Title: Probing magnetic-field like effects

Speakers: Alex Sushkov

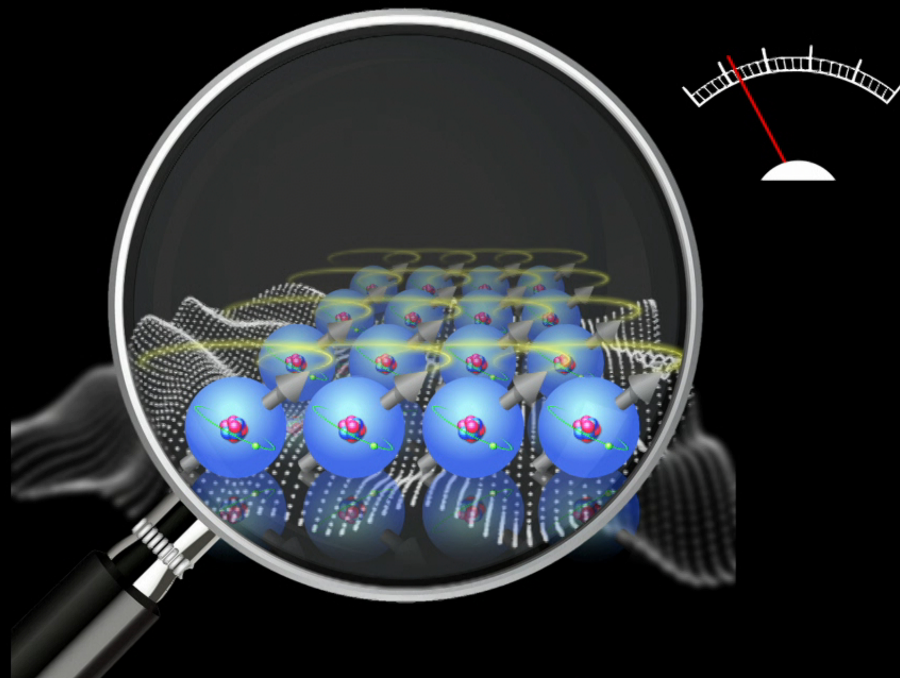
Collection: School on Table-Top Experiments for Fundamental Physics

Date: September 20, 2022 - 3:15 PM

URL: https://pirsa.org/22090012

Table-top fundamental physics: probing magnetic field-like effects 2

Alex Sushkov



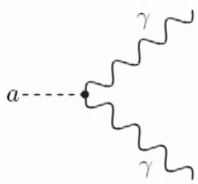
BOSTON UNIVERSITY

Main points

▪ Lecture 1: lumped element searches for the electromagnetic interaction of axion-like dark matter

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

$$\mathcal{L}_{a\gamma\gamma} = g_{a\gamma\gamma} a \boldsymbol{E} \cdot \boldsymbol{B}$$

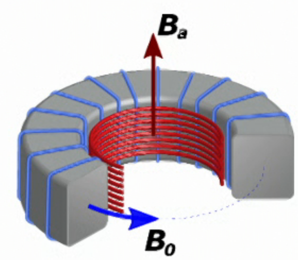


key experimental parameters:

- magnetic field B → larger is better
- volume V → larger is better
- temperature → colder is better
- sensor noise and back-action

SHAFT
ABRA
DM radio

- resonant experiments are most sensitive
- on-resonance sensitivity is limited by thermal and quantum noise
- back-action evasion via squeezing can expand sensitive bandwidth, and thus speed up cavity scan



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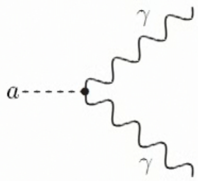

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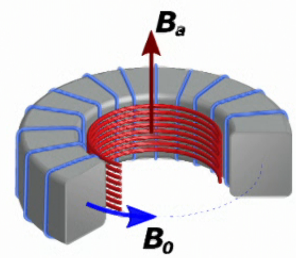

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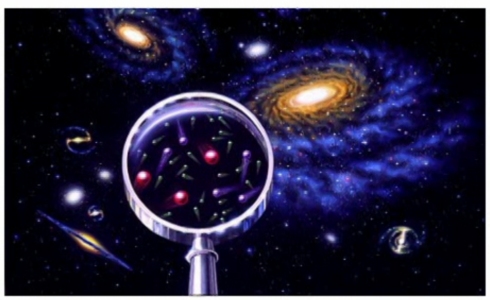
▪ Lecture 2: searches for the interactions of axion-like dark matter with spins

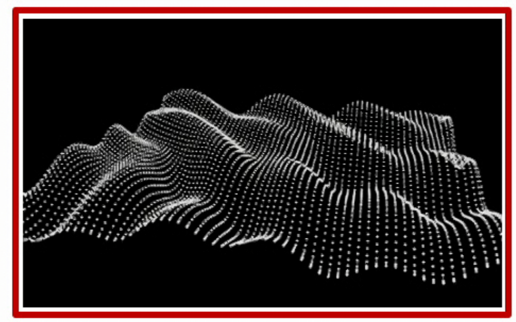
What is dark matter?

[Nature **562**, 51 (2018)]



particle-like dark matter (eg: WIMPs):
mass ~ 100 GeV

[*Phys. Rev. D* **96**, 035009 (2017)]



wave-like dark matter (eg: axions)
mass << eV

[Phys. Rev. Lett. **118**, 061302 (2017)]

Axions and axion-like particles, axion-like dark matter

1. Pseudoscalar light particle: spin = 0, wide range of possible masses [Phys. Rev. D **98**, 035017 (2018)]
2. Proposed to solve the **strong CP problem** of Quantum Chromodynamics
3. Axion-like particles (ALPs) arise naturally in string theories, symmetries broken at GUT (10^{16} GeV) or Planck (10^{19} GeV) scales
4. Well-motivated and thoroughly-studied **dark matter** candidate: $a(t) = a_0 \cos \omega_a t$

ALP mass range $m_a c^2 < \mathrm{meV}$

+

dark matter energy density: $\rho_{\mathrm{DM}} \approx 0.4 \frac{\mathrm{GeV}}{\mathrm{cm}^3} \approx (0.05\,\mathrm{eV})^4$

↓

large number of particles per de Broglie wavelength

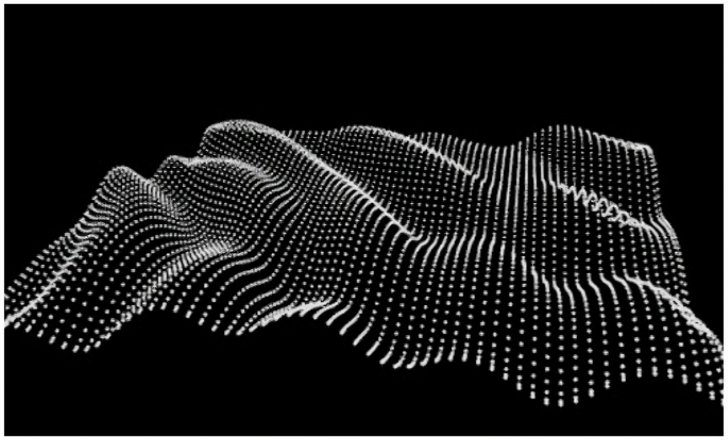
↓

ALP dark matter acts as a classical field

axion-like 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



Tomorrow: searches for interactions of axions with nuclear spins

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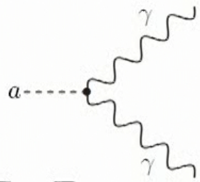
5. Only 3 possible (non-gravitational) interactions with standard model particles:

interaction with photons:

ALP field amplitude → symmetry breaking scale →

$$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$$



$$\mathcal{L}_{a\gamma\gamma} = g_{a\gamma\gamma} a \boldsymbol{E} \cdot \boldsymbol{B}$$

→ ALP ↔ photon conversion in a magnetic field
→ precision electromagnetic sensors

ADMX, HAYSTAC, DMradio, SHAFT, ABRA, ALPS, CAST, IAXO, CAPP, ORGAN, BREAD, SLIC, LC circuit, MADMAX, KLASH, BRASS, many others

interaction with gluons: (defines QCD axion)

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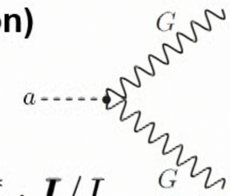

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→ nuclear spin $\boldsymbol{I}$ interacts with an oscillating electric dipole moment (EDM) $d_n = g_d a$ in presence of effective electric field $\boldsymbol{E}^*$.

CASPEr-electric

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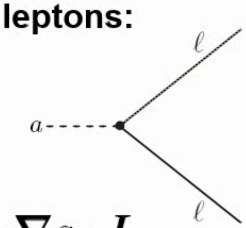

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co-magnetometers
force mediator → ARIADNE
electron spin → QUAX

CASPEr-gradient

[*Rev. Mod. Phys.* ***93***, 015004 (2021)]
[*arXiv:2203.14923* (2022)]

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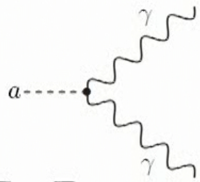

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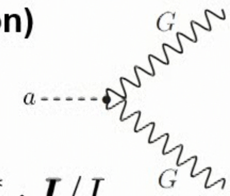

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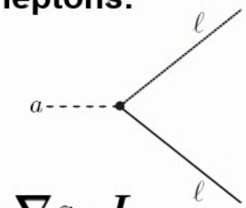

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Searches for electromagnetic interaction of axion-like dark matter

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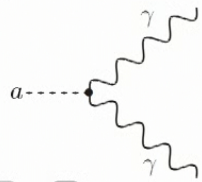

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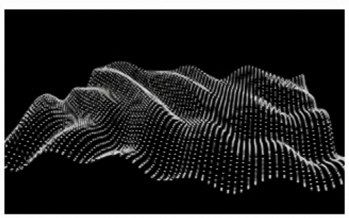
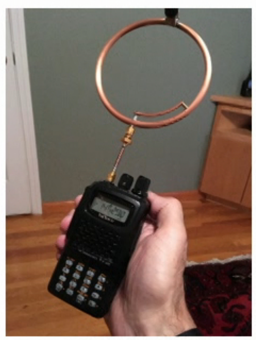
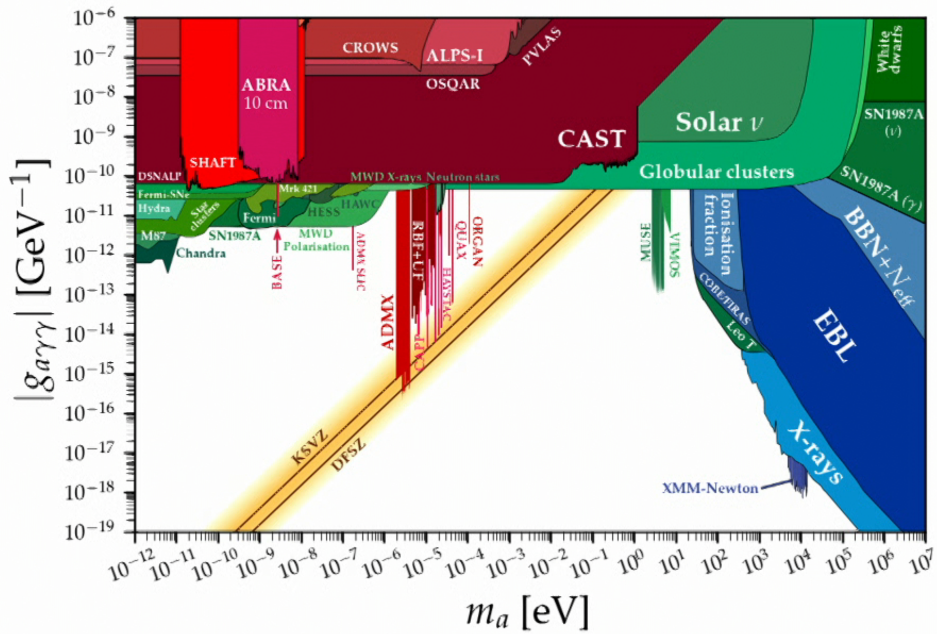


axion-like dark matter

+



sensor measures electromagnetic field



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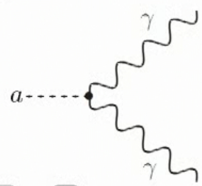

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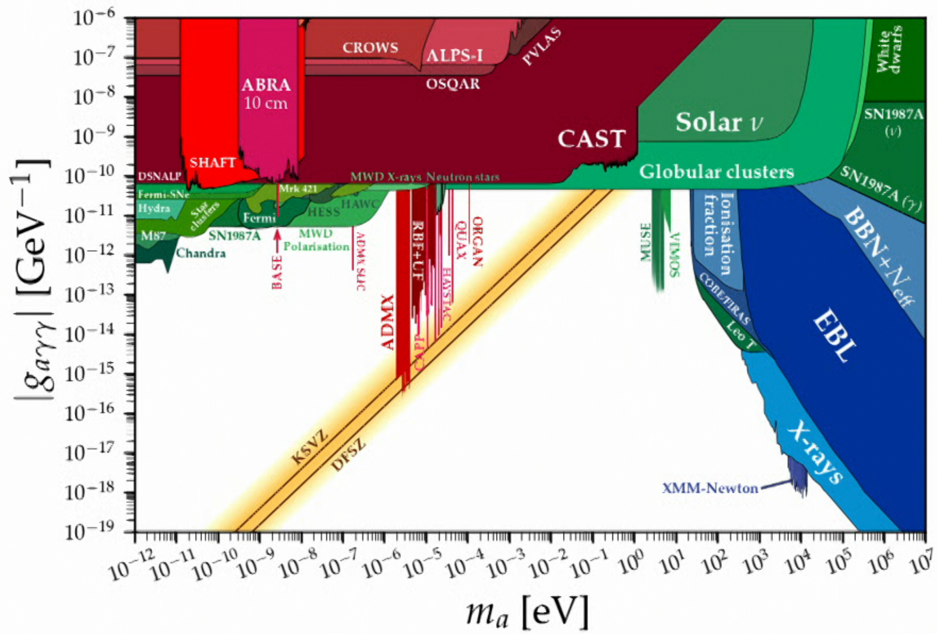

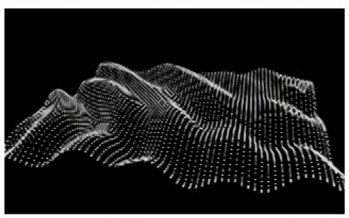

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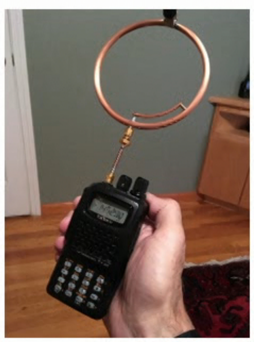

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Spin ensemble as the transducer for detecting axion-like particles

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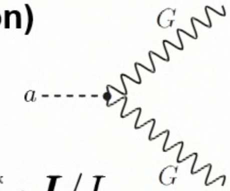

