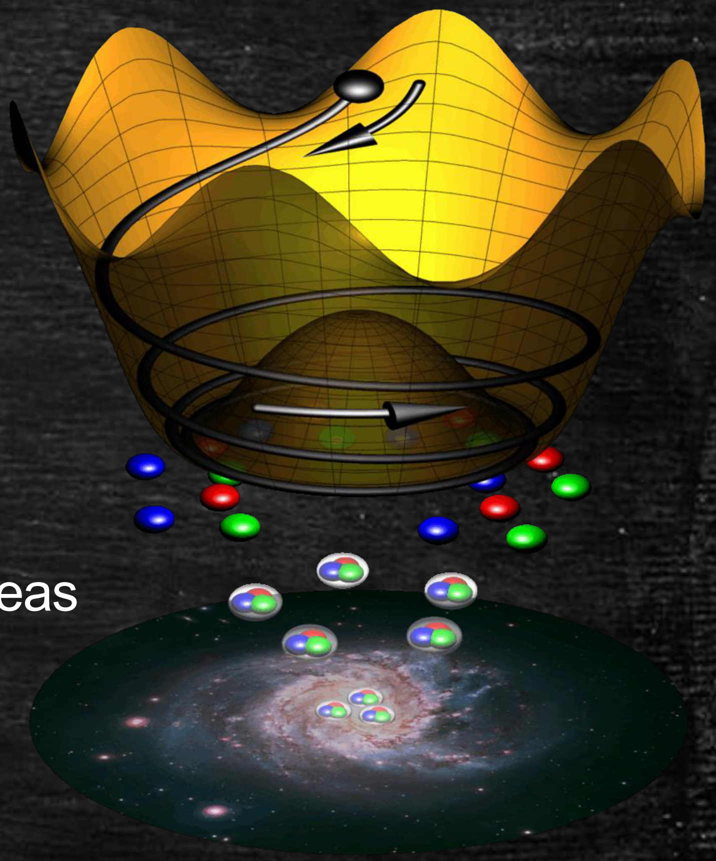
Axiogenesis and Kinetic Misalignment with Dissipation from Dark Magnetic Monopoles



CETUP*
Center for Theoretical Underground Physics and Related Areas

June 24th, 2026

Raymond Co

Indiana University

2511.10603 RC, K. Harigaya, I. R. Wang, and H. Xiao

Today

Nobel Prize in Physics 1982

for his discovery of cosmic radiation

Victor Franz Hess

born on

June 24th 1883

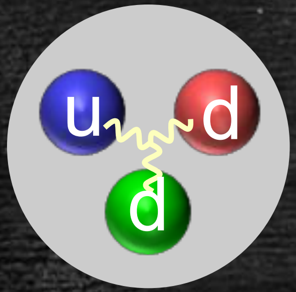
passed away on

December 17th 1964

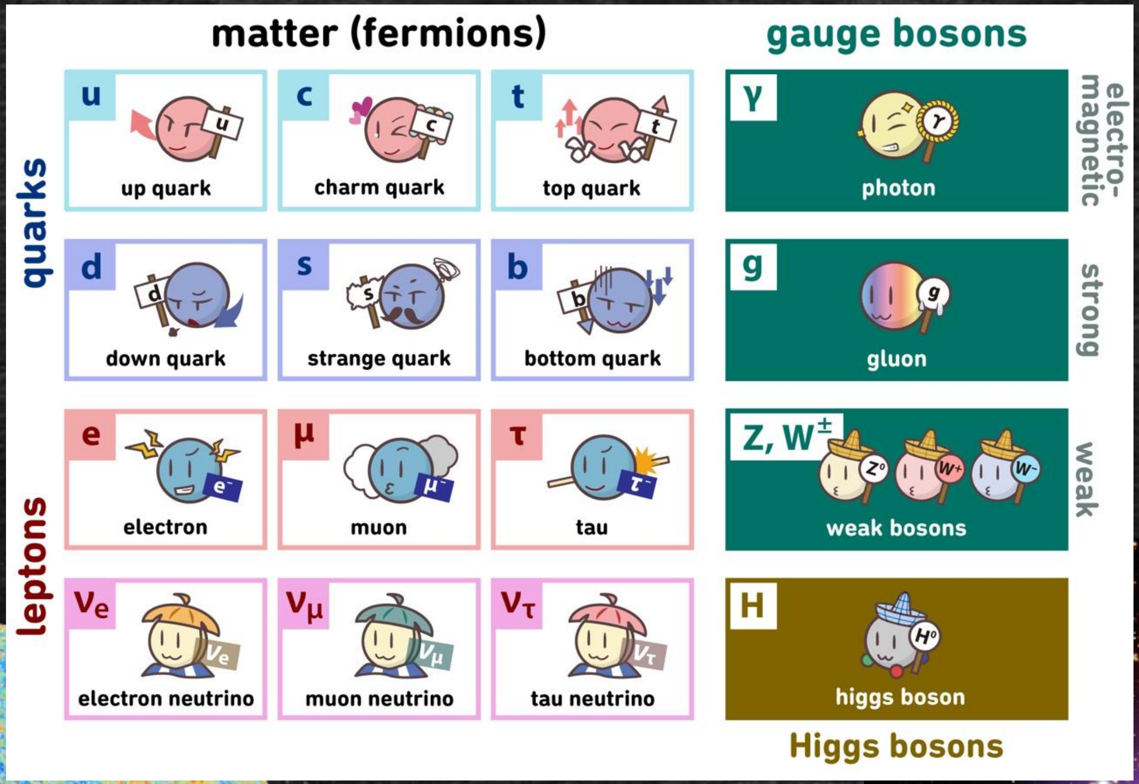
https://www.nobelprize.org/prizes/physics/1936/hess/facts/

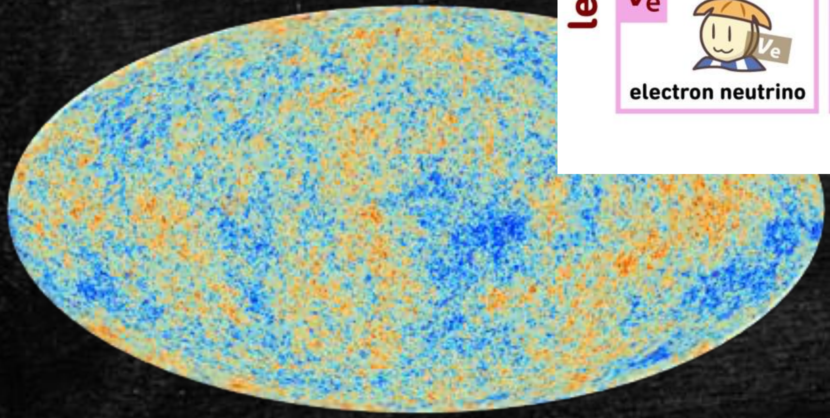
Outline of the Talk

strong CP problem



neutron





Source: Planck

+

axion?

matter-antimatter asymmetry

dark matter

Review of the QCD Axion

Strong CP Problem

solution

$$\mathcal{L} \supset \bar{\theta} \frac{\alpha_s}{8\pi} G_b^{\mu\nu} \widetilde{G}_{b\mu\nu}$$

Peccei, Quinn 1977
Weinberg 1978
Wilczek 1978

QCD axion

Promoted to a dynamical field: $$\mathcal{L} \supset \left(\bar{\theta} + \frac{a}{f_a} \right) \frac{\alpha_s}{8\pi} G_b^{\mu\nu} \widetilde{G}_{b\mu\nu}$$

decay constant

QCD effects automatically generate an axion potential $$V(a) = m_a^2 f_a^2 \left[1 - \cos\left(\bar{\theta} + \frac{a}{f_a} \right) \right]$$

This potential dynamically drives the axion to a field value that cancels $\bar{\theta}$. Problem solved!

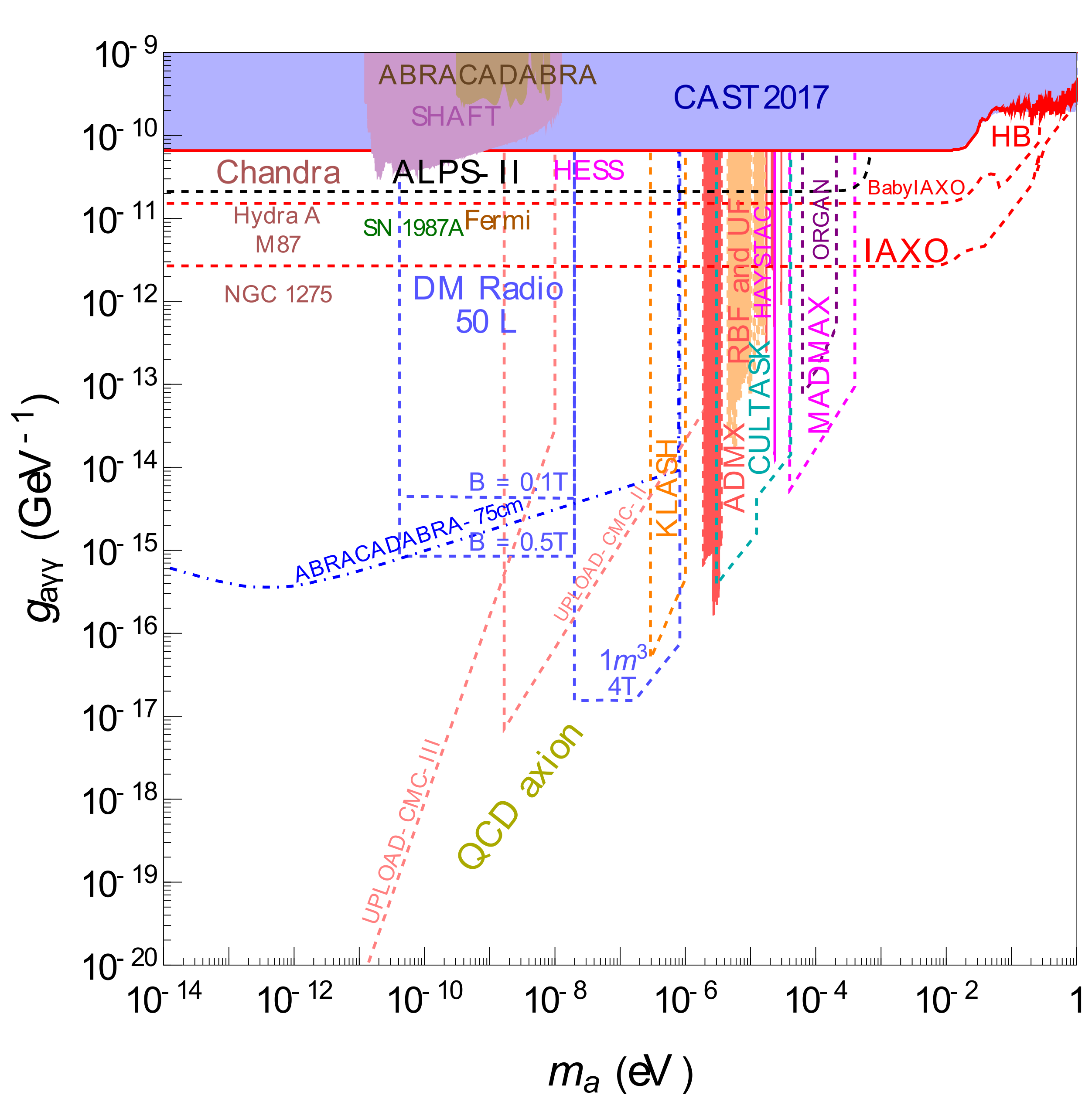
Status of Axion Dark Matter

Experimental Searches

Experimental progress

shaded regions: excluded

broken lines: future sensitivities



Axion Dark Matter Abundance

damped simple harmonic oscillator

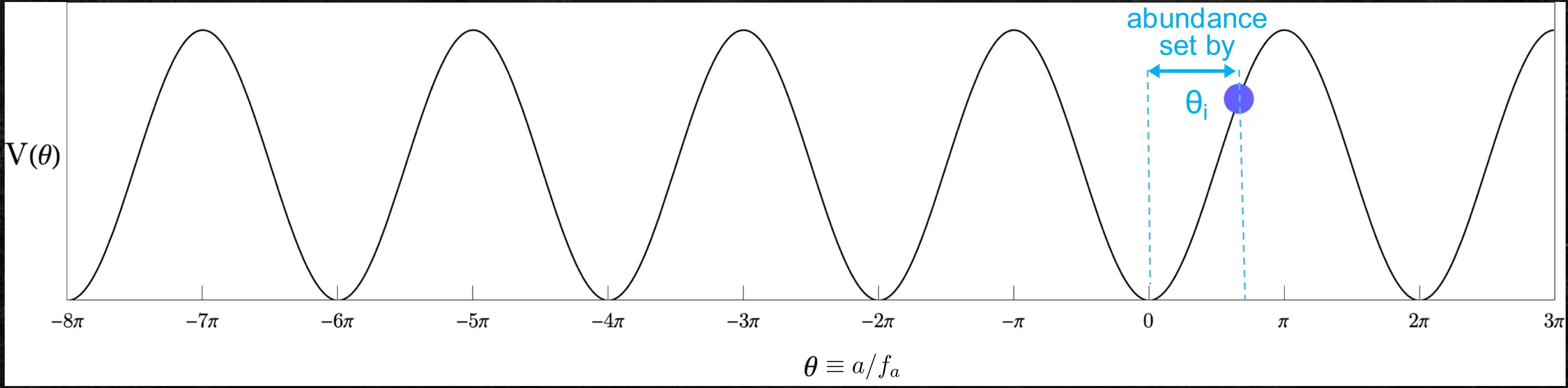
Equation of motion: $$\left(\partial_t^2 + 3H\partial_t + m_a^2\right) a = 0$$

Hubble “friction”
(from cosmic expansion)

Misalignment Mechanism

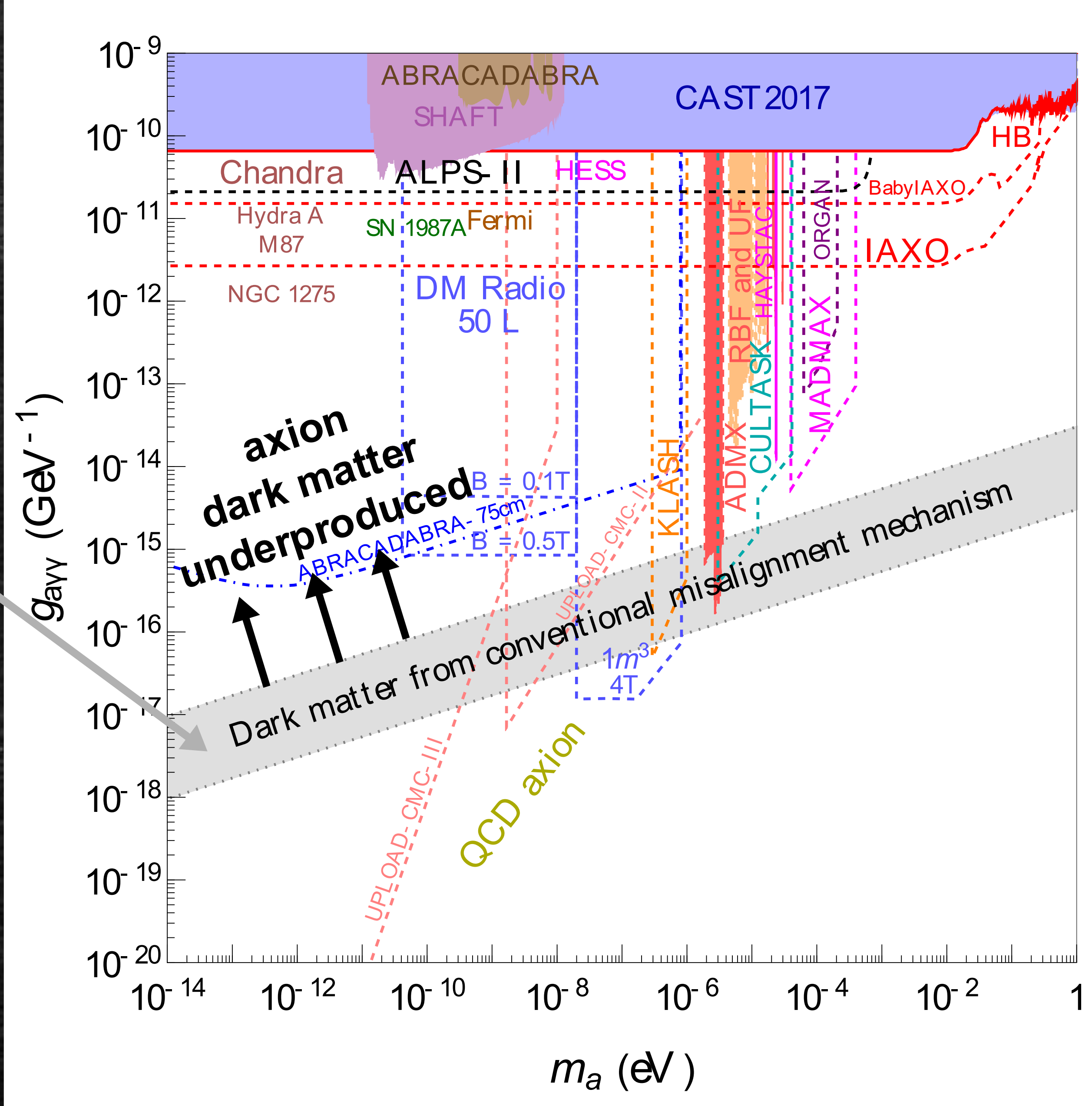
Preskill, Wise, Wilczek 1983
Abbott, Sikivie 1983
Dine, Fischler 1983

