CPAD Instrumentation Frontier Workshop 2021

in synergy with IN TIUM

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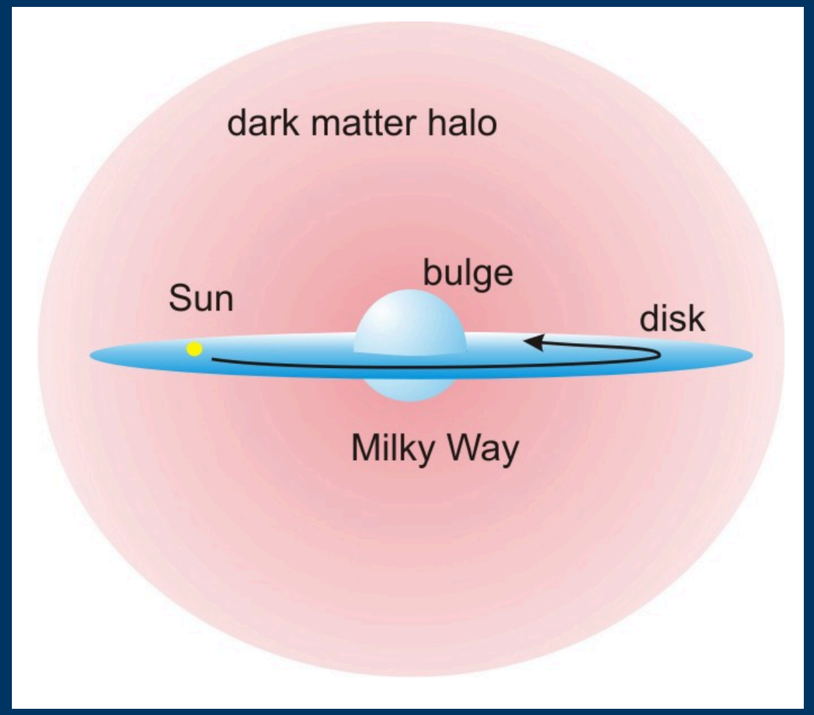
The **CYGNO** TPC: Optical Readout for Directional Study of Rare Events

F. Amaro, E. Baracchini, L. Benussi, S. Bianco, C. Capoccia, M. Caponero, G. Cavoto, A. Cortez, R. J. de Cruz Roque, I. A. Costa, E. Dané, E. Di Marco, G. D'Imperio, G. Dho, F. Di Giambattista, R. R. M. Gregorio, F. Iacoangeli, H. P. Lima Júnior, G. Maccarrone, R. D. P. Mano, M. Marafini, G. Mazzitelli, A. G. Mc Lean, A. Messina, M. L. Migliorini, R. A. Nóbrega, A. Orlandi, I. F. Pains, E. Paoletti, L. Passamonti, F. Petrucci, S. Pelosi, S. Piacentini, D. Piccolo, D. Pierluigi, D. Pinci, A. Prajapati, F. Renga, F. Rosatelli, A. Russo, J. Santos, G. Saviano, A. da Silva Lopes Júnior, N. Spooner, R. Tesauro, S. Tomassini, S. Torelli

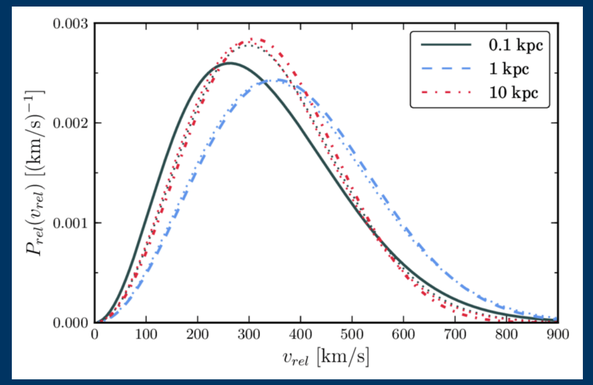
DARK MATTER AND WIMPS

One of possible constituents of Dark Matter are the Weakly Interacting Massive Particles: neutral particles with a very low interaction probability with ordinary matter;



Our Milky Way, like most galaxies, is surrounded by an approximately spherical halo of WIMPs.

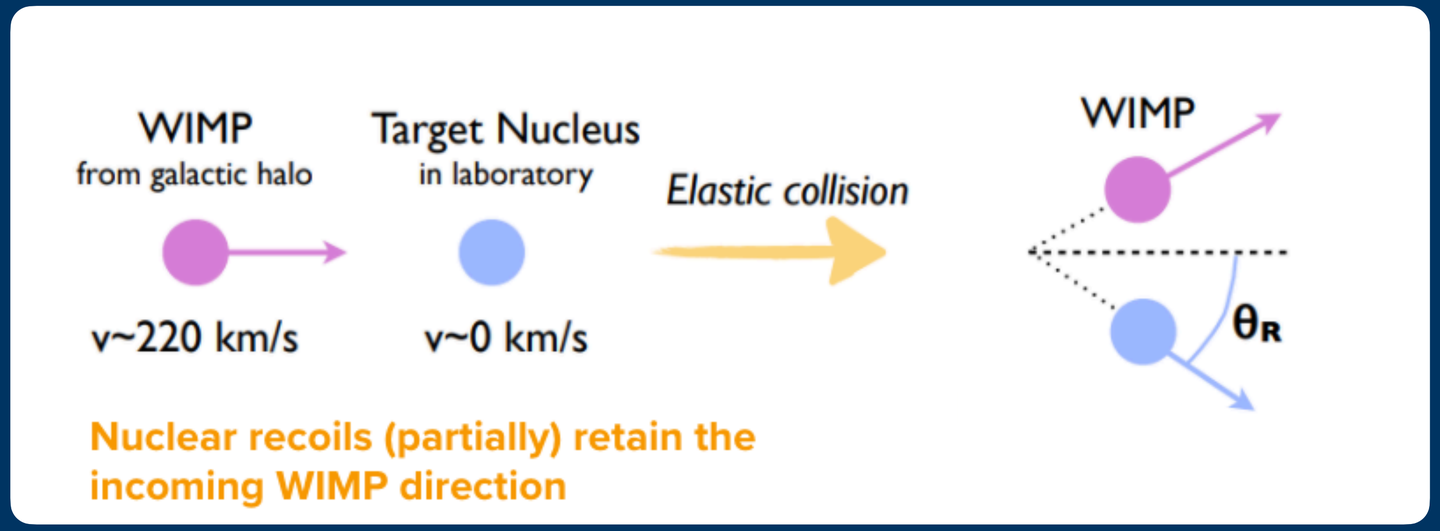
The Sun and the planets move through this halo preceded by the CYGNUS constellation intercepting a WIMP wind originating from it

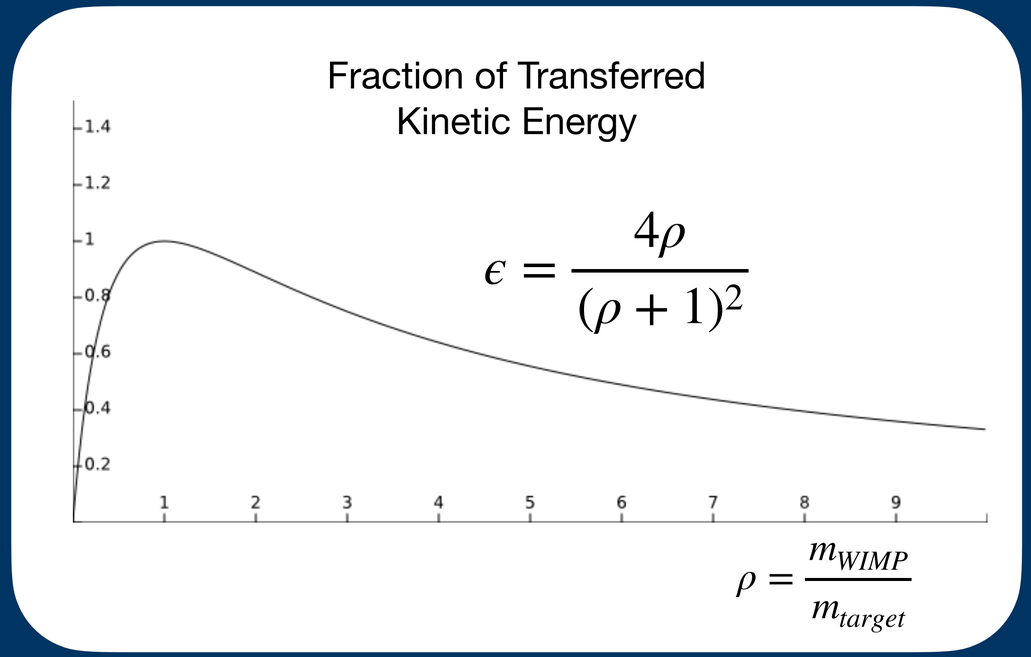


- How can a few GeV neutral particle running at 300 km/h be detected?