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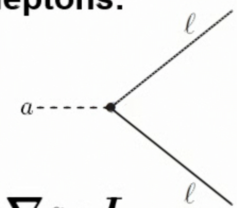

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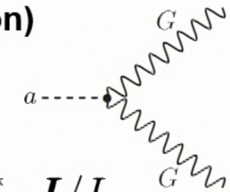

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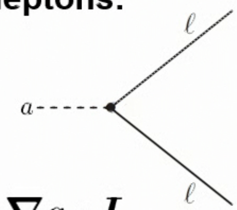

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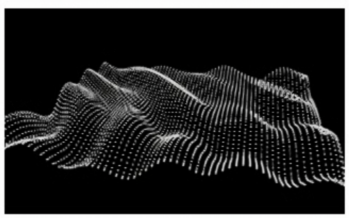
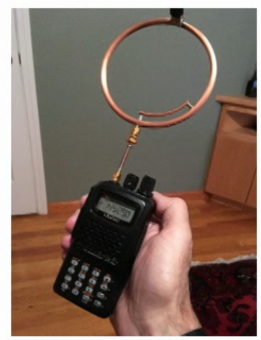


axion-like field



electromagnetic sensor measures spin ensemble evolution

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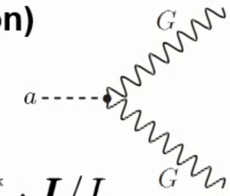

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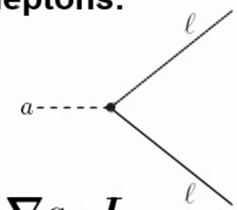

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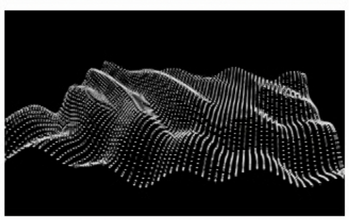

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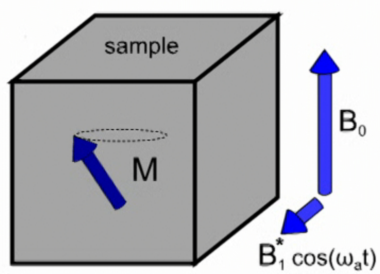
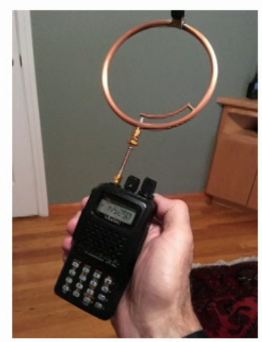


spin ensemble acts as the transducer



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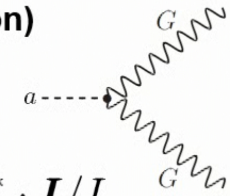

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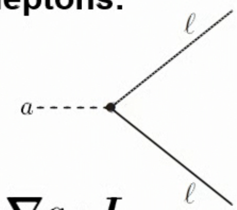

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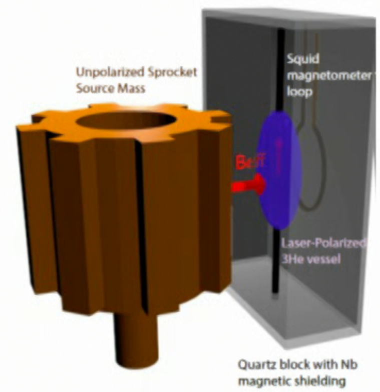
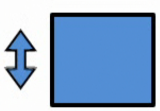
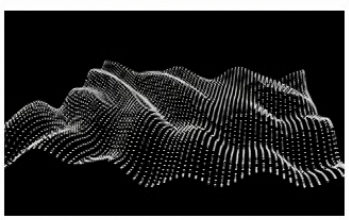


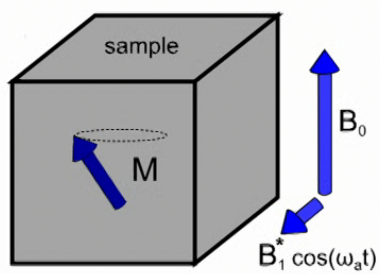
ARIADNE



oscillating mass



axion-like field



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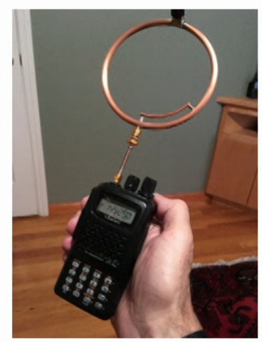
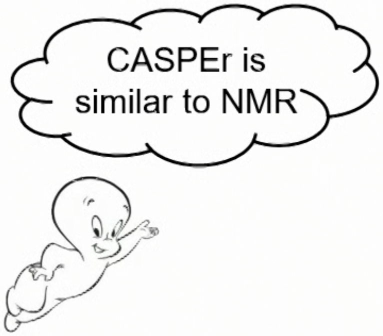
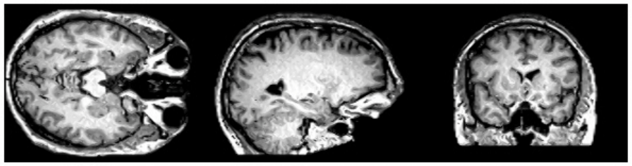


electromagnetic sensor measures spin ensemble evolution

flexibility to optimize spin ensemble parameters to optimize transducer efficiency → maximize sensitivity

Aside: magnetic resonance





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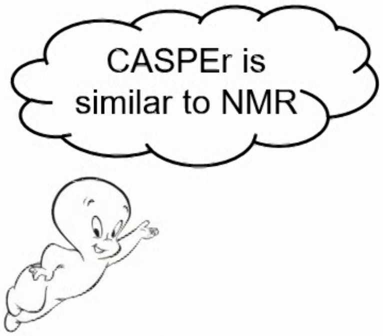

(nuclear gyromagnetic ratio) → γ_I

interaction: $\mathcal{H}_{\mathrm{NMR}} = -\hbar\gamma_I \boldsymbol{B} \cdot \boldsymbol{I}$

Aside: magnetic resonance

CASPEr is similar to NMR

(nuclear gyromagnetic ratio) → γ_I

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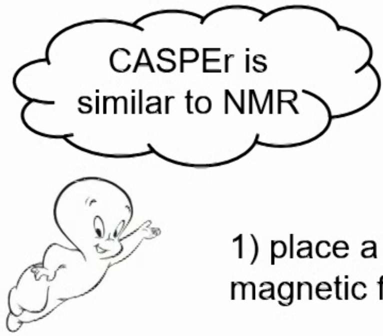
$$\mathcal{H}_{\text{NMR}} = -\hbar\gamma_I \boldsymbol{B}_0 \cdot \boldsymbol{I} - \hbar\gamma_I (\boldsymbol{B}_1 \cos\omega_0 t) \cdot \boldsymbol{I}$$

- constant bias magnetic field $\boldsymbol{B}_0$
- radiofrequency (RF) magnetic field $\boldsymbol{B}_1 \cos\omega_0 t$

1) place a spin-1/2 into an external magnetic field splits the spin states by $\gamma_I B_0$

Aside: magnetic resonance



(nuclear gyromagnetic ratio)

interaction: $\mathcal{H}_{\rm NMR} = -\hbar\gamma_I \boldsymbol{B}\cdot\boldsymbol{I}$

$$\mathcal{H}_{\rm NMR} = -\hbar\gamma_I \boldsymbol{B}_0\cdot\boldsymbol{I} - \hbar\gamma_I(\boldsymbol{B}_1\cos\omega_0 t)\cdot\boldsymbol{I}$$

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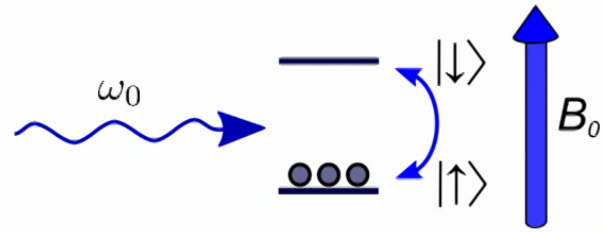
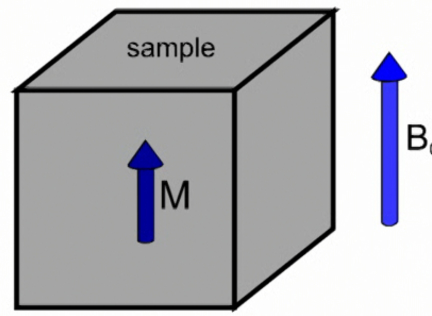
2) spin polarization (thermal or optical) in a cm^3 sample

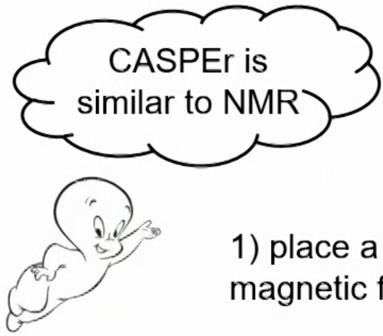
3) resonance: $\omega_0 = \gamma_I B_0$

➡ RF magnetic field can now flip spins!





Aside: magnetic resonance



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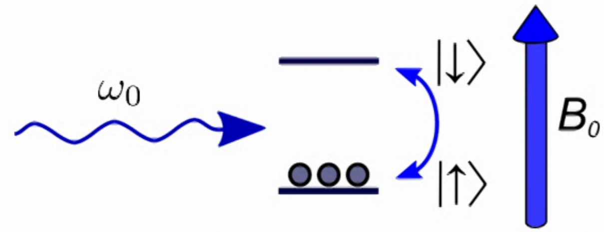

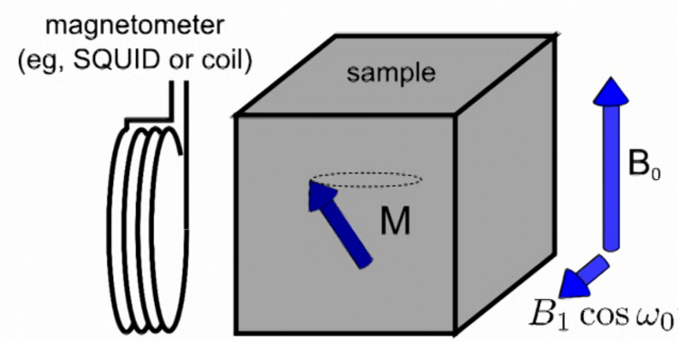

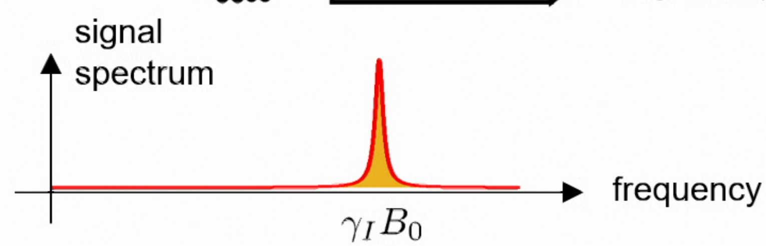

Aside: magnetic resonance

CASPEr is similar to NMR

(nuclear gyromagnetic ratio)

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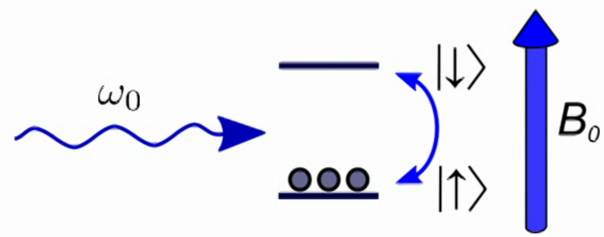

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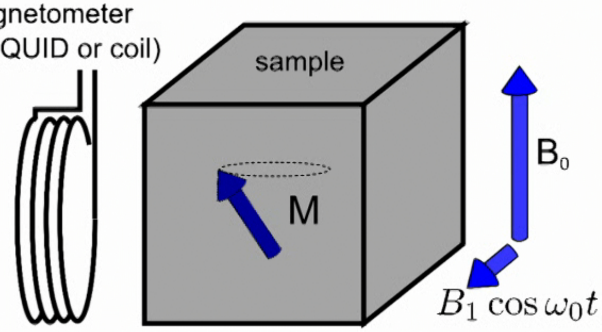
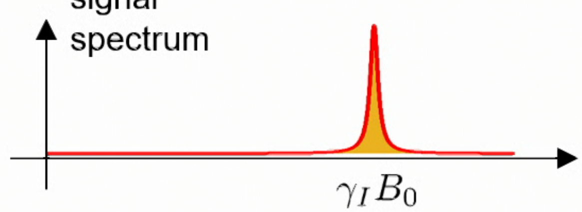


a tool for non-invasive imaging (MRI, EPR) and studying molecular structure (NMR)

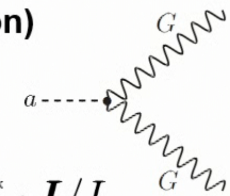


Interaction of axion-like particles with spins

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

interaction with gluons:
(defines QCD axion)

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

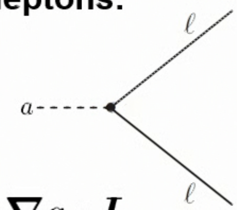


$$\mathcal{H}_{\mathrm{EDM}} = g_d a \boldsymbol{E}^* \cdot \boldsymbol{I}/I$$

→ nuclear spin $\boldsymbol{I}$ interacts with an oscillating electric dipole moment (EDM) $d_n = g_d a$ in presence of effective electric field $\boldsymbol{E}^*$.

interaction with leptons:

$$\frac{\partial_\mu a}{f_a} \bar{\psi}_\ell \gamma^\mu \gamma_5 \psi_\ell$$



$$\mathcal{H}_{aNN} = g_{aNN} \boldsymbol{\nabla} a \cdot \boldsymbol{I}$$

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Axion-like dark matter → pseudo-magnetic field

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

CASPEr-electric

$$\mathcal{H}_{\rm EDM} = g_d a \boldsymbol{E}^* \cdot \boldsymbol{I}/I$$

CASPEr-gradient

$$\mathcal{H}_{aNN} = g_{aNN} \boldsymbol{\nabla} a \cdot \boldsymbol{I}$$

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

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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

$$\mathcal{H}_{\mathrm{EDM}} = (g_d a_0 \boldsymbol{E}^* \cos \omega_a t) \cdot \boldsymbol{I}/I$$

$$\mathcal{H}_{aNN} = (g_{aNN} \boldsymbol{\nabla} a_0 \cos \omega_a t) \cdot \boldsymbol{I}$$

$$\mathcal{H}_{\mathrm{CASPEr}} = -(\hbar \gamma_I \boldsymbol{B}_1^* \cos \omega_a t) \cdot \boldsymbol{I}$$

effective magnetic field due to ALP dark matter

oscillating at ALP Compton frequency

nuclear spin

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

Searching for axionic coupling to spin with magnetic resonance

effective interaction: $\mathcal{H}_{\text{CASPEr}} = -(\hbar\gamma_I \boldsymbol{B}_1^* \cos\omega_a t)\cdot \boldsymbol{I}$

