Axion Dark Matter (theory & experiment)

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Outline

- Motivation for axion dark matter
- Axion Dark Matter Theory
- Experiment：Astroparticle
- 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)

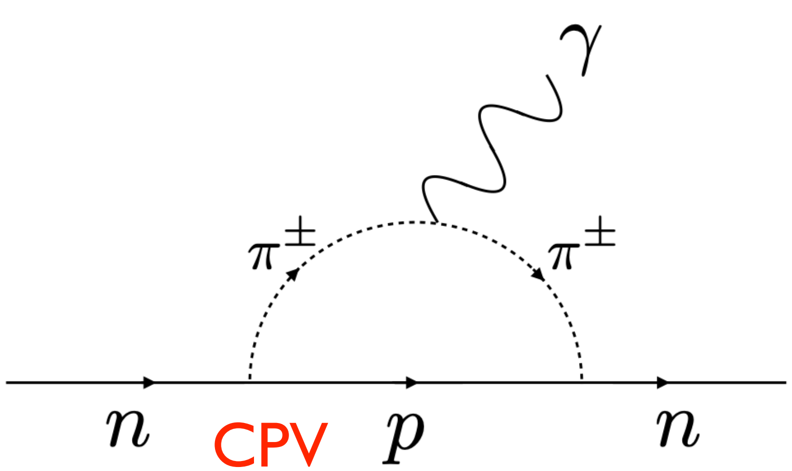
$$q_i \to e^{i\alpha_i\gamma_5} q_i \qquad M \to e^{-2i\alpha} M \qquad \theta \to \theta - 2N_f\alpha$$

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

This \theta term also contribute to the neutron EDM

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

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

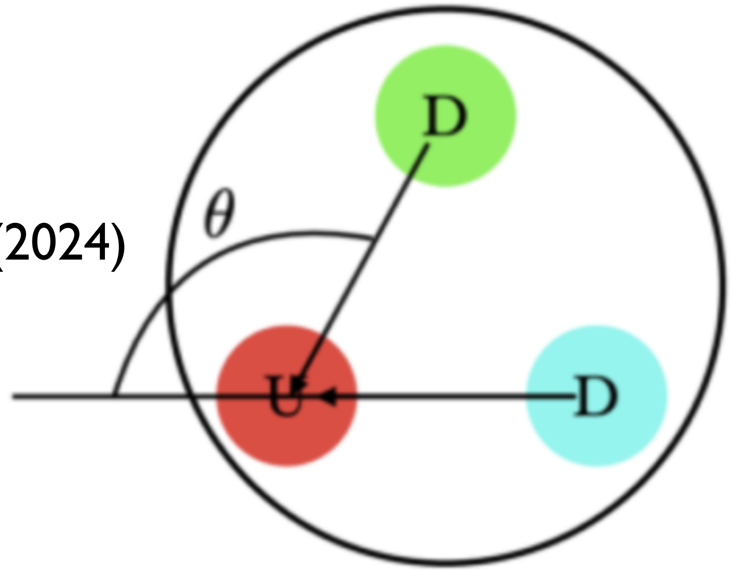


Motivation for Axion

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

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

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

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

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

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

In memorial of Peccei

1991

2019

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

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

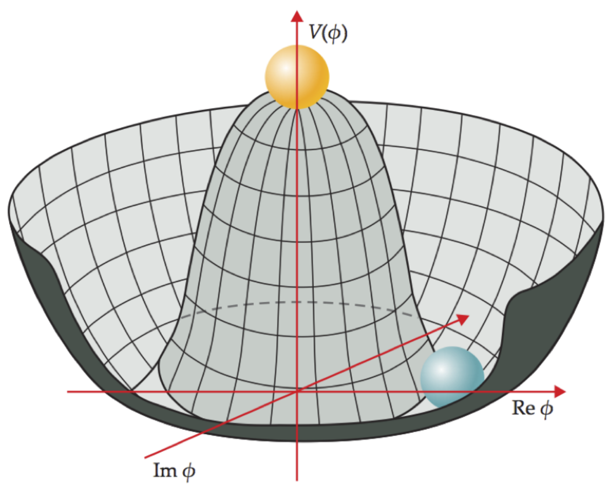
Axion quality problem:

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

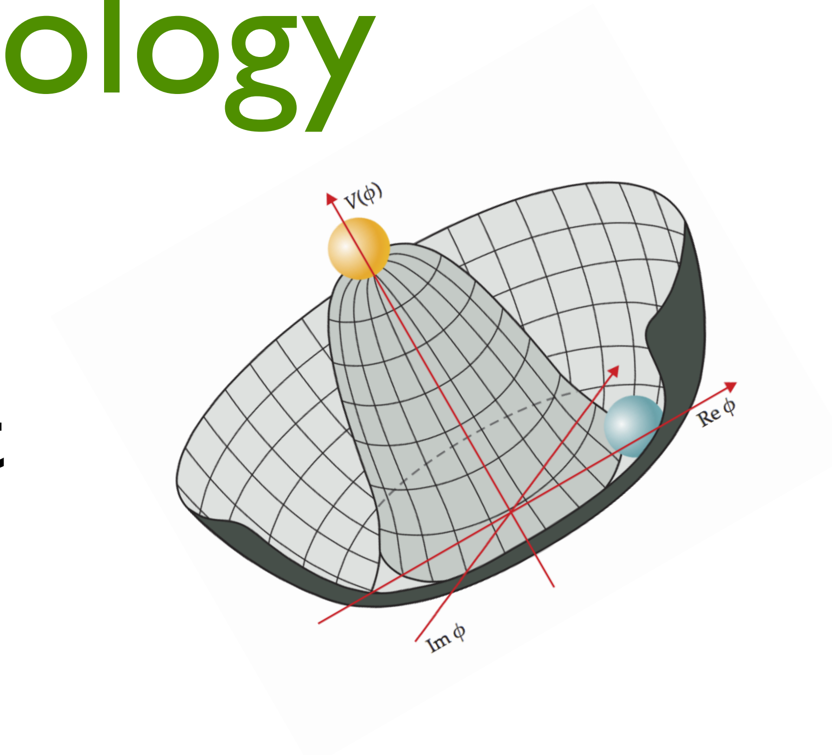
Need many powers of suppression

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

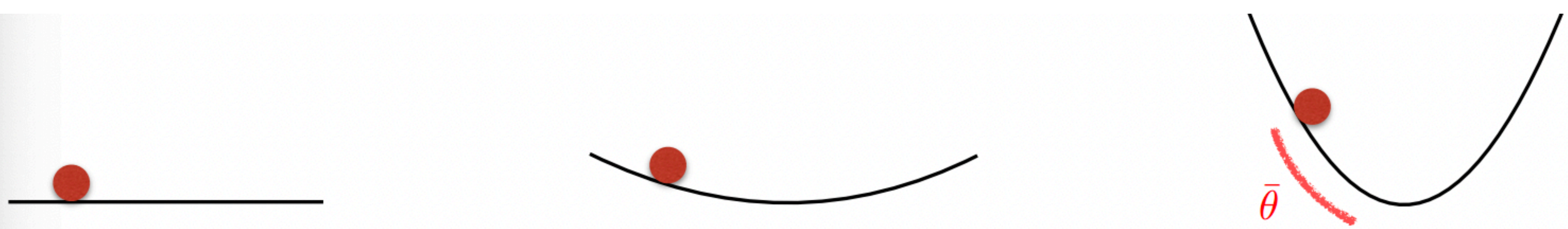
Axion cosmology



Misalignment



Axion evolution



$$\theta \equiv a/f_a$$

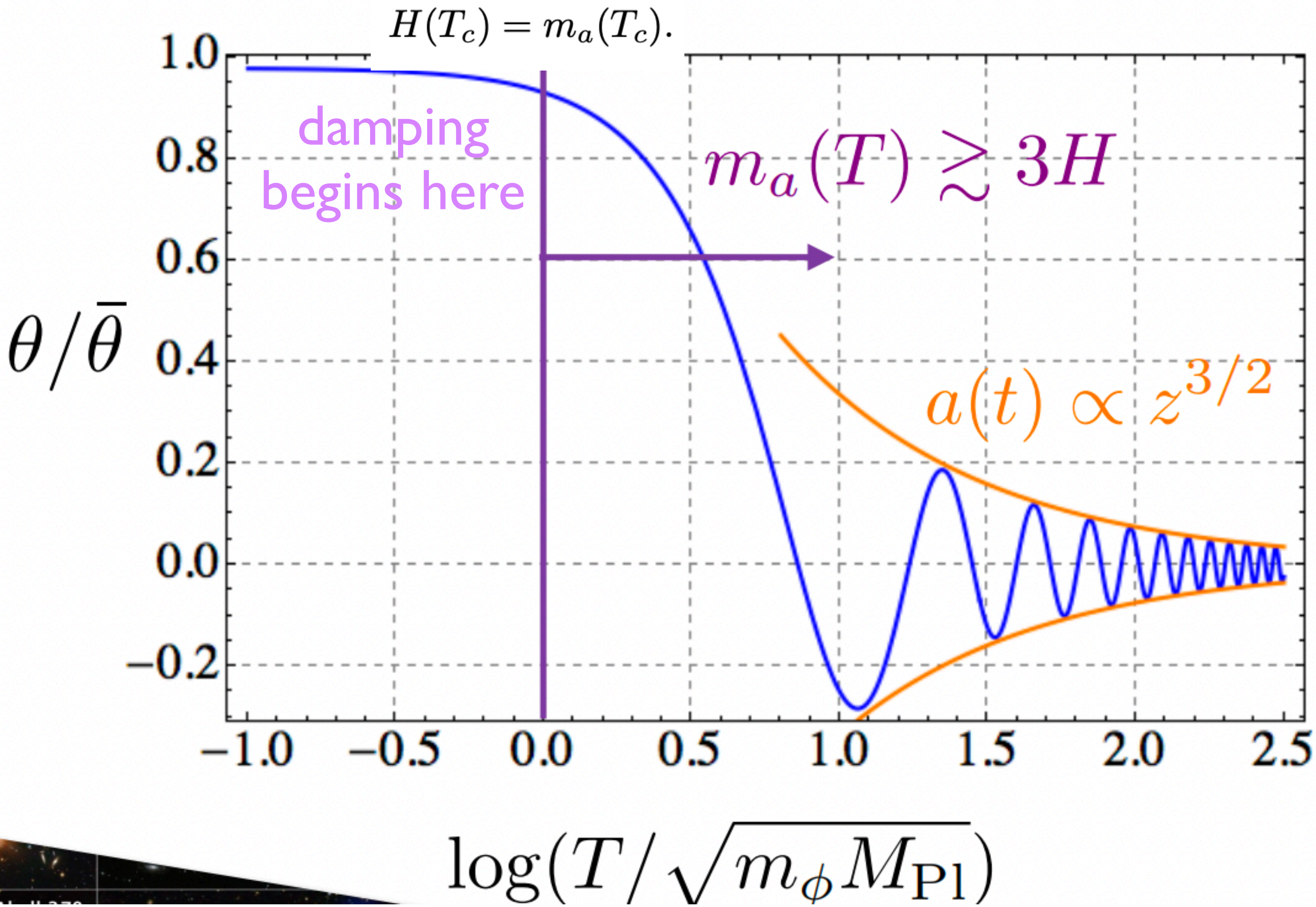
$$\ddot{\theta} + 3H\dot{\theta} + m_a^2(T)\theta = 0$$

“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

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

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

Energy conservation

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

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

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 theta small for large f_a, or damp the E out of axion。
- theta ~ \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: $\omega_a \simeq \mathrm{GHz}\,\frac{m_a}{10^{-6}\ \mathrm{eV}}$

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

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

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

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

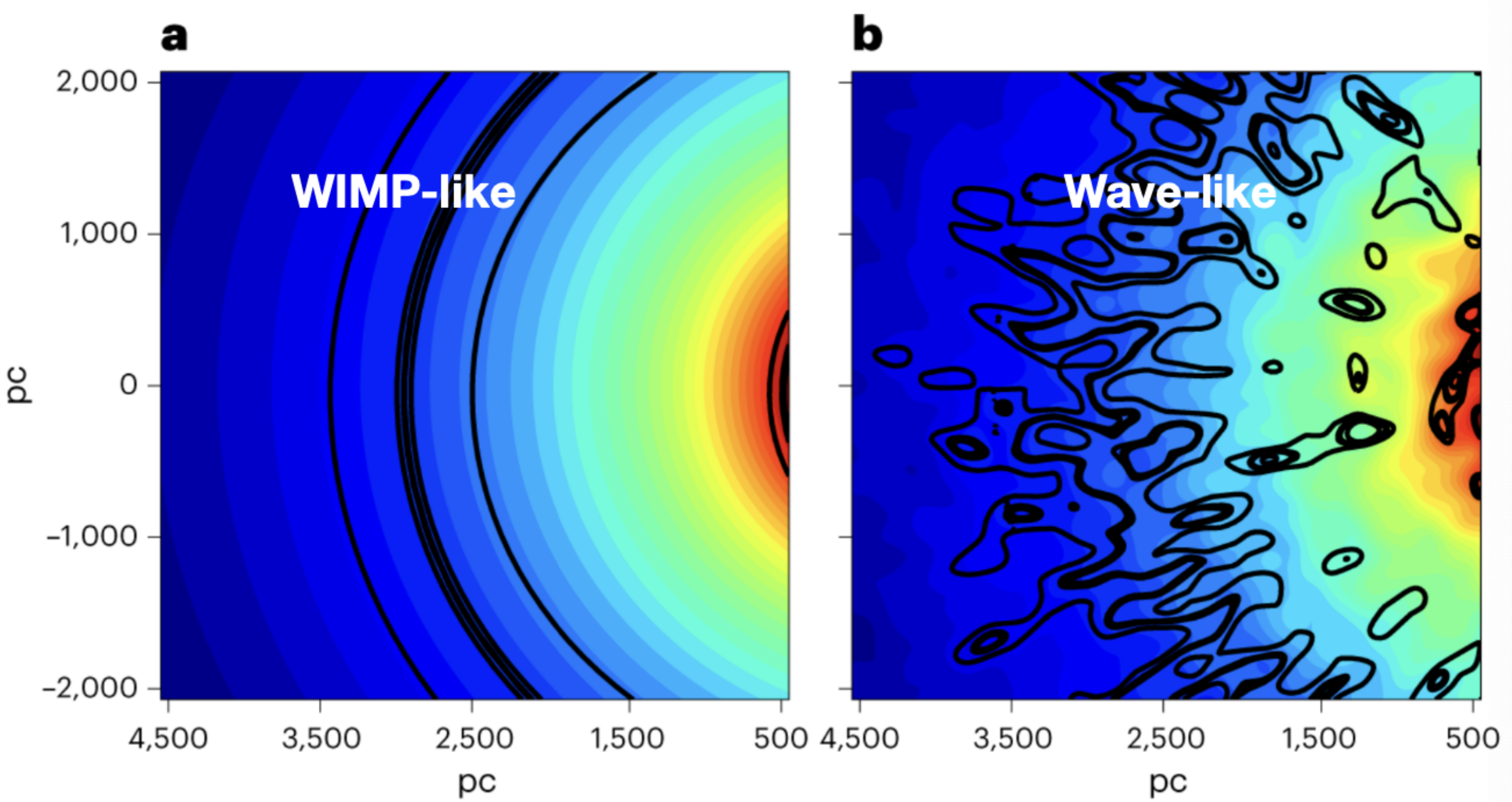
Bandwidth of axion DM is 10^-6

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 width10^-3

波动型暗物质在小尺度结构上的不同

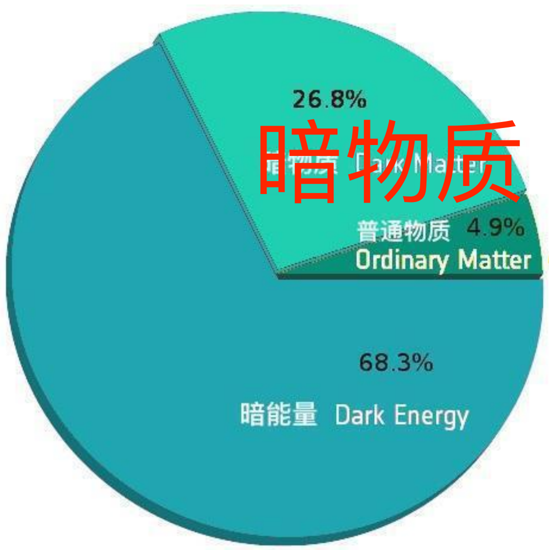


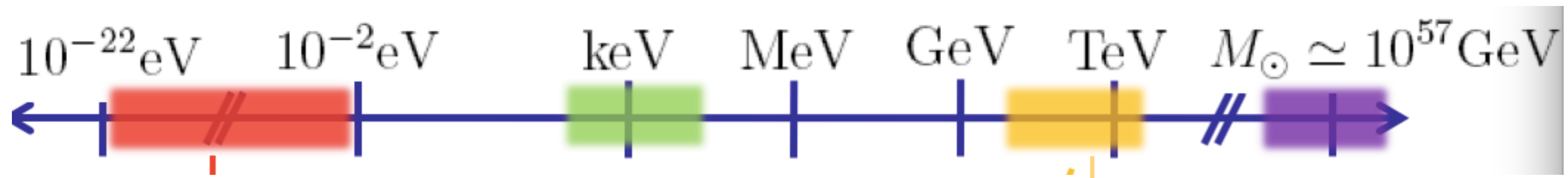
Nature Astronomy 7, 736 (2023)

