Searching for dark matter with a 1000 km baseline interferometer

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Axion-like particles (ALPs) arise from well-motivated extensions to the Standard Model and could account for dark matter. ALP dark matter would manifest as a nearly monochromatic field oscillating at an (as of yet) unknown frequency. The frequency depends on the ALP mass, which could plausibly range from $10^{-22}\,\mathrm{eV}/c^2$ to $10\,\mathrm{eV}/c^2$. We report on a direct search for ALP dark matter through the ALP-nucleon interaction by interfering the signals of two atomic K-Rb-^{3}He comagnetometers, with one situated in Mainz, Germany, and the other in Kraków, Poland. We use the ALP dark matter's spatiotemporal coherence properties assuming the standard halo model of dark matter in the Milky Way to improve the sensitivity and exclude spurious candidates. The search extends over nine orders of magnitude in ALP mass. In this range, no significant evidence of an ALP signal is found. We thus place new upper limits on the ALP-neutron and ALP-proton couplings of $g_{aNN} < 10^{-5}\,\mathrm{GeV}^{-1}$ and $g_{aPP} < 5 \times 10^{-4}\,\mathrm{GeV}^{-1}$ at a mass of $10^{-22}\,\mathrm{eV}/c^2$ and extending to a mass of $10^{-15}\,\mathrm{eV}/c^2$ where the upper limits reach below $g_{aNN} < 10^{-9}\,\mathrm{GeV}^{-1}$ and $g_{aPP} < 10^{-7}\,\mathrm{GeV}^{-1}$, respectively. For both neutron and proton couplings, this work is an improvement of up to four orders of magnitude compared to previous laboratory constraints.

[1] D. Gavilan-Martin, G. Lukasiewicz et al, arXiv: 2408.02668
[2] M. Padniuk et al, Phys. Rev. Research 6, 013339 (2023)

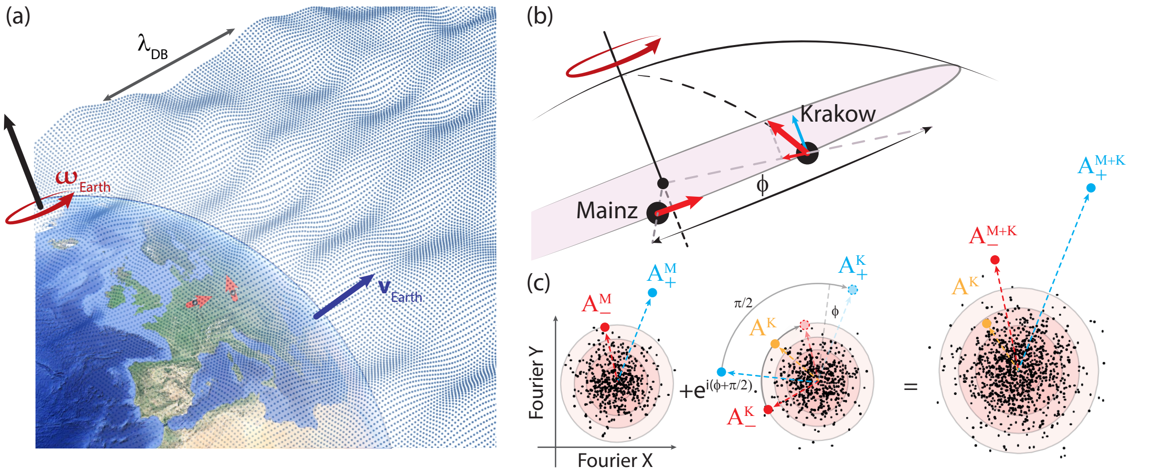

Figure 1. a) Interferometer schematic. The two comagnetometers comprising the interferometer are indicated in their respective host cities Mainz and Kraków. The red arrows point in the direction of their respective sensitivity axes. Earth is rotating at the sidereal frequency ω_e and moving at velocity v_e with respect to the galactic rest frame through the ALP DM field, characterized by its de Broglie wavelength λ_{DB}. Note, that the smallest de Broglie wavelength in the presented search is more than a thousand times larger than the radius of the Earth. (b) Orientation of the sensitive axes of the comagnetometer stations with respect to the rotation axis of the Earth. The sensitive axes of the comagnetometers can be decomposed into components along the rotation axis and perpendicular to it. The former results in an ALP signal component at the Compton frequency of the ALP constituent particle (carrier) while the latter results in (generally asymmetric) sidebands separated from the carrier by the sidereal frequency. (c) Signal interferometry in the data analysis. ALP constituents in this search would have the same properties in Mainz and Kraków and would appear as signals at the carrier and sideband frequencies. Both stations would detect sideband signals while the carrier signal would only appear in the Kraków data. To coherently add ALP signals from Mainz and Kraków, the phase differences due to the different sensitive axis orientation ($\pi/2$) as well as due to the different locations (ϕ) need to be taken into account. In this way, the signal amplitudes add linearly while the noise adds in quadrature, improving the signal-to-noise ratio by over $\sqrt{2}$. The signals at the three different frequencies, Kraków carrier with amplitude A^K and the combined lower (A_-^{K+M}) and upper (A_+^{K+M}) sidebands are then combined in quadrature to construct the signal estimator used to search for evidence of ALP DM.