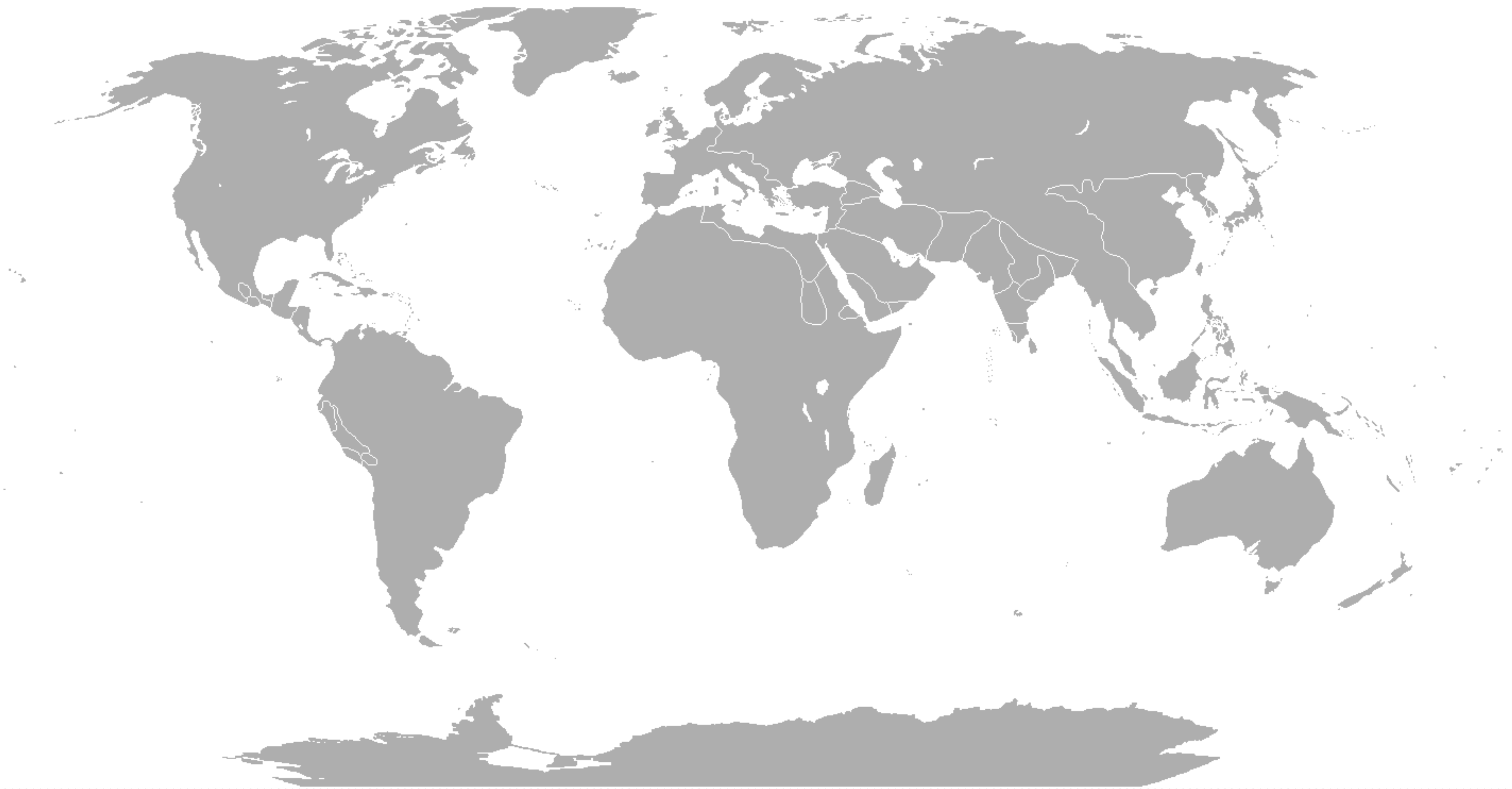
CASPEr: the Cosmic Axion Spin Precession Experiment

Derek F. Jackson Kimball

HEISING - SIMONS
FOUNDATION

Collaboration



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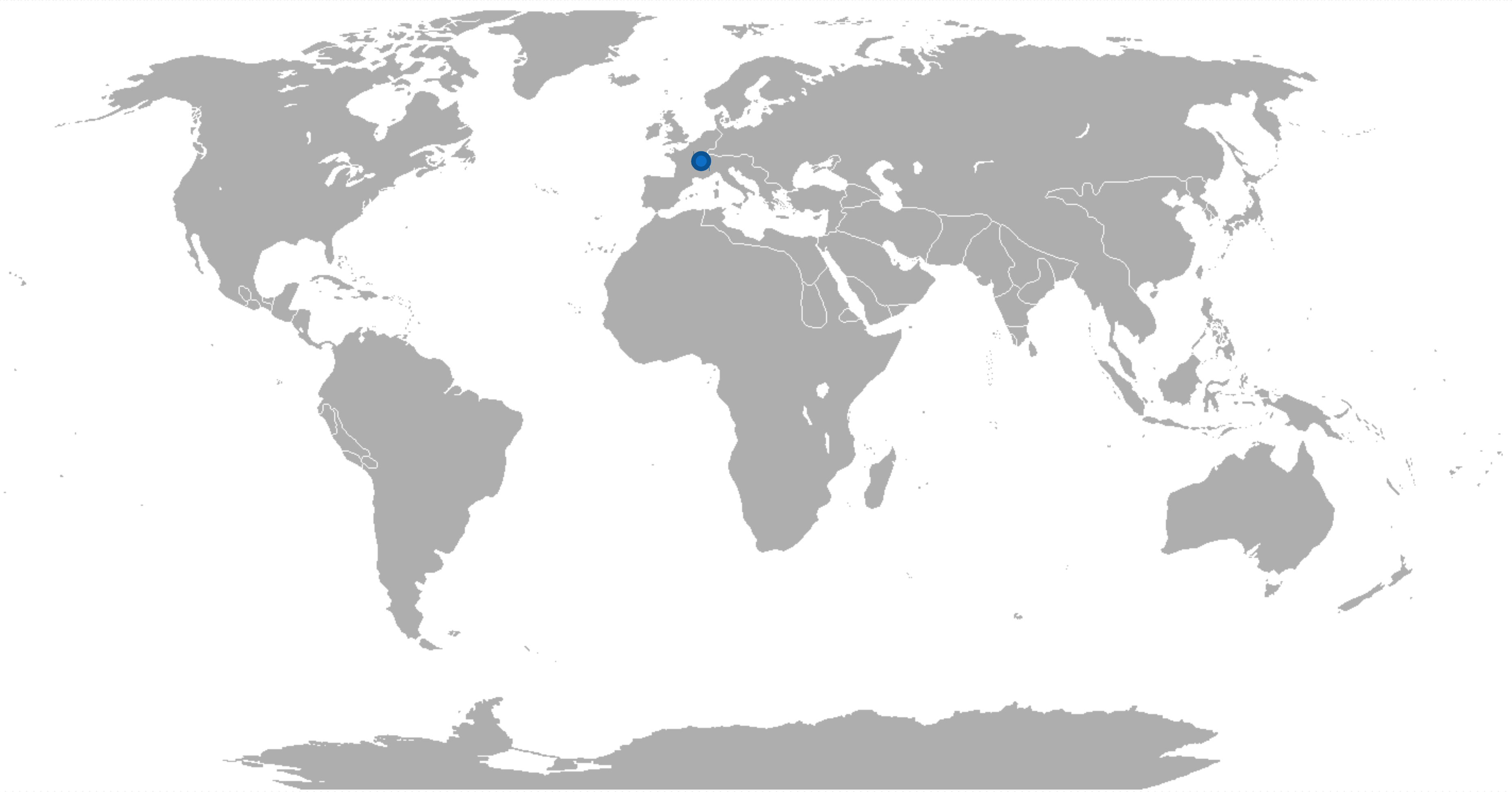

Collaboration

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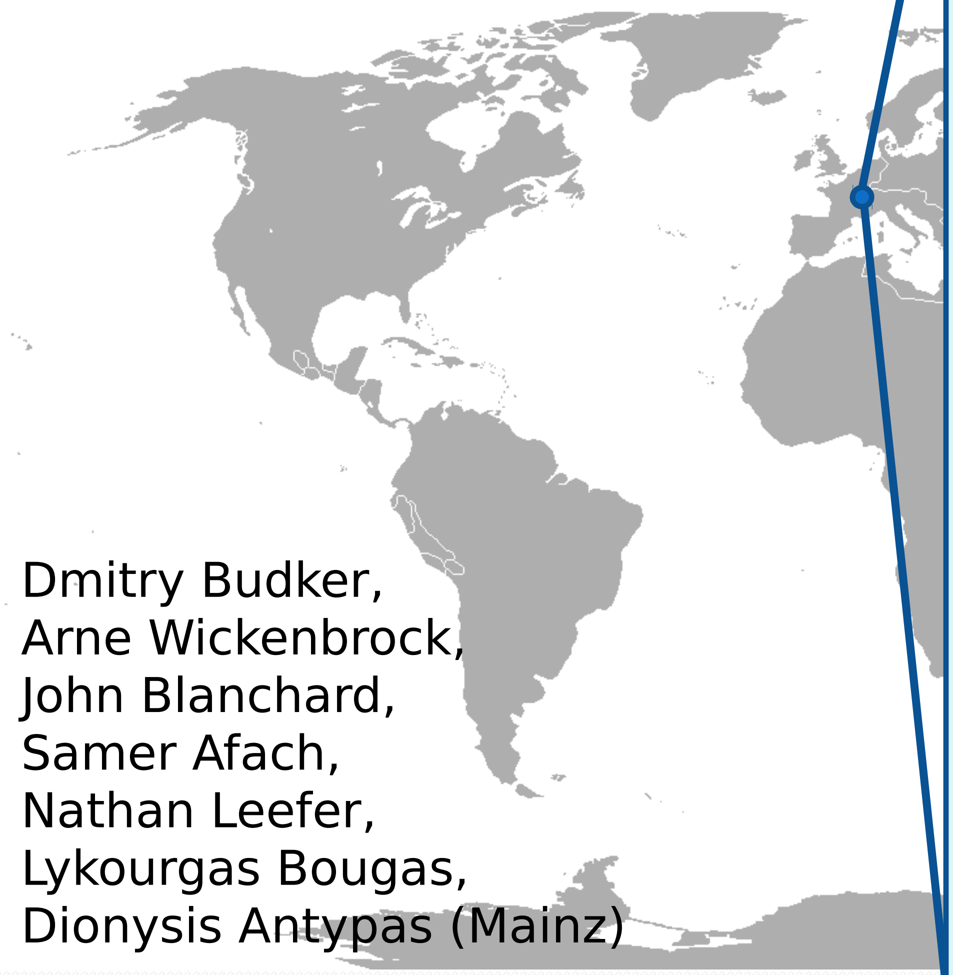
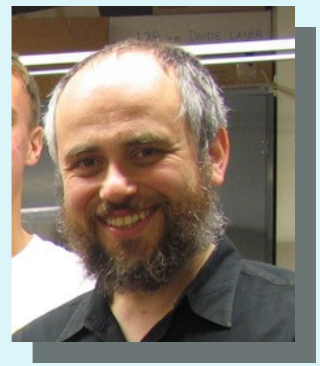
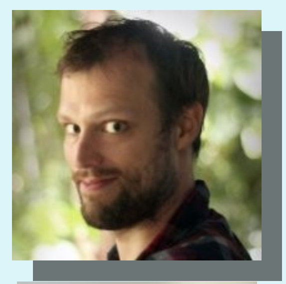
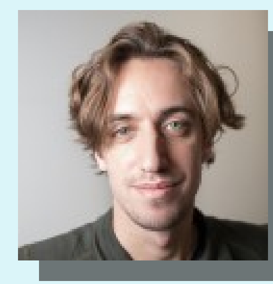


