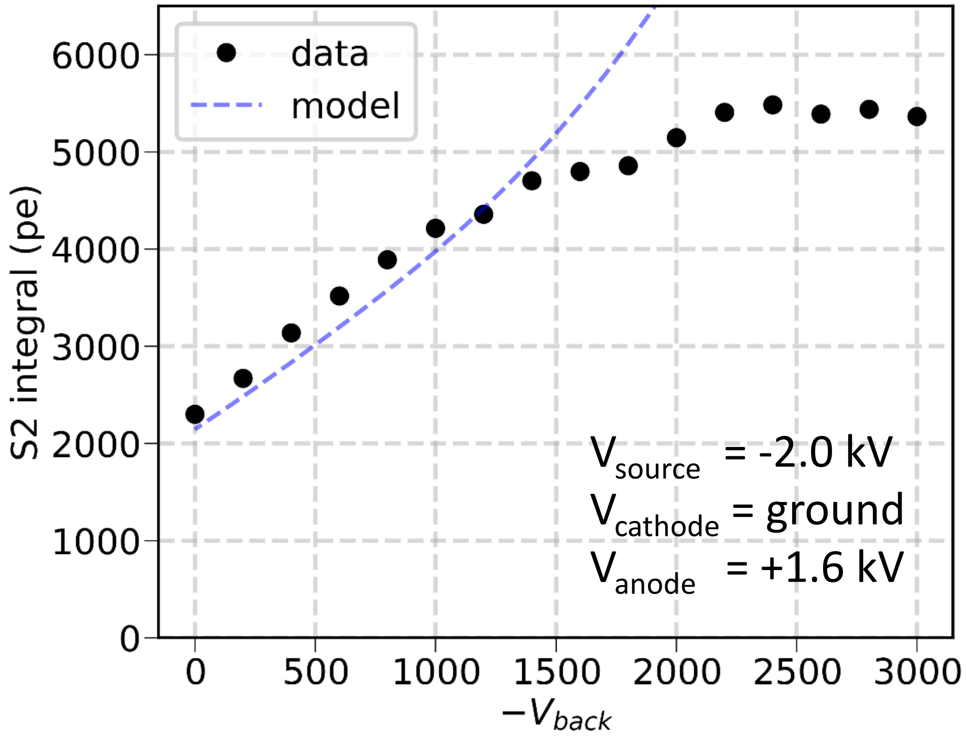
Ω ~ 10.5 %
T ~ 81%
QE ~ 28%
N_{ie} ~ 15500 ~ 2.5 fC



Data fitted to the a CM & EL model (APRILE 2014)

➔ EL threshold (θ_4) **~ 465 kV/cm**
➔ CM threshold (θ_2) **~ 785 kV/cm**
➔CM **~x3 @ 2 kV**
In agreement with Aprile 2014 (412/725 kV/cm)

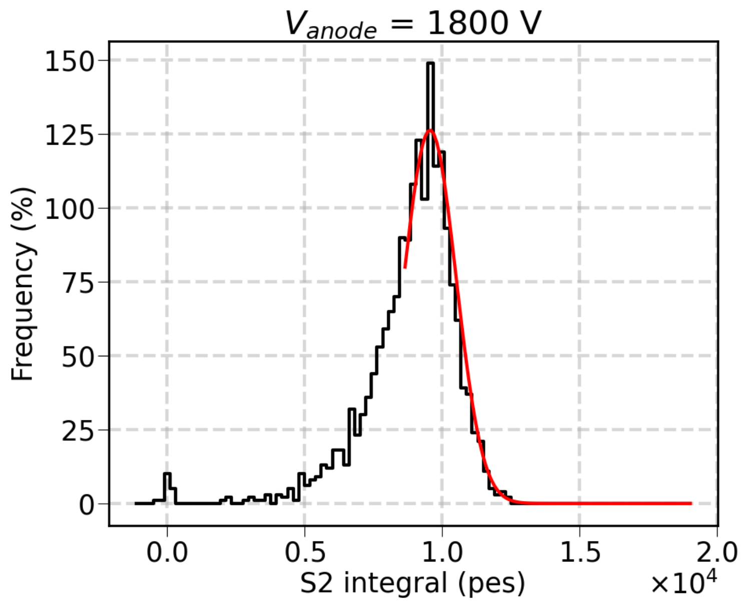
Backplane bias

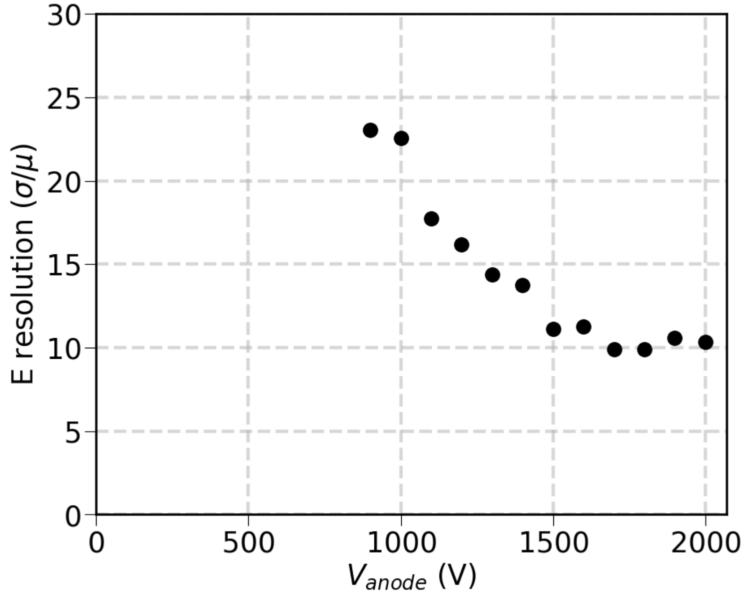


The discrepancy between data and finite-element COMSOL computations plus EL & CM model (Aprile 2014): might be due the nature of the glass substrate (slightly conductive?)

