PHOTOPHILIC HADRONIC AXION FROM HEAVY MAGNETIC MONOPOLES

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based on arXiv: 2104.02574 (to appear in JHEP)

Deutsches Elektronen-Synchrotron DESY, Hamburg

16th PATRAS workshop on Axions, WIMPs and WISPs

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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

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

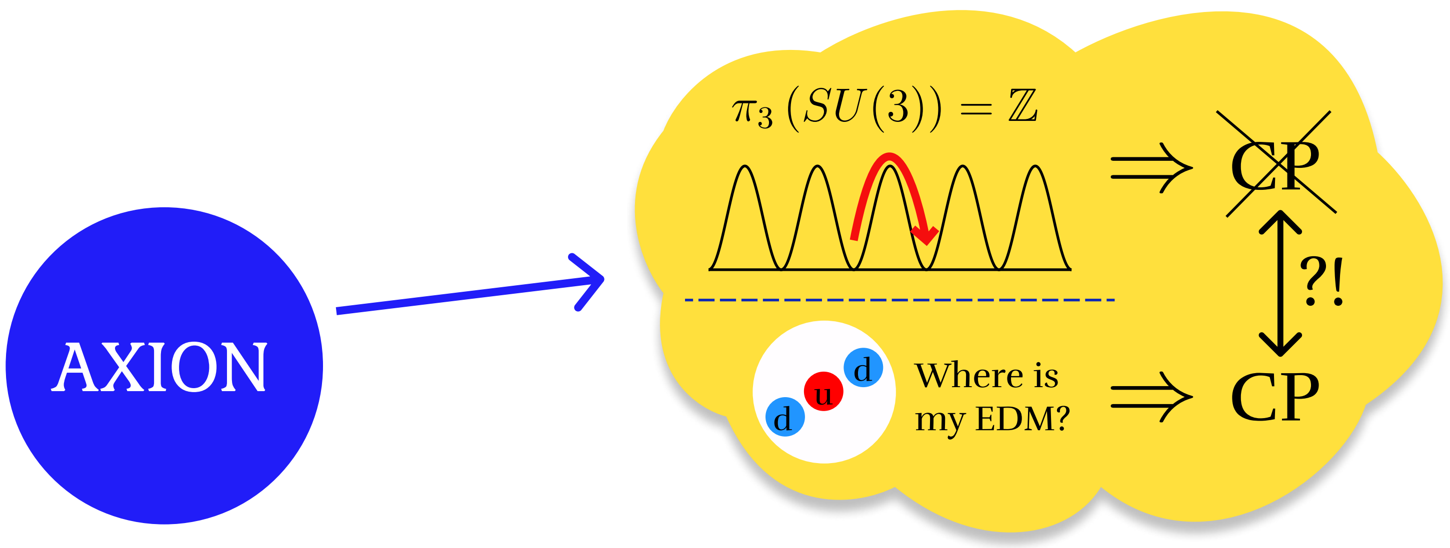
- Axion model involving non-Abelian monopole

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

MOTIVATION: OBSERVATIONAL HINTS

AXION

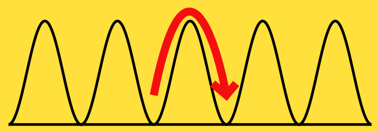
MOTIVATION: OBSERVATIONAL HINTS



MOTIVATION: OBSERVATIONAL HINTS

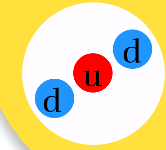
AXION

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



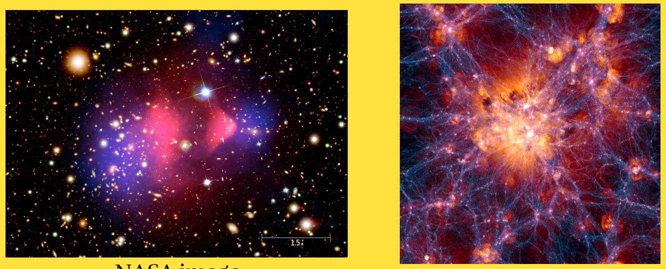
$\Rightarrow$ ~~CP~~

?!



