Gaseous photomultipliers and liquid hole-multipliers for future noble-liquid detectors

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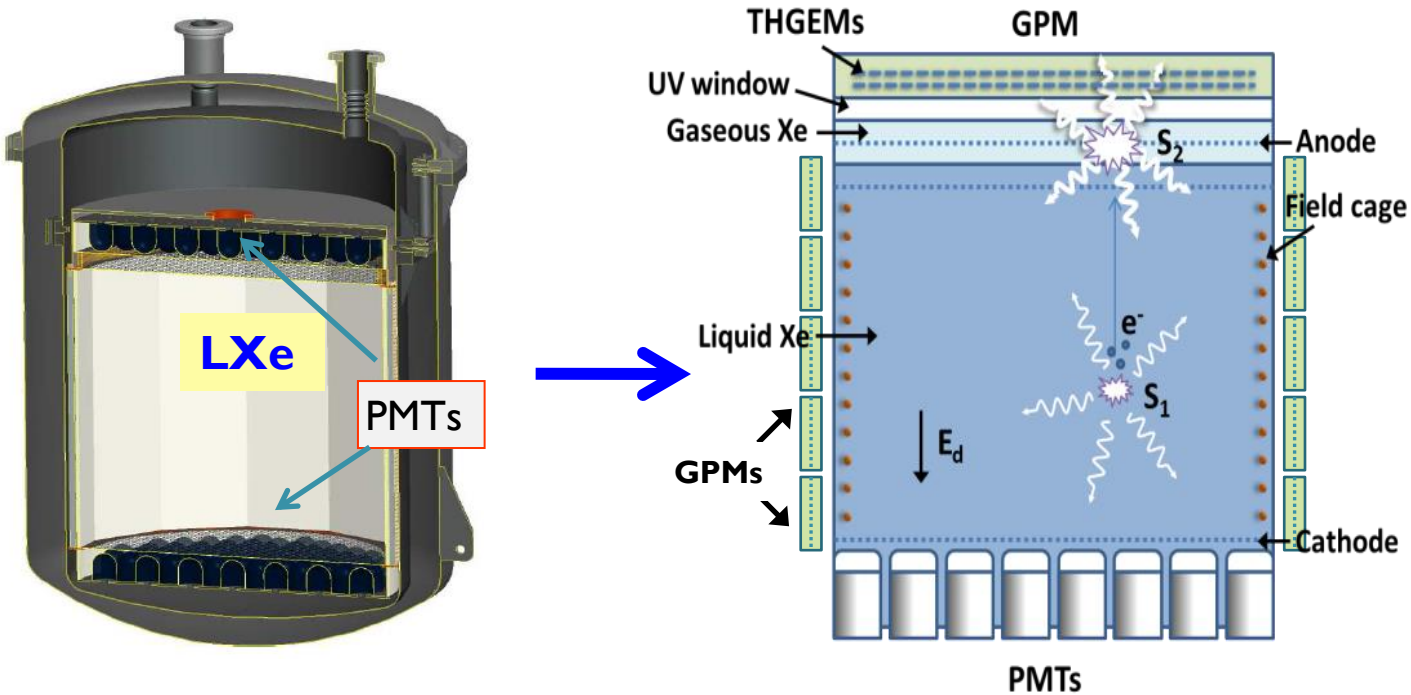
7th Symposium on Large TPCs for Low-Energy Rare-Event Detection, Paris

November 14, 2014

CRYOGENIC GASEOUS PHOTOMULTIPLIERS

Dual-phase LXe TPC with **Gaseous Photo-Multipliers (GPMs)**

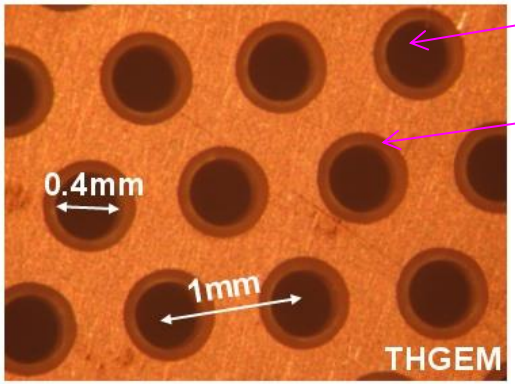


- ***Potentially* low-cost** (in-house module assembly)
- **4π coverage** (improved sensitivity to low-mass WIMPs)
- **90-95% filling factor** (compared to 50-60% with PMTs)
- **~10-fold better position resolution** through smaller pixels → better calibration and background discrimination?

Thick Gas Electron Multiplier (THGEM)

