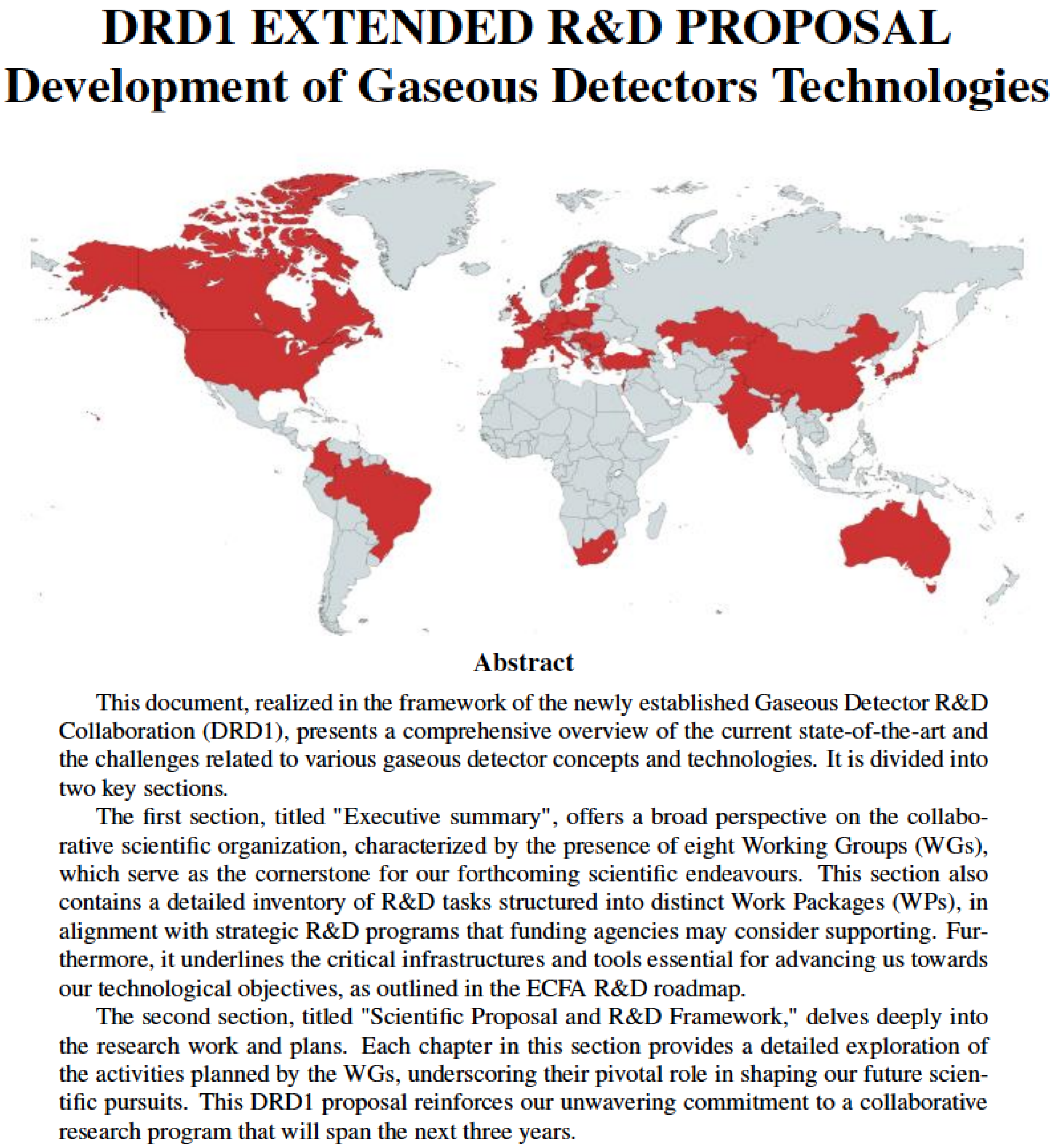
# The future of TPC R&D

talk focused on readout structures!
(biased but hopefully representative)

D. González-Díaz
(30-1-2024)

DRD1 meeting

IGFAE
Instituto Galego de Física de Altas Enerxías



# DRD1 EXTENDED R&D PROPOSAL
# Development of Gaseous Detectors Technologies

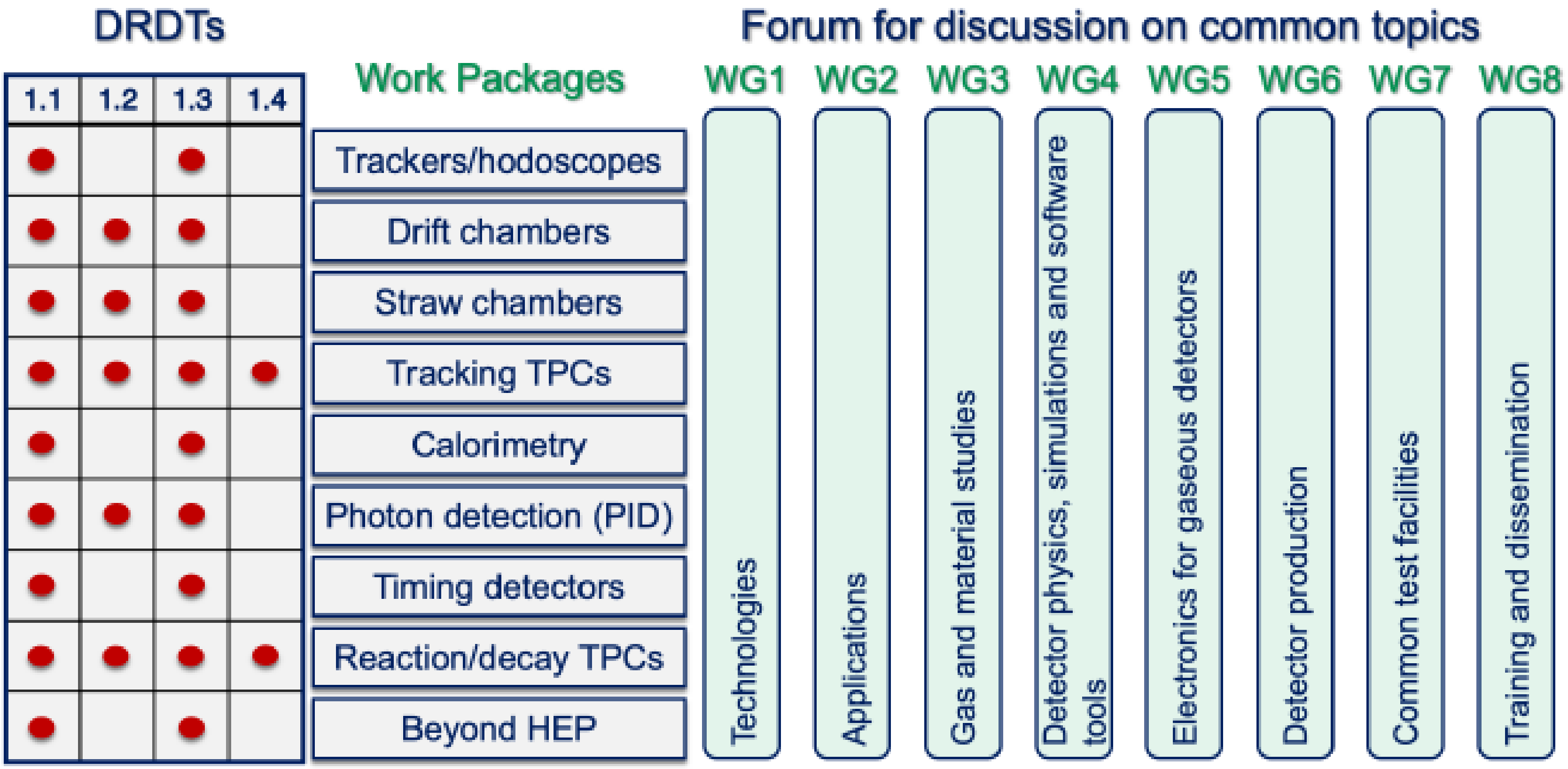
## Abstract

This document, realized in the framework of the newly established Gaseous Detector R&D Collaboration (DRD1), presents a comprehensive overview of the current state-of-the-art and the challenges related to various gaseous detector concepts and technologies. It is divided into two key sections.

The first section, titled "Executive summary", offers a broad perspective on the collaborative scientific organization, characterized by the presence of eight Working Groups (WGs), which serve as the cornerstone for our forthcoming scientific endeavours. This section also contains a detailed inventory of R&D tasks structured into distinct Work Packages (WPs), in alignment with strategic R&D programs that funding agencies may consider supporting. Furthermore, it underlines the critical infrastructures and tools essential for advancing us towards our technological objectives, as outlined in the ECFA R&D roadmap.

The second section, titled "Scientific Proposal and R&D Framework," delves deeply into the research work and plans. Each chapter in this section provides a detailed exploration of the activities planned by the WGs, underscoring their pivotal role in shaping our future scientific pursuits. This DRD1 proposal reinforces our unwavering commitment to a collaborative research program that will span the next three years.

# DRD1 STRUCTURE



DRDTs

| 1.1 | 1.2 | 1.3 | 1.4 | Work Packages |
|---|---|---|---|---|
| ● | | ● | | Trackers/hodoscopes |
| ● | ● | ● | | Drift chambers |
| ● | ● | ● | | Straw chambers |
| ● | ● | ● | ● | Tracking TPCs |
| ● | | ● | | Calorimetry |
| ● | ● | ● | | Photon detection (PID) |
| ● | | ● | | Timing detectors |
| ● | ● | ● | ● | Reaction/decay TPCs |
| ● | | ● | | Beyond HEP |

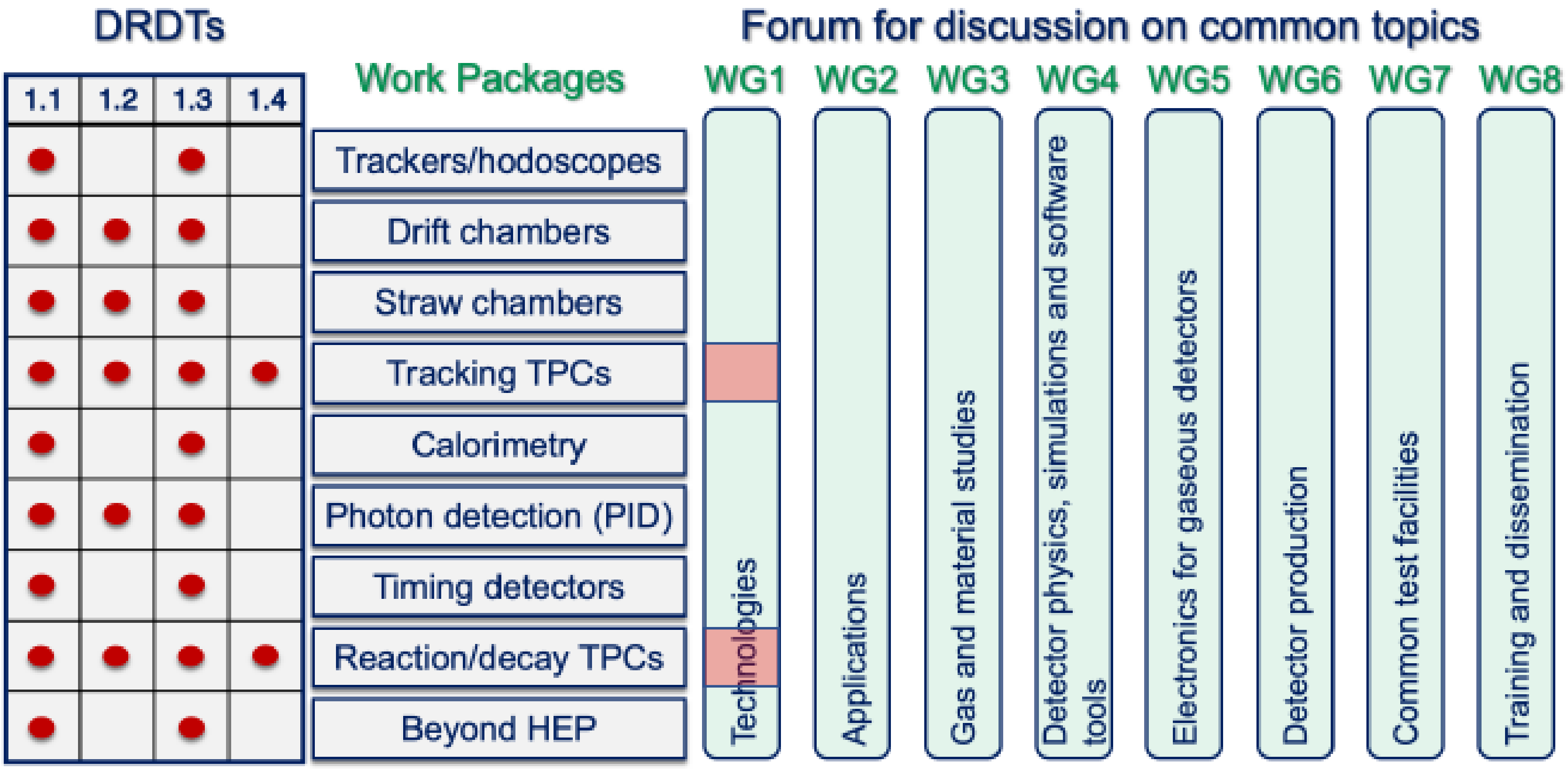
Forum for discussion on common topics

| WG1 | WG2 | WG3 | WG4 | WG5 | WG6 | WG7 | WG8 |
|---|---|---|---|---|---|---|---|
| Technologies | Applications | Gas and material studies | Detector physics, simulations and software tools | Electronics for gaseous detectors | Detector production | Common test facilities | Training and dissemination |

Figure 2: DRD1 Scientific Organization

# DRD1 STRUCTURE

72 intersections



DRDTs

Work Packages

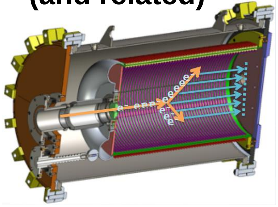
| Work Packages | 1.1 | 1.2 | 1.3 | 1.4 |
|---|---|---|---|---|
| Trackers/hodoscopes | ● |  | ● |  |
| Drift chambers | ● | ● | ● |  |
| Straw chambers | ● | ● | ● |  |
| Tracking TPCs | ● | ● | ● | ● |
| Calorimetry | ● |  | ● |  |
| Photon detection (PID) | ● | ● | ● |  |
| Timing detectors | ● |  | ● |  |
| Reaction/decay TPCs | ● | ● | ● | ● |
| Beyond HEP | ● |  | ● |  |

Forum for discussion on common topics

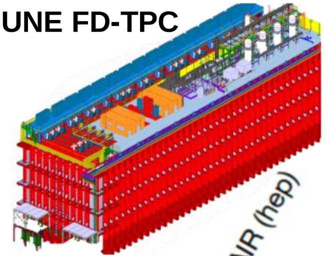
- WG1 Technologies
- WG2 Applications
- WG3 Gas and material studies
- WG4 Detector physics, simulations and software tools
- WG5 Electronics for gaseous detectors
- WG6 Detector production
- WG7 Common test facilities
- WG8 Training and dissemination

