The CYGNO Experiment

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Dark Matter

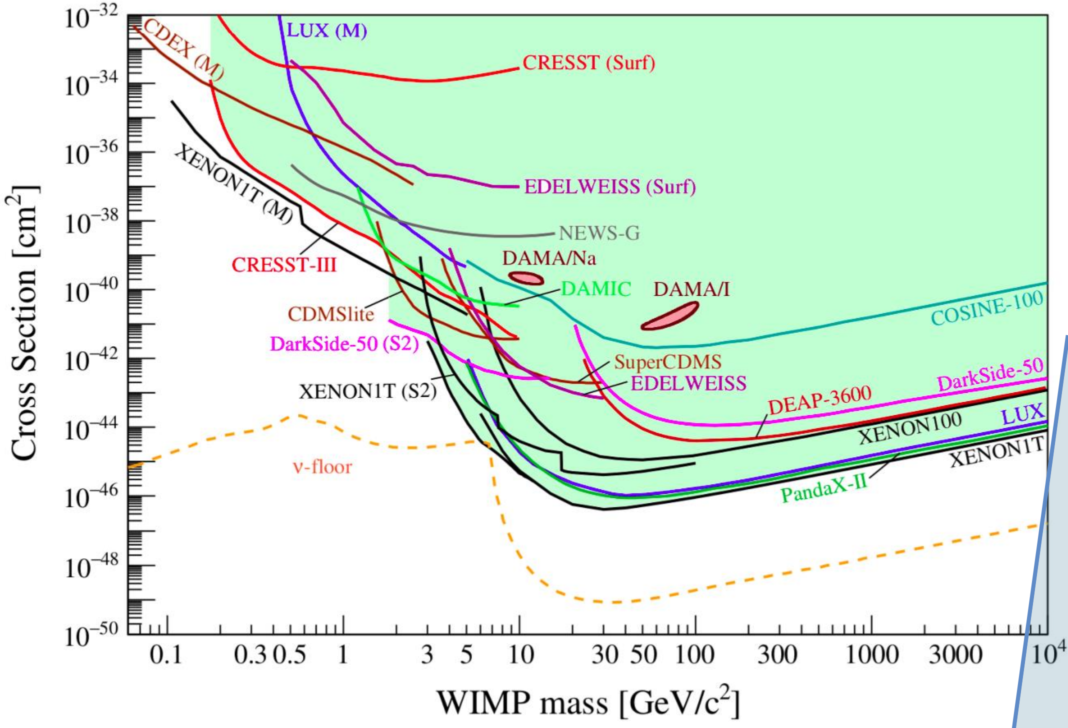
- In the cold dark matter assumption of the ΛCDM model, WIMP-like or sub-GeV particles can rarely interact with regular matter inducing electron and **nuclear recoils** (O(1) keV)

- 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

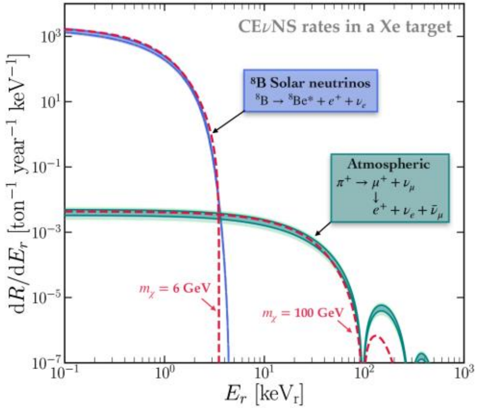
Current experiments are sensitive only to the energy of the recoils and exploit different techniques to discriminate background (ER: electron recoils) from signal (NR: nuclear recoils)

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

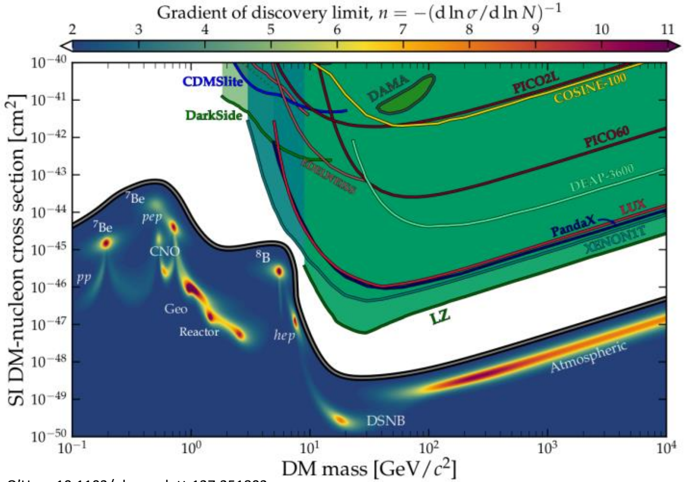
- Soon large exposure experiments will be sensitive to neutrino-induced nuclear recoils (CevNs) and will have their search hindered by the **neutrino fog**

- **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

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



O'Hare at IDM 2022



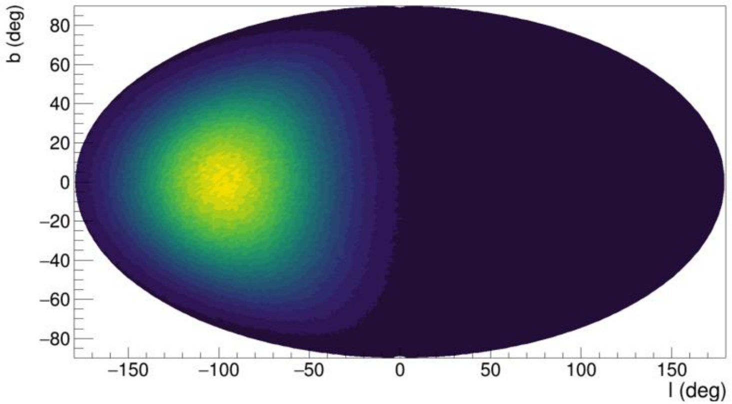
O'Hare 10.1103/physrevlett.127.251802

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

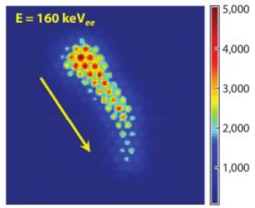
10 GeV WIMP

Fluorine target

Strong anisotropic distribution

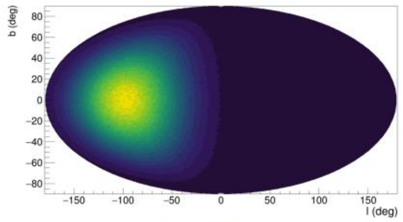
Relevant directional parameters

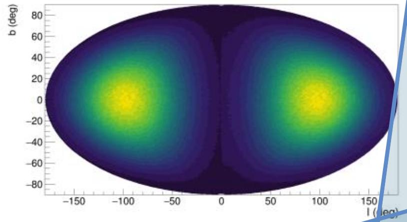
- **Head-tail** recognition
- **3D** reconstruction
- **Angular resolution**



Vahsen et al., Annual review

Full HT





no HT

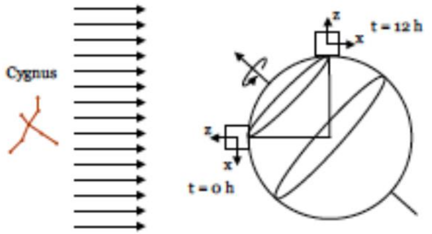
Advantages

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

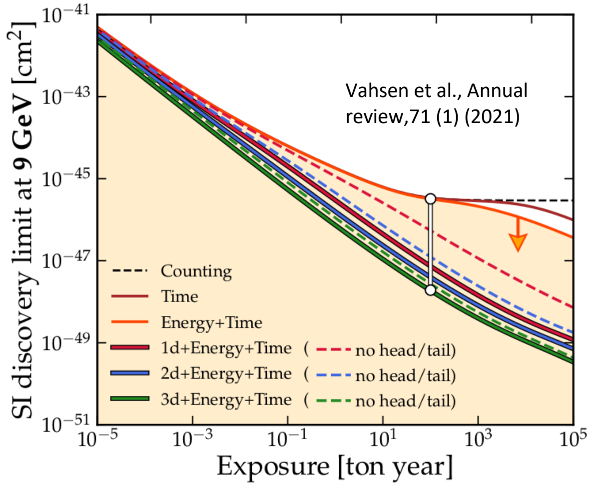
- The neutrino fog can be sidestepped (almost completely for Solar neutrinos) with nice directional performances (HT>75%, ang res>20^o)

