In Search of Dark Matter: MIMPs at the COSINE-100 Experiment

V. H. A. Machado, N. Carlin, L. E. F. M. França, B. B. Manzato, R. L. C. Pitta, on Behalf of COSINE-100U experiment

IFUSP
Instituto de Física da USP

MIMPS: an introduction

- Multiply Interacting Massive Particles (MIMPs) are Ultra-Heavy Dark Matter particles with mass $m_\chi \gtrsim 10^{10}$ GeV/c^2, which interacts strongly with baryonic matter but may have evaded detections due to the low density number required to form local dark matter halo.
- Super-massive relic particles with per-nucleon cross section in the 10^{-40}-10^{-20} cm^2 range arise naturally in unifying theories that predict colored and electroweak stable states [1], as well as supersymmetric models [2], and can be produced out of equilibrium in the early Universe [3].

Direct Detection

- Similarly to WIMPs, MIMPs can also interact with Standard Model (SM) particles by elastically scattering off nuclei, providing a detection mechanism. The MIMP-nucleon cross section parameterizes the interaction strength between the MIMPs and SM. Depending on the underlying coupling, the interaction may be classified as spin-independent (SI) or spin-dependent (SD). This work presents only the SI case.
- Canonical definitions for the dark matter-nucleon cross section in the SI case were adopted [4]. For a target nucleus with atomic number A, dark matter-nucleus reduced mass $\mu_{N\chi}$, and dark matter-nucleon reduced mass $\mu_{n\chi}$, the SI per-nucleon cross sections in terms of the per-nucleus cross sections is given by:

$$\sigma_{n\chi} = \left(\frac{\mu_{n\chi}}{\mu_{N\chi}}\right)^2 \frac{1}{A^2}\sigma_{N\chi}^{SI(0)} \propto \left(\frac{1}{A^4}\right)\sigma_{N\chi}^{SI(0)} \qquad (1)$$

- The differential dark matter-nucleus SI scattering cross section is described by:

$$\frac{d\sigma_{N\chi}^{SI}}{dE_R} = \frac{m_N}{2\mu_{N\chi}^2 v_\chi^2}\left(\frac{\mu_{N\chi}}{\mu_{p\chi}}\right)^2 A^2 \sigma_{p\chi}^{SI}|F_N(E_R)|^2 \qquad (2)$$

- MIMPs are slowed by multiple scatterings in the atmosphere, Earth overburden, and shielding. Larger MIMP–nucleon cross sections eventually make the particles undetectable. This defines an upper sensitivity boundary.
- Above the saturation cross section ($\sigma_{SOS} = n^{-2/3}$) the overburden becomes effectively opaque, and further increases in cross section no longer produce additional energy loss. The overburden density is assumed as n = 2.7g/cm^3 for ~1-2 km overburden. For SI scattering σ_{SOS} = 1,3.10^{-20} cm^2.

The COSINE-100 Experiment

- COSINE is a NaI(Tl) direct detection dark matter experiment, a collaboration between the DM-Ice and KIMS experiments [5]. The first phase of the experiment deployed 106 kg of NaI(Tl) at Yangyang underground laboratory in South Korea, with ~700m of rock overburden. COSINE-100 was started taking data in summer 2016.
- The detector is contained within a nested arrangement of shielding components. From Fig.1, the shielding components include plastic scintillator panels (blue), a lead brick enclosure (grey) and a copper box (reddish brown). The eight encapsulated sodium iodide crystal assemblies are located inside the copper box and are immersed in scintillating liquid.
- COSINE-100 experiment searches for dark matter directly through three detectors: muon panels, scintillating liquid and NaI(Tl) crystals.