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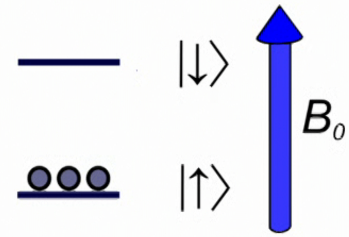

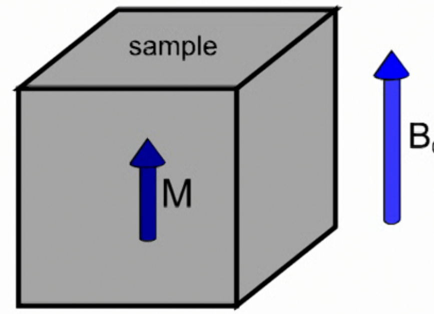

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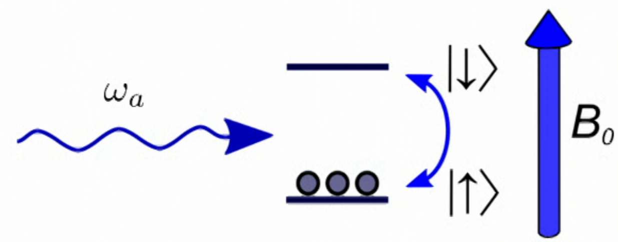
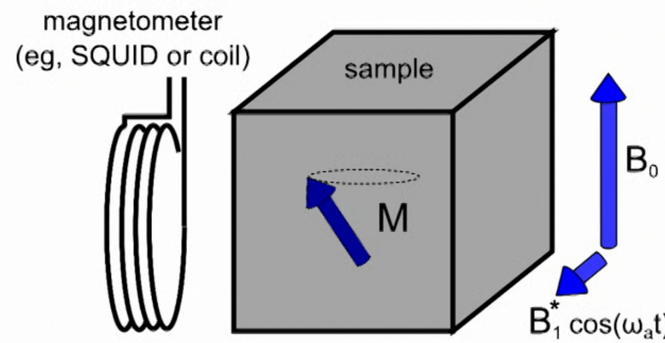
3) resonance: $\omega_a = \gamma_I B_0$

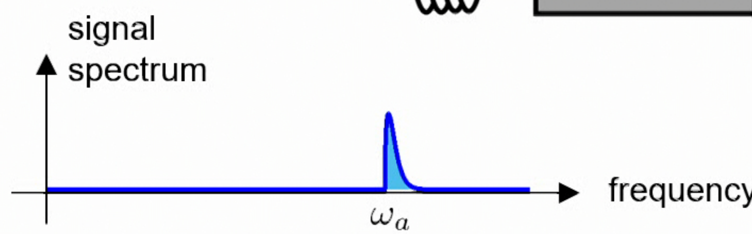
- axion-spin interaction can now flip spins!
- sample magnetization tilts and precesses

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

5) search for unknown frequency ω_a by sweeping bias magnetic field B_0, look for resonance







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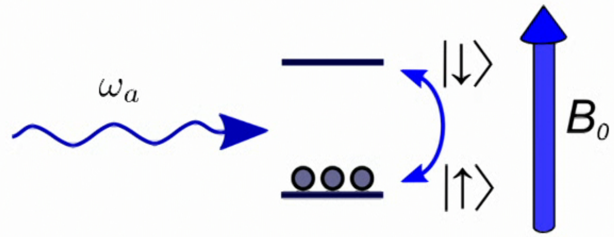
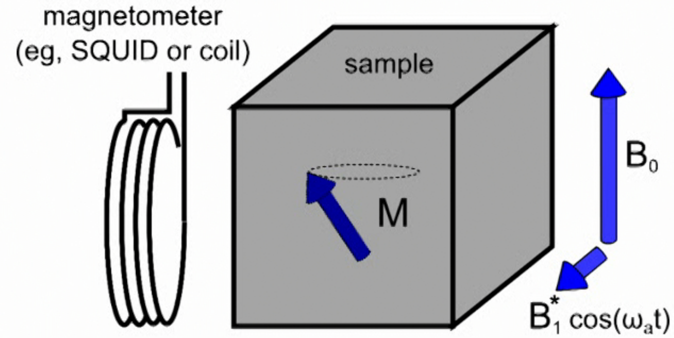
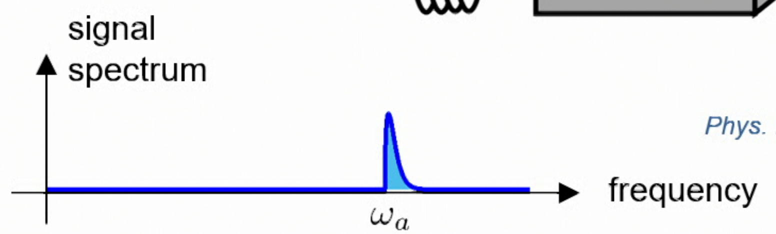
an NMR experiment with no RF magnetic field, instead axion-like dark matter flips spins





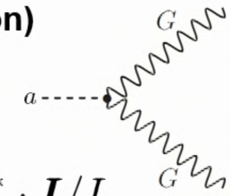


[D. Budker et al., *Phys. Rev. X* **4**, 021030 (2014)]

Spin ensemble as the transducer for detecting axion-like particles

interaction with gluons:
(defines QCD axion)

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



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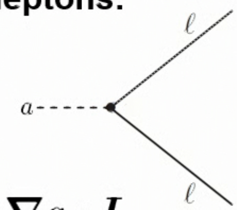
$$\frac{\partial_\mu a}{f_a} \bar{\psi}_\ell \gamma^\mu \gamma_5 \psi_\ell$$



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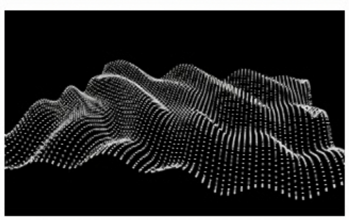
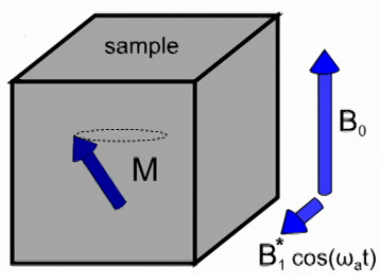
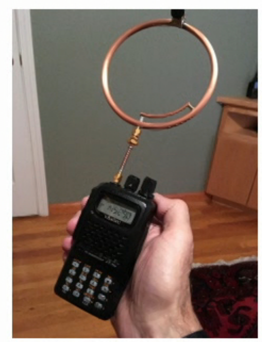


axion-like field



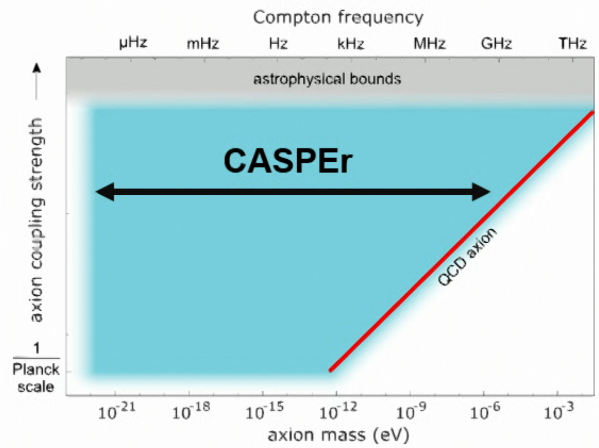
spin ensemble acts as the transducer



electromagnetic sensor measures spin ensemble evolution

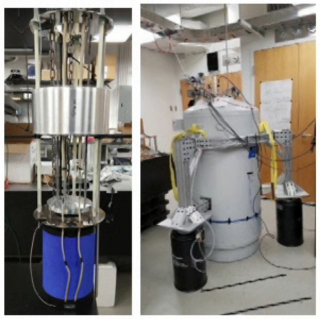
flexibility to optimize spin ensemble parameters to optimize transducer efficiency → maximize sensitivity

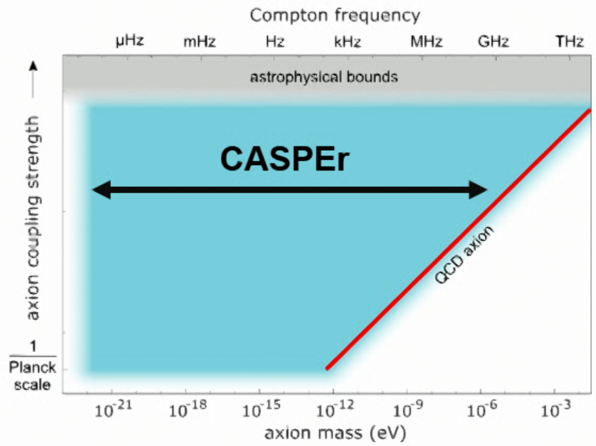
CASPEr program



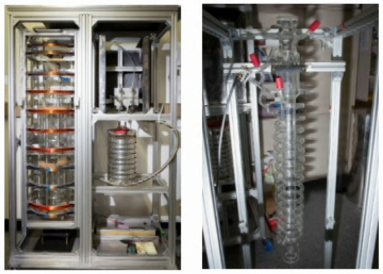
CASPEr program

Boston University:
CASPEr-electric using spins in solids
→ sensitive to both $\mathcal{H}_{\mathrm{EDM}} = g_d a \boldsymbol{E}^* \cdot \boldsymbol{I}/I$
$\mathcal{H}_{aNN} = g_{aNN} \boldsymbol{\nabla} a \cdot \boldsymbol{I}$





Mainz:
CASPEr-gradient using hyperpolarized liquids
→ sensitive to $\mathcal{H}_{aNN} = g_{aNN} \boldsymbol{\nabla} a \cdot \boldsymbol{I}$

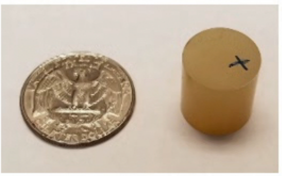


CASPEr-e: experimental details

sample: 4mm

^{207}Pb nuclear spins in ferroelectrically-polarized PMN-PT

$(PbMg_{1/3}Nb_{2/3}O_3)_{2/3}(PbTiO_3)_{1/3}$



3×10^{20} spins

[D. Aybas et al., *Phys. Rev. Lett.* **126**, 160505 (2021)]

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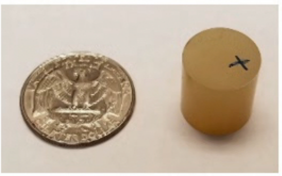

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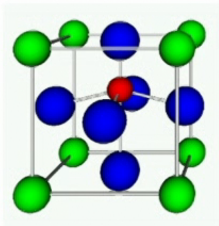

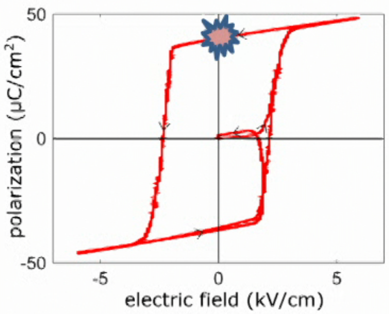

$E^* = 340\,\mathrm{kV/cm}$

(similar to a polar molecule

ACME [*Science* **343**, 269 (2013)]
[*Nature* **562**, 355 (2018)])

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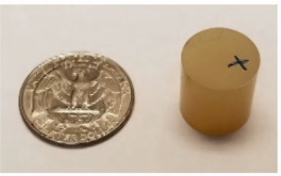
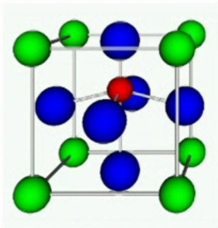

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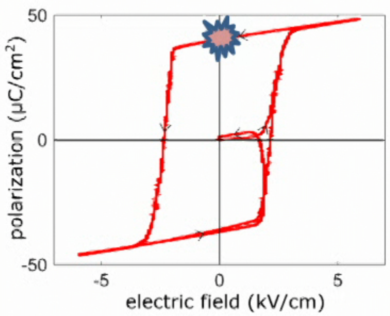

$$E^* = 340\,\mathrm{kV/cm}$$

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ACME [*Science* **343**, 269 (2013)]
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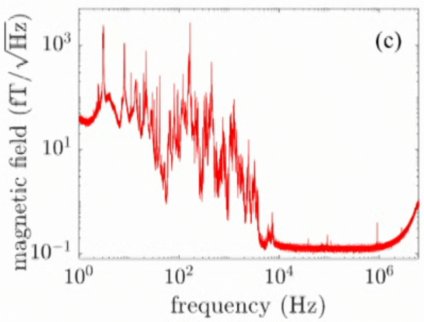
sensor:

low-noise radiofrequency amplifier

SQUID



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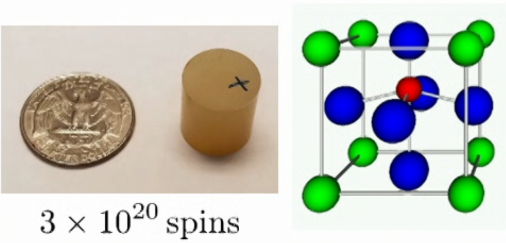
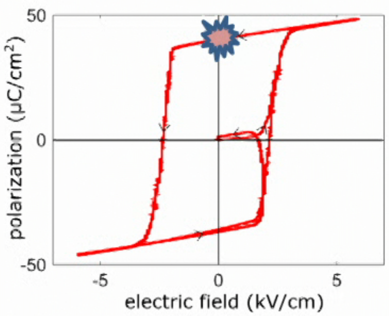


3×10^{20} spins



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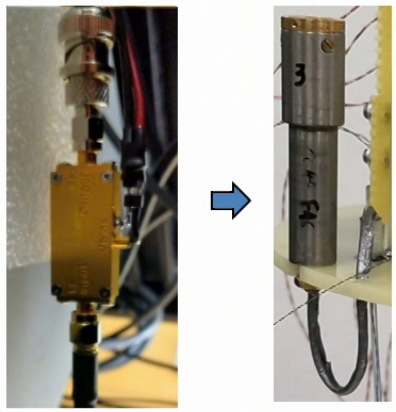
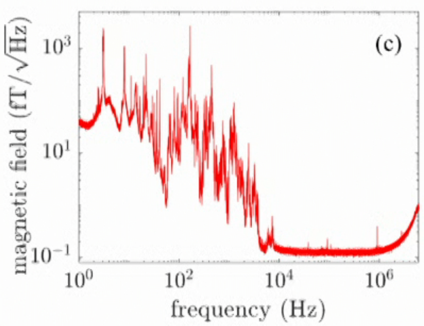
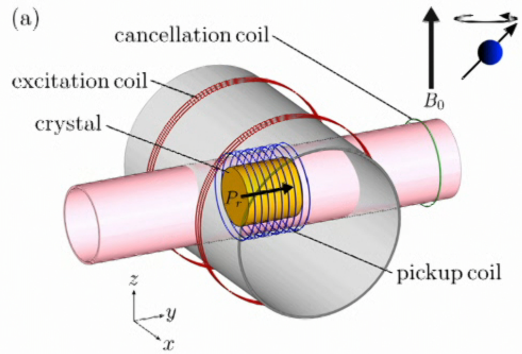