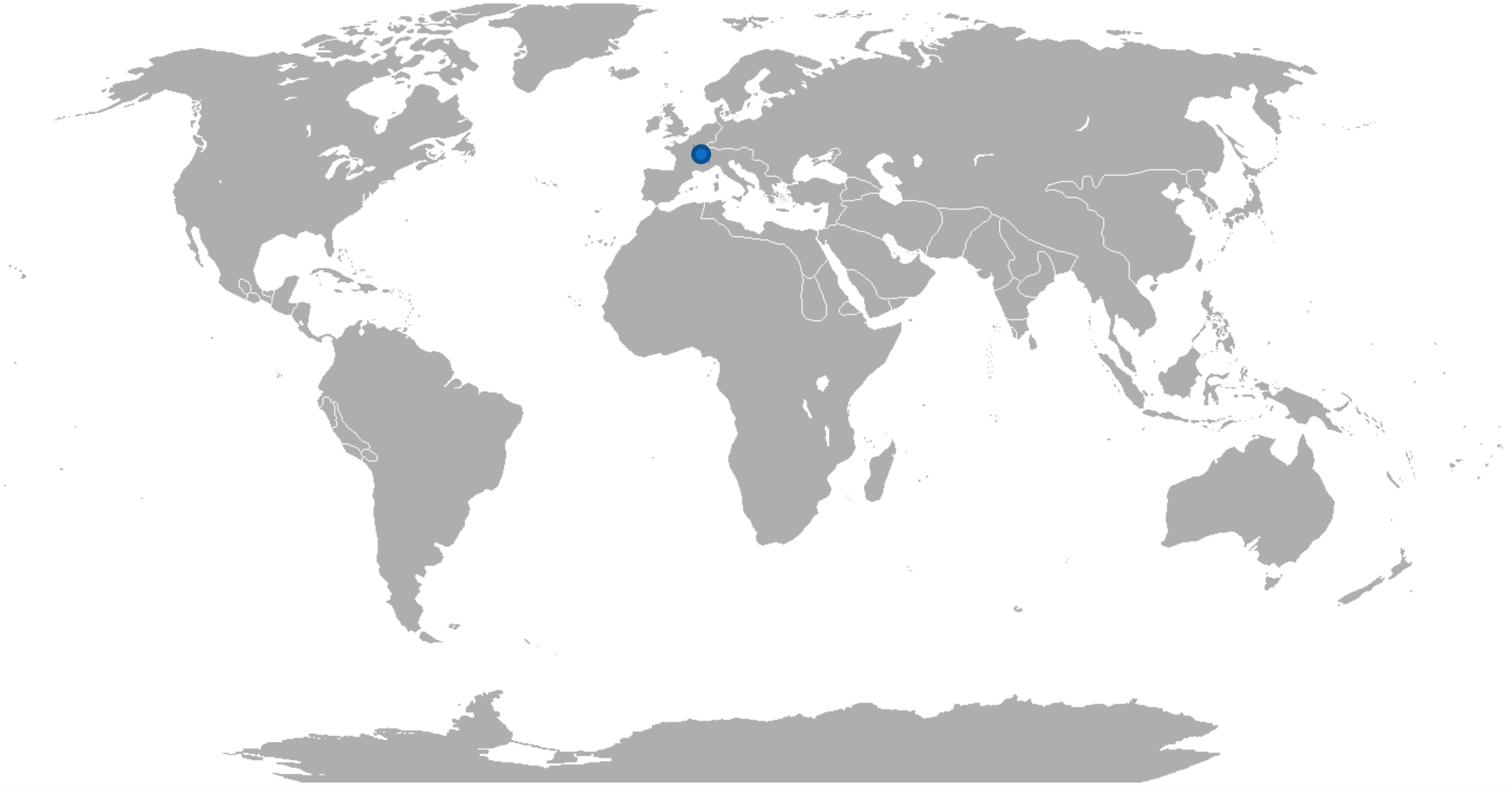






Dmitry Budker,
Arne Wickenbrock,
John Blanchard,
Samer Afach,
Nathan Leefer,
Lykourgas Bougas,
Dionysis Antypas (Mainz)

Collaboration



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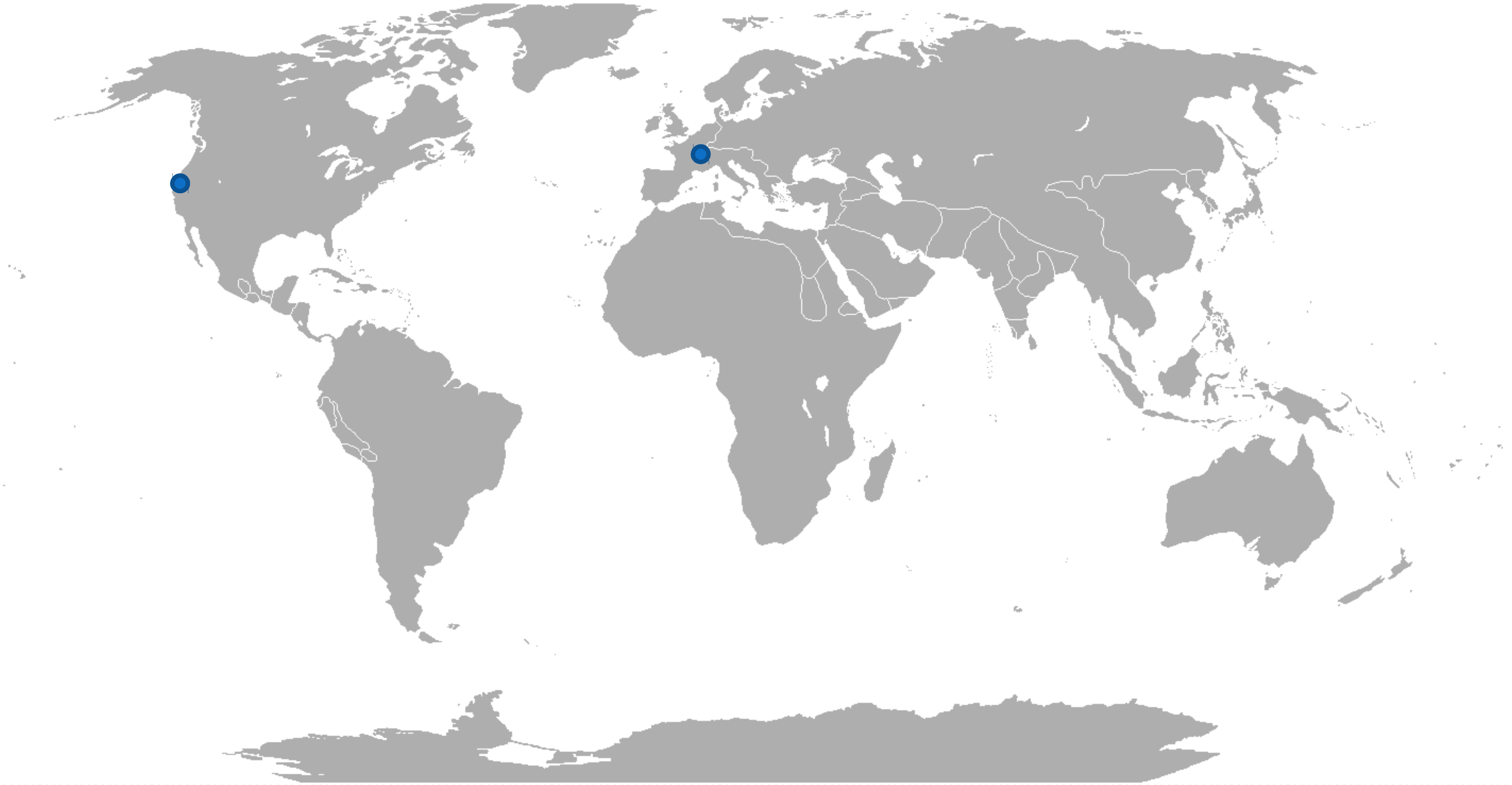

