PHOTOPHILIC HADRONIC AXION FROM HEAVY MAGNETIC MONOPOLES

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OUTLINE OF THE TALK

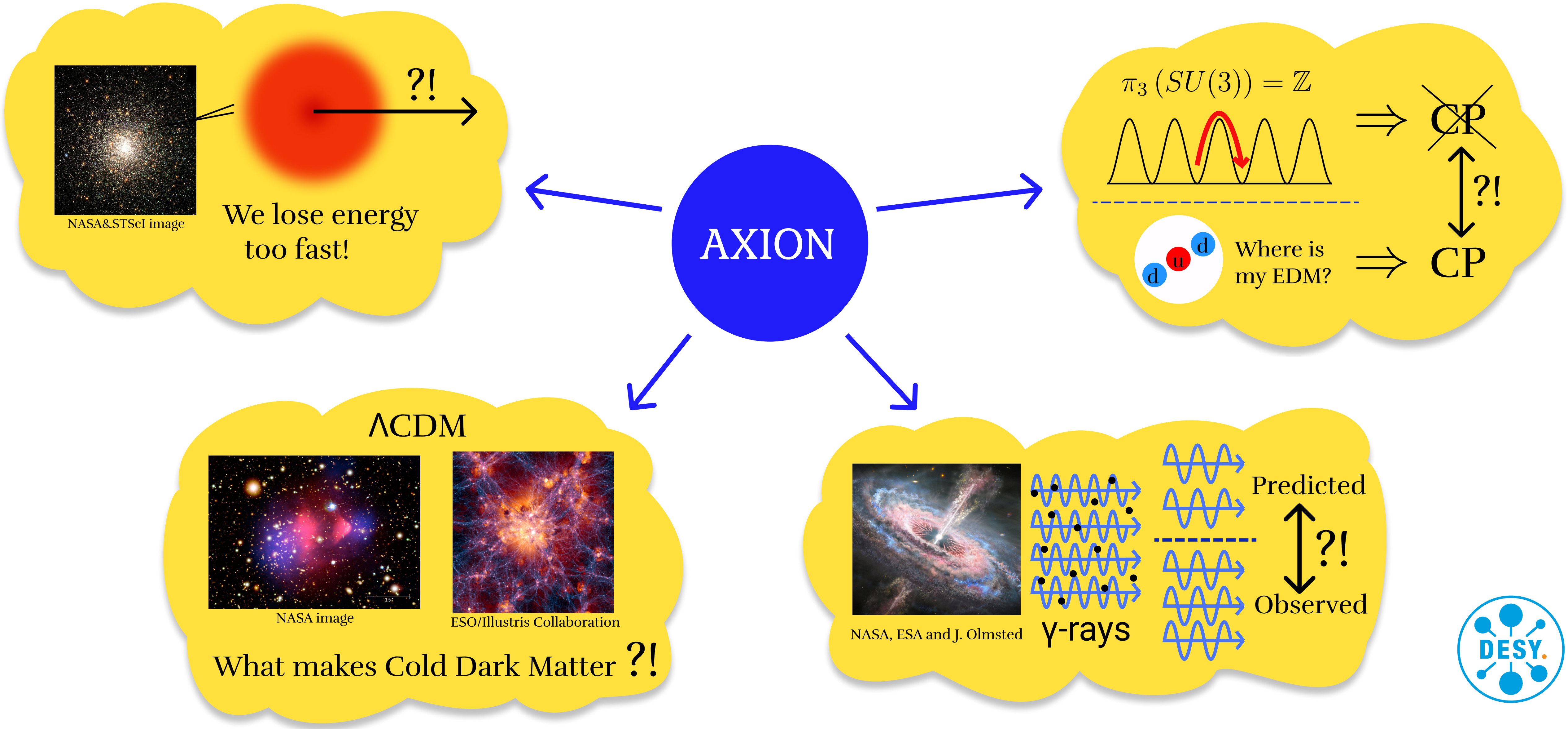
- Motivation
  - various experimental hints
  - Occam's razor view on KSVZ-like axion models
- Reminder on quantum electromagnetodynamics
- Axion model involving Abelian monopole

$$\psi\ [U_M(1) \times SU(3)]$$

- Axion model involving non-Abelian monopole

$$\psi\ [U_M(1) \times SU_M(3)]$$

MOTIVATION: OBSERVATIONAL HINTS



MOTIVATION: KSVZ-LIKE AXION MODELS

1. Introduce PQ field Φ with potential $V(\Phi)$ breaking $U(1)_{PQ}$ spontaneously

2. Introduce exotic vector-like quark ψ charged under $SU(3)_c \times U(1)_{\text{em}}$:

$$\mathcal{L} \supset i\bar{\psi}\gamma_\mu D^\mu \psi + y\left(\Phi\,\bar{\psi}_L \psi_R + \text{h.c.}\right)$$

3. Integrate ψ out and obtain effective IR Lagrangian:

$$\mathcal{L}_{\text{IR}} \supset g^0_{a\gamma\gamma} a\vec{E}\vec{H} + \frac{\alpha_s}{8\pi}\frac{a}{f_a}G\tilde{G}$$

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$$\mathcal{L}_{\text{IR}} \supset g^0_{a\gamma\gamma} a \vec{E}\vec{H} + \frac{\alpha_s}{8\pi}\frac{a}{f_a} G\tilde{G}$$

Can one relax any of the assumptions in 1. and 2. ?

