CASPER:

THE COSMIC AXION SPIN PRECESSION EXPERIMENT

DEREK F. JACKSON KIMBALL

SIMONS FOUNDATION
erc
DFG
HEISING - SIMONS FOUNDATION
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NSF

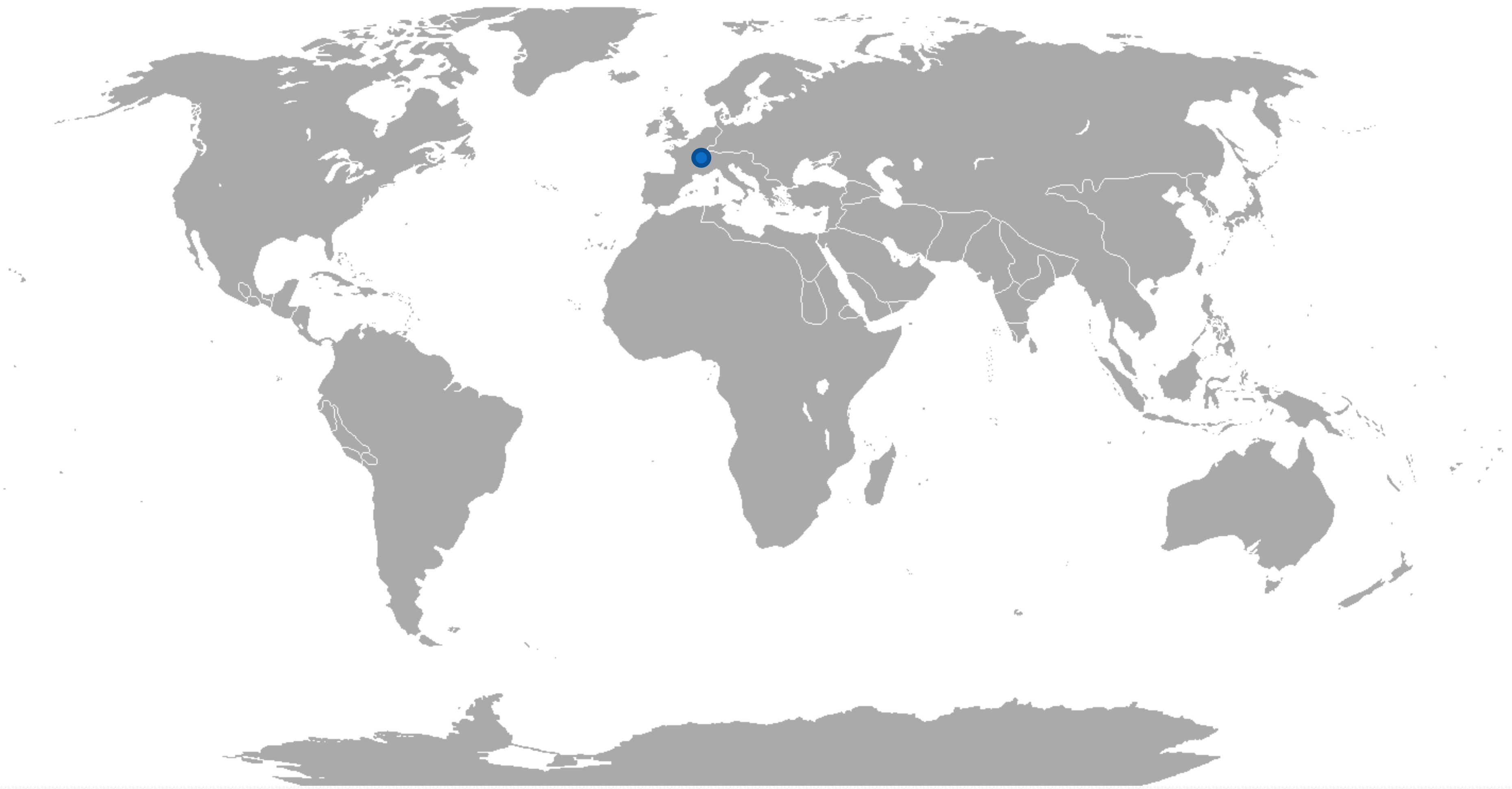
What we really need to search for dark matter…

Dmitry Budker

Optimism!

FANTASTIC COLLABORATION!

Collaboration



Collaboration

Dmitry Budker,
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Marina Gil Sendra,
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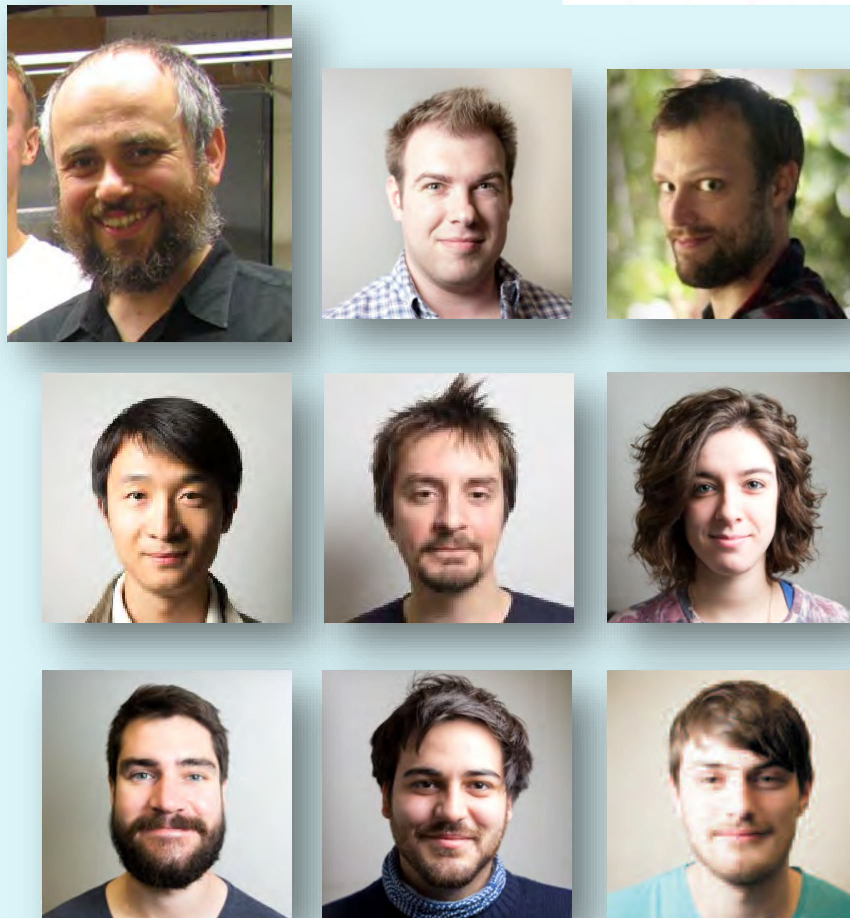
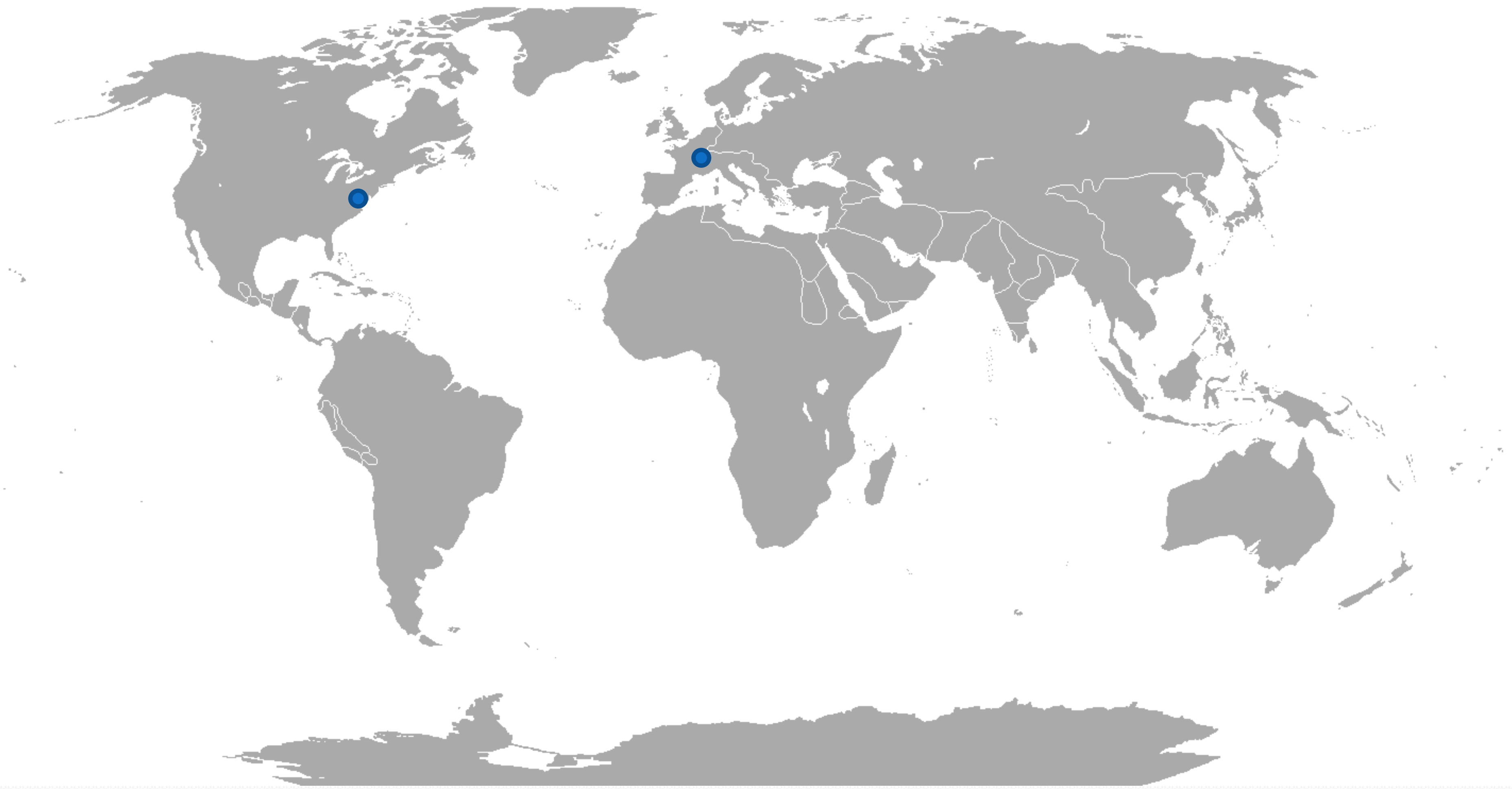
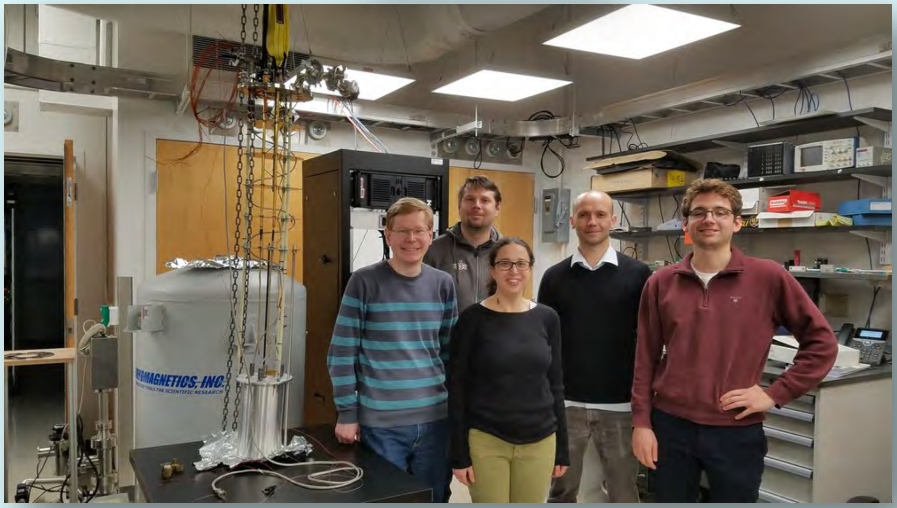


Collaboration



Collaboration



Alex Sushkov,
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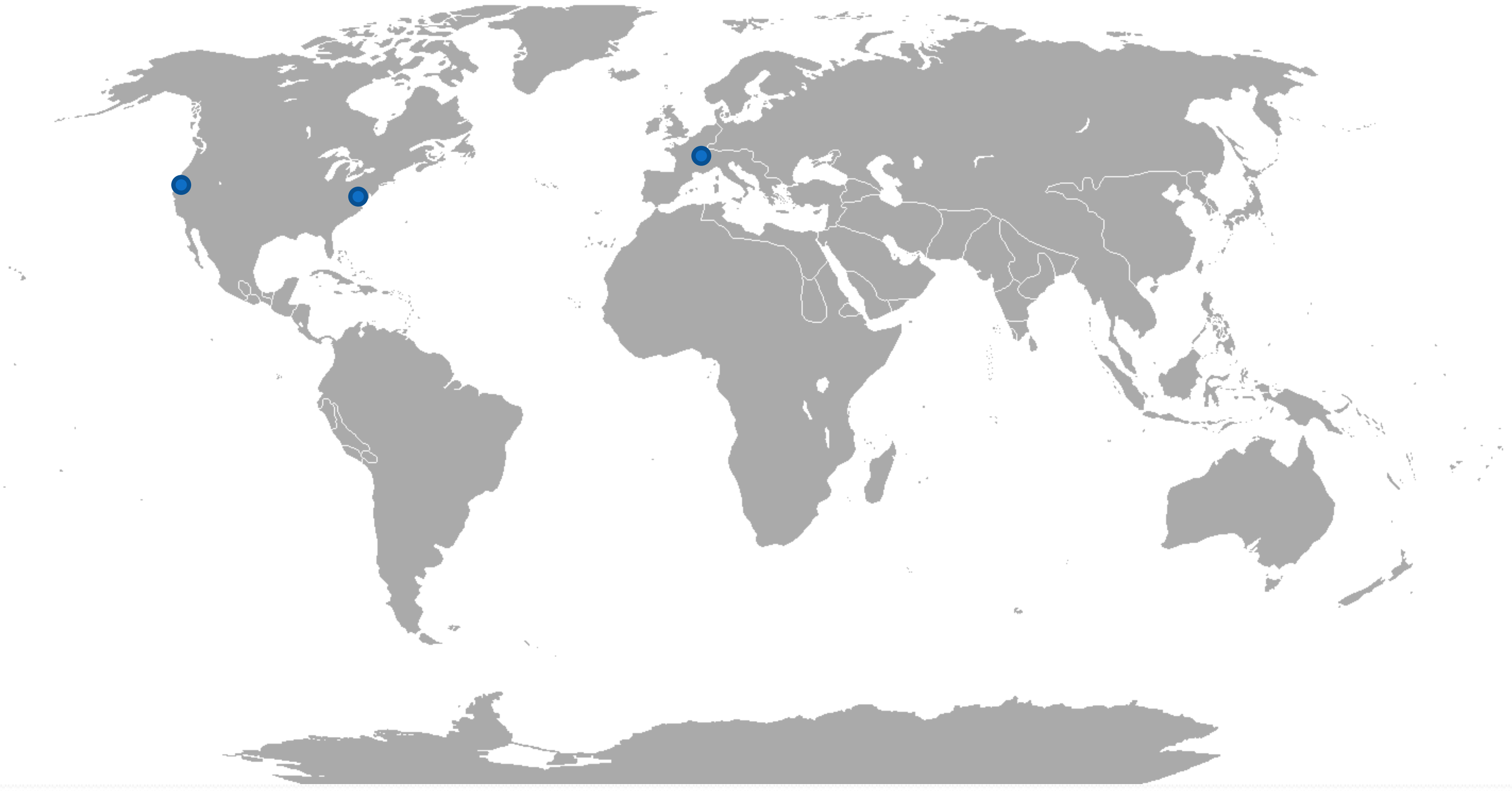
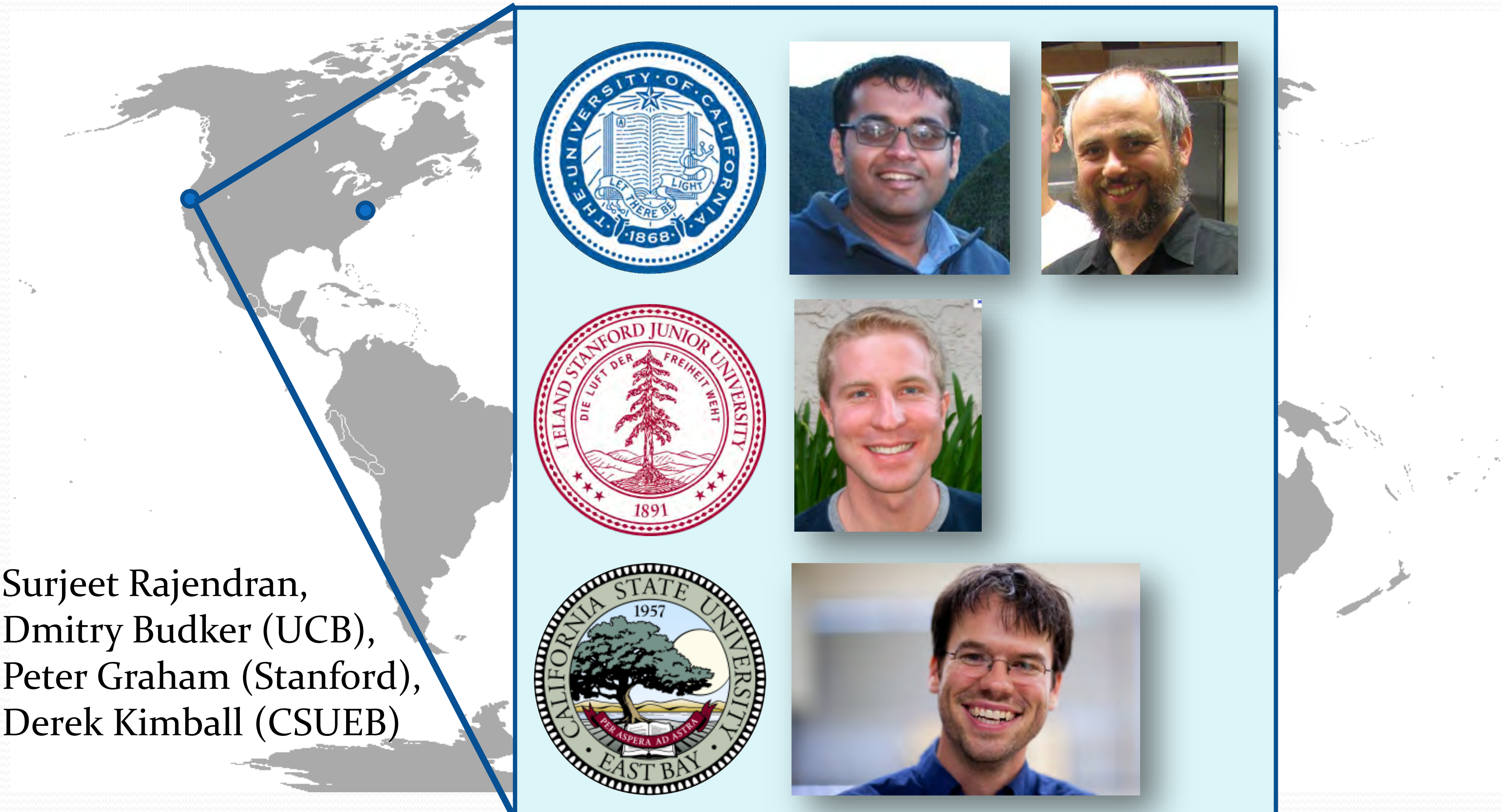
Janos Adam,
Jack Stropko