WIMPS AND HOW TO DETECT THEM

- One possibility is trying to detect the products of its interactions with ordinary matter, in particular with charged particles that we know how to detect;

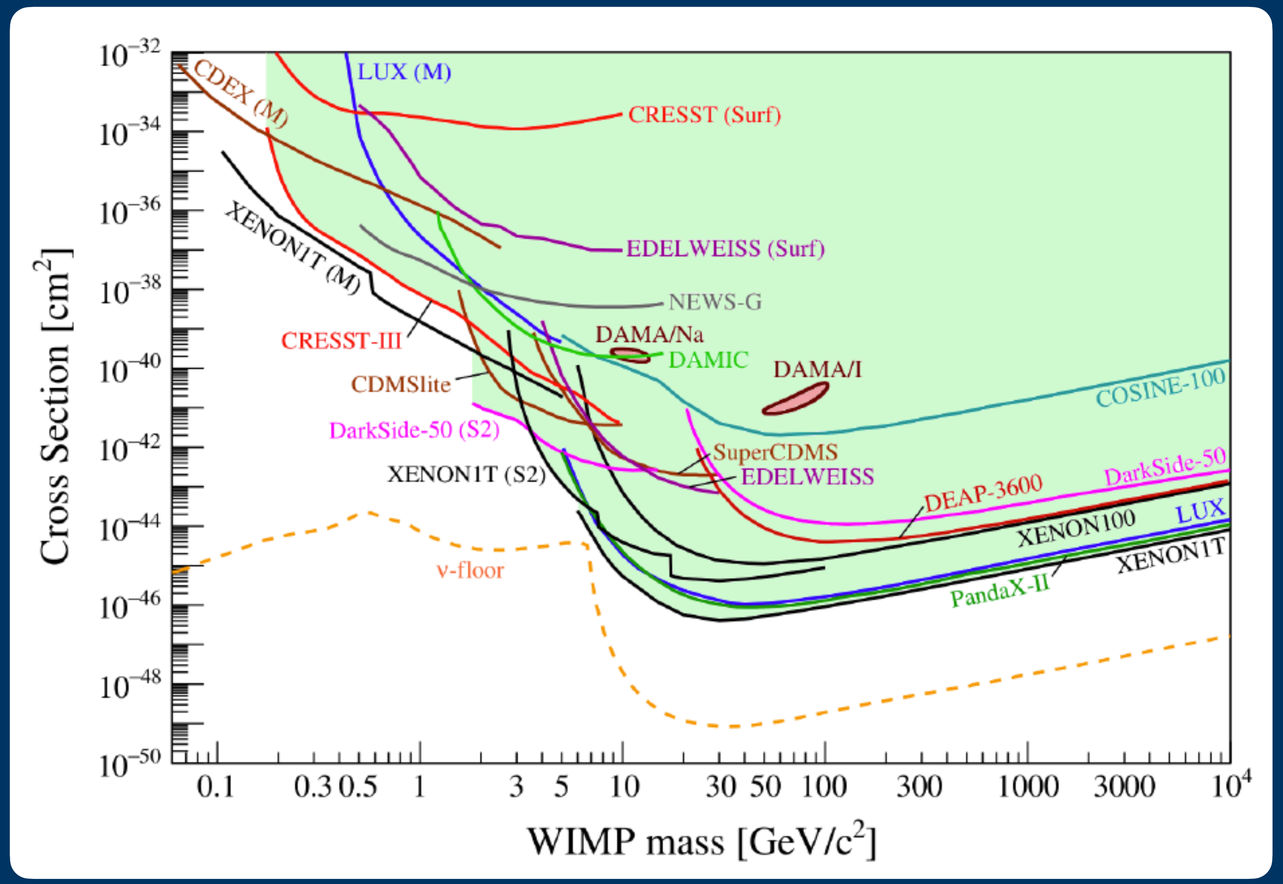




- In order to maximise the fraction of transferred energy it is then crucial to have target of almost same mass

WIMP

- Large regions of high masses spectrum already explored without any confirmed evidence of WIMP;



- Future focus on masses below 10 GeV;

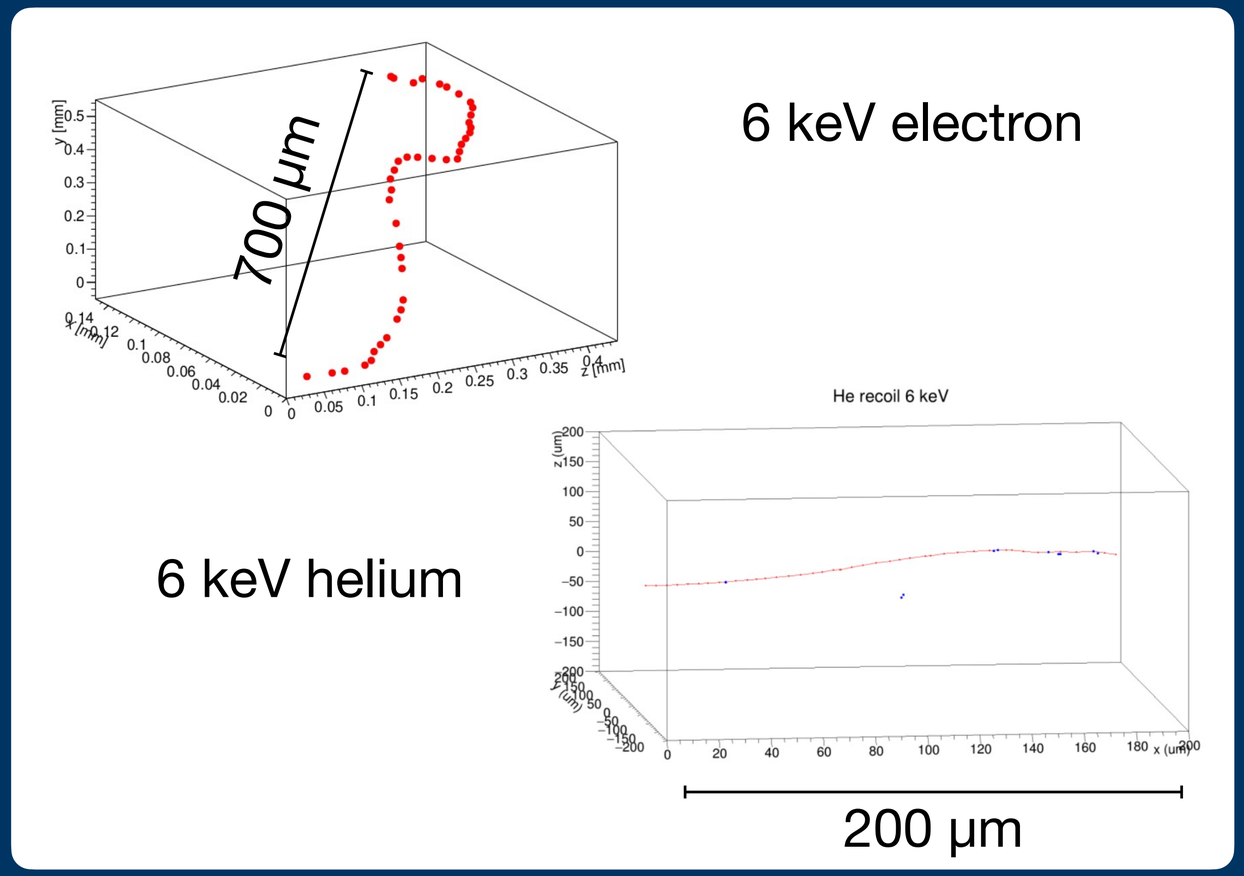
Element	Max E transferred by a 1 GeV DM particle	Min DM particle mass with 1 keV threshold
Ar	0.04 keV	5.0 GeV
H	0.5 keV	2.4 GeV
He	0.32 keV	2.2 GeV
C	0.14 keV	3.1 GeV
F	0.01 keV	3.7 GeV
S	0.06 keV	4.6 GeV
Xe	0.015 keV	8.6 GeV

(assuming $\beta = 10^{-3}$)

- To explore the GeV mass range, best candidates are He and H

WIMP

- Hydrogen is a complicated gas to manipulate (but we have some idea, see Cristina's talk, https://indico.fnal.gov/event/46746/contributions/210370/)
- so a good starting point is an atmosphere of He;

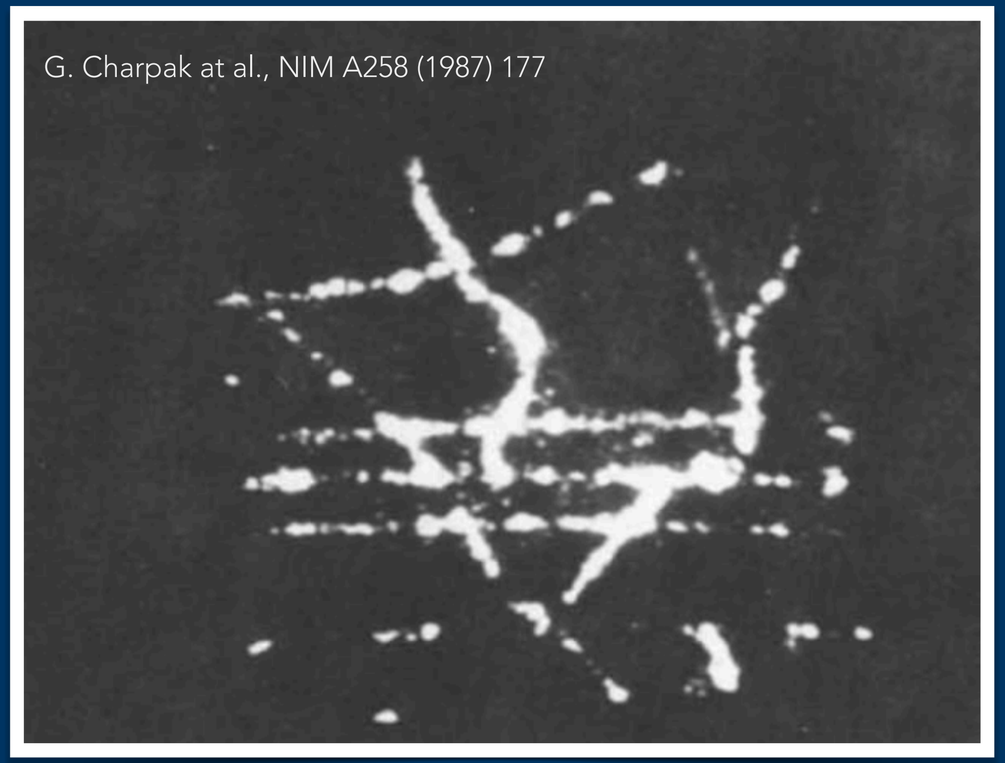


- In a Helium (based) gas mixture a 6 keV He nucleus has an average range of 100 μm, 5 time lesser than an electron;
- 10% of them have almost the double.

