PHOTOPHILIC HADRONIC AXION FROM HEAVY MAGNETIC MONOPOLES

based on J. High Energ. Phys. 06, 123 (2021)

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Deutsches Elektronen-Synchrotron DESY, Hamburg

XXI International Seminar on High-Energy Physics

QUARKS 2020

Online Workshop "Dark Matter"

June 22-24, 2021

OUTLINE OF THE TALK

- Motivation
  - various experimental hints
  - Occam's razor view on KSVZ-like axion models

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- Axion model involving non-Abelian monopole

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MOTIVATION: OBSERVATIONAL HINTS

AXION

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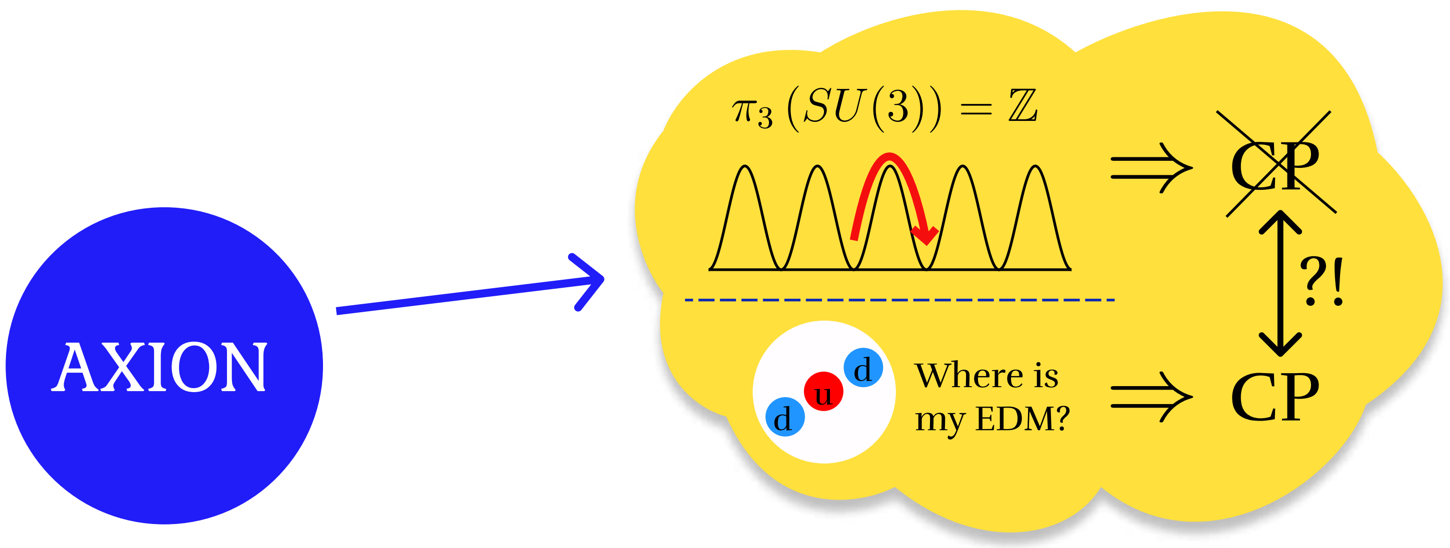
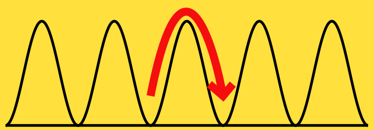


MOTIVATION: OBSERVATIONAL HINTS

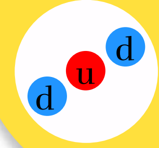
AXION

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



$\Rightarrow \cancel{\mathrm{CP}}$

$\updownarrow$?!



