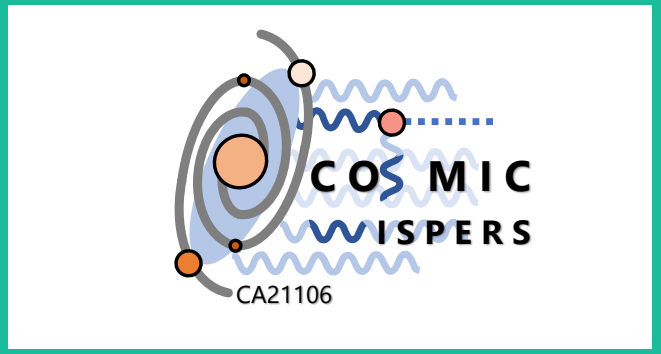


Search for ALPs

by

GNOME and nEDM experiments

…and why do we need optically pumped magnetometers...

Outline

- Introduction to optically pumped magnetometers (OPMs)
- GNOME experiment
  - Idea
  - Implementation
  - Results
- NEDM experiment
  - Motivation
  - Experimental setup
  - Search for Alps
- Conclusion

Optically pumped magnetometers

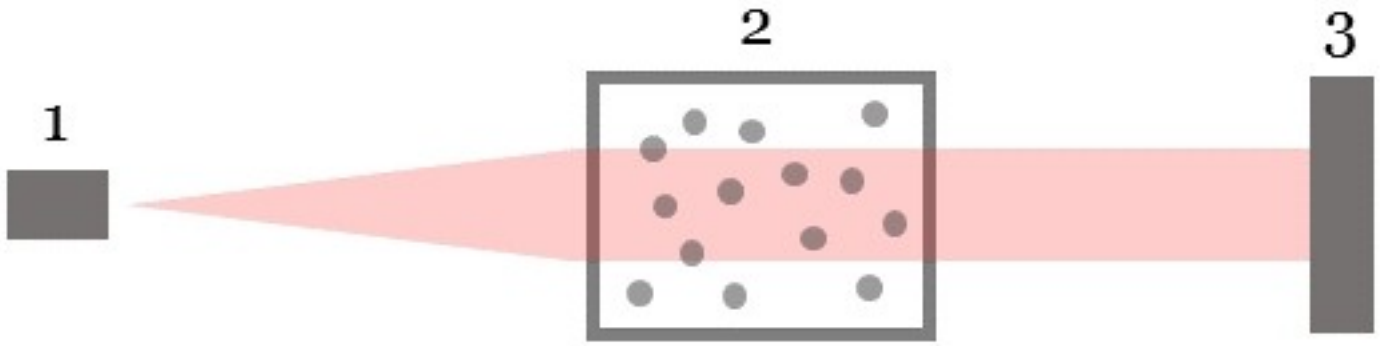
- Rb, Cs, He, K, Hg
- Use of electronic spin detection
  spin orientation or spin alignment
- Scalar magnetometers! Measure Larmor frequency
- Antirelaxation coatings like paraffin, silane, alkene
- Buffer gas: He, N, Ar and mixtures

OPM – Principle of operation

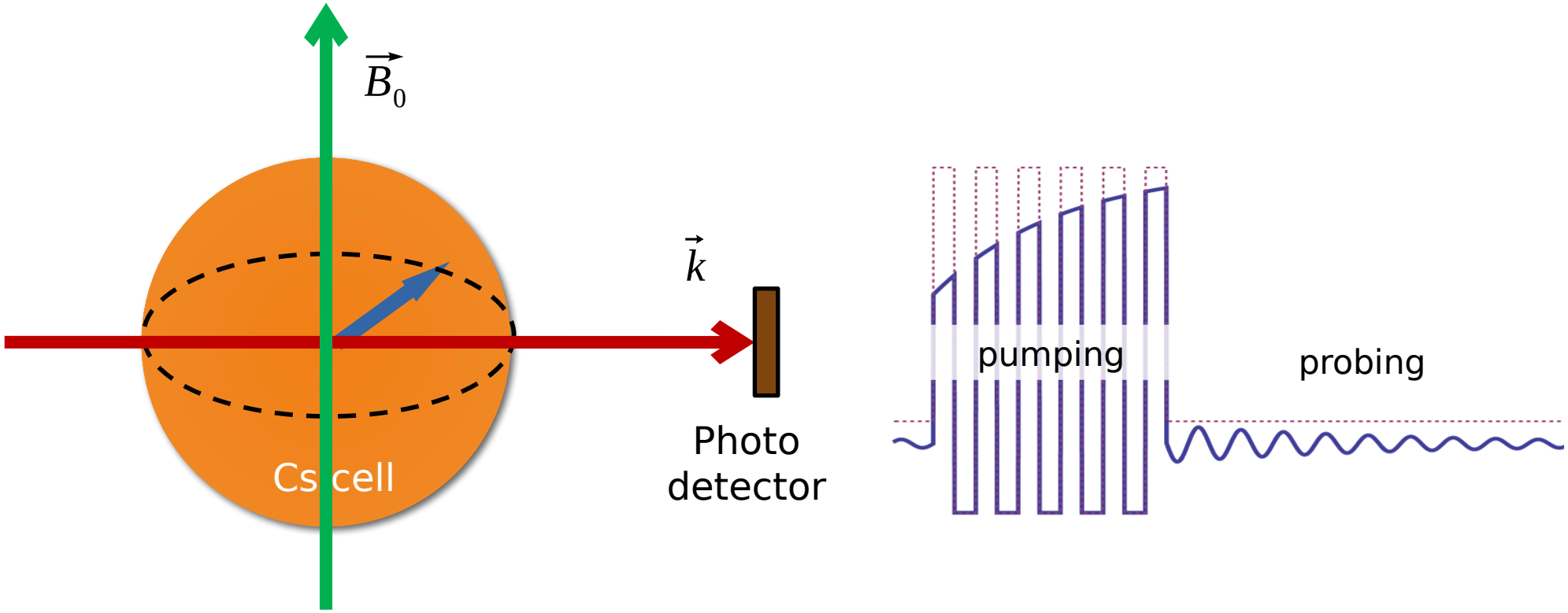
1) Optical pumping produce electronic spin polarization

2) Spin precession in magnetic field B_0

3) Optical detection of electronic spin state



All optical Free Spin Precession magnetometer



GNOME experiment

Coupling electronic spin of a atom to ALPs

GNOME experiment - IDEA

Ann. Phys. (Berlin) **525**, No. 8–9, 659–670 (2013) / DOI 10.1002/andp.201300061

annalen der physik

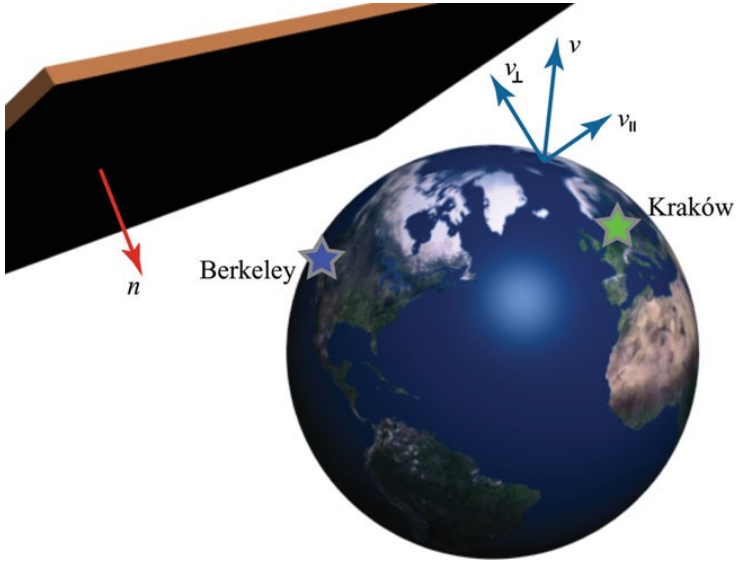
The Global Network of Optical Magnetometers for Exotic physics (GNOME): A novel scheme to search for physics beyond the Standard Model

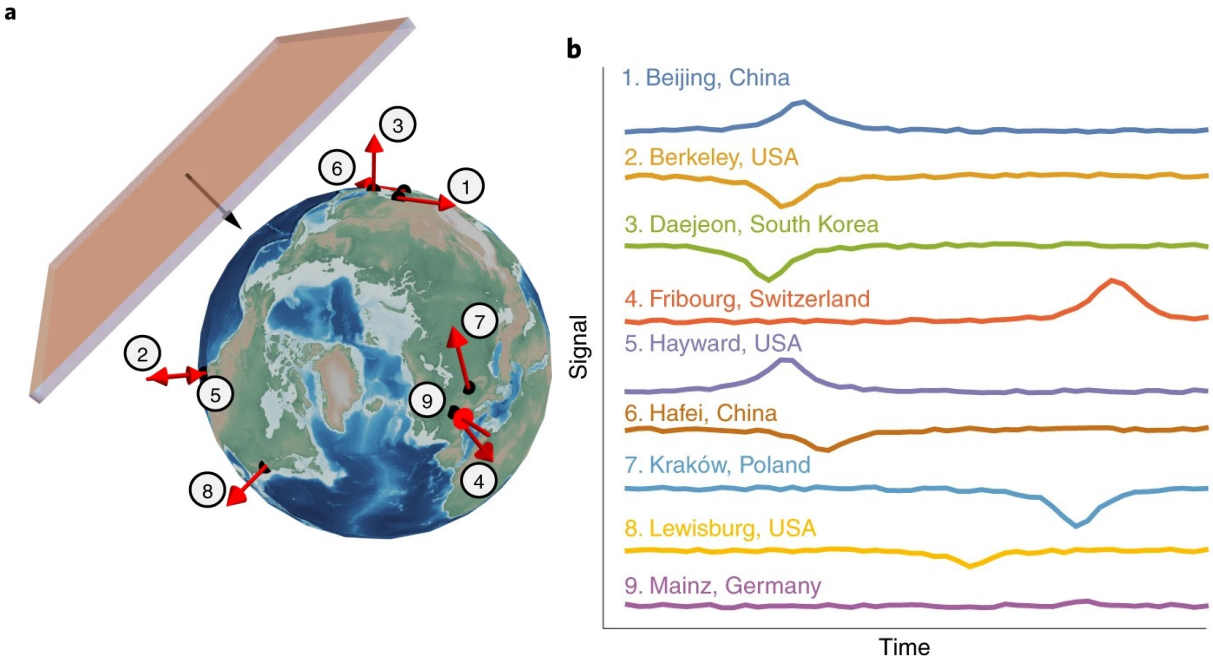
Szymon Pustelny[1,2,], Derek F. Jackson Kimball[3], Chris Pankow[4], Micah P. Ledbetter[2,**], Przemyslaw Wlodarczyk[5], Piotr Wcislo[1,6], Maxim Pospelov[7,8], Joshua R. Smith[9], Jocelyn Read[9], Wojciech Gawlik[1], and Dmitry Budker[2,10]*