NMR calibration

crossed excitation and pickup coils



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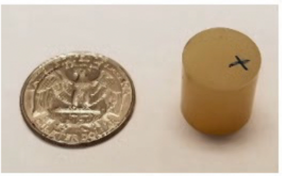
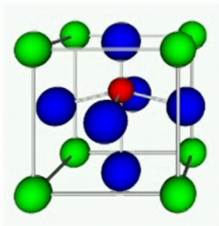
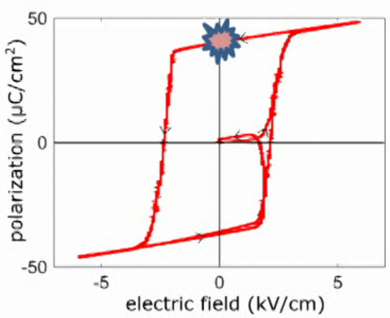




3×10^{20} spins

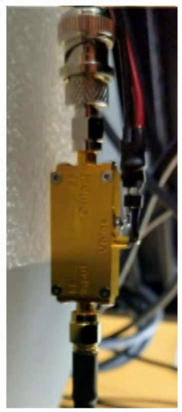


$E^* = 340\,\mathrm{kV/cm}$

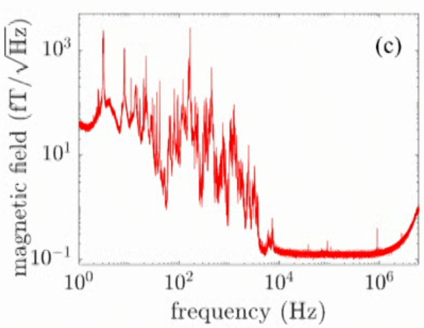
(similar to a polar molecule
ACME [*Science* **343**, 269 (2013)]
[*Nature* **562**, 355 (2018)])

sensor:

low-noise radiofrequency amplifier

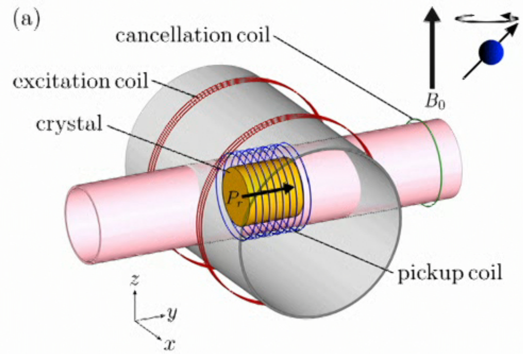


SQUID

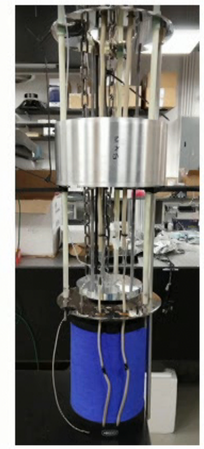


NMR calibration

crossed excitation and pickup coils



liquid helium (4 K) bath cryostat with 9T magnet



[D. Aybas et al., *Phys. Rev. Lett.* **126**, 160505 (2021)]

Millimeter-scale CASPEr-e axion-like dark matter search

CASPEr-e limits on nucleon EDM and gradient interactions of axion-like dark matter

$$\mathcal{H}_{\text{EDM}} = g_d a \boldsymbol{E}^* \cdot \boldsymbol{I}/I$$
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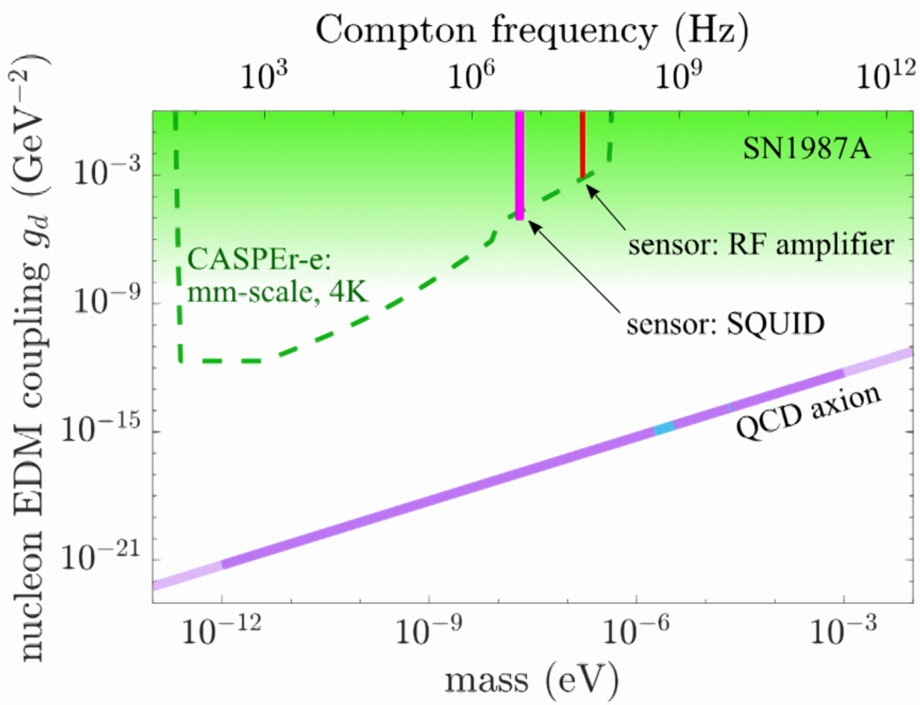

[D. Aybas et al., *Phys. Rev. Lett.* **126**, 160505 (2021)]
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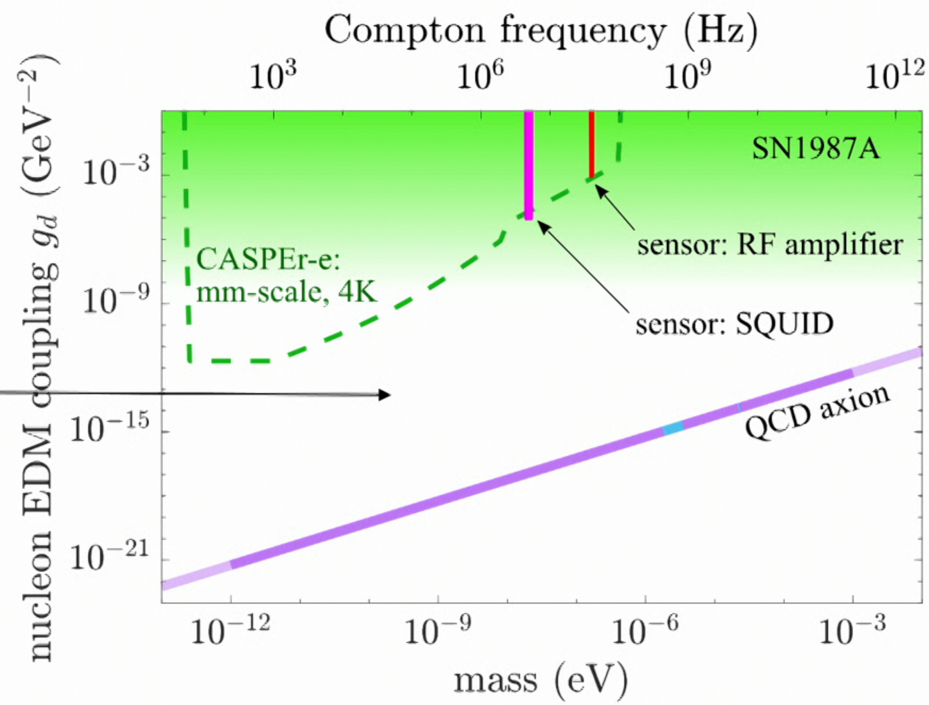
→ limits on oscillation amplitudes of neutron EDM and θ_{QCD}:

$$|d_n| < 1.0 \times 10^{-21}\ \mathrm{e \cdot cm}$$
$$|\theta| < 4.3 \times 10^{-6}$$

how do we probe the unexplored parameter space?



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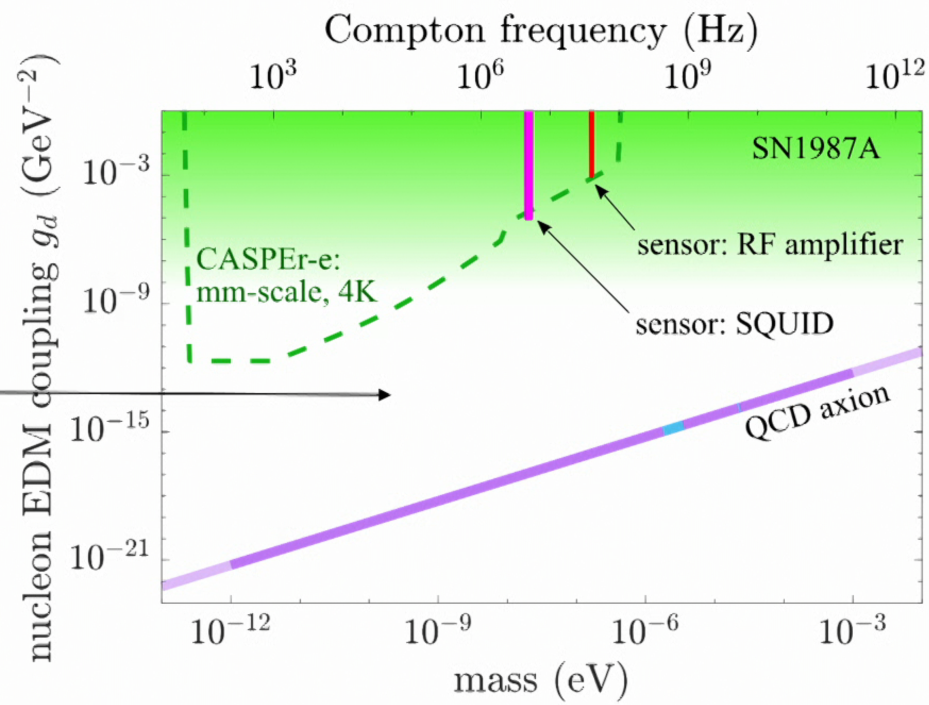

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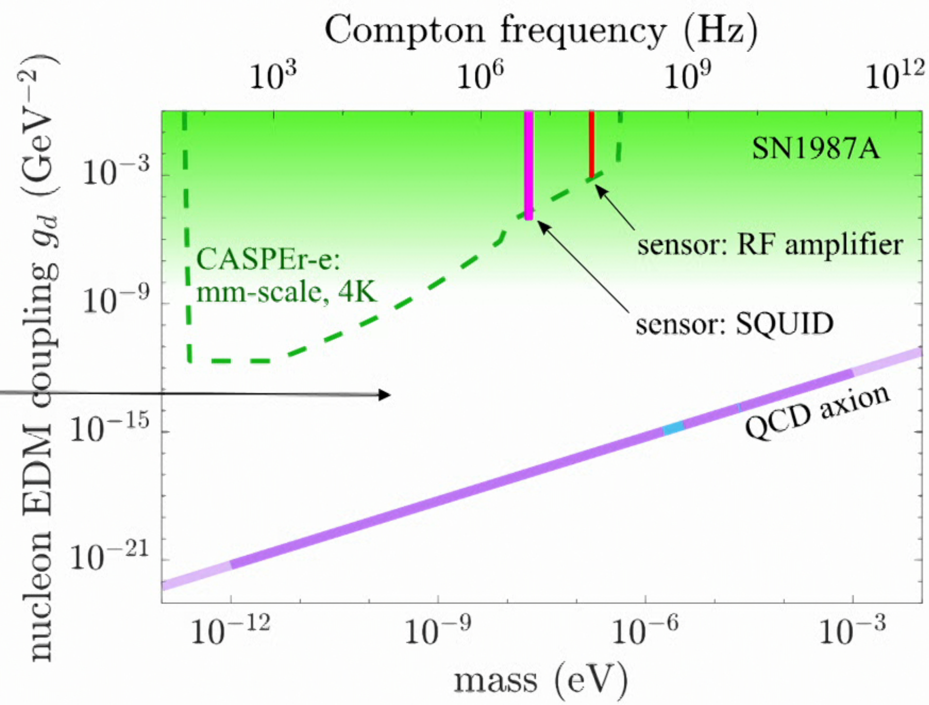

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- broad-band: tune frequency by changing magnetic field (i.e. current) → can cover 4-5 decades in axion mass

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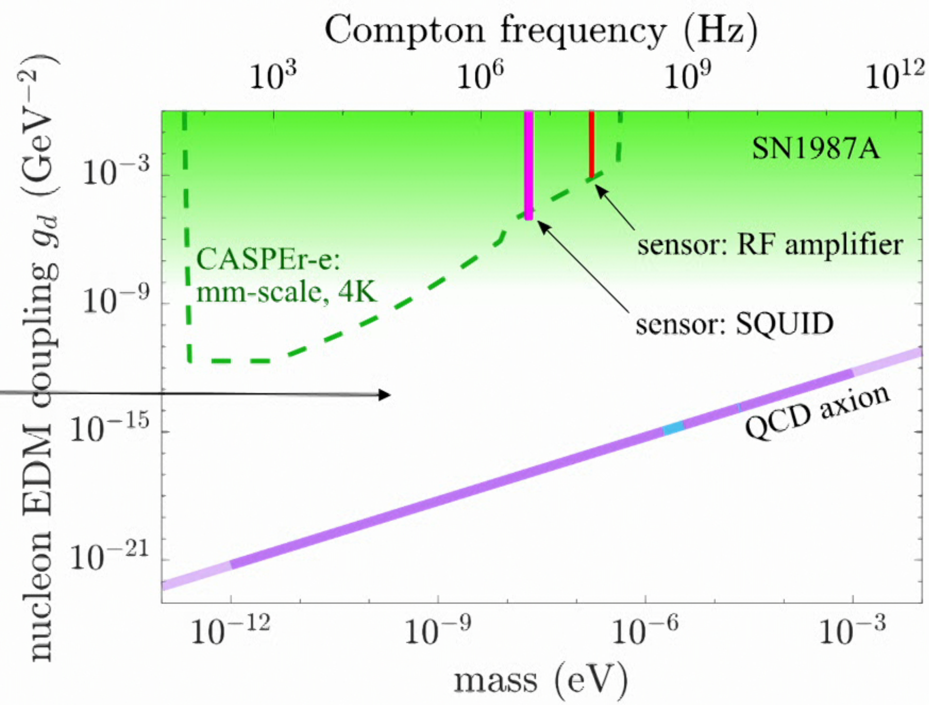