Collaboration



Collaboration



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

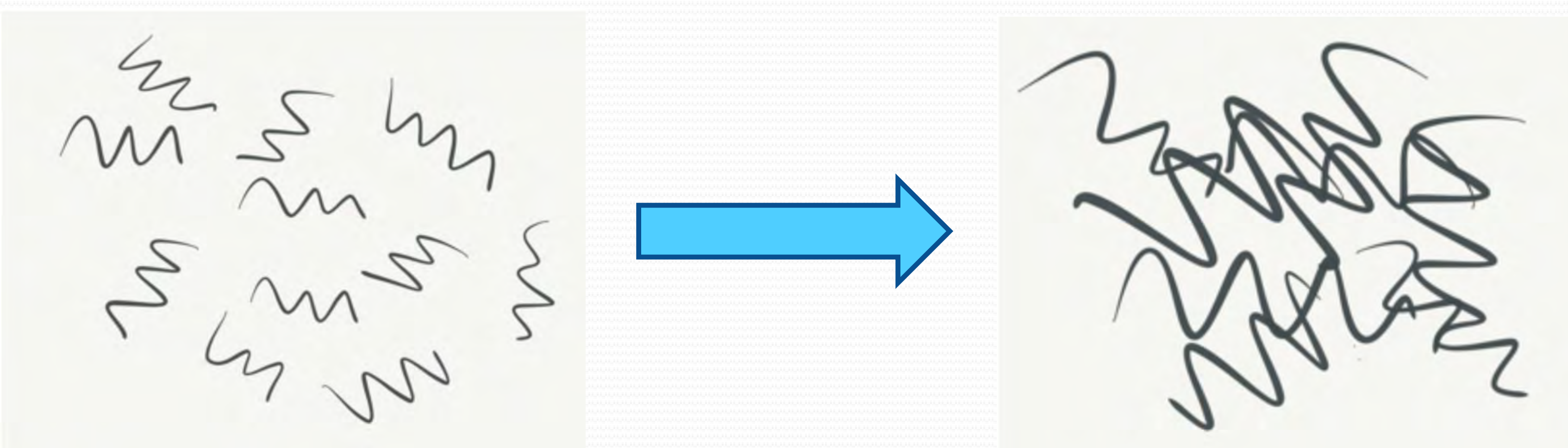
OUTLINE

- Ultralight bosonic dark matter and axions.
- CASPEr-electric.
- CASPEr-wind Ultralow Field.
- CASPEr-wind Low Field.

Ultralight bosonic dark matter

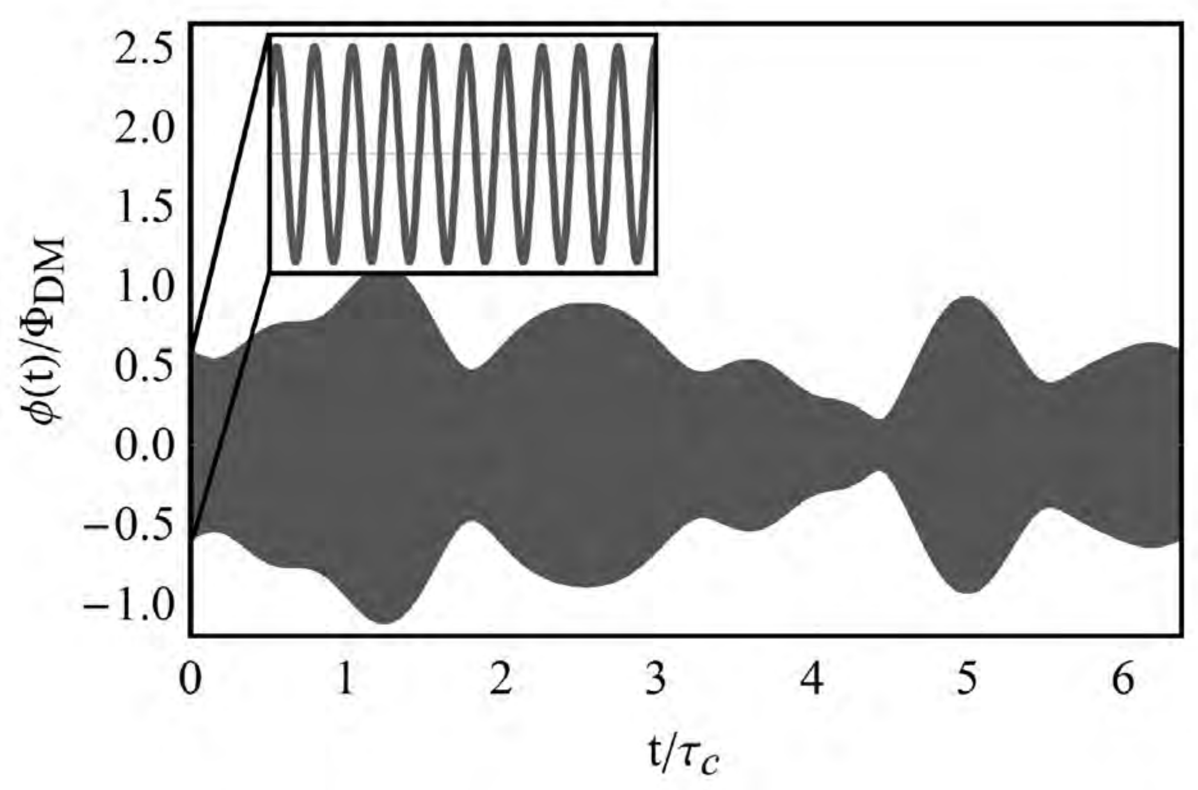
Many ultralight bosons can occupy a single state.

Standard Halo Model: manifest as a classical oscillating field with a coherence length given by their deBroglie wavelength.



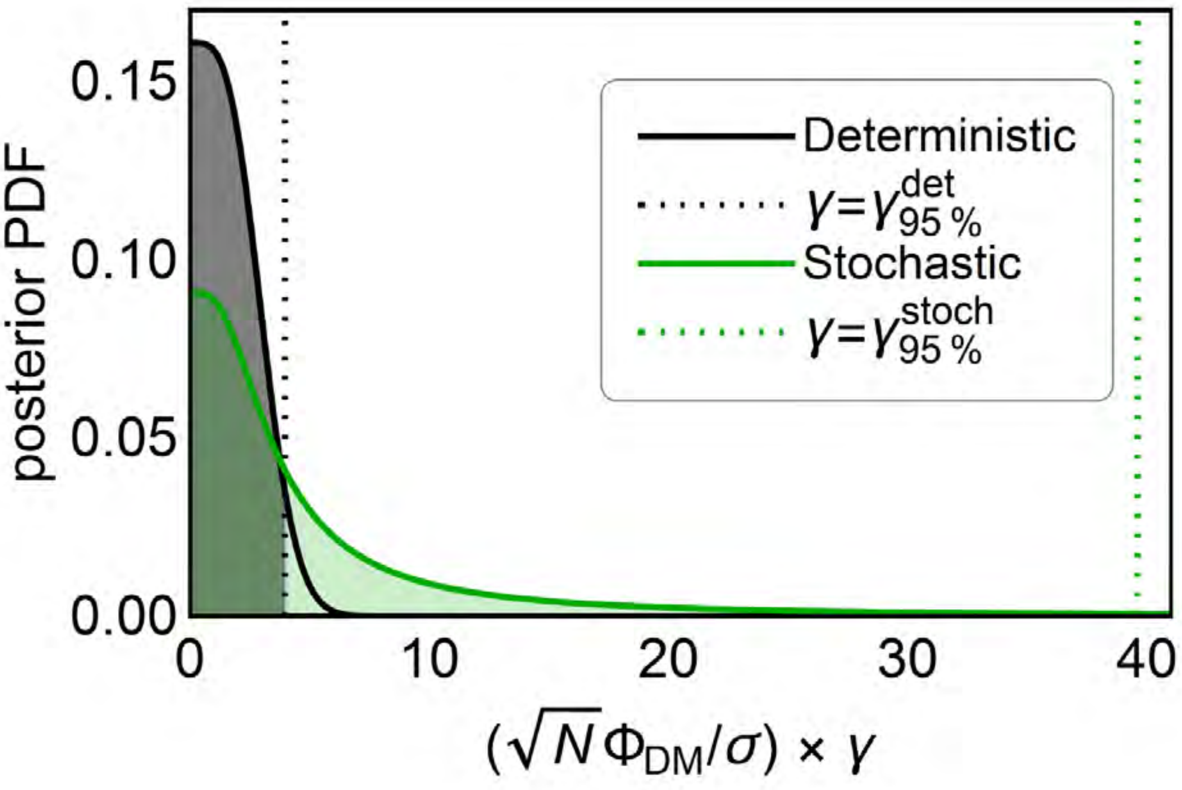
Ultralight bosonic dark matter

Locally observed dark matter amplitude is the result of interference of bosonic waves with random phases, thus has stochastic fluctuations (akin to chaotic light).



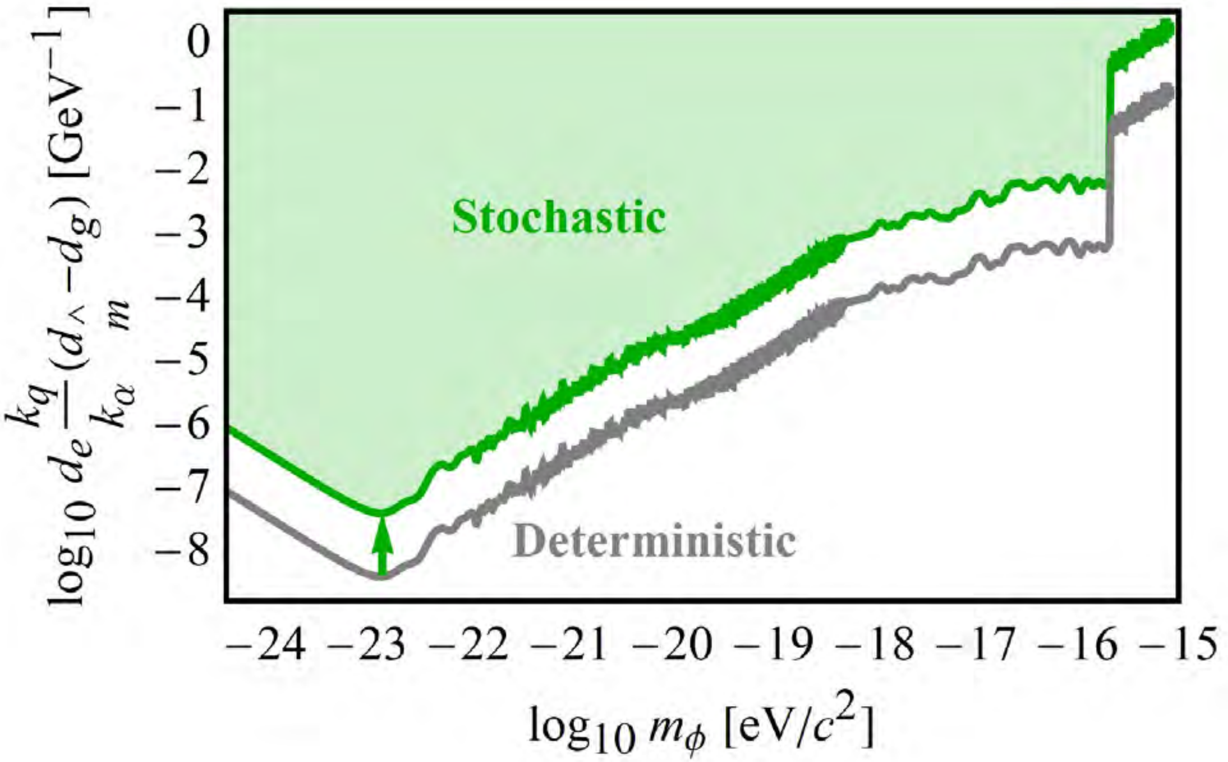
Ultralight bosonic dark matter

Locally observed dark matter amplitude is the result of interference of bosonic waves with random phases, thus has stochastic fluctuations (akin to chaotic light).



Ultralight bosonic dark matter

Affects interpretation of data if few coherence times are sampled in experiment!



Discussed in
Centers et al., arXiv:1905.13650.

Axions

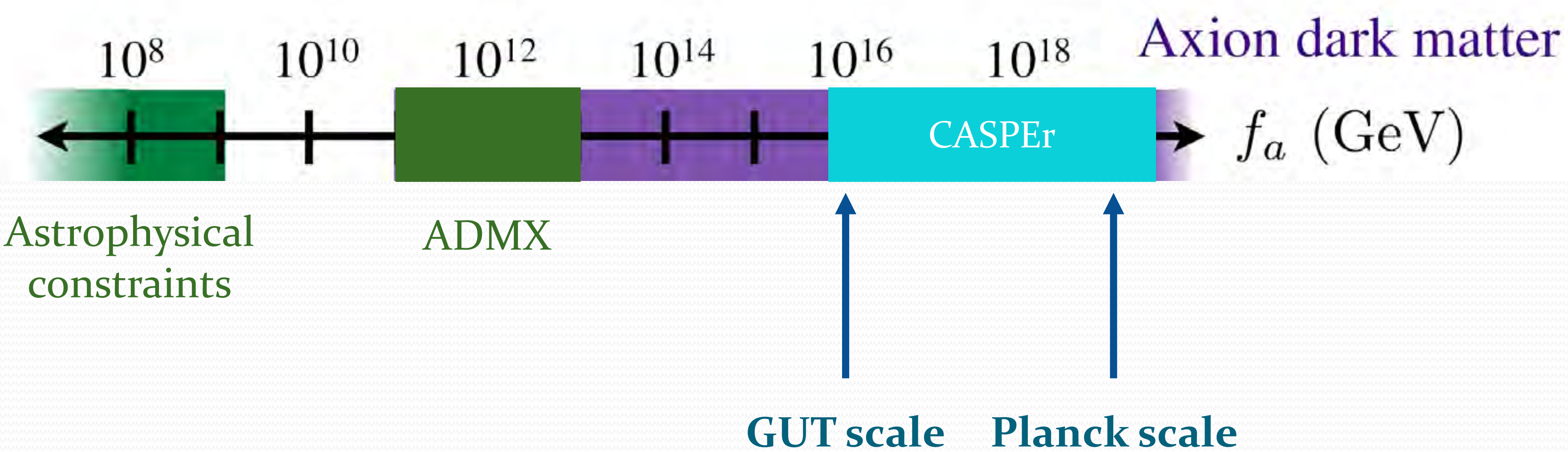
Axions are spin-zero bosons that arise due to symmetries broken at a high energy scale f_a.

They appear in many extensions of the Standard Model (e.g., in string theory and in solutions to the hierarchy problem).

The axion mass is proportional to the symmetry-breaking scale:

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

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 fermions

CASPEr Wind

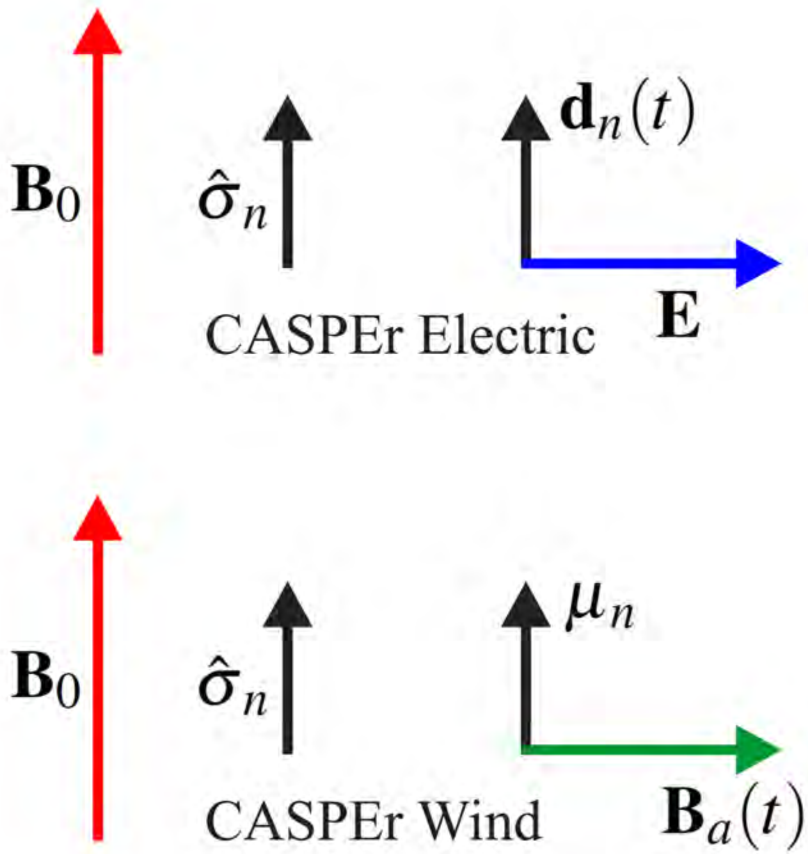
Axion-induced spin precession

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

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

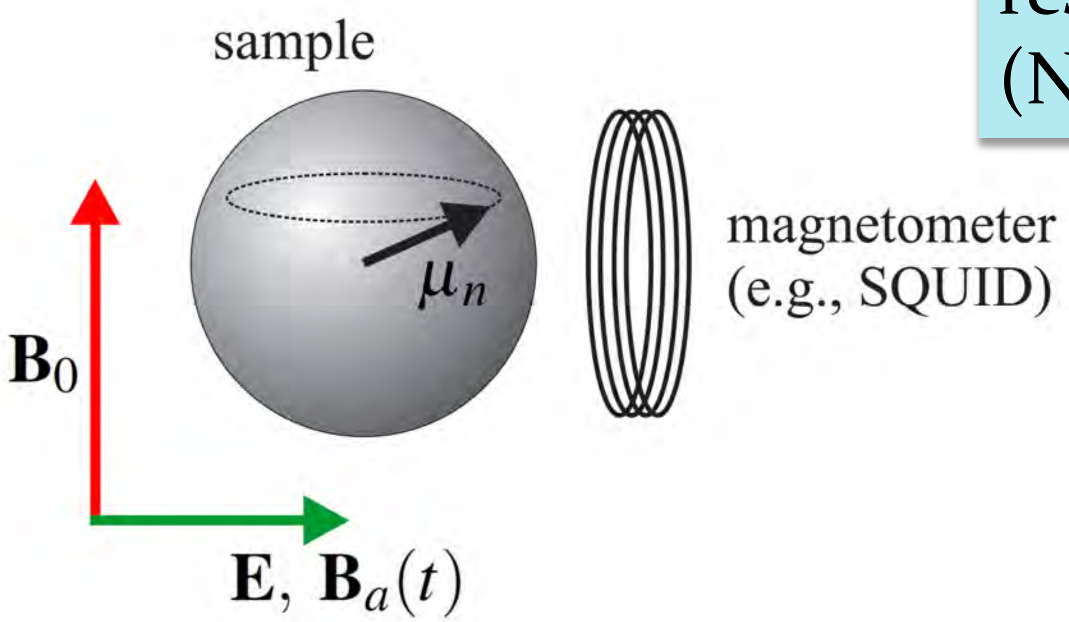
$$\tau_{\text{wind}} = \mu_n \times \mathbf{B}_a(t)$$

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



Axion field detection

Completely analogous to nuclear magnetic resonance (NMR)!