Received 18 March 2013, revised 10 July 2013, accepted 22 July 2013
Published online 21 August 2013

GNOME experiment - IDEA

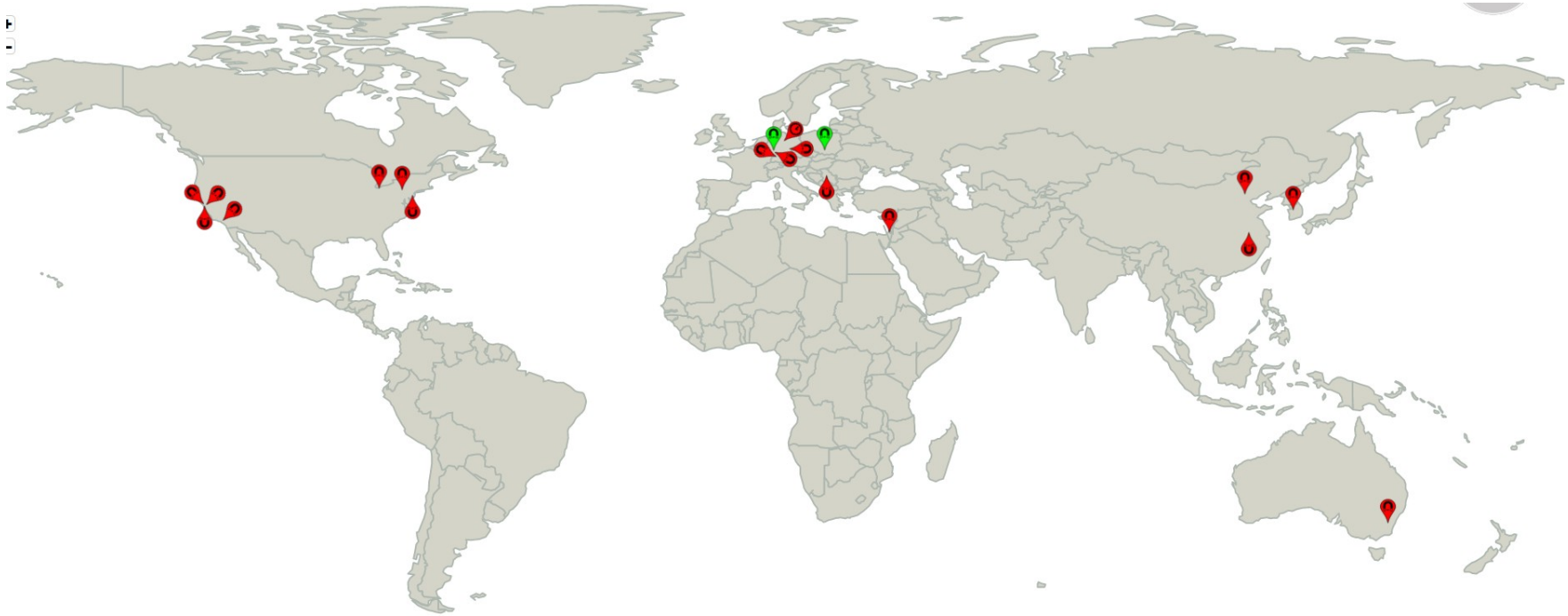
- Multiple stations
- Get correlated events





GNOME map

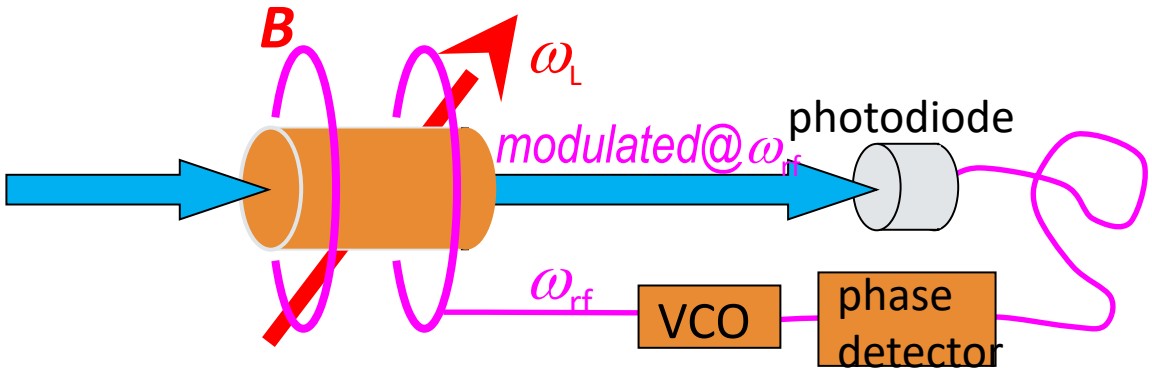
https://budker.uni-mainz.de/gnome/ - 19 nodes

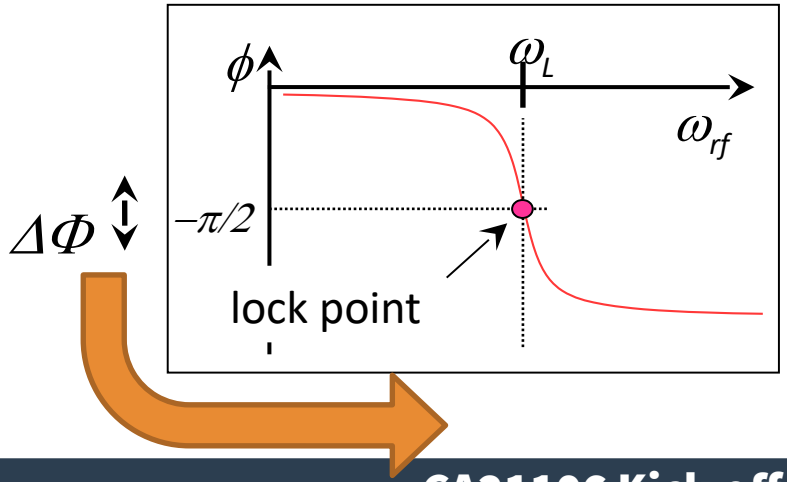


What is a GNOME station

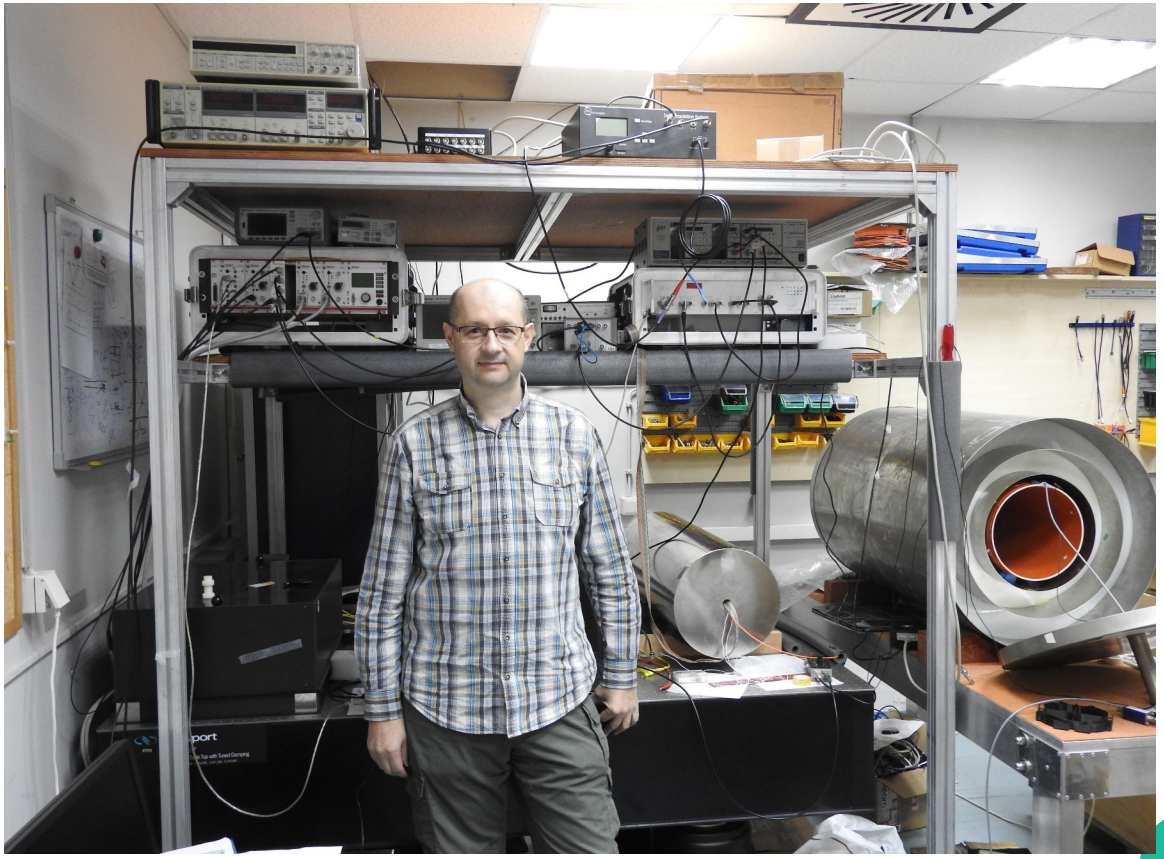
- Shielded (μ metal) high-sensitivity Optically-pumped magnetometer (OPM)
- Controlling electronic
- “The box” data recording device with PC for buffering and uploading data to GNOME server

