SAPIENZA
UNIVERSITÀ DI ROMA

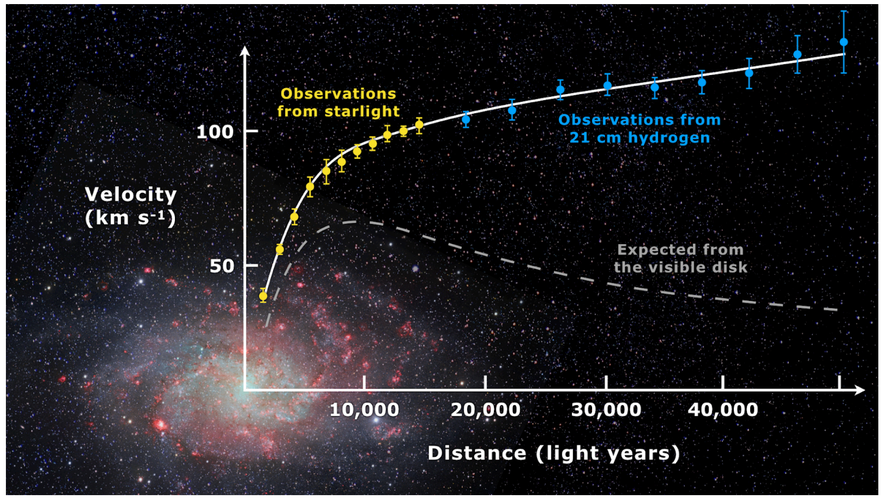
INFN
Istituto Nazionale di Fisica Nucleare

Directional Direct Dark Matter Searches with the CYGNO experiment

Stefano Piacentini

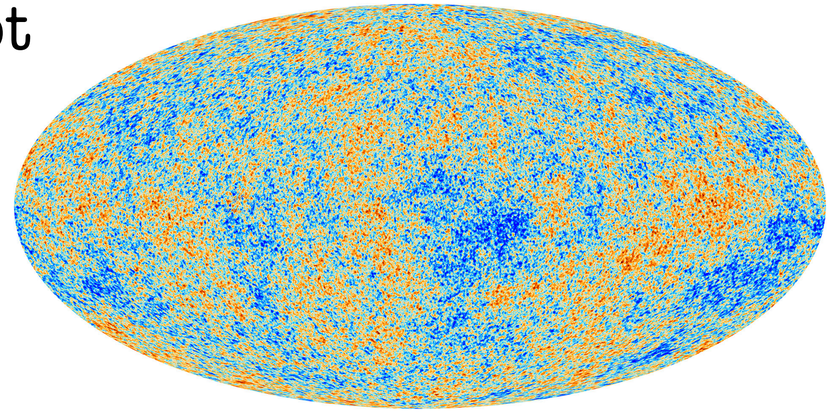
07 / 03 / 2023

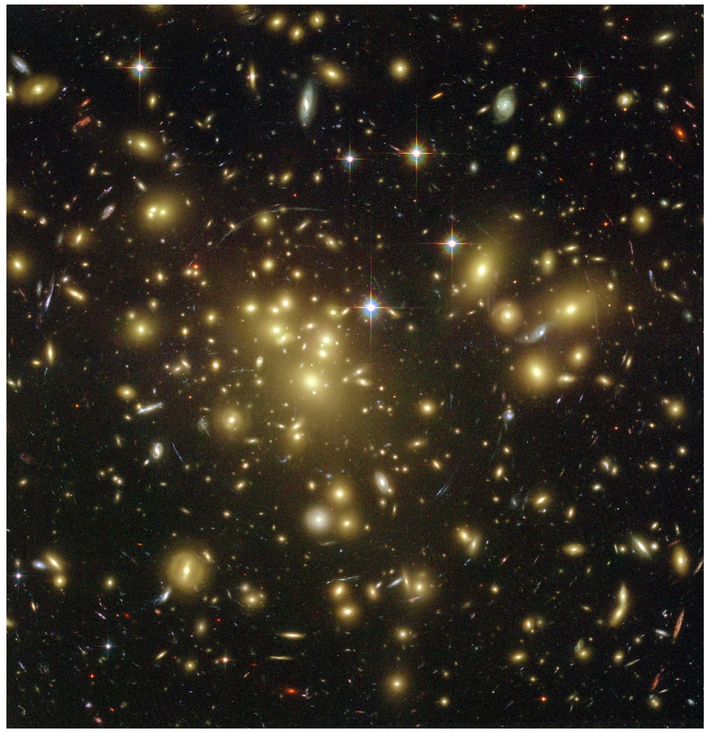
The dark matter problem



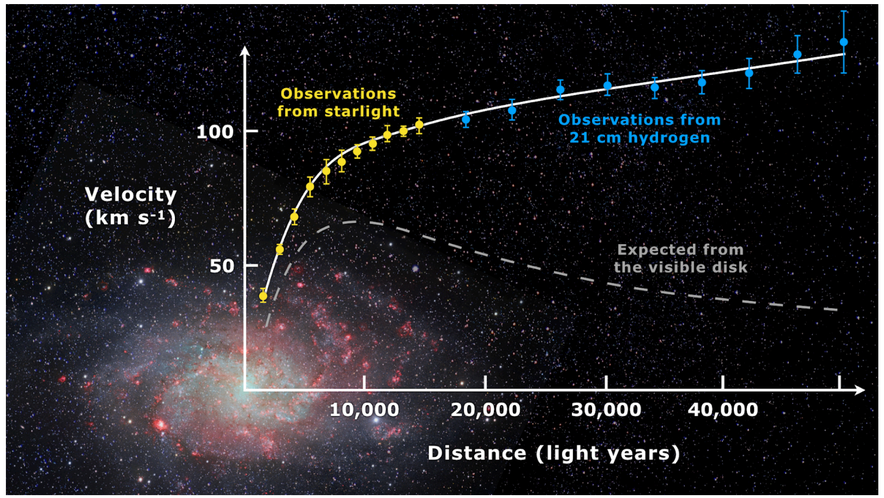
Cosmological and astronomical observations at very different scales strongly support the existence of dark matter (DM)

However its nature - i.e. its mass, interactions with the Standard Model (SM), etc. - has not yet been revealed.

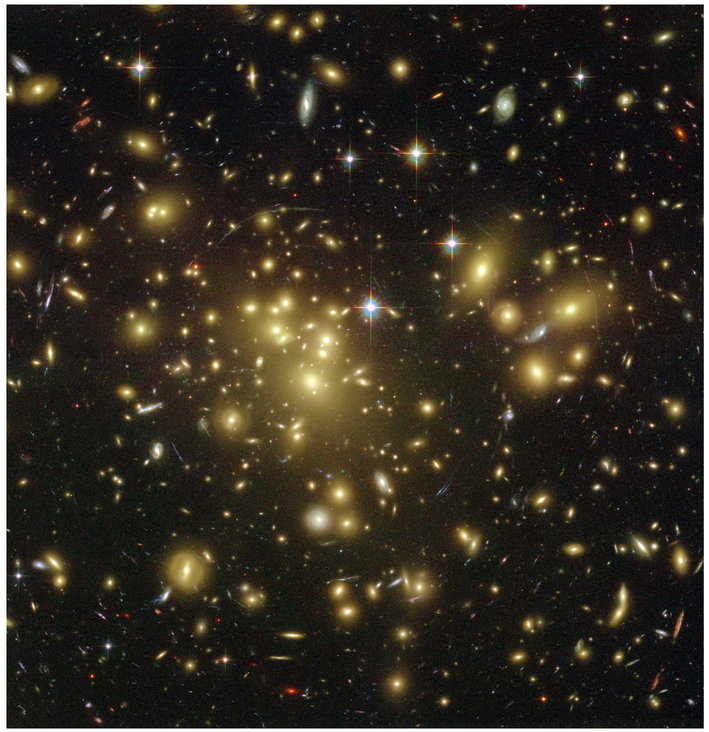


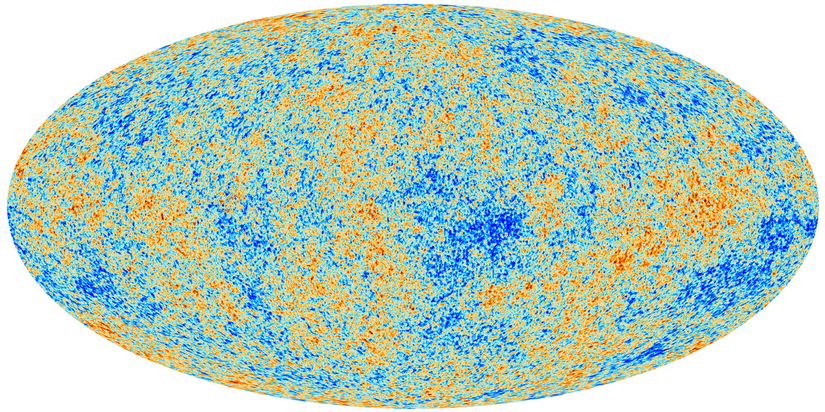


Dark matter evidence



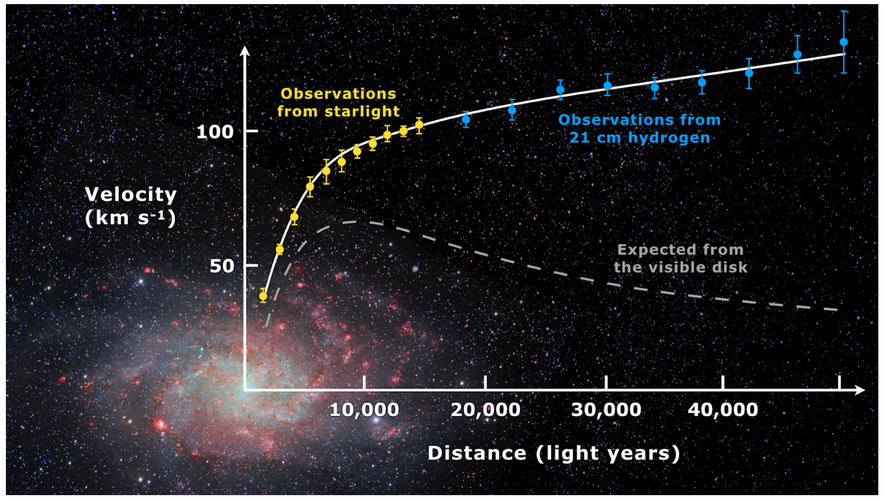
- Spiral galaxy rotation curve Begeman, Broeils, Sanders
- Gravitational lensing arXiv:1003.5567 arXiv:1411.0115 Paczynski (1986)
- Cosmic Microwave Background (CMB) anisotropies arXiv:1807.06209
- Large scale structure formation arXiv:2105.13549
- Bullet cluster astro-ph/0608407





