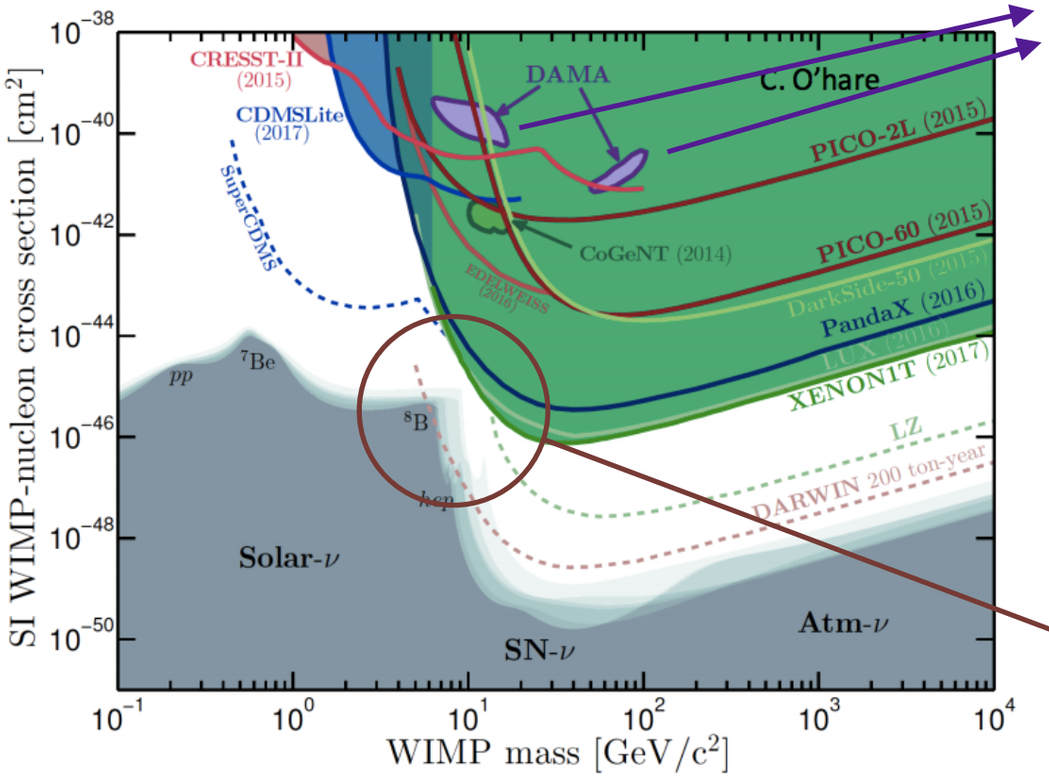
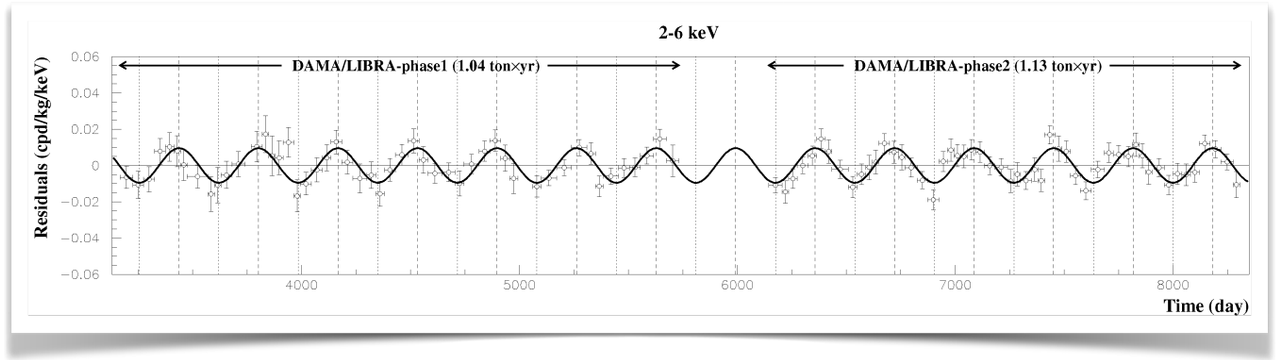
# Directional Dark Matter searches with the CYGNO experiment and the INITUM Project

Francesco Renga
INFN Roma

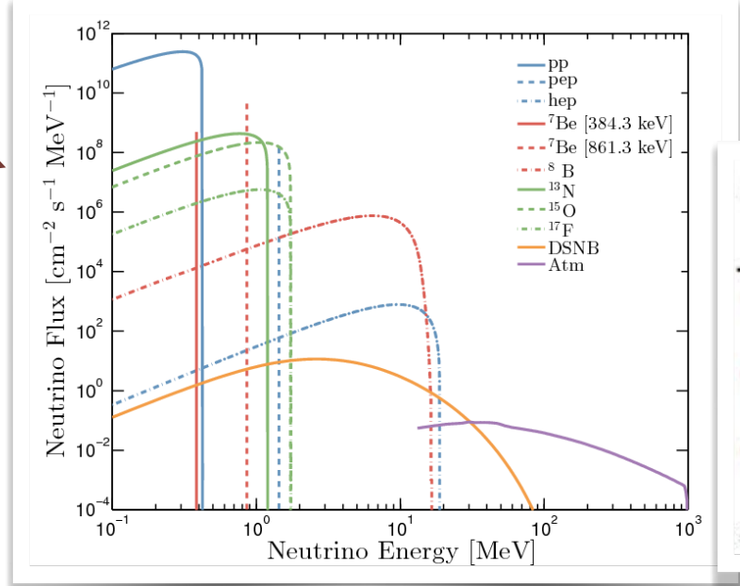
# Dark Matter searches

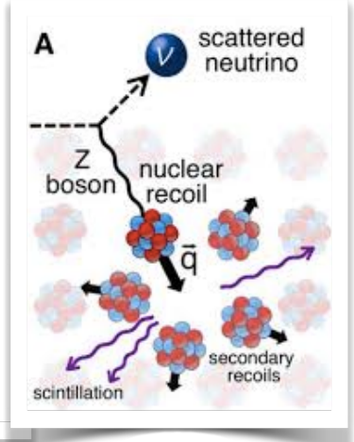
- Dark matter (DM) detectors in the GeV - TeV range exploit nuclear or electron recoils induced by DM scattering, either with or without background identification




**DAMA/LIBRA**
**Universe 4 (2018), no. 11, 116**



# Identifying a Dark Matter signal

- An **unambiguous evidence** for Dark Matter observation requires the identification of a peculiar feature

- **Discrimination** of dark matter **against coherent neutrino scattering** requires the identification of a peculiar feature

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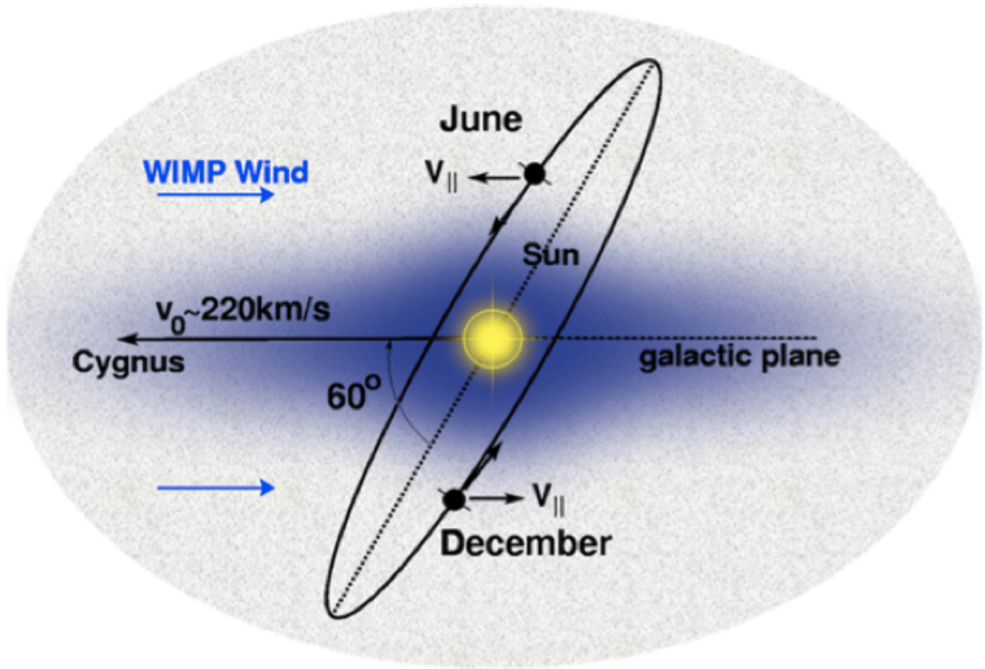


- **Discrimination** of dark matter **against coherent neutrino scattering** requires the identification of a peculiar feature

*Earth motion in the DM halo enhances the scattering rate for particles observed in the direction of the earth motion (Cygnus constellation)*

