

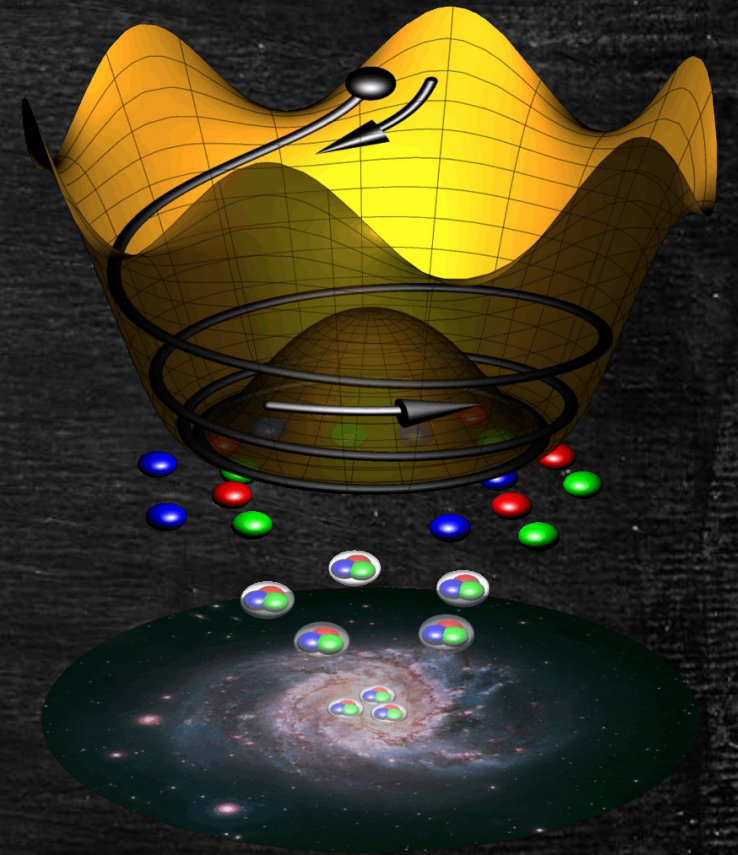
Adding Flavors to Axiogenesis and Spicing Up Cosmological Mysteries

University of California, Irvine
FLASY 2024

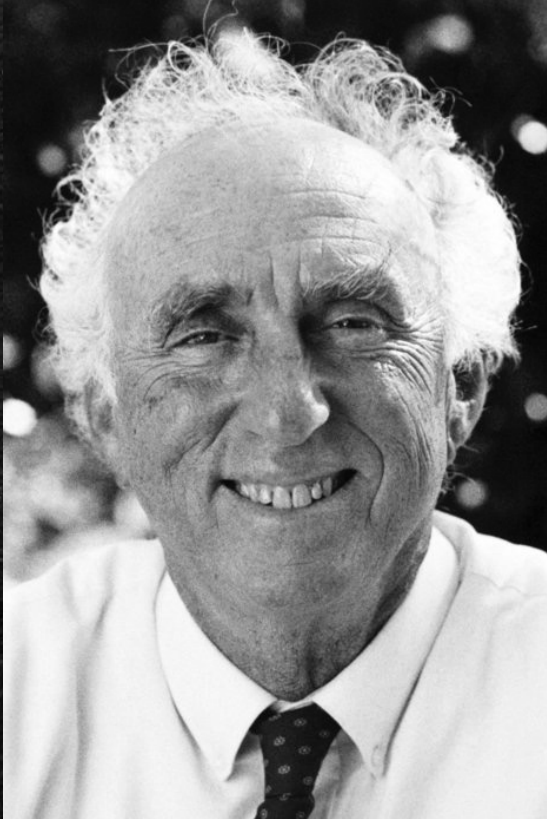
June 24th, 2024

Raymond Co

Indiana University



Today



Nobel Prize in Physics 1995

for pioneering experimental contributions to lepton physics"
jointly with one half to Martin L. Perl "for the discovery of the tau lepton"

Martin L. Perl

born on
June 24th 1927

Axions and Flavors

Fermion masses and mixings: Froggatt-Nielsen C. Froggatt and H. B. Nielsen 1979

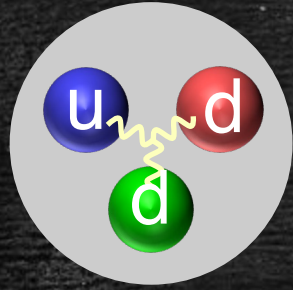
- “flaxion” Y. Ema et al. 2017, C. D. Carone and M. Merchand 2020
- “axiflavoron” L Calibbi et al. 2017, F. Arias-Aragon and L. Merlo 2017, M. Linster and R. Ziegler 2018
- “flavorful axion” F. Bjorkerorth et al. 2018, Q. Bonnefoy et al. 2020

Muon $g-2$: D. Chang et al. 2001, W. J. Marciano et al. 2016, M. Bauer et al. 2017 2020 2021,
C. Cornella et al. 2020, M. Chala et al. 2021, M. Buen-Abad 2021

MeV-scale ALP dark matter production P. Panci et al. 2023

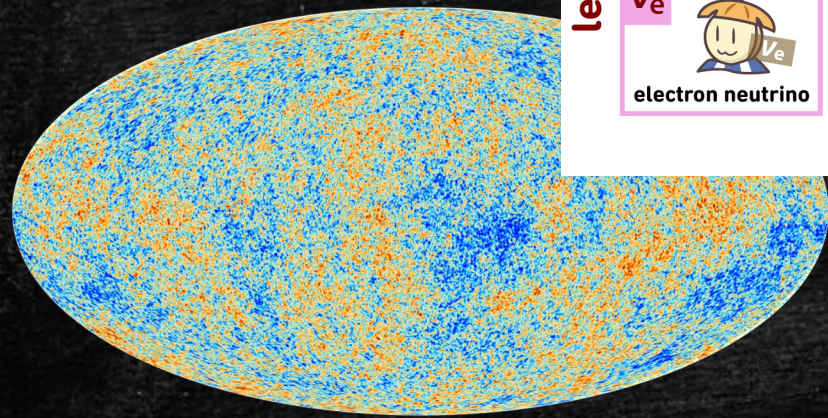
Outline of the Talk

strong CP problem



neutron

| | matter (fermions) | | | gauge bosons | |
|---------|---|---------------------------------------|--------------------------------------|--|------------------|
| quarks | u up quark | c charm quark | t top quark | γ photon | electro-magnetic |
| | d down quark | s strange quark | b bottom quark | g gluon | strong |
| | e electron | μ muon | τ tau | Z, W[±] weak bosons | weak |
| leptons | ν_e electron neutrino | ν_μ muon neutrino | ν_τ tau neutrino | H higgs boson | Higgs bosons |



Source: Planck



matter-antimatter asymmetry

dark matter

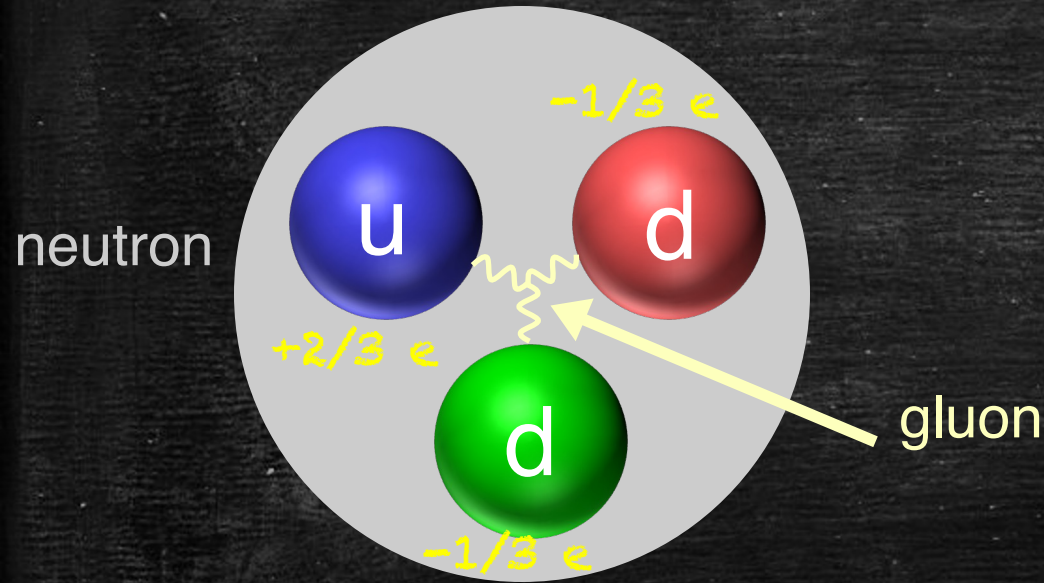


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Review of the QCD Axion

Strong CP Problem

“Charge-Parity” symmetry



Quantum field theory:

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

gluon

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

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

Experiments:

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

PRL 97, 131801 2006, PRL 124, 081803 2020

Strong CP problem:

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

Why exceedingly small?

Strong CP Problem solution



Peccei

Quinn

2017  Quanta magazine

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

Peccei, Quinn 1977
Weinberg 1978
Wilczek 1978

QCD axion

Promoted to a dynamical field:

$$\mathcal{L} \supset \left(\bar{\theta} + \frac{a}{f_a} \right) \frac{\alpha_s}{8\pi} G_b^{\mu\nu} \tilde{G}_{b\mu\nu}$$

decay constant

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

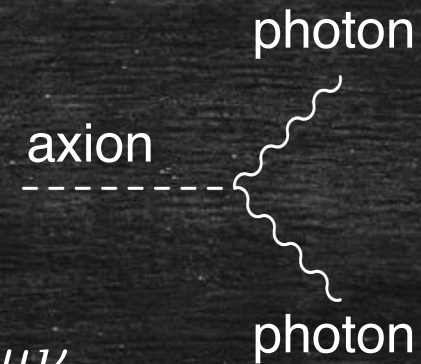
This potential dynamically drives the axion to a field value that cancels $\bar{\theta}$. Problem solved!

Status of Axion Dark Matter

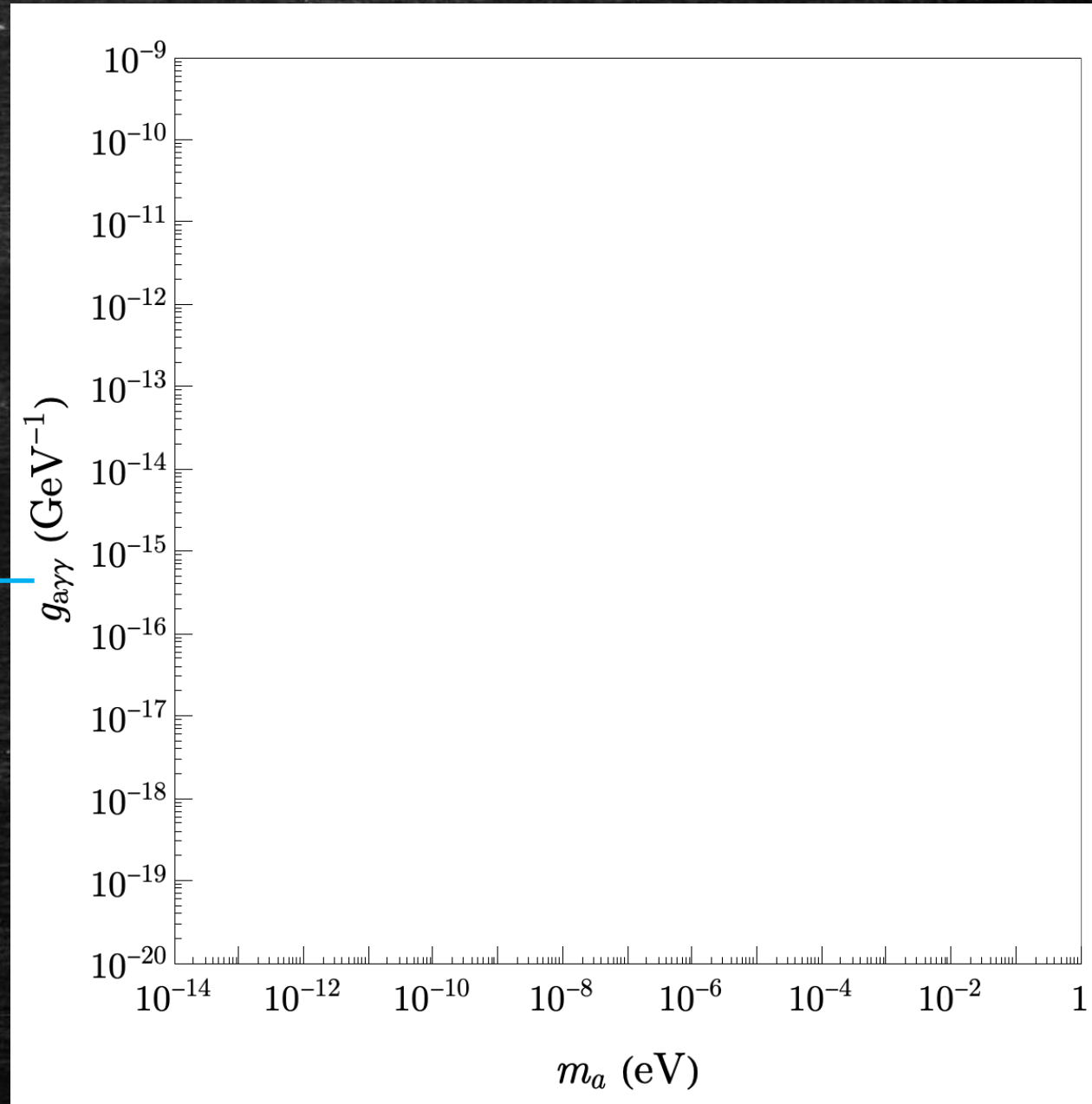
QCD Axion Prediction

For illustration, we show the axion-photon coupling

$$\mathcal{L} \supset \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$



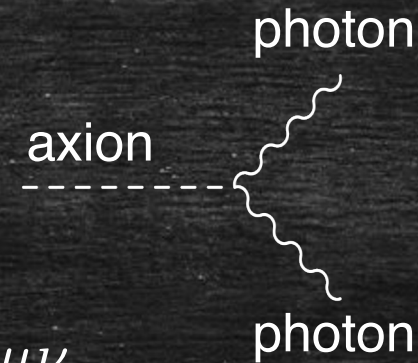
$$g_{a\gamma\gamma} \sim \frac{10^{-3}}{f_a}$$



QCD Axion Prediction

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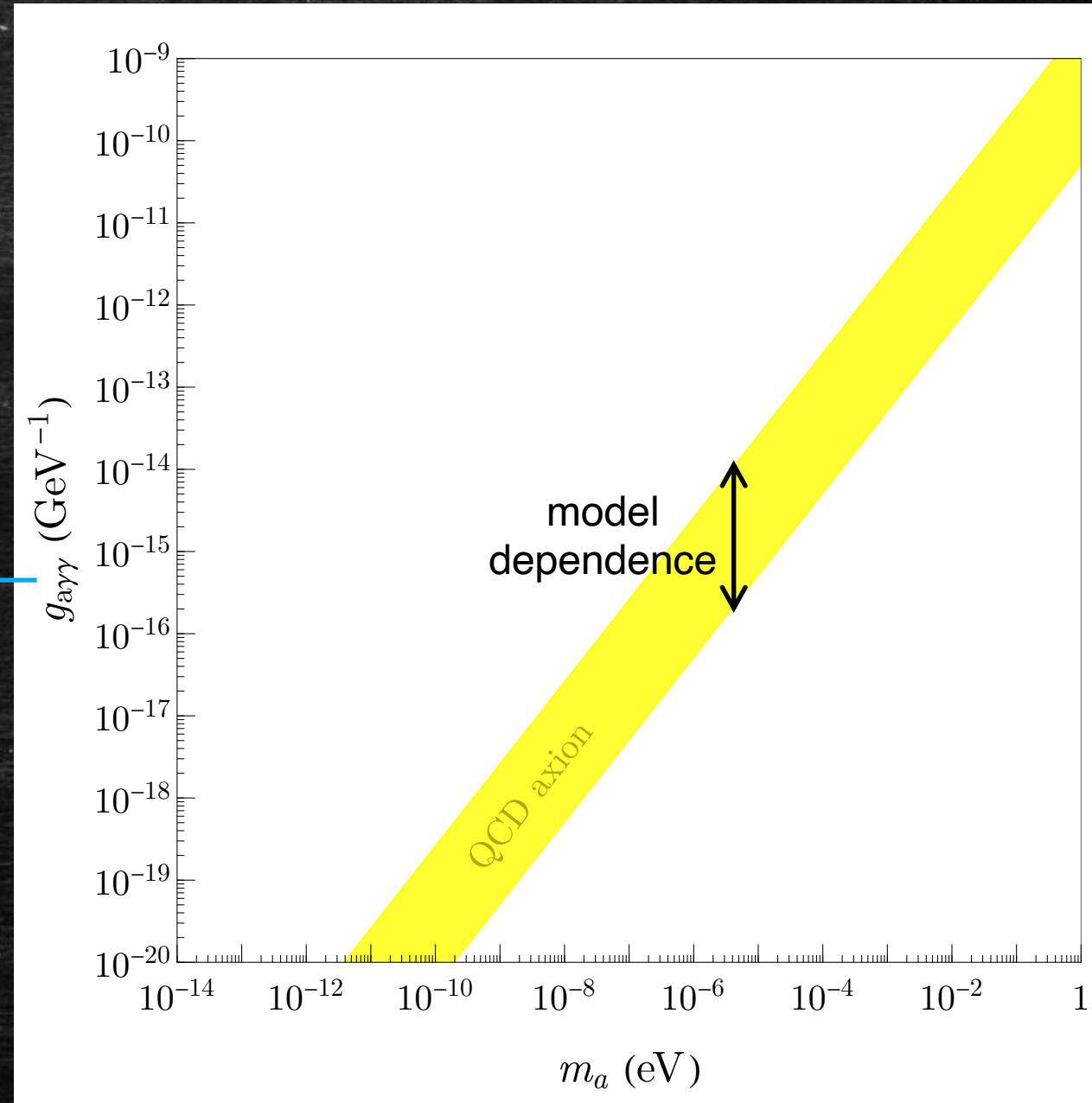
$$\mathcal{L} \supset \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$



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QCD effects automatically generate an axion potential

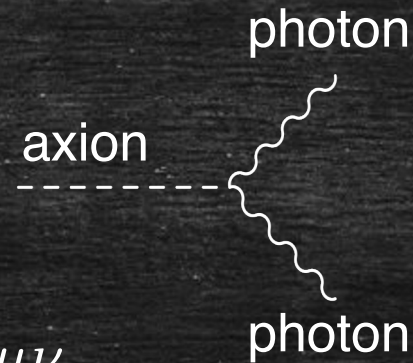
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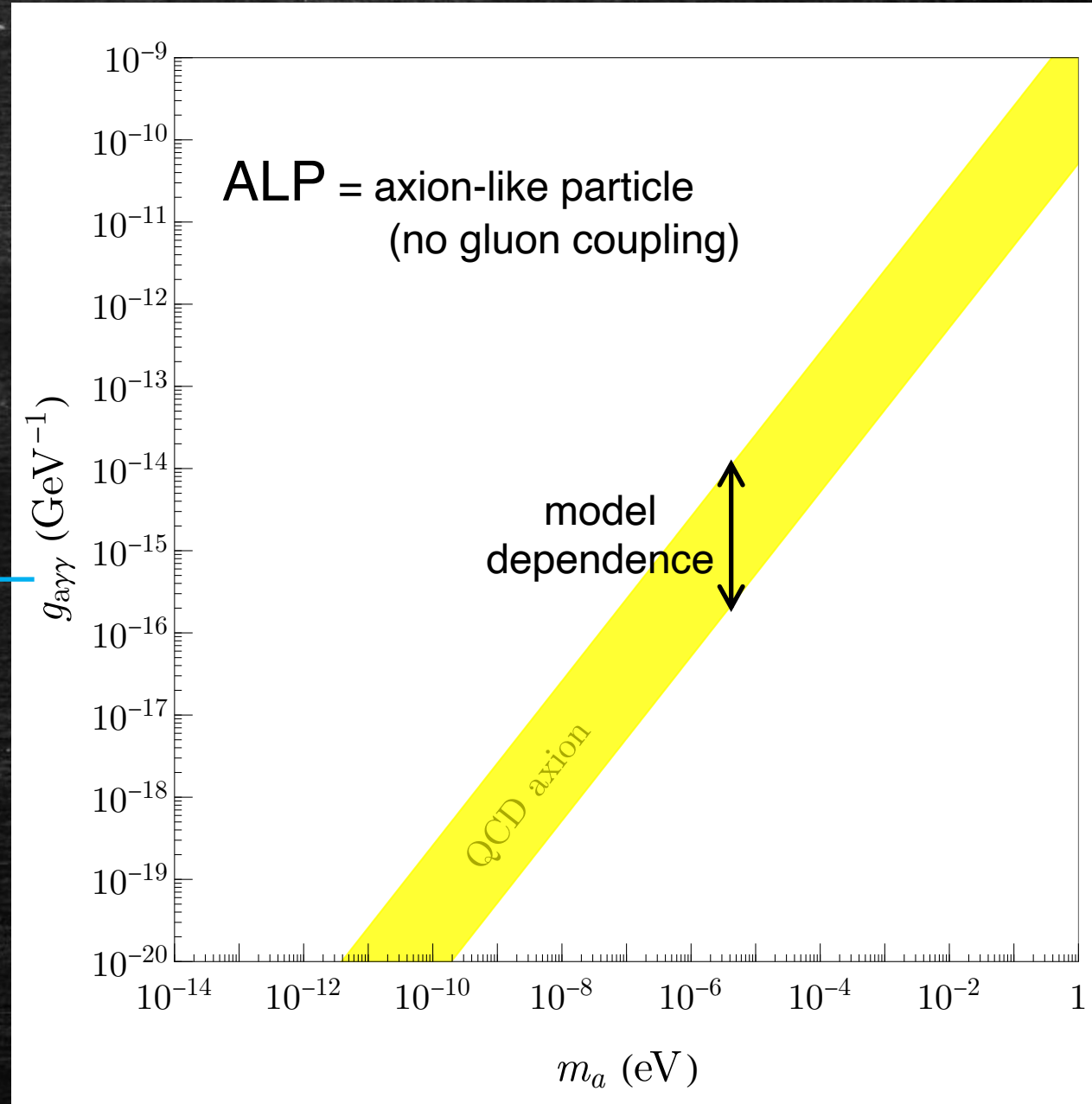
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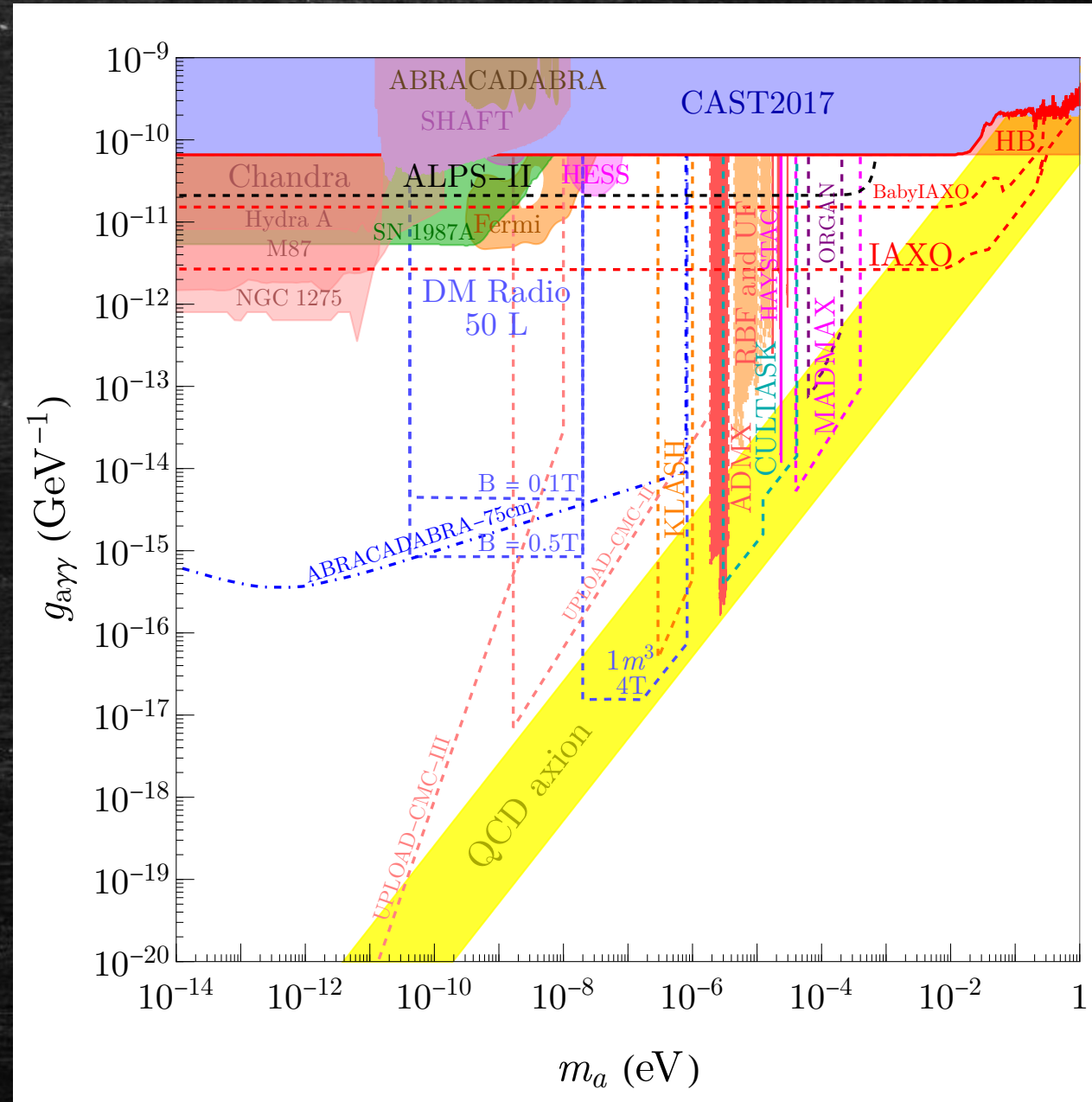


