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Gravitational waves from axion clumps and axion searches

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Based on : arXiv: 2003.10527, 2206.13543

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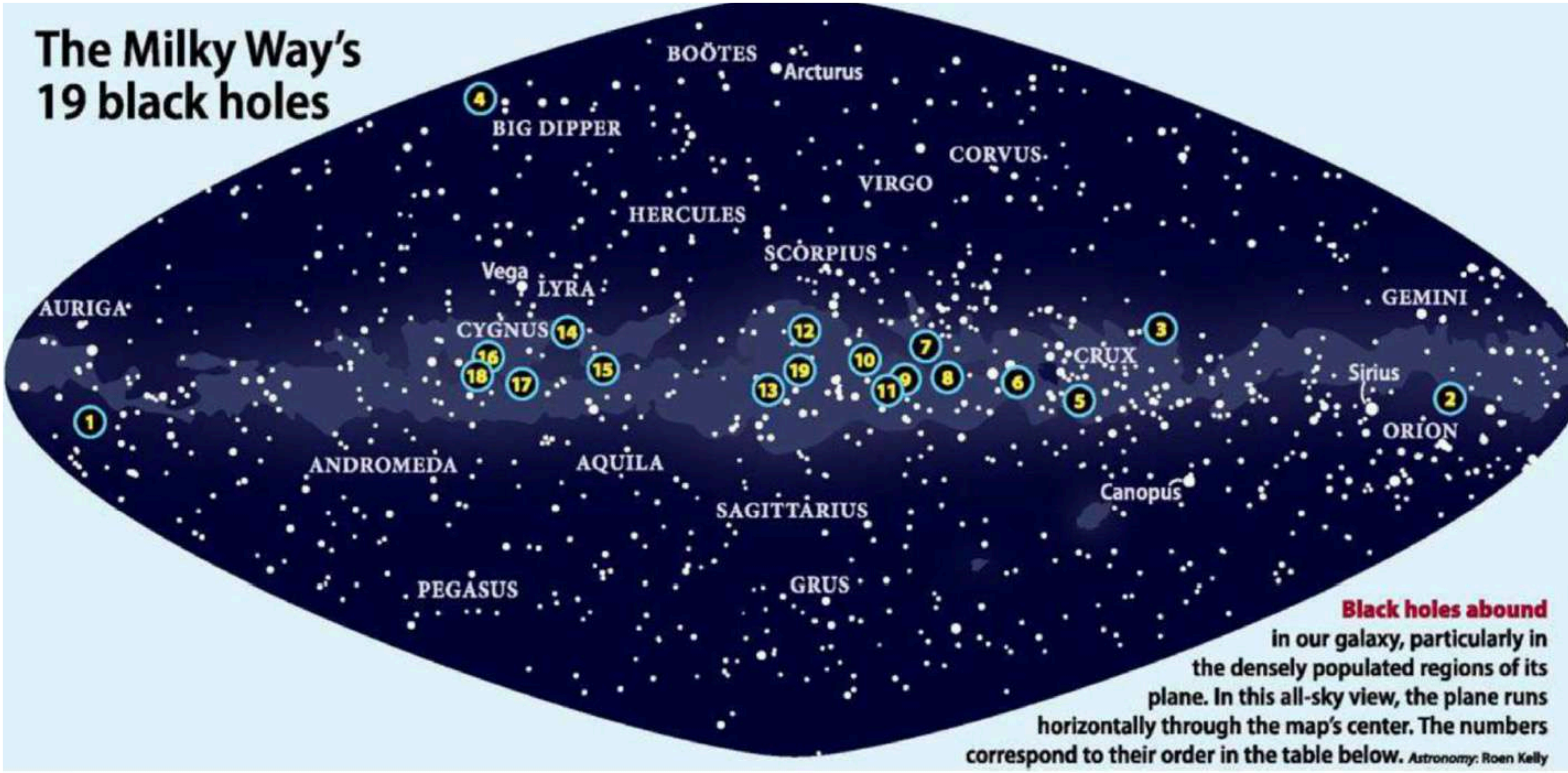
Outline

- Axion resonance effects
- Induced Gravitational waves in difference frequencies
- Superradiance around the primordial blackhole.
- Axion detection （RE-LEAP）

The Milky Way's 19 black holes



Black holes abound in our galaxy, particularly in the densely populated regions of its plane. In this all-sky view, the plane runs horizontally through the map's center. The numbers correspond to their order in the table below. *Astronomy*: Roen Kelly

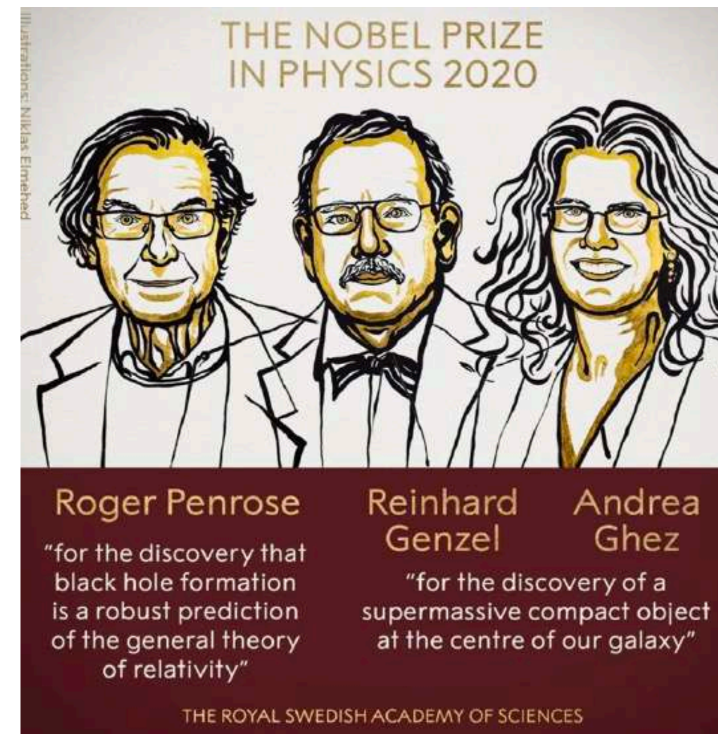
Active Galactic Nuclei（AGN）and Black hole binary(BHB)

- Sgr A（Supermassive Compact Object）in the galaxy center, Nobel prize in physics(2020)