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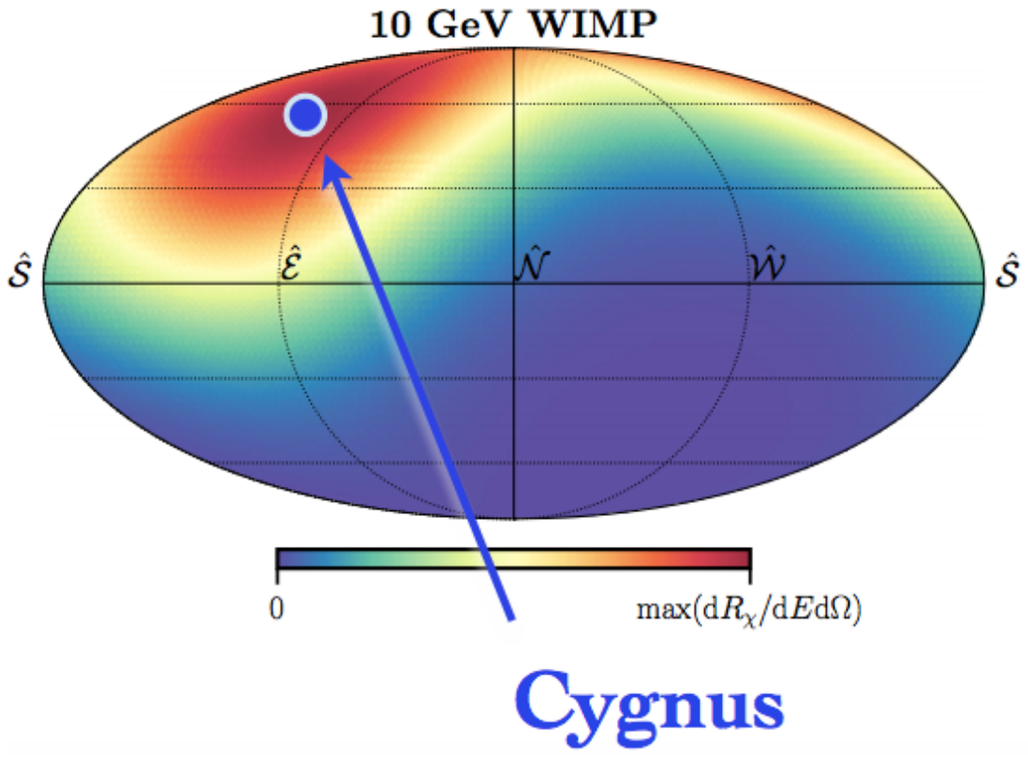


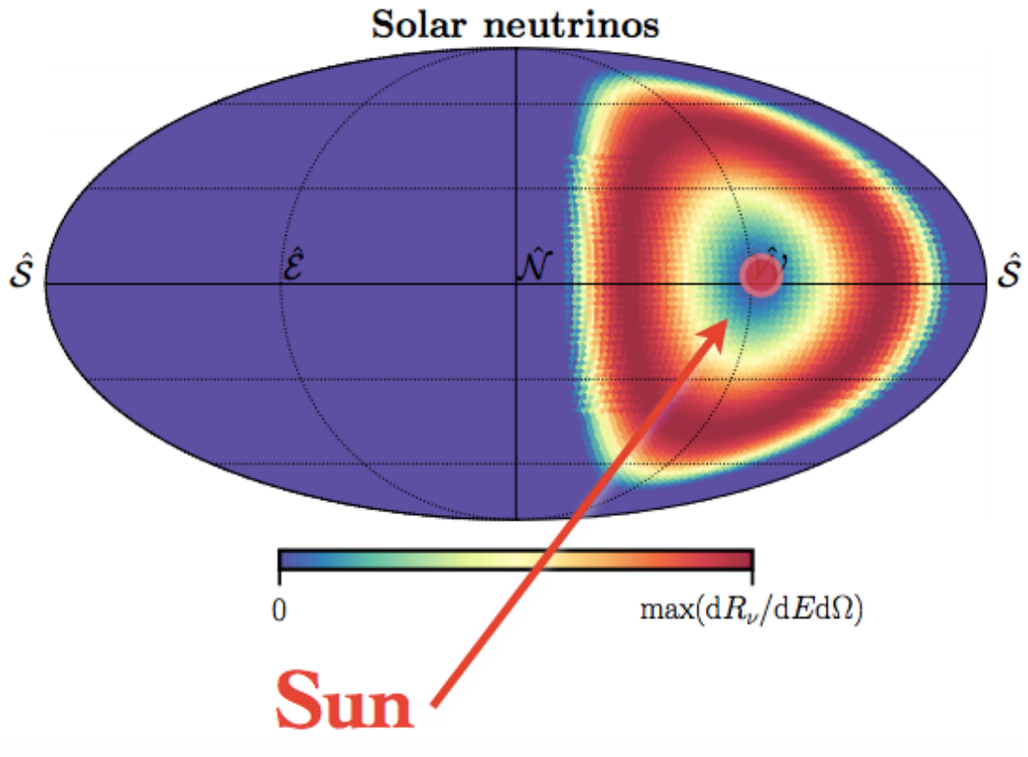


**C. O'Hare, CYGNUS2019**

*Expected rate of DM-induced recoils*

# Identifying a Dark Matter signal

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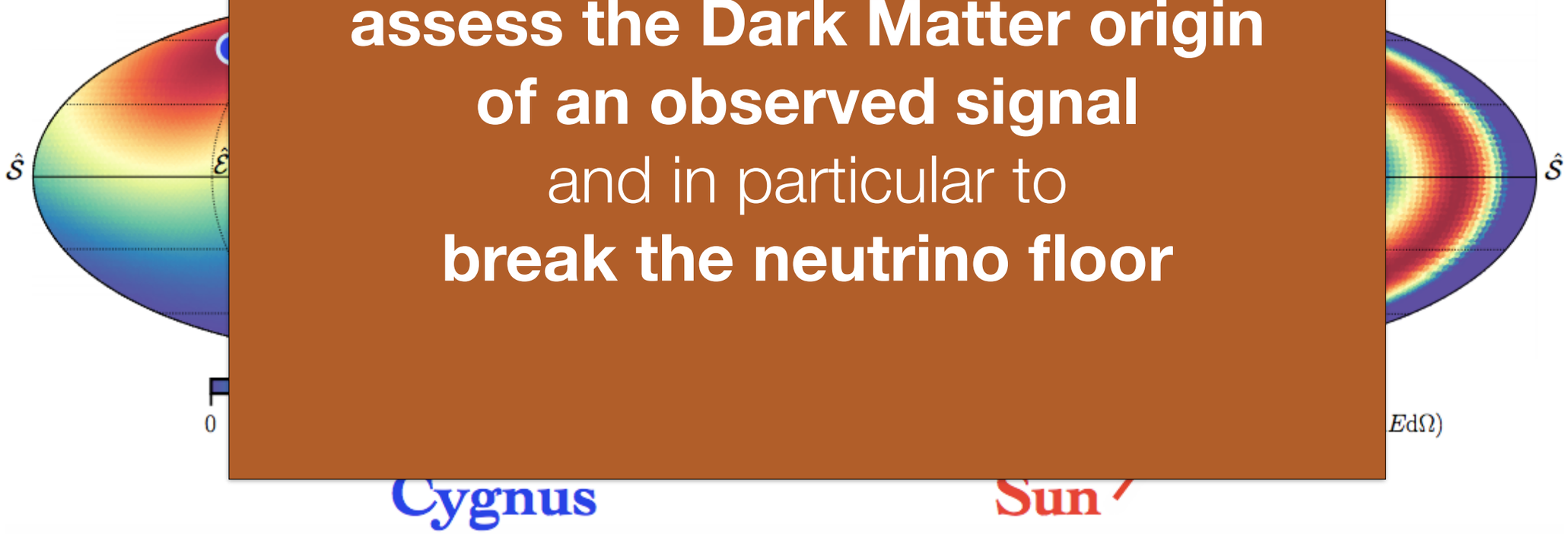
Directionality provides a unique tool to **assess the Dark Matter origin of an observed signal** and in particular to **break the neutrino floor**

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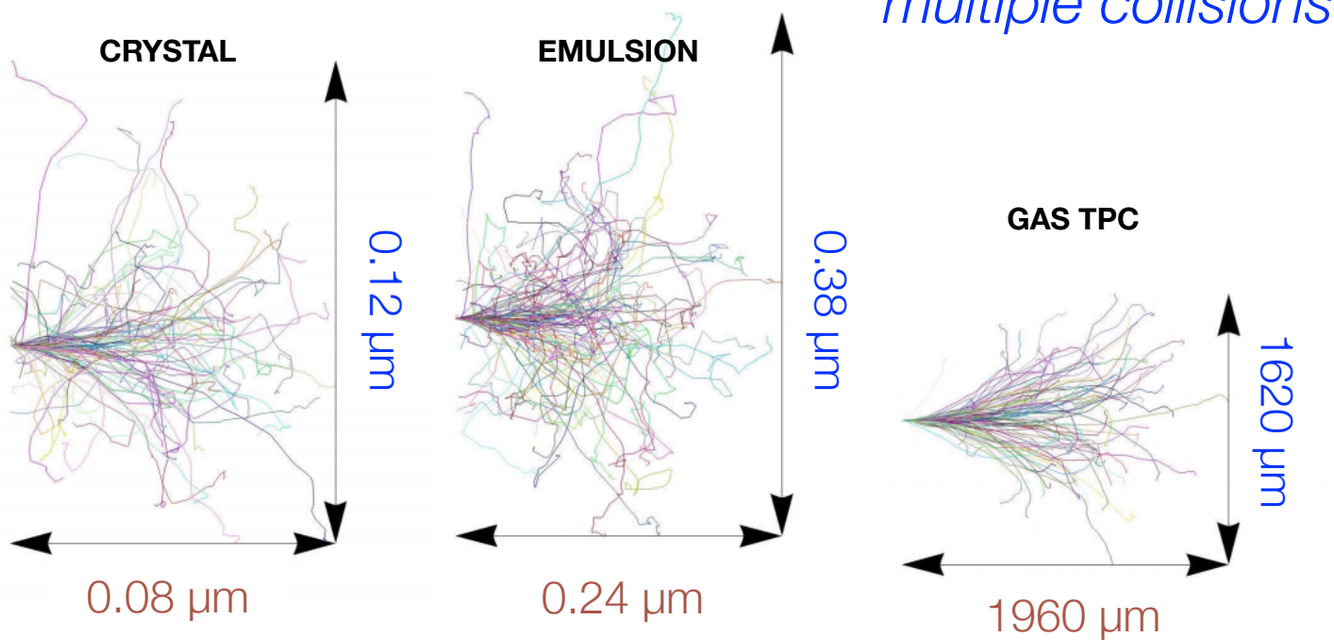
*Expected rate of DM-induced recoils*

# Experimental challenges of directional searches

**1 TeV WIMP, max. recoil energy**




*recoil direction information quickly deteriorated by multiple collisions*

*Very short tracks —> 3 options*
*1) high granularity*
*2) strong detector anisotropy*
*3) tiny statistical effects in isotropic (e.g. columnar recombination) or slightly anisotropic detectors*

