Monopole-philic axion: theory and experiment

Anton Sokolov

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[AS, Ringwald '21, '22, '23]

[Tobar, AS et al, '22, '23]

Dark Matter beyond the Weak Scale II

IPPP

Durham

28/03 2024

WHY AXIONS

- Dark matter

ΛCDM

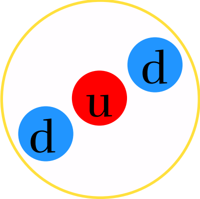

NASA image


ESO/Illustris Collaboration

What makes Cold Dark Matter ?!

- CP conservation in strong interactions

n =



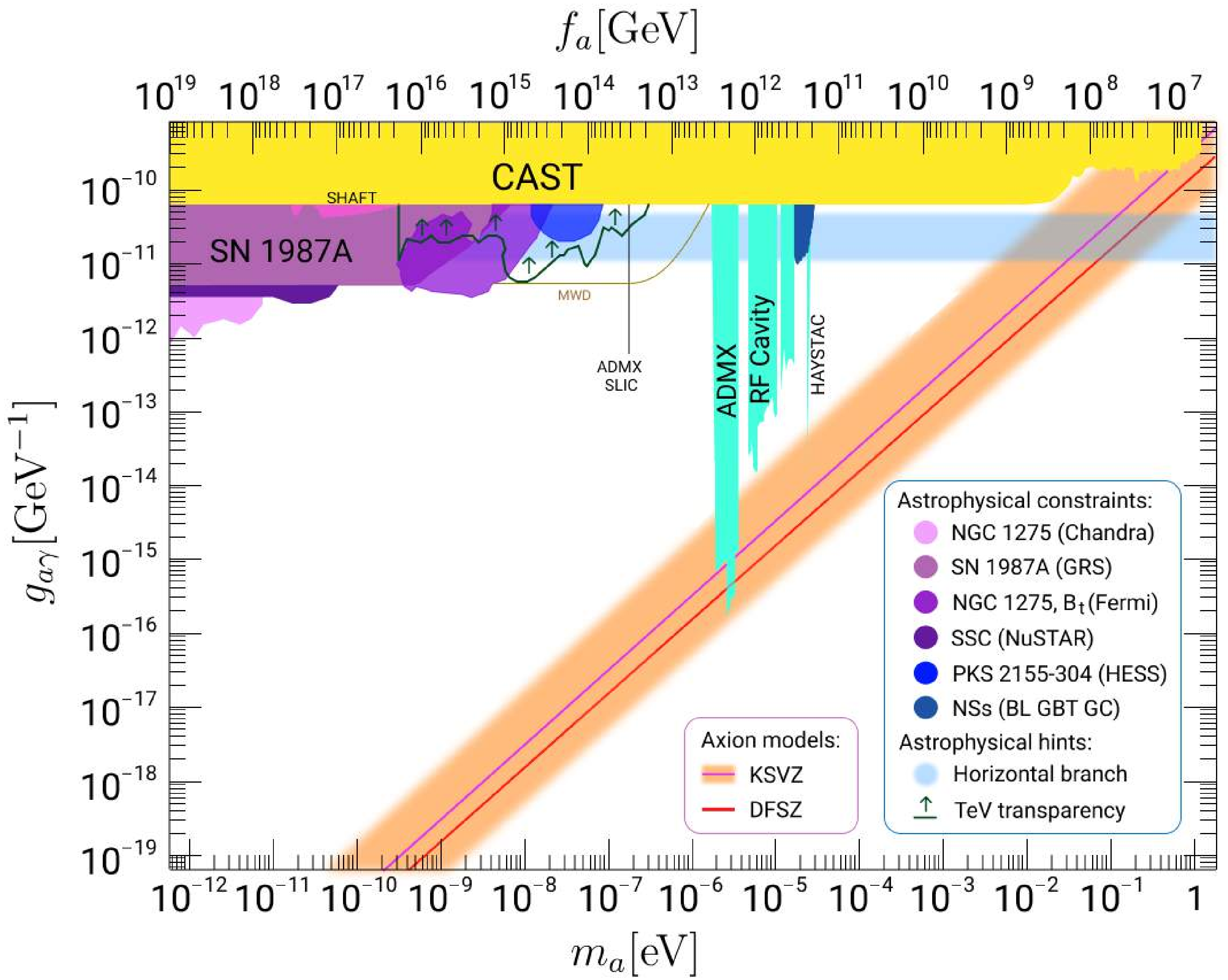
$\Rightarrow$ axions

$$d_n = 2.4\,(1.0)\cdot 10^{-16}\,\bar{\theta}\; e\cdot\mathrm{cm}$$
$$|d_n| < 1.8\cdot 10^{-26} e\cdot\mathrm{cm}$$
$$\Rightarrow \; |\bar{\theta}| \lesssim 10^{-10}$$

Why is there no electric dipole moment ?!

Why $\bar{\theta} \simeq 0$?!

AXION-PHOTON COUPLING: PARAMETER SPACE



$$\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$
$$= g_{a\gamma\gamma} a \vec{E}\vec{H}$$

- axion-photon conversion in external magnetic field (astro, LSW, high-mass-axion haloscopes)
- Primakoff effect: axion production in stars (helioscopes, HB stars)
- extra axion-induced magnetic field component in external magnetic field (low-mass-axion haloscopes)

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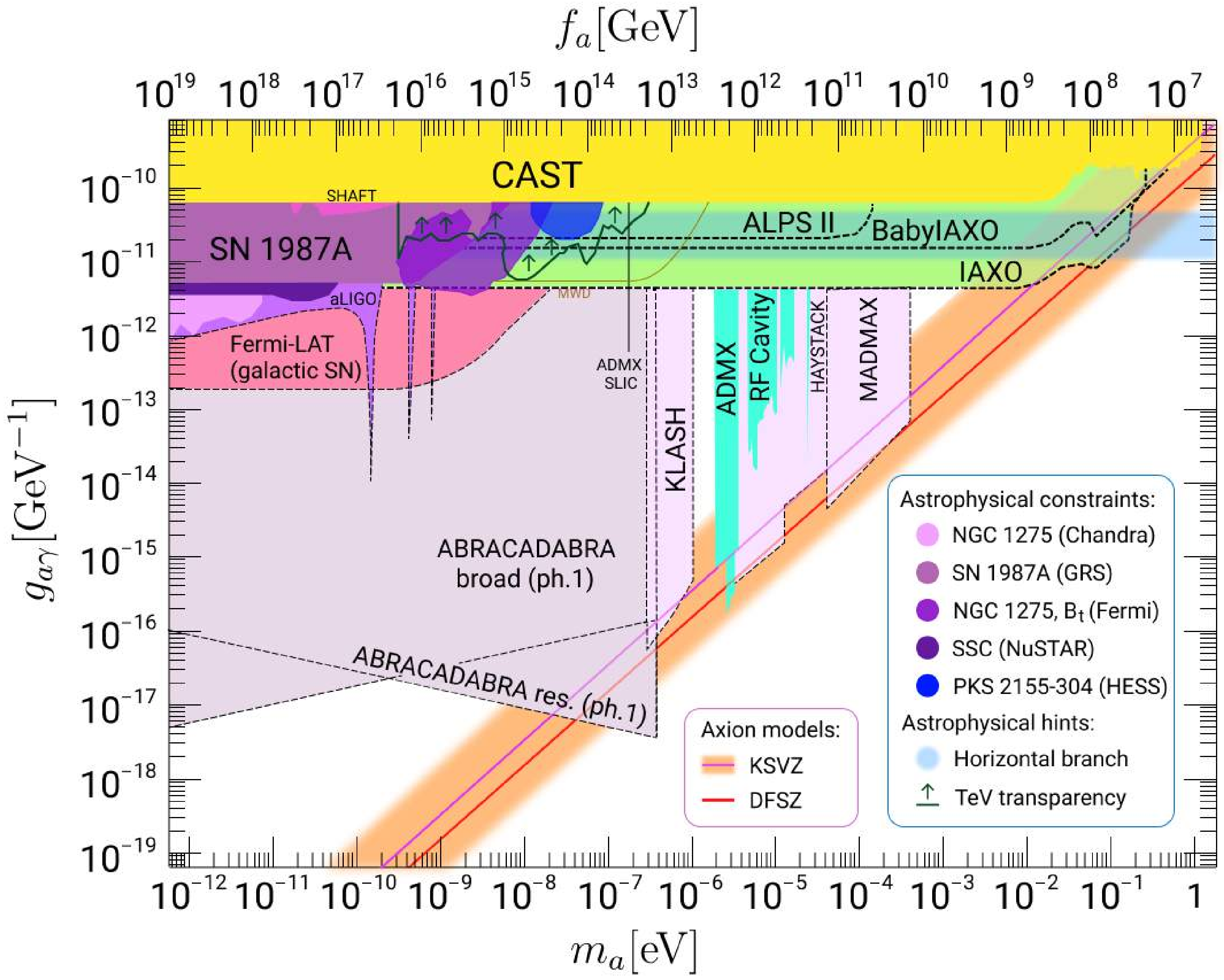

