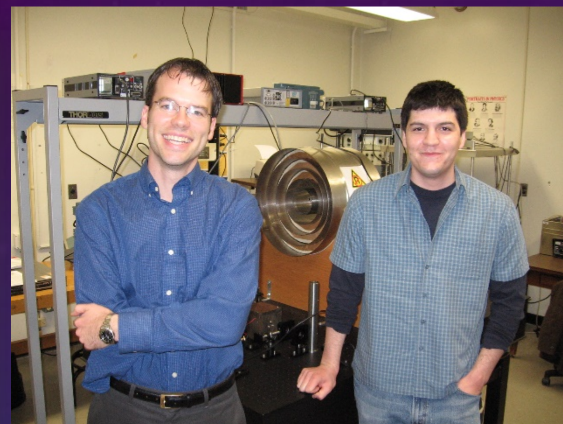
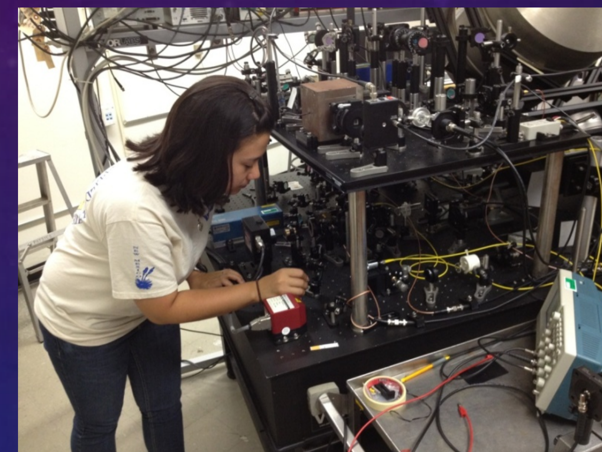
Global Network of Optical Magnetometers for Exotic Physics searches (GNOME)

Derek F. Jackson Kimball

GNOME COLLABORATION

THANKS TO MANY, MANY FANTASTIC UNDERGRADUATE STUDENTS





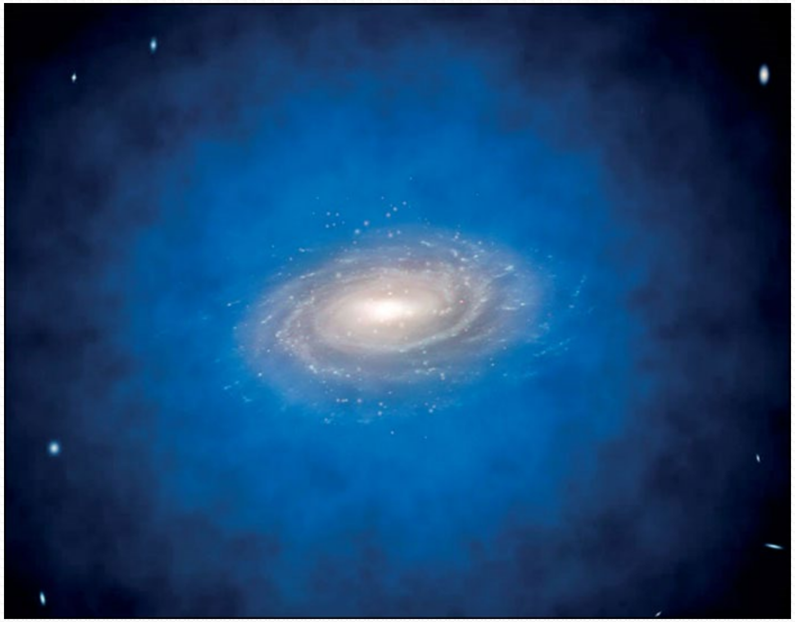
OUTLINE

- Ultralight bosonic dark matter
- GNOME concept & architecture
- Searches for:
  - Axion domain walls
  - Exotic Low-mass Fields (ELFs)
  - Stochastic fluctuations of bosonic DM fields
  - Boson stars
  - Solar axion halos
  - … and more!

ULTRALIGHT BOSONIC DARK MATTER!

Ultralight bosonic dark matter

Dark matter may be ultralight bosons with long de Broglie wavelengths. Many ultralight bosons occupy a single mode; their effect on detectors can be modeled as wave-like.



Axions

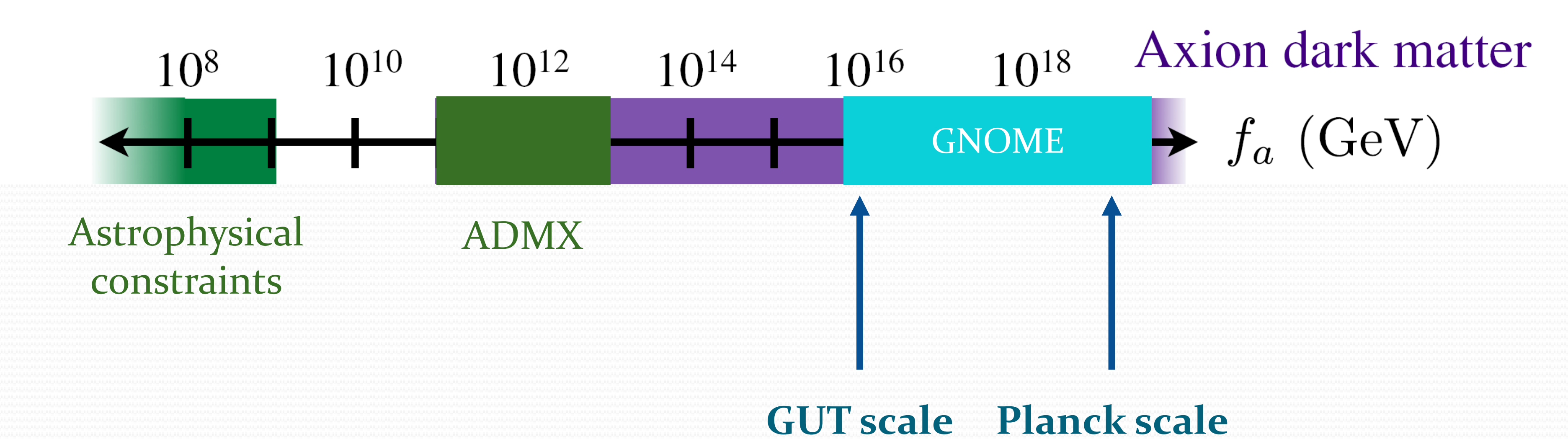
Axions are ultralight, spin-zero bosons generated by symmetry breaking at a high energy scale f_a.

Appear in many extensions of the Standard Model: related to strong-CP problem, hierarchy problem, string theory, and baryogenesis.

Axion mass is proportional to the symmetry-breaking scale:

$$m_a \propto \frac{1}{f_a}$$

Probing high energy scales by searching for ultralight axions



Coupling of atomic spins to axions

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

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

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

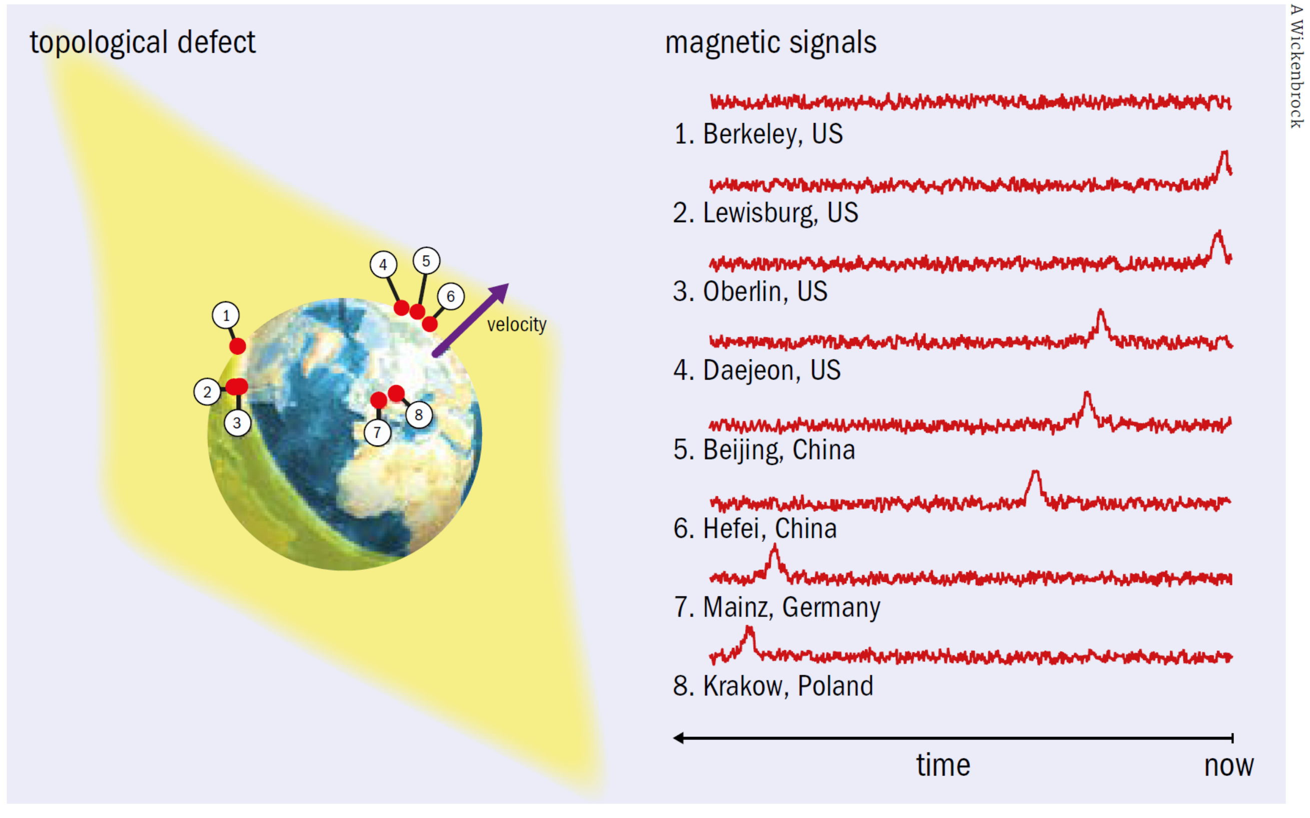
Zeeman Hamiltonian: ordinary interaction of spin with magnetic field.

GNOME CONCEPT & ARCHITECTURE

TRANSIENT DARK-MATTER ENCOUNTERS

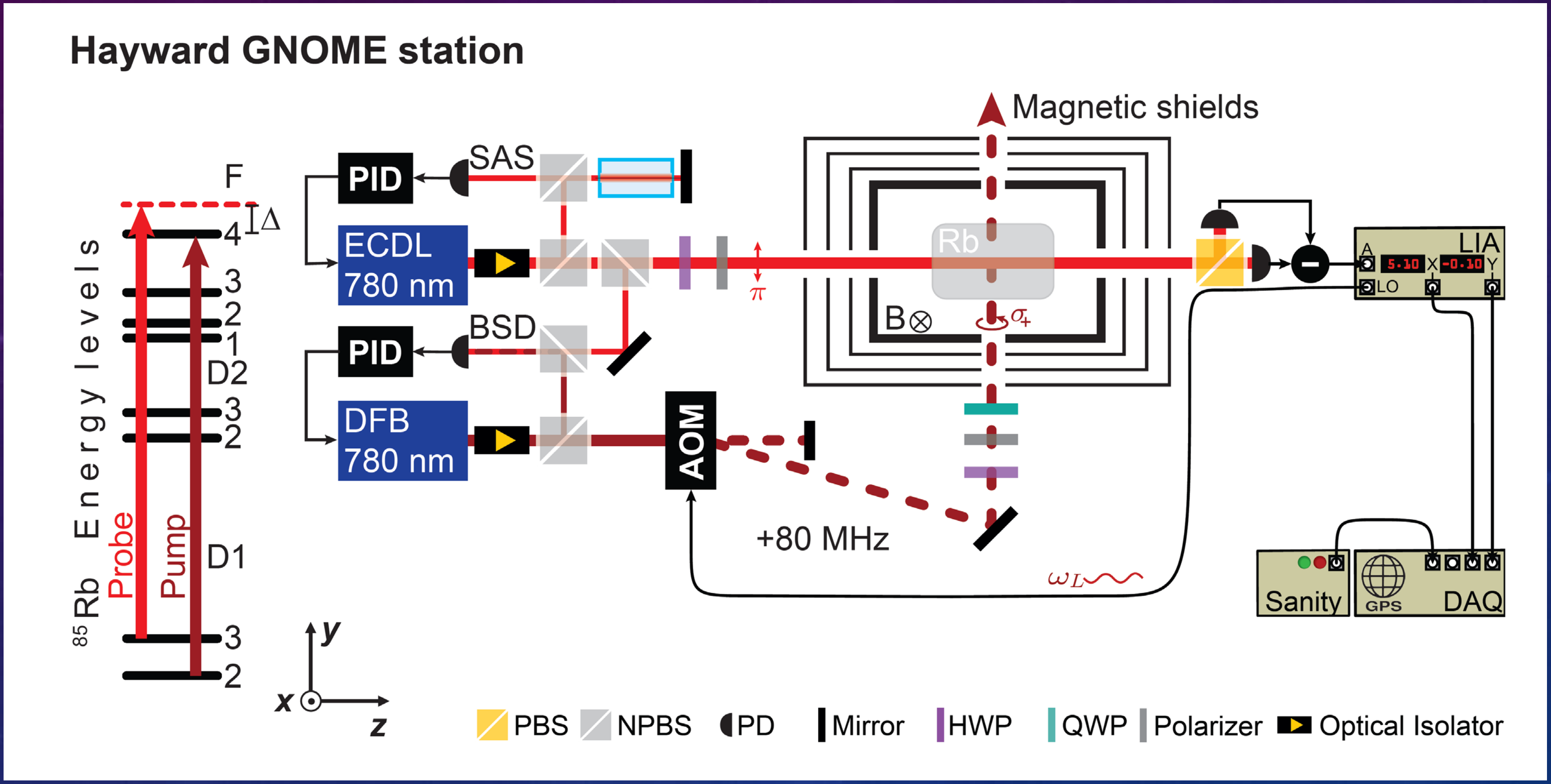
What can we say about transient encounters with compact dark-matter objects?

A single sensor would struggle to distinguish signal from noise.

