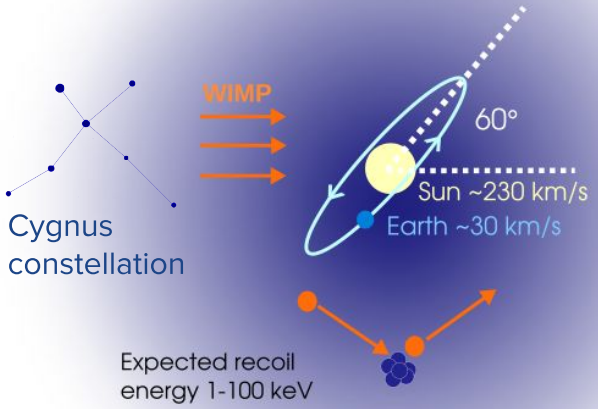
CYGNO: a gaseous TPC with optical readout for dark matter directional search

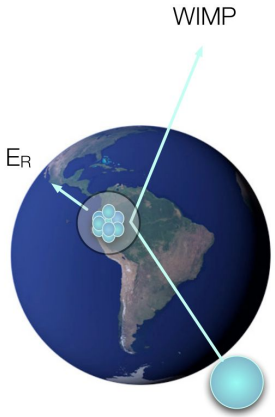
Giulia D'Imperio on behalf of CYGNO collaboration

Instrumentation for Colliding Beam Physics
24-28/02/20 Novosibirsk, Russia

Dark matter “direct” detection

- Dark matter (DM) makes up ~85% of the mass of the universe
- DM form a halo around the galaxy
- Weakly Interacting Massive Particles (WIMPs) are natural candidates





Direct detection:
DM elastic scattering off target nuclei

$$E_R = \frac{q^2}{2m_N}$$

$$\phi = \frac{\rho_\chi}{m_\chi} < v >$$

WIMP flux on Earth: **10^5 cm^{-2} s^{-1}**
~ 10 millions through your hand every second

The **recoil energy** is **1-100 keV** for a 10-1000 GeV WIMP

Expected rate

Astrophysics

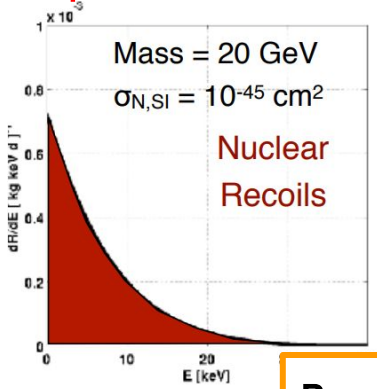
$$R \propto N \frac{\rho_\chi}{m_\chi} \sigma_{\chi N} \cdot \langle v \rangle$$

Particle Physics

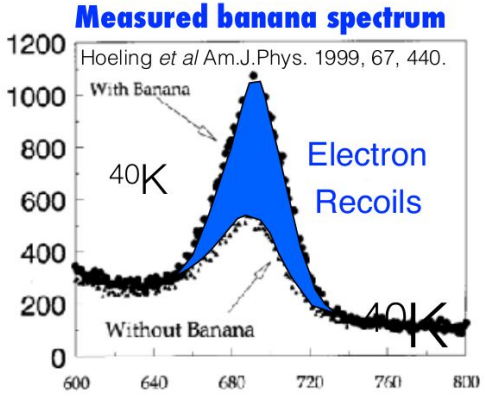
ρ Local dark matter density in the Milky Way: ~0.3 GeV/cm^3
<v> WIMP average velocity ~220 km/s

m_χ WIMP mass (~ 1-1000 GeV)
$\sigma_{\chi N}$ WIMP-nucleus elastic scattering cross section

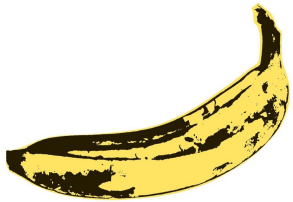
Expected DM rate



~1 event / kg / year



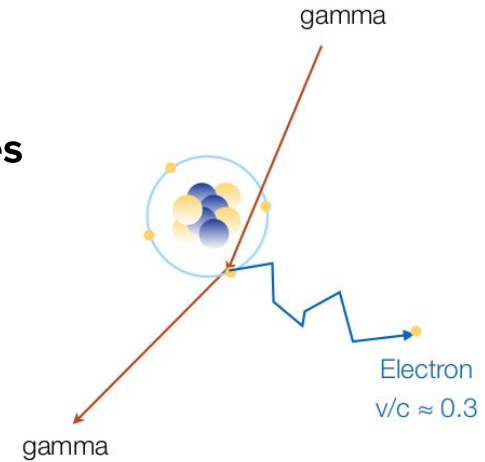
~100 event/kg/ s



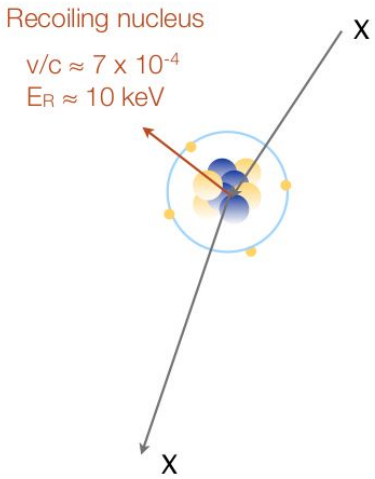
Rare interactions → Experimental challenge: detect tiny signal over large background

Background sources

- **Ambient neutrons/gammas**
  (radioactivity of the laboratory)
- **"Radiogenic" neutrons/gammas**
  (radioactive materials in setup)
- **Cosmogenically activated isotopes**
  (activation from cosmic rays)
- **Cosmogenic neutrons**
  (cosmic muons interactions)



Most of the background from **electron recoils (ER)** caused by **β/γ events**



Neutrons produce **nuclear recoils (NR)** similar to WIMPs

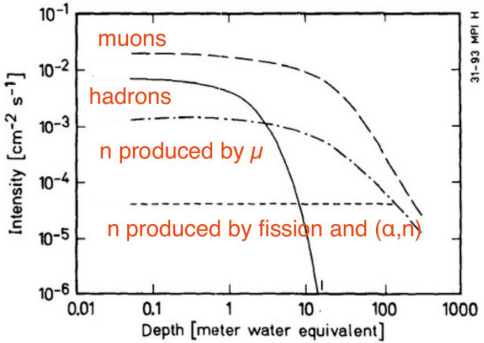
Background rejection

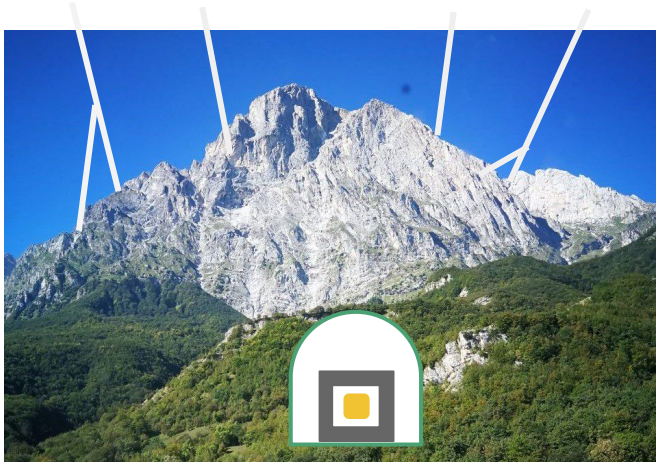
- **Ambient neutrons/gammas**
  (radioactivity of the laboratory)
- **"Radiogenic" neutrons/gammas**
  (radioactive materials in setup)
- **Cosmogenically activated isotopes**
  (activation from cosmic rays)
- **Cosmogenic neutrons**
  (cosmic muons interactions)