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AXION-MAXWELL EQUATIONS

$$\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} = g_{a\gamma\gamma} a \vec{E}\vec{H}$$

$$g_{a\gamma\gamma} = \frac{e^2}{8\pi^2 f_a} \cdot \left(\frac{E}{N} - 1.92 \right)$$

KSVZ: $E/N = 5/3 - 44/3$

DFSZ: $E/N = 8/3$

- Equations of motion $\delta S[A_\mu] = 0$:

$$\nabla \cdot \mathbf{E} = \rho - g_{a\gamma\gamma} \mathbf{H} \cdot \nabla a \,,$$

$$\nabla \cdot \mathbf{H} = 0 \,,$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{H}}{\partial t} \,,$$

$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{E}}{\partial t} + \mathbf{J} - g_{a\gamma\gamma} \left(\mathbf{E} \times \nabla a - \frac{\partial a}{\partial t} \mathbf{H} \right) .$$

- Axion dark matter: $a = a_0 \exp i(\omega_a t - \mathbf{k}_a \mathbf{r})$

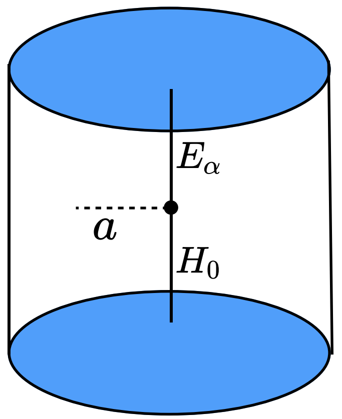
Non-relativistic $\xrightarrow{v_a \to 0}$ only $\mathbf{H}$ remains in the axion terms

EXAMPLE: RESONANT AXION HALOSCOPES

- Given strong magnetic field H_0 , dark matter axions excite resonant modes of the cavity

- The power going into the α-mode of the cavity is:

$$P_\alpha = \underbrace{g^2_{a\gamma\gamma}\rho_a}_{\text{local DM density}} H_0^2\, V C_\alpha \underbrace{Q_\alpha}_{\text{quality factor}} / m_a \,,$$

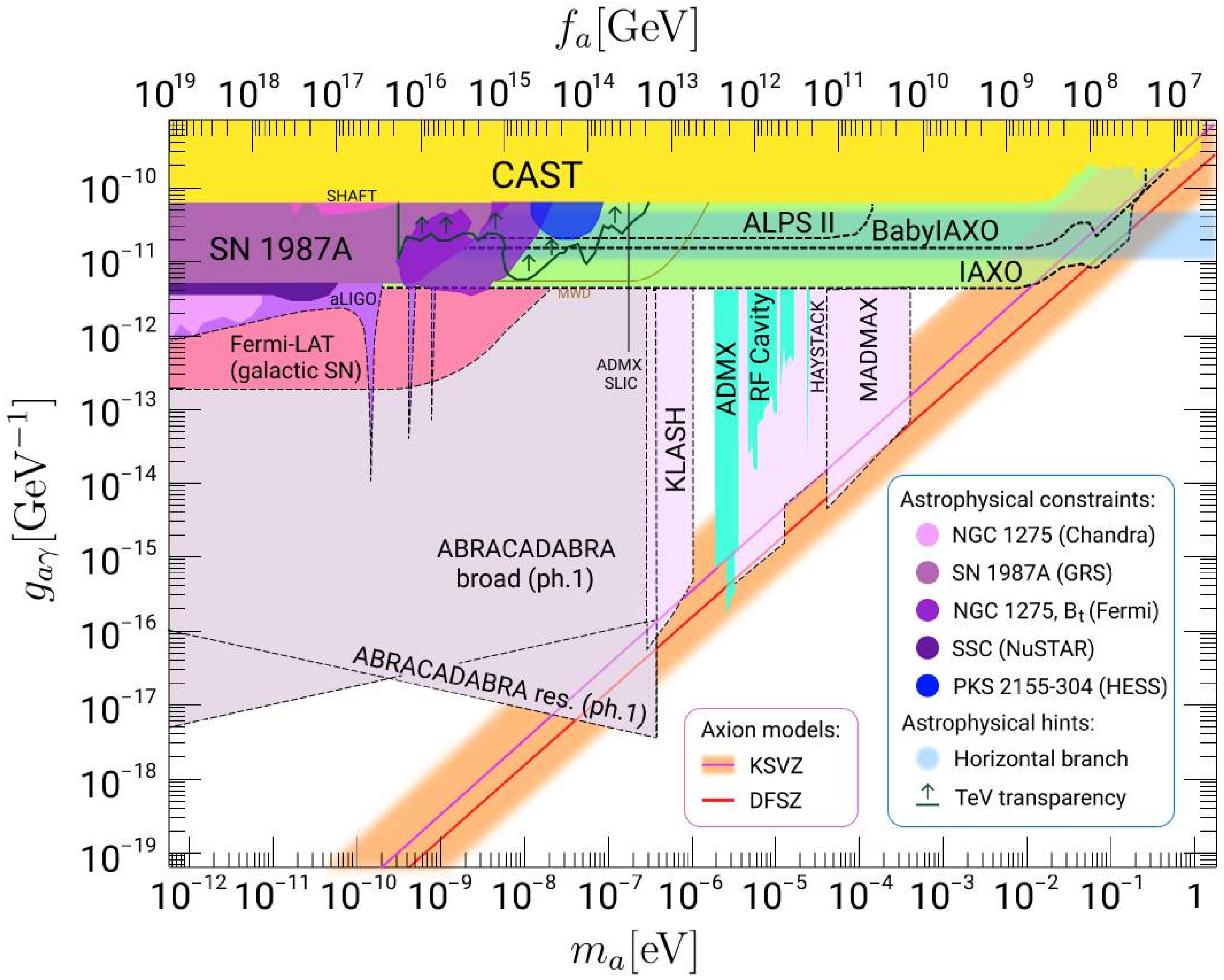


[Sikivie '83]

- The so-called cavity form-factor is:

$$C_\alpha = \frac{\left(\int d^3x\, \mathbf{H_0}\cdot \mathbf{E}_\alpha\right)^2}{H_0^2 V \int d^3x\, \mathbf{E}_\alpha\cdot\mathbf{E}_\alpha} \longrightarrow \text{only TM modes can be excited}$$

AXION-PHOTON COUPLING: PARAMETER SPACE



$$\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

$$= g_{a\gamma\gamma} a \vec{E}\vec{H}$$

- Naively interchange $\vec{E}$ and $\vec{H}$

$$\downarrow$$

- Sensitivity of haloscopes decreases by orders of magnitude?!
- Can no longer reach axion band?!

ELECTRIC-MAGNETIC DUALITY SYMMETRY

- SO(2) invariance of free Maxwell equations:

$$\begin{aligned} &\boldsymbol{\nabla}\times\mathbf{H}-\dot{\mathbf{E}}=0\,,\\ &\boldsymbol{\nabla}\times\mathbf{E}+\dot{\mathbf{H}}=0,\\ &\nabla\cdot\mathbf{H}=0\,,\\ &\boldsymbol{\nabla}\cdot\mathbf{E}=0 \end{aligned}$$

inv. wrt

$$\begin{aligned} \mathbf{E} &\to \mathbf{E}\cos\theta+\mathbf{H}\sin\theta\,,\\ \mathbf{H} &\to \mathbf{H}\cos\theta-\mathbf{E}\sin\theta \end{aligned}$$

- In the Lagrangian approach: [Deser, Teitelboim '75]

$$S_{\mathrm{EM}} = \frac{1}{2}\int d^4x\,(\mathbf{E}^2-\mathbf{H}^2)$$

breaks SO(2)?! No, since $S_{\mathrm{EM}} = S_{\mathrm{EM}}[\mathbf{A^T}]$

where $\mathbf{E}=-\dot{\mathbf{A}}^{\mathrm{T}}\,,\quad \mathbf{H}=\boldsymbol{\nabla}\times\mathbf{A}^{\mathrm{T}}\,.$

$$S_{\mathrm{EM}}[\mathbf{A^T}] = \frac{1}{2}\int d^4x\left\{\left(\dot{\mathbf{A}}^{\mathrm{T}}\right)^2-(\boldsymbol{\nabla}\times\mathbf{A}^{\mathrm{T}})^2\right\}$$

preserves SO(2):

inv. wrt $\delta\mathbf{A}^{\mathrm{T}} = -\theta\,\boldsymbol{\nabla}^{-2}\,\boldsymbol{\nabla}\times\dot{\mathbf{A}}^{\mathrm{T}}$ as $\mathcal{L}\to\mathcal{L}+df/dt$

AXION-PHOTON COUPLING VS DUALITY SYMMETRY

$$\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} = g_{a\gamma\gamma} a \vec{E} \vec{H}$$

$$g_{a\gamma\gamma} = \frac{e^2}{8\pi^2 f_a} \cdot \left(\frac{E}{N} - 1.92 \right)$$

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$\longrightarrow$ break SO(2)

- (Pseudo)scalar fields coupled to $F_{\mu\nu} F^{\mu\nu}$ or $F_{\mu\nu} \tilde{F}^{\mu\nu}$ break duality symmetry.

