DARK MATTER SEARCHES WITH MAGNETIC RESONANCE TECHNIQUES

DEREK F. JACKSON KIMBALL

SIMONS FOUNDATION

HEISING - SIMONS FOUNDATION

NSF

CALIFORNIA STATE UNIVERSITY EAST BAY 1957 PER ASPERA AD ASTRA

OUTLINE

- Ultralight bosonic dark matter.
- NMR search for uniformly distributed bosonic dark matter (CASPEr).
- Search for spin-dependent interactions mediated by ultralight bosons.
- Search for compact objects made of bosonic dark matter (GNOME).

Ultralight dark matter

If dark matter is made of ultralight particles ($m \lesssim$ a few eV) they have long deBroglie wavelengths and high occupation number, thus manifest as waves at terrestrial detectors.

Axions & axion-like particles (ALPs)

Pseudoscalar bosons that arise due to symmetries broken at an energy scale f_a.

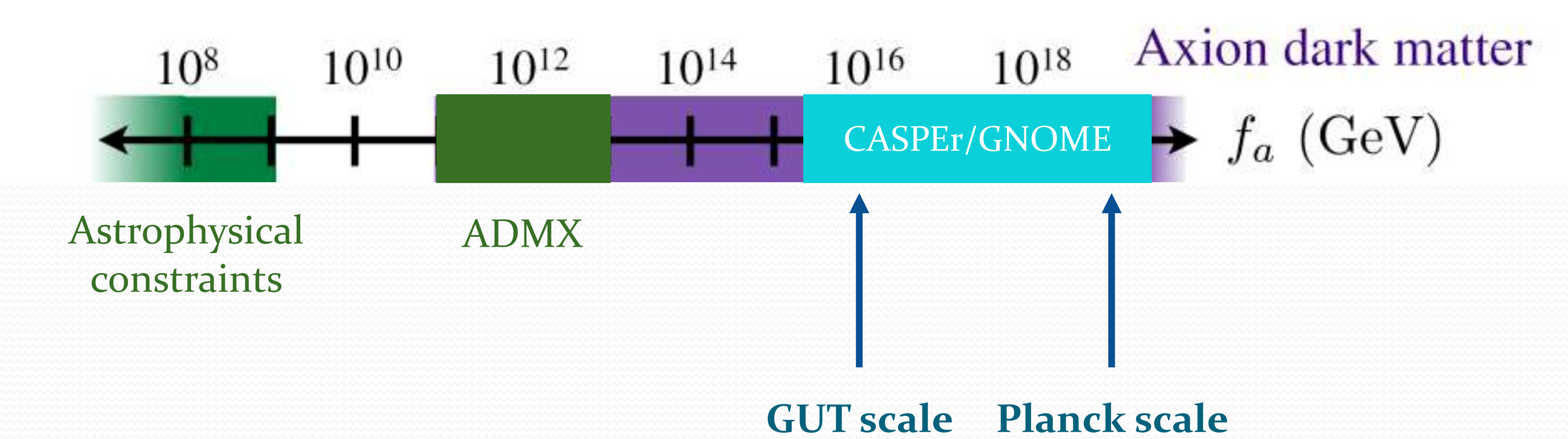
Appear in many extensions of the Standard Model (e.g., solutions to the strong CP problem and hierarchy problem, string theory, etc.).

The axion/ALP mass is given by:

$$m_a \approx \frac{\Lambda^2}{f_a}$$

For axions Λ = QCD confinement scale; ALPs may have different Λ and f.

Probing high energy scales by searching for ultralight bosons



Axion couplings

$$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$$ ← Coupling to electromagnetic field

$$\frac{a}{f_a} G_{\mu\nu} \tilde{G}^{\mu\nu}$$ ← Coupling to gluon field

CASPEr Electric

$$\frac{\partial_\mu a}{f_a} \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$$ ← Coupling to fermion spins

CASPEr Wind, GNOME

Dark photons

Low mass spin-1 bosons that couple weakly to standard model fermions.

Manifests as an oscillating dark electric field in rest frame:

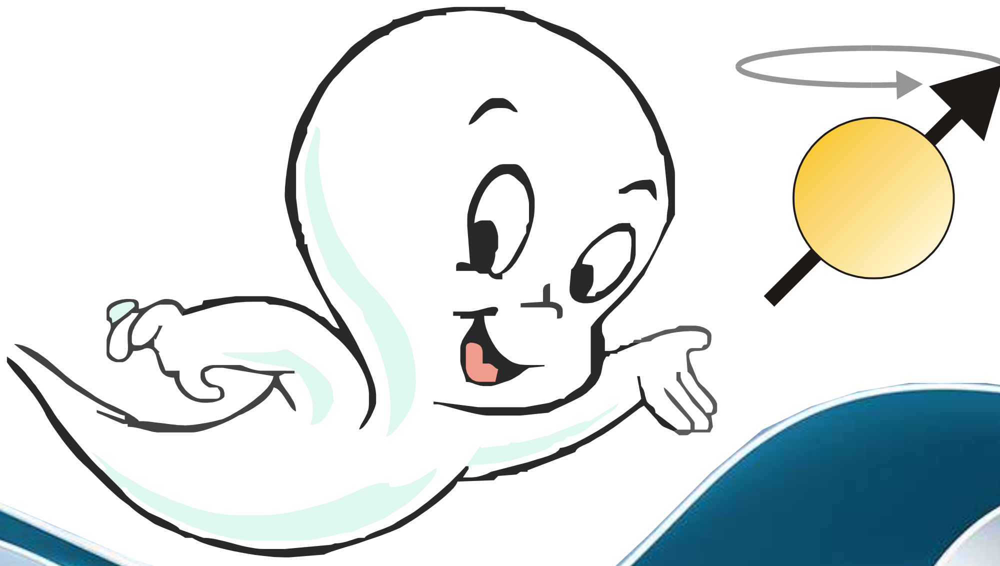
$$\rho_{\mathrm{DM}} = \frac{1}{8\pi}(E')^2 \qquad E' \approx 40\ \mathrm{V/cm}$$

There is a dark magnetic field due to the motion of Earth through the DM halo:

$$B' \approx \frac{v}{c}E' \approx 10^{-4}\ \mathrm{G}$$

Can have dark electric dipole and dark magnetic dipole couplings.

Cosmic Axion Spin Precession Experiment (CASPEr)



Cosmic Axion Spin Precession Experiment

PHYSICAL REVIEW X **4**, 021030 (2014)

Proposal for a Cosmic Axion Spin Precession Experiment (CASPEr)

Dmitry Budker,[1,5] Peter W. Graham,[2] Micah Ledbetter,[3] Surjeet Rajendran,[2] and Alexander O. Sushkov[4]

[1]*Department of Physics, University of California, Berkeley, California 94720, USA*
and Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA
[2]*Department of Physics, Stanford Institute for Theoretical Physics, Stanford University,*
Stanford, California 94305, USA
[3]*AOSense, 767 North Mary Avenue, Sunnyvale, California 94085-2909, USA*
[4]*Department of Physics and Department of Chemistry and Chemical Biology, Harvard University,*
Cambridge, Massachusetts 02138, USA
[5]*Helmholtz Institute Mainz, Johannes Gutenberg University, 55099 Mainz, Germany*

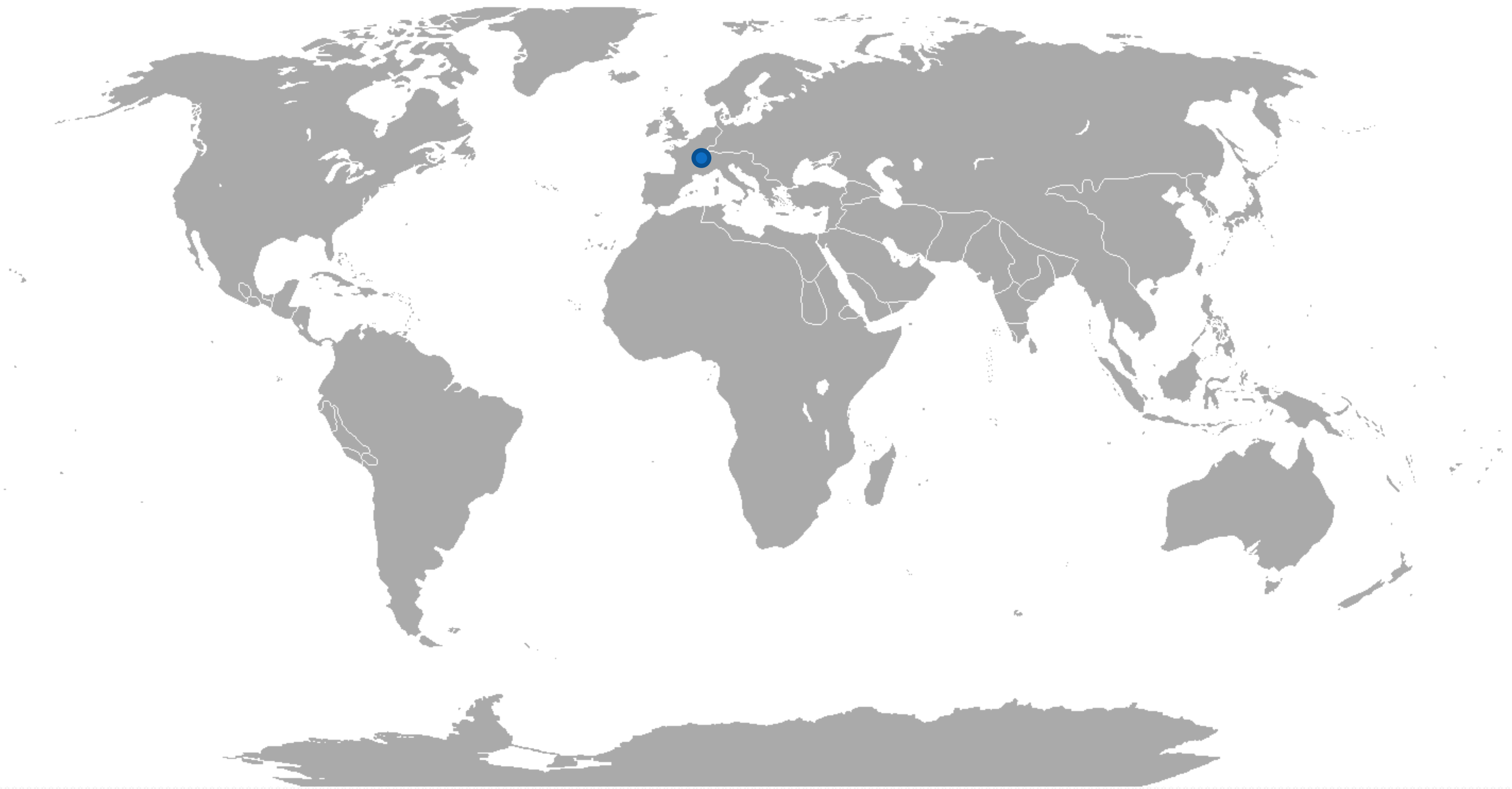
(Received 9 July 2013; published 19 May 2014)

We propose an experiment to search for QCD axion and axionlike-particle dark matter. Nuclei that are interacting with the background axion dark matter acquire time-varying *CP*-odd nuclear moments such as an electric dipole moment. In analogy with nuclear magnetic resonance, these moments cause precession of nuclear spins in a material sample in the presence of an electric field. Precision magnetometry can be used to search for such precession. An initial phase of this experiment could cover many orders of magnitude in axionlike-particle parameter space beyond the current astrophysical and laboratory limits. And with established techniques, the proposed experimental scheme has sensitivity to QCD axion masses $m_a \lesssim 10^{-9}$ eV, corresponding to theoretically well-motivated axion decay constants $f_a \gtrsim 10^{16}$ GeV. With further improvements, this experiment could ultimately cover the entire range of masses $m_a \lesssim \mu$ eV, complementary to cavity searches.

DOI: 10.1103/PhysRevX.4.021030 Subject Areas: Cosmology

D. Budker et al., Phys. Rev. X **4**, 021030 (2014).

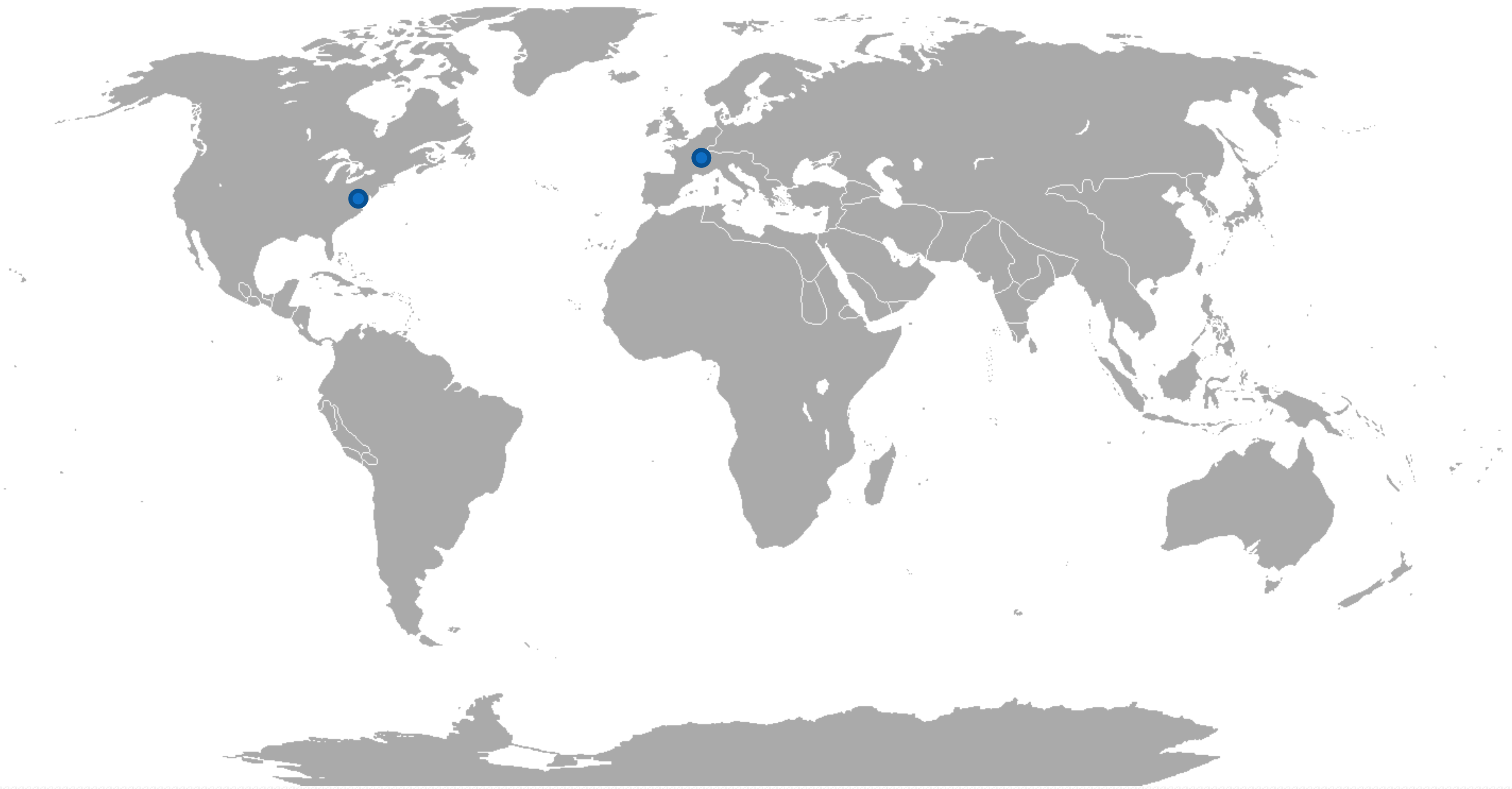
Collaboration



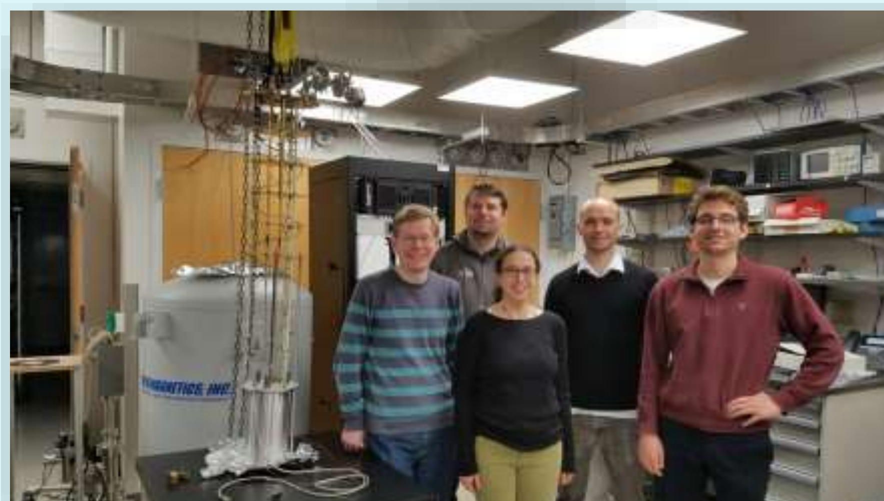
Collaboration

Dmitry Budker,
John Blanchard,
Arne Wickenbrock,
Teng Wu,
Antoine Garcon,
Marina Gil Sendra,
Gary Centers,
Nataniel Figueroa,
Martin Engler (Mainz)

Collaboration

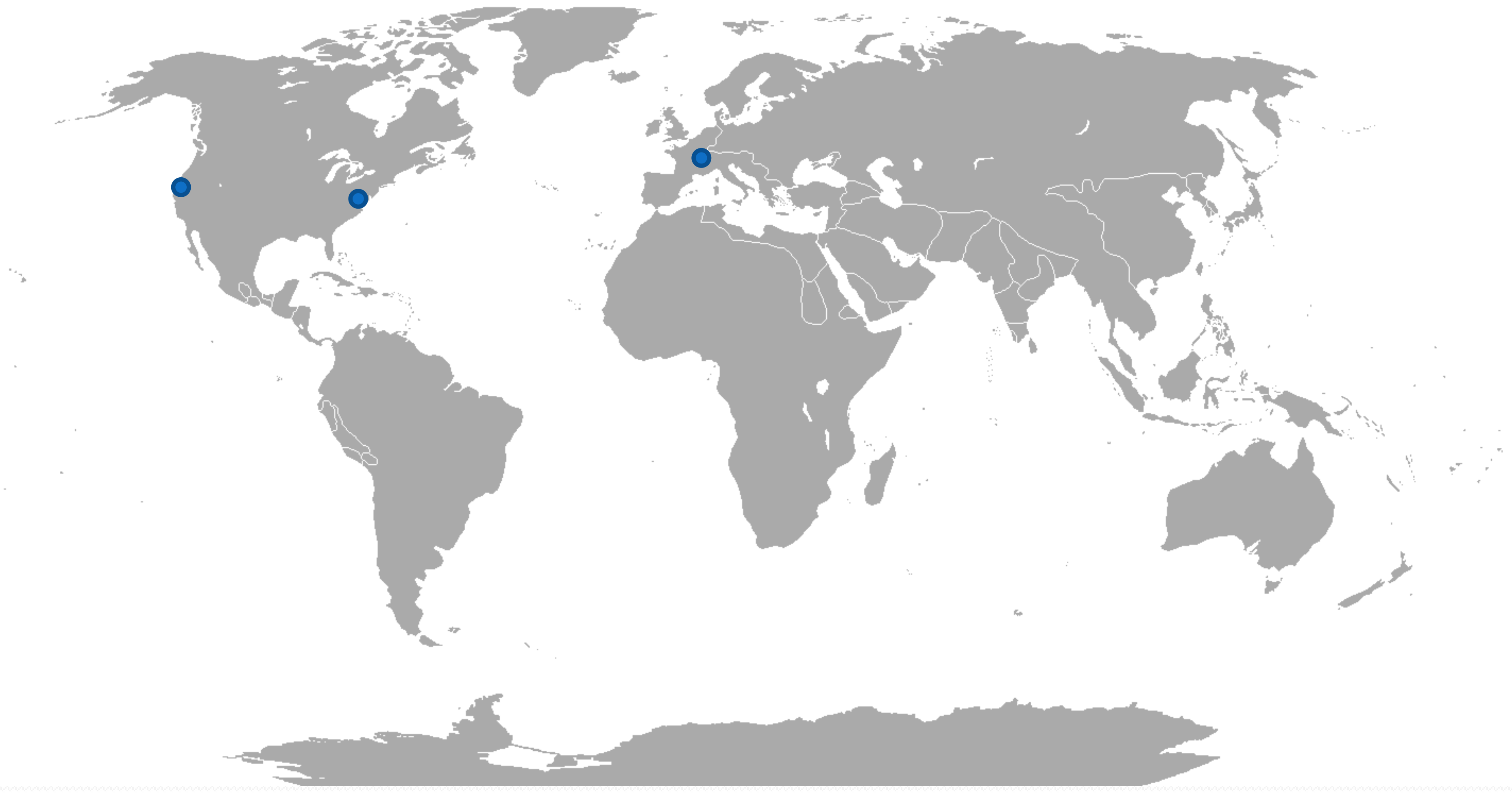


Collaboration



Alex Sushkov,
Deniz Aybas,
Alexander Wilzewski,
Janos Adam,
Jack Stropko (Boston University)

Collaboration



Collaboration

Surjeet Rajendran,
Tao Wang,
Dmitry Budker (UCB),
Peter Graham (Stanford),
Derek Kimball (CSUEB)

