Searching for ALP Dark Matter with a 1000 km baseline interferometer

20^{th} Rencontres du Vietnam: The Axion Quest, Quy Nhon

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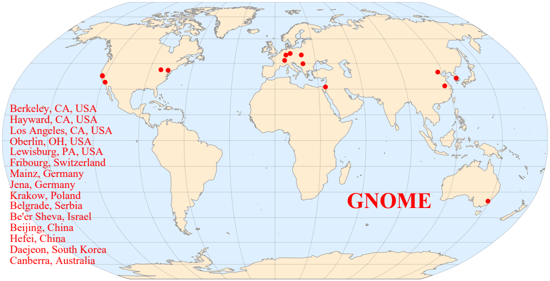
What is a GNOME?[1]

- **G**lobal **N**etwork of **O**ptical **M**agnetometers for **E**xotic physics searches
- Looking for transient and background dark matter signals
- Sensitive to Axion-nucleon coupling:

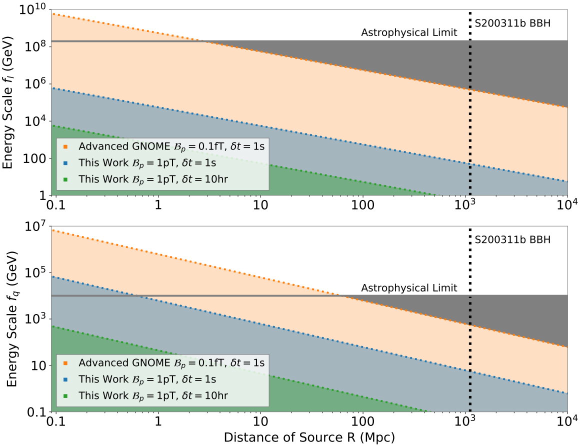
$$\mathcal{H}_N = g_{aNN} \nabla a \cdot \sigma_N \, ,$$
$$\mathcal{H}_P = g_{aPP} \nabla a \cdot \sigma_P \, ,$$

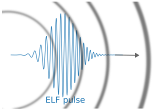


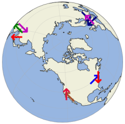
[1] Phys.Dark Univ. 22 (2018), 162-180

What can a GNOME do?[2] Look for ELFs[3]

- Multimessenger Exotic Low-mass Field (ELF)







- Large energy astrophysical events detected by GW detectors

[2] Afach et al. ANNALEN DER PHYSIK 2023, 2300083
[3] Khamis et al. arXiv: 2407.13919

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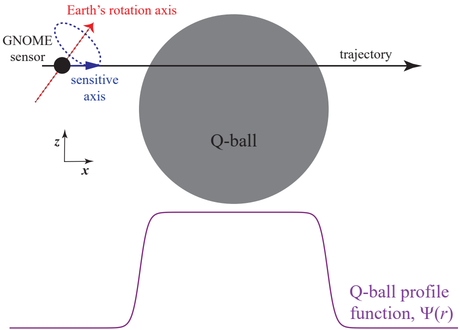
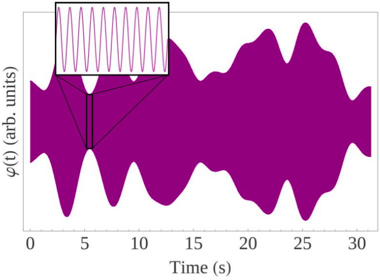
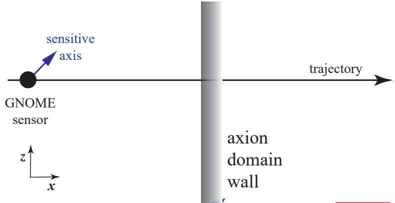
What can a GNOME do?

- Stochastic ALP DM field fluctuations
- Axion Domain Walls[4]
- Q-balls
- and much more!



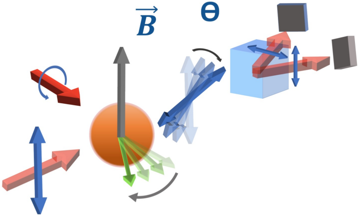




[4] Afach et al. Nat. Phys. 17, 1396–1401 (2021).

How does a GNOME work?

