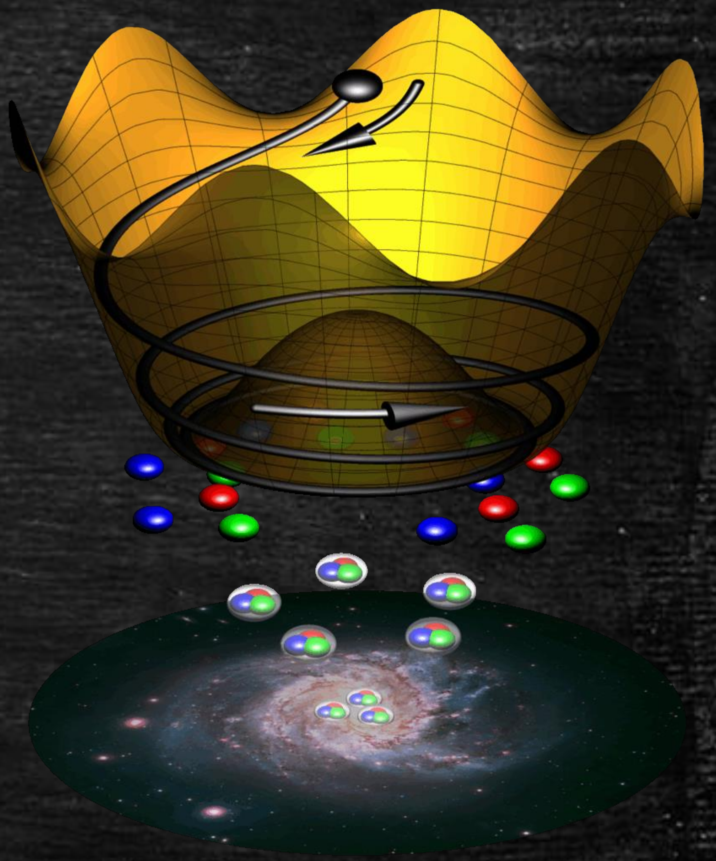
Impacts and Imprints of Axion Dynamics

UC Berkeley
Unraveling the Particle World and the Cosmos at Berkeley
Workshop in Honor of Lawrence Hall and Hitoshi Murayama

September 28th, 2024

Raymond Co

Indiana University



For the record, Co is my last name and I do not represent a company.

Raymond Co

[10] A recent paper by Raymond Co. et. al. [38], points out that for models of gravitino or axino dark matter with high reheat temperature, such as our model, the decay of the saxions can produce 3 orders of magnitude of entropy in the case that the saxion vev, s_I, equals the PQ breaking vev, V_{PQ} and $s_I = V_{PQ} \approx 10^{14}$ GeV (see Eqn. 2.9, Ref. [38]). This would make the plateau of our baryon-to-entropy ratio of order the observed experimental value.

For the record, Co is my last name and I do not represent a company.

I still remember being so excited to see my full name appear in a paper when I was a grad student at Berkeley. However, I quickly said what Lawrence likes to say a lot: “wait a minute!” Why is there a period after Co?

Raymond Co

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The paper was written by Stuart.

Reheating and Leptogenesis after Pati-Salam F-term Subcritical Hybrid Inflation

B. Charles Bryant, Zijie Poh, and Stuart Raby

Department of Physics
The Ohio State University
191 W. Woodruff Ave, Columbus, OH 43210, USA

June 15, 2021

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The paper was written by Stuart.

It's too bad that Staurt had to leave this workshop early. When I took this opportunity and sent him an email to introduce myself, he kindly invited me to give a seminar at OSU. However, to this date, I still have not visited OSU.

[hep-ph] 13 Dec 2016

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That email also reminded of what Yasunori said to me at the time.

“You should be happy because Lawrence suddenly becomes the employee of your company now!”

