CASPEr: the Cosmic Axion Spin Precession Experiment

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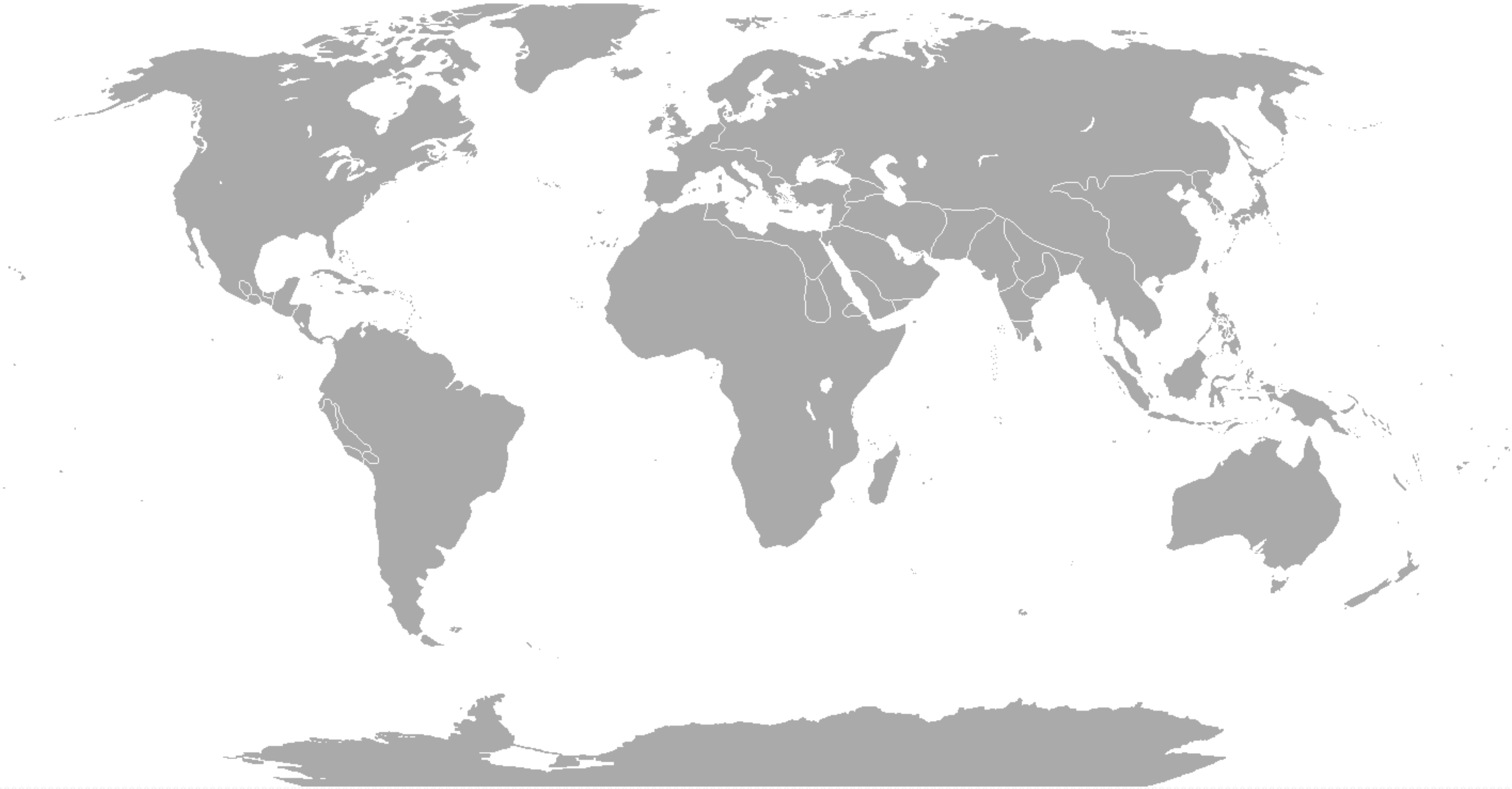

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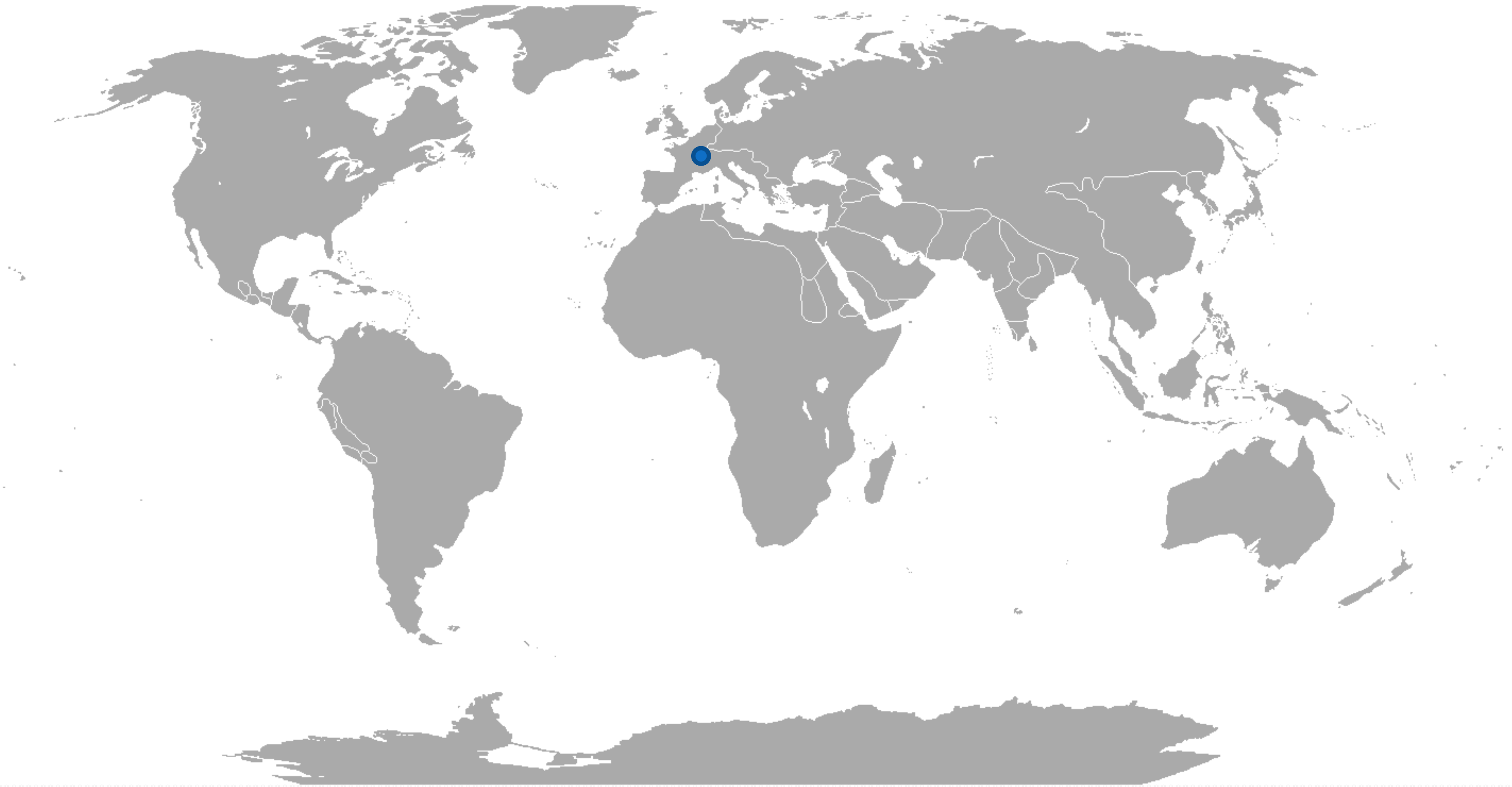

Collaboration

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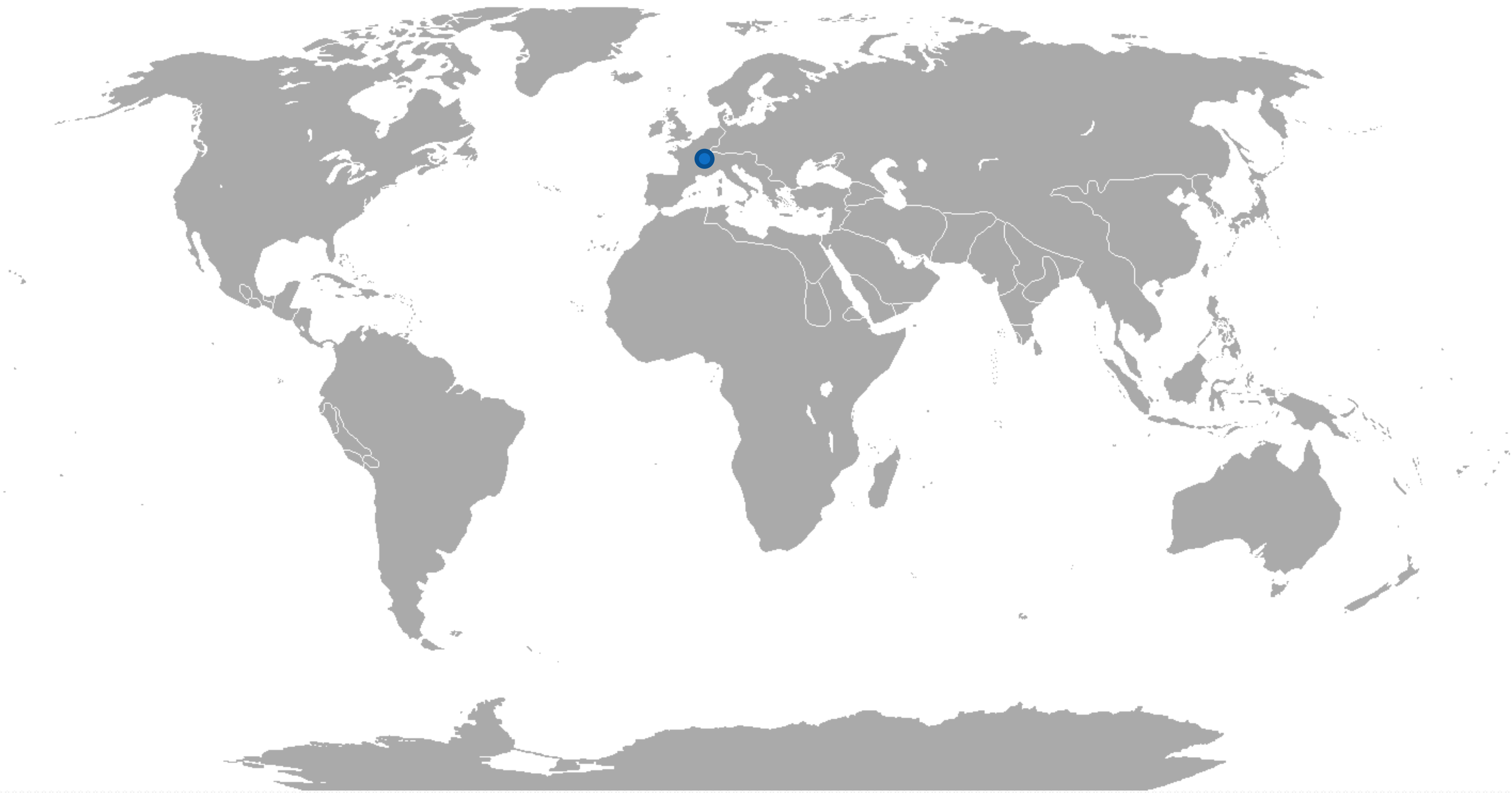