Figure 2: DRD1 Scientific Organization

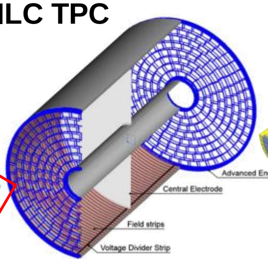
**AT-TPC (and related)**



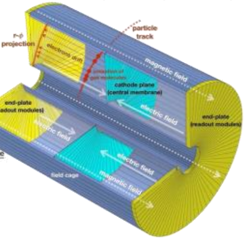
**DUNE FD-TPC**



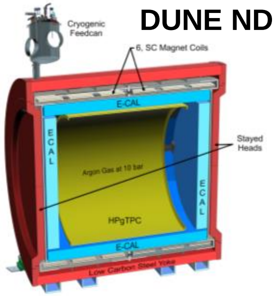
**ILC TPC**



**CEPC TPC**



**DUNE NDGAr**

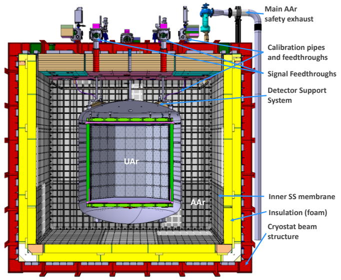


*accelerator*

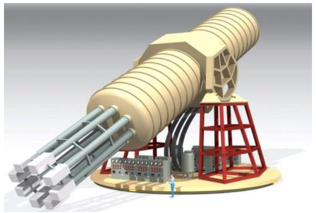
AT-TPC*
SPS fixed target
Other fixed target, FAIR (hep)
Belle II
ALICE LS3
PIP-II/LBNF/DUNE/Hyper-K
ALICE 3
LHCb (≥ LS4)
EIC
LHeC
ILC & CEPC*
DUNE-NDGAr*
FCC-ee
CLIC
FCC-hh
FCC-eh
Muon Collider

| < 2030 | 2030-2035 | 2035-2040 | 2040-2045 | > 2045 |
|---|---|---|---|---|

*ECFA roadmap* (*In grey: added)



**DARKSIDE-20**



**IAXO**

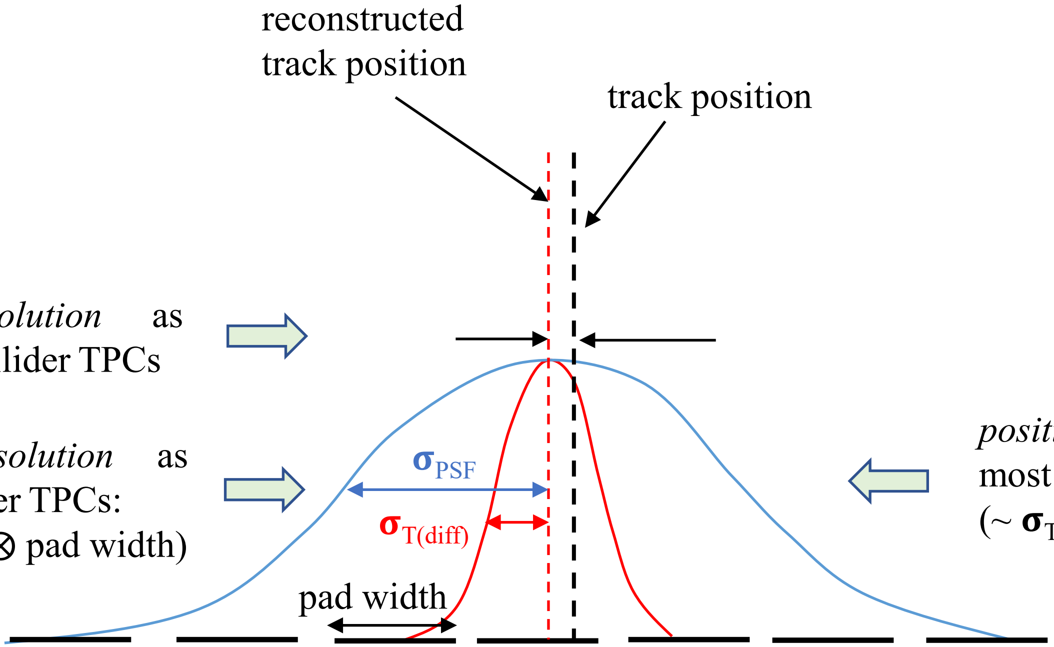
*non-accelerator*

Neutrino Telescopes (km$^3$)
Axions, ALPs, Dark Matter (DM)
Light DM Detectors
Multi-tonne Scale DM Detectors
Tonne Scale 0nbb
100 m Atom Interferometry
Mu3e Phase II / COMET Phase II
Future Muegamma Experiment
Neutrino Telescopes (km$^3$)
Axions, ALPs, DM
Light DM Detectors
Hundred-tonne Scale DM detectors
Tonne-Scale 0nbb
Proof of Principle Quantum Sensor HE
Dark Radiation
Km Scale Atom Interferometry
Future Mu3e Experiment
Neutrino Telescopes (km$^3$)
Light DM Detectors
Hundred-tonne Scale DM Detectors
Multi-tonne Scale 0nbb
Prototype Quantum Sensor HEP Detectors
Large Scale Quantum Sensor Networks
Space-based Quantum Sensors
Big Bang (CNB) Detectors
Space-based Quantum Sensor Networks
Functional Quantum Sensor HEP Detectors
PRISM

| < 2025 | 2025-2030 | 2030-2035 | > 2035 |
|---|---|---|---|

**"Technical" Start Date of Facility**
(This means, where the dates are not known, the earliest technically feasible start date is indicated - such that detector R&D readiness is not the delaying factor)

# Quick note (please bear with me)



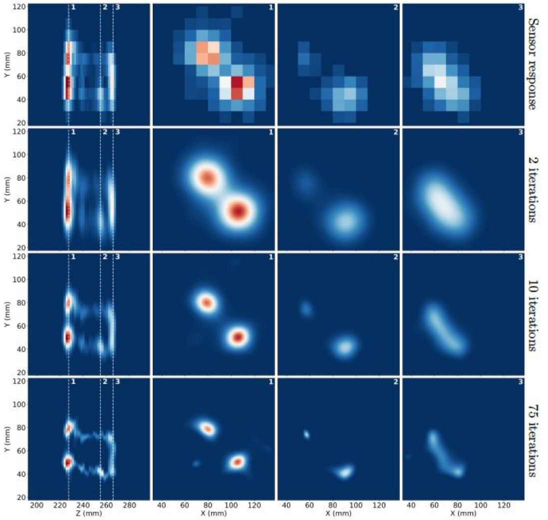
*position resolution* as defined for collider TPCs

*2-hit/2-track resolution* as defined for collider TPCs:
(~ $\boldsymbol{\sigma}_{\mathrm{T(diff)}} \otimes \boldsymbol{\sigma}_{\mathrm{PSF}} \otimes$ pad width)

*position resolution* outside most collider TPCs:
(~ $\boldsymbol{\sigma}_{\mathrm{T(diff)}} \otimes \boldsymbol{\sigma}_{\mathrm{PSF}} \otimes$ pad width)

raw

after deconvolution



the extent to which this can be deconvoluted in an actual experiment is far from understood (a lot of potential!)

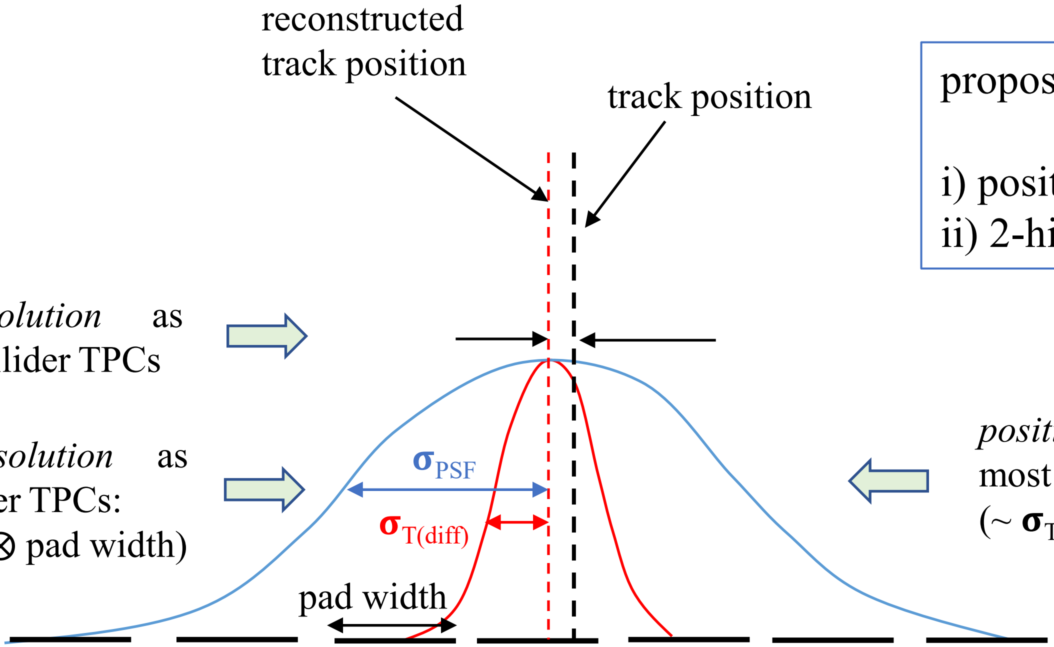
**A. Simón, arXiv: 2102.11931**

# Quick note (please bear with me)

sorting this out will help greatly (and quickly)!

proposal, try to stick to these two:

i) position resolution
ii) 2-hit resolution



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raw

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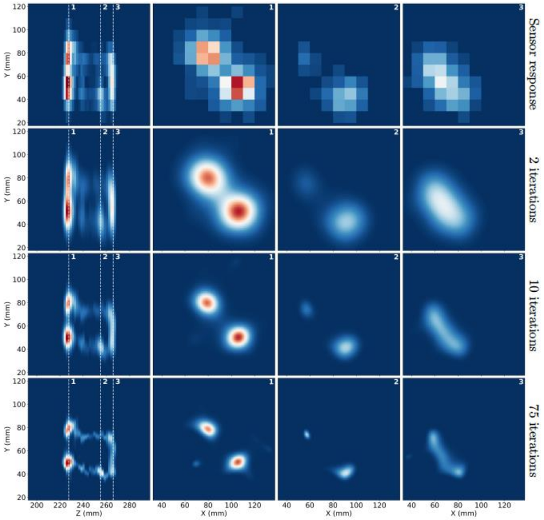

A. Simón, arXiv: 2102.11931

arXiv: 2003.01116

# Collider-type TPCs (tracking)

## ILC/CEPC TPC

| Parameter | | |
|---|---|---|
| Geometrical parameters | $r_{\mathrm{out}}$<br>~2m | z<br>~2.5 m |
| Solid angle coverage | up to $\cos\theta \simeq 0.98$ (10 pad rows) | |
| TPC material budget | $\simeq 0.05\ \mathrm{X}_0$ including outer fieldcage in $r$<br>$< 0.25\ \mathrm{X}_0$ for readout endcaps in $z$ | |
| $\sigma_{\mathrm{point}}$ in $r\phi$ | $\simeq 60\ \mu$m for zero drift, $< 100\ \mu$m overall | |
| $\sigma_{\mathrm{point}}$ in $rz$ | $\simeq 0.4 - 1.4$ mm (for zero – full drift) | |
| 2-hit resolution in $r\phi$ | $\simeq 2$ mm | |
| 2-hit resolution in $rz$ | $\simeq 6$ mm | |
| dE/dx resolution | $\simeq 5$ % | |
| Momentum resolution at B=3.5 T | $\delta(1/p_t) \simeq 10^{-4}$/GeV/c (TPC only) | |
| B | $\simeq$ 3.5 T | |
| gain x IBF | $\simeq$ 5 | (distorsions <40um @CEPC) |

arXiv: 2003.01116

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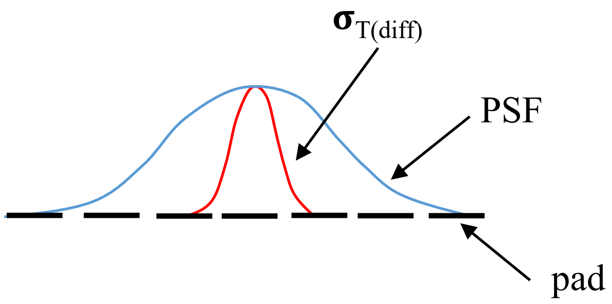


**pads**

Pads can beat the $\Delta x/\sqrt{12}$ resolution limit by a factor of ~x6, at least, by tuning the Point Spread Function (PSF):

- GEMs: adjust the PSF by tuning the distance to the induction plane.
- Micromegas: tune the PSF through resistive coating (AC coupling!).

**pixels**

Limited by diffusion:

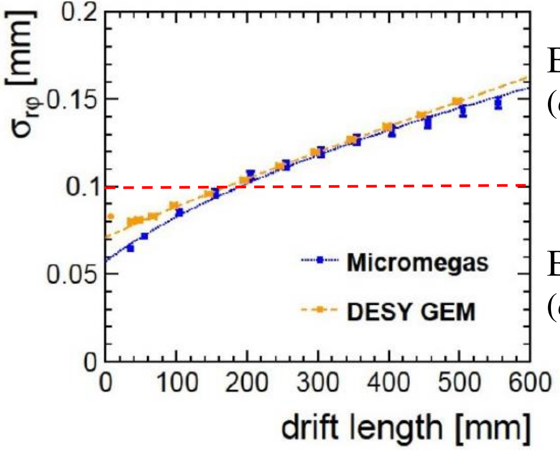
$$\frac{D_T^*(B)}{D_T^*(0)} = \sqrt{1/(1+\omega^2\tau^2)}$$

$$\omega = (q_e/m_e)|B|$$

arXiv: 2003.01116

# Collider-type TPCs (tracking)

1mm (r$\phi$) x 6mm (r) pads



B=1T
($\sigma_T$ = 91um/√cm)

B=3.5T
($\sigma_T$ = 30um/√cm)

## ILC/CEPC TPC

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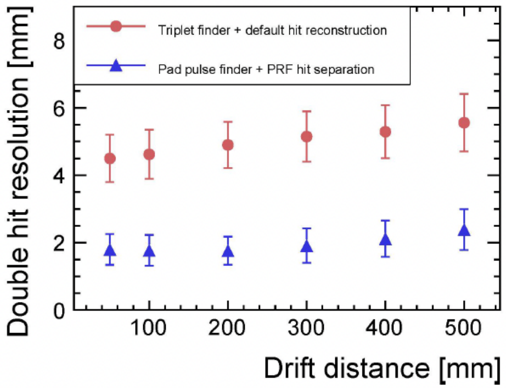
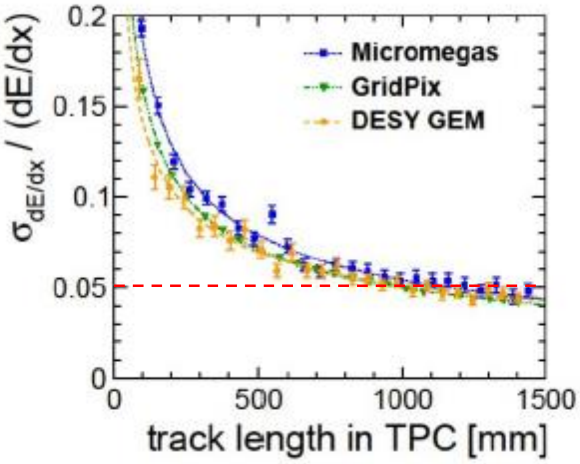




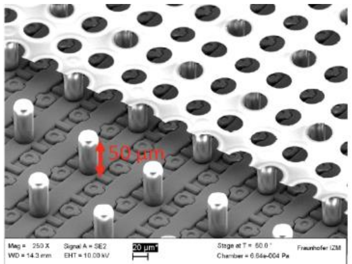
'pads' vs 'pixels'?

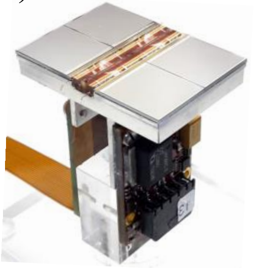
change of paradigm?