→ **Passive/active shieldings**

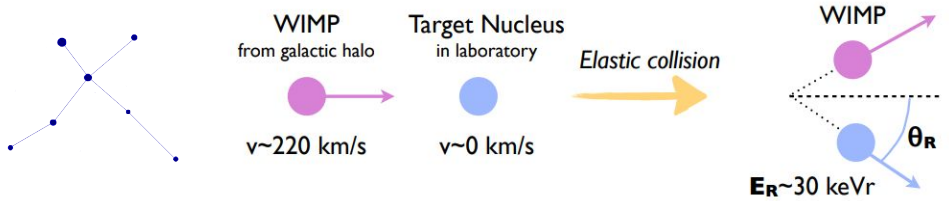
→ **Careful choice of low radioactivity materials**

→ **Underground laboratories**



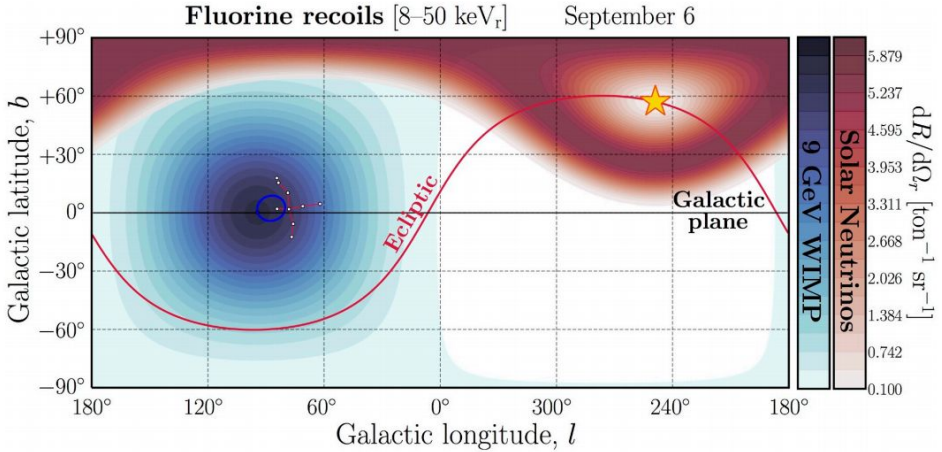


Detection strategy: directionality



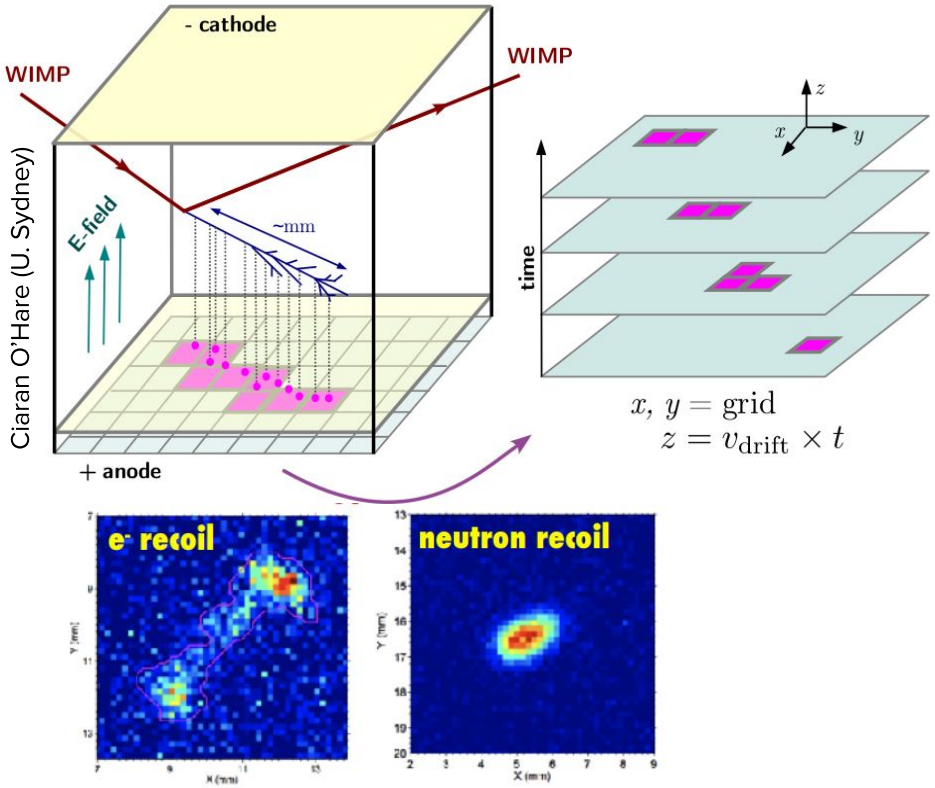
Nuclear recoils (partially) retain the incoming WIMP direction

- **Dark matter** particles arrive from a **precise direction** in the sky (Cygnus)
- Radioactivity neutron background
  ➜ no preferred direction
- Solar neutrinos
  ➜ Sun never in the same position of the Cygnus



Directionality could be an important **tool to discover DM** and go beyond the neutrino floor

The CYGNUS concept

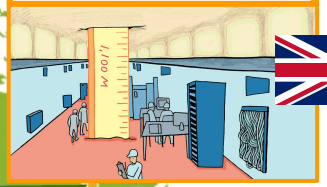


- **Time Projection gas Chamber** technique to track the nuclear recoil
- Very **low threshold** (~1 keV) and sensitivity to ~1 GeV DM ➜ use gas mixture with He
- Measuring the **shape of the recoil** (rejection of electron recoils) down to few keV
- Measuring the **direction** of the recoil for energies >20 keV

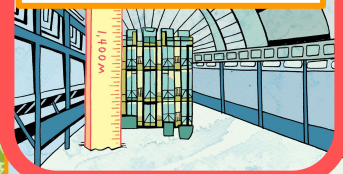
CYGNUS possible sites

GSSI
INFN Roma & Sapienza University
INFN LNF
Centro Fermi

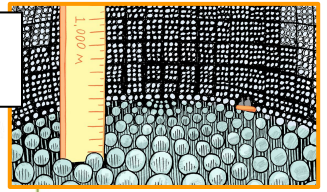
CYGNUS-10
@Boulby, UK



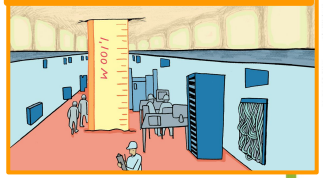
CYGNO
@LNGS, Italy



CYGNUS-KM
@Kamioka, Jap.