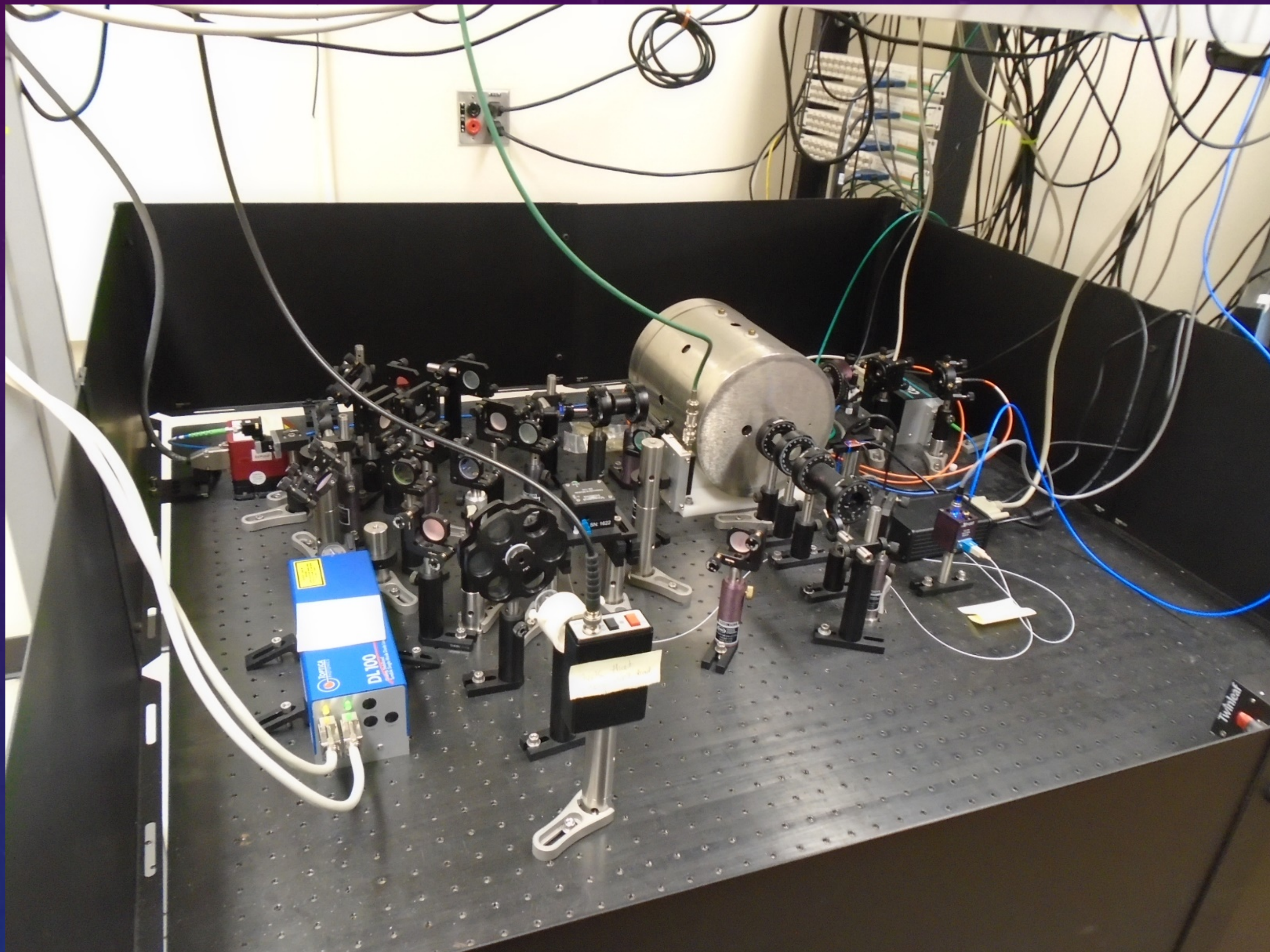


However, a global array of sensors could confidently detect transient events!

OPTICAL ATOMIC MAGNETOMETER

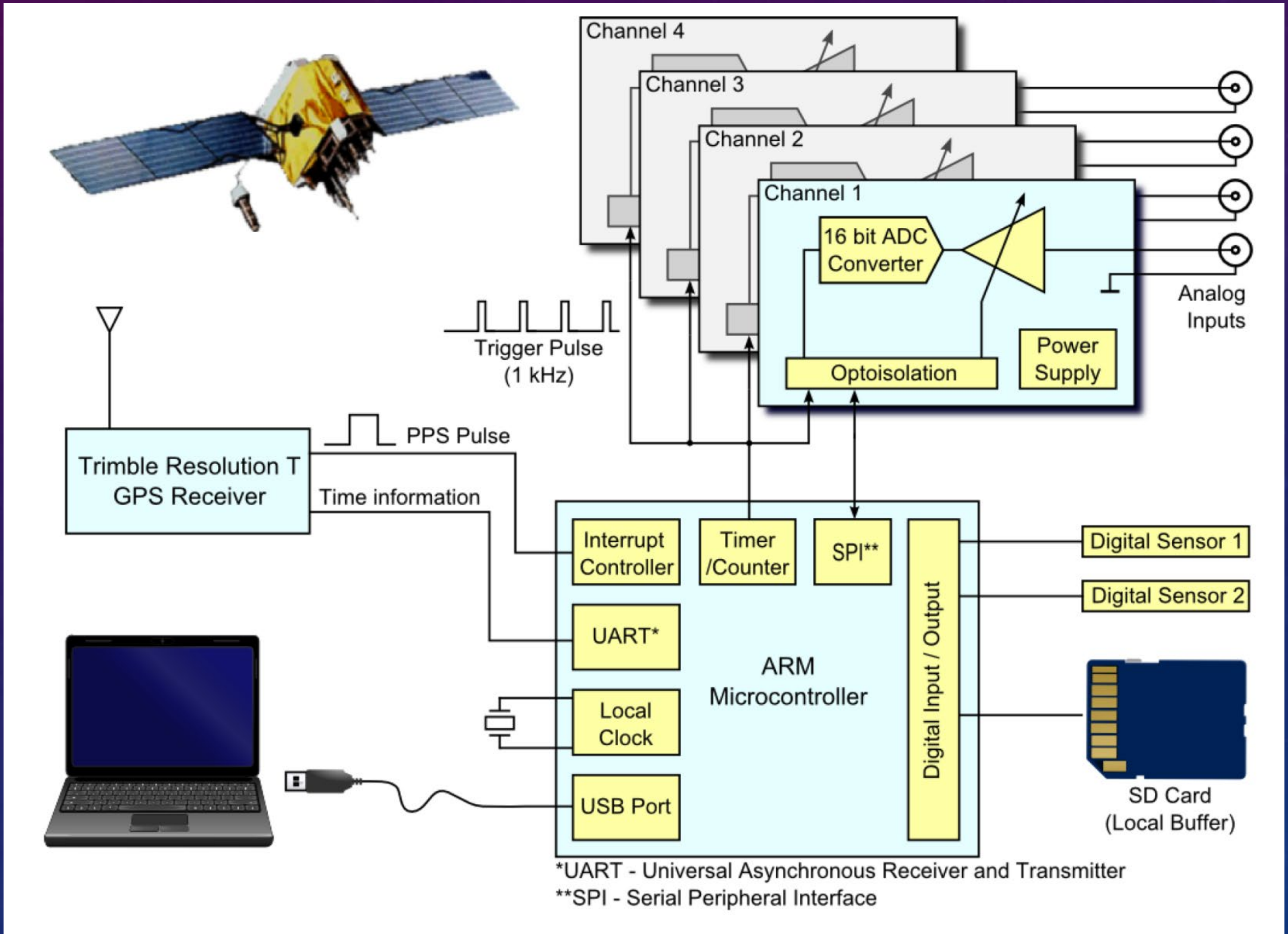


S. Afach et al., Physics of the Dark Universe **22**, 162 (2018).



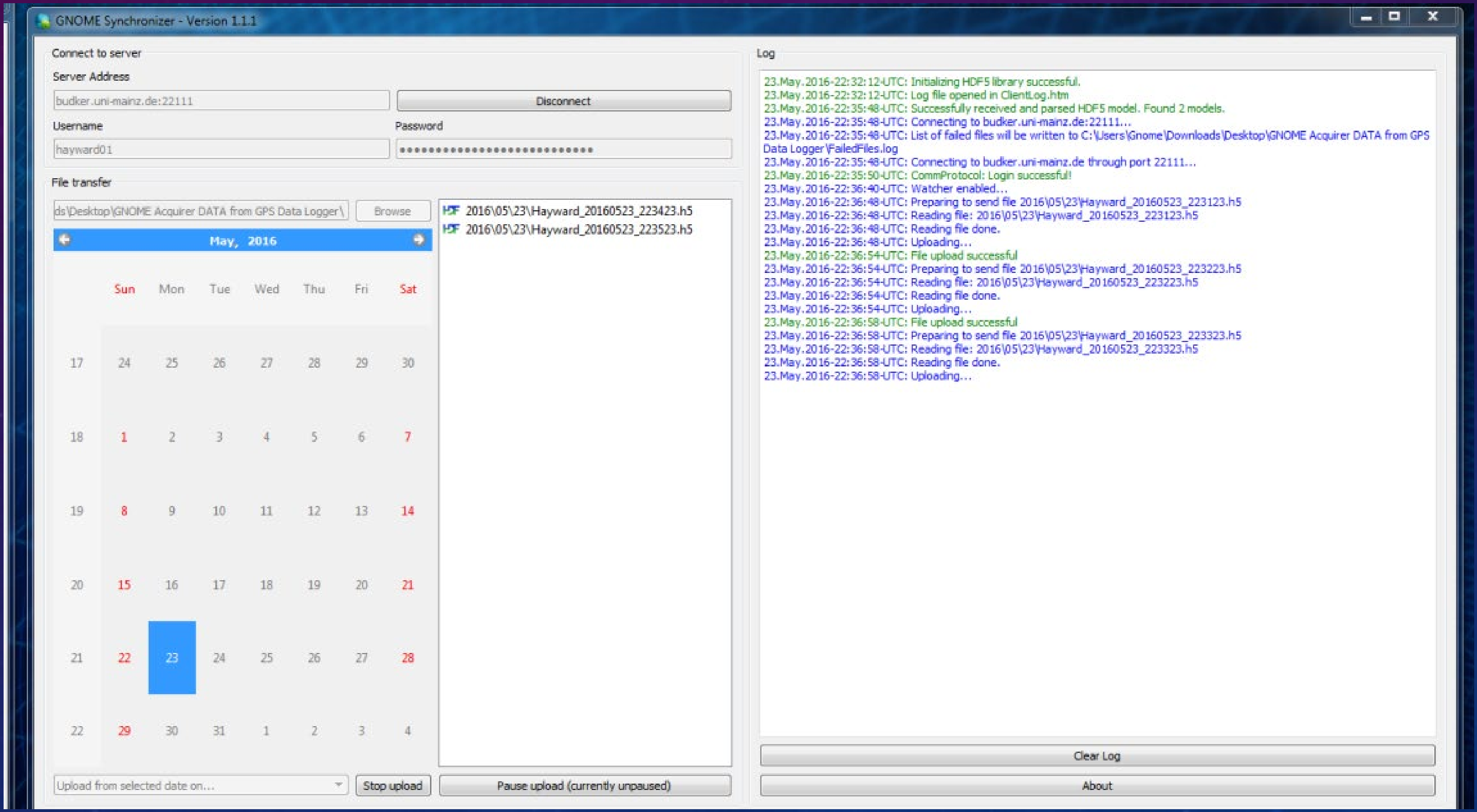
S. Afach et al., Physics of the Dark Universe **22**, 162 (2018).

GPS-DISCIPLINED DATA ACQUISITION

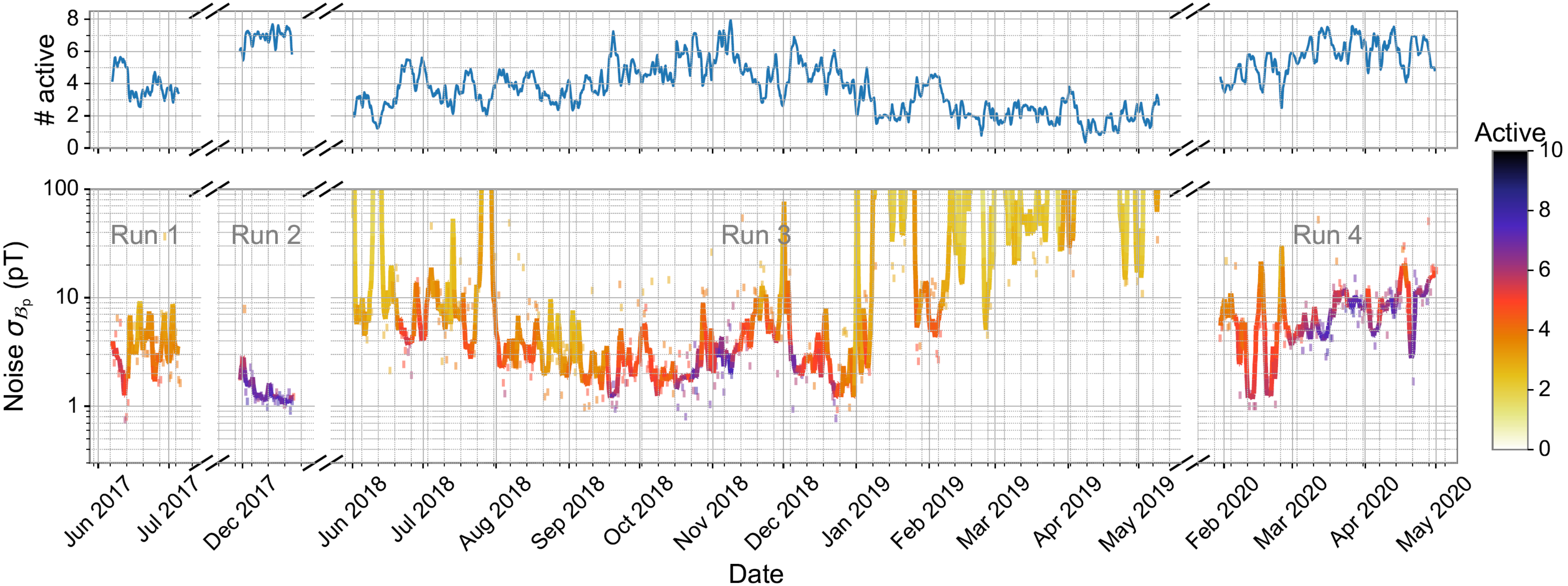


Włodarczyk et al., Nucl. Instrum. Methods. Phys. Res. A **763**, 150 (2014).