~ 10-fold expanded GEM

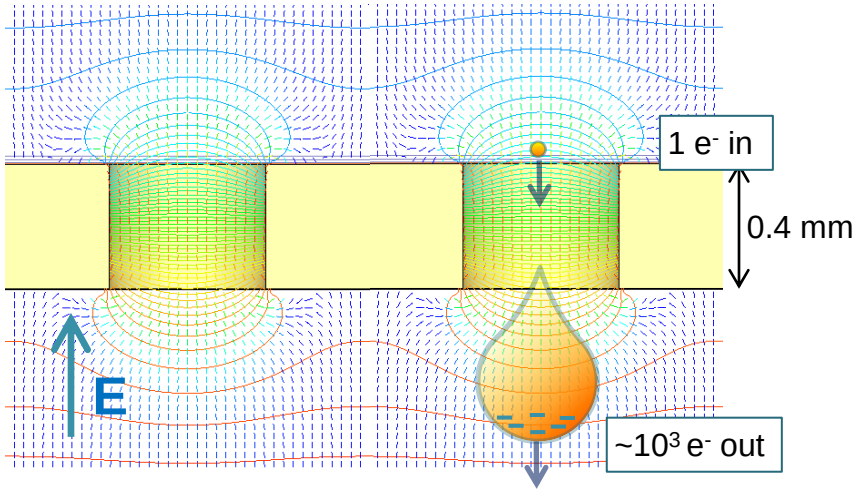
Chechik VIENNA 2004



drilled

etched

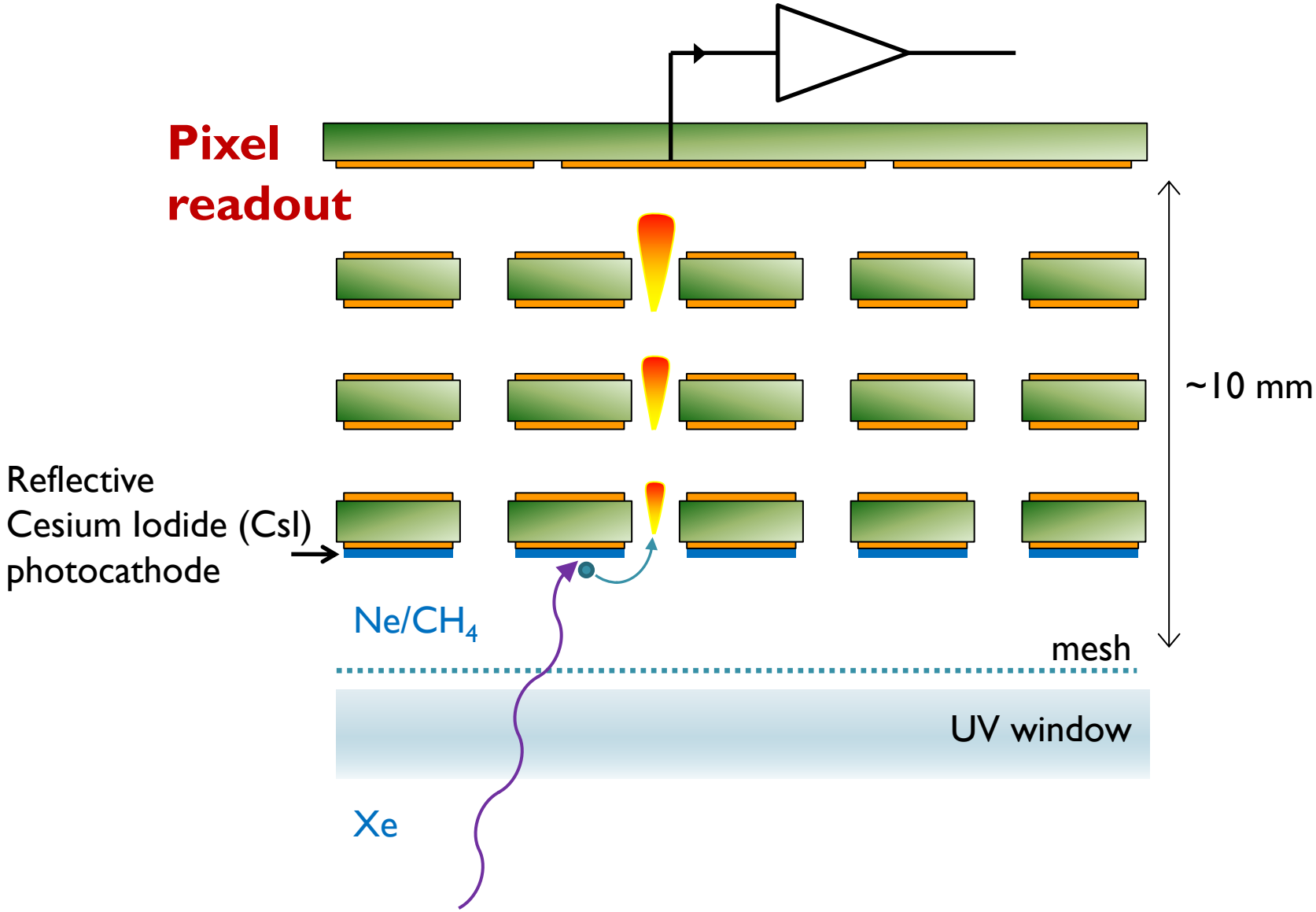
Thickness 0.4-1mm



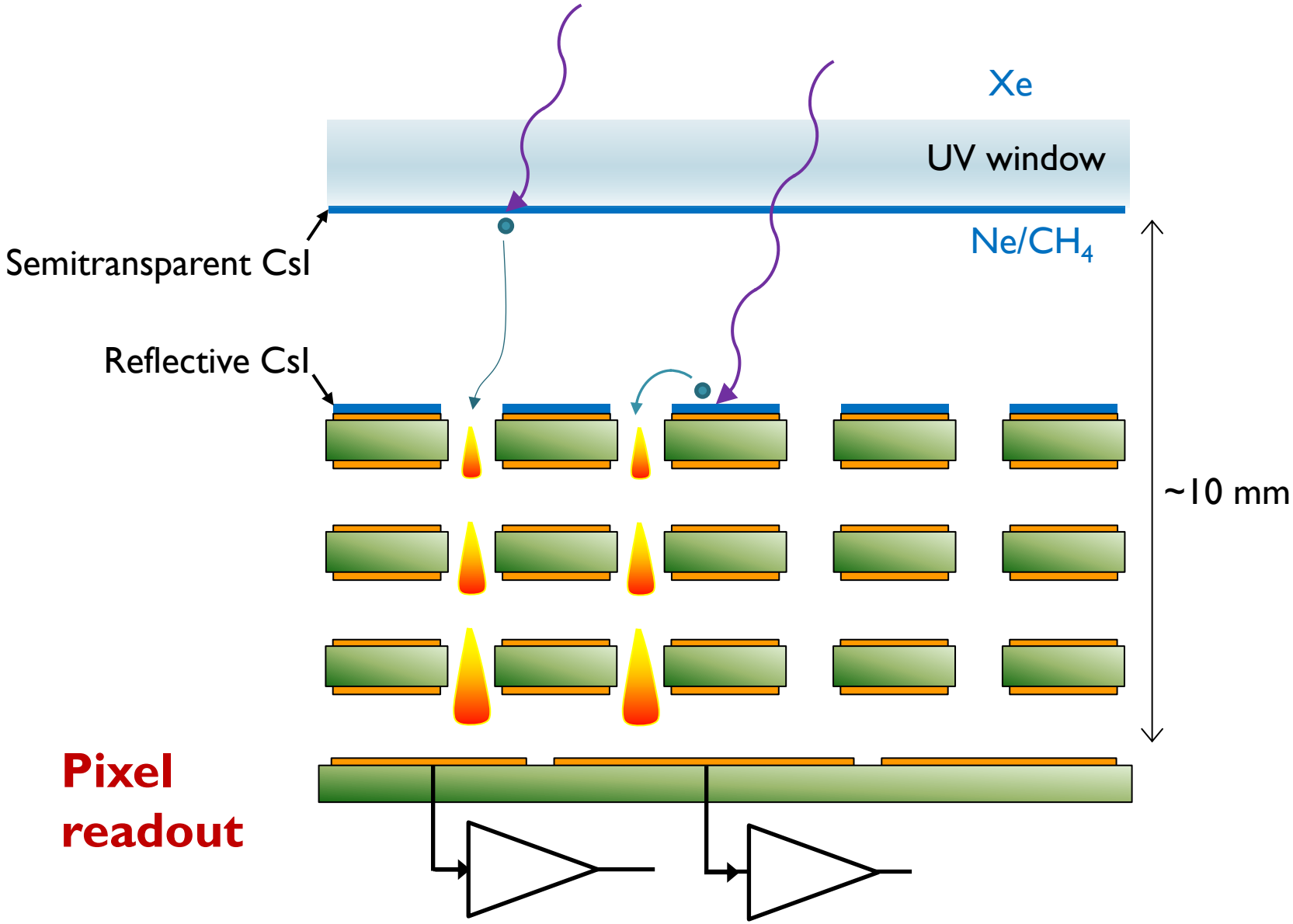
SIMPLE, ROBUST, LARGE-AREA
Printed Circuit-Board Technology

- Robust, if discharge no damage
- Can be cascaded for high gain
- Effective single-photon detection when coupled to a photocathode
- Few-ns RMS time resolution
- Sub-mm position resolution
- Can be made of radio-pure materials
- Cryogenic operation: OK
- Broad pressure range: 1mbar - few bar

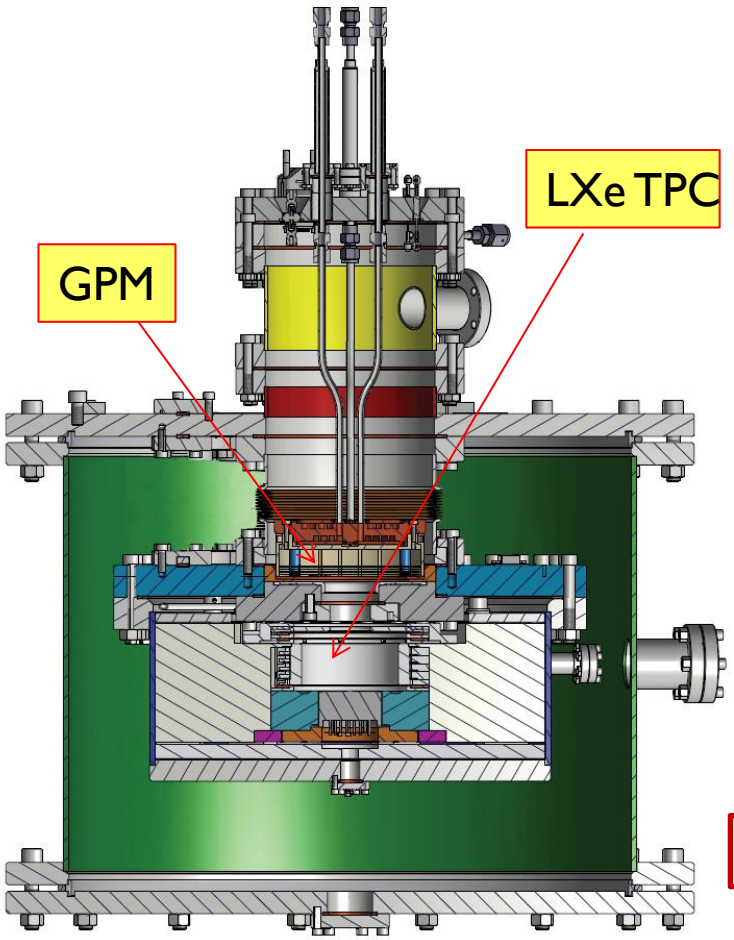
Top array GPM – triple THGEM with reflective CsI



