CYGNO Experiment

Importance of directionality in the search for dark matter below the neutrino fog. The CYGNO Experiment

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ASTROCENT SEMINAR SERIES

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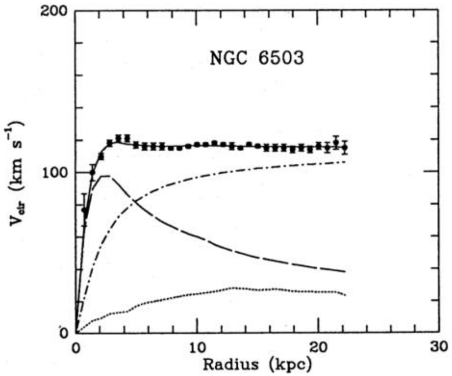
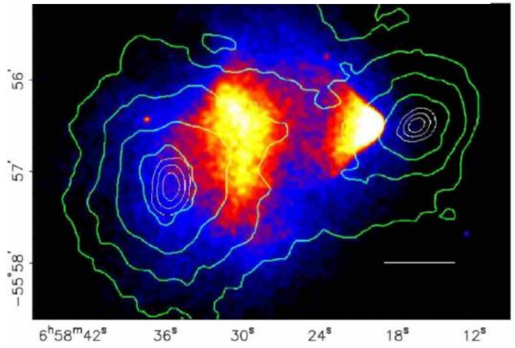
erc
European Research Council
Established by the European Commission

DARK MATTER

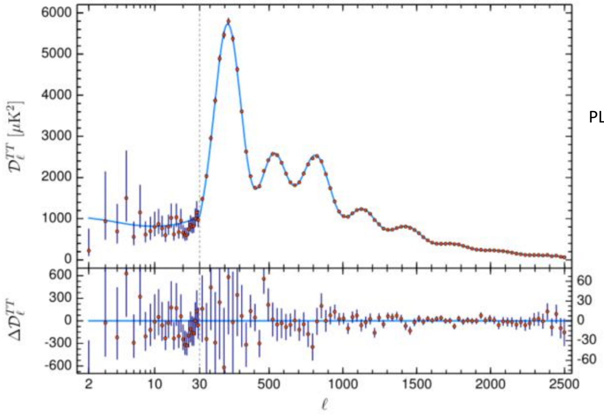
- Standard Model and General Relativity are the most successful theories of modern physics
- Astrophysical and cosmological measurements indicate that the picture is still incomplete
- Deviations from expectations are observed across all scales
- All these measurements are related to gravitational effects
- Dark matter (DM) considered an established paradigm of modern physics (84% of all matter)



Begeman et al, R.A.S., 249 (3) (1991)



Clowe et al, AJ, 648 (2) (2006)



PLANCK, A.A., 641 (2020)

DARK MATTER CANDIDATES

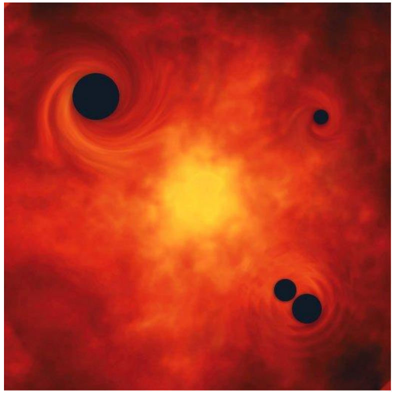
- Our knowledge of gravity is incomplete

MOND

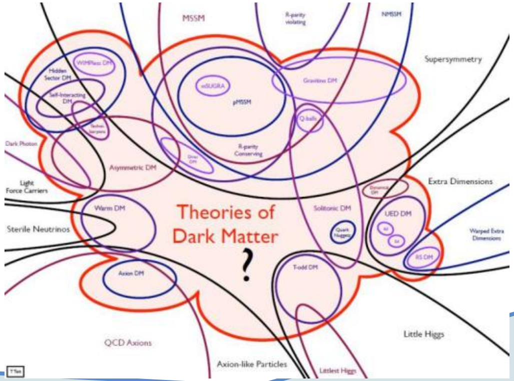
$$R_{\mu\nu}+\frac{1}{2}g_{\mu\nu}R+\alpha f_{\mu\nu}(g_{\mu\nu}) = \frac{8\pi G}{c^4}T_{\mu\nu}$$

- Unobserved astrophysical object cause the gravitational effects measured

PBH



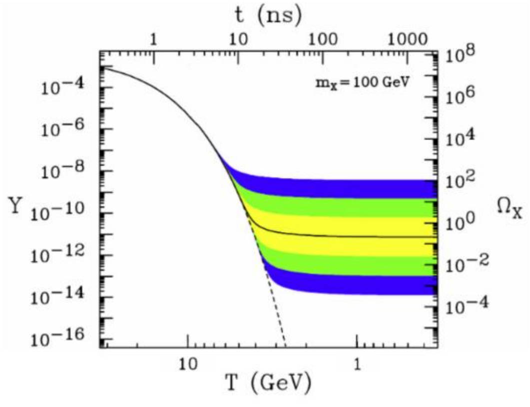
- New particle or set of them is responsible



Dark Matter As Particle(s)

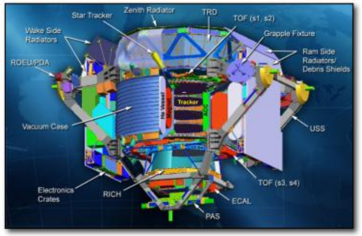
- To be consistent with the measurements, particles need to be:
  - Non-baryonic
  - Neutral and colour-free
  - Stable
  - Abundant (Ω = 0.26)
  - Weakly interacting
  - Warm or cold

- Particle candidates can behave as coherent waves or actual particles
  - Axions
  - ALPs
  - WIMP-like particles
    - Naturally predicted by many SM extensions
    - Freeze-out mechanism allows to reproduce current abundance
    - Cold candidate
    - Mass O(1) GeV/c^2 to O(1) TeV/c^2



DETECTION STRATEGIES

AMS-02



- Looking for the production of excess of regular matter induced by DM phenomena

DM

DM

Detection by Annihilation

Detection by Production

SM

Direct Detection

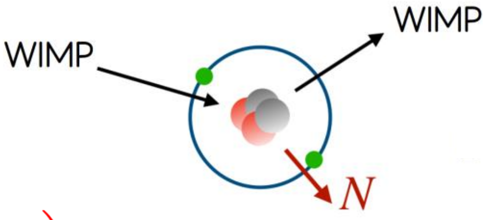
SM

- Looking for the production of DM as missing momentum
- LHC leads the search in TeV scale

- Looking for scattering of particles with target material
- (For wave-like) conversion resonances in cavities

Direct Detection

- WIMPs are expected to populate the Galaxy with an almost isothermal halo (Standard Halo Model)
- This weak interaction can be exploited to detect recoils of regular matter



Nuclei preferred due to kinematic energy transfer

Differential rate per unit mass

$$\frac{dR}{dq^2 d\Omega} \propto \frac{N_0}{A_{mol}} \frac{\rho_0}{m_\chi} \frac{d\sigma}{dq^2} \int \delta\left(\cos\theta - \frac{q}{2\mu_A v}\right) v f(\vec{v}) d^3 v$$

Target material chosen:

- Abundance of target
- Kinematic coupling with DM

Nuclear physics:

- Differential cross section of the process
- Interaction considered elastic
- Spin independent or dependent interactions assumed

Astronomical parameters:

- Standard Halo Model for the velocity distribution structure
- DM density at Earth position
- Earth's relative motion with respect to Galaxy

DIRECTIONALITY

- Most of the experiment can only measure the energy of the recoils

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

1 more physical degree of freedom

Directionality

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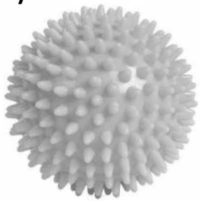
Only wave intensity



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Coloured

Adding wavelength

Only wave intensity

DIRECTIONALITY

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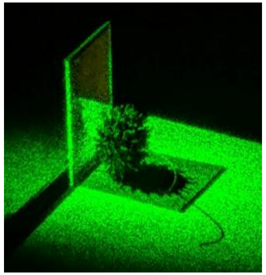
Adding phase



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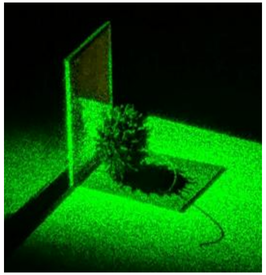
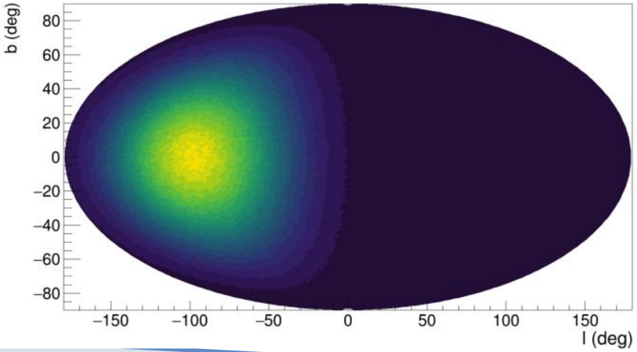


- WIMP expected recoil distribution is expected highly anisotropical thanks to Sun and Earth's motion

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



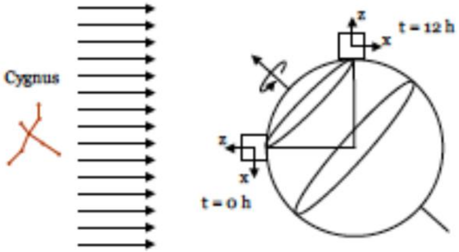
Galactic coord

10 GeV WIMP

Fluorine target

DIRECTIONALITY FEATURES

- The strongly anisotropic signal in contrast to an expected flat background enhances the power of limits or discovery of DM interactions



Vahsen et al., Annual review

- Directional information is more powerful than energy one

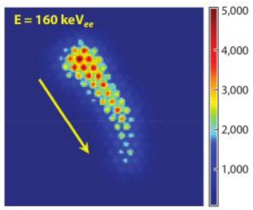
Energy	Angle	In case no signal is statistically different from expected background
Exponential signal over **exponential** background	**Peaked dipole** signal over **flat** background →	**BETTER LIMITS**

- How well can the dipole be seen?

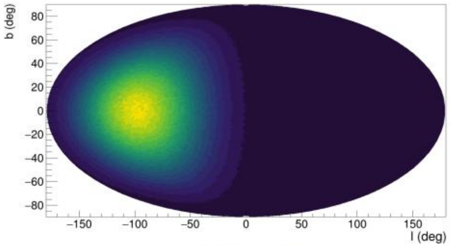
Head-tail (HT)

3D/2D

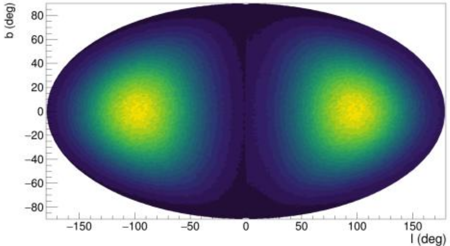
angular resolution



Vahsen et al., Annual review



Full HT



no HT

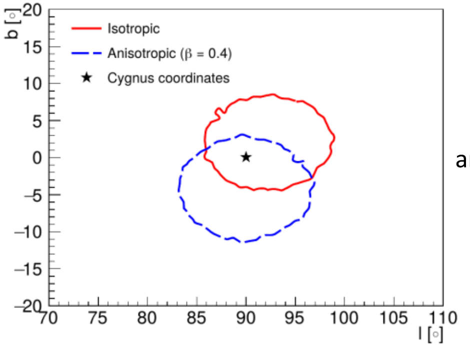
Billard, Mayet, Santos (Physical Review D ,85(3) (2012)

DIRECTIONALITY ADVANTAGES

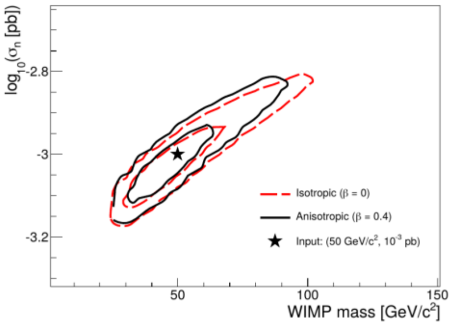
- Akin to limits, an excess over background can be found with same significance with less exposure (factor ~ 100 with perfect head-tail and background recognition)

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

- A measured arrival direction of WIMPs can lead to a positive claim of Galactic DM



Recoil average arrival direction for different Halo models

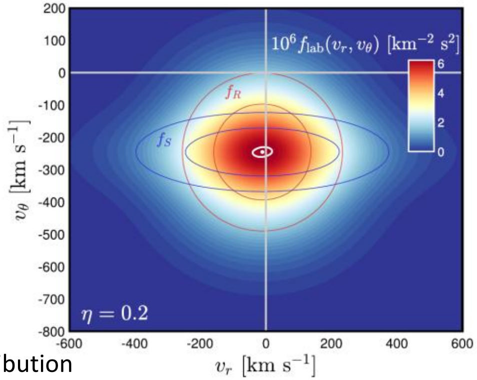


Mayet et al., P.R., 627 (2016)

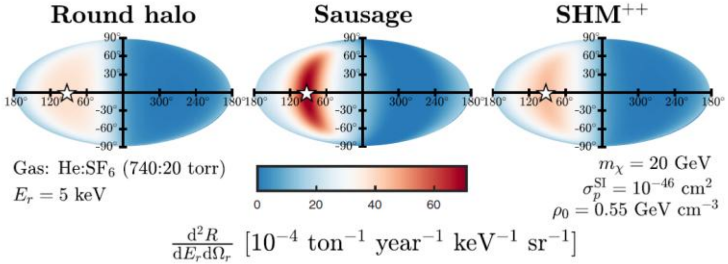
- High performance directional detector will be able to estimate the **3D structure of the velocity distribution**, actively probing DM theories

$$\frac{dR}{dE} \propto \int f(v)dv$$

$$\frac{dR}{d\Omega} \propto \int f(\boldsymbol{v})d^3v$$



Velocity distribution



Evans et al., P.R.D, 99 (2019)

RARE SEARCHES BACKGROUND

- Current limits point at less than 1 event/kg/y with energies well below 100 keV

Rare Searches

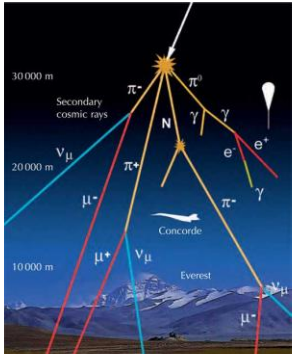
- The quest can be hindered by many backgrounds:

Cosmic Rays

-High energetic secondary cosmic rays
can overwhelm signal

Solution:

- Underground operation to shield aginst them



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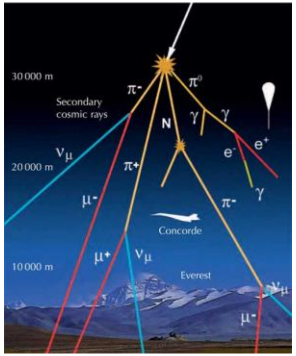
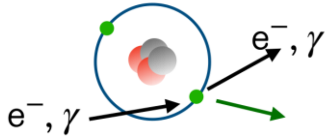


Gamma rays

- Interact in the detector inducing electron recoils (ERs)
- At low energy hard to distinguish from NRs
- Come from natural radiactivity of both laboratory and detector materials

Solution:

- Shield (high Z) against environment, radiopure material
- Exploit detector feature to distinguish NR from ER



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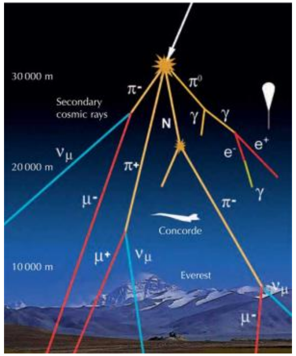
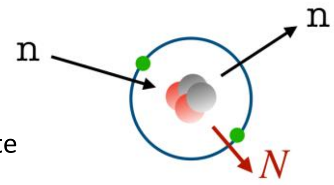


Neutrons

- Interact in the detector inducing NRs
-Originated by muon spallation in rocks or by (α,n) phenomenon

Solution:

- Shield with hydrogen rich materials to moderate and capture them
- Radiopure materials



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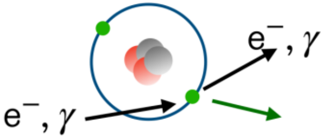

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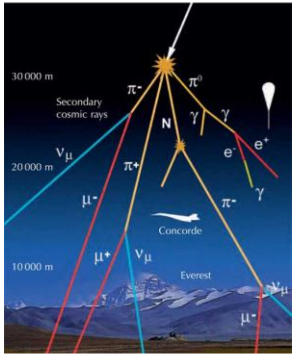

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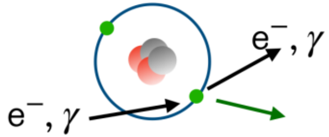

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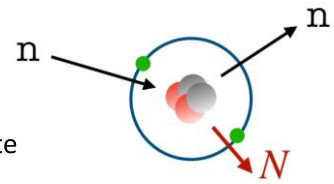


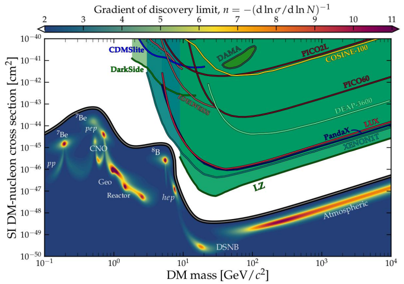
Neutrinos

- Cross any type of shield and produce both ERs and NRs
- Origin from Sun, atmosphere, extragalactic

- Strongly harden the direct search:

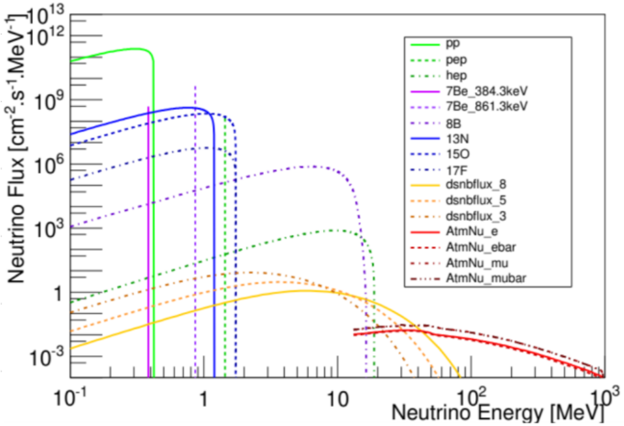
Neutrino floor and fog

O'Hare, P.R.L., 127 (25) (2021)



NEUTRINO PROBLEM

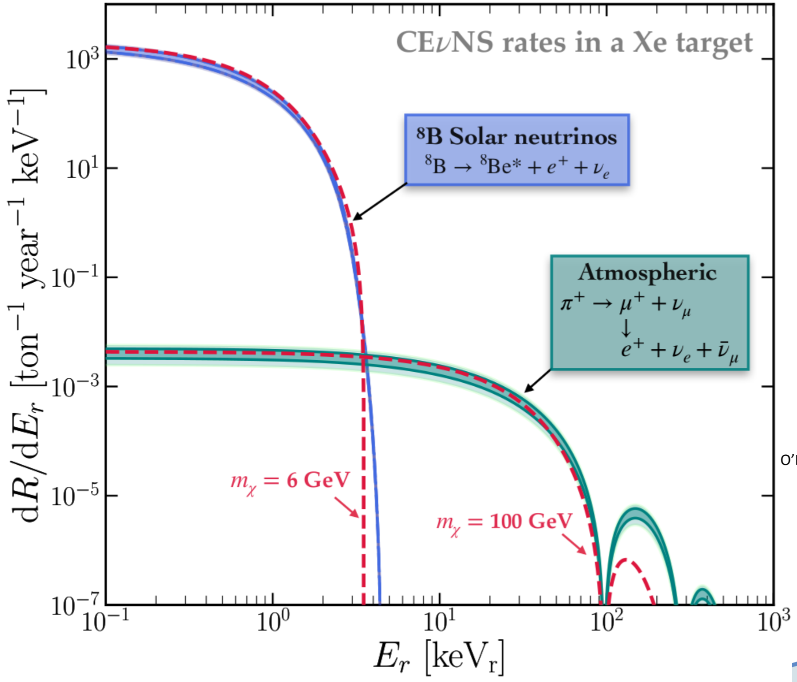
- Soon large exposure experiments will be sensitive to neutrino-induced nuclear recoils (CEvNs)



Billard er al, 10.1103/physrevd.89.023524

- Background indistinguishable on event-by-event basis

- But also energy distributions are quite similar



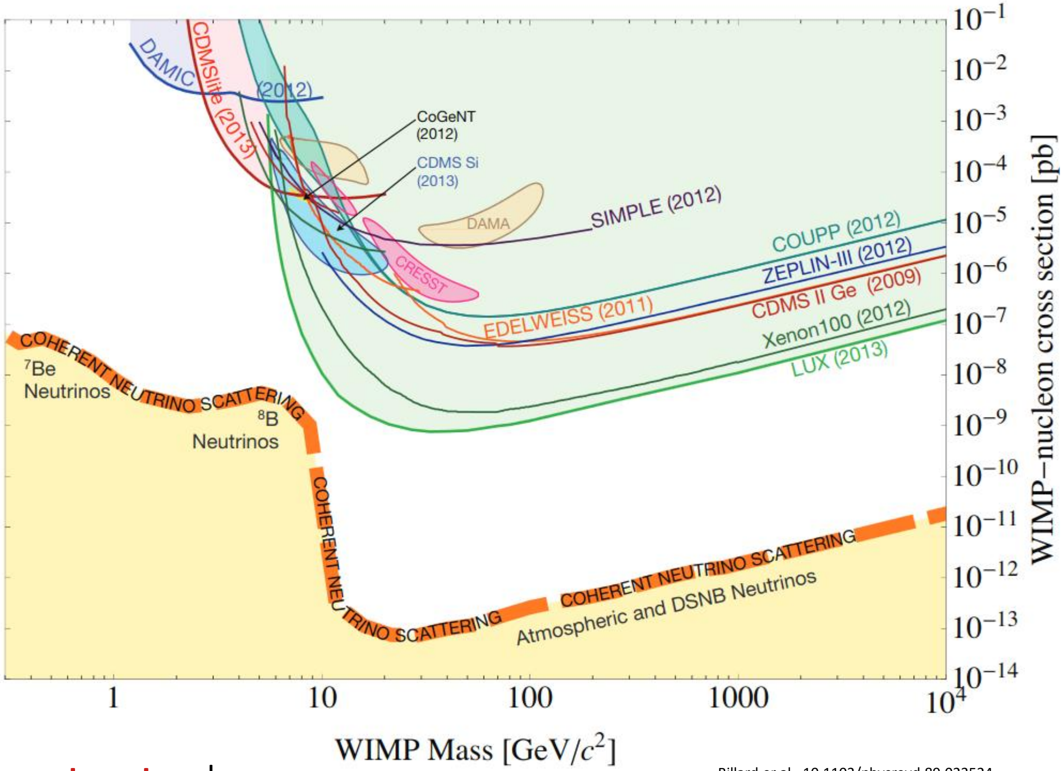
O'Hare at IDM 2022

NEUTRINO FLOOR

- If the energy spectra of DM-induced and neutrino-induced a
  problems will arise when you start seeing neutrinos

