Contribution Prospectives 2020

Gas Detectors for Direct and Directional Dark Matter Detection

and Axion-Like Particle exploration

(NEWS-G and MIMAC)

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The hypothesis of the existence of non-baryonic dark matter (DM) is supported by all astrophysical observations performed from cosmological to local scales. The measurement of one clear experimental signal of these particles represents one of the most important challenges for particle physics and cosmology today.
At the local scale, our galaxy should have a halo composed of these particles.
The direct detection of a nuclear recoil of the active volume produced by an elastic collision of a weakly interacting massive particle (WIMP), the most accepted candidate for such a matter, has to be discriminated from those produced by the background.
NEWS-G (New Experiment for Wimps detection with a Sphere filled with Gas) project is dedicated to the direct search for very-low mass WIMPs, from 0.1 to 10 GeV. The main characteristics of the detector are [1]: sub-keV energy threshold, fiducialisation and background rejection by pulse shape analysis, ability to operate at pressures up to 10 bars, tens of kg of gas with various light targets as H, He, Ne nuclei. The installation of NEWS-G at SNOLAB is scheduled to start in November 2019.

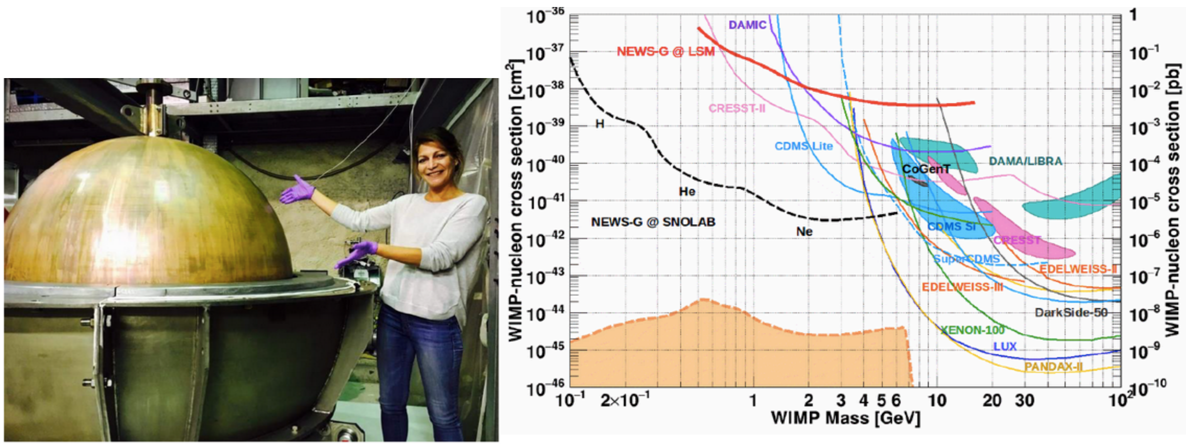

Figure 1: (left): The 1.4 m diameter sphere mounted inside a half of its lead shielding at Modane (August 2019). (right): The exclusion curves predicted using H, He or Ne as targets for a 1 year run at SNOLAB (Canada) [2].

A very important parameter in the observation of such low energy nuclear recoils is the ionization-quenching factor measured at Grenoble by an original method [3].

The only non-ambiguous signature to be able to discriminate the WIMP events from neutron~~s~~ or neutrino~~s~~ -induced events is to correlate these elastic collisions in the detector with the relative motion of our Solar system with respect to the galactic halo. The measurement of the direction of the nuclear recoil track of a few keV is called "directional detection". The directional detection opens a new field in cosmology: it brings the possibility to build a map of nuclear recoils exploring the galactic halo [4,5]. The MIMAC (MIcro-tpc MAtrix of Chambers) collaboration has developed in the last years an original prototype detector based on the direct coupling of a pixelized Micromegas with a specially developed fast self-triggered electronics showing the feasibility of a new generation of directional detectors [6]. The flexibility of the MIMAC detector to change the nucleus target,~~-~~its mass and spin, offers an alternative to confirm or discard candidates proposed by the large mass direct detection projects as LUX, Xenon1T, SCDMS, Edelweiss. **In the next five or ten years, these large mass detectors will either detect some candidates or they will be limited by the neutrino background floor. In both cases a directional detector will be needed to confirm the galactic halo origin of such candidates or to go further the neutrino background.**

