Title: Probing magnetic-field like effects

Speakers: Alex Sushkov

Collection: School on Table-Top Experiments for Fundamental Physics

Date: September 19, 2022 - 10:45 AM

URL: https://pirsa.org/22090003

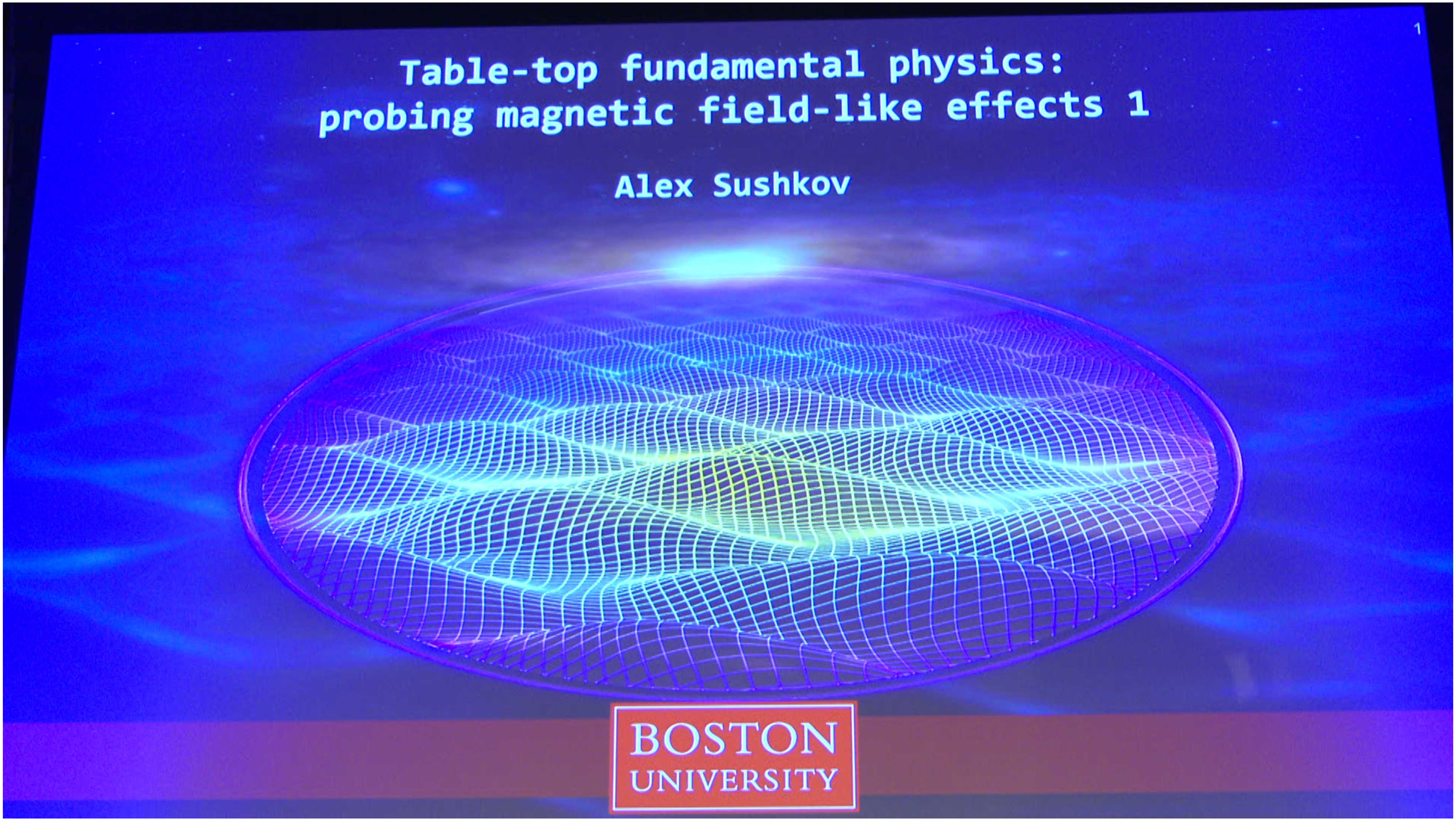
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Table-top fundamental physics:
probing magnetic field-like effects 1
Alex Sushkov
BOSTON
UNIVERSITY

Main points

- Introduction: table-top searches for new fundamental physics

$\longrightarrow$ ultralight dark matter

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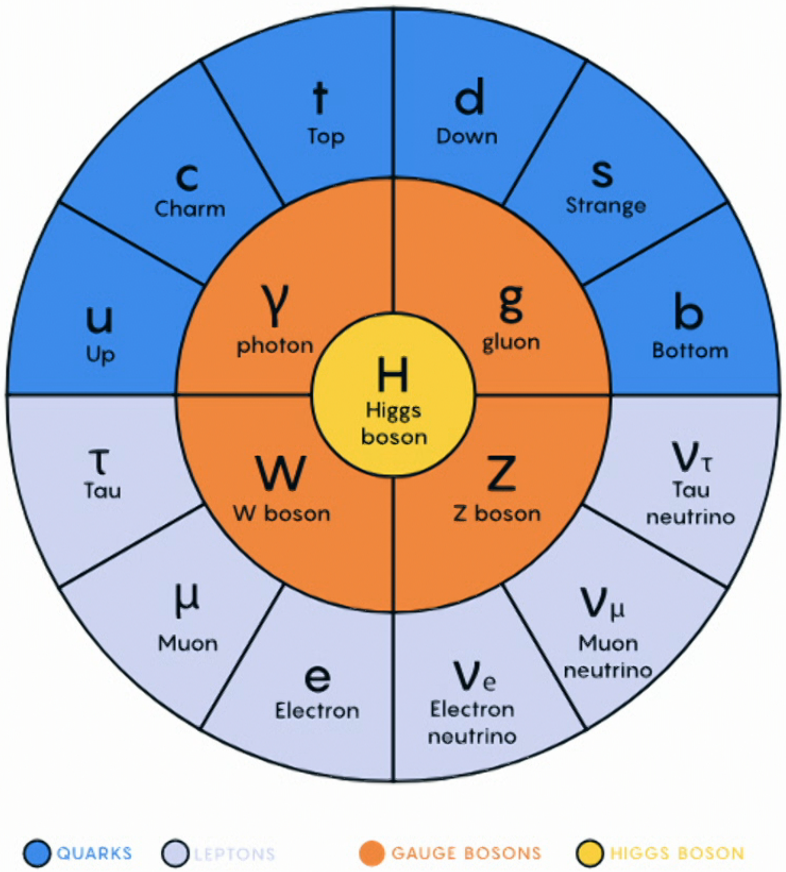
$\longrightarrow$ ultralight dark matter

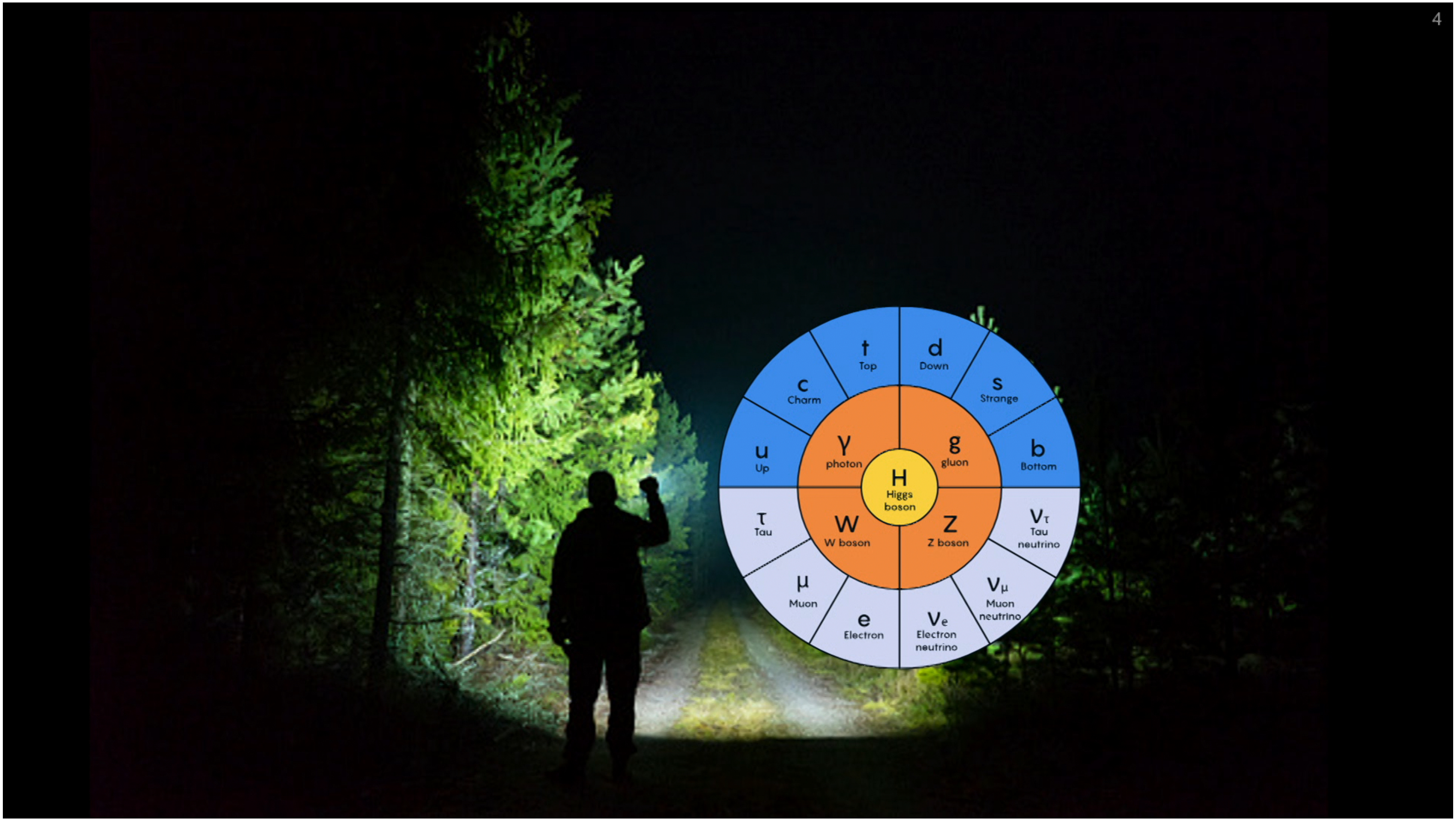
- Lecture 1: lumped-element searches for the electromagnetic interaction of axion-like dark matter

Main points

- Introduction: table-top searches for new fundamental physics → ultralight dark matter
- Lecture 1: lumped-element searches for the electromagnetic interaction of axion-like dark matter
- Lecture 2: searches for interactions of axion-like dark matter with spins

The standard model

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Top
d
Down
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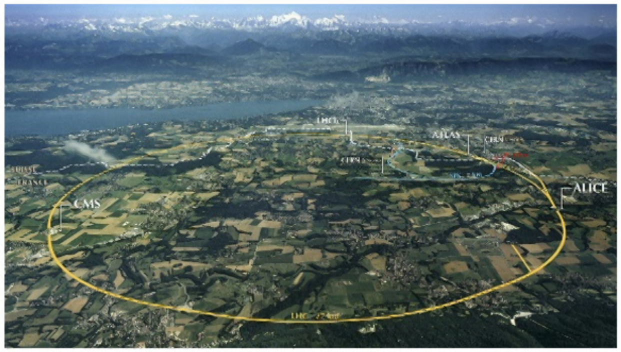
Charm
s
Strange
u
Up
b
Bottom
γ
photon
g
gluon
H
Higgs boson
W
W boson
Z
Z boson
τ
Tau
ντ
Tau neutrino
μ
Muon
νμ
Muon neutrino
e
Electron
νe
Electron neutrino

The tools

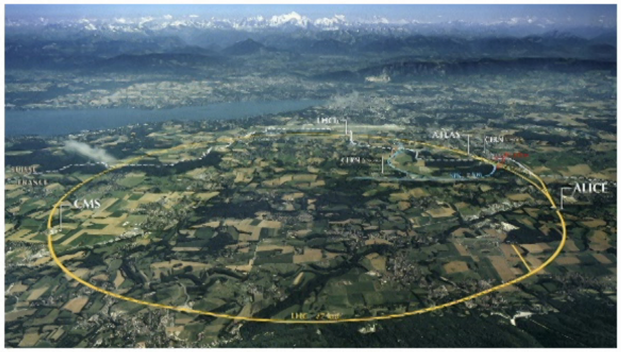
particle accelerators



terrestrial telescopes

The tools

particle accelerators



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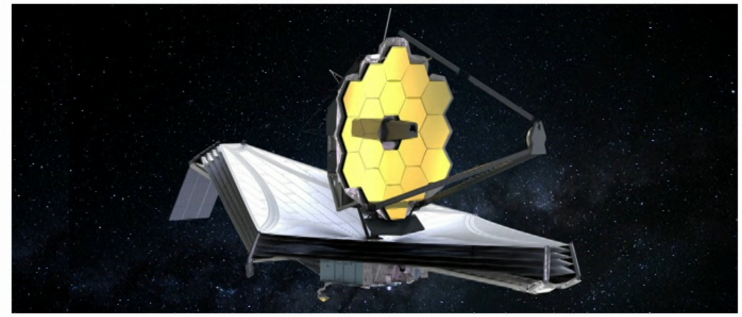
space telescopes



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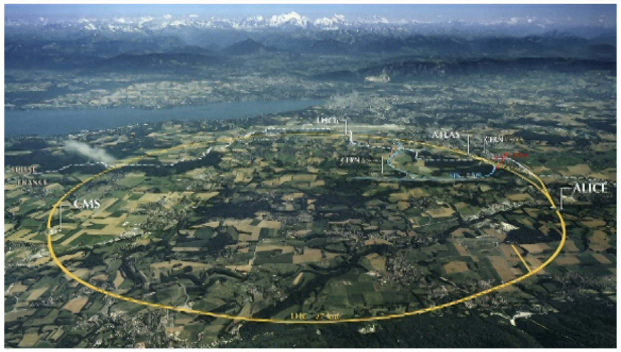

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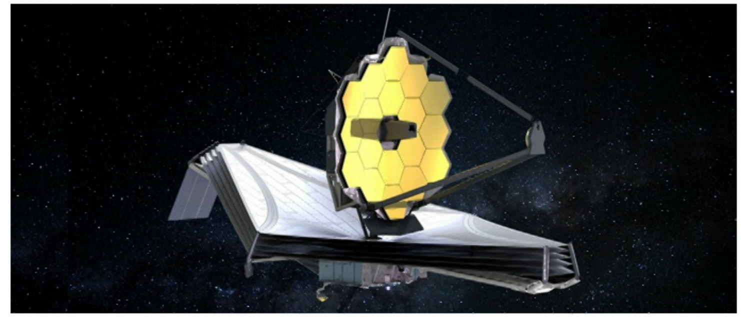

rare event detectors (eg, WIMPs)

The tools

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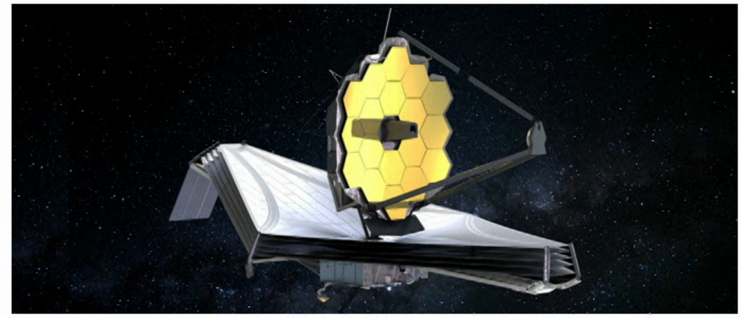
terrestrial telescopes