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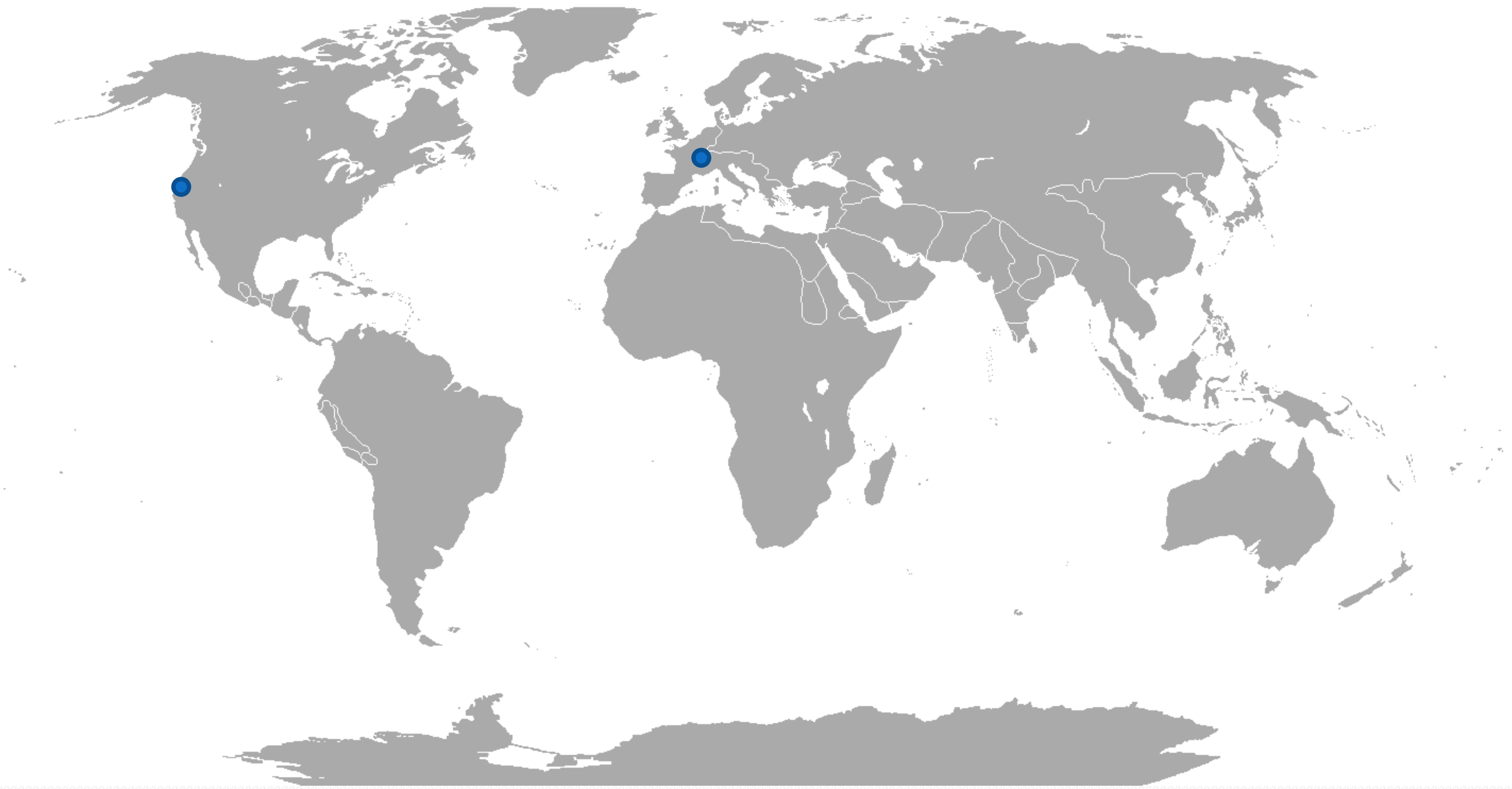

Collaboration

Surjeet Rajendran,
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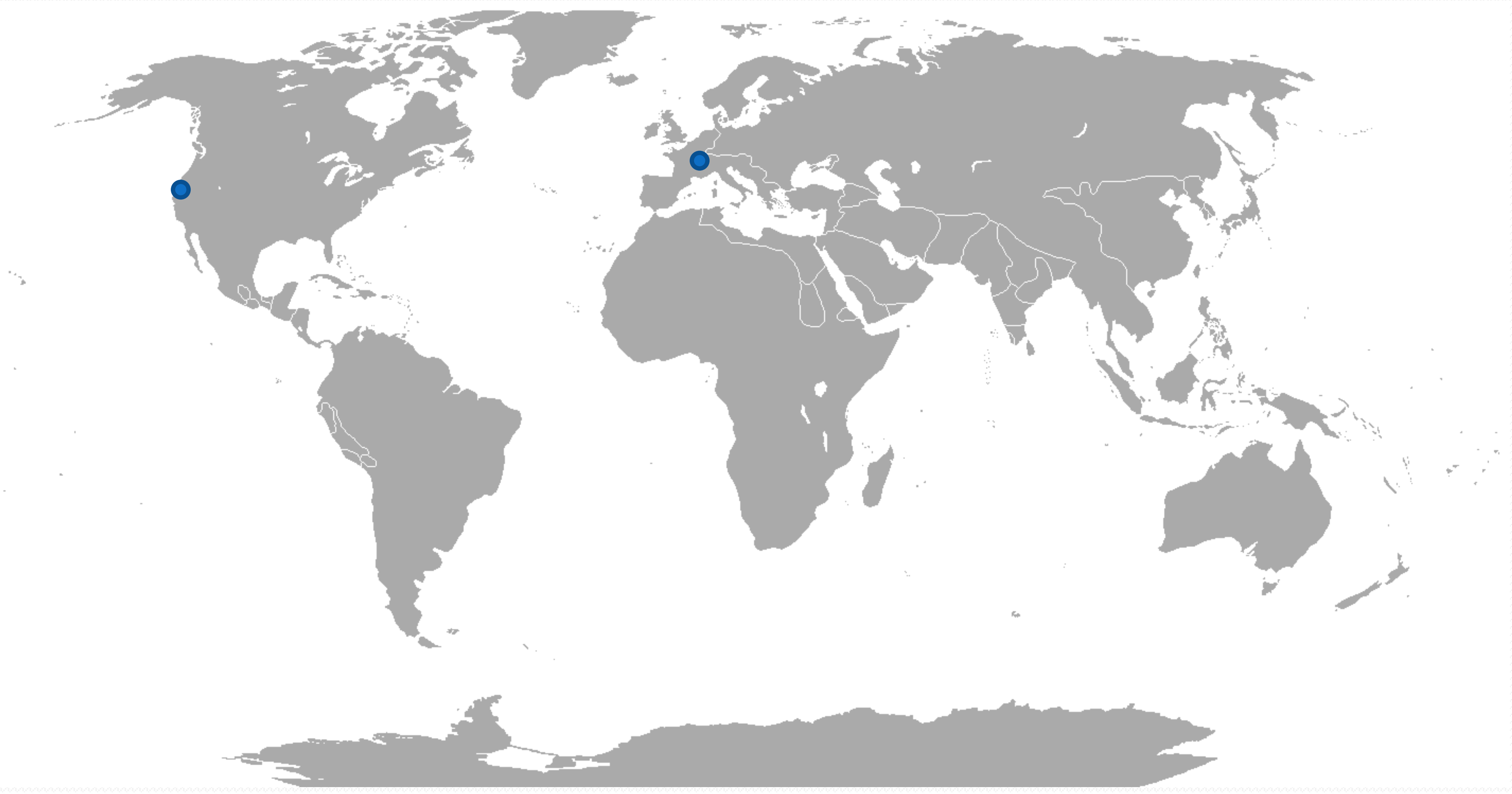
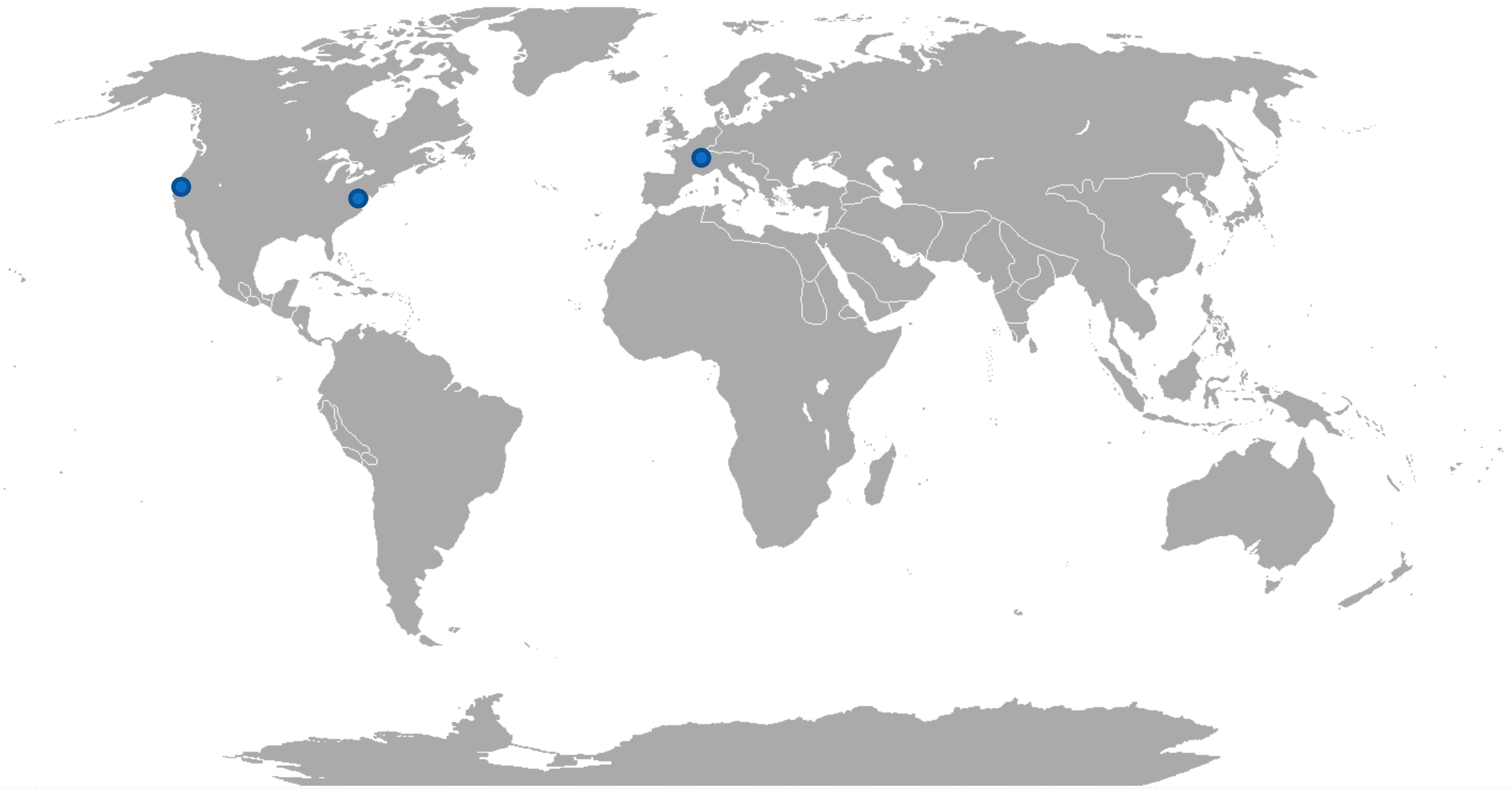
Peter Graham (Stanford),
Derek Kimball (CSUEB)

