The Global Network of Optical Magnetometers for Exotic physics searches (GNOME)

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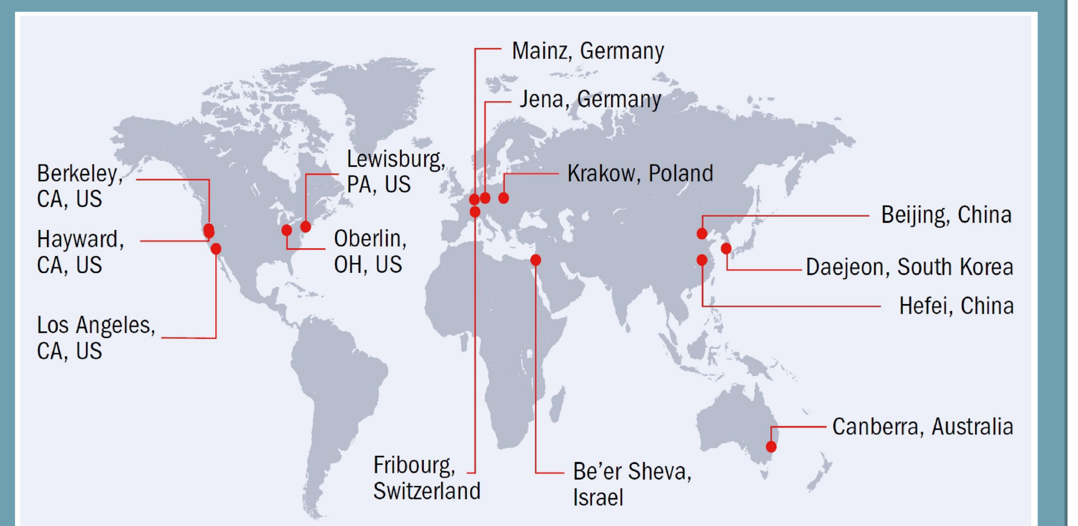
GNOME Overview

What can we say about short bursts of weird physics? Like encounters with compact, composite dark-matter objects? Or transient pulses of exotic, beyond-the-Standard-Model fields from astrophysical sources? A geographically distributed array of sensors (like GNOME) can confidently detect such transient events by searching for correlations.



GNOME is a worldwide network of more than a dozen time-synchronized optical atomic magnetometers (OAMs) searching for correlated signals heralding beyond-the-Standard-Model physics, with stations in Europe, North America, Asia, the Middle East, and Australia. GNOME data can be used to test a variety of hypotheses that could explain dark matter or even dark energy.

Dark matter may consist of ultralight bosons such as axions or axion-like particles (ALPs) with very low mass (<< 1 eV), which behave as a oscillating field. Due to, e.g., self-interactions, ultralight bosonic fields can form stable, macroscopic composite objects such as "axion stars" or domain walls. Colliding black holes may produce intense bursts of exotic ultralight bosonic fields. In these scenarios, instead of being bathed in a uniform dark matter field, terrestrial detectors will witness transient events when the dark matter field passes through Earth.

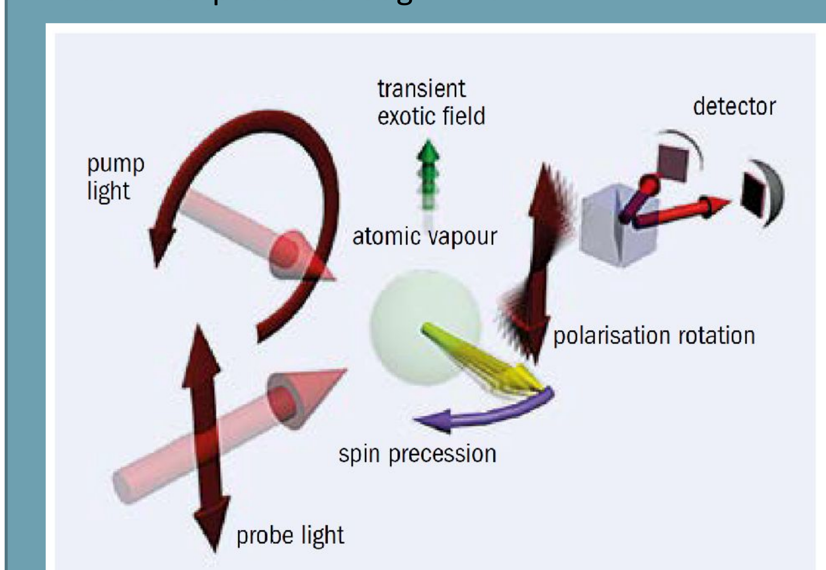
Axion/ALP coupling to atomic spins

$$\hat{H}_{\text{lin}} = -\frac{(\hbar c)^{3/2}}{f_L}\frac{\boldsymbol{S}}{\|S\|}\cdot\nabla a(\boldsymbol{r},t)$$