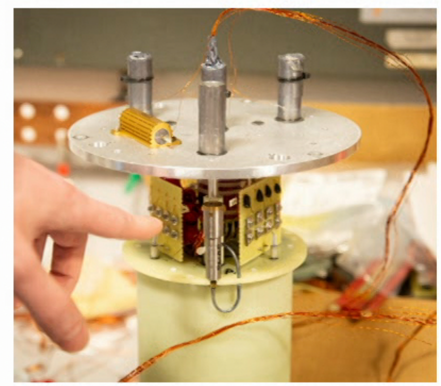
space telescopes



rare event detectors (eg, WIMPs)

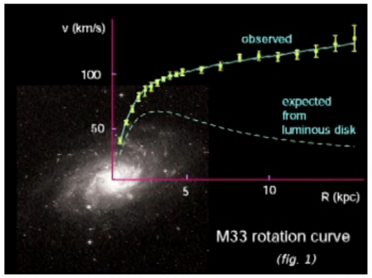
gravitational wave observatories

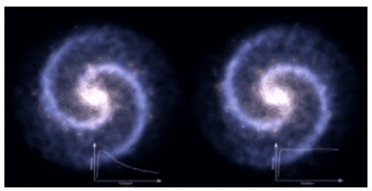
precision lab-scale experiments



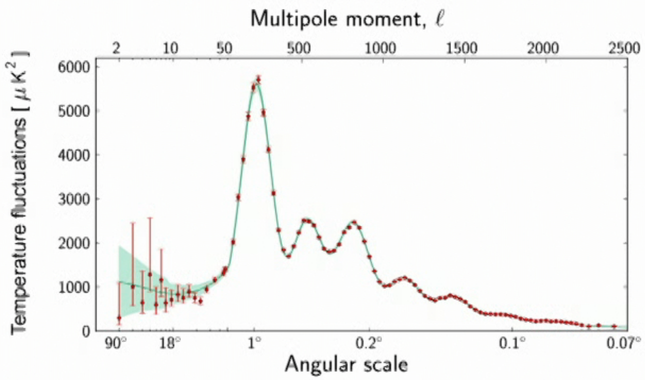
The dark matter problem

galaxy rotation curves

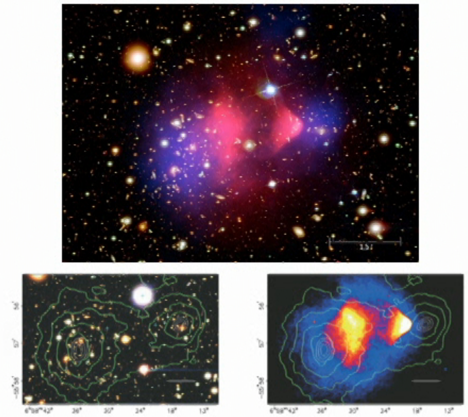




CMB angular power spectrum



galaxy clusters: Bullet cluster



+ many others

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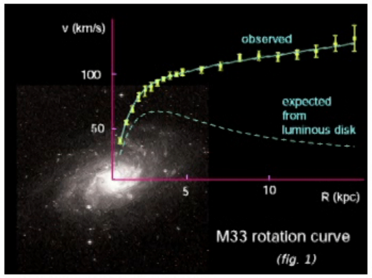

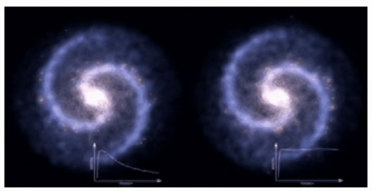

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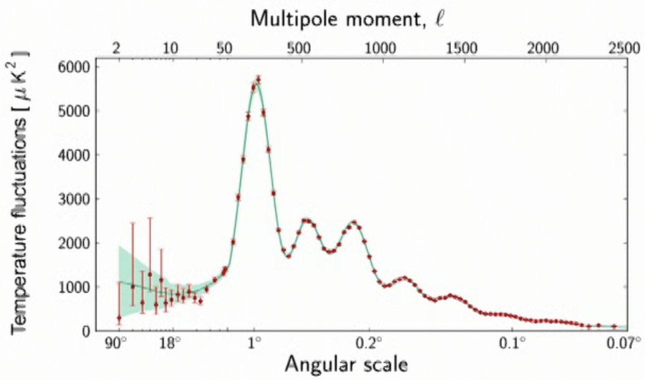

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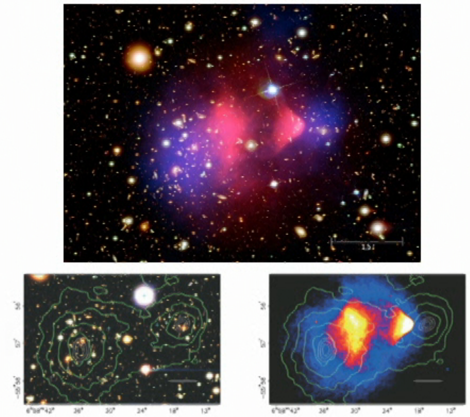

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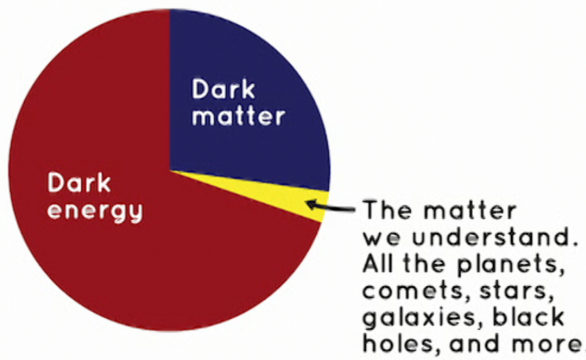
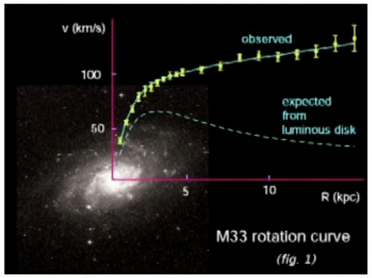
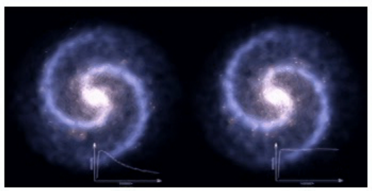


local dark matter energy density: $\rho_{\rm DM} \approx 0.4\,{\rm GeV/cm^3}$

The dark matter problem

galaxy rotation curves





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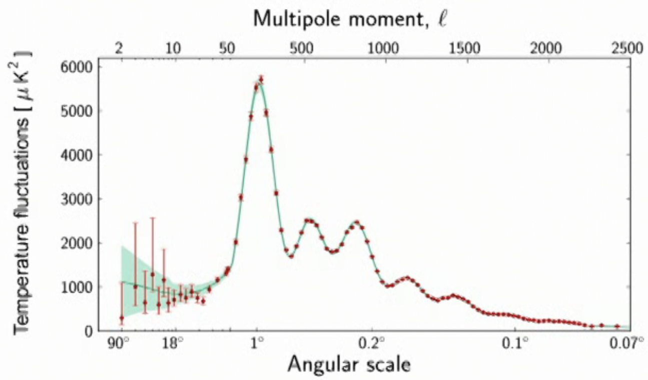

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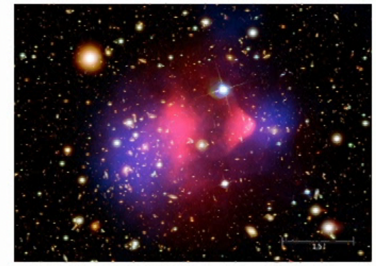

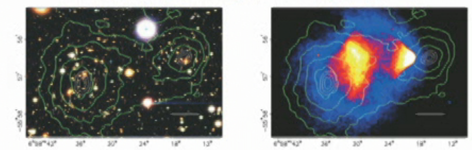

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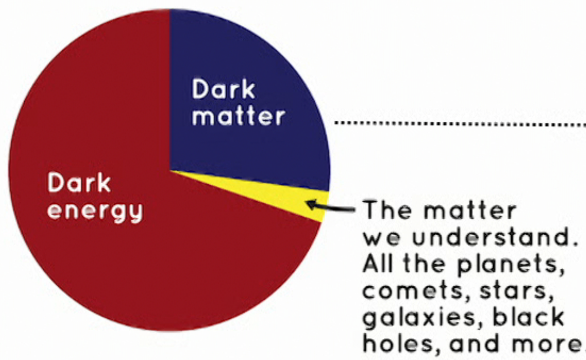

[Nature **562**, 51 (2018)]

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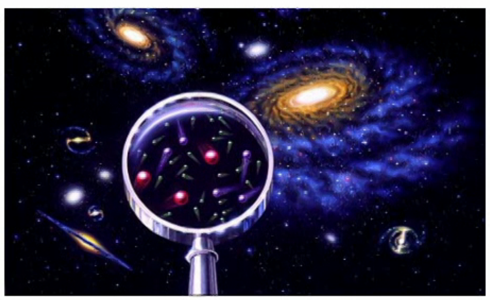
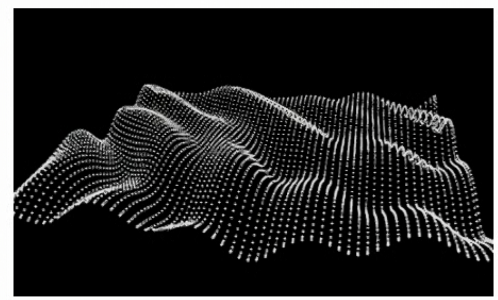
What is dark matter?

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



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

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

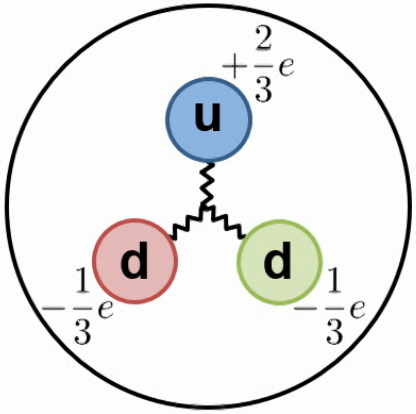


wave-like dark matter (eg: axions)
mass << eV

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

The strong-CP problem

neutron →

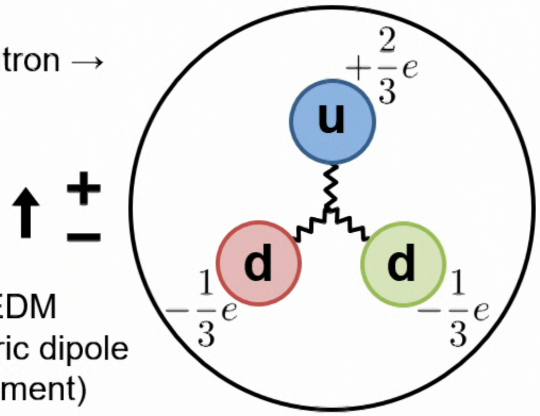


The strong-CP problem

neutron →

d_n

EDM
(electric dipole
moment)



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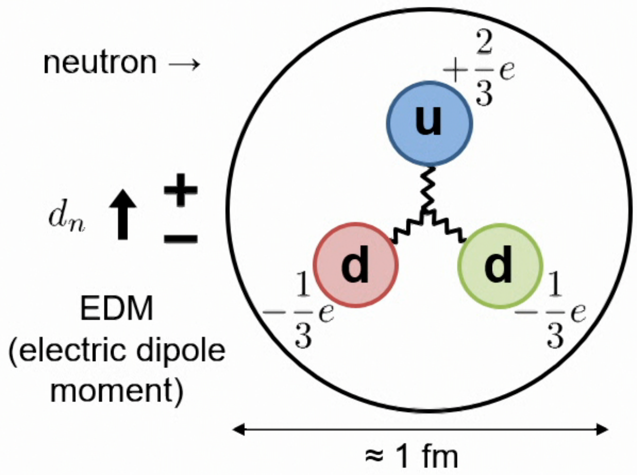


(very!) naïve estimate:

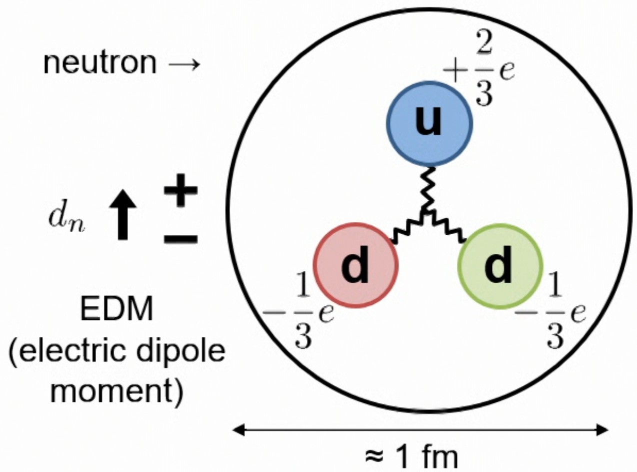
$$d_n \approx e \cdot \text{fm} = 10^{-13}\, e \cdot \text{cm}$$

experimental limit:

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

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

The strong-CP problem



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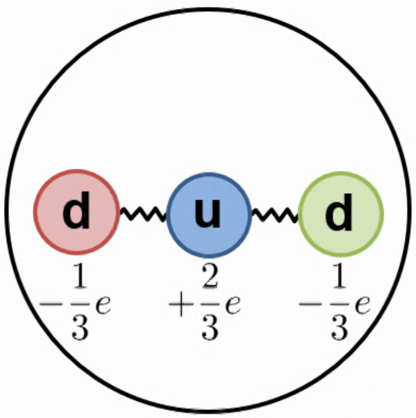
better model for
a neutron →



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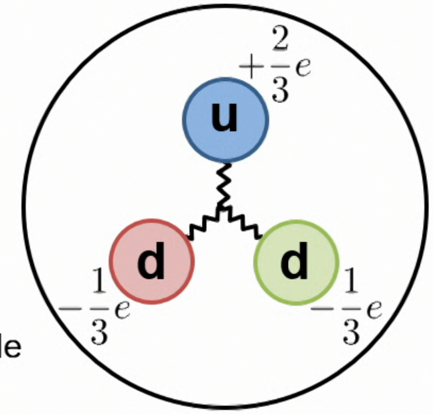
neutron →



d_n ±

EDM
(electric dipole
moment)

≈ 1 fm

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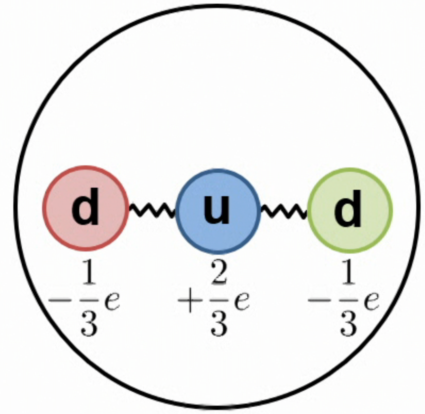
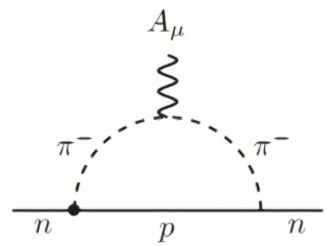


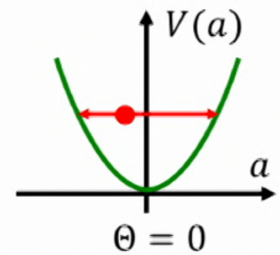
CP-violating θ-term in
QCD Lagrangian →

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



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

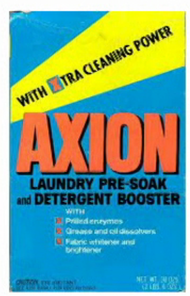
$\langle\theta\rangle = \langle a \rangle = 0$



➡ 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)]

