The CYGNO Experiment

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DRD1 meeting – WP2 session

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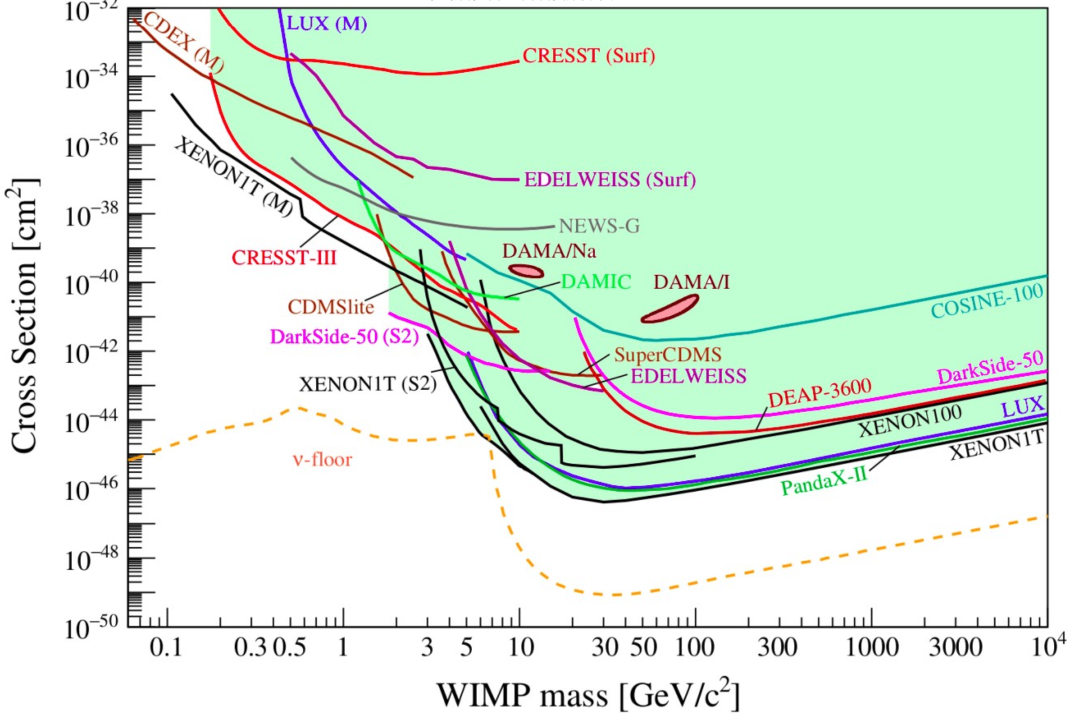
Dark Matter

- In the cold dark matter assumption of the ΛCDM model, WIMP-like or sub-GeV particles can rarely interact with regular matter inducing electron and **nuclear recoils** (O(1) keV)
- Direct detection experiments seek this signature with large and very sensitive detectors (<1 evt/year/ton)
- No signal has been found yet and confidence limits are placed
- Next generation of larger detectors (based on xenon and argon) will achieve sensitivities to extremely low cross section values

Billard et al, 10.1088/1361-6633/ac5754



Energy-only Limitations

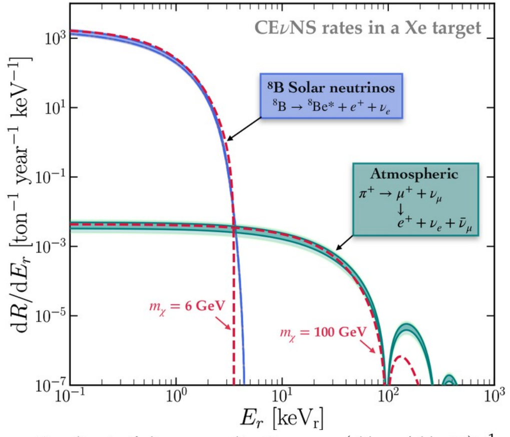
Current experiments are sensitive only to the energy of the recoils and exploit different techniques to discriminate background (ER: electron recoils) from signal (NR: nuclear recoils)

- Signal and background energy distributions are both falling exponential at first order

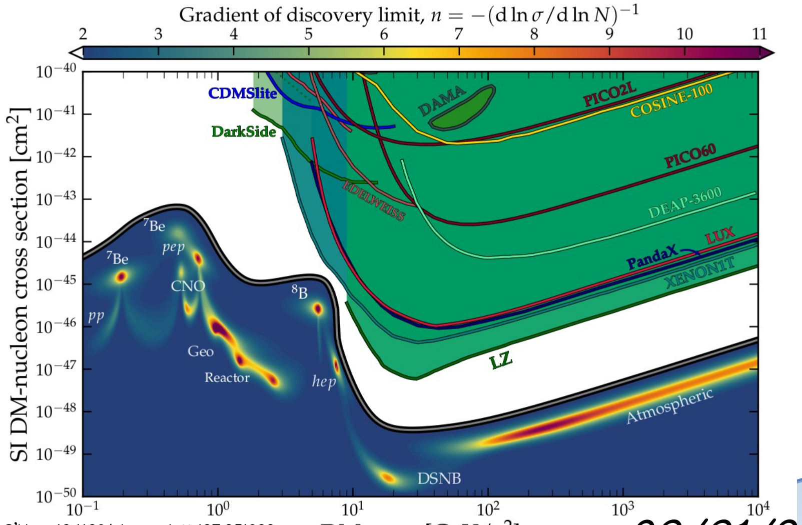
- Soon large exposure experiments will be sensitive to neutrino-induced nuclear recoils (CEνNS) and will have their search hindered by the **neutrino fog**

- **Physics:** to study the Galactic distribution of DM one needs to infer velocity distribution properties.
  Energy measurements can only provide a projection of this distribution

$$\frac{dR}{dE} \propto f\left(|\vec{v}|\right)$$



O'Hare at IDM 2022



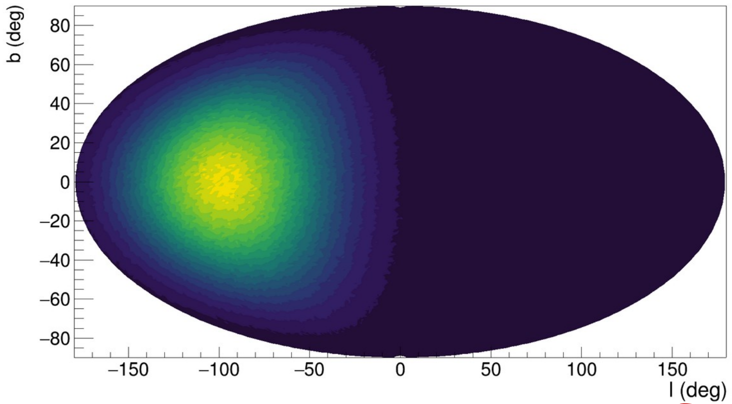
O'Hare 10.1103/physrevlett.127.251802

DIRECTIONALITY

- Nuclear recoils have also an angular distribution that could be measured

- This is an addition of an **extra degree of freedom**

$$\frac{dR}{d\cos\gamma} \propto \int_{E_{thr}}^{E_{max}} e^{-\frac{(v_{lab}\cos\gamma - v_{min})^2}{v_p^2}}$$



Galactic coord

10 GeV WIMP

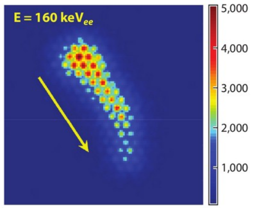
Fluorine target

Strong anisotropic distribution

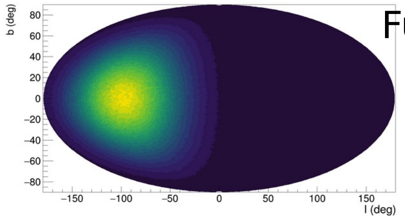
Relevant directional parameters

- **Head-tail** recognition

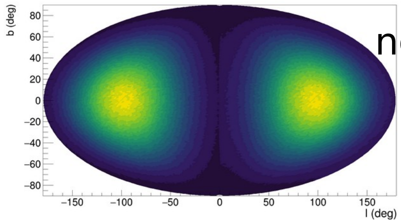
Vahsen et al., Annual review



- Angular resolution



Full HT

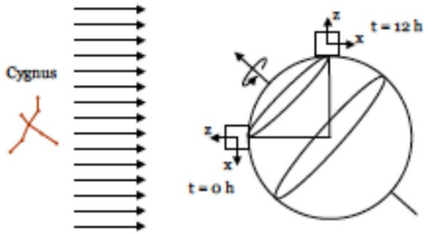


no HT

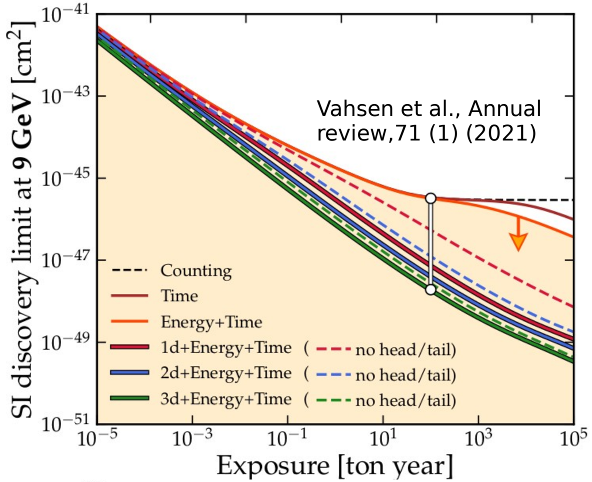
Advantages

- In Galactic coordinates the background is generally isotropic, making the WIMP dipolar one easier to discriminate **(Positive claim of WIMP DM discovery)**