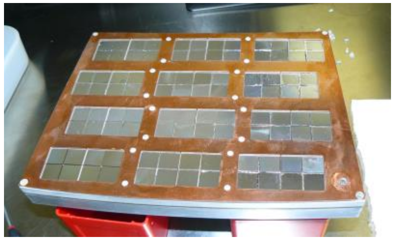
50-200um x 50-200um pixels, GridPix (alternative)

- Much improved 2-hit resolution (down to diffusion limit).
- Improved energy resolution (~electron counting).
- Low gain and low IBF (IBF x gain ~ 2-4).
- Built-in ASIC.

- But… present 50um probably too small (optimization/cost reduction!).



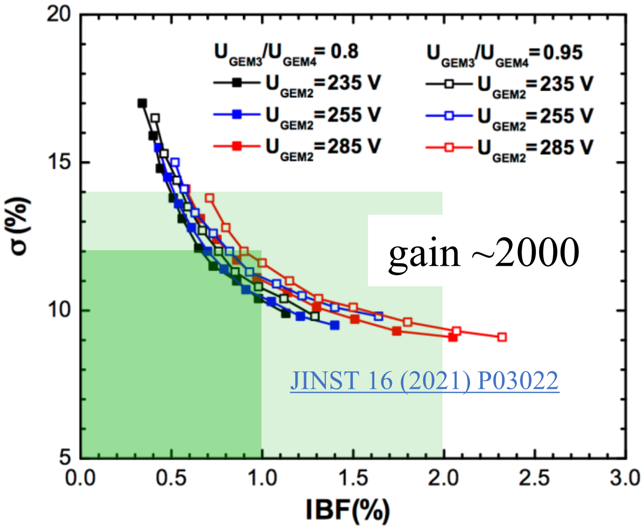




# Collider-type TPCs (ion back-flow)

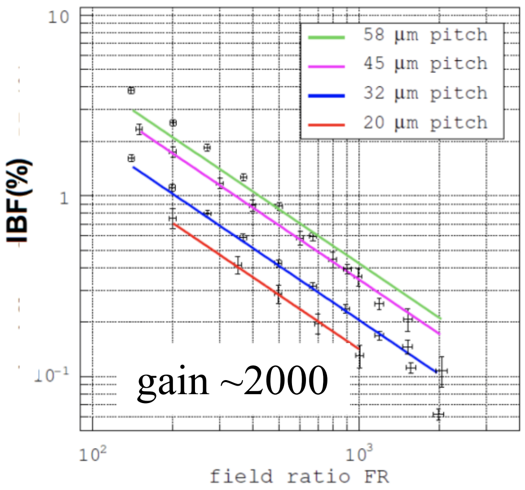
A surprise in 2024: no universal solution to reach the ‘TPC limit’ of IBF x gain ≲1

ALICE 4-GEM (***IBF x G ~ 20***)



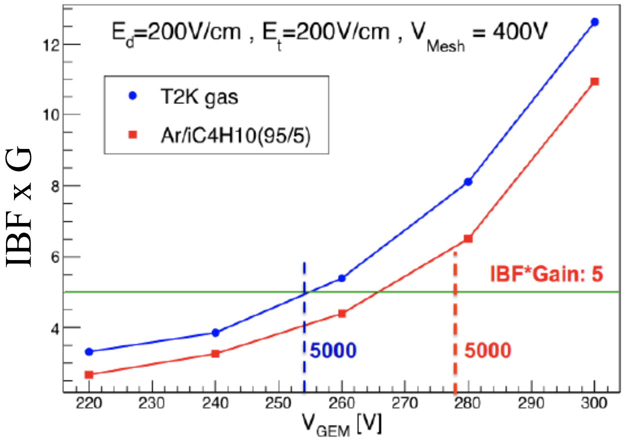
JINST 16 (2021) P03022

GridPix (***IBF x G ~ 2-4***)

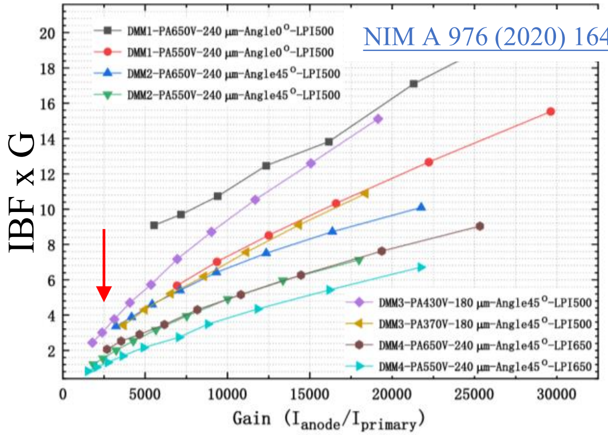


M. Chefdeville, PhD Thesis (2009)

GEM + MM (***IBF x G ~ 5***)

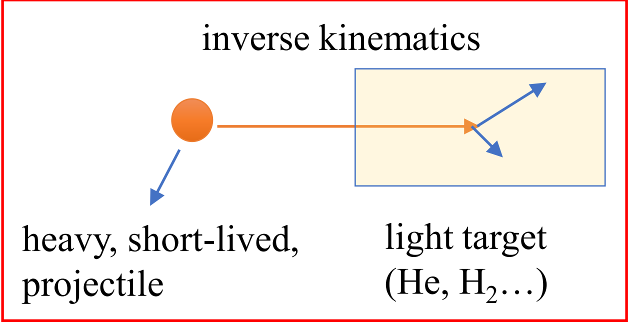


double-mesh (***IBF x G ~ 1-2***)



NIM A 976 (2020) 164282

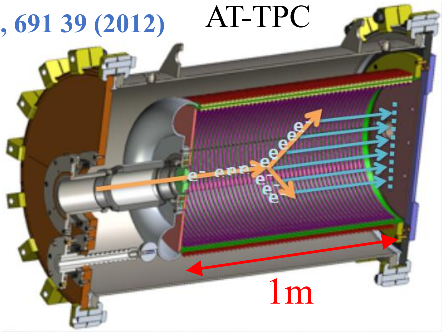
# TPCs for low-energy Nuclear Physics (aims)

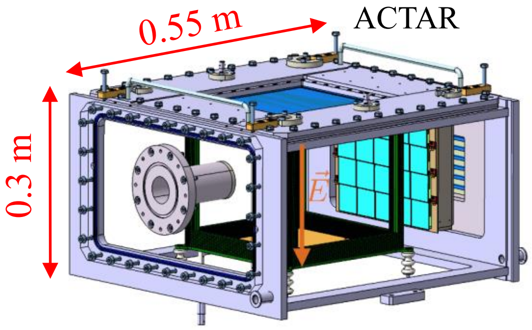

inverse kinematics

heavy, short-lived,
projectile

light target
(He, $H_2$…)

**NIM A, 691 39 (2012)**

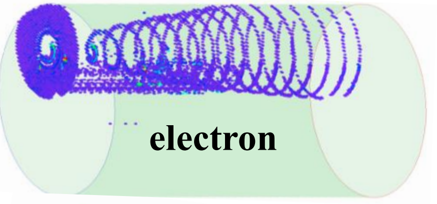

AT-TPC

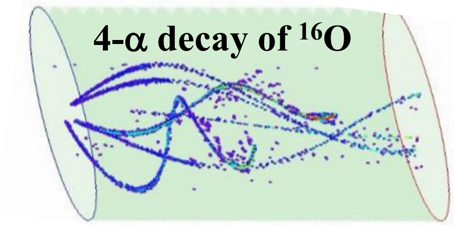


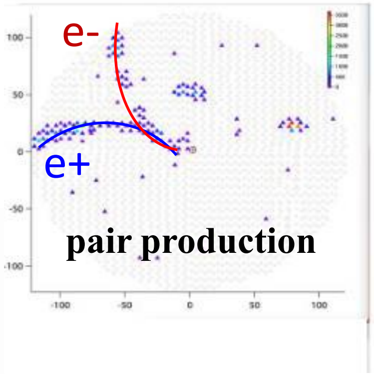
**NIM A 940 (2019), 498-504**

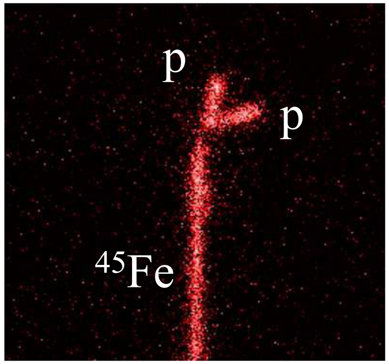
… up to ~5-10 similar facilities

- Study rare nuclei and production of new isotopes.
- $4\pi$-reconstruction of all reaction products (nuclei, p, e+/e-).
- Adjustable target pressure (enables optimization of containment, interaction probability, energy loss).


**electron**

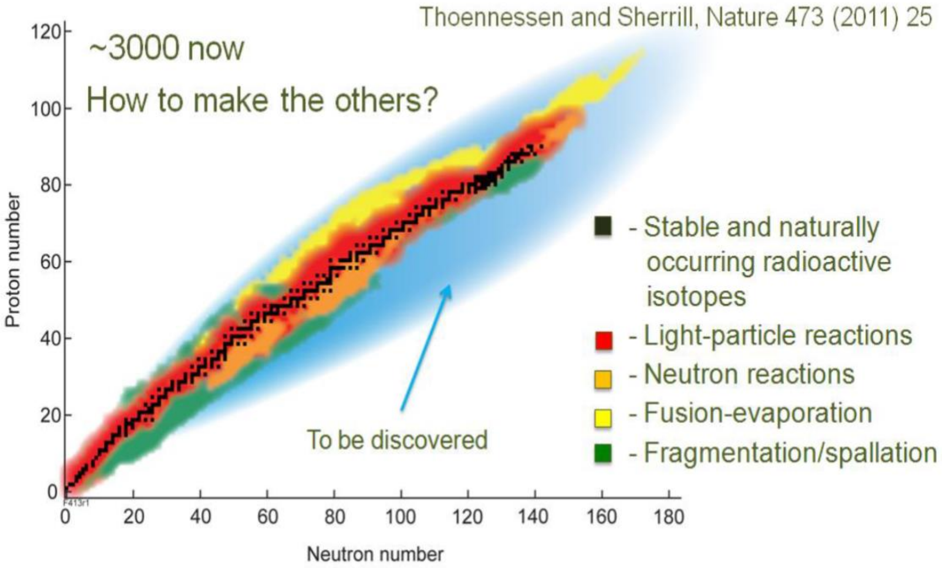

**4-α decay of $^{16}$O**


**pair production**



(gated operation)

a lot to do!

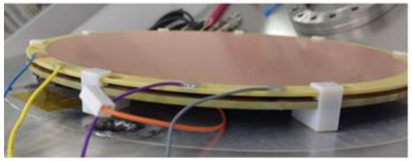

Thoennessen and Sherrill, Nature 473 (2011) 25

~3000 now

How to make the others?

- ■ - Stable and naturally occurring radioactive isotopes
- 🟥 - Light-particle reactions
- 🟧 - Neutron reactions
- 🟨 - Fusion-evaporation
- 🟩 - Fragmentation/spallation

# TPCs for low-energy Nuclear Physics (main assets)

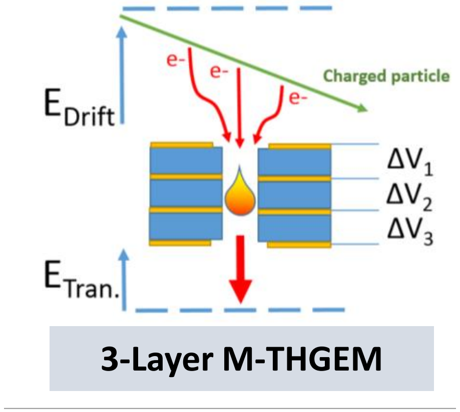


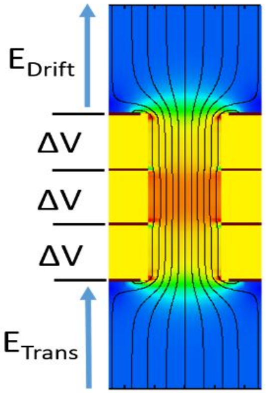
1. Space resolution (‘2-hit separation’) ~ few mm. Fine granularity needed!.

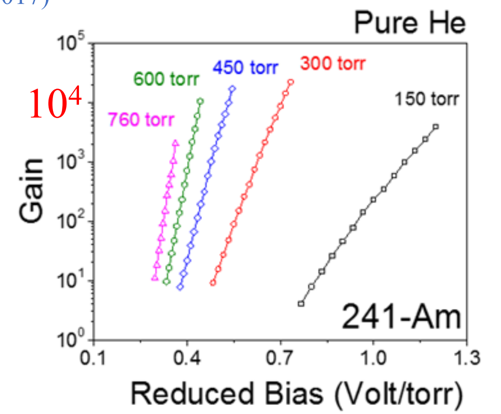
Cortesi et al., Rev. Sci. Ins. 88, 013303 (2017)

2. Avalanche-readout in pure noble gas (He!).

   -> multi-layer THGEM



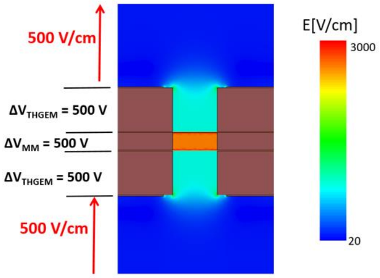


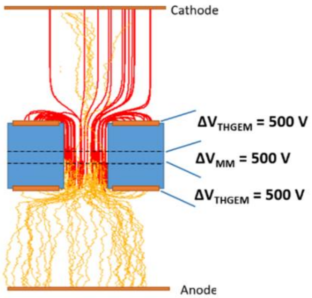


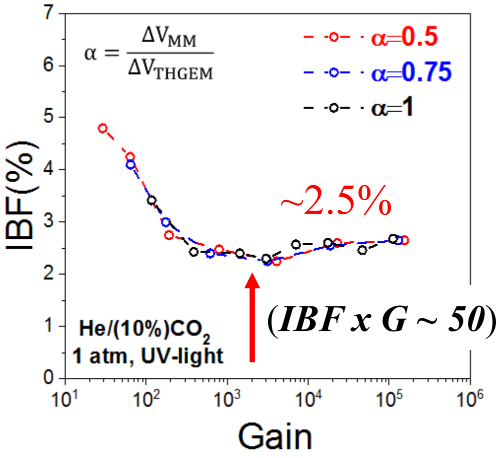
de Oliveira & Cortesi 2018 JINST P06019

3. Operation with low IBF.

   -> multi-mesh THGEM

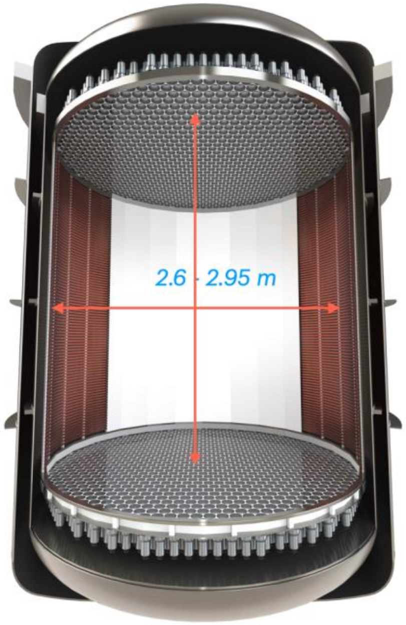






4. Dynamic range
   - Readout electronics (minimize signal saturation and add *more bits*).
   - Stability (e.g., *resistive protection*).
   - Linearity **unsolved** for differences in ionization by factors $10^3 – 10^4$.