- If it would be possible to "observe" these events, not only it would be possible to distinguish them, but also to measure their direction (from CYGNUS?)

OPTICALLY READOUT TPC

- 3D tracking (position and direction);
- total released energy measurement and dE/dx profile (pid, head-tail);
- reduced readout channel number;



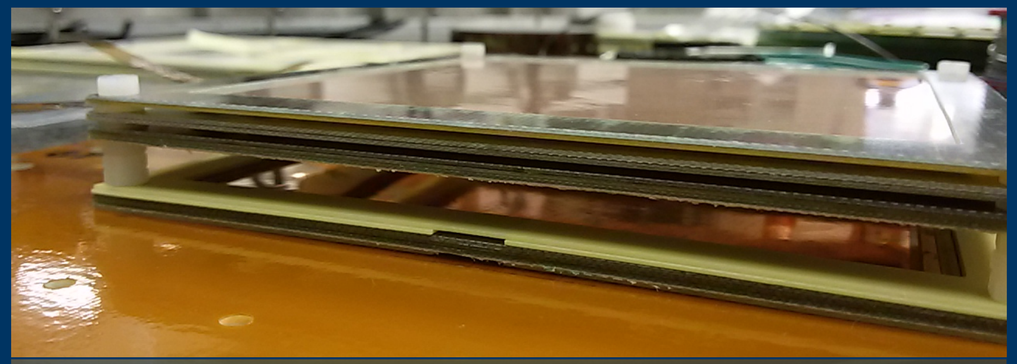
We propose to readout the light produced during the multiplication process:

- optical sensors are able to provide high granularities along with very low noise level and high sensitivity;
- optical coupling allows to keep sensor out of the sensitive volume (no interference with HV operation and lower gas contamination);
- suitable lens allow to acquire large surfaces with small sensors;

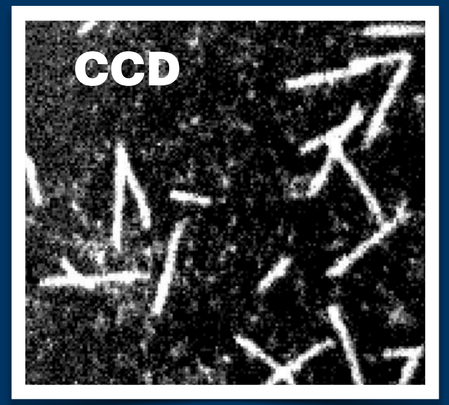
ORANGE: AN OPTICALLY READOUT GEM

Triple GEM structure (10x10 cm^2) with 1 cm sensitive gap.

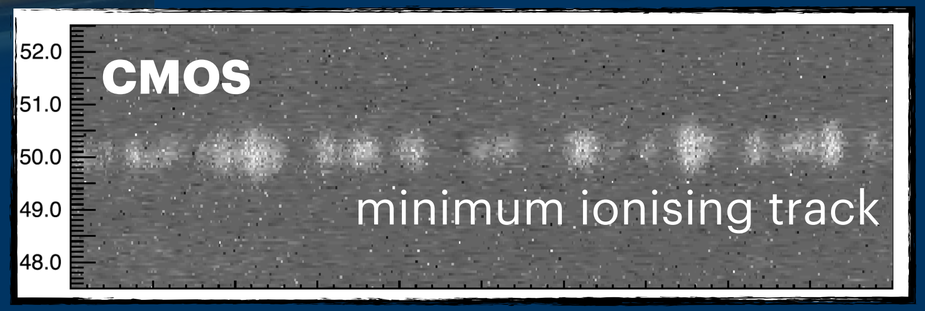
An He/CF_4 (60/40) mixture was used at atmospheric pressure

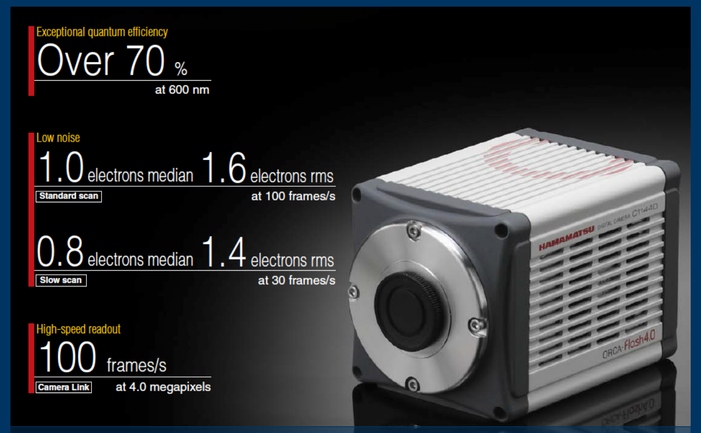


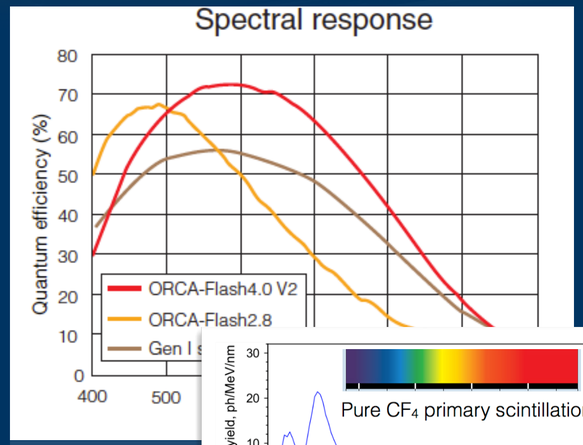
highly ionising tracks

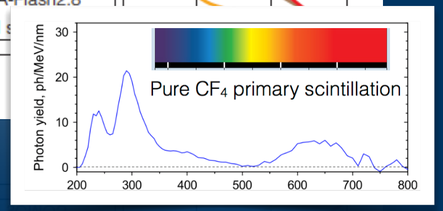


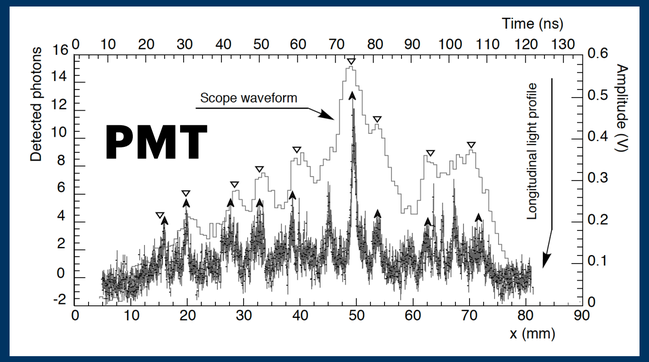
Significantly **lower noise** level of **CMOS** w.r.t **CCD** sensors resulted in a higher sensitivity

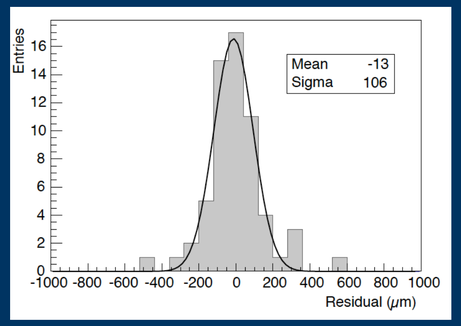












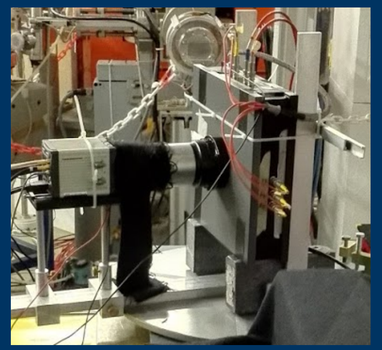
sCMOS sensors provide very low noise and 4MPx granularity and sensitivity

PROJECT PHASES

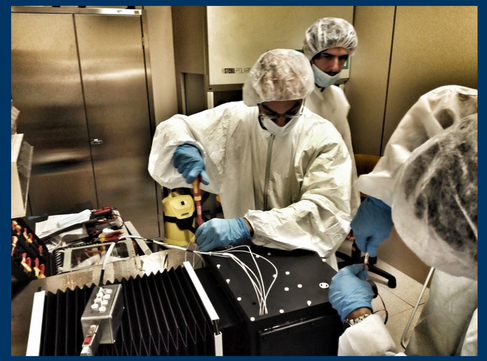
PHASE 0: R&D

PHASE 1: ~1 m³ Demonstrator

2015/16	2017/18	2019/20	2021/22	2023
@ ROMA1	@ LNF	@ LNF/LNGS	@ LNF/LNGS	@ LNGS
ORANGE	LEMON	LIME	Construction & test	Installation & commissioning