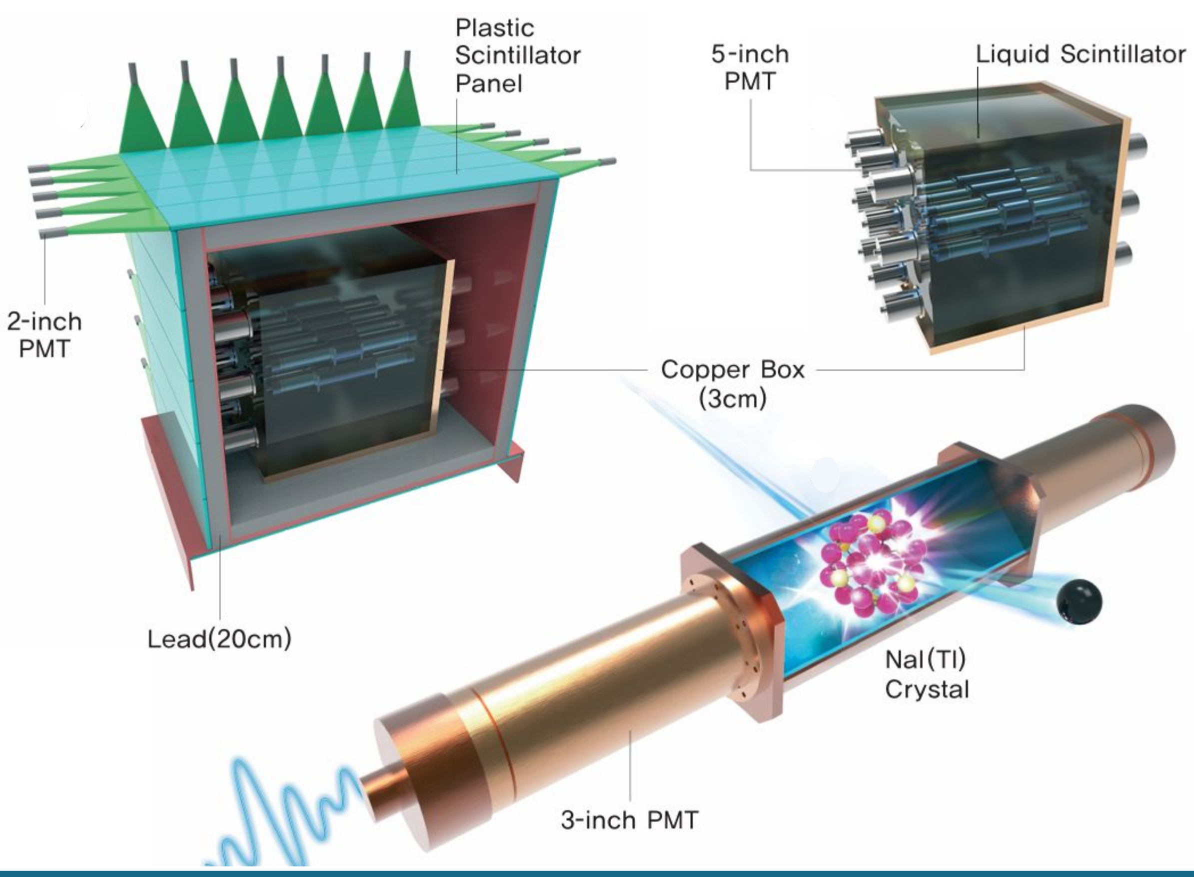


Fig. 1 – Schematic images of the COSINE-100 detector. The detector is contained within a nested arrangement of shielding components, as indicated by different colours. The main purpose of the shield is to provide 4π coverage against external radiation from various background sources.

SI interaction signal model

- This work aims to investigate the apparent signal of a MIMP, characterized by an ionization pulse, in up to three of the detectors, from the backgrounds present in the detectors comparing the number of selected events and events expected for the background in order to test any excess signal. COSINE-100 data from September 2016 to July 2019 will be analyzed, called SET 3.
- The energy loss of MIMPs in the Earth's overburden before reaching the detector was numerically calculated using Verne dark matter library [5]. Figure 2 and 3 report the speed distribution and the recoil energy spectrum for a MIMP with mass $m_\chi = 10^{13}$ GeV/c^2 and SI cross section $\sigma^{SI}_{p\chi} = 10^{-24}$ cm^2, respectively.

