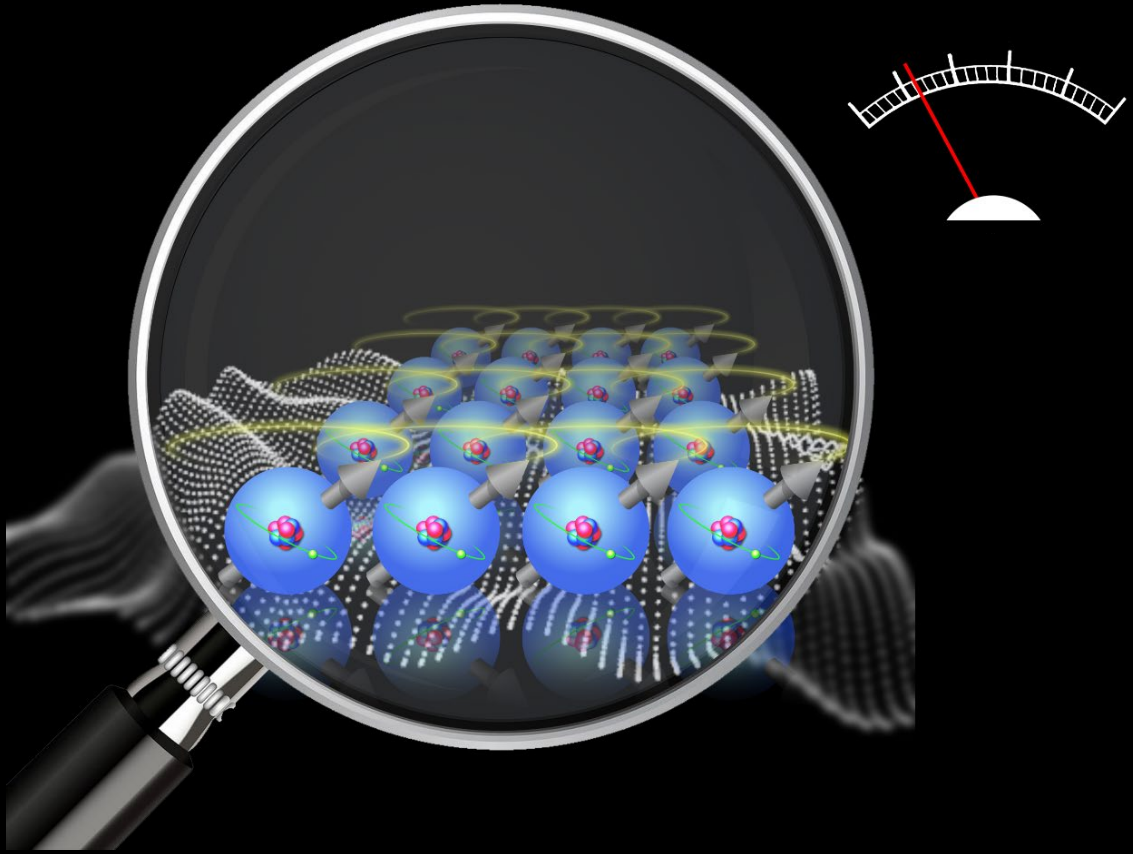
Quantum sensing and dark matter searches

Alex Sushkov



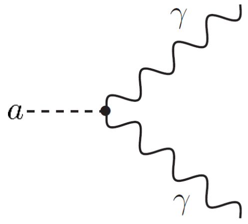
BOSTON UNIVERSITY

Main points

- Lecture 1: searches for electromagnetic interaction of axion-like dark matter

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

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

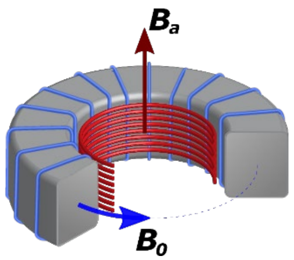


key experimental parameters:

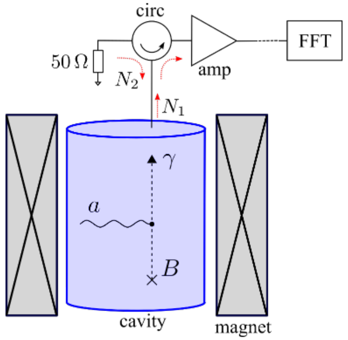
- magnetic field B → larger is better
- volume V → larger is better
- temperature → colder is better
- sensor noise and back-action

- 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

SHAFT
ABRA
DM radio



ADMX
HAYSTAC



- Lecture 2: searches for interaction of axion-like dark matter with nuclear spins

What is dark matter?

Dark matter

Light bosons
Axion-like particles
Fuzzy dark matter
QCD axions

Neutrinos
Standard-model neutrinos
Sterile neutrinos

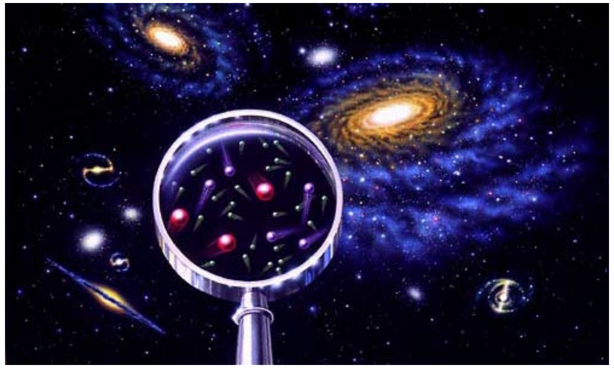
Weak scale
Super-symmetry
Extra dimensions
Little Higgs
Simplified models
Effective field theory

Other particles
WIMPzilla
Superfluid
Self-interacting

Macroscopic
Macros
Primordial black holes
MaCHOs

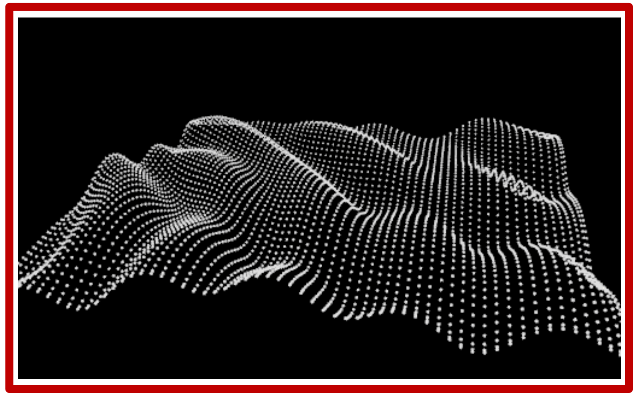
Modified gravity
MOG
TeVeS
MOND
Emergent gravity

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



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

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

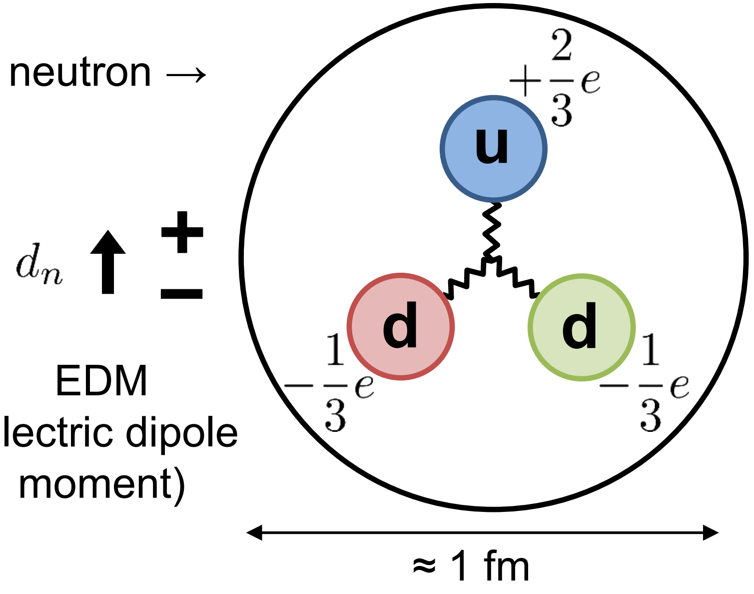


wave-like dark matter (eg: axions)
mass << eV

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

The strong-CP problem

neutron →



EDM
(electric dipole
moment)

(very!) naïve estimate:

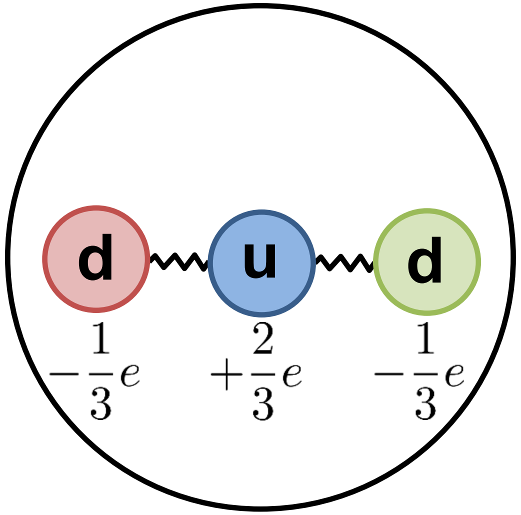
$$d_n \approx e \cdot \mathrm{fm} = 10^{-13}\, e \cdot \mathrm{cm}$$

experimental limit:

$$d_n < 1.8 \times 10^{-26}\, e \cdot \mathrm{cm}$$

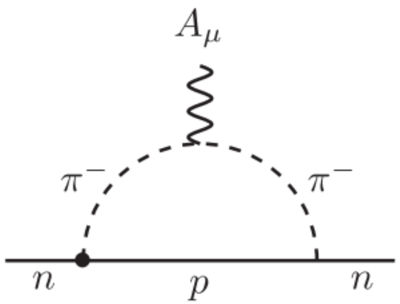
[Phys. Rev. Lett. **124**, 081803 (2020)]

better model for
a neutron →



CP-violating θ-term in
QCD Lagrangian →

$$\mathcal{L}_\theta = \theta(\alpha_s/8\pi)G^{(a)}_{\mu\nu}\tilde{G}^{(a)\mu\nu}$$



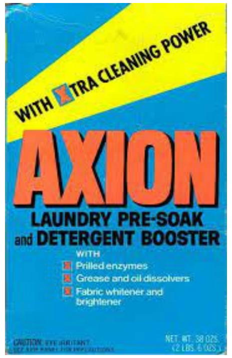
⇨ neutron EDM: $d_n = \theta \times (2.4 \times 10^{-16})\, e \cdot \mathrm{cm}$

⇨ $\theta < 10^{-10}$

why is θ so small?