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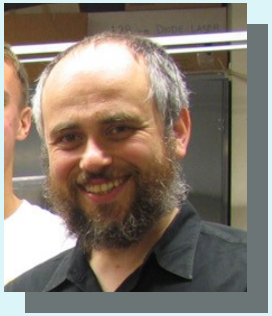
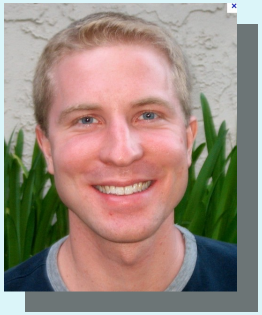
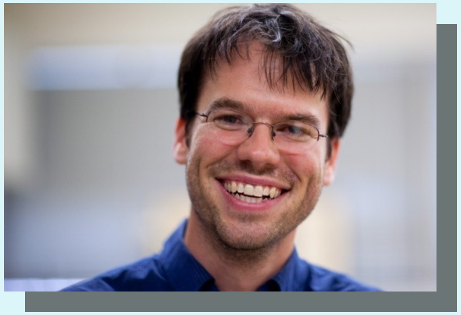
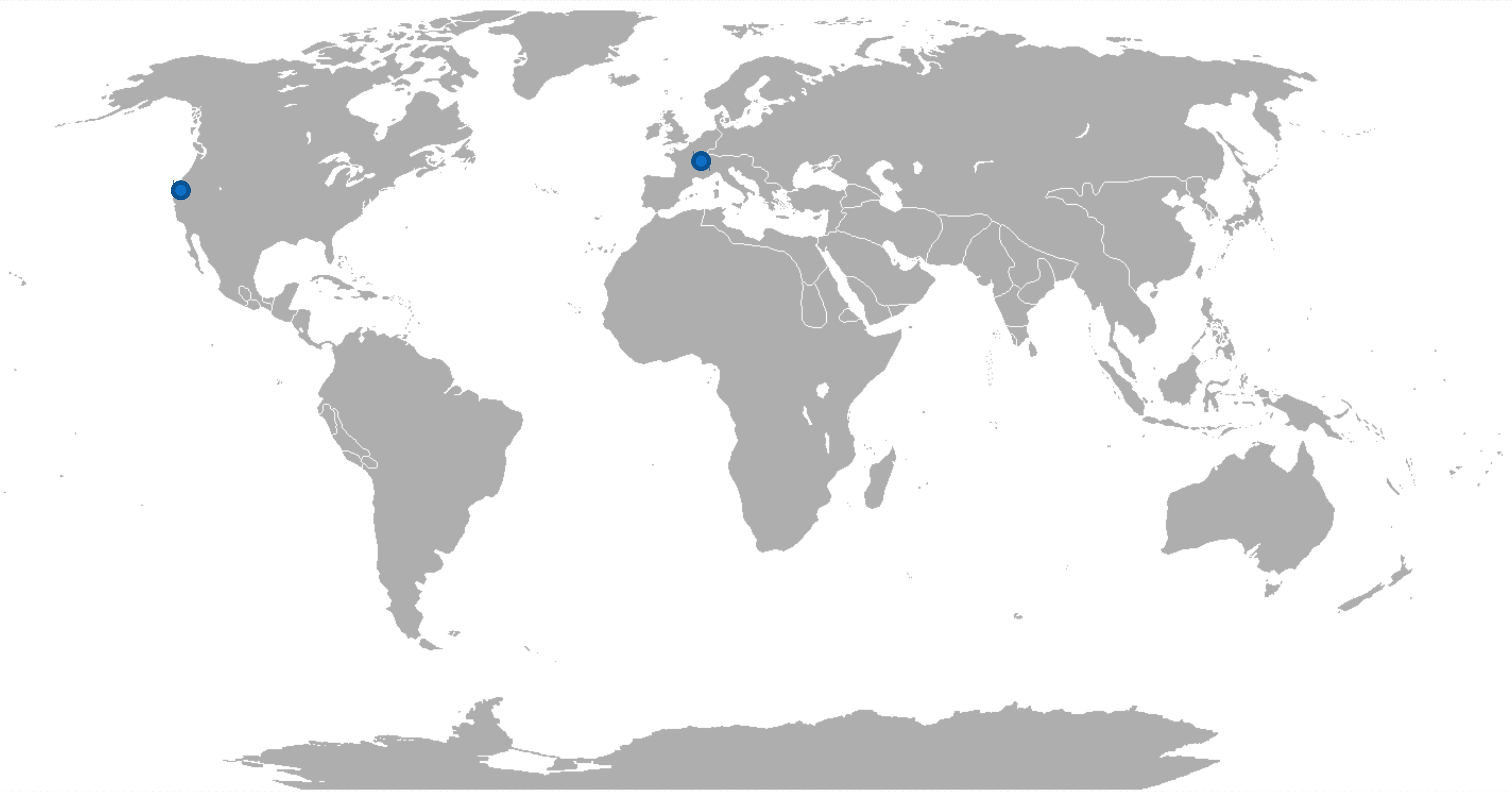






Surjeet Rajendran, Dmitry Budker (UCB)
Peter Graham (Stanford)
Derek Kimball (CSUEB)

Collaboration



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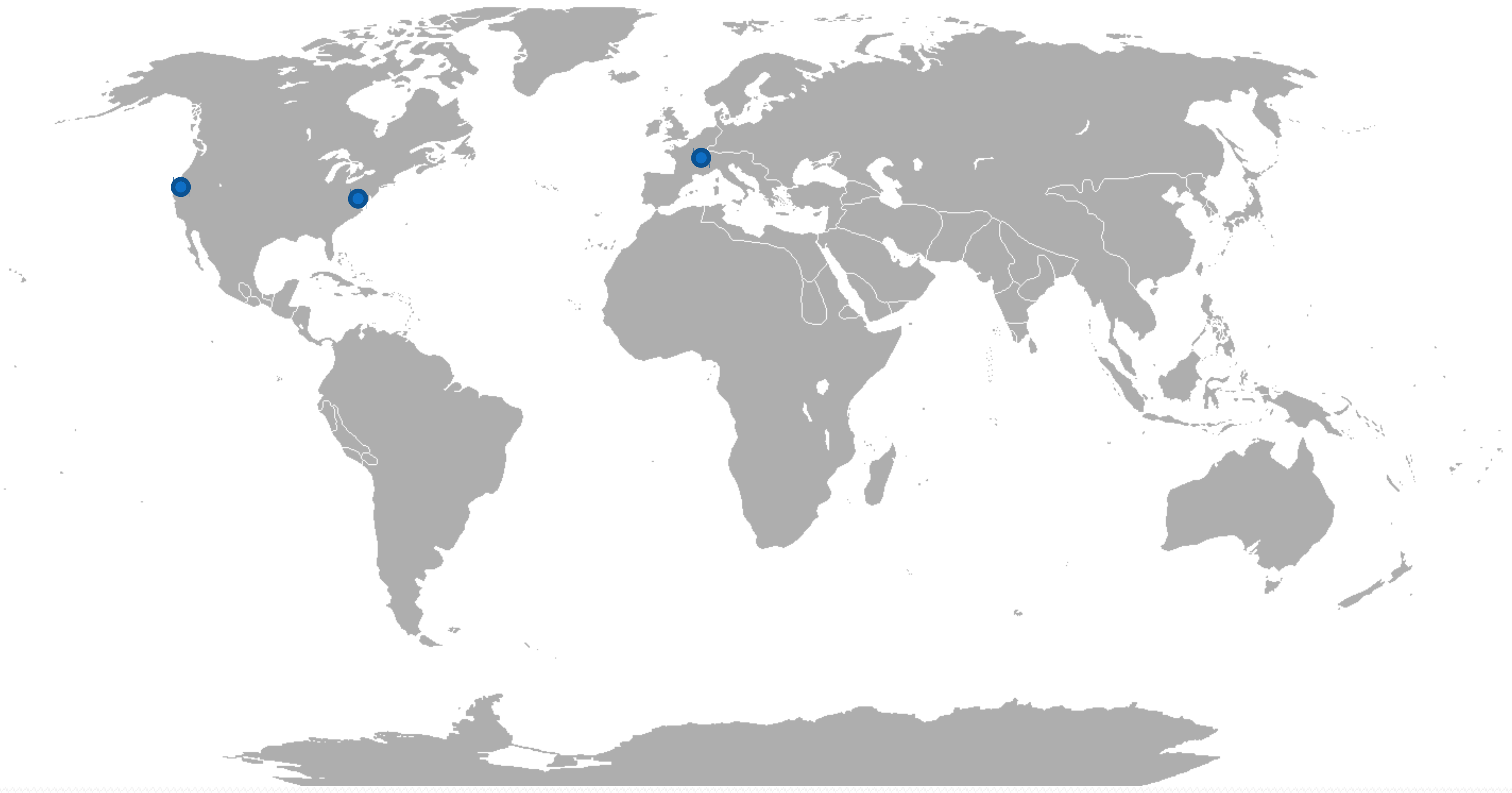