Billard, Mayet, Santos (Physical Review D ,85(3) (2012)



- The neutrino fog can be sidestepped (almost completely for Solar neutrinos) with nice directional performances (HT>75%, ang res>20°)

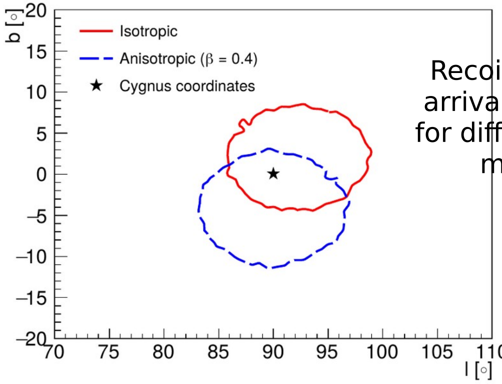


Vahsen et al., Annual review,71 (1) (2021)

- High performance directional detector will be able to estimate the **3D structure of the velocity distribution,** actively probing DM theories

$$\frac{dR}{dE} \propto f\left(\vec{v}\right)$$

Mayet et al., P.R., 627 (2016)

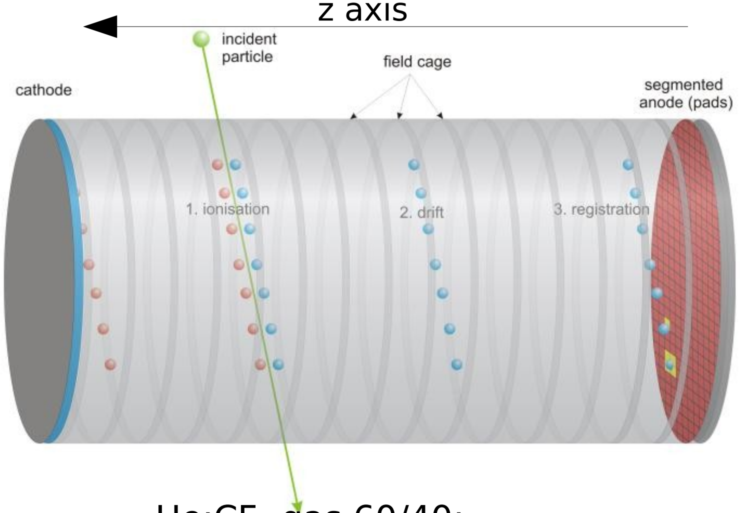


Recoil average arrival direction for different Halo models

CYGNO EXPERIMENT

- CYGNO project aims to construct a large directional detector, O(10–100) m^3, for rare event searches (DM, Solar neutrinos)

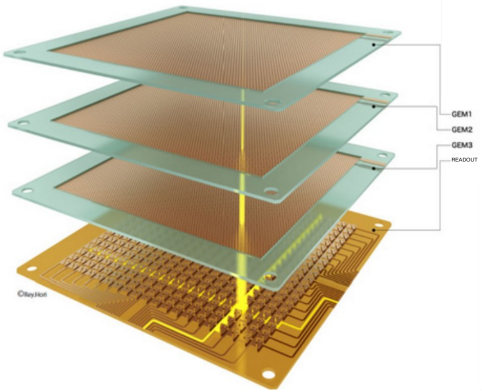
TPC



He:CF_4 gas 60/40:
room temperature
atmospheric pressure

F gives SD sensitivity
He for low DM mass sensitivity
CF_4 scintillates in visible range

Amplification Stage



Gas Electron Multipliers (GEMs)

Grants large gains
with high granularity O(50) um

Optical readout

PMT
sCMOS cameras

Decoupled from gas,
less contamination

CYGNO Experiment Optical Readout

sCMOS Camera

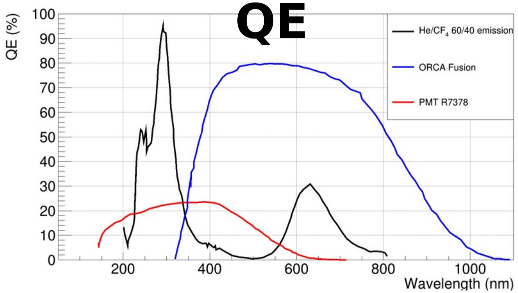
- Highly sensitive and granular sensor

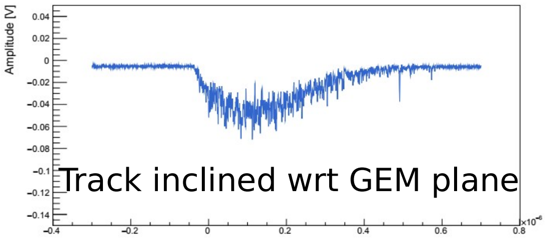
  (1 camera can image a 35x35 cm^2 area 62 cm away from the amplification pane with 155x155 m^2 granularity)
- Low noise per pixel (modern below 0,7 e^- RMS)
- Market pulled
- Provides
  - Energy information from number of photons
  - dE/dx on X–Y plane
  - X–Y positionand topology

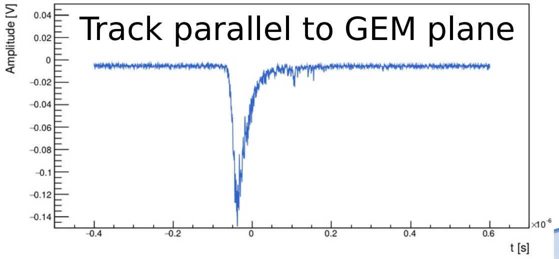
PMT

- Fast light detector
- Provides
  - Energy information from number of photons
  - Z direction topology and development