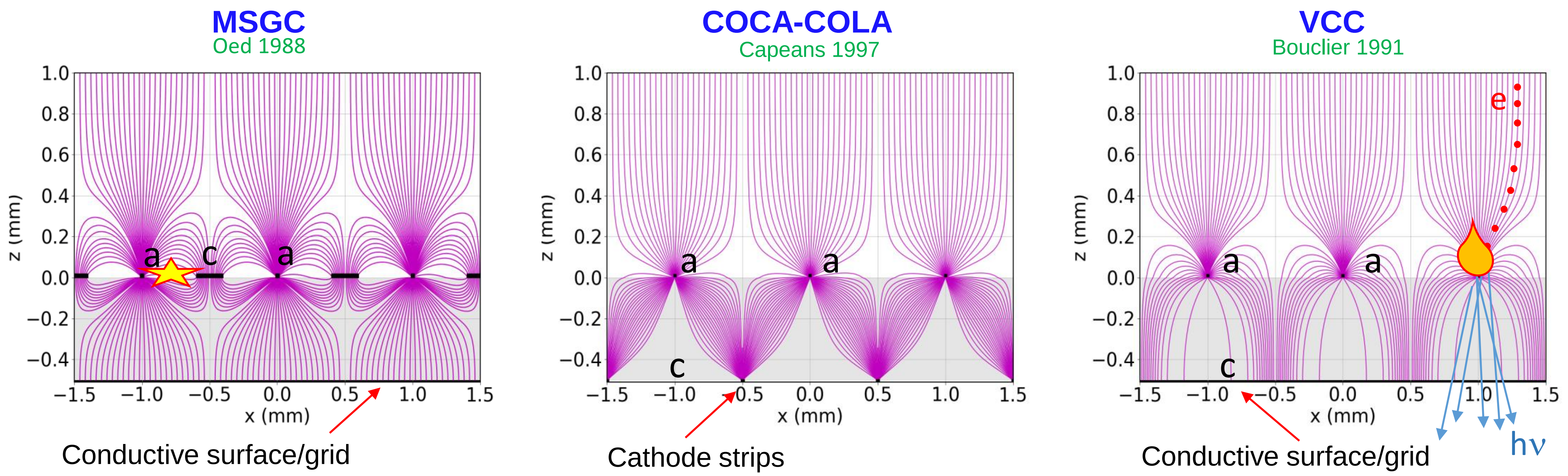
Energy resolution

- Gaussian fit to the high-energy side
- σ/μ = 9.9 % @ 1800 V
- Similar to the results obtained with 10 μm wires by Aprile 2014
- Can be improved with other configurations



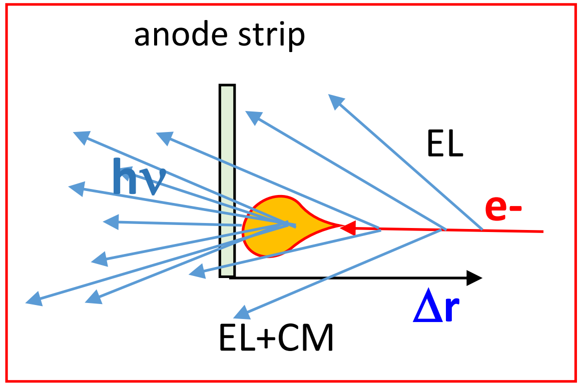


Prospects: MSGC vs COCA-COLA vs VCC



- MSGC has the best field configuration
  But operation (discharge limit) is limited to ~2kV a-to-c

- COCA-COLA & VCC can operate at higher V without discharges
  ➔ higher expected photoyields



Field vs Δr : MSGC vs COCA-COLA vs VCC

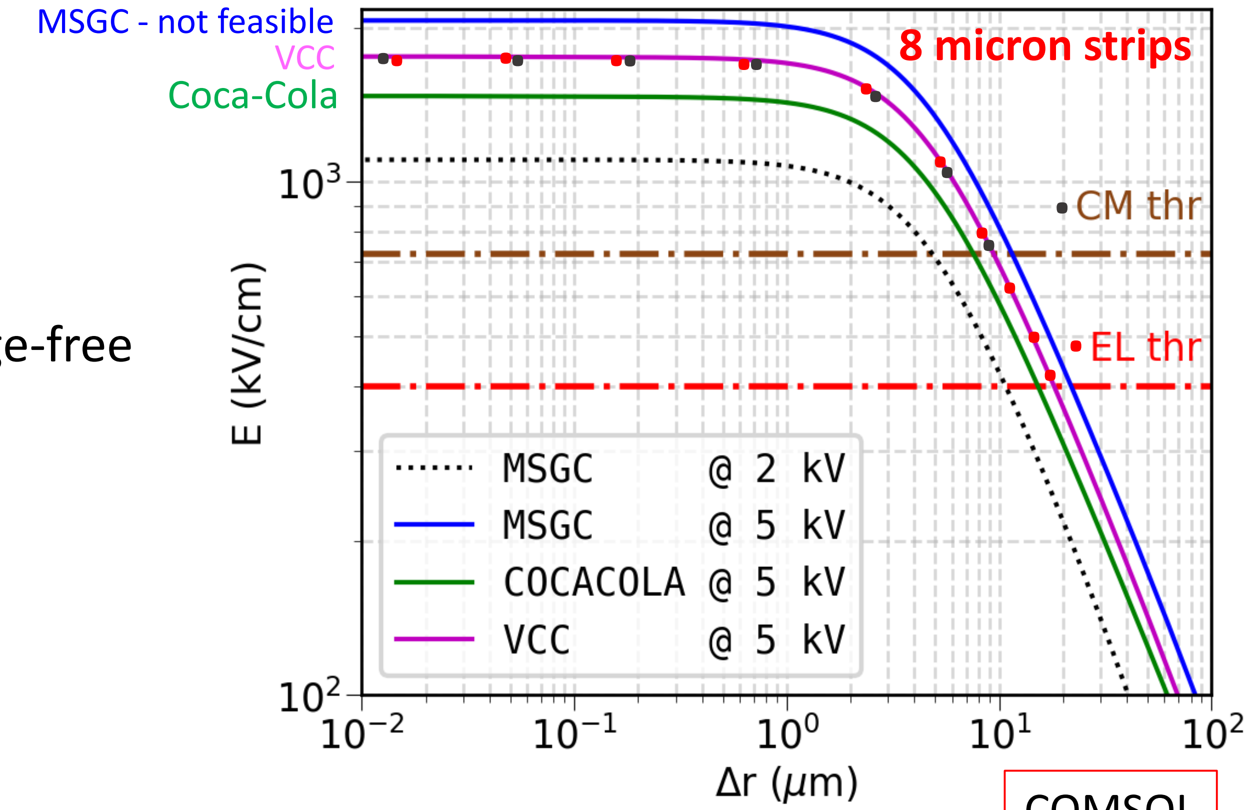
- MSGC: the best field configuration
  - But operation is limited to ~2 kV a-to-c
- COCA-COLA & VCC : higher potentials discharge-free
  - Higher e^- multiplication & light yields