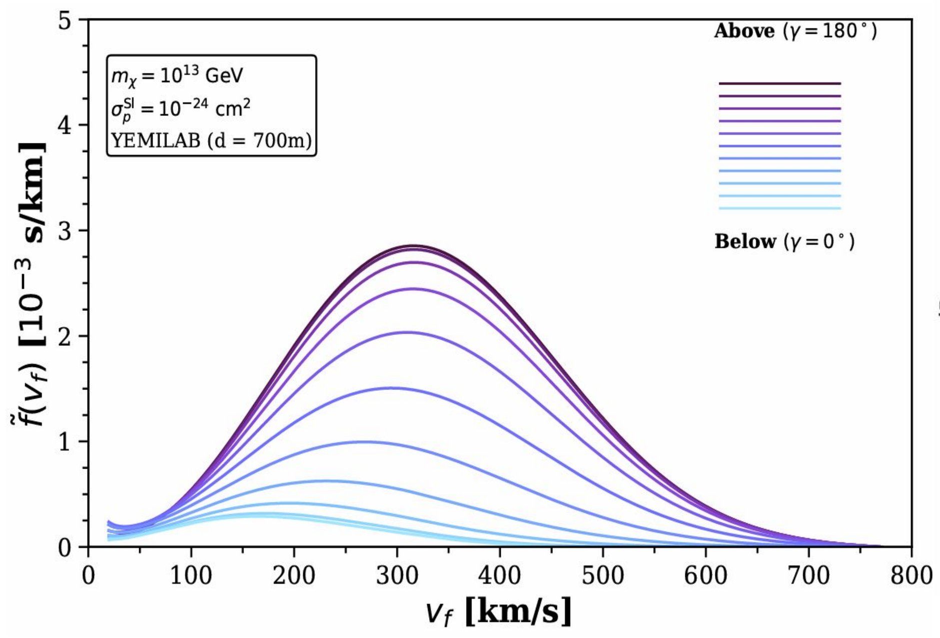


Fig. 2 – Velocity distribution in the detector rest frame for different incoming directions with respect to the detector's vertical axis (γ). Darker colors represent candidates traveling the shortest path to the detector (from above) and lighter colors through most of Earth's overburden before reaching the detector (from below).

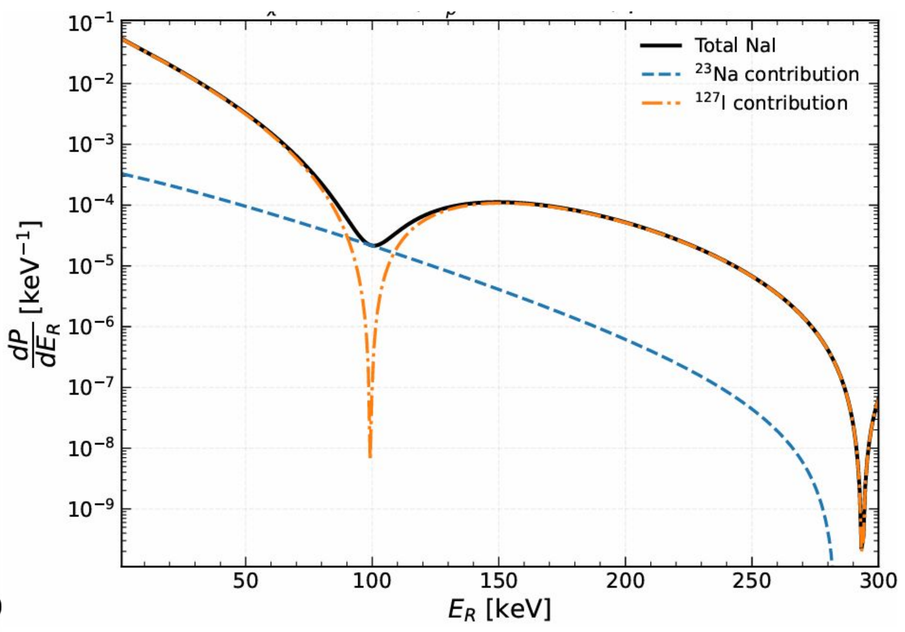
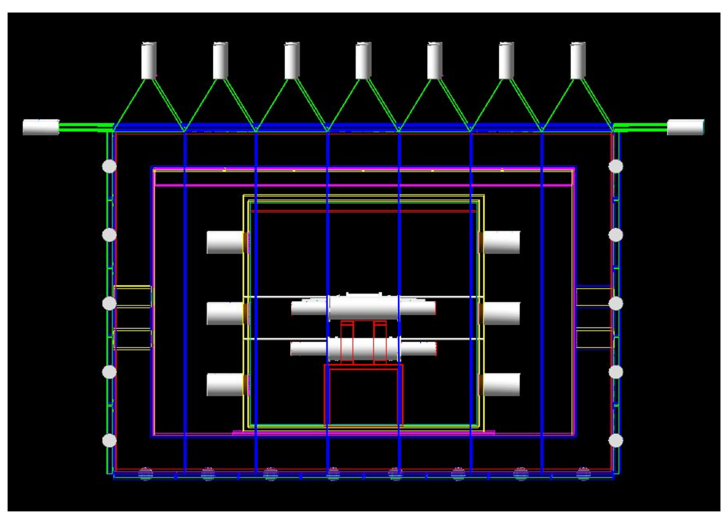


Fig. 3 – Energy spectrum of a MIMP arriving at the detector with γ=144°. The iodine dominates most of the spectrum, while the sodium contributes mainly at lower recoil energies. The oscillatory features and minima are produced by the Helm form factor, encoding loss of nuclear coherence at high momentum transfer.