Experimental Searches

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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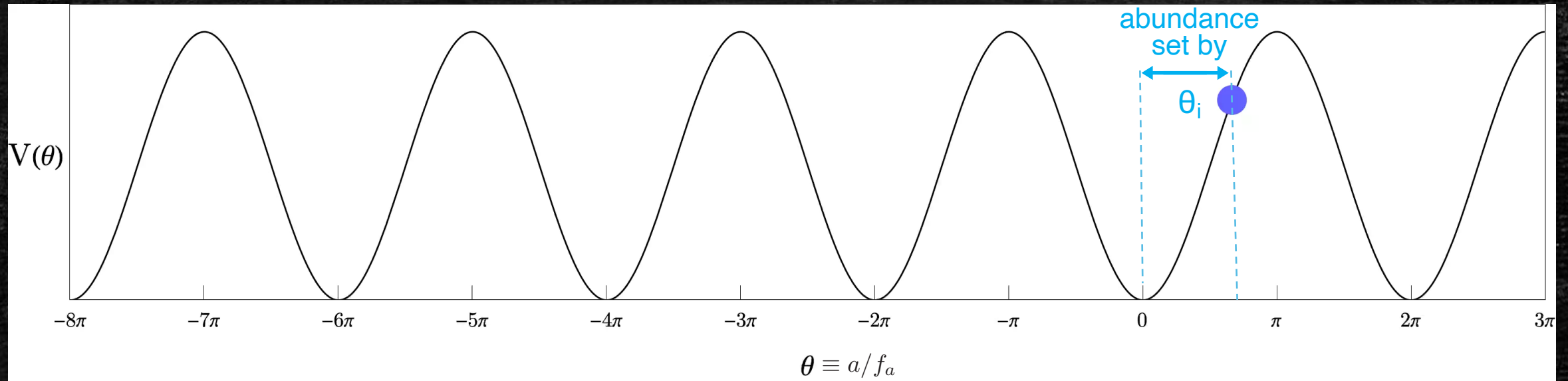
Hubble "friction"
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Misalignment Mechanism

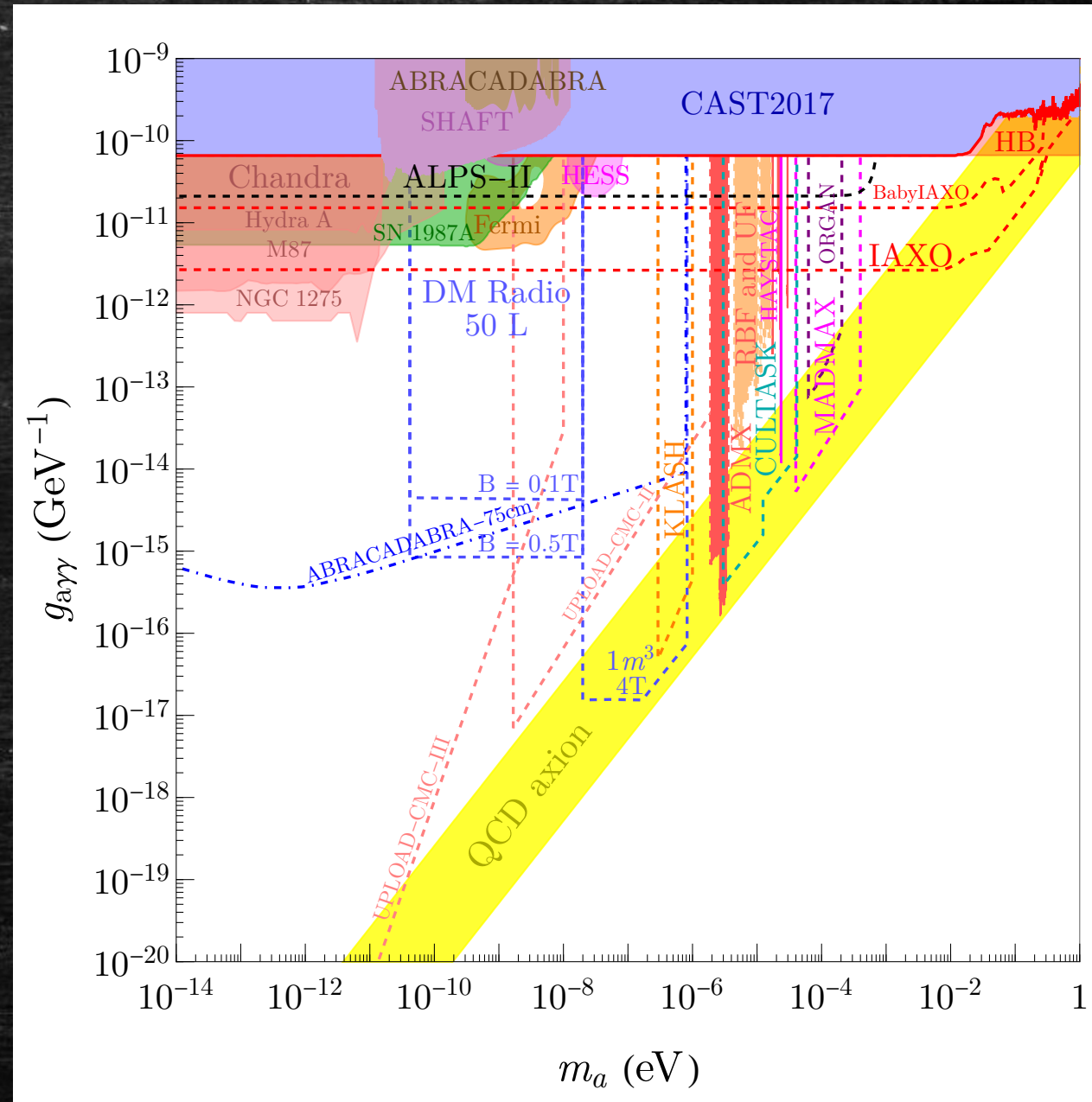
Preskill, Wise, Wilczek 1983
Abbott, Sikivie 1983
Dine, Fischler 1983

oscillations start when

$$H \lesssim m_a$$

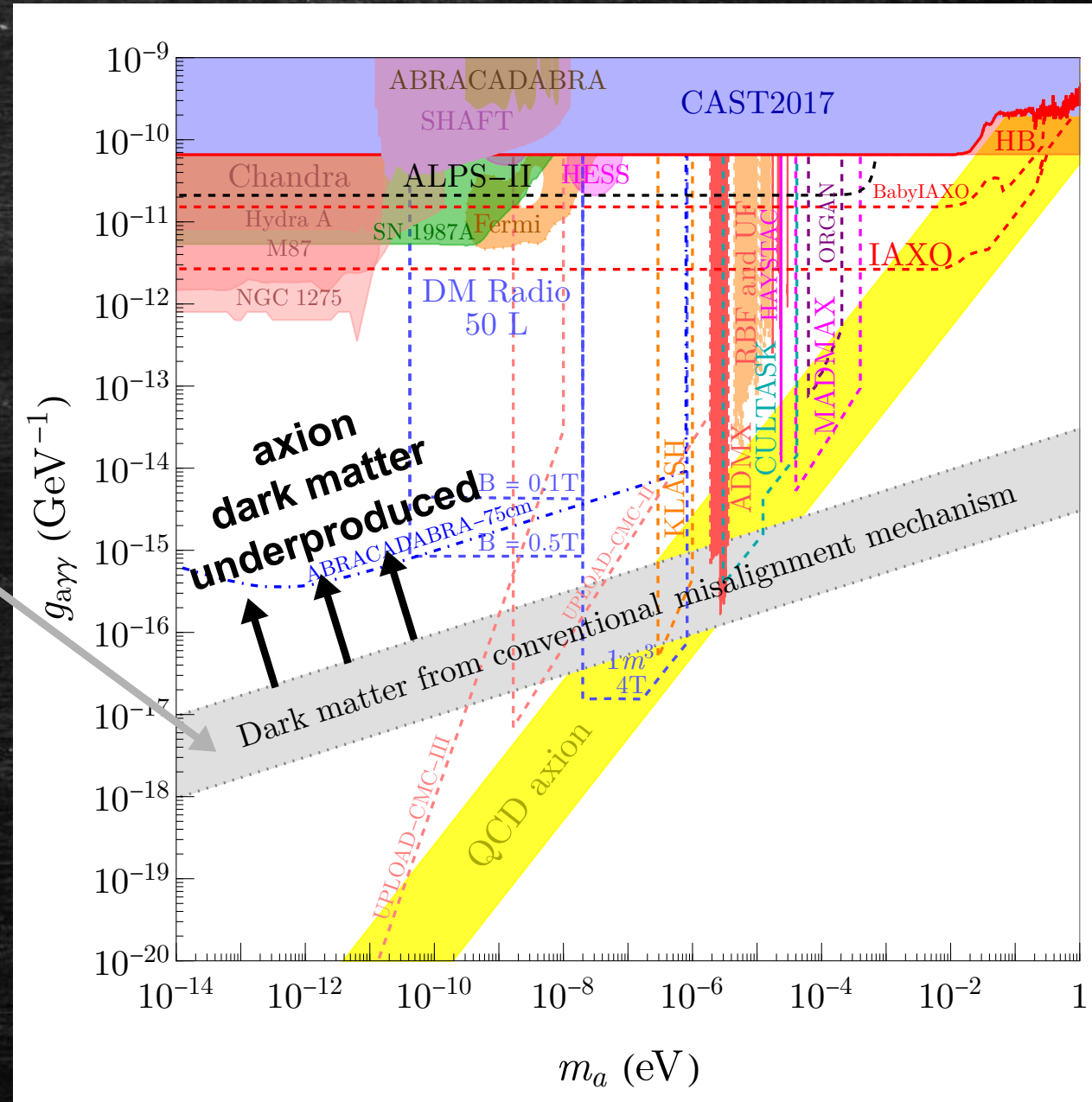


Axion Dark Matter Abundance



Axion Dark Matter Abundance

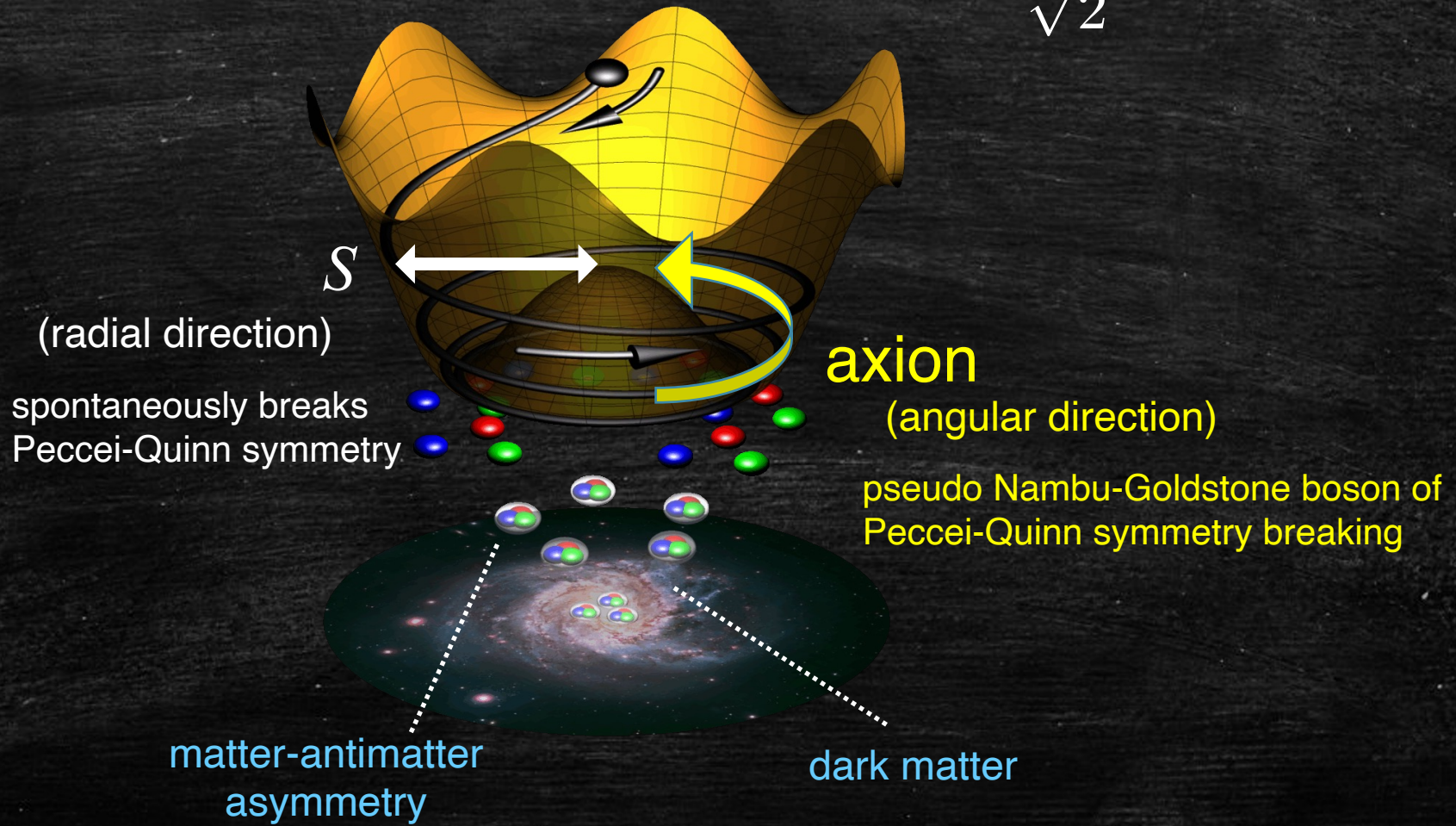
We assume $\theta_i = \mathcal{O}(1)$ here.



Axion Rotation

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

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



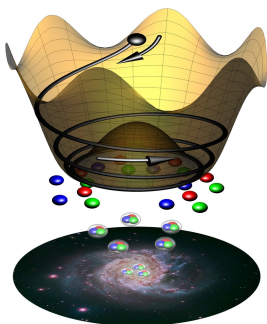
PHYSICAL REVIEW LETTERS

Articles published week ending 20 MARCH 2020



Paper sheds light on infant universe and origin of matter

10 March 2020



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."

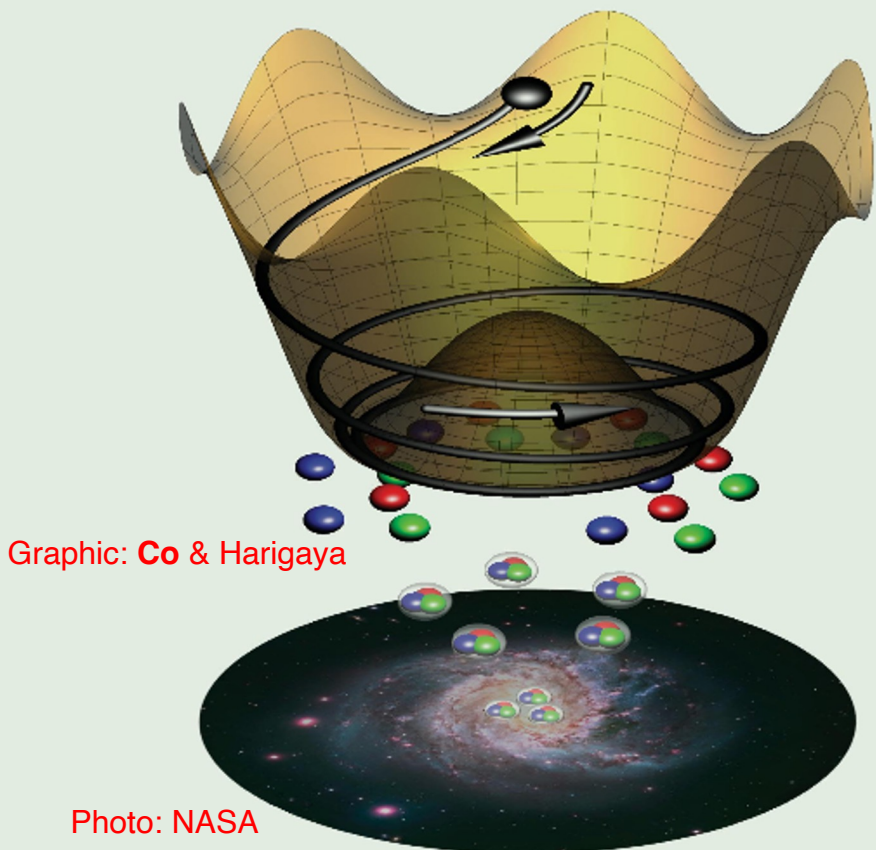
Infinitesimally light, the QCD axion—at least one billion times lighter than a proton—is nearly ghost-like. Millions of these particles pass through ordinary matter every second without notice. However, the subatomic level interaction of the QCD axion can still leave detectable signals in experiments 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

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



Graphic: Co & Harigaya

Photo: NASA



Quanta magazine

Physics

Mathematics

Bio

ABSTRACTS 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.