$$\hat{H}_{\text{quad}} = -\frac{\hbar^2 c^2}{f_Q^2}\frac{\boldsymbol{S}}{\|S\|}\cdot\nabla\,|a(\boldsymbol{r},t)|^2$$

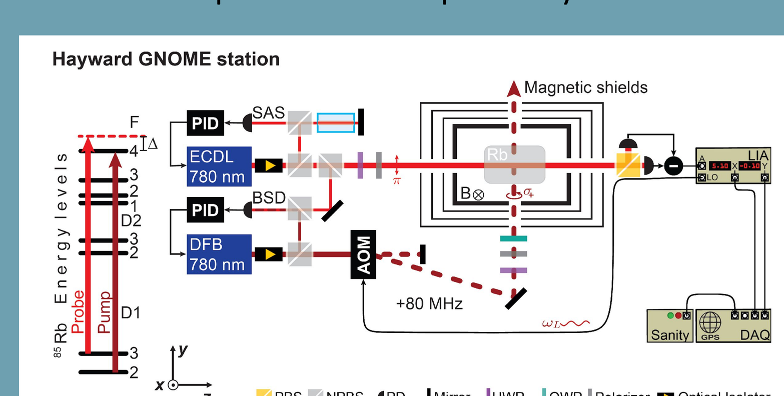
$$\hat{H}_Z = -\gamma\boldsymbol{S}\cdot\boldsymbol{B}$$

Zeeman Hamiltonian: ordinary interaction of spin with magnetic field.

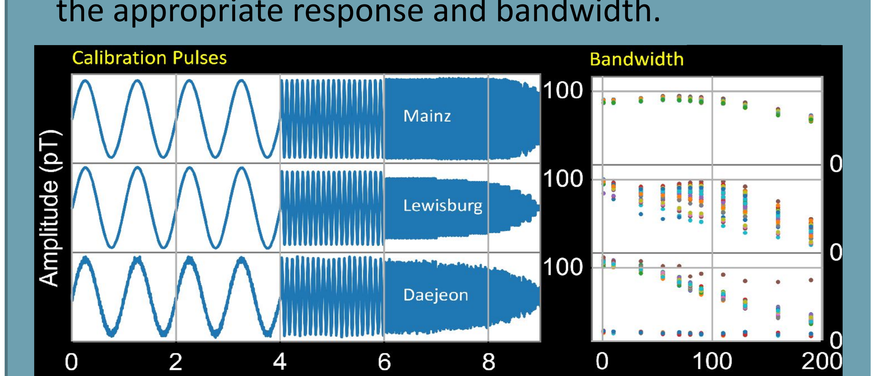


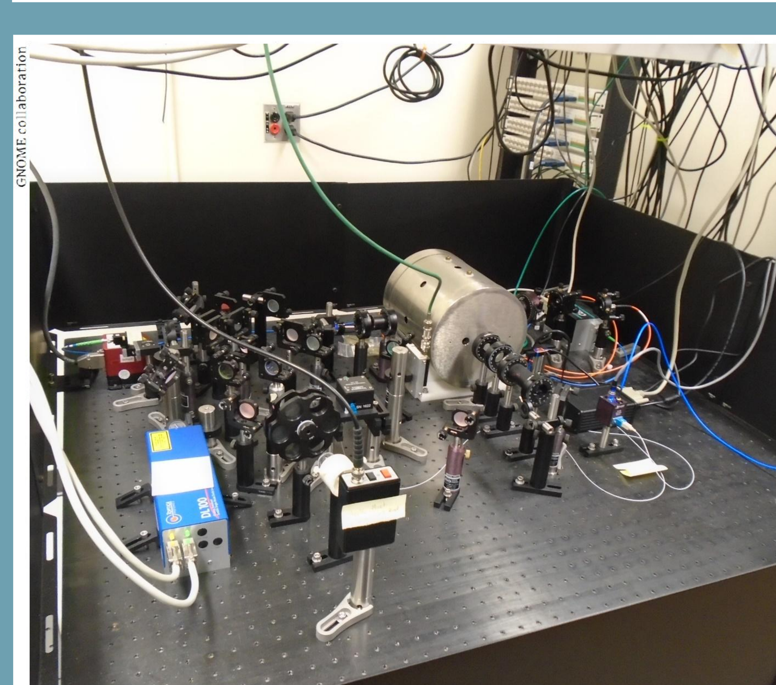
Optical rotation *In a GNOME optical atomic magnetometer, linearly polarised light optically pumps atomic-spin alignment along the light polarisation axis, making the atomic vapour optically anisotropic. If a transient torque from an exotic field causes the spins to precess, the axis of the optical anisotropy, parallel to the spin alignment, also rotates. This causes optical rotation of the light polarisation, which can be precisely measured with a polarimeter.*