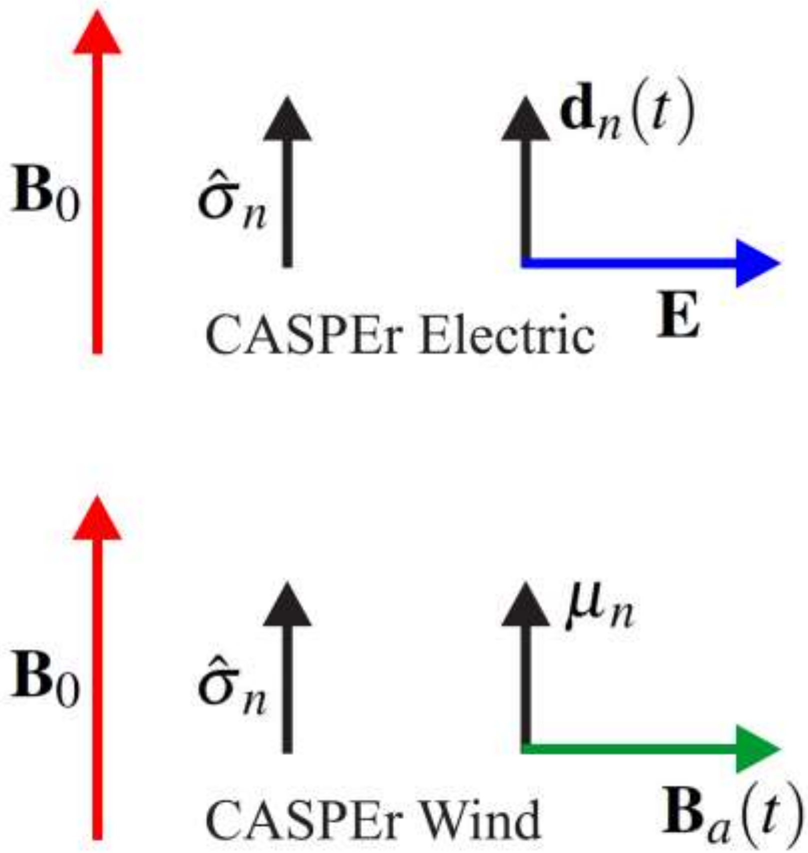
Axion/ALP-induced spin precession

$$\tau_{\rm EDM} = \mathbf{d}_n(t) \times \mathbf{E}$$

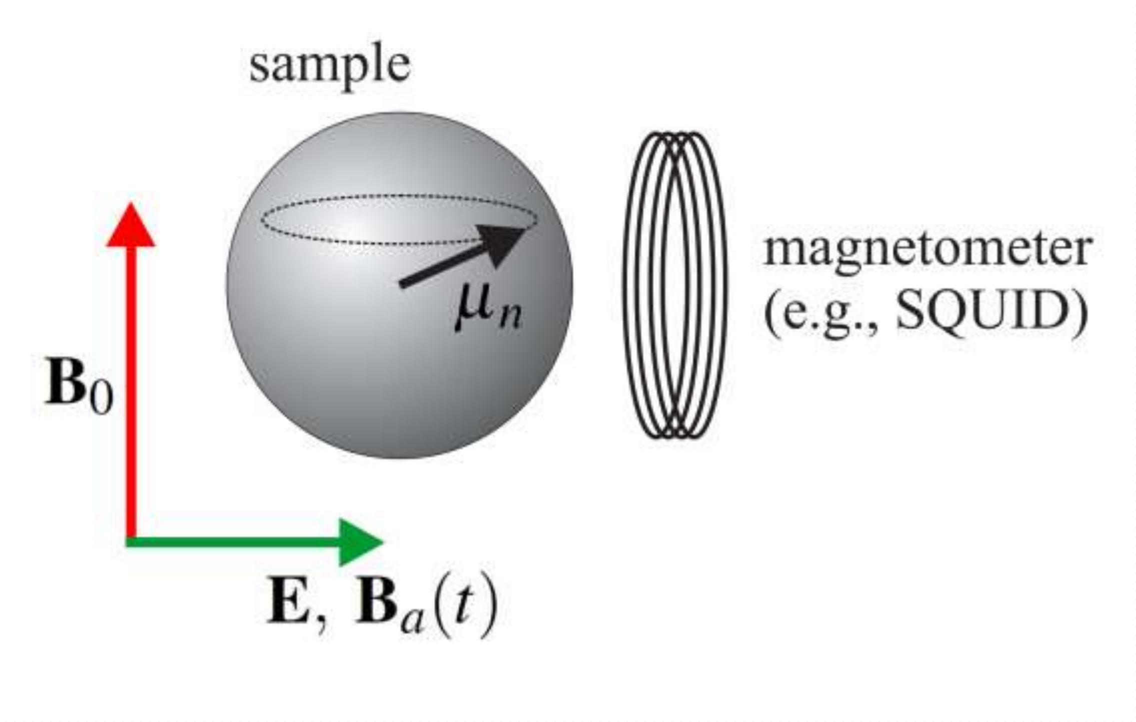
$$d_n = g_d a_0 \approx \frac{g_d}{m_a}\sqrt{\frac{2\hbar^3}{c}\rho_{\rm DM}}$$

$$\tau_{\rm wind} = \mu_n \times \mathbf{B}_a(t)$$

$$B_a \approx 10^{-3} \times \frac{g_{aNN}}{\hbar\gamma_n}\sqrt{2\hbar^3 c^3 \rho_{\rm DM}}$$



Axion field detection via NMR



Larmor frequency = axion Compton frequency
➔ resonant enhancement.

CASPEr Electric

CASPEr Electric sample

$$E^* \approx 3 \times 10^8 \ \frac{\mathrm{V}}{\mathrm{cm}} \ !$$

Need maximum number of polarized spins, large electric field (also small Schiff suppression), and long T_2.

Ferroelectric crystal, likely PMN-PT or $PbTiO_3$.

PHYSICAL REVIEW A **77**, 022102 (2008)

Nuclear-spin relaxation of ^{207}Pb in ferroelectric powders

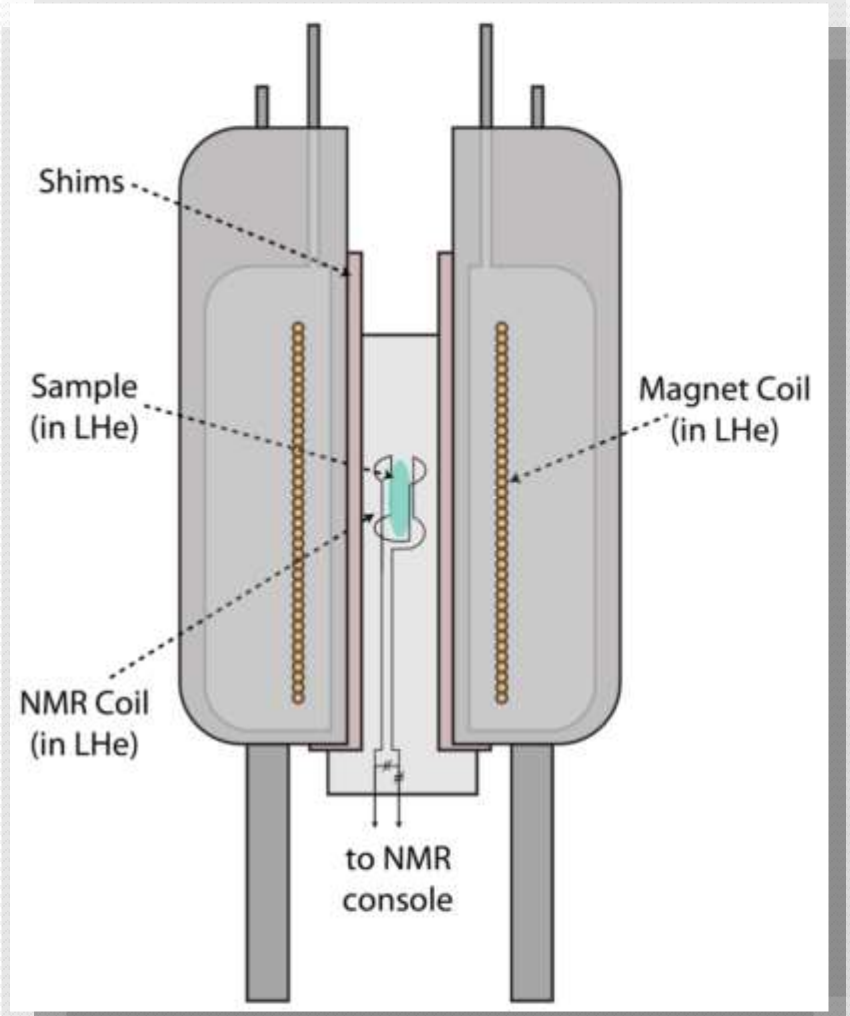
L.-S. Bouchard,[1,*] A. O. Sushkov,[2,†] D. Budker,[2,3,‡] J. J. Ford,[4,§] and A. S. Lipton[4,‖]
[1]*Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[2]*Department of Physics, University of California at Berkeley, Berkeley, California 94720-7300, USA*
[3]*Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[4]*Environmental Molecular Sciences Laboratory, Pacific North-West National Laboratory, Richland, Washington 99352, USA*
(Received 15 November 2007; published 4 February 2008)

Experimental strategy

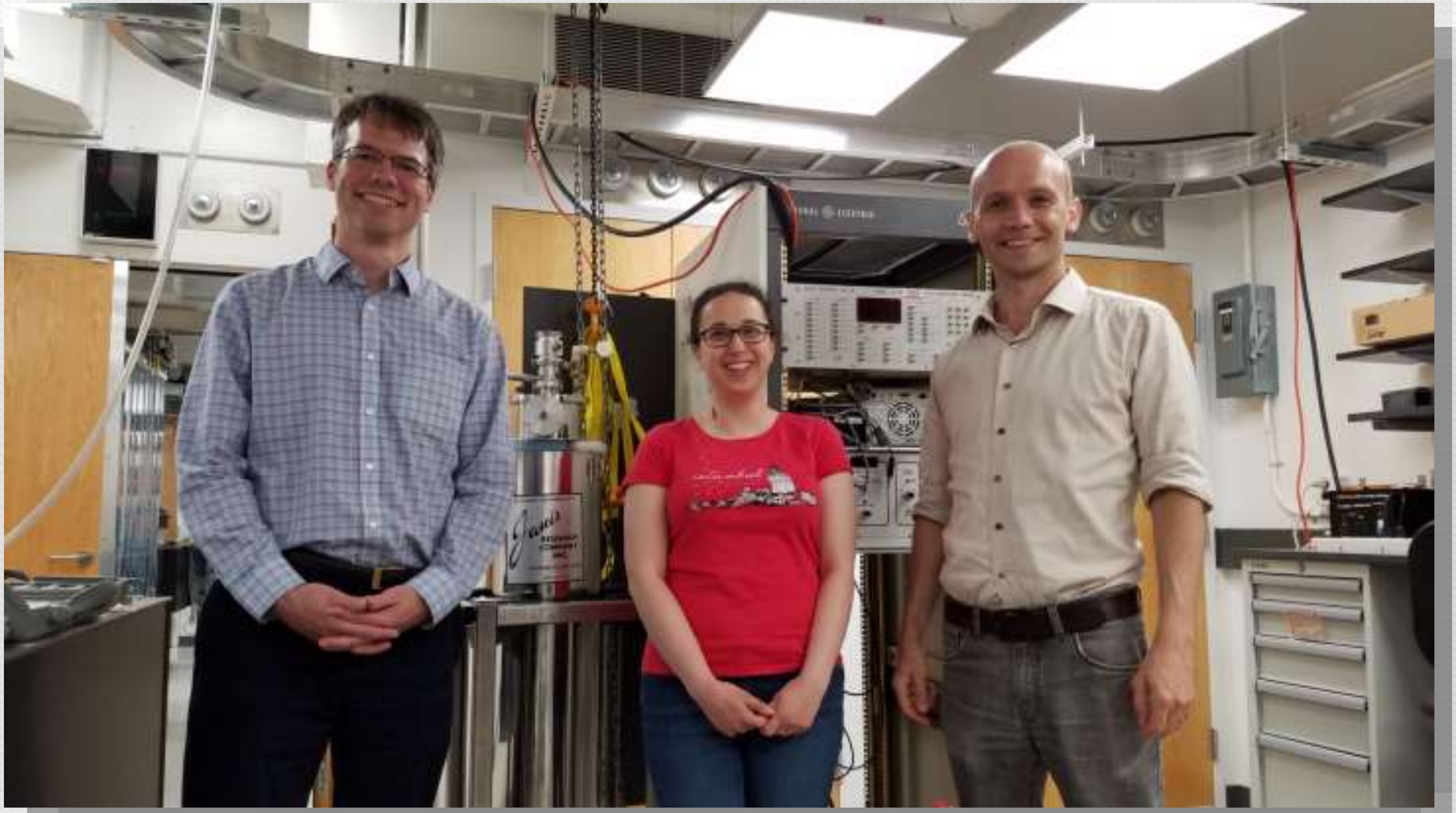
(1) Thermally polarize spins in a cryogenic environment at high magnetic field (~ 10 T);

(2) Scan magnetic field down from 10 T -- Larmor frequency decreases from 45 MHz;

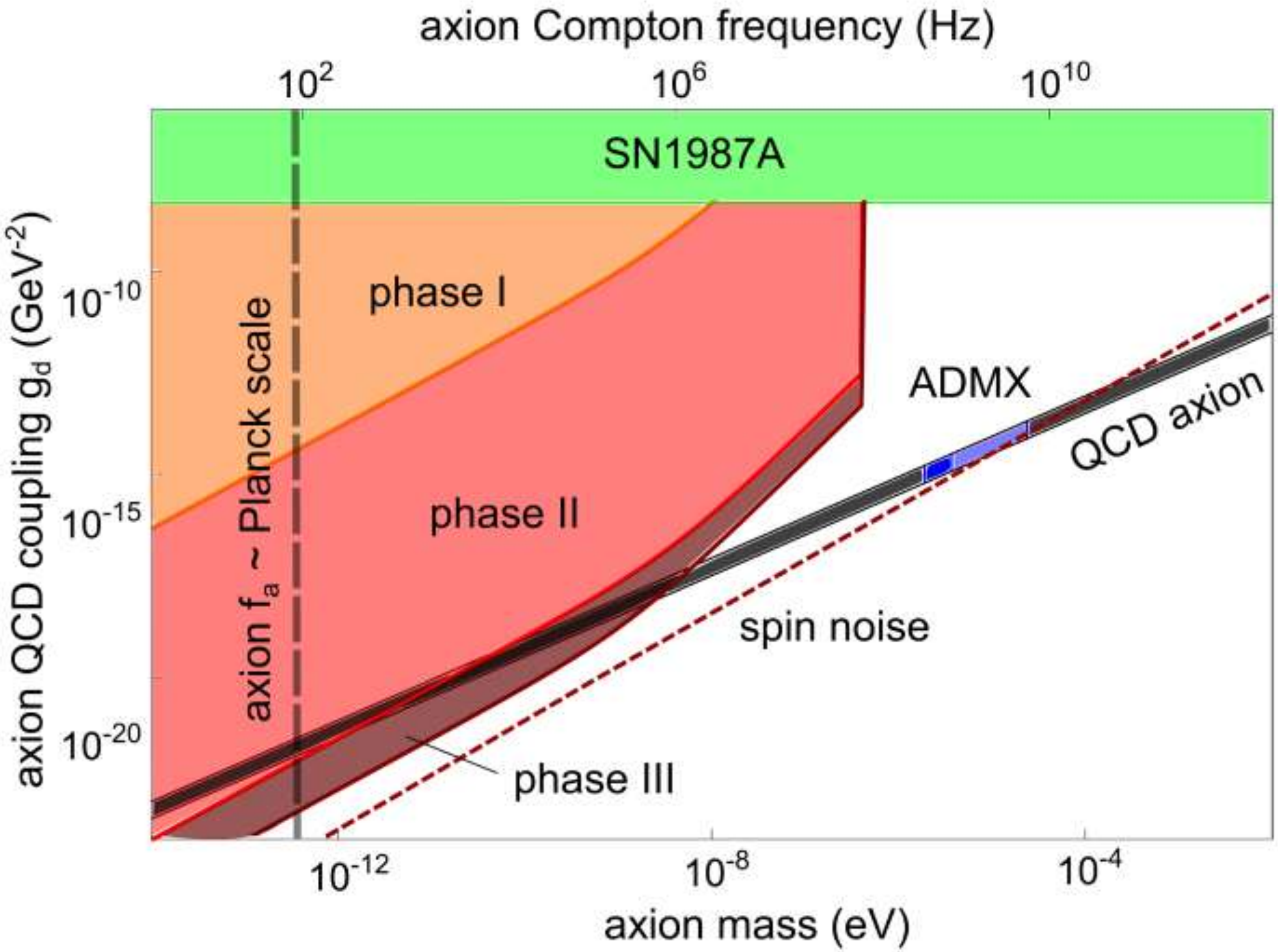
(3) Integrate for about 20 ms at each frequency, a complete scan takes around 1000 s ≈ T_1 to complete.



Experiments beginning!



CASPEr Electric sensitivity



CASPEr Wind

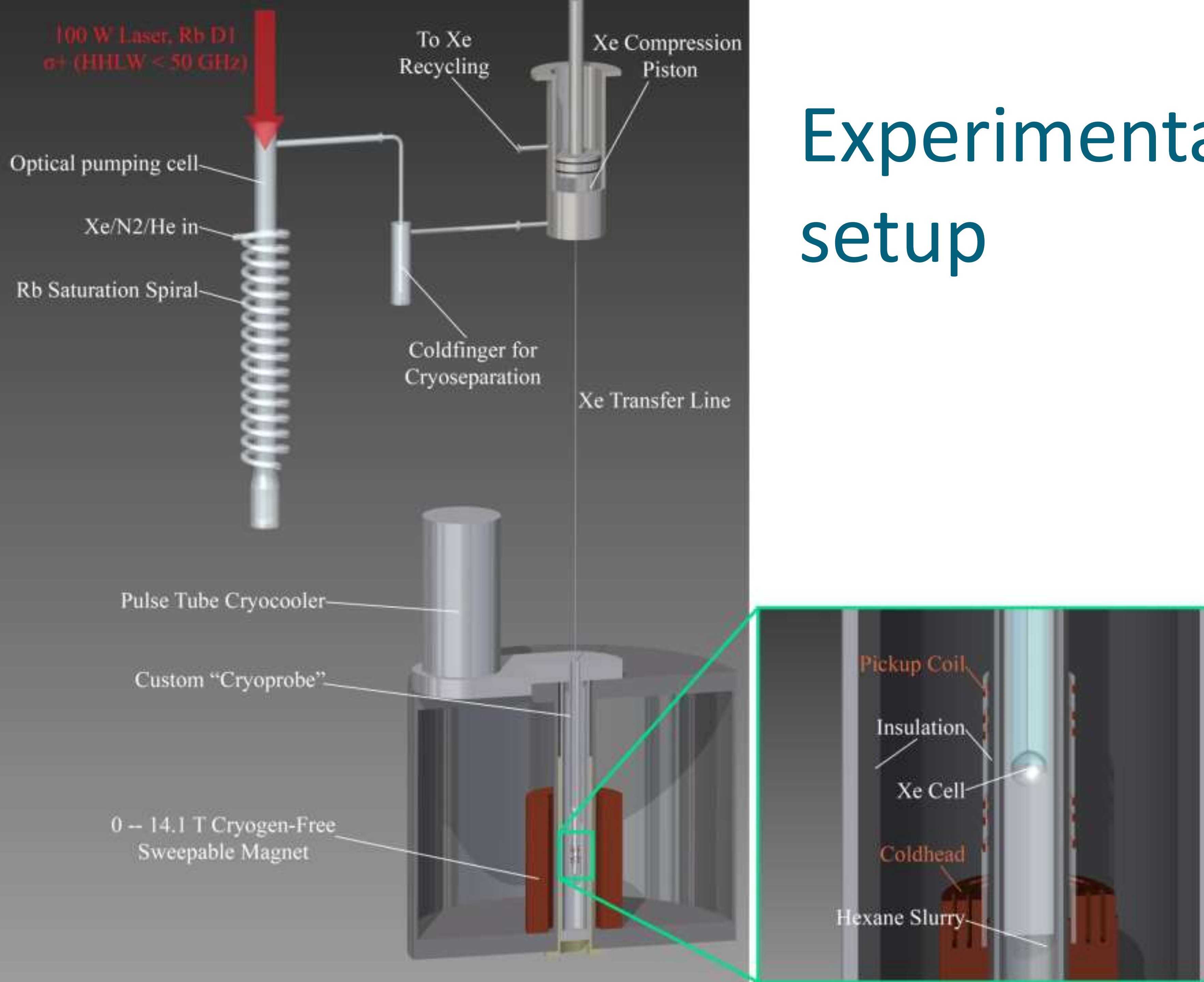
CASPEr Wind sample: liquid Xenon

Density (n)	Magnetic Moment (μ)	T_2
$1.3 \times 10^{22} \frac{1}{\text{cm}^3}$	$0.35\,\mu_N$	1300 s

Relatively large sample can be hyperpolarized.

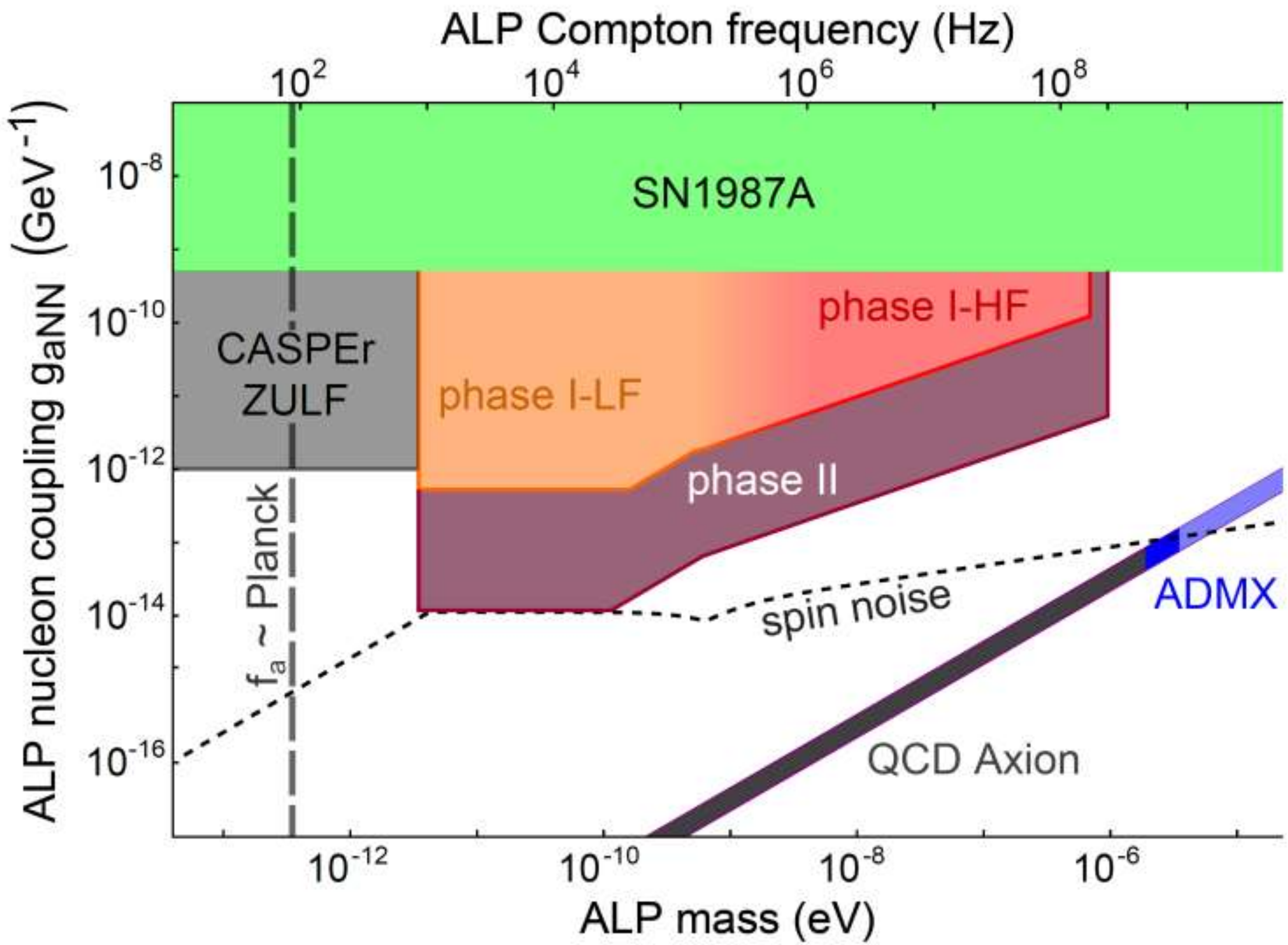
The enhancement factor can be on the order of 10^6.