Where is my EDM? $\Rightarrow$ CP

ΛCDM

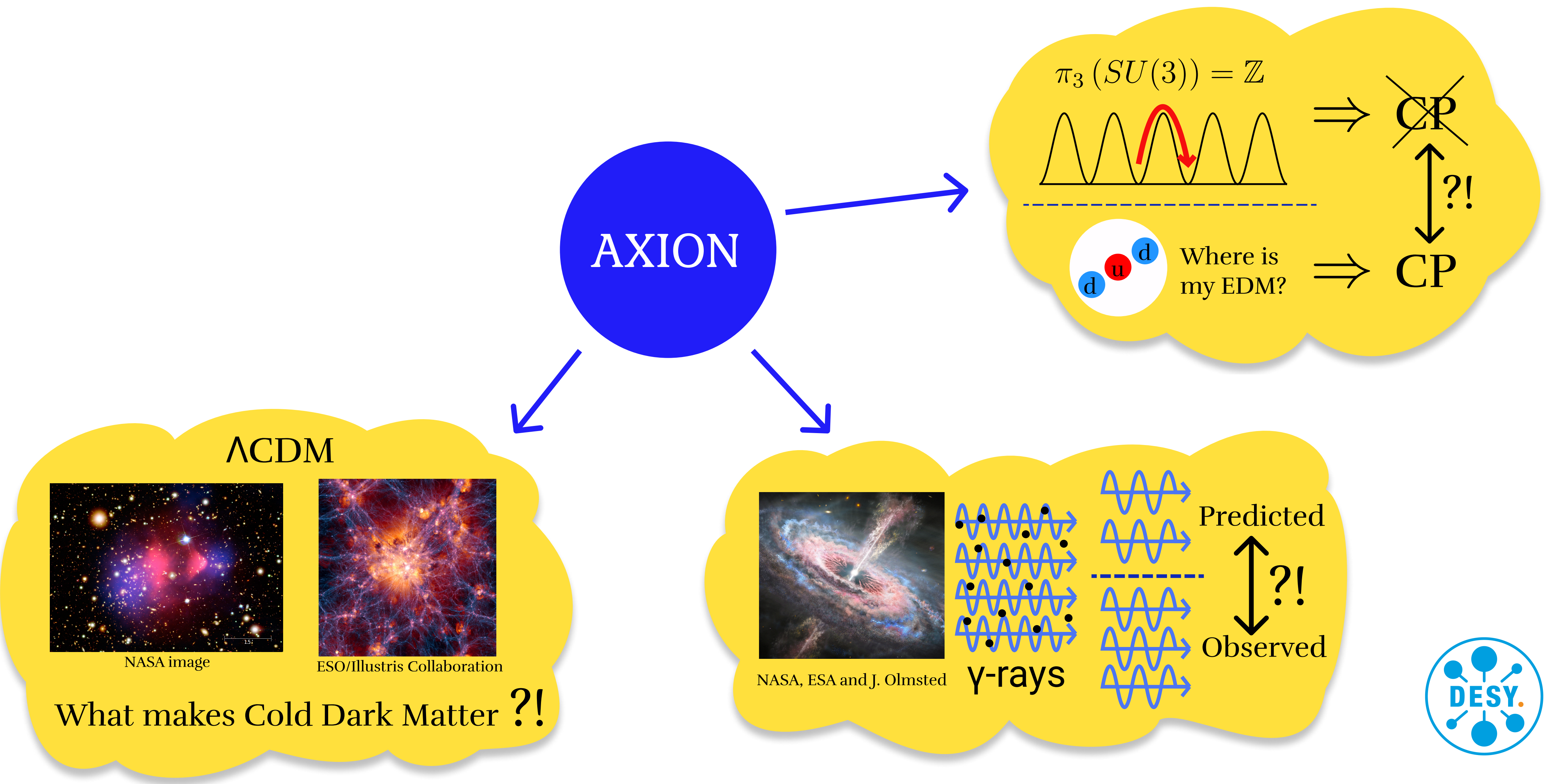


NASA image

ESO/Illustris Collaboration

What makes Cold Dark Matter ?!

MOTIVATION: OBSERVATIONAL HINTS



MOTIVATION: OBSERVATIONAL HINTS

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

MOTIVATION: KSVZ-LIKE AXION MODELS

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

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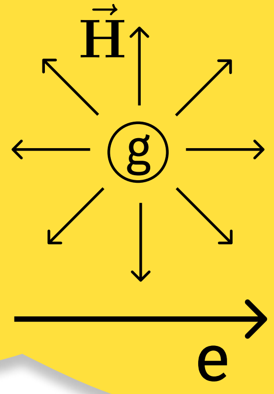
3. Integrate ψ out and obtain effective IR Lagrangian:

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

GAUGE INTERACTIONS IN QUANTUM THEORY

1931 DIRAC



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

- interactions can be electric or magnetic
- quantisation of charge explained
- *"one would be surprised if Nature had made no use of it"*
- no magnetic charges found, so probably they are very heavy

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
- $(\text{spin } 0)_E + (\text{spin } 0)_M$ = ✌️ , $(\text{spin } 1/2)_E + (\text{spin } 1/2)_M$ = ✌️

DESY.