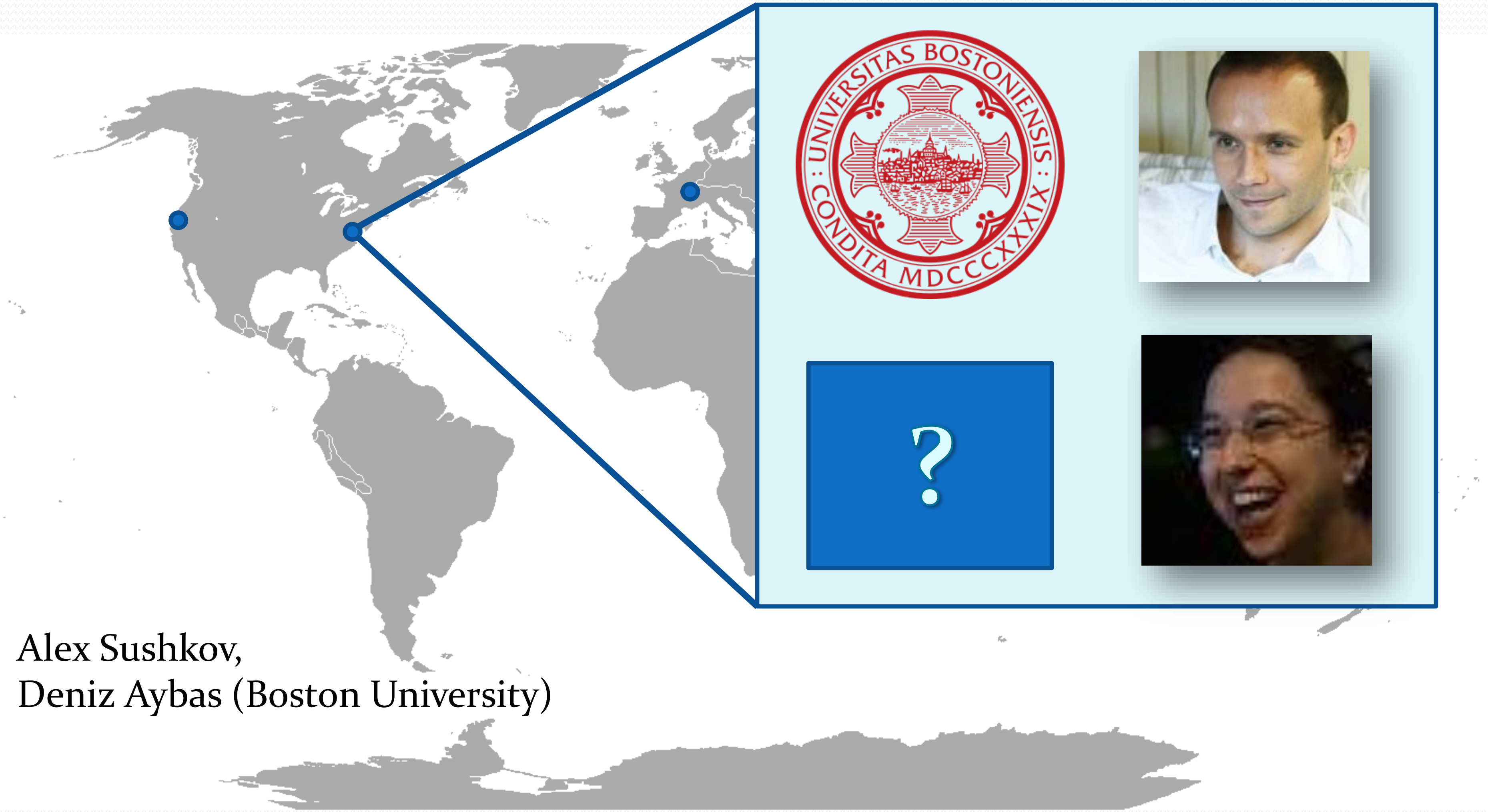
Collaboration



Collaboration

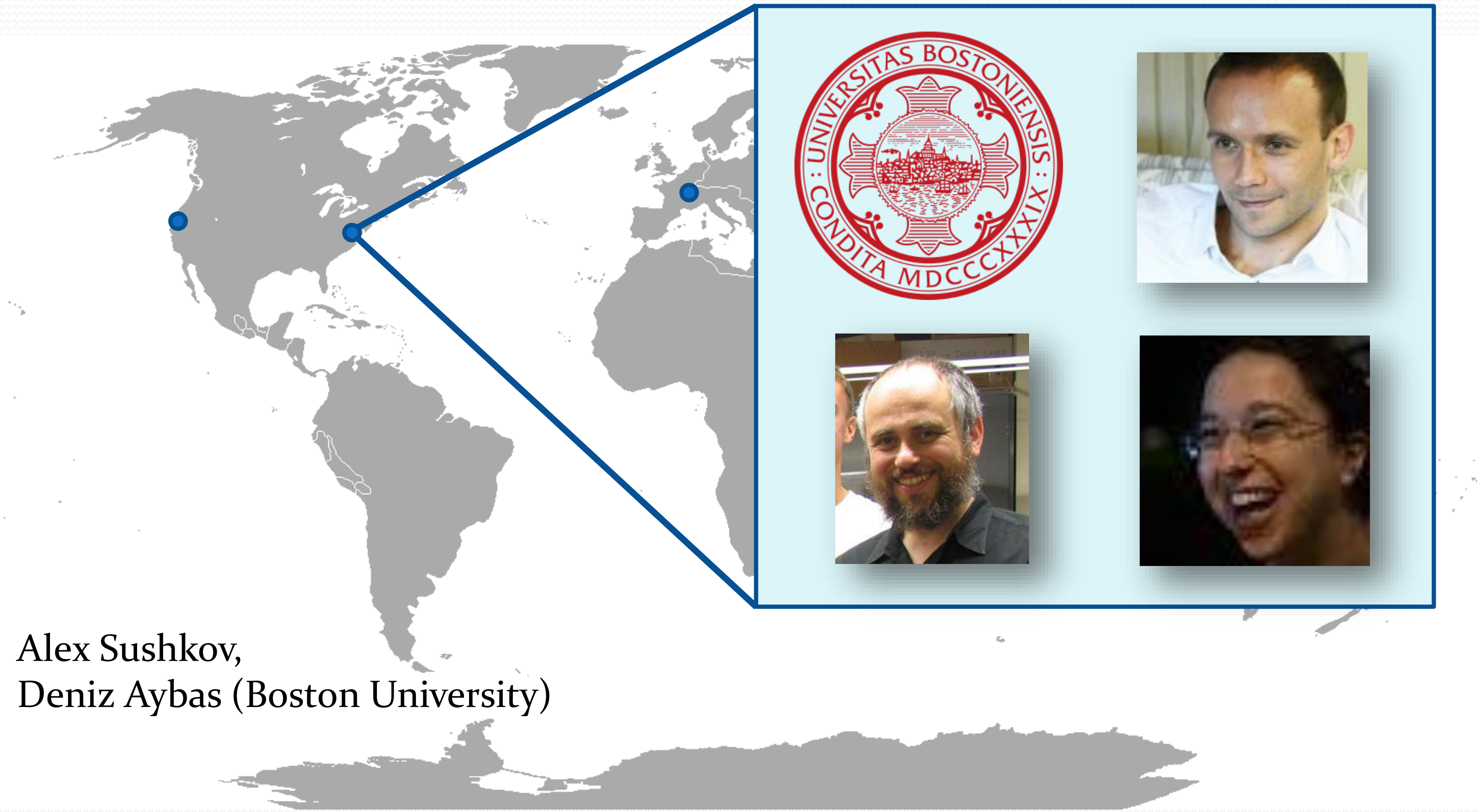


Collaboration



Alex Sushkov,
Deniz Aybas (Boston University)

Collaboration

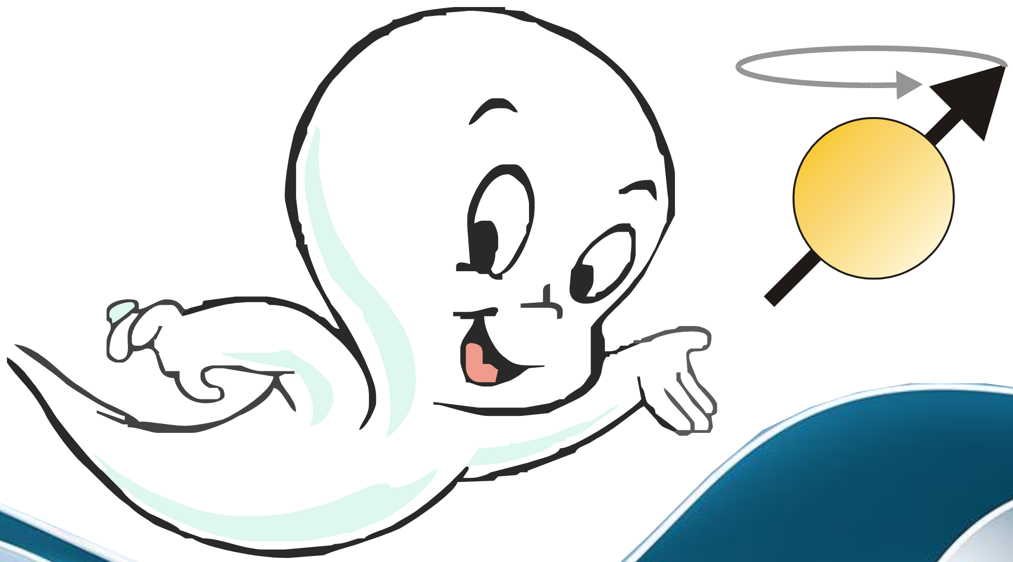


Alex Sushkov,
Deniz Aybas (Boston University)

Outline

- Motivation and theory;
- CASPEr Electric;
- CASPEr Wind;
- New idea: a precessing ferromagnetic needle;
- Conclusions.

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)

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(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.

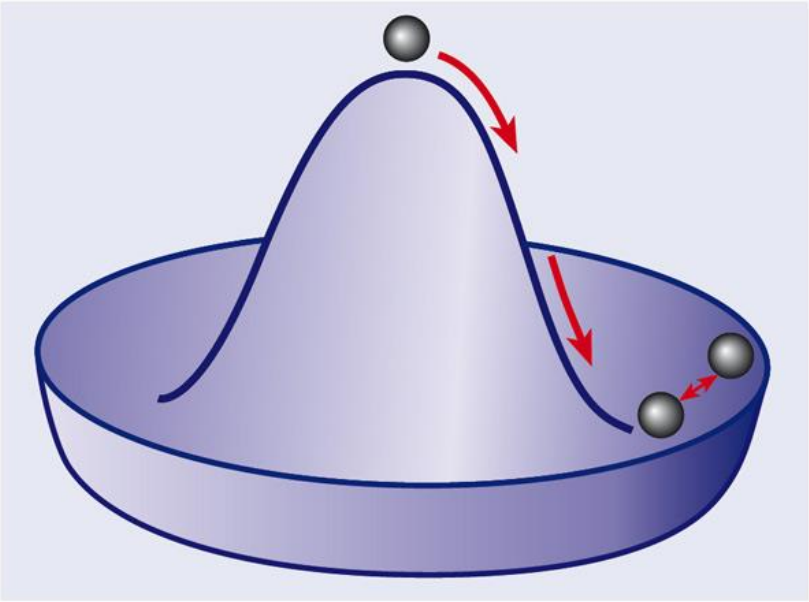
DOI: 10.1103/PhysRevX.4.021030 Subject Areas: Cosmology

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

Motivation and theory

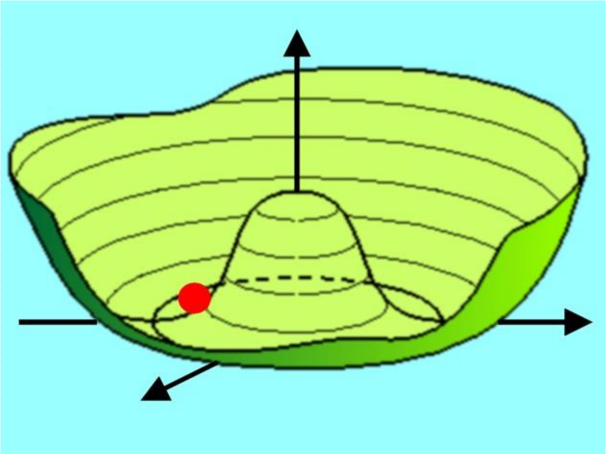
Axions

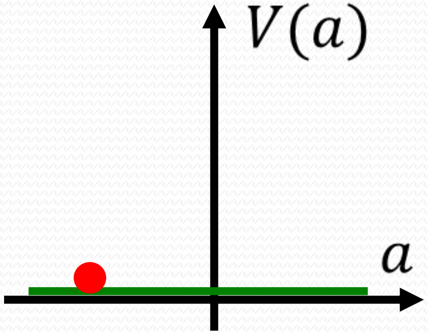
Axions and axion-like particles (ALPs) are pseudo-Goldstone bosons of global symmetries broken at an energy scale f_a.



Axions: misalignment

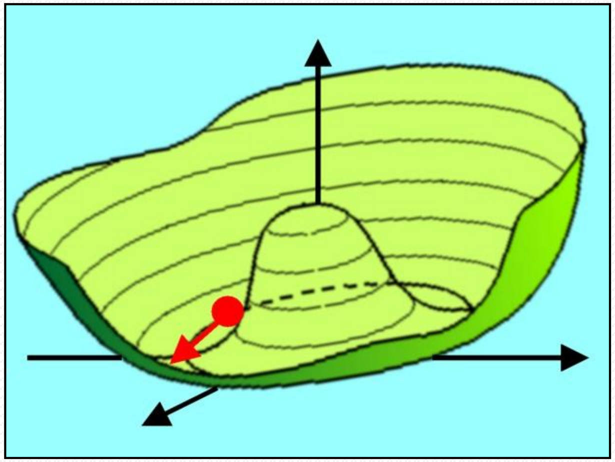
When axions are produced after the Big Bang upon the breaking of the global symmetry, they are initially massless and can take on any initial field value a_0.

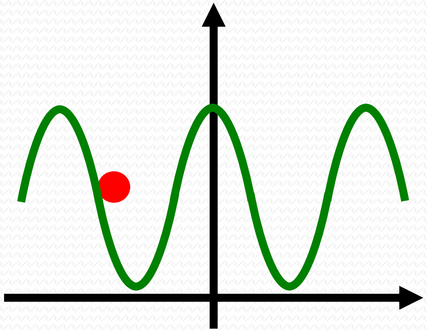




Axions: misalignment

However, when non-perturbative effects due to, for example, QCD become important, a potential develops for the axion.





Axion mass

The QCD axion mass is given by:

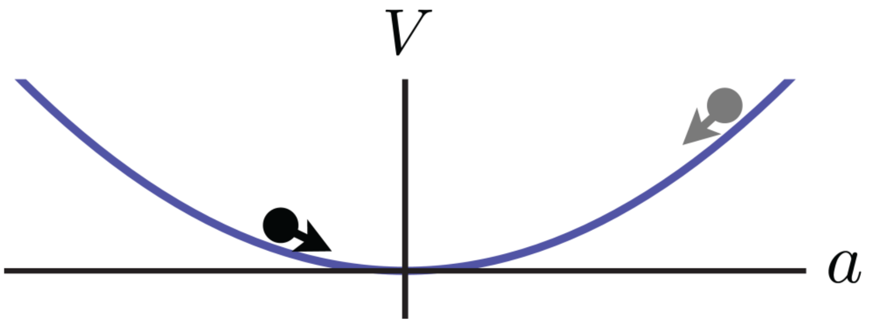
$$m_a \sim \frac{{\Lambda_{\mathrm{QCD}}}^2}{f_a}\ .$$

$\Lambda_{\mathrm{QCD}} \sim 200$ MeV is the QCD confinement scale.