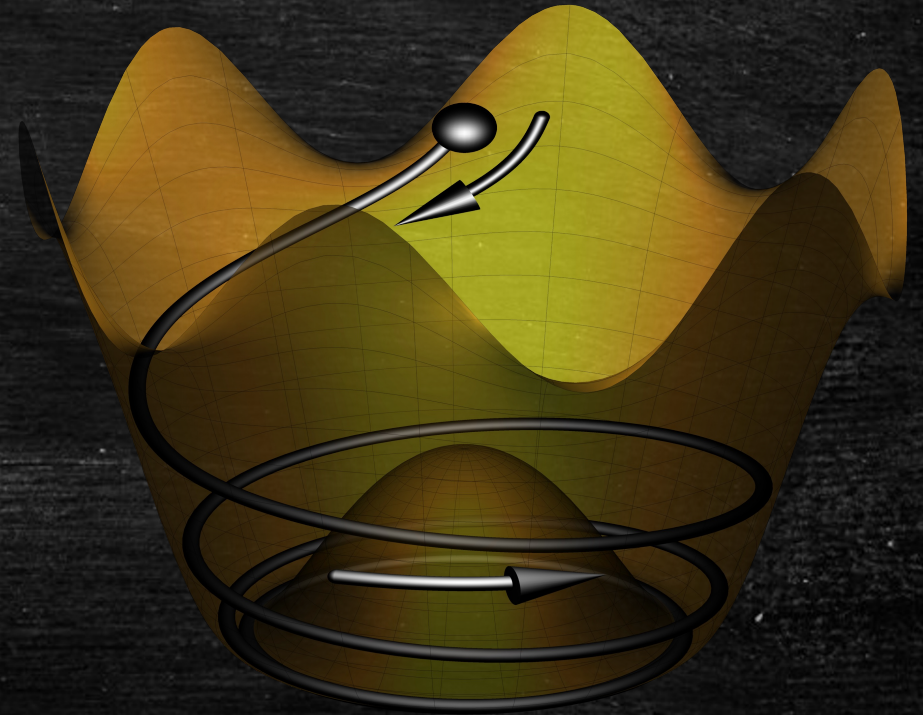
Published by
American Physical Society



Volume 124, Number 11

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 :

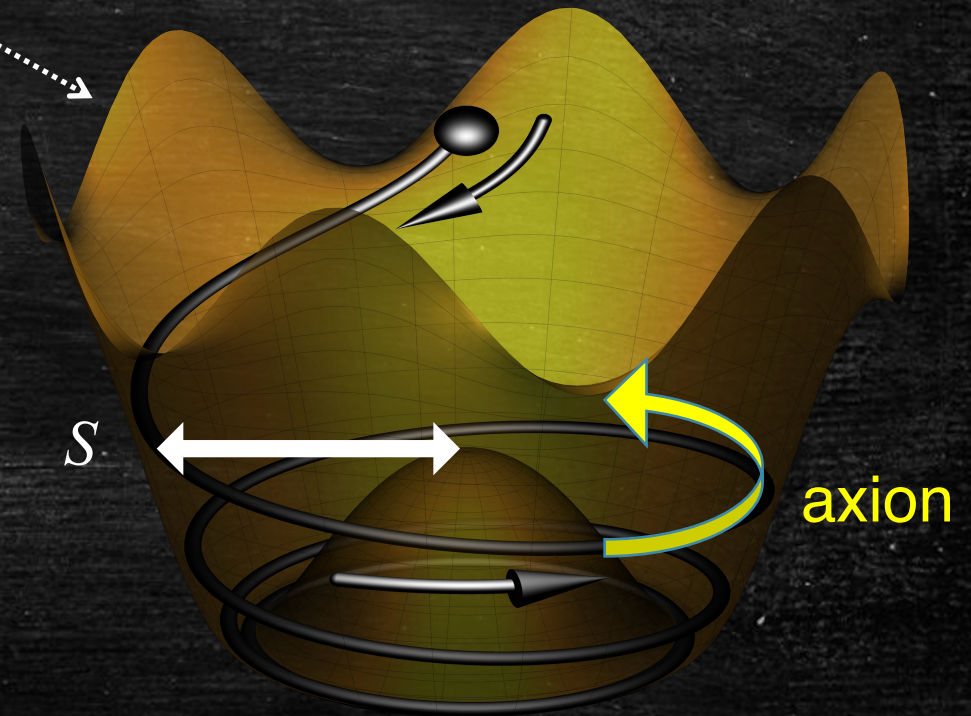
$$V(P) \sim \frac{P^n}{M^{n-4}} e^{i\varphi} + \text{h.c.} \sim \frac{|P|^n}{M^{n-4}} \cos\left(n \frac{a}{f_a} + \varphi\right)$$

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

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 :

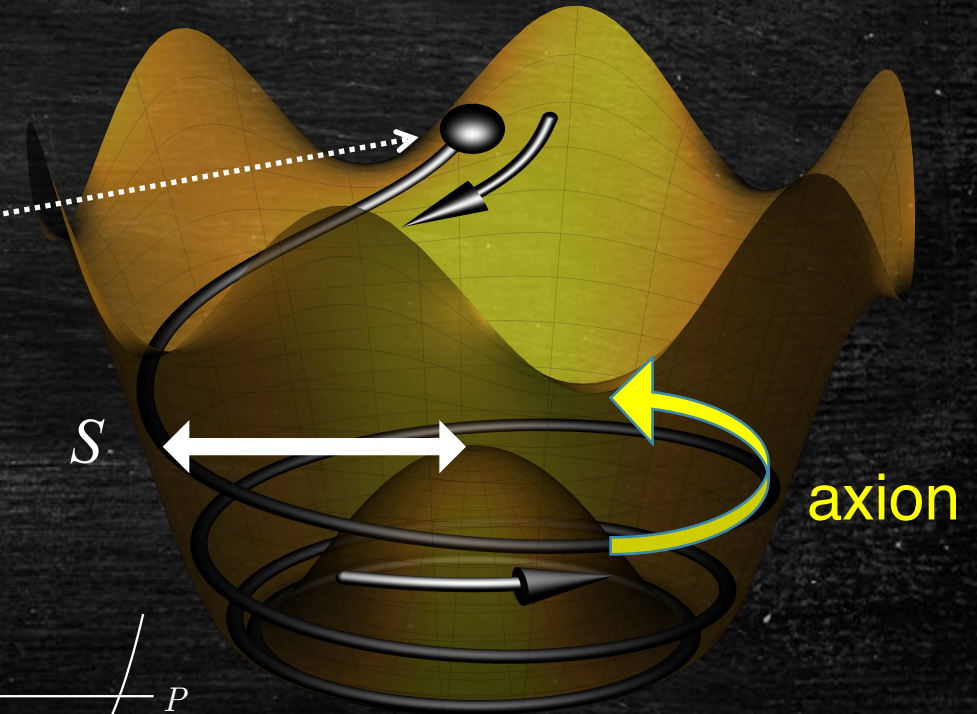
Flat potential

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

I. Affleck and M. Dine 1991

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

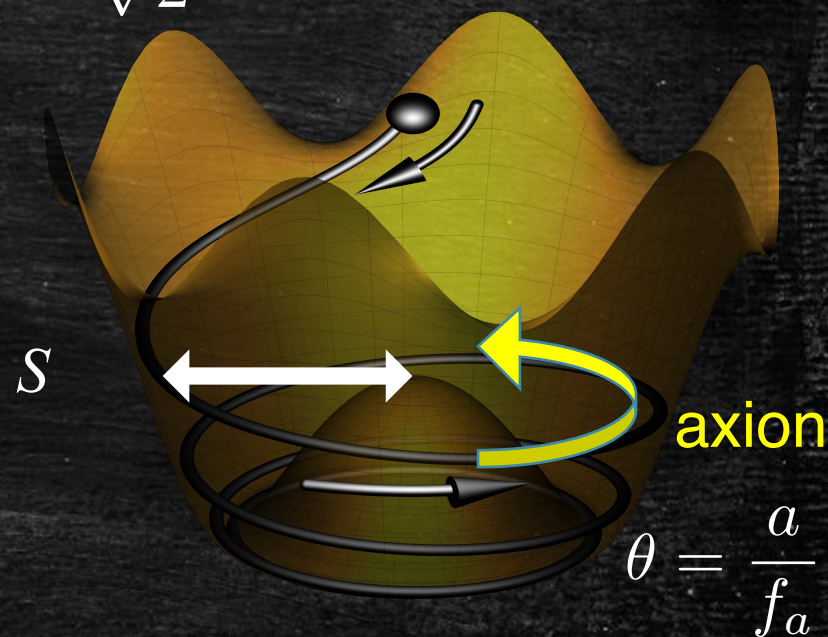
$$n_\theta = S^2 \dot{\theta}$$

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

Noether charge associated with the shift symmetry

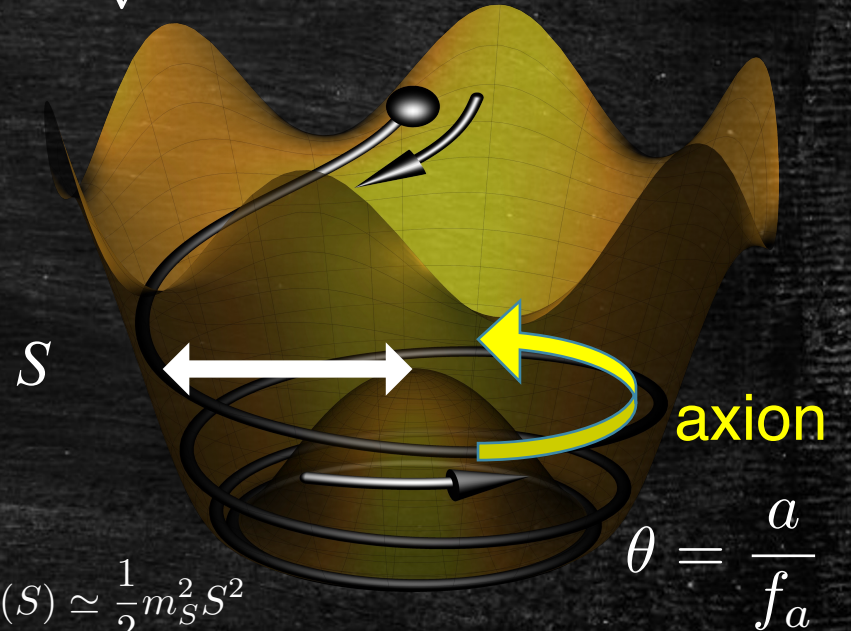
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PQ asymmetry
PQ charge density = Rotation of PQ field

This is conserved soon after the initial kick.



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

$$F_c = m a_c$$

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

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

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

from supersymmetry

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

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

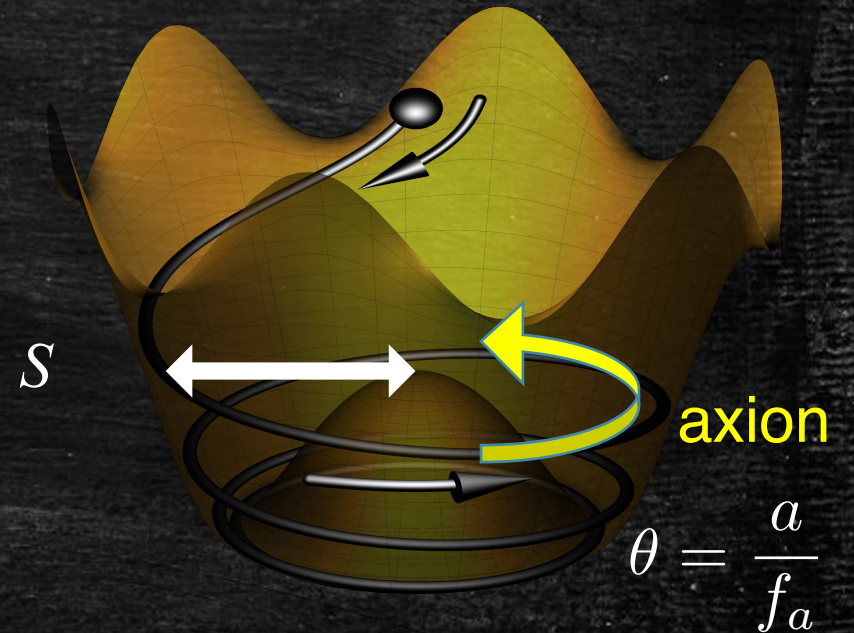
PQ Charge Evolution

Charge conservation:

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

scale factor of the universe

dilution due to cosmic expansion



PQ Charge Evolution

Charge conservation:

$$n_\theta = S^2 \dot{\theta} \propto \frac{R^{-3}}{\text{scale factor of the universe}}$$

Large field ($S \gg f_a$):

$$S^2 \propto R^{-3}$$

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

$$\dot{\theta} = \text{constant}$$

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

matter

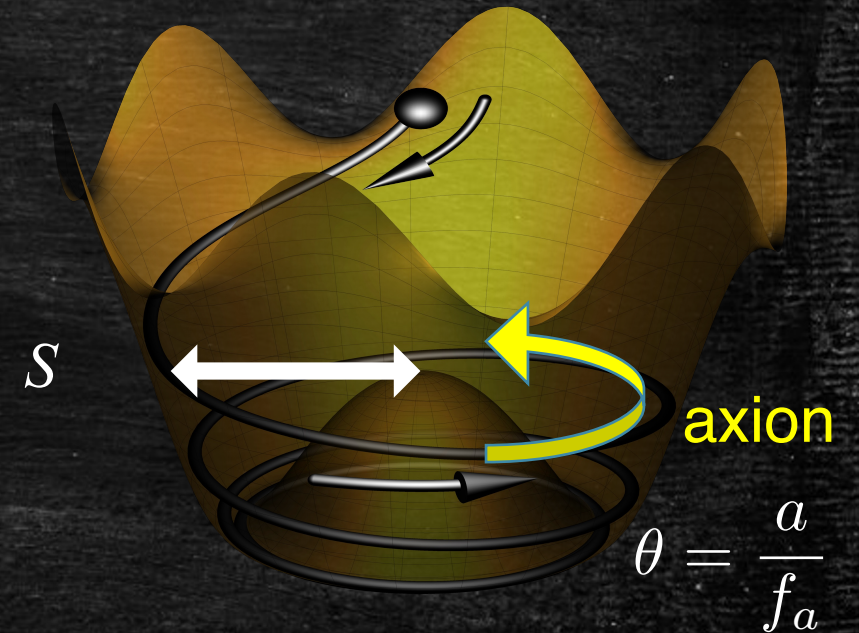
At the minimum:

$$S^2 = f_a^2$$

$$\dot{\theta} \propto R^{-3}$$

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

kination



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

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

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

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

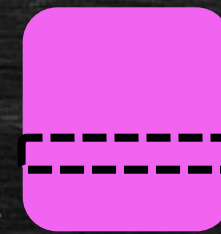
Most of the PQ charge remains in the rotation!

thermal bath

$$n_{\text{th}} \simeq T^3$$

rotation

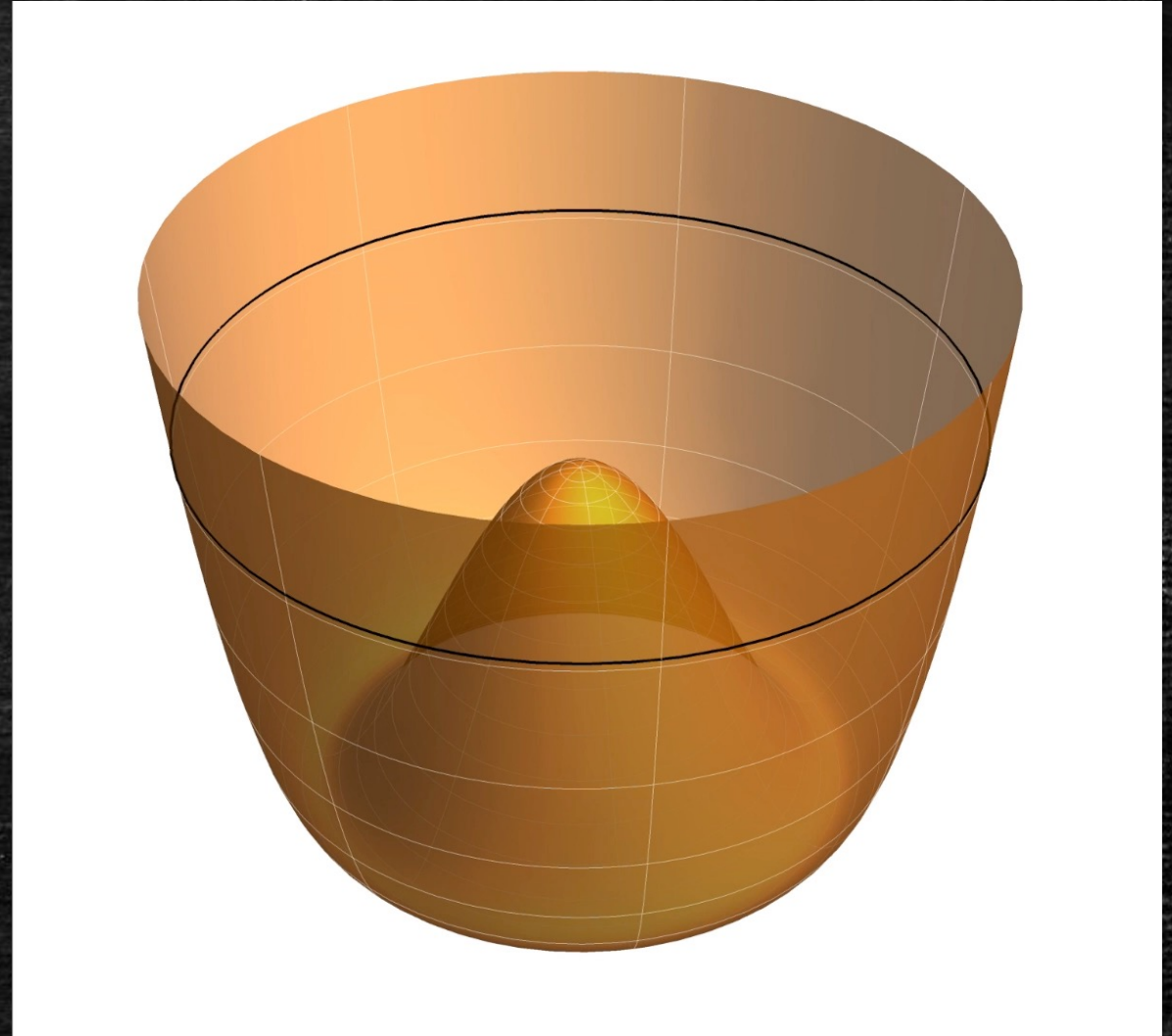
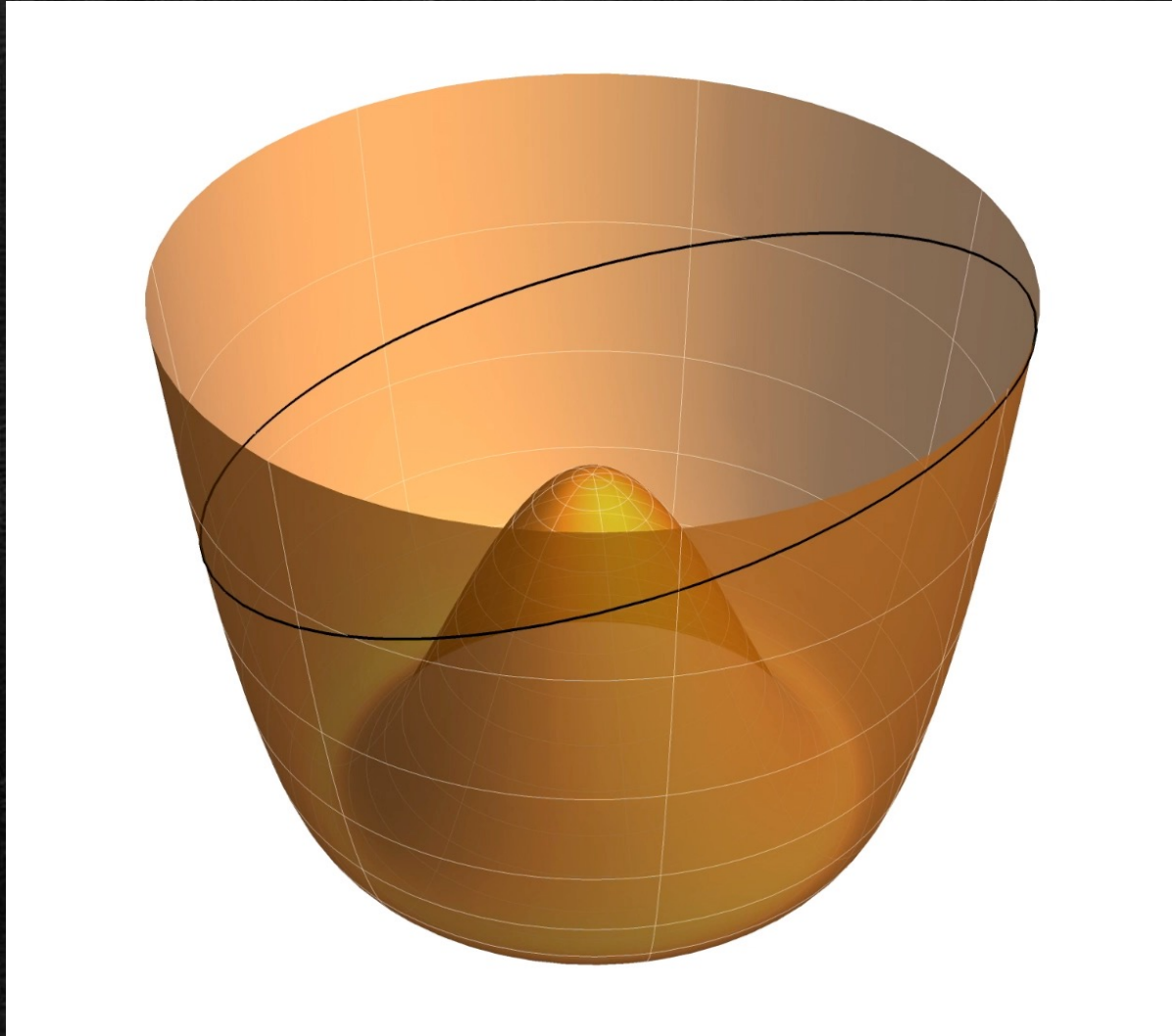
$$n_{\text{PQ}} = \dot{\theta} S^2$$



$$n_\psi \simeq \dot{\theta} T^2$$

Asymmetries in Thermal Equilibrium

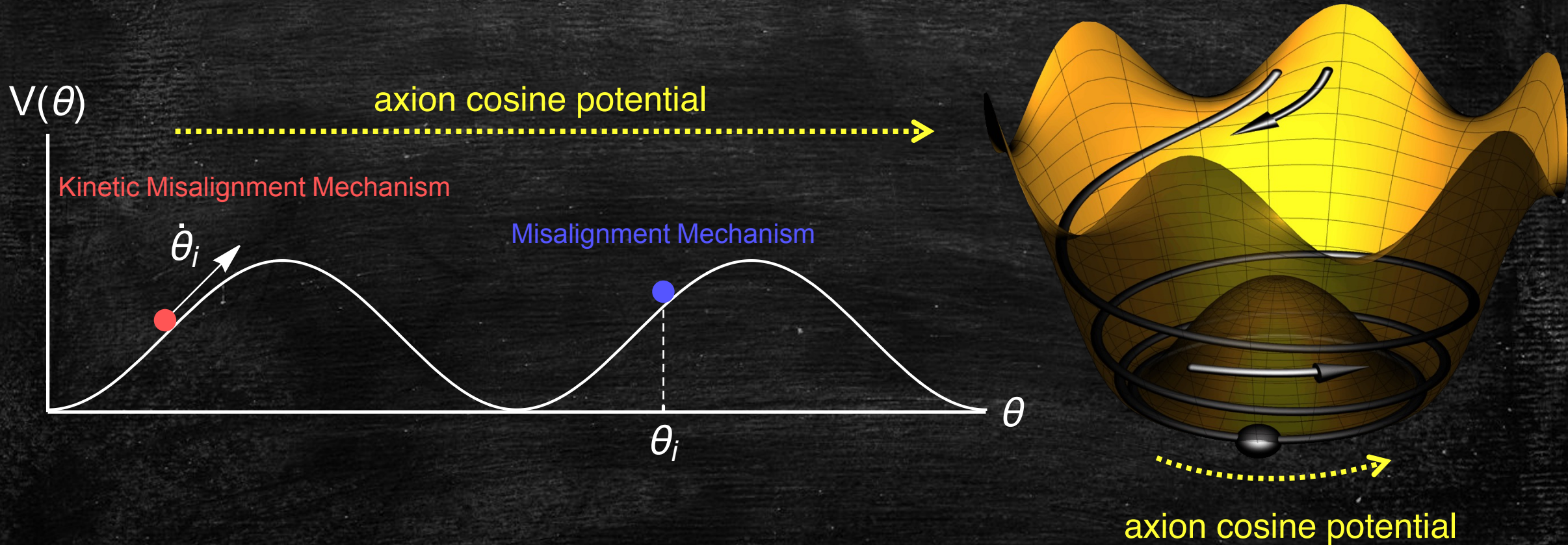
Thermalization $n_{\text{PQ}} = S^2 \dot{\theta}$ Redshift



Axion Dark Matter

Kinetic Misalignment Mechanism

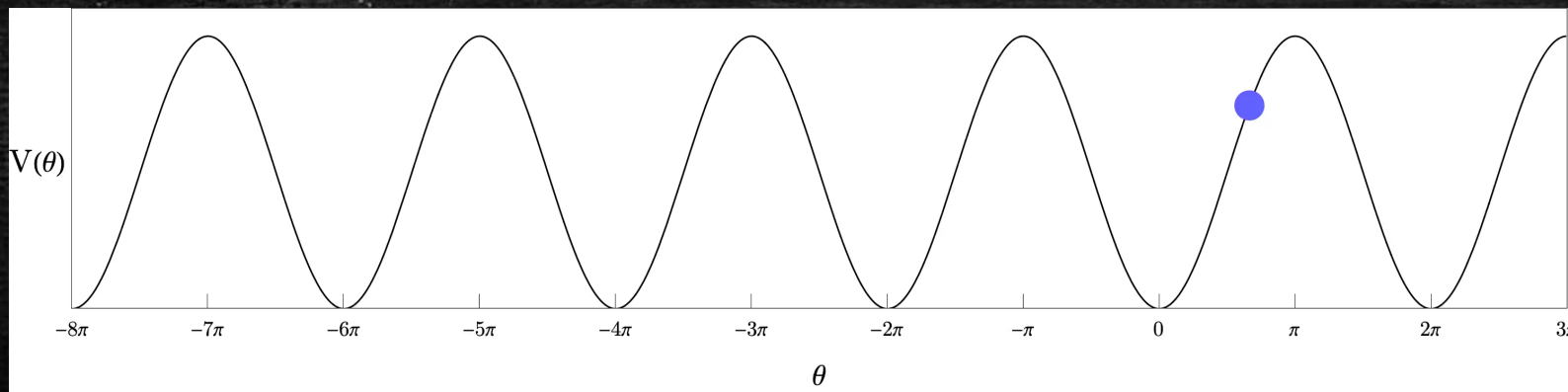
a novel scenario where the axion field has a nonzero initial velocity, e.g., from axion rotations.



