Searching for axion-like dark matter with ensembles of nuclear spins

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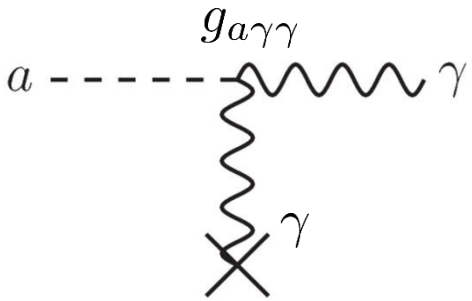
Searching for axions and axion-like particles

1. Pseudoscalar light field: spin = 0, wide range of possible masses [PRD 98, 035017 (2018)]
2. Proposed to solve the strong CP problem of Quantum Chromodynamics [PRL 38, 1440 (1977)]
3. ALPs arise naturally in string theories, symmetries broken at GUT (10^{16} GeV) or Planck (10^{19} GeV) scales
4. Possible couplings to standard model particles:

axion field: $a(t) \approx a_0 \cos \omega_a t$

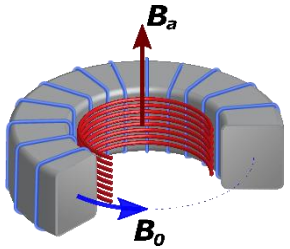
symmetry breaking scale ⟶ $\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$



coupling to photons

ADMX, HAYSTAC, DM radio, ABRA, ALPS, CAST, IAXO, …

SHAFT → a search using toroidal magnetic cores



[A. Gramolin et al., *Nature Physics* **17**, 79 (2021)]

$\frac{a}{f_a} G_{\mu\nu} \tilde{G}^{\mu\nu}$

coupling to gluons

→ creates oscillating nucleon electric dipole moment (EDM) (this is why axions were invented)

→ spin $\boldsymbol{\sigma}$ to axion coupling:

$$H_e \propto a \boldsymbol{\sigma} \cdot \boldsymbol{E}^*$$

CASPEr-electric

$\frac{\partial_\mu a}{f_a} \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$

coupling to fermions

→ via axion field gradient

→ spin $\boldsymbol{\sigma}$ to axion gradient coupling:

$$H_g \propto \boldsymbol{\sigma} \cdot \boldsymbol{\nabla} a$$

CASPEr-gradient

CASPEr (Cosmic Axion Spin Precession Experiments) searches for experimental signatures of these couplings

[*arXiv*:2101.01241 (2021)]

Axion-like dark matter field

CASPEr-electric

$$H_{\mathrm{e}} \propto \vec{\boldsymbol{\sigma}} \cdot (a\vec{\boldsymbol{E}}^*)$$

CASPEr-gradient

$$H_{\mathrm{g}} \propto \vec{\boldsymbol{\sigma}} \cdot \vec{\boldsymbol{\nabla}} a$$

axion (or ALP) field

$$a(t) = a_0 \cos \omega_a t$$

$\omega_a = m_a c^2/\hbar$ → ALP Compton frequency

$\rho_{\mathrm{DM}} \propto a_0^2$ → dark matter density

$$H_{\mathrm{e}} \propto \vec{\boldsymbol{\sigma}} \cdot (a_0\vec{\boldsymbol{E}}^*) \cos \omega_a t$$

$$H_{\mathrm{g}} \propto \vec{\boldsymbol{\sigma}} \cdot (\vec{\boldsymbol{\nabla}} a_0) \cos \omega_a t$$

$$H_{\mathrm{CASPEr}} = \vec{\boldsymbol{\sigma}} \cdot \vec{\boldsymbol{B}}_1^* \cos \omega_a t$$

spin

effective magnetic field due to ALP dark matter

oscillating at ALP Compton frequency

[*Phys. Rev. X* **4**, 021030 (2014)]

Searching for axion coupling to spin with magnetic resonance

effective interaction: $H_{\mathrm{CASPEr}} = \vec{\boldsymbol{\sigma}} \cdot \vec{\boldsymbol{B}}_1^* \cos \omega_a t$

$$H = \vec{\boldsymbol{\sigma}} \cdot \vec{\boldsymbol{B}}_0 + \vec{\boldsymbol{\sigma}} \cdot \vec{\boldsymbol{B}}_1^* \cos \omega_a t$$

- constant bias magnetic field $\boldsymbol{B}_0$
- spin-axion interaction plays the role of the radiofrequency magnetic field $\boldsymbol{B}_1$

1) placing a spin-1/2 into an external magnetic field splits the spin states by $g\mu B_0$

2) spin polarization (thermal or optical) in a cm³ sample

3) resonance: $\hbar\omega_a = g\mu B_0$

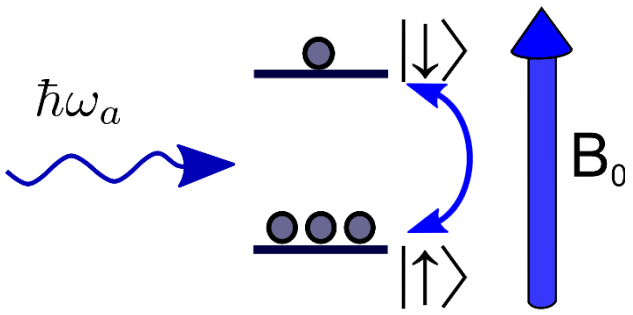
➡ axion-spin interaction can now flip spins!

