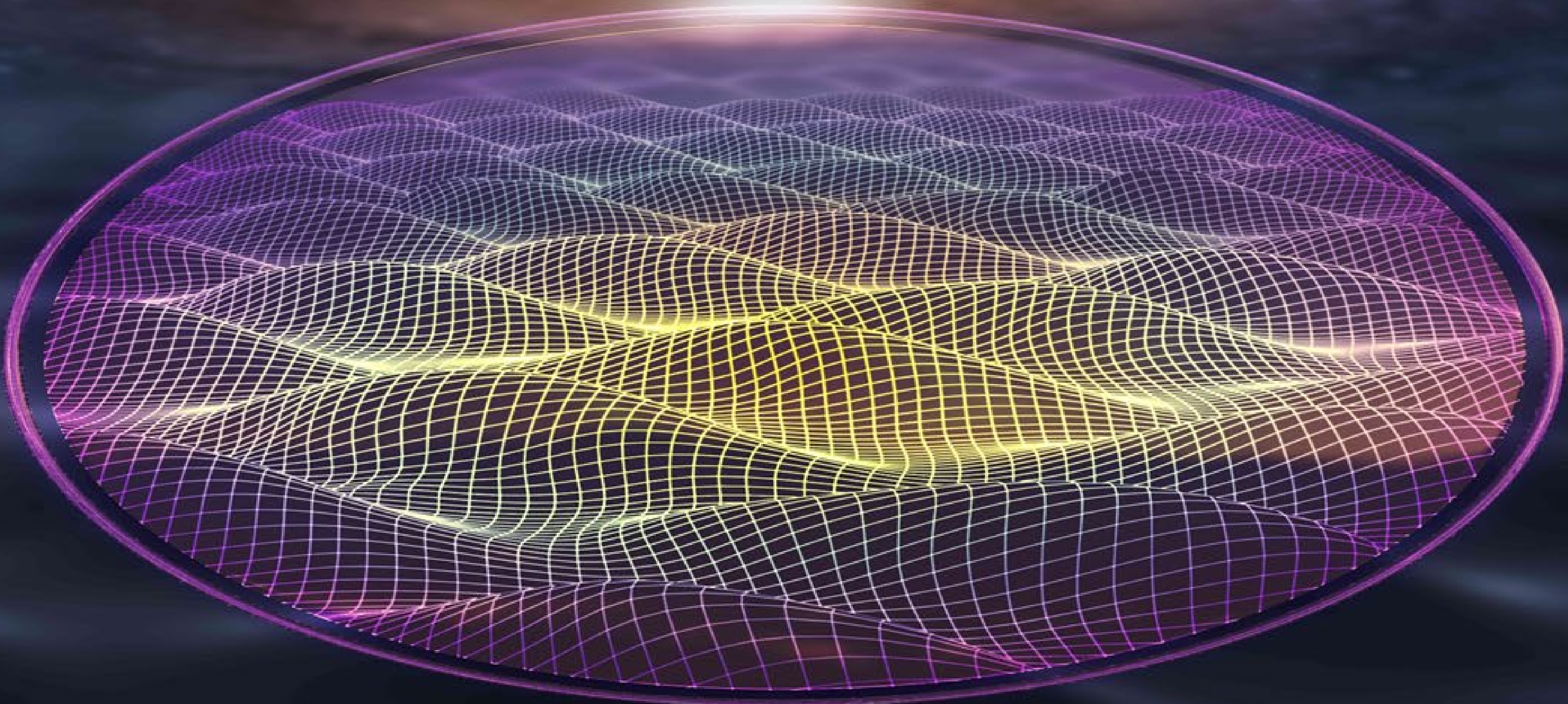
Quantum sensing and dark matter searches

Alex Sushkov

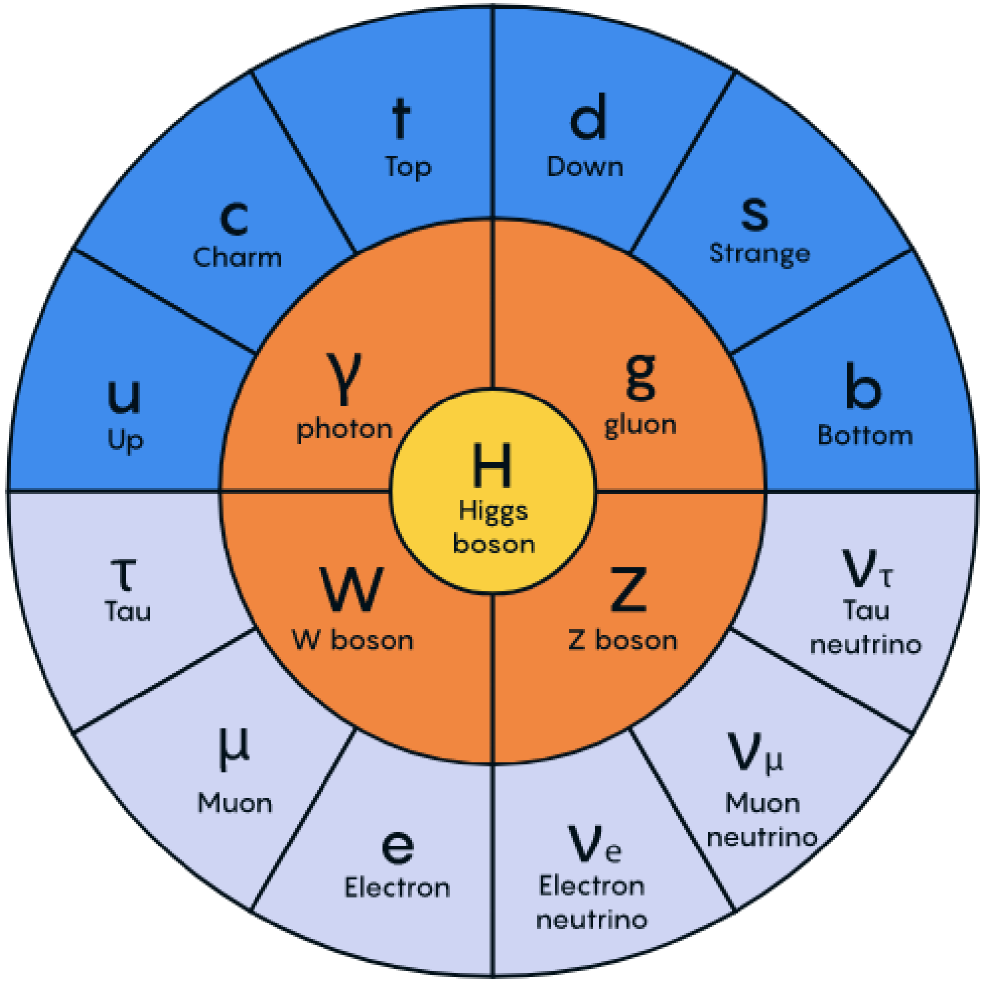


BOSTON UNIVERSITY

Main points

- Introduction: quantum sensing, dark matter
- Lecture 1: quantum approaches to searching for the electromagnetic interaction of axion-like dark matter
- Lecture 2: quantum approaches to searching for the interaction of axion-like dark matter with nuclear spins

The standard model



● QUARKS ○ LEPTONS ● GAUGE BOSONS ● HIGGS BOSON

DARK MATTER

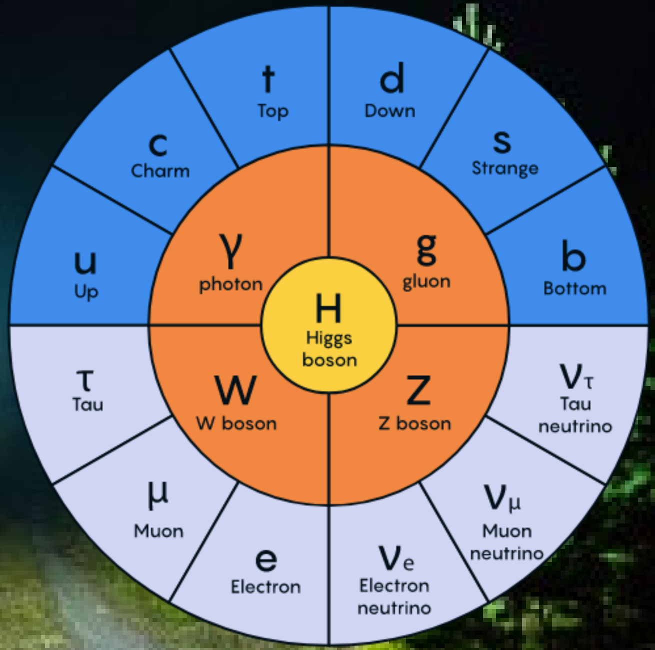
STRONG-CP PROBLEM

HIERARCHY PROBLEM

COSMIC INFLATION

BLACK HOLE INFORMATION PROBLEM

QUANTUM GRAVITY

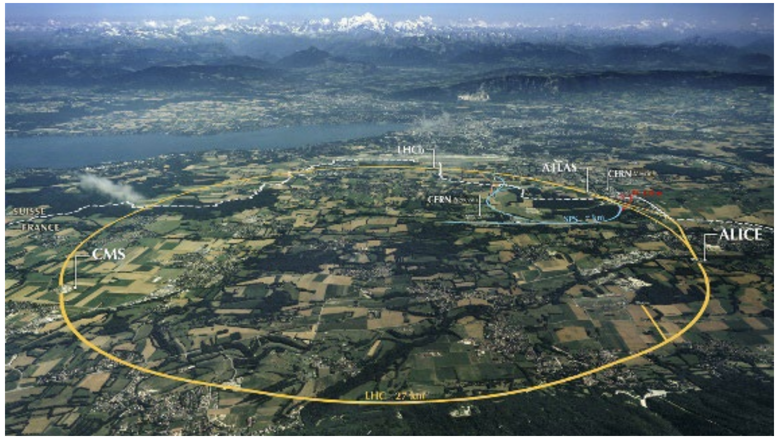


NEUTRINO MASS

DARK ENERGY

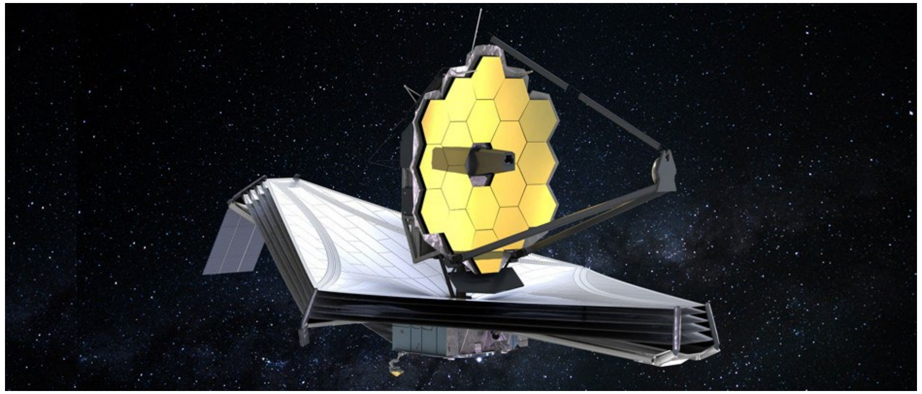
The tools

particle accelerators



terrestrial telescopes

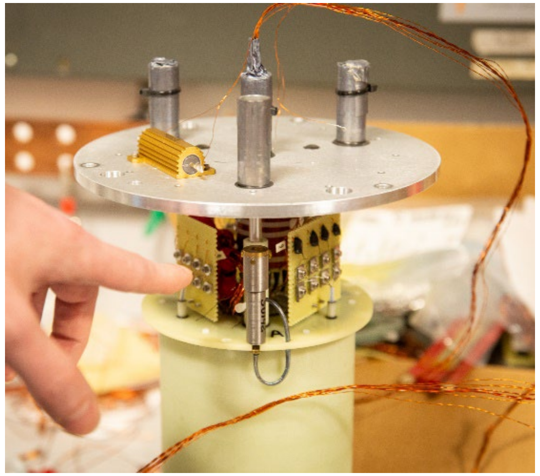
space telescopes



rare event detectors (eg, WIMPs)

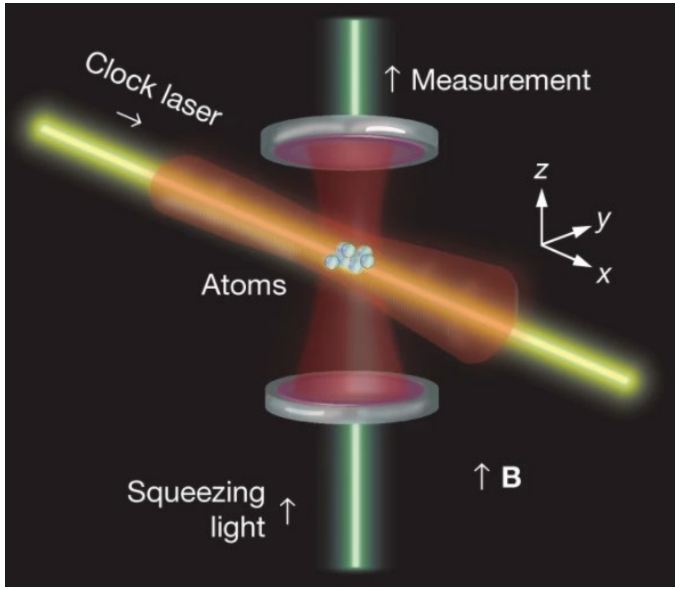
gravitational wave observatories

precision lab-scale experiments



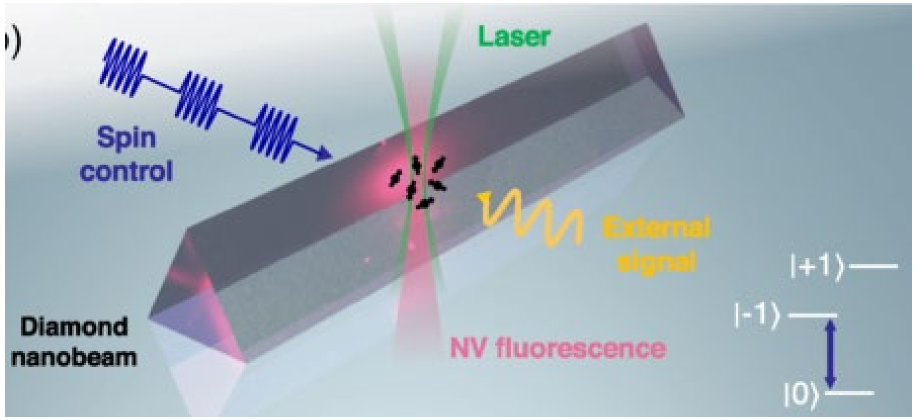
Precision measurements, quantum metrology and sensing

entanglement-enhanced atomic sensors



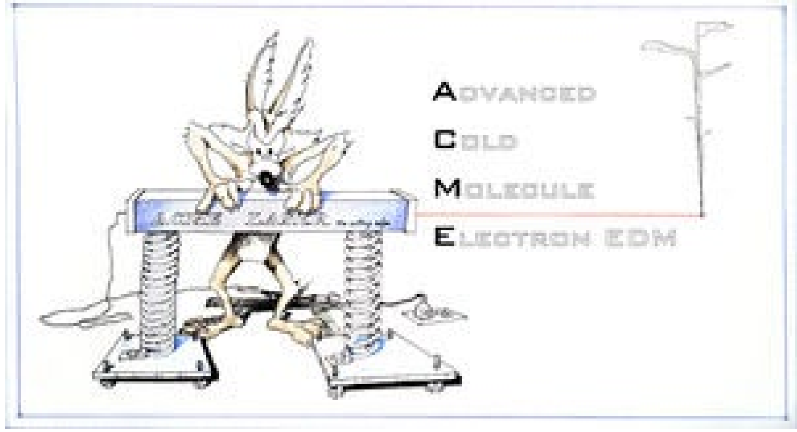
[Nature **588**, 414 (2020)]
[arXiv:2106.03754 (2021)]

NV centers in diamond



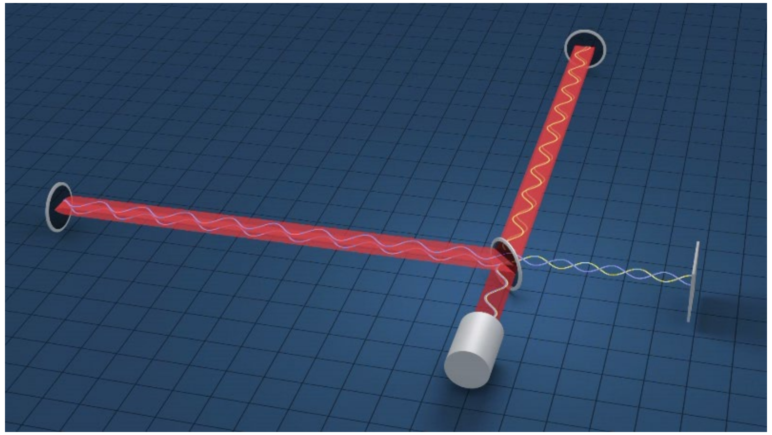
[PRX **10**, 031003 (2020)]

precisions measurements with molecules



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

interferometry



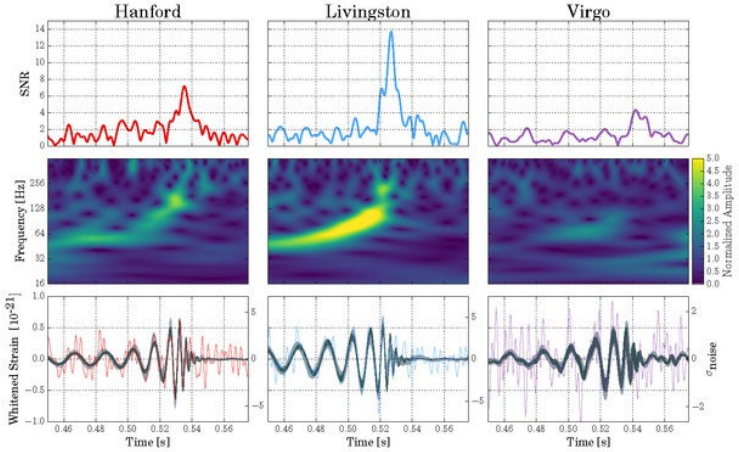
[Phys. Rev. Lett. **123**, 231107 (2019)]
[Phys. Rev. Lett. **124**, 171102 (2020)]

quantum sensing review:

