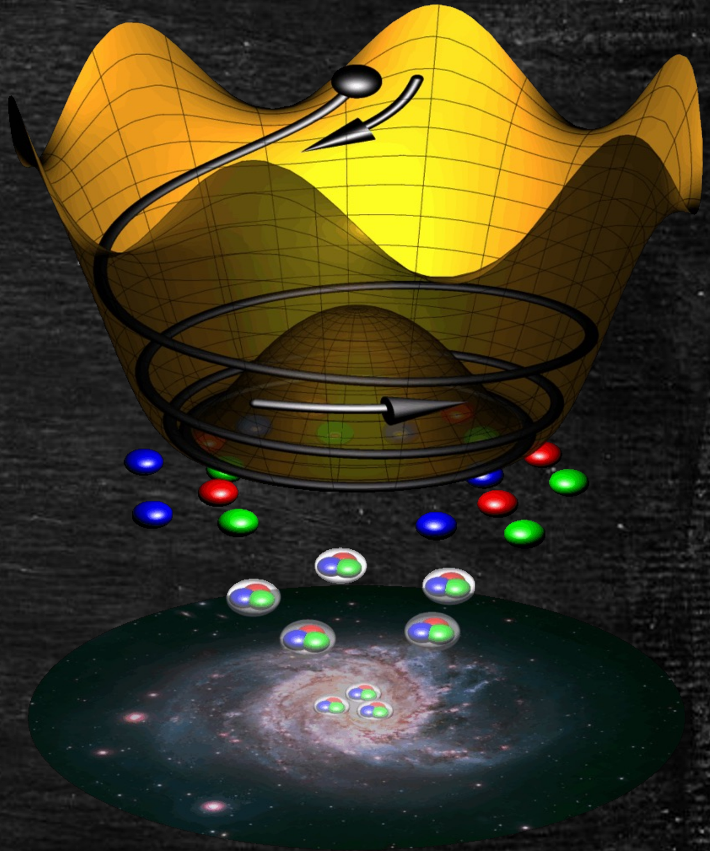
Cosmological Implications of Axion Rotations



PNU-IBS workshop on Axion Physics : Search for axions
Haeundae beach, Busan, South Korea

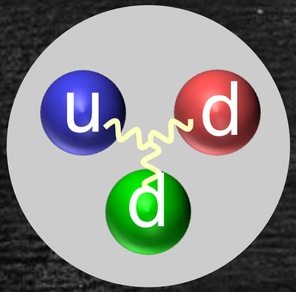
December 8th, 2023

Raymond Co

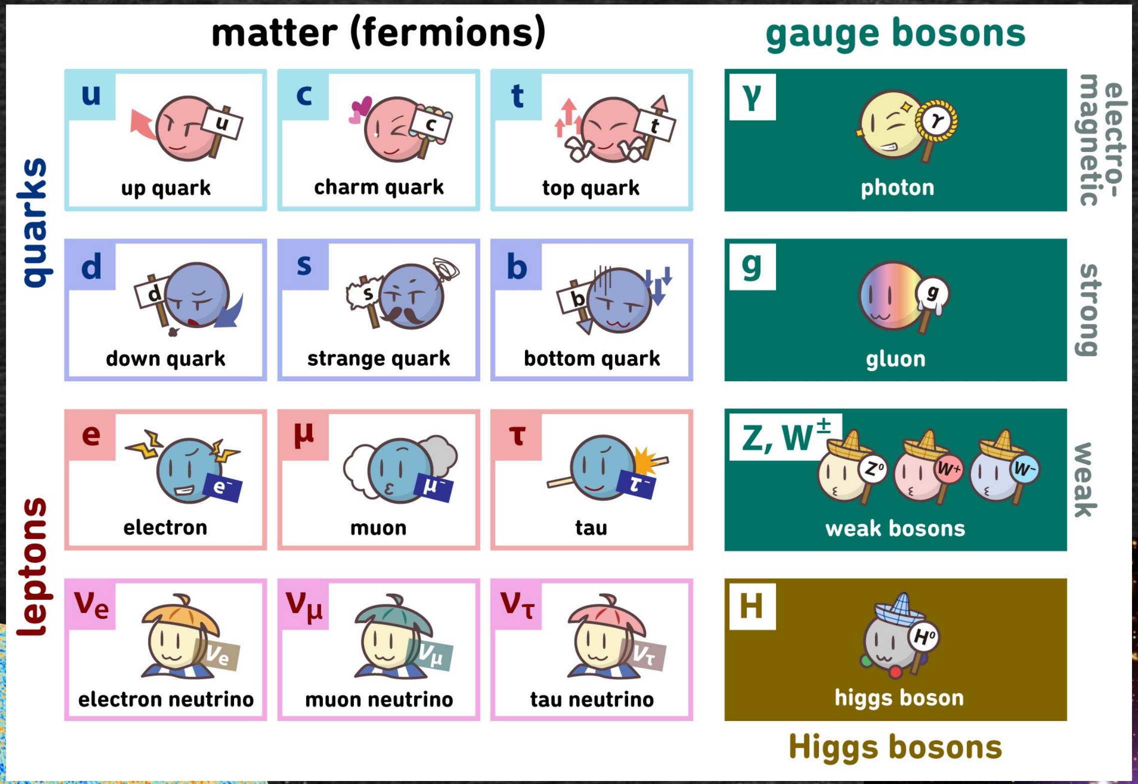
Indiana University

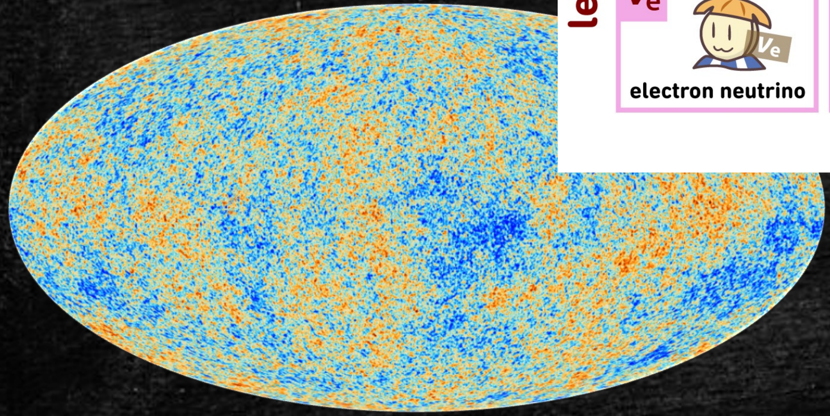
Outline of the Talk

strong CP problem



neutron





Source: Planck

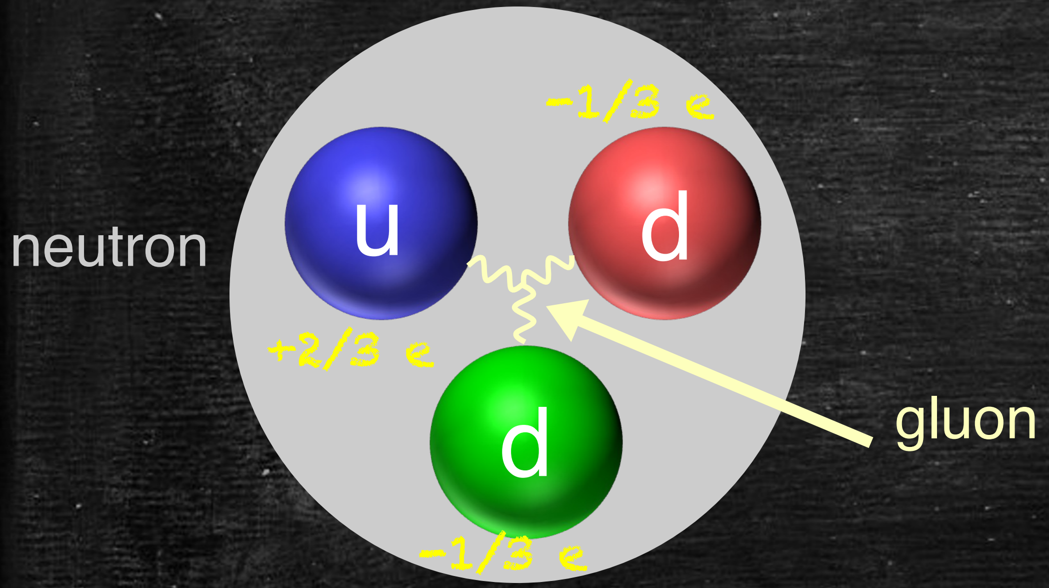
matter-antimatter asymmetry

dark matter

Review of the QCD Axion

Strong CP Problem

"Charge-Parity" symmetry



Quantum field theory:

gluon

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

$$|d_n| \simeq 2.4 \times 10^{-16}\ \bar{\theta}\ \mathrm{e} \cdot \mathrm{cm}$$

Crewther, Di Vecchia, Veneziano, Witten 1979, Pospelov, Ritz 2000

Experiments:

$$|d_n| \lesssim 1.8 \times 10^{-26}\ \mathrm{e} \cdot \mathrm{cm}$$

PRL 97, 131801 2006, PRL 124, 081803 2020

Strong CP problem:

$$\bar{\theta} \lesssim 10^{-10}$$

Why exceedingly small?

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!

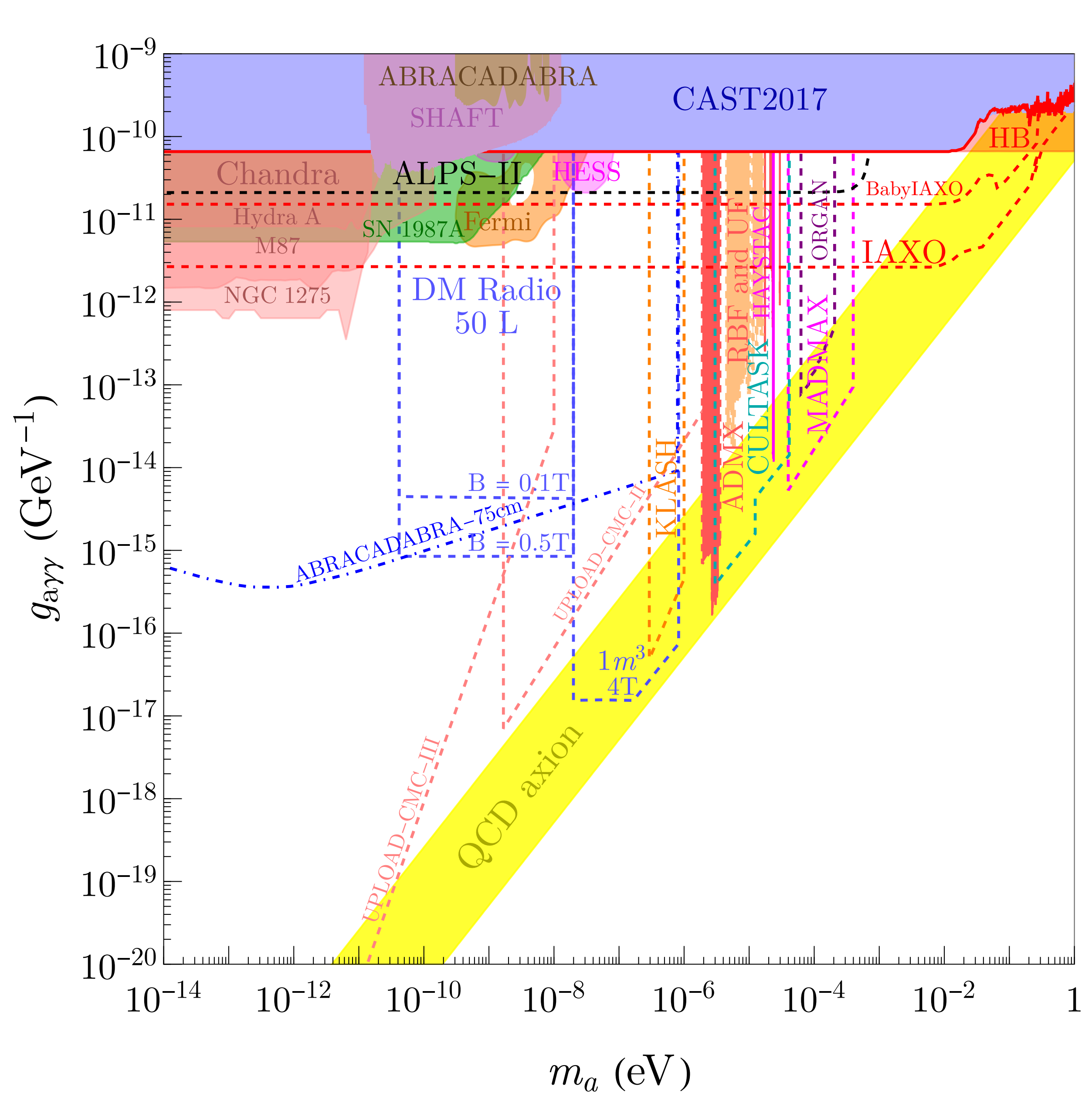
Status of Axion Dark Matter

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)

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damped simple harmonic oscillator

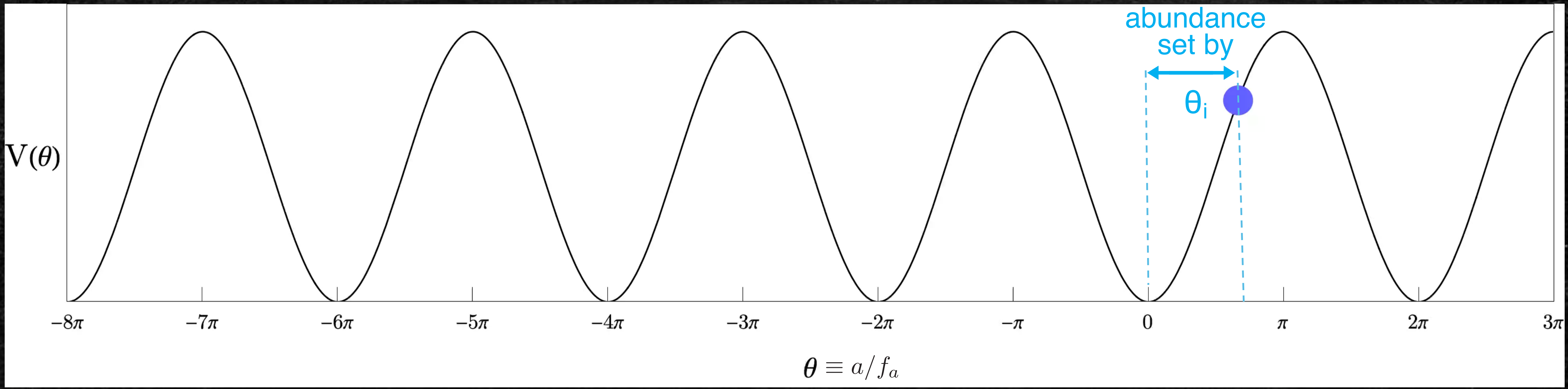
Equation of motion: $$\left(\partial_t^2 + 3H\partial_t + m_a^2\right) a = 0$$

Hubble "friction"
(from cosmic expansion)

Misalignment Mechanism

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

oscillations start when
$H \lesssim m_a$



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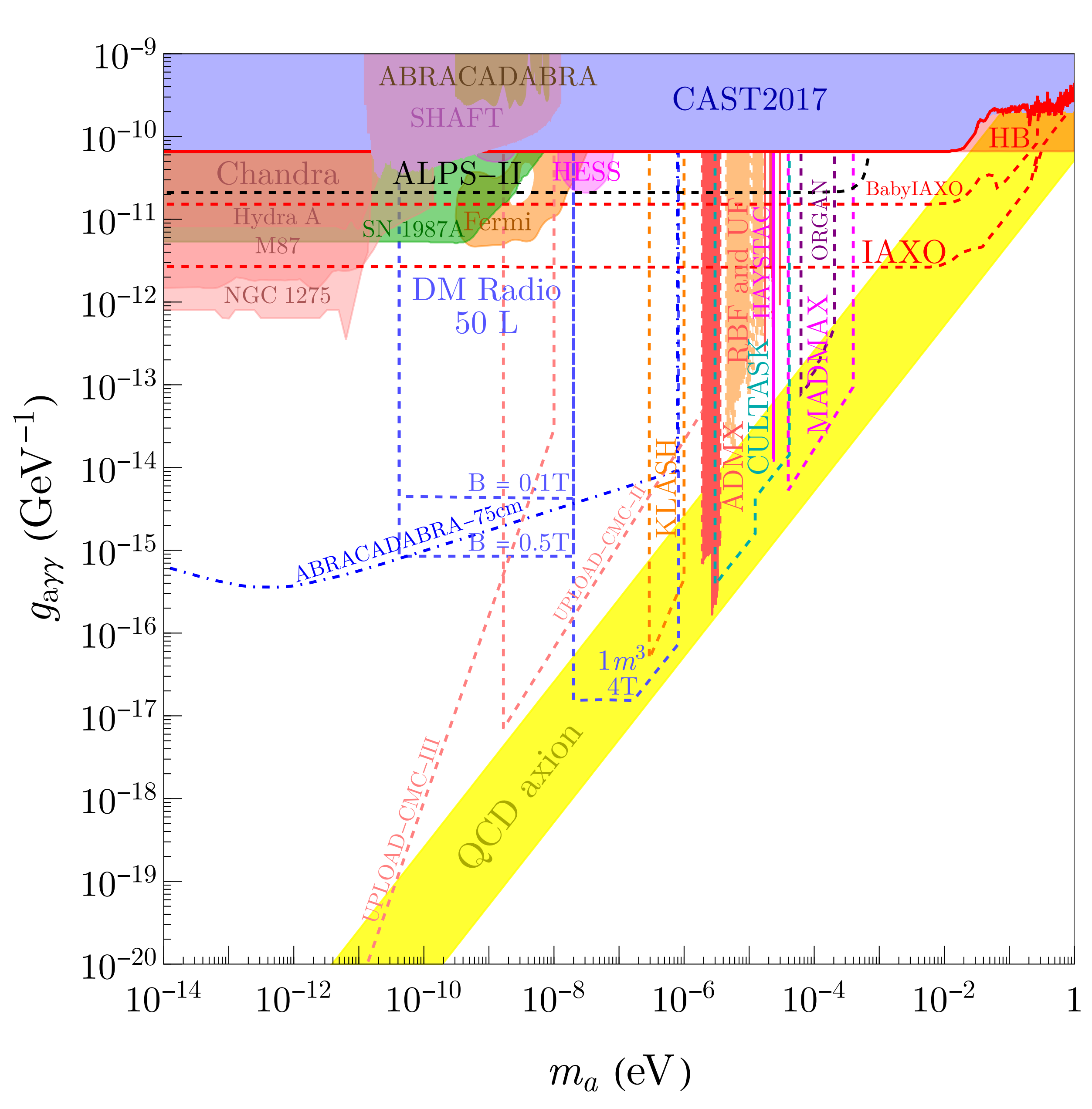
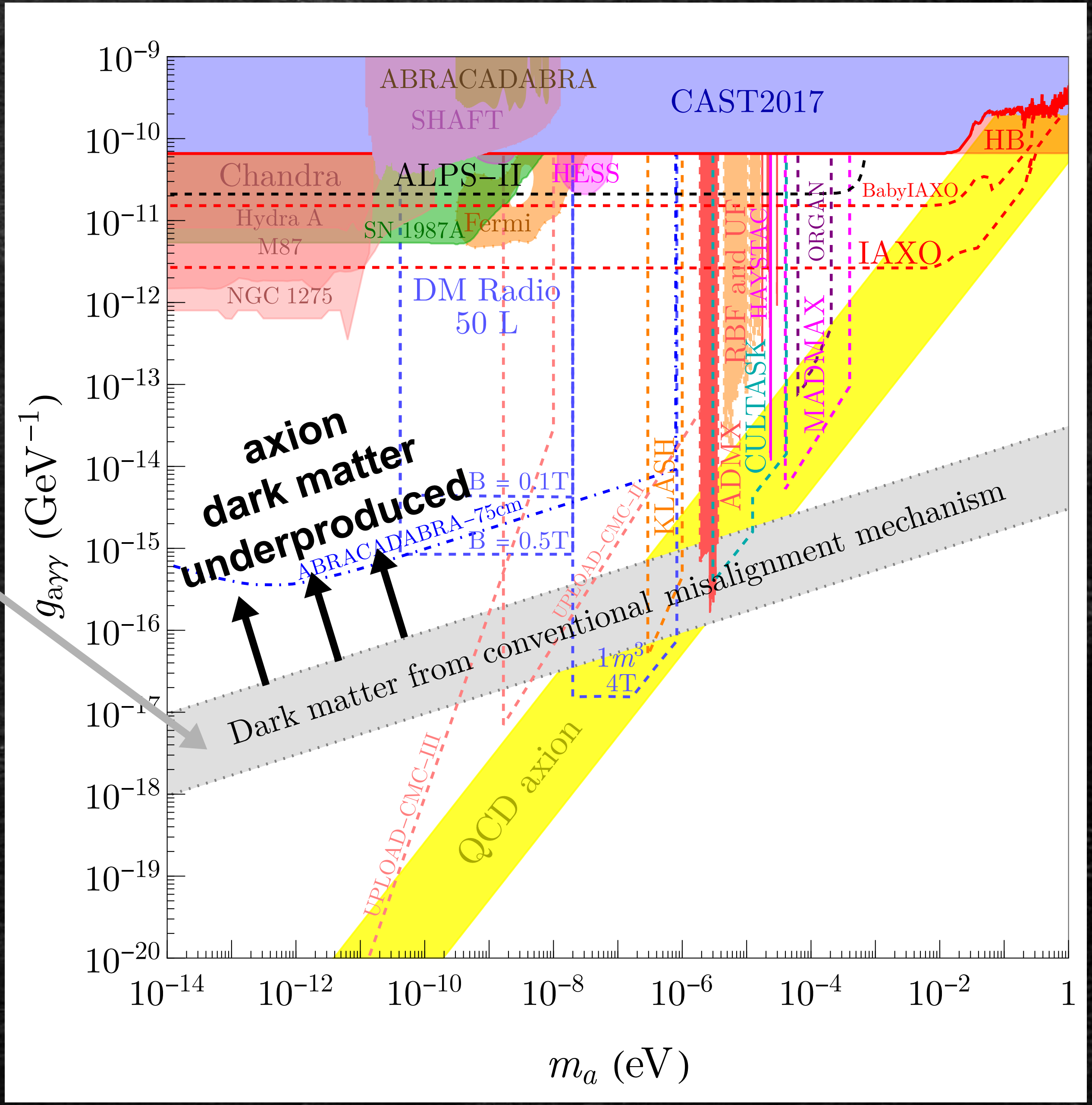