MOTIVATION: KSVZ-LIKE AXION MODELS

1. Introduce PQ field Φ with potential $V(\Phi)$ breaking $U(1)_{PQ}$ spontaneously

generic vector-like fermion

2. Introduce ~~exotic vector-like quark~~ ψ ~~charged under $SU(3)_c \times U(1)_{\mathrm{em}}$~~ :

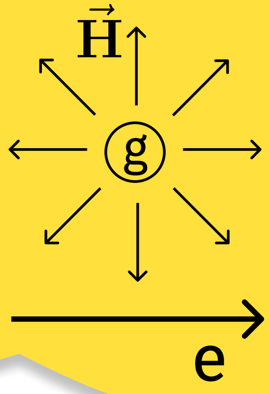
$$\mathcal{L} \supset i\bar{\psi}\gamma_\mu D^\mu \psi + y\left(\Phi\,\bar{\psi}_L \psi_R + \mathrm{h.c.}\right)$$

3. Integrate ψ out and obtain effective IR Lagrangian:

$\mathcal{L}_{\mathrm{IR}}$ = ?

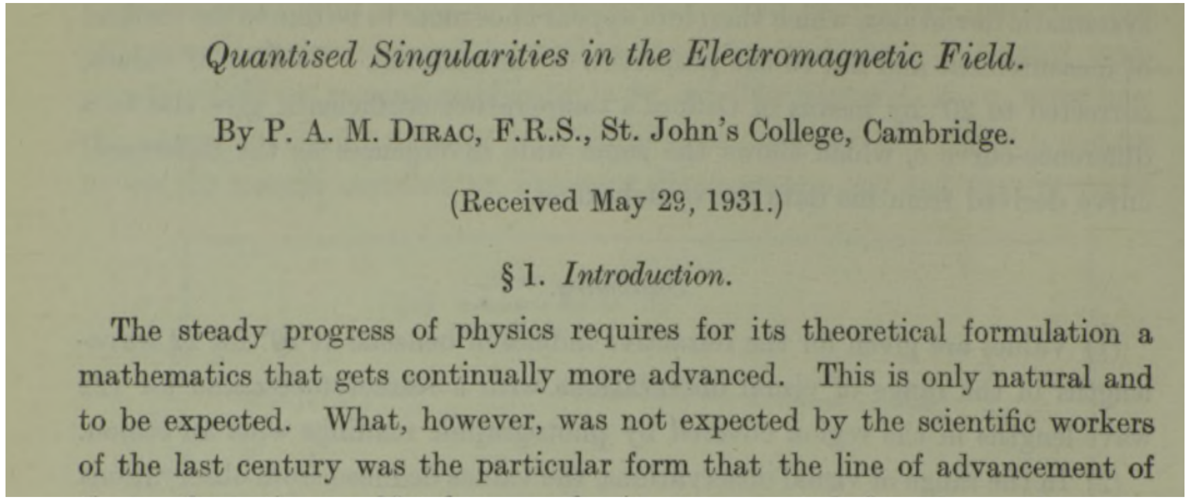
GAUGE INTERACTIONS IN QUANTUM THEORY

<u>1931 DIRAC</u>



QM:

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



Quantised Singularities in the Electromagnetic Field.

By P. A. M. Dirac, F.R.S., St. John's College, Cambridge.

(Received May 29, 1931.)

§ 1. *Introduction.*

The steady progress of physics requires for its theoretical formulation a mathematics that gets continually more advanced. This is only natural and to be expected. What, however, was not expected by the scientific workers of the last century was the particular form that the line of advancement of

$$\Psi_1 = \Psi_{r_1} e^{i\beta_1}, \quad \Psi_2 = \Psi_{r_2} e^{i\beta_2}$$

$|\langle \Psi_1 | \Psi_2 \rangle|^2$ – has definite value $\Rightarrow$

$$\Rightarrow \quad \oint d\beta_1 = \oint d\beta_2 + 2\pi n,\ n \in \mathbb{Z}$$