M_x alkali vapor OPM

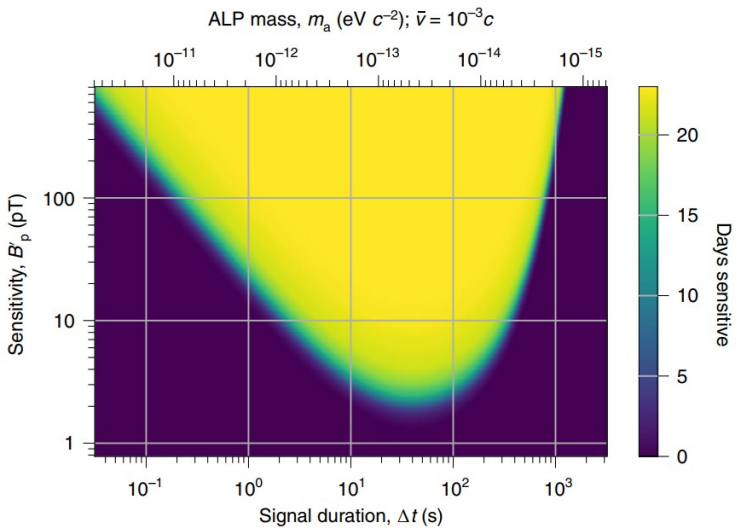




“Typical” GNOME station



Sensitivity of the GNOME network to domain walls



ARTICLES
https://doi.org/10.1038/s41567-021-01393-y
nature physics
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Search for topological defect dark matter with a global network of optical magnetometers

Samer Afach[1,2], Ben C. Buchler[3], Dmitry Budker[1,2,4], Conner Dailey[5,26], Andrei Derevianko[5], Vincent Dumont[6], Nataniel L. Figueroa[1,2], Ilja Gerhardt[7], Zoran D. Grujić[8,9], Hong Guo[10], Chuanpeng Hao[11], Paul S. Hamilton[12], Morgan Hedges[3], Derek F. Jackson Kimball[13], Dongok Kim[14,15], Sami Khamis[12], Thomas Kornack[16], Victor Lebedev[9], Zheng-Tian Lu[17], Hector Masia-Roig[1,2] ✉, Madeline Monroy[4,13], Mikhail Padniuk[18], Christopher A. Palm[13], Sun Yool Park[19,27], Karun V. Paul[3], Alexander Penaflor[13], Xiang Peng[10], Maxim Pospelov[20,21], Rayshaun Preston[13], Szymon Pustelny[18], Theo Scholtes[9,22], Perrin C. Segura[19,28], Yannis K. Semertzidis[14,15], Dong Sheng[11], Yun Chang Shin[14], Joseph A. Smiga[1,2] ✉, Jason E. Stalnaker[19], Ibrahim Sulai[23], Dhruv Tandon[19], Tao Wang[24], Antoine Weis[9], Arne Wickenbrock[1,2], Tatum Wilson[13], Teng Wu[10], David Wurm[25], Wei Xiao[10], Yucheng Yang[10], Dongrui Yu[10] and Jianwei Zhang[10]

Bounds on the Alp parameter space

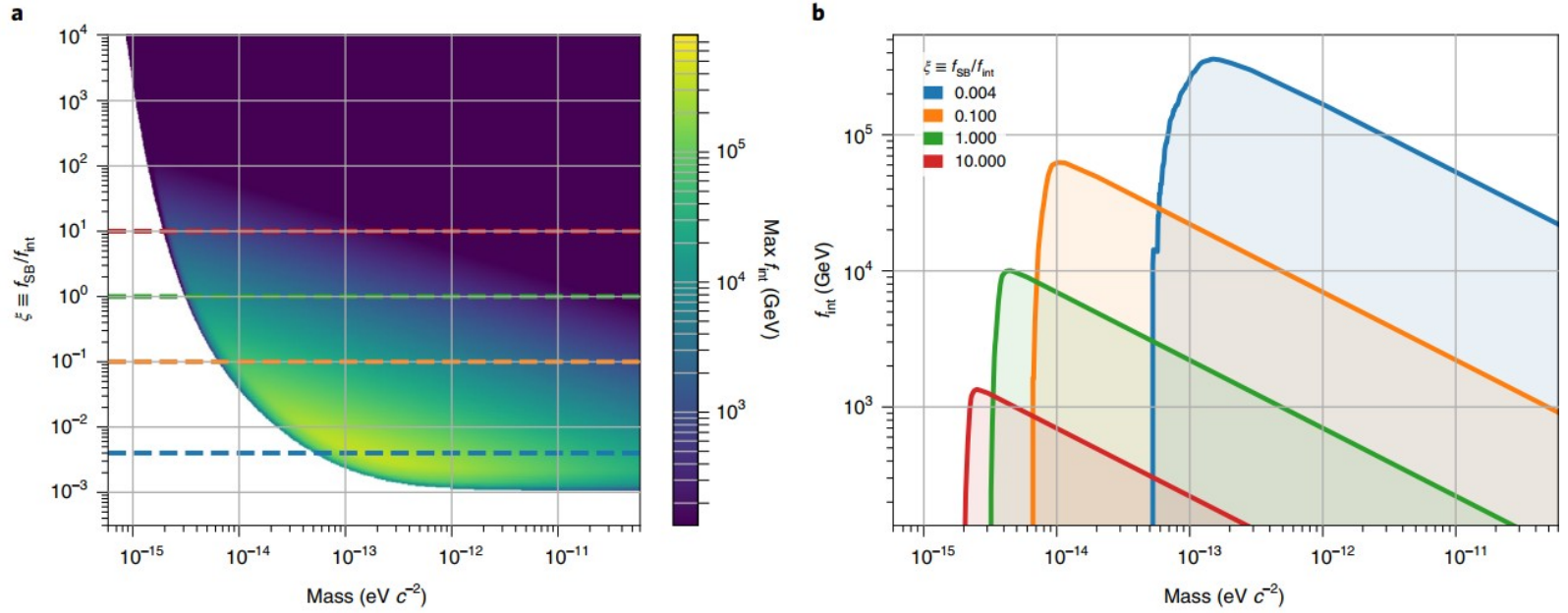
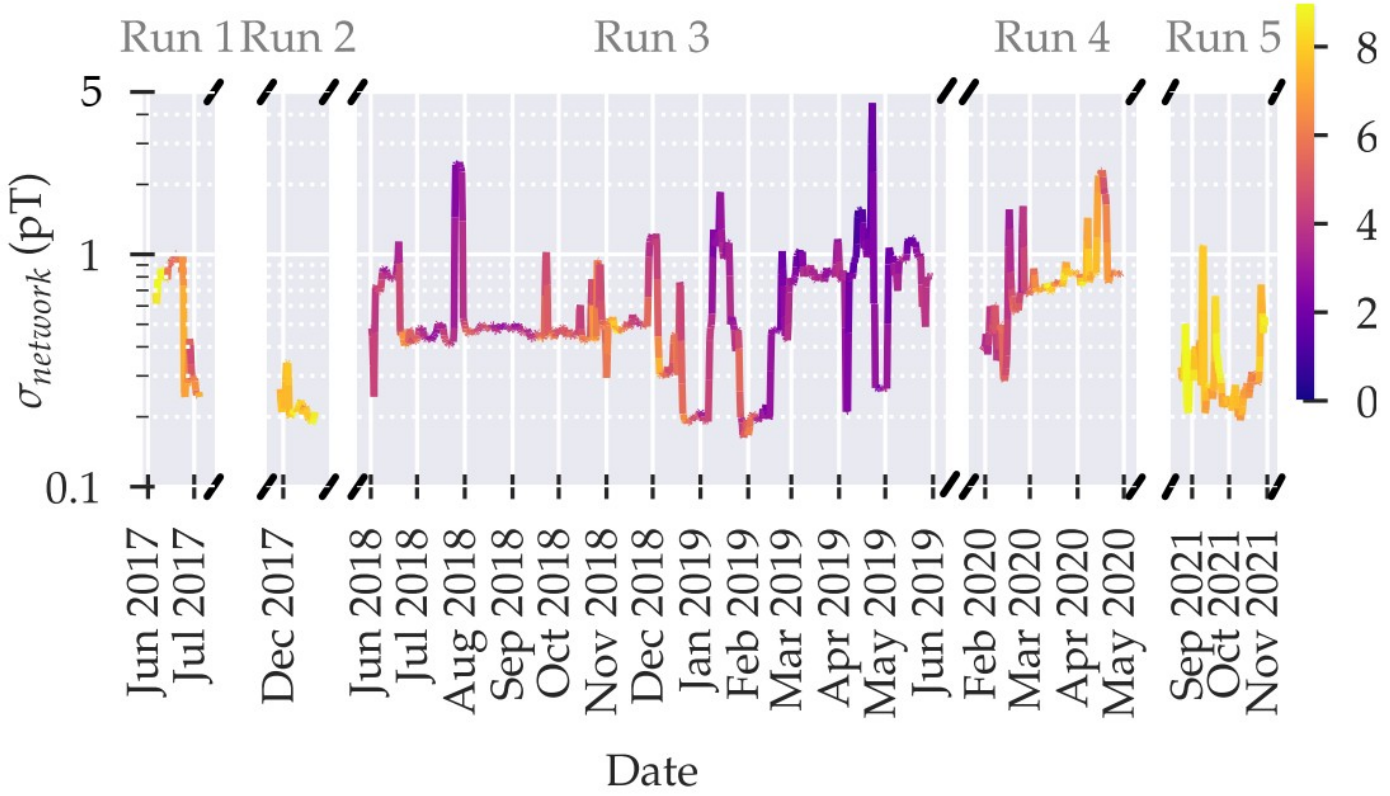


Fig. 4 | Bounds on the ALP parameter space. The bounds are drawn from the presented analysis of Science Run 2 with 90% confidence level. Relationship between the parameters from ALP theory and measured quantities is discussed in Supplementary Section II. **a**, In colour, upper bound on the interaction scale for axion–nucleon coupling, f_{int}, to which GNOME was sensitive as a function of m_a and the ratio between symmetry-breaking and interaction scales ($\xi \equiv f_{SB}/f_{int}$). The dashed horizontal lines highlight the cross-section used in **b** with the respective colour. **b**, Cross-sections of the excluded parameter volume in **a** for different ξ ratios. We note that the domain walls may not be the only form of dark matter; therefore, $\rho_{DW} < 0.4\,\mathrm{GeV\,cm^{-3}}$. If the domain-wall energy density is substantially smaller, this would affect the bounds shown here.