There are a limited number of "portals" through which ultralight bosonic fields couple to Standard Model particles, among them the spin-dependent interaction portal. Optical atomic magnetometers (OAMs) have excellent sensitivity to spin-dependent energy shifts. GNOME's OAMs are inside multi-layer magnetic shields, reducing effects of external magnetic fields by more than a million times; dark matter fields penetrate unimpeded by the shields.



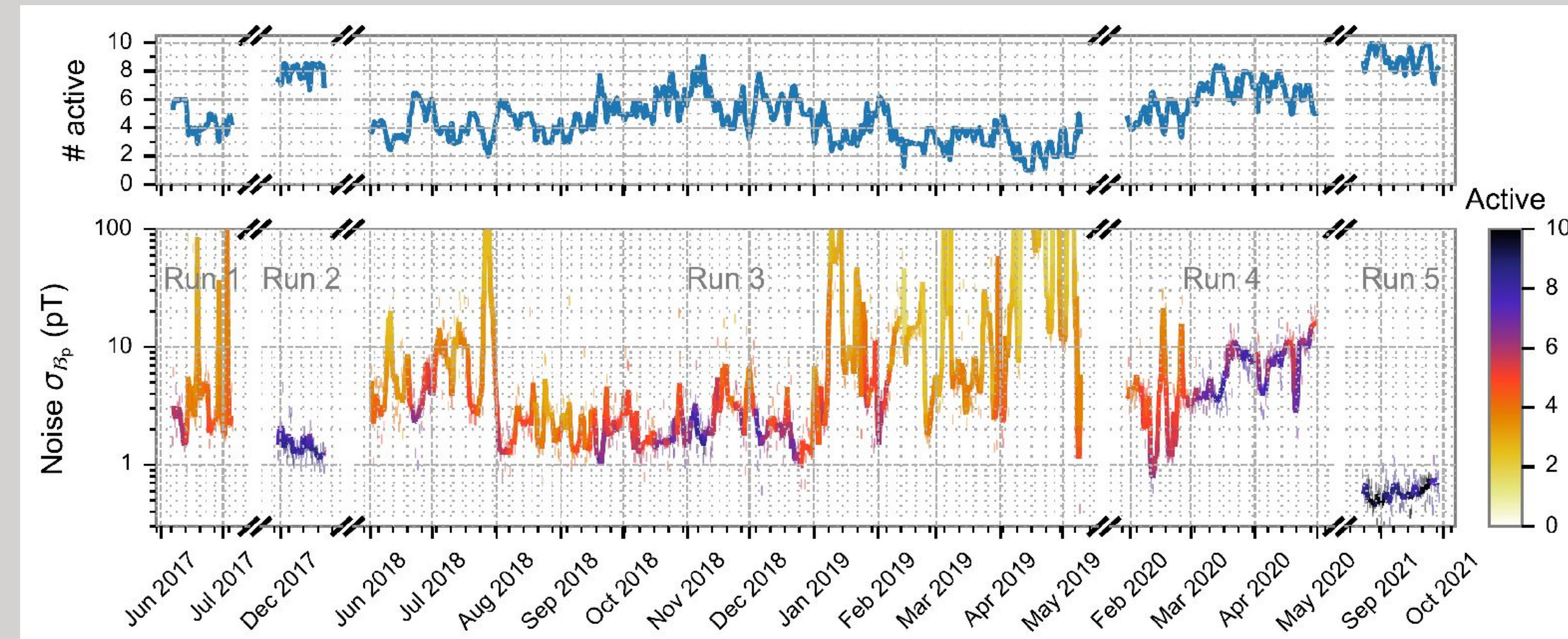
OAMs measure spin-dependent energy shifts by controlling and monitoring atomic spins via angular momentum exchange between atoms and light. The high efficiency of optical pumping and probing, along with an array of techniques to minimize spin relaxation (even at high atomic vapor densities), enable OAMs to achieve sensitivities well below 10^{-20} eV after only one second of integration. GNOME uses hourly calibrations to ensure that stations have the appropriate response and bandwidth.