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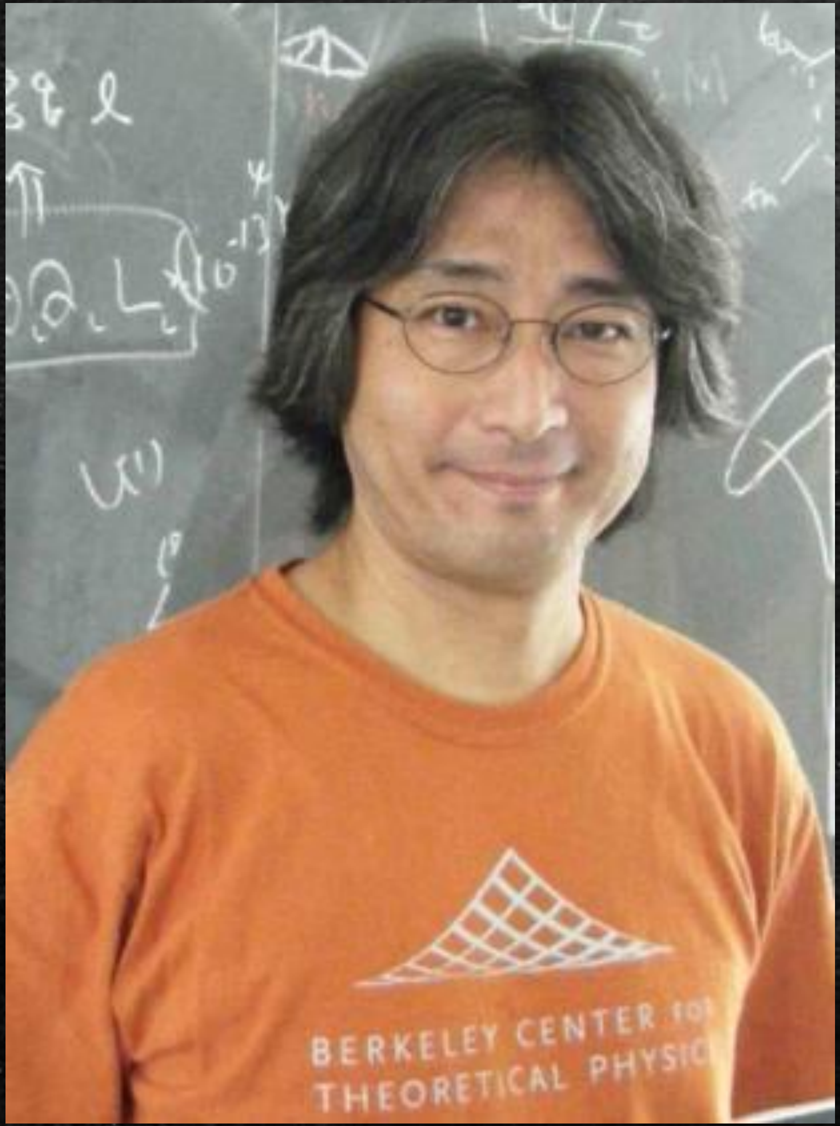
Happy Birthday, Hitoshi



Happy Birthday, Hitoshi

Myths about Hitoshi I have heard during grad school

1. Hitoshi’s average speed is 40 mph throughout the year.

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1. Hitoshi's average speed is 40 mph throughout the year.

$$D = 40 \text{ mph} \times 365 \text{ days} \times 16 \text{ hours/day} \simeq 233\text{k miles}$$

$$\text{USA-JPN trip distance} \simeq 5\text{k miles}$$

	0 domestic flight	10 domestic flight	20 domestic flight	30 domestic flight
# of USA-JPN trips	23	19	15	11

assuming domestic flight is 2k miles each way

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Data collected: I was in Hitoshi's QFT class, we had to reschedule classes every two weeks due to his trips to Japan

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$$D = 40 \text{ mph} \times 365 \text{ days} \times 16 \text{ hours/day} \simeq 233\text{k miles}$$