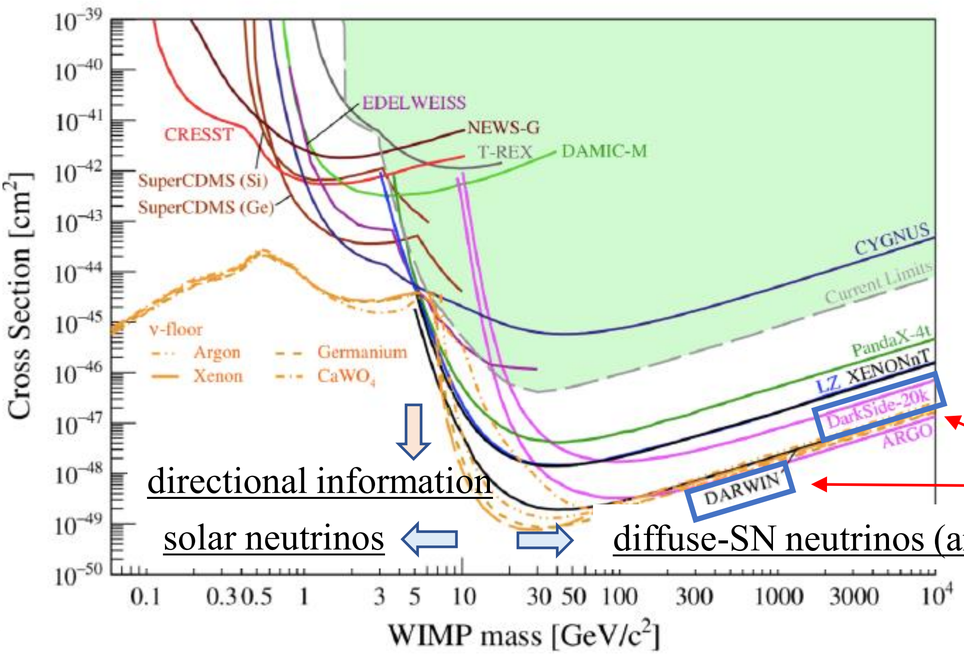
DARWIN (40ton fiduc.)



LZ, PANDAX…

well-understood technologies!

## Dual-phase TPCs

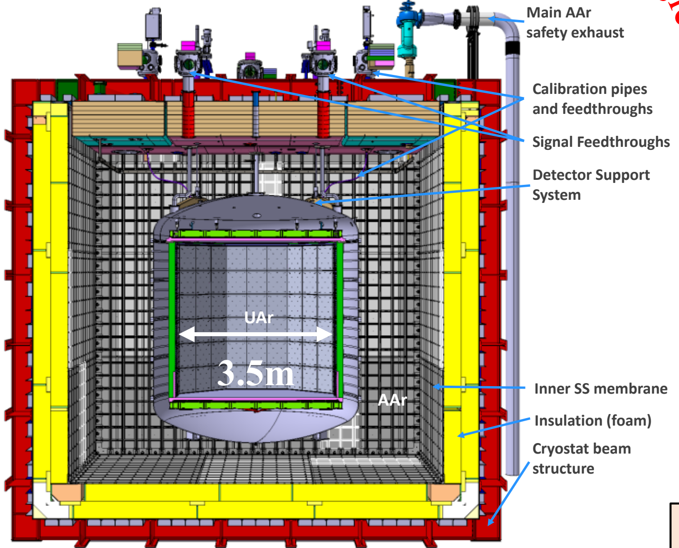


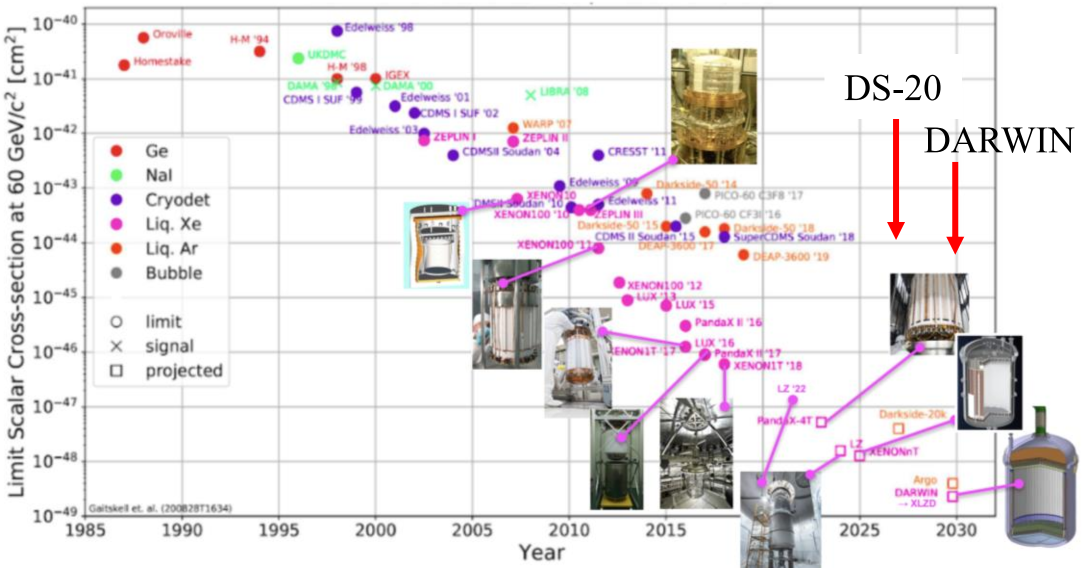
directional information

solar neutrinos

diffuse-SN neutrinos (and atmospheric)

DarkSide20 (20 ton fiduc.)



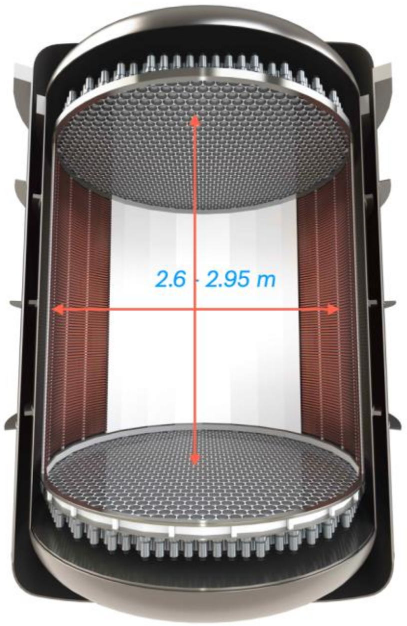


DS-20

DARWIN

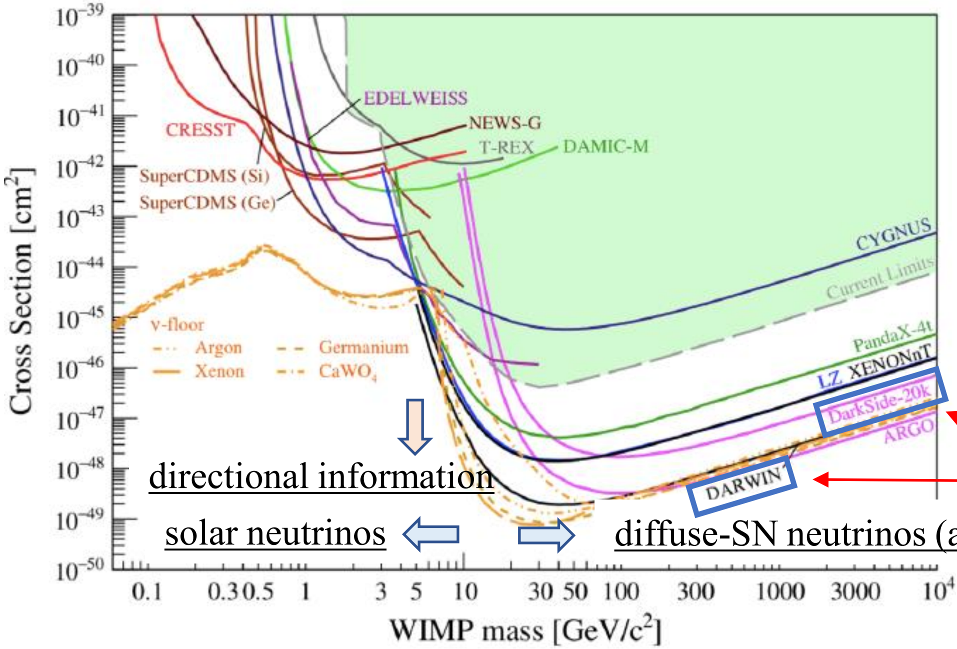
The community will be busy for the next ~10years…

DARWIN (40ton fiduc.)



LZ, PANDAX…

# Dual-phase TPCs



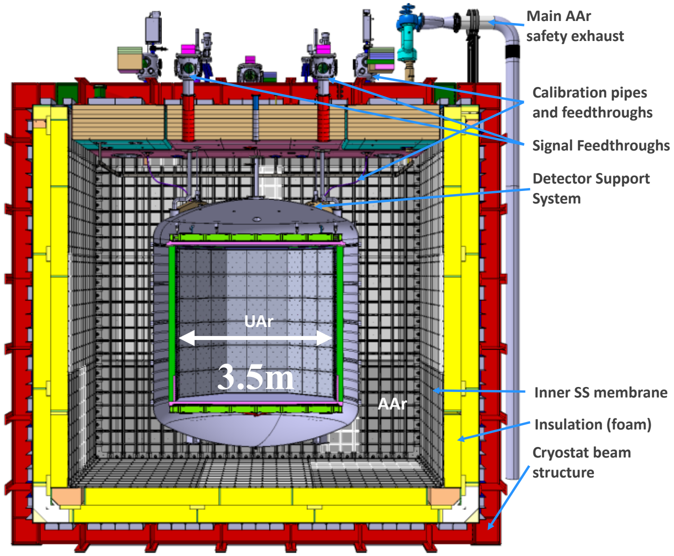
directional information

solar neutrinos

diffuse-SN neutrinos (and atmospheric)

what else could take off at that time scale?

DarkSide20 (20 ton fiduc.)

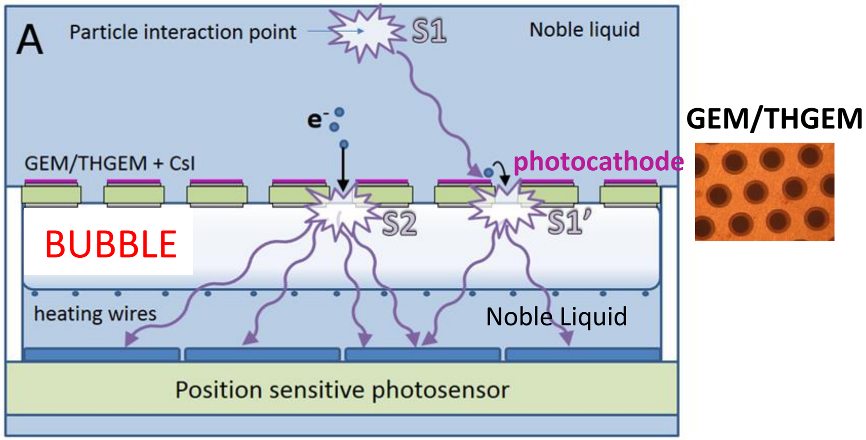


- Improved EL-readouts (scalability, maximum voltage, no sagging).
- Electroluminescence (EL) directly in the liquid.
- Operability at single-electron threshold (background control/mitigation).
- Digital SiPMs? (~individual pixel digitization)
- IR detection and IR photosensors?.
- Cover the barrel with photosensors?
- Improved spatial resolution (combined light/charge readout).
- New Rn mitigation strategies.
- Doping and optical track imaging *(for neutrino physics)*.

# Dual-phase TPCs (improved EL-readouts)

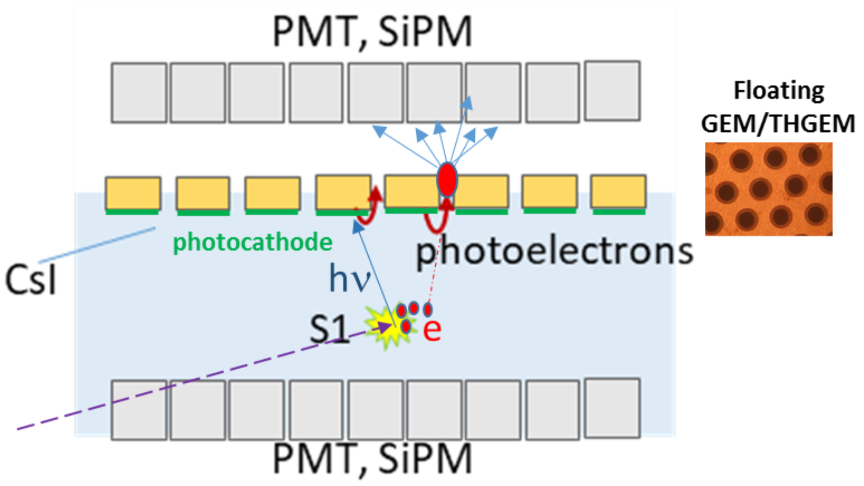
*small-area R&D covered by DRD1!

## Bubble-assisted Liquid Hole Multiplier (LHM)



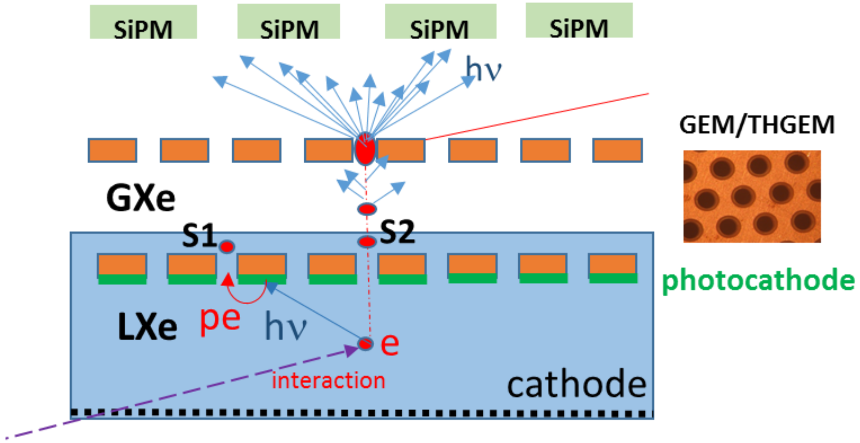
https://doi.org/10.1088/1748-0221/13/12/P12008

## Floating Hole Multiplier (FHM)



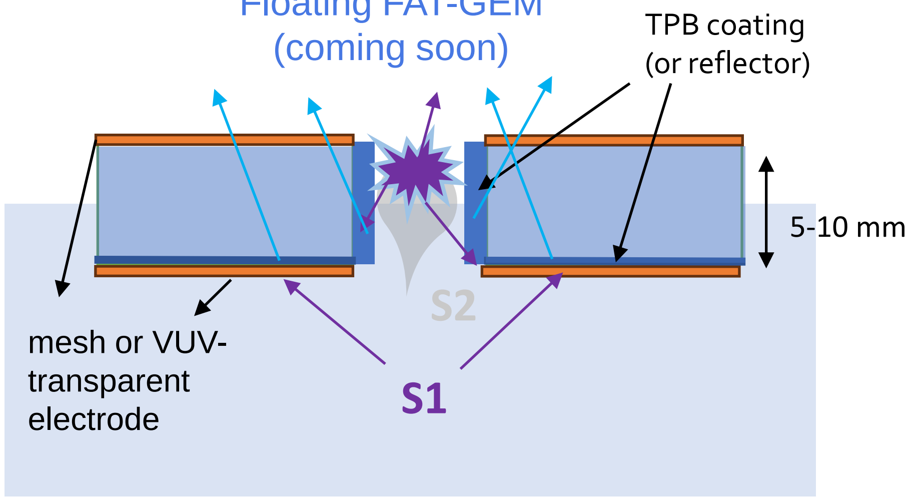
https://doi.org/10.1088/1748-0221/18/05/P05013

## Cascaded Liquid Hole Multiplier (LHM)



https://arxiv.org/abs/2308.08314

## Floating FAT-GEM (coming soon)



https://arxiv.org/abs/1907.03292
https://arxiv.org/abs/2106.03773
https://arxiv.org/abs/2401.09905

arXiv:2207.11127 arXiv:1808.02969

arXiv:1912.10133

arXiv: 2311.09568

# Dual-phase TPCs (charge readout)

*small-area R&D covered by DRD1!