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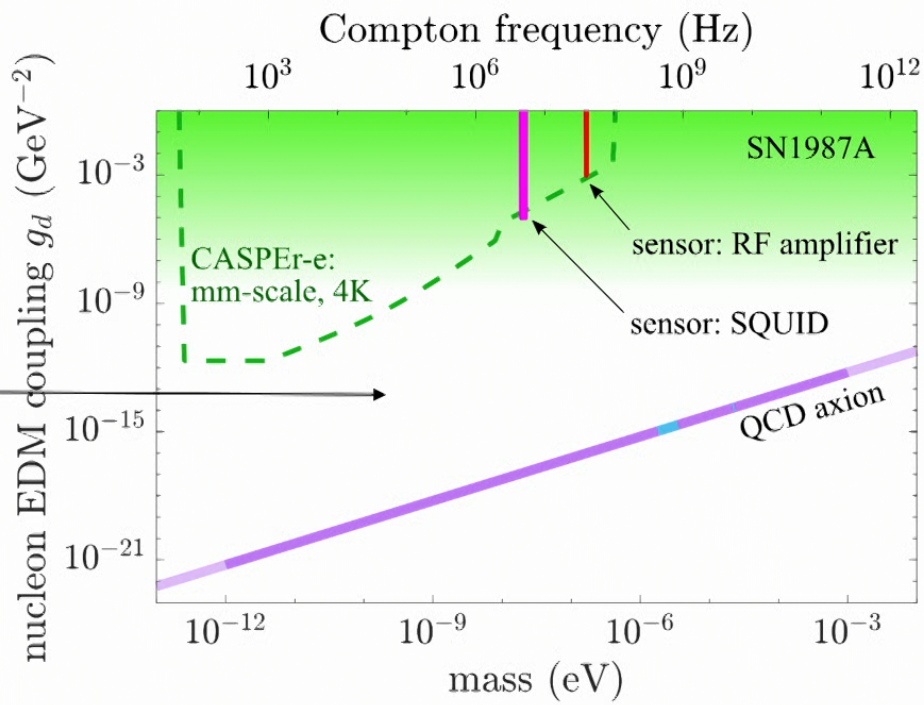

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- flexible: sensitivity can be improved by choice of material (→ *E**), as well as by scaling up the experimental volume
- searching for QCD interaction: this is the defining interaction of the QCD axion

[D. Aybas et al., *Phys. Rev. Lett.* **126**, 160505 (2021)]
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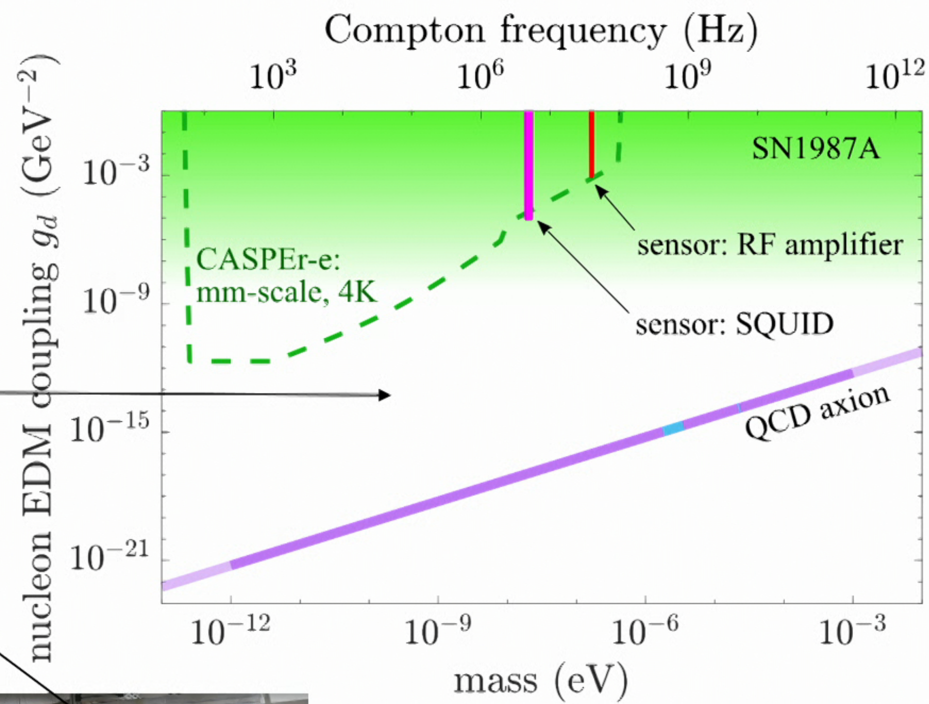

path forward →

- cool to 100 mK

[D. Aybas et al., *Phys. Rev. Lett.* **126**, 160505 (2021)]
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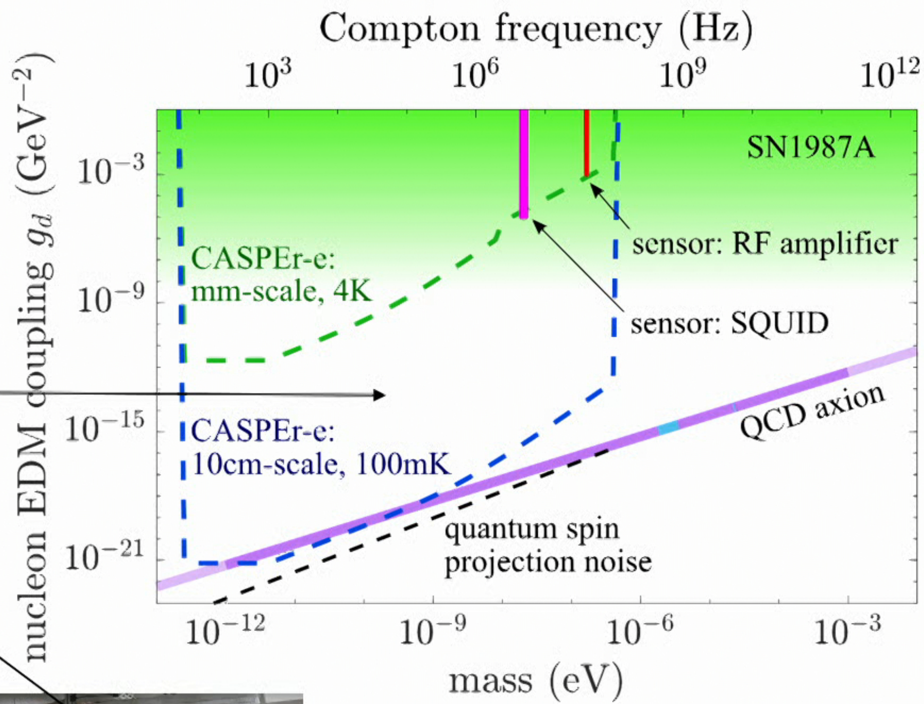
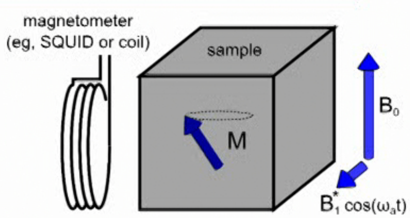


path forward →

- cool to 100 mK
- find the optimal material: PMN-PT, PZT, …
- reach the fundamental quantum limit and beyond
- scale up to centimeter-scale



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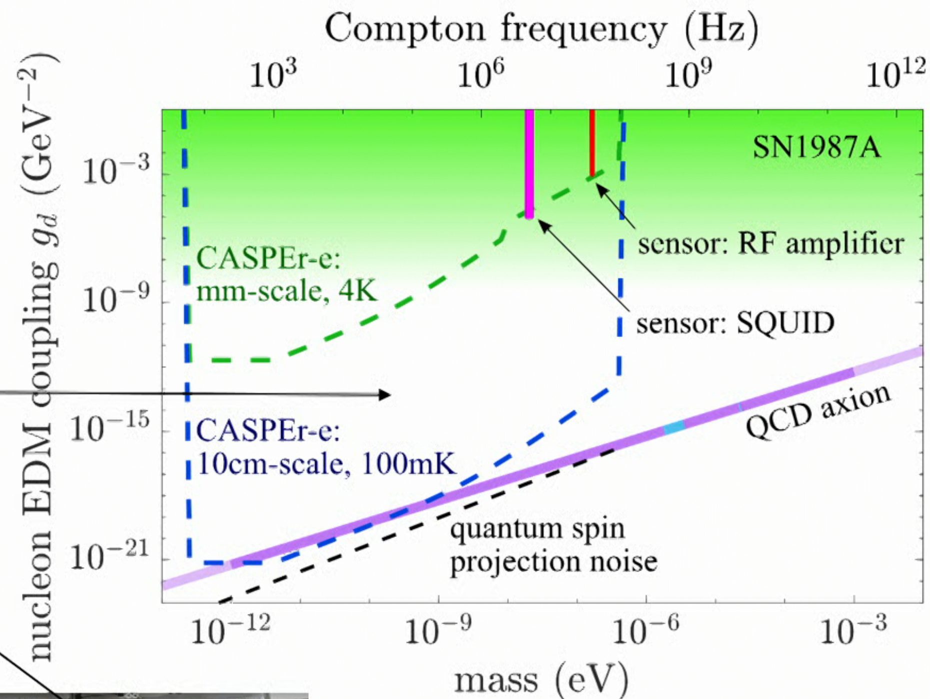

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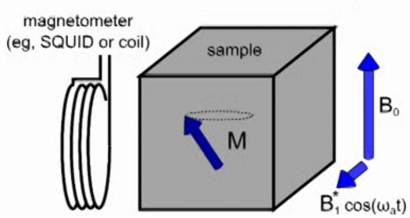

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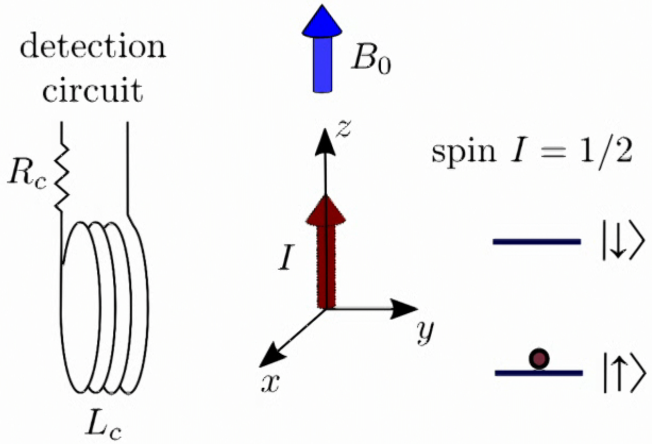
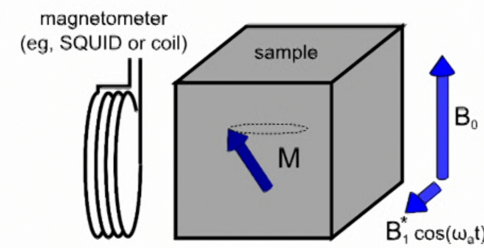
Fundamental quantum noise: spin projection noise (standard quantum limit)





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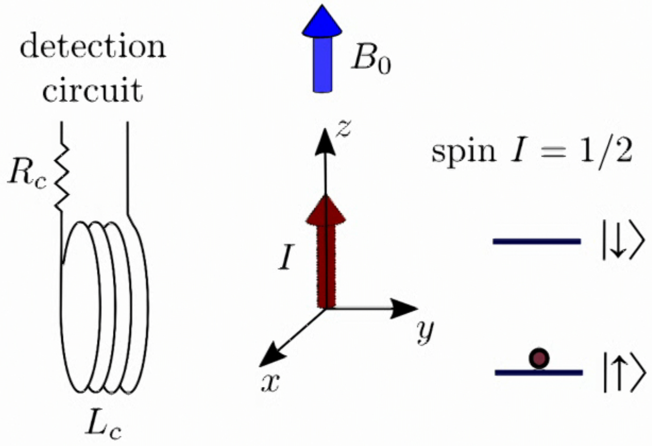

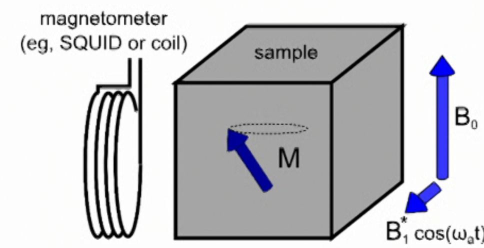

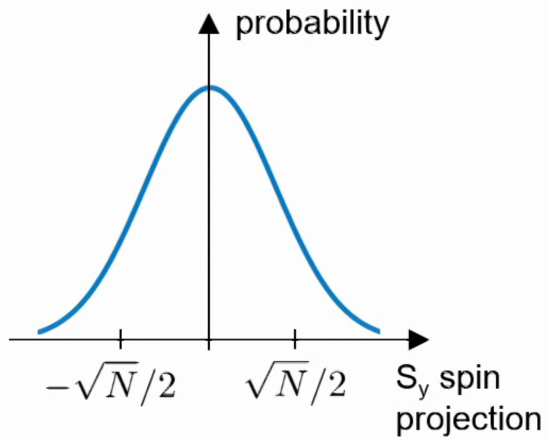

[F. Bloch, *Phys. Rev.* **7-8**, 460 (1946)]

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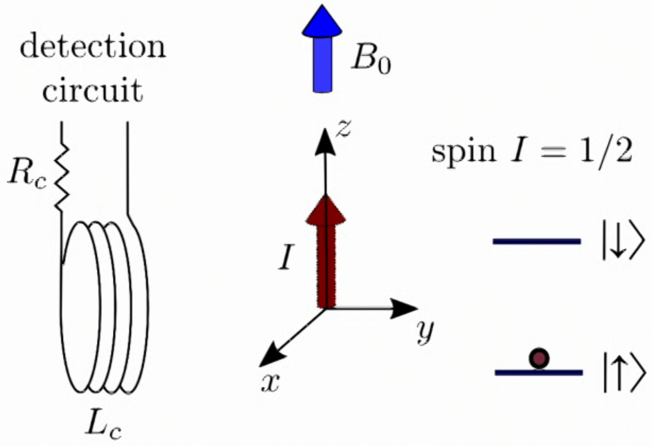
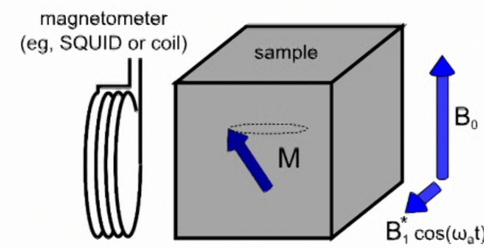
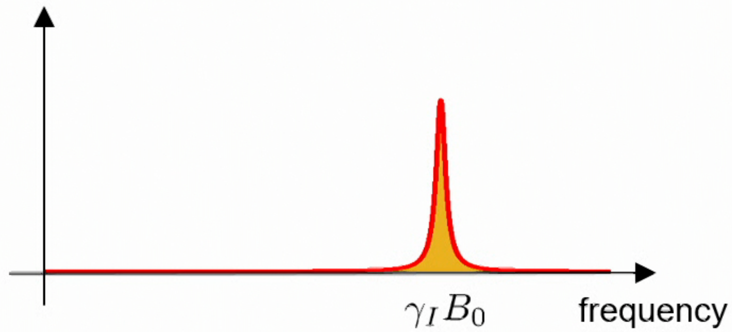
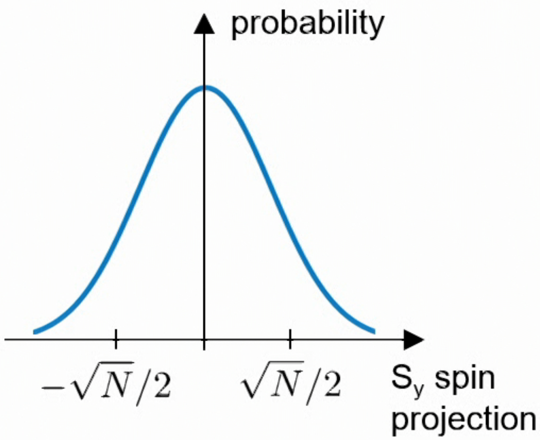