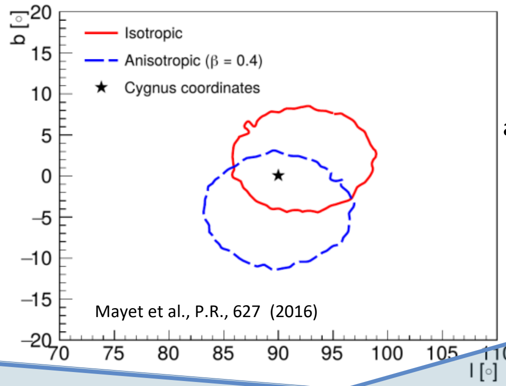
- High performance directional detector will be able to estimate the **3D structure of the velocity distribution**, actively probing DM theories

$$\frac{dR}{d\Omega} \propto f(\vec{v})$$



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



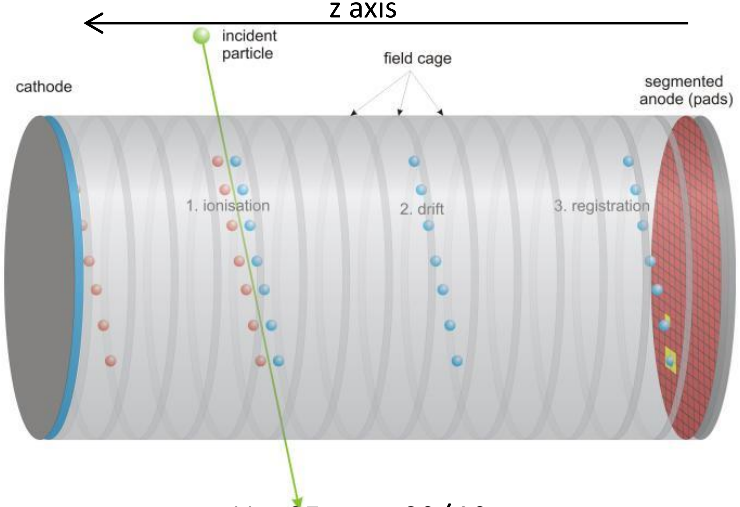


Recoil average arrival direction for different Halo models

CYGNO Experiment

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

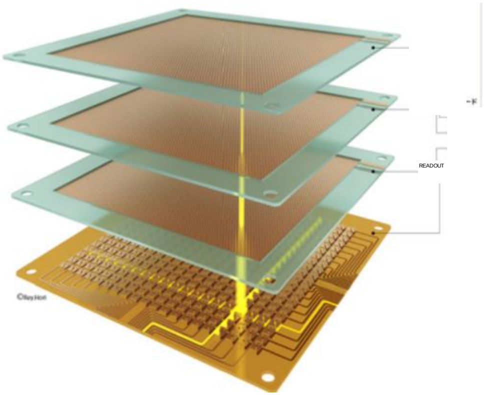
TPC



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

F gives spin dependent 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

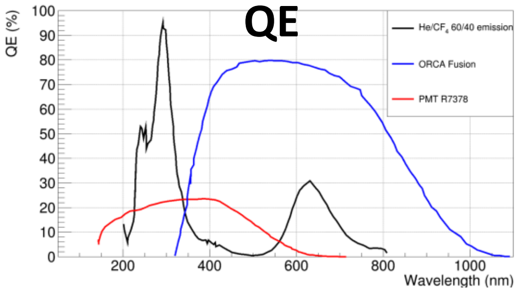
Decoupled from gas, less contamination

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 μm^2 granularity)
- Low noise per pixel (modern below 0,7 e^- RMS)
- Market pulled

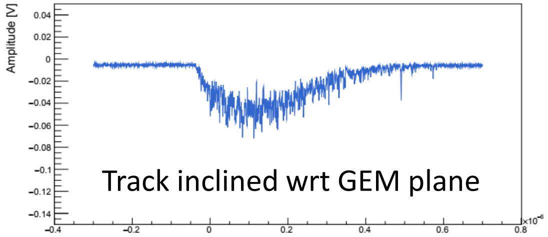
- Provides
- Energy information from number of photons
- dE/dx on X-Y plane
- X-Y positionand topology



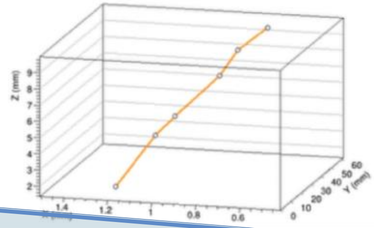
PMT

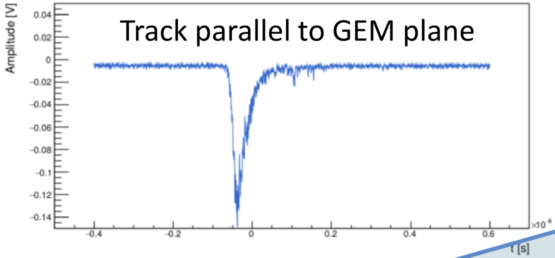
- Fast light detector

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



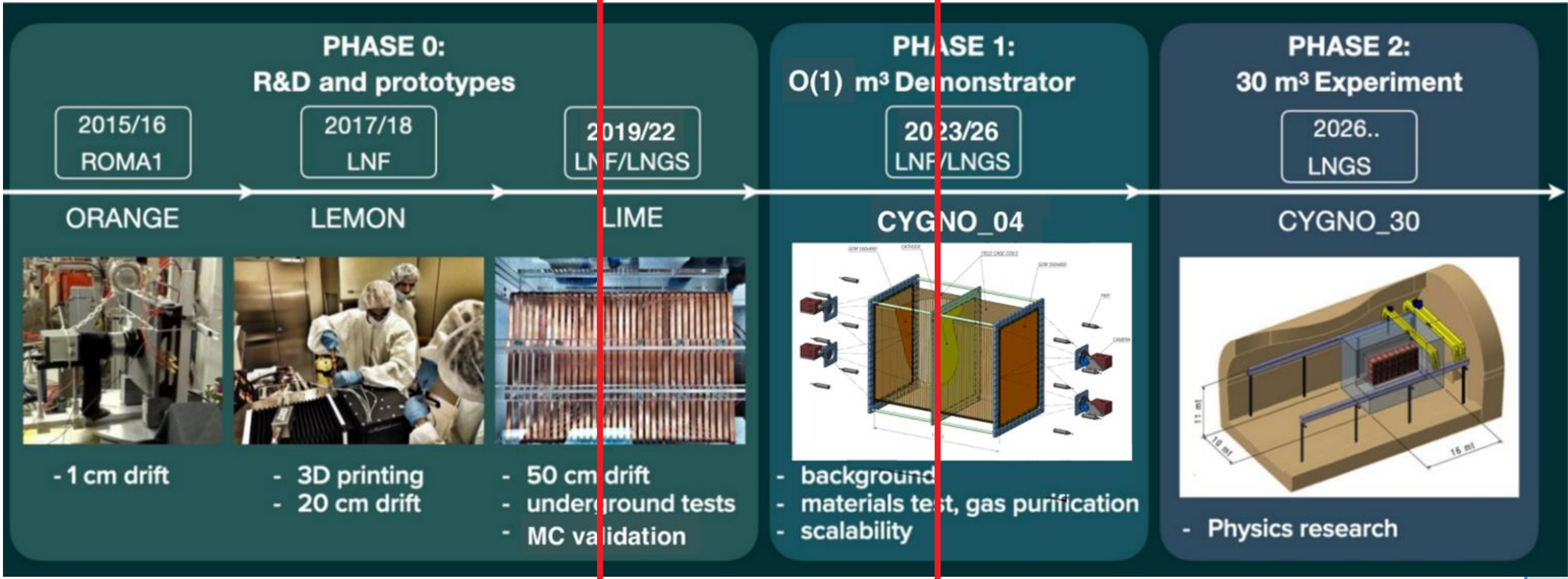
The combination allows energy and 3D topological measurement of each track





CYGNO Timeline

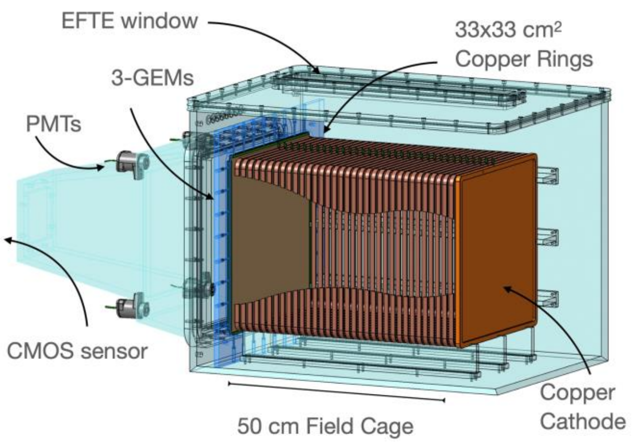
FUNDED

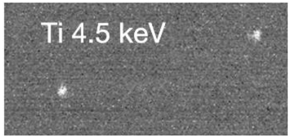


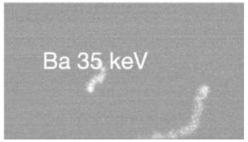
NOW

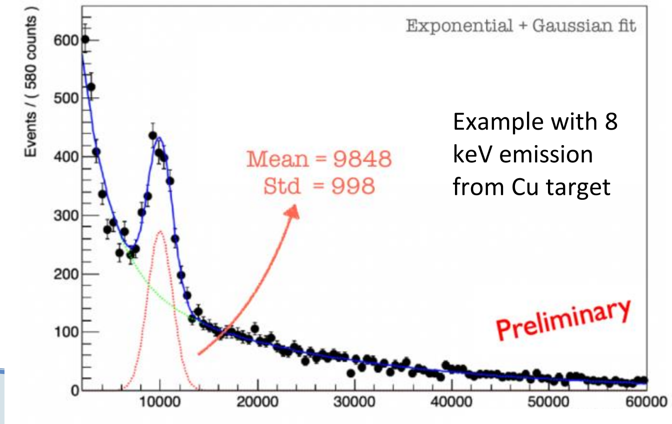
LIME (Long Imaging ModulE)