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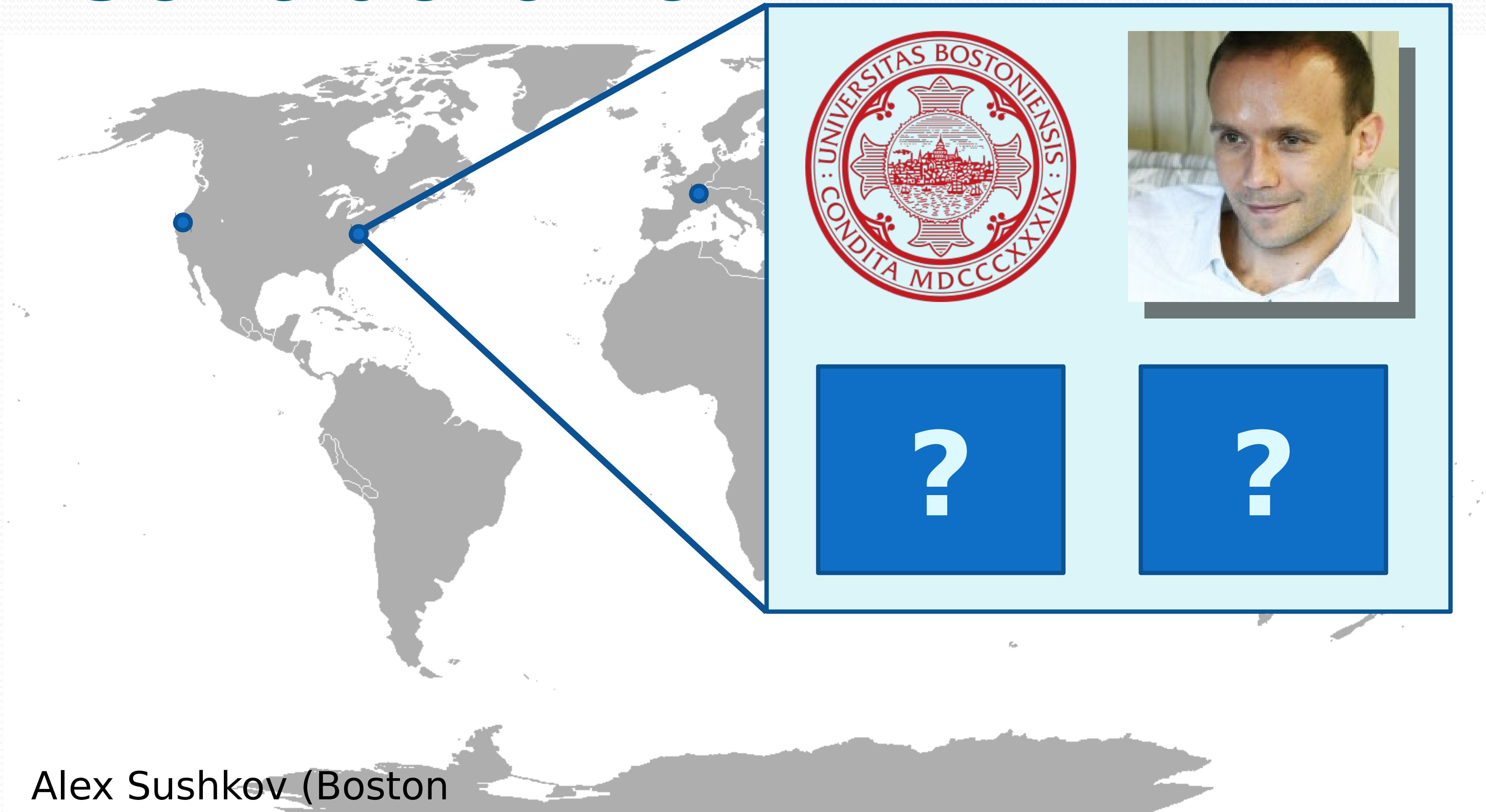
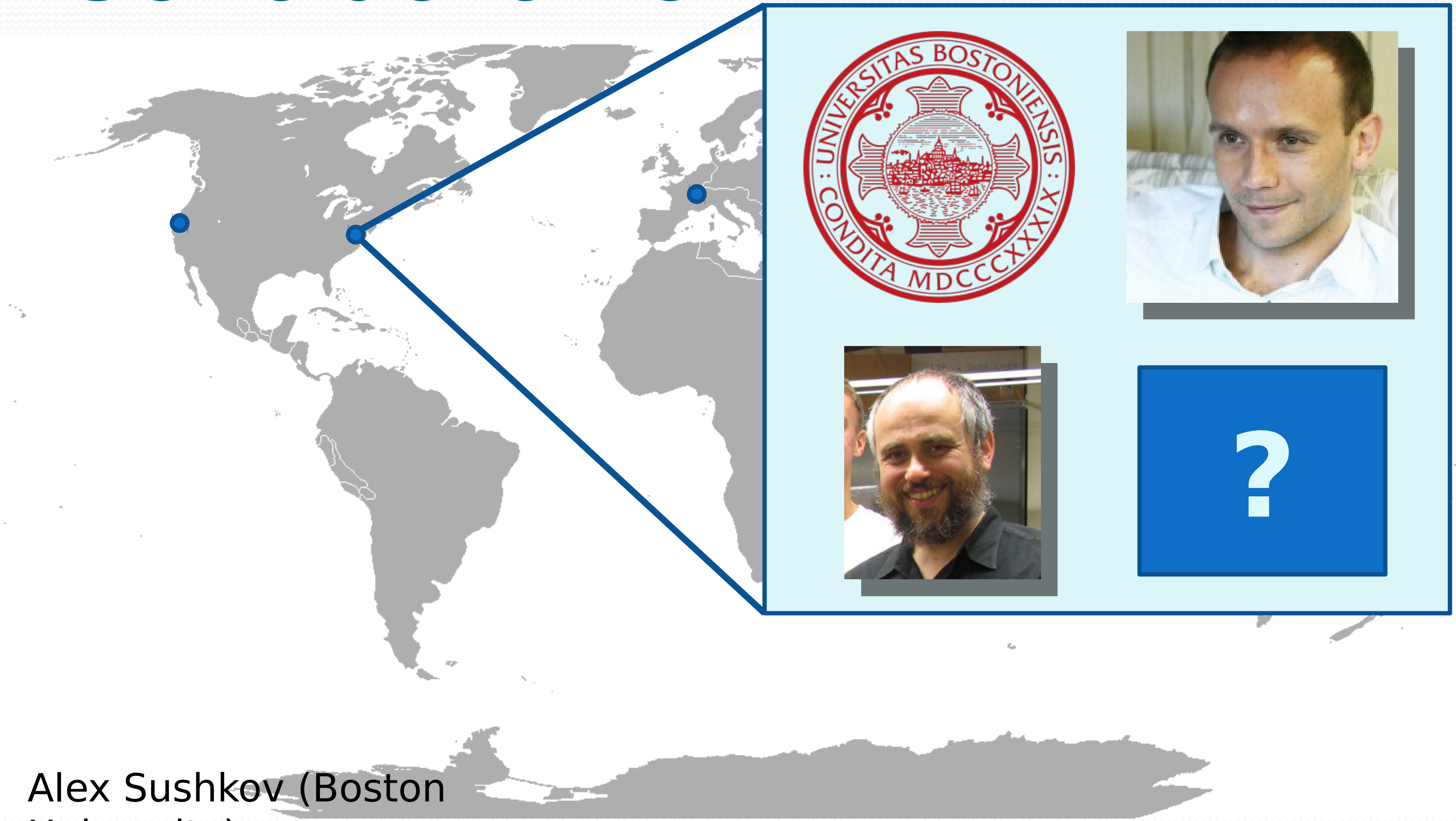


Alex Sushkov (Boston University)

Collaboration



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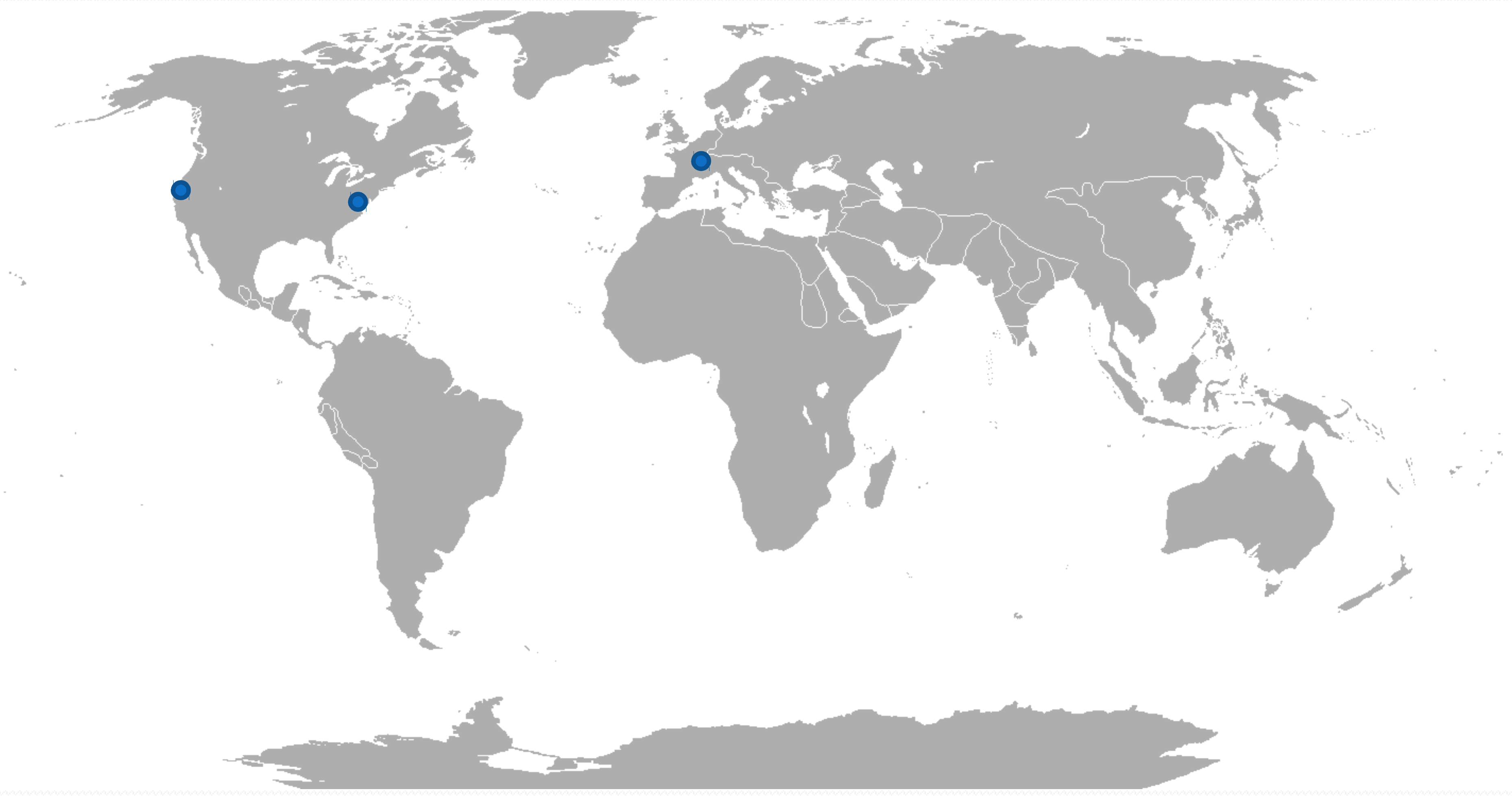
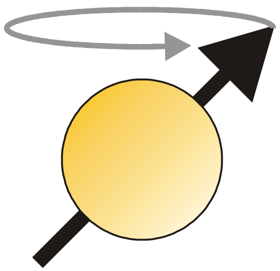


Cosmic **A**xion **S**pin **P**recession **E**xpe**r**iment **(CASPEr)**



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*

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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).