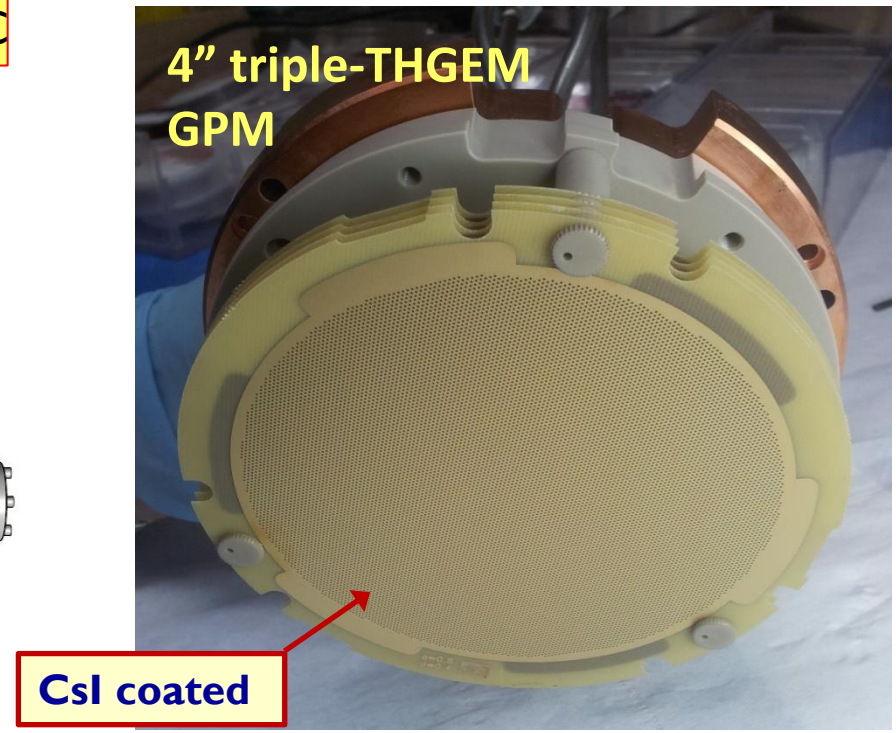
Wall GPM – semitransparent + reflective CsI



WIS Liquid Xenon (WILiX) facility: playground for detector R&D

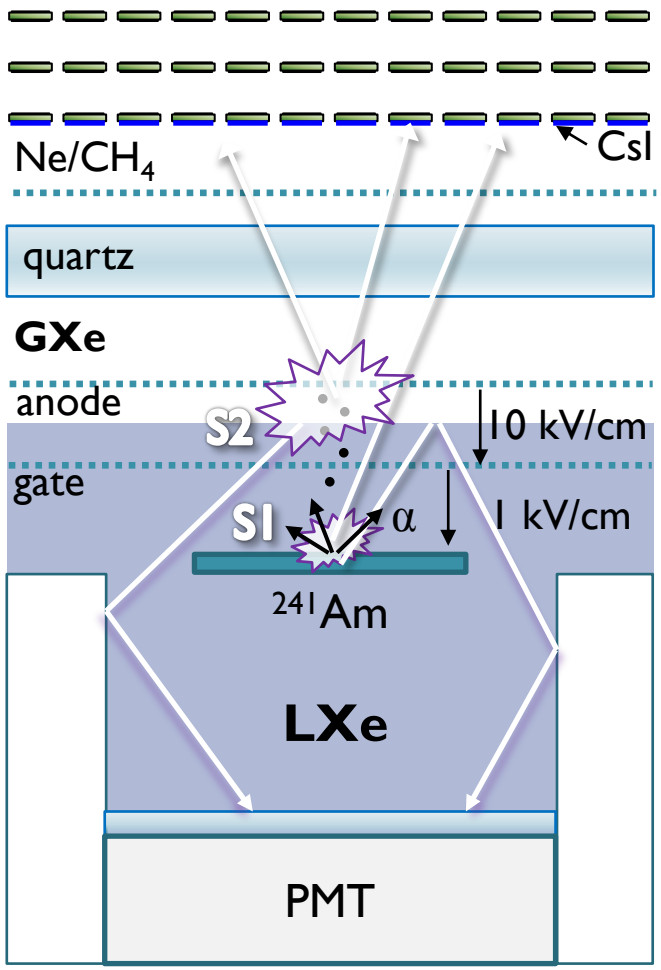


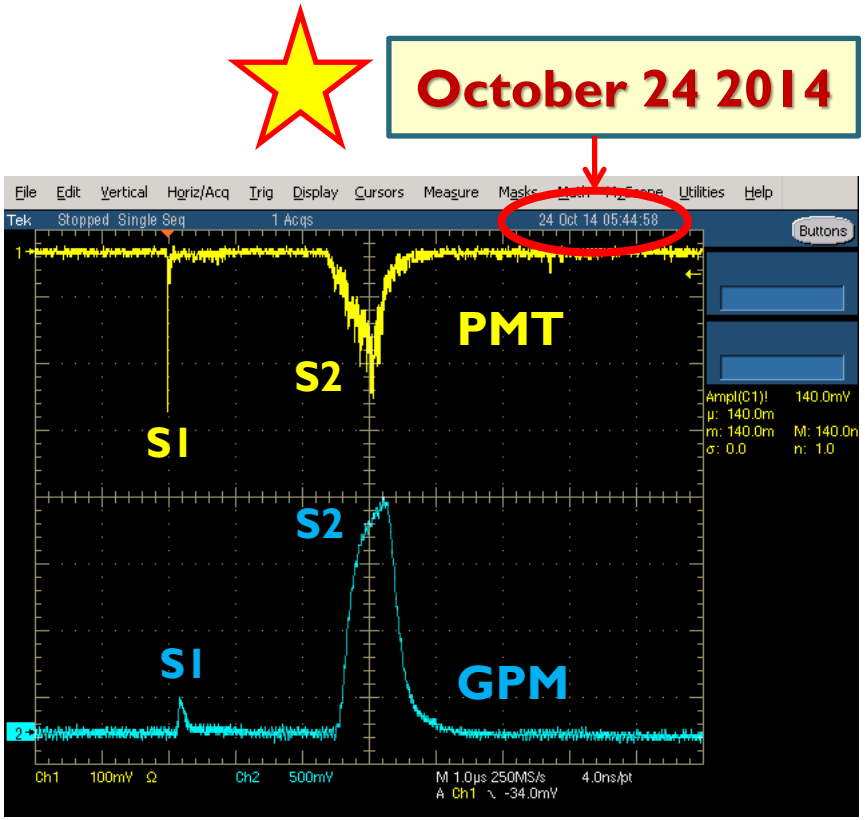
WILiX schematic view



Smaller cryo-GPM see: Duval 2011 JINST 6 P04007

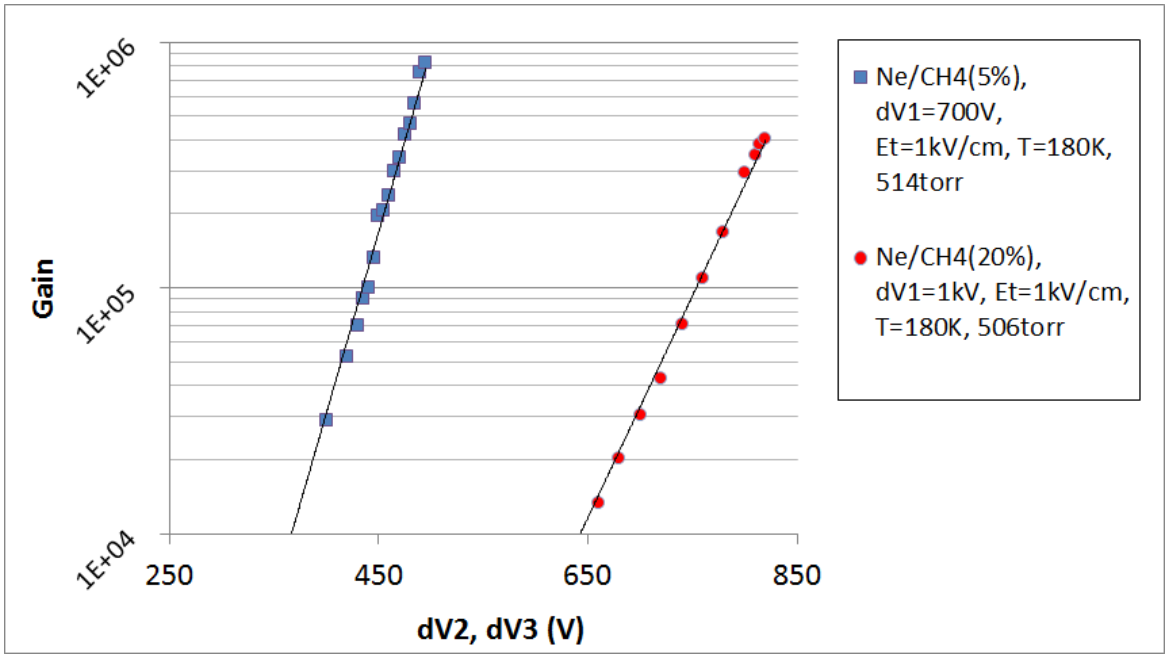
First-ever demonstration of S1 & S2 recording by GPM coupled to dual-phase LXe TPC !