ALPs may have different Λ and f.

Axion oscillations

Because of the random misalignment between the axion field a_o and the potential minimum, the axion field oscillates at the Compton frequency.



$$a(t) \sim a_0 \cos\left(m_a t\right)$$

Inflation and axion cosmology

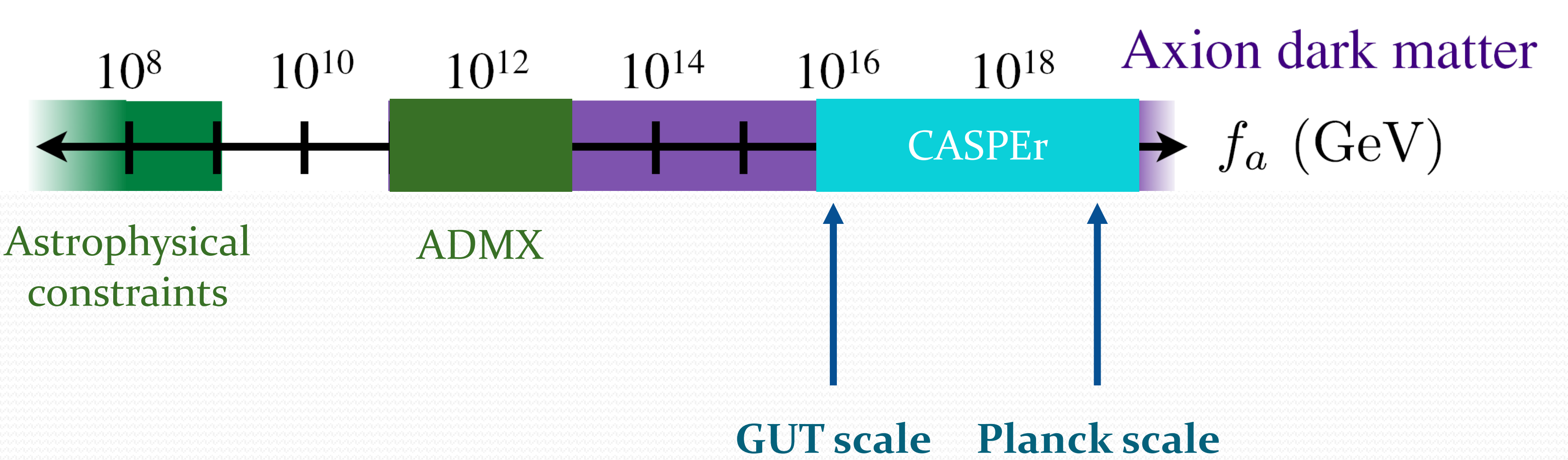
If the initial misalignment angle ~ 1 in the early universe, then for the QCD axion:

$$f_a \lesssim \quad \mathrm{GeV}\ .$$ The "anthropic" window.

However, if the inflation scale is lower than f_a the universe before inflation can have an inhomogeneous distribution of a_0.

Any local patch can inflate into our visible universe with a uniform value of a_0, and, of course, our visible universe has a dark matter density small enough to avoid overclosure.

Inflation and axion cosmology



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 fermions

CASPEr Wind

CASPEr Electric

Axion-induced electric dipole moments (EDMs)

Nuclear EDM from the strong interaction (strong CP problem):

$$d \approx 3 \times 10^{-16}\ \mathrm{e} \cdot \mathrm{cm} \times \theta_{\mathrm{QCD}}\ .$$

Nuclear EDM from axion field:

$$d \approx 3 \times 10^{-16}\ \mathrm{e} \cdot \mathrm{cm} \times \frac{a}{f_a}\ ,$$

$$\approx \frac{3 \times 10^{-16}\ \mathrm{e} \cdot \mathrm{cm}}{f_a} \times a_0 \cos\left(m_a t\right)\ .$$

Can be thought of as an oscillating θ_{QCD}.

Axion oscillation frequency

Determined by the axion mass, related to the global symmetry breaking scale f_a :

$$m_a \sim \frac{(200\ \mathrm{MeV})^2}{f_a} \sim \mathrm{MHz} \times \left(\frac{10^{16}\ \mathrm{GeV}}{f_a}\right) .$$

f_a at GUT scale $\rightarrow$ MHz frequencies,

f_a at Planck scale $\rightarrow$ kHz frequencies.

Axion-induced oscillating EDM

Assuming axions are the dark matter, the dark matter density fixes the ratio a_o/f_a:

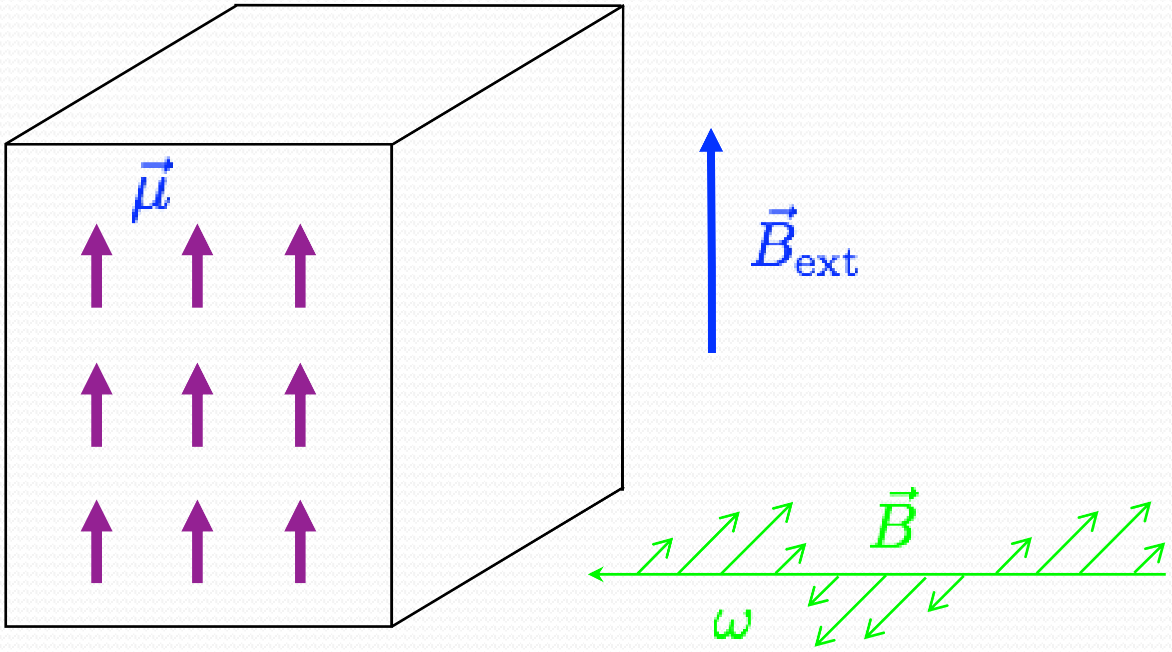
$$\rho_{\rm DM} \sim m_a^2 a_0^2 \sim \frac{(200\ {\rm MeV})^4}{f_a^2} a_0^2 \sim 0.3\ \frac{\rm GeV}{\rm cm^3}\ ,$$

$$\frac{a_0}{f_a} \sim 3 \times 10^{-19}\ .$$

This generates an oscillating EDM:

$$d \sim 10^{-34}\ {\rm e \cdot cm} \times \cos\left(m_a t\right)\ .$$

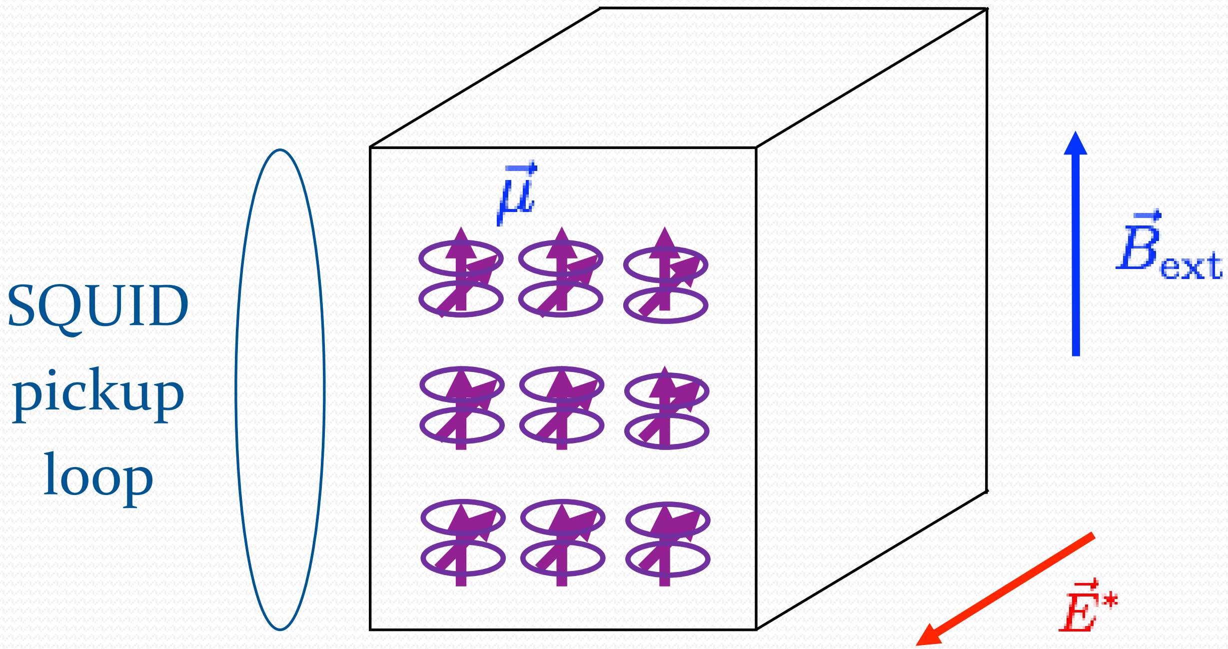
Nuclear Magnetic Resonance (NMR)



NMR resonant spin flip when Larmor frequency

$$2\mu B_{\text{ext}} = \omega$$

EDM coupling to axion plays role of oscillating transverse magnetic field



Larmor frequency = axion Compton frequency
➔ resonant enhancement.

Signal estimate

$$\frac{\sin\left[(\Omega_L - m_a)t\right]}{\Omega_L - m_a} \approx T_2$$

$$M(t) \approx (np\mu) \times (\epsilon_S d E^*) \times \frac{\sin\left[(\Omega_L - m_a)t\right]}{\Omega_L - m_a} \sin(\Omega_L t) \ ,$$

n = atomic density;
p = nuclear polarization;
μ = magnetic moment;
E^* = effective electric field;
ε_S = Schiff suppression;
Ω_L = Larmor frequency.

Sample choice

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

Need maximum n, p, E^*, and ε_S, and long T_2.

For the first generation CASPEr-Electric experiment, we plan to use a ferroelectric crystal, likely $PbTiO_3$.

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

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

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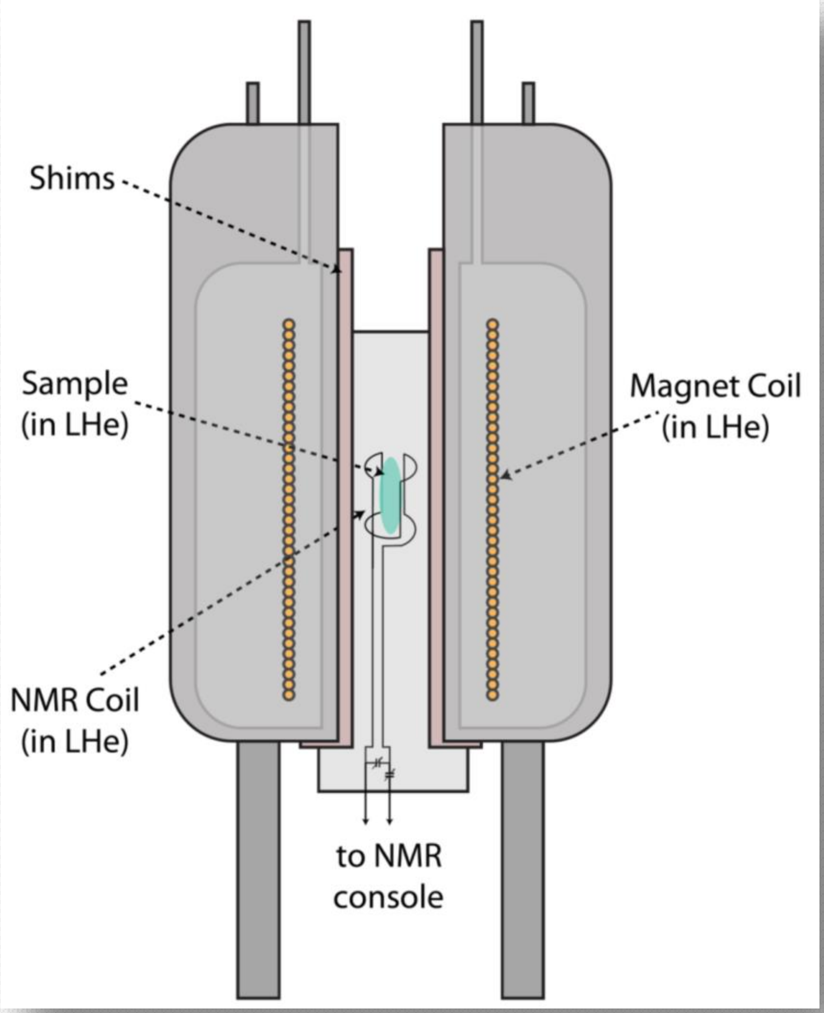
(Received 15 November 2007; published 4 February 2008)