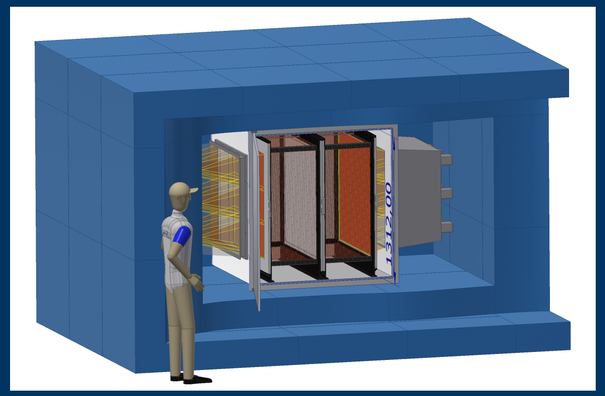


- 1 cm drift



- 3D printing
- 20 cm drift

- 50 cm drift
- underground tests
- shielding



- background
- materials test
- gas purification
- scalability

CYGNUS 30-100 m³

CYGNUS_RD - CSN5

CYGNO - CSN2

NITEC

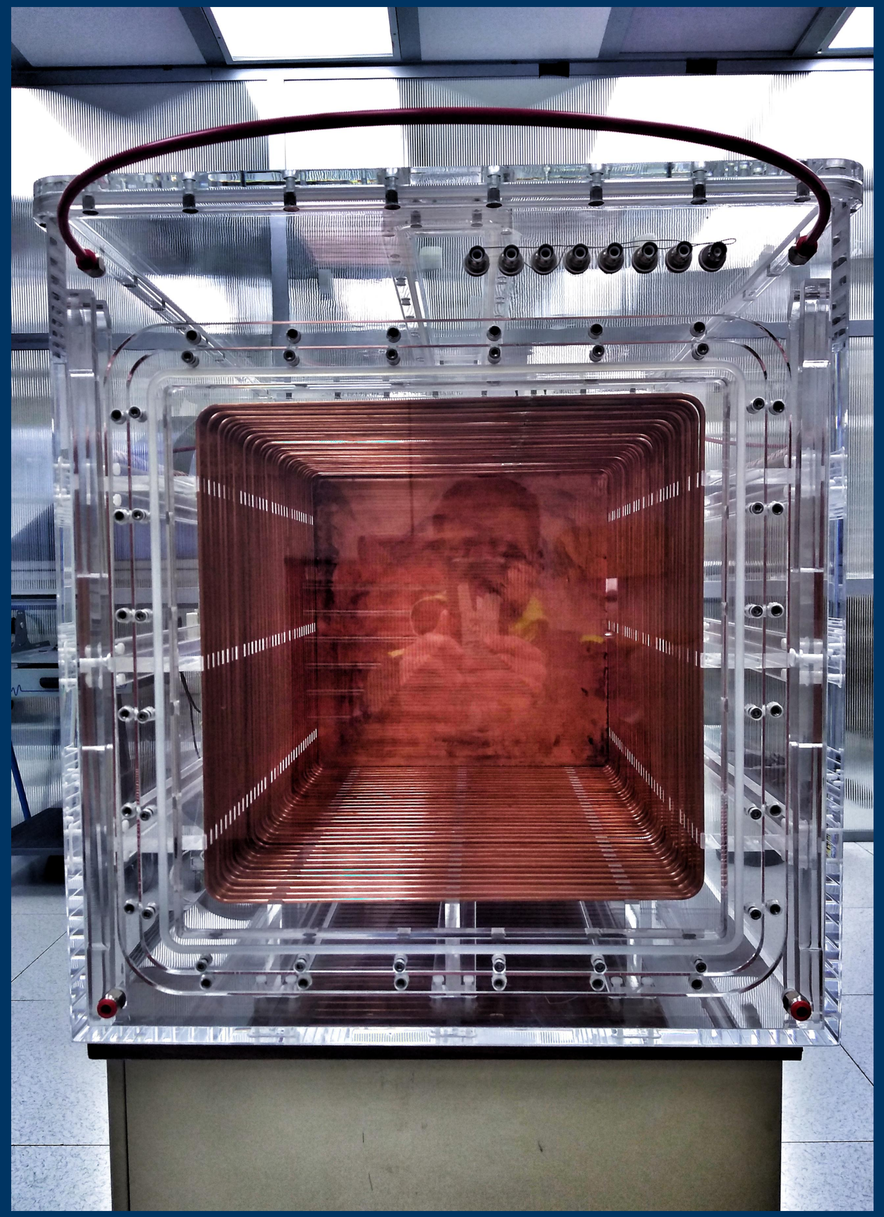
INITIUM

LIME

50 litre sensitive volume:

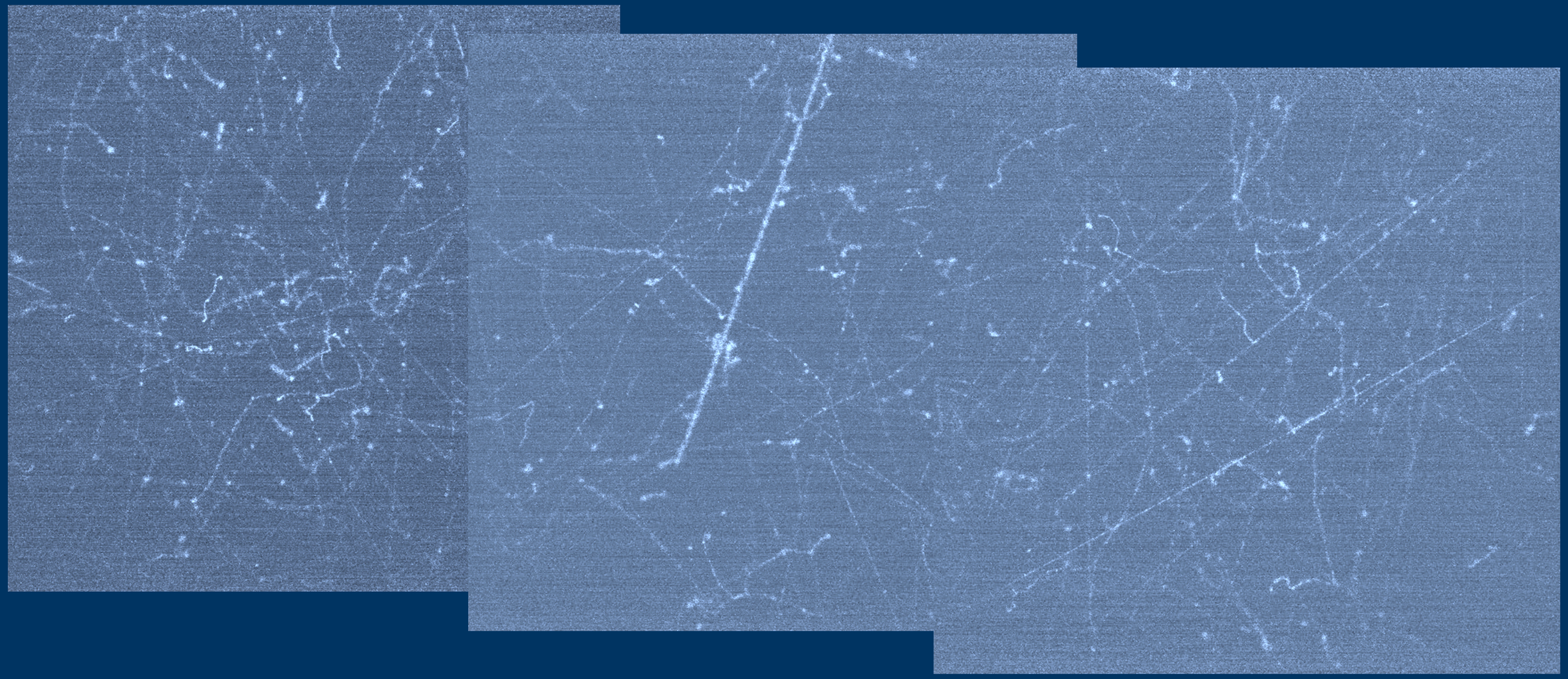
- **33 x 33 ~ 1000 cm²** GEM surface;
- **50 cm** drift path;