$n = 0$ — electric, $n \neq 0$ — magnetic

- charges can be electric and magnetic
- quantisation of charge explained
- *"one would be surprised if Nature had made no use of it"*
- our low energy theories are electric, but the reason is unknown

QUANTUM ELECTROMAGNETODYNAMICS

1971 ZWANZIGER

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

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

1977 ZBN

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

- TWO vector-potentials describe ONE particle - photon
- partition function is Lorentz-invariant

AXION MODEL WITH ABELIAN MONOPOLE

- $[U_M(1) \times SU(3)] \longrightarrow g^0_{a\gamma\gamma} a \vec{E}\vec{H}$

AXION MODEL WITH ABELIAN MONOPOLE

$$\bullet\,[U_M(1)\times SU(3)] \longrightarrow g^0_{a\gamma\gamma}\, a\vec{E}\vec{H}$$

$\bullet = \psi$

$$\mathcal{L} \supset i\bar{\psi}\gamma^\mu\partial_\mu\psi + \boxed{g\bar{\psi}\gamma^\mu B_\mu\psi} + y\left(\Phi\,\bar{\psi}_L\psi_R + \text{h.c.}\right) - \lambda_\Phi\left(|\Phi|^2 - \frac{v_a^2}{2}\right)^2$$

Peccei-Quinn field

AXION MODEL WITH ABELIAN MONOPOLE

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Peccei-Quinn field

- Since ψ is a quark, PQ mechanism realized via KSVZ-like construction ensures that the strong CP problem is solved

DESY.

AXION MODEL WITH ABELIAN MONOPOLE

$$\bullet\,[U_M(1)\times SU(3)] \longrightarrow g^0_{a\gamma\gamma}\,a\vec{E}\vec{H}$$

$\bullet = \psi$

$$\mathcal{L} \supset i\bar{\psi}\gamma^\mu\partial_\mu\psi + \boxed{g\bar{\psi}\gamma^\mu B_\mu\psi} + y\left(\Phi\,\bar{\psi}_L\psi_R + \text{h.c.}\right) - \lambda_\Phi\left(|\Phi|^2 - \frac{v_a^2}{2}\right)^2$$

$\min\{g\} = 6\pi/e$

Peccei-Quinn field

- Since ψ is a quark, PQ mechanism realized via KSVZ-like construction ensures that the strong CP problem is solved
- SM quarks having $-e/3$ charges implies minimal magnetic charge $g = 6\pi/e$

INTEGRATING OUT HEAVY MONOPOLES

$$\bullet\, [U_M(1) \times SU(3)] \longrightarrow g^0_{a\gamma\gamma} a \vec{E}\vec{H}$$

$$\boldsymbol{\Phi = \frac{v_a + \sigma + ia}{\sqrt{2}}} \Rightarrow \mathcal{L} \supset i\bar{\psi}\gamma^\mu \partial_\mu \psi + g\bar{\psi}\gamma^\mu B_\mu \psi + \frac{y v_a}{\sqrt{2}} \bar{\psi}\psi + \boxed{\frac{iy}{\sqrt{2}} a\bar{\psi}\gamma_5\psi}$$

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Schwinger proper time method (non-perturbative) can be used:

$$\langle\, B\, |\bar{\psi}(x)\gamma_5\psi(x)|\, B\rangle = \frac{-3i}{16\sqrt{2}\pi^2 y v_a}\, \epsilon_{\mu\nu\lambda\rho}\, (\partial \wedge B)^{\mu\nu} (\partial \wedge B)^{\lambda\rho}$$