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

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

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↓

large number of particles per de Broglie wavelength

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↓

large number of particles per de Broglie wavelength

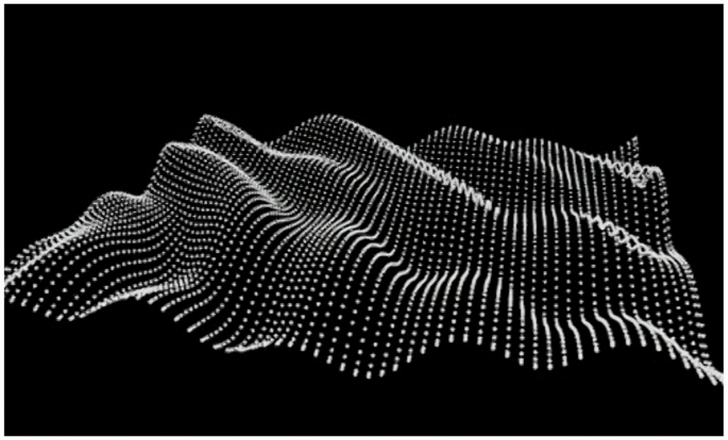
↓

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



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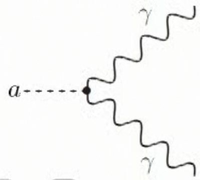
interaction with photons:

ALP field amplitude → a; symmetry breaking scale → f_a

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



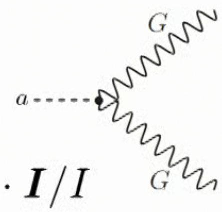
$$\mathcal{L}_{a\gamma\gamma} = g_{a\gamma\gamma} a \boldsymbol{E} \cdot \boldsymbol{B}$$

→ 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 (strong-CP) defines QCD axion:

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



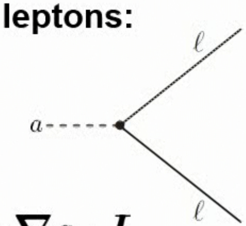
$$\mathcal{H}_{\mathrm{EDM}} = g_d a \boldsymbol{E}^* \cdot \boldsymbol{I}/I$$

→ 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)]

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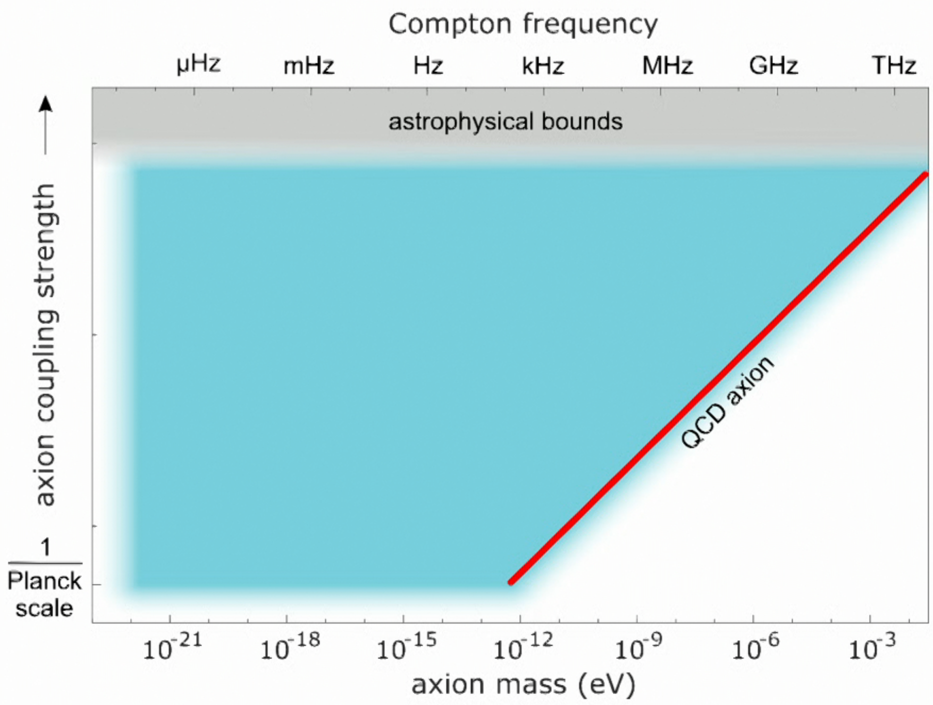

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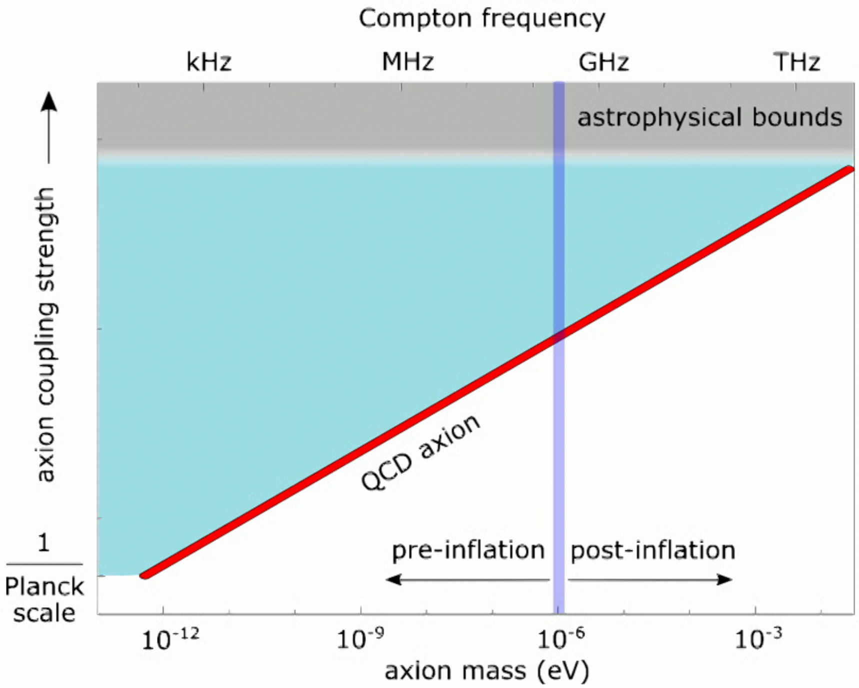

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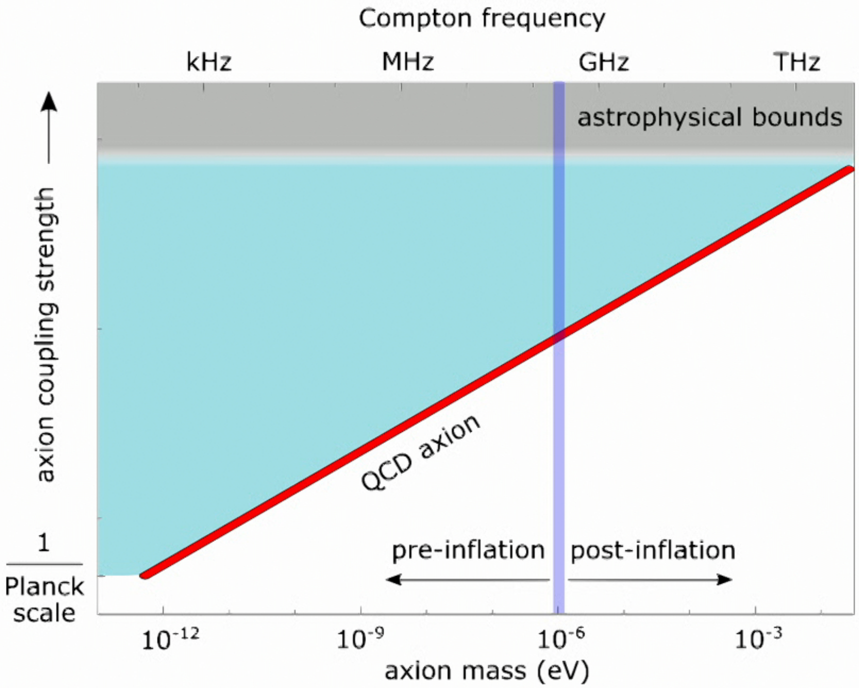

detection of axion dark matter
↓
insight into energy scale of inflation

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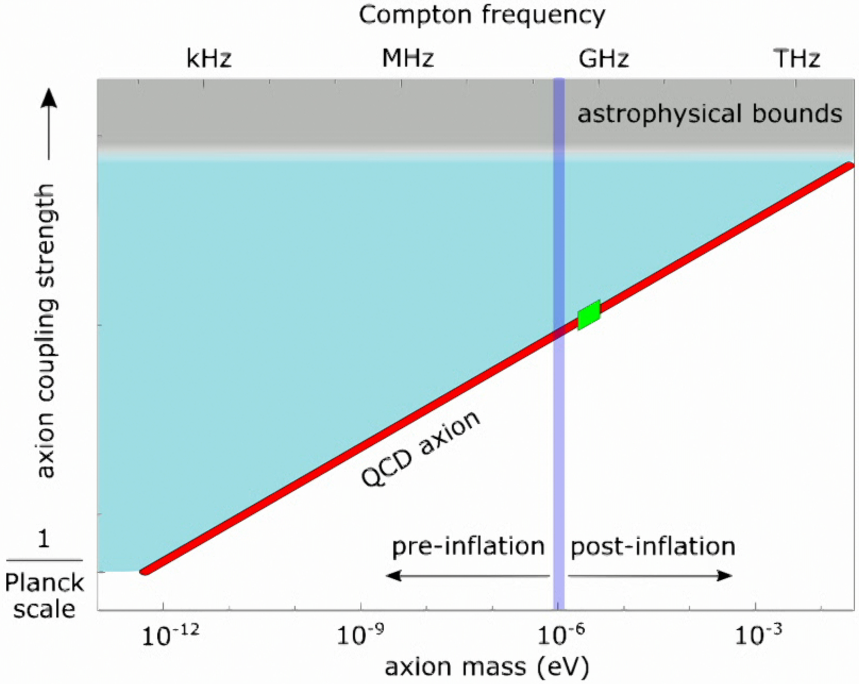

Axions and axion-like particles: basics and motivation

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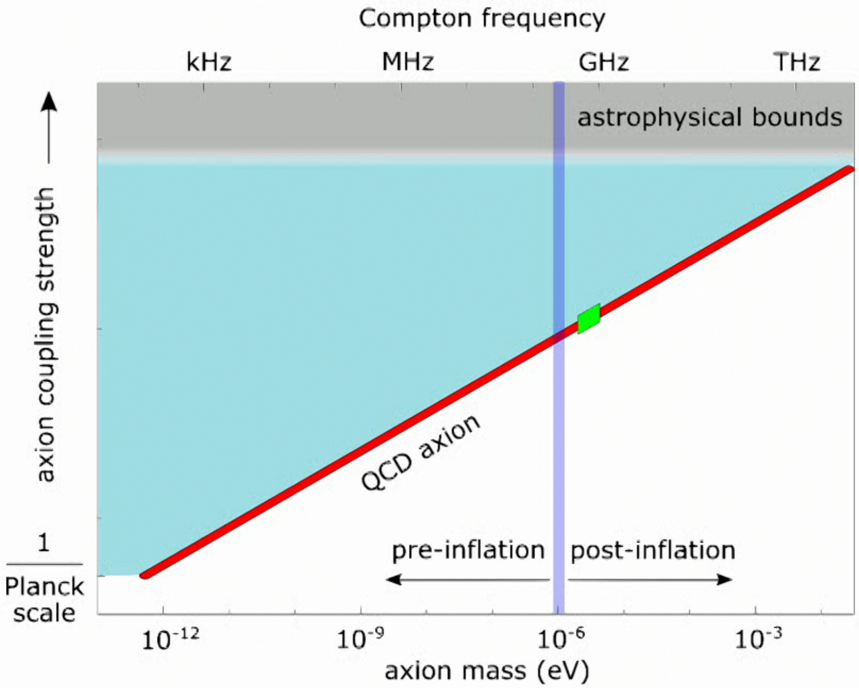

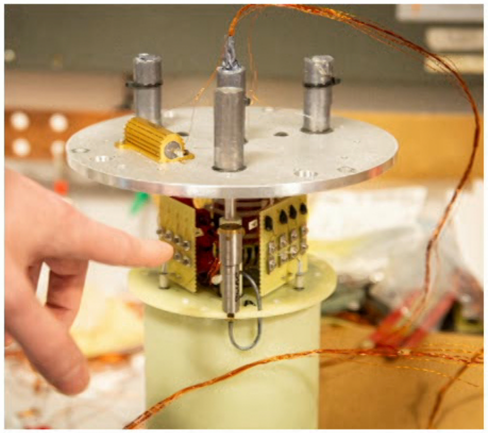

laboratory-scale experimental searches can explore the axion parameter space

[*Science* **357**, 990 (2017)]

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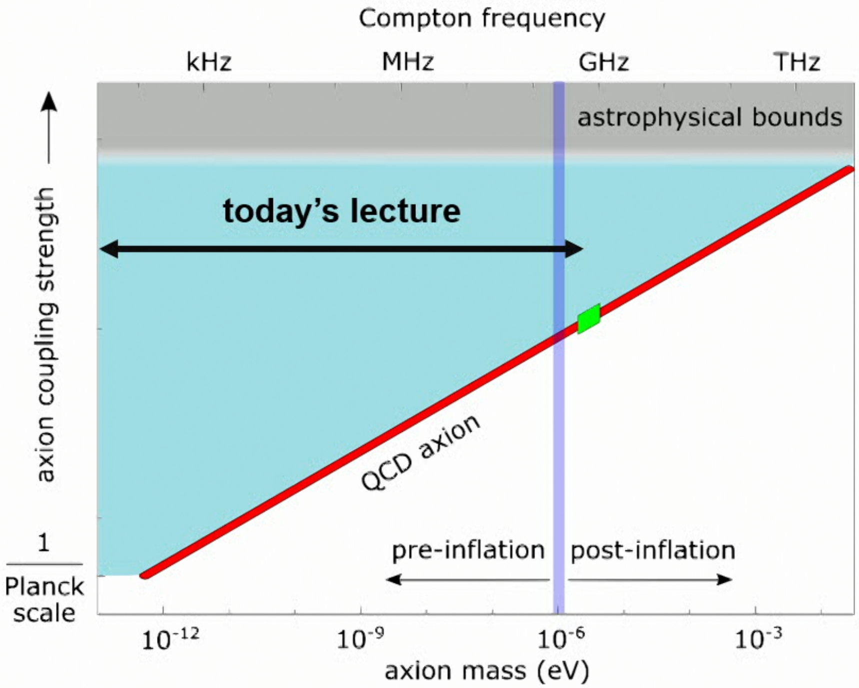

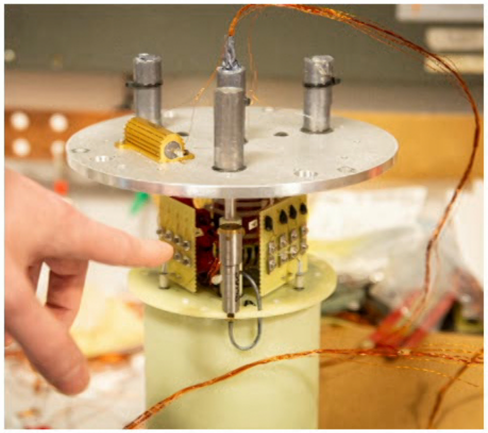

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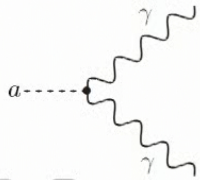
interaction with photons:

ALP field amplitude → $\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$ ← symmetry breaking scale



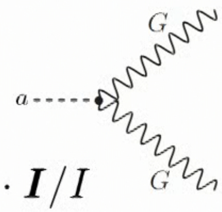
$$\mathcal{L}_{a\gamma\gamma} = g_{a\gamma\gamma} a \boldsymbol{E} \cdot \boldsymbol{B}$$

→ 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 (strong-CP) defines QCD axion:

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



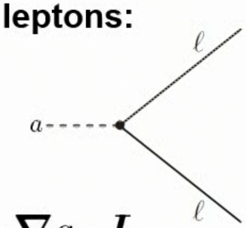
$$\mathcal{H}_{\mathrm{EDM}} = g_d a \boldsymbol{E}^* \cdot \boldsymbol{I}/I$$

→ 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)]

Searches for electromagnetic interaction of axion-like dark matter

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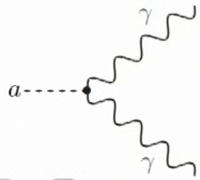

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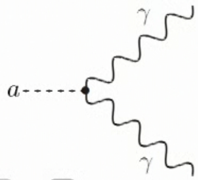

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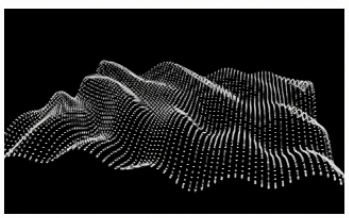
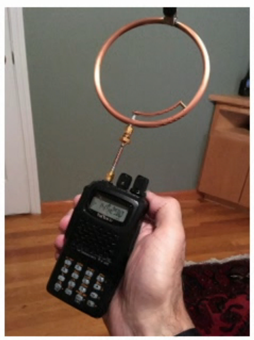


axion-like dark matter

+



sensor measures electromagnetic field

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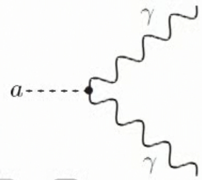

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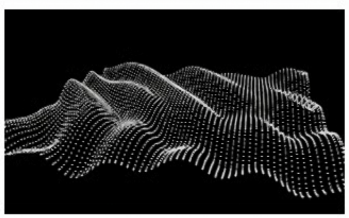
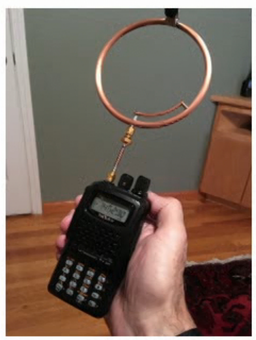


axion-like dark matter

➕



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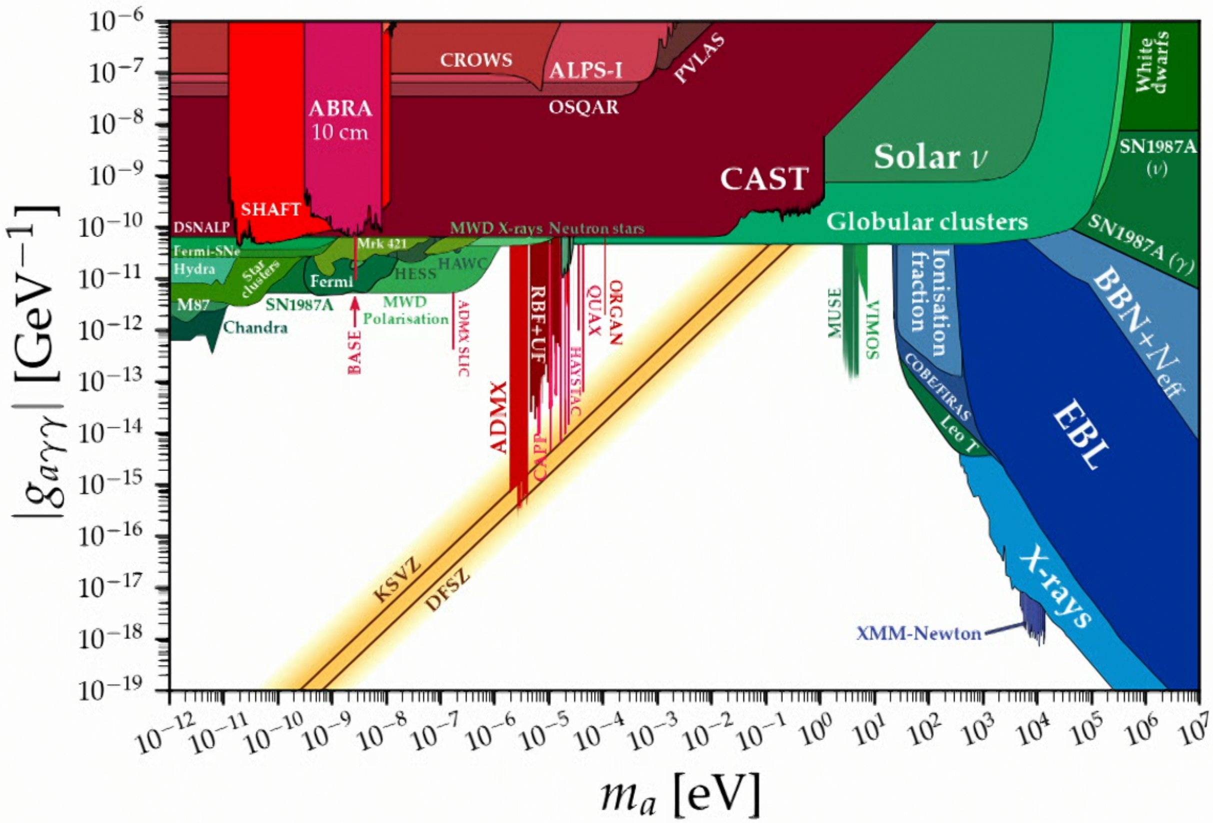

[https://cajohare.github.io/]

Lumped-element searches for axion-like dark matter

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goal: search for electromagnetic coupling of axion-like dark matter in in mass (frequency) range where experiment size << wavelength

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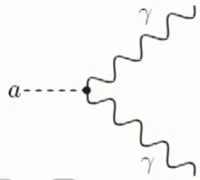

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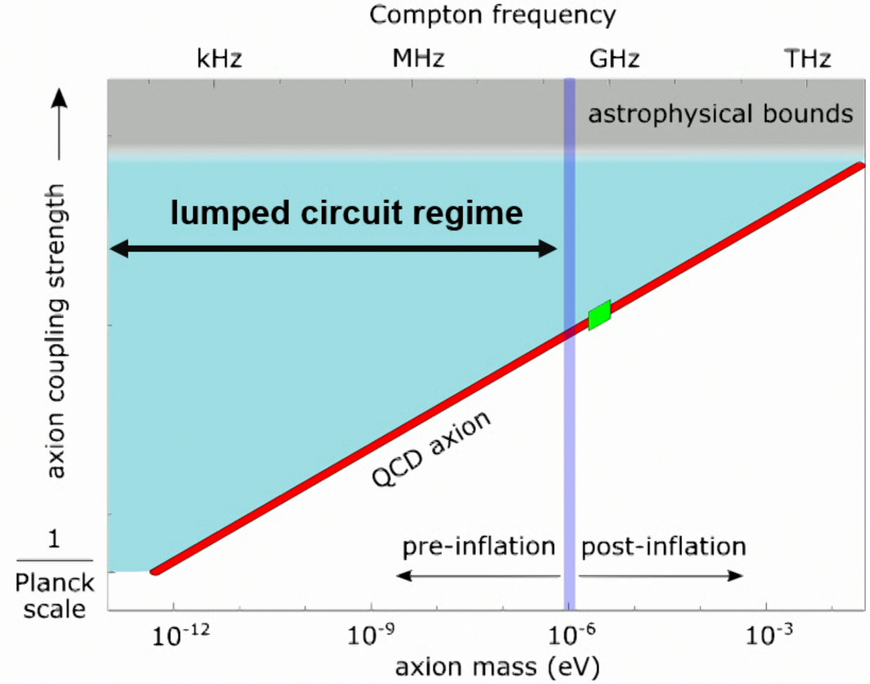

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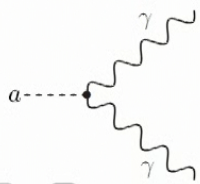

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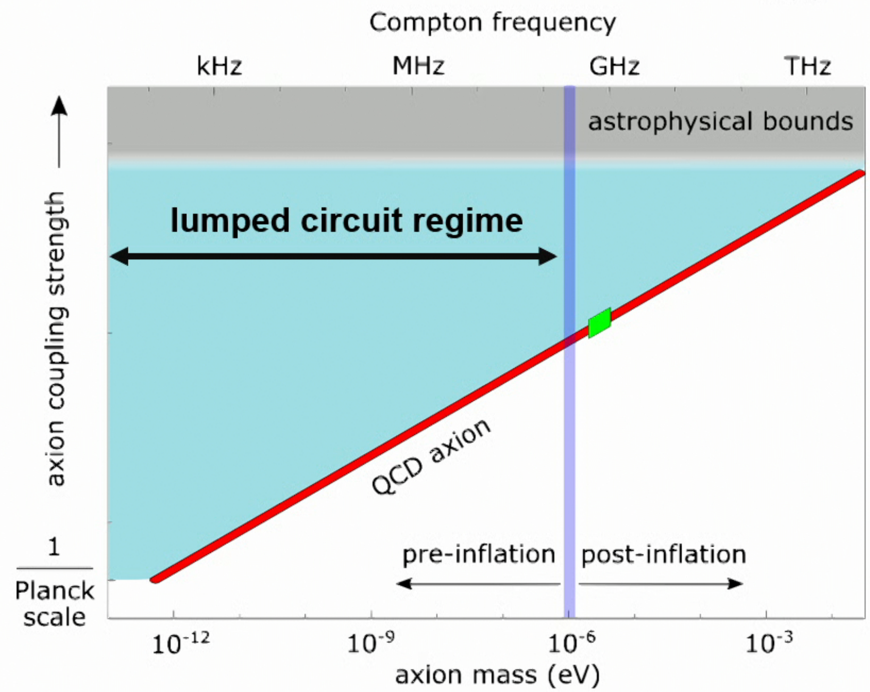

Maxwell's equations (SI units) ⇨

$$\nabla \cdot \boldsymbol{B} = 0 \qquad \nabla \cdot \boldsymbol{E} = \frac{\rho}{\epsilon_0} - c g_{a\gamma\gamma} \nabla a \cdot \boldsymbol{B}$$

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t} \qquad \nabla \times \boldsymbol{B} - \frac{1}{c^2}\frac{\partial^2 \boldsymbol{E}}{\partial t^2} = \mu_0 \boldsymbol{J} + \frac{g_{a\gamma\gamma}}{c}\left(\frac{\partial a}{\partial t}\boldsymbol{B} + \nabla a \times \boldsymbol{E}\right)$$

[arXiv: 1612.07057 (2016)]

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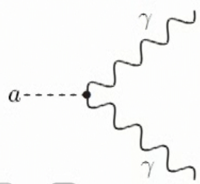

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→ ALP ↔ photon conversion in a magnetic field
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approach → additional term in Ampere's law

$$\boldsymbol{\nabla} \times \boldsymbol{H} = \boldsymbol{J}_f$$

[Phys. Rev. Lett. **112**, 131301 (2014)]
[Phys. Rev. D **92**, 075012 (2015)]
[Phys. Rev. Lett. **117**, 141801 (2016)]
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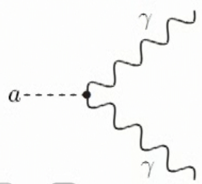

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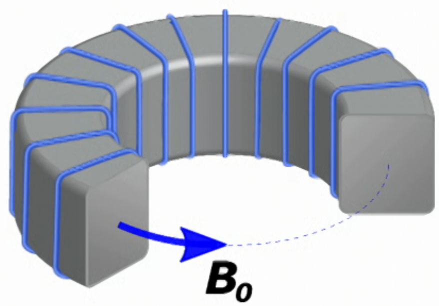
azimuthal static magnetic field B_0



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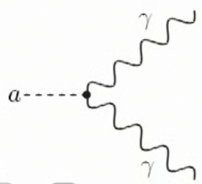

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azimuthal static magnetic field B_0

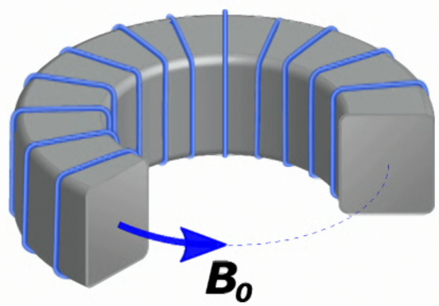
+

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

⇩

azimuthal effective current

$$\boldsymbol{J}^* = \frac{g_{a\gamma\gamma}}{\mu_0 c}\frac{\partial a}{\partial t}\boldsymbol{B}_0$$



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Lumped-element searches for axion-like dark matter

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goal: search for electromagnetic coupling of axion-like dark matter in in mass (frequency) range where experiment size << wavelength

interaction with photons:

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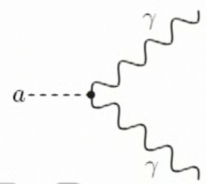

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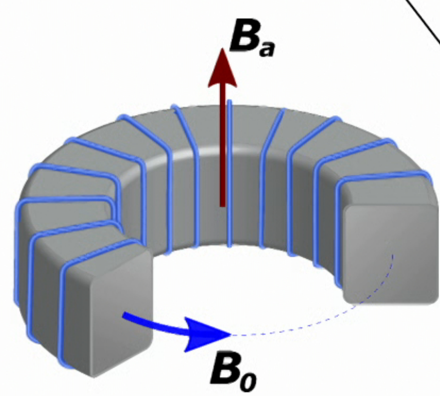

azimuthal static magnetic field B_0

+

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

⇩

azimuthal effective current

$$\boldsymbol{J}^* = \frac{g_{a\gamma\gamma}}{\mu_0 c} \frac{\partial a}{\partial t} \boldsymbol{B}_0$$

⇩

axial oscillating magnetic field B_a

[Phys. Rev. Lett. **112**, 131301 (2014)]
[Phys. Rev. D **92**, 075012 (2015)]
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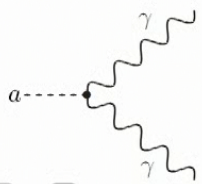

$$\mathcal{L}_{a\gamma\gamma} = g_{a\gamma\gamma} a \boldsymbol{E} \cdot \boldsymbol{B}$$

→ ALP ↔ photon conversion in a magnetic field
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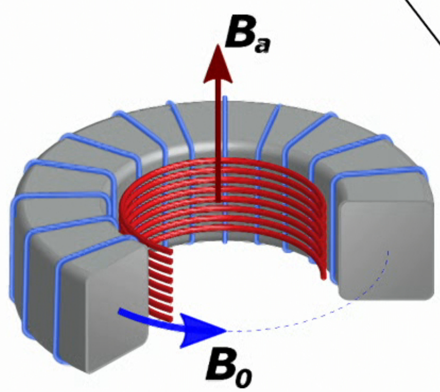
key experimental parameters:

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

approach → additional term in Ampere's law

$$\nabla \times \boldsymbol{H} = \boldsymbol{J}_f + \underbrace{\frac{g_{a\gamma\gamma}}{\mu_0 c} \frac{\partial a}{\partial t} \boldsymbol{B}}_{\boldsymbol{J}^*}$$



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azimuthal static magnetic field B_0

+

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

⇩

azimuthal effective current
$$\boldsymbol{J}^* = \frac{g_{a\gamma\gamma}}{\mu_0 c} \frac{\partial a}{\partial t} \boldsymbol{B}_0$$