Summary of the GNOME performance during the five Science Runs from 2017 to 2021

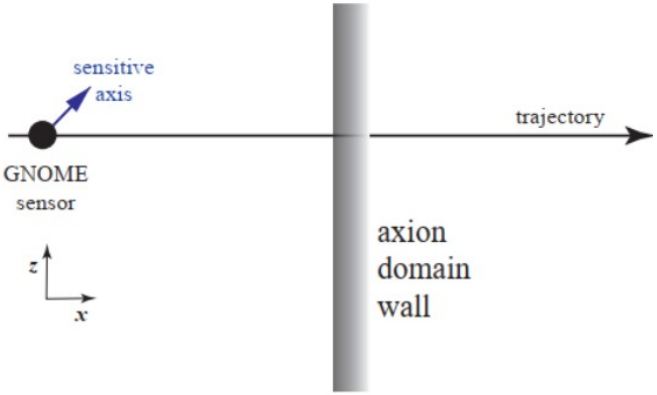


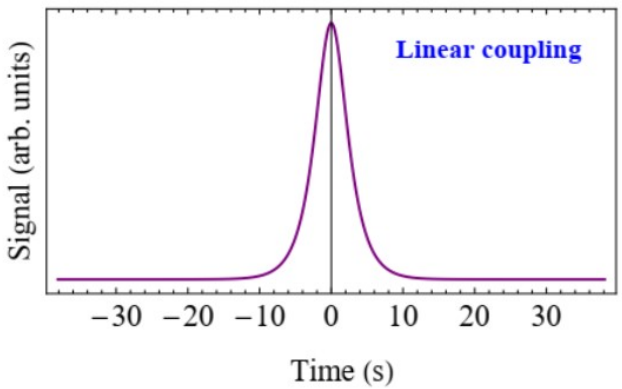
Temporal characteristics of a variety of possible signals

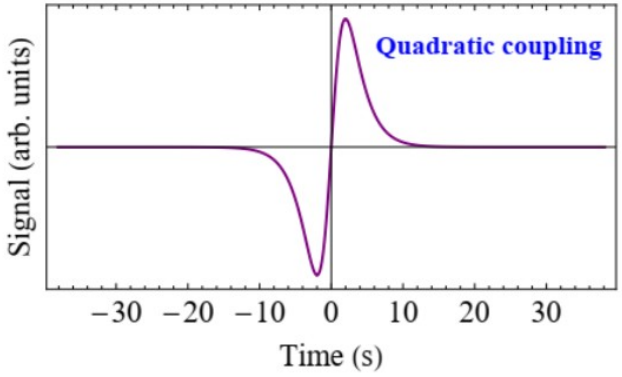
Topological defect of dark matter:

- axion-like particle domain walls,
- axion-like particle stars,
- solitons of complex-valued scalar fields (Q-balls),
- stochastic fluctuations of bosonic dark matter fields,
- a solar axion-like particle halo,
- bursts of ultralight bosonic fields produced by cataclysmic astrophysical events such as binary black hole mergers

Interaction with domain wall

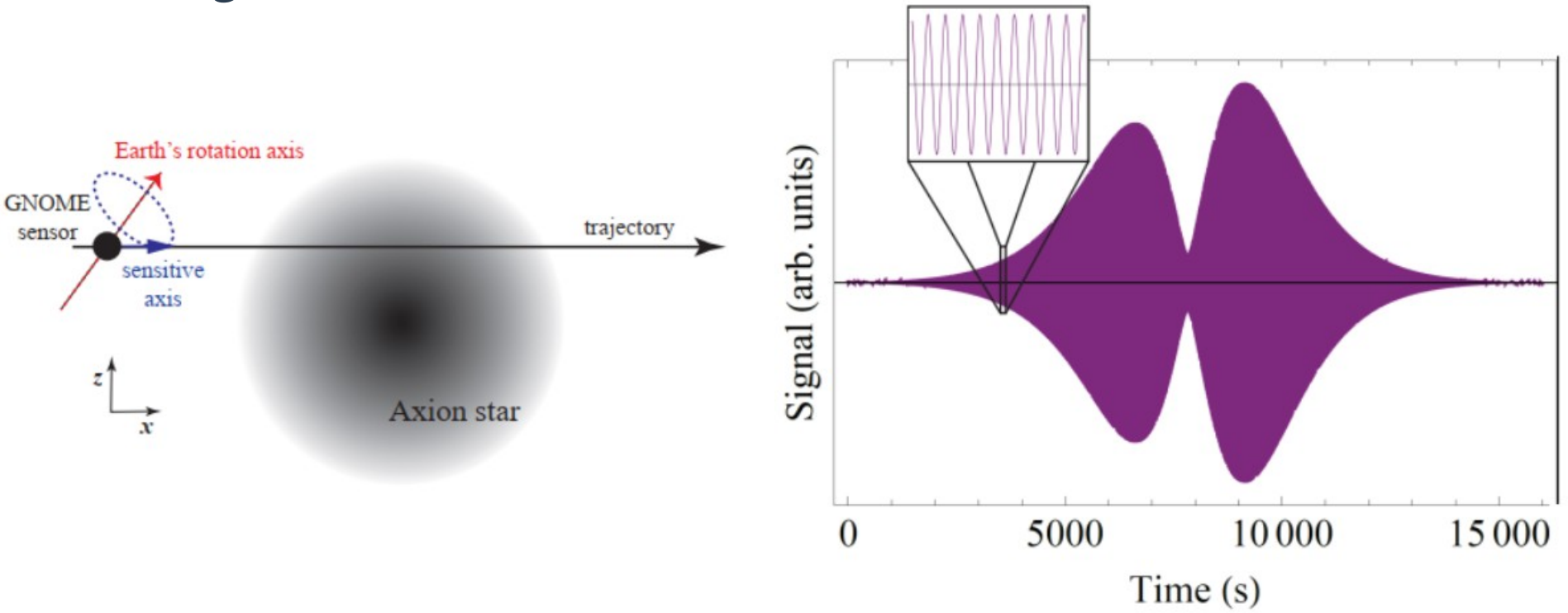






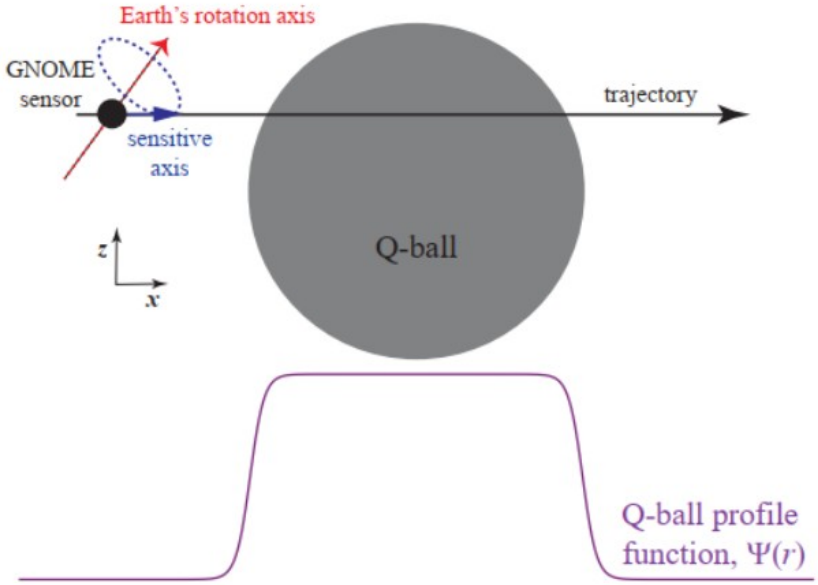
Interaction with Axion star

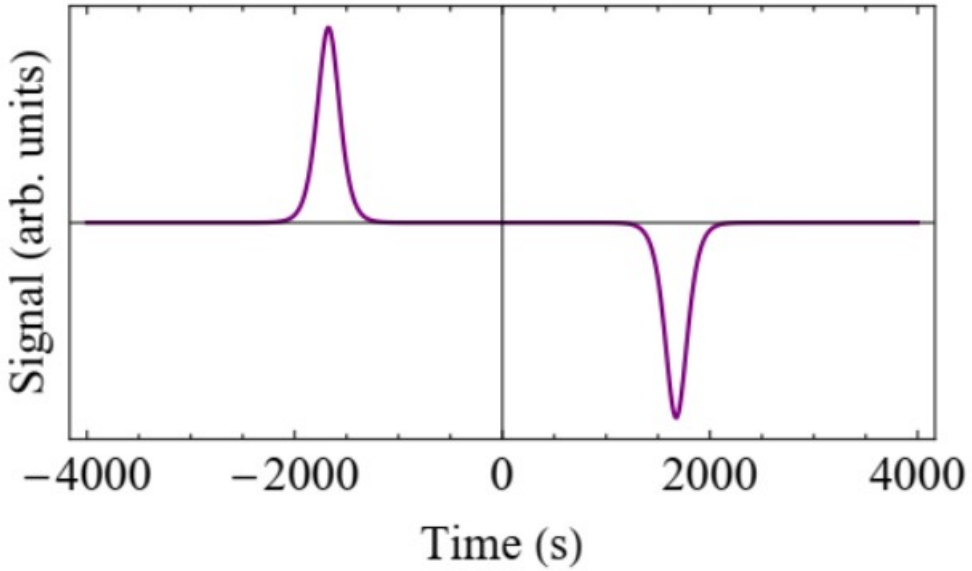
- Held together via self-interactions oscillons or axitons