Many observations at very different scales can be explained by the existence of DM

Dark matter evidence



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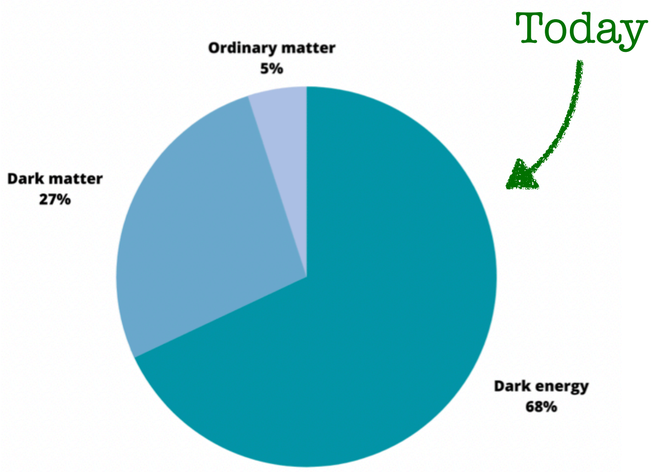


Many observations at very different scales can be explained by the existence of DM

Dark matter candidates

Properties it has to satisfy:

- it has a non-zero **mass**
- it is **not baryonic** (to explain CMB)
- it is **electrically neutral** (it doesn't have EM interactions)
- if coupled to the SM, the **interactions** have to be **weak** (we have not observed them yet)
- it is **stable** on a cosmological timescale (DM is still there and it is not decayed yet)
- it is mainly "**cold**", i.e. non-relativistic

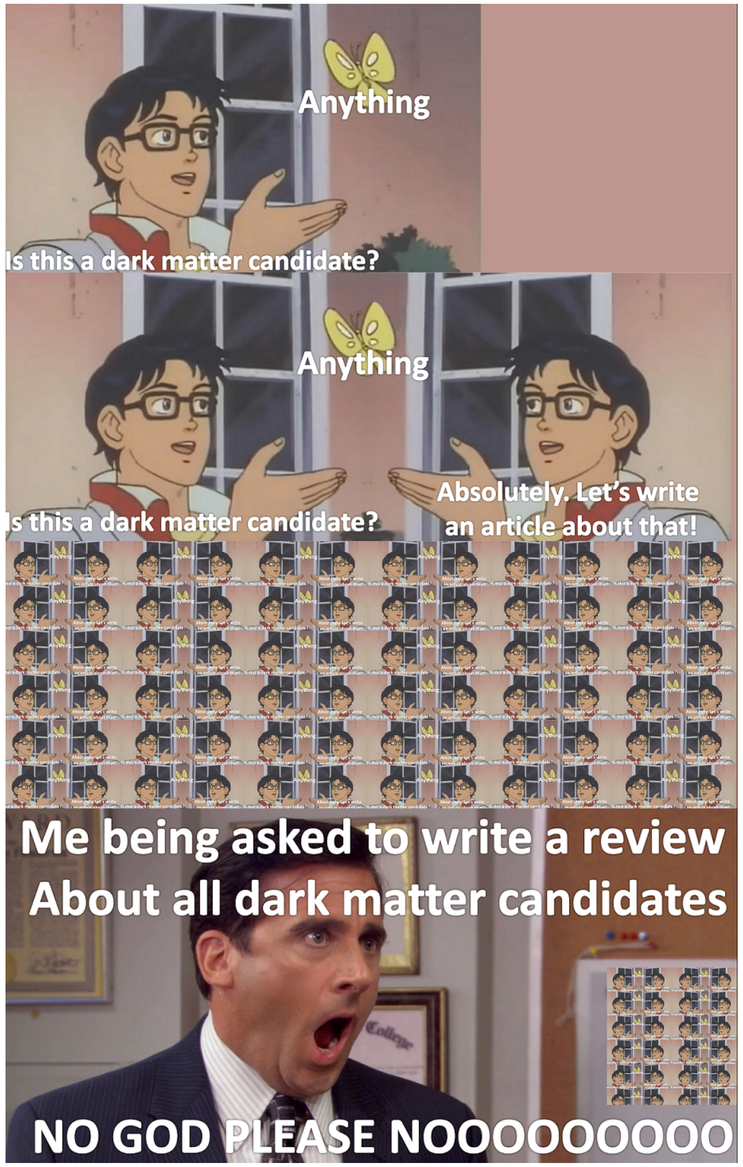
Required to explain large scale structure formation ["hot" component at most ~1% of the total DM]

[arXiv:2105.13549]

Dark matter candidates

- A **pletora** of possible **theoretical models** that can be tested with different experimental setups

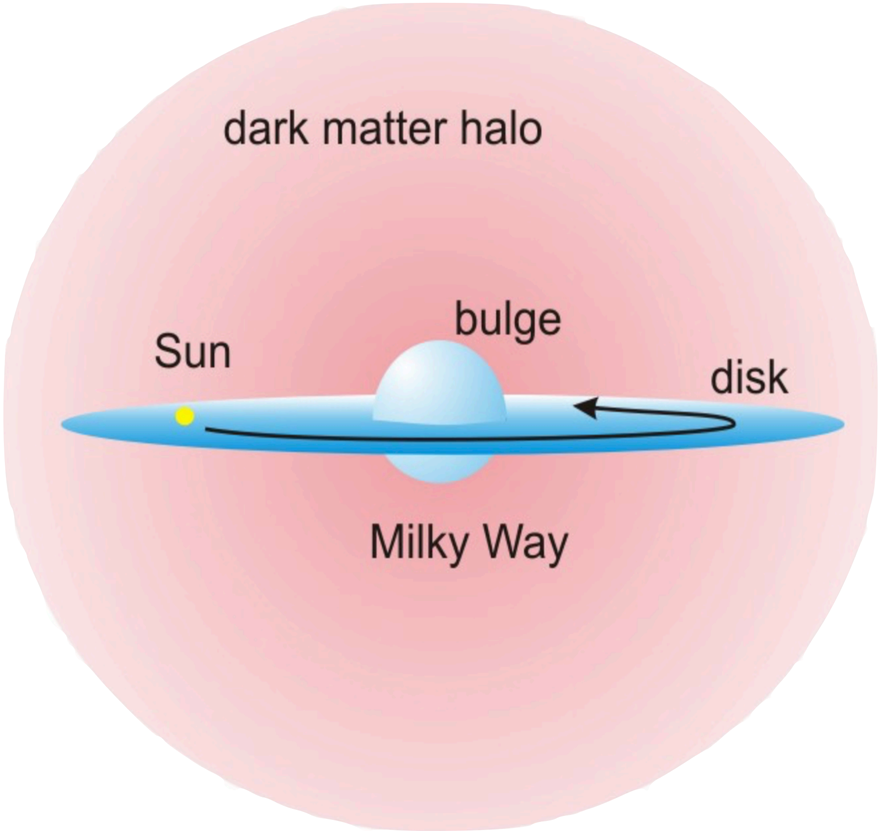
- Other than DAMA, the **null results** of these experiments translates to tighter and tighter **constraints** to the parameters of the models



arXiv:1810.01668

Standard Galactic Halo Model

The Standard galactic Halo Model (**SHM**): DM distribution in the Milky Way.



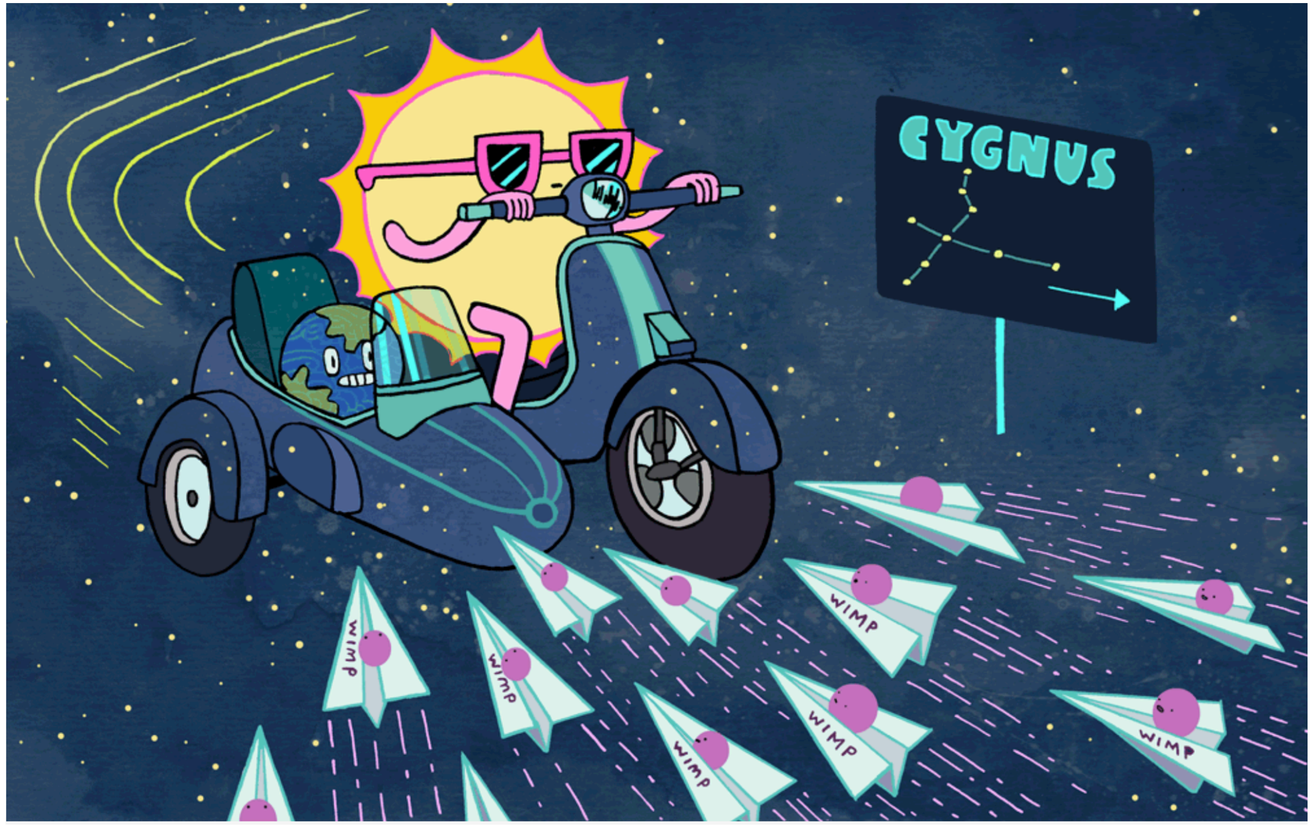
The **DM halo:**

- isothermal isotropic collisionless gas-like halo
- DM velocity $\sim$ Maxwell-Boltzmann distribution

Commonly adopted parameters:

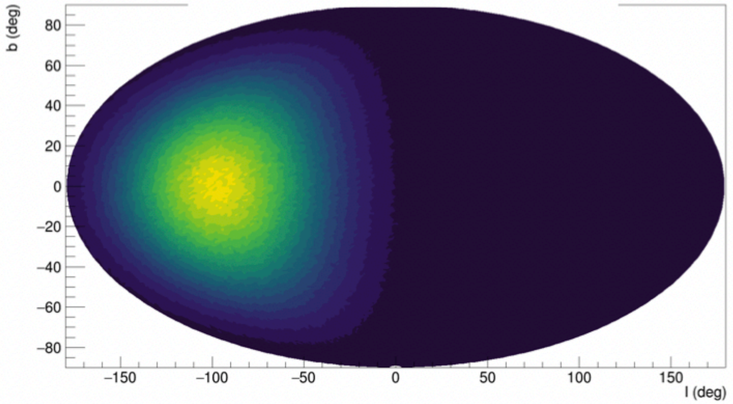
- local circular speed $v_c(R_\odot) = v_0 = 230\ \mathrm{km\ s^{-1}}$
- local escape speed $v_{esc}(R_\odot) = 544\ \mathrm{km\ s^{-1}}$
- local DM density $\rho(R_\odot) = 0.3\ \mathrm{GeV cm^{-3} c^{-2}} \sim$ /

In our reference frame

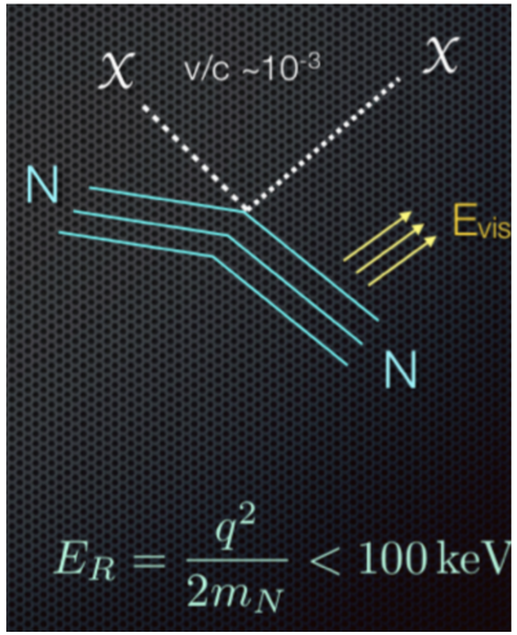


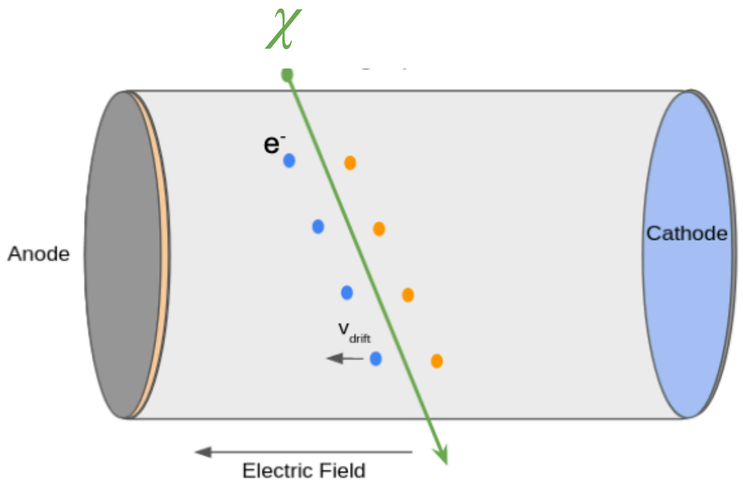
- Apparent **DM wind** coming from the direction of the Cygnus constellation

We would expect to observe the following angular distribution



Direct detection experiments





The energy can be released in the form of:

➡ **Ionization**

➡ **Scintillation**

➡ **Heat** (phonons)

DM-nucleus energy spectrum is ~ exponentially decreasing:

$$\frac{dR}{dE_R} \sim \frac{R_0}{E_0}\exp\left[-\frac{E_R}{E_0}\right]$$

diff. rate

total rate

recoil energy

a constant given by the kinematics

Main backgrounds

Cosmic rays or external radioactivity

↓

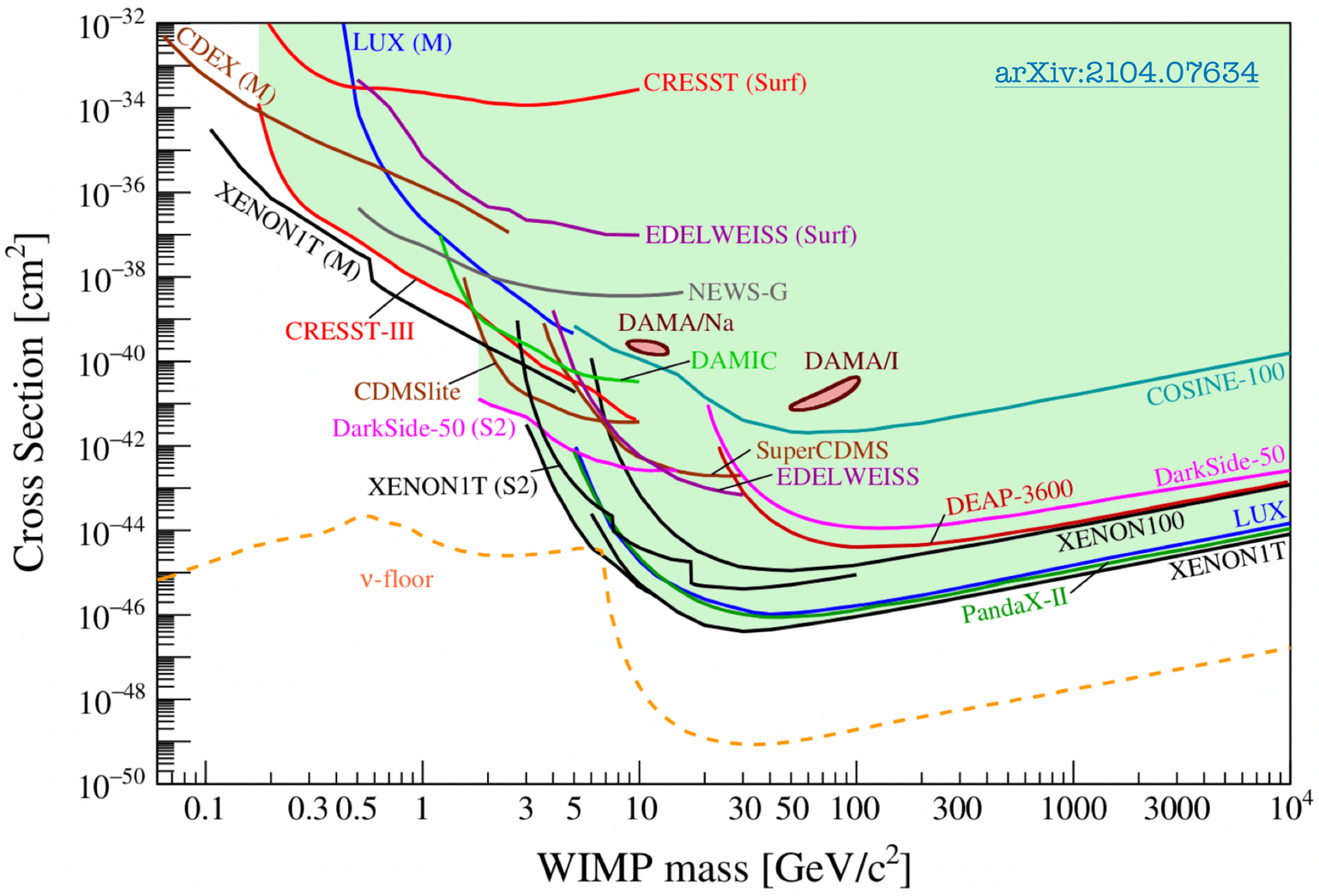
Put the detector **underground**

Internal radioactivity of the detector materials

↓

Use **radiopure** materials

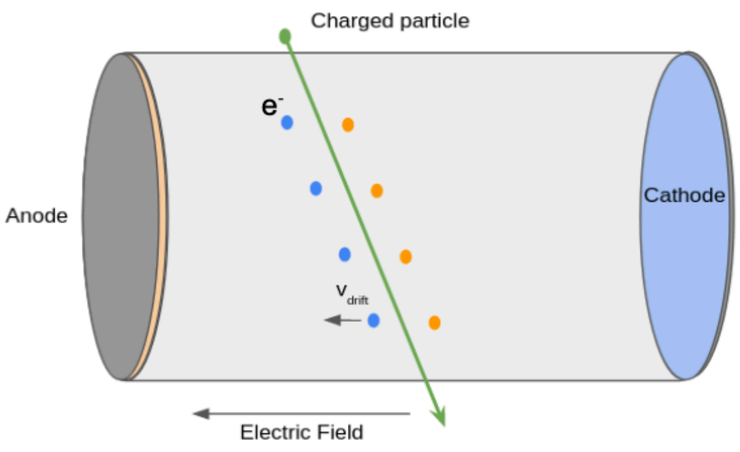
Direct detection experiments

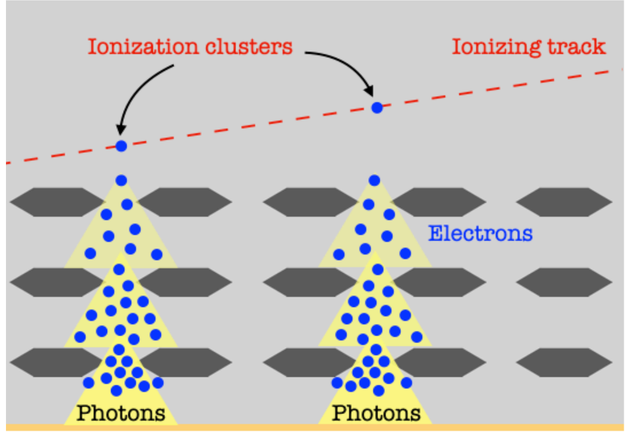


- The majority of these experiment measures **only the energy**
- Intrinsic limitation: the coherent neutrino scattering background (**neutrino fog**)
- **Energy + direction** of the recoils:
  - ➡ venturing the neutrino fog
  - ➡ in case of evidence, get the direction of the astrophysical source