oscillations start when
$H \lesssim m_a$



Axion Dark Matter Abundance

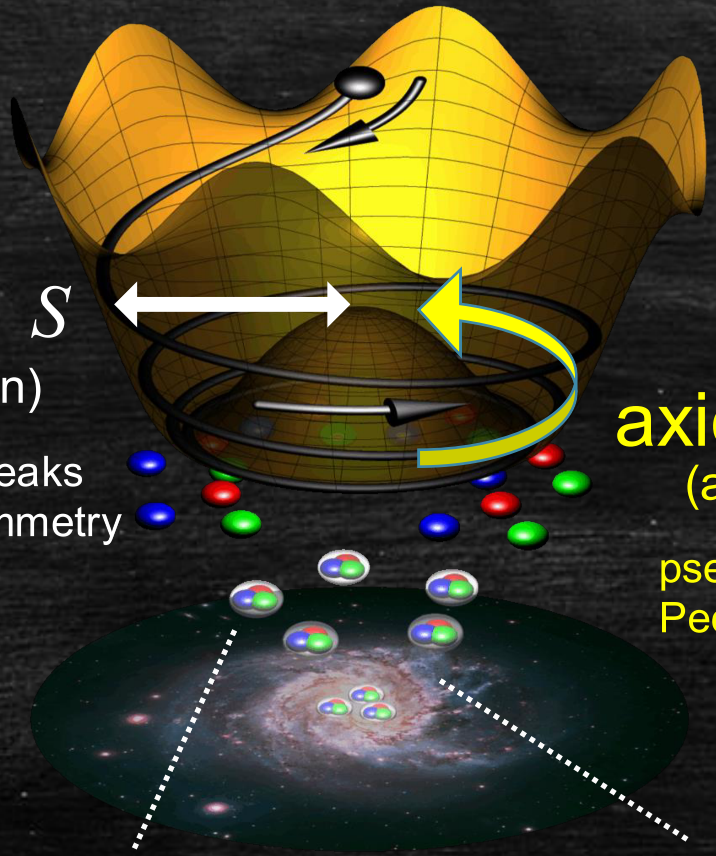
We assume $\theta_i = \mathcal{O}(1)$ here.

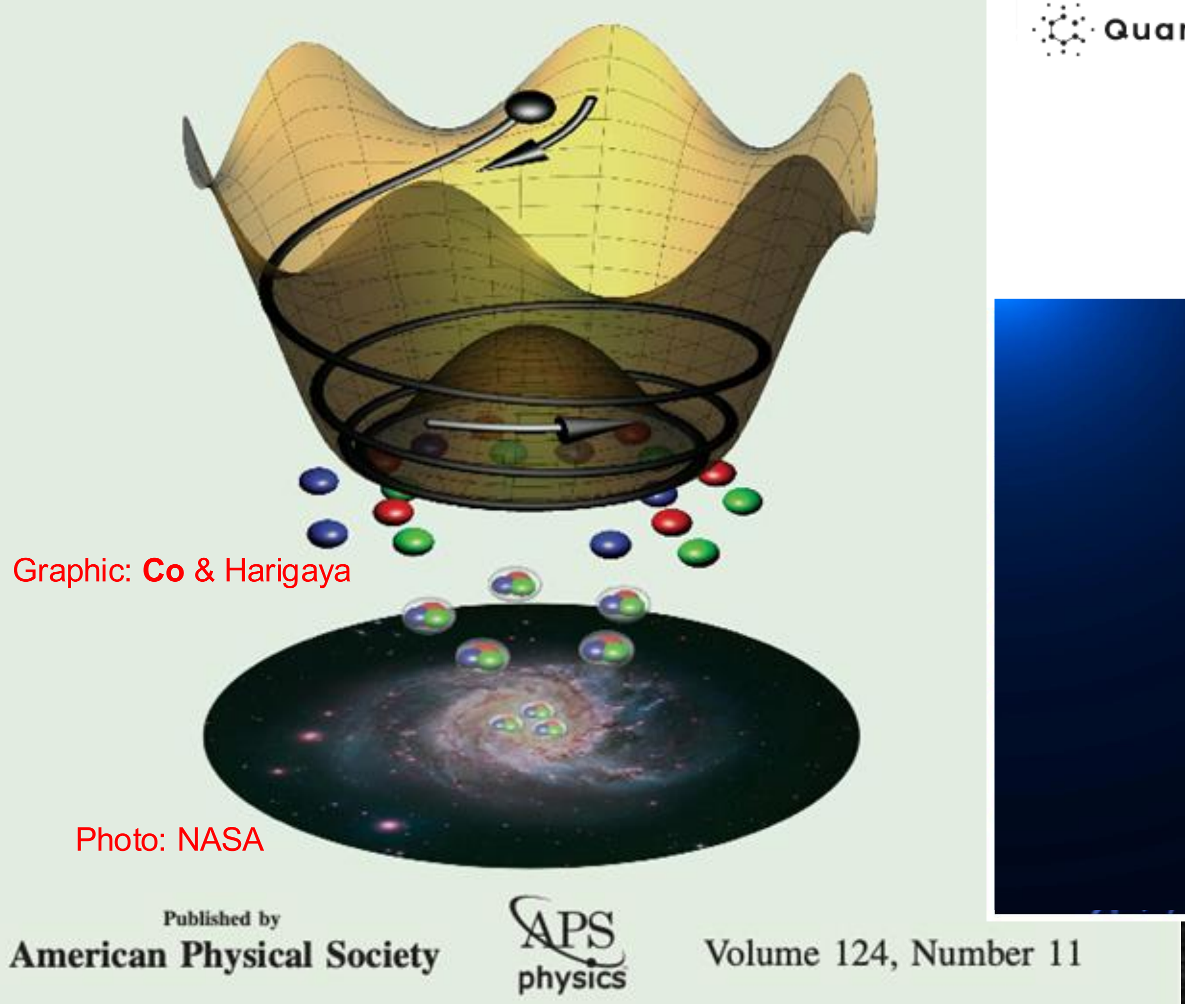


Axion Rotation

$$\mathcal{L} \supset \frac{\alpha_s}{8\pi}\frac{a}{f_a}G_b^{\mu\nu}\widetilde{G}_{b\mu\nu}$$

$$P = \frac{S + f_a}{\sqrt{2}}e^{i\frac{a}{f_a}}$$

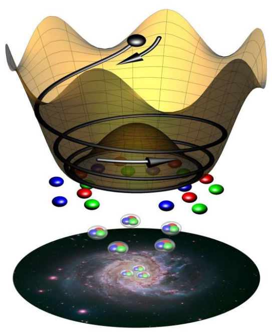




PHYS.ORG

Paper sheds light on infant universe and origin of matter

10 March 2020



The rotation of the QCD axion (black ball) produces an excess of matter (colored balls) over antimatter, allowing galaxies and human beings to exist. Credit: Graphic: Harigaya and Co; Photo: NASA

A new study, conducted to better understand the origin of the universe, has provided insight into some of the most enduring questions in fundamental physics: How can the Standard Model of particle physics be extended to explain the cosmological excess of matter over antimatter? What is dark matter? And what is the theoretical origin of an unexpected but observed symmetry in the force that binds protons and neutrons together?

In the paper "Axiogenesis," scheduled to be published in *Physical Review Letters* on March 17, 2020, researchers Keisuke Harigaya, Member in the School of Natural Sciences at the Institute for Advanced Study, and Raymond T. Co of the University of Michigan, have presented a compelling case in which the quantum chromodynamics (QCD) axion, first theorized in 1977, provides several important answers to these questions.

"We revealed that the rotation of the QCD axion can account for the excess of matter found in the universe," stated Harigaya. "We named this mechanism axiogenesis."

Infinitesimally light, the QCD axion—at least one billion times lighter than a proton—is nearly ghost-like. Millions of these particles pass through ordinary matter every second without notice. However, the subatomic level interaction of the QCD axion can still leave detectable signals in experiments with unprecedented sensitivities. While the QCD axion has never been directly detected, this study provides added fuel for experimentalists to hunt down the elusive particle.

"The versatility of the QCD axion in solving the mysteries of fundamental physics is truly amazing," stated Co. "We are thrilled about the unexplored theoretical possibilities that this new aspect of the QCD axion can bring. More importantly, experiments may soon tell us whether the mysteries of nature truly hint towards the QCD axion."

Harigaya and Co have reasoned that the QCD axion is capable of filling three missing pieces of the physics jigsaw puzzle simultaneously. First, the QCD axion was originally proposed to explain the so-called strong CP problem—why the strong force, which binds protons and neutrons together, unexpectedly preserves a symmetry called the Charge Parity (CP) symmetry. The CP symmetry is inferred from the observation that a neutron does not react with an electric field despite its charged constituents. Second, the QCD axion was found to

1 / 3

Quanta magazine | Physics | Mathematics | Bio

ABSTRACTIONS BLOG

Axions Would Solve Another Major Problem in Physics

6

In a new paper, physicists argue that hypothetical particles called axions could explain why the universe isn't empty.

Axion Rotations

Axion Kination

- ✓ **RC** *et al.* 2108.09299
- ✓ Gouttenoire *et al.* 2108.10328
- ✓ Gouttenoire *et al.* 2111.01150

Dark Matter

- ✓ **RC** *et al.* 1910.14152
- ✓ Chang *et al.* 1911.11885
- ✓ **RC** *et al.* 2004.00629
- ✓ Di Luzio *et al.* 2102.01082
- ✓ Rusov *et al.* 2109.01833
- ✓ Barman *et al.* 2111.03677
- ✓ Eröncel *et al.* 2206.14259
- ✓ Eröncel *et al.* 2207.10111
- ✓ Oikonomou 2208.05544
- ✓ Kozów *et al.* 2212.03518
- ✓ Chatrchyan *et al.* 2305.03756
- ✓ Lee *et al.* 2310.17710
- ✓ **RC** *et al.* 2312.17730
- ✓ Eröncel *et al.* 2503.04880
- ✓ **RC** *et al.* 2503.04888

Baryogenesis

- ✓ **RC** *et al.* 1910.02080
- ✓ **RC** *et al.* 2006.04809
- ✓ Domcke *et al.* 2006.03148
- ✓ **RC** *et al.* 2006.05687
- ✓ Harigaya *et al.* 2107.09679
- ✓ Chakraborty *et al.* 2108.04293
- ✓ Kawamura *et al.* 2109.08605
- ✓ **RC** *et al.* 2110.05487
- ✓ **RC** *et al.* 2206.00678
- ✓ Barnes, **RC** *et al.* 2208.07878
- ✓ **RC** *et al.* 2211.12517
- ✓ Berbig 2307.14121
- ✓ Chao *et al.* 2311.06469
- ✓ Chun *et al.* 2311.09005
- ✓ Wada 2404.10283
- ✓ Datta *et al.*2405.07003
- ✓ **RC** *et al.* 2405.12268

Gravitational Waves

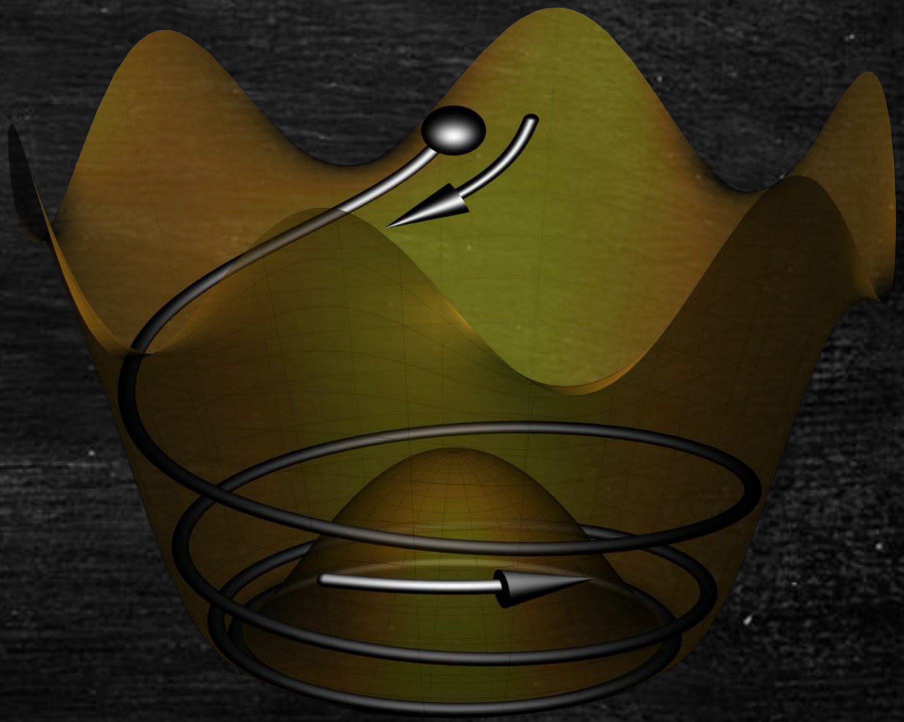
- ✓ **RC** *et al.* 2104.02077
- ✓ Madge *et al.* 2111.12730
- ✓ Harigaya *et al* 2305.14242

Cosmic Perturbations

- ✓ **RC** *et al.* 2202.01785
- ✓ **RC** *et al.* 2412.13246
- ✓ **RC** *et al.* 2510.01308

Why Rotation?

$$P = \frac{S + f_a}{\sqrt{2}} e^{i\frac{a}{f_a}}$$



Dynamics analogous to that in Affleck-Dine baryogenesis

I. Affleck and M. Dine 1991

PRL 92, 011301 (2004) T. Chiba, F. Takahashi, M. Yamaguchi

PRL 124, 111602 (2020) RC and K. Harigaya

Why Rotation?