GEANT4 application

- MIMP-induced events were modeled with Geant4 using the full COSINE-100 detector geometry developed by the collaboration, as shown in Fig. 4.
- The simulation framework was extended with a new created MIMP particle, a discrete MIMP–nucleus scattering process, and a dedicated DMPhysicsList.



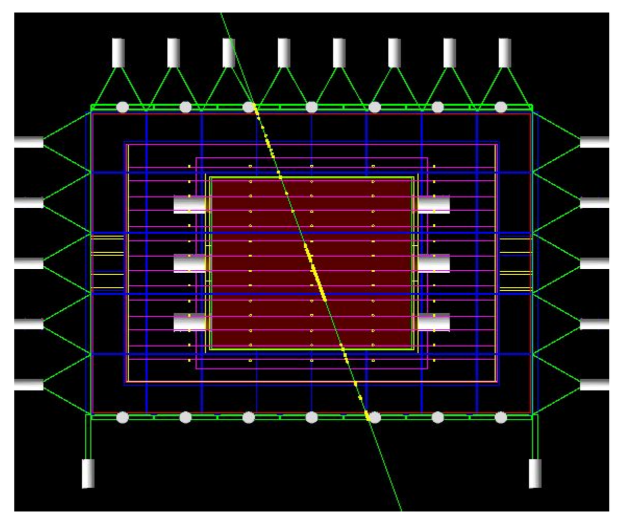


Fig. 5 –Simulation result of a MIMP (green line) traversing the detector geometry. The elastic scatters are represented by the yellow dots. It is possible to see many MIMP interactions inside the LSVetoSystem region.

Fig. 4 – COSINE-100 full detector geometry developed by the collaboration. From outer to inner: muon panels (green) with photomultipliers (PMTs) attached, lead (blue) and copper (orange) shields, the acrylic box (yellow) with PMTs attached and the crystals array (opaque grey cylinders) with one PMT at each side.

SI interaction first results and projected sensitivity

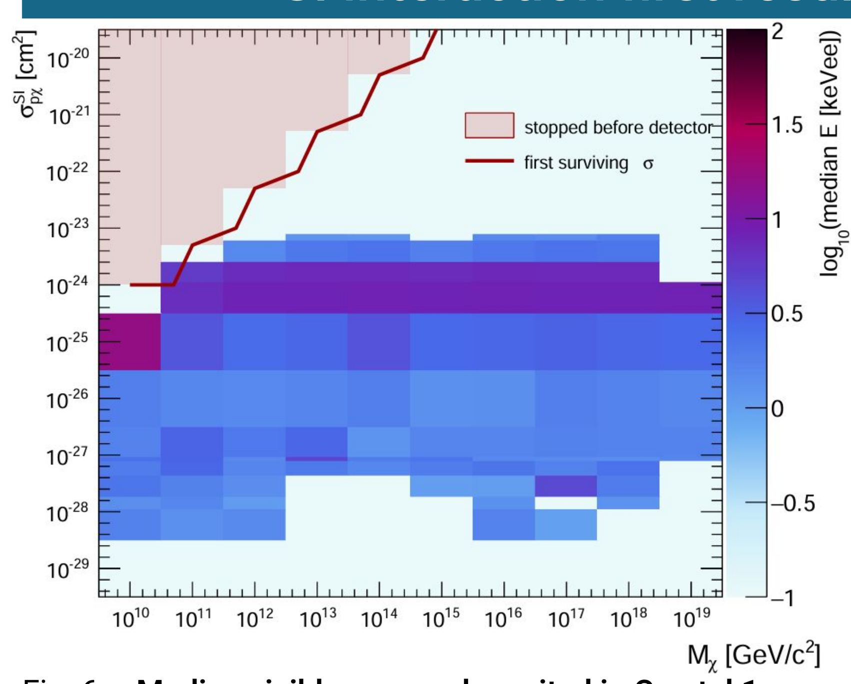


Fig. 6 – Median visible energy deposited in Crystal 1 as a function of MIMP mass and MIMP–nucleon cross section. Each bin corresponds to one simulated parameter-space point. The red shaded region (upper left) indicates parameter points for which MIMPs are stopped before reaching the detector. The red line marks the first surviving cross section for each mass, separating the accessible and inaccessible regions of parameter space.