Experimental strategy

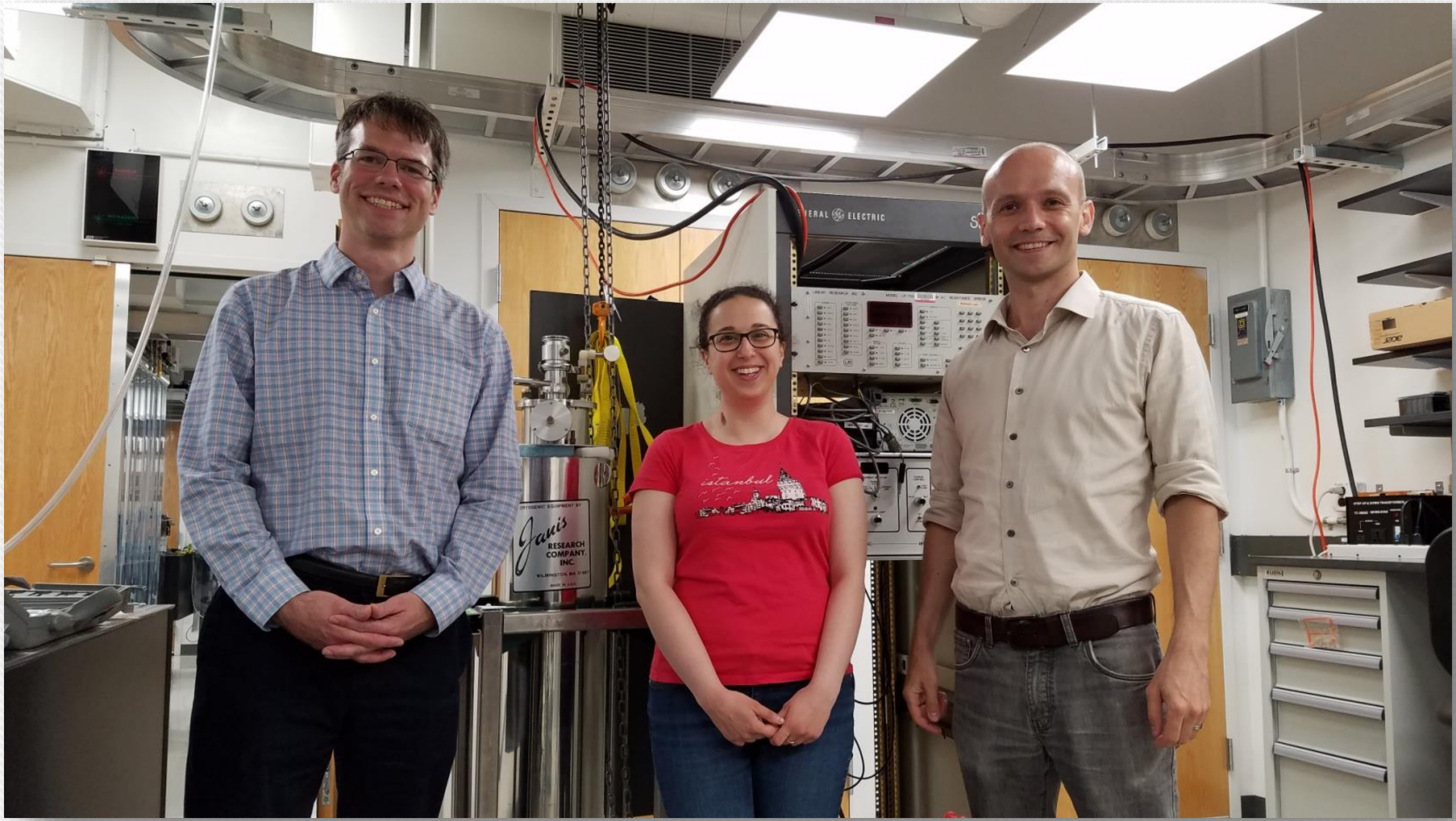
(1) Thermally polarize spins in a cryogenic environment at high magnetic field (~ 10 T);

(2) Scan magnetic field down from 10 T -- Larmor frequency decreases from ~ 50 MHz;

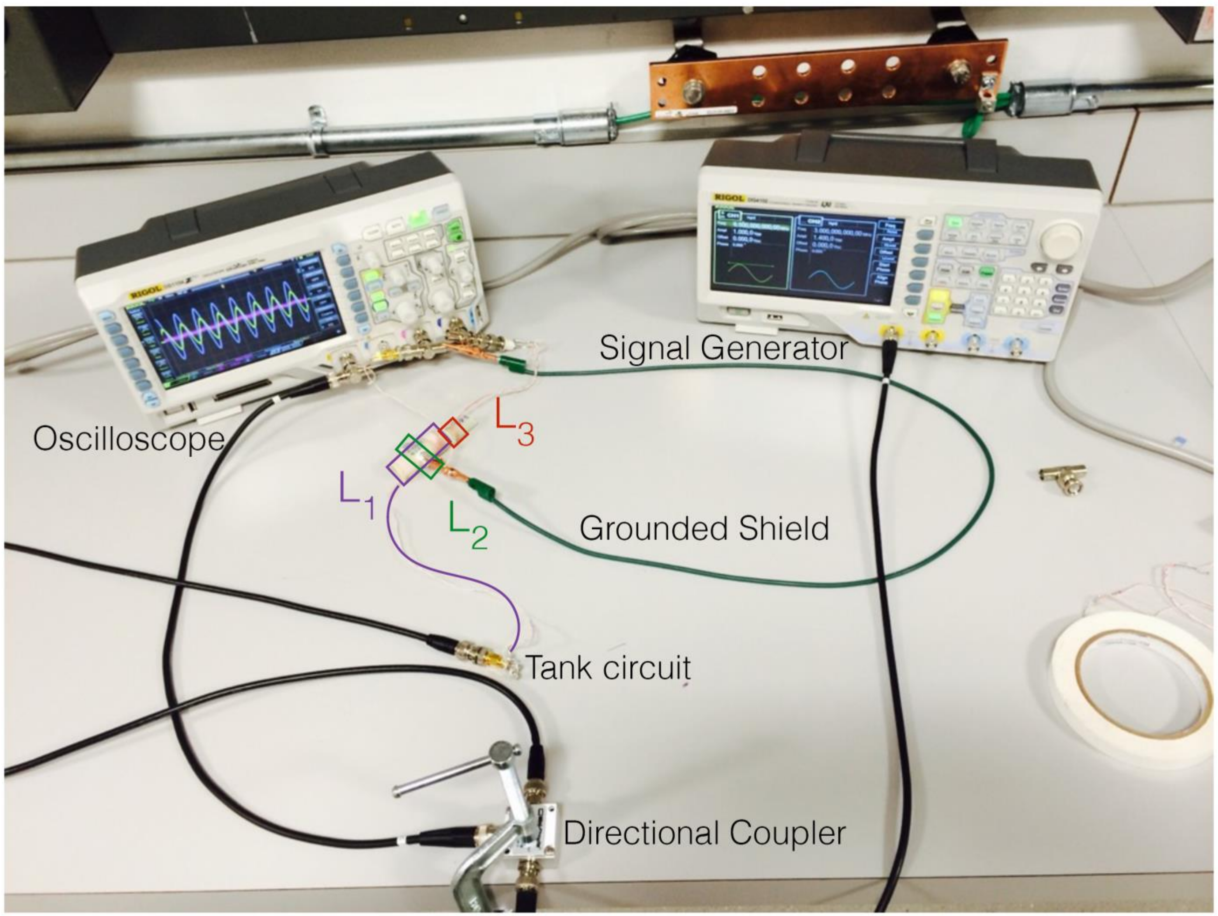
(3) Integrate for ~ 10 ms at each frequency, complete scan takes around 1000 s ≈ T_1 to complete.



Experiments beginning!



Experiments beginning!



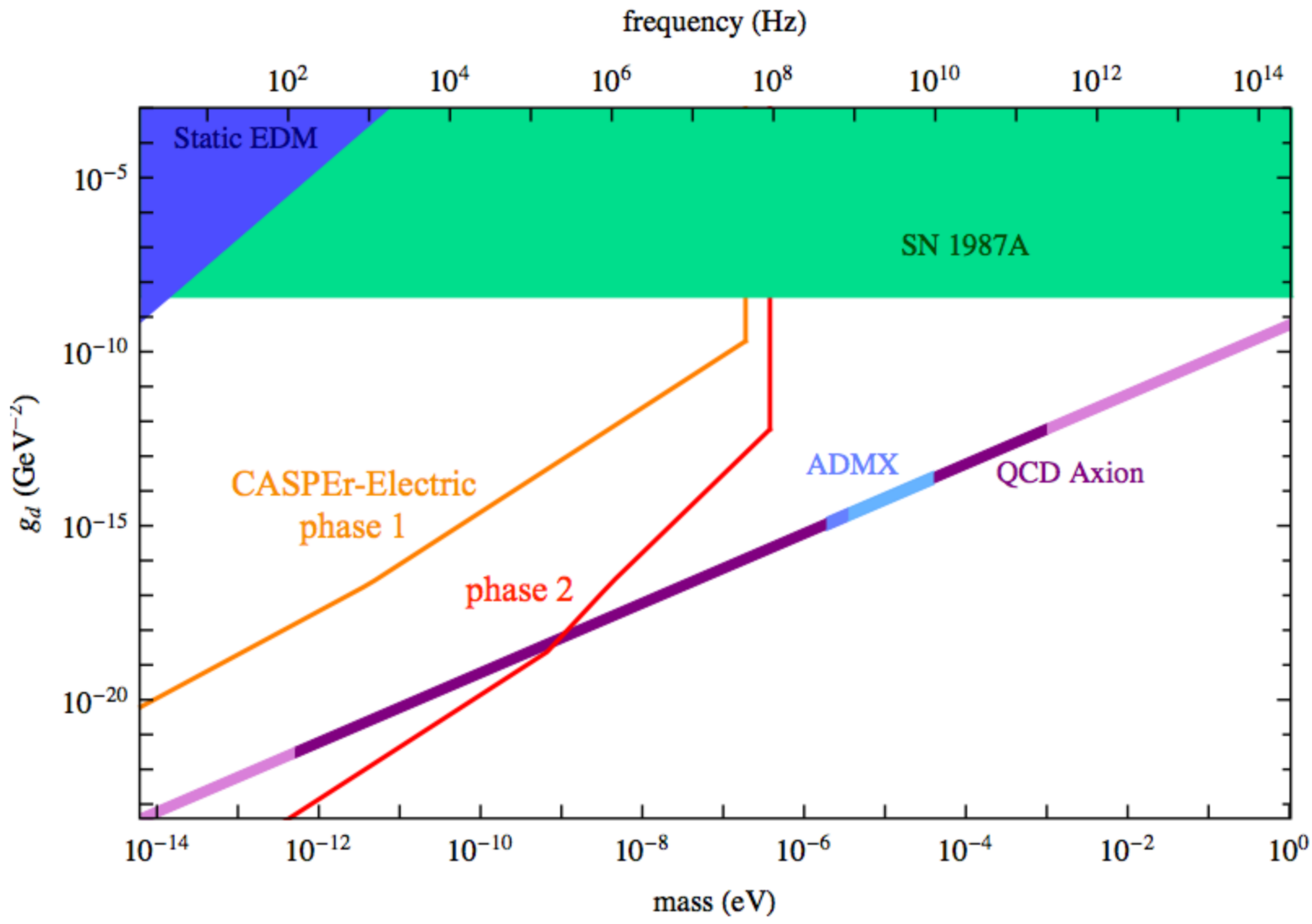
Challenges

(1) T_1 acquires field dependence due to paramagnetic impurities – long T_1 at high fields, short T_1 at low fields: this is a problem for duty cycle and maintaining polarization at low fields.

(2) The chemical shift anisotropy (CSA) can broaden the resonance.

(3) Vibrations can be an issue for low frequencies/fields.

- Estimates of thermal drifts and magnetic field fluctuations indicate that they shouldn't be a major problem.



Experimental sensitivity

Phase 2 requirements

(1) Longer coherence time: $T_2 \approx 1$ s.

(2) Hyperpolarization: $p \approx 1$.

(3) Larger sample size: $V \approx 100\text{-}1000$ cm^3.