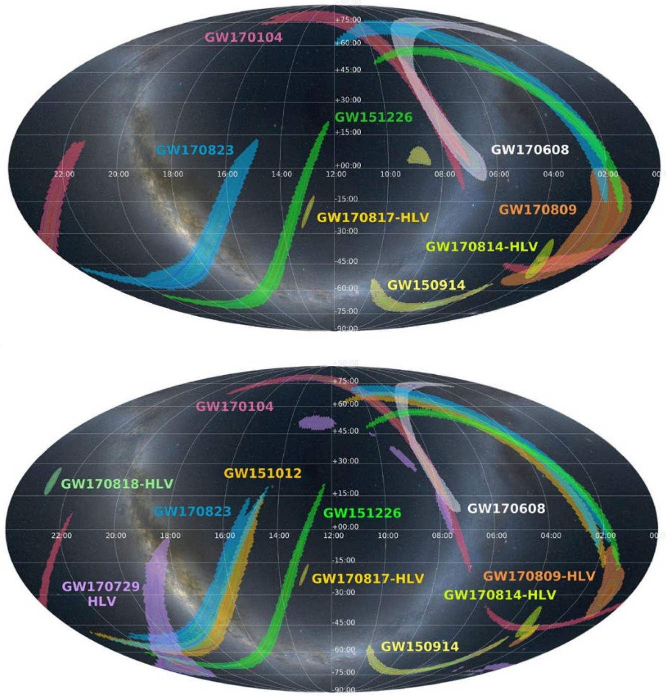
[*Rev. Mod. Phys.* **89**, 035002 (2017)]

LIGO: an inspiration for quantum metrology

first gravitational wave detection
(GW150914, 2015)

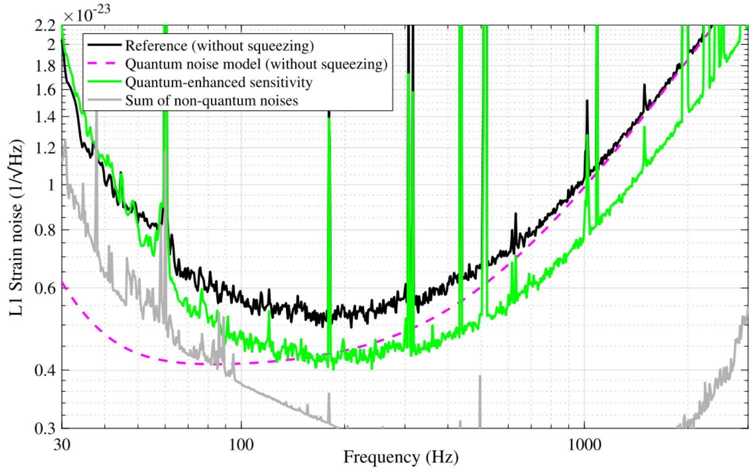


GW events detected in O1 and O2



[Phys. Rev. Lett. **123**, 231107 (2019)]
[Phys. Rev. Lett. **124**, 171102 (2020)]
[Liv. Rev. Rel. **23**, 1 (2020)]

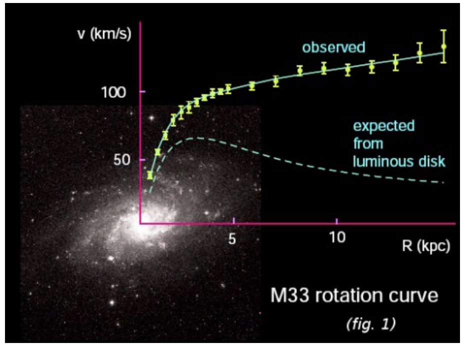
added a squeezed vacuum
source for O3 run (2019-2020)

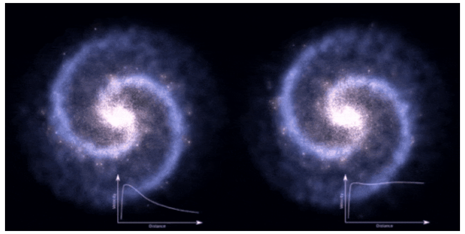


- extended detection range by ≈ 15%
- increased detection rate by ≈ 45%

The dark matter problem

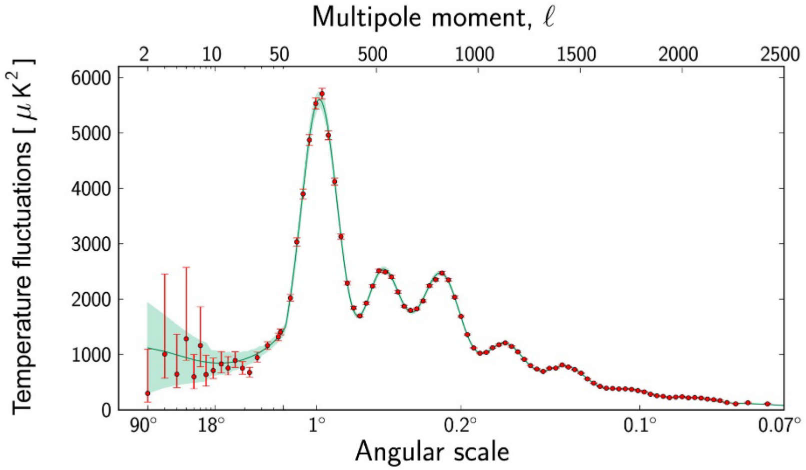
galaxy rotation curves

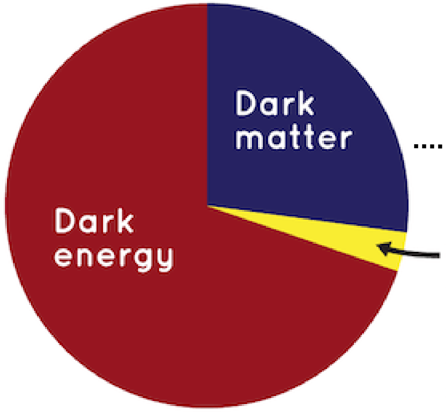




+ many others

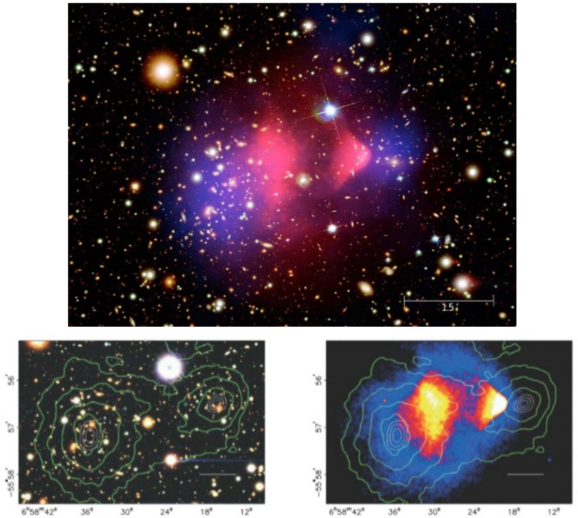
CMB angular power spectrum





The matter we understand. All the planets, comets, stars, galaxies, black holes, and more.

galaxy clusters: Bullet cluster



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

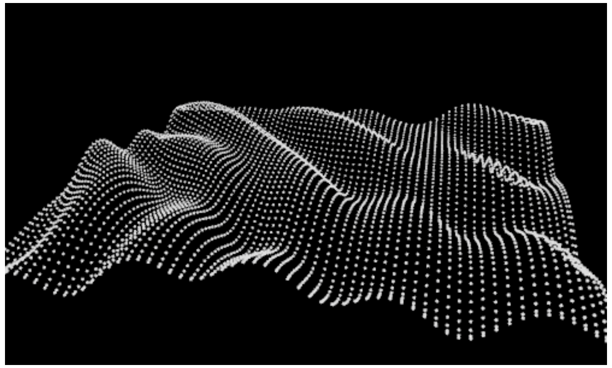
local dark matter energy density: $\rho_{\rm DM} \approx 0.4\,{\rm GeV/cm^3}$

What is dark matter?

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

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

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



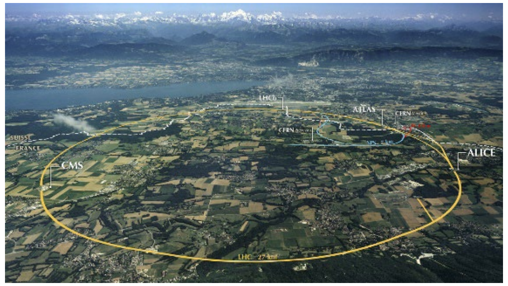
wave-like dark matter (eg: axions)
mass << eV

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

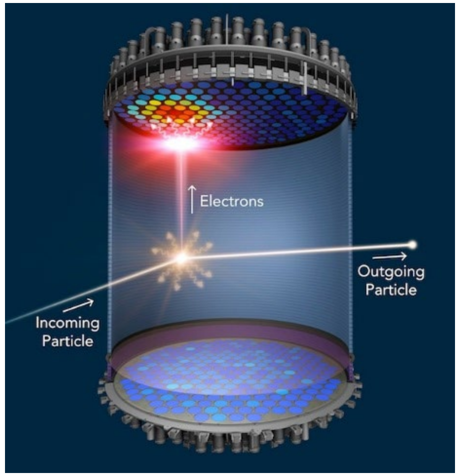
Searching for WIMP-like dark matter

indirect detection

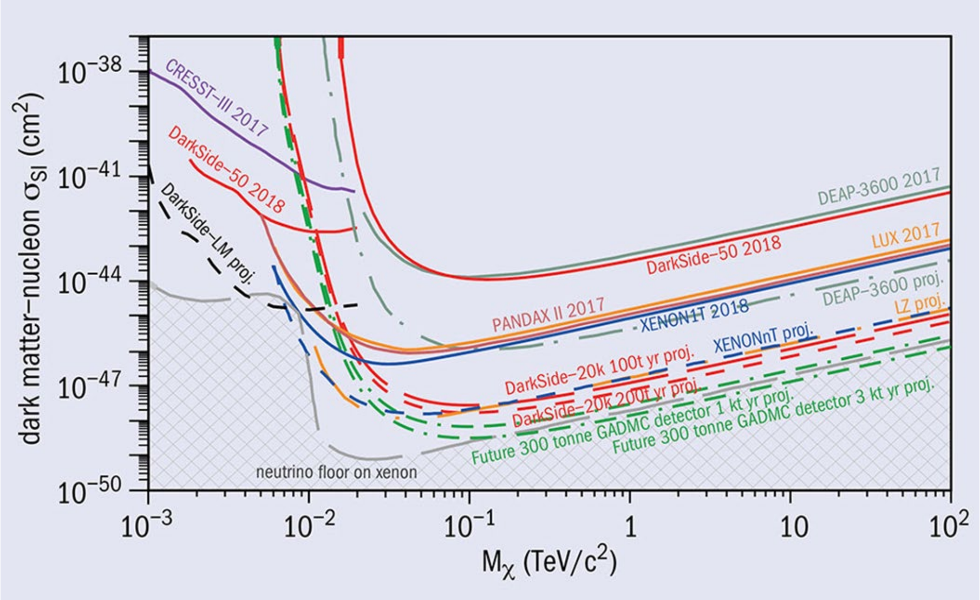
accelerator searches



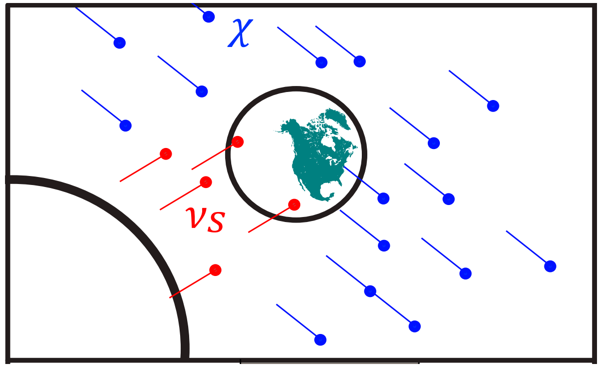
direct detection



a number of extremely sensitive experimental searches

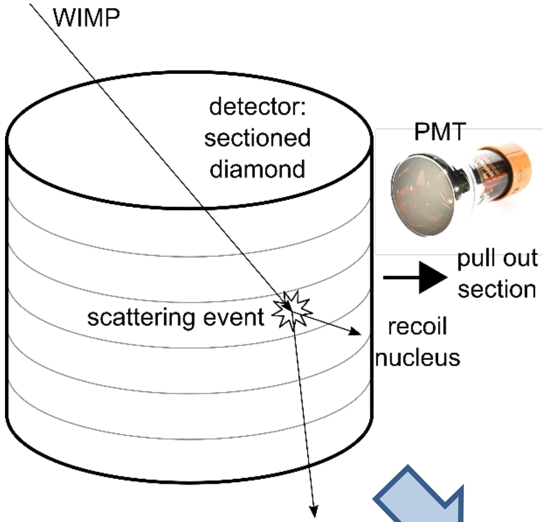


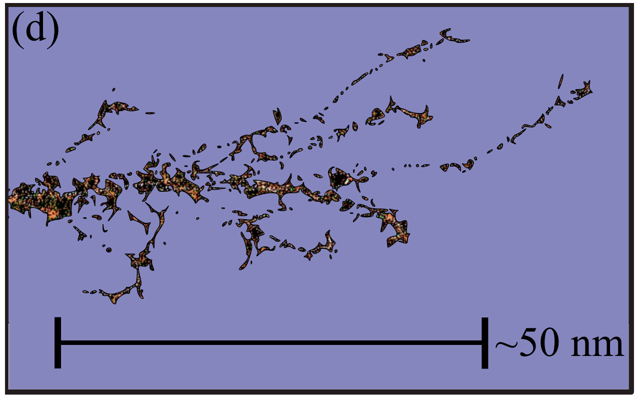
to go beyond the neutrino floor we can use directional information

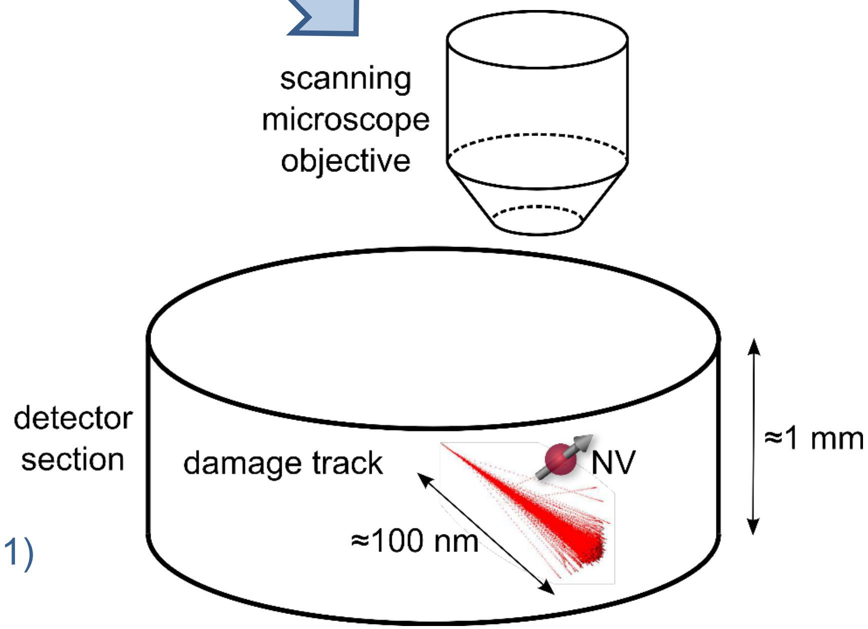


Idea: direction-sensitive WIMP detector based on quantum defects in diamond

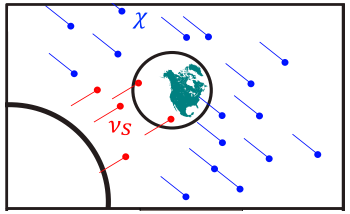
1. detector volume is made up of diamond sections, surrounded by PMTs and/or charge readout sensors
2. a WIMP scattering event is detected and localized via charge collection and scintillation
3. the recoil nucleus produces a track of vacancies ≈ 100 nm long
4. the detector section where the scattering event occurred is pulled out and examined
5. measurements of crystal strain using NV centers allow reconstruction of vacancy distribution, and hence the WIMP momentum direction







→ a directional detector for WIMP dark matter



details: S. Rajendran *et al.* arXiv:1705.09760; *Phys. Rev. D* (2017)
M. Marshall *et al.* arXiv: 2009.01028; *Quantum Sci. Technol.* (2021)
M. Marshall *et al.* arXiv:2103.08388; *Phys. Rev. Appl.* (Subm.)
M. Marshall *et al.* arXiv:2107.xxxxx (in preparation)

What is dark matter?