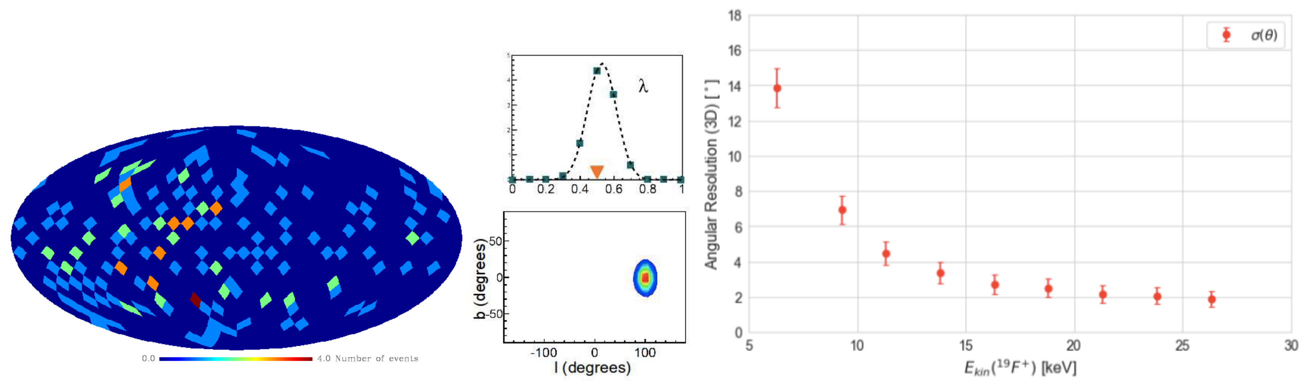

Figure 2 : (Left) The map made with 100 events assuming the neutron background at the same level than the signal (S/B=1) that means 50 Wimp events and 50 of background [4,5]. (Centre) The result of a maximum likelihood analysis of the map shown in (Left) giving the correct number of Wimp events (λ=S/(S+B)~0.5) and the directionality in galactic coordinates (l=90°,b=0°). (Right) Angular resolution of ^{19}F recoils measured as a function of its kinetic energy by MIMAC from 6 to 26 keV [7]

Theoretical candidates for Dark Matter particles cover a huge mass range from ultra light (10^{-33} eV) up to heavy particles (1 TeV). The absence of any robust signal from the direct detection and Large Hadron Collider (LHC) experiments along with other problems in particle physics and astrophysics compels us to open the scope of the experimental exploration. We propose a new mass window of experimental exploration from 100 eV up to 20 keV, performed by an original matrix detector, a new generation of micro-TPCs, having a low energy threshold (100 eV) with a high spatial 3D resolution in a large active volume having a lot of discrimination observables to cope with the different backgrounds, describing and understanding them.

The Axion-Like Particle (ALP) exploration is a very active research domain, both from the theoretical and experimental point of view-[8,9,16]. A very complete review has been recently published [10] covering masses lighter than 1 eV. The huge range of masses to be explored makes the experimental task very rich from the viewpoint of detection technology.

In our proposed region of exploration, most of the exclusion limits have been provided by astrophysics observation and cosmological constraints [36]. A few underground laboratory experiments have used their data and give the first exclusion limits on the axion-gamma $g_{a\gamma\gamma}$ and axion-electron g_{ae} couplings [11,12,13]. The main limitations of the two identical photons decay search, come from the active volume available for the decay. In a large volume, the background of photons or electrons in the range of interest is huge.

In order to improve the discrimination, a matrix detector of 2 m^3 based on small bi-chamber modules having individually a lower background count rate and sharing the same high discrimination quality, can give two orders of magnitude better on exclusion limits. This matrix concept increases the total discrimination and efficiency when all the chambers of the matrix are correlated. In such a way the active volume becomes an important and controlled degree of freedom for a rare events exploration.

Axions are pseudo Nambu-Goldstone bosons associated to the breaking of a global U(1) Peccei Quinn (PQ) symmetry, and they have been proposed to solve the strong CP-problem [14].