Model predictions @V_{anode} 5kV*:

- COCA-COLA potential ~180 photons/e
- VCC potential ~ 550 photons/e

* V_{anode} = 5kV taken as feasible example

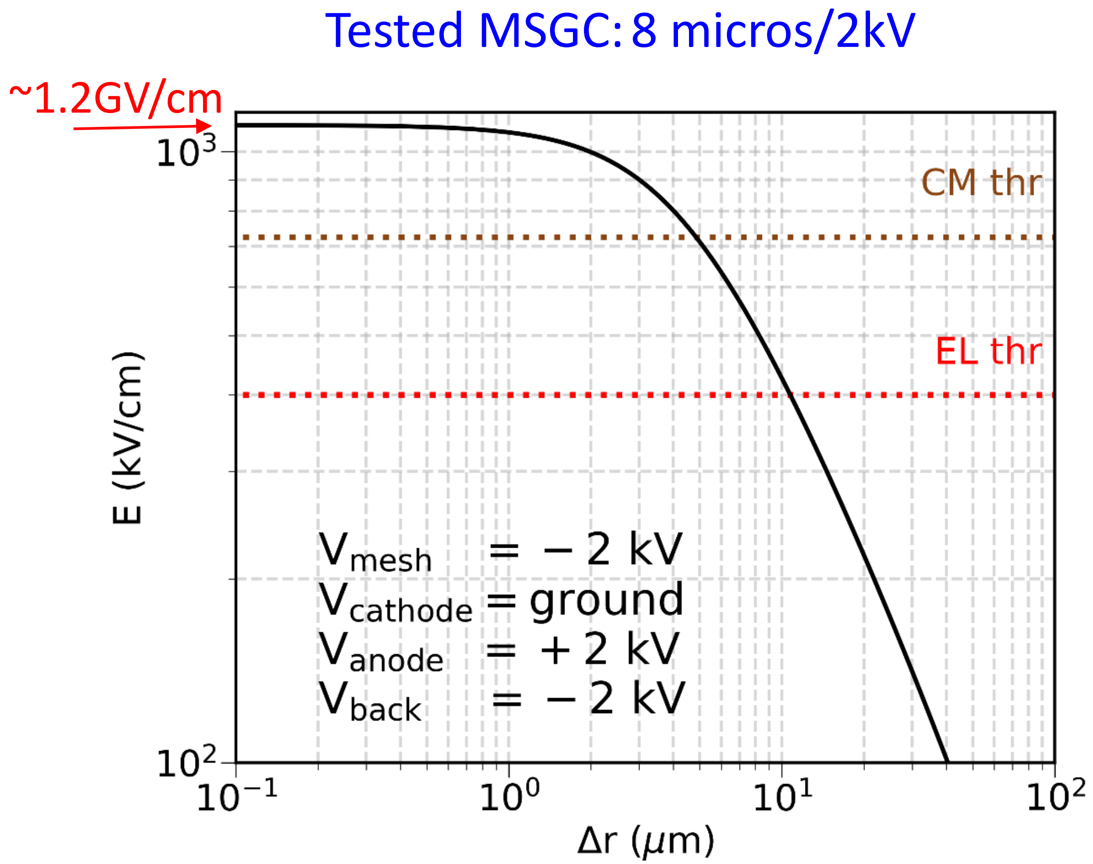
Field vs distance from strip surface