Experimental setup



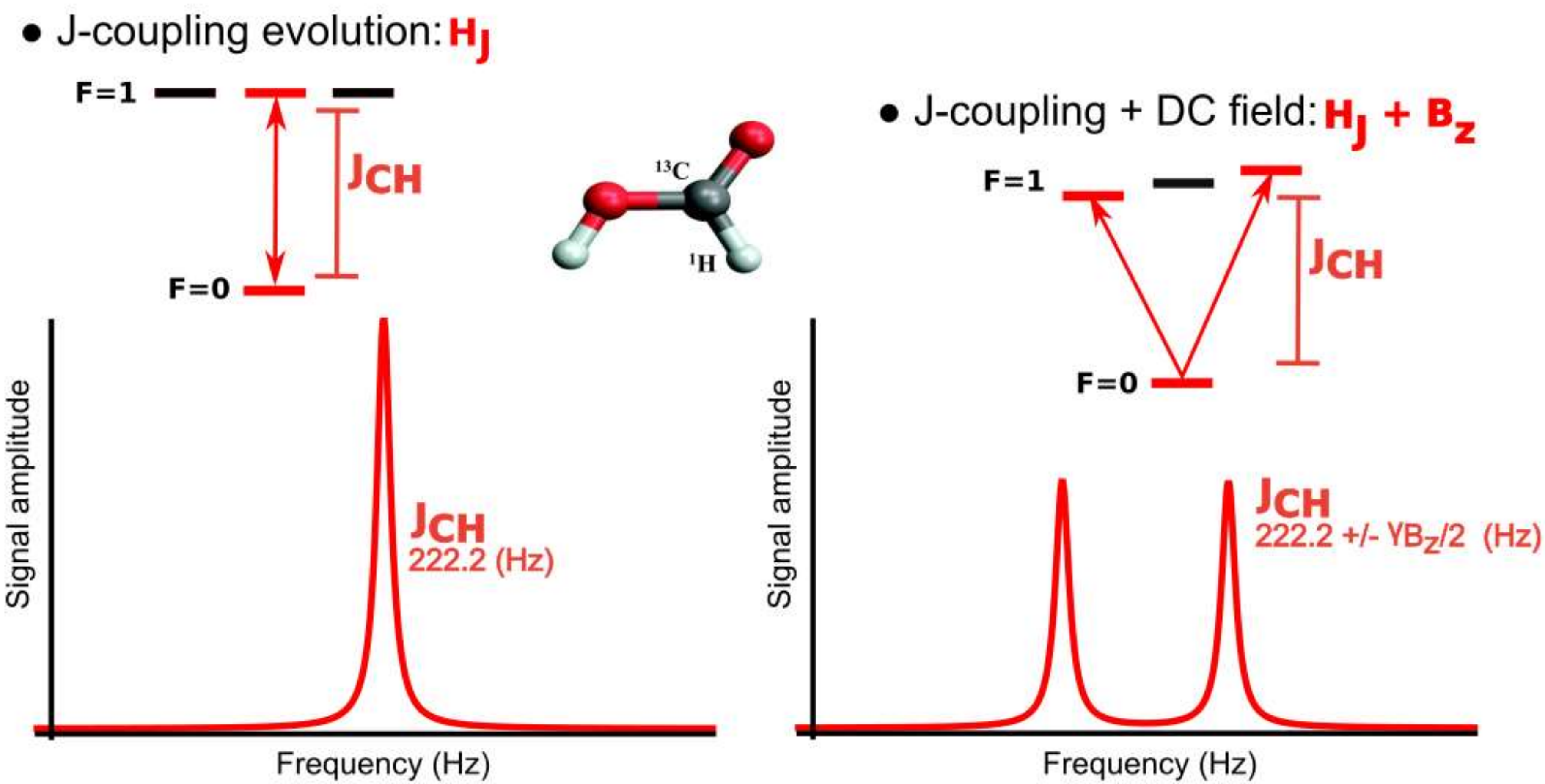
Experiments beginning!

CASPEr Wind sensitivity

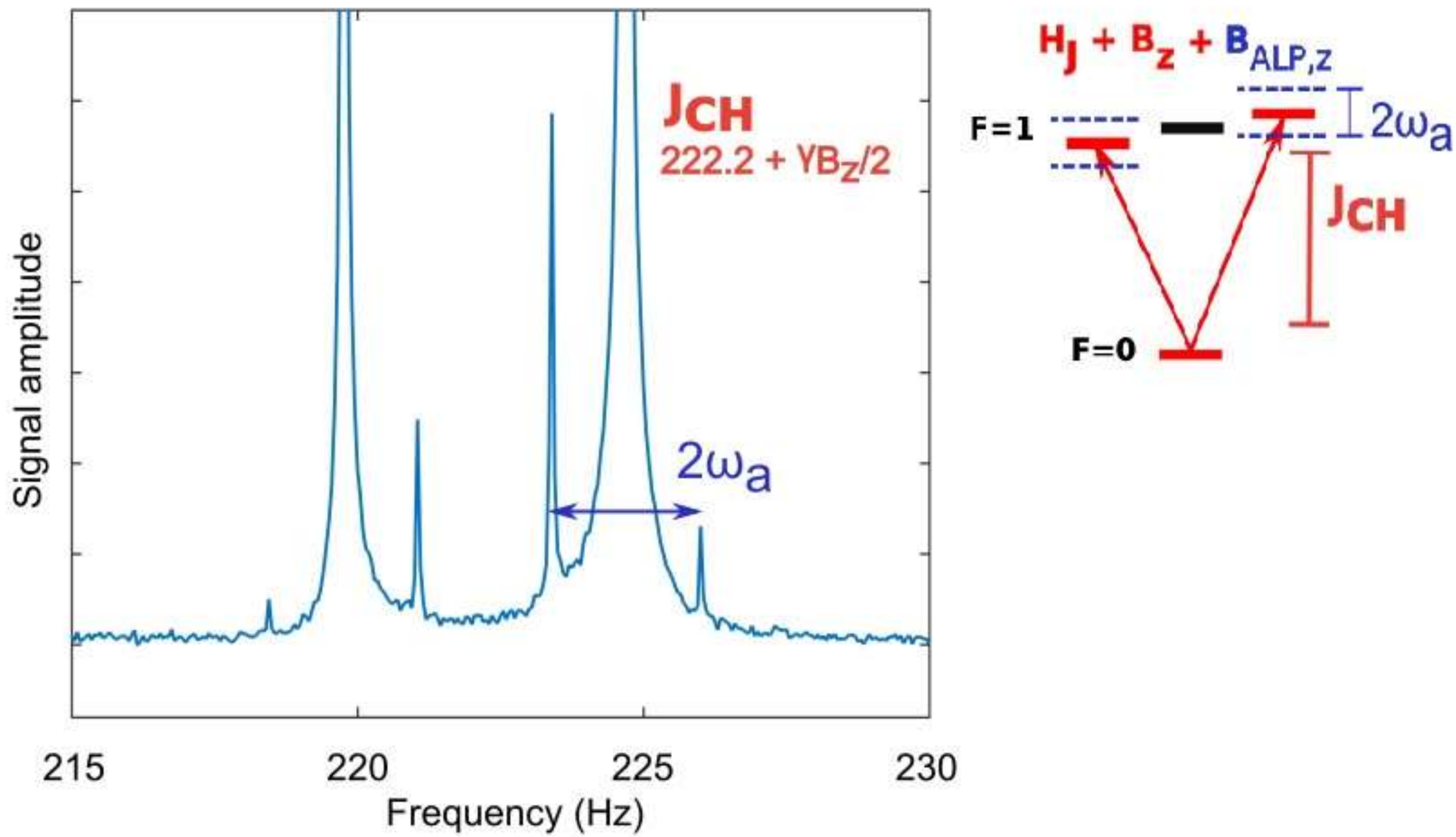


CASPEr Wind:
zero-to-ultralow field (ZULF)

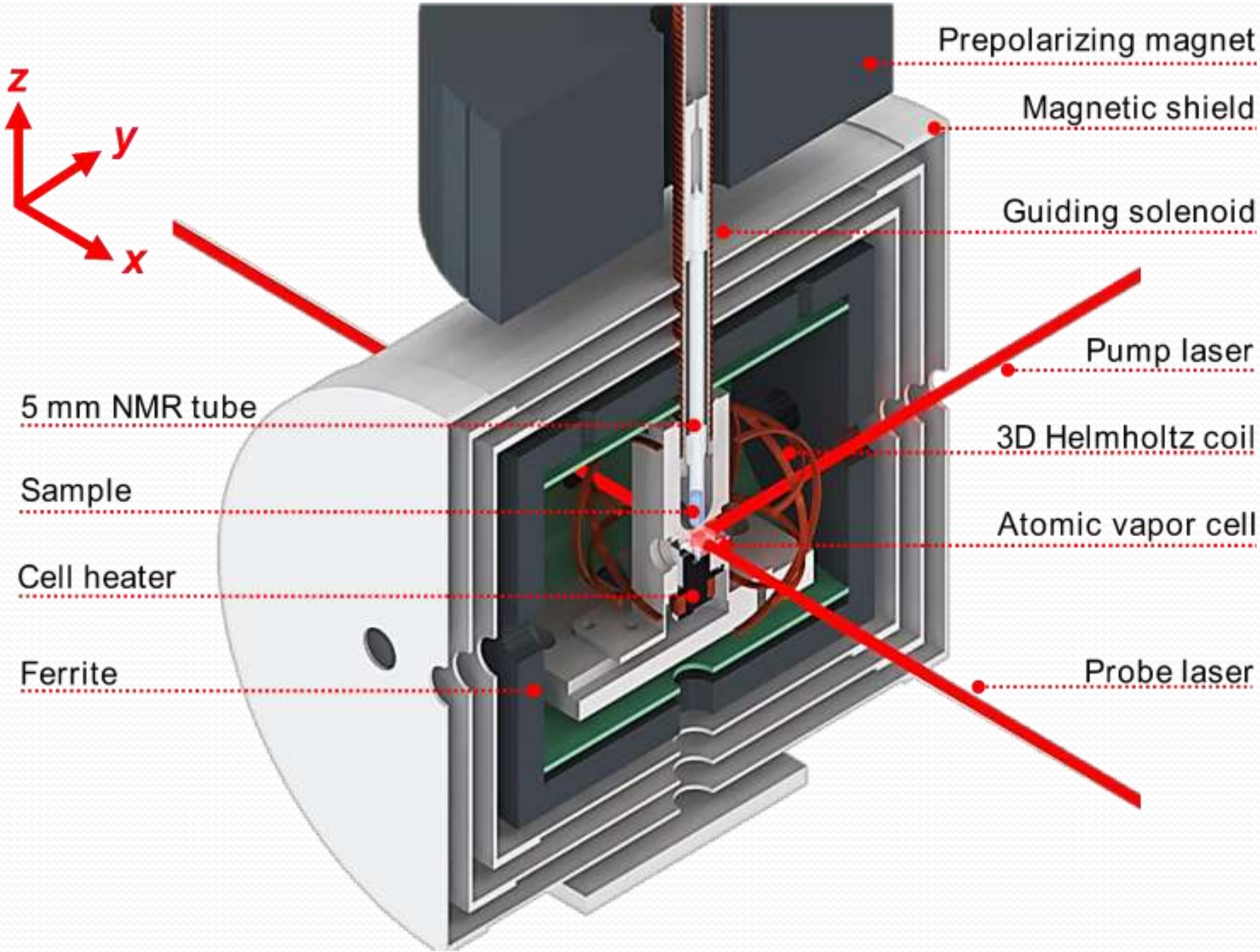
CASPEr ZULF sample: formic acid



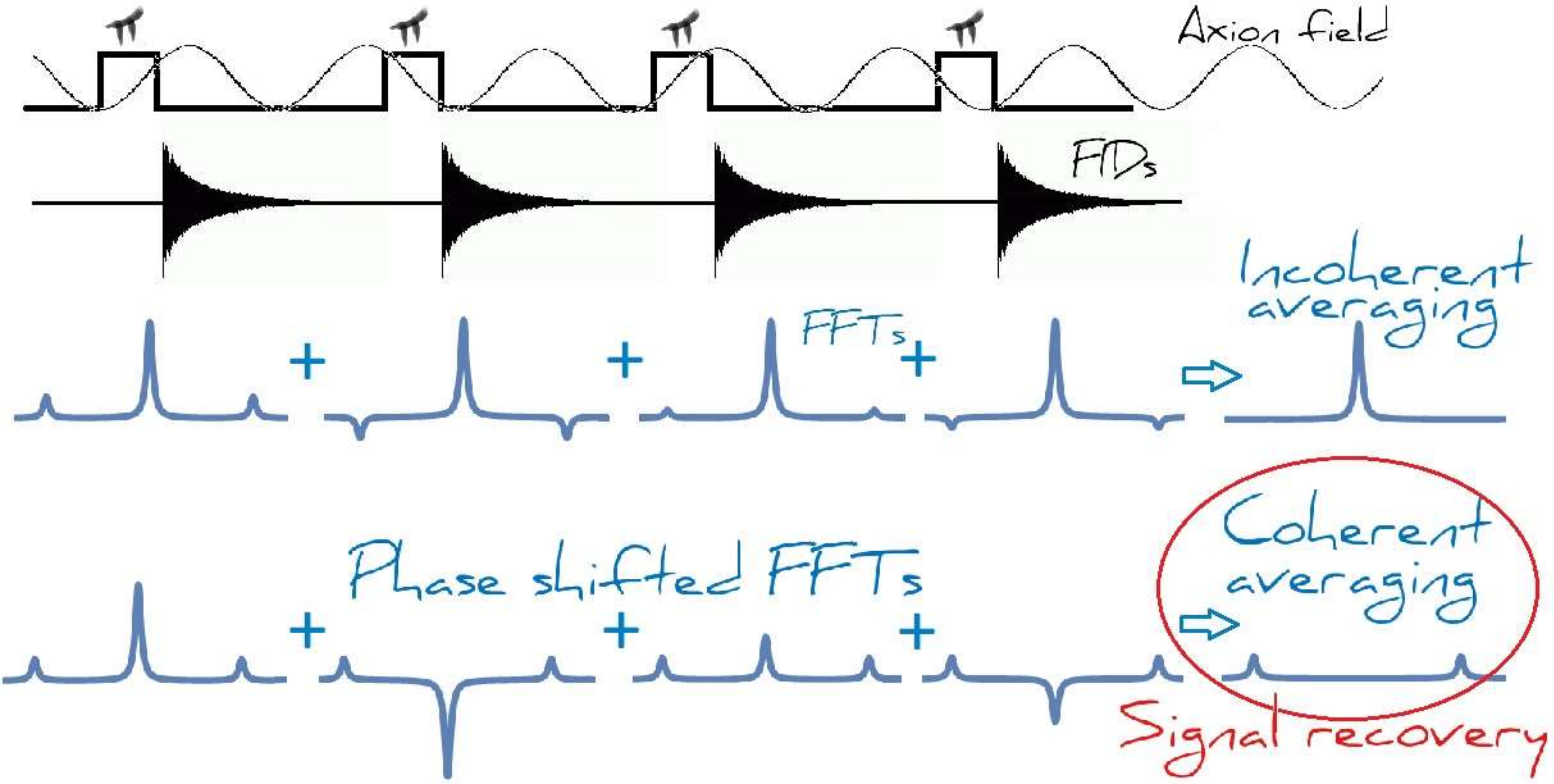
Oscillating field ⟶ sidebands



Experimental setup

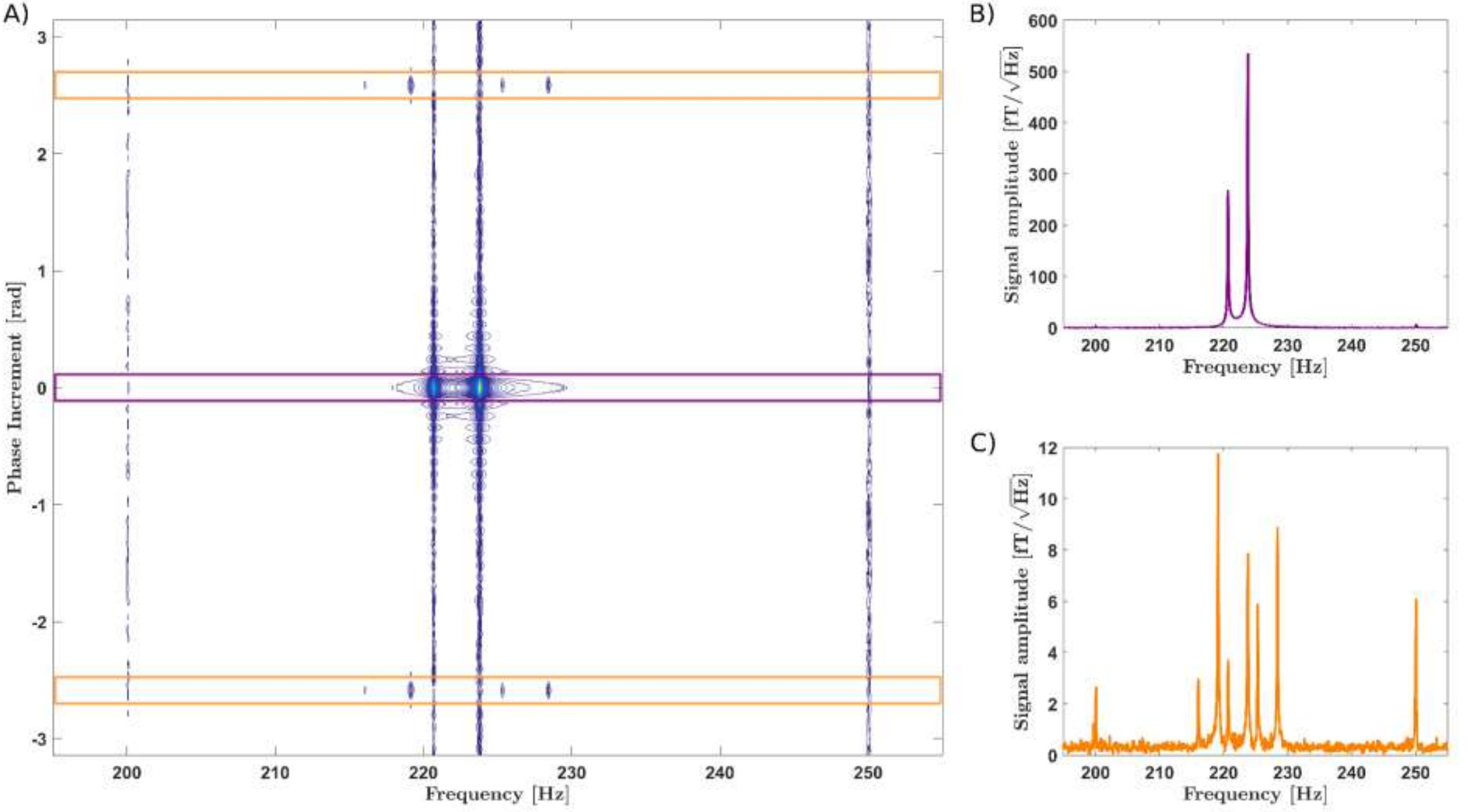


Procedure

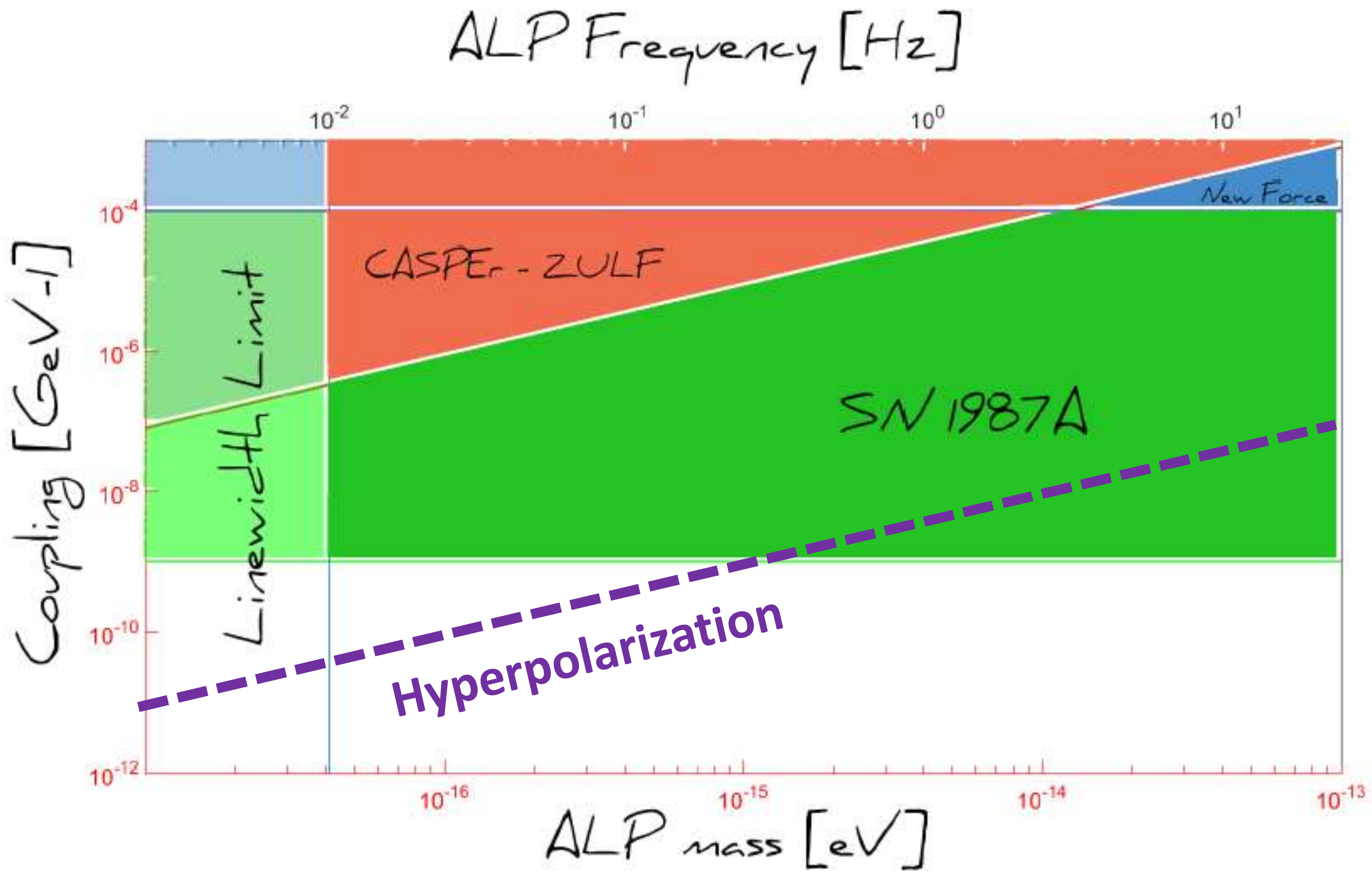


π
π
π
π
Axion field
FIDs
Incoherent averaging
FFTs
+
+
+
Phase shifted FFTs
+
+
+
Coherent averaging
Signal recovery