- Magnetometers as Dark Matter sensors



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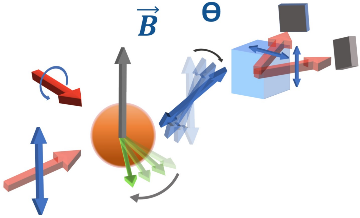
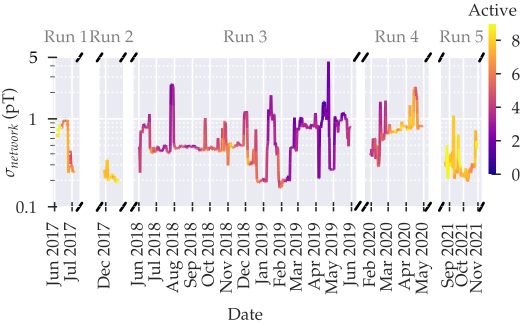
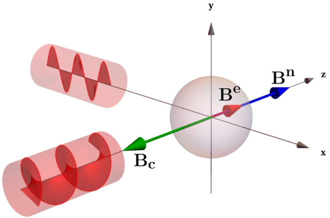


- 5 Science Runs since 2017
- Science Run 6 starting soon!



Advanced GNOME: K-Rb-^{3}He Comagnetometer

- Hot vapour cell with K, Rb and He magnetically shielded
- Polarize Rb electron → K electron and He nucleus polarization



Advanced GNOME: K-Rb-^{3}He Comagnetometer

- Hot vapour cell with K, Rb and He magnetically shielded
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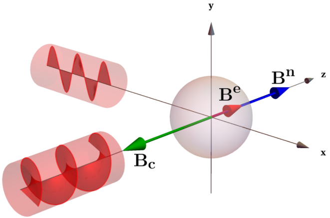
- Apply a compensation field
- More sensitive to spin couplings, including rotations and exotic interactions



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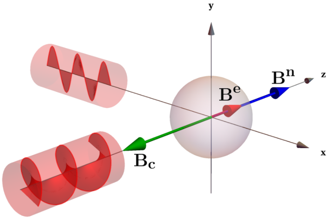
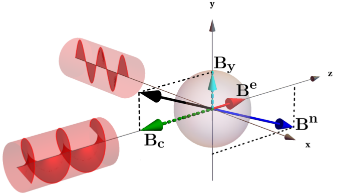


Perturbation



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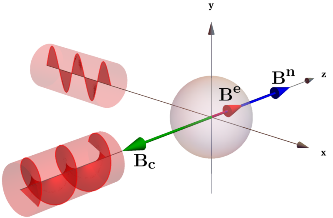

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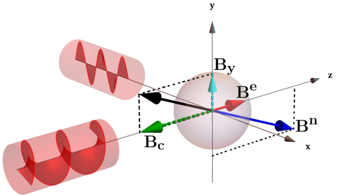


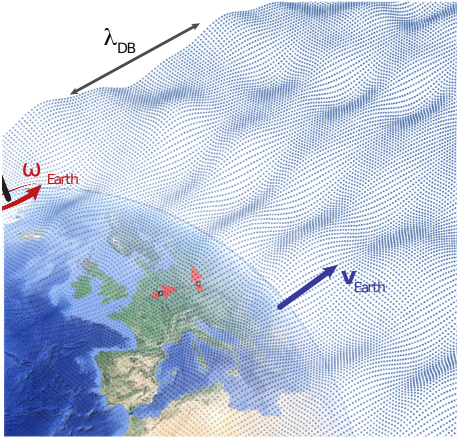
How sensitive are they?

Most stringent constraints on ALP DM at $\mathcal{O}(1)$ Hz. What about lower frequencies?

Contents

Two comagnetometers as an interferometer

- Situated in Mainz and Krakow, $\sim 1000\,\mathrm{km}$ apart
- Time synchronized measurement
- Lower frequency regime $\rightarrow$ coherent signal
- We calibrate the frequency response of the comagnetometers[2]every 25 h



[3]Padniuk et al. Phys. Rev. Research 6, 013339

3D Gradient of the ALP field

- Spread of frequencies

$$\Delta\omega \approx \omega_a \frac{v_0^2}{c^2} \approx \omega_a \times 10^{-6}$$

- Coherence time $\tau \sim 1/\Delta\omega$

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$$\nabla a(t) \sim \frac{1}{\sqrt{N}} \sum_n^N \boldsymbol{v}_n \cos(\omega_a t + \phi_n)$$
$$= \hat{\boldsymbol{x}}\alpha_x \cos(\omega_a t + \phi_x) + \hat{\boldsymbol{y}}\alpha_y \cos(\omega_a t + \phi_y) + \hat{\boldsymbol{z}}\alpha_z \cos(\omega_a t + \phi_z)\,,$$

$\nabla a(t)$ depends on six random parameters:

- α: Rayleigh distributed random number
- ϕ: phase of the field in each ortogonal direction

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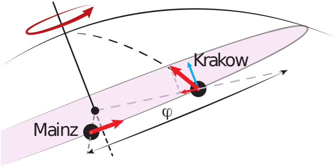

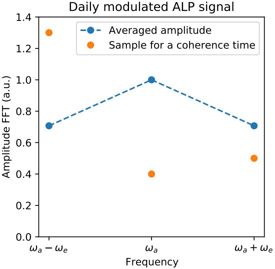

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- α: Rayleigh distributed random number
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ALP signature in the frequency domain