INTEGRATING OUT HEAVY MONOPOLES

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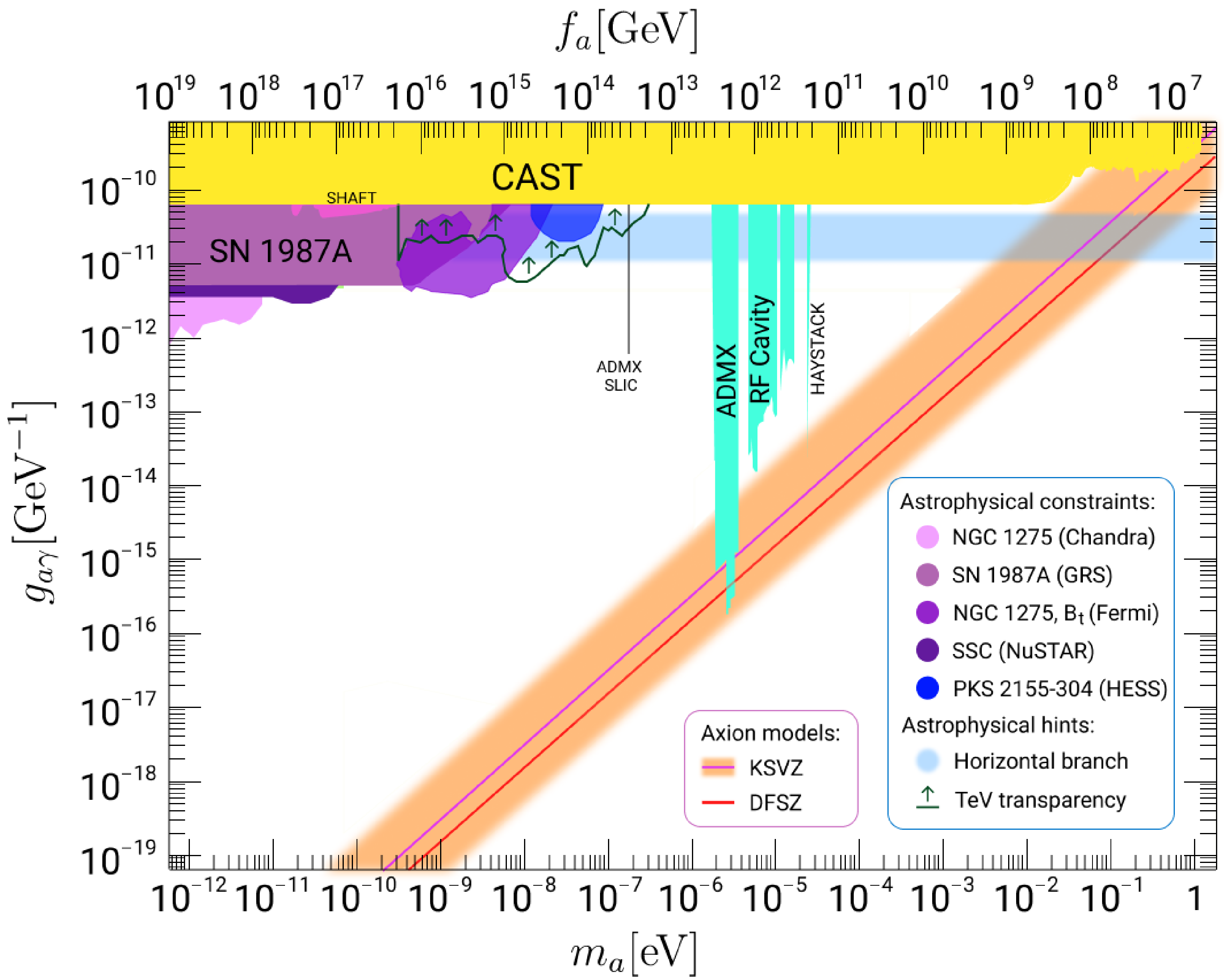
$$\langle\, B\, |\bar{\psi}(x)\gamma_5\psi(x)|\, B\rangle = \frac{-3i}{16\sqrt{2}\pi^2 y v_a}\epsilon_{\mu\nu\lambda\rho}(\partial \wedge B)^{\mu\nu}(\partial \wedge B)^{\lambda\rho}$$

Relation between the potentials $(\partial \wedge A)_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\lambda\rho}(\partial \wedge B)^{\lambda\rho}$ yields:

$$\mathcal{L}_{\text{eff}} \supset \frac{iyg^2}{\sqrt{2}} a \langle\, B\, |\bar{\psi}(x)\gamma_5\psi(x)|\, B\rangle = -\frac{a}{16\pi^2 v_a}\cdot\frac{27}{\alpha^2} e^2 \vec{E}\vec{H}$$