- A statistical study showed that increasing the amount of neu
  detected the discovery limit for DM got stuck

- A definition of an inevitable insurmountable limit was name
  floor



Billard er al., 10.1103/physrevd.89.023524

Floor boundaries depend on **energy threshold** chosen, **target** and arbitrary definition of
how many neutrino events are too many for DM to be discovered

Somewhat arbitrary neutrino floor level

Neutrino Fog

- But is it so insurmountable?
- A new statistical study based on profile likelihood ratio by Ciaran O'Hare demonstrated how below the neutrino floor there is a fog hard to navigate in, but it is possible to see DM

O'Hare 10.1103/physrevlett.127.251802

- In the end, DM-induced and neutrino-induced are similar, but not identical
- The study is focused on how the sensitivity to DM improves with the increase of exposure of a detector

$$n = -\left(\frac{d\ln\sigma_{n,SI}}{d\ln N}\right)^{-1}$$

No background → n=1

Poissonian background → n=2

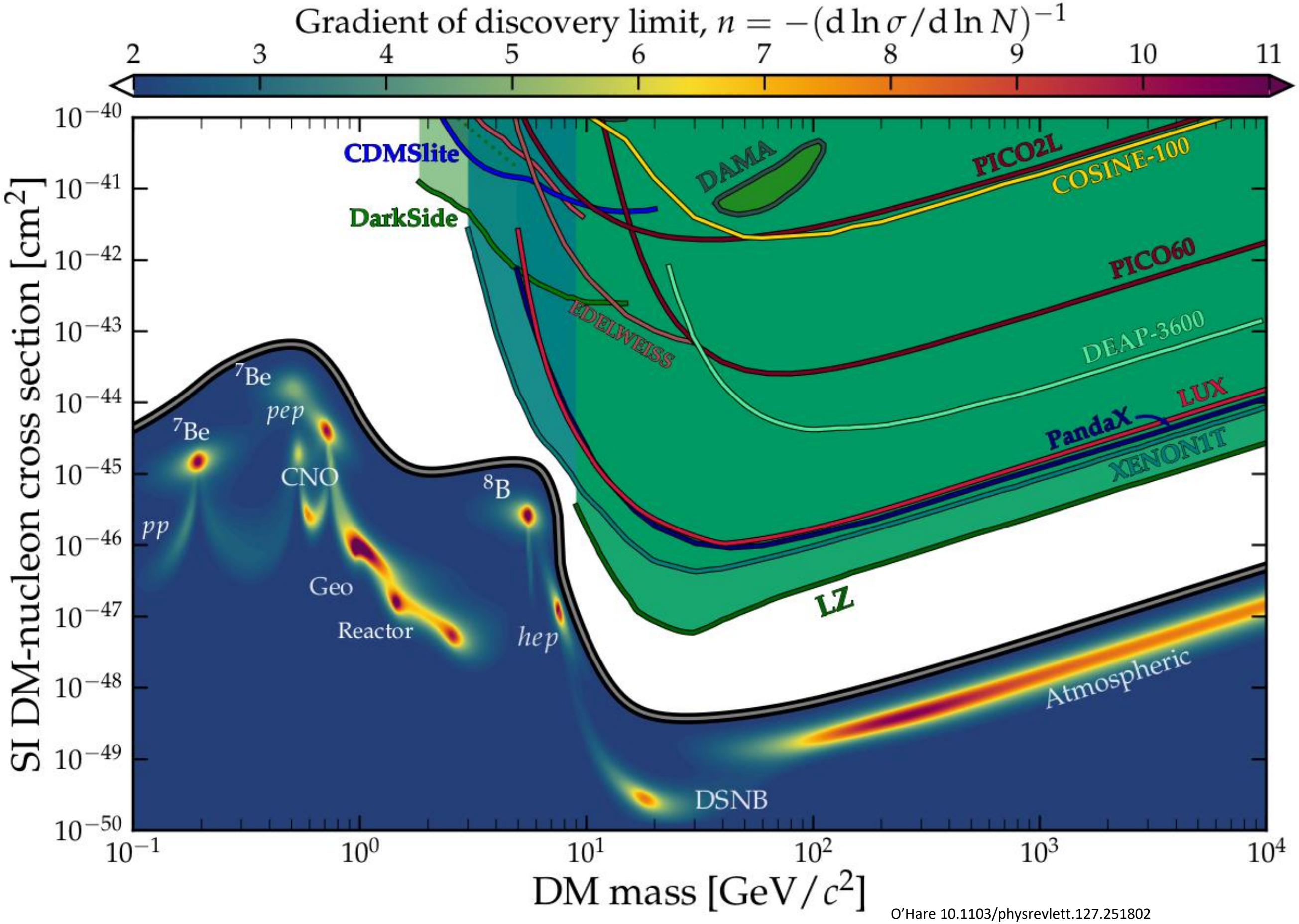
Worse → n>2

NEUTRINO FOG

$$n = -\left(\frac{d \ln \sigma_{n,SI}}{d \ln N}\right)^{-1}$$

Denser fog signals where the investment in increasing exposure does not return advantages in DM sensitivity

Neutrino floor is defined as the cross section where n>2



O'Hare 10.1103/physrevlett.127.251802

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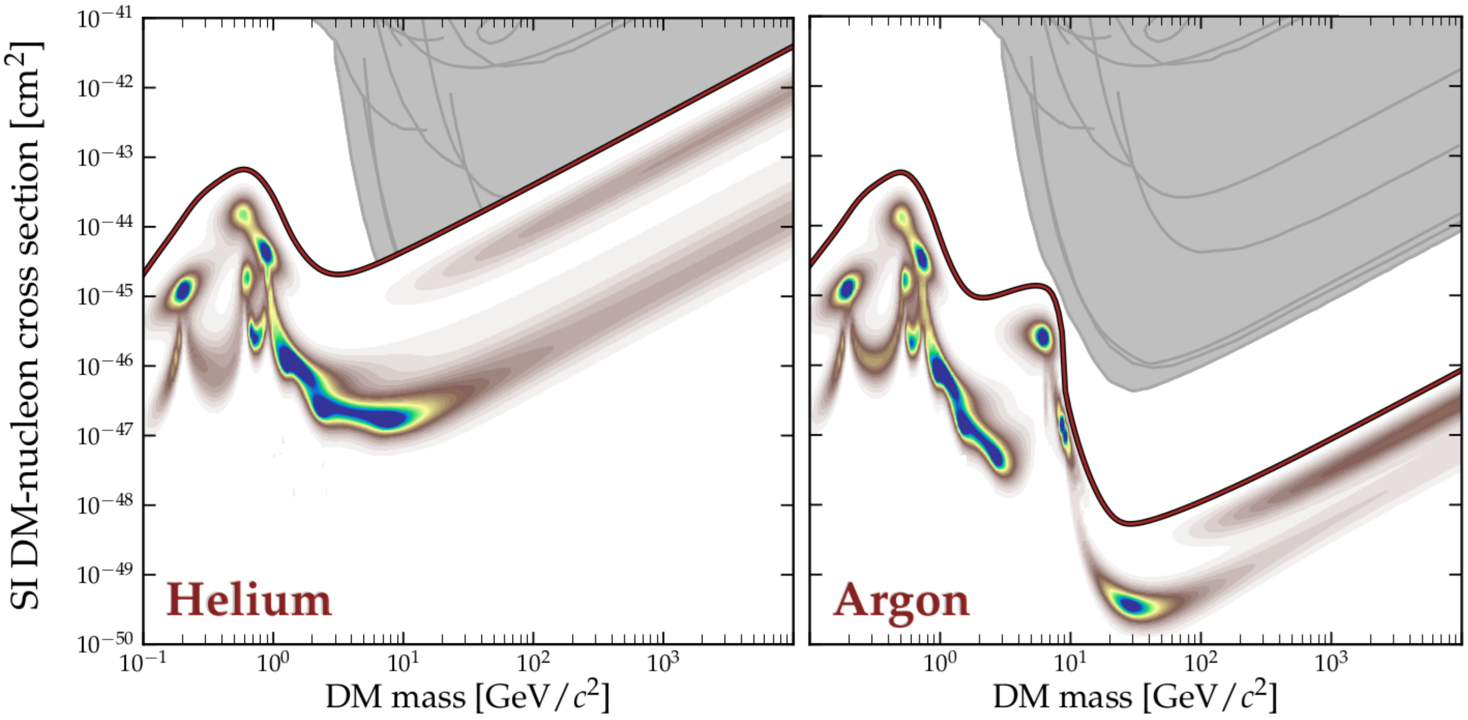


$$A = 4 \qquad\qquad 40$$

Still depends on target

O'Hare 10.1103/physrevlett.127.251802

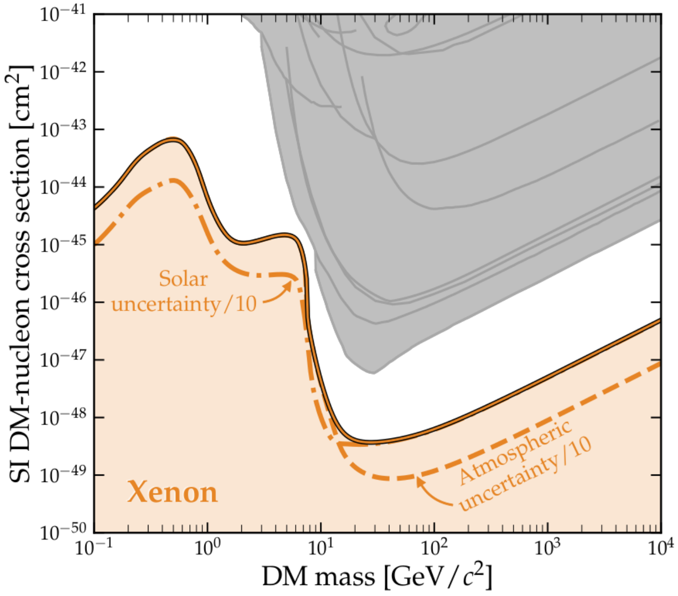
Deal With It

Vahsen et al, A.R., 71 (1) (2021)

Improve neutrino flux uncertainties

Not up to DM community

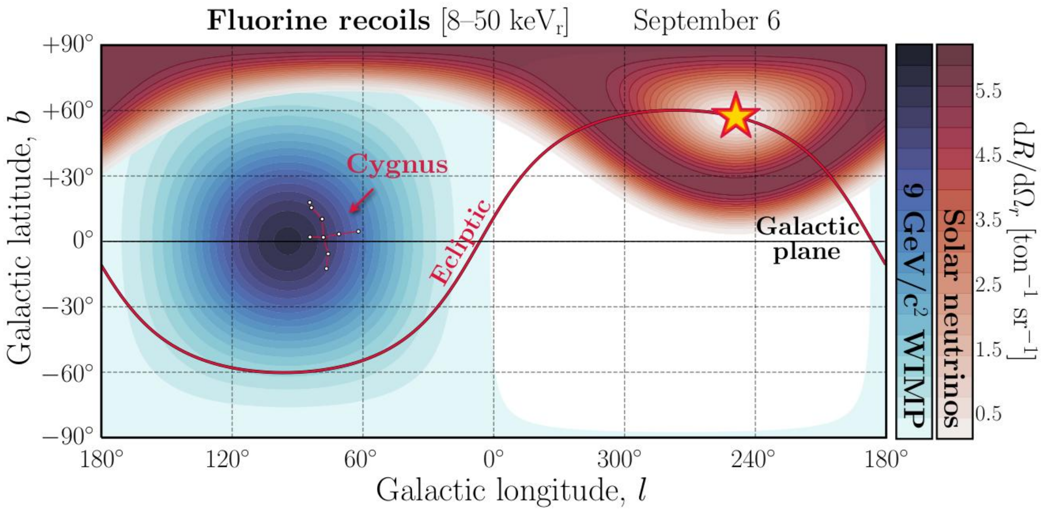
Mainly lowers the neutrino floor position



O'Hare 10.1103/physrevlett.127.251802

Employ directionality

Look at the signal from another perspective!



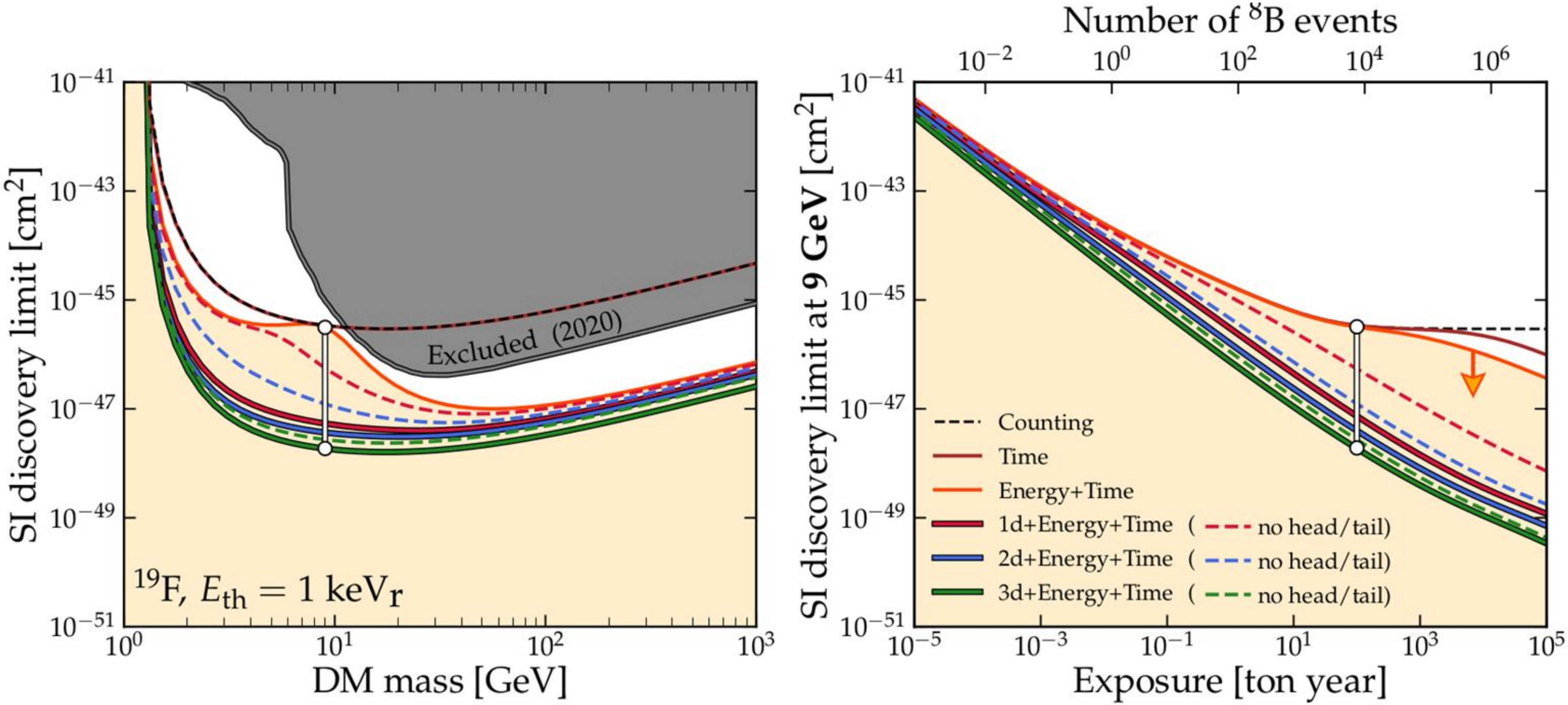
The neutrino fog can be sidestepped (almost completely for Solar neutrinos) with nice directional performances:

HT>75% ang res < 20 Fluorine case

E res <20% Time res < hr

Deal With It Directionally

- Through directionality, the fog can be naturally breached

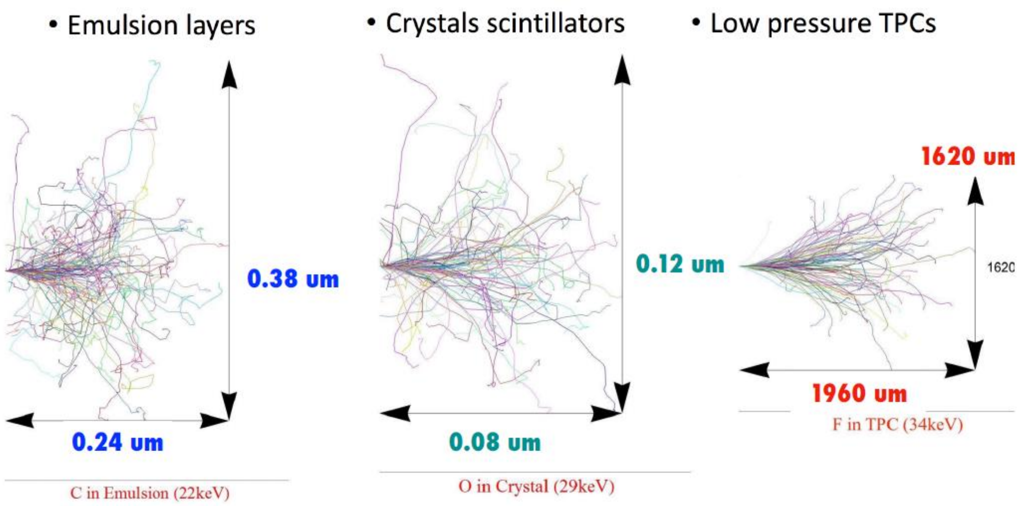


Vahsen et al, A.R., 71 (1) (2021)

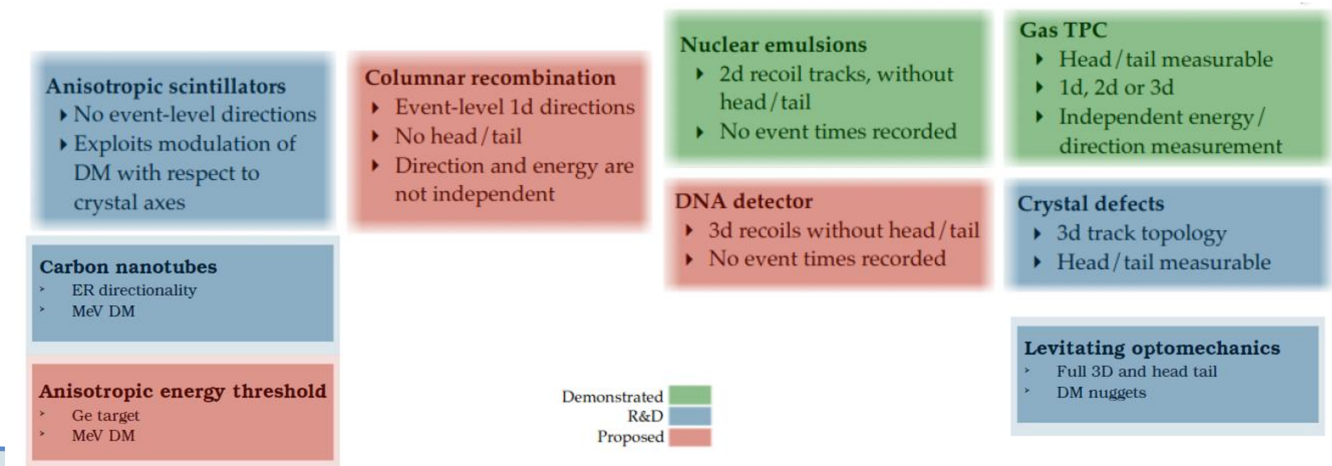
How To Be Directional

- To measure direction you need readout more granular than the track length

SRIM simulations



- Different techniques on different R&D or experimental stage



TPC

- Need for intrinsic 3D detector with granular readout

Time Projection Chamber (TPC)

- Looking for very low energy O(1) keV nuclear recoils

Gaseous target

- Searching for rare events O(1) evt/year/ton

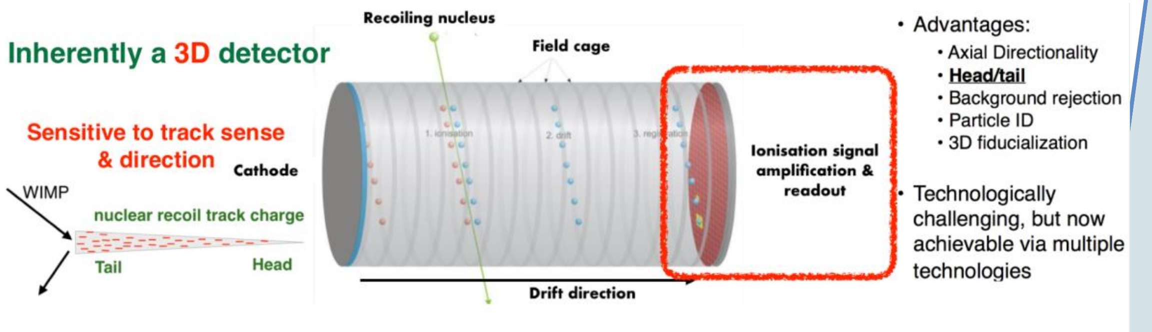
Large exposure

Charge readout

closer to gas volume, expensive to cover very large areas

Optical redout

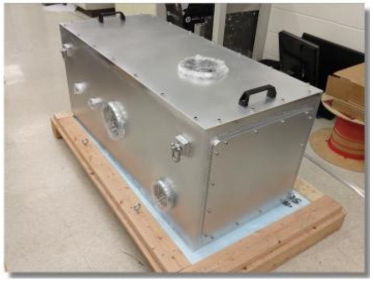
far from gas volume, scalable to large area, require high gain