DATA TRANSFER TO SERVERS IN GERMANY AND SOUTH KOREA



GNOME SCIENCE RUNS 1 - 4



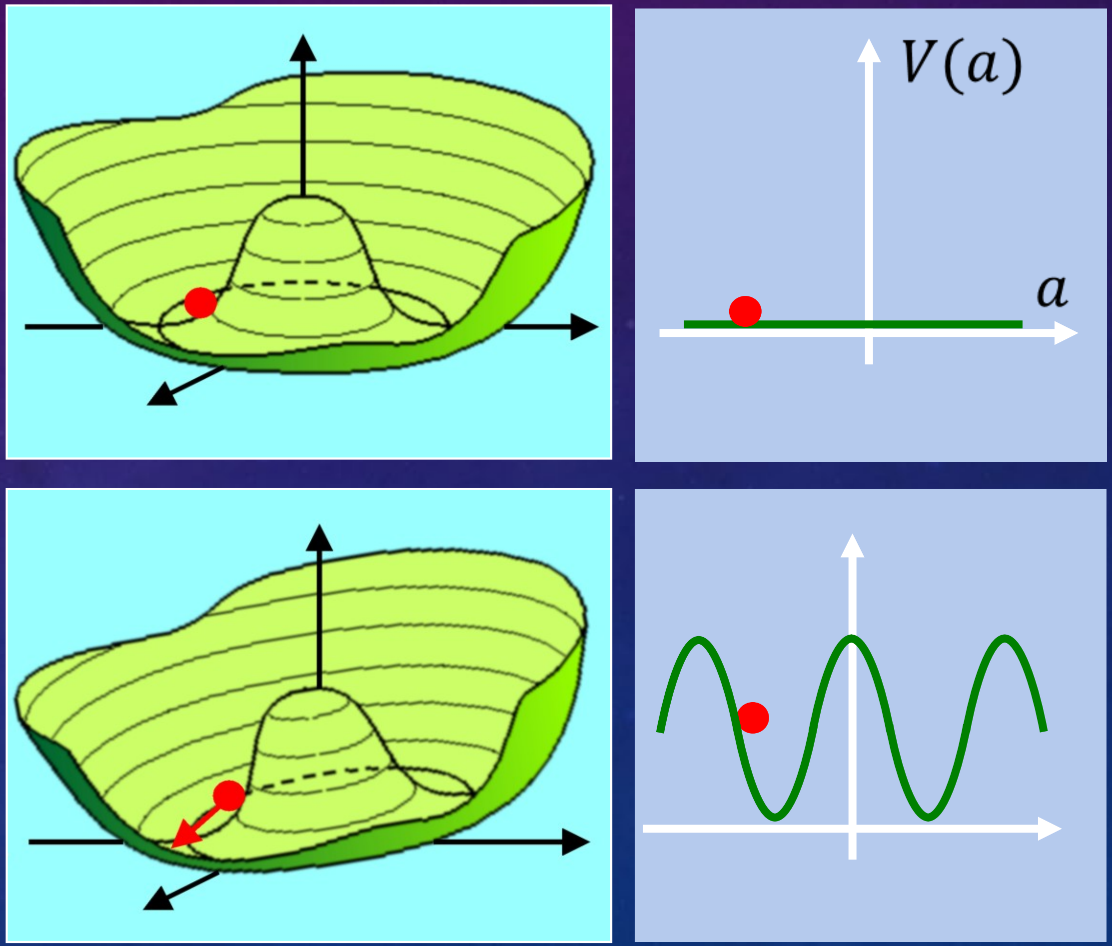
S. Afach et al., arXiv:**2102.13379** (2021).

SEARCH FOR AXION DOMAIN WALLS

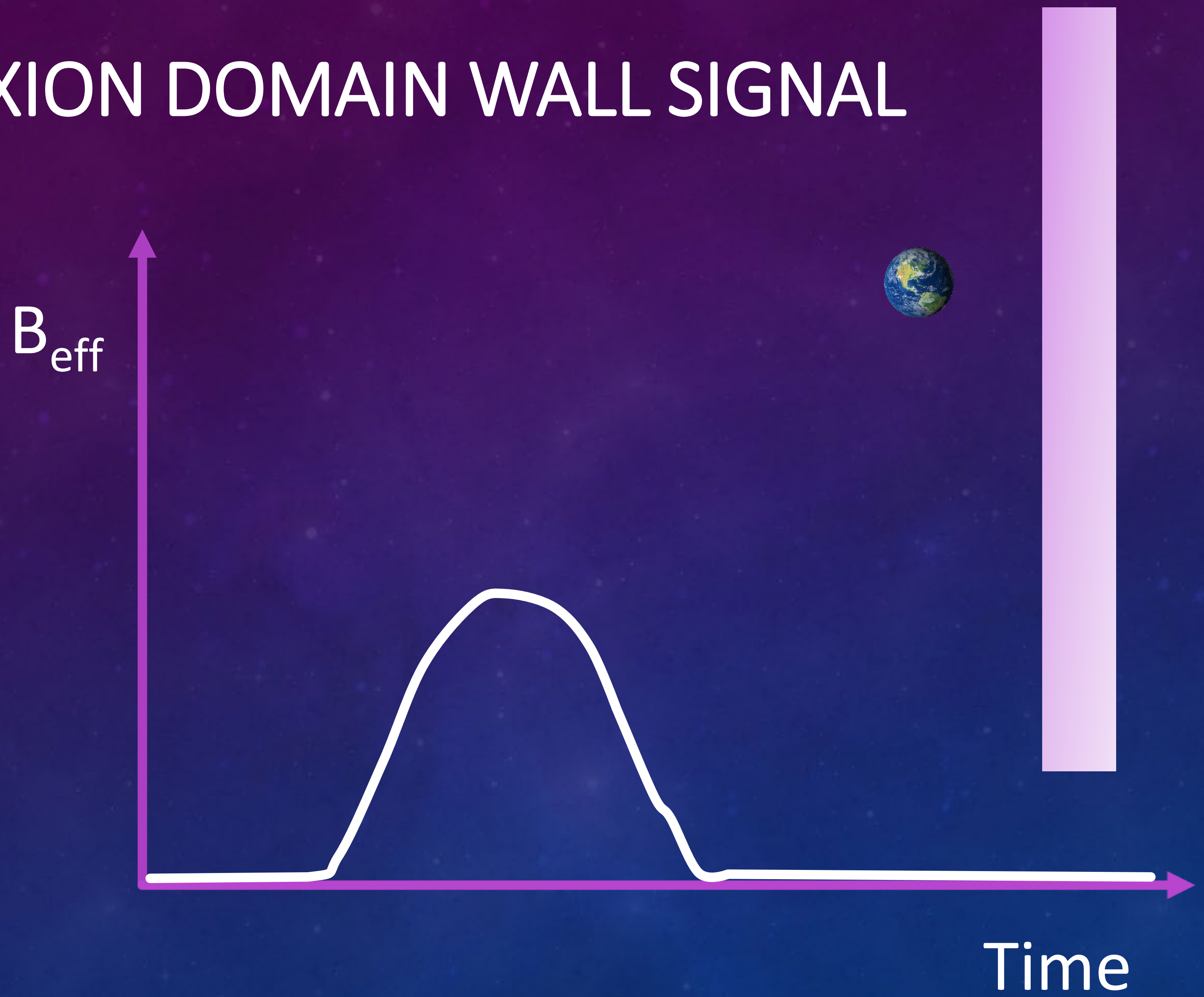
AXION DARK MATTER DOMAIN WALLS

Regions of space with different axion vacuum states can form when axion mass is generated by spontaneous symmetry breaking: separated by topological defects (**domain walls**).

At the domain walls: gradient of ALP field gives atomic spins a “kick” that could be detected.