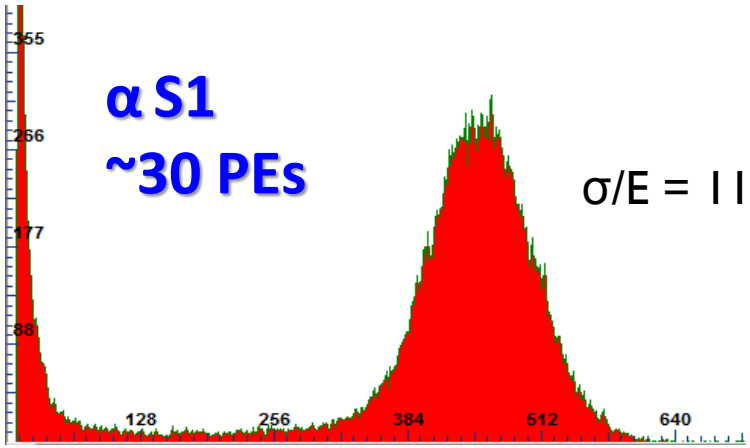
Detect single photons AND massive S2 signals!

Gain and stability



- ~$1 \cdot 10^5$ enough for >90% single-PE detection above noise
- Gain reproducible to 10-15% over many days
- **NO SPARKS** at $1.1 \cdot 10^5$ for alpha S1+S2 with ~100-fold larger cosmics S2! (discharge probability < $3 \cdot 10^{-6}$)

Energy resolution

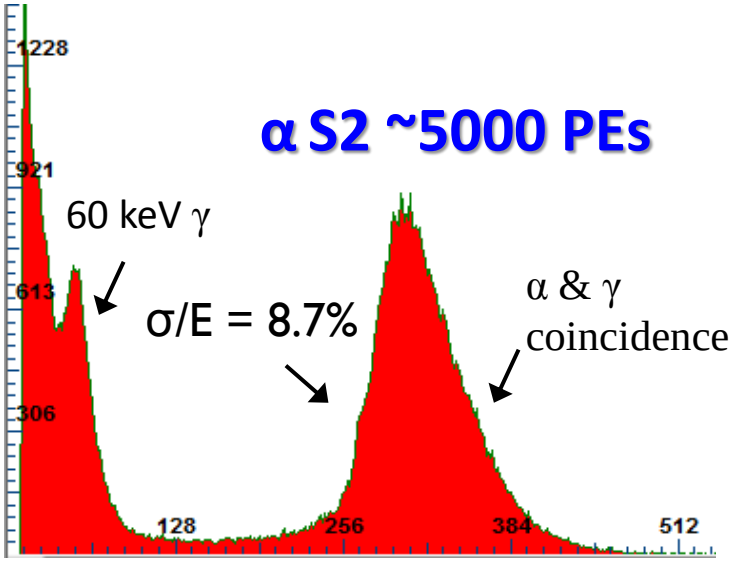


α S1
~30 PEs

σ/E = 11%

$Ne/CH_4(5\%)$
514 torr, 180K
Gain $1.1 \cdot 10^5$

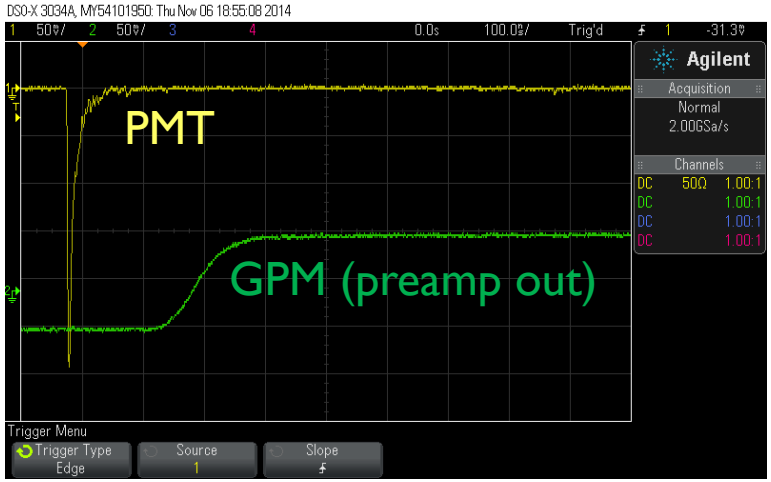
S2 energy resolution similar to XENON100



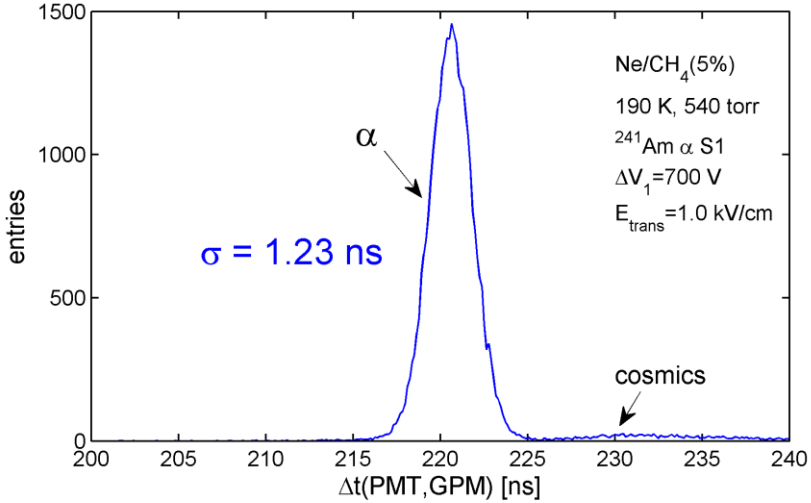
α S2 ~5000 PEs

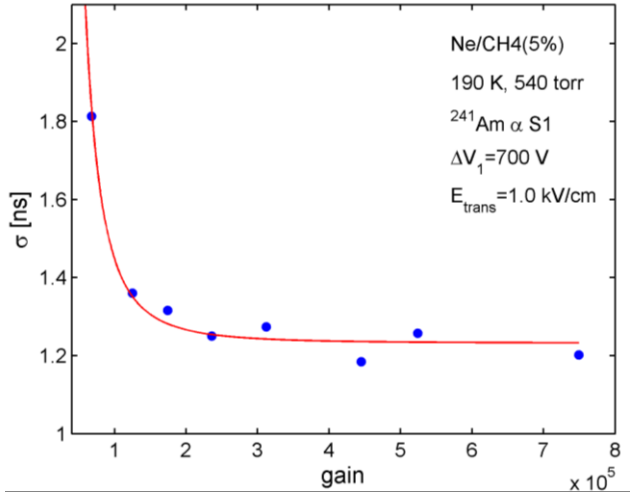
Time resolution

GPM signal lags by ~200 ns after PMT



But with only ~1.2 ns jitter!

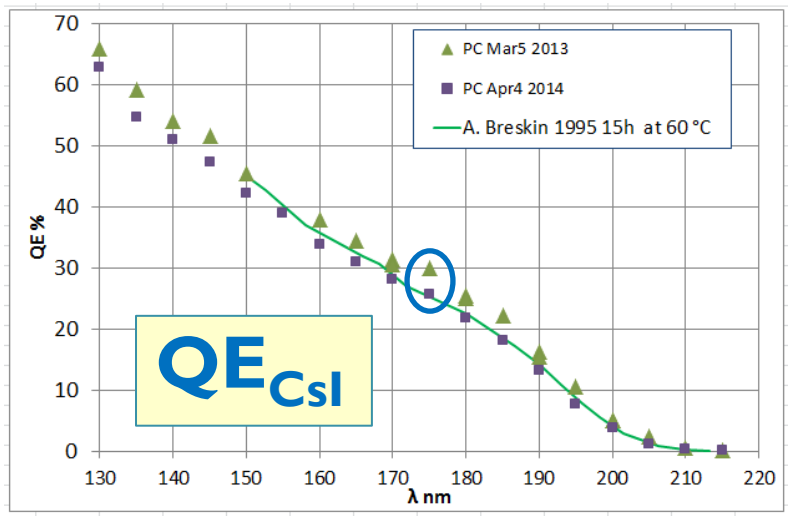


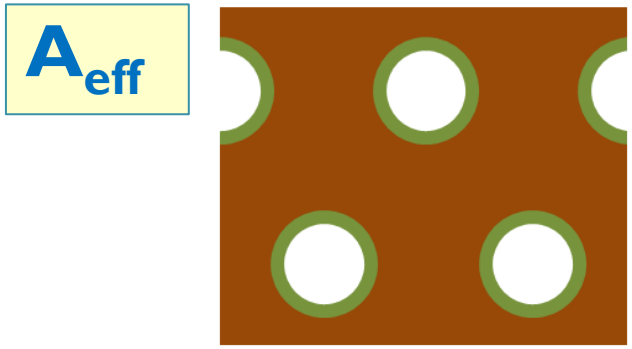


Overall QE and expected PDE (top array)

