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


in synergy with

funded from ERC in Horizon 2020 program (grant agreement 818744)
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;

\[
\rho = \frac{m_{\text{WIMP}}}{m_{\text{target}}}
\]

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

\[
\epsilon = \frac{4\rho}{(\rho + 1)^2}
\]
- Large regions of high masses spectrum already explored without any confirmed evidence of WIMP;

- Future focus on masses below 10 GeV;

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

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

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

G. Charpak at al., NIM A258 (1987) 177
Triple GEM structure (10x10 cm$^2$) with 1 cm sensitive gap.

An He/CF$_4$ (60/40) mixture was used at atmospheric pressure.

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

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

Highly ionising tracks.
**PROJECT PHASES**

**PHASE 0: R&D**
- 2015/16
  - ORANGE
    - 1 cm drift
  - LEMON
    - 3D printing
    - 20 cm drift
  - LIME
    - 50 cm drift
    - underground tests
    - shielding

**PHASE 1: ~1 m³ Demonstrator**
- 2017/18
  - Construction & test
- 2019/20
  - Installation & commissioning
- 2021/22
  - CYGNUS RD - CSN5
  - NITEC
- 2023
  - CYGNO - CSN2
  - INITIUM
  - CYGNUS
  - 30-100 m³

**PROJECT PHASES**

CPAD Instrumentation Frontier Workshop 2021 - D. Pinci INFN Roma1 on behalf of CYGNO Collaboration
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
- 95% collection efficiency for Drift Field of 0.75 kV/cm
- Sensor noise below 200 photons (i.e. 400 eV)

$D_T = \frac{135 \mu m}{\sqrt{cm}}$

Measured Diffusion coefficient in agreement with Garfield expectations.
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 $\eta = S/A$ increases.

Both methods gives 12% precision: $\sigma_z \sim 6$ cm @ 50 cm.
PERFORMANCE WITH NUCLEAR RECOILS

A sizeable efficiency in the range 5-10 keV was measured while more than $95\%$ ($99\%$) $^{55}\text{Fe}$ photons were rejected.
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/
1 m³ of He/CF₄ 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 $\mu$m²
- 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

Spin Independent

Spin Dependent

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

Directionality will be crucial

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

\[ R = N_e \cdot \int_{E_{\text{min}}}^{E_{\text{max}}} w(E) \varphi_{\text{ppt}}(E) \sigma(E) dE \]

\[ R = 2.9 \times 10^{-8} \frac{\text{events}}{s \cdot m^3} = 0.9 \frac{\text{events}}{y \cdot m^3} \]
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!