Where is my EDM? $\Rightarrow$ CP

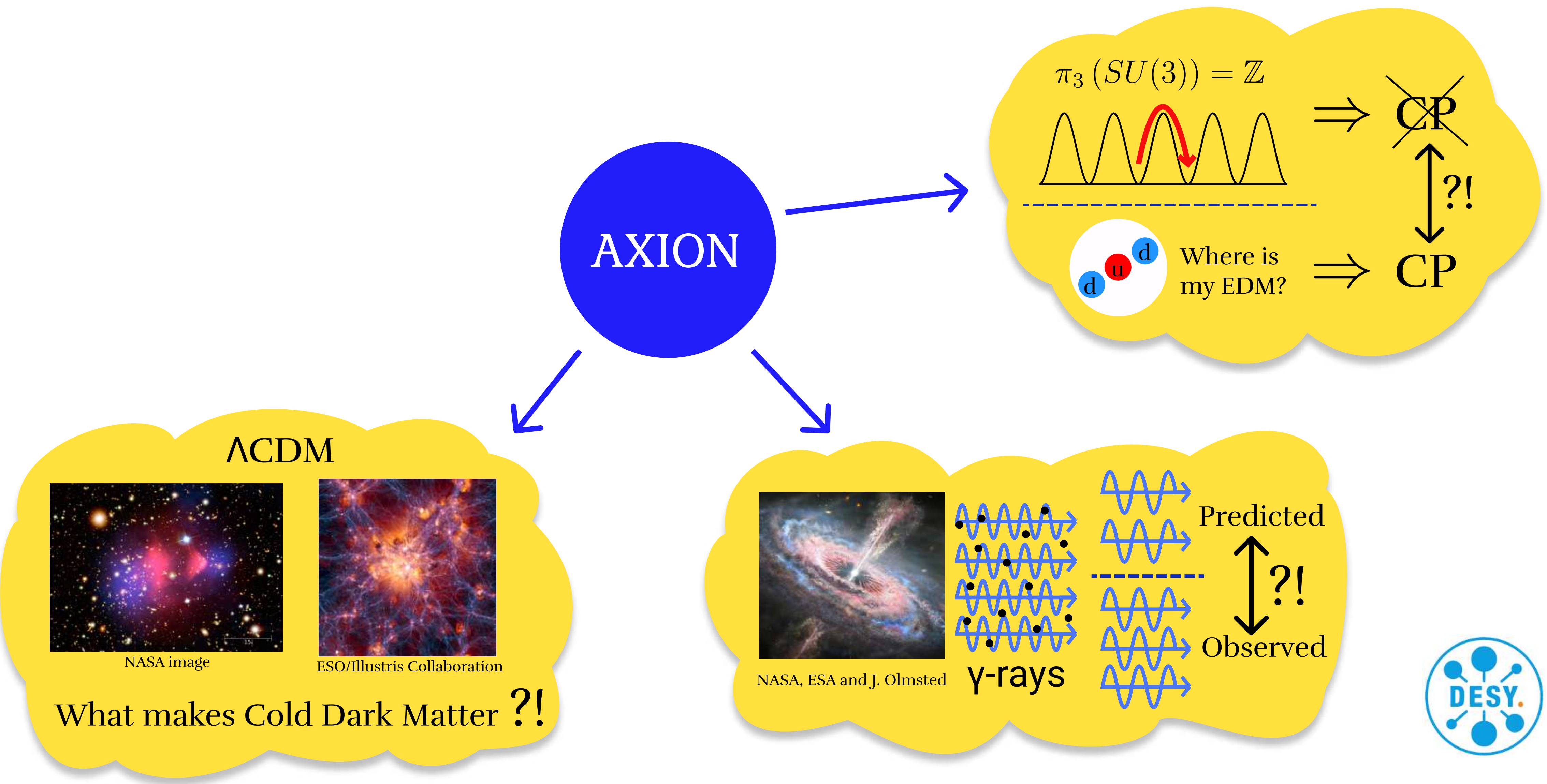
ΛCDM

NASA image

ESO/Illustris Collaboration

What makes Cold Dark Matter ?!

