Electromagnetic Couplings of Axions

based on

arXiv:2205.02605

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Deutsches Elektronen-Synchrotron DESY, Hamburg

16th Kosmologietag in Bielefeld

5–6 May 2022

AXIONS: OBSERVATIONAL HINTS

AXION

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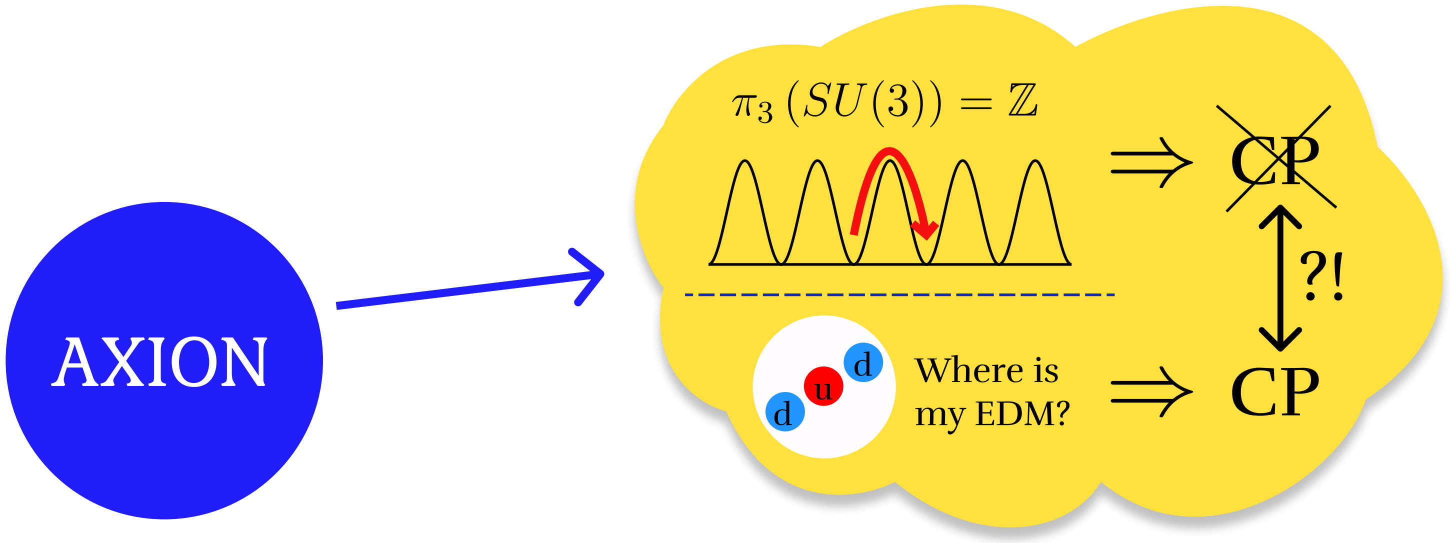
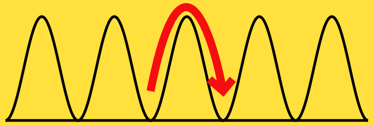


AXIONS: OBSERVATIONAL HINTS

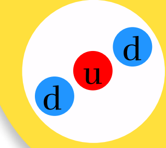
AXION

$\pi_3\left(SU(3)\right) = \mathbb{Z}$



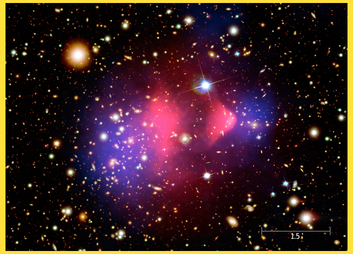
$\Rightarrow \cancel{CP}$

$\updownarrow$?!



Where is my EDM? $\Rightarrow CP$

ΛCDM



NASA image

ESO/Illustris Collaboration

What makes Cold Dark Matter ?!

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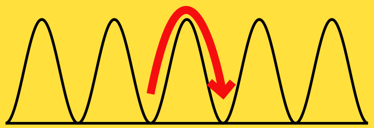
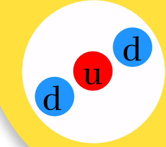


$\Rightarrow$ ~~CP~~

?!



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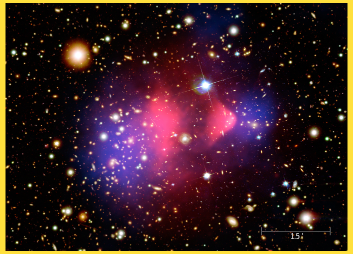

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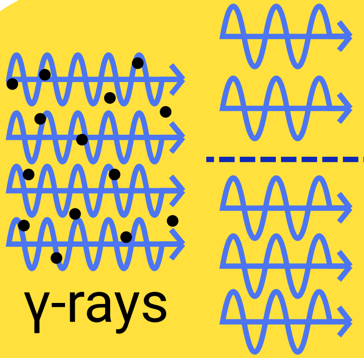
NASA, ESA and J. Olmsted



Predicted

?!