- 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

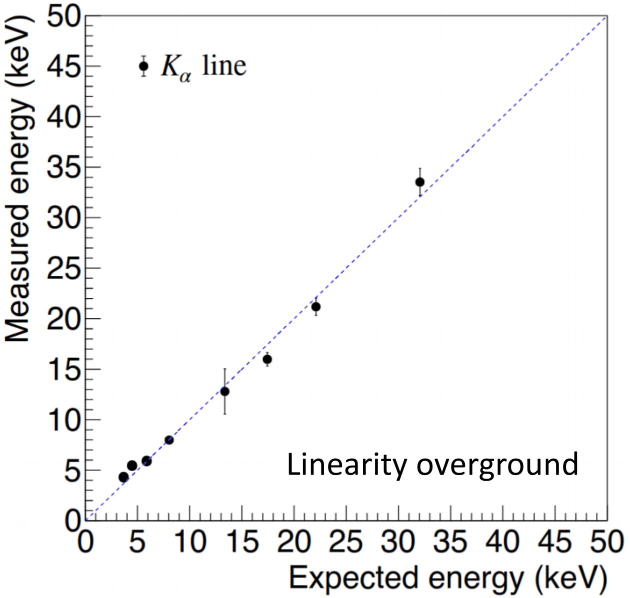


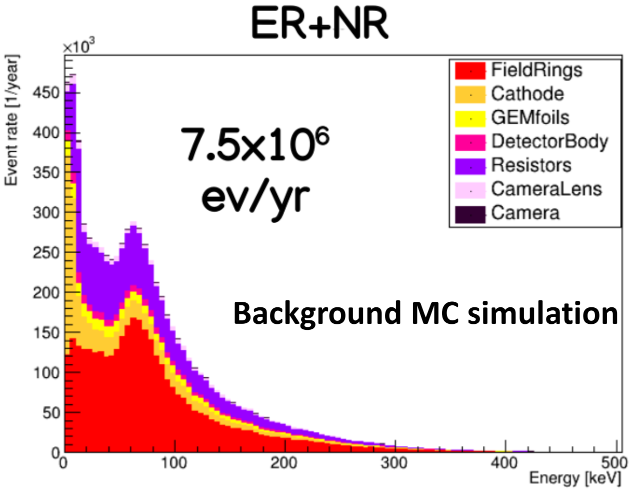






Photonsx2

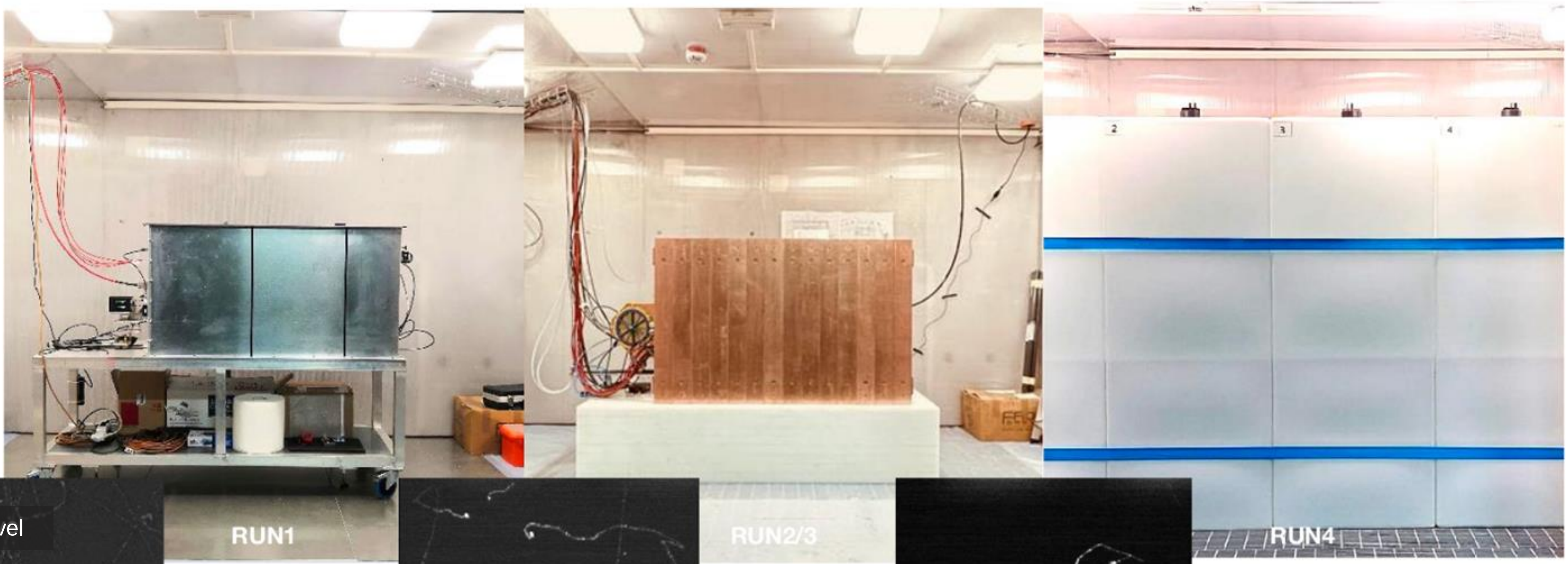


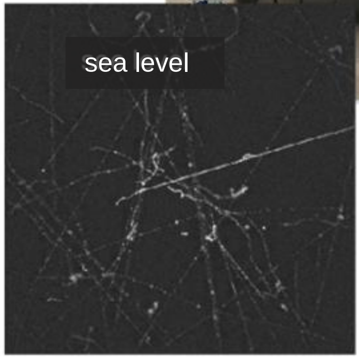


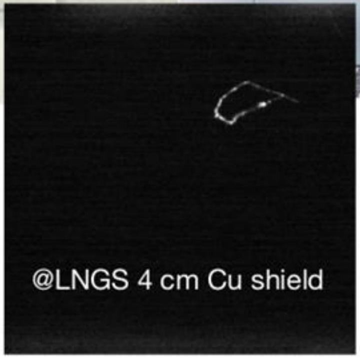
LIME at LNGS

No shield configuration	**Run1**	Characterization of the detector with ^{55}Fe sources **External background studies**, to cross-check simulation	Nov-Dec 22	35 Hz
4 cm copper	**Run2**	Characterization of the detector with ^{55}Fe sources **External background studies**, to cross-check simulation	Feb-Mar 23	3.5 Hz
10 cm copper	**Run3**	**External background studies**,to cross-check simulations, ^{241}AmBe, ^{241}Am, ^{33}Ba, Eu measurements,	May-Nov 23	1.3 Hz
10 cm copper and 40 water	**Run4**	**Internal background studies** for final MC validation, Internal and external background expected to have comparable intensity	Dec 23 – Apr 24	0.7 Hz
10 cm copper	**Run5**	**Neutron flux measurement** and calibration with radioactive sources (^{55}Fe,AmBe)	May 24 – End 24	