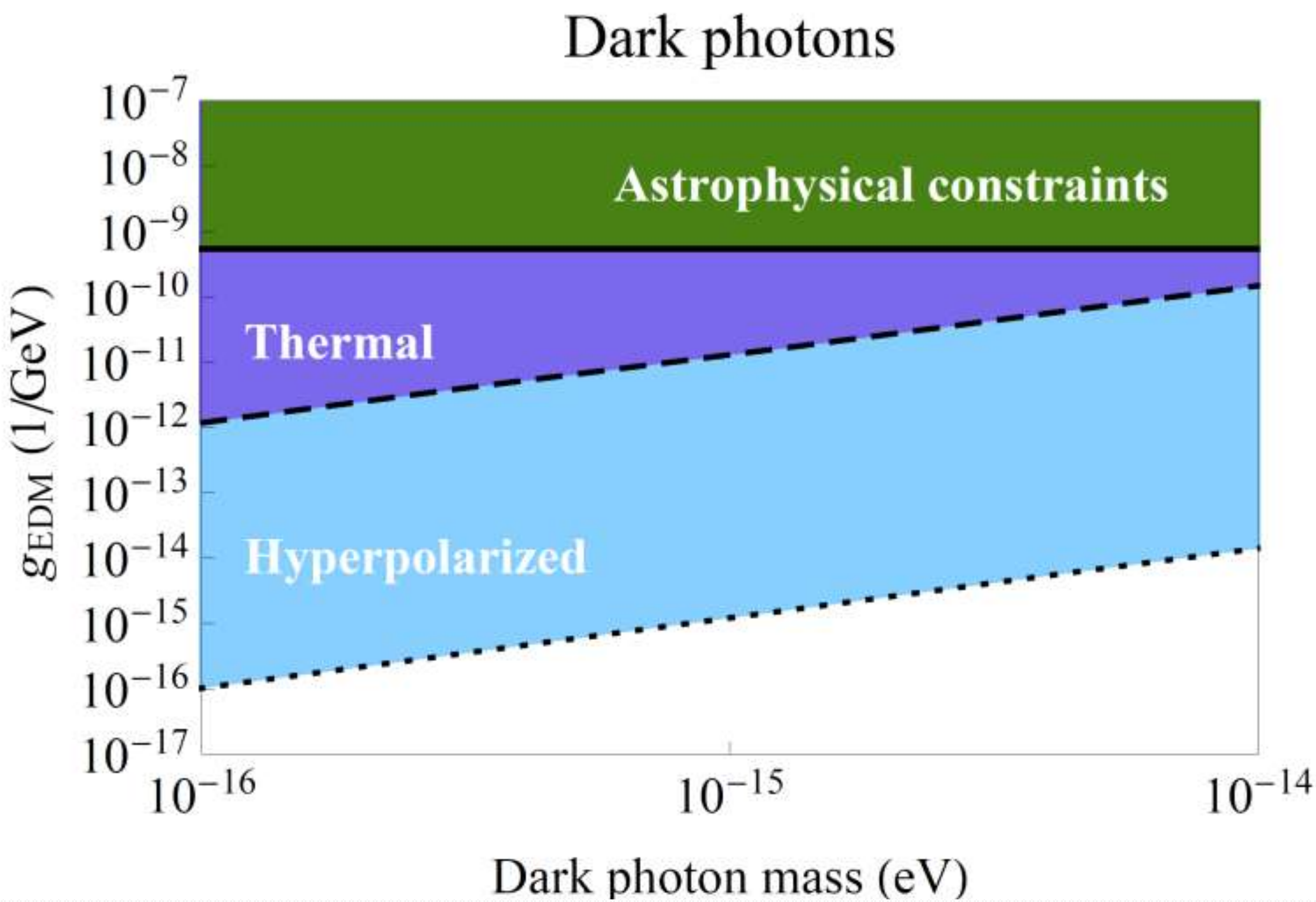
Scanning phase for coherent averaging



Initial results: ALPs

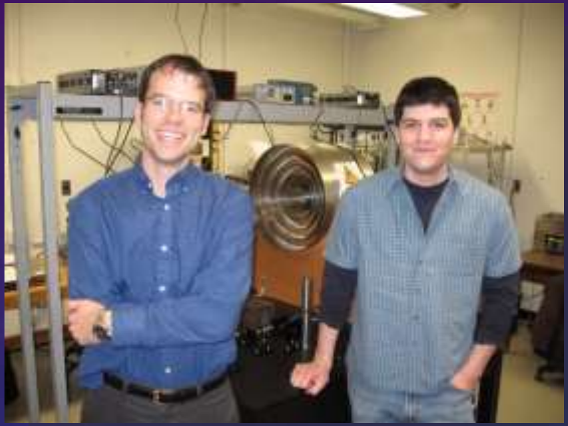


Initial results: Dark photons

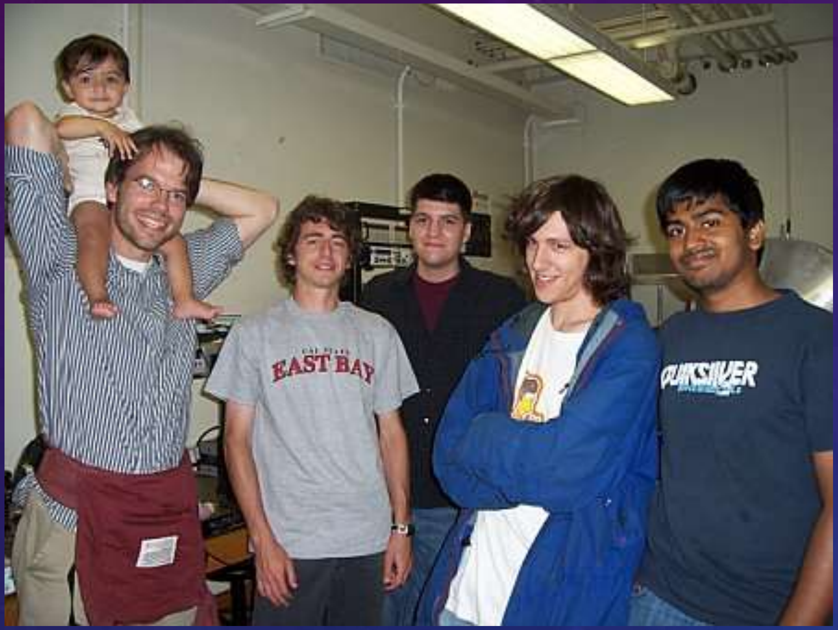


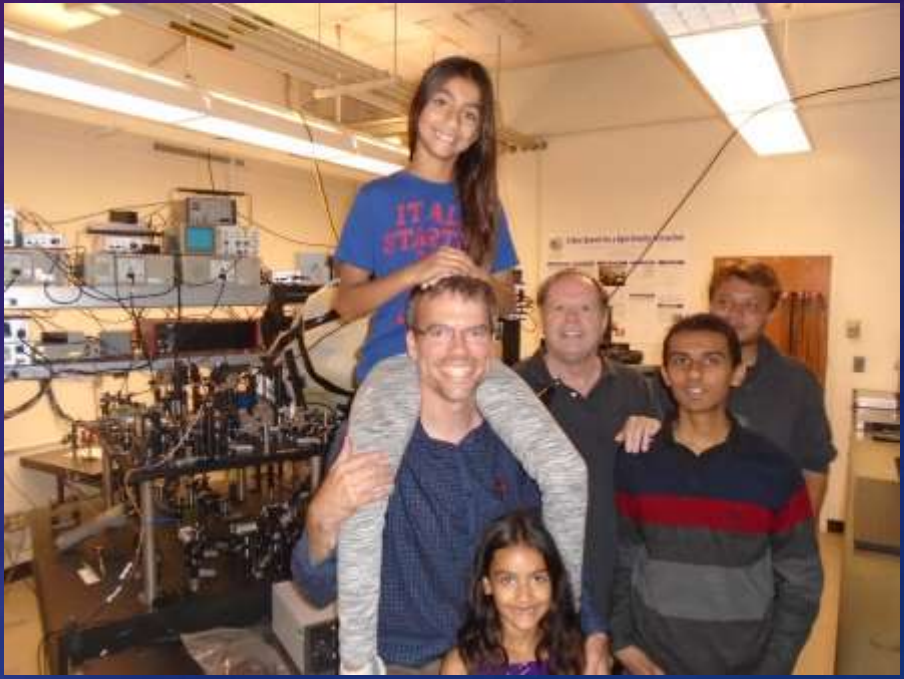
SEARCH FOR MONOPOLE-DIPOLE (SPIN-GRAVITY) COUPLING BETWEEN PROTONS AND THE EARTH

THANKS TO MANY, MANY FANTASTIC UNDERGRADUATE STUDENTS



THESE EXPERIMENTS CAN TAKE A WHILE…





PHYSICAL REVIEW D

covering particles, fields, gravitation, and cosmology

ANNOUNCEMENT

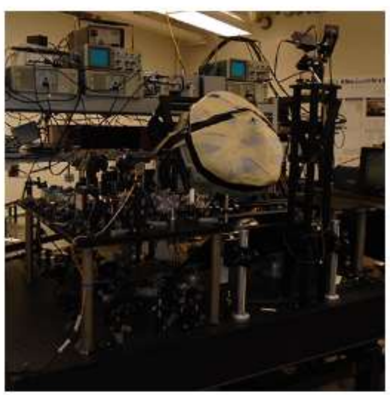
2017 Nobel Prize in Physics

October 3, 2017

APS congratulates Rainer Weiss, Barry C. Barish, and Kip S. Thorne for winning the 2017 Nobel Prize in Physics "for decisive contributions to the LIGO detector and the observation of gravitational waves."

APS News Article

Read More | More News



EDITORS' SUGGESTION

Constraints on long-range spin-gravity and monopole-dipole couplings of the proton

Using an ensemble of Rubidium isotopes, the authors test for exotic monopole-dipole couplings that may arise in modified theories of gravity or with new long-range forces. They improve the limits on such interactions from terrestrial experiments by three orders of magnitude.

Derek F. Jackson Kimball *et al.*

Phys. Rev. D **96**, 075004 (2017)

NEW SPIN-0 OR SPIN-1 BOSONS CAN GENERATE NEW FORCES

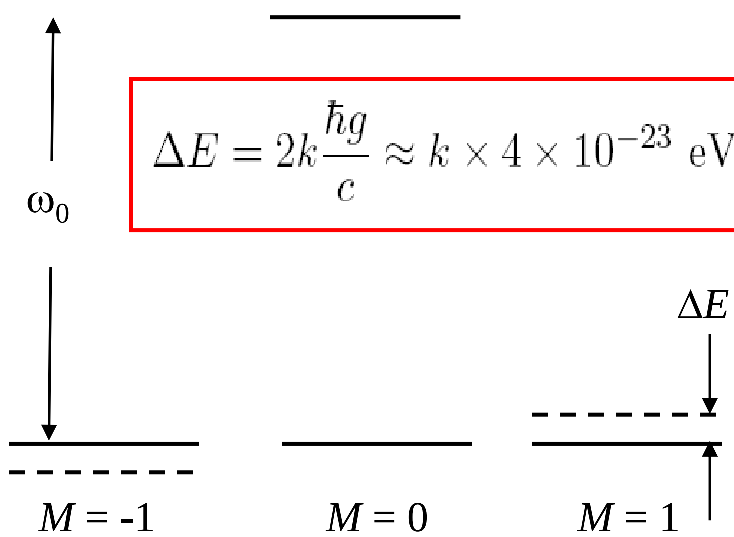
$$\mathcal{V}_{9,10}(r) = \frac{g_p^X g_s^Y \hbar}{8\pi m_X c} \boldsymbol{\sigma}_X \cdot \hat{\mathbf{r}} \left(\frac{1}{r\lambda} + \frac{1}{r^2} \right) e^{-r/\lambda}$$

J. E. Moody and F. Wilczek, Phys. Rev. D **30**, 130 (1984);
B. A. Dobrescu and I. Mocioiu, J. High Energy Phys. **11**, 5 (2006).

SPIN-GRAVITY COUPLING

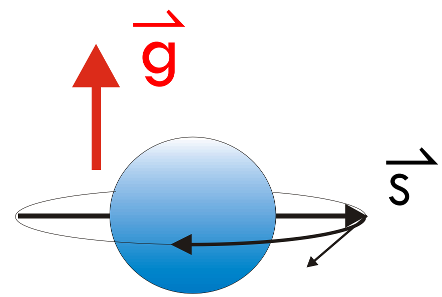
Hamiltonian in Earth's field: $H_g = k\frac{\hbar}{c}\boldsymbol{\sigma}\cdot\boldsymbol{g}$

Shift of Zeeman sublevels



$$\Delta E = 2k\frac{\hbar g}{c} \approx k \times 4 \times 10^{-23}\ \text{eV}$$

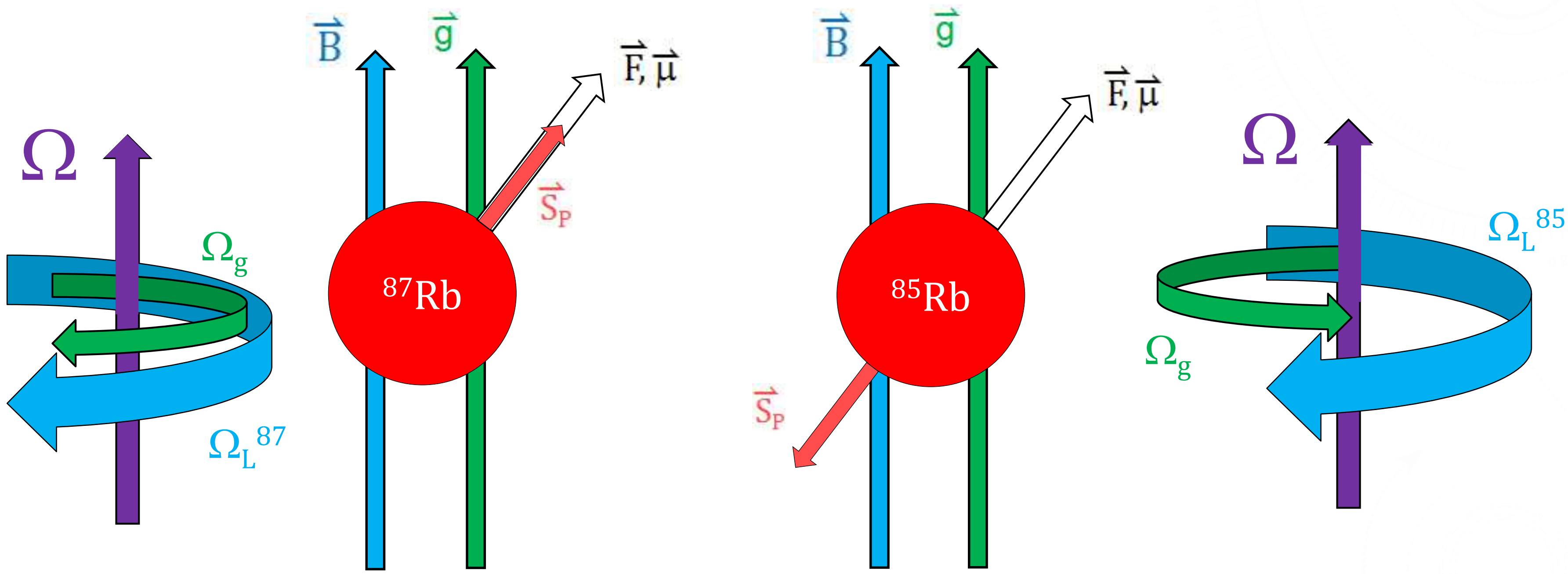
Spin precession



$$\Omega_g = 2k\frac{g}{c} \approx k \times 2\pi \times 10^{-8}\ \text{Hz}$$

D. F. Jackson Kimball et al., Phys. Rev. D **96**, 075004 (2017).

DUAL-ISOTOPE RUBIDIUM COMAGNETOMETER



$$\Omega_{85} = |\gamma_{85} B + \chi_{85} g| \ ,$$
$$\Omega_{87} = |\gamma_{87} B + \chi_{87} g| \ .$$

where γ_A is the gyromagnetic ratio and χ_A is the "gyro-gravitational" ratio of isotope A.

DUAL-ISOTOPE RUBIDIUM COMAGNETOMETER

Form ratio of difference/sum of precession frequencies:

$$\mathcal{R} = \frac{\Omega_{85} - \Omega_{87}}{\Omega_{85} + \Omega_{87}}$$

$$\mathcal{R}_{\pm} \approx \left(\frac{\gamma_{85} - \gamma_{87}}{\gamma_{85} + \gamma_{87}}\right)\left(1 \pm 2\frac{\chi_p g}{\mu_0 B}\right) ,$$

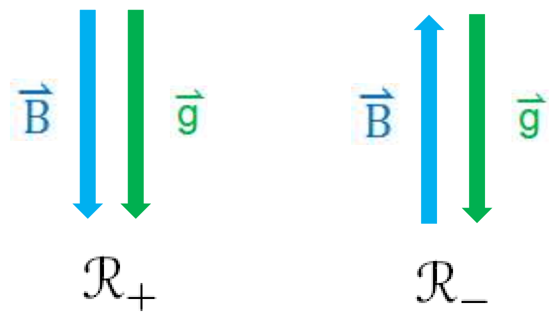
where χ_p is the gyro-gravitational ratio for the proton and μ_0 is the Bohr magneton, and $\pm$ refers to orientation of $\mathbf{B} \uparrow$ or $\downarrow$ to $\mathbf{g}$.

$$\Delta\mathcal{R} = \mathcal{R}_{+} - \mathcal{R}_{-} = 4\left(\frac{\gamma_{85} - \gamma_{87}}{\gamma_{85} + \gamma_{87}}\right)\frac{\chi_p g}{\mu_0 B} .$$

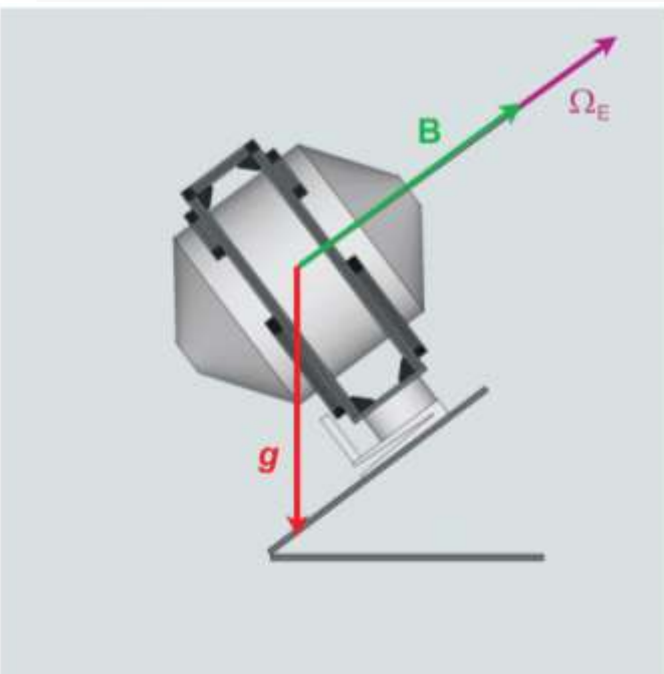
DUAL-ISOTOPE RUBIDIUM COMAGNETOMETER

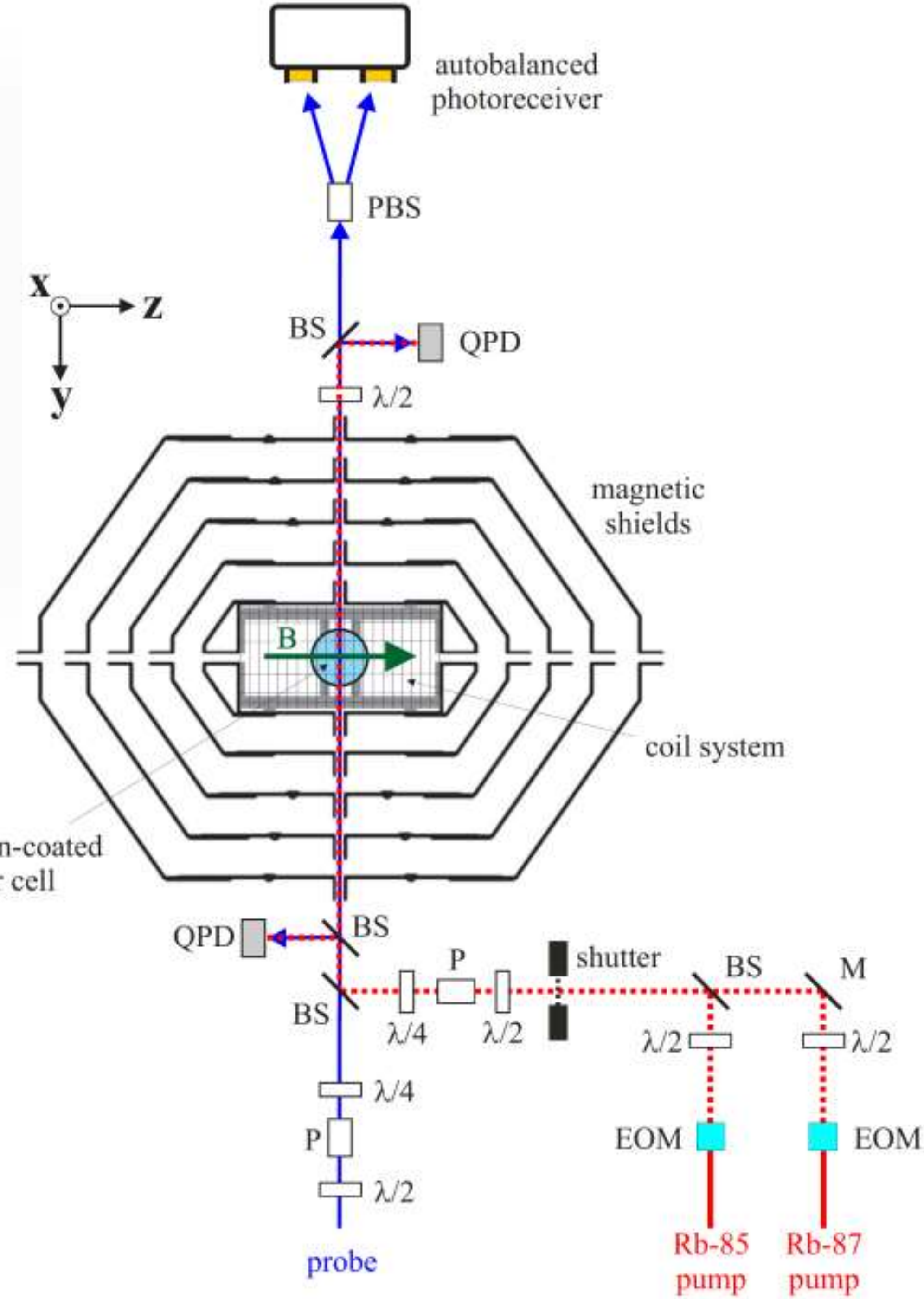
Form ratio of difference/sum of precession frequencies:

$$\mathcal{R} = \frac{\Omega_{85} - \Omega_{87}}{\Omega_{85} + \Omega_{87}}$$

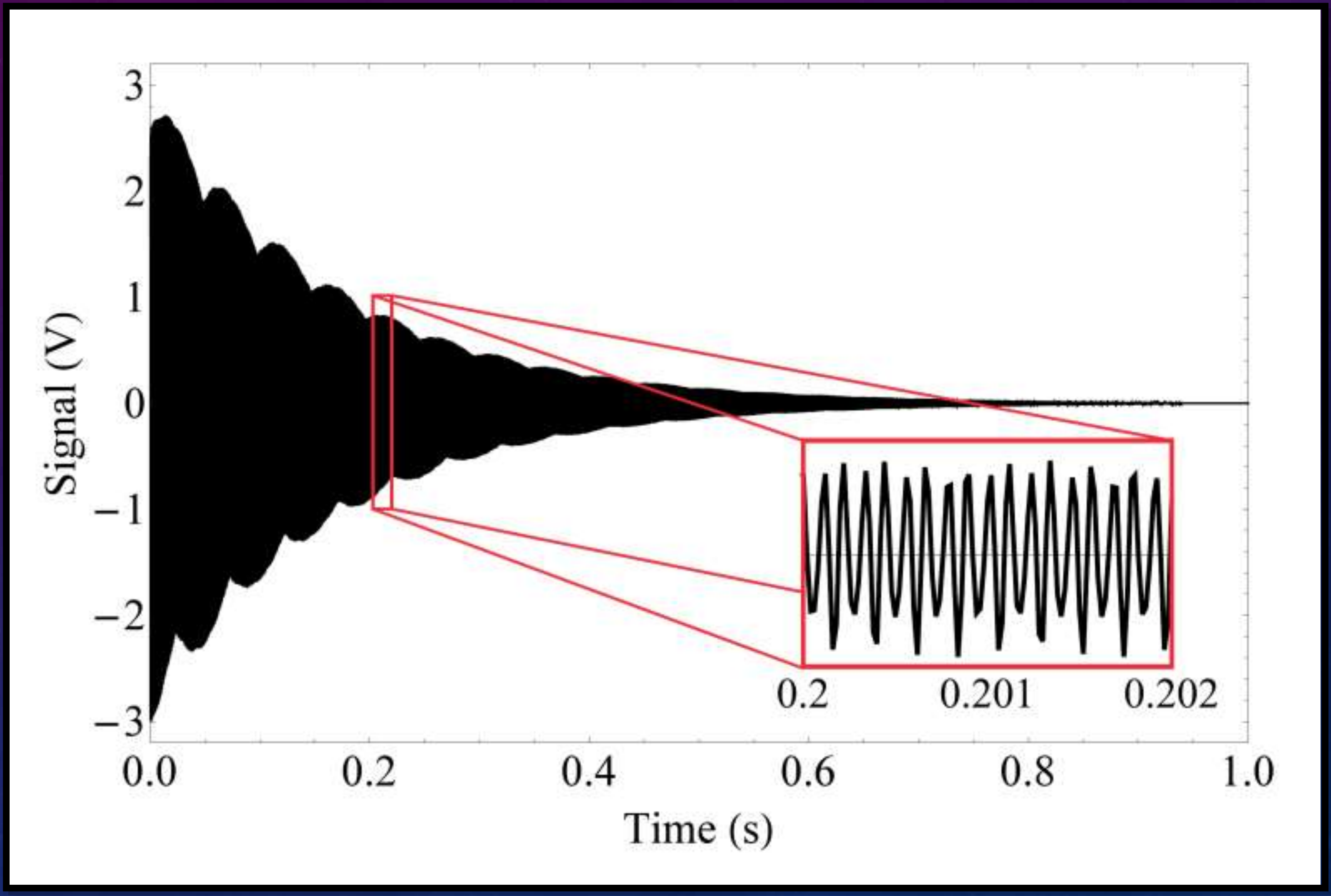


$$\Delta\mathcal{R} = \mathcal{R}_+ - \mathcal{R}_- \begin{cases} = 0 \text{ if there is no spin-gravity interaction,} \\ \neq 0 \text{ if there is a spin-gravity interaction.} \end{cases}$$

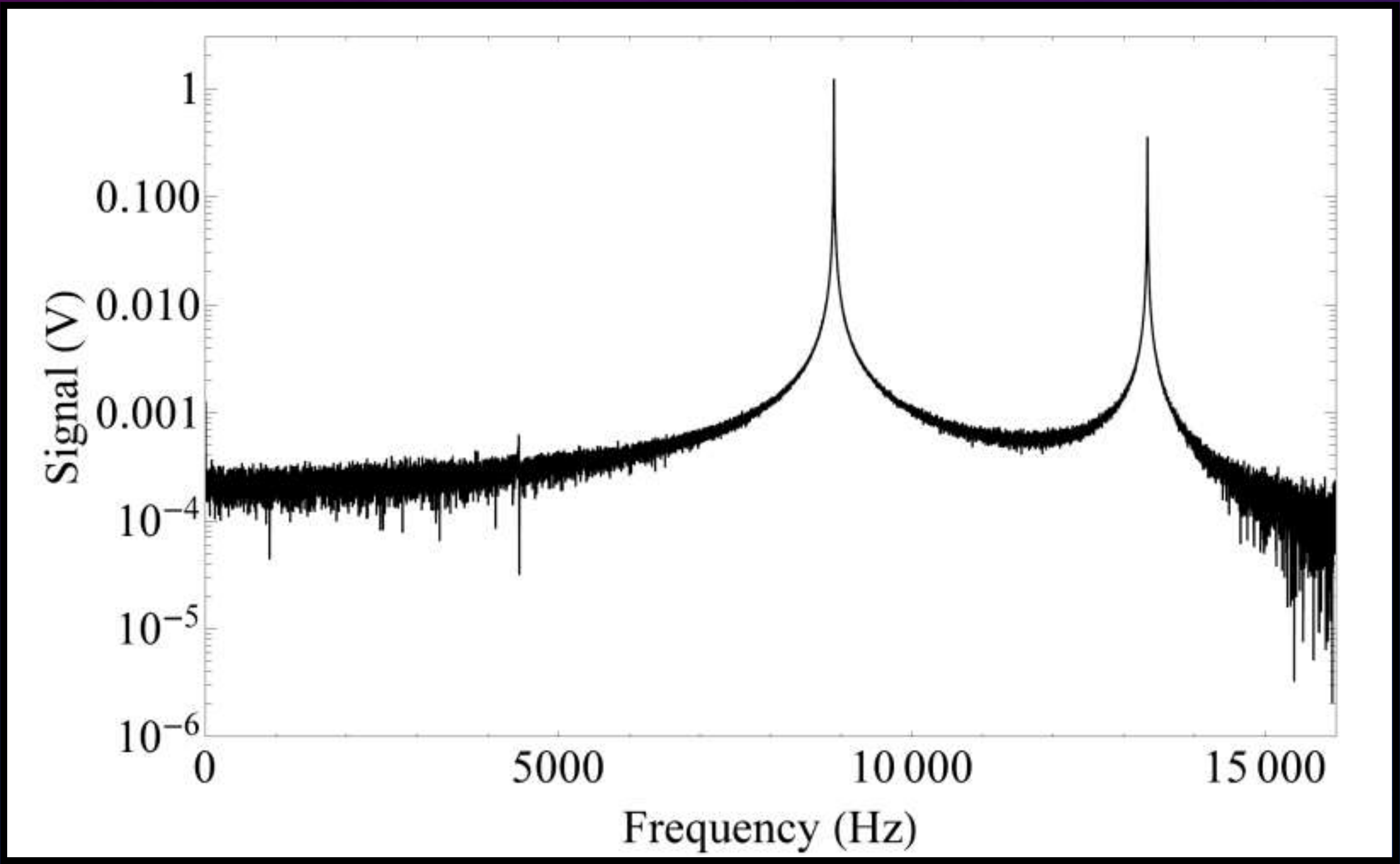

B
Ω_E
g


autobalanced photoreceiver
PBS
x
z
y
BS
QPD
λ/2
magnetic shields
B
coil system
antirelaxation-coated Rb vapor cell
QPD
BS
P
shutter
BS
M
BS
λ/4
λ/2
λ/2
λ/2
λ/4
P
λ/2
EOM
EOM
probe
Rb-85 pump
Rb-87 pump

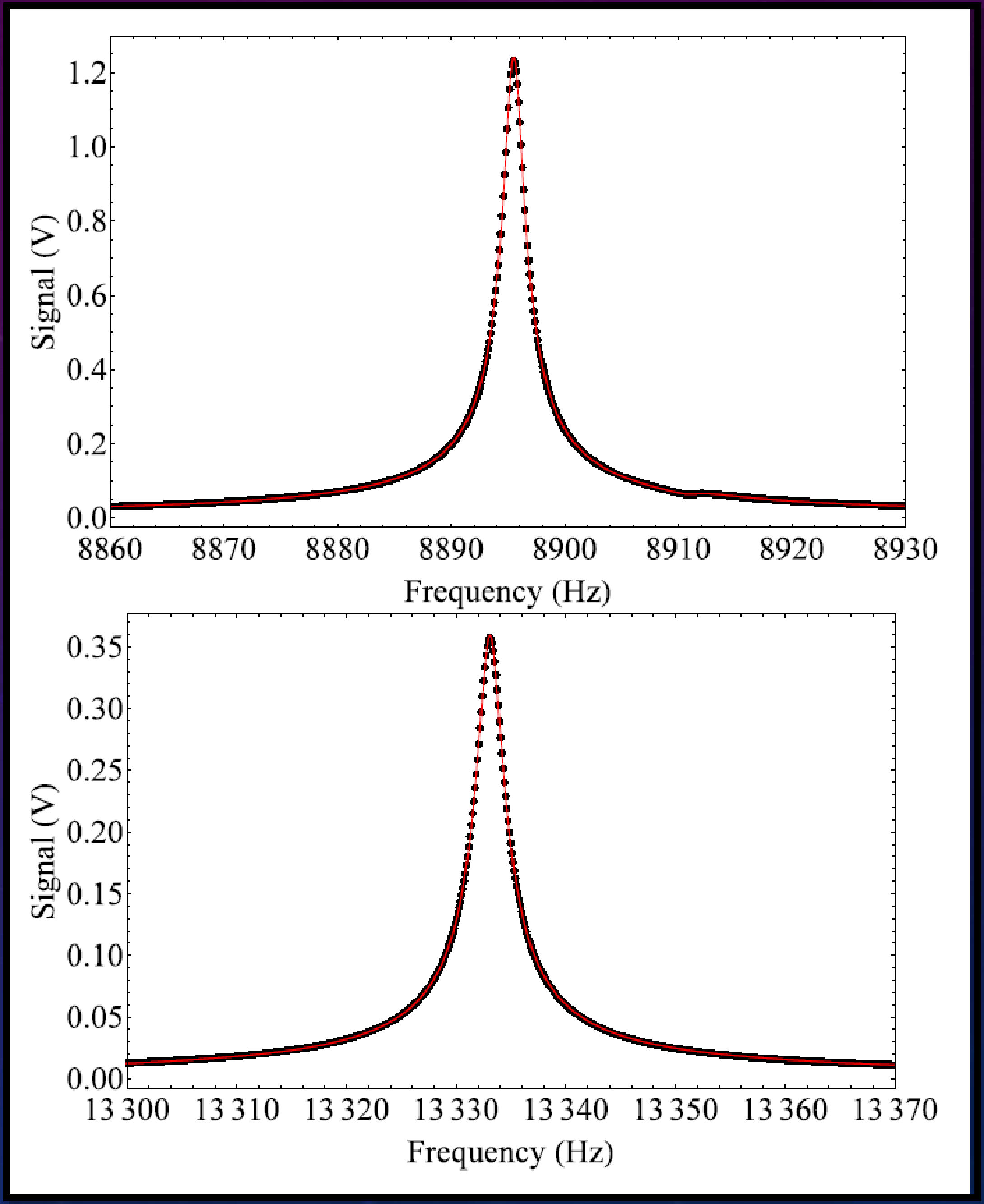
TIME DOMAIN SIGNAL



FREQUENCY DOMAIN SIGNAL



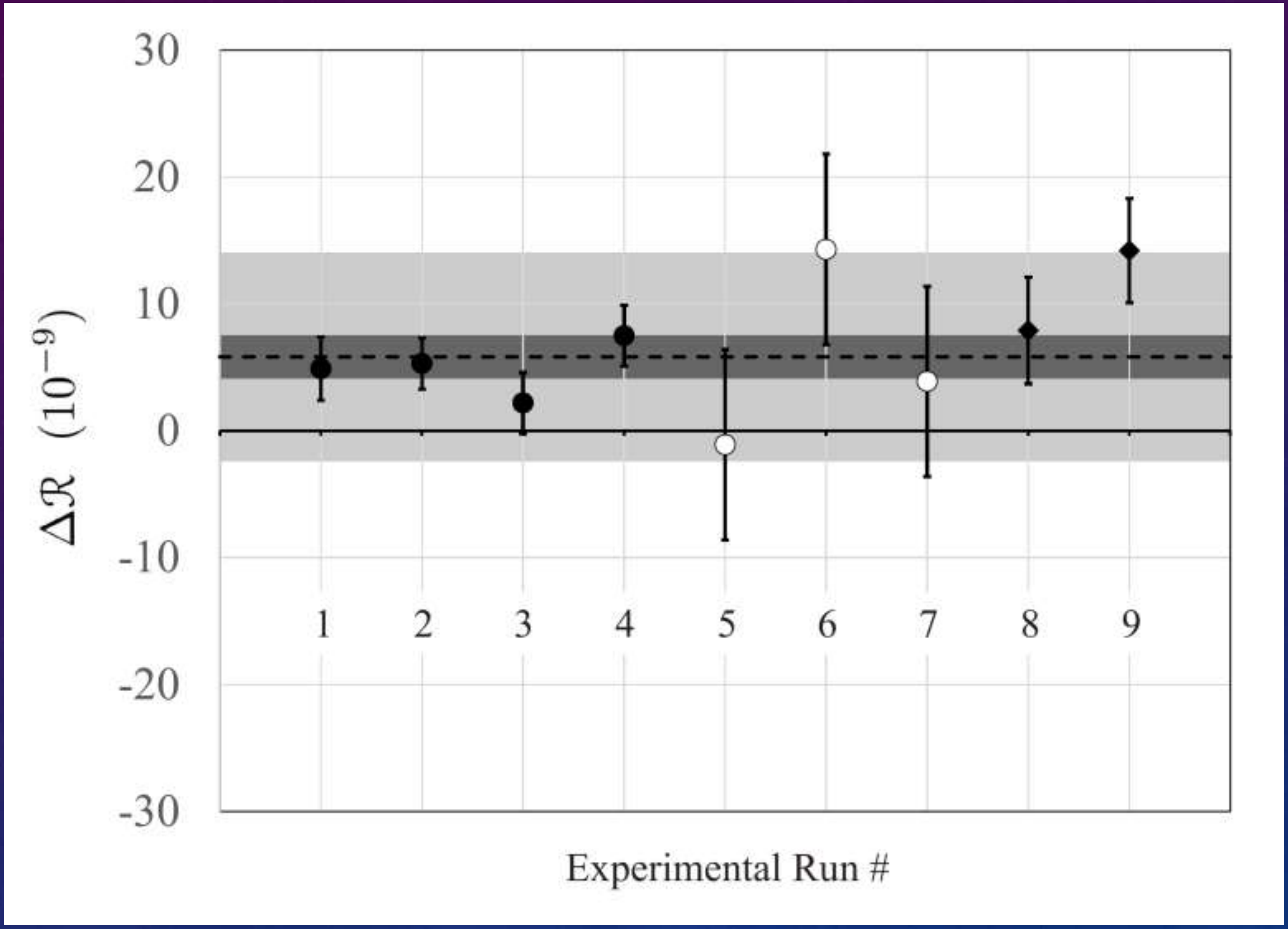
FITS TO DATA



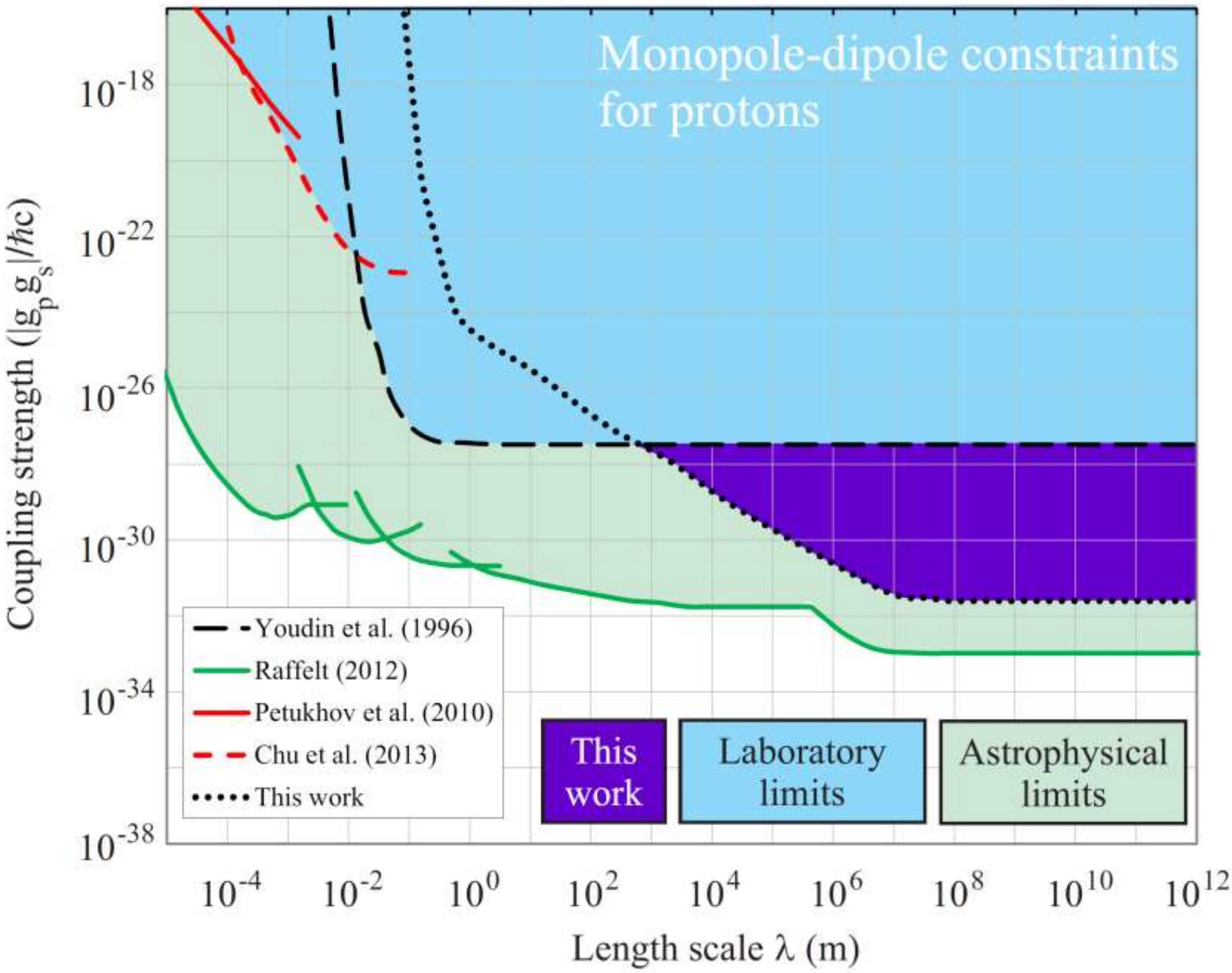
$$\frac{\delta\Omega}{2\pi} \approx 100\ \mu\text{Hz}$$

SUMMARY OF SYSTEMATIC ERRORS

Description	Effect on $\Delta\mathcal{R}$
Scattered pump light along $\mathbf{B}$	5×10^{-9}
Magnetic field gradients	3×10^{-9}
Excess noise for $-\mathbf{B}$	3×10^{-9}
Asynchronous optical pumping	10^{-9}
Tensor shifts + polarization along $\mathbf{B}$	2×10^{-10}
Vector light shifts from probe beam ϵ	3×10^{-11}
Gyro-compass effect	10^{-13}
ac Zeeman effect	10^{-14}
Wall collisions*	10^{-16}
Nuclear magnetic moments*	10^{-16}
Transverse spin-exchange collisions*	2×10^{-18}



$$\Delta\mathcal{R} = 5.8 \pm 1.7_{(\mathrm{stat})} \pm 6.6_{(\mathrm{sys})} \times 10^{-9}$$



Monopole-dipole constraints for protons
Coupling strength ($|g_p g_s|/\hbar c$)
10^{-18}
10^{-22}
10^{-26}
10^{-30}
10^{-34}
10^{-38}
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
10^{6}
10^{8}
10^{10}
10^{12}
Length scale λ (m)
Youdin et al. (1996)
Raffelt (2012)
Petukhov et al. (2010)
Chu et al. (2013)
This work
This work
Laboratory limits
Astrophysical limits

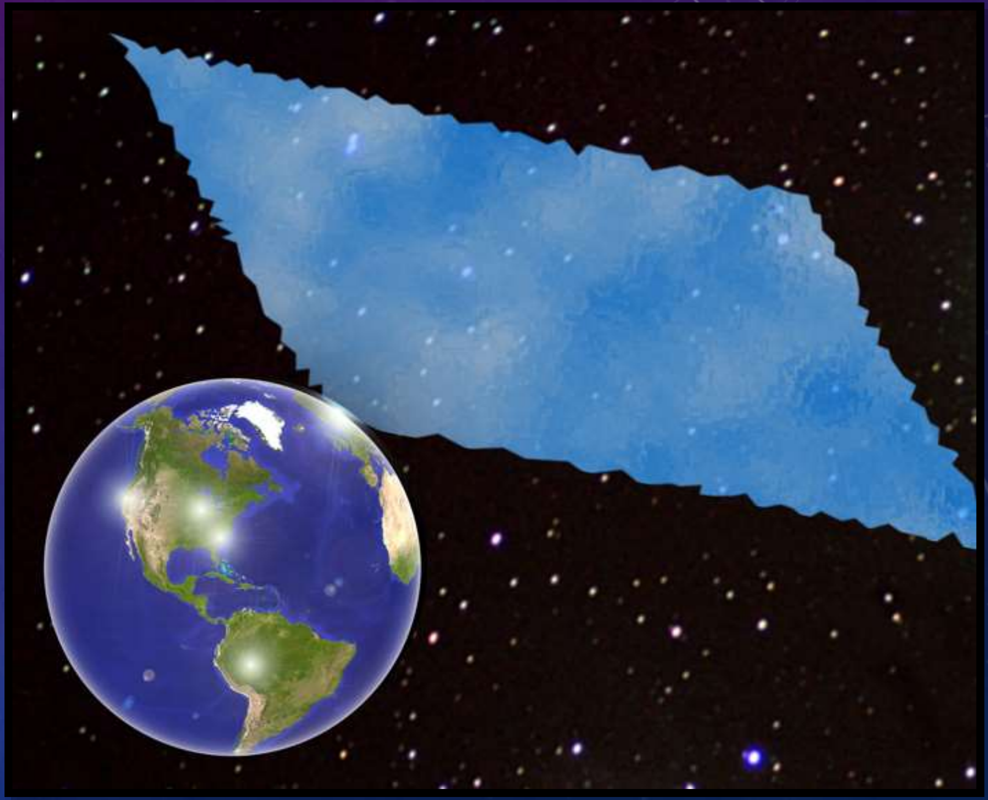
Global **N**etwork of **O**ptical **M**agnetometers to search for **E**xotic Physics **(GNOME)**

TRANSIENT SPIN INTERACTIONS

What can we say about exotic transient fields of astrophysical origin?