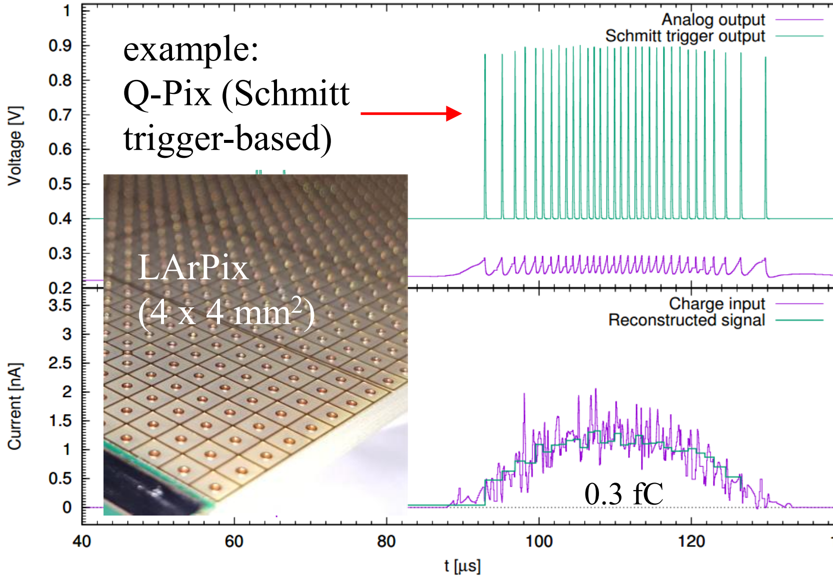
arXiv:2307.02343

arXiv:2305.12899

arXiv:2304.04044

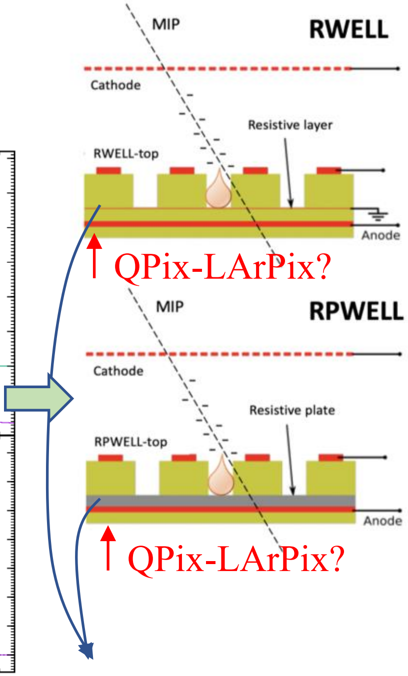
pixelated readouts for LAr/LXe TPCs:

LAr-Pix (2018) and Q-Pix (in production)


example:
Q-Pix (Schmitt trigger-based)

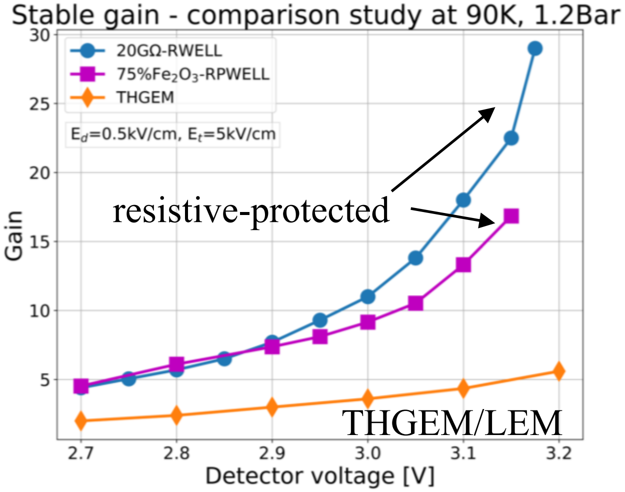
LArPix
(4 x 4 mm$^2$)

0.3 fC


QPix-LArPix?

QPix-LArPix?

resistive protection


Stable gain - comparison study at 90K, 1.2Bar

resistive-protected

THGEM/LEM

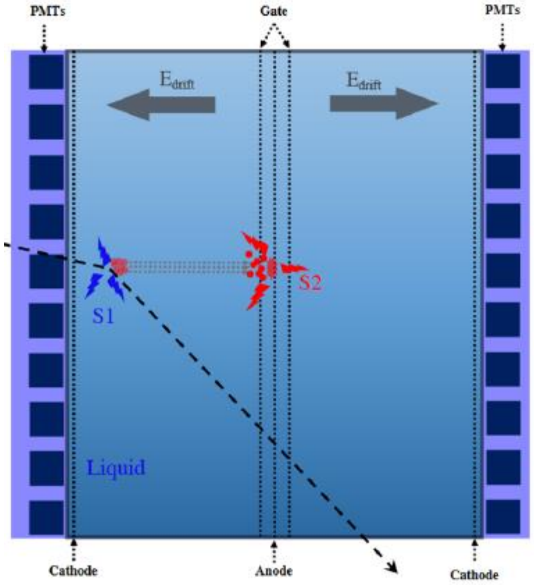
an appealing possibility: couple to avalanche amplification!

*GridPix-style (CsI can be added to the THGEM gate)*

good for O(10keV) thresholds in large-volume detectors

*not covered by DRD1!

# Dual-phase TPCs (morphing into single liquid-phase?)



Qing Lin JINST 16 P08011, 2021

Jianyang Qi arXiv: 2301.12296, JINST 2023

Yu Wei, arXiv: 2111.09112, JINST 2022

A cylindrical Single-Phase LXe detector design (thin anode wire in the center) was **first proposed by Lin (2102.06903, JINST).**

- **No liquid-gas interface: No trapped electrons!**
- **S2 in LXe (~20 photon/e-) is typically much smaller than S2 in GXe: induce less delayed e-**
- **Weak field on the cathode: less micro discharges; anode/gate surface area is very small: less e- from metal surface**
- **More photosensor coverage, no reflection at liquid/gas interface: higher light collection (lower S1 threshold, better sensitivity for low-mass DM)**

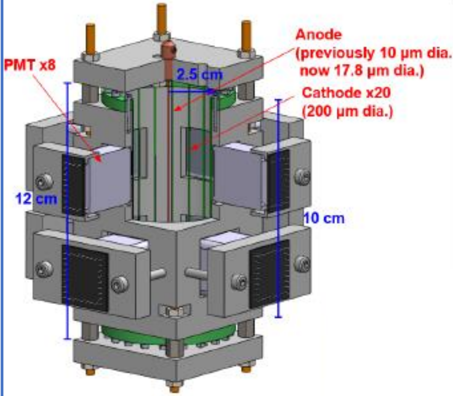
(previous)

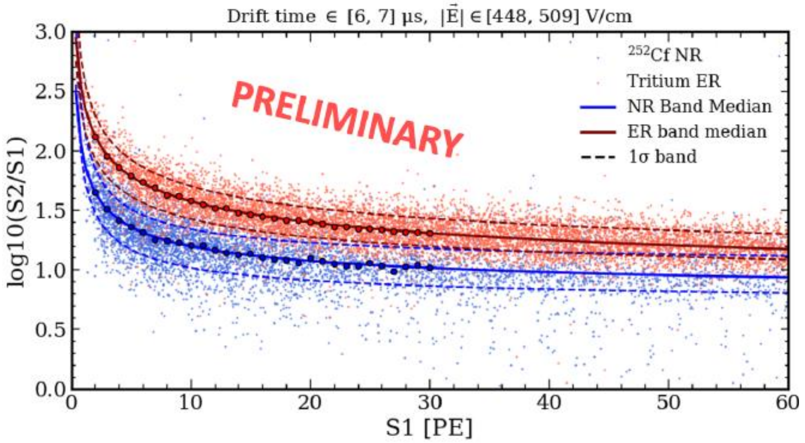
Aprile et al., 1408.6206

Juyal, Giboni et al., 2107.07798

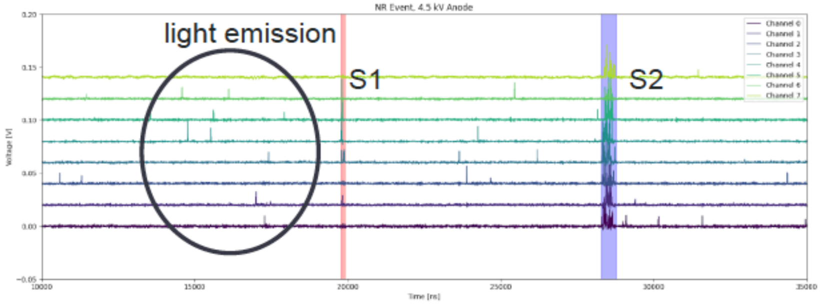
Kuger et al. 2112.11844

single-wire demonstrator



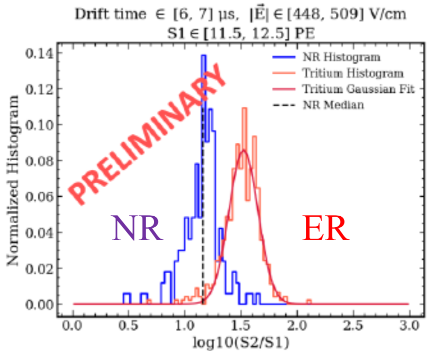


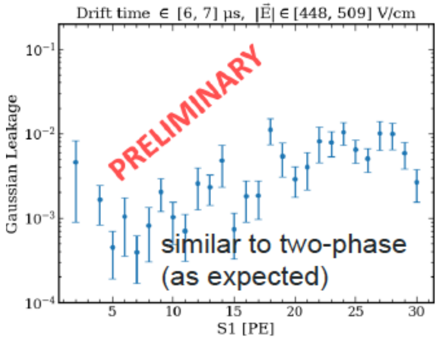
## a low energy nuclear recoil event (Anode: 4.5 kV)



downside: spurious single-photon activity

…preferrable to high electron activity!

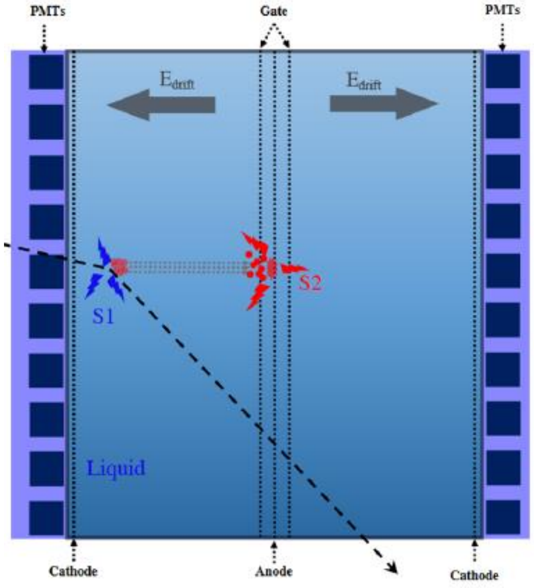




similar to two-phase (as expected)

*not covered by DRD1!

# Dual-phase TPCs (morphing into single liquid-phase?)



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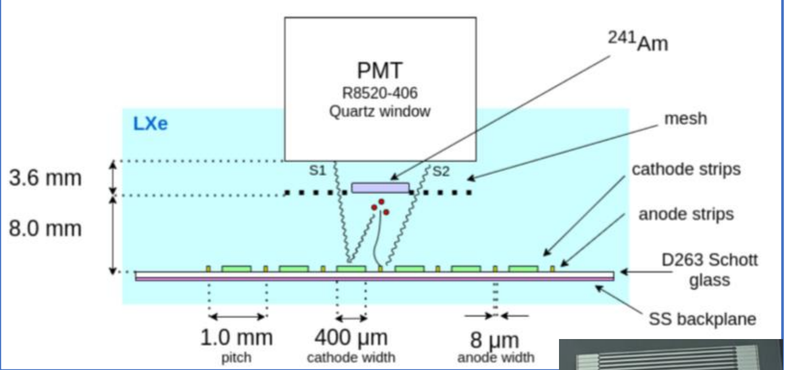
  **surface area is very small: less e- from met**
- **More photosensor coverage, no reflection at liquid/gas interface: higher light collection (lower S1 threshold, better sensitivity for low-mass DM)**

MSGC alternative



Qing Lin JINST 16 P08011, 2021

Jianyang Qi arXiv: 2301.12296, JINST 2023

Yu Wei, arXiv: 2111.09112, JINST 2022

(previous)

Aprile et al., 1408.6206

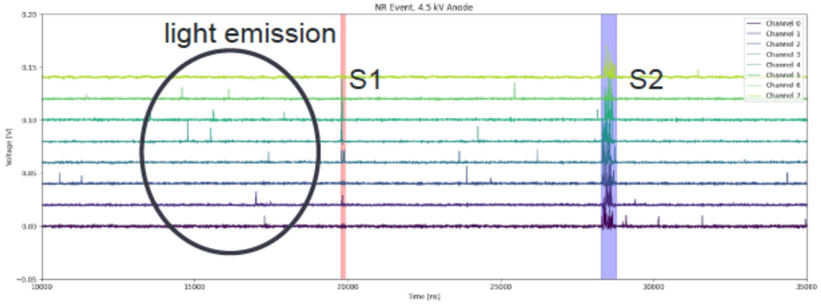
Juyal, Giboni et al., 2107.07798

Kuger et al. 2112.11844

very recent

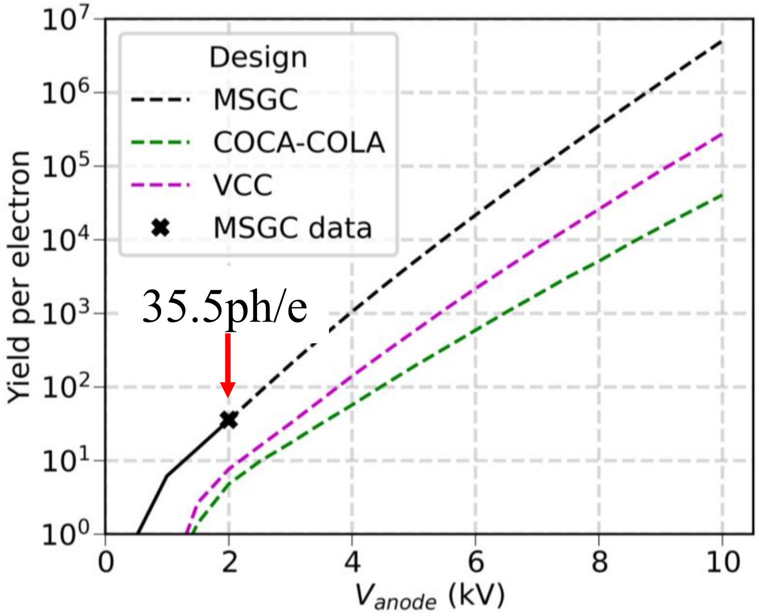
G. Martínez-Lema, et al 2312.14663

a low energy nuclear recoil event (Anode: 4.5 kV)



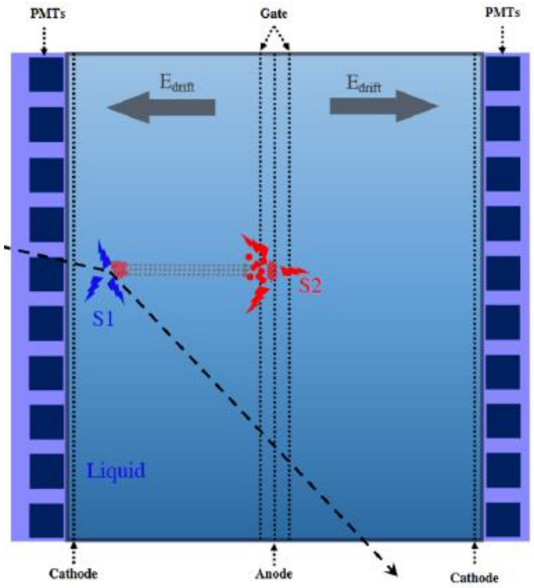
downside: spurious single-photon activity

…preferrable to high electron activity!