# Experimental challenges of directional searches

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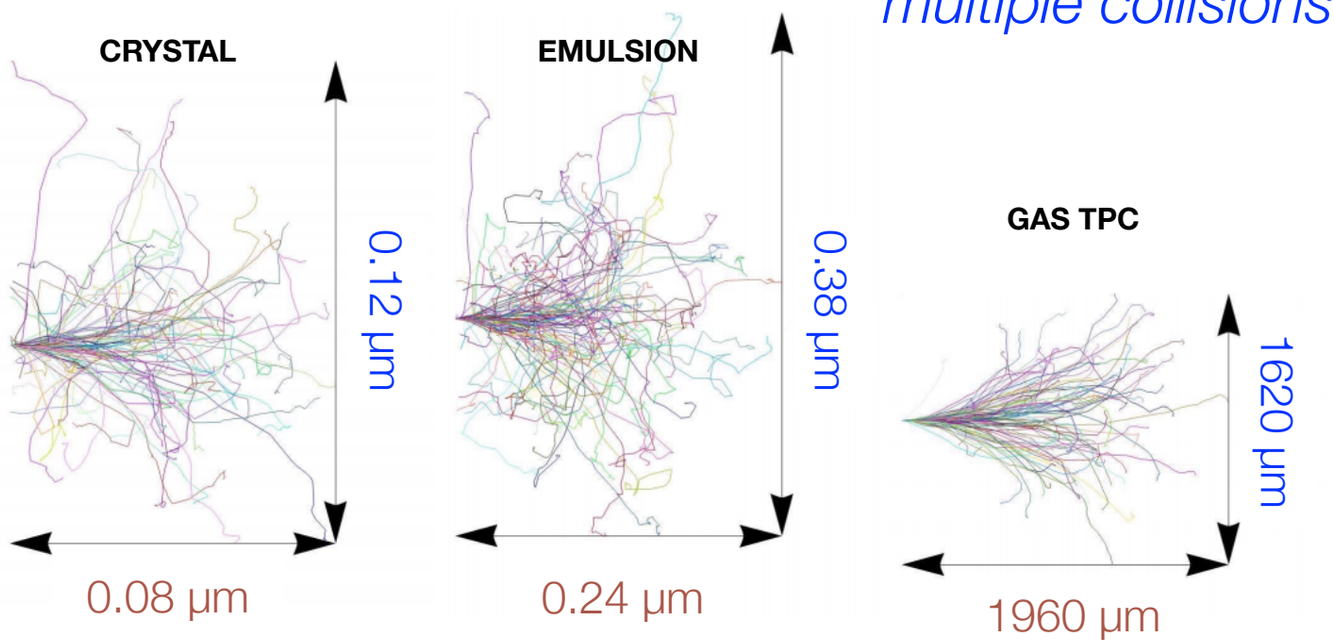
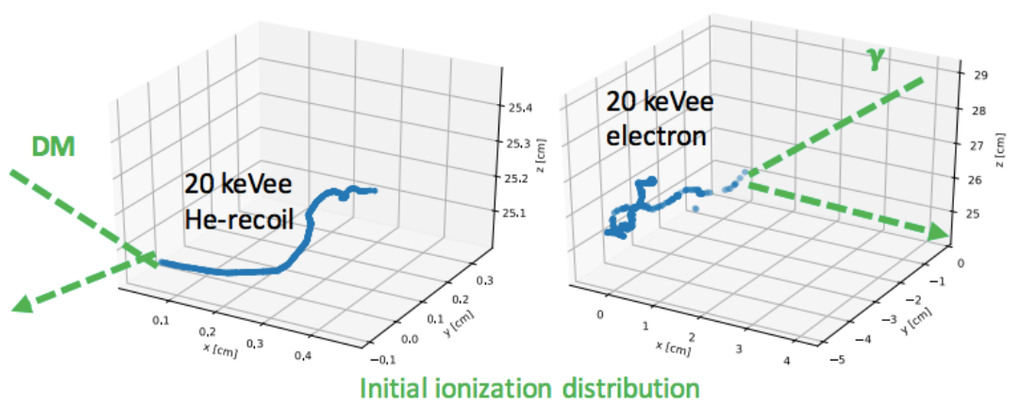
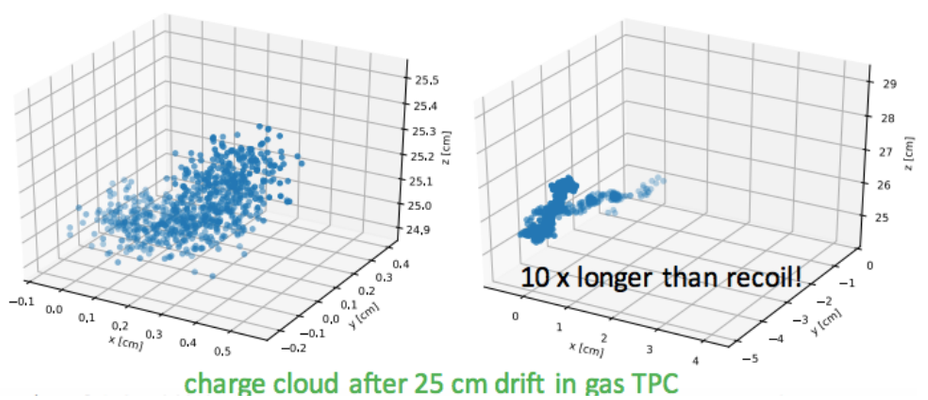



*recoil direction information quickly deteriorated by multiple collisions*

Gaseous TPC = low density
= O(mm) tracks
+
high granularity readout

**Direction can be reconstructed event-by-event**




*Very short tracks —> 3 options*

***1) high granularity***

*2) strong detector anisotropy*

*3) tiny statistical effects in isotropic (e.g. columnar recombination) or slightly anisotropic detectors*

# The CYGNO project

*ESSENTIAL BIBLIOGRAPHY*

F. D. Amaro *et al.*, *Instruments* 6 (2022) 1, 6

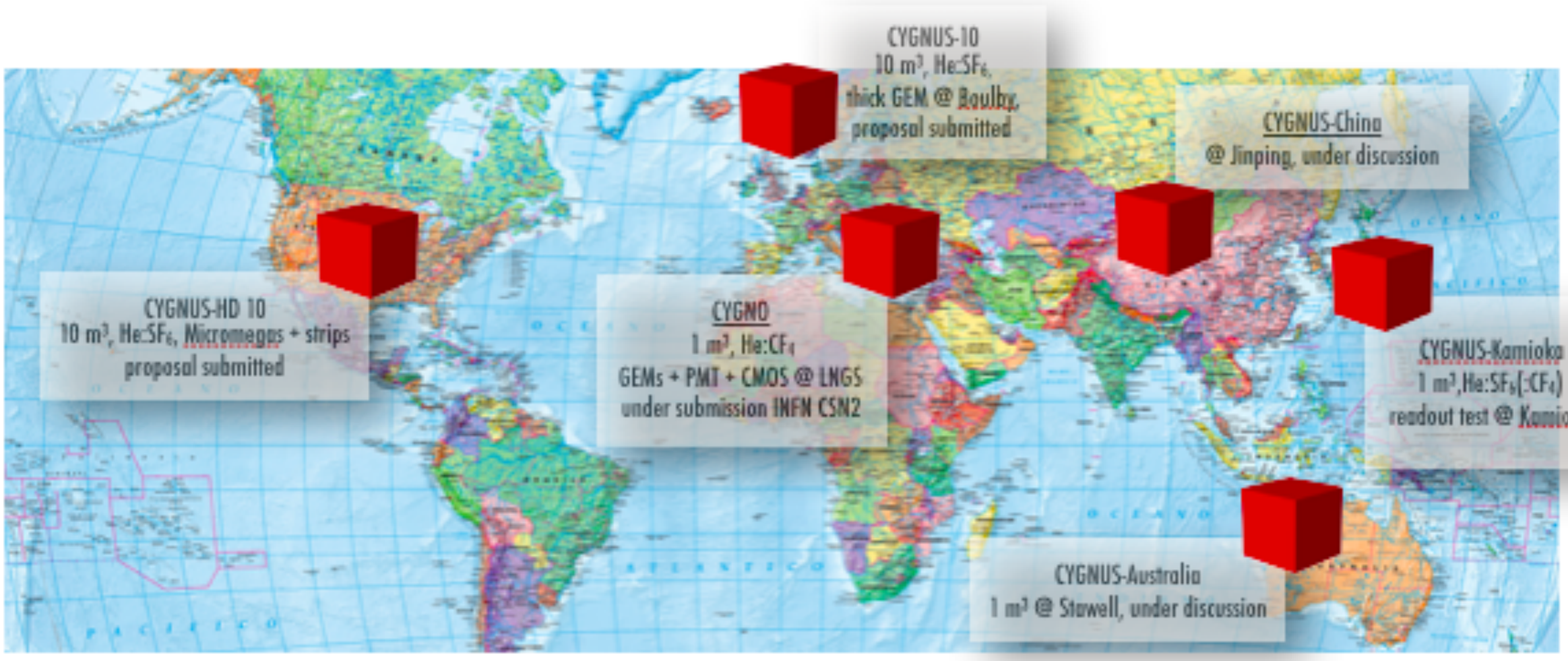
E. Baracchini *et al.*, *Measur.Sci.Tech.* 32 (2021) 2, 025902

E. Baracchini *et al.*, *JINST* 15 (2020) 10, P10001

V. C. Antiochi *et al., JINST* 13 (2018) 05, P05001

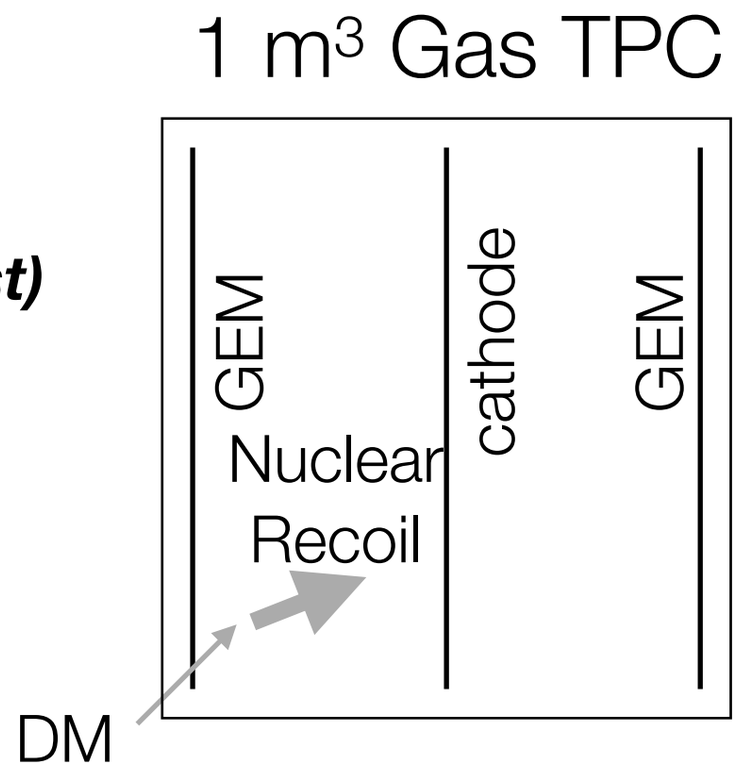
# A worldwide community

- The CYGNUS network connects several experimental efforts around the world for the search of dark matter with  gaseous directional detectors



