Axion Dark Matter (theory & experiment)

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Outline

- Motivation for axion dark matter
- Axion Dark Matter Theory
- Experiment： Astro-particle
- Experiment： Table-top
- Summary and Outlook

Motivation of ultra-light dark matter

Motivation for Axion

In QCD, we have the Lagrangian that

$$\mathcal{L}_\theta = \frac{\theta_{\rm QCD} g_s^2}{32\pi^2} G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

However, a quark axial rotation will shift this theta term and the quark mass phase. (axial U(1) is anomalous under SU(3) QCD instanton)

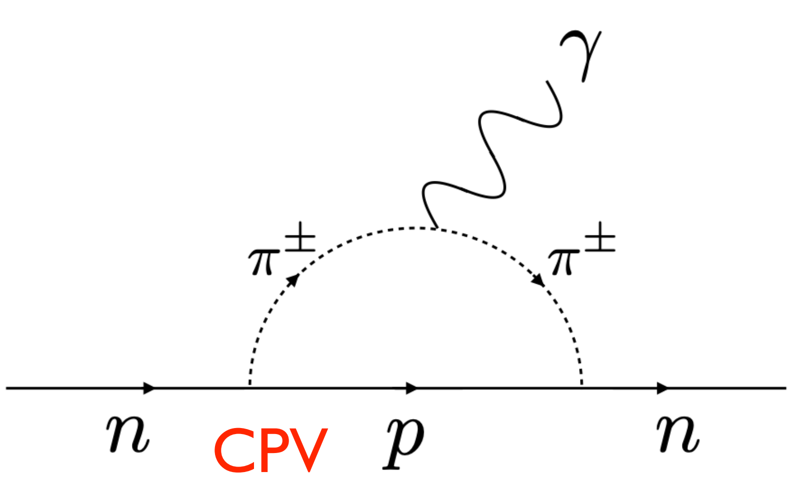
$$q_i \to e^{i\alpha_i\gamma_5} q_i \qquad M \to e^{-2i\alpha} M \qquad \theta \to \theta - 2N_f\alpha$$

Physical: $\theta_{\rm eff} = \theta + \arg\det M_q$

This \theta term also contribute to the neutron EDM

$$\mathcal{L}_{\pi N}^{\rm CPV} \supset \bar{g}_0\, \bar{N}\vec{\tau}\cdot\vec{\pi}N$$

$$\bar{g}_0 \sim \theta_{\rm eff}\cdot\frac{m_u m_d}{m_u + m_d}\cdot\frac{1}{f_\pi}$$

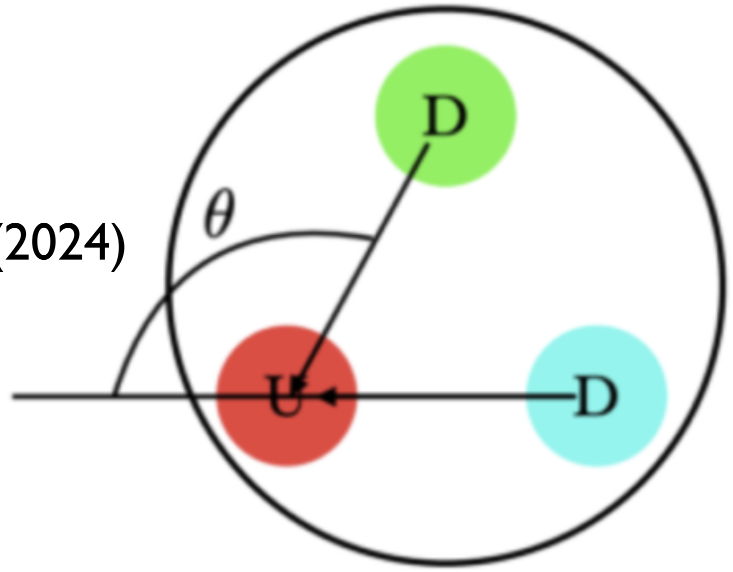


Motivation for Axion

Therefore, we obtain

$$d_n|_{\beta=-1} \sim (0.5-1.5) \times 10^{-16}\, e\,\mathrm{cm} \times \bar{\theta}.$$

Yohei Ema, Ting Gao, Maxim Pospelov and Adam Ritz, Phys. Rev. D 110, 034028 (2024)



Consider the current limit

$$|d_n| < 1.8 \times 10^{-26}\, e \cdot \mathrm{cm} \quad (90\%\ \mathrm{CL}$$

nEDM Collaboration, *Phys. Rev. Lett.* **124**, 081803 (2020)

$$|\theta_{\mathrm{QCD}}| \lesssim 10^{-10}$$

Why it is so small?

One natural question is that is the theta term zero?

If yes, is there a symmetry to protect it?

Dynamical tunning from symmetry

Motivation for Axion

Consider theta as a dynamical field, introduce the "axion" a

$$\mathcal{L} \supset \left(\frac{a}{f_a} + \theta\right) \frac{1}{32\pi^2} G\tilde{G}$$

The anomalous axial U(1) symmetry is the shift symmetry fro axion

$$a \to a + \alpha f_a, \quad \theta \to \theta - \alpha,$$ PQ symmetry

Peccei

Quinn

Dirac Medal 2000

Below QCD scale, described by the Chiral perturbation theory

$$\mathcal{L}_\chi \supset \frac{f_\pi^2}{4} \mathrm{Tr}[M_q \Sigma^\dagger + \Sigma M_q^\dagger]$$

Generated by the QCD instanton effect

$$\Sigma(x) = \exp\left(\frac{2i\pi^a(x)T^a}{f_\pi}\right)$$

$$E(\theta) = m_\pi^2 f_\pi^2 \cos(\theta).$$

$$\langle a \rangle = -\bar{\theta} f_a.$$

$$V = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4 m_u m_d}{(m_u + m_d)^2} \sin^2\left(\frac{a}{2f_a} + \frac{\bar{\theta}}{2}\right)}.$$

$$d_n \propto \frac{a}{f_a} + \bar{\theta} = 0.$$

Motivation for Axion

Expanding on small theta, we have

$$m_a = \frac{m_\pi f_\pi}{f/N}\sqrt{\frac{m_u m_d}{2(m_u+m_d)^2}} \approx 6\,\mu\text{eV}\,\frac{10^{12}\,\text{GeV}}{f/N}.$$

The strong dynamics of QCD generates a potential for the axion, which relaxes it to the value that cancels the θ term, explaining why we do not see a nonzero neutron EDM. The axion mass is of order $m_\pi f_\pi/f$. The axion is very light and very weakly coupled when f is a UV scale.

Light axion, high breaking scale

PQ symmetry may also be anomalous under SU(2)

$$\mathcal{L} \supset \frac{a}{f_B}\frac{1}{32\pi^2}B\tilde{B} + \frac{a}{f_W}\frac{1}{32\pi^2}W\tilde{W}.$$

$$\frac{\partial_\mu a}{f_Q} Q^\dagger \sigma^\mu Q.$$

Quark couplings are there, or generated by the RG runing

KSVZ Axion, DFSZ

Original PQ break at the EW scale

Ruled out by various experiments

"Invisible" axion: Small PQ symmetry breaking

KSVZ axion

DFSZ axion

$$V_{\rm PQV}(\theta) = 2|c|M_{\rm Pl}^4\left(\frac{f}{\sqrt{2}M_{\rm Pl}}\right)^n \cos\left(n\theta+\varphi\right).$$

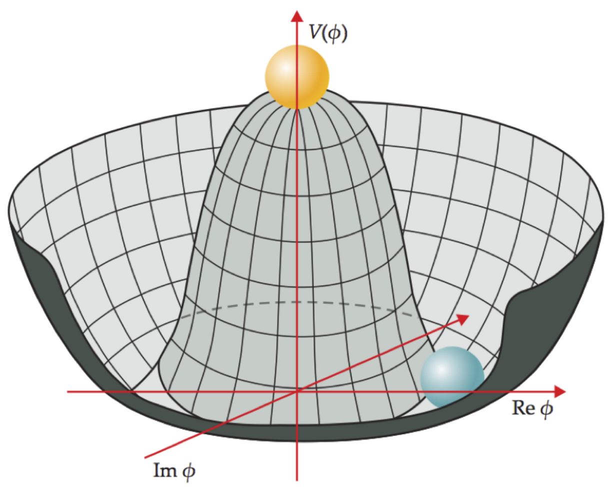
Axion quality problem:

- Large explicit PQV terms.
- Gravitational breaking of PQ symmetry.

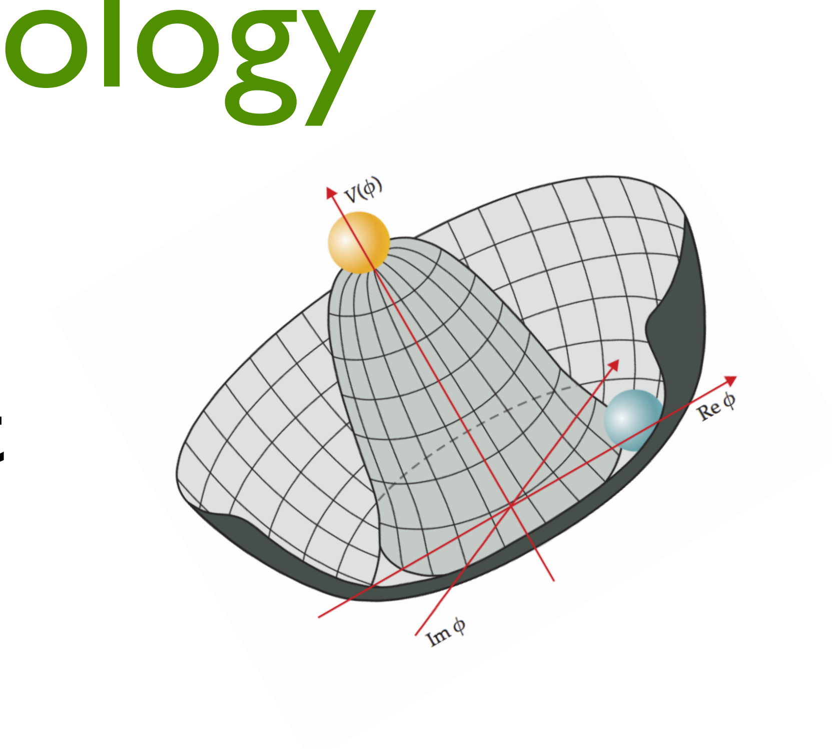
Need many powers of suppression

Extra dimension (gauged PQ in the 5-th dim), string theory, etc

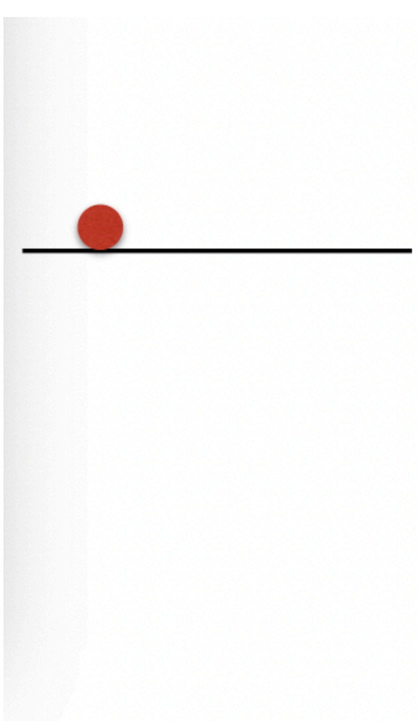
Axion cosmology

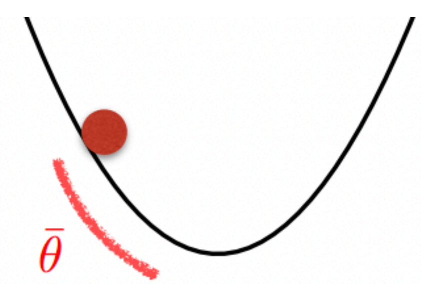


Misalignment



Axion evolution





$$\theta \equiv a/f_a$$

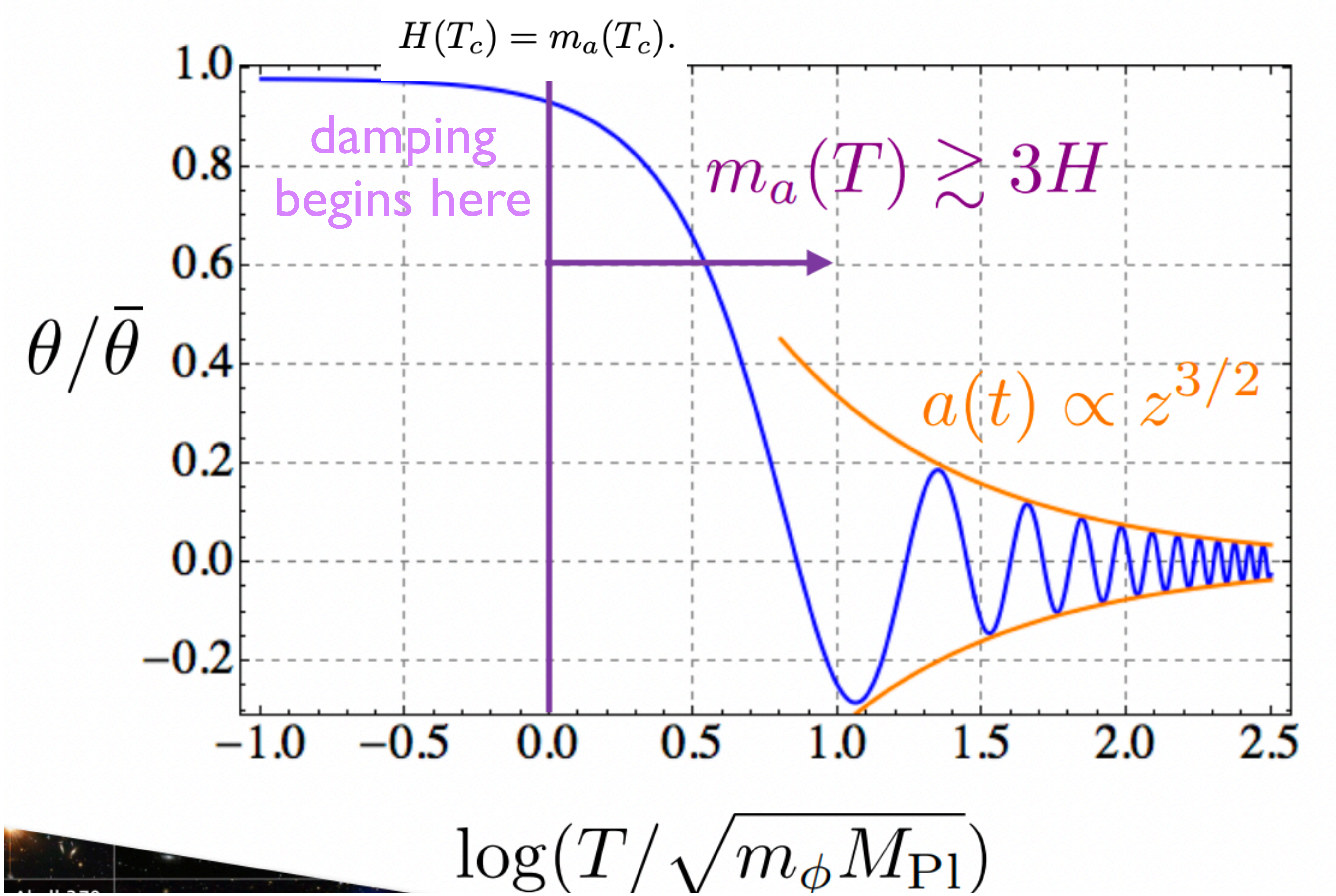
$$\ddot{\theta} + 3H\dot{\theta} + m_a^2(T)\theta = 0$$

"Friction" "Oscillation"

Hubble term

Axion cosmology

$$\ddot{\theta} + 3H\dot{\theta} + m_a^2(T)\theta = 0$$



behave like
CDM

Axion cosmology

Axion mass at finite T

$$V \sim m_u m_d m_s T e^{-8\pi^2/g_3^2(T)} \cos\left(\frac{a}{f_a} + \bar{\theta}\right) \sim m_u m_d m_s \frac{\Lambda^9}{T^8} \cos\left(\frac{a}{f_a} + \bar{\theta}\right)$$

$$m_a(T)^2 \sim \frac{m_u m_d m_s}{f_a^2} \frac{\Lambda^9}{T^8}.$$

Too light, non-thermal

$$a = \theta_0 f_a, \qquad H > m_a(T). \qquad\qquad H(T_c) = m_a(T_c).$$

$$a = \theta_0 f_a \sqrt{\frac{m_a(T_c)}{m_a(T)}} \left(\frac{R(T_c)}{R(T)}\right)^{3/2} \cos m_a t, \qquad T < T_c.$$

Energy conservation

$$\rho_a \sim \theta_0^2 \Lambda_{QCD}^4 \frac{m_a(T_c)}{m_a} \left(\frac{\Lambda_{QCD}}{T_c}\right)^3 \sim \theta_0^2 \Lambda_{QCD}^4 \frac{f_a \Lambda_{QCD}}{T_c M_p} \sim \rho_{DM} \sim \text{eV}\, \Lambda_{QCD}^3,$$

$$T_c \sim \text{GeV and } f_a \sim 10^{11} \text{ GeV}. \qquad\qquad f_a \sim 10^{12} \text{ GeV}$$

Lattice simulation suggests a slightly large f

Axion Cosmology

$$\Omega_a h^2 = 0.01\theta_0^2 \left(\frac{f_a}{10^{11}\,\mathrm{GeV}}\right)^{1.19}$$

To have different f_a

- Initial θ_0 small for large f_a, or damp the E out of axion。
- $\theta_0 \sim \pi$ for small f_a, or some other particles decay into axion

Except misalignment from post-inflation, the axion can also produced fro the decay of topological defects

Axion mini-cluster, axion star, etc.