PHENOMENOLOGY



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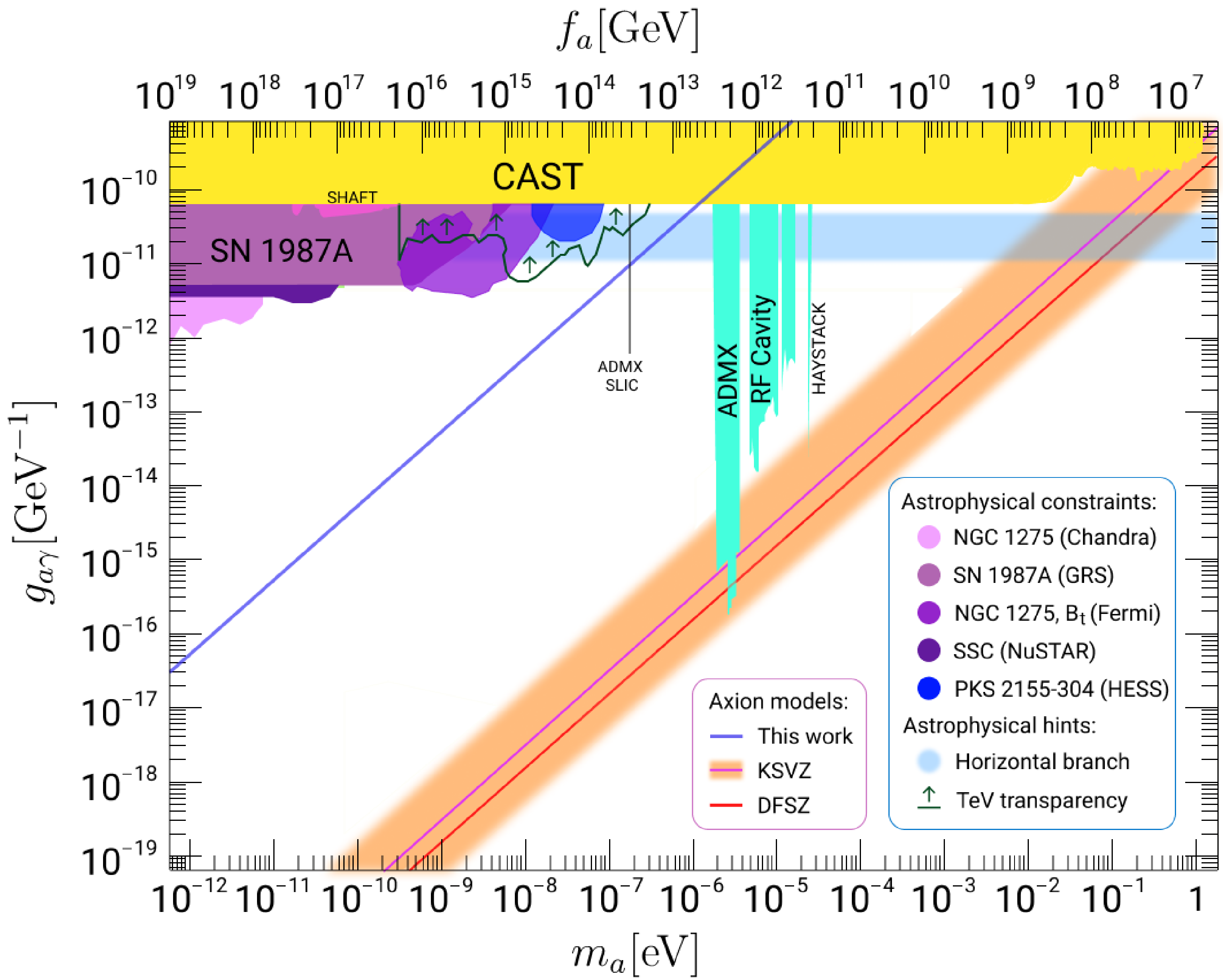
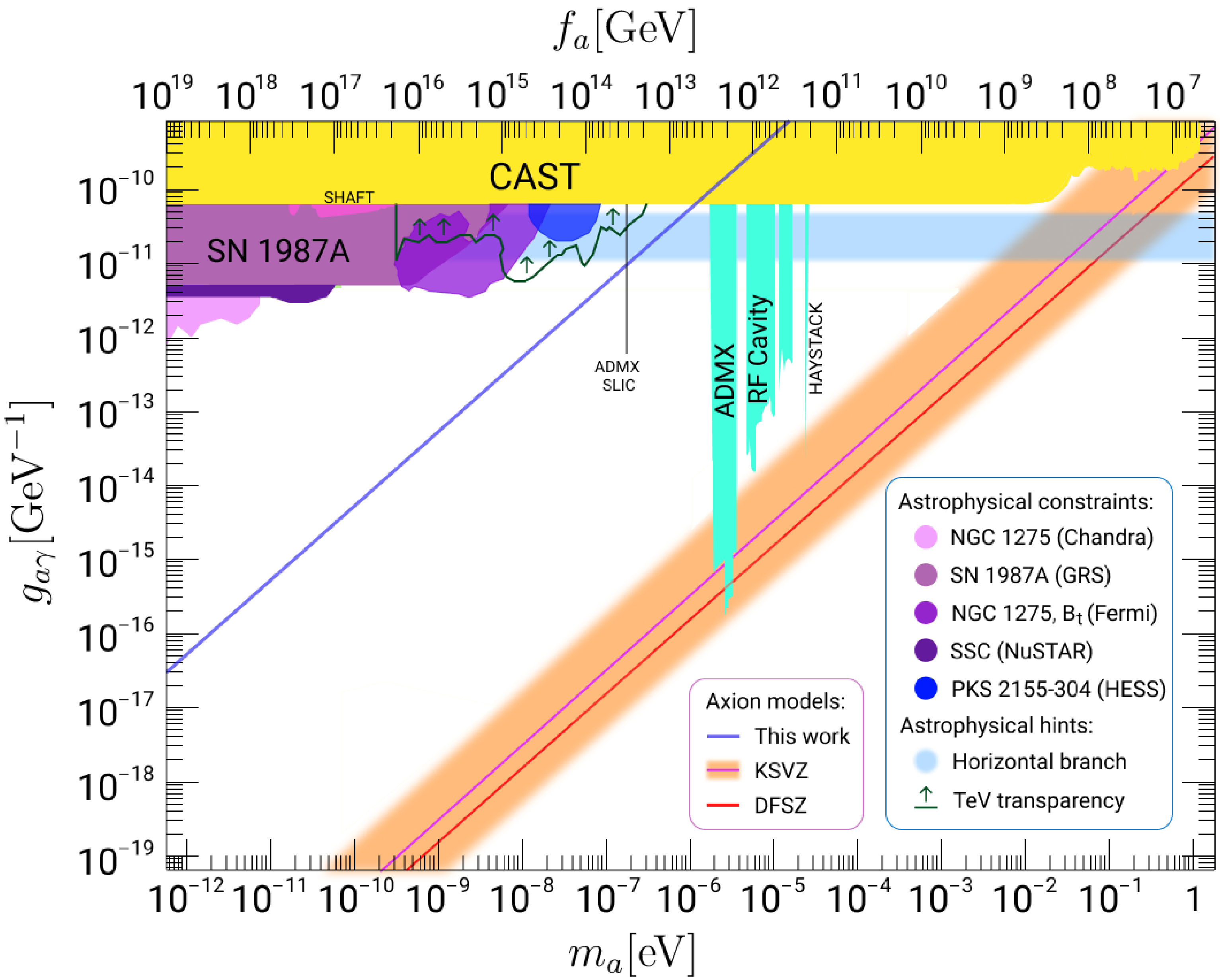