➡ detected spectrum with a <u>noiseless detection circuit</u>





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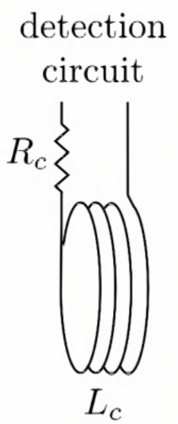

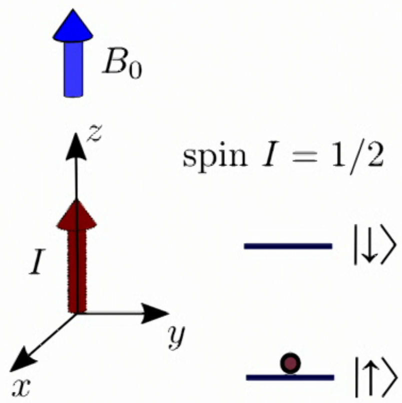

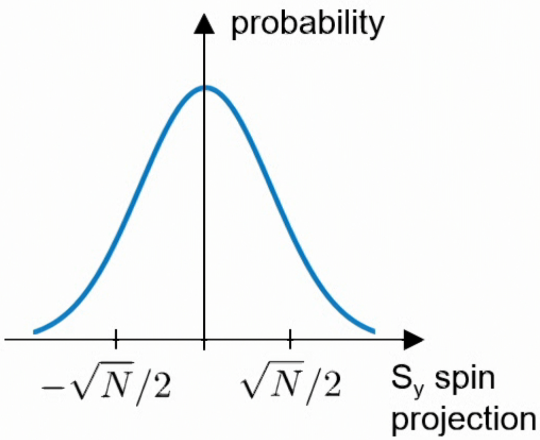

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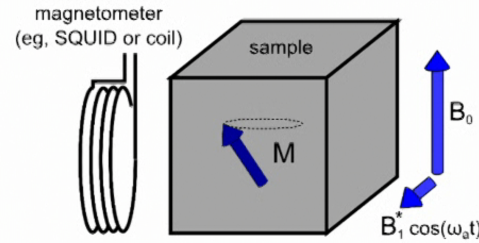
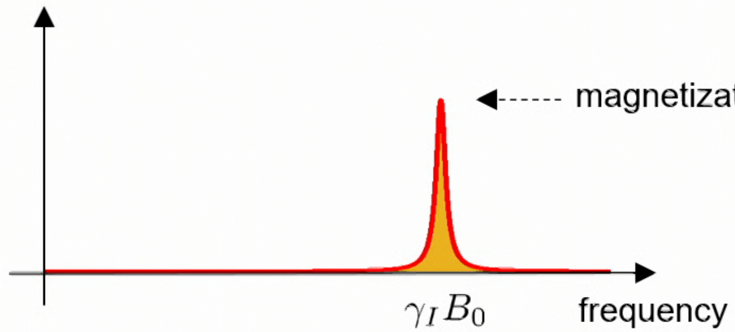
detected spectrum with a noiseless detection circuit





standard quantum limit (SQL): $\dfrac{\delta M_\perp}{M_0} \approx \dfrac{1}{\sqrt{N}}$ ← spin projection measurement uncertainty

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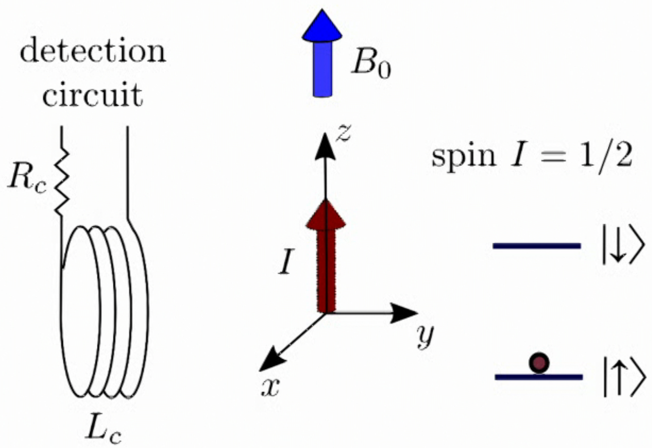

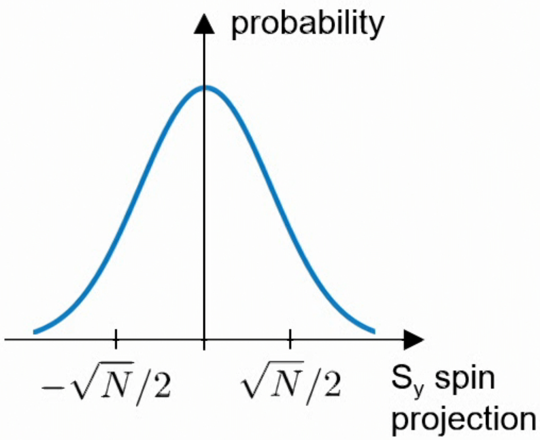

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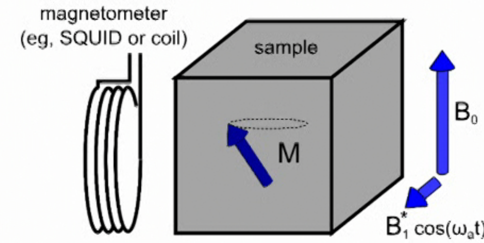

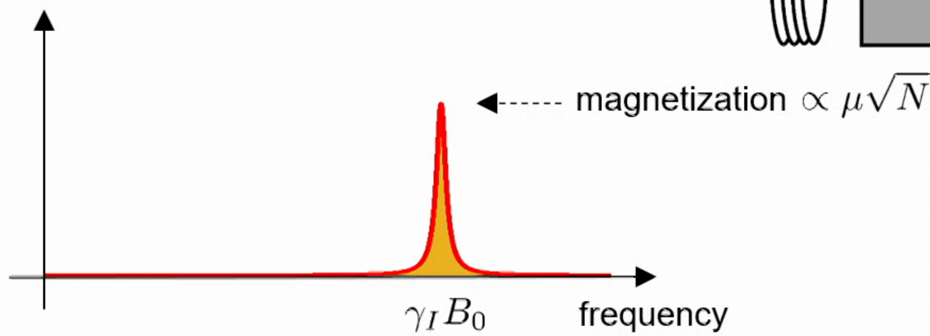

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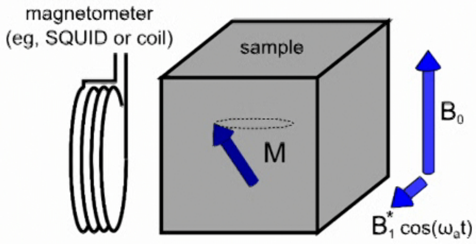
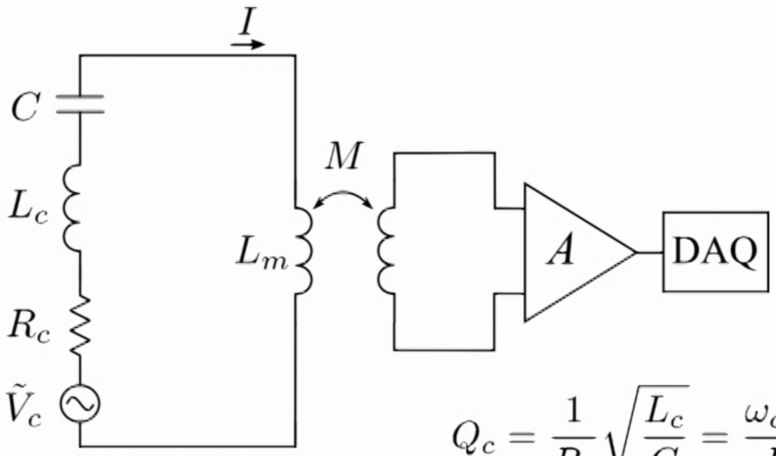
spin projection noise has been detected in NMR experiments

[T. Sleator et al., *Phys. Rev. Lett* **55**, 1742 (1985)]
[M.A. McCoy, R.R. Ernst., *Chem. Phys. Lett.* **159**.5, 587 (1989)]
[M. Gueron, J. L. Leroy., *J. Mag. Res.* **85**.1, 209 (1989)]

What do we need to do to build an NMR experiment limited by spin projection noise?



resonant detection circuit with a noiseless amplifier:



$$Q_c = \frac{1}{R_c}\sqrt{\frac{L_c}{C}} = \frac{\omega_c L_c}{R_c}$$

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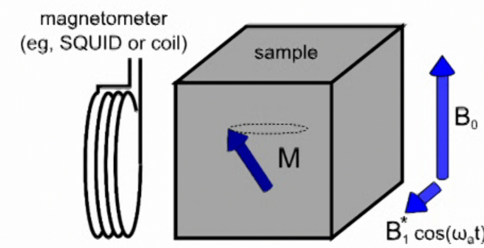

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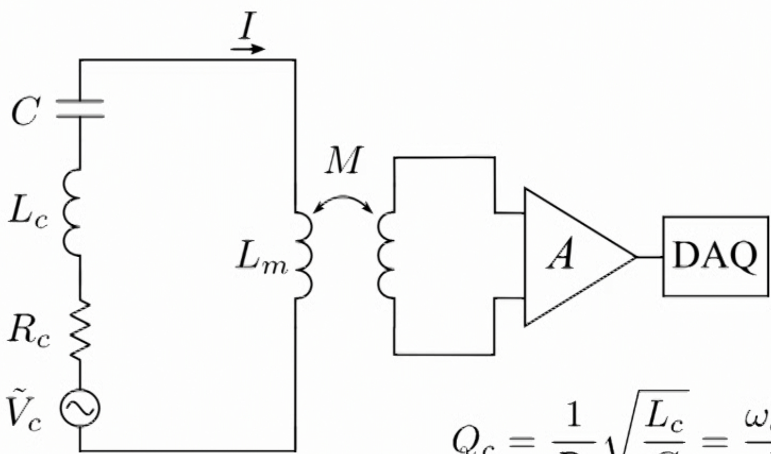

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Johnson noise in circuit resistor:

$$\tilde{V}_n^2(\omega) = \tilde{V}_c^2(\omega)$$

$$= \frac{2R_c k_B \theta_c}{\pi}$$

circuit temperature

noise spectral density

[D. Aybas et al., *Quant. Sci. Tech.* **6**, 034007 (2021)]

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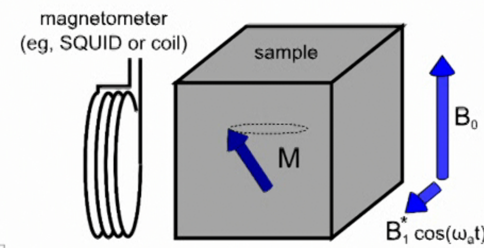
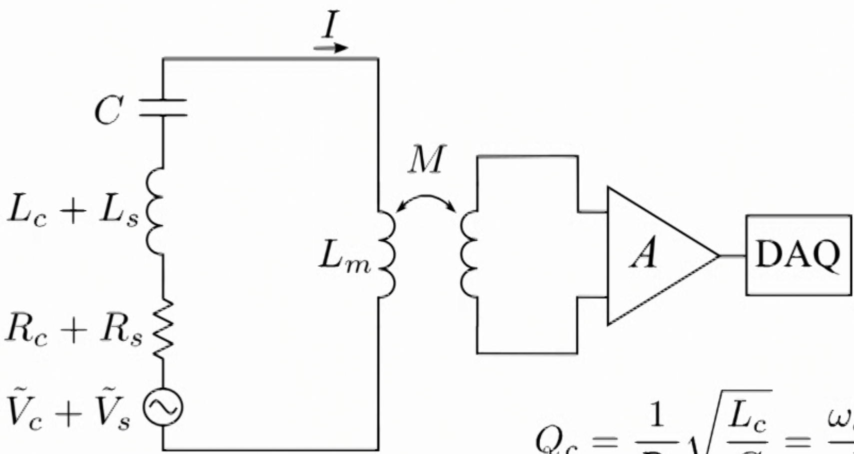


NMR sample + resonant detection circuit with a noiseless amplifier:



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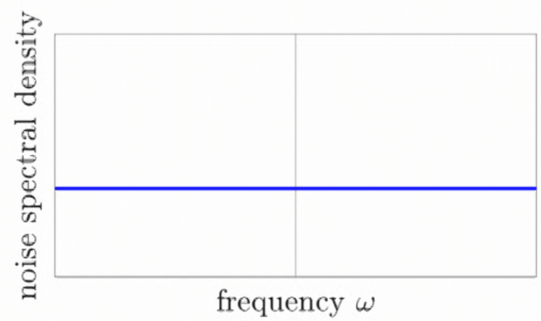

Johnson noise in circuit resistor + spin projection noise:

$$\tilde{V}_n^2(\omega) = \tilde{V}_c^2(\omega) + \tilde{V}_s^2(\omega)$$

$$= \frac{2R_c k_B \theta_c}{\pi} + \frac{2R_s k_B \theta_s}{\pi}$$ ← spin temperature

filling factor → $$\frac{q}{2\pi}(\mu_0 n \hbar^2 \gamma^2) L_c T_2^* \omega^2 \frac{1}{1 + (\omega - \omega_s)^2 T_2^{*2}}$$

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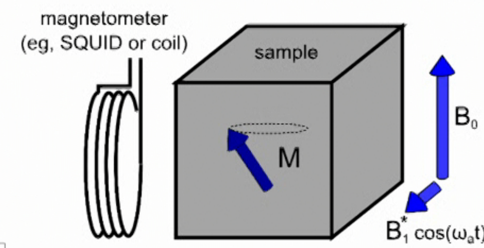