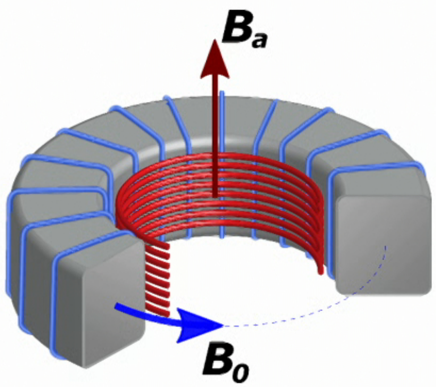
⇩

axial oscillating magnetic field B_a

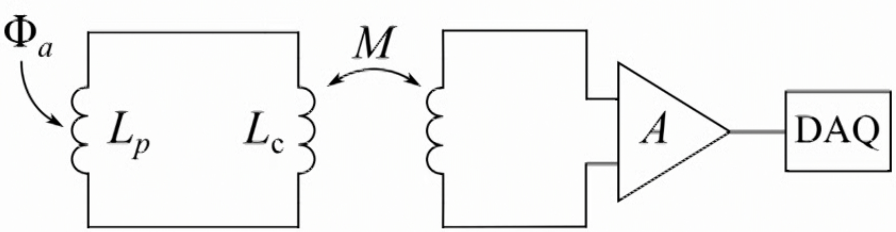
⇩

signal detected by sensor $\propto B_0$

Experimental setup, broadband searches: SHAFT, ABRACADABRA



$\Phi_a \rightarrow$ magnetic flux due to axion-like dark matter



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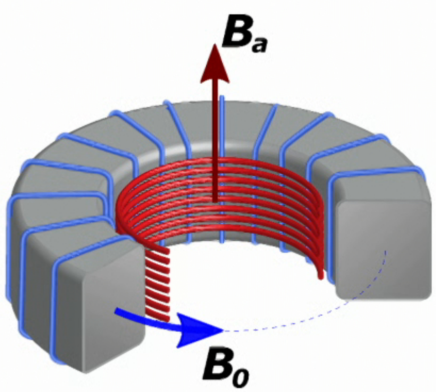

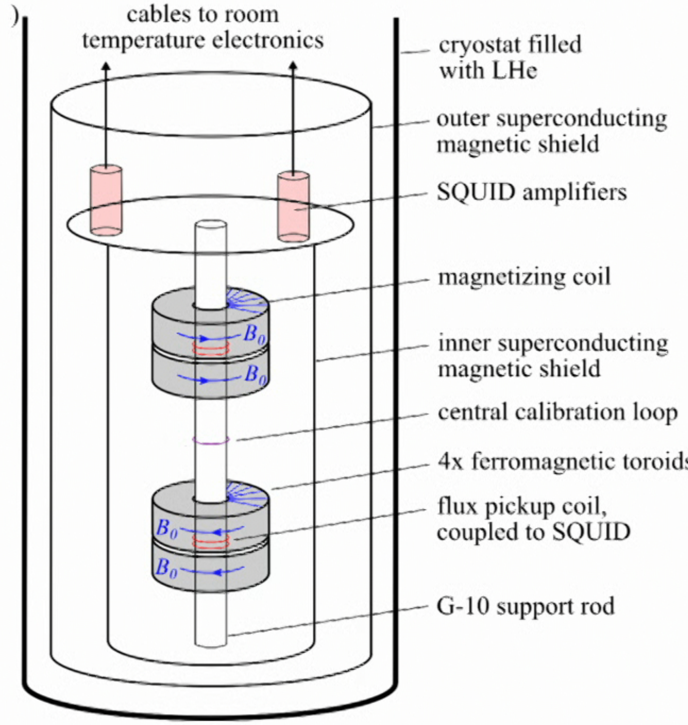

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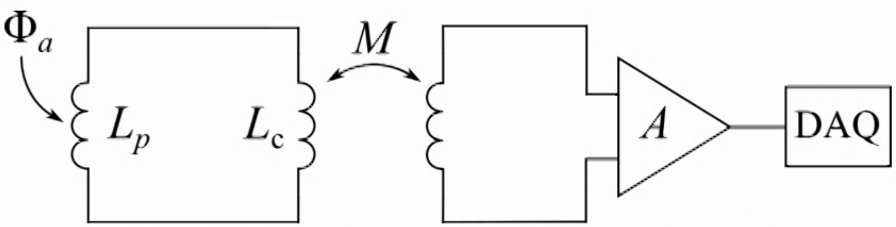

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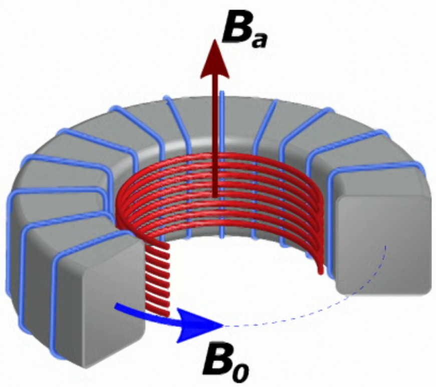
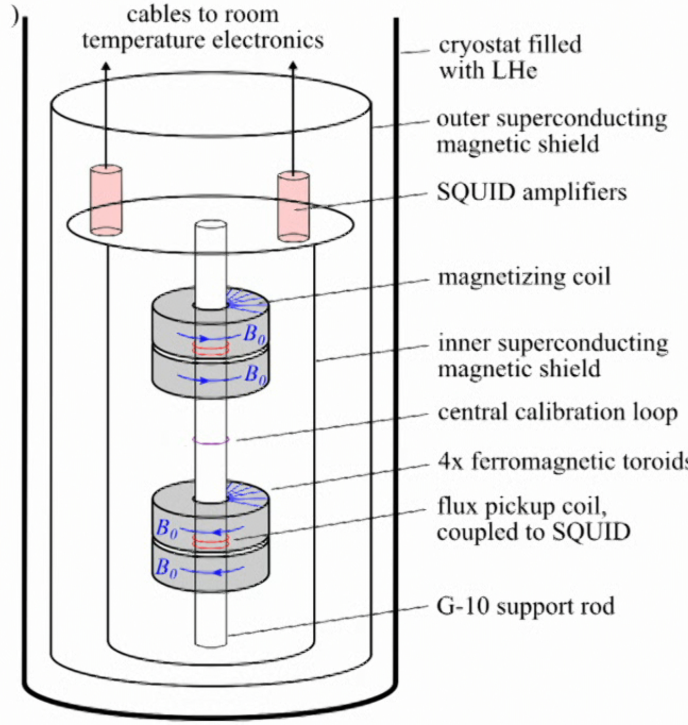
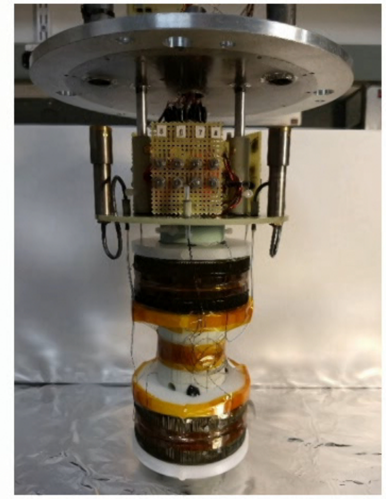
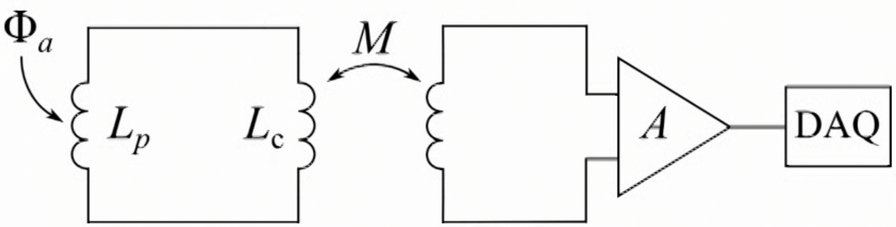


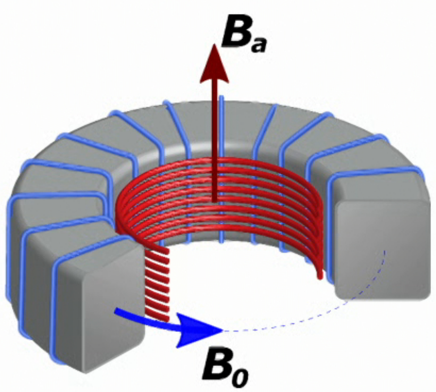




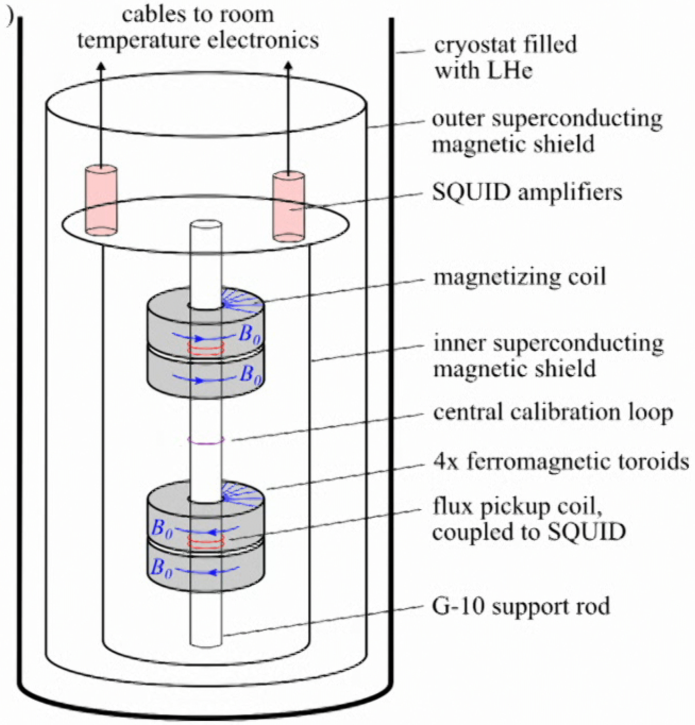
$\Phi_a \rightarrow$ magnetic flux due to axion-like dark matter

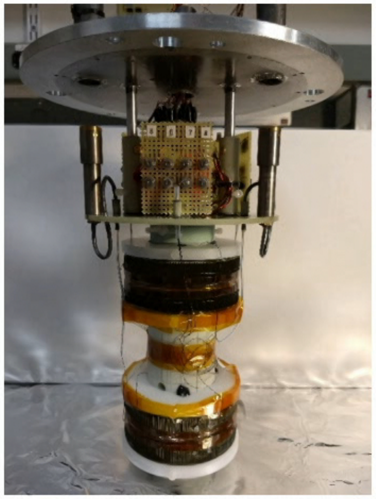


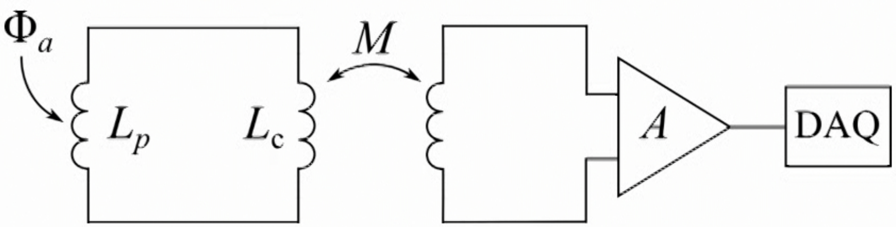
Experimental setup, broadband searches: SHAFT, ABRACADABRA



$\Phi_a \rightarrow$ magnetic flux due to axion-like dark matter







sensitivity limited by amplifier imprecision noise

[A.Gramolin et al., *Nature Physics* **17**, 79 (2021)]
[C. Salemi et al., Phys. Rev. Lett. **127**, 081801 (2021)]

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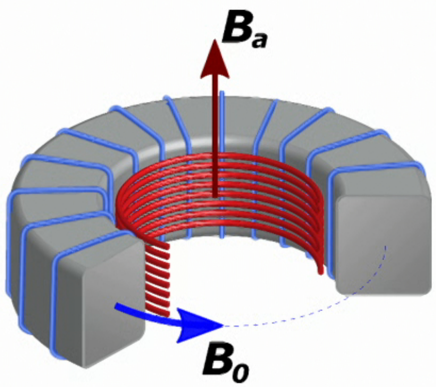

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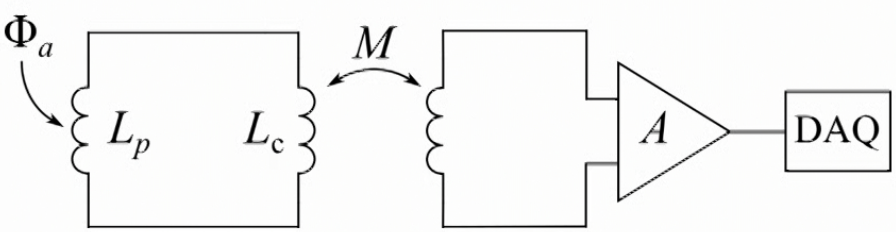

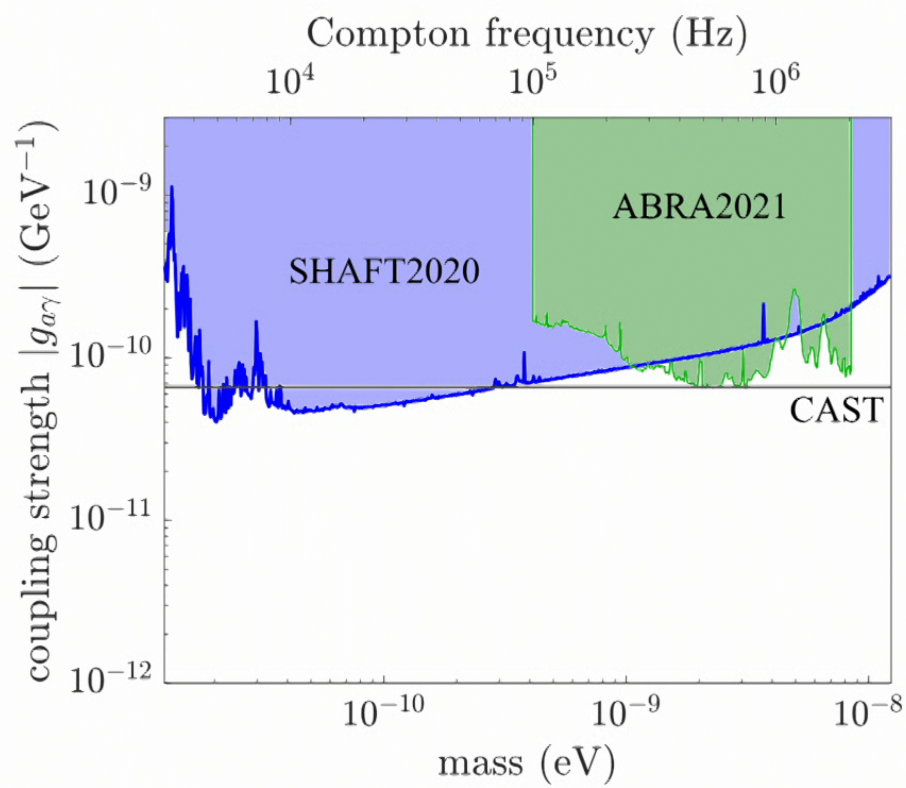

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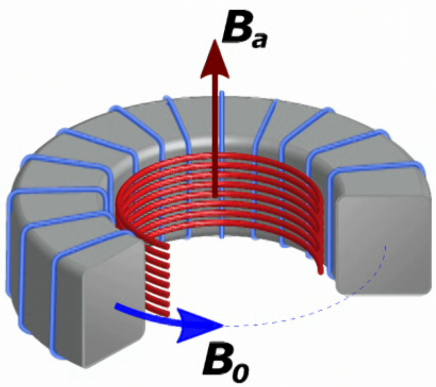

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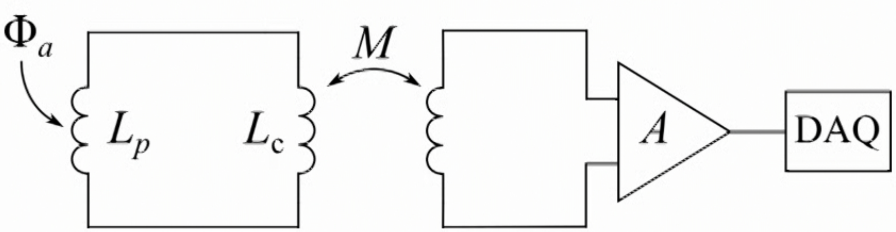