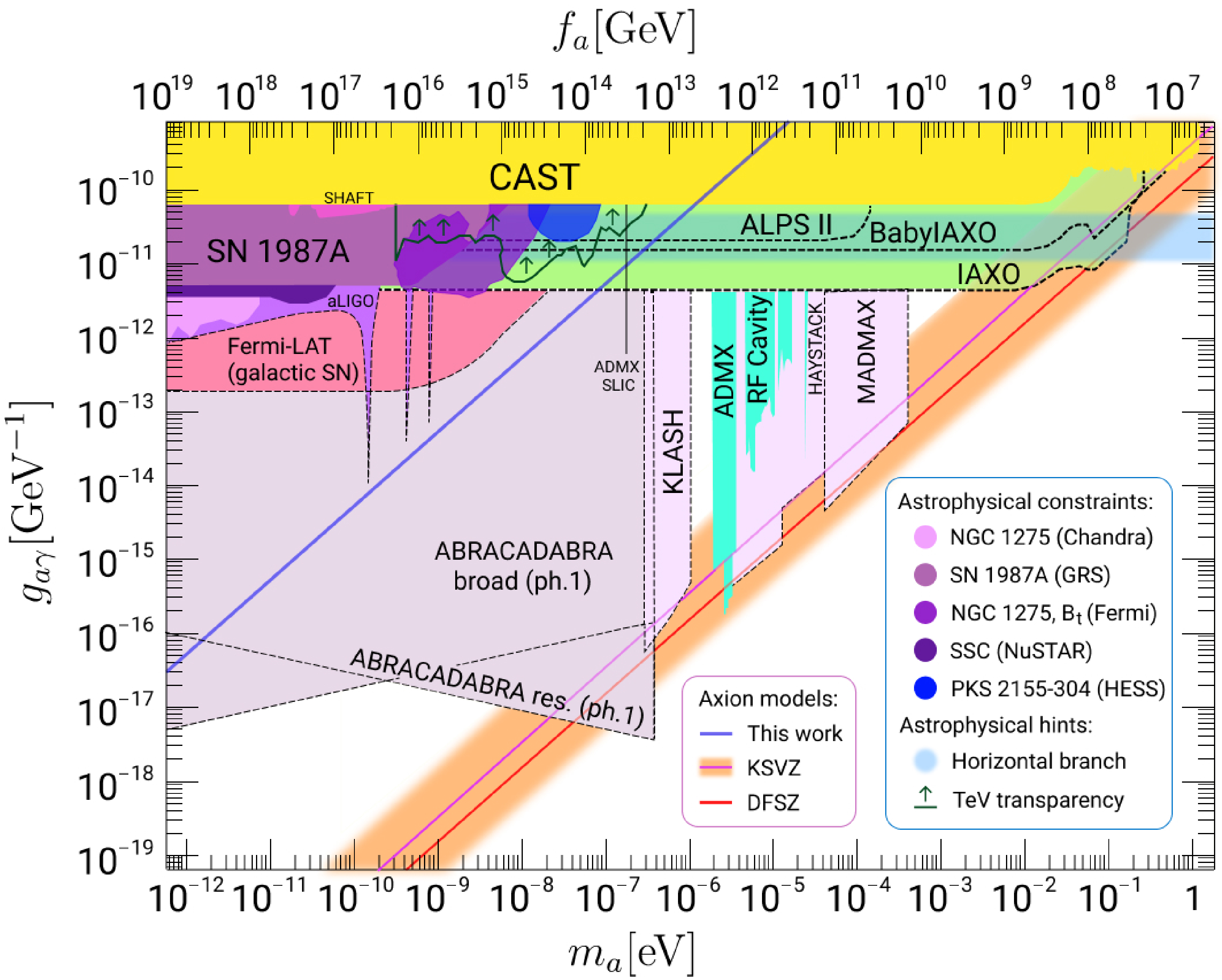
- Axion-photon coupling is hugely enhanced