CYGNUS-HD10
@Lead, USA



CYGNUS-OZ
@Stawell, Aus.

Boulby Underground Laboratory, UK
Laboratorio Subterráneo de Canfranc, Spain
Sandford Underground Research Facility, USA
Soudan Underground Laboratory, USA
Kamioka Observatory, Japan
Yangyang Underground Laboratory, Korea
China JinPing Underground Laboratory, China
NEW!
Stawell Underground Laboratory, Australia

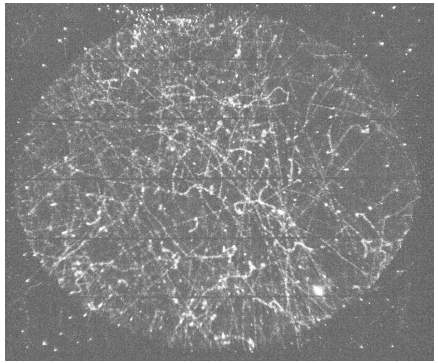
Network of TPC detectors for DM
Target mass ~1000 m^3

First UL in southern hemisphere

CYGNO: a **CYGN**us TPC module with **O**ptical readout

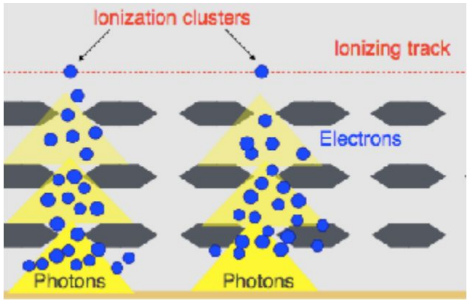
X-Y readout sCMOS

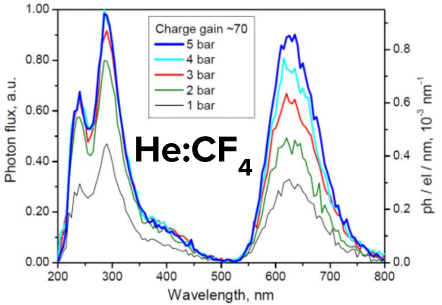
Slow O(10-100 ms)
High granularity XY
Low noise (<2 e^- RMS)
High quantum efficiency
>70% @600 nm



➜ 2D tracks
➜ Energy

GEM electron amplification produces light in gas

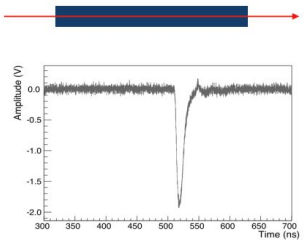




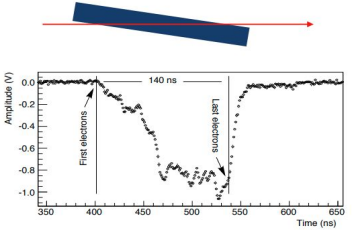
Z readout PMT

Fast light detector
➜ Time (z coord.)
➜ Energy

Straight track



Tilted track



CYGNO roadmap and synergy with INITIUM

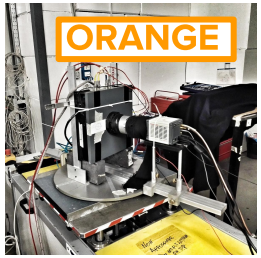
CYGNUS-RD | **CYGNO-Phase0** | **CYGNO-Phase1** | **CYGNO-Phase2**

2015 — 2018 — 2019 — 2020 — 2021 — 2022

$He:CF_4$
1 atm

@ ROMA1/LNF

ORANGE



1 sCMOS, 1 PMT
10 x 10 cm^2 area
1 cm drift

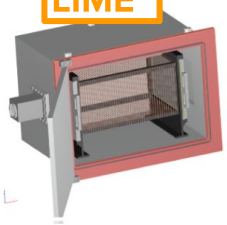
@ LNF

LEMOn

1 sCMOS, 1 PMT
20 x 24 cm^2 area
20 cm drift

@ LNF

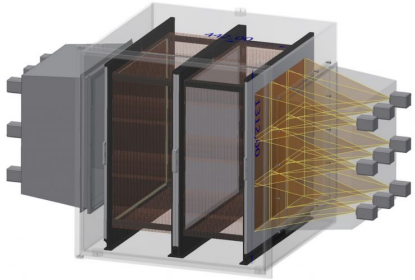
LIME



1 sCMOS + 4 PMT
33 x 33 cm^2 area
50 cm drift

@ LNF/LNGS

CYGNO



18 sCMOS
1 x 1 m^2 area
2 x 50 cm drift regions

CYGNO 30-100 m^3

$He:CF_4:SF_6$
0.8-1 atm
Negative ion drift

NITEC
4 Timepix chips
3 x 3 cm^2 area
50 cm^3

MANGO
1 sCMOS
10 x 10 cm^2 area
500 cm^3

INITIUM erc

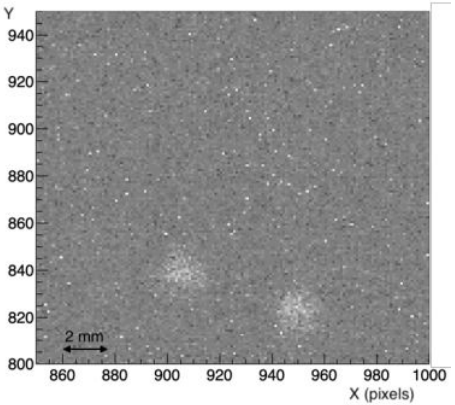
2015 — 2018 — 2019 — 2020 — 2021 — 2022

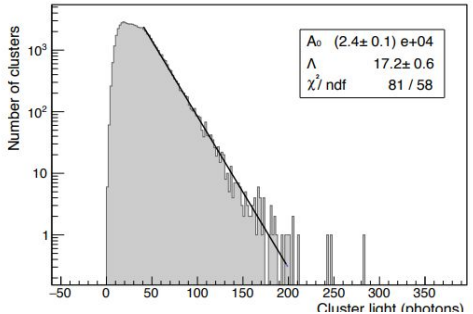
Low energy electrons

Typical operation conditions

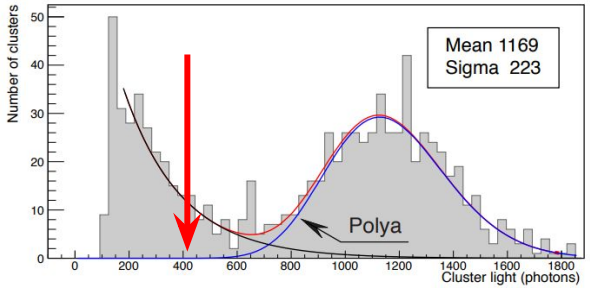
- He:CF_4 60:40 gas mixture atmospheric pressure
- Drift field E_d = 600 V/cm
- V_{GEM} = 460 V for each GEM plane
- Transfer field E_t = 2 kV/cm