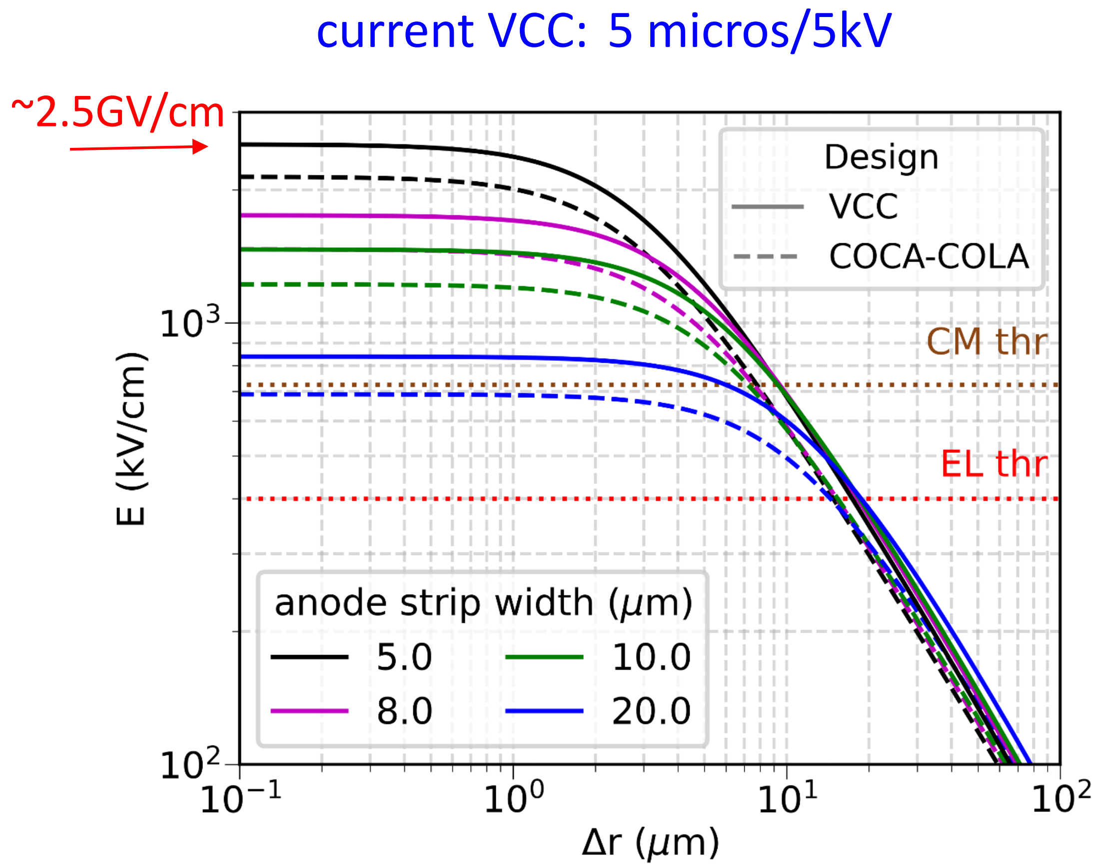


COMSOL

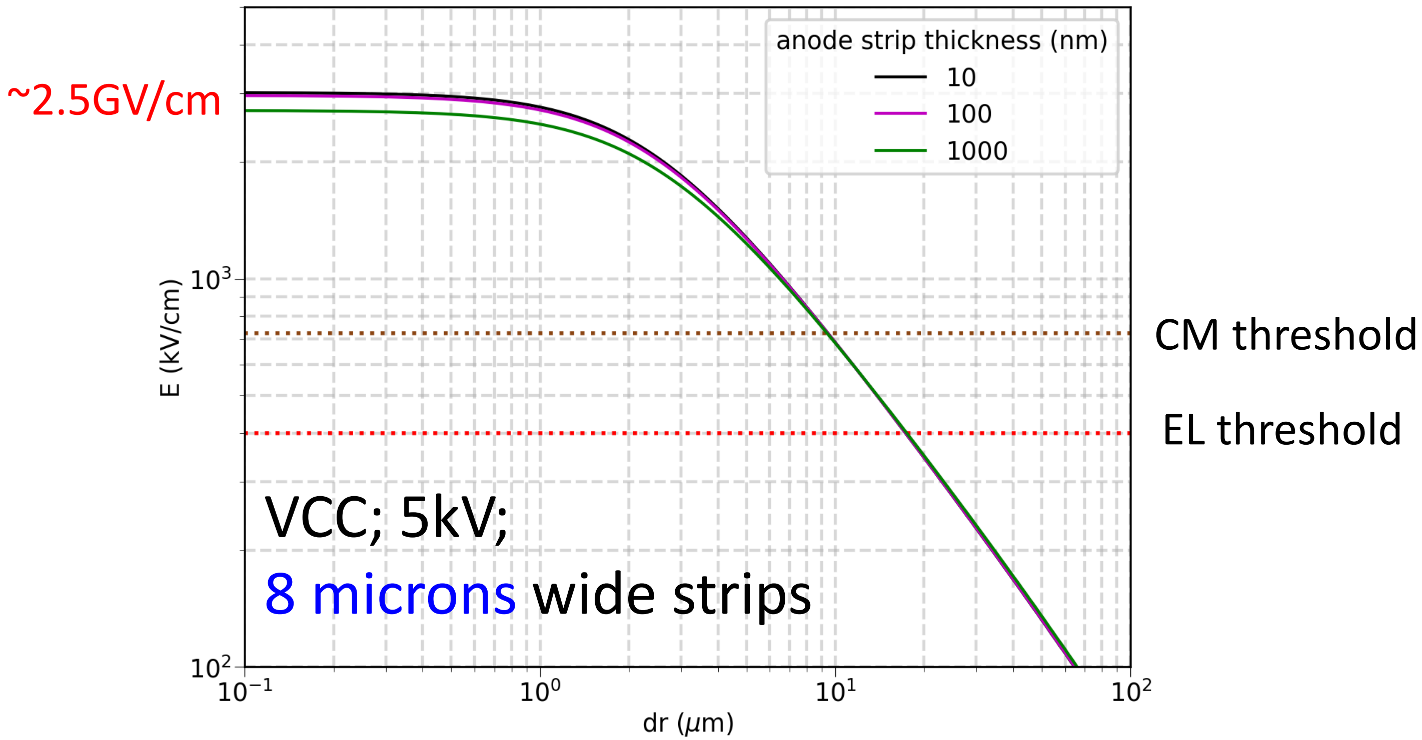
Strip thickness	1-10 nm
Anode strips	8 μm wide
COCA-COLA cathode strips	200 μm wide
MSGC cathode strips	400 μm wide