Spectrum of Ultra-light Dark Matter

The Virial Theorem: the velocity of dark matter near Earth is approximately 10^{-3} boosted by gravity.

$$a(t) = \frac{\sqrt{2\rho_{\rm DM}}}{m_a}\cos(m_a t + \phi)$$

Frequency: $\omega_a \simeq {\rm GHz}\,\frac{m_a}{10^{-6}\ {\rm eV}}$

Coherence: $\tau_a \simeq {\rm ms}\,\frac{10^{-6}\ {\rm eV}}{m_a}$

Max Exp. Size: $\lambda_a \simeq 200\ {\rm m}\,\frac{10^{-6}\ {\rm eV}}{m_a}$

Axion DM as an example, same for other kinds (DPDM, etc)

$$\tau_a \sim 1/m_a\langle v_{\rm DM}^2\rangle \sim Q_a/m_a \sim 10^6/m_a$$

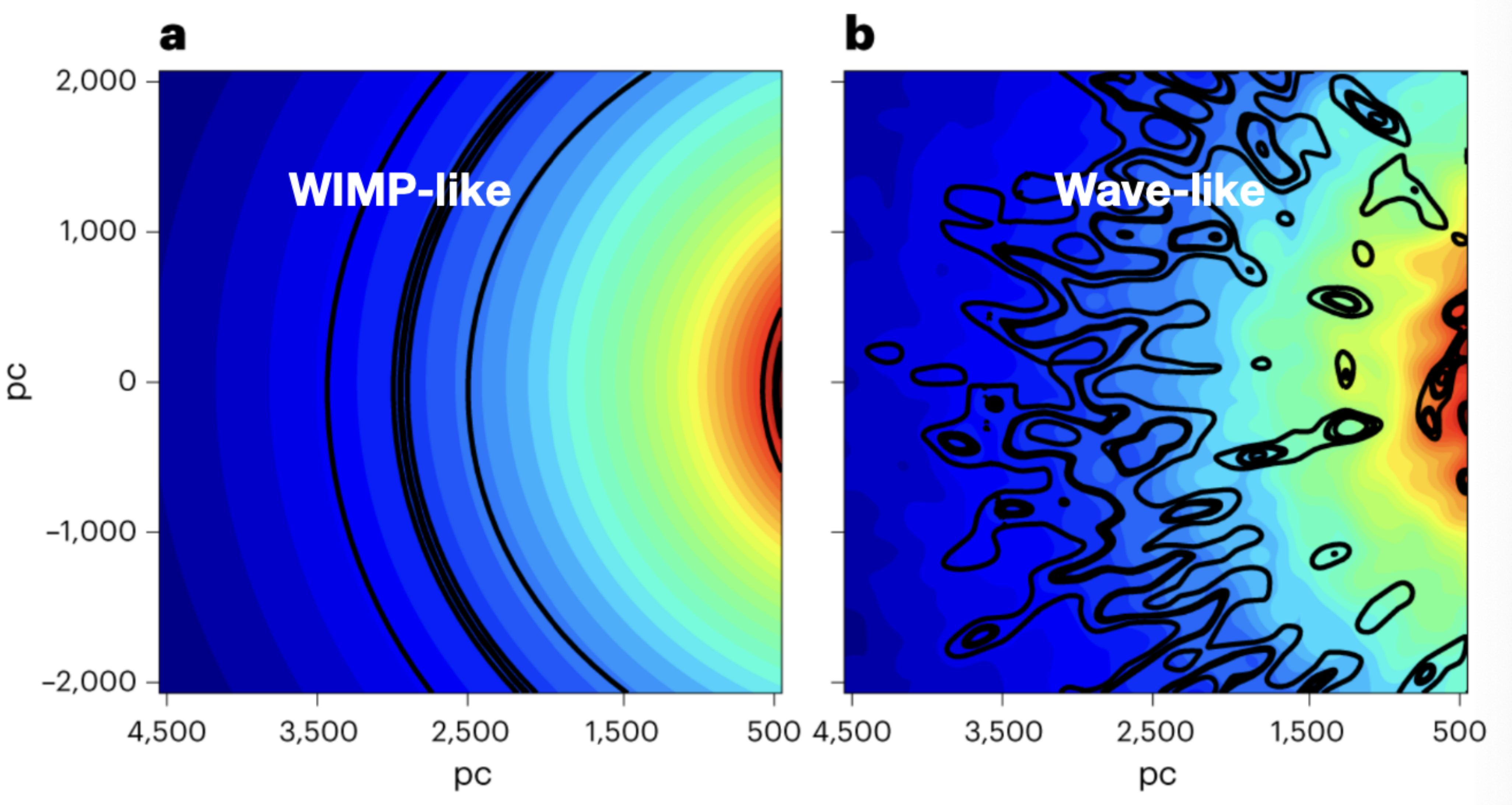
Bandwidth of axion DM is 10^{-6}

Detector bandwidth < 10^{-6} accelerate the scan rate

$$\lambda_a \sim 1/m_a\sqrt{\langle v_{\rm DM}^2\rangle} \sim 10^3/m_a$$

Momentum width 10^{-3}

Differences of Wavelike DM in Small-Scale Structures

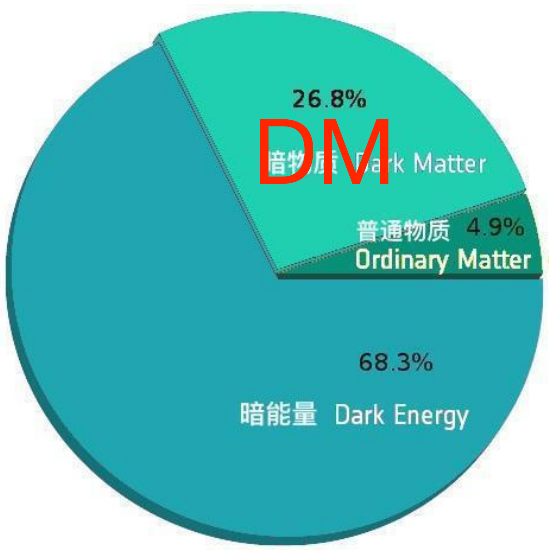


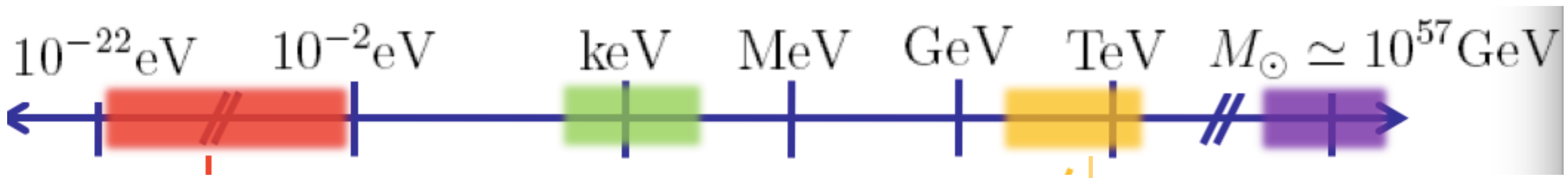
Nature Astronomy 7, 736 (2023)

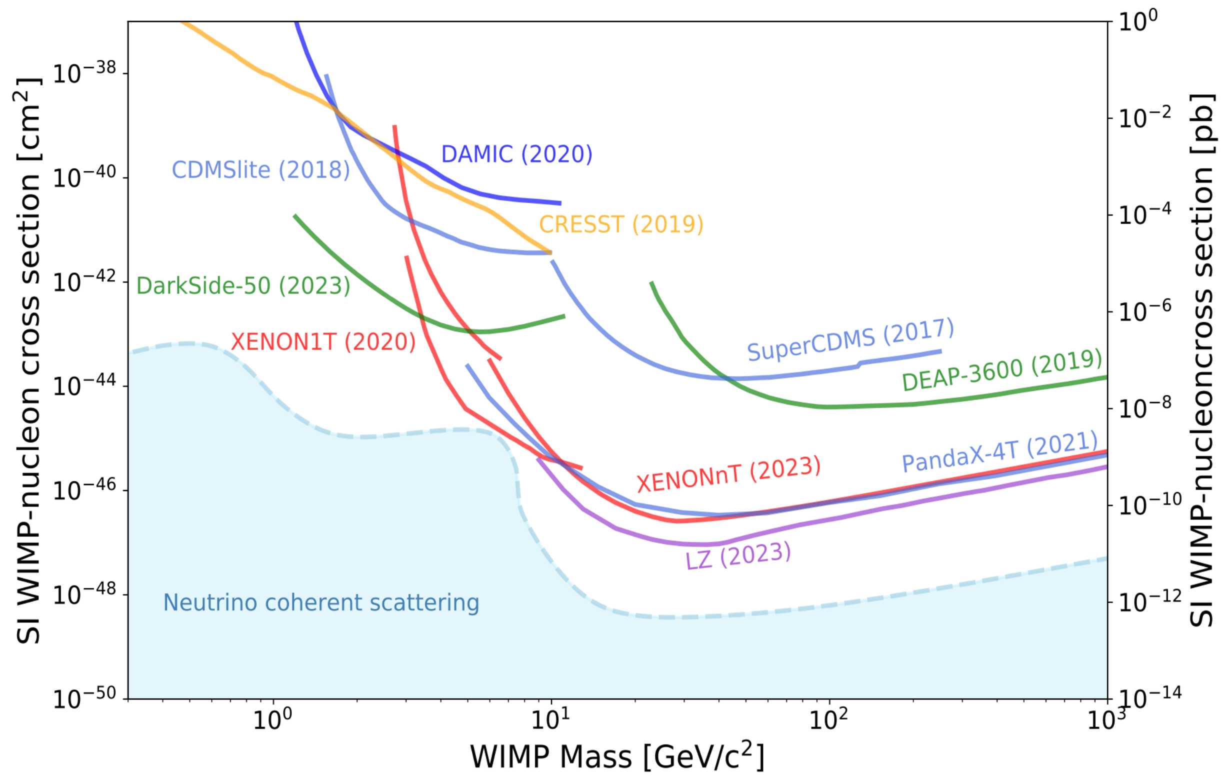
Axion detection

Traditional DM

The nature of dark matter remains unknown, and its possible candidates span an extremely wide range of masses.



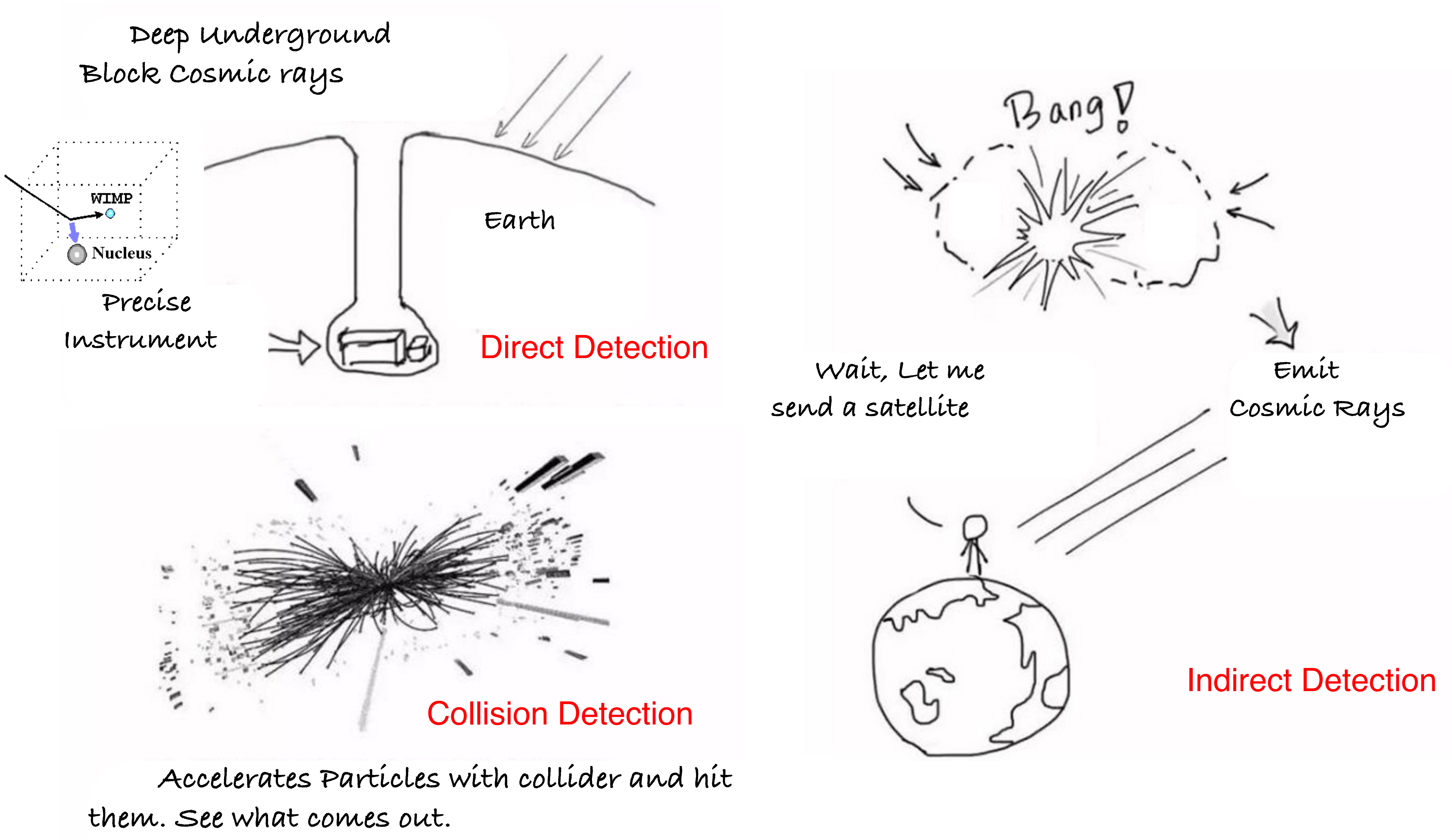




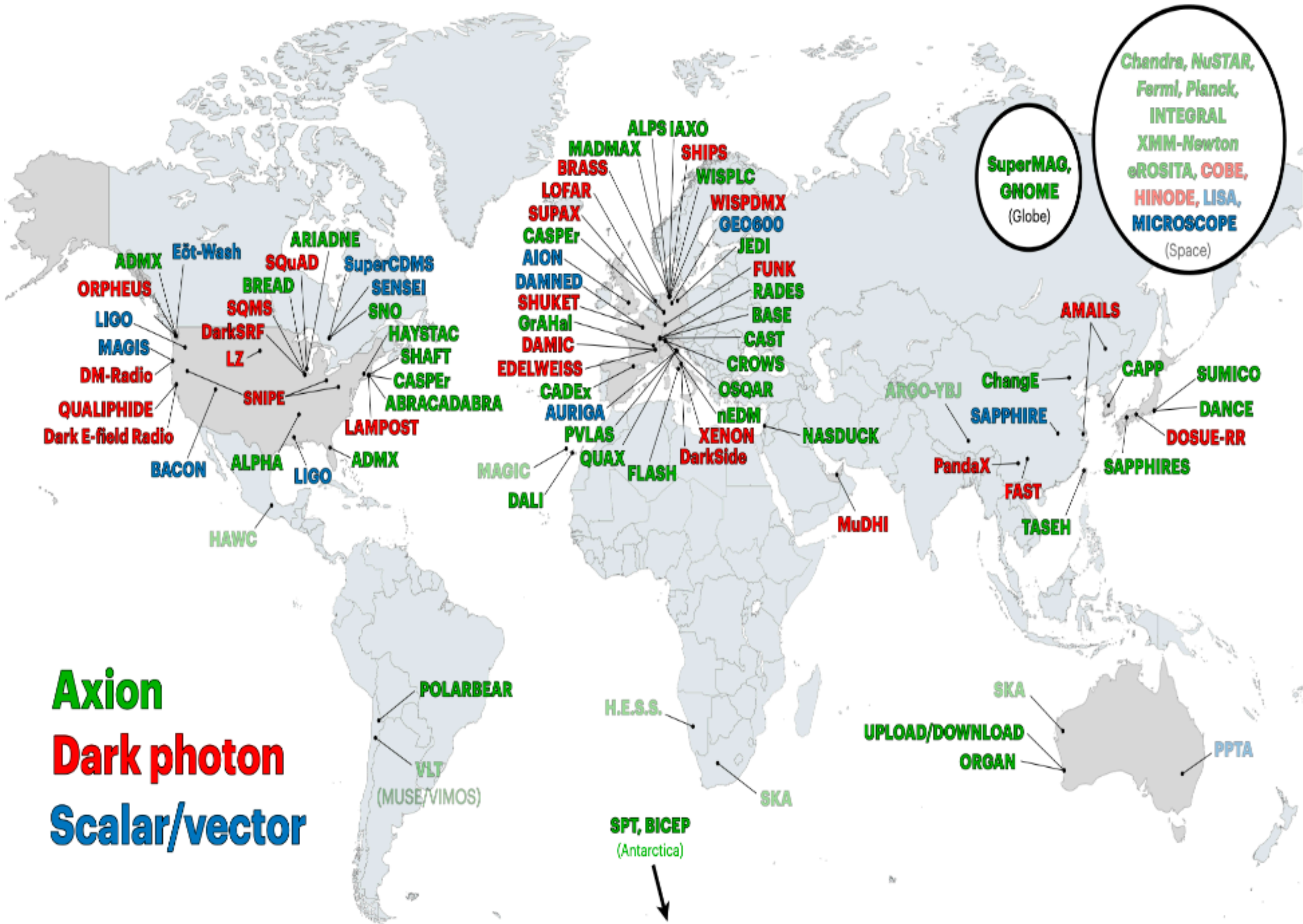
Particle Data Goup, Phys. Rev. D 110, 030001 (2024)

WIMPs: Tightly constrained, with narrowing discovery prospects

Particle-like DM search: From the Cosmos to Underground Labs



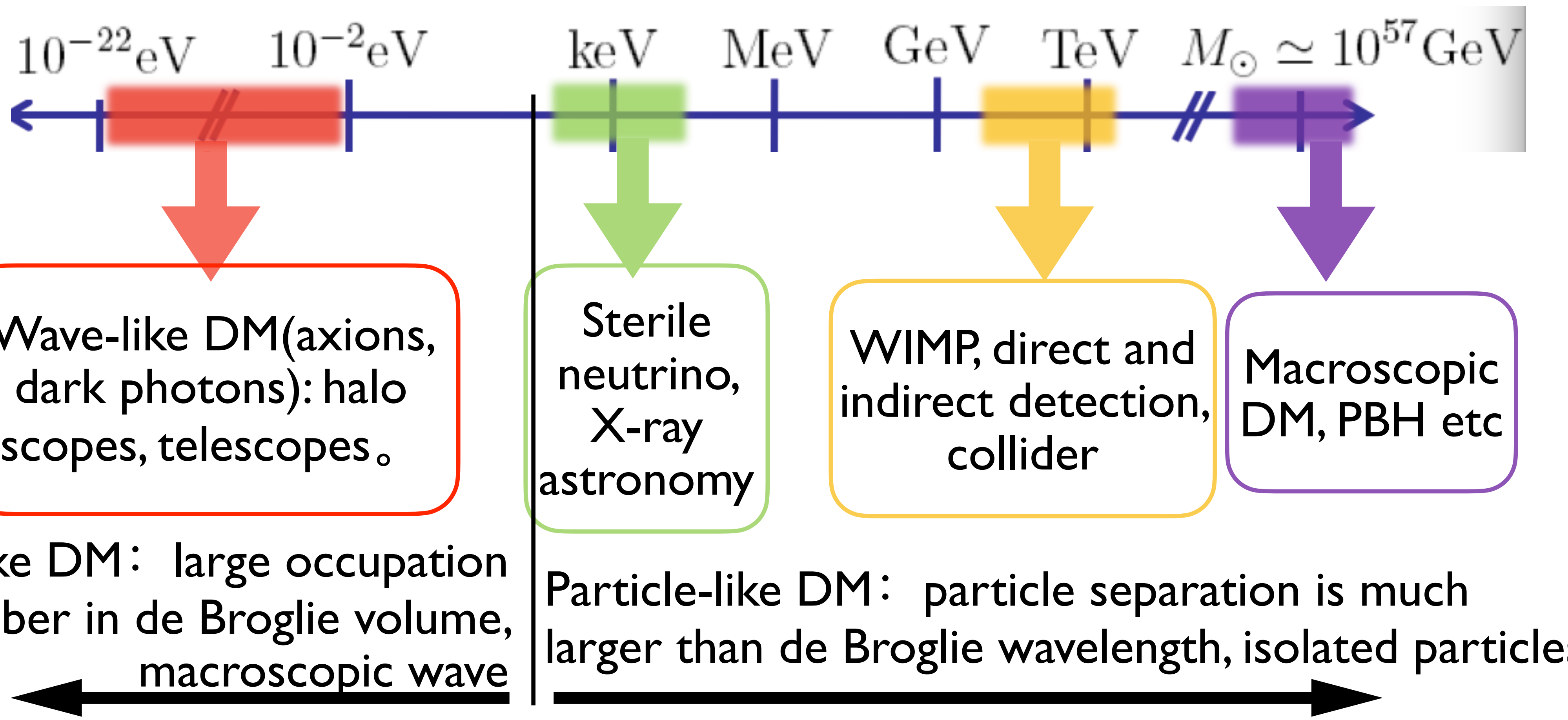
Various wave-like DM search



Wave-like DM

- The Central Question： What Is Dark Matter?