Axion Dark Matter Abundance

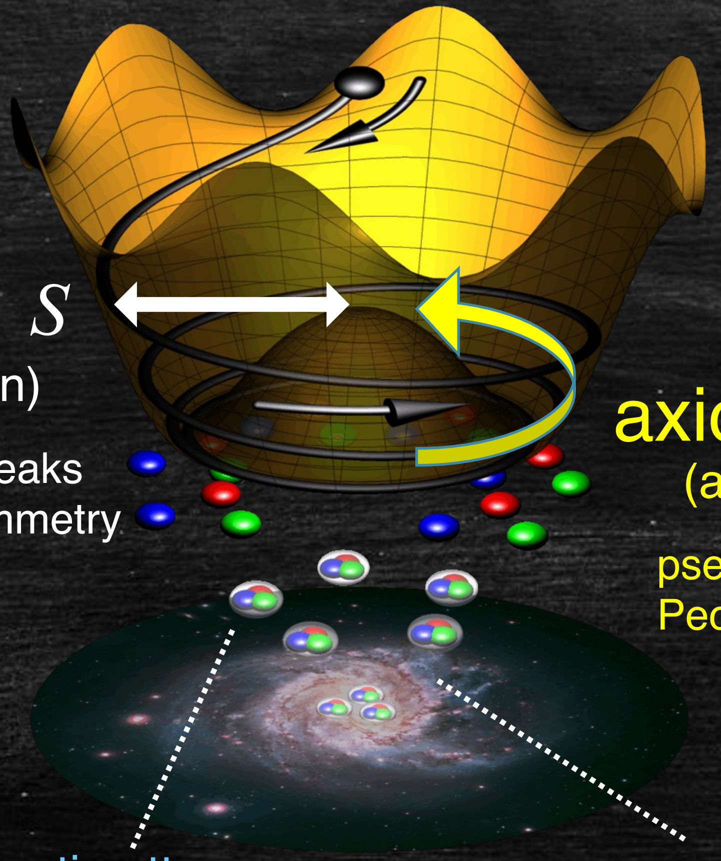
We assume $\theta_i = \mathcal{O}(1)$ here.



Axion Rotation

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

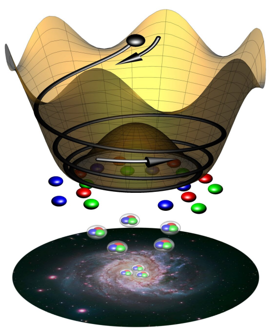
$$P = \frac{S + f_a}{\sqrt{2}} e^{i\frac{a}{f_a}}$$



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

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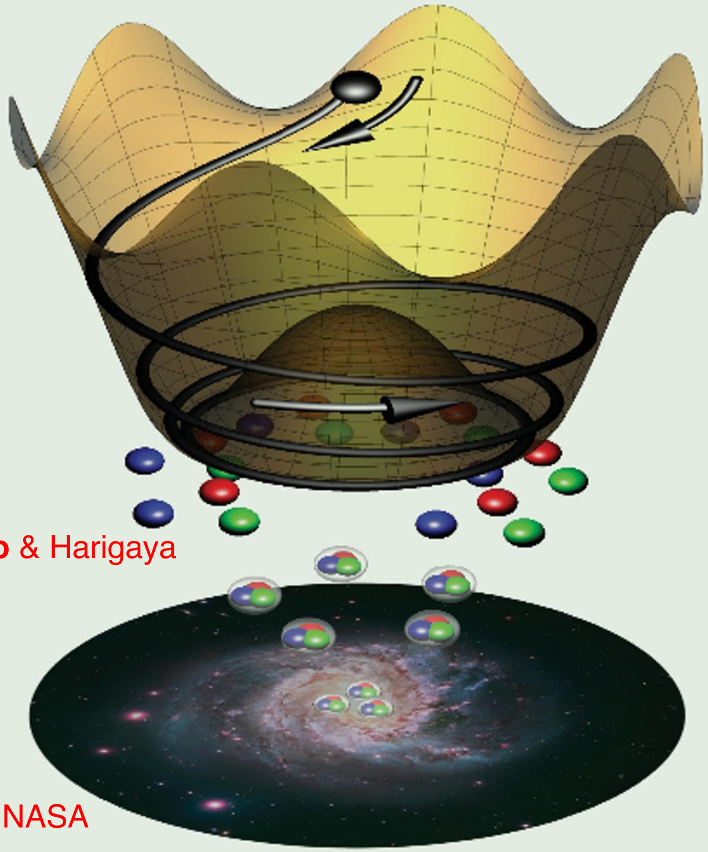
PHYSICAL REVIEW LETTERS

Articles published week ending 20 MARCH 2020



Graphic: **Co** & Harigaya

Photo: NASA

Published by American Physical Society

APS physics

Volume 124, Number 11

Quanta magazine | Physics | Mathematics | Bio

ABSTRACTIONS BLOG

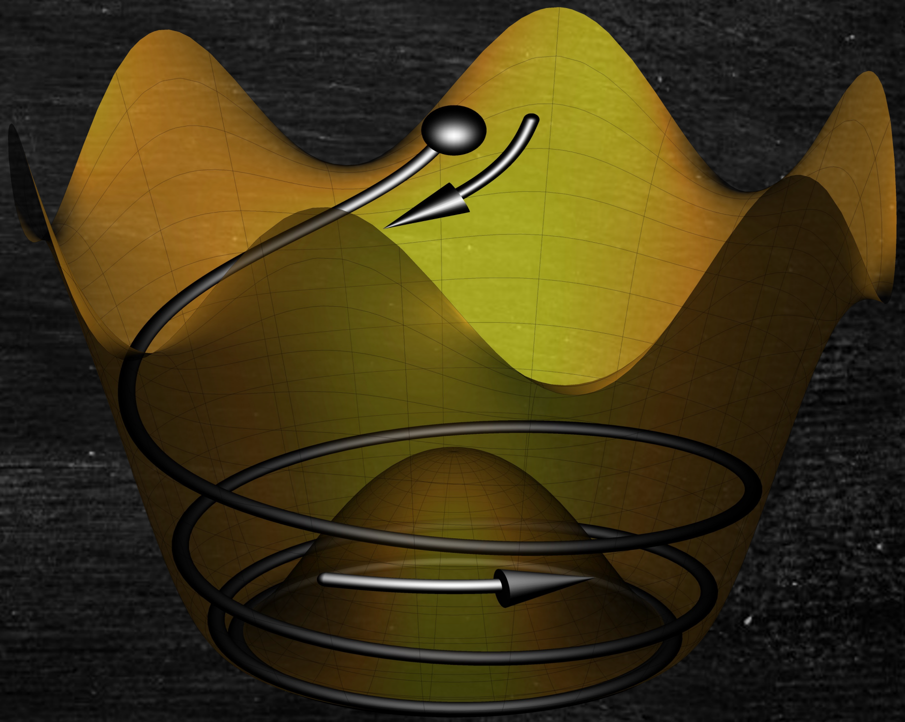
Axions Would Solve Another Major Problem in Physics

6

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

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 :

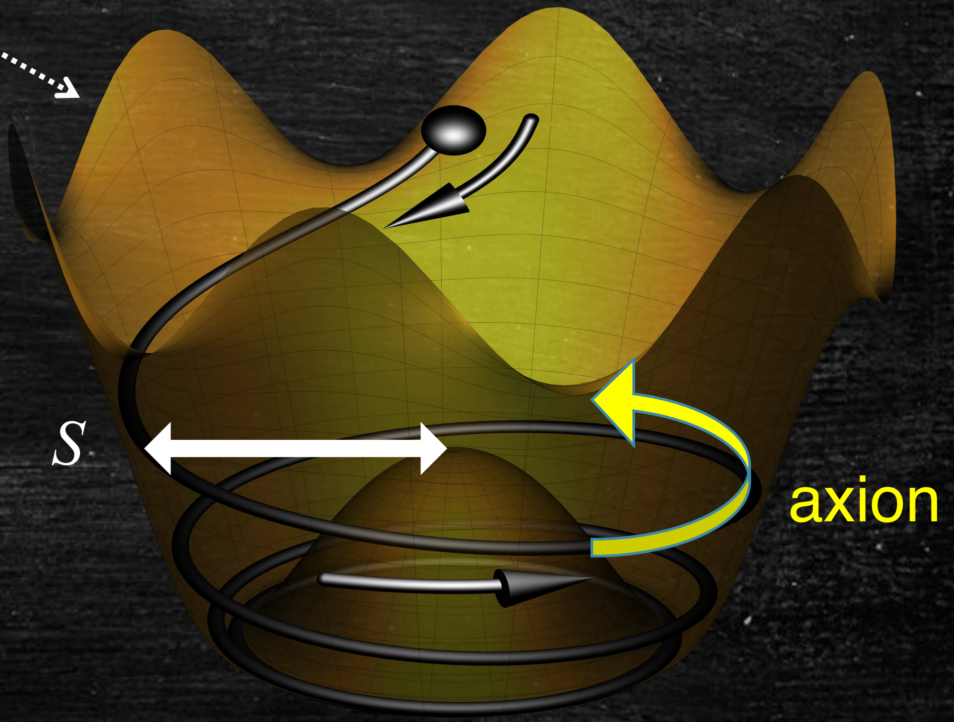
$$V(P) \sim \frac{P^n}{M^{n-4}} e^{i\varphi} + \text{h.c.} \sim \frac{|P|^n}{M^{n-4}} \cos\left(n\frac{a}{f_a} + \varphi\right)$$

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

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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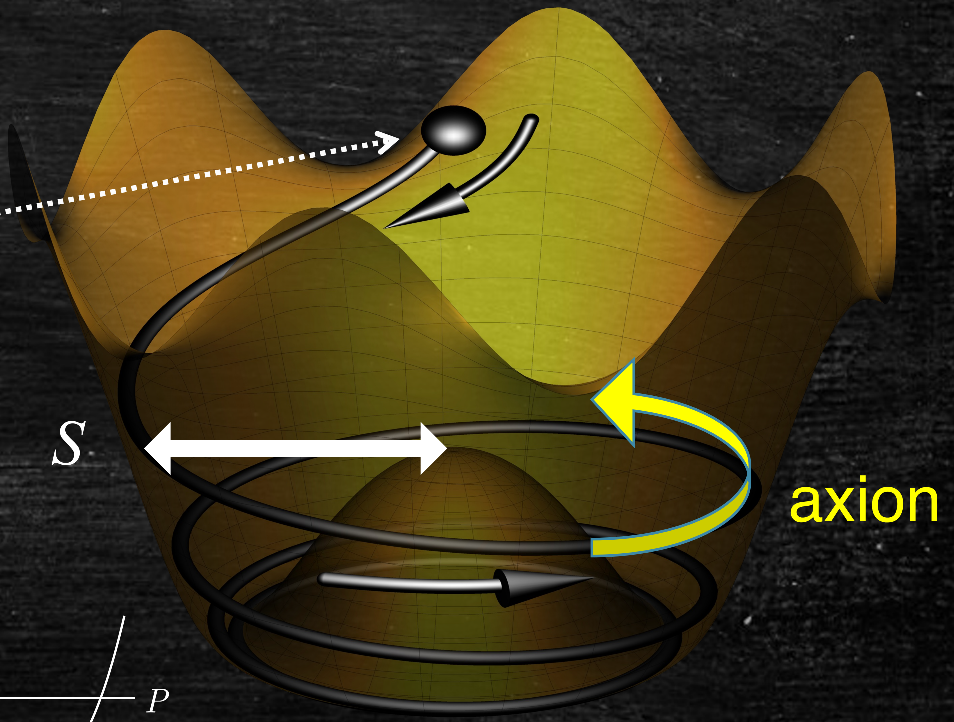


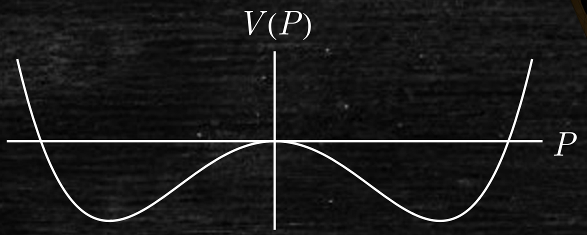
Large field value :

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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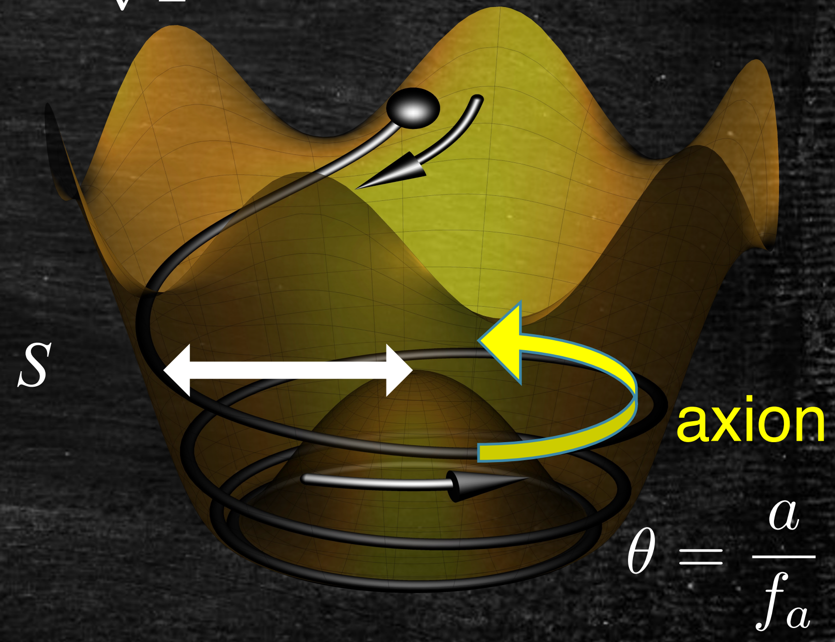
Asymmetry of PQ Charge

Noether charge associated with the shift symmetry

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

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

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



PQ asymmetry
PQ charge density = Rotation of PQ field

This is conserved soon after the initial kick.

Asymmetry of PQ Charge

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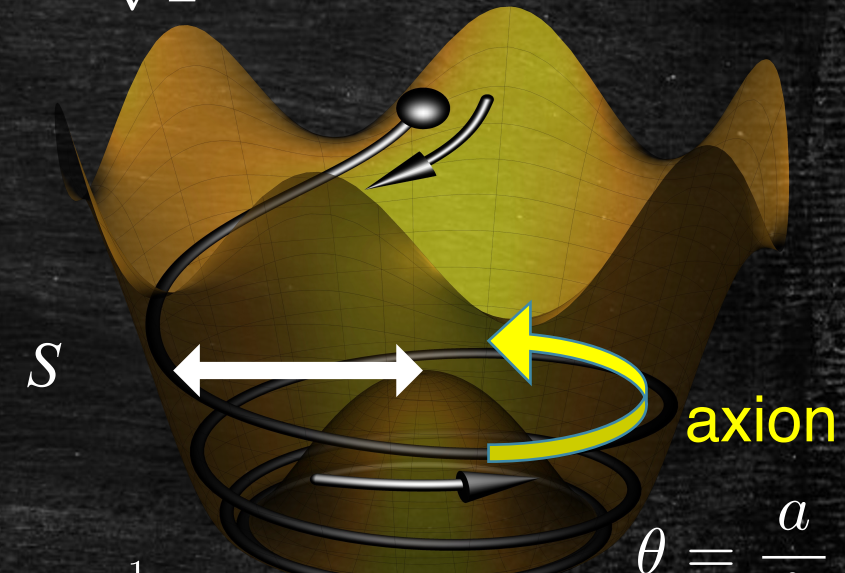


$$\theta = \frac{a}{f_a}$$

PQ asymmetry
PQ charge density = Rotation of PQ field

This is conserved soon after the initial kick.

What determines $\dot{\theta}$? Centripetal force!

$$F_c = ma_c$$

$$V'(S) = S\dot{\theta}^2$$

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

$V(S) \simeq \frac{1}{2}m_S^2 S^2$
from supersymmetry

$\dot{\theta} = m_S$ which is in turn set by supersymmetry scale.