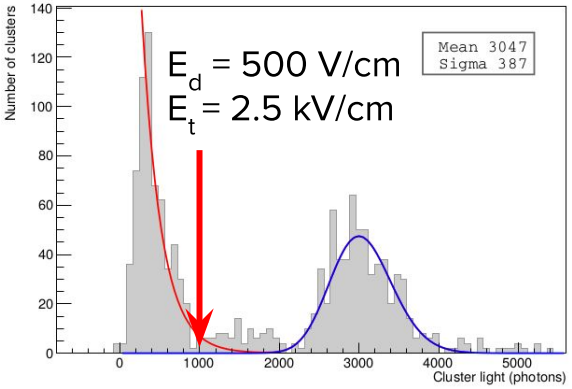
5.9 keV x-rays
(^{55}Fe source)





Noise distribution
(light outside the
sensitive region)

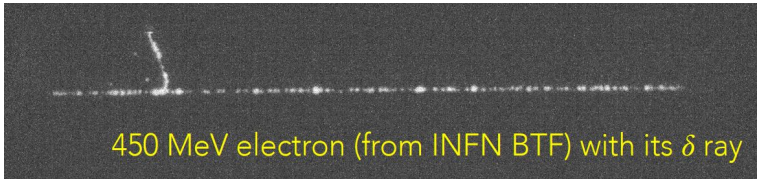


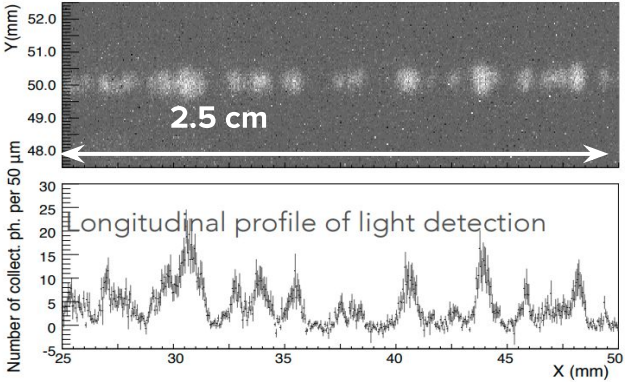


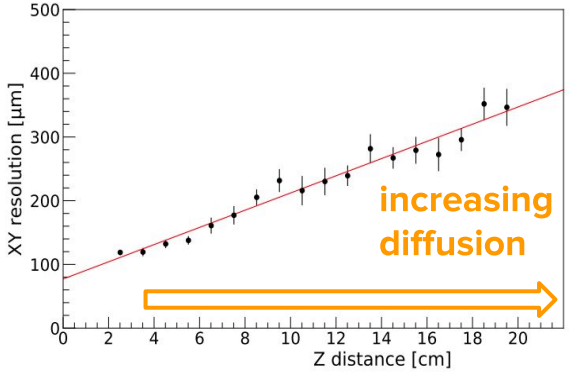
Energy threshold → 2 keV

JINST 14 P07011 (2019)

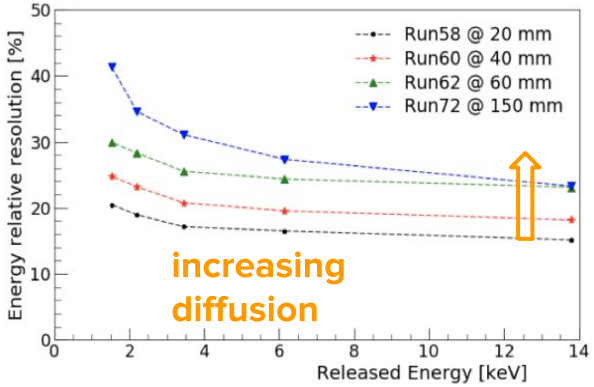
High energy electron tracks







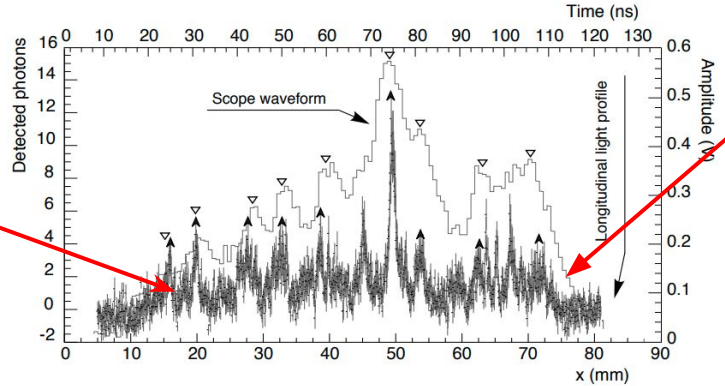
XY resolution vs Z drift length
➔ **100 µm @Z = 2 cm**
➔ **300 µm @Z = 20 cm**



Energy resolution
@different Z drift length
~**20-30%** for **2-5 keV**

3D tracking: combined readout

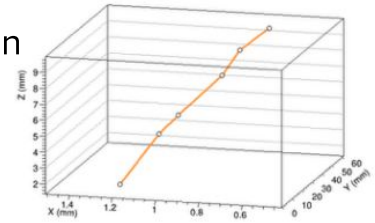
Light profile along the track (X, Y from sCMOS)

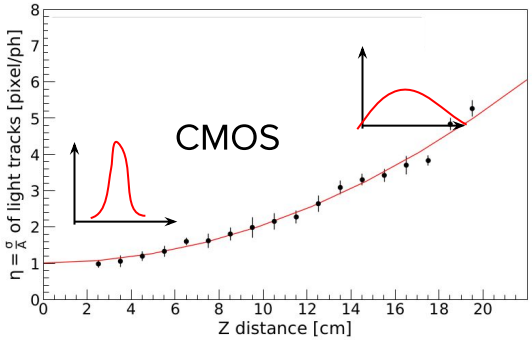


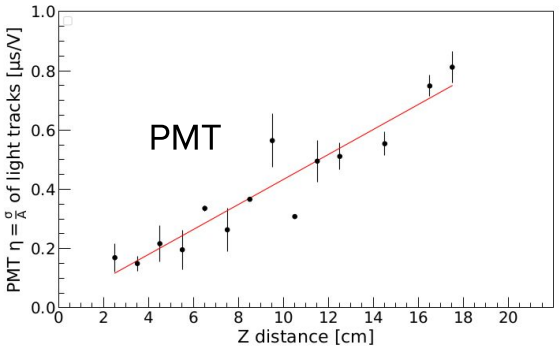
Fast waveform (time from a PMT)
Drift velocity 7.2 cm/µs