Dark matter

Light bosons
Axion-like particles
Fuzzy dark matter
QCD axions

Neutrinos
Standard-model neutrinos
Sterile neutrinos

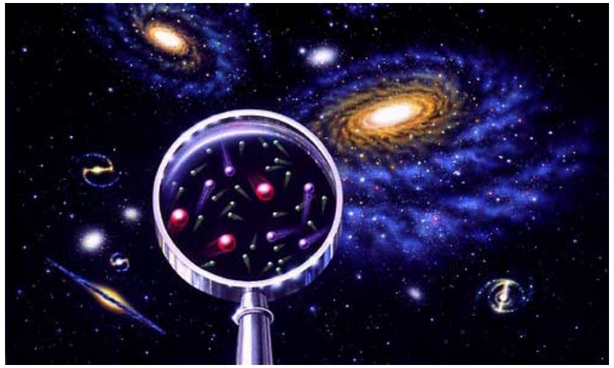
Weak scale
Super-symmetry
Extra dimensions
Little Higgs
Simplified models
Effective field theory

Other particles
WIMPzilla
Superfluid
Self-interacting

Macroscopic
Macros
Primordial black holes
MaCHOs

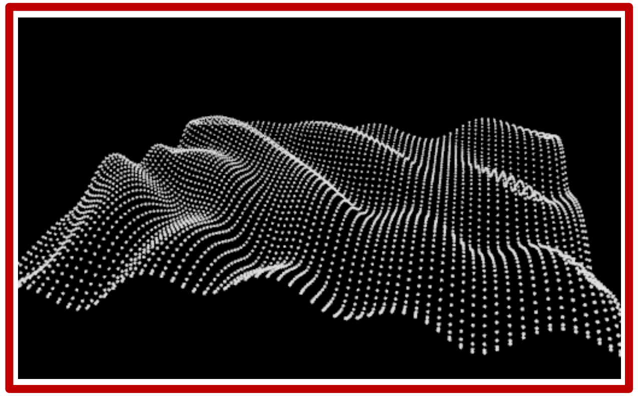
Modified gravity
MOG
TeVeS
MOND
Emergent gravity

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



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

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

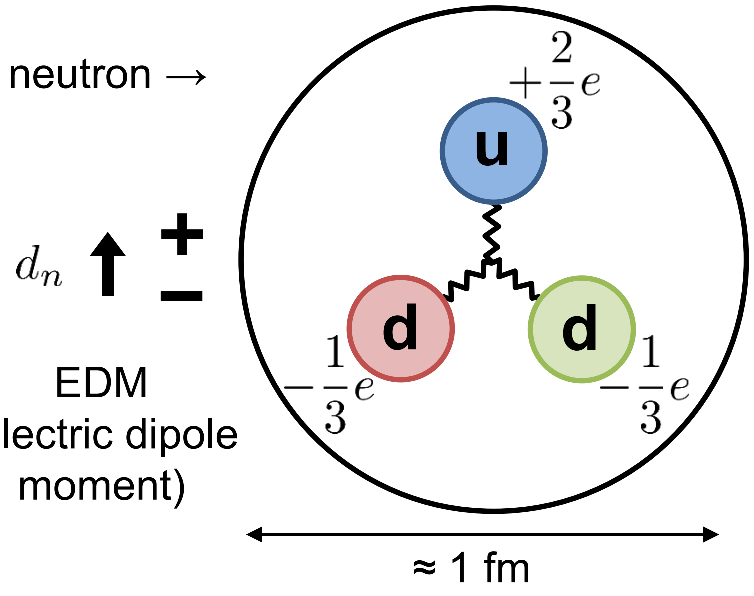


wave-like dark matter (eg: axions)
mass << eV

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

The strong-CP problem

neutron →



EDM
(electric dipole
moment)

(very!) naïve estimate:

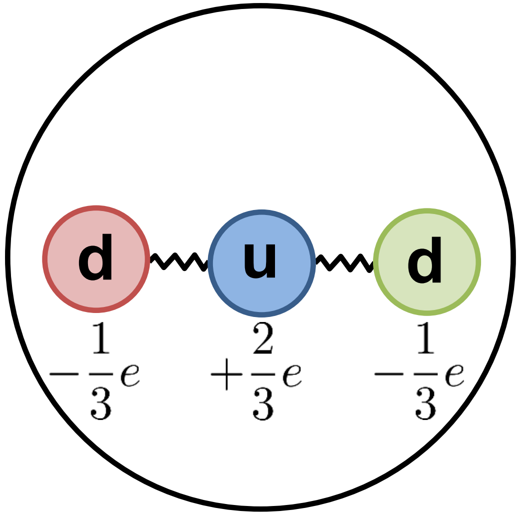
$$d_n \approx e \cdot \mathrm{fm} = 10^{-13}\, e \cdot \mathrm{cm}$$

experimental limit:

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

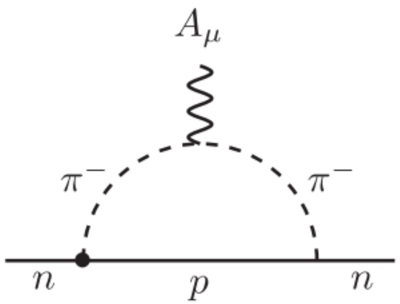
[Phys. Rev. Lett. **124**, 081803 (2020)]

better model for
a neutron →



CP-violating θ-term in
QCD Lagrangian →

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



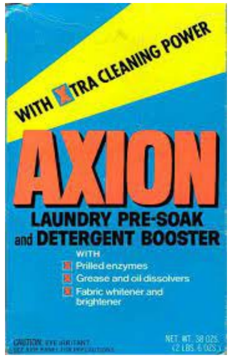
⇨ neutron EDM: $d_n = \theta \times (2.4 \times 10^{-16})\, e \cdot \mathrm{cm}$

⇨ $\theta < 10^{-10}$

why is θ so small?

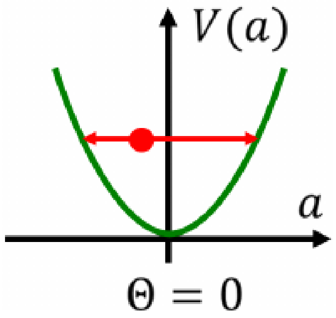
[Rev. Mod. Phys. **82**, 557 (2010)]

⇨



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

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



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

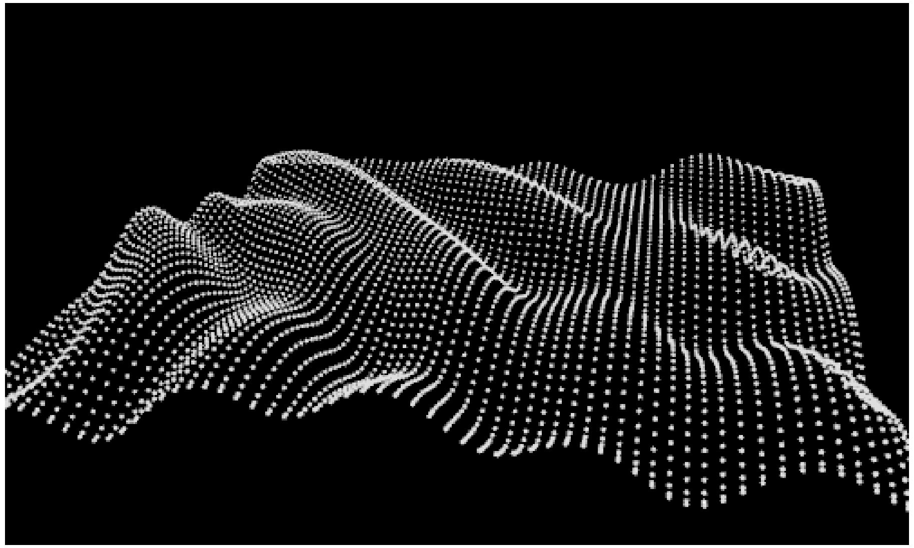
↓

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



Axions and axion-like particles: basics and motivation

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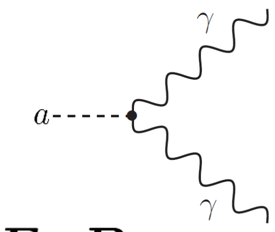
5. Only 3 possible (non-gravitational) interactions with standard model particles:

interaction with photons:

ALP field amplitude

symmetry breaking scale

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



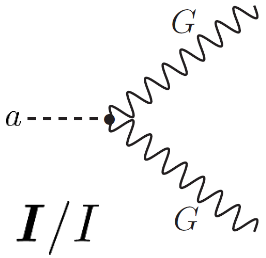
$$\mathcal{L}_{a\gamma\gamma} = g_{a\gamma\gamma} a \boldsymbol{E} \cdot \boldsymbol{B}$$

→ 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 (strong-CP) defines QCD axion:

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



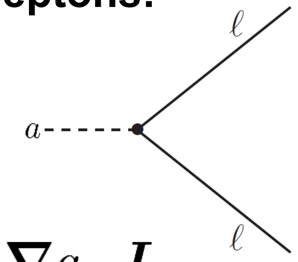
$$\mathcal{H}_{\text{EDM}} = g_d a \boldsymbol{E}^* \cdot \boldsymbol{I}/I$$

→ 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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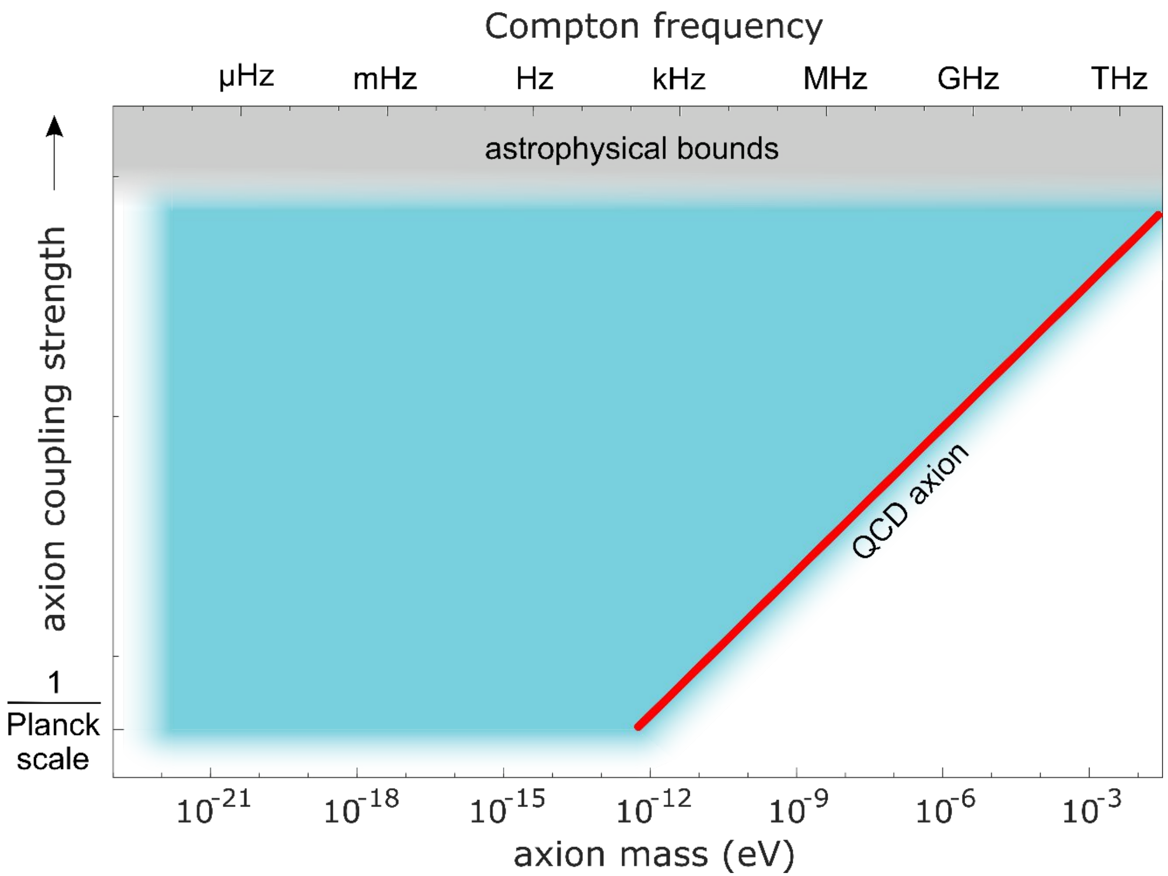

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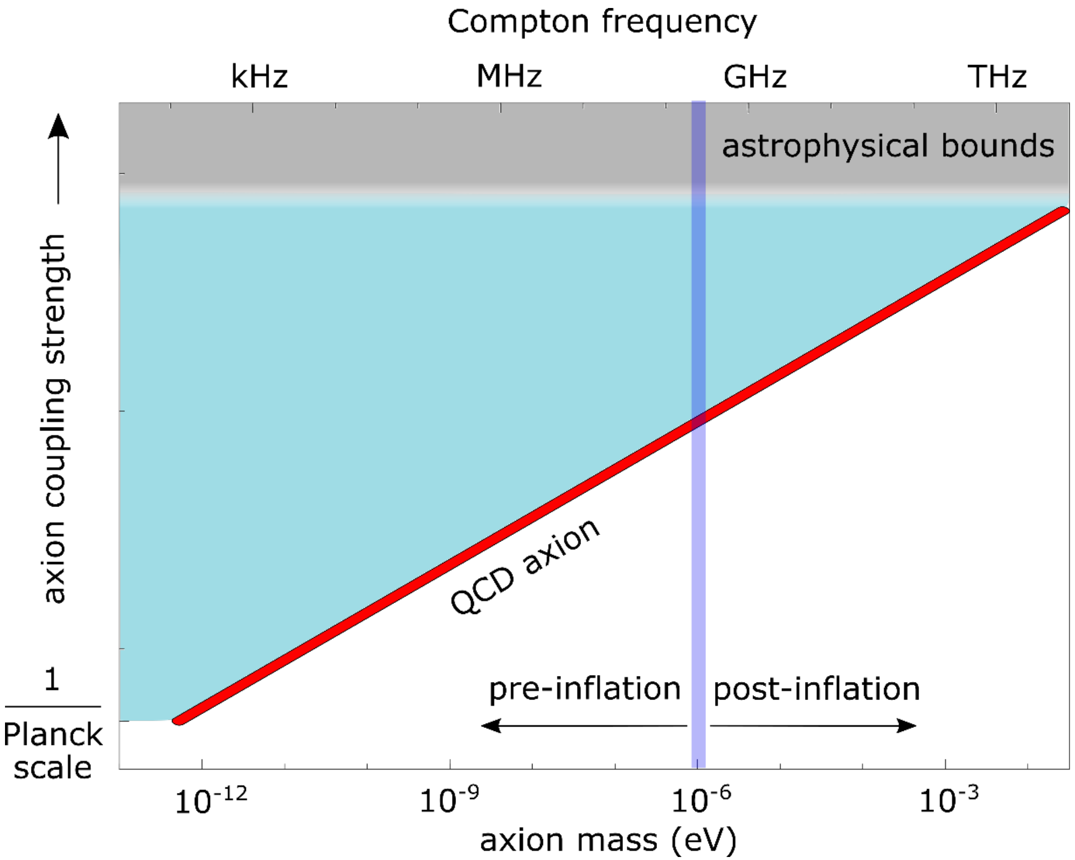
6. Detection of axion dark matter → insight into energy scale of **inflation**



detection of axion dark matter
↓
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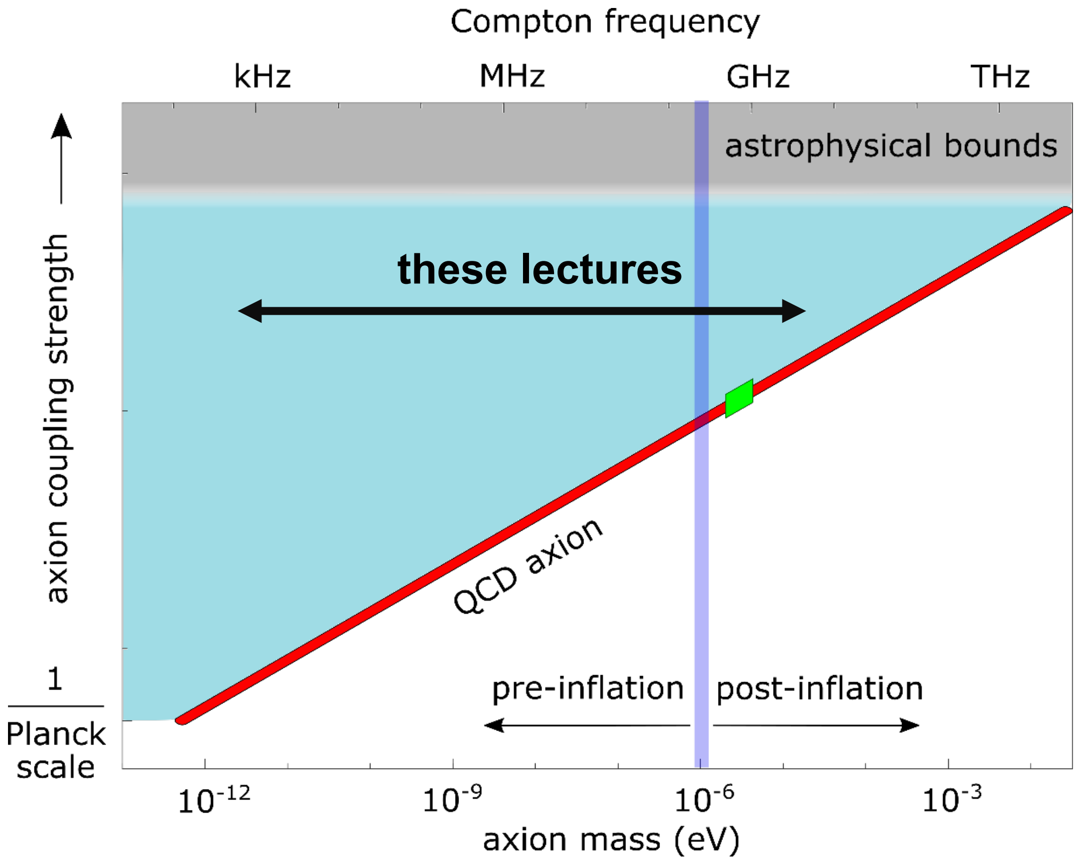