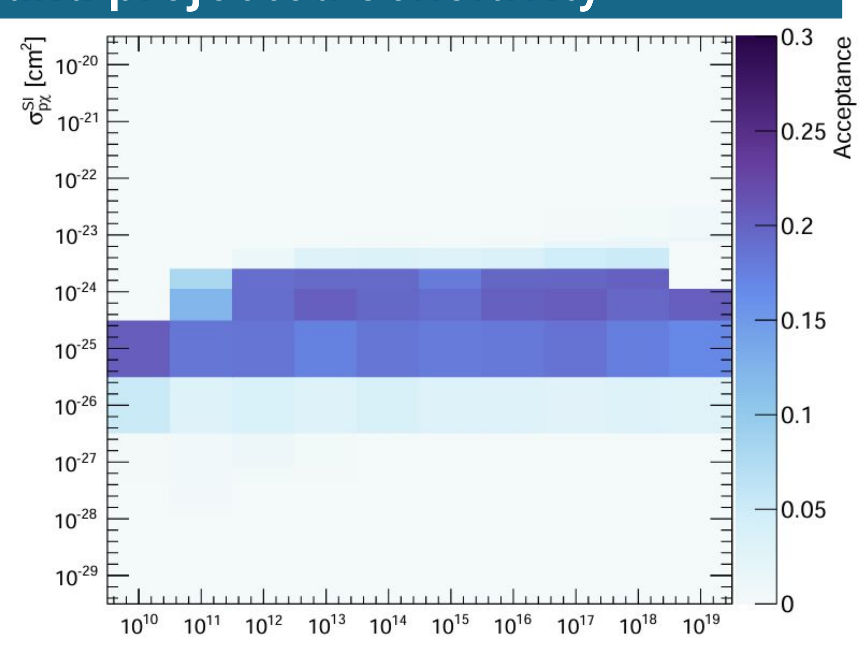


Fig. 7 – Accepted events are required to have one or more NaI(Tl) crystals with visible energy above 1 keVee within the DAQ time window from −2.4 μs to +5.6 μs relative to the trigger [5]. The color scale represents the detector acceptance after applying both crystal energy threshold and time integration window. The high-acceptance band appears where MIMPs are likely to scatter in the detector while still retaining sufficient flux to reach the COSINE-100 crystals.

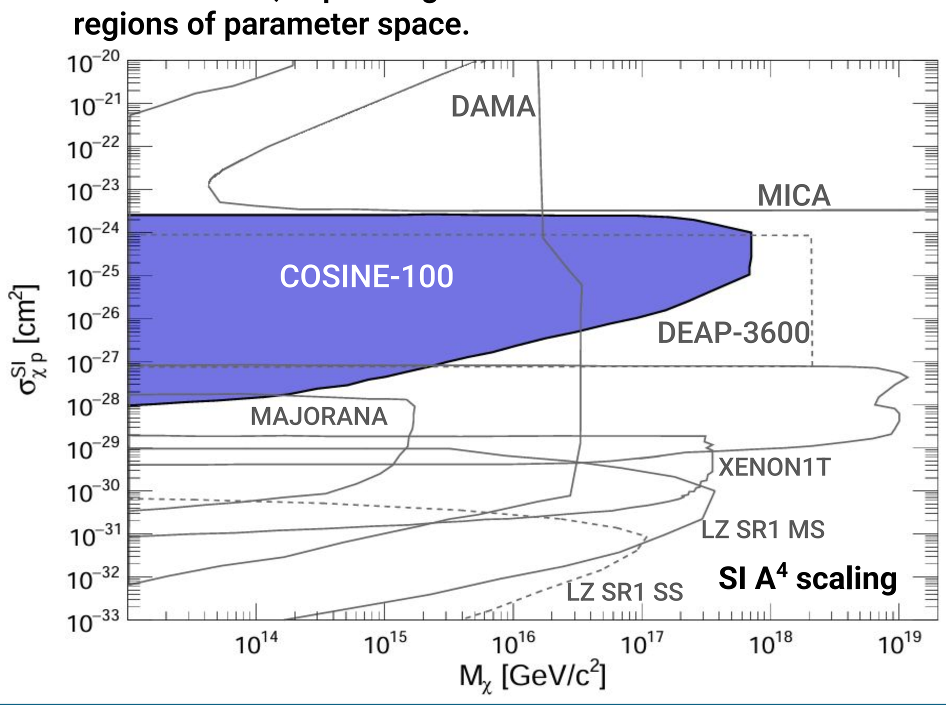


Fig. 8 – The blue contour delimits the expected MIMP signal region at COSINE-100 for SI interactions. It represents the expected region of detected MIMP events for each mass–cross-section point after flux attenuation, exposure, detector response, and selection efficiency. The COSINE-100 black contour marks N_{sig}= 2.30, the 90% CL Poisson upper-limit threshold for zero observed events and negligible background. Parameter points inside the contour predict more than 2.30 events and are therefore excluded at 90% CL under the null hypothesis. Existent results from the MIMP search analysis are shown as grey solid labeled lines [7].

References:

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