Larmor frequency = axion field oscillation frequency
➔ resonant enhancement.

CASPEr Electric

Axion-induced electric dipole moments (EDMs)

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

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

Nuclear EDM from axion field:

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

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

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:

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

Signal estimate

$$M \approx nP\mu_n \varphi_{\mathrm{EDM}} \approx nP\mu_n \frac{\varepsilon_S d_n E^* T_2}{\hbar}$$

$$\approx nP\mu_n \frac{\varepsilon_S E^* T_2}{\hbar} \frac{g_d}{m_a} \sqrt{\frac{2\hbar^3}{c} \rho_{\mathrm{DM}}} \, ,$$

n = nuclear spin density,
P = nuclear polarization,
μ_n = magnetic moment,
E^* = effective electric field,
ε_S = Schiff suppression,
Ω_L = Larmor frequency.

Sample choice

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

Better sensitivity with larger n, P, E^*, and long T_2.

For the first generation CASPEr-Electric experiment, we use a ferroelectric crystal: PMN-PT.

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

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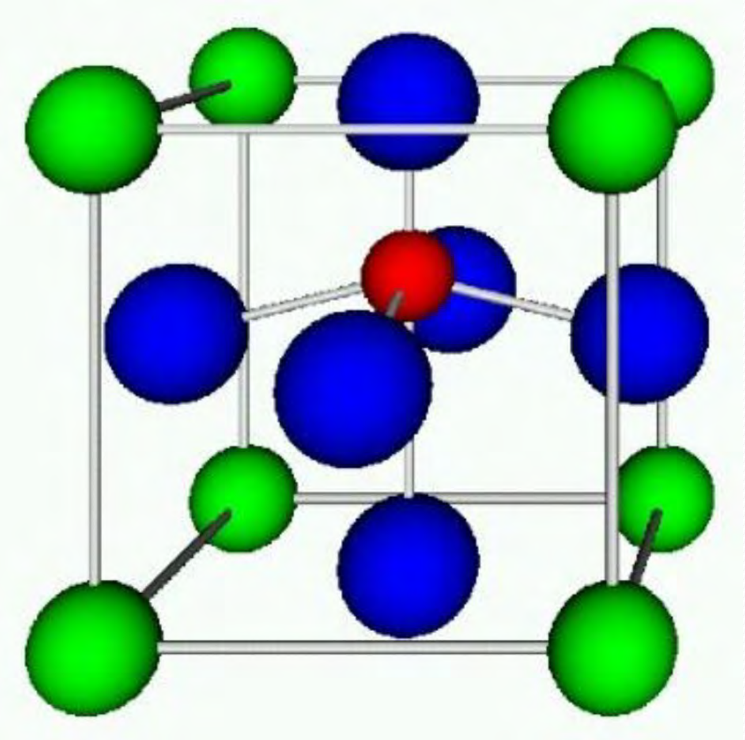
(Received 15 November 2007; published 4 February 2008)

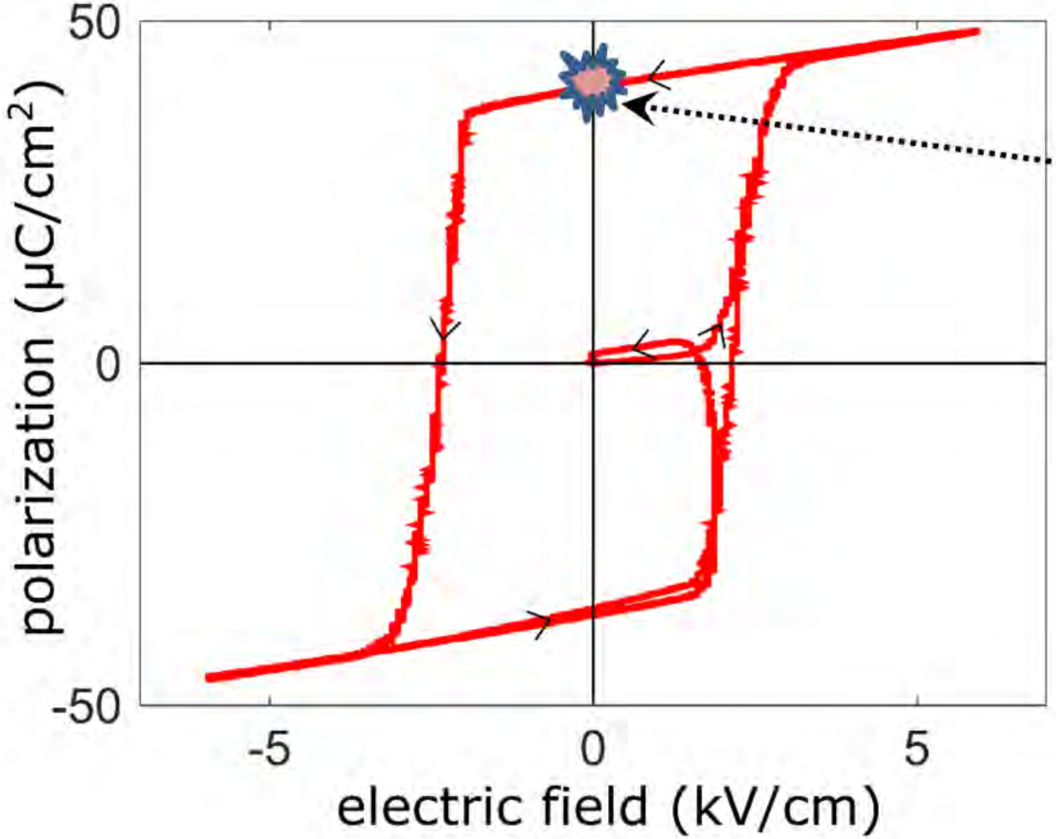
PMN-PT

In a ferroelectric oxide, oxygen electrons penetrate into the Pb ion core, creating a gradient of electron density at the Pb nucleus.

Avoids Schiff cancellation via finite size nucleus and relativistic effects.



PMN-PT



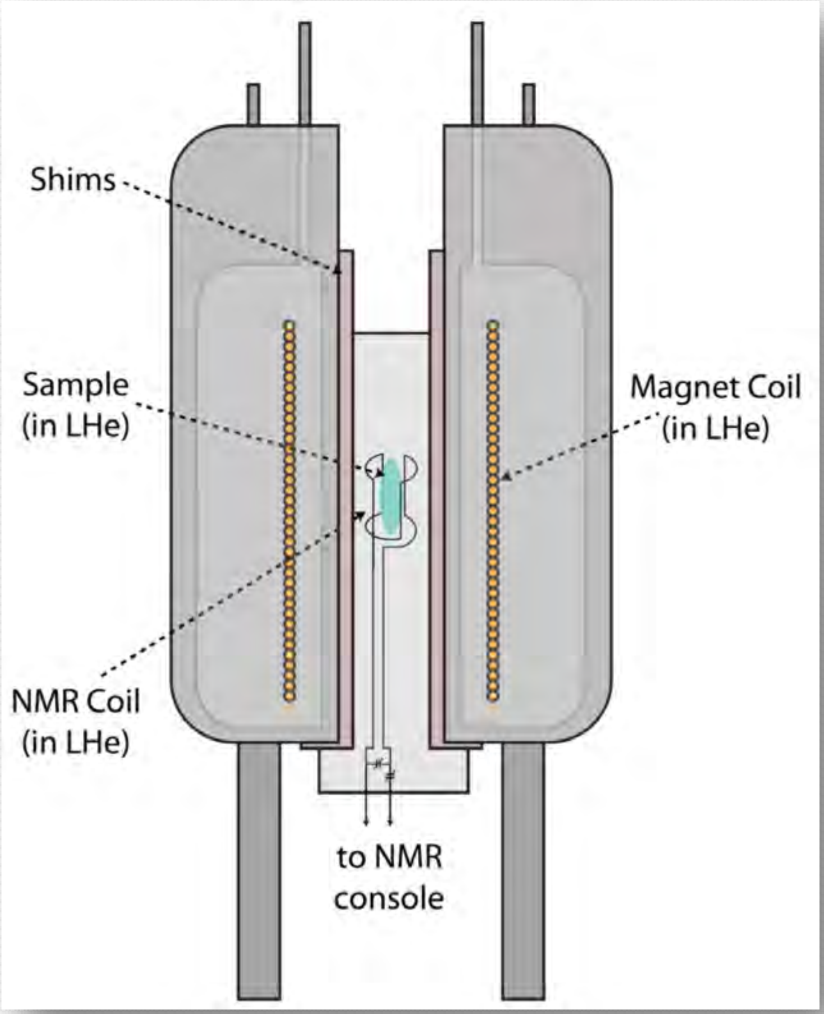
remanent polarization consistent with $E^* = 3 \times 10^8 \, \mathrm{V/cm}$

Experimental strategy

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

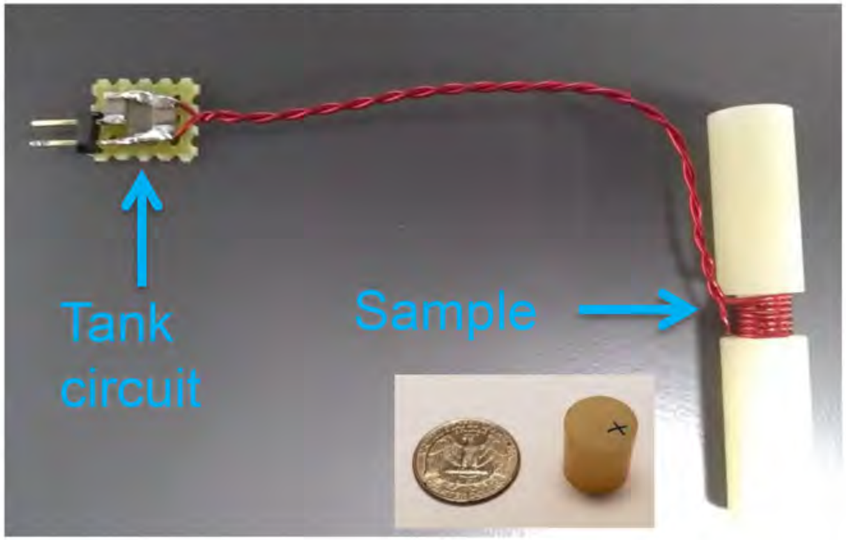
(2) Scan magnetic field down from 10 T -- Larmor frequency decreases from ~ 50 MHz;

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

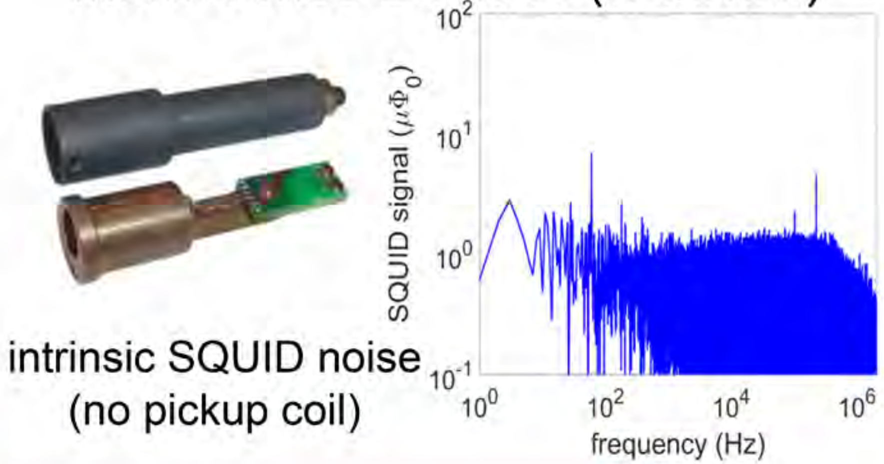


Detection

Low Noise Amplifier



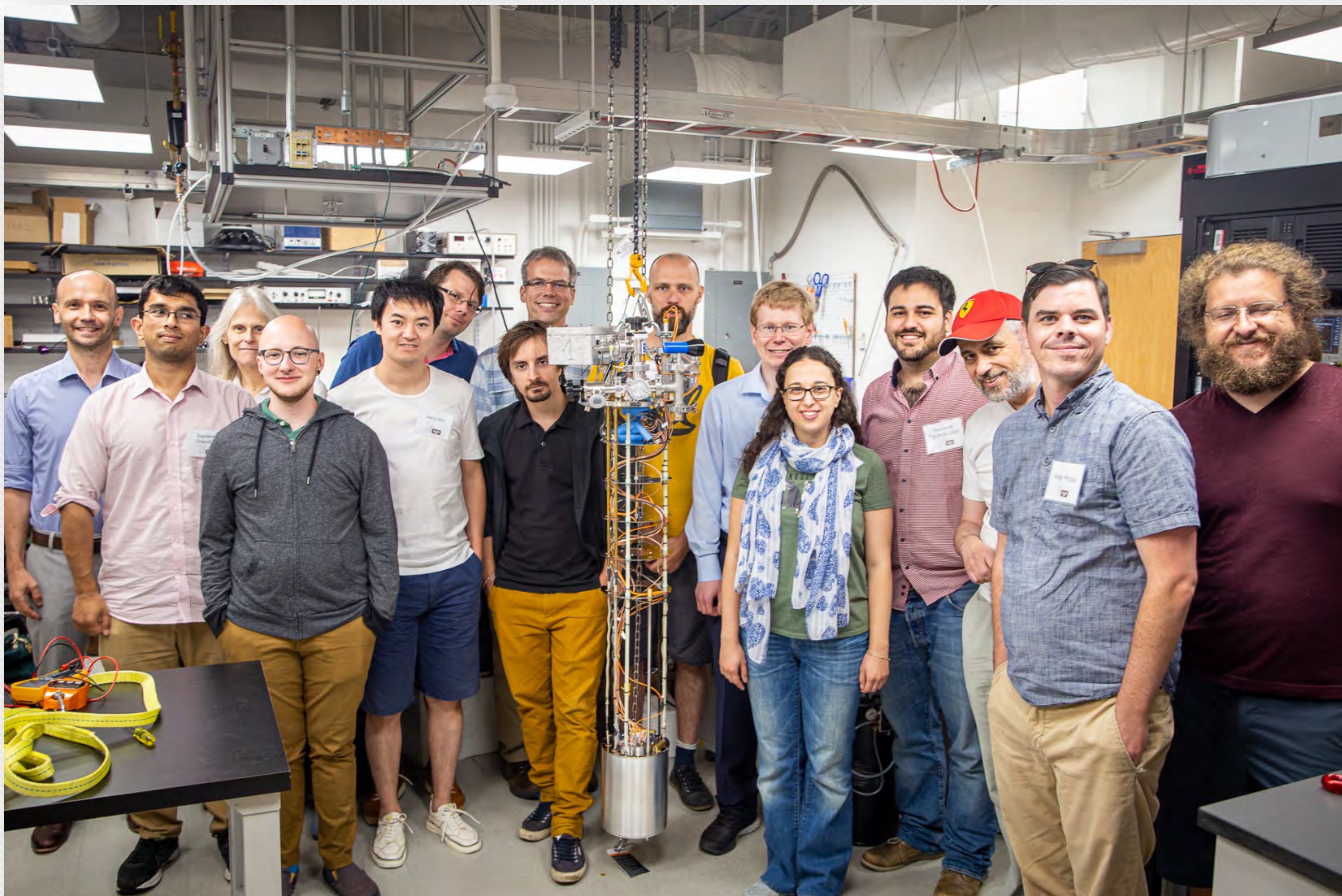
Superconducting Quantum Interference Devices (SQUIDs)

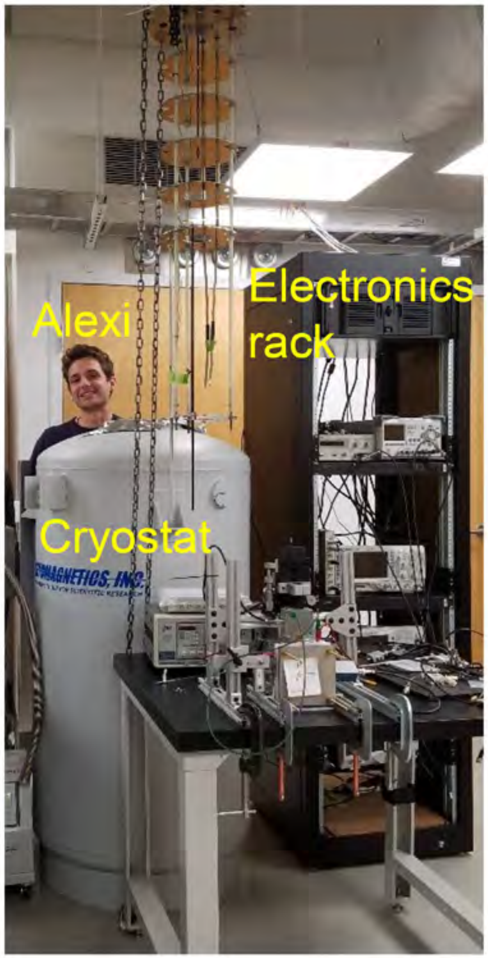


- Tuned probes
- Low noise amplifiers at 300K and 4K

- Measured noise level on order of $\mu\Phi_0/\sqrt{Hz}$
- Broadband

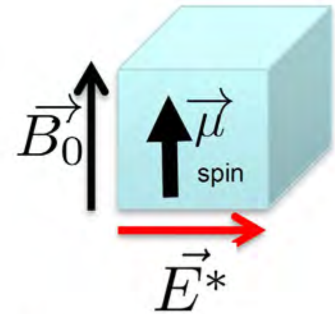
Experiments are underway!

