MIMAC
(Micro-tpc MAtrix of Chambers)
searching for Axion-Like Particles (ALPs)
and opening the possibility for directional DM

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DSU- Buenos Aires (Argentina), July 17th 2019
Directional detection: principle

The signature able to correlate the rare events in a detector to the galactic halo !!
There are many possible “angles” for nuclear recoils... it’s an angular distribution. 3D tracks are needed...

Map of recoils in galactic coordinates (HealPix)

$10^8$ Events with $E_R = [5,50]$ keV
Robust with respect to Background events

100 WIMP evts + 100 Background evts
Phenomenology: **Discovery**

**Proof of discovery:** **Signal pointing toward the Cygnus constellation**

**Blind likelihood analysis in order to establish the galactic origin of the signal**

$\mathcal{L}(\ell, b, m_\chi, \lambda)$

*Strong correlation* with the direction of the Constellation *Cygnus* even with a large background contamination

**J. Billard et al., PLB 2010**

**J. Billard et al., arXiv:1110.6079**
MIMAC: Detection strategy

Scheme of a MIMAC µTPC

Evolution of the collected charges on the anode

Measurement of the ionization energy:
Charge integrator connected to the mesh coupled to a FADC sampled at 50 MHz

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D. Santos (LPSC Grenoble)
MIMAC-bi-chamber module prototype

- Light WIMP mass
- Axial coupling

**MIMAC Target:** $^{19}\text{F}$
Dedicated fast electronics (self-triggered)
Based on the MIMAC chip (64 channels)

3D - track

D. Santos (LPSC Grenoble)
MIMAC (bi-chamber module) at Modane Underground Laboratory (France)

- working at 50 mbar
  \((\text{CF}_4 + 28\% \text{ CHF}_3 + 2\% \text{ C}_4\text{H}_{10})\)

- in a permanent circulating mode
- Remote controlled and commanded
- Calibration control twice per week

Many thanks to LSM staff

D. Santos (LPSC Grenoble)
In any case one needs to measure the ionization released by the particles in the active volume.

Example of calibration (MIMAC)

X-ray generator producing fluorescence photons from Cd, Fe, Cu foils.
Threshold ~ 1 keV (but not a max. gain!)

Circulation system:
Excellent Gain stability in time
A “recoil event” (~ 34 keVee)
Angular resolution measured with COMIMAC ($^{19}$F ions at known kinetic energies) (Y. Tao, I. Moric, et al. (arXiv1903.02159))

**Figure 8.** MIMAC angular resolution as a function of $^{19}$F ion kinetic energy. At lower energies, the ion tracks are shorter and have more straggling resulting in worse angular resolution and bigger error bars. The angular resolution is better than 20° down to a kinetic energy of 6.3 keV, and is below 10° for a kinetic energy of 9.3 keV. Error bars are derived from the pixel strips pitch and reconstructed track length as described in the text.
Standard Axion (QCD axion)

Strong CP problem and AXION:

→ QCD has a CP violation term,

→ but this violation is not at all observed!

→ Global Symmetry Broken $U(1)_{PQ} \Rightarrow$ axion

Effectif Lagrangian after broken symmetry $U(1)_{PQ}$:

\[ L^{\text{eff}} = L_{QCD} + \frac{1}{2} \left( \partial_{\mu} a \right)^{2} - \frac{1}{2} m_{PQ}^{2} a^{2} \]
\[ + \frac{a}{f_{PQ}} \xi \frac{g_{s}^{2}}{32\pi^{2}} G^{\mu\nu}_{a} \tilde{G}_{a\mu\nu} + \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}_{\mu\nu} \]
Standard Axion

\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{QCD} + \frac{1}{2} (\partial_\mu a)^2 - \frac{1}{2} m_{PQ}^2 a^2 \]

\[ + \frac{a}{f_{PQ}} \xi \frac{g_s^2}{32\pi^2} G_\mu^a G_\mu^a + \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}_{\mu\nu} \]

Parameters:

- \( f_{PQ} \): Symmetry broken scale
- \( g_{a\gamma\gamma} = \frac{\alpha_{em}}{2\pi f_{PQ}} \left( \frac{E}{N} - 1.92(4) \right) \)
- \( \frac{E}{N} = \begin{cases} 0 & \text{for KSVZ} \\ \frac{8}{3} & \text{for DFSZ} \end{cases} \)
- \( m_{PQ} = 5.70(7) \left( \frac{10^{12} \text{GeV}}{f_{PQ}} \right) \mu\text{eV} \)
- \( \tau_{a\rightarrow\gamma\gamma} = \frac{64\pi}{g_{a\gamma\gamma}^2 m_{PQ}^3} \)
Standard Axion

\[ \mathcal{L}^{\text{eff}} = \mathcal{L}_{QCD} + \frac{1}{2} (\partial_\mu a)^2 - \frac{1}{2} m_{PQ}^2 a^2 + \frac{a}{f_{PQ}} \xi \frac{g_s^2}{32\pi^2} G_\alpha^{\mu\nu} \tilde{G}_\alpha^{\mu\nu} + \frac{g_{\alpha\gamma\gamma}}{4} a F^{\mu\nu} \tilde{F}_{\mu\nu} \]

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Constrains :

- \( 10^9 \lesssim f_{PQ} \lesssim 10^{12} \text{ GeV} \)
- \( 10^{-5} \lesssim m_{PQ} \lesssim 10^{-2} \text{ eV} \)
- \( 10^{30} \lesssim \tau_{a\rightarrow\gamma\gamma} \lesssim 10^{45} \text{ jours} \)

⇒ Dark Matter candidate but \( a \rightarrow \gamma\gamma \)

needs an external magnetic field to force the decay...
Axions in compactified extra-dimensions

Compactified Spatial Extra-dimensions:

- SM particles confined in $(1 + 3)D$
- Singlet gage bosons (axion, graviton, ...) can propagate in $(1 + 3 + \delta)D$ space-time with $\delta \leq n$ extra dimensions
- Extra-dimensions with a compactification radius $R < 30 \mu m$

\[ M_P = (2\pi R M_S)^{n/2} M_S \]
with $M_S \sim \mathcal{O}(\text{TeV})$

\[ \hat{f}_{PQ} \equiv (2\pi R M_S)^{\delta/2} f_{PQ} \]
\[ \hat{f}_{PQ} \gg f_{PQ} \]
Kaluza-Klein decomposition:

\[ a(x^\mu, y) = \sum_{n=0}^{\infty} a_n(x^\mu) \cos \left( \frac{ny}{R} \right) \]

- In observable space, the axion would be a superposition of KK continuum states

\[ \mathcal{L}_{\delta=1}^{\text{eff}} \supset \frac{\xi}{f_{PQ}} \frac{g_s^2}{32\pi^2} \left( \sum_{n=0}^{\infty} r_n a_n \right) G_{\alpha}^{\mu\nu} \tilde{G}_{\alpha\mu\nu} \]
Axions in extra-dimensions

Decay $a_n \rightarrow \gamma \gamma$:

$$\tau(a_n \rightarrow \gamma \gamma) \sim \left(\frac{m_{PQ}}{m_{a_n}}\right)^3 \tau(a_0 \rightarrow \gamma \gamma)$$

- Each KK-axion decay $\Rightarrow$ continuum
- In the Sun, $m_{a_n} \sim \mathcal{O}(10 \text{ keV})$

$$\Rightarrow 10^{11} \lesssim \tau_{a_n \rightarrow \gamma \gamma} \lesssim 10^{17} \text{ days}$$

$a_n \rightarrow \gamma \gamma$ is detectable
Solar Kaluza-Klein Axions production

Kaluza-Klein Axions with masses between $(1 - 30)$ keV
Two sources of production in the Sun (Primakoff effect + photon Coalescence)

\[ \delta=n=2 \; ; \; R=10^3 \text{ keV}^{-1} \]

\[ g_{\gamma \gamma} = 9.2 \times 10^{-14} \text{ GeV}^{-1} \]
KK- axion Orbits for different velocities

$V_{\text{esc}} = 617 \text{ km/s}$

t=1.593 \times 10^8 \text{ s}

D. Santos (LPSC Grenoble)
KK-axion orbits

$t = 1.593 \times 10^9$ s
$v(R_{\text{sun}}) = 0.9993v_{\text{esc}}$

D. Santos (LPSC Grenoble)
Event rate expected from the direct flux and gravitationally trapped ALP's.
Efficiency as a function of the Gas and pressure