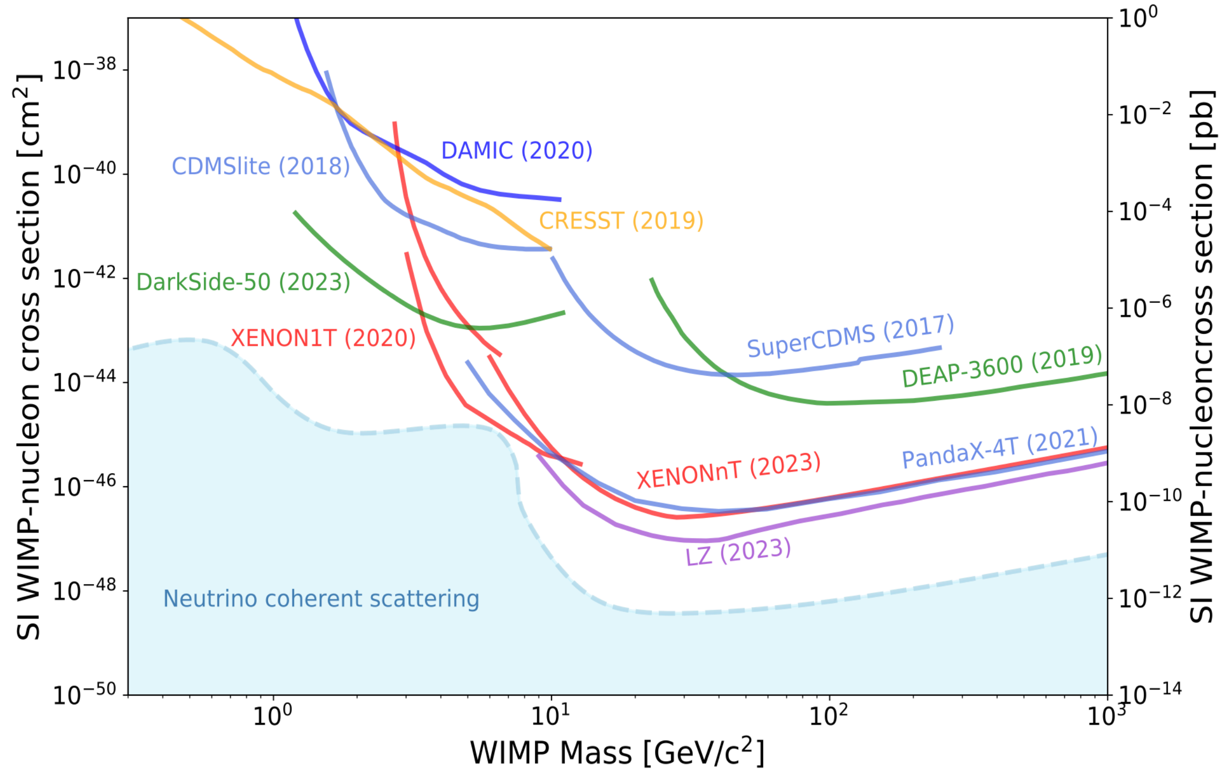
Axion detection

传统暗物质

当前暗物质组成未知，可能候选者质量范围跨越非常大



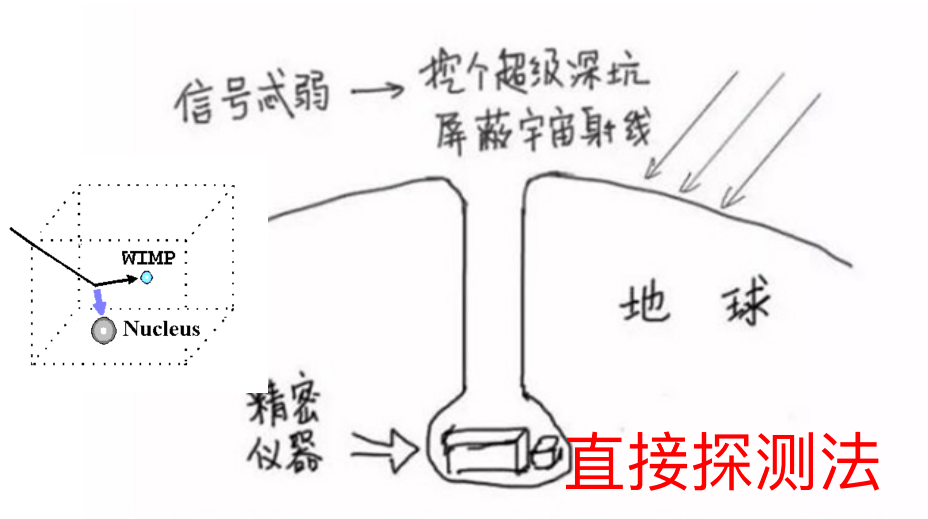




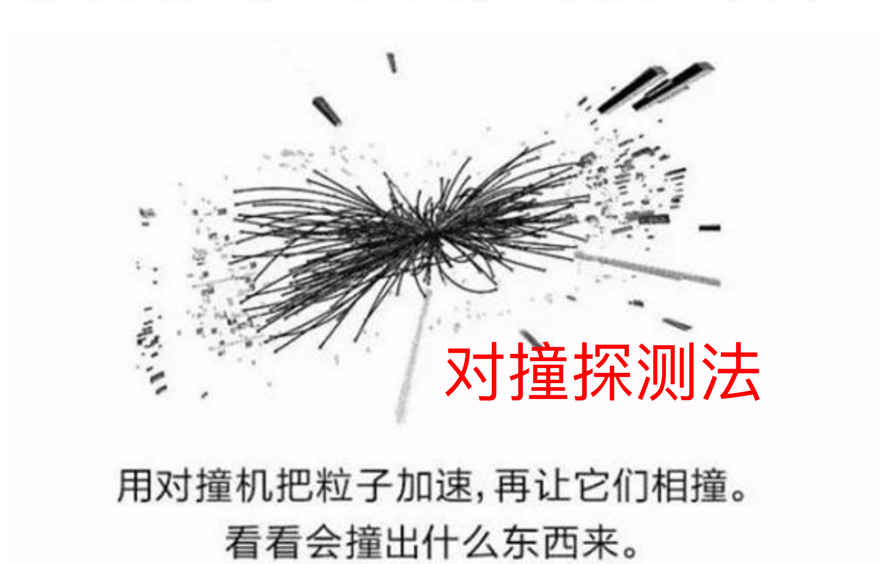
Particle Data Goup, Phys. Rev. D 110, 030001 (2024)

传统的WIMP
暗物质当前限
制严，未来探

上天入地探测粒子型暗物质



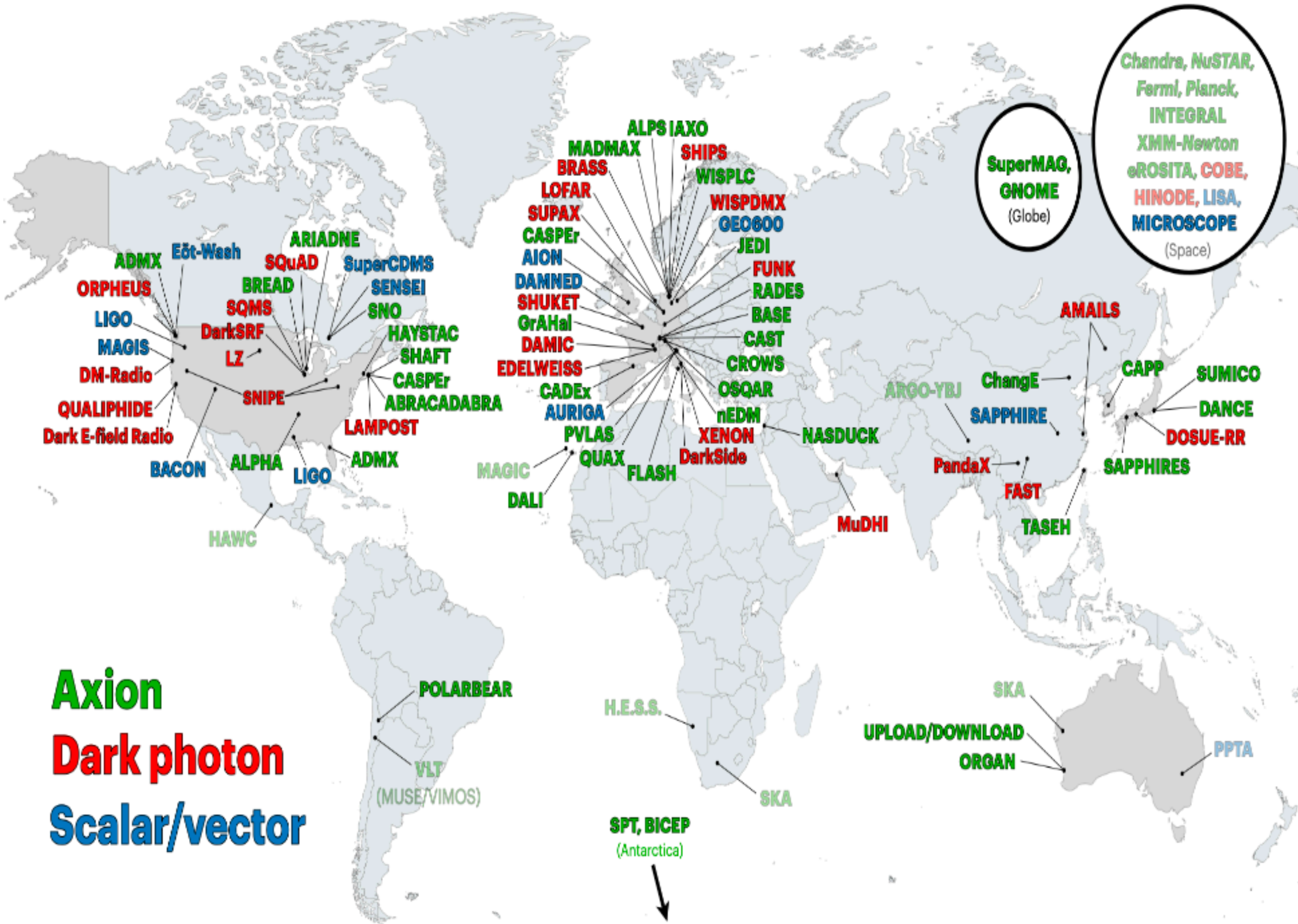
直接探测法



对撞探测法

间接探测法

波动型暗物质探测：百花齐放

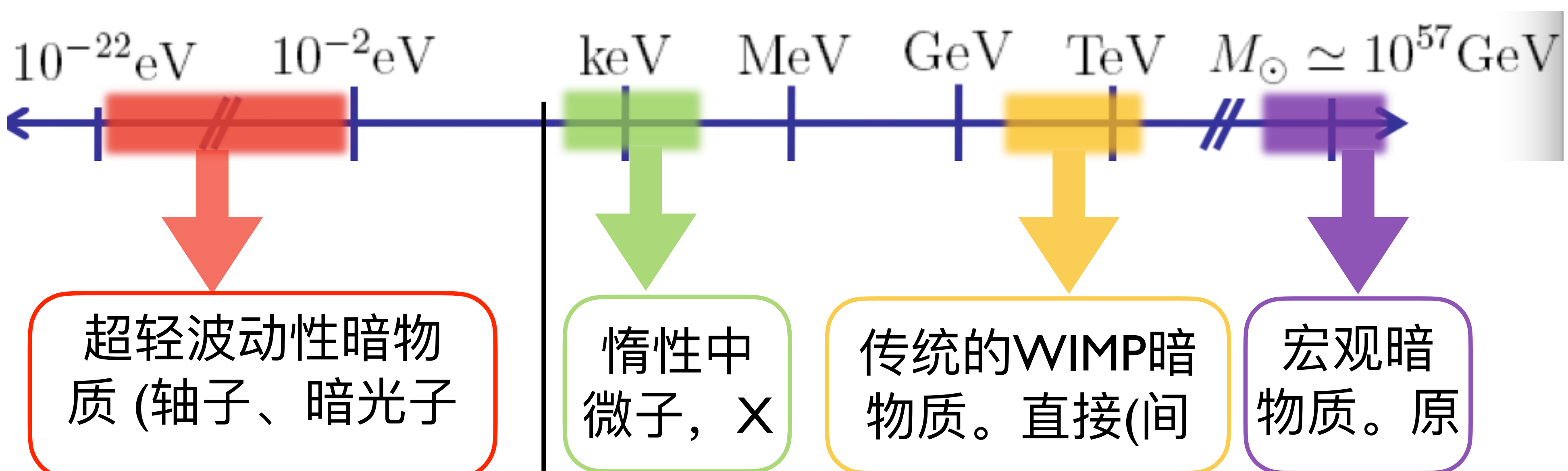


波动性暗物质

- 困扰物理学界的重点问题：**暗物质是什么?**

宇宙中约1/4的能量物质来源于未知的暗物质

暗物质组成未知，可能候选者质量范围跨越非常大



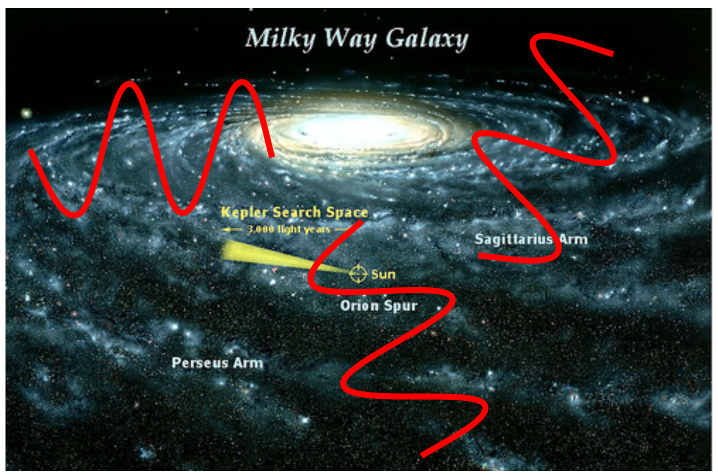
波动性暗物质：每个粒子的德布罗意波长互相重叠，表现为宏观波动

粒子型暗物质：粒子间间隔远大于粒子德布罗意波长，表现为若干孤立粒子

Axion粒子探测 see Ning Zhou’s talk

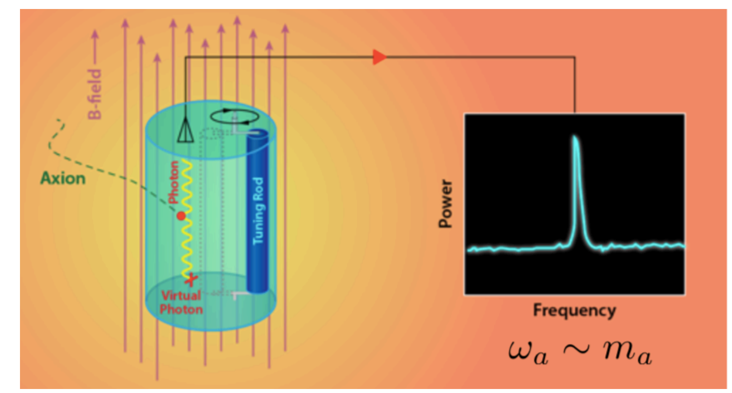
(波动型)超轻暗物质

量子力学：物质都有粒子性和波动性



(m~10^{-22} eV)

超轻暗物质波长在宏观尺度, 宏观上表现为波动的背景场



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

德布罗意波长达到星系尺度(kpc)

有别于传统暗物质探测(不再基于粒子散射)发展空间巨大

康普顿波长达到实验室尺度(m)

依赖于天文观测(时间，空间位置的测量)