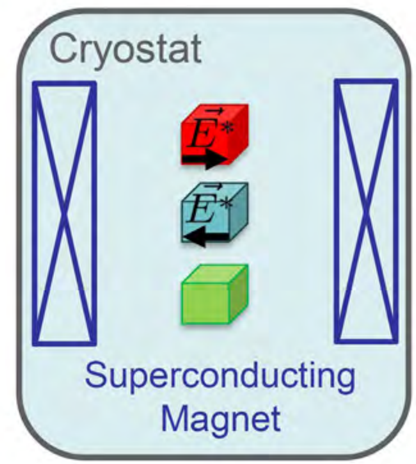



Alexi
Electronics
rack
Cryostat


Superconducting
Magnet

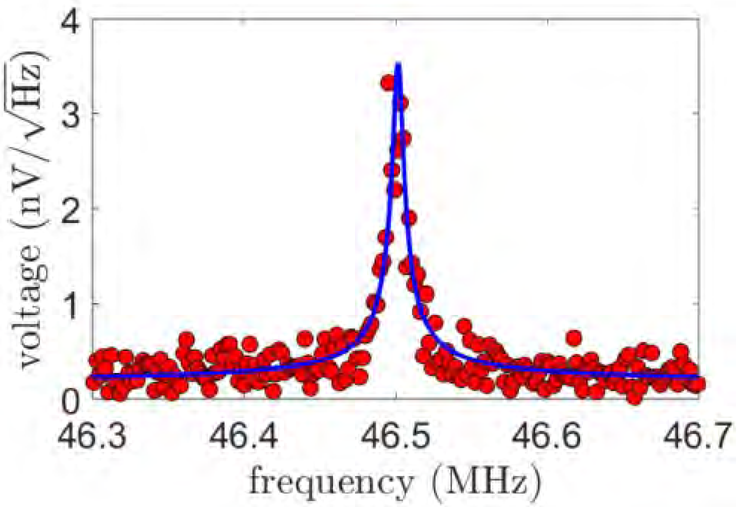

Sample
Holder


$\vec{B}_0$
$\vec{\mu}_{spin}$
$\vec{E}^*$

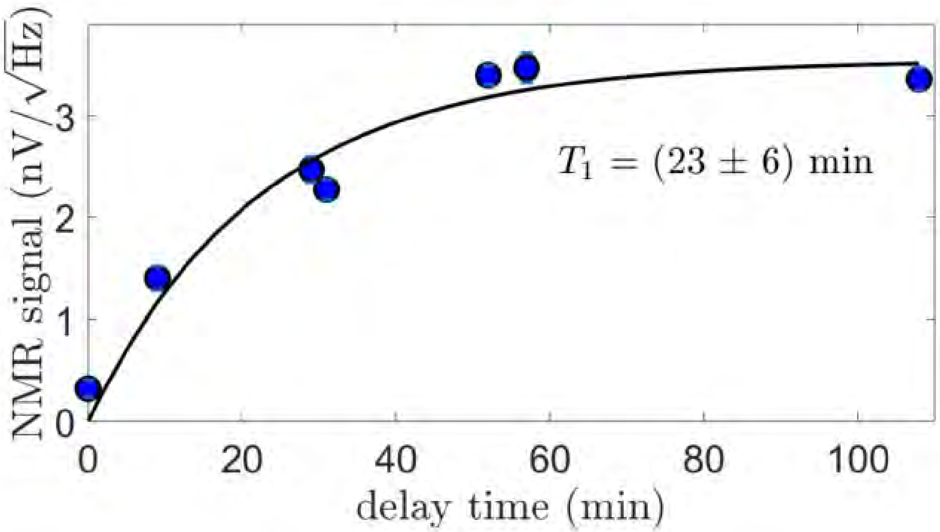

Cryostat
$\vec{E}^*$
$\vec{E}^*$
Superconducting
Magnet

NMR of Pb in PMN-PT

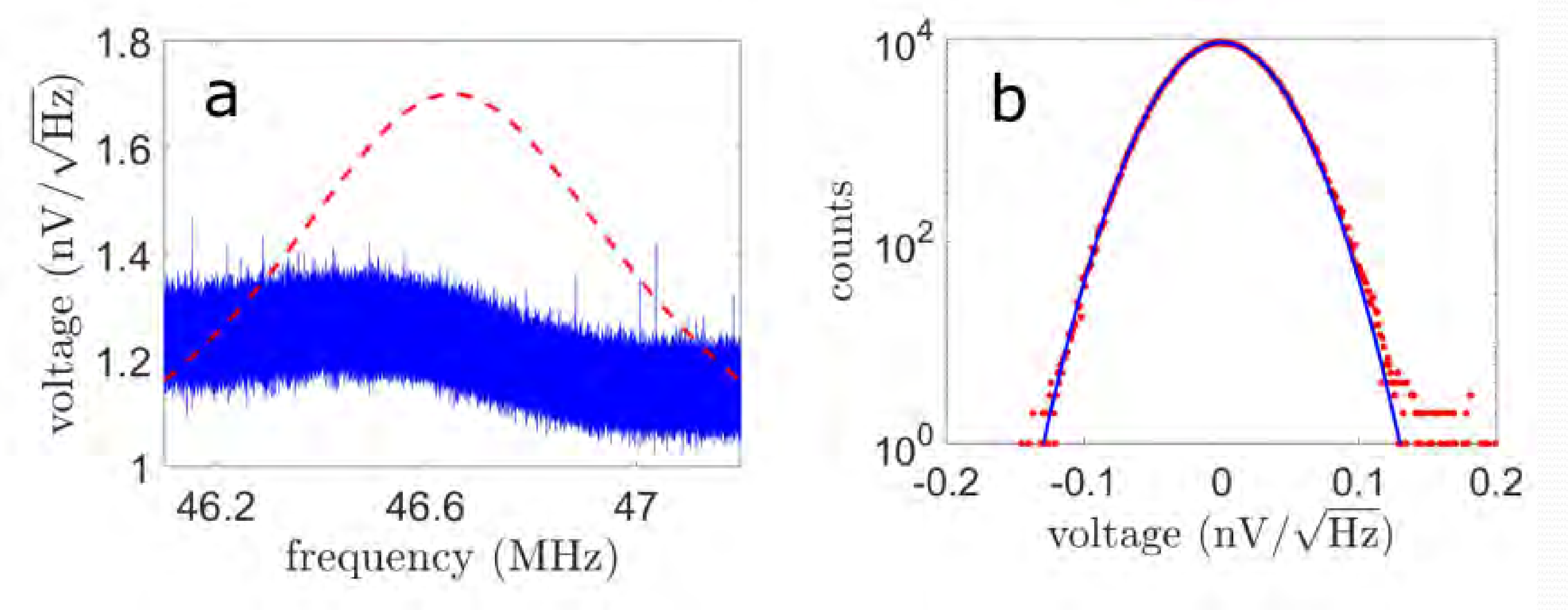
a

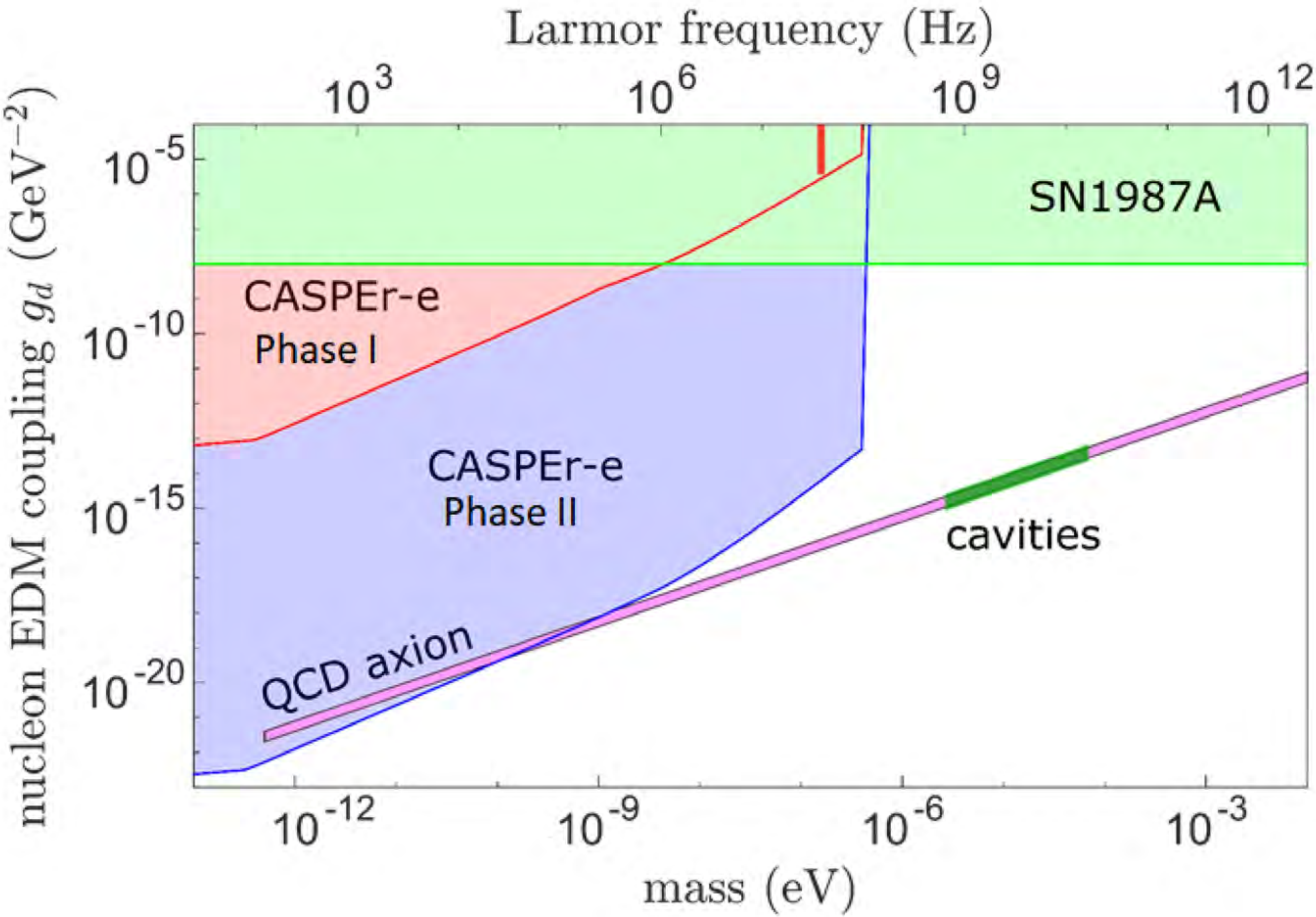


b



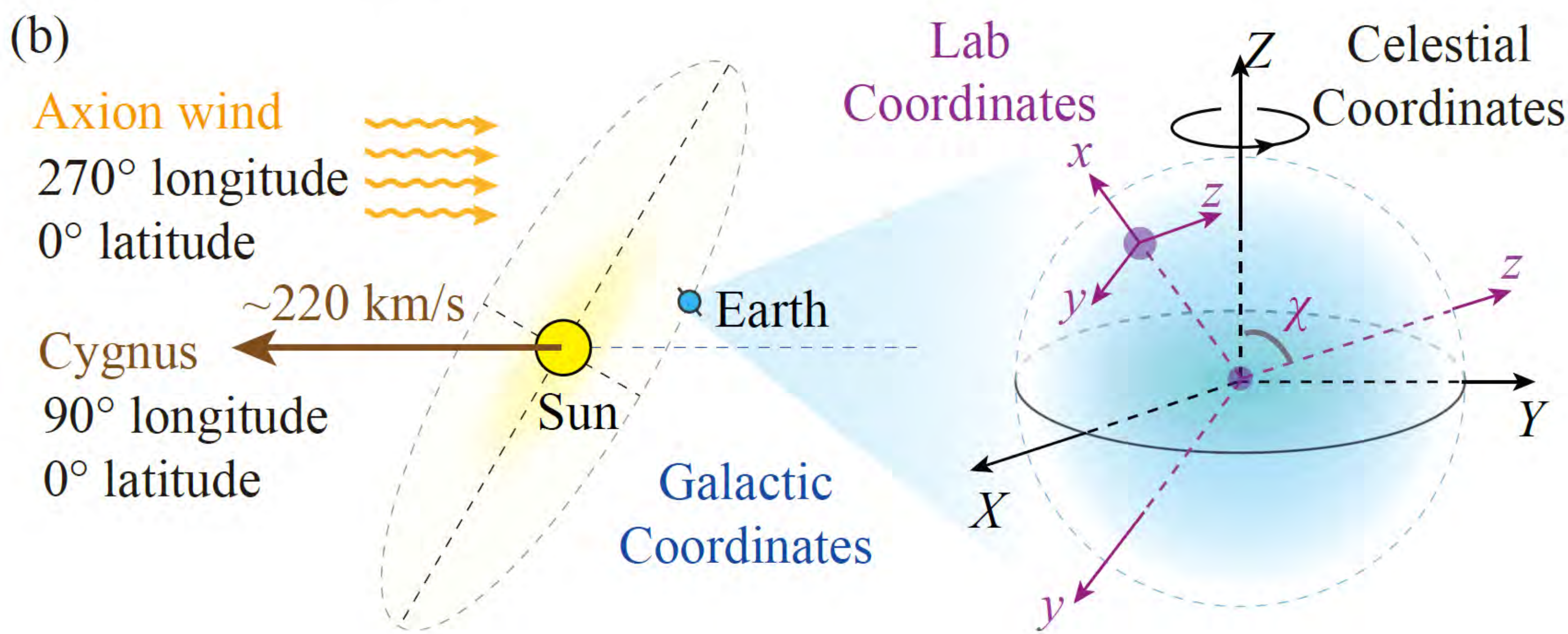
Preliminary search for axions





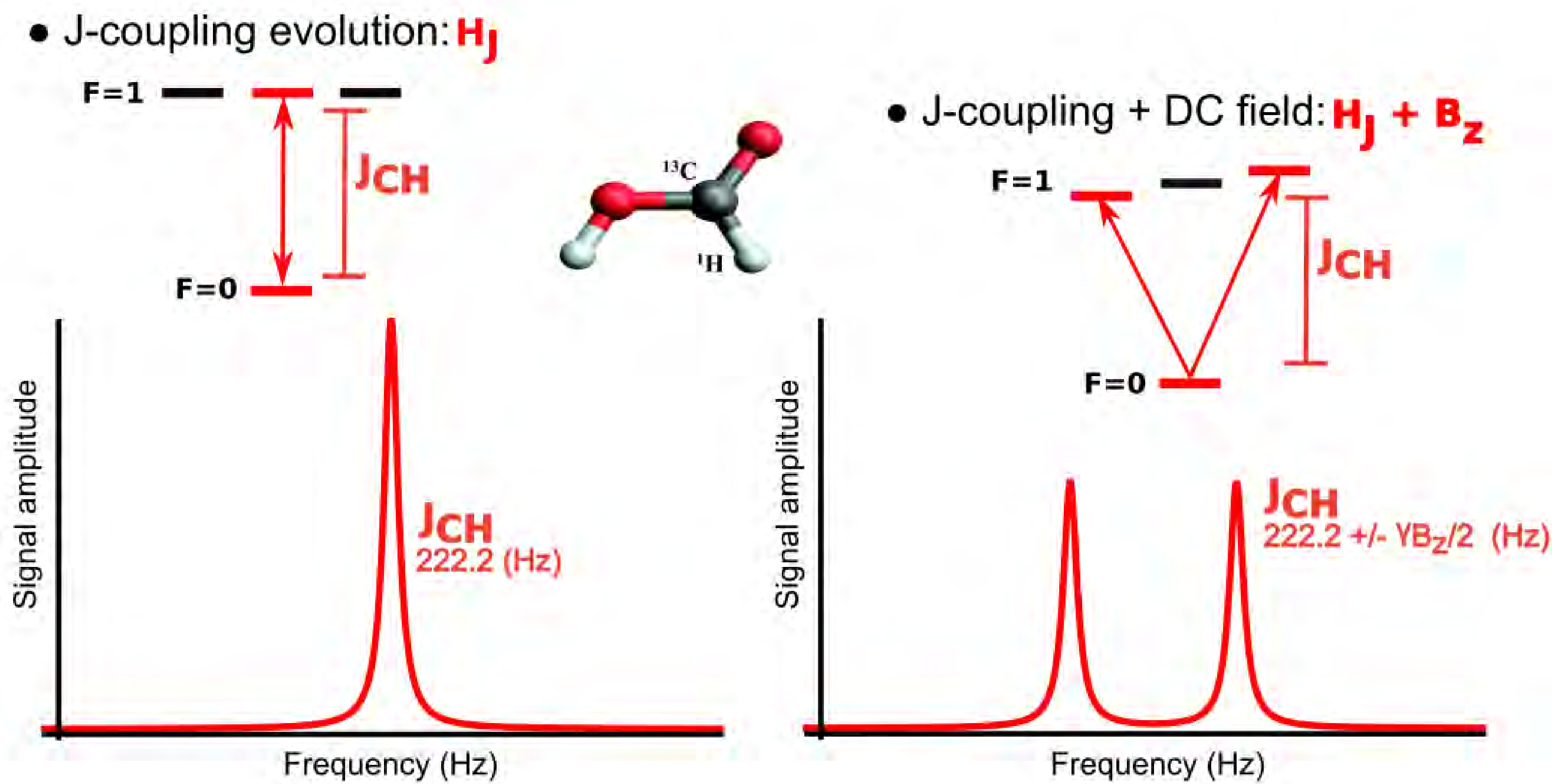
Larmor frequency (Hz)
10^3
10^6
10^9
10^{12}
nucleon EDM coupling g_d (GeV^{-2})
10^{-5}
10^{-10}
10^{-15}
10^{-20}
SN1987A
CASPEr-e
Phase I
CASPEr-e
Phase II
cavities
QCD axion
10^{-12}
10^{-9}
10^{-6}
10^{-3}
mass (eV)