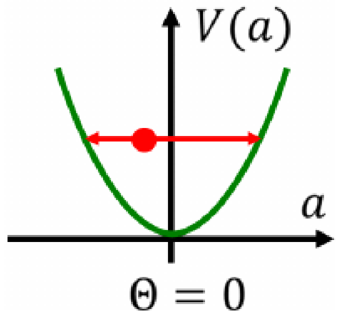
[Rev. Mod. Phys. **82**, 557 (2010)]

⇨



$$\theta \rightarrow \frac{a}{f_a}$$

$$\langle\theta\rangle = \langle a\rangle = 0$$



axion solves the
strong-CP problem

[Phys. Rev. Lett. **38**, 1440 (1977)] [Phys. Rev. Lett. **40**, 223 (1978)]
[Phys. Rev. D **16**, 1791 (1977)] [Phys. Rev. Lett. **40**, 279 (1978)]

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

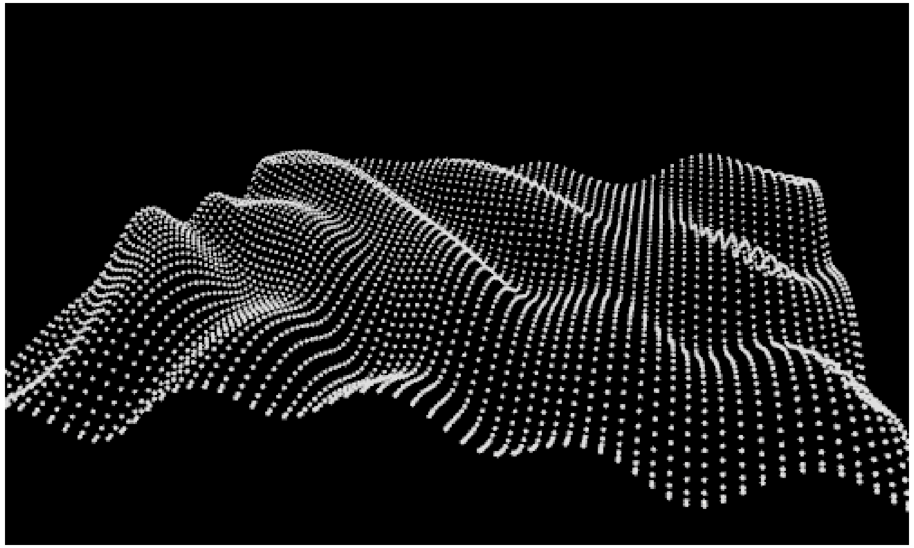
↓

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

1. Pseudoscalar light particle: spin = 0, wide range of possible masses [Phys. Rev. D **98**, 035017 (2018)]
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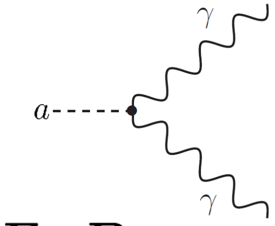
4. Well-motivated and thoroughly-studied **dark matter** candidate: $a(t) = a_0 \cos \omega_a t$
5. Only 3 possible (non-gravitational) interactions with standard model particles:

interaction with photons:

ALP field amplitude → a

symmetry breaking scale → f_a

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



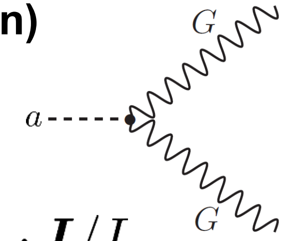
$$\mathcal{L}_{a\gamma\gamma} = g_{a\gamma\gamma} a \boldsymbol{E} \cdot \boldsymbol{B}$$

→ 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)

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



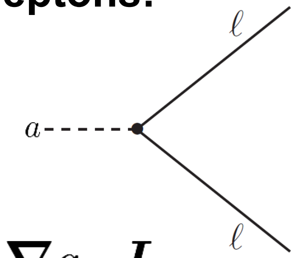
$$\mathcal{H}_{\mathrm{EDM}} = g_d a \boldsymbol{E}^* \cdot \boldsymbol{I}/I$$

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

CASPEr-electric

interaction with leptons:

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



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

→ nuclear spin $\boldsymbol{I}$ interacts with an effective magnetic field $\boldsymbol{\nabla} a$.

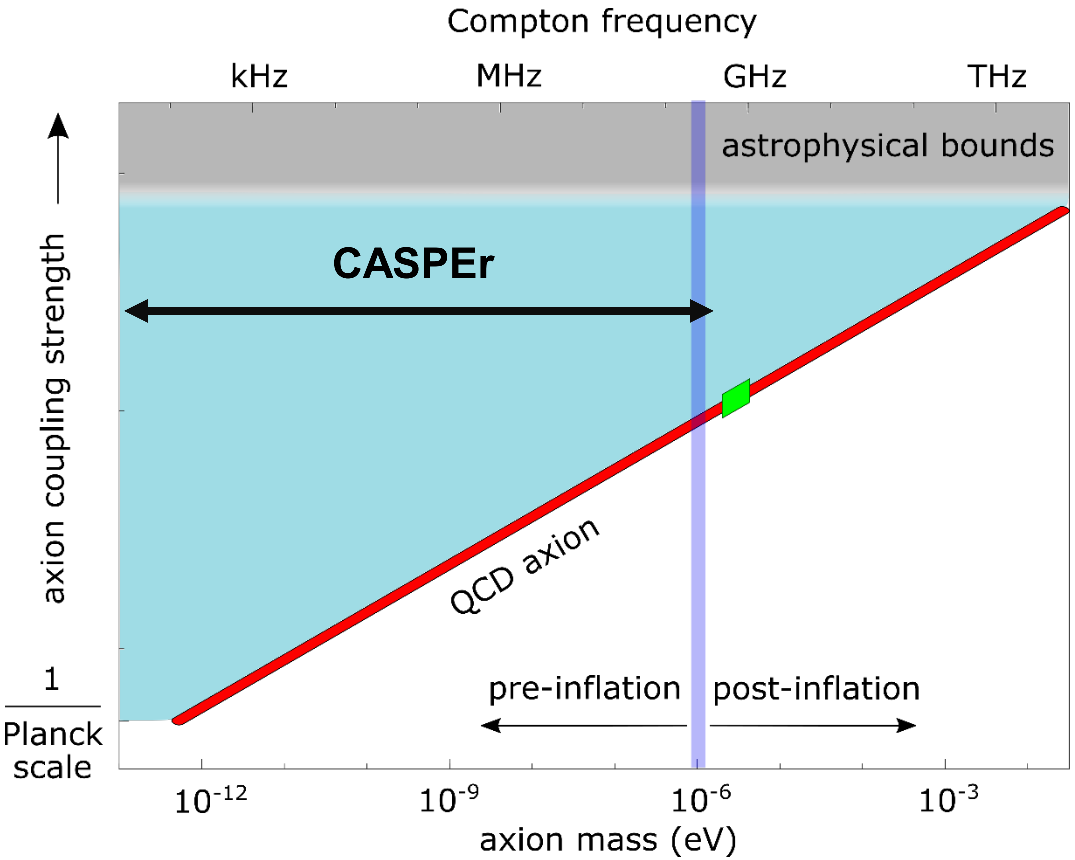
co-magnetometers
force mediator → ARIADNE
electron spin → QUAX

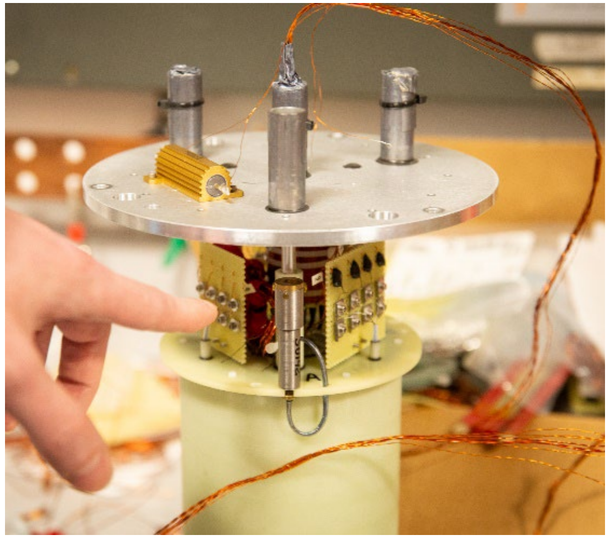
CASPEr-gradient

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

Axions and axion-like particles: basics and motivation

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 [Phys. Rev. Lett. **38**, 1440 (1977)]
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: $a(t) = a_0 \cos \omega_a t$
5. Only 3 possible (non-gravitational) interactions with standard model particles
6. Detection of axion dark matter → insight into energy scale of **inflation**





Structure of today's lecture

axion dark matter

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

θ-term in QCD Lagrangian

$$\mathcal{L}_\theta = \theta(\alpha_s/8\pi) G^{(a)}_{\mu\nu} \tilde{G}^{(a)\mu\nu}$$

P,T – violating
nuclear force

nuclear EDM
(electric dipole moment)

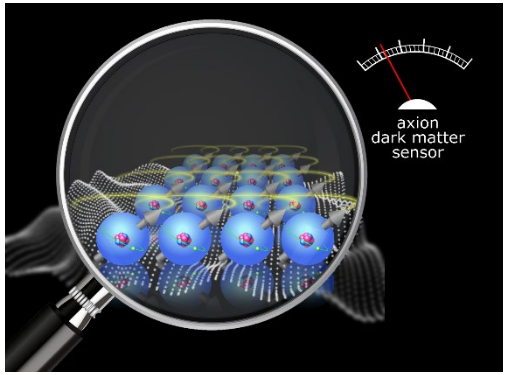
atomic energy shift
in an electric field

nuclear
Schiff moment

effective
electric field

magnetic resonance
Hamiltonian

magnetic resonance
experimental search
for axion dark matter



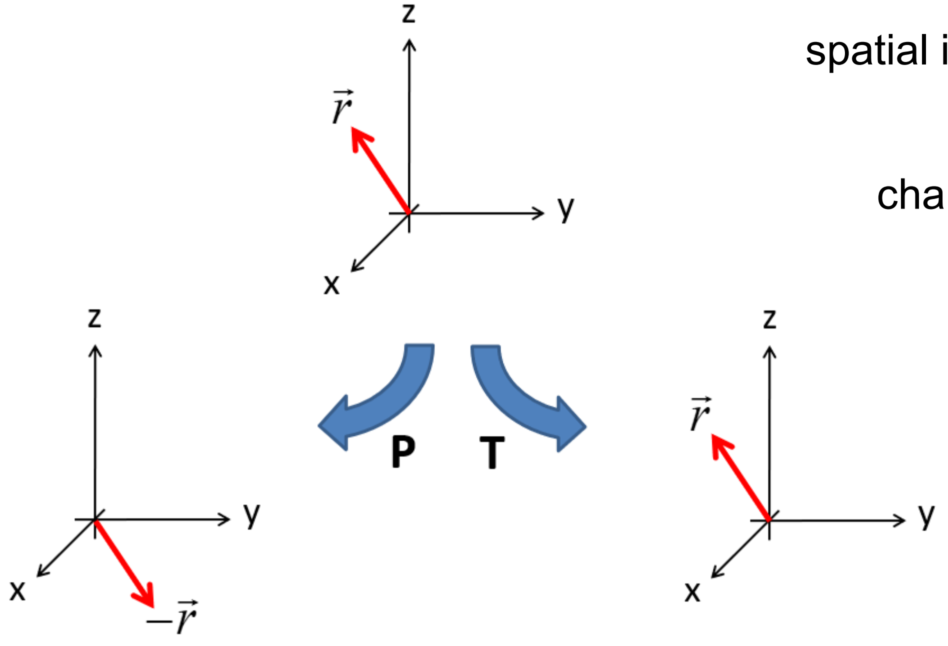
[*Sov. Phys. JETP* **60**, 873 (1984)]
[*Nucl. Phys. A* **449**, 750 (1986)]
[*Phys. Rev. Lett.* **113**, 103003 (2014)]
[Khriplovich, Lamoreaux, "*CP Violation Without Strangeness*"]