类似于引力波的探测

共振谐振腔量子放大器

利用天文观测实验

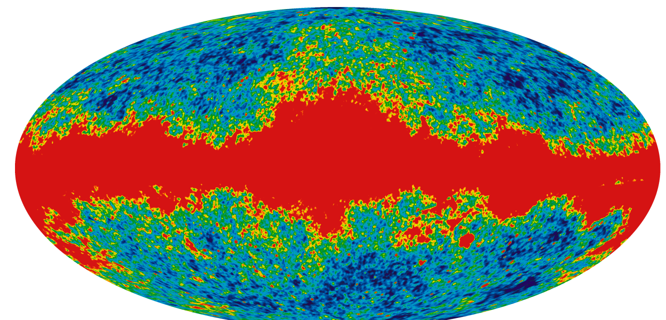
提出新的量子探测实验

Astro-particle detection

背景介绍

射电天文学是当今物理学的热点领域

2018
基础物理突破奖：

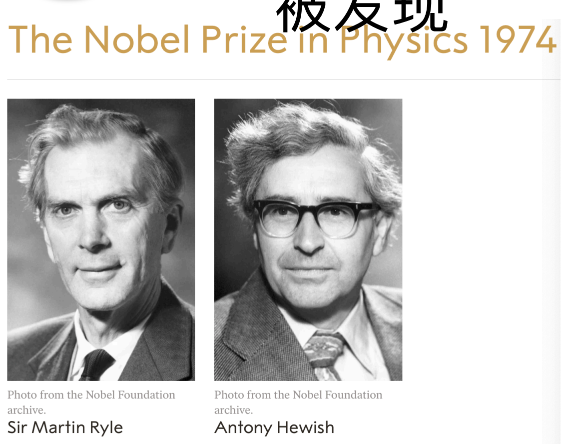


WMAP测量宇宙微波背景辐射各向异性

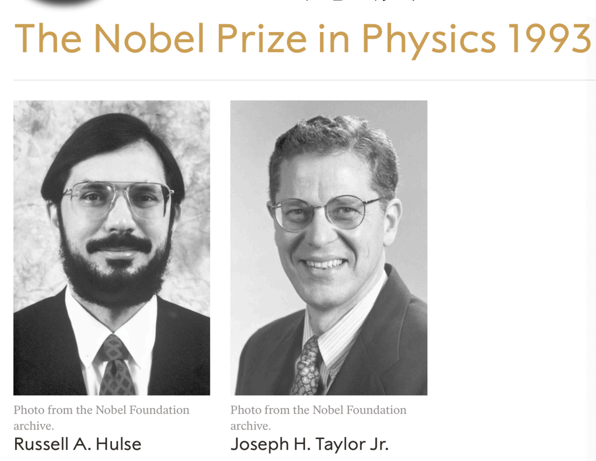
2020
基础物理突破奖：

EHT拍摄黑洞射电照片

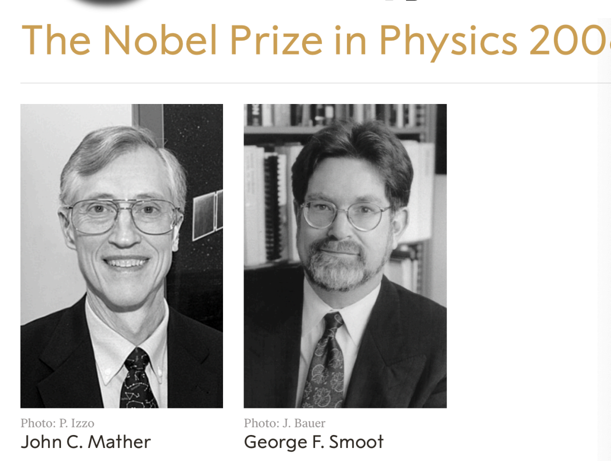
射电天文的发展、脉冲星首次被发现



脉冲双星证实引力波

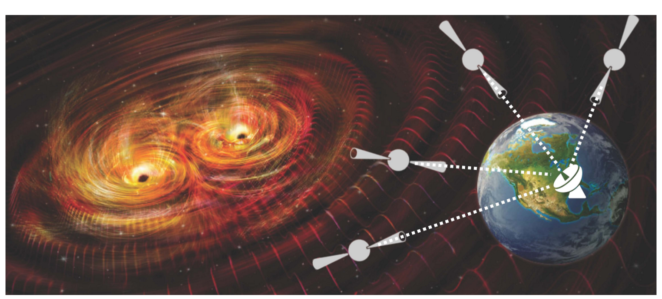


微波背景辐射

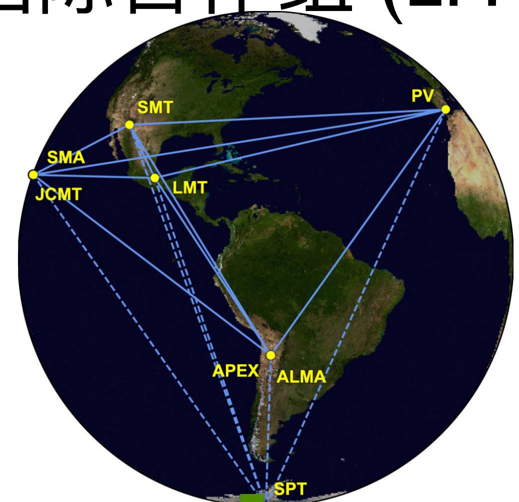


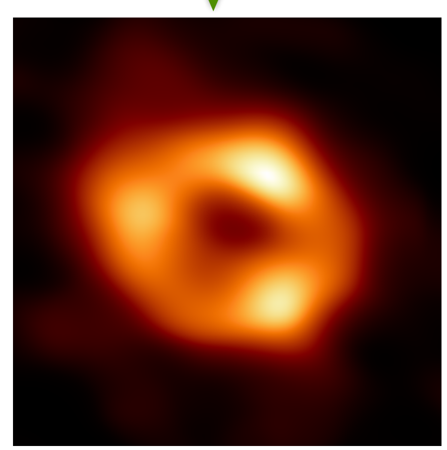
大型射电天文观测装置

脉冲星计时阵列 国际合作组（PTA）

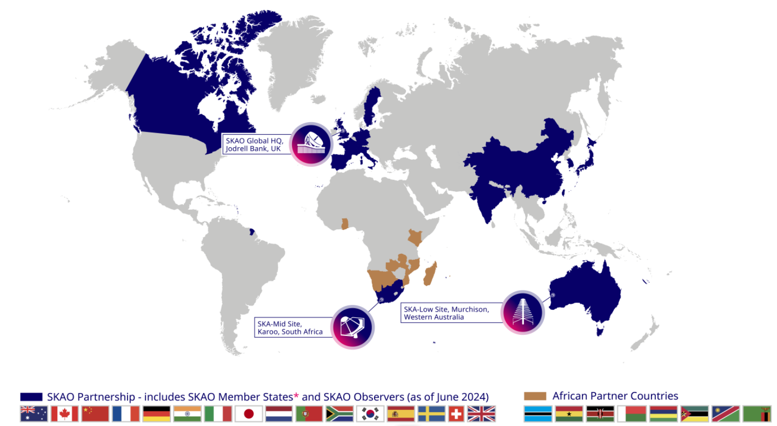


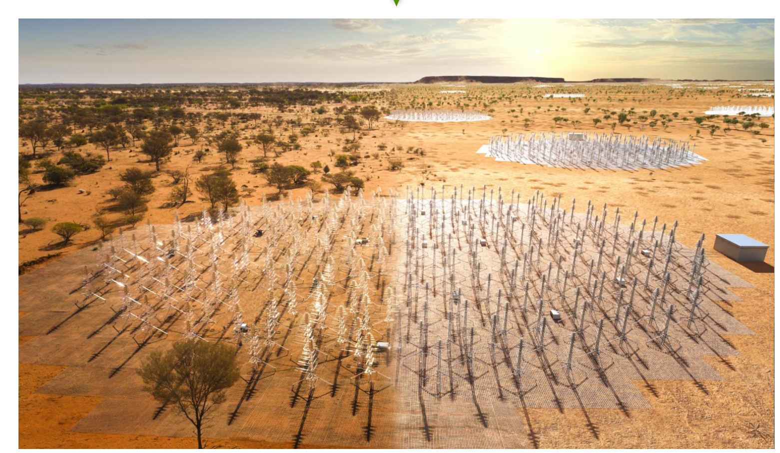
黑洞视界望远镜 国际合作组 (EHT)





平方公里阵列 （SKA）

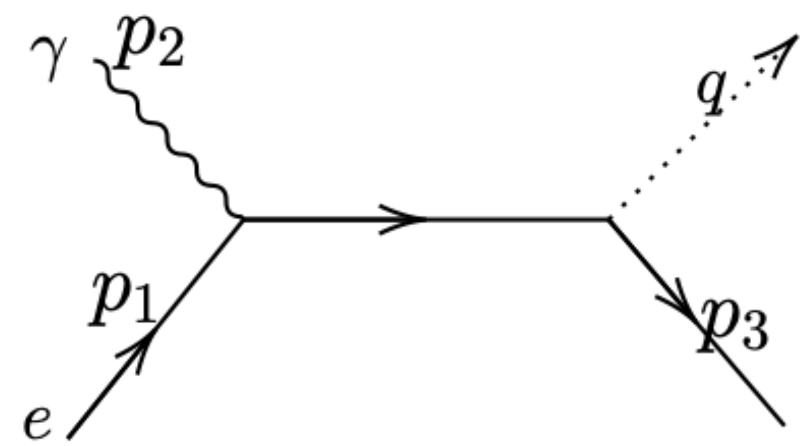


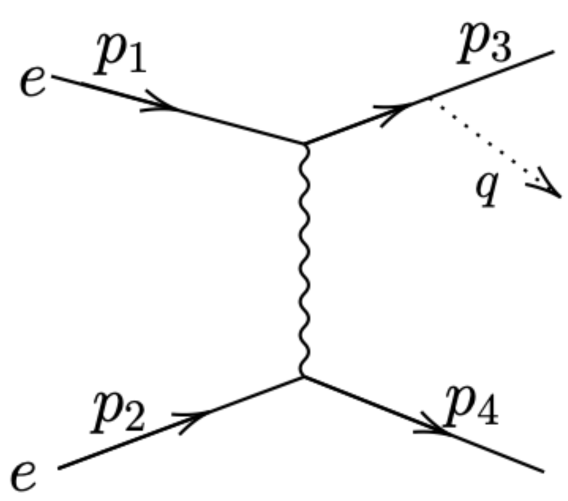


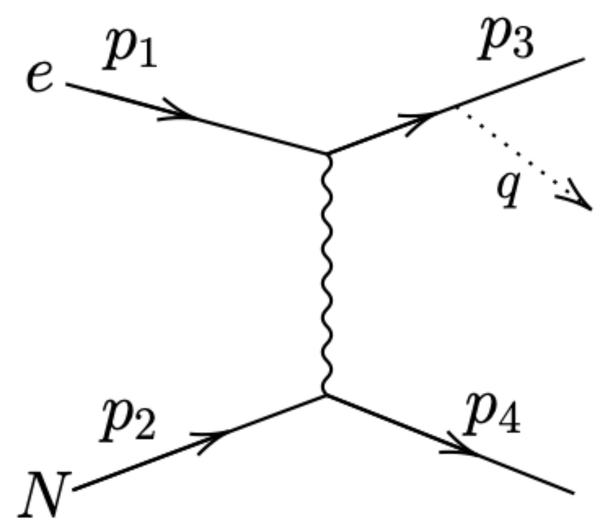
未来大型射电天文学观测数据

Stellar cooling

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

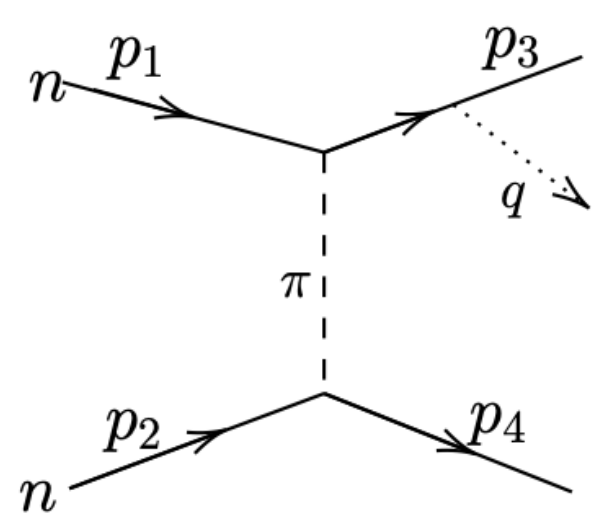






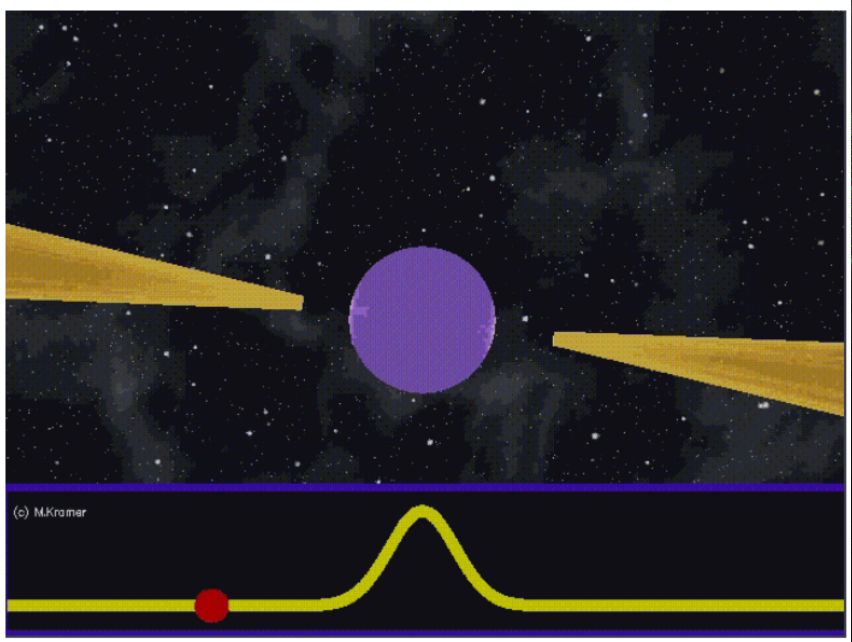
- $N - N$ bremsstrahlung: $N + N \to N + N + b$;
- pion-proton scattering: $\pi^- + p^+ \to n + b$,

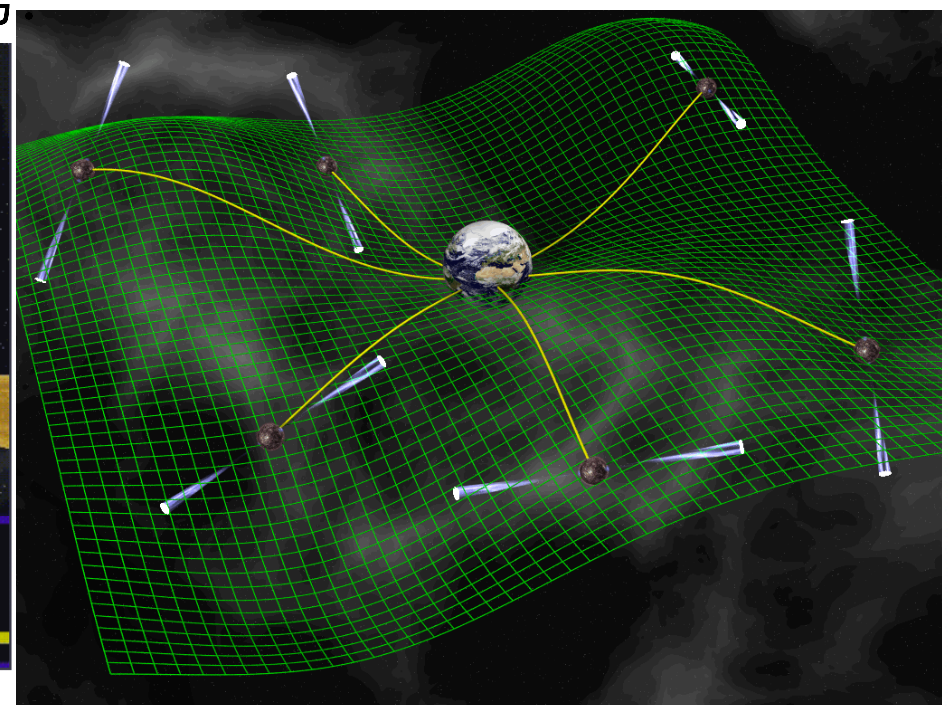
where N can be proton or neutron and p^+ is proton.