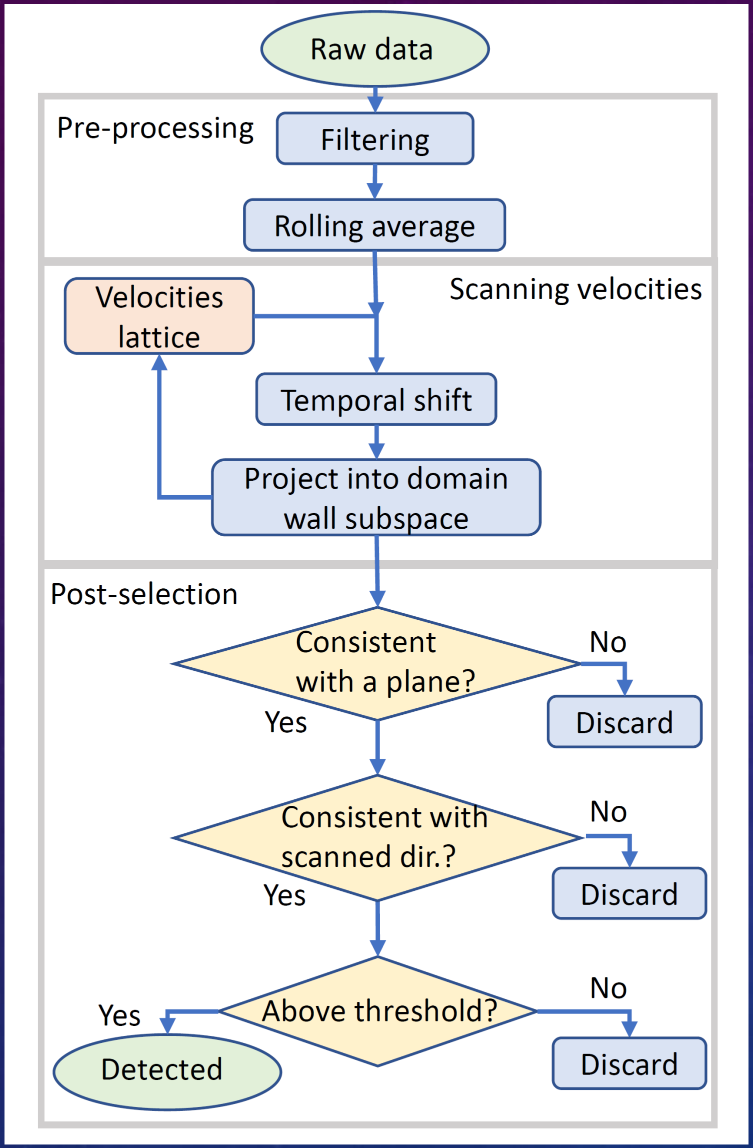


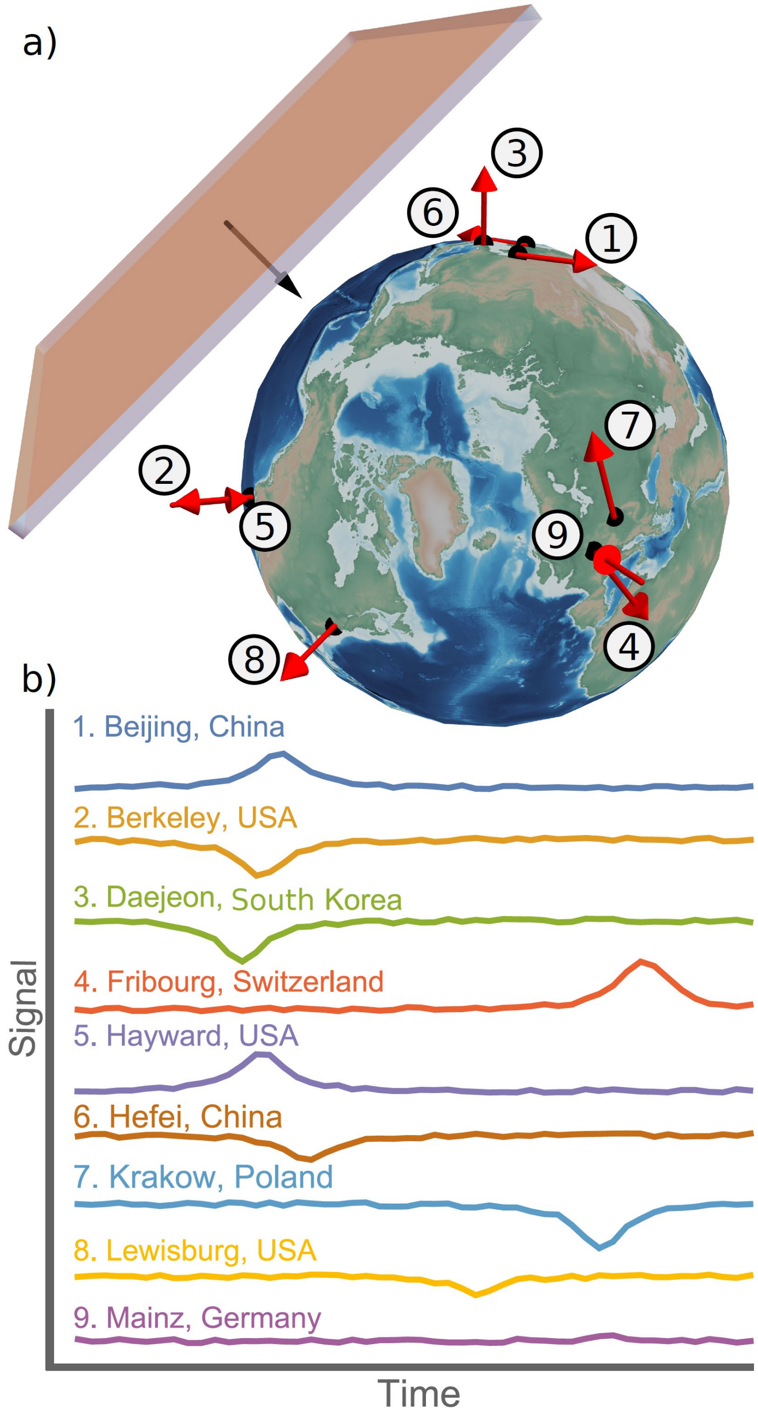
AXION DOMAIN WALL SIGNAL



M. Pospelov et al., Phys. Rev. Lett. **110**, 021803 (2013).

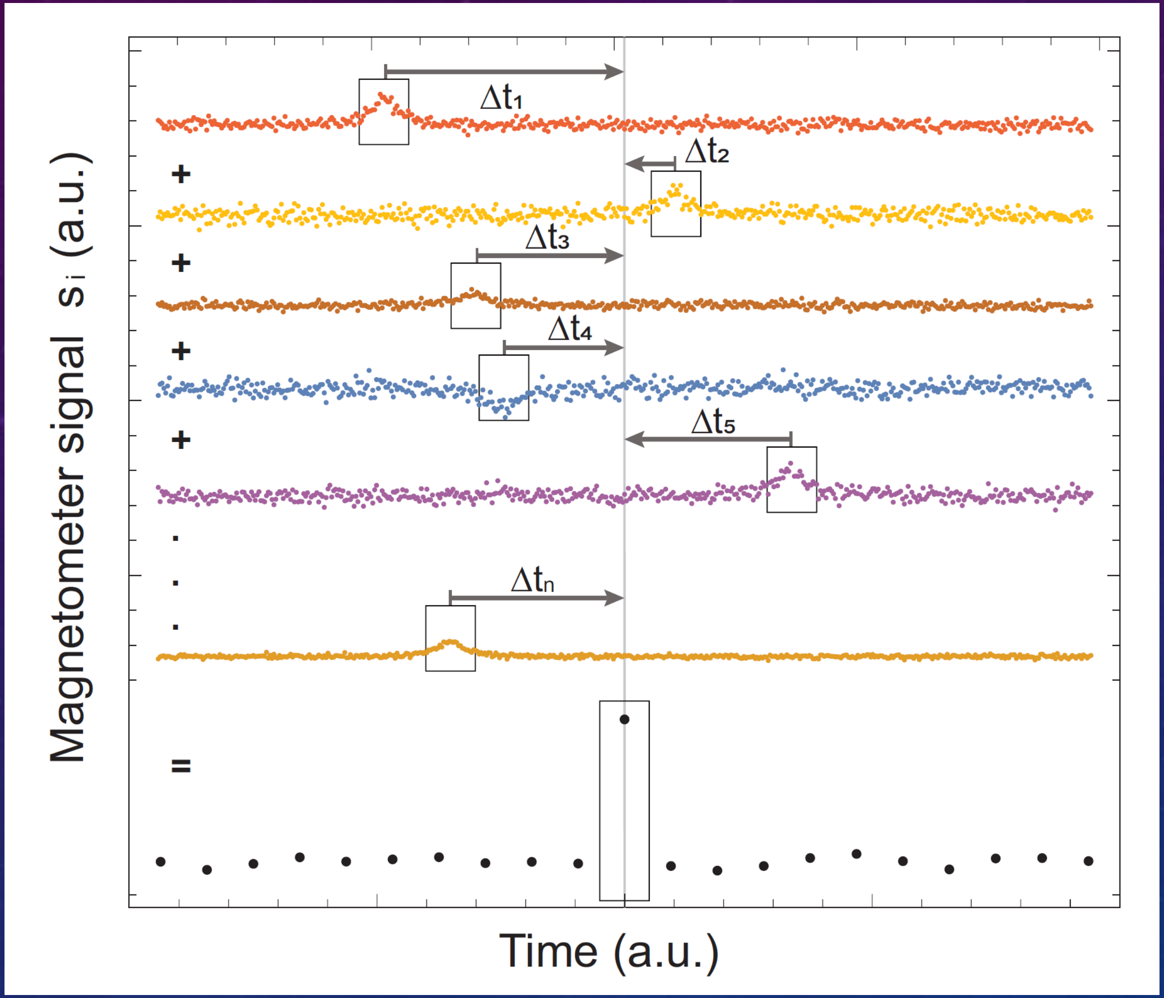
DOMAIN WALL SEARCH





Masia-Roig et al., Physics of the Dark Universe **28**, 100494 (2020).

DOMAIN WALL SEARCH



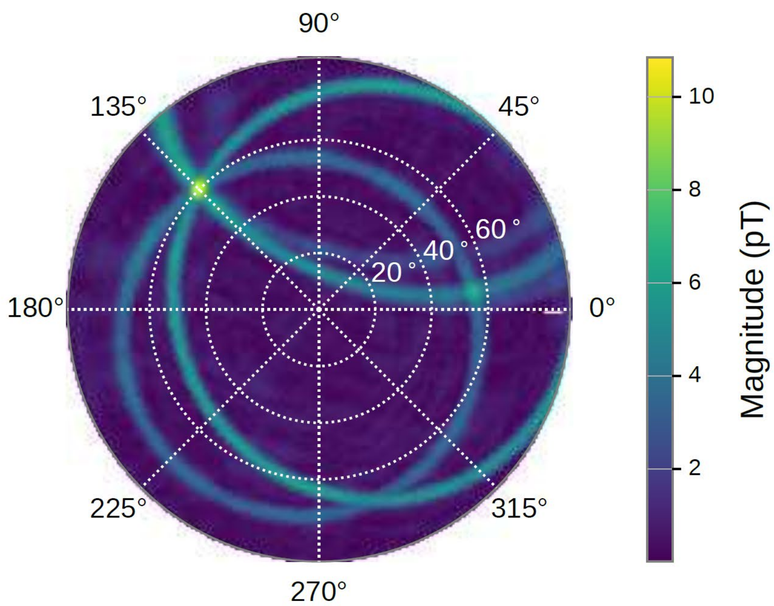
For a chosen domain wall velocity, magnetometer signals are shifted in time so that they should overlap.

Then data is binned and averaged to increase signal-to-noise.

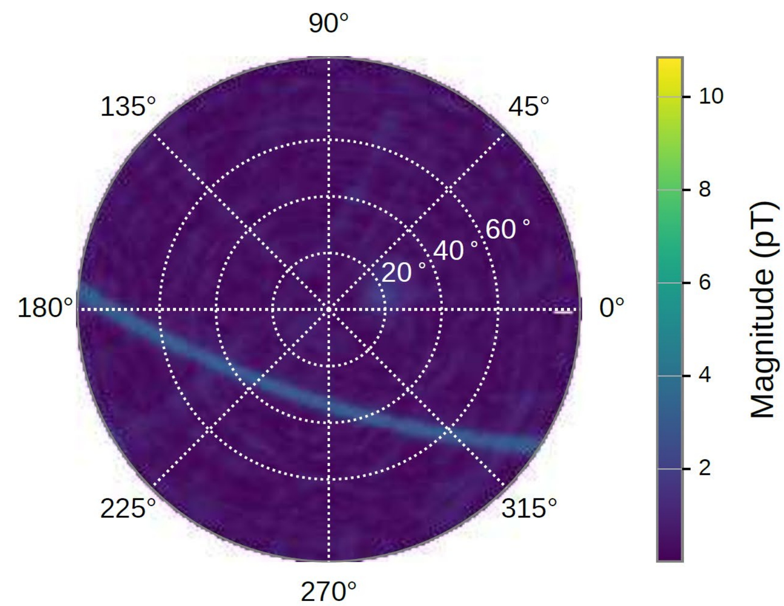
Masia-Roig et al., Physics of the Dark Universe **28**, 100494 (2020).

DOMAIN WALL SEARCH

Scan over all different possible velocities.

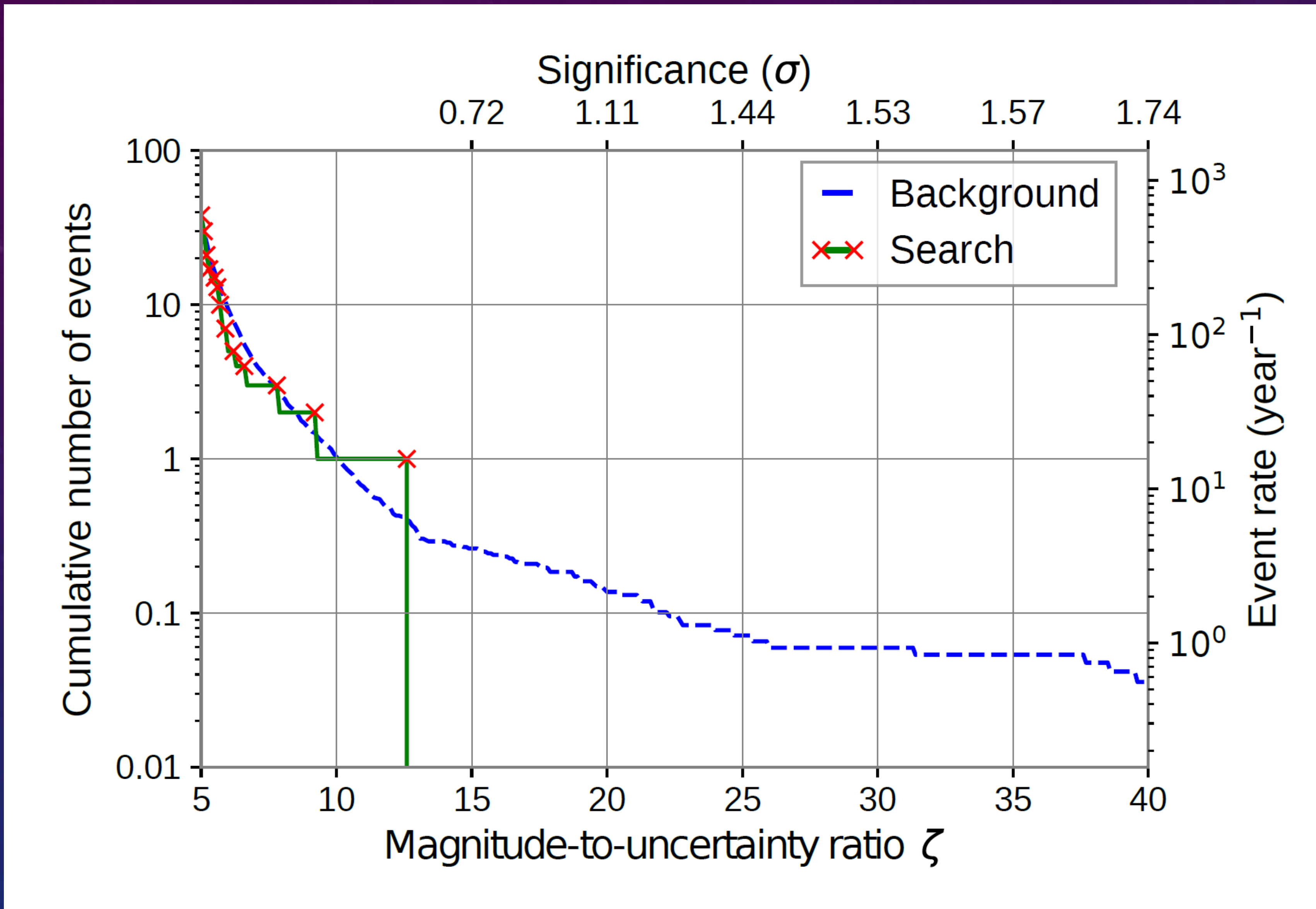


Signal injected, timing consistent with domain wall: unique ***v*** synchronizes pulses.



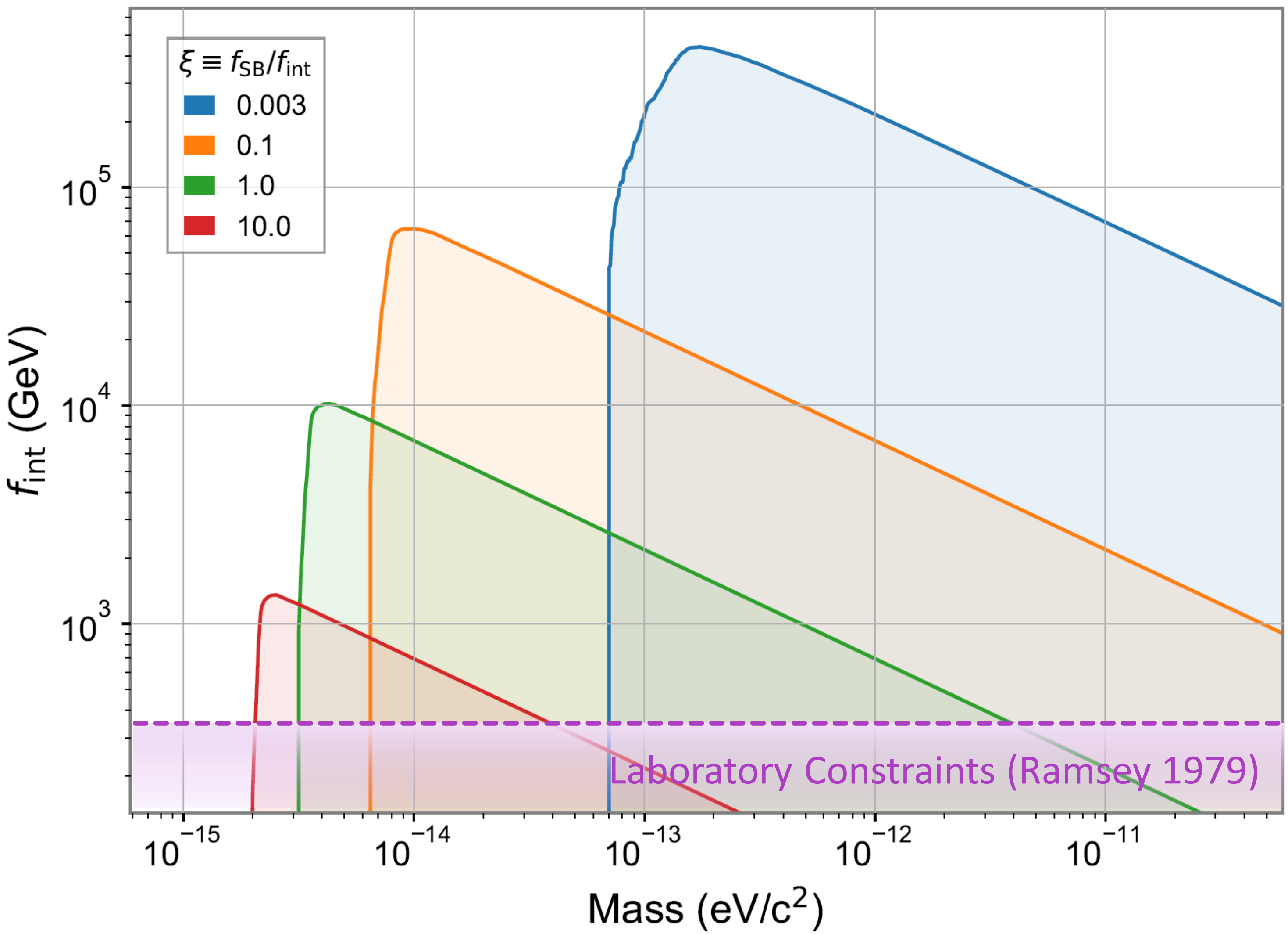
Signal injected in all stations, random timing: no particular enhancement for any ***v***.

Masia-Roig et al., Physics of the Dark Universe **28**, 100494 (2020).