Wiggles :

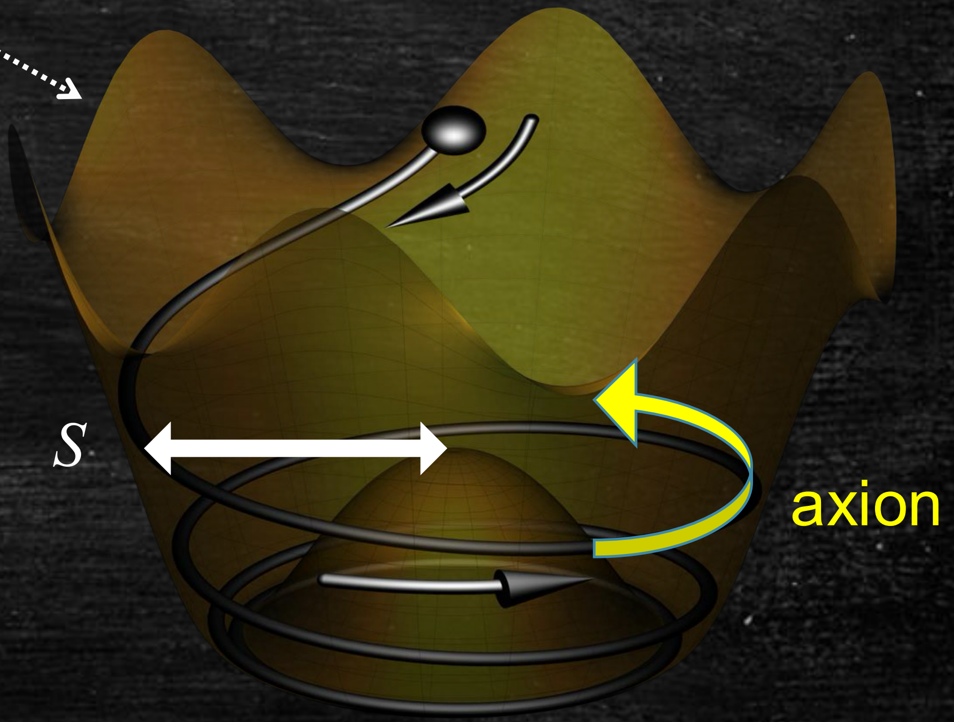
$$V(P) \sim \frac{P^n}{M^{n-4}} e^{i\varphi} + \text{h.c.} \sim \frac{|P|^n}{M^{n-4}} \cos\left(n\frac{a}{f_a} + \varphi\right)$$

$$P = \frac{S + f_a}{\sqrt{2}} e^{i\frac{a}{f_a}}$$

Explicit PQ breaking

expected from quantum gravity
or PQ as an accidental symmetry

S. Giddings et al. 1988
S. Coleman 1988
G. Gilbert 1988



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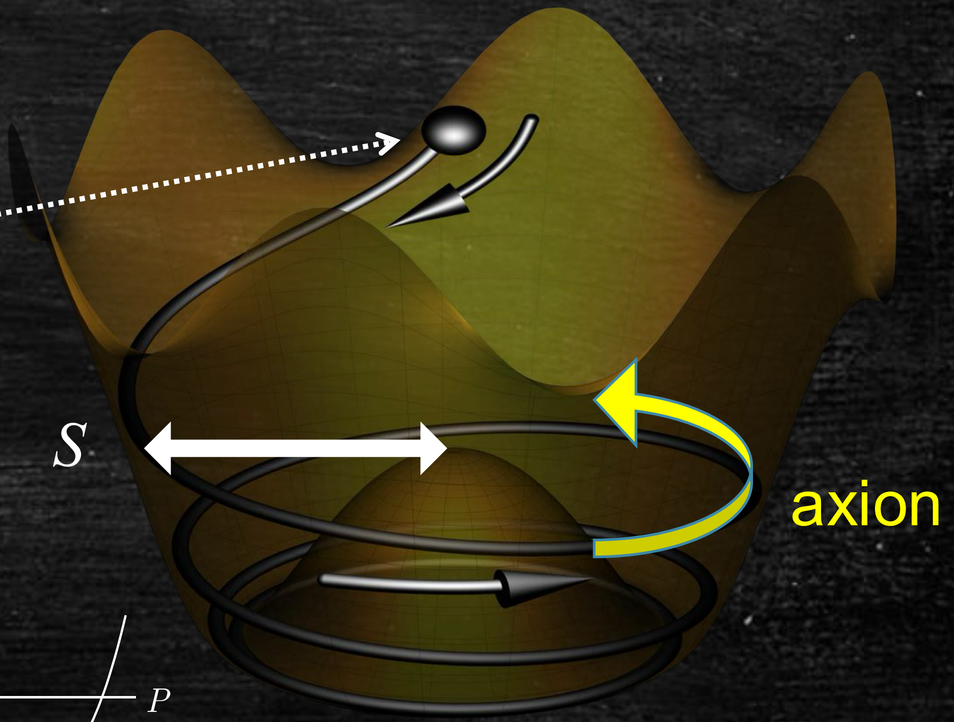


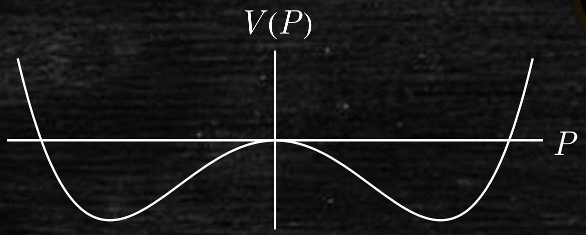
Large field value :

Flat potential

For example, as an initial condition or
set dynamically by inflationary dynamics

$$V(|P|) \sim -H_I^2 |P|^2 + \frac{|P|^d}{M^{d-4}}$$

Hubble-induced mass



M. Dine, L. Randall, and S. D. Thomas 1991

Dynamics analogous to that in Affleck-Dine baryogenesis

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PRL 92, 011301 (2004) T. Chiba, F. Takahashi, M. Yamaguchi
PRL 124, 111602 (2020) RC and K. Harigaya

Asymmetry of PQ Charge

Noether charge associated with the shift symmetry

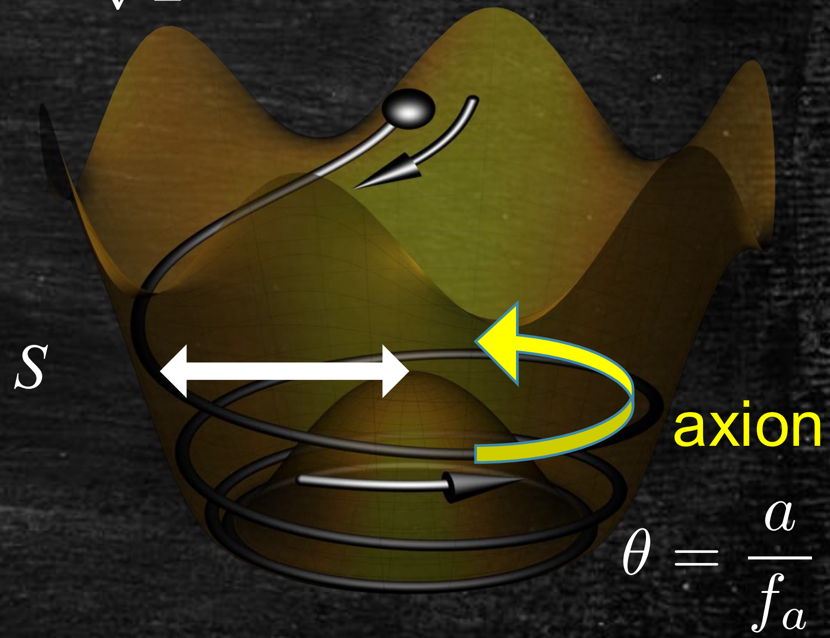
$$P = \frac{S + f_a}{\sqrt{2}} e^{i\frac{a}{f_a}}$$

$$n_\theta = S^2 \dot{\theta}$$

this is nothing but
"angular momentum" $r^2\omega$

PQ asymmetry
PQ charge density = Rotation of PQ field

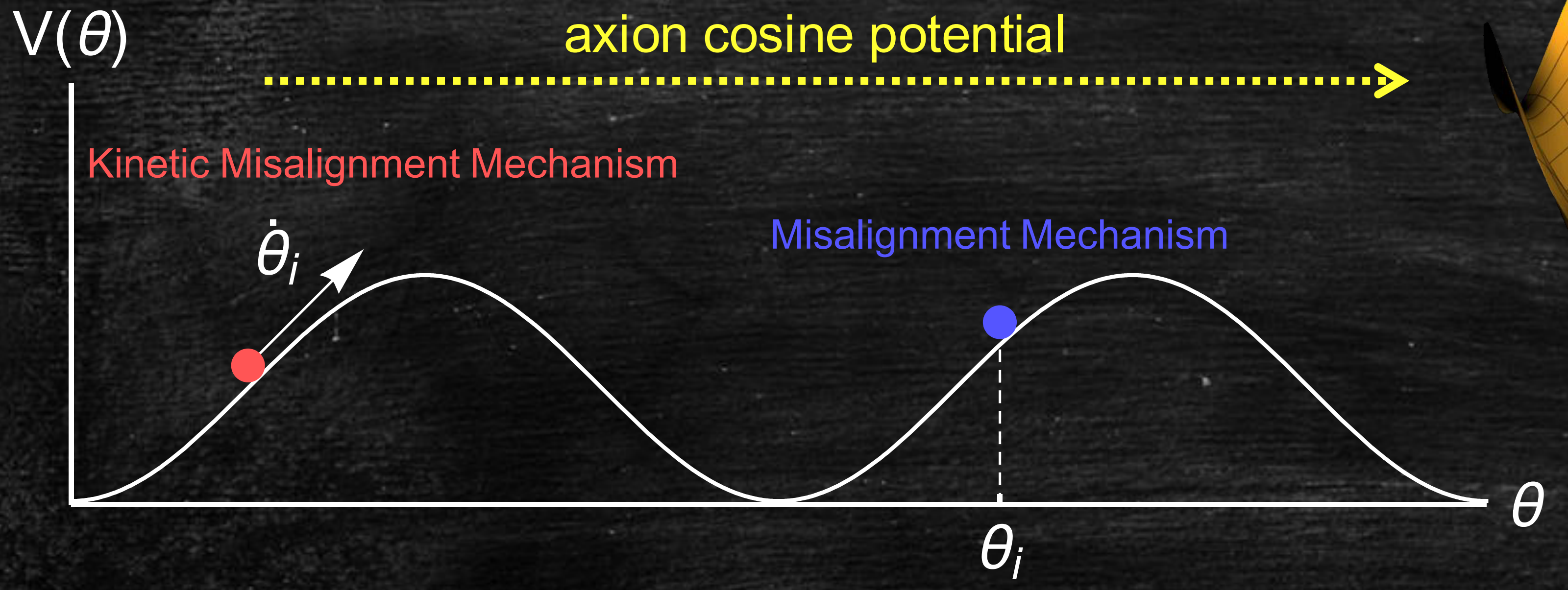
This is conserved soon after the initial kick.

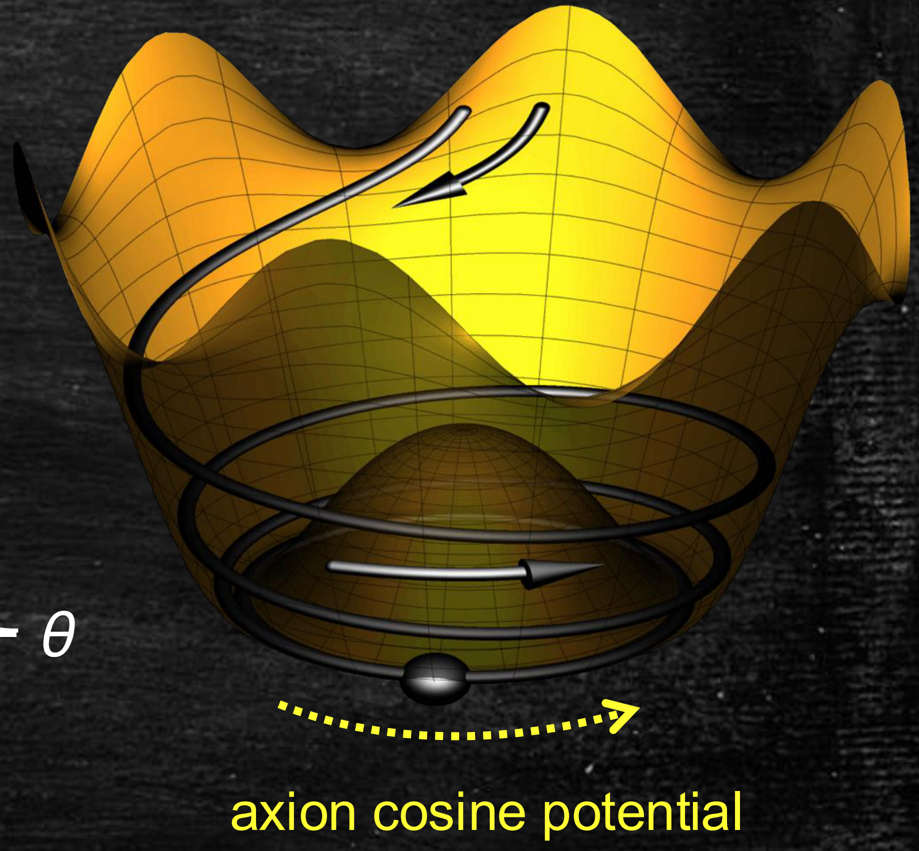


Axion Dark Matter

Kinetic Misalignment Mechanism

a novel scenario where the axion field has a nonzero initial velocity, e.g., from axion rotations.



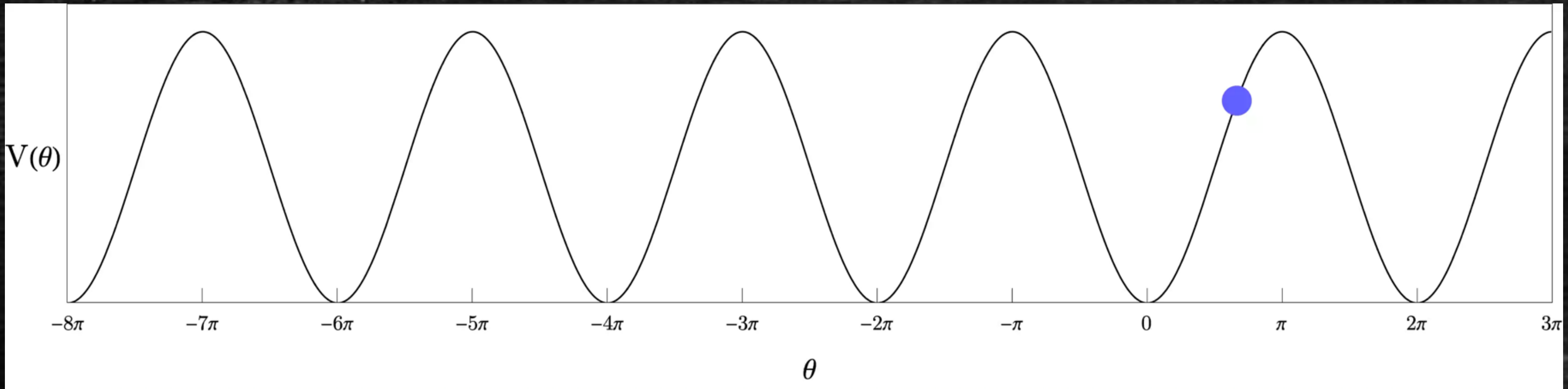


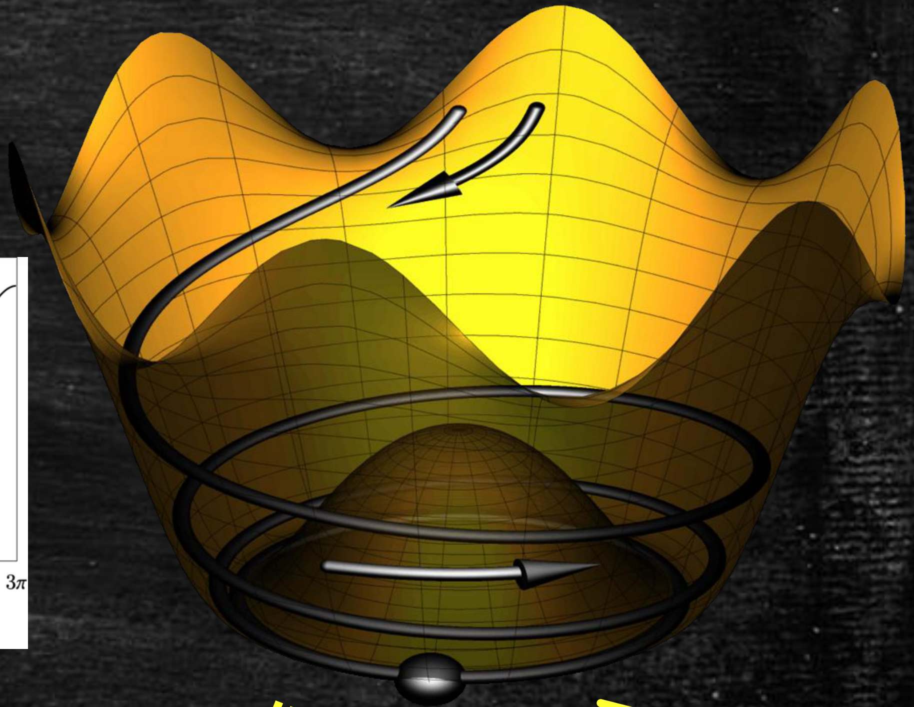
PRL 124, 251802 (2020) RC, L. Hall, K. Harigaya

Kinetic Misalignment Mechanism

a novel scenario where the axion field has a nonzero initial velocity, e.g., from axion rotations.