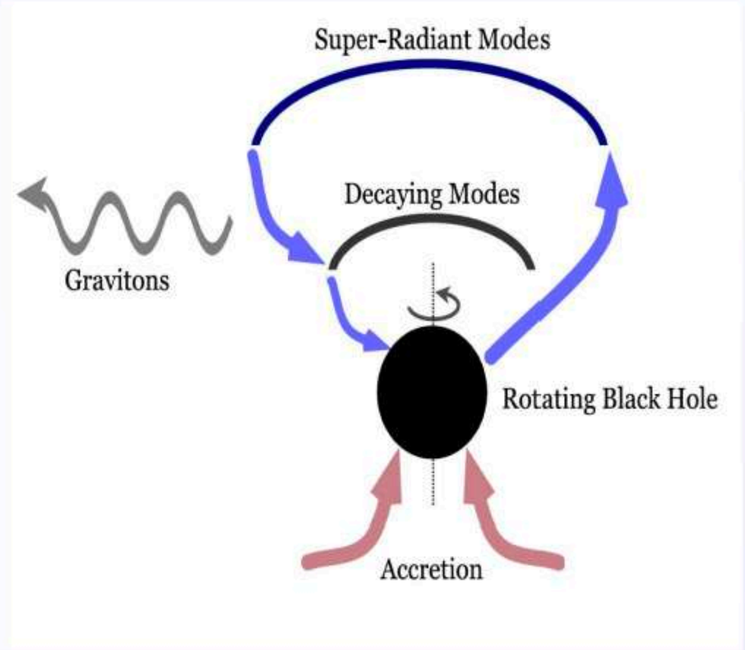
- Active Galactic Nuclei

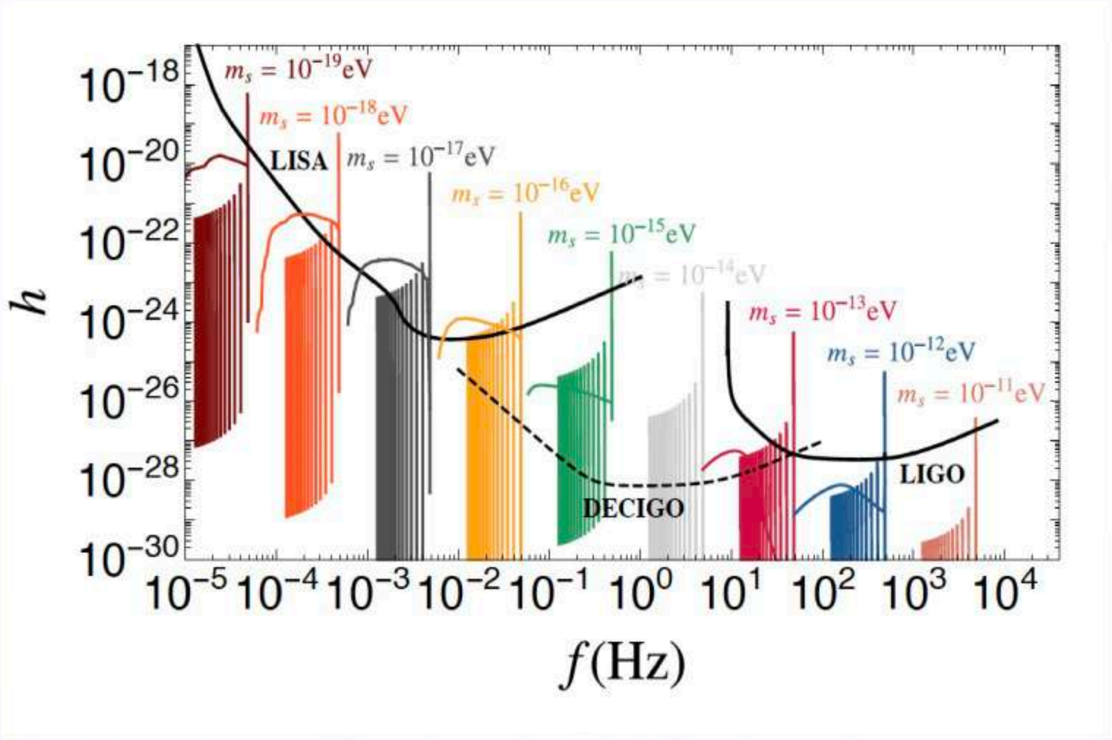
Credit: NASA/JPL-Caltech

Illustration of MAXI J1820+070. Credit: John Paice.



Black hole energy levels and gravitational waves





- Energy transition $\vartheta^{+} \to \vartheta^{-} + h$, Strain $h \sim 10^{-19} - 10^{-27}$
- [cf. Brito-Cardoso-Pani, Superradiance 2020]

Comparing different channels:

- Summary of different channels with different Chern-Simons types of couplings:

$$\mathbf{a}_+ \to \mathbf{a}_- + \mathbf{g}$$
$$\mathbf{a} \to \mathbf{gg}.$$
$$\mathbf{a}\mathbf{a} \to g$$

$$\mathbf{a} \to \gamma\gamma \text{ or } \mathbf{aa} \to \gamma\gamma$$

- A conference white paper
- (Living Reviews in Relativity (2021) 1, 4 • e-Print: 2011.12414, Impact Factor: 40.43 (2020)):

Ultra-High-Frequency GWs: A Theory and Technology Roadmap

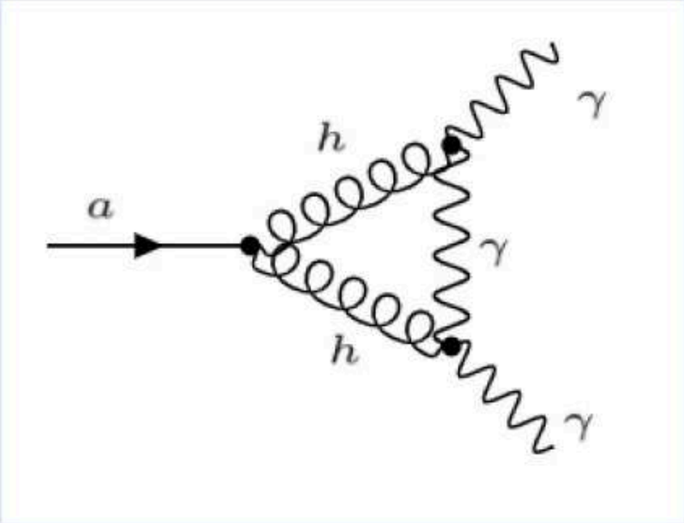
Oct 12 – 15, 2021
CERN
Europe/Zurich timezone

Challenges and Opportunities of Gravitational Wave Searches at MHz to GHz Frequencies

- N. Aggarwal[a,*], O.D. Aguiar[b], A. Bauswein[c], G. Cella[d], S. Clesse[e], A.M. Cruise[f], V. Domcke[g,h,i,*], D.G. Figueroa[j], A. Geraci[k], M. Goryachev[l], H. Grote[m], M. Hindmarsh[n,o], F. Muia[p,i,*], N. Mukund[q], D. Ottaway[r,s], M. Peloso[t,u], F. Quevedo[p,*], A. Ricciardone[t,u], J. Steinlechner[v,w,x,*], S. Steinlechner[v,w,*], S. Sun[y,z], M.E. Tobar[l], F. Torrenti[α], C. Unal[β], G. White[γ]

Branch Ratio and Triangle Feynman Diagram

- The triangle Feynman diagram, where the axion-photon coupling is generated from CS gravity coupling.