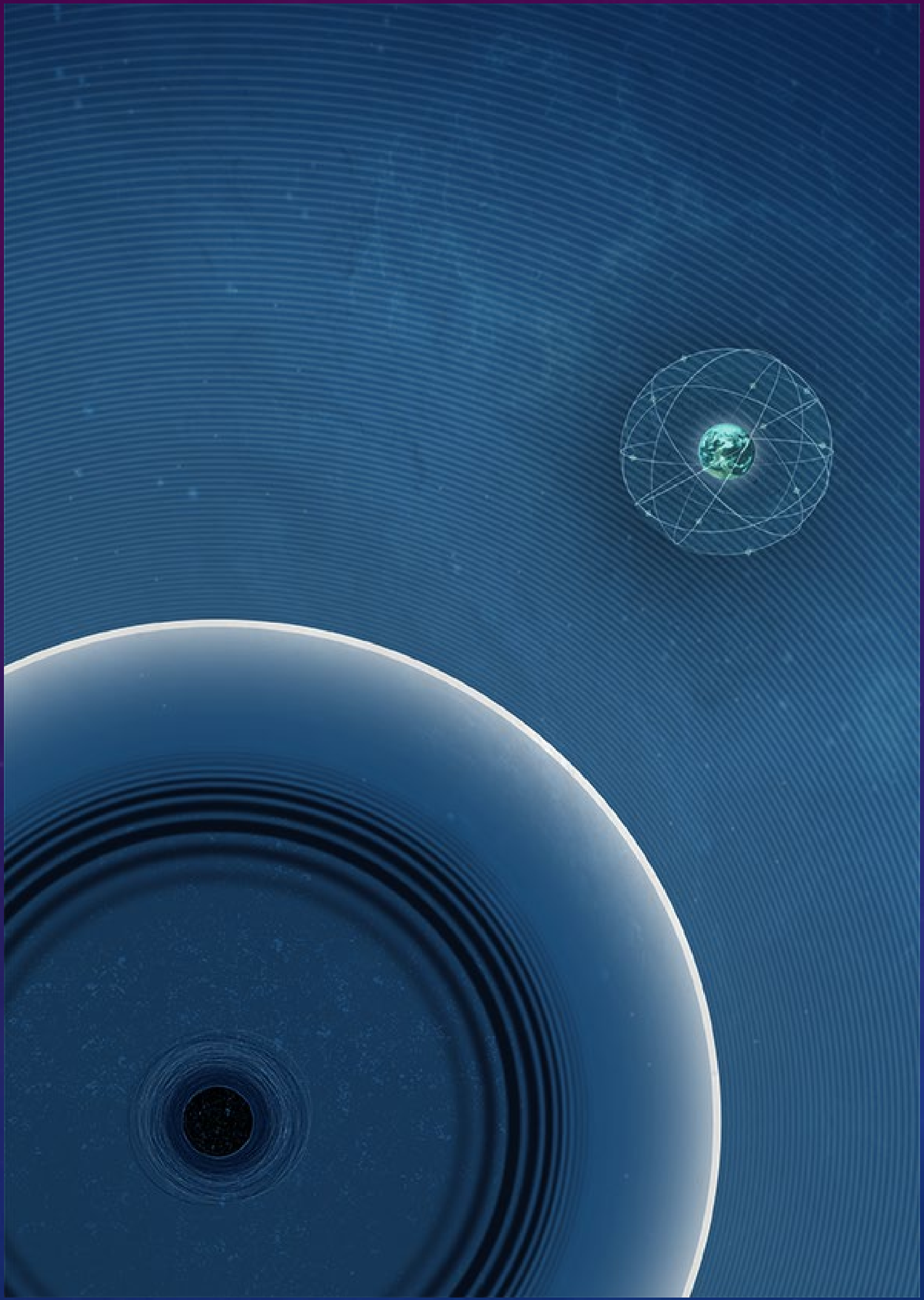
S. Afach et al., arXiv:**2102.13379** (2021).

CONSTRAINTS ON AXION-LIKE DOMAIN WALLS



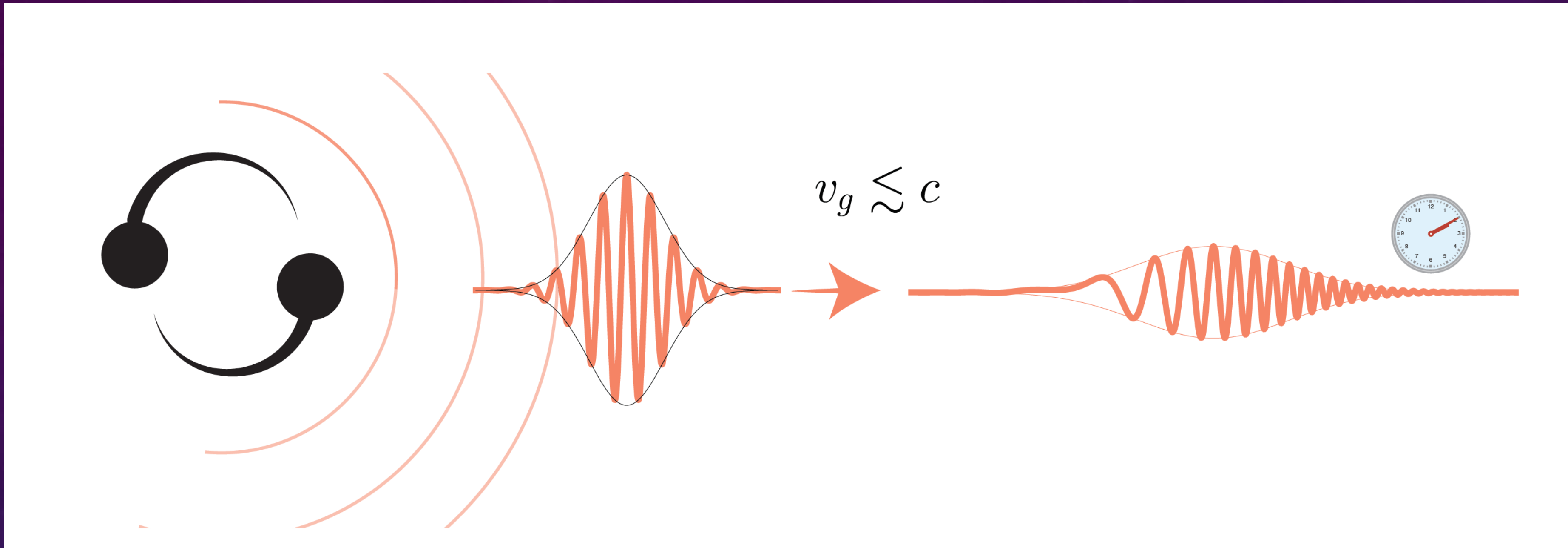
S. Afach et al., arXiv:**2102.13379** (2021).

GNOME SEARCHING FOR ELFS

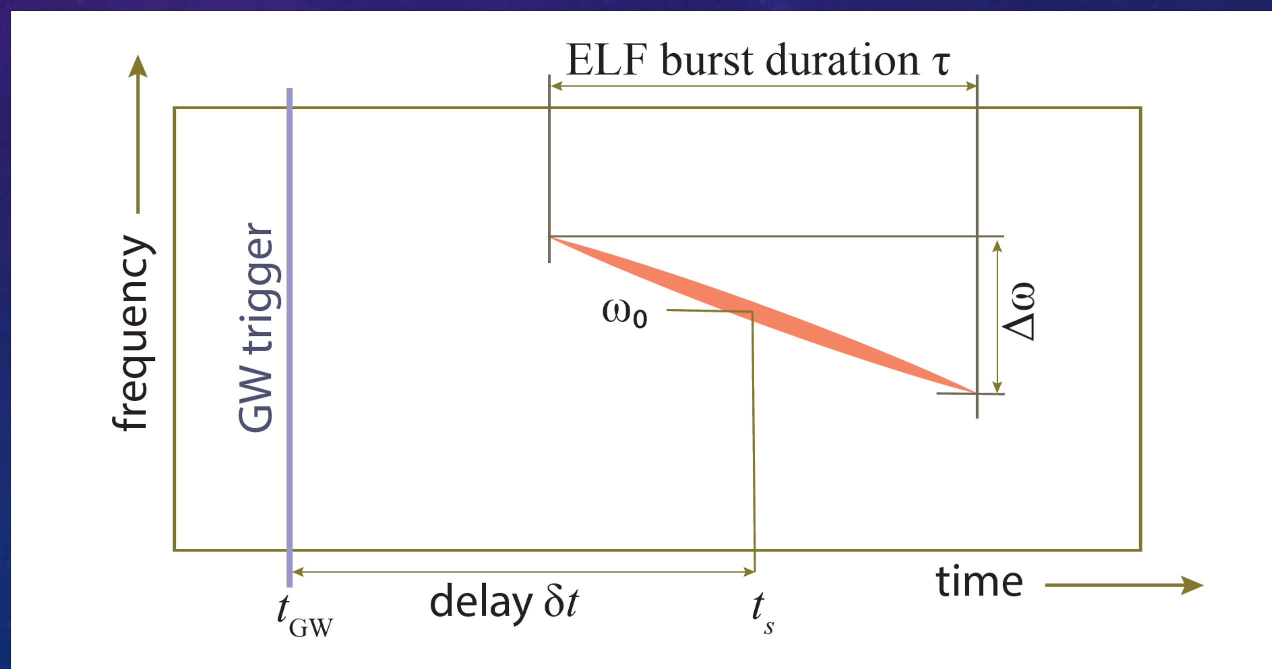


High-energy astrophysical events (e.g., black hole mergers) might produce exotic low-mass fields (ELFs) detectable by GNOME or atomic clock networks (like GPS).

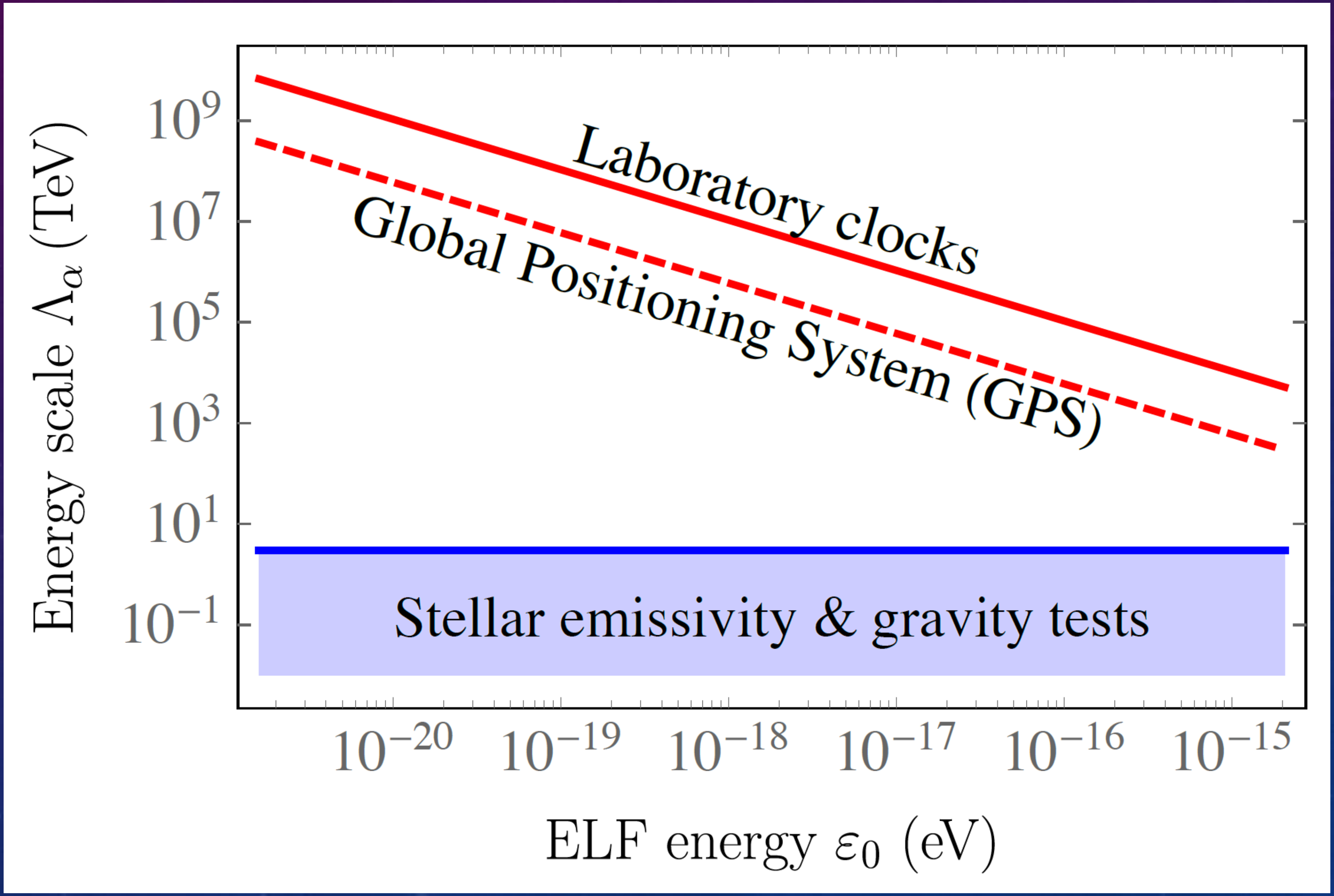
C. Dailey, C. Bradley, D. F. Jackson Kimball, I. Sulai, S. Pustelny, A. Wickenbrock, and A. Derevianko, Nature Astronomy **5**, 150 (2021); *arXiv:2002.04352*.



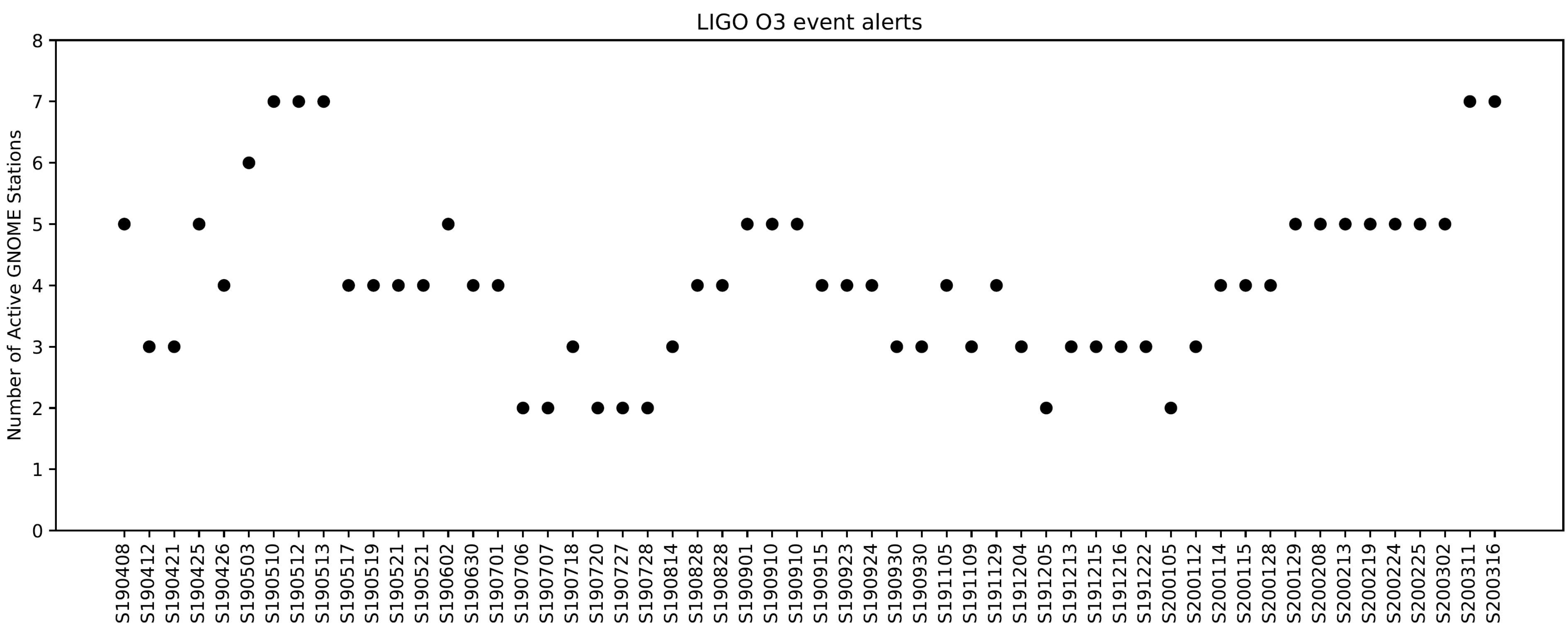
Notable feature: frequency dispersion due to the bosons' mass.