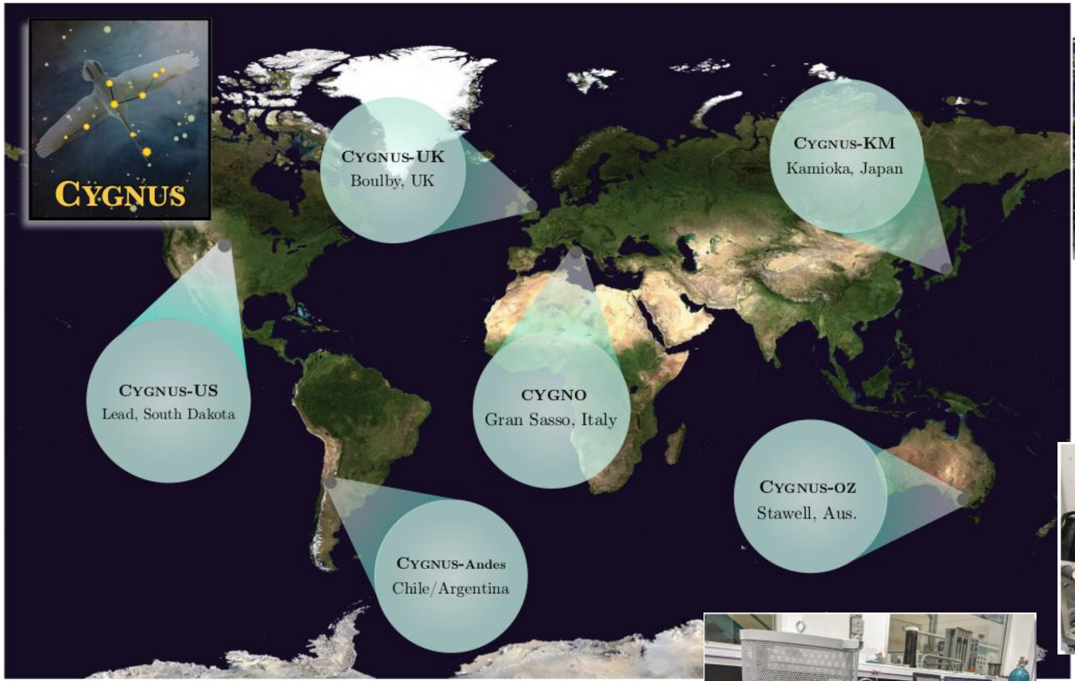
CYGNUS Protocollaboration

- Proto-collaboration which aims for the construction of a multi-target, multi-site Galactic Observatory at the tonne scale to probe DM and measure Solar neutrinos based on the gas TPC technology

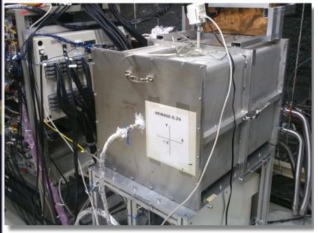
Drift coll., J.C.A.P., 2021 (7) (2021)



Vahsen et al, NIM A 788 (2015)

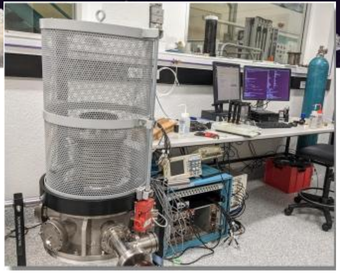


CYGNUS white paper:
https://arxiv.org/abs/2008.12587



Ikeda et al, Prog. T. E.P., 202

Amaro et al, Instruments 6



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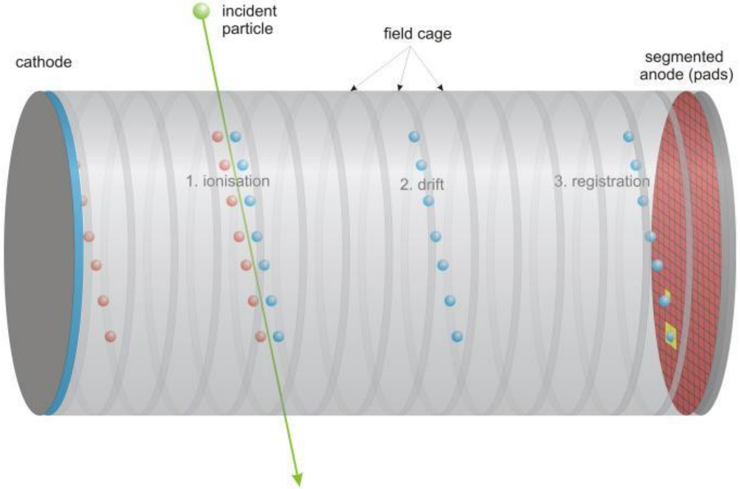
- Foreseen operation with both electron and negative ion drift, charge and optical readout

CYGNO EXPERIMENT

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

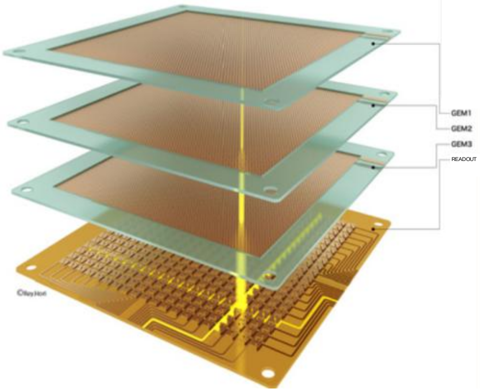
TPC

z axis



He:CF_4 gas
room temperature
atmospheric pressure

Amplification Stage



Gas Electron Multipliers
(GEMs)

Grants large gains
with high granularity

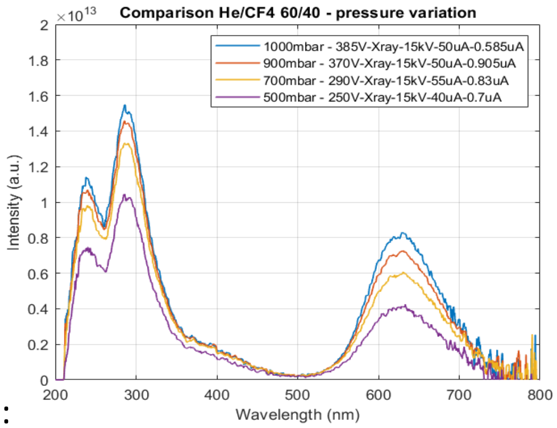
Optical readout

PMT
sCMOS cameras

Decoupled from gas,
less contamination
less noise

GAS: HE:CF_4

- Combination of a light noble gas with molecular scintillating gas (CF4)



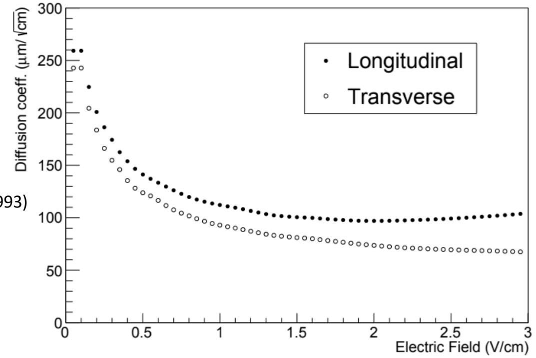
- Optimised to a 60/40 He:CF4 mixture

Density:
~ 1,59 kg/m^3

W-value:
35 eV

- CF4 is a cold gas

Veenhof, Conf Proc., 9306149 (1993)



Low diffusion:
Transverse ~100μm/cm$^{1/2}$ at 1 kV/cm

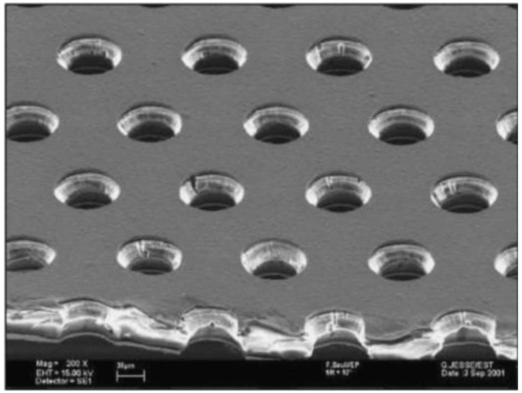
- Light He is excellent for low WIMP mass searches (down to 1 GeV/c2)

$$E_{max} = \frac{1}{2} r m_\chi v^2$$

r maximum with WIMP and target mass equal

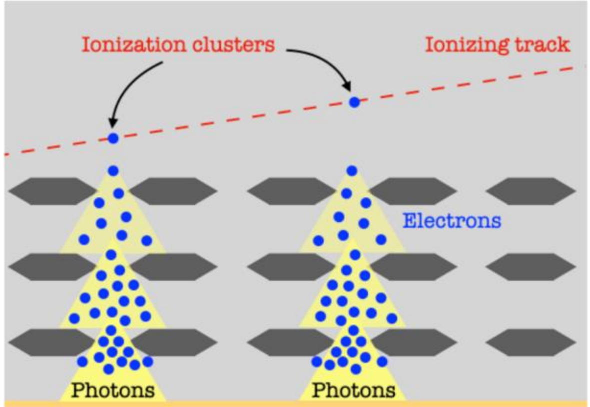
- Fluorine has spin odd nucleus with high sensitivity to SD coupling

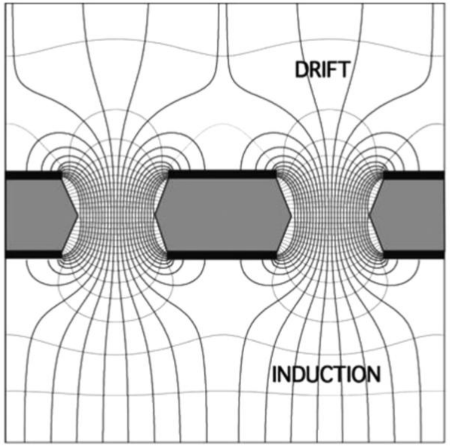
AMPLIFICATION: GEM



- Insulator cladded in copper conductor with plenty of small etched holes (~5000/cm^2)

- The strong electric fields in the holes generate electron avalanches





- Triple structure of 50 μm thin GEMs to grant high gains (up to 10^6)

- Production of photons during amplification due to neutral and charged fragmentation of CF4 (0.07 ph/e$^-$)

READOUT: OPTICAL

PMT

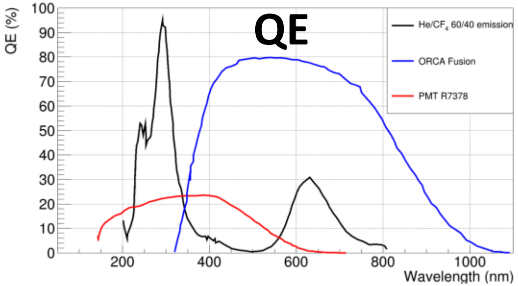
- Fast light detector

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

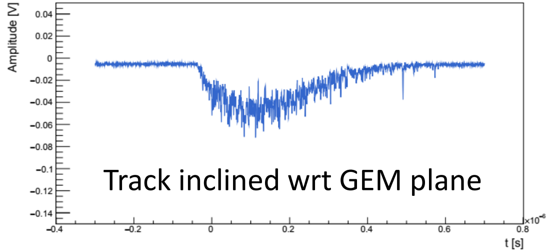
sCMOS Camera

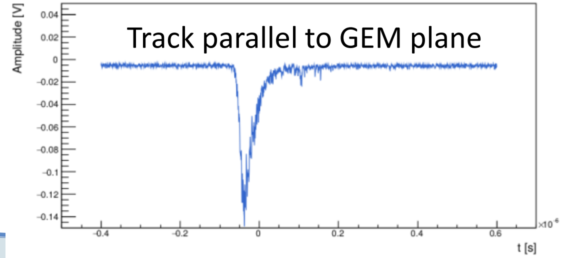
- Highly sensitive and granular sensor
- (1 camera can image a 35x35 cm^2 area with 155x155 μm^2 granularity)
- Low noise per pixel (modern below 0.4 e$^-$ RMS)
- Market pulled

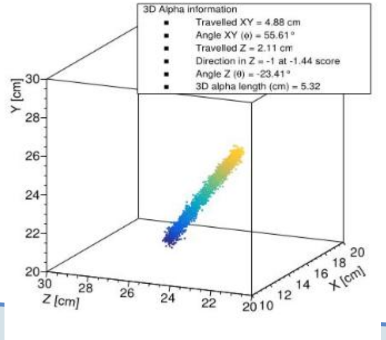
- Provides
- Energy information from number of photons
- dE/dx on X-Y plane
- X-Y positionand topology



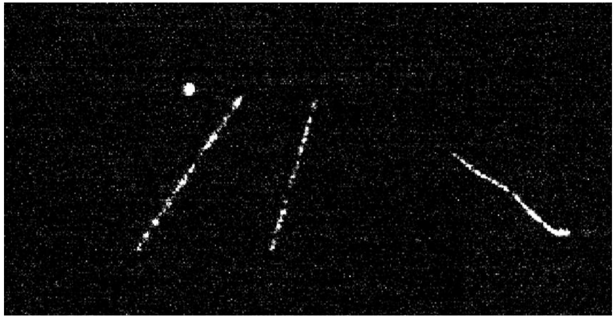
The combination allows energy and 3D topological measurement of each track







READOUT: CAMERA



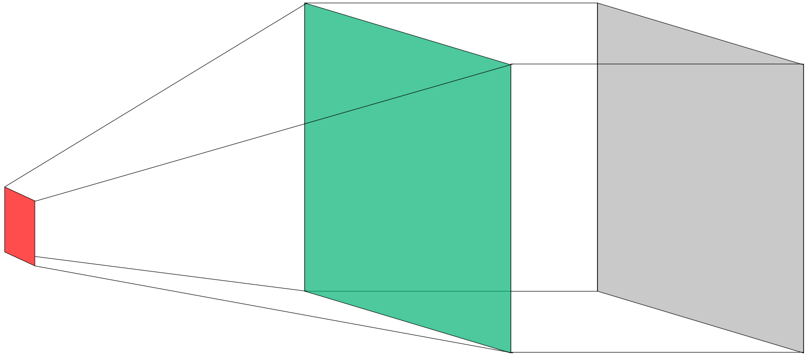
- MPGD allowed to equip TPC with fast (O(1) ns) and granular (O(10) um) amplification stages

- Active Pixel Sensors (CCDs and CMOS) coupled to suitable optics allows to image wide areas with single detector

Area covered	Granularity	Solid angle
36x36 cm^2	155x155 um^2	
10x10 cm^2	41x41 um^2	~ 10^{-3}

- **Pro**: with modern technology, high granularity (O(10) um) can be achieved with a single sensor place O(10) cm away from amplification region

- **Con**: the farther the sensor the less the solid angle acceptance which reduces the signal intensity

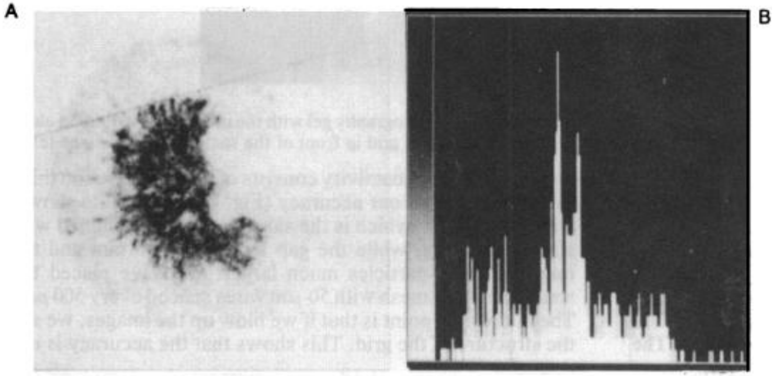


READOUT: CAMERA

Parallel plates readout with CCDs (1989)

Alpha particles readout with CCDs (2000)

Low energy electrons and MIP-like readout with sCMOS (now)

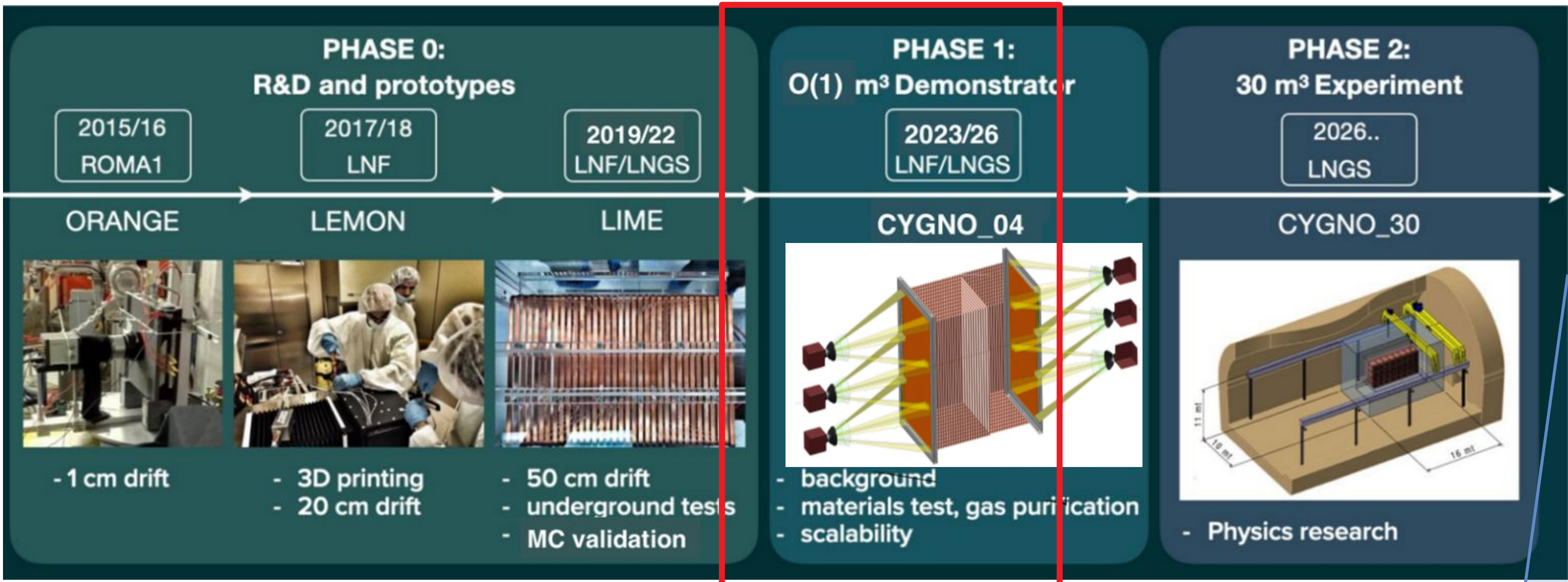


Charpak et al., doi:10.1073/pnas.86.6.1741

NIM A 471 (2001)

TIMELINE

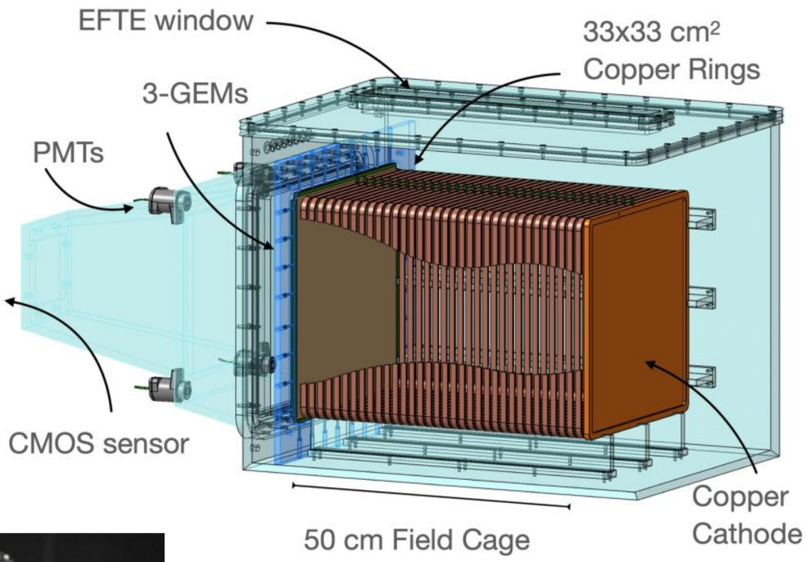
FUNDED

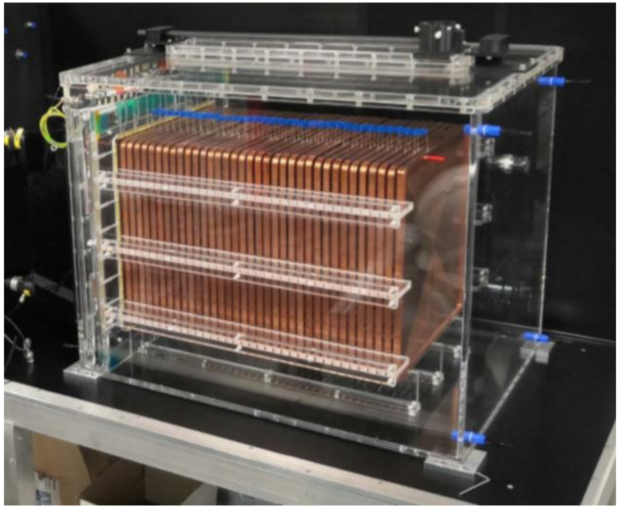


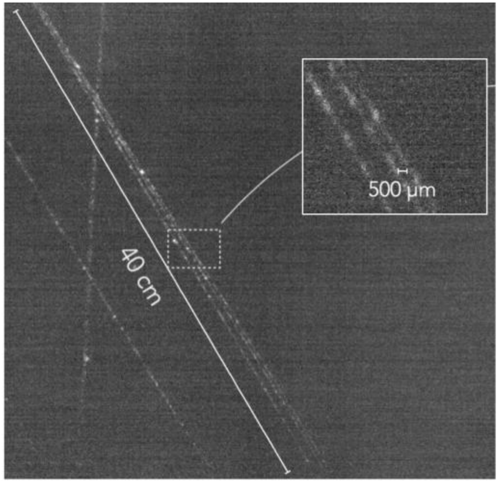
NOW

LIME

- Large readout area (33x33 cm^2) imaged by 4 PMTs and 1 sCMOS
- 50 l volume, with 50 cm drift
- **Goal:** Operate it underground at LNGS-INFN and validate MC simulation chain of the background