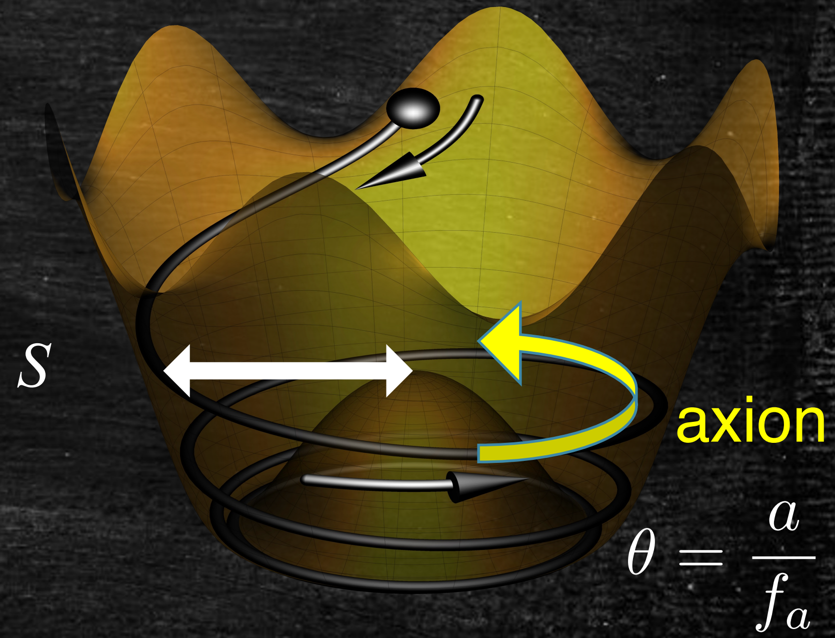
PQ Charge Evolution

Charge conservation:

scale factor of the universe

$$n_\theta = S^2 \dot{\theta} \propto \underline{R^{-3}}$$

dilution due to
cosmic expansion



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

PQ Charge Evolution

Charge conservation:

scale factor of the universe

$$n_\theta = S^2 \dot{\theta} \propto R^{-3}$$

dilution due to cosmic expansion

Large field ($S \gg f_a$):

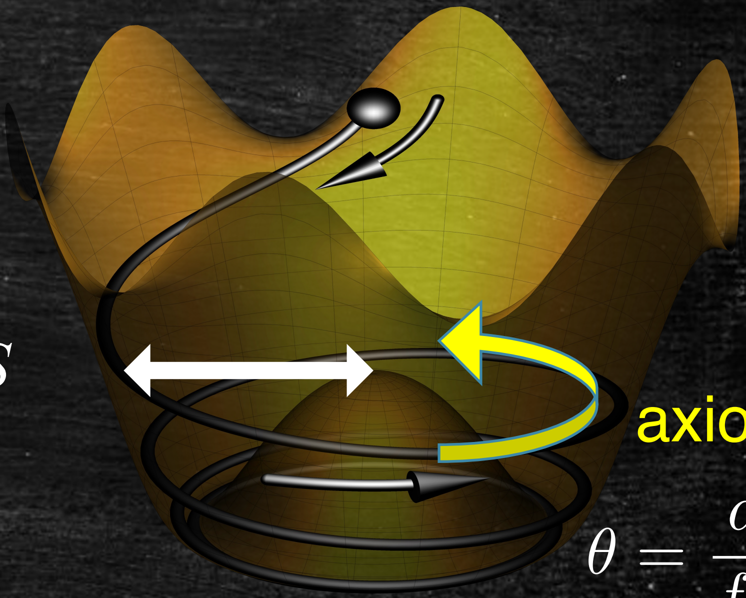
$S^2 \propto R^{-3}$ $\dot{\theta} = \text{constant}$

for quadratic potential

$V(S) \simeq \frac{1}{2} m_S^2 S^2$

$\rho_\theta = \dot{\theta}^2 S^2 \propto R^{-3}$

matter



At the minimum:

$S^2 = f_a^2$ $\dot{\theta} \propto R^{-3}$

$\rho_\theta = \dot{\theta}^2 f_a^2 \propto R^{-6}$

kination

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

Asymmetries in Thermal Equilibrium

The free energy is minimized at equilibrium.

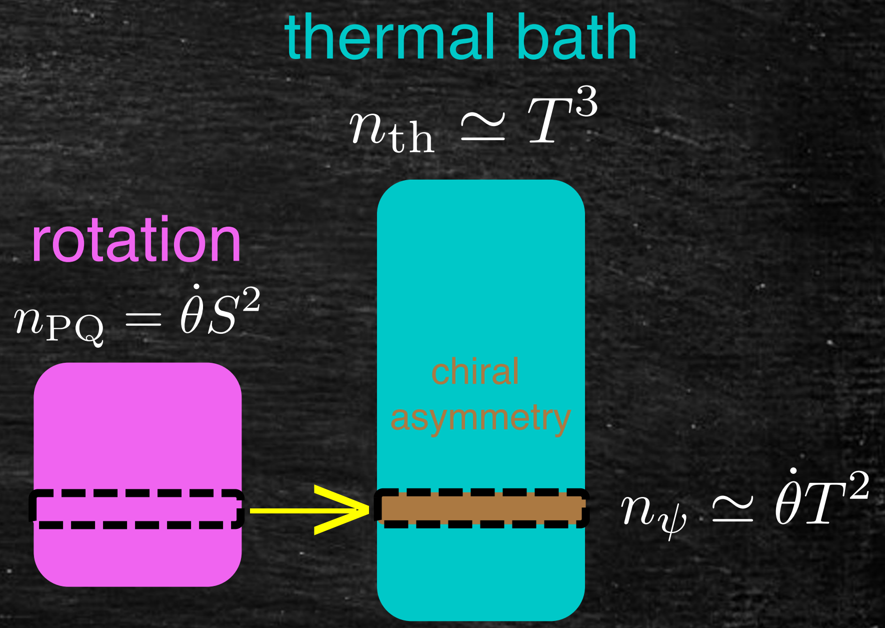
fermion asymmetry

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

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!

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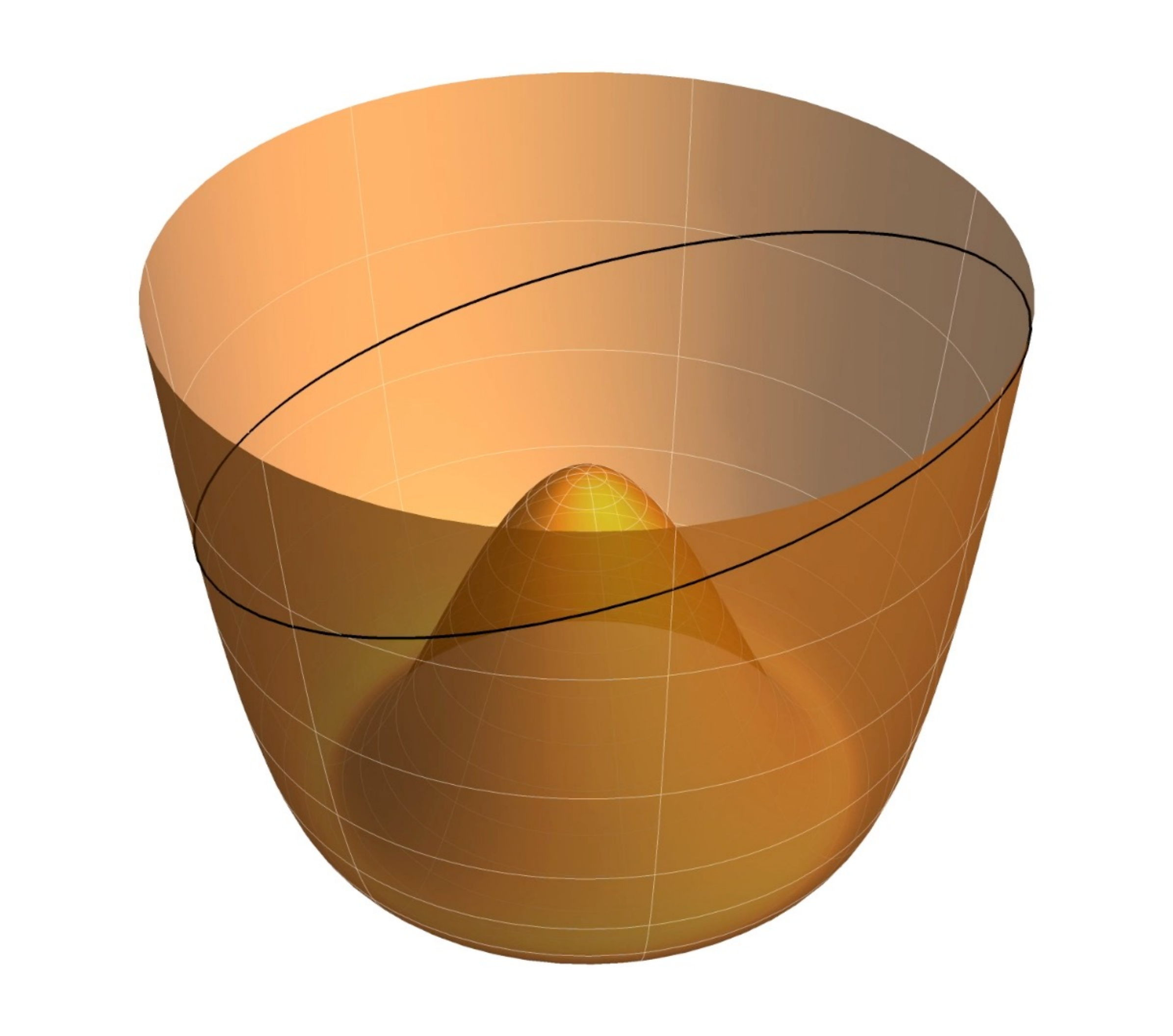
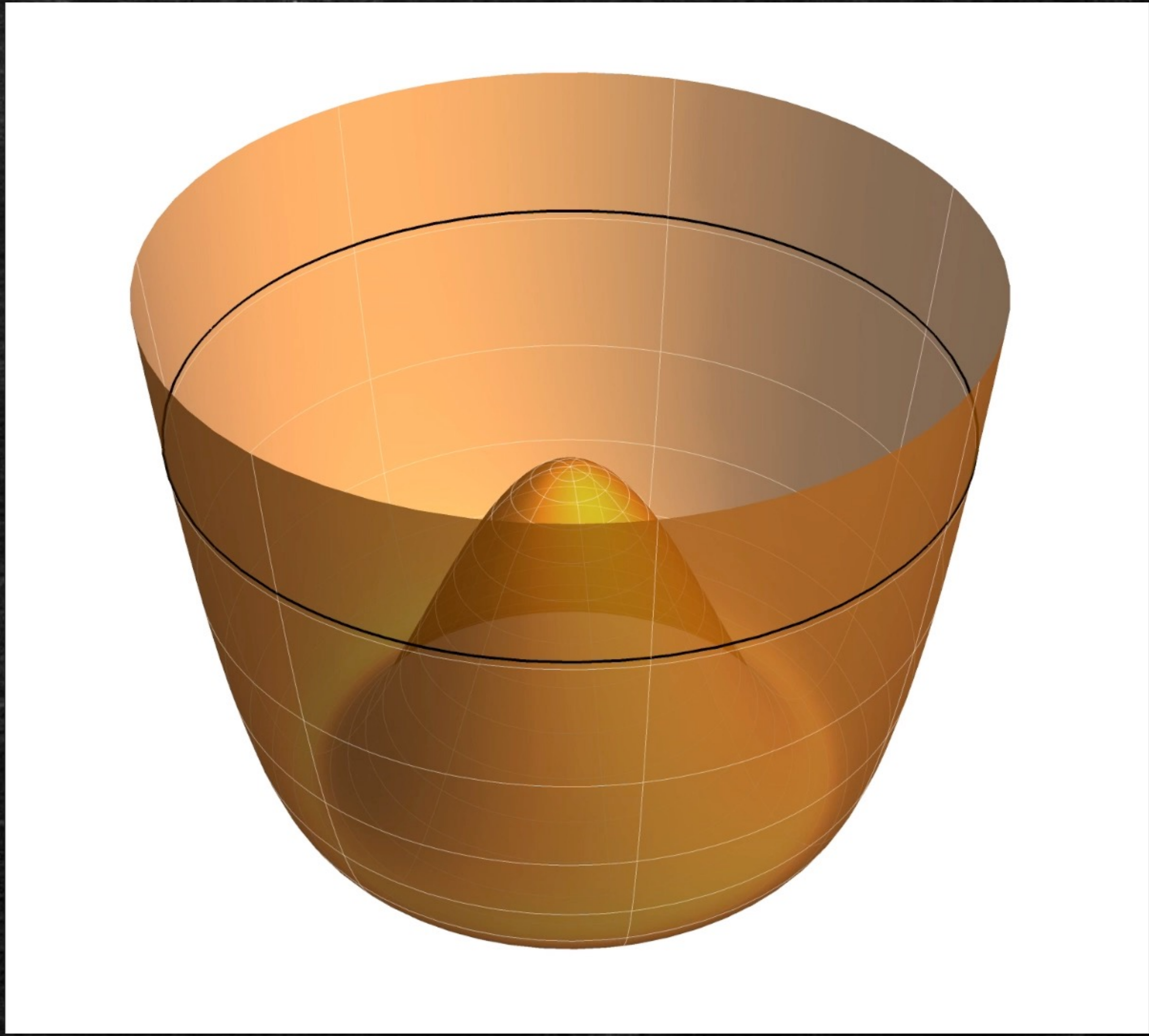
Asymmetries in Thermal Equilibrium

Thermalization $n_{\rm PQ} = S^2 \dot{\theta}$ Redshift





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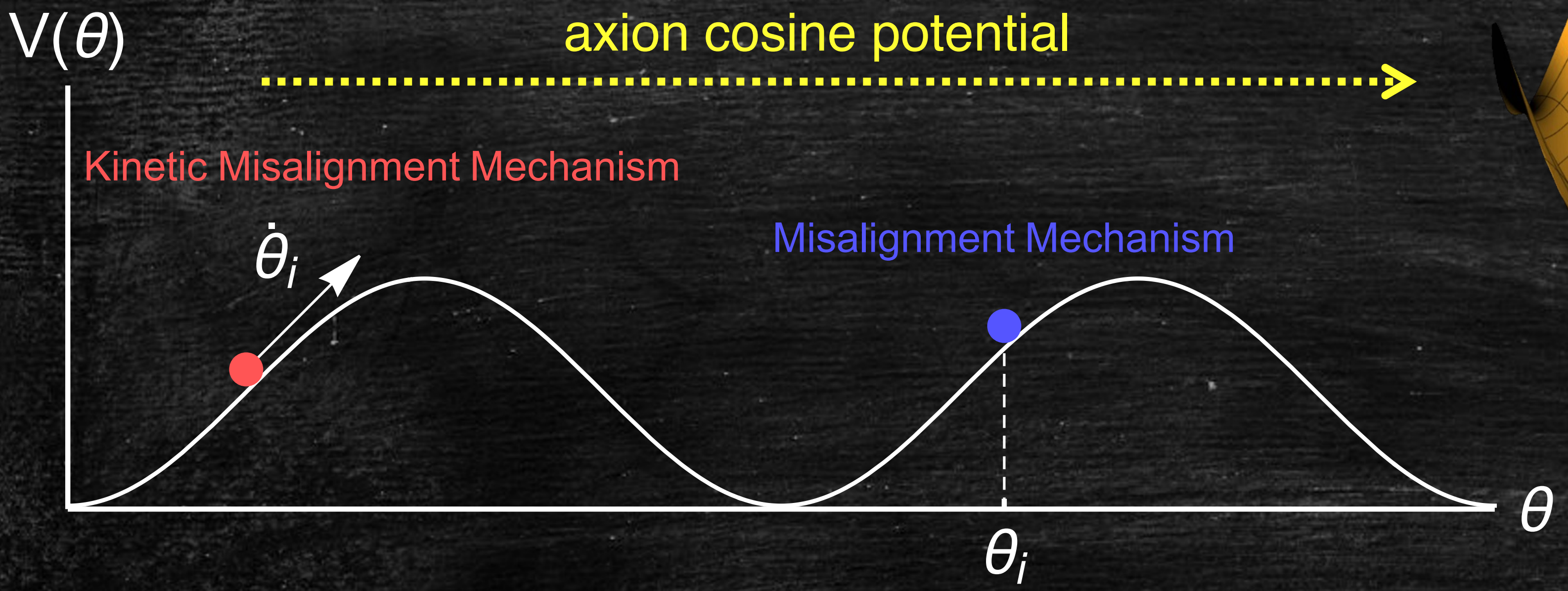
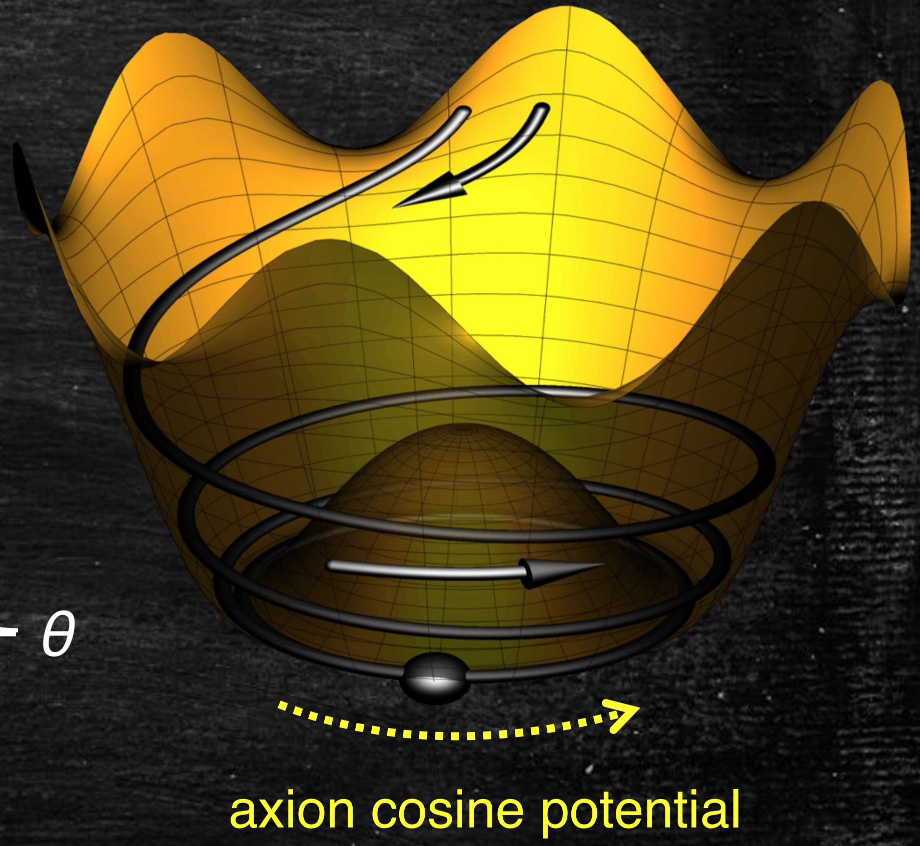
Axion Dark Matter