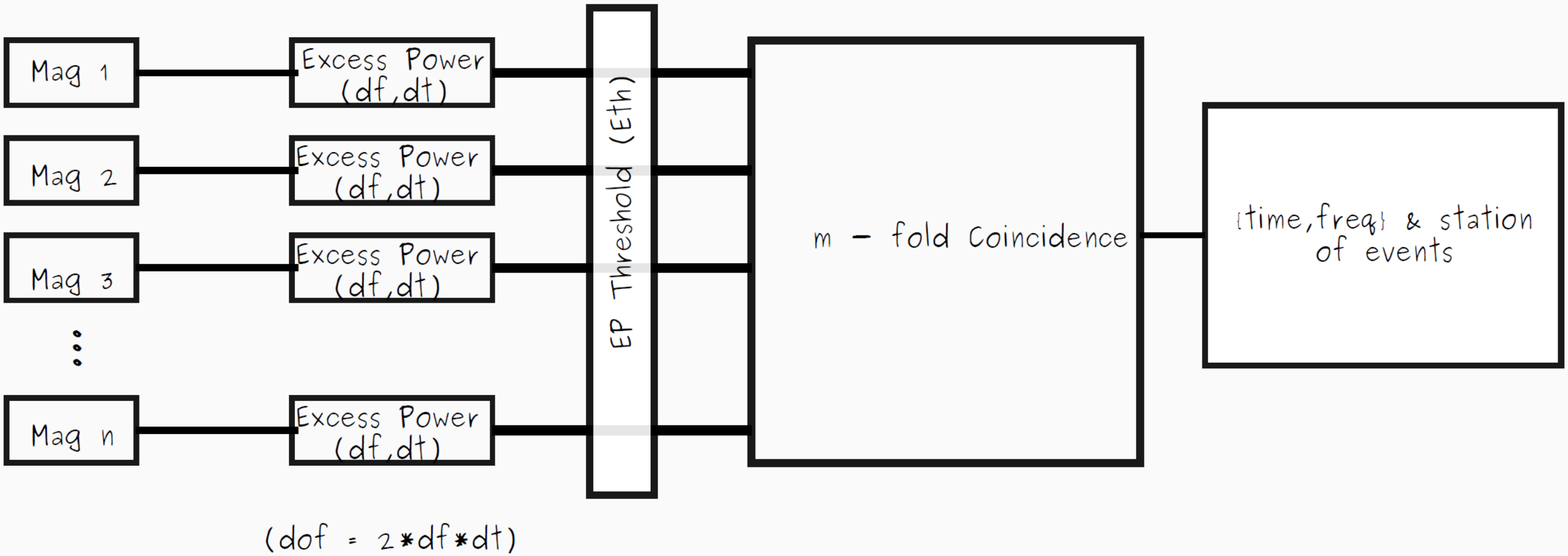
Atomic clocks have sufficient sensitivity to probe vast regions of unexplored parameter space.



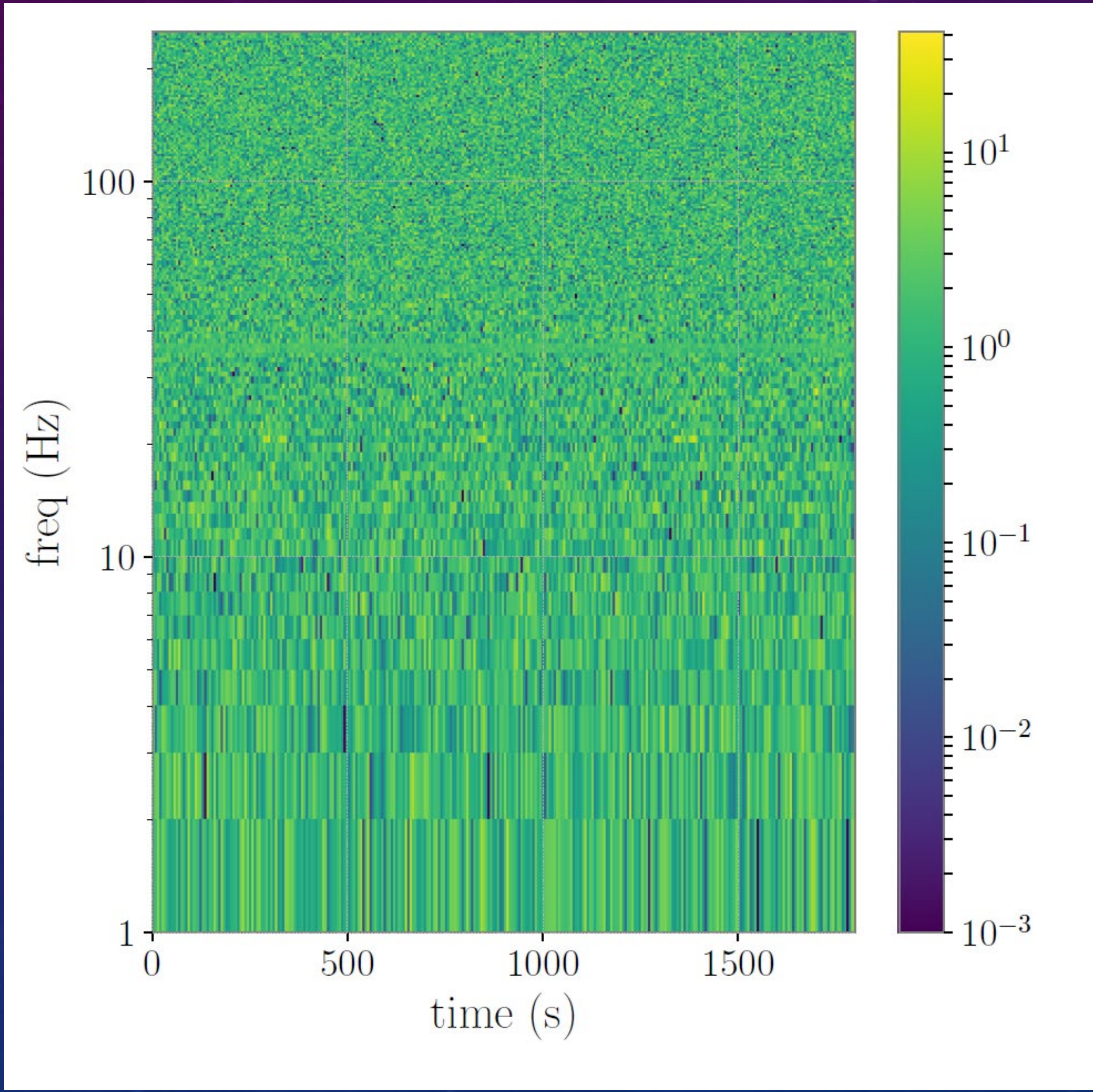
GNOME activity during gravitational wave events observed by LIGO



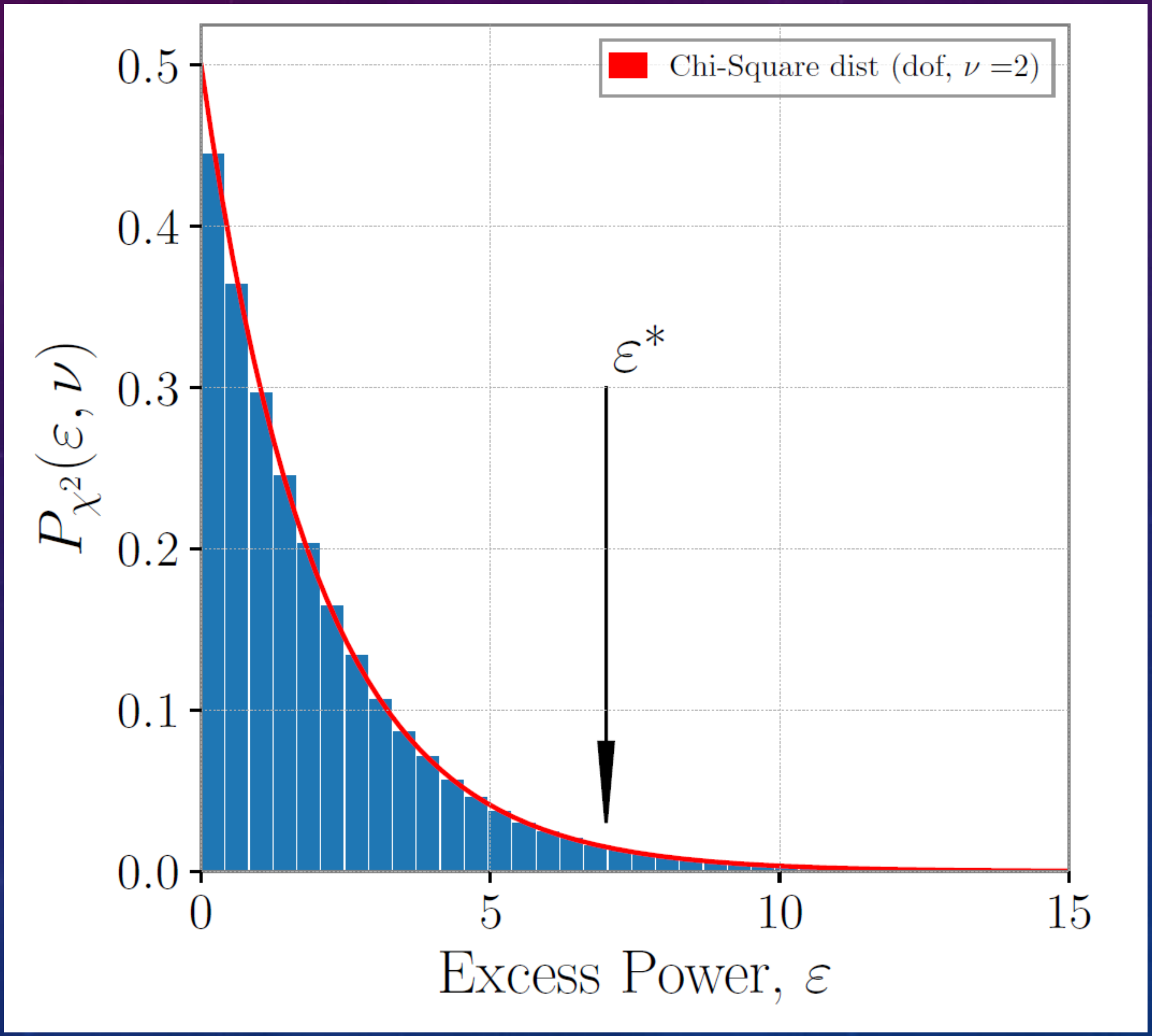
GNOME search for ELFs: analysis strategy



