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SEARCH FOR LIGHT DARK MATTER WITH GAS DETECTORS: LATEST DEVELOPMENTS

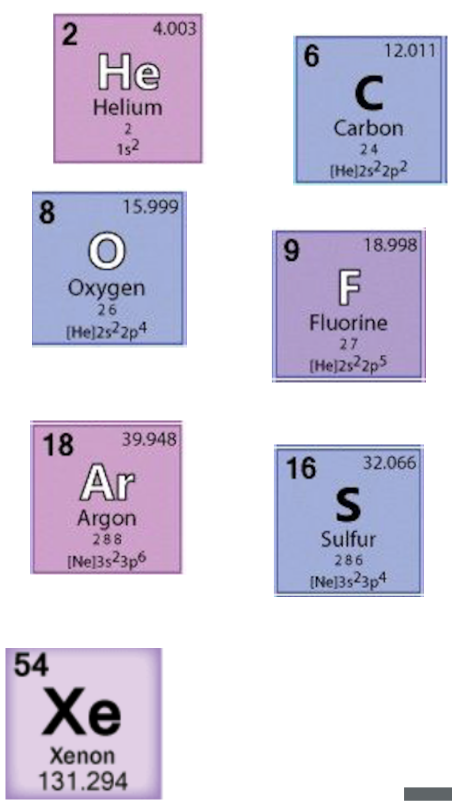
INTERACTION PROBABILITY

- WIMP detectors look at nuclear recoils
- Probability of creating a nuclear recoil

$$R \propto 0.13 \left(\frac{A}{100} \frac{\sigma_{WN}}{10^{-38}\mathrm{cm}^2} \frac{v}{220\ \mathrm{km/s}} \frac{\rho_0}{0.3\ \mathrm{GeV/cm}^3} \frac{\mathrm{mass}}{\mathrm{kg}} \right) \left[\frac{\mathrm{events}}{\mathrm{year}} \right]$$

Target Cross Section
(i. e. High Mass Number)

Target Mass

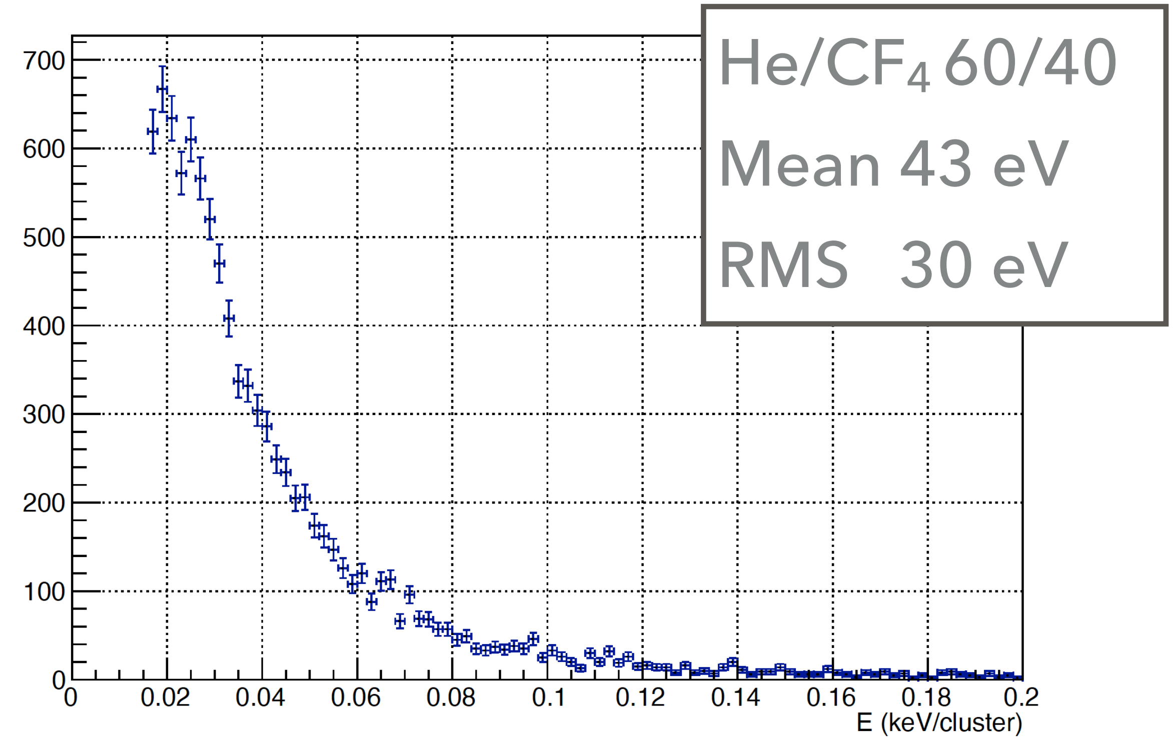


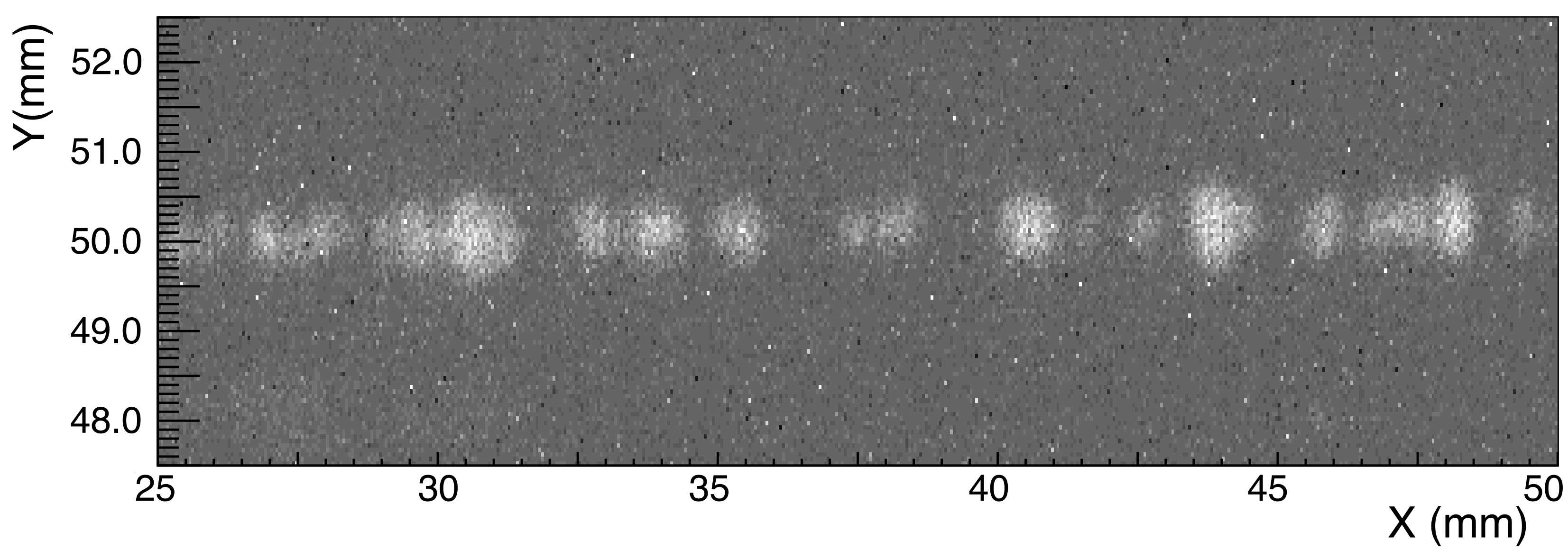
Gas	A_{eff}	kg/m^3	$A \times mass/m^3$
Ar	39.9	1.8	71.0
He	4.0	0.2	0.7
CO_2	44.0	1.8	81.0
CF_4	88.0	3.7	327.4
SF_6	146.0	6.2	900.8

Liquid	A_{eff}	kg/l	A x mass/l
Ar	39.9	1.4	55.9
Xe	131.3	3.0	393.9

SIGNAL DETECTION

- Primary signal in gaseous detector is always due to ionization of gas molecules;
  - Given the large fraction of energy released in ionising processes, the effective average energy release per e-ion pair is 2-3 times larger than single ionization (i.e. 20-50 eV/pair);





Gas	eV/pair
Ar	26
He	42
CO_2	33
CF_4	54
SF_6	51

- In principle energies releases of few tens of eV are clearly detectable.

SIGNAL FORMATION

- In DM detector, the ionizing particles can be nuclear or electron recoils;
- The maximum energy that can be transferred by a DM particle to a recoil of mass m_N, is given by:

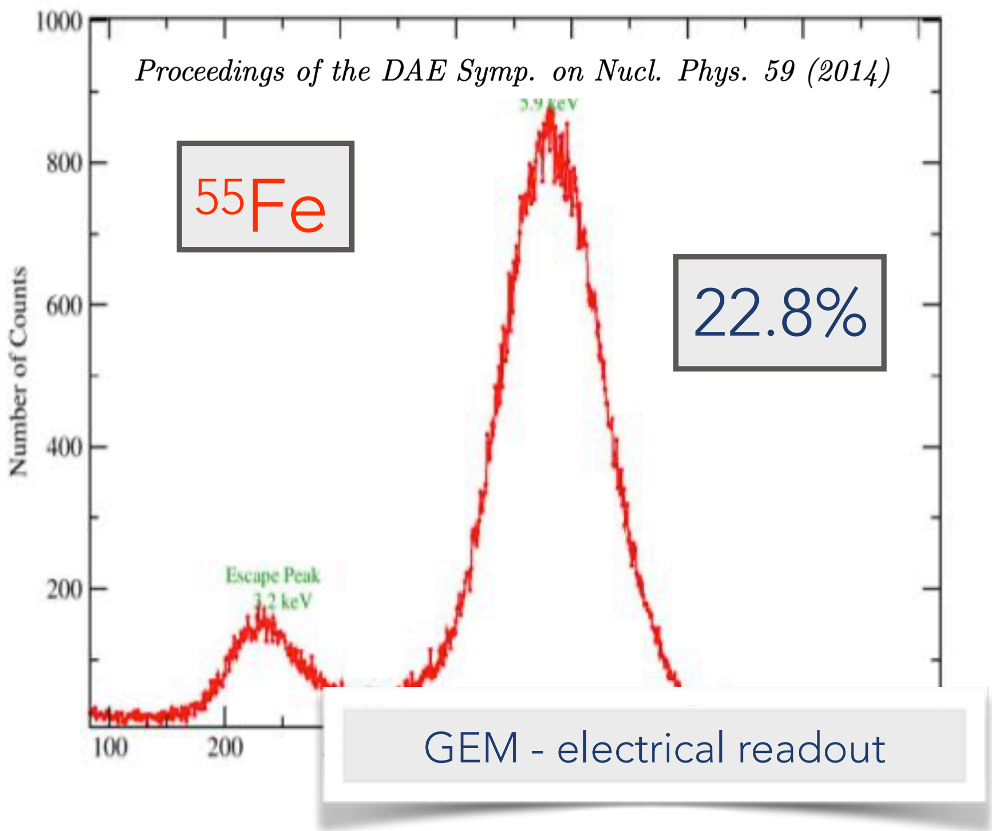
$$\epsilon = \frac{4\rho}{(\rho+1)^2} \quad \text{where} \quad \rho = \frac{m_N}{m_{WIMP}}$$

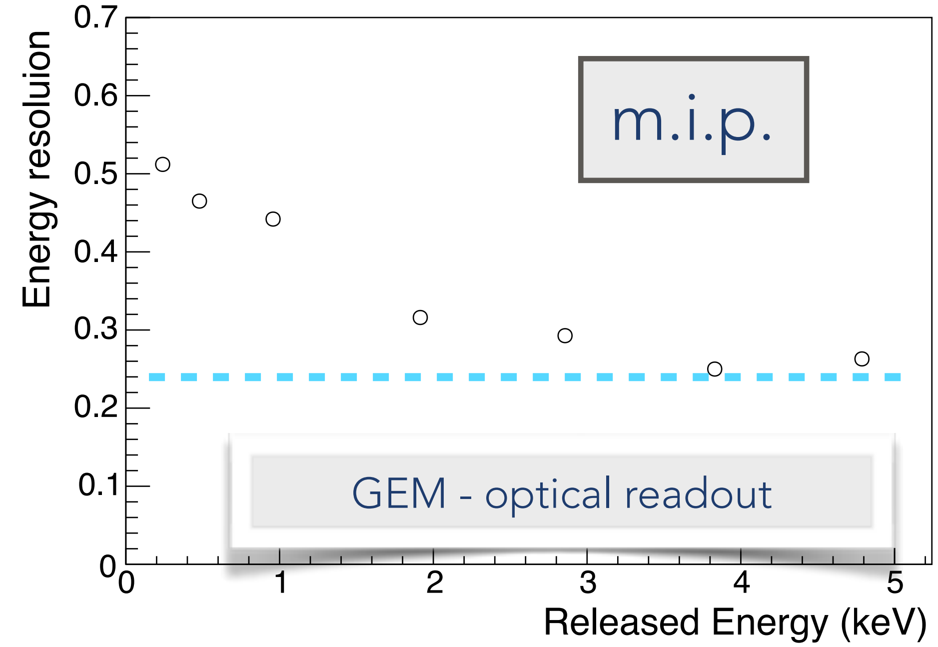
Element	Max E transferred by a 1GeV DM particle	Min DM particle mass with 1 keV threshold
Ar	0.2 keV	5.25 GeV
He	1.2 keV	0.78 GeV
C	0.6 keV	1.76 GeV
F	0.4 keV	2.63 GeV
S	0.2 keV	4.25 GeV
Xe	0.06 keV	16.6 GeV

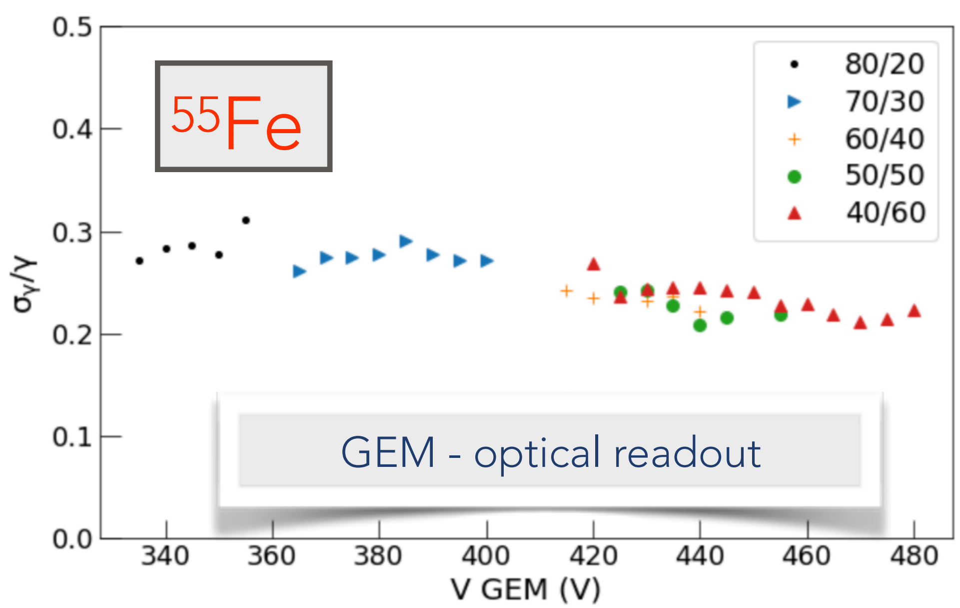
The use of light atoms would allow larger Energy Transfers

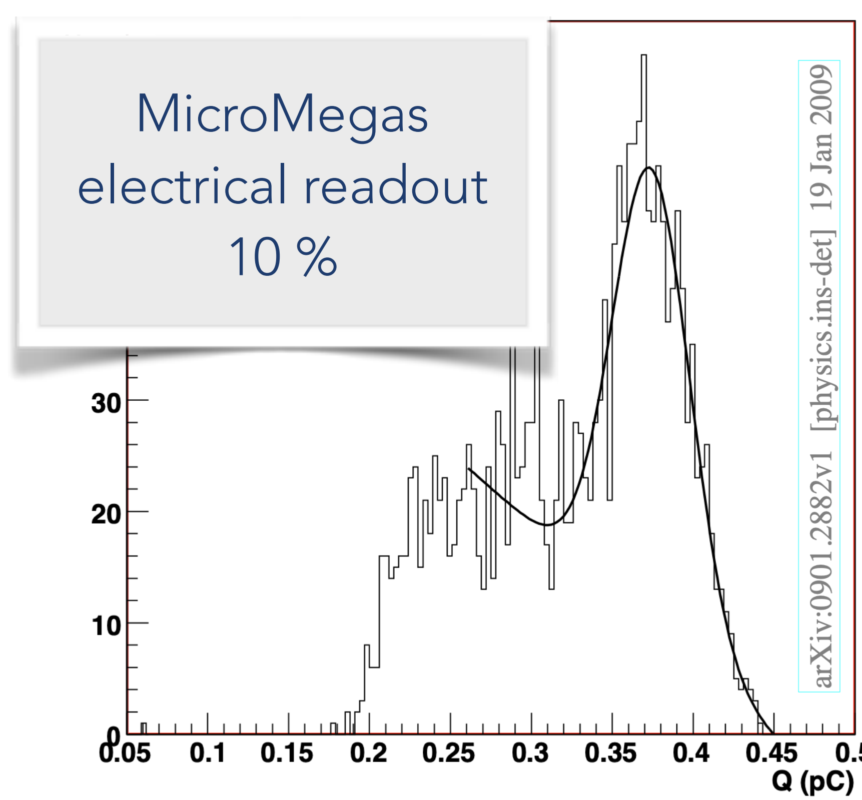
ENERGY MEASUREMENT

- Gaseous detectors operated in proportional regime have a good (not exceptional) energy resolution:

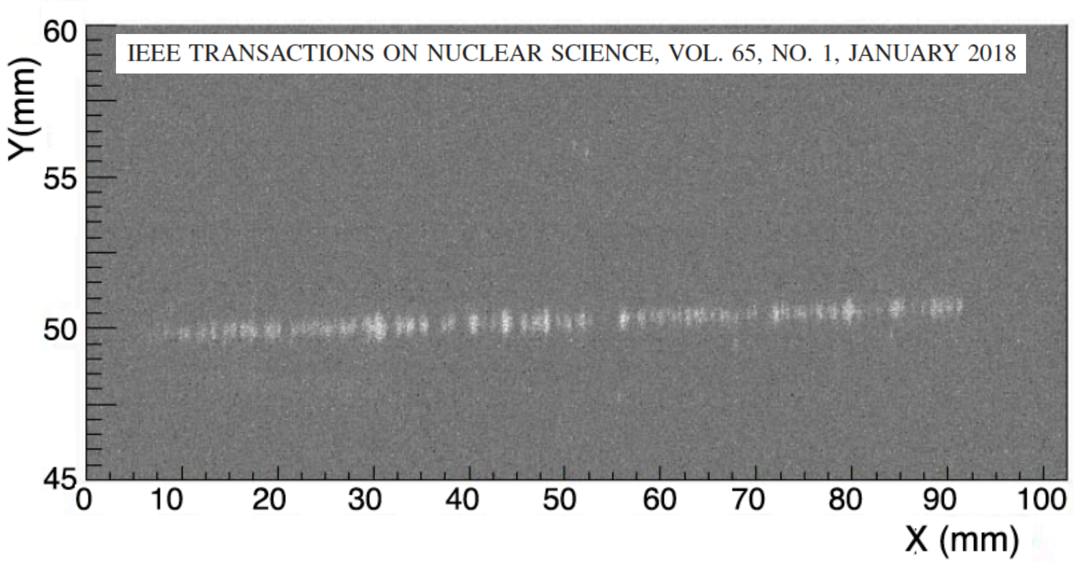


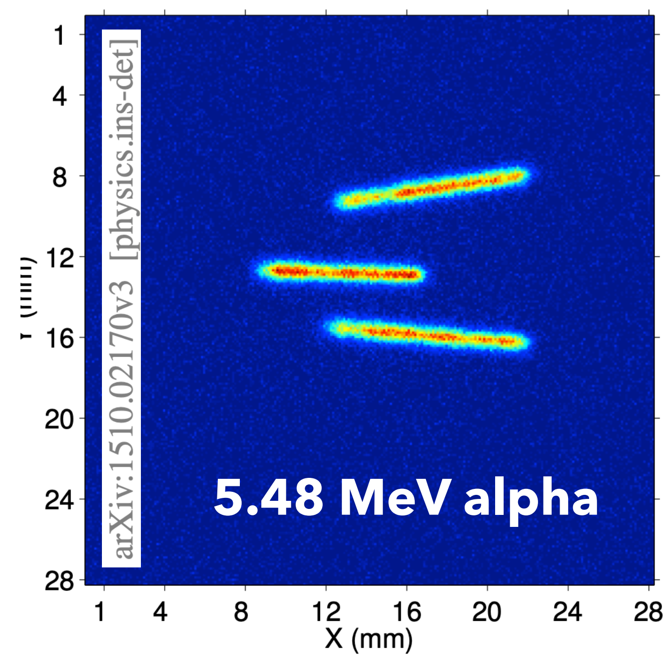




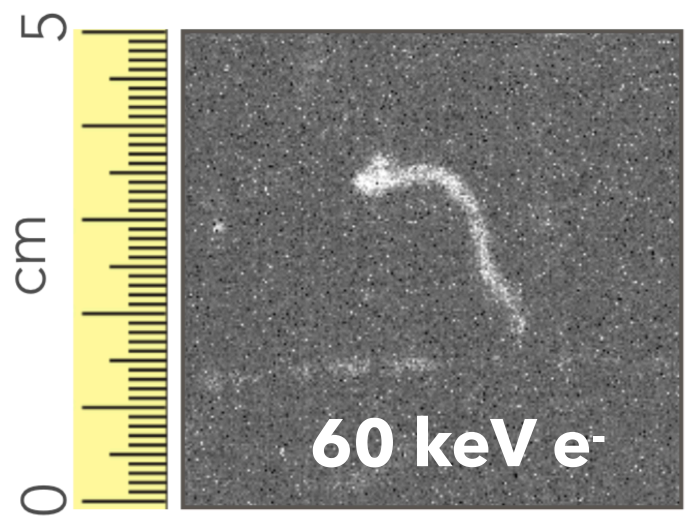


DIRECTION MEASUREMENT

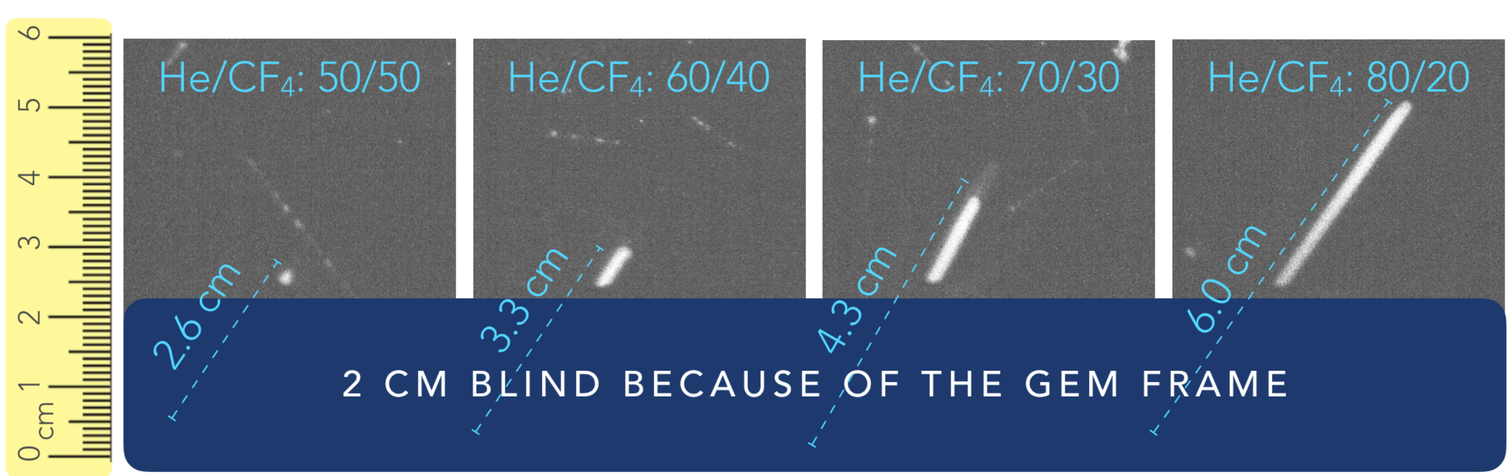


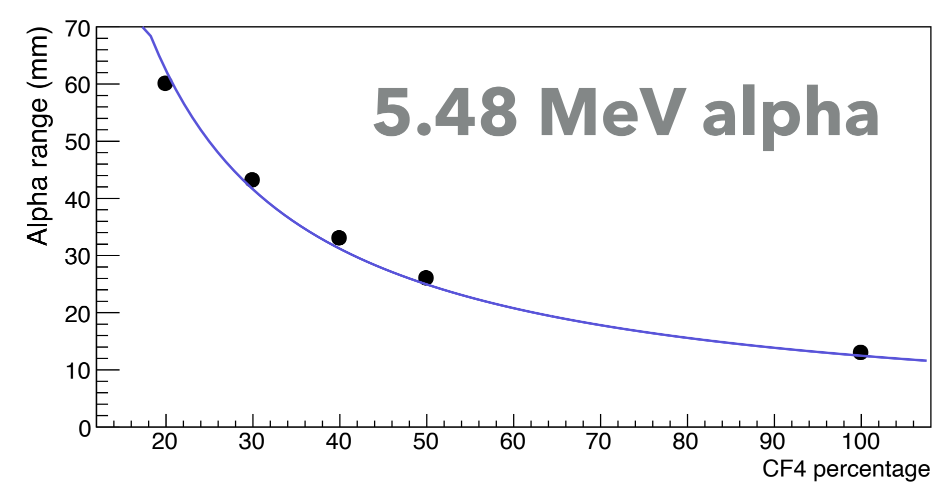


- High energy particles create very long tracks in gas (from centimetres to meters) with a very clear direction.



- Low energy particles create sizeable tracks in gas (from millimetres to centimetres) with a less clear direction.





Particle range can be tuned by the choice of the gas mixture

BACKGROUND REJECTION

Low radioactivity:

Gases and the light structures of gas vessels (acrylic, copper) are usually less radioactive than more complex apparati (e.g. cryogenic ones);

Directionality:

3D reconstruction of tracks to exploit asymmetries and direction modulation of the Dark Matter signals for background discrimination;

Sensitive Volume Fiducialization:

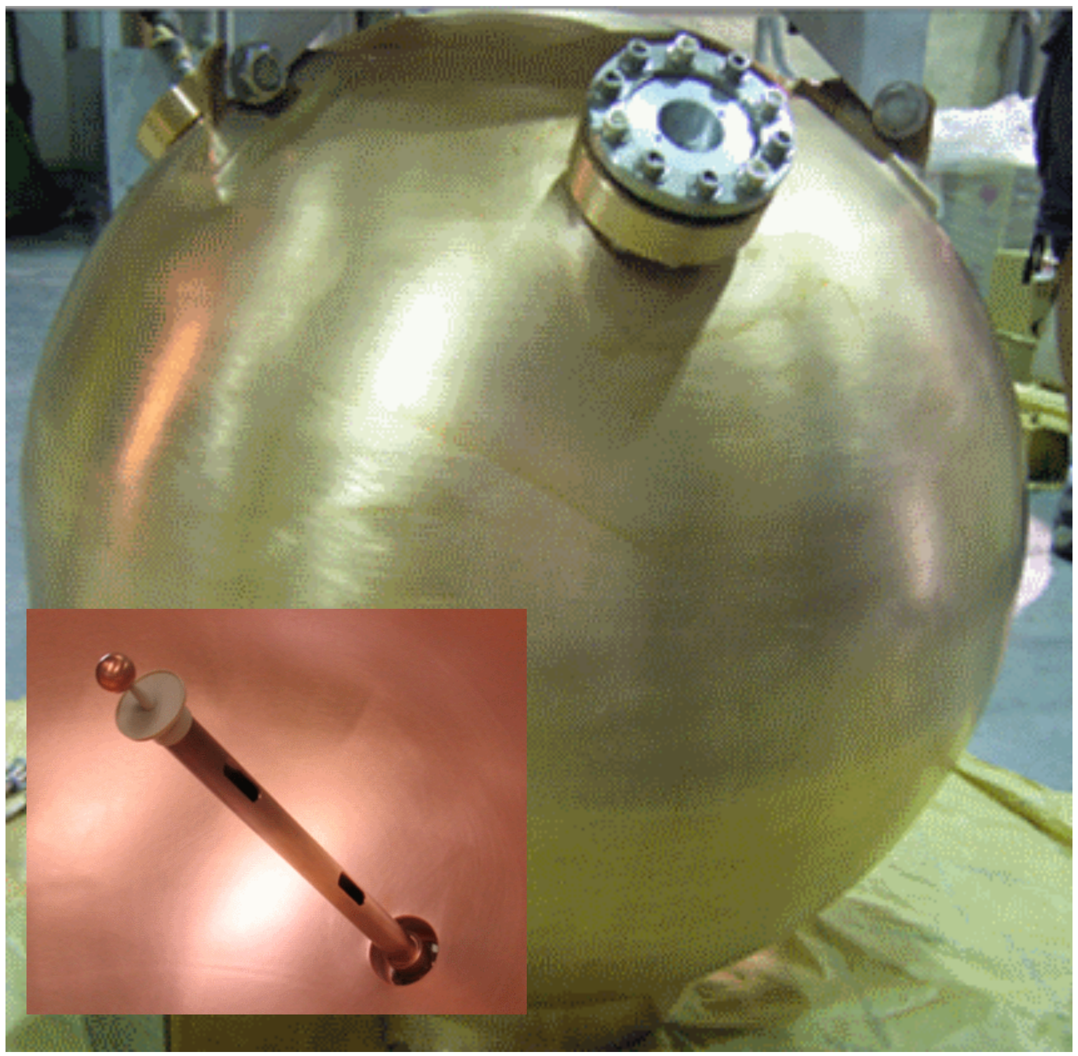
Measurement of the event position within the detector to reject events close the detector walls, very likely due to decays of radioactive materials

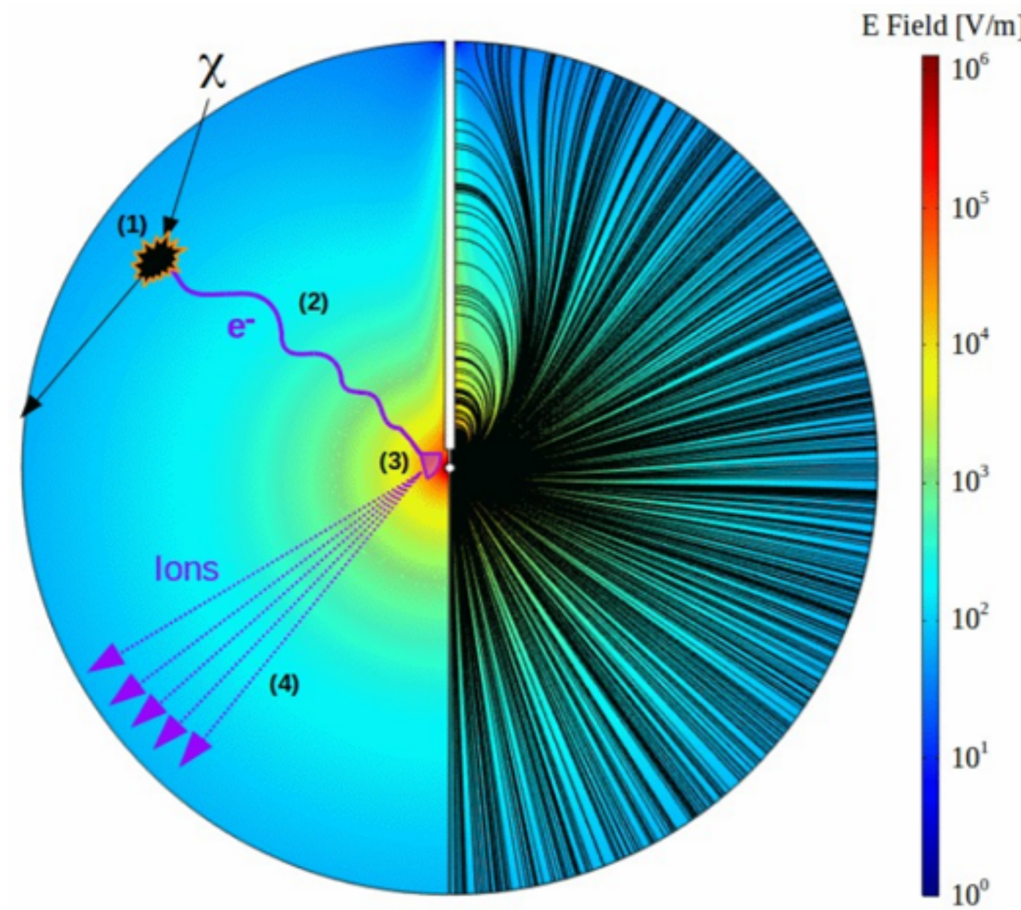
Particle identification:

dE/dx of electrons and nuclear recoils are quite different giving rise to different signal development in space and time.