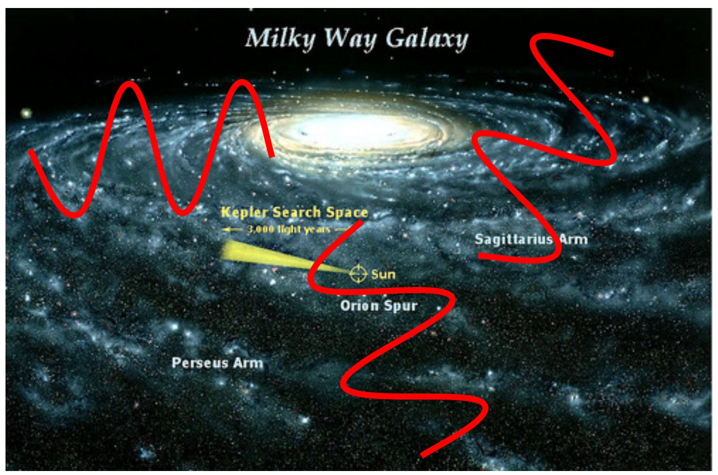
The composition of DM remains unknown, with candidate particles spanning an extremely wide mass range.



Particle-like DM direct detection, see plenary talks in the morning

Wave-like dark matter

Quantum mechanics： All matter exhibits both particle-like and wave-like properties



(m~10^{-22}eV)

De Broglie wavelength reach galactic scale(kpc)

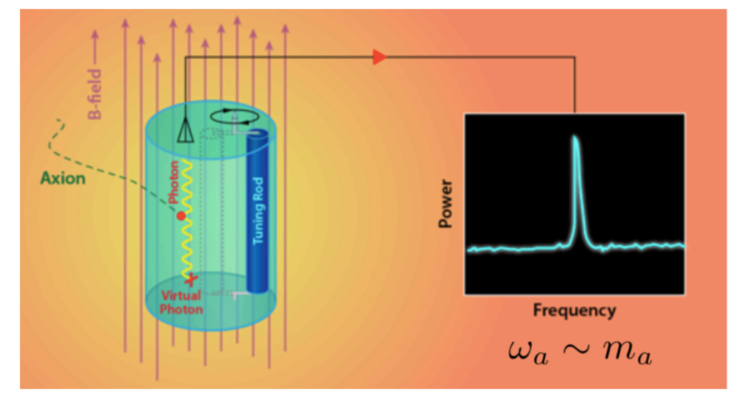
Depends on astronomy observation(spacetime measurement)

Utilizing Astronomical Observations for Detection

Wave-like dark matter has a de Broglie wavelength on macroscopic scales, manifesting as a coherent oscillating background field on large scales.

Distinct from traditional dark matter detection, more to explore

Like GW detection



$m_a \sim \mathrm{GHz} \sim 10^{-6}\ \mathrm{eV}$

Compton wavelength reach lab scale(m)

Resonant cavity and quantum amplifier

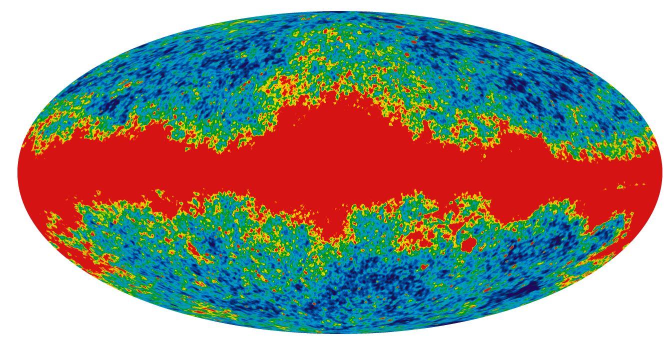
Proposed new quantum detection experiments

Astro-particle detection

Background

Radio astronomy is popular

2018 BPPF：

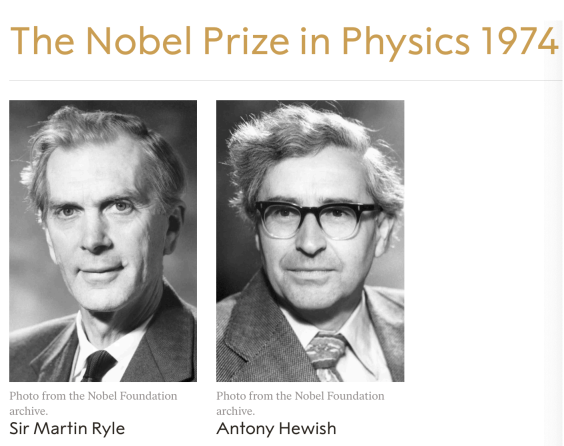


CMB anisotropy
from WMAP

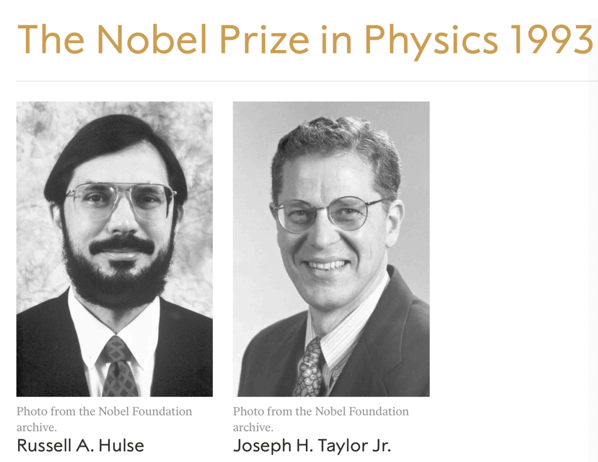
2020 BPPF：

Black hole
image from EHT

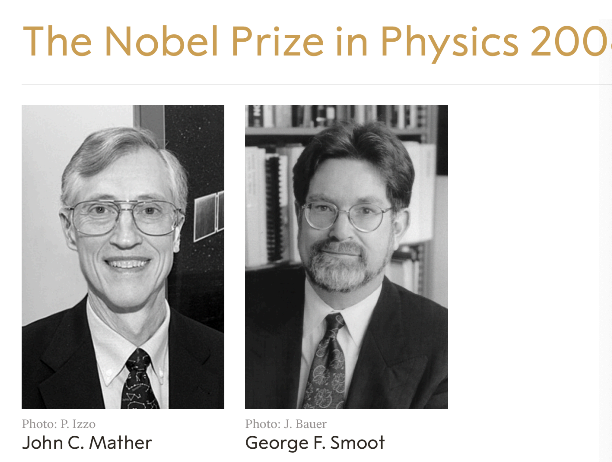
Radio astronomy
development、
discovery of pulsar



Binary pulsars to
confirm GW
existence

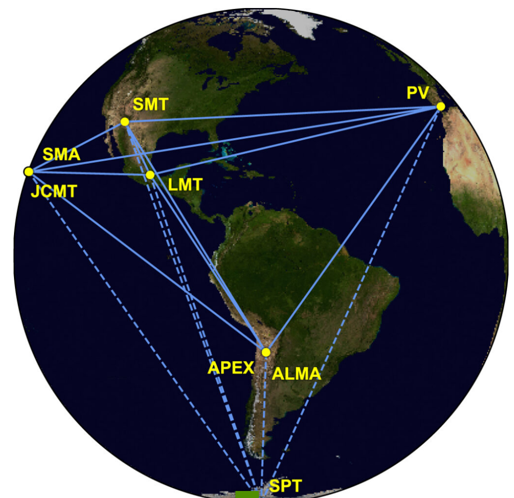


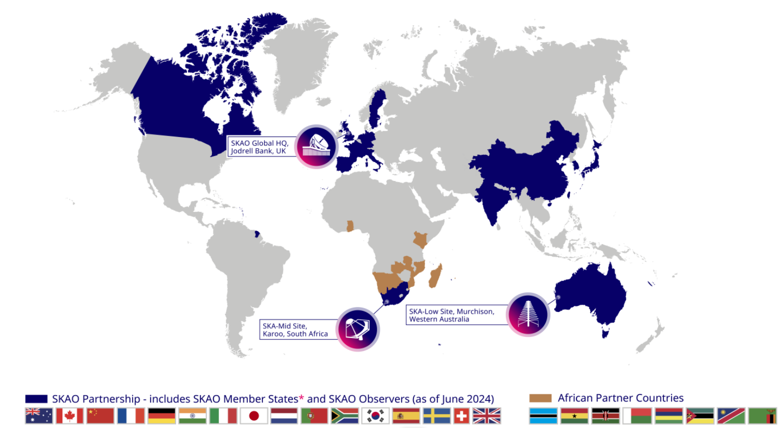
Cosmic
microwave
background

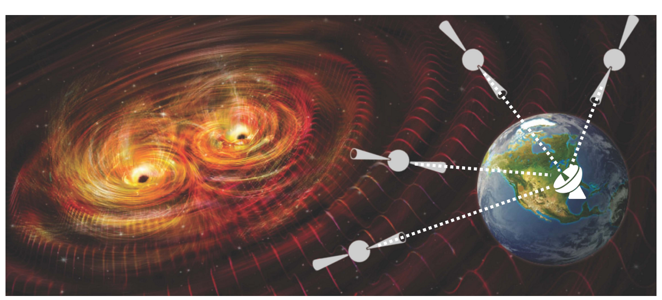


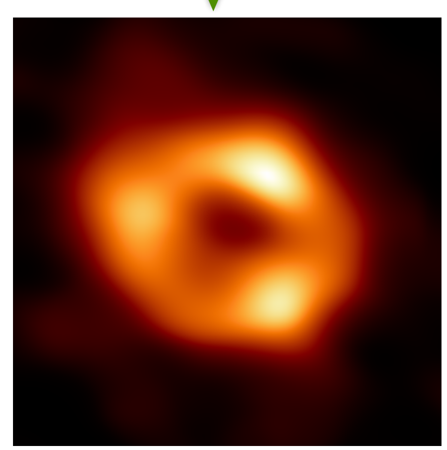
Large-Scale Radio Astronomical Observatories

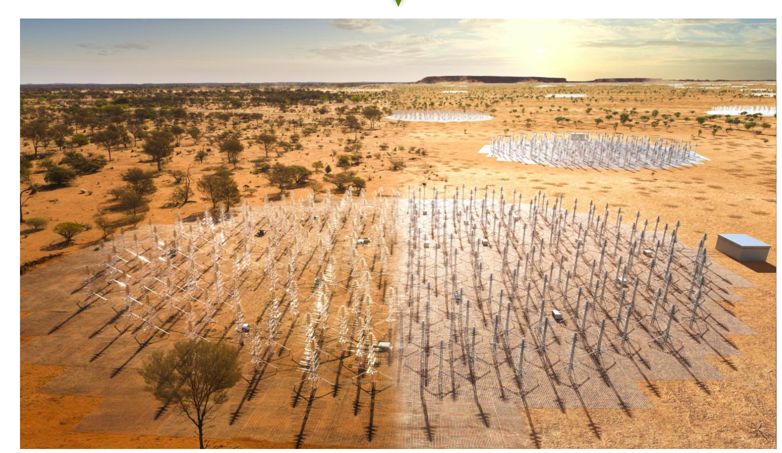
Pulsar Timing Array (PTA)	Event Horizon Telescope (EHT)	Square Kilometre Array (SKA)







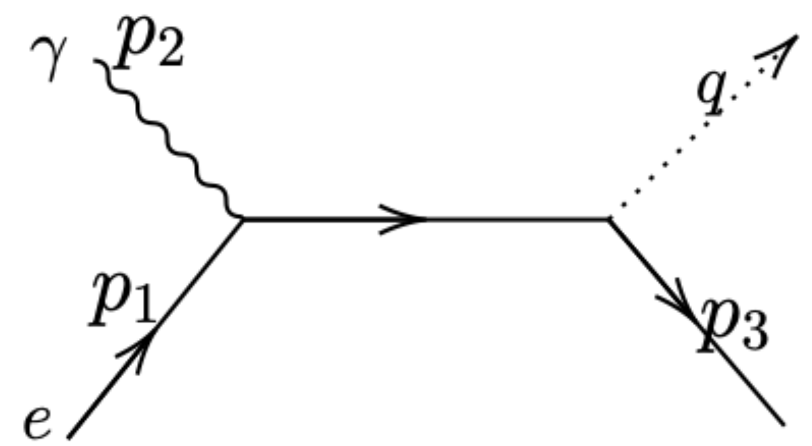


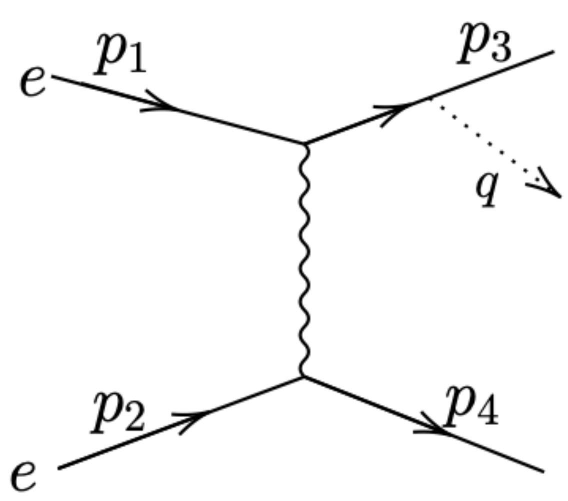


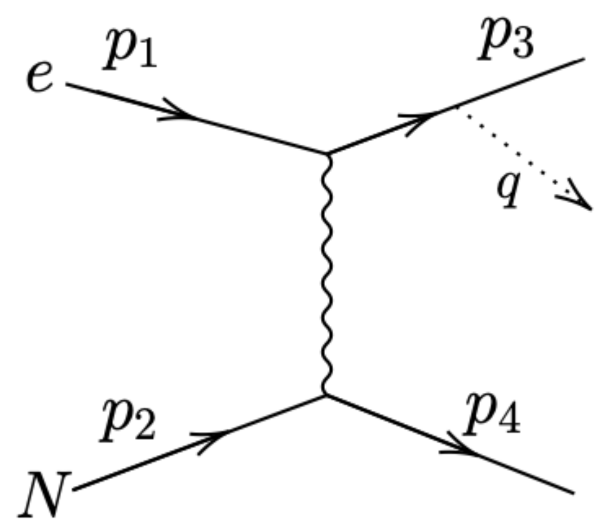
Radio astronomical observation can provide data

Stellar cooling

- Compton scattering: $\gamma + e^- \to e^- + b$;
- $e - N$ bremsstrahlung: $e^- + N \to e^- + N + b$;
- $e - e$ bremsstrahlung: $e^- + e^- \to e^- + e^- + b$,

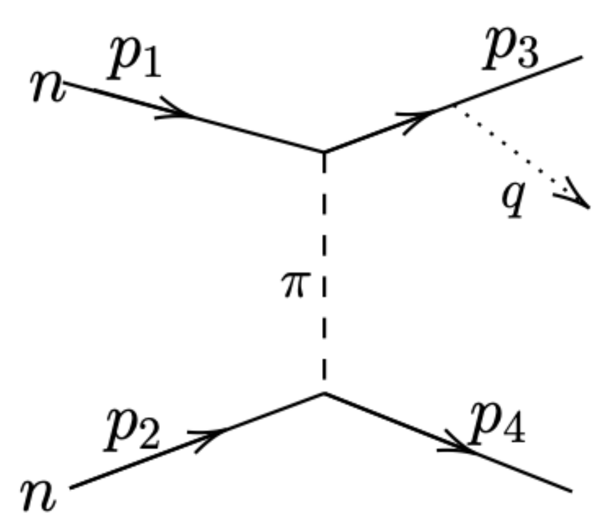






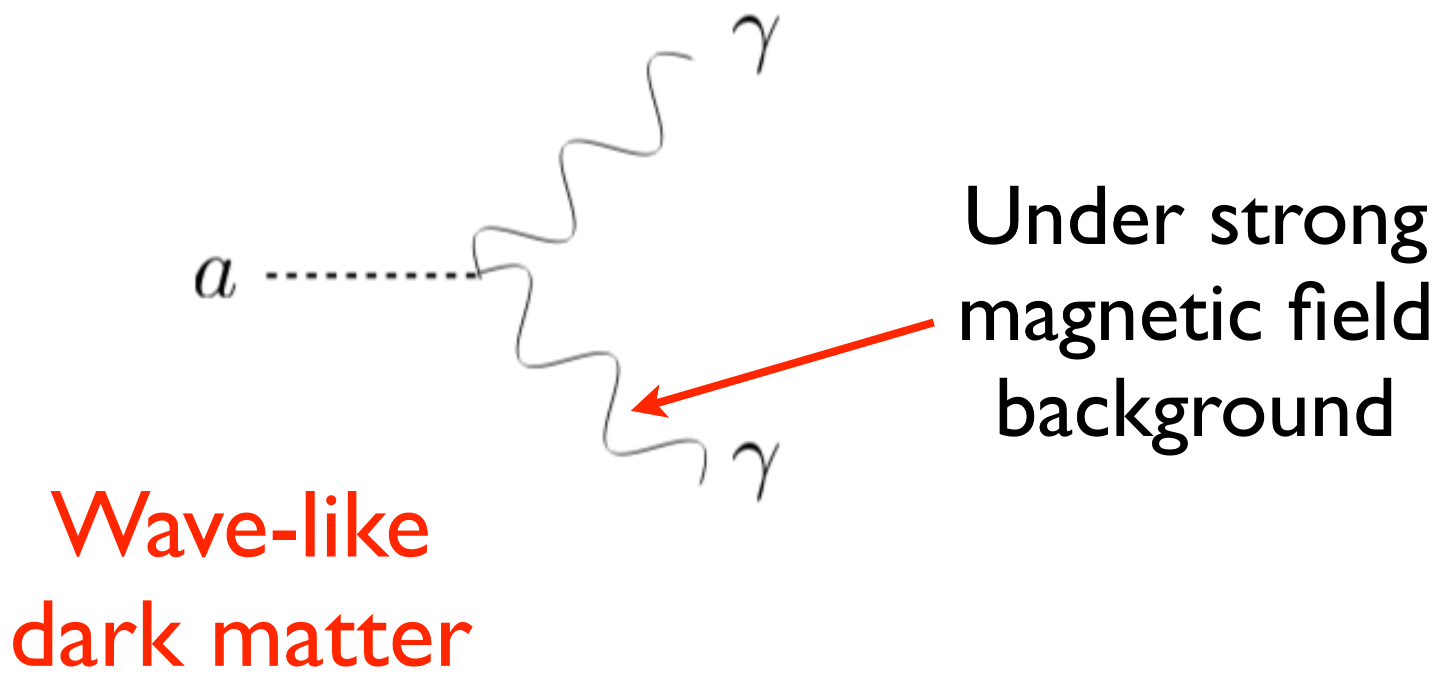
- $N - N$ bremsstrahlung: $N + N \to N + N + b$;
- pion-proton scattering: $\pi^- + p^+ \to n + b$,

where N can be proton or neutron and p^+ is proton.