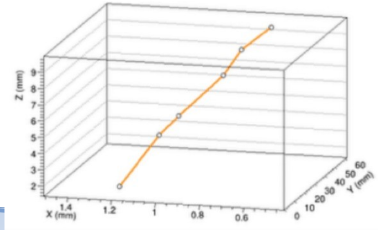
QE





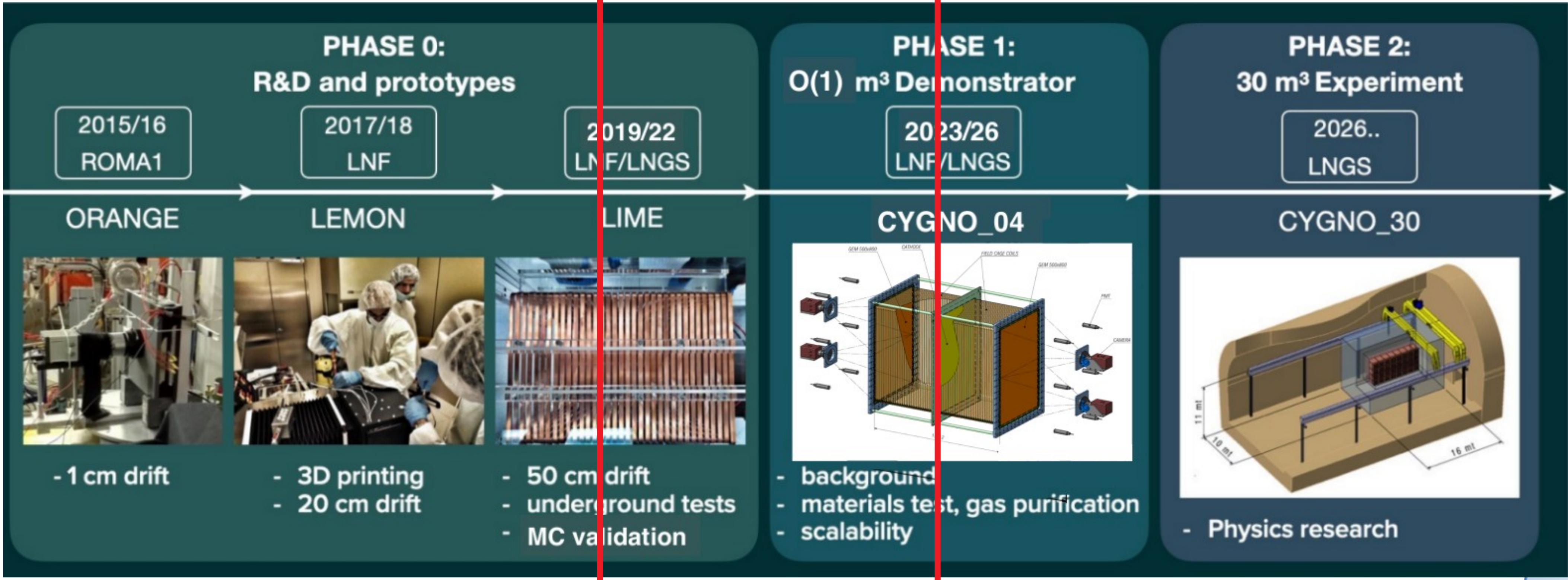


The combination allows energy and 3D topological measurement of each track



CYGNO Timeline

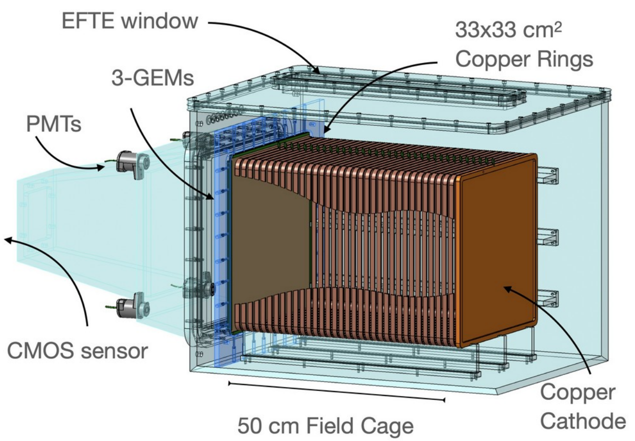
FUNDED

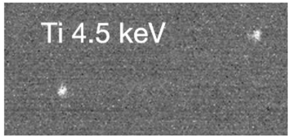


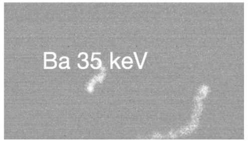
NOW

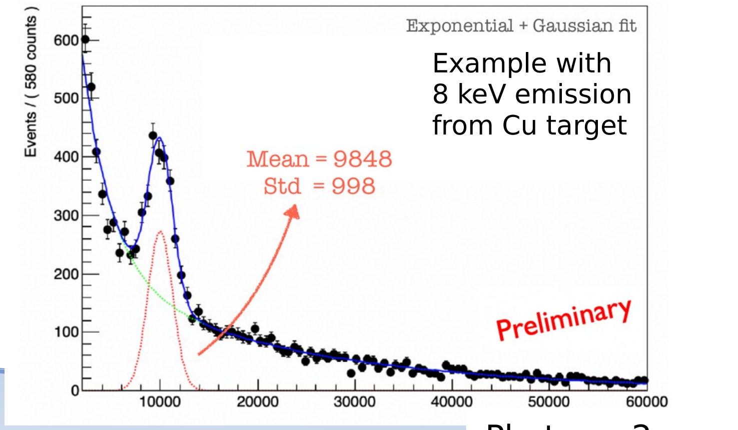
LIME (Long Imaging ModulE)

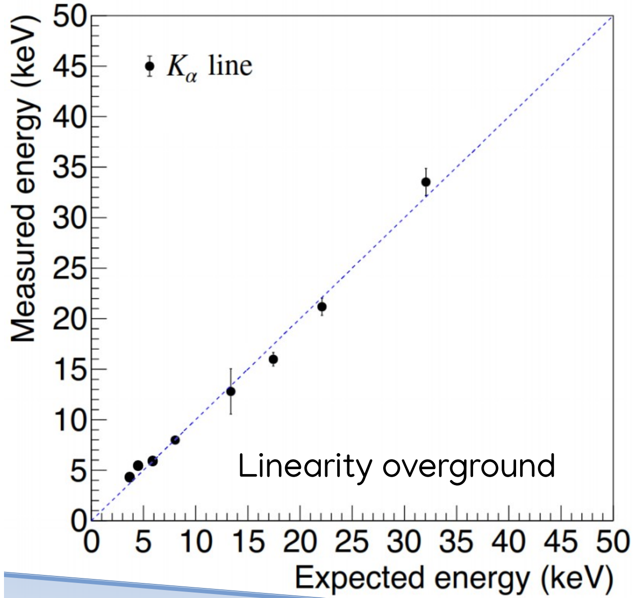
- Large readout area (33x33 cm^2) imaged by 4 PMTs and 1 sCMOS
- 50 l volume, with 50 cm drift
- Nice linearity in the low energy band (3–35 keV$_{ee}$)
- Underground at LNGS-INFN to validate MC simulation of the background

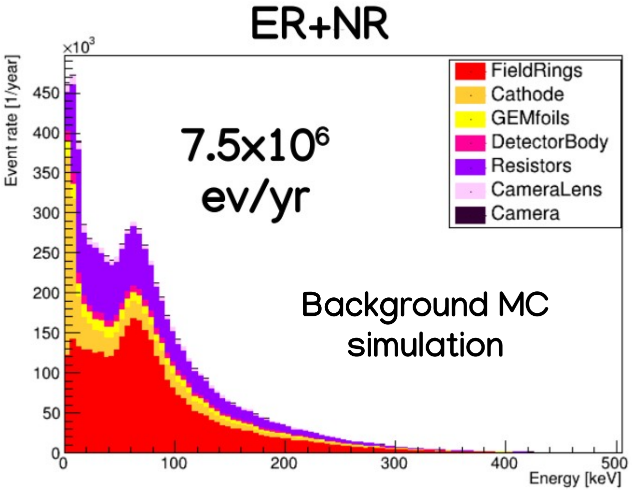








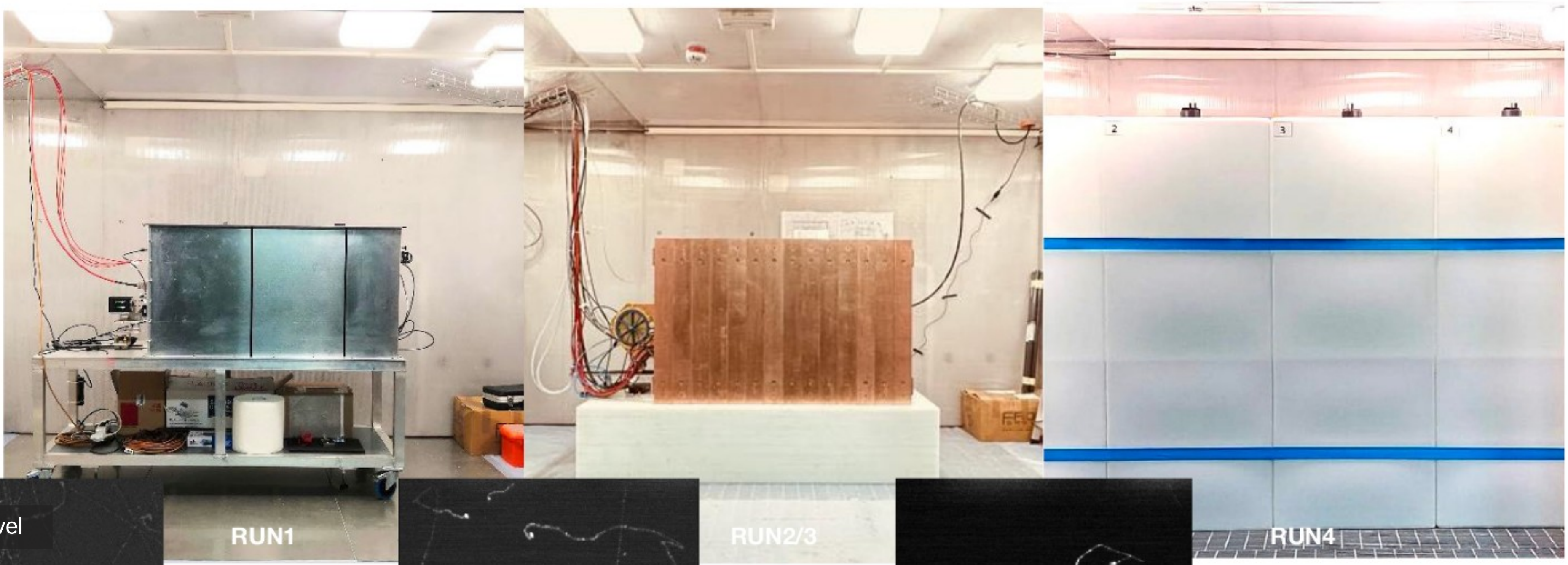


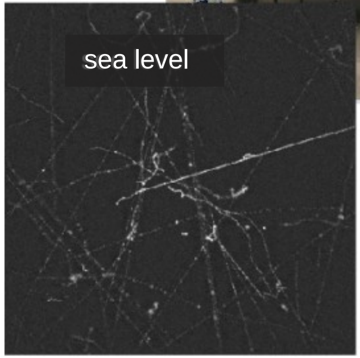


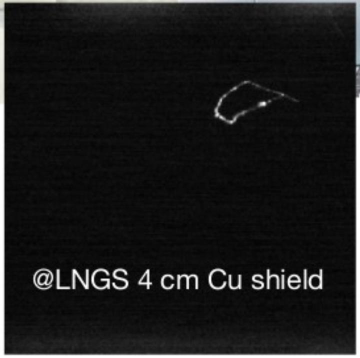
LIME at LNGS

No shield configuration	Run1	✗ Characterization of the detector with ^{55}Fe sources ✗ **External background studies**, to cross-check simulation	Nov-Dec 22	~ 34 Hz
4 cm copper	Run2	✗ Characterization of the detector with ^{55}Fe sources ✗ **External background studies**, to cross-check simulation	Feb-Mar 23	~ 3-4 Hz
10 cm copper	Run3	✗ **External background studies**,to cross-check simulations, ✗ $^{241}AmBe$, ^{241}Am, ^{33}Ba, Eu measurements,	May-Nov 23	1.7 Hz
10 cm copper and 40 water	Run4	✗ **Internal background studies** for final MC validation, Internal and external background expected to have same intensity	Dec 23 – 3 months	1.0 Hz