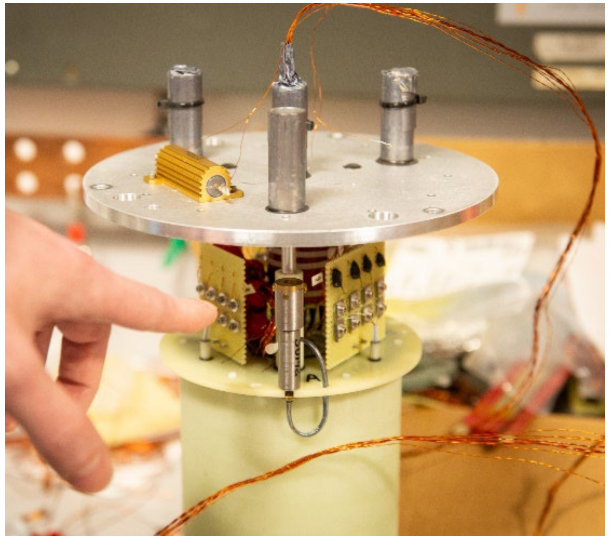

laboratory-scale experimental searches can explore the axion parameter space

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

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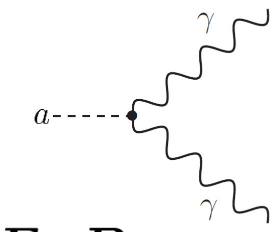

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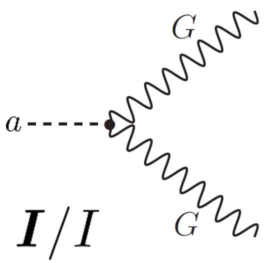


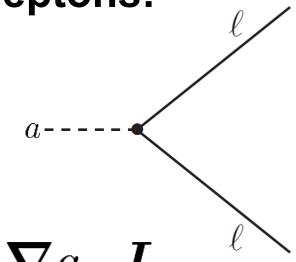
$$\mathcal{H}_{\text{EDM}} = g_d a \boldsymbol{E}^* \cdot \boldsymbol{I}/I$$

→ 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

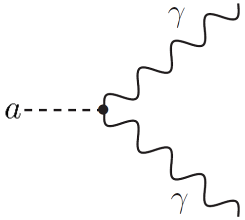
$$a(t) = a_0 \cos \omega_a t$$

interaction with photons:

ALP field amplitude

symmetry breaking scale

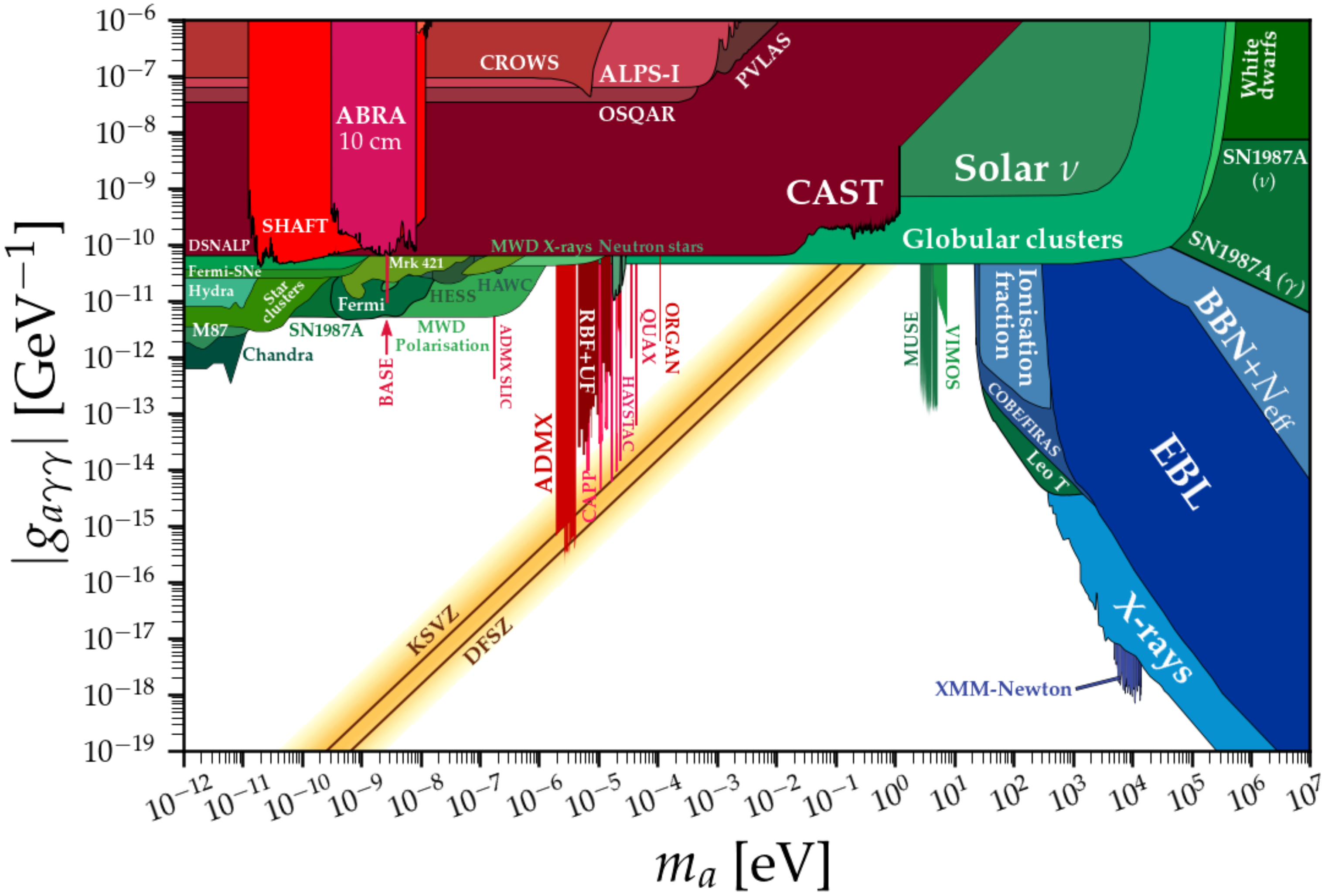
$$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$$



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

→ ALP ↔ photon conversion in a magnetic field

→ precision electromagnetic sensors



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

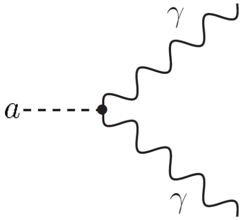
Lumped-element searches for axion-like dark matter

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

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

interaction with photons:

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



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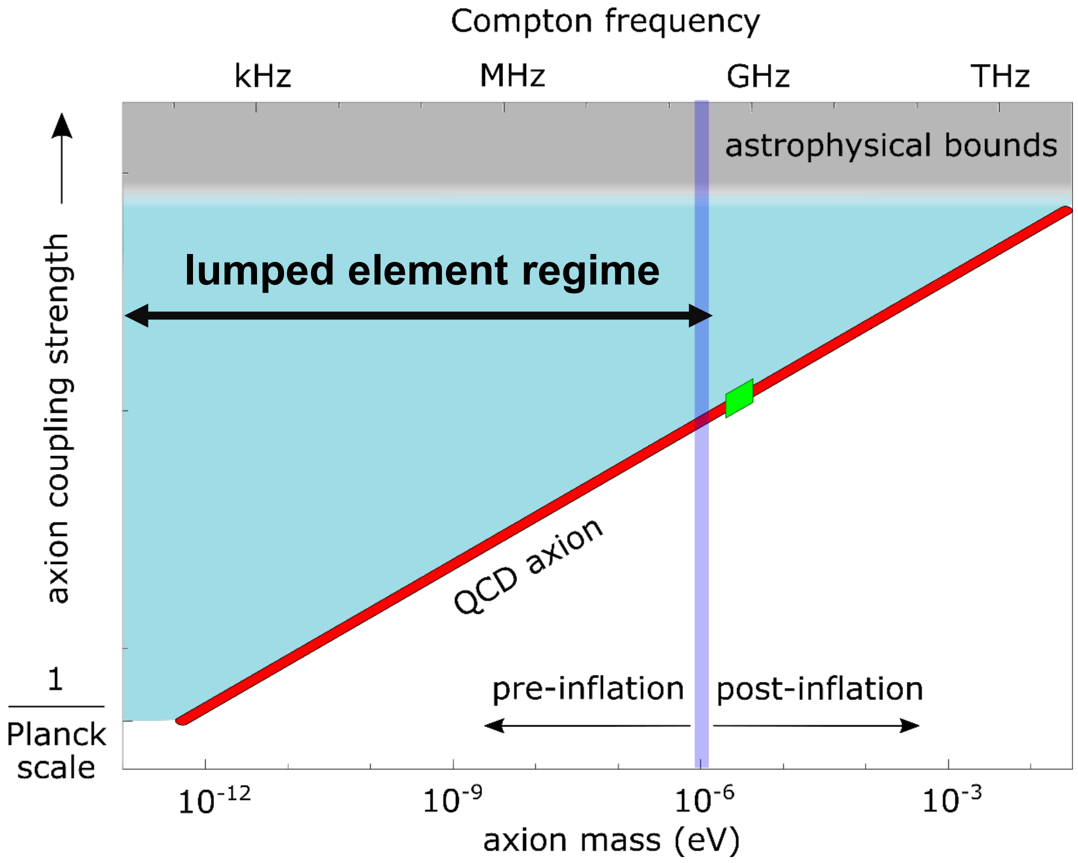

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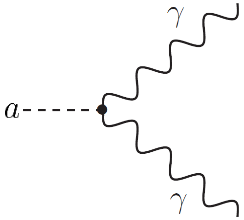
interaction with photons:

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

approach → additional term in Ampere's law

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

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

[Phys. Rev. Lett. **112**, 131301 (2014)]
[Phys. Rev. D **92**, 075012 (2015)]
[Phys. Rev. Lett. **117**, 141801 (2016)]
[*arXiv: 1811.03231* (2018)]
[Phys. Rev. Lett. **122**, 121802 (2019)]

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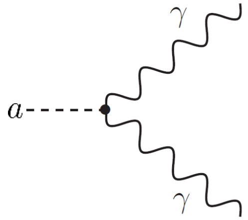

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→ ALP ↔ photon conversion in a magnetic field
→ precision electromagnetic sensors

approach → additional term in Ampere's law

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

azimuthal static magnetic field B_0

+

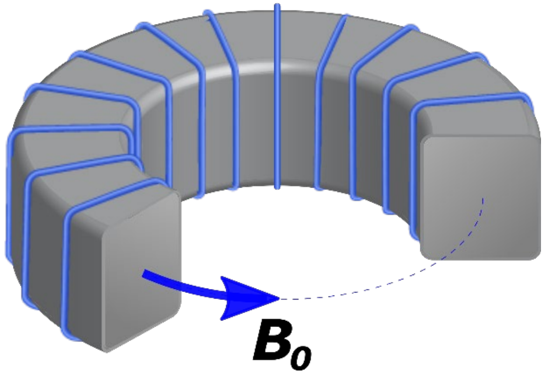
axion field

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

⇩

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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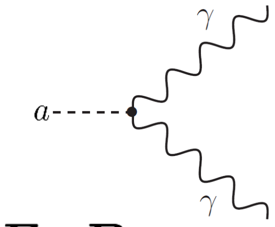
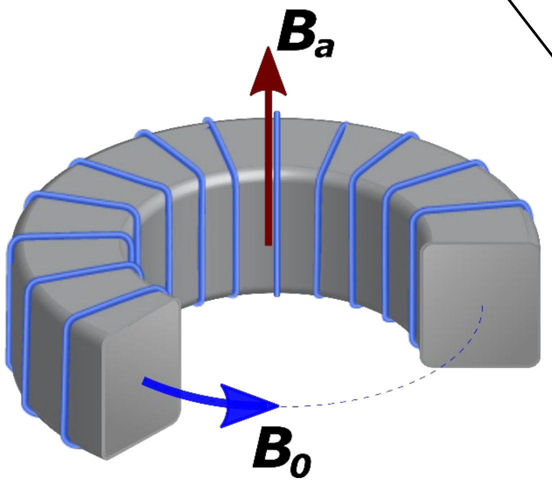


$$\mathcal{L}_{a\gamma\gamma} = g_{a\gamma\gamma} a \boldsymbol{E} \cdot \boldsymbol{B}$$

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

approach → additional term in Ampere's law

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



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[Phys. Rev. Lett. **122**, 121802 (2019)]
[*Nature Physics* **17**, 79 (2021)]

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

Lumped-element searches for axion-like dark matter

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

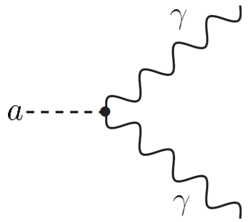
goal: search for electromagnetic coupling of axion-like dark matter in in mass (frequency) range where experiment size << wavelength

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

approach → additional term in Ampere's law

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

azimuthal static magnetic field B_0

+

axion field

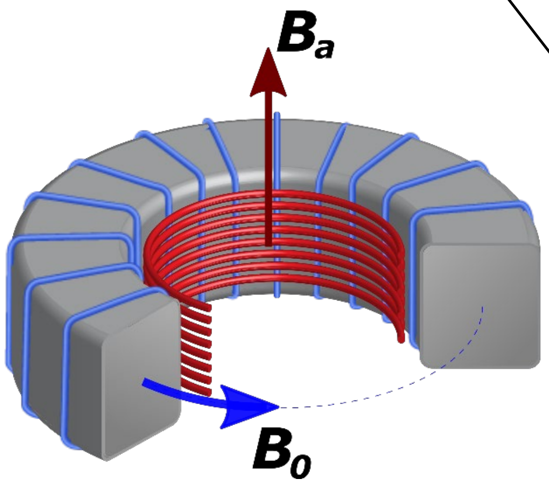
$$a(t) = a_0 \cos \omega_a t$$

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 SQUID $\propto B_0$



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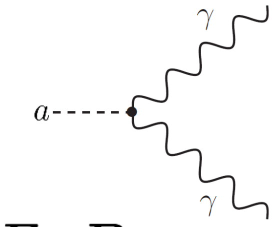
interaction with photons:

ALP field amplitude

symmetry breaking scale

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



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

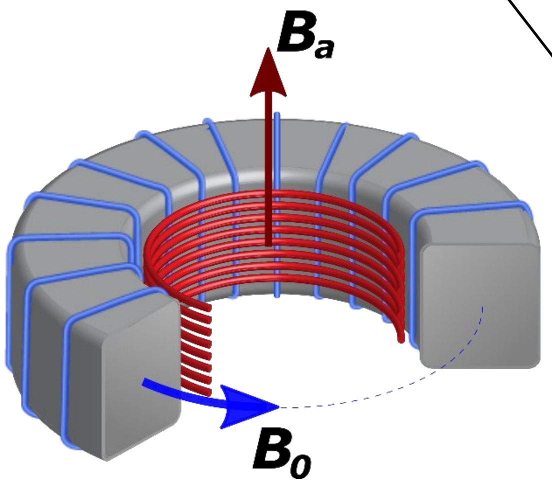
→ ALP ↔ photon conversion in a magnetic field
→ precision electromagnetic sensors