Kinetic Misalignment Mechanism

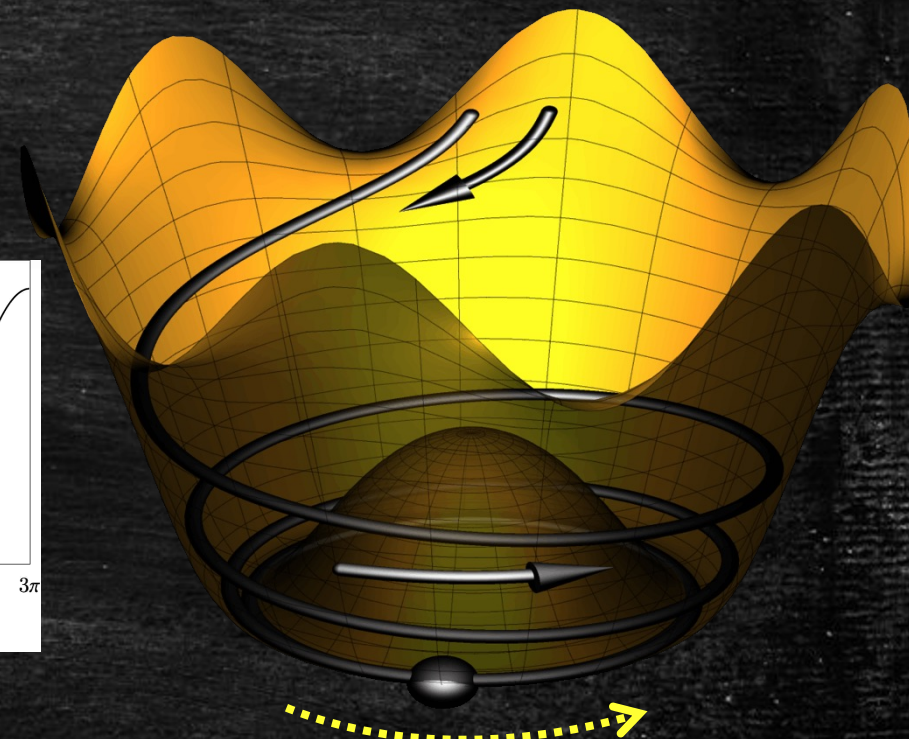
a novel scenario where the axion field has a nonzero initial velocity, e.g., from axion rotations.

axion cosine potential



kinetic energy > potential energy

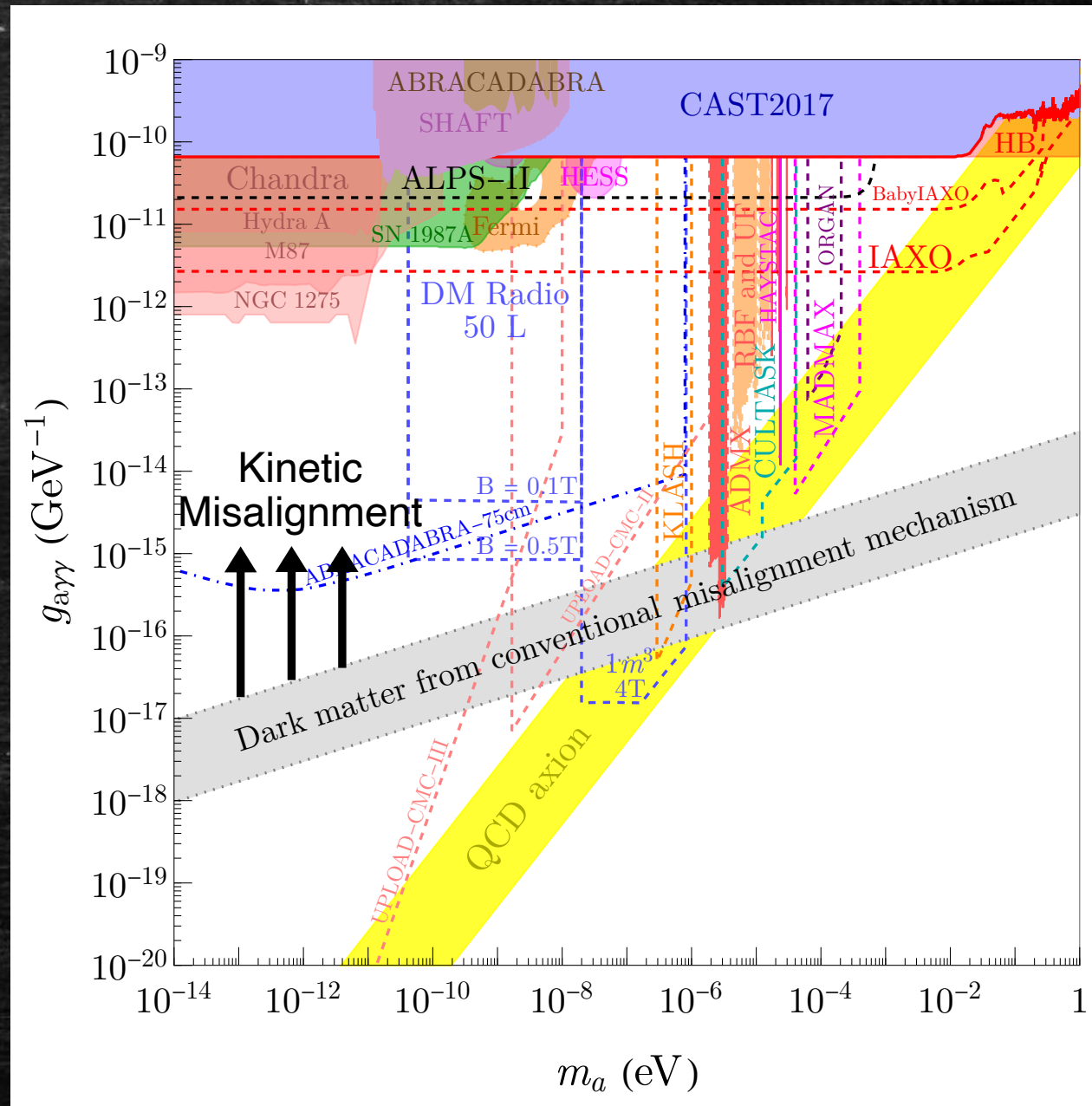
enhancing axion abundance



axion cosine potential

Kinetic Misalignment Mechanism

giving a strong motivation for axion dark matter experiment



Kinetic Misalignment Mechanism

Kinetic Misalignment*

charge yield

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

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

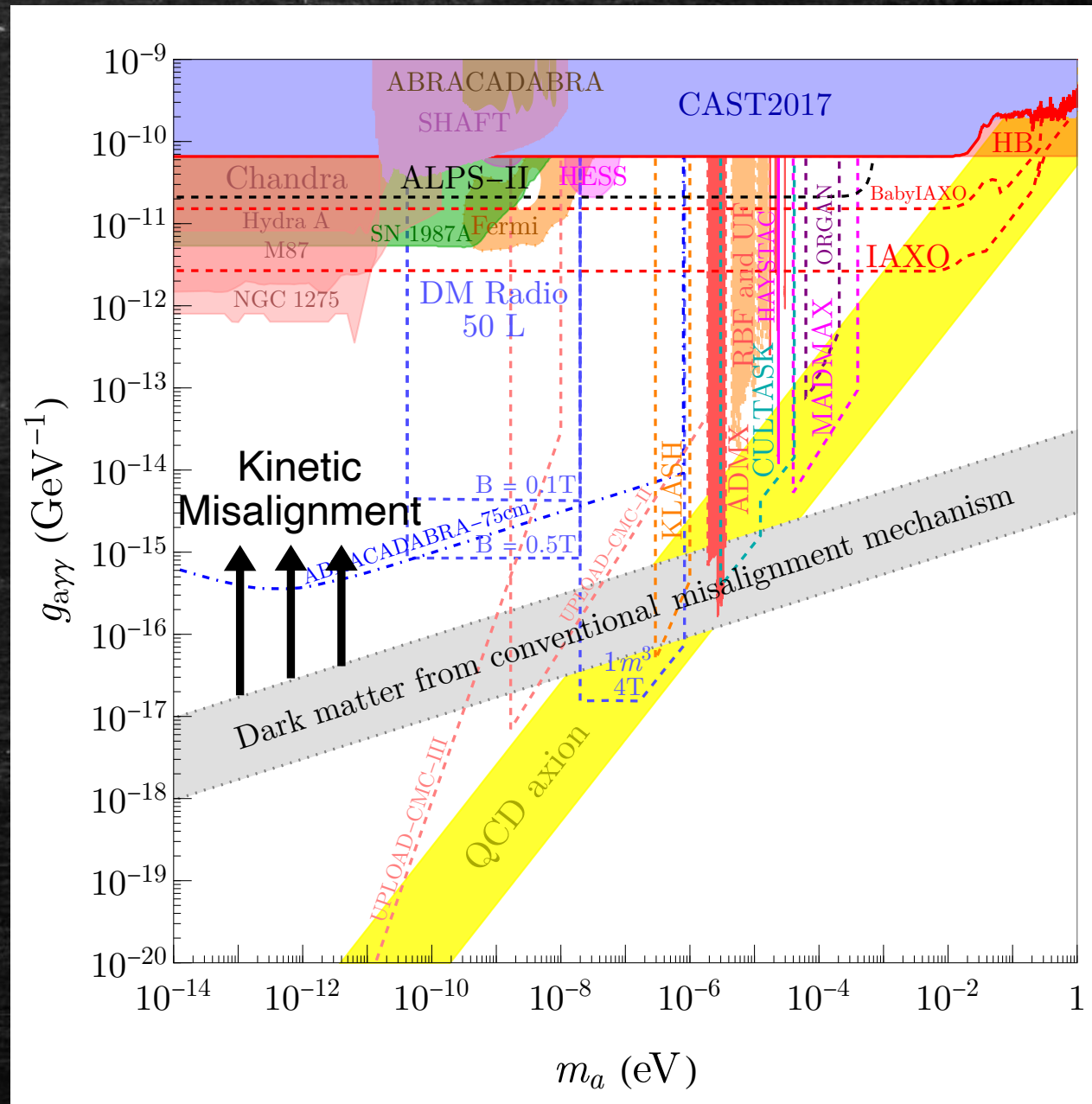
abundance

Observed dark matter abundance

$$\frac{\rho_{\text{DM}}}{s} \simeq 0.44 \text{ eV} \quad (\text{Planck 2018})$$

Thus, dark matter relates

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

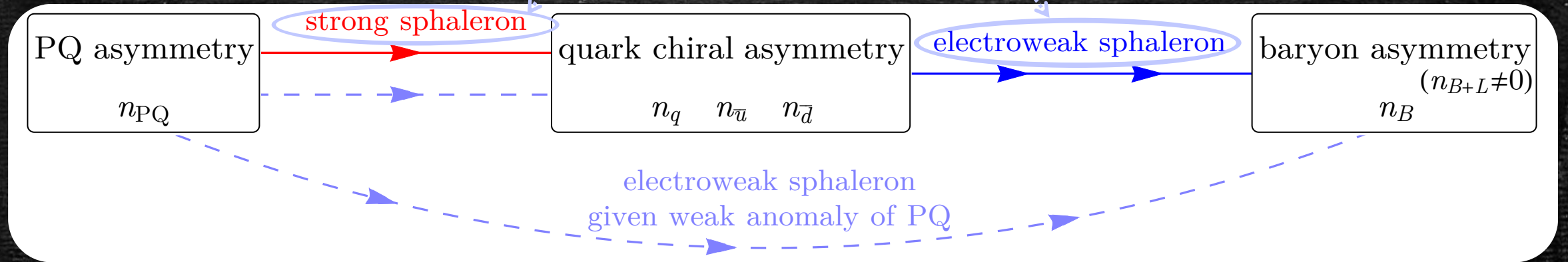


Baryon Asymmetry Axionogenesis

Axiogenesis

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

matter-antimatter asymmetry



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

produced by axion rotations

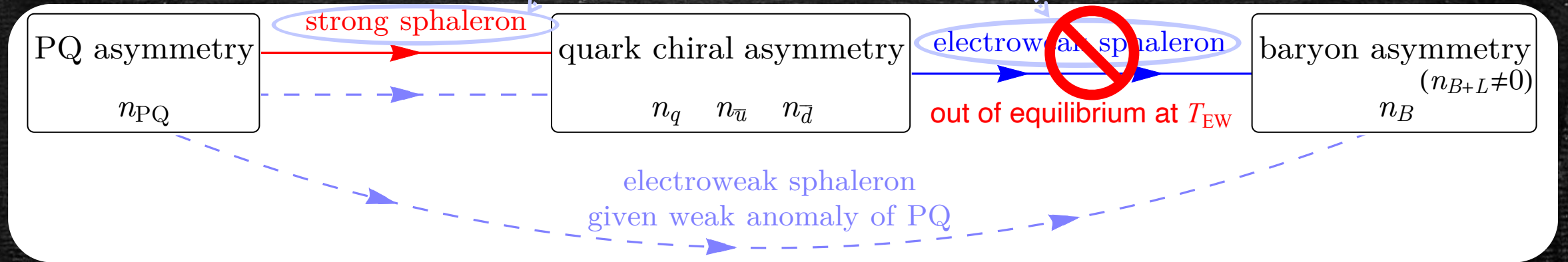
$$Y_B^{\text{obs}} \simeq 8.7 \times 10^{-11}$$

experimentally measured value
(Planck 2018)

Axiogenesis

Baryogenesis is automatic, thanks to Standard Model processes
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Namely, the baryon asymmetry relates

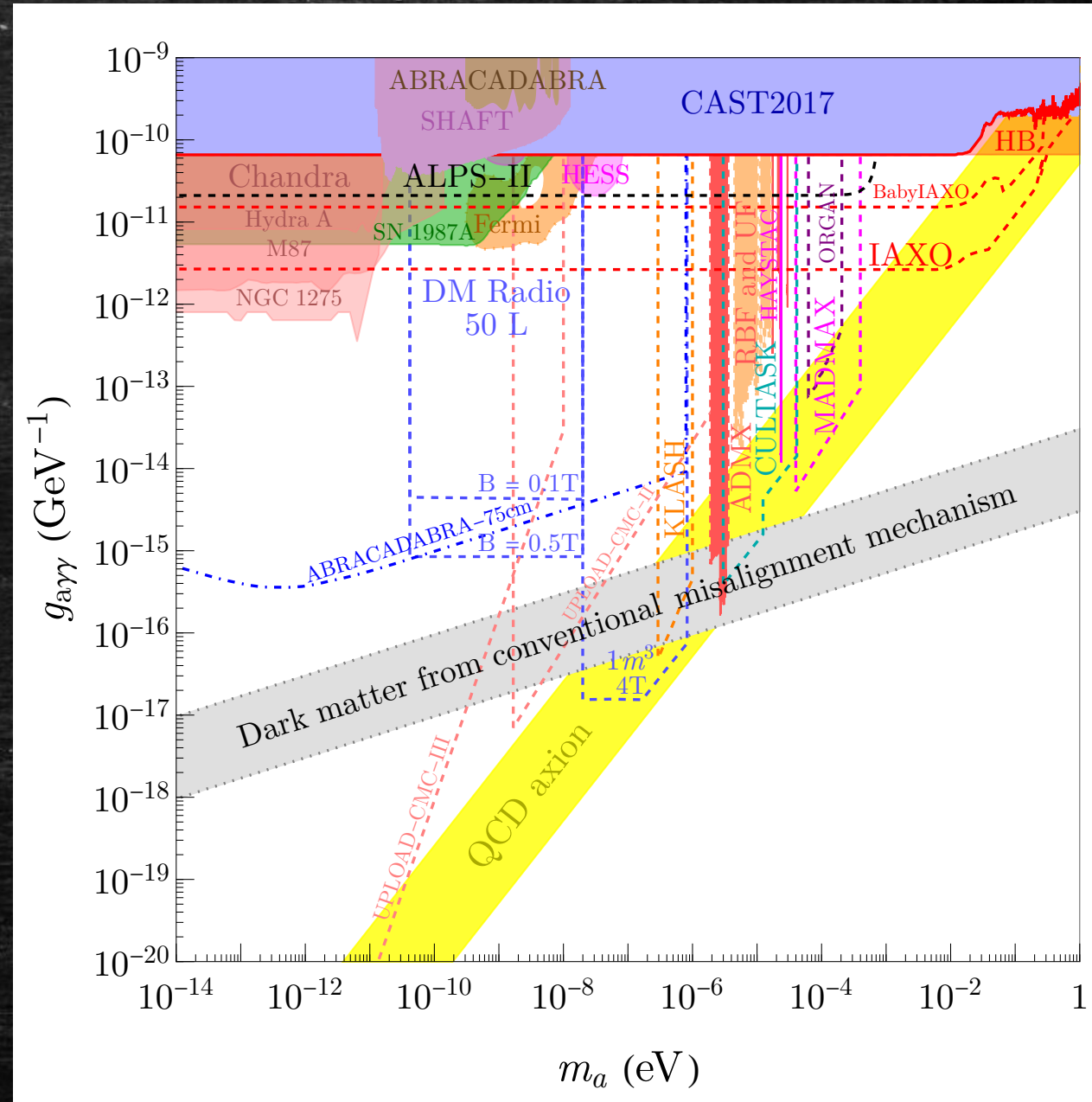
$$\left(\frac{T_{EW}}{f_a} \right)^2 \xleftrightarrow{Y_B} Y_\theta$$

Axion/ALP Cogenesis

Kinetic Misalignment + Axionogenesis

Prediction:

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



Kinetic Misalignment + Axionogenesis

Prediction:

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

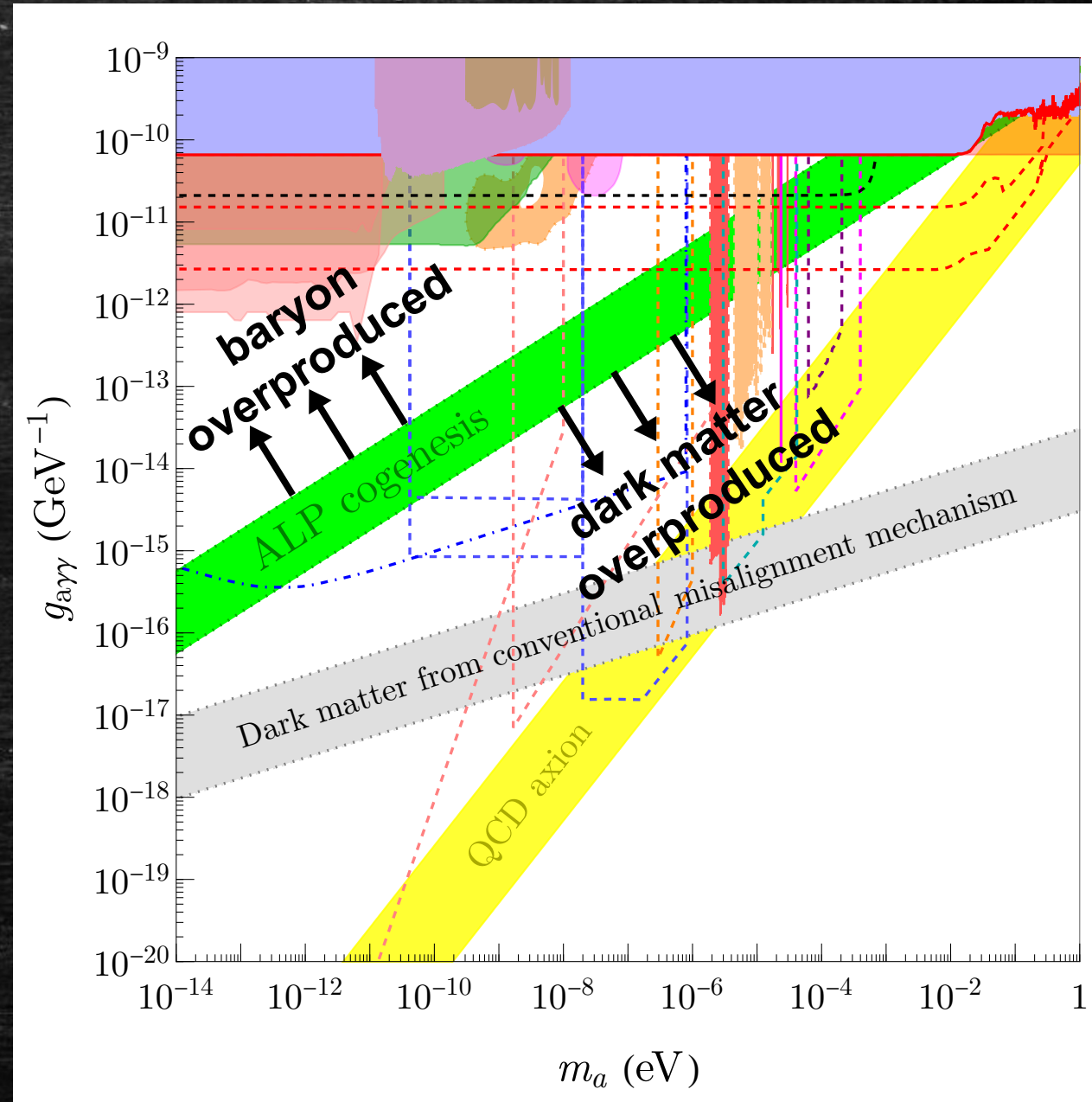
ALPogenesis :