  Can they break it differently?

MAXWELL THEORY VS MONOPOLES

- Suppose there exist magnetic charges:

$$\epsilon_{ijk}\partial_i F_{jk} = \rho_{\mathrm{m}} \neq 0 \quad \Rightarrow \quad [\partial_i,\, \partial_j] A_k \neq 0$$

- The four-potential A_μ is no longer a good dynamical variable, need a new approach

Wu-Yang

Cut holes where A_μ is problematic $\rightarrow$

$\rightarrow$ non-trivial topology of spacetime

Monopoles are non-dynamical $(M \to \infty)$

[Wu, Yang '75]

Dirac

$F_{\mu\nu} \to \mathcal{F}_{\mu\nu}$

$\mathcal{F}_{\mu\nu} \equiv \partial_\mu A_\nu - \partial_\nu A_\mu - \tilde{G}_{\mu\nu}$

Can switch duality frames

[Dirac '48], [Cardy, Rabinovici '81]

Two-potential (Schwinger-Zwanziger)

A_μ and B_μ $\longleftrightarrow$ EM field

$\mathcal{L} = \mathcal{L}_{\mathrm{kin}}(A_\mu, B_\mu, n_\mu) - j_e^\nu A_\nu - j_m^\nu B_\nu$

[Schwinger '65], [Zwanziger '71]

CHANGE OF A VIEWPOINT

- Due to the duality invariance of the free EM field, absolute directions in the electric-magnetic plane have no physical meaning $\longrightarrow$ one can think of the SM particles as "magnetic monopoles" of the dual potential.
- In such a dual picture, the EM field is derived from a dual four-potential:

$$\mathbf{E} = -\boldsymbol{\nabla}\times\mathbf{B}\,, \quad \mathbf{H} = -\dot{\mathbf{B}} - \boldsymbol{\nabla}B_0$$

- Consider again $\mathcal{L}_{a\gamma} = -\frac{1}{4}\bar{g}_{a\gamma\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu} = \bar{g}_{a\gamma\gamma}a\vec{E}\vec{H}$
- Equations of motion $\delta S[B_\mu] = 0$:

$$\boldsymbol{\nabla}\cdot\mathbf{E} = 0\,, \quad \boldsymbol{\nabla}\cdot\mathbf{H} = \bar{g}_{a\gamma\gamma}\mathbf{E}\cdot\boldsymbol{\nabla}a\,, \quad \boldsymbol{\nabla}\times\mathbf{E} = -\frac{\partial\mathbf{H}}{\partial t} + \bar{g}_{a\gamma\gamma}\left(\mathbf{H}\times\boldsymbol{\nabla}a + \frac{\partial a}{\partial t}\mathbf{E}\right), \quad \boldsymbol{\nabla}\times\mathbf{H} = \frac{\partial\mathbf{E}}{\partial t}$$

DIFFERENT AXION-MAXWELL EQUATIONS

$$\mathcal{L}_{a\gamma} = -\frac{1}{4}\bar{g}_{a\gamma\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu} = \bar{g}_{a\gamma\gamma} a \vec{E}\vec{H}$$

$\bar{g}_{a\gamma\gamma} \propto 1/M$ ↖ monopole mass

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$\bar{g}_{a\gamma\gamma} \propto 1/M$ monopole mass

What could be the UV completion?

[AS, Ringwald ‘21, ‘23]

Implications for axion haloscopes

[Tobar, AS et al. ‘22]
[Tobar, AS et al. ‘23]

WHY MAGNETIC CHARGES

- Quantization of charge

u $+\frac{2}{3}$ d $-\frac{1}{3}$ e -1 ?!

- Explained if there exist magnetic monopoles

Arise naturally in Grand Unified theories

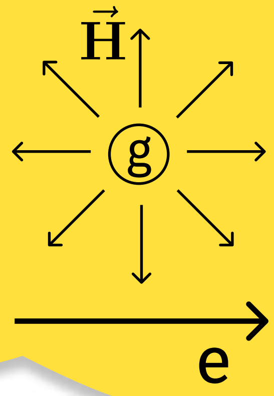
['t Hooft, Polyakov '74]

Unification of forces

Arise in any consistent quantum gravity theory with quantized charges

[Banks, Seiberg '11]

1931 DIRAC



QM:

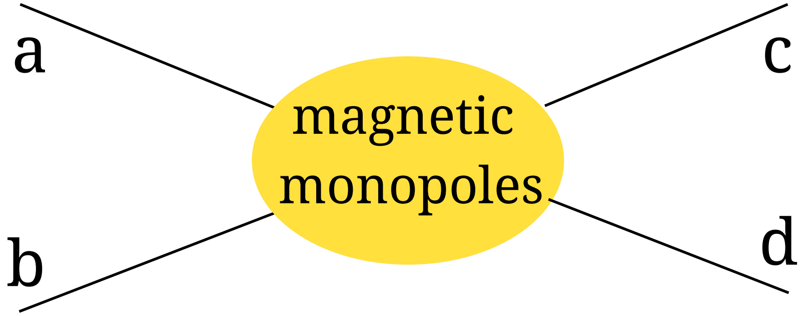
$$eg = 2\pi n, \; n \in \mathbb{Z}$$

INDIRECT EFFECTS OF MONOPOLES

- Polchinski: “existence of magnetic monopoles seems like one of the safest bets that one can make about physics not yet seen” [Polchinski '02]

- But: the mass is not known and many models predict superheavy monopoles

- Solution: look for the indirect effects of monopoles



- Precisely what the haloscopes can do!

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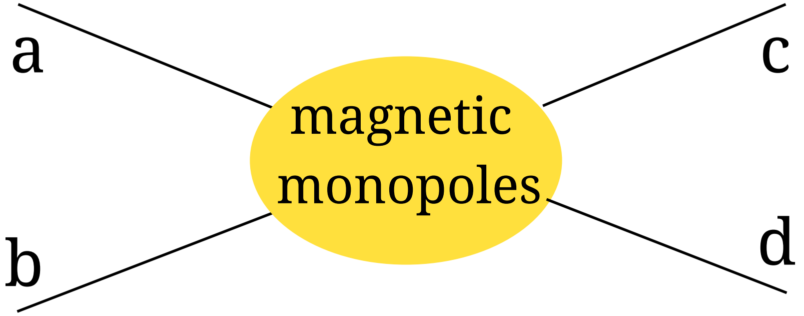

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$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{E}}{\partial t}$$

- Precisely what the haloscopes can do!