Interaction with Q-ball

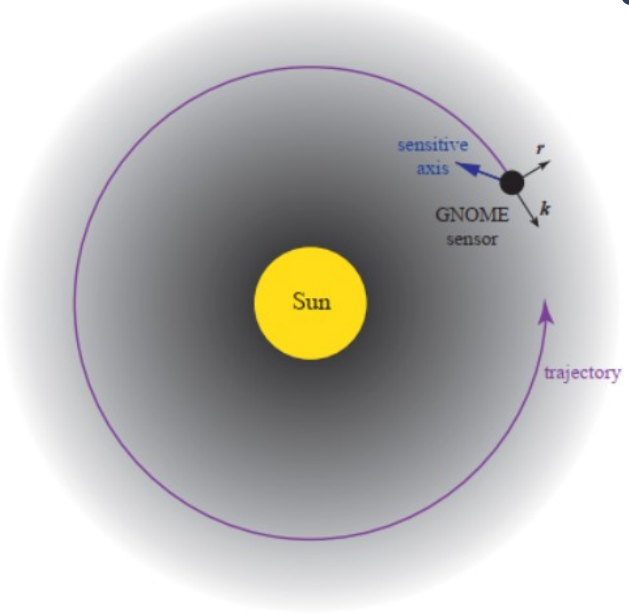
- Q-ball – true solitons

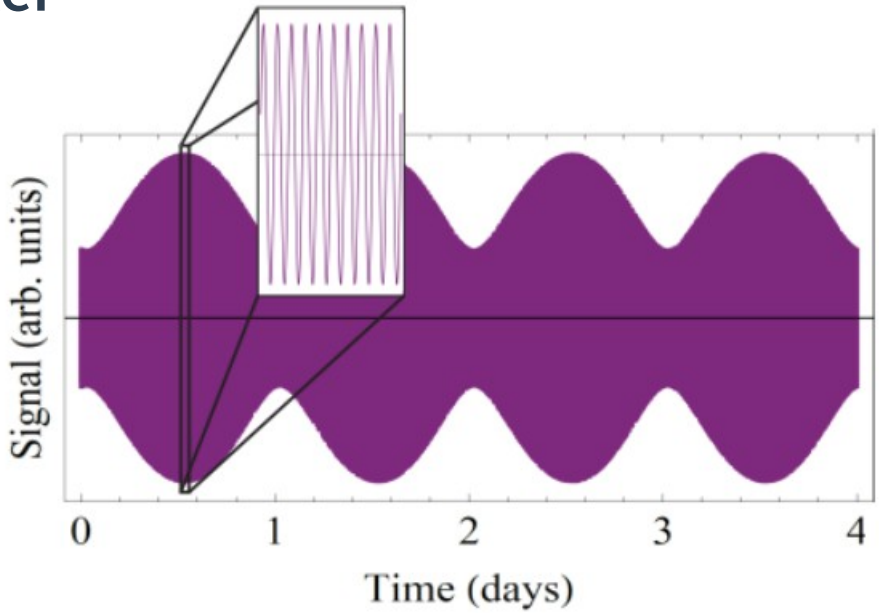




Solar axion halo

- Amplitude modulation due daily rotation of sensitive axis of a magnetometer





GNOME collaboration

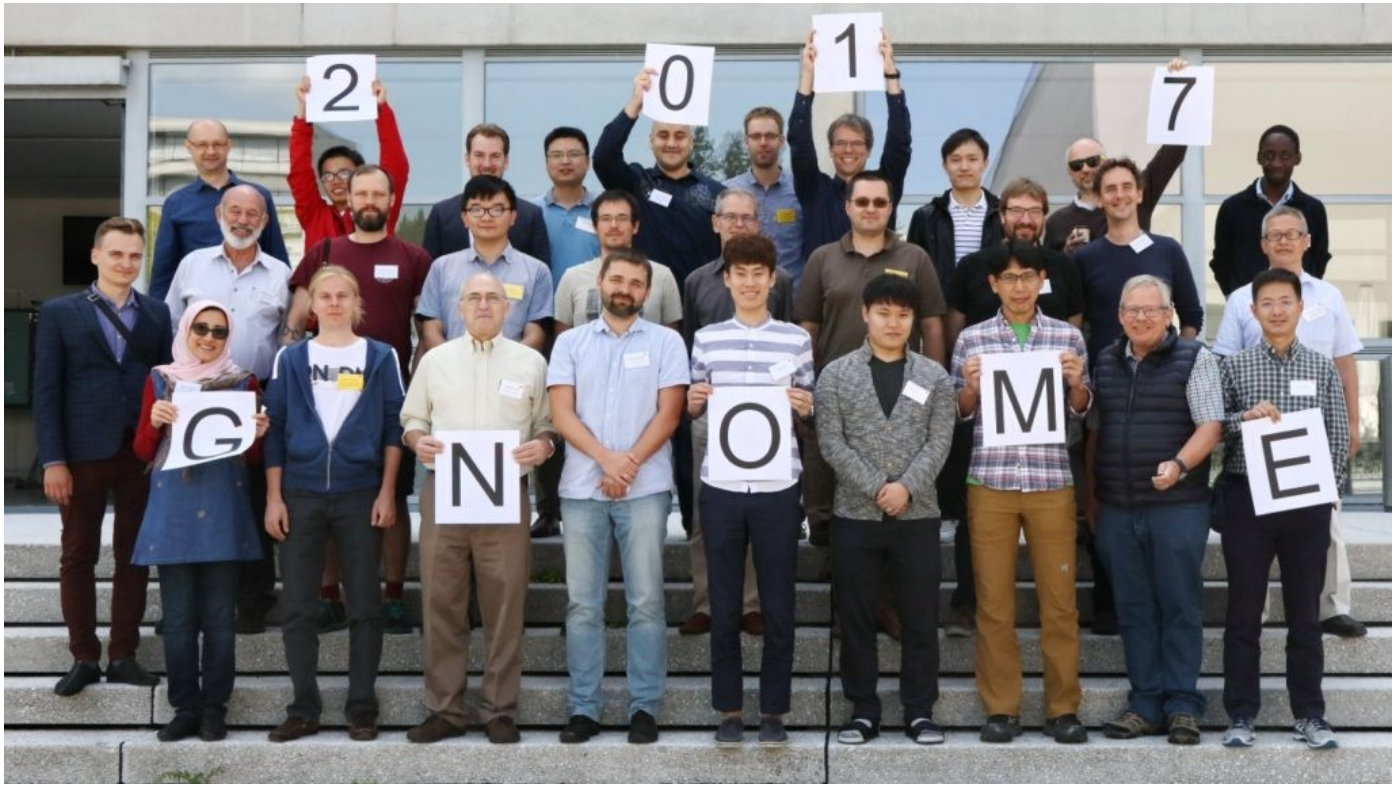
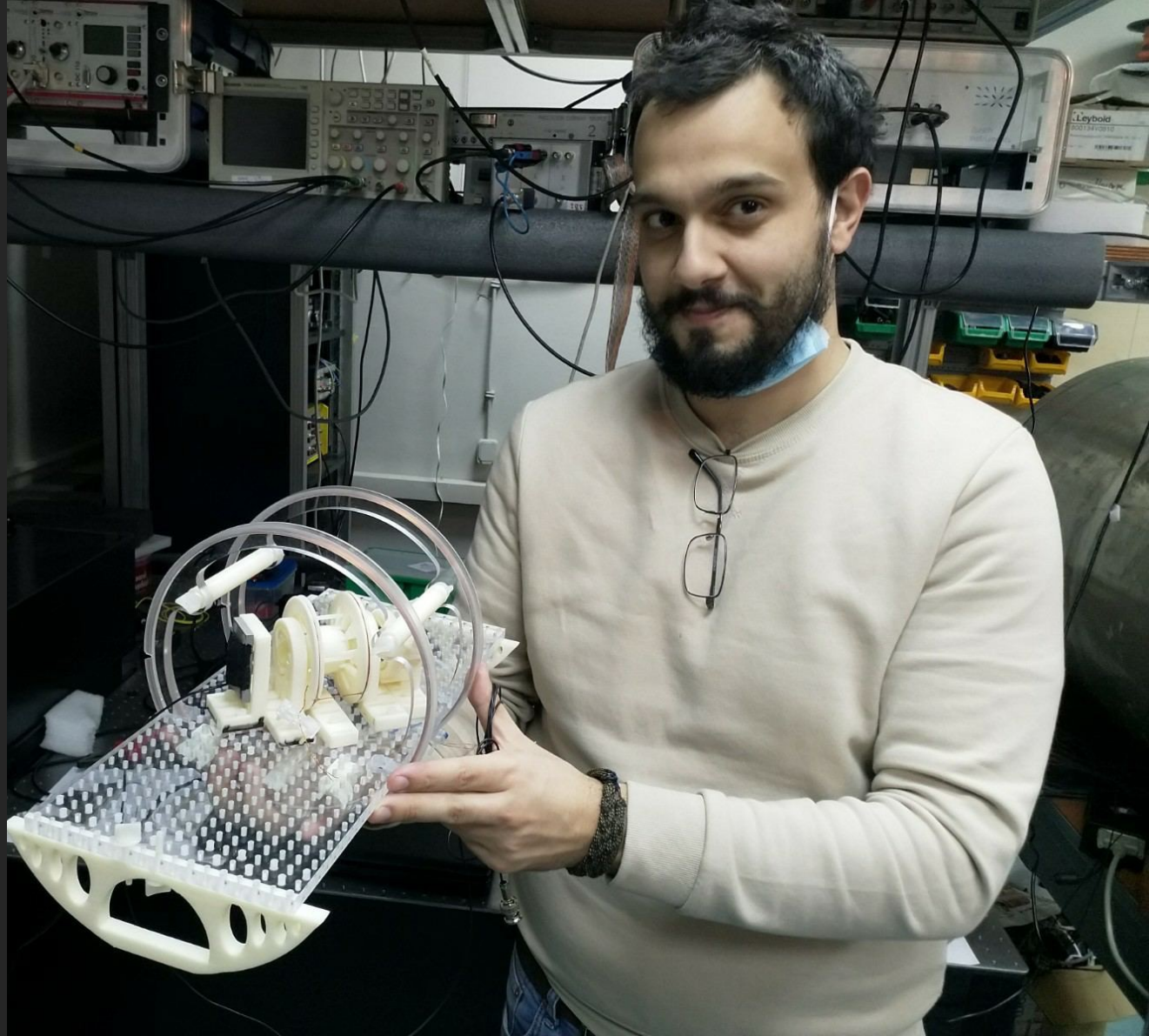