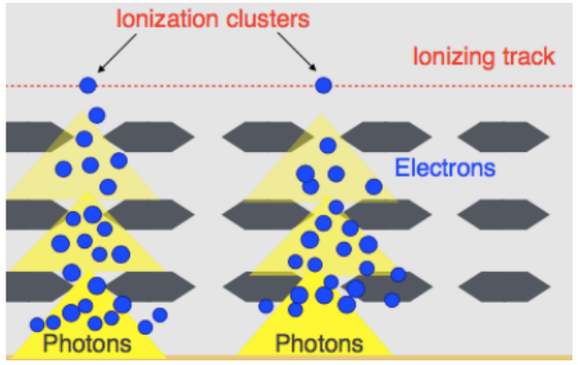
# The CYGNO project

- ***Helium-$CF_4$ gas mixture:***
  - Helium —> light, O(GeV) dark matter sensitivity
  - Fluorine —> Spin-dependent sensitivity
- ***GEM with double optical readout (high granularity + fast)***



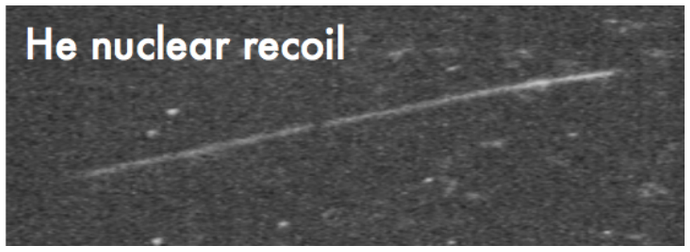

- To be installed at **Laboratori Nazionali del Gran Sasso**
- Synergy with **INITIUM ERC Grant** (E. Baracchini - negative ion drift with $He:CF_4:SF_6$):
  - reduce the electron diffusion
  - improve fiducialization

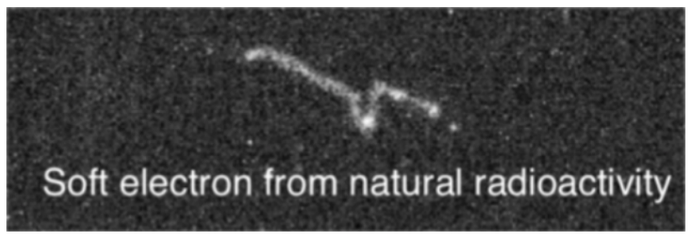
# Optical readout of GEMs




In He:$CF_4$ mixtures (typ. 60:40), scintillation light is produced in the avalanche

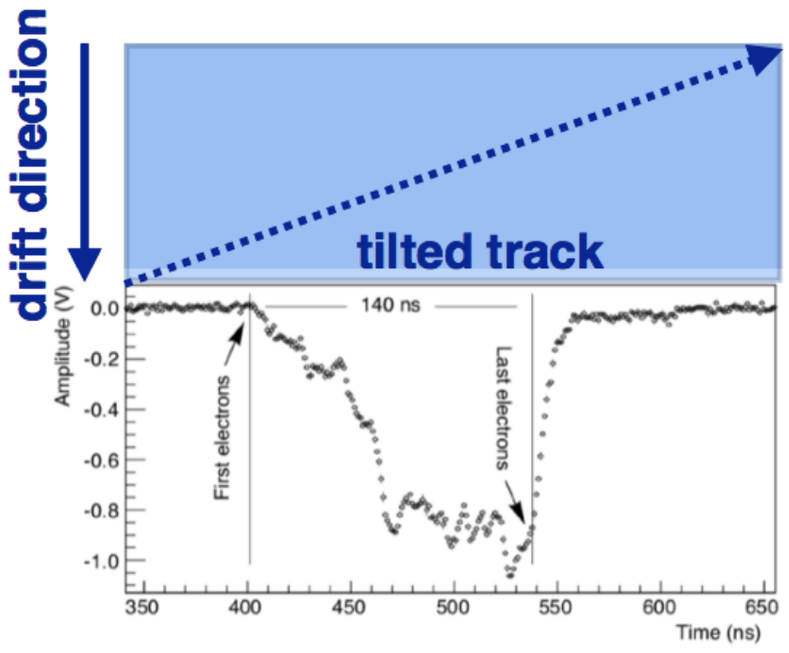
- Light readout with a sCMOS camera allows for a high granularity imaging of the event




***Hamamatsu Orca Flash 4.0 + 25.6 mm, f/0.95 optics***
***4MP imaging ~ 26x26 cm² —> ~ 100 µm granularity***
***16-bit***
***70% Q.E.***
***1.6 electrons noise***
***0.9 counts/photon***

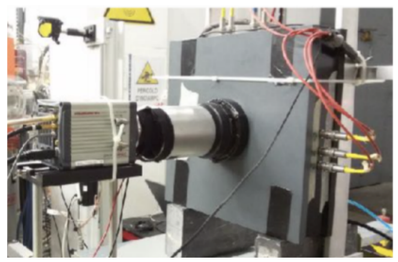
- Light readout with fast detectors (PMT, SiPM) allows for reconstruction of the event topology in the 3rd dimension

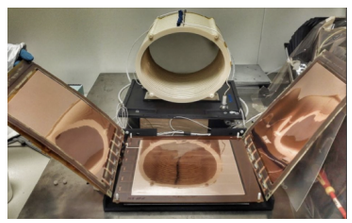


# The CYGNO roadmap

2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026

ORANGE LEMON





**10x10x1 cm³** **20x24x20 cm³**

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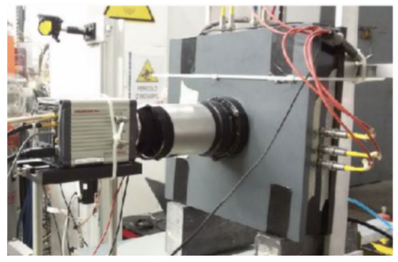
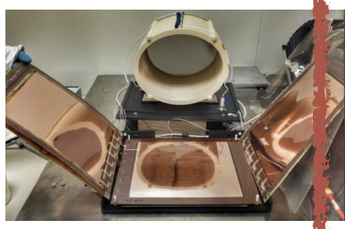
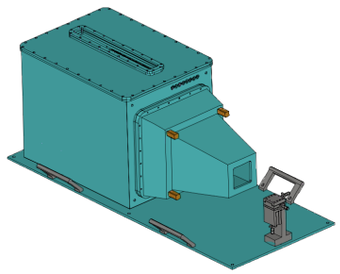
ORANGE | LEMON | LIME





**10x10x1 cm³ 20x24x20 cm³**

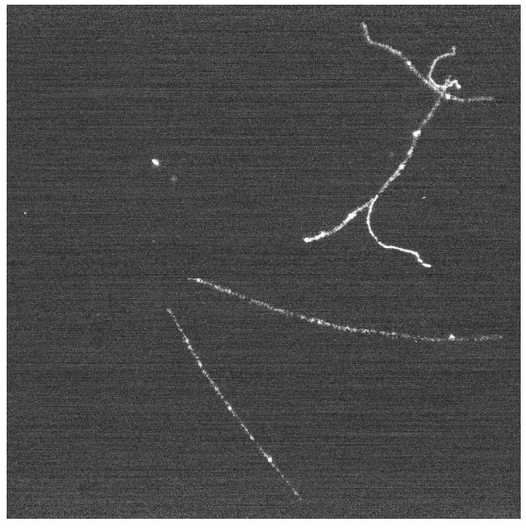


**33x33x50 cm³ (54 l)**

After a long campaign of overground tests, now under **commissioning underground at LNGS**