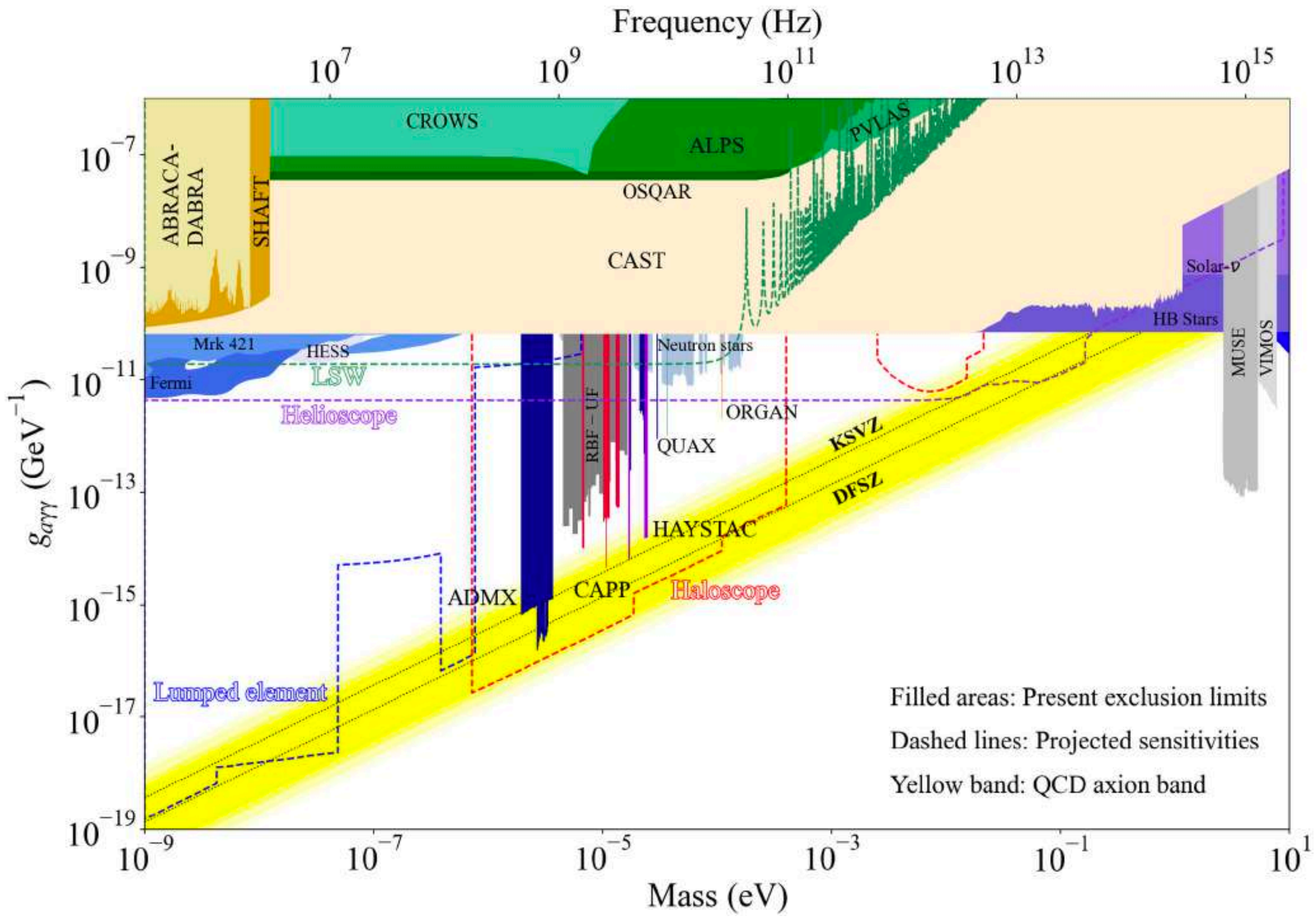


-
- $\mathcal{L}_{\vartheta F\tilde{F}} = -\frac{\alpha_\gamma}{4}\vartheta F_{\mu\nu}\tilde{F}^{\mu\nu}, \quad \mathcal{L}_{\vartheta R\tilde{R}} = \frac{\alpha_{\rm g}}{4}\vartheta R^{\beta}{}_{\alpha\gamma\delta}\tilde{R}^{\alpha}{}_{\beta}{}^{\gamma\delta}.$
- This diagram is quadratically divergent, with 4 extra powers of momentum from 3 vertices in the loop and two powers of M_{pl} from $h_{\mu\nu}T^{\mu\nu}$ coupling
- It is evaluated as $\alpha_\gamma \sim \alpha_{\rm g}(\Lambda/M_{pl})^4$, where Λ is the cut-off for Chern-Simons theory.

Resonant Electric Probe to Axionic Dark Matter 2206.13543

- Axion detection communities:

  - Cavities:ADMX [26], HAYSTAC [27], CAPP [28],QUAX-aγ [29], TASEH [30], DANCE [31], ORGAN [32], CAST-RADES [33],
  - non-cavity high-frequency designs:MADMAX [34], BREAD [35], etc
  - lower axion masses : ADMX-SLIC [37], DM-Radio [38], BASE [39], ABRA CADARA [40, 41]

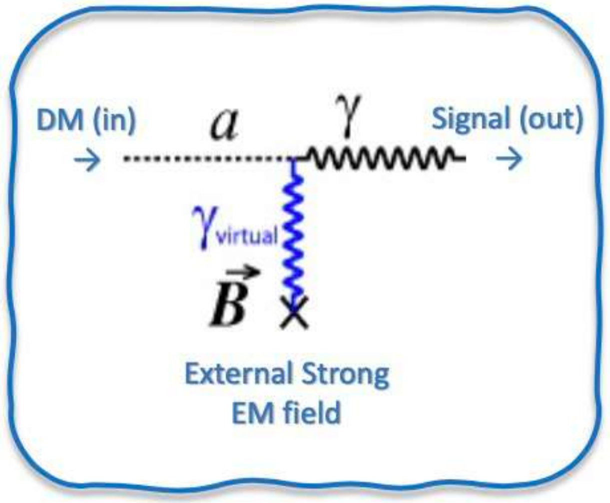


$$\mathcal{L}_{a\gamma\gamma} = -g_{a\gamma} a \vec{E} \cdot \vec{B} \ ,$$

Axion modified Electromagnetism

$$\vec{\nabla} \cdot \vec{E} = \rho_e - g_{a\gamma} \vec{B} \cdot \vec{\nabla} a,$$

$$\vec{\nabla} \times \vec{B} - \frac{\partial \vec{E}}{\partial t} = \vec{j}_e - g_{a\gamma} \vec{E} \times \vec{\nabla} a + g_{a\gamma} \vec{B} \frac{\partial a}{\partial t},$$



- Axion dark matter: $a(x,t) \approx a_0 \cos\left(m_a \vec{v} \cdot \vec{x} - \omega t + \phi_0\right)$,

$$\rho_a = -g_{a\gamma} B_0 (\vec{v} \cdot \hat{z}) \sqrt{2\rho_{\mathrm{DM}}} \cos\left(\omega t\right),$$

$$\vec{j}_a = \hat{z} g_{a\gamma} B_0 (1 + \frac{1}{2} v^2) \sqrt{2\rho_{\mathrm{DM}}} \cos\left(\omega t\right),$$

- Axion effective charge and current satisfies:

$$\partial_t \rho_a + \nabla \cdot \vec{j}_a = 0 ,$$

W/O cavity? – `aQED' induction effects

- axion-modified Maxwell equations:

Effective charge: (suppressed as $v_a \ll 1$)
(j^0 of the locally conserved 4-current $\partial_\mu j_a^\mu = 0$)

$$\vec{\nabla} \cdot \vec{E} = \rho_e + g\vec{B} \cdot \nabla a$$
$$\vec{\nabla} \times \vec{B} - \frac{\partial \vec{E}}{\partial t} = g\vec{E} \times \vec{\nabla} a - g\vec{B}\frac{\partial a}{\partial t} + \vec{j}_e$$
$$\vec{\nabla} \cdot \vec{B} = 0$$
$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} ,$$

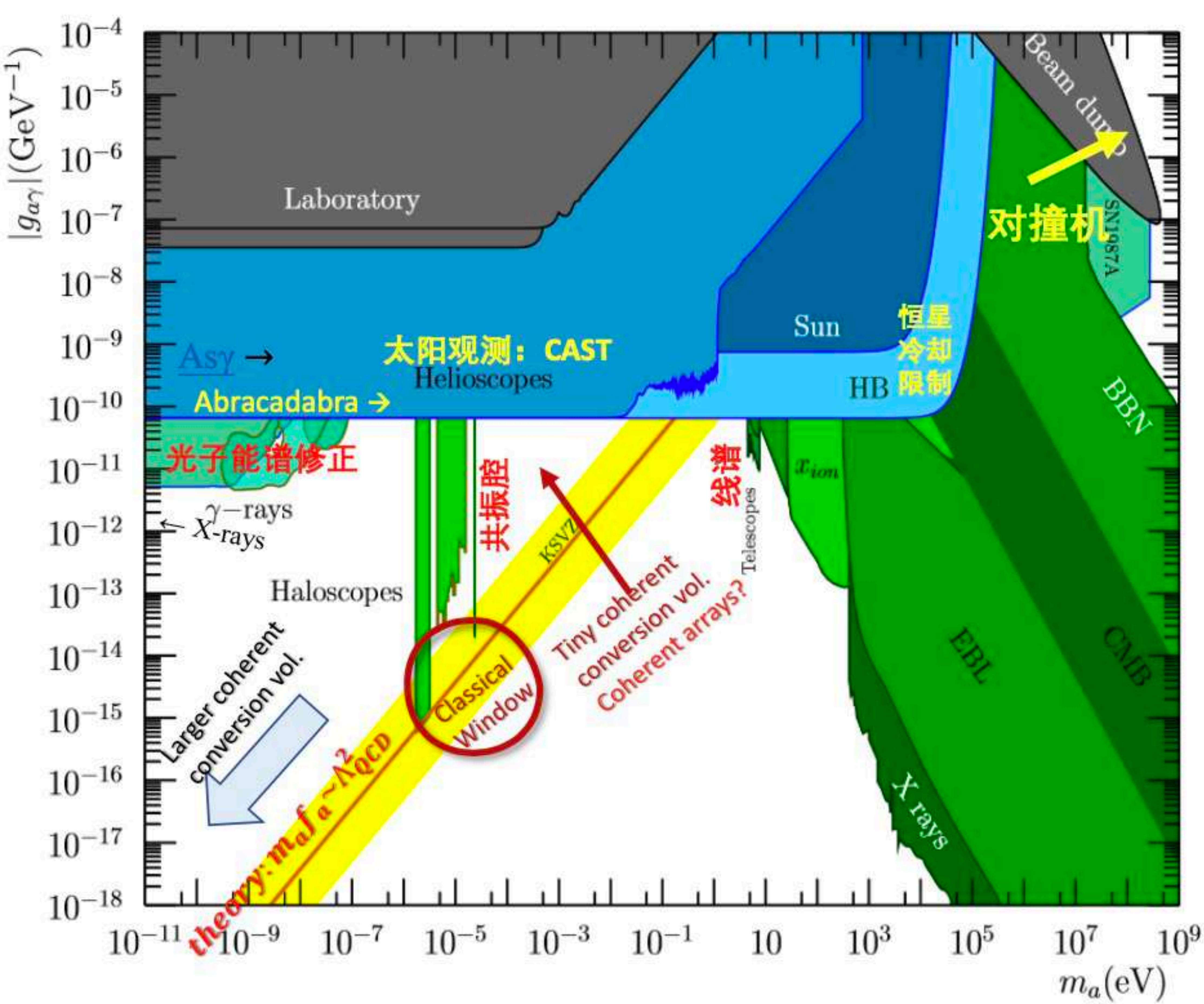
Axio-magnetic current:
LC, Abracadabra, ADMX-SLIC, DM-Radio, etc

Axio-electric current $\vec{j}_a = g\vec{E} \times \vec{\nabla} a$

Axion's effective sources:

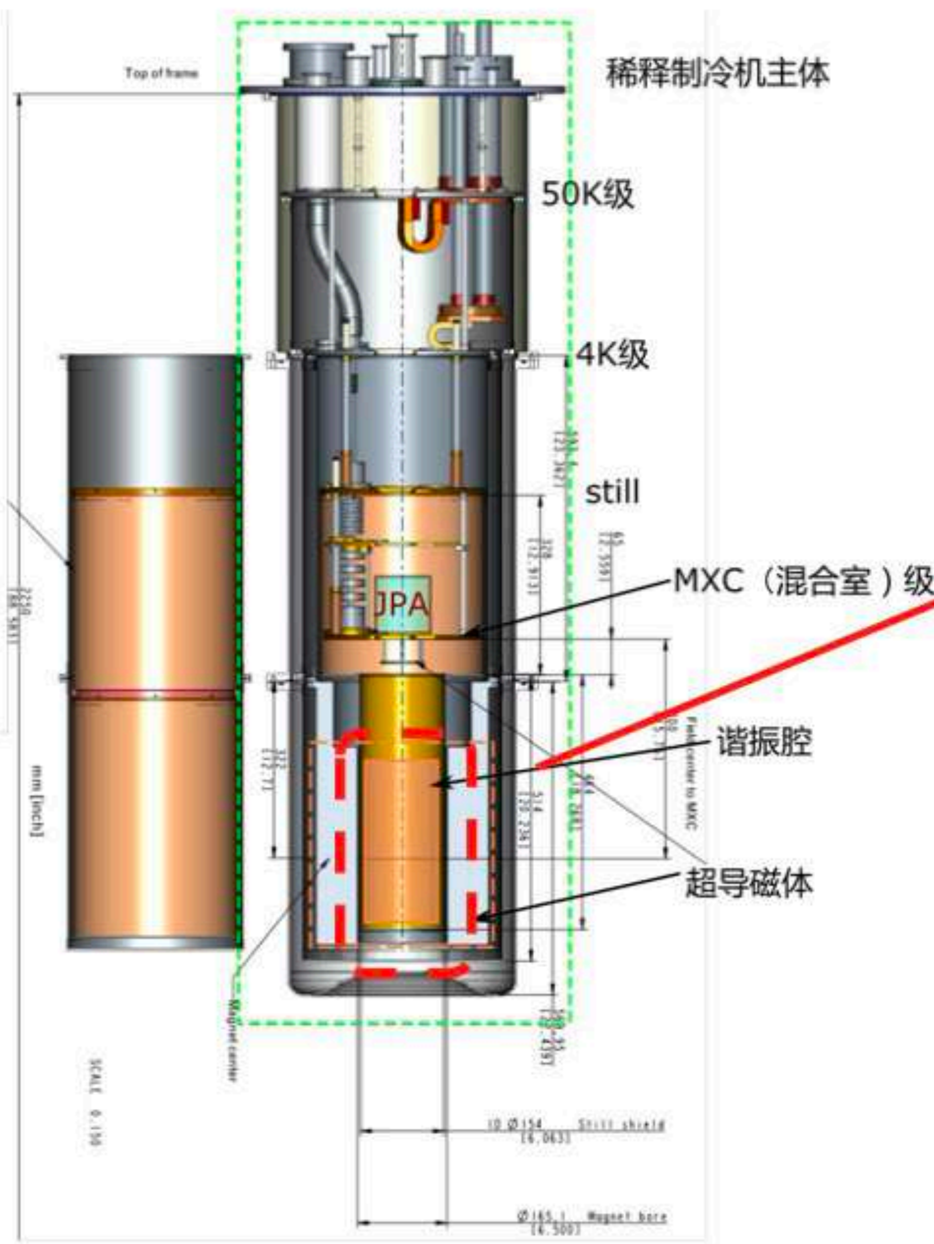
effective (moving) charge &
effective displacement currents