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

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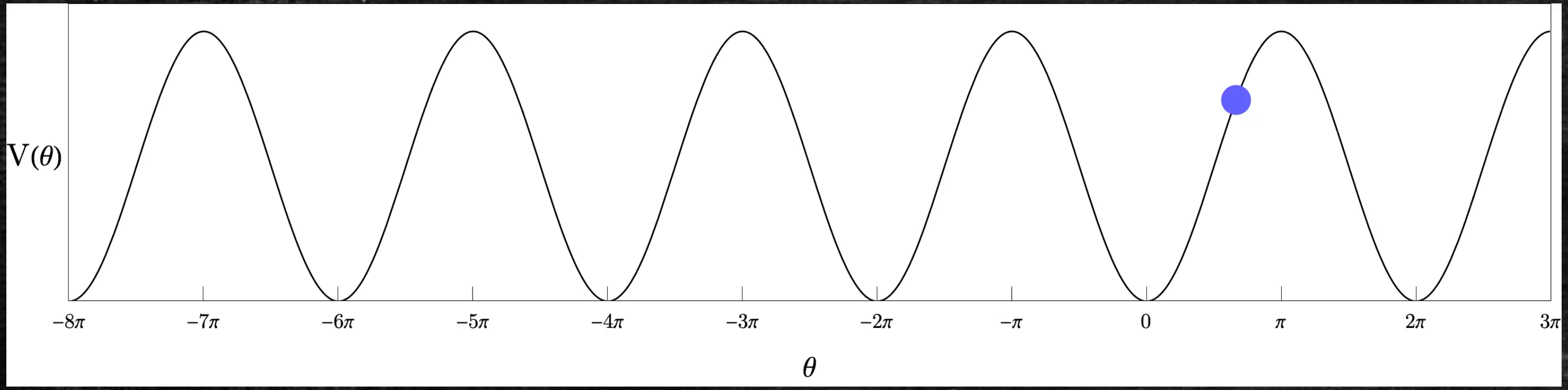
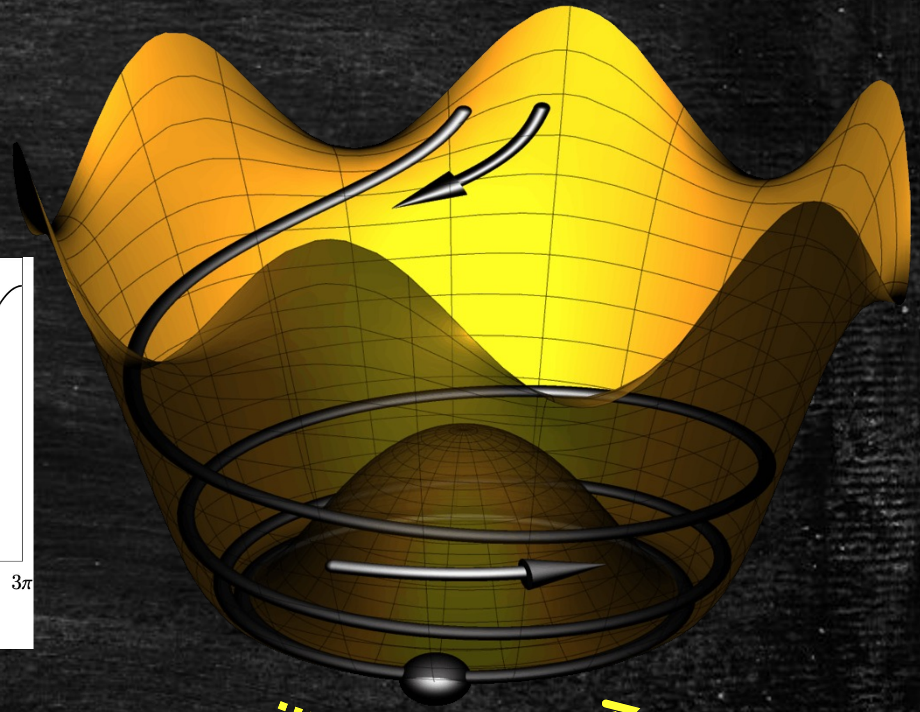
axion cosine potential





axion cosine potential

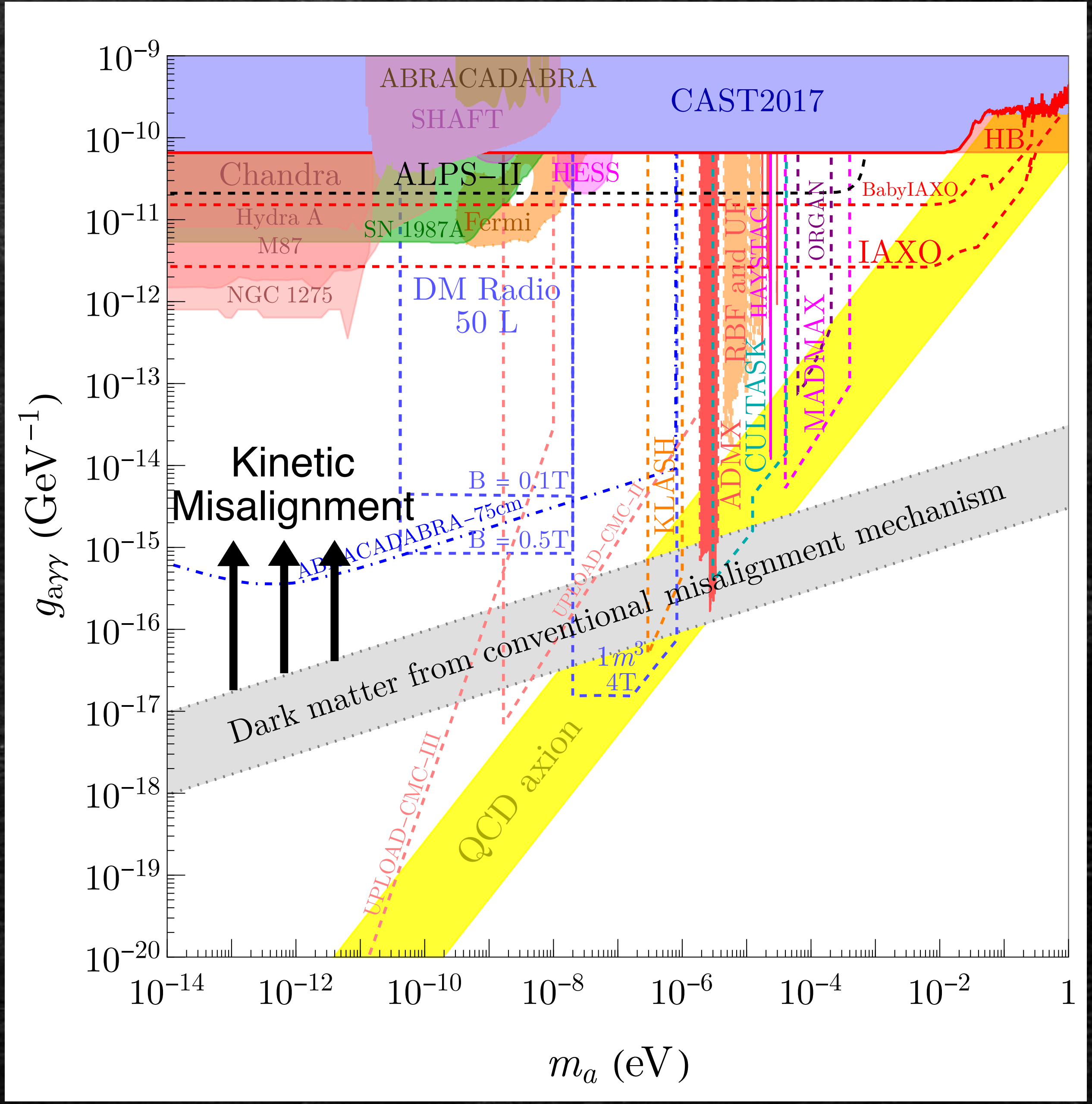
kinetic energy > potential energy

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

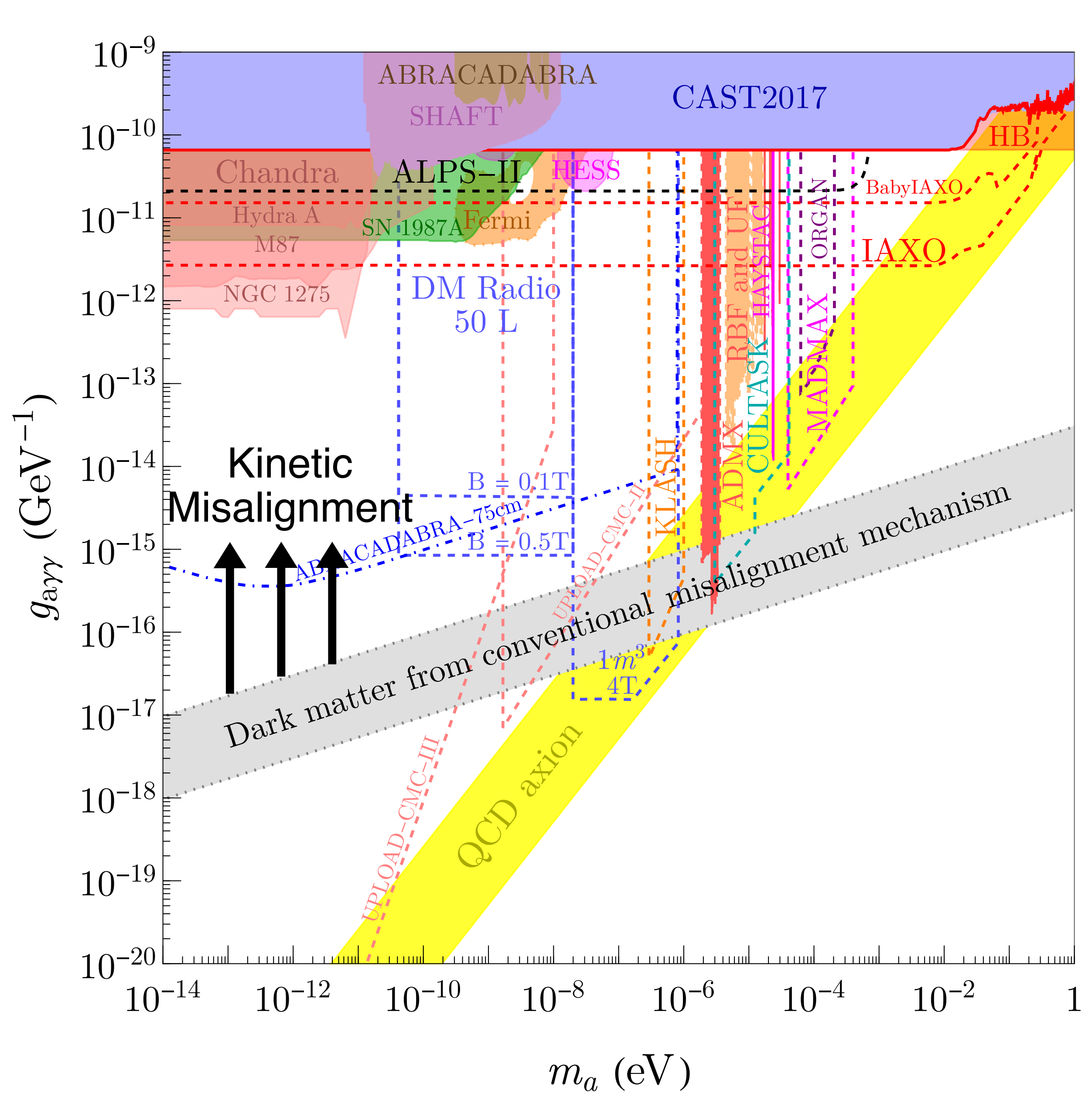
Observed dark matter abundance

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

(*Planck* 2018)

Thus, dark matter relates

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

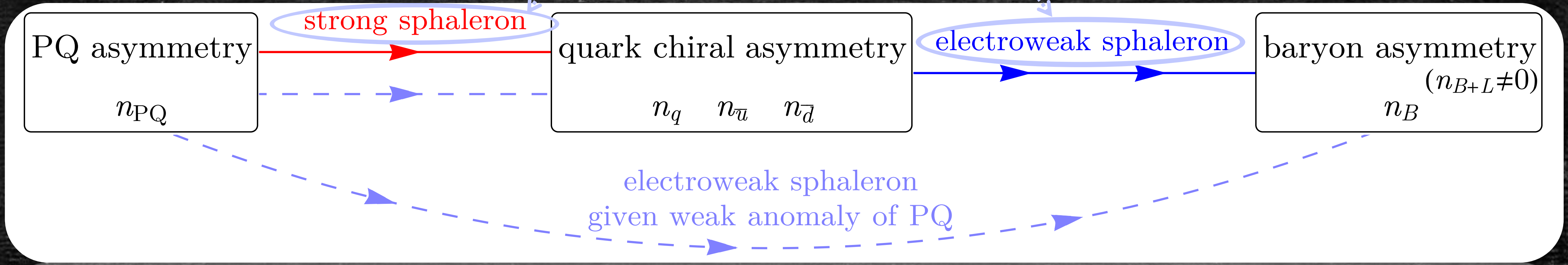


Baryon Asymmetry

Axiogenesis

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

matter-antimatter asymmetry



$$Y_B \equiv \frac{n_B}{s} = c_B Y_\theta \left(\frac{T_{\rm EW}}{f_a}\right)^2 \qquad Y_B^{\rm obs} \simeq 8.7 \times 10^{-11}$$

produced by axion rotations

experimentally measured value
(*Planck* 2018)

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

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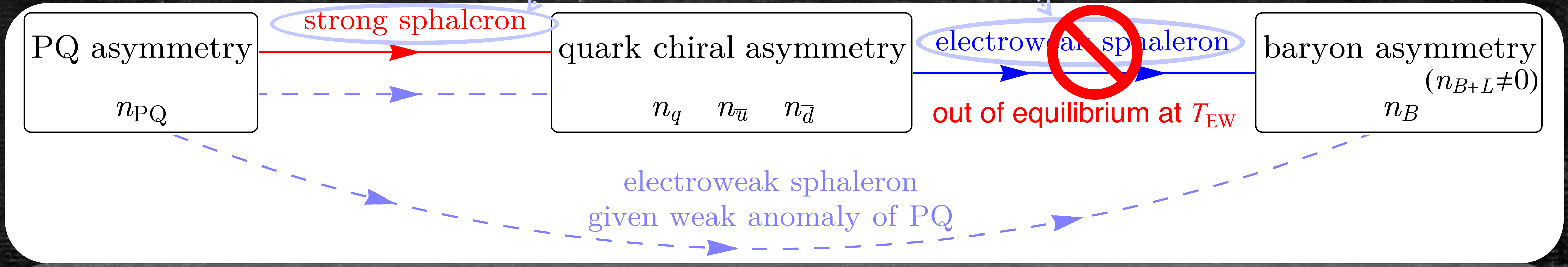
matter-antimatter asymmetry



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

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

experimentally measured value
(*Planck* 2018)

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

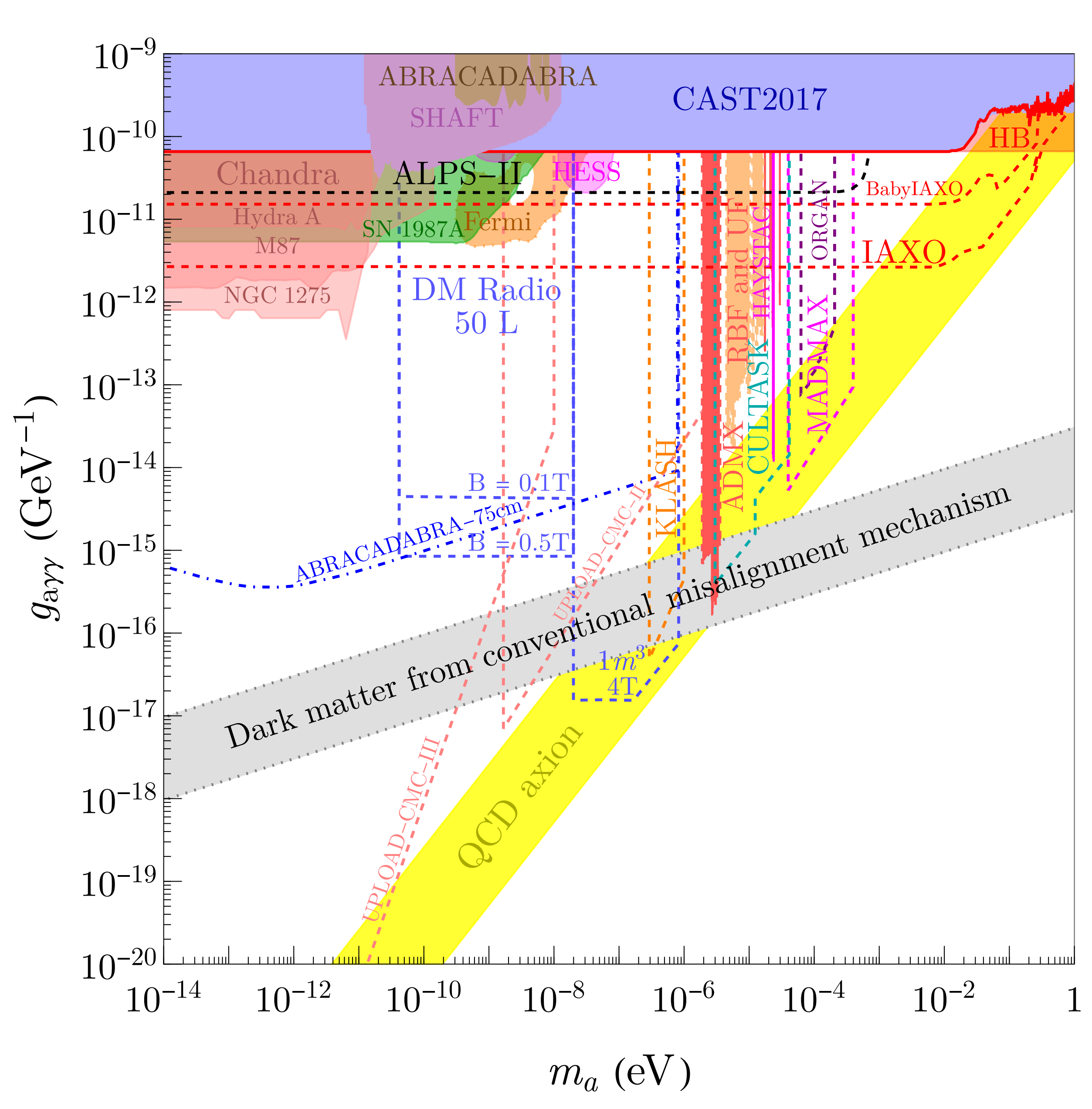
PRL 124, 111602 (2020) RC and K. Harigaya

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:

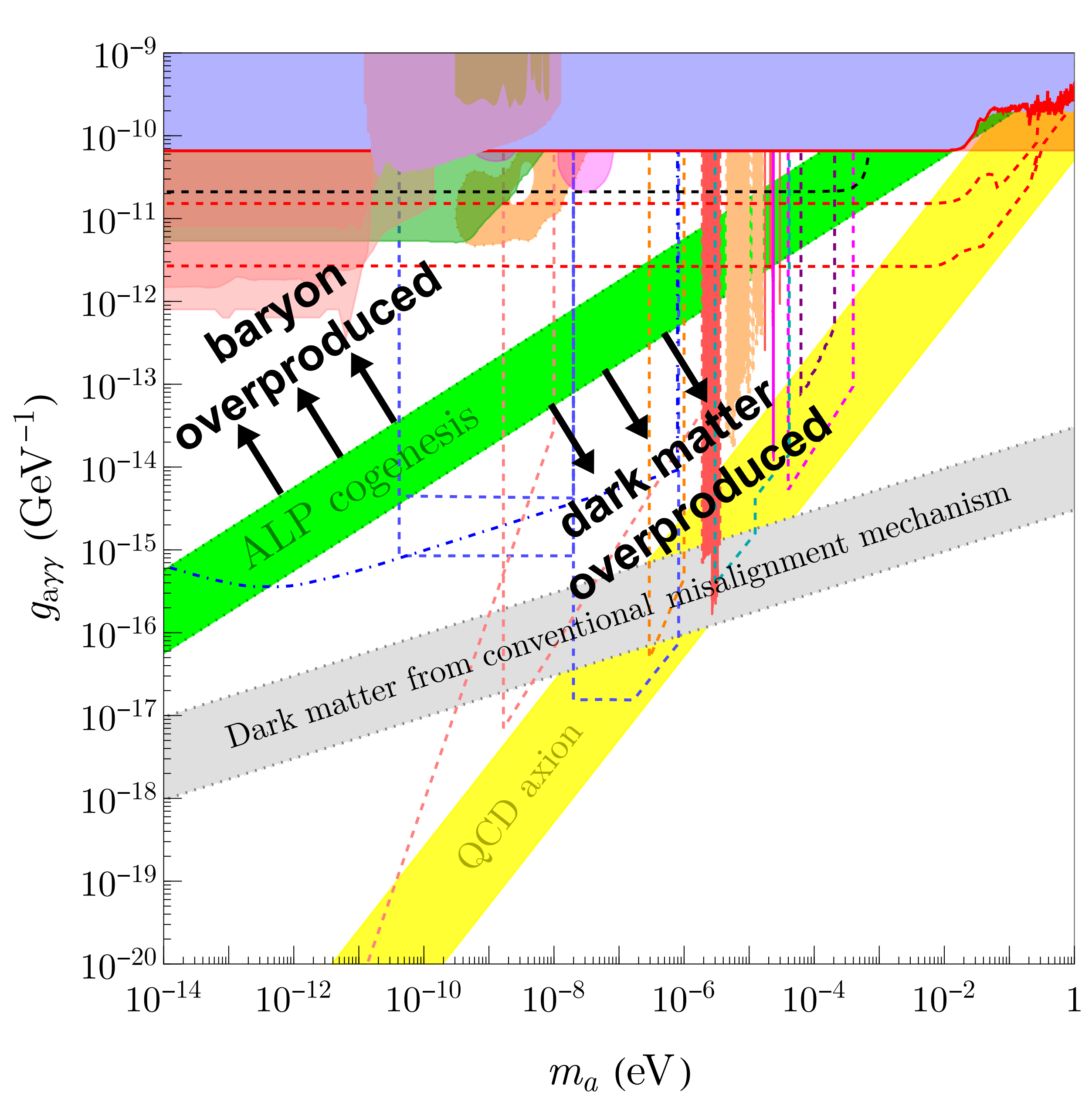
$$m_a \overset{\text{DM}}{\longleftrightarrow} Y_\theta \overset{Y_B}{\longleftrightarrow} \left(\frac{T_{\text{EW}}}{f_a}\right)^2$$