MOTIVATION: OBSERVATIONAL HINTS



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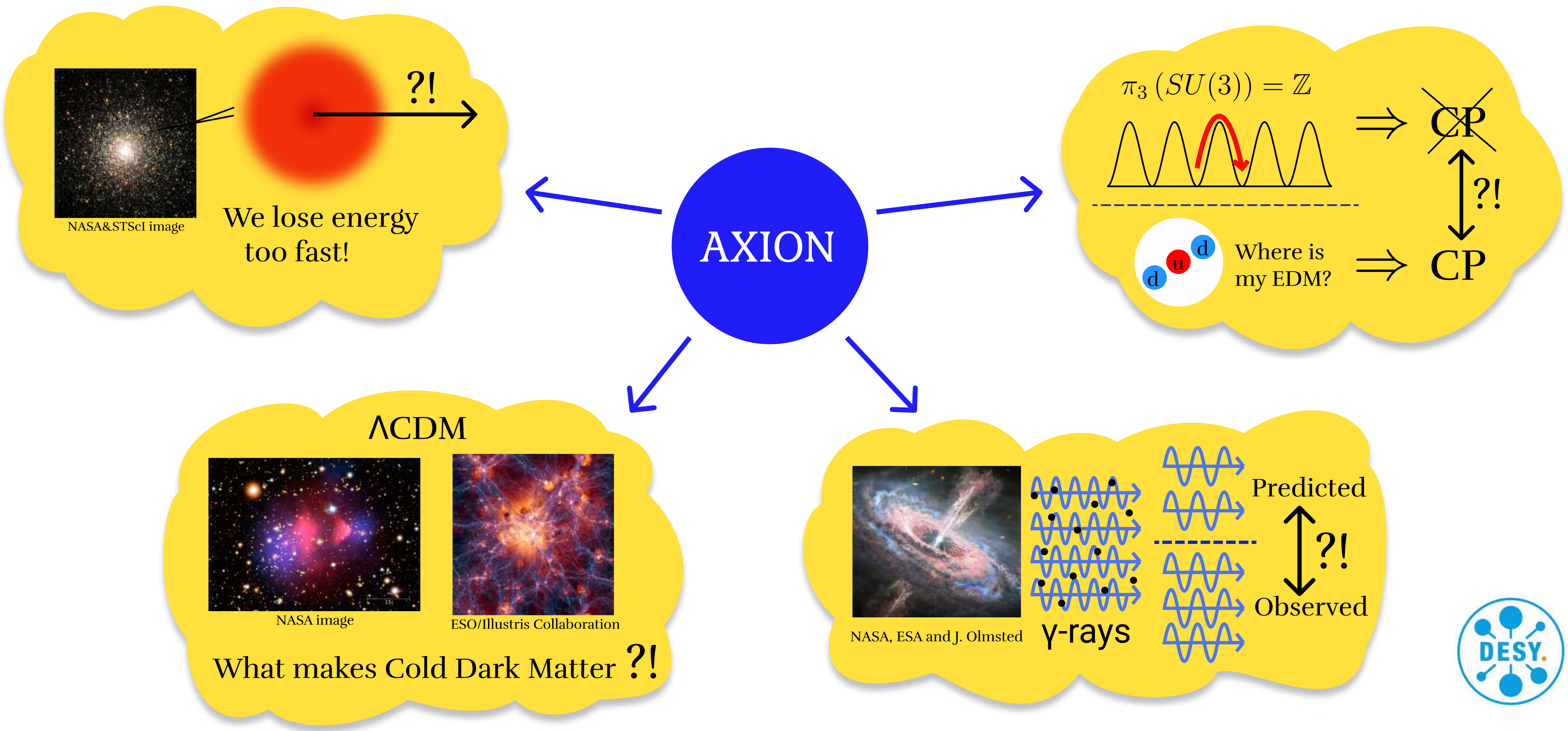

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3. Integrate ψ out and obtain effective IR Lagrangian:

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

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

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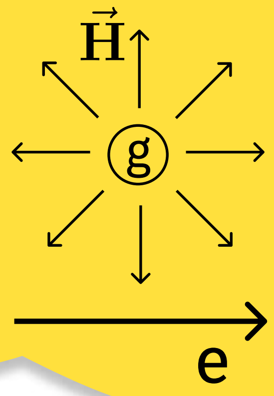
$\mathcal{L}_{\text{IR}}$ = ?

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.)

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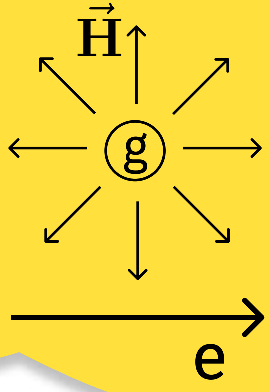

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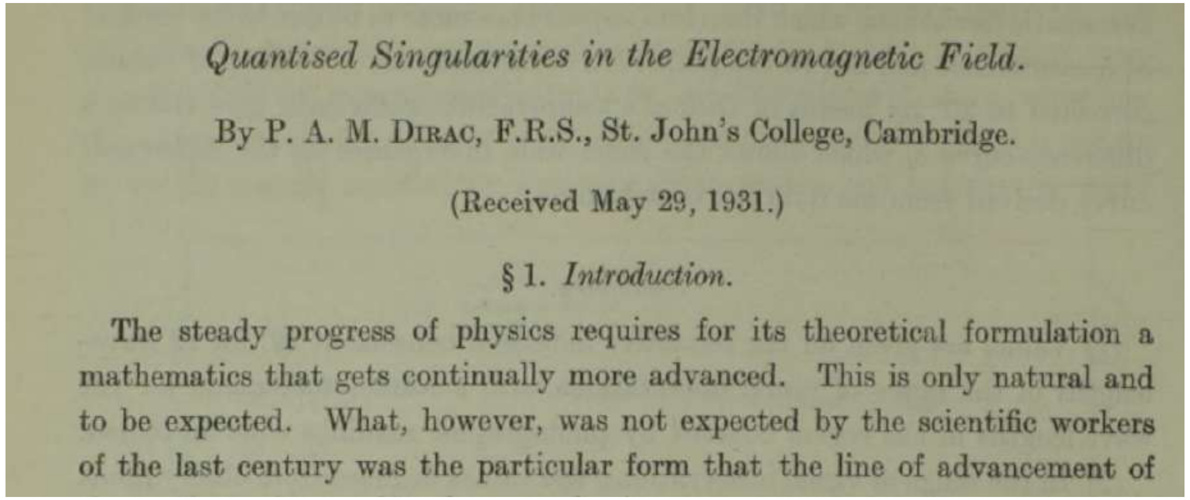
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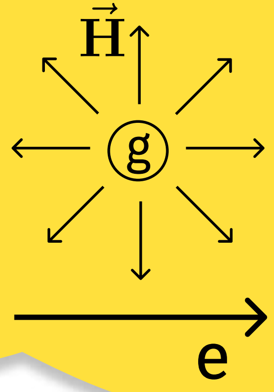