TWO-POTENTIAL APPROACH: ZWANZIGER LAGRANGIAN

Zwanziger Lagrangian

A_μ **and** $B_\mu \longleftrightarrow$ photon

$$\mathcal{L} = \mathcal{L}_{\text{kin}}\left(A_\mu, B_\mu, n_\mu\right) - j_e^\nu A_\nu - j_m^\nu B_\nu$$

n-independence

$$Z\left(a, b, \cancel{n_\mu}\right) = \int \exp\left\{i\left(\mathcal{S}[\mathbf{A}_\mu, \mathbf{B}_\mu, \mathbf{n}_\mu, \chi, \bar{\chi}] + j_e a + j_m b\right)\right\} \times \mathcal{D}\mathbf{A}_\mu\, \mathcal{D}\mathbf{B}_\mu\, \mathcal{D}\chi\, \mathcal{D}\bar{\chi}$$

- TWO vector-potentials describe ONE particle - photon
- theory is Lorentz-invariant, kinetic part is dual-invariant
- theory is generally not CP-invariant

TWO-POTENTIAL APPROACH: ZWANZIGER LAGRANGIAN

- Adopt simplified notations: $(\partial \wedge A)_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$, $(G)^d = \tilde{G}$
- Consider the Lagrangian by Zwanziger which makes the duality symmetry obvious:

$$\mathcal{L}_{\rm kin} = \frac{1}{2n^2}\Big\{[n\cdot(\partial \wedge B)]\cdot[n\cdot(\partial \wedge A)^d] - [n\cdot(\partial \wedge A)]\cdot[n\cdot(\partial \wedge B)^d]$$
$$- [n\cdot(\partial \wedge A)]^2 - [n\cdot(\partial \wedge B)]^2\Big\}$$

- The electric-magnetic duality transformations are rotations in (A, B) plane of four-potentials:

$$n\cdot F = n\cdot(\partial \wedge A) \quad \text{and} \quad n\cdot F^d = n\cdot(\partial \wedge B)$$

- n^μ is a fixed four-vector, which does not enter physical observables

EQUATIONS OF MOTION

$$\mathcal{L} = \frac{1}{2n^2}\Big\{[n\cdot(\partial\wedge B)]\cdot[n\cdot(\partial\wedge A)^d] - [n\cdot(\partial\wedge A)]\cdot[n\cdot(\partial\wedge B)^d]$$

$$-[n\cdot(\partial\wedge A)]^2 - [n\cdot(\partial\wedge B)]^2\Big\} - j_e^{\nu}A_\nu - j_m^{\nu}B_\nu + \mathcal{L}_G$$

Gauge-fixing part: $\mathcal{L}_G = -\frac{1}{2n^2}\Big\{[\partial(n\cdot A)]^2 + [\partial(n\cdot B)]^2\Big\}$

EOMs:

$$\frac{n\cdot\partial}{n^2}\left(n\cdot\partial A^\mu - \partial^\mu n\cdot A - n^\mu \partial\cdot A - \epsilon^\mu{}_{\nu\rho\sigma}n^\nu\partial^\rho B^\sigma\right) = j_e^\mu\,,$$

$$\frac{n\cdot\partial}{n^2}\left(n\cdot\partial B^\mu - \partial^\mu n\cdot B - n^\mu \partial\cdot B - \epsilon^\mu{}_{\nu\rho\sigma}n^\nu\partial^\rho A^\sigma\right) = j_m^\mu\,.$$

Differential operator factorizes $\longrightarrow$ effectively 1st order system!

Impose boundary conditions $\longrightarrow$ $\partial_\mu F^{\mu\nu} = j_e^{\nu}\,,\ \ \partial_\mu F^{d\,\mu\nu} = j_m^{\nu}\,.$

GENERAL AXION-PHOTON EFT

$$(\partial \wedge A)_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \quad , \quad (G)^d = \tilde{G}$$

All dimension-five operators consistent with the symmetries:

$$\mathcal{L} = \mathcal{L}_{\text{kin}}(A, B, n)$$

Kinetic part

$$-\frac{1}{4} g_{aEE}\, a\, \text{tr}\left\{(\partial \wedge A)(\partial \wedge A)^d\right\} - \frac{1}{4} g_{aMM}\, a\, \text{tr}\left\{(\partial \wedge B)(\partial \wedge B)^d\right\}$$

Anomalous axion-photon interactions, CP-conserving

$$-\frac{1}{2} g_{aEM}\, a\, \text{tr}\left\{(\partial \wedge A)(\partial \wedge B)^d\right\}$$

Anomalous axion-photon interaction, CP-violating

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$\mathcal{L} \;=\; \mathcal{L}_{\mathrm{kin}}\,(A\,,B\,,n\,)$	Kinetic part
$-\frac{1}{4}\,g_{aEE}\,a\,\mathrm{tr}\Big\{(\partial\wedge A)\,(\partial\wedge A)^d\Big\} - \frac{1}{4}\,g_{aMM}\,a\,\mathrm{tr}\Big\{(\partial\wedge B)\,(\partial\wedge B)^d\Big\}$	Anomalous axion-photon interactions, CP-conserving
$-\frac{1}{2}\,g_{aEM}\,a\,\mathrm{tr}\Big\{(\partial\wedge A)\,(\partial\wedge B)^d\Big\}$	Anomalous axion-photon interaction, CP-violating

- This Effective Field Theory is valid for any axion or axion-like particle.
- Scaling of the four-potentials with e and g implies:

$$g_{aEE} \propto e^2/M\,, \quad g_{aMM} \propto g^2/M\,, \quad g_{aEM} \propto eg/M$$

GENERAL AXION MAXWELL EQUATIONS

Classical equations of motion corresponding to our Lagrangian are the axion Maxwell equations:

$$\delta S[A_\mu] = 0 \qquad \partial_\mu F^{\mu\nu} - g_{aEE}\,\partial_\mu a\, F^{d\,\mu\nu} + g_{aEM}\,\partial_\mu a\, F^{\mu\nu} = 0\,,$$

$$\delta S[B_\mu] = 0 \qquad \partial_\mu F^{\mu\nu} + g_{aMM}\,\partial_\mu a\, F^{\mu\nu} - g_{aEM}\,\partial_\mu a\, F^{d\,\mu\nu} = 0\,,$$

$$\delta S[a] = 0 \qquad (\partial^2 + m_a^2)a = -\frac{1}{4}\,(g_{aEE} - g_{aMM})F_{\mu\nu}F^{d\,\mu\nu} - \frac{1}{2}\,g_{aEM}F_{\mu\nu}F^{\mu\nu}$$

In terms of electric and magnetic fields:

$$\nabla\times\mathbf{B}_a - \dot{\mathbf{E}}_a = g_{a\mathrm{EE}}\,(\mathbf{E}_0\times\nabla a - \dot{a}\mathbf{B}_0) + g_{a\mathrm{EM}}\,(\mathbf{B}_0\times\nabla a + \dot{a}\mathbf{E}_0)\,,$$

$$\nabla\times\mathbf{E}_a + \dot{\mathbf{B}}_a = -g_{a\mathrm{MM}}\,(\mathbf{B}_0\times\nabla a + \dot{a}\mathbf{E}_0) - g_{a\mathrm{EM}}\,(\mathbf{E}_0\times\nabla a - \dot{a}\mathbf{B}_0)\,,$$

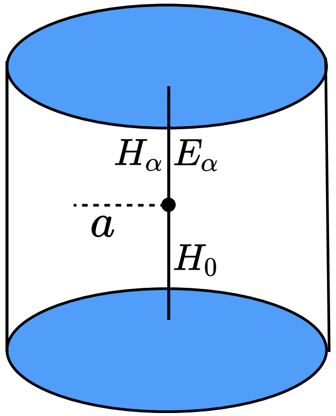
$$\nabla\cdot\mathbf{B}_a = -g_{a\mathrm{MM}}\,\mathbf{E}_0\cdot\nabla a + g_{a\mathrm{EM}}\,\mathbf{B}_0\cdot\nabla a\,,$$

$$\nabla\cdot\mathbf{E}_a = g_{a\mathrm{EE}}\,\mathbf{B}_0\cdot\nabla a - g_{a\mathrm{EM}}\,\mathbf{E}_0\cdot\nabla a\,,$$

$$(\Box + m_a^2)\,a = -(g_{a\mathrm{EE}} - g_{a\mathrm{MM}})\,\mathbf{E}_0\cdot\mathbf{B}_0 + g_{a\mathrm{EM}}\,(\mathbf{E}_0^2 - \mathbf{B}_0^2)\,,$$

where we separated external fields sustained in the detector and axion-induced fields.