ALP cogenesis :

ALP = axion-like particle (no gluon coupling)

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

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



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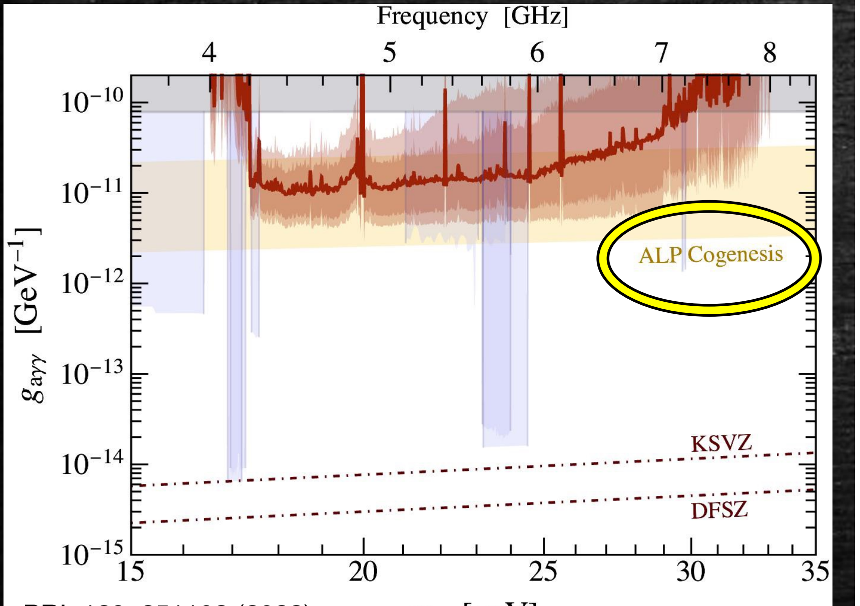
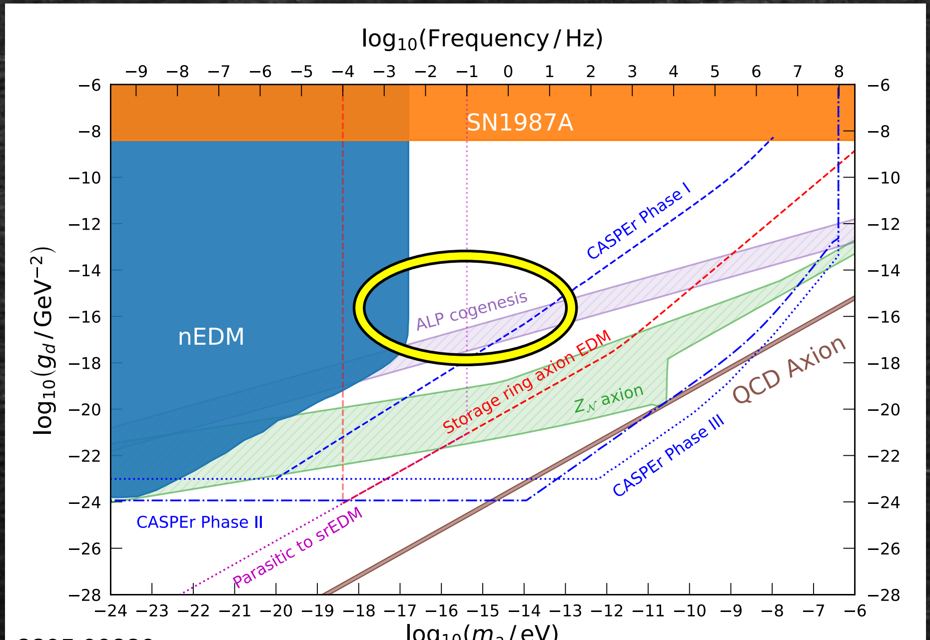
ALP Cogenesis

Experimental probes are happening!



PRL 129, 251102 (2022)



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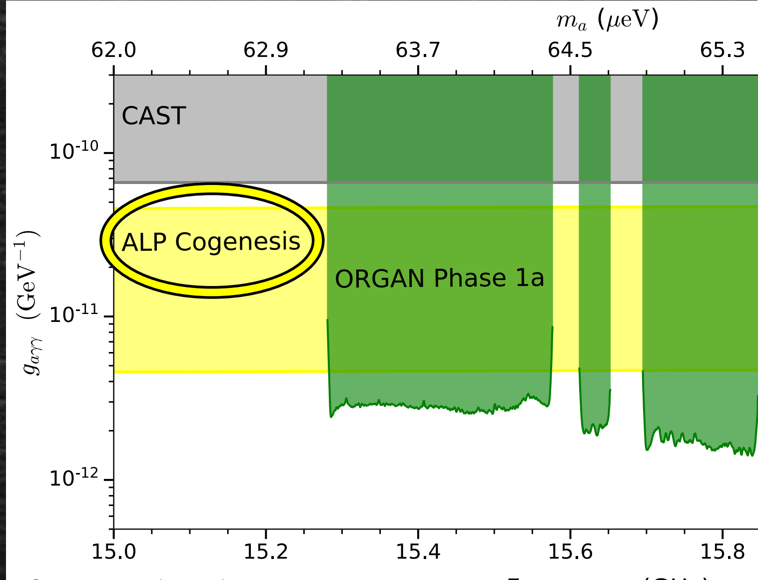
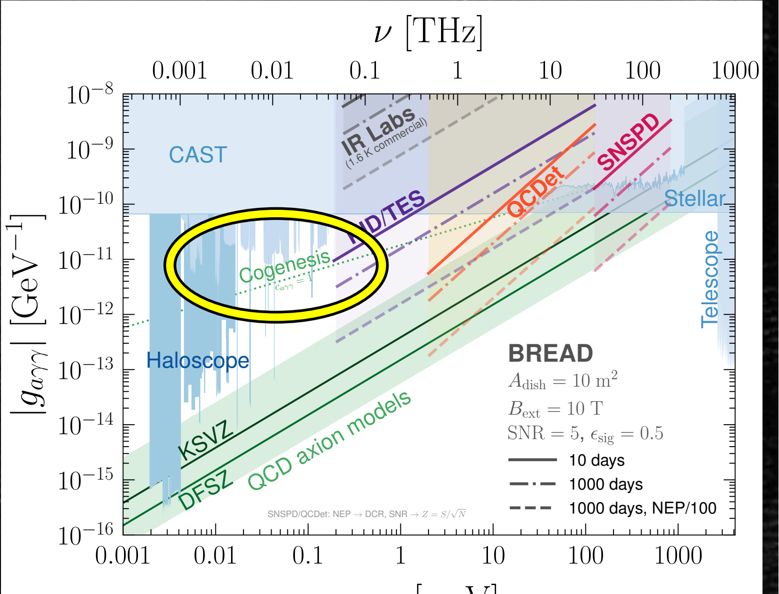
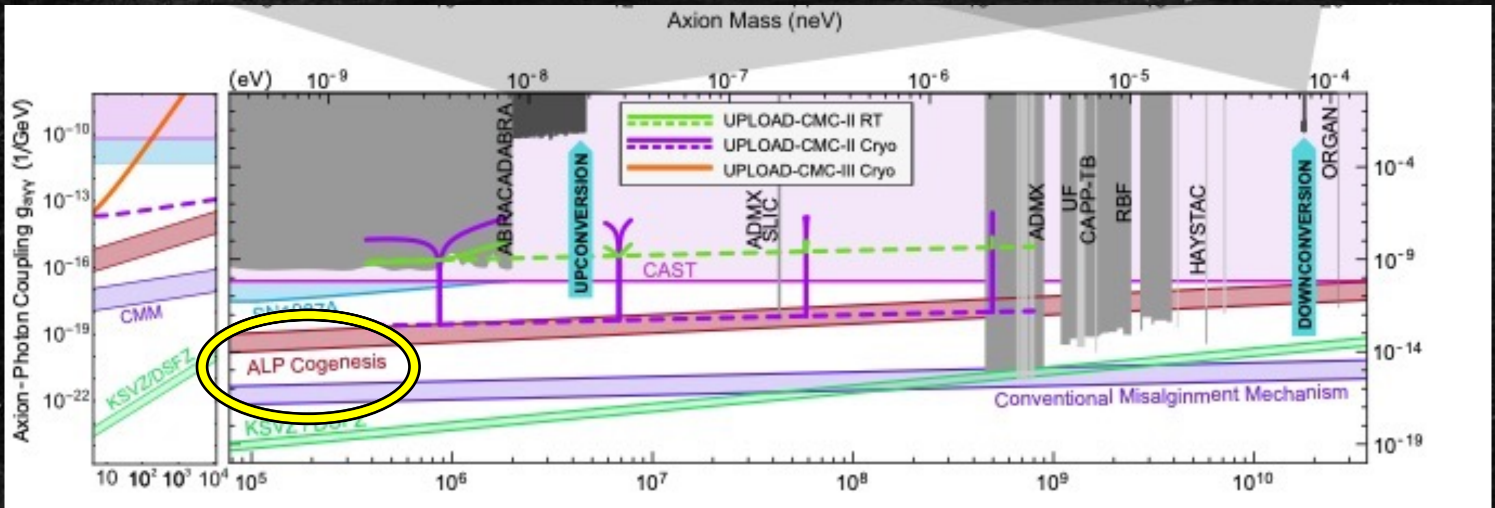


Sci.Adv. 8 (2022) 27, abq3765



PRL 128 (2022) 13, 131801



PRL 126 (2021) 8, 081803

Kinetic Misalignment + Axiogenesis

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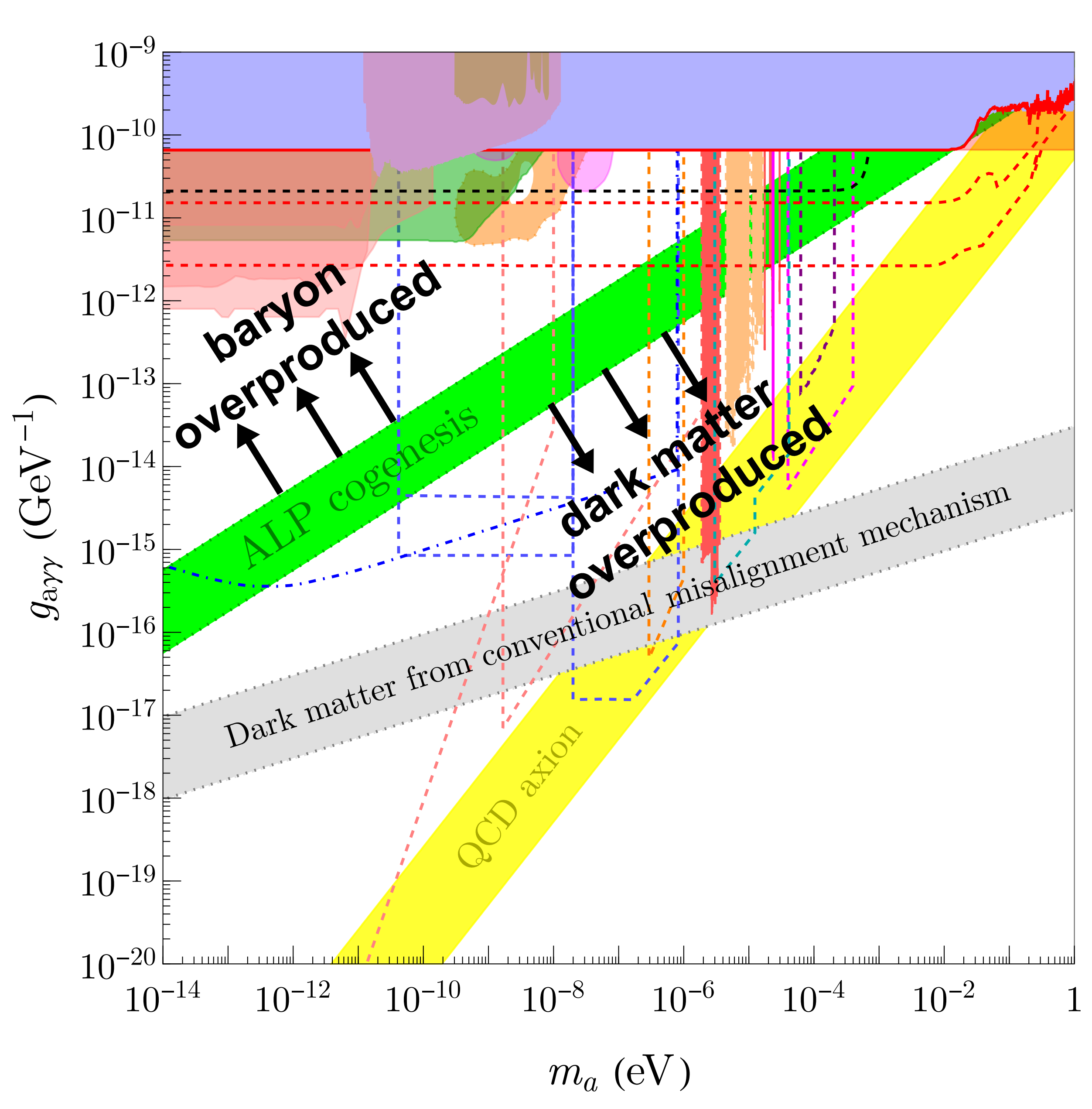
QCD axion cogenesis?

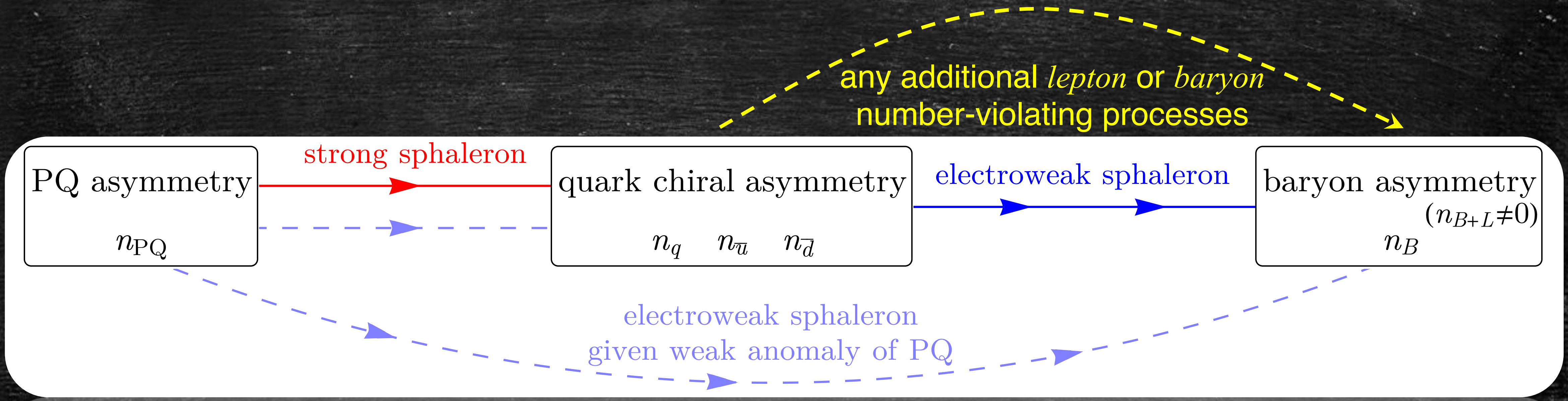
Can the QCD axion be compatible with cogenesis from axion rotations?

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



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

Extensions of Axiogenesis



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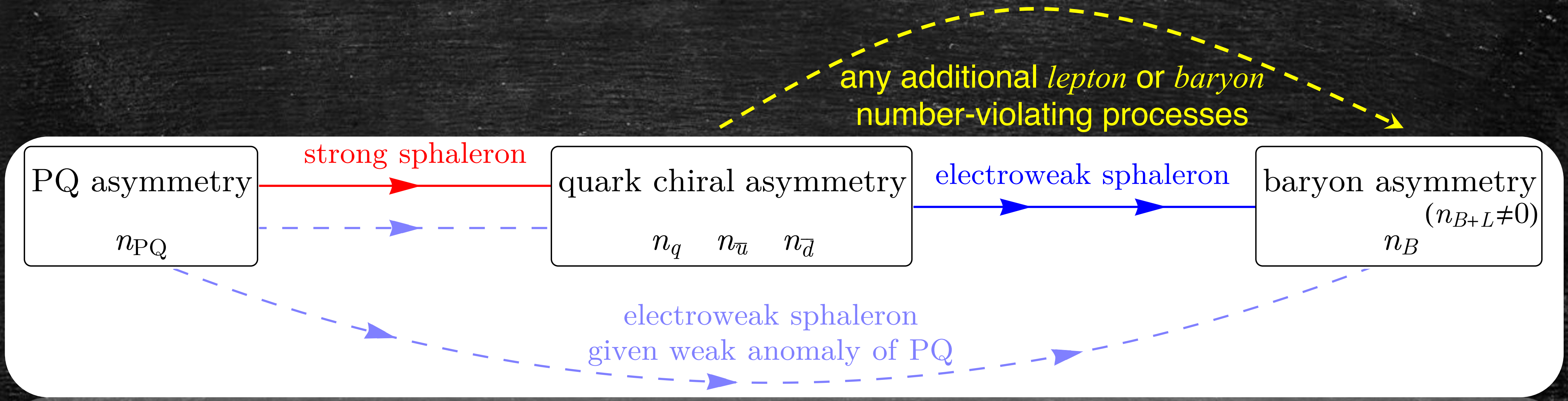


Lepto-Axiogenesis

$$\mathcal{L} \supset \frac{m_\nu}{2v_{\rm EW}^2} \ell\ell\, H^\dagger H^\dagger$$

e.g., from the seesaw mechanism, or the Zee-Babu model

This Weinberg operator gives Majorana neutrino masses, breaks lepton number, and thus affects the charge transfer.