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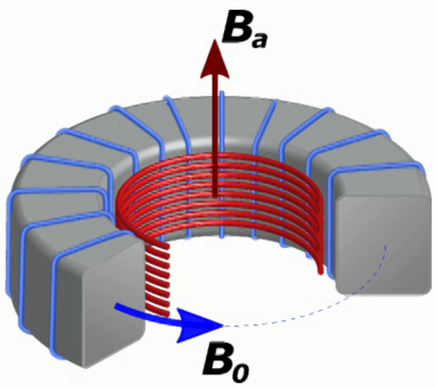

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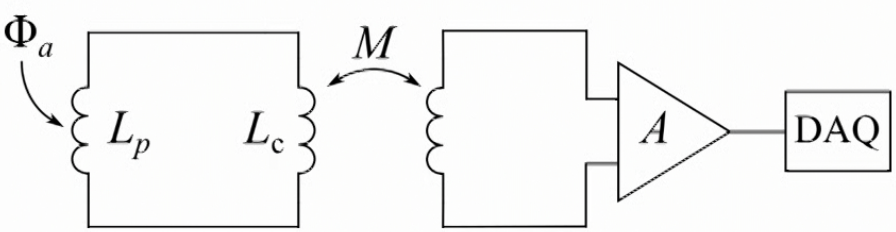

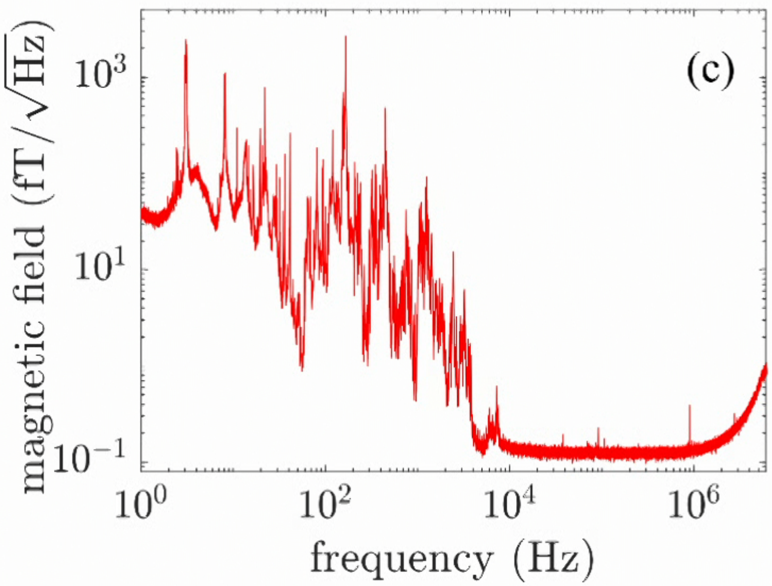

- magnetic field sensitivity $\rightarrow 150\,\mathrm{aT}/\sqrt{\mathrm{Hz}}$ ≈ **broadband record**

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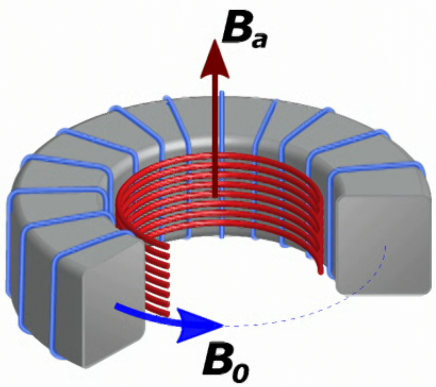

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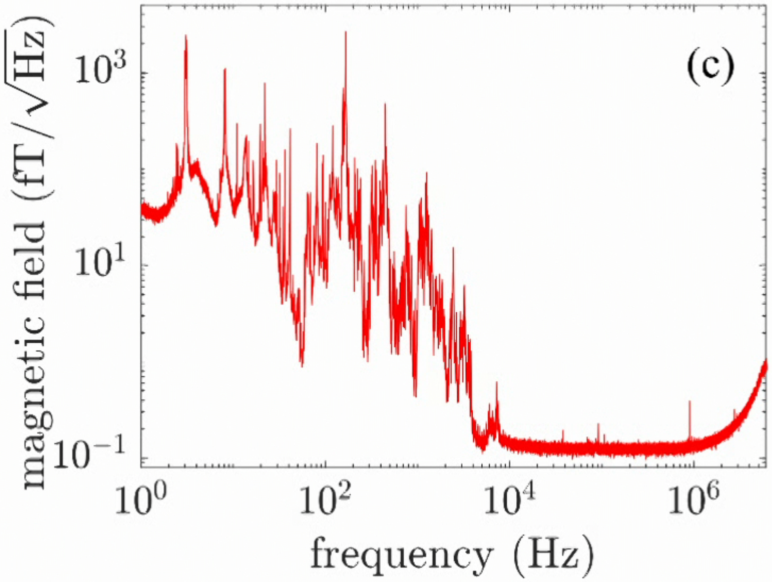

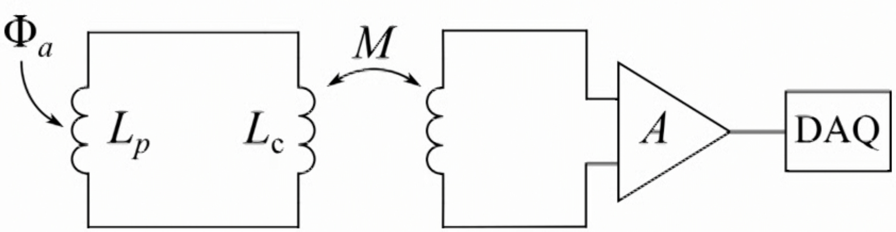

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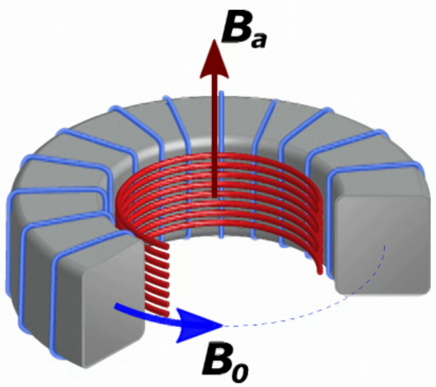
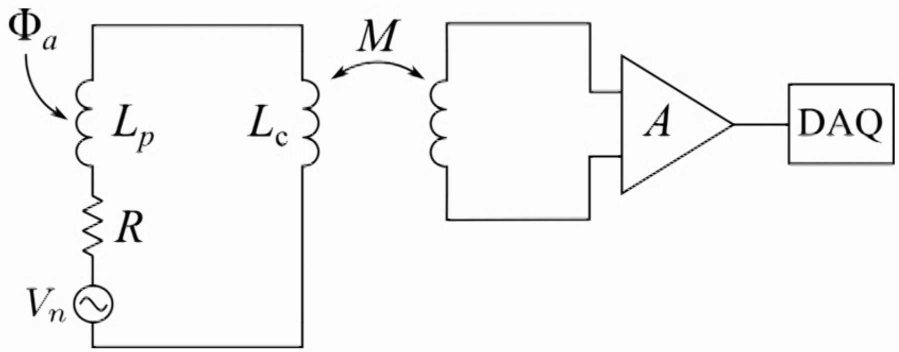
Fundamental sensitivity limit?





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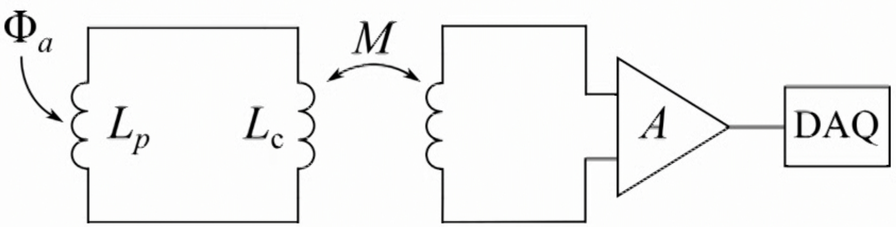

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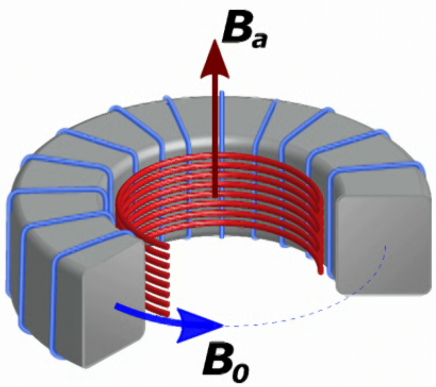

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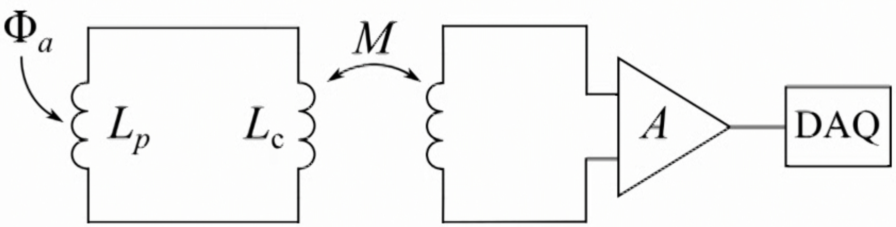
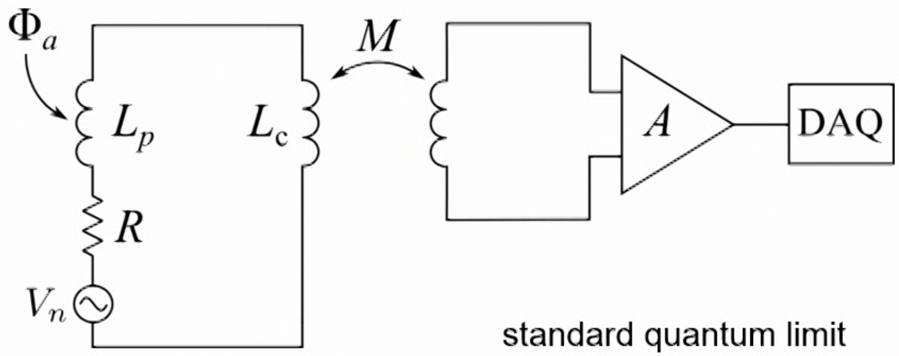




standard quantum limit (SQL)

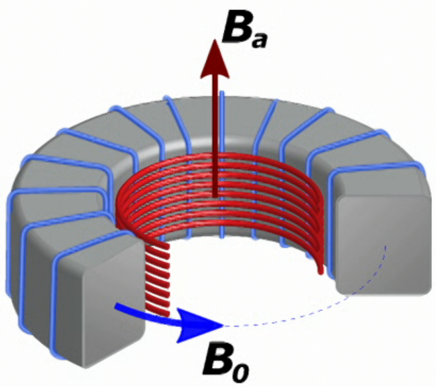
photon population: $N(\omega) = \frac{1}{e^{\hbar\omega/k_B T} - 1} + \frac{1}{2}$

in the lumped element regime $\hbar\omega \lesssim k_B T$

➡ sensitivity is limited by thermal noise

Experimental setup, resonant searches: DM radio

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



- V_n → thermal + quantum noise
- V_b → back-action noise
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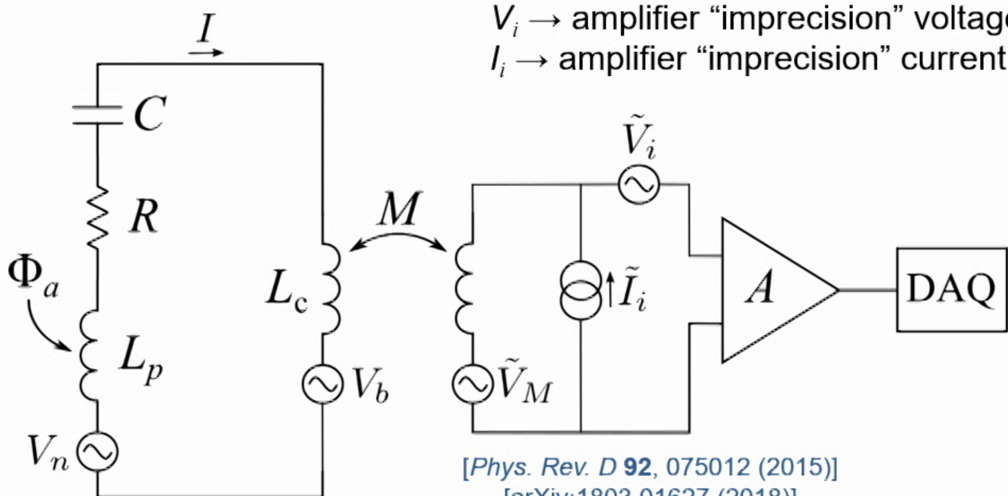

[*Phys. Rev. D* **92**, 075012 (2015)]
[arXiv:1803.01627 (2018)]

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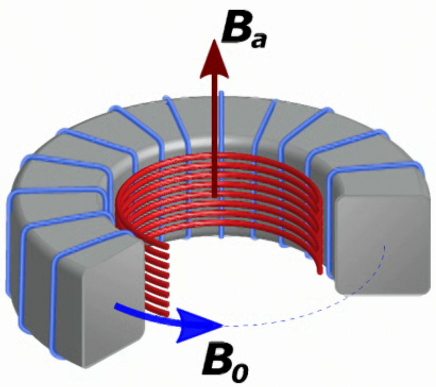

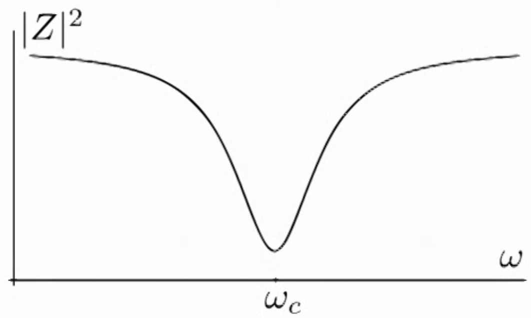

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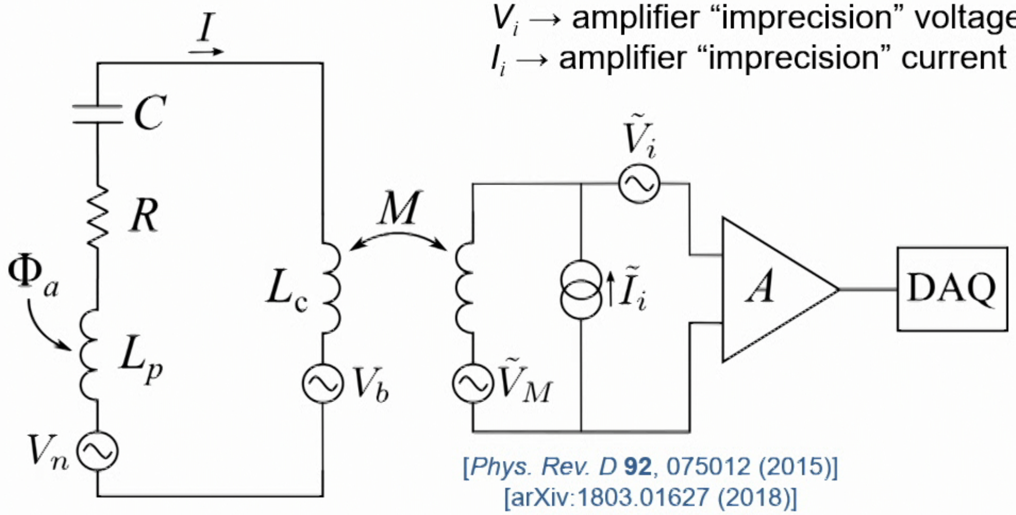