Copper ring field cage



Acrylic gas vessel

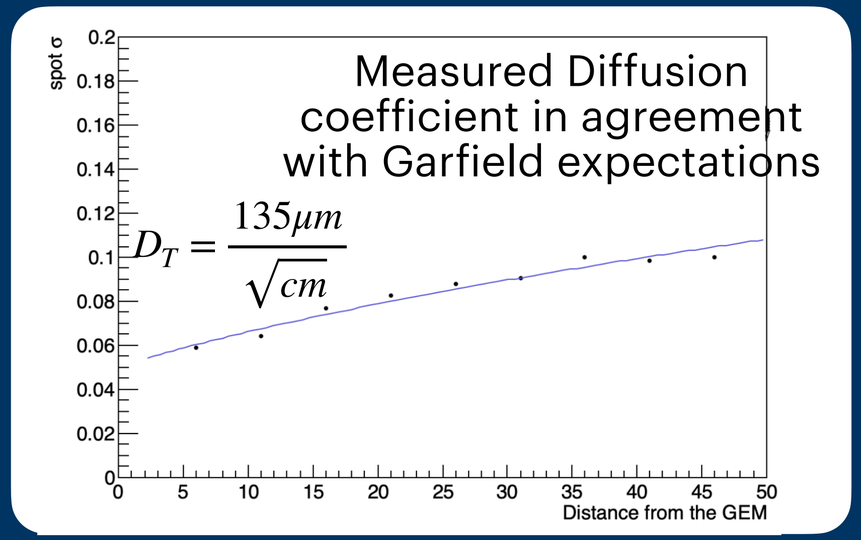
LIME: COSMICS AND NUCLEAR RECOILS

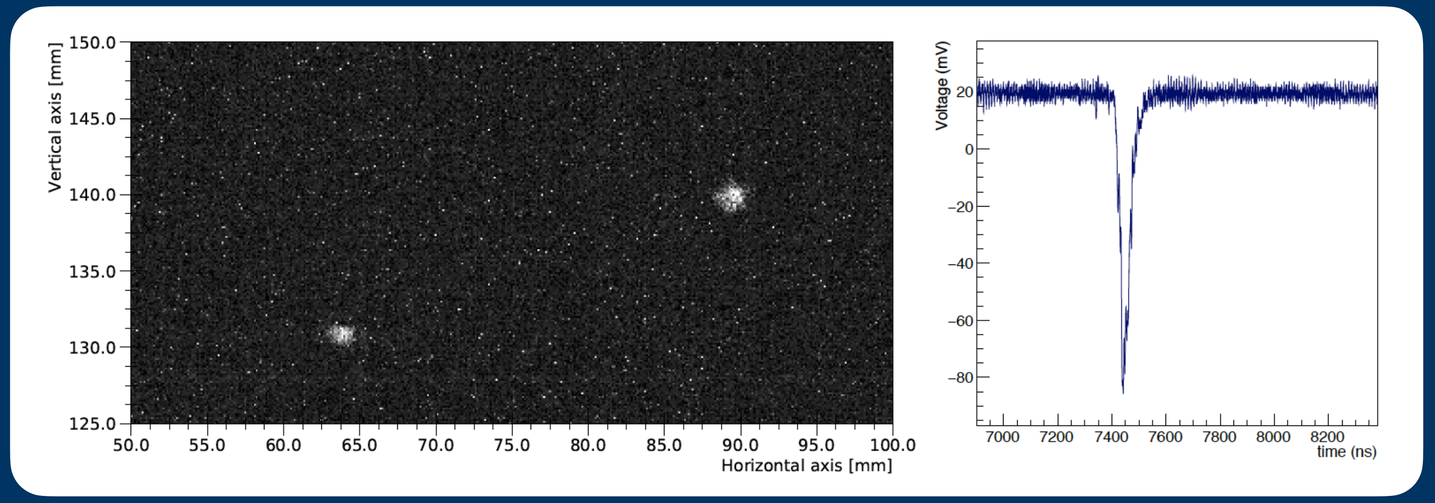


33 cm

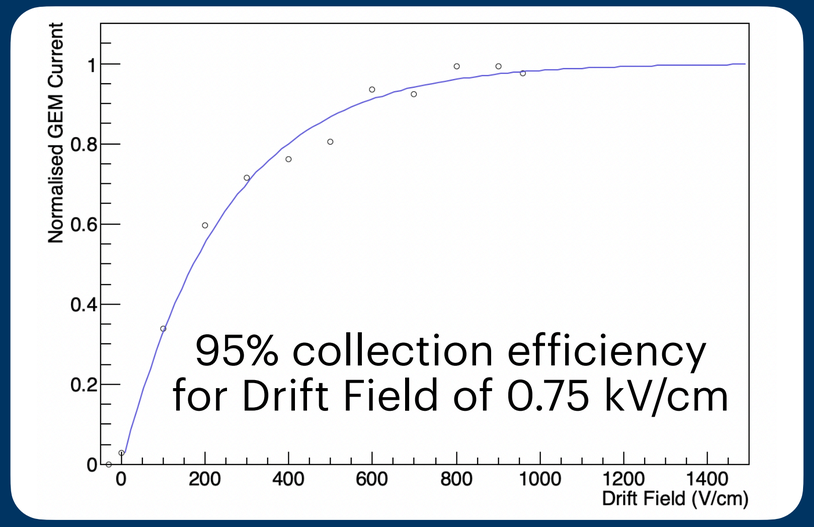
PERFORMANCE WITH ^{55}FE: SPOT SIGNALS

5.9 keV photons from ^{55}Fe source were used to test detection efficiency and light yield.



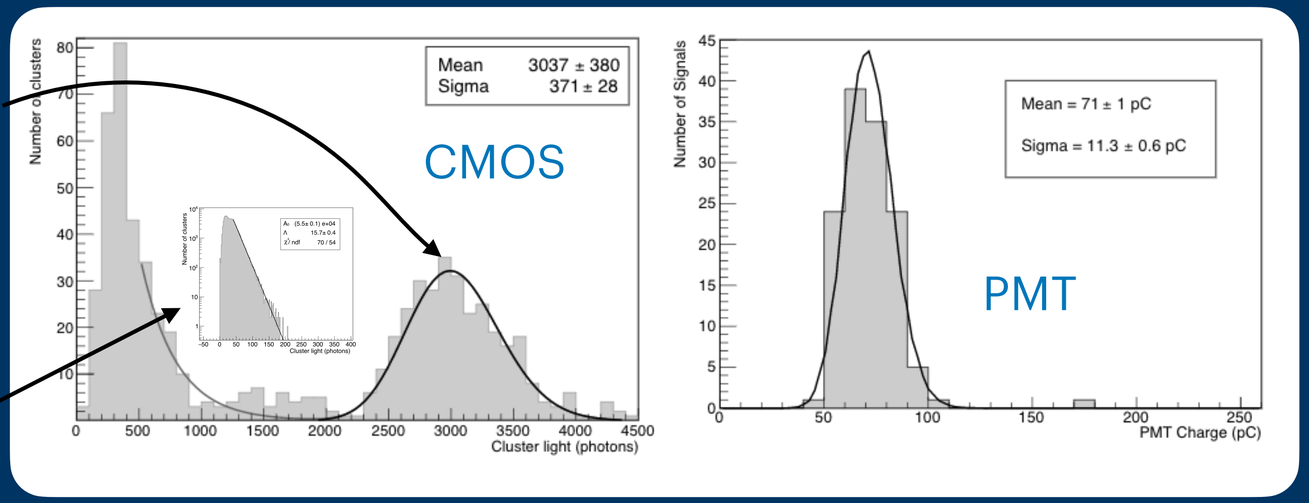


Energy resolution of 15% with CMOS and PMT



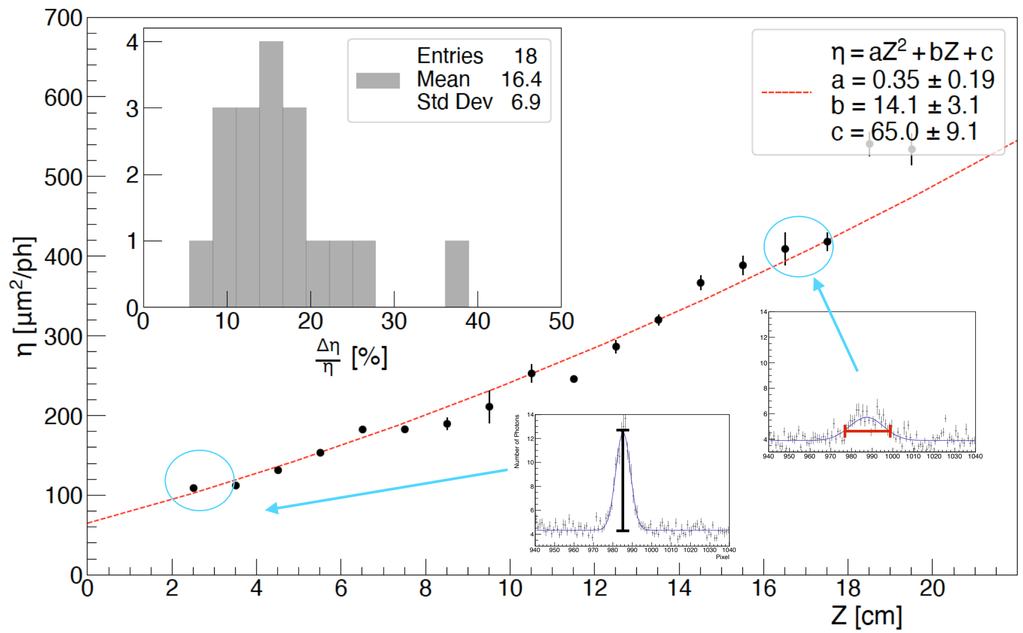
500 photons collected per keV

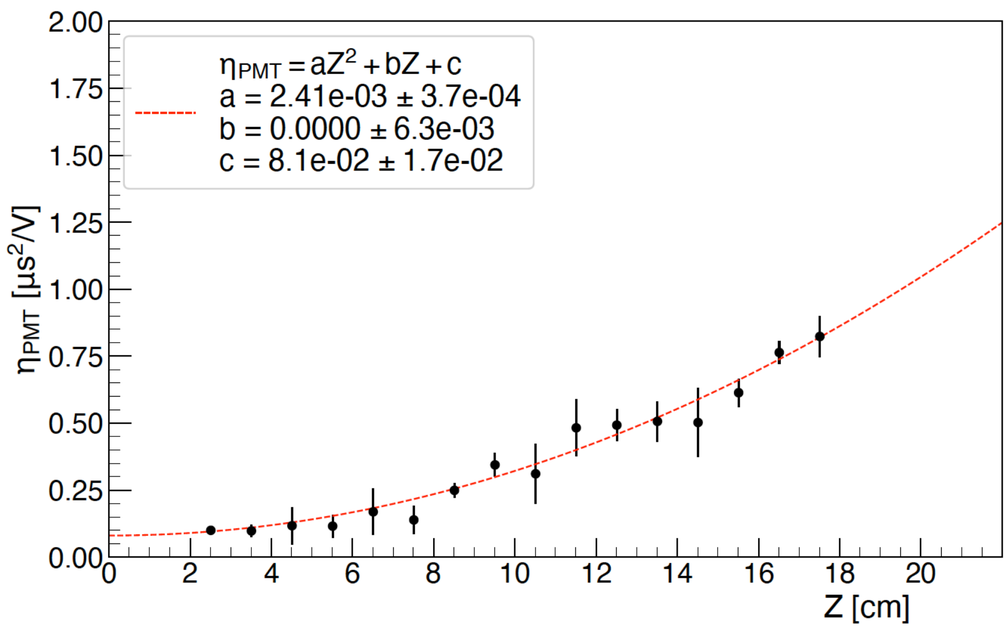
Sensor noise below 200 photons (i.e. 400 eV)