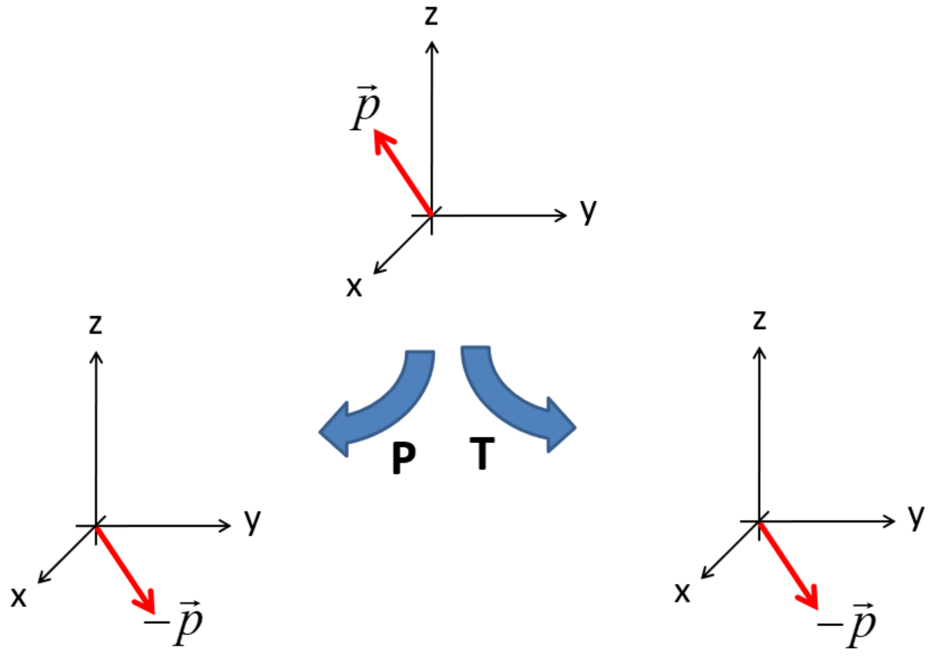
Discrete symmetries of nature

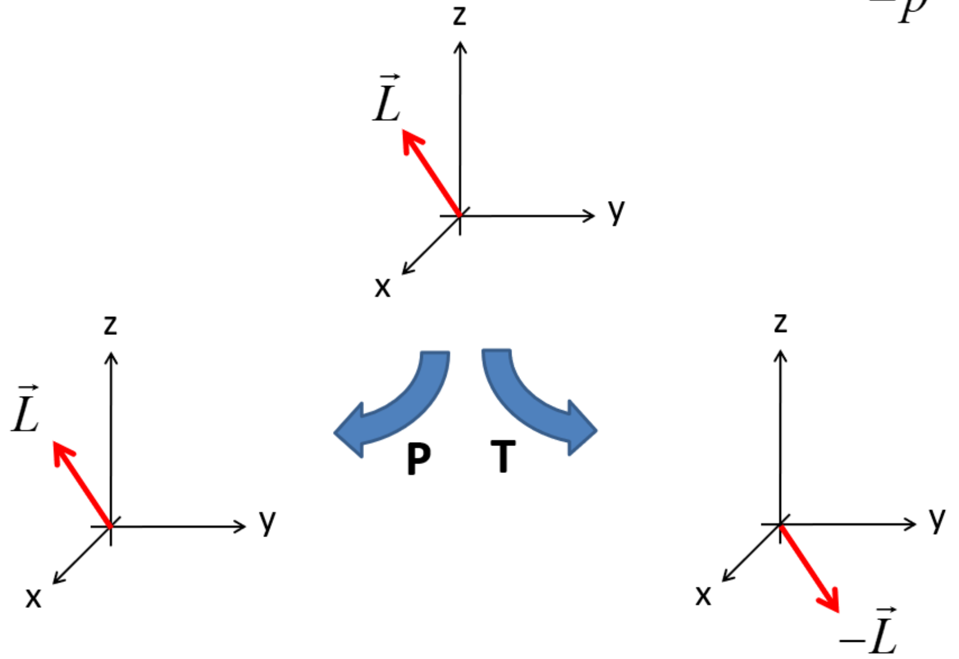
spatial inversion, parity (P): $\boldsymbol{r} \rightarrow -\boldsymbol{r}$

time reversal (T): $t \rightarrow -t$

charge conjugation (C): $\psi \rightarrow \bar{\psi}$







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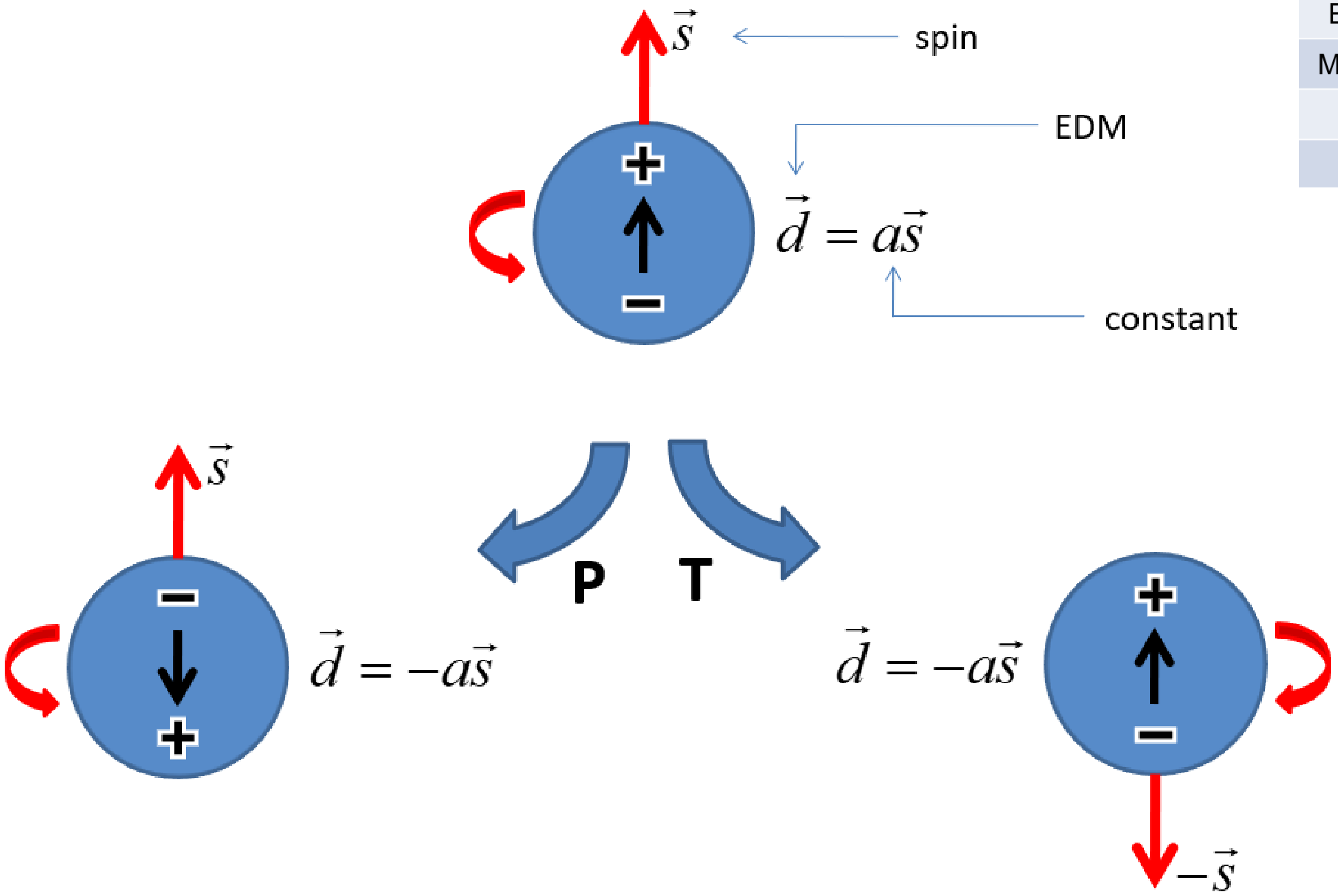
		Parity (P)	Time reversal (T)
Position		(odd)	(even)
Momentum		(odd)	(odd)
Angular momentum (spin)		(even)	(odd)
Electric dipole moment		(odd)	(even)
Magnetic dipole moment		(even)	(odd)
Electric field		(odd)	(even)
Magnetic field		(even)	(odd)

Permanent electric dipole moment (EDM)

a permanent electric dipole moment (EDM)
violates P,T symmetries

		Parity (P)	Time reversal (T)
Position		(odd)	(even)
Momentum		(odd)	(odd)
Angular momentum (spin)		(even)	(odd)
Electric dipole moment		(odd)	(even)
Magnetic dipole moment		(even)	(odd)
Electric field		(odd)	(even)
Magnetic field		(even)	(odd)



Axion dark matter ↔ oscillating θ_{QCD}

axion dark matter

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

θ-term in QCD Lagrangian

$$\mathcal{L}_\theta = \theta(\alpha_s/8\pi) G^{(a)}_{\mu\nu} \tilde{G}^{(a)\mu\nu}$$

P,T – violating
nuclear force

nuclear EDM
(electric dipole moment)

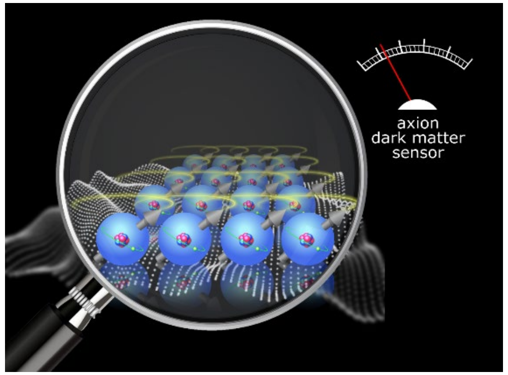
atomic energy shift
in an electric field

nuclear
Schiff moment

effective
electric field

magnetic resonance
Hamiltonian

magnetic resonance
experimental search
for axion dark matter



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$\theta_{QCD} \leftrightarrow$ P,T-violating nuclear force

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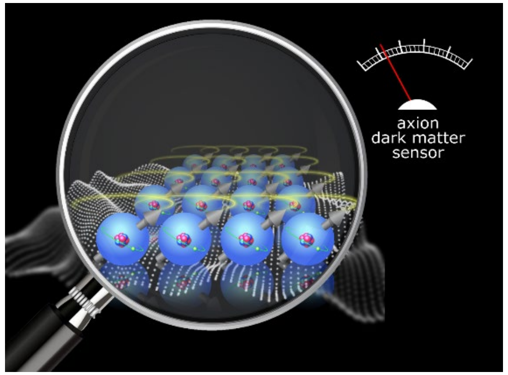

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P,T-violating nuclear force ↔ nuclear EDM

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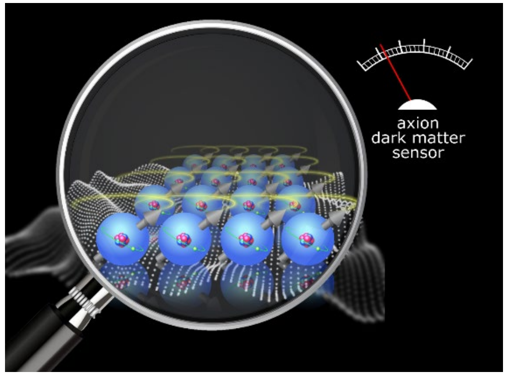

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nuclear EDM ↔ nuclear Schiff moment

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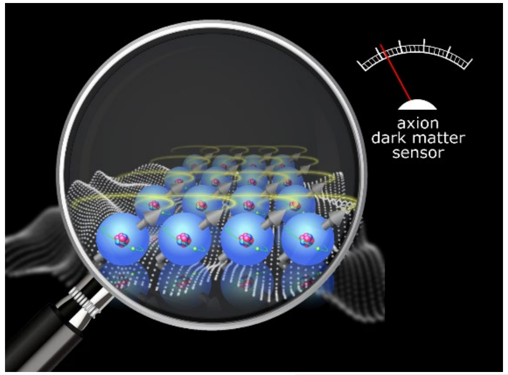