RESONANT AXION HALOSCOPES



- The power going into the α-mode of the cavity is:

$$P_{i\alpha} = g_i^2 \rho_a H_0^2 V C_{i\alpha} Q_\alpha / m_a \,,$$

- For different couplings i, the form factors are:

$$C_{\alpha\, aEE} = \frac{\left(\int d^3x\, \mathbf{H_0} \cdot \mathbf{E}_\alpha\right)^2}{B_0^2 V \int d^3x\, \mathbf{E}_\alpha \cdot \mathbf{E}_\alpha} \qquad C_{\alpha\, aEM} = \frac{\left(\int d^3x\, \mathbf{H_0} \cdot \mathbf{H}_\alpha\right)^2}{H_0^2 V \int d^3x\, \mathbf{H}_\alpha \cdot \mathbf{H}_\alpha}\,, \qquad C_{\alpha\, aMM} = 0$$

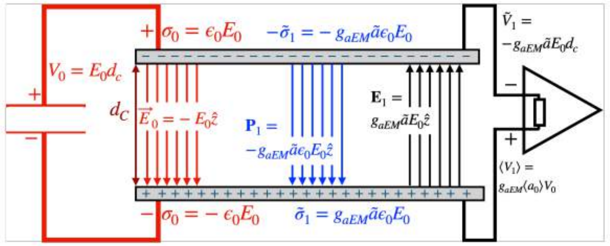
- For $\mathbf{H_0} = \mathbf{H_0 e_z}$ in a cylindrical cavity, $C_{\alpha\, aEM} = 0$: the sensitivity to new couplings is not automatic

HIGH VOLTAGE CAPACITOR AXION HALOSCOPE

[Tobar, AS, Ringwald, Goryachev '23]

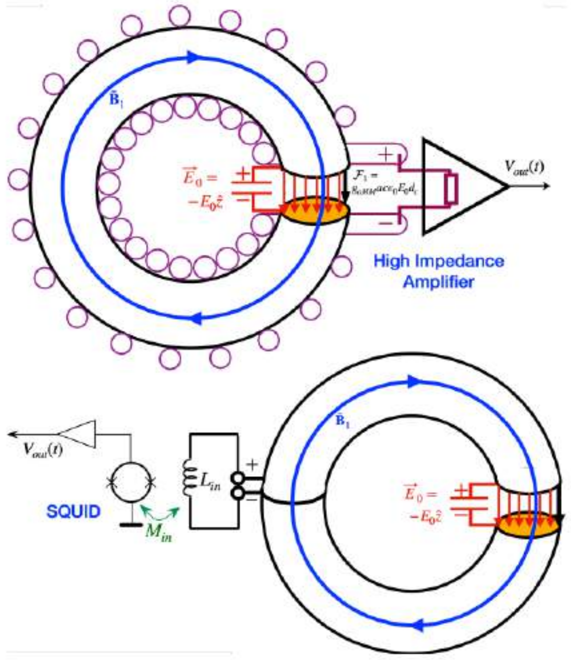
- Create strong electric field using capacitor

$$\boldsymbol{\nabla}\cdot\mathbf{E}_1 = -g_{aEM}\mathbf{E}_0\cdot\boldsymbol{\nabla}a$$

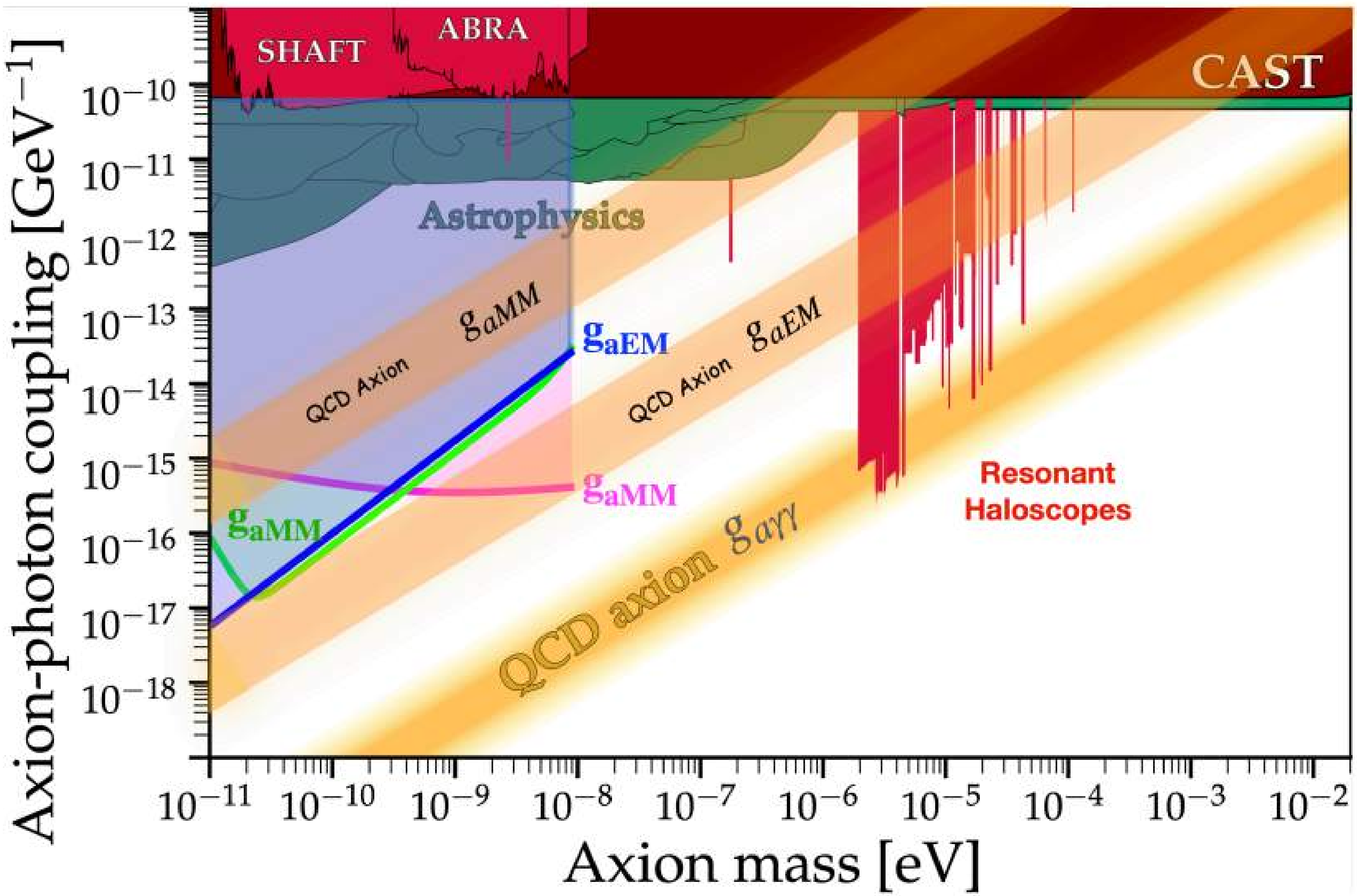


- Measure axion-induced effective polarization and magnetization

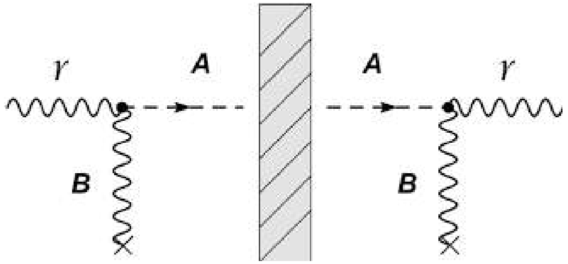
$$\boldsymbol{\nabla}\cdot\mathbf{B}_1 = -g_{aMM}\mathbf{E}_0\cdot\boldsymbol{\nabla}a$$



PROJECTIONS



LSW EXPERIMENTS



For Light-Shining-Through-Wall experiments, such as ALPS II, the effect depends on the polarization of the incoming light:

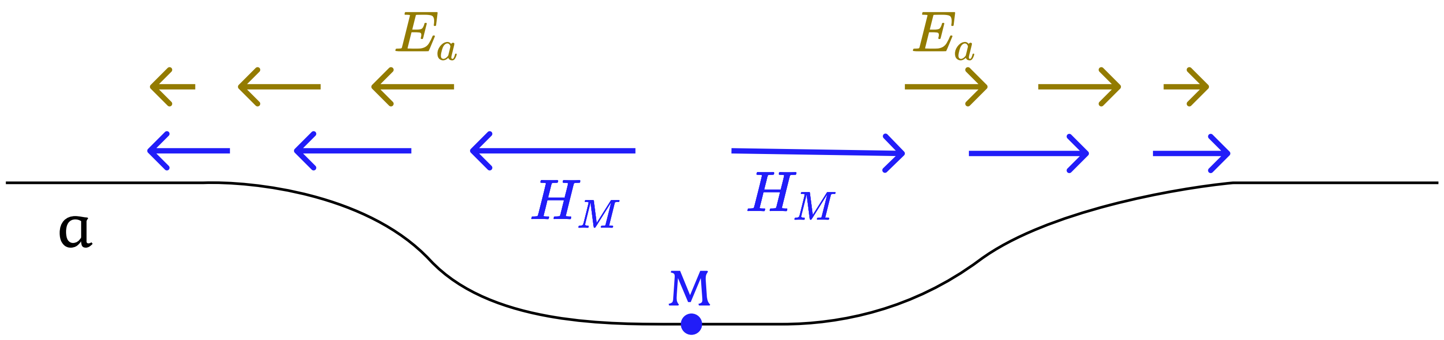
$$P(\gamma_{\parallel} \to a \to \gamma) \simeq 16\, \frac{(g_{a\mathrm{BB}}\omega B_0)^4}{m_a^8} \sin^4\left(\frac{m_a^2 L_{B_0}}{4\omega}\right),$$

$$P(\gamma_{\perp} \to a \to \gamma) \simeq 16\, \frac{(g_{a\mathrm{AB}}\omega B_0)^2 (g_{a\mathrm{BB}}\omega B_0)^2}{m_a^8} \sin^4\left(\frac{m_a^2 L_{B_0}}{4\omega}\right)$$

This means that in the case of a signal detected in both channels, one can compare the theoretically derived ratio of CP-violating and CP-conserving couplings in a given model with the experiment.