ALP = axion-like particle
(no gluon coupling)

cogenesis

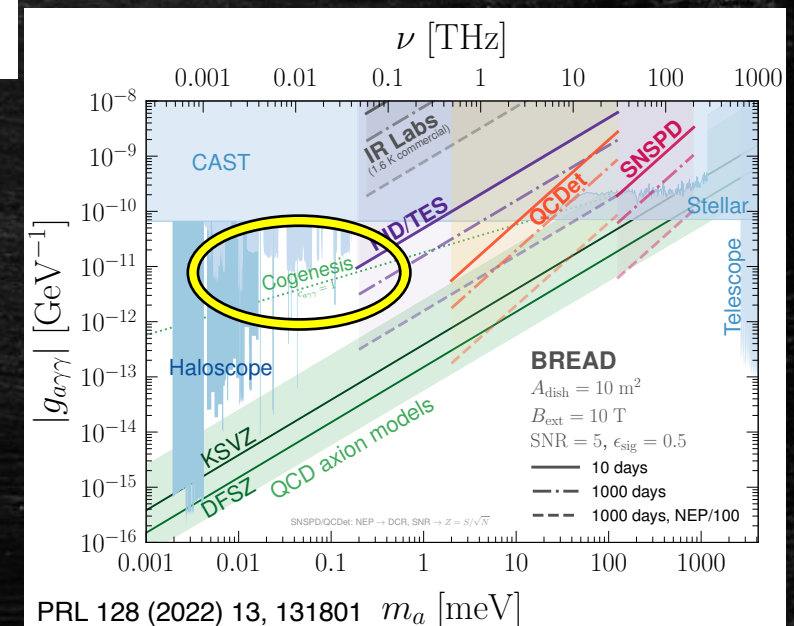
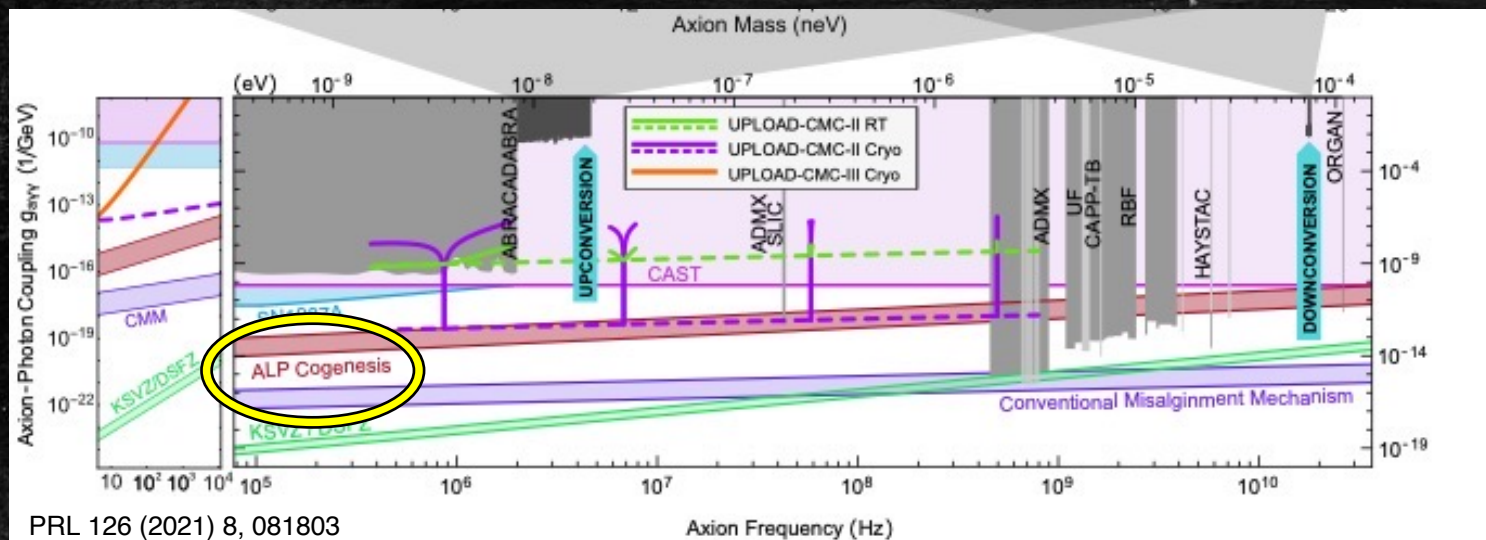
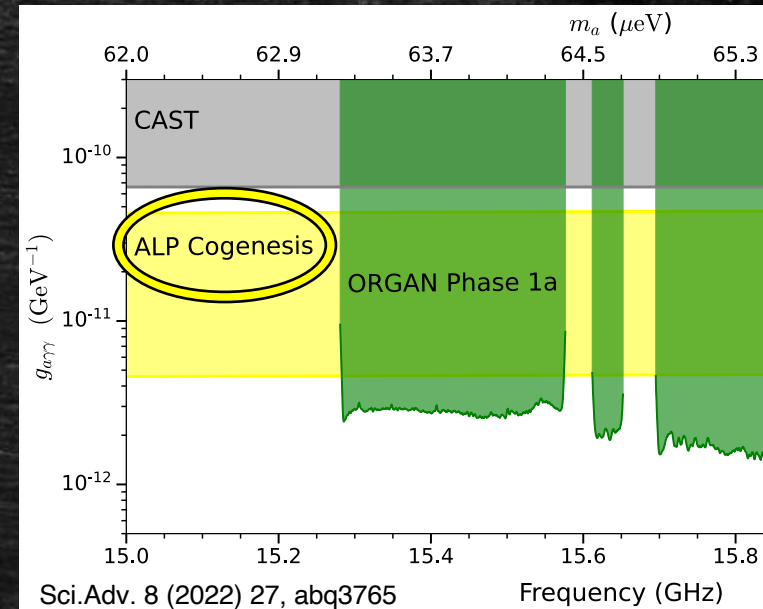
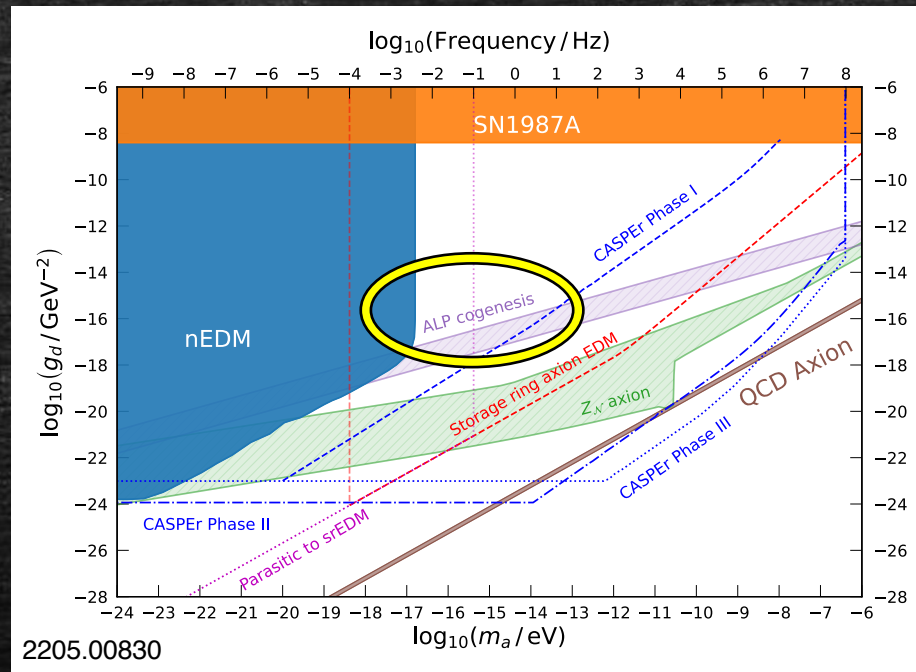
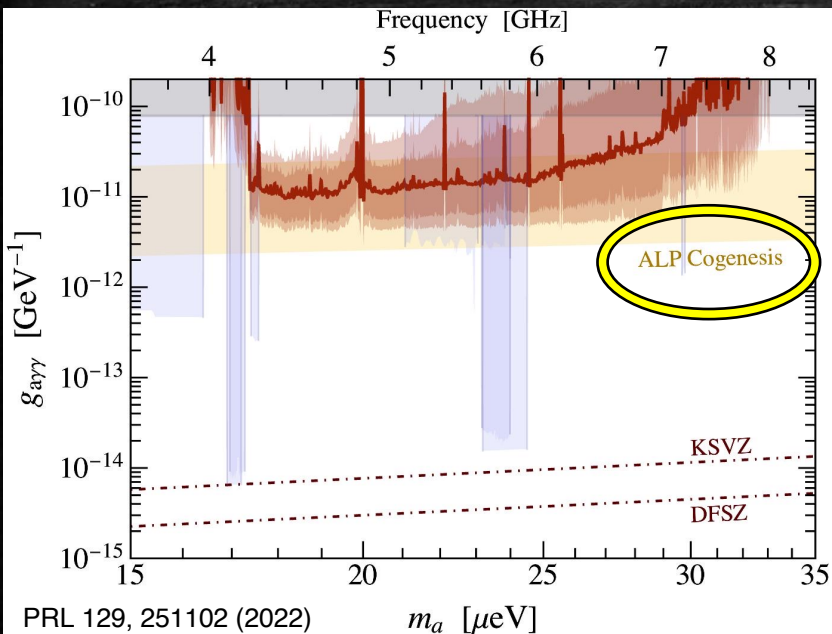
= production of both dark matter
& matter-antimatter asymmetry

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



ALP Cogenesis

Experimental probes are happening!



Kinetic Misalignment + Axionogenesis

Prediction:

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

ALPogenesis :

ALP = axion-like particle
(no gluon coupling)

cogenesis

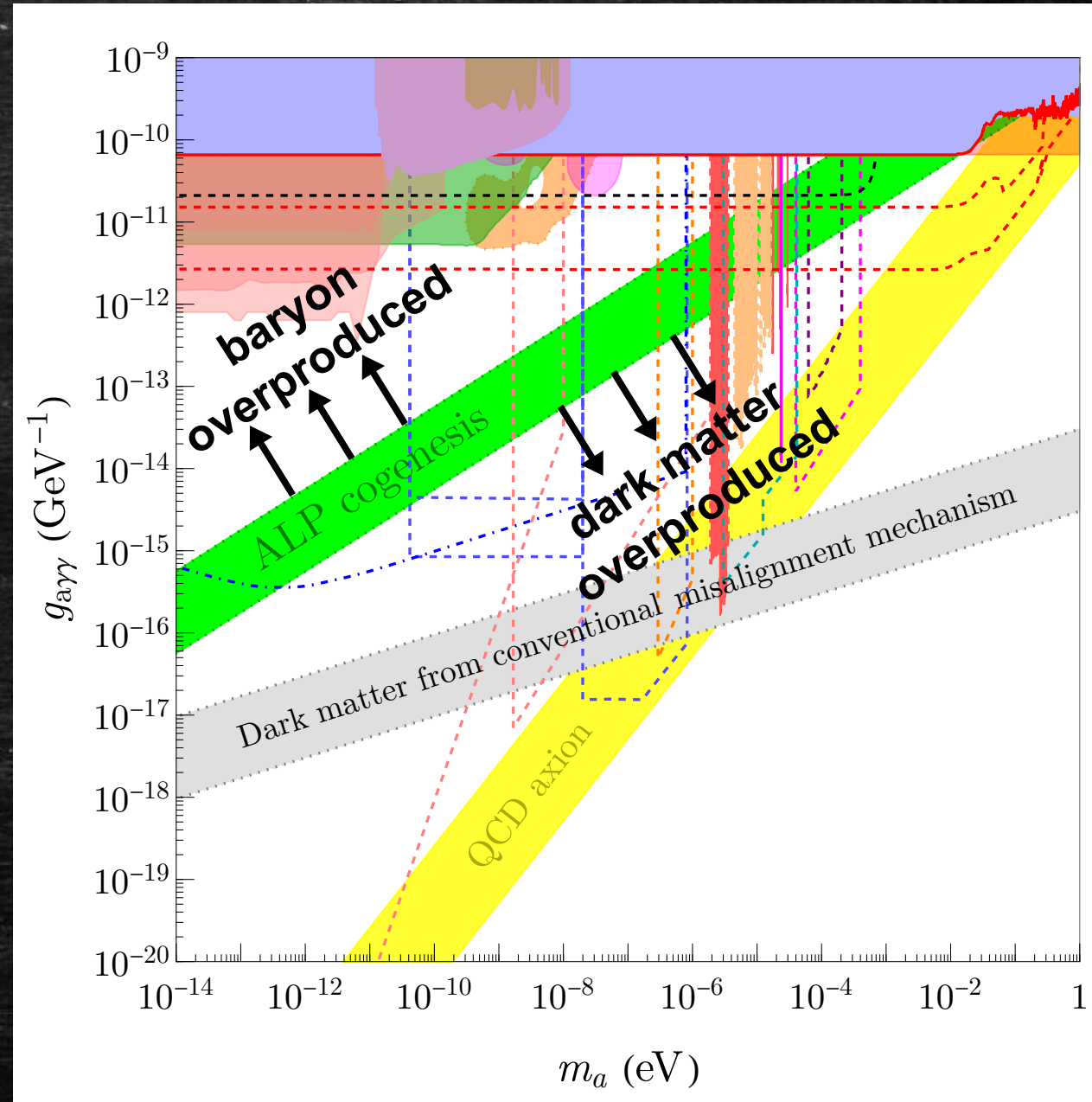
= production of both dark matter
& matter-antimatter asymmetry

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

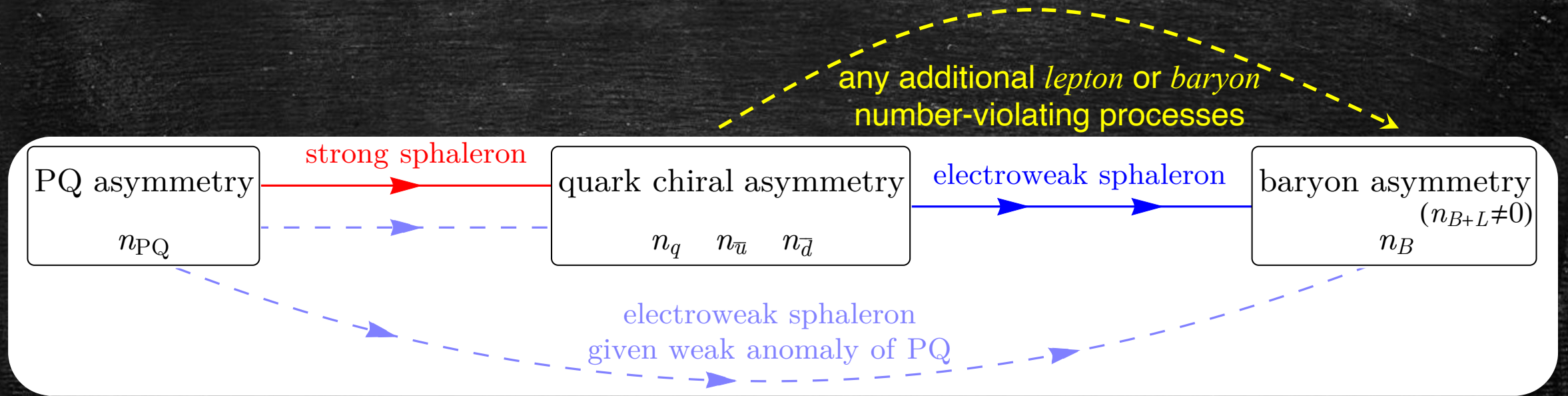
QCD axionogenesis?

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!