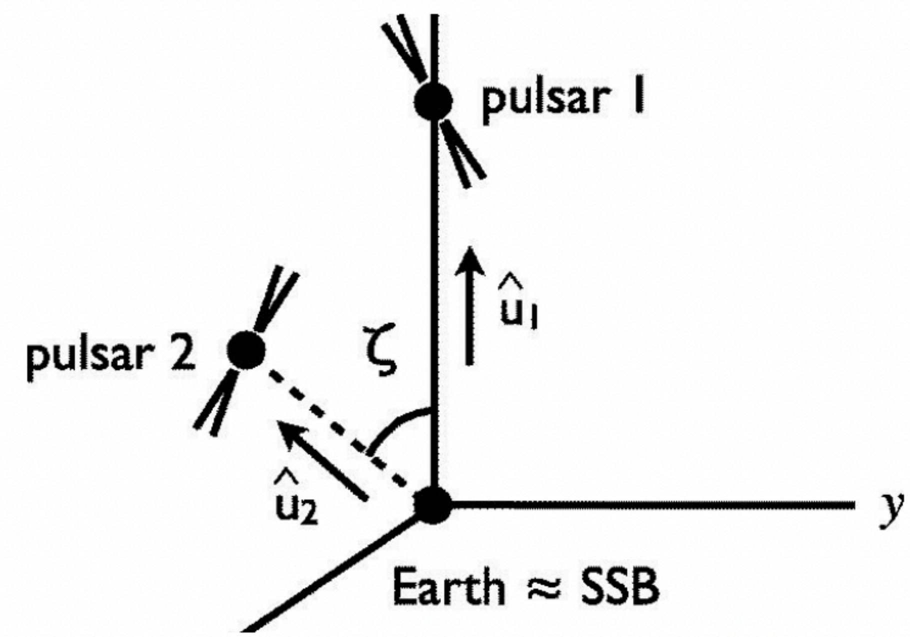
PTA：(波动型)超轻暗物质

脉冲星是一个高度磁化的旋转中子星， 在磁轴线上辐射出强电磁场，周期性发射脉冲信号





脉冲星计时阵列 (PTA) 是对多个脉冲星做 脉冲信号时序测量，看信号之间的关联。



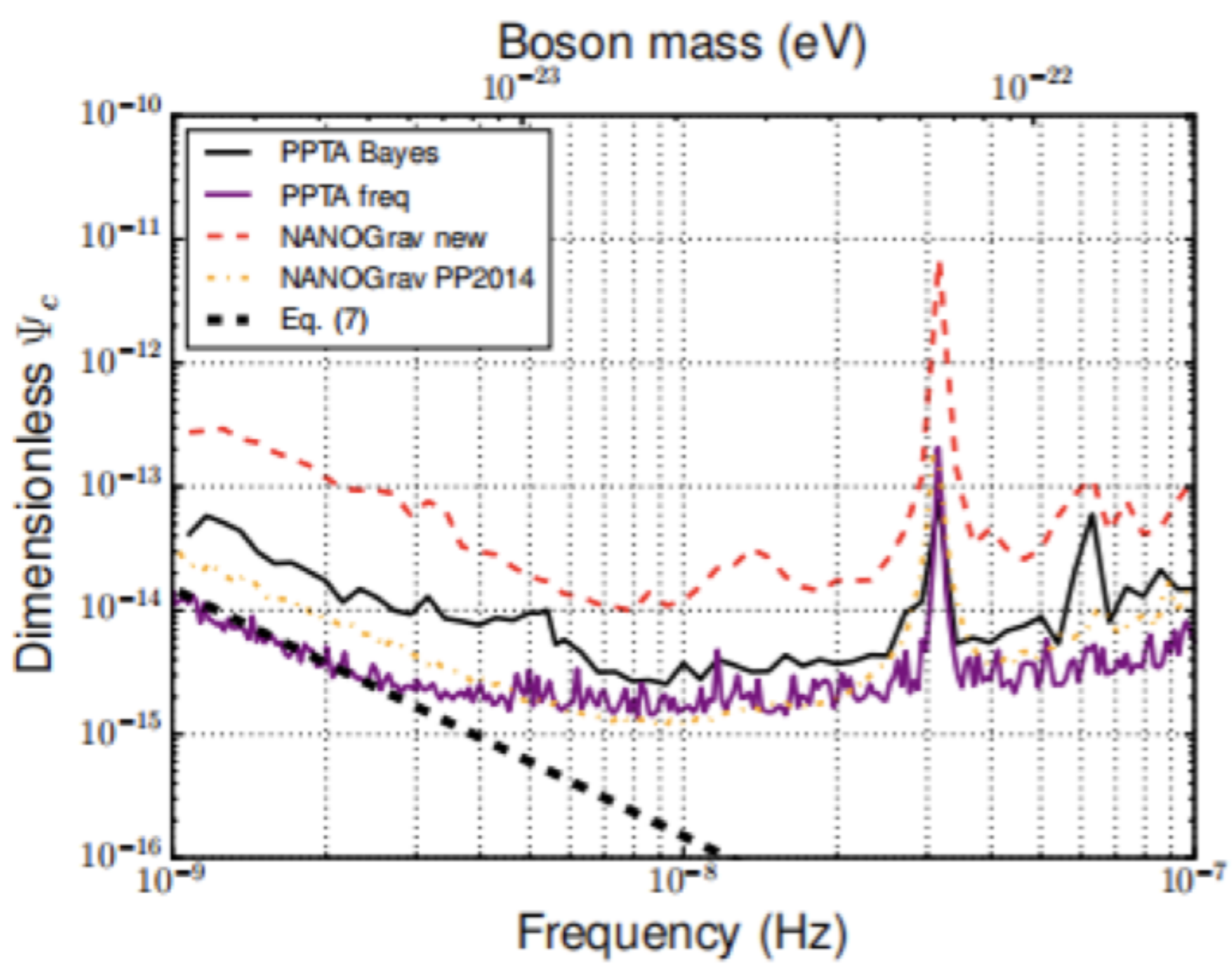
脉冲星计时观测是在固定观测频率上,以原子时为参考,获得一系列脉冲星脉冲到达时间,并与脉冲星时间分析模型给出的预测值相比较。

PTA：(波动型)超轻暗物质

暗物质（振荡的场）的引力势能，会改变周围的能量动量张量，从而改变电磁脉冲过来的时间间隔

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

1810.03227

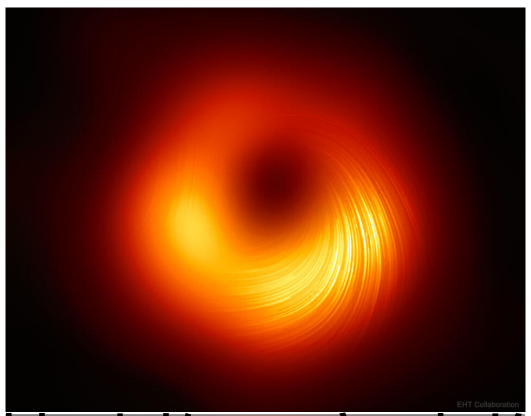


EHT极化探测轴子暗物质

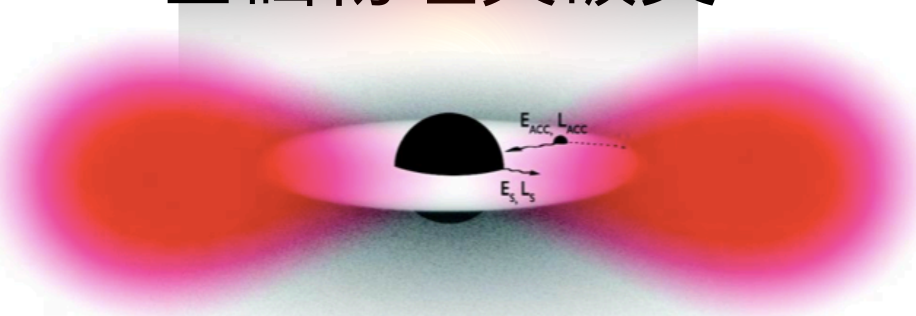
- 视界望远镜极化数据探测轴子超轻暗物

2020年诺贝尔物理学奖

黑洞视界望远镜(EHT)



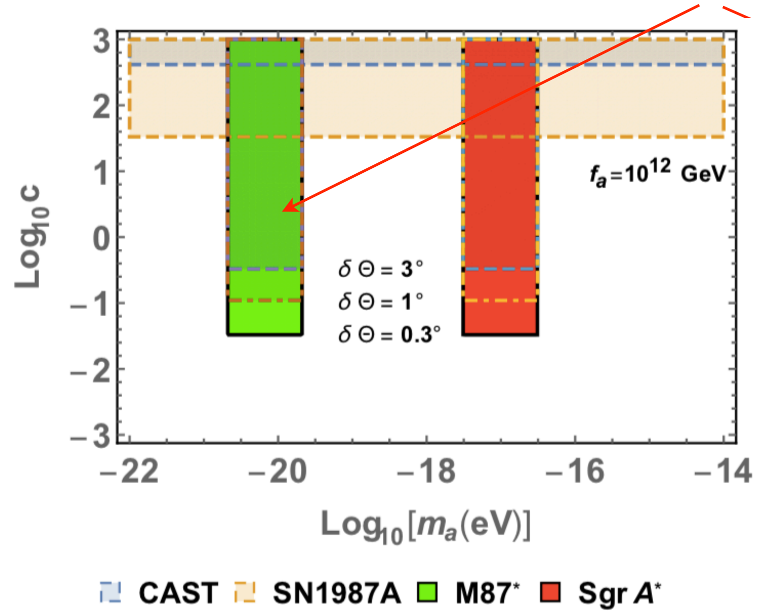
基础物理突破奖



如果存在超轻暗物质(轴子), 类似霍金辐射，旋转的黑洞会辐射轴子，从而在黑洞附近形成轴子云

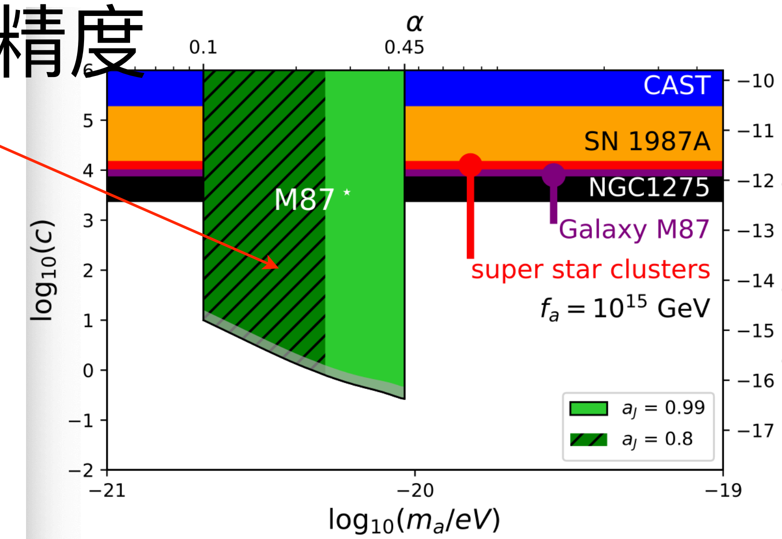
黑洞还可以用来探测超轻暗物质(轴子)!

最高实验精度



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

黑洞视界望远镜(EHT)极化数据，探测限制轻(暗)极化粒子



黑洞附近的电磁波穿过轴子云，类似于双折射效应，极化角随时间周期变化

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

Super-radiance slow down BH spin rotation。 ref?

Table-top detection

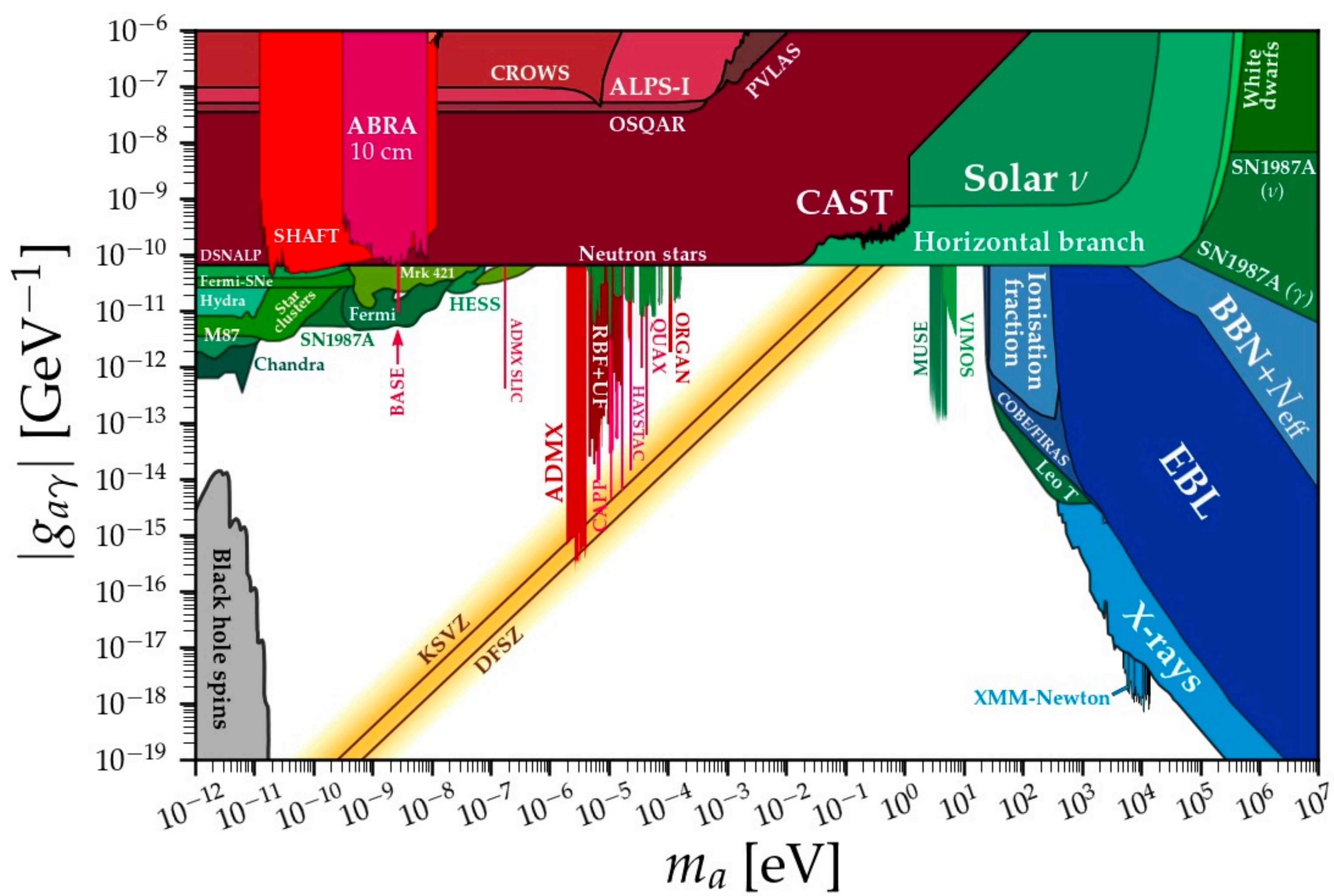
Current status

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

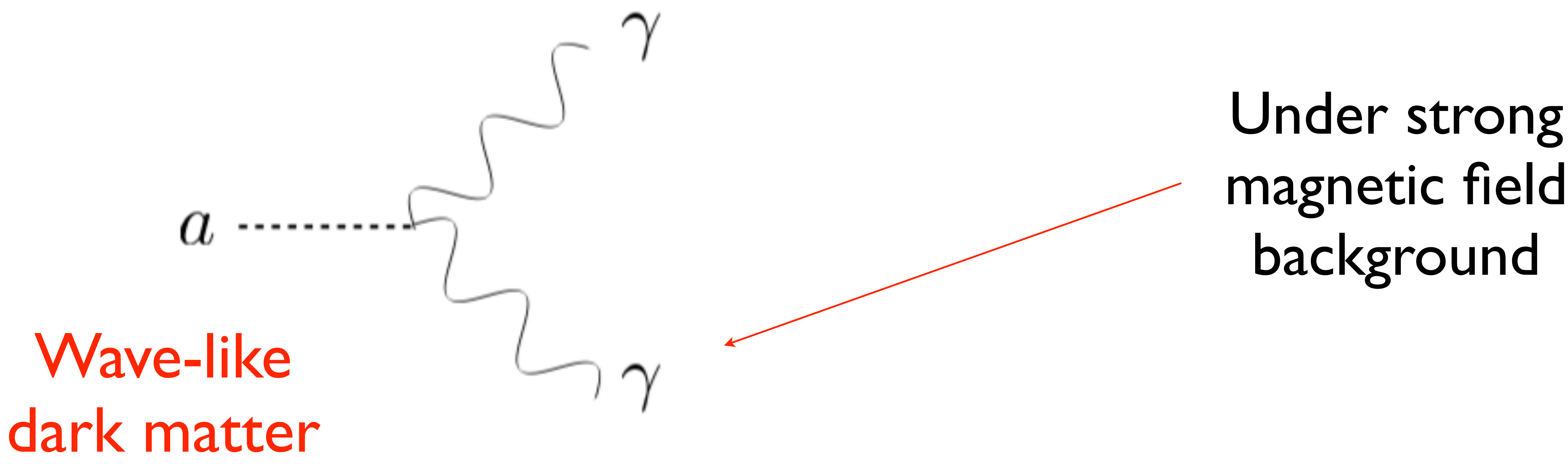
  …

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

A huge parameter space to be explored!