Use transversal (CMOS) and longitudinal (PMT) diffusion to measure z

Cluster 3D reconstruction



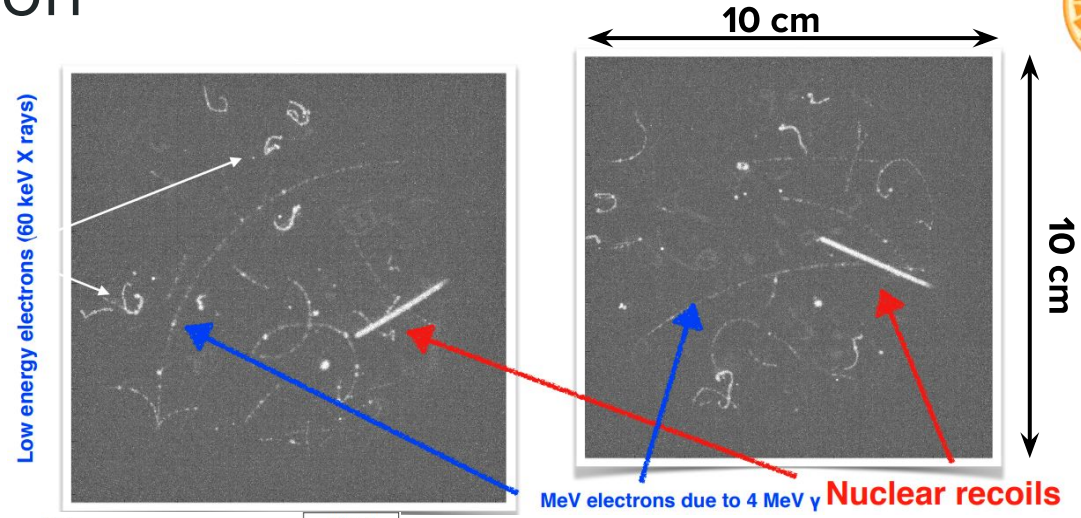


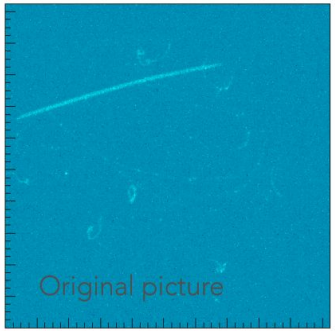


Particle identification

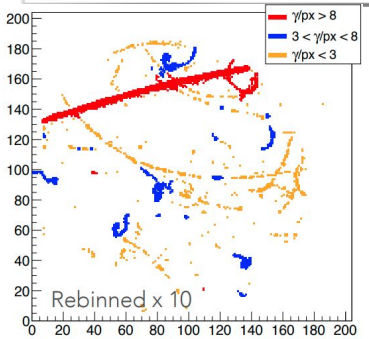
Am-Be source

- 1-10 MeV neutrons
- 4 MeV and 60 keV gamma
- 0.2 T permanent magnet

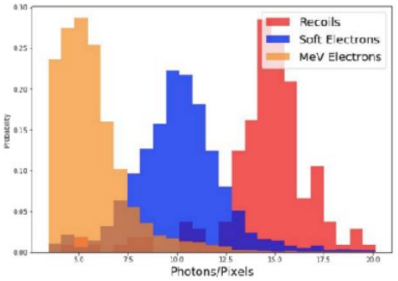




Analyzed with iterative algorithm iDBscan

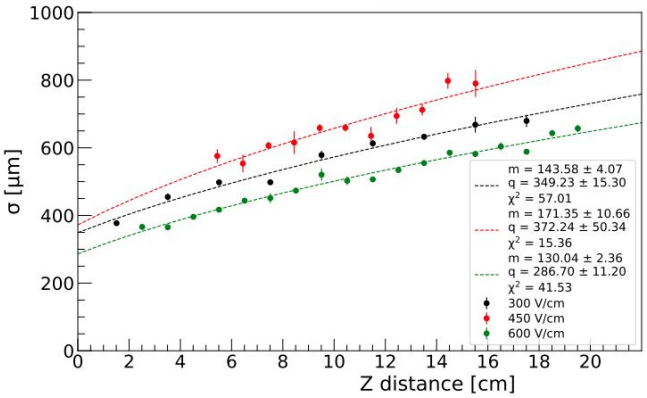


clusterize 3 different species of tracks based on density γ/px



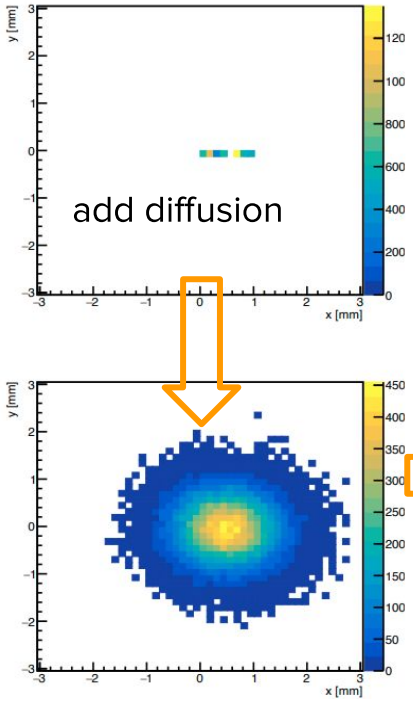
Note: only ionisation density used. PID can be complement and largely improved combining it with track topology and track length vs energy

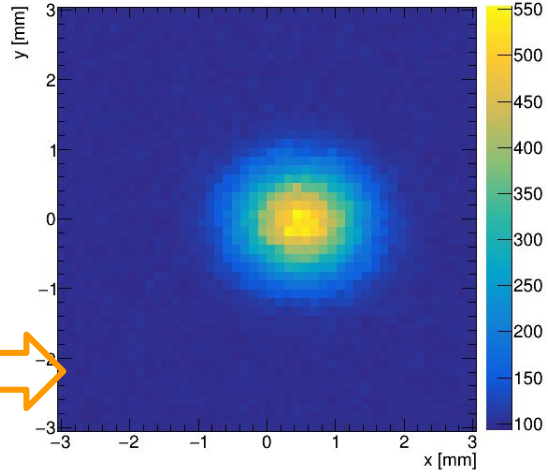
Simulated tracks in CYGNO



- Diffusion measured with LEMOn
- Apply diffusion and noise to the MC truth recoil tracks
- Possible to apply reconstruction algorithm (same used for data)