LIME at LNGS



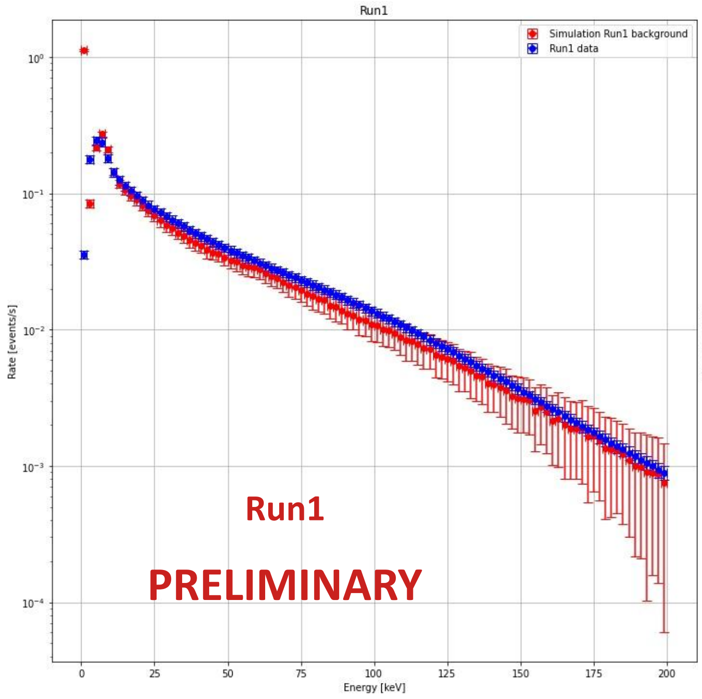


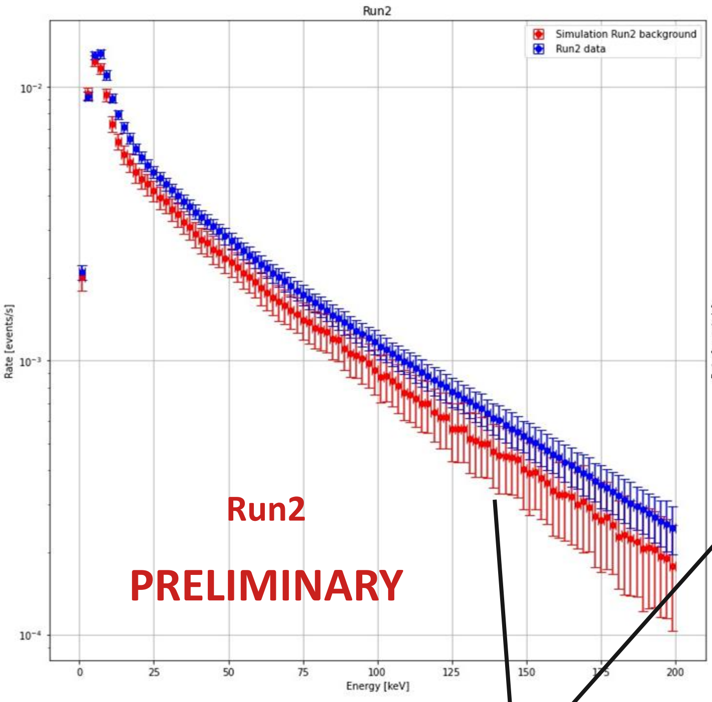


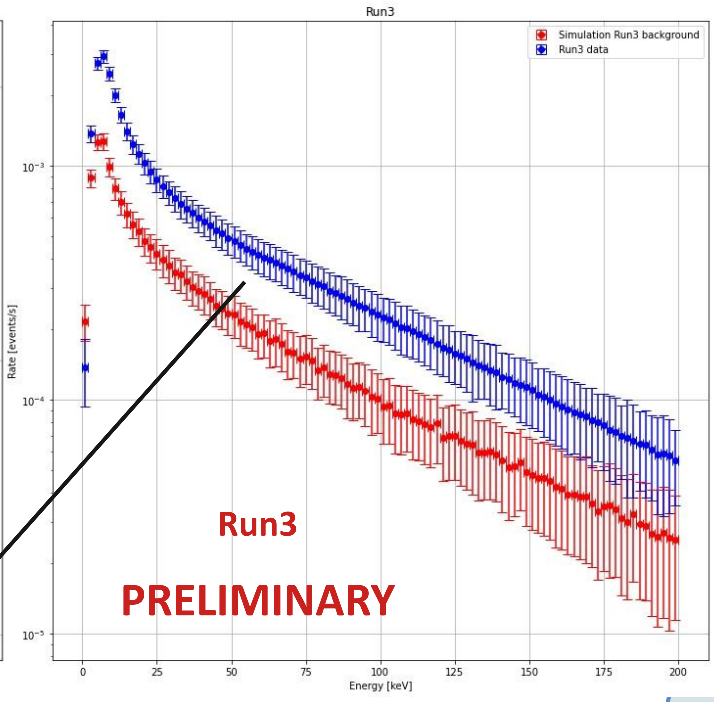
LIME Run1-3

- Energy spectrum of Run1-3 superimposed to MC data

Extremely low energy, MIP-like and high energy alphas removed







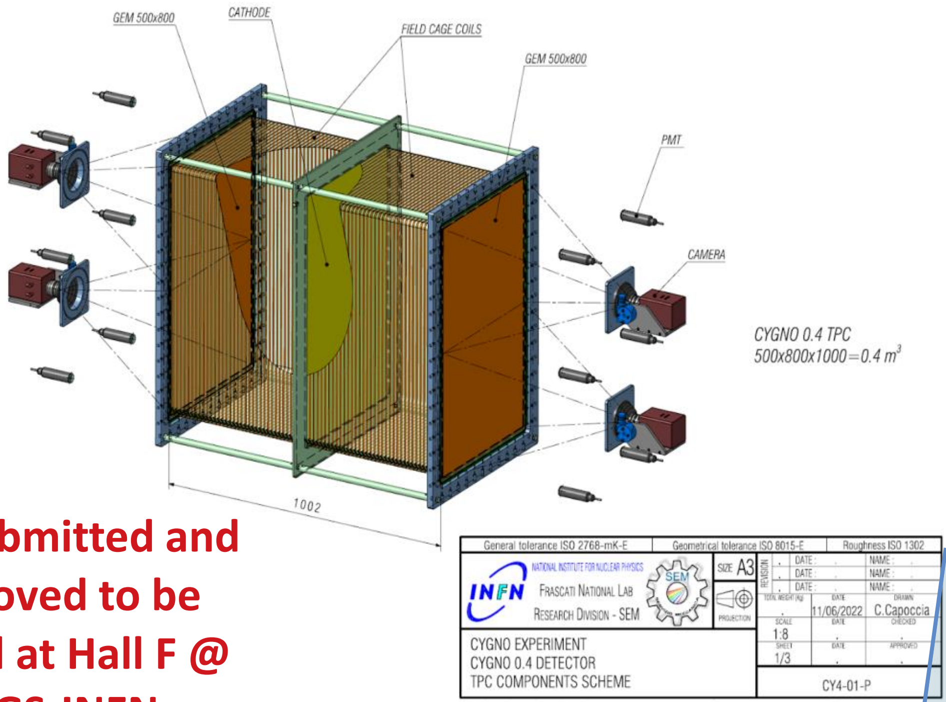
Difference is relatively larger
but extremely similar in absolute value

Internal contamination likely detected

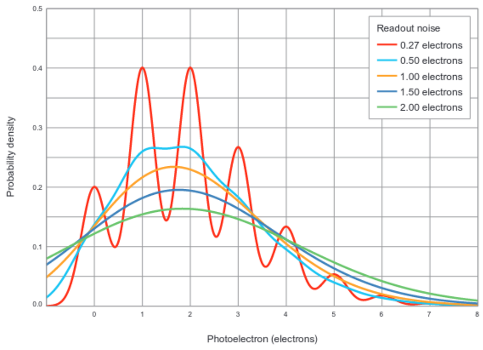
Future of CYGNO

CYGNO-04

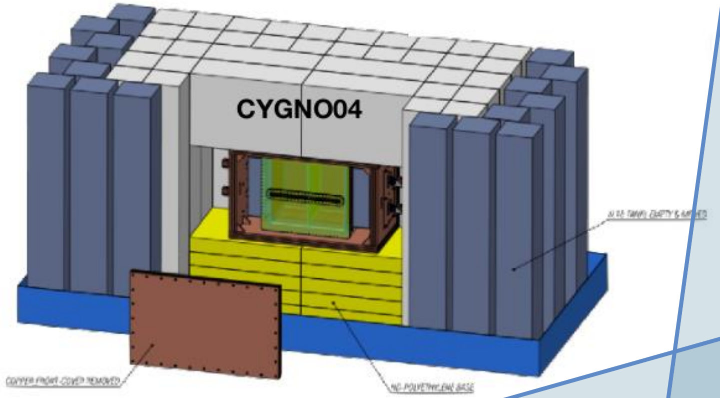
- **Structure**: TPC in back-to-back configuration, 50 cm drift per side and 0,4 m^3 total volume
- **Amplification**: Triple standard GEM stack of 50x 80 cm^2 per side
- **Readout**: Optical with 3 sCMOS (Hamamatsu ORCA Quest) and 6 PMTs per side



Extremely low noise



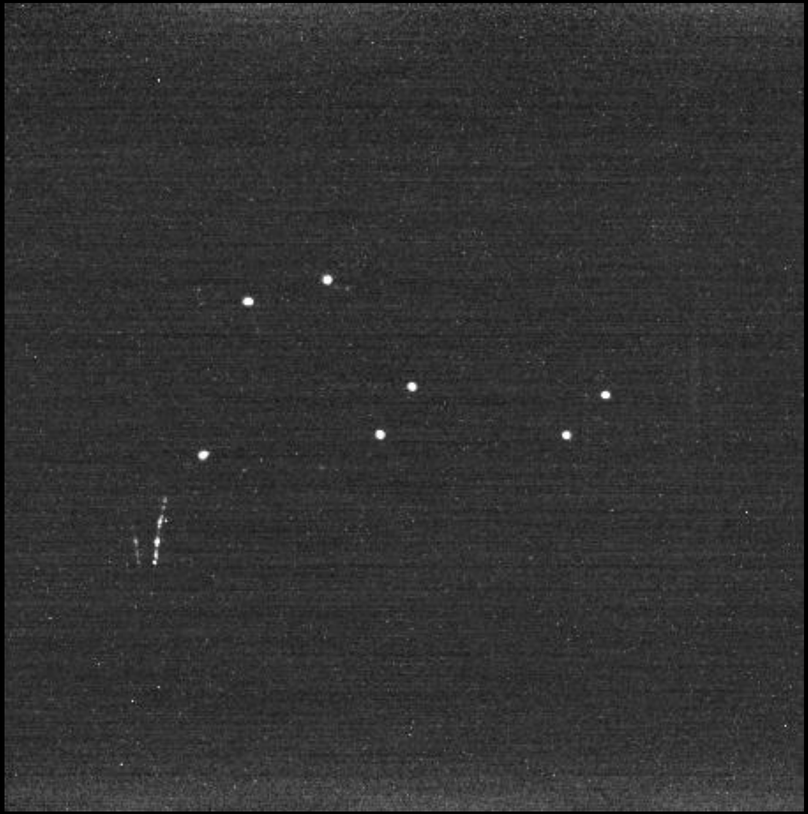
TDR submitted and approved to be hosted at Hall F @ LNGS-INFN

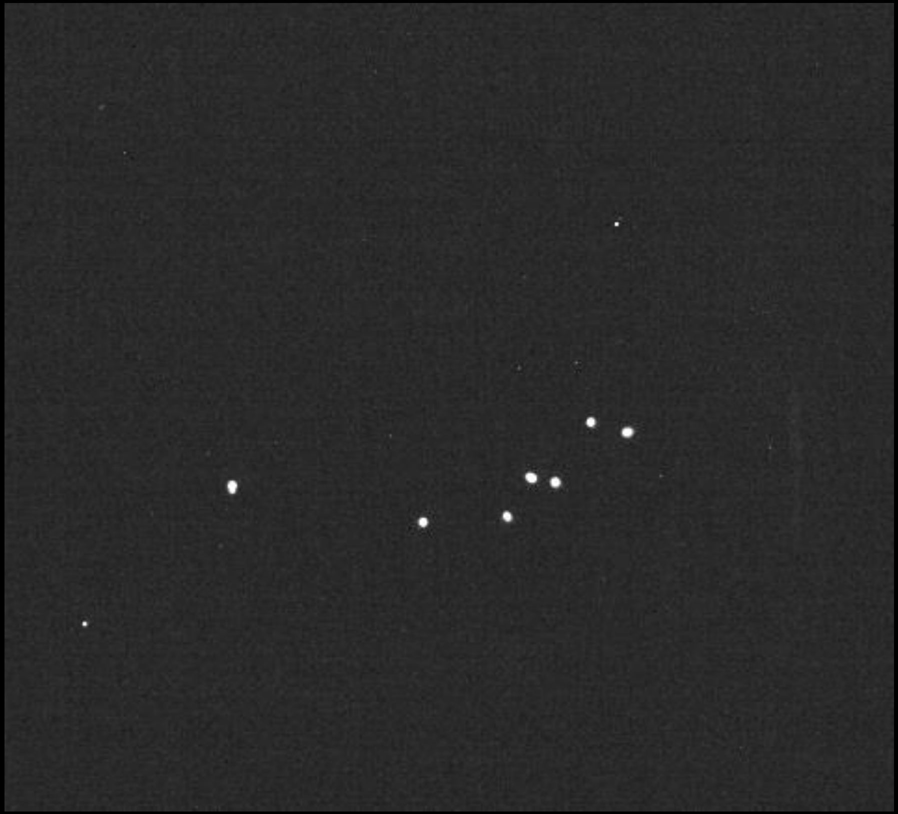


Purpose:

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

Change of Sensor

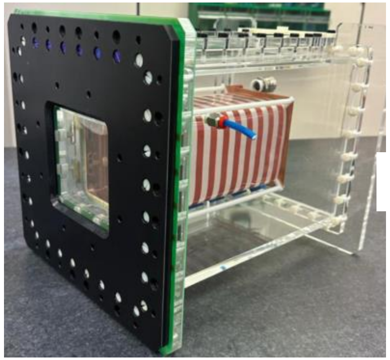




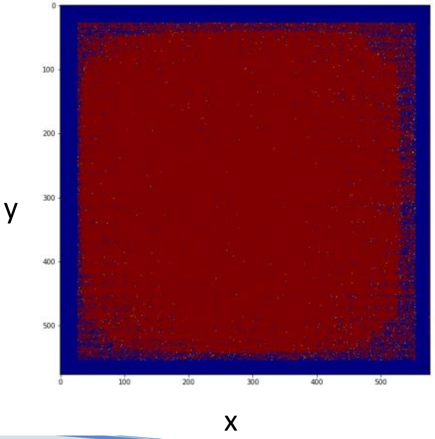
R & D Activities

GIN prototype (here at LNF)

- 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!)**

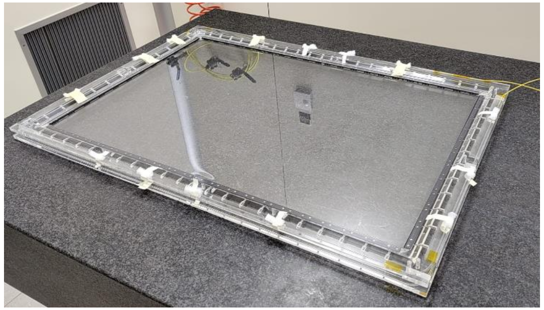


Background intensity map



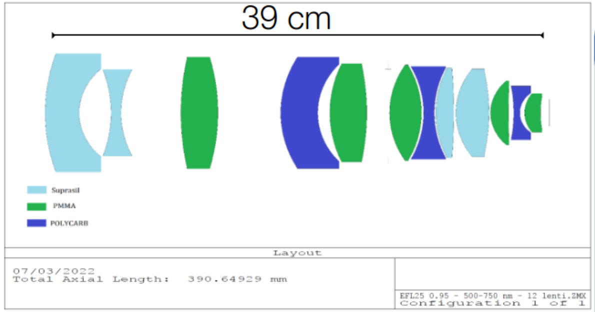
Large GEM and materials (here at LNF)

- 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
(in collab. with LOBRE)

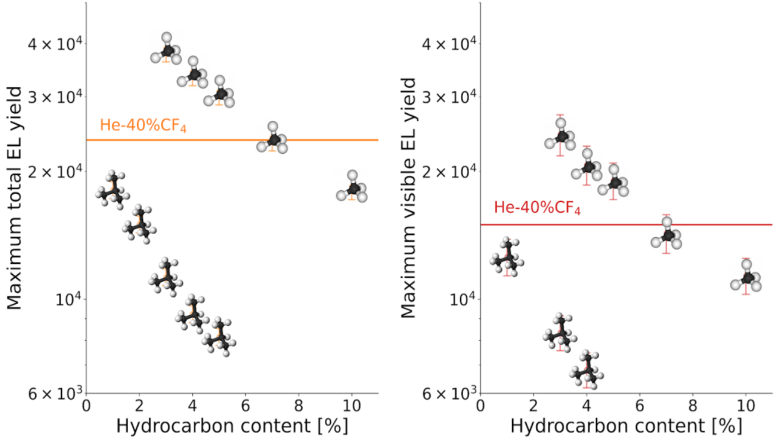
- Studied to have the same optical performance as commercial one
- Made of Suprasil to reduce radioactivity



CYGNO-04 Activities

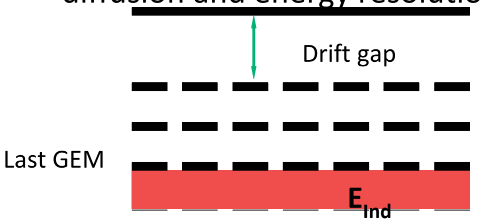
Hydrogen-rich gas (made in Coimbra)

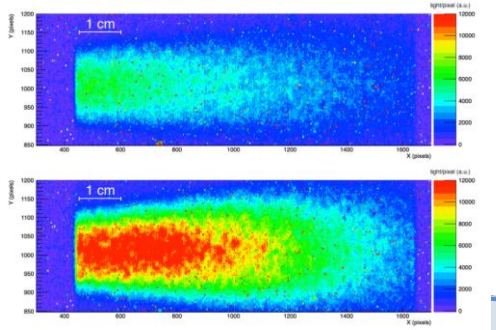
- Addition of H rich gases to increase sensitivity to low WIMP masses
- Tests with isobutane and methane
- Similar light yield wrt no H-gas



Enhanced light yield (made at GSSI and at LNF)

- Addition of extra electrode below the last GEM to initiate a strong electric field
- Modification of the electric field close to the GEM holes increases light yield without degrading diffusion and energy resolution





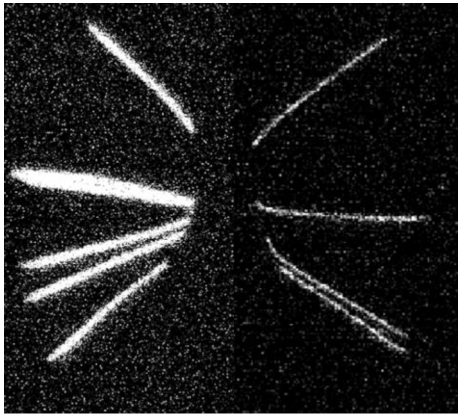
High field turned on

Negative Ions Drift operation (made at GSSI)

- Addition of small amount of SF_6 to induce capture of primary electron and drift of ion
- Strong reduction of diffusion to improve tracking capabilities

Raw sCMOS camera images

He:CF_4 (60:40)



Same light intensity He:CF_4:SF_6 (59:39.4:1.6)

Conclusions

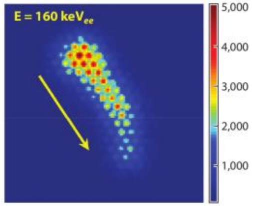
- In the search for DM, the directional detectors can play a major role in the direct detection context both in terms of physics, positive claim of discovery and neutrino background suppression.
- CYGNO collaboration fits in this scenario with the goal of building a large gaseous TPC with optical readout for rare event searches
- A 50 l prototype is taking data in the underground laboratories of Gran Sasso showing promising results
- A long data taking is now foreseen to measure the LNGS underground neutron flux
- 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