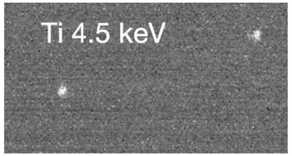


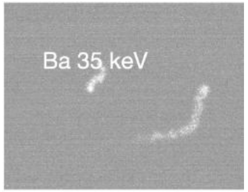


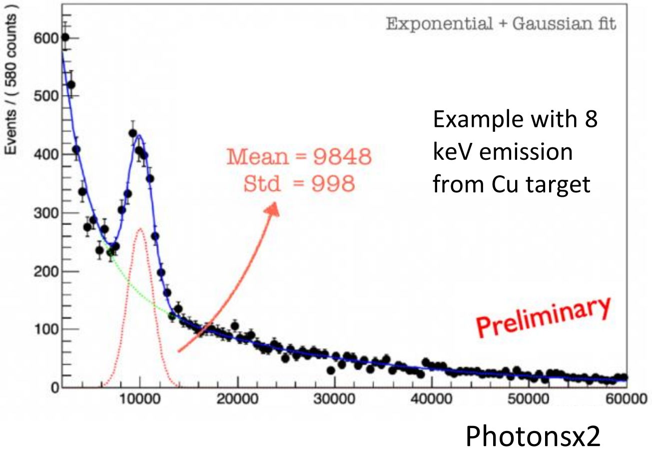


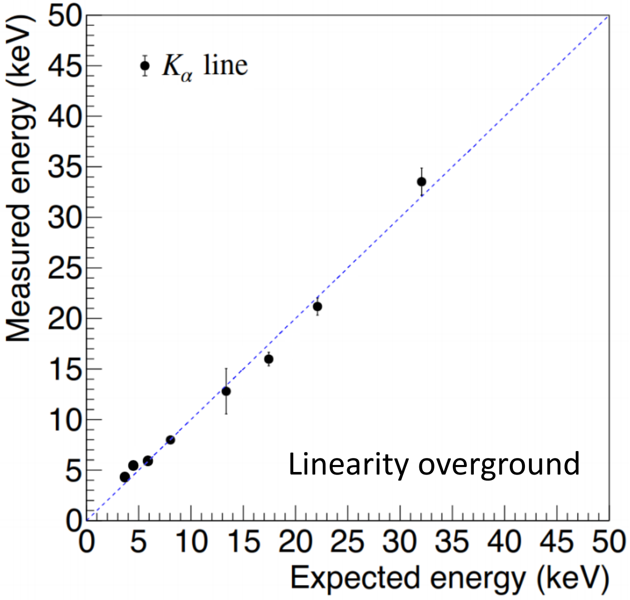
LIME OVERGROUND

- Response tested with X-ray sources at LNF INFN laboratories



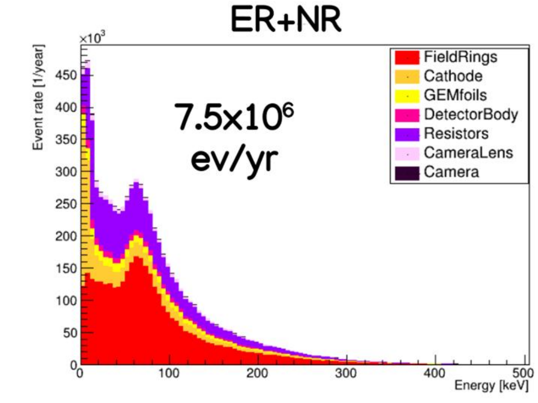


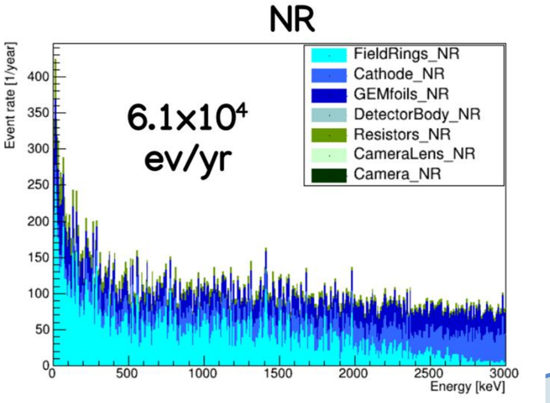




- Estimated background underground

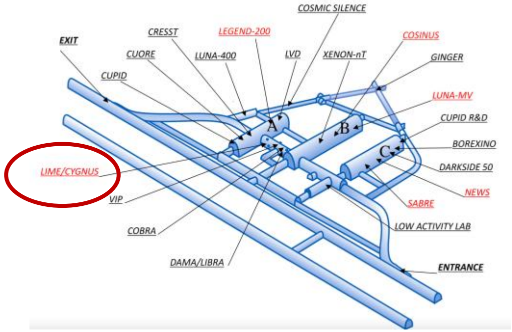
Not radiopure!!





LIME UNDERGROUND INSTALLATION

- Installation at LNGS labs

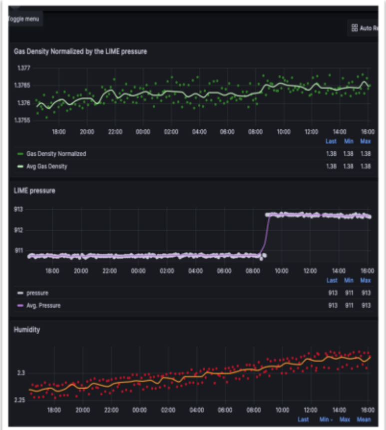


DAQ

- NIM and VME logic with fast and slow digitizers (V1742, V1720)
- Slow control of environmental variables (pressure, oxygen level..)
- MIDAS software integration

Storage and services

- Tester of INFN-Cloud project – common resources used as PaaS and SaaS
- Data reconstruction queue of 40 CPUs
- Almost real time monitor of data in Grafana server



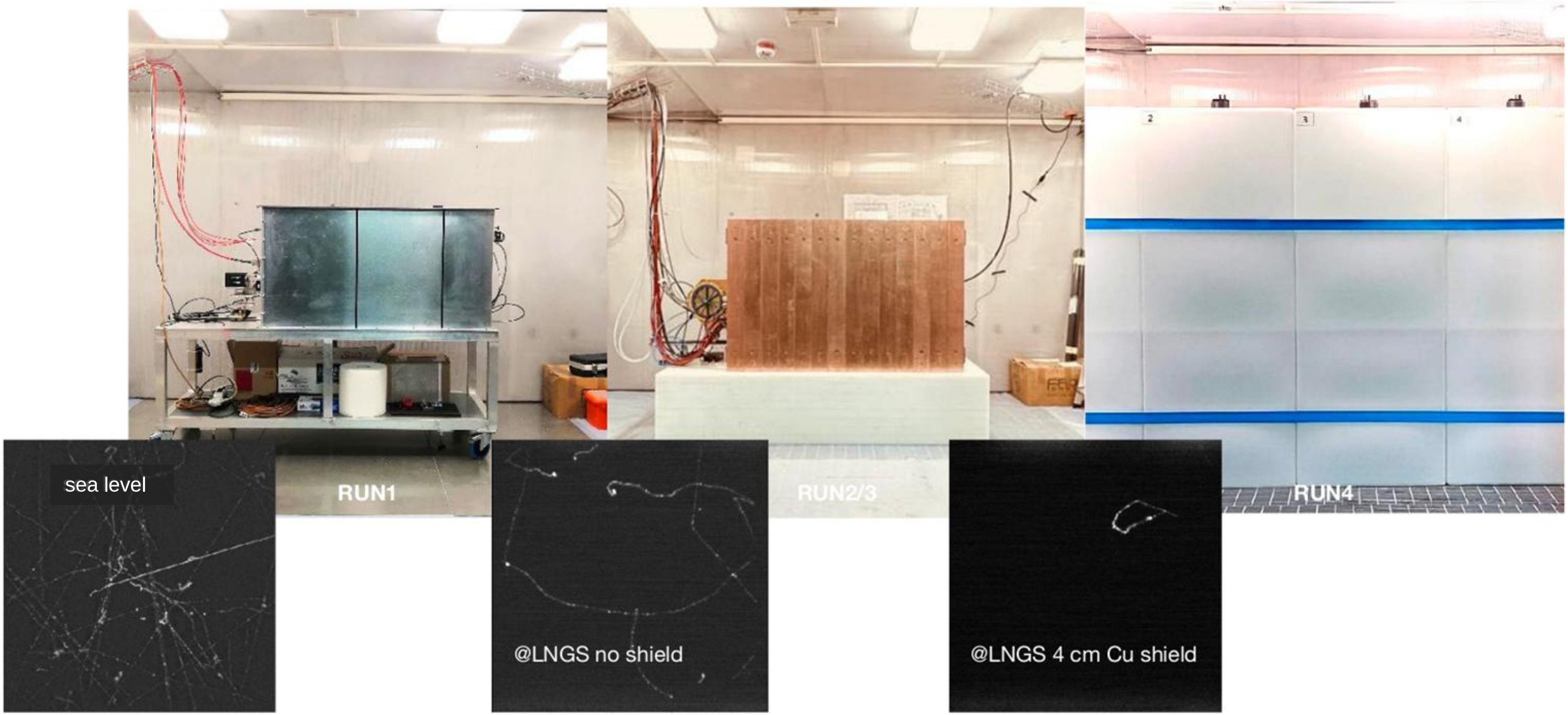
Gas system

- Regulates internal gas pressure
- Radon, oxygen, humidity filters
- Recirculation circuit with only 20% of gas fresh (5 l/h)

LIME UNDERGROUND RUNS

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 campaigns	May-Nov 23	1.3 Hz
10 cm copper and 40 water	**Run4**	- **Internal background studies** for final MC chain validation, Internal and external background expected to have same intensity	Dec 23 – Apr 24	0.9 Hz
10 cm copper	**Run5**	- **Long data taking** without neutron shielding to measure neutron flux Nice test for search of low energy NR	May-Dec 24	1.3 Hz

LIME UNDERGROUND RUNS

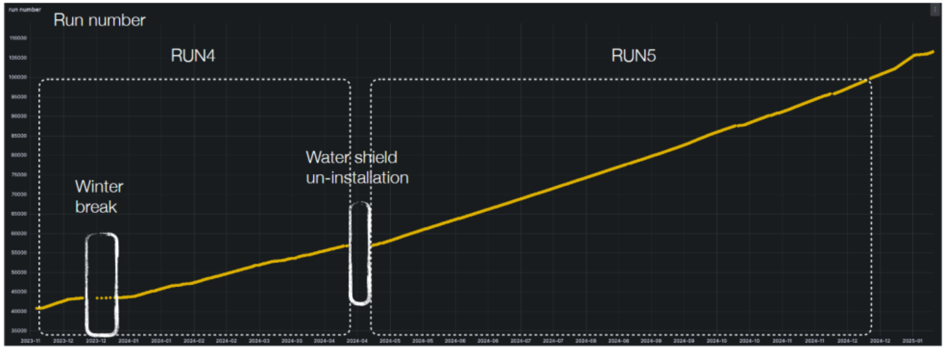


STABILITY DATA TAKING

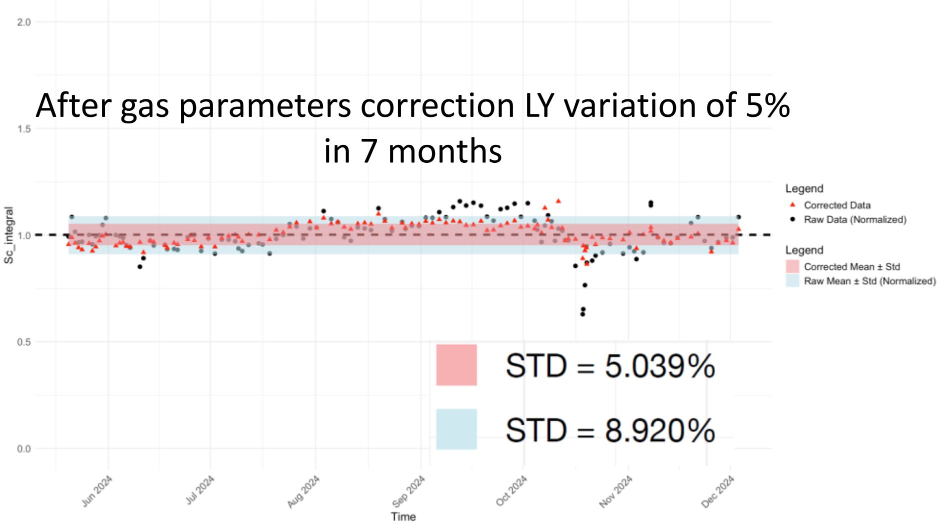
- Are we able to take data in underground environment with recirculation for long time?

Yes!

Duty cycle >90%



After gas parameters correction LY variation of 5% in 7 months



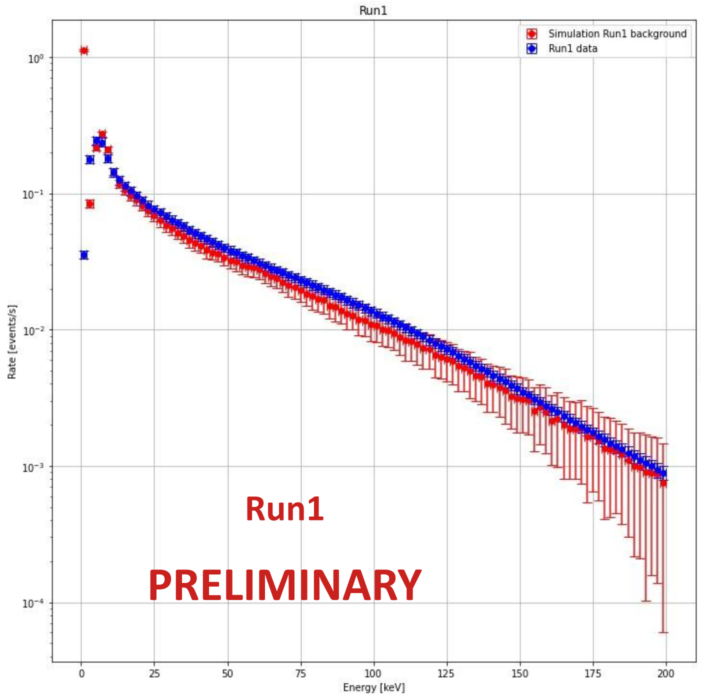
PRELIMINARY

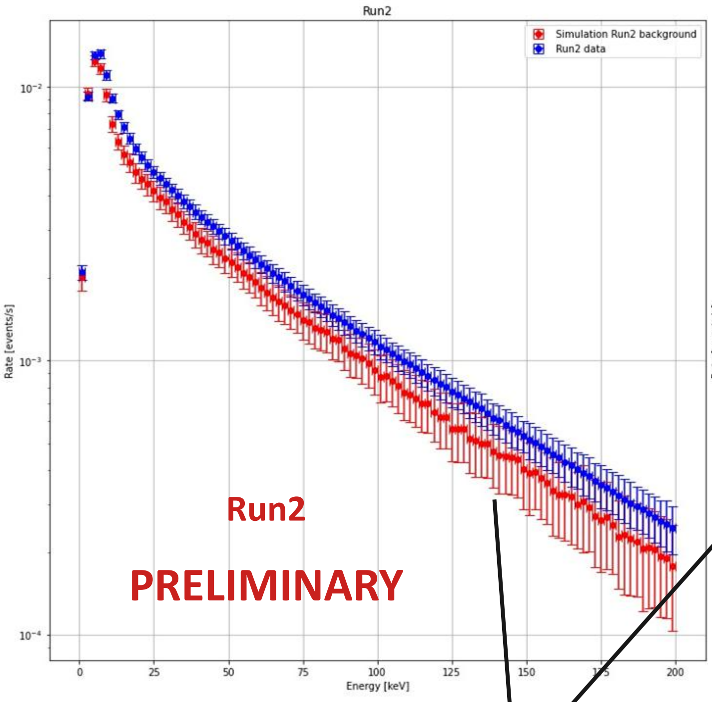
DATA MC COMPARISON

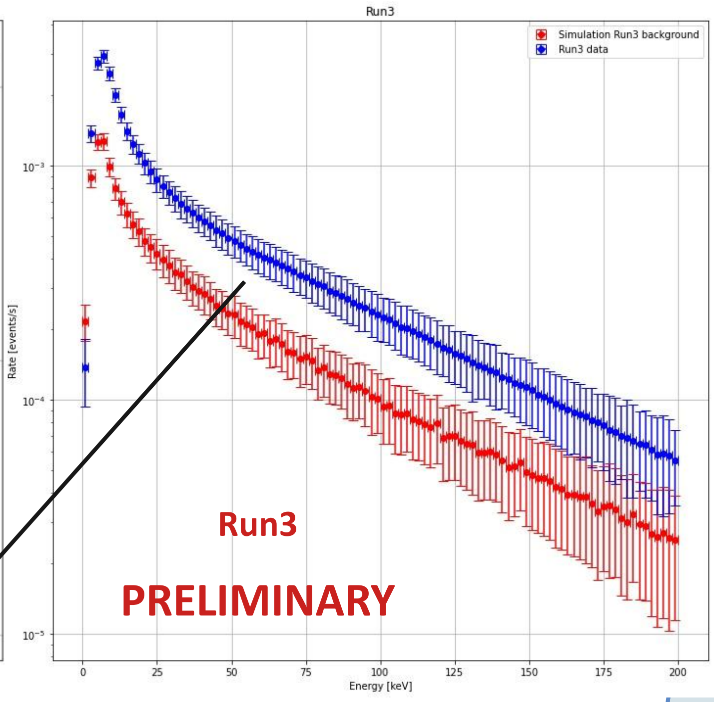
Run4 and 5 under analysis

- Energy spectrum of Run1-3 superimposed to MC data

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







We did not know the radioactivity of the detector

Correct shape validates MC chain

Difference is relatively larger but extremely similar in absolute value

Internal contamination likely detected

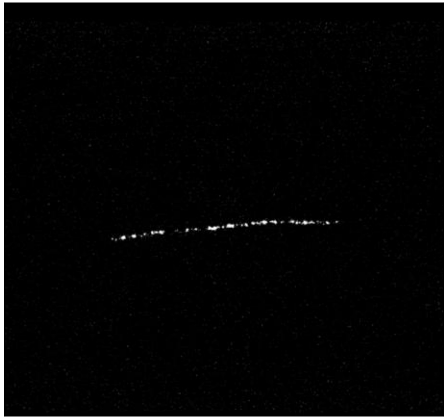
DIRECTIONAL RECONSTRUCTION

- Special reconstruction on track cluster tested on ER to estimate direction (based on IXPE data analysis

- Uses only camera images for the moment

Exposure time 300 ms

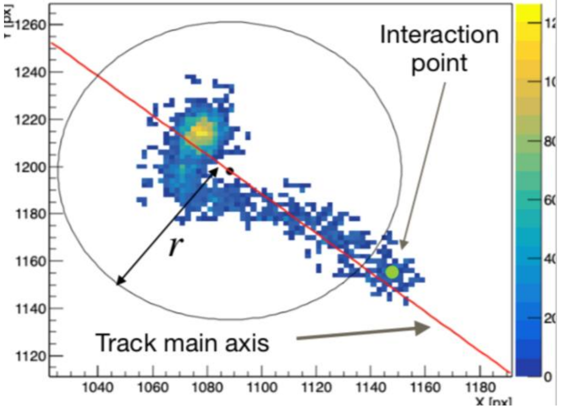
Raw data



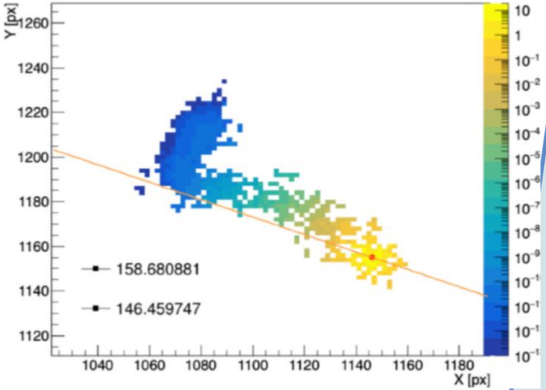
After reco

Selection of interesting pixels
Separation of different tracks
Energy estimation

Direction evaluation



Determination of impact point
Determination of sense of direction

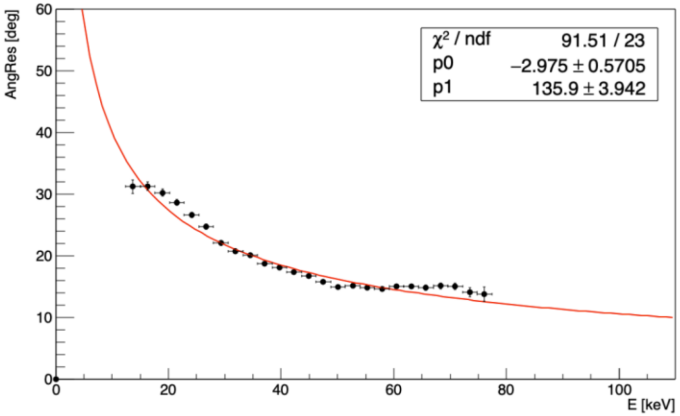


Fit weighted on distance from impact point
Determination of direction

DIRECTIONAL RECONSTRUCTION

- Applied on

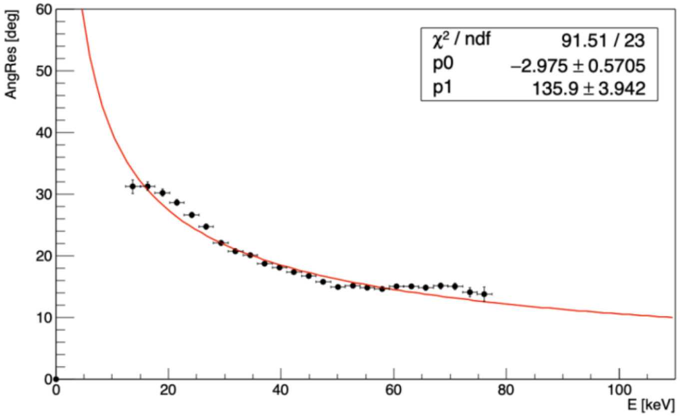
Simulated LIME data

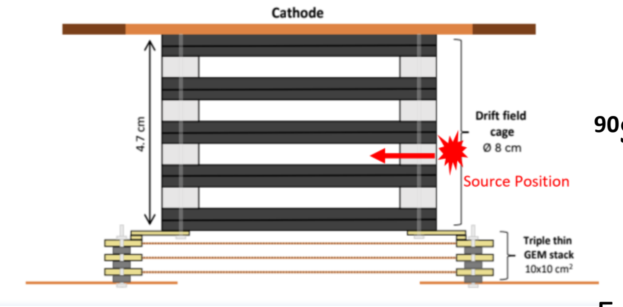


DIRECTIONAL RECONSTRUCTION

- Applied on

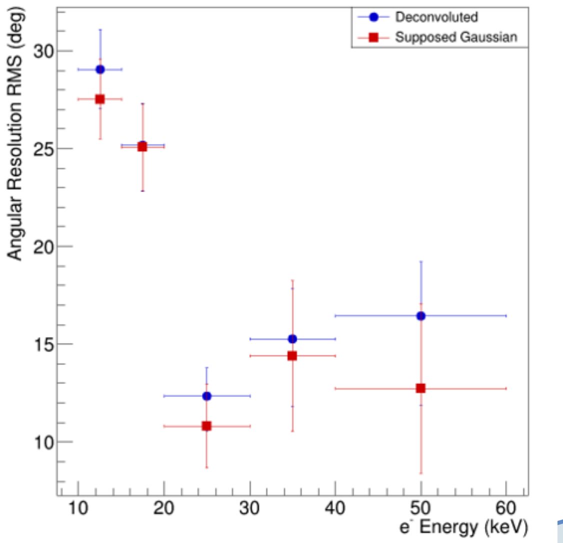
Simulated LIME data





^{90}Sr beta emission in smaller prototype

Extracting angular resolution deconvolving the Geant4 simulated beta distribution