$$D_{\text{earth,moon}} \simeq 239\text{k miles}$$

Happy Birthday, Hitoshi

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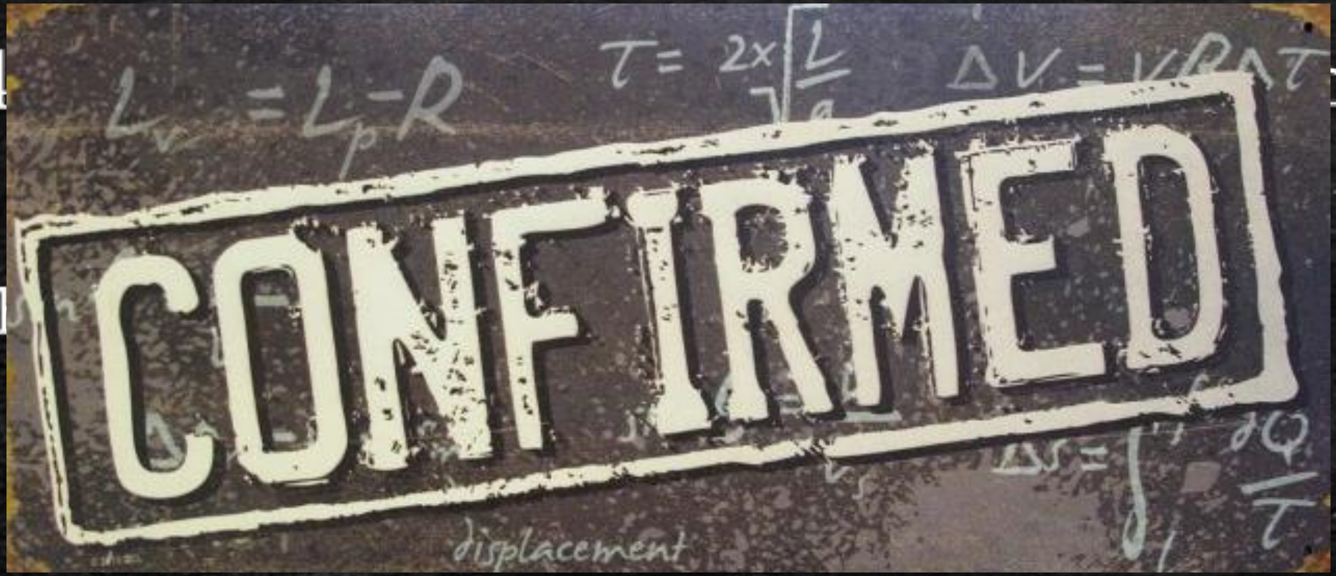
$D = 4$ $\simeq 233\text{k miles}$

D_{eart}



Happy Birthday, Hitoshi

SaxiGUTs and their Predictions

-ph] 11 Oct 2016

Raymond T. Co[1,2], Francesco D'Eramo[3,4] and Lawrence J. Hall[1,2]

[1] *Berkeley Center for Theoretical Physics, Department of Physics, University of California, Berkeley, CA 94720, USA*
[2] *Theoretical Physics Group, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*
[3] *Department of Physics, University of California Santa Cruz, Santa Cruz, CA 95064, USA*
[4] *Santa Cruz Institute for Particle Physics, Santa Cruz, CA 95064, USA*

Happy Birthday, Hitoshi

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On 2/29/2016, I gave a 4D seminar. Hitoshi soon raised a serious concern that would basically kill our entire project. After the talk, he explained the issue in detail, but then

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On 2/29/2016, I gave a 4D seminar. Hitoshi soon raised a serious concern that would basically kill our entire project. After the talk, he explained the issue in detail, but then he immediately offered a solution..

Happy Birthday, Hitoshi

SaxiGUTs and their Predictions

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In principle the PQ symmetry could be an R symmetry, as in the case of both the Nilles-Raby $SU(5)$ theory [6] and the Hall-Raby $SO(10)$ theory [21]. However, it has been shown quite generally that in flat space supersymmetric theories with a continuous R symmetry broken at scale V_{PQ} the vacuum value of the superpotential is bounded by $|\langle W \rangle| \leq F V_{PQ}/2$ where F is the scale of supersymmetry breaking [22]. Such values of $|\langle W \rangle|$ are insufficient to cancel the cosmological constant in supergravity unless V_{PQ} is of order the reduced Planck mass. Hence we restrict our attention to non-R symmetries.