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nuclear Schiff moment ↔ atomic energy shift

axion dark matter

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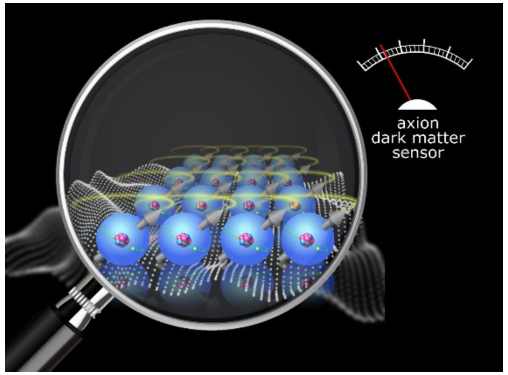

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Effective electric field

axion dark matter

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

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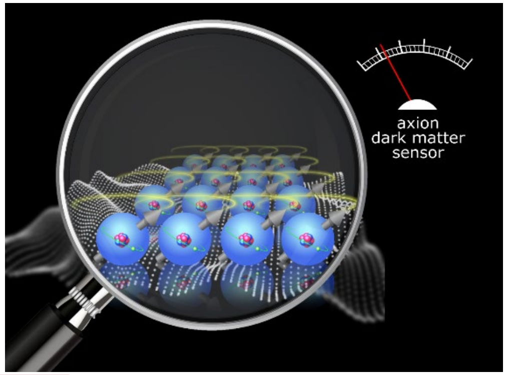

[D. Aybas et al., *Phys. Rev. Lett.* **126**, 160505 (2021)]

Magnetic resonance Hamiltonian

axion dark matter

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

θ-term in QCD Lagrangian

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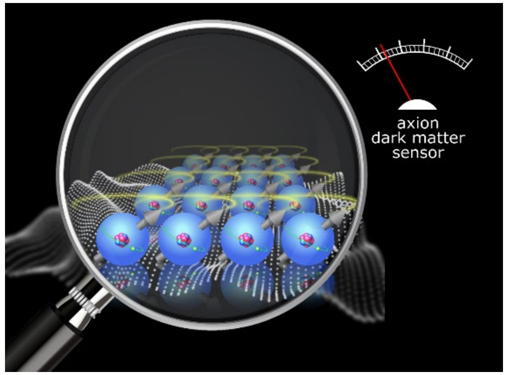
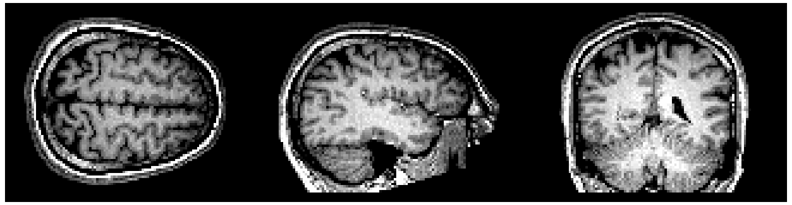


[D. Aybas et al., *Phys. Rev. Lett.* **126**, 160505 (2021)]

Aside: magnetic resonance

CASPEr is similar to NMR



Aside: magnetic resonance

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

(nuclear gyromagnetic ratio)

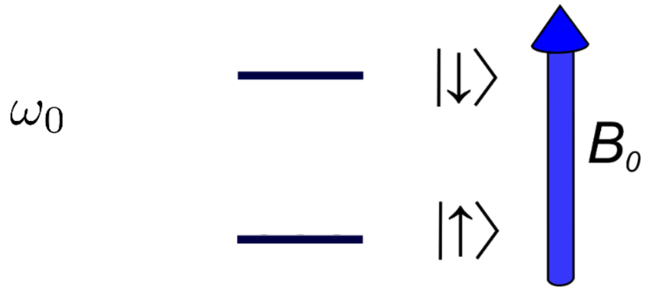
interaction: $\mathcal{H}_{\mathrm{NMR}} = -\hbar \gamma_I \boldsymbol{B} \cdot \boldsymbol{I}$

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

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

CASPEr is similar to NMR

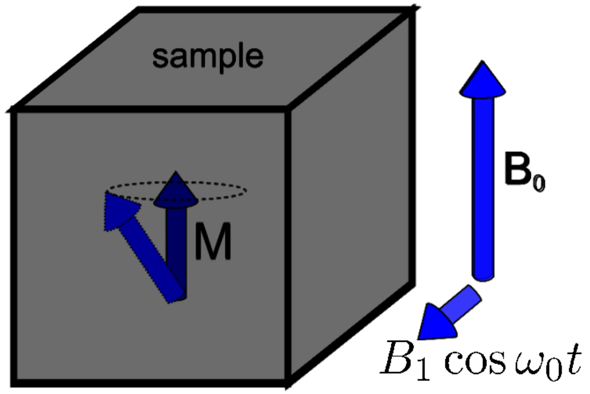
1) place a spin-1/2 into an external magnetic field splits the spin states by $\gamma_I B_0$



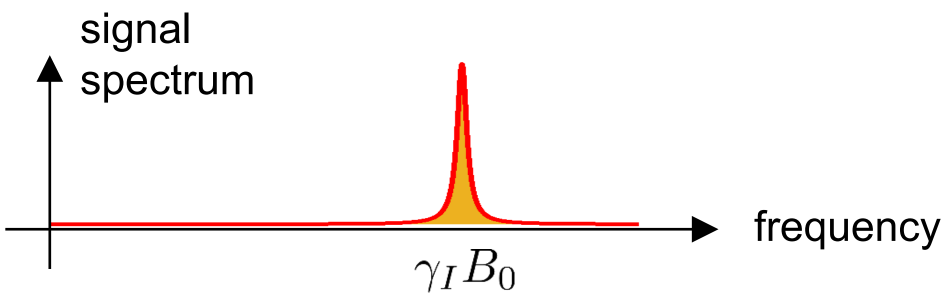
2) spin polarization (thermal or optical) in a cm^3 sample

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

- RF magnetic field can now flip spins!
- sample magnetization tilts and precesses



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



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

Axion-like dark matter → pseudo-magnetic field

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

CASPEr-electric

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

CASPEr-gradient

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

axion (or ALP) field

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

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

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

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

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

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

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

$$\mathcal{H} = -\hbar\gamma_I \boldsymbol{B}_0\cdot\boldsymbol{I} - (\hbar\gamma_I \boldsymbol{B}_1^* \cos\omega_a t)\cdot\boldsymbol{I}$$

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

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

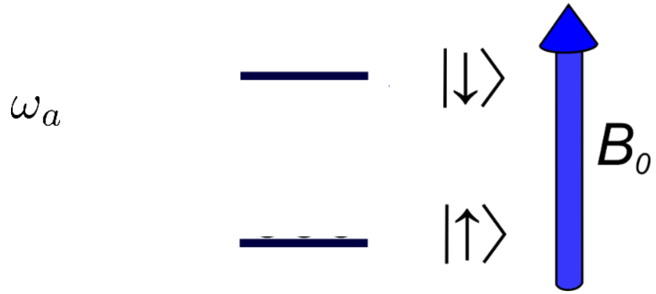
2) spin polarization (thermal or optical) in a cm^3 sample

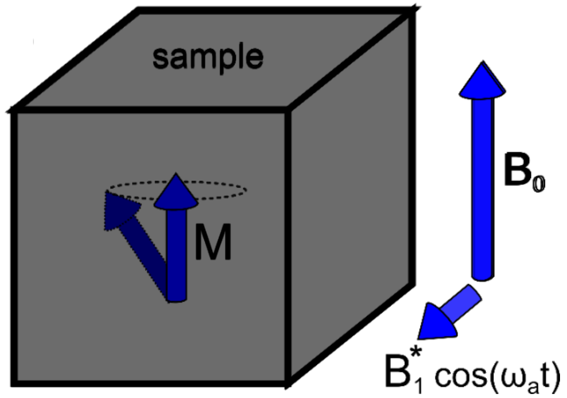
3) resonance: $\omega_a = \gamma_I B_0$

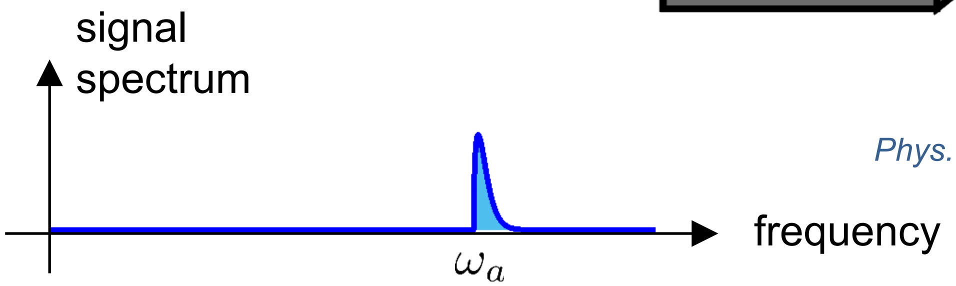
- axion-spin interaction can now flip spins!
- sample magnetization tilts and precesses

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





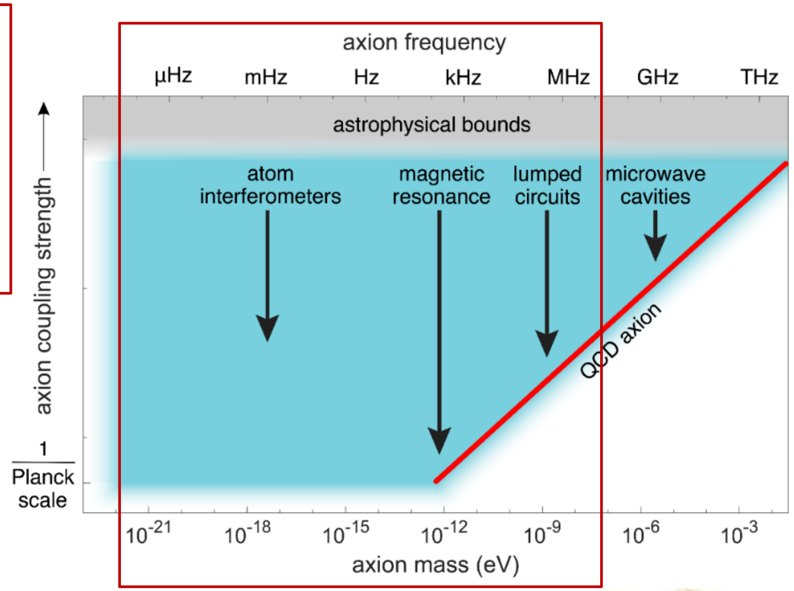


an NMR experiment with no RF magnetic field, instead axion-like dark matter flips spins

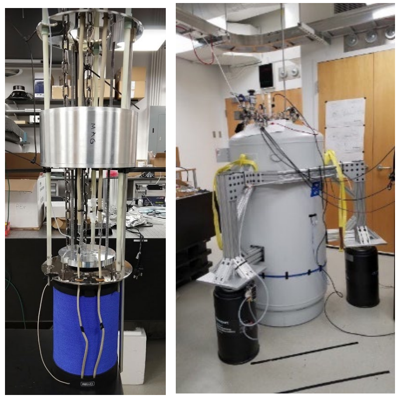
[D. Budker et al., *Phys. Rev. X* **4**, 021030 (2014)]

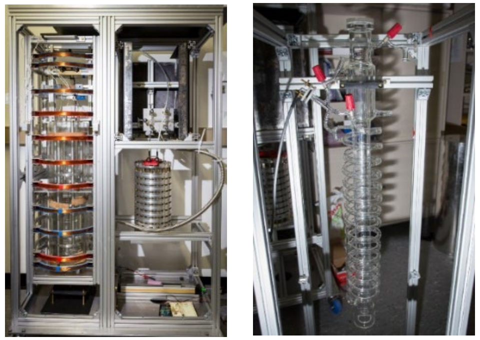
CASPEr program

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



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





Deniz Aybas
Alex Wilzewski
Janos Adam
Sasha Gramolin
Dorian Johnson
Annalies Kleyheeg
Arne Wickenbrock
John Blanchard