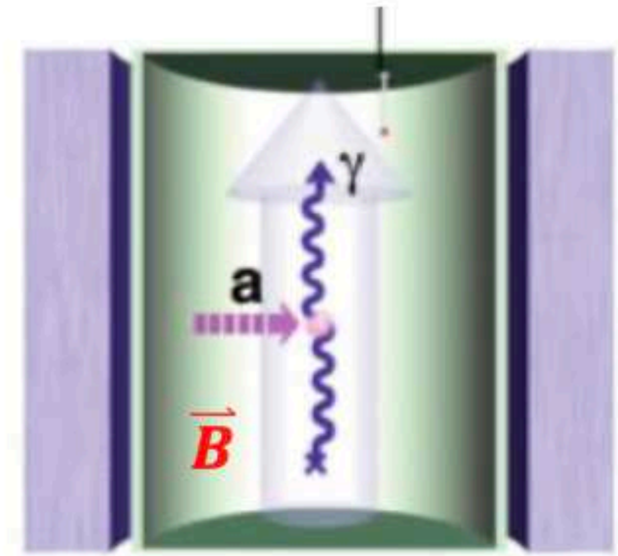
DM axion flow Induces a magnetic signal
inside E field: see 2012.13946 (broad-band)
& 2204.14033 (narrow-band)



$|g_{a\gamma}|(\mathrm{GeV}^{-1})$
Laboratory
Beam dump
对撞机
SN1987A
Sun
恒星
冷却
限制
HB
太阳观测：CAST
Asγ →
Helioscopes
Abracadabra →
光子能谱修正
共振腔
线谱
Telescopes
x_{ion}
BBN
γ−rays
X-rays
Haloscopes
KSVZ
Tiny coherent
conversion vol.
Coherent arrays?
Larger coherent
conversion vol.
Classical
Window
theory: $m_a f_a \sim \Lambda_{QCD}^2$
EBL
CMB
X rays
m_a(eV)

Cryogenic resonant EM cavity





Cavity frequency tuned to expected axion decay signal frequency

QCD axion DM: emergence of a microwave signal

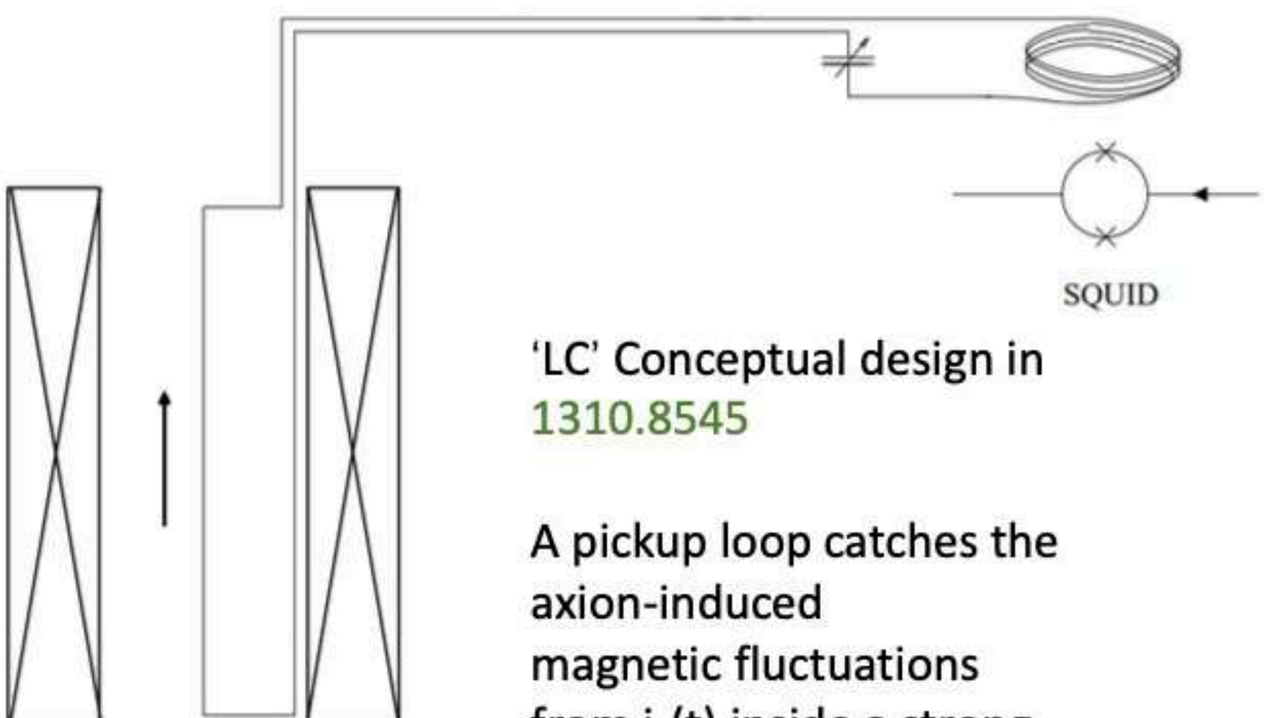
$$P_{\text{axion}} = 2.2 \cdot 10^{-23}\ \text{W}(\frac{V}{136\ \text{L}})(\frac{B}{7.6\ \text{T}})^2(\frac{C}{0.4}) \cdot (\frac{g_\gamma}{0.36})^2(\frac{\rho_a}{0.45\ \text{GeV cm}^{-3}})(\frac{f}{740\ \text{MHz}})(\frac{Q}{30000})$$

- single photon level: O(10) photons s^{-1}

Magnetic signal from B field

- ‘LC’-type designs: ADMX-SLIC, Abracadabra, DM-Radio, etc.