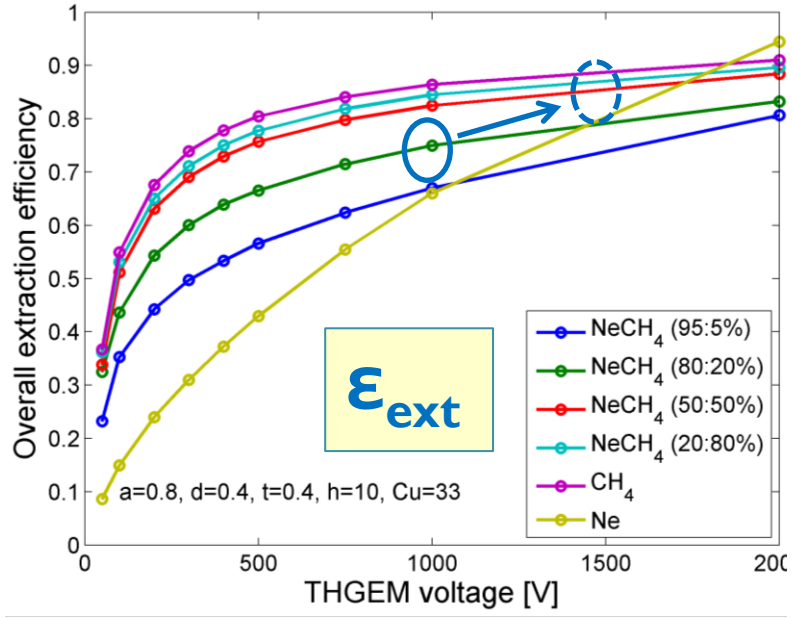
$$QE_{eff} = QE_{CsI} \times A_{eff} \times \varepsilon_{ext} \times \varepsilon_{col}$$

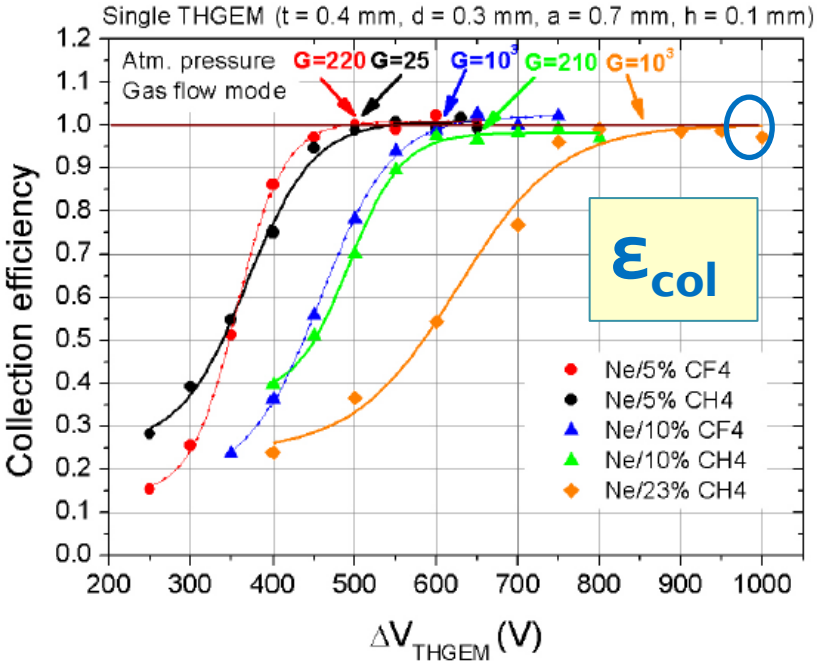
- QE_{eff} : probability to get a photoelectron into a THGEM hole per photon passing the window
- QE_{CsI} : intrinsic CsI QE (at LXe temp)
- A_{eff} : fraction of detector area covered with CsI
- ε_{ext} : extraction efficiency – the probability that a photoelectron will not be **backscattered** to the CsI
- ε_{col} : collection efficiency – the probability that an extracted photoelectron will be pulled to a THGEM hole





Now 0.77
Can be optimized to >0.85



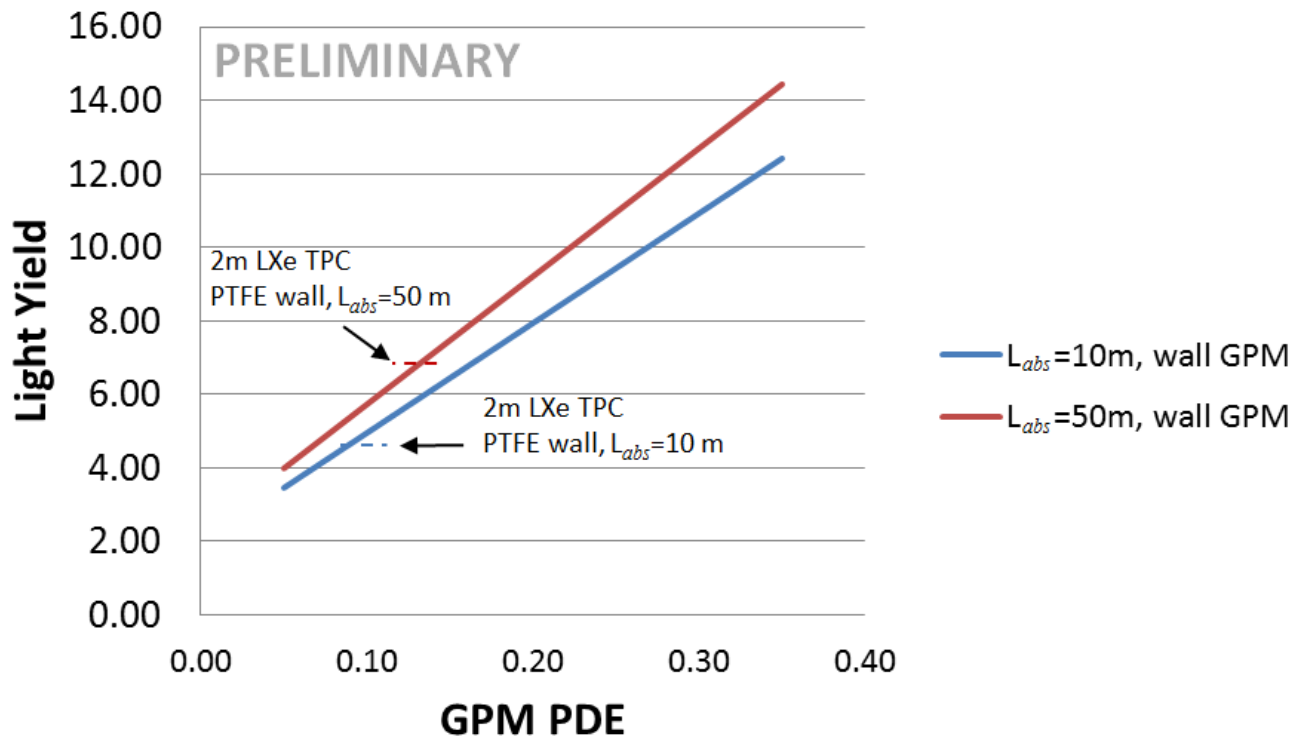


QE/PDE of top GPM array - bottom (optimistic) line

$$QE_{eff} = QE_{CsI} \times A_{eff} \times \varepsilon_{ext} \times \varepsilon_{col}$$
$$\sim 0.25 \times 0.85 \times 0.85 \times 1 = 0.18$$

- Including window transmission (0.9) and probability for signal above noise (~ 0.95) **we expect PDE≈0.15**
- With a filling factor of 0.9-0.95 the overall PDE is expected to be ~ 0.14
- PMTs: for QE=0.36, collection efficiency 0.9 and filling factor 0.5 → PDE = 0.16
- For wall GPM we expect PDE > 0.2

Light Yield with 4π coverage (wall GPM)



- DARWIN-like 2m LXe TPC with wall GPMs & 90% transparent field cage
- Top & bottom arrays: PMTs (QE=36%, CE=90%, filling factor=55%), or GPMs with equivalent overall PDE; XENON1t-like meshes

LIQUID HOLE MULTIPLIERS

BIGGER IS BETTER?