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- quantisation of charge explained
- *"one would be surprised if Nature had made no use of it"*

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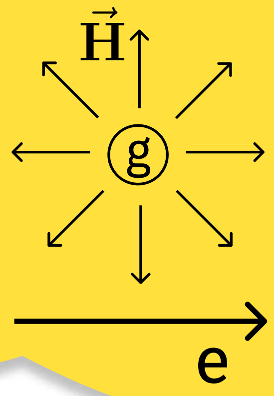

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- *"one would be surprised if Nature had made no use of it"*
- our low energy theories are electric, but the reason is unknown

QUANTUM ELECTROMAGNETODYNAMICS

1971 ZWANZIGER

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

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

- TWO vector-potentials describe ONE particle - photon

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1977 ZBN

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

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DESY.

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

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- SM quarks having $-e/3$ charges implies minimal magnetic charge $g = 6\pi/e$

INTEGRATING OUT HEAVY MONOPOLES

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

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

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

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

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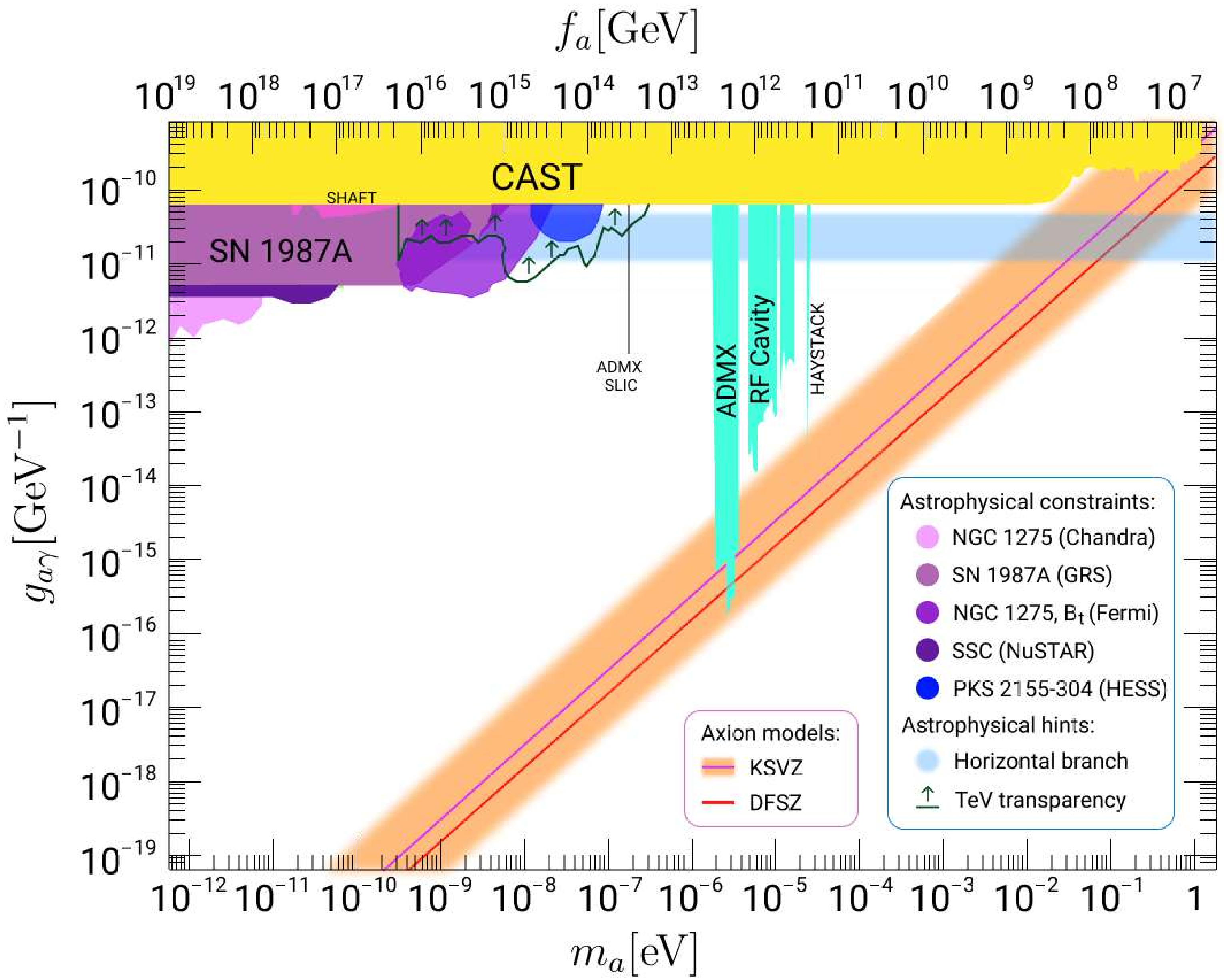
Relation between the potentials $(\partial \wedge A)_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\lambda\rho} (\partial \wedge B)^{\lambda\rho}$ yields:

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

DESY.

PHENOMENOLOGY



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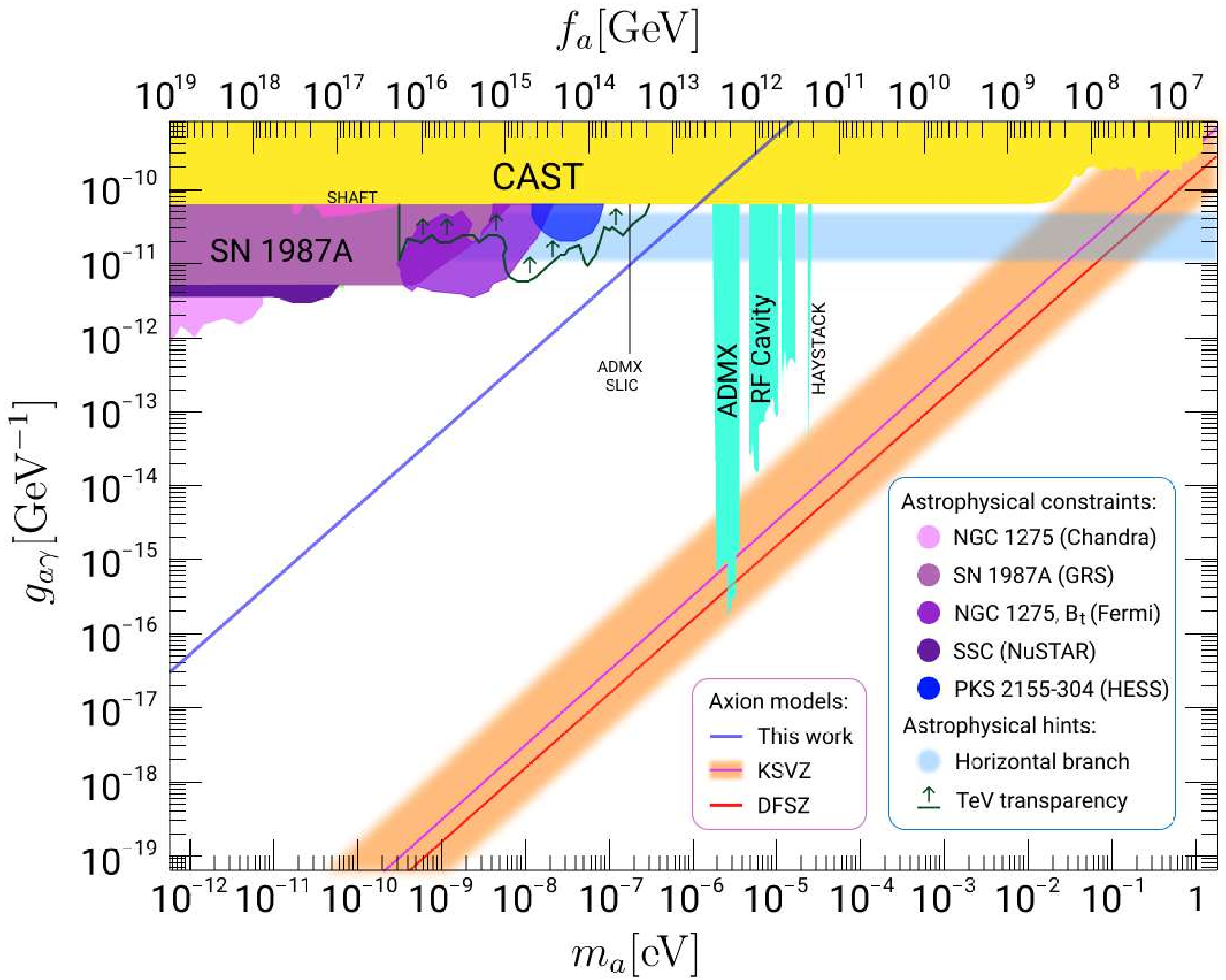