Enhanced by LC resonance and measured with a quantum magnetometer

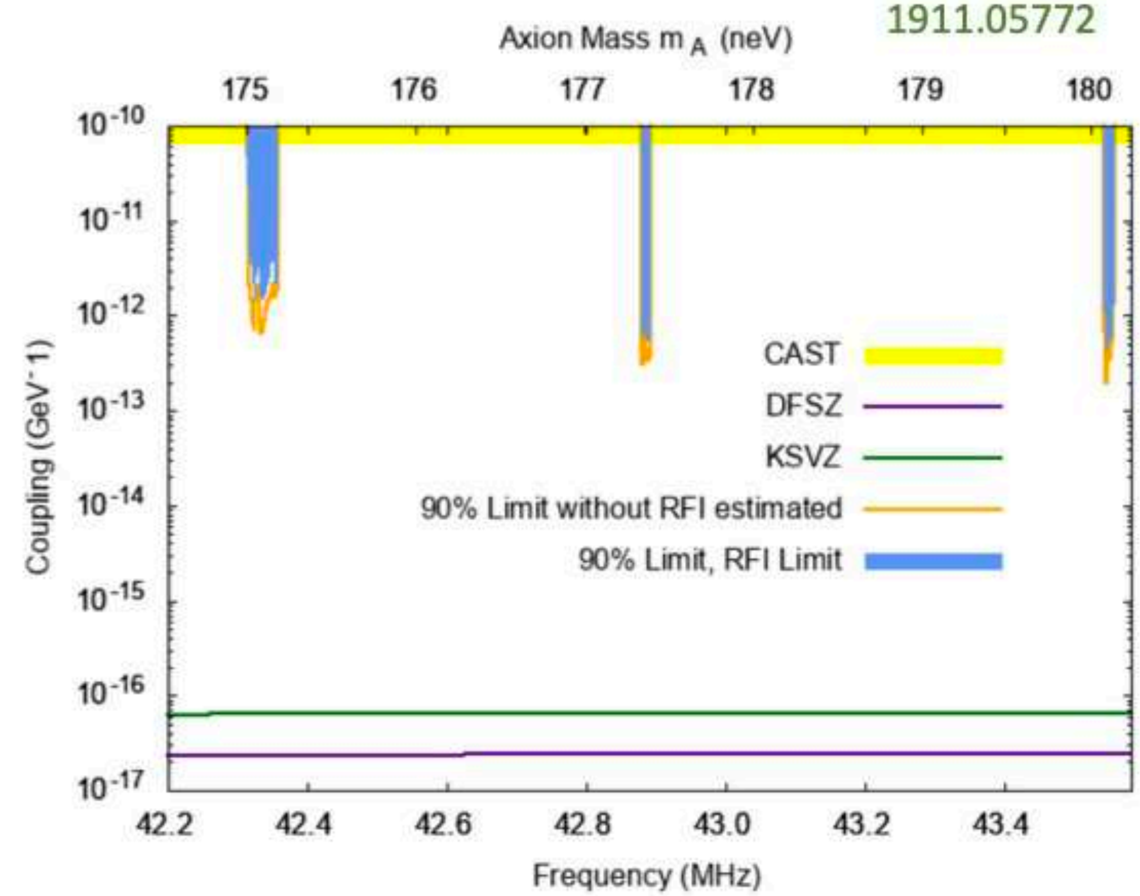


‘LC’ Conceptual design in 1310.8545

A pickup loop catches the axion-induced magnetic fluctuations from $j_a(t)$ inside a strong lab *B* field

Realization in ADMX-SLIC (2019)

1911.05772



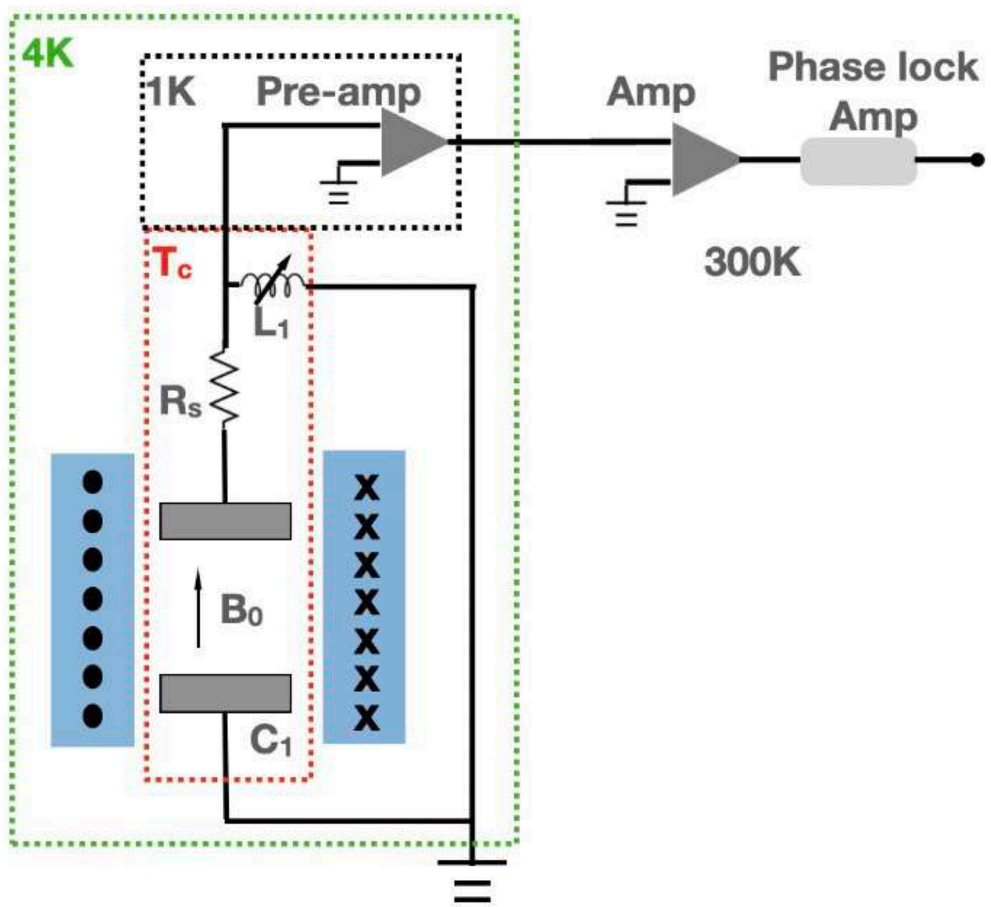
Long solenoid solutions

$$E_{a,r} = -\cos\omega t\ \hat{r}\cdot\begin{cases}\frac{1}{2}g_{a\gamma}B_0 v_z\sqrt{2\rho_{\rm DM}}\,r, & r\le R,\\ \frac{1}{2}g_{a\gamma}B_0 v_z\sqrt{2\rho_{\rm DM}}\frac{R^2}{r}, & r\ge R,\end{cases}$$

$$E_{a,z} = \frac{j_a}{\omega}e^{i\omega t}\cdot\begin{cases}\alpha(\omega)J_0(\omega r)-1, & r\le R,\\ \beta(\omega)H_0^+(\omega r), & r\ge R,\end{cases}$$