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

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



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[*Nature Physics* **17**, 79 (2021)]

azimuthal static magnetic field B_0

✚

axion field

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

⇩

azimuthal effective current

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

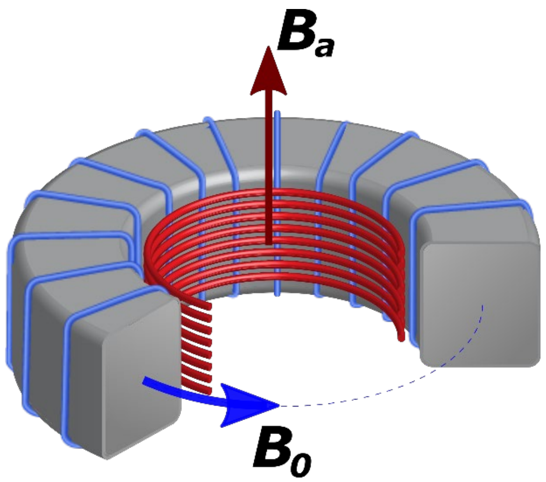
⇩

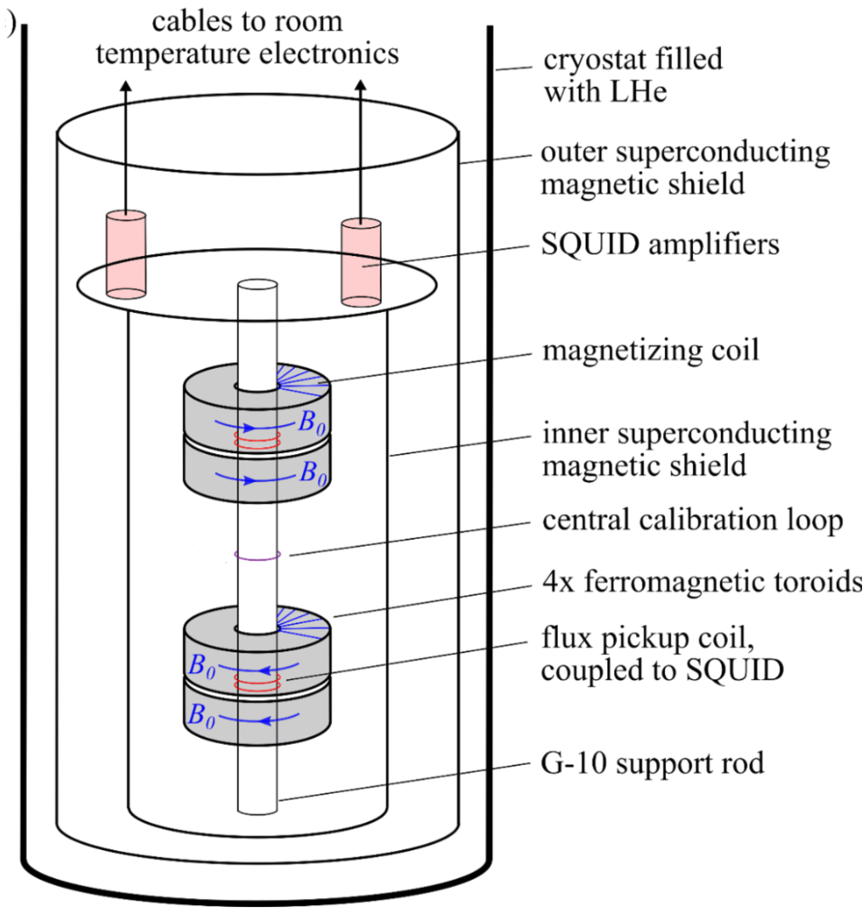
axial oscillating magnetic field B_a

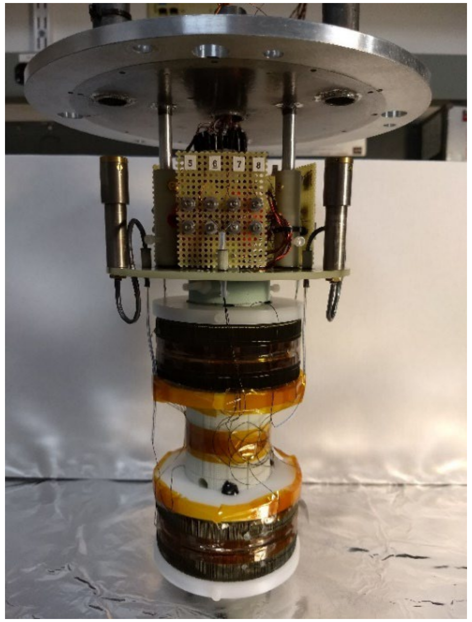
⇩

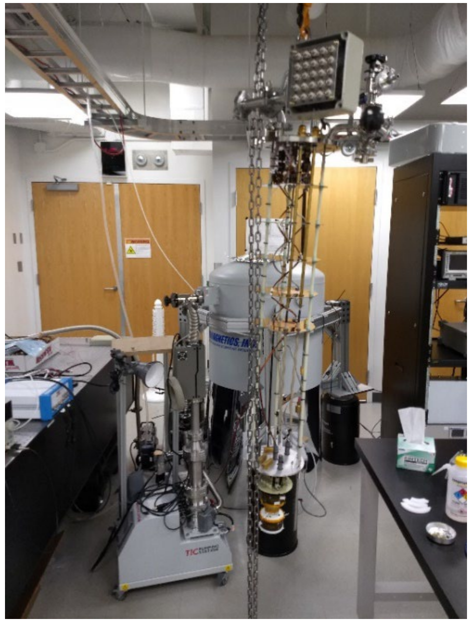
signal detected by SQUID $\propto B_0$

Experimental setup, broadband searches: SHAFT, ABRACADABRA

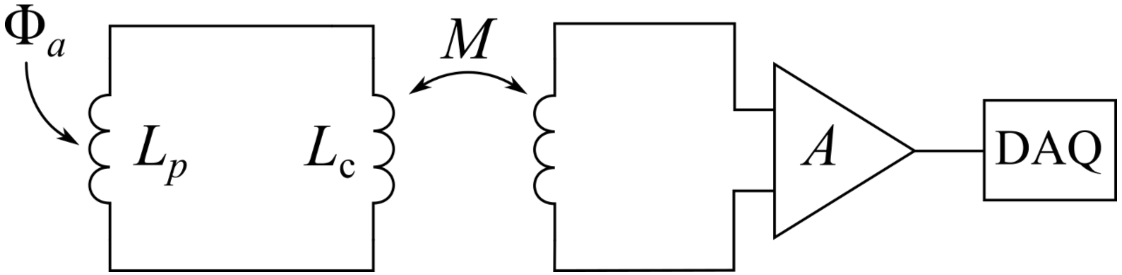








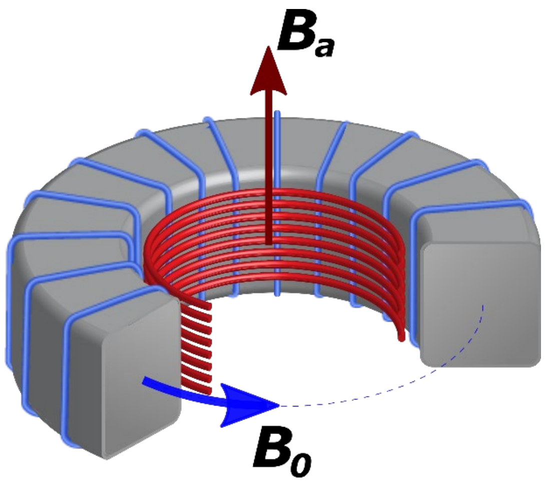
Φ_a → magnetic flux due to axion-like dark matter



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)]

Experimental setup, broadband searches: SHAFT, ABRA



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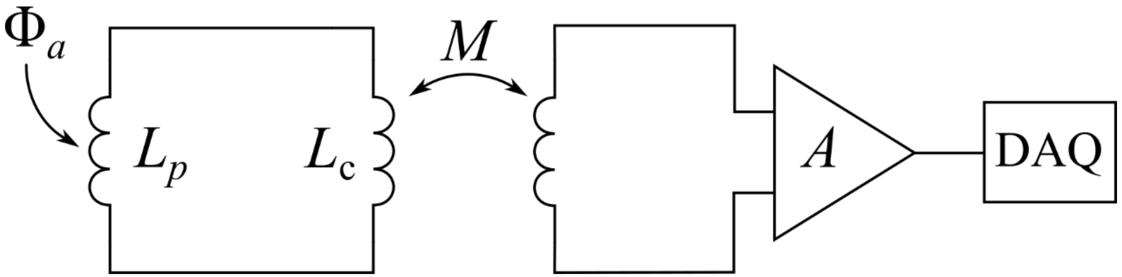
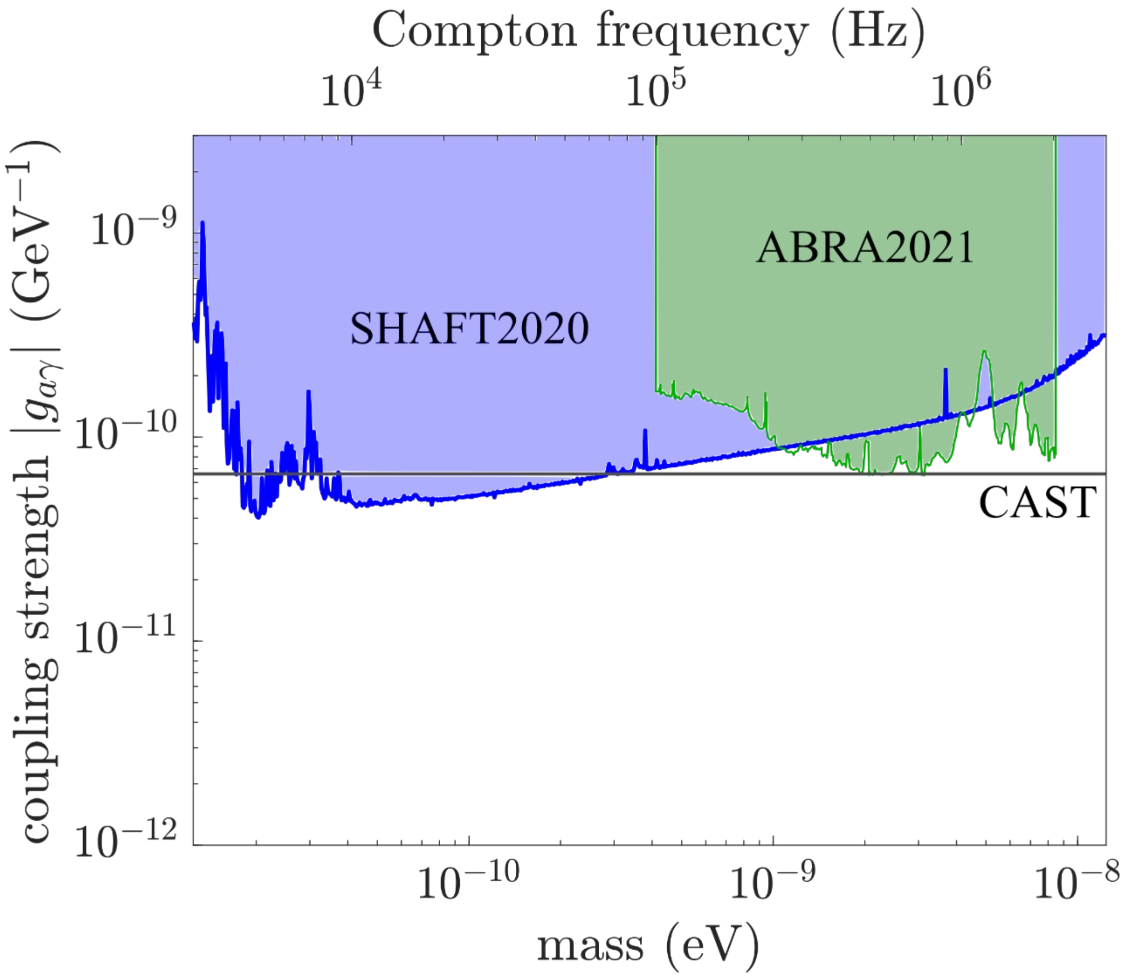


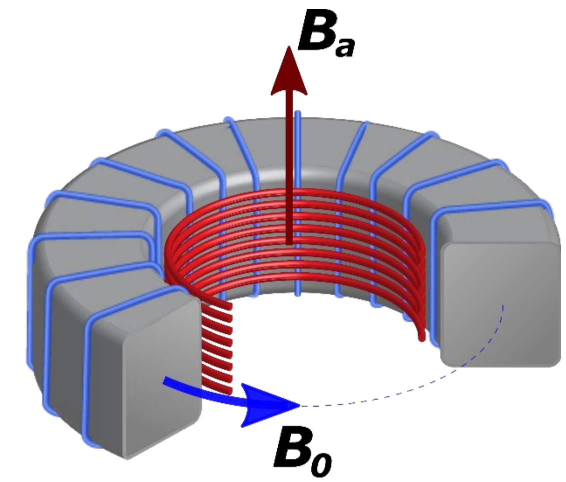


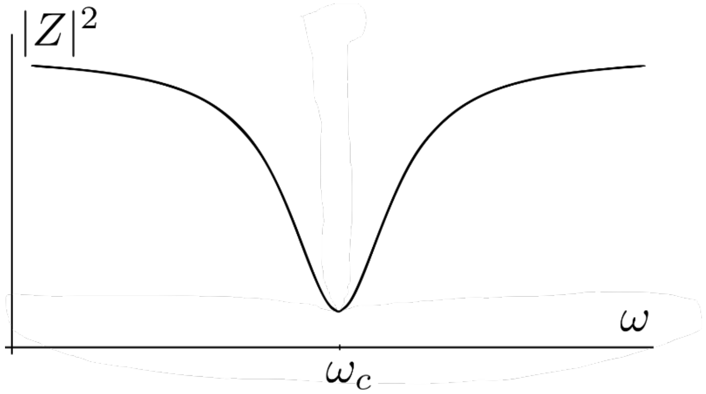
sensitivity limited by amplifier imprecision noise

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

Experimental setup, resonant searches: DM radio

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

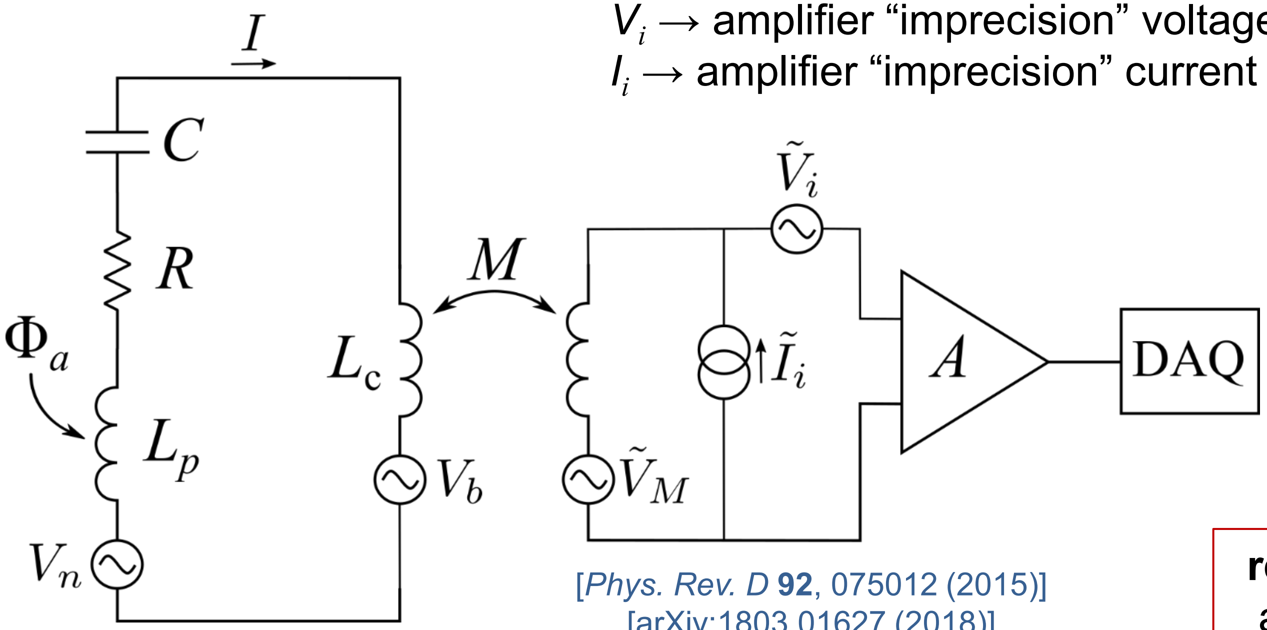




search for unknown axion mass (Compton frequency) is performed by scanning the resonance frequency

➡ this is what makes these searches hard

V_n → thermal + quantum noise
V_b → back-action noise
V_i → amplifier “imprecision” voltage noise
I_i → amplifier “imprecision” current noise



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

standard quantum limit (SQL)

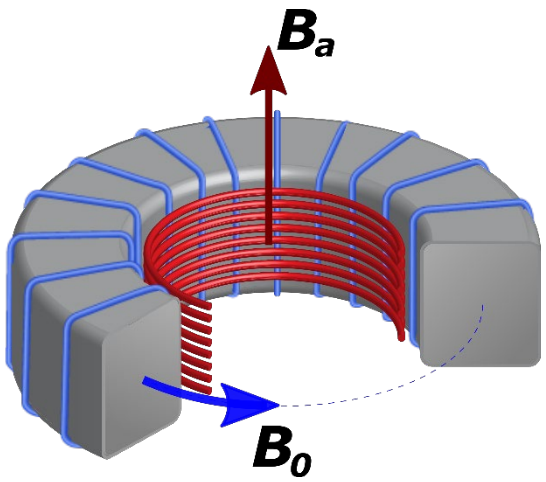
$$N(\omega) = \frac{1}{e^{\hbar\omega/k_B T} - 1} + \frac{1}{2}$$

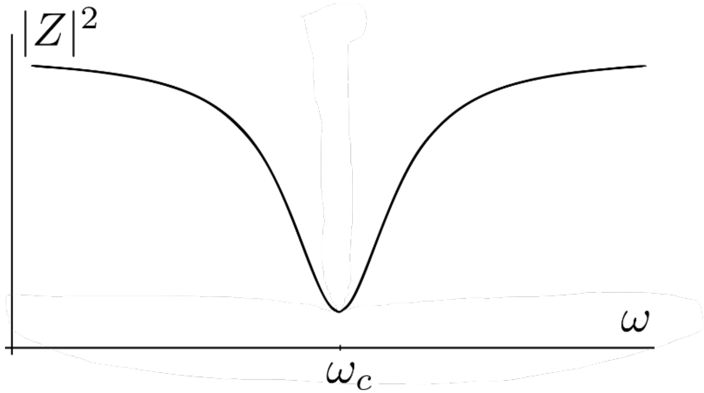
in the lumped element regime $\hbar\omega \lesssim k_B T$