AXION EFFECTS ON CHARGED PARTICLES

- An analogue of the Witten effect in axion electrodynamics:



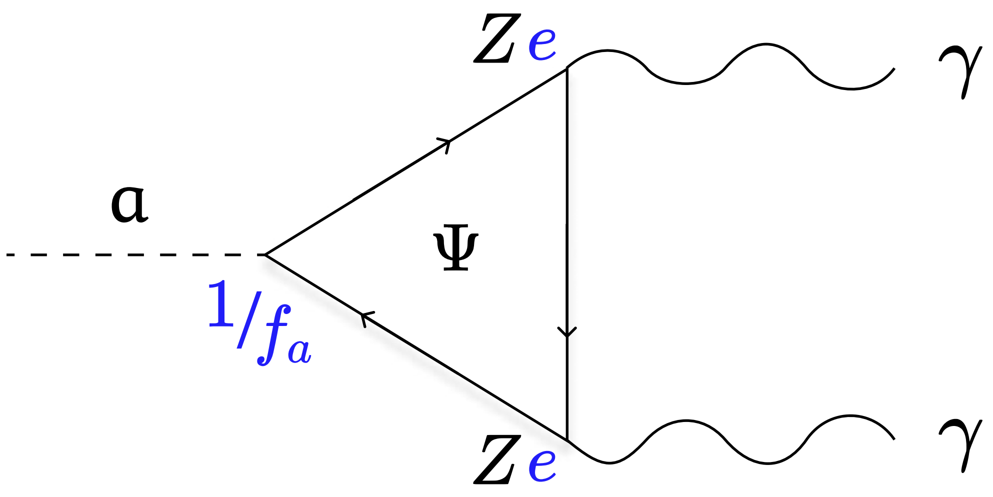
$$\nabla \cdot \mathbf{E}_a = g_{a\gamma\gamma}\,\mathbf{H}_0 \cdot \nabla a$$

fictitious charge density

- Magnetic monopole looks like a dyon
- No new charged particle states are produced: fictitious charge can only be generated at distance scales $r \gtrsim \omega_a^{-1}$, and so it is never point-like in a given axion EFT
- Axion shift symmetry is preserved since dependence only on ∇a

AXION-PHOTON COUPLING — MODELS

$$g_{a\gamma\gamma} = C_{a\gamma\gamma} \cdot \frac{e^2}{8\pi^2 f_a}$$



- DFSZ-like models:
  Ψ is from Standard model
- KSVZ-like (hadronic) models:
  Ψ is a new heavy particle carrying charge Z

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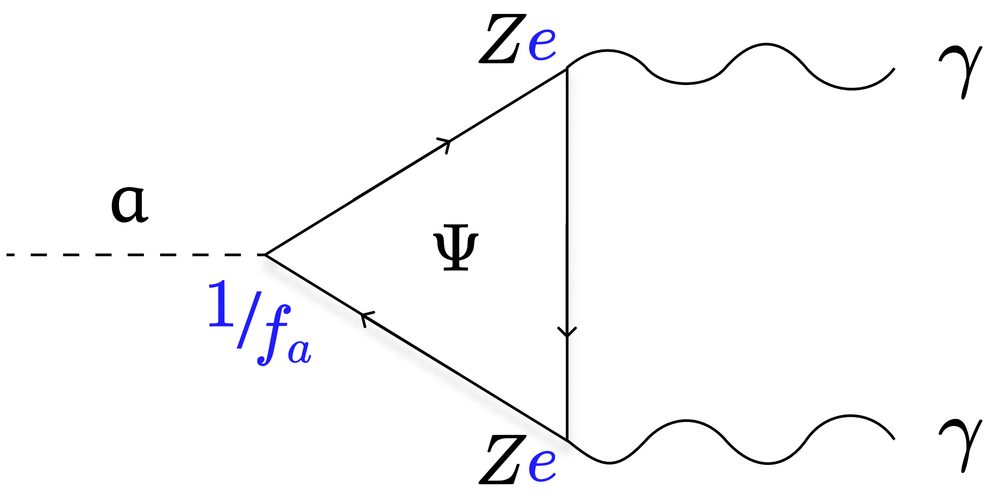

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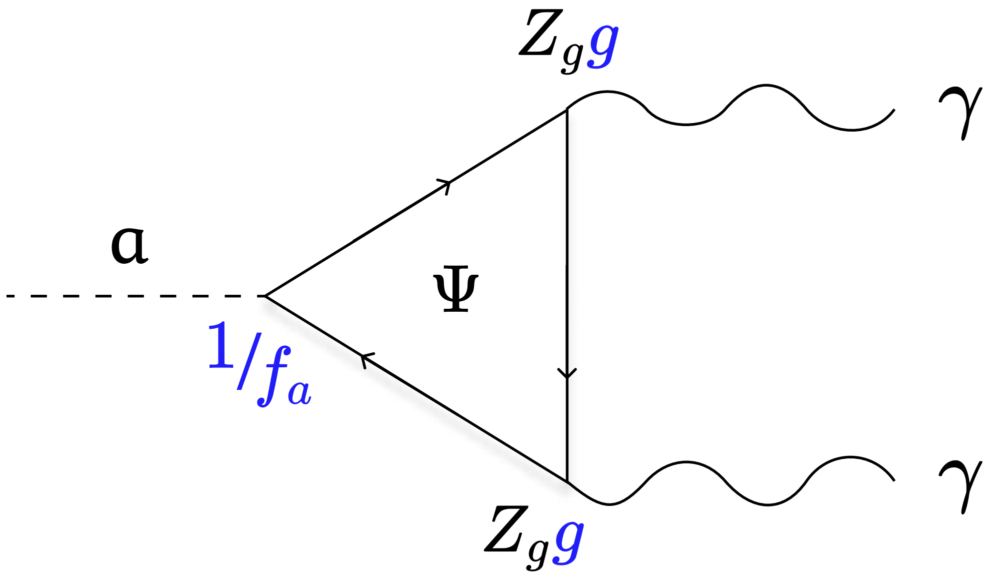
NEW AXION-PHOTON COUPLING — ORIGIN

$$g_{aMM} = C_{aMM} \cdot \frac{g^2}{8\pi^2 f_a}$$



- In "EM-rotated" hadronic model:
  Ψ is a new heavy particle
  with magnetic charge Z_g

- $g = \dfrac{2\pi n}{e} \gg e$

NEW AXION-PHOTON COUPLING — ORIGIN

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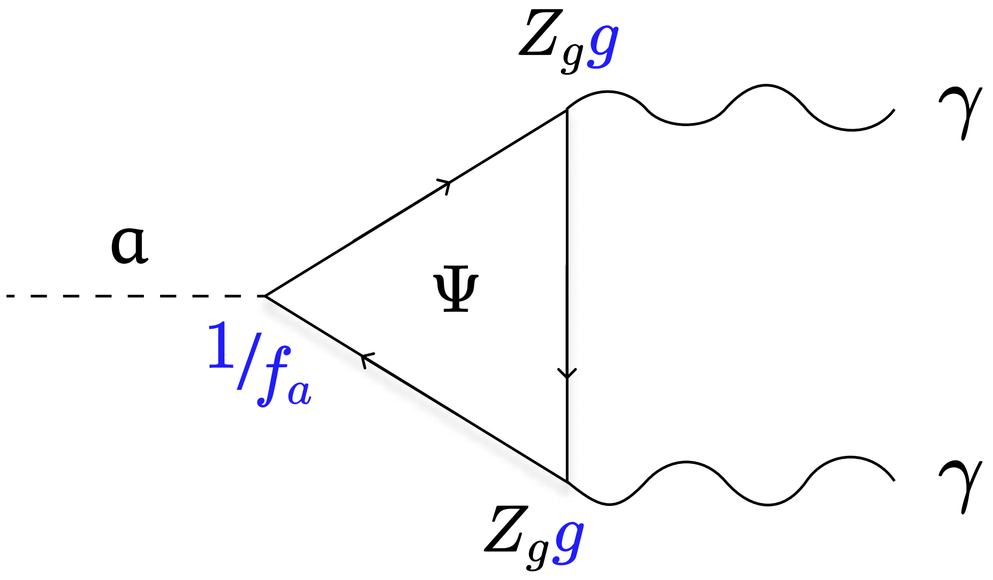