$$\alpha(\omega) = \frac{i\pi\omega R}{2}H_1^+(\omega R),$$

$$\beta(\omega) = \frac{i\pi\omega R}{2}J_1(\omega R),$$



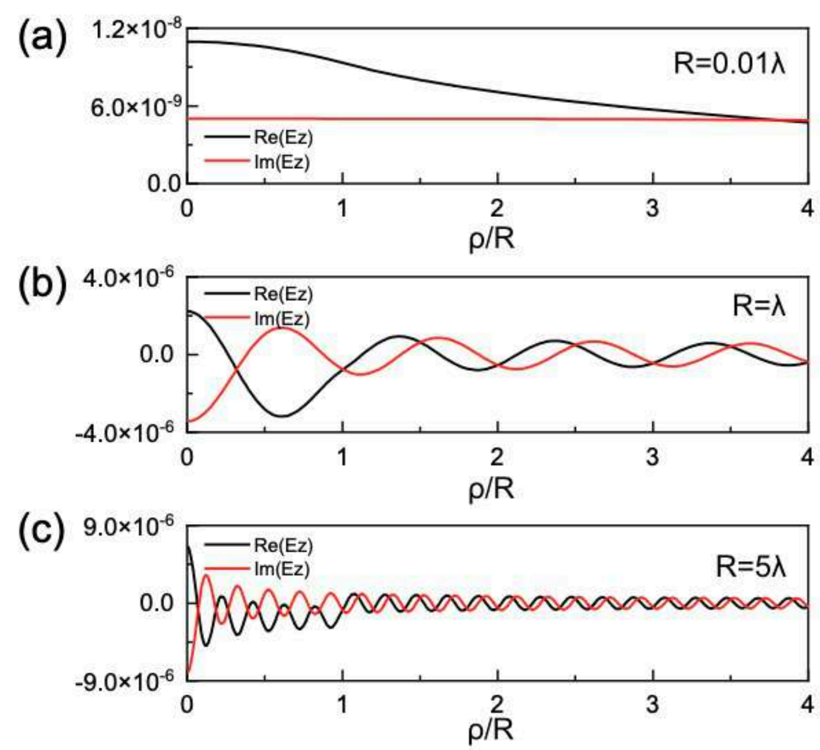
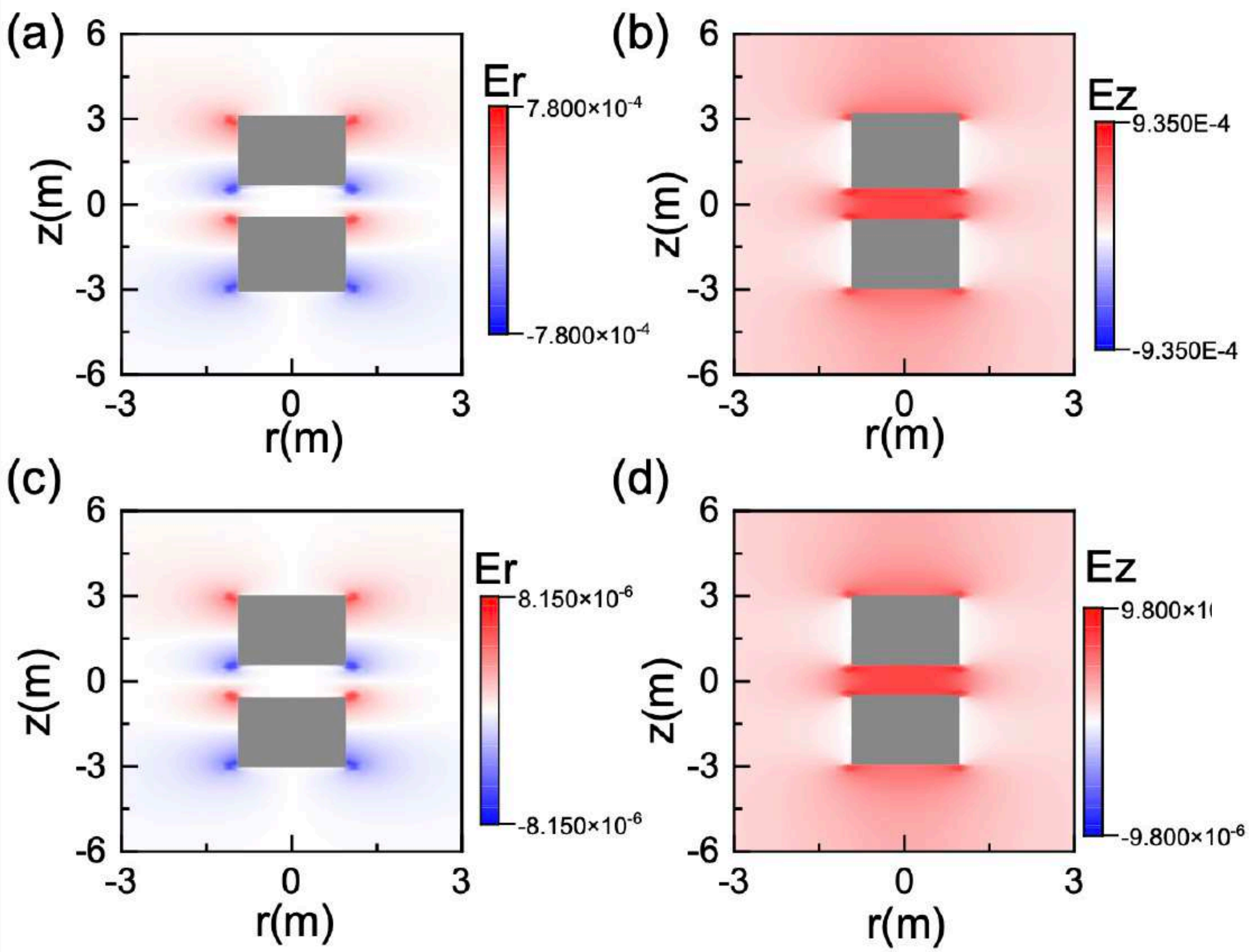


FIG. 4. Validation 2D plots by EM simulation to compare with analytic antsaz. E_z are in the unit of V/m

Numerical solutions:

- With COMSOL Multiphysics:



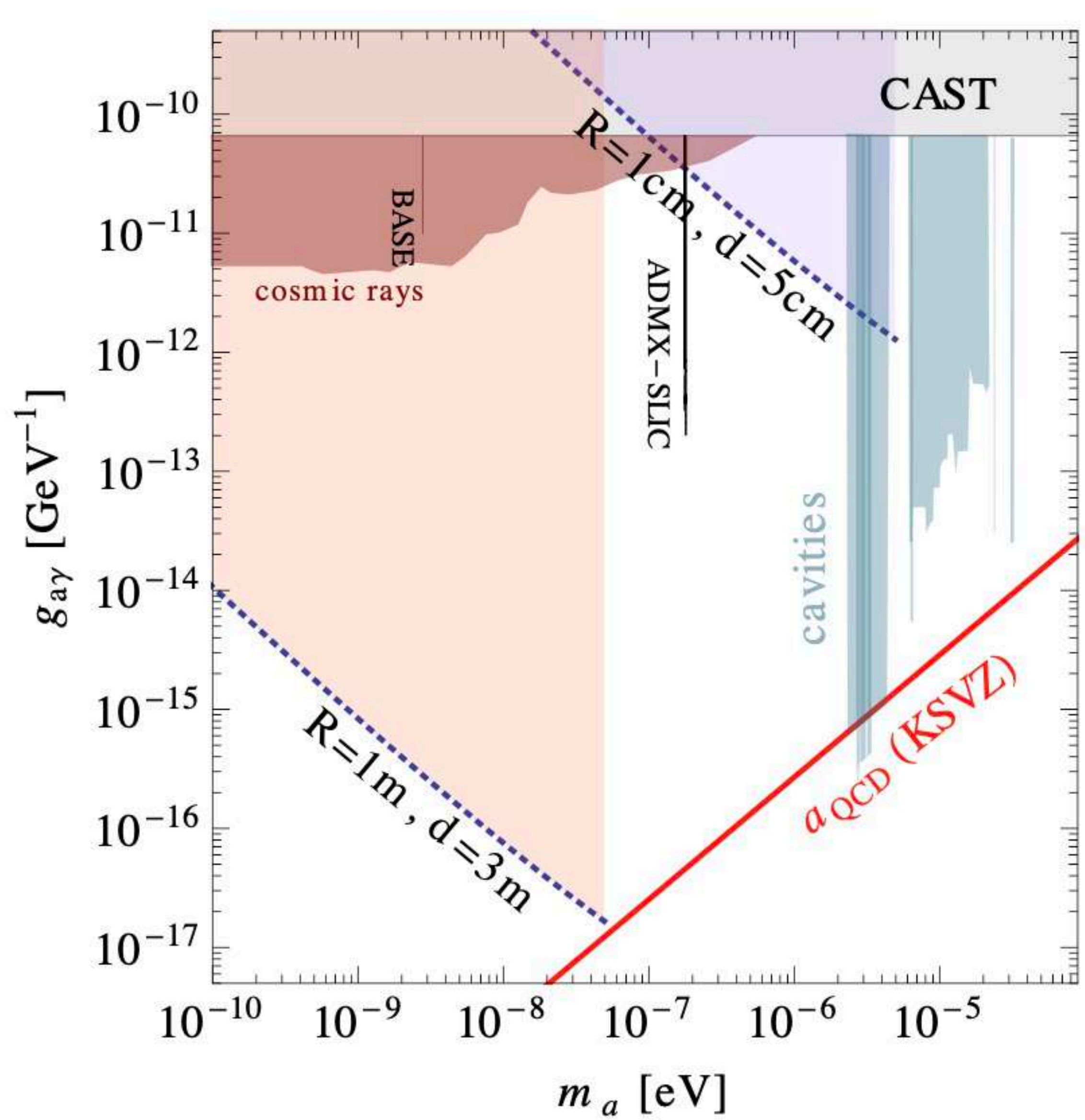
$$\eta(\omega) \equiv \frac{\int \vec{E}_a \cdot \mathrm{d}\vec{A}}{\int g_{a\gamma} a \vec{B}_0 \cdot \mathrm{d}\vec{A}}$$

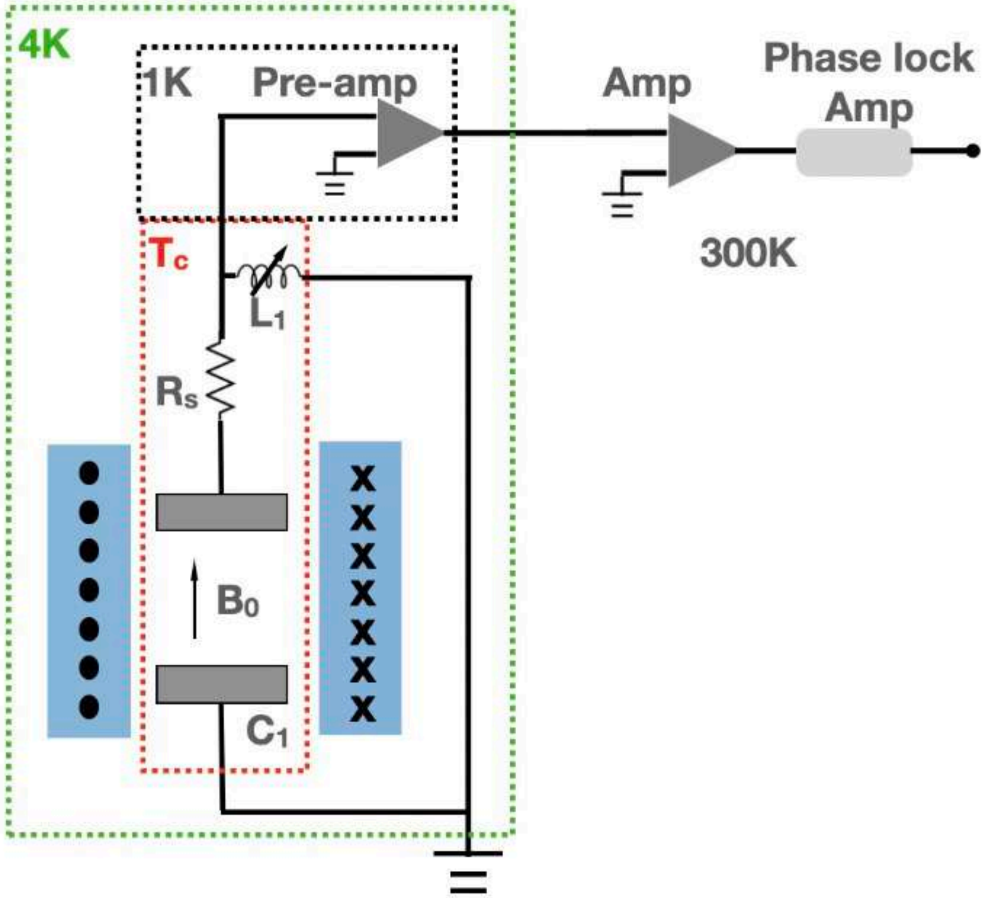
ωR	$2R : d = 2 : 1$	$2R : d = 2 : 5$
1	1.81×10^{-2}	1.48×10^{-2}
0.1	1.87×10^{-4}	2.31×10^{-4}
0.01	$5.04\ \times10^{-6}$	2.58×10^{-6}

Experimental setups:
Resonant ELEctric Axion Probe(RE-LEAP)

$$\mathrm{SNR} = \frac{P_{\mathrm{sig.}}}{k_{\mathrm{B}} T_N} \sqrt{\frac{\Delta t}{\Delta f}}$$

$$= \frac{Q_c g_{a\gamma}^2 \eta^2 f_c^{-1} \rho_{\mathrm{DM}} B_0^2 (\pi R^2 d)}{k_B T_{\mathrm{N}}} \sqrt{Q_c \frac{2\pi}{m_a^3} \Delta t.}$$





Summary

- We have many ways to detect axions.

Direct (Lab) vs indirect (through gravitational waves!)

Thank you

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