Data taking with different shields to validate the background simulations

Neutron flux measurement



***one of the first pictures underground***

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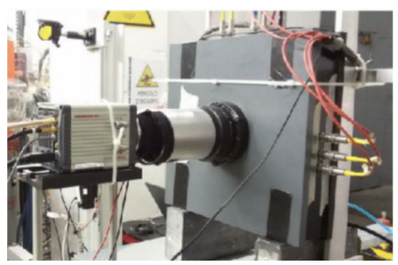
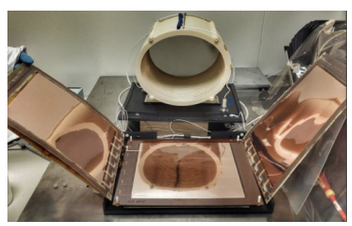
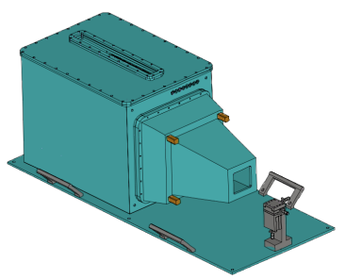
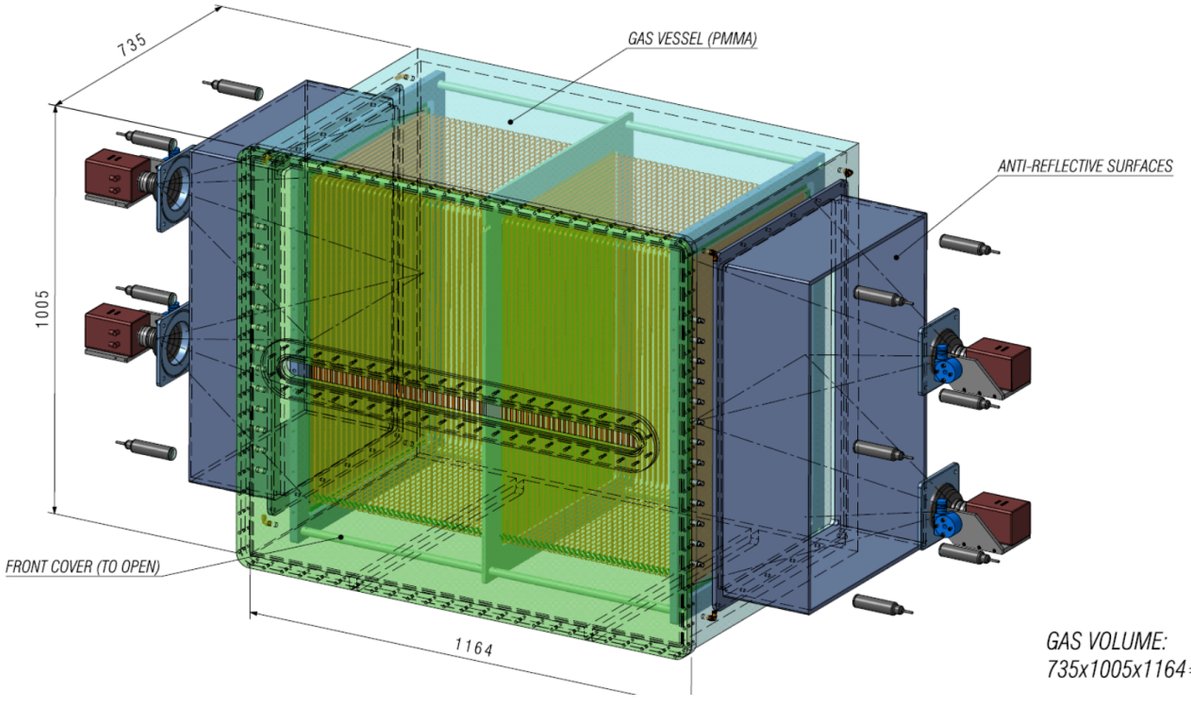
ORANGE | LEMON | LIME







**10x10x1 cm³** **20x24x20 cm³** **33x33x50 cm³ (54 l)**




GAS VOLUME:
735x1005x1164=860 lt

CYGNO

DESIGN | CONSTR. | RUN

**Toward O(m³) scale: CYGNO-04**

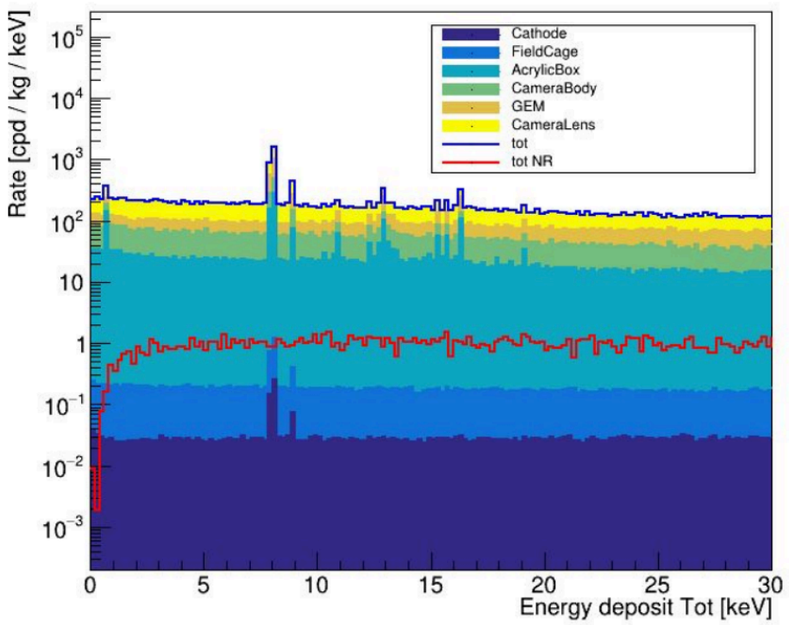
50x80x100 cm³ (0.4 m³ - 0.6 kg)

*the demonstrator for a* ***multisite directional Dark Matter observatory***

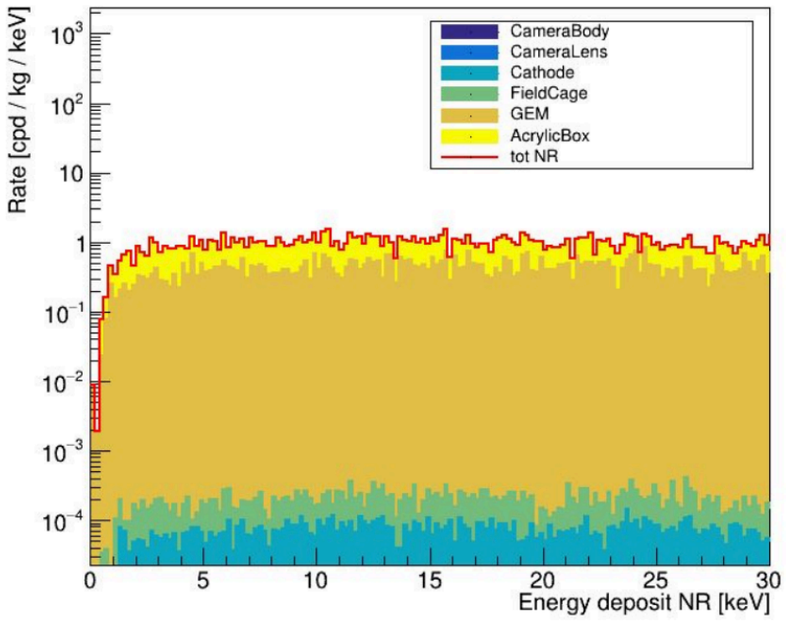
# Background reduction & Signal identification

## Detailed simulation models (1 m³)

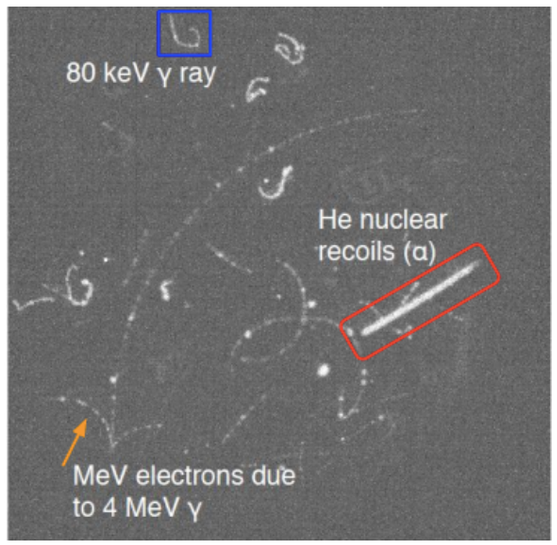
- **ER rate [1-20] keV = 2.3x10⁶ cts/yr**

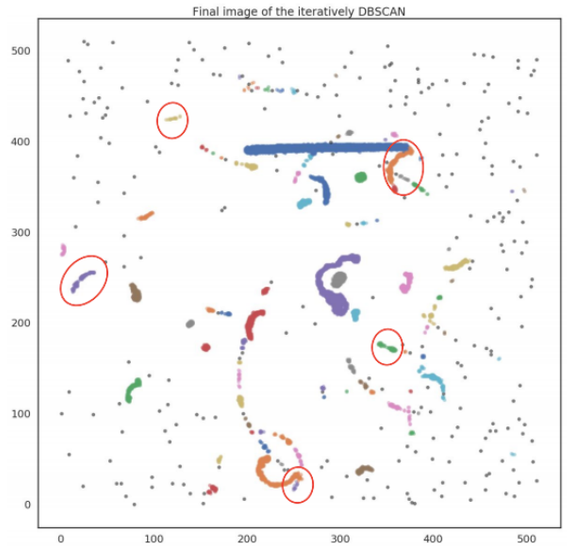



- **NR rate [1-20] keV = 1.1x10⁴ cts/yr**




## Background identification algorithms



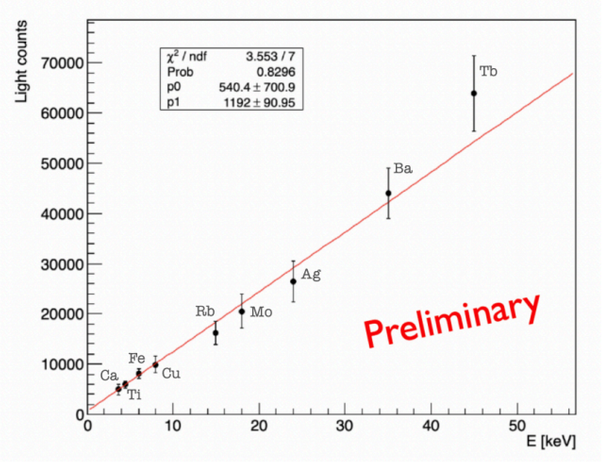

Bkg. rejection validated with LIME

gamma ~ $10^{-4}$ (fiducialization + ID)

neutrons ~ $10^{-2}$ (fiducialization)

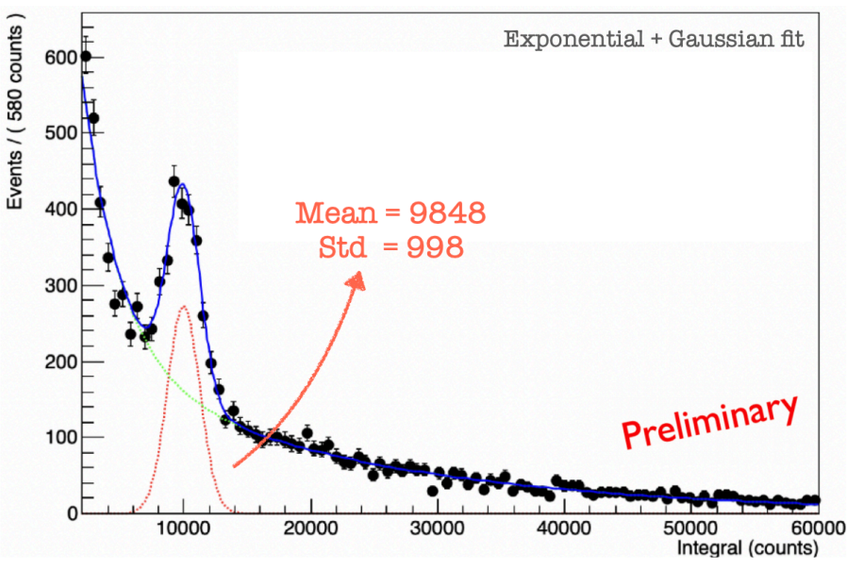
## Energy reconstruction

Electronic recoil (ER) calibration:



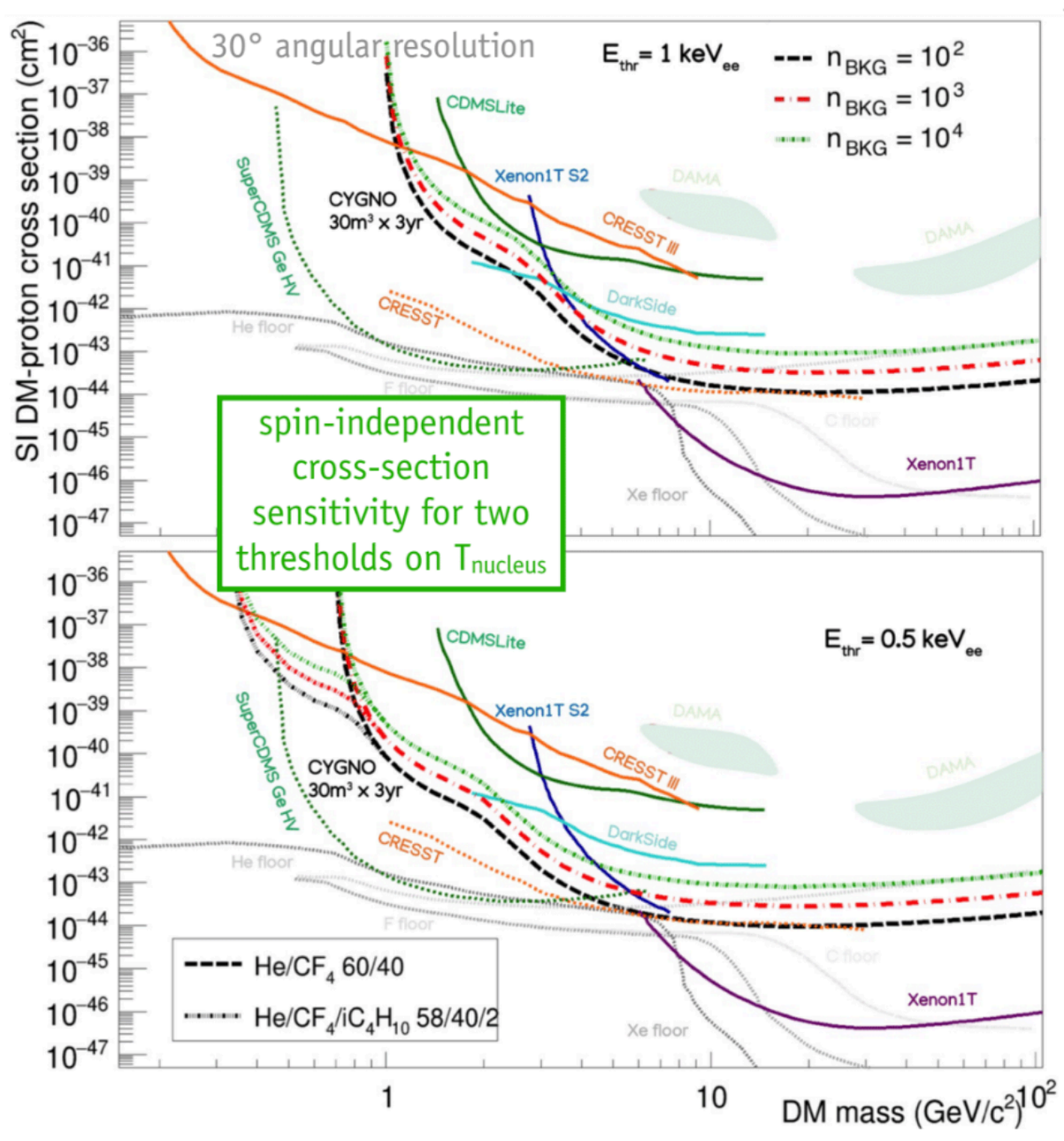

- **~ 13% energy resolution**
- **good linearity** in the response

Example: calibration with the 8 keV Cu X-rays



# Critical issues and Sensitivity

- gamma radioactivity from sCMOS camera and optics, extremely difficult to shield
  - $10^6$ electron recoils/year/$m^3$
  - dedicated R&D activities to develop radio-pure devices
- Non-linearities from GEM saturation
  - dedicated calibrations and software compensation algorithms



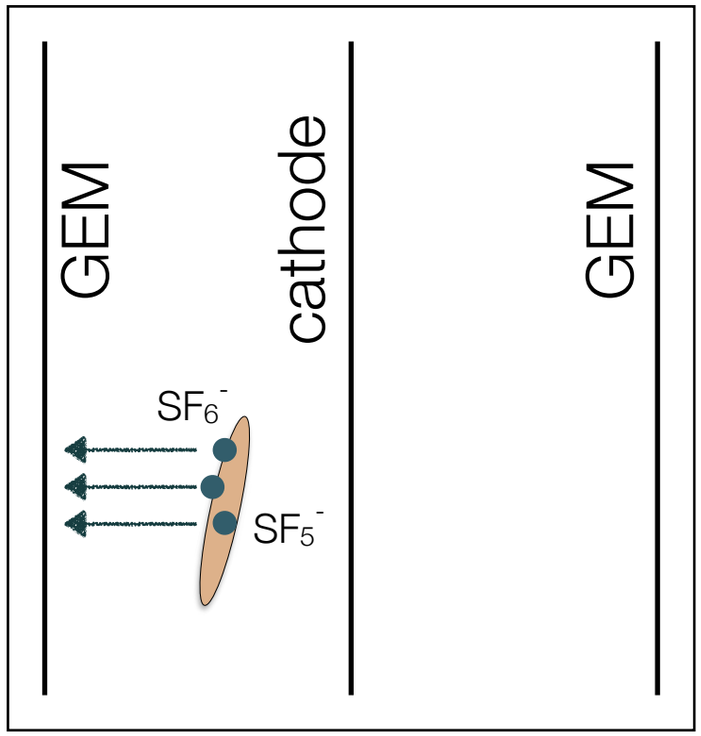
# The INITIUM Project

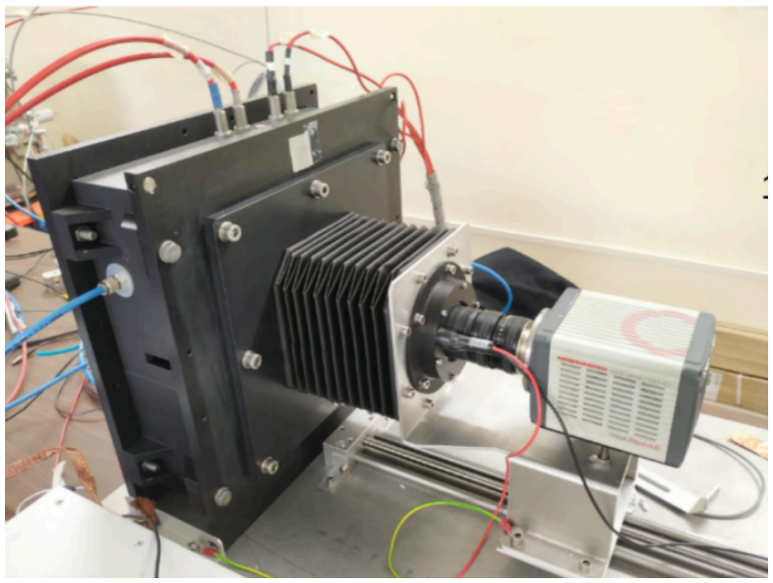
- Some molecules with high electron affinity (e.g. $SF_6$) can **capture** the **primary ionization electrons** and drift as *negative ions*

  - ion diffusion << $e^-$ diffusion

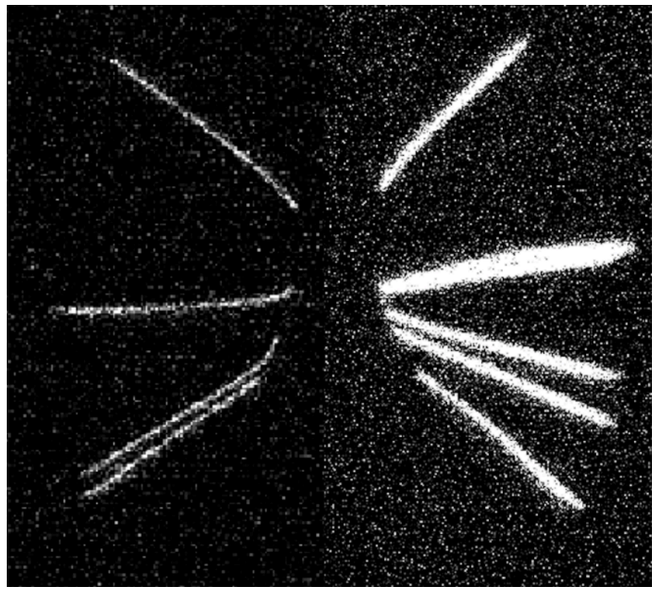
  - different ion species can form (e.g. $SF6^-$, $SF5^-$, etc.) with different drift velocities —> comparison of drift times gives a measurement of the drift distance —> fiducialization

We are exploring the possibility of **negative ion drift** in a **He based gas mixture at atmospheric pressure** with a small addition of $SF_6$