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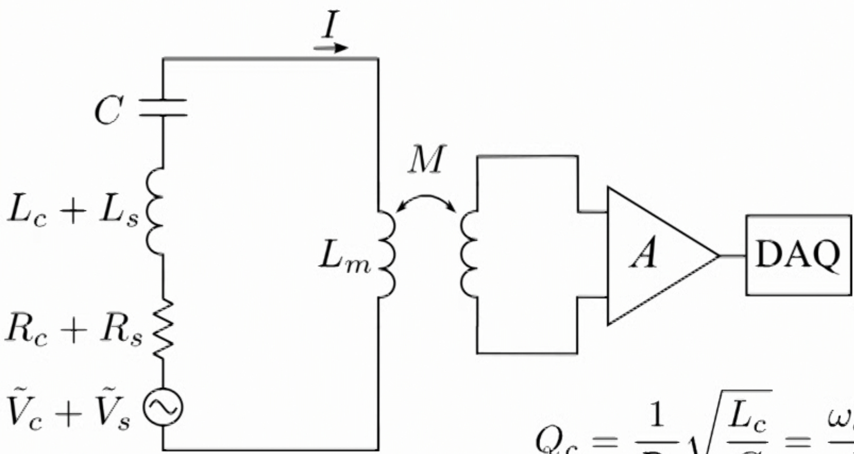

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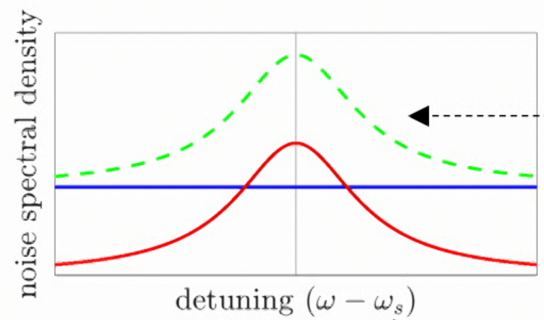


spin Larmor frequency: $\omega_s = \gamma_I B_0$

condition for an experiment limited by spin projection noise:

$$\tilde{V}_c^2(\omega) < \tilde{V}_s^2(\omega = \omega_s)$$

Johnson noise in circuit resistor + spin projection noise:

$$\tilde{V}_n^2(\omega) = \tilde{V}_c^2(\omega) + \tilde{V}_s^2(\omega)$$

$$= \frac{2R_c k_B \theta_c}{\pi} + \frac{2R_s k_B \theta_s}{\pi}$$ ← spin temperature

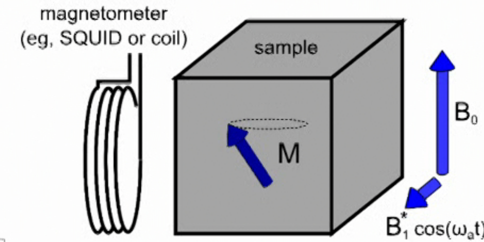
filling factor → $$\frac{q}{2\pi}(\mu_0 n \hbar^2 \gamma^2) L_c T_2^* \omega^2 \frac{1}{1 + (\omega - \omega_s)^2 T_2^{*2}}$$

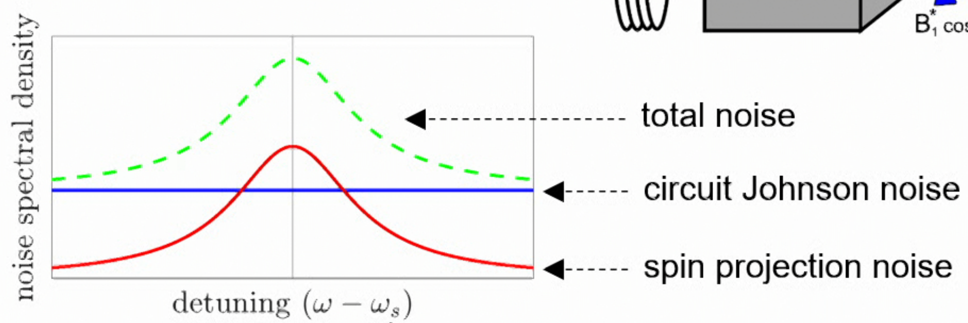
[D. Aybas et al., *Quant. Sci. Tech.* **6**, 034007 (2021)]

Mainz CASPEr-gradient search for the gradient coupling

CASPEr-gradient at Mainz

➡ liquid ^{129}Xe NMR apparatus in a high-homogeneity magnet





spin Larmor frequency: $\omega_s = \gamma_I B_0$

condition for an experiment limited by spin projection noise:

$$\tilde{V}_c^2(\omega) < \tilde{V}_s^2(\omega = \omega_s)$$

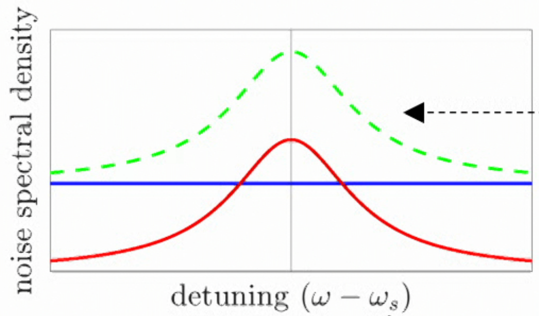
$$\Rightarrow \quad k_B \theta_c < \frac{q}{4} (\mu_0 n \hbar^2 \gamma^2)\, \omega_s T_2^* Q_c$$

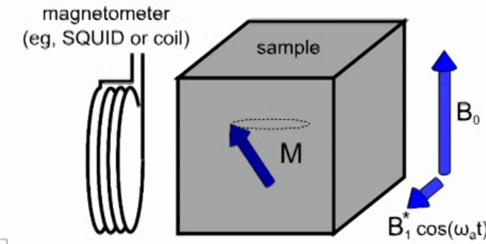
CASPEr-gradient at Mainz ➡ $\mu_0 n \hbar^2 \gamma^2 = 50\,\mathrm{nK}$, $\omega_s T_2^* = 10^6$ ➡ $\theta_c = 20\,\mathrm{K}$, $Q_c > 3 \times 10^3$

[D. Aybas et al., *Quant. Sci. Tech.* **6**, 034007 (2021)]

Boston CASPEr-electric search for the EDM coupling

CASPEr-electric at Boston





spin Larmor frequency: $\omega_s = \gamma_I B_0$

- solid-state NMR apparatus in a BlueFors dilution refrigerator
- spin projection noise-limited NMR search for axion-like dark matter

condition for an experiment limited by spin projection noise:

$$\tilde{V}_c^2(\omega) < \tilde{V}_s^2(\omega = \omega_s)$$

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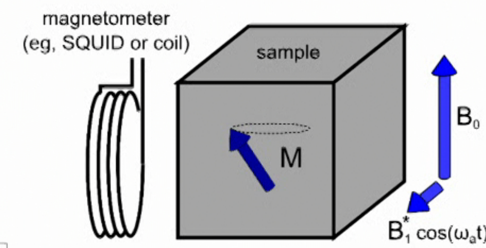
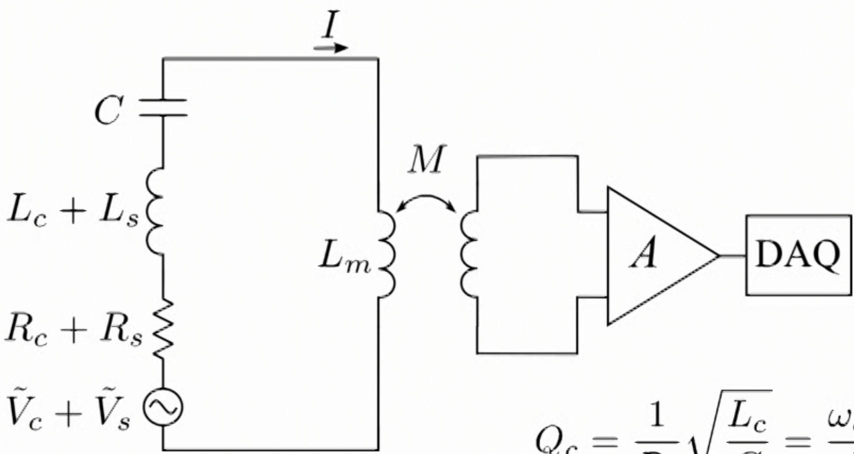
CASPEr-electric at Boston ⇒ $\mu_0 n \hbar^2 \gamma^2 = 10\,\mathrm{nK}$, $\omega_s T_2^* = 10^3$ ⇒ $\theta_c = 50\,\mathrm{mK}$, $Q_c > 3 \times 10^4$

[D. Aybas et al., *Quant. Sci. Tech.* **6**, 034007 (2021)]

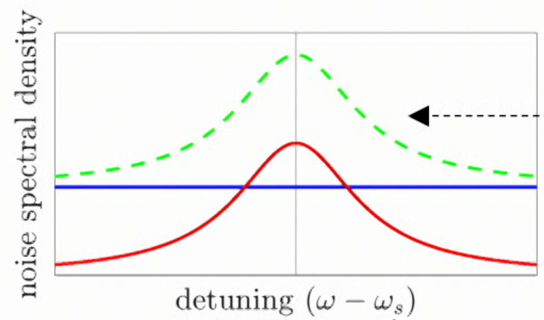
What do we need to do to build an NMR experiment limited by spin projection noise?



NMR sample + resonant detection circuit with a noiseless amplifier:



$$Q_c = \frac{1}{R_c}\sqrt{\frac{L_c}{C}} = \frac{\omega_c L_c}{R_c}$$



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← spin temperature

filling factor → $\frac{q}{2\pi}(\mu_0 n \hbar^2 \gamma^2) L_c T_2^* \omega^2 \frac{1}{1 + (\omega - \omega_s)^2 T_2^{*2}}$

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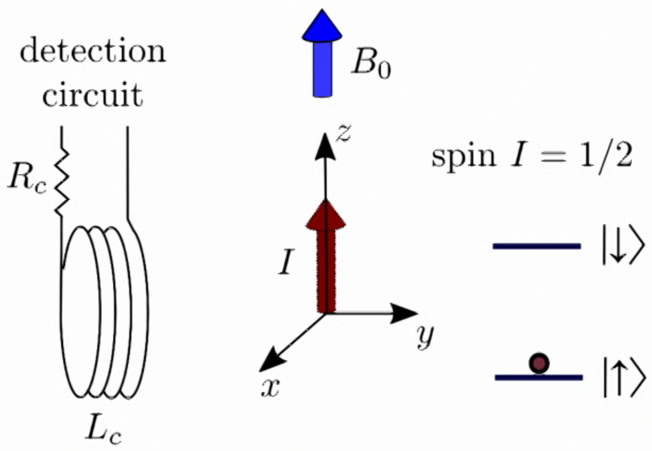
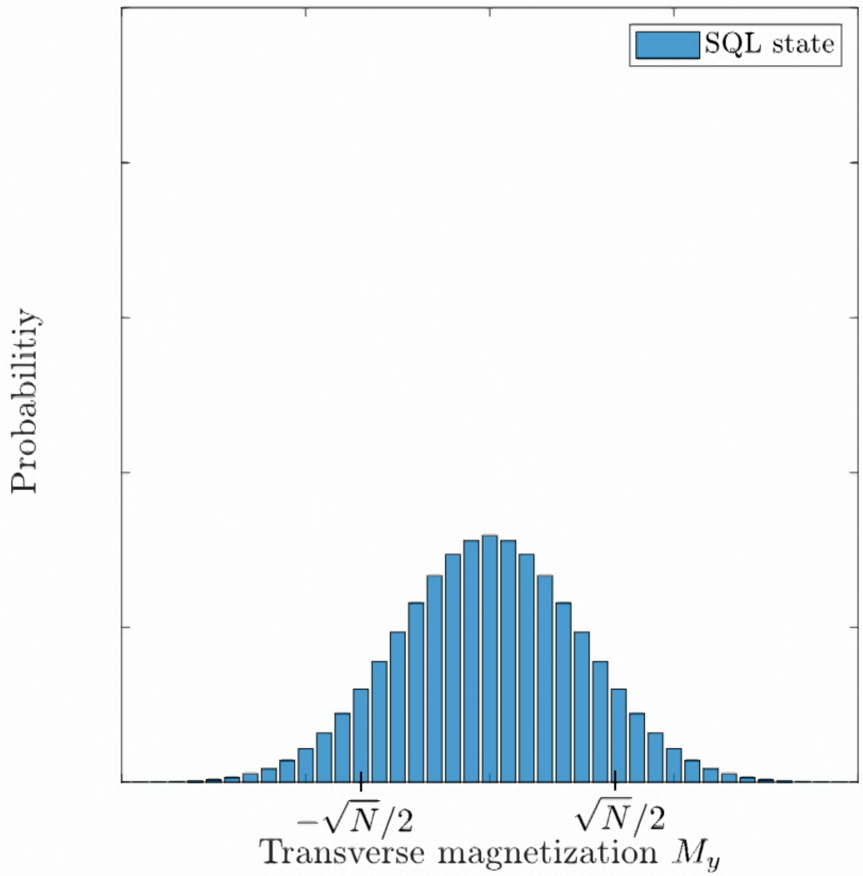
[D. Aybas et al., *Quant. Sci. Tech.* **6**, 034007 (2021)]

Spin squeezing

standard quantum limit (SQL): $\frac{\delta M_\perp}{M_0} \approx \frac{1}{\sqrt{N}}$





[*Phys. Rep.* **509**, 89 (2011)]