Light axion radiation

Axion-photon conversion



$$\nabla \times \mathbf{B} \simeq \partial_t \mathbf{E} + \mathbf{J} + \underline{g_{a\gamma\gamma} \mathbf{B}\, \partial_t a}$$

Axion dark matter induces an effective current under strong magnetic field.

$$J_{\text{eff}}(t) \sim g_{a\gamma\gamma} B_0(t) \sqrt{\rho_{\text{DM}}} \cos m_a t$$

Axion-photon conversion

- Effects of axion-photon conversion in the NS, magnetar, etc

A. Hook, Y. Kahn, B. R. Safdi, Z-q Sun, *Phys.Rev.Lett.* 121 (2018) 24, 241102

B. R. Safdi, Z-q Sun, A.Y.Chen, *Phys.Rev.D.* 99 (2019) 12, 123021

- Radio telescope

Green Bank Radio Telescope

J.Foster et.al., *Phys.Rev.Lett.* 125 (2020) 17, 171301

J.Foster et.al., *Phys.Rev.Lett.* 129 (2022) 25, 251102

J1745-2900

J. Darling, *Phys. Rev. Lett. 125, 121103 (2020)*

Other works based on mini-cluster, axion star, etc.

- Constrain from CMB

CMB/FIRAS, Spectral distortions

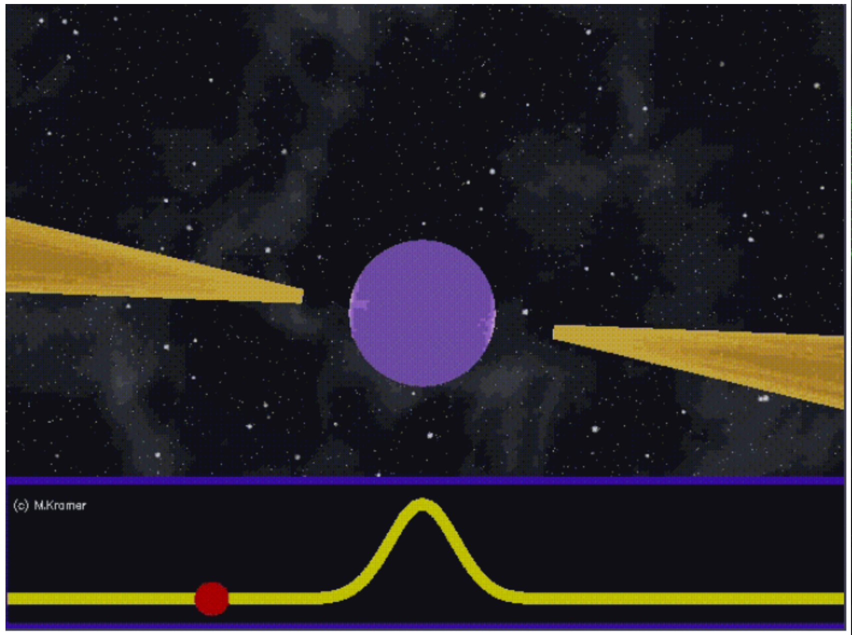
A. Mirizzi, J. Redondo, G. Sigl, *JCAP08 (2009) 001*

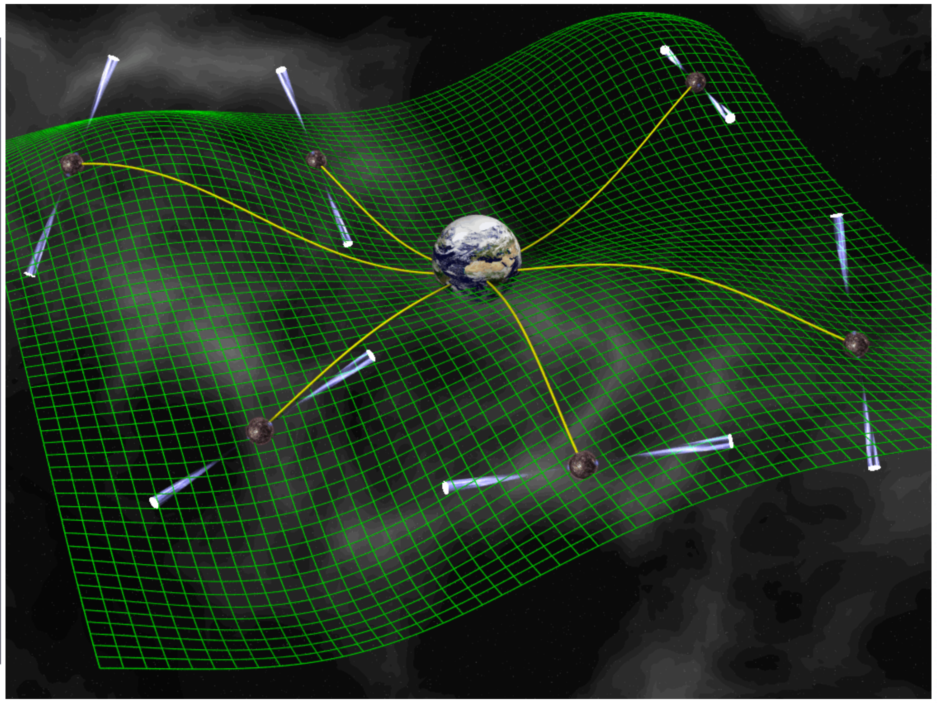
Anisotropies and "patchy screening"

S. Goldstein, *Phys.Rev.Lett.* 134 (2025) 8, 081001

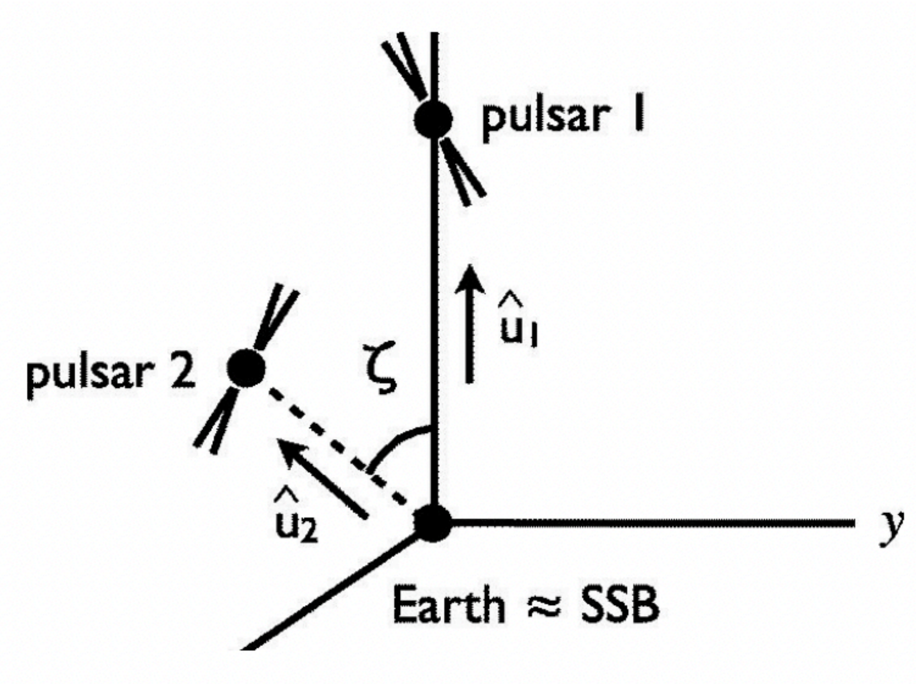
PTA： wave-like DM

A pulsar is a highly magnetized, rotating neutron star that emits beams of strong electromagnetic radiation along its magnetic axis, producing periodic pulses of emission.





PTA correlates signal pulses from multiple pulsars

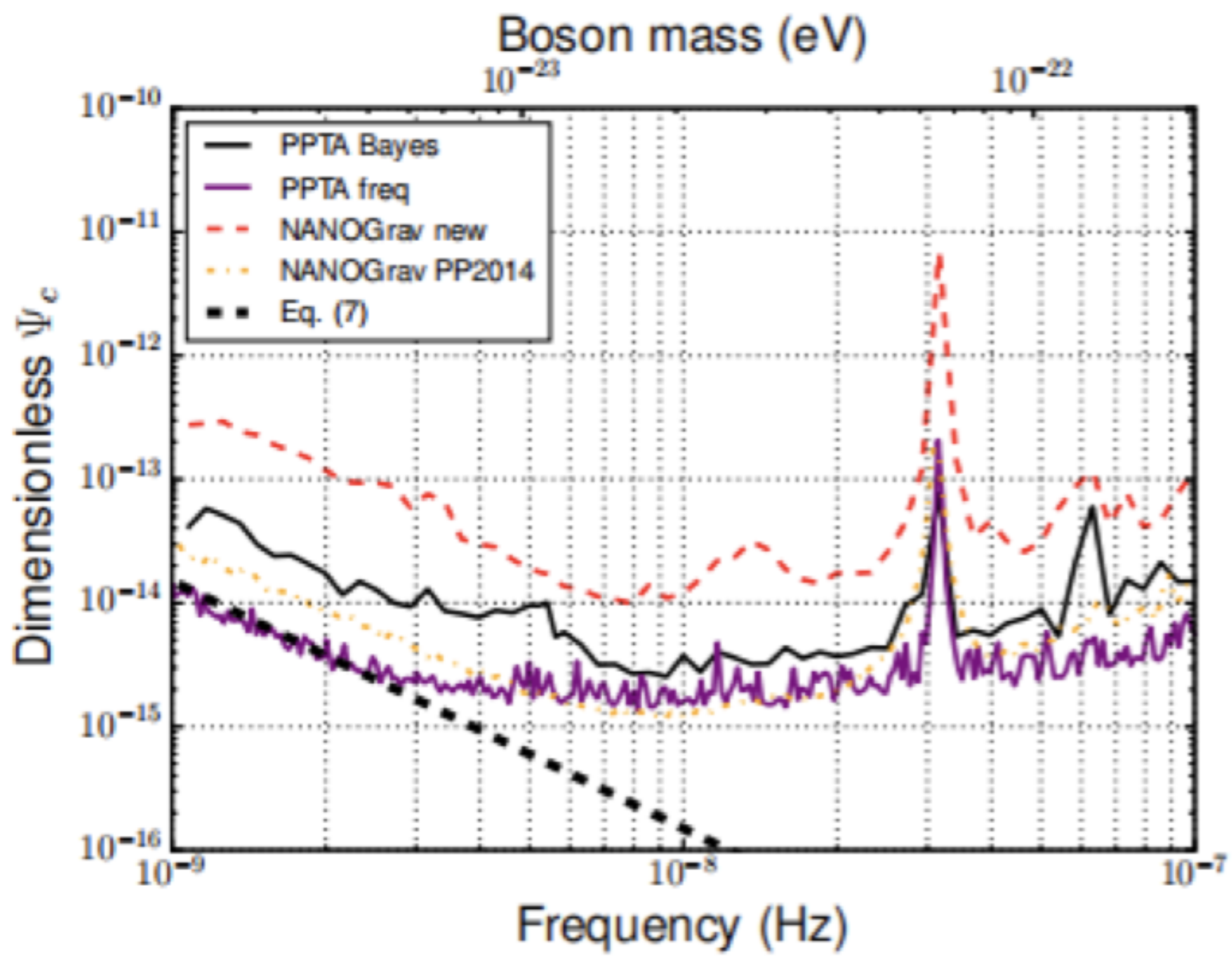


Pulsar timing observations involve obtaining a series of pulse arrival times at a fixed observational frequency, referenced to atomic time, and comparing these measured values with predictions derived from a pulsar timing model.

PTA： wave-like DM

Gravitational potential of oscillating DM field will change the energy-momentum tensor around, thus change the arrival time of EM pulses

$$s(t) = \frac{\Psi_c}{\pi f} \sin(\alpha_e - \theta_p) \cos(2\pi f t + \alpha_e + \theta_p)$$



PPTA collaboration, *Phys.Rev.D* 98 (2018) 10, 102002

EPTA collaboration, *Phys.Rev.Lett.* 131 (2023) 17, 171001

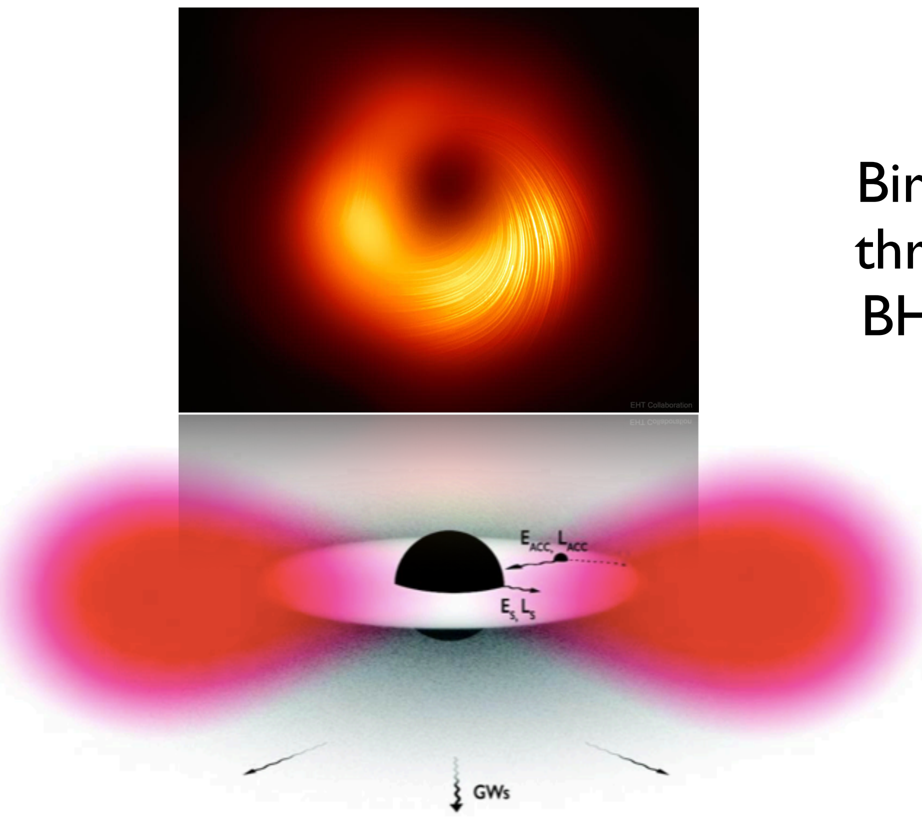
Exclude a small mass window
10^-24.0 ~ 10^-23.3

Polarization observation of EHT to search axions

- Utilize polarization data of EHT to search axion DM

Black hole can be used to search wave-like DM (axions)

Event Horizon Telescope

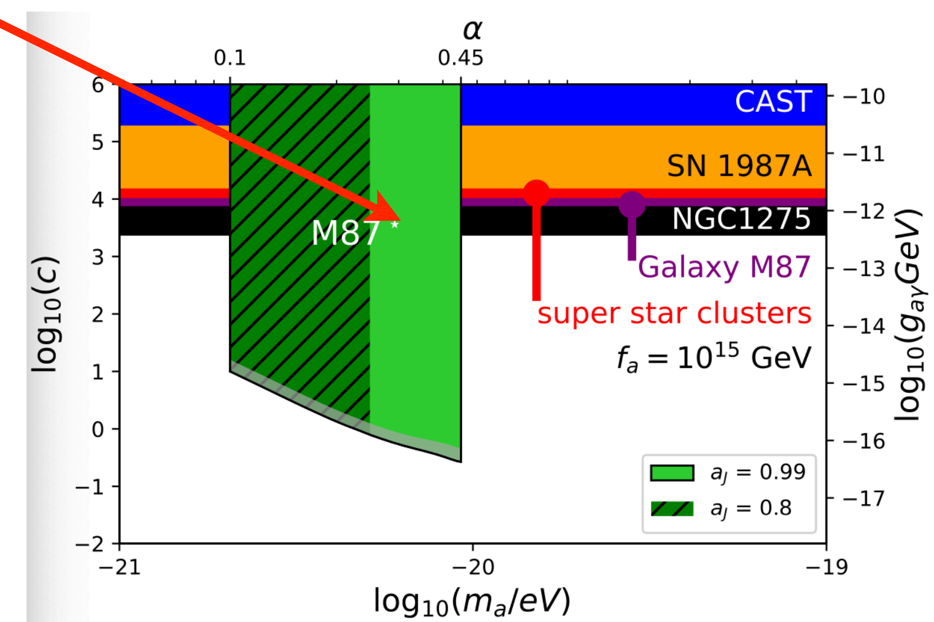


Most sensitive

Birefringence when photons pass through the axion cloud near the BH, polarization angle changes in time periodically

Y.F. Chen, J. Shu, X. Xue, Q. Yuan, Y. Zhao, *Phys. Rev. Lett. 124 (2020) no6, 061102*

Y-f. Chen, … J. Shu., et al, *Nature Astronomy (2022) 5, 592-598*



If wave-like DM exists, like Hawking radiation, rotating BH will radiate axions and form axion cloud near the BH

Super-radiance slow down BH spin rotation (Zel'Dovich, et la (1971).)