MC truth (SRIM)
He recoil of 100 keV



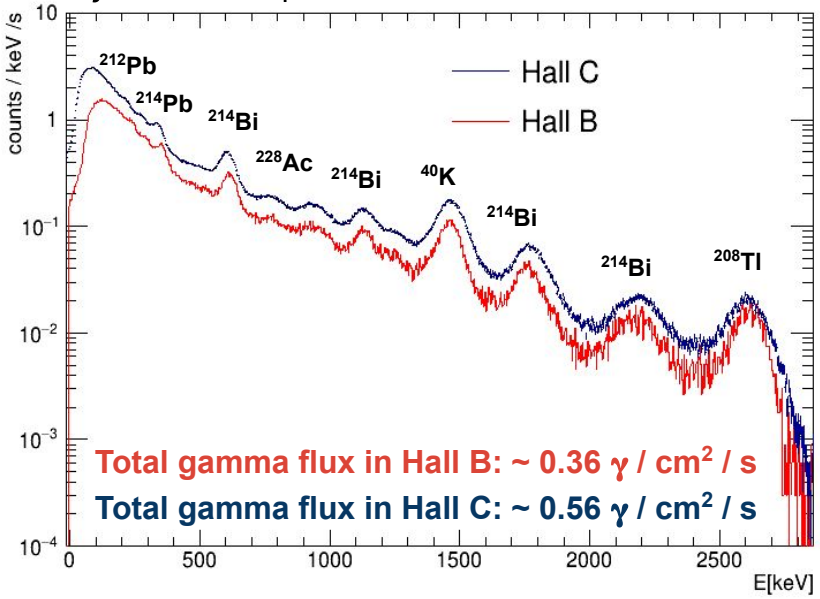


add pedestal with RMS 2 ph/px

Simulation: ambient background

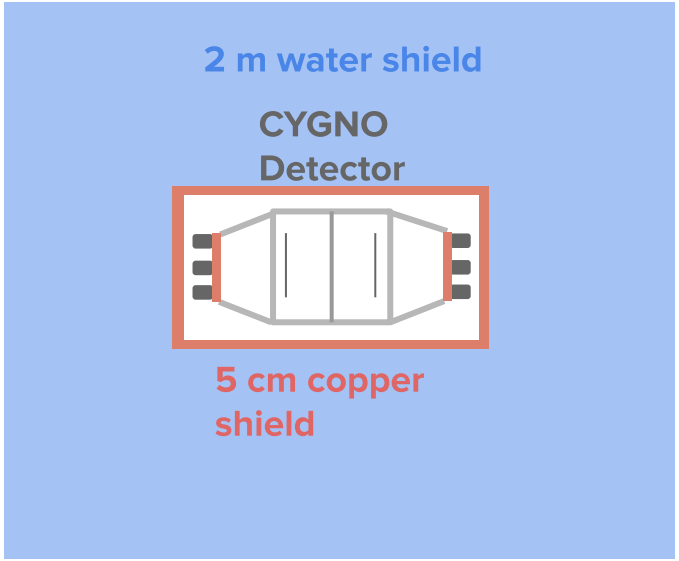
Goal total background < 10^4 cpy in [0-20] keV

Input ➔ gamma flux measured by SABRE experiment @LNGS



Shielding choice:

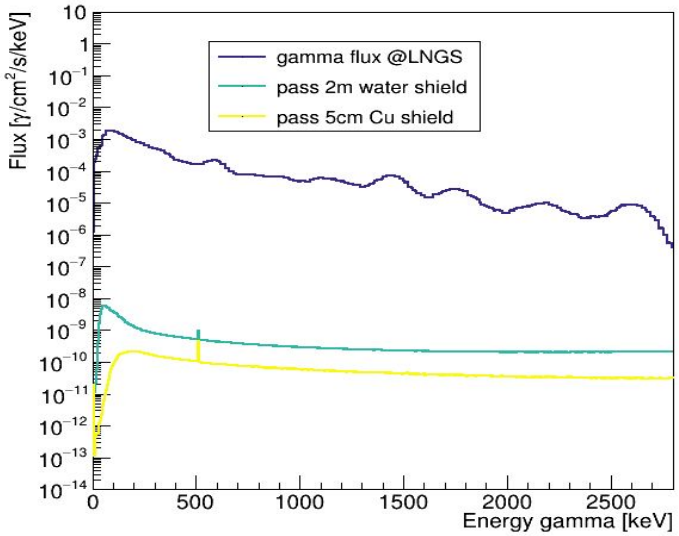
- **2 m of water**
  modular tanks, start with 1 m
- **5 cm of copper**



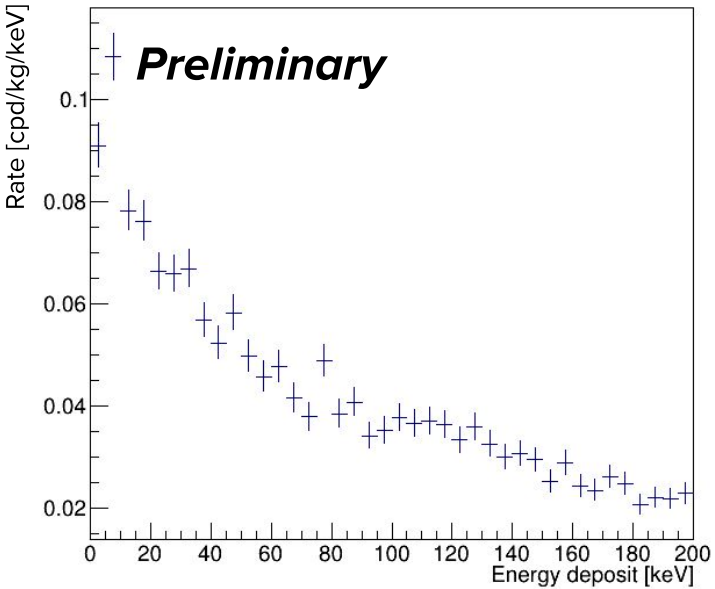
Simulation: external gammas

200 cm water + 5 cm Cu

Gamma Flux at LNGS 0.56 $cm^{-1}\ s^{-1}$
Gamma Flux after 2 m water shield 1.4 10^{-6} $cm^{-1}\ s^{-1}$
Gamma Flux after 5 cm Cu shield 2 10^{-7} $cm^{-1}\ s^{-1}$



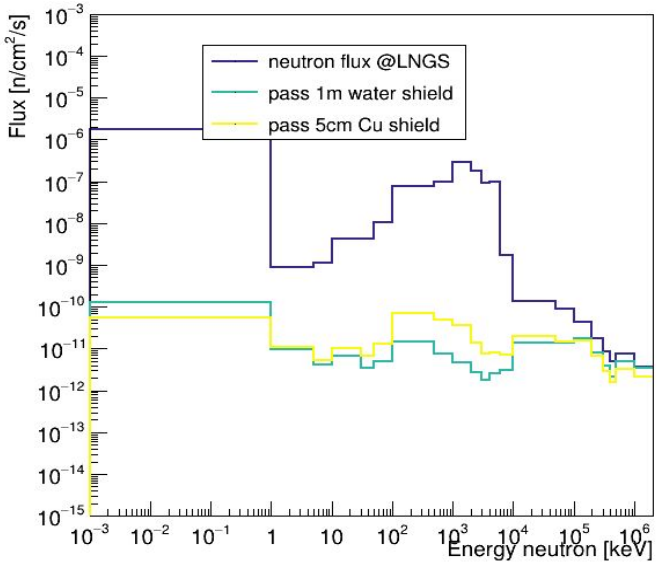
Rate [0-20] keV = 9 10^{-2} cpd/kg/keV
➔ **10^3 cts/yr** [0-20] keV in CYGNO detector