LIME AT LNGS

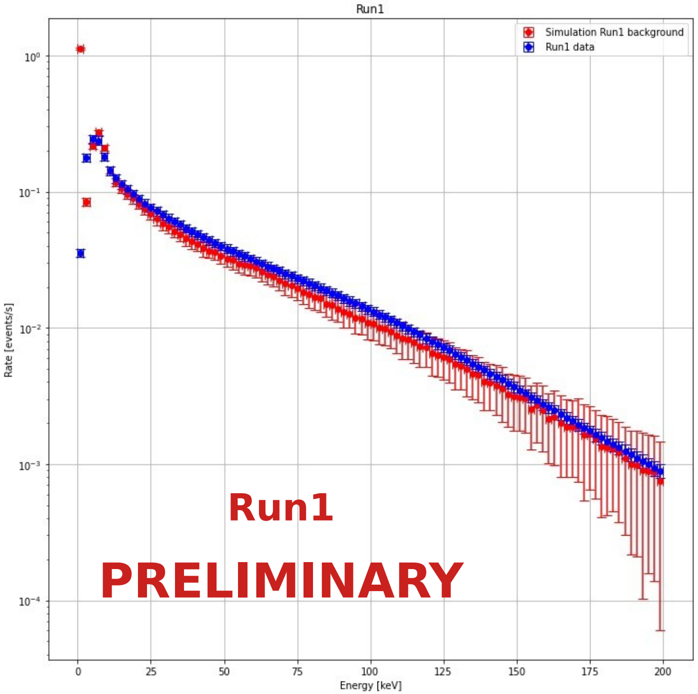


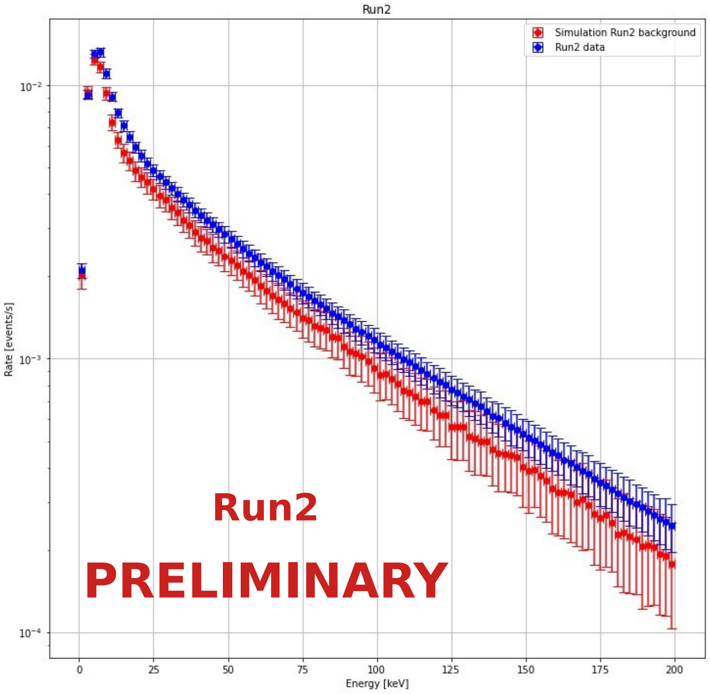


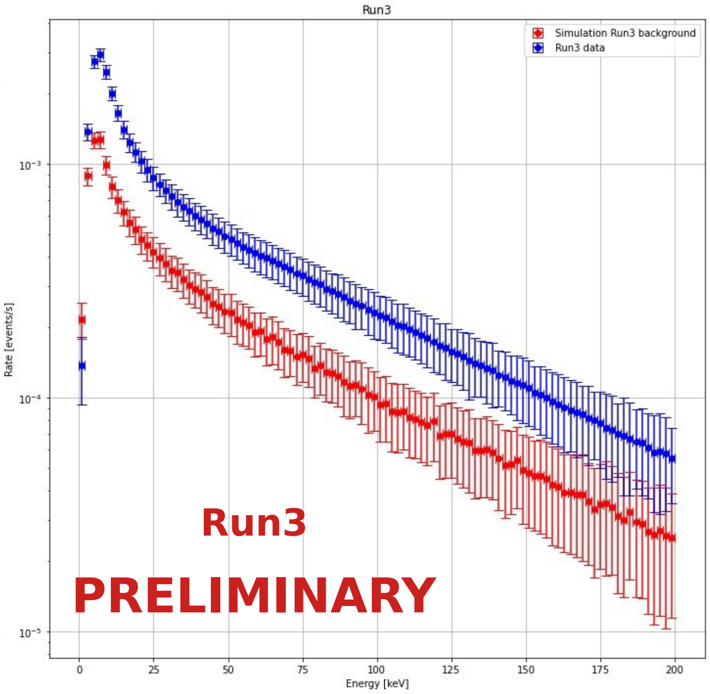


LIME Run1-3

- Energy spectrum of Run1–3 superimposed to MC data (extremely low density tracks removed)







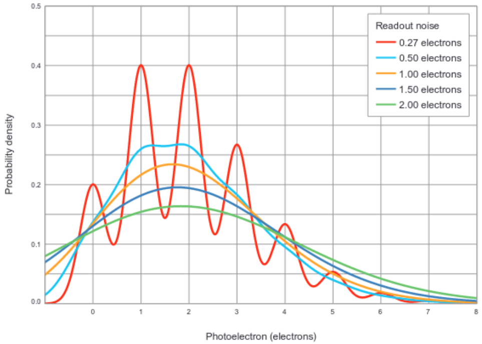
Contamination likely detected

Future of CYGNO

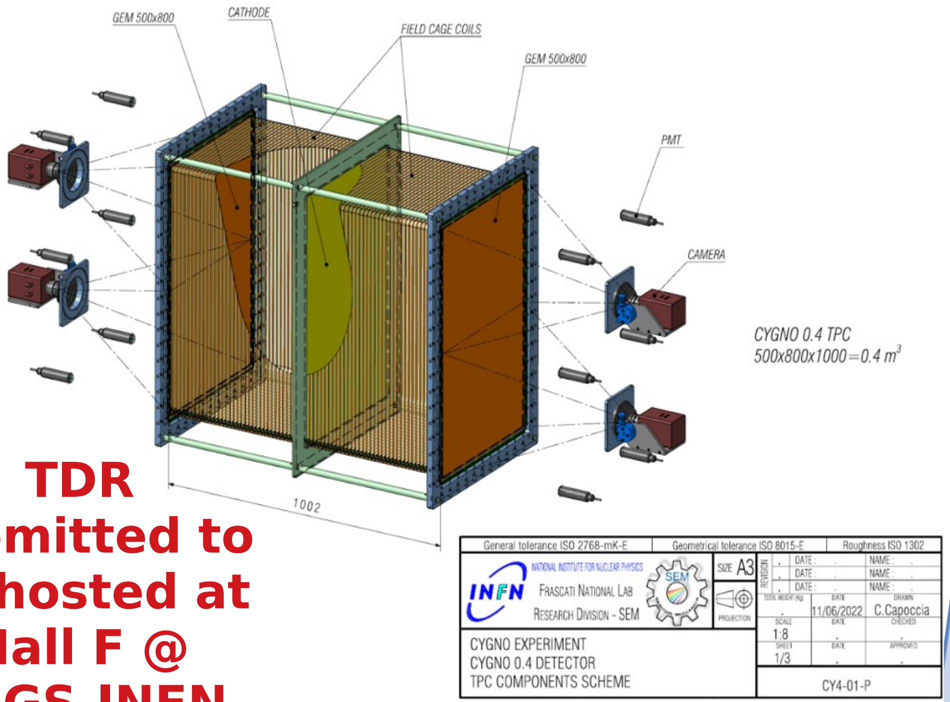
CYGNO-04

- **Structure:** TPC in back-to-back configuration, 50 cm drift per side and 0,4 m^3 total volume
- **Amplification:** Triple thin GEM stack of 50x 80 cm^2 per side
- **Readout:** Optical with 2 sCMOS (Hamamatsu ORCA Quest) and 6 PMTs per side

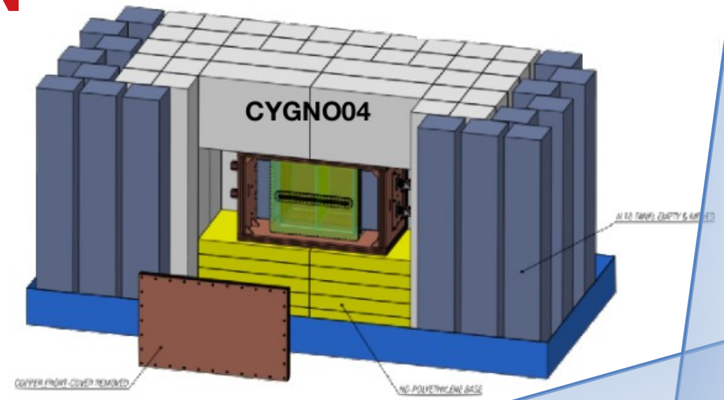
Extremely low noise



- **Purpose:**
  - Prove the scalability of the technology to large volumes using **two cameras per side** (better than LIME)
  - Employ as low radioactive materials for gas detectors as possible



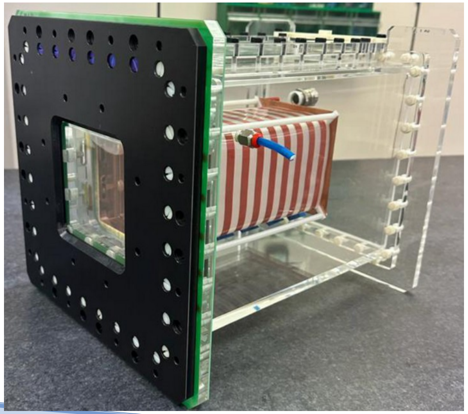
TDR submitted to be hosted at Hall F @ LNGS-INFN



CYGNO-04 Activities

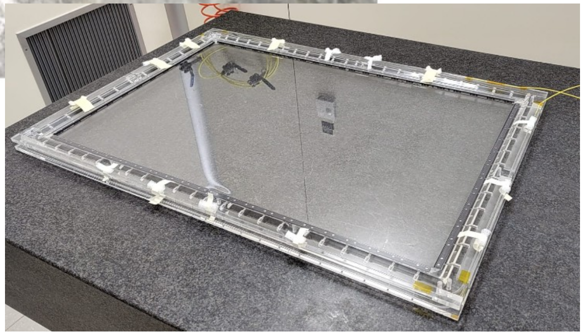
GIN prototype

- Smaller 10x10x23 cm^3 prototype
- Validation of field cage and cathode
- Field cage tests on PET+copper deposits
- Aluminised Mylar cathode (DRIFT-like) to reduce the NR coming from cathode
(Already working!)