H. Davoudiasl, P. B Denton, *Phys.Rev.Lett.* 123 (2019) 2, 02110

paper

Table-top detection

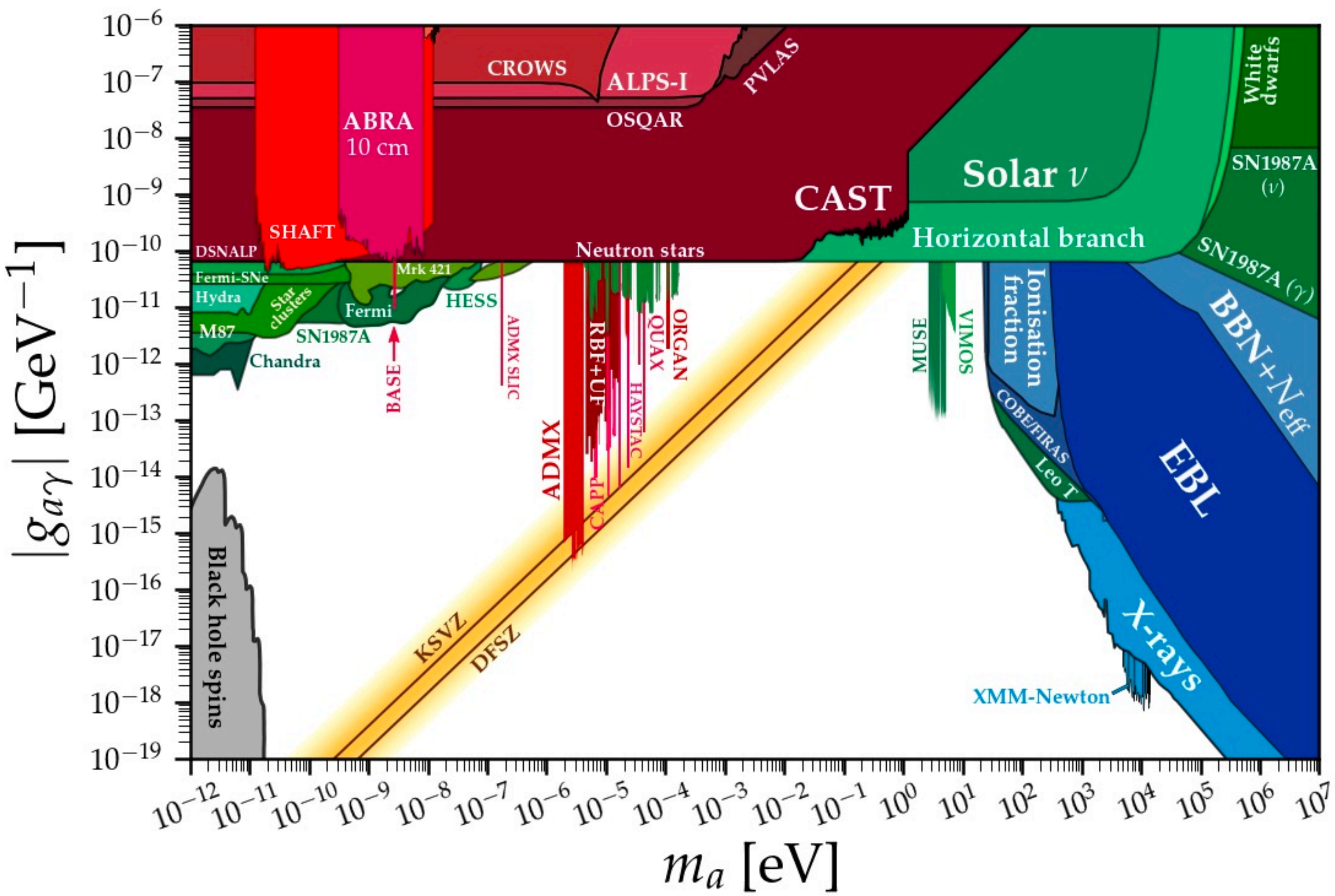
Current status

- Axon dark matter detection competition :
  - Traditional resonant cavity: ADMX, CAPP, HAYSTACK
  - LC circuit: DM Radio, ABRACADABRA
  - Nuclear Magnetic Resonance: CASPER, Spin amplifier (USTC)

  …

- The main experimental limits come from the resonant cavity, CAST, and stellar cooling.

A huge parameter space to be explored!



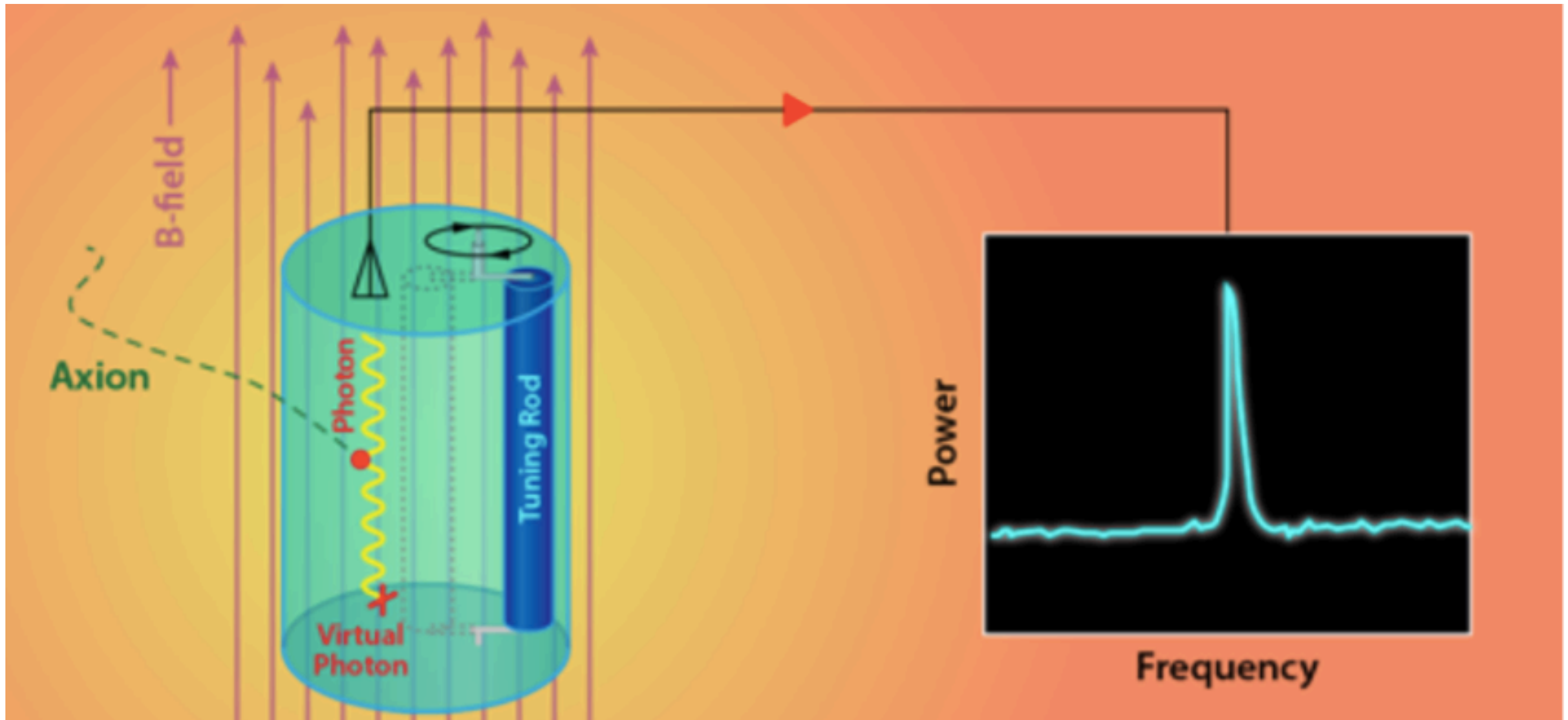
Cavity with static B field

$$\left(\partial_t^2 + \frac{m_a}{Q_1}\partial_t + m_a^2\right)\mathbf{E}_1 \sim m_a \cos m_a t$$

$$Q_a \sim 10^6$$

Quantum amplifier to readout the signal.

$$m_a \sim \mathrm{GHz} \sim 10^{-6}\ \mathrm{eV}$$



$\omega_a \sim m_a$

Cavity size ~ (axion mass)^-1

Signal power decreases with axion mass

e.g. ADMX, HAYSTACK

Resonant EM detection of axion dark matter

Cavity mode equation

Source: **a**
(almost monochromatic)

$$\sum_n \left(\partial_t^2 + \frac{\omega_n}{Q_n}\partial_t + \omega_n^2\right)\mathbf{E}_n = g_{a\gamma\gamma}\partial_t(\mathbf{B}\partial_t a)$$

Signal Mode: $\mathbf{E}_\mathbf{n}$

Pump Mode: **B**

- Traditional resonant detection matches axion mass with the resonant frequency by using a static B field.

$$\omega_1 \simeq m_a \qquad \partial_t(\mathbf{B}) \simeq 0$$

$$\left(\partial_t^2 + \frac{m_a}{Q_1}\partial_t + m_a^2\right)\mathbf{E}_1 = g_{a\gamma\gamma}\mathbf{B}\sqrt{\rho_{\mathrm{DM}}}m_a \cos m_a t$$

SRF with AC B field

Signal Mode: $\mathbf{E_1}$

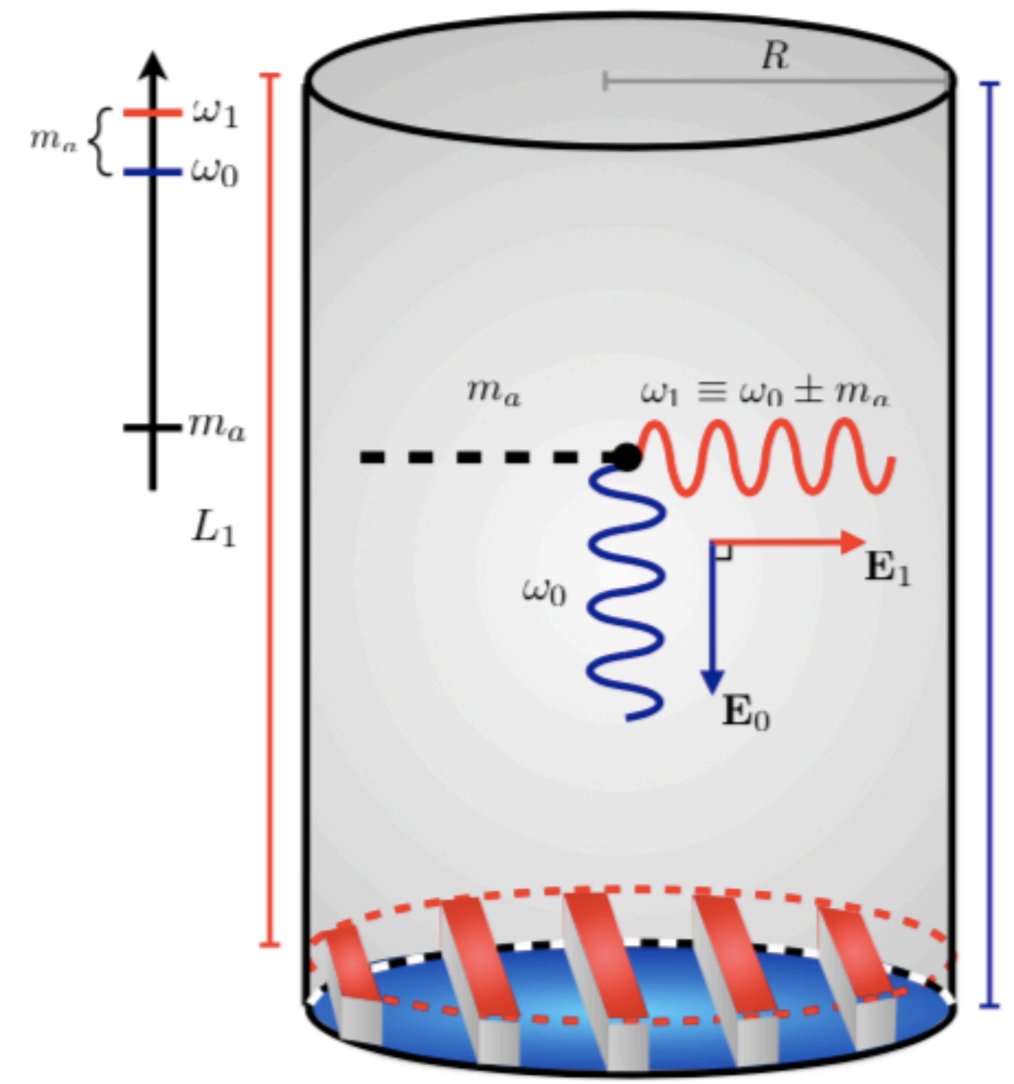
Source: **a**
(almost monochromatic)

$$\sum_n \left(\partial_t^2 + \frac{\omega_n}{Q_n}\partial_t + \omega_n^2\right)\mathbf{E}_n = g_{a\gamma\gamma}\partial_t(\mathbf{B}\partial_t a)$$

Pump Mode: $\mathbf{B_0}$

Oscillating $\mathbf{B_0}$:

$$\omega_1 \simeq \omega_0 + m_a \qquad \partial_t(\mathbf{B}) \simeq i\omega_0\mathbf{B}$$



Scanning the axion mass by tuning the differences between two quasi-degenerate modes

A.Berlin, R.T. D'Agnolo, et al, JHEP07(2020)no.07, 088.

Axion Dark Matter Detection Using SRF

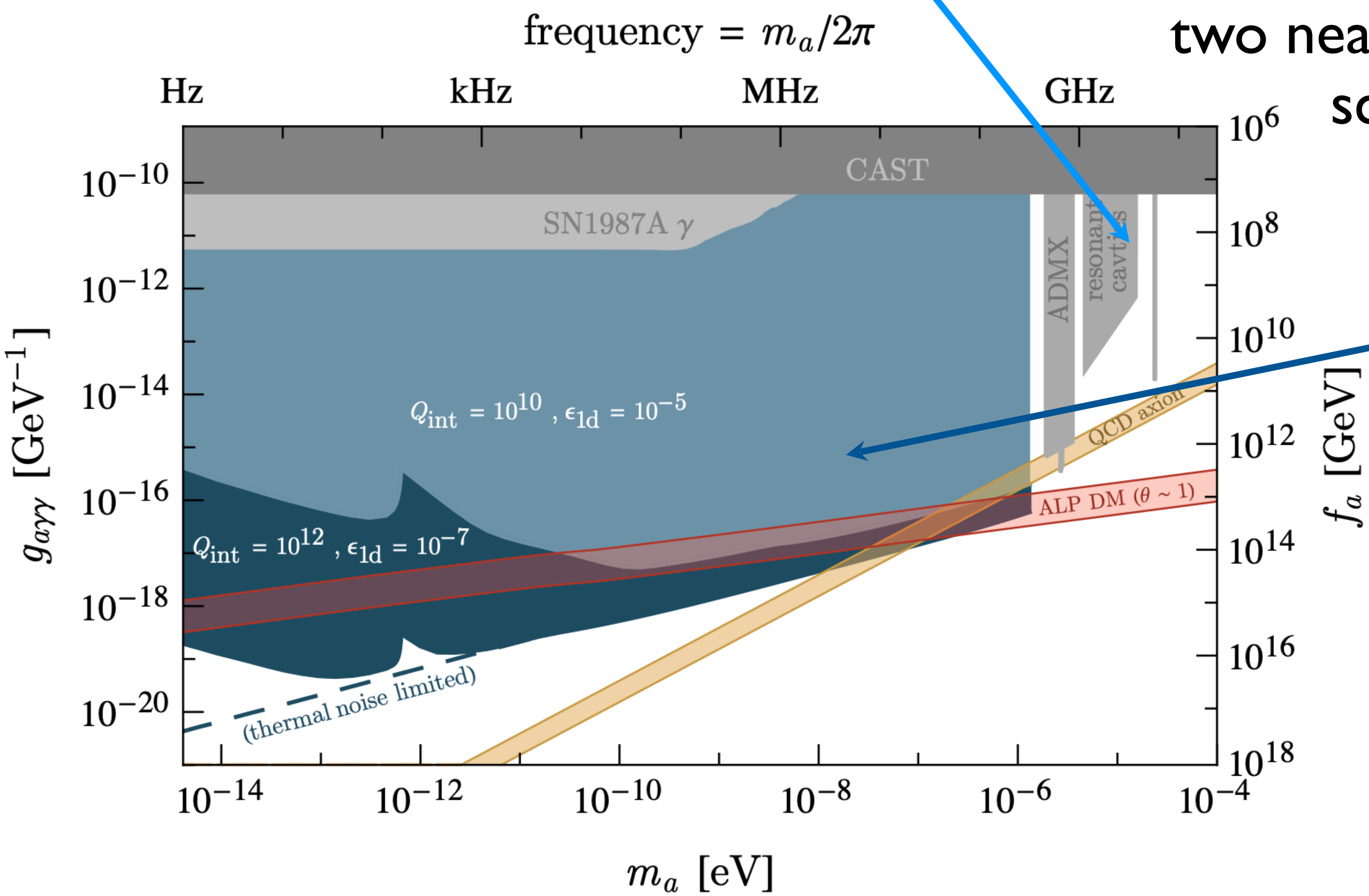
Hard to scan for a broad mass window in traditional cavity!

$\omega_1 \simeq m_a \qquad \partial_t(\mathbf{B}) \simeq 0$

narrow mass window due to size of the cavity

$\omega_1 \simeq \omega_0 + m_a \qquad \partial_t(\mathbf{B}) \simeq i\omega_0\mathbf{B}$

The AC magnetic field inside the SRF and two nearly degenerate modes enable the scan of axion mass from the frequency splitting.



Much broader detection mass window at lower frequency.

Only gray region is excluded.