Z RESOLUTION

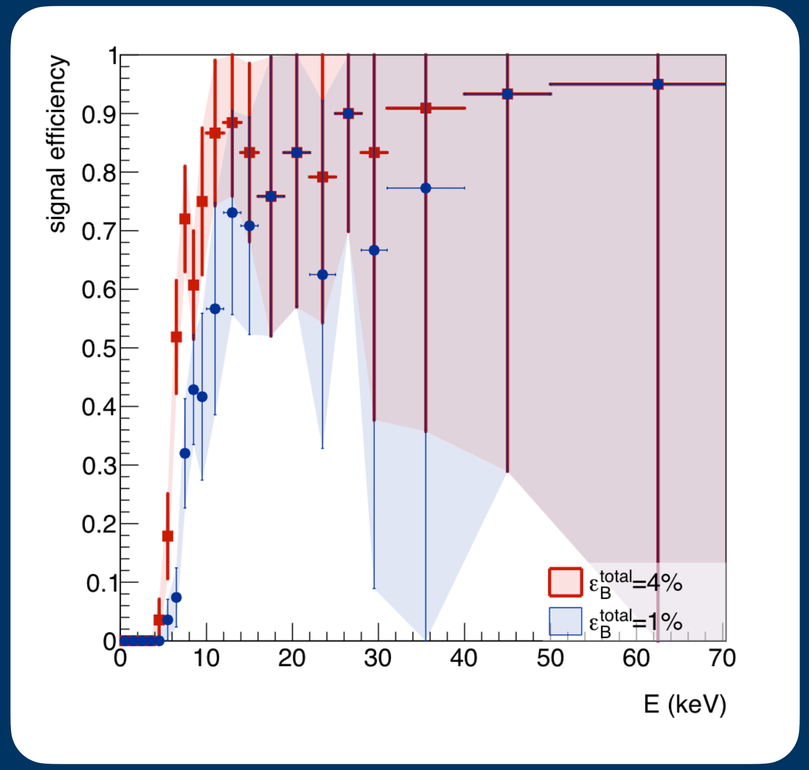
Electron diffusion in the drift gap can be exploited to evaluate the Z of the event.
The transverse light profile and the PMT signal waveform are expected to become lower and larger as long as the event is far from the GEM;
Since the width (S) increases and the amplitude (A) decreases with Z, their ratio η = S/A increases



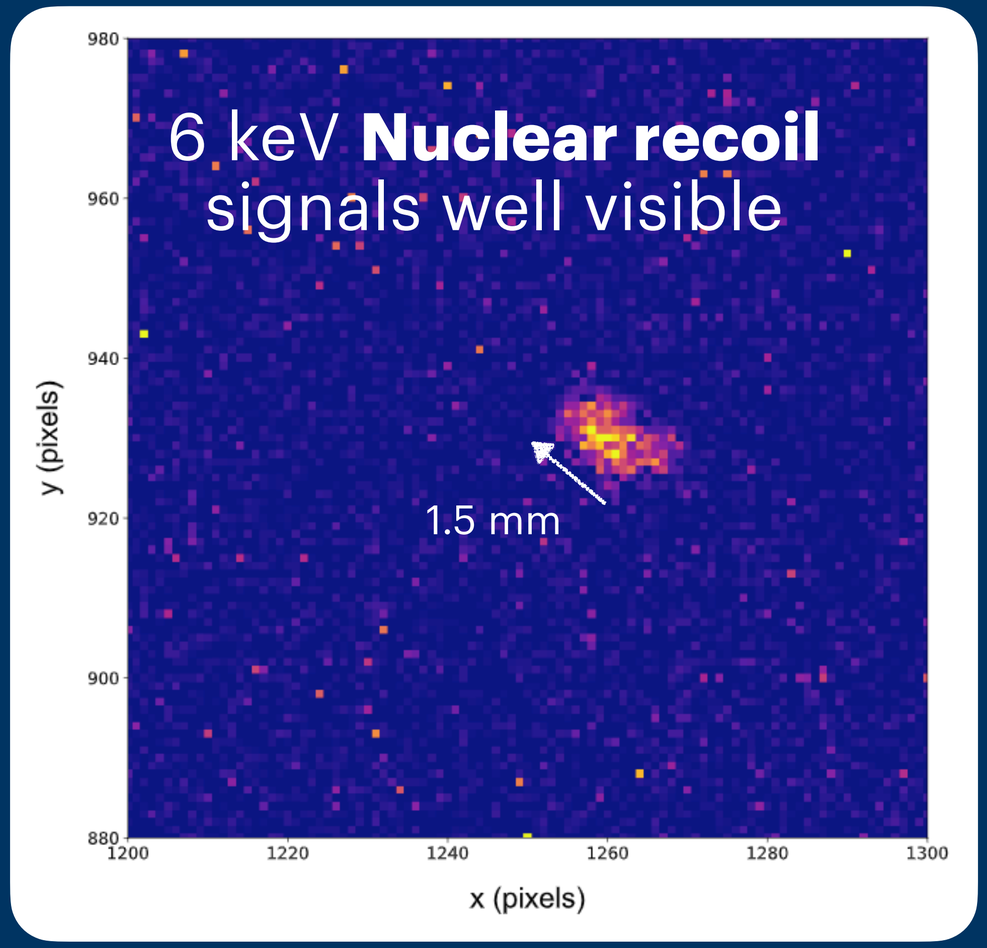


Both methods gives 12% precision: σ_z ~ 6 cm @ 50 cm

PERFORMANCE WITH NUCLEAR RECOILS



working point	Signal efficiency			Background efficiency		
	ε_S^{presel}	ε_S^{δ}	ε_S^{total}	ε_B^{presel}	ε_B^{δ}	ε_B^{total}
WP_{50}	0.98	0.51	0.50	0.70	0.050	0.035
WP_{40}	0.98	0.41	0.40	0.70	0.012	0.008



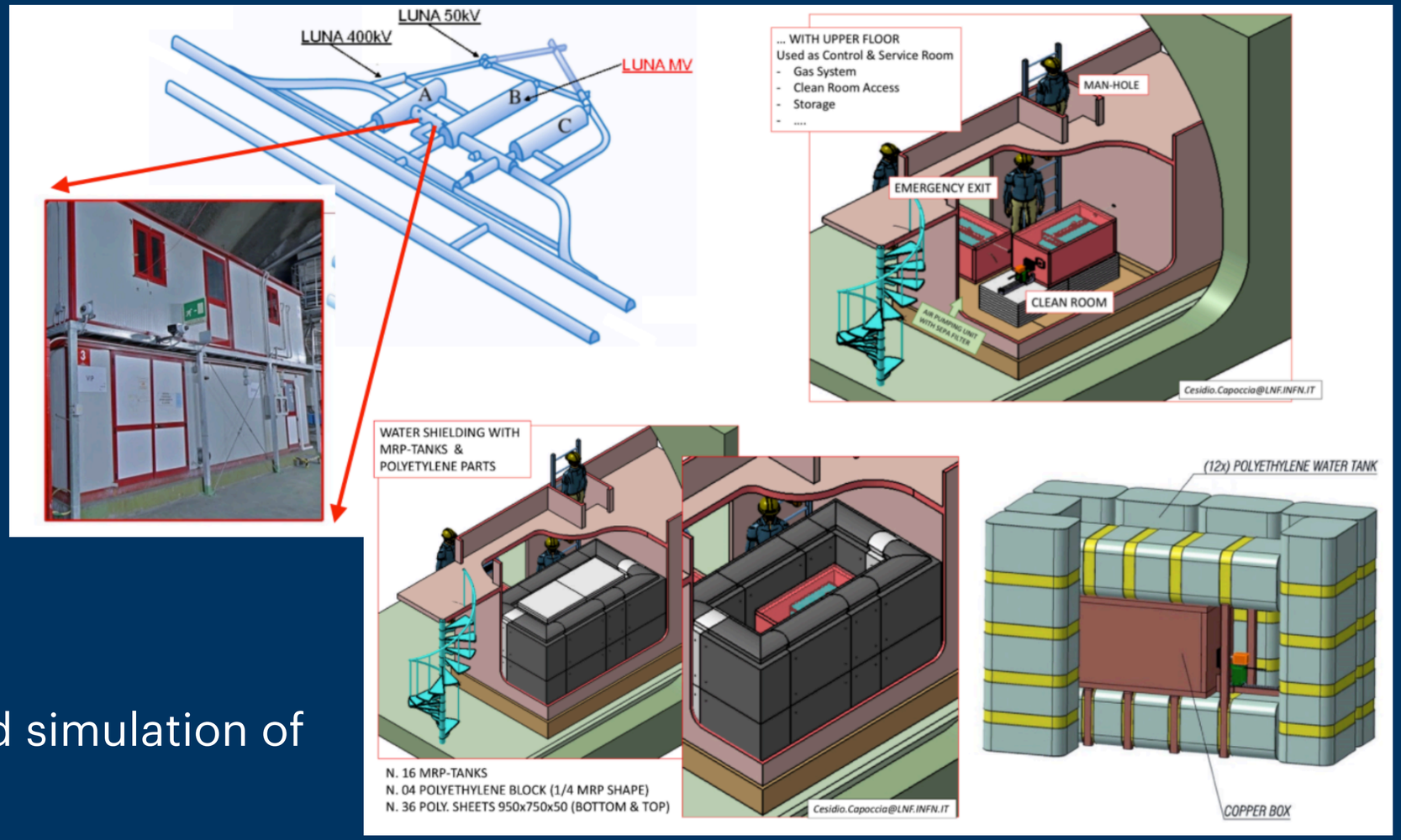
A sizeable efficiency in the range 5-10 keV was measured while more than **95% (99%) ^{55}Fe photons** were **rejected**

LIME UNDERGROUND

Lime is expected to be installed underground at LNGS (3600 m.w.e.) by the summer;

Neutron and other background flux will be studied.