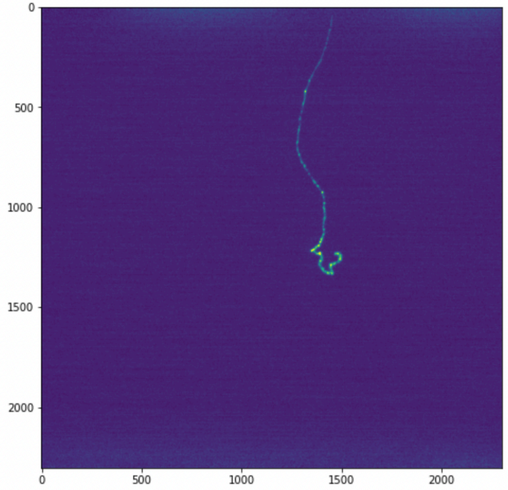
The CYGNO project

- **Aiming at** a large detector for high precision **3D tracking of rare low energy nuclear recoils (keV)** as for example WIMPs.
- **Experimental challenges:** rate O(evt/kg/day), background rejection, and energy threshold (keV)
- **Strategy: photograph nuclear recoil** in a (1 atm) He:CF_4 TPC with a GEM amplification stage
  - 3D tracking: position and direction
  - total released energy, dE/dx (head/tail)
  - **optical sensors:** high granularity, very low noise, and high sensitivity





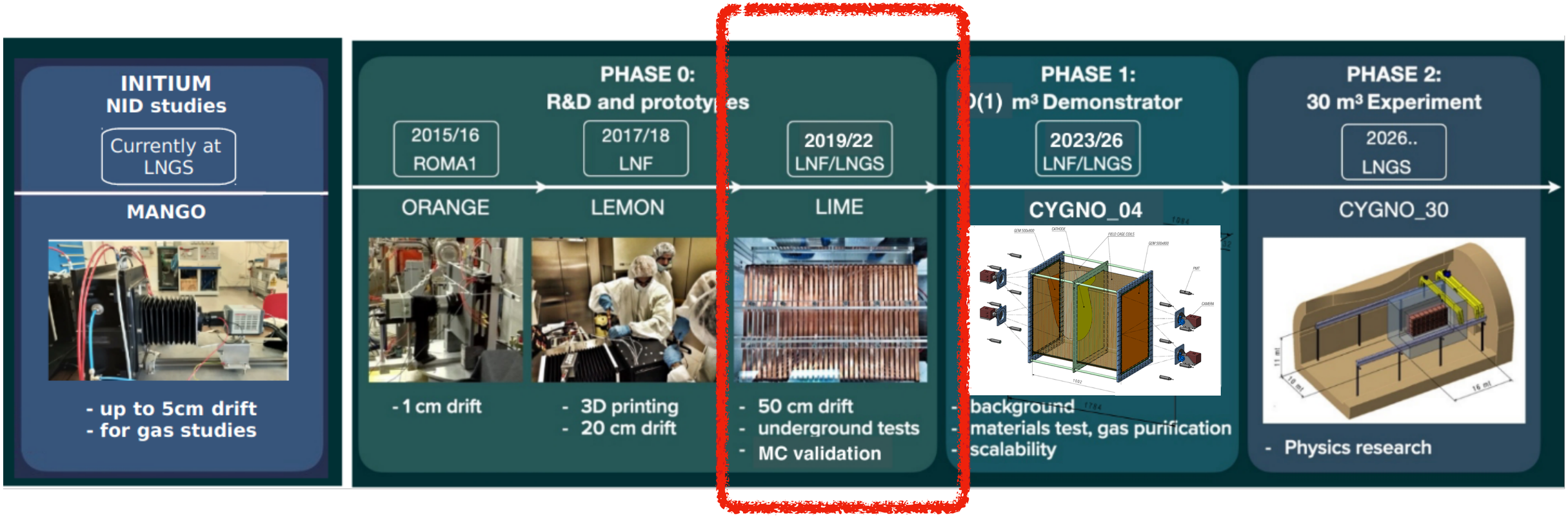
Picture collected by LIME underground



sCMOS camera [Hamamatsu Orca-Fusion]

PMTs [Hamamatsu R7378]

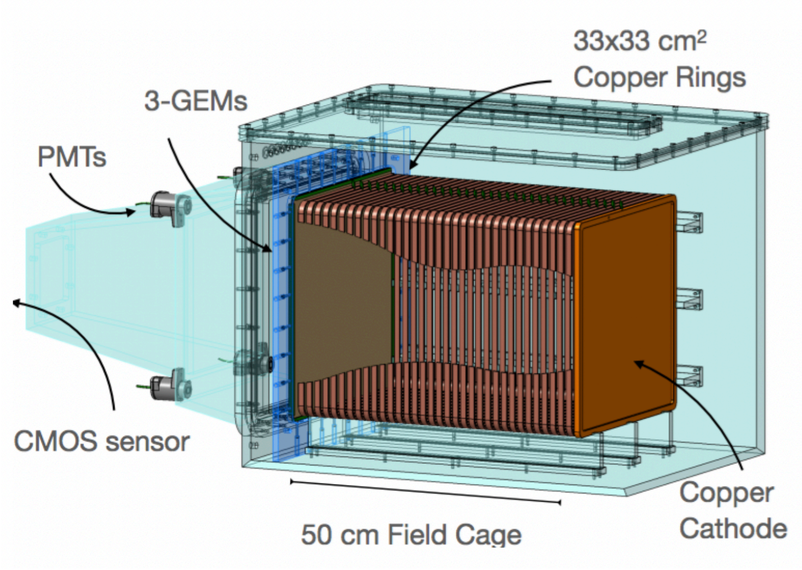
The CYGNO timeline

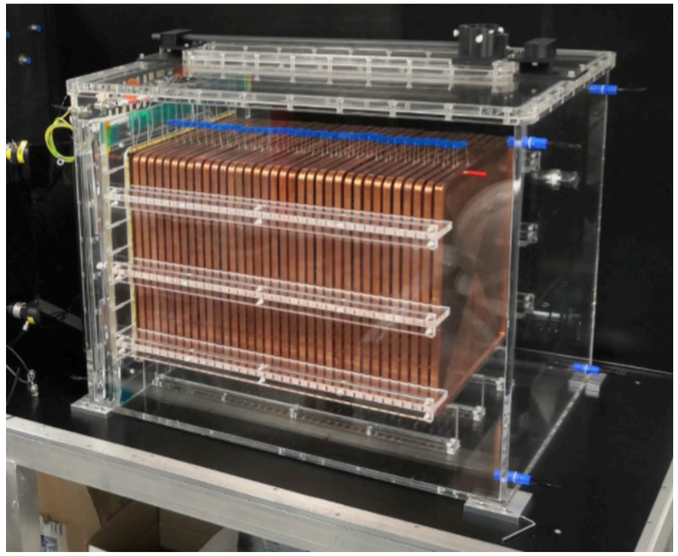


Instruments 6 (2022) 1, 6
JINST 15 (2020) 12, T12003
JINST 15 (2020) P08018
Measur.Sci.Tech. 32 (2021) 2, 025902

JINST 15 (2020) P10001
2019 JINST 14 P07011
NIM A 999 (2021) 165209

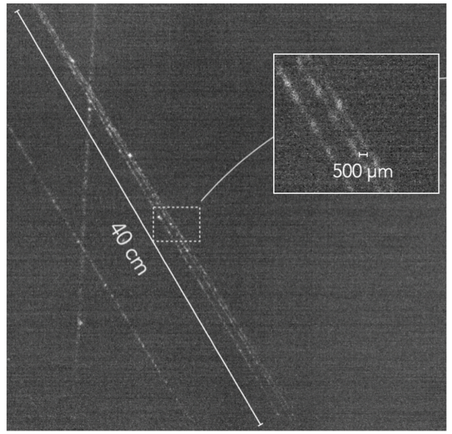
CYGNO PHASE 0: the LIME prototype



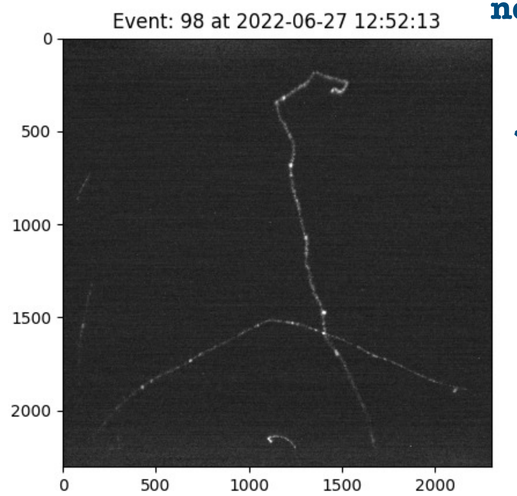


- $He:CF_4$ @ 1 atm
- Copper ring field cage, 50 cm drift
- 1 sCMOS sensor + 4 PMT
- 3 GEMs for a 33 x 33 cm^2 sensitive area

Cosmic rays (overground, no shielding)



Natural radioactivity (underground, no shielding)

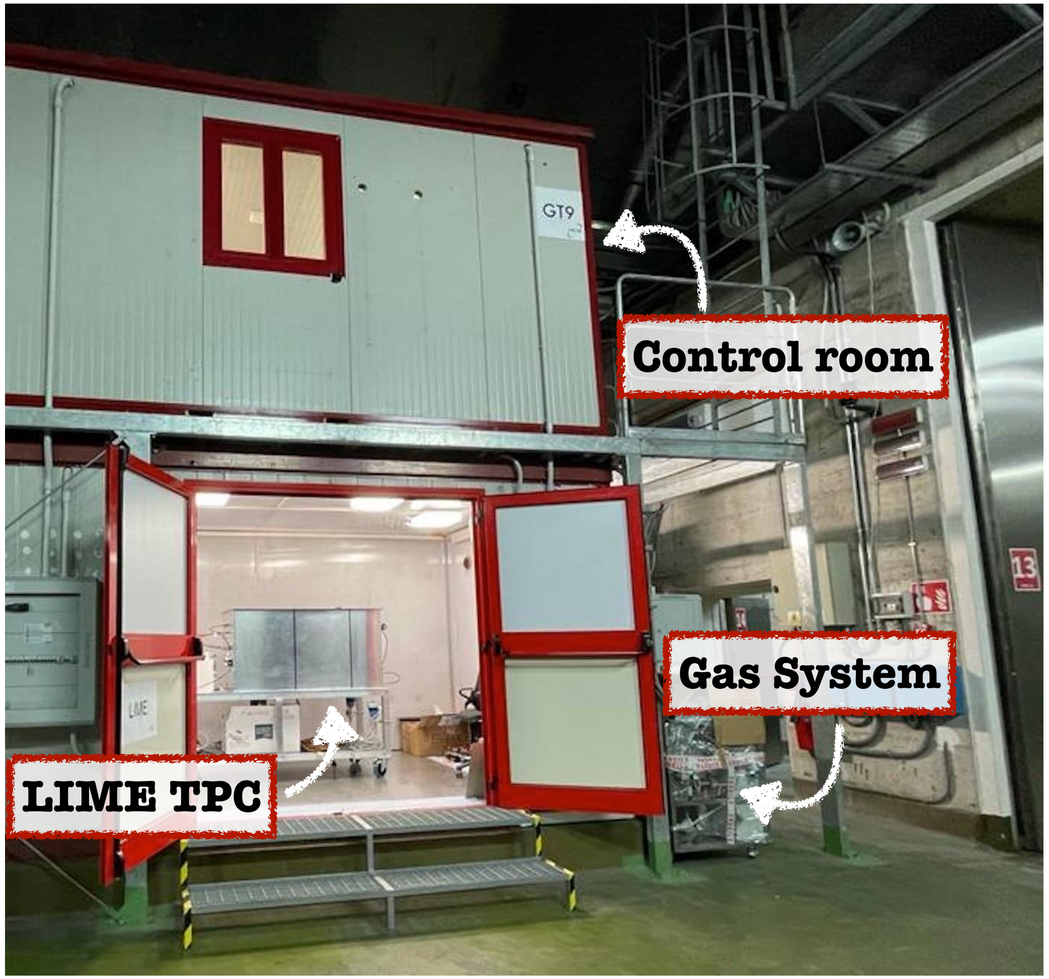


Underground installation

- The LIME prototype has been preliminarily assembled and **tested overground** at Laboratori Nazionali di Frascati (**LNF**)
- **Moved underground** at Laboratori Nazionali del Gran Sasso (**LNGS**) the beginning of 2022