Field vs strip width





VCC: Field vs Δr – dependence on strip thickness

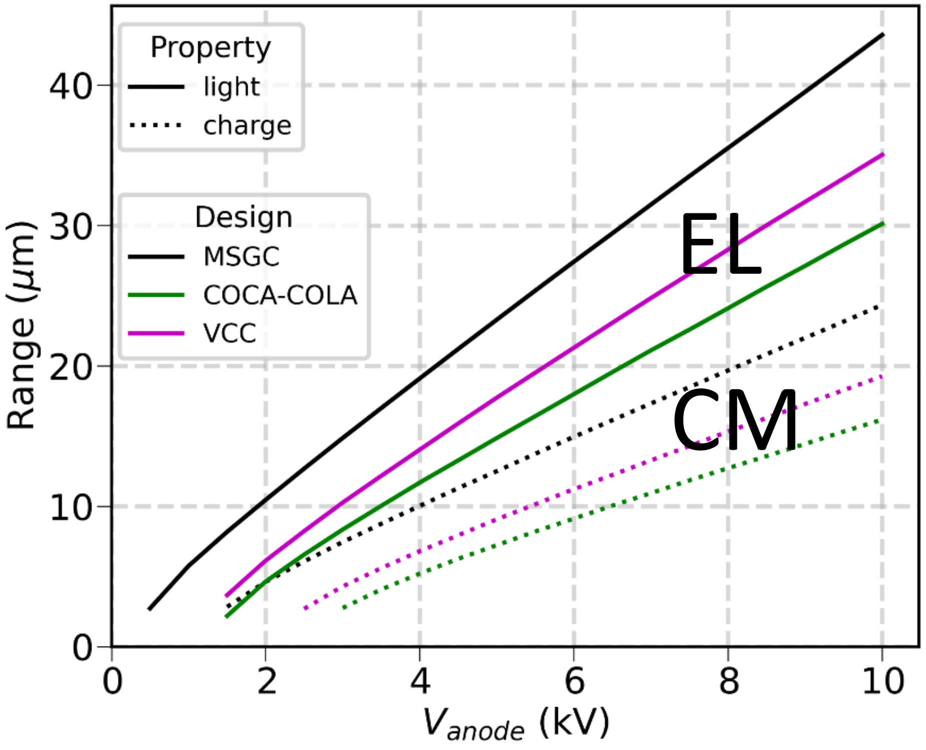


Low dependence of field on strip thickness

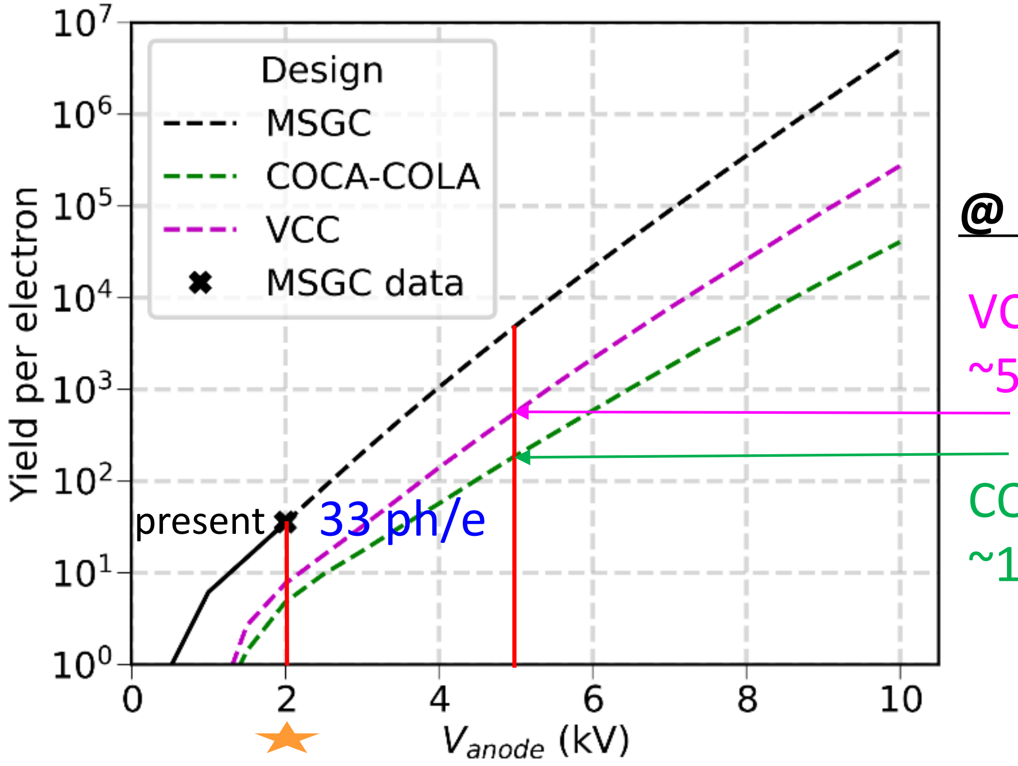
Model* Predictions

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

Range for CM & EL above $E_{threshold}$



Photoyield



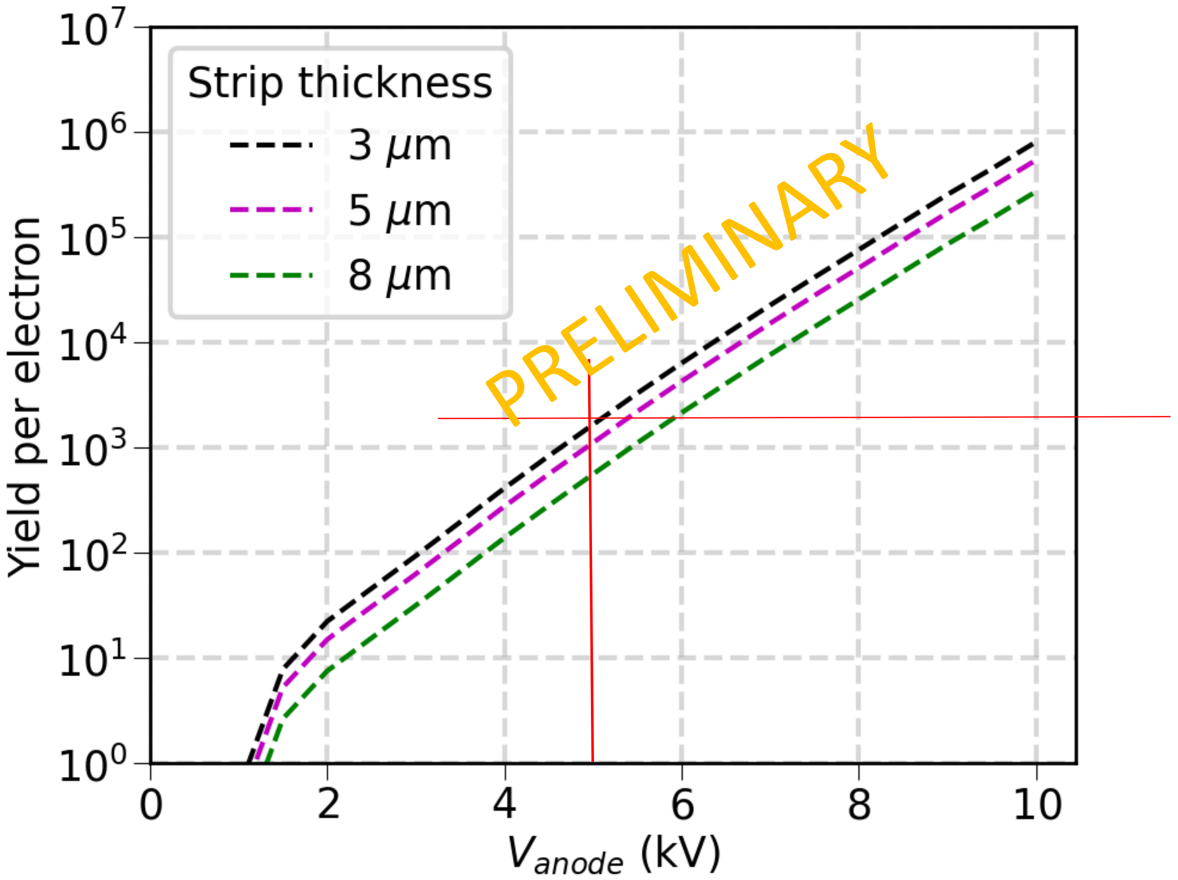
@ 5kV/8μm strips:

VCC:
~550 photons/e

COCA-COLA:
~180 photons/e

* Model: Aprile JINST 2014

VCC: photoyield – strip width

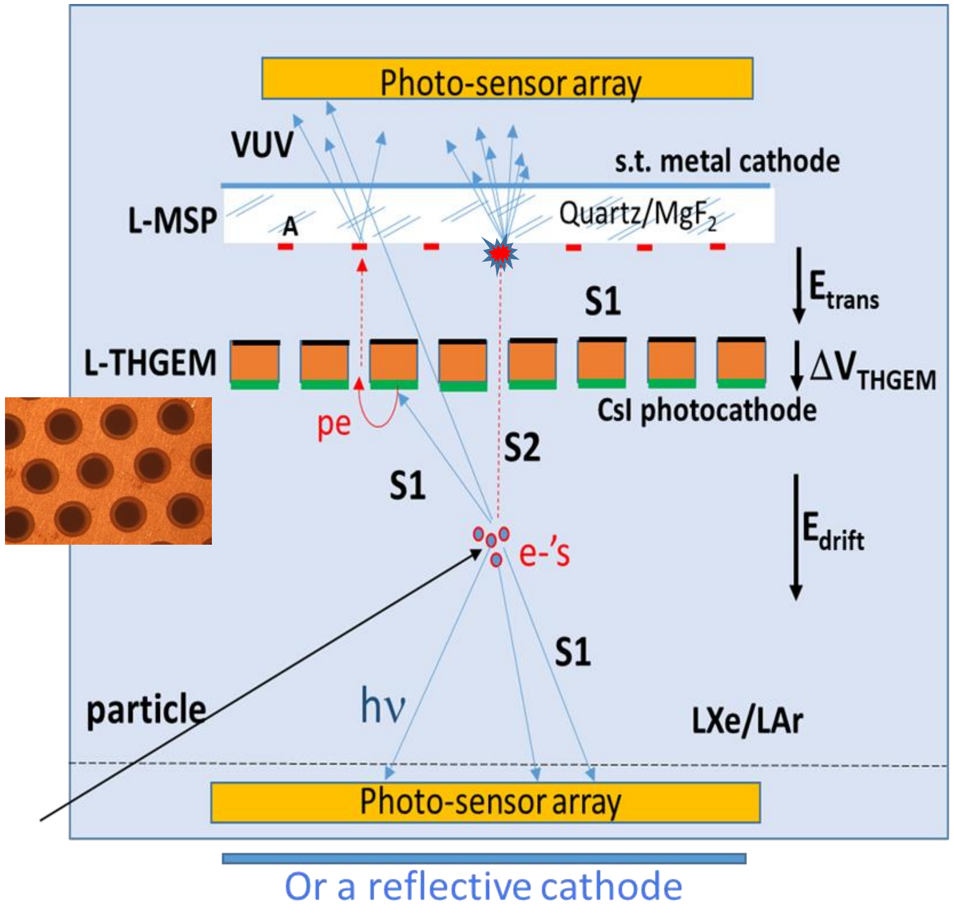


3micron strips/5kV:
~ 1700 photons/e

S2 + S1
“dreams”

e & **hν** multiplication with cascaded microstructures

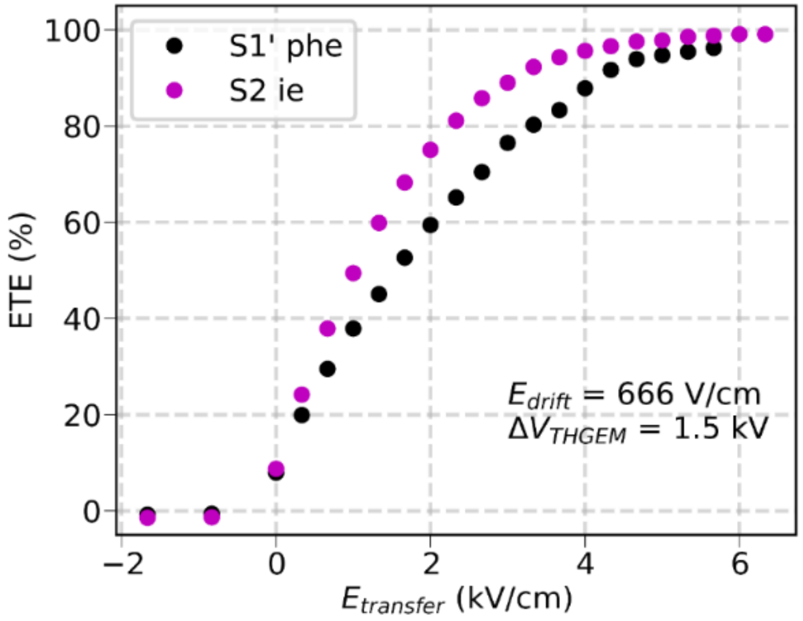
Combined S1 & S2 detection



- 2-stage single-phase TPC with CsI-coated perforated electrode (L-THGEM) followed by a L-MSP
- **S2 e** & **S1 VUV-pe** collected into L-THGEM holes & <u>efficiently</u> transferred to the L-MSP.
- EL+CM VUV photons emitted at the microstructure - detected above, 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).