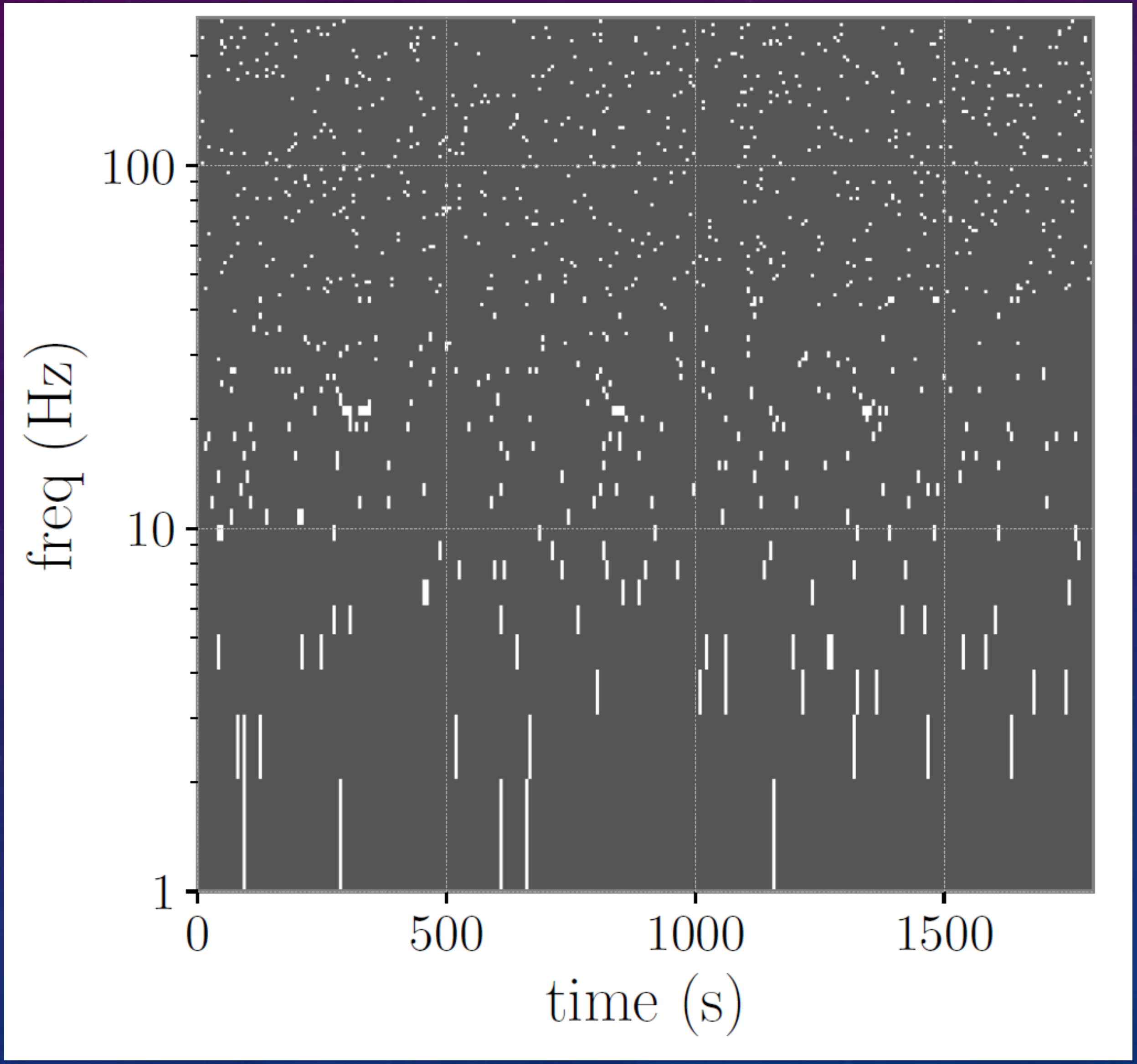
Excess Power Map



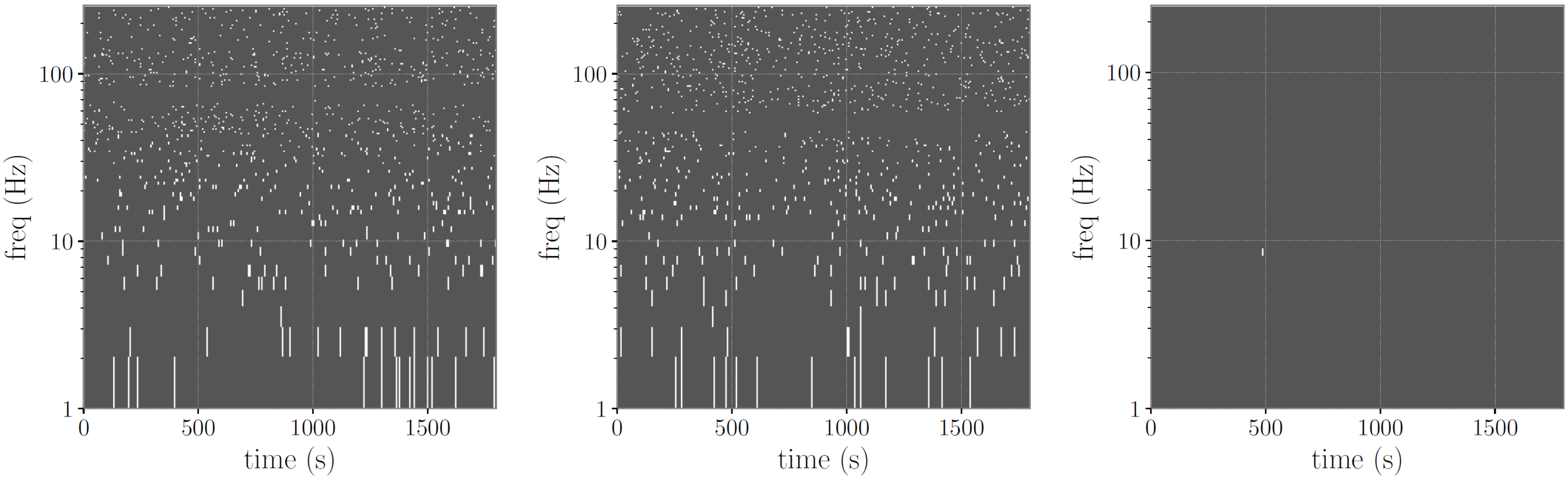
Excess Power Histogram



Excess Power Events above Threshold



Coincidences 10 hours after GW170608



(a.) Berkeley1 (b.) Mainz (c.) 3-station coincidence

Threshold (ε^*)	False Pos. Prob. (β_c)	Num. of Coincident Events (exp.)	(meas.)	(meas*)
8	1.2×10^{-4}	442	395	397
10	6.1×10^{-6}	22	25	20
12	2.8×10^{-7}	1	0	1

SEARCH FOR STOCHASTIC FLUCTUATIONS OF BOSONIC DARK MATTER FIELDS

In the standard halo model for axions, they are a virialized cloud trapped in the Milky Way's gravitational potential (do not cluster into boson stars or form domain walls).

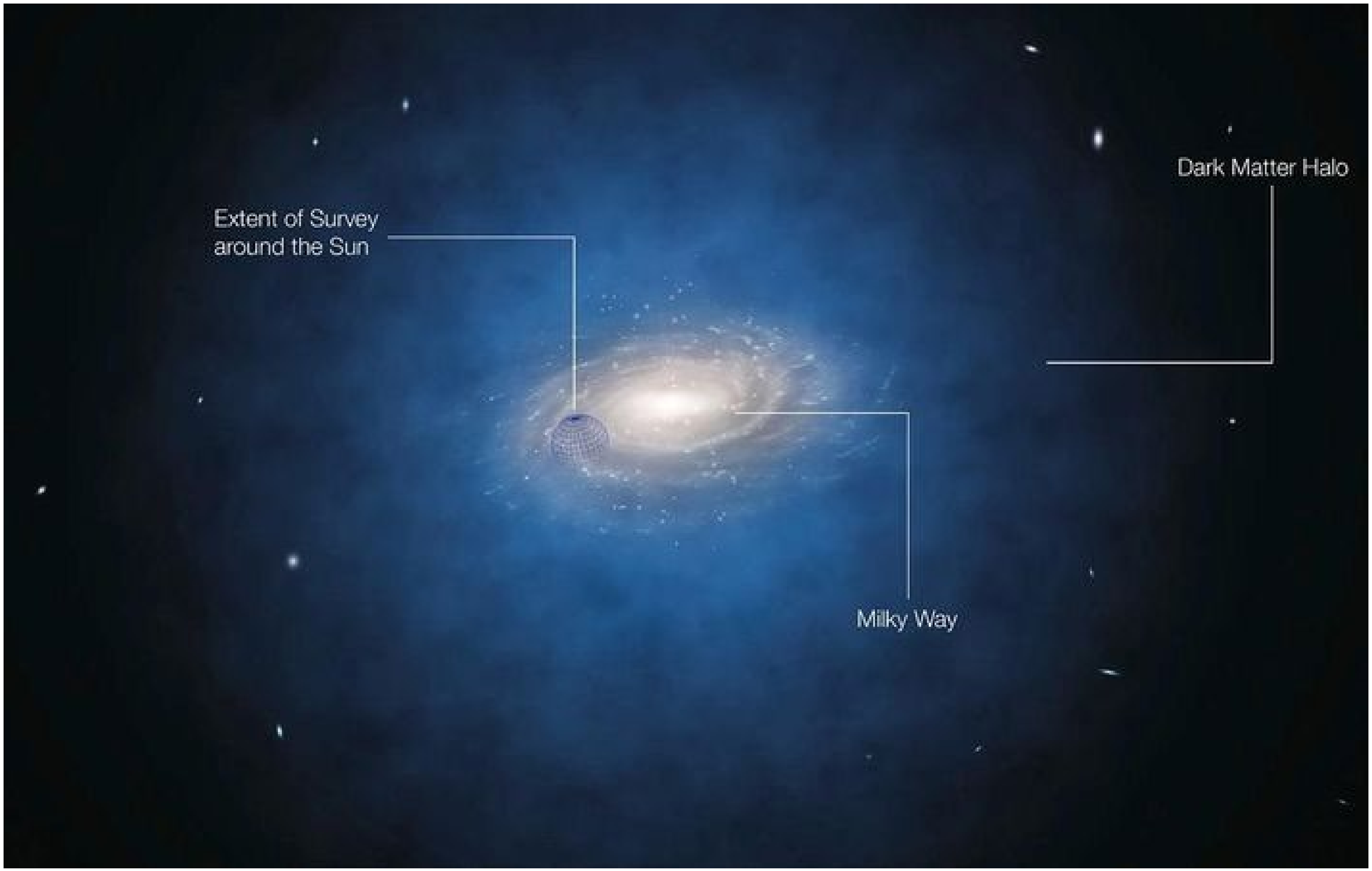
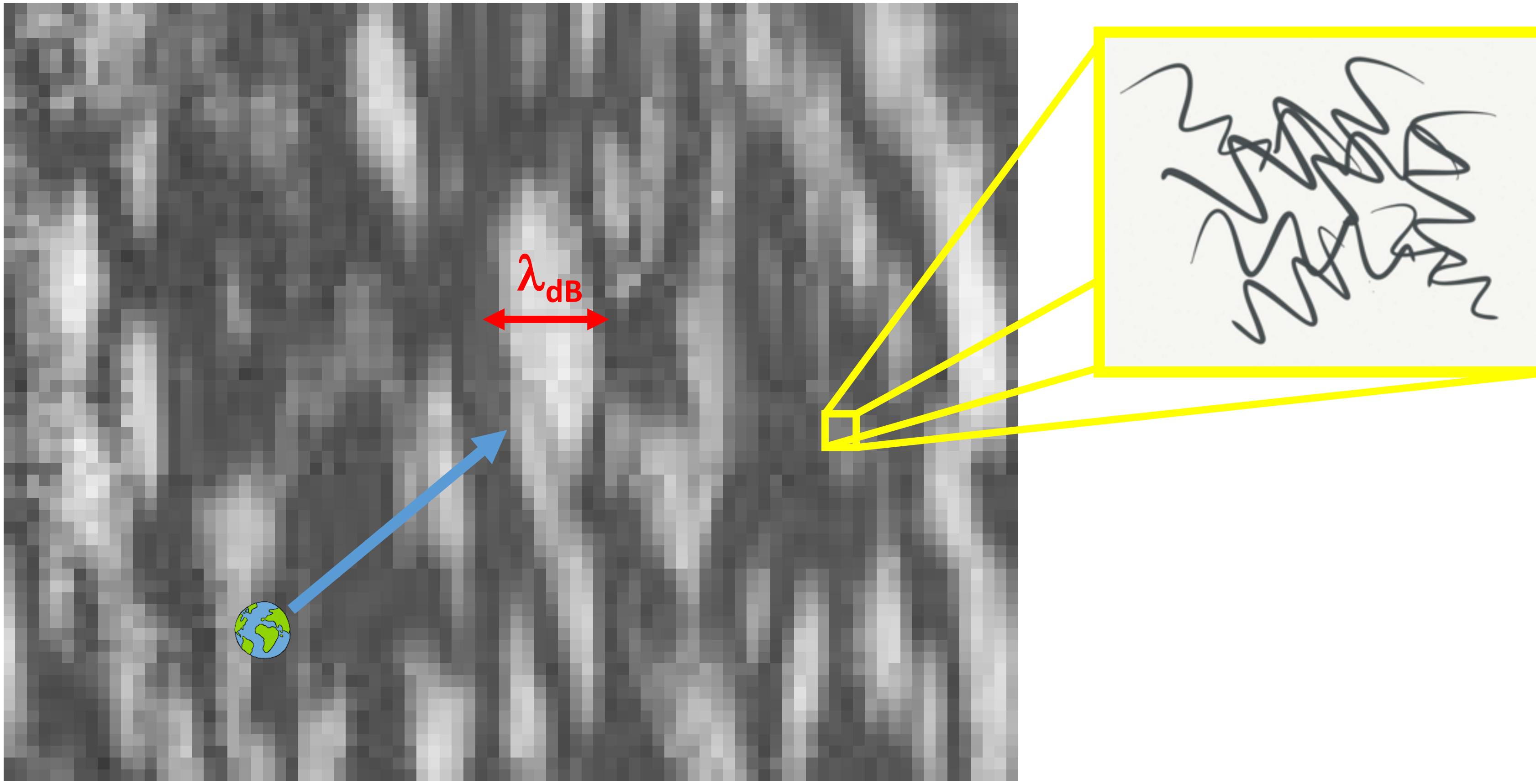
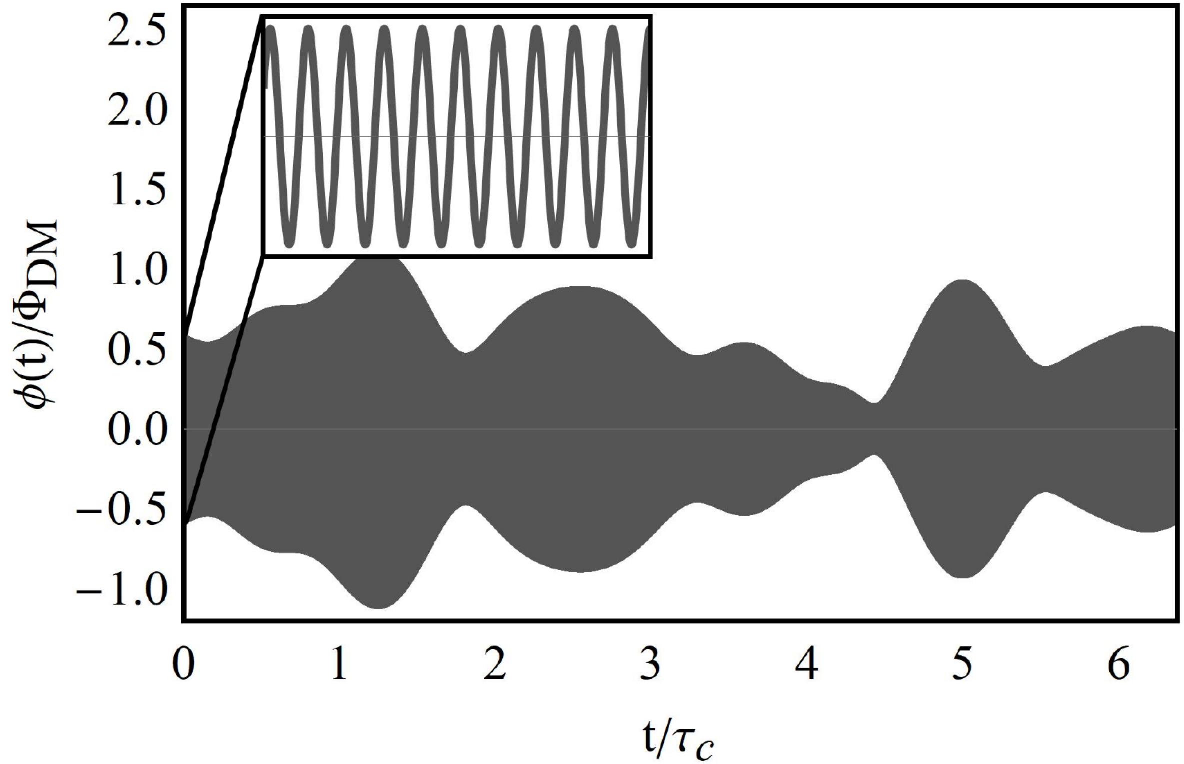


Image credit: L. Calçada (ESO).



Local dark matter results from interference of many axion "waves" – phase, amplitude, velocity, frequency all vary over coherence volume.

Characteristic size of "coherence patches" given by de Broglie wavelength. Phenomenology analogous to thermal (chaotic) light.



The locally measured axion amplitude undergoes stochastic fluctuations with characteristic time scale given by $\tau_{coh} \approx v/\lambda_{dB}$.