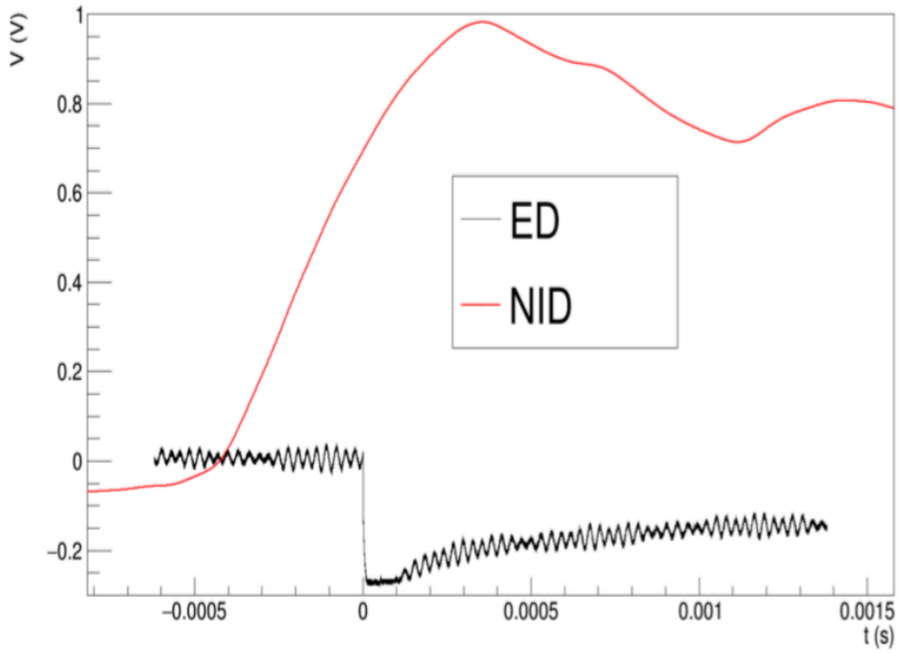



# Negative-ion drift in He:CF4:$SF_6$



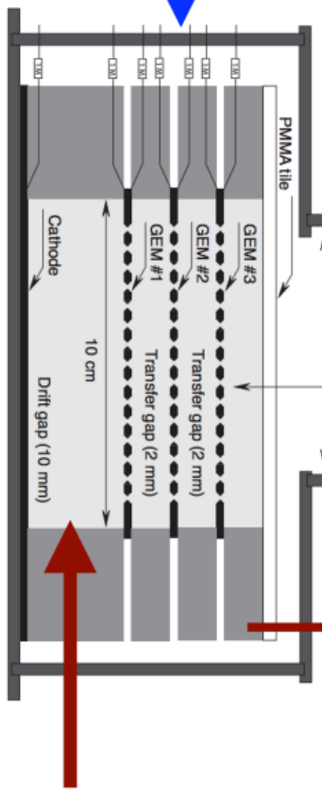
$He:CF_4:SF_6$
59:39.4:1.6
0.4 kV/cm
(NID)

$He:CF_4$
60:40
1 kV/cm
(ED)




**GEM preamp output**
O(us) rise for ED
O(ms) rise for NID

**Triple thin 50 um GEM stack**
**10 x 10 cm²**

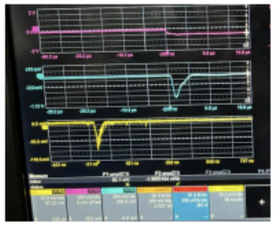



**PMT**


**Drift gap (variable from 5 to 15 cm)**

**Charge sensitive preamplifier**
300 us decay time
0.113 mV/fC

**Shaper amplifier**
shaping time
0.5 us (ED)/ 10 us (NID)



**Oscilloscope**
Trigger on GEM preamp output

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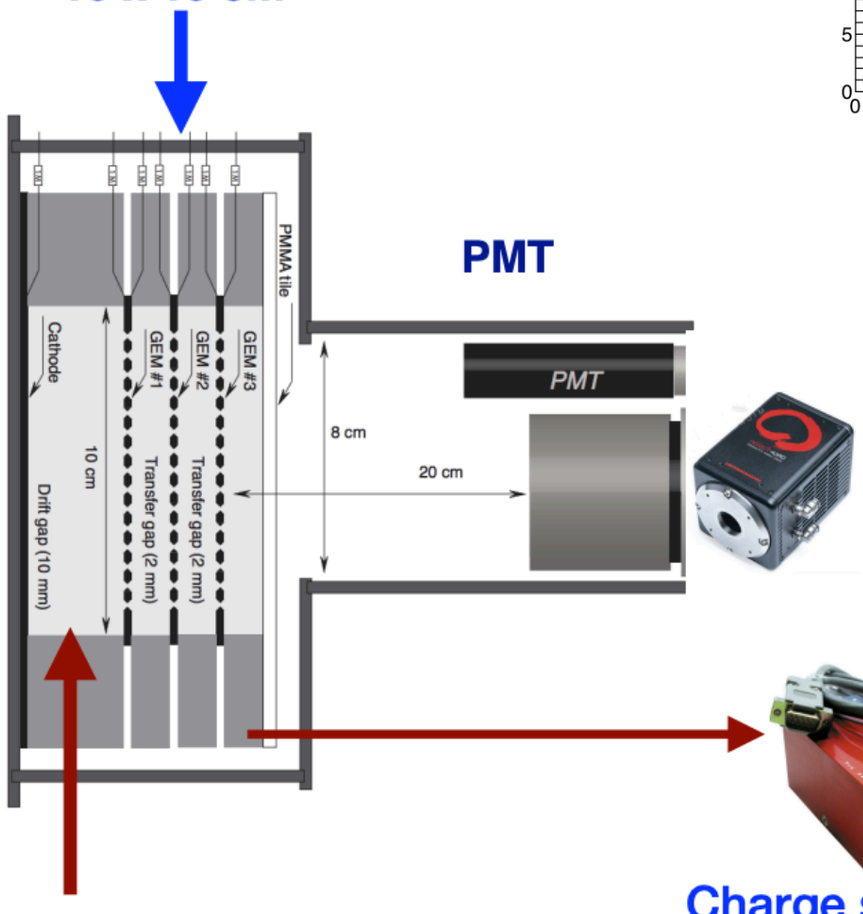
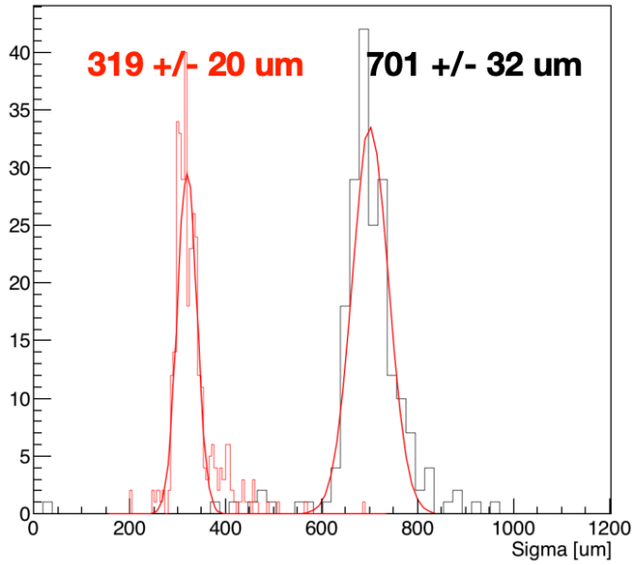



**Drift gap (variable from 5 to 15 cm)**

**Diffusion at 12.5 cm**

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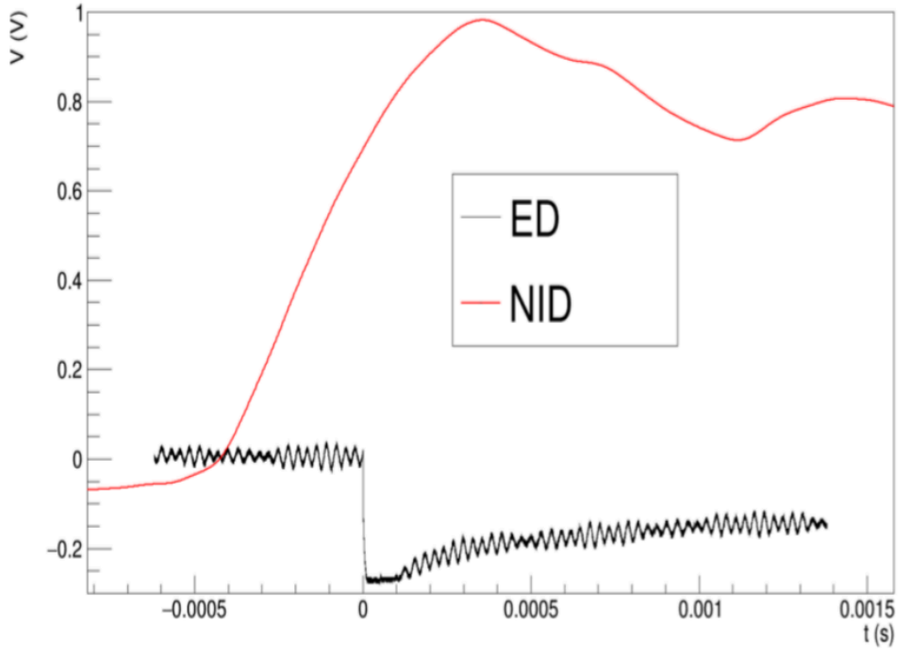
**59:39.4:1.6**
**0.4 kV/cm**
**(NID)**

**$He:CF_4$**
**60:40**
**1 kV/cm**
**(ED)**

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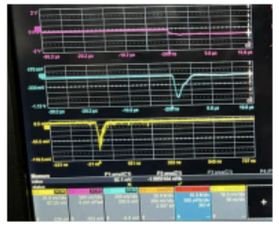

**Oscilloscope**
Trigger on GEM preamp output

# Conclusions

- Dark Matter with directional capabilities with CYGNO:
  - enhanced sensitivity to GeV and sub-GeV Dark Matter
  - aim at limits competitive with non-directional experiments
  - further handles to improve performances with negative ion drift
  - **the path toward a dark matter astronomy**


The CYGNO collaboration:

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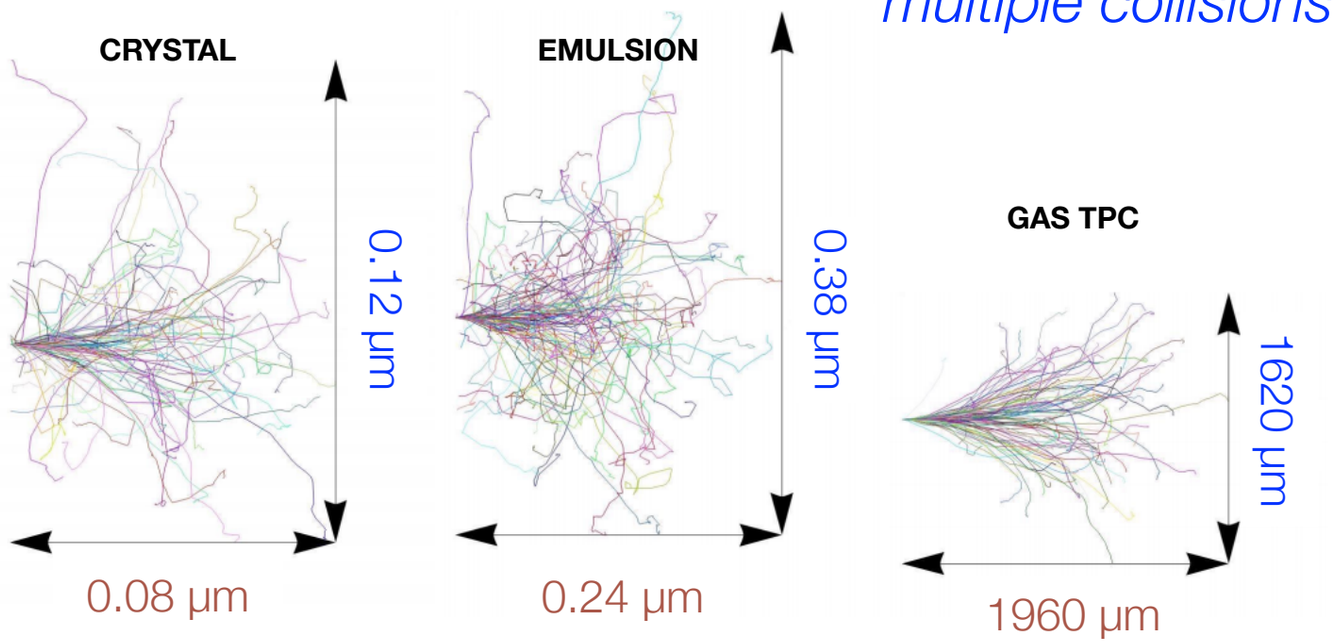
# Backup

# Experimental challenges of directional searches

**1 TeV WIMP, max. recoil energy**




*recoil direction information quickly deteriorated by multiple collisions*

*Very short tracks —> 3 options*

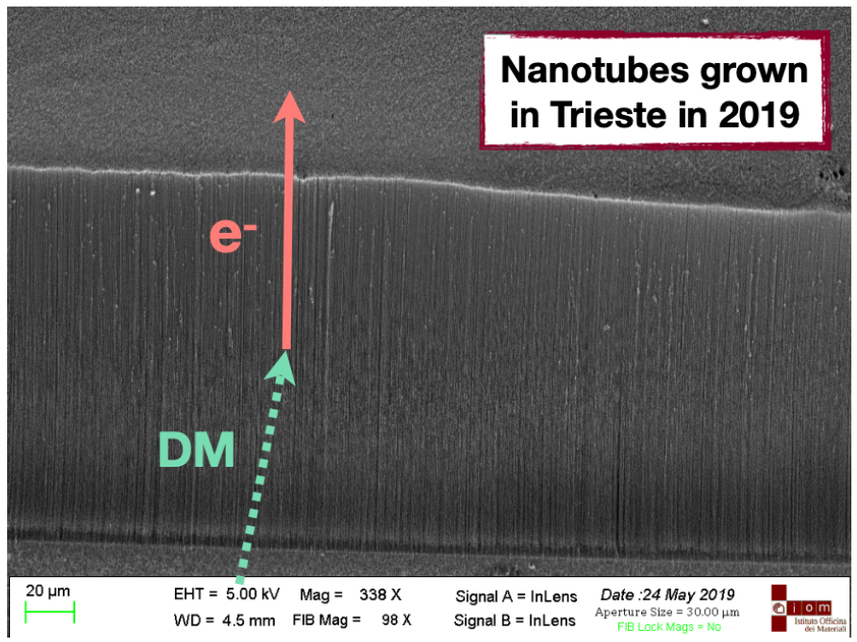
*1) high granularity*

***2) strong detector anisotropy***

*3) tiny statistical effects in isotropic (e.g. columnar recombination) or slightly anisotropic detectors*

Channeling in carbon nanotubes (CNTs)

**Only electron recoils in a specific direction can be efficiently reconstructed**



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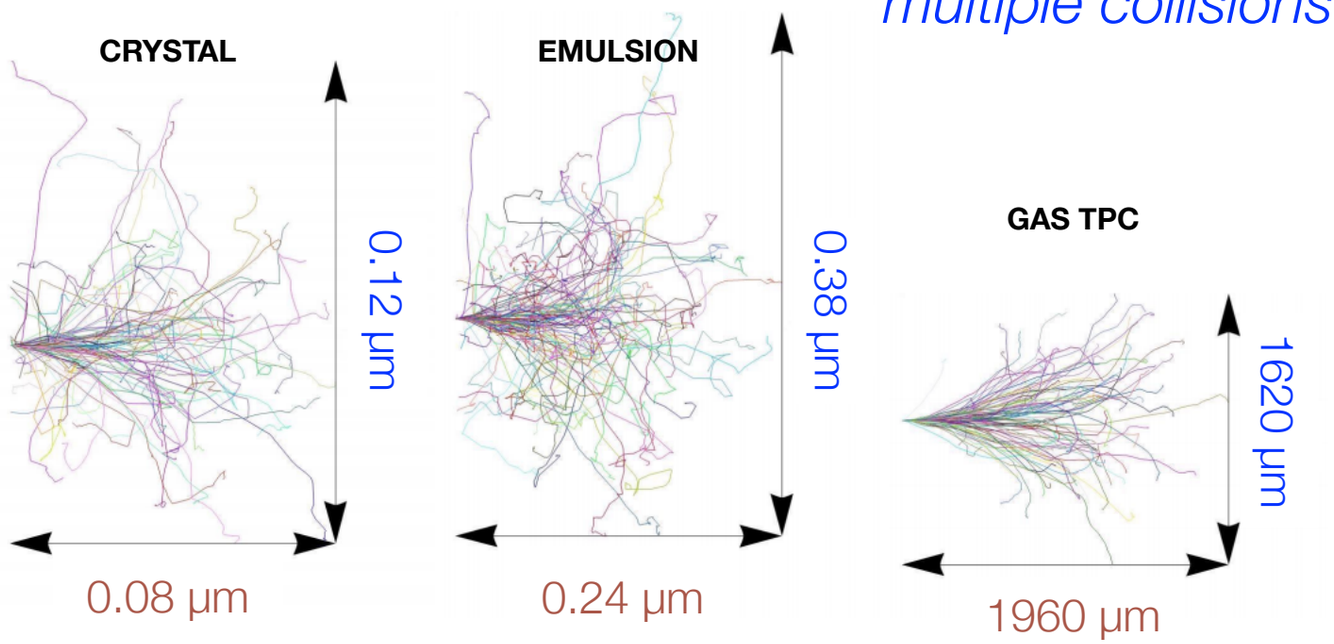


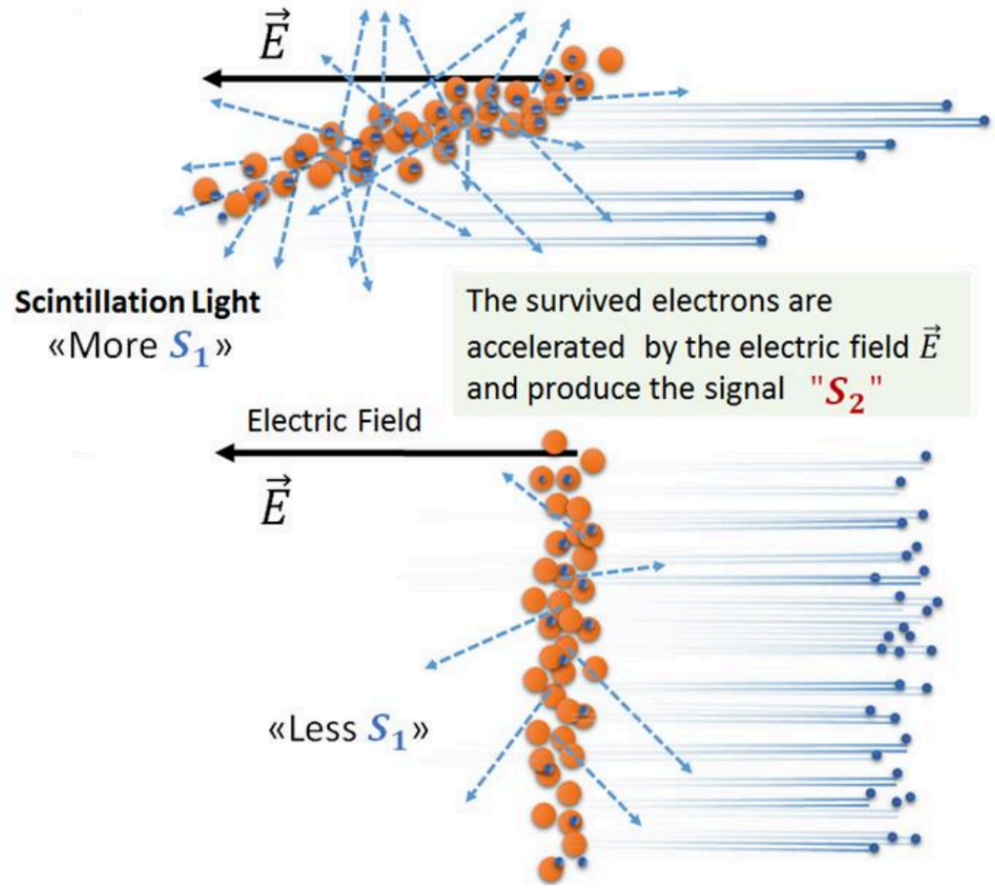


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