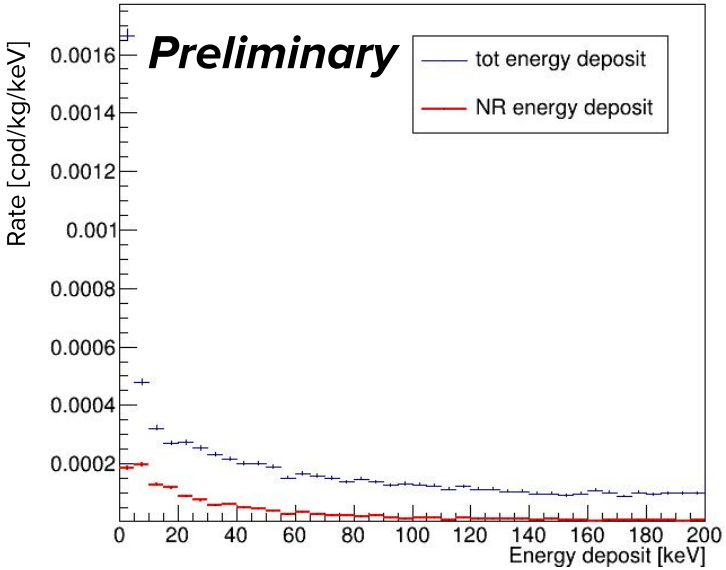
Simulation: neutrons (and secondaries)

200 cm water + 5 cm Cu

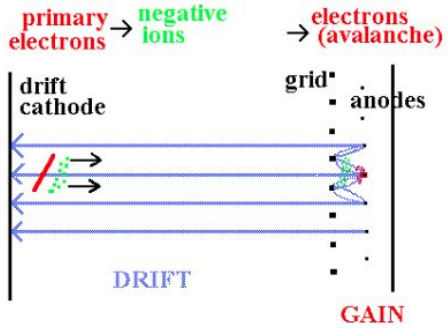
Neutron Flux @LNGS 2.7 10^{-7} cm^{-2} s^{-1}
Neutron Flux after water shield 2 $10^{-10}$$cm^{-2}$ s^{-1}
Neutron Flux after Cu shield 3 10^{-10} cm^{-2} s^{-1}

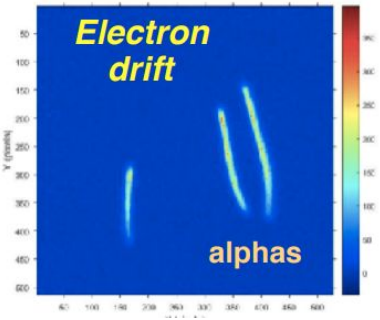


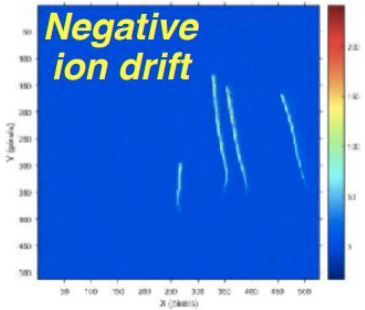
Rate [0-20] keV = 7 10^{-4} cpd/kg/keV
➔ **8 cts/yr** [0-20] keV in CYGNO detector
➔ **O(1) NR/yr**



Negative ion drift: INITIUM

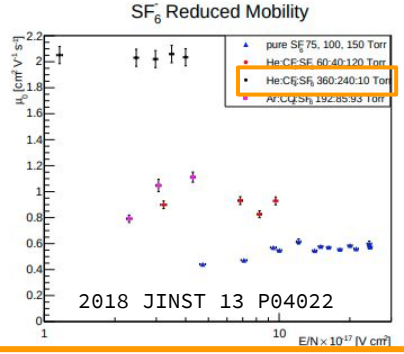






- Ionization e- captured at ≤ 100 µm ➜ **negative ions**
- **Anions drift** to the anode
- Extra e- stripped from the negative ions ➜ **electron avalanche**
- **Ion longitudinal diffusion ~ 1 mm/m** (~ 20 mm/m for electron drift)

Gas mixture
±80% He
±19% CF_4
±1% SF_6

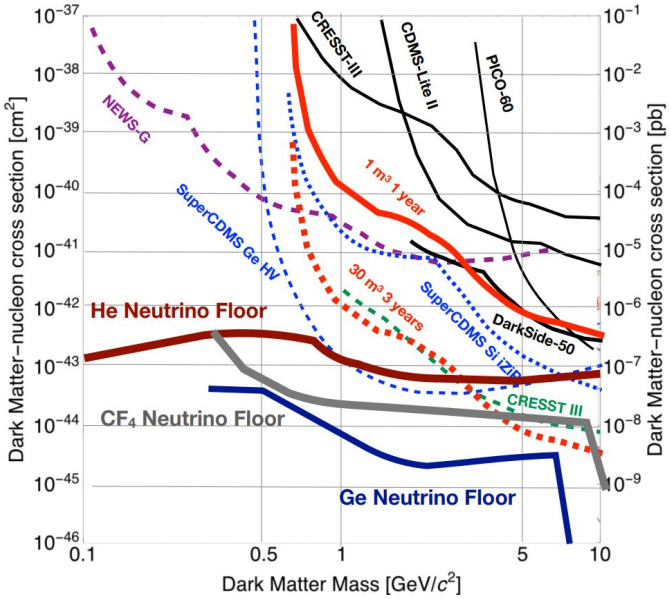


First ever negative ion operation at nearly atmospheric pressure with SF_6

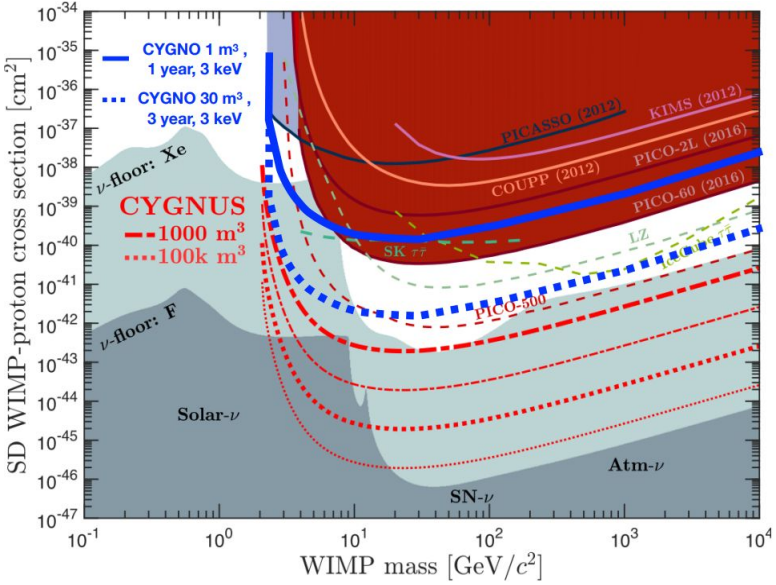
Part of this project has received fundings under the European Union's Horizon 2020 research and innovation programme from the Marie Sklodowska-Curie grant agreement No 657751 and from the European Research Council (ERC) grant agreement No 818744