Then, gamma (10 cm copper) and neutron (50cm water) shields will be put in place to take date in shielded mode



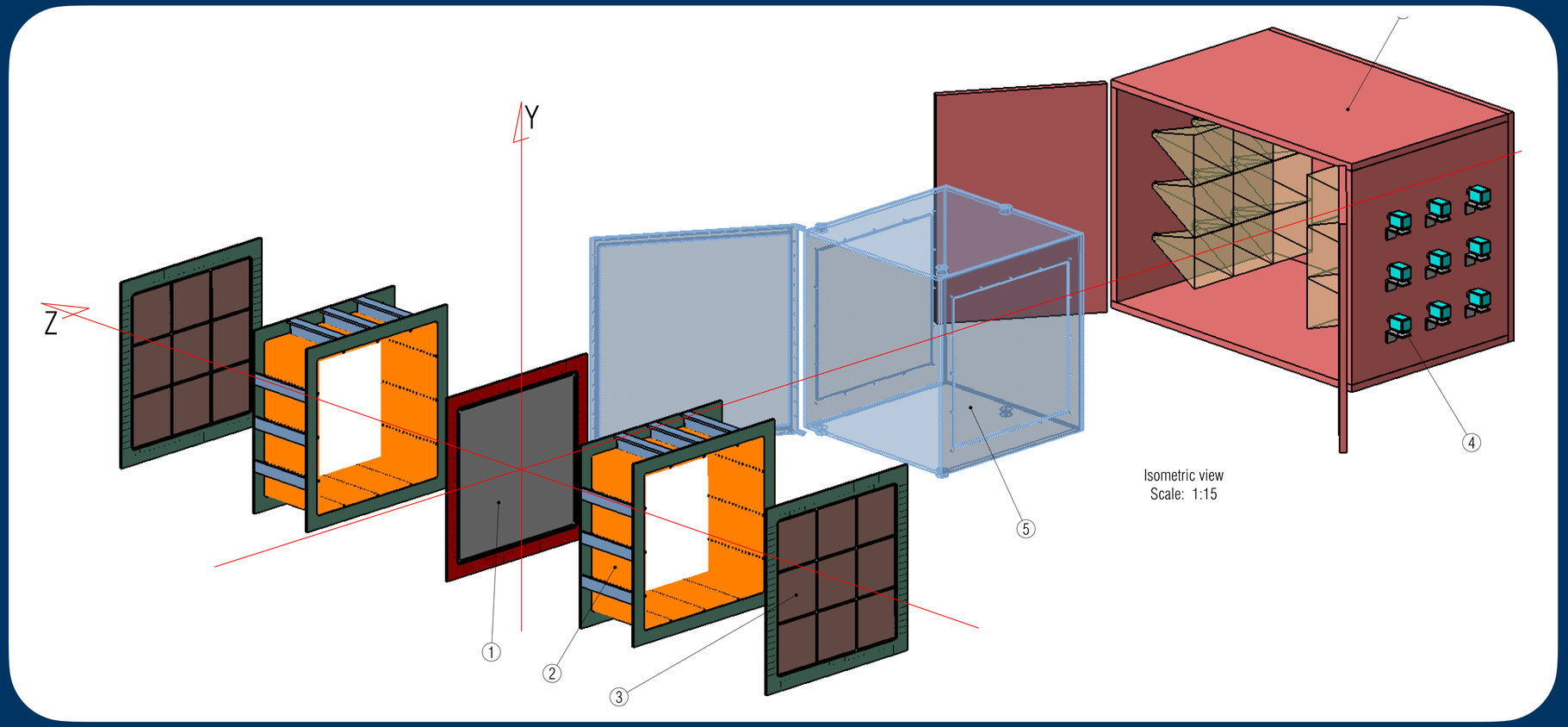
See Flaminia's talk about detailed simulation of detector and background:

https://indico.fnal.gov/event/46746/contributions/210387/

1M³ DEMONSTRATOR: BASELINE LAYOUT

1 m³ of **He/CF_4 60/40** (1.6 kg) at **atmospheric pressure** with a composed by two 50 cm long TPC with a central cathode and a drift field of about 1 kV/cm;

Acrylic vessel ensuring gas tightness and high voltage insulation;



Each side equipped by a 3x3 matrix of LIME-like:

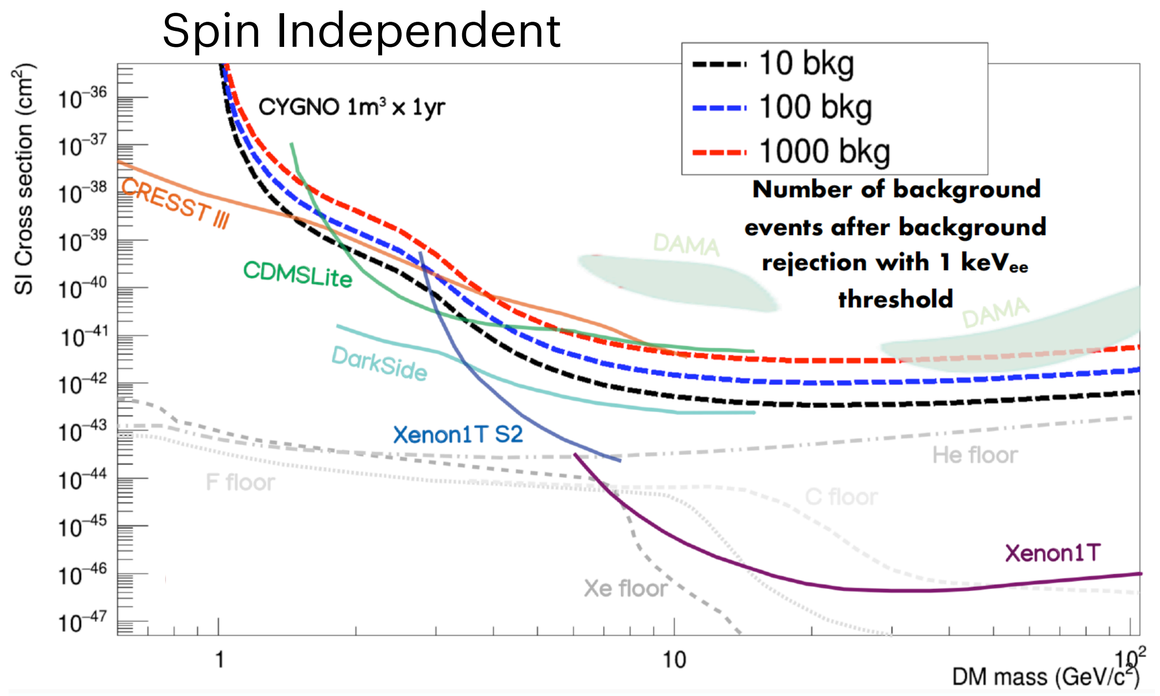
- sCMOS sensor 65 cm away;
- Almost 10^8 readout pixels 165 x 165 μm^2
- Fast light detector (PMT or SiPM).

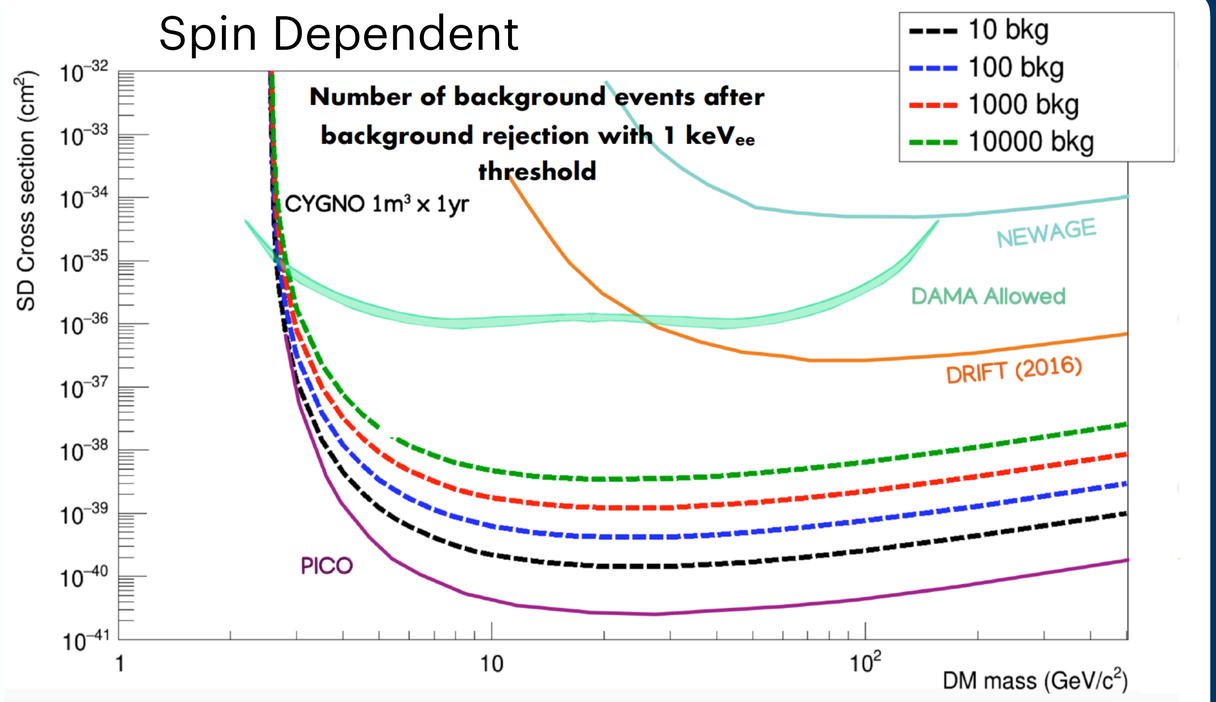
Radioactivity shielding:

- **5 cm** thick **copper** box (Faraday cage too);
- **200 cm** of water.