- A carrier at ω_a (A) and two sidebands at $\omega_a \pm \omega_e$ ($A_\pm$)

$$A \sim \alpha_z \,,$$
$$A_- \sim \frac{1}{2}\sqrt{\alpha_x^2 + \alpha_y^2 - 2\alpha_x\alpha_y \sin(\phi_x - \phi_y)} \,,$$
$$A_+ \sim \frac{1}{2}\sqrt{\alpha_x^2 + \alpha_y^2 + 2\alpha_x\alpha_y \sin(\phi_x - \phi_y)} \,.$$

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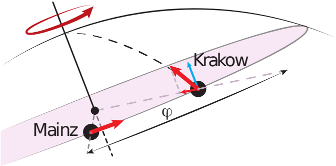
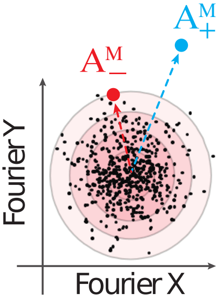
- Sidebands are in general asymmetric!





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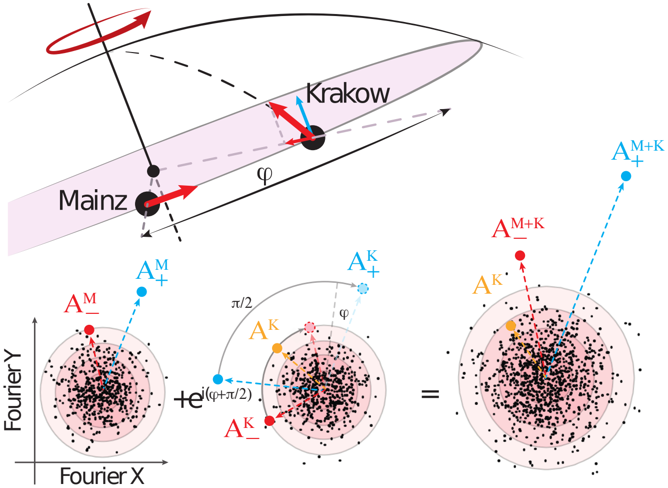
Search strategy

- We combine the ALP signatures properly shifted



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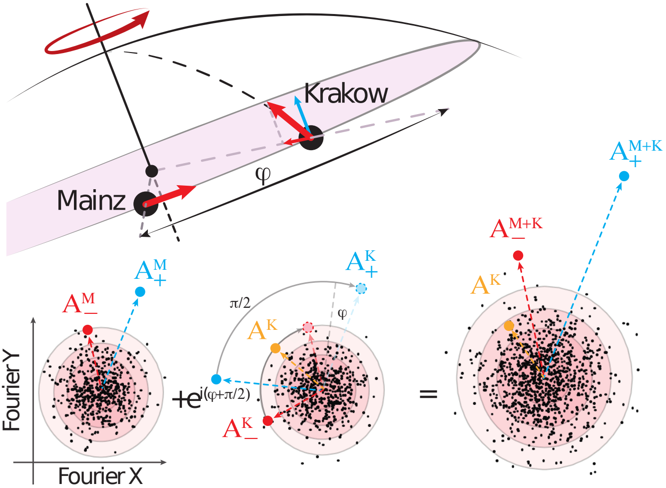
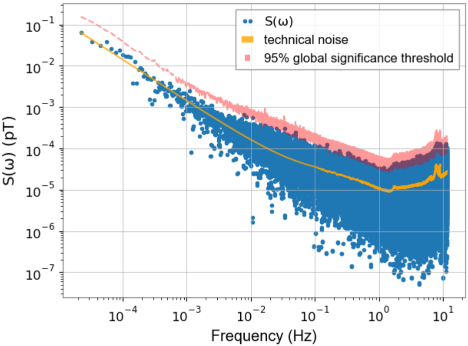


Search results

- No ALP candidate is found



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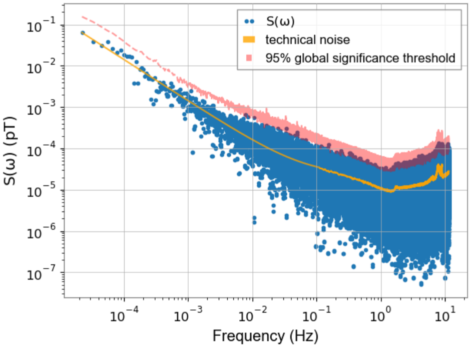
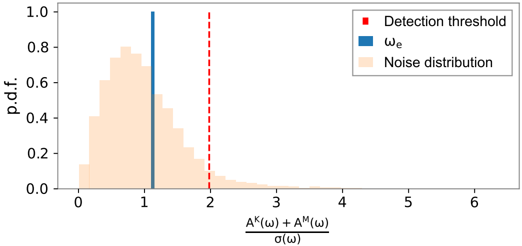
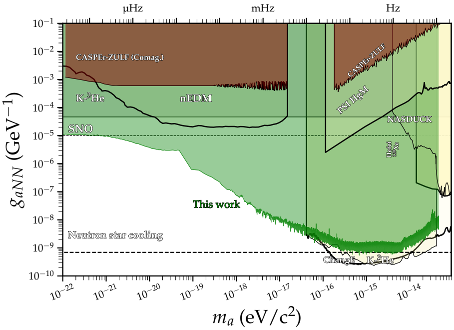