Hendrik Bekker
Antoine Garcon
Gary Centers
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Marina Gil Sendra
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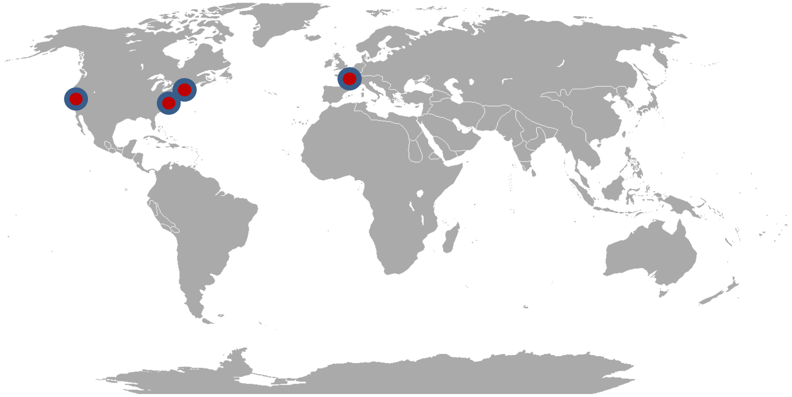


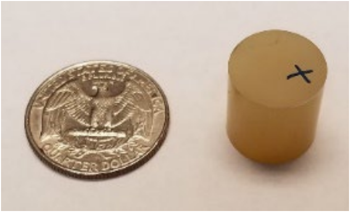
Dmitry Budker, Peter Graham, Derek Kimball, Surjeet Rajendran, Alex Sushkov

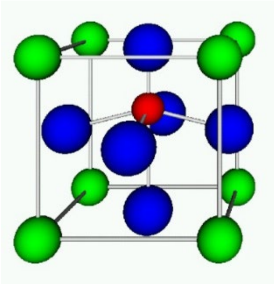
CASPEr-e: experimental details

sample: 4mm

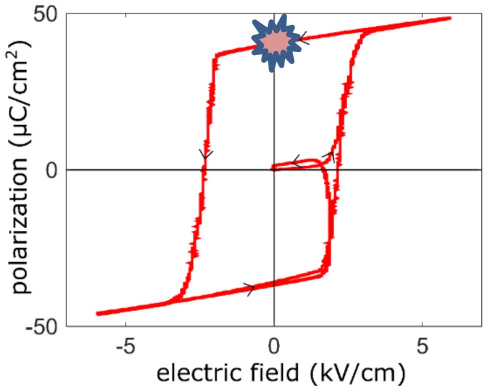
^{207}Pb nuclear spins in ferroelectrically-polarized PMN-PT

$(\mathrm{PbMg}_{1/3}\mathrm{Nb}_{2/3}\mathrm{O}_3)_{2/3}(\mathrm{PbTiO}_3)_{1/3}$





3×10^{20} spins



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

(similar to a polar molecule

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

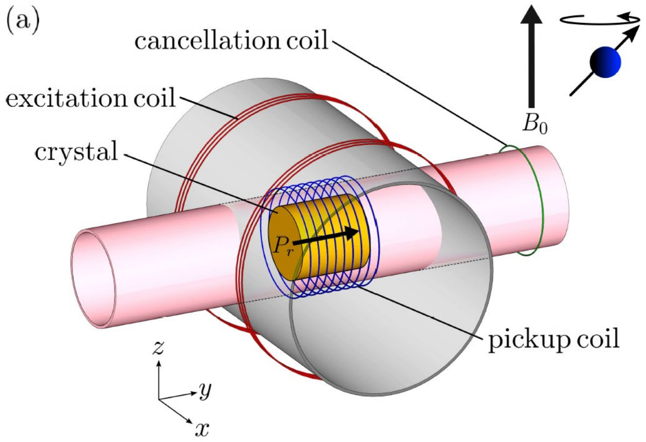
sensor:

low-noise radiofrequency amplifier

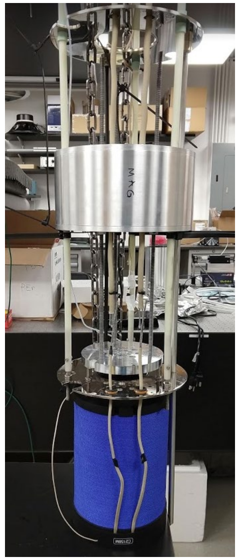
SQUID

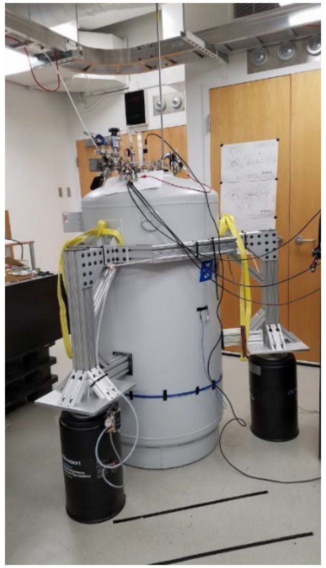
NMR calibration

crossed excitation and pickup coils



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





millimeter-scale CASPEr-e search based on nuclear magnetic resonance

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

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

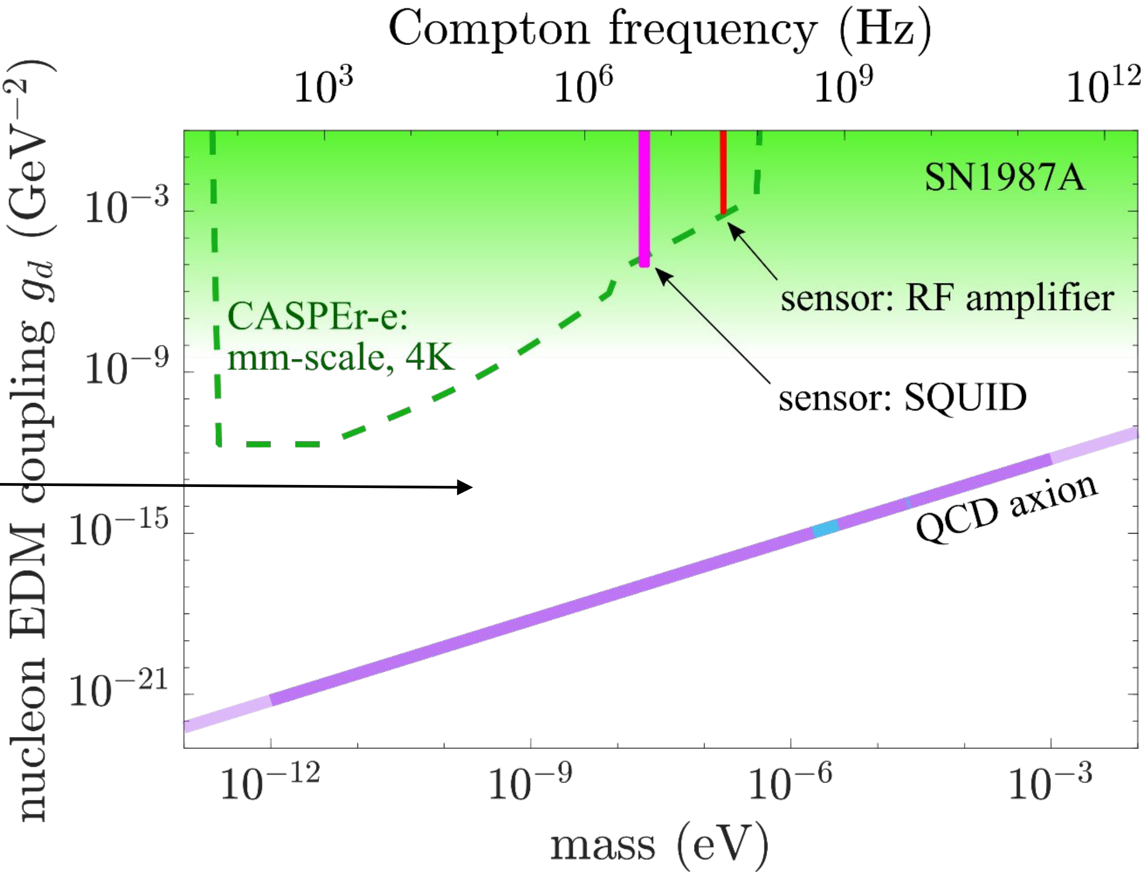
CASPEr-e limits on nucleon EDM and gradient interactions of axion-like dark matter

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

→ 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?



common solution: scale up experimental volume

unique features of the magnetic resonance approach →

- broad-band: tune frequency by changing magnetic field (i.e. current) → can cover 4-5 decades in axion mass
- 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)]
[D. Aybas et al., *Quant. Sci. Tech.* **6**, 034007 (2021)]

CASPEr-e axion-like dark matter search

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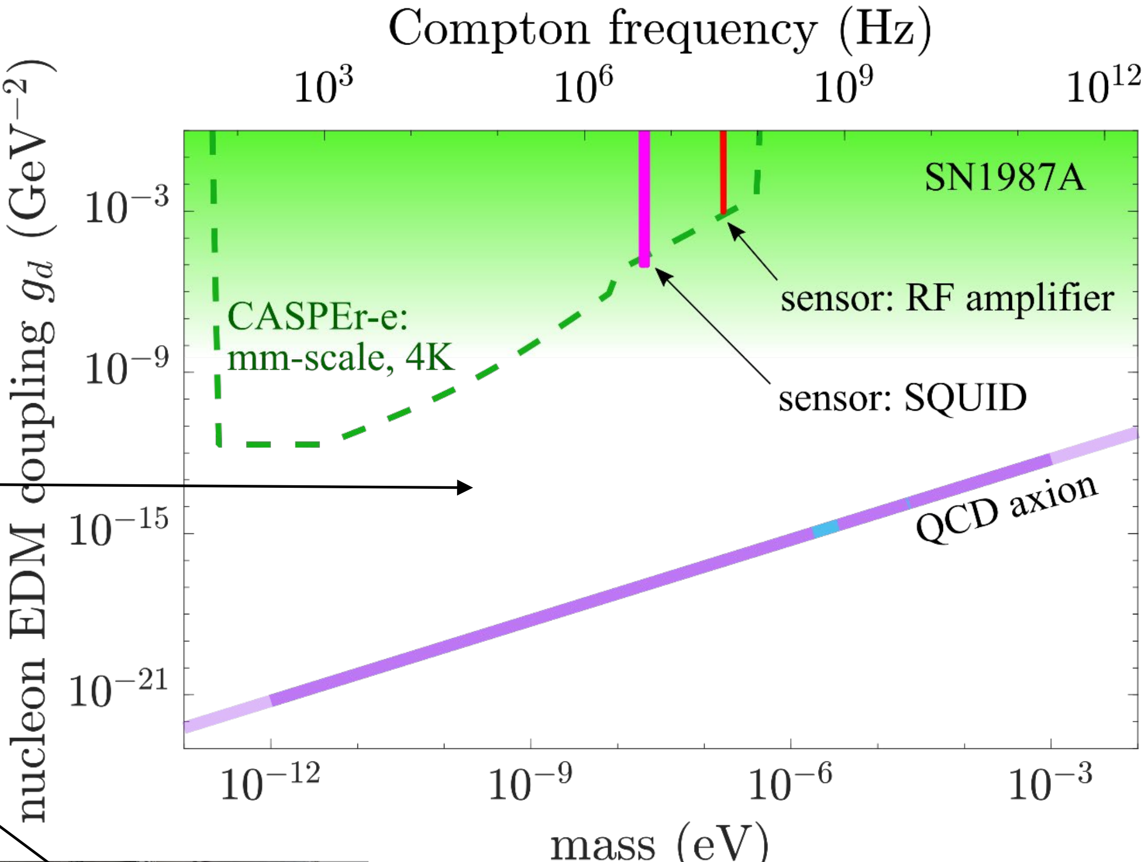

path forward →

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

[D. Aybas et al., *Phys. Rev. Lett.* **126**, 160505 (2021)]
[D. Aybas et al., *Quant. Sci. Tech.* **6**, 034007 (2021)]
[J. Adam et al., manuscript in preparation]