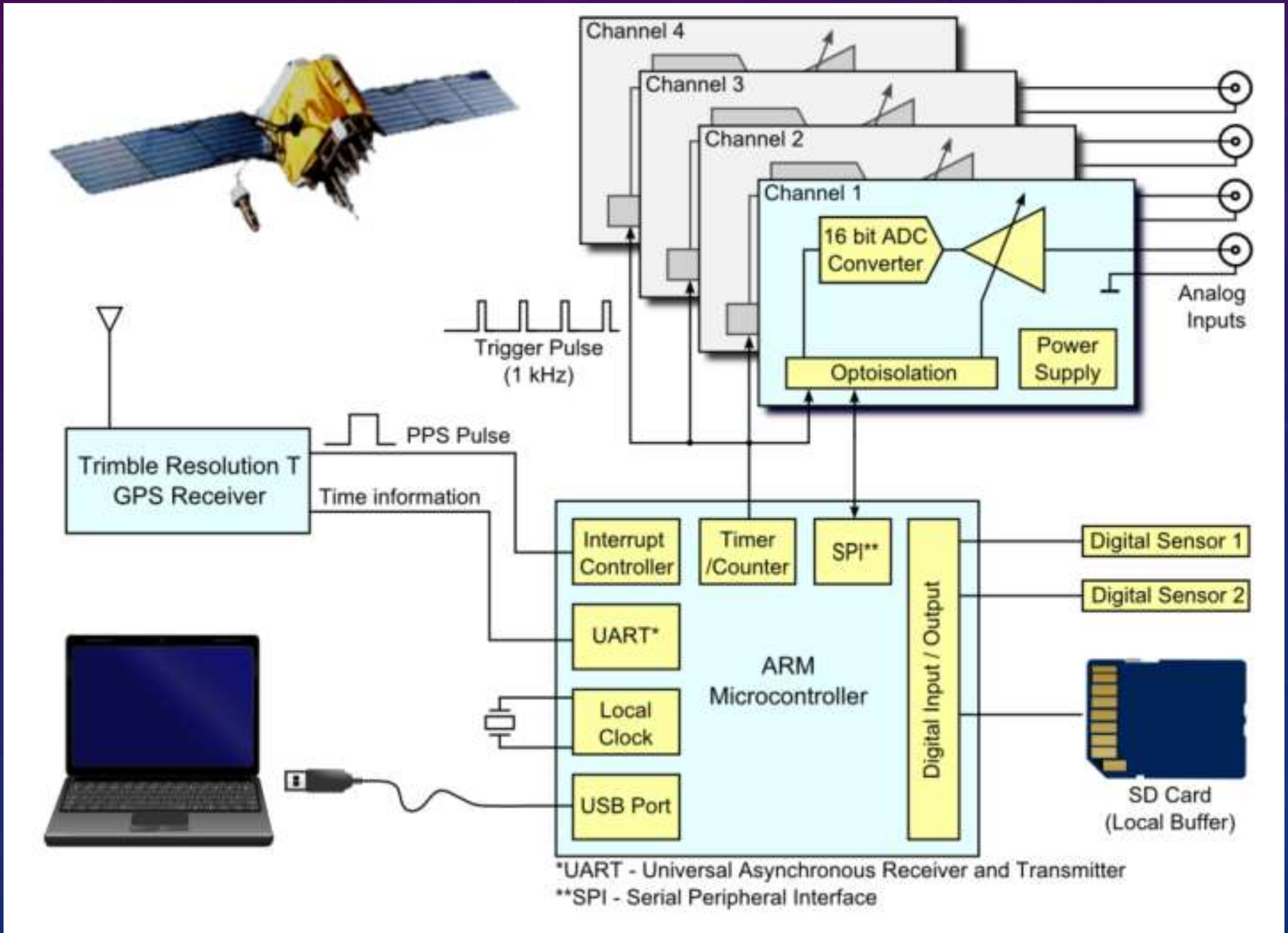
A transient event at a single sensor could not be distinguished from noise.

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

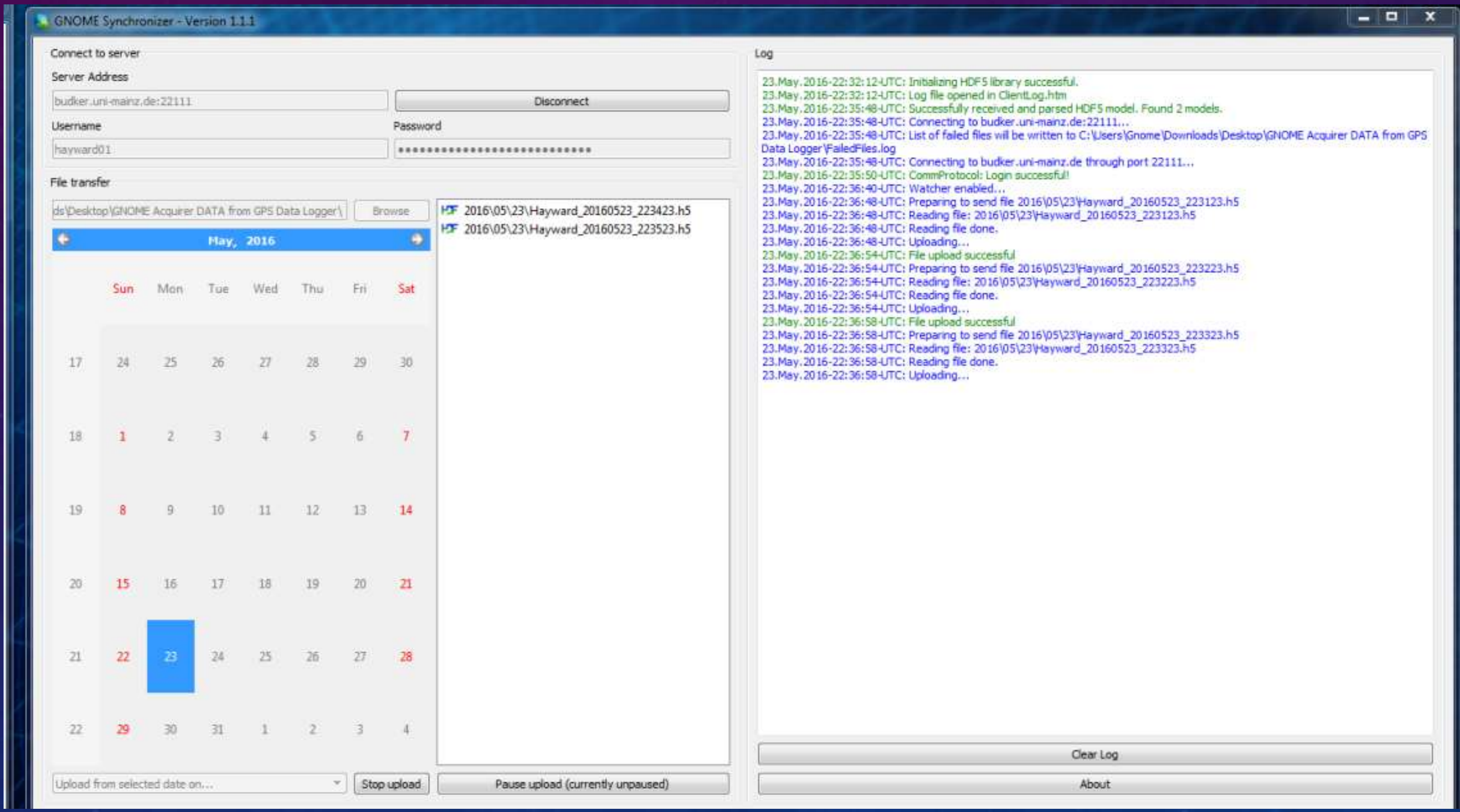


GNOME TODAY

GPS-DISCIPLINED DATA ACQUISITION

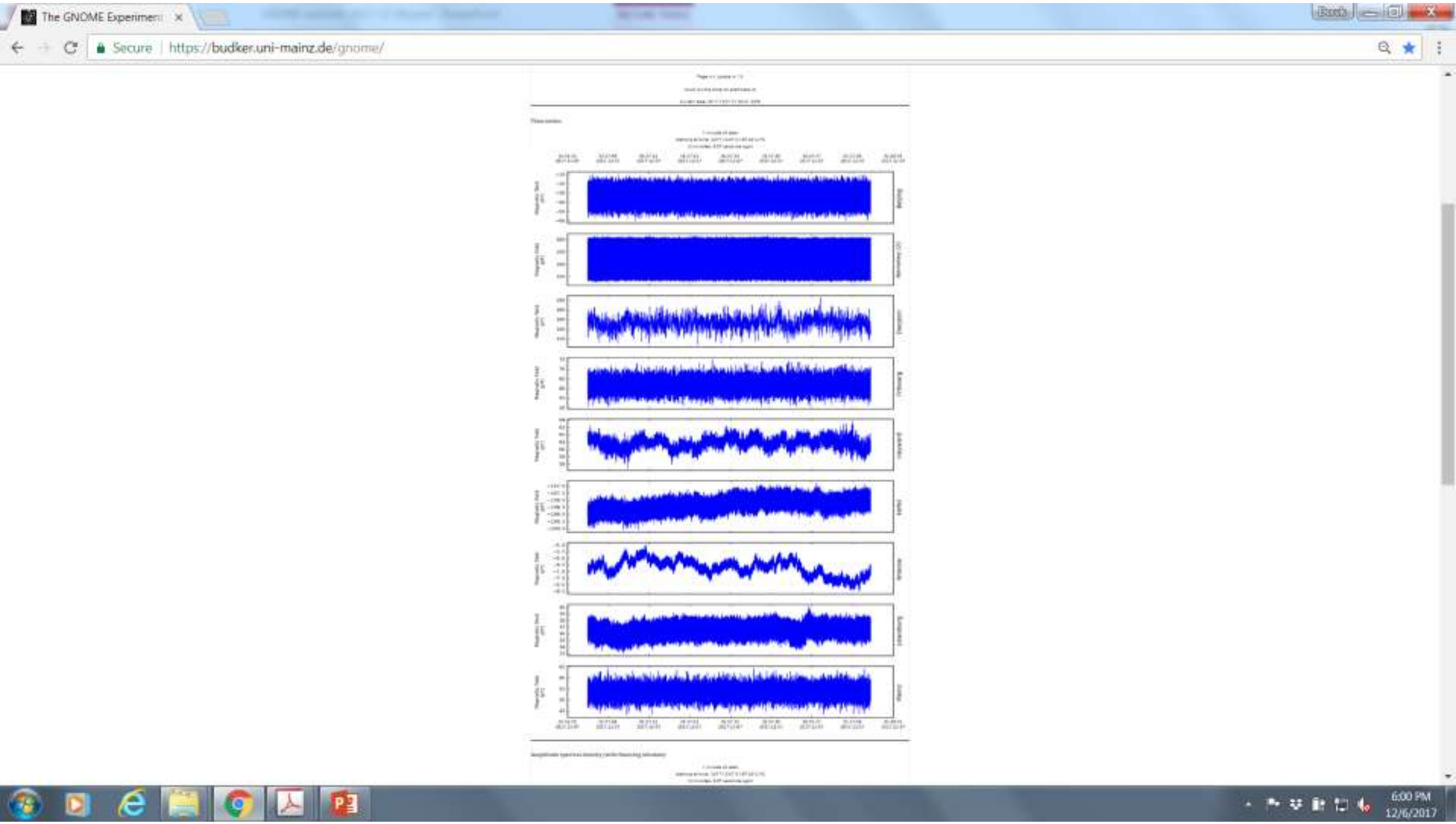


DATA TRANSFER TO SERVER IN MAINZ

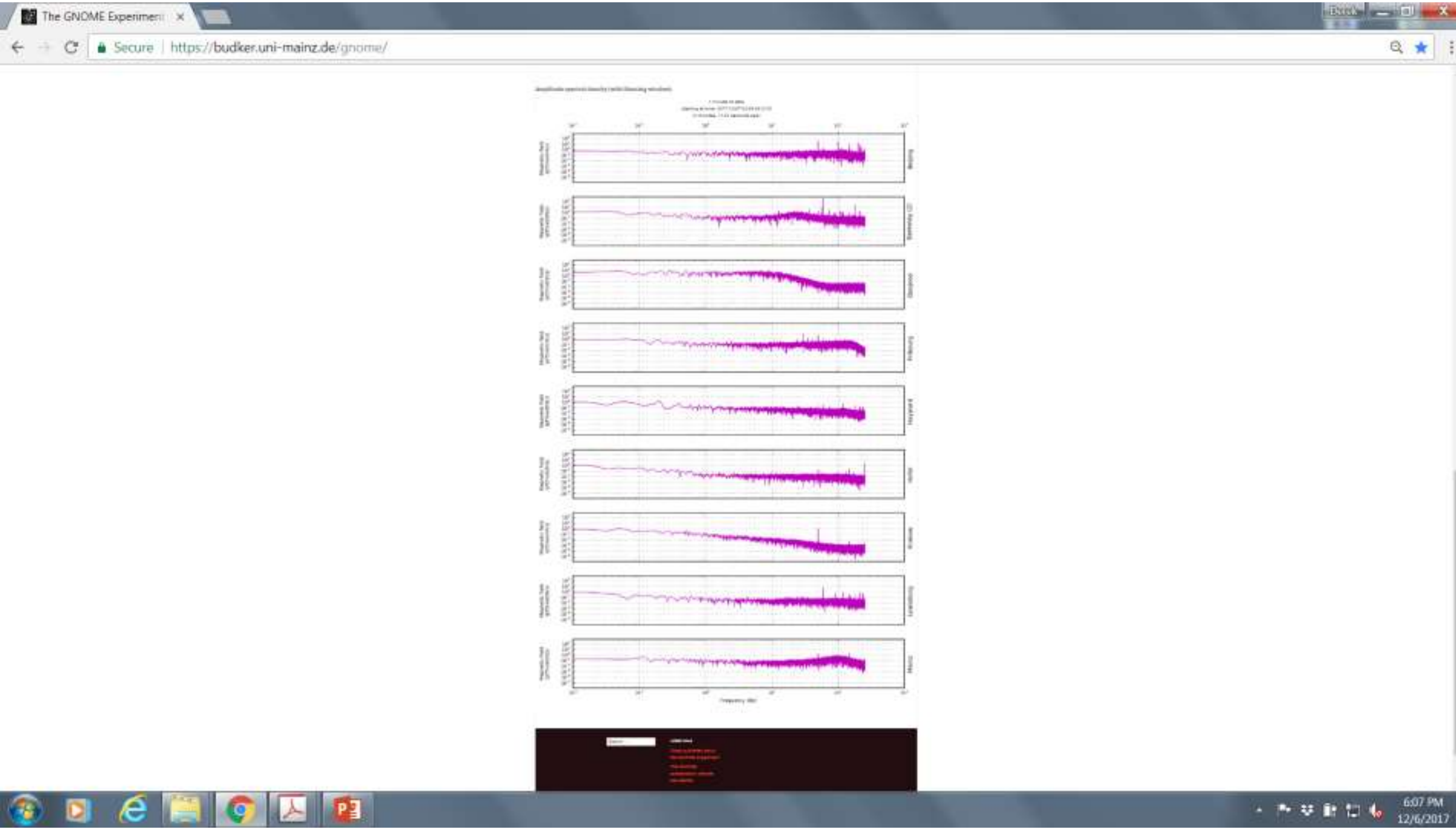


https://budker.uni-mainz.de/gnome/

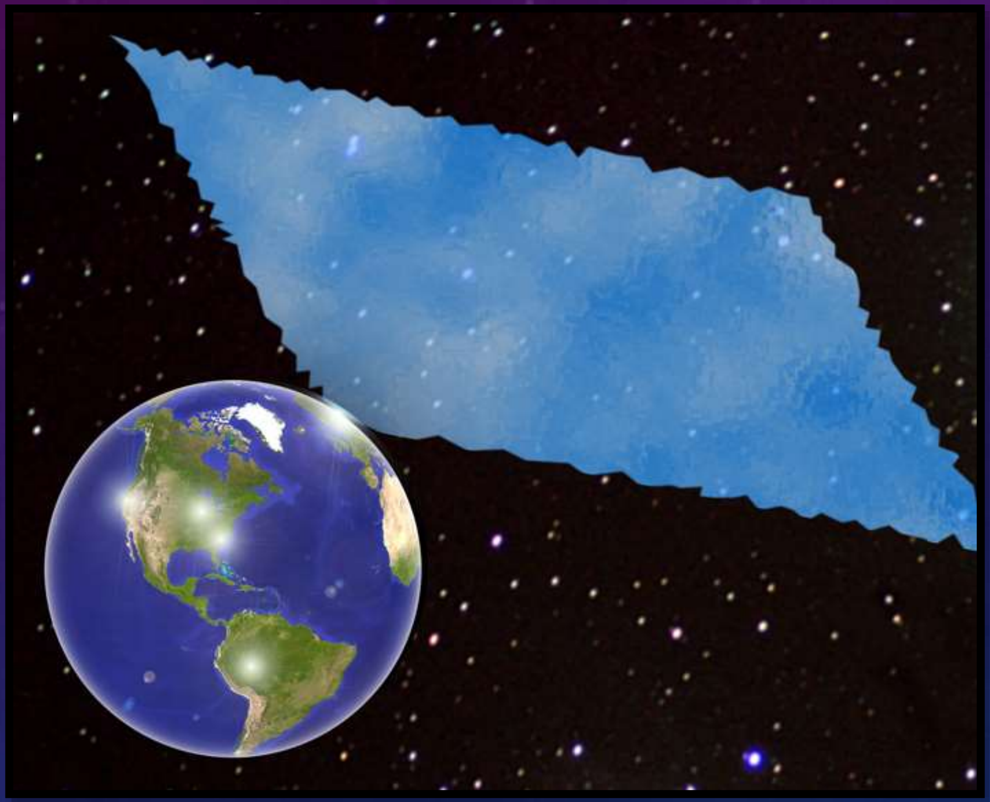
https://budker.uni-mainz.de/gnome/



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



SEARCH TARGETS



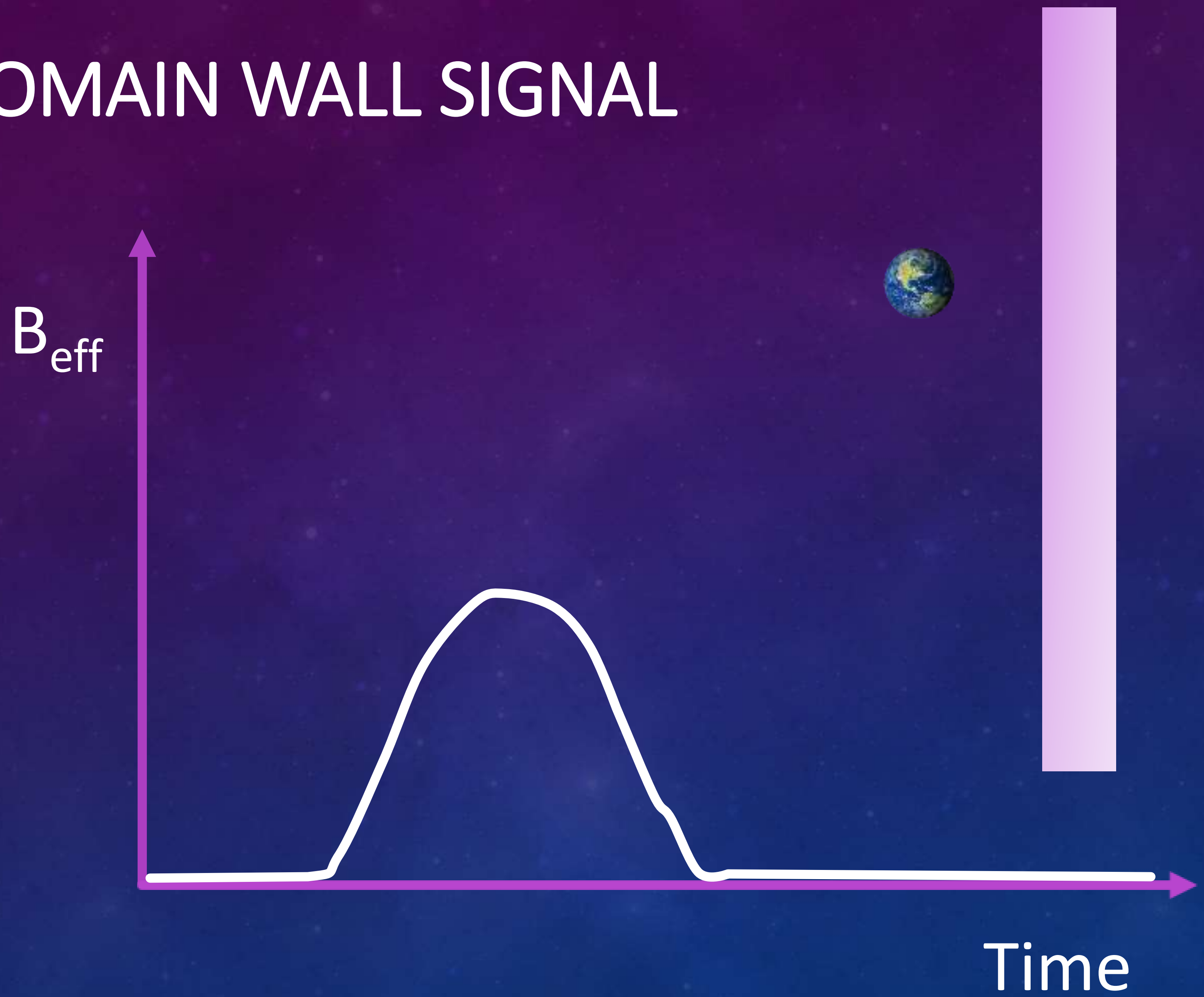
Initial GNOME research will focus on searches for compact dark matter objects composed of ALPs:

- ALP domain walls
- ALP stars

Future search targets:

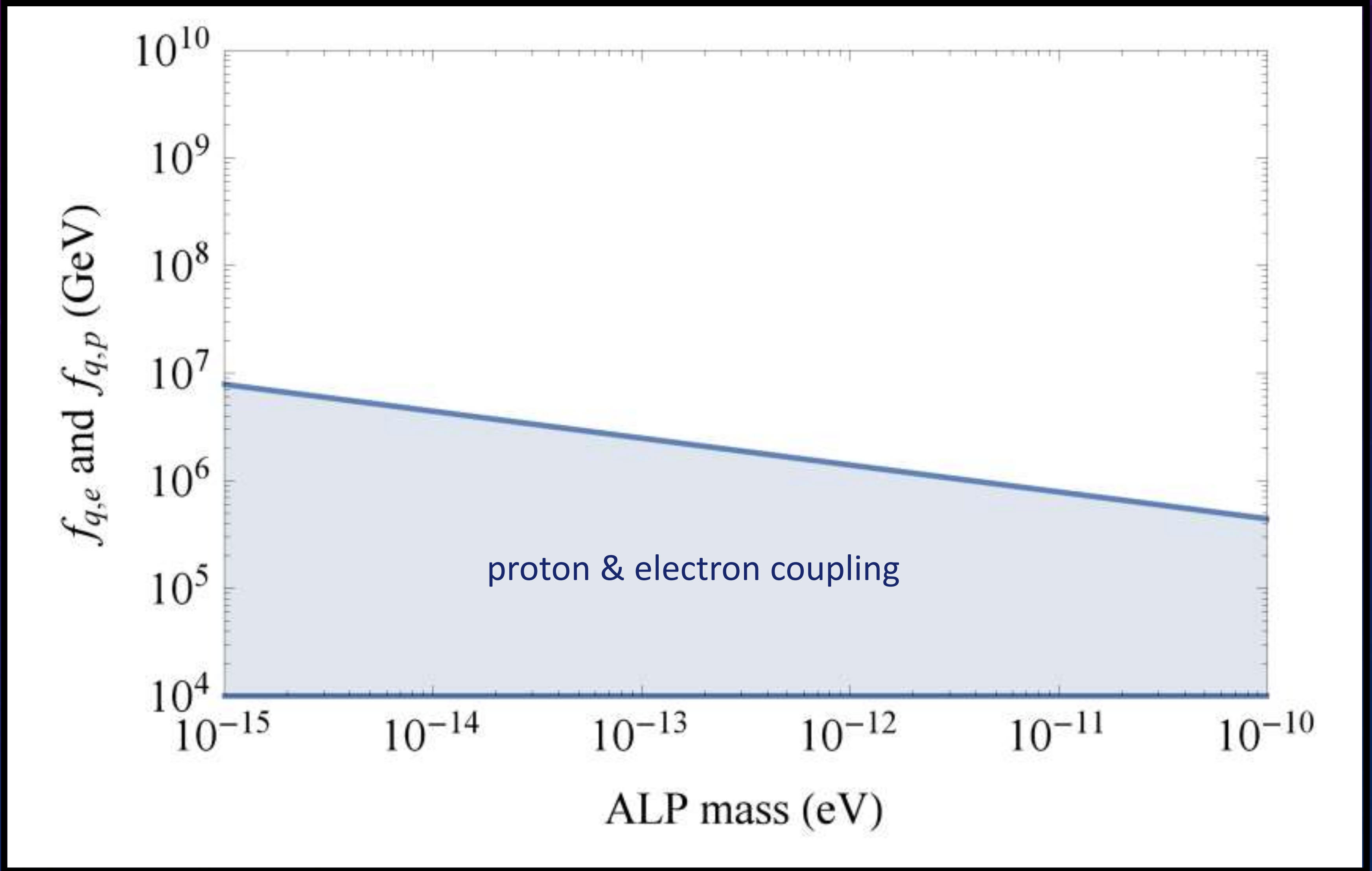
- ALP bursts from black holes, supernovae, neutron star mergers, fast radio bursts… ?
- Continuous oscillating signals
- Correlated stochastic background

DOMAIN WALL SIGNAL

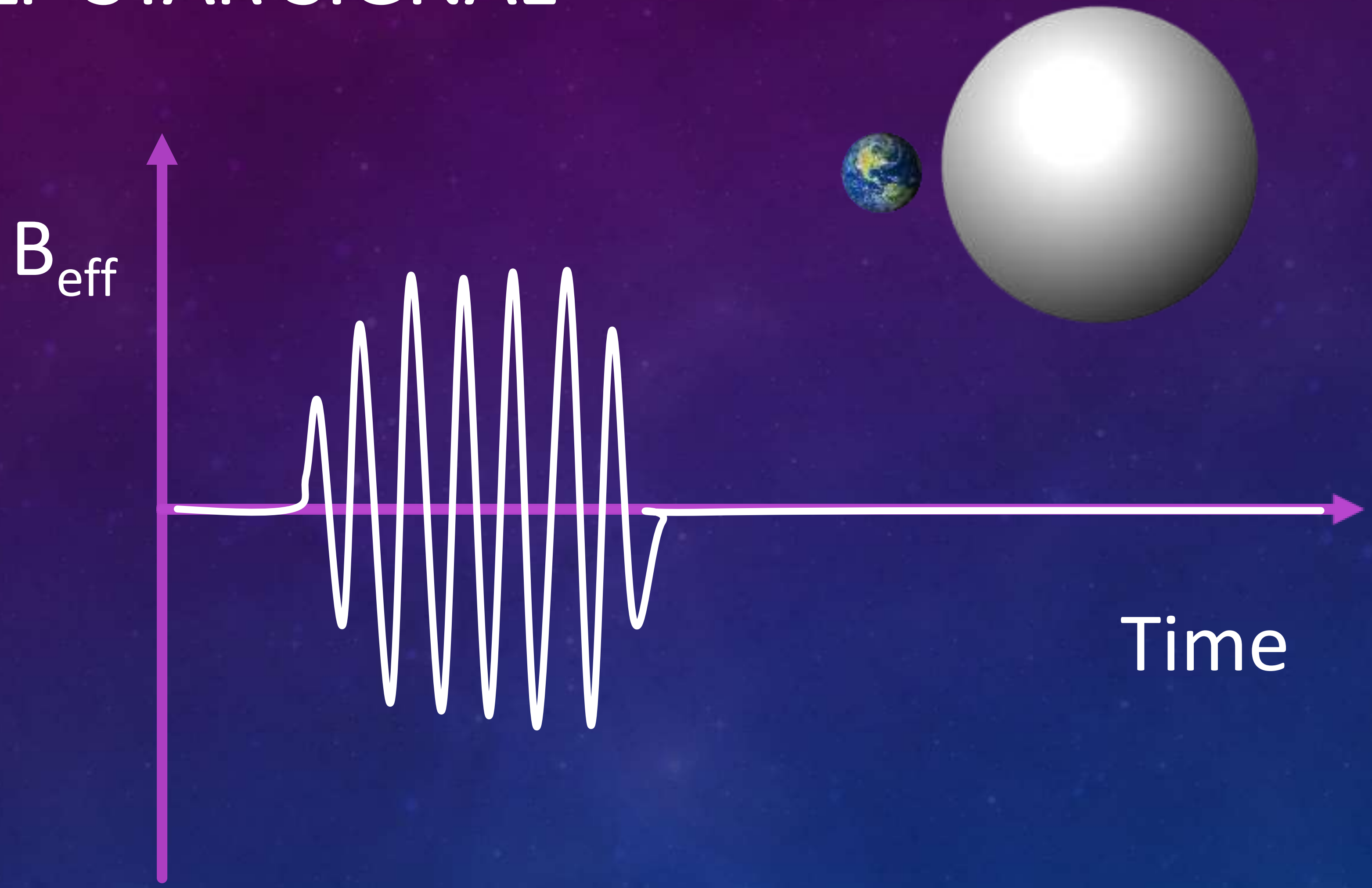


M. Pospelov et al., Phys. Rev. Lett. **110**, 021803 (2013).

ALP DOMAIN WALLS: QUADRATIC INTERACTION

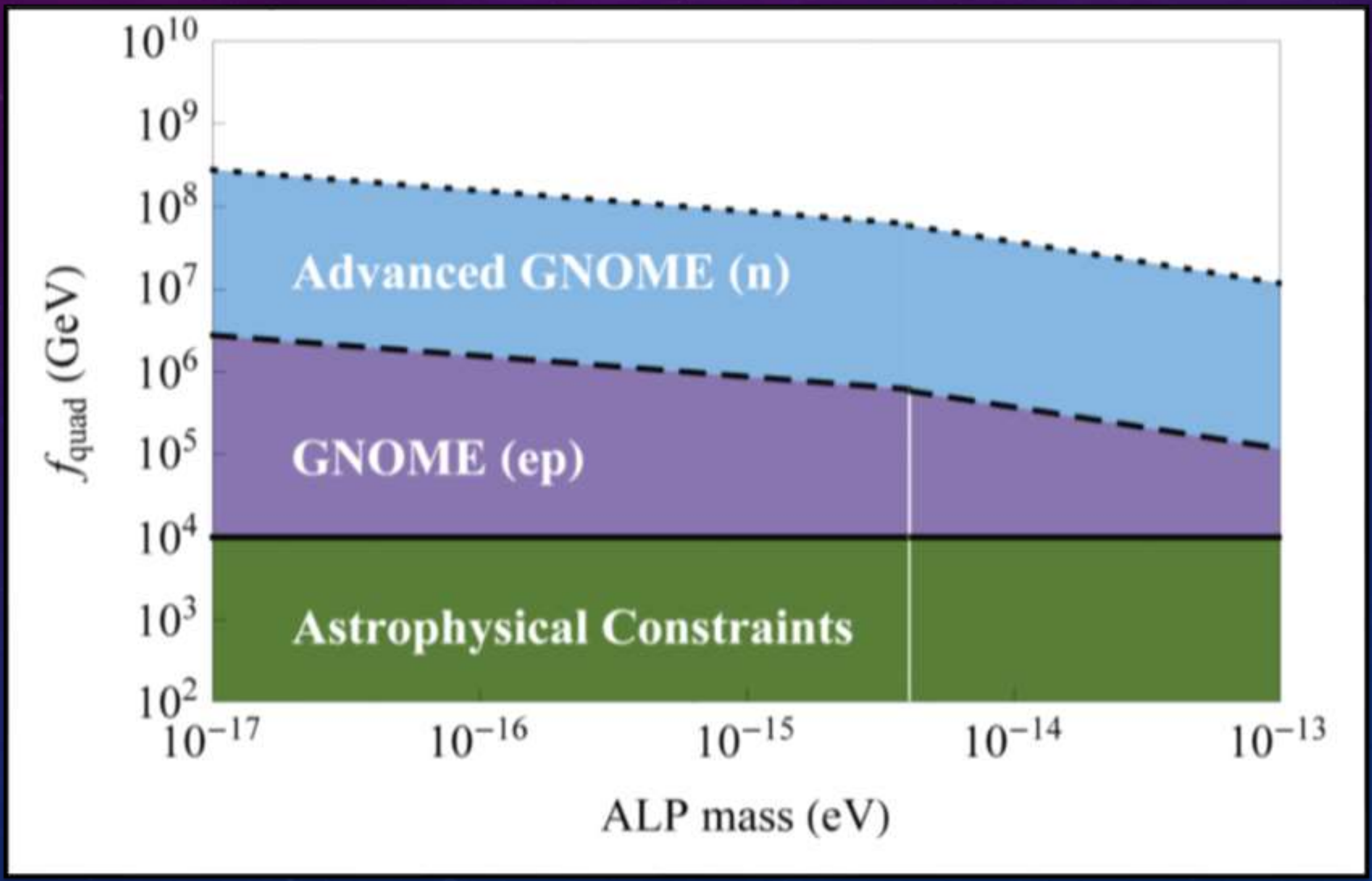


ALP STAR SIGNAL

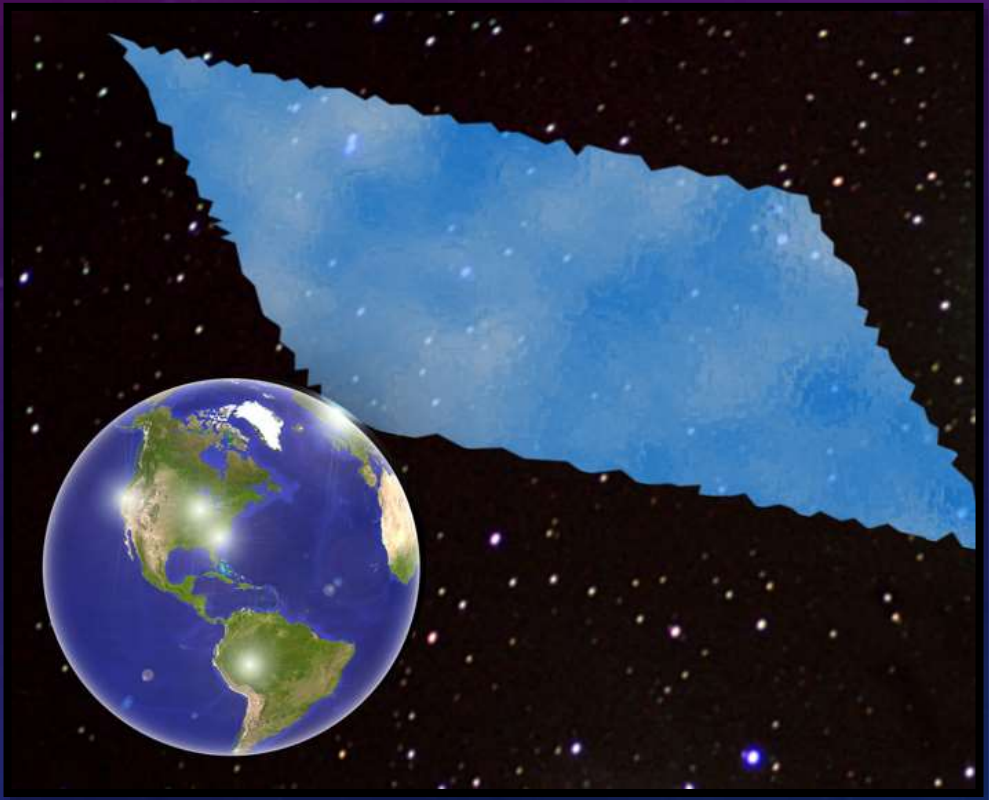


D. F. Jackson Kimball et al., arXiv:1710.04323 (2017).

ALP STARS QUADRATIC INTERACTION



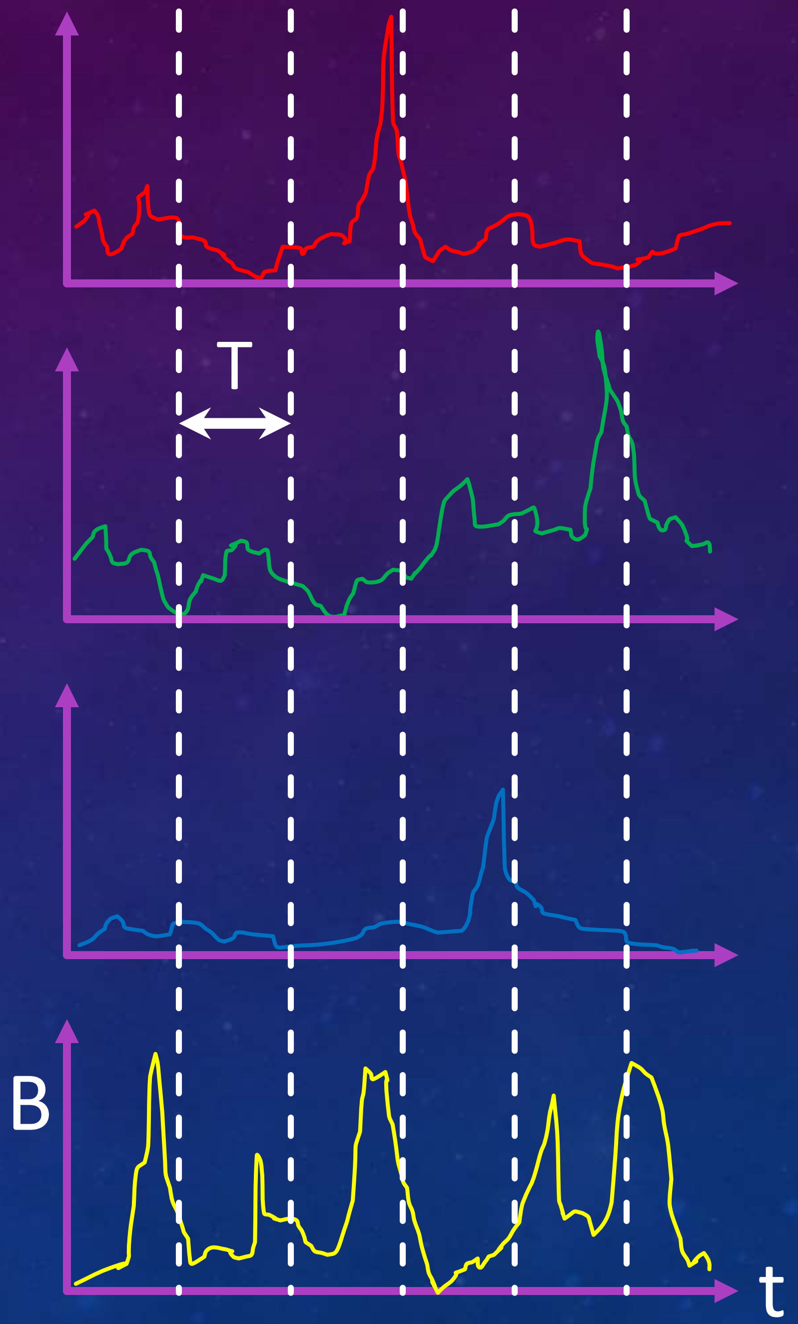
ANALYSIS: BASIC IDEA



- ALP domain walls: DC pulse.
- ALP stars: AC pulse.
- Coincidence analysis: look for common transient events within time window.
- Coherent analysis: look for transient events with consistent temporal delays & amplitudes for common wall velocity.
- Background: Foreground is compared to time-shifted background to determine event significance, set limits.

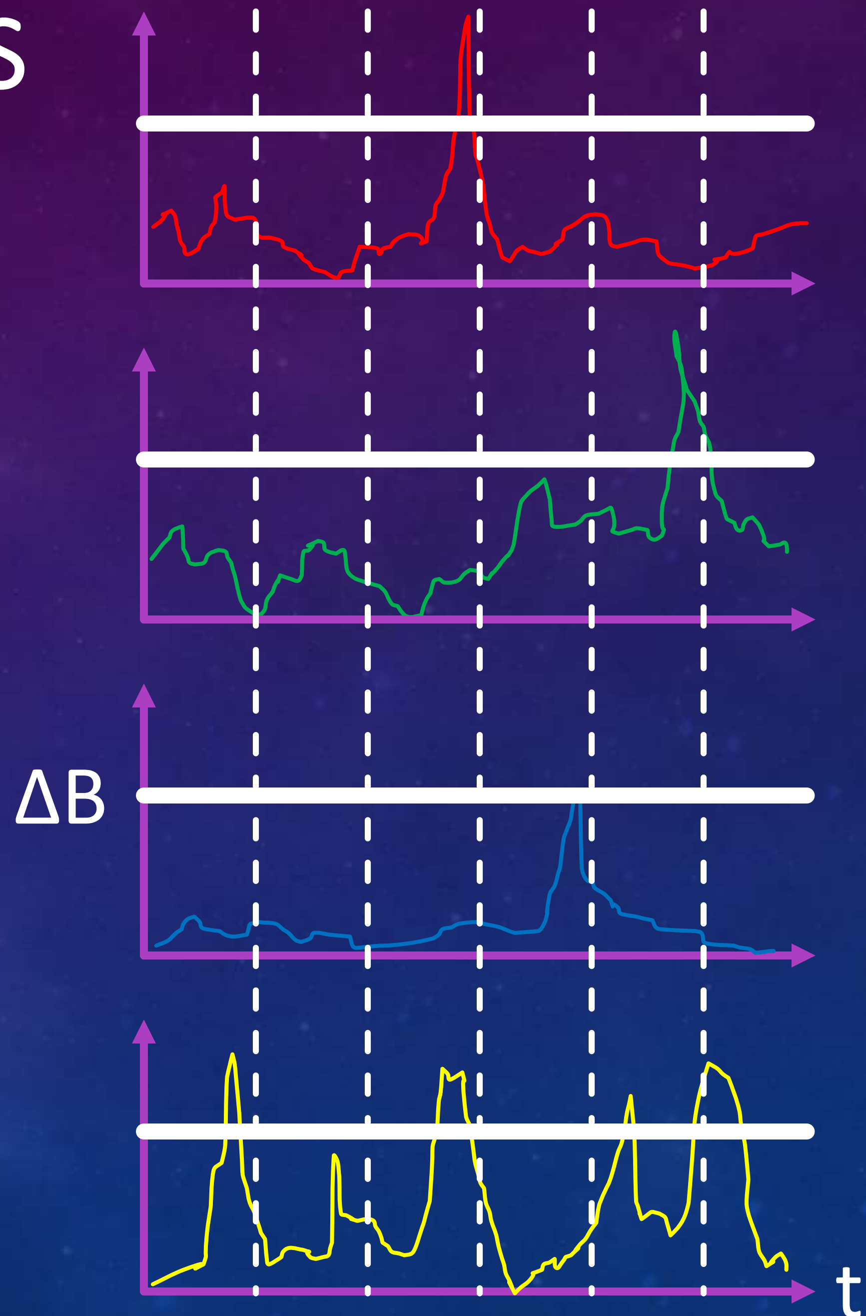
COINCIDENCE ANALYSIS

- Define **time window**: all magnetometers should see signal within $T \approx 2R_E/v$.



COINCIDENCE ANALYSIS

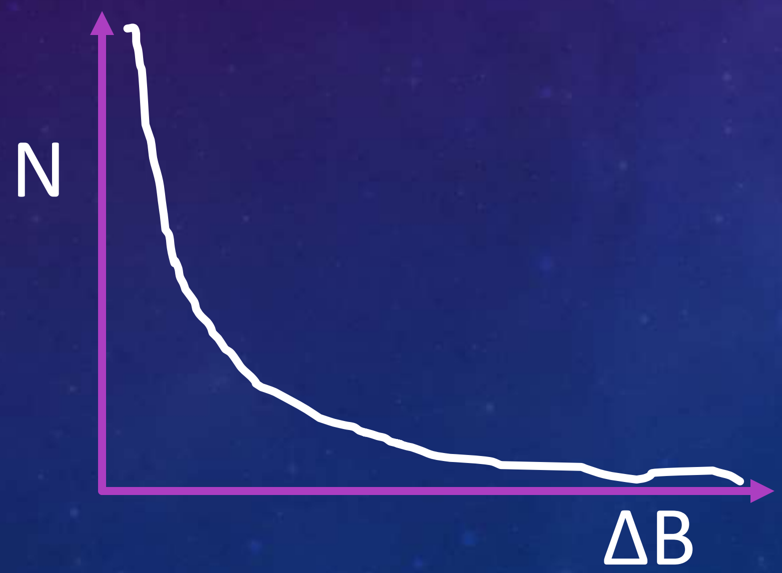
- **<u>Time window</u>**: all magnetometers should see signal within $T \approx 2R_E/v$.
- **<u>Threshold</u>**: find magnetometers with signals above threshold ΔB in each window.