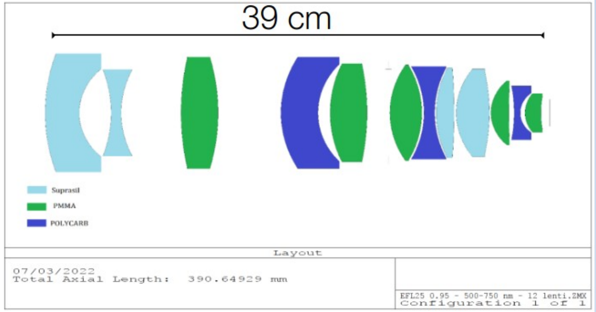
Large GEM and materials

- Stress and mechanical tests of 50x80 cm^2 GEMs and cathode
- Radioactive and mechanical tests of Nylon6 due to its low radioactivity



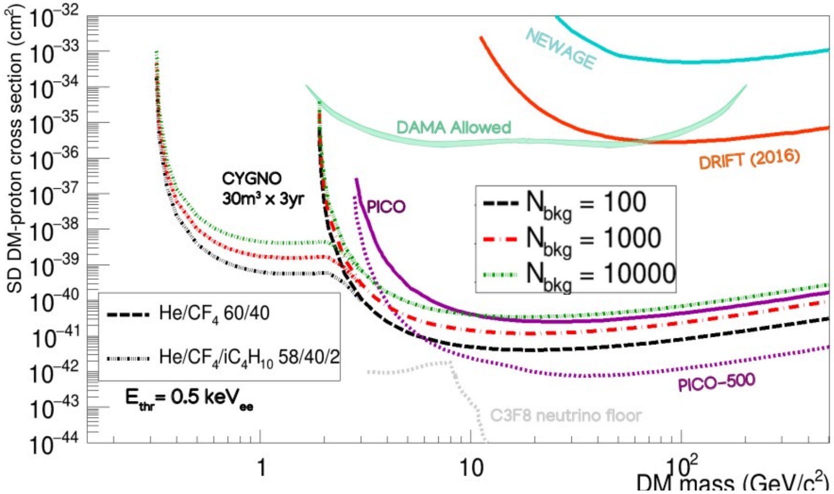
Custom low radioactive lens

- Studied to have the same optical performance as commercial one
- Made of Suprasil to reduce radioactivity

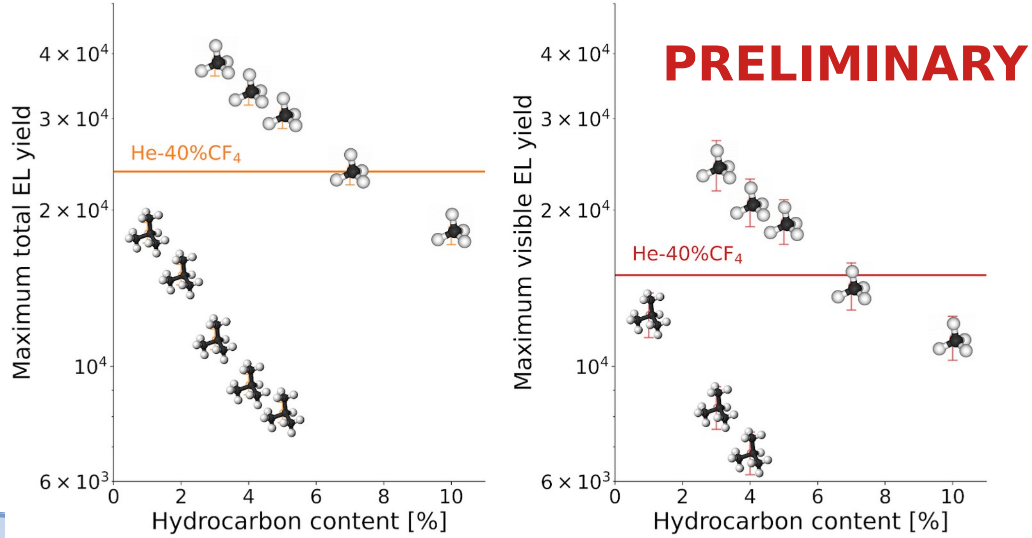


R&D: Hydrocarbons

- The possibility of adding hydrogen rich gas is under study to gain sensitivity to lower DM masses



- Both isobutane and methane in <10% concentration were tested



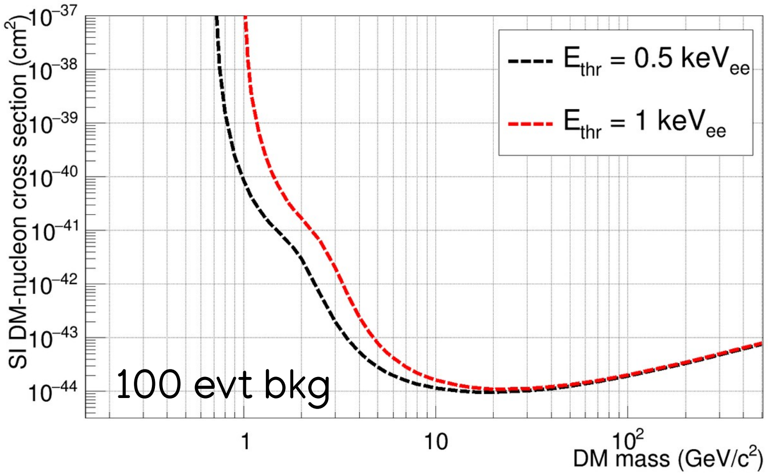
Visible and UV light resulted quenched

Methane gave larger stability allowing an absolute larger gain than He:CF_4 alone

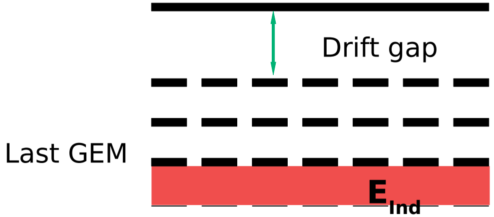
Paper submitted

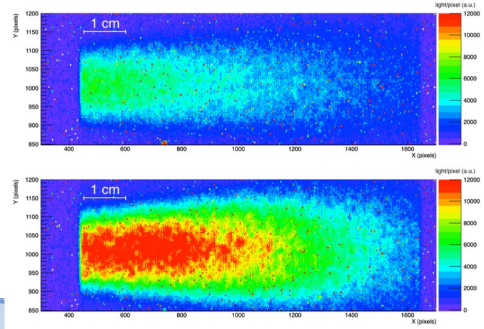
R&D: Enhanced Light Yield

- The possibility of increasing the light yield is under study to lower the energy threshold



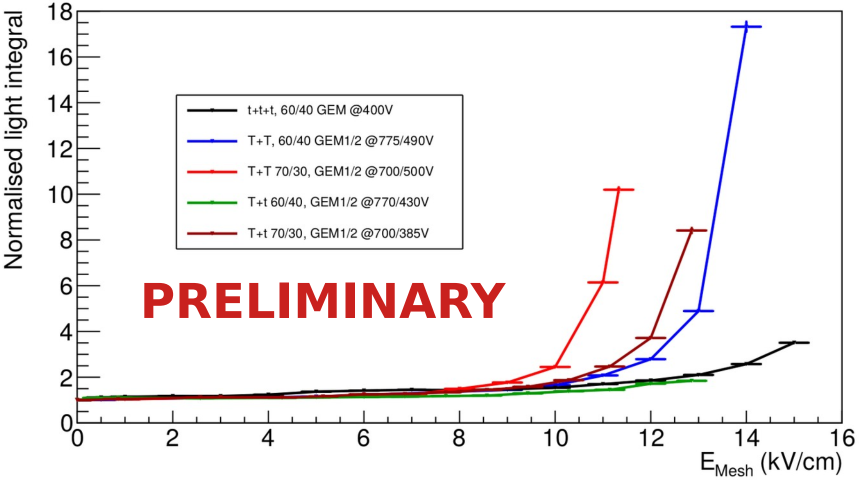
- An extra ITO electrode was added below the last amlification GEM in order to induce strong electric field





High field turned on

Light vs extra electric field



Light was found to increase up to factor 2 without degrading diffusion and energy resolution

Paper almost ready

Conclusions

- In the search for DM, the directional detectors can play a major role in the direct detection context both in terms of physics, positive claim of discovery and neutrino background suppression.
- CYGNO collaboration fits in this scenario with the goal of building a large gaseous TPC with optical readout for rare event searches
- A 50 l prototype is taking data in the underground laboratories of Gran Sasso showing promising results
- A 0.4 m^3 demonstrator is funded and its construction is starting with the goal of proving the scalability to large dimensions and low radioactivity materials
- Several R&Ds are undertaken to improve the performances of the future experiment
- Negative Ion results with optical readout are promising for future development and it appears to be the next game changer in the low energy rare events imaging TPCs

DRD1

WG2 - WP8

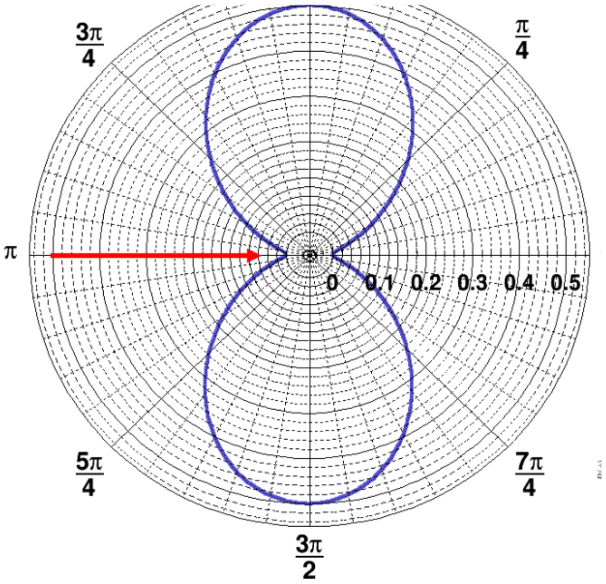
- T1 — Enhanced operation of optical readout
- T4 — Ultra-low energy reconstruction (including NID)
- T5 — Determination of time of interaction
- T6 — Microscopic gas properties
- T7 — Radiopurity