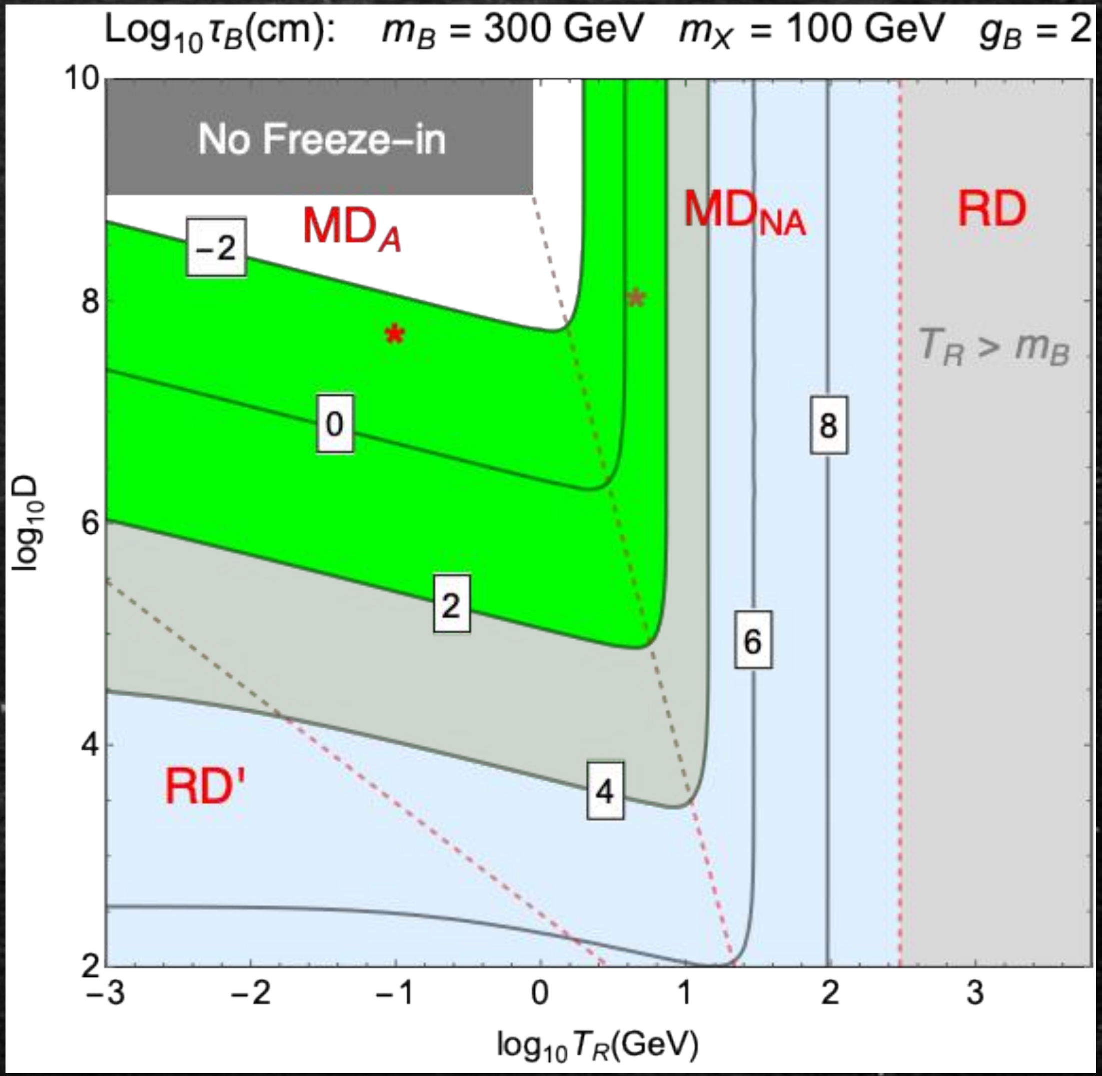
Acknowledgments

We thank Michael Dine, Keisuke Harigaya and Hitoshi Murayama for useful discussions. This work was supported in part by the Director, Office of Science, Office of High Energy and Nuclear