Observed

[De Angelis et al. '07]
[Horns, Meyer '12]

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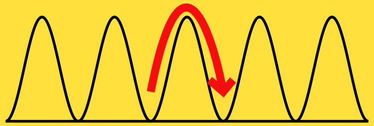

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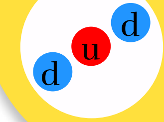

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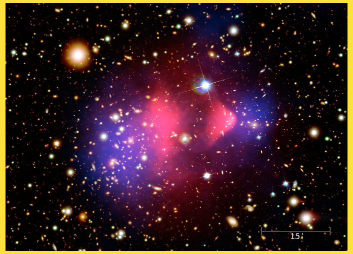

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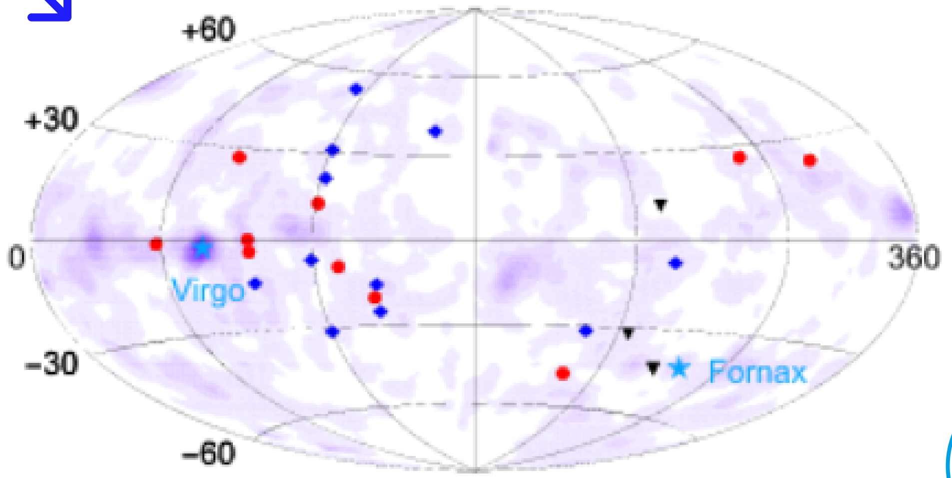

[Troitsky '21]

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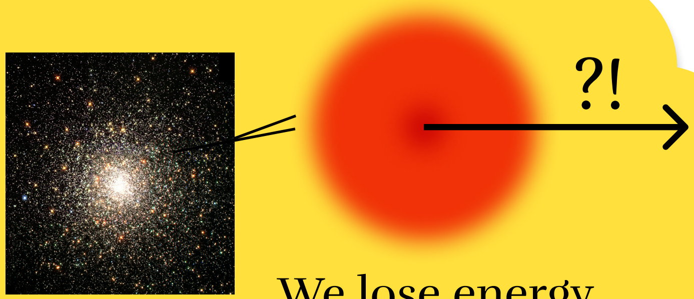

NASA&STScI image

We lose energy too fast!

[Ayala et al. '14]

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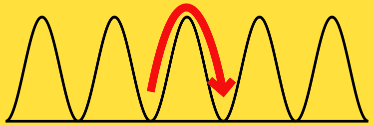

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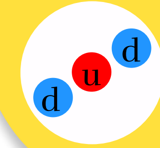

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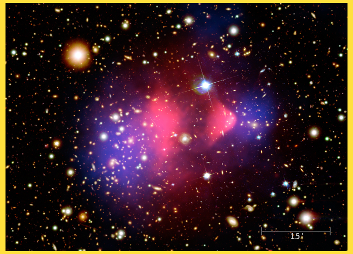

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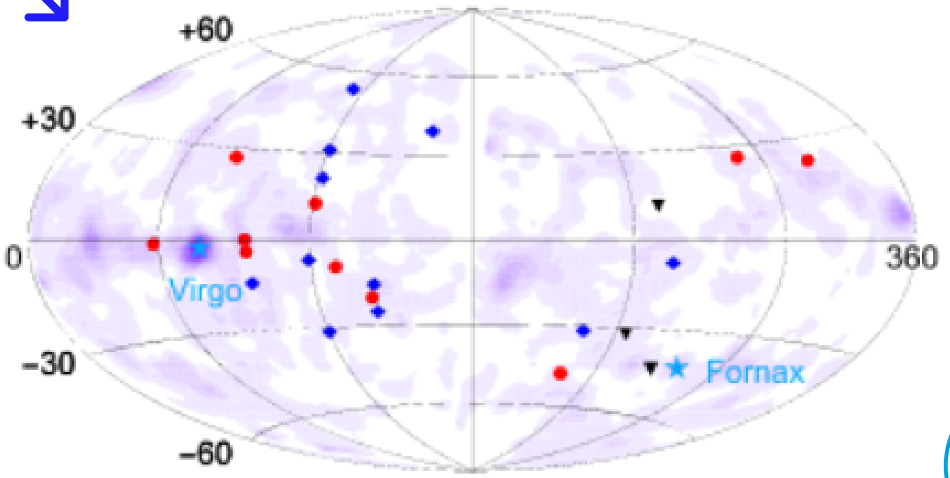
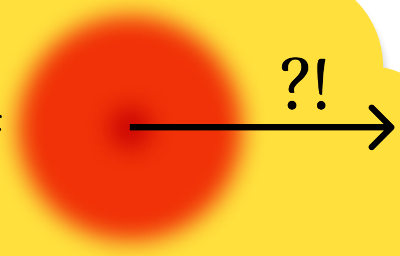


[Troitsky '21]

ALPS: OBSERVATIONAL HINTS


NASA&STScI image



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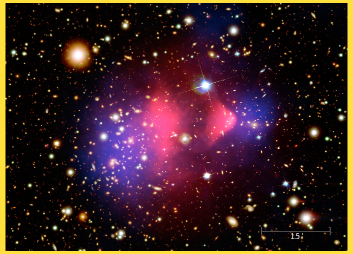
ALP