axion cosine potential





axion cosine potential

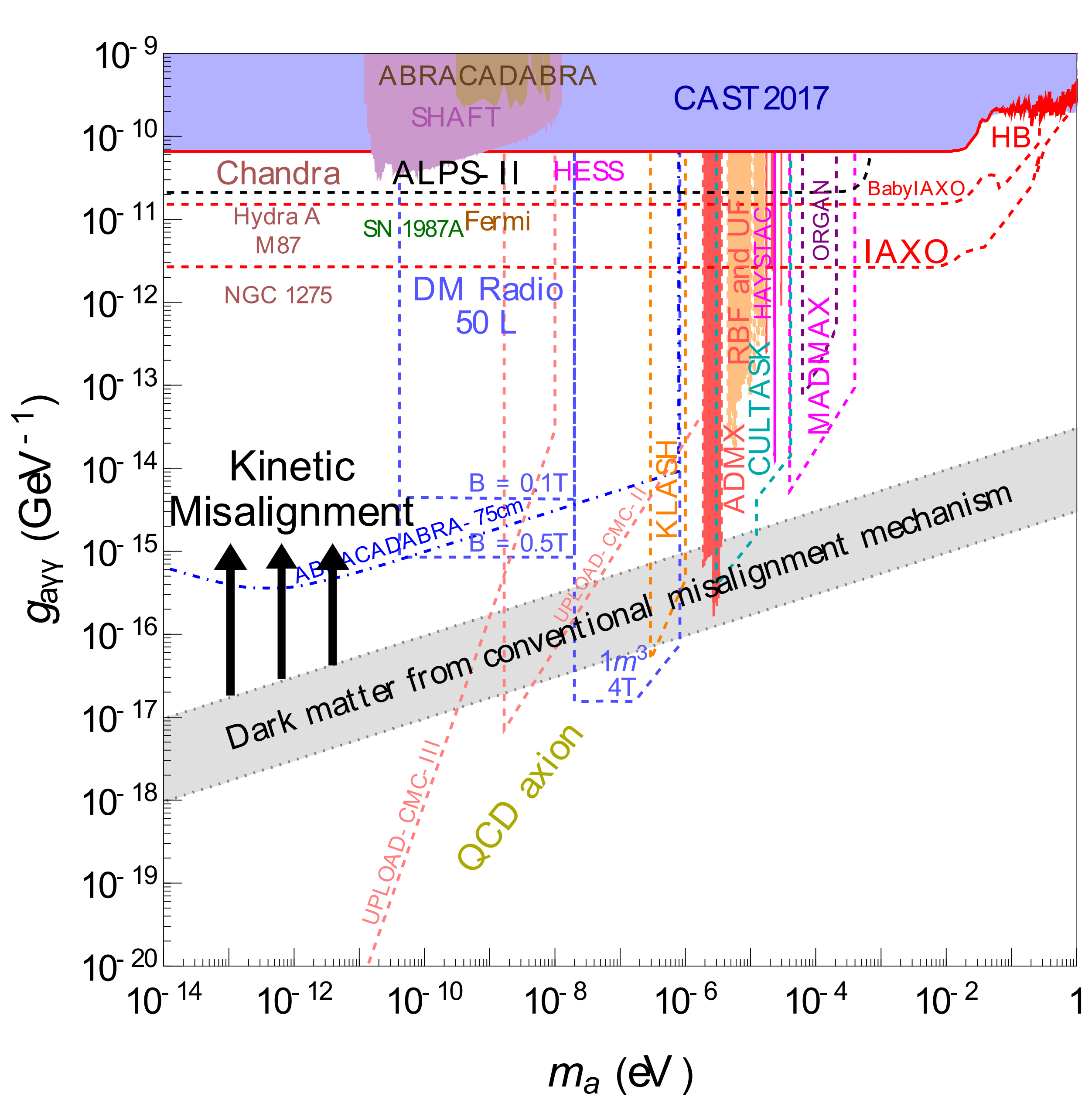
kinetic energy > potential energy

enhancing axion abundance

PRL 124, 251802 (2020) RC, L. Hall, K. Harigaya

Kinetic Misalignment Mechanism

giving a strong motivation for axion dark matter experiment



Kinetic Misalignment Mechanism

Kinetic Misalignment*

charge yield

$$Y_\theta = \frac{n_\theta}{s}$$

$$\frac{\rho_a}{s} \simeq m_a Y_\theta$$

abundance

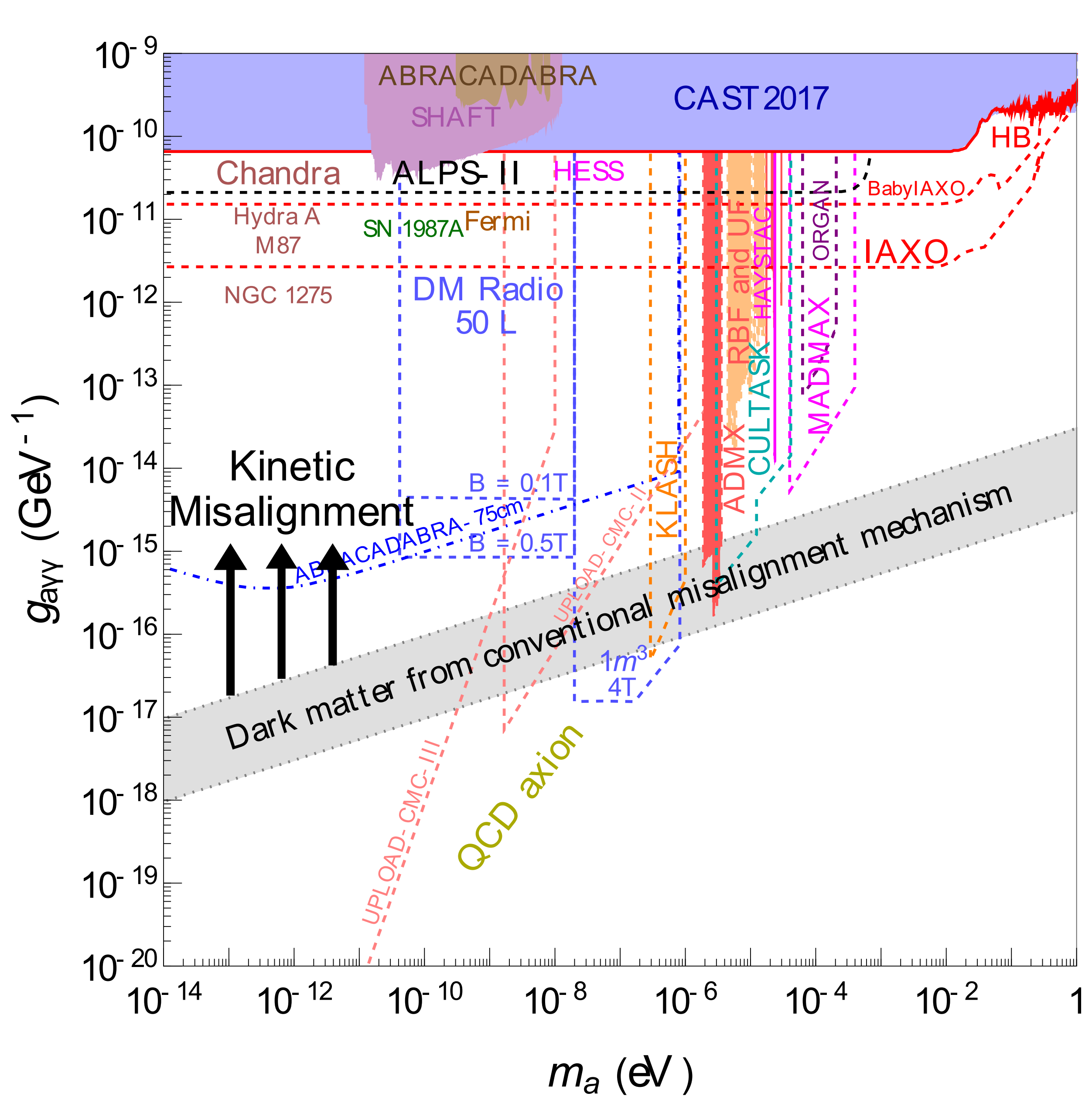
Observed dark matter abundance

$$\frac{\rho_{\rm DM}}{s} \simeq 0.44 \text{ eV}$$

(*Planck* 2018)

Thus, dark matter relates

$$m_a \overset{\rm DM}{\longleftrightarrow} Y_\theta$$



Baryon Asymmetry

Axiogenesis

Asymmetries in Thermal Equilibrium

The free energy is minimized at equilibrium.

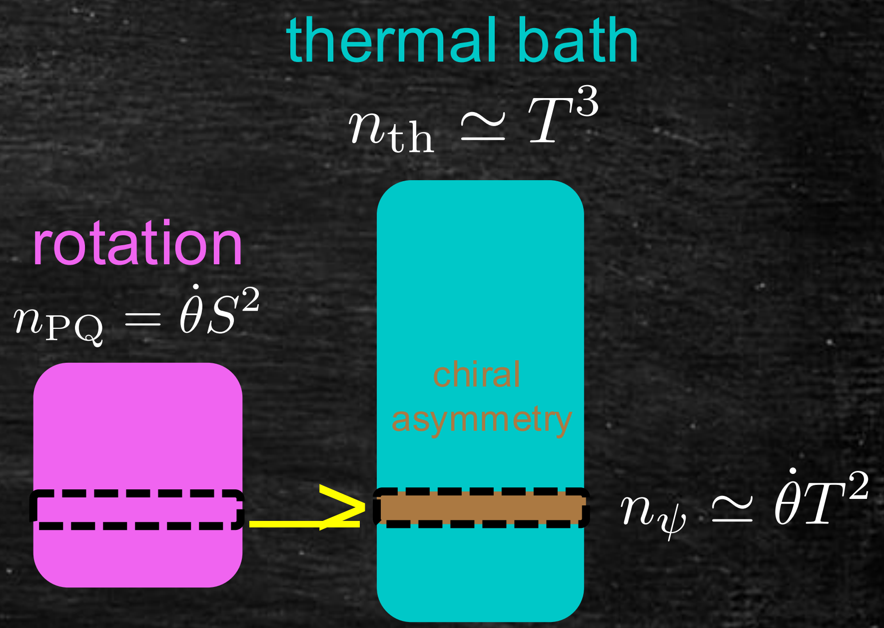
fermion asymmetry

$$n_\psi \equiv n_{+\mu} - n_{-\mu} \sim \mu T^2$$

Change of the free energy

$$\Delta F_{\rm th} \sim \Delta\rho - T\Delta s \sim \frac{n_\psi^2}{T^2}$$

$$\Delta F_{\rm rot} \sim -\dot\theta n_\psi$$



$\Delta F_{\rm tot}$ is minimized when $$n_\psi \sim \dot\theta T^2 \ll \dot\theta S^2 = n_{\rm PQ}$$

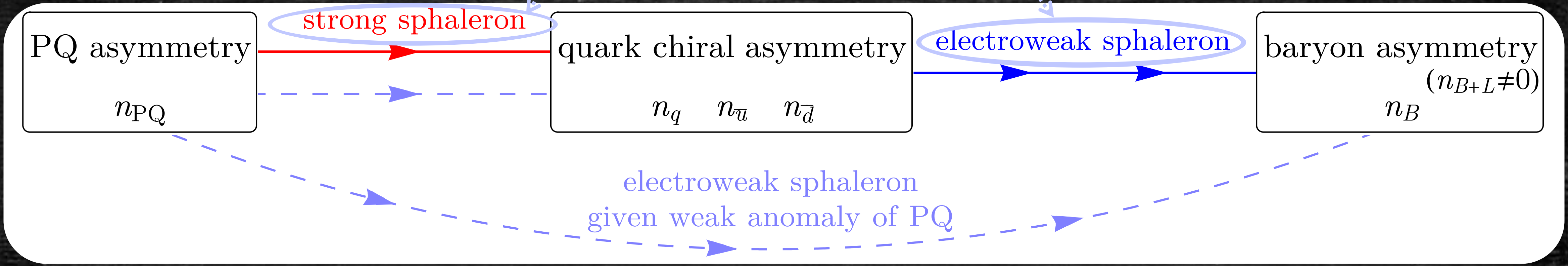
Most of the PQ charge remains in the rotation!

PRL 124, 111602 (2020) RC and K. Harigaya

Axiogenesis

Baryogenesis is automatic, thanks to Standard Model processes
(production of baryon asymmetry)

matter-antimatter asymmetry



$$Y_B \equiv \frac{n_B}{s} = c_B Y_\theta \left(\frac{T_{\rm EW}}{f_a}\right)^2$$

produced by axion rotations

$$Y_B^{\rm obs} \simeq 8.7 \times 10^{-11}$$

experimentally measured value
(*Planck* 2018)

PRL 124, 111602 (2020) RC and K. Harigaya

Axiogenesis

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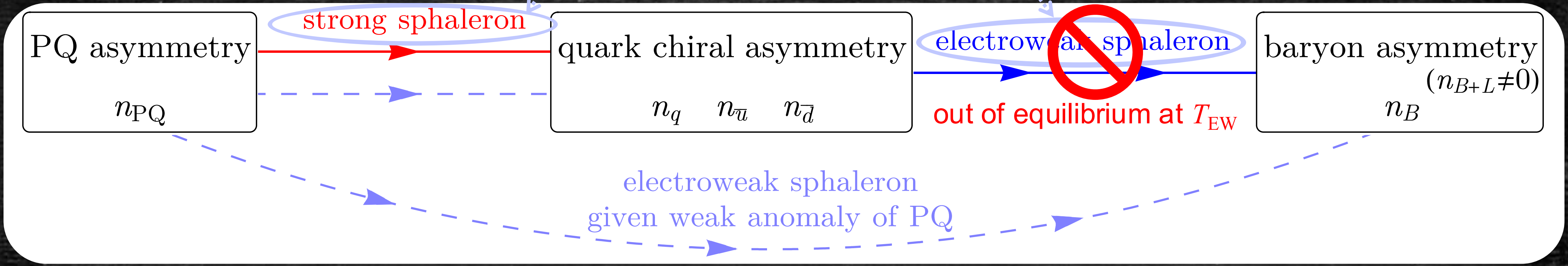


$$Y_B \equiv \frac{n_B}{s} = c_B Y_\theta \left(\frac{T_{EW}}{f_a}\right)^2$$

$$Y_B^{obs} \simeq 8.7 \times 10^{-11}$$

experimentally measured value
(*Planck* 2018)

Namely, the baryon asymmetry relates $\left(\frac{T_{EW}}{f_a}\right)^2 \overset{Y_B}{\longleftrightarrow} Y_\theta$

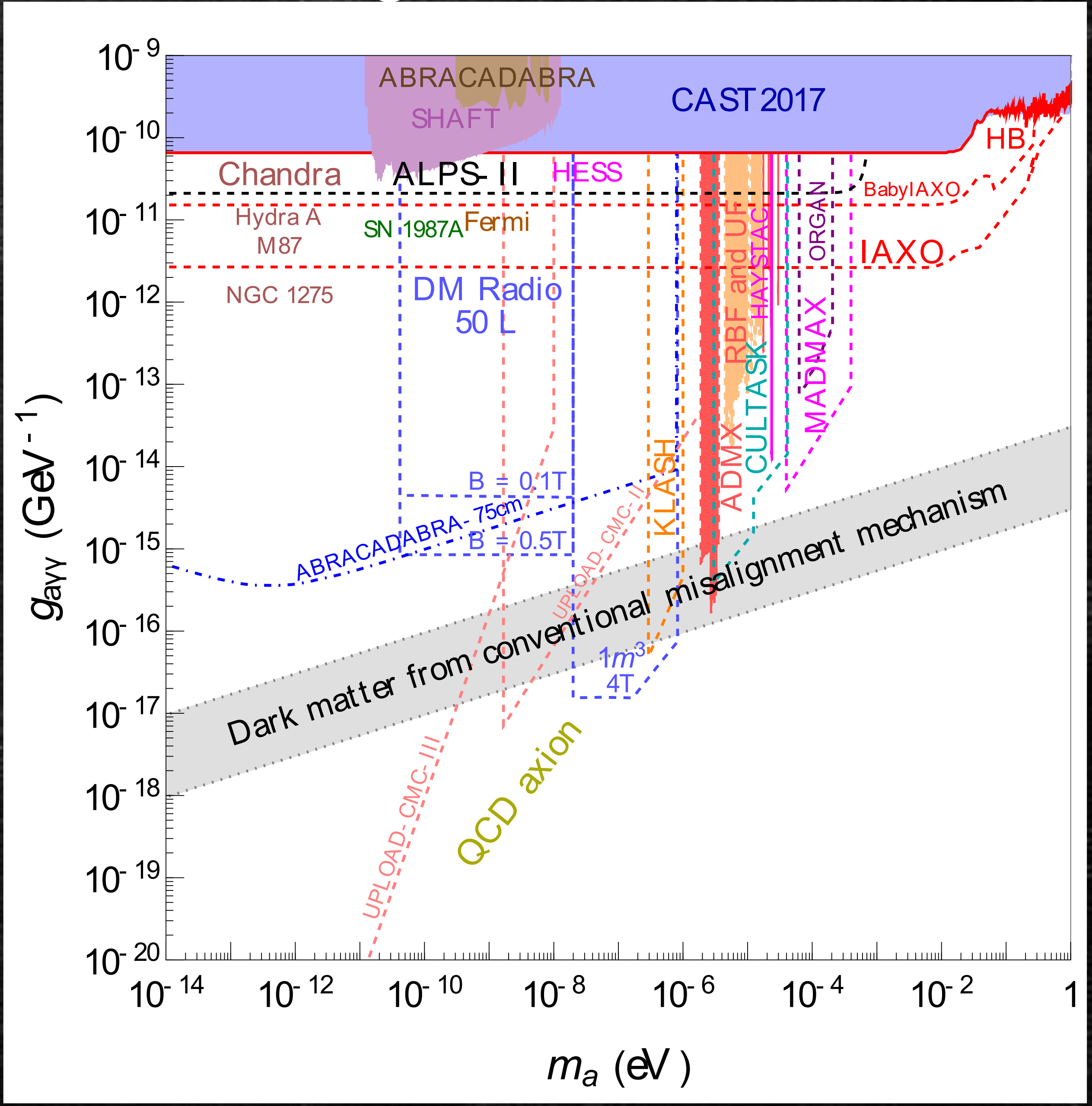
PRL 124, 111602 (2020) RC and K. Harigaya