*not covered by DRD1!

# Dual-phase TPCs (morphing into single liquid-phase?)



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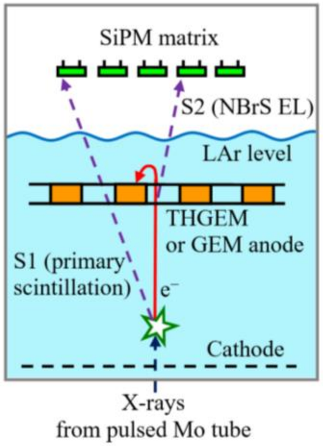
(previous)

Aprile et al., 1408.6206

Juyal, Giboni et al., 2107.07798

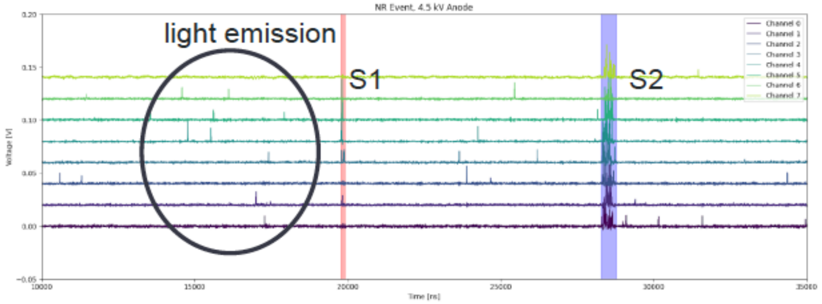
Kuger et al. 2112.11844

GEM alternative



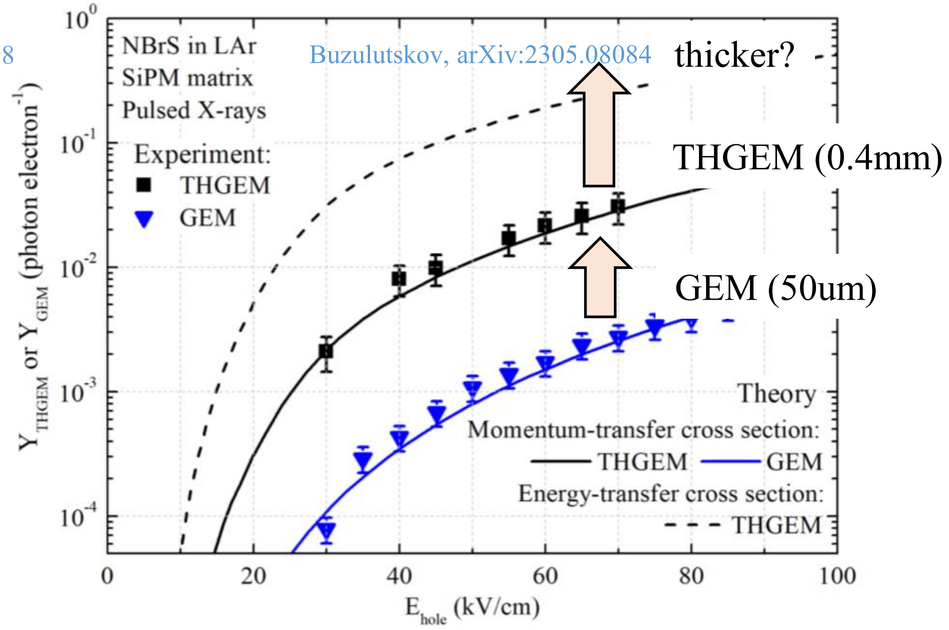
***neutral bremsstrahlung*** in the liquid (not EL!)

a low energy nuclear recoil event (Anode: 4.5 kV)



downside: spurious single-photon activity

…preferrable to high electron activity!



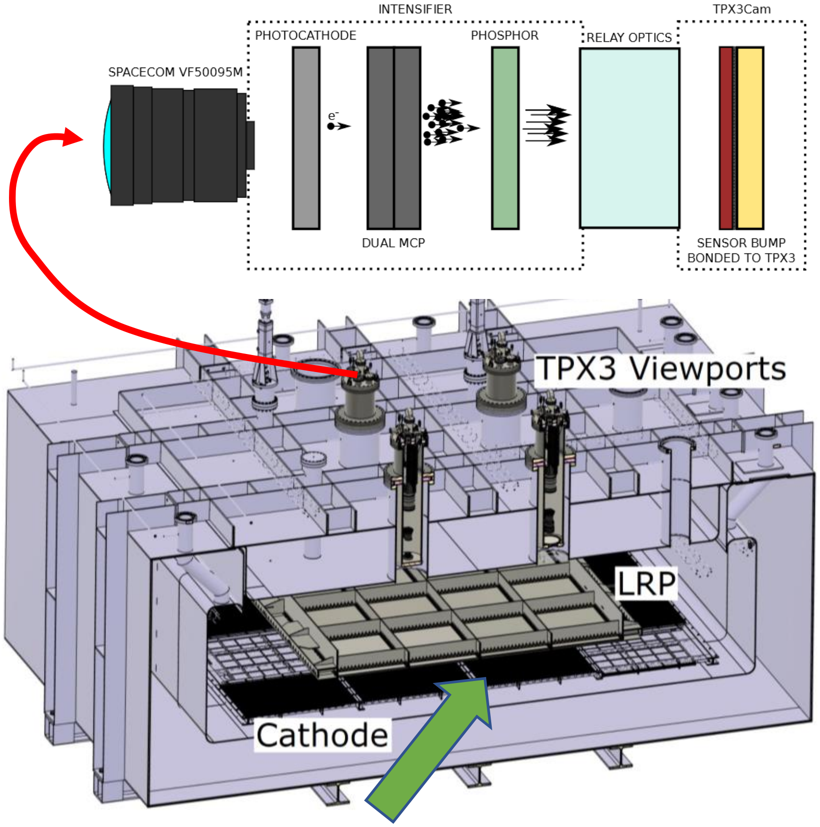
Buzulutskov, arXiv:2305.08084

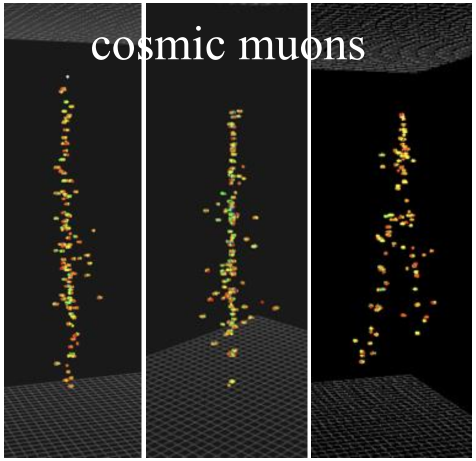
not viable for DM, but not excluded for neutrino TPCs

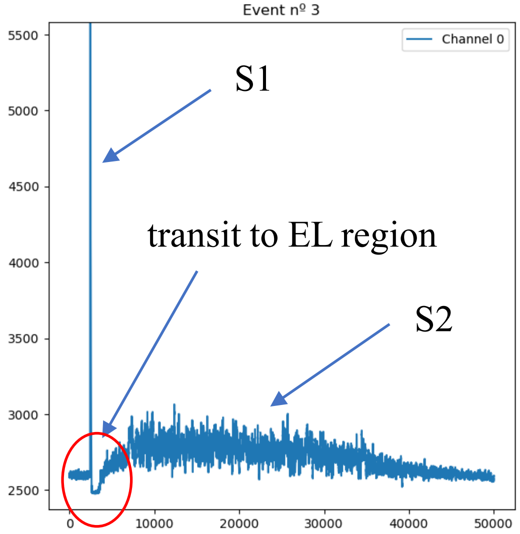
arXiv: 2301.02530

https://doi.org/10.3390/instruments4040035

# Full3D – camera-based optical tracking (pure argon TPC)

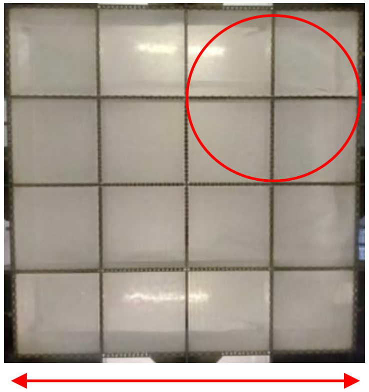






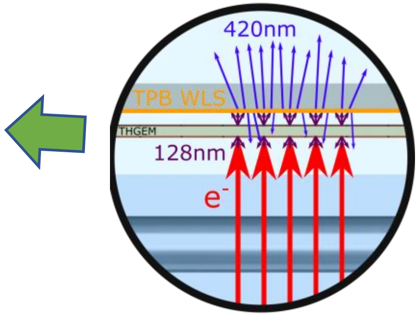
## *TPX3Cam*

- Raw data is 3D. Just need to convert ToA to z position using known drift velocity in the TPC and (x,y) pixel number to mm using the known field of view of the lens.
- Huge readout rates are possible (80MHits/s)
- Zero-suppressed readout (~few KBytes per event)
- Relies on Timepix sensor
- Comparatively low cost
- Same readout is possible for dual-phase and gas TPCs



2m

~1m$^2$ -> $\Delta_x = 4$mm



glass GEM + TPB plate

# Full3D – camera-based optical tracking (argon + $CF_4$ TPC)

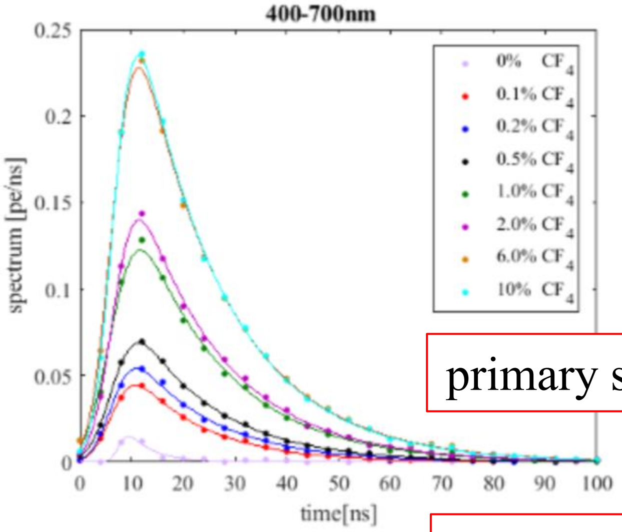
$CF_4$-doping in argon works well down to **1%**, possibly even less, enables tracking and $T_0$-tagging on large volumes

P. Amedo, arXiv: 2306.09919

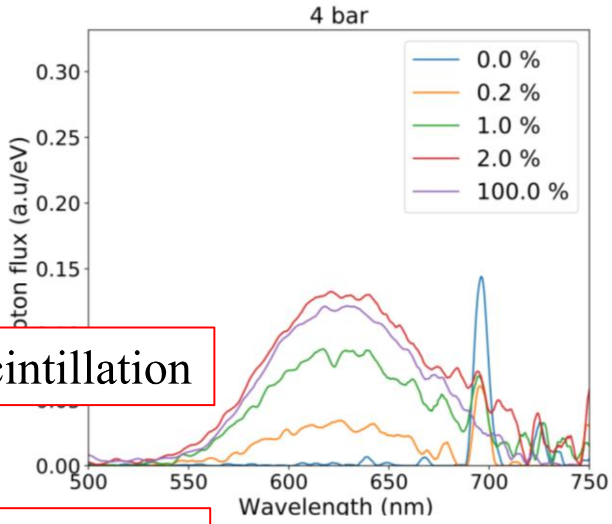
A. Saá-Hernández https://arxiv.org/abs/2401.09920

P. Amedo et al., Primary scintillation yields induced by alpha particles in gas mixtures of Argon/$CF_4$ at 10~bar (in preparation)

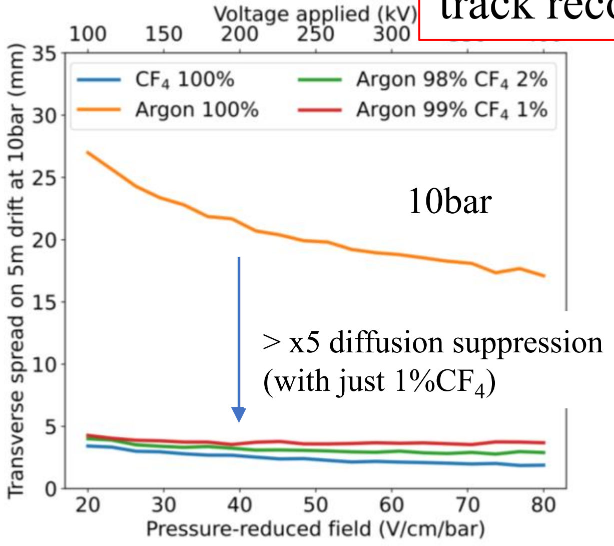
(3D-optical imaging soon to follow)



primary scintillation



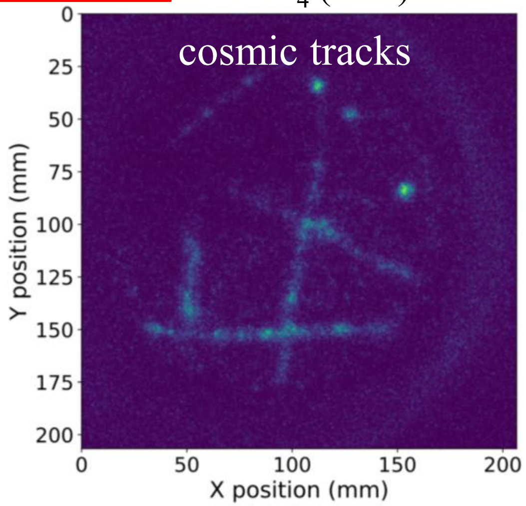
track reconstruction



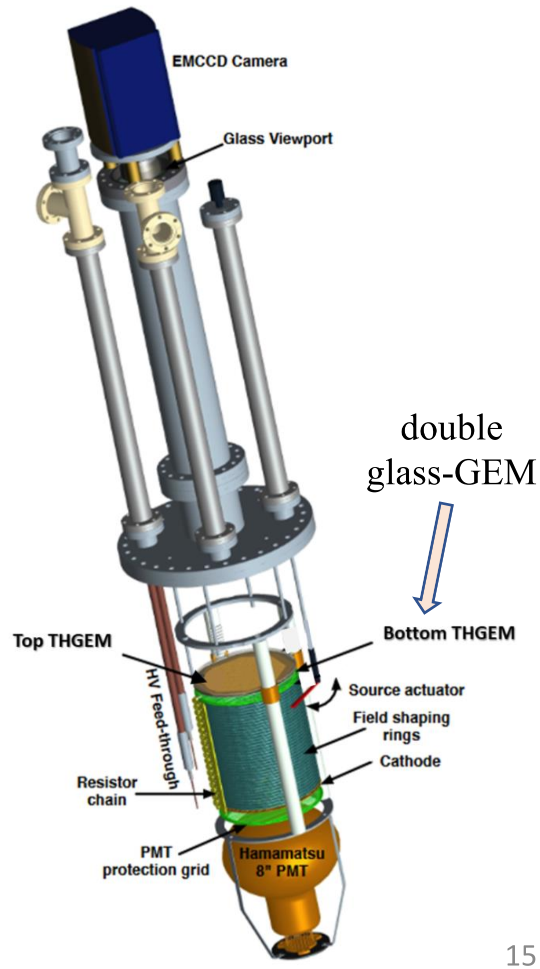
10bar

> x5 diffusion suppression (with just 1%$CF_4$)