Outline

- Motivation and theory;
- CASPEr Electric;
- CASPEr Wind;
- Conclusions.

Motivation and theory

Axions

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

The strong interaction creates a potential for the QCD axion:

$$V_{\mathrm{QCD}} \approx \frac{1}{2} m_a^2 a^2 \ ,$$

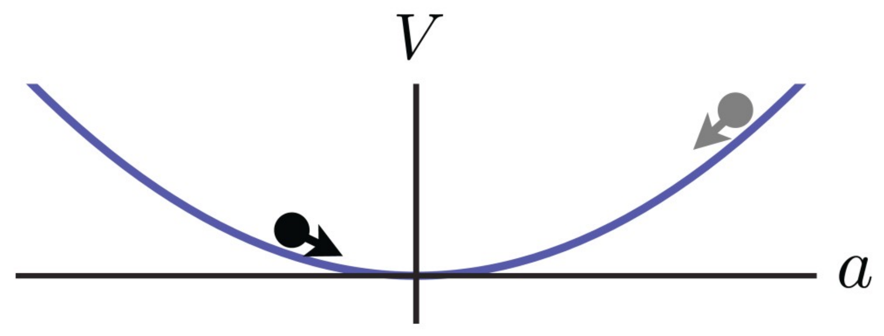
and the QCD axion mass is given by:

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

ALPs may have differen Λ and *f*.

Axion oscillations

When axions are produced after the Big Bang, the field can generally take on any initial value, and thus axions appear as a classical coherent oscillating field.



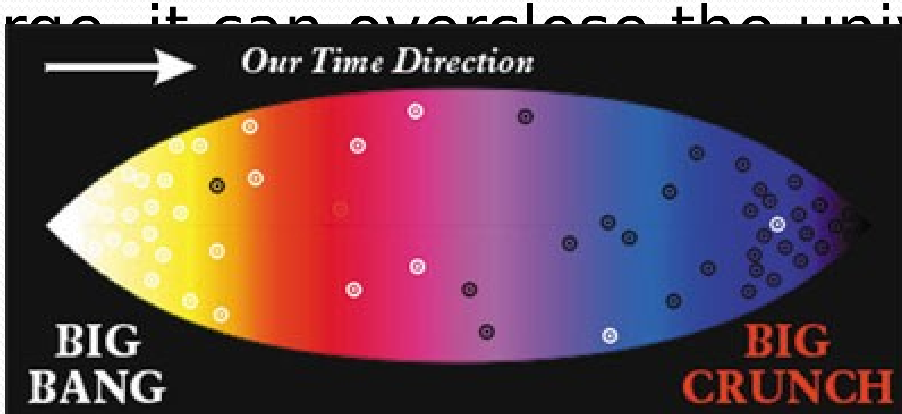
$$a(t) \sim a_0 \cos(m_a t)$$

Axions as dark matter

Axion oscillations store energy that can be the dark matter:

$$\rho_{\mathrm{DM}} \sim \frac{1}{2} m_a^2 a_0^2 \ .$$

In fact, if the energy density of the oscillating axion field is too large, it can overclose the universe!



Inflation and axion cosmology

If $\theta_{QCD} \sim 1$ in the early universe, then for the QCD axion:

$f_a \lesssim$ [illegible] GeV . The "anthropic" window

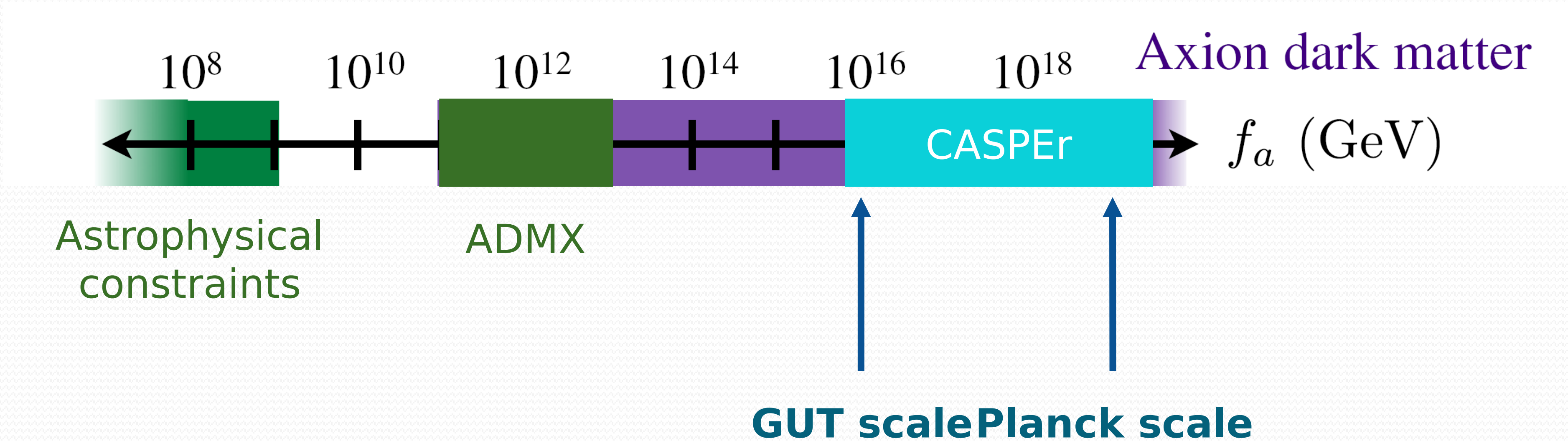
However, if the inflation scale is lower than f_a the universe before inflation can have an inhomogeneous distribution of a_0.

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

If $\theta_{QCD} \sim 1$ in the early universe, then for the QCD axion:

$f_a \lesssim$ GeV The “anthropic” window



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:

$$\begin{aligned} d &\approx 3 \times 10^{-16}\ \mathrm{e} \cdot \mathrm{cm} \times \frac{a}{f_a}\ , \\ &\approx \frac{3 \times 10^{-16}\ \mathrm{e} \cdot \mathrm{cm}}{f_a} \times a_0 \cos\left(m_a t\right)\ . \end{aligned}$$

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 EDM coupling

Assuming axions are the dark matter, the dark matter density fixes the ratio a_0/f_a:

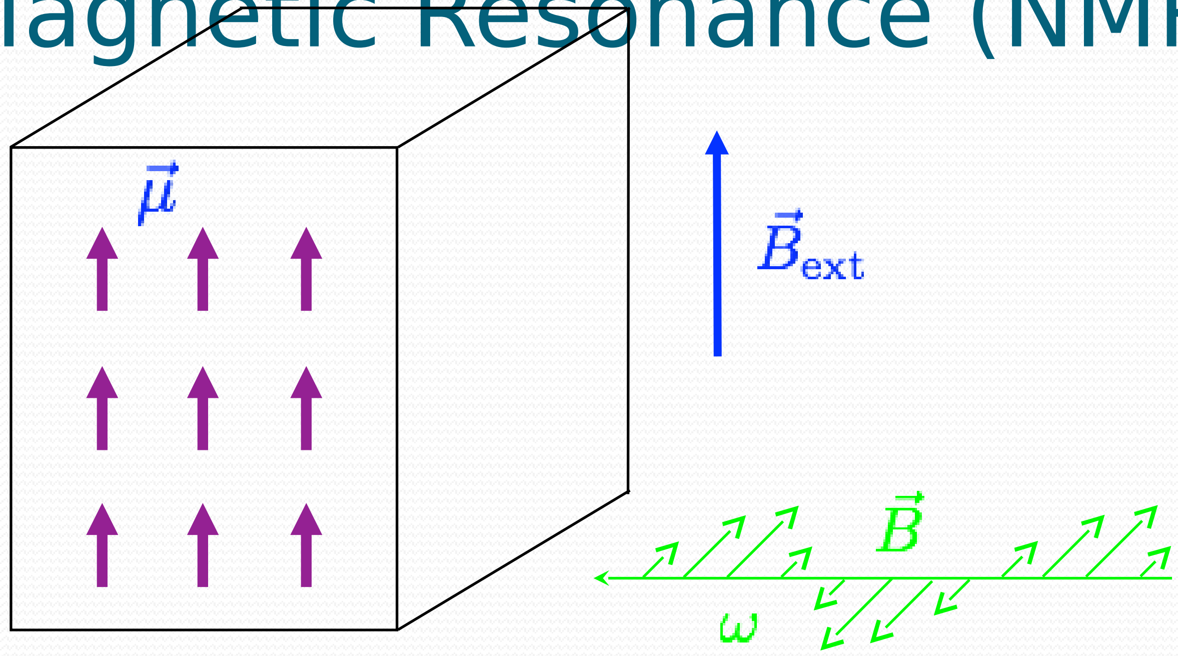
$$\rho_{\mathrm{DM}} \sim m_a^2 a_0^2 \sim \frac{(200\ \mathrm{MeV})^4}{f_a^2} a_0^2 \sim 0.3\ \frac{\mathrm{GeV}}{\mathrm{cm}^3}\ ,$$

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

This generates an oscillating EDM:

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

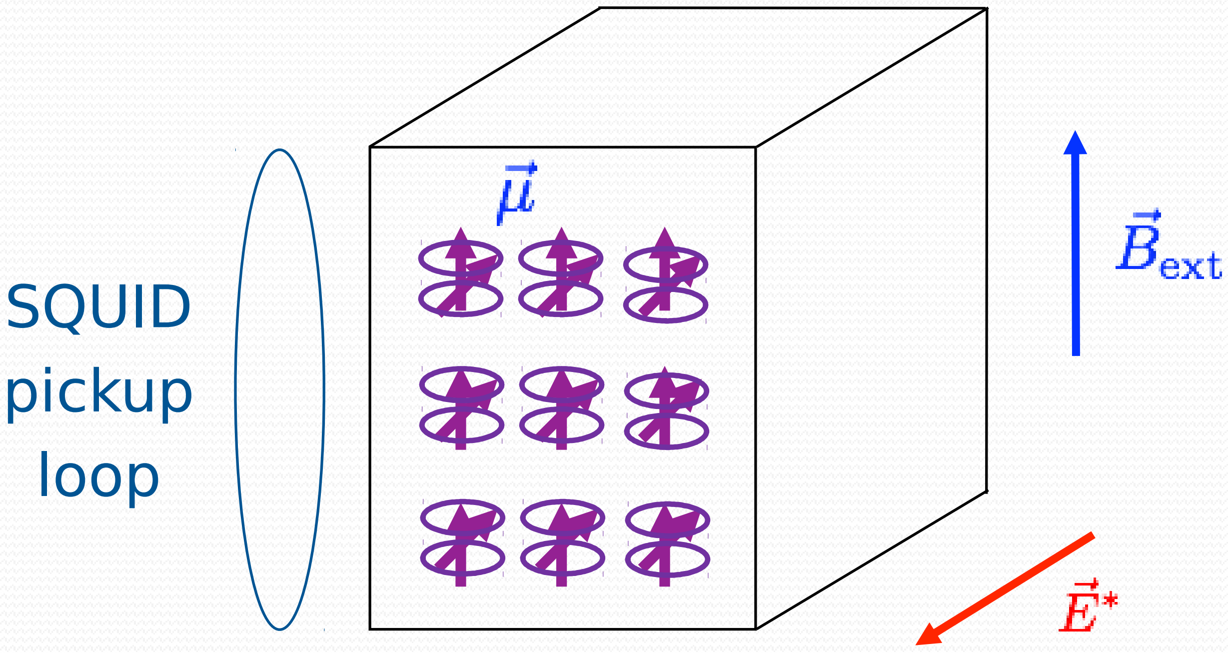
Nuclear Magnetic Resonance (NMR)



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 mass ➔ resonant enhancement.

Signal estimate

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

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

SQUID sensitivity:

$$\delta B \approx 10^{-11} \frac{\mathrm{G}}{\sqrt{\mathrm{Hz}}} \ .$$

Sample choice

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

Need maximum n, p, E^*, and ε_S, and (up to a point) long T_2.

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

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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*

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Coherence time

Coherence length of the axion field is given by its de Broglie wavelength:

$$\lambda \sim \frac{\hbar}{m_a v} \ ,$$

which translates to a coherence time as the Earth moves through the axion field:

$$\tau_{\mathrm{a}} \sim \frac{\lambda}{v} \sim \frac{\hbar}{m_a v^2} \ ,$$

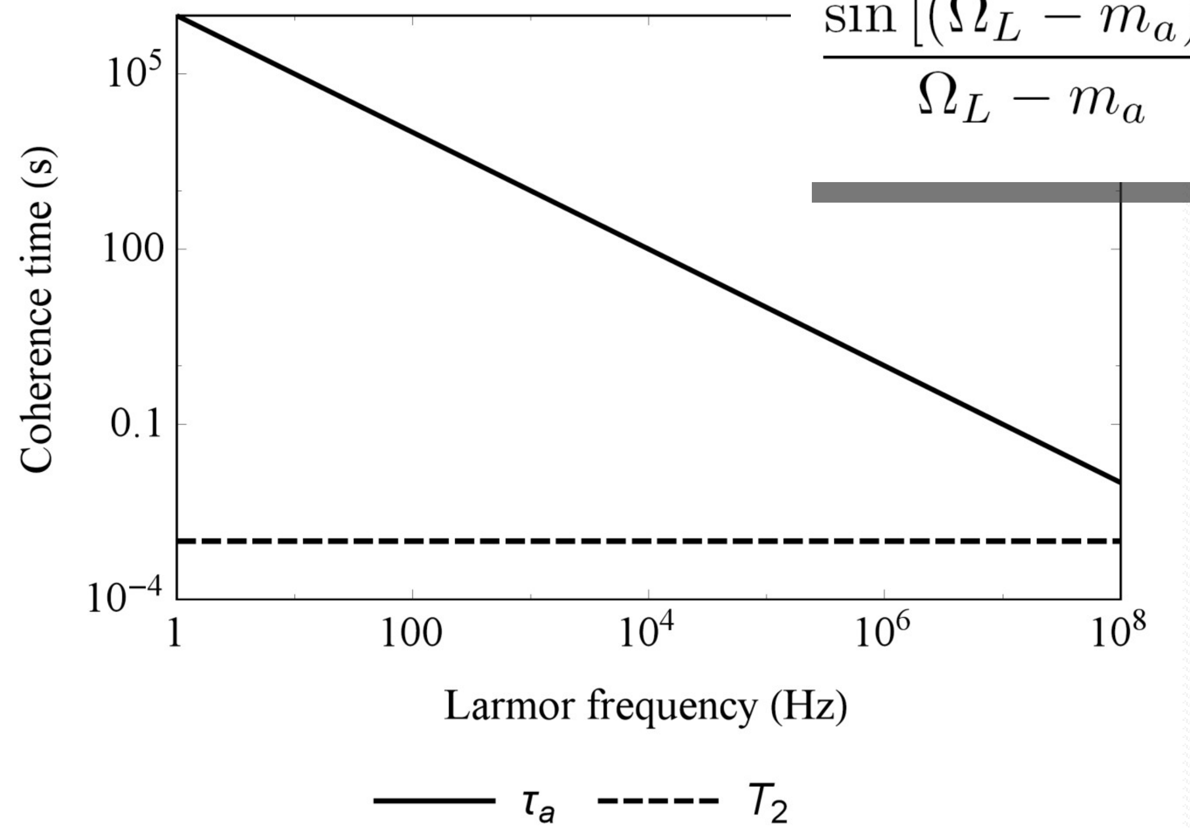
with virial velocity:

$$v \sim 10^{-3} c \ .$$

Coherence time

Measured coherence time in $PbTiO_3$ is $T_2 \approx 1$ ms, at cryogenic temperatures $T_1 \approx 1000$ s

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



Signal estimate

Oscillating magnetization is given by:

$$M(t) \approx (np\mu) \times (\epsilon_S dE^*) \times T_2 \times \sin(\Omega_L t) \ ,$$

For $PbTiO_3$ under our experimental conditions:

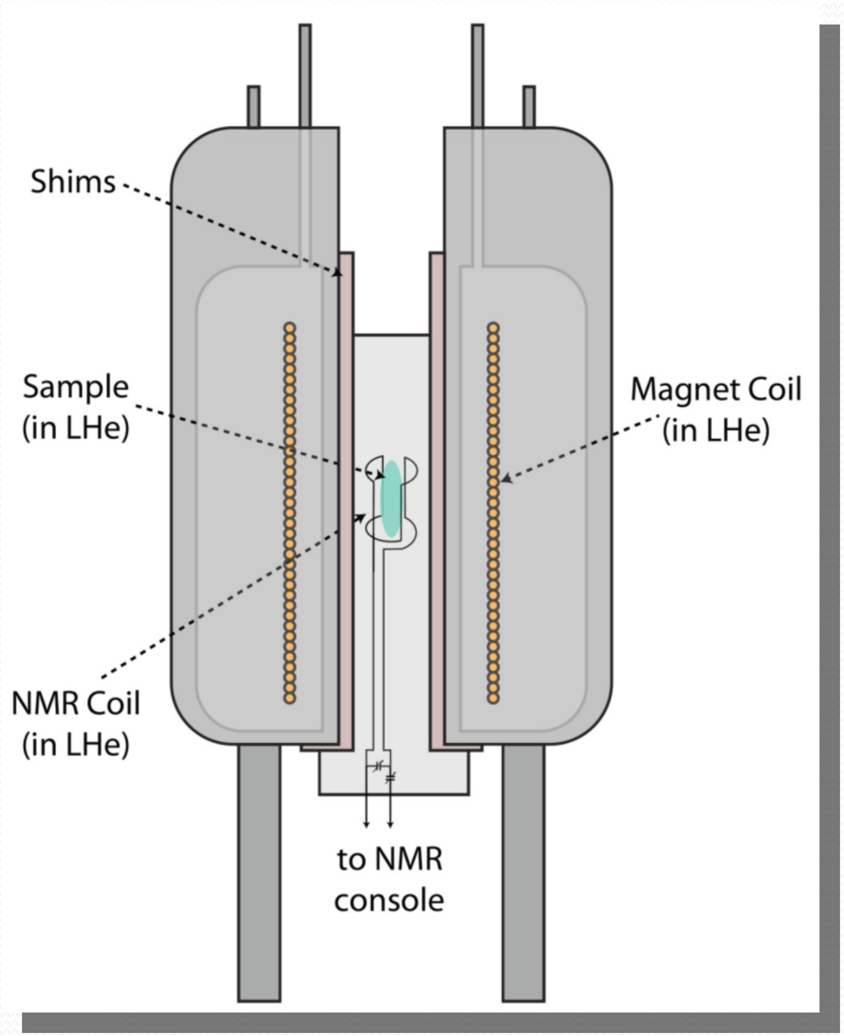
$$M(t) \approx 10^{-11} \ \mathrm{G} \times \left(\frac{g_d \left[\mathrm{GeV}^{-2}\right]}{m_a [\mathrm{eV}]} \right) \times \sin(\Omega_L t) \ .$$