Axion/ALP Cogenesis

Kinetic Misalignment + Axiogenesis

Prediction:

$$m_a \overset{\text{DM}}{\longleftrightarrow} Y_\theta \overset{Y_B}{\longleftrightarrow} \left(\frac{T_{\text{EW}}}{f_a}\right)^2$$



JHEP 01 (2021) 172 RC, L. Hall, K. Harigaya

Kinetic Misalignment + Axiogenesis

Prediction:

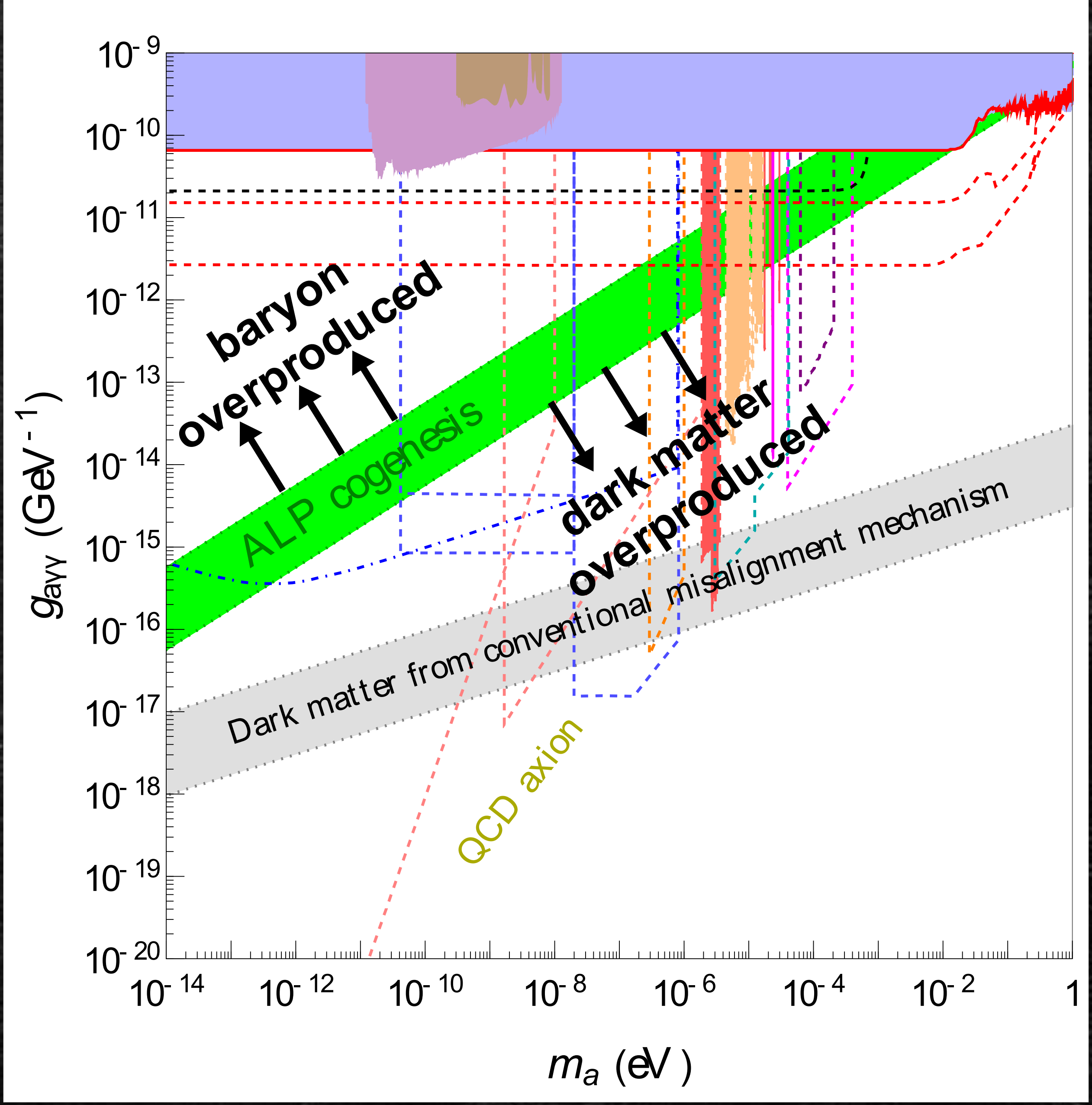
$$m_a \overset{\mathrm{DM}}{\longleftrightarrow} Y_\theta \overset{Y_B}{\longleftrightarrow} \left(\frac{T_{\mathrm{EW}}}{f_a}\right)^2$$

ALP cogenesis :

ALP = axion-like particle
(no gluon coupling)

cogenesis
= production of both dark matter
& matter-antimatter asymmetry

We assume $T_{\mathrm{EW}} = 130\ \mathrm{GeV}$.



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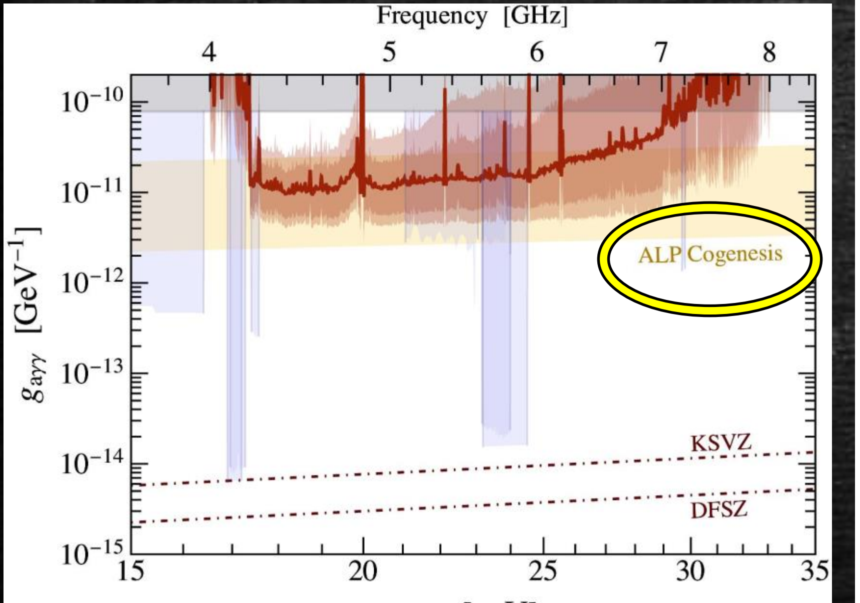
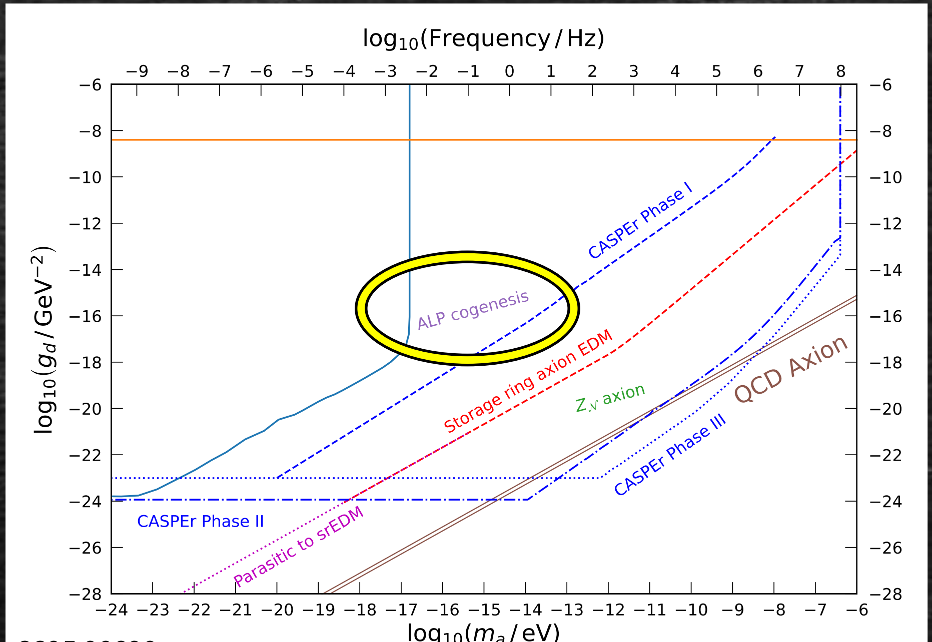
ALP Cogenesis

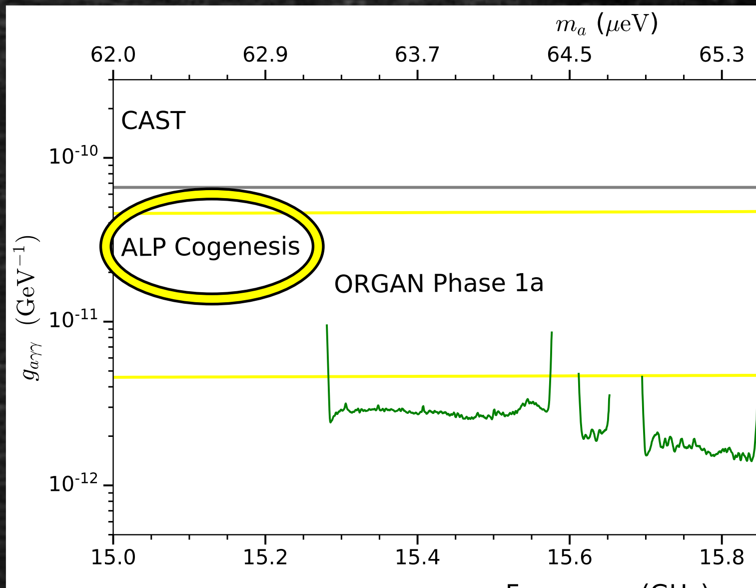
Experimental probes are happening!



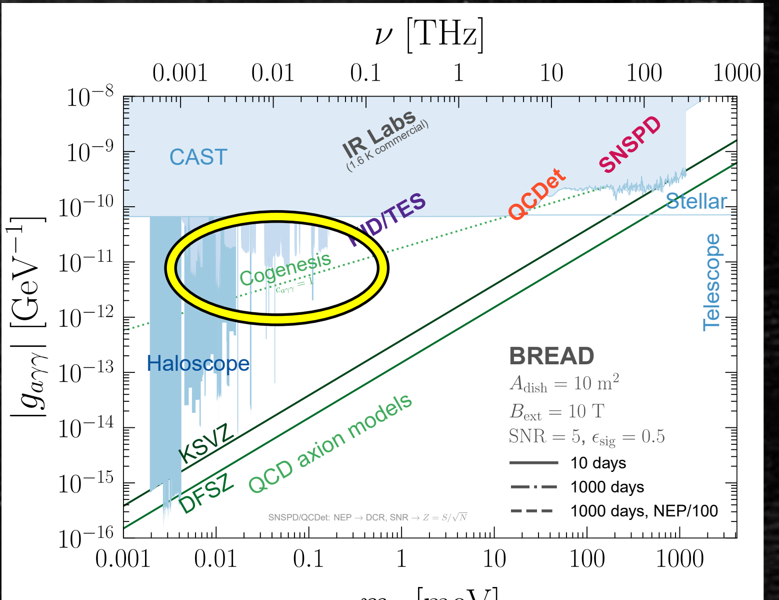
PRL 129, 251102 (2022)



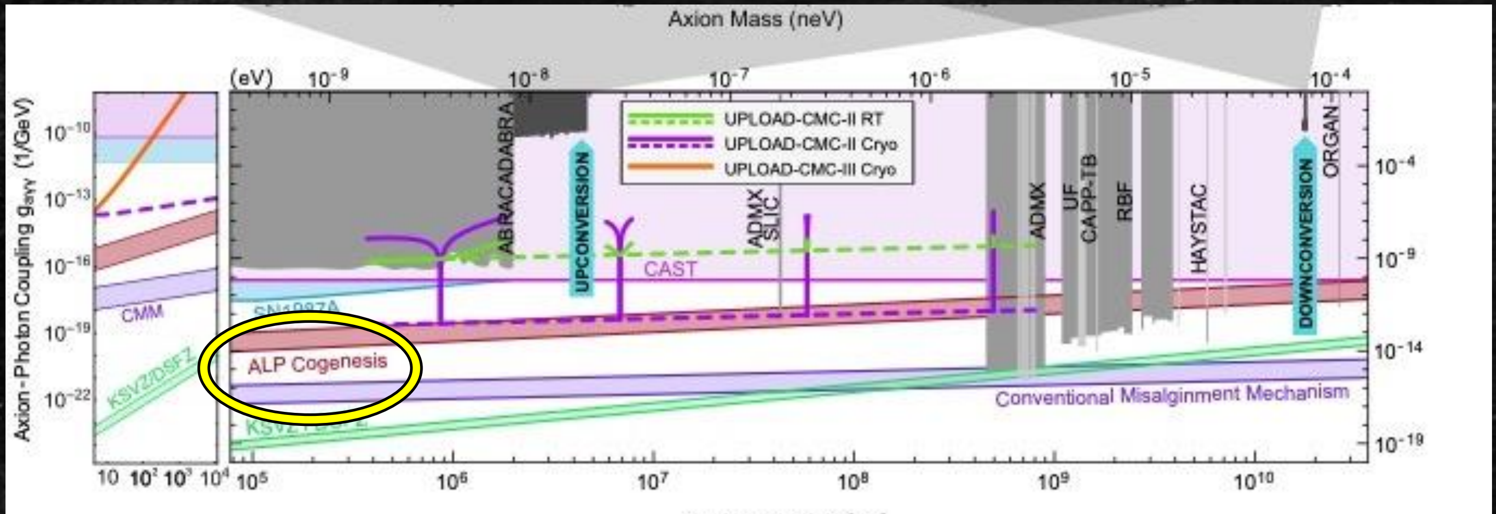
2205.00830



Sci.Adv. 8 (2022) 27, abq3765



PRL 128 (2022) 13, 131801



PRL 126 (2021) 8, 081803

Kinetic Misalignment + Axiogenesis

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$$m_a \overset{\text{DM}}{\longleftrightarrow} Y_\theta \overset{Y_B}{\longleftrightarrow} \left(\frac{T_{\text{EW}}}{f_a}\right)^2$$

ALP cogenesis :

ALP = axion-like particle (no gluon coupling)