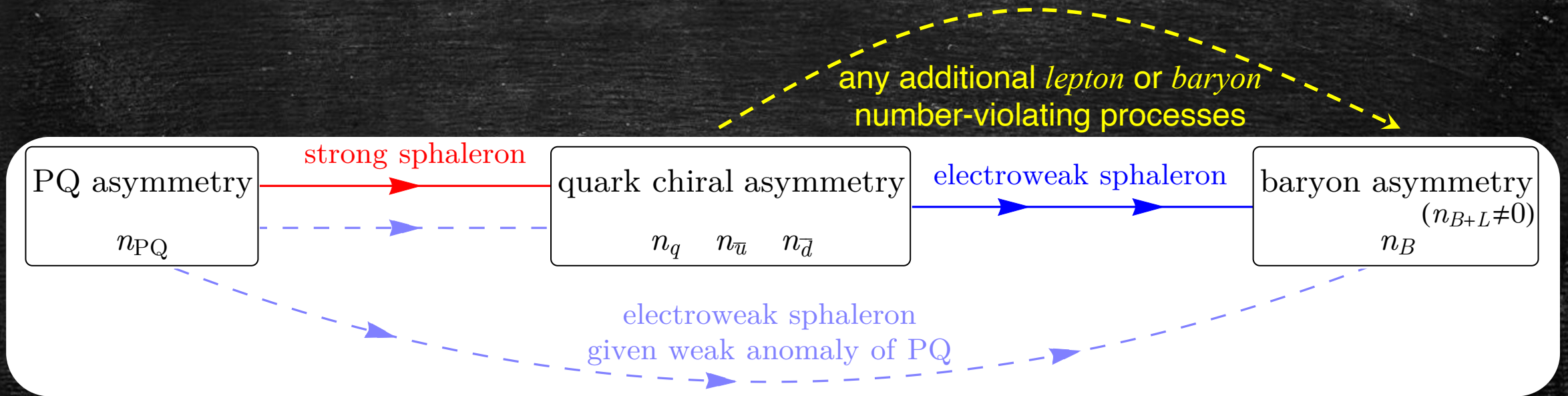
Extensions of Axiogenesis



Baryon Asymmetry

Lepto-Axiogenesis

Extensions of Axiogenesis



Lepto-Axiogenesis

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

e.g., from the seesaw mechanism

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

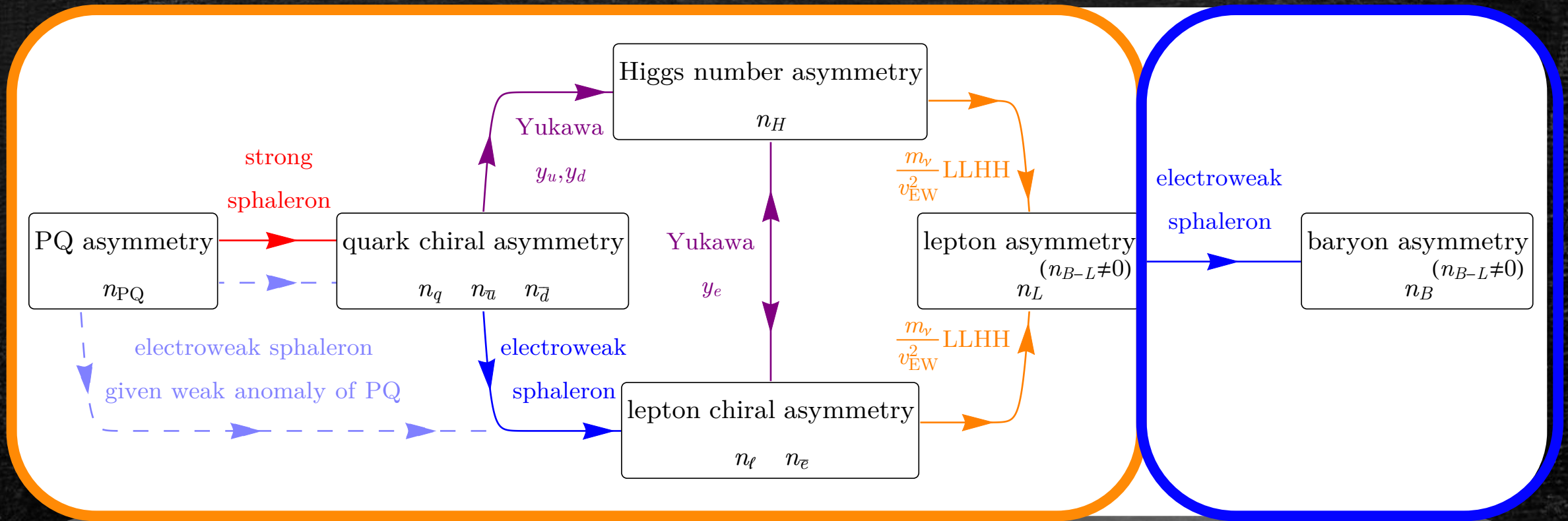
other extensions

- ✓ 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

Lepto-Axiogenesis

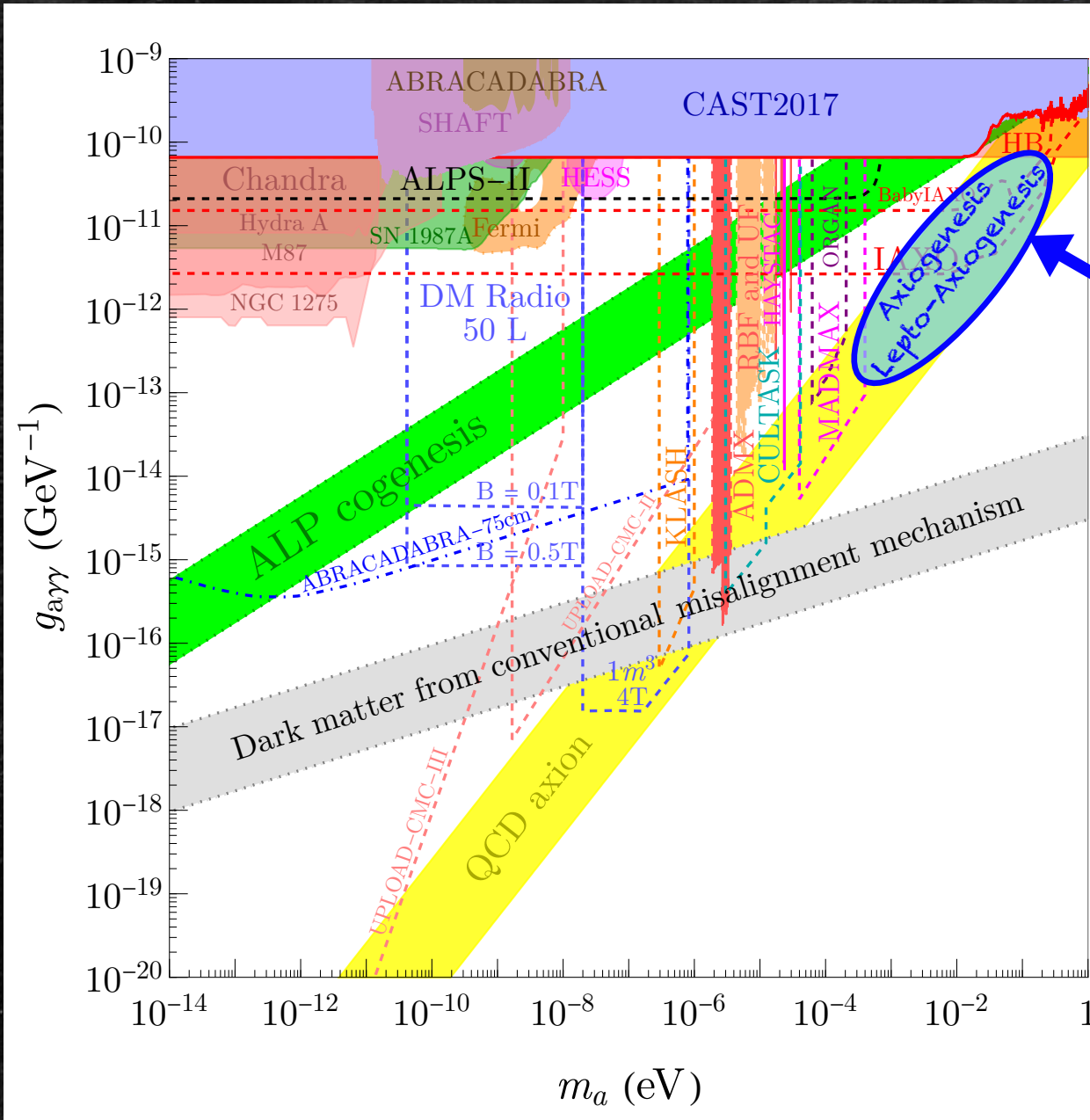
Producing L at high temperatures

Converting to B at T_{EW}



$J^f = J^s$

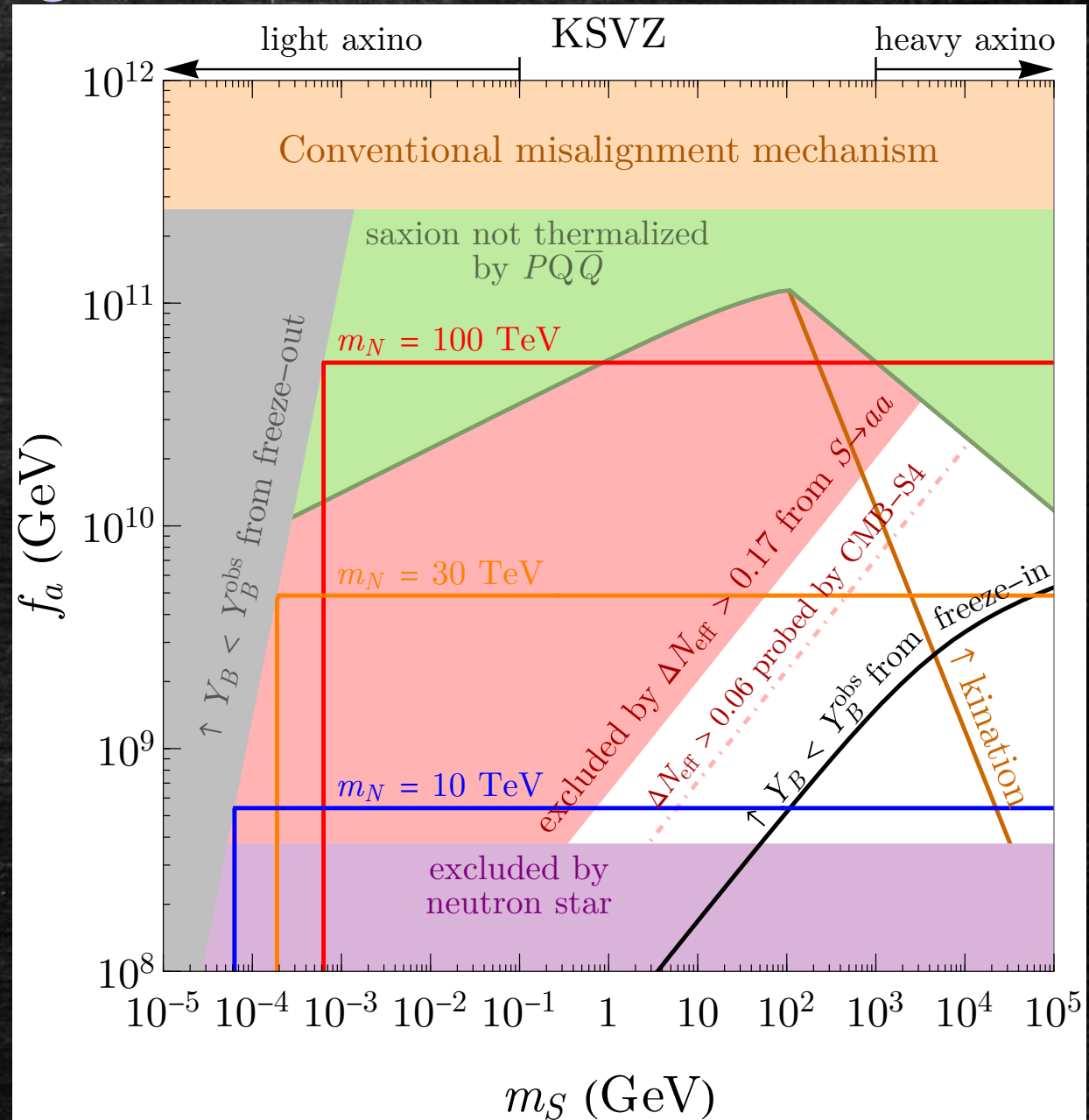
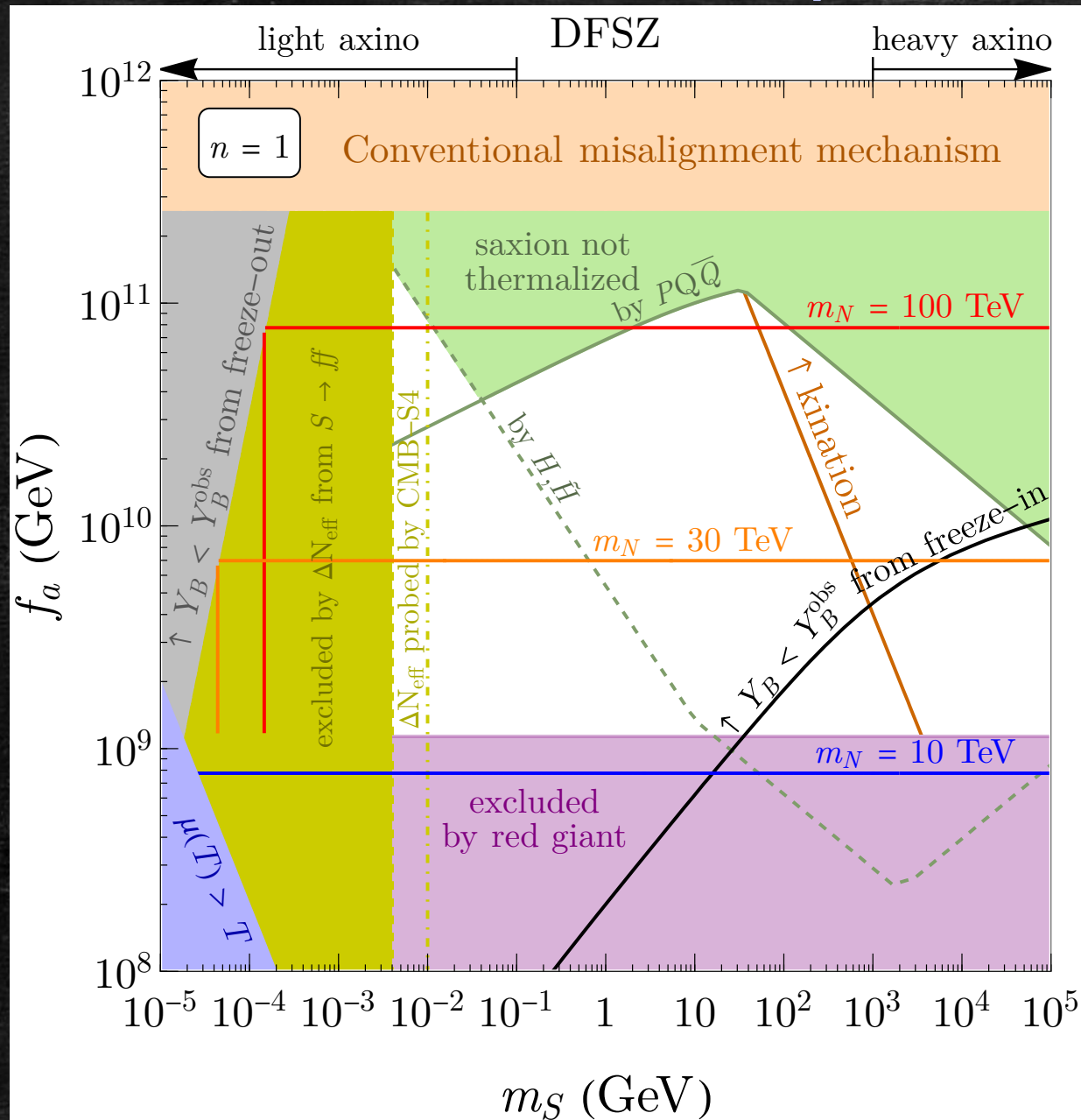
Lepto-Axiogenesis



Lepto-Axiogenesis achievement:

- simultaneous production of
- dark matter
 - matter-antimatter asymmetry
- in the framework with
- QCD axion
 - Majorana neutrinos

Low-Scale Lepto-Axiogenesis



Heavy QCD Axion

Potential from QCD effects

$$V(a) = m_a^2 f_a^2 \left[1 - \cos \left(\bar{\theta} + \frac{a}{f_a} \right) \right]$$

✓ Axion quality problem

- Neutron EDM $|d_n| \lesssim 1.8 \times 10^{-26} \text{ e} \cdot \text{cm}$
- Current bound $\bar{\theta}_{\text{eff}} \leq 10^{-10}$
- CP violation $V(a)_{\text{CPV}} \sim \frac{f_a^n}{M^{n-4}} \cos \left(\frac{a}{f_a} + \varphi \right)$
- To improve “quality”
 - Large m_a enhances CP-conserving potential
 - Small f_a suppresses CP-violating potential

✓ Model constructions

- 4D UV instantons
- 5D UV instantons
- Mirror QCD

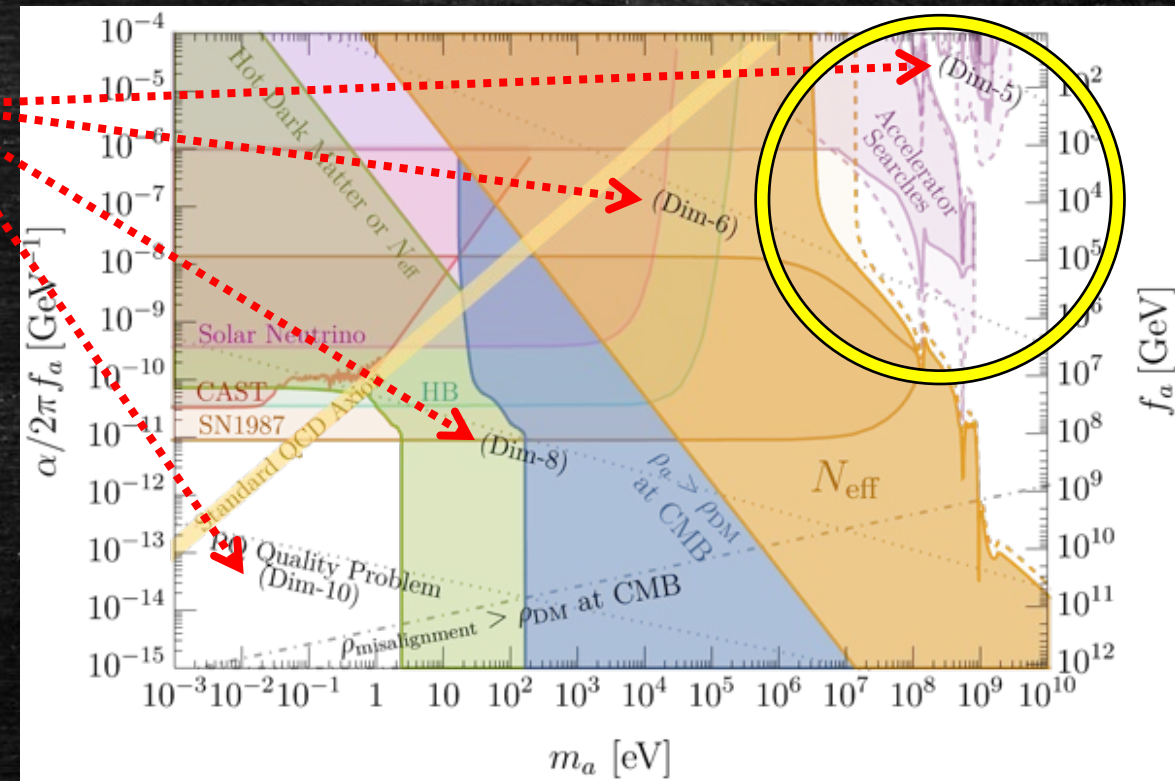
P. Agrawal et al. [2017](#), C. Csaki et al. [2019](#)

T. Gherghetta et al. [2020](#)

V. Rubakov [1997](#), Z. Berezhiani et al. [2000](#),

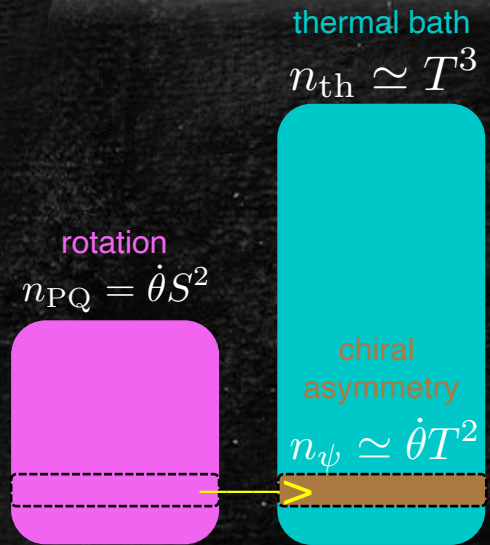
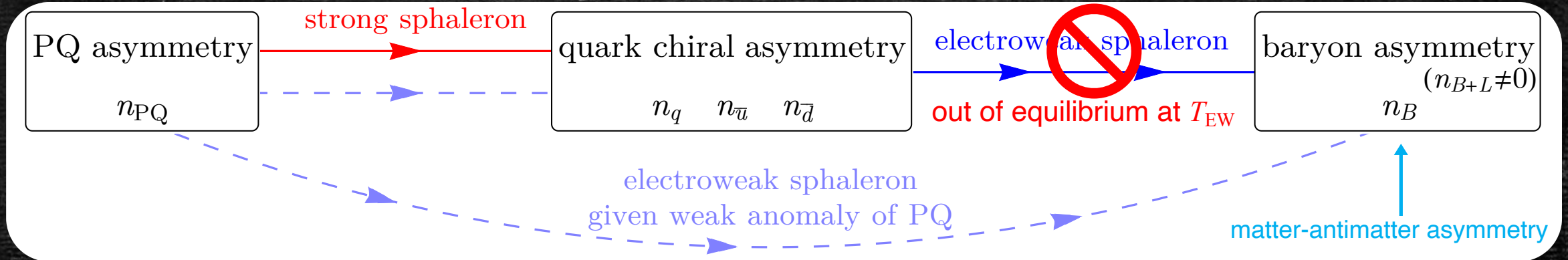
A. Hook [2014](#), H. Fukuda et al. [2015](#),

A. Hook et al. [2019](#)



Axiogenesis with **Heavy** QCD Axion

JHEP 10 (2022) 121 RC, T. Gherghetta, K. Harigaya



$$Y_B \equiv \frac{n_B}{s} = \frac{c_B \dot{\theta} T^2}{s}$$

model-dependent
electroweak phase transition temperature

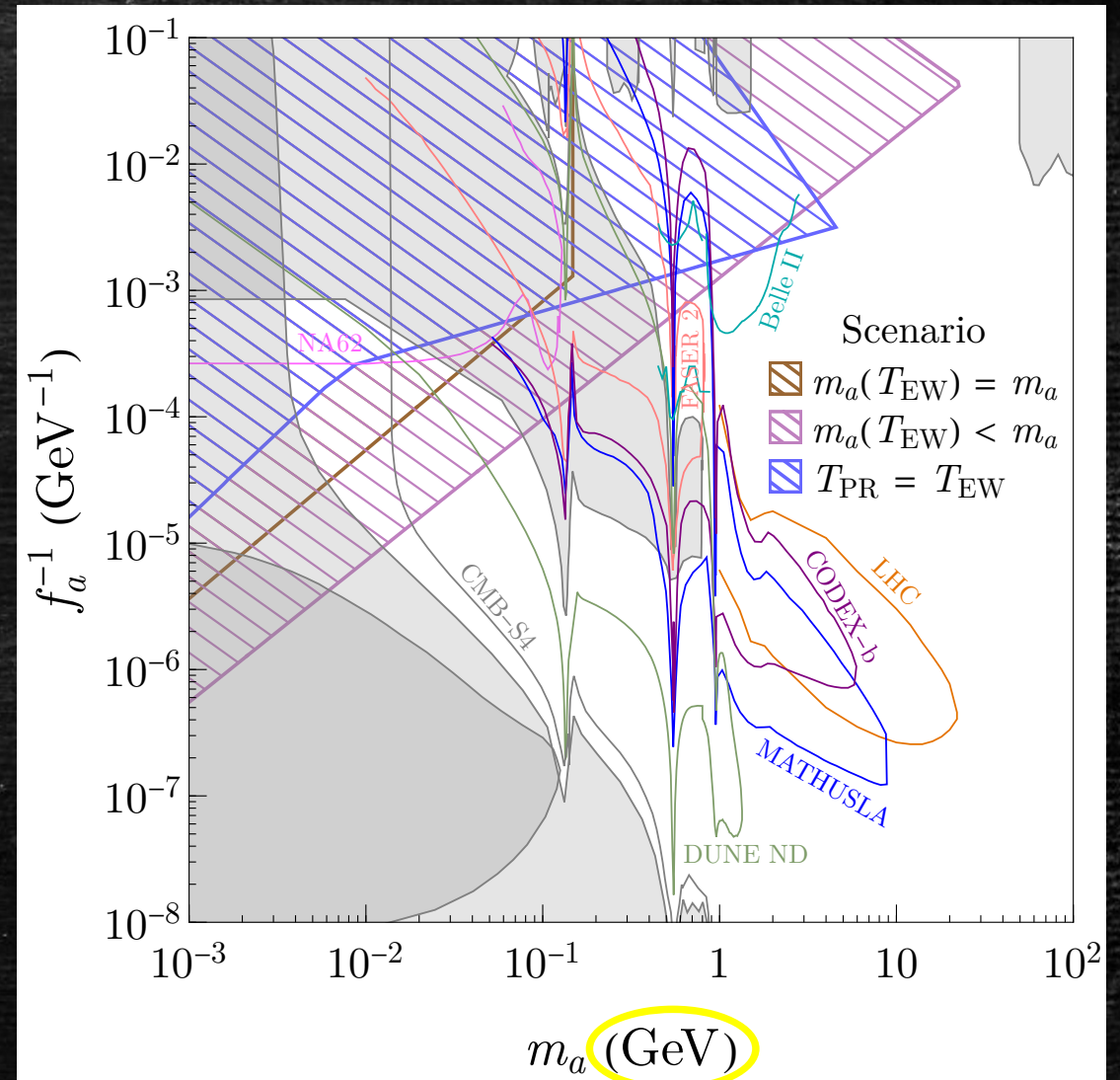
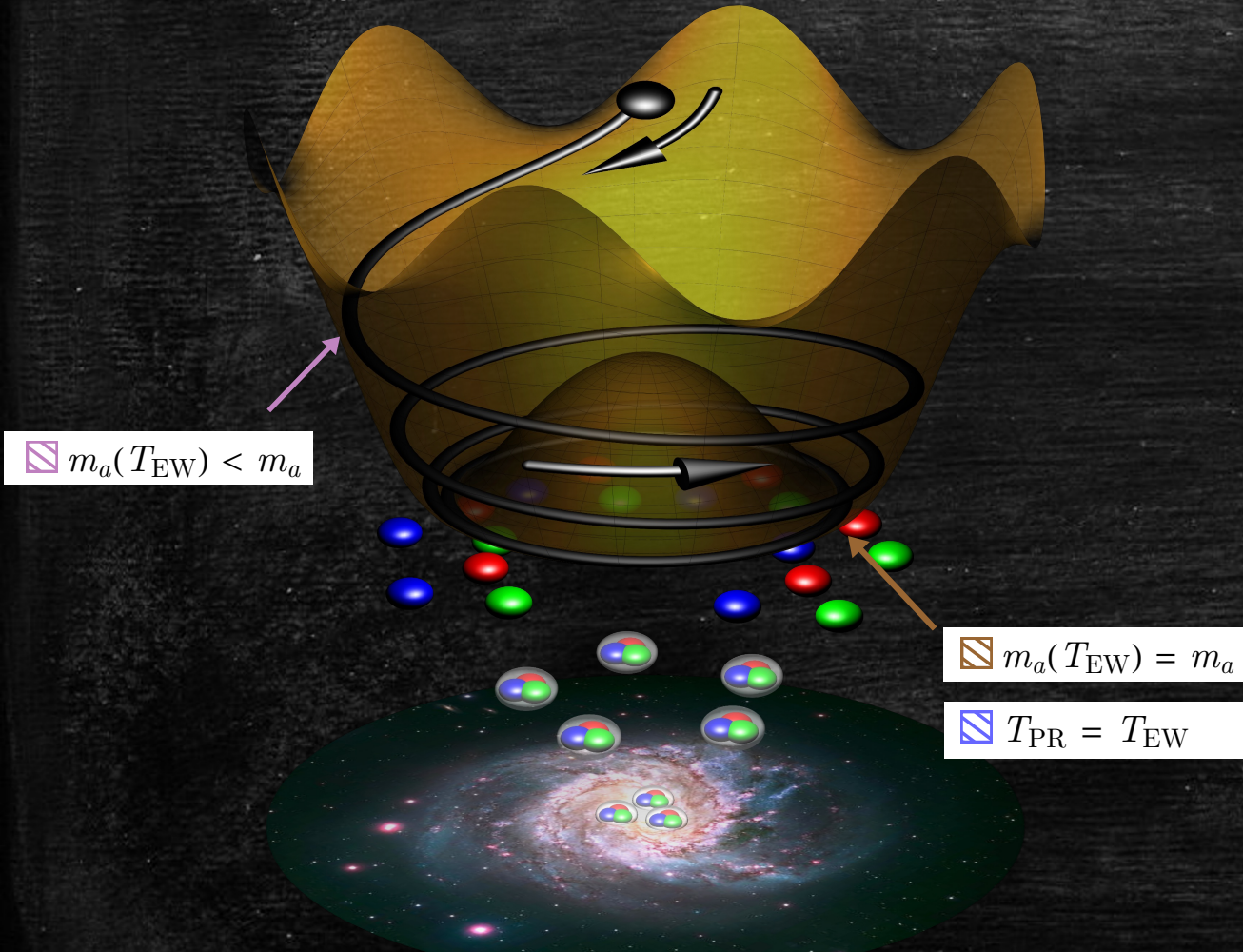
$$= 8.7 \times 10^{-11} \left(\frac{c_B}{0.1} \right) \left(\frac{\dot{\theta}(T_{EW})}{5.3 \text{ keV}} \right) \left(\frac{130 \text{ GeV}}{T_{EW}} \right)$$