Inverse Primakoff Effect



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

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

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

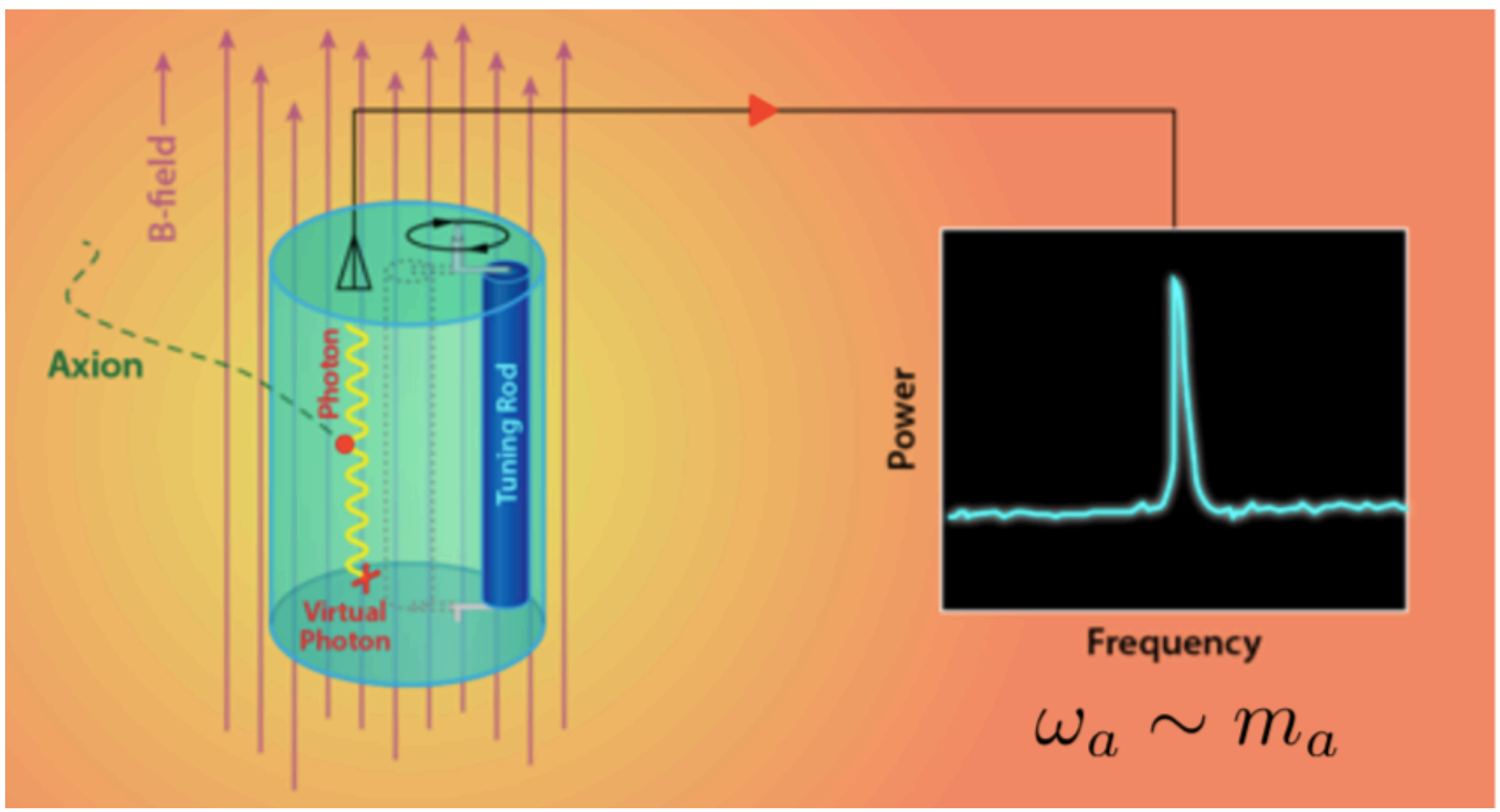
Cavity with static B field

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

$$Q_a \sim 10^6$$

Quantum amplifier to readout the signal.

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



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: $\mathbf{E_n}$

Pump Mode: **B**

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

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

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

SRF with AC B field

Signal Mode: $\mathbf{E_1}$

Source: **a**
(almost monochromatic)

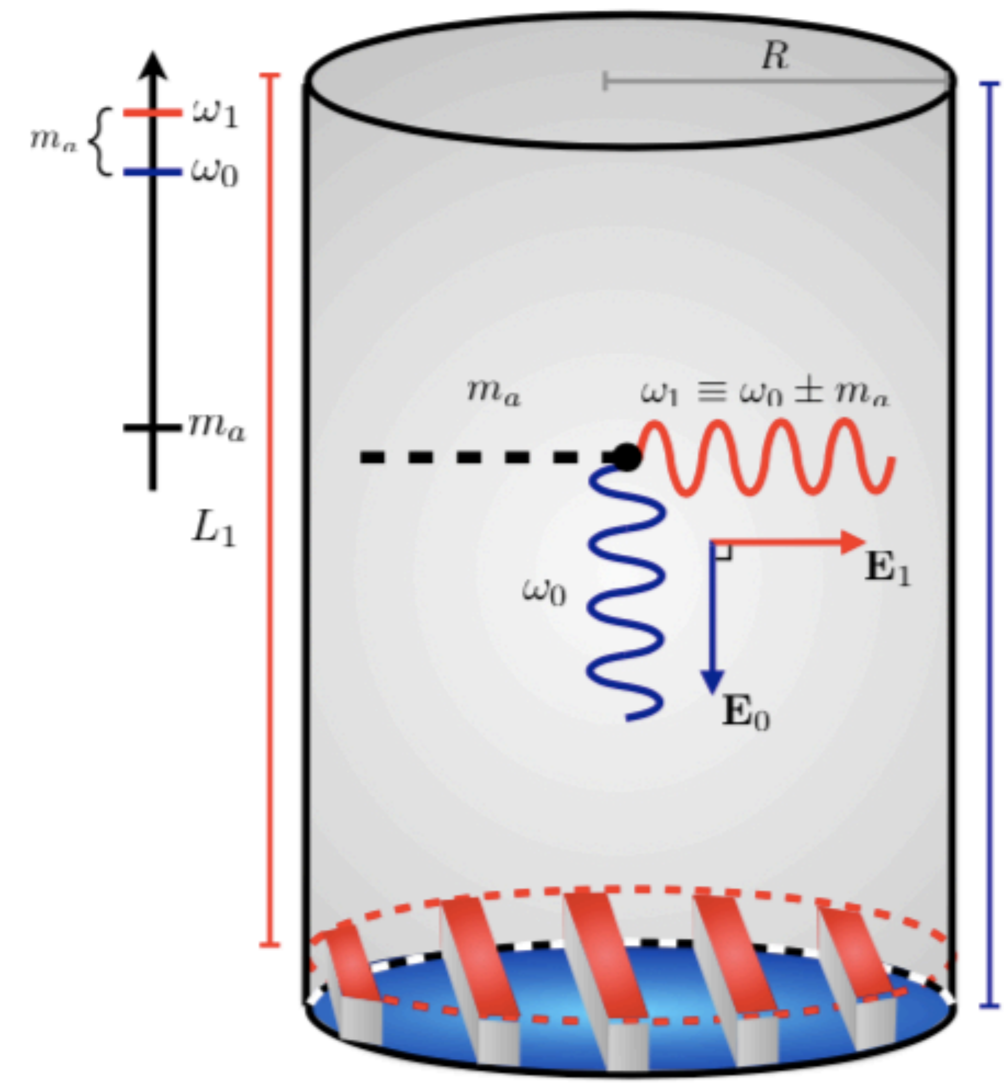
$$\sum_n \left(\partial_t^2 + \frac{\omega_n}{Q_n}\partial_t + \omega_n^2\right)\mathbf{E}_n = g_{a\gamma\gamma}\partial_t(\mathbf{B}\partial_t a)$$

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

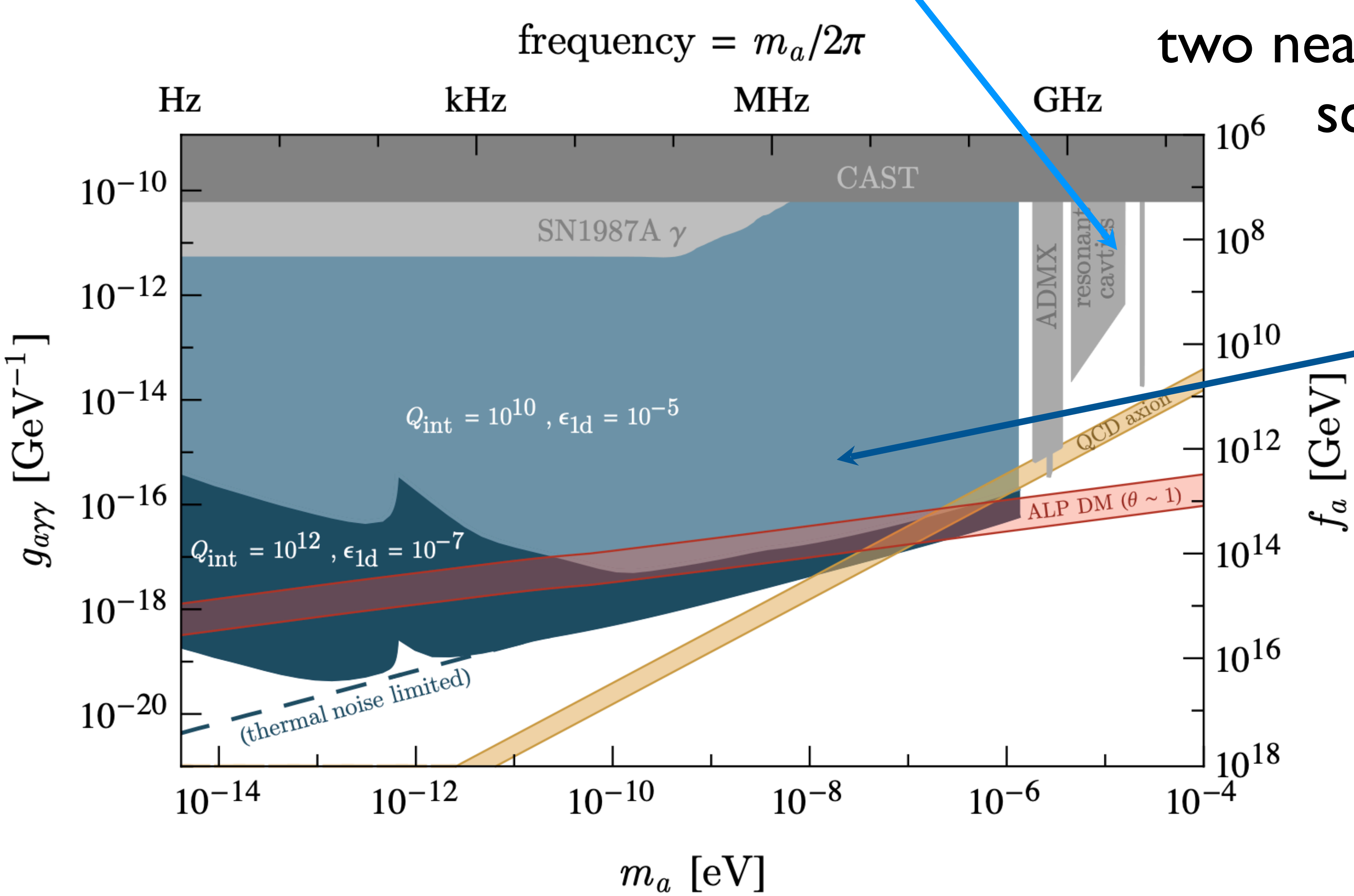
Hard to scan for a broad mass window in traditional cavity!

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

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.

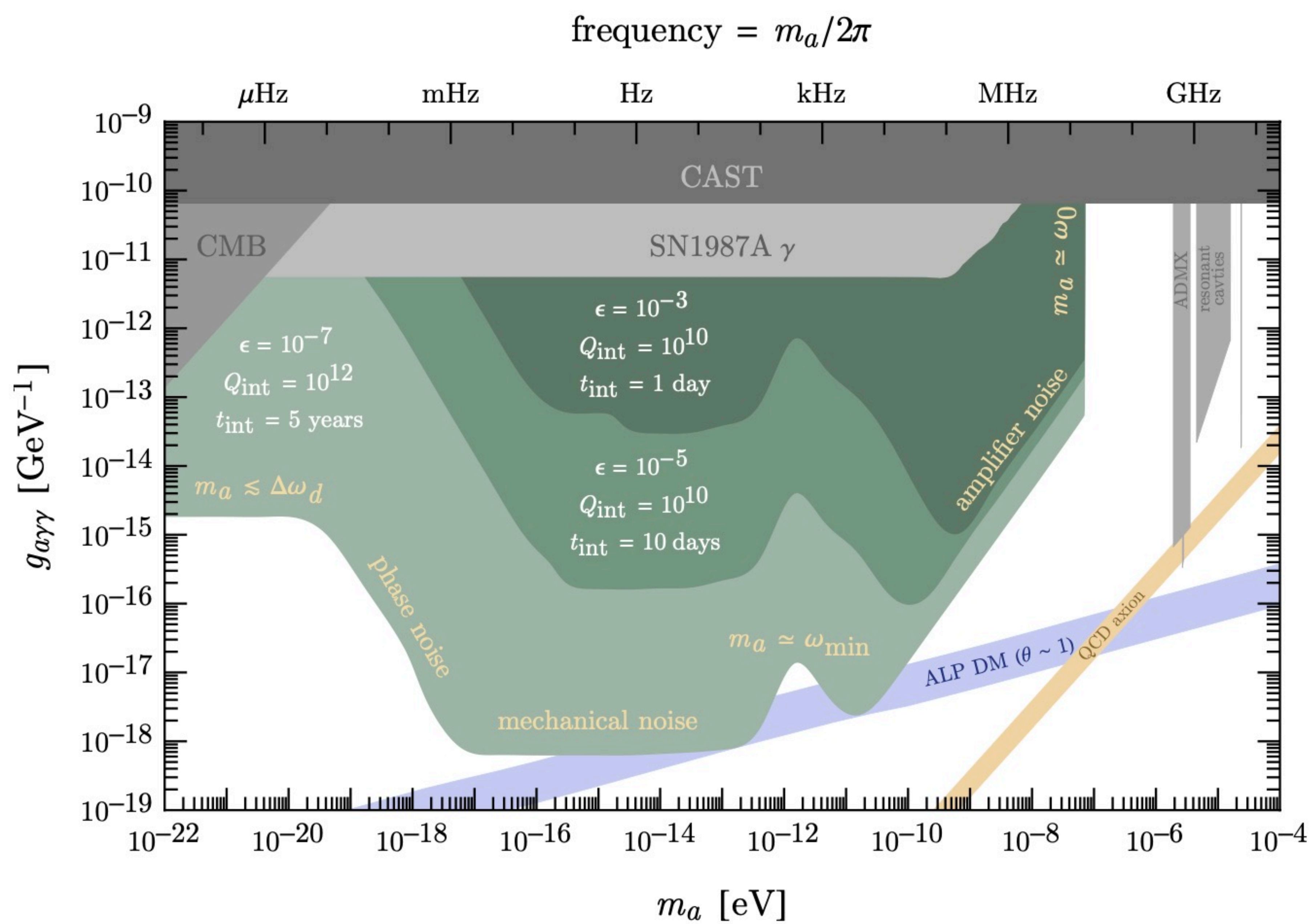
Large unexplored parameter space!

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]].