- S2/S1 discrimination in XENON100 and LUX – fantastic!
- Will it work on a few-meter diameter TPC?
- Grids and liquid surface must be **parallel everywhere at all times**

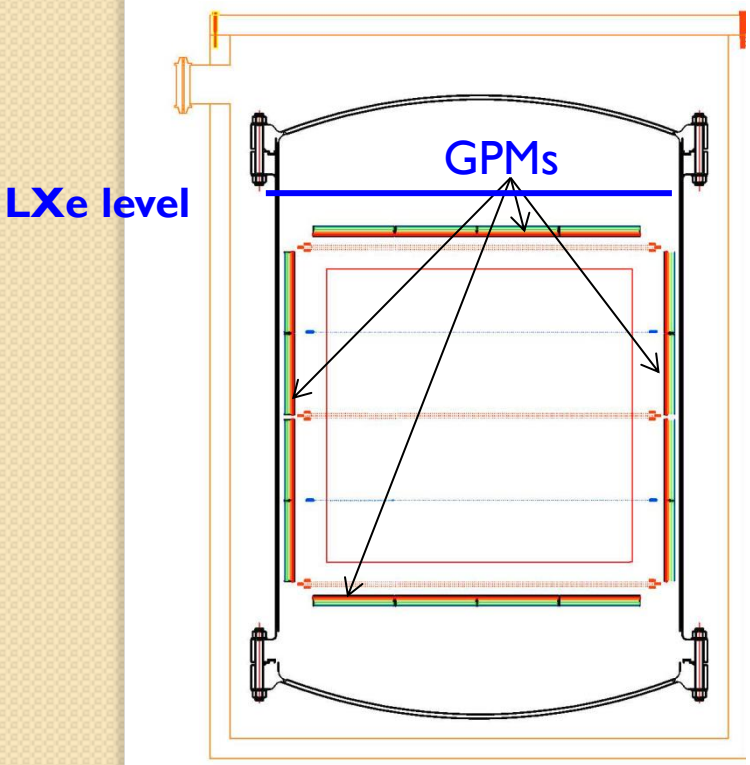
$$S_2 \sim N_{e^-} E_{gas} d_{gas}$$

- Concerns: tilt, ripples, grid deformation, level variations with conditions

  → ***loss of S_2 resolution*** → loss of discrimination power!

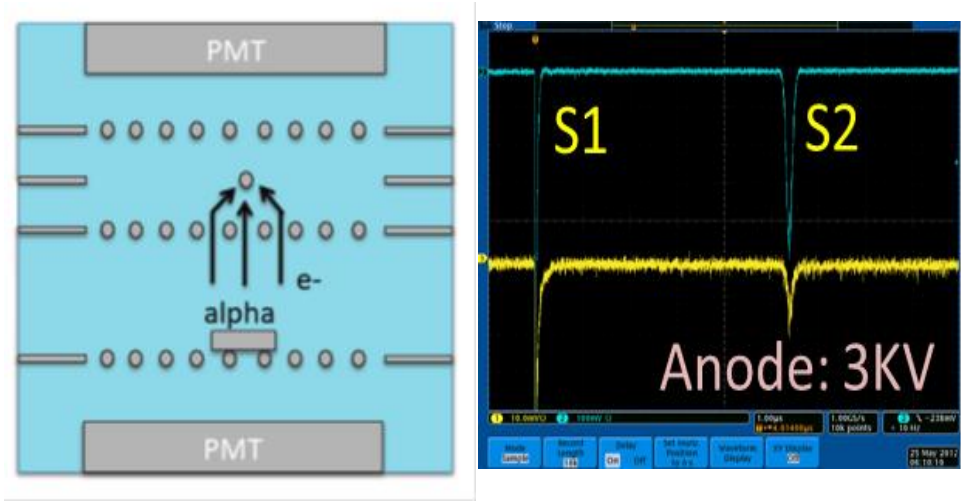
Can one have S_1+S_2 in ***single phase*** liquid-only TPC?

4π geometry with immersed GPMs



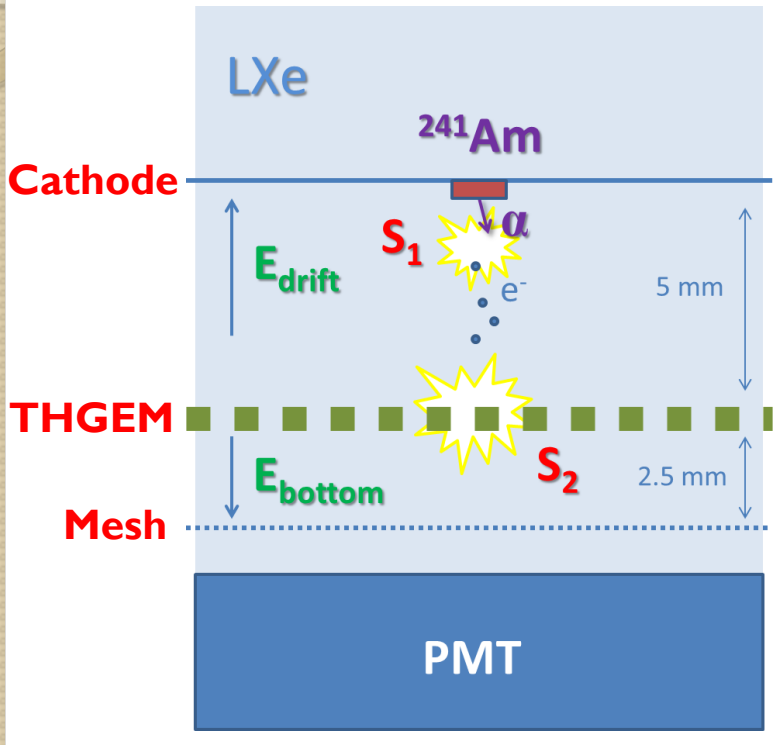
K. Giboni 2011
2014 *JINST* **9** C02021, 2014 *JINST* **9** P12007

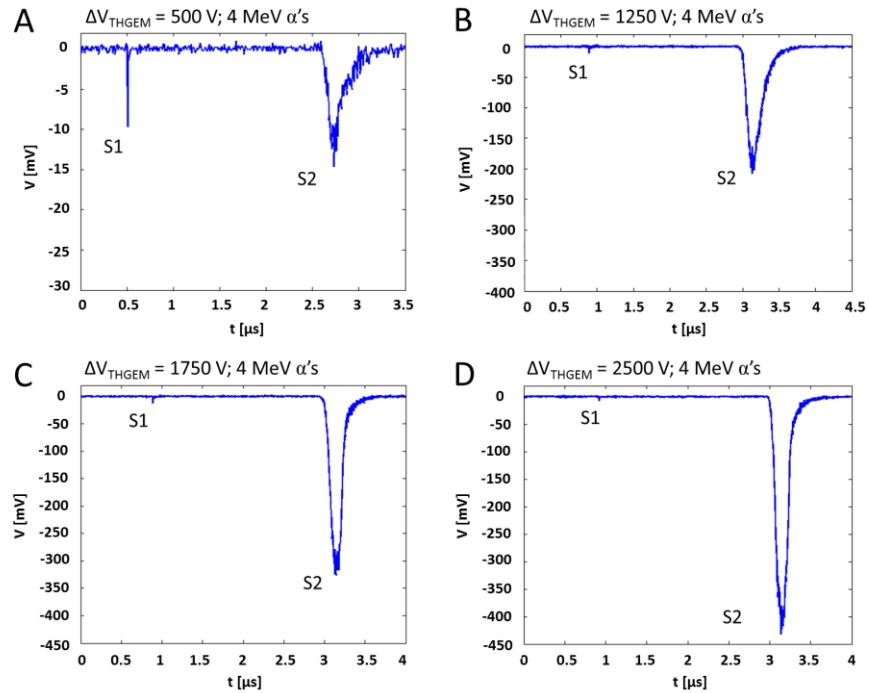
E. Aprile *et al*; 2014 *JINST* **9** P11012



Recent alpha-induced scintillation S1 and S2 electroluminescence signals recorded from a 10 micron diameter wire in LXe.

Can we generate S2 in the holes of an immersed THGEM?