Happy Birthday, Lawrence

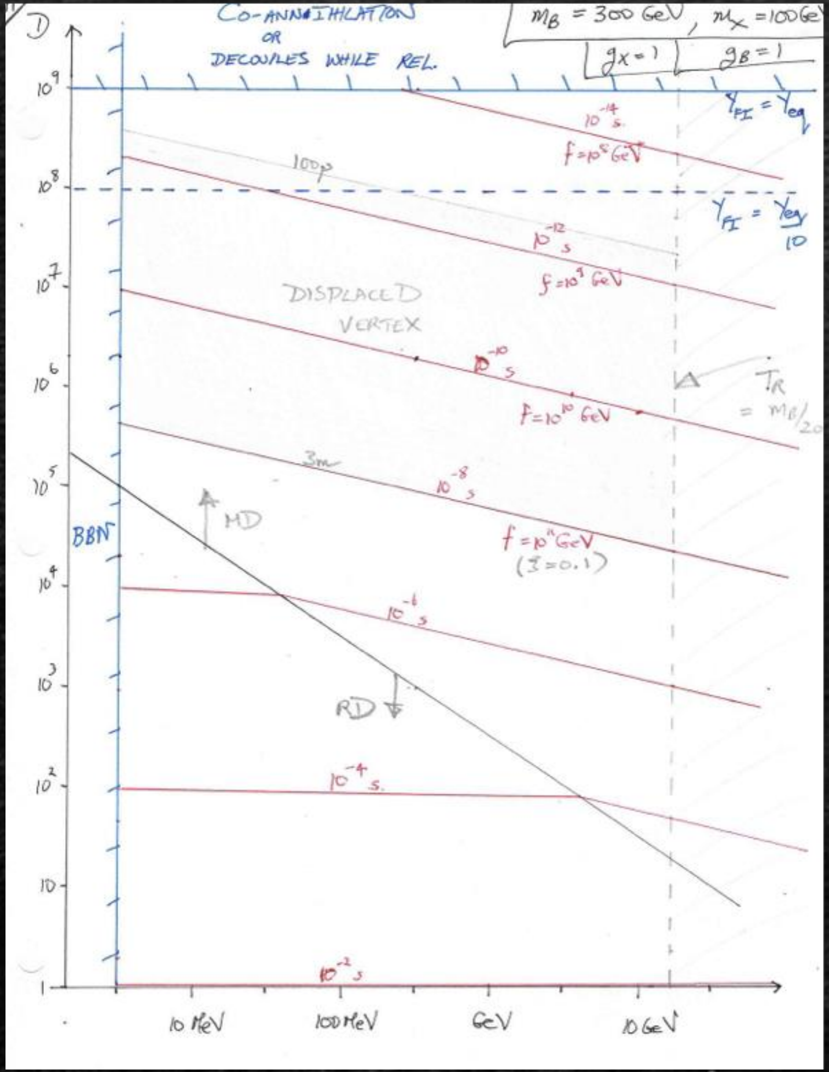
Happy Birthday, Lawrence

Whenever I had some results after a long calculation in Mathematica to show Lawrence. He always pulled out his notes and checked my results using this hand-drawn figures. He was often able to catch my mistakes in O(1) factors, line slopes, and crossing points.