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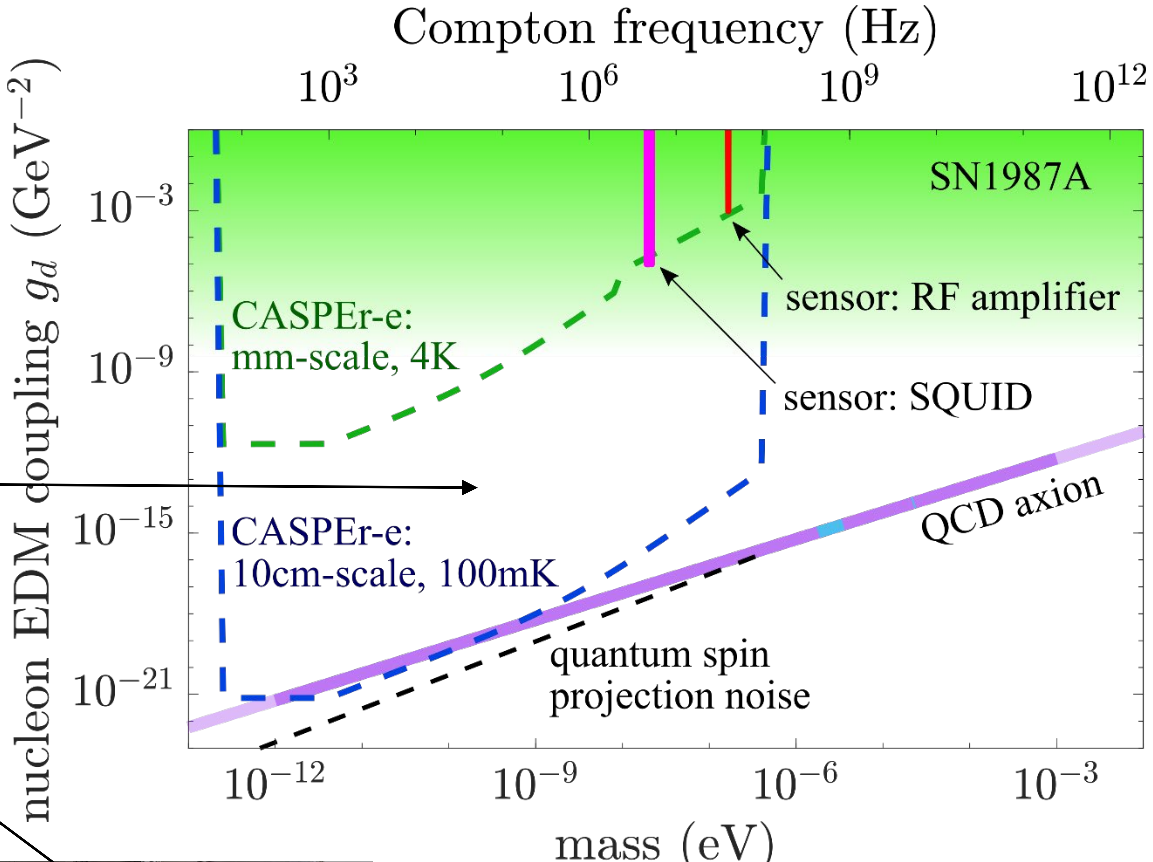

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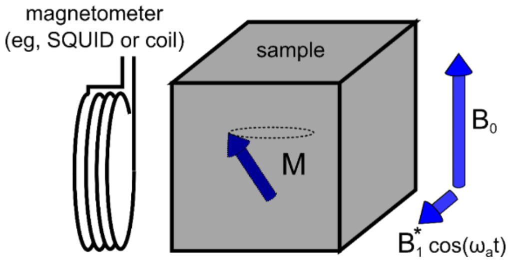
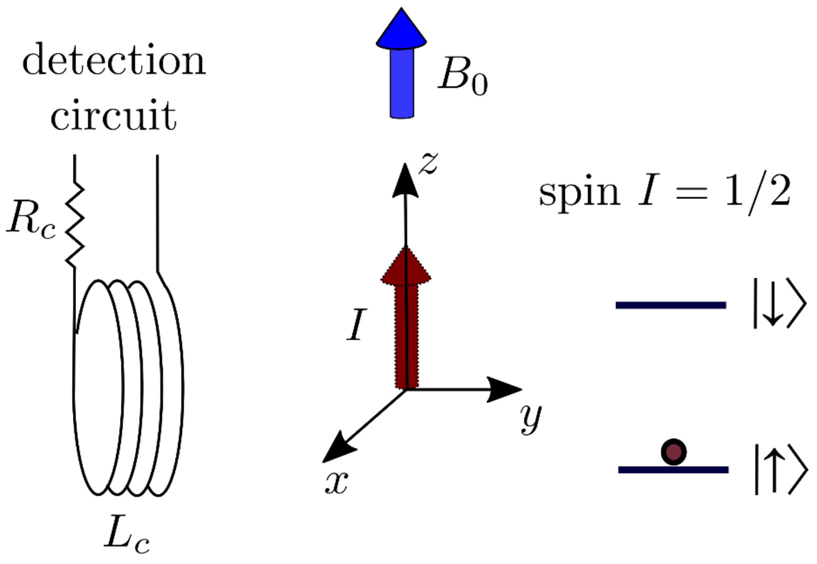
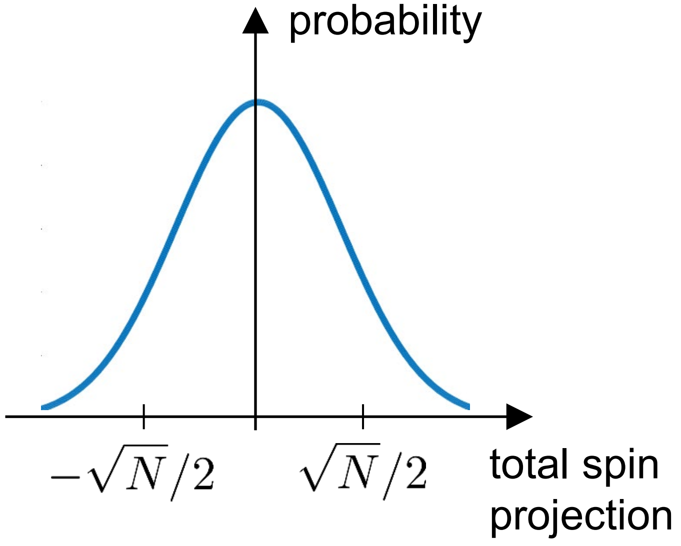


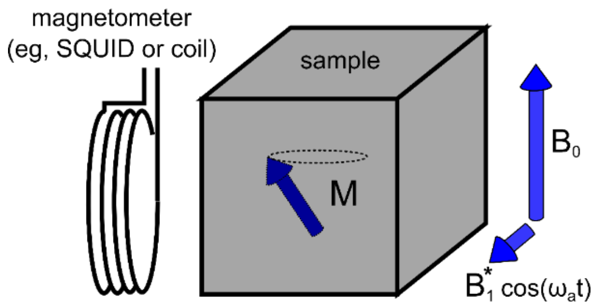
[D. Aybas et al., *Phys. Rev. Lett.* **126**, 160505 (2021)]
[D. Aybas et al., *Quant. Sci. Tech.* **6**, 034007 (2021)]
[J. Adam et al., manuscript in preparation]
[A. Gramolin et al., *Nature Physics* **17**, 79 (2021)]

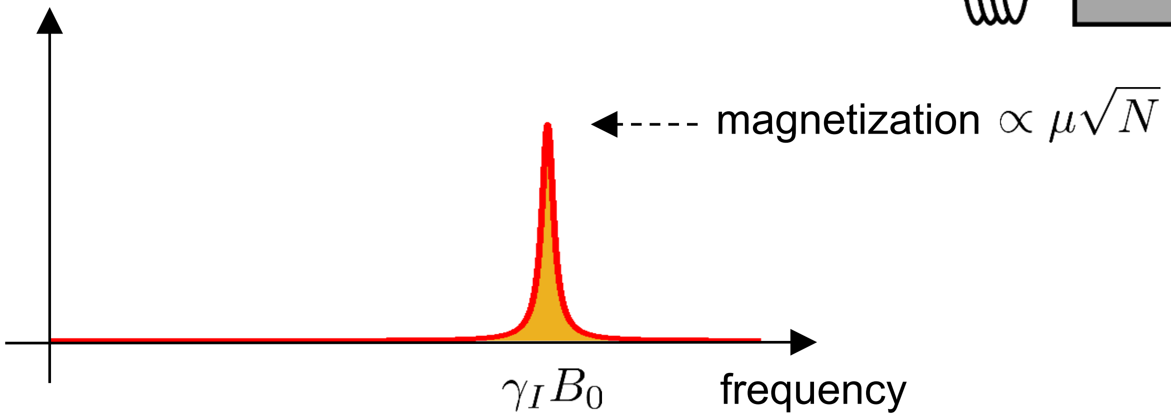
Quantum spin projection noise (standard quantum limit)





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





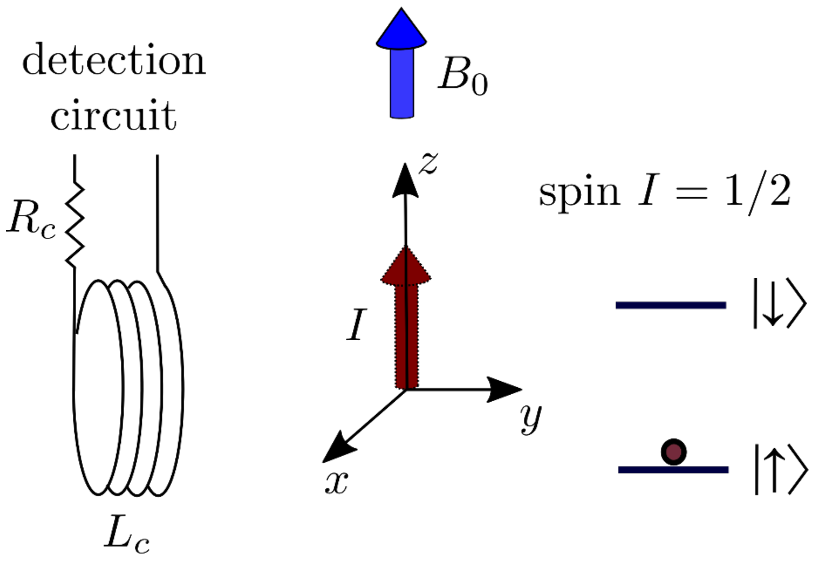
standard quantum limit (SQL): $\theta \approx \dfrac{1}{\sqrt{N}}$