Table top experiment

The hart of the future BGMagLab GNOME station



nEDM experiment

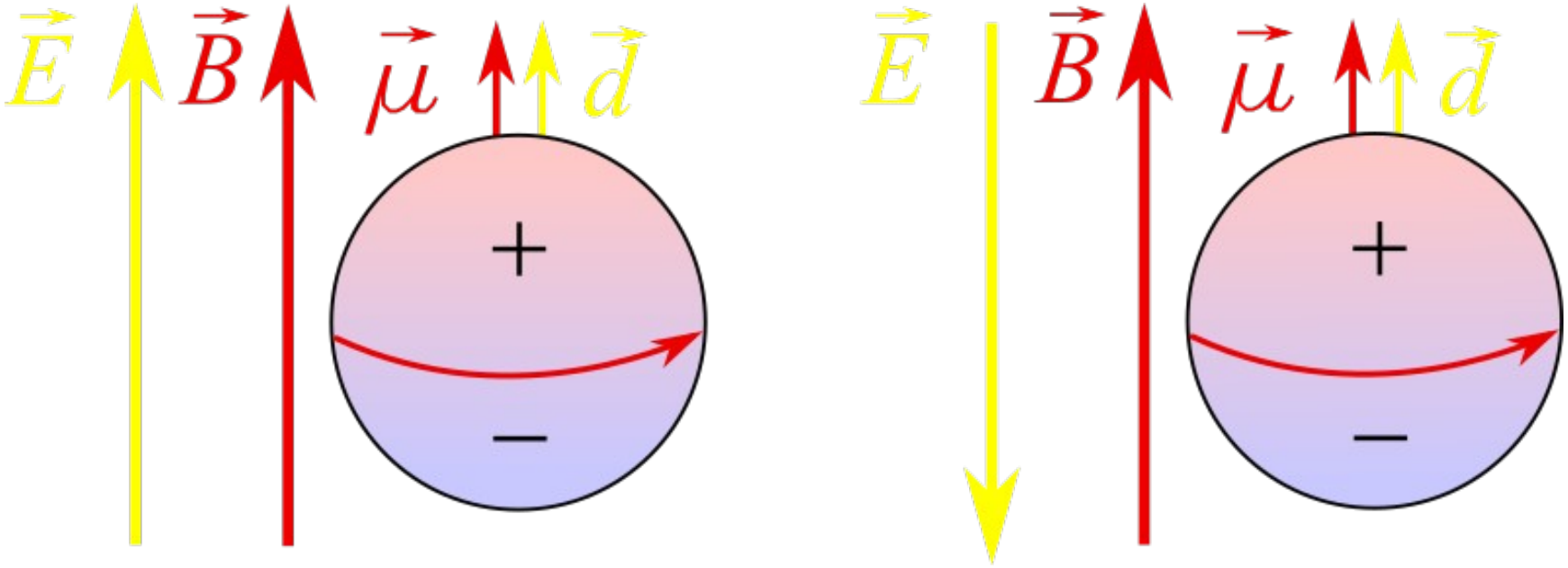
nEDM collaboration based at PSI, Switzerland

NEDM - motivation

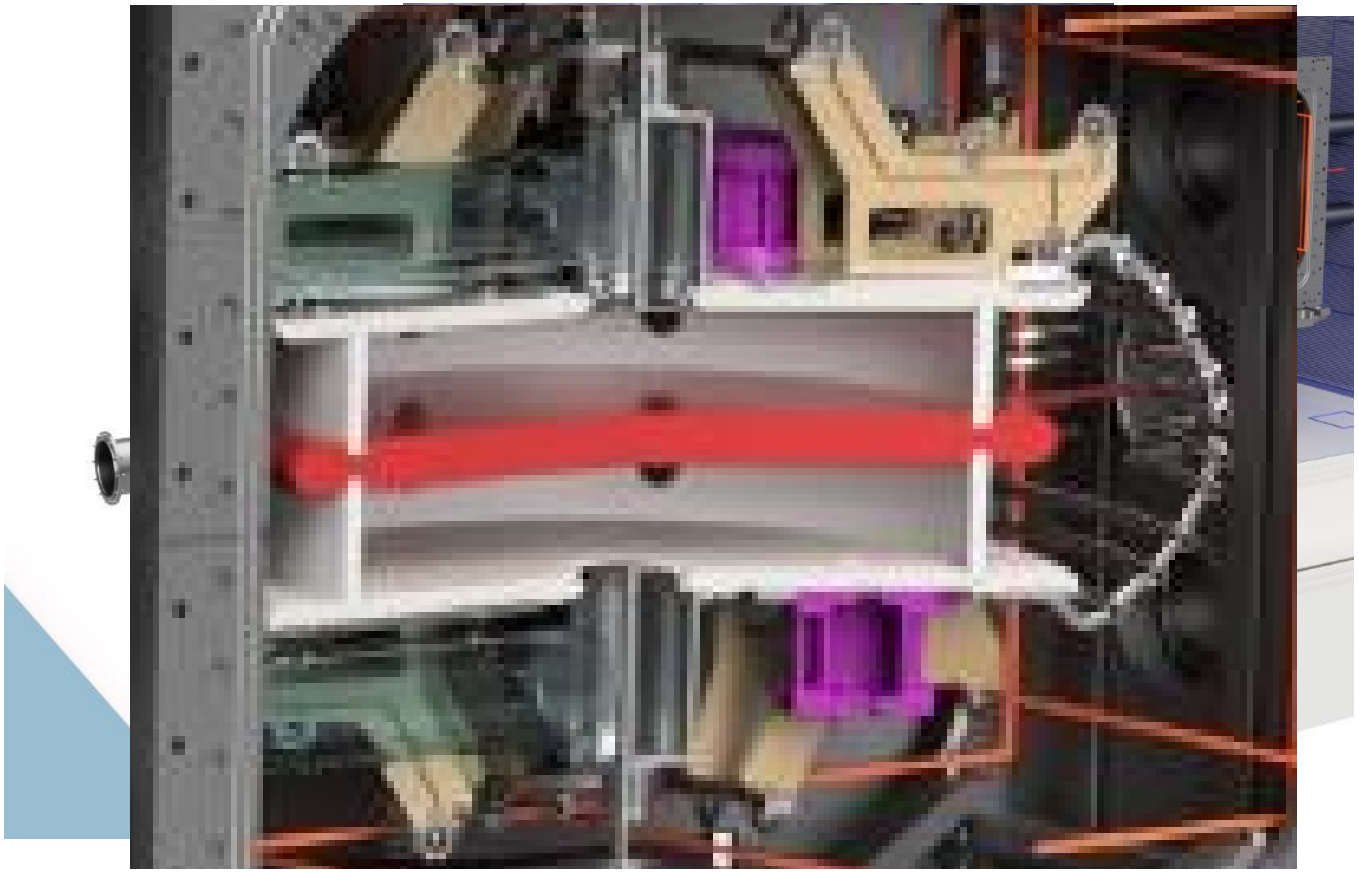
- Very narrow constraints are set by values of Electrical Dipole Moments (EDMs), as they brake parity and time-reversal symmetries, on the models beyond standard model (SM) of particle physics. They must include low level of CP (charge, parity) violation in K (decays of the neutral K mesons) and B (beauty mesons) systems and to explain the large baryon asymmetry of the Universe in the same time. The current limit of the neutron Electrical Dipole Moment (nEDM) has already set requirements for considerable fine-tuning of MSSM parameters - the so-called "SUSY CP problem".
- The most sensitive nEDM experiment was operated by nEDM international collaboration (2015-2017, results published PRL) at the Paul Scherrer Institute (PSI) in Switzerland. Currently the nEDM collaboration is constructing improved version of the experiment (n2EDM) using the same PSI infrastructure.

nEDM simplified method

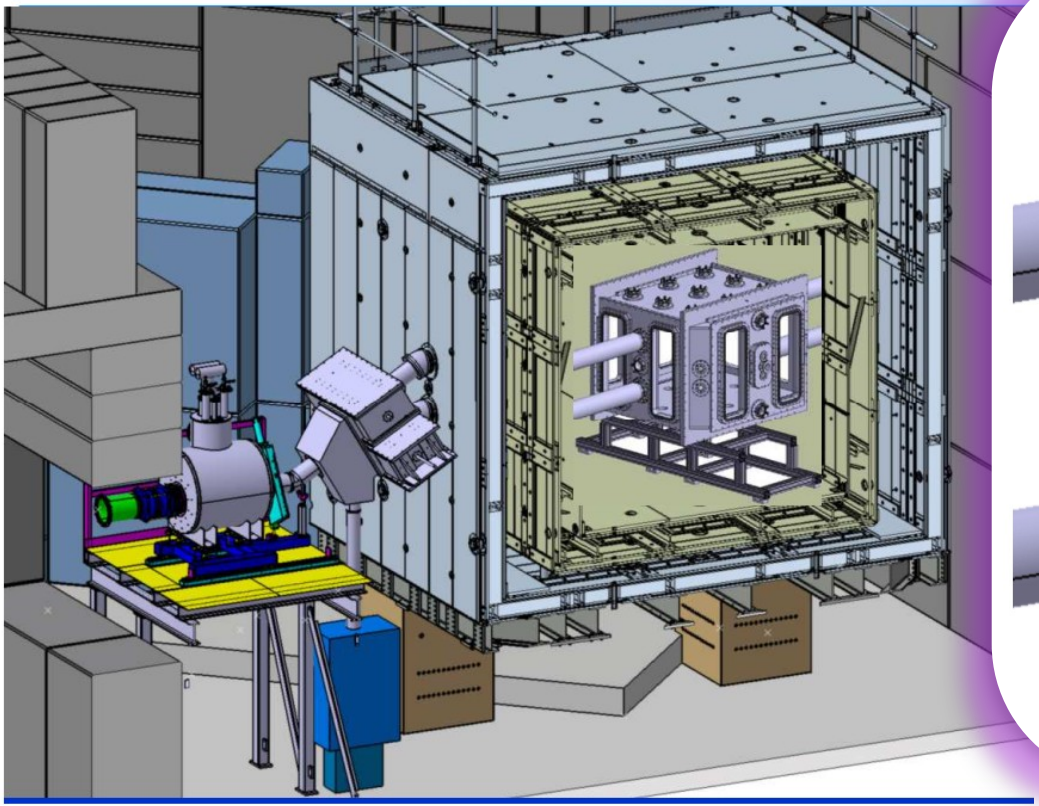
- How to measure neutron Electrical Dipole Moment - nEDM