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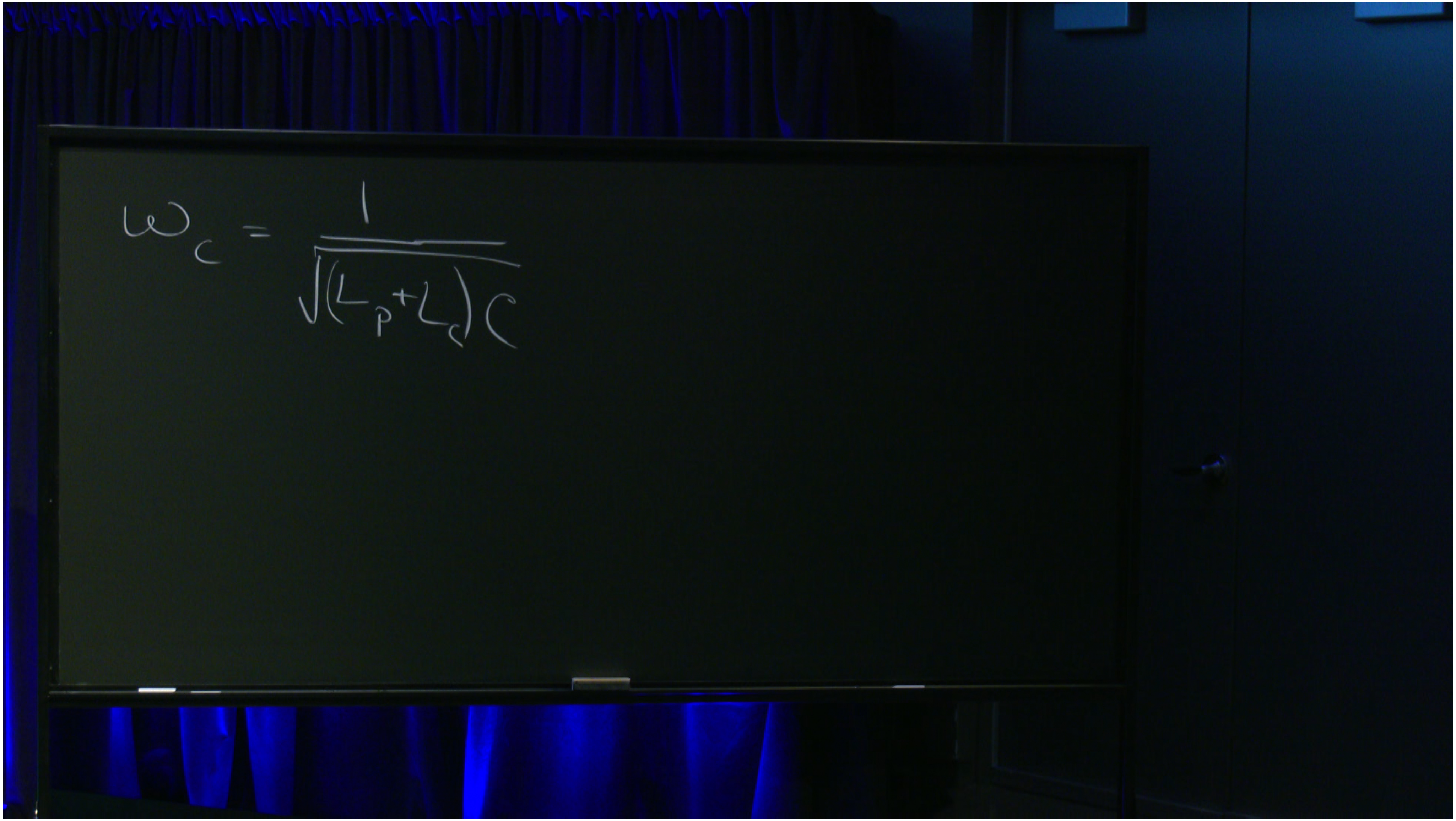
$\omega_c = \frac{1}{\sqrt{(L_p + L_c)C}}$

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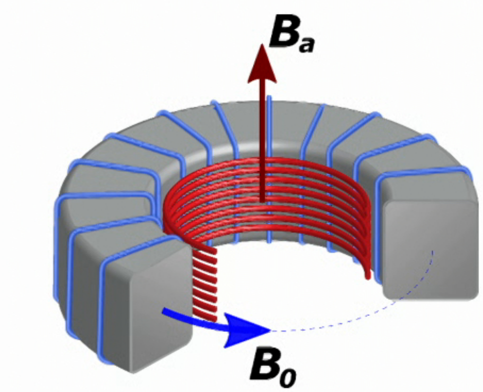

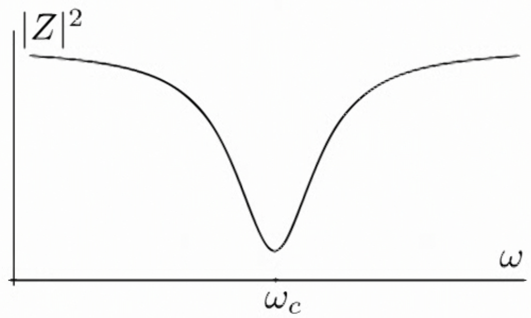

search for unknown axion mass (Compton frequency) is performed by scanning the resonance frequency

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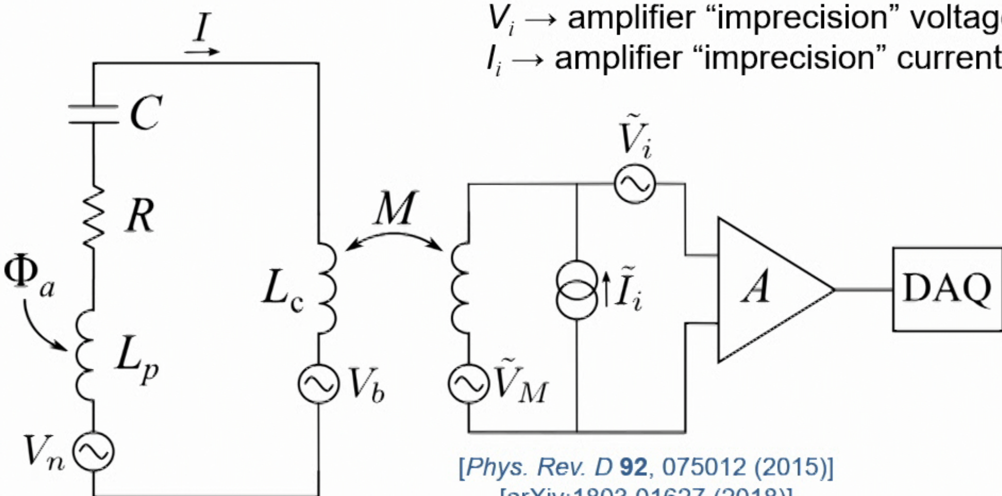

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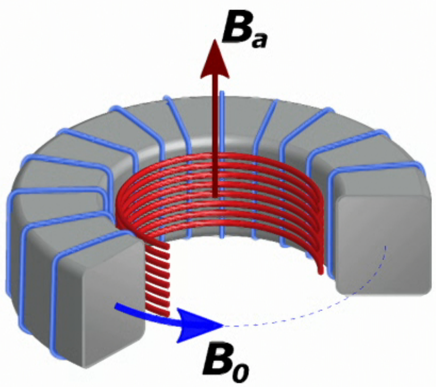

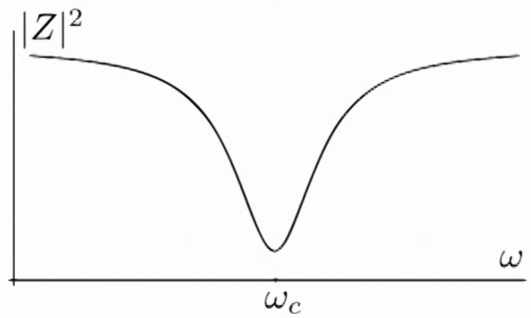

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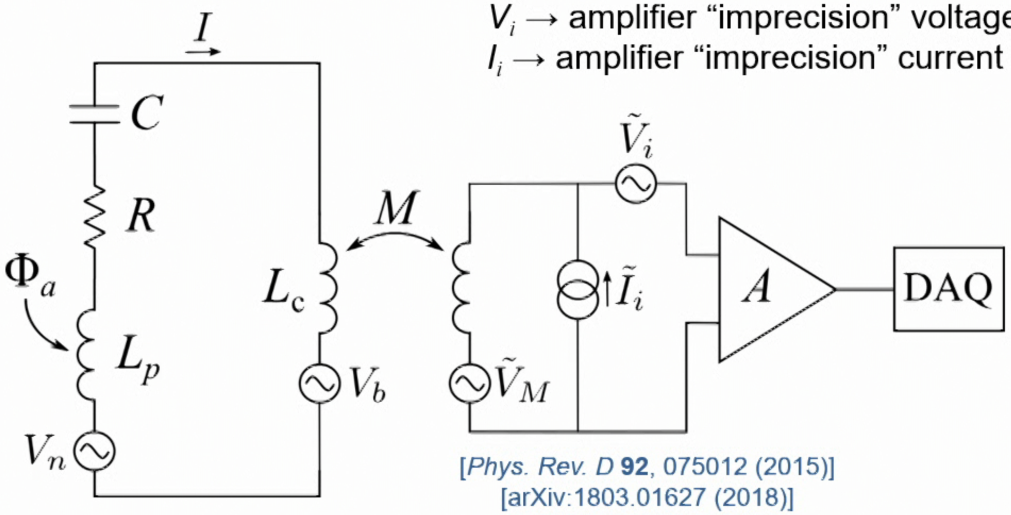

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this is what makes these searches hard: if we knew the axion Compton frequency, detecting its effects could become an undergraduate lab experiment

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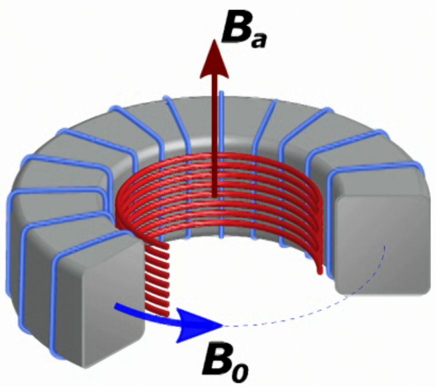

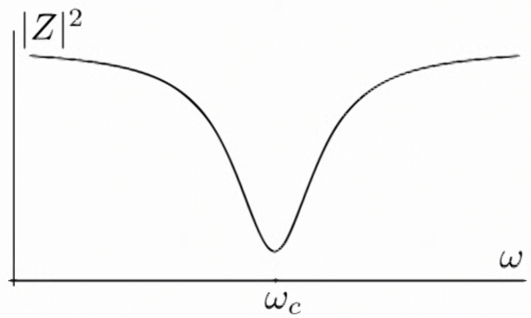

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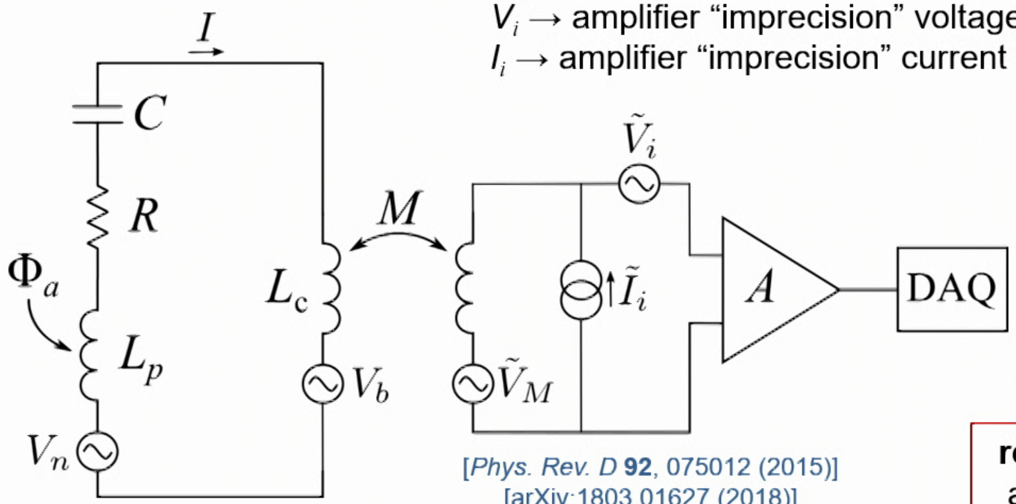
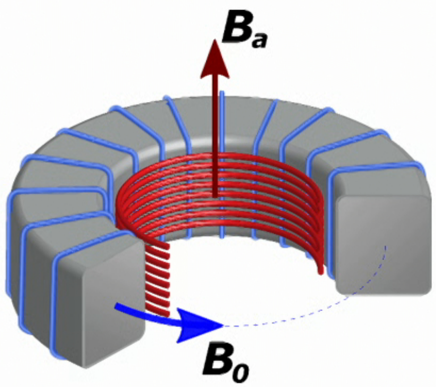
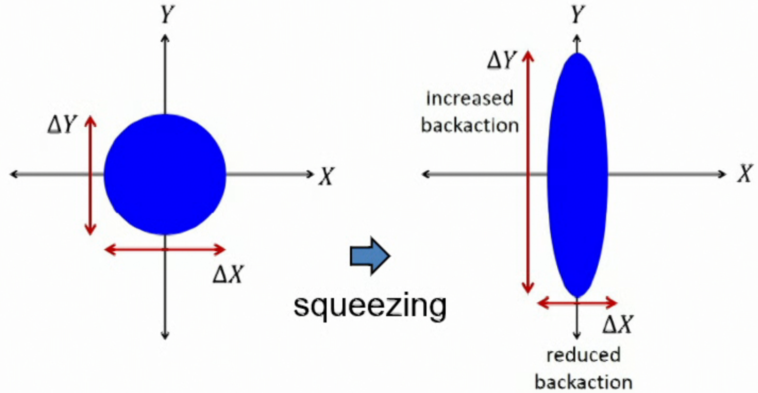


[*Phys. Rev. D* **92**, 075012 (2015)]
[arXiv:1803.01627 (2018)]

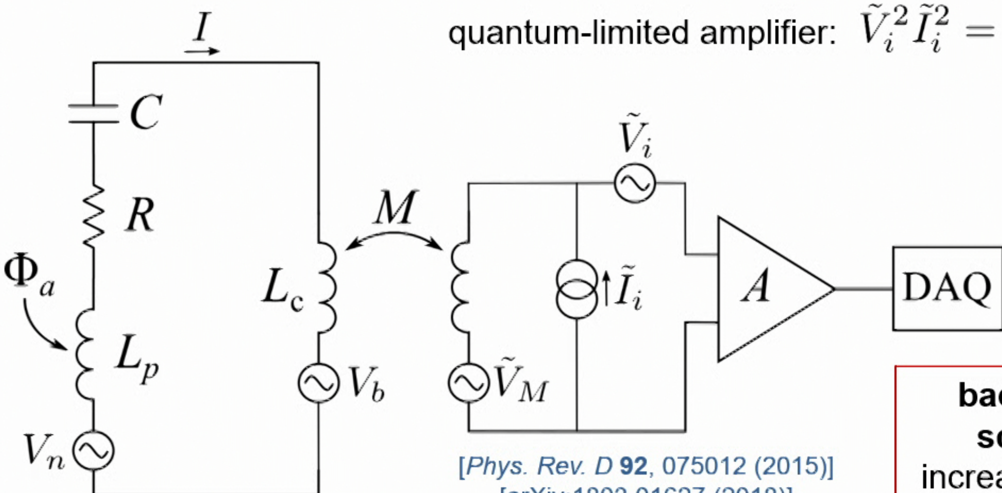
resonant pickup circuit → sensitivity is limited by thermal noise; amplifier imprecision and back-action limits sensitivity bandwidth