WHAT CYGNO CAN DO: DM SEARCH AND STUDY

1 cubic meter, 1 year exposure





DAMA region covered even with 1000 bkg events

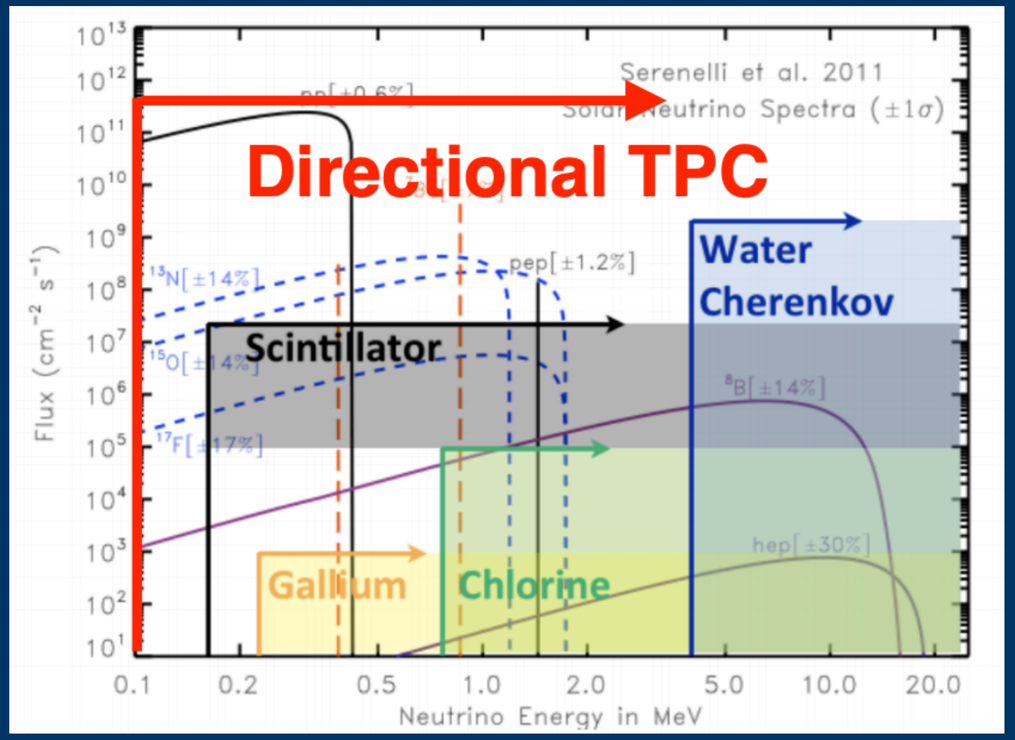
Already competitive with 1 m³

If DM is found, directionality will be crucial to confirm discovery and individuate its source

30 cubic meters, 3 year = 150 kgyr exposure

WHAT CYGNO CAN DO: NEUTRINO SPECTROSCOPY

Elastic neutrino - electron scattering with gaseous TPC: revitalising old ideas

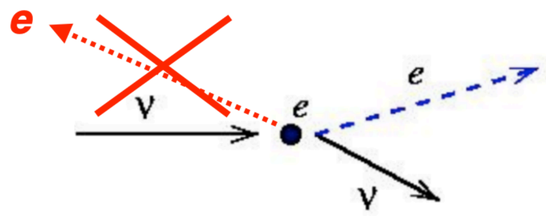


- sub-millimetre tracking capability (Borexino is 12 cm)
- 10 keV directional threshold on electrons
- keV energy resolution
- low mass

For 1 m³ of He:CF₄ 60:40 with 20 keV threshold

$$R = N_e \cdot \int_{E_{min}}^{E_{max}} w(E)\varphi_{ppI}(E)\sigma(E)dE \qquad R = 2.9 \cdot 10^{-8}\ \frac{events}{s \cdot m^3} = 0.9\ \frac{events}{y \cdot m^3}$$

Given the Sun position, recoils in opposite direction are kinematically forbidden



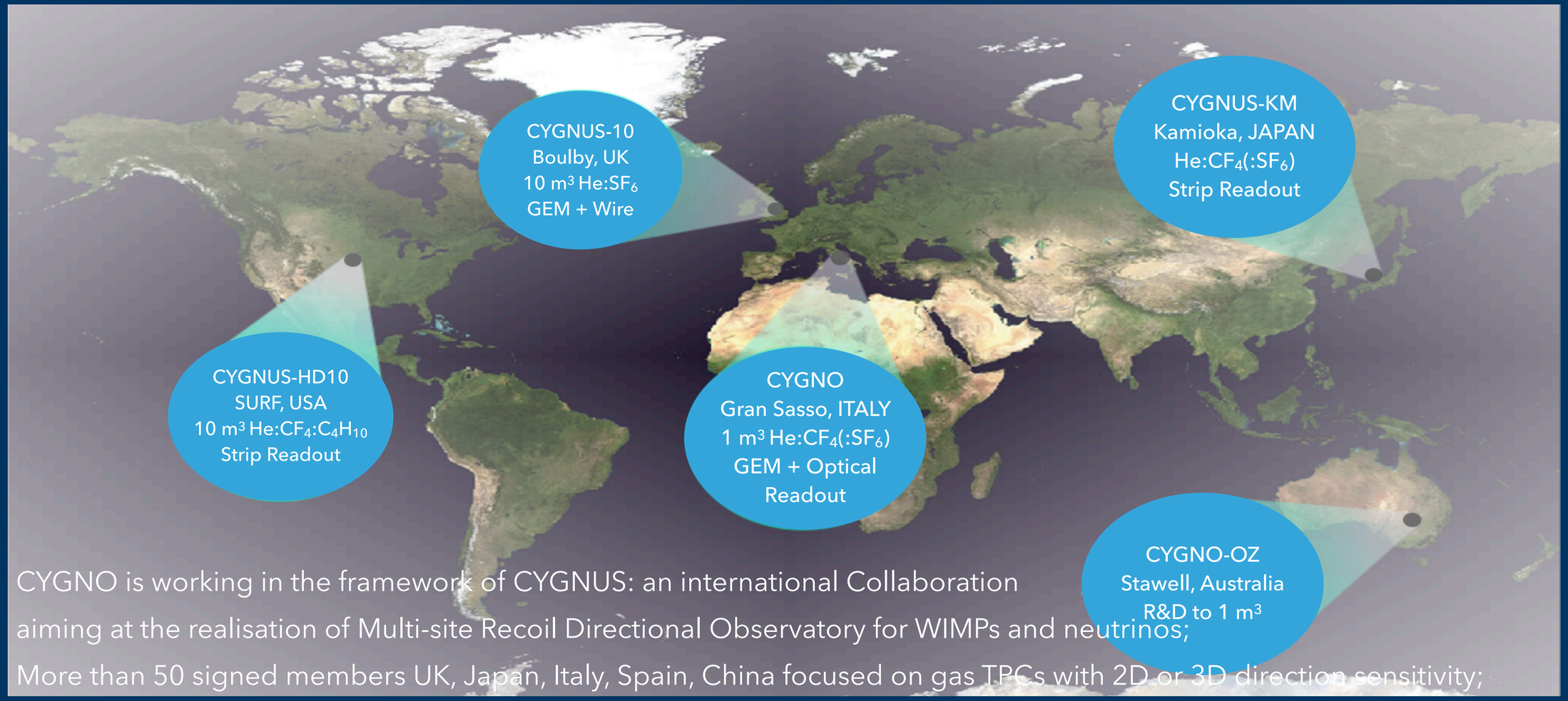
Differently from WIMPs, background can be measured on sidebands data

- Directionality will be crucial

CONCLUSION

CYGNO project is developing a **GEM-based TPC optically readout** for rare event studies

Very promising performance was found in the (few) keV region



CYGNO is working in the framework of CYGNUS: an international Collaboration aiming at the realisation of Multi-site Recoil Directional Observatory for WIMPs and neutrinos;

More than 50 signed members UK, Japan, Italy, Spain, China focused on gas TPCs with 2D or 3D direction sensitivity;

THANKS!


FISICA
FISICO
MARCONI
CYGNUS 2019
10 - 12 July 2019
Seventh workshop on directional dark matter searches
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