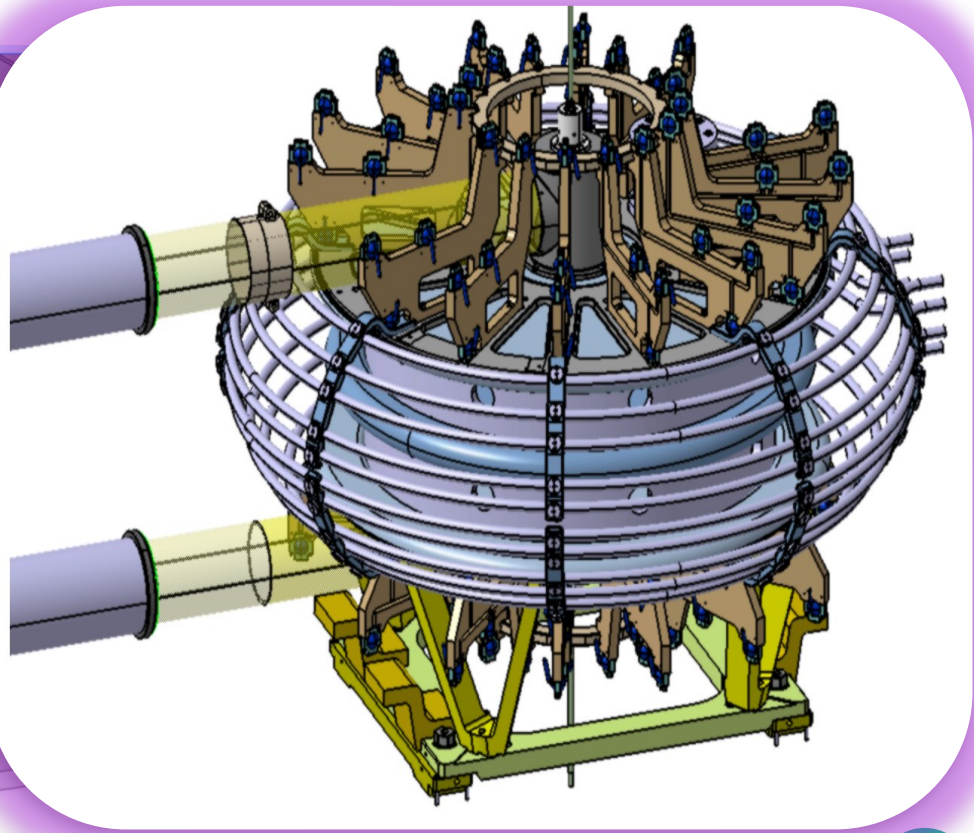


nEDM Experimental setup



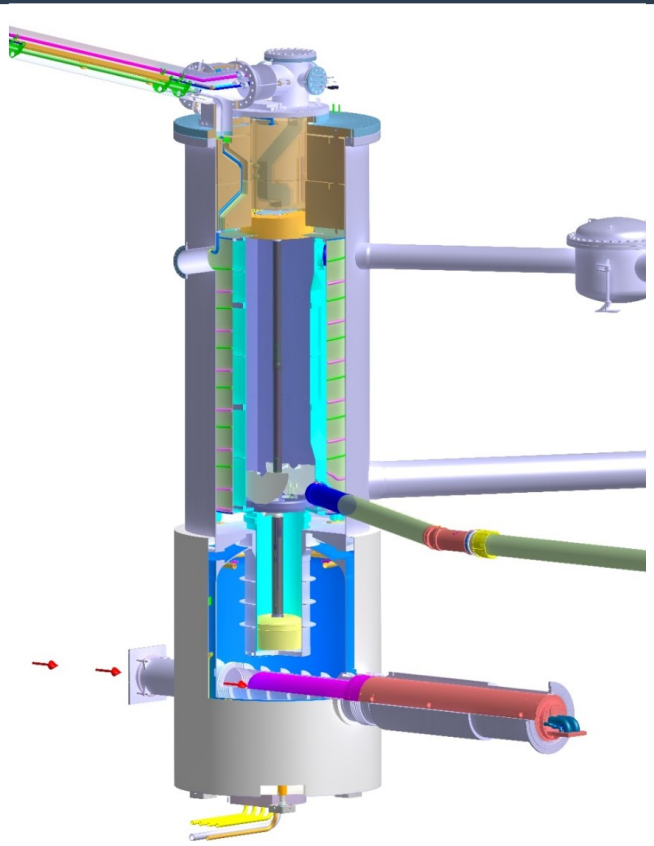
View of nEDM experiment





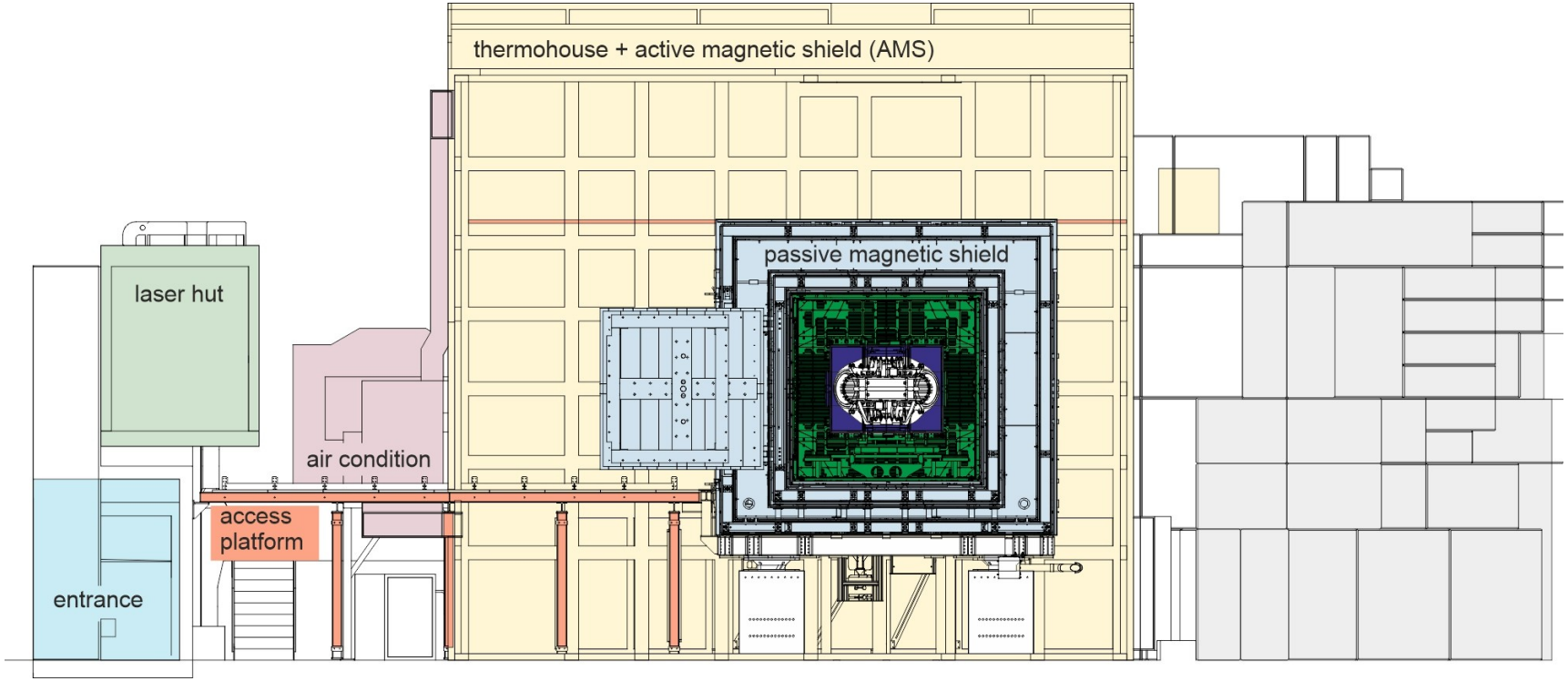
The high-intensity proton accelerator (HIPA)

UCN Source



- Up to 8s proton beam pulse
- Neutron moderation in heavy water and solid deuterium
- Central storage flaps close shortly before end of pulse
- UCN are trapped in storage vessel and guided to the experiment

nEDM experiment



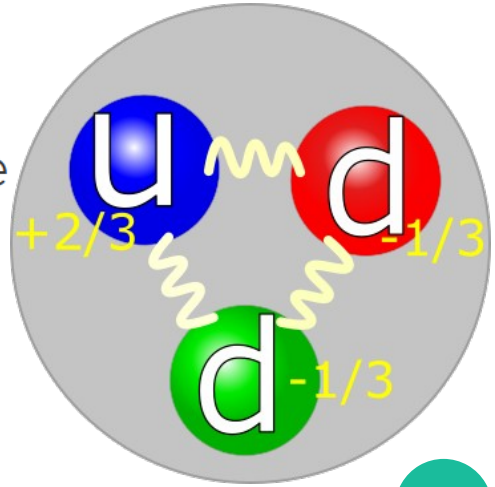
Currently the best measurement of nEDM

$$d_n = (0.0 \pm 1.1\ \text{stat} \pm 0.2\ \text{sys}) \times 10^{-26}\ e\ \text{cm}$$