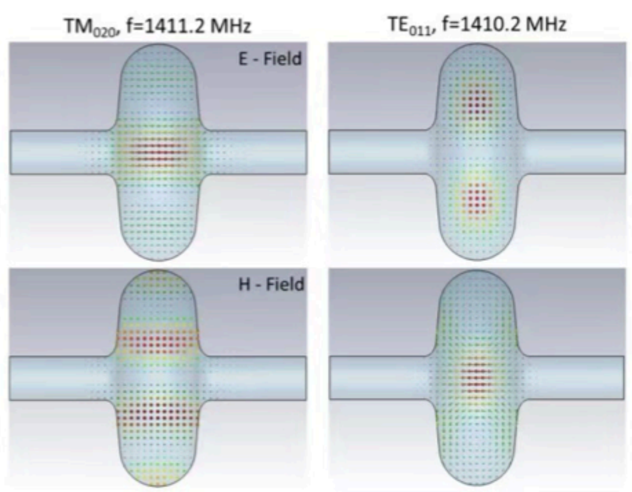
Axion search

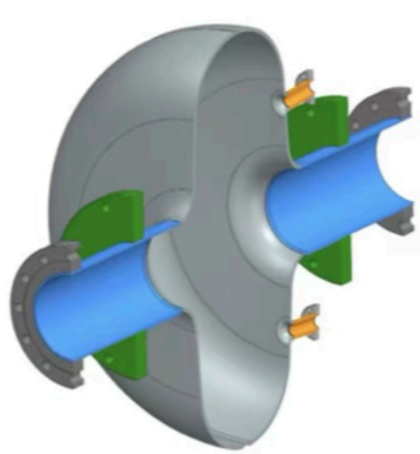
TDR like

SHANHE collaboration

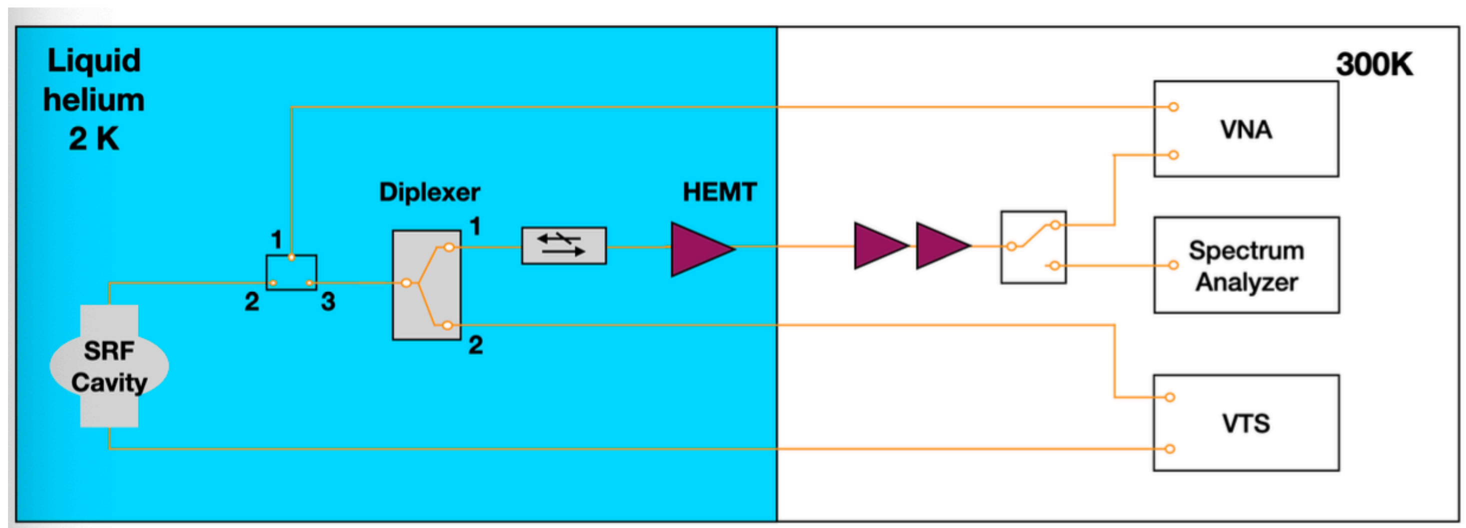
Fermilab

arXiv:2207.11346

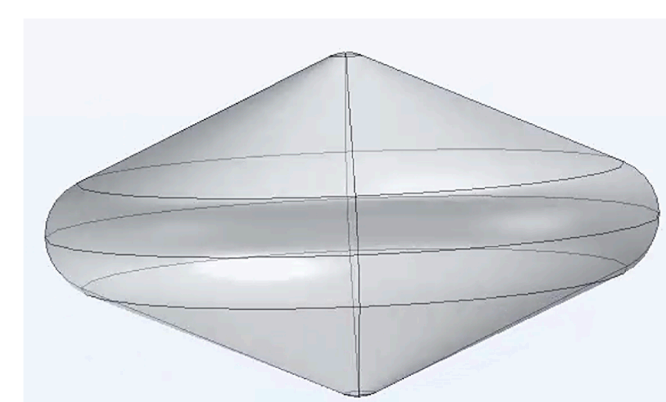




Using the existing 1.3G cavity as a pathfinder



New designed cavity will be operated in the future.



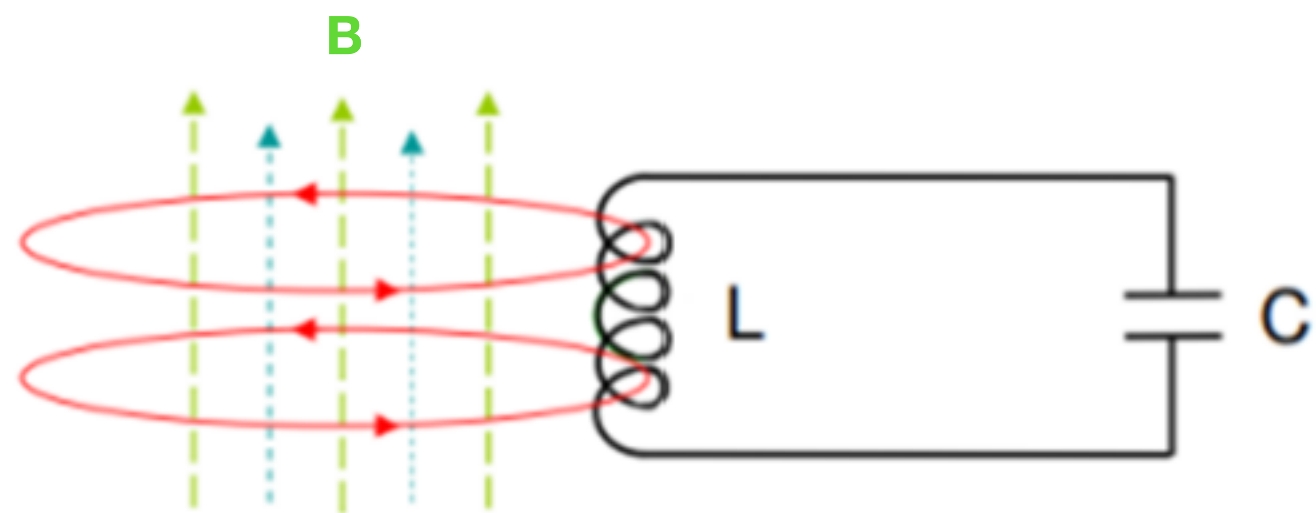
LC Circuit with static B field

- Resonant conversion happens when

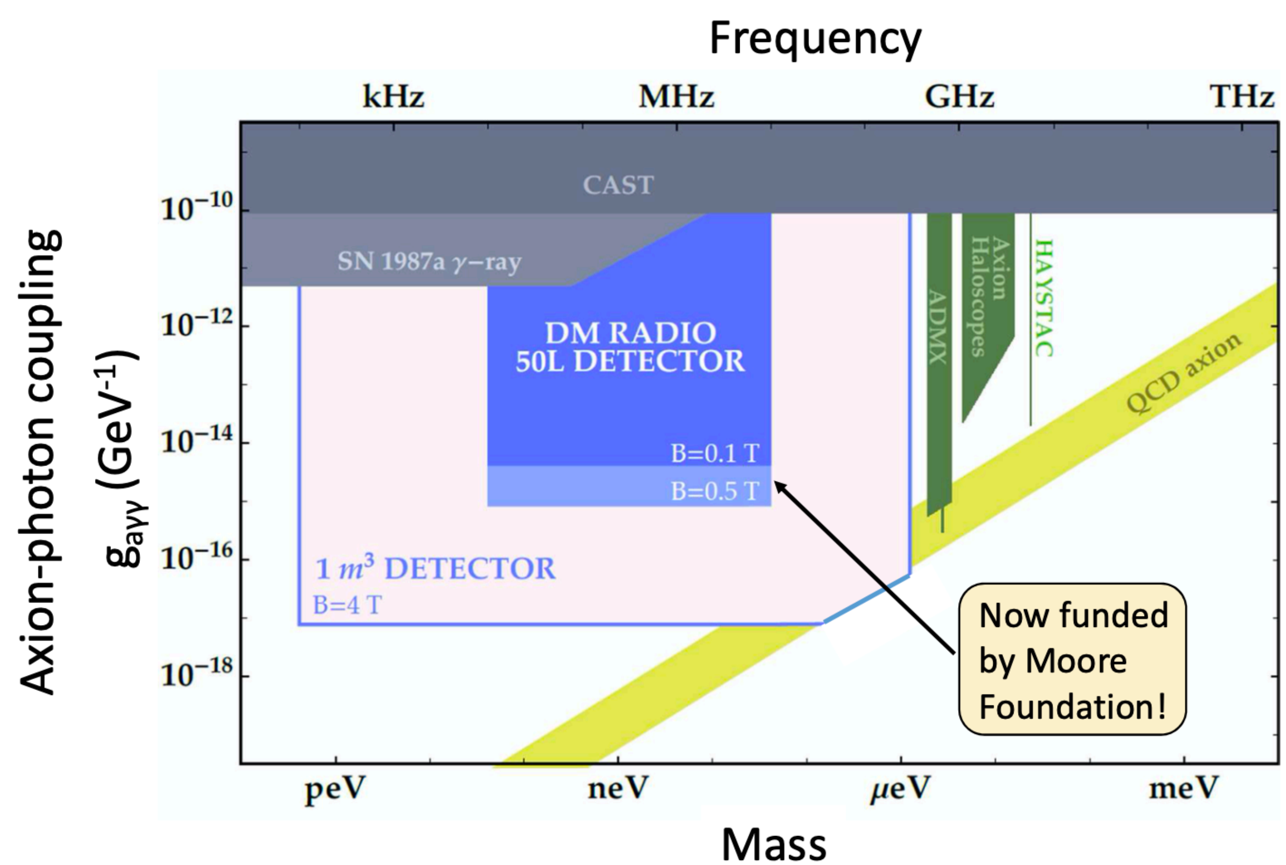
$$m_a = \omega = \frac{1}{\sqrt{LC}}$$

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

e.g. DM radio, ADMX-SLIC



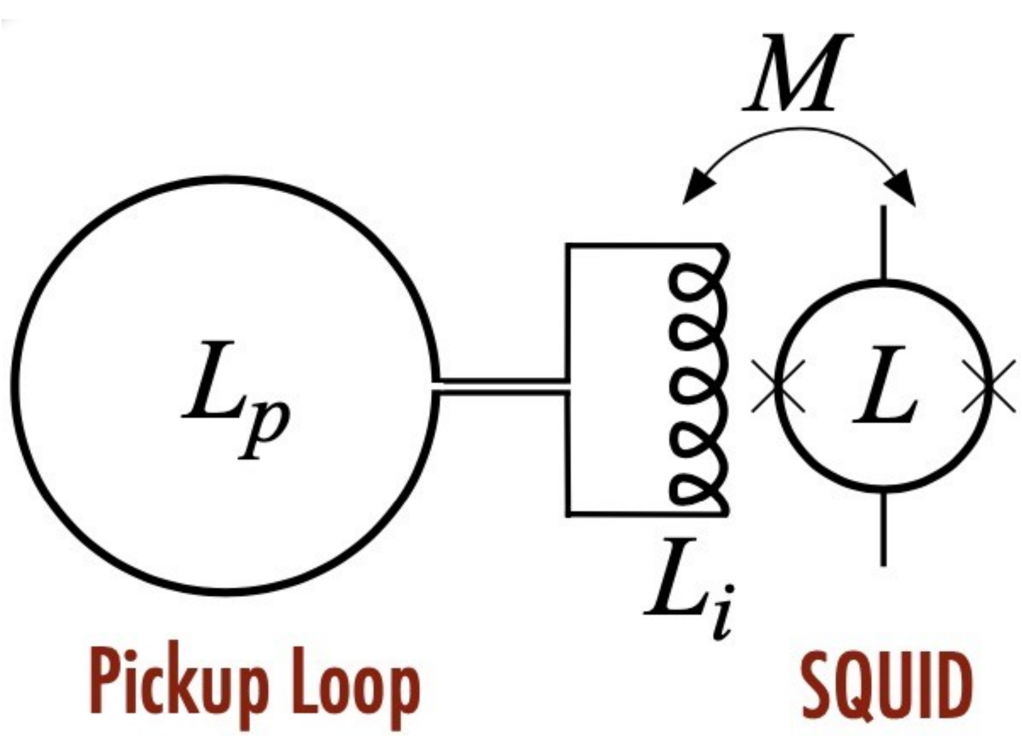
DM Radio science: axions

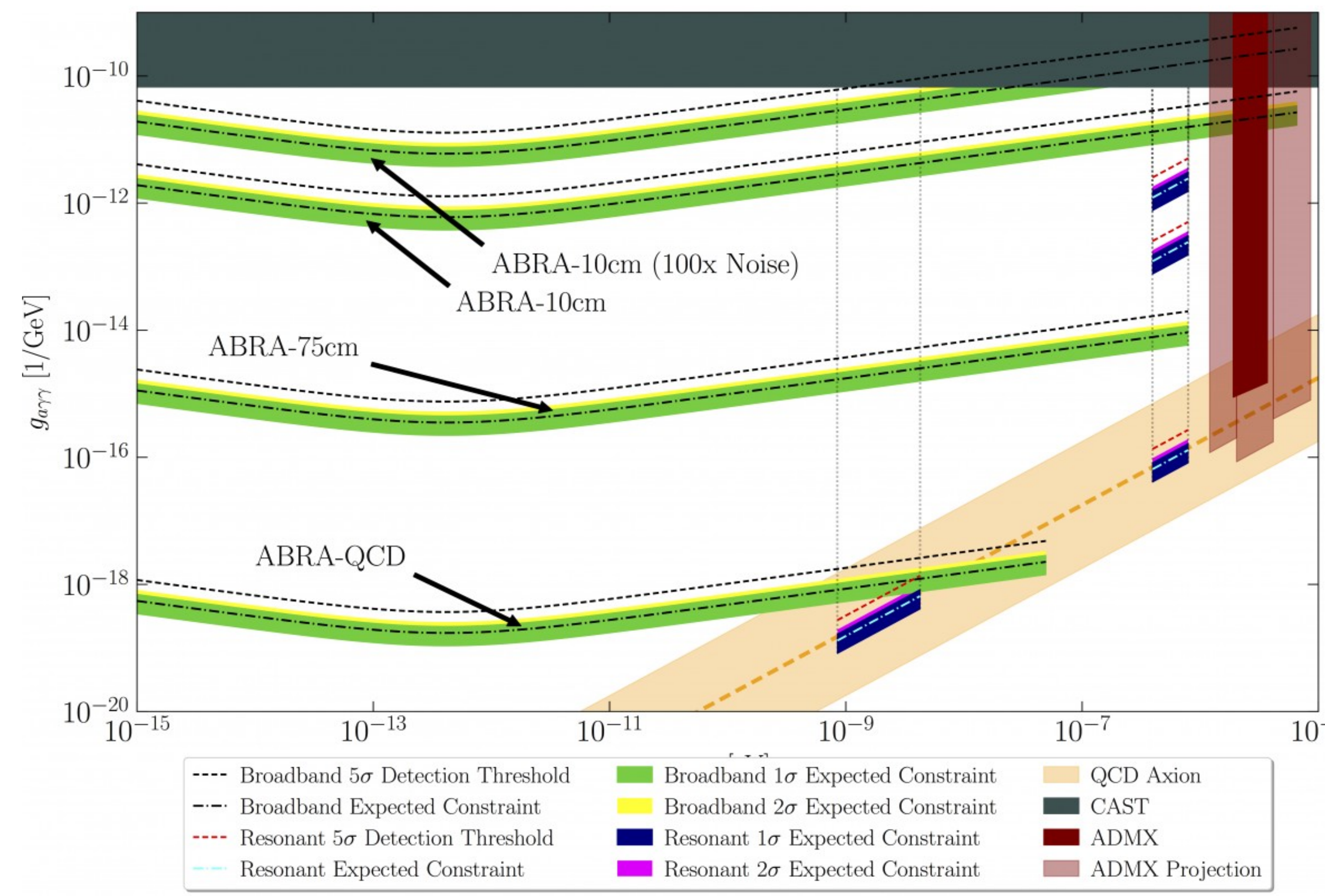


Assumptions: T=10 mK, Q=10^6, 3.5 year integration time, quantum-limited readout

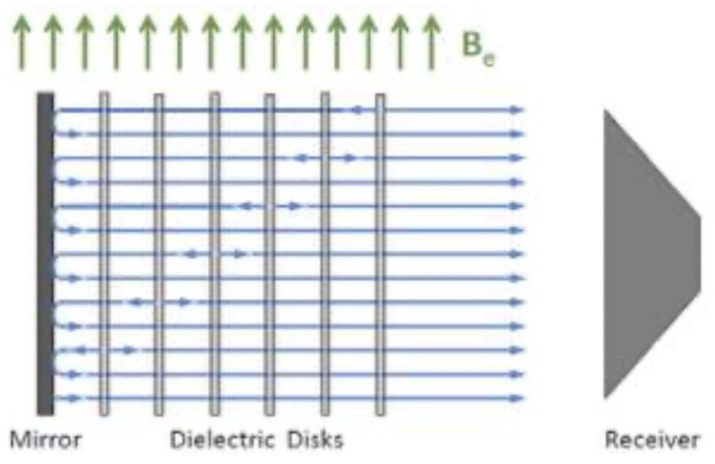
Broadband Detection

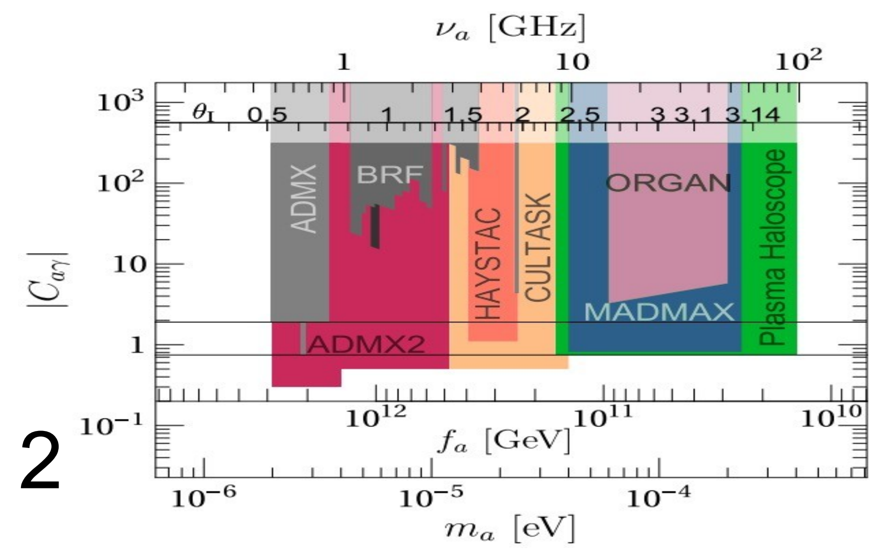
- ABRACADABRA: no capacitor, **simultaneous scan of broad frequencies using SQUID**. [Y.Kahn, B. Safdi, J. Thaler 16']