ΛCDM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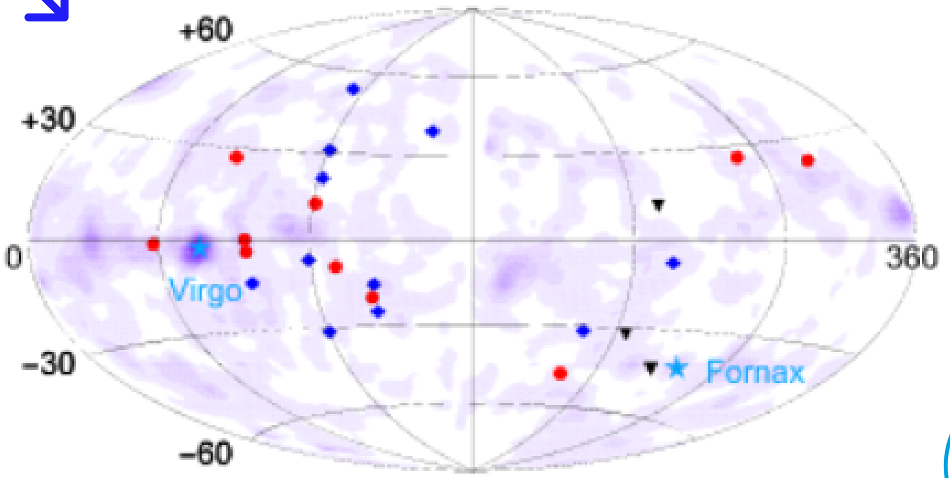
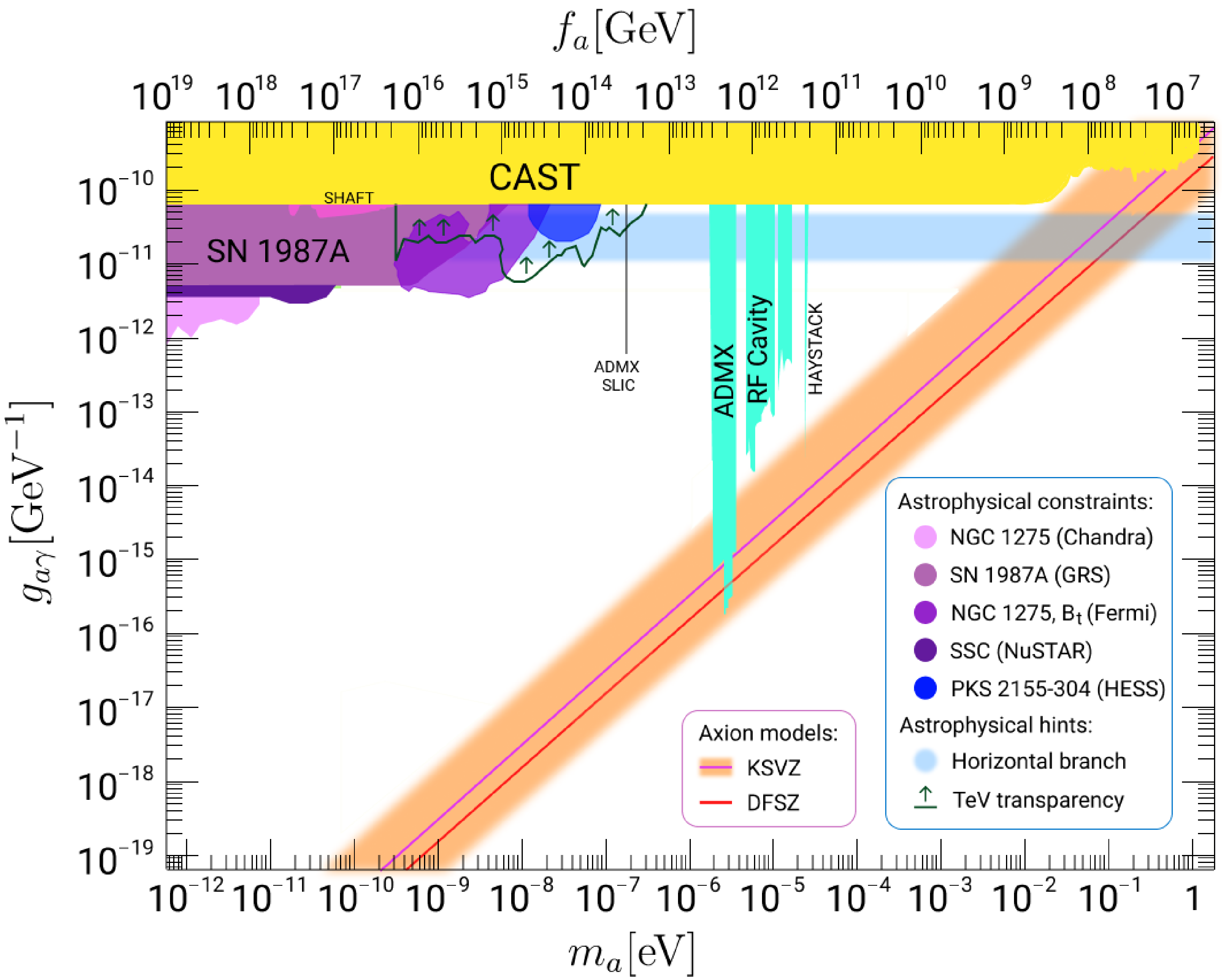


[Troitsky '21]