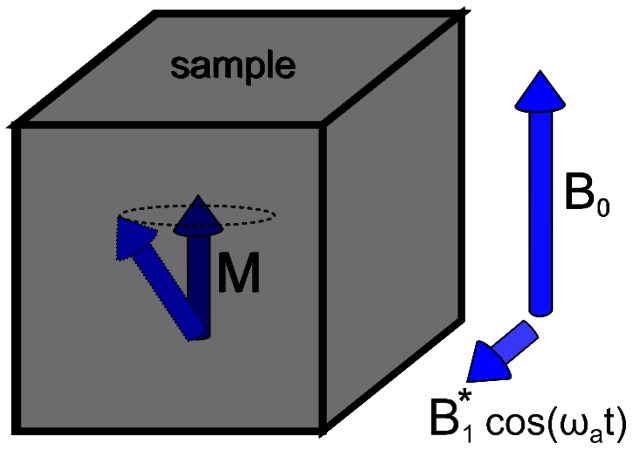
➡ sample magnetization tilts and precesses

4) a magnetometer next to the sample detects the magnetic field created by this precessing magnetization

⬇

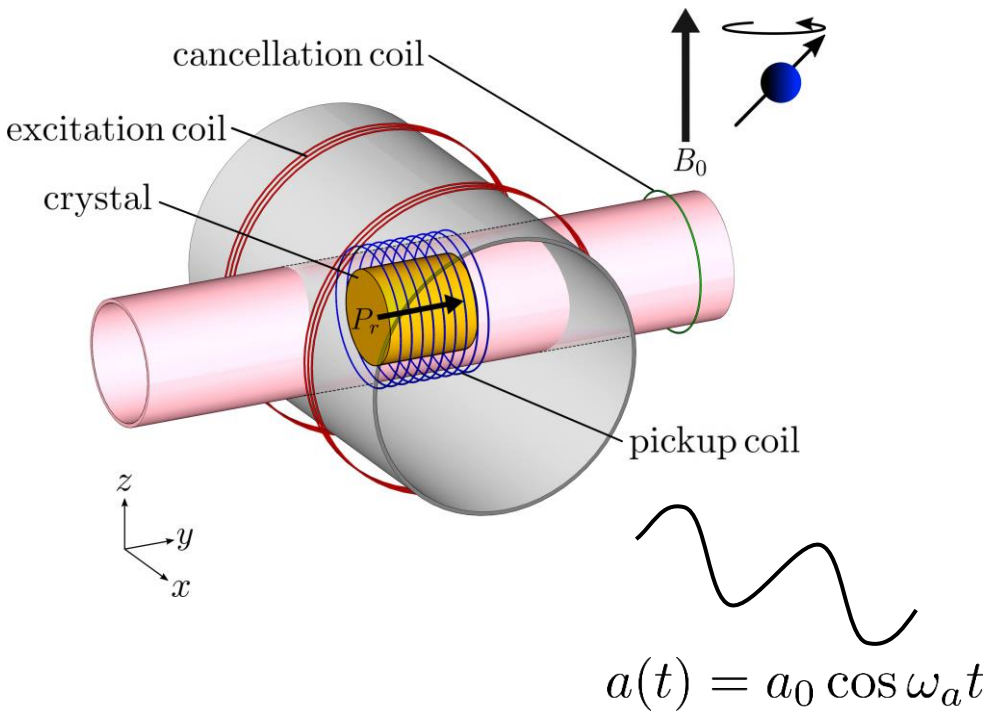
an NMR experiment with no RF magnetic field, instead axion dark matter flips spins

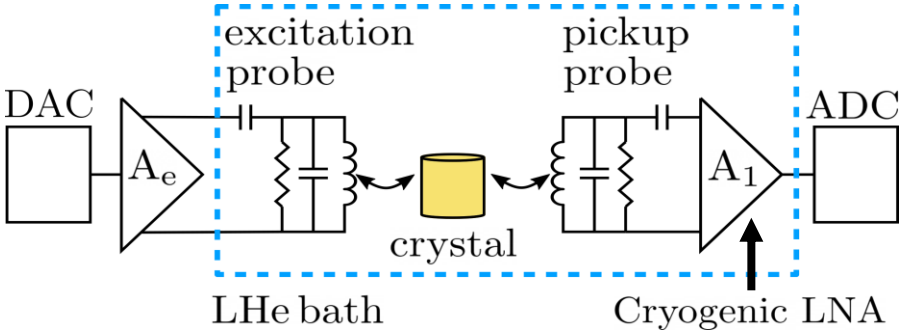




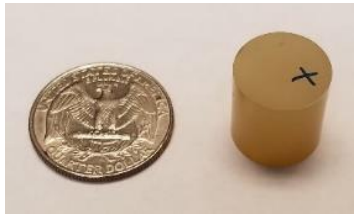
[*Phys. Rev. X* **4**, 021030 (2014)]

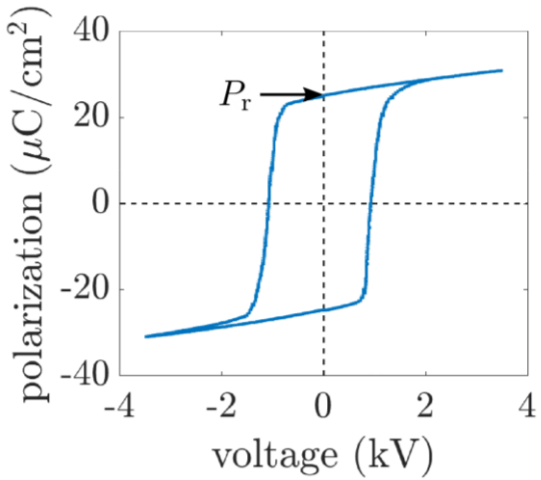
CASPEr-electric setup





PMN-PT ferroelectric crystal with ^{207}Pb :