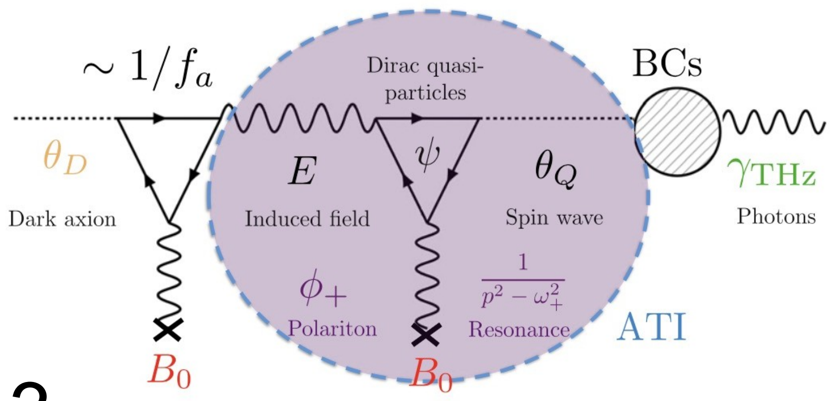




Higher Frequency Electromagnetic Resonant Detection

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

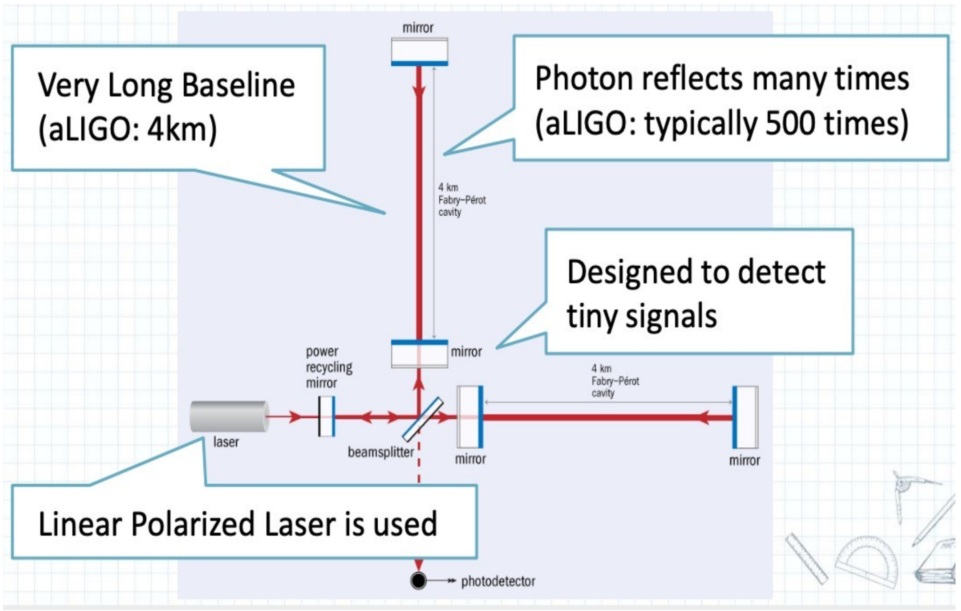
$$\begin{aligned} \Delta\Theta &= g_{a\gamma} \Delta a(t_{\rm obs}, \mathbf{x}_{\rm obs}; t_{\rm emit}, \mathbf{x}_{\rm emit}) \\ &= g_{a\gamma} \int_{\rm emit}^{\rm obs} ds\; n^{\mu}\; \partial_{\mu} a \\ &= g_{a\gamma} [a(t_{\rm obs}, \mathbf{x}_{\rm obs}) - a(t_{\rm emit}, \mathbf{x}_{\rm emit})],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

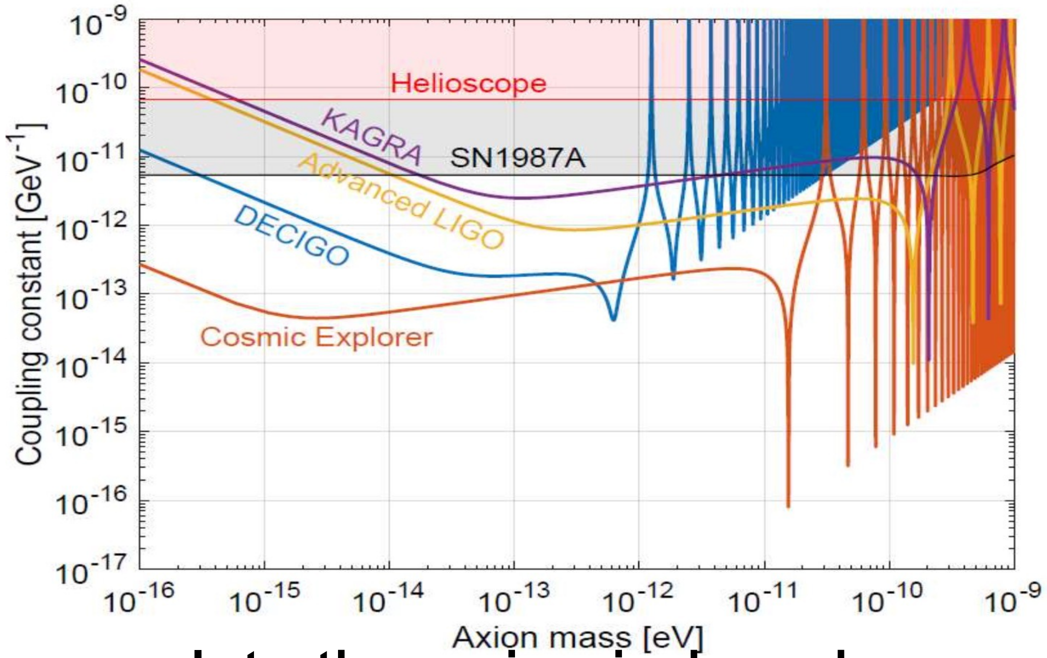
Measure the change of the position angle:

Requires polarimetric measurements

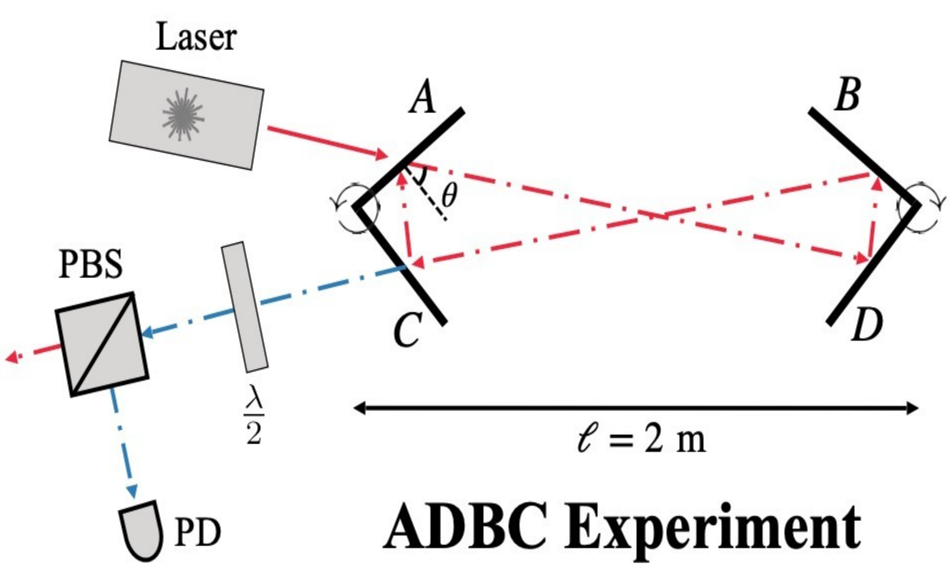
GW Interferometers and Birefringent Cavity

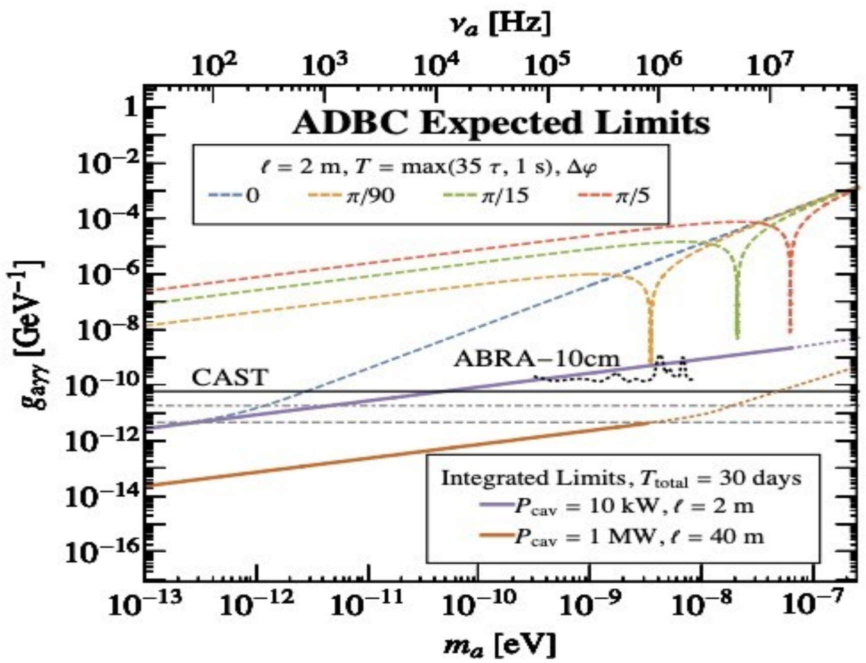
- Interferometer: using vertically polarized laser and measuring the horizontal component, resonant when baseline matches λ_c. [DeRocco, Hook 18']



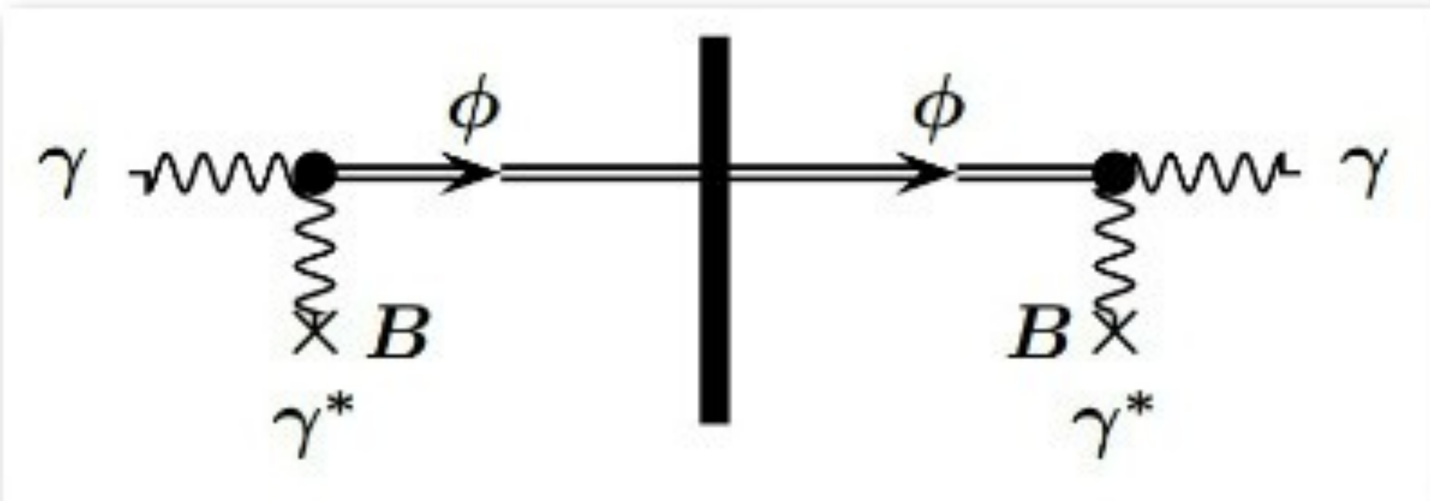


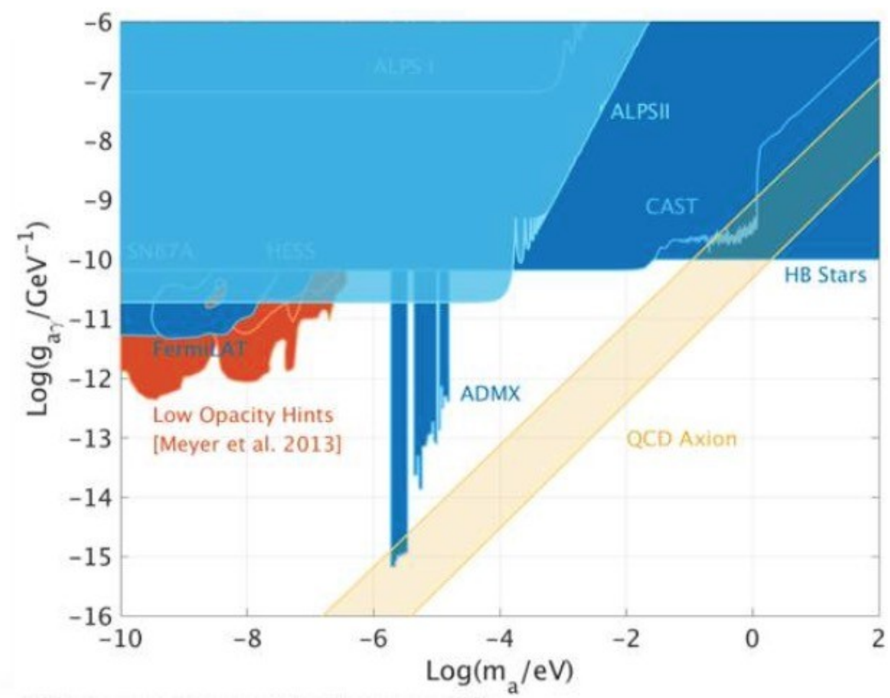
- Birefringent cavity: using mirror to accumulate the axion induced sideband. [Liu, Elwood et al 18']





Light Shining Through Walls [Redondo, Ringwald 10']