other extensions

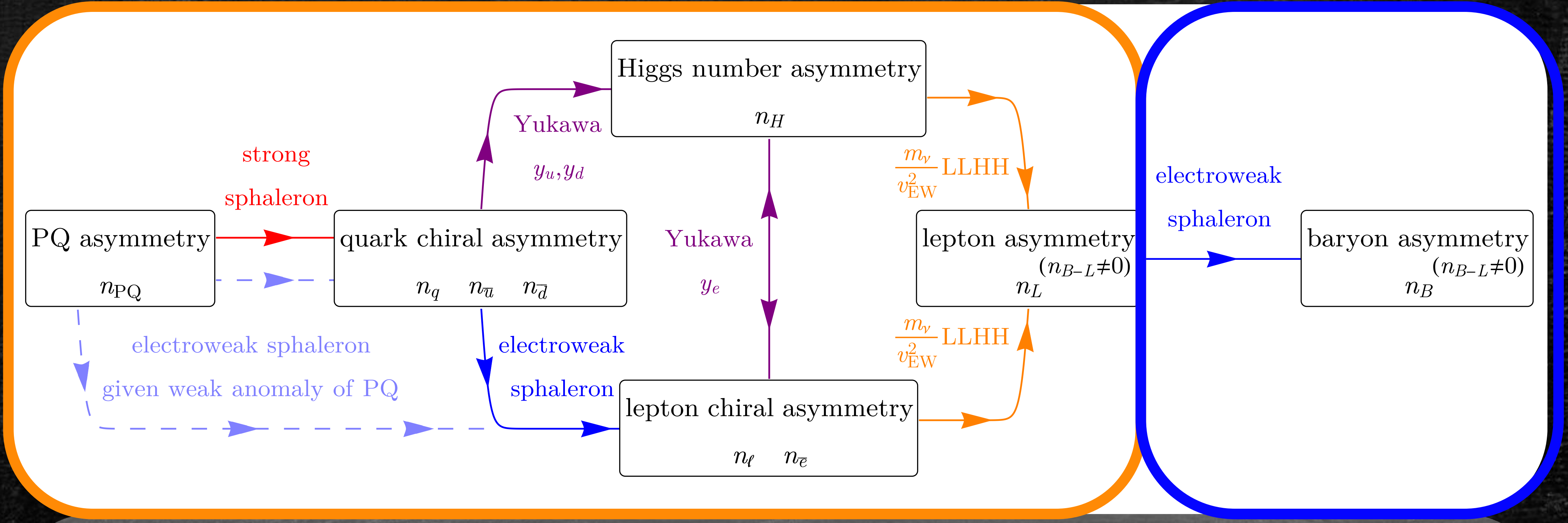
- ✓ RC *et al.* 1910.02080
- ✓ Harigaya *et al.* 2107.09679
- ✓ Chakraborty *et al.* 2108.04293
- ✓ Kawamura *et al.* 2109.08605
- ✓ RC *et al.* 2110.05487
- ✓ RC *et al.* 2206.00678
- ✓ Barnes, RC *et al.* 2208.07878
- ✓ RC *et al.* 2211.12517

JHEP 03 (2021) 017 RC, N. Fernandez, A. Ghalsasi, L. Hall, K. Harigaya

Lepto-Axiogenesis

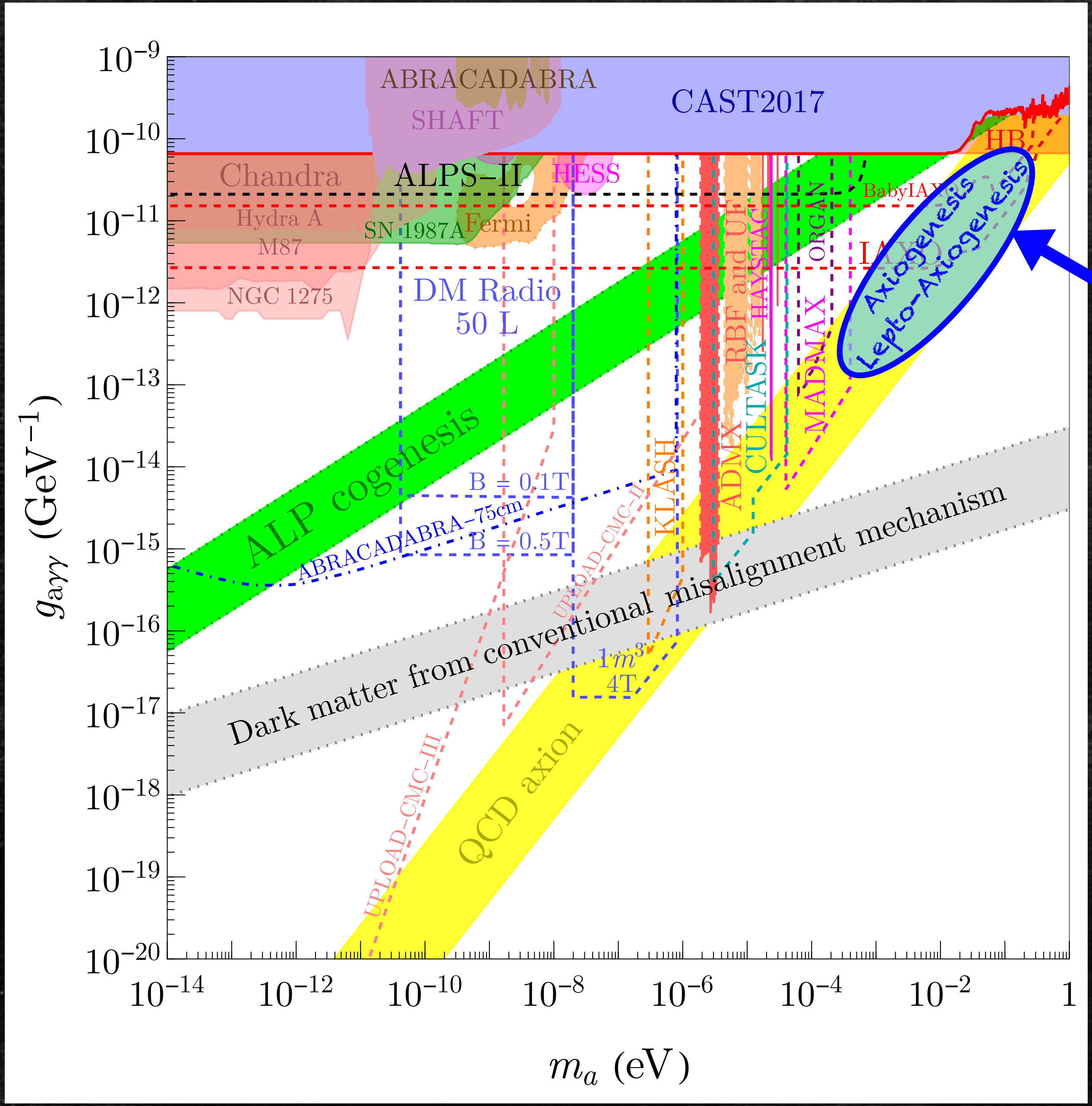
Producing L at high temperatures

Converting to B at T_{EW}



JHEP 03 (2021) 017 RC, N. Fernandez, A. Ghalsasi, L. Hall, K. Harigaya

Lepto-Axiogenesis

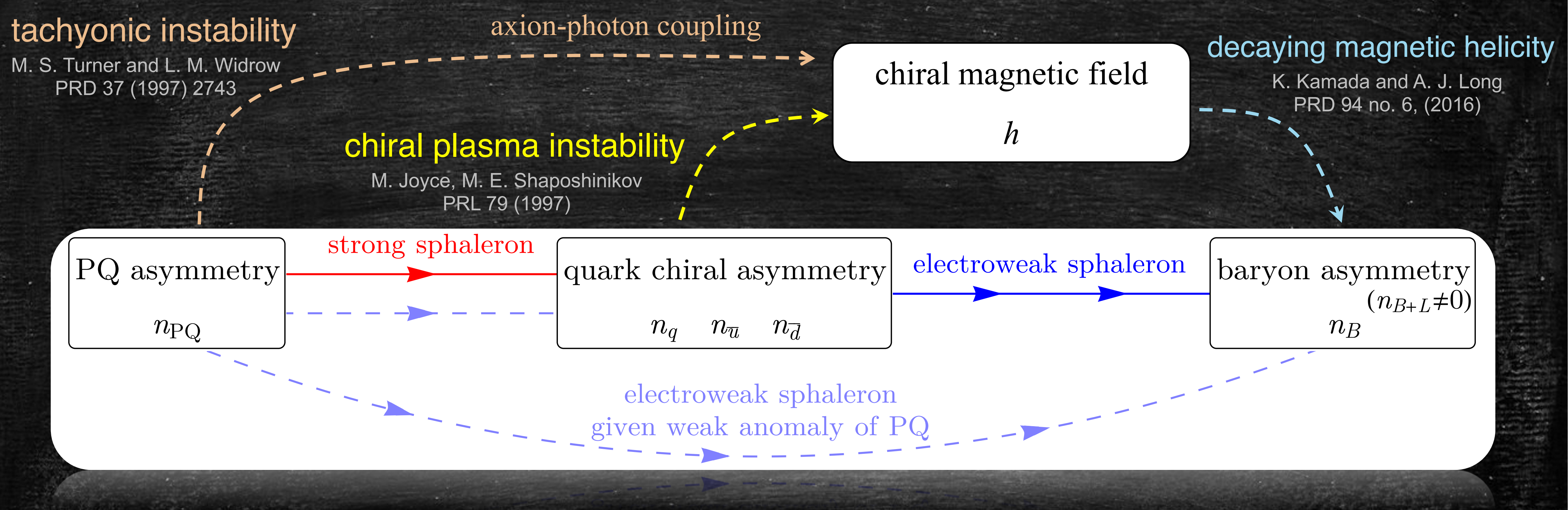


Lepto-Axiogenesis achievement:

simultaneous production of
- dark matter
- matter-antimatter asymmetry

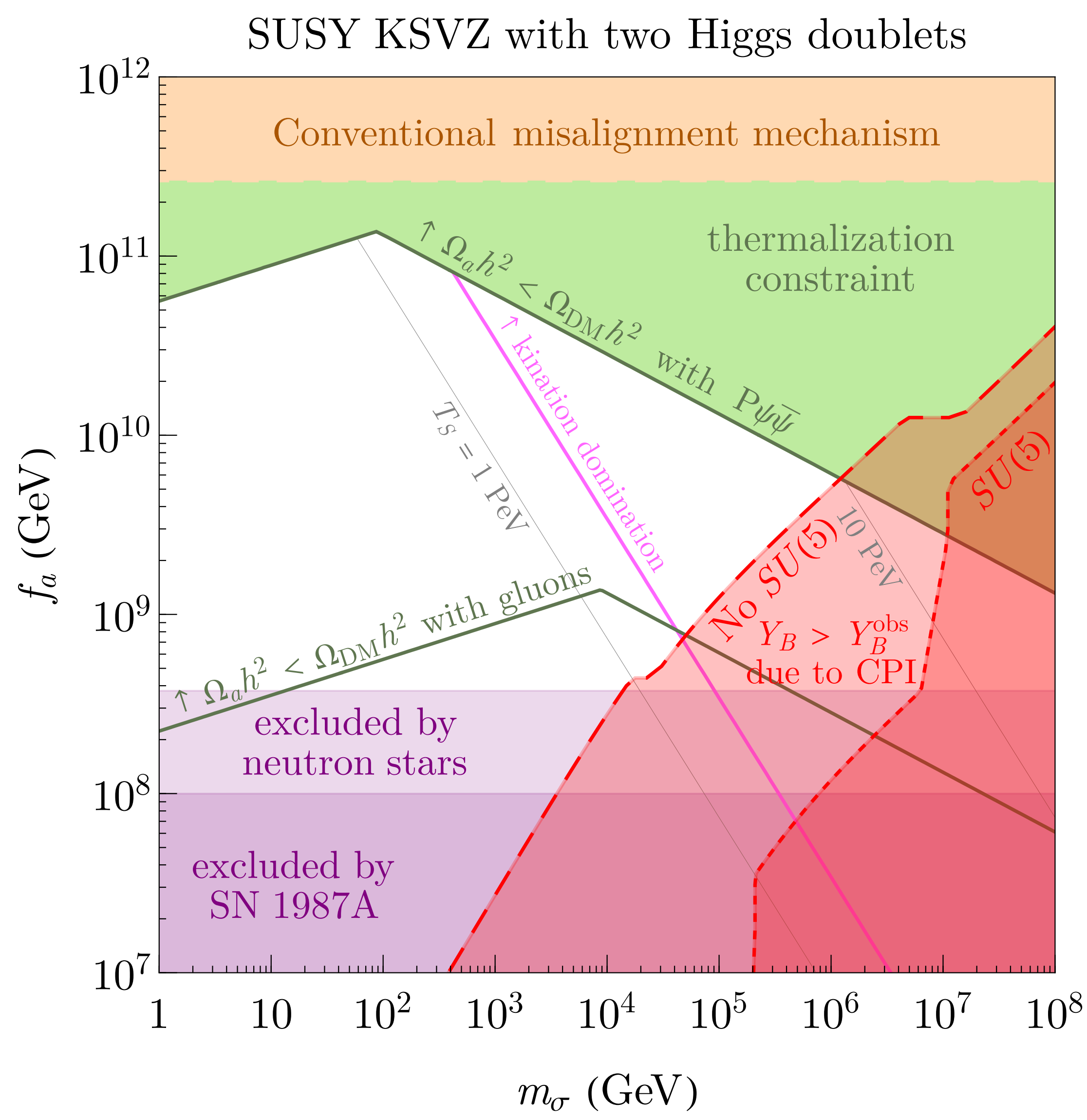
in the framework with
- QCD axion
- Majorana neutrinos

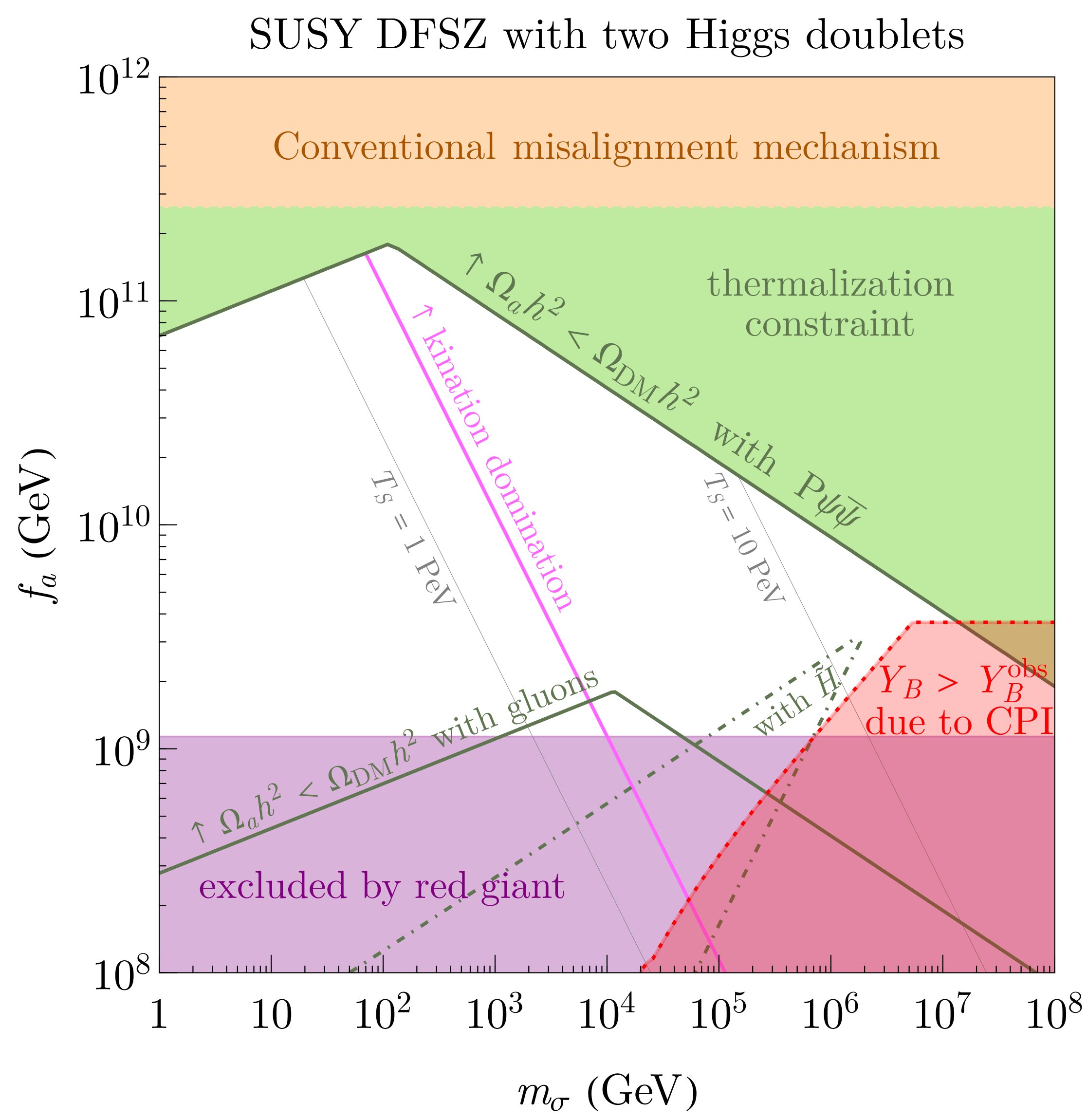
Baryogenesis from Decaying Magnetic Helicity in Axiogenesis



JHEP 07 (2023) 179 RC, V. Domcke, K. Harigaya

Baryogenesis from Decaying Magnetic Helicity in Axiogenesis



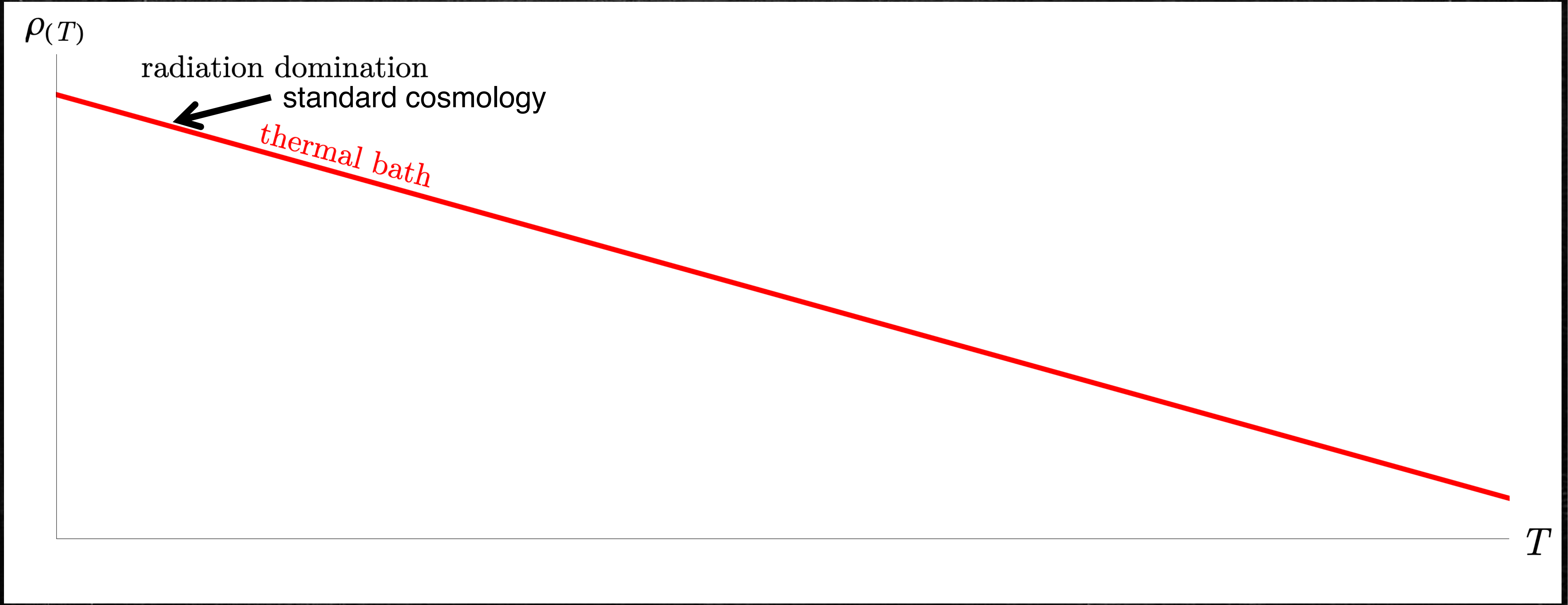


JHEP 07 (2023) 179 RC, V. Domcke, K. Harigaya

Gravitational Wave Signatures

Evolution of Energy Densities

The energy content determines the universe's expansion rate.



Over time, the universe cools and temperature drops.