Detectable events - MC simulations 2m³ (Solar KK axion model)
X-rays calibration in $^{40}$Ar + 5% C$_4$H$_{10}$ (300 mbar)

Calibration

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>$\chi^2 / \text{ndf}$</td>
<td>2225 / 323</td>
</tr>
<tr>
<td>Amplitude 3keV</td>
<td>517.7 ± 7.2</td>
</tr>
<tr>
<td>Mean 3keV</td>
<td>300.1 ± 0.4</td>
</tr>
<tr>
<td>Width 3keV</td>
<td>41.34 ± 0.51</td>
</tr>
<tr>
<td>Amplitude 5keV</td>
<td>45.85 ± 6.34</td>
</tr>
<tr>
<td>Mean 5keV</td>
<td>447.2 ± 6.5</td>
</tr>
<tr>
<td>Width 5keV</td>
<td>35.55 ± 4.54</td>
</tr>
<tr>
<td>Amplitude 6keV</td>
<td>57.7 ± 4.0</td>
</tr>
<tr>
<td>Mean 6keV</td>
<td>556.5 ± 9.1</td>
</tr>
<tr>
<td>Width 6keV</td>
<td>54.89 ± 6.54</td>
</tr>
<tr>
<td>Amplitude 8keV</td>
<td>159.1 ± 2.4</td>
</tr>
<tr>
<td>Mean 8keV</td>
<td>743.9 ± 2.9</td>
</tr>
<tr>
<td>Width 8keV</td>
<td>95.23 ± 2.21</td>
</tr>
</tbody>
</table>

3 keV (XL-Cd)

8 keV – XK-Cu)
COMIMAC

A calibration tool for gas detectors
(Electrons and Nuclei of known kinetic energies)

Electrons of 7 keV
Electrons Performance

3 keV

mean = 102.28
FWHM = 18.5%
Electrons

9 keV

mean = 309.87
FWHM = 12.3%
Two $e^-$ (4 keV) sent by COMIMAC (in less than 2 us)

Energies
1st cluster: 447 ADC
2nd cluster: 448 ADC

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D. Santos (LPSC Grenoble)
Mean free path of photons in Ar +5% isobutane (300 mbar) as a function of their energy (keV)
Efficiency in the Argon mixture at 300 mbar vs. KK-axion mass
Event rate vs. KK-axion energy

95% Ar + 5% C\textsubscript{4}H\textsubscript{10} - 300 mBar
MIMAC 2m\textsuperscript{3}
\(\delta=n=2\); \(R=10^3\) keV\textsuperscript{-1}
\(g_{a\gamma\gamma} = 9.2\times10^{-14}\) GeV\textsuperscript{-1}

71% detected

D. Santos (LPSC Grenoble)
Exclusion curves

Sensitivity to trapped axions

95% Ar + 5% C$_2$H$_4$ - 300 mBar
MIMAC 2m$^3$ - 365 days
\(\delta=n=3 : R=10^5\) keV

Preliminary results

Log$_{10}$ coupling \(g_{\text{av},\tau}\) [GeV$^{-1}$]

Log$_{10}$ axion density on Earth [m$^3$]

MIMAC preliminary exclusion
XMASS exclusion limit
Solar KK axion model

D. Santos (LPSC Grenoble)
New MIMAC low background detector

Kapton micromegas readout
Piralux Pilar

Gaz : MIMAC 50 mbar
HT grille : -560 V
Drift field : -150 V/cm

16.3 % FWHM (6 keV)
Gain ~25 000
Energy threshold <1 keV
D. Santos (LPSC Grenoble)
The 35 cm “new technology” MIMAC detector compared to the old one
MIMAC \(- 2m^3 = 16\) bi-chamber modules \((2 \times 35 \times 35 \times 52 \text{ cm}^3)\)

New technology anode
35cmx35cm

Stretched thin (12 um) grid at 512um.

New electronic board (1792 channels)

Only one big chamber
Conclusions

- A new directional detector of nuclear recoils at low energies has been developed giving a lot of flexibility on targets, pressure, energy range…

- MIMAC with its 3D tracks at high spatial resolution opens a new window in the exploration of rare events!

- MIMAC-2m3 will explore ALPs and compactified dimensions

- At the same time the low energy H “recoils” from the C$_4$H$_{10}$ will be “3D tracked” exploring the low mass directional WIMP detection.