NEWSG

- Spherical Proportional Counters (SPC): low capacitance, low energy threshold, excellent energy resolution, single readout channel



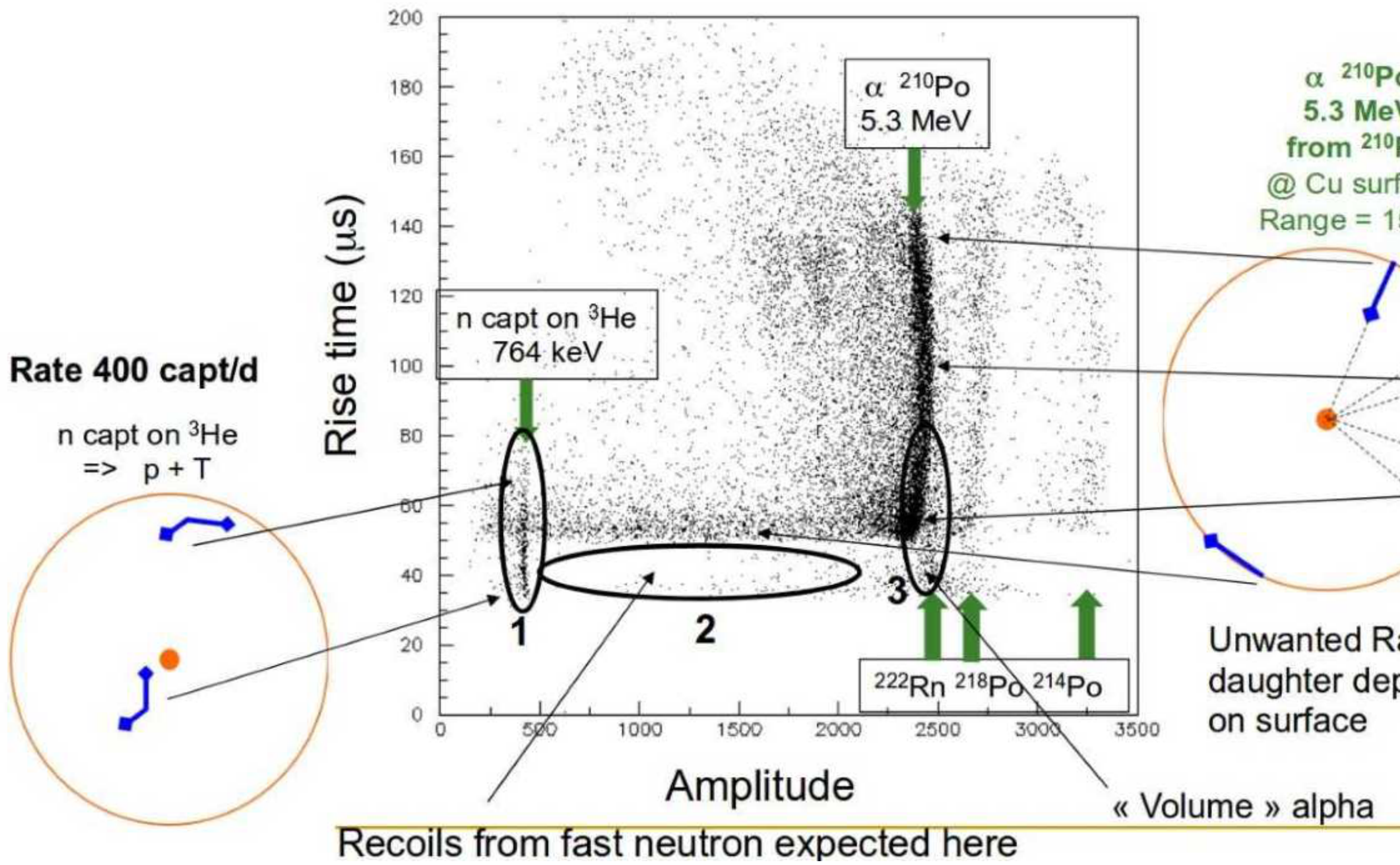


Energy detection thresholds as low as 10 eV

A 60 cm diameter SPC prototype made of high purity copper has been set-up at the **L**aboratoire **S**outerrain de **M**odane (LSM)

NEWSG

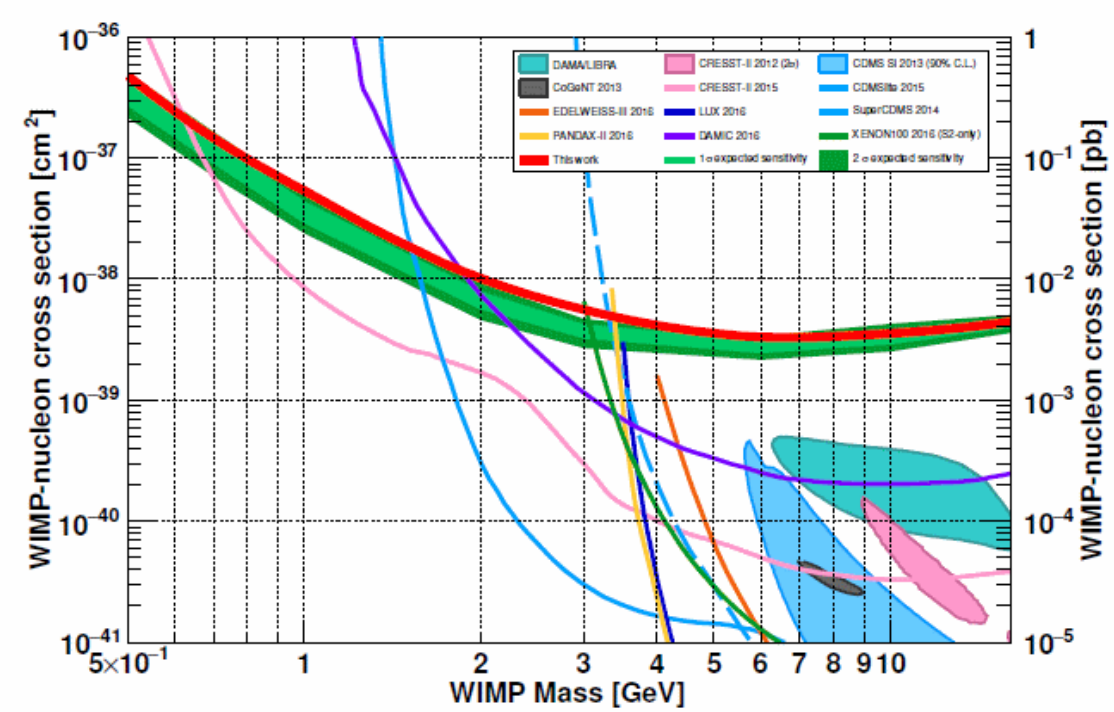
Electron diffusion translates into pulses exhibiting longer rise times for energy depositions occurring further away from the sensor



Pulse shape analysis allows the discrimination, if operated at low pressure (100 mbar), between point-like nuclear recoils and short tracks due to electron recoils

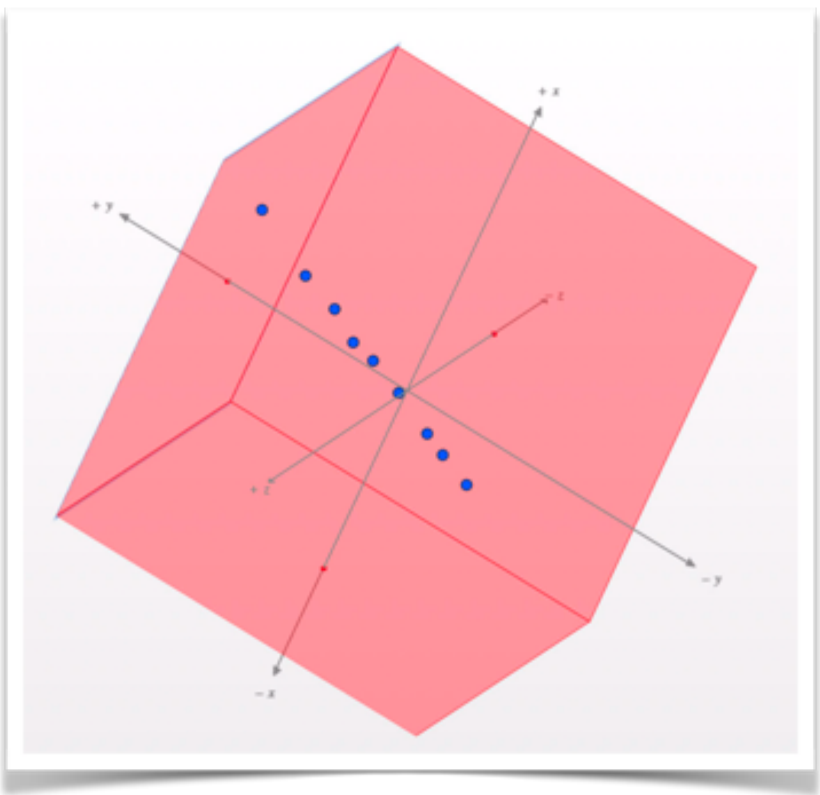
World-leading constraint on the WIMP elastic scattering cross section for a WIMP mass of 0.5 GeV.

1.4 m diameter detector to be located at SNOLAB in construction

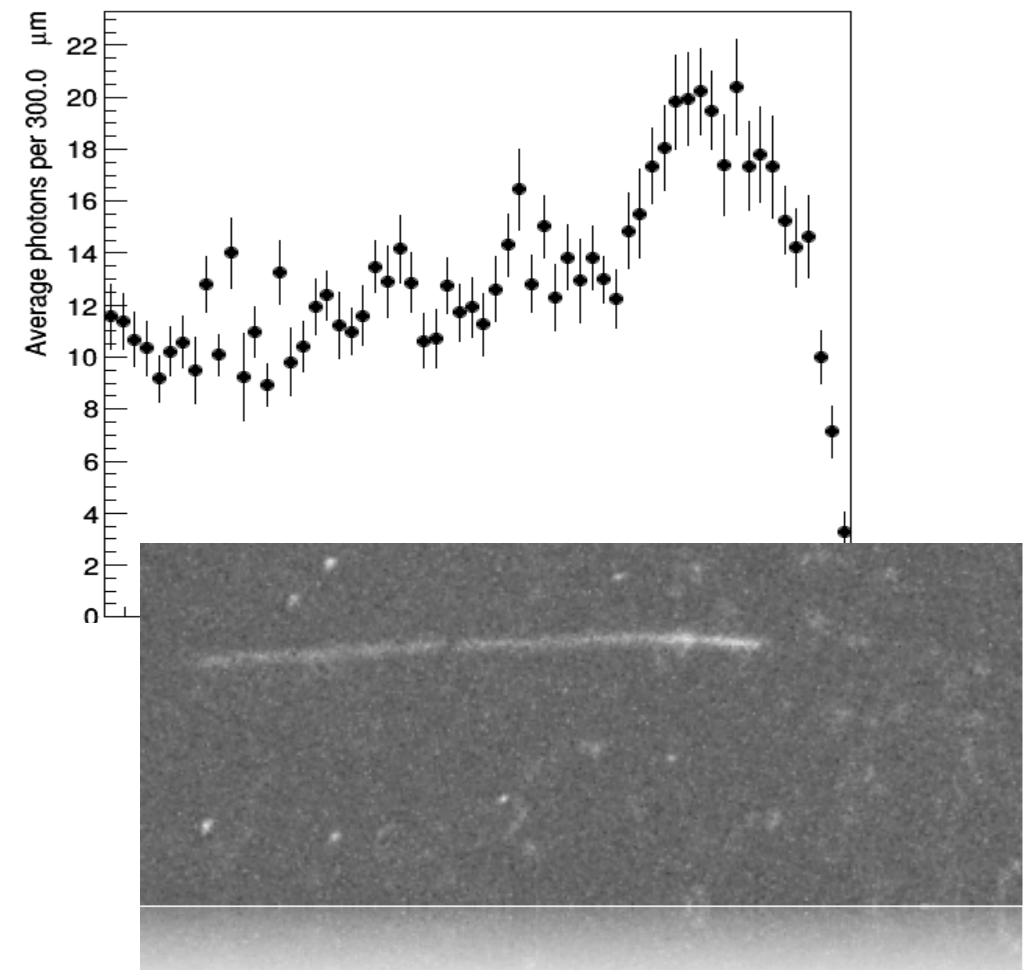


WHY TPC?

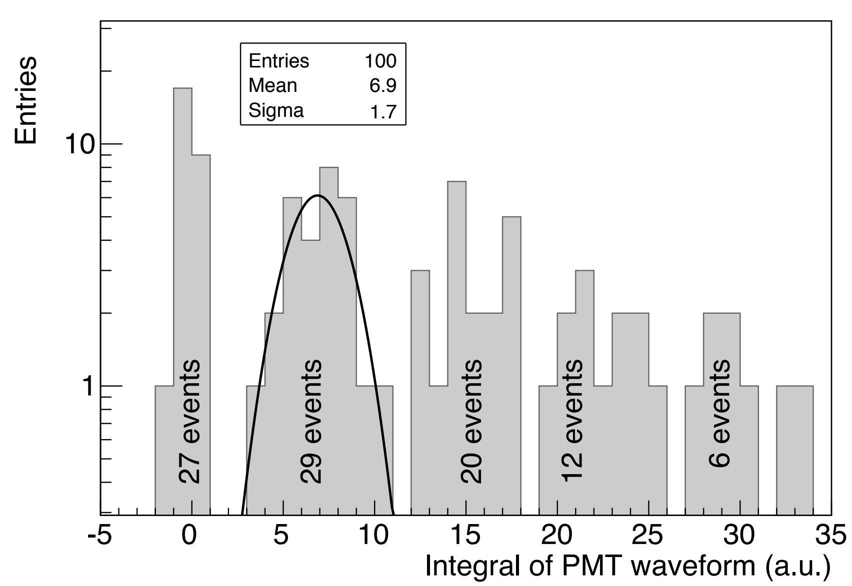
Time Projection Chambers provide:



3D tracking (position and direction);



total released energy measurement;

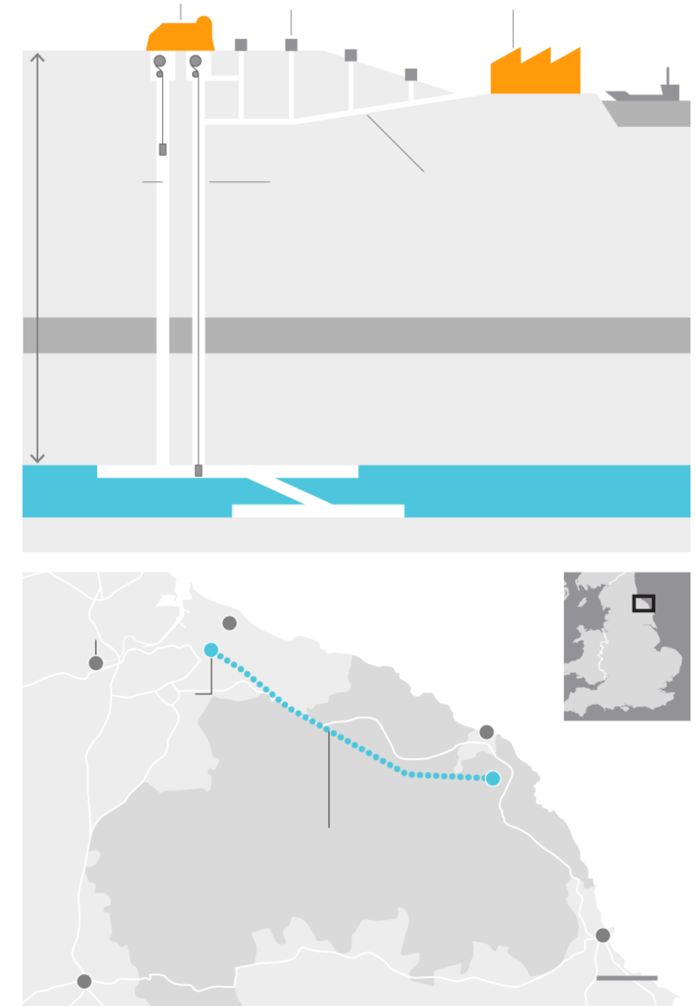


dE/dx profile (pid, head-tail);

relatively small amount of readout channels;

DRIFT

- 1.5 m^3 steel vacuum vessel
- target gas, typically 30 Torr CS_2 + 10 Torr CF_4
- MWP readout



Located in Boulby mine.

Demonstrates the use of dE/dx measurement, tuned so the detector essentially never triggers on the large background of Compton recoil electrons yet retains high efficiency for nuclear recoils;

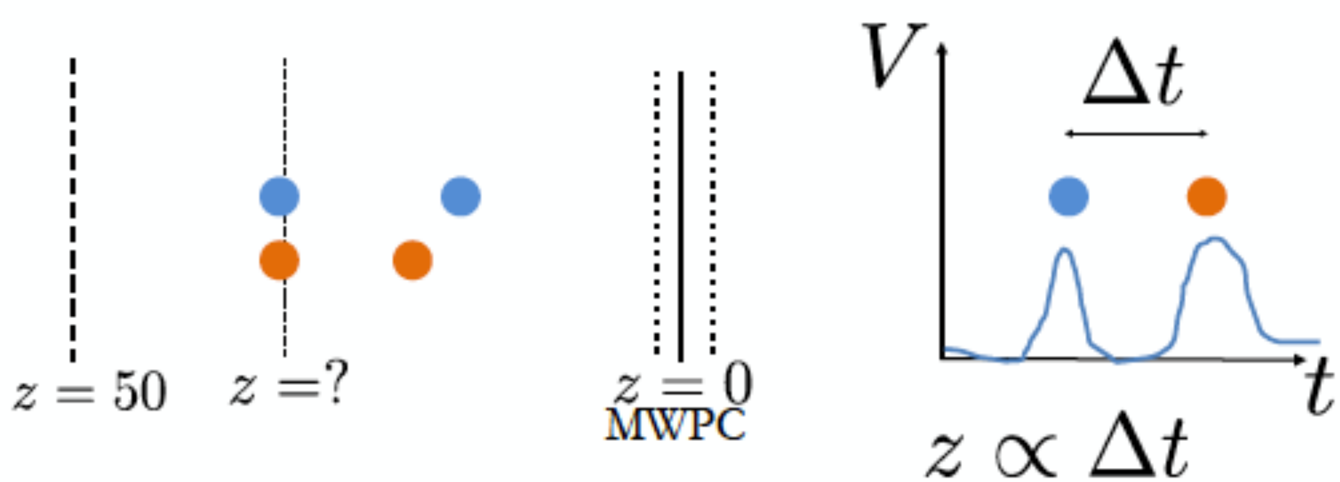
A nuclear recoil detection efficiency of ~60% was achieved with a gamma rejection factor, measured using ^{137}Cs, of 2×10^{-7}