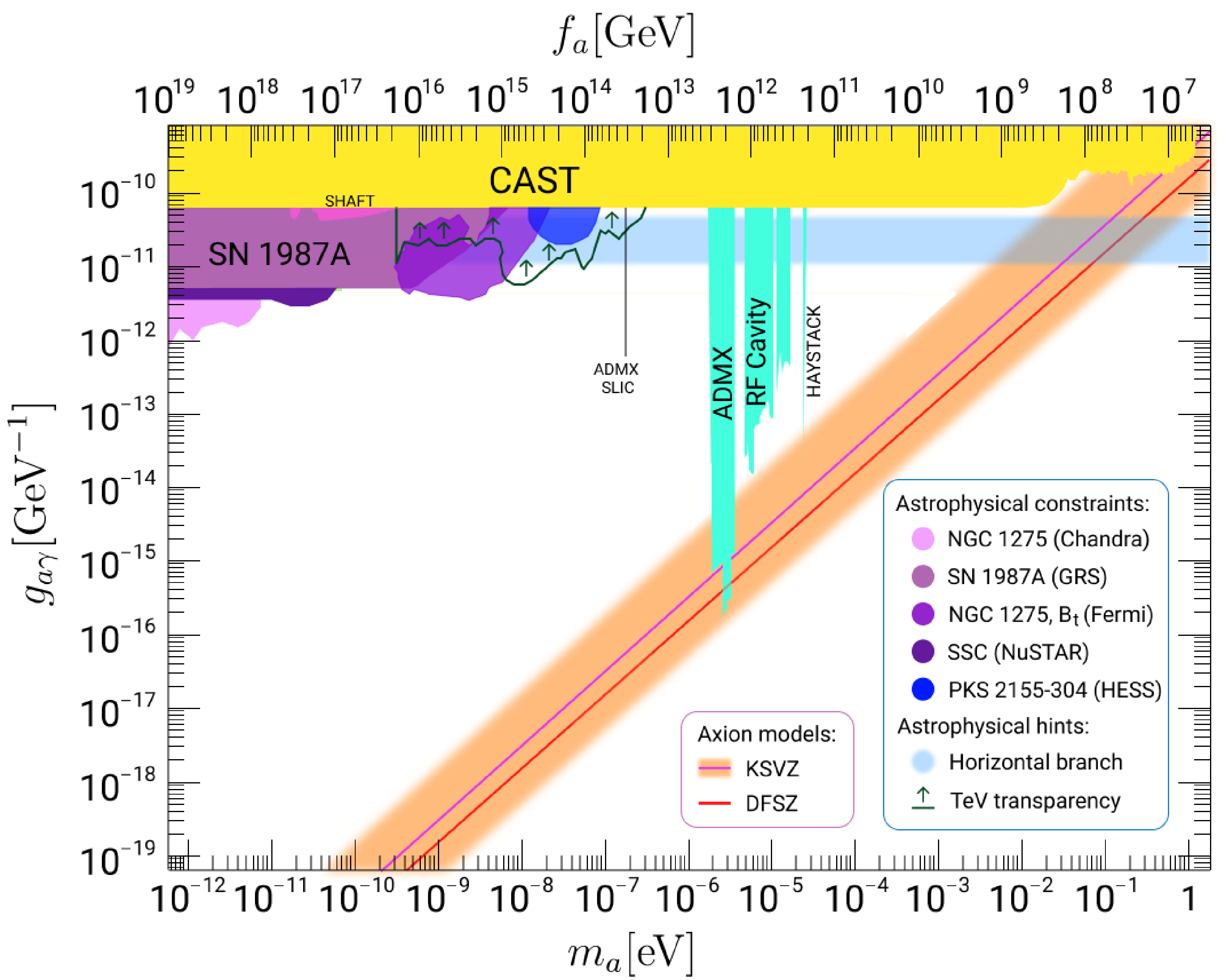
AXION-PHOTON COUPLING



$$\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma\gamma} a F F^d$$

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

AXION-PHOTON COUPLING

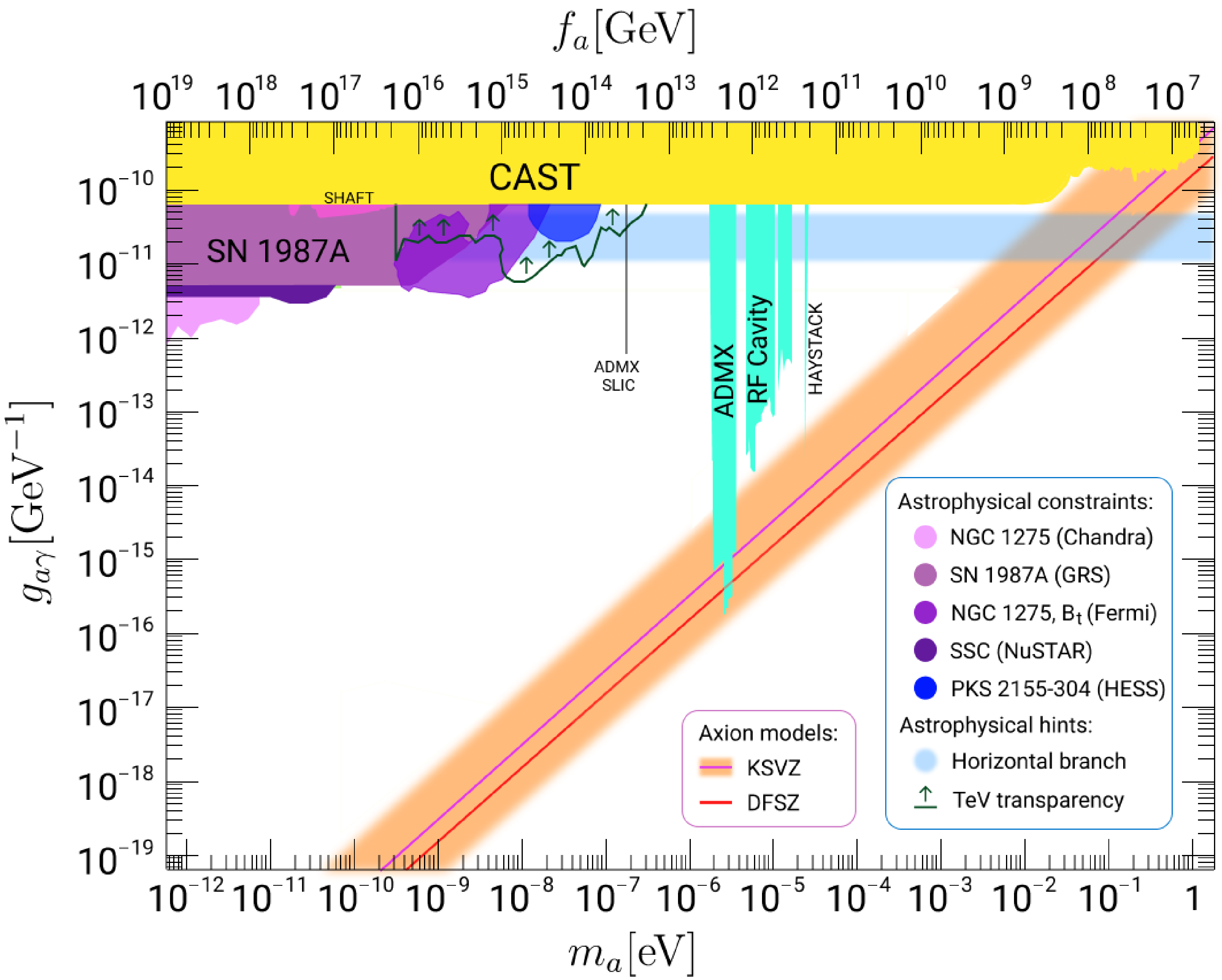


$$\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma\gamma} a F F^d$$

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

- axion-photon conversion in external magnetic field (astro + 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)

AXION-PHOTON COUPLING



$$\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma\gamma} a F F^d$$

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

$$F = \partial \wedge A$$

Is this the most general axion-photon Lagrangian consistent with the symmetries?

Axion shift symmetry:

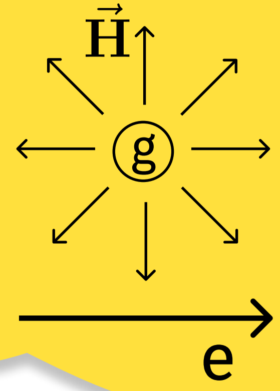
$$a \to a + 2\pi n,\ n \in \mathbb{Z}$$

The answer is no, if there exist heavy magnetic monopoles

MAGNETIC MONOPOLES

- Dirac: magnetic monopoles fit perfectly into quantum mechanics
- quantization of charge explained
- Zwanziger: magnetic monopoles fit perfectly into QFT
- 't Hooft and Polyakov: magnetic monopoles arise in the low energy phase of non-Abelian theories -> Grand Unified theories
- Banks and Seiberg: quantum gravity implies existence of magnetic monopoles with any magnetic charge allowed by the quantization condition
- Polchinski: "existence of magnetic monopoles seems like one of the safest bets that one can make about physics not yet seen"

<u>1931 DIRAC</u>



QM:

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

QUANTUM ELECTROMAGNETODYNAMICS

1971 ZWANZIGER

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

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

1977 ZBN

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

- TWO vector-potentials describe ONE particle - photon
