Snowmass2021 - Letter of Interest

Global Network of Optical Magnetometers to search for Exotic physics (GNOME)

Thematic Areas:

■ (CF2) Dark Matter: Wavelike
■ (IF1) Quantum Sensors
■ (RF3) Fundamental Physics in Small Experiments

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Abstract:

A host of astrophysical and cosmological measurements have established that the majority of matter in the Universe is dark matter; understanding its nature is of paramount importance to astrophysics, cosmology, and particle physics. A well-motivated possibility is that the dark matter consists of ultralight bosons such as axions or axion-like particles (ALPs) with very low mass ($\ll$ 1 eV), in which case their phenomenology is well-described by a classical field. Due to topology or self-interactions, ultralight bosonic fields can form stable, macroscopic field configurations in the form of boson stars or topological defects (e.g., domain walls). Even in the absence of topological defects or self-interactions, bosonic dark matter fields exhibit stochastic fluctuations. Additionally, it is possible that high-energy astrophysical events could produce intense bursts of exotic ultralight bosonic fields. In any of these scenarios, instead of being bathed in a uniform flux, terrestrial detectors will witness transient events when ultralight bosonic fields pass through Earth. The Global Network of Optical Magnetometers to search for Exotic physics (GNOME) is an array of geographically separated, time-synchronized atomic magnetometers designed to search for correlated signals heralding beyond-the-Standard-Model physics. There are a limited number of "portals" through which ultralight bosonic fields can couple to Standard Model particles, prominent among them spin-dependent interactions to which the GNOME is particularly sensitive. The GNOME can search a wide range of unexplored parameter space for such ultralight bosonic fields.

Physics goals: The **G**lobal **N**etwork of **O**ptical **M**agnetometers to search for **E**xotic physics (GNOME) is sensitive to the gradient coupling of axion-like-particle (ALP) fields ϕ to nuclear spins. The GNOME searches for a class of signals different from that probed by most other experiments, namely transient and stochastic effects that could arise from ALP fields of astrophysical origin passing through the Earth during a finite time. In particular, GNOME is searching for dark matter in the form of ALP domain walls [1] (Fig. 1), boson stars [2], or stochastic fluctuations [3], and is also sensitive to bursts of ALPs generated by binary black hole merger events or other cataclysmic astrophysical events [4]. Depending on the particular hypothesis tested, GNOME is sensitive to ALPs in the mass range between $\approx 10^{-17}$ eV and $\approx 10^{-9}$ eV, and has the ability to probe parameter space unconstrained by existing laboratory experiments and astrophysical observations. GNOME is sensitive to couplings of the nuclear spins $\mathbf{S}$ through the linear Hamiltonian [5]

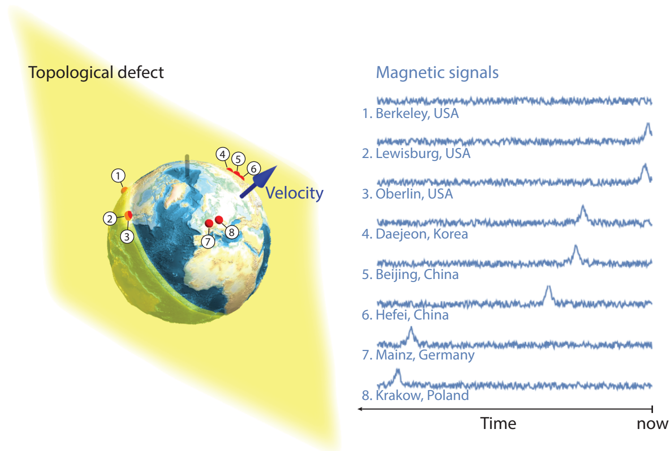

Figure 1: Schematic representation of the Earth passing through a topological defect of an axion-like field in the form of a domain wall (left). As various GNOME stations pass through the topological defect, signals appear in the optical atomic magnetometer data at particular times (right). In this representation, for simplicity the simulated magnetic field data has been normalized so that the domain-wall signals have the same amplitude and sign.

$$\hat{H}_L = -2g_{aNN}(\hbar c)^{3/2}\mathbf{S}\cdot\boldsymbol{\nabla}\phi(\mathbf{r},t)\ , \tag{1}$$

as well as the quadratic Hamiltonian [1, 6]

$$\hat{H}_Q = -2g_Q^2(\hbar c)^2\mathbf{S}\cdot\boldsymbol{\nabla}\phi(\mathbf{r},t)^2\ . \tag{2}$$

Experimental technique: GNOME uses precision optical atomic magnetometers [7] to search for spin torques induced by interaction of axion-like fields with nuclear spins [Eqs. (1) and (2)]. There are a number of recent and ongoing experiments using atomic magnetometers [7] to search for exotic fields mediating spin-dependent interactions [5]. The basic concept of such experiments is to search for anomalous spin-dependent energy shifts of Zeeman sublevels caused by exotic fields rather than ordinary electromagnetic fields. For example, there are experiments searching for exotic spin-dependent interactions constant in time as evidence of new long-range monopole-dipole [8, 9] and dipole-dipole interactions [10], where the Earth is