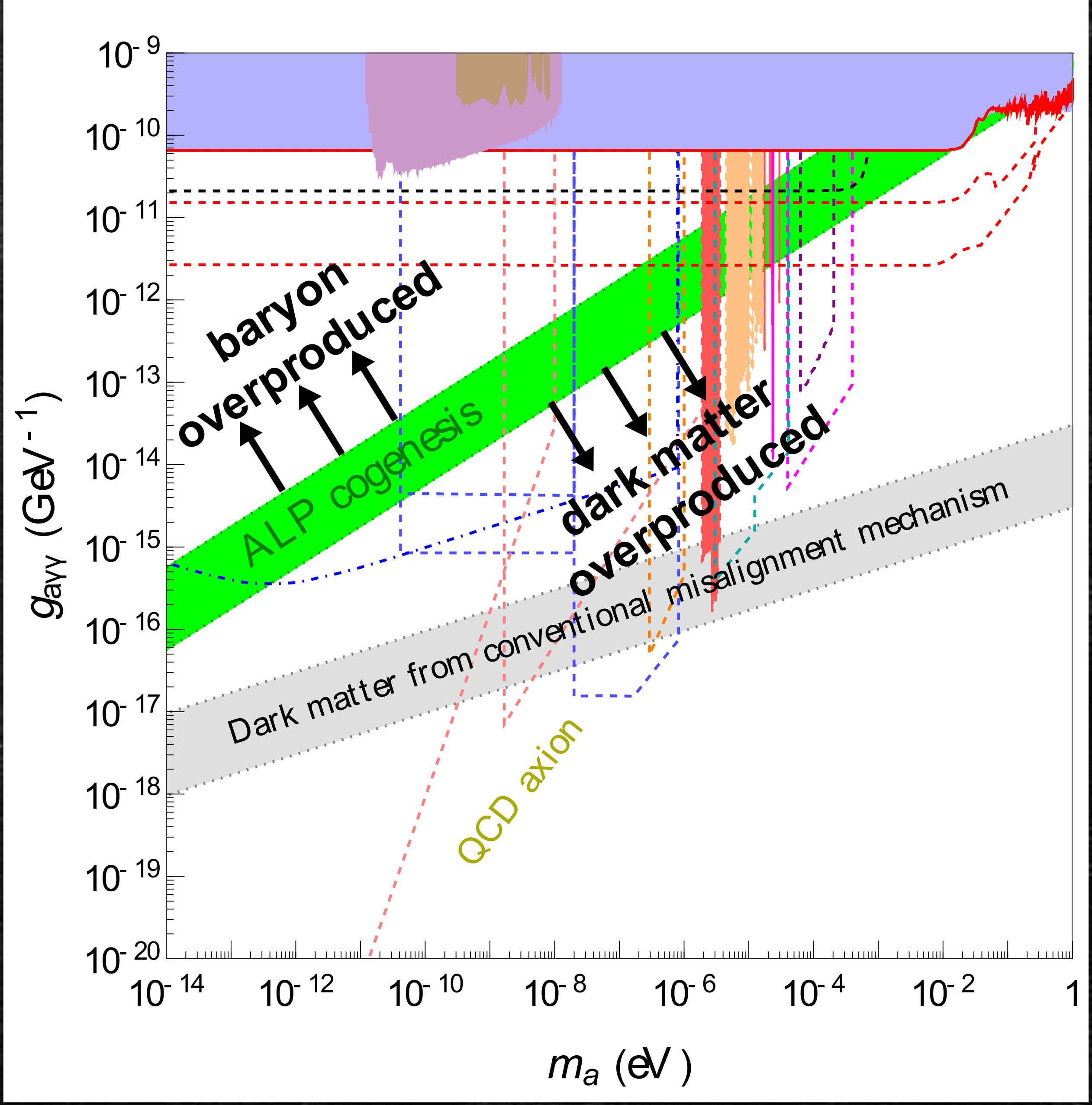
cogenesis = production of both dark matter & matter-antimatter asymmetry

We assume $T_{\text{EW}} = 130\ \text{GeV}$.

QCD axion cogenesis?

Can the QCD axion be compatible with cogenesis from axion rotations?

Yes. This is a great opportunity to bring other open questions into the picture!



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QCD Axion Cogenesis

Kinetic Misalignment + Axiogenesis

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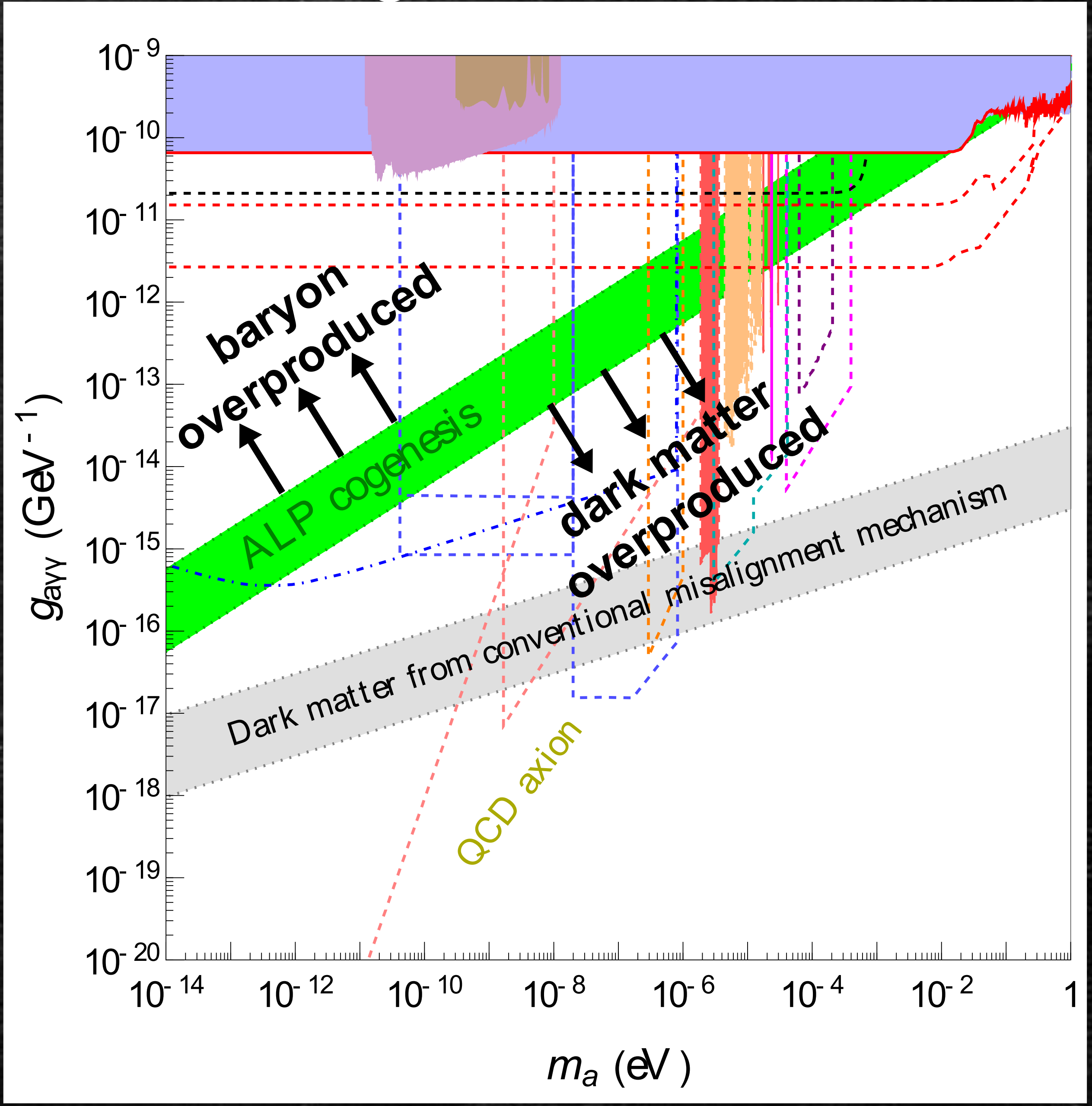
QCD axion cogenesis?

Issue: <u>too much</u> dark matter assuming baryon asymmetry from axiogenesis.



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Kinetic Misalignment + Axiogenesis

Prediction:

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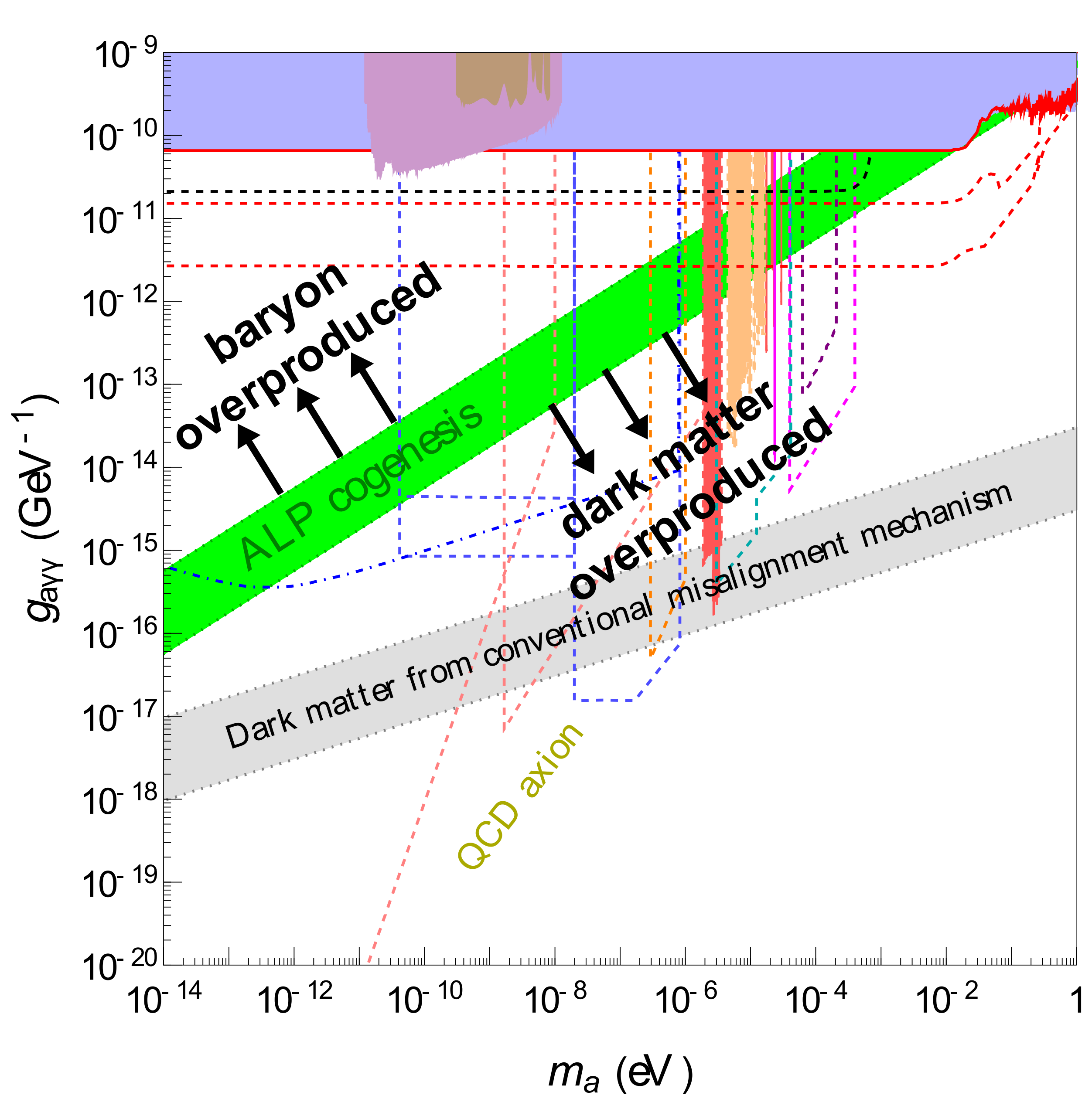
Resolution:

1. Enhancing baryon asymmetry production efficiency.
2. Reducing dark matter production efficiency.



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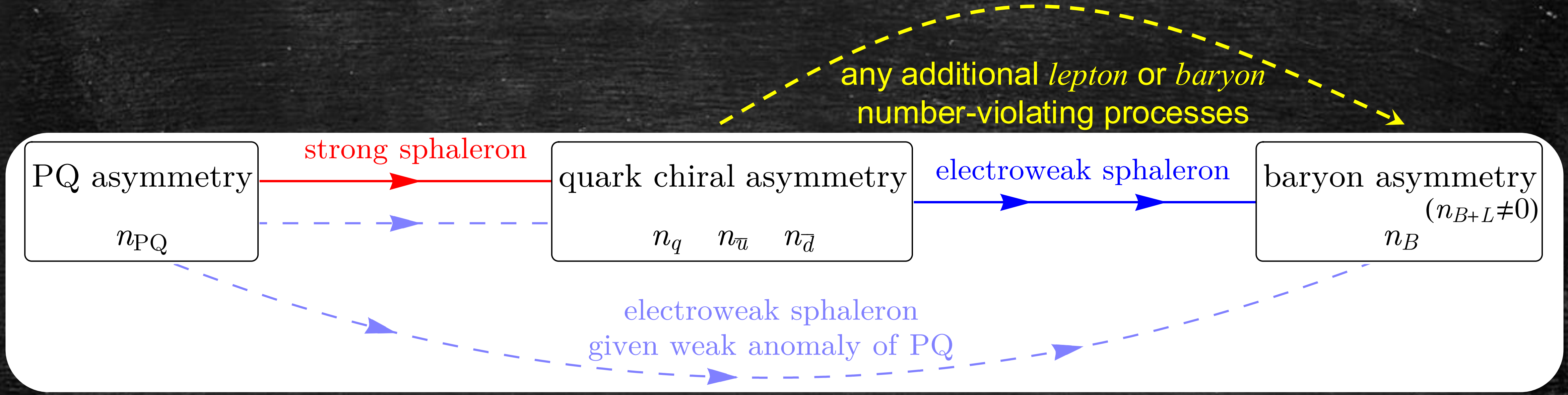
Extensions of Axiogenesis

Resolution:

1. Enhancing baryon asymmetry production efficiency.
2. Reducing dark matter production efficiency.

Extensions of Axiogenesis



Resolution:

1. Enhancing baryon asymmetry production efficiency.
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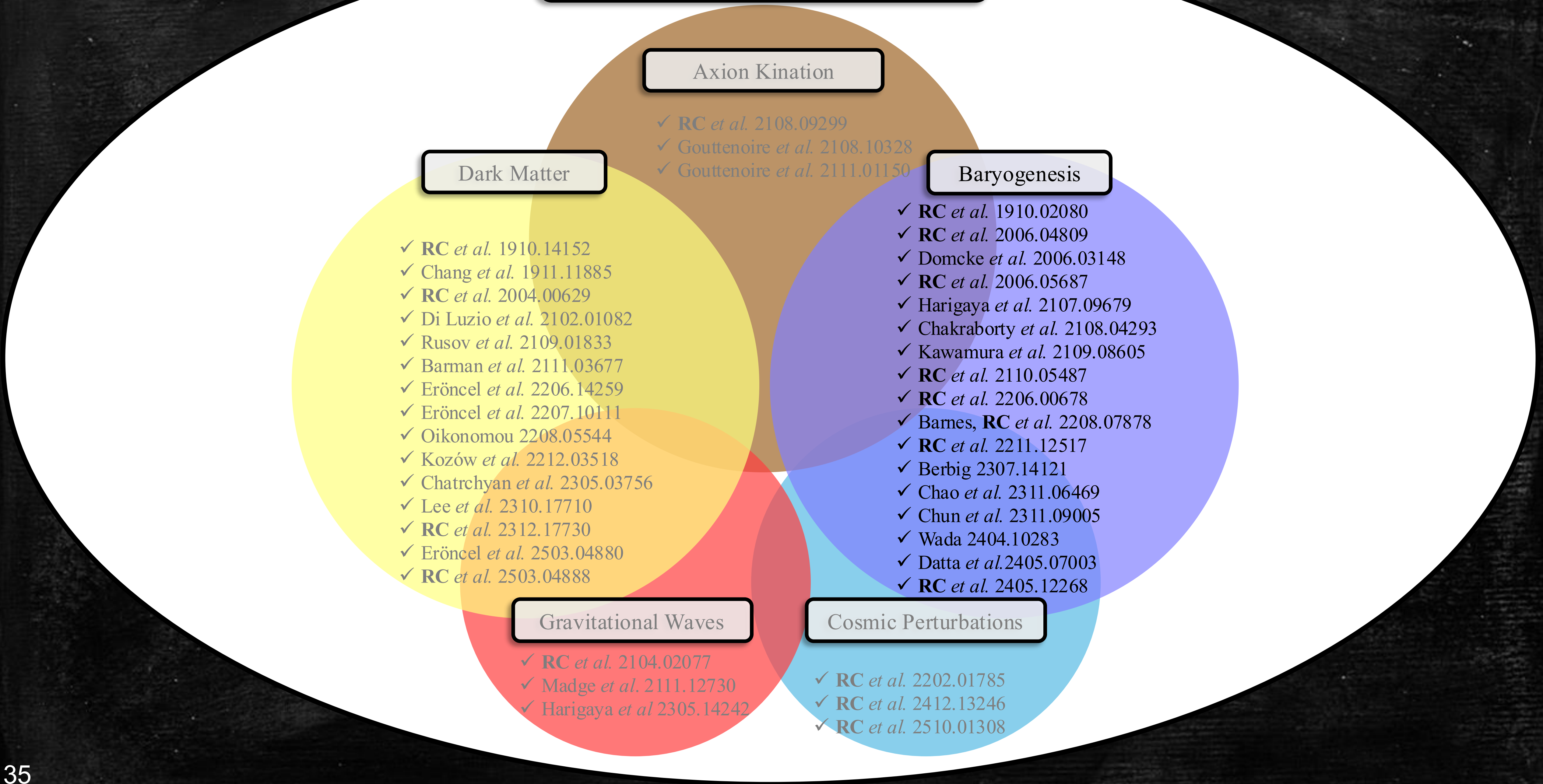
Known extensions:

1. Lepto-axiogensis (neutrino mass)
   2006.05687, 2108.04293, 2208.07878, 2402.10263, 2405.12268, …
2. RPV axigoenesis (R-parity violation in SUSY)
   2110.05487
3. Baryon asymmetry from magnetic helicity
   2211.12517
4. …

Axion Rotations

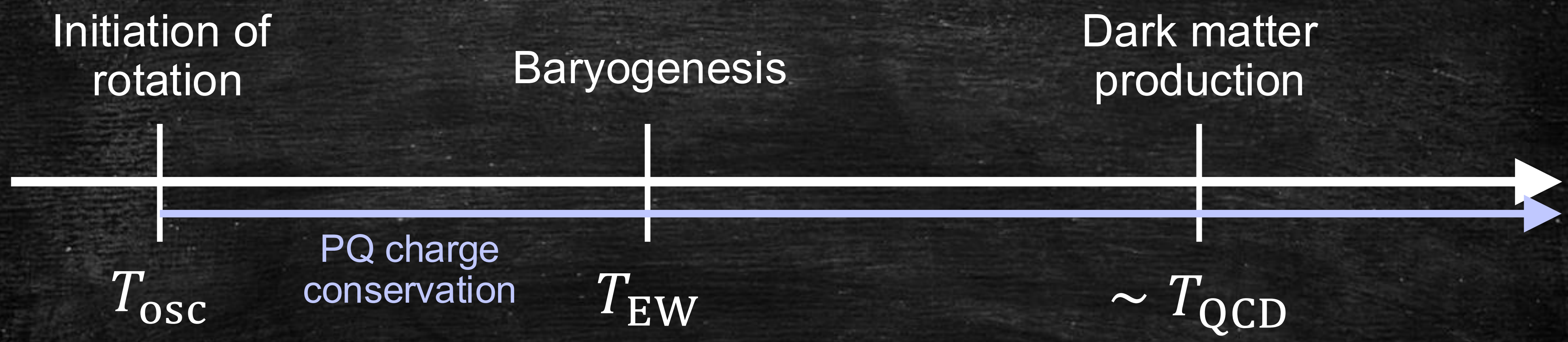


Modification of Kinetic Misalignment

Resolution:

1. Enhancing baryon asymmetry production efficiency.
2. Reducing dark matter production efficiency.

QCD Axion Cogenesis



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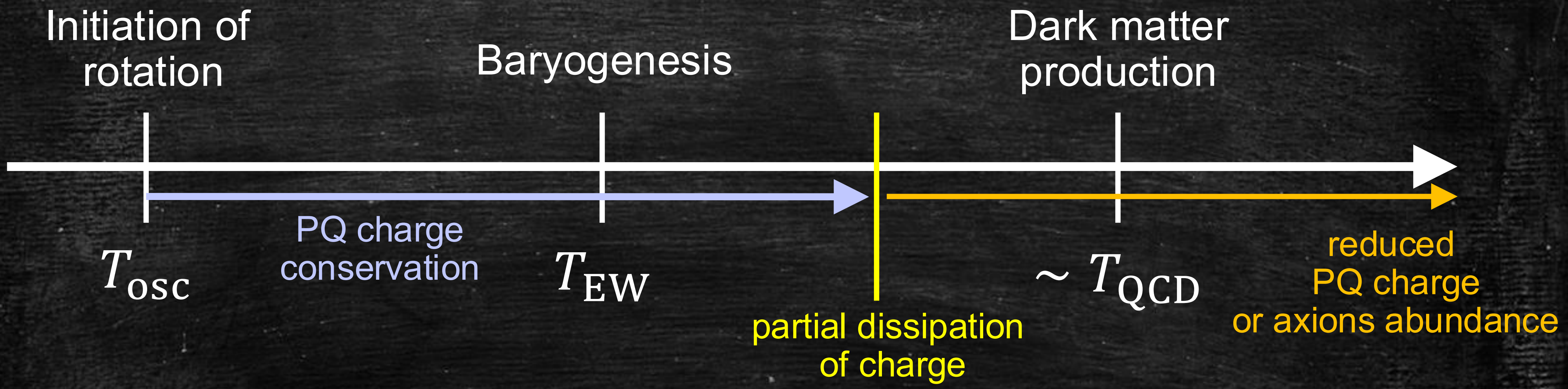
2511.10603 RC, K. Harigaya, I. R. Wang, and H. Xiao
2511.15794 P. Asadi, D. Cyncynates, and Stefania Gori

Modification of Kinetic Misalignment



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Axion-Monopole Interactions
dissipation mechanism

Dark Sector Model

$$\mathcal{L}_{\rm dark} \supset -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + \frac{1}{2}(D_\mu \Phi)^2 - V(\Phi) + \bar{f}\, i\gamma^\mu D_\mu f - y\, \Phi\, \bar{f} f + \frac{a}{f_a}\frac{\alpha_D}{8\pi} F^a_{\mu\nu}\tilde{F}^{a\mu\nu}.$$

Φ adjoint Higgs breaks SU(2) to U(1)

$$\mathcal{L}_{\rm IR} \supset -\frac{1}{4} F_{D\mu\nu} F_D^{\mu\nu} + \bar{f}\, i\gamma^\mu D_\mu f - m_f \bar{f} f + \frac{a}{f_a}\frac{\alpha_D}{8\pi} F_{D\mu\nu}\tilde{F}_D^{\mu\nu}$$

Monopoles exist

Witten effect

Monopole becomes dyons
Dyon mass becomes axion-dependent $m_D(a)$

As the axion rotates, the dyons become heavy enough to decay to dark fermions, dissipating axions' kinetic energy. Ultimately, axion dark matter overproduction is avoided

Monopoles

- Gauge symmetry breaking can inevitably lead to topological defects

  For $G \to H$, if $\pi_2(G/H) \neq 0$, ’t Hooft–Polyakov monopoles exist.

- The simplest example is for $G = SU(2), H = U(1)$.

  This breaking is achieved by an adjoint Higgs field.

$$\pi_2(SU(2)_D/U(1)_D) = \mathbb{Z}$$

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- Additionally, we assume the presence of

$$\mathcal{L} \supset \theta \frac{\alpha_D}{8\pi} F'_{\mu\nu}\tilde{F}'^{\mu\nu}$$ and light dark fermions f charged under $SU(2)$

Dirac Quantization Condition

- A monopole produces magnetic flux through a sphere

$$\Phi = \int_{S^2} \mathbf{B} \cdot d\mathbf{S} = Q_M$$

- A charged particle moving around a magnetic flux picks up a phase in the Aharonov–Bohm effect

$$\Delta\varphi = e_{\min}\Phi$$

- Wavefunction must be single-valued

$$e_{\min} Q_M = 2\pi n$$

Witten Effect

- Gauss's law in the presence of $\mathcal{L} \supset \theta \frac{\alpha_D}{8\pi} F'_{\mu\nu} \tilde{F}'^{\mu\nu}$

$$Q_{\text{enclosed}} = \oint_S \mathbf{D} \cdot d\mathbf{S} \qquad \mathbf{D} = \mathbf{E} + \frac{e_D^2 \theta}{8\pi^2} \mathbf{B}$$

light fermion charge

- Charge enclosed $Q_M = \frac{4\pi n}{e_D}$ from Dirac quantization with $e_{\text{min}} = \frac{e_D}{2}$

$$Q_{\text{enclosed}} = e_D n + \frac{e_D^2 \theta}{8\pi^2} Q_M = e_D \left(n - \frac{\theta}{2\pi} \right)$$

n = dyon level

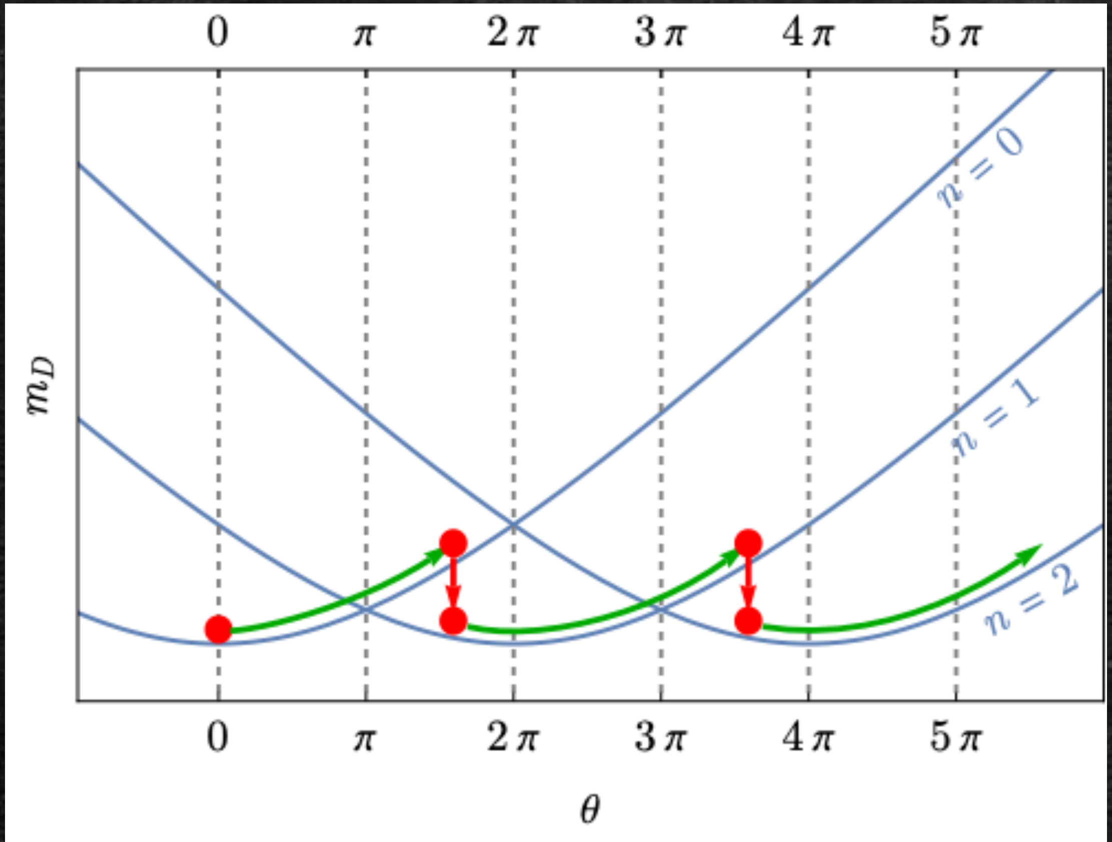
The monopole becomes a dyon whose electric charge depends on the axion.

This leads to

$$m_D \approx 2\, m_f \sin^2 \left(\frac{\pi}{2} \left[n - \frac{\theta}{2\pi} \right] \right) + \frac{\alpha_D}{2} m_f \left(n - \frac{\theta}{2\pi} \right)^2$$

A. Hook, C. Ristow, JHEP 03 (2025) 042

Magnetic Monopoles Dissipation Mechanism



As θ rotates, the axion kinetic energy is being converted into dyon mass energy: the dyon mass increases along a branch.

At the level crossing, the dyon drops to a lower branch and releases energy. That released energy goes into dark fermions.

Axion kinetic energy is hence dissipated.

2309.16570 K. S. Jeong, S. Nakagawa, F. Takahashi, M. Yamada
2511.10603 RC, K. Harigaya, I. R. Wang, and H. Xiao

The dyon mass in the presence of light fermions is given by

$$m_D \approx 2\,m_f \sin^2\left(\frac{\pi}{2}\left[n - \frac{\theta}{2\pi}\right]\right) + \frac{\alpha_D}{2} m_f \left(n - \frac{\theta}{2\pi}\right)^2$$

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Magnetic Monopoles Dissipation Mechanism

Summary

As the axion field evolves, it acts as a time-dependent θ-angle,

- ✓ shifting the spectrum of the dyon (particle with electric and magnetic charges)
- ✓ causing the dyon's preferred electric charge level and mass to change
- ✓ leading to level crossings, where the dyon transitions to a lower-energy state by emitting light fermions
- ✓ dissipating the axion kinetic energy in each crossing

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Axion Energy Dissipation

- The energy dissipation rate of the axion is given by

$$m_M = \frac{4\pi v_D}{e_D} = \frac{m_W}{\alpha_D}$$

$$\dot\rho_\theta = \frac{\dot\theta}{2\pi} n_M \cdot (2m_f) = \frac{\dot\theta}{\pi}\rho_M \frac{m_f}{m_M} = \frac{\dot\theta}{\pi}\rho_M \alpha_D \frac{m_f}{m_W}$$

rate of level crossing

monopole number density

energy dissipated per monopole decay

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- The axion rotational energy density is given by

$$\rho_\theta = \frac{1}{2}\dot{\theta}^2 f_a^2 = \frac{1}{2}\dot{\theta} n_\theta$$

kinetic energy

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- The dissipation rate due to level crossing of monopoles

$$\Gamma_\theta \equiv \frac{\dot{\rho}_\theta}{\rho_\theta} = \frac{2\alpha_D}{\pi}\frac{m_f}{m_W}\frac{1}{Y_\theta}\boxed{\frac{\rho_M}{s}} = \frac{2\alpha_D}{\pi}\frac{m_f}{m_W}\frac{f_M \xi_{\rm DM}}{Y_\theta}$$

initially redshift invariant

$f_M \xi_{\rm DM}$ $\qquad \xi_{\rm DM} \simeq 0.44\ {\rm eV}$

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Axion Energy Dissipation

Dissipation starts when $\Gamma_\theta > H$ and continues until the axion is trapped by the potential, ending the necessary level crossing.