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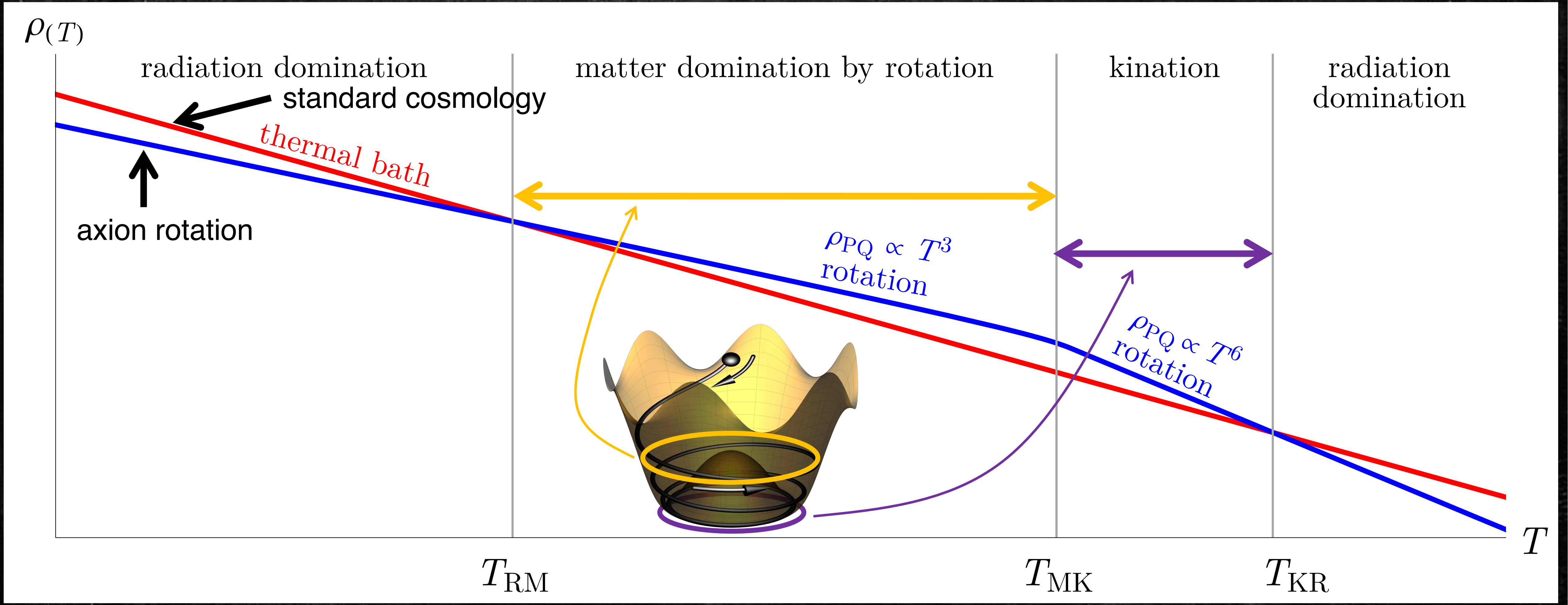

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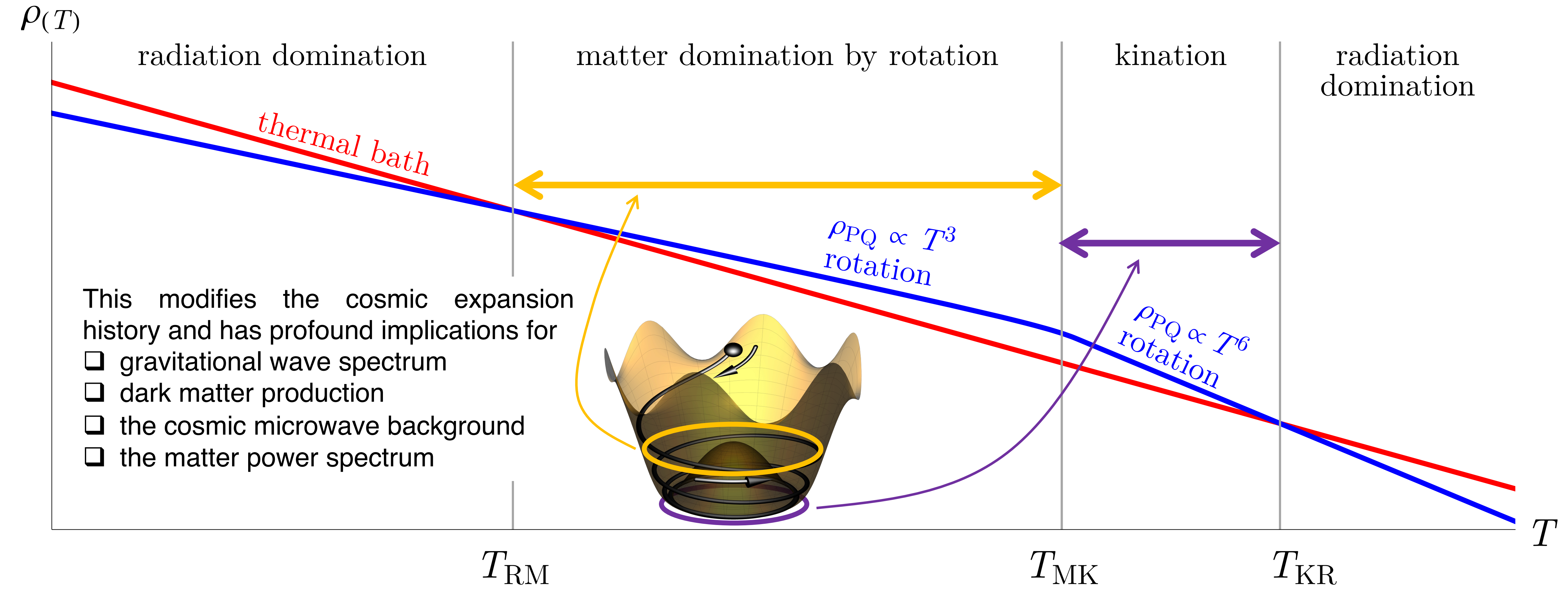
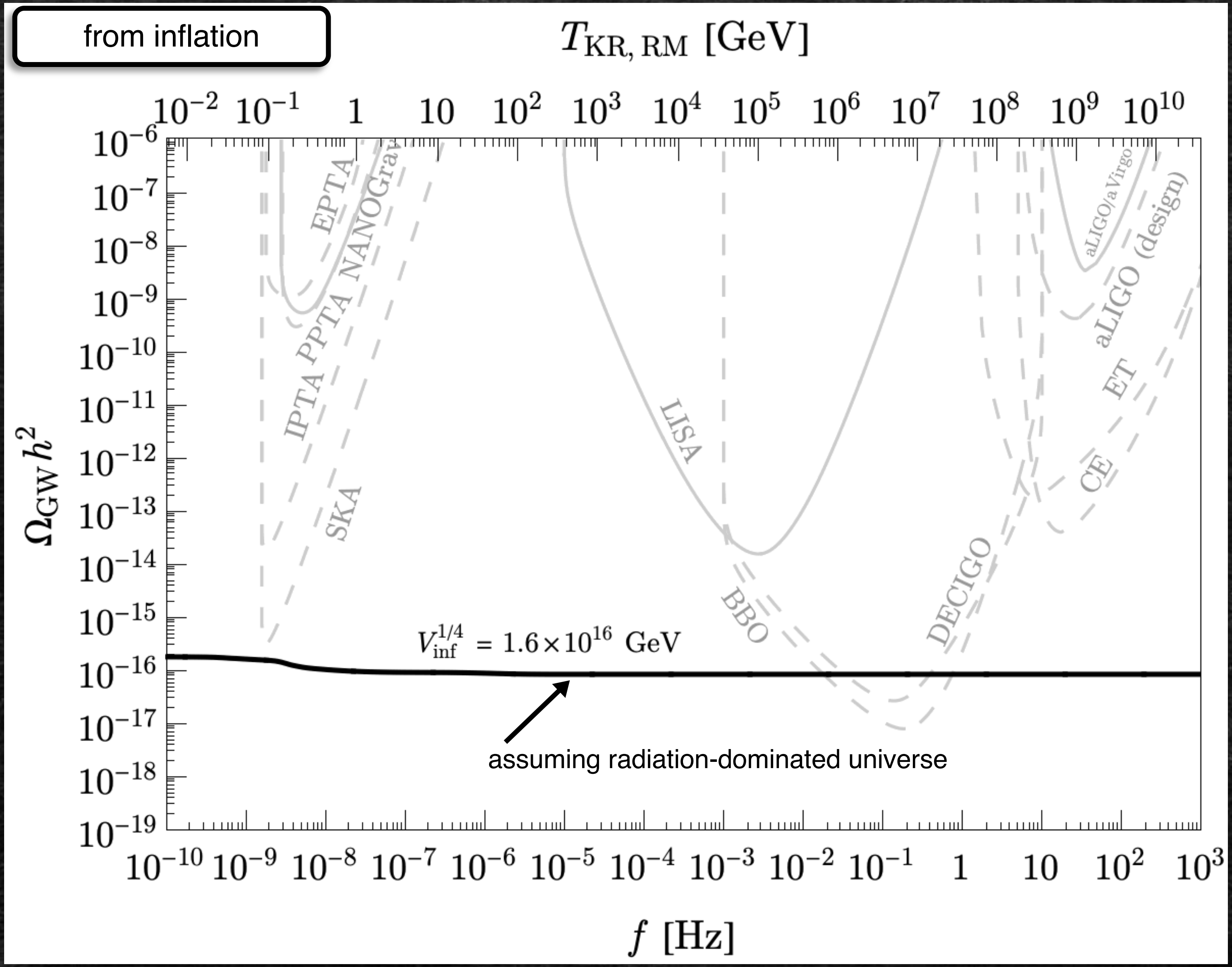


This modifies the cosmic expansion history and has profound implications for

- ❑ gravitational wave spectrum
- ❑ dark matter production
- ❑ the cosmic microwave background
- ❑ the matter power spectrum

Smoking Gun: Triangular Peak in Gravitational Wave Spectra



2108.09299 JHEP 09 (2022) 116 RC, D. Dunsky, N. Fernandez, A. Ghalsasi, L. Hall, K. Harigaya, J. Shelton

2108.10328, 2111.01150 Y. Gouttenoire, G. Servant, P. Simakachorn

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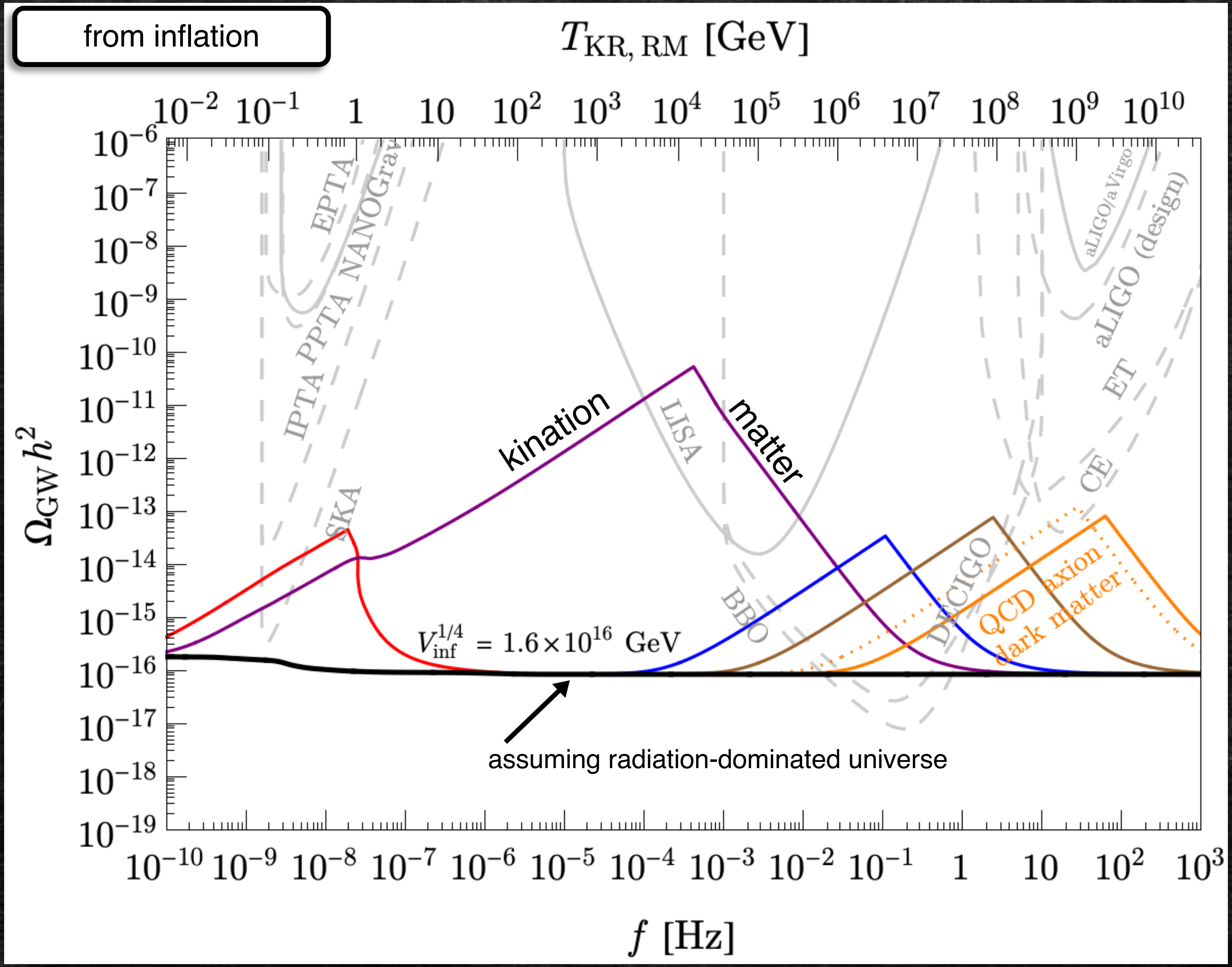

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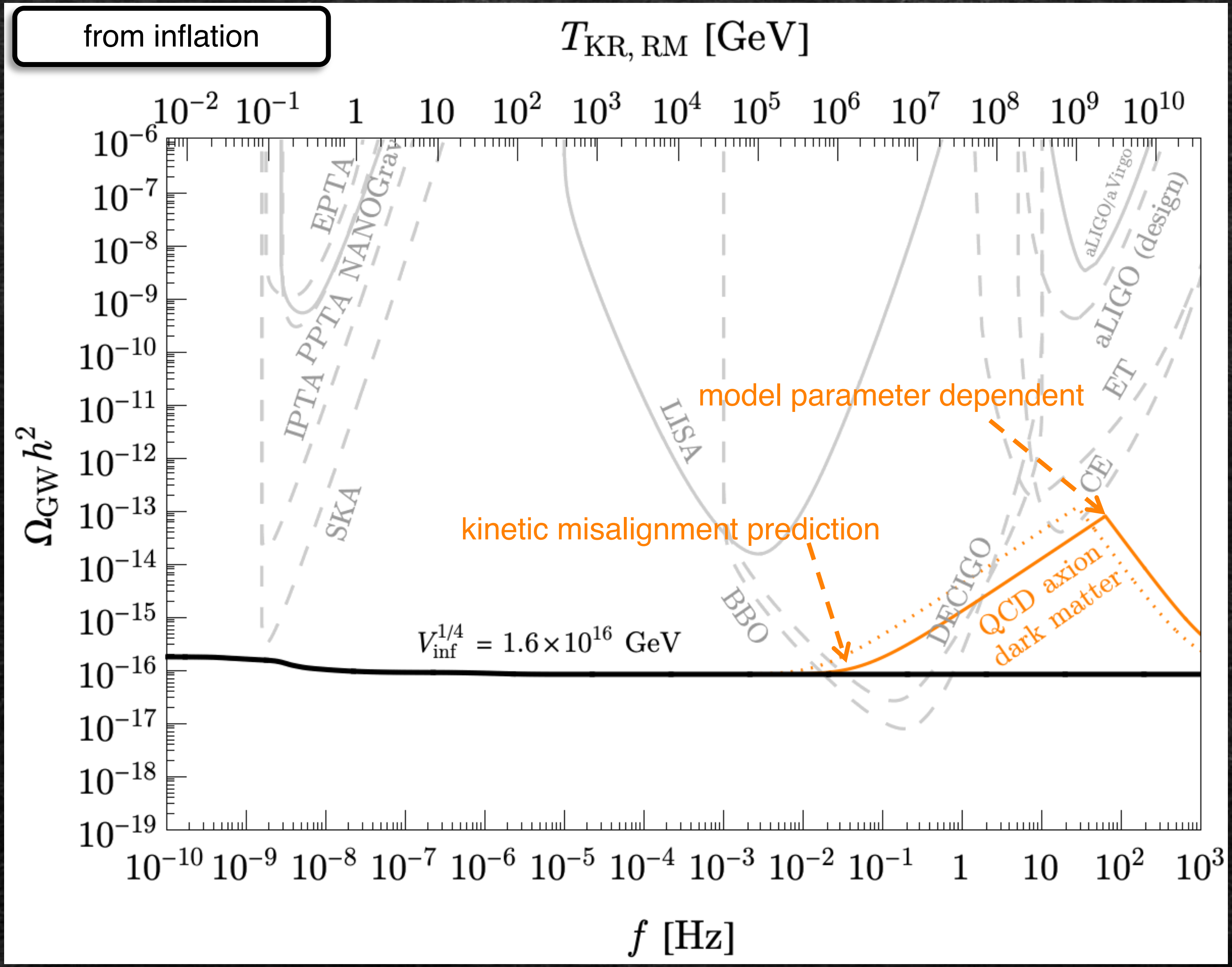

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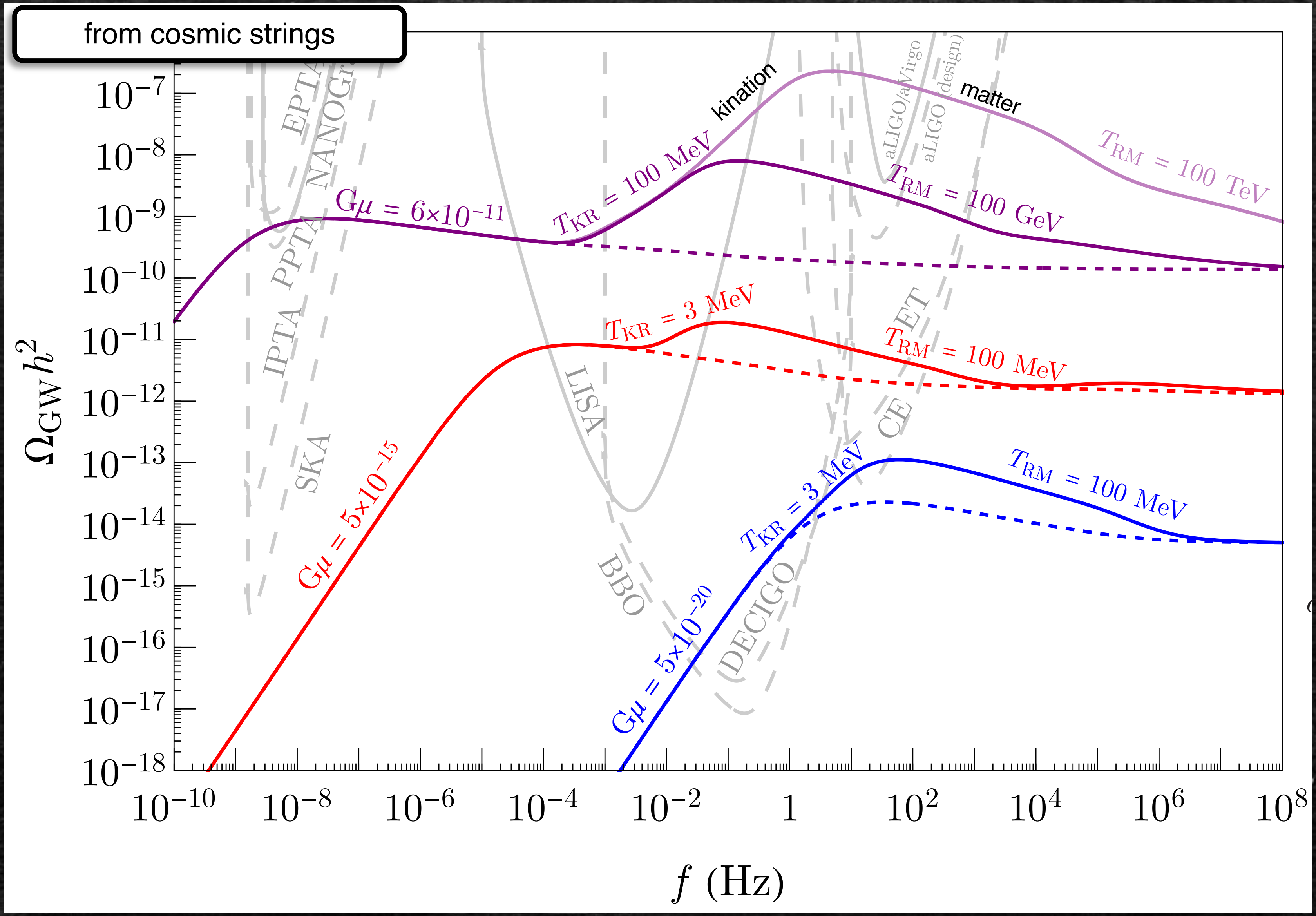