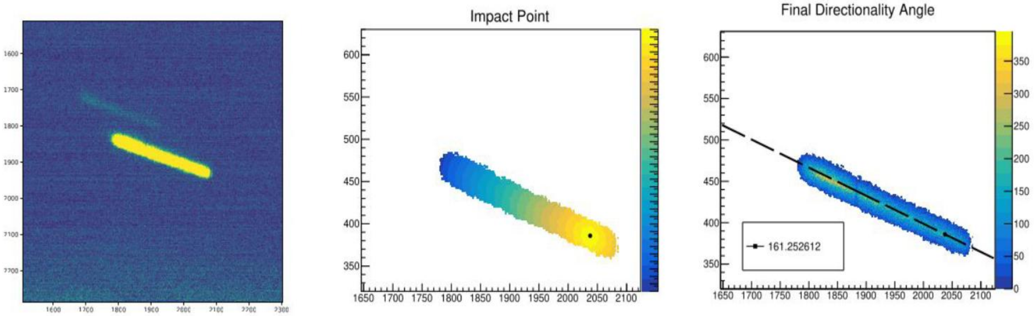
Nice match!

Angular resolution for ER below 30 deg down to 10 keV
and
close to 100% HT

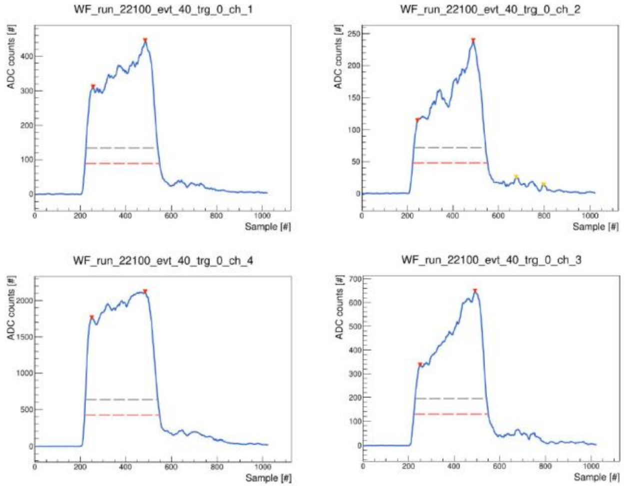
3D RECONSTRUCTION

- To develop the 3D reconstruction algoritm we started simple ⟶ long, straight, not-so-rare tracks: **alphas**
- 2 detector type:

Camera



PMT



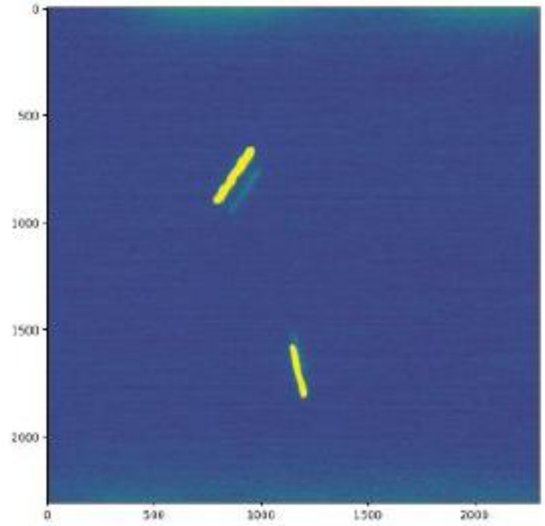
From X-Y pixel distribution and intensity we can obtain:

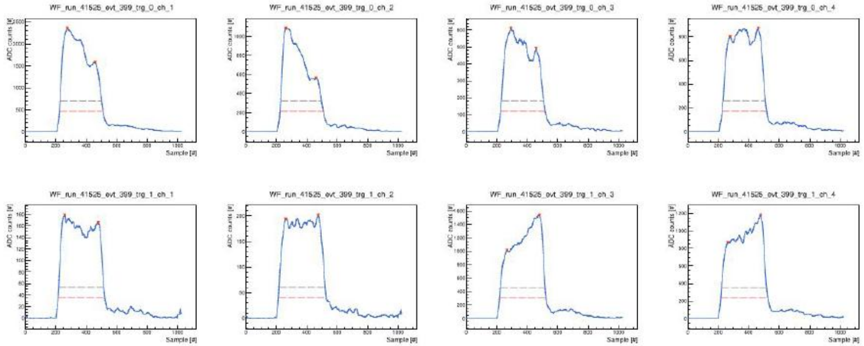
- bidimensional angle of direction (Φ)
- sense of direction in 2D
- Projected length in 2D

From relative intensity of PMT signals, Time over threshold and waveform shape we can obtain:

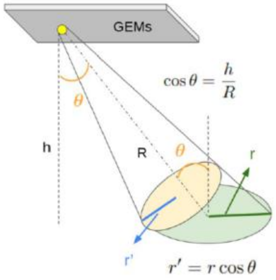
- sense of direction in Z
- Projected length in Z

3D RECONSTRUCTION II





- Different response of the 4 PMTs in LIME

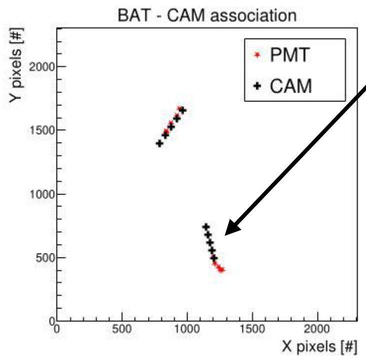


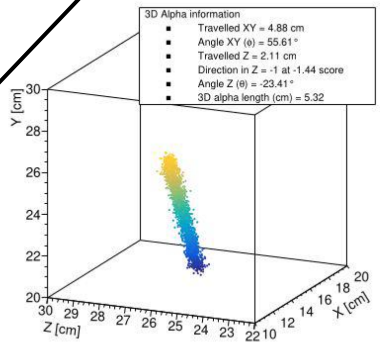
- Multivariate Bayesian fit procedure

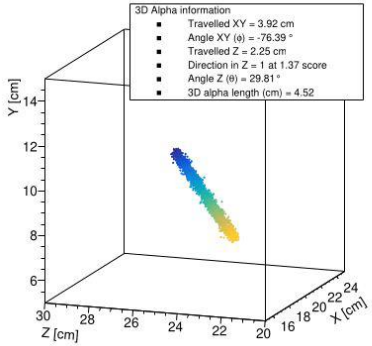
$$p(\{x_{ij}\}\,|\,\theta) = \prod_{j=1}^{N_{points}} \prod_{i=1}^{4} \mathcal{N}(\{x_{ij}\}\,|\,L'_{ij}(\theta))$$

- Calibrated on ^{55}Fe source
- **Precision of ~1 cm**

(e)



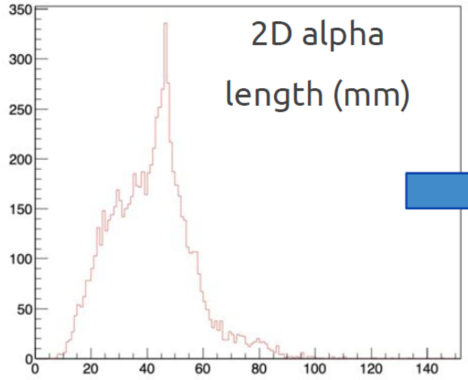




Soon paper out!

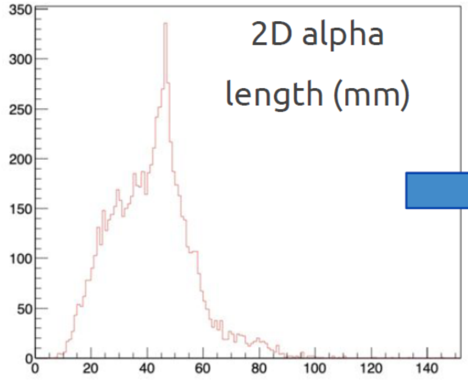
3D Reconstruction III

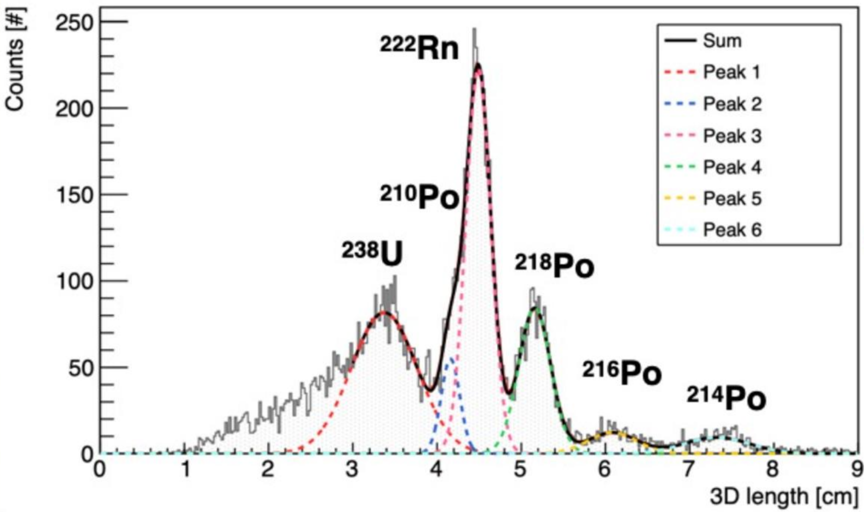
- With 3D recoed tracks we can look at lengths



3D RECONSTRUCTION III

- With 3D recoed tracks we can look at lengths





Theory + *detector effect* (7% error)

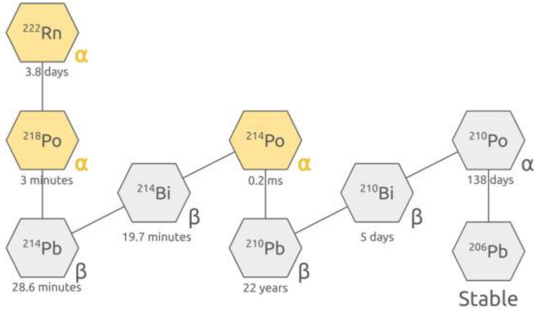
- ^{238}U -> 4.17 MeV -> 33.7 mm
- ^{216}Po -> 6.78 MeV -> 61.6 mm
- ^{210}Po -> 5.30 MeV -> 43.1 mm

Measured (5% error)

- 33 mm
- 61 mm
- 41.6 mm

Contamination from border and GEM

- Expecting Radon contamination:



Theory + *detector effect* (7% error)

- ^{222}Rn -> 5.50 MeV -> 45.7 mm
- ^{218}Po -> 6.00 MeV -> 51 mm
- ^{214}Po -> 7.69 MeV -> 71 mm

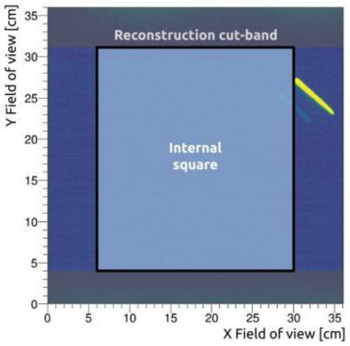
Measured (1% error)

- 44.3 mm
- 51.2 mm
- 72.9 mm

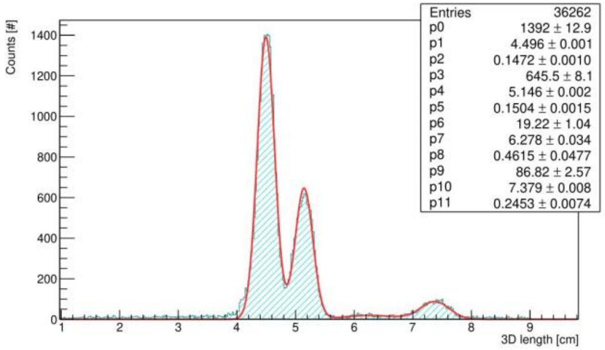
Radon contamination confirmed

3D RECONSTRUCTION II

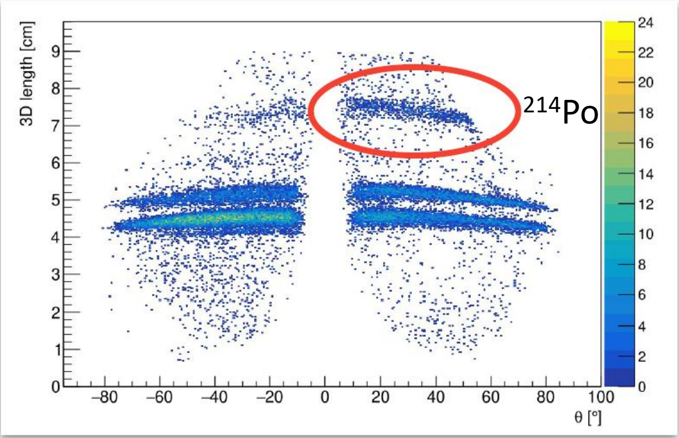
- What about orientation of these Rn daughter alphas?
- Selection in the centre to include cathode, GEM and detector gas (no borders with resistors and field rings)
- Inclination angle and rough estimation of absolute z coordinate support Radon daughter behaviour



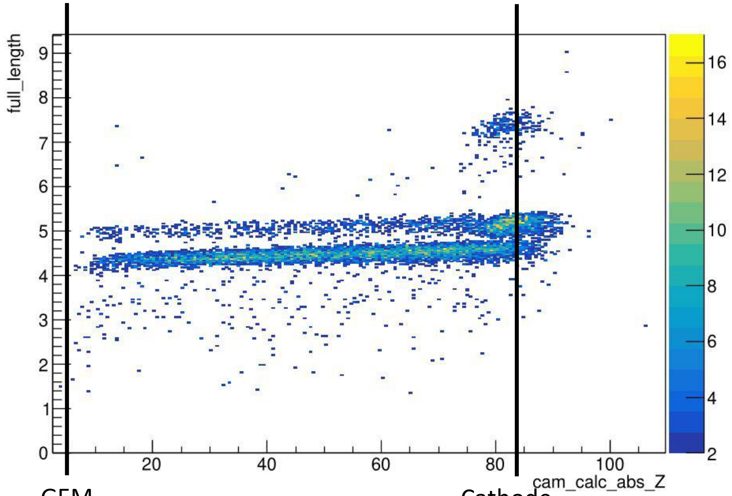
(a) Geometrical cut - central square



(b) 3D length of alphas



Toward cathode Toward GEM



GEM Cathode

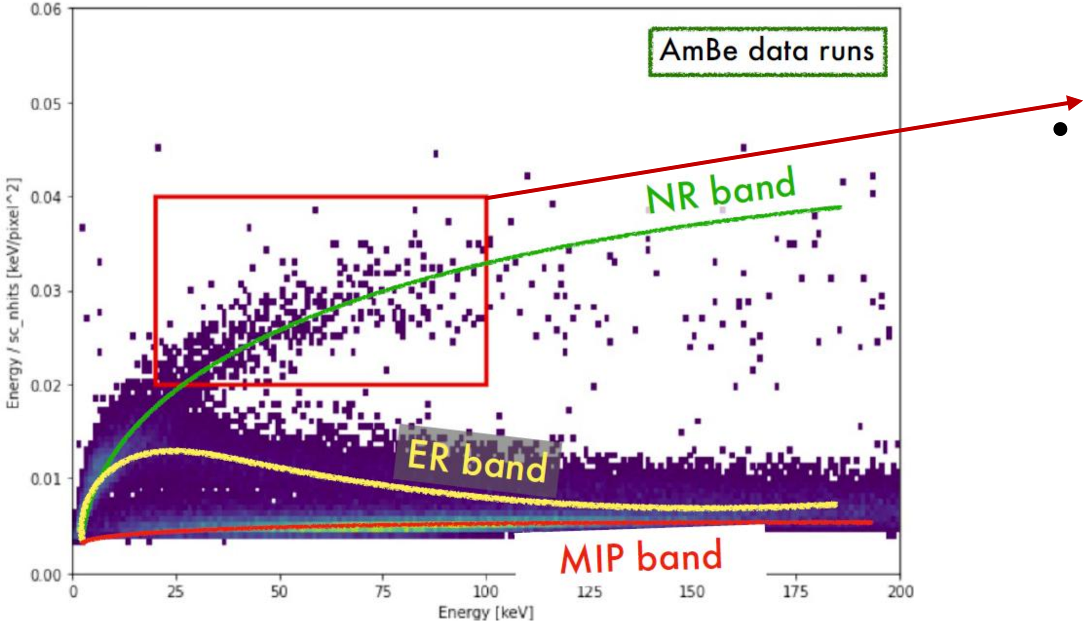
Daughters, generated positively charged, will move to the cathode:

- Higher Z (closer to cathode)
- Emission mostly toward GEM

Potential of 3D just starts unveiling!