- partition function is Lorentz-invariant
- theory is generally not CP-invariant

GENERIC AXION-PHOTON EFT

All dimension-five operators consistent with the symmetries:

$$
\begin{aligned}
\mathcal{L} \; &= \; \mathcal{L}_{\text{kin}}\,(A\,, B\,, n\,) \\
&- \frac{1}{4}\, g_{aAA}\, a\, \mathrm{tr}\Big\{(\partial \wedge A)\,(\partial \wedge A)^{d}\Big\} \; - \; \frac{1}{4}\, g_{aBB}\, a\, \mathrm{tr}\Big\{(\partial \wedge B)\,(\partial \wedge B)^{d}\Big\} \\
&- \frac{1}{2}\, g_{aAB}\, a\, \mathrm{tr}\Big\{(\partial \wedge A)\,(\partial \wedge B)^{d}\Big\} \\
&- \left(\bar{j}_e + \frac{e^2 a}{4\pi^2 v_a}\, j_m^{\phi}\right) \cdot (A - \partial\phi) - j_m \cdot B
\end{aligned}
$$

$\mathcal{L}_{\text{kin}}$ term	Kinetic part
g_{aAA}, g_{aBB} terms	Anomalous axion-photon interactions, CP-conserving
g_{aAB} term	Anomalous axion-photon interaction, CP-violating
j_m^{ϕ} term	Witten effect induced axion-photon interaction, includes j_m^{ϕ} - current of ‘t Hooft-Polyakov monopoles

This Effective Field Theory is valid for any axion or axion-like particle.

In each particular UV model, one can calculate the coefficients g_{aAA}, g_{aBB} and g_{aAB}.

General feature due to the quantization condition: $g_{a\mathrm{BB}} \gg |g_{a\mathrm{AB}}| \gg g_{a\mathrm{AA}}$.

AXION MAXWELL EQUATIONS

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

$$\begin{aligned} \partial_\mu F^{\mu\nu} - g_{a\mathrm{AA}}\,\partial_\mu a\, F^{d\,\mu\nu} + g_{a\mathrm{AB}}\,\partial_\mu a\, F^{\mu\nu} - \frac{e^2 a}{4\pi^2 v_a}\, j_m^{\phi\,\nu} &= \bar{j}_e^{\,\nu}\,, \\ \partial_\mu F^{d\,\mu\nu} + g_{a\mathrm{BB}}\,\partial_\mu a\, F^{\mu\nu} - g_{a\mathrm{AB}}\,\partial_\mu a\, F^{d\,\mu\nu} &= j_m^{\nu}\,, \\ \left(\partial^2 - m_a^2\right) a &= -\frac{1}{4}\left(g_{a\mathrm{AA}} + g_{a\mathrm{BB}}\right) F_{\mu\nu} F^{d\,\mu\nu} - \frac{1}{2}\, g_{a\mathrm{AB}} F_{\mu\nu} F^{\mu\nu} \end{aligned}$$