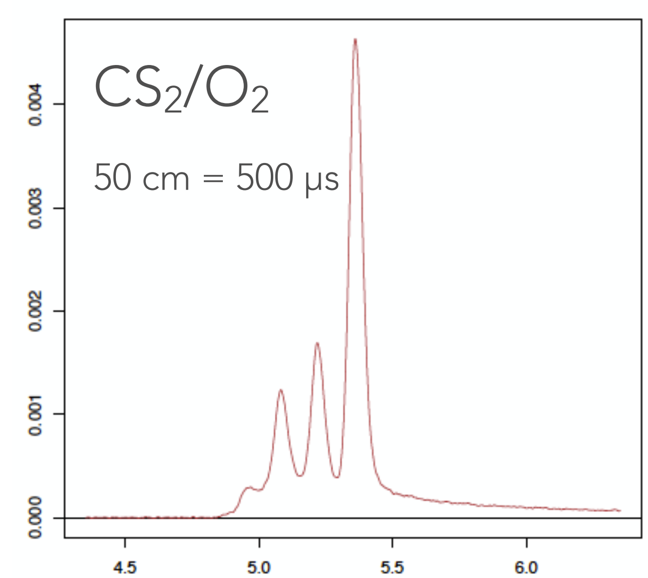
NEGATIVE ION DRIFT

With penetrating tracks (e.g. HEP) an external trigger can be exploited to measure the electron drift time to evaluate the event "Z";

In DM applications an alternative technique is the "negative ion drift":

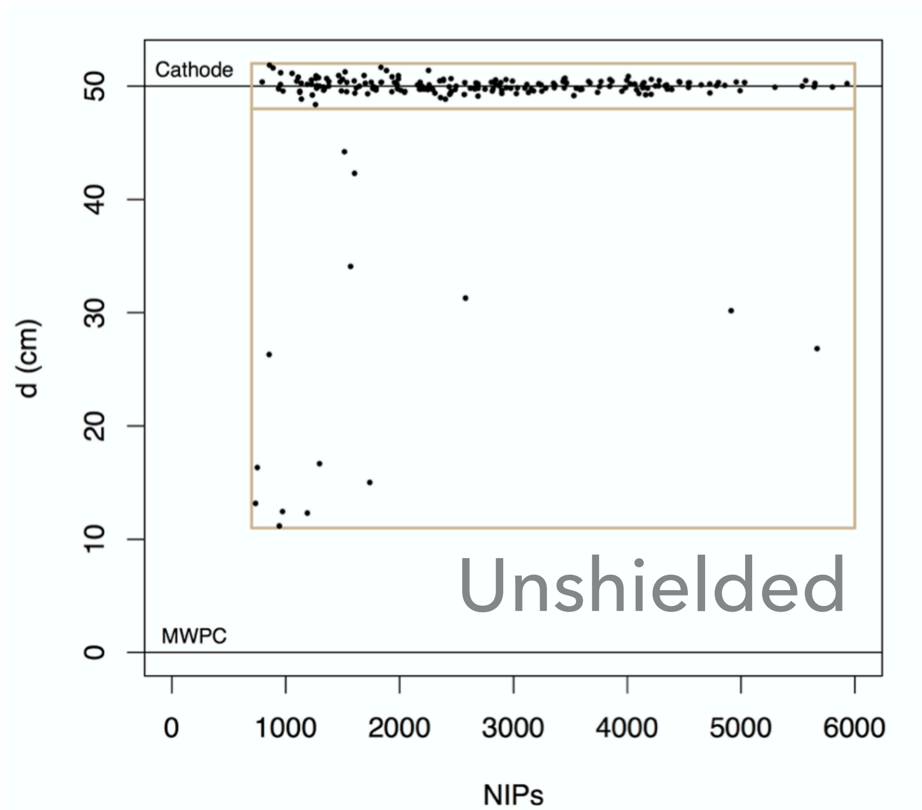
- ionization electrons can be absorbed by a high electronegative component of gas mixture (SF_6, CS_2);
- negative ions start to drift in the electric fields;
- at the multiplication stage, electrons are released and avalanches develop;

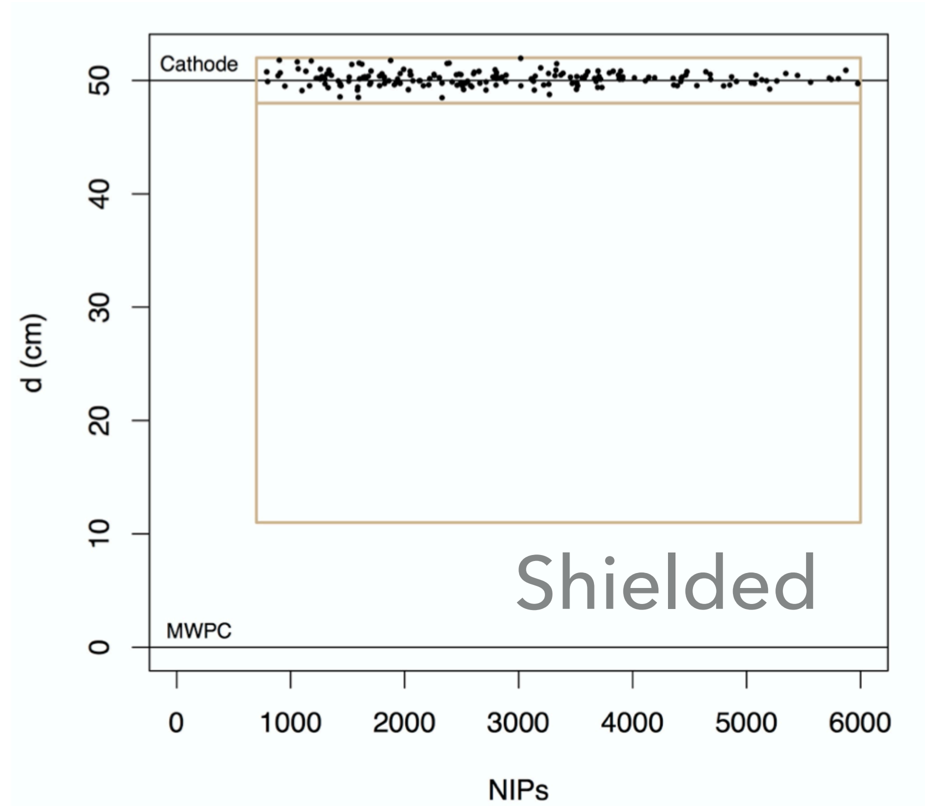




- The Z of the event is evaluated from the measurement of the difference of the time of arrival of ions with different masses and mobilities

DRIFT - NEGATIVE ION DRIFT (NID)



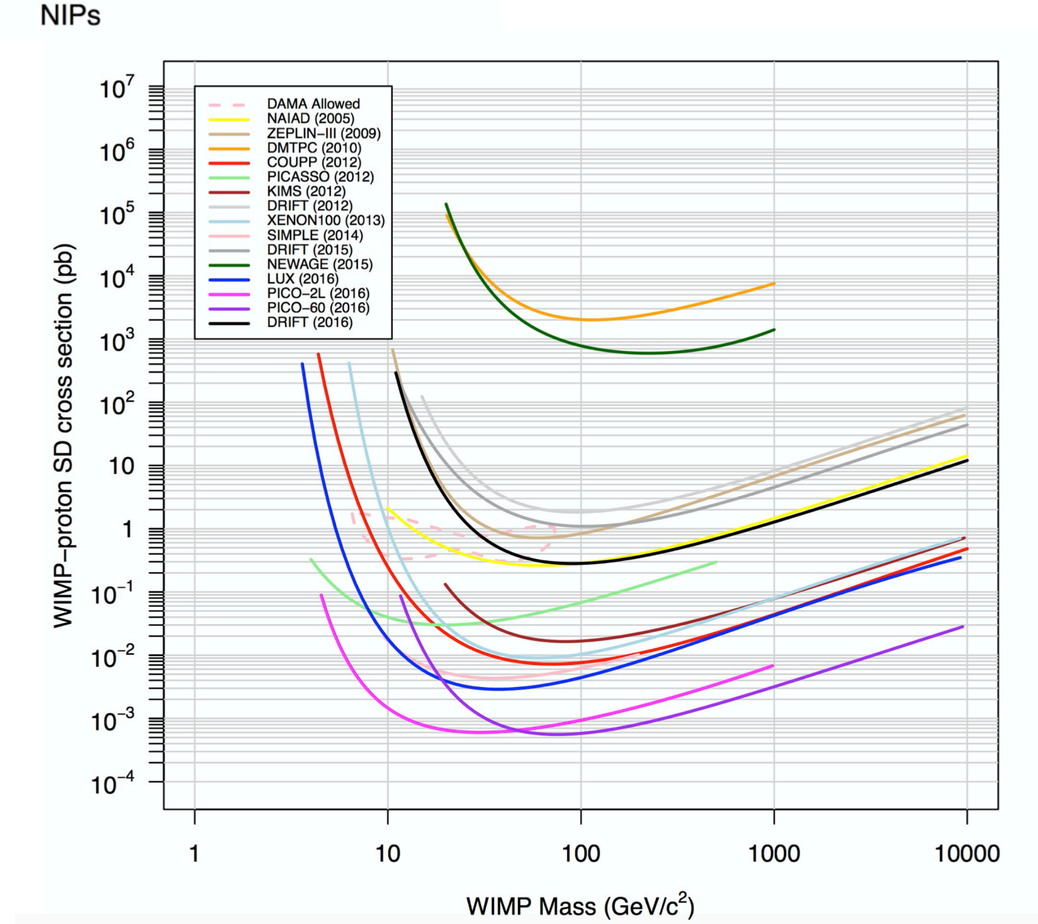


Experiment DRIFT observed 185 events in 54.7 shielded day data taking.

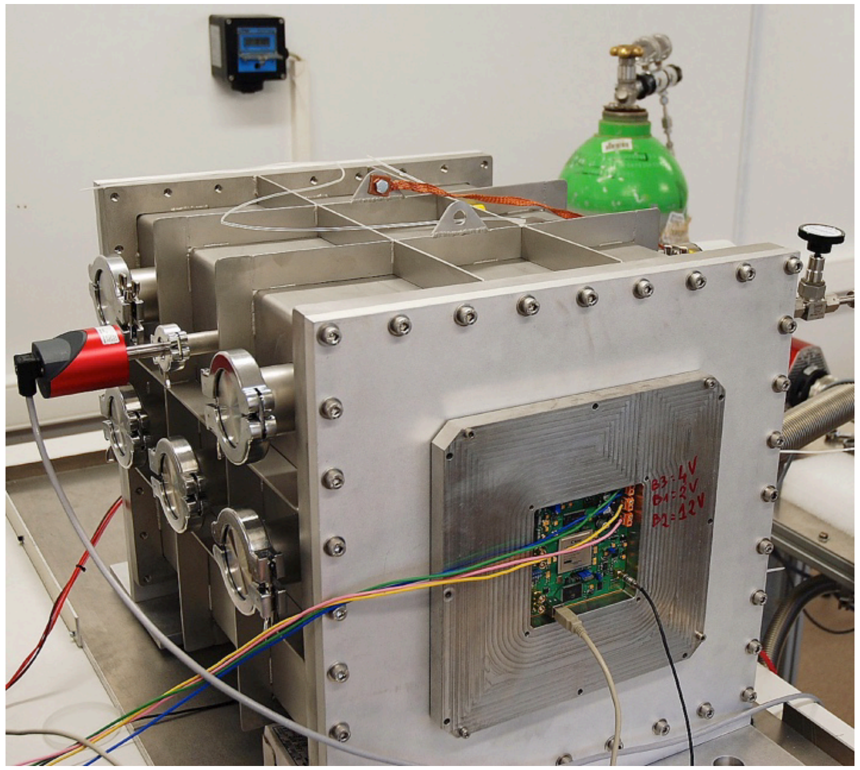
All of them were reconstructed to be produced close to the cathode plane and due radioactivity inside the material.

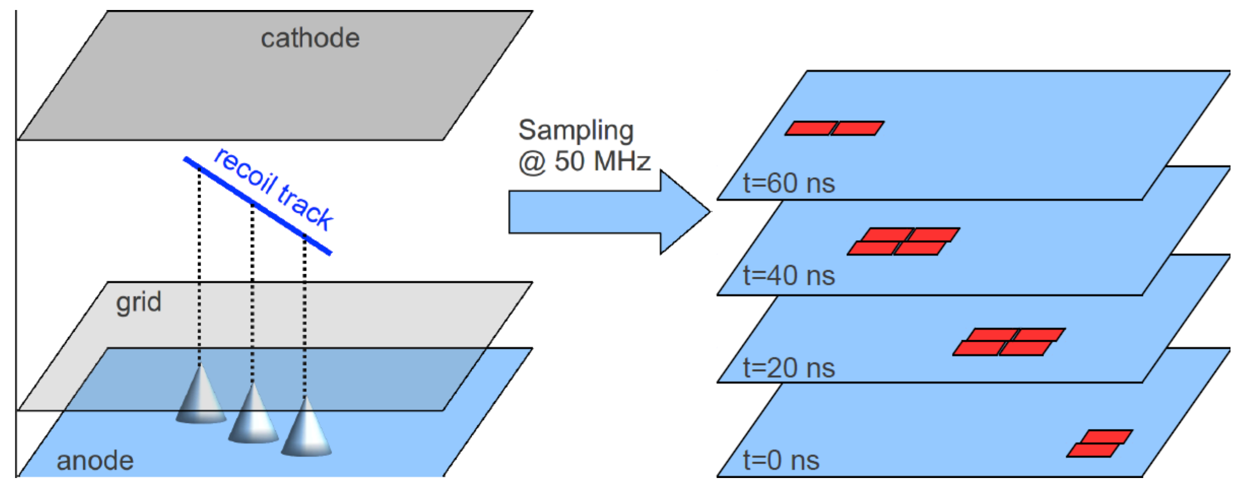
This allowed to set a 90% C.L. upper limits on the WIMP-proton spin-dependent;

First directional detector that excluded a fraction of DAMA region.



MIMAC

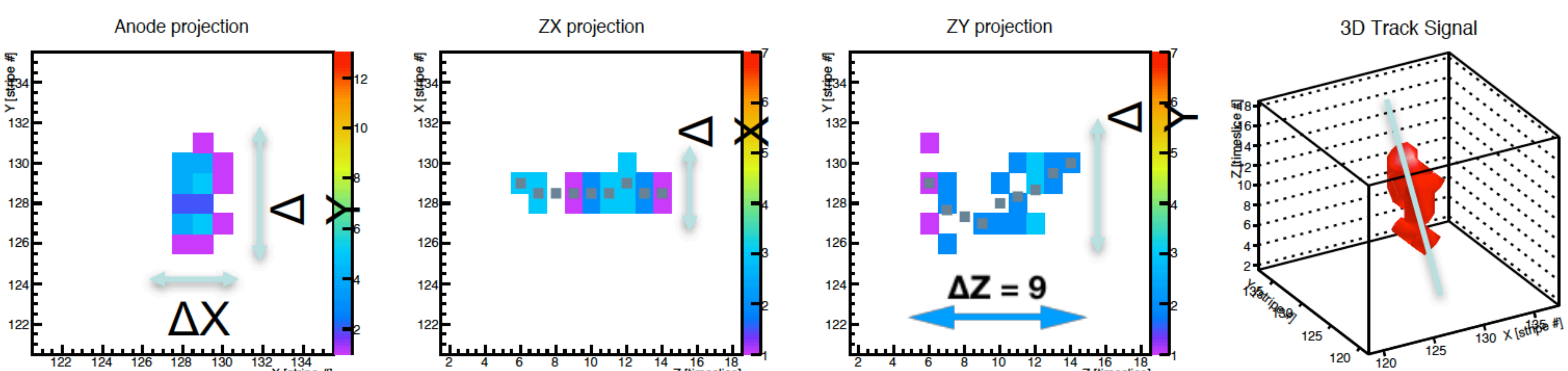




TPC with a Micromegas-based readout;

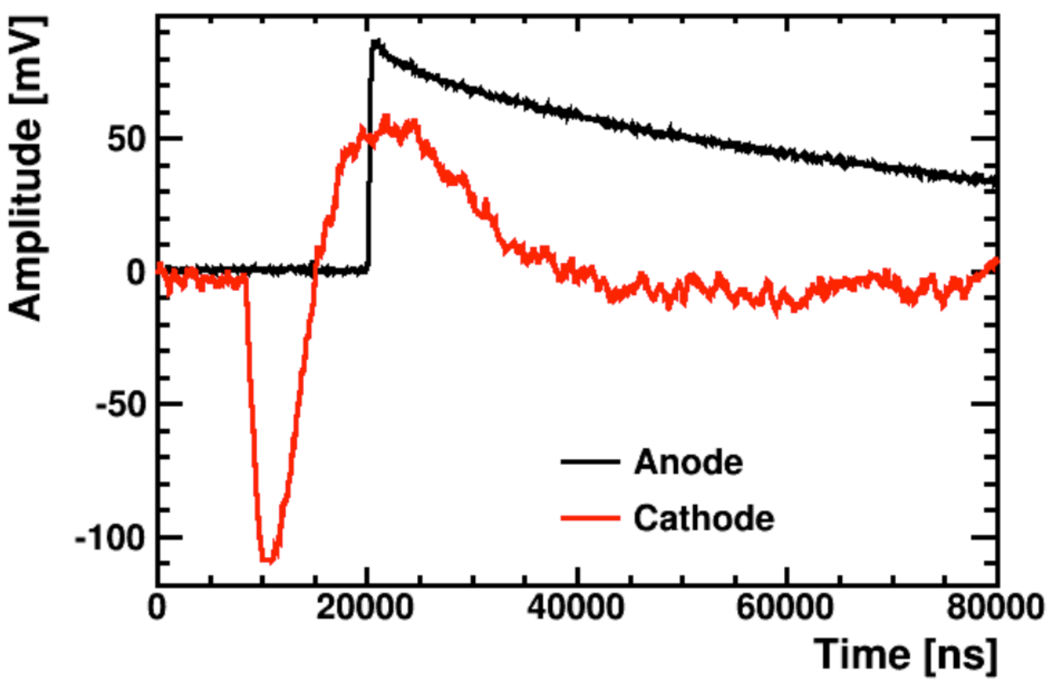
Charge integrator connected to the mesh coupled to a FADC sampled at 50 MHz