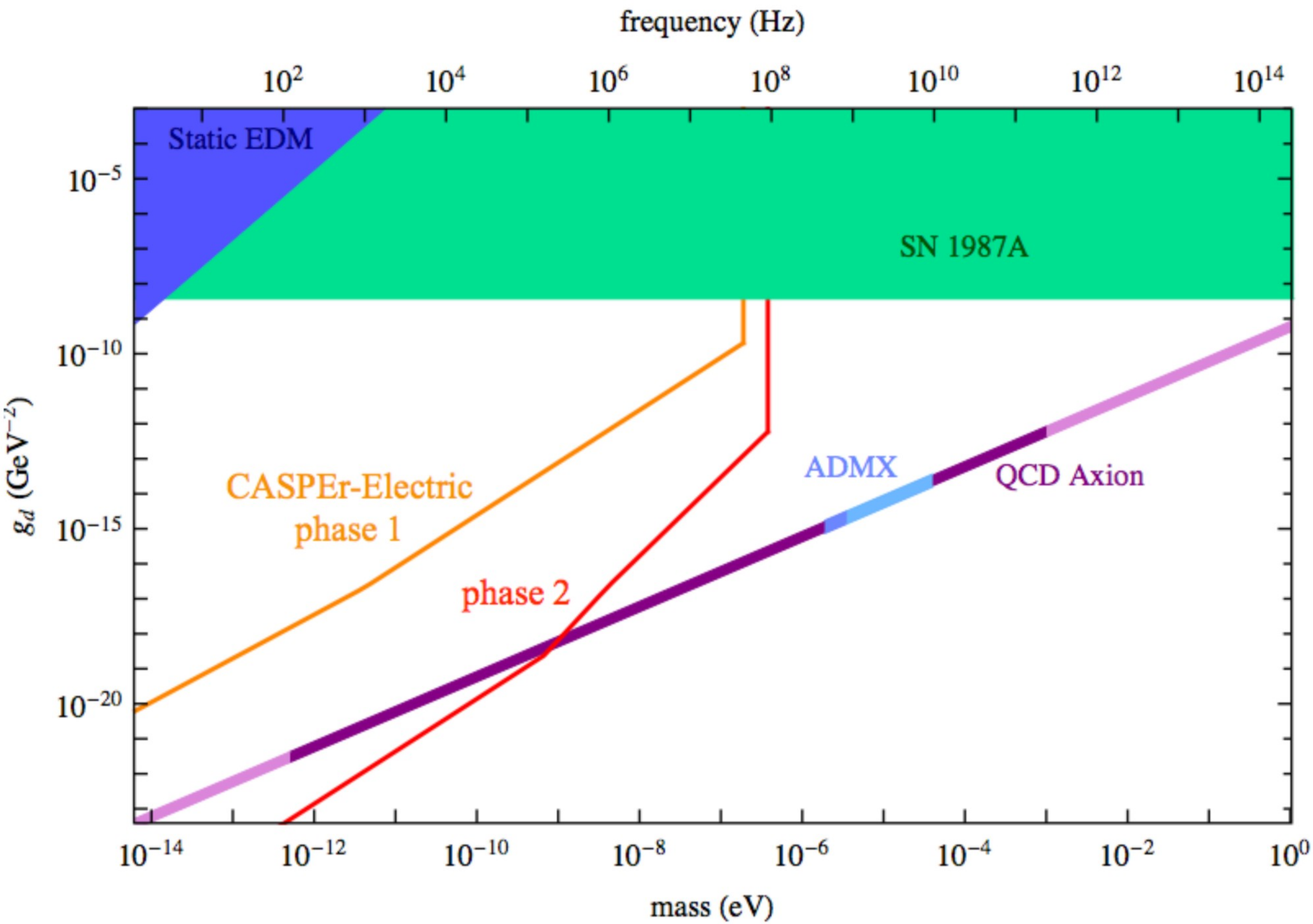
Experimental strategy

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

(2) Scan magnetic field from
10 T $\rightarrow$ 0 T; Larmor frequency decreases from 45 MHz;

(3) Integrate for about 20 ms at each frequency, a





Experimental sensitivity

Phase 2 requirements

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

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

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

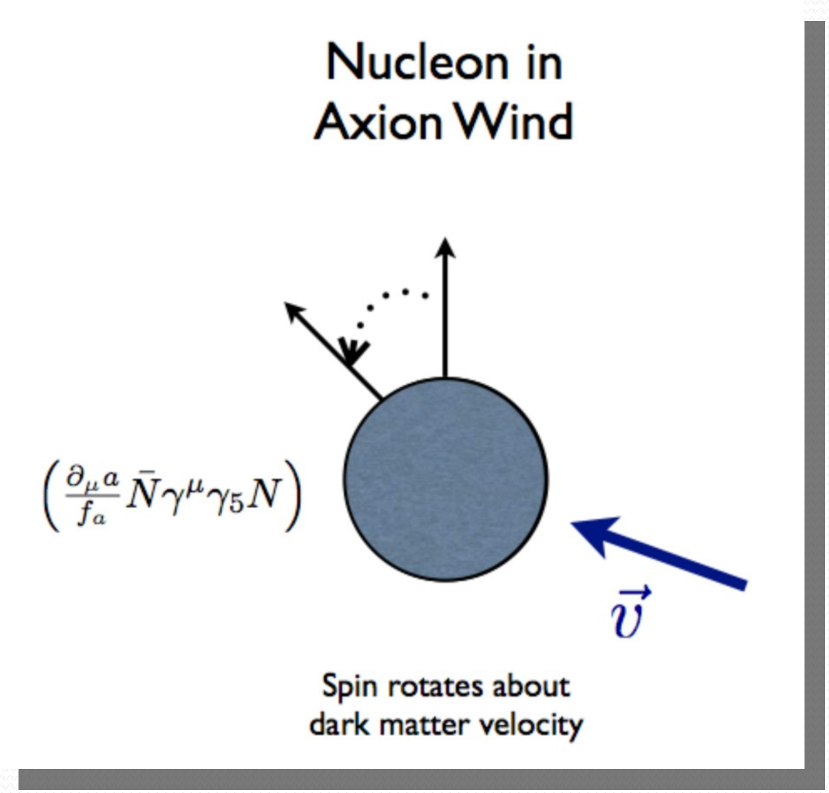
R&D required!

CASPEr Wind

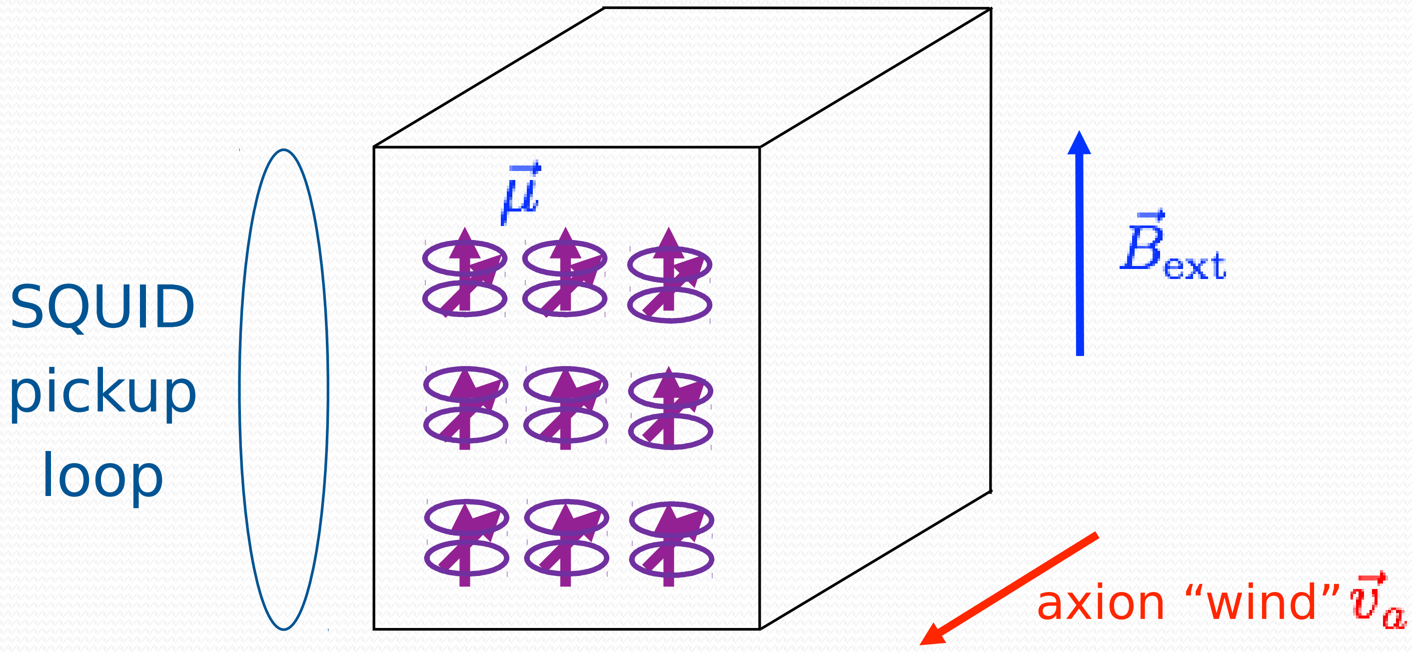
Axion/ALP-induced spin precession (axion wind)

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



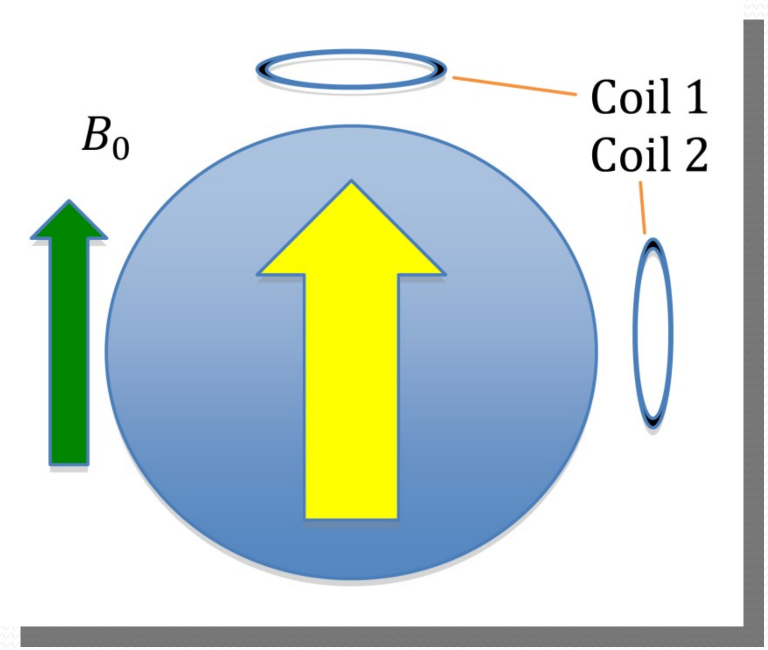
Larmor frequency = axion mass ➔ resonant enhancement.