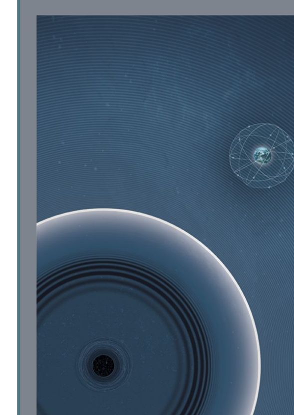
Benchtop physics *The OAM setup at the GNOME station at California State University – East Bay in Hayward, California.*

GNOME Science Runs

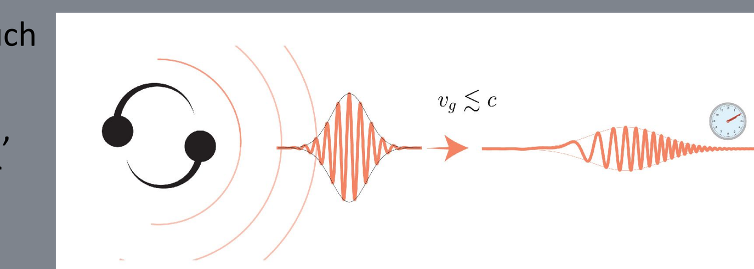


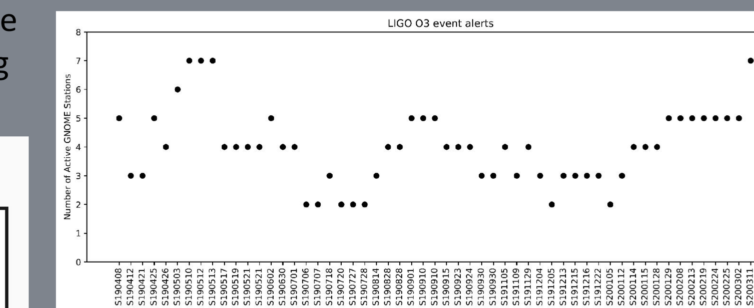
The above plot summarizes GNOME performance during the five Science Runs from 2017 to 2021. Magnetometer data are averaged for 20s and their standard deviation is calculated over 1-2 hour segments. For each binned point, the combined network noise considering the worst case signal directionality is evaluated.

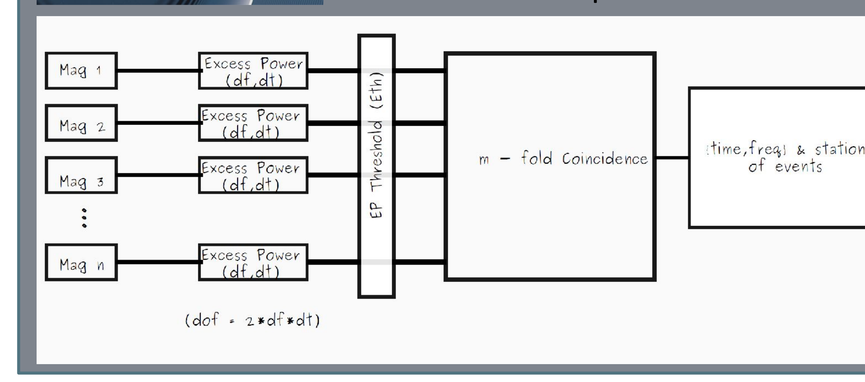
GNOME hunts for ELFs: Multimessenger Astronomy



Cataclysmic astrophysical events, such as black hole mergers, neutron star mergers, fast radio bursts (FRBs), etc., could release a small fraction of their energy in bursts of exotic low-mass fields (ELFs). ELFs would have high mode occupation number and behave as coherent classical waves, satisfying the relativistic dispersion relation.