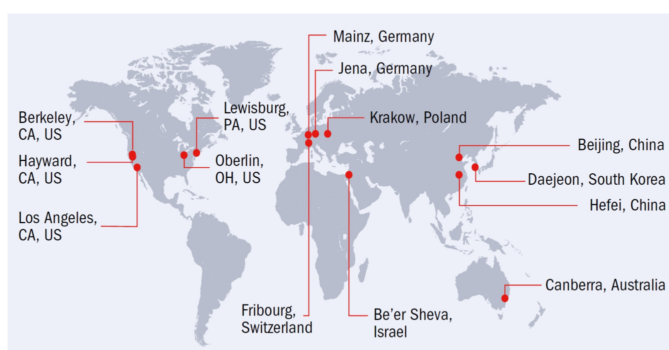

Figure 2: Locations of GNOME stations.

the source of mass or polarized electrons, respectively. There are also experiments searching for shorter-range exotic spin-dependent interactions using local sources that can be modulated, such as laboratory-scale masses or polarized spin samples [11, 12].

While a single magnetometer system could detect transient and stochastic events associated with axion-like fields, it is difficult to confidently distinguish a true signal generated by exotic physics from false positives induced by changes of magnetometer operational conditions (e.g., magnetic-field spikes, laser mode hops, electronic noise, etc.). Effective vetoing of prosaic noise and transient events (false positives) requires an array of individual, spatially distributed magnetometers to eliminate spurious local effects. Furthermore, a global distribution of sensors is beneficial for event characterization, providing the ability to resolve the velocity of the exotic field by observing the relative timing and amplitude of transient events at different sensors [1, 14]. GNOME is a growing network of more than a dozen optical atomic magnetometers, with stations in Europe, North America, Asia, and Australia (Fig. 2).

Projected sensitivity: The existing GNOME has demonstrated a magnetometric sensitivity of better than $\approx 10^{-12}$ T in 1 second of integration [16], and the Advanced GNOME which will employ nuclear spin (co)magnetometers [11, 12] is expected to reach a magnetometric sensitivity of better than $\approx 10^{-15}$ T in 1 second of integration. These magnetometric sensitivities can be translated into exotic physics parameter space as discussed in Refs. [1, 2, 13, 14]. The sensitivity to ALP field coupling constants for representative cases is shown in Fig. 3; the crucial point is that in each case the GNOME has sensitivity to dark matter physics scenarios presently unconstrained by astrophysical observations [15].

Projected timeline: The GNOME has already collected over a year of data. Over the next year we plan another Science Run with the existing network, aiming for more continous operation of all magnetometers and hope to improve overall sensitivity by an order-of-magnitude to a variety of exotic physics scenarios. Within 2-3 years we anticipate construction and testing of Advanced GNOME, a network of nuclear spin (co)magnetometers with $\approx 100-1000$ times greater sensitivity. Results from Advanced GNOME are expected within 4 years.

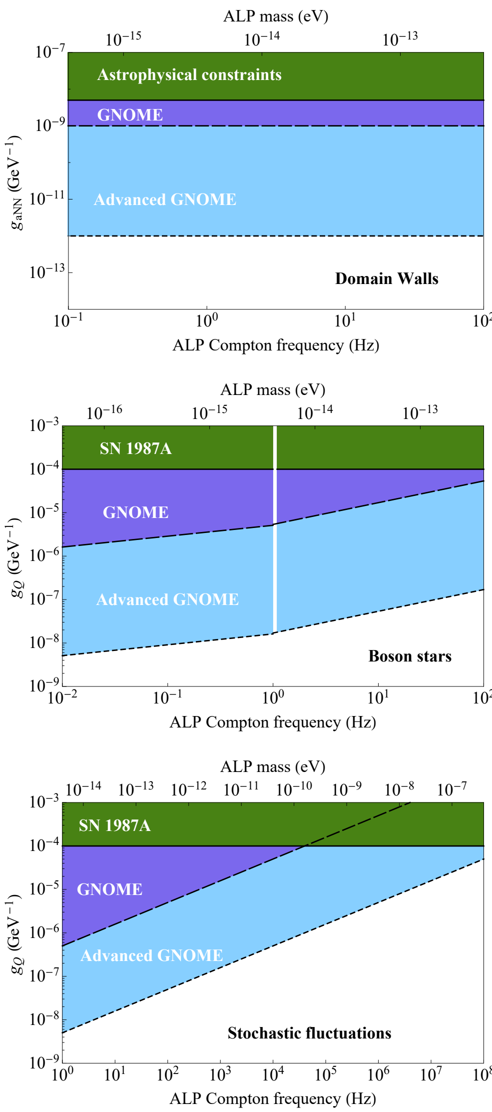

Figure 3: Projected sensitivity of GNOME (dashed line, purple shaded region) and Advanced GNOME (dotted line, light blue shaded region) to various dark matter scenarios in terms of ALP field coupling to nuclear spins [Eqs. (1) and (2)] and ALP mass (Compton frequency): the top plot shows sensitivity to ALP domain walls [1, 13, 14], the middle plot shows sensitivity to boson stars [2], and the bottom plot shows sensitivity to ALP field stochastic fluctuations [3]. Astrophysical constraints (solid line, green shaded region) based on, for example, observations of SN1987A, are from Ref. [15].