experimentally measured value (*Planck* 2018) of the baryon asymmetry

too large of a velocity for conventional axion dynamics, while the axion rotation solves the problem!

Axiogenesis with **Heavy** QCD Axion

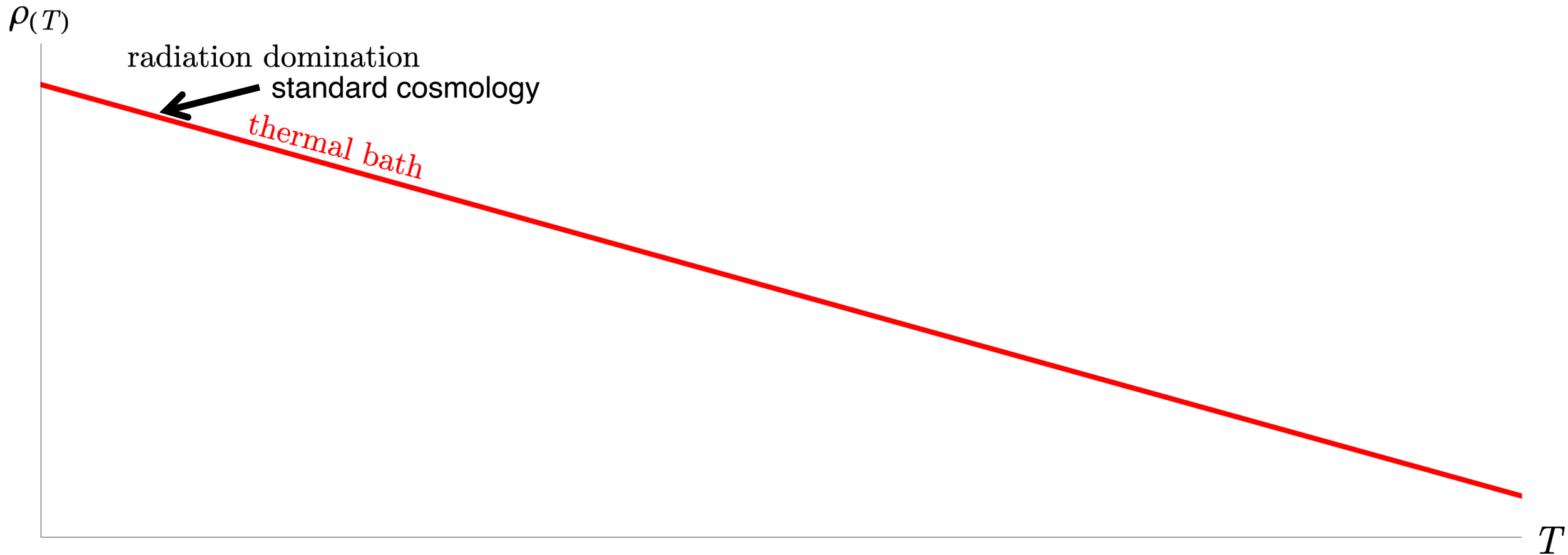
Different cosmological scenarios:



Gravitational Wave Signatures

Evolution of Energy Densities

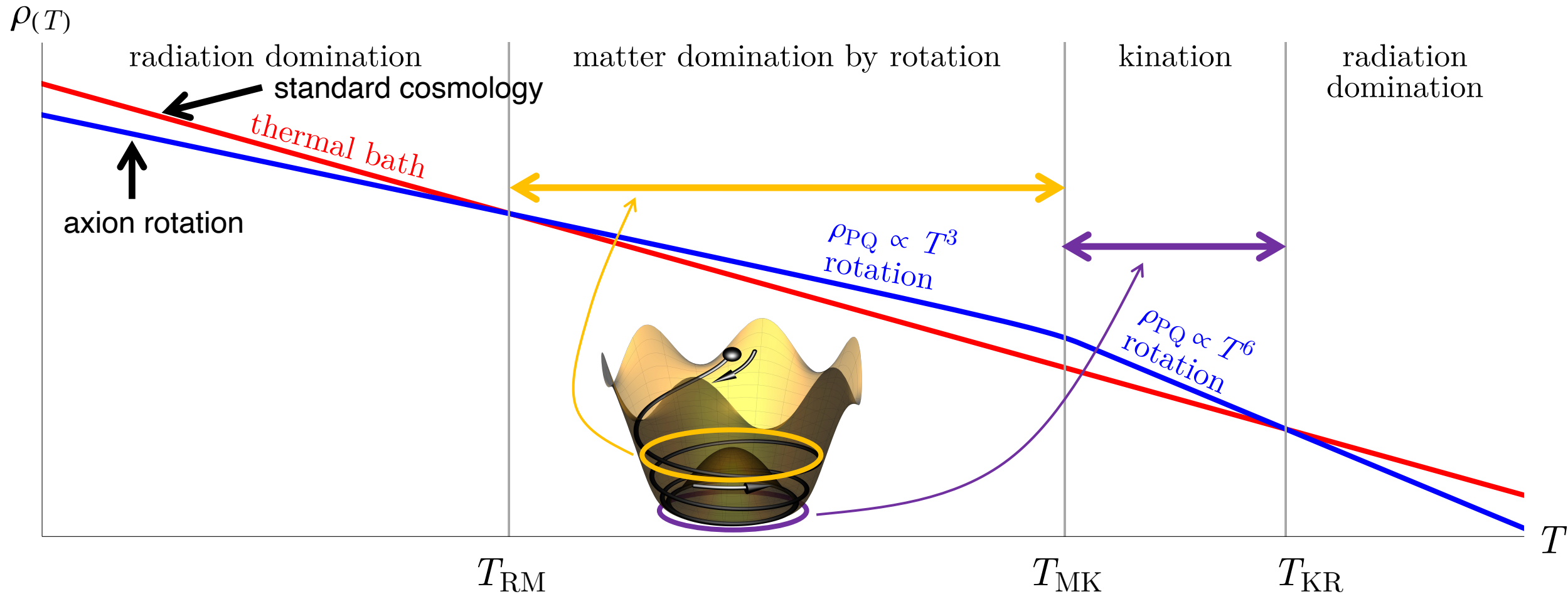
The **energy content** determines the universe's **expansion rate**.



Over time, the universe cools and temperature drops.

Evolution of Energy Densities

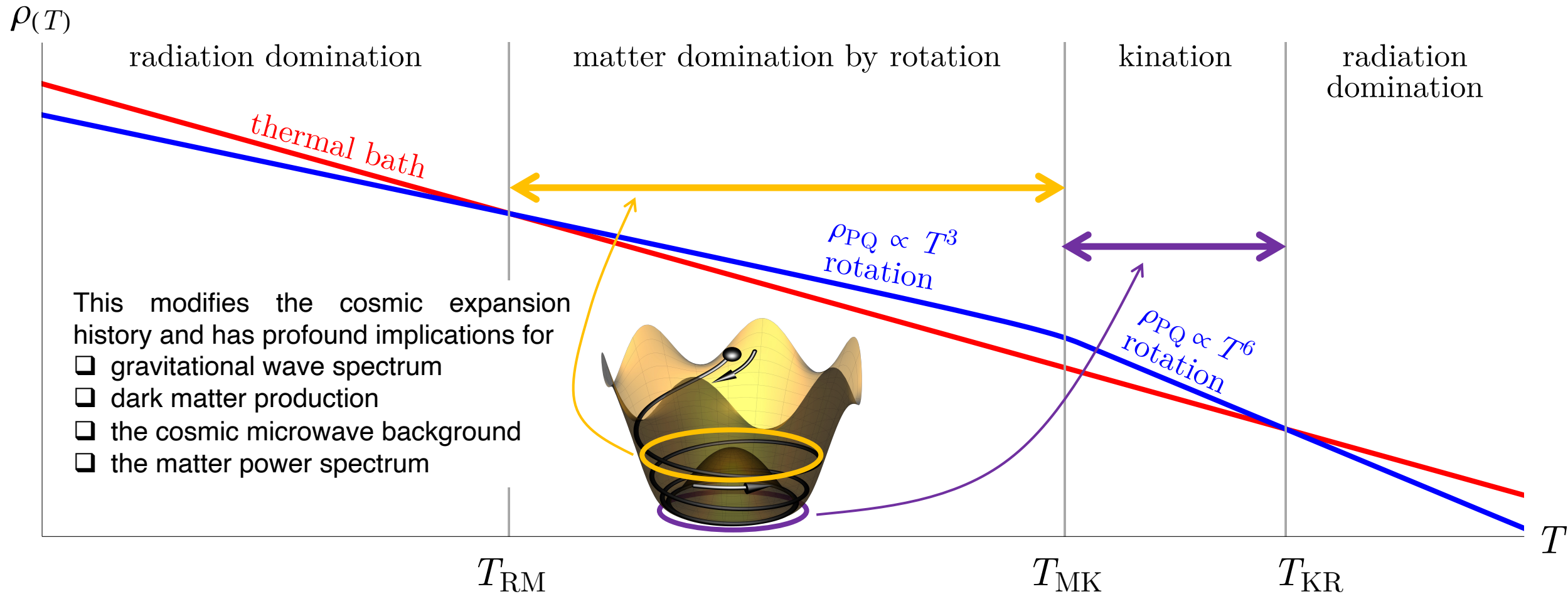
The **energy content** determines the universe's **expansion rate**.



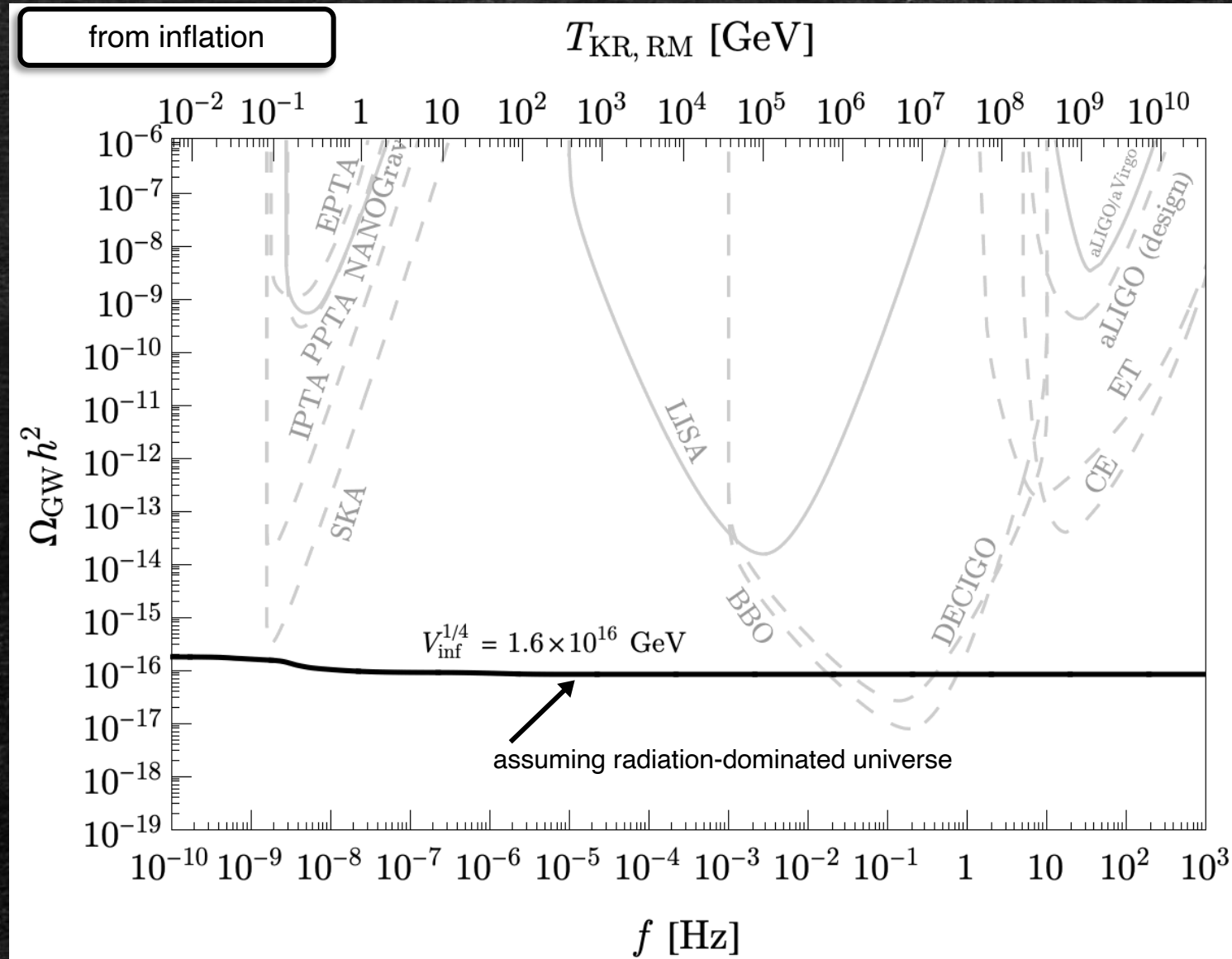
Over time, the universe cools and temperature drops.

Evolution of Energy Densities

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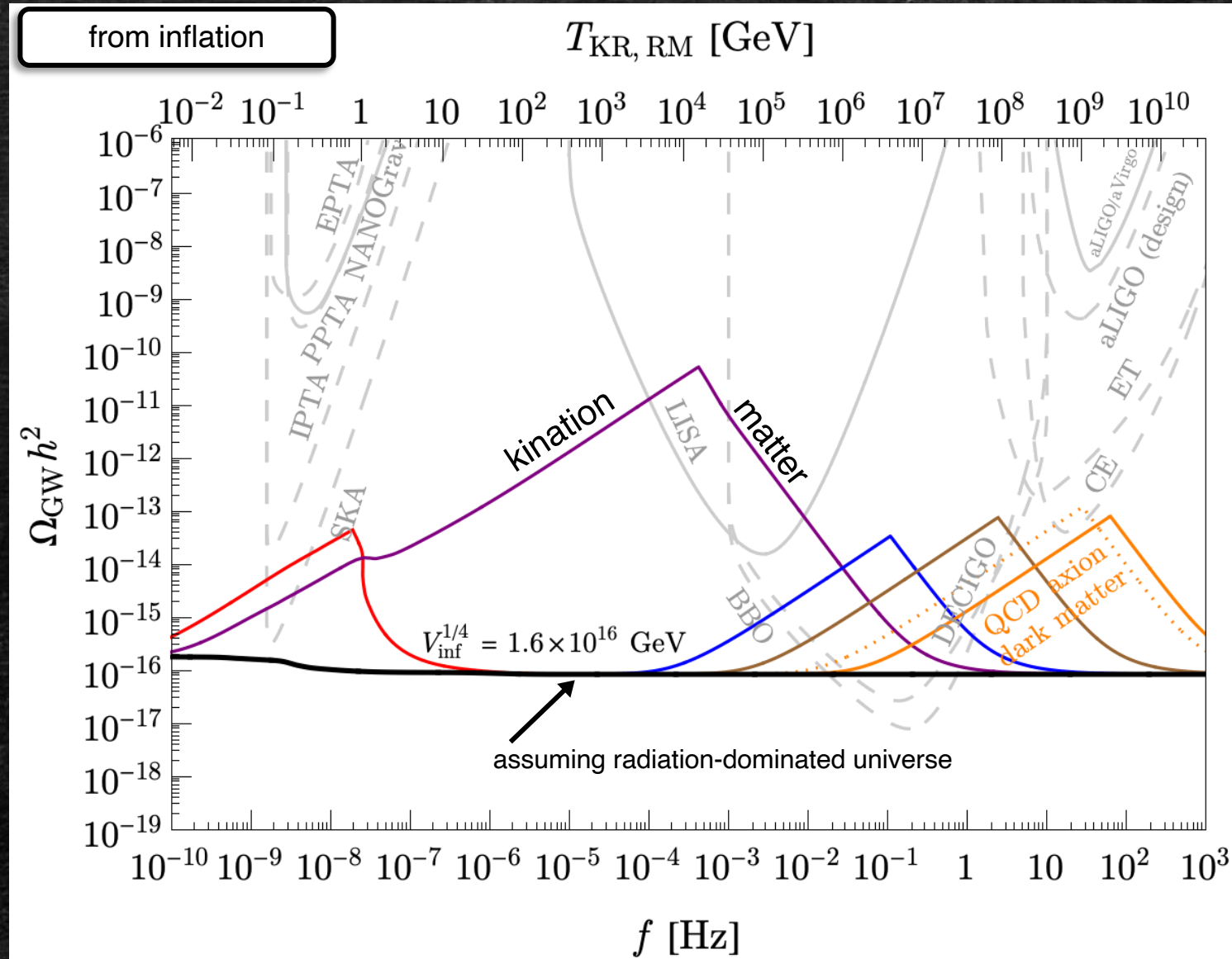
Smoking Gun: Triangular Peak in Gravitational Wave Spectra