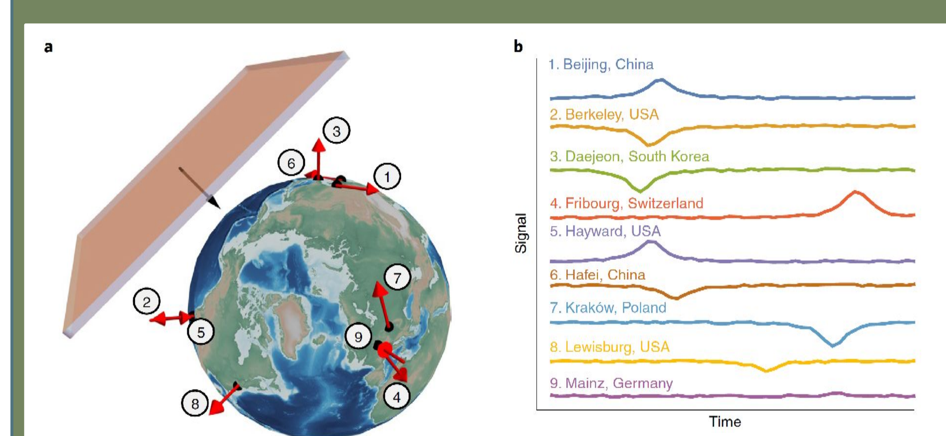






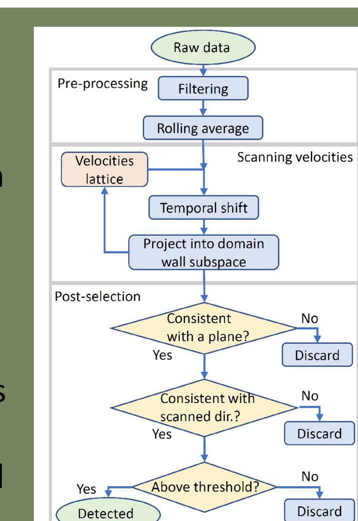
GNOME can search for ELFs that couple to atomic spin. The search is triggered on observations of gravitational waves (GWs) or FRBs.