In the experimentally relevant case, in terms of electric and magnetic fields:

$$\begin{aligned} &\boldsymbol{\nabla}\times\mathbf{B}_a - \dot{\mathbf{E}}_a = g_{a\mathrm{AA}}\left(\mathbf{E}_0\times\boldsymbol{\nabla}a - \dot{a}\mathbf{B}_0\right) + g_{a\mathrm{AB}}\left(\mathbf{B}_0\times\boldsymbol{\nabla}a + \dot{a}\mathbf{E}_0\right)\,, \\ &\boldsymbol{\nabla}\times\mathbf{E}_a + \dot{\mathbf{B}}_a = -g_{a\mathrm{BB}}\left(\mathbf{B}_0\times\boldsymbol{\nabla}a + \dot{a}\mathbf{E}_0\right) - g_{a\mathrm{AB}}\left(\mathbf{E}_0\times\boldsymbol{\nabla}a - \dot{a}\mathbf{B}_0\right)\,, \\ &\boldsymbol{\nabla}\cdot\mathbf{B}_a = -g_{a\mathrm{BB}}\,\mathbf{E}_0\cdot\boldsymbol{\nabla}a + g_{a\mathrm{AB}}\,\mathbf{B}_0\cdot\boldsymbol{\nabla}a\,, \\ &\boldsymbol{\nabla}\cdot\mathbf{E}_a = g_{a\mathrm{AA}}\,\mathbf{B}_0\cdot\boldsymbol{\nabla}a - g_{a\mathrm{AB}}\,\mathbf{E}_0\cdot\boldsymbol{\nabla}a\,, \\ &\left(\partial^2 - m_a^2\right) a = \left(g_{a\mathrm{AA}} + g_{a\mathrm{BB}}\right)\mathbf{E}_0\cdot\mathbf{B}_0 + g_{a\mathrm{AB}}\left(\mathbf{E}_0^2 - \mathbf{B}_0^2\right)\,, \end{aligned}$$

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

HALOSCOPE EXPERIMENTS FOR LOW-MASS AXION DM

For axion DM detection, leaving only the dominant terms on the right-hand side, we obtain:

$$\begin{aligned}
&\boldsymbol{\nabla}\times\mathbf{B}_a-\dot{\mathbf{E}}_a=0\,,\\
&\boldsymbol{\nabla}\times\mathbf{E}_a+\dot{\mathbf{B}}_a=-g_{a\mathrm{BB}}\left(\mathbf{B}_0\times\boldsymbol{\nabla}a+\dot{a}\mathbf{E}_0\right)+g_{a\mathrm{AB}}\dot{a}\mathbf{B}_0\,,\\
&\boldsymbol{\nabla}\cdot\mathbf{B}_a=0\,,\\
&\boldsymbol{\nabla}\cdot\mathbf{E}_a=0\,,
\end{aligned}$$

$$\xrightarrow{m_aL\ll 1} \quad E_a \gg B_a$$

m_a - axion mass

L - detector size

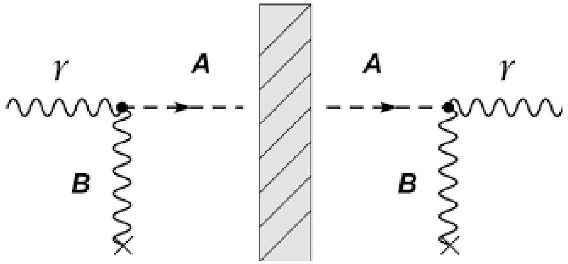
This is to be contrasted with the conventional axion Maxwell equations used for axion DM detection:

$$\begin{aligned}
&\boldsymbol{\nabla}\times\mathbf{B}_a-\dot{\mathbf{E}}_a=-g_{a\mathrm{AA}}\dot{a}\mathbf{B}_0,\\
&\boldsymbol{\nabla}\times\mathbf{E}_a+\dot{\mathbf{B}}_a=0\,,\\
&\boldsymbol{\nabla}\cdot\mathbf{B}_a=0\,,\\
&\boldsymbol{\nabla}\cdot\mathbf{E}_a=0\,,
\end{aligned}$$

$$\xrightarrow{m_aL\ll 1} \quad B_a \gg E_a$$

The models with and without super heavy monopoles have completely different low energy phenomenology! One should aim to measure both electric and magnetic axion-induced fields.

LSW EXPERIMENTS



For LSW experiments, the effect can be calculated using the axion equation of motion:

$$(\partial^2 - m_a^2)a = (g_{aAA} + g_{aBB})\,\mathbf{E}\cdot\mathbf{B} + g_{aAB}\,(\mathbf{E}^2 - \mathbf{B}^2)$$