Backup

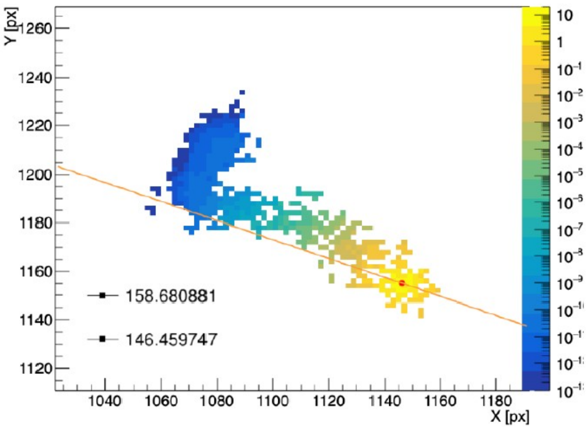
HypeX

- Why stop at DM? Directional detectors can be employed in measuring X-rays from cosmic sources (range 2–40 keV)
- IXPE mission is a dedicated satellite taking unprecedented data on X-ray polarimetry

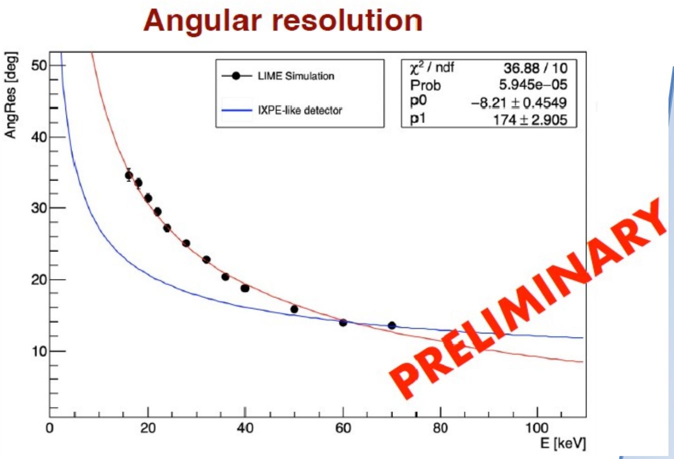
Photoelectrons from polarized photons have preferential direction of emission



Algorithm can reconstruct original direction



Angolar resolution can be used to estimate *modulation factor* used to determine mimal polarization detectable



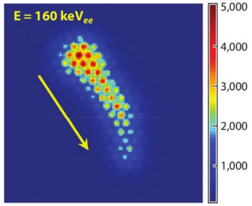
Work ongoing with data taking with polarized source foreseen this year

Relevenat Parameters for Discovery Potential

- Billard, Mayet, Santos (Physical Review D ,85(3) (2012)) found out the most relevant parameters for a limit or discovery potential of WIMP:

Energy threshold **Background level** **Head-tail** **3D** **angular res** **energy res**

Only directional



Vahsen et al., Annual review

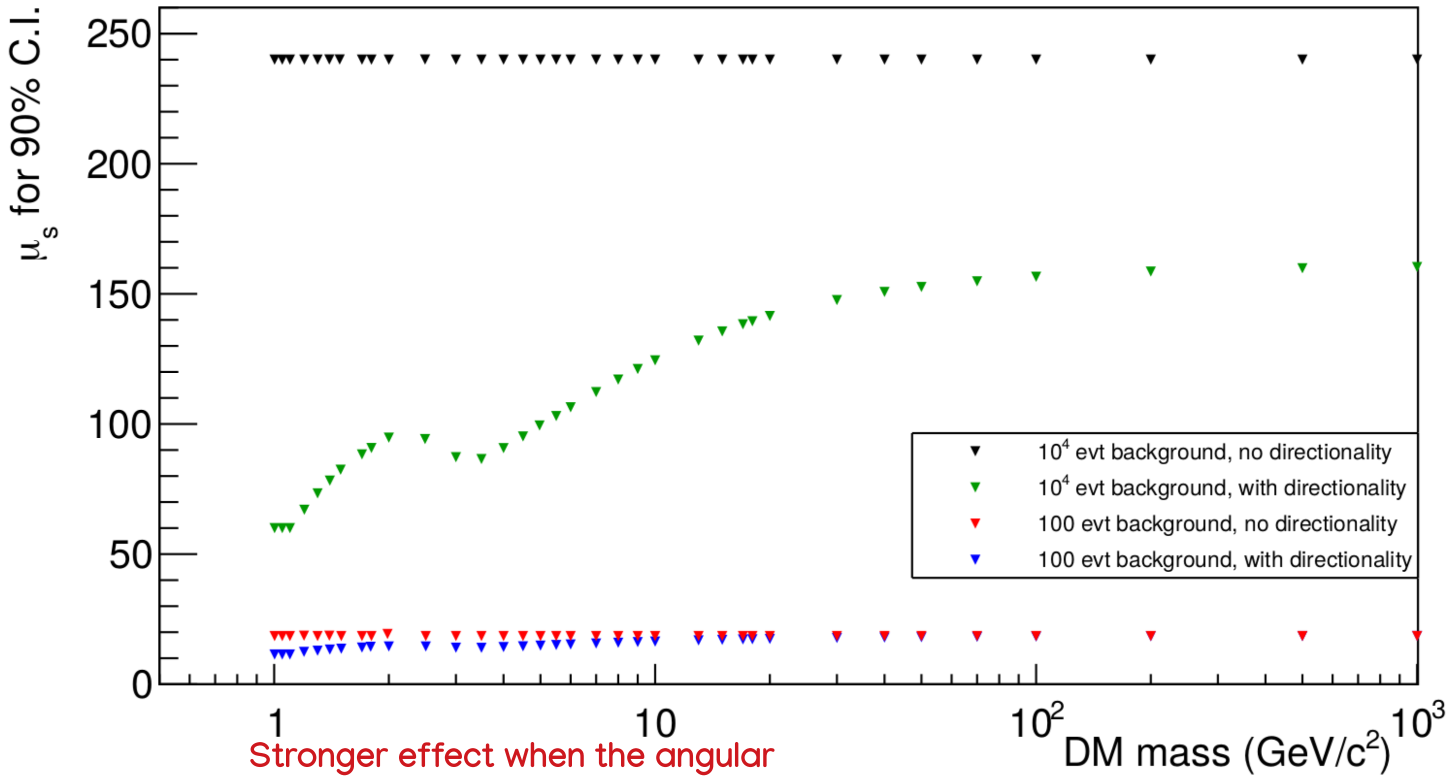
- The WIMP masses which can induce detectable recoils depend on the E_{thr}

$$E_{max} = \frac{1}{2} m_\chi r (v_{lab} \cos\gamma + v_{esc})^2$$

	1 keV$_{ee}$		0.5 keV$_{ee}$	
	$E_{thr,nr}$ (keV$_{nr}$)	Min DM mass (GeV/c^2)	$E_{thr,nr}$ (keV$_{nr}$)	Min DM mass (GeV/c^2)
H	1.4	0.5	0.8	0.3
He	2.1	1.0	1.2	0.7
C	3.1	1.9	1.8	1.4
F	3.8	2.5	2.2	1.9

Directional Effect

- 90% C.I. evaluated with and without profiling on the angular distribution

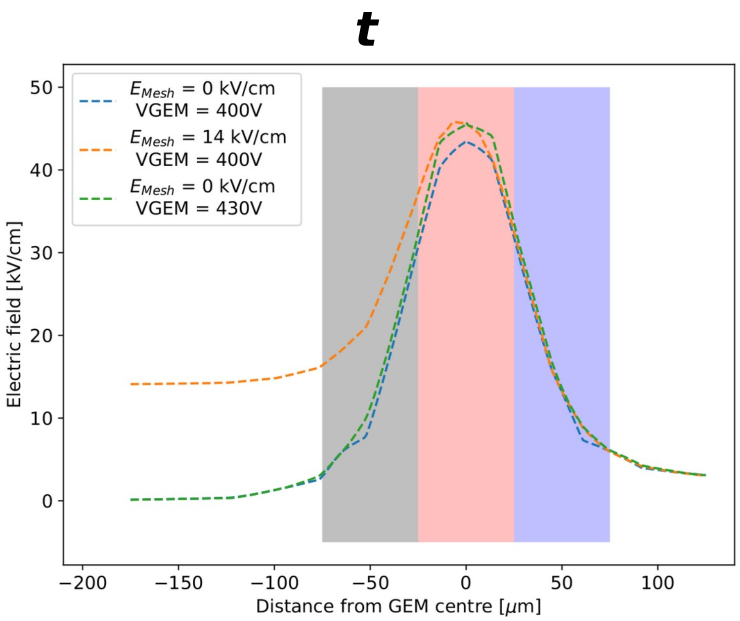


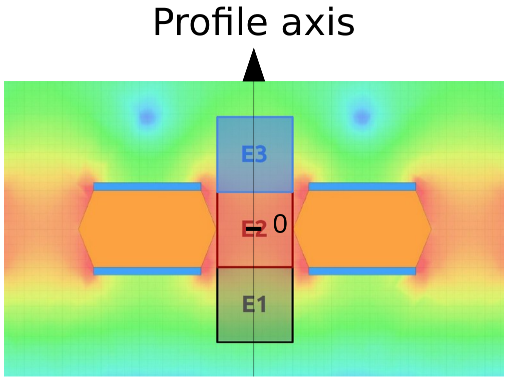
Stronger effect when the angular distribution is more peaked