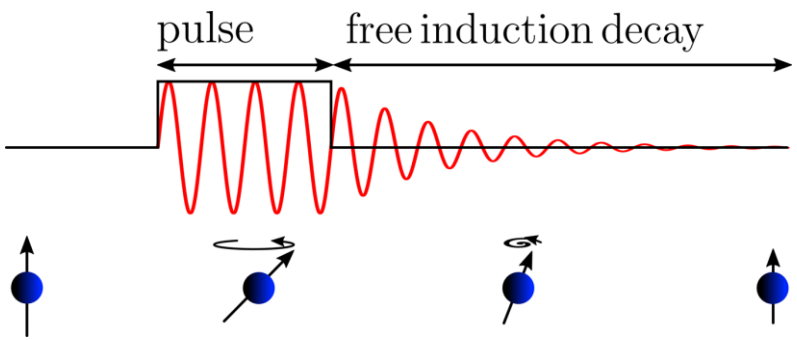




It is feasible to use solid-state NMR in search for the axion-like dark matter

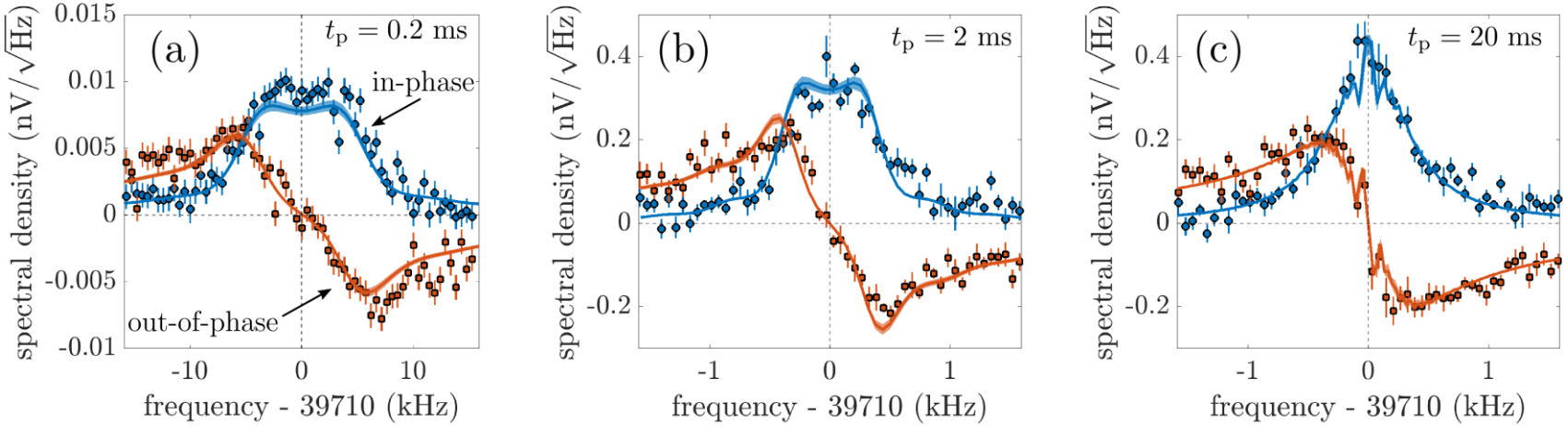
[arXiv:2101.01241]

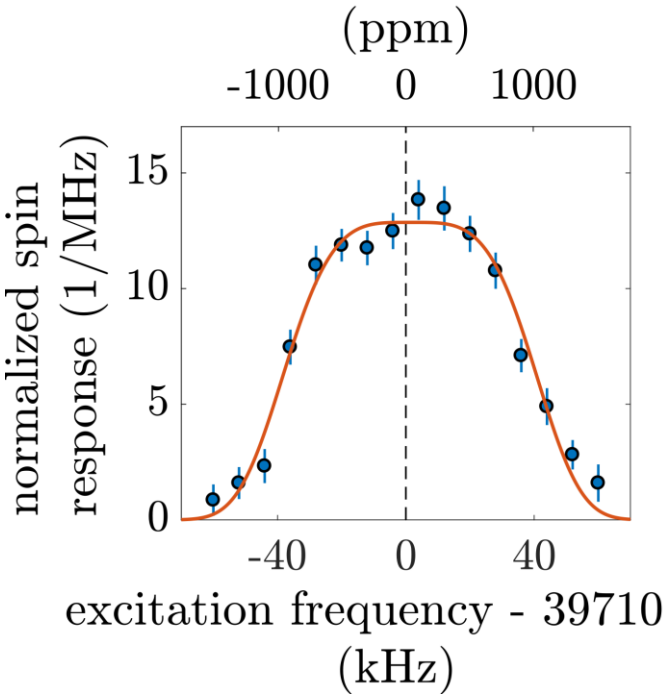
System calibration with pulsed NMR measurements



We simulate spin response with the Bloch equations.

We fit to data with 3 free parameters: T_2, and pickup and excitation conversion factors.