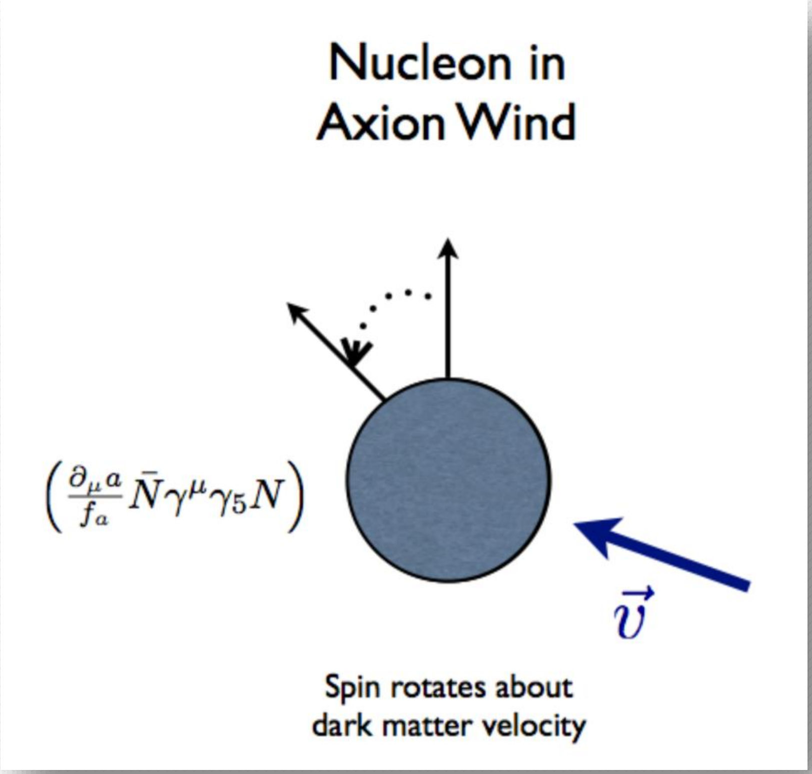
R&D required!

CASPEr Wind

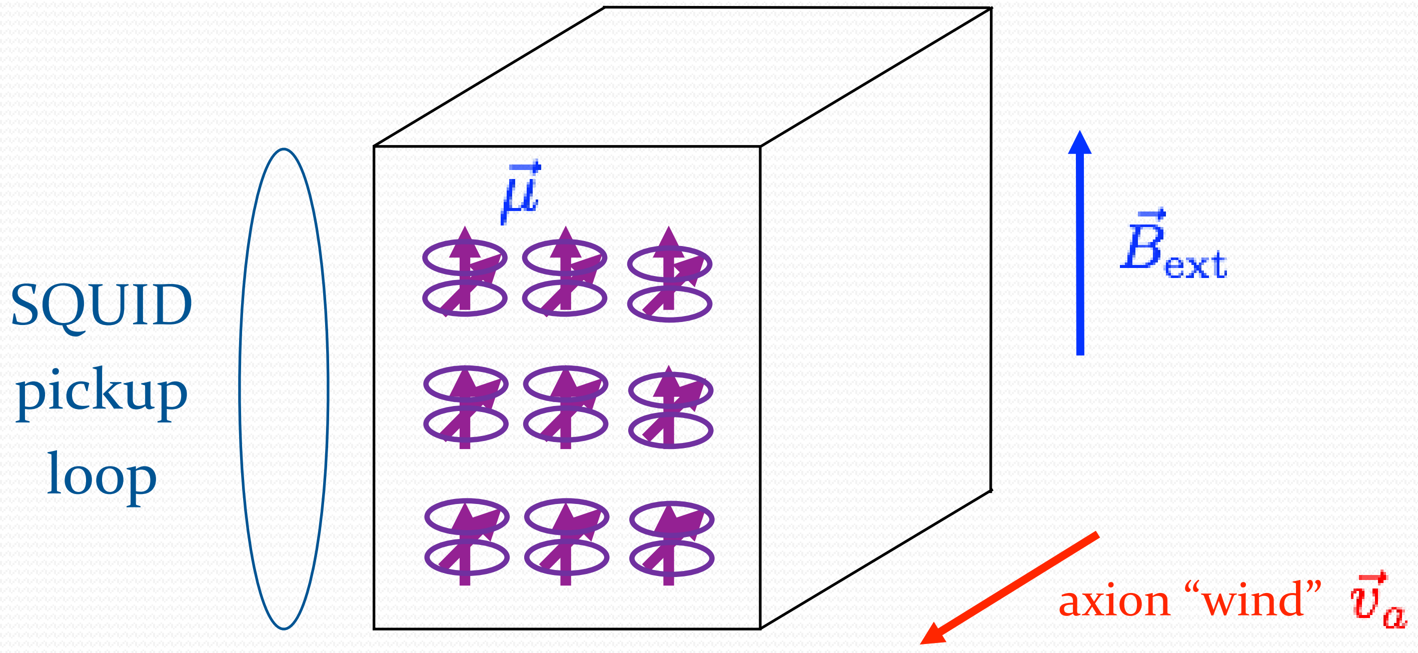
Axion/ALP-induced spin precession (axion wind)

Nonrelativistic limit of the axion-fermion coupling yields a Hamiltonian:

$$H_{\text{wind}} \approx g_{aNN} \nabla a \cdot \boldsymbol{\sigma}_N \ .$$



Axion wind detection



Larmor frequency = axion Compton frequency
➔ resonant enhancement.

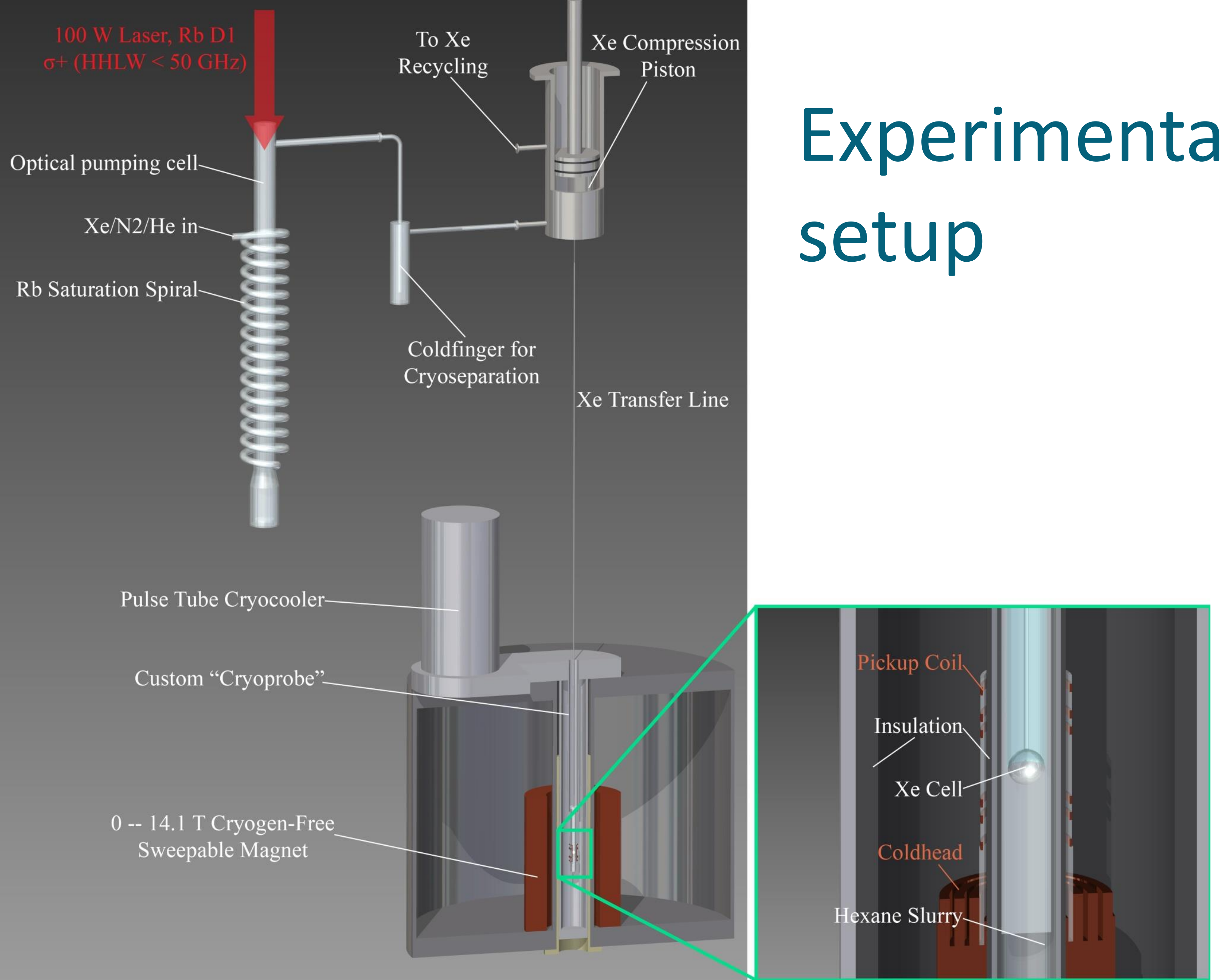
Sample choice: liquid Xenon

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

Relatively large sample can be hyperpolarized.

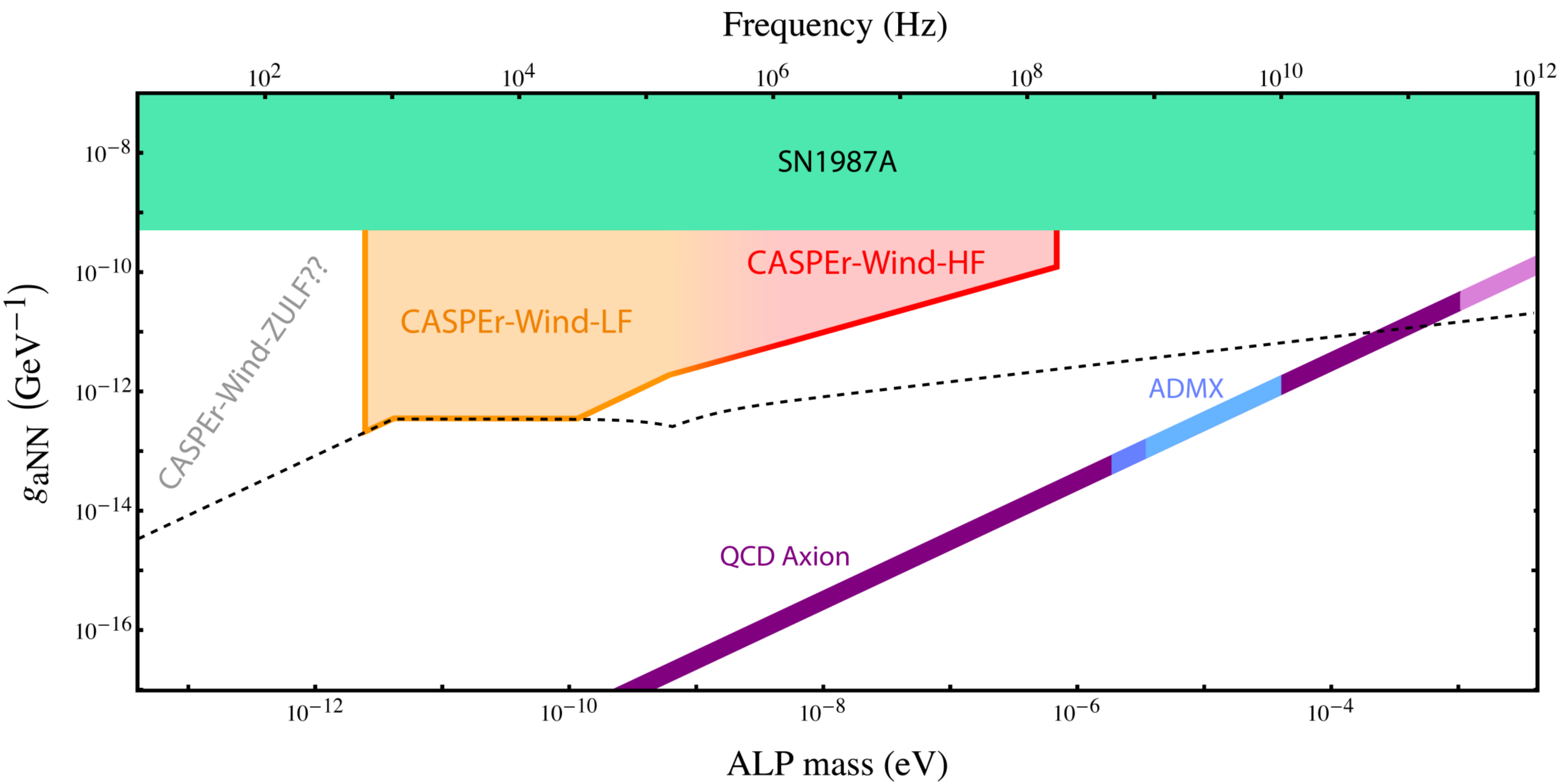
The enhancement factor can be on the order of 10^6.

Experimental setup



Experiments beginning!