CASPEr Wind: Ultralow Field

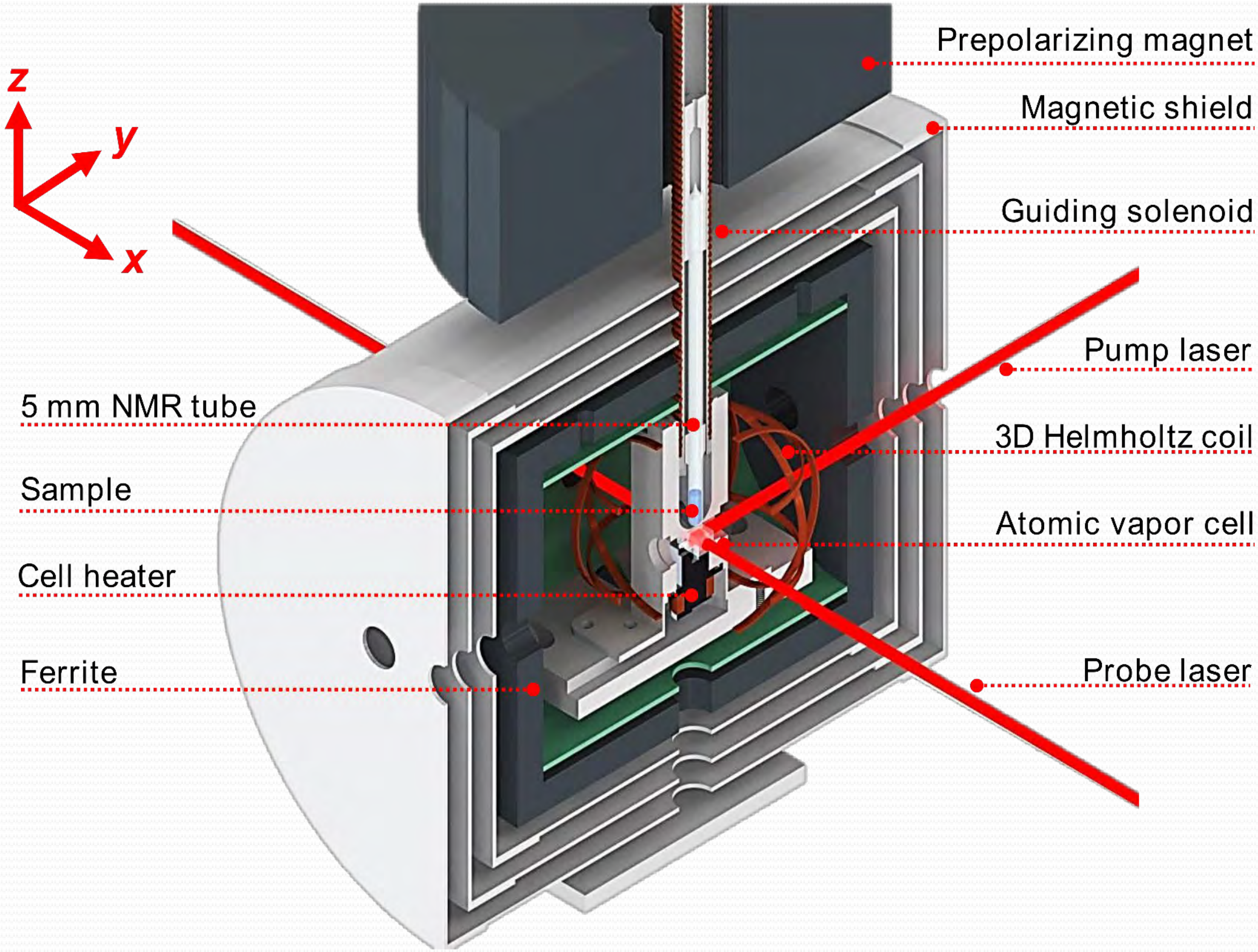


(b)
Axion wind
270° longitude
0° latitude
~220 km/s
Cygnus
90° longitude
0° latitude
Sun
Earth
Galactic
Coordinates
Lab
Coordinates
Celestial
Coordinates
Z
Y
X
x
y
z
χ

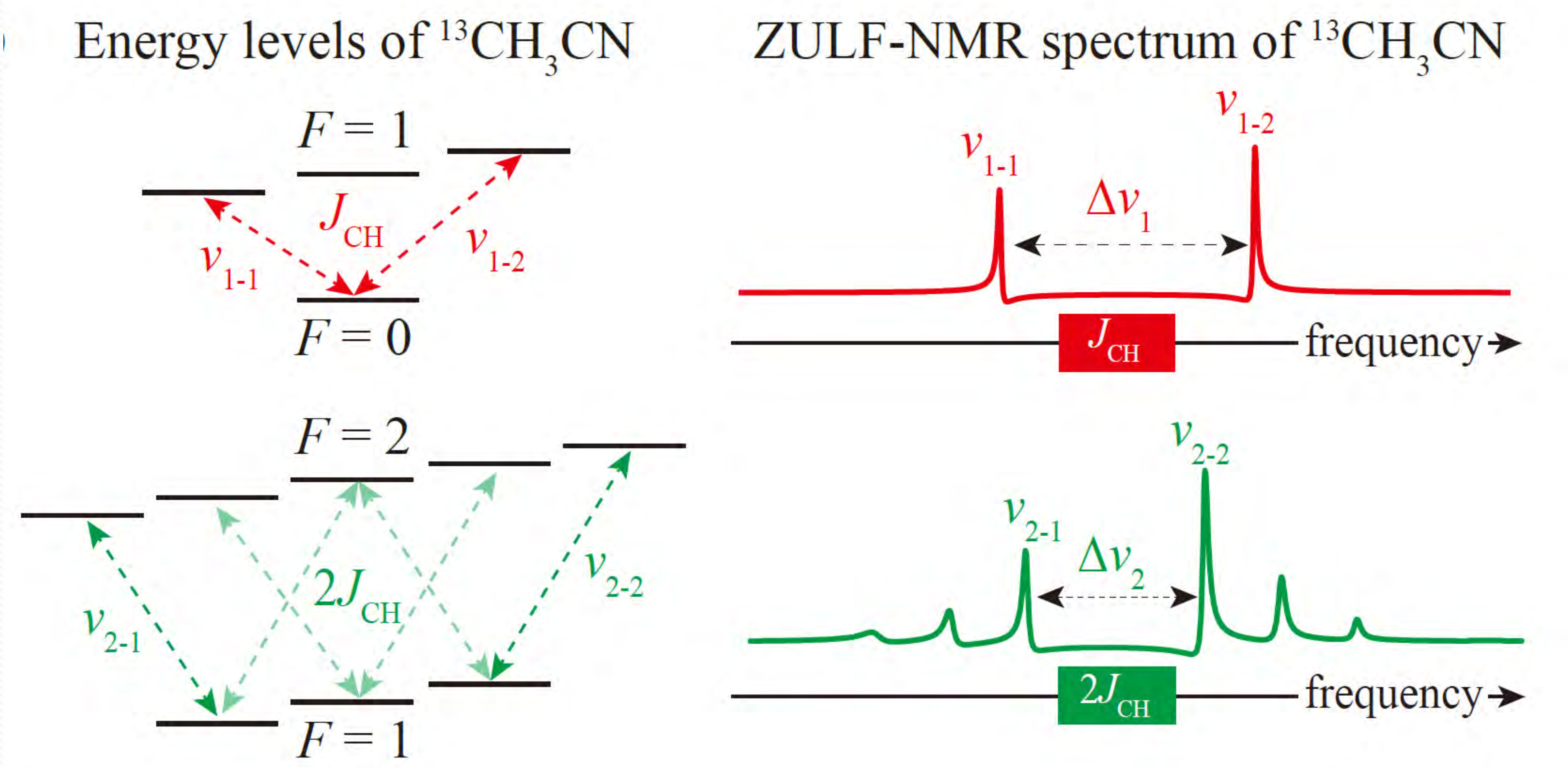
Zero-to-ultralow field (ZULF) NMR

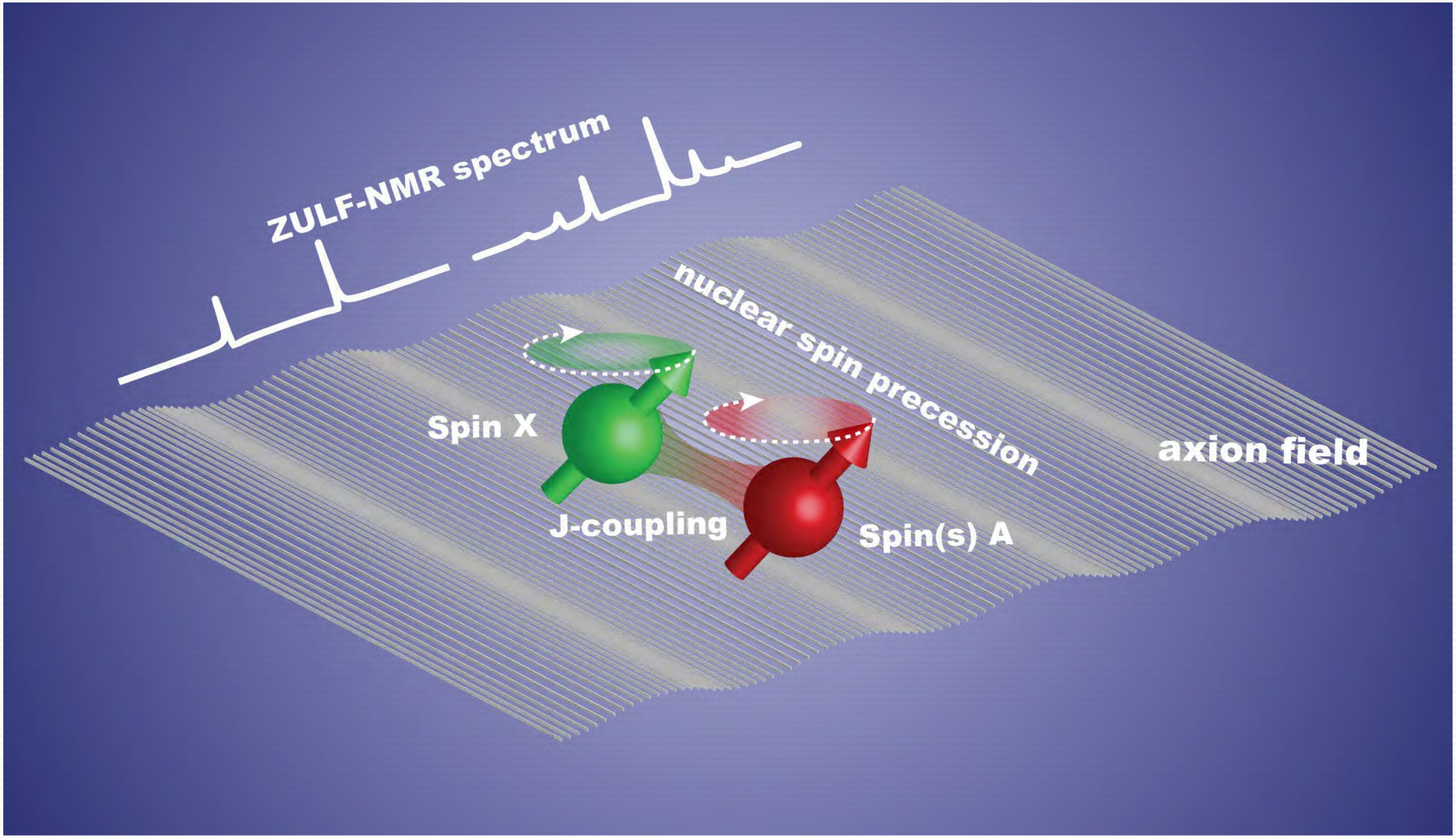


Experimental setup

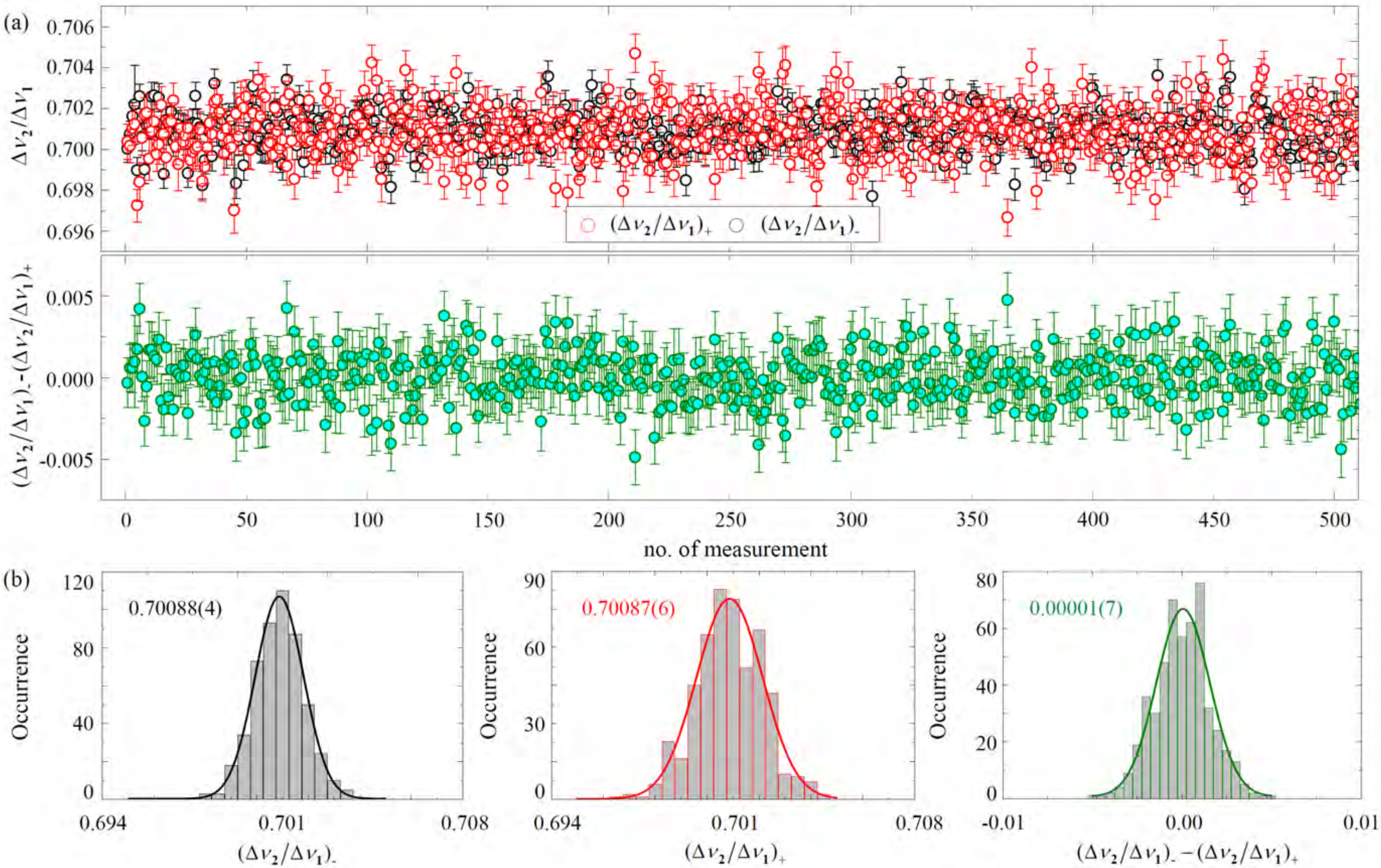


Comagnetometry

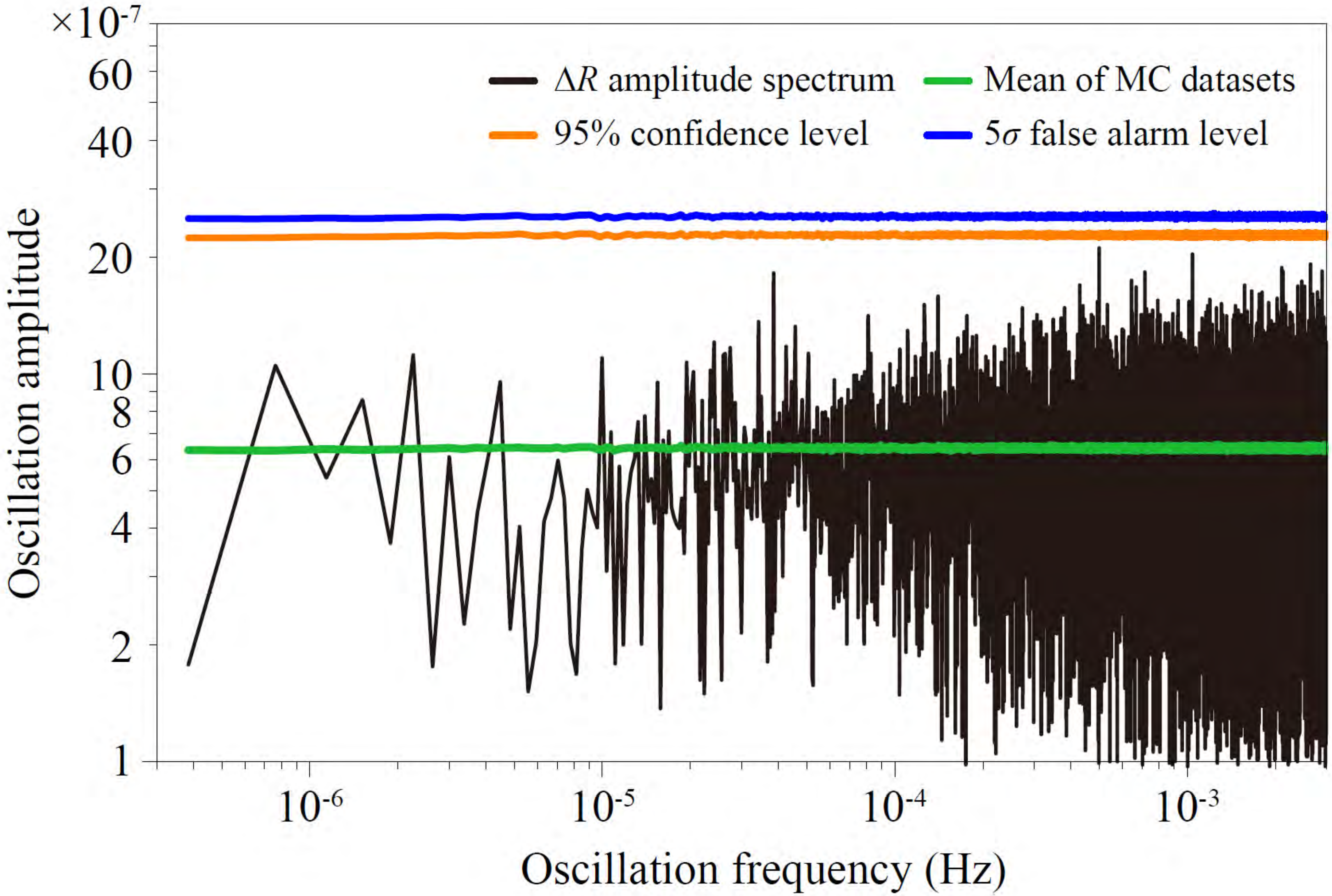



ZULF-NMR spectrum
nuclear spin precession
Spin X
J-coupling
Spin(s) A
axion field