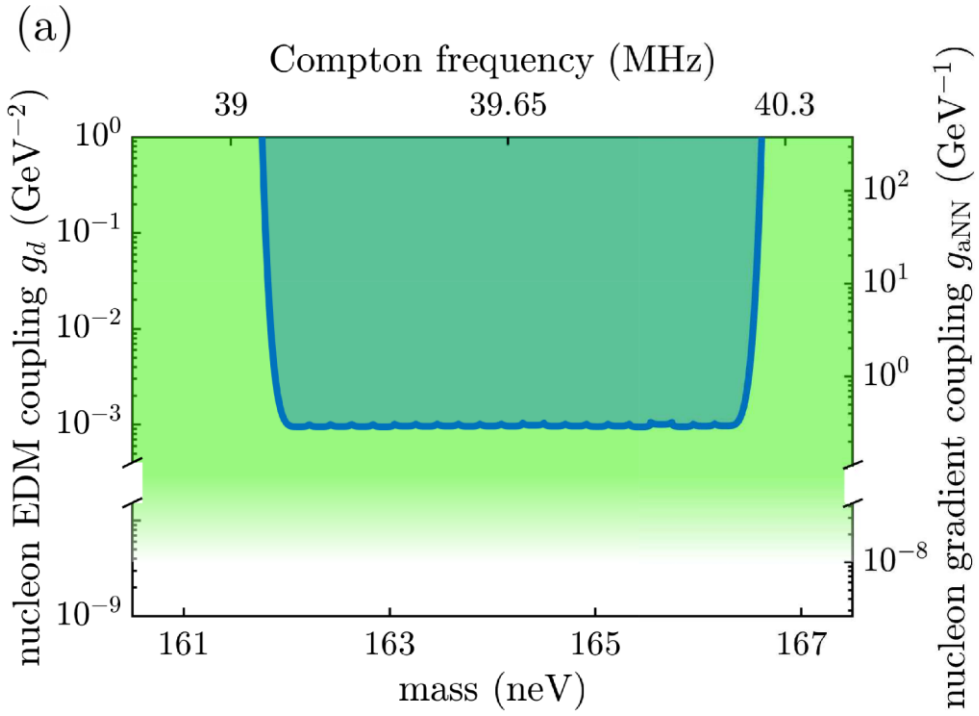
We characterize the excitation spectrum and relaxation parameters of the nuclear spin ensemble with pulsed NMR

[arXiv:2101.01241]

Analysis of data sensitive to axion-like dark matter

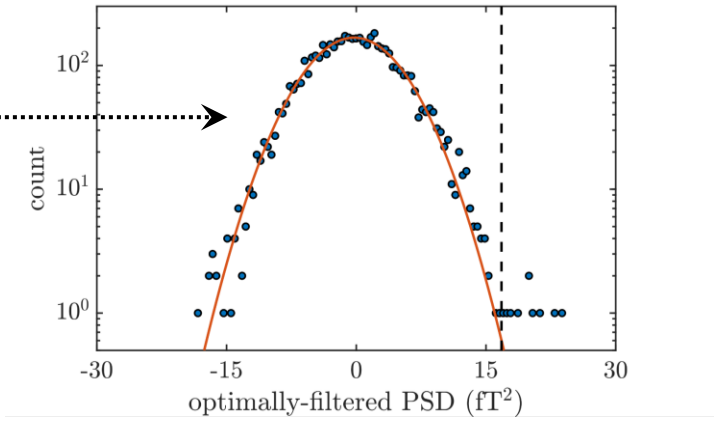
- Use parameters extracted from NMR fits.
- Optimally filter data by convolving PSD with the expected axion-like dark matter lineshape.

Sweep B_0 to change resonant frequency: $\hbar\omega_a = g\mu B_0$



detection threshold

histogram of data points

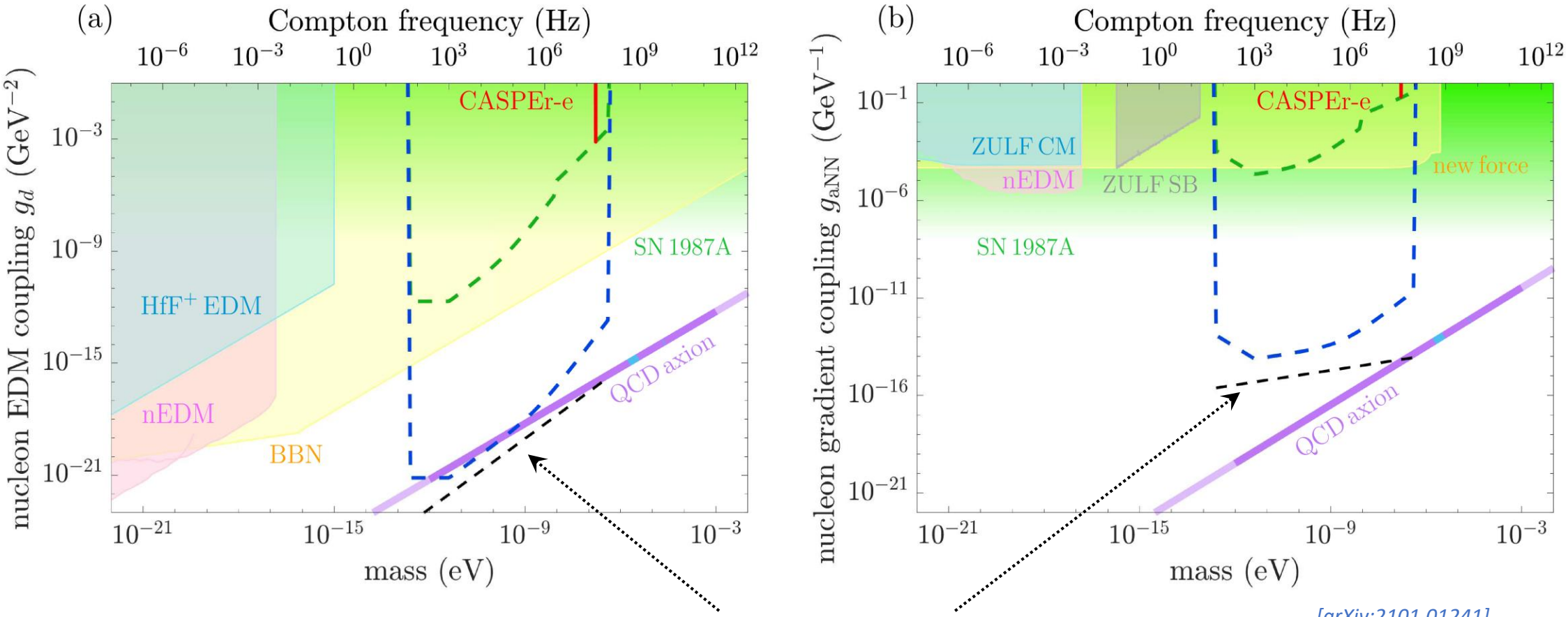


Analysis placed upper bounds of $|g_d| < 9.5 \times 10^{-4}$ GeV^{-2} and $|g_{aNN}| < 2.8 \times 10^{-1}$ GeV^{-1}

Sensitivity was limited by 0.05 nV/$\sqrt{\text{Hz}}$ input noise of the amplifier, corresponding to a magnetic field sensitivity of 2 fT/$\sqrt{\text{Hz}}$.