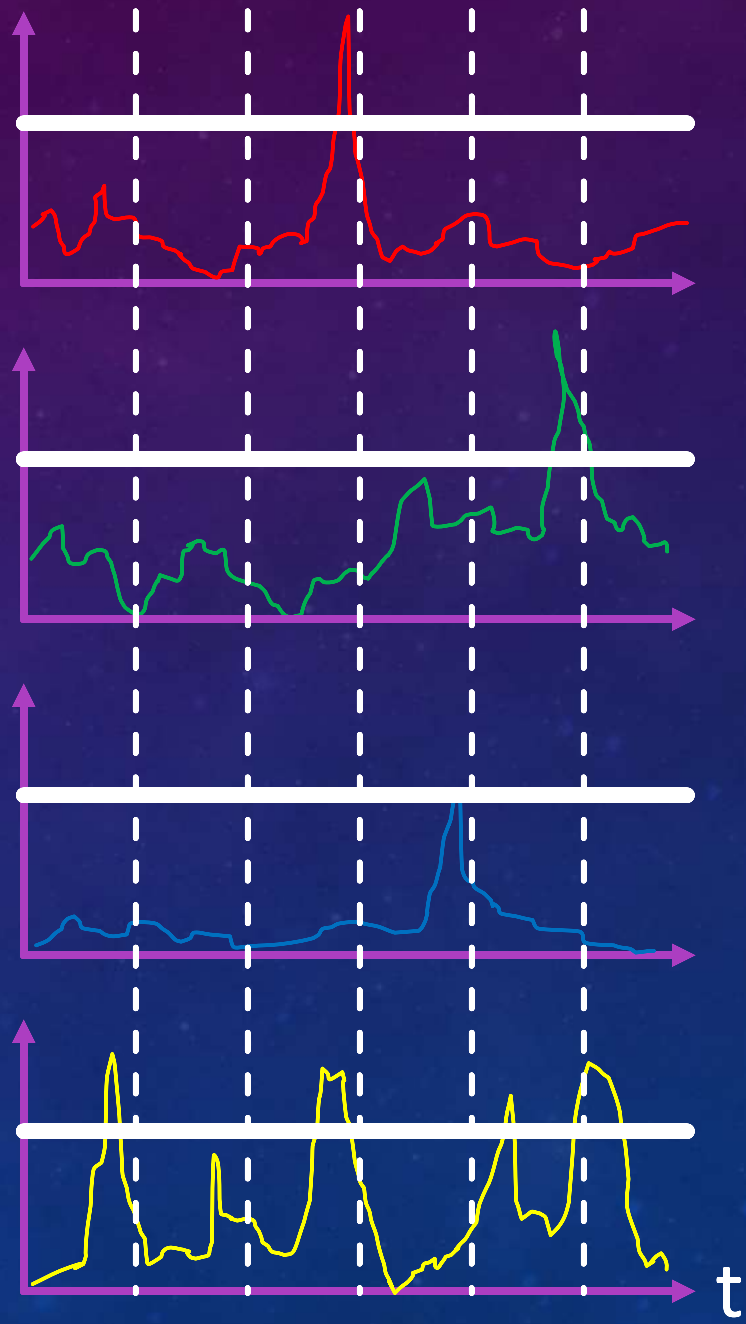


COINCIDENCE ANALYSIS

- **Time window**: all magnetometers should see signal within $T \approx 2R_E/v$.

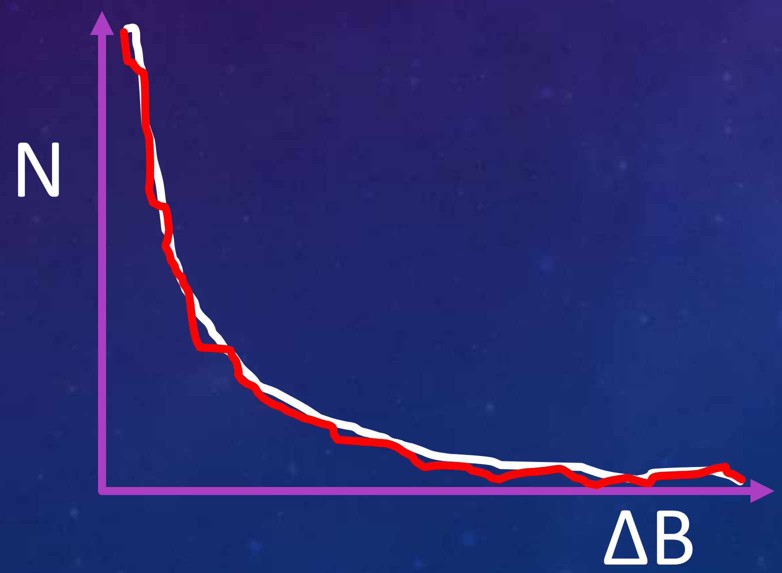
- **Threshold**: find magnetometers with signals above threshold ΔB in each window.

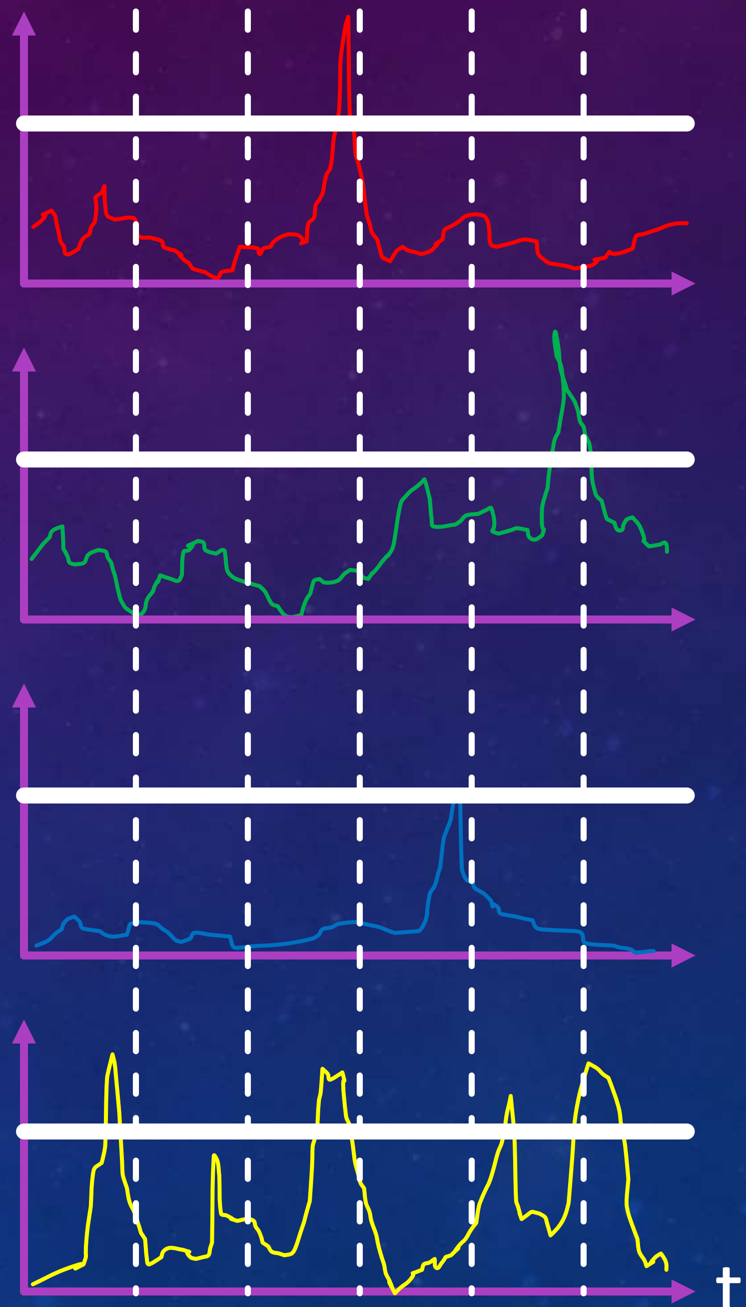




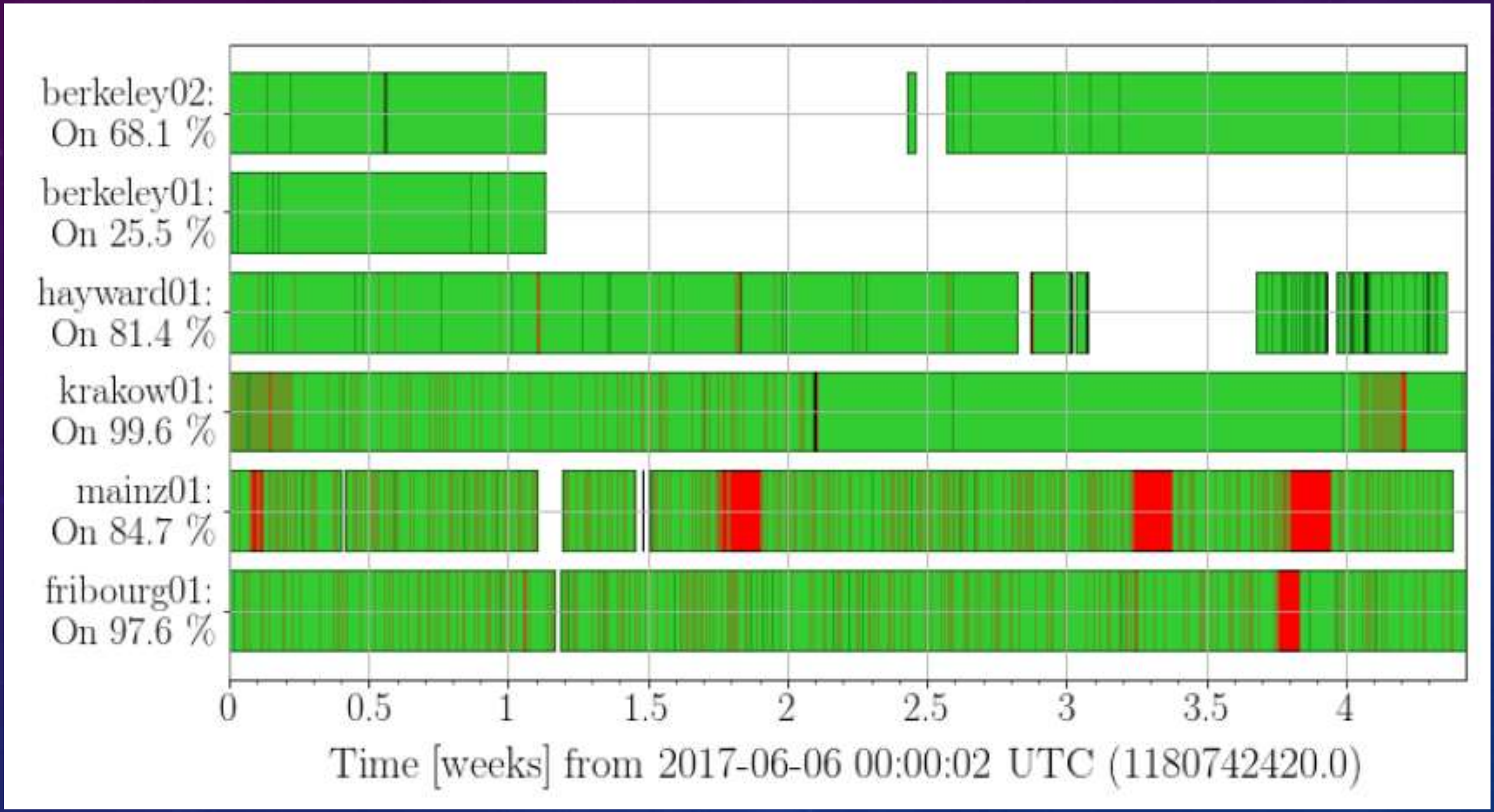
BACKGROUND

- Time shift data sets >> T.
- Count coincidences.

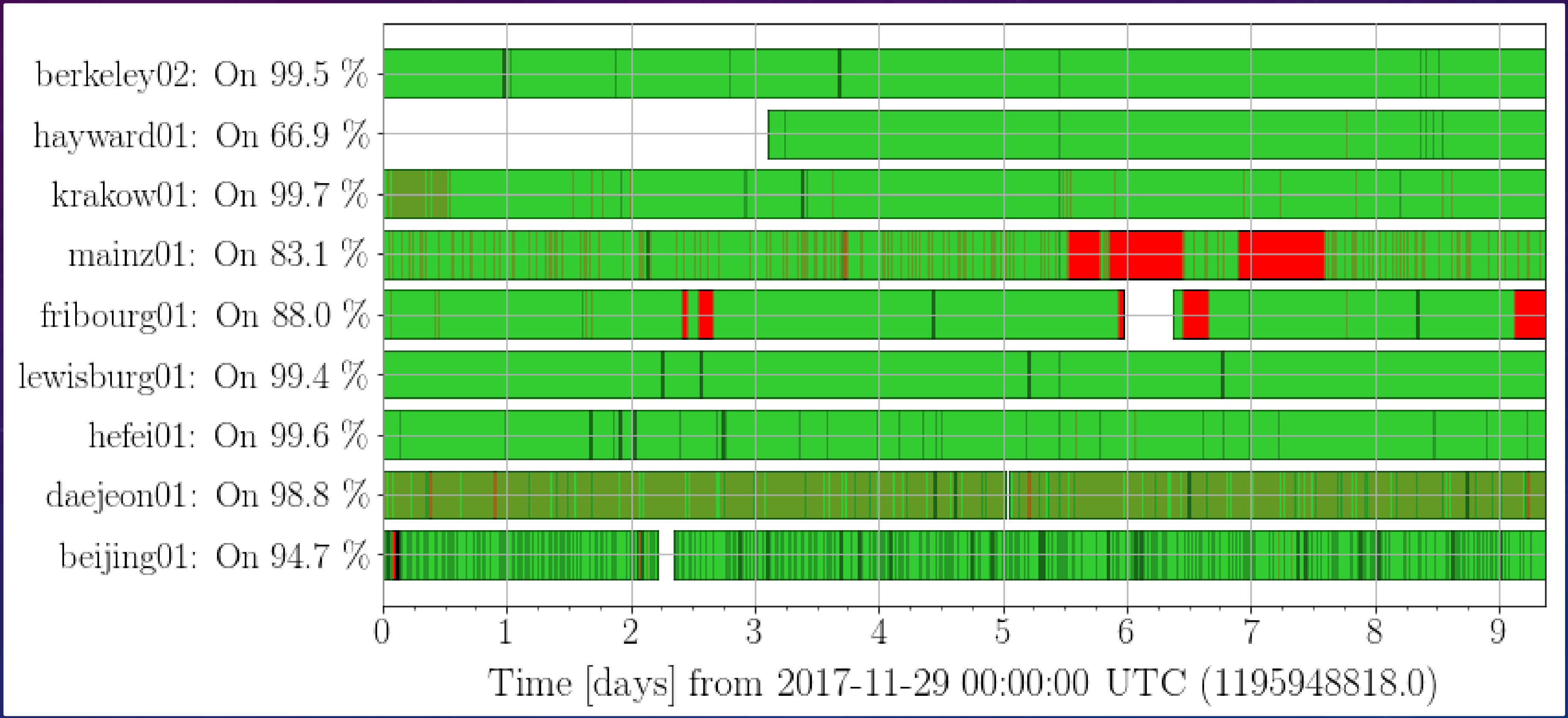




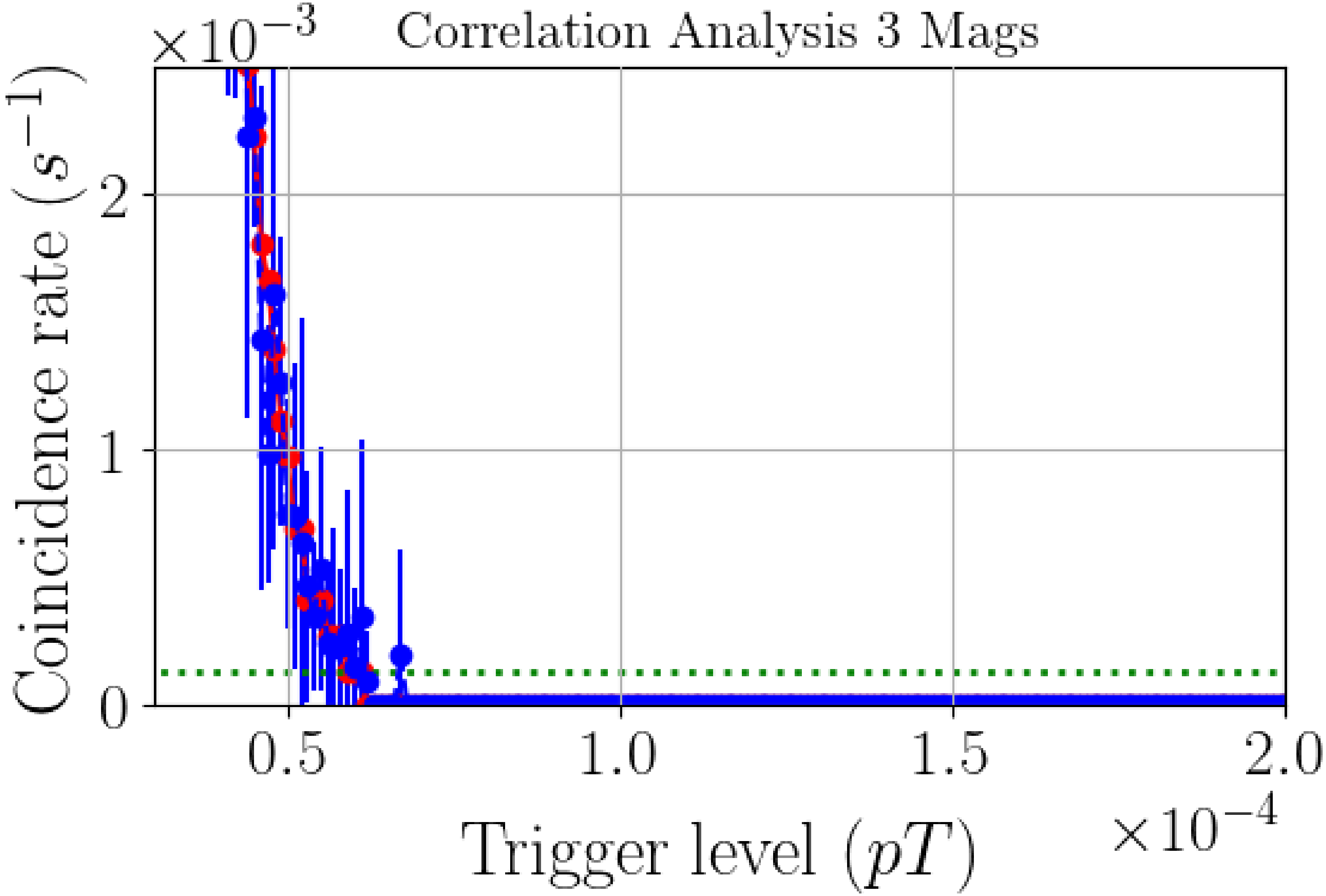
SCIENCE RUN 1: JUNE 2017



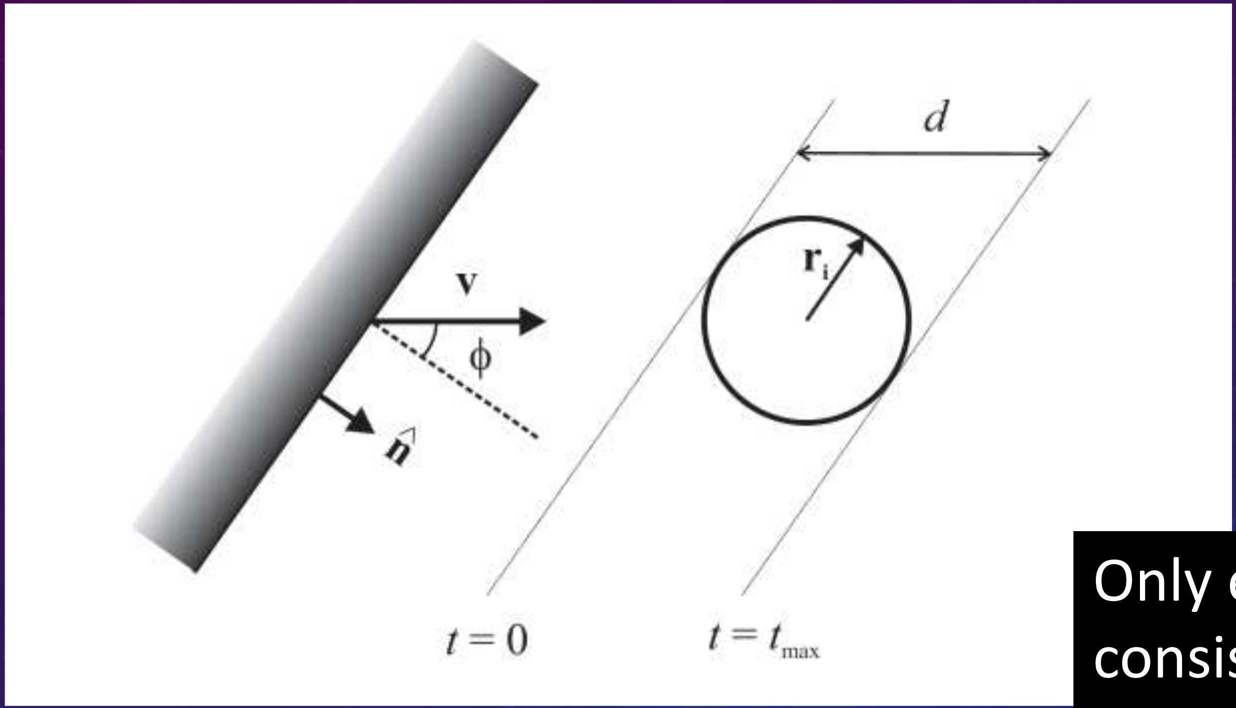
SCIENCE RUN 2: NOW!



SCIENCE RUN 1: JUNE 2017



COHERENT ANALYSIS



$$t_i = \frac{R_E}{\mathbf{v} \cdot \hat{\mathbf{n}}}\left(1 + \frac{\mathbf{r}_i \cdot \hat{\mathbf{n}}}{R_E}\right)$$

Only events that are consistent with single values of **v** and **n** are counted.

Significantly lowers background for N > 4 stations!

COHERENT VS. COINCIDENT ANALYSIS

Background coincident event rate $\Gamma(\Delta B)$.

Background coherent event rate = $\Gamma(\Delta B) \times (dt/\tau)^{N-4}$
where τ is the average time between spikes of size ΔB for the magnetometers and $dt \approx 10\text{ms}$ is the GNOME time resolution.

More geographically separated stations & new coherent analysis tools will be powerful!

Thank you!!!