➡ sensitivity is limited by thermal noise

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

Experimental setup, resonant searches: DM radio





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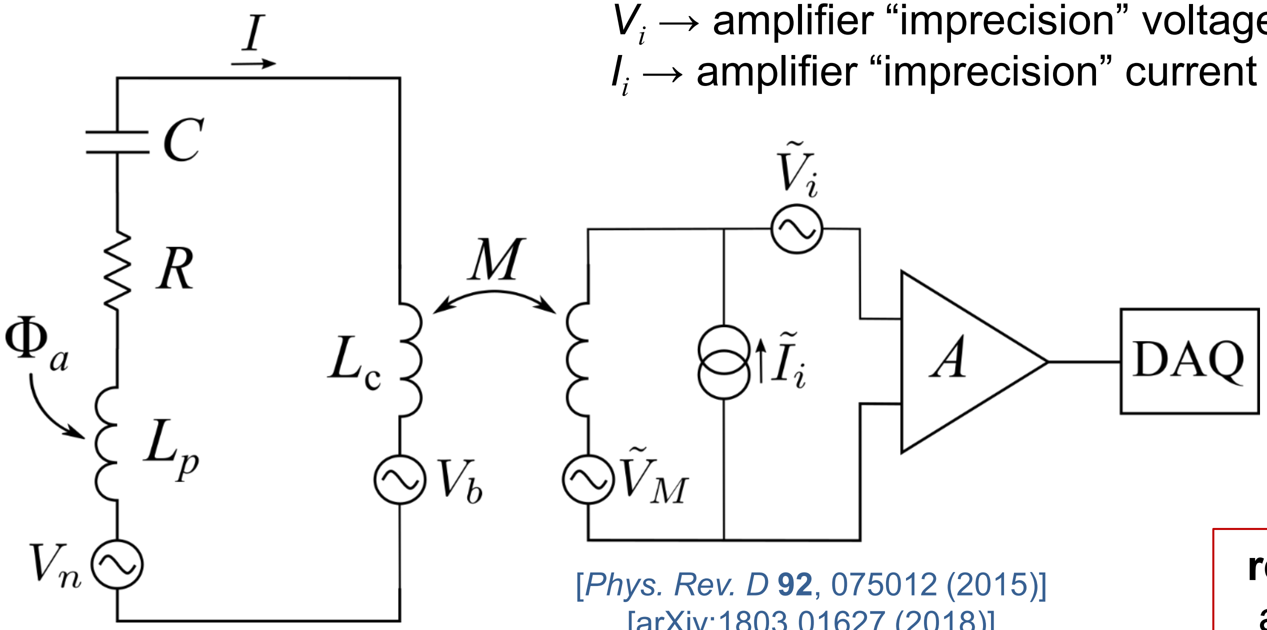

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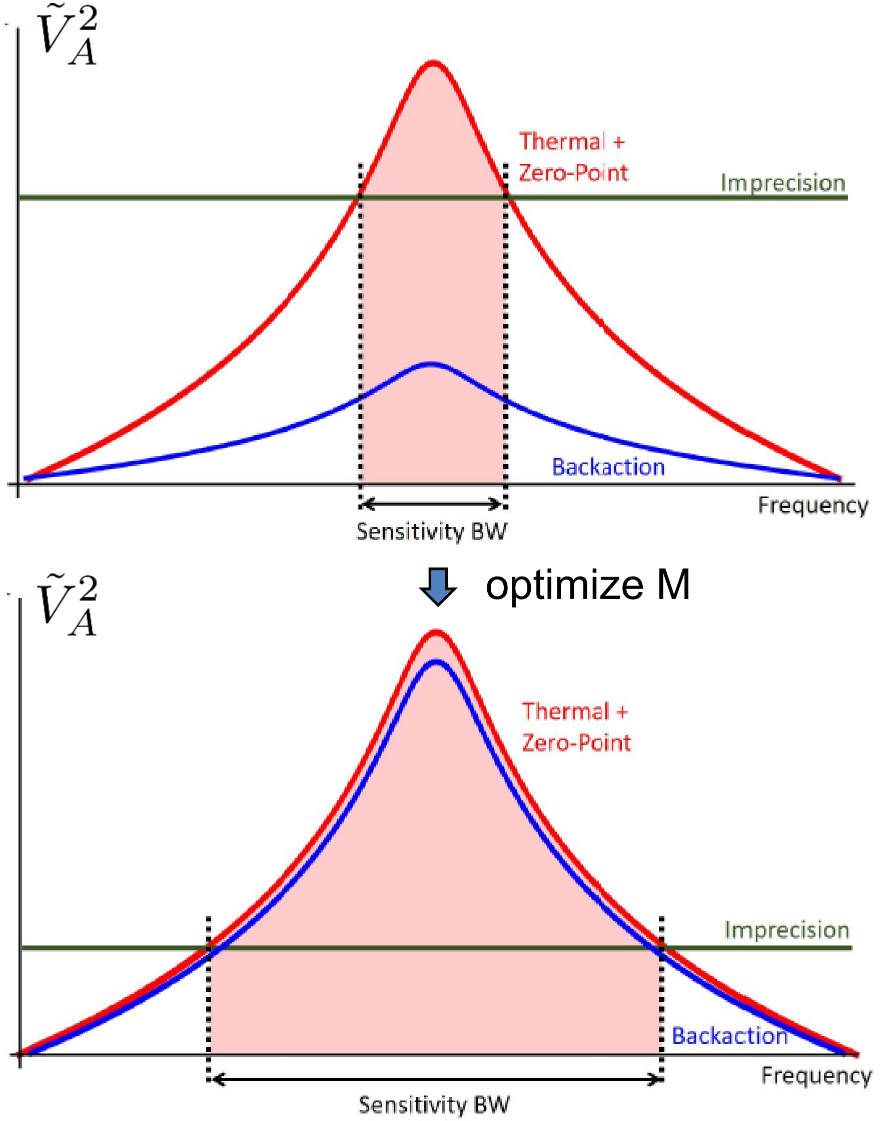
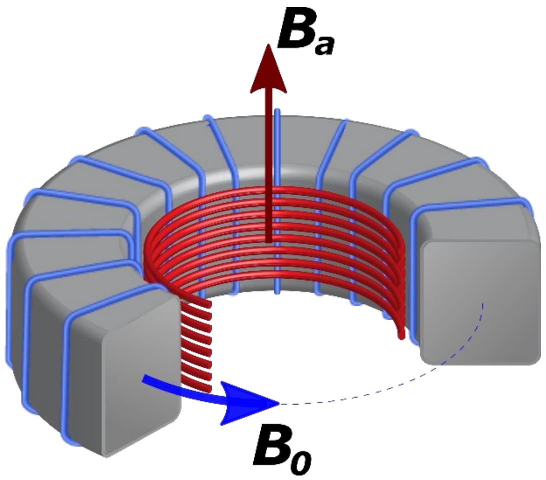
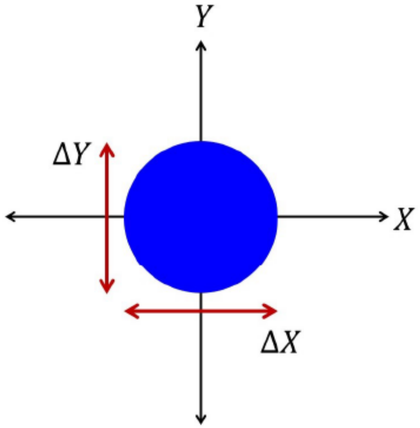


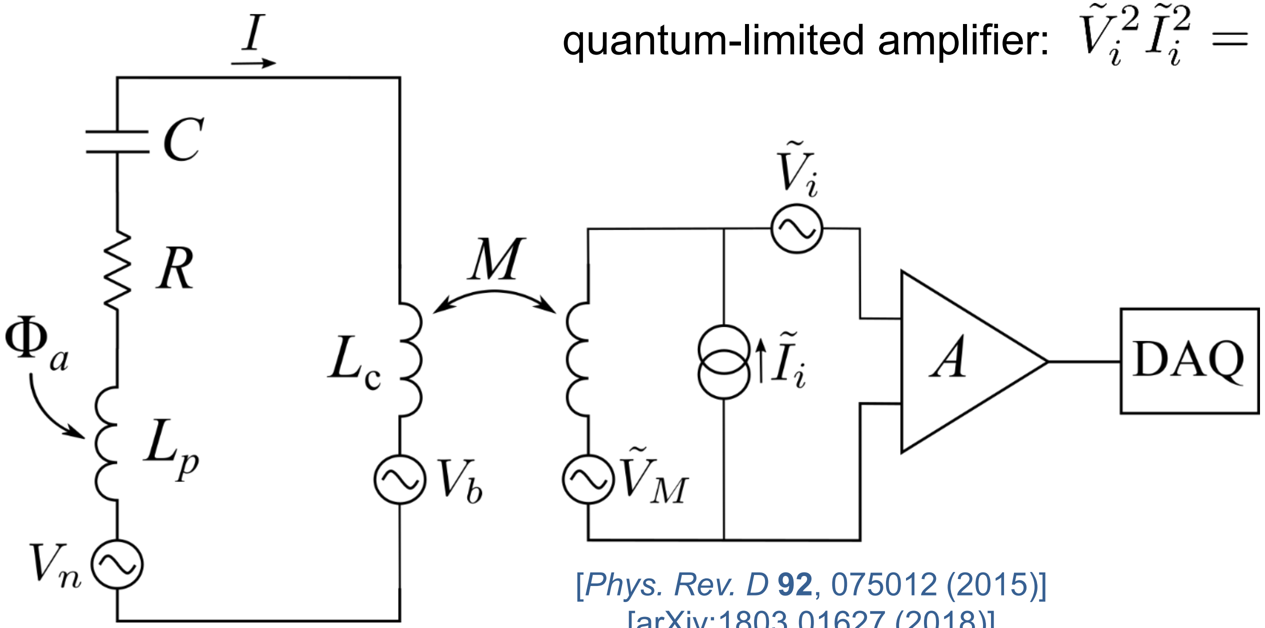
resonant pickup circuit → sensitivity is limited by thermal noise; amplifier imprecision and back-action limits sensitivity bandwidth

Quantizing the resonant LC circuit → back action evasion





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



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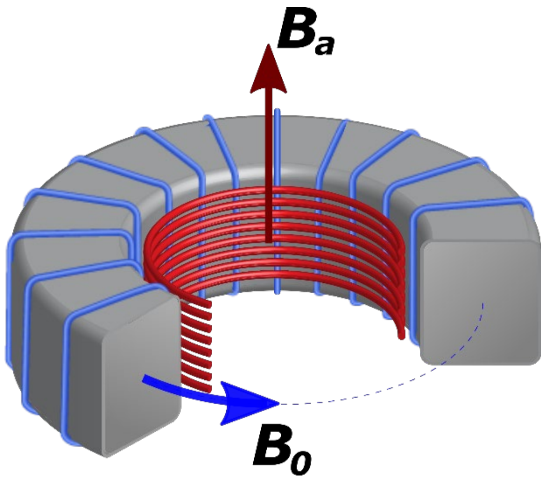
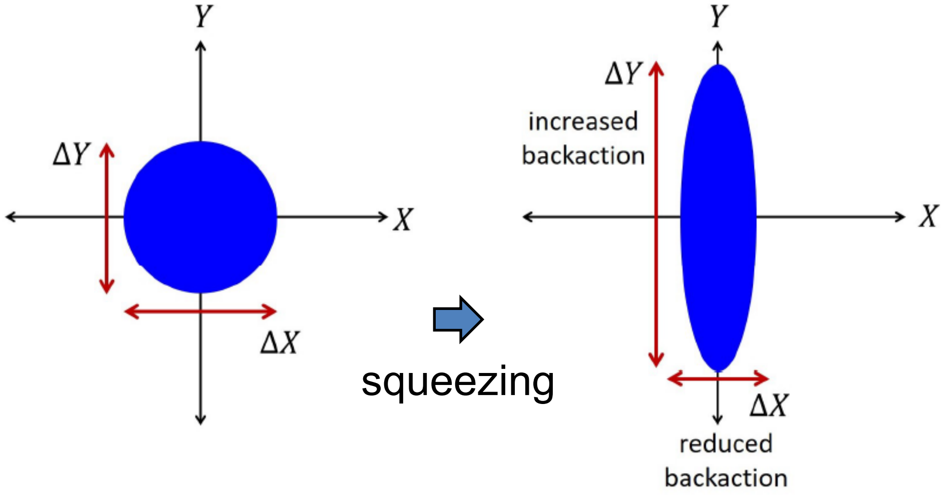
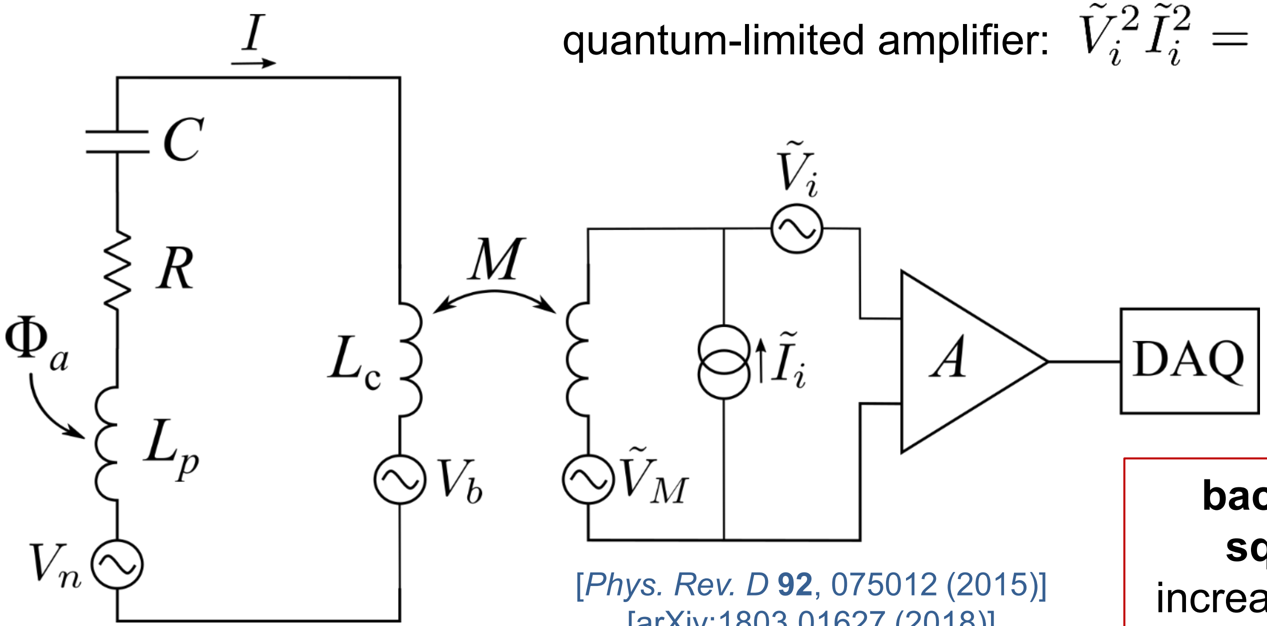




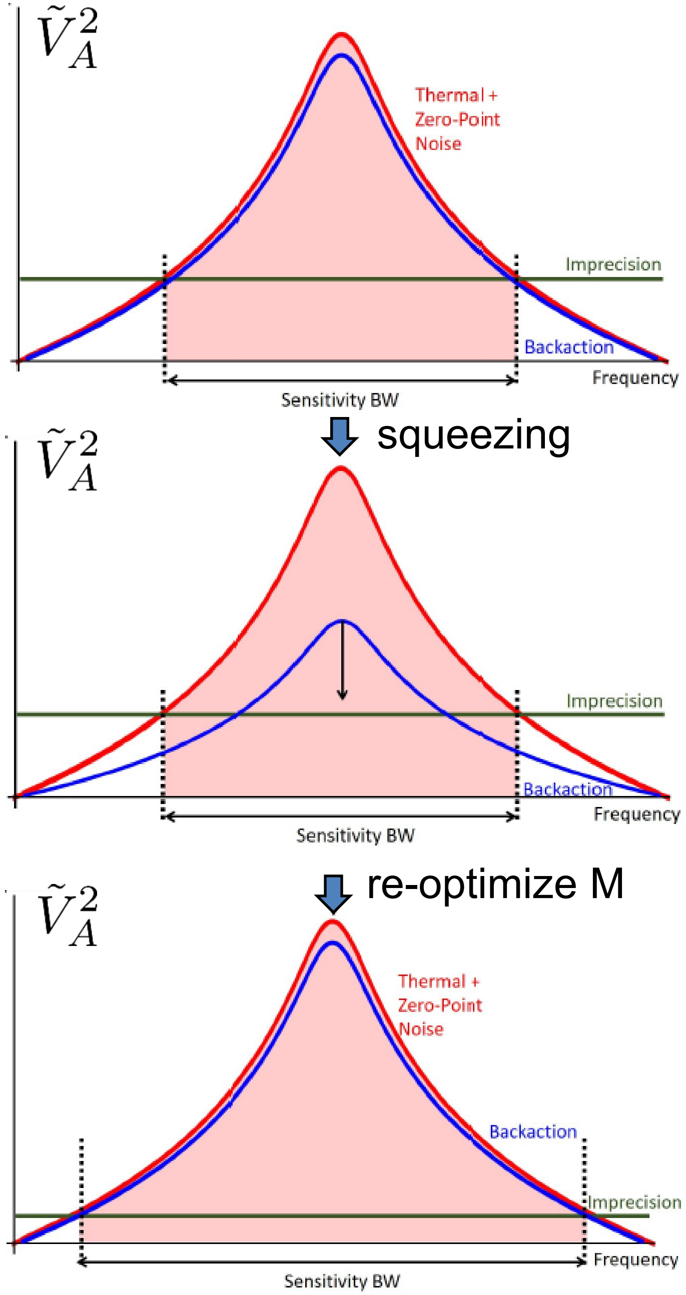
squeezing

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



squeezing

re-optimize M

Cavity haloscope searches for axion-like dark matter

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

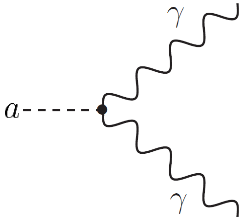
goal: search for electromagnetic coupling of axion-like dark matter in in mass (frequency) range where experiment size ≈ wavelength

interaction with photons:

ALP field amplitude

symmetry breaking scale

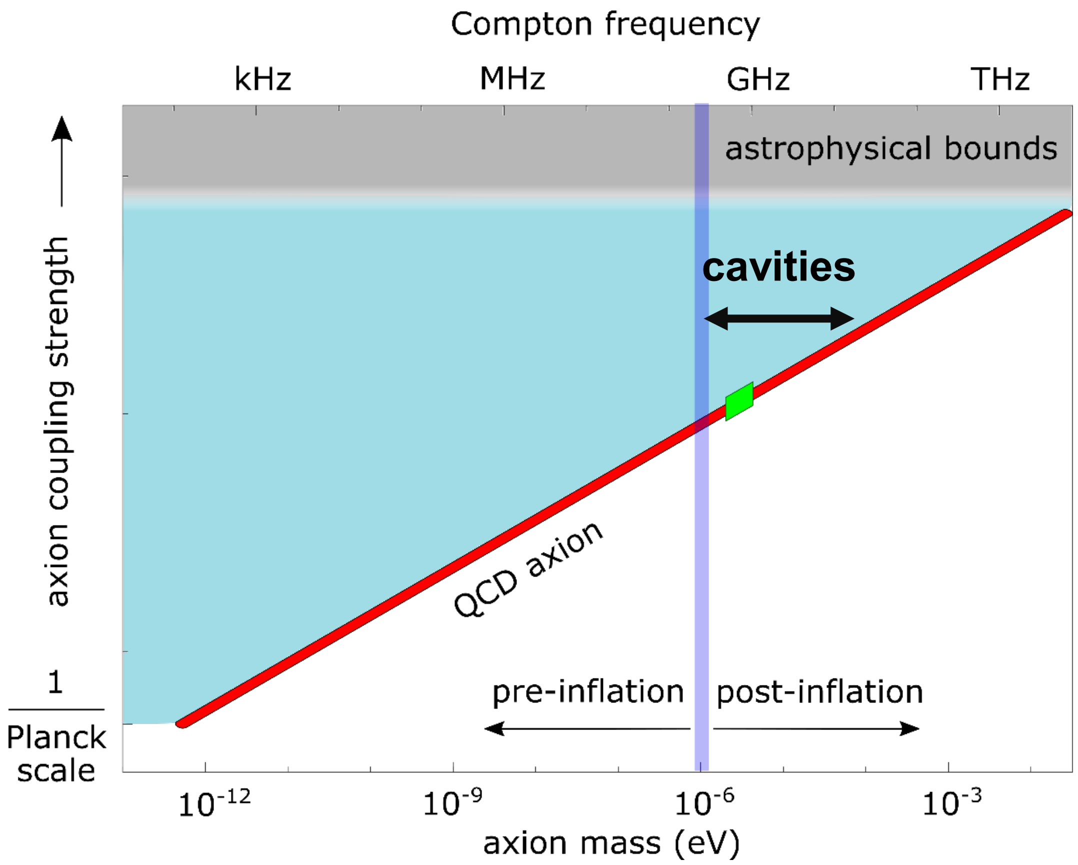
$$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$$



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

→ ALP ↔ photon conversion in a magnetic field

→ precision electromagnetic sensors



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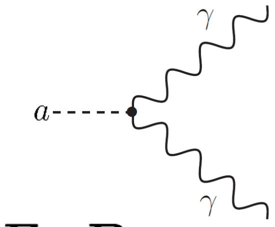

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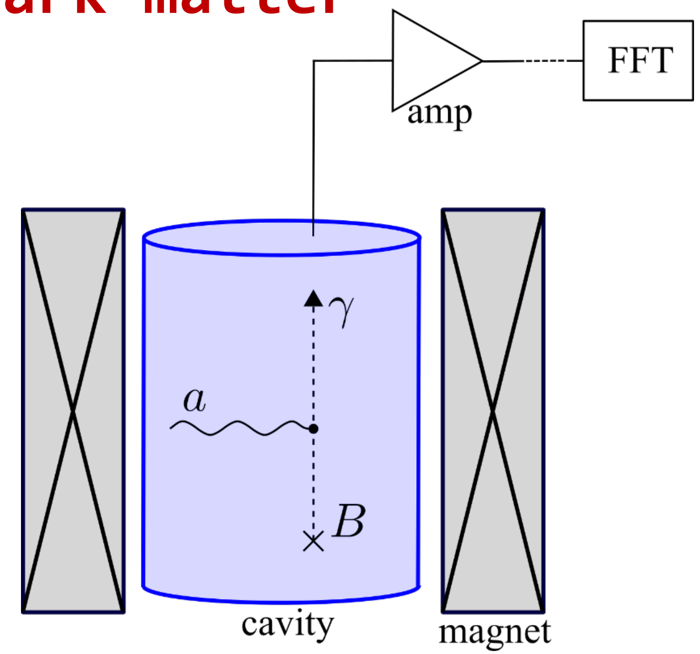


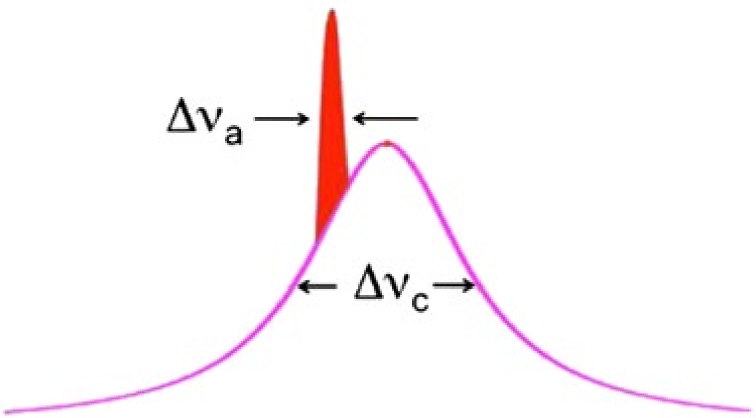
axion signal power: $P_{a\to\gamma} = \frac{g_{a\gamma\gamma}^2 \rho_a}{m_a} \eta C B_0^2 V Q_c$

$$\eta = \frac{\beta}{1+\beta}$$

$$Q_c = \frac{Q}{1+\beta}$$

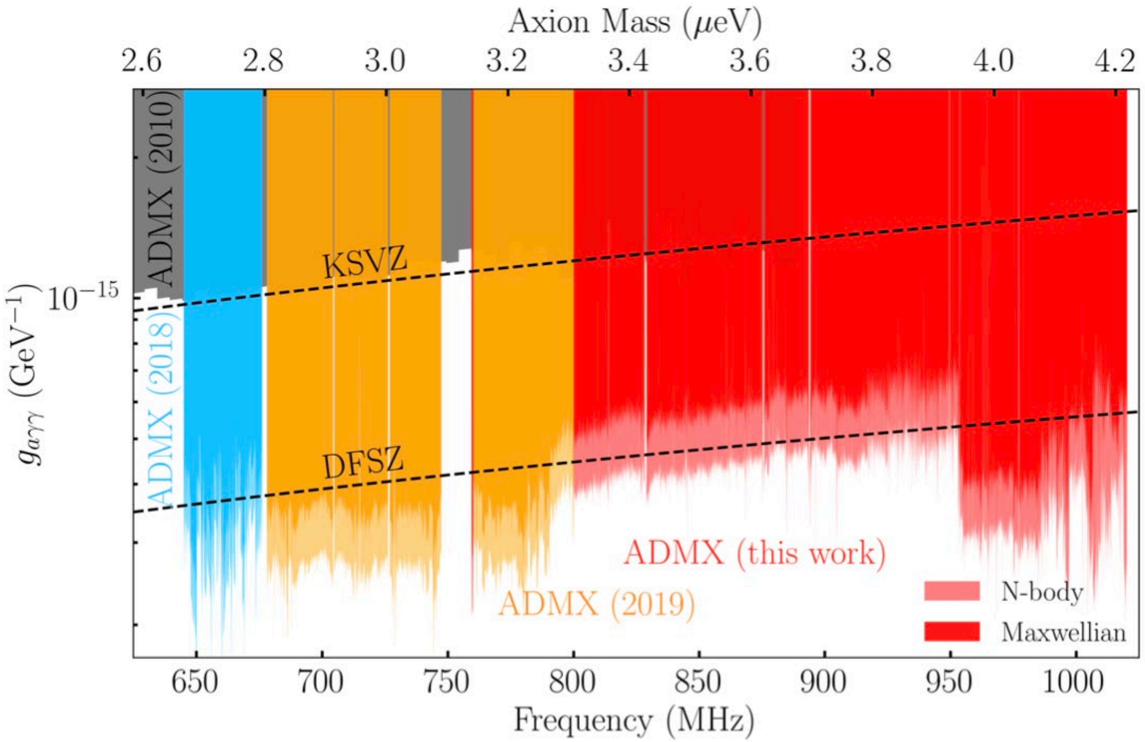
$$\beta = \frac{\text{power output}}{\text{power dissipated}}$$

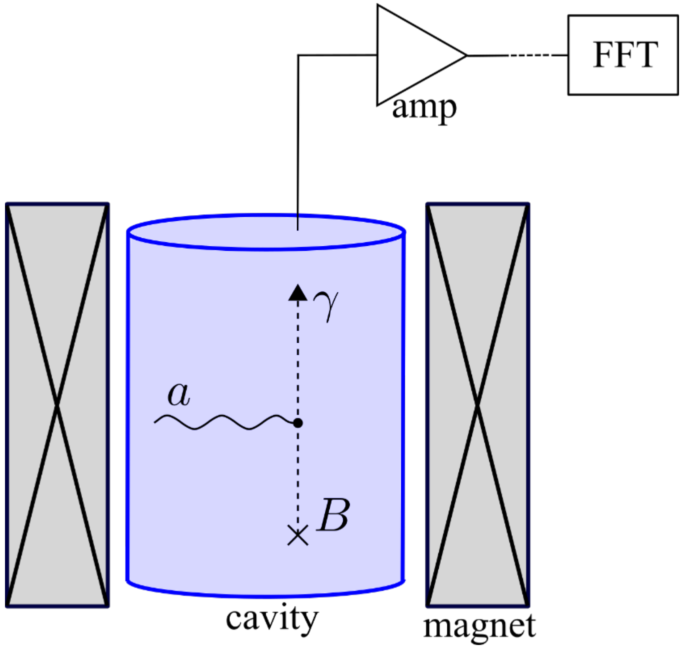
↑
cavity coupling factor



[*Phys. Rev. D* **88**, 035020 (2013)]
[*Rev. Mod. Phys.* ***93***, 015004 (2021)]

ADMX



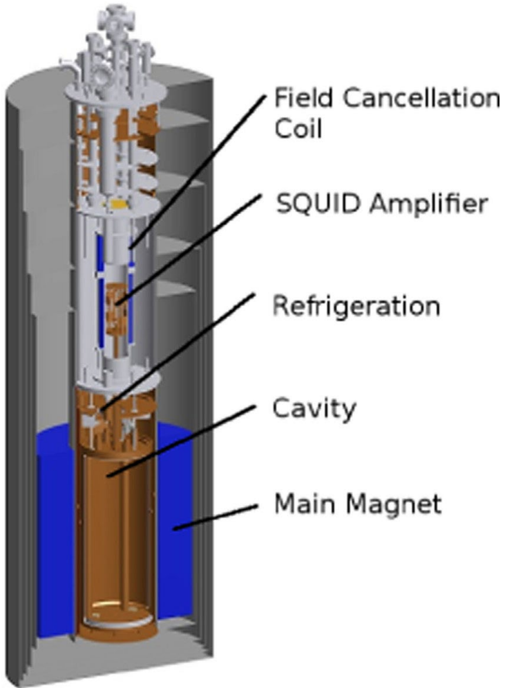


axion signal power: $P_{a\to\gamma} = \dfrac{g_{a\gamma\gamma}^2 \rho_a}{m_a} \eta C B_0^2 V Q_c$

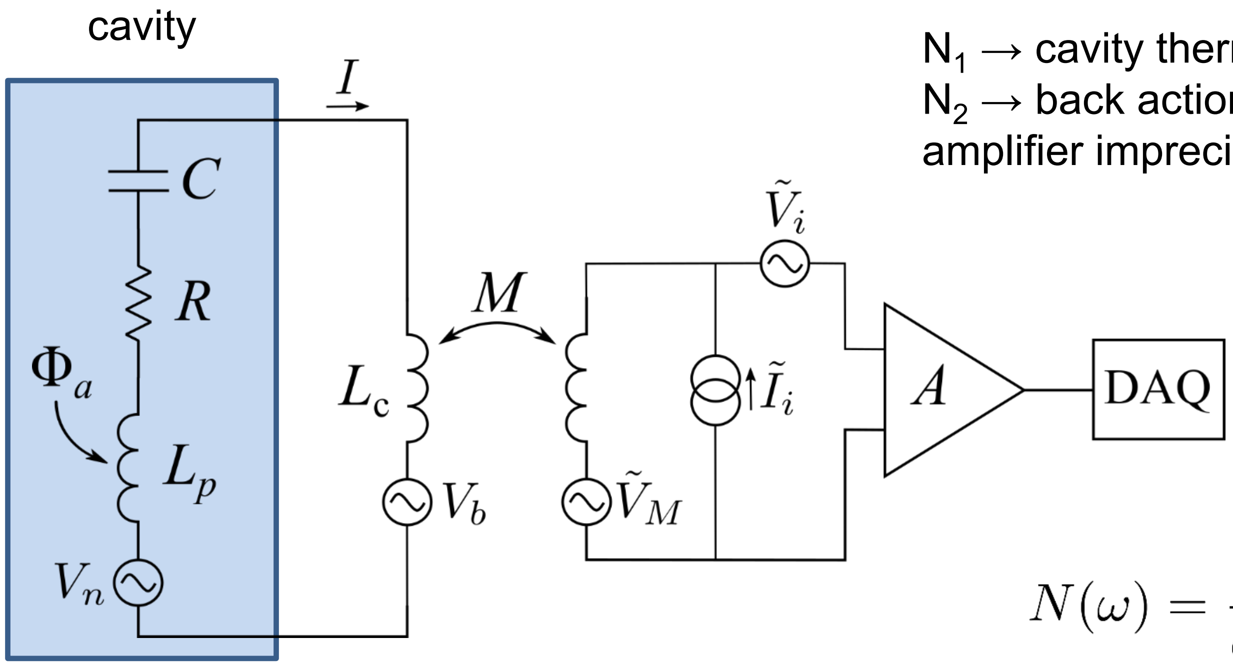
$P_{a\to\gamma} \approx 10^{-23}$ W sensitivity of a radio receiver $\approx 10^{-15}$ W

ADMX has started to explore the axion-photon coupling at the level of the QCD axion

[*Phys. Rev. Lett.* **127**, 261803 (2021)]

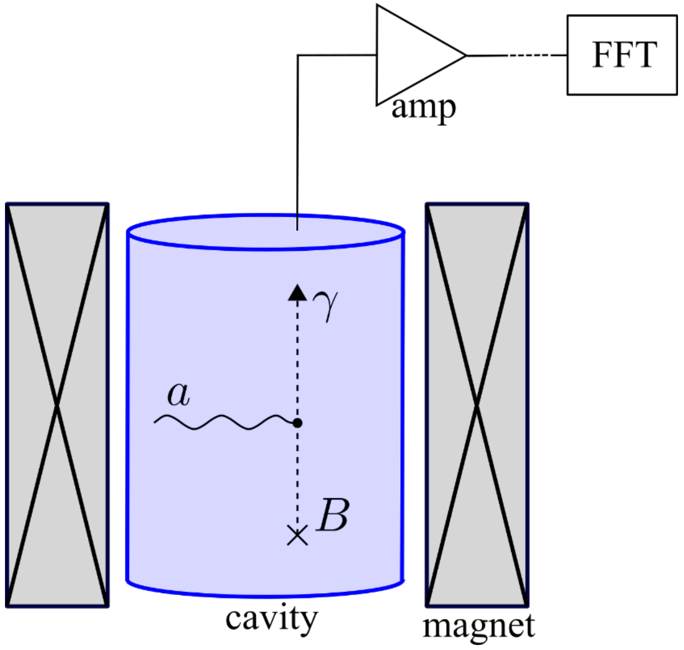


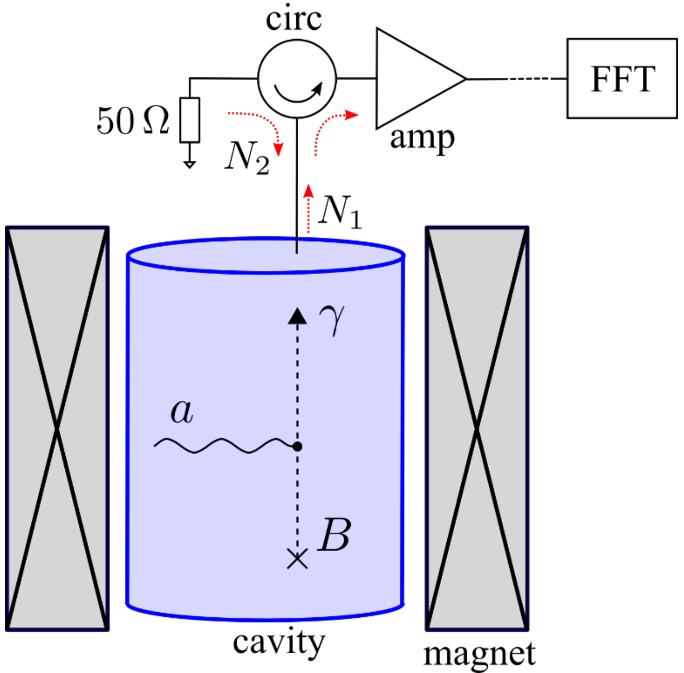
Noise in cavity haloscopes



N_1 → cavity thermal + zero-point noise ↔ V_n
N_2 → back action ↔ V_b
amplifier imprecision noise is negligible