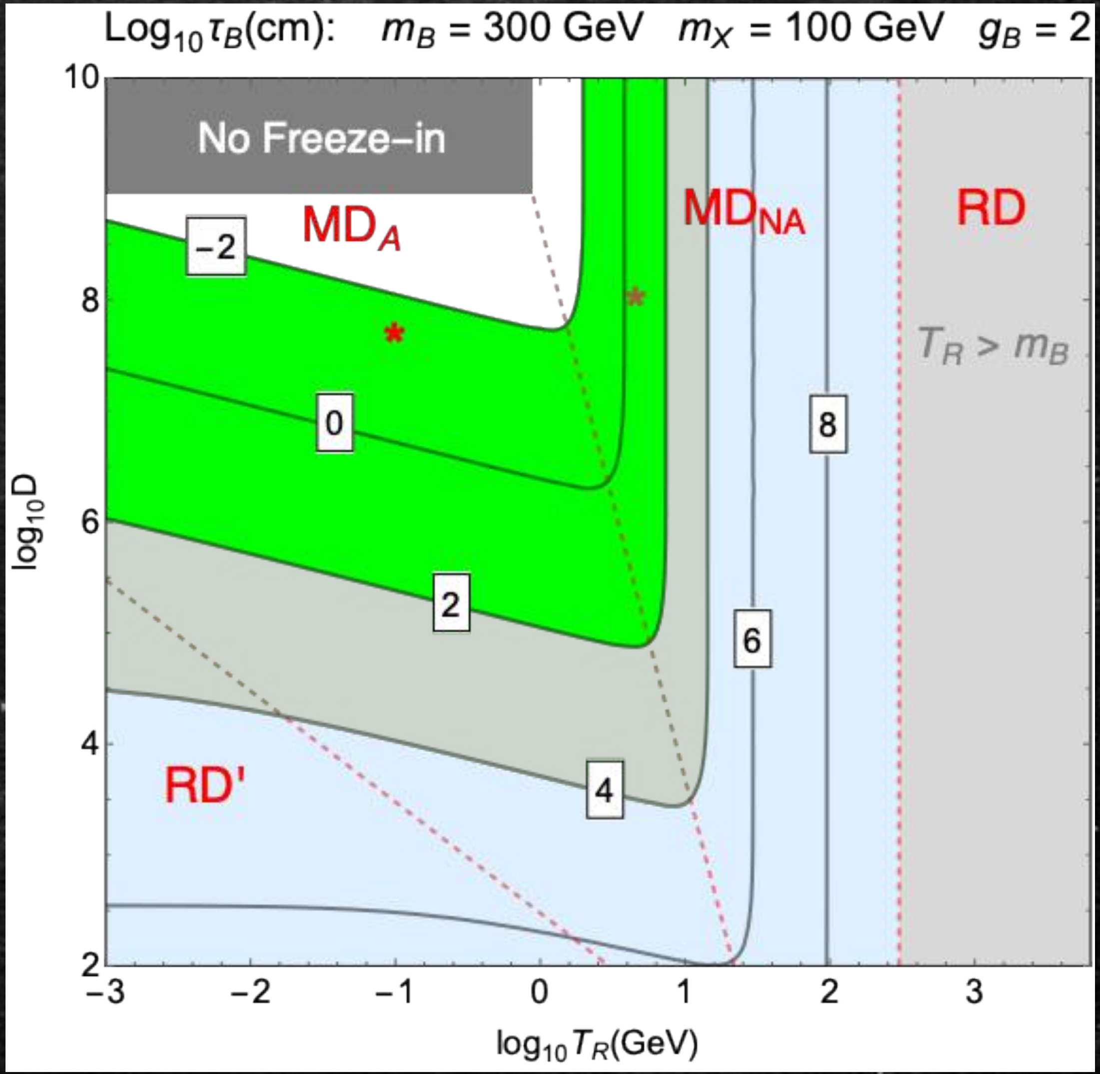


Mathematica calculation

Happy Birthday, Lawrence



Lawrence hand-drawn



Mathematica calculation

Happy Birthday, Lawrence

One time we encountered a serious problem in our project.
I found a solution in the literature and explained to Lawrence.
He was immediately amazed by the existing solution and asked who wrote the paper.

Happy Birthday, Lawrence

One time we encountered a serious problem in our project.
I found a solution in the literature and explained to Lawrence.
He was immediately amazed by the existing solution and asked who wrote the paper.

It was him.

Happy Birthday, Lawrence

9/12/2015
Tahoe Summit 2015

9/27/2024
Lawrence/Hitoshi Fest

Happy Birthday, Lawrence

“ As a grad student, I am not allowed to give you any presents that are worth a lot of money. Therefore, instead of spending a lot of money, I spent a lot of time making this present. And I am sure everyone here will agree that a grad student's time is worth no money.

9/12/2015
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Happy Birthday, Lawrence

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(Actually, after 9 years and having just gotten my own grant, I now take it back. Grad students' time is expensive.)

Happy Birthday, Lawrence

made for Lawrence’s birthday celebration during Tahoe Summit 2015

“As a grad student, I am not allowed to give you any presents that are worth a lot of money. Therefore, instead of spending a lot of money, I spent a lot of time making this present. And I am sure everyone here will agree that a grad student's time is worth no money.

This is a picture of Lawrence, made of 999 dice. This is not a printed picture but literally 999 dice. We know God does not play dice with the Universe. Neither does Lawrence. However, I do. I simply put all of the dice in the box and kept shaking it until the face of Lawrence emerged.”

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(Lawrence, I hope you have not shaken it since. I have to remind you that I am now faculty and do not have the time to shake it back. Just kidding. For you, I will do a lifetime warranty.)

Happy Birthday, Lawrence

Disclaimer: I do not own any shares of the company.