- In "EM-rotated" hadronic model: Ψ is a new heavy particle with magnetic charge Z_g
- $g = \dfrac{2\pi n}{e} \gg e$

Adler-Bardeen theorem $\Rightarrow$ no higher order corrections in g

MAGNETIC ANOMALY COEFFICIENTS

- Magnetic couplings dominate low energy physics of hadronic axion

$$\mathcal{L}_{a\gamma\gamma} = -g_{aMM} a \vec{E}\vec{H}$$

$$g_{aMM} = \frac{M}{N} \cdot \frac{g^2}{8\pi^2 f_a}, \quad M = \sum_{\psi} M_{\psi} = \sum_{\psi} Z_g^2(\psi) \cdot d(C_{\psi})$$

- M_{ψ} – magnetic anomaly coefficients
- $d(C_{\psi})$ – dimension of the color representation of ψ

COMPARISON WITH KSVZ MODELS

- Consider a simple conventional hadronic model

  with one new heavy quark having $Z_e = 1/3$:

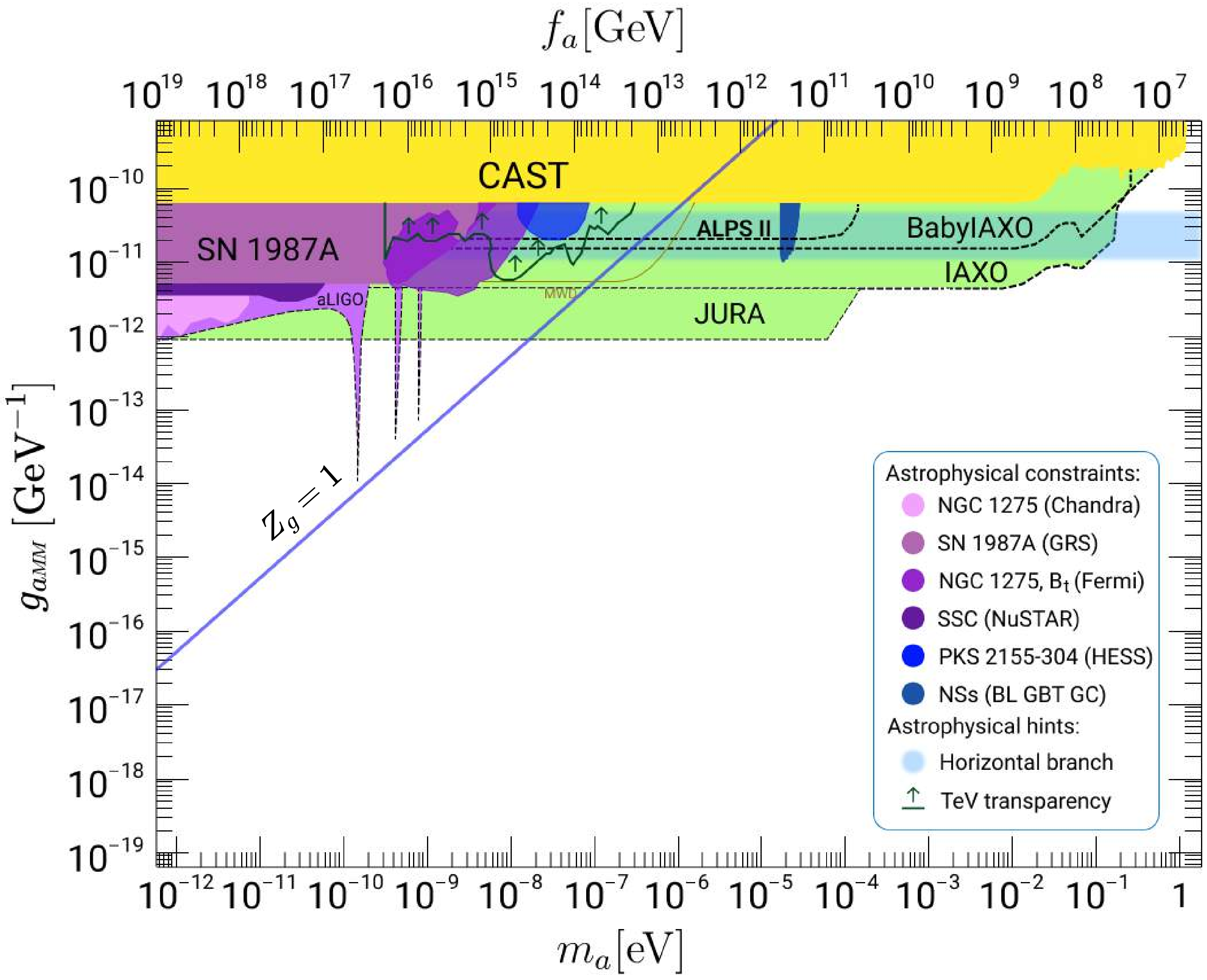
$$g_{a\gamma\gamma} = \frac{e^2}{8\pi^2 f_a} \cdot \left(\frac{E}{N} - 1.92 \right) = -\frac{e^2}{8\pi^2 f_a} \cdot 1.26$$

- Compare with the result of the general hadronic model:

$$g_{aMM} = \frac{g^2}{8\pi^2 f_a} \cdot \frac{M}{N} = -g_{a\gamma\gamma} \cdot \frac{g^2}{e^2} \cdot \frac{M/N}{1.26} = -g_{a\gamma\gamma} \cdot 2 \cdot 10^5 Z_g^2$$