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





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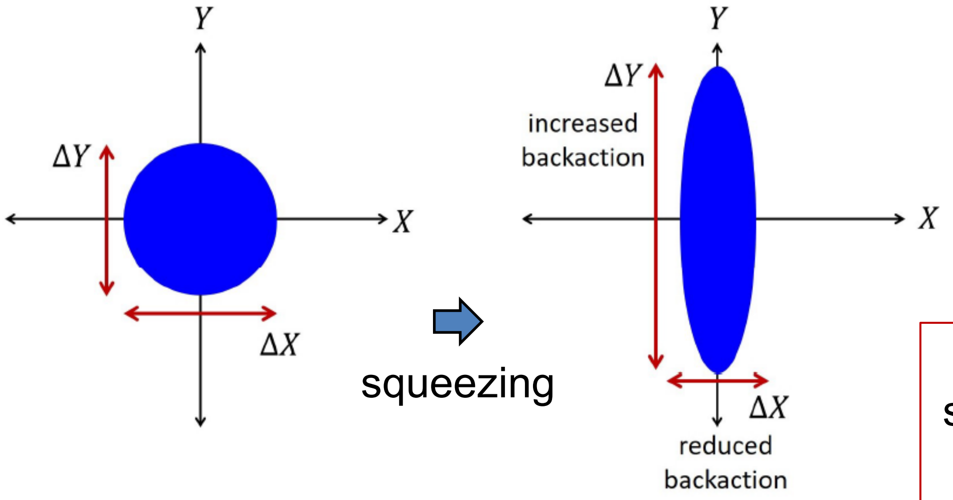
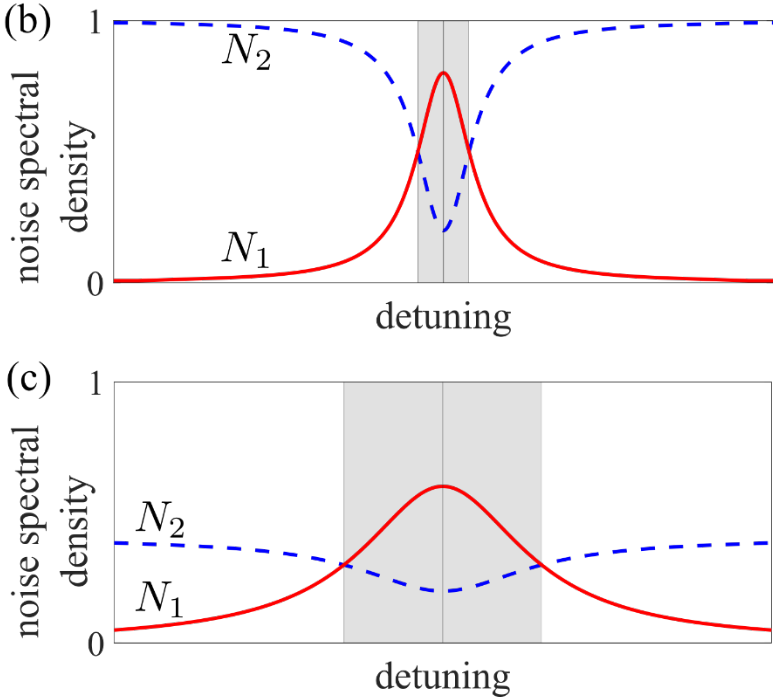
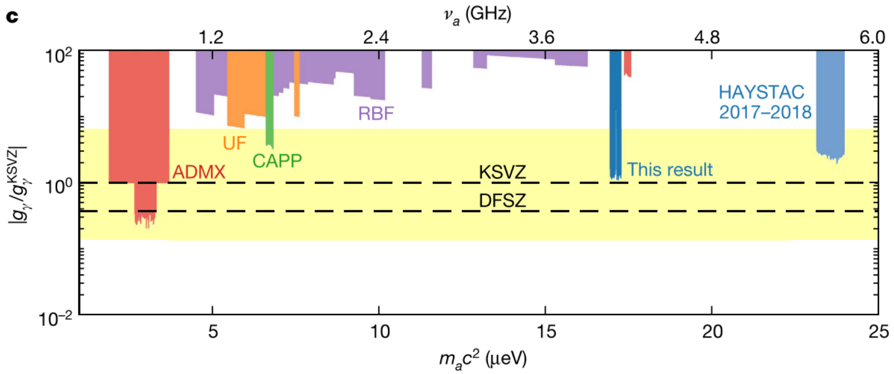
$P_{a\to\gamma} \approx 10^{-23}\,\mathrm{W}$ sensitivity of a radio receiver $\approx 10^{-15}\,\mathrm{W}$

Haloscope At Yale Sensitive To Axion CDM: HAYSTAC

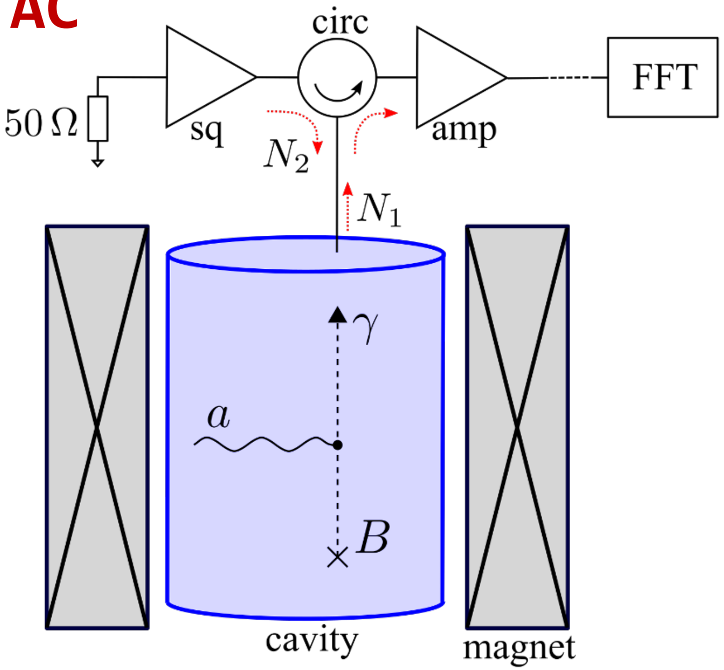


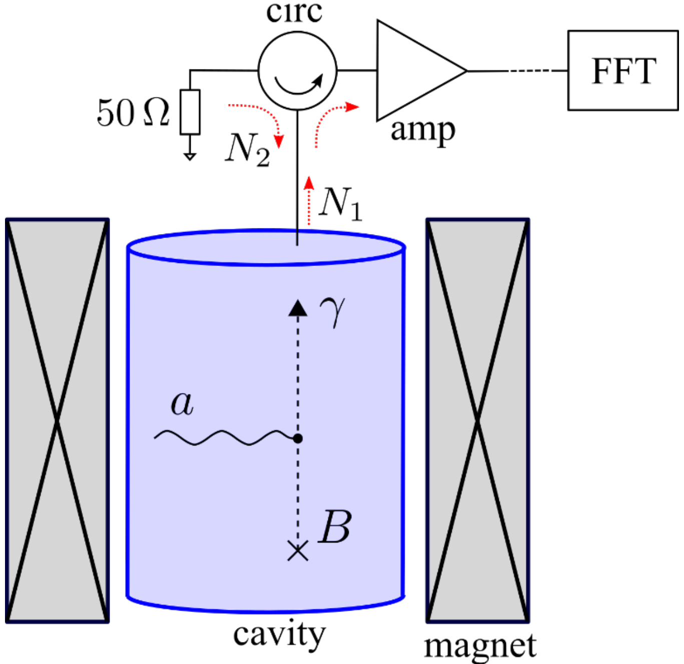


HAYSTAC uses squeezing to increase their sensitivity bandwidth, and thus speed up they cavity scan, by a factor of 1.9 compared to SQL



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





Counting single photons to search for axion-like dark matter

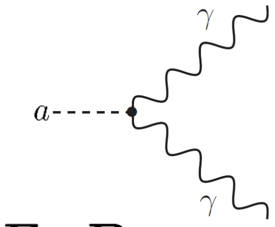
$$a(t) = a_0 \cos \omega_a t$$

interaction with photons:

ALP field amplitude

symmetry breaking scale

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

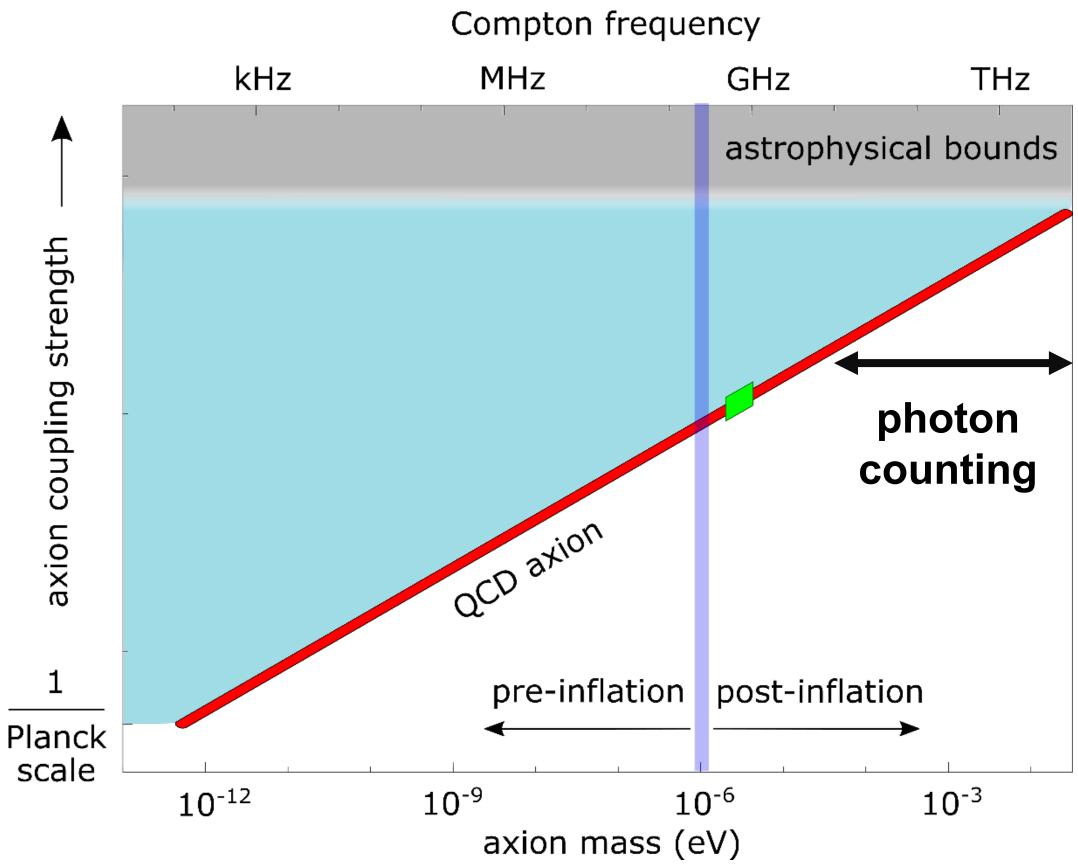


$$\mathcal{L}_{a\gamma\gamma} = g_{a\gamma\gamma} a \boldsymbol{E} \cdot \boldsymbol{B}$$

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

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)]



Summary: searches for axion-photon interaction

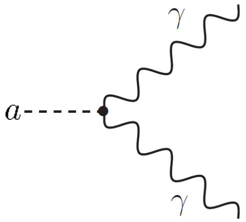
$$a(t) = a_0 \cos \omega_a t$$

interaction with photons:

ALP field amplitude → a

symmetry breaking scale → f_a

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



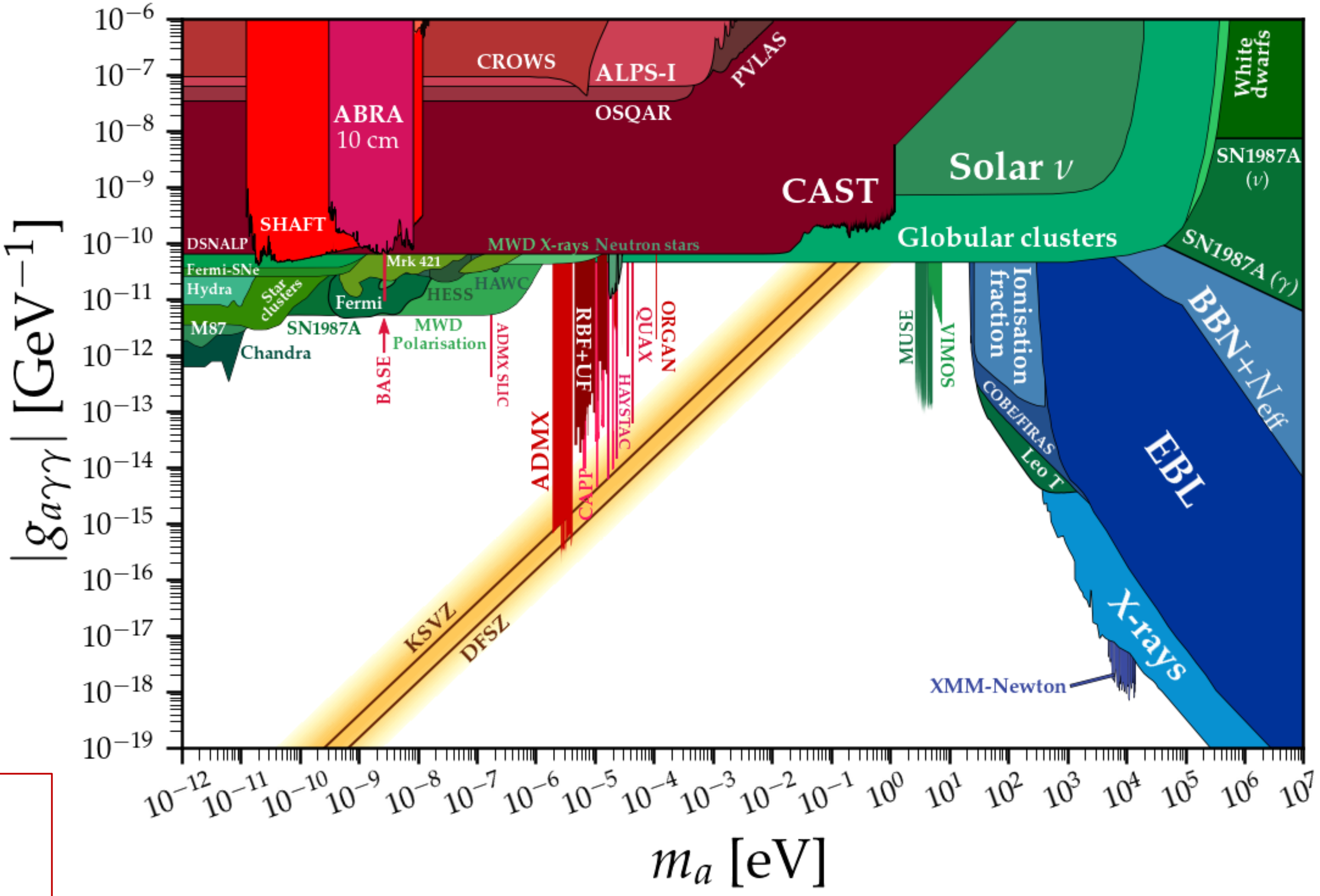
$$\mathcal{L}_{a\gamma\gamma} = g_{a\gamma\gamma} a \boldsymbol{E} \cdot \boldsymbol{B}$$

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

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 nuclear spins

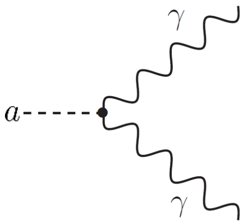
1. Pseudoscalar light particle: spin = 0, wide range of possible masses [Phys. Rev. D **98**, 035017 (2018)]
2. Proposed to solve the **strong CP problem** of Quantum Chromodynamics [Phys. Rev. Lett. **38**, 1440 (1977)]
3. Axion-like particles (ALPs) arise naturally in string theories, symmetries broken 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

symmetry breaking scale

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



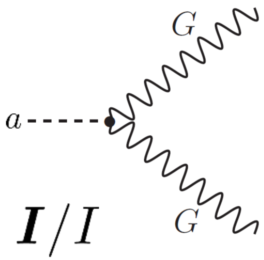
$$\mathcal{L}_{a\gamma\gamma} = g_{a\gamma\gamma} a \boldsymbol{E} \cdot \boldsymbol{B}$$

→ 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 (strong-CP) defines QCD axion:

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



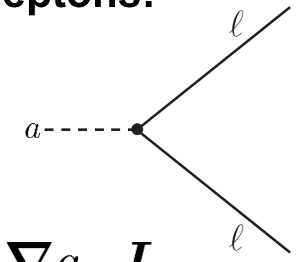
$$\mathcal{H}_{\text{EDM}} = g_d a \boldsymbol{E}^* \cdot \boldsymbol{I}/I$$

→ 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)]