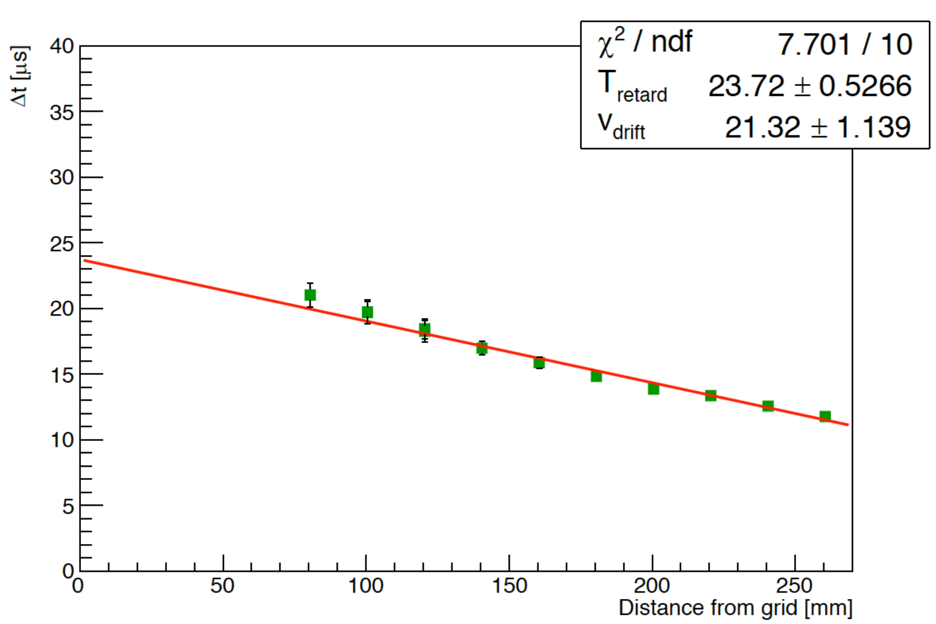
Fluorine 6.3 keV (~2 keVee)



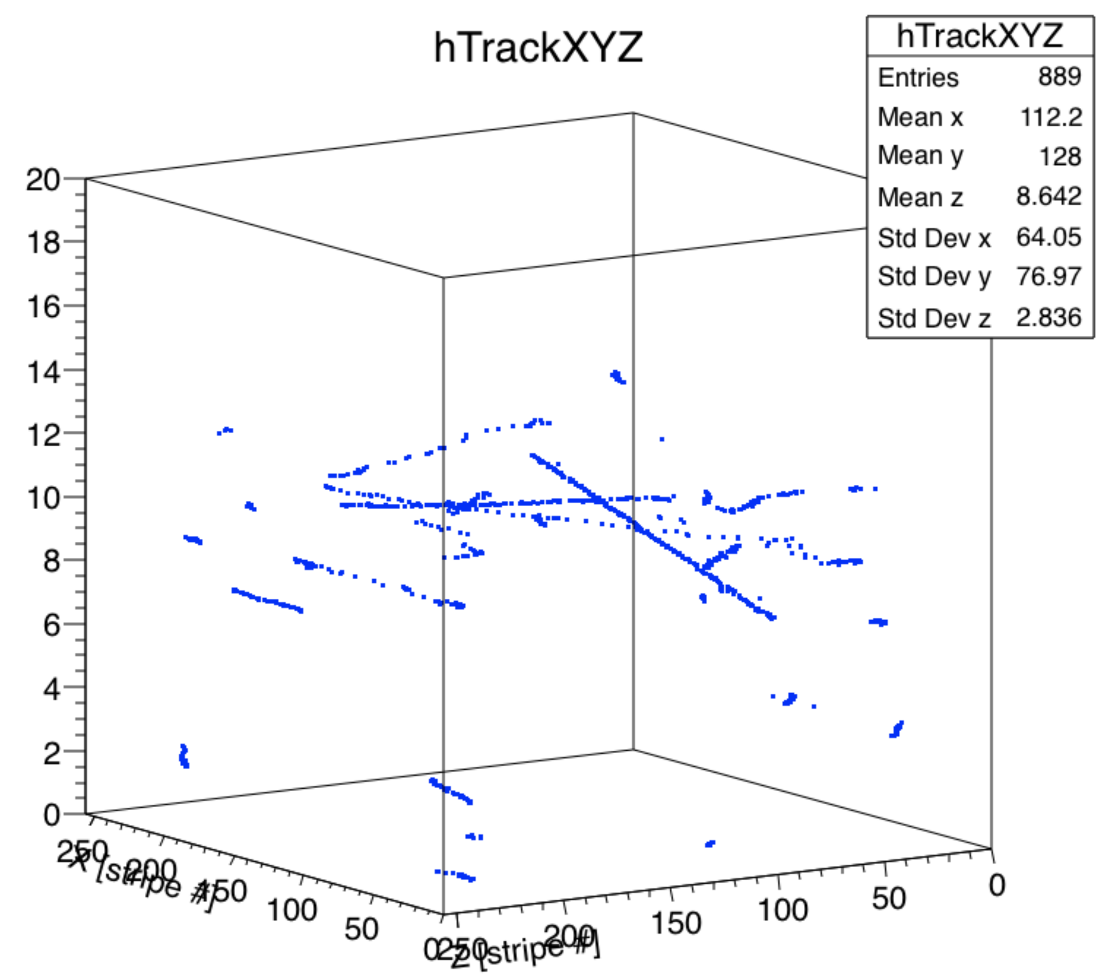
MIMAC - CATHODE SIGNAL TO PLACE 3D-TRACKS

The cathode signal is produced by the primary electrons before the anode signal before the avalanche.



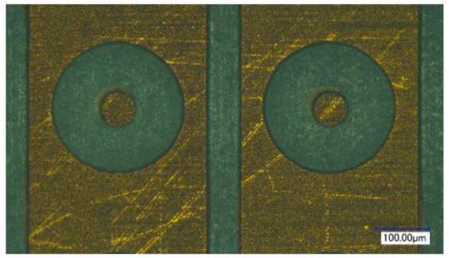


Measurement in a MIMAC chamber of an alpha passing through the active volume parallel to the cathode at 10 cm distance.



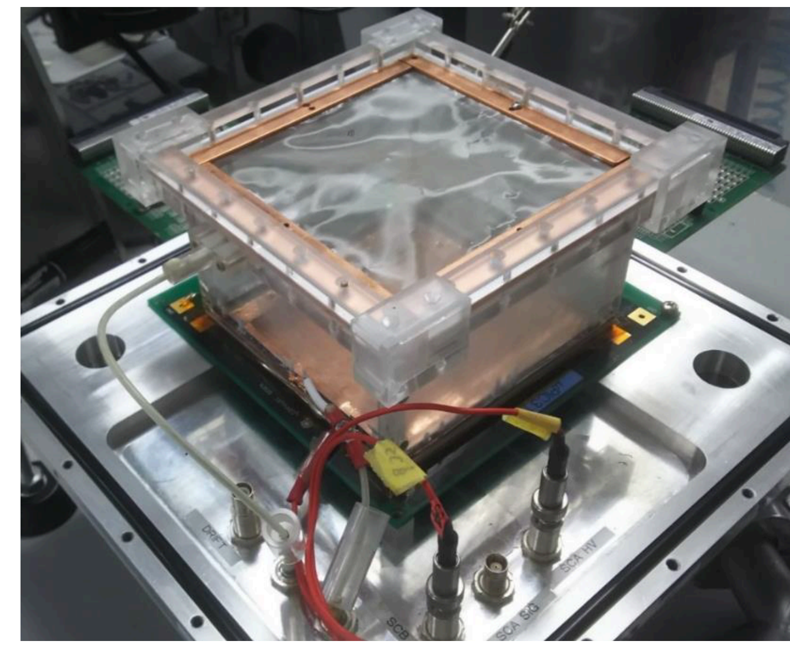
Resolution of about 1 cm in Z

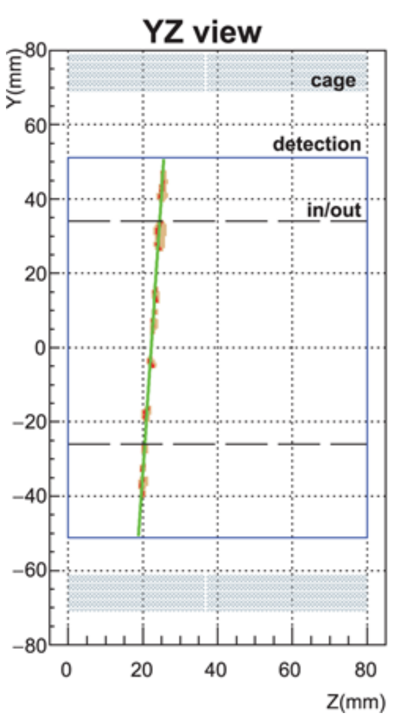
NEWAGE

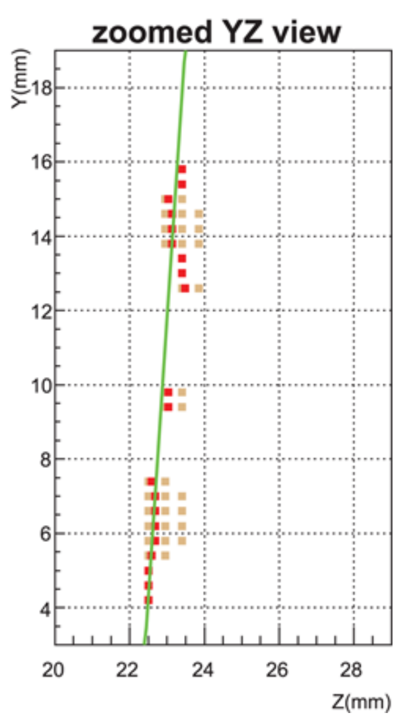


μPIC based TPC with CF_4 based gas mixtures

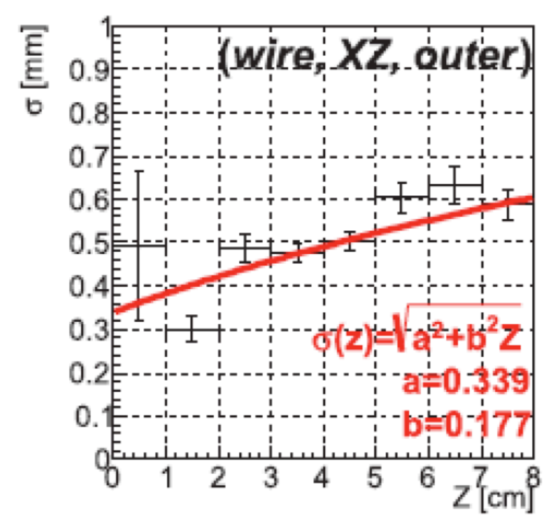
Field Cage with sheet resistor (SR) to overcome distortion of field cage and radioactive background