Backup

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 WI

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



Vahsen et al., Annual review

Only directional

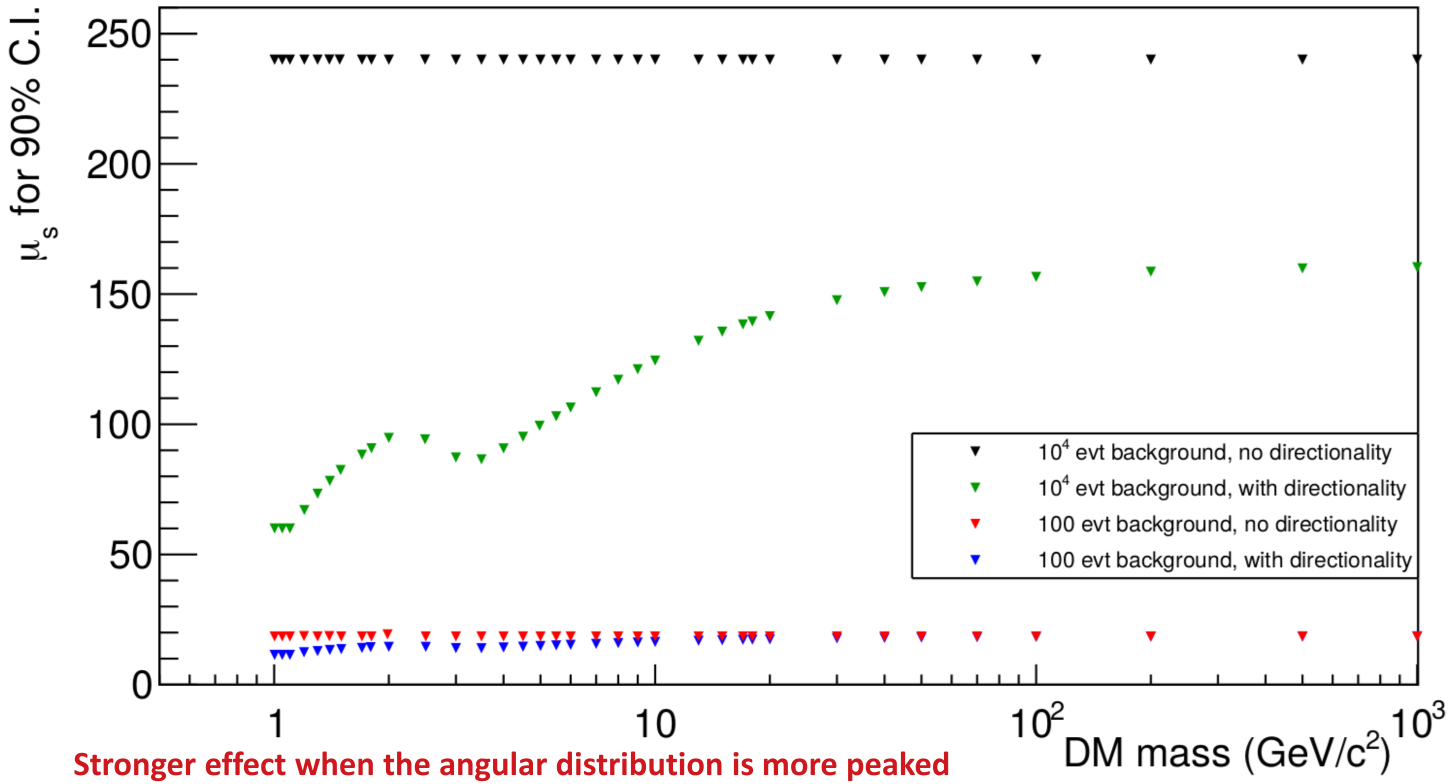
- The WIMP masses which can induce detectable recoils depend on the E_{thr}

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

	1 keV$_{ee}$		0.5 keV$_{ee}$	
	$E_{thr,\mathrm{nr}}$ (keV$_{\mathrm{nr}}$)	Min DM mass (GeV/c^2)	$E_{thr,\mathrm{nr}}$ (keV$_{\mathrm{nr}}$)	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

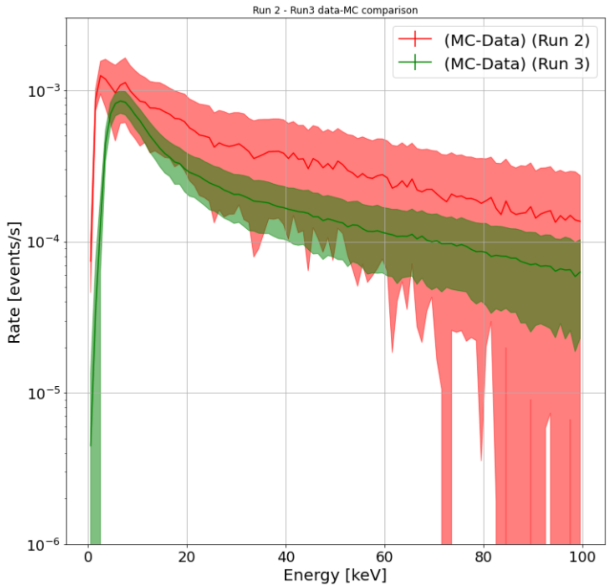
Direction more effective with more background

↓

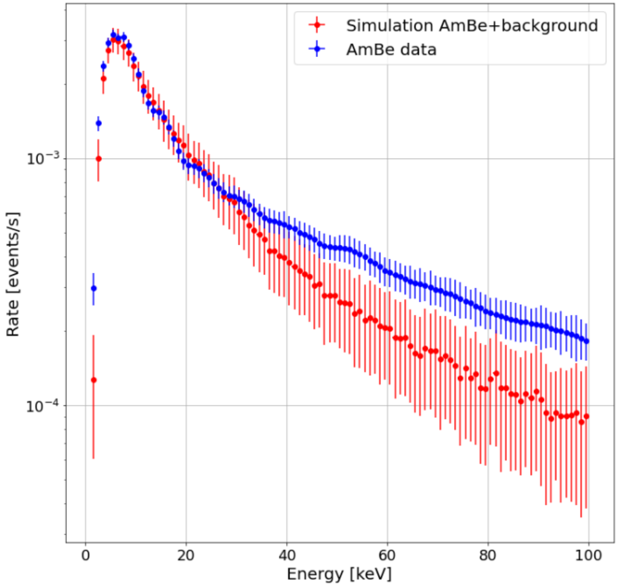
For directional detectors, sensitivity improves with backgrounds

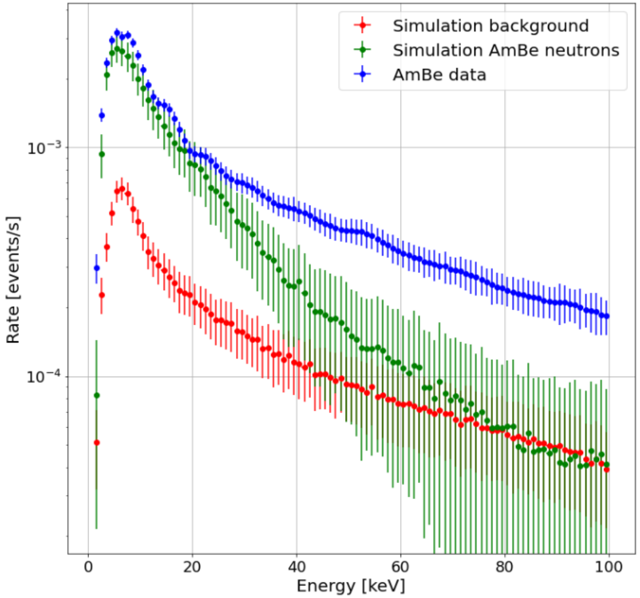
LIME RUN Analysis

Difference between Run2 and Run3 very similar in absolute value



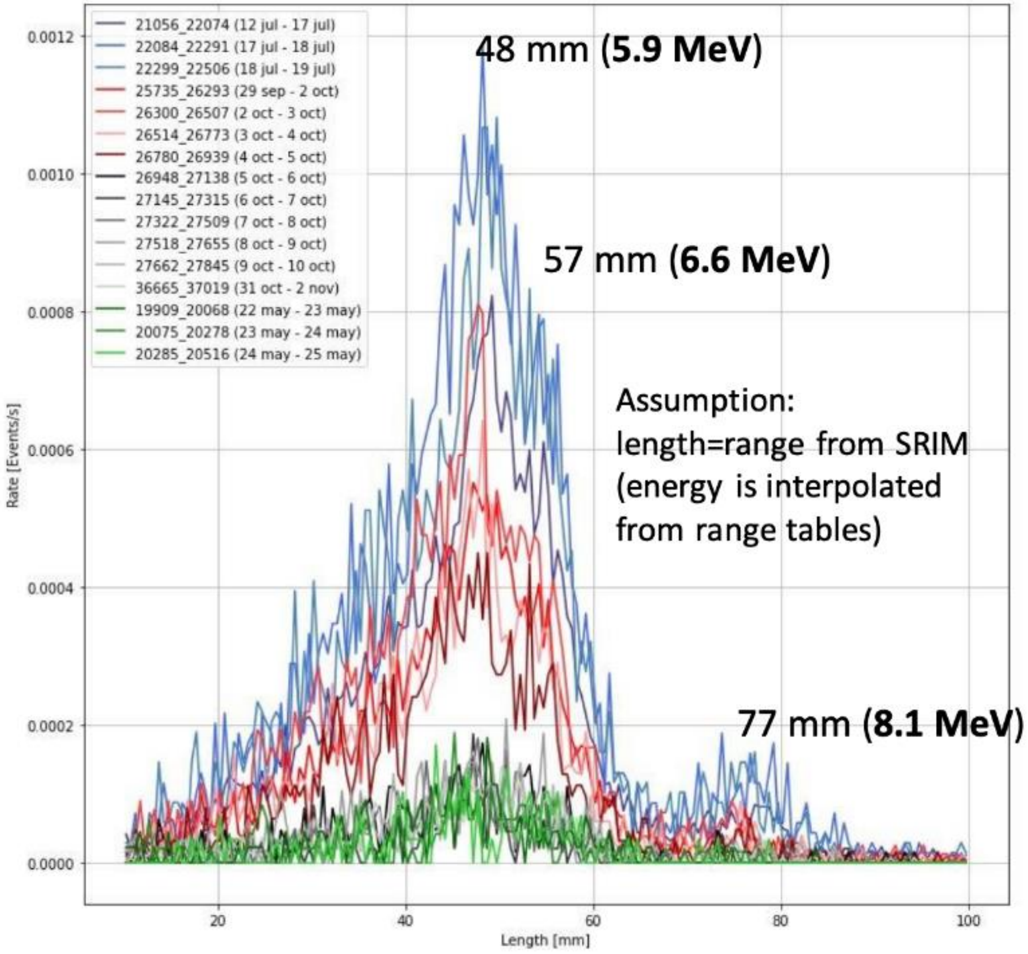
Simulation of AmBe gamma spectrum is correctly reproduced when background does not dominate