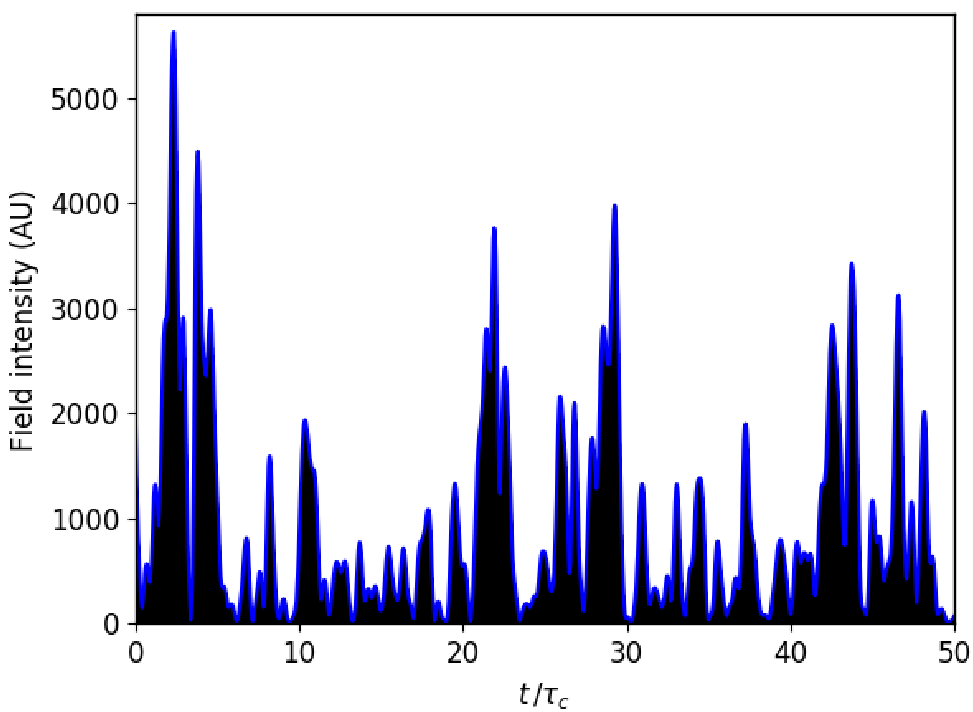
$$\boxed{\frac{1}{\tau_{coh}} \approx \frac{v^2}{c^2}\omega_c \approx 10^{-6}\omega_c}$$

Centers et al., arXiv:**1905.13650** (2019).

The quadratic axion interaction with spins:

$$H = g_Q{}^2(\hbar c)^2\vec{S}\cdot\nabla|a|^2$$

enables our GNOME magnetometers to measure the "intensity" of the ALP "wind" – fluctuating at characteristic frequency $\approx 1/\tau_{coh}$.



Use cross-correlation: common-mode fluctuations would appear in all GNOME magnetometers for

$$\lambda_{dB} \gg R_E\ .$$

Analogous to Hanbury Brown & Twiss interferometry:

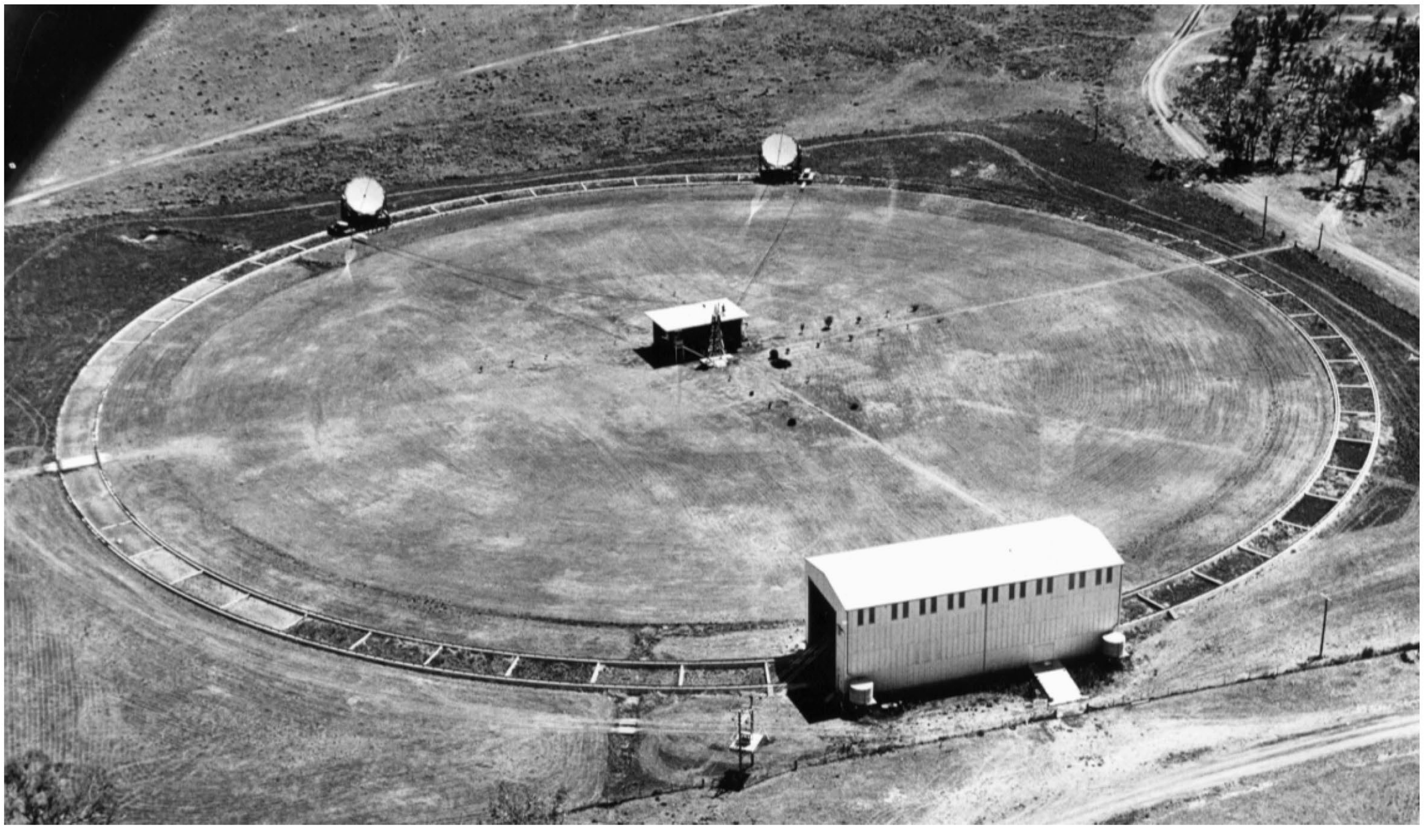
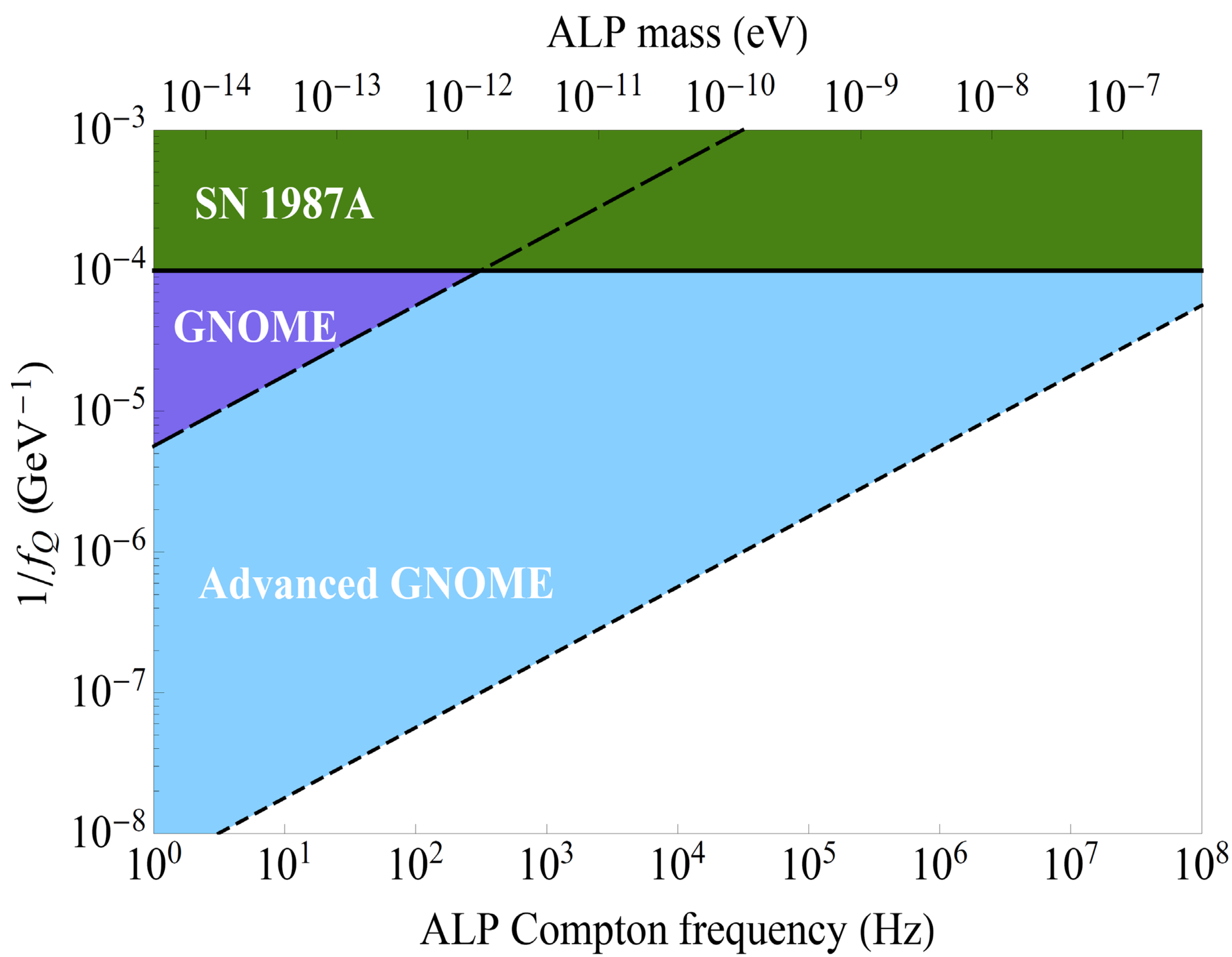


Figure 2.7: View of the Narrabri Stellar Intensity Interferometer showing the two 6.5-meter flux collectors on the circular track. The building in the middle is the control building and the one at the lower part of the picture is the garage for the reflectors. Figure from [15].



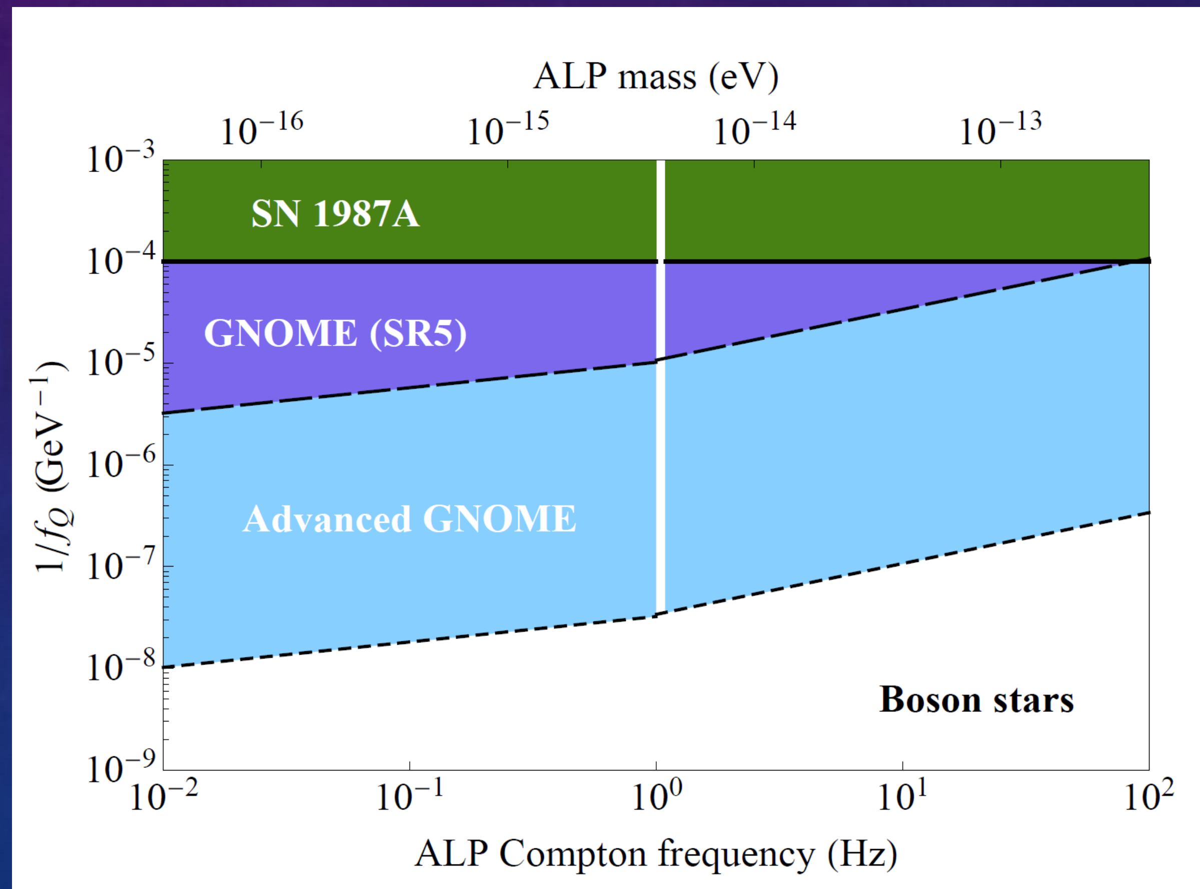
Estimated sensitivity for 1 month (3 months) integration with noise floor at 100 fT (1 fT).

AND MORE...

PHYSICAL REVIEW D **97**, 043002 (2018)

Searching for axion stars and Q-balls with a terrestrial magnetometer network

D. F. Jackson Kimball,[1,*] D. Budker,[2,3,4,5] J. Eby,[6,7] M. Pospelov,[8,9] S. Pustelny,[10] T. Scholtes,[11] Y. V. Stadnik,[2,3] A. Weis,[11] and A. Wickenbrock[2]



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Searching for Earth/Solar axion halos

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PHYSICAL REVIEW D **98,** 115020 (2018)

Detecting dark blobs

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There are more things in heaven and Earth than are dreamt of in your philosophy.

- Hamlet