AXION MODEL WITH ABELIAN MONOPOLE

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

$\bullet = \psi$

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

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

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 $g = 6\pi/e$

DESY.

INTEGRATING OUT HEAVY MONOPOLES

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

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

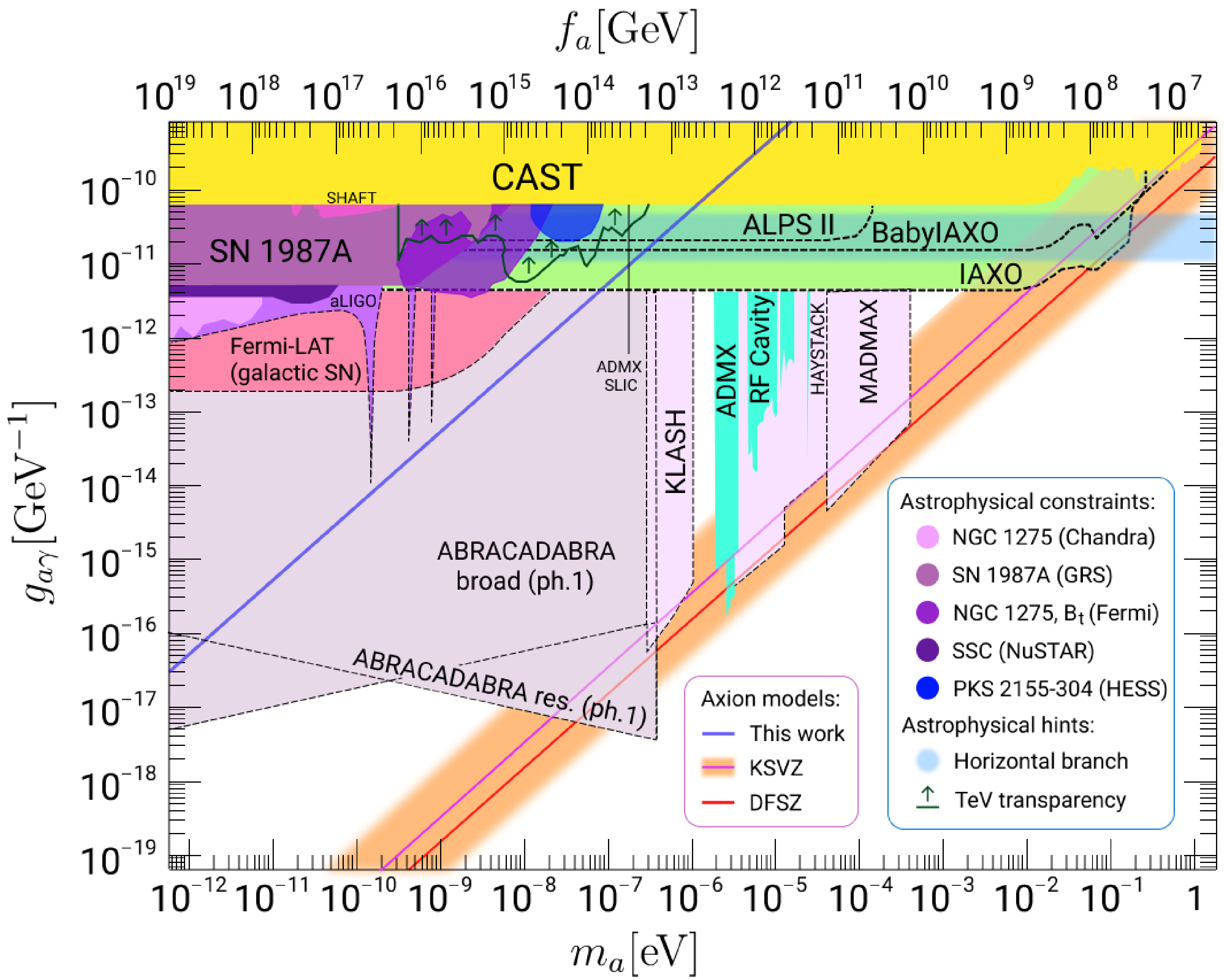
Schwinger proper time method (non-perturbative) can be used:

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

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



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

MODEL WITH NON-ABELIAN MONOPOLE: THEORY

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

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

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

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

Strong CP

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

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

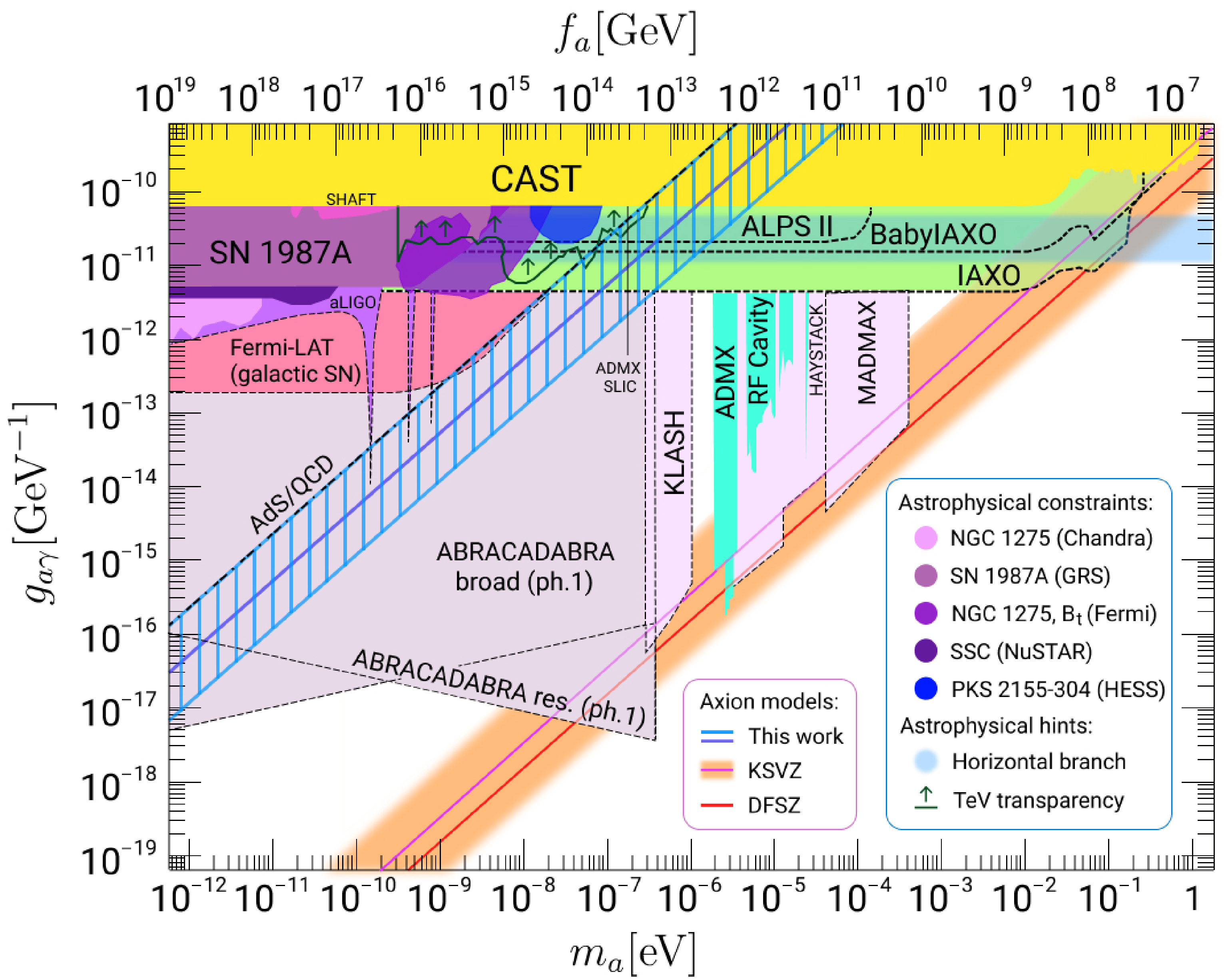
Low energy physics

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

$\mathcal{L}_{\text{off}} \to$ 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
- AdS/QCD: $\alpha_s = \pi$ in IR
- In the strong sector, the model is NOT analogous to KSVZ due to $\mathcal{L}_{\text{off}}$, but 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

- Each model adds to SM one heavy particle ψ + Peccei-Quinn field Φ
- Both models yield "large" axion-photon coupling which can be probed in near-future experiments
- Both 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

DESY.