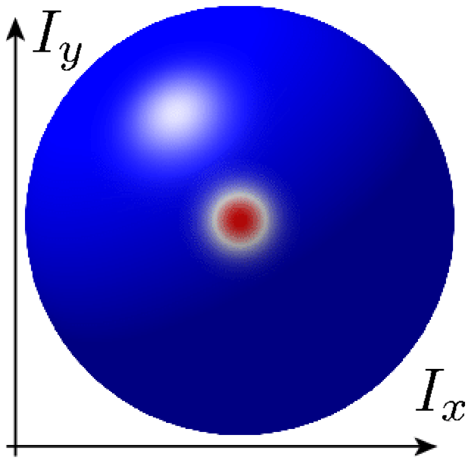
spin projection measurement uncertainty

spin projection noise (SQL) sensitivity has been achieved in NMR

[T. Sleator et al., *Phys. Rev. Lett* **55**, 1742 (1985)]
[D. Aybas et al., *Quant. Sci. Tech.* **6**, 034007 (2021)]

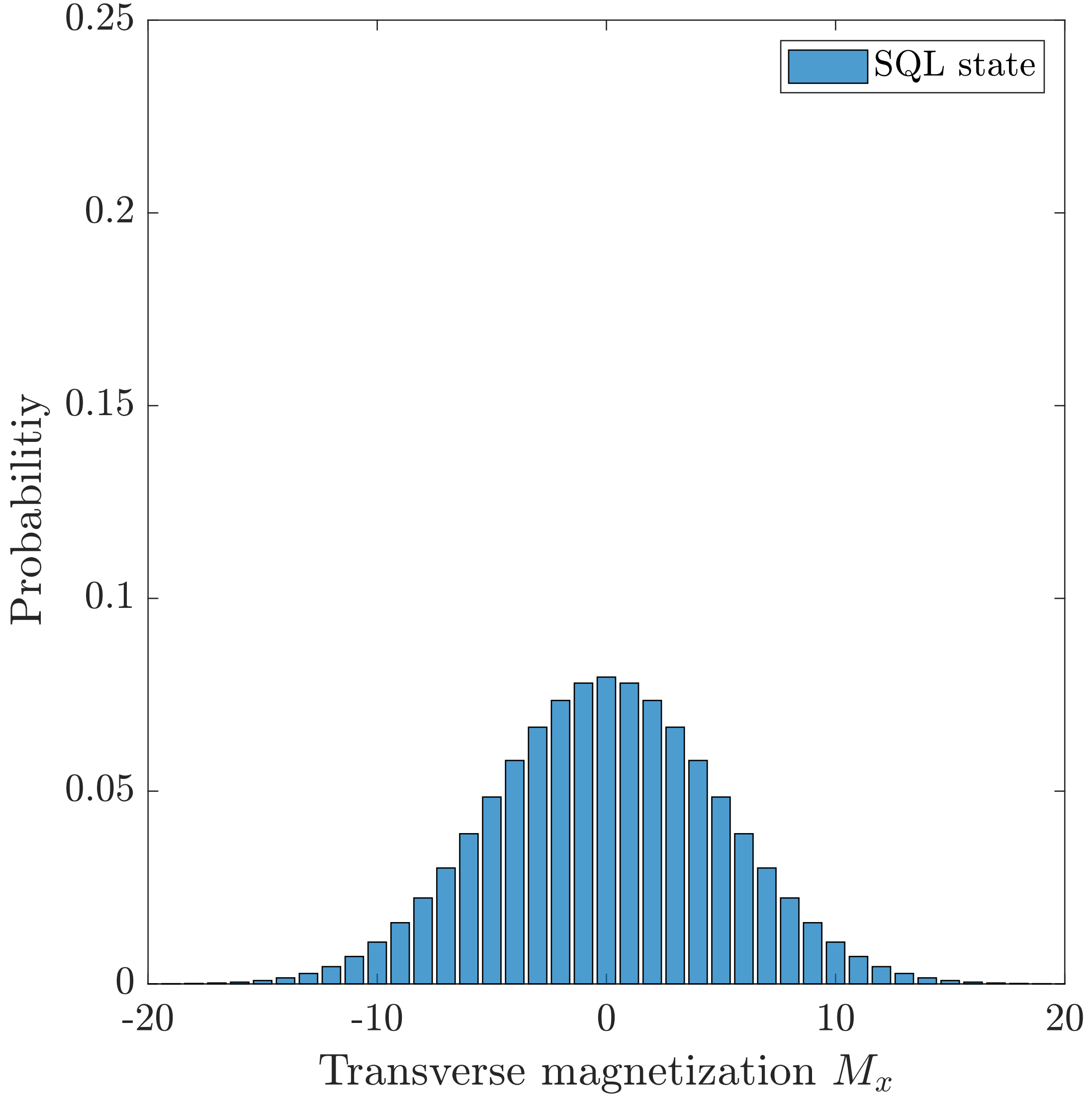
Spin squeezing



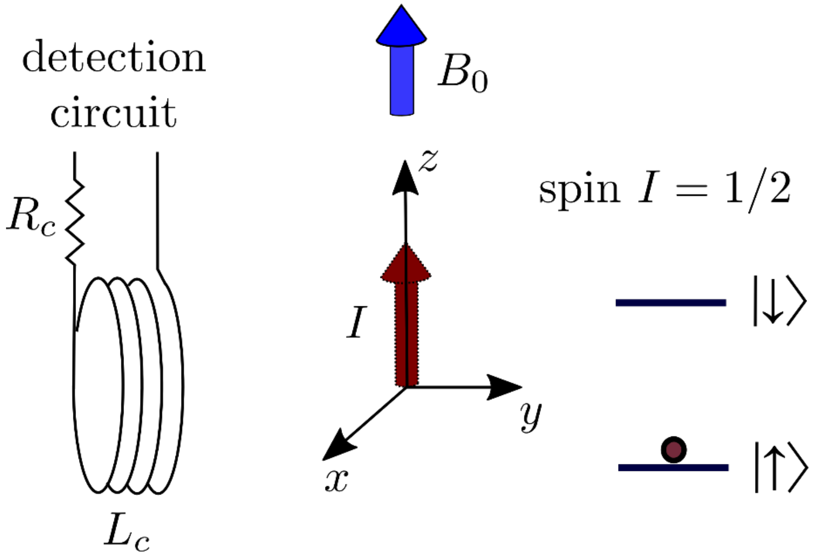


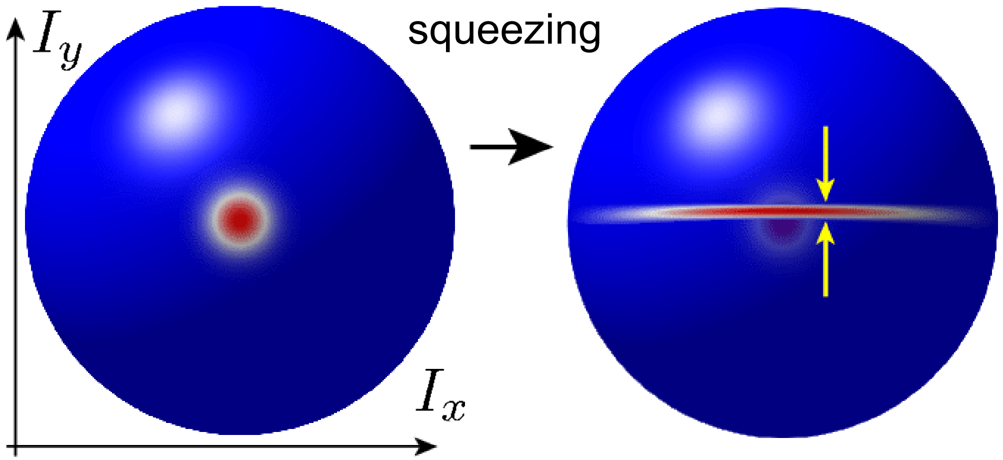
[*Phys. Rep.* **509**, 89 (2011)]

standard quantum limit (SQL): $\theta \approx \frac{1}{\sqrt{N}}$



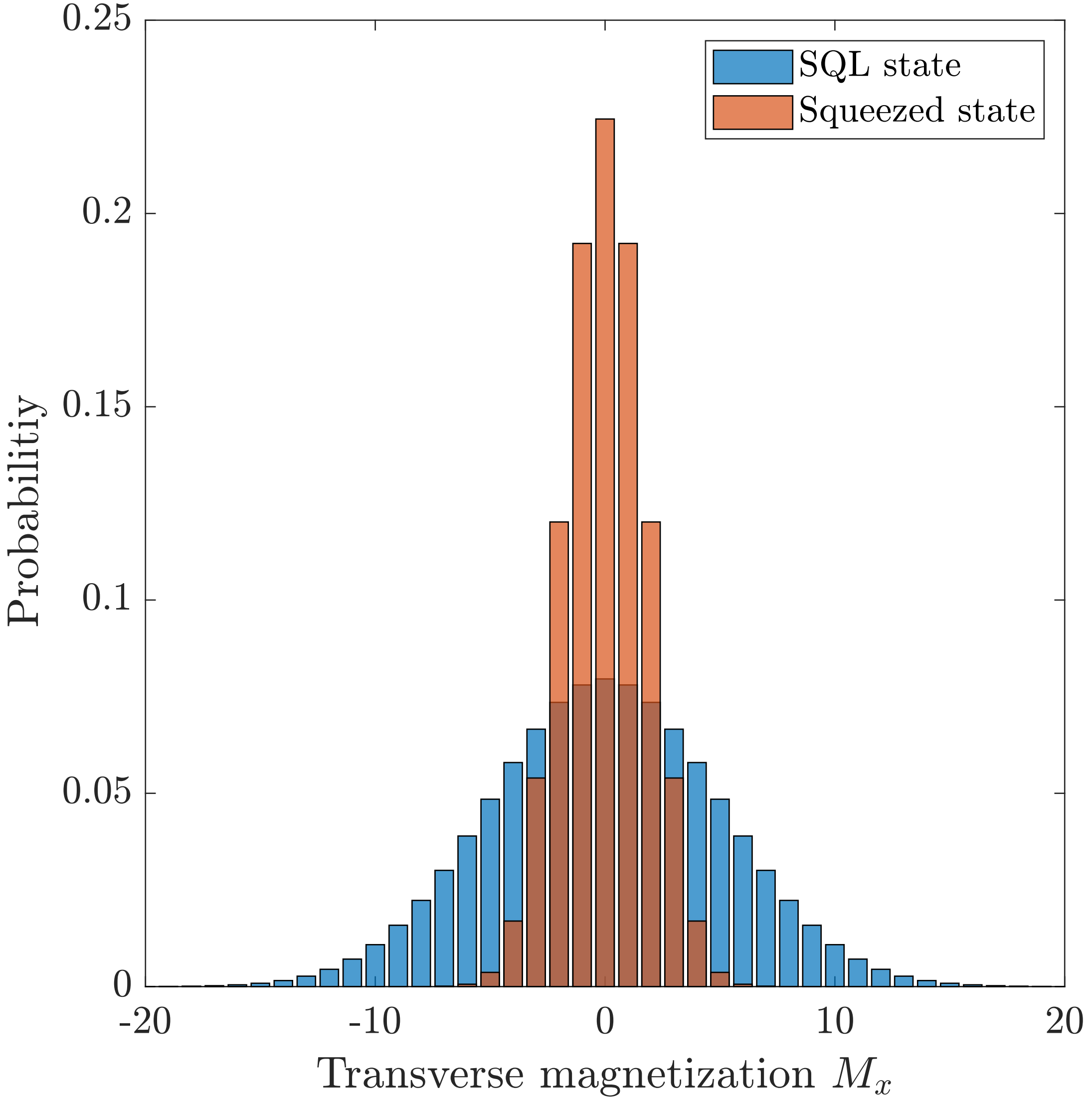
Spin squeezing



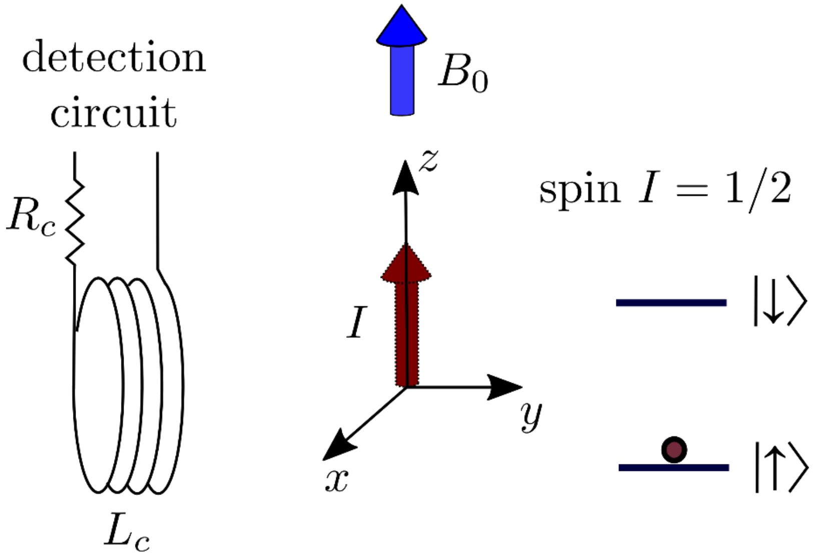


[*Phys. Rep.* **509**, 89 (2011)]