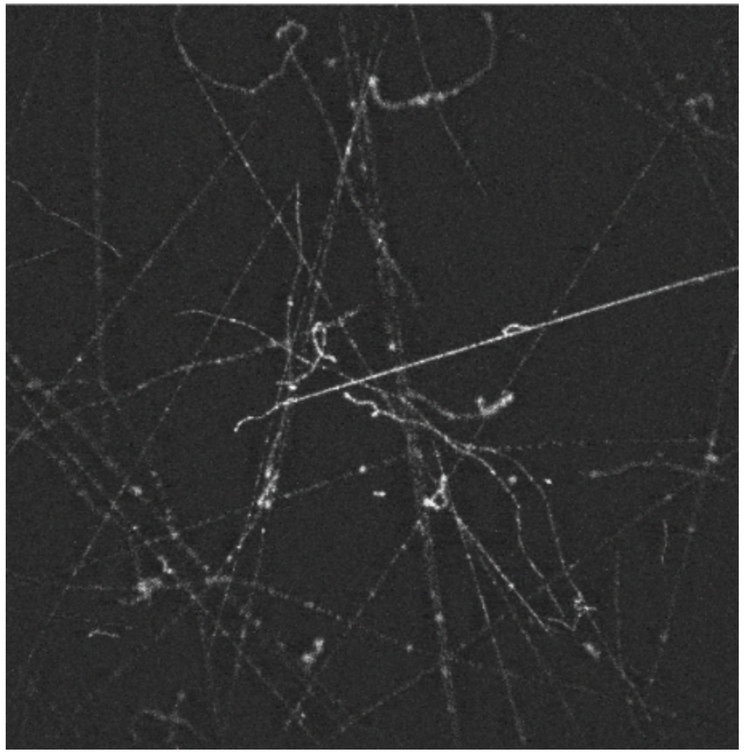
The TPC inside the Faraday cage

HV and DAQ crate

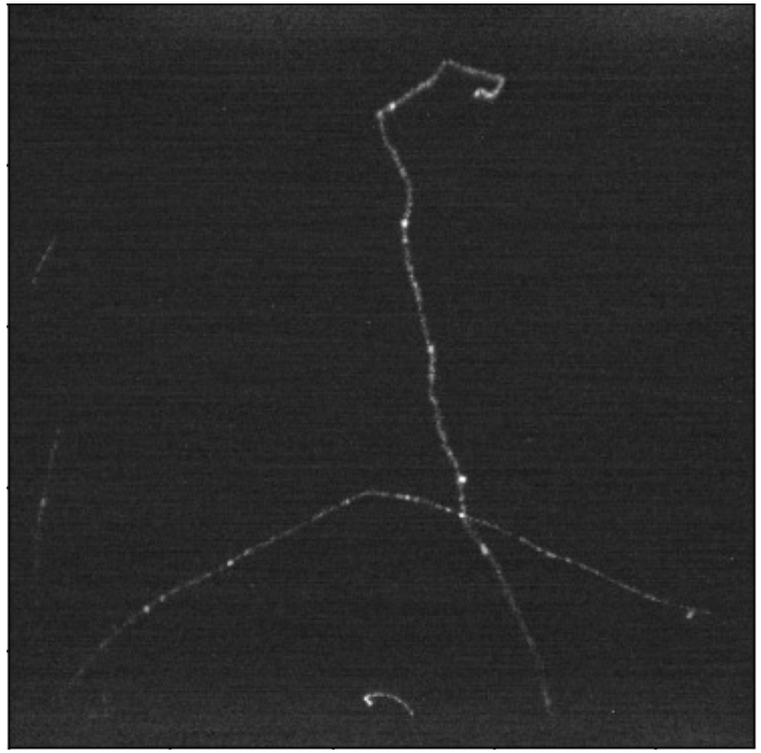


Overground vs underground pictures

Overground @ LNF



Underground @ LNGS

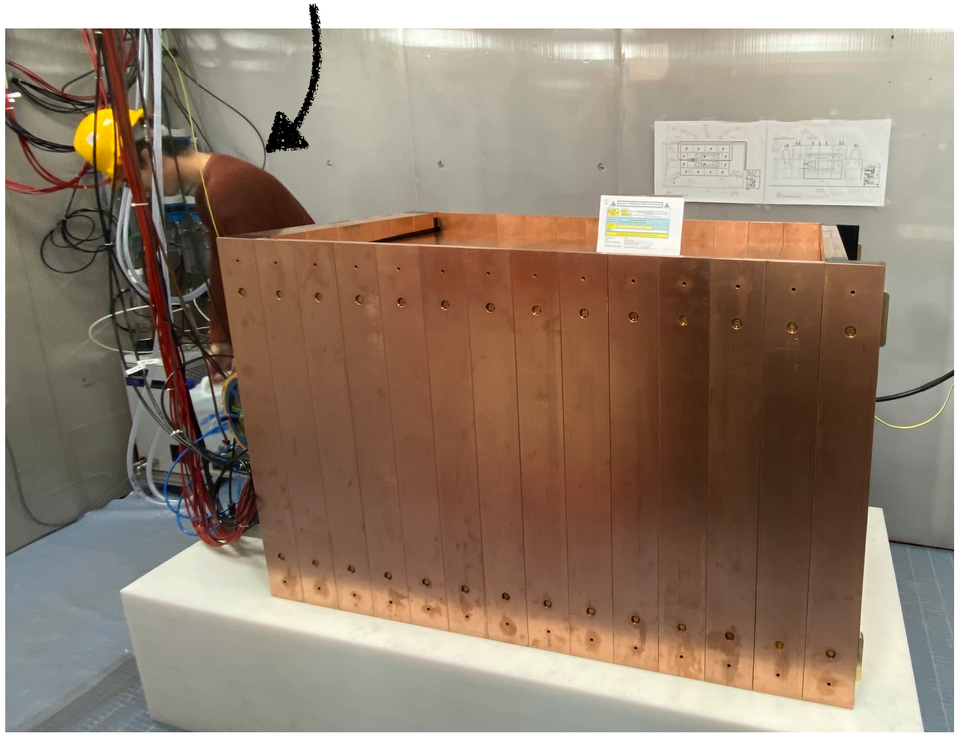


- **LIME is currently collecting its data** underground @ LNGS

- In parallel, a clone of LIME, called **LIME2**, has been installed at **LNF** for additional tests and R&D activities

The 4 cm copper shield

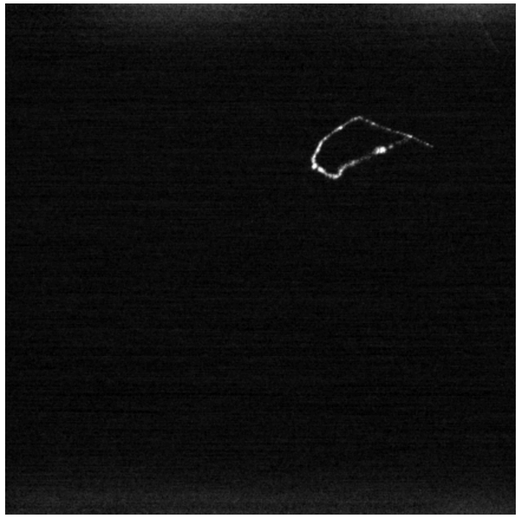
(Me, throwing gasoline on the experiment 😈)



- Observed event rate:
  - without shielding: ~ 34 Hz
  - with 4 cm Cu shielding: ~ 4 Hz

Without shielding:

4 cm Cu shielding:

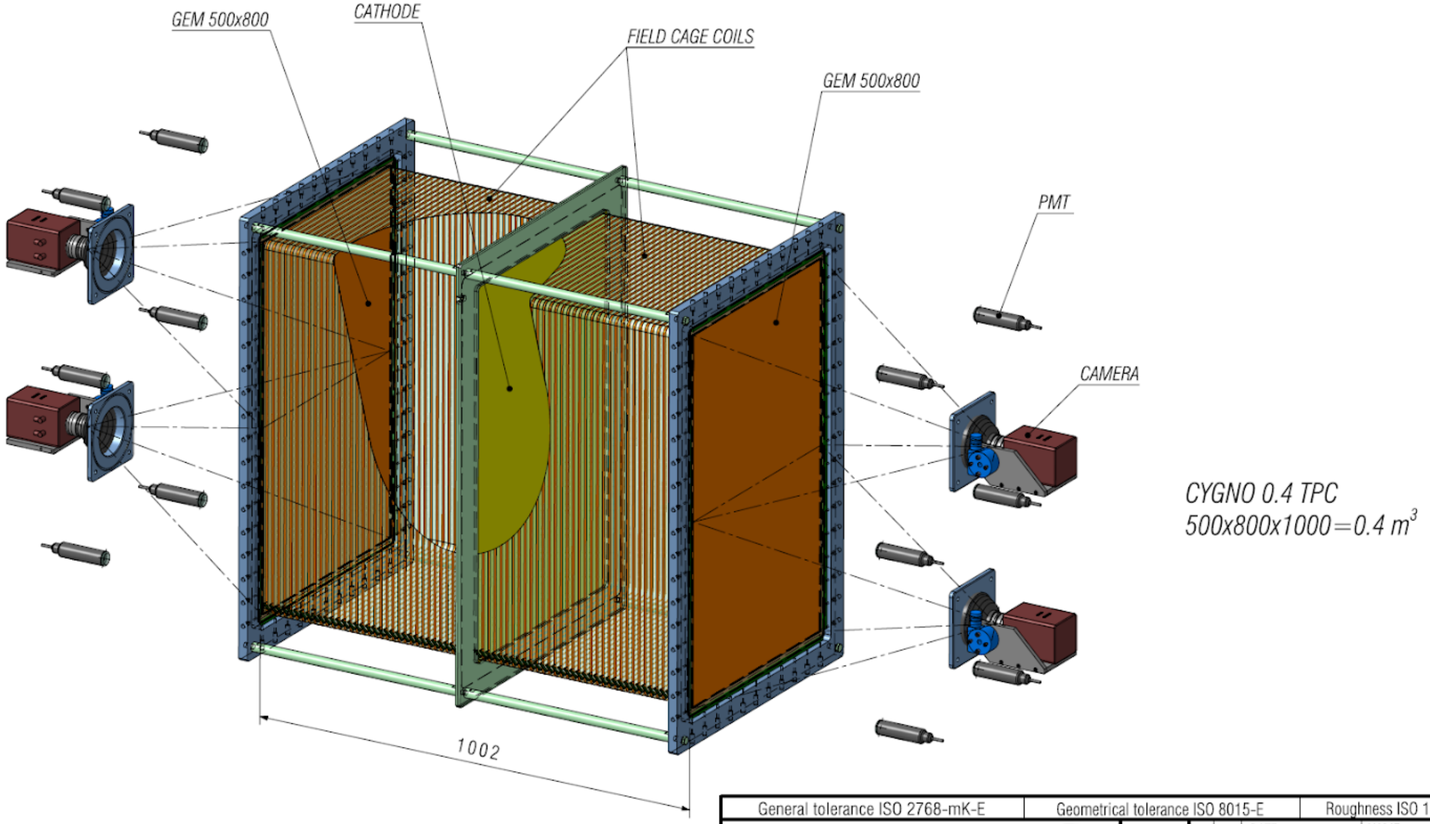


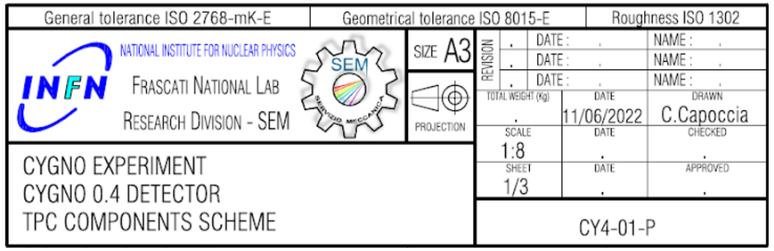
- Next steps:
  - ➡ 10 cm Cu shielding
  - ➡ 10 cm Cu + 40 cm water shielding

CYGNO PHASE 1: CYGNO_04

- **Preliminary design:**
  - TPC made of **2 chambers** with a **common cathode.**
  - Closed by 2 sets of **50 cm x 80 cm triple GEMs**
  - **Readout** of each GEM side: 2 cameras with rectangular sensors (ORCA Quest) + 6 PMTs
  - **Vessel:** low radioactivity PMMA
  - **Shielding:** 10 cm copper + 100 cm water with a polyethylene base

Designed at LNF and to be installed at LNGS

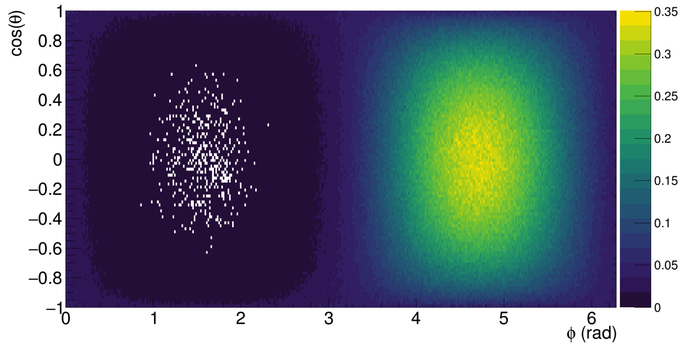




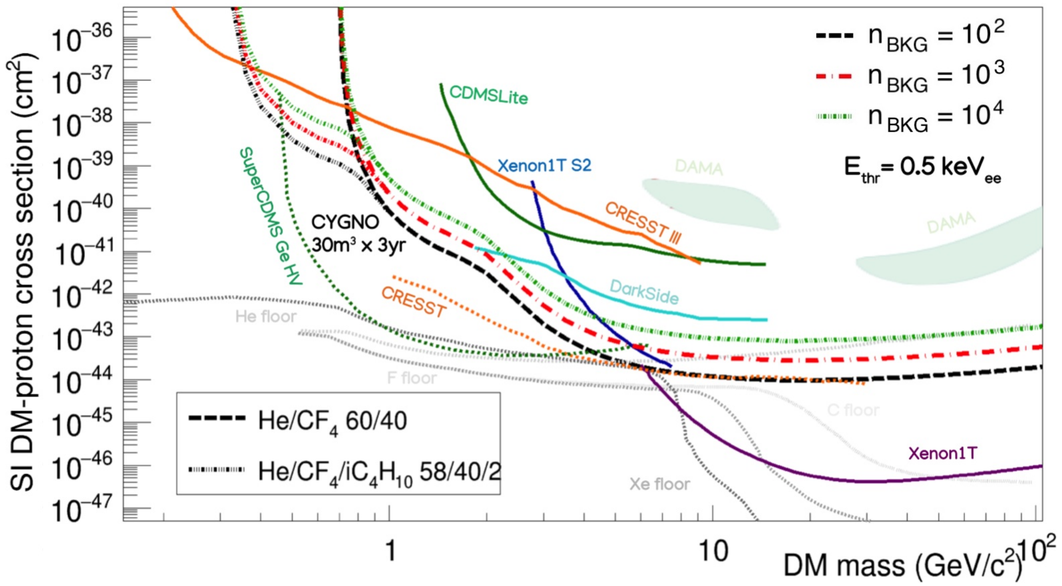
CYGNO PHASE 2: the 30 m^3 experiment for low mass DM searches

- $\mathcal{O}$(**30-100 m^3**) **detector** for directional dark matter (**DM**) **search** in the ~**GeV**/c^2 **mass region**.
- Preliminary sensitivity projections. **Assumptions**:
  - Low energy **threshold**: 1 keV (0.5 keV)
  - **Quenching Factor**: SRIM simulation
  - **Observable**: angular distribution
  - **Angular resolution**: 30°
  - **Background**: different scenarios (isotropic background)

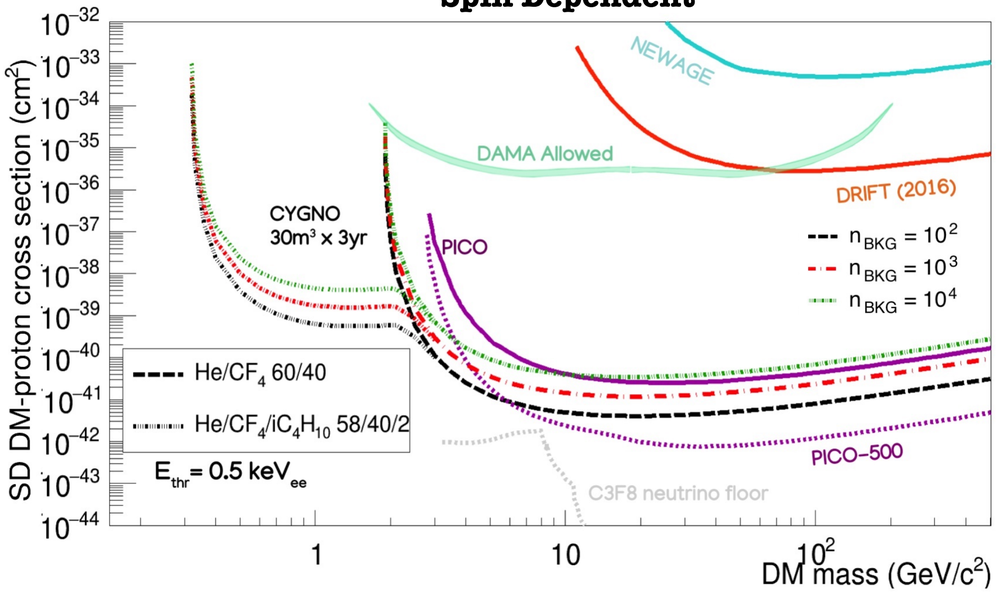
10 GeV/c^2 WIMP-like signal



Spin Independent



Spin Dependent



Conclusions

- The CYGNO collaboration is developing a **gaseous TPC with optical readout** for directional DM search.

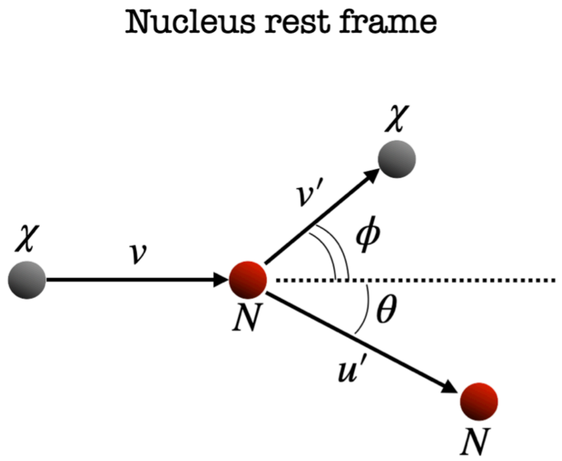
- An experiment with **good directional capabilities** would be crucial to confirm the origin of the astrophysical source in case of a signal, and to reject the irreducible coherent neutron background.

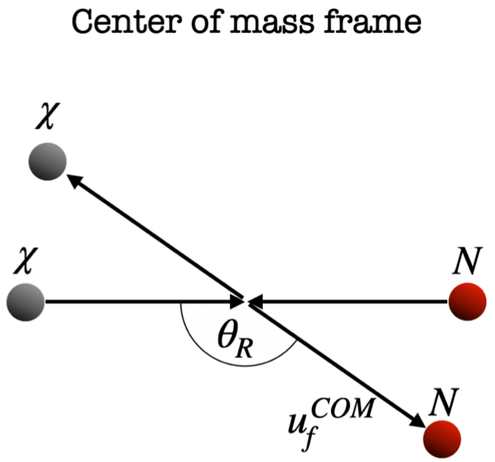
- **LIME**, a 50 L prototype, has recently been moved @ LNGS and is now taking data.