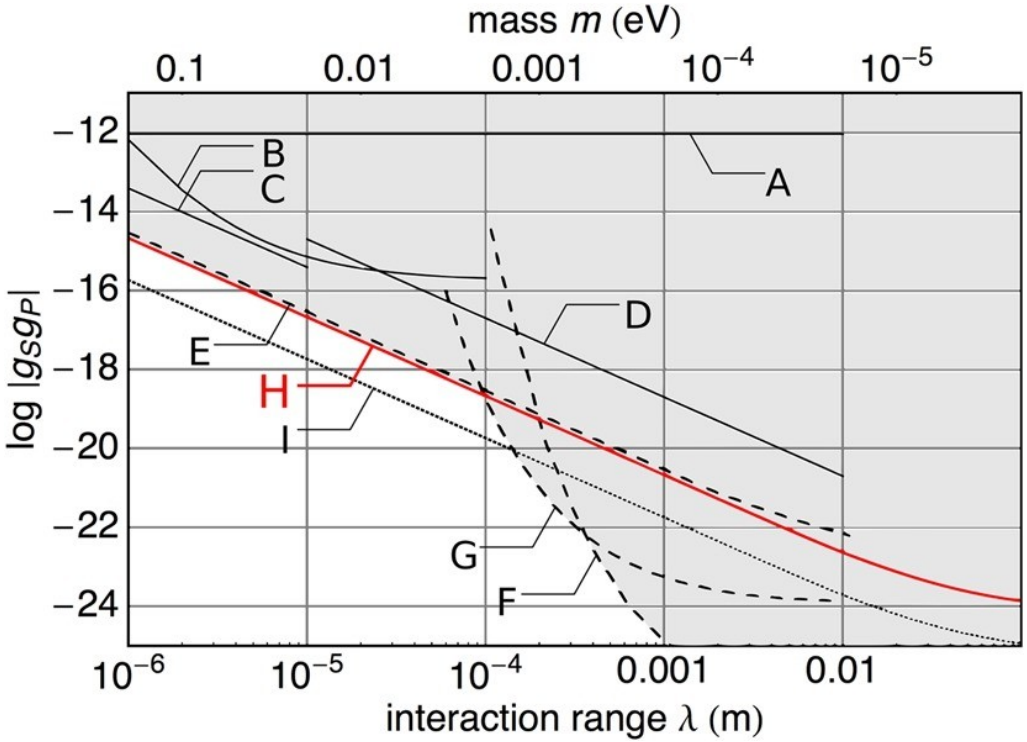
Measurement of the Permanent Electric Dipole Moment of the Neutron

C. Abel *et al.*
Phys. Rev. Lett. **124**, 081803 – Published 28 February 2020

Physics See Focus story: New Limit on the Neutron's Internal Charge Asymmetry



UCNs and axions



- 95 % confidence level
- Solid line limits were obtained using cold or ultracold neutrons.
- Dashed line limits were obtained using 3He, 129Xe, or 131Xe
- H this work
- 3x better limit if Al replaced by Cu
- I (dotted) achievable limit if asymmetric Al+Cu

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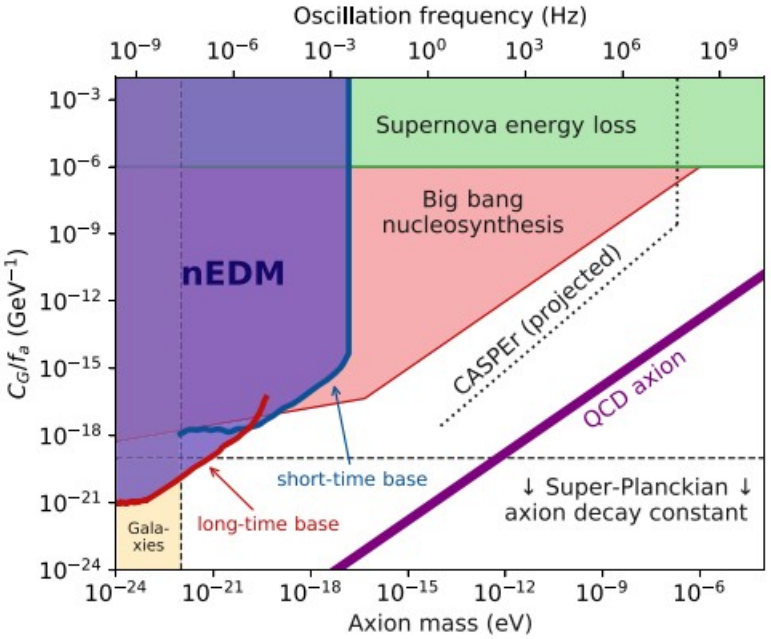
Physics Letters B

Volume 745, 18 May 2015, Pages 58-63

Constraining interactions mediated by axion-like particles with ultracold neutrons

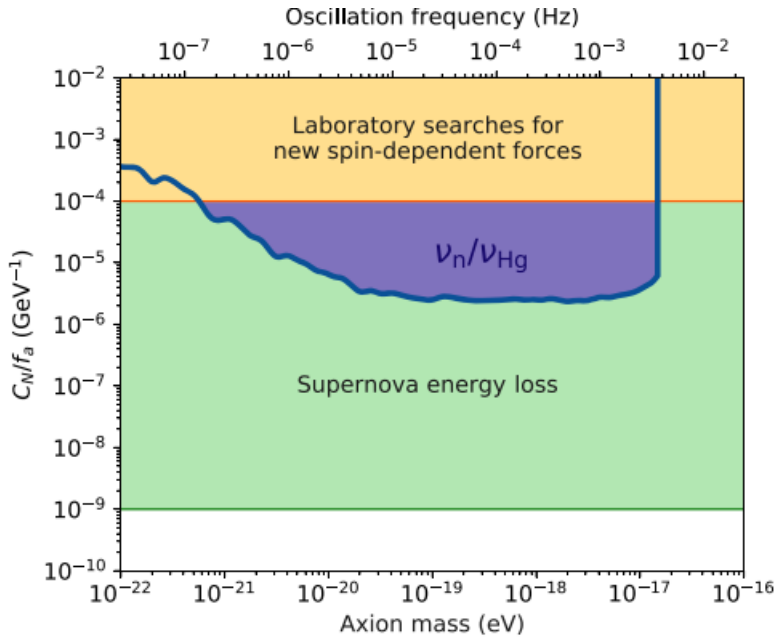
Oscillating nEDM and ALPs



Gluons

ALPs interacting with

Nucleons

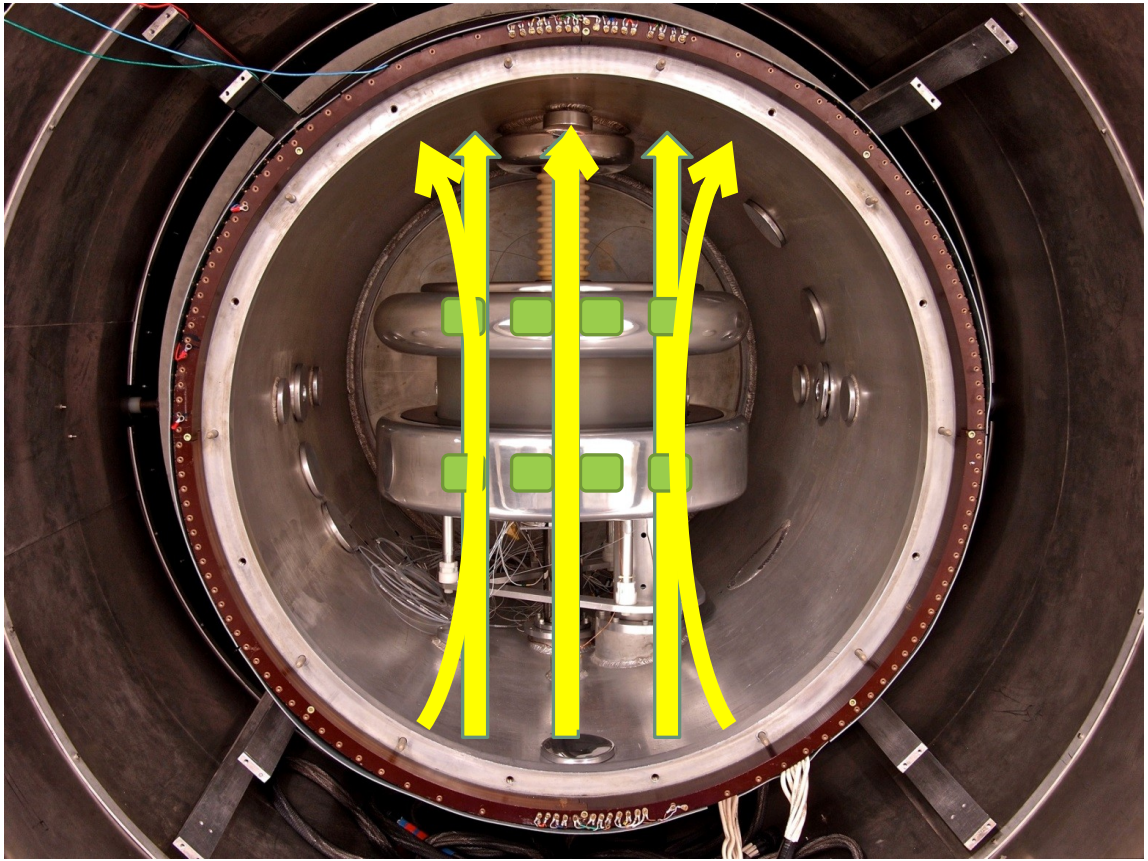


PHYSICAL REVIEW X 7, 041034 (2017)

Search for Axionlike Dark Matter through Nuclear Spin Precession in Electric and Magnetic Fields

Why do wee need magnetometers for nEDM?

- Hg comagnetometer
- Cs array



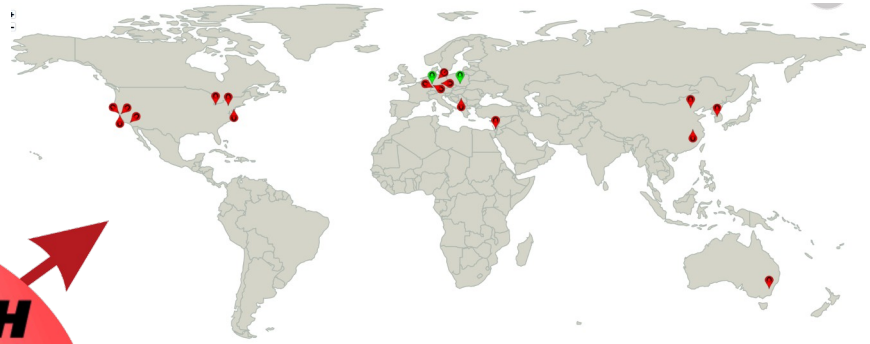
Conclusion

- **GNOME – network of tabletop experiments**
  - Development of more sensitive magnetometers
  - Special magnetometers sensitive to changes of B
- **nEDM – requires monitoring of homogeneity of magnetic field**
  - Development of high accuracy magnetometers

Thank you!

Institute of Physics Belgrade

GNOME map



nEDM

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The end