standard quantum limit (SQL): $\theta \approx \frac{1}{\sqrt{N}}$

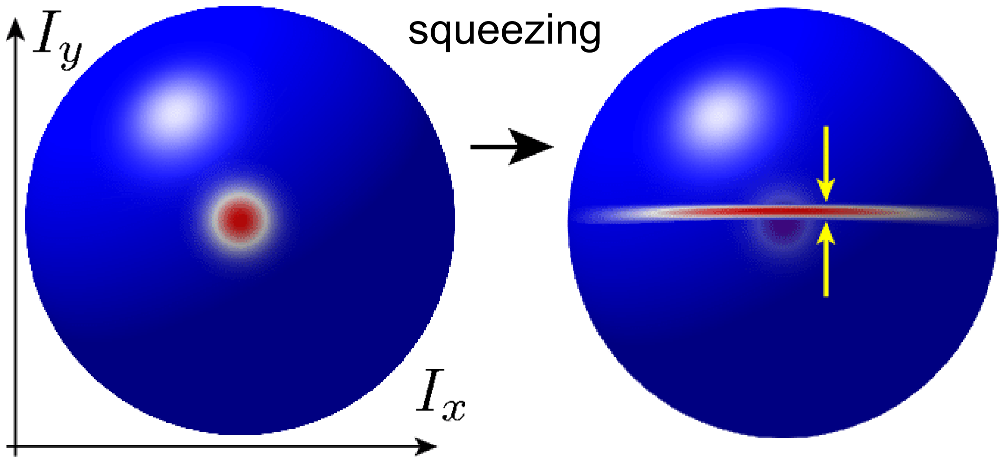


Spin squeezing



standard quantum limit (SQL): $\theta \approx \frac{1}{\sqrt{N}}$

- 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
- due to spin decoherence, spin squeezing does not improve sensitivity of a resonant experiment
- analogous to EM case, spin squeezing does improve sensitivity bandwidth, and thus accelerates scanning



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

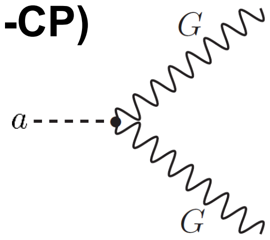
[D. Aybas et al., *Quant. Sci. Tech.* **6**, 034007 (2021)]

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

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

interaction with gluons (strong-CP) defines QCD axion:

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



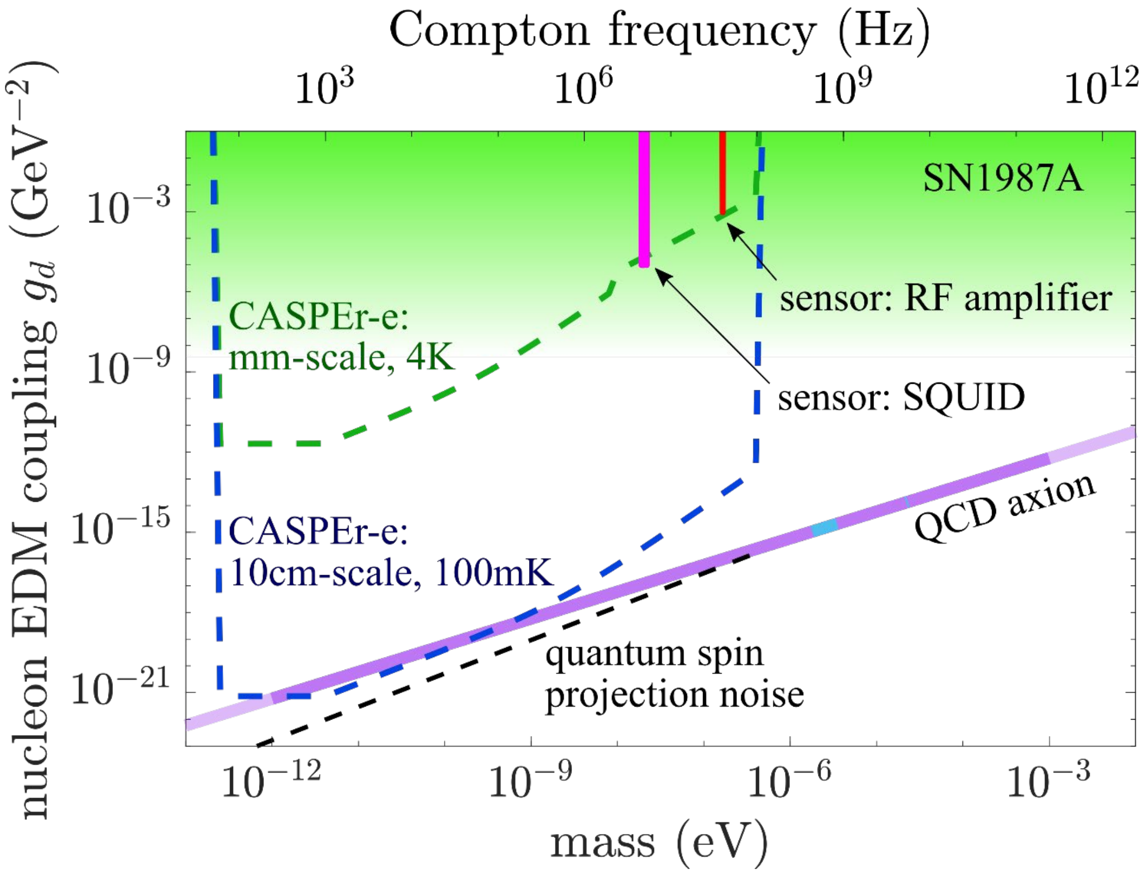
$$\Rightarrow \mathcal{H}_{\mathrm{EDM}} = g_d a \boldsymbol{E}^* \cdot \boldsymbol{I}/I$$

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

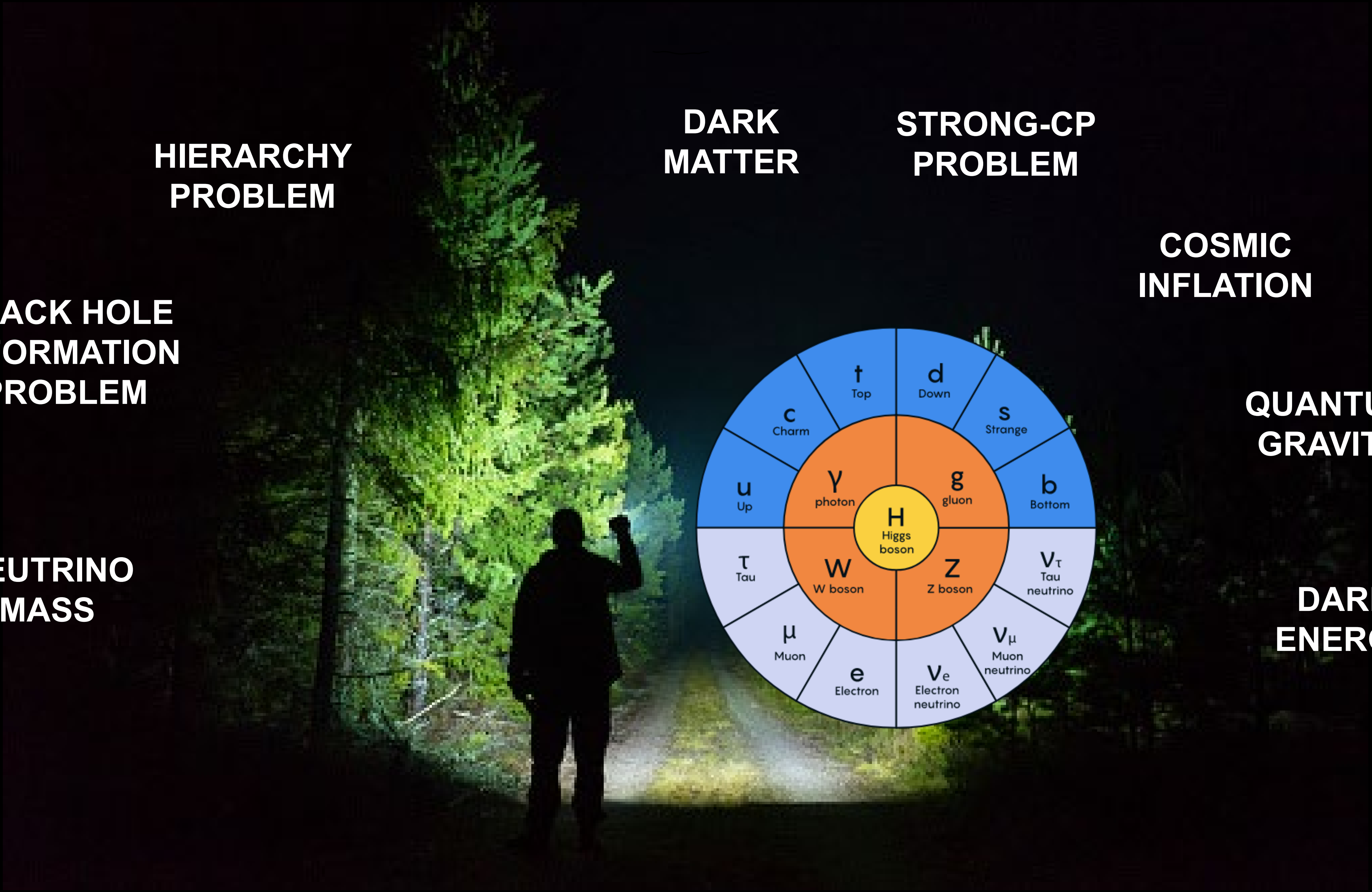
key experimental parameters:

- nuclear spin polarization → larger is better
- nuclear spin coherence time → longer is better
- spin ensemble volume → larger is better
- sensor noise, back-action, spin projection noise
- **effective electric field (unique to spins)** → larger is better

└→ **nuclear, atomic, and condensed-matter physics input needed!**



- current experiments (mm-scale) are limited by thermal spin polarization and sensor noise
- achieving QCD axion sensitivity is feasible with 10cm-scale experiment
- spin squeezing may enable reaching QCD axion sensitivity with a smaller-scale experiment



HIERARCHY PROBLEM

DARK MATTER

STRONG-CP PROBLEM

COSMIC INFLATION

BLACK HOLE INFORMATION PROBLEM

QUANTUM GRAVITY

NEUTRINO MASS

DARK ENERGY