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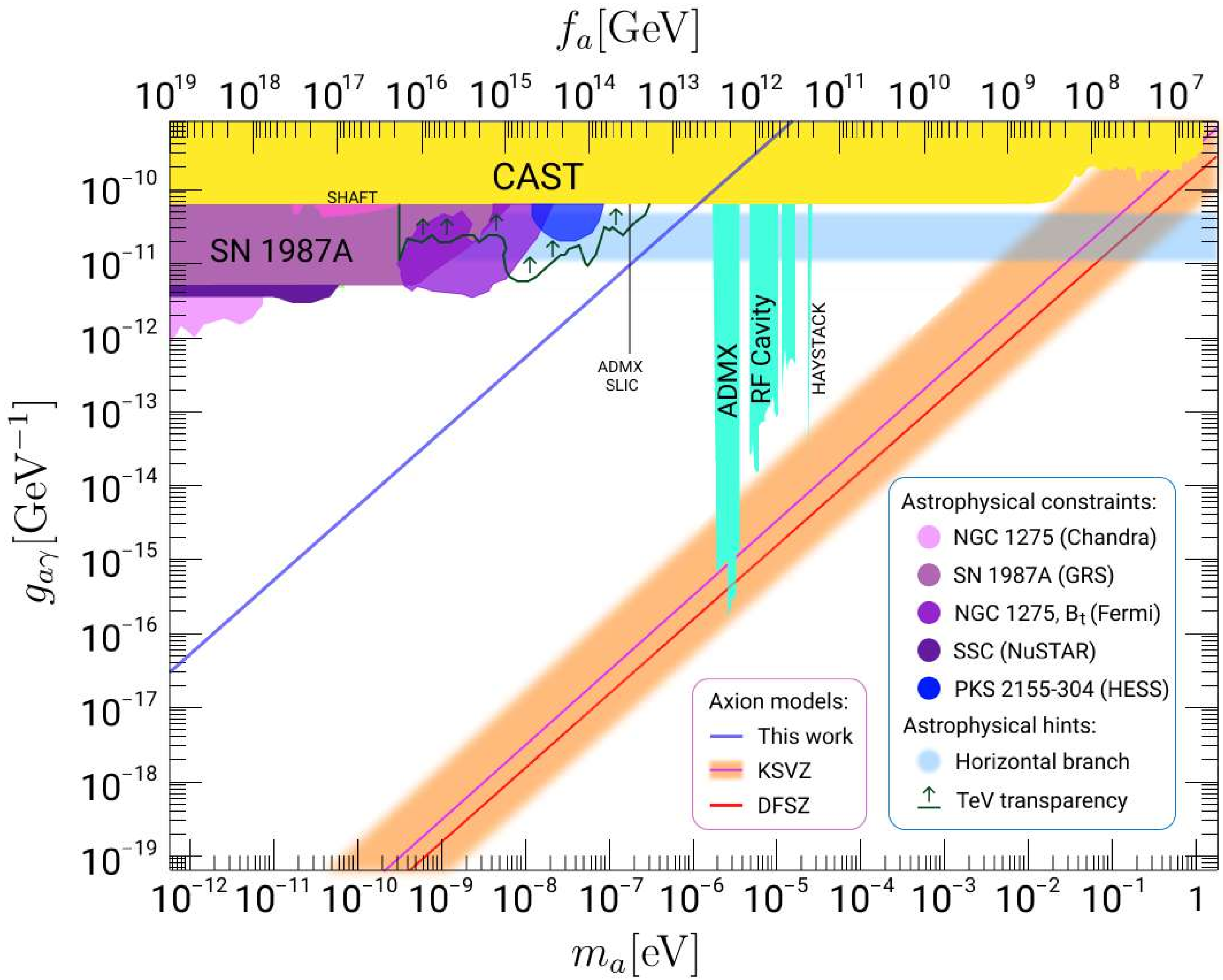

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  - same CDM abundance
  - same EDM coupling