[arXiv:2101.01241]

Future sensitivity projections and quantum sensitivity limits



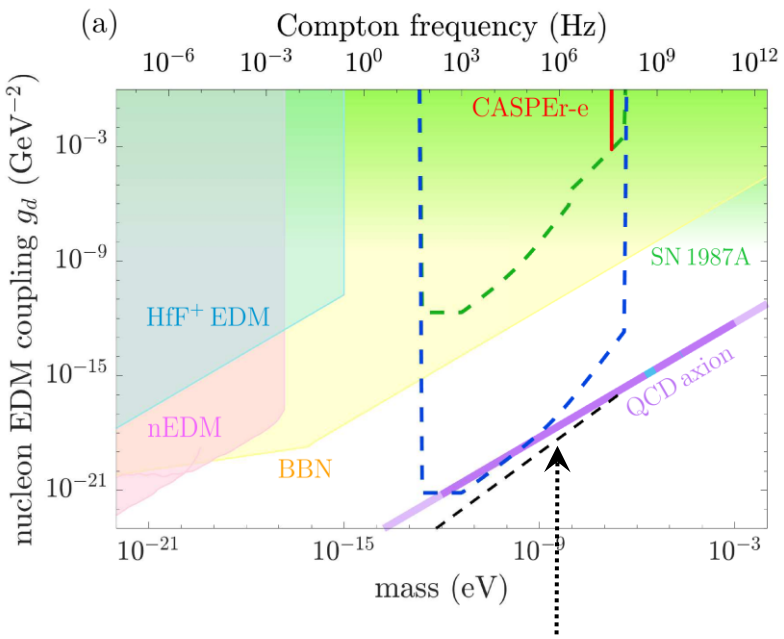
[arXiv:2101.01241]

quantum sensitivity limit

Current generation of CASPEr-e will surpass astronomical limits in sensitivity to EDM coupling using Superconducting Quantum Interference Devices (SQUIDs) as the magnetometer **below 1 MHz**.

Next generation CASPEr-e will reach the QCD axion in EDM coupling by increasing the sample size and the spin polarization.

Next generation CASPEr-e



quantum sensitivity limit

[arXiv:2101.01241]

We will reach the QCD axion in EDM coupling by increasing the sample size and the **spin polarization**:

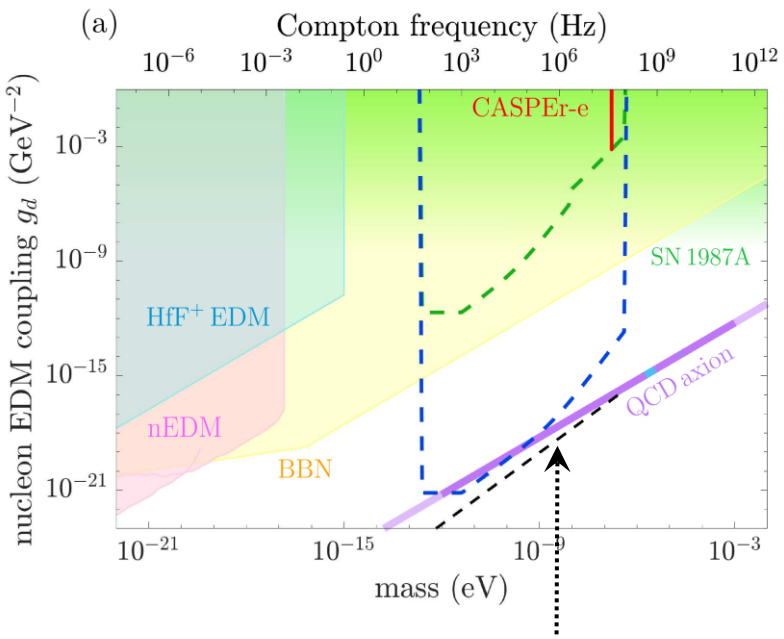
Dynamic Nuclear Polarization (DNP)

Transferring polarization from unpaired electron spins to nuclear spins (hyperpolarization).