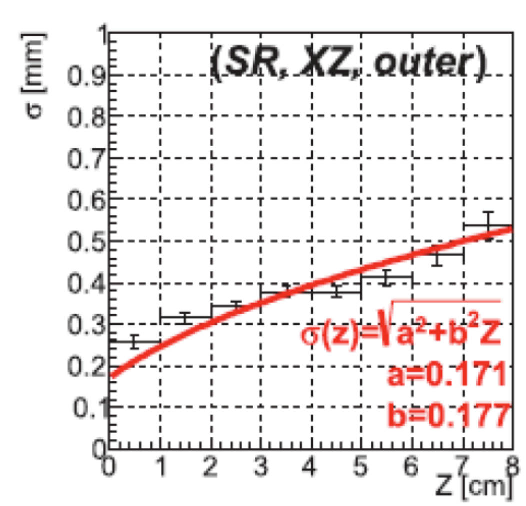




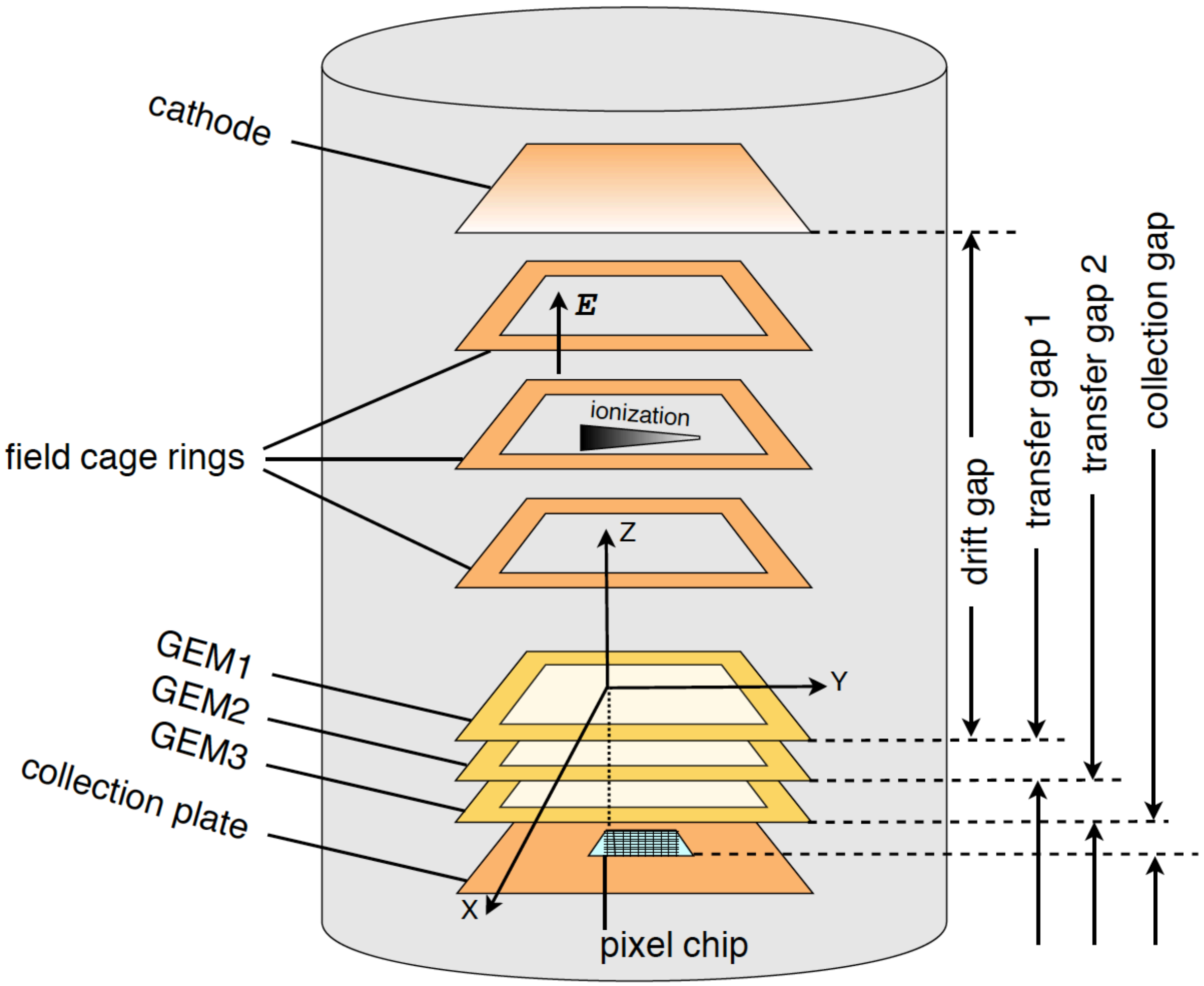


Better track reconstruction in the whole volume w.r.t wire Field Cage



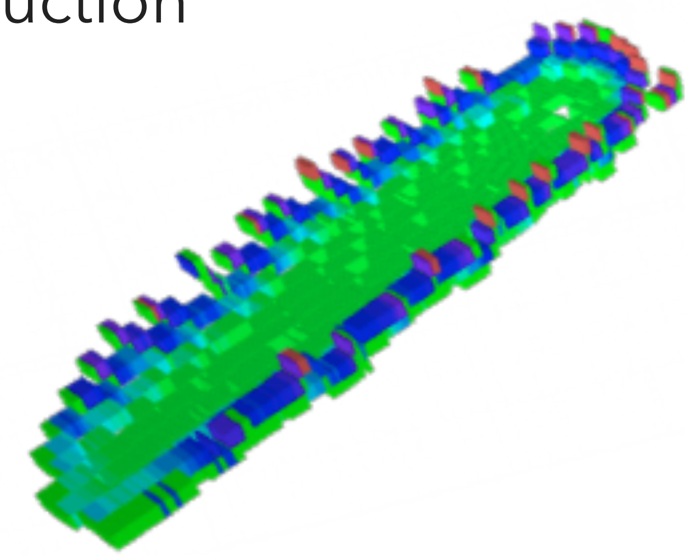


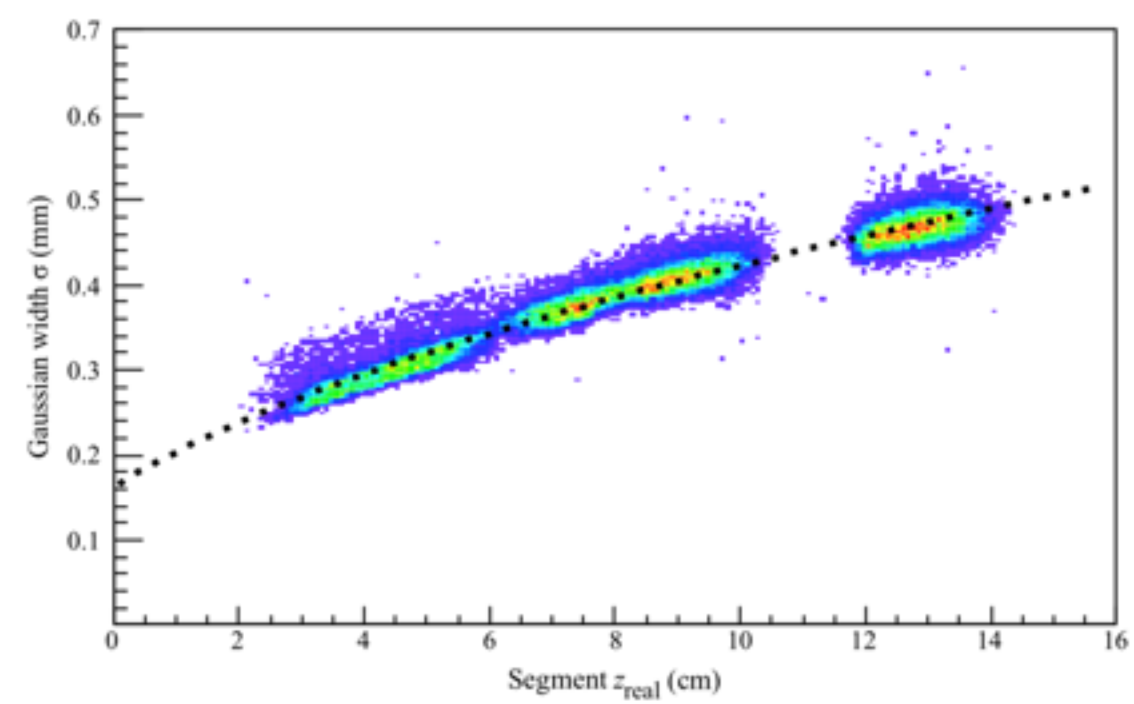
D³: DIRECTIONAL DARK-MATTER DETECTOR



TPC with GEM and pixel chip

Allows for vector 3D high resolution track reconstruction





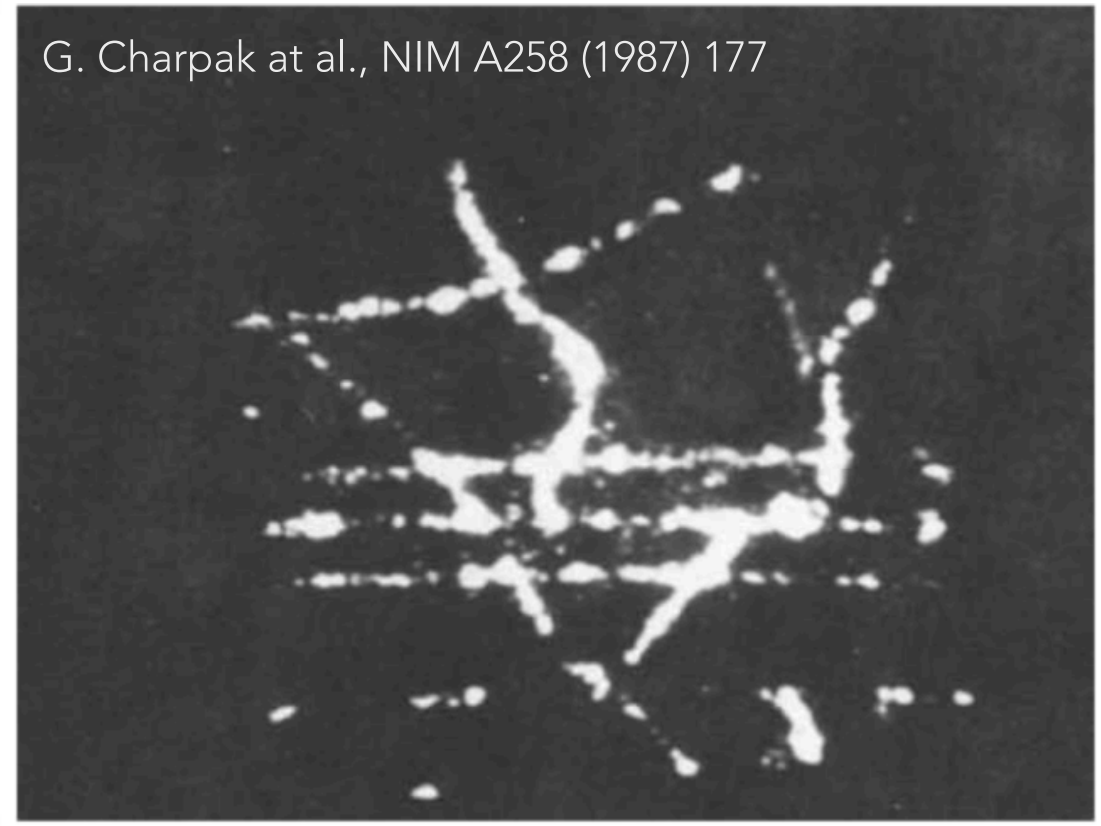
Charge diffusion:

- gives a one-to-one relationship between z and charge profile width
- allows for absolute z to be measured within ~ 1 cm

LIGHT: A CHANGE OF PARADIGM

During the multiplication process, photons are produced along with electrons by the gas through atomic and molecular de-excitation;

The CYGNO collaboration proposed to readout the light instead of electric signal.

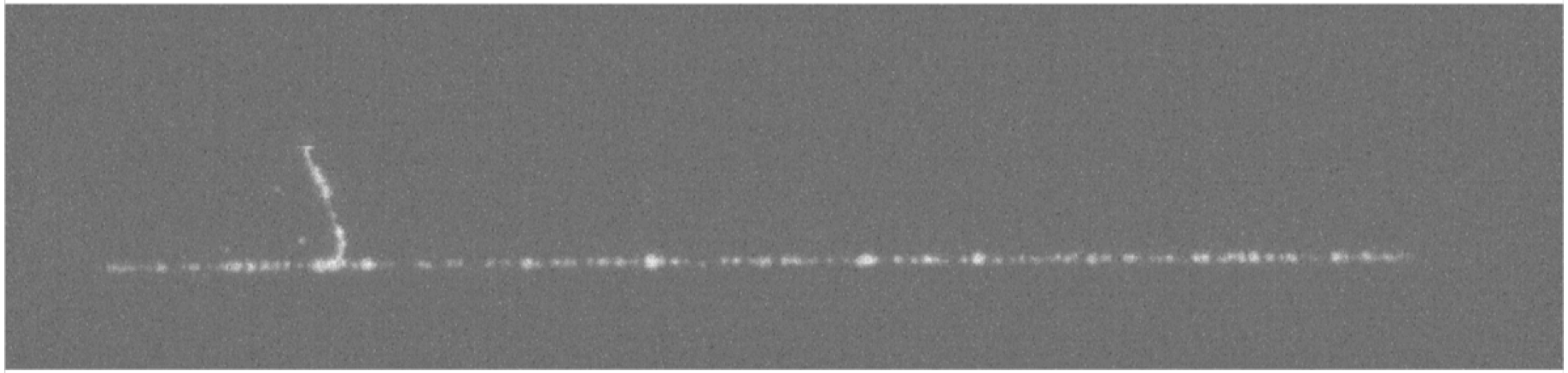


Optical readout of gas detectors offers several advantages:

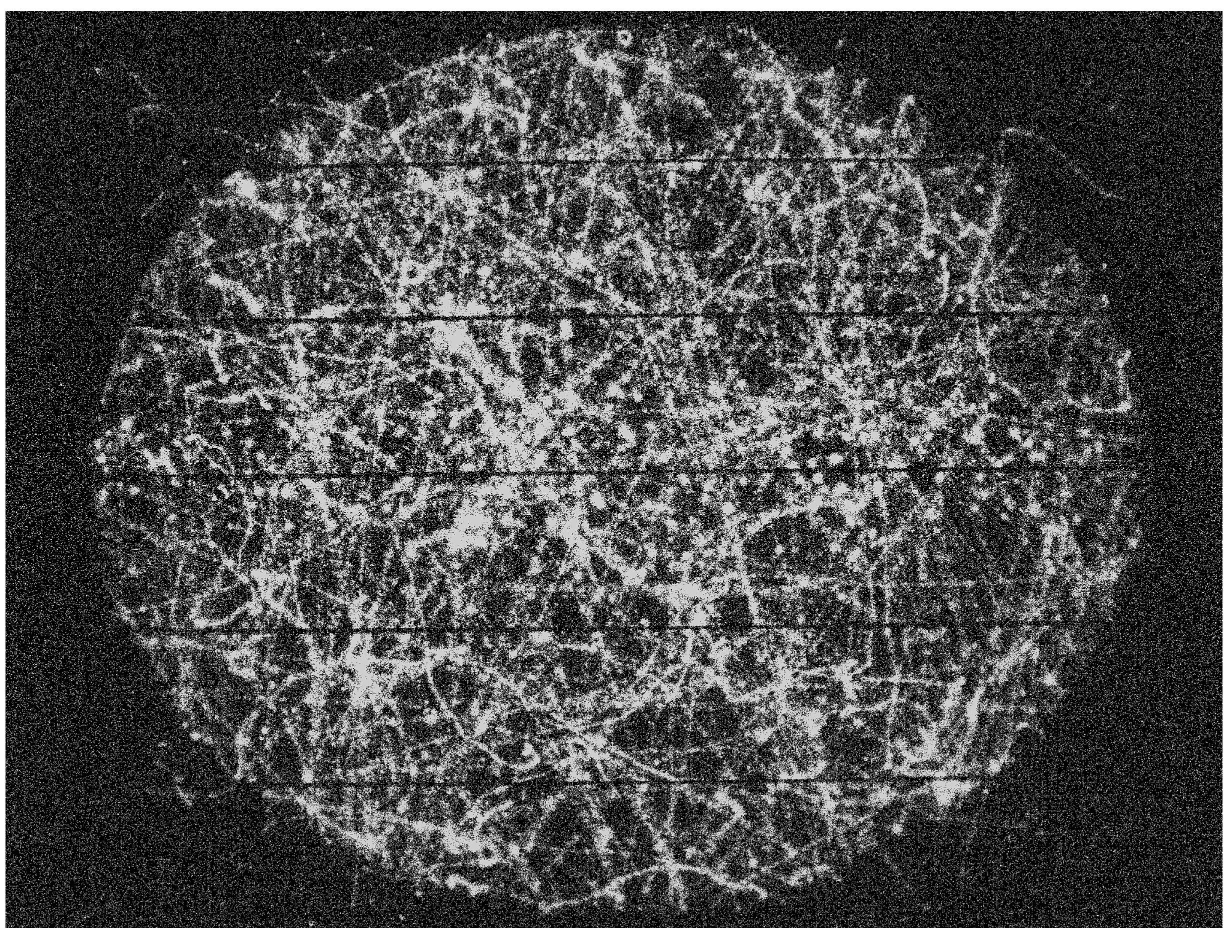
- optical sensors are able to provide high granularities along with very low noise level and high sensitivity;
- optical coupling allows to keep sensor out of the sensitive volume (no interference with HV operation and lower gas contamination);
- suitable lens allow to acquire large surfaces with small sensors;

CYGNO: SOME IMAGE

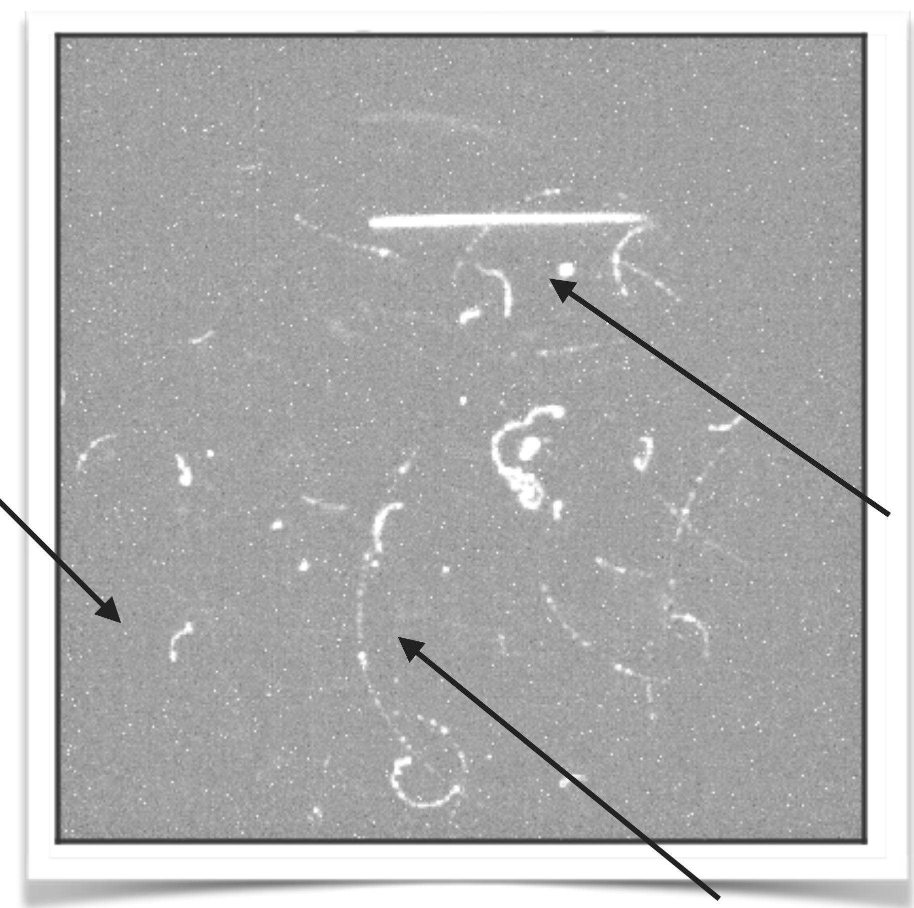
450 MeV electron with a δ ray



5 sec of natural background



Low energy electrons due to X rays

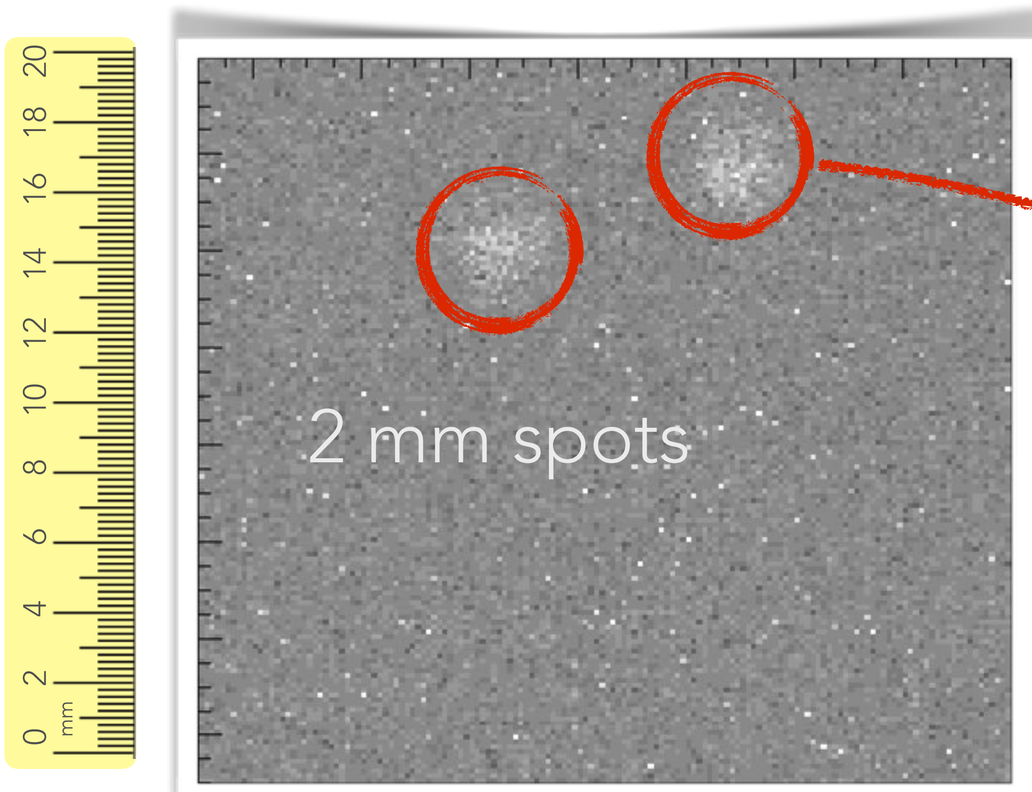


He nuclear recoils (α)

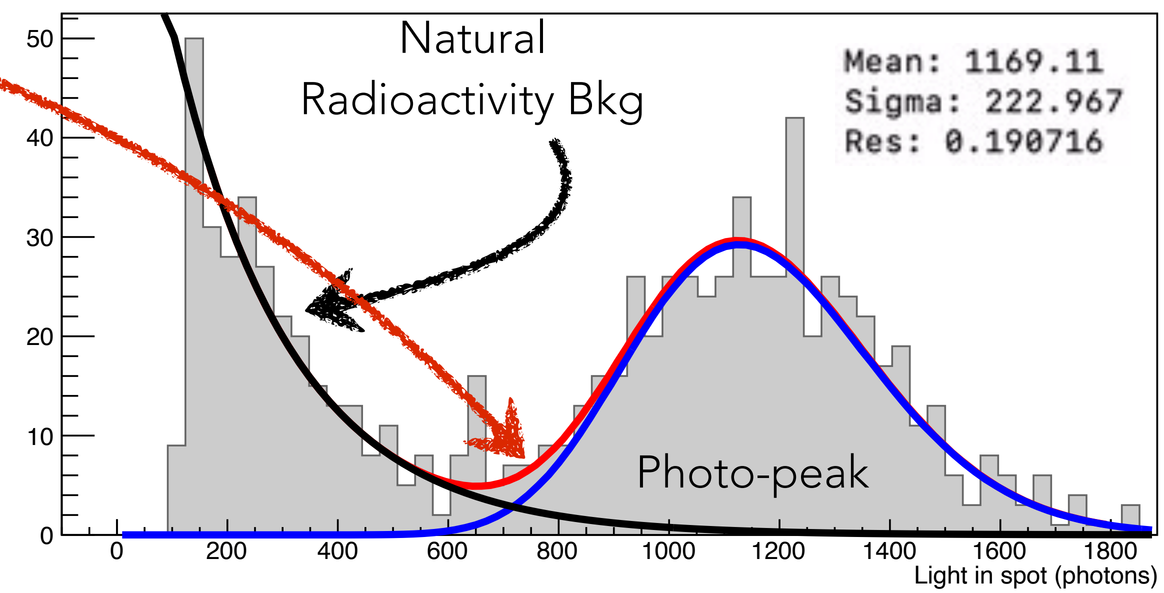
MeV electrons due to 4 MeV γ

PERFORMANCE AT LOW ENERGY

Light response to 5.9 keV ^{55}Fe measured with a source 20 cm far from the GEM.