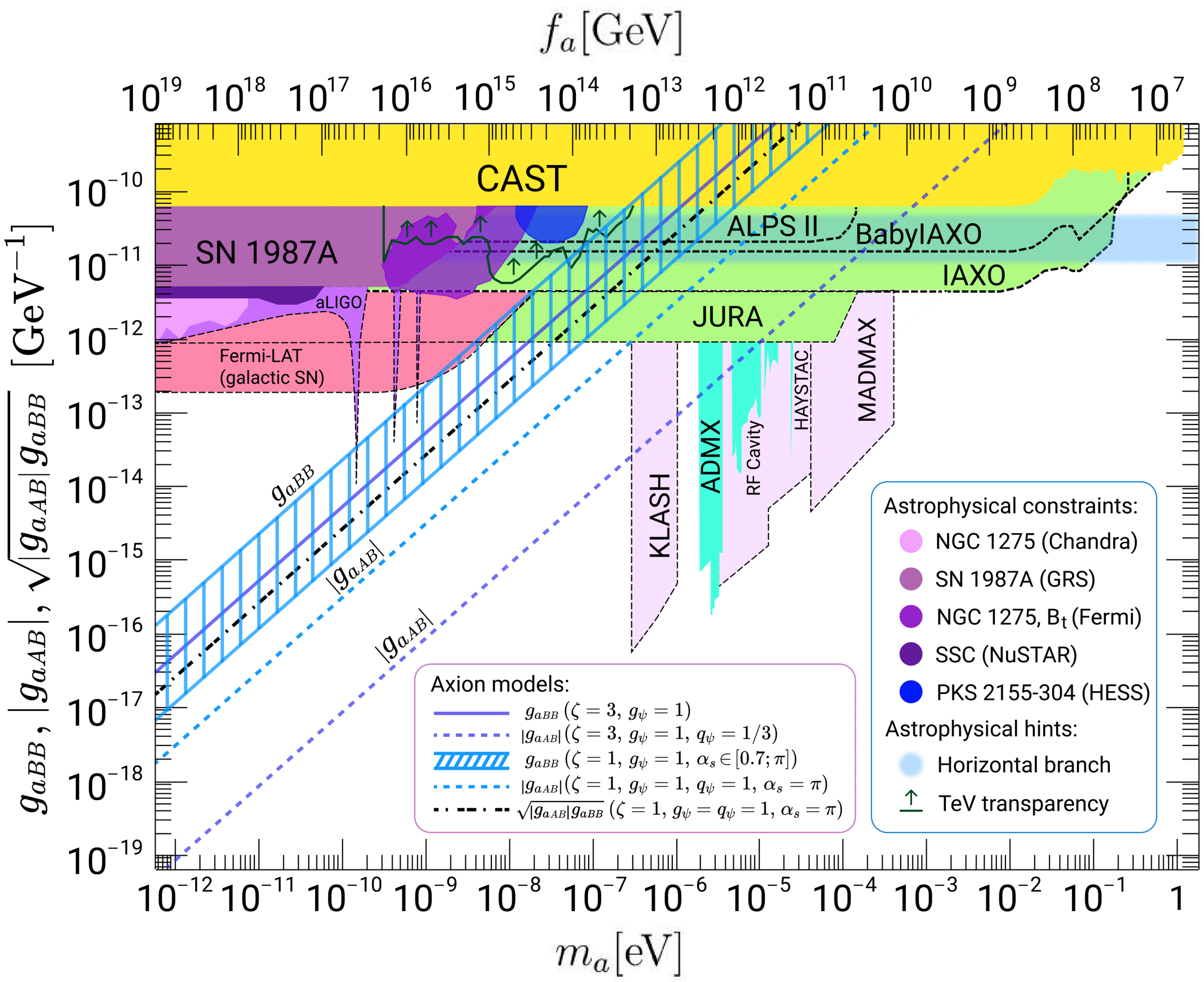
The effect depends on the polarization of the incoming light:

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

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

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.

PHENOMENOLOGY OF THE NEW COUPLINGS



- Axion DM could be easier to detect
- Haloscopes with electric sensors have to be constructed
- ALPS II is sensitive to the QCD axion

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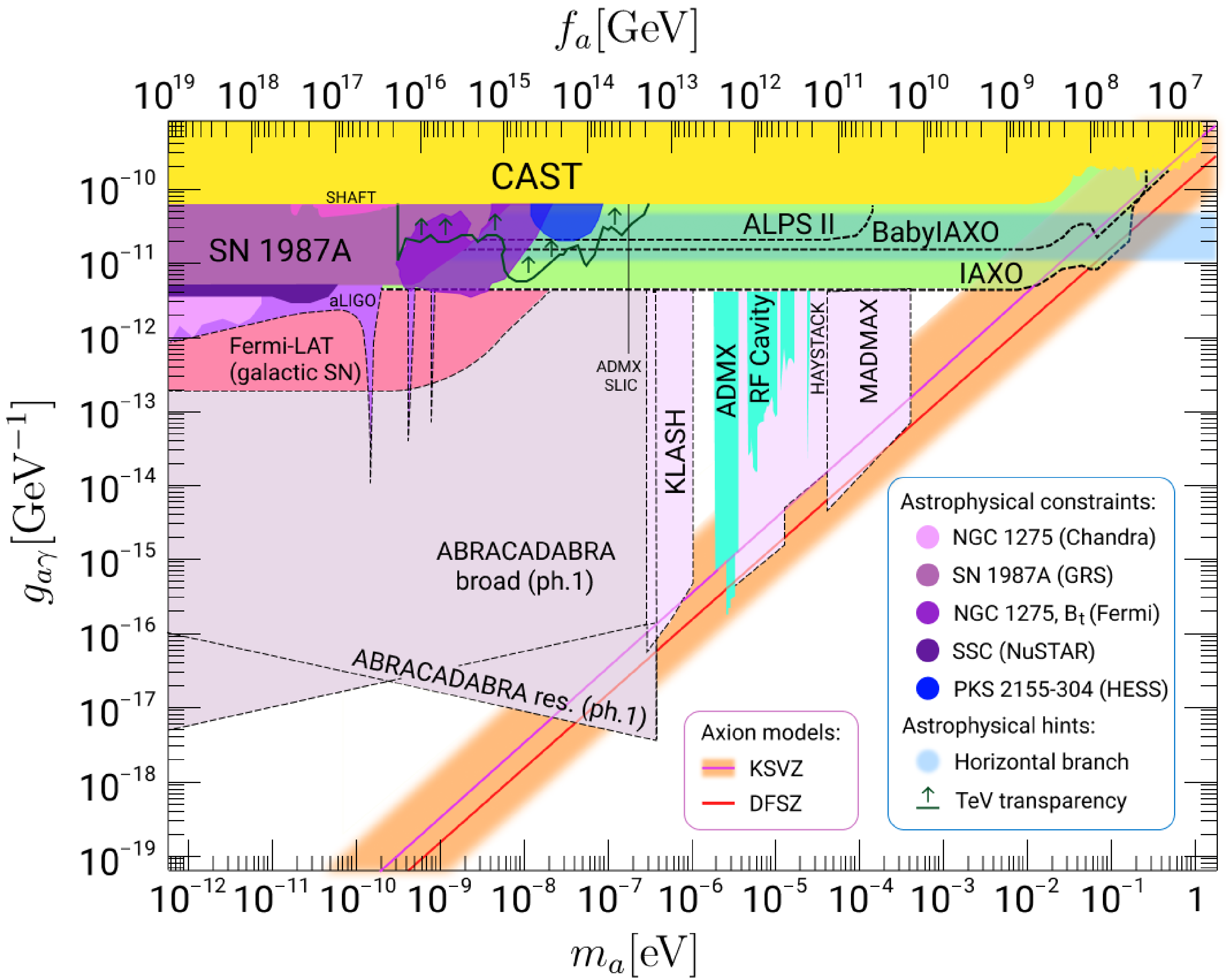