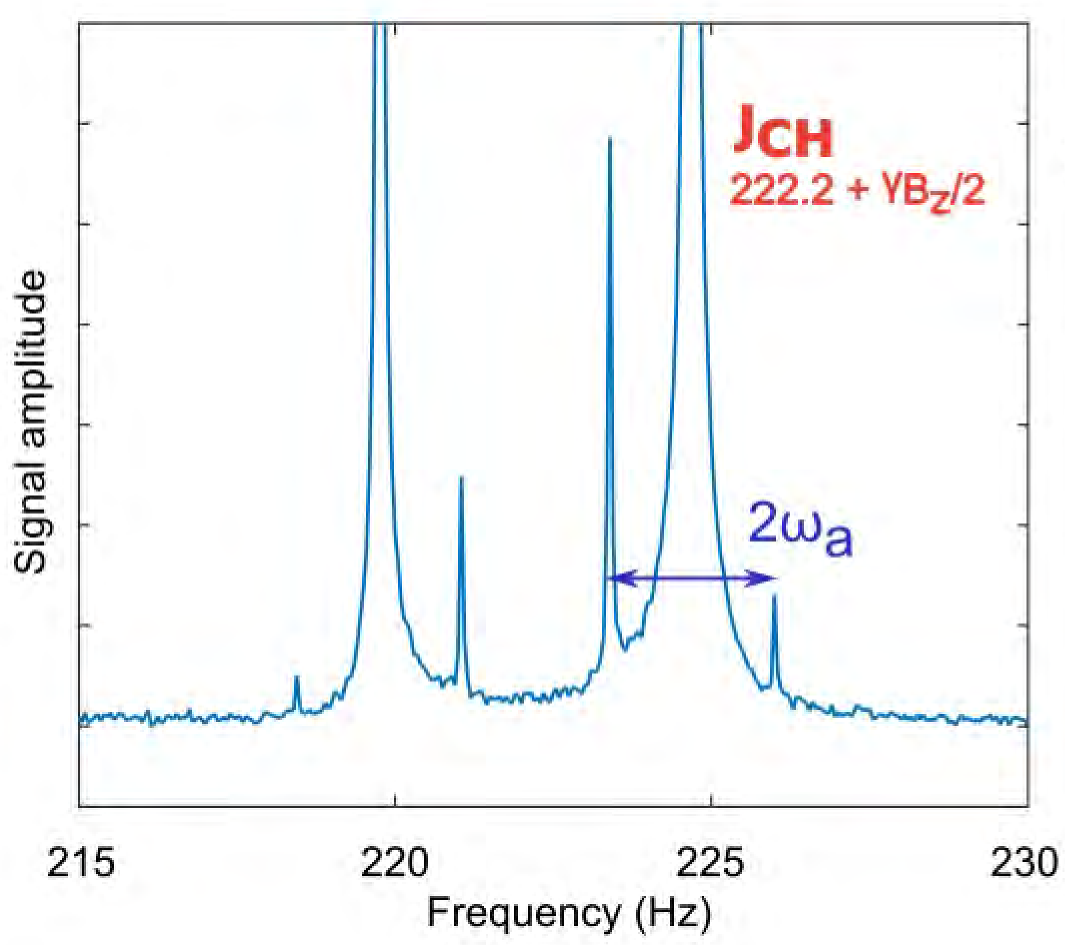
Comagnetometry

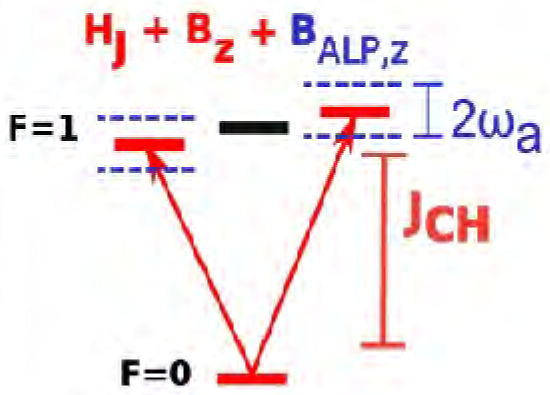


Comagnetometry

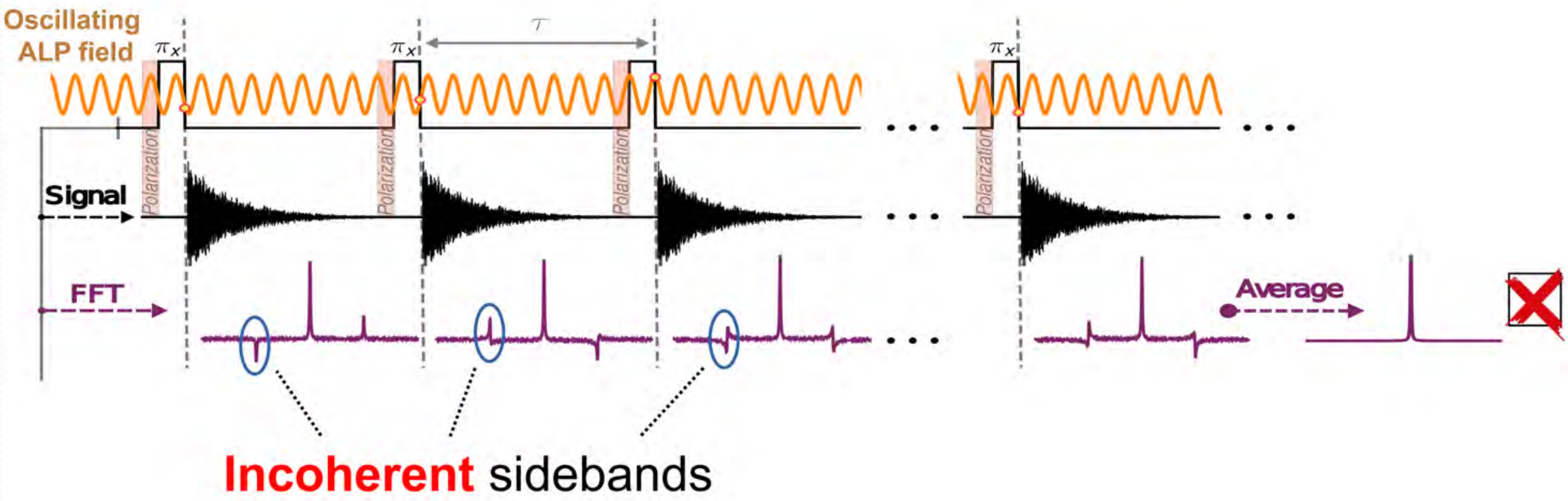


Higher frequencies: Oscillating axion field ⟶ sidebands





NMR sideband detection

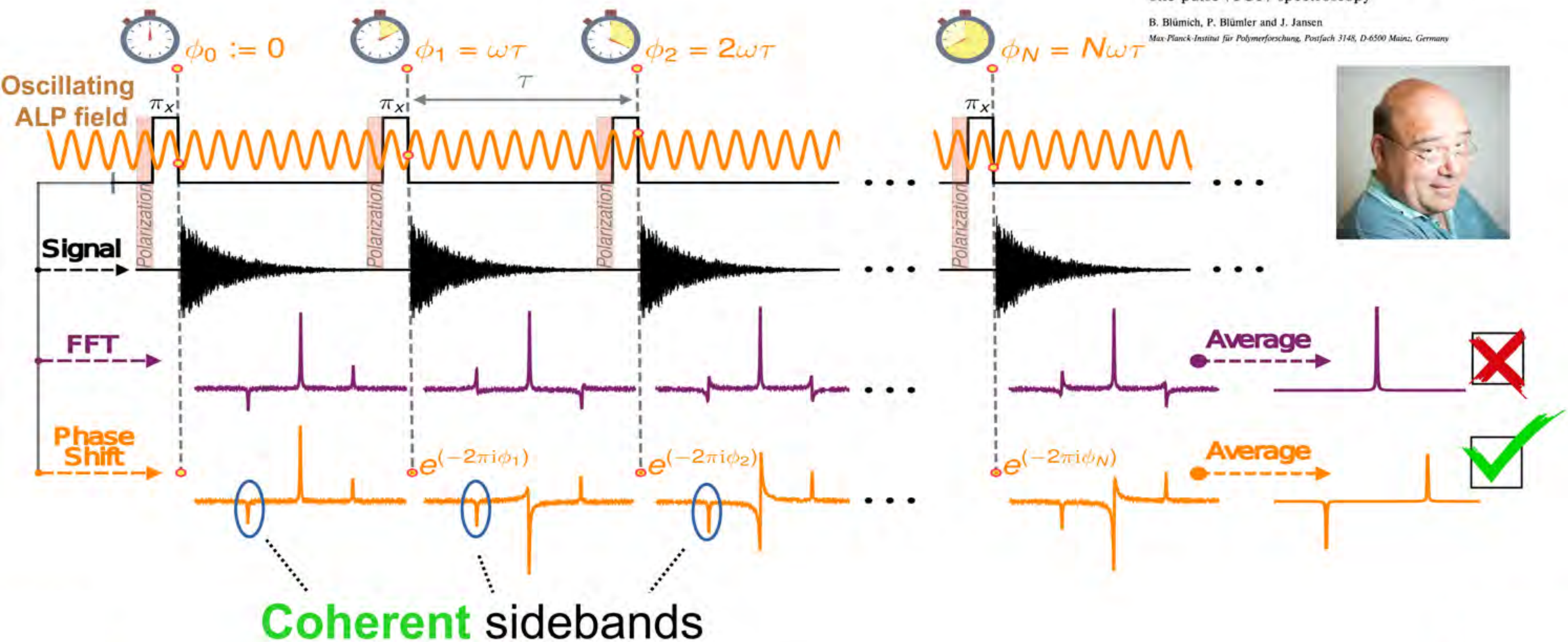


NMR sideband detection

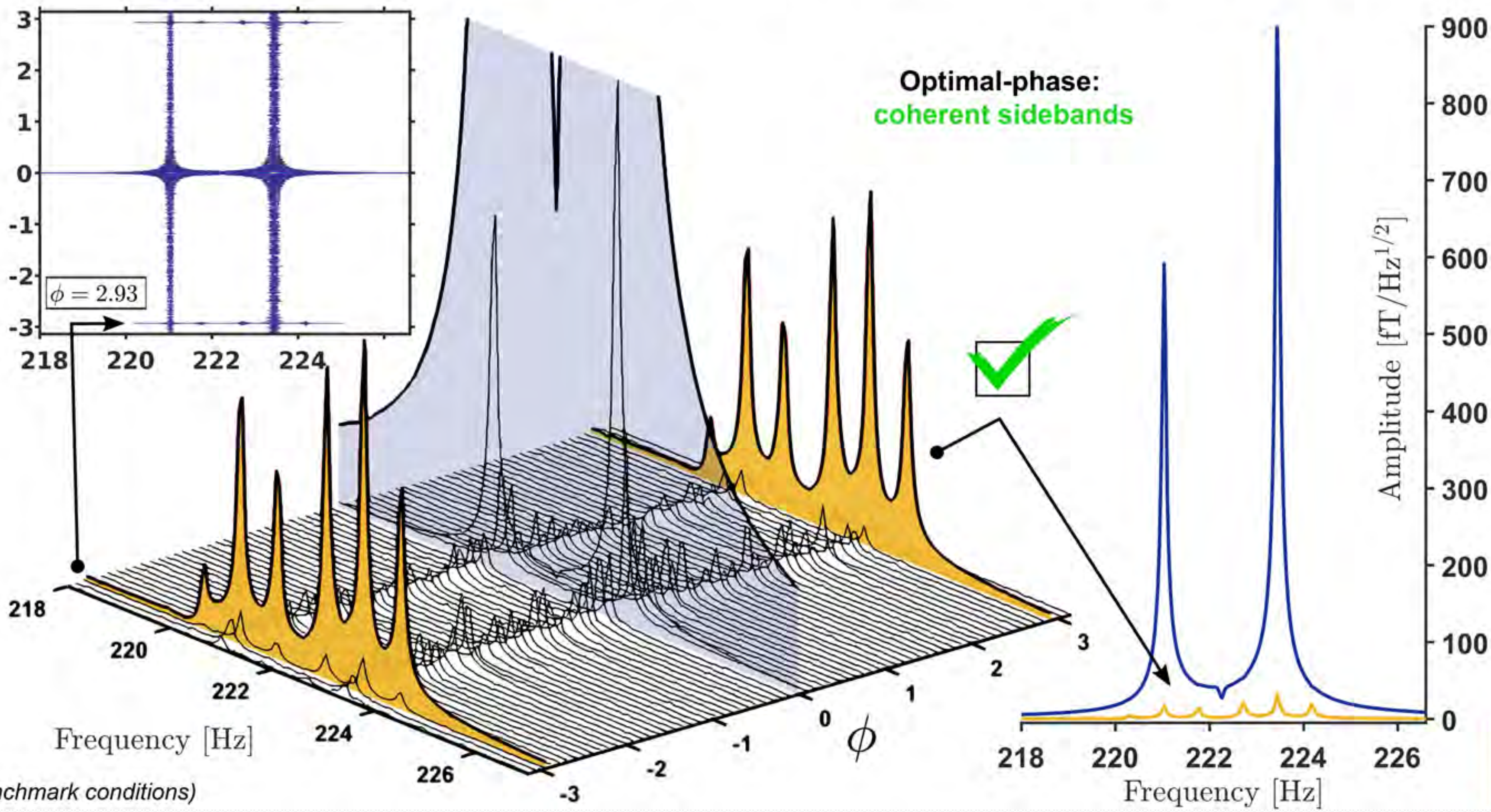
Presentation of sideband envelopes by two-dimensional one-pulse (TOP) spectroscopy