Signal amplification

$$B(Coil\ 1) = \frac{8\pi\mu}{3} n\ .$$

During coherence time τ, polarized spins rotate by angle:

$$\varphi \approx B_{ALP} \mu \tau\ ,$$

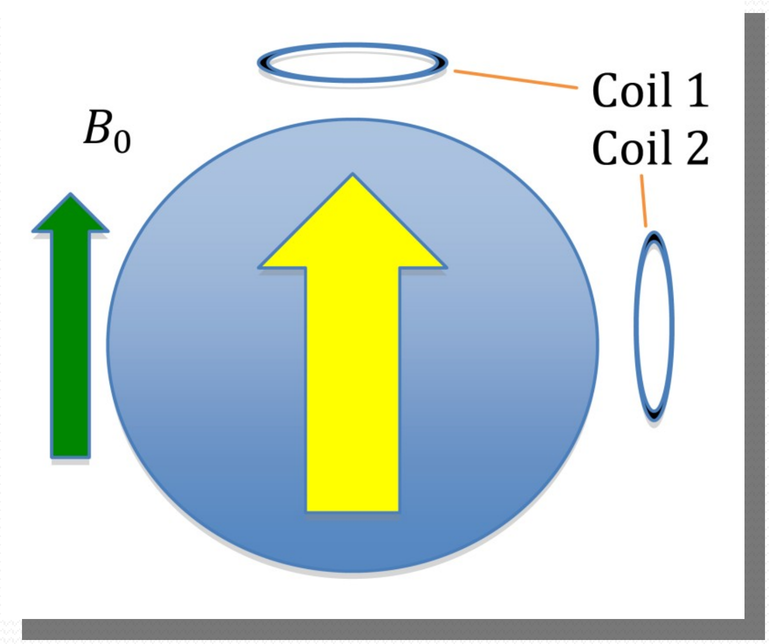


Signal amplification

Oscillating field detected by Coil 2 is given by:

$$B(Coil\ 2) \approx B(Coil\ 1)\varphi = \boxed{\frac{8\pi}{3} n\mu^2\tau} \cdot B_{ALP}\ .$$

Enhancement factor!



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

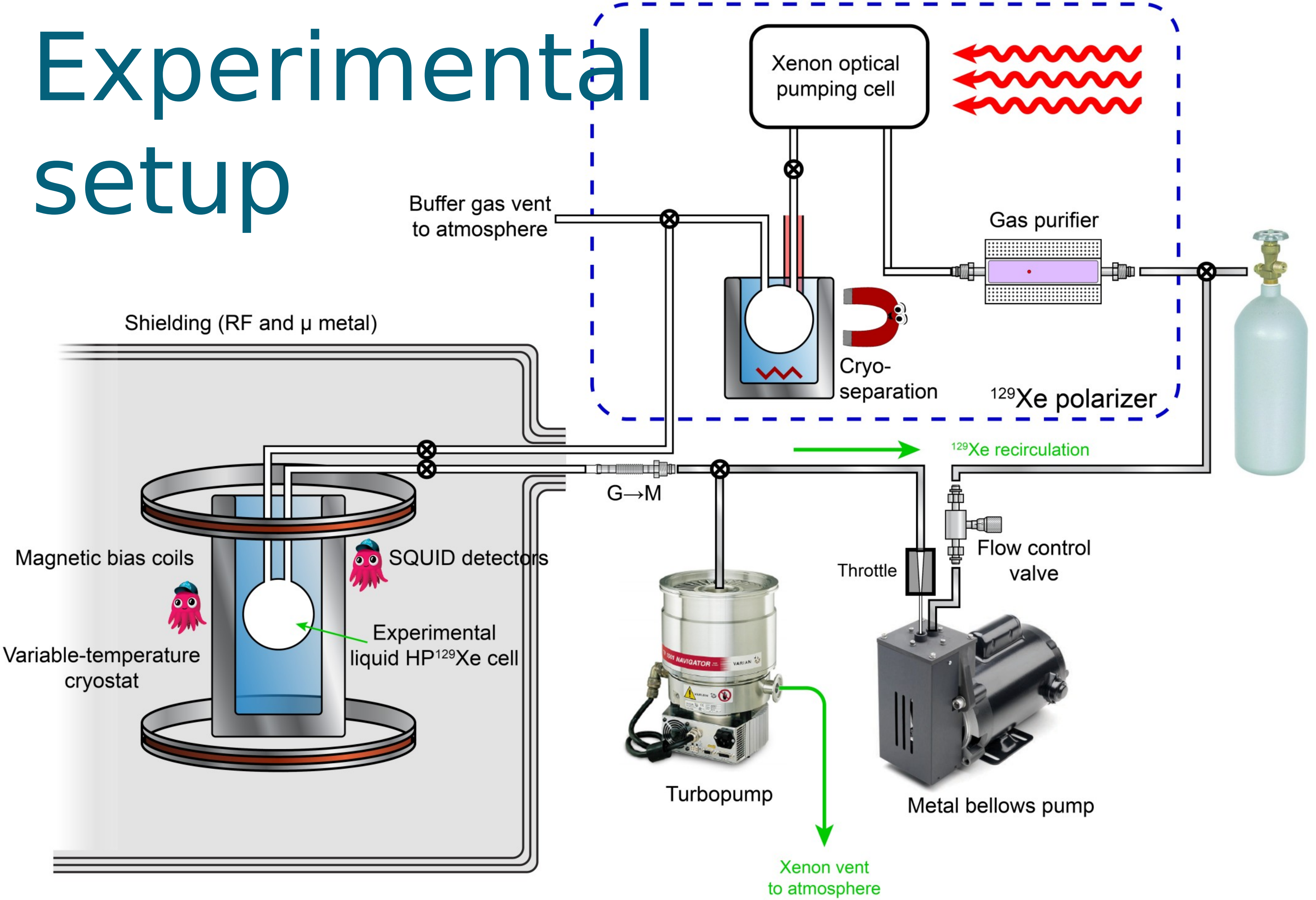
Relatively large sample can be hyperpolarized.

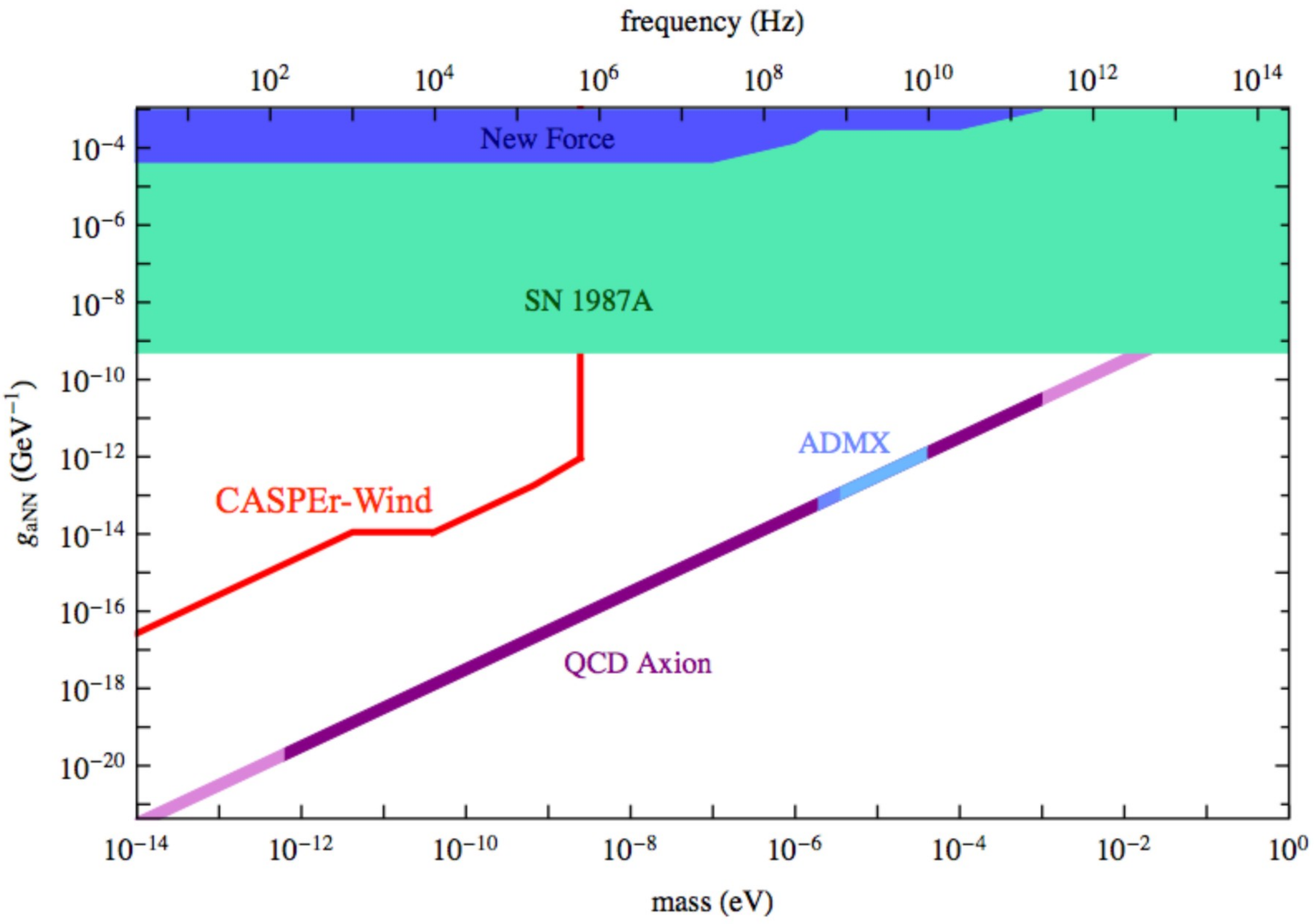
n this case, the enhancement factor can be on the order of 1

Coupling constant in magnetic field units is:

$$g_{aNN} \approx 3 \times 10^3 \times B[\mathrm{G}]\ \mathrm{GeV}^{-1}\ .$$

Experimental setup





Experimental sensitivity

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!