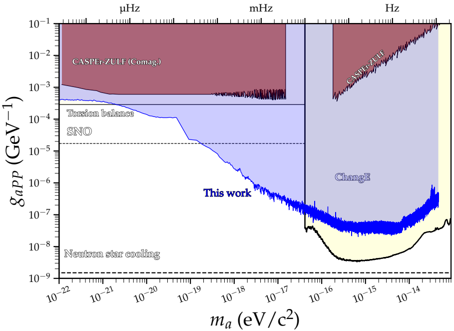
- Independent analysis of amplitudes at ω_e



Exclusions plots for proton and neutron coupling

- Constraints rescaled by nuclear spin content of ^{3}He
- Reduction of sensitivity due to incoherence of the field for frequencies $> 10^{-2}$ Hz





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Outlook

- We present a search in the ultra-low ALP mass range
- It extends for nine orders of magnitude in laboratory unconstrained space in both neutron and proton coupling.
- The experimental set up is based on two comagnetometers in separate locations.
- The comagnetometers are part of Advanced GNOME and will run together as a network to look for transient DM events (ELFs, axion domain walls, Q-balls, ...)

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Acknowledgements

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Mikhail Padniuk

Dmitry Budker

Alexander Sushkov

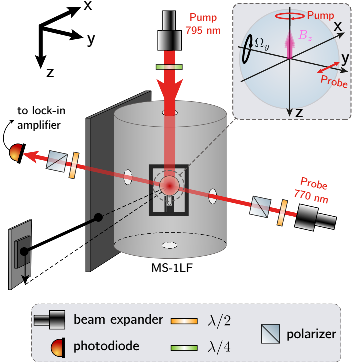
Szymon Pustelny

Read me!

Polarization dynamics in a comagnetometer

- Frequency response for arbitrary perturbation:

$$\mathcal{F}_{\pm}^{r} = -a\frac{\omega_n(\alpha_e - \alpha_n) + (\pm\omega + \gamma_n\Delta_{B_z} - i|R_n|)\alpha_e}{(\pm\omega + \omega_e + \Delta_{B_z}\gamma_e/q - i|R_e|)(\pm\omega + \omega_n + \gamma_n\Delta_{B_z} - i|R_n|) - \omega_e\omega_n}$$



- α = interaction coupling
- a = amplitude
- Δ_{B_z} = detuning from compensation point
- R = Relaxation rate
- ω = Larmor frequency

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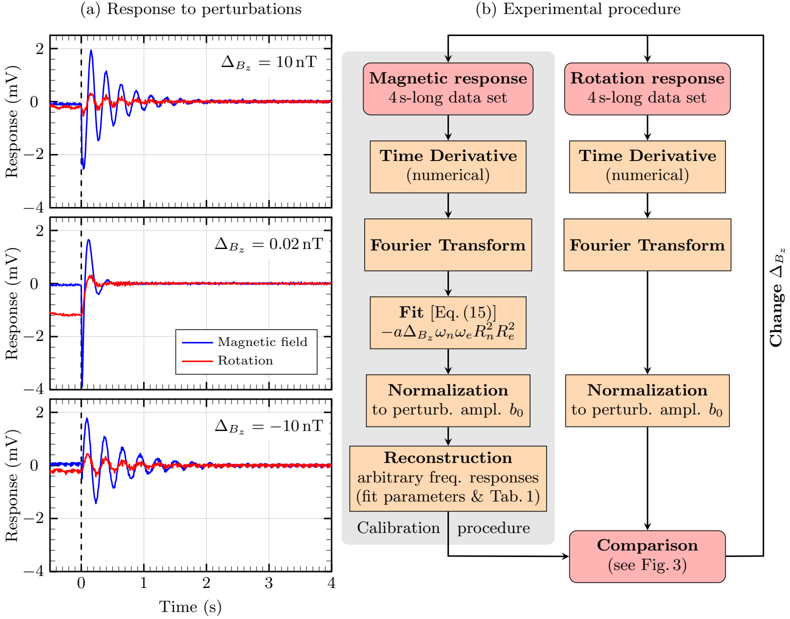
Comagnetometer response calibration routine



Comagnetometer response demonstration