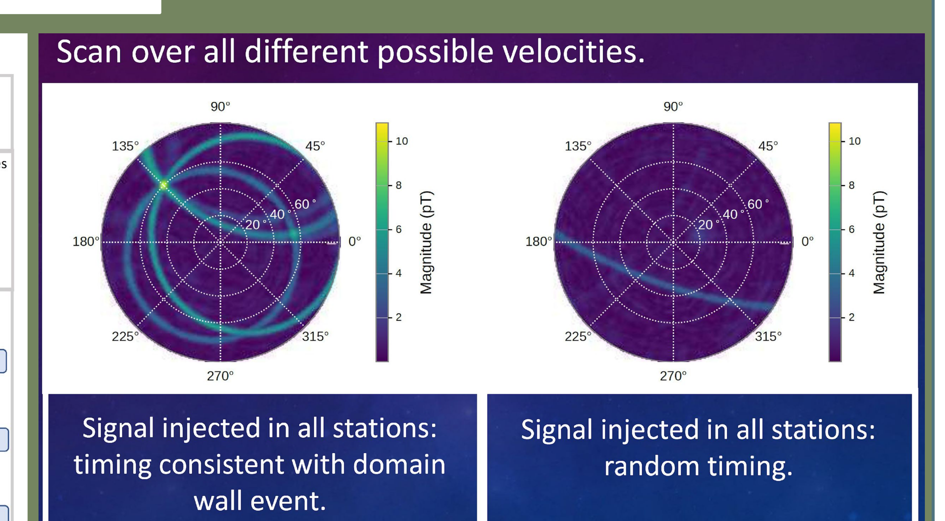
Search for axion domain walls

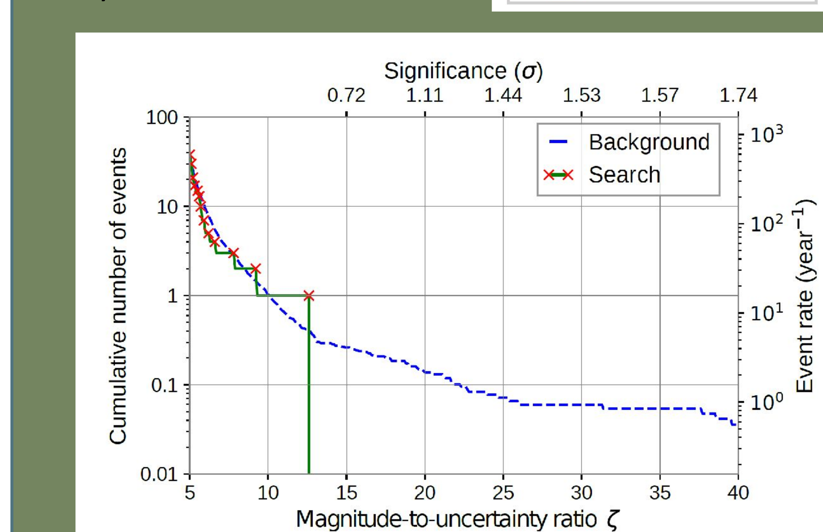


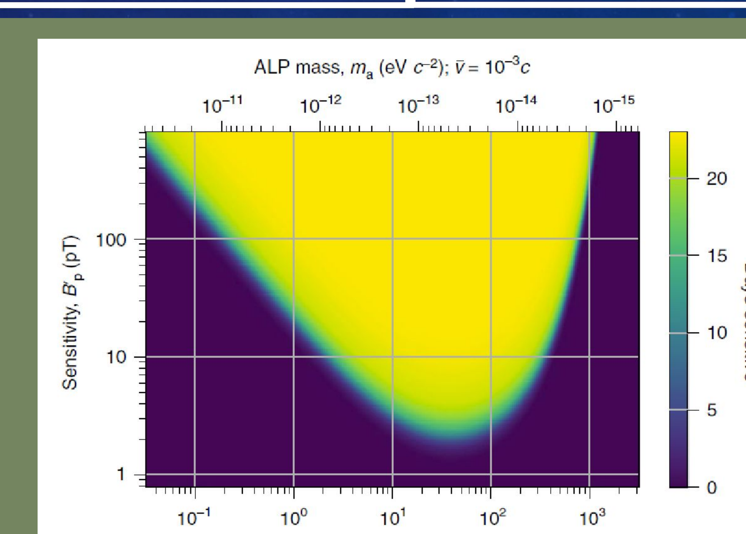
The originally proposed search targets for GNOME were ALP domain walls, a class of topological defects between regions of space with different energy-degenerate vacua of an ALP field. Domain walls concentrate the energy density of the ALP field in compact composite objects potentially much larger than Earth.

If there is an ALP domain-wall-crossing, GNOME sees a global pattern of pulses that point along a common axis, have the same duration, and exhibit a characteristic timing pattern. We developed a data analysis algorithm to search for ALP domain walls, and completed analysis for Science Run 2.