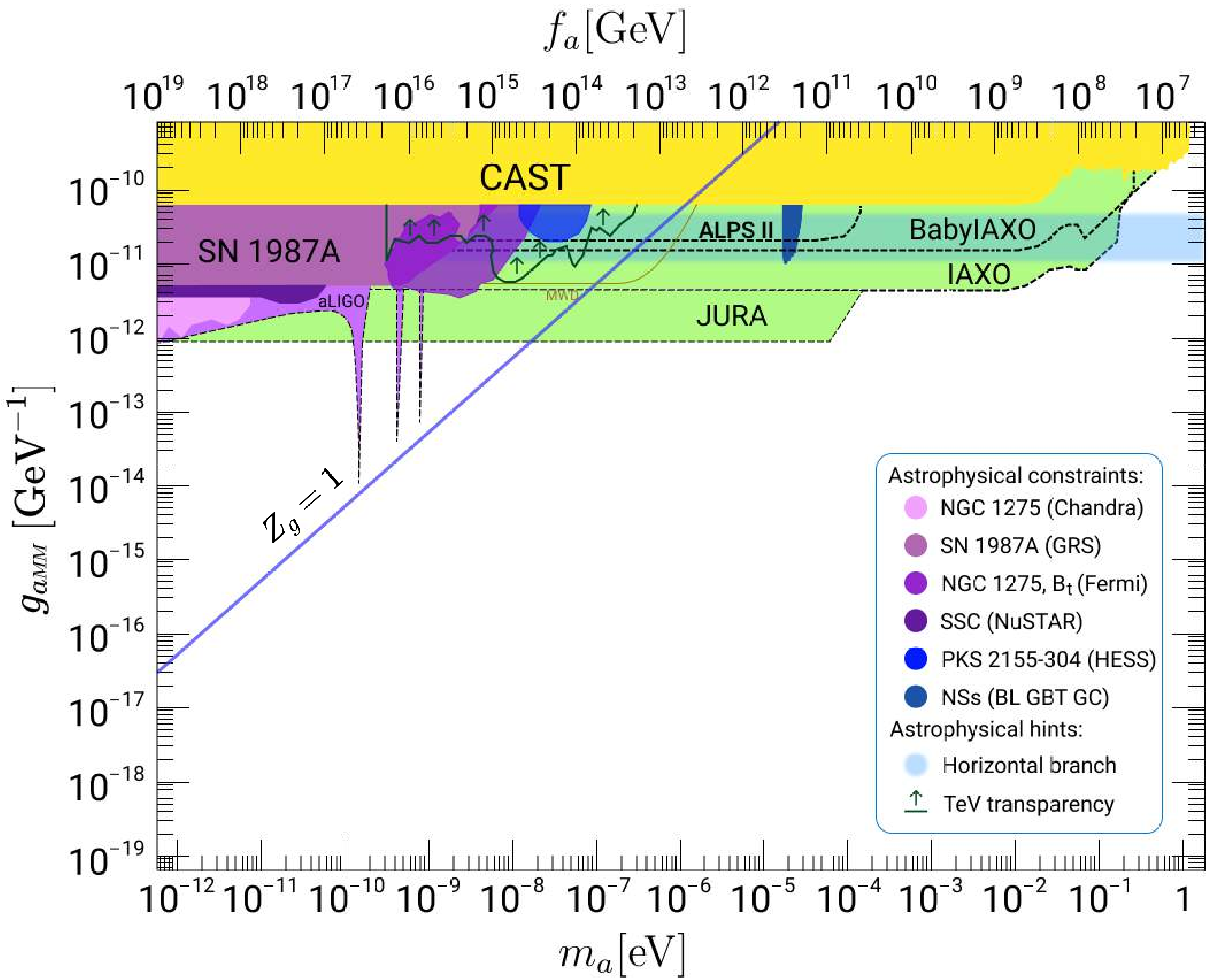
where we took into account $g = 6\pi/e$

COMPARISON PLOT



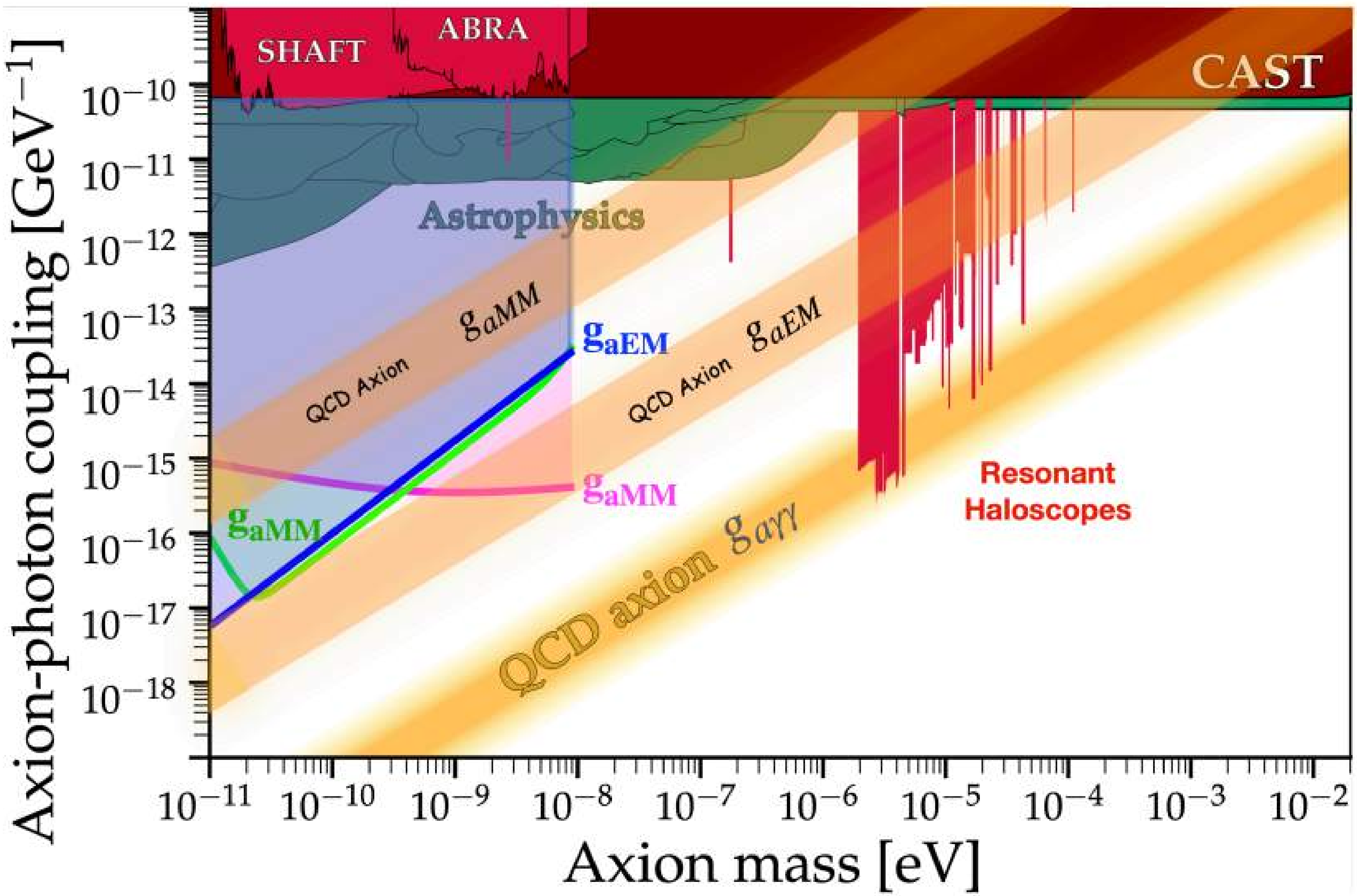
- Axion-photon coupling is hugely enhanced

COMPARISON PLOT



- Axion-photon coupling is hugely enhanced
- In the strong sector, the model is analogous to KSVZ $\Rightarrow$
  - same CDM abundance
  - same EDM coupling

PROJECTIONS



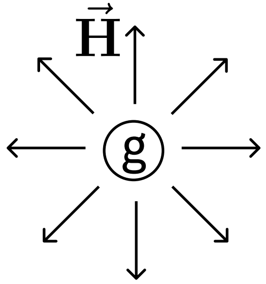
CONCLUSIONS

- General form for the axion Maxwell theory was found. Simple UV-completions were analyzed.
- There arise two new couplings in addition to the standard one.
- New axion-photon couplings give unique signatures in haloscopes searching for ALP dark matter and in some other experiments.
- New haloscope experiment based on a high voltage capacitor was proposed.
- Some future directions and open questions:

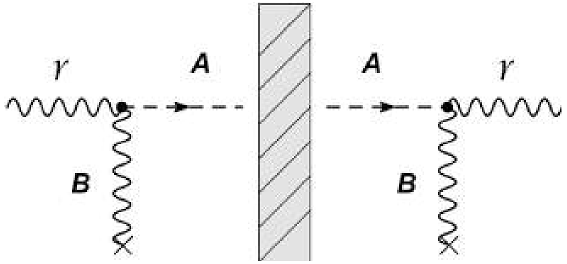
  -analyze further implications for haloscope experiments

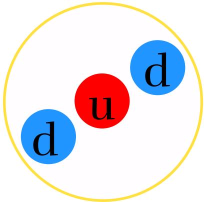
  -search for signatures of new couplings in astrophysical settings

  -calculate values of new couplings in more complicated UV-completions such as GUTs and string theory

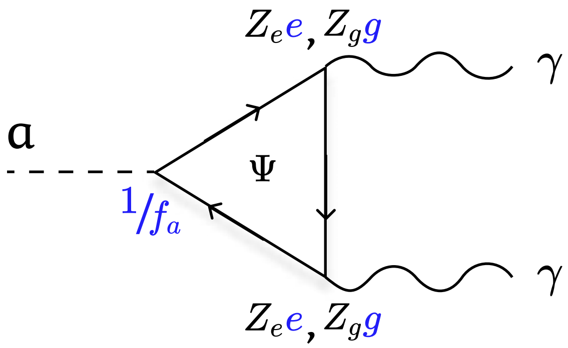


THANK YOU FOR YOUR ATTENTION!





MIXED ELECTRIC-MAGNETIC ANOMALY COEFFICIENT



$$g_{aAB} = \frac{D}{N} \cdot \frac{eg}{8\pi^2 f_a},$$

$$D = \sum_\psi D_\psi = \sum_\psi Z_e(\psi) Z_g(\psi) \cdot d(C_\psi).$$

- D_ψ — electric-magnetic anomaly coefficients
- $d(C_\psi)$ — dimension of the color representation of ψ

- CP violation is transfered from heavy dyons to axion-photon interactions

PHENOMENOLOGY OF THE NEW COUPLINGS