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

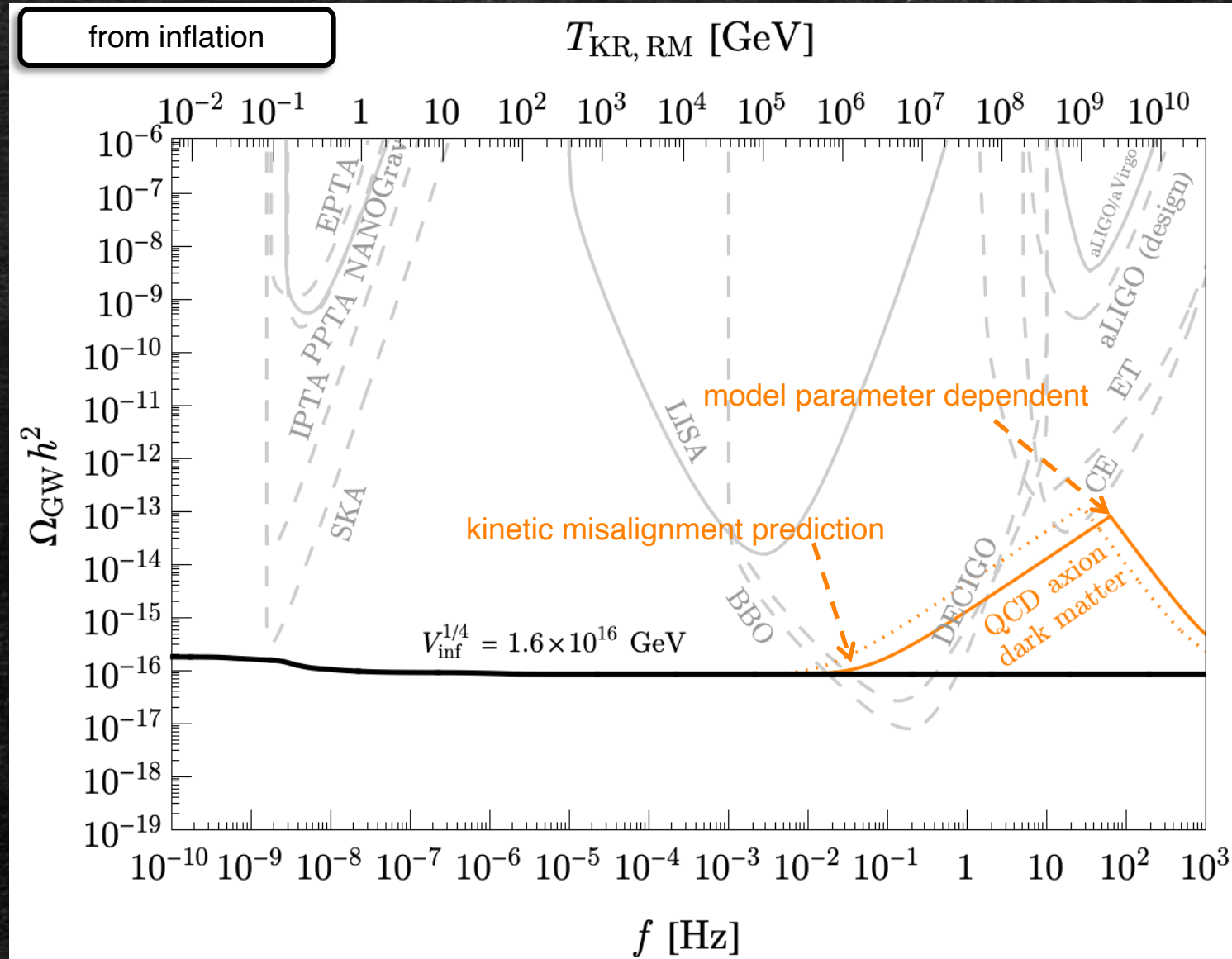
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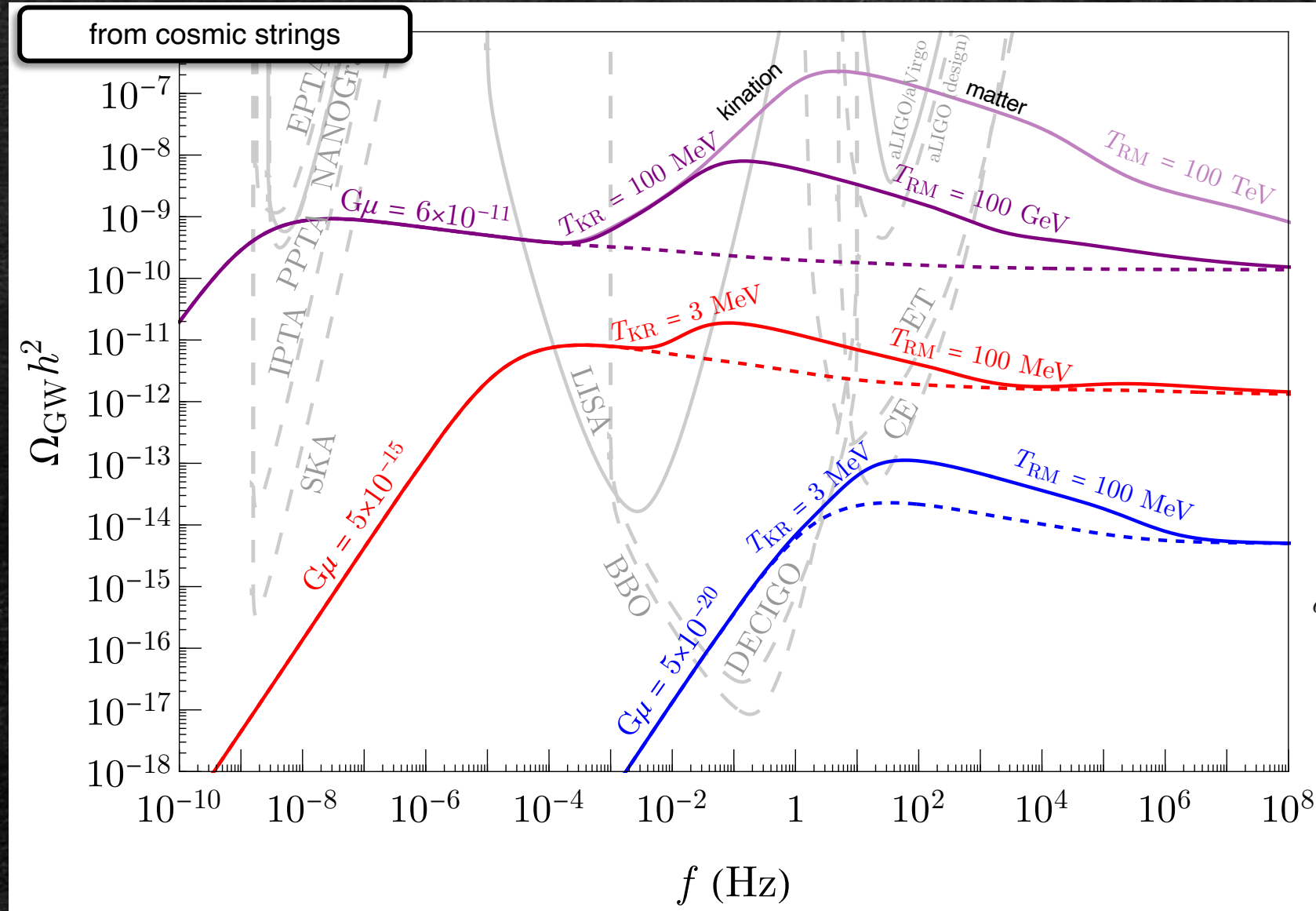
Smoking Gun: Triangular Peak in Gravitational Wave Spectra



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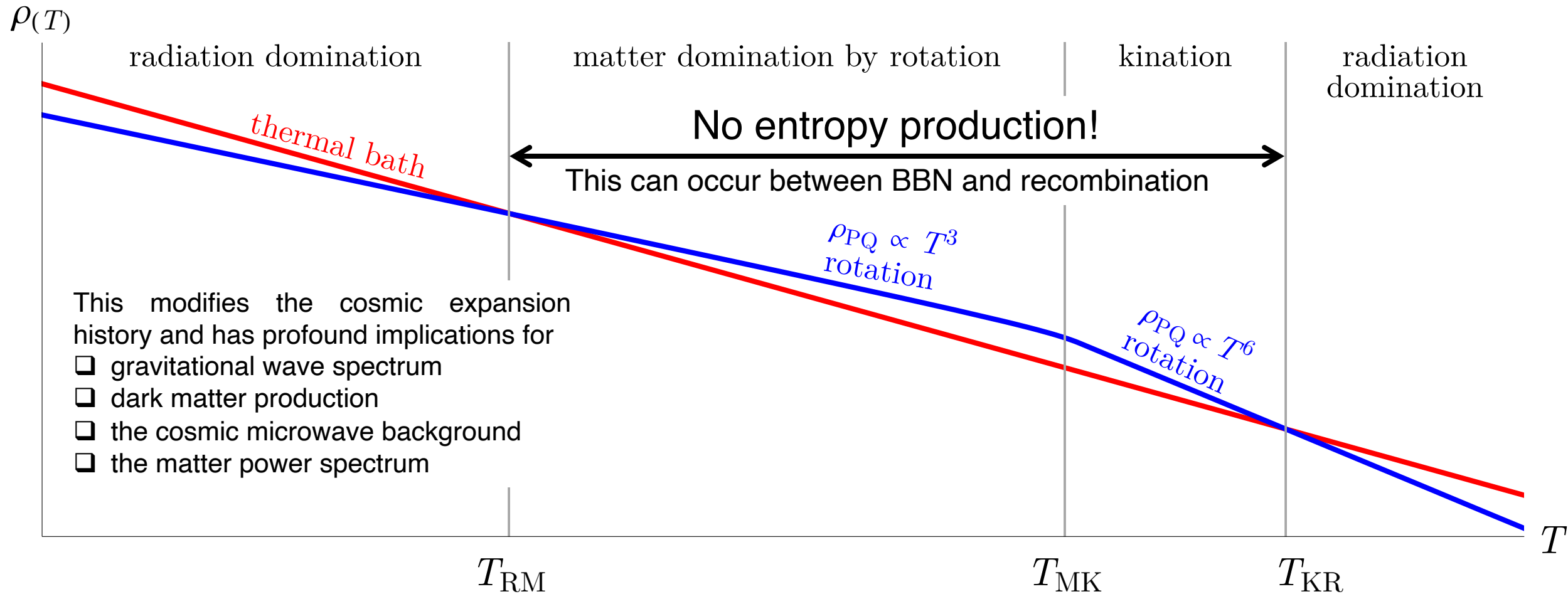


2108.09299 JHEP 09 (2022) 116 RC, D. Dunsy, N. Fernandez, A. Ghalsasi, L. Hall, K. Harigaya, J. Shelton

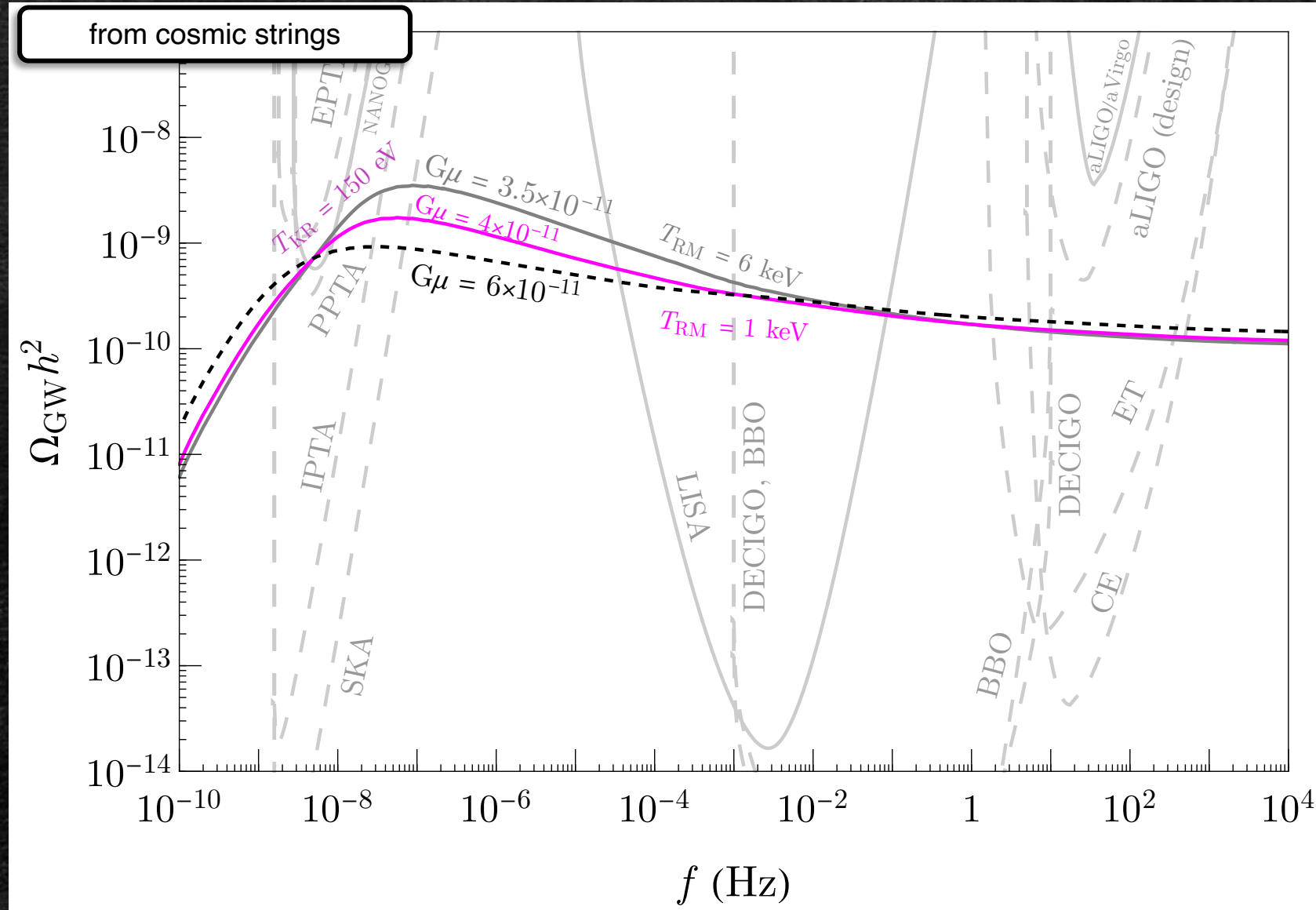
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2108.10328, 2111.01150 Y. Gouttenoire, G. Servant, P. Simakachorn

Probing PQ-breaking Potential

Piecewise approximation

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

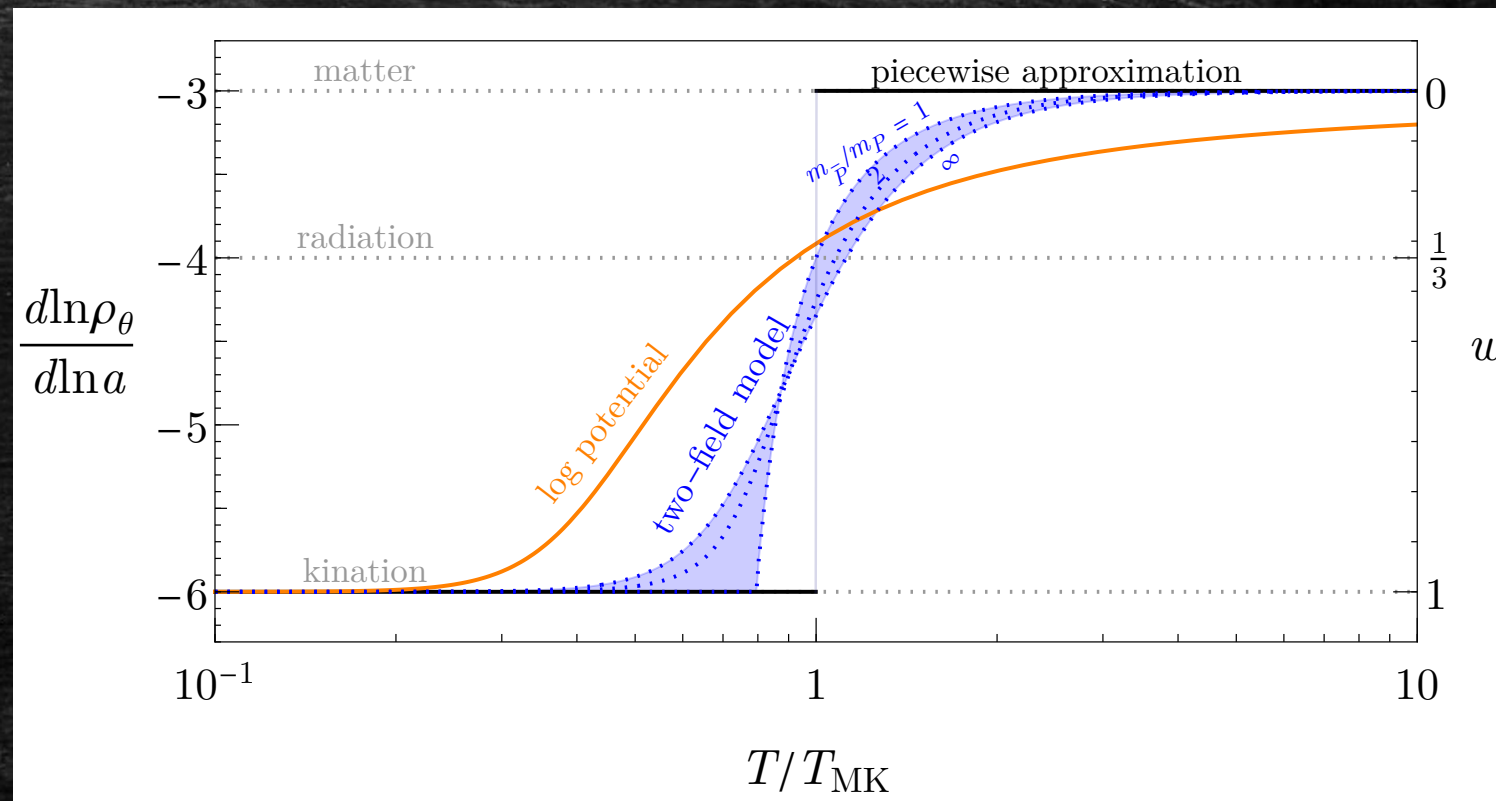
log potential

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

Two-field model

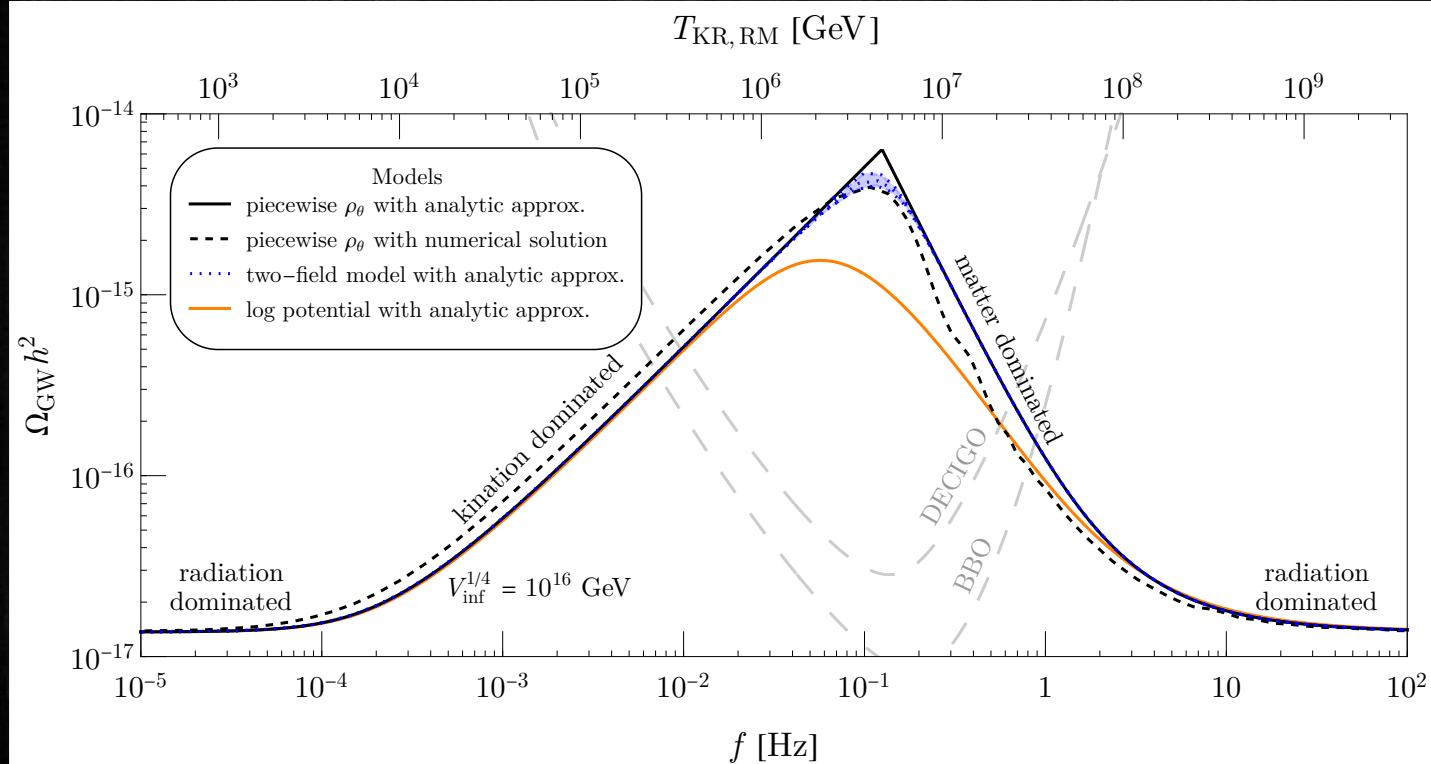
$$W = X(P\bar{P} - v_P^2)$$

$$V_{\text{soft}} = m_P^2 |P|^2 + m_{\bar{P}}^2 |\bar{P}|^2$$

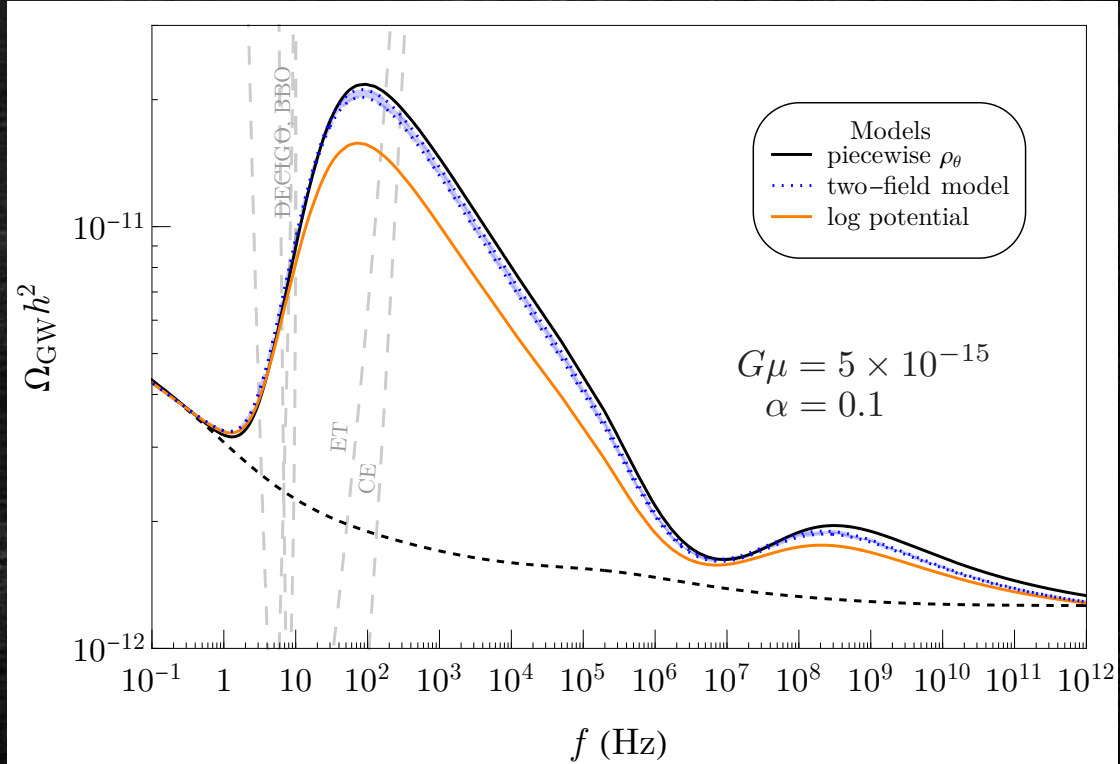


Probing PQ-breaking Potential

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
- ✓ *RC et al.* 2312.17730

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

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 including **flavor**