LIME RUN Analysis

Length of tracks with large density

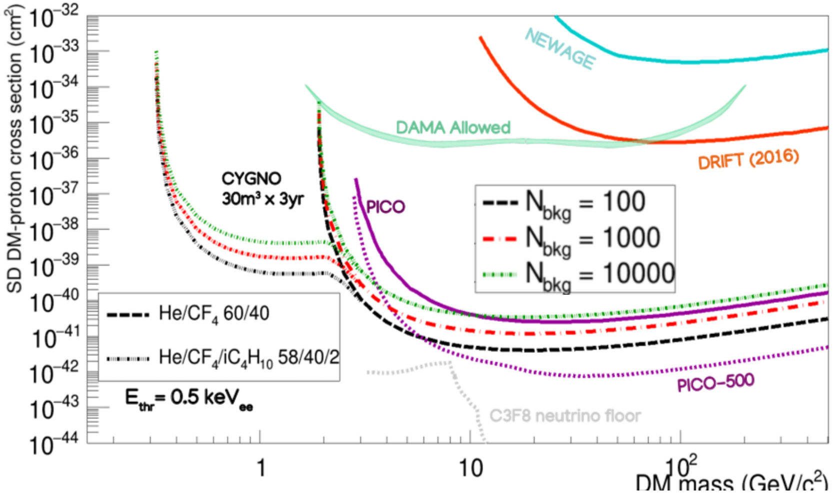


Expected alphas from radon chains

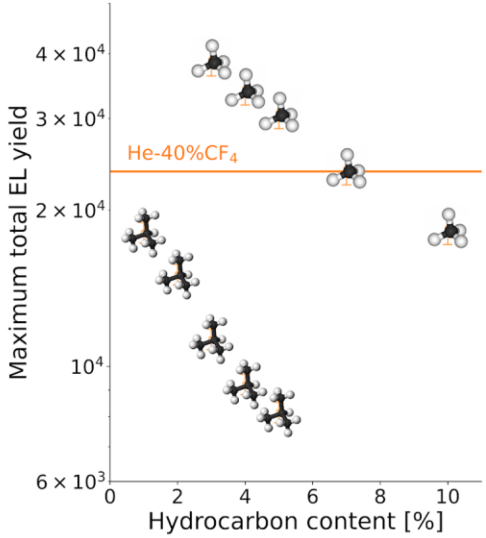
Rn222	5.59 MeV
Po218	6.6 MeV
Po214	7.8 MeV

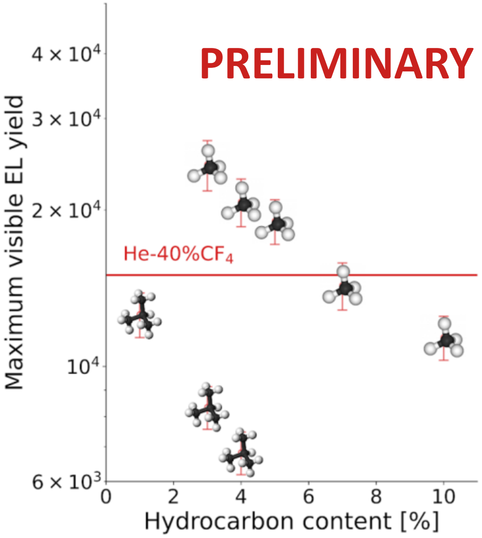
R&D Activities

- 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





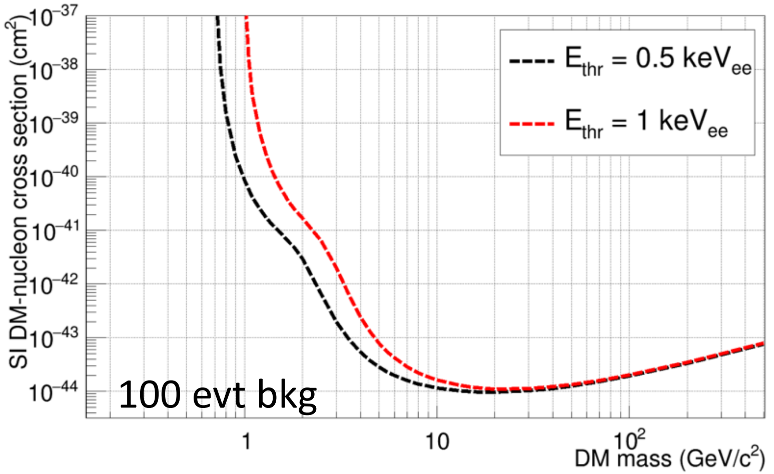
Visible and UV light resulted quenched

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

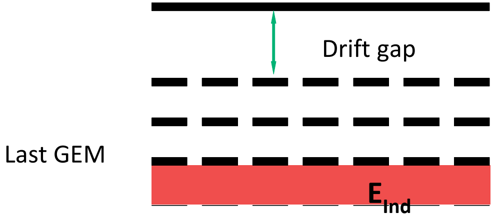
Paper submitted

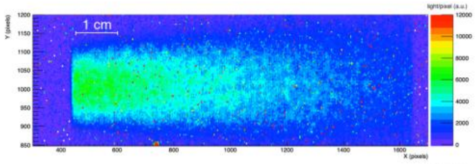
R&D: Enhanced Light Yield

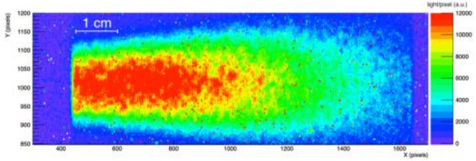
- The possibility of increasing the light yield is under study to lower the energy threshold



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

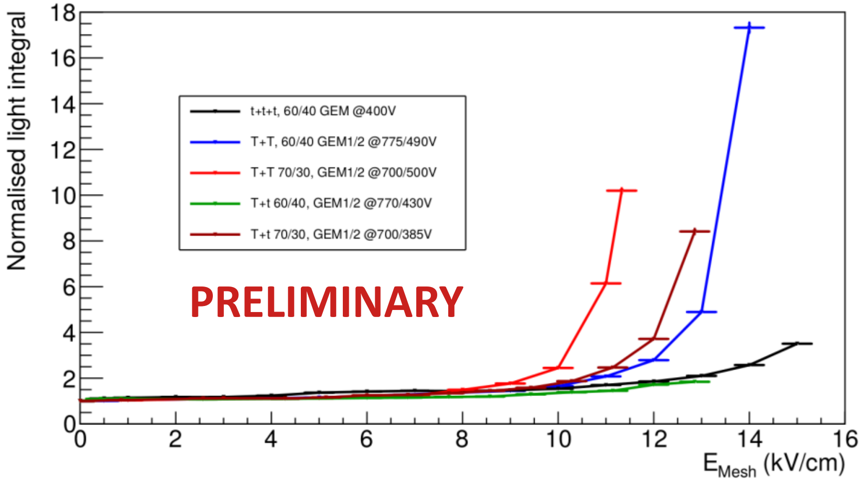






High field turned on

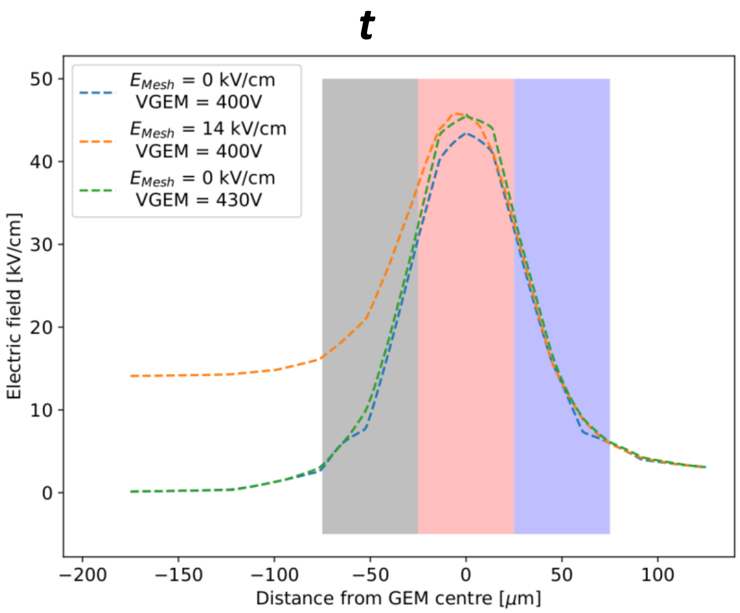
Light vs extra electric field



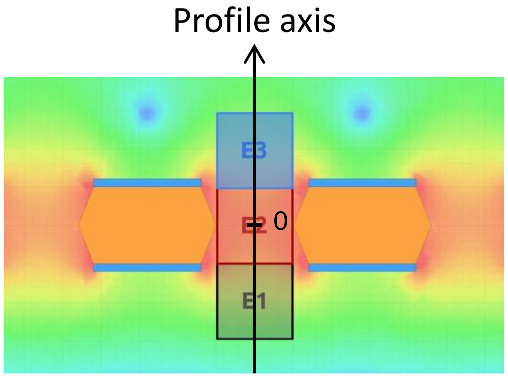
Light was found to increase up to factor 2 without degrading diffusion and energy resolution