"For those lucky few who have used it, it can truly be called the *Michael Jordan* of chalk, the *Rolls Royce* of chalk."

https://math.williams.edu/dream-chalk/

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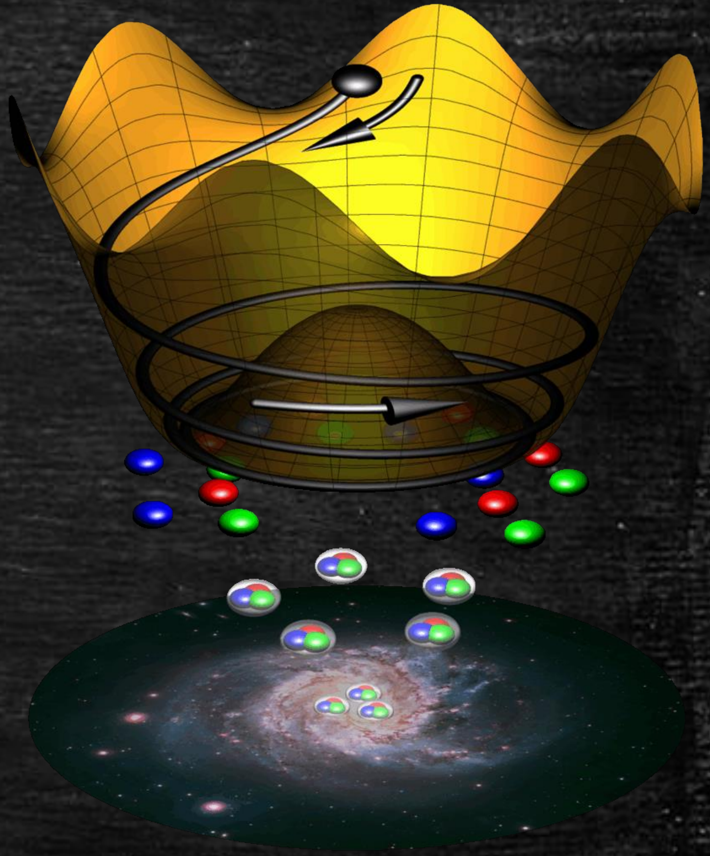
Lawrence, I would like to offer you an unlimited supply for life. Here is the first box. Just shoot me an email when you run out of it.

Impacts and Imprints of Axion Dynamics



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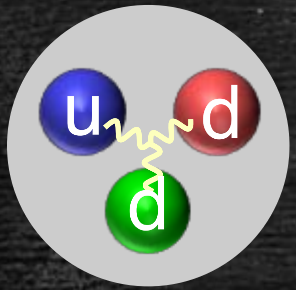
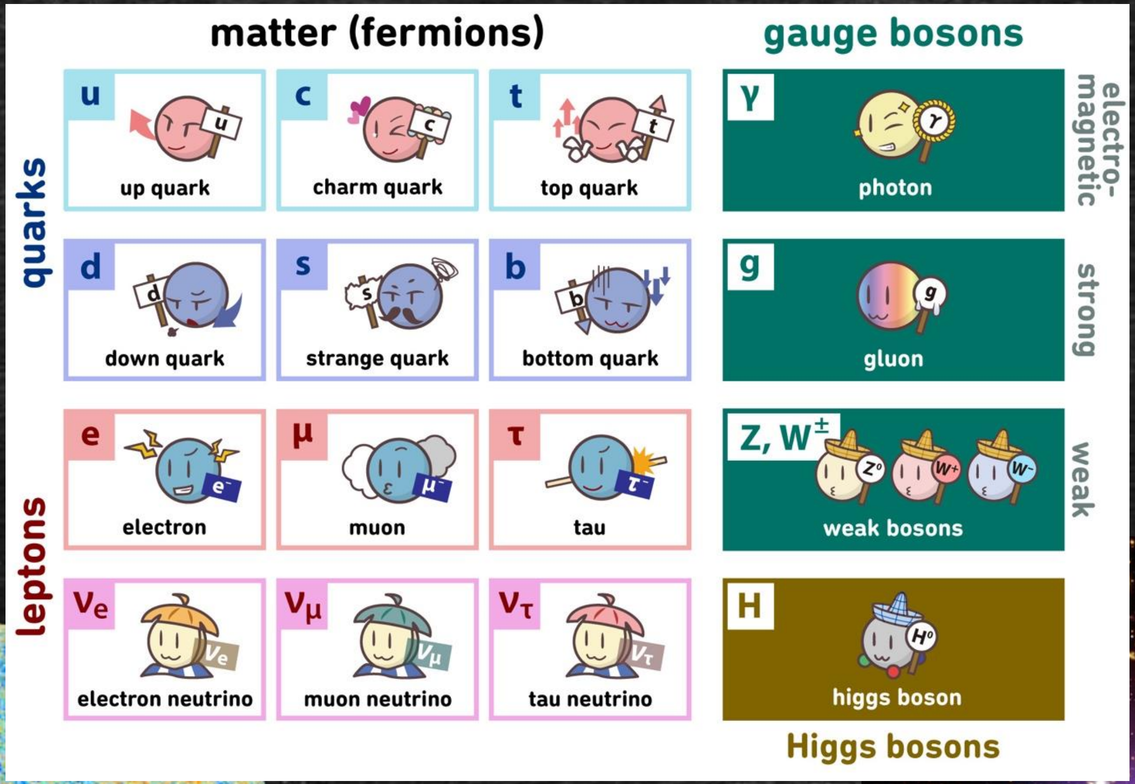
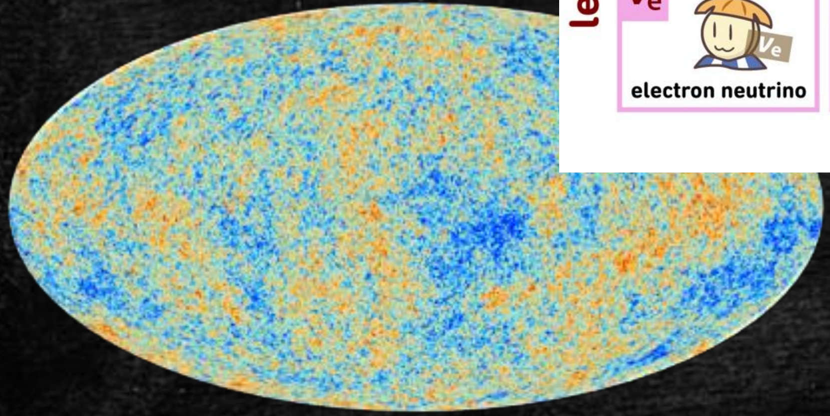
Outline of the Talk