NR Calibration

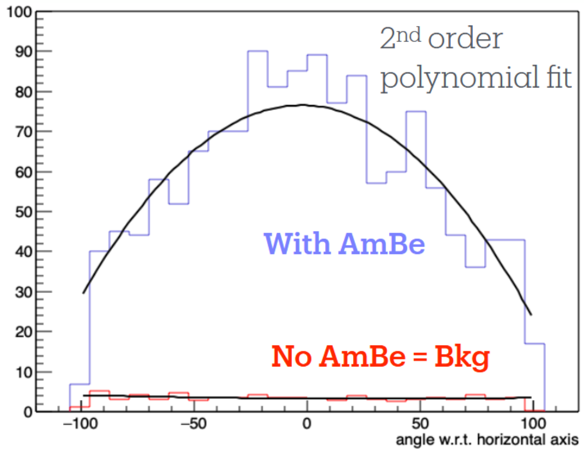
- Special data taking with AmBe neutron source (NR generation)



Abundance of NR can help

determine **directional** capabilities on NR

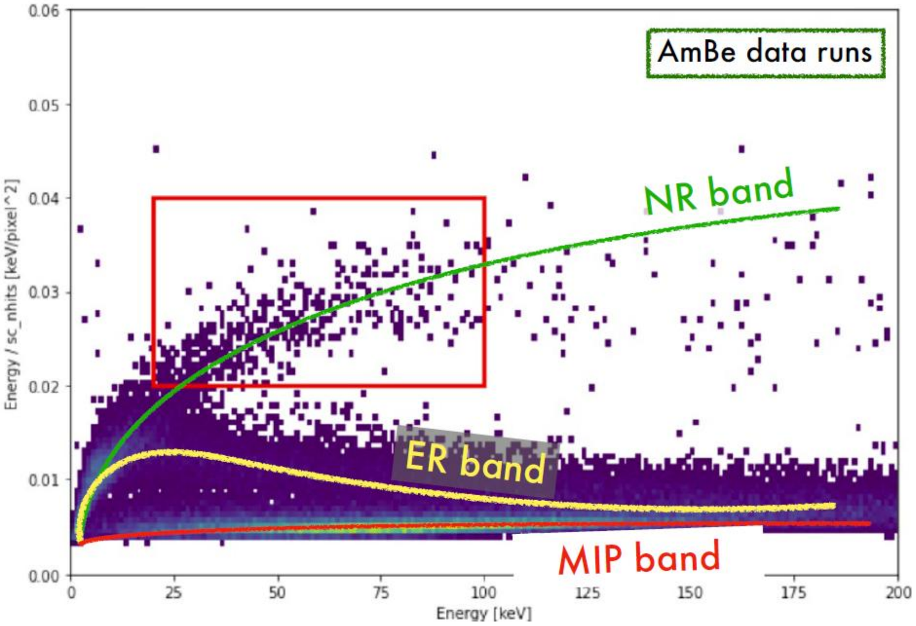
- On energies above 80 keV_{nr} (>20 keV_{ee}) selection is simple
- Estimation of the recoil direction with a simple PCA decomposition yields



- 45° angular resolution achieved effortlessly
- Can be improved dramatically

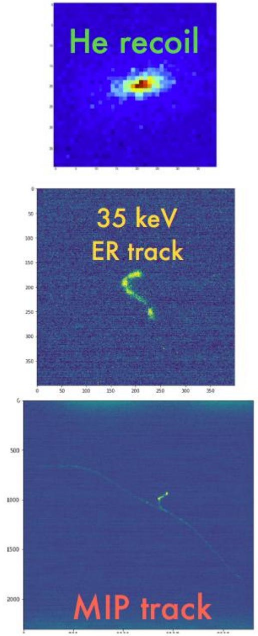
NR CALIBRATION

- Special data taking with AmBe neutron source (NR generation)



Abundance of NR can help

determine **directional** capabilities on NR

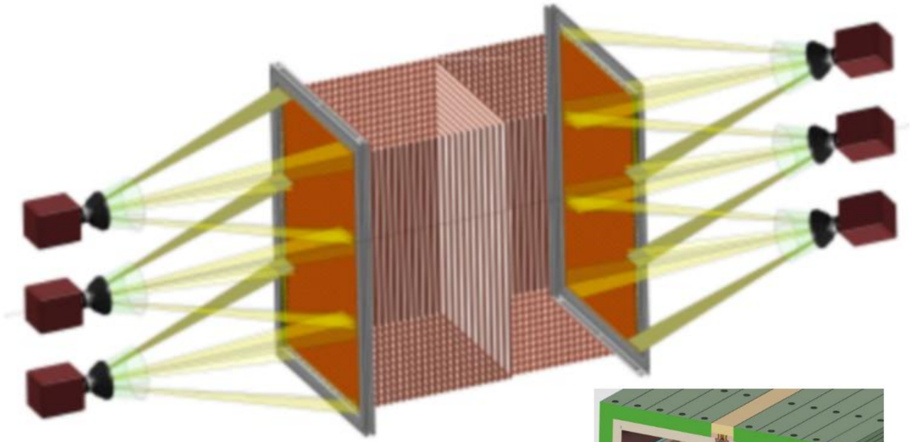


Discrimination between ER (background) and NR (signal) under study via machine learning techniques:

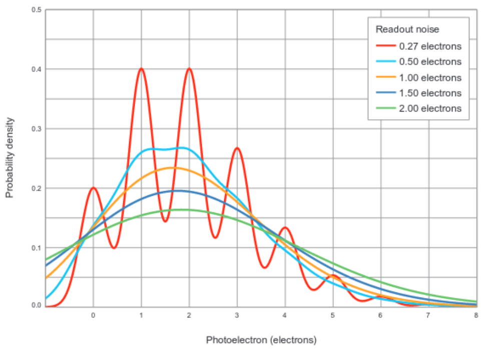
- Exploiting shape of tracks as reconstructed by the standard analysis code
  - Preliminary results suggest 10^6 above 20 keV_{ee} and 10^4 achievable below 4 keV_{ee}
- Directly feeding images to CNN

CYGNO-04

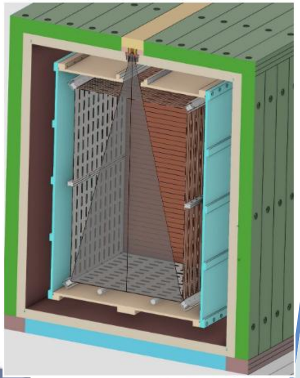
- **Structure**: TPC in back-to-back configuration, 50 cm drift per side and 0.4 m^3 total volume
- **Amplification**: Triple standard GEM stack of 50x 80 cm^2 per side
- **Readout**: Optical with 3 qCMOS (Hamamatsu ORCA Quest) and 8 PMTs per side
- **Shield**: 10 cm Cu + 100 cm water

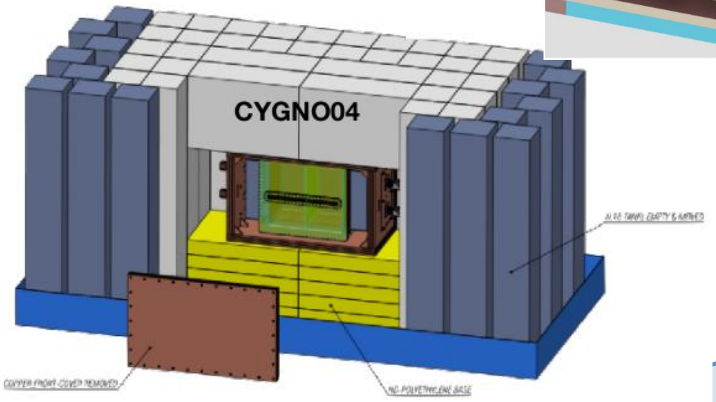


New sensor with extremely low noise



To be hosted at Hall F @ LNGS-INFN

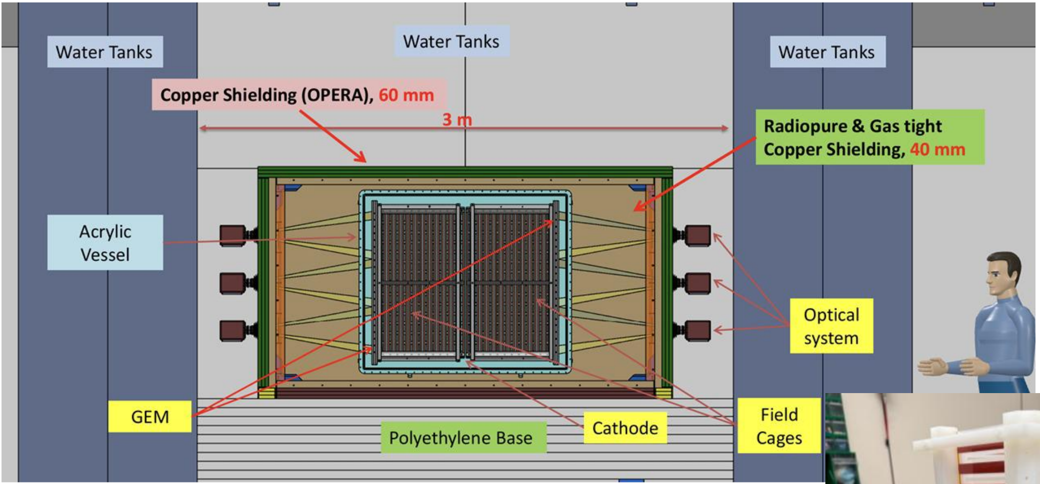




Purpose:

- 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

CYGNO-04



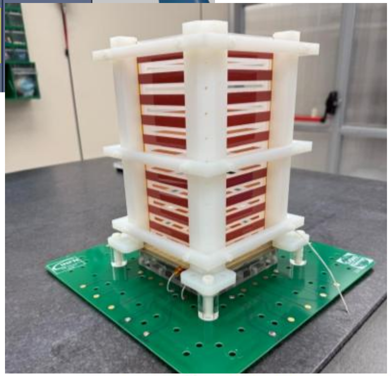
Ongoing work on Hall F at LNGS

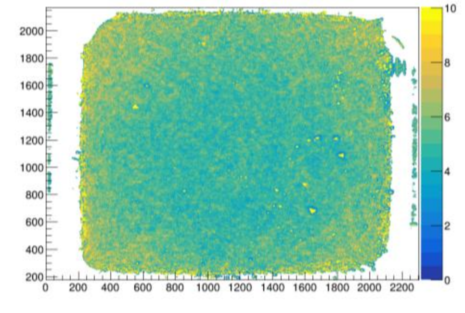
- Infrastructure with services completed
- Gas system and ancillary systems soon to be installed

Hall F 6 weeks ago

Study of Field cage structure and material

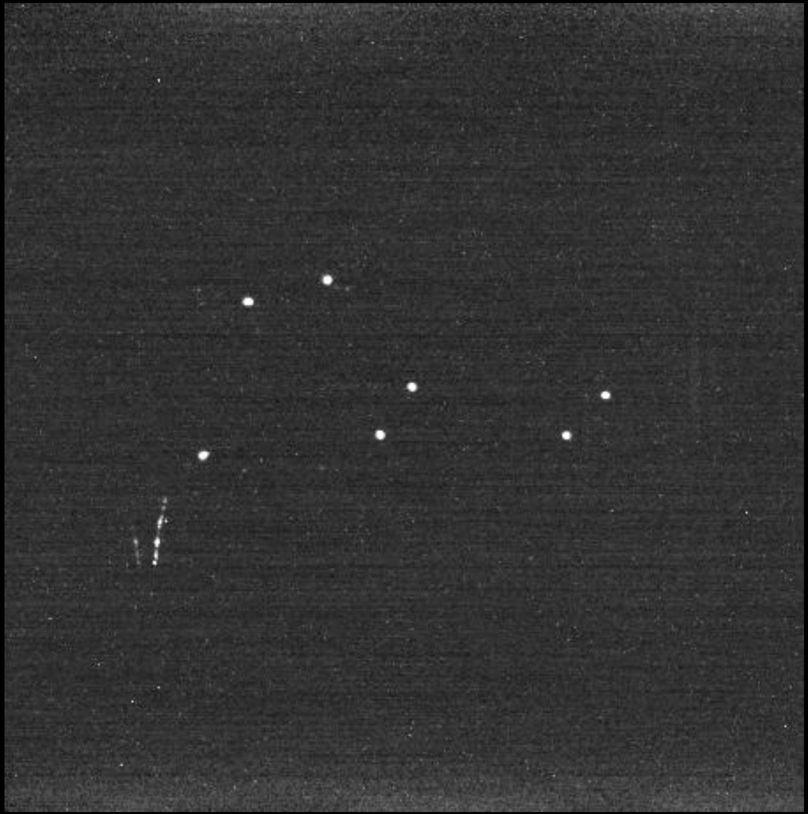
- Disuniformity below 6%
- Nylon66 material with low radioactivity
- Field cage: Kapton sheet (50 μm) with Cu deposited (35 μm). (Cathode similar)

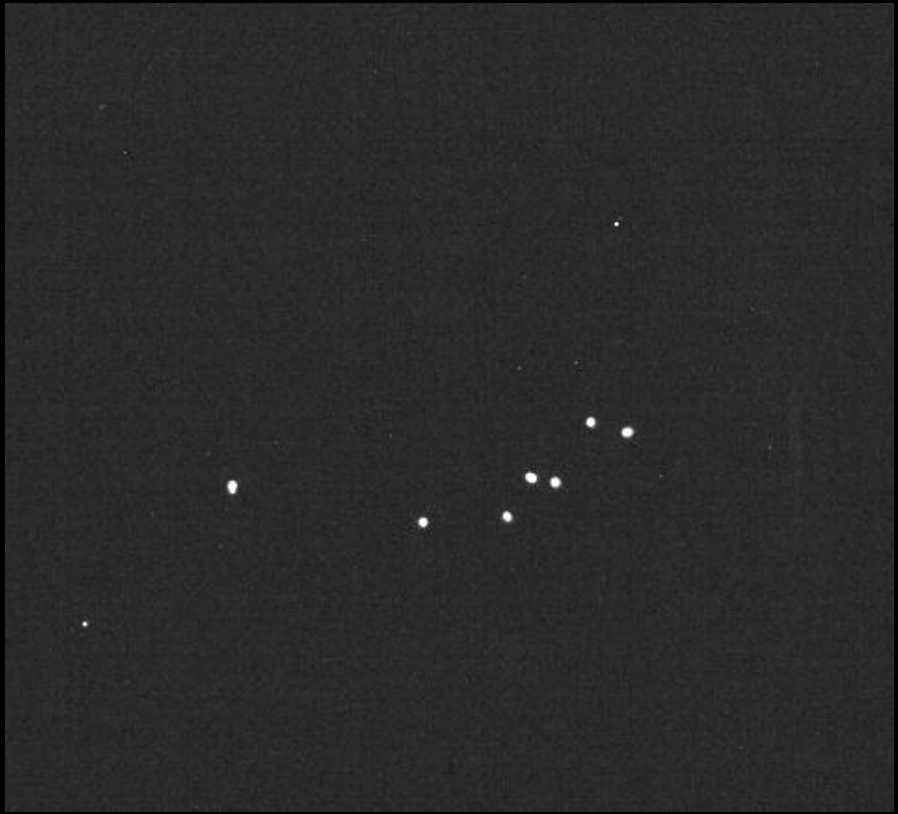




NEW SENSOR

- Hamamatsu QUEST2: 8 Mpixel camera, extremely low noise (0.3 e$^-$ RMS), more uniform, higher granularity

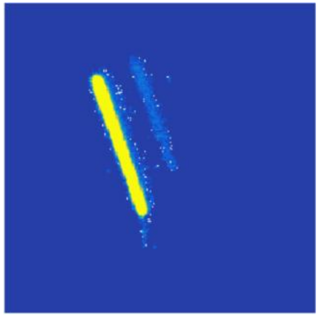




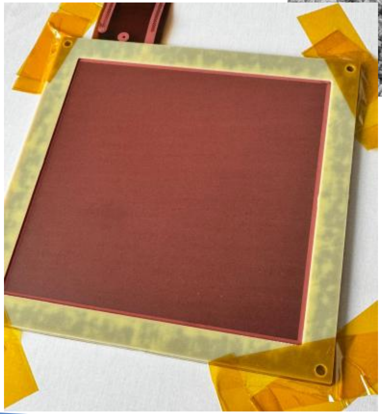
GEMs And Data Acquisition

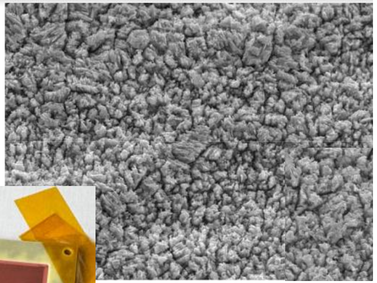
GEM

- 50x80 sheet single masked almost ready with Nylon66 frame
- GEM facing the optical window will be V-Bonded to roughen the surface (reduce refection of optical photons



Old smooth GEMs

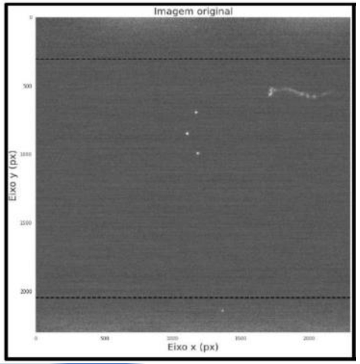


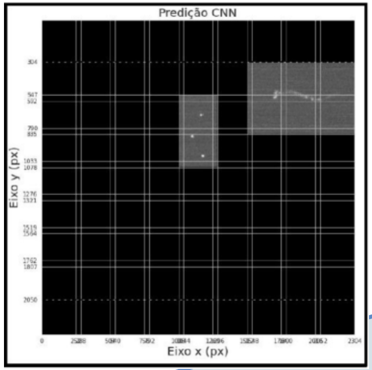


V-Bond

Data acquisition and reduction

- 6 cameras of 8 MP in continuous data taking would translate into a 10 TB/day unsustainable
- Cameras and PMTs will be taken in separate chains, zero suppressed and merged based on time information. **Synchronization is key**
- Data reduction of camera expected to keep only relevant pixels (rediction of factor 100 expected)





Larger Detector for Physics Search

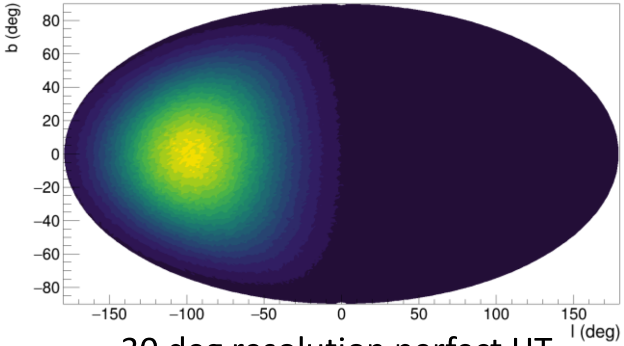
- If CYGNO-04 demonstrates the feasibilty of a larger detector, the O(30) m^3 should provide first physics compelling results
- Sensitivity studies performed with Bayesian technique on simulated data for a 30 m^3 detector with 3 y exposure

$$\mu_1(90\%CI) : \int_0^{\mu_1(90\%CI)} p(\mu_1|\vec{x}, H)d\mu_1 = 0.9$$

$$\mathcal{L}(\vec{x}|\mu_s, \mu_b, H_1) = (\mu_b + \mu_s)^{N_{evt}} e^{-(\mu_b+\mu_s)} \prod_{i=1}^{N_{\rm bins}} \left[\left(\frac{\mu_b}{\mu_b + \mu_s} P_{i,b} + \frac{\mu_s}{\mu_b + \mu_s} P_{i,s} \right)^{n_i} \frac{1}{n_i!} \right]$$

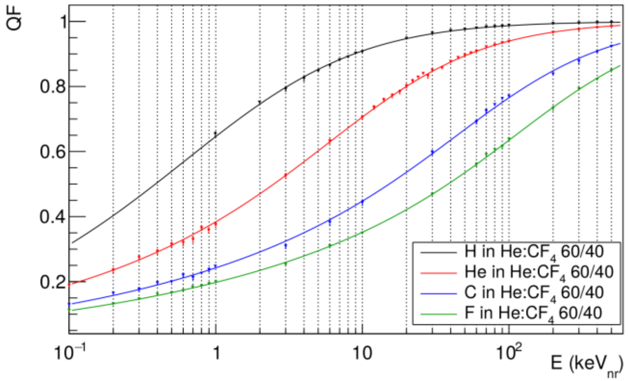
- Detector effects are considered like E_{thr}, background and

Angular distribution of signal and background

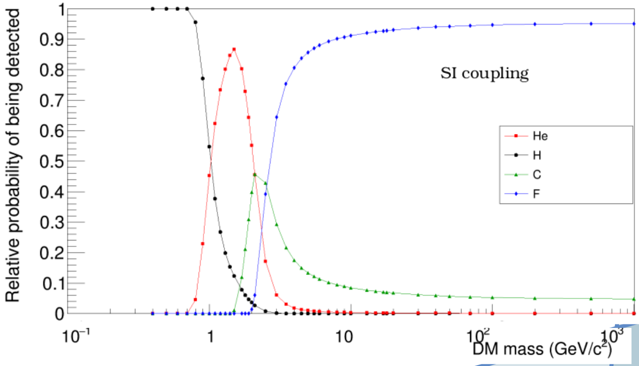


30 deg resolution perfect HT

Quenching factor of elements in gas



Mixture composition

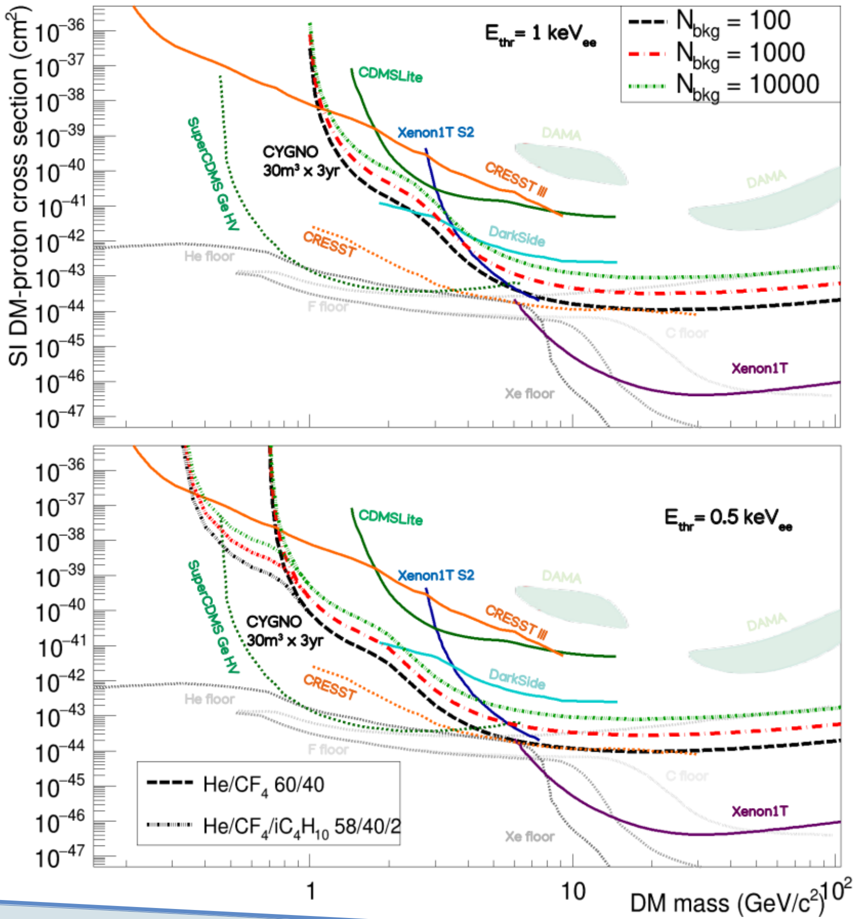


EXPECTED SENSITIVITY

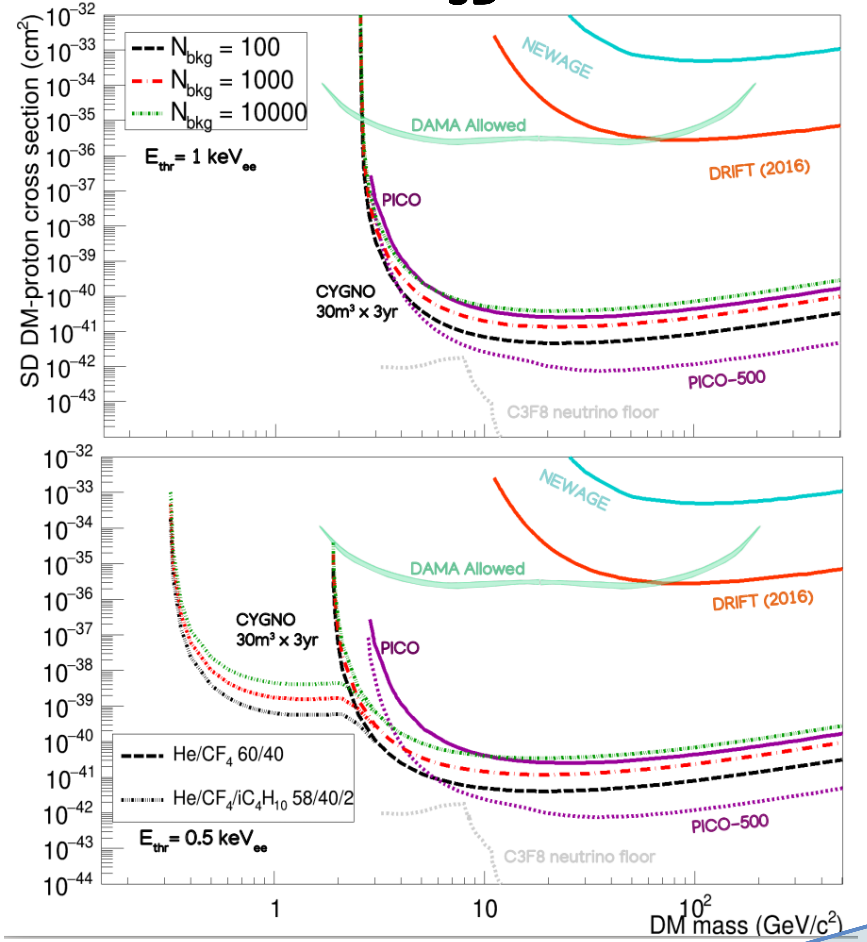
Solid lines	**current limits**
Dotted lines	**future limits**