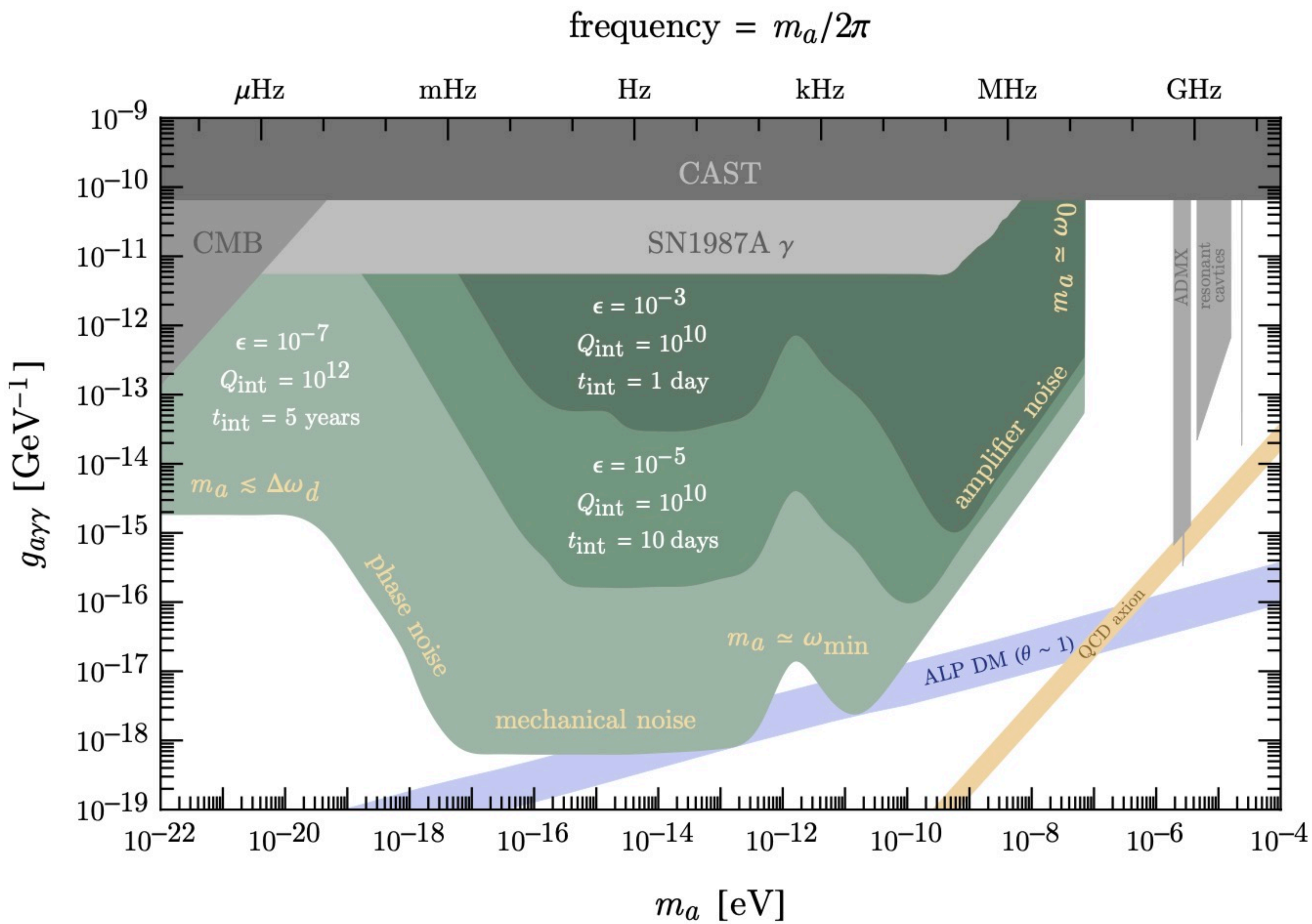
Large unexplored parameter space!

A.Berlin, R.T. D'Agnolo, et al, JHEP07(2020)no.07, 088.

Broadband case

For ultra-light axion, $\omega_1 = \omega_0 + m_a \simeq \omega_0$

Two degenerate and transverse modes can reach the ultra-light region!



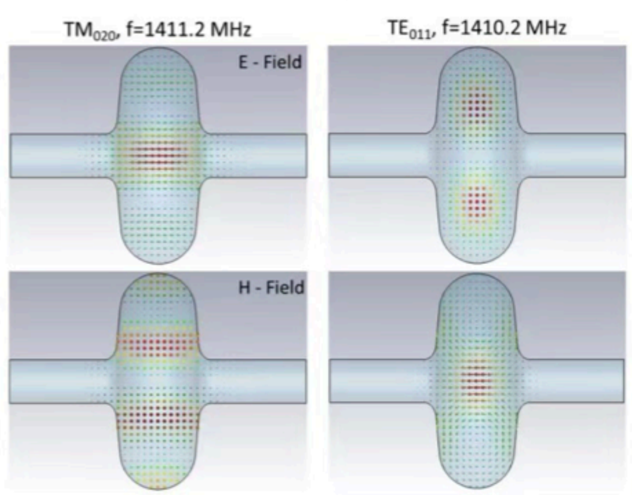
A.Berlin, R.T. D'Agnolo, et al, [arXiv:2007.15656 [hep-ph]].

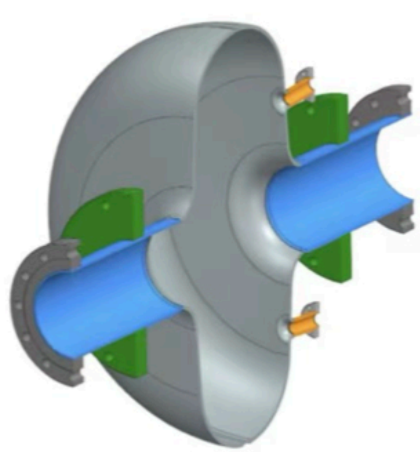
Axion search

TDR like

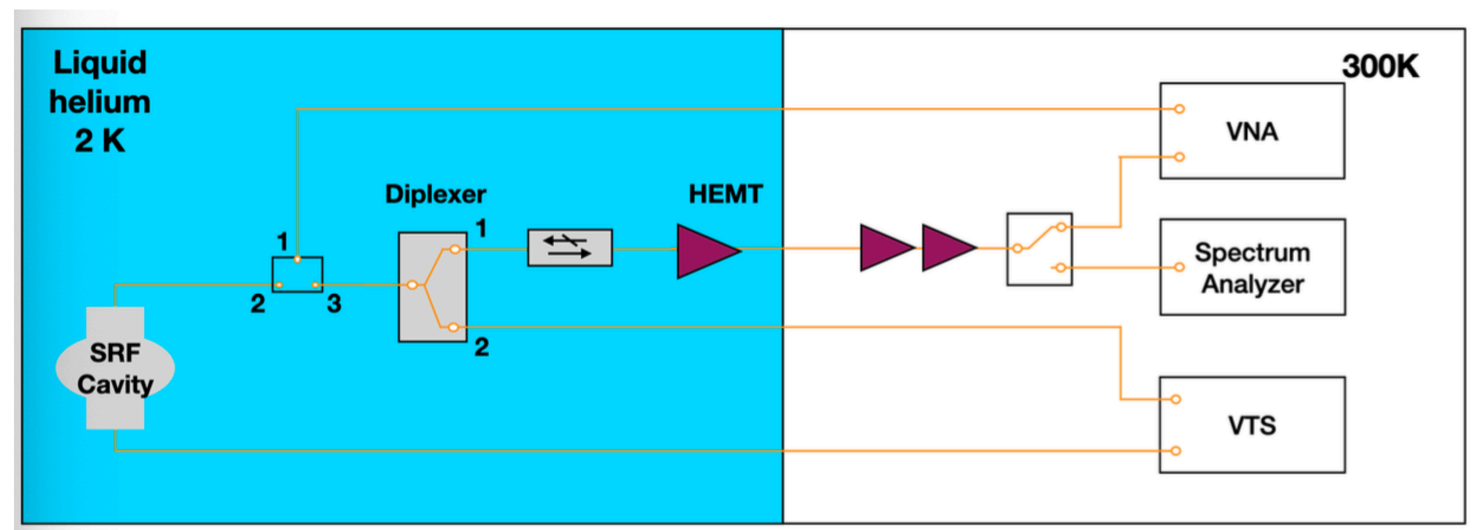
SHANHE collaboration

arXiv:2207.11346

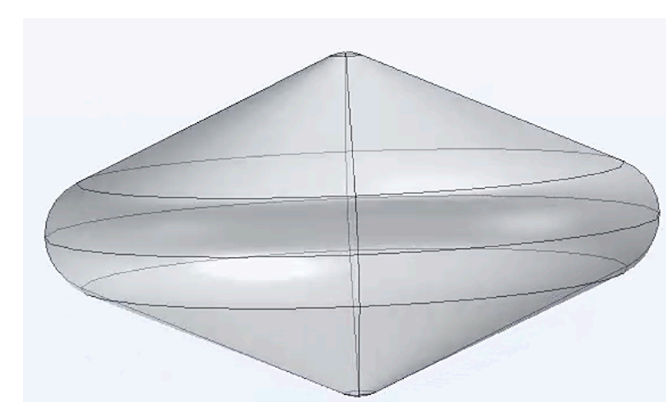




Using the existing 1.3G cavity as a pathfinder



New designed cavity will be operated in the future.