Peak evaluated by a Polya fit



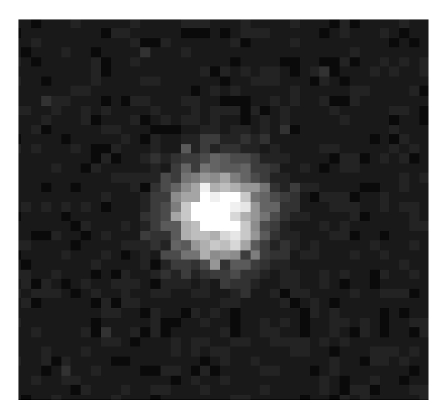
About 1170 photons are detected:

i.e. 200 photons per keV released.

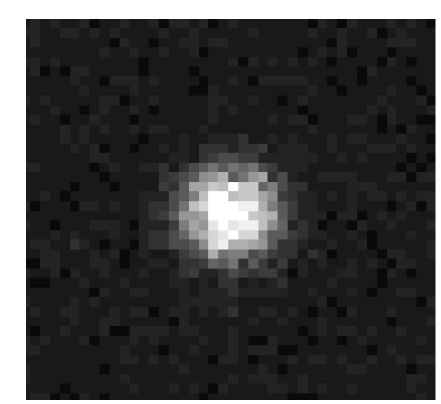
Eccentricity: $\rho = \dfrac{(A/\sigma)_y}{(A/\sigma)_x}$

$\rho_{NoDir} = 0.98 \pm 0.01$ and $\rho_{Dir} = 1.10 \pm 0.03$

10 keV helium

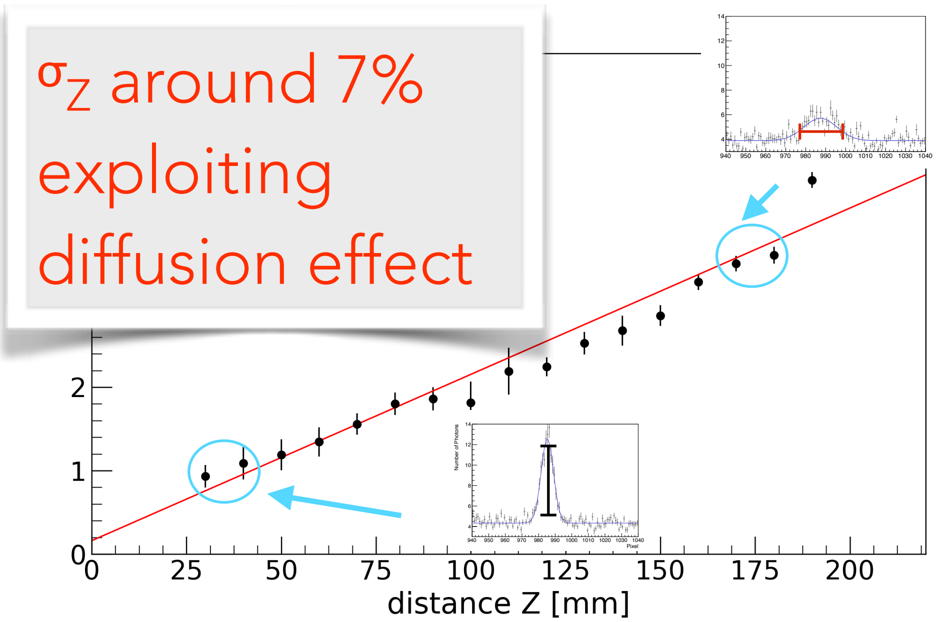


(pint-like before diffusion)

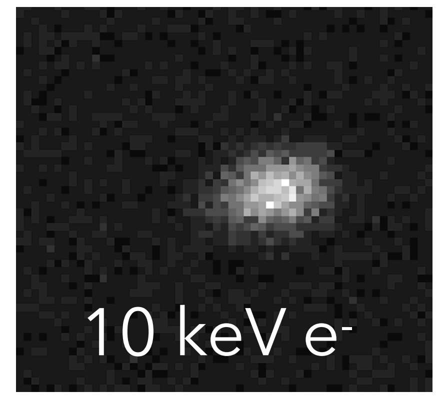


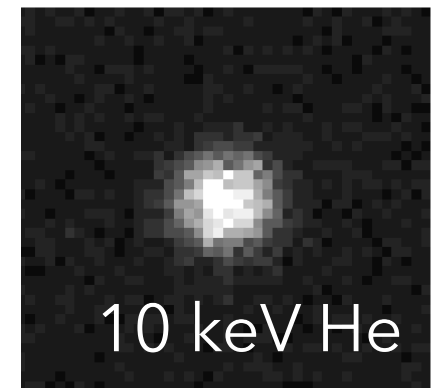
(170 μm before diffusion)

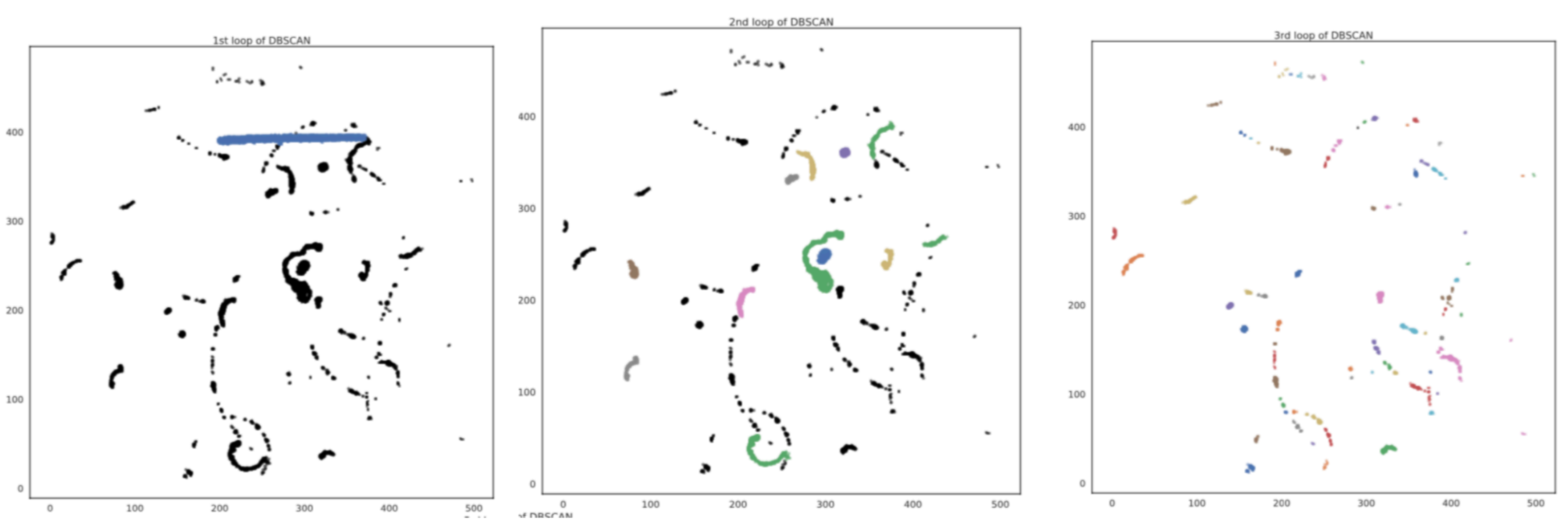
FIDUCIALIZATION AND BACKGROUND REJECTION

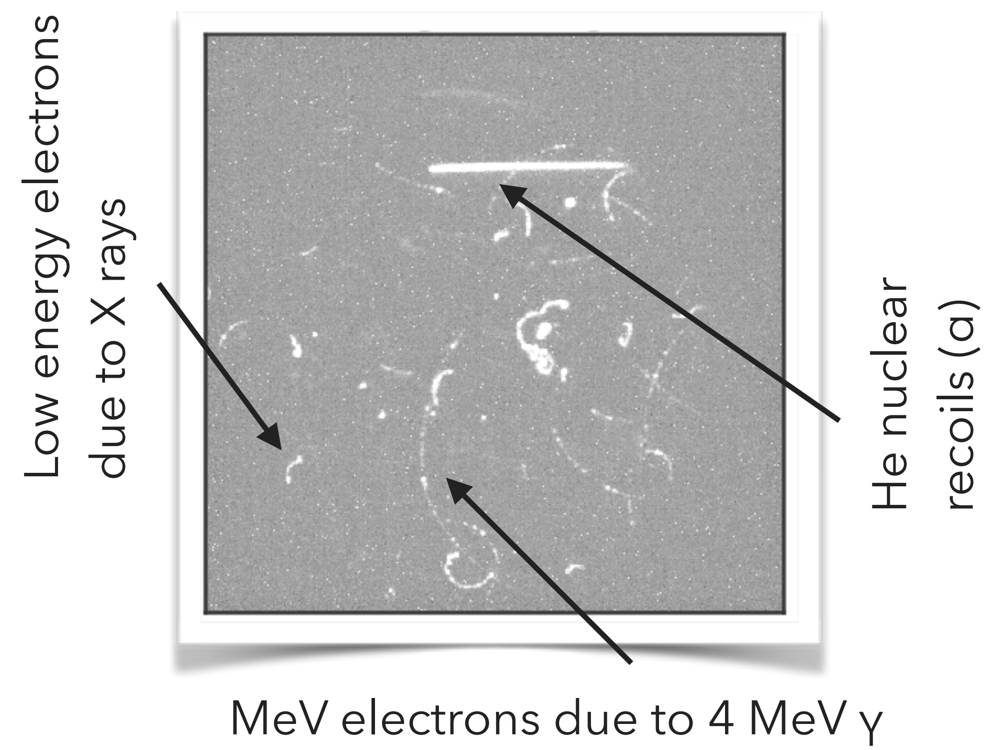


All information provided by the optical readout, allow to distinguish different particle tracks







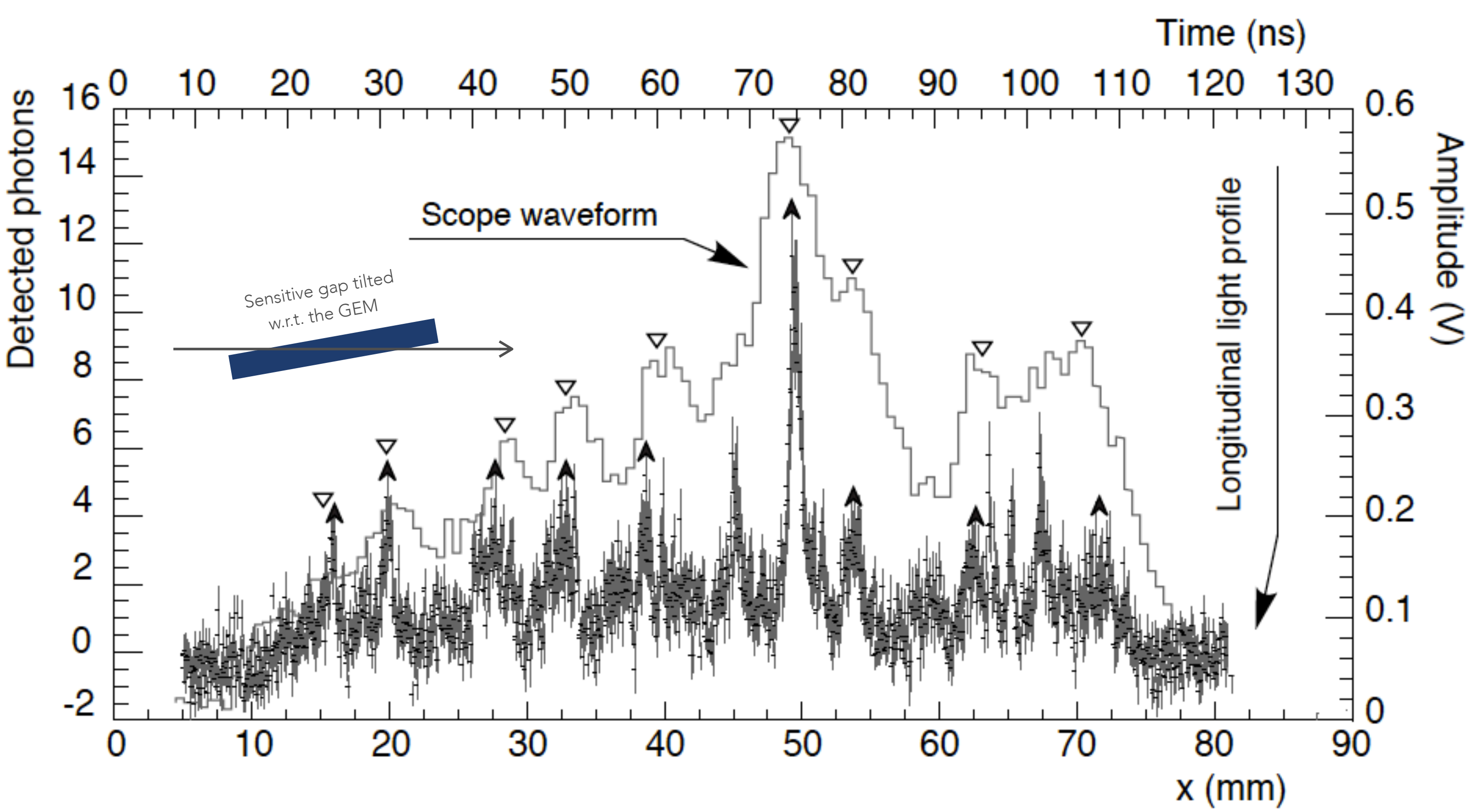


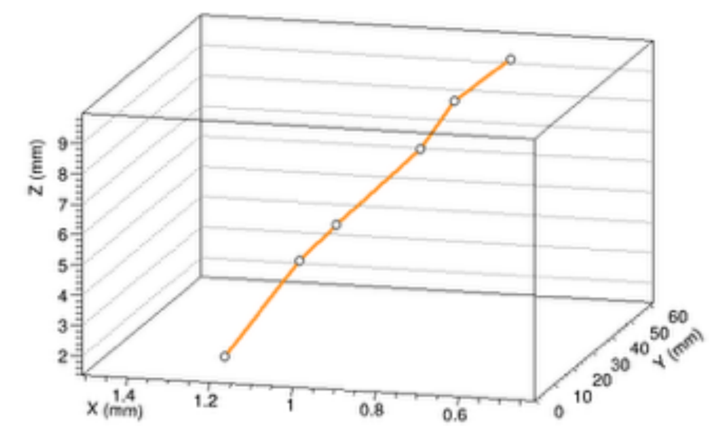
Track shape, brightness, size can be used by suitable algorithms to identify different particles

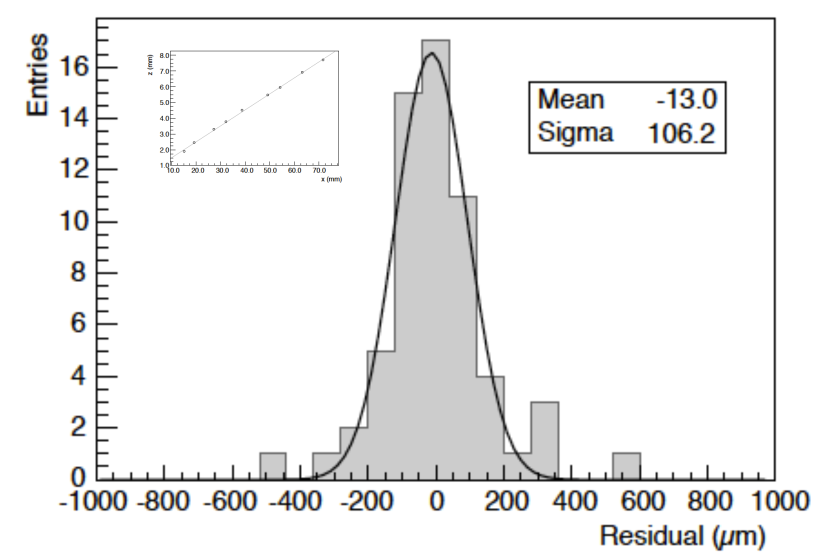
PMT+CMOS COMBINED READOUT

Single cluster 3D position reconstruction can be obtained by comparing the light profile along the track (X, Y) and the PMT waveform (t);