Amaro et al, Instruments 6 (1) (2022)

SI



SD

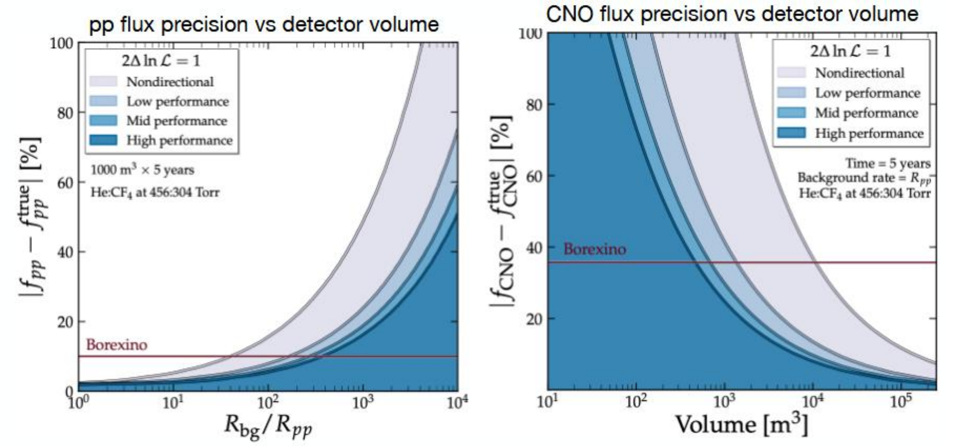


OTHER APPLICATIONS

- The same detector technology can be applied to other fields

Solar neutrinos

- Promote background ER to signal (about 1 ev/y/m^3)
- Background shape can be modeled in data in the non-physical region of Solar neutrino recoils
- Background levels and exposure key to discovery potential (CYGNUS)

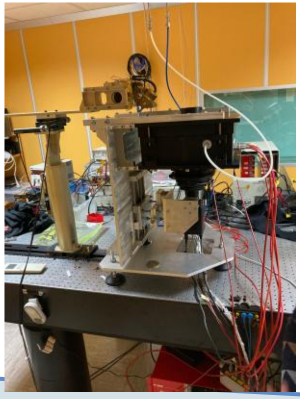


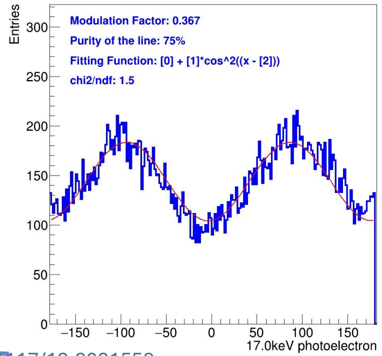
Lissotti et al, https://doi.org/10.1140/epjc/s10052-024-13392-3

X-ray Polarization

- Imaging TPCs can measure X-ray polarization in the 2 -60 keV range
- State of the art IXPE telescope is providing new insights on astrophysical objects measuring polarization in 2-8 keV range
- Optical TPC with large readout can unlock new horizons on wide field of view and higher energies (GRBs, Solar flares, etc)

Measurements with polarized source with CYGNO prototype (HypeX project)





Fiorina et al, https://doi.org/10.1117/12.3021559

Conclusions

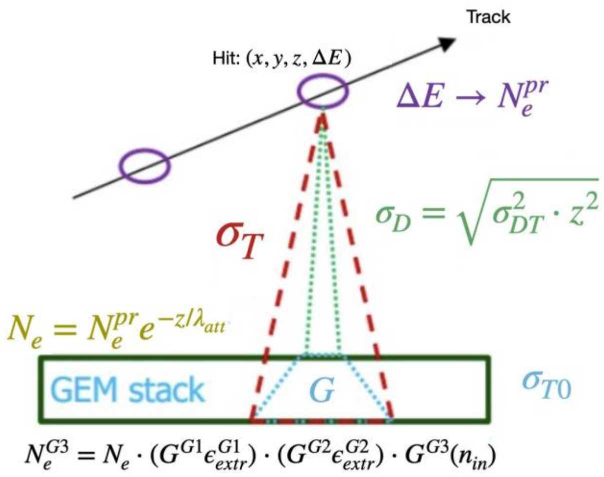
- Dark matter is still believed to be a great candidate to explain unresolved mysteries of our Universe
- Given the assumptions of WIMP-like dark matter, the Earth is expected to cross a sea of them and possibly to directly probe them
- Directional detectors can provide enormous insight in both fundamental and astrophysical aspects of dark matter, sidestepping the neutrino fog problem
- CYGNO experiment aims to prove gaseous optical TPCs are an excellent candidates for directional dark matter searches (and not only!)
- LIME prototype took data for two years at the underground LNGS laboratories allowing to start assessing the capabilities of imaging optical TPCs
- CYGNO-04 demonstrator is about to start construction and with the goal of proving the scalability and feasibiity of the project

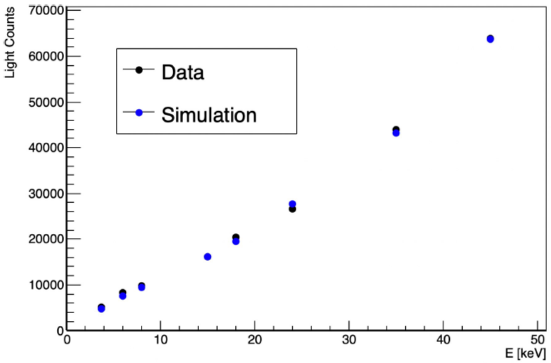
BACKUP

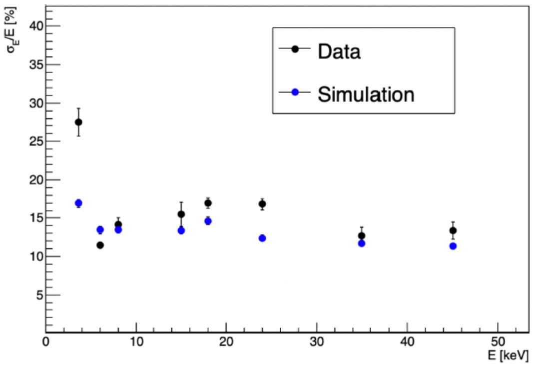
Data Simulation

- It starts with Geant4 simulation of energy deposits and shield interaction

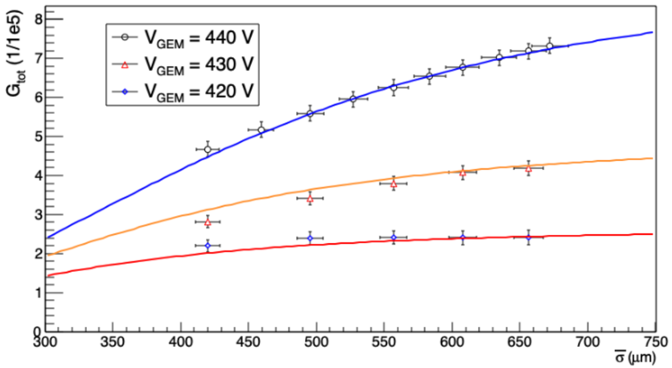
- Then a fast simulation translates Geant4 hits into images representing the different detector effects







Also GEM gain saturation effects

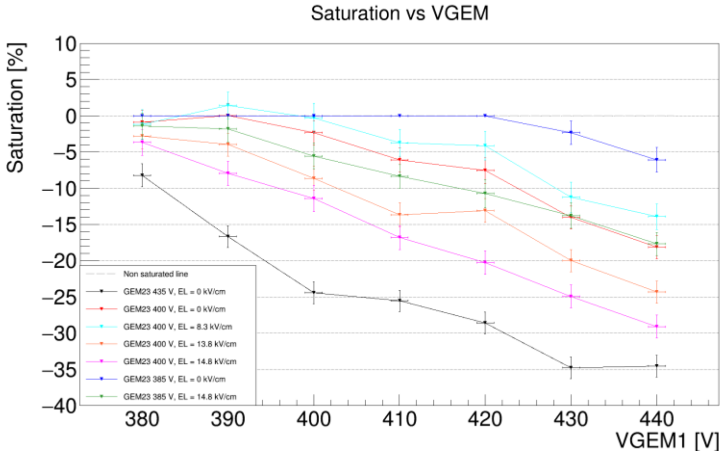


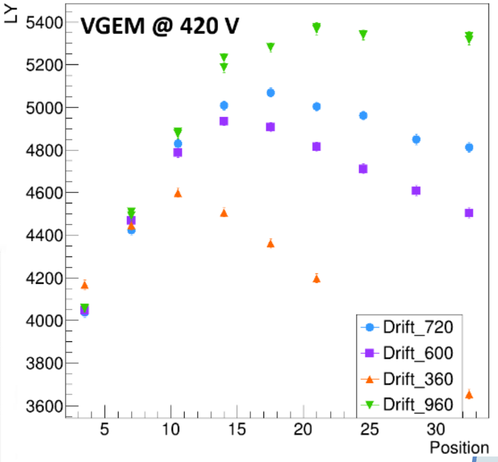
https://arxiv.org/pdf/2505.06362

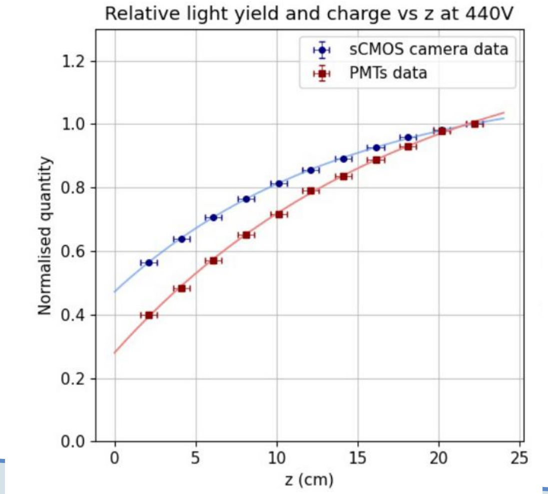
SATURATION OF GAIN

- How to deal with saturation?
- Use of ITO seems the most promising. But it is not ready for CYGNO-04:

  tests on larger distances, stability tests (myself)
- Lowering VGEM and drift field does not fully solve but strongly mitigates (DavideF)
- Measurements with GIN lead to the possibility of PMT saturating differently from CMOS. (to be confirmed and in case further studied)







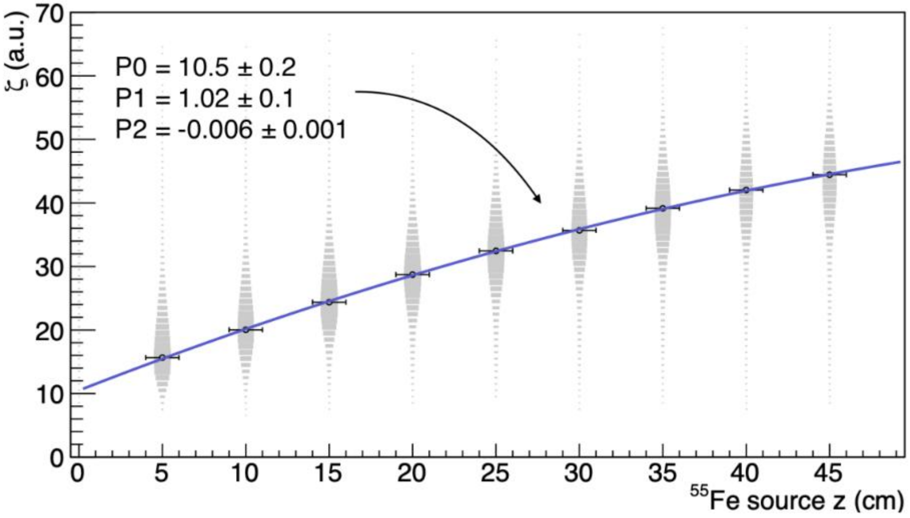
G.Dho

FIDUCIALIZATION

- Determination of absolute z is the only way to fiducialize the detector for events close to cathode or GEM

- Studies suggested 4 cm resolution close to GEM and 8 cm close to cathode. **Should be improved**

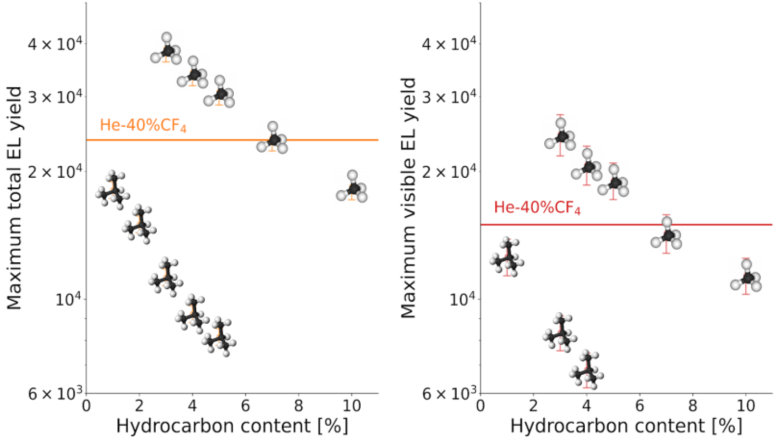
- Machine learning techniques based on CNN and point spread functions are under test to improve the resolution



R & D Activities

Hydrogen-rich gas (made in Coimbra)

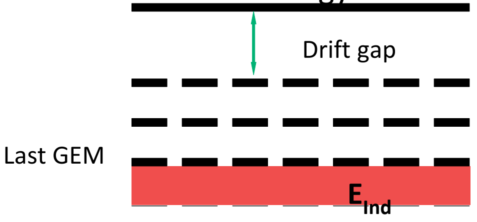
- Addition of H rich gases to increase sensitivity to low WIMP masses
- Tests with isobutane and methane
- Similar light yield wrt no H-gas

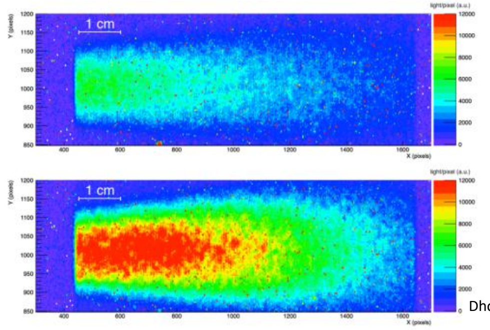


Amaro et al, https://doi.org/10.1016/j.physletb.2024.138759

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

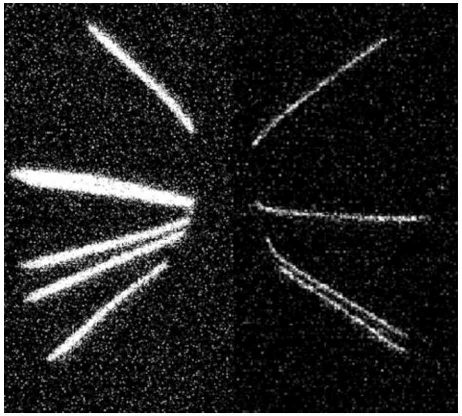
Dho et al, https://doi.org/10.1140/epjc/s10052-024-13471-5

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)



He:CF$_4$:SF$_6$ (59:39.4:1.6)

Same light intensity

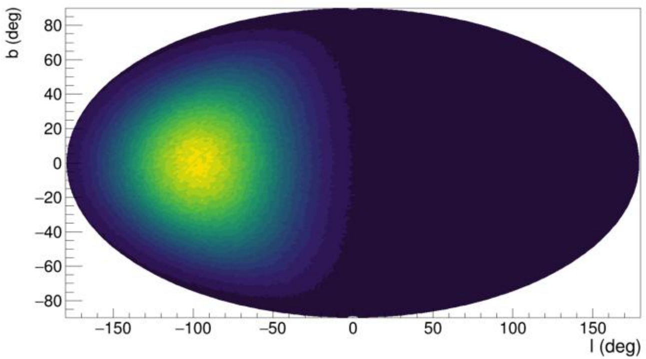
DIRECTIONAL EFFECT

- Only the angular distribution is considered in the study

$$\frac{dD}{d\cos\gamma} = \alpha_0 \int_{E_{thr}}^{E_{max}} S(E)\left(e^{-\frac{\left(\frac{\sqrt{2m_A E}}{2\mu_A} - v_{lab}\cos\gamma\right)^2}{v_p^2}} - e^{-\frac{v_{esc}^2}{v_p^2}}\right) dE$$

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

γ = angle between recoil and Sun's opposite motion



Angular performances

- **30°x30° deg** on all energy range
- Full **head-tail**

E range assumptions

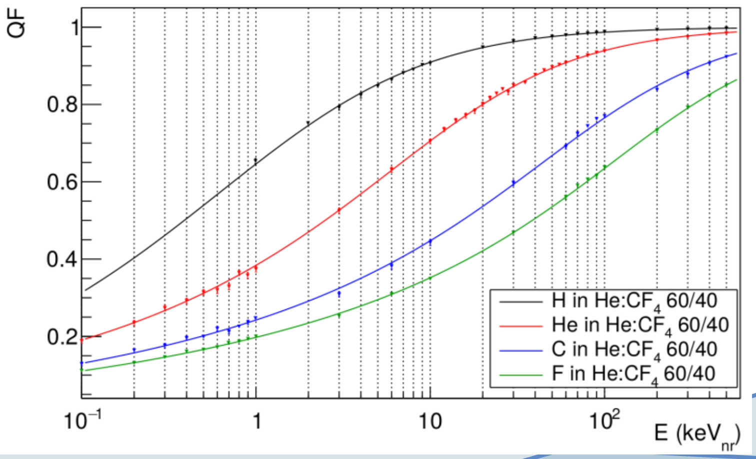
- E_{max} maximum possible allowed by the escape velocity of the Galaxy
- E_{thr} taken as 1 keV_{ee} (conservative) 0.5 keV_{ee} (realistic)

Prior assumption

- Taken flat between 0 and 1000

- The composiion of CYGNO gas mixture and the quenching factor are taken into account

  - Elements He, C, F (He:CF_4) and H (for R&D He:CF_4:iC_4H_{10})
  - Differently from electrons, nuclear recoils dissipate energy in other interactions that do not produce ionization
  - Effectively **each element has different energy threshold**



G.Dho

Directional Effect

- With separate energy thresholds, each element has a different angular distribution

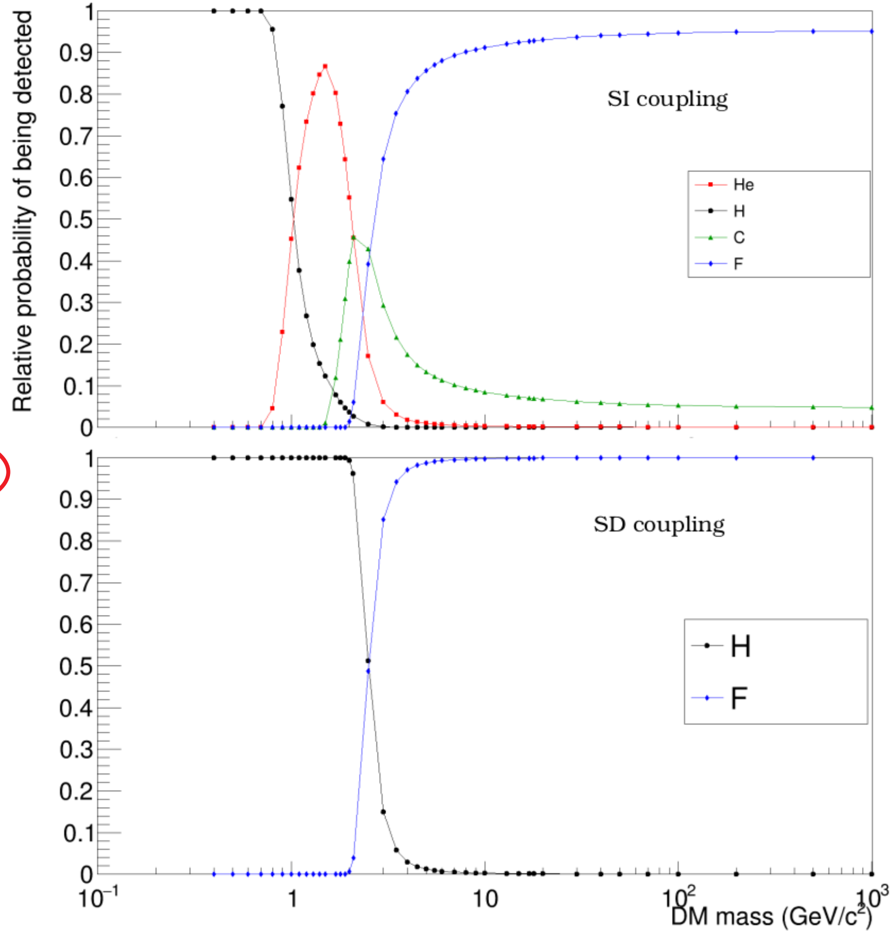
- To correctly account for the probability of each element to recoil and be detected, the total number of events is used as a weight function

$$N_{DMevt} = tV \frac{P}{P_{atm}} \frac{T_0}{T} \sum_i^{n_{mol}} \sum_j^{n_{el,i}} \rho_i k_i \frac{N_0}{A_{mol,i}} N_{at,i,j} \frac{2\rho_0 \sigma_{n,SI}}{m_\chi^2 r_j} \frac{\mu_{A,j}^2}{\mu_n^2} A_j^2 I_j^{E\gamma}(m_\chi, E_{thr,j})$$