B. Blümich, P. Blümler and J. Jansen

Max-Planck-Institut für Polymerforschung, Postfach 3148, D-6500 Mainz, Germany

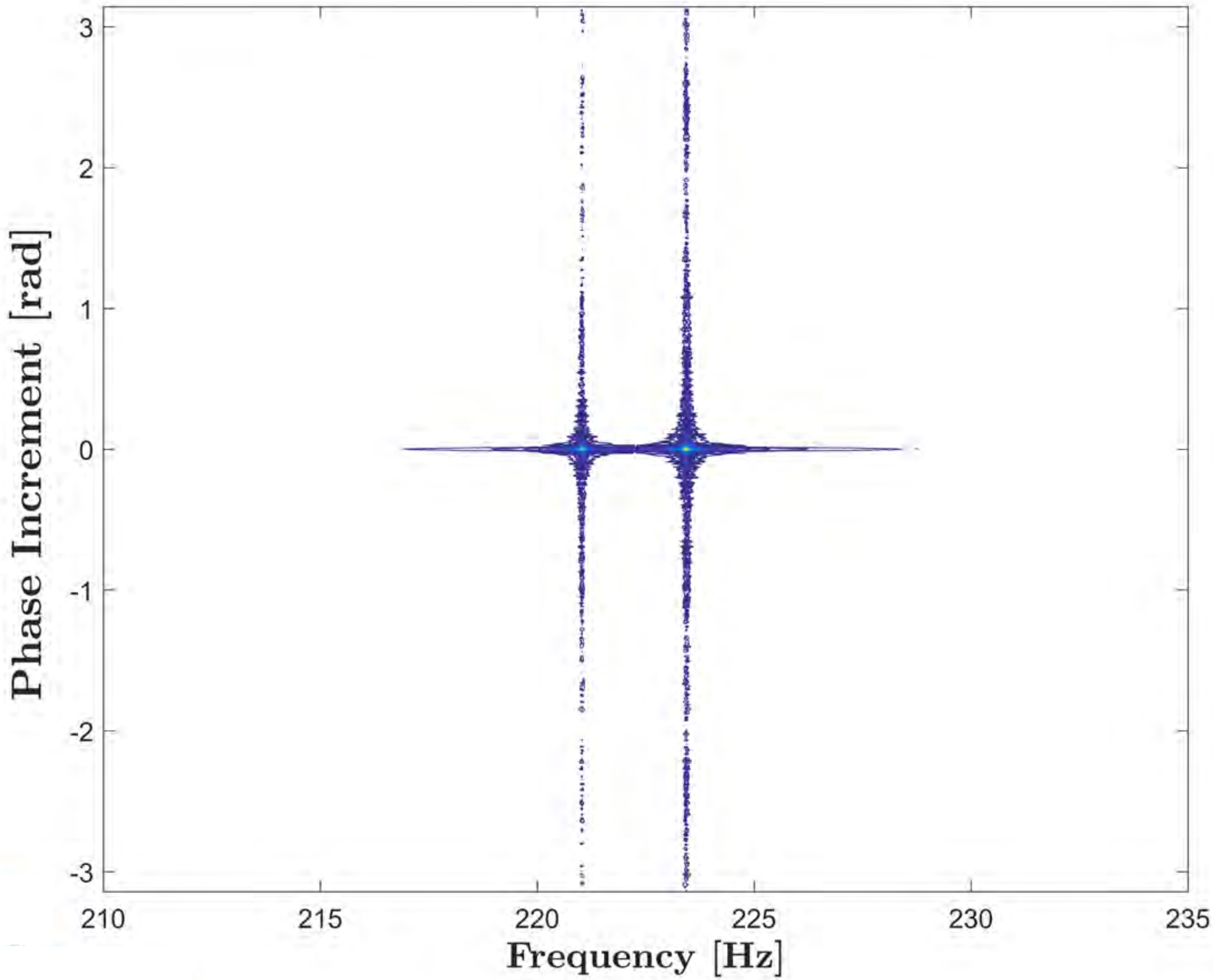


Detection: best phase search

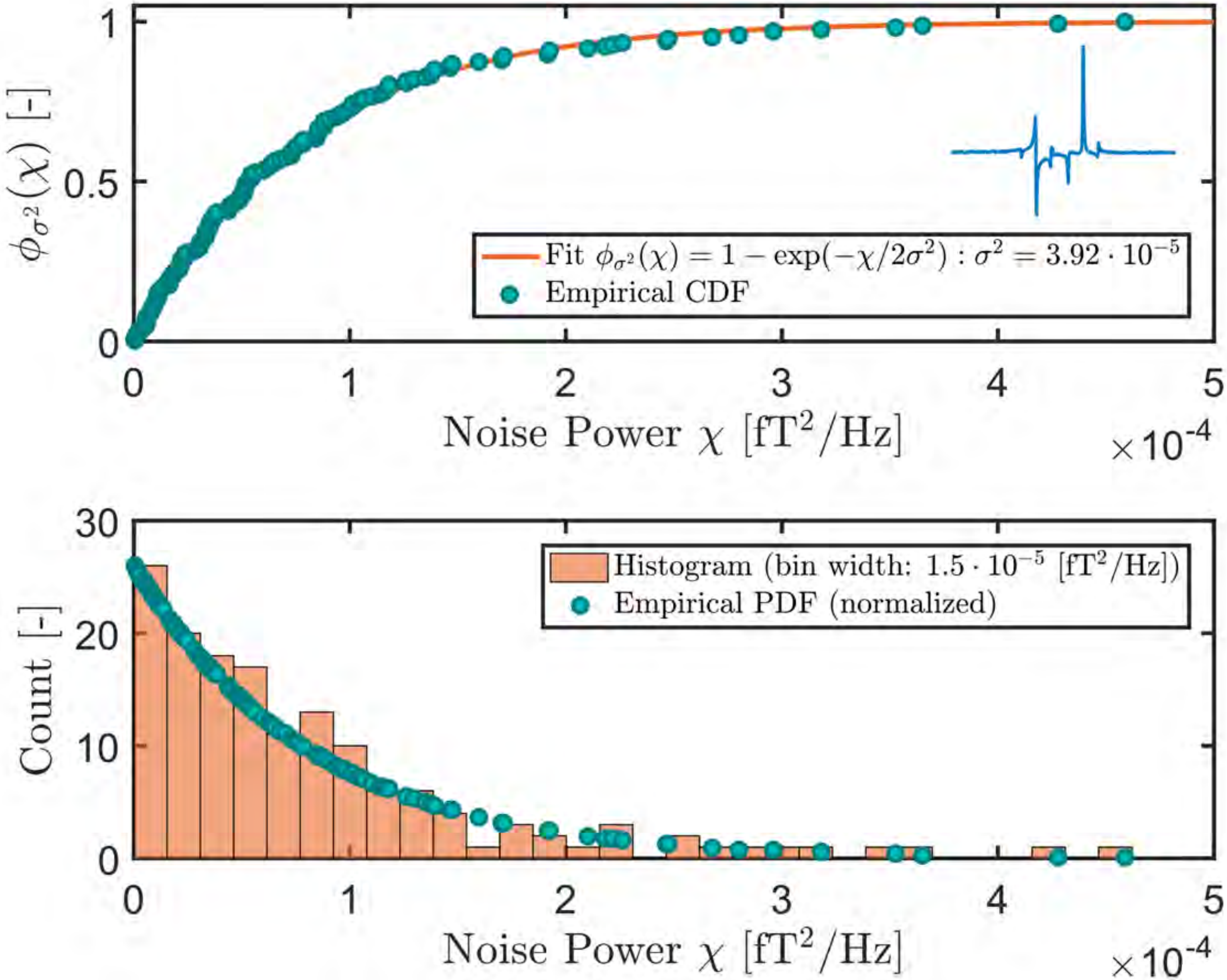


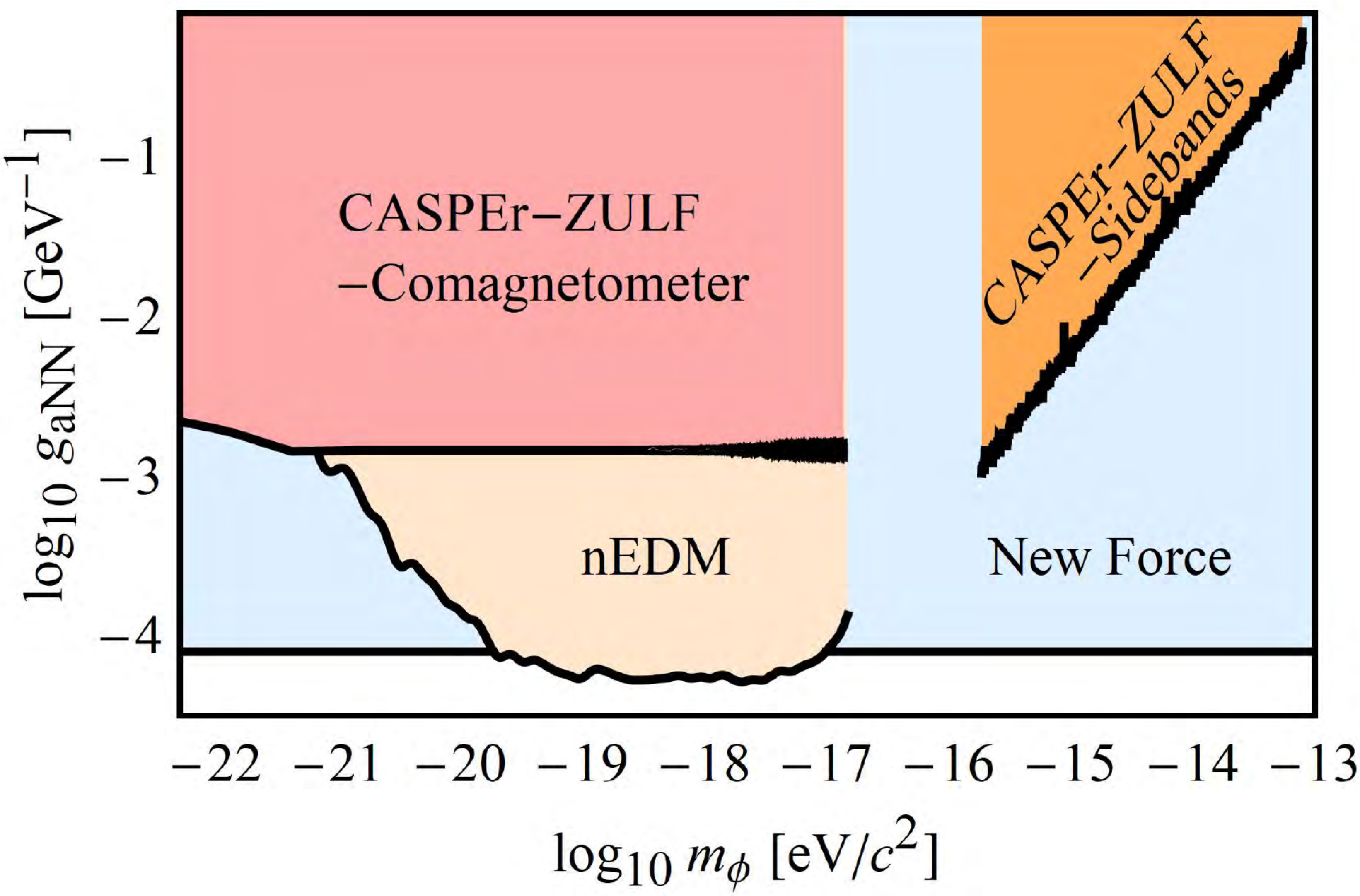
(*benchmark conditions)

No signal detected in search

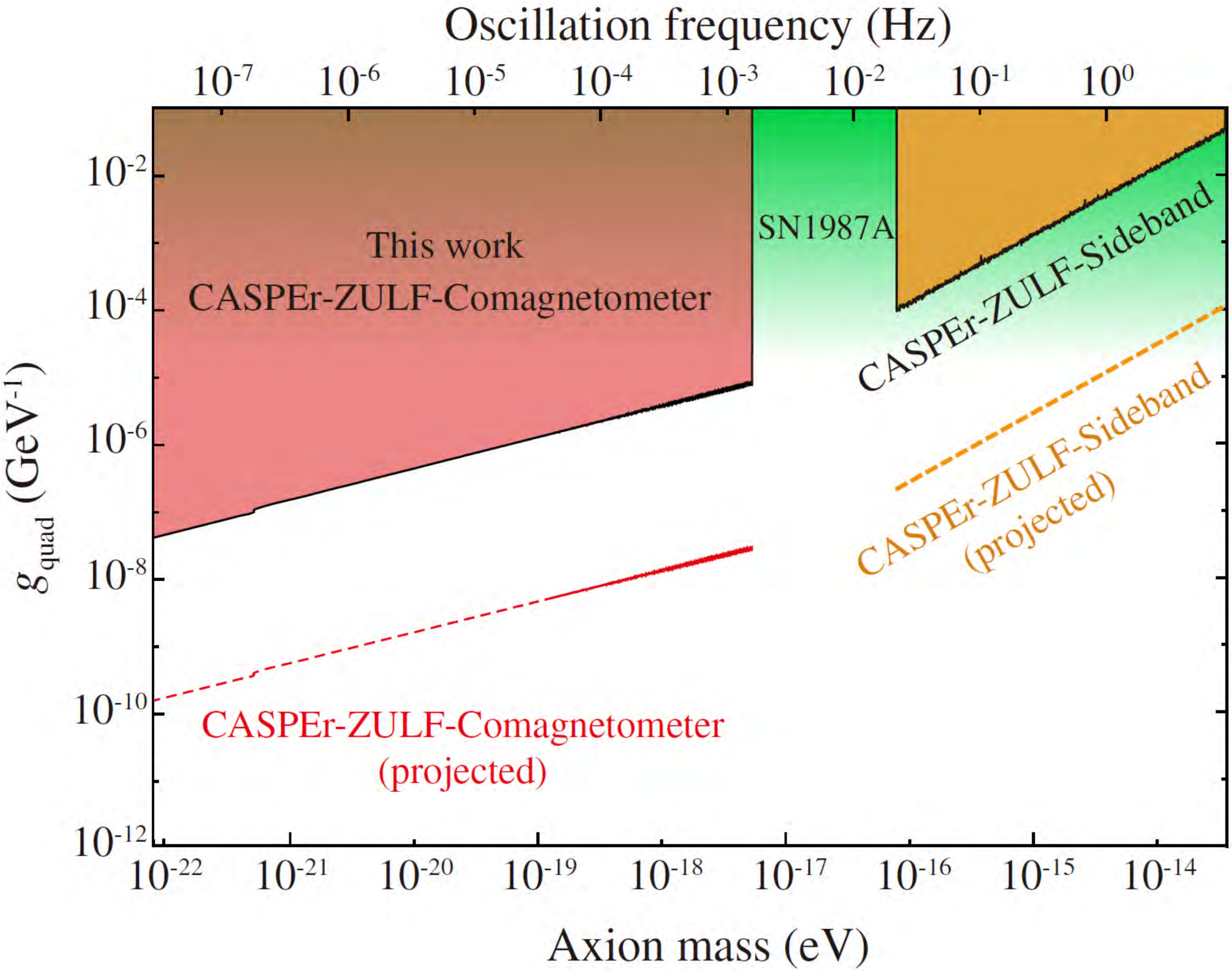


No signal detected in search





CASPEr−ZULF
−Comagnetometer
CASPEr−ZULF
−Sidebands
nEDM
New Force
−1
−2
−3
−4
−22
−21
−20
−19
−18
−17
−16
−15
−14
−13
log10 gaNN [GeV−1]
log10 mφ [eV/c2]



Oscillation frequency (Hz)
10-7
10-6
10-5
10-4
10-3
10-2
10-1
100
10-2
10-4
10-6
10-8
10-10
10-12
g quad (GeV-1)
This work
CASPEr-ZULF-Comagnetometer
SN1987A
CASPEr-ZULF-Sideband
CASPEr-ZULF-Sideband
(projected)
CASPEr-ZULF-Comagnetometer
(projected)
10-22
10-21
10-20
10-19
10-18
10-17
10-16
10-15
10-14
Axion mass (eV)

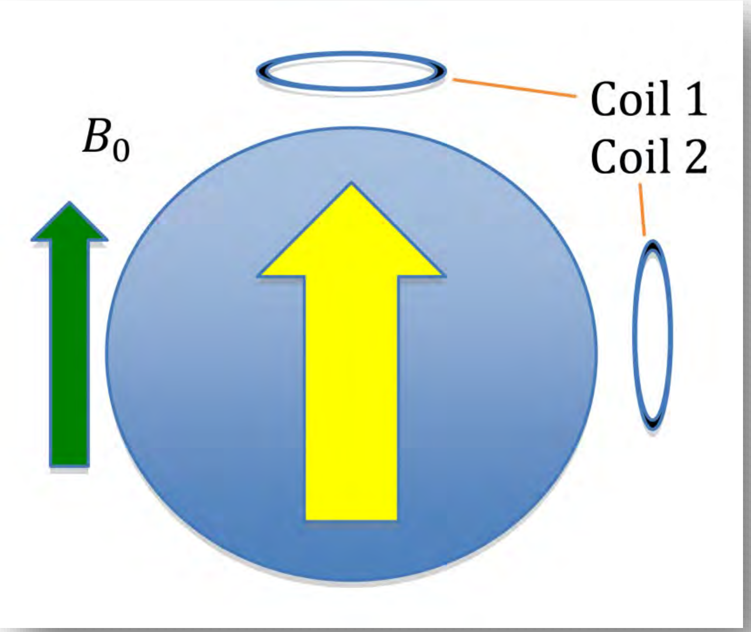
CASPEr Wind: Low Field

Signal amplification

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

During coherence time τ, polarized spins rotate by angle:

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

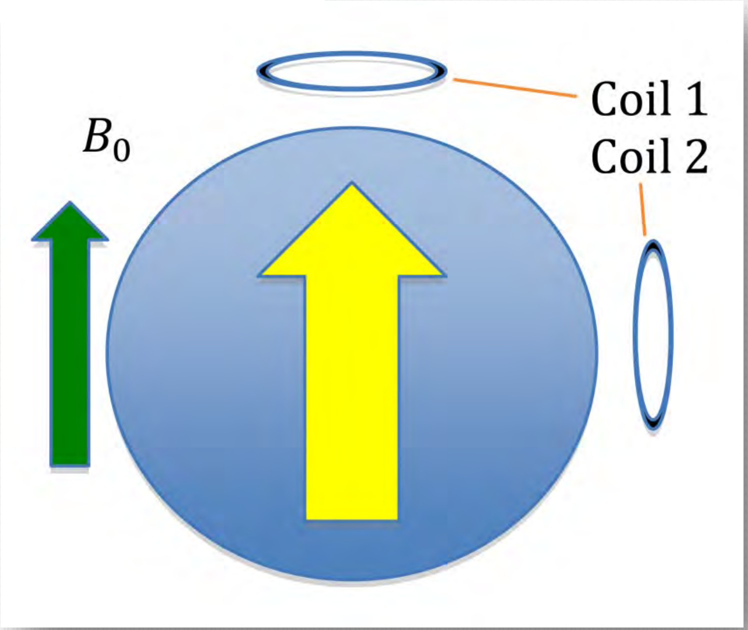


Signal amplification

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

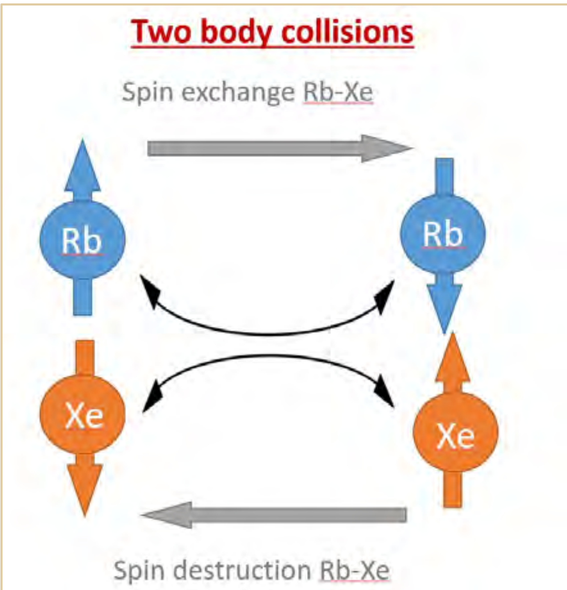
Density (n)	Magnetic Moment (μ)	T_2
$1.3 \times 10^{22} \frac{1}{\text{cm}^3}$	$0.35\,\mu_N$	1300 s

Relatively large sample can be hyperpolarized.

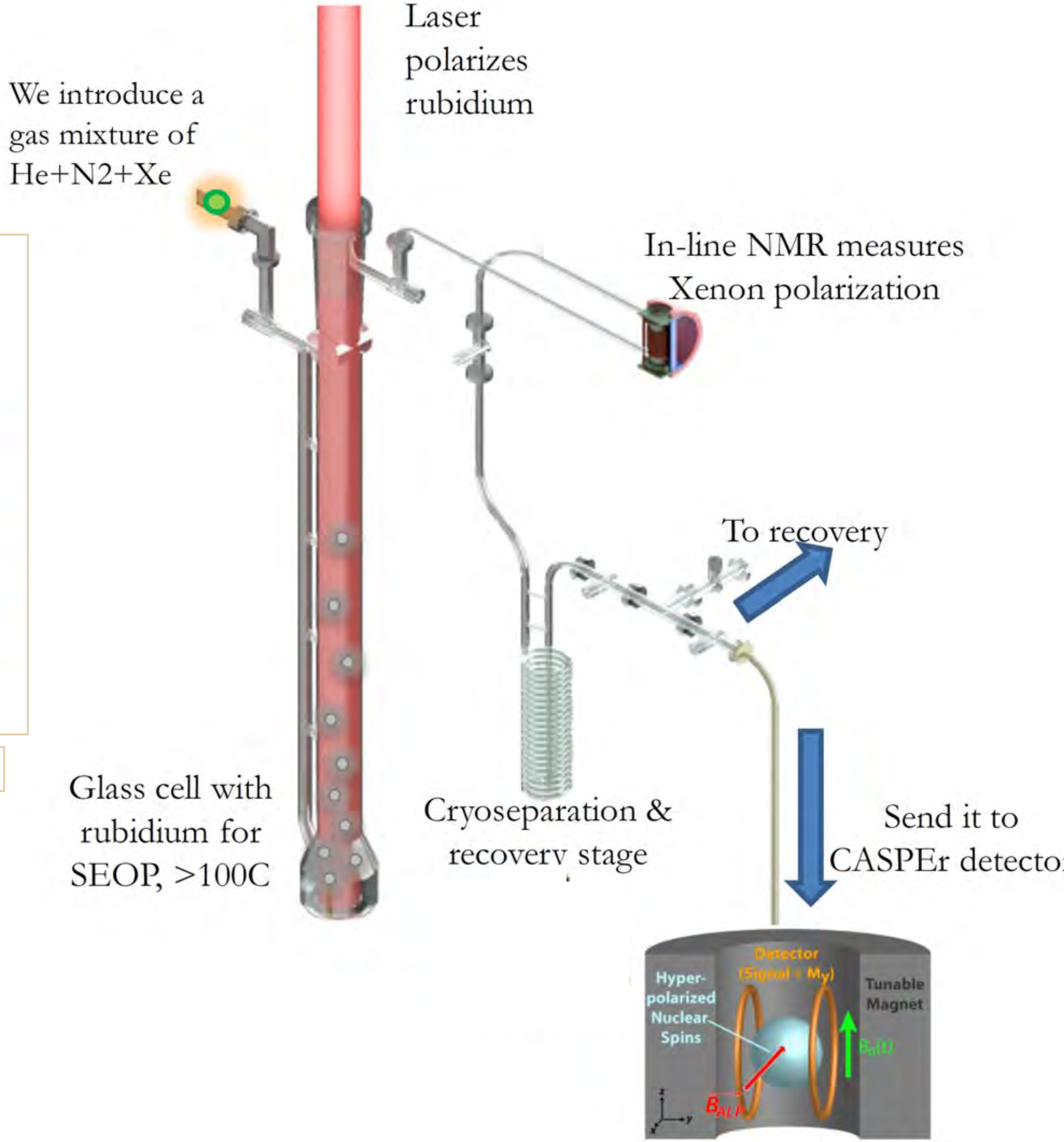
The enhancement factor can be on the order of 10^6.