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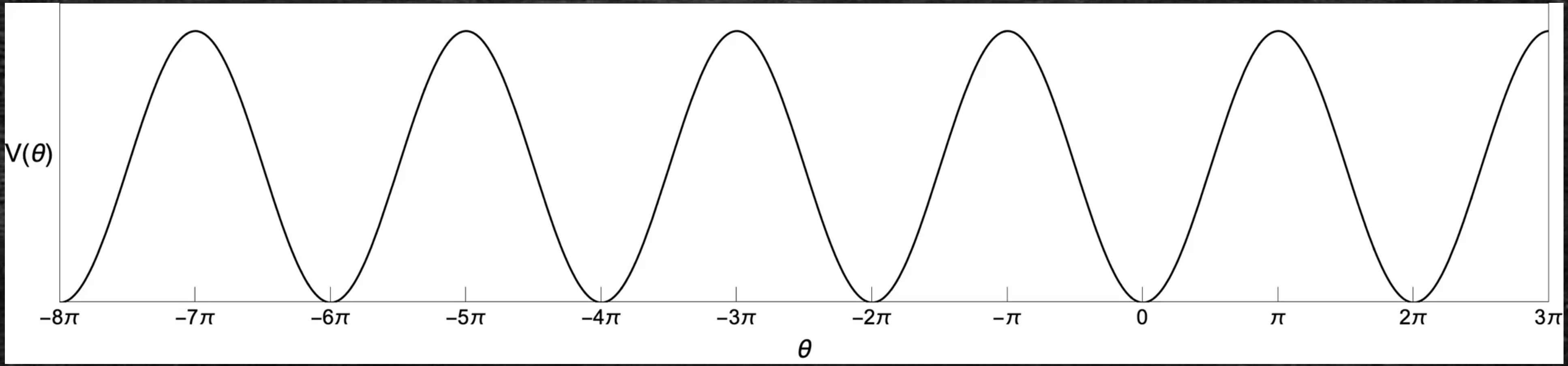

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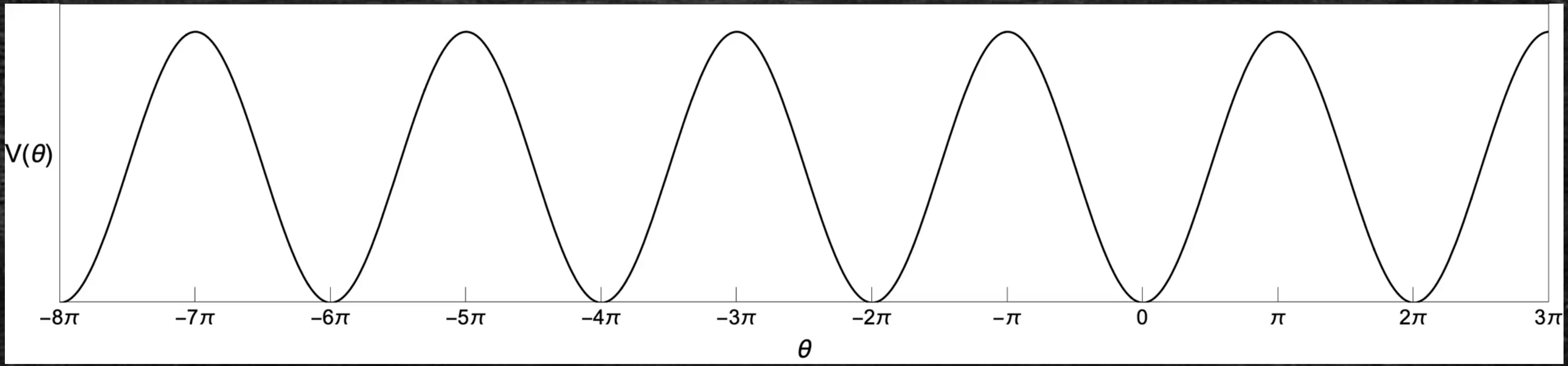

This axion potential can come from QCD or from dyons

$$V_a(\theta) = V_{\text{QCD}}(\theta) + V_{\text{dyon}}(\theta)$$

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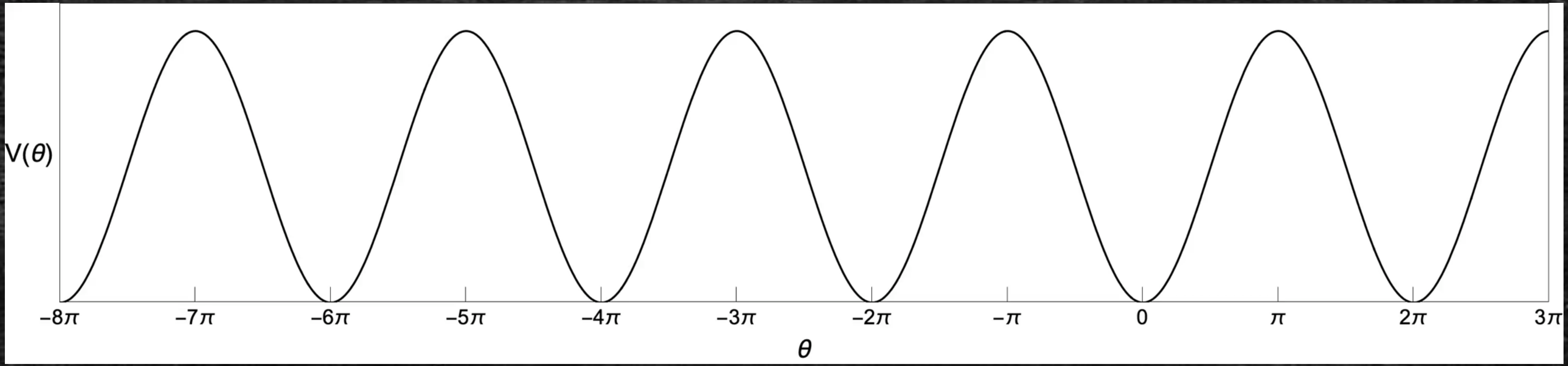

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$$V_a(\theta) = V_{\mathrm{QCD}}(\theta) + V_{\mathrm{dyon}}(\theta)$$

Namely, there always remains a nonzero axion abundance.

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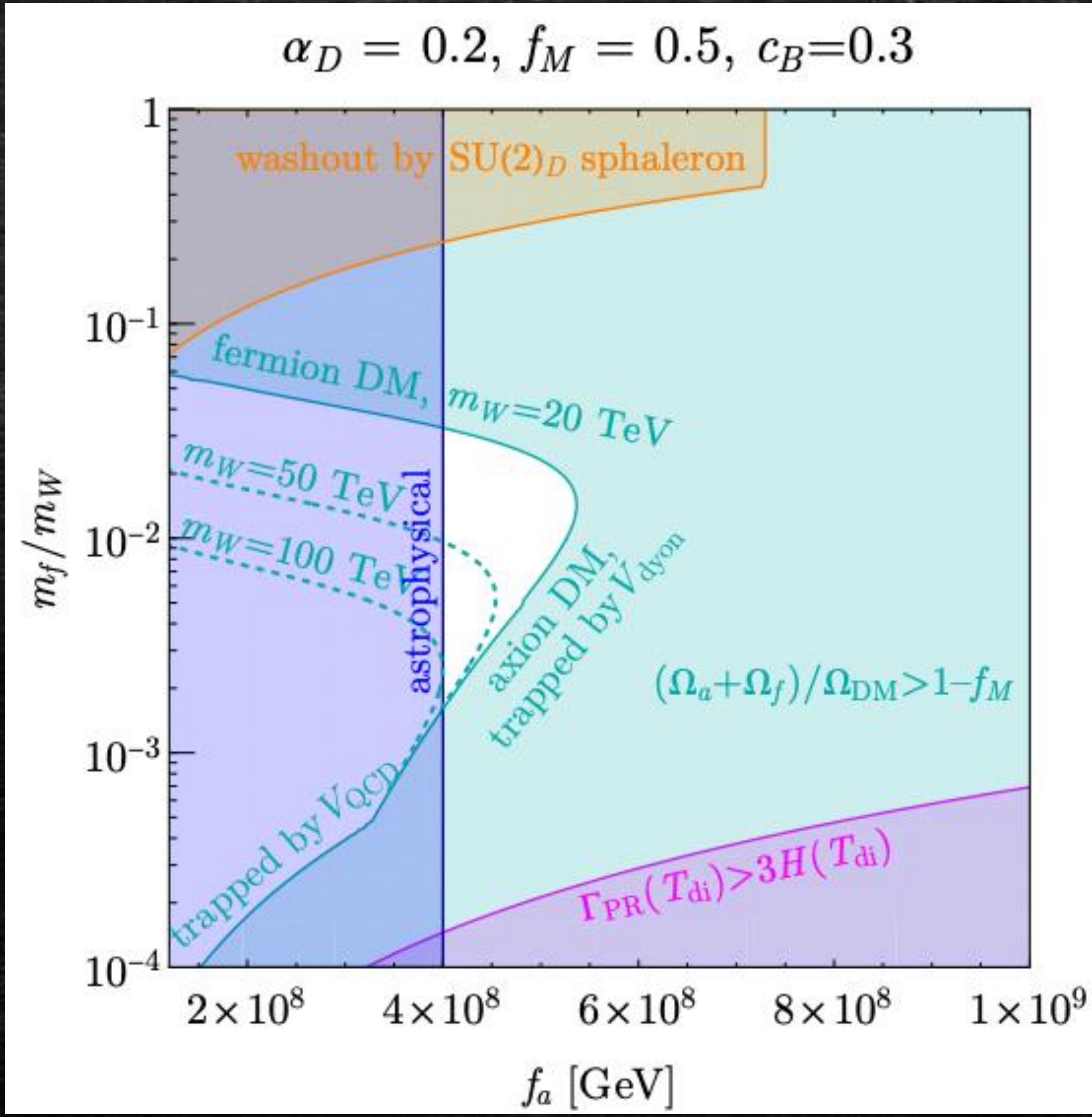
Parameter Space for a QCD Axion

Dissipation rate

$$\Gamma_\theta = \frac{2\alpha_D}{\pi}\frac{m_f}{m_W}\frac{f_M \xi_{\rm DM}}{Y_\theta}$$



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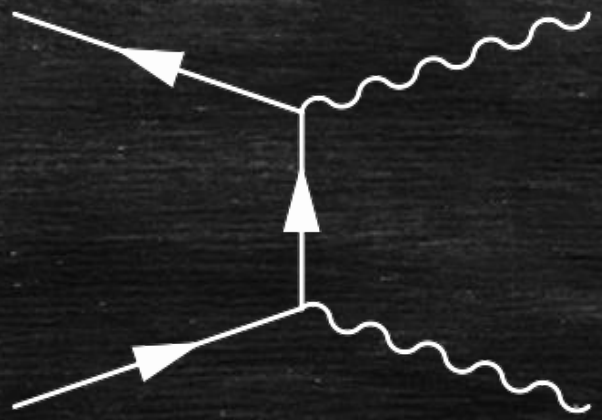
Fermion Abundance

Dark fermions produced from dyon decays annihilate and the relics contributes to the dark matter abundance.

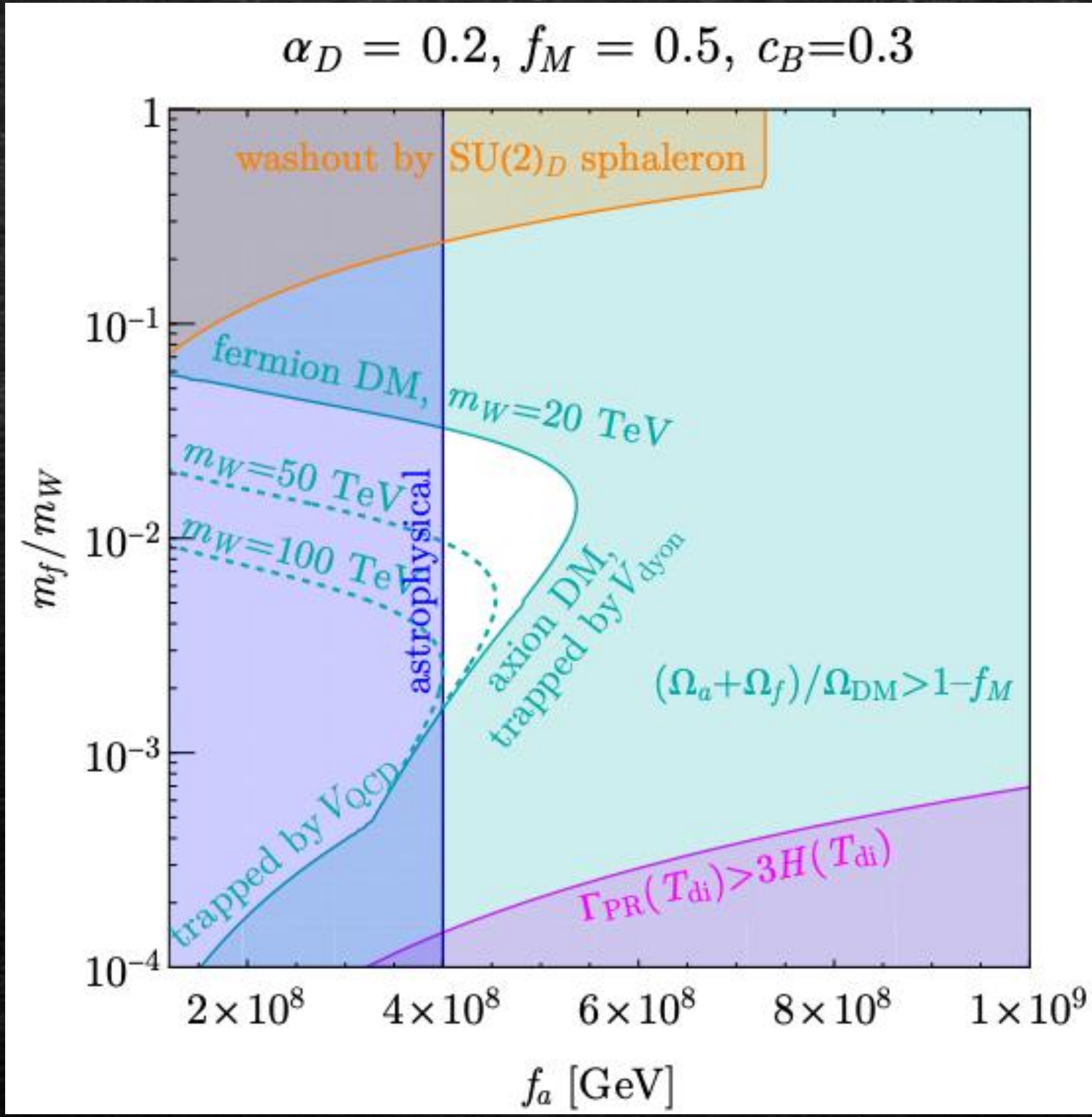


$$(\sigma v)_0 \simeq \frac{\pi \alpha_D^2}{16 m_f^2}$$

Freeze-out condition:

$$n_f \langle \sigma v \rangle = 3H = \Gamma_\theta$$

Parameter Space for a QCD Axion



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Axion Rotations

Axion Kination

- ✓ **RC** *et al.* 2108.09299
- ✓ Gouttenoire *et al.* 2108.10328
- ✓ Gouttenoire *et al.* 2111.01150

Dark Matter

- ✓ **RC** *et al.* 1910.14152
- ✓ Chang *et al.* 1911.11885
- ✓ **RC** *et al.* 2004.00629
- ✓ Di Luzio *et al.* 2102.01082
- ✓ Rusov *et al.* 2109.01833
- ✓ Barman *et al.* 2111.03677
- ✓ Eröncel *et al.* 2206.14259
- ✓ Eröncel *et al.* 2207.10111
- ✓ Oikonomou 2208.05544
- ✓ Kozów *et al.* 2212.03518
- ✓ Chatrchyan *et al.* 2305.03756
- ✓ Lee *et al.* 2310.17710
- ✓ **RC** *et al.* 2312.17730
- ✓ Eröncel *et al.* 2503.04880
- ✓ **RC** *et al.* 2503.04888

Baryogenesis

- ✓ **RC** *et al.* 1910.02080
- ✓ **RC** *et al.* 2006.04809
- ✓ Domcke *et al.* 2006.03148
- ✓ **RC** *et al.* 2006.05687
- ✓ Harigaya *et al.* 2107.09679
- ✓ Chakraborty *et al.* 2108.04293
- ✓ Kawamura *et al.* 2109.08605
- ✓ **RC** *et al.* 2110.05487
- ✓ **RC** *et al.* 2206.00678
- ✓ Barnes, **RC** *et al.* 2208.07878
- ✓ **RC** *et al.* 2211.12517
- ✓ Berbig 2307.14121
- ✓ Chao *et al.* 2311.06469
- ✓ Chun *et al.* 2311.09005
- ✓ Wada 2404.10283
- ✓ Datta *et al.*2405.07003
- ✓ **RC** *et al.* 2405.12268

Gravitational Waves

- ✓ **RC** *et al.* 2104.02077
- ✓ Madge *et al.* 2111.12730
- ✓ Harigaya *et al* 2305.14242

Cosmic Perturbations

- ✓ **RC** *et al.* 2202.01785
- ✓ **RC** *et al.* 2412.13246
- ✓ **RC** *et al.* 2510.01308

Conclusions

- ✓ New axion dynamics allows the QCD axion to simultaneously explain
  - ✓ Strong CP problem
  - ✓ dark matter abundance
  - ✓ baryon asymmetry
- ✓ This paradigm predicts exciting phenomenology
  - ✓ specific axion mass-coupling relations
- ✓ Other possible signatures include
  - ✓ gravitational lensing of axion mini-clusters
  - ✓ axion kination: unique gravitational wave spectra
  - ✓ enhanced matter power spectrum
  - ✓ warm axion dark matter
- ✓ New model building opportunities
  - ✓ other open questions across disciplines