1%$CF_4$ (1bar)



double glass-GEM

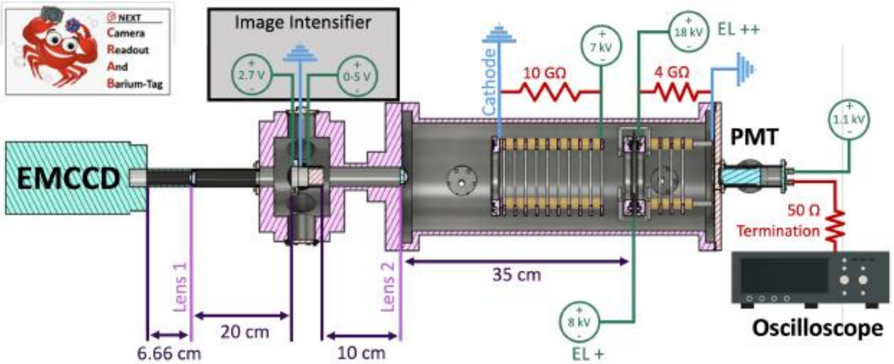


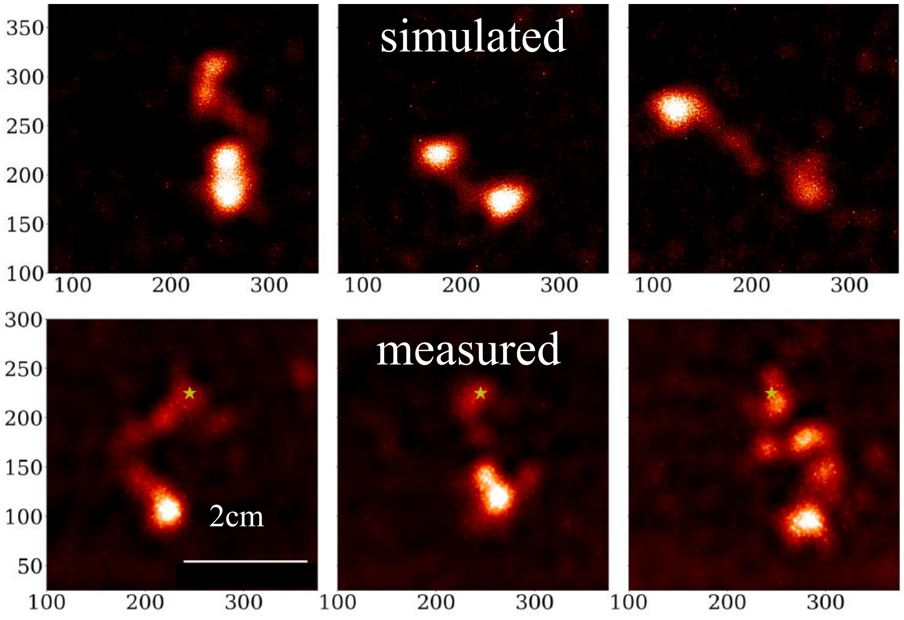
# Full3D – camera-based optical tracking (pure xenon TPC)

camera-read in xenon at 10bar!

(3D-optical imaging soon to follow)

arXiv:2304.06091





simulated

measured

2cm

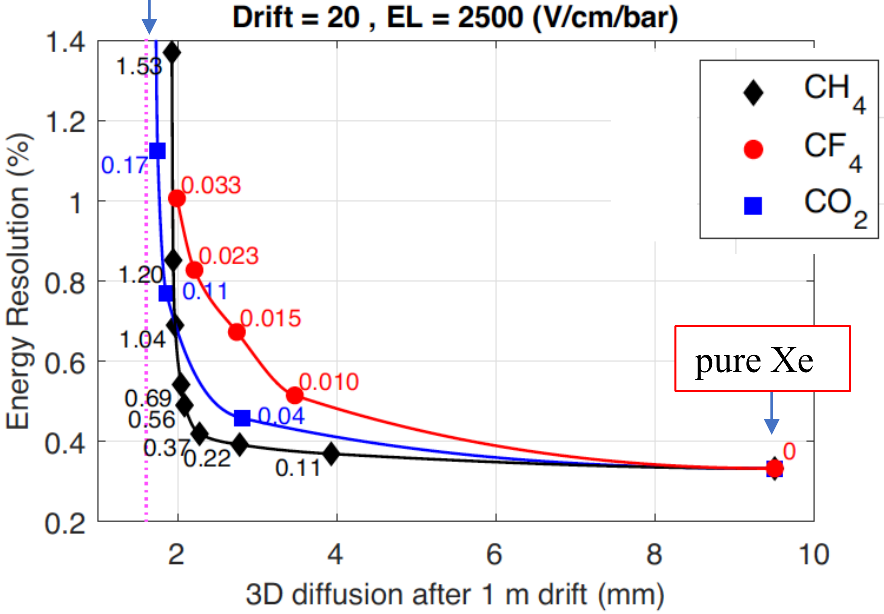
proxy for ‘one half’ of a $\beta\beta0\nu$ decay

diffusion suppression seems possible!

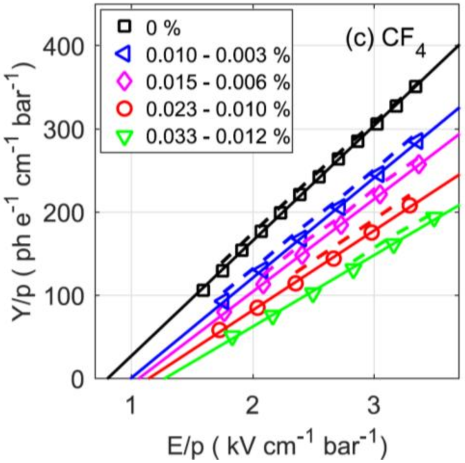
thermal limit

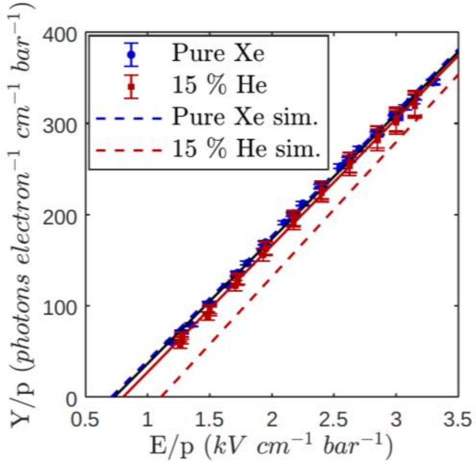
C. Henriques (PhD thesis)

JHEP01 (2019) 027
JHEP04 (2020) 034



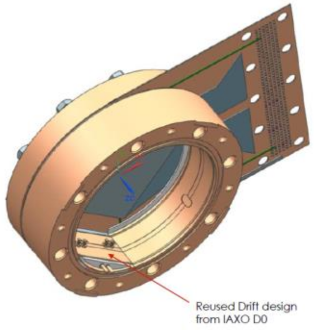
pure Xe

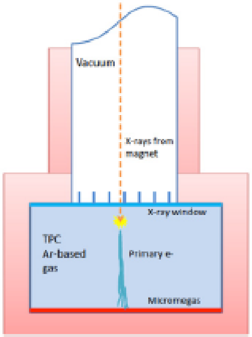


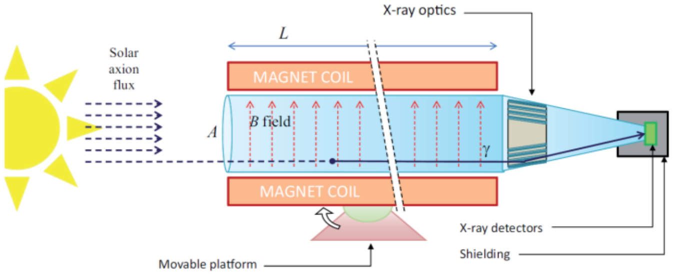


# Low-mass DM TPCs

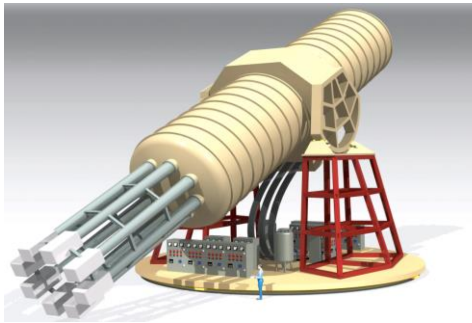
Micromegas



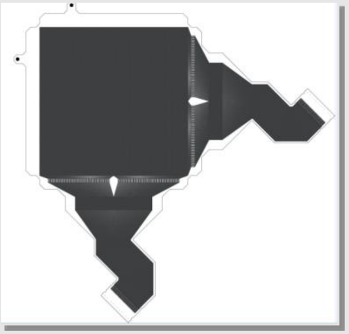


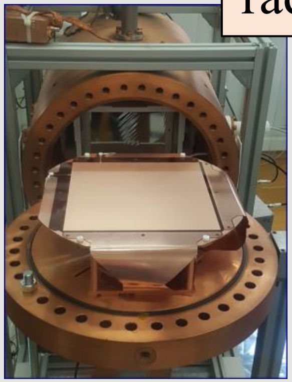


IAXO (solar axions)



Micromegas

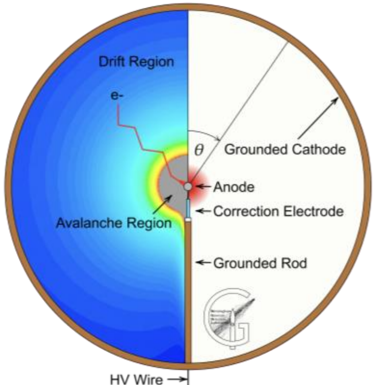


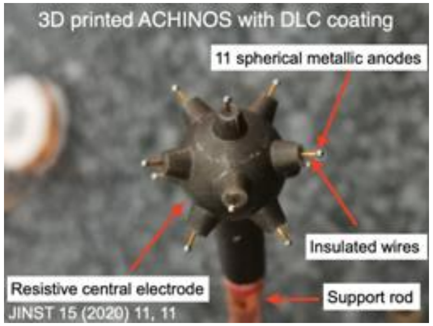


radiopurity!

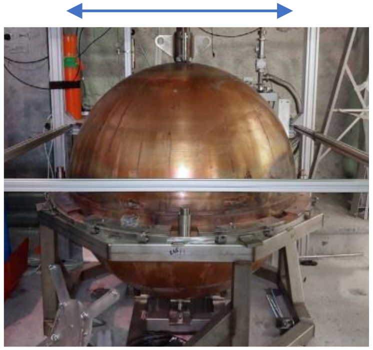
TREX-DM (low mass WIMPs)

Spherical detector

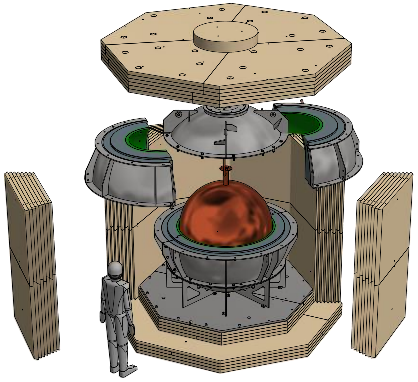




140cm



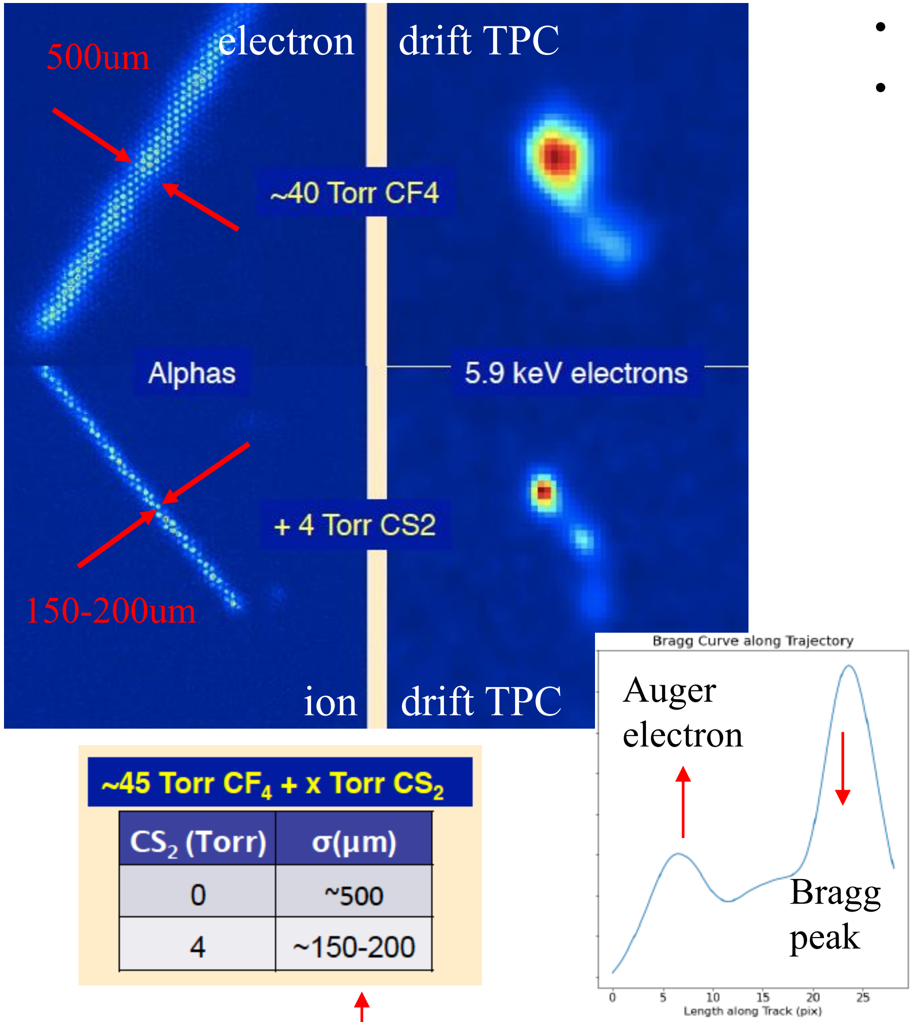
NEWS-G (low mass WIMPs)



# Very-low-energy tracking (DM) TPCs

negative-ion optical TPC is a reality!

good optical gain in GEMs



**~45 Torr $CF_4$ + x Torr $CS_2$**

| $CS_2$ (Torr) | σ(μm) |
|---|---|
| 0 | ~500 |
| 4 | ~150-200 |

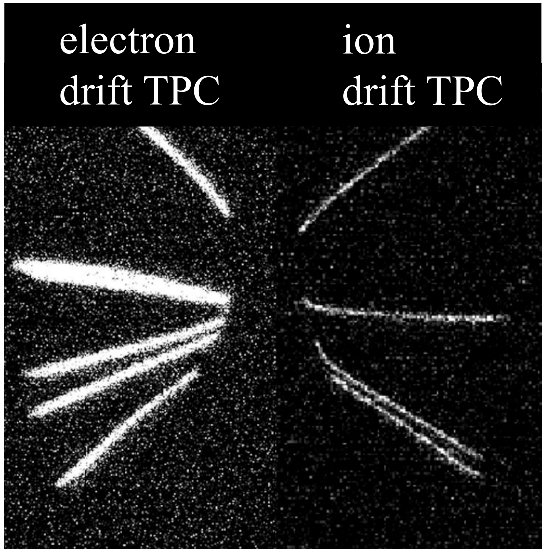
at least x100 smaller than a typical collider TPC (e.g., ALICE)

*resolution here refers to ~PSF
(~2-hit separation in collider physics)

D. Loomba (in preparation)

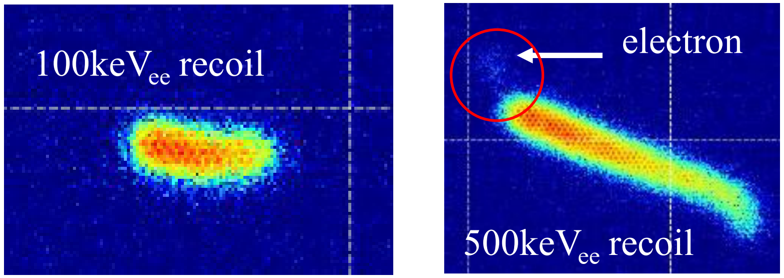
- Some strides on $SF_6$ mixtures at near atmospheric pressure!.
- Operation under ($He/CF_4/SF_6$ at 59/39.4/1.6) demonstrated at around 1bar!