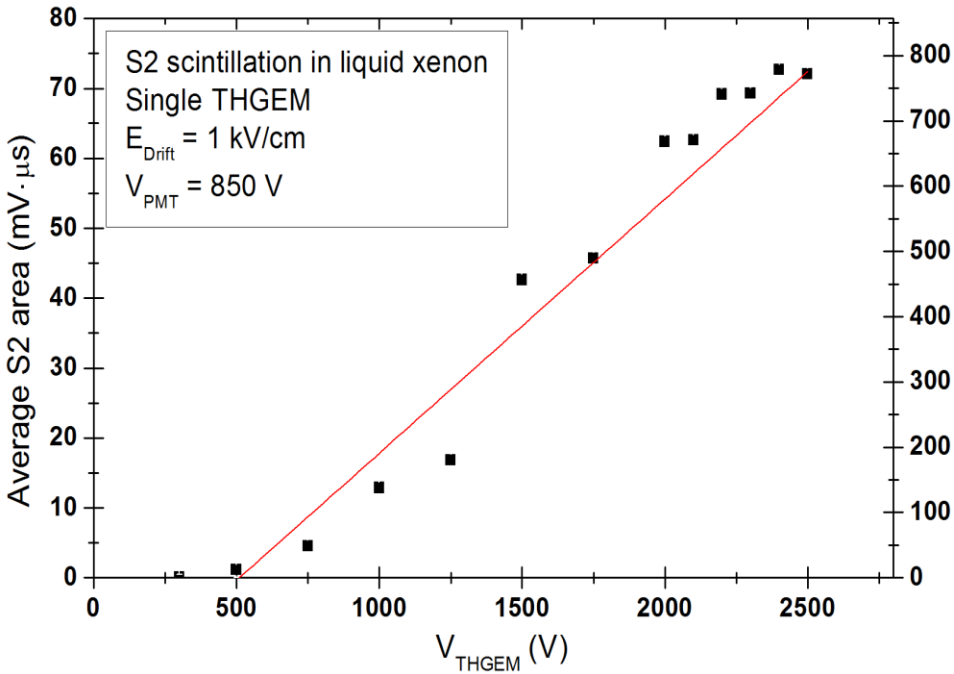




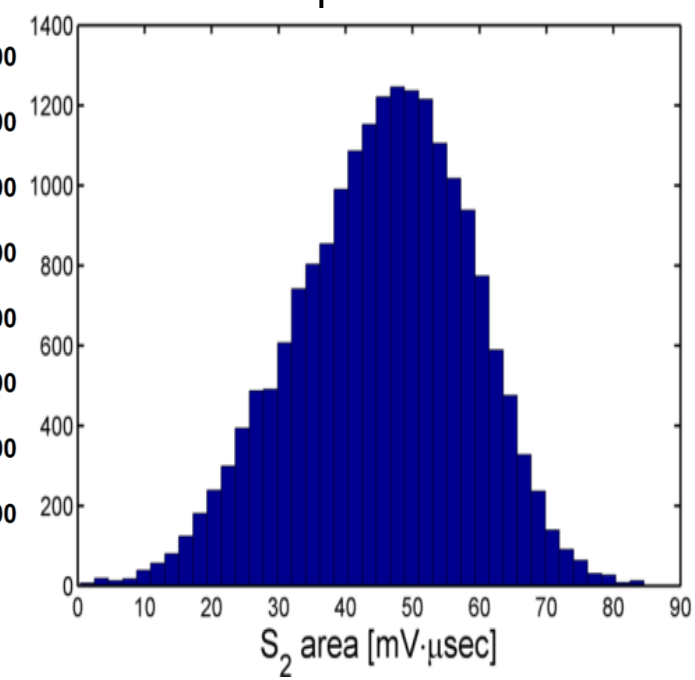
YES WE CAN!

Arazi *et al* 2013 *JINST* **8** C12004

Too good to be true?



S2 spectrum

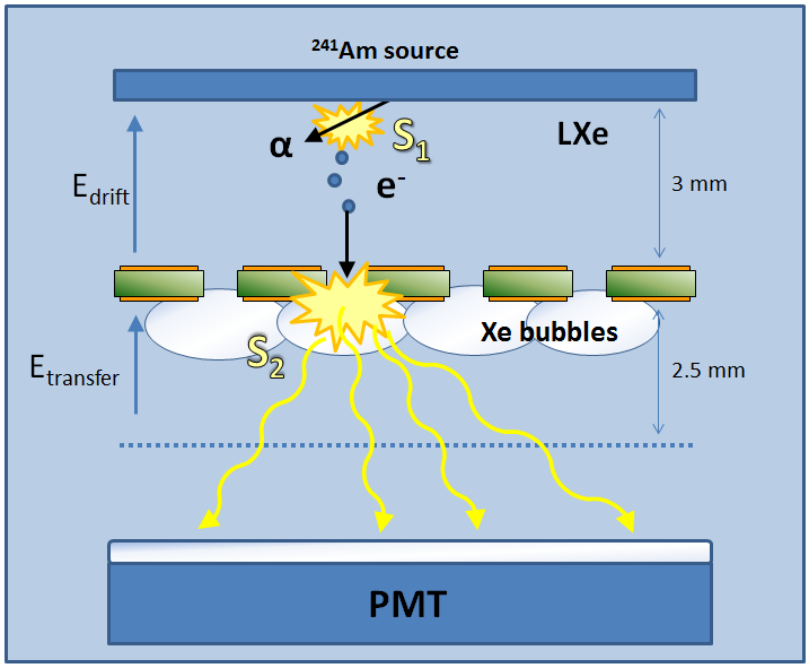


- Photon yield: ~600 photons/e in THGEM hole at ~30 kV/cm
- S2 onset: few kV/cm

Arazi *et al* 2013 *JINST* **8** C12004

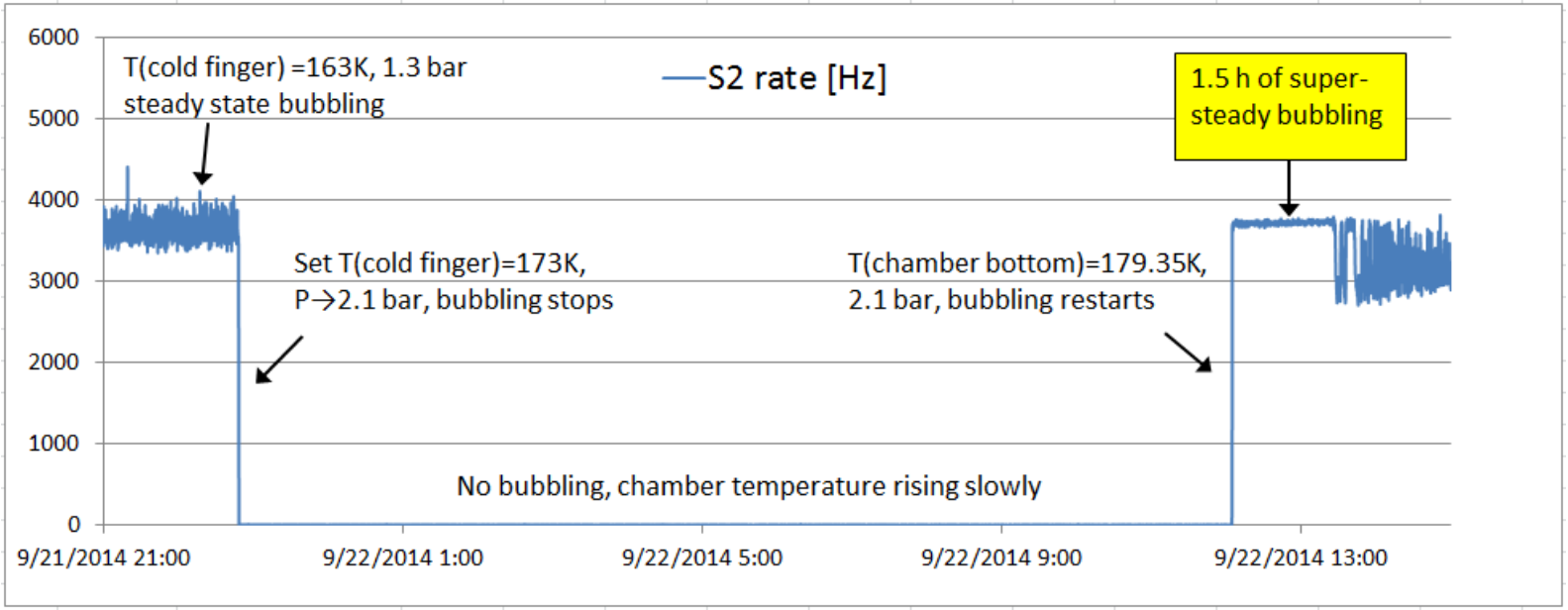
Our present understanding: a "Bubble Chamber"

- **S2 signals already at few kV/cm** *(as in Xe gas)*
- **S2 responds to pressure:**
  - Disappears after step increase in pressure *(bubbles collapse)*
  - Reappears when decreasing pressure *(bubbles form again)*