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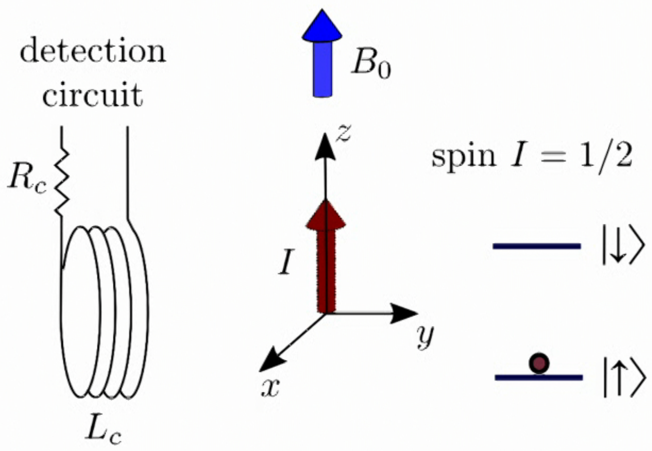
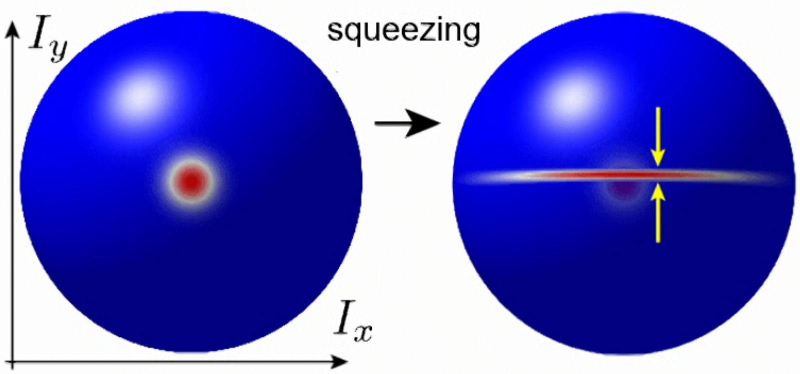
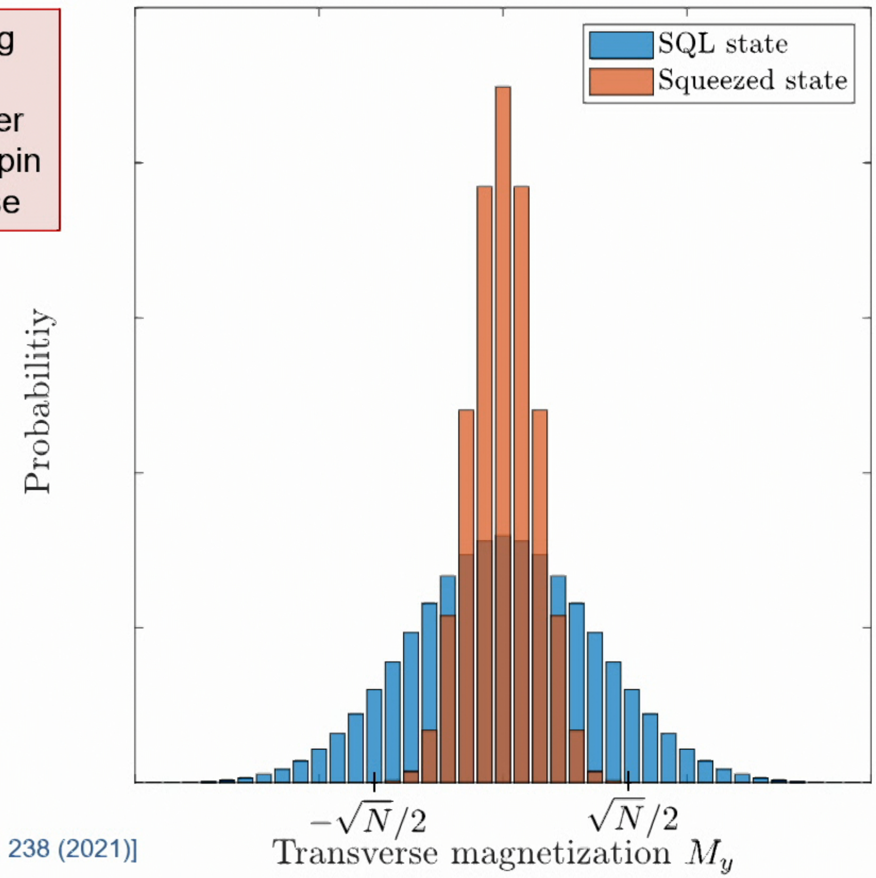


spin squeezing may give us sensitivity better than quantum spin projection noise





[*Phys. Rep.* **509**, 89 (2011)]

[K. Backes et al., *Nature* **590**, 238 (2021)]

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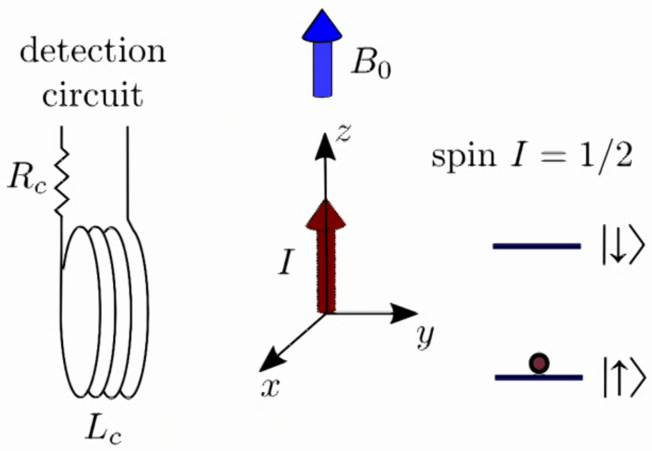
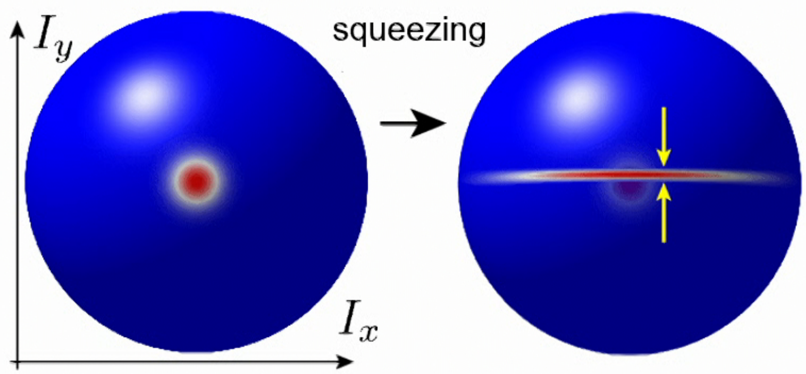




[*Phys. Rep.* **509**, 89 (2011)]

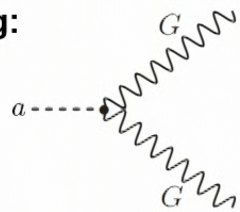
- spin projection noise sensitivity has been achieved in NMR
- spin squeezing has been demonstrated with atomic ensembles
- spin squeezing may be possible in a solid-state NMR experiment

[D. Aybas et al., *Quant. Sci. Tech.* **6**, 034007 (2021)]

Summary: searches for interaction of axion-like dark matter with spins

interaction with gluons (strong-CP) defining QCD axion coupling:

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

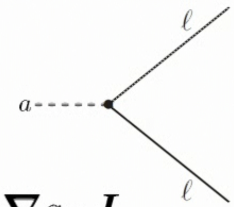


$\Rightarrow$ $\mathcal{H}_{\rm EDM} = g_d a \boldsymbol{E}^* \cdot \boldsymbol{I}/I$

CASPEr-electric (BU)

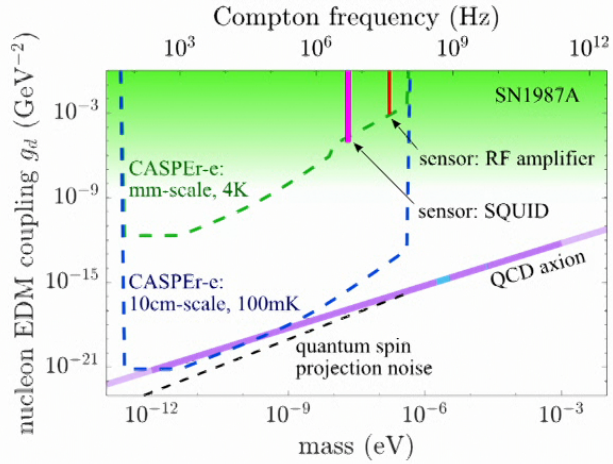
interaction with leptons:

$$\frac{\partial_\mu a}{f_a} \bar{\psi}_\ell \gamma^\mu \gamma_5 \psi_\ell$$



$\Rightarrow$ $\mathcal{H}_{aNN} = g_{aNN} \boldsymbol{\nabla} a \cdot \boldsymbol{I}$

CASPEr-gradient (Mainz)



[A. Gramolin et al., *Phys. Rev. D* **105**, 035029 (2022)]
[A. Gramolin et al., *Nature Physics* **17**, 79 (2021)]
[G. Centers et al., *Nature Comms* **12**, 7321 (2021)]
[D. Aybas et al., *Phys. Rev. Lett.* **126**, 160505 (2021)]
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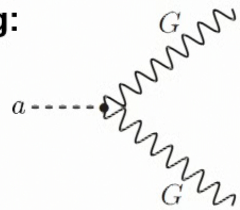

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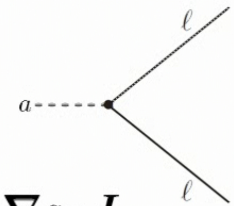

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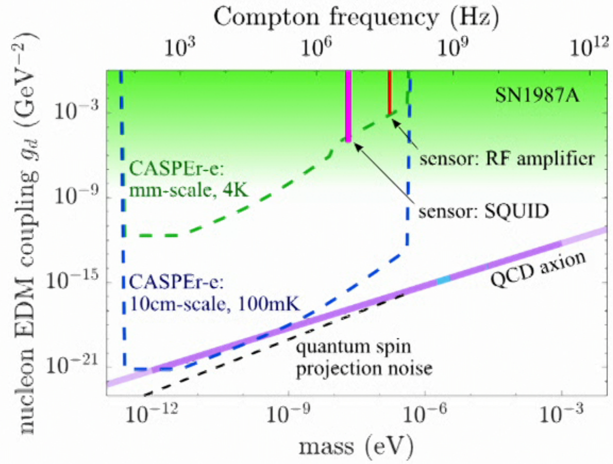

- using spin ensembles to search for axion-like dark matter gives flexibility to optimize experimental parameters

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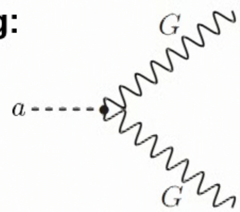

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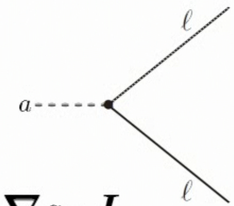

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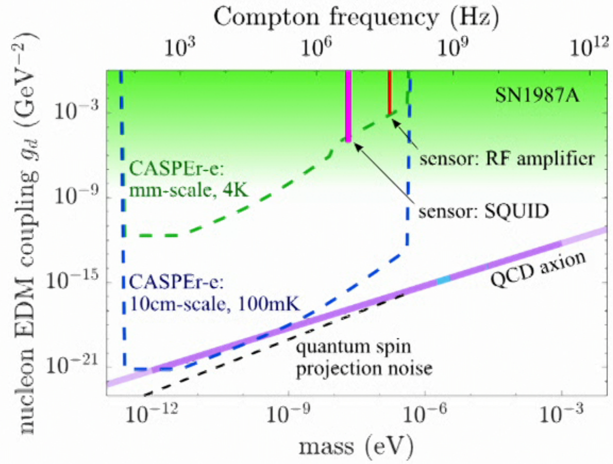

- using spin ensembles to search for axion-like dark matter gives flexibility to optimize experimental parameters → **nuclear, atomic, and condensed-matter physics input needed!**

[A. Gramolin et al., *Phys. Rev. D* **105**, 035029 (2022)]
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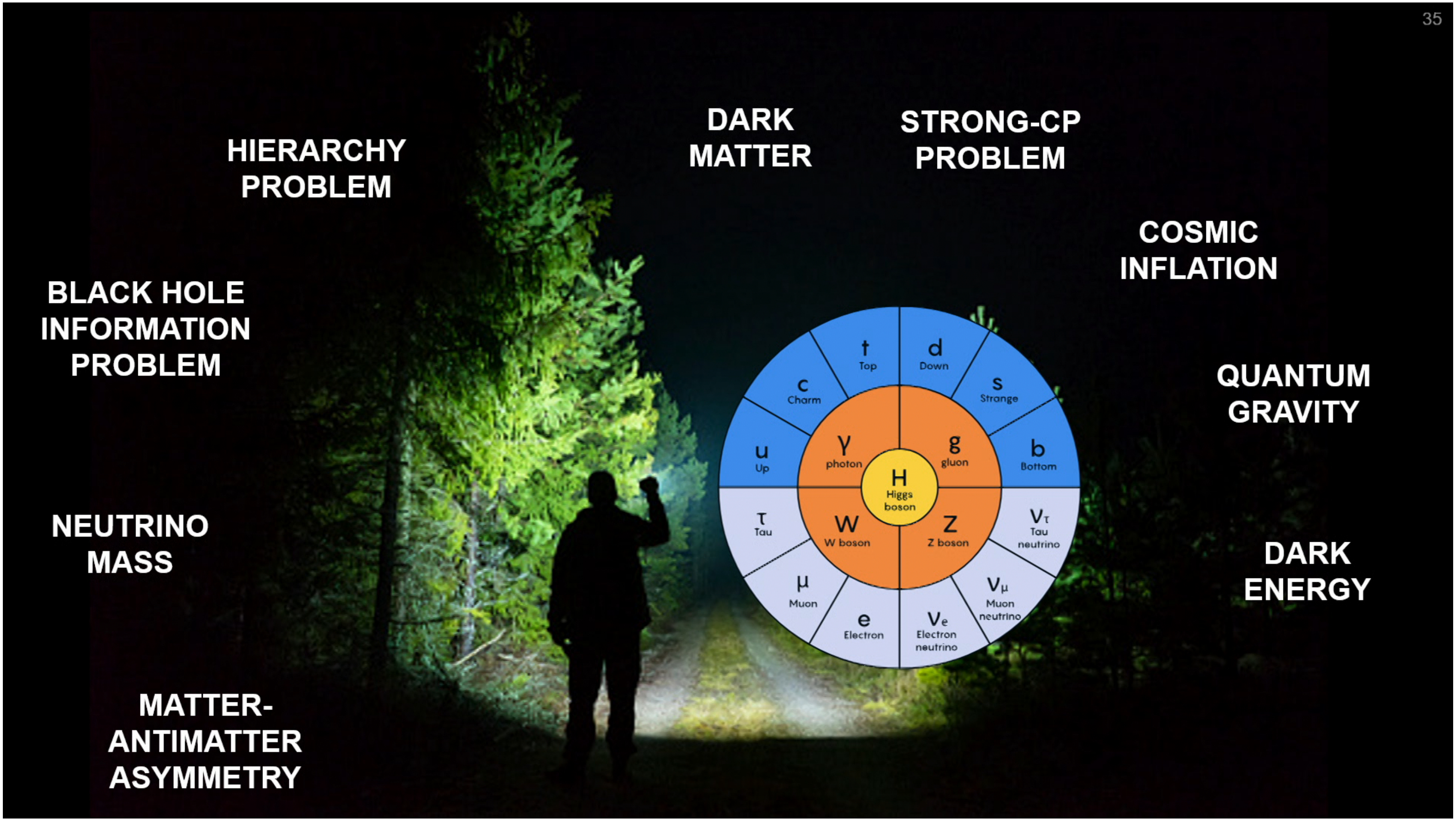
35
HIERARCHY PROBLEM
DARK MATTER
STRONG-CP PROBLEM
COSMIC INFLATION
BLACK HOLE INFORMATION PROBLEM
QUANTUM GRAVITY
NEUTRINO MASS
DARK ENERGY
MATTER-ANTIMATTER ASYMMETRY
t Top
d Down
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s Strange
u Up
b Bottom
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g gluon
H Higgs boson
W W boson
Z Z boson
τ Tau
ντ Tau neutrino
μ Muon
νμ Muon neutrino
e Electron
νe Electron neutrino


AXION
Derek
Kimball
Gray
Rybka