Experimental sensitivity



New idea: a precessing ferromagnetic needle

Precessing Ferromagnetic Needle Magnetometer

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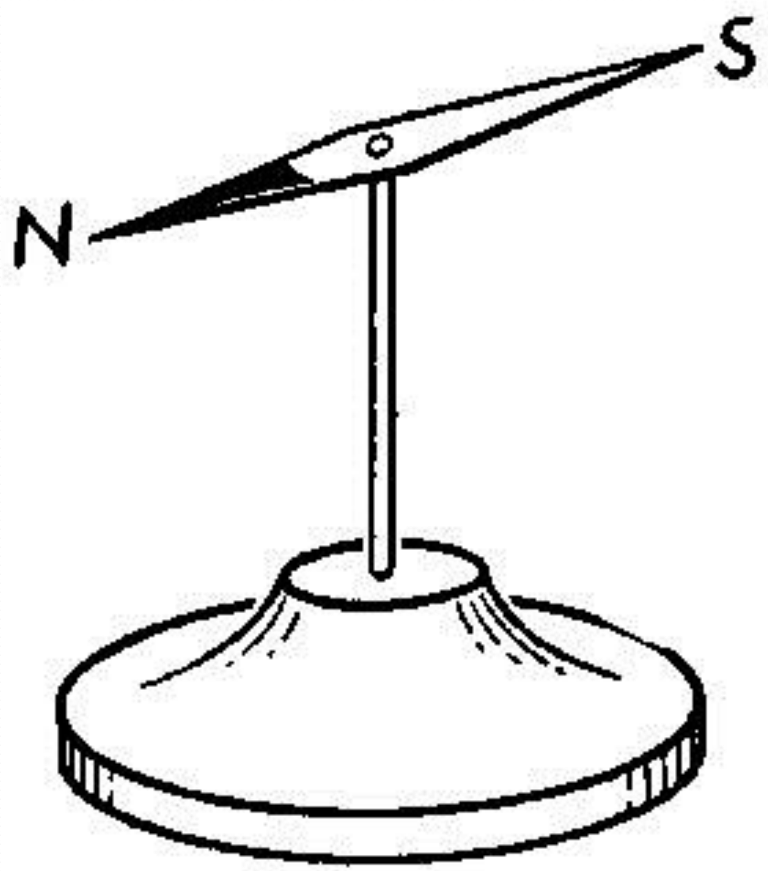
(Received 8 February 2016; published 13 May 2016)

A ferromagnetic needle is predicted to precess about the magnetic field axis at a Larmor frequency Ω under conditions where its intrinsic spin dominates over its rotational angular momentum, $N\hbar \gg I\Omega$ (I is the moment of inertia of the needle about the precession axis and N is the number of polarized spins in the needle). In this regime the needle behaves as a gyroscope with spin $N\hbar$ maintained along the easy axis of the needle by the crystalline and shape anisotropy. A precessing ferromagnetic needle is a correlated system of N spins which can be used to measure magnetic fields for long times. In principle, by taking advantage of rapid averaging of quantum uncertainty, the sensitivity of a precessing needle magnetometer can far surpass that of magnetometers based on spin precession of atoms in the gas phase. Under conditions where noise from coupling to the environment is subdominant, the scaling with measurement time t of the quantum- and detection-limited magnetometric sensitivity is $t^{-3/2}$. The phenomenon of ferromagnetic needle precession may be of particular interest for precision measurements testing fundamental physics.

DOI: 10.1103/PhysRevLett.116.190801

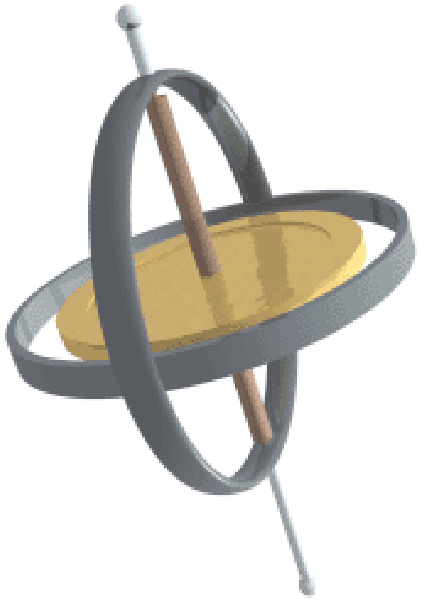
D. F. Jackson Kimball, A. O. Sushkov, and D. Budker,
Phys. Rev. Lett. **116**, 190801 (2016).

Ferromagnetic needles



Why do compass needles orient themselves along the ambient magnetic field, while atomic and nuclear spins precess about the field?

Ferromagnetic needles



Why do compass needles orient themselves along the ambient magnetic field, while atomic and nuclear spins precess about the field?

Two regimes: tipping & precessing

Precessing regime: $S \gg L$;

Tipping regime: $L \gg S$.

Threshold for precession

Threshold in magnetic field to realize precession of a ferromagnetic needle (with moment of inertia I):

$$L \ll S \qquad \Rightarrow \qquad I\Omega \ll N\hbar \; ,$$

$$\Omega \ll \Omega^* = \frac{N\hbar}{I} \; ,$$

$$B \ll B^* = \frac{\hbar\Omega^*}{g\mu_B} \; .$$

Threshold for precession

For example, for a cobalt needle with $\ell \approx 10\ \mu\text{m}$ and $r \approx 1\ \mu\text{m}$:

$$\Omega^* \approx 100\ \text{s}^{-1}$$

and

$$B^* \approx 10^{-5}\ \text{G}\ ,$$

a field value that can be achieved in the laboratory with appropriate shielding.

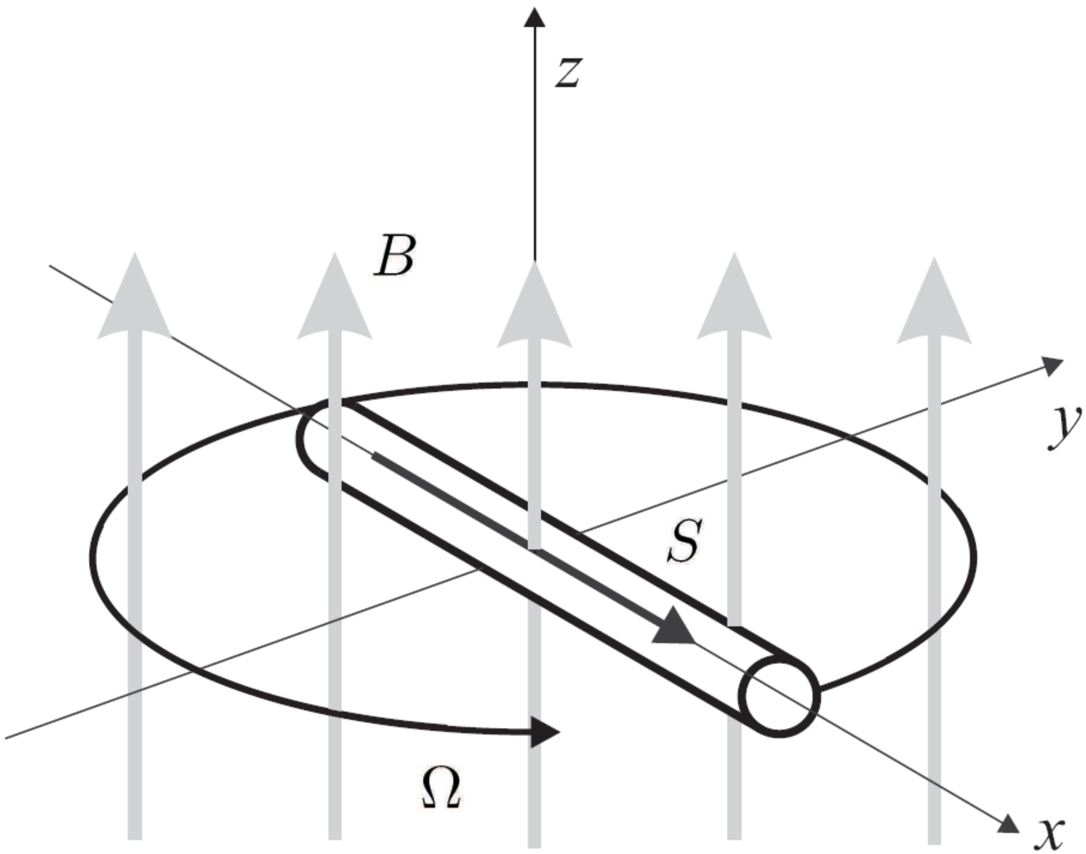
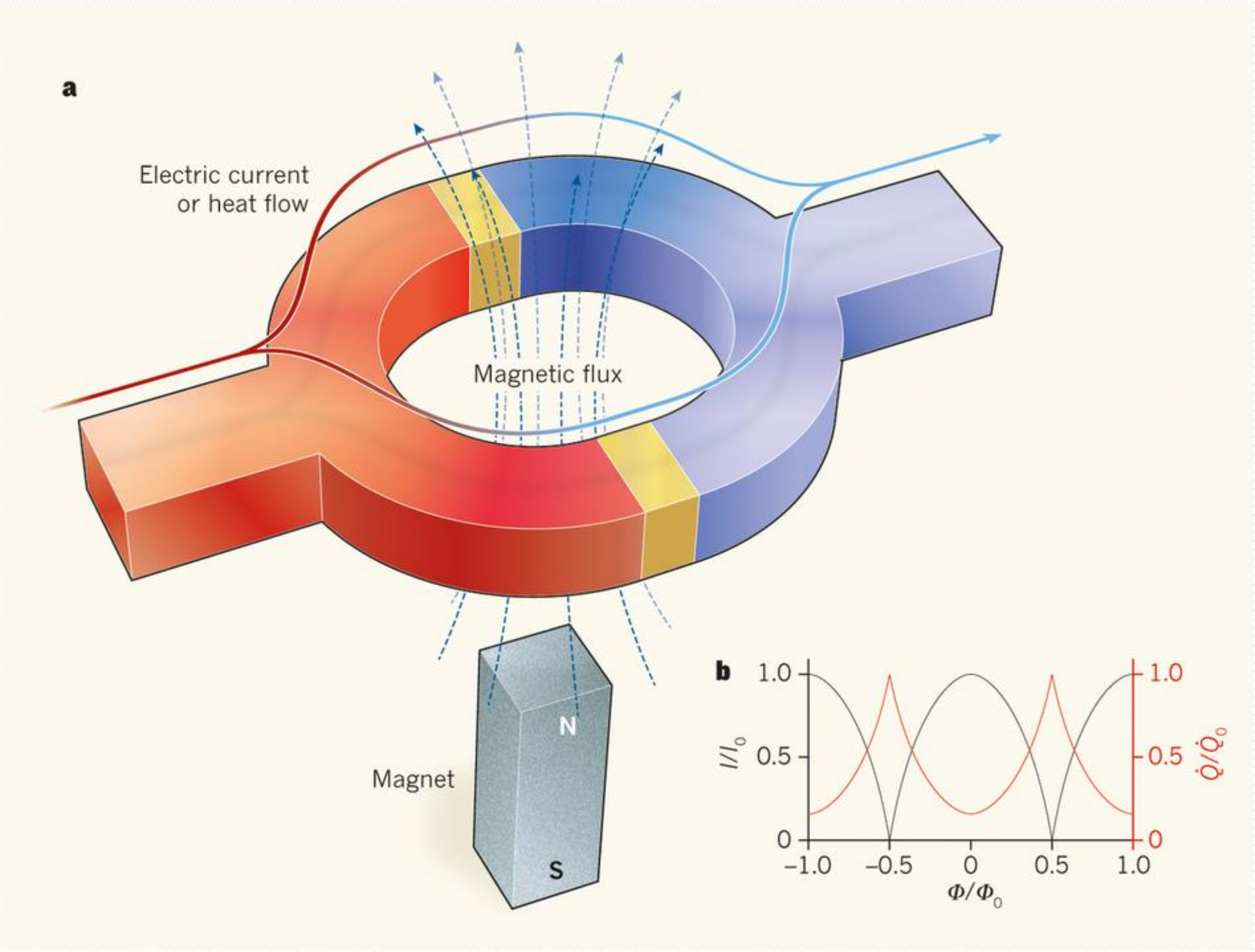


FIG. 1: A ferromagnetic needle with spin $S = N\hbar$ along its long axis precesses at a frequency Ω in a magnetic field $B \ll B^*$

Idealized experiment



Magnetic field measurement

To determine B, measure S_y and extract the value of B from the precession angle

$$\begin{aligned}\phi &= \Omega t = g\mu_B Bt/\hbar \\ &\approx \frac{S_y}{S_x} \approx \frac{S_y}{N\hbar} ,\end{aligned}$$

assuming $\phi \ll 1$; Ω is the Larmor frequency, g is the Landé factor, μ_B is the Bohr magneton.

Sensitivity

Imagine a freely floating micron-scale needle near a SQUID, completely decoupled from the environment.