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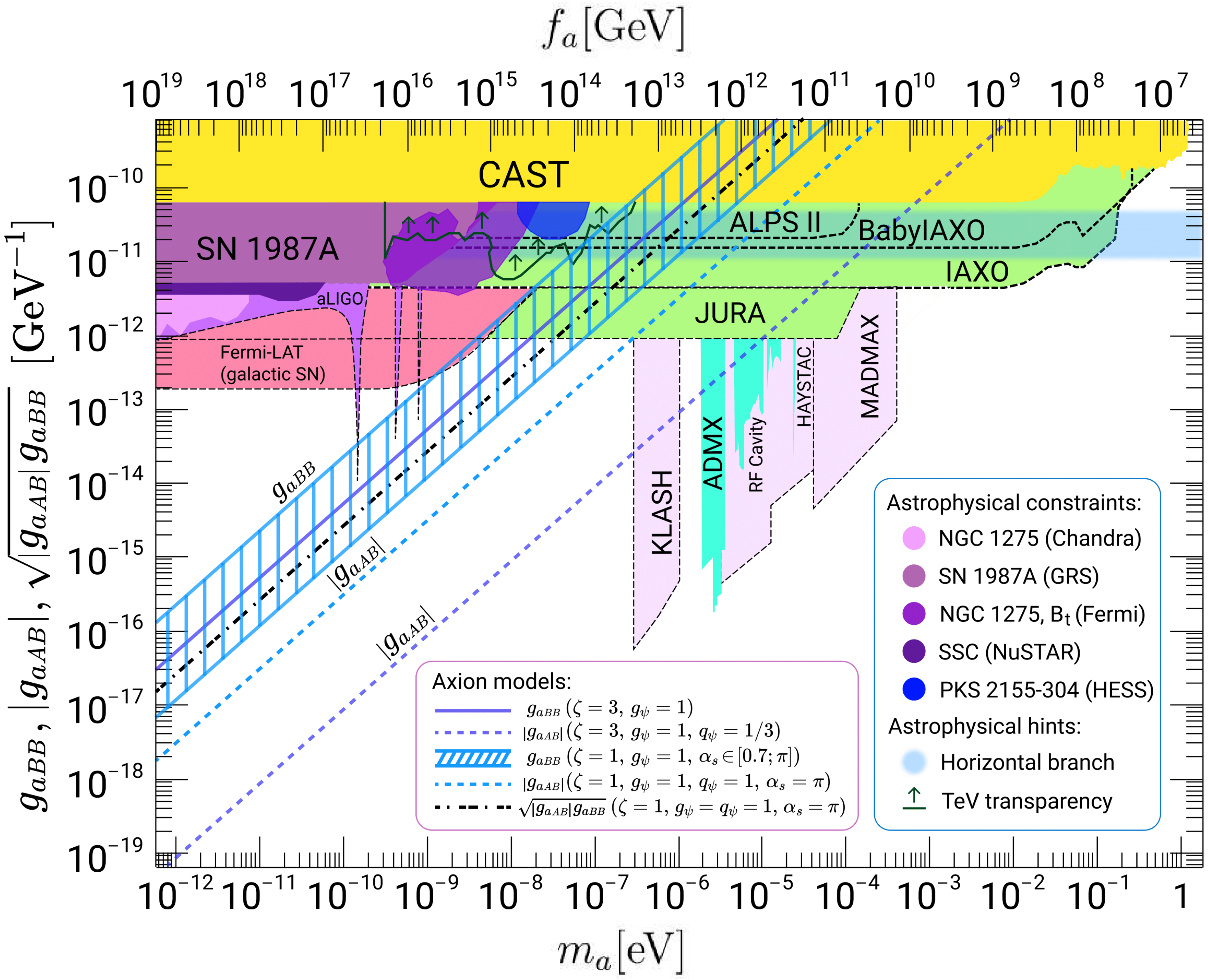

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CONCLUSIONS

- Heavy magnetic monopoles can influence low energy physics through axion-photon couplings and thus can be indirectly probed in this way.
- New axion-photon couplings give unique signatures in haloscopes searching for low-mass ALP dark matter and in some other experiments.
- Axion-photon interaction can violate CP.
- Low-mass axion dark matter could be detected earlier than previously thought.
- We clarified some issues within axion theory, such as axion mass from monopoles, Witten-effect induced axion interaction and quantization of the axion-photon coupling.