- **Other R&D activities:**
  - **Internal background reduction:** custom sCMOS sensor, custom lens
  - **Studies of the gas mixture:** addition of hydrogen-rich gas (CH_4), study of the light yield from hydrocarbons, possible eco-friendly gas mixture to substitute CF_4
  - **Negative ion drift:** negative ions with the addition of SF_6 for better fiducialization, 1 atm tests with encouraging results

Backup

Nuclear Recoil (NR) kinematics





$$v_{DM} \sim 10^{-3}c \qquad \mu = \frac{m_{DM} m_N}{m_{DM} + m_N}$$

$$K^0_{DM} = \frac{1}{2} m_{DM} v^2_{DM} \sim 5\ \text{keV} \left(\frac{m_{DM}}{10\ \text{GeV/c}^2} \right)$$

$$v_N \sim \sqrt{\frac{2k_B T}{m_N}} \sim 10^{-6}c \qquad \Rightarrow \qquad \text{Nucleus} \sim \text{at rest in the lab frame}$$

$$E_R = \frac{\mu^2}{m_N} v^2_{DM} \left(1 - \cos\theta_R\right)$$

$$E_R^{max} = 2\frac{\mu^2}{m_N} v^2_{DM} = r K^0_{DM} \qquad r = 4\frac{m_{DM} m_N}{\left(m_N + m_{DM}\right)^2}$$

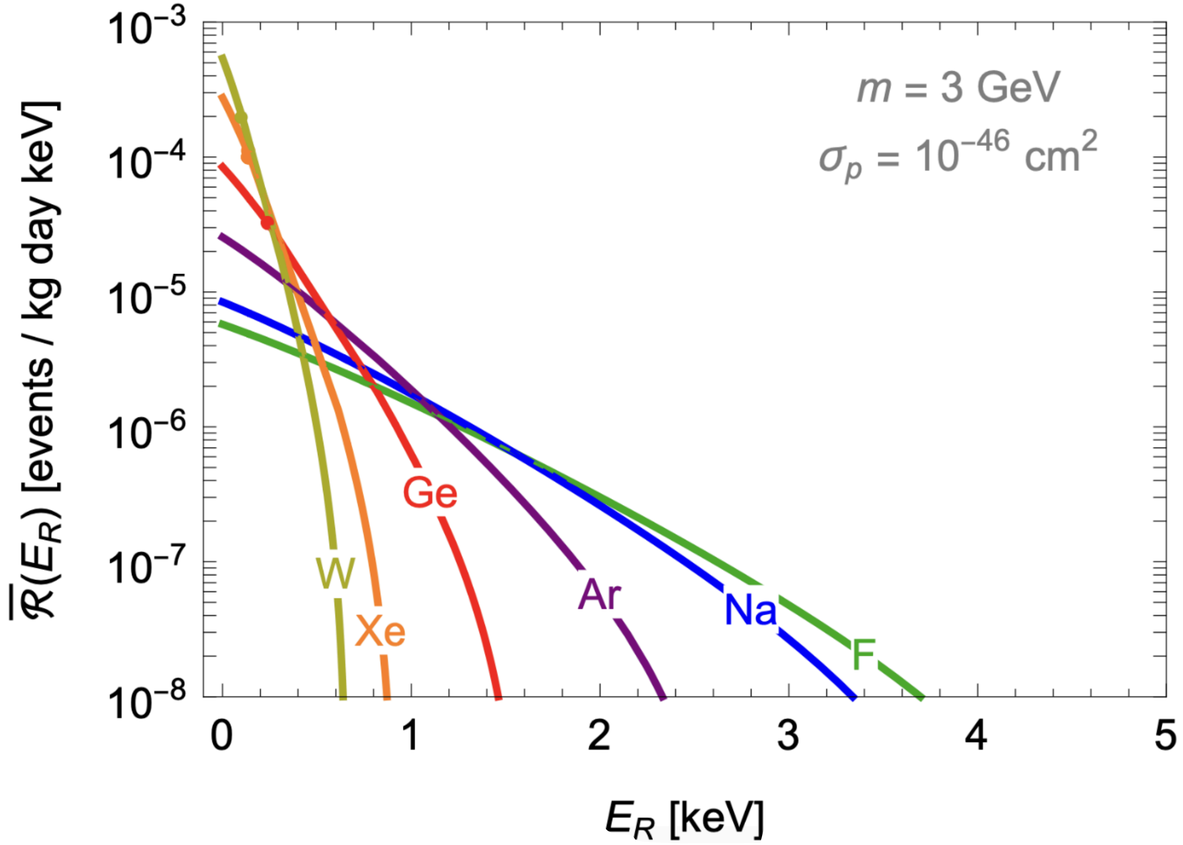
(Model independent)

NR rate

$$N = tnvN_T\sigma$$

$$\frac{\mathrm{d}N}{\mathrm{d}E_R} = tnN_T\int_{v_{min}(E_R)}^{v_{esc}} vf(\boldsymbol{v})\frac{\mathrm{d}\sigma}{\mathrm{d}E_R}\mathrm{d}\boldsymbol{v}$$

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = \frac{\rho_0}{m_{DM}m_N}\int_{v_{min}(E_R)}^{v_{esc}} vf(\boldsymbol{v})\frac{\mathrm{d}\sigma}{\mathrm{d}E_R}\mathrm{d}\boldsymbol{v}$$



arXiv:2104.12785 :

low momentum transfer $q^2 \sim 0$

~ 1

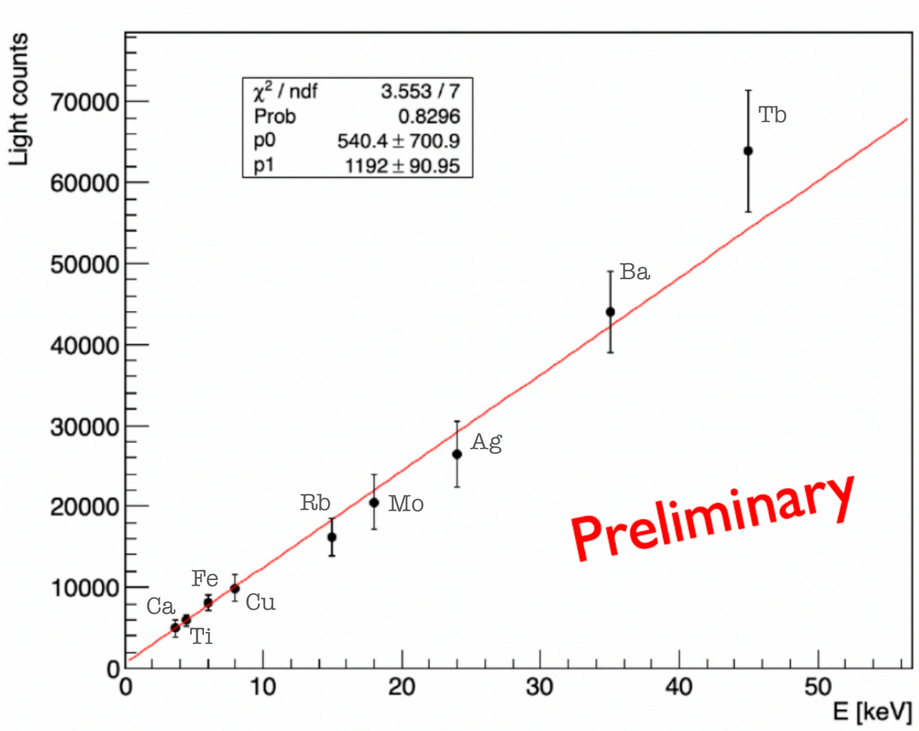
$$\frac{d\sigma}{dE_R} = \frac{m_N}{2\mu^2 v^2}\left[\sigma_0^{SI}F_{SI}^2(q^2) + \sigma_0^{SD}F_{SD}^2(q^2)\right]$$

$$\sigma_0^{SI} = \sigma_p\frac{\mu^2}{\mu_p^2}A^2 \qquad \sigma_0^{SD} = 0 \quad \text{in Ar}$$

SI = Spin Independent
SD = Spin Dependent

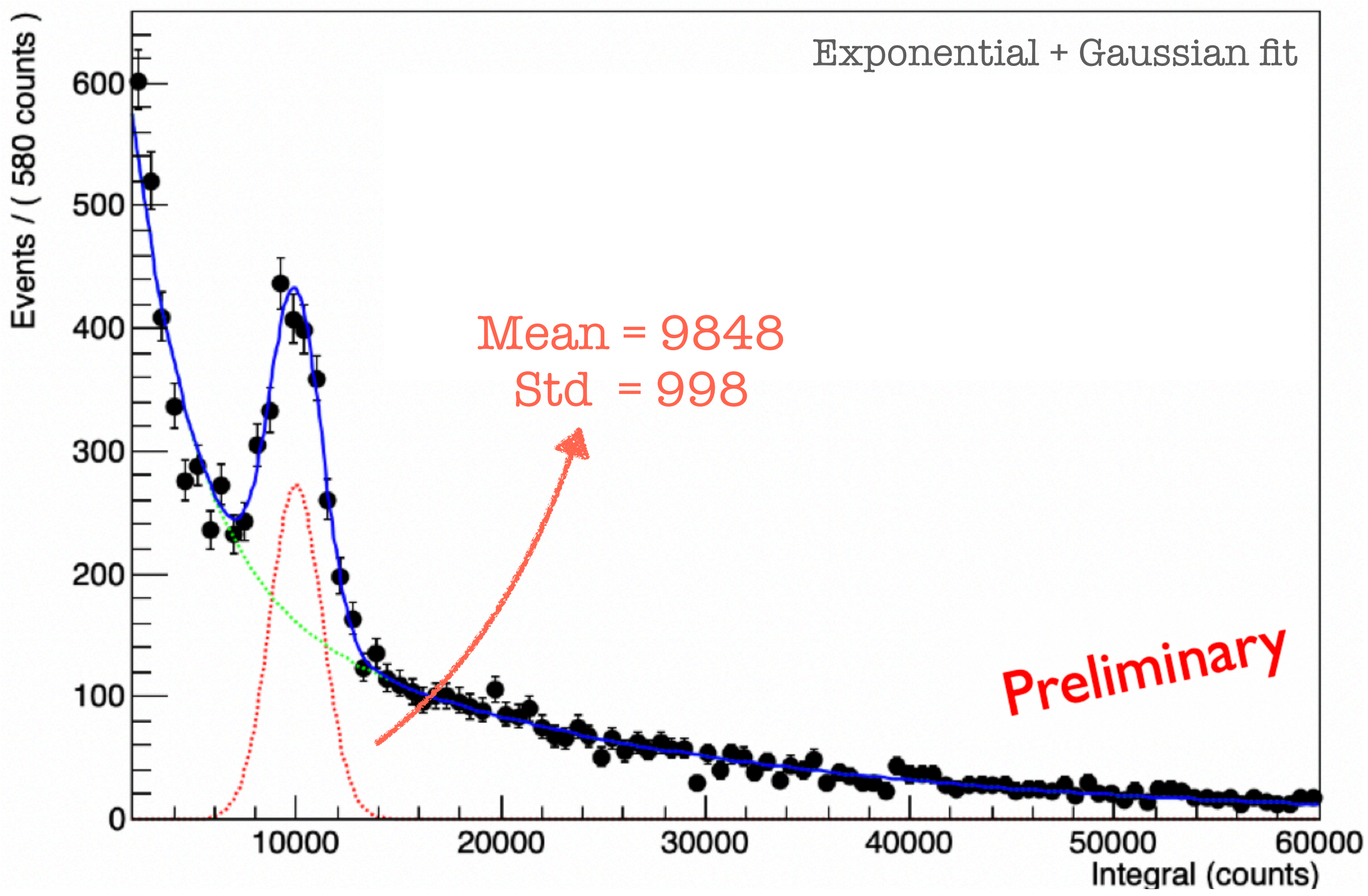
Overground tests: ER energy response

Electronic recoil (ER) calibration:



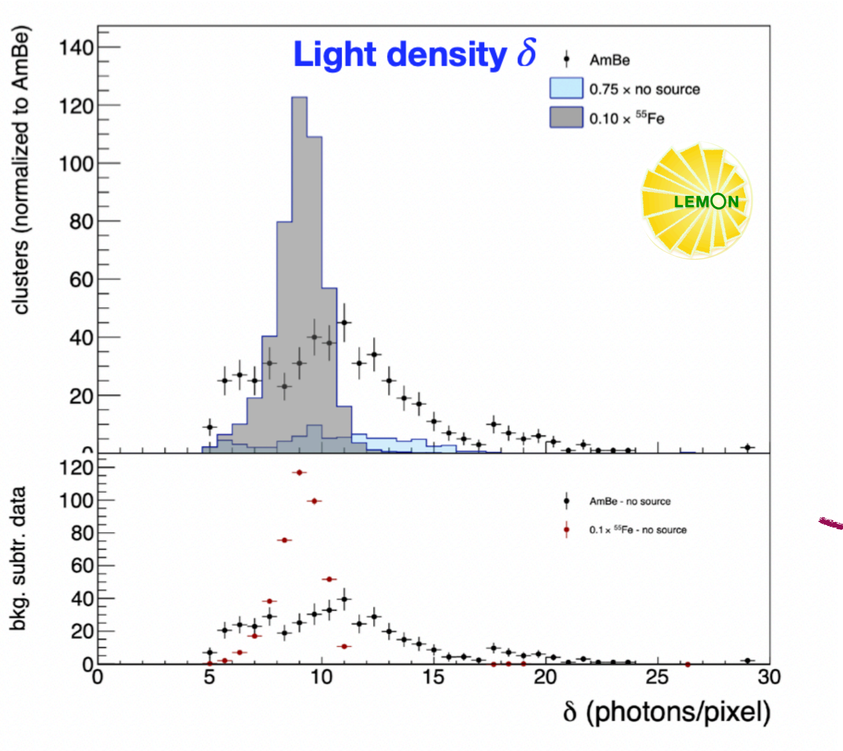
- ~ **13% energy resolution**
- **good linearity** in the response

Example: calibration with the 8 keV Cu X-rays

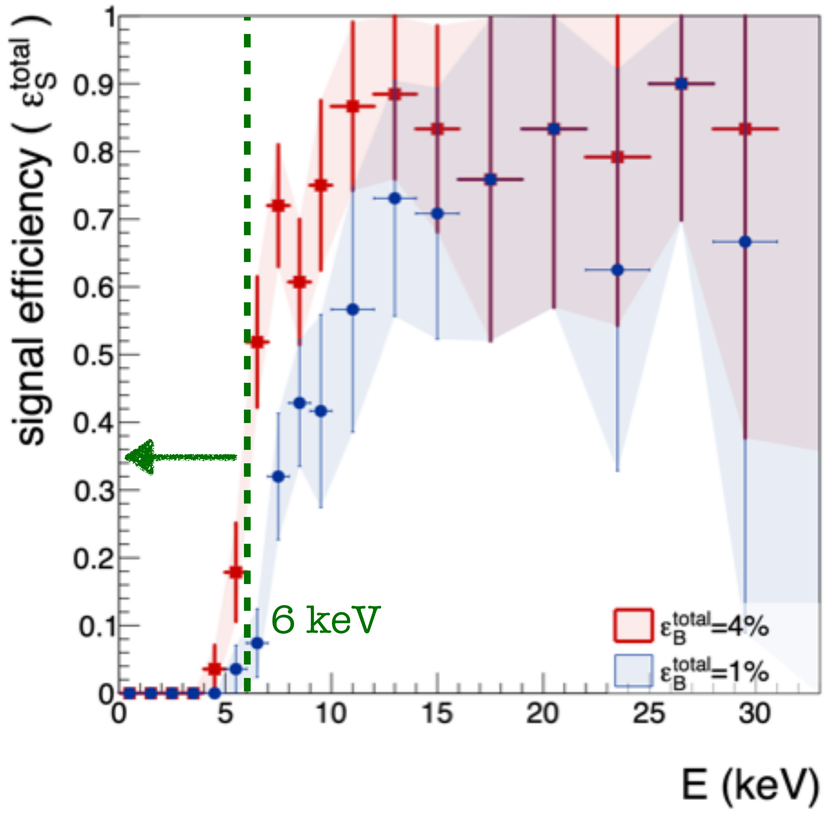


NR vs ER discrimination

- NR vs ER discrimination power: preliminarily assessed with the AmBe LEMOn campaign



A cut on δ

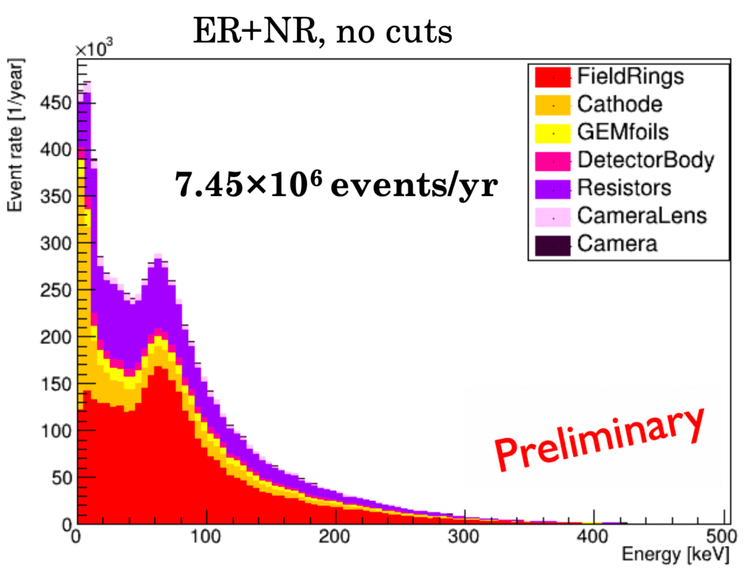


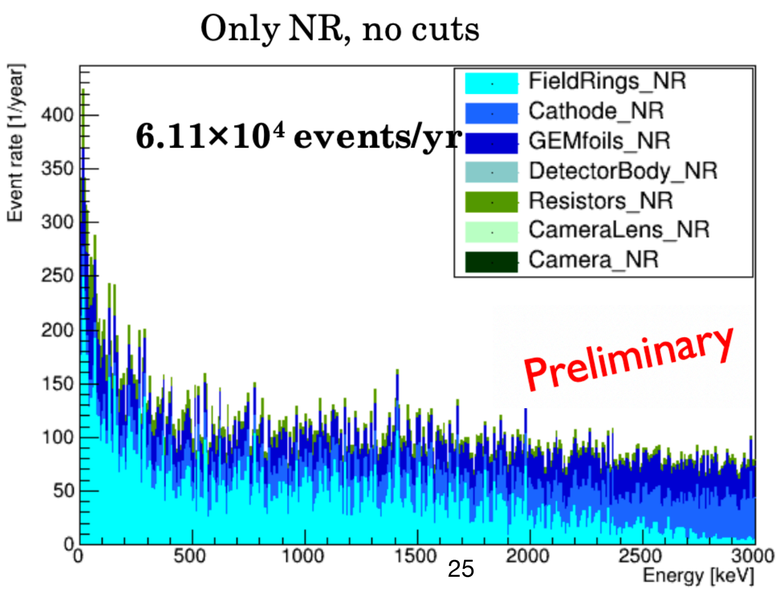
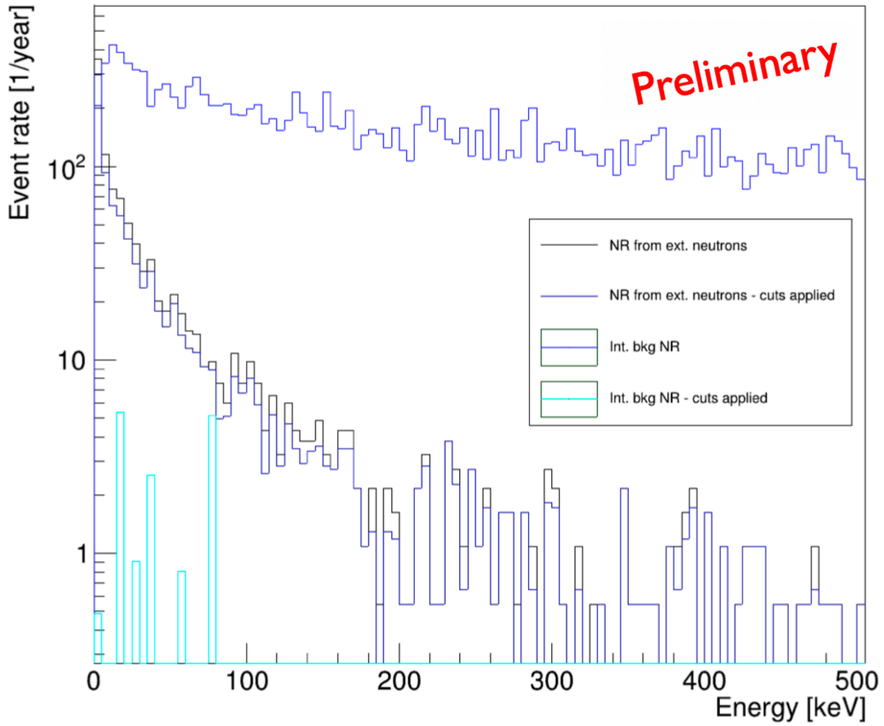
40% NR efficiency at 6 keV$_{ee}$ obtained with 96% rejection against ^{55}Fe

Background studies for LIME

- **Activity** of the **components**: **measured** @ LNGS
- Main contribution to the **internal backgrounds**: copper rings, resistors, GEM/cathode
- 96% (99%) reduction of ER (NR) events with **fiducial cuts**
- **Studies** about the **shielding** are **ongoing** (10 cm copper + 40 cm water for the underground campaign)

ER and NR internal background





Neutron external background