Direction more effective with more background

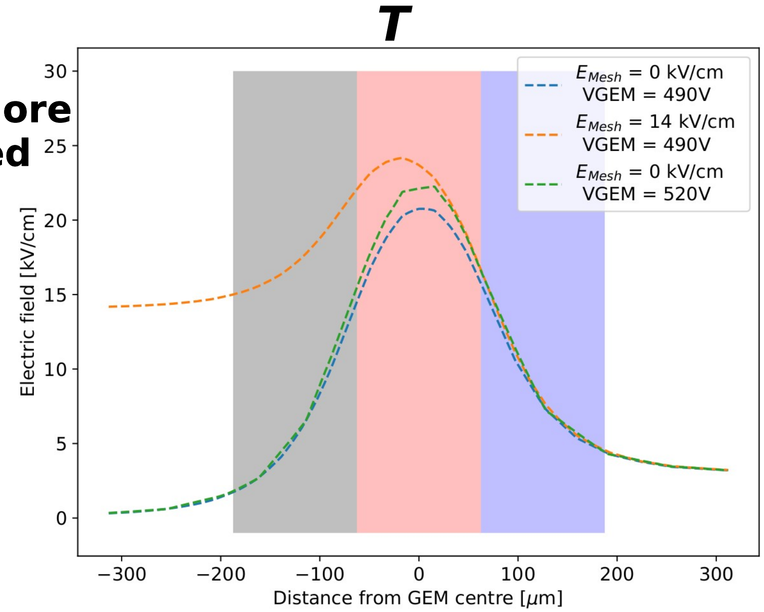
For directional detectors, sensitivity improves with backgrounds

GEM Fields Dependence

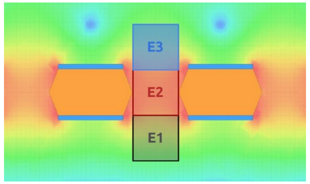


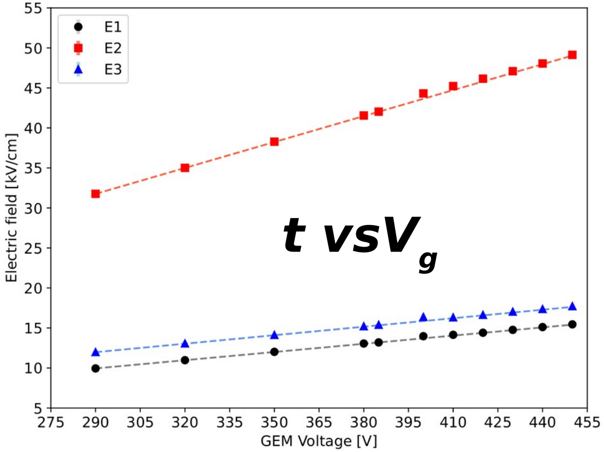


T GEM more affected

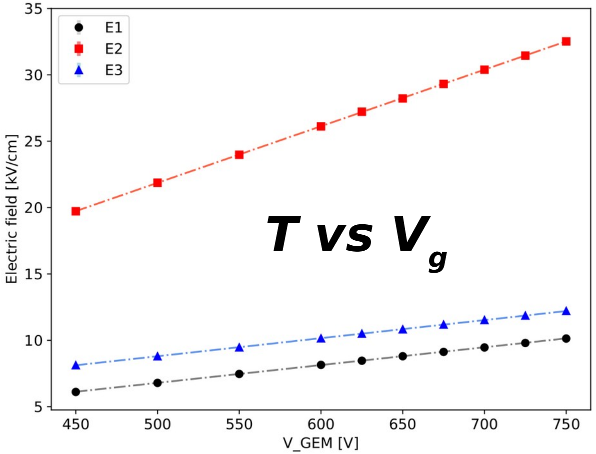


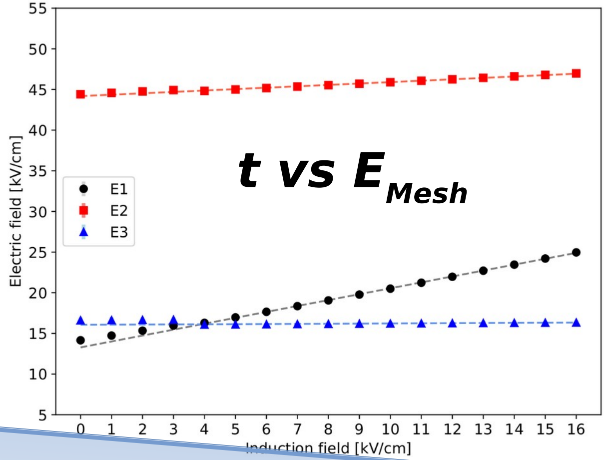
GEM Fields Dependence

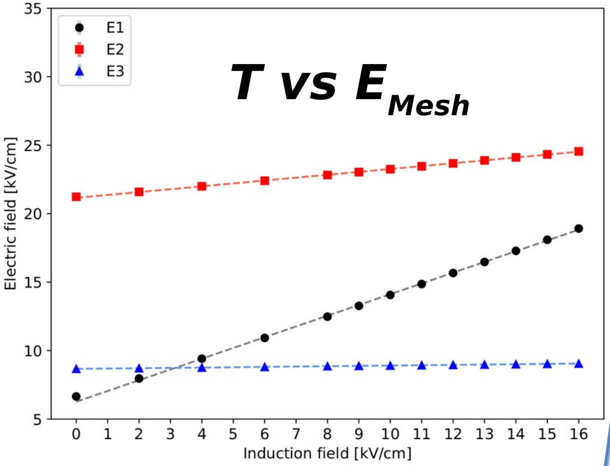




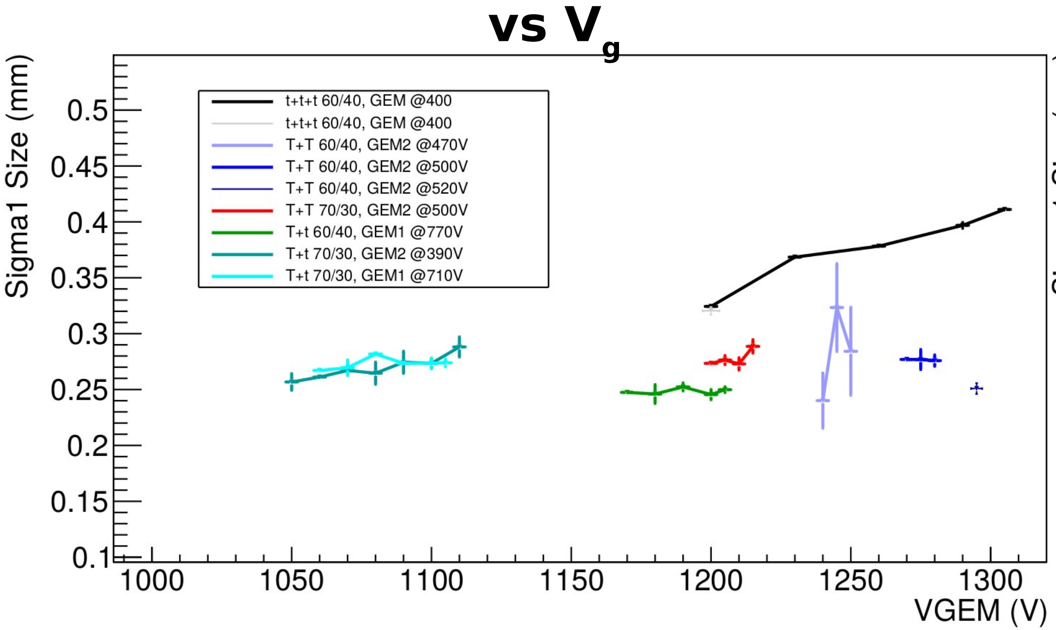
- The induction field does not affect the field above the GEM
- The induction field increses the field inside the GEM hole, but less than V_g (**Compatible with linear increase**)
- The field below the GEM is strongly enhanced up to values where amplification is achievable
- *T* GEM has intrinsically lower fields, so the induction field is relatively larger (**Compatible with *T* GEM granting larger light amplification**)