Hypothesis:
S2 produced in gas bubbles trapped under the THGEM

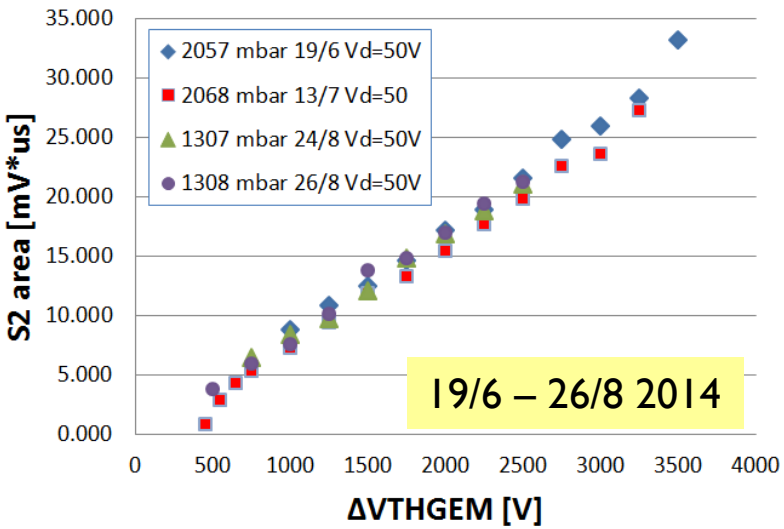
Bubbles formation



Near future : controlled bubbling by carefully-adjusted heating → high resolution

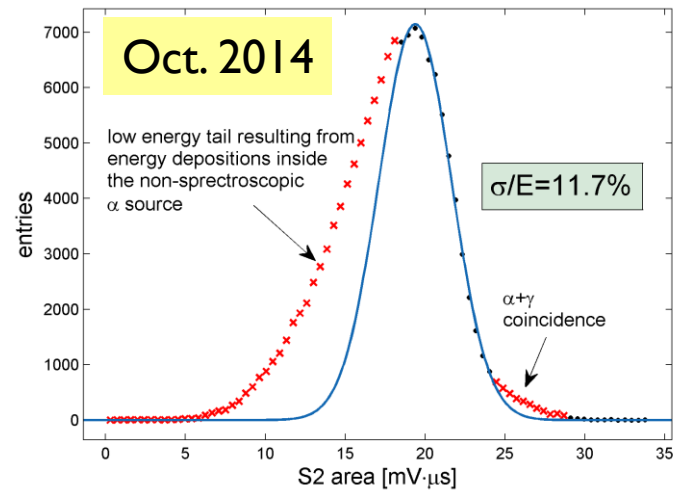
S2 generation in bubbles is surprisingly steady

Repeatable S2 yields over many weeks



Several tens of photons/e- @ 3kV

Energy resolution with non-spectroscopic alpha source

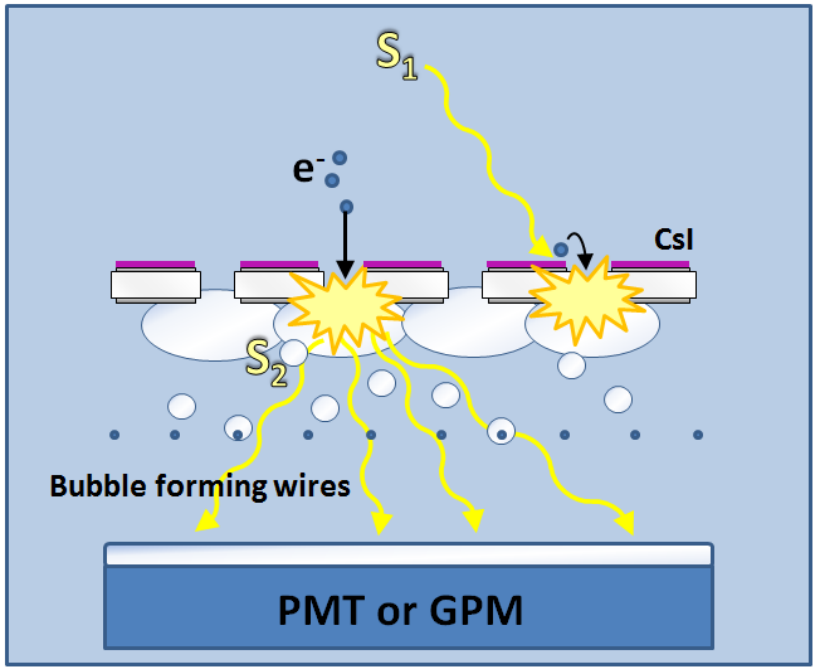


Resolution ~ 12%
Getting close to XENON100 with PMTs

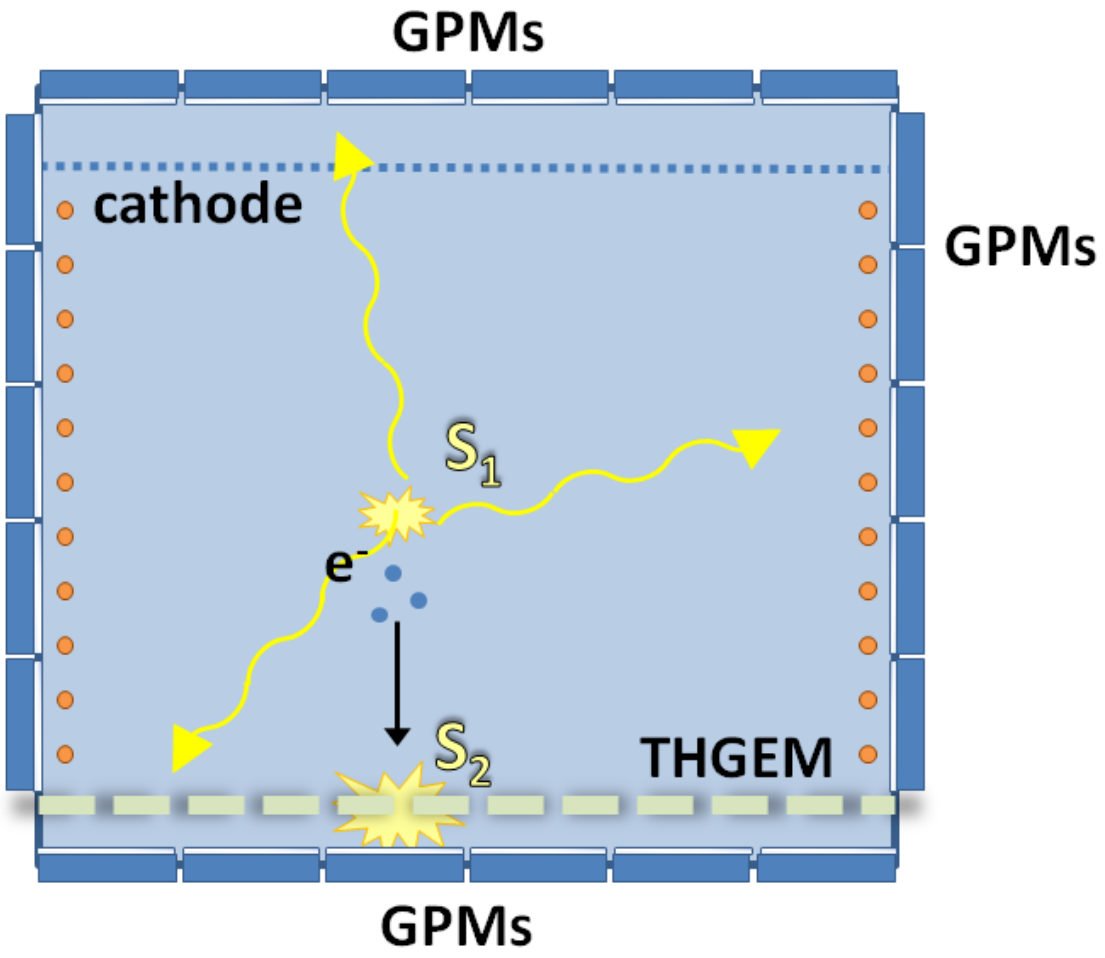
Stability + controlled effect + resolution + low-field operation
➔ should be exploited towards single-phase noble-liquid DM detectors!

Proposed Implementation in single-phase TPC

- THGEM top coated with CsI
- **Resistive wires underneath, to form bubbles in controlled way**
- **S1** photoelectrons & **S2** electrons focused into holes, inducing electroluminescence in bubbles
- If THGEM field too low – replace by GEM, or GEM+CsI followed by THGEM



Maybe something like this?



Summary

- Future large scale dark matter experiments call for new solutions
- Gaseous detectors *raison d'être:* **affordable large-area coverage**
- 4π coverage by GPMs → **large improvement in sensitivity** for low-mass WIMPs
- Top-array GPMs will have **10-fold better position resolution** → better calibration, background estimation and rejection?
- In-house assembly → **significant reduction in cost** compared to PMTs
- First results with 4" GPM (top array): **large dynamic range, good stability, energy and temporal resolution**; **overall PDE close to PMTs**
- **R&D on wall GPM underway**
- LHMs: for now a curiosity, but may open new options for multi-ton experiments