Decrease temperature to 100 mK

$$p \sim \frac{\mu B_0}{k_B T}$$

Next generation CASPEr-e



quantum sensitivity limit

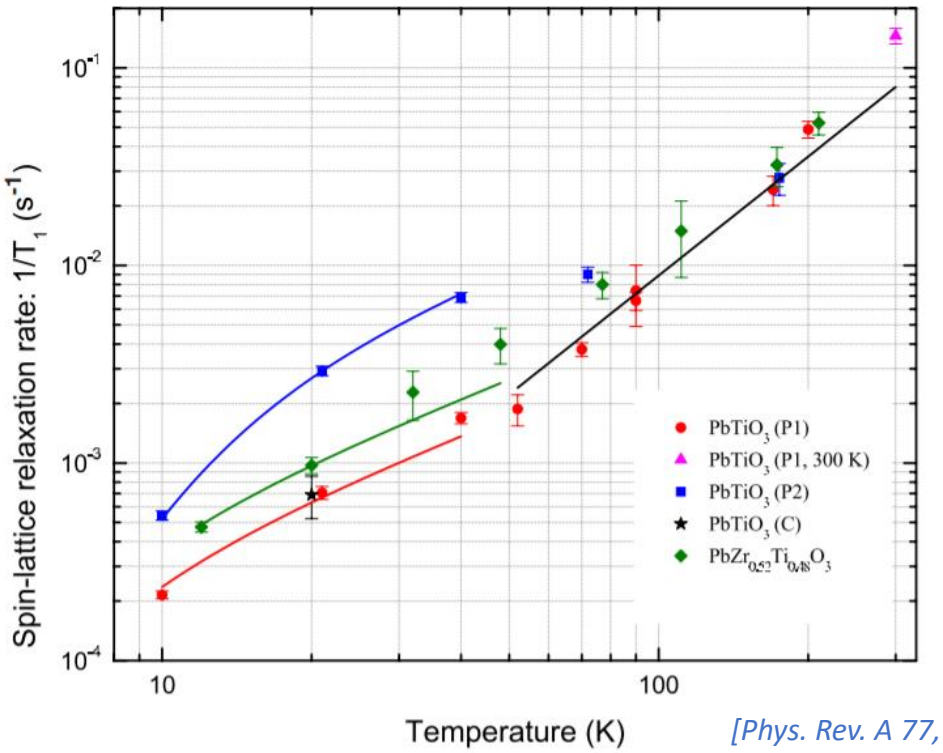
[arXiv:2101.01241]

We will reach the QCD axion in EDM coupling by increasing the sample size and the **spin polarization**:

Decrease temperature to 100 mK

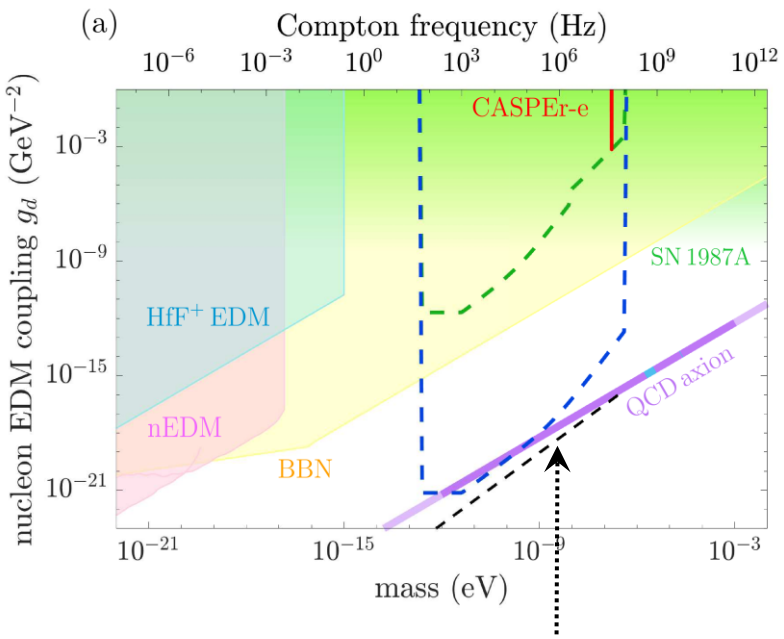
$$p \sim \frac{\mu B_0}{k_B T}$$

$T_1 \sim$ hours



[Phys. Rev. A 77, 022102 (2008)]

Next generation CASPEr-e



quantum sensitivity limit

[arXiv:2101.01241]

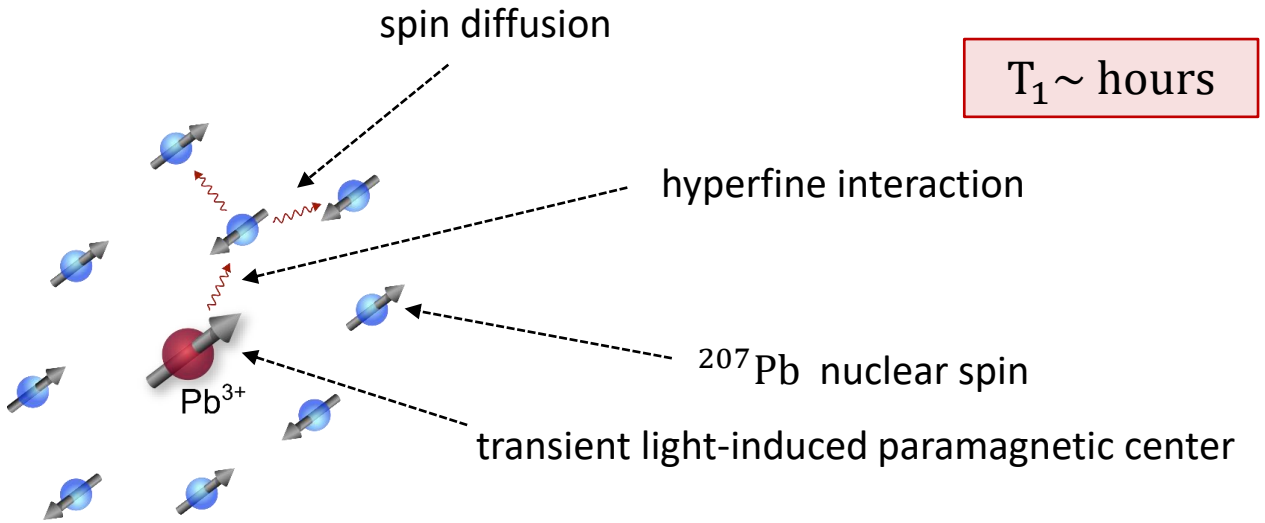
We will reach the QCD axion in EDM coupling by increasing the sample size and the **spin polarization**:

Decrease temperature to 100 mK

$$p \sim \frac{\mu B_0}{k_B T}$$

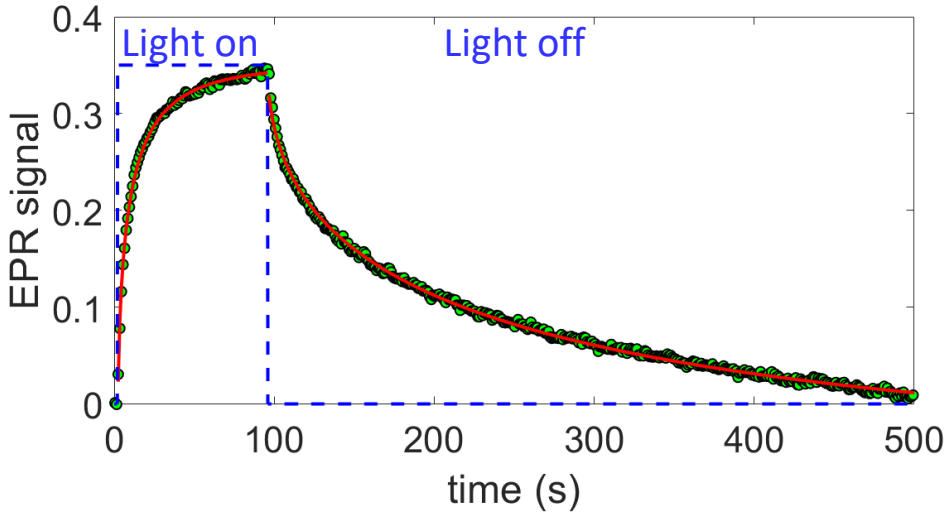
$T_1 \sim$ hours

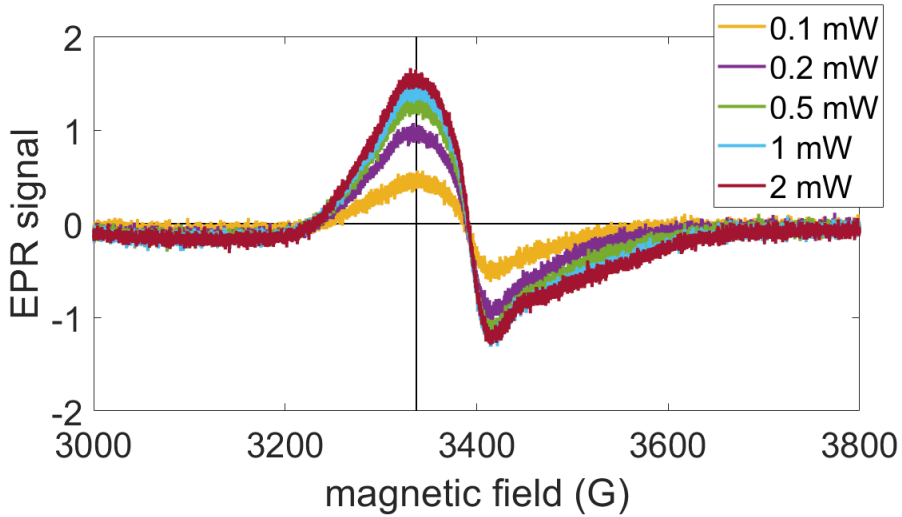
405 nm laser



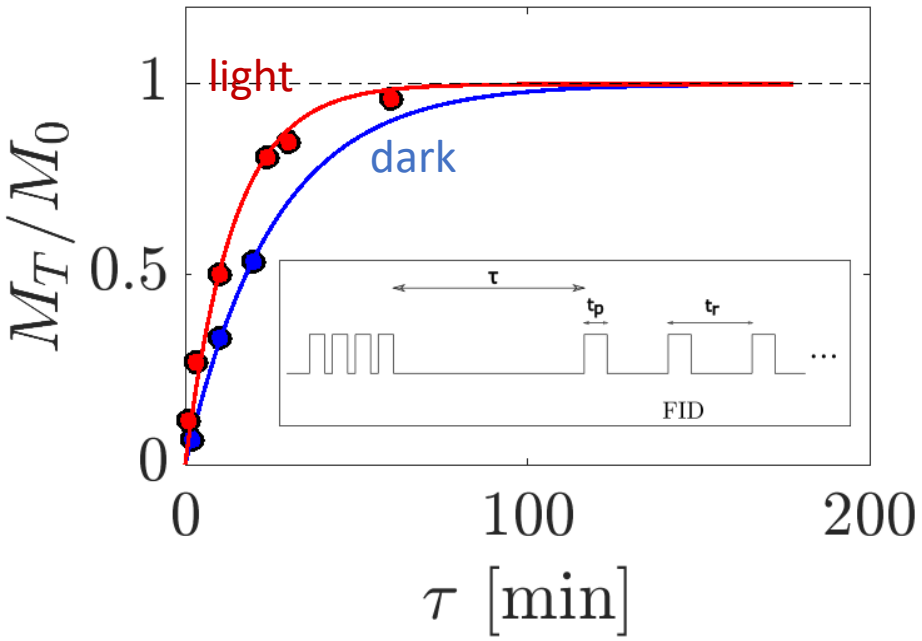
By shining light, we can excite electrons and reduce T_1.