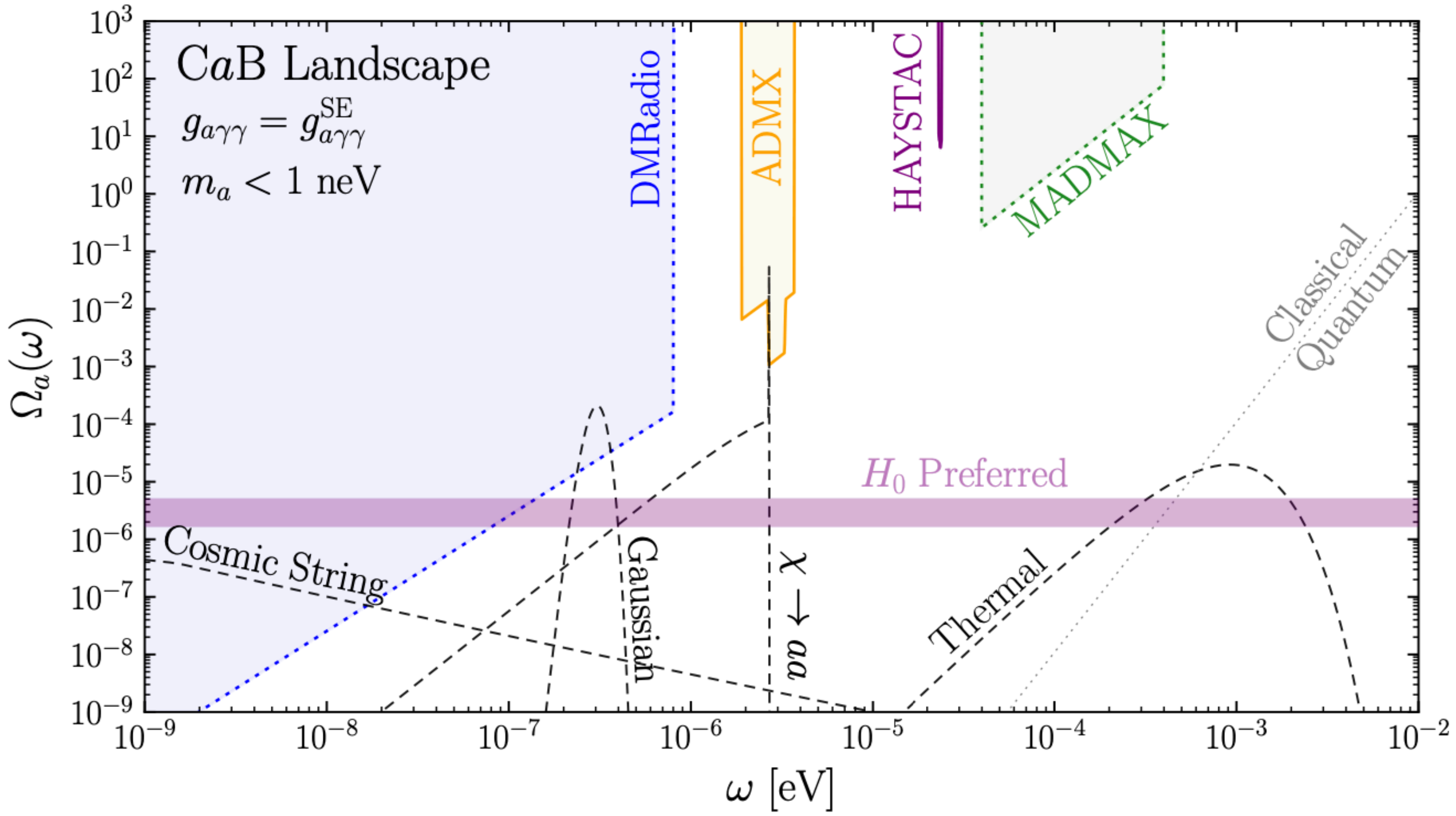


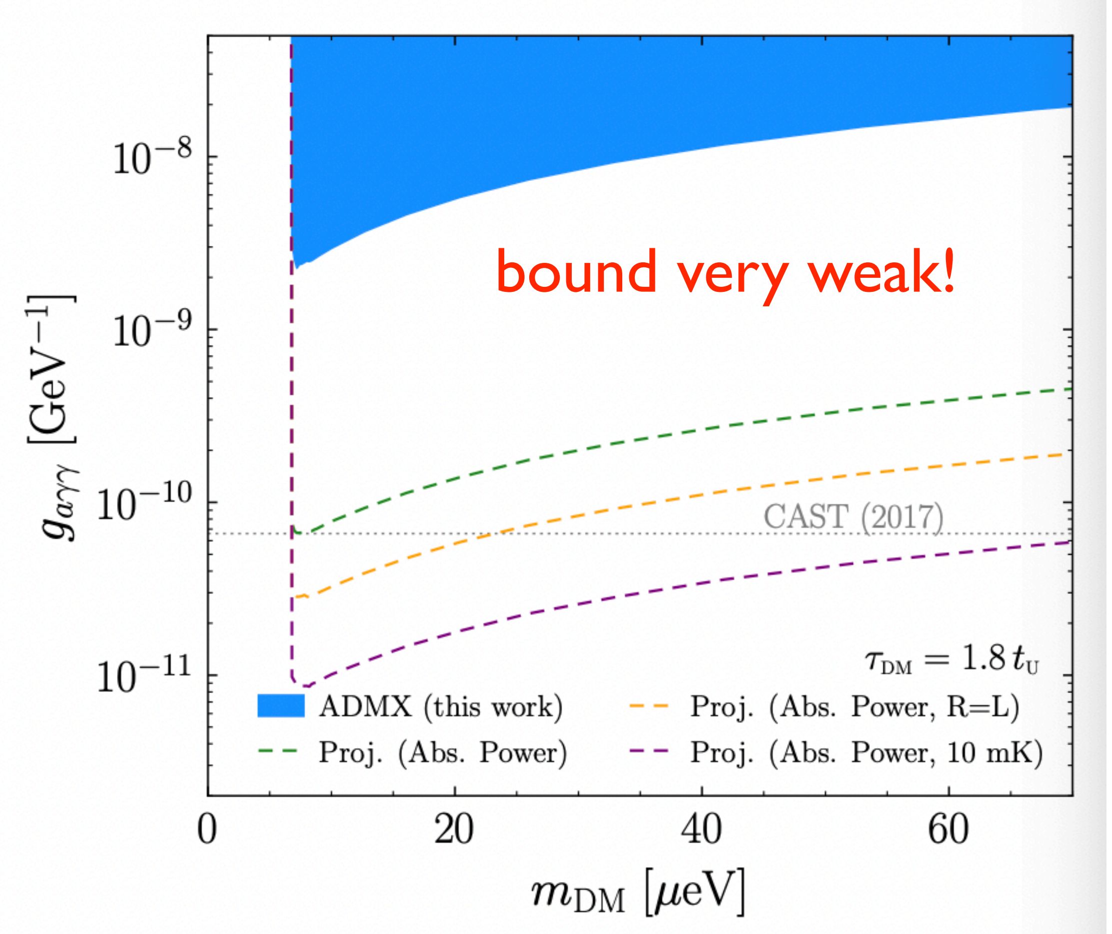


- Photons **convert into axions in B field, pass through a wall and convert back into photons.**
- Both optical and SRF cavity [Janish et al 19'].
- Not dependent on if axion is the major dark matter.

Cosmic axion backgrounds

Axion can also be served as the cosmic backgrounds.





- Relativistic
- Anisotropic

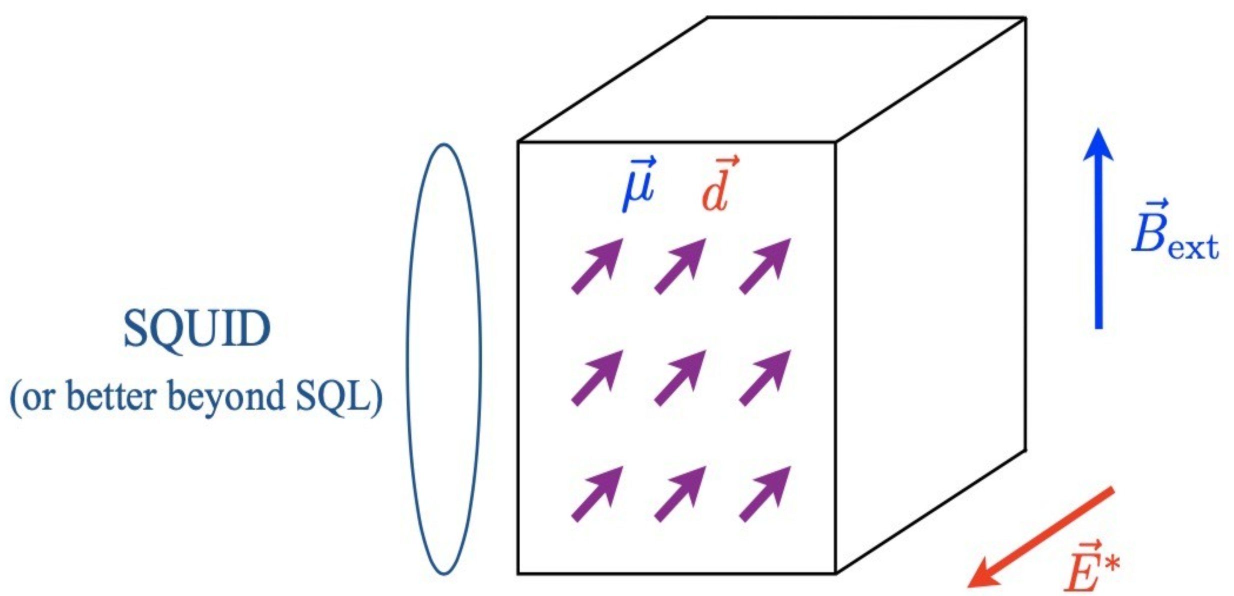
T. Nitta et al. (ADMX), Phys. Rev. Lett. 131, 101002 (2023)

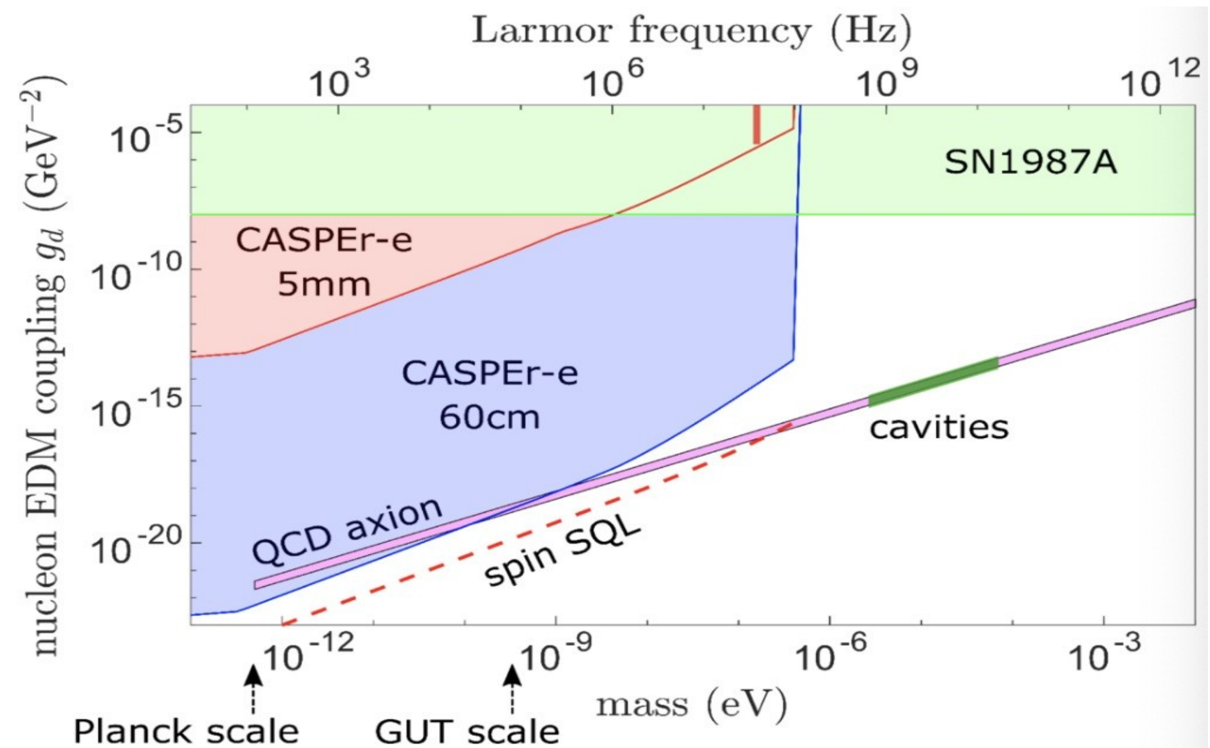
The Cosmic Axion Background

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']

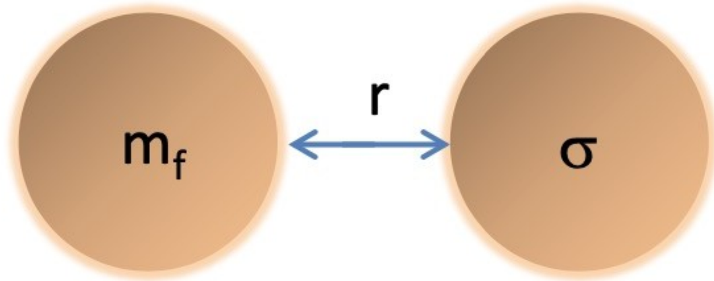
- **CASPEr Electric**: axion gluon coupling leads to oscillating EDM.
- **CASPEr-Wind:** axion nucleons coupling ~ **∇a · σ$_N$ leads to precession of the spin, proportional to axion DM velocity (wind).**





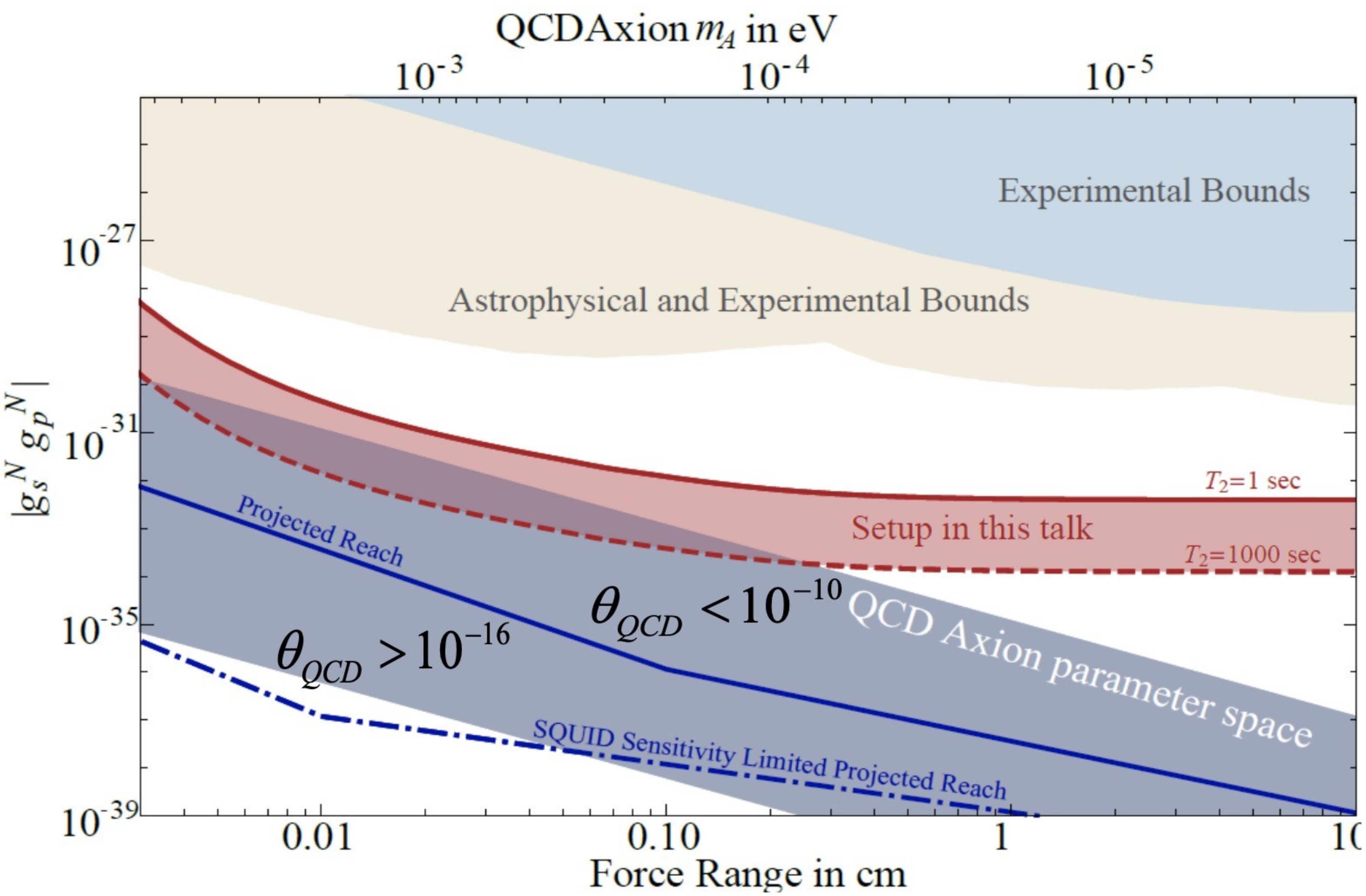
Larmor frequency $2\,\mu B_{ext} = m_a$ leads to NMR-like resonant enhancement.

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



Monopole-Dipole axion exchange

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



[ARIADNE 14']

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