G. Dho



pure optical readout already used for Migdal studies!

$CF_4$ (50Torr)



P. Majewski with glass-GEMs

# Conclusions and outlook

- New gas mixtures and amplification structures are being introduced for the readout of TPCs:
    1. Double-mesh (low IBF x G).
    2. M-THGEM (operation in pure noble elements).
    3. Liquid-hole and Floating-hole multipliers for extraction in dual-phase TPCs.
    4. RWELL/RPWELL for cryogenic TPCs.
    5. FAT-GEMs for TPCs working with electroluminescence.
    6. Sand-blasted Large-Area Glass-GEMs.

    …

- Wires, MSGCs, GEMs, THGEMs are all capable of producing usable scintillation in the liquid. Scaled-up concepts already on their way.

- Full3D camera-based optical tracking used or considered by several collaborations.

- Radiopurity of amplification structures continues to be key.

- Optical readout of negative-ion TPCs achieved at around 1bar!. Perhaps surprisingly… resorting to GEM structures with a classical design and no particular optimization.

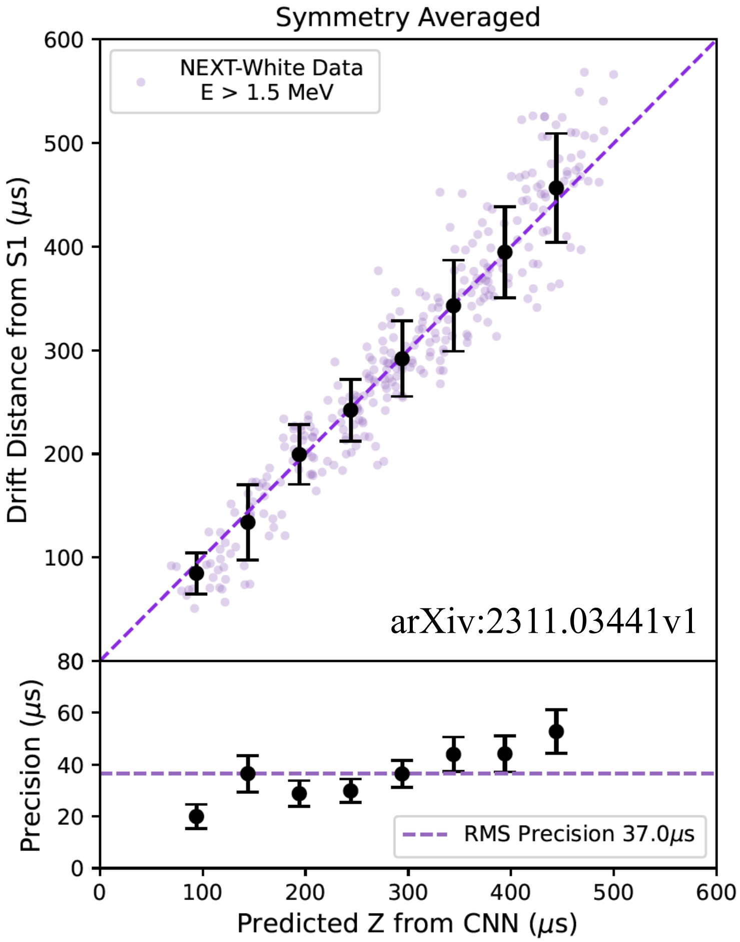
- Continued success of MPGD structures developed decades ago (GEMs, THGEMs).
- However new production techniques and optimization, keeping the up and coming new applications seem inevitable

# Appendix

# Electroluminescence in gas TPCs

demonstration of absolute-z determination through diffusion

new multi-hole EL structures for large area

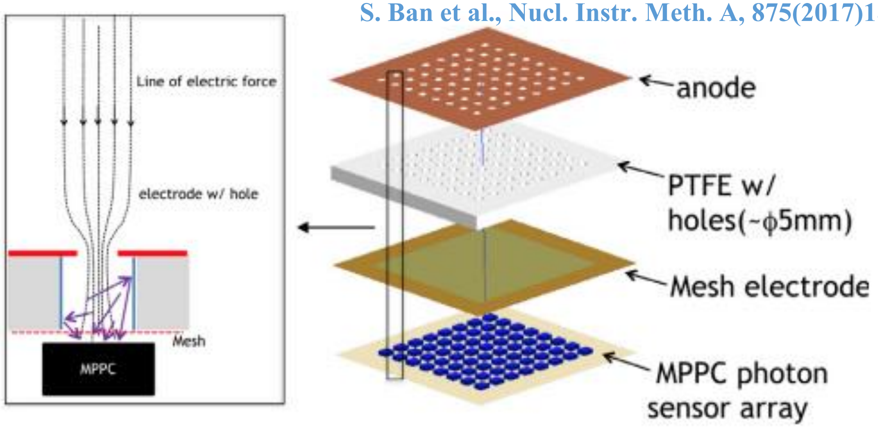


arXiv:2311.03441v1

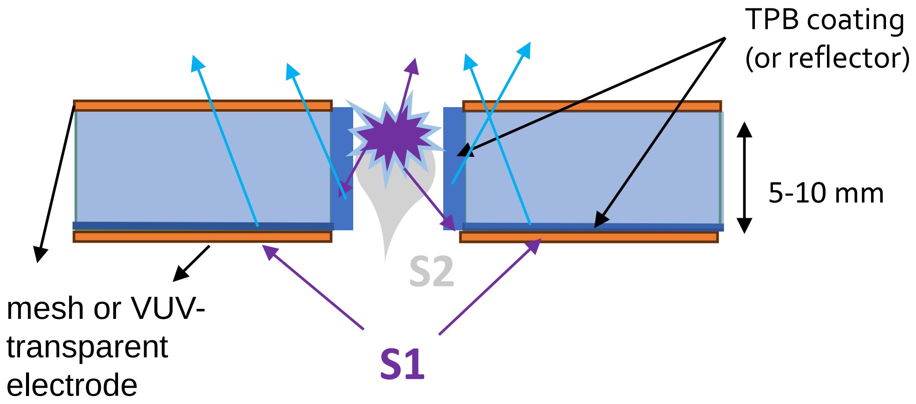
*Δz*~33mm

### I. ELCC (structure == light reflector)

S. Ban et al., Nucl. Instr. Meth. A, 875(2017)185



### II. FAT-GEMs (structure == transparent light collector)



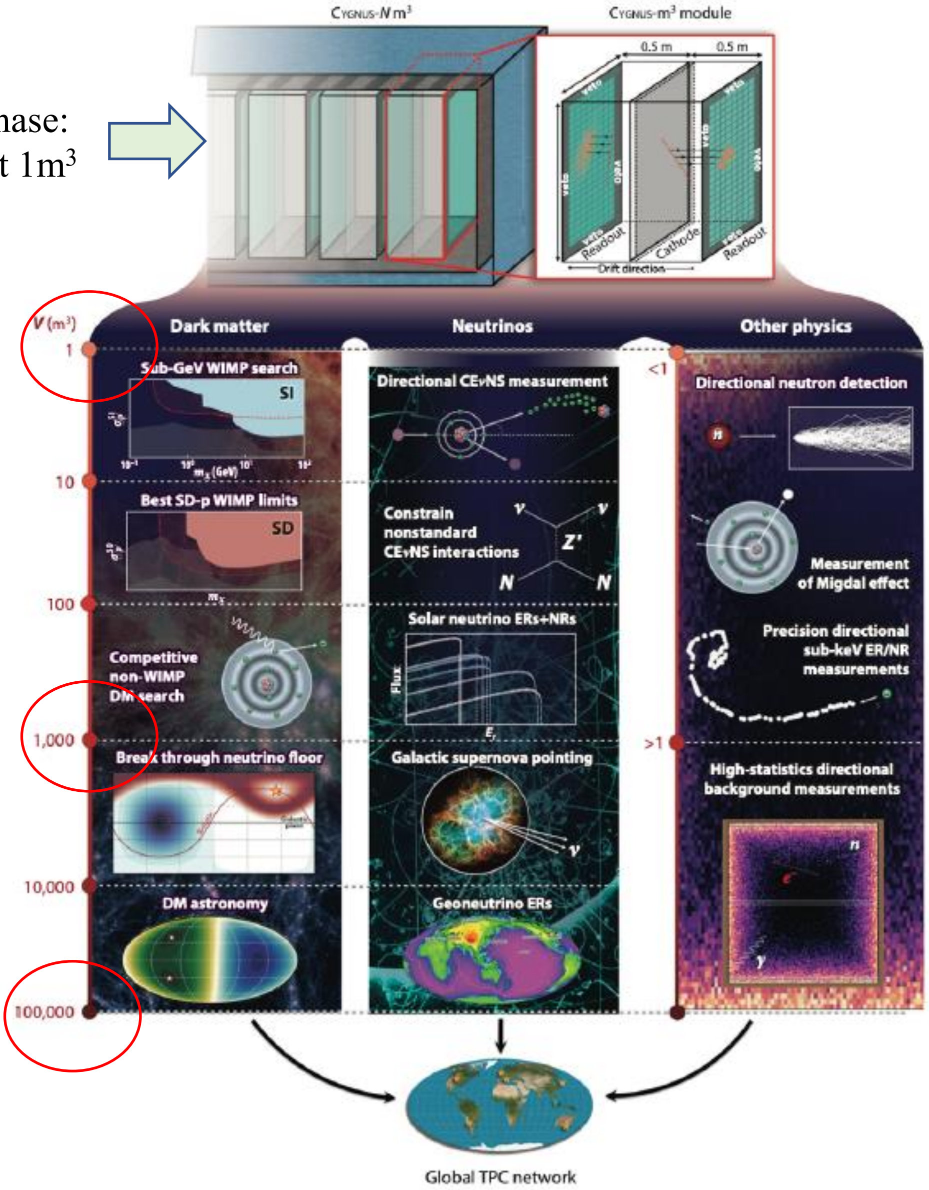
https://arxiv.org/abs/1907.03292, https://arxiv.org/abs/2106.03773

FAT-GEMs: (Field Assisted) Transparent Gaseous-Electroluminescence Multipliers, S. Leardini et al (in preparation)

# Very-low-energy tracking (DM) TPCs

a roadmap for the next decades!

upcoming phase:
prototypes at 1m$^3$



**from G. Dho**

‘perfect’ detector for measuring nuclear recoils?:

- He/CF$_4$/SF$_6$ at around atmospheric pressure.
- 3D optical readout via CMOS cameras down to 50um vixel size.

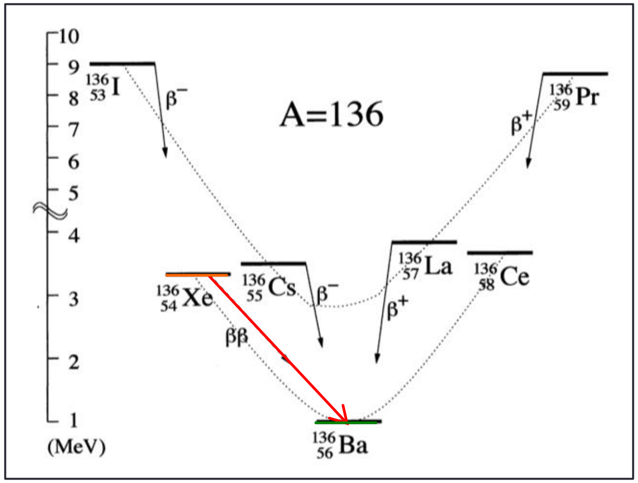
*(speed requirements are of the order of ~0.1 Mfps, already within the reach of ultra-fast cameras)

# Single-ion tagging

a background-free method, particularly for studying decays

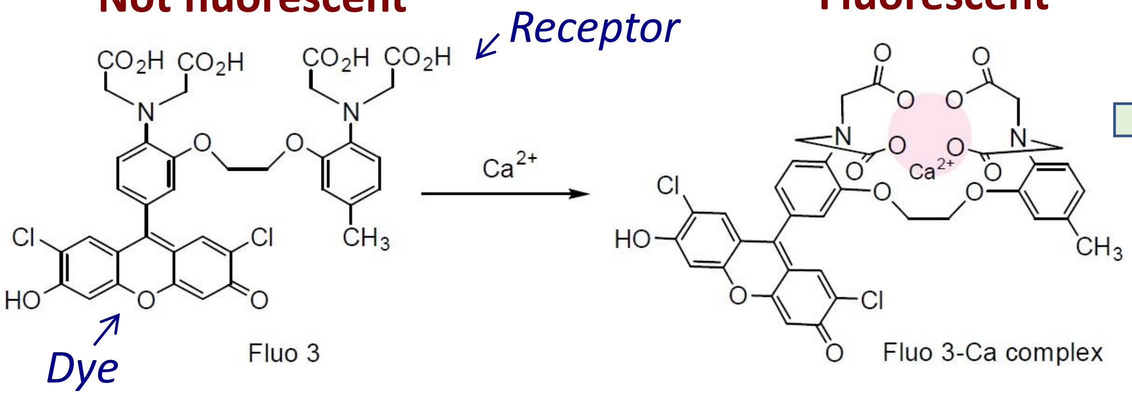
One of the possibilities: resort to the chemistry of the species.

-> adapting SMFI (single molecule fluorescent imaging)



**Not fluorescent**

**Fluorescent**

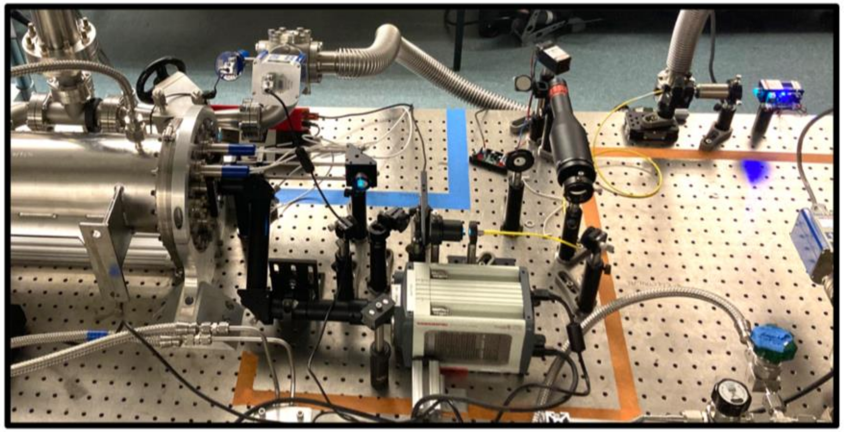


Fluo 3

Fluo 3-Ca complex

but novel dry fluorophores are in need!

**Phys. Rev. Lett. 120 (2018) 13, 132504**
**Sci. Rep. 9, 15097 (2019)**
**ACS Sens 2021, 6, 1, 192–202**
**Nature 583 (2020) 7814, 48–54**
**Nat. Comm. 13, 7741 2023**



**$1mm^2$ –scan at the Abbe limit in HPGXe**