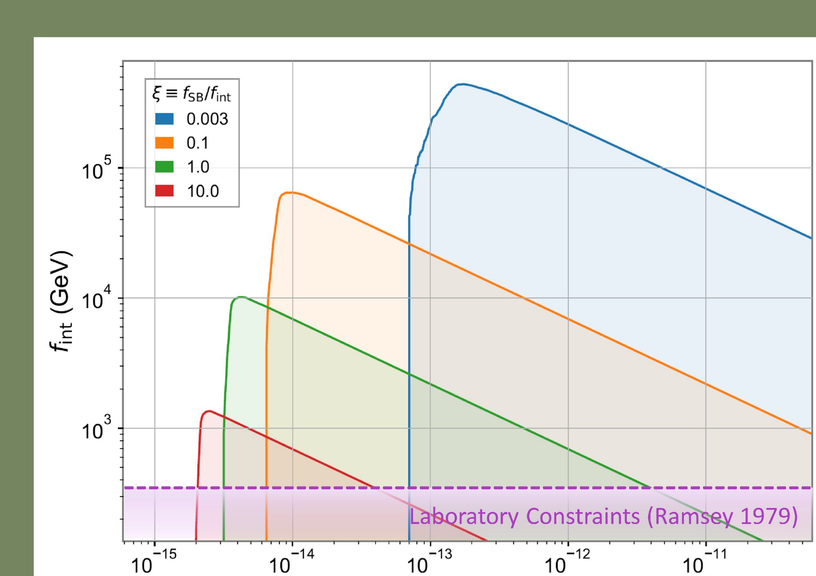




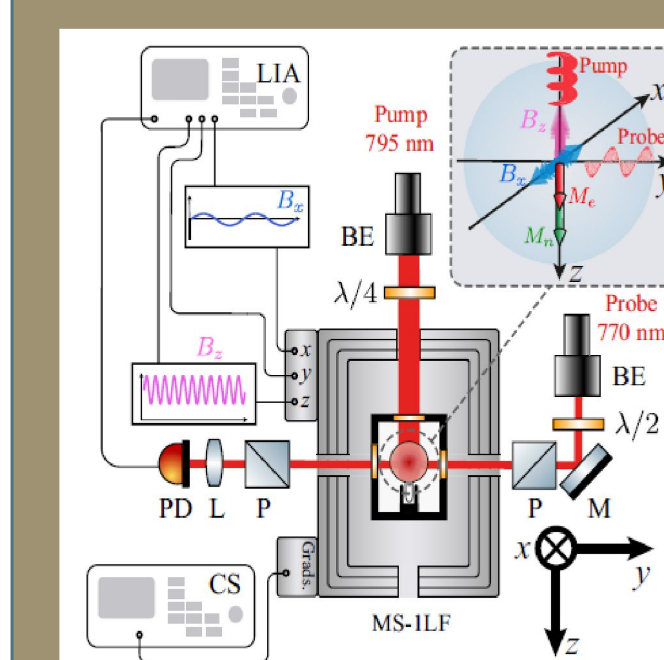




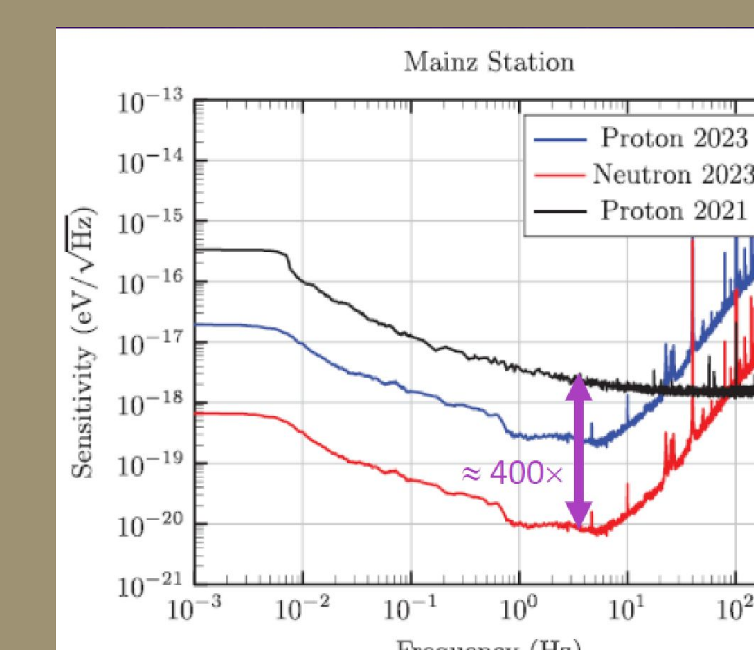
Analysis of the GNOME data did not find any significant excess of events above the background. The above figure on the left shows the number of events expected from the background (blue dashed line) in 23 days of data as compared to the measured event rate (solid green line). (10.7 years of time-shuffled data are used to evaluate the background.) The above plot on the right shows the amount of time for which GNOME had a given sensitivity to ALP domain walls of a given duration throughout Science Run 2. The characteristic shape of the sensitive region is a result of the filtering and averaging of the raw data. The lower plot on the right shows derived bounds on ALP domain wall characteristics assuming they comprise the totality of dark matter.