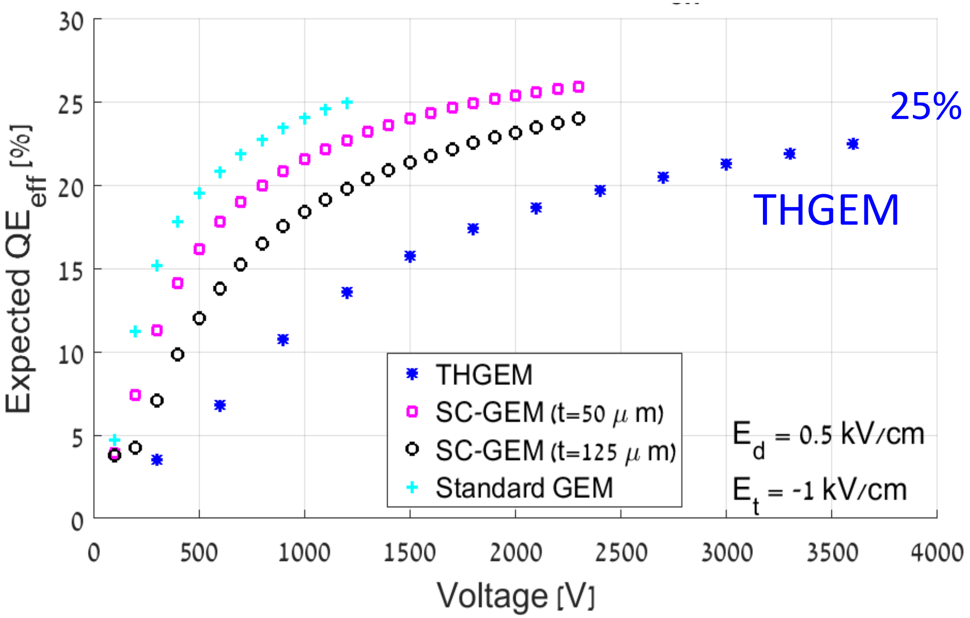
THGEM: Electron transfer and CsI Quantum Efficiency in LXe

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

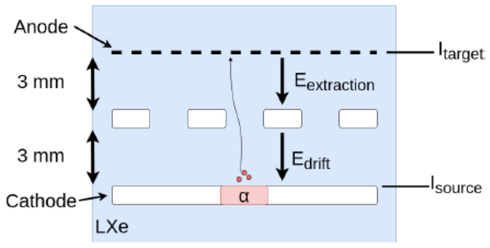


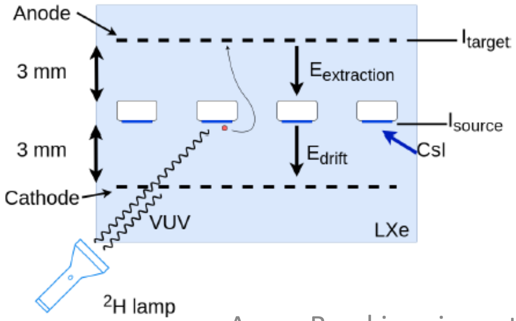
Martinez-Lema 2023 https://doi.org/10.1088/1748-0221/19/01/P01030

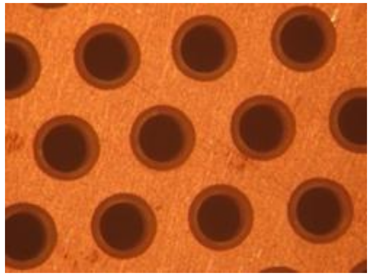
QE_{eff} of CsI in LXe



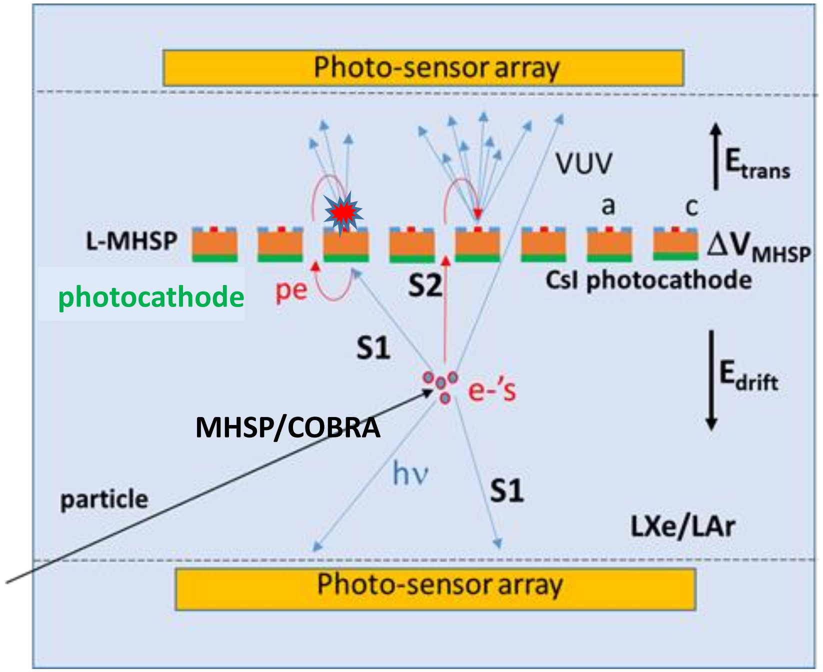
Erdal 2021 https://jinst.sissa.it/jinst/theses/2021_JINST_TH_002.jsp

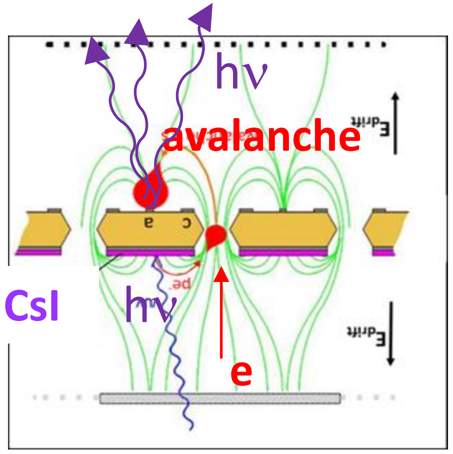


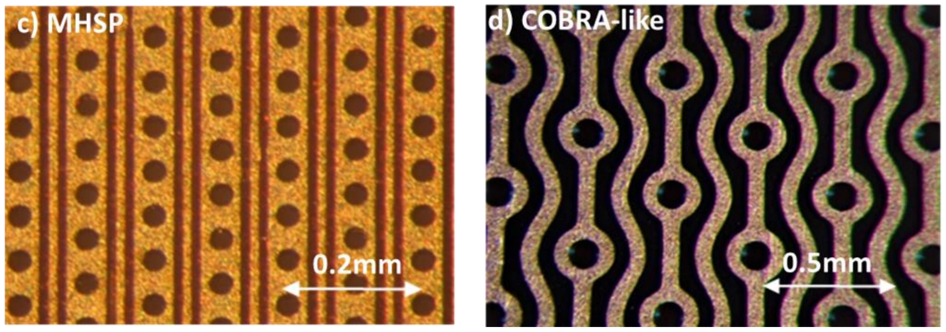




Single-phase with single Micro Hole & Strip Plate (MHSP)