A peak finding algorithm was used to highlight the main cluster signals;





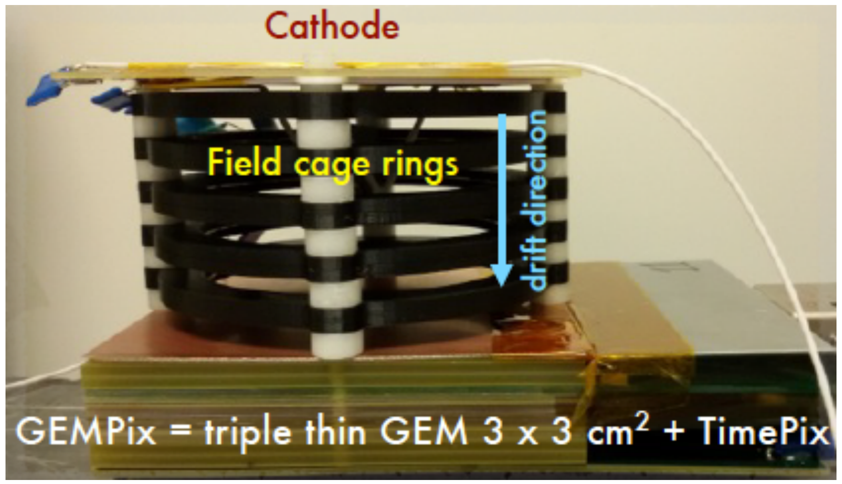


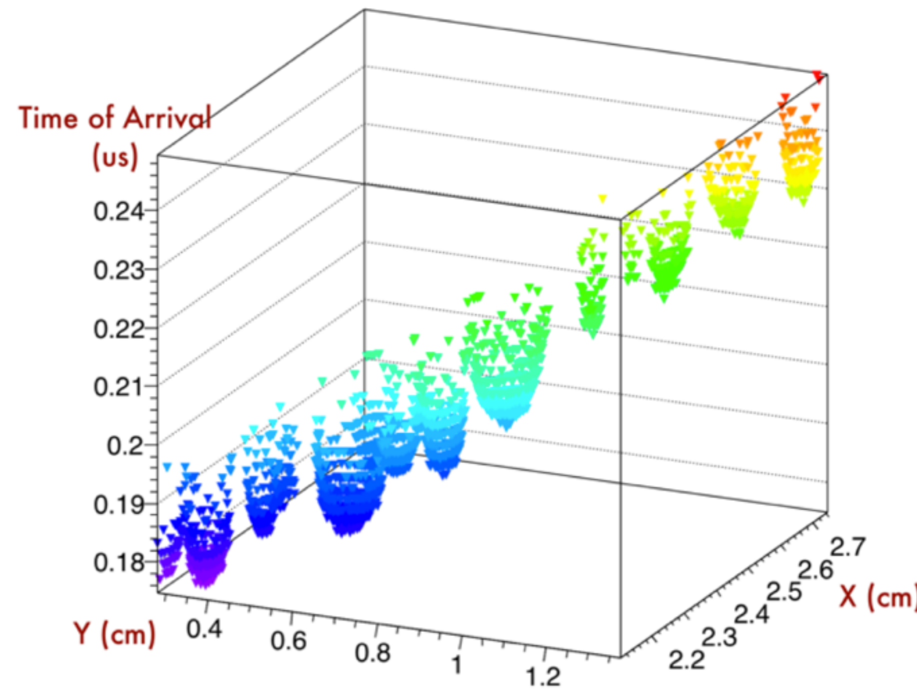
Residual distribution to a 3D fit allows to compute a resolution on Z of 100 μm.

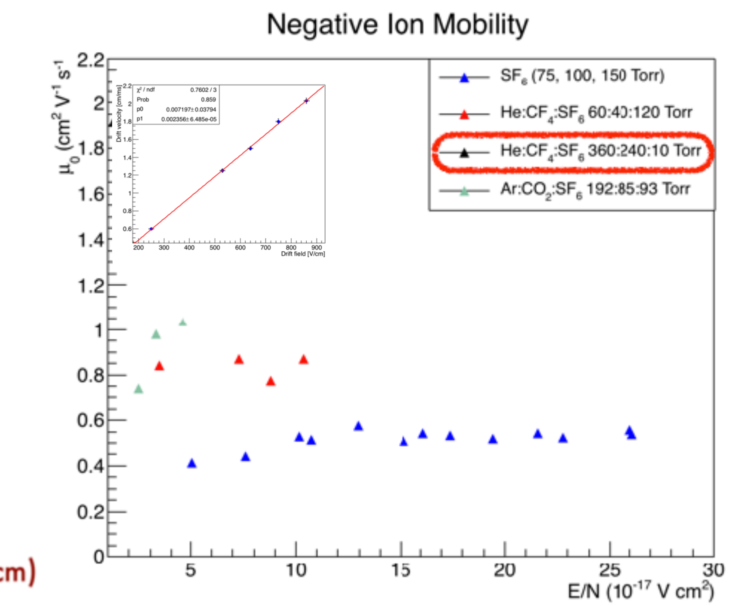
INITIUM: NEGATIVE ION DRIFT WITH OPTICAL READOUT

European Research Council

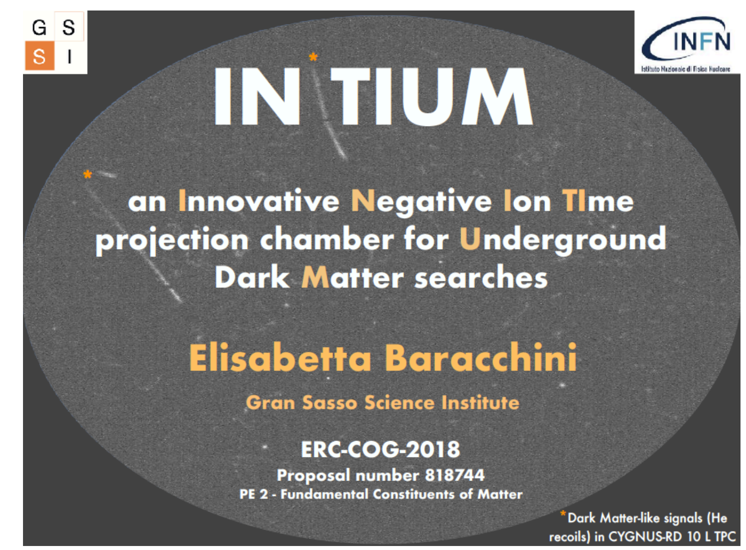
NITEC
a Negative Ion Time Expansion Chamber
for directional Dark Matter searches







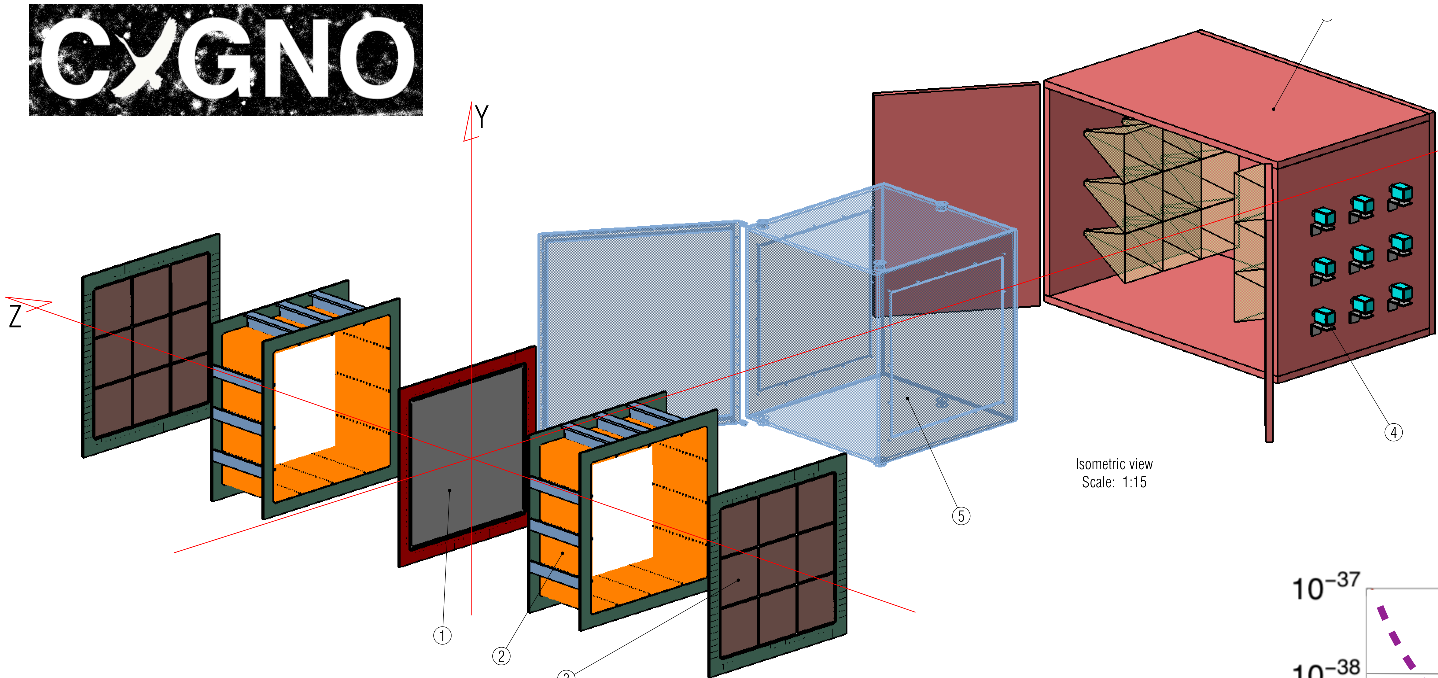
After having demonstrated the feasibility of Negative Ion Drift at nearly atmospheric pressure (610 Torr), within the CYGNO collaboration Elisabetta Baracchini (GSSI) won an ERC Consolidator Grant with (INITIUM) for



“the development and operation of the first 1 m^3 Negative Ion TPC (NITPC) with Gas Electron Multipliers (GEMs) amplification [in He/CF_4/SF_6 mixture] and optical readout with CMOS-based cameras and PMTs”

CYGNO DEMOSTRATOR

1 m^3 of He/CF_4(/SF_6) 60/40 (1.6 kg) at atmospheric pressure subdivided in two 50 cm long parts by the cathode with a drift field of about 500 V/cm

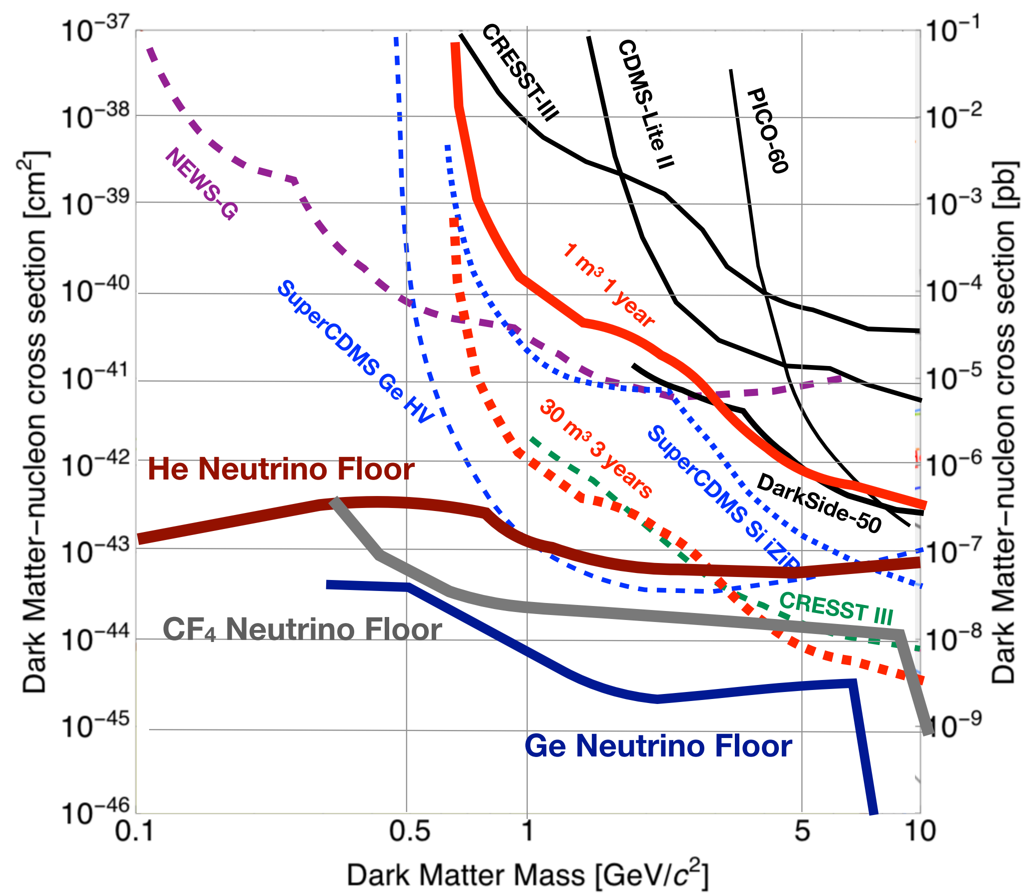


Each side equipped by a 3x3 matrix of:

- sCMOS sensor 65 cm away;
- Fast light detector (PMT or SiPM).

One year of operation of CYGNO (expected for 2022) will already explore new low mass regions;

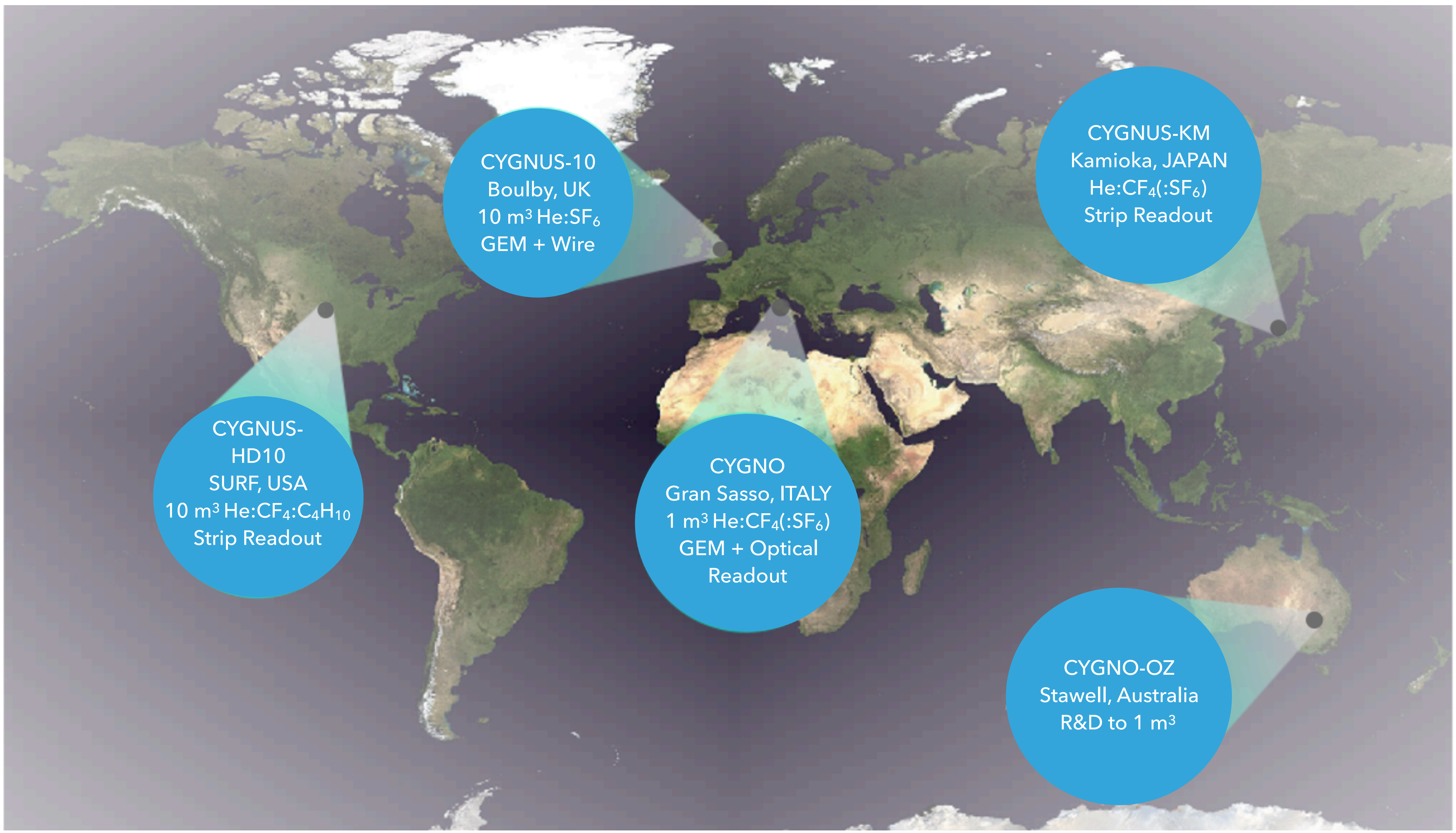
A 30-100 m^3 experiment would be able to reach the neutrino floor.



CYGNUS

Multi-site Galactic Recoil Directional Observatory for WIMPs and neutrinos;

More than 50 signed members UK, Japan, Italy, Spain, China focused on gas TPCs with 2D or 3D direction sensitivity;



THANK YOU!