Quantizing the resonant LC circuit → back action evasion



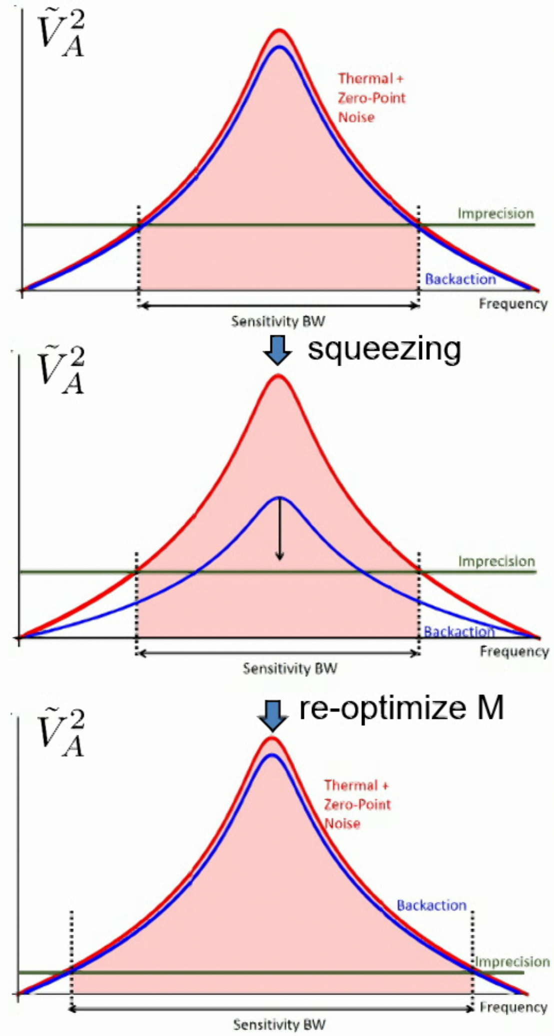


quantum-limited amplifier: $\tilde{V}_i^2 \tilde{I}_i^2 = (\hbar\omega)^2$



[*Phys. Rev. D* **92**, 075012 (2015)]
[arXiv:1803.01627 (2018)]

back action evasion via **squeezing** can further increase sensitivity bandwidth

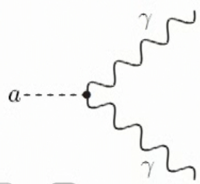


Cavity haloscope searches for axion-like dark matter

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

interaction with photons:

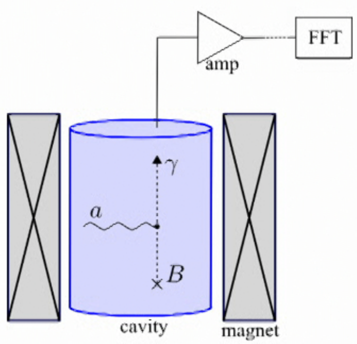
ALP field amplitude → $\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$ ← symmetry breaking scale

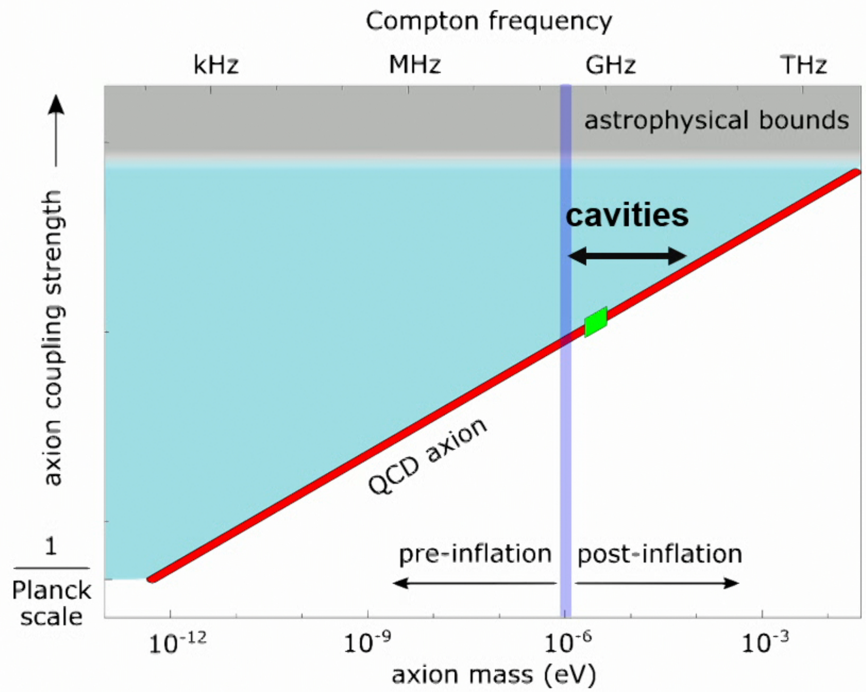


$$\mathcal{L}_{a\gamma\gamma} = g_{a\gamma\gamma} a \boldsymbol{E} \cdot \boldsymbol{B}$$

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

cavities: search for electromagnetic coupling of axion-like dark matter in in mass (frequency) range where experiment size ≈ wavelength





Konrad Lehnert

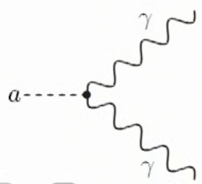
Counting single photons to search for axion-like dark matter

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

interaction with photons:

ALP field amplitude → $\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$

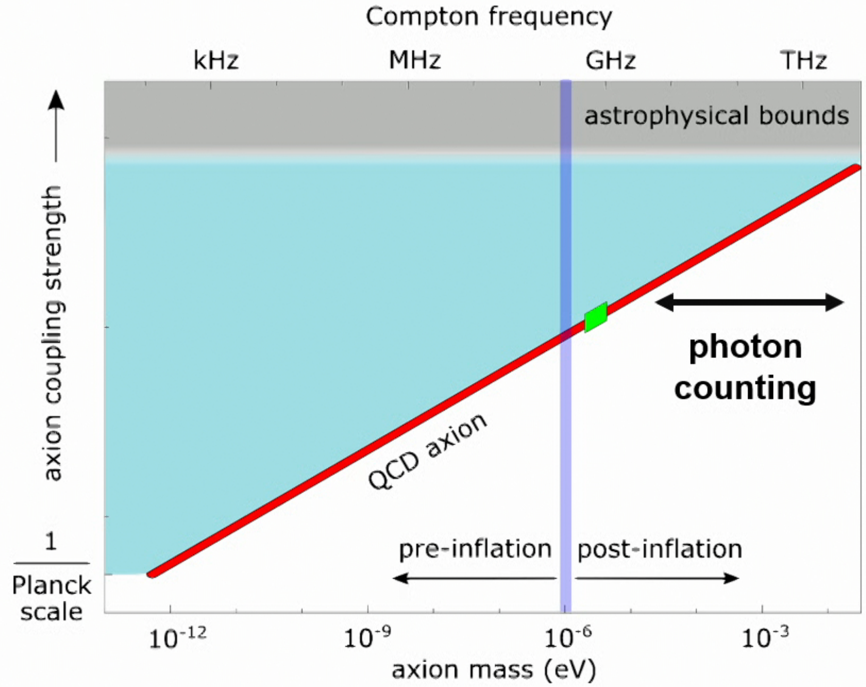
symmetry breaking scale →



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

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

at Compton frequencies ≥ 10 GHz, single photon counting (bolometric detection) becomes the favourable detection approach



[*Phys. Rev. D* **88**, 035020 (2013)]
[*Phys. Rev. Lett.* ***126***, 141302 (2021)]

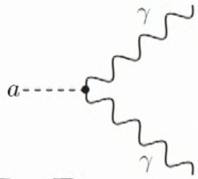
Sae Woo Nam

Summary: searches for axion-photon interaction

interaction with photons:

ALP field amplitude → $\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$

symmetry breaking scale ↗



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→ ALP ↔ photon conversion in a magnetic field
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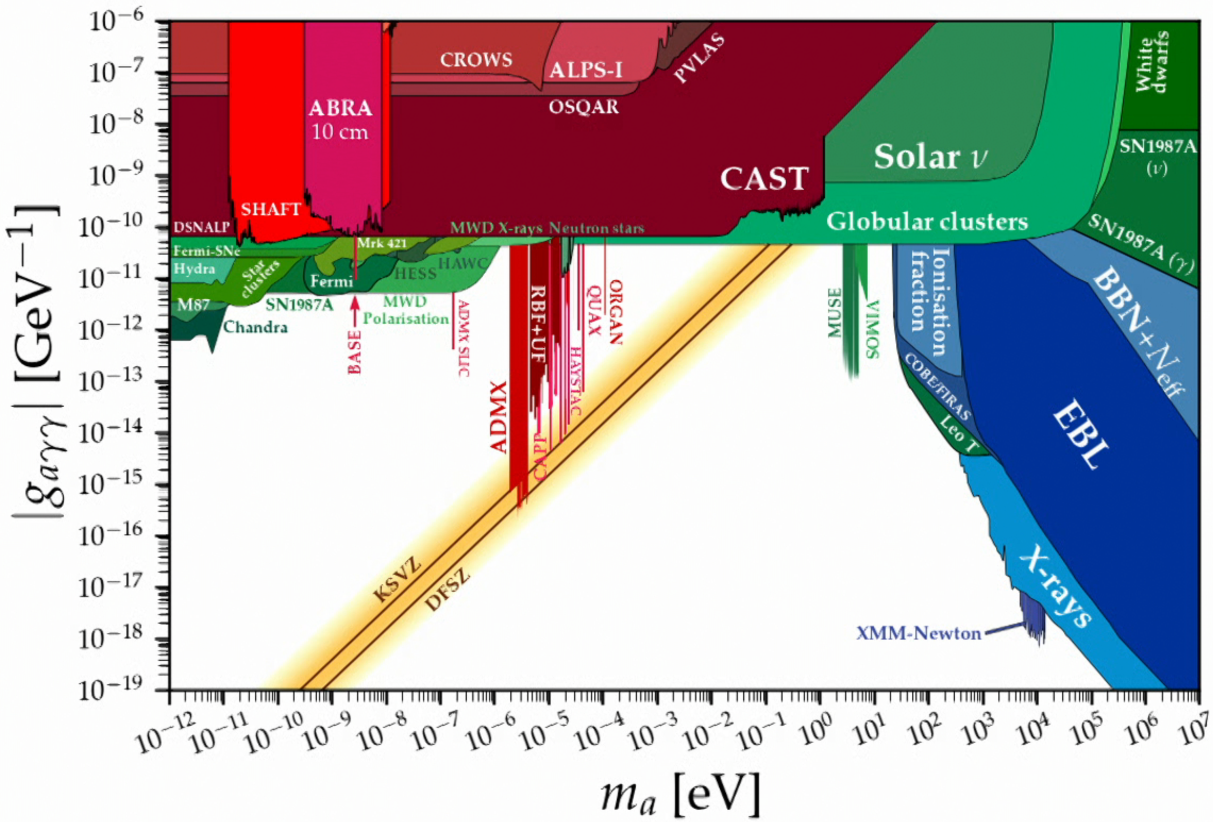
$$a(t) = a_0 \cos \omega_a t$$



key experimental parameters:

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

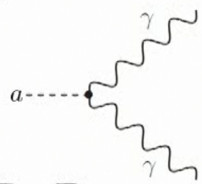
Summary: searches for axion-photon interaction

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

interaction with photons:

ALP field amplitude ⇢ $\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$

symmetry breaking scale ⇢ f_a



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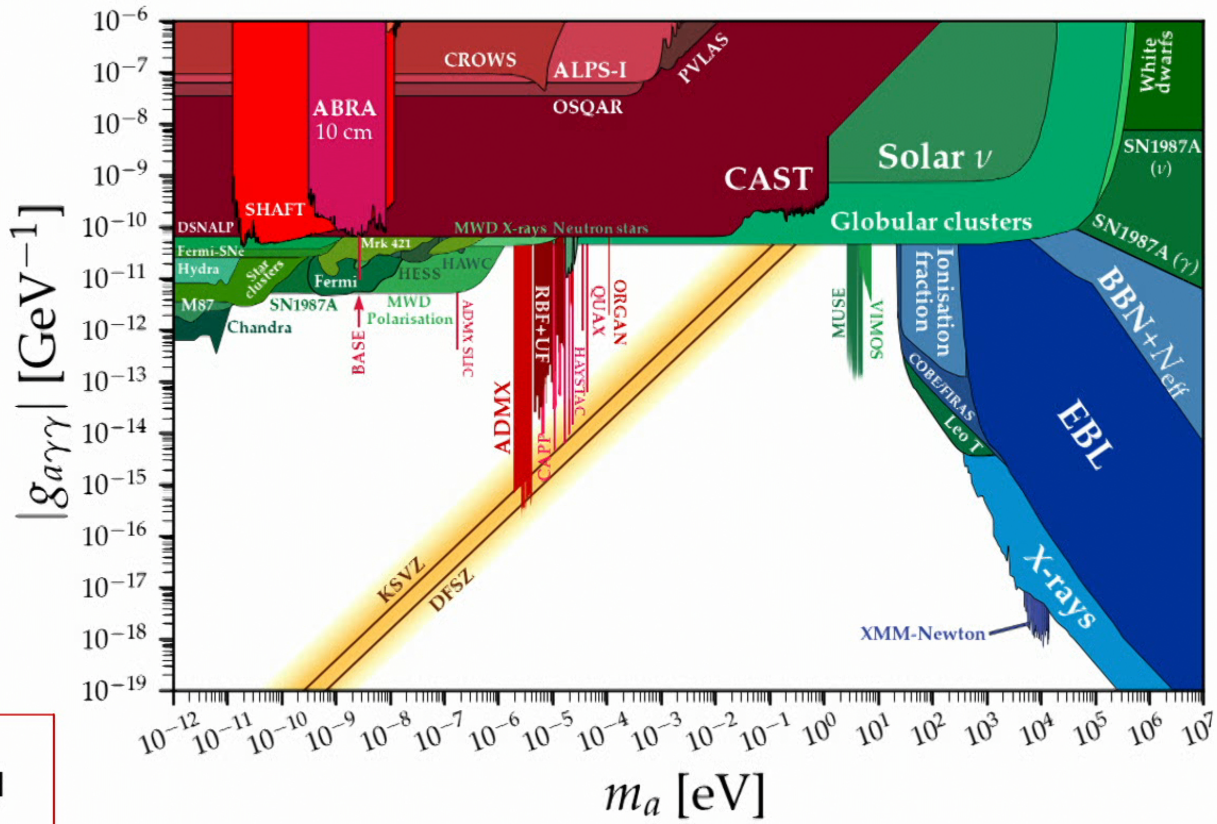


key experimental parameters:

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

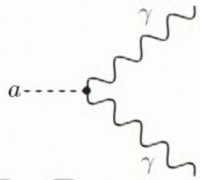
- resonant experiments are most sensitive
- on-resonance sensitivity is limited by thermal and quantum noise
- back-action evasion via squeezing can expand sensitive bandwidth, and thus speed up cavity scan

Tomorrow: searches for interactions of axions with spins

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:

interaction with photons:

ALP field amplitude → $\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$ ← symmetry breaking scale



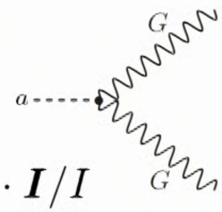
$\mathcal{L}_{a\gamma\gamma} = g_{a\gamma\gamma} a \boldsymbol{E} \cdot \boldsymbol{B}$

→ 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 (strong-CP) defines QCD axion:

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



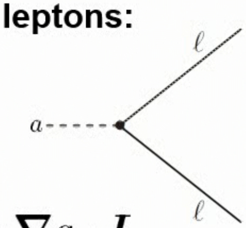
$\mathcal{H}_{\mathrm{EDM}} = g_d a \boldsymbol{E}^* \cdot \boldsymbol{I}/I$

→ 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)]