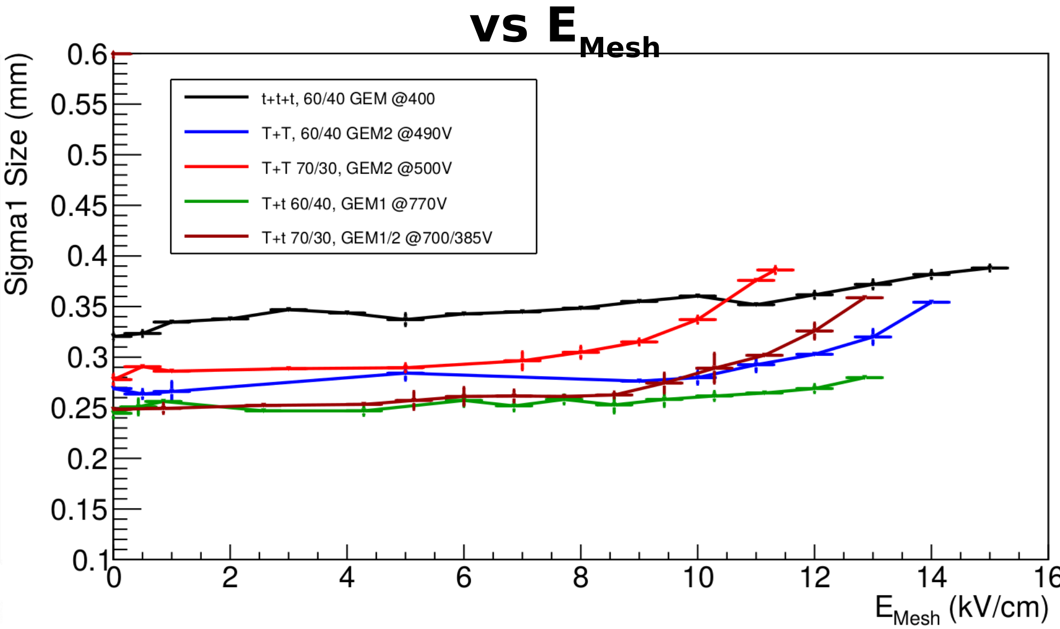






Diffusion

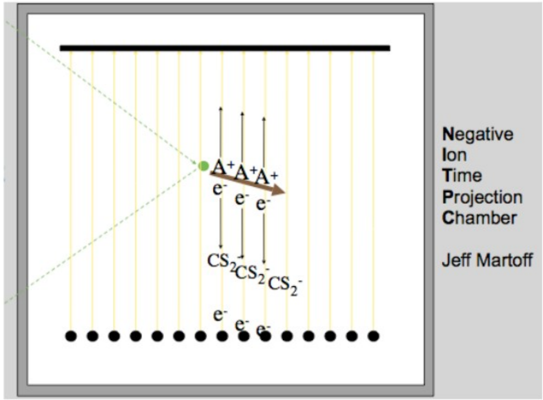

vs V_g
Sigma1 Size (mm)
VGEM (V)
t+t+t 60/40, GEM @400
t+t+t 60/40, GEM @400
T+T 60/40, GEM2 @470V
T+T 60/40, GEM2 @500V
T+T 60/40, GEM2 @520V
T+T 70/30, GEM2 @500V
T+t 60/40, GEM1 @770V
T+t 70/30, GEM2 @390V
T+t 70/30, GEM1 @710V


vs E_{Mesh}
Sigma1 Size (mm)
E_{Mesh} (kV/cm)
t+t+t, 60/40 GEM @400
T+T, 60/40 GEM2 @490V
T+T 70/30, GEM2 @500V
T+t 60/40, GEM1 @770V
T+t 70/30, GEM1/2 @700/385V

Negative Ion Drift (NID)

- Small addition of electronegative gas (CS_2,SF_6) which captures free electrons in O(1-100) m

Martoff et al, D.A.E., 440 (2) (2000)



- The negative ion is carrying the information to the readout plane

- Slower drift velocity O(1) cm/ms

- Intense electric fields required to extract the electron from the negative ion

- Pioneered by Martoff and DRIFT (CS_2) and New Mexico group (SF_6) (low pressure 10-100 Torr)

Martoff et al, D.A.E., 440 (2) (2000) Phan et al, JINST., 12 (2016)

- Gas mixture of He:CF_4:SF_6 (59/39,4/1,6) was demonstrated a NID mixture with charge readout (610 Torr)

Baracchini et al,JINST, 13(04) (2018)

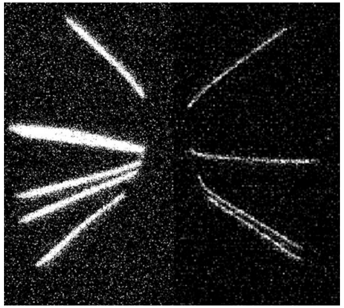
Negative Ion Drift (NID)

- Advantages:

Diffusion

- The large mass of ions allows better energy exchange with neutral component
- Large reduction on the diffusion during drift (from 300 $\frac{\mu m}{\sqrt{cm}}$ of typical gas mixture to <100 $\frac{\mu m}{\sqrt{cm}}$)

ED mix



NID mix

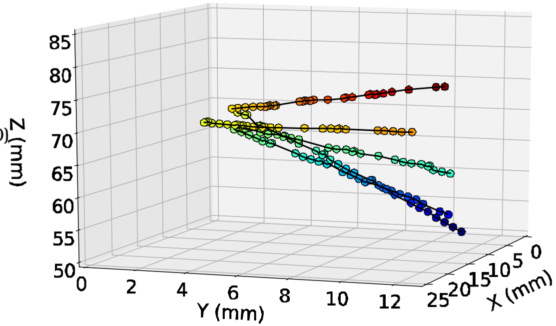
Fiducialisation

- Different species with different masses can be generated

$$z = \frac{v_m v_M}{v_m + v_M} \Delta T$$

- Delay in arrival time allows very precise fiducialisation (130 m res)

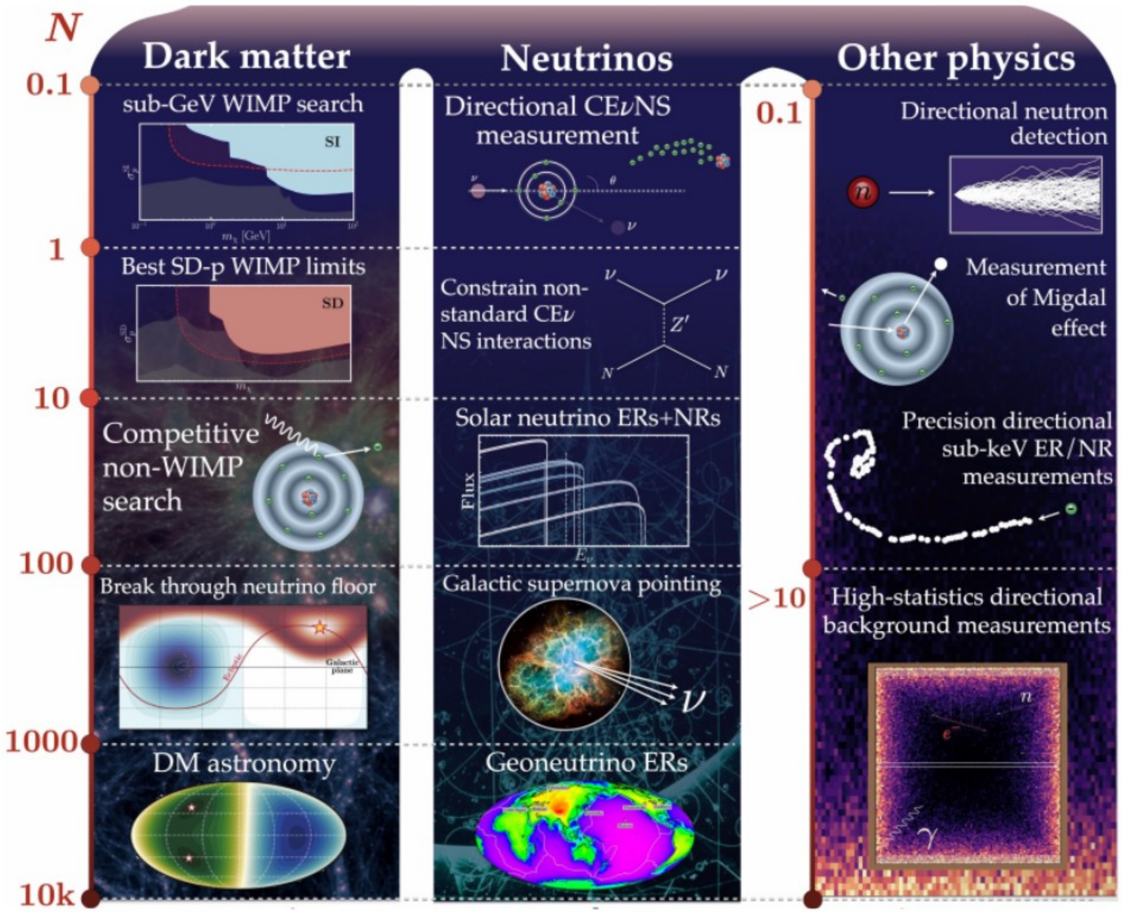
Iketa et al, JINST 15 (07) (2020)



CYGNUS

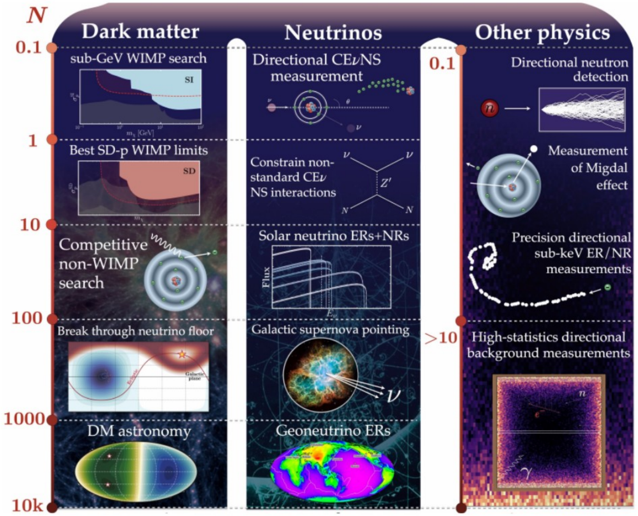
- CYGNUS physics reach as a function of exposure

- Studies performed simulating NID operation with 80 $\frac{\mu m}{\sqrt{cm}}$ diffusion



Other Applications

- Neutrino detector:



X-ray polarimetry

ct

- **HypeX:**
  Measuring polarization from space of 5-40 keV electron recoils to infer X-ray polarization

- Employ optical readout to He:CF_4 and Ar:CF_4