PHENOMENOLOGY



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

PHENOMENOLOGY



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- In the strong sector, the model is analogous to KSVZ $\Rightarrow$
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AXION MODEL WITH NON-ABELIAN MONOPOLE

- $[U_M(1) \times SU_M(3)]$

- QFT involving electric + magnetic non-Abelian charges is unknown
- Goddard, Nuyts and Olive made an important observation

$$\exp(4\pi i \beta_i T_i) = 1 \quad \Rightarrow \quad \beta_i \text{ lie in the weight lattice of } G^V$$

Laglands dual of G

GNO conjecture:

$$G_M = (G_E)^V$$
$$g_m = 2\pi/g$$

$(U(1))^V = U(1)$	$(SU(3)/\mathbb{Z}_3)^V = SU(3)$

AXION MODEL WITH NON-ABELIAN MONOPOLE

● $[U_M(1) \times SU_M(3)]$

● $= \psi$

Due to the GNO conjecture we introduce: $C_\mu = gB_\mu + g_m B_\mu^a t^a$

Lagrangian of the PQ field Φ and fermion ψ is standard:

$$\mathcal{L} \supset i\bar{\psi}\gamma^\mu\partial_\mu\psi + \bar{\psi}\gamma^\mu C_\mu\psi + y\left(\Phi\,\bar{\psi}_L\psi_R + \text{h.c.}\right) - \lambda_\Phi\left(|\Phi|^2 - \frac{v_a^2}{2}\right)^2$$

Since monopole ψ has color-magnetic charge, the quantization condition allows for the minimal Dirac magnetic charge value:

$\min\{g\} = 2\pi/e$

MODEL WITH NON-ABELIAN MONOPOLE: THEORY

GNO conjecture: $G_M = (G_E)^V$, $g_m = 2\pi / g_s$

$(U(1))^V = U(1)$ | $(SU(3)/\mathbb{Z}_3)^V = SU(3)$

- $[U_M(1) \times SU_M(3)]$ $\quad C_\mu = g B_\mu + g_m B_\mu^a t^a$ $\quad \min\{g\} = 2\pi / e$

$$\mathcal{L} \supset i\bar{\psi}\gamma^\mu \partial_\mu \psi + \bar{\psi}\gamma^\mu C_\mu \psi + y\left(\Phi\, \bar{\psi}_L \psi_R + \text{h.c.}\right) - \lambda_\Phi \left(|\Phi|^2 - \frac{v_a^2}{2}\right)^2$$

Strong CP

$\underline{SU(3) \to U(1)^2}$: $\quad \mathcal{G}^\alpha_{\mu\nu} \equiv (\partial \wedge A^\alpha)_{\mu\nu}$

$$\mathcal{S}_{\text{QCD}} \supset \frac{\bar{\theta} g_s^2}{32\pi^2} \int d^4x \sum_{\alpha=3,8} \mathcal{G}^\alpha_{\mu\nu} \tilde{\mathcal{G}}^{\alpha\,\mu\nu} + \frac{a g_{\text{m}}^2}{32\pi^2 v_a} \int d^4x \sum_{\alpha=3,8} \mathcal{G}^\alpha_{\mu\nu} \tilde{\mathcal{G}}^{\alpha\,\mu\nu}$$