CYGNO projected sensitivity

Spin Independent



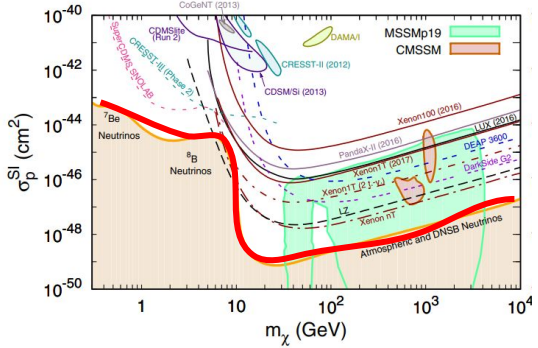
Spin Dependent



- Zero background assumed
- 1 keV threshold on He, 2 keV on C and 3 keV on F

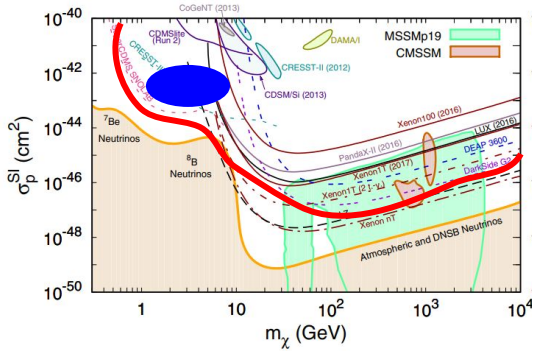
Direct DM search future

DM is excluded to the neutrino floor



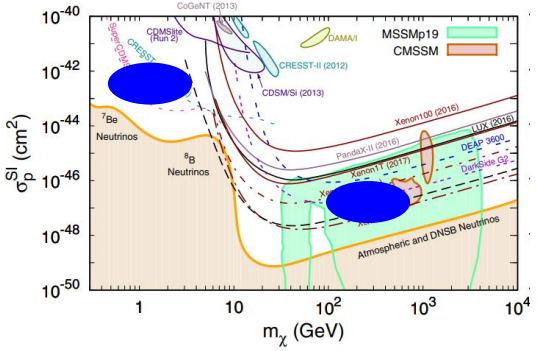
Only a **directional experiment** can continue DM searches and study neutrinos

Incompatible results



Only a **directional experiment** can test the galactic origin of the observed signal

DM is observed

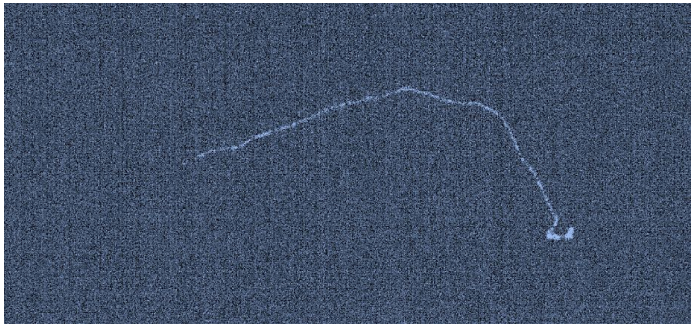


Only a **directional experiment** can perform DM astronomy

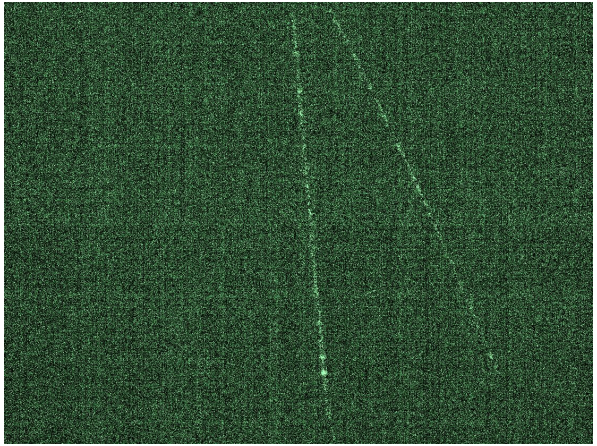
Backup

Some picture with LEMOn detector

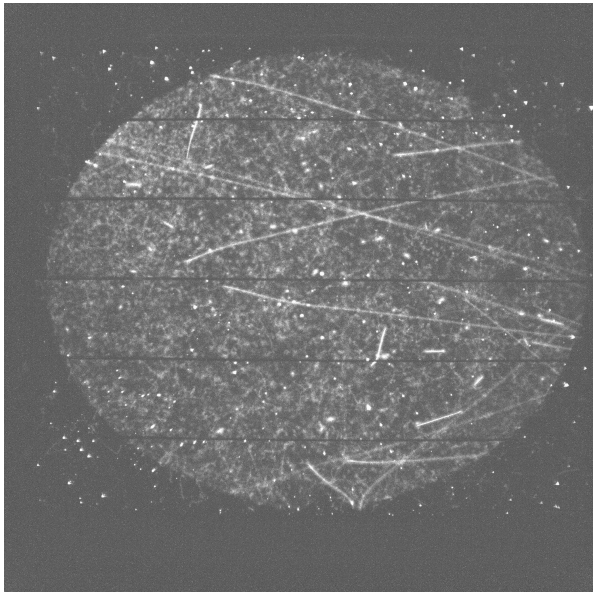
Compton electron



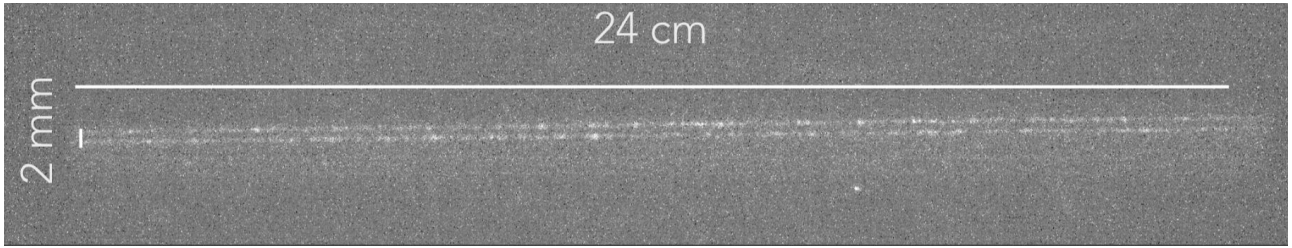
Cosmic rays



Neutrons @FNG 2.45 MeV



Electrons from BTF (450 MeV)



Diffusion effect