$I^{E\gamma}_i$ integral of the velocity distribution

$$P_X = \frac{N_{DMevt,X}}{N_{DMevt}} = \frac{\sum_i^{n_{mo}} F_{i,X}}{\sum_i^{n_{mo}} \sum_j^{n_{el,i}} F_{i,j}}$$

$F_{i,j}$ term of the total event which depends on the gas *jth* atom in the *ith* molecule



Different thresholds represent different WIMP mass threshold sensitivity

	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

- Likelihood include both signal and background
- Based on a profiled event bin likelihood

$$\mathcal{L}(\vec{x}|\mu_s,\mu_b,H_1) = (\mu_b+\mu_s)^{N_{evt}} e^{-(\mu_b+\mu_s)} \prod_{i=1}^{N_{\text{bins}}} \left[\left(\frac{\mu_b}{\mu_b+\mu_s} P_{i,b} + \frac{\mu_s}{\mu_b+\mu_s} P_{i,s} \right)^{n_i} \frac{1}{n_i!} \right]$$

Poissonian fluctuation of total events

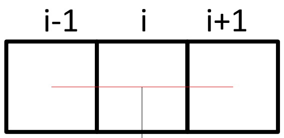
Product on all the bin of the histogram

Probability of event to end in the *ith* bin weighted on signal to background proportion

Weighting factor

$$P_{i,x} = \sum_{j=i}^{N_{adjacent}} \left[P^{\text{migrate}}_{j\to i} \sum_{k}^{n_{el}} P^{theo}_{k,j,x} P^{el}_{k,x} \right]$$

Estimated from element probability



Resolution

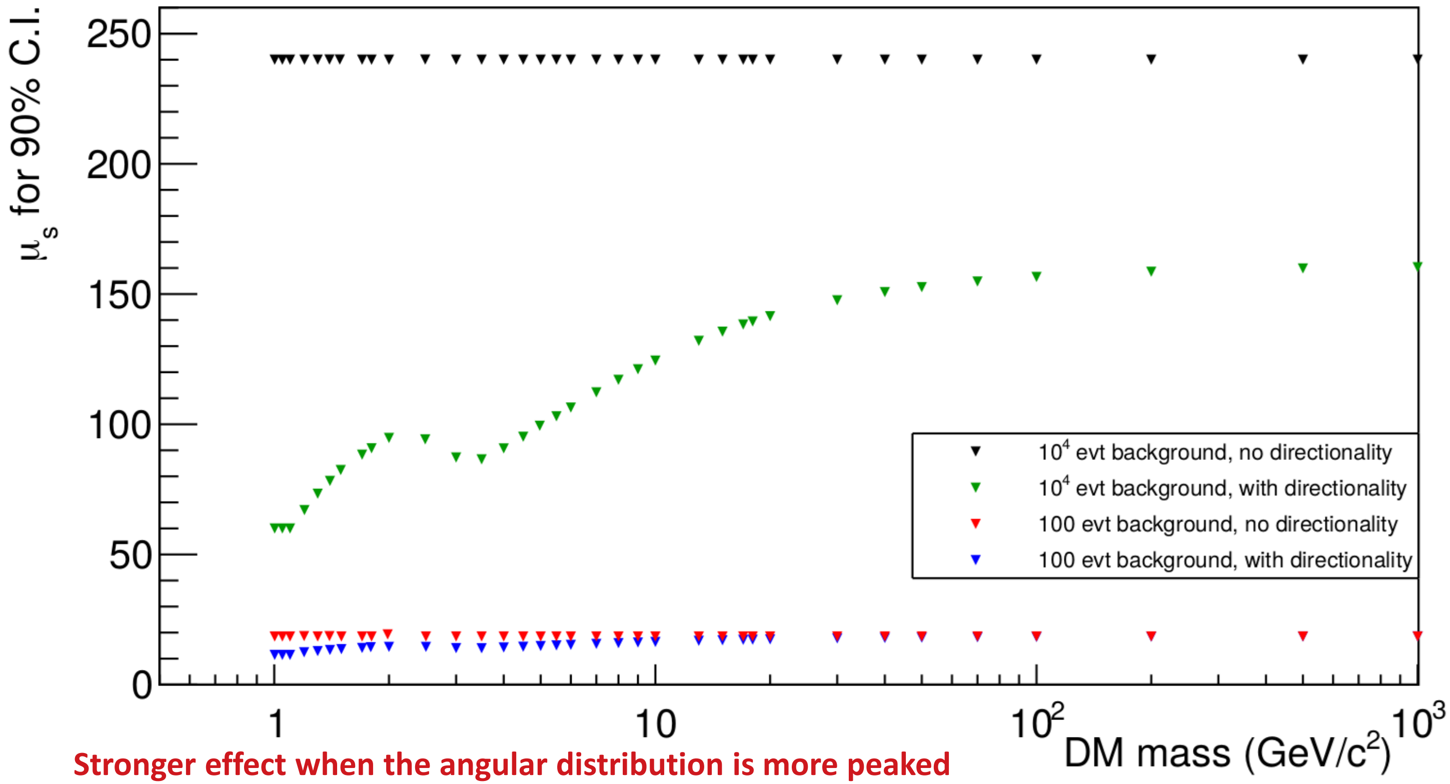
From theory

Migration probability from one bin to another due to resolution

From theoretical distribution

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

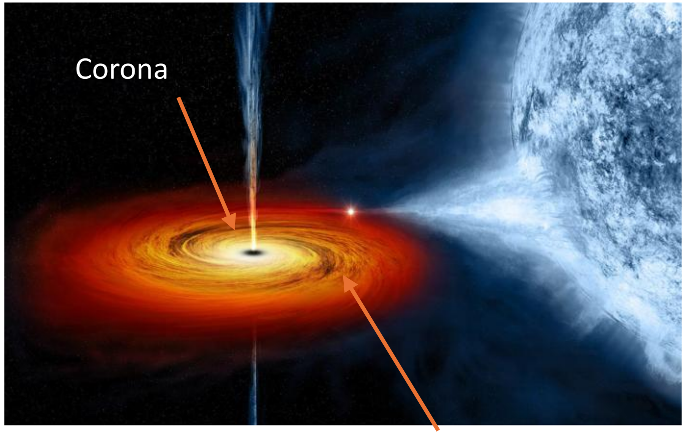
So Why Polarized X-Rays

- The polarization of X-rays depends on magnetic field structures, geometry of gas clouds and fundamental interactions

- Its measurements can unlock knowledge on astrophysical objects no other method is able to

Shape of coronas and accretion geometry

(Accreting black hole binaries for example)

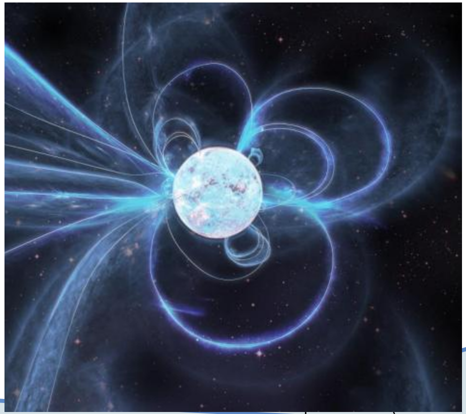


Acceleration mechanisms in jets and shocks

(Blazars, SuperNovae Renant)

Behaviour in extremely strong magnetic fields

(Magnetars)

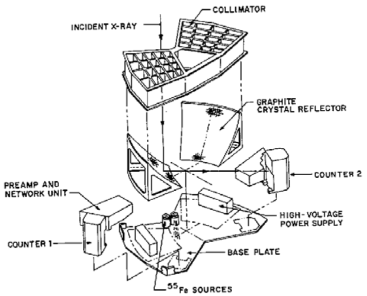


2024)

How to Measure X-Rays Polarization

- Different methods to measure polarimetry with space detectors

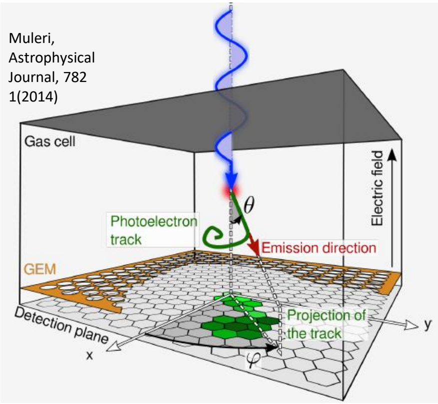
Thomson & Bragg Diffraction



Weisskopf 1978

- Early flights in ‘70s and OSO-8 (weisskopf 1978)
- Modern employ multilayered diffractor materials for <1 keV goal (Stokesat DeRoo, Marshall)
- Polarization measured through Bragg or Thomson diffusion
- Very narrow energy bands sensitivity

Photoelectric effect



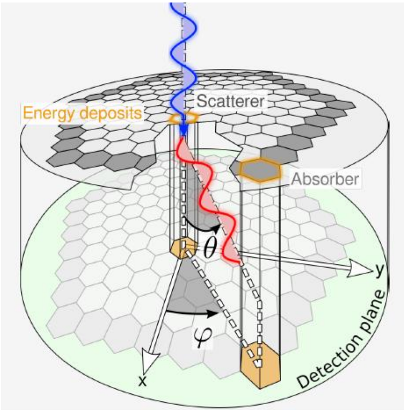
Austin and Ramsey (1992)

- Many proposed, now IXPE in orbit
- Azimuthal distribution of photoelectrons

$$\frac{d\sigma}{d\Omega} \propto \cos^2 \phi \frac{\sin^2 \theta}{(1-\beta \cos \theta)^4}$$

- Sensitive to initial low energy deposits of photoelectron

Compton Scatter



Muleri, ASI school

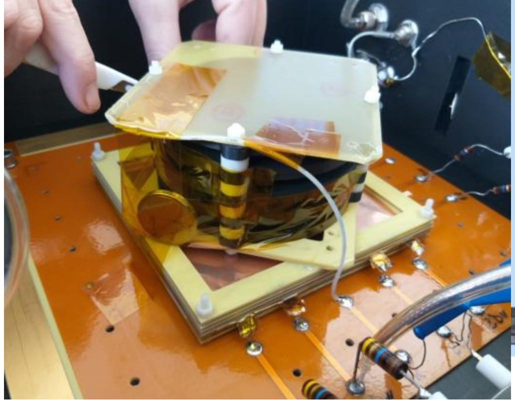
- Baloon and orbit one proposed (XL-Calibur [15-80 keV], COSI [0.2-5 MeV])
- Azimuthal distribution of scattered photon

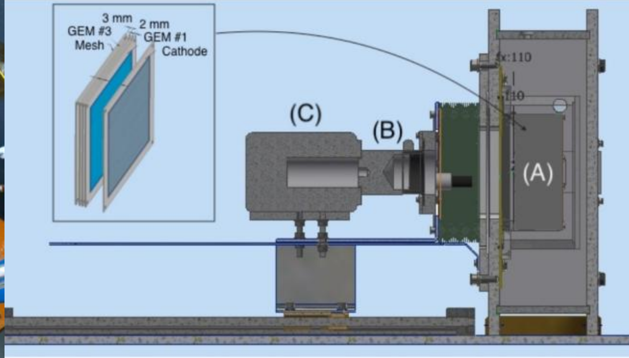
$$\frac{d\sigma}{d\Omega} \propto \left[\frac{E}{E'} + \frac{E'}{E} - 2\sin^2\theta \cos^2\phi\right]$$

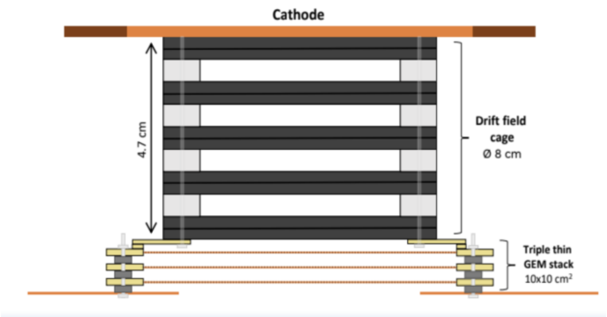
- Loses sensitivity at high energy

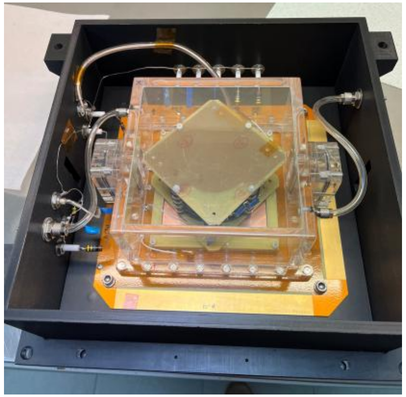
MANGO Prototype

- Prototype in use for these tests is of the potential dimensions for a polarimetry mission
- Drift gap 4.7 cm with cylindrical field cage of 4 cm radius (40.24 cm^2 readout area)
- ORCA Fusion camera (1.49x1.49 cm^2 sensor size)
- Effective granularity of image sensor 48x48 μm^2 (can image with same granularity 10x10 cm^2 area)
- Intrinsic diffusion from amplification stage about 300 μm in standard deviation
- PMT used only for trigger in these tests









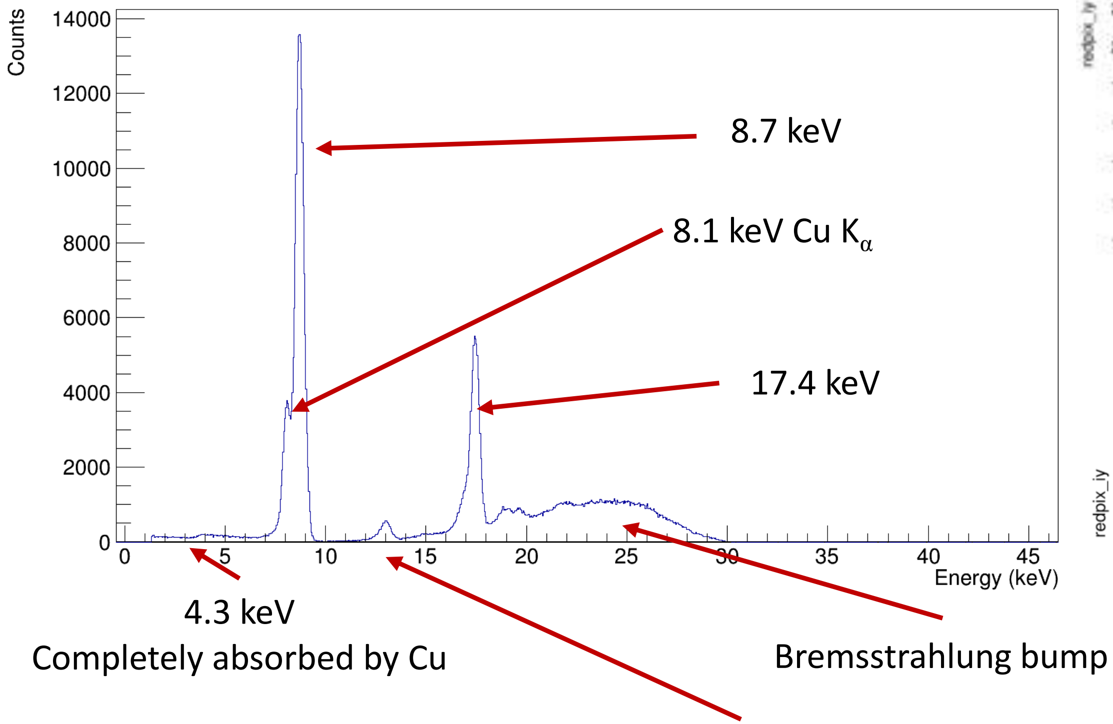
Measurement campaigns

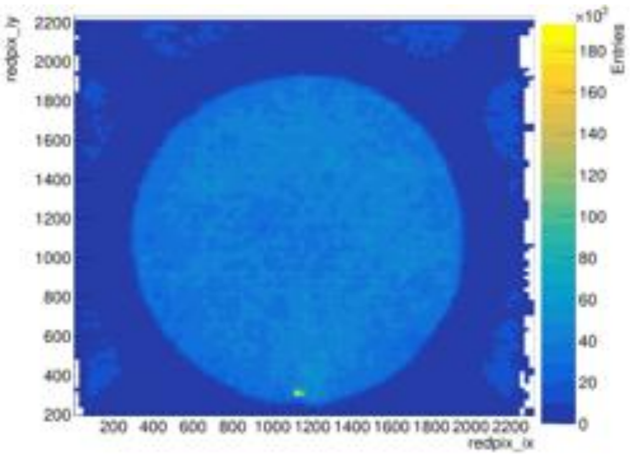
- **^{90}Sr source to estimate angular resolution**
- **Polarized source to measure modulation factor**

G.Dho

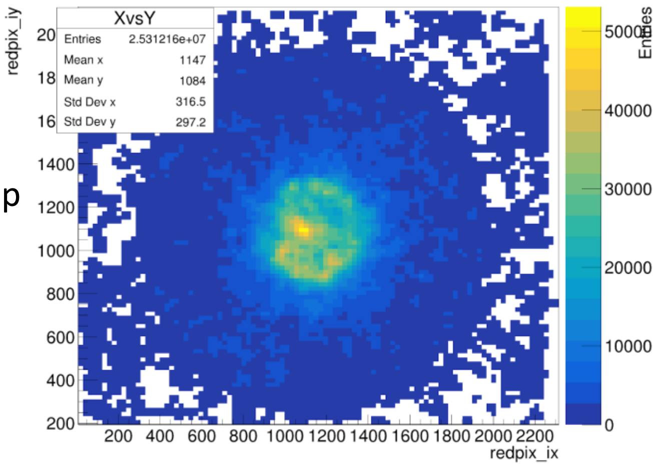
Data Sets and Source

- Spectrum of the source measured with a solid state CdTe detector positioned below a piece of foil of our cathode





Cosmic map
FC uniformity



Source map

Concentrated in 1 cm radius

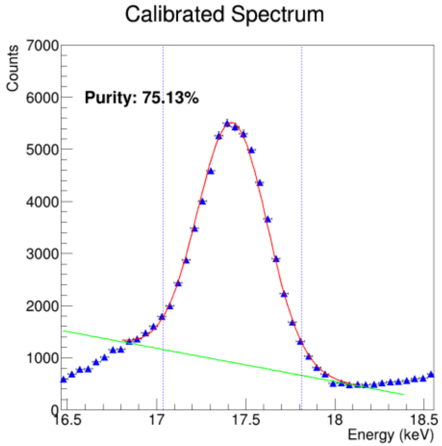
Concern: Pile up

Exposure time 200 ms
Rate ~ 30 Hz

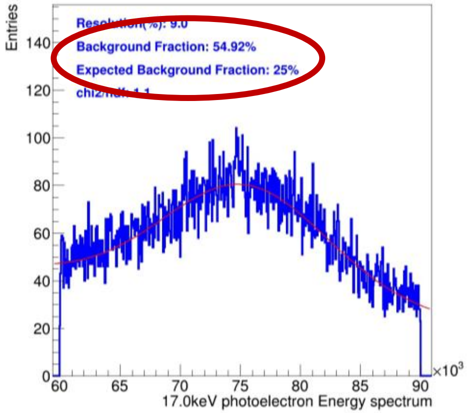
Data Analysis (early stage)

PRELIMINARY

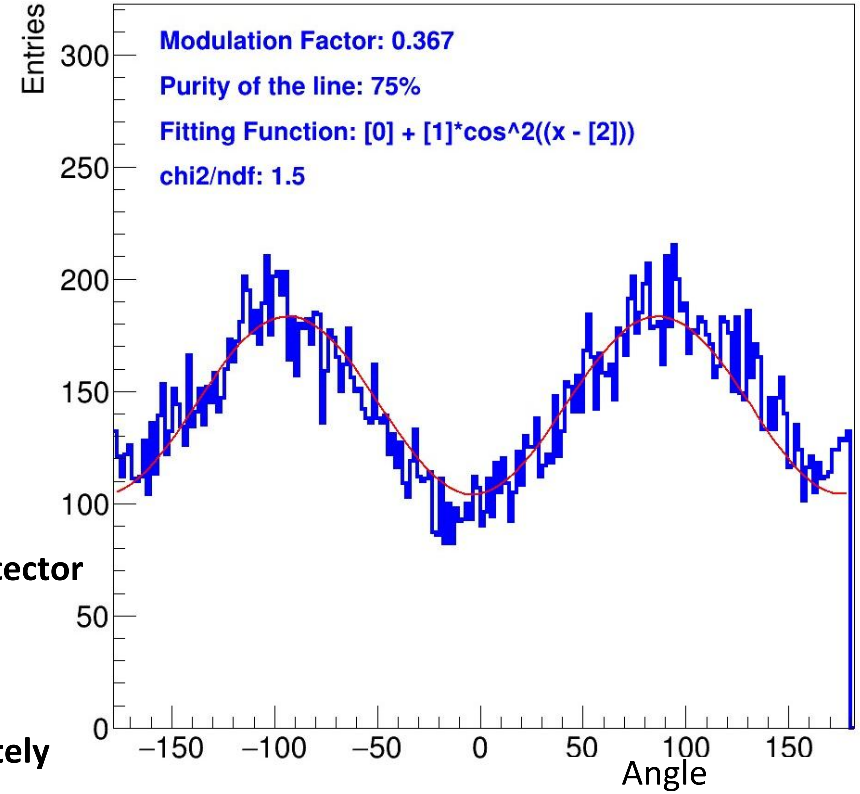
- Energy spectrum calibrated with ^{55}Fe (5.9 keV) and ^{109}Cd (22 and 80 keV) sources.
- Selection of events in energy range of interest but some background is present (purity of the line estimation from CdTe spectrum)



Simple trapezoidal method (can be improved)



Measured 17.4 keV peak



First ever modulation measured with our detector

Half of our prediction with angular resolution

Large background to be removed. **Can definetely improve**

G.Dho