The mass of the PQ-axion or QCD-axion is constrained by astrophysical (upper limit) and cosmological considerations (lower limit) [10] to be in the range: $10^{-5}\, eV \, < \, m_a \, < \, 10^{-2}\, eV$

Due to their coupling to photons, the axion lifetime is given by [15]: $\tau_a = 64\pi/(\, g_{a\gamma\gamma}^2 m_a^3)$

which gives, for a QCD-axion, a lifetime much larger than the age of the universe, rendering the axion effectively stable. This also rules out the possibility of detecting the axion directly through this decay channel. Direct axion searches like CAST [19] look for axions coming from the sun in a strong magnetic field, forcing the decay by a Primakoff effect, and-[20] reported the limit:

$$g_{a\gamma\gamma} < 6.6\, 10^{-11}\, GeV^{-1} \;\; for \;\; m_a \, < \, 0.02\, eV$$

In parallel, in theories with n large extra dimensions [21], where gravity is free to propagate in all dimensions, the fundamental gravitational scale M_s can be much lower than the Planck scale M_P due to the extra dimensions volume suppression: $M_P = (2\pi R M_s)^{n/2} M_s$, where R is the common radius of the compact dimensions. The fundamental scale Ms has to be in the TeV range, in order to solve the hierarchy problem in the SM [22]. However, the case with n = 1 and $M_s \sim \mathcal{O}$ (1 TeV) would lead to too large extra dimensions and is already excluded [23, 36]. $M_s > 5.6$ TeV is the present limit on n=2, the cases $n \geq 2$ are not still excluded [35]. For an updated summary of the present experimental limits on large extra-dimensions (LEDs), see for example [23].

While the Standard Model particles only propagate in 3+1 dimensions, any other extra particle (singlet under the SM symmetry) may propagate in $\delta \leq$ n extra dimensions. This can be the case for the axions, and similarly to the gravitational scale, the 4-dimensional axion scale f_a can be much larger than the fundamental axion scale $\widehat{f_a} \sim M_s$ of the full theory: $f_a = (2\pi R M_s)^{\delta/2}\ \widehat{f_a}$. Without introducing any other fundamental constants besides M_s and the compactification radius R, i.e. taking $\widehat{f_a} = M_s$, if the axion propagates in the same number of extra dimensions than gravity, then the 4d axion scale will be at the Planck scale.
In these models, together with the standard QCD-axion, there is a tower of massive Kaluza-Klein (KK) states the lightest one providing the solution to the strong CP problem and a good candidate for DM. The KK axions, although they share with the "standard" axion a_0 the same coupling to the electromagnetic tensor, have masses orders of magnitude larger than m_a and therefore shorter lifetimes.

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

giving for $m_{a_n} \sim \mathcal{O}(10\ keV)$ a lifetime interval $\Rightarrow\ 10^{11} < \tau(a_n \to \gamma\gamma) < 10^{17}\ days$
This opens up the possibility of detecting this ALPs through their decay into two photons without the need of a strong magnetic field to force it.
Different experiments [24] and observations [25] have reported limits on ALPs. ALPs are just axion particles for which the PQ coupling-mass relation does not necessarily holds. KK-axions enter into this category. However, where ALPs are just single fields, KK-axions imply the existence of a tower of massive states, i.e., when computing fluxes from different processes all possible massive states should be added [18, 30].

Trapped ALPs from the Sun

An interesting and old astrophysics problem concerns the solar corona temperature ($T \sim 2\ 10^6$ K) [26]. The Solar corona is the layer starting at roughly 2000 km from the Sun surface, just after the chromosphere layer at 500 km from the Sun surface, which has a temperature of 5800 K [27]. The corona layer emits most of its thermal radiation in X-rays. In order to explain its high temperature an external heating source is needed. This additional X-ray source could be provided by solar ALPs decaying in two photons [28].

Axions can be produced in the Sun primarily due to the axion-photon coupling, either by the Primakoff process $\gamma + Ze \to a + Ze$ [29], or by photon coalescence $\gamma + \gamma \to a$ [30]. The later process is suppressed for small masses, as that of the QCD-axion. But KK-axions or ALPs can be produced by coalescence, up to masses of some keV. In [30], the solar flux of KK-axions by these two processes was computed.

Axions produced inside the Sun reaching the Sun surface with a velocity smaller than the escape velocity will be trapped by the Sun gravitational field. But if the velocity is too small, the bound orbits will not reach the Earth. Solving for the trajectory of a point particle in the external gravitational field of the Sun, we can estimate that this velocity must be close to the Sun escape velocity, v_{esc}= 617.3 km/s, to reach the Earth. In units of the speed of light, the velocity $\beta = v/c$ must be within the range $[2.054 \times 10^{-3}, 2.058 \times 10^{-3}]$. For this non-relativistic velocities, the energy is then given by $E = m(1 + \beta^2/2)$, with m the ALP mass.