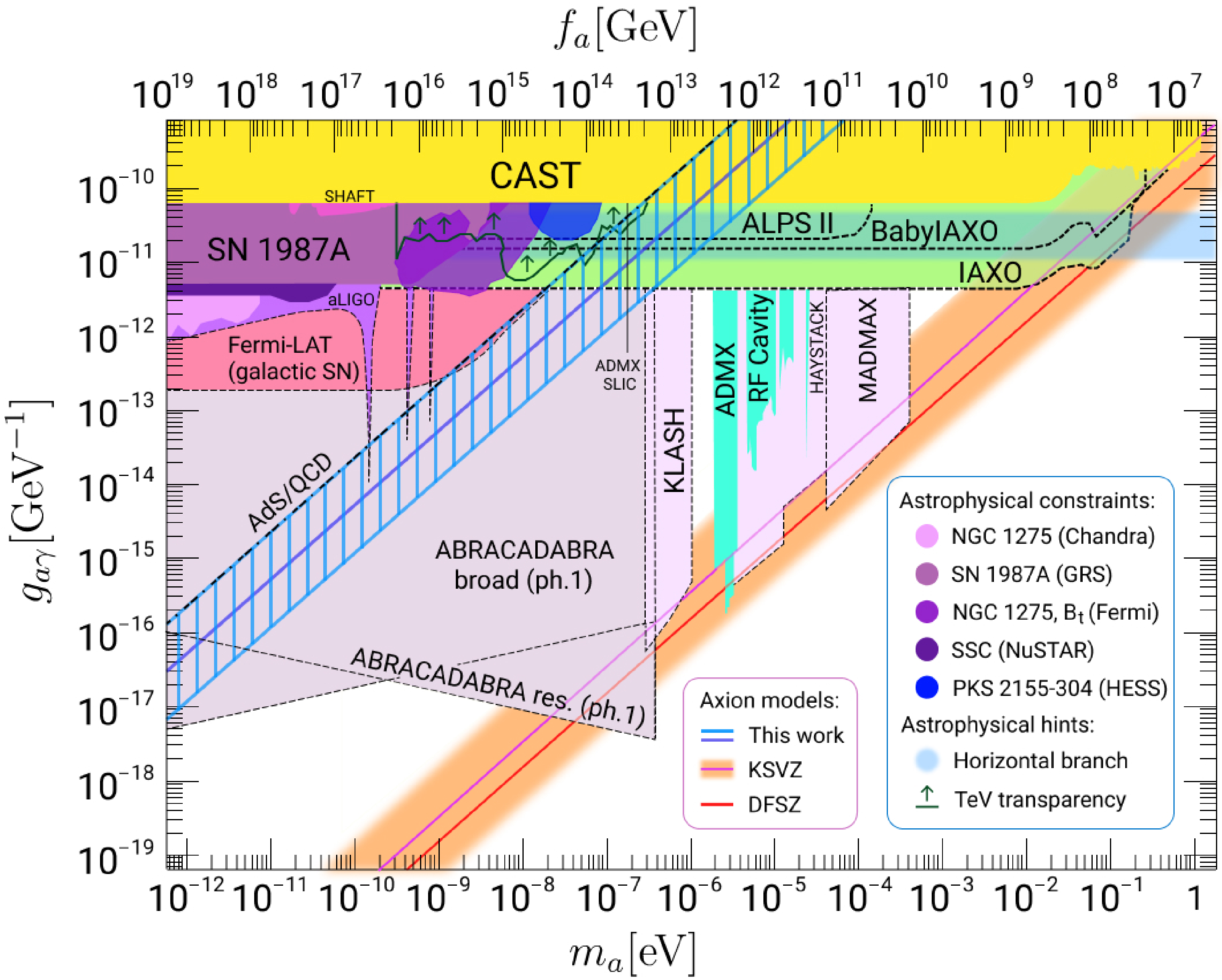
Low energy physics

$$\mathcal{L}_{\text{eff}} \supset -\frac{1}{4} g^0_{a\gamma}\, a\, F_{\mu\nu} \tilde{F}^{\mu\nu} - \frac{a g_s^2}{32\pi^2 f_a} G^a_{\mu\nu} \tilde{G}^{a\,\mu\nu} + \mathcal{L}_{\text{off}}$$

0 in IR

$$g^0_{a\gamma} = 3\alpha_s^2 / (\pi \alpha f_a)$$

MODEL WITH NON-ABELIAN MONOPOLE: PHENOMENOLOGY



- Axion-photon coupling depends on α_s

$$\boxed{g^0_{a\gamma} = 3\alpha_s^2/\left(\pi\alpha f_a\right)}$$

- AdS/QCD: $\alpha_s = \pi$ in IR

- In the strong sector, IR Abelian dominance $\Rightarrow$
  - $\approx$ same CDM abundance
  - $\approx$ same EDM coupling

CONCLUSION

- We relaxed an unnecessary assumption of KSVZ-like axion models and

found a new family of QCD axion models → with Abelian monopole
→ with non-Abelian monopole

- These models add to SM one heavy particle ψ + Peccei-Quinn field Φ
- These models yield "large" axion-photon coupling which can be probed in near-future experiments
- These models can explain various "hints": strong CP conservation, quantisation of charge, anomalous TeV-transparency of the Universe, observed dark matter abundance, cooling of horizontal branch stars in globular clusters