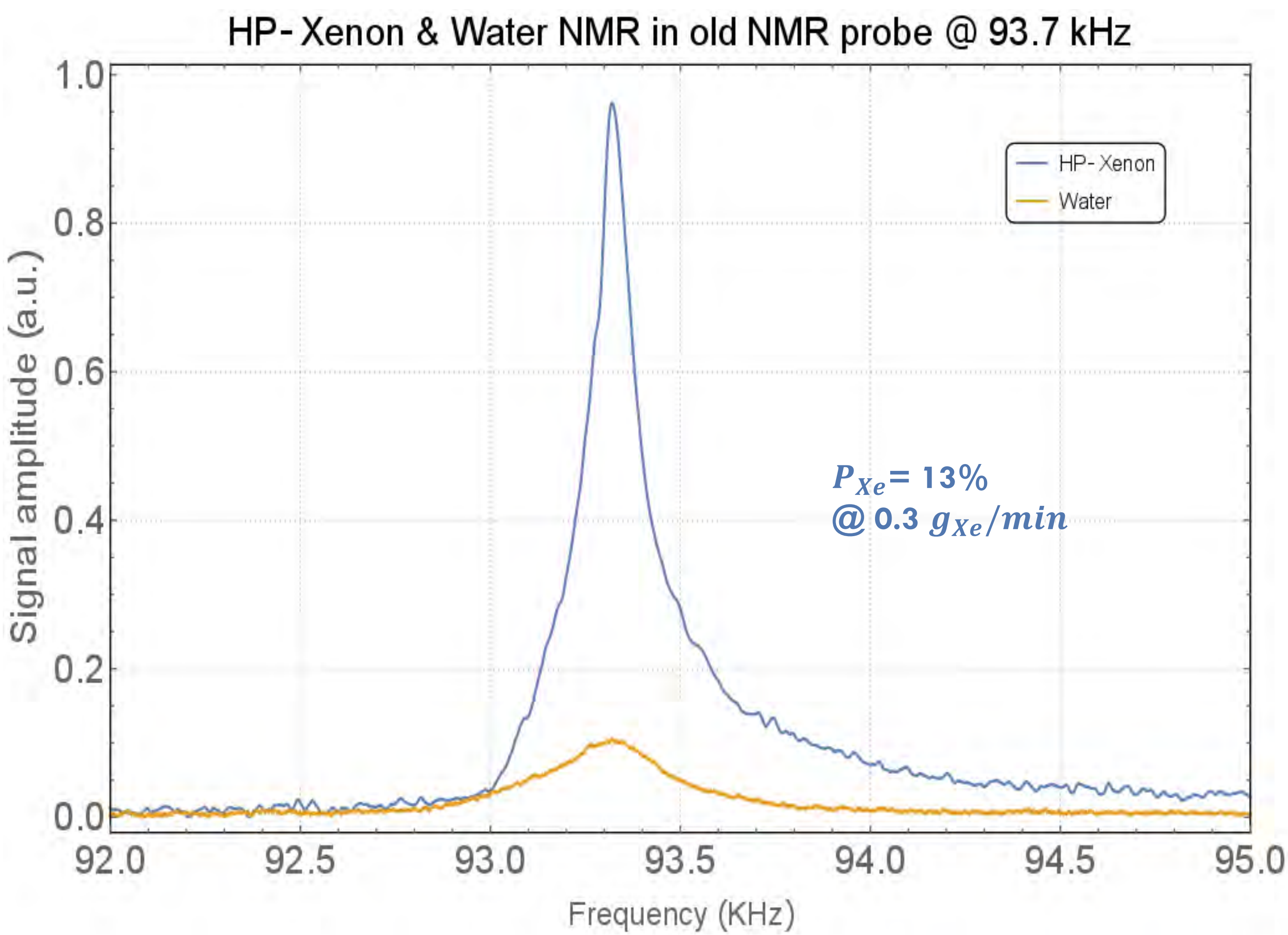
Coupling constant in magnetic field units is:

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

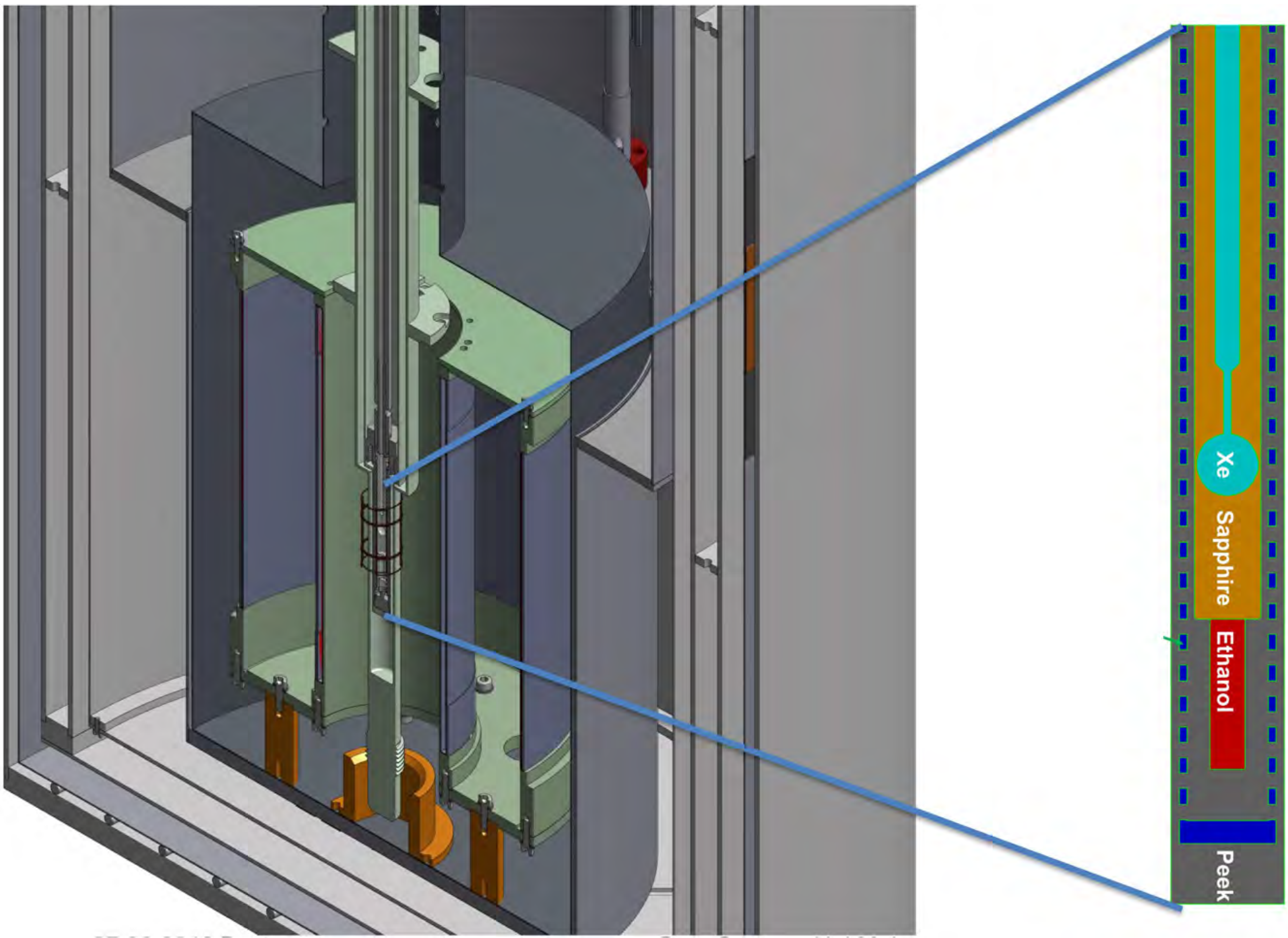


$\uparrow$ Rb+ $\downarrow$ Xe $\rightarrow \downarrow$ Rb+ $\uparrow$ Xe

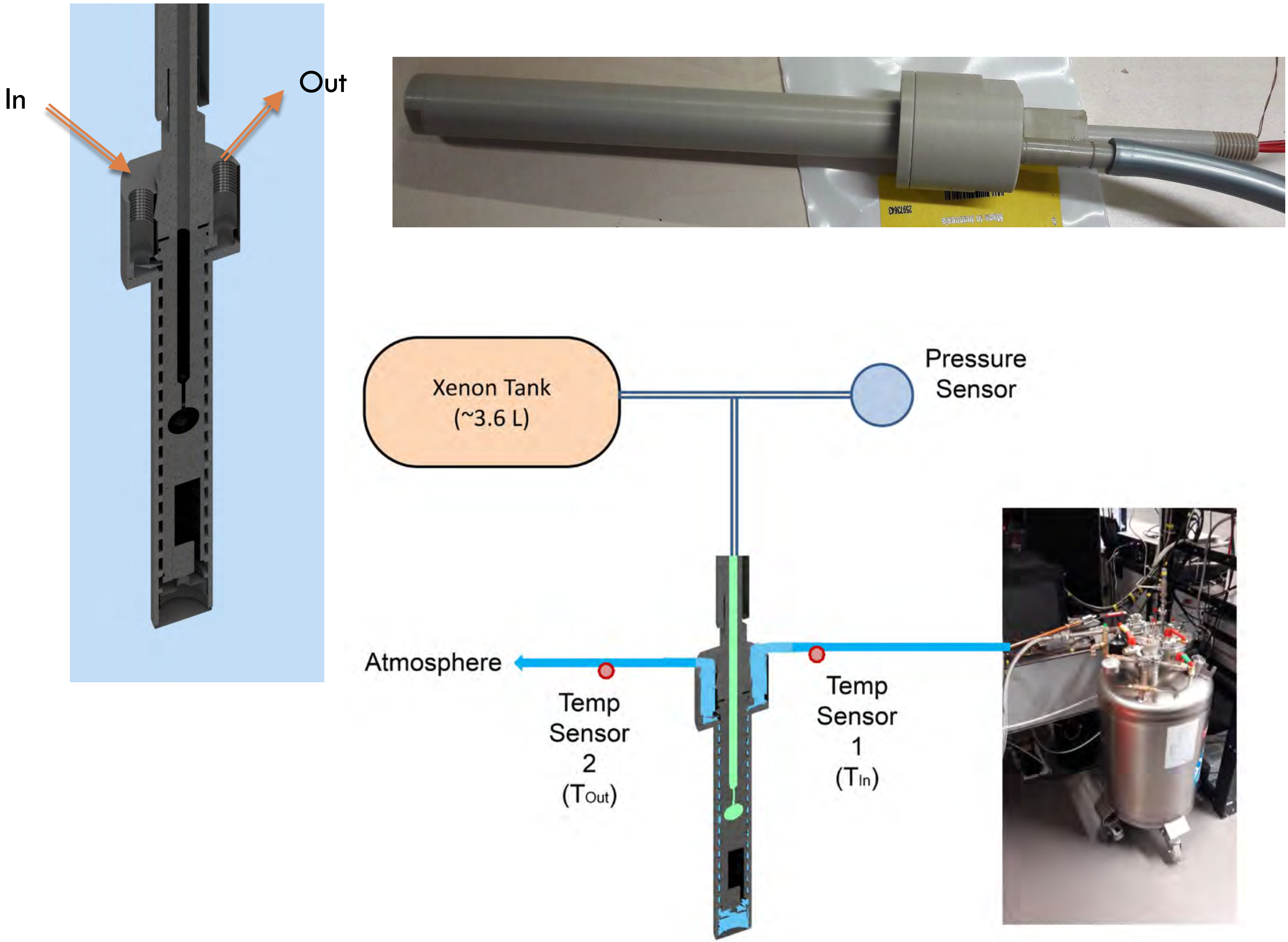




HP- Xenon & Water NMR in old NMR probe @ 93.7 kHz
HP- Xenon
Water
P_{Xe}= 13%
@ 0.3 g_{Xe}/min
Signal amplitude (a.u.)
Frequency (KHz)
1.0
0.8
0.6
0.4
0.2
0.0
92.0
92.5
93.0
93.5
94.0
94.5
95.0

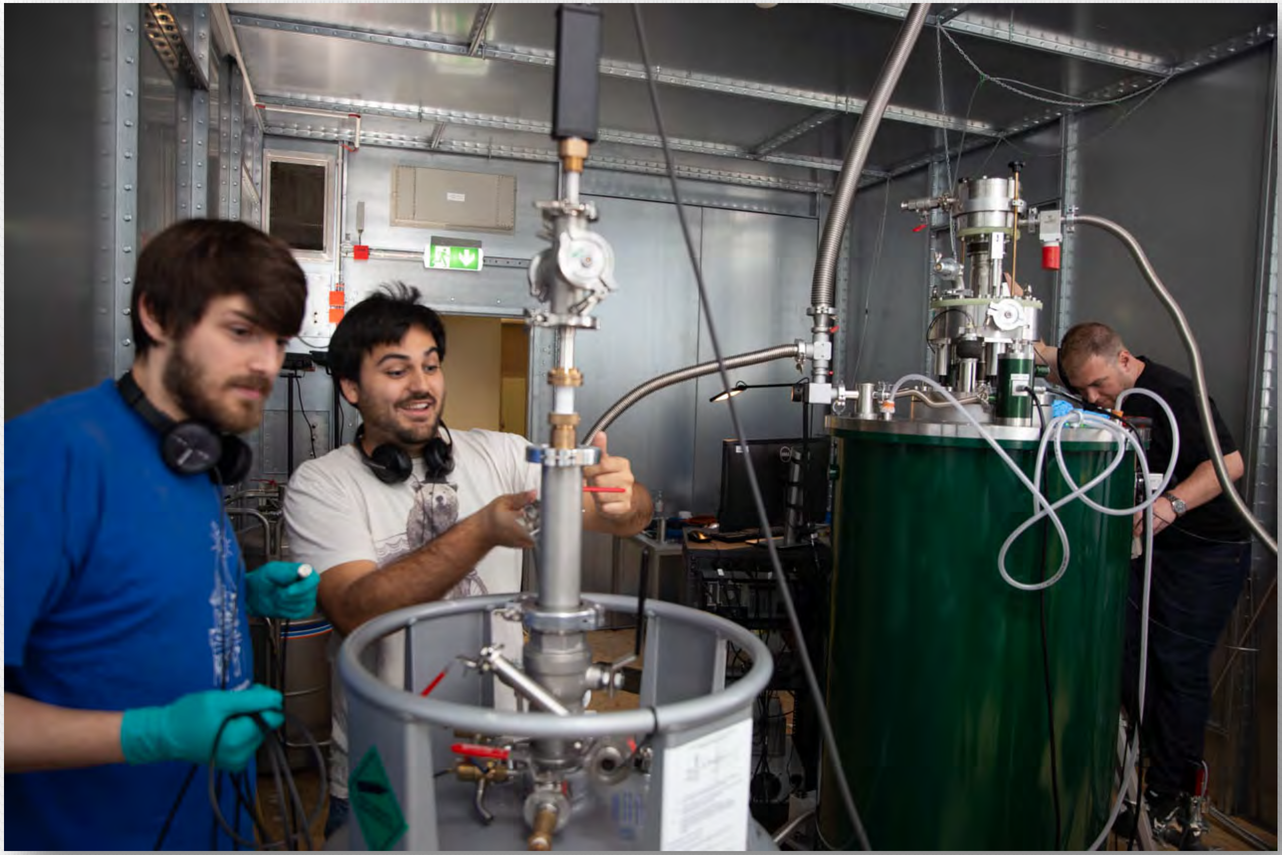


Xe
Sapphire
Ethanol
Peek

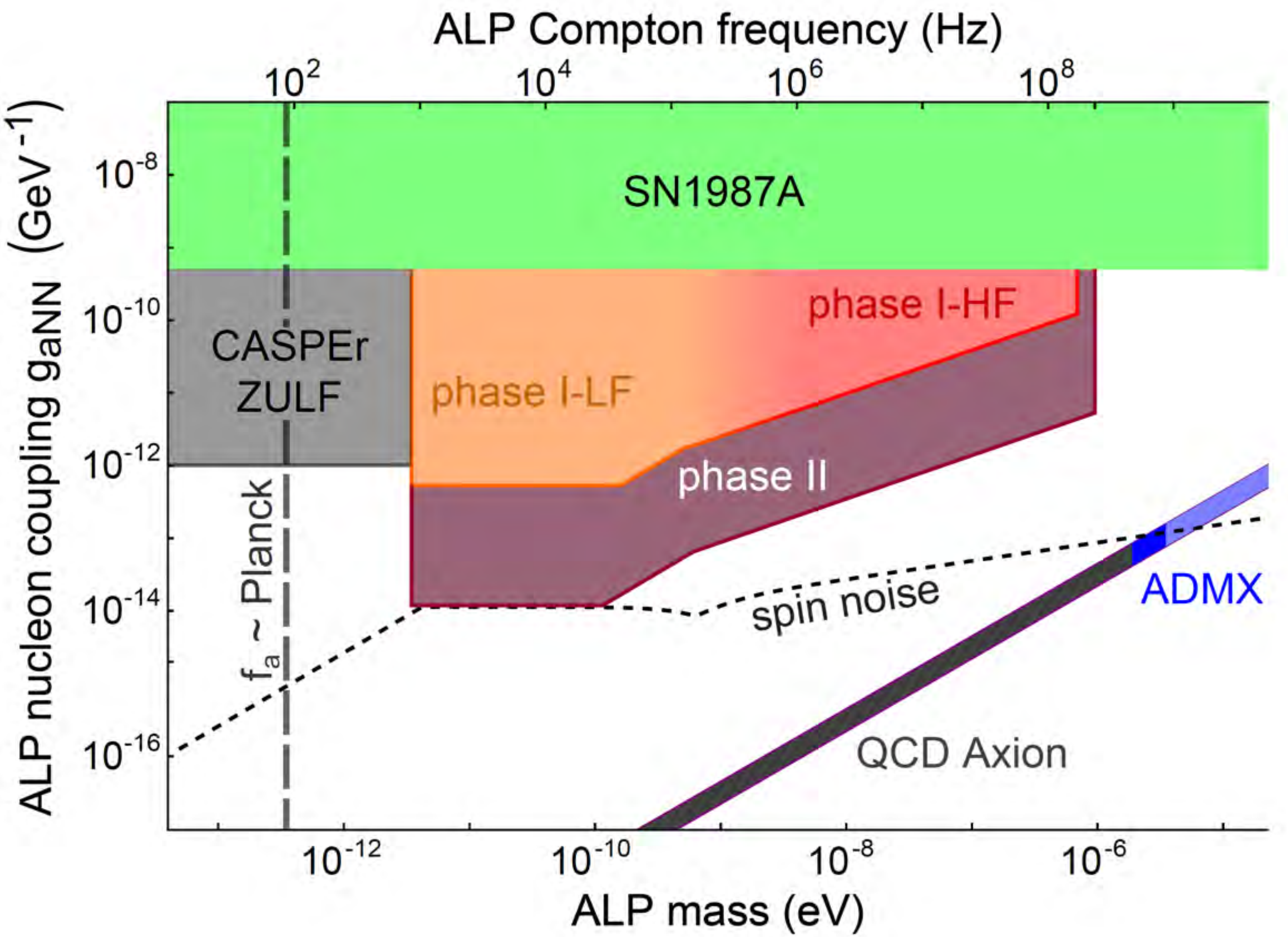

In
Out
Xenon Tank
(~3.6 L)
Pressure
Sensor
Atmosphere
Temp
Sensor
2
(T Out)
Temp
Sensor
1
(T In)

Experiments underway!

Experiments underway!



CASPEr Wind sensitivity



Thank you!

Cosmic Axion Spin Precession Experiment