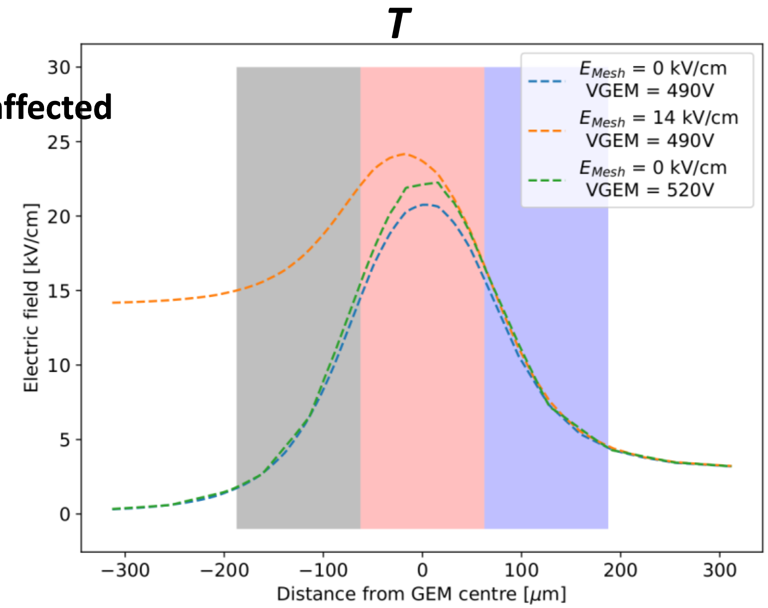
Paper almost ready

GEM Fields Dependence



T GEM more affected



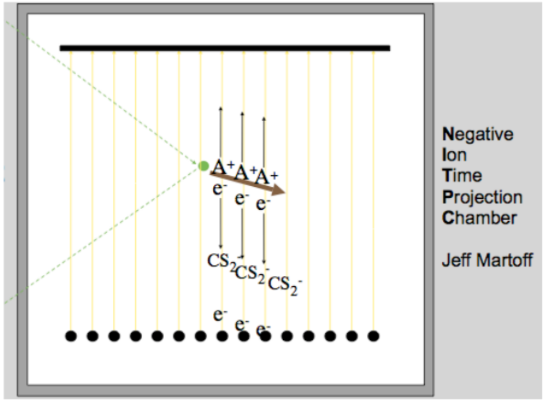


G.Dho

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

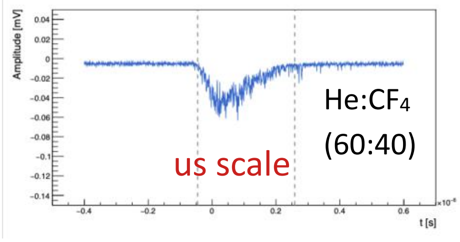
- Pioneered by Martoff and DRIFT (CS_2) and New Mexico group (SF_6) (low pressure 10-100 Torr)
  Martoff et al, D.A.E., 440 (2) (2000) Phan et al, JINST., 12 (2016)

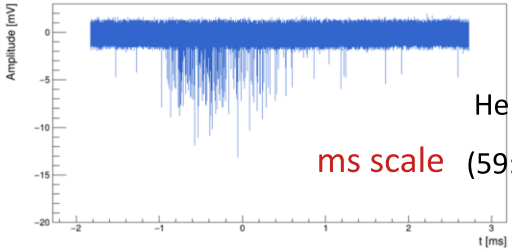
- Gas mixture of He:CF_4:SF_6 (59/39,4/1,6) was demonstrated a NID mixture with charge readout (610 Torr)
  Baracchini et al,JINST, 13(04) (2018)

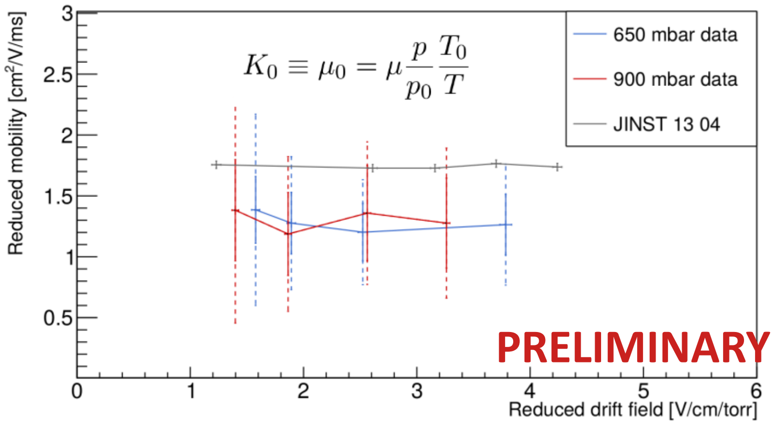
R&D: Negative Ion Drift (NID)

- Interesting results on NID with $He:CF_4:SF_6$ (59,39.4:1.6) mixture
- PMT analysis clearly shows ionic drift

Alpha source in use





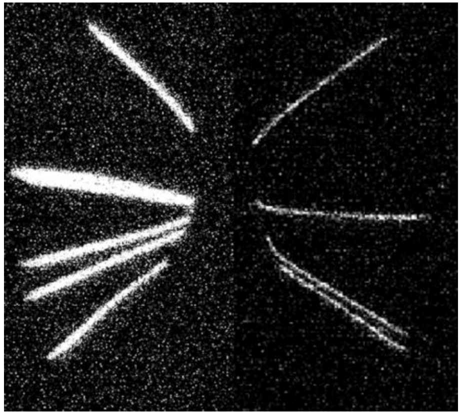


- sCMOS images show extremely large reduction of diffusion

Raw sCMOS camera images

$He:CF_4$ (60:40)

Same light intensity



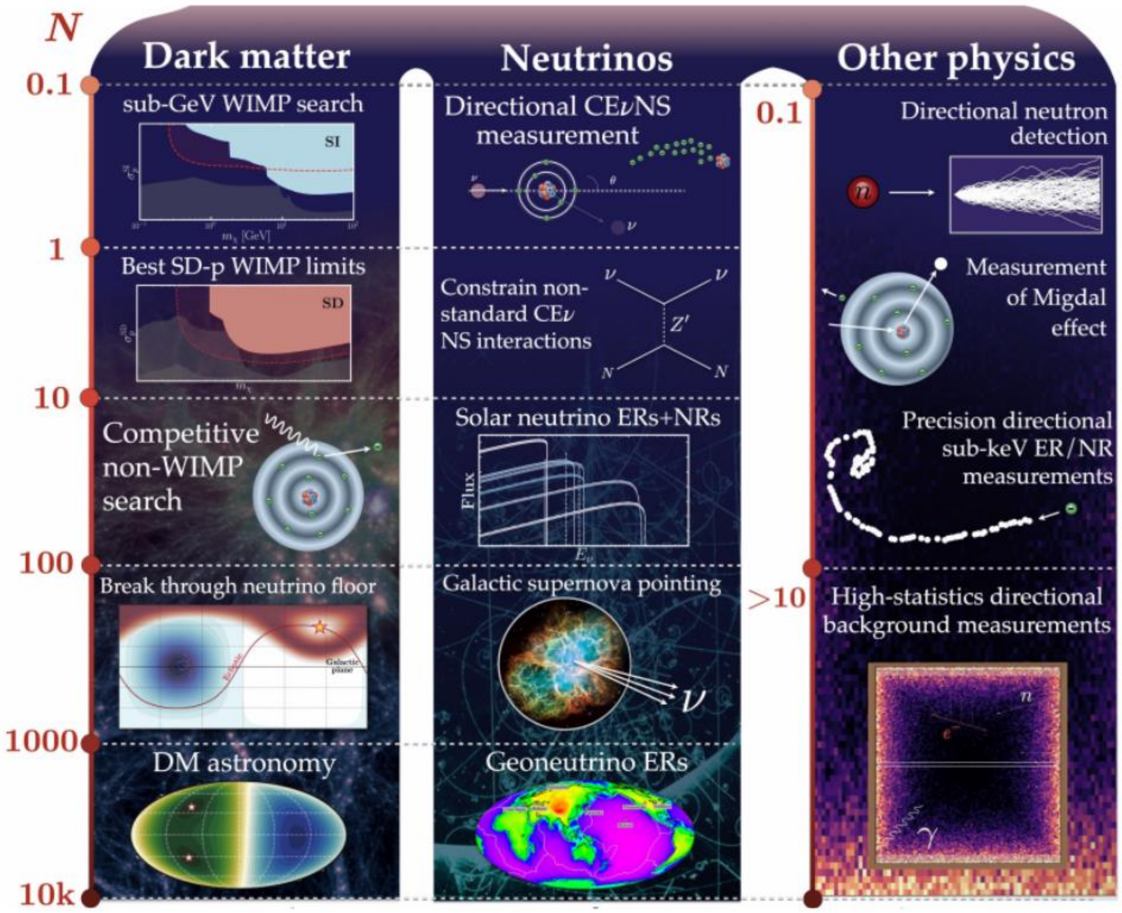
$He:CF_4:SF_6$ (59:39.4:1.6)

To our knowledge,this is the first time ever NID operation at 900 mbar with optical readout is measured

CYGNUS

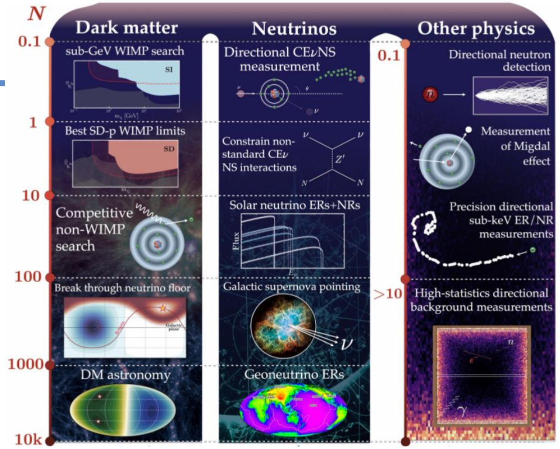
- CYGNUS physics reach as a function of exposure

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



Other Applications

- Neutrino detector:



X-ray polarimetry

Migdal effect

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