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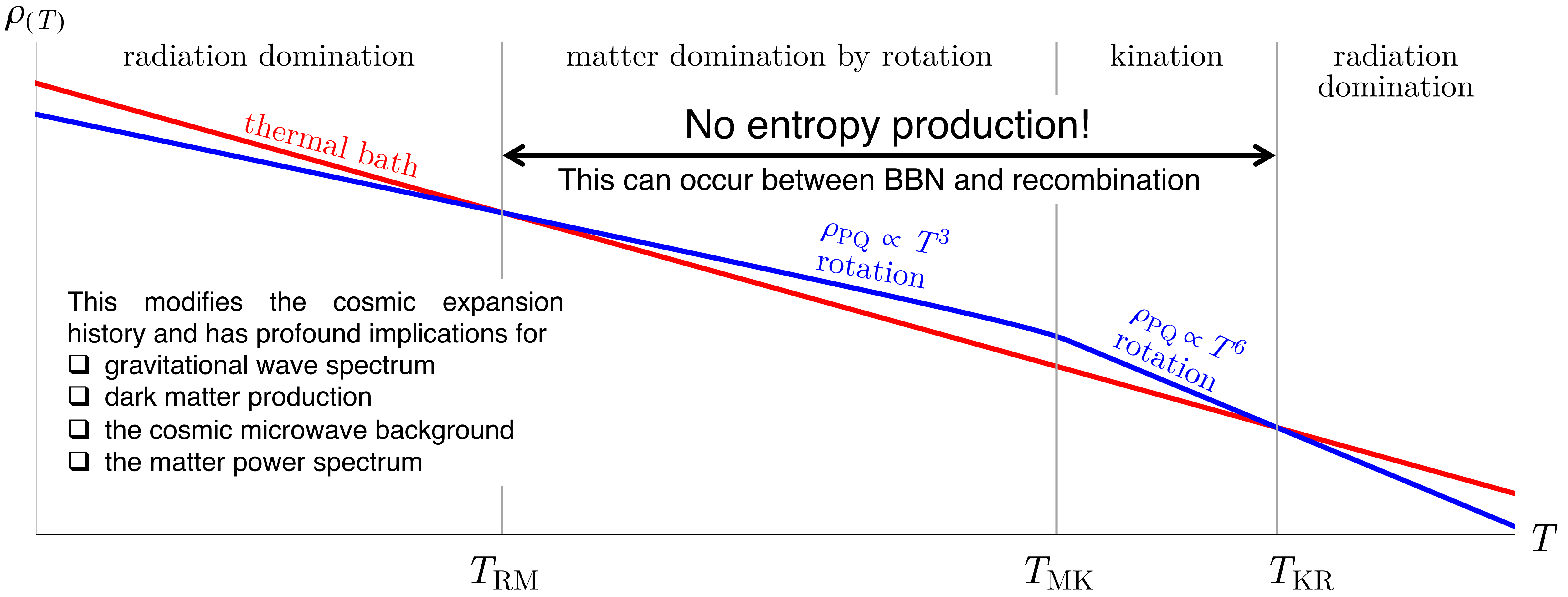

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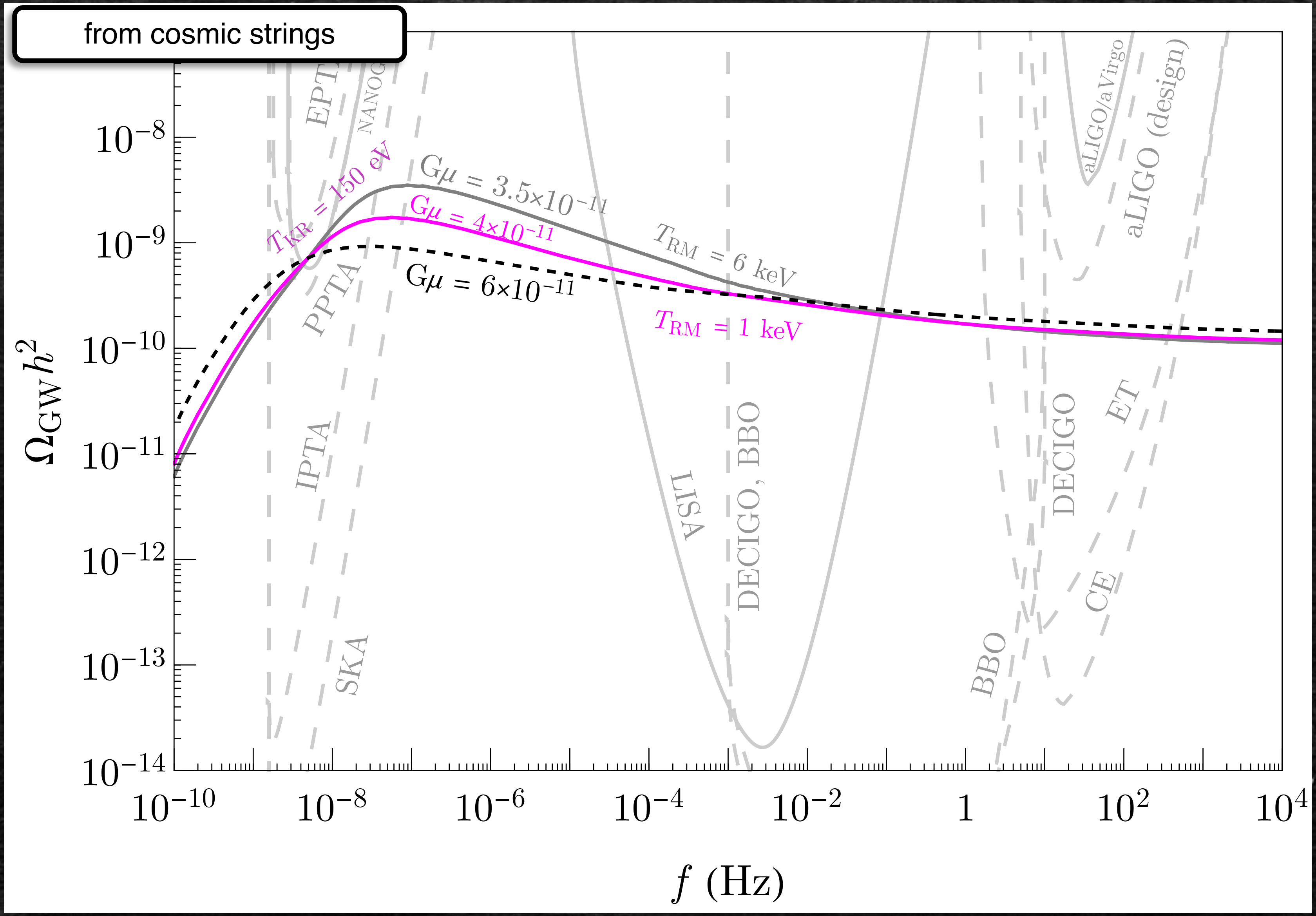

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Probing PQ-breaking Potential

Piecewise approximation

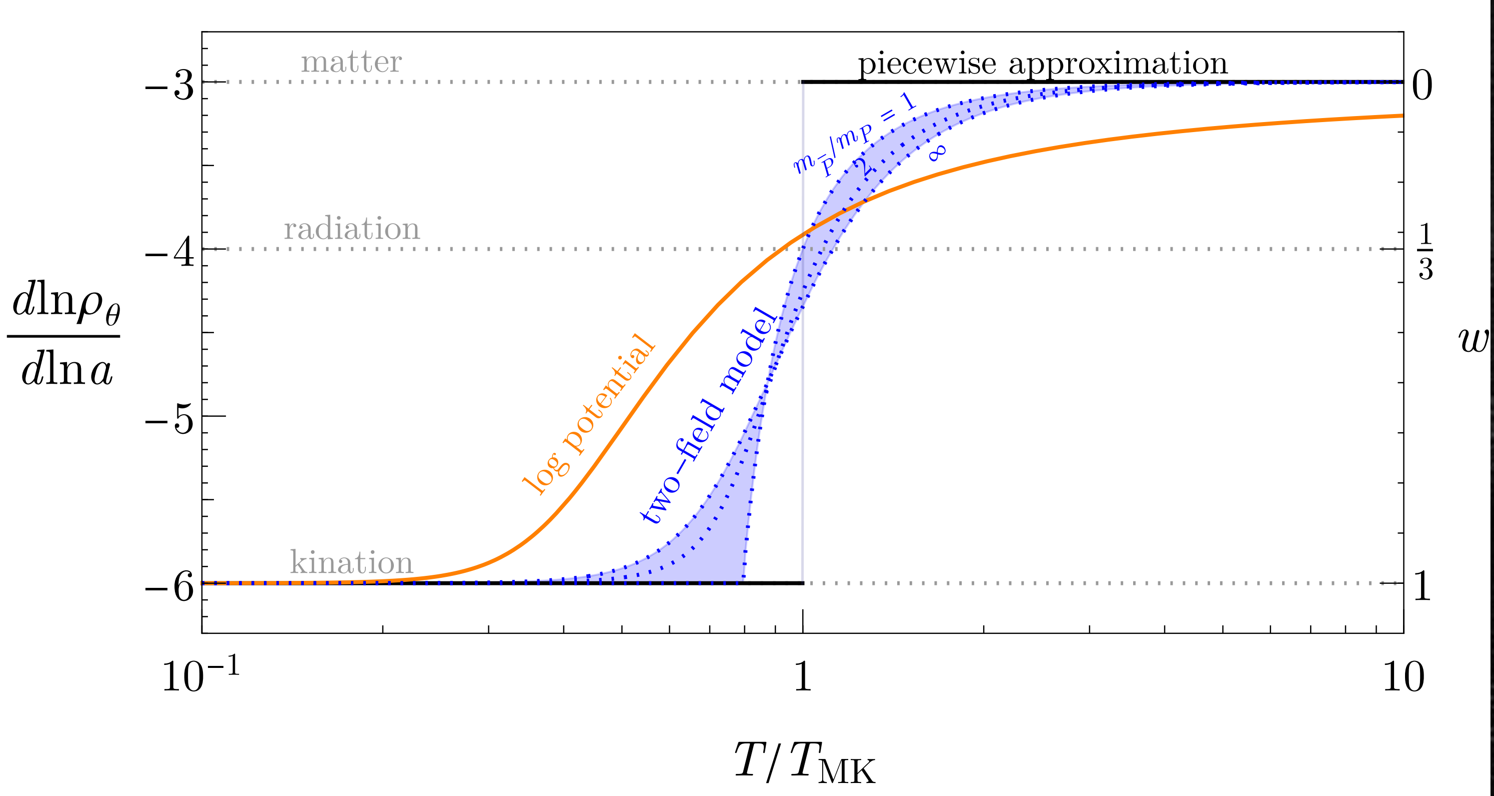
$$\rho_\theta \propto \begin{cases} R^{-3} & \text{for} \quad S \gg f_a \quad i.e. \quad T \gg T_{\rm MK} \\ R^{-6} & \text{for} \quad S \simeq f_a \quad i.e. \quad T \ll T_{\rm MK} \end{cases}$$

log potential

$$V(P) = m_S^2 |P|^2 \left(\ln \frac{2|P|^2}{f_a^2} - 1 \right)$$

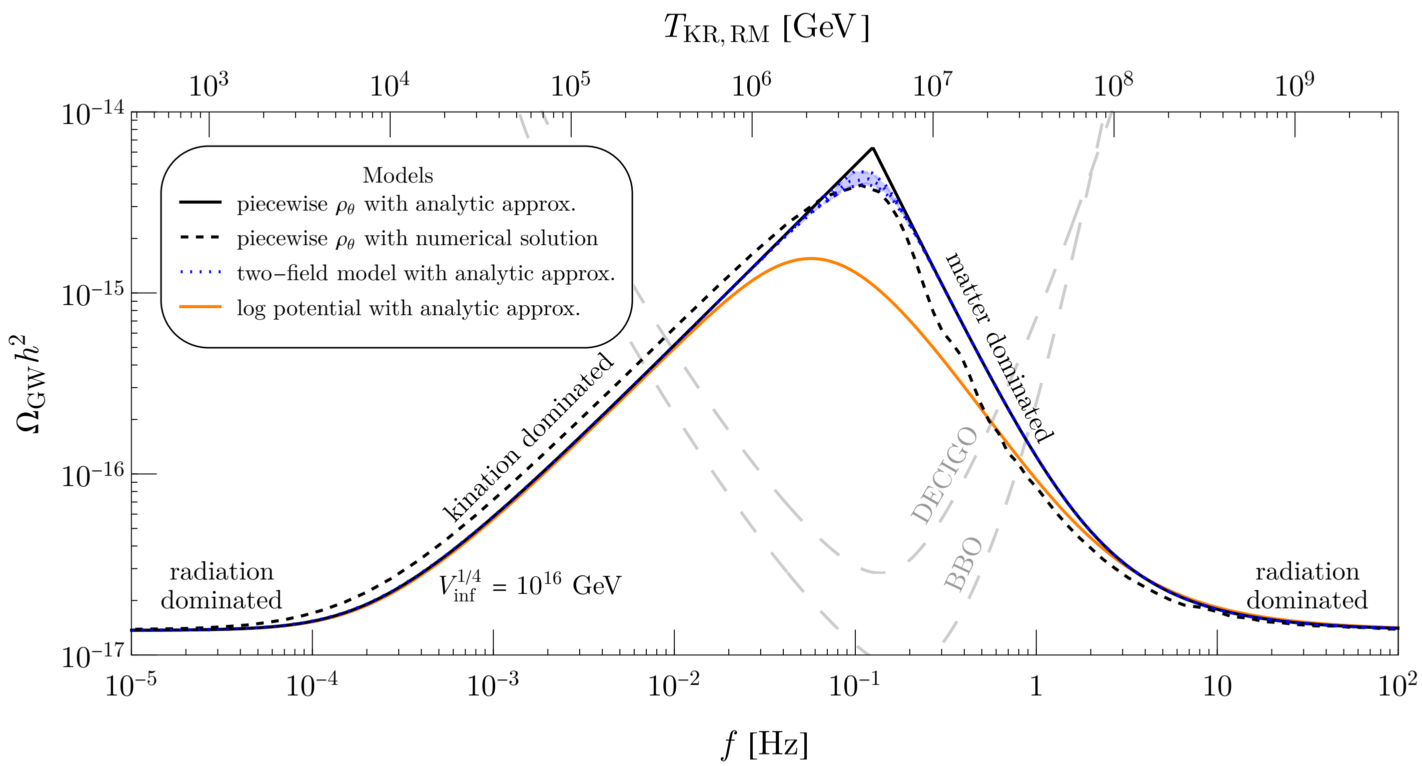
Two-field model

$$W = X(P\bar{P} - v_P^2)$$
$$V_{\rm soft} = m_P^2 |P|^2 + m_{\bar{P}}^2 |\bar{P}|^2$$

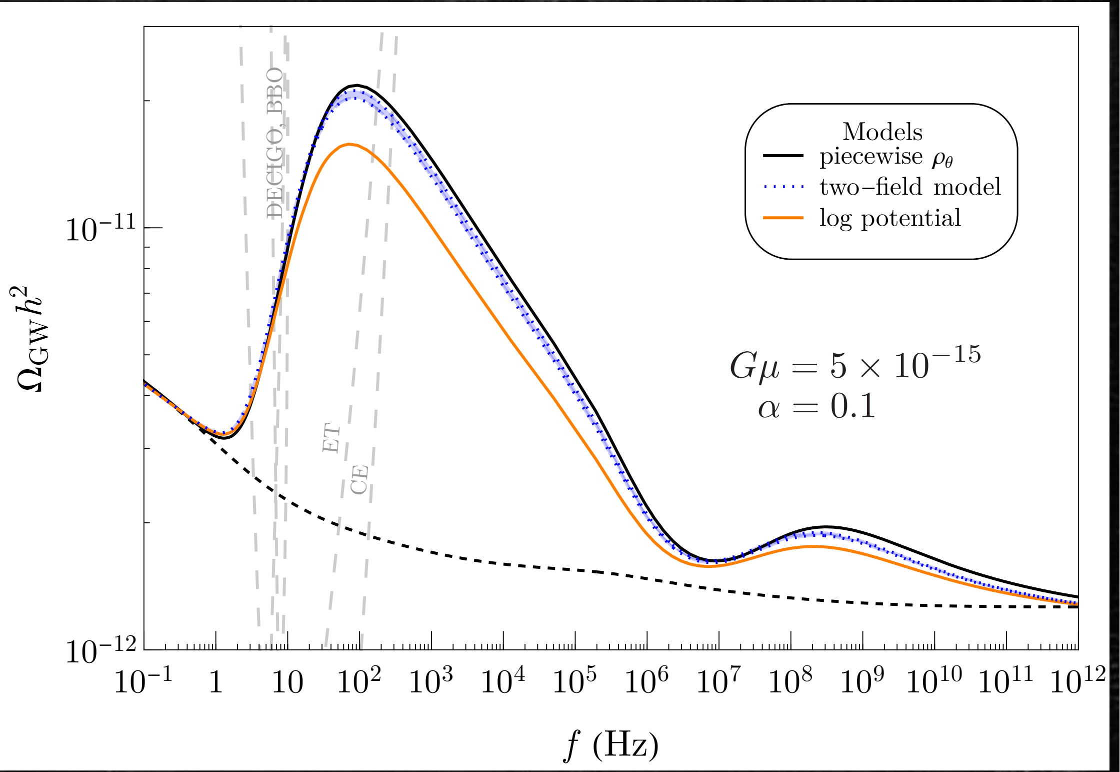


Probing PQ-breaking Potential

from inflation



from cosmic strings



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

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
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- ✓ Barnes, **RC** *et al.* 2208.07878
- ✓ **RC** *et al.* 2211.12517
- ✓ Berbig 2307.14121
- ✓ Chao *et al.* 2311.06469
- ✓ Chun *et al.* 2311.09005

Gravitational Waves

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

Cosmic Perturbations

- ✓ **RC** *et al.* 2202.01785

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
  - ✓ axion kination: unique gravitational wave spectra
- ✓ Other possible signatures include
  - ✓ gravitational lensing of axion mini-clusters
  - ✓ enhanced matter power spectrum
  - ✓ warm axion dark matter
  - ✓ Majorana neutrinos
- ✓ New model building opportunities
  - ✓ other open questions across disciplines