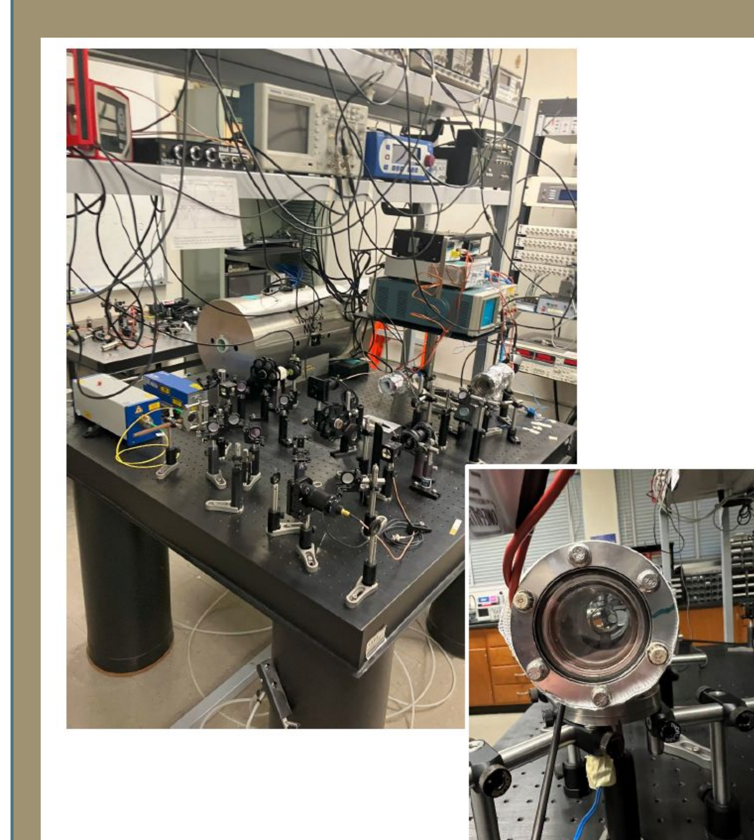
Future GNOME: Rb/K/He-3 Comagnetometers



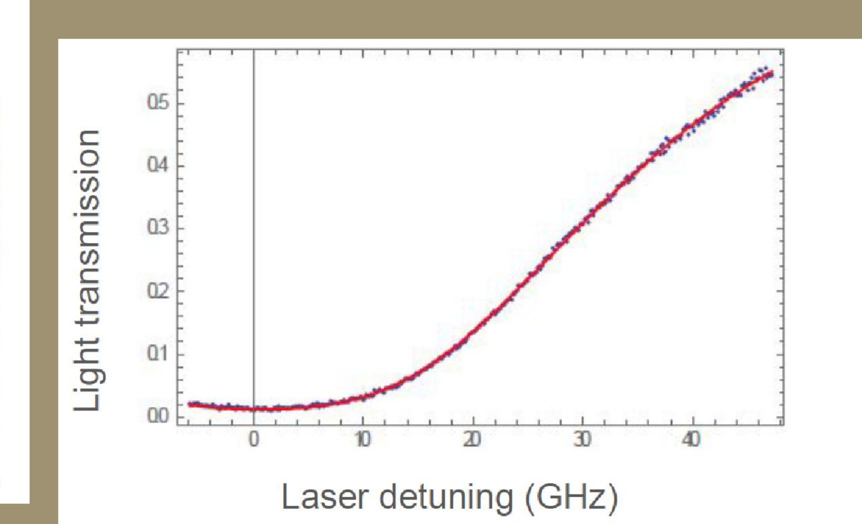
The new setup for our GNOME dark matter sensor is a three-species comagnetometer. The vapor cell at the center is filled with a high density (3 atm) He-3 gas. The He-3 spins are aligned by collisions with laser polarized Rb atoms. If the dark matter affects the He-3 spins, they in turn affect K spins. We monitor the K spins by measuring optical rotation of 770nm laser light tuned near the K D1 transition.



Compared to the OAMs we previously used in GNOME, our new comagnetometer will have orders-of-magnitude greater sensitivity to dark matter fields. Data from our collaborators in Mainz are shown in a plot on the right. The black line shows the GNOME magnetometer sensitivity to energy shifts from 2021. The blue and red lines show the sensitivity of the new comagnetometer, demonstrating the improved sensitivity.



Presently, we are testing vapor cells manufactured by our collaborators at TwinLeaf in order to optimize the K/Rb atomic density ratio. We are measuring absorption spectra at different cell temperatures and fitting the data to calculated spectra to measure the densities of K and Rb. We also measure the pressure broadening of the spectral lines due to collisions with He-3, which tells us the He-3 density.



Blue points = data, red line = fit to atomic theory