References:

[1] M. Pospelov, S. Pustelny, M. P. Ledbetter, D. F. Jackson Kimball, W. Gawlik, and D. Budker, "Detecting domainwalls of axionlike models using terrestrial experiments", Phys. Rev. Lett. **110**, 021803 (2013).

[2] D. F. Jackson Kimball, D. Budker, J. Eby, M. Pospelov, S. Pustelny, T. Scholtes, Y. V. Stadnik, A. Weis, and A. Wickenbrock, "Searching for axion stars and Q-balls with a terrestrial magnetometer network", Phys. Rev. D **97**, 043002 (2018).

[3] G. P. Centers, J. W. Blanchard, J. Conrad, N. L. Figueroa, A. Garcon, A. V. Gramolin, D. F. Jackson Kimball, M. Lawson, B. Pelssers, J. A. Smiga, et al., "Stochastic fluctuations of bosonic dark matter", arXiv: 1905.13650 (2019).

[4] C. Dailey, C. Bradley, D. F. Jackson Kimball, I. Sulai, S. Pustelny, A. Wickenbrock, and A. Derevianko, "Quantum sensor networks as exotic field telescopes for multi-messenger astronomy", arXiv: 2002.04352 (2020).

[5] M. Safronova, D Budker, D DeMille, D. F. Jackson Kimball, A Derevianko, and C. W. Clark, "Search for new physics with atoms and molecules", Rev. Mod. Phys. **90**, 025008 (2018).

[6] K. A. Olive and M. Pospelov, "Environmental dependence of masses and coupling constants", Phys. Rev. D **77**, 043524 (2008).

[7] D. Budker and D. F. Jackson Kimball, *Optical magnetometry* (Cambridge University Press, 2013).

[8] B. J. Venema, P. K. Majumder, S. K. Lamoreaux, B. R. Heckel, and E. N. Fortson, "Search for a coupling of earth's gravitational field to nuclear spins in atomic Mercury", Phys. Rev. Lett. **68**, 135 (1992).

[9] D. F. Jackson Kimball, J. Dudley, Y. Li, D. Patel, and J. Valdez, "Constraints on long-range spin-gravity and monopole-dipole couplings of the proton", Phys. Rev. D **96**, 075004 (2017).

[10] L. Hunter, J. Gordon, S. Peck, D. Ang, and J.-F. Lin, "Using the Earth as a polarized electron source to search for long-range spin-spin interactions", Science **339**, 928 (2013).

[11] G. Vasilakis, J. M. Brown, T. W. Kornack, and M. V. Romalis, "Limits on new long range nuclear spin-dependent forces set with a K-^{3}He comagnetometer", Phys. Rev. Lett. **103**, 261801 (2009).

[12] J. Lee, A. Almasi, and M. Romalis, "Improved limits on spin-mass interactions", Phys. Rev. Lett. **120**, 161801 (2018).

[13] S. Pustelny, D. F. Jackson Kimball, C. Pankow, M. P. Ledbetter, P. Wlodarczyk, P. Wcislo, M. Pospelov, J. R. Smith, J. Read, W. Gawlik, and D. Budker, "The Global Network of Optical Magnetometers for Exotic physics (GNOME): a novel scheme to search for physics beyond the Standard Model", Ann. Phys. (Berl.) **525**, 659–670 (2013).

[14] H. Masia-Roig, J. A. Smiga, D. Budker, V. Dumont, Z. Grujic, D. Kim, D. F. J. Kimball, V. Lebedev, M. Monroy, S. Pustelny, et al., "Analysis method for detecting topological defect dark matter with a global magnetometer network", Physics of the Dark Universe **28**, 100494 (2020).

[15] J. H. Chang, R. Essig, and S. D. McDermott, "Supernova 1987A constraints on sub-GeV dark sectors, millicharged particles, the QCD axion, and an axion-like particle", Journal of High Energy Physics **2018**, 51 (2018).

[16] S Afach, D. Budker, G DeCamp, V. Dumont, Z. D. Grujić, H Guo, D. J. Kimball, T. Kornack, V. Lebedev, W Li, et al., "Characterization of the global network of optical magnetometers to search for exotic physics (GNOME)", Physics of the Dark Universe **22**, 162 (2018).

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