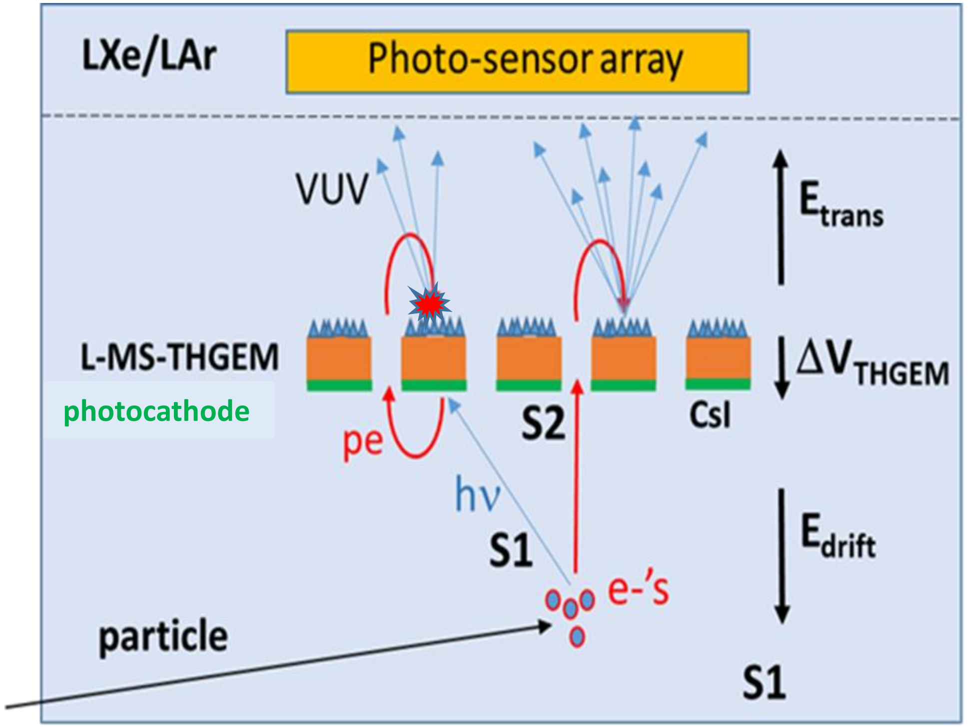


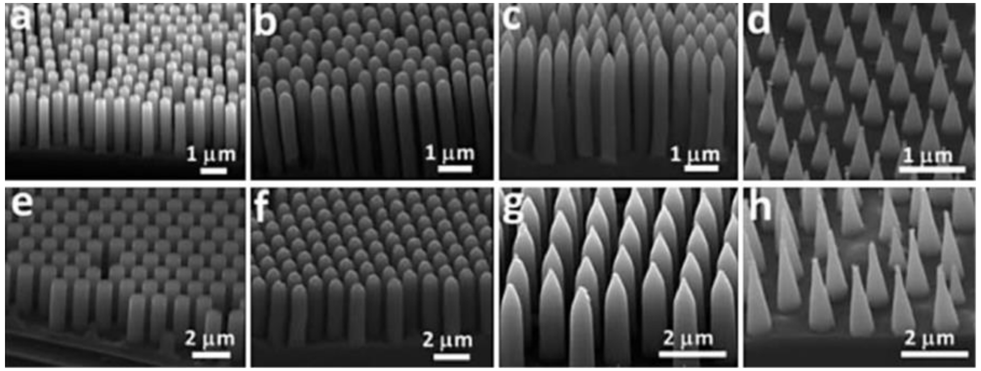
MHSP: Veloso, Rev Sci. Instr. 71, 2371 (2000)
https://doi.org/10.1063/1.1150623

Current technologies➔ few-µm strips possible

- A single-phase TPC with CsI-coated **L-MHSP** on insulating substrate.
- S2 e & VUV pe 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 or reflected to the CsI surface (not shown).

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.
- S2 e & S1 VUV pe collected into the holes towards the micro-structured top surface
- VUV photons emitted by EL + CM at the “anode tips”, are detected by top photo-sensors.
- Other fraction of S1 photons are detected by bottom photo-sensors or reflected surface(not shown).

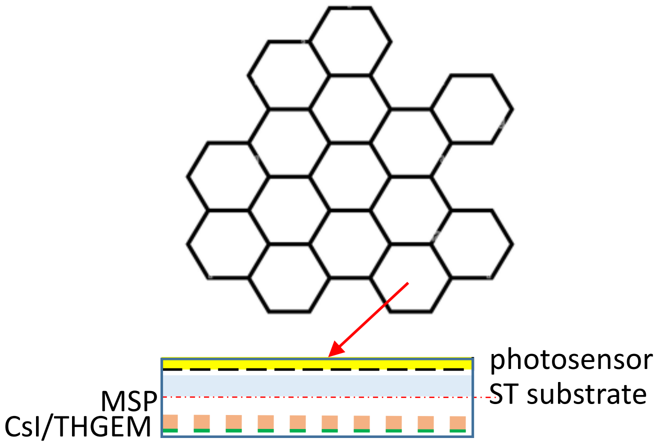
Summary & Outlook

AIMS:

- Single-element and cascaded micro-structured multipliers for S2 & S1+S2

POTENTIAL ADVANTAGES:

- Potentially Robust & Modular
- Intense (**100's of photons/e**) & fast S2(&S1) light flashes
  - ➔ permits "high dark-noise" photosensors (SiPM, SPAD, …)
  - ➔ Potentially reduces detection threshold



Example: cascaded S1/S2 sensor module

R&D:

- Currently: **VCC** light-emission studies in LXe (soon: LAr).
- Tasks (LAr, LXe): maximizing photoyield, stability – electrical & photocathode in NL, physical parameters in LXe/LAr, multiplier/sensor technologies, radio-purity etc.

Open to collaborations – seeking for students/postdocs!

Thank you!