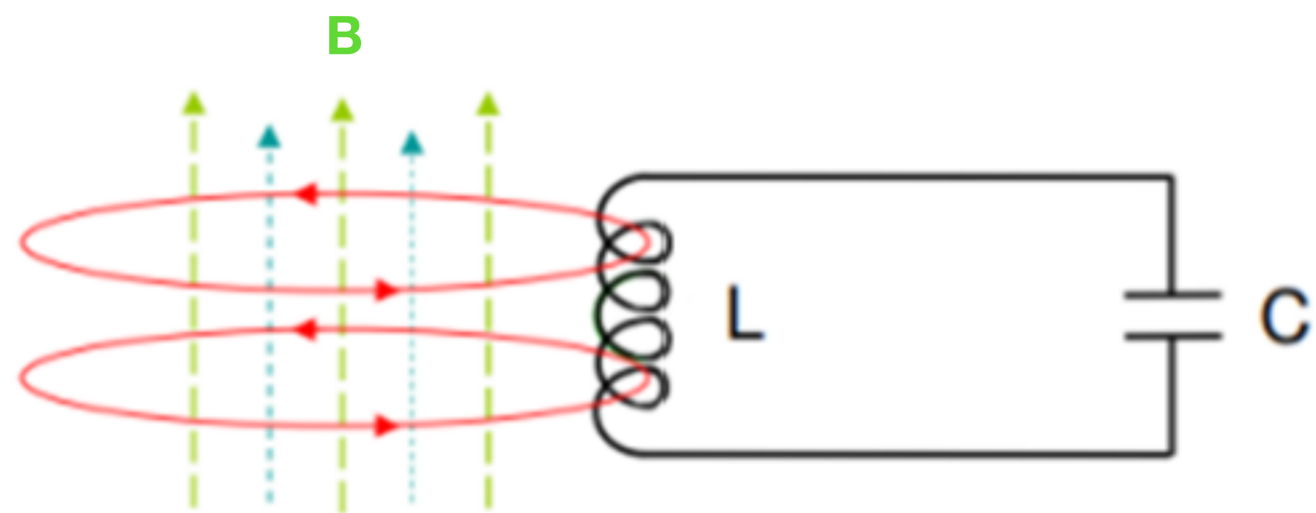
LC Circuit with static B field

- Resonant conversion happens when

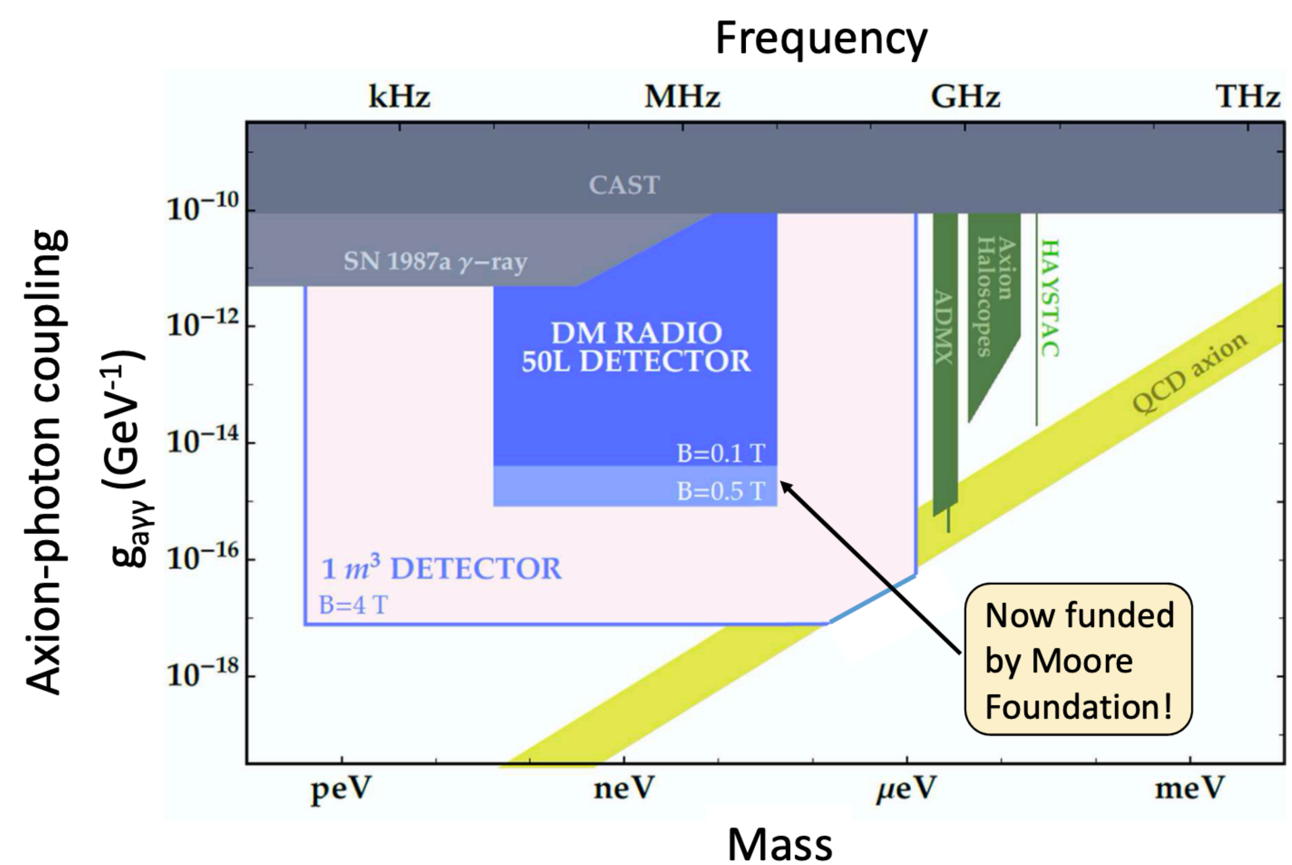
$$m_a = \omega = \frac{1}{\sqrt{LC}}$$

- Scan the mass from 100 Hz to 100 MHz by tuning the capacitor C

e.g. DM radio, ADMX-SLIC



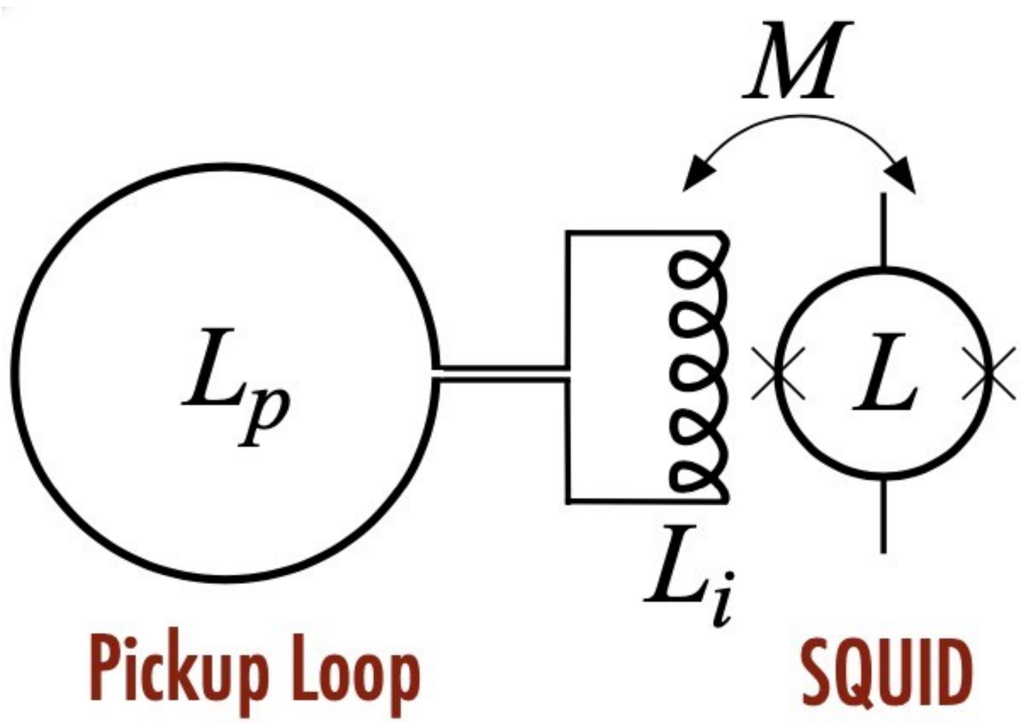
DM Radio science: axions

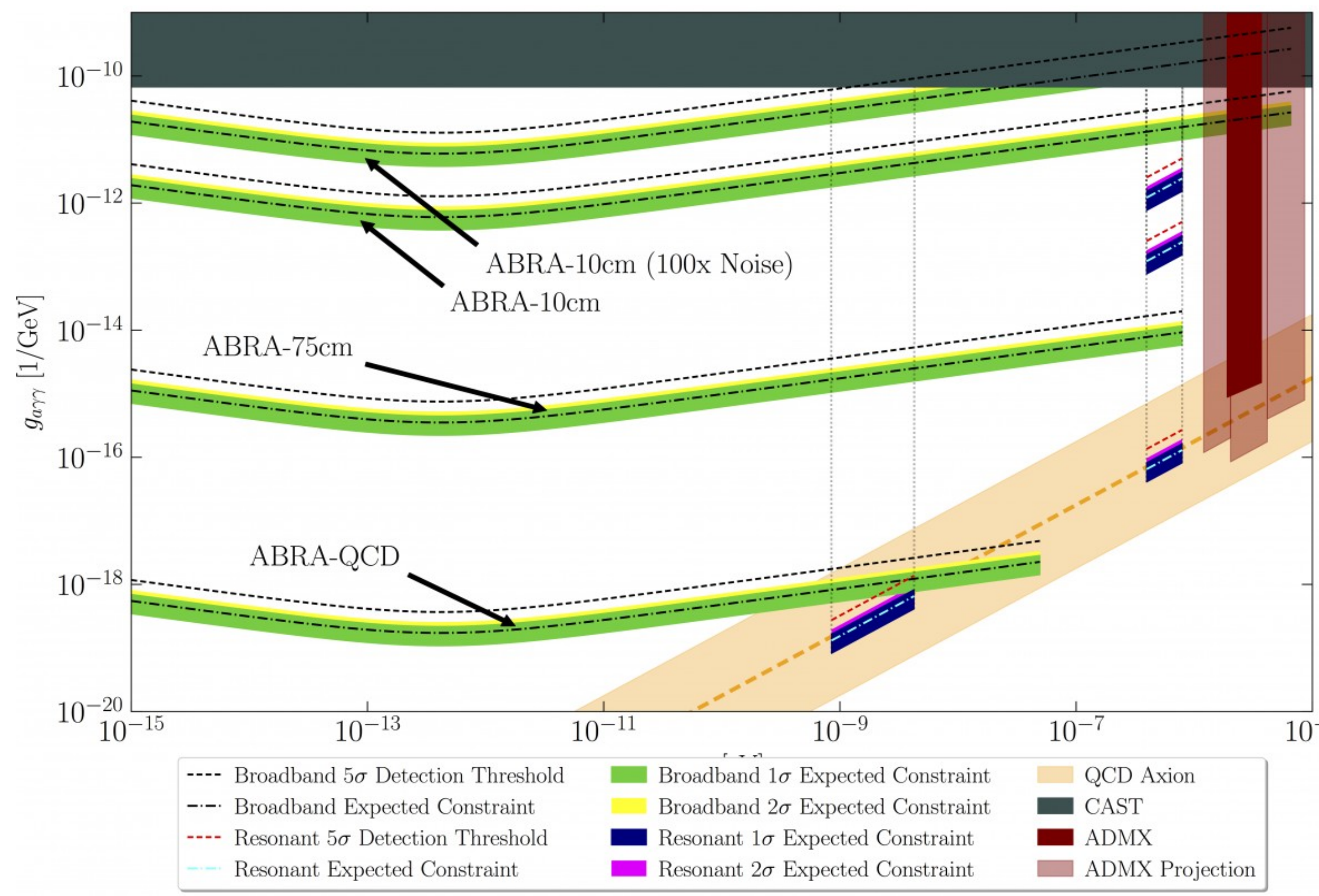


Assumptions: T=10 mK, Q=10^6, 3.5 year integration time, quantum-limited readout

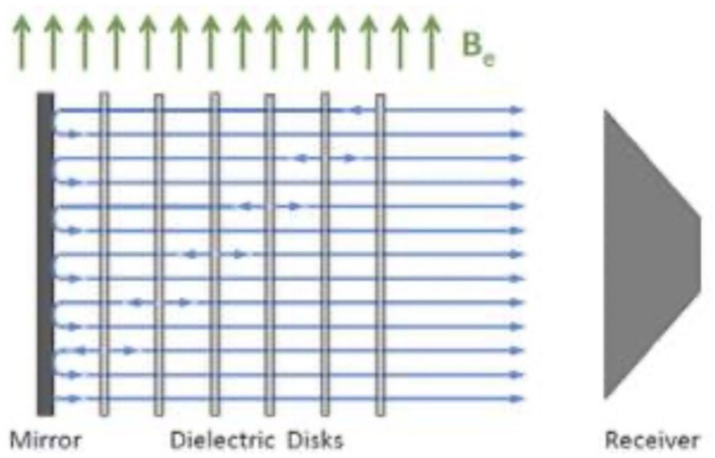
Broadband Detection

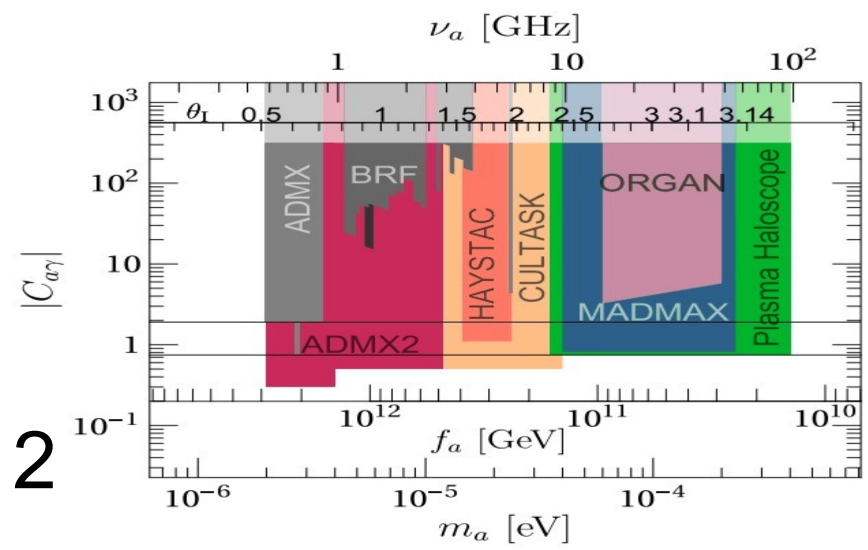
- ABRACADABRA: no capacitor, **simultaneous scan of broad frequencies using SQUID**. [Y.Kahn, B. Safdi, J. Thaler 16']

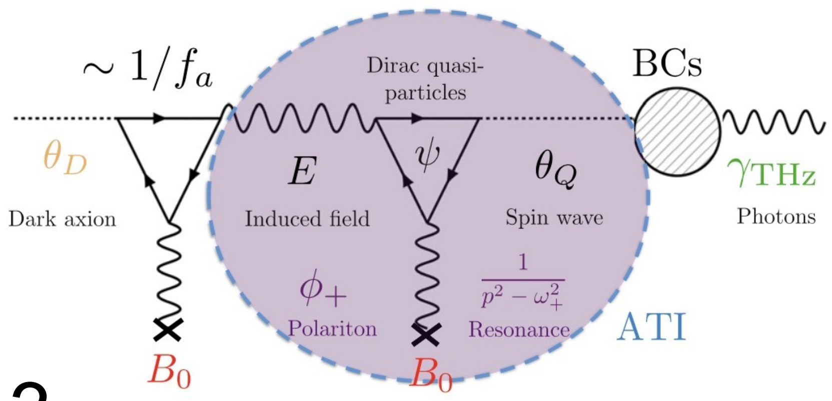




Higher Frequency Electromagnetic Resonant Detection

1


2


3


- 1 **Dielectric Haloscope**: discontinuity of E-field leads to coherent emission of photons from each surface, up to 50 GHz. [A.Caldwell et al 17']
- **2.Plasma Haloscope**: using tunable cryogenic plasma to match axion mass, up to 100 GHz. [M.Lawson et al 19']
- **3.Topological Insulator**: quasiparticle in it mixing with E field becomes polariton whose frequency can be tuned by magnetic field, up to THz. [D.J.E.Marsh et al 19']

Birefringent effect

Axion induced birefringent effect

$$\Box A_\pm = \pm 2 i g_{a\gamma}[\partial_z a \dot{A}_\pm - \dot{a}\partial_z A_\pm],$$

$$\omega_\pm \approx k \pm \tfrac{1}{2} g \left(\frac{\partial \varphi}{\partial t} + \nabla \varphi \cdot \frac{\boldsymbol{k}}{k} \right)$$

different phase velocities for +/- helicities

For linearly polarized photons

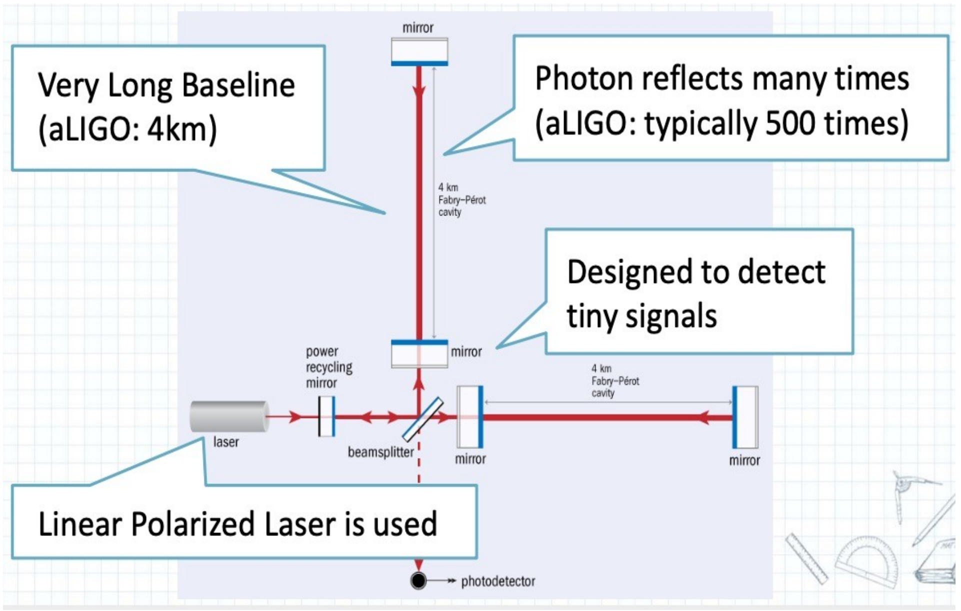
$$\begin{aligned} \Delta\Theta &= g_{a\gamma}\Delta a(t_{\rm obs}, \mathbf{x}_{\rm obs}; t_{\rm emit}, \mathbf{x}_{\rm emit}) \\ &= g_{a\gamma} \int_{\rm emit}^{\rm obs} ds\; n^\mu\; \partial_\mu a \\ &= g_{a\gamma}[a(t_{\rm obs}, \mathbf{x}_{\rm obs}) - a(t_{\rm emit}, \mathbf{x}_{\rm emit})], \end{aligned}$$

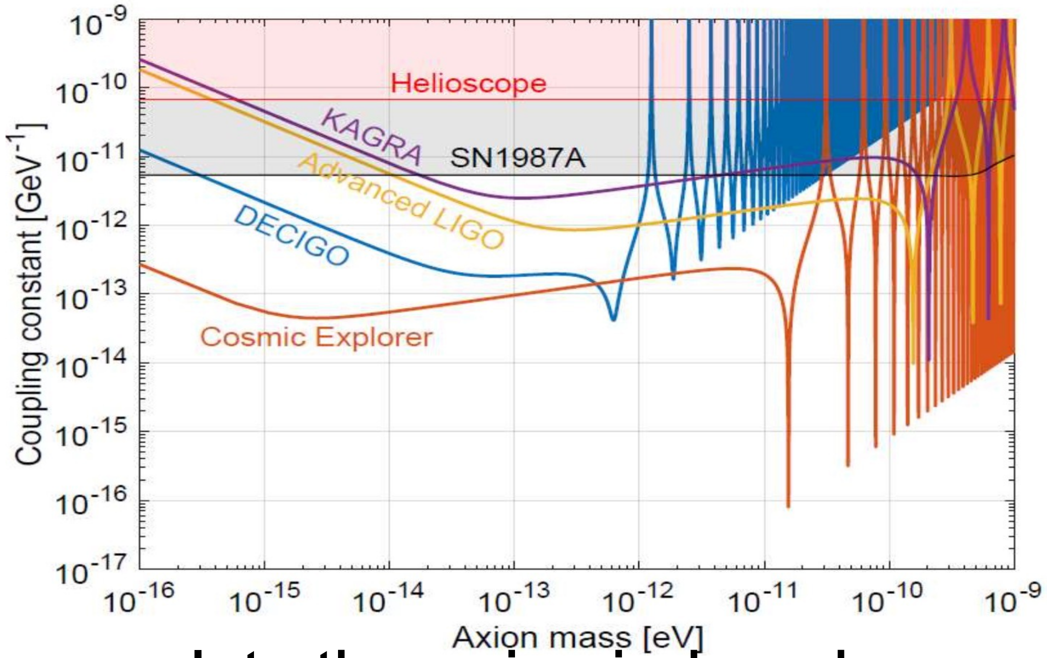
Measure the change of the position angle:

Requires polarimetric measurements

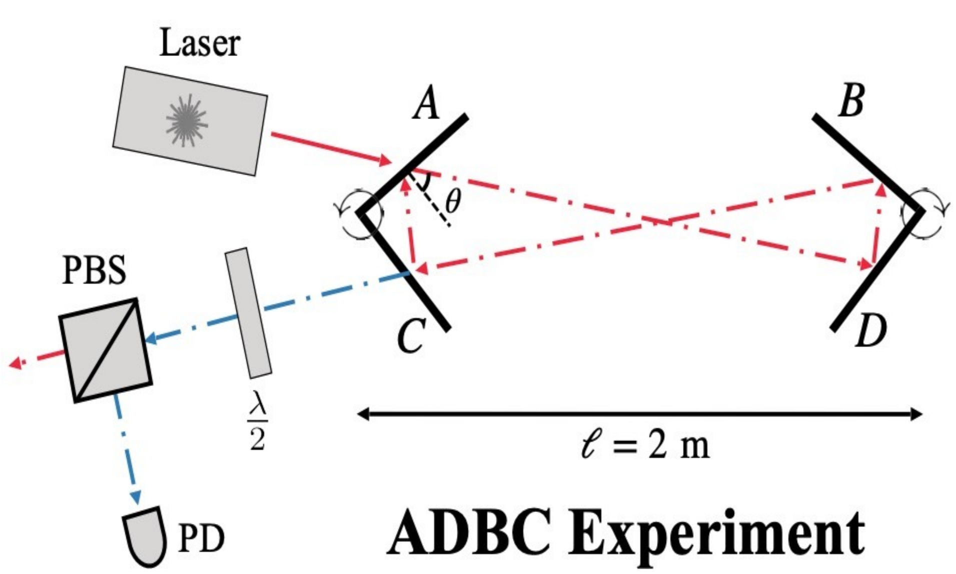
GW Interferometers and Birefringent Cavity

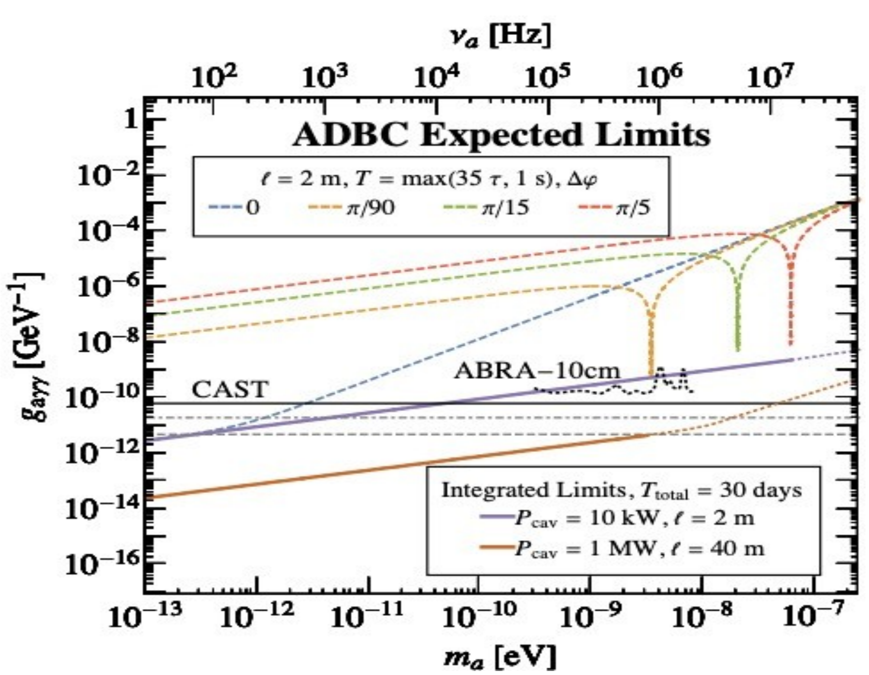
- Interferometer: using vertically polarized laser and measuring the horizontal component, resonant when baseline matches λ_c . [DeRocco, Hook 18']



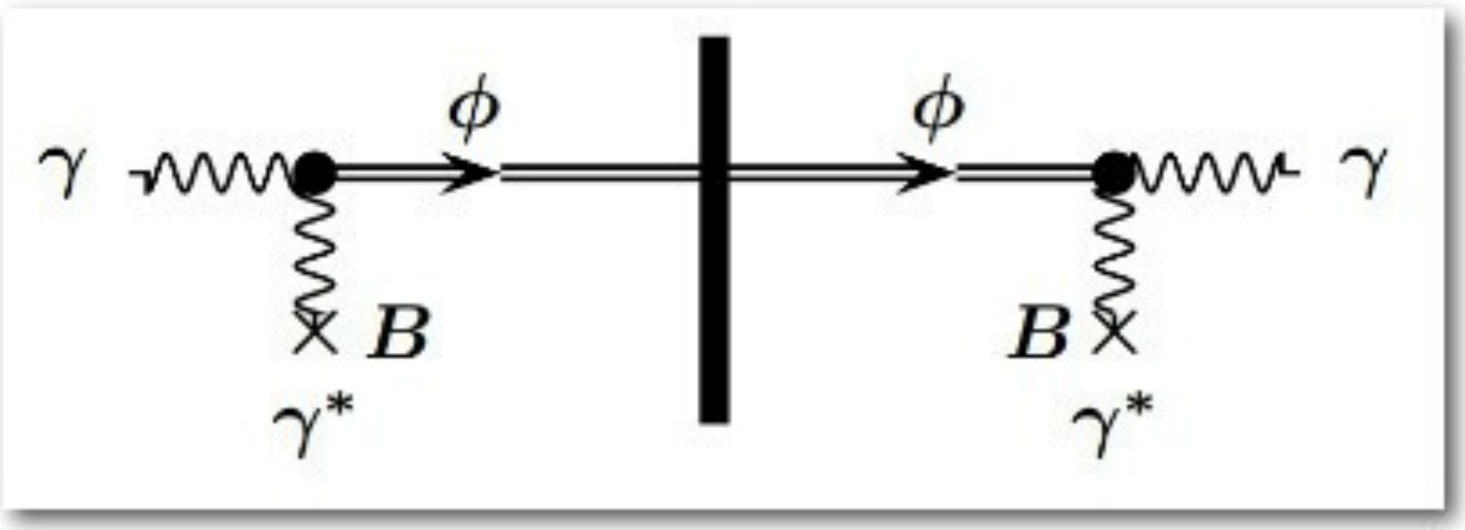


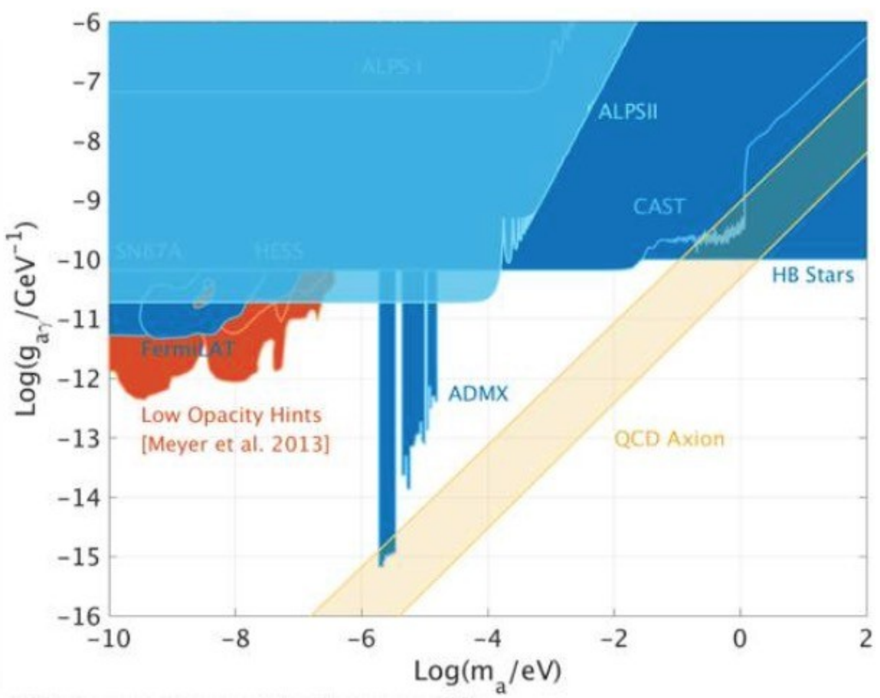
- Birefringent cavity: using mirror to accumulate the axion induced sideband. [Liu, Elwood et al 18']