Given the amplitude of the magnetic flux from the needle ($\Phi \approx 10^{-4}\ \mathrm{G} \cdot \mathrm{cm}^2$) and the sensitivity of a low-T_c SQUID ($\delta\Phi \lesssim 10^{-13}\ \mathrm{G} \cdot \mathrm{cm}^2/\sqrt{\mathrm{Hz}}$), we estimate a detection-limited uncertainty in B of

$$\Delta B_{\mathrm{det}} \approx 10^{-16}(t[\mathrm{s}])^{-3/2}\ \mathrm{G}\ .$$

What about the Uncertainty Principle?

For N spins, the standard quantum limit (SQL) on measurement of ϕ is

$$\Delta\phi \approx \sqrt{\frac{\Gamma_{\mathrm{rel}} t}{N}}$$

after time $t \gg 1/\Gamma_{\mathrm{rel}}$; Γ_{rel} = spin relaxation rate.

This is a random walk in angle with step size $1/\sqrt{N}$ consisting of $\Gamma_{\mathrm{rel}} t$ steps.

What about the Uncertainty Principle?

In the $\Gamma_{\text{rel}} \to 0$ limit,

$$\Delta\Omega = g\mu_B \Delta B/\hbar = \frac{1}{t\sqrt{N}} \ ,$$

and so it would seem the best you could possibly do is:

$$\Delta B_{\text{SQL}} \approx 10^{-13}(t[\text{s}])^{-1} \ \text{G} \ .$$

Averaging away the uncertainty?

But what if you average the measurements?

$$\Delta\phi \to \frac{1}{\sqrt{N}}\frac{1}{\sqrt{N_m}} ,$$

where N_m is the number of measurements.

Averaging away the uncertainty?

The rapid averaging occurs due to the spin-lattice interaction within the needle.

Because of gyroscopic stability ($S \gg L$), there is no random walk in ϕ.

Fluctuation-dissipation

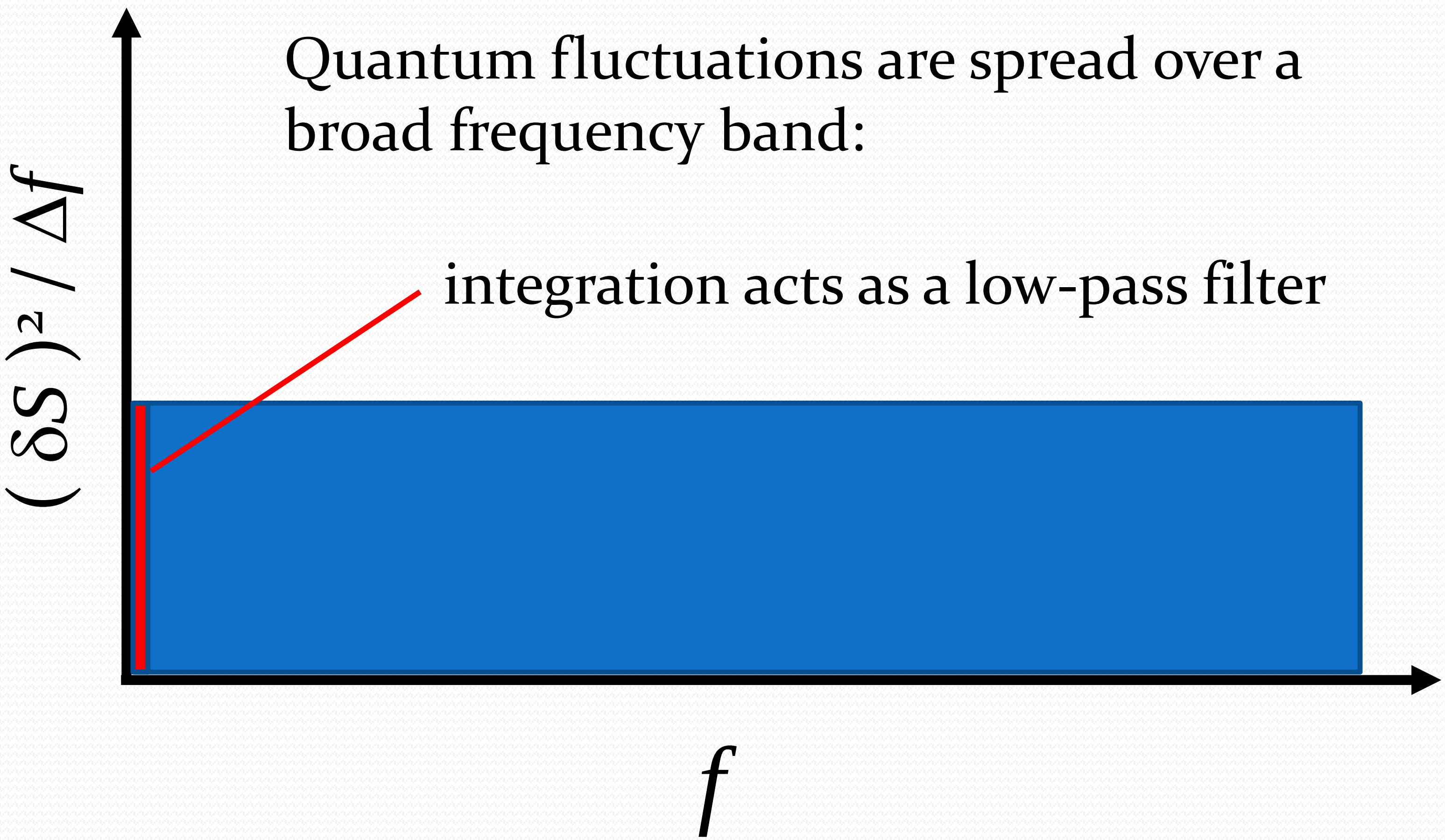
Resultant quantum uncertainty can be estimated from the fluctuation-dissipation theorem:

$$\Delta B_{\mathrm{Q}} \approx \frac{\hbar}{g\mu_B}\sqrt{\frac{2\alpha k_B T}{\hbar\omega_0^2}}\frac{1}{\sqrt{Nt^3}} ,$$

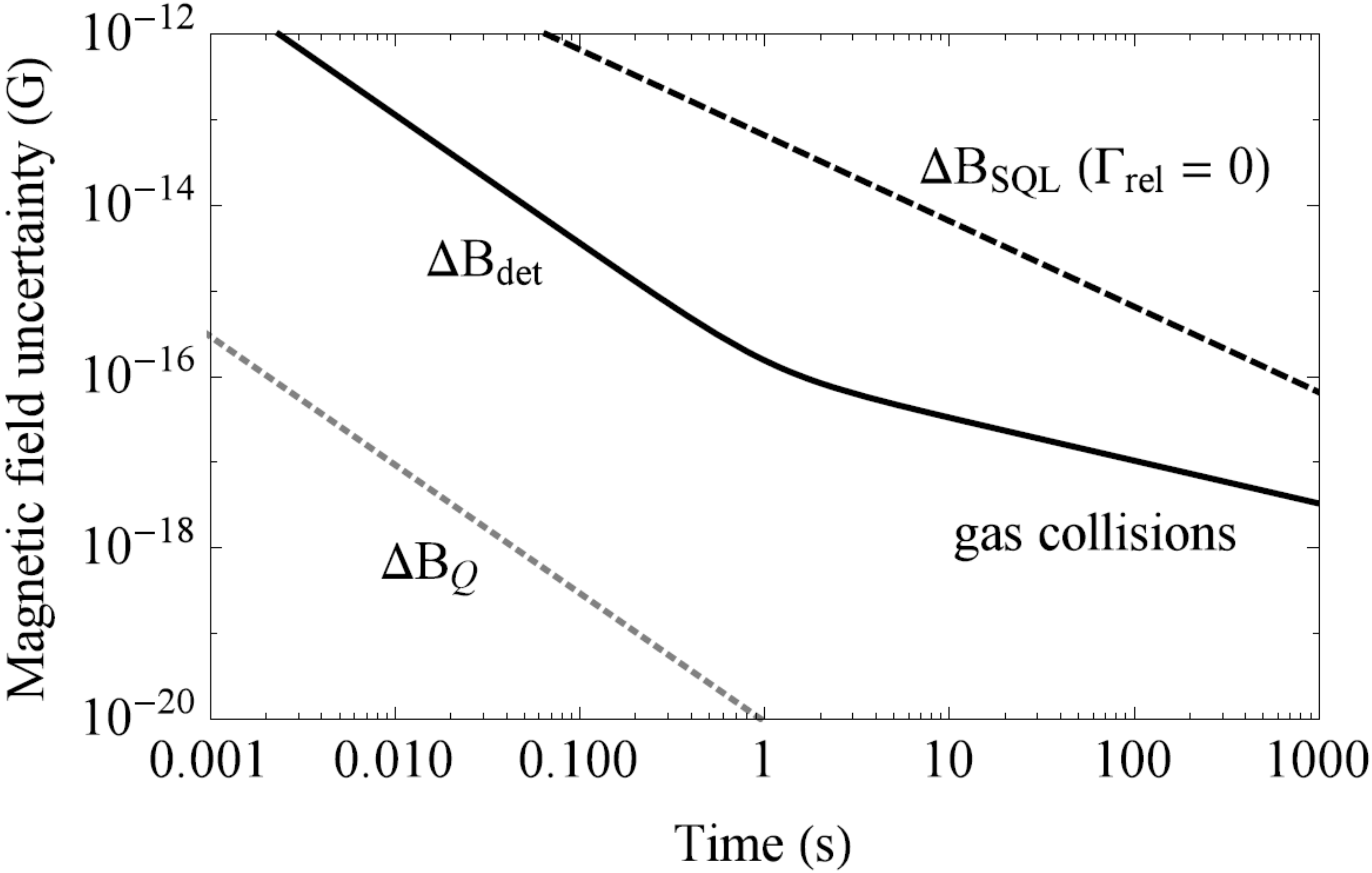
where k_B is Boltzmann's constant, T is the needle's temperature, and $\omega_0 \approx 2\pi \times 10^{11}$ Hz is the ferromagnetic resonance frequency related to the anisotropy and exchange fields within the ferromagnet.

Spectral density of quantum fluctuations

Quantum fluctuations are spread over a broad frequency band:



(Needle floating in cryogenic vacuum, T ≈ 0.1K.)

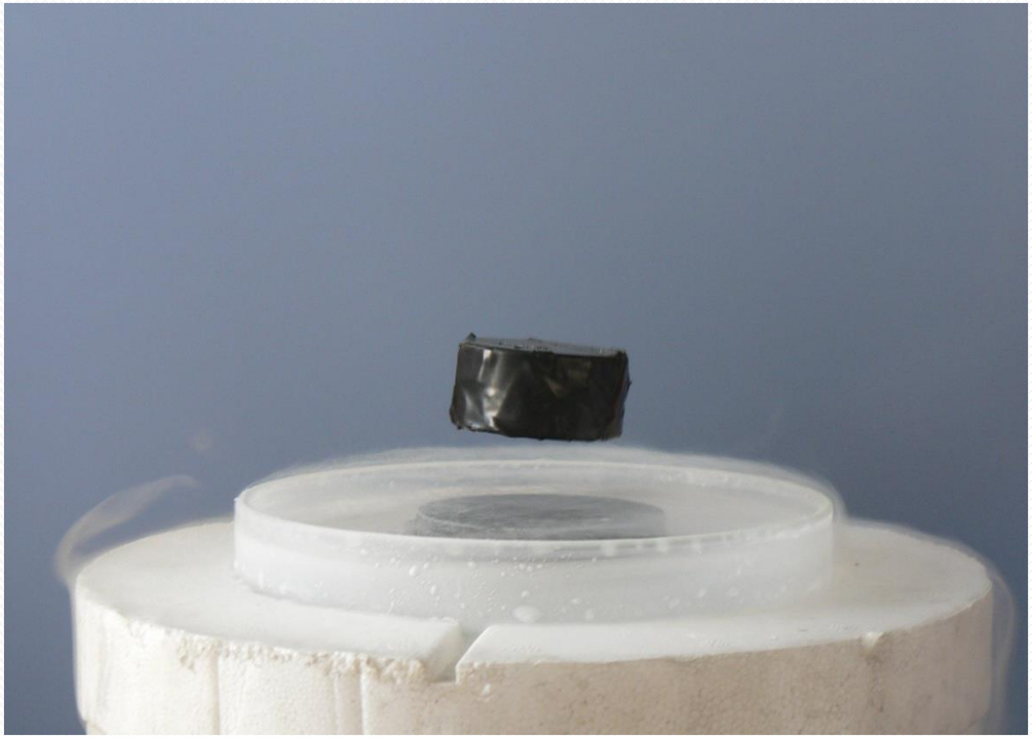


Noise

- Magnons,
- Phonons,
- Thermal currents (Johnson-Nyquist noise),
- **Collisions with residual gas molecules,**
- Black-body radiation.

Suspension?

Seemingly cannot use light or mechanical support to reach ultimate sensitivity… still thinking…



Conclusions

New searches for oscillating moments induced by coherent oscillations of the axion/ALP field offer the possibility to investigate a significant fraction of unexplored parameter space!

If research and development of new samples and new hyperpolarization techniques succeed, we may be able to search for the QCD axion with f_a near the GUT and Planck scale!

New sensors based on precessing ferromagnetic needles could open new possibilities for precision measurements.