We show in figure 3 the event rate from the direct flux from the Sun and those trapped by the Sun gravitational potential.

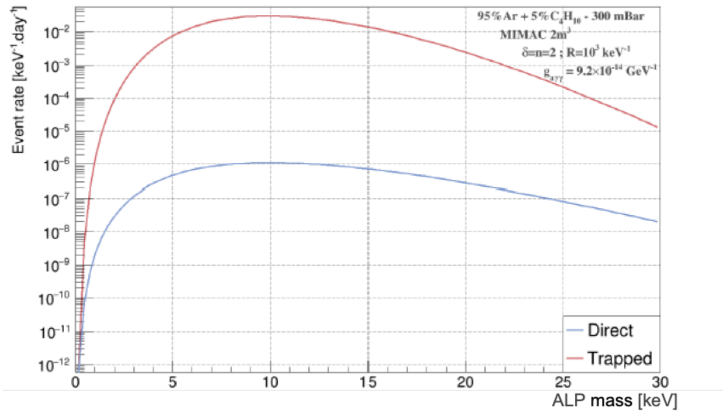

Figure 3: Event rate of KK-axion decay eventually detected in our active volume (2 m^3) at 300 mbar of ^{40}Ar + 5% C_4H_{10}, for $\delta = 2$ and R= 10^3 keV^{-1} with $g_{a\gamma\gamma} = 9.2\ 10^{-14} GeV^{-1}$ from the direct flux from the Sun (blue) and those trapped by the Sun gravitational potential (red).

We propose to search for these ALP decays into two identical photons, event by event, with a clear discrimination from the background in a large active volume (2 m^3) filled with an Argon based gas mixture at 300 mbar, by means of the Matrix-strategy detection improving by two orders of magnitude the present limits, see figure 4.

In [32], the XMASS collaboration searched for solar KK-axions by annual modulation. They considered the KK-axions trapped gravitationally in the solar system, leading to a time dependent number density $n_a(t)$. The exclusion limit is shown in figure 4 as a red curve.

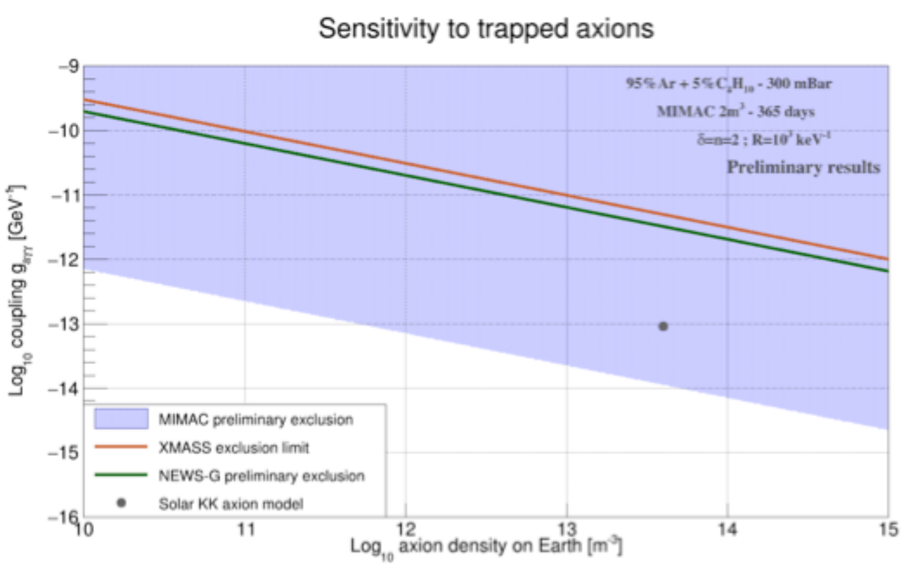

Figure 4: MIMAC (2m^3)-Exclusion region (blue) as a function of the axion density on Earth expected for 365 days compared with the XMASS exclusion limited by the red curve [25] and NEWS-G exclusion limited by the green curve (preliminary internal report [27]). The dot point shows the solar KK-axion model not yet excluded.

The NEWS-G collaboration [33] is proposing to search for these ALP decays by using the spherical gas detector with a 1.4 m diameter. The preliminary exclusion limit has recently been estimated for 1 year and it is shown in figure 4 as a green curve [34].

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