Light Shining Through Walls [Redondo, Ringwald 10']





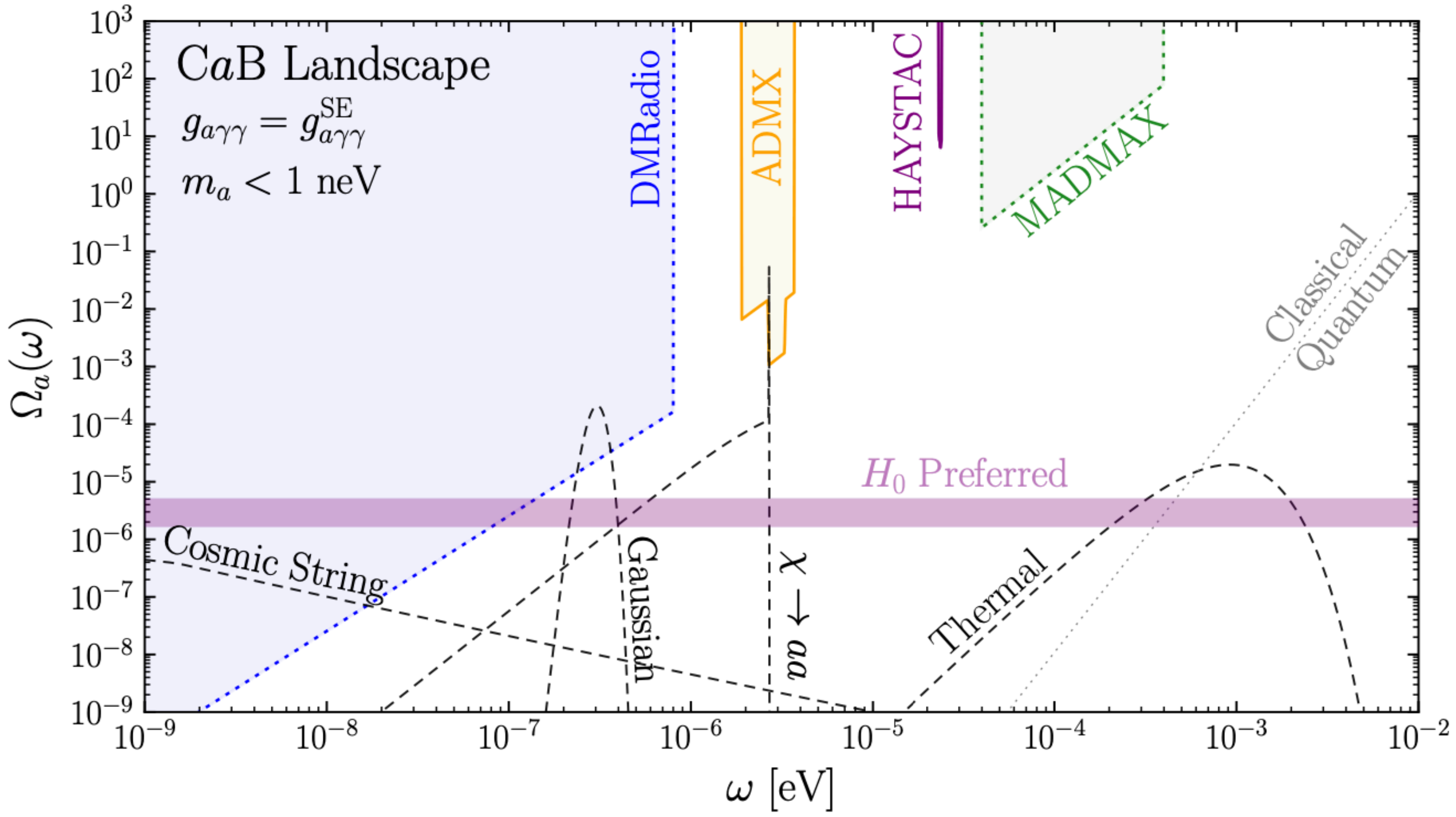
- Photons **convert into axions in B field, pass through a wall and convert back into photons.**

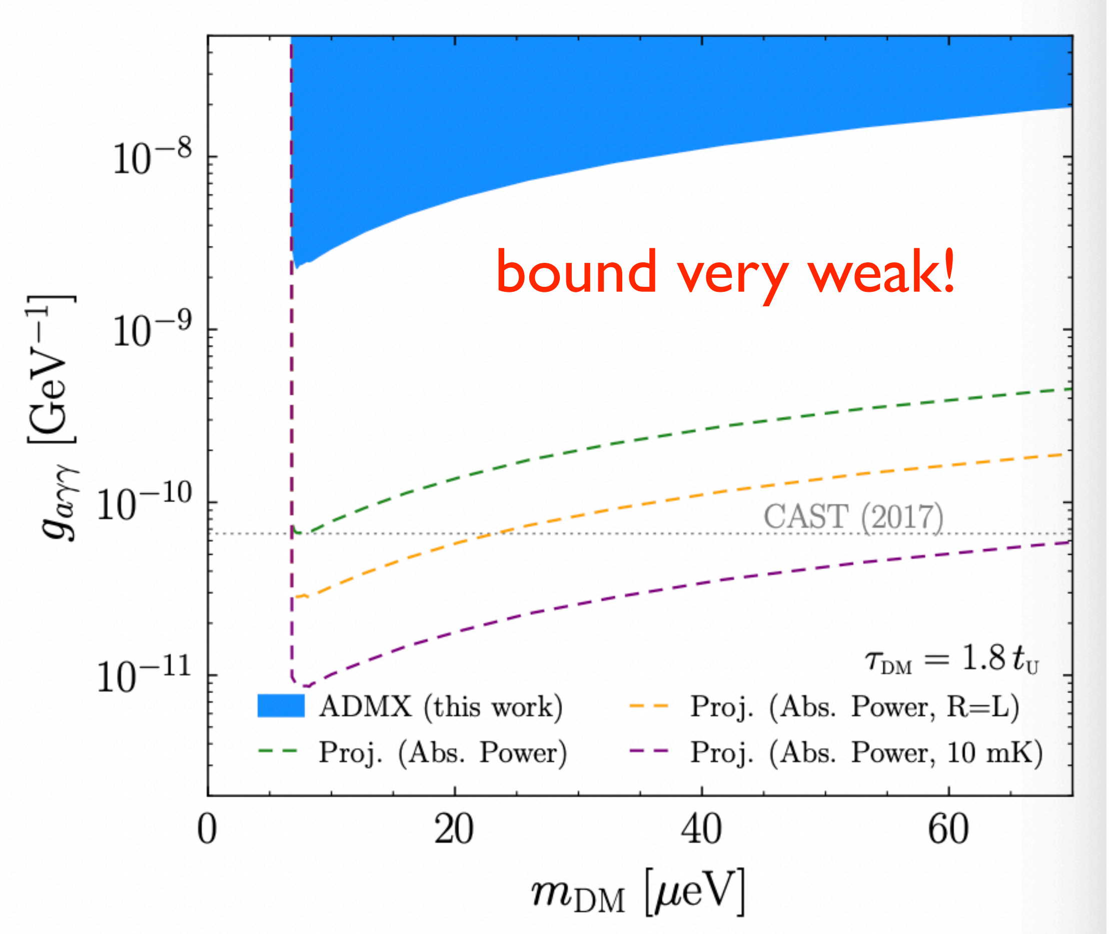
- Optical cavity [Janish et al 19'].

- Not dependent on if axion is the major dark matter.

Cosmic axion backgrounds

Axion can also be served as the
cosmic backgrounds.





- Relativistic
- Anisotropic

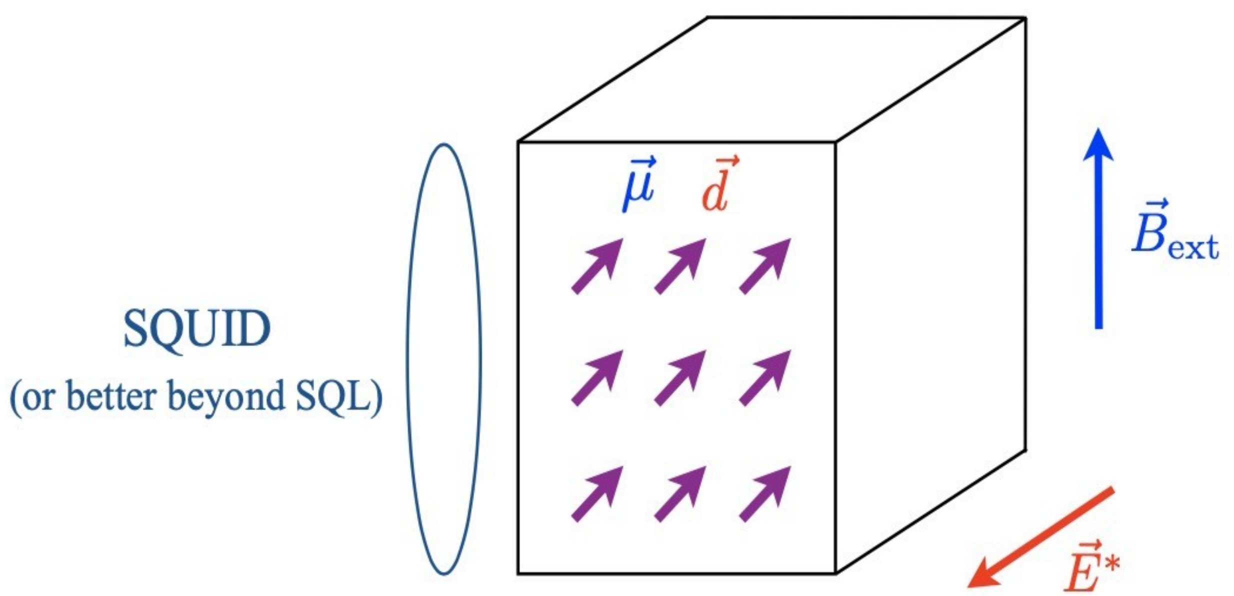
T. Nitta et al. (ADMX), Phys. Rev. Lett. 131, 101002 (2023)

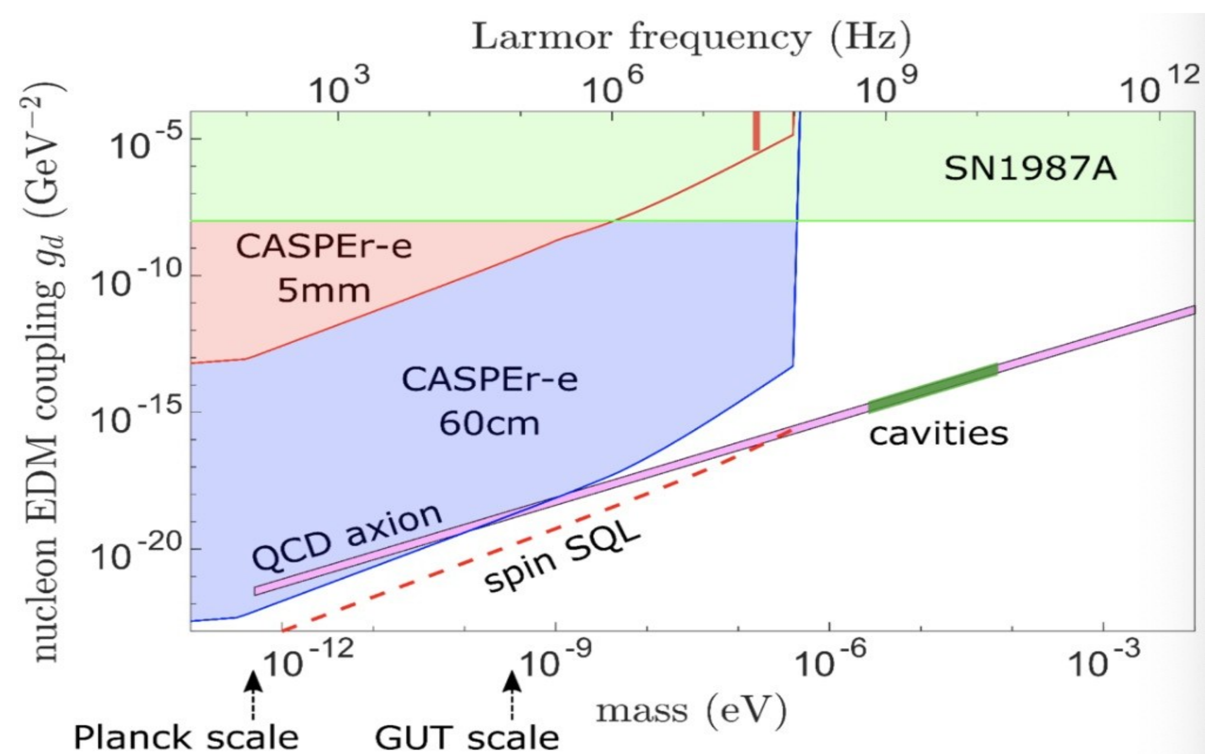
The Cosmic Axion Background

Jeff A. Dror,[1,2,3,*] Hitoshi Murayama,[2,3,4,†] and Nicholas L. Rodd[2,3,‡]

Nuclear Magnetic Resonance [Budker, Graham et al 13']

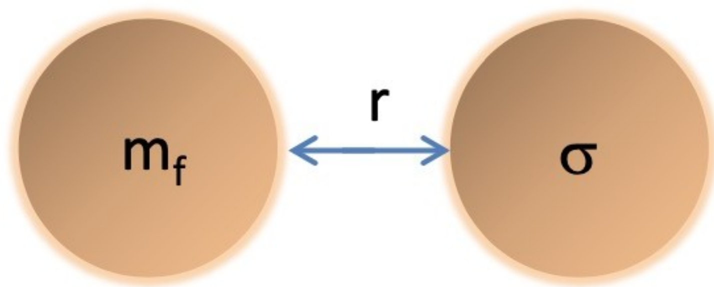
- **CASPEr Electric**: axion gluon coupling leads to oscillating EDM.
- **CASPEr-Wind:** axion nucleons coupling ~ **∇a · σ_N leads to precession of the spin, proportional to axion DM velocity (wind).**





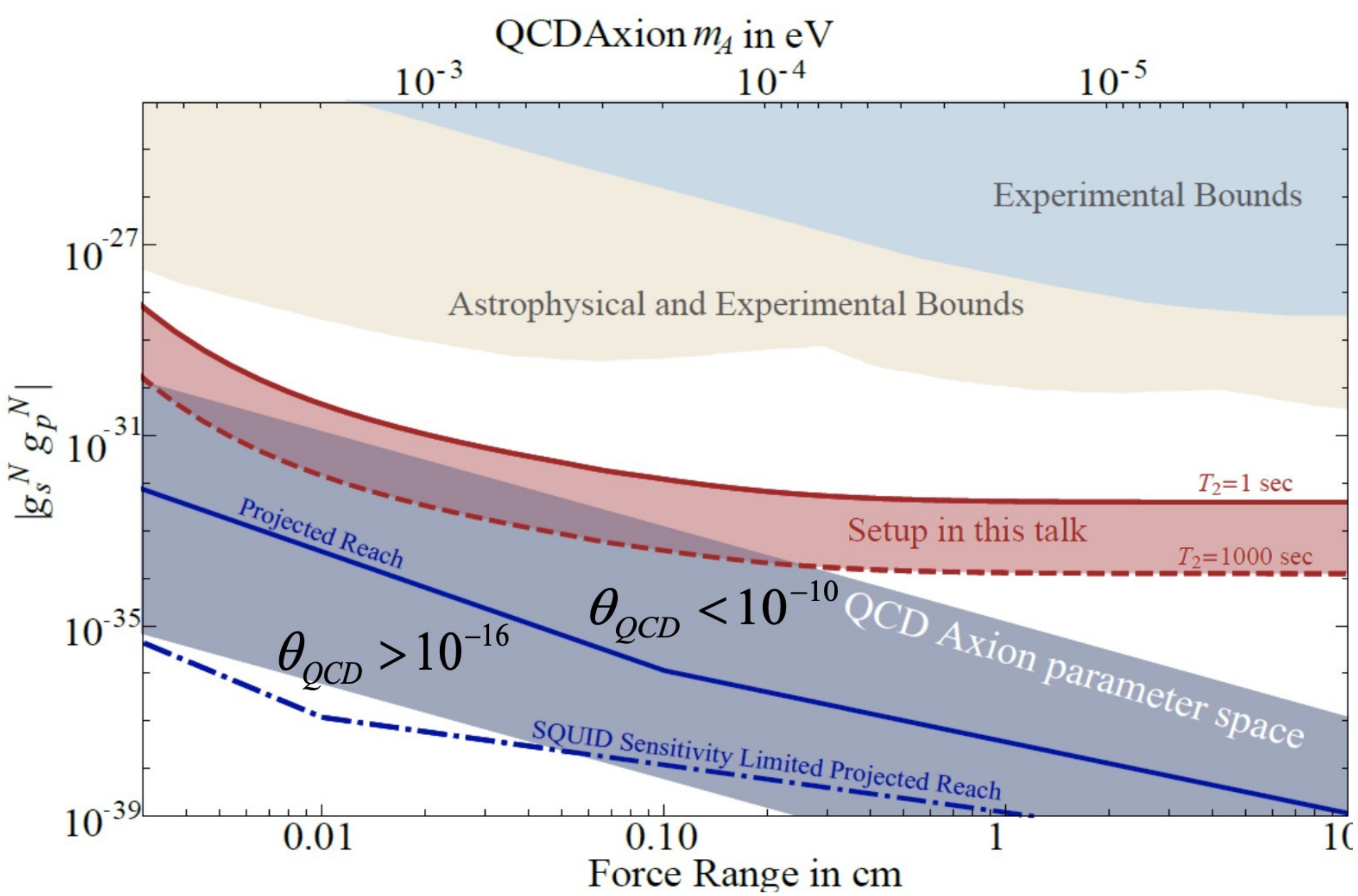
Larmor frequency $2\mu B_{ext} = m_a$ leads to NMR-like resonant enhancement.

Axion-Induced Fifth Force [Moody, Wilczek, 84']



Monopole-Dipole axion exchange

Axion-mediated **monopole-dipole interaction** between nucleons:



[ARIADNE 14']

Many many papers

Summary and outlook

Summary and outlook

- Axion is very theory motivated particle, even though its invisible property needs some care.
- Natural wave-like.
- Astro-particle and quantum search can be boomed in the future.

Backup