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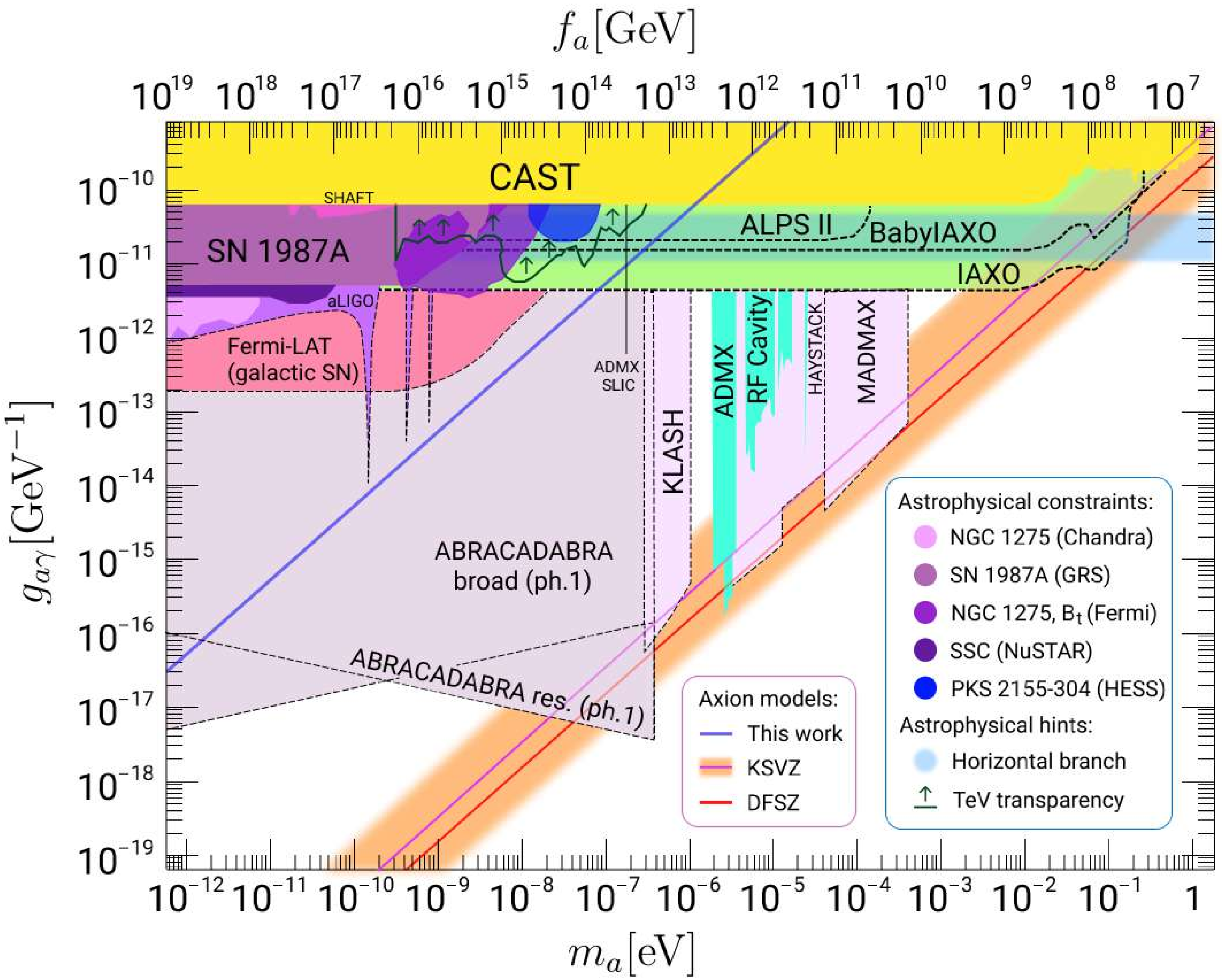

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$$\exp(4\pi i \beta_i T_i) = 1 \quad \Rightarrow \quad \beta_i \text{ lie in the weight lattice of } G^V$$

magnetic charges

Cartan generators of G

Laglands dual of G

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GNO conjecture:

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

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

DESY.

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

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

SOLUTION TO THE STRONG CP PROBLEM

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

$$\Phi = \frac{1}{\sqrt{2}}(v_a + \sigma) \cdot \exp\left(-ia/v_a\right)$$

$$\psi \to \exp\left(ia\gamma_5/2v_a\right) \cdot \psi$$

$$\longrightarrow \quad \mathcal{L}_{\mathrm{Fuj}} = -\frac{a}{16\pi^2 v_a} \operatorname{tr} C_{\mu\nu}\tilde{C}^{\mu\nu}$$

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In the Abelian 't Hooft gauges: $\displaystyle \int d^4x \sum_{a=1}^{8} C^a_{\mu\nu}\tilde{C}^{a\,\mu\nu} = \int d^4x \sum_{\alpha=3,8} \mathscr{C}^\alpha_{\mu\nu}\tilde{\mathscr{C}}^{\alpha\,\mu\nu},$

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$$\mathscr{C}^\alpha_{\mu\nu} = \tilde{\mathscr{G}}^\alpha_{\mu\nu} \equiv (\partial \wedge \underset{\text{gluons}}{A^\alpha})_{\mu\nu} \quad \Rightarrow \quad \mathcal{S}_{\text{QCD}} \supset \frac{\bar{\theta} g_s^2}{32\pi^2} \int d^4x \sum_{\alpha=3,8} \mathscr{G}^\alpha_{\mu\nu}\tilde{\mathscr{G}}^{\alpha\,\mu\nu} + \frac{a g_m^2}{32\pi^2 v_a} \int d^4x \sum_{\alpha=3,8} \mathscr{G}^\alpha_{\mu\nu}\tilde{\mathscr{G}}^{\alpha\,\mu\nu}$$