EPR study of transient light-induced paramagnetic centers





$$n_{\mathrm{Pb}3+} \approx 2 \times 10^{17}\mathrm{cm}^{-3}$$

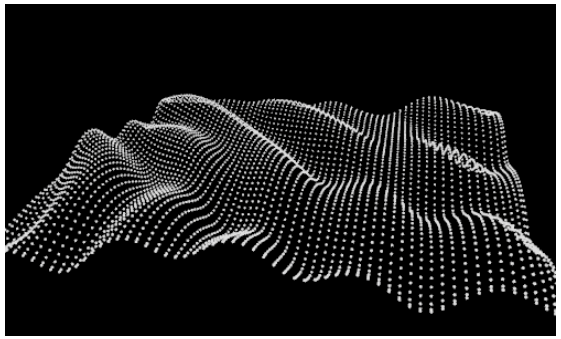


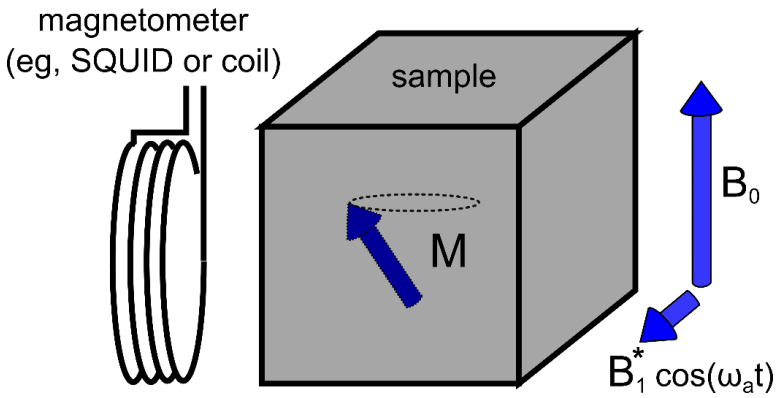
$$T_1^{\mathrm{dark}} = 25.8 \pm 0.7 \text{ min}$$
$$T_1^{\mathrm{light}} = 14.2 \pm 1.1 \text{ min}$$

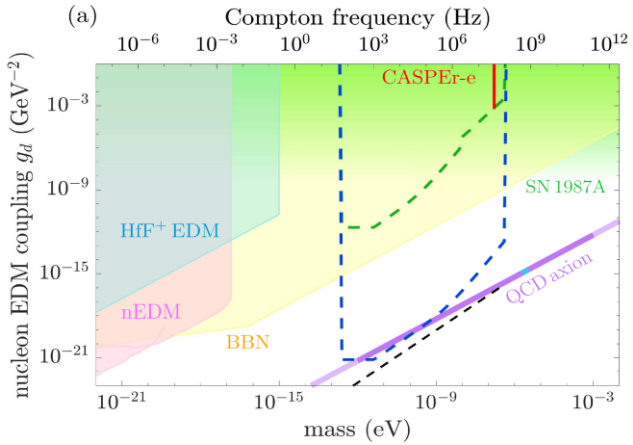
We can control the relaxation properties of the spin ensemble using transient light-induced paramagnetic centers.

Searching for axion-like dark matter with ensembles of nuclear spins

axion field: $a(t) \approx a_0 \cos \omega_a t$







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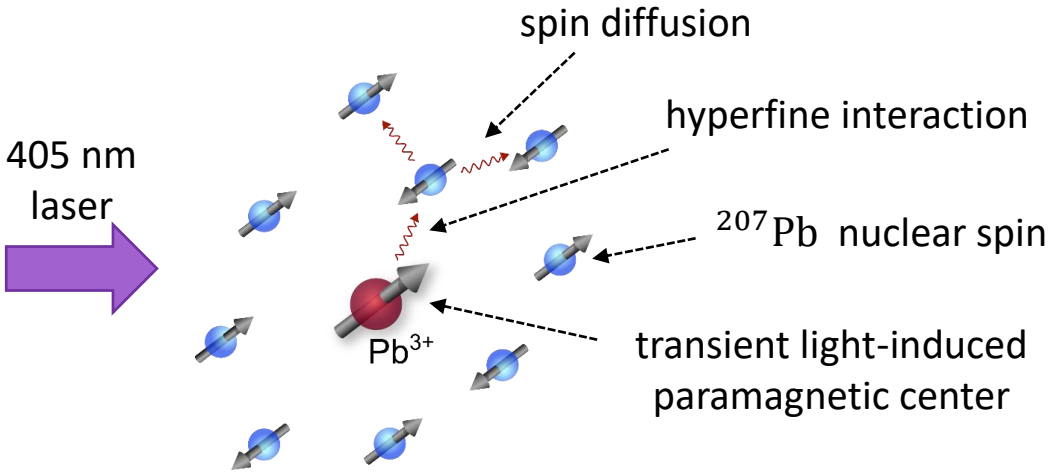

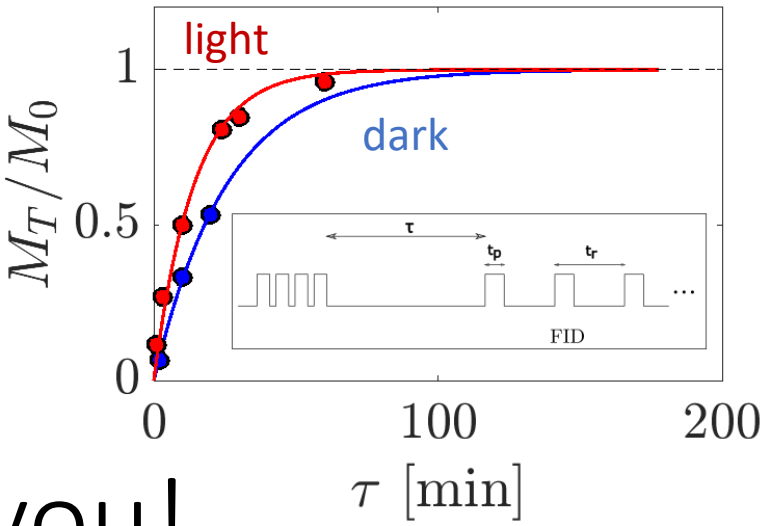

Thank you!

I'm in the Postdoc market!