EFFECTIVE LOW ENERGY LAGRANGIAN

● $[U_M(1) \times SU_M(3)]$

Low energy physics

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

0 in IR

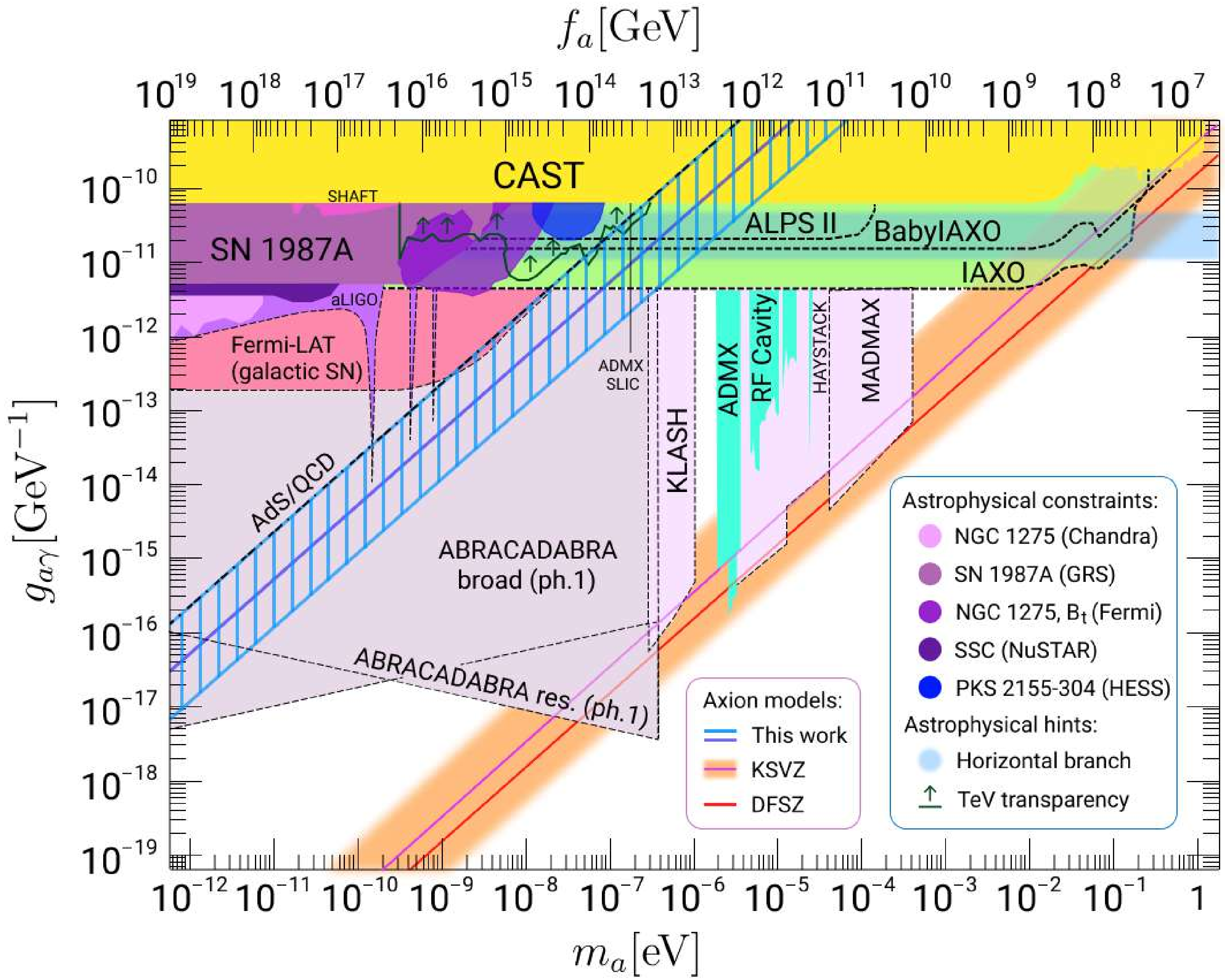
$$g^0_{a\gamma} = 3\alpha_s^2/\left(\pi\alpha f_a\right)$$

- Schwinger proper time method used
- $\mathscr{C}^{\alpha}_{\mu\nu} = \tilde{\mathscr{G}}^{\alpha}_{\mu\nu}$ for Abelian field strengths
- Abelian dominance of IR QCD

suggests that $\mathcal{L}_{\rm off}$ is small

- Axion-gluon coupling is special

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

- 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