strong CP problem



neutron





Source: Planck

+

axion?

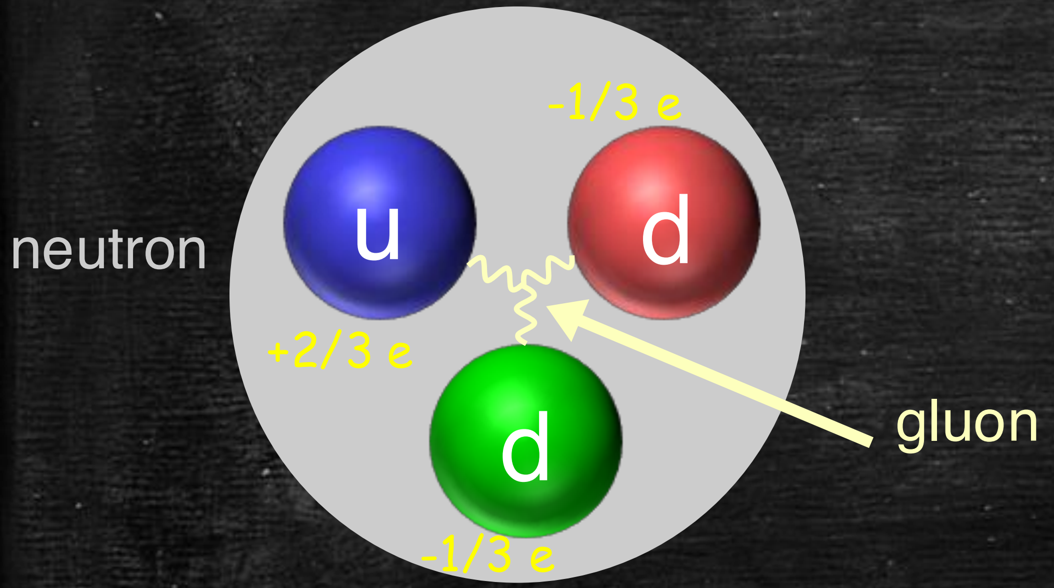
matter-antimatter asymmetry

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:

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

PRL 97, 131801 2006, PRL 124, 081803 2020

Strong CP problem:

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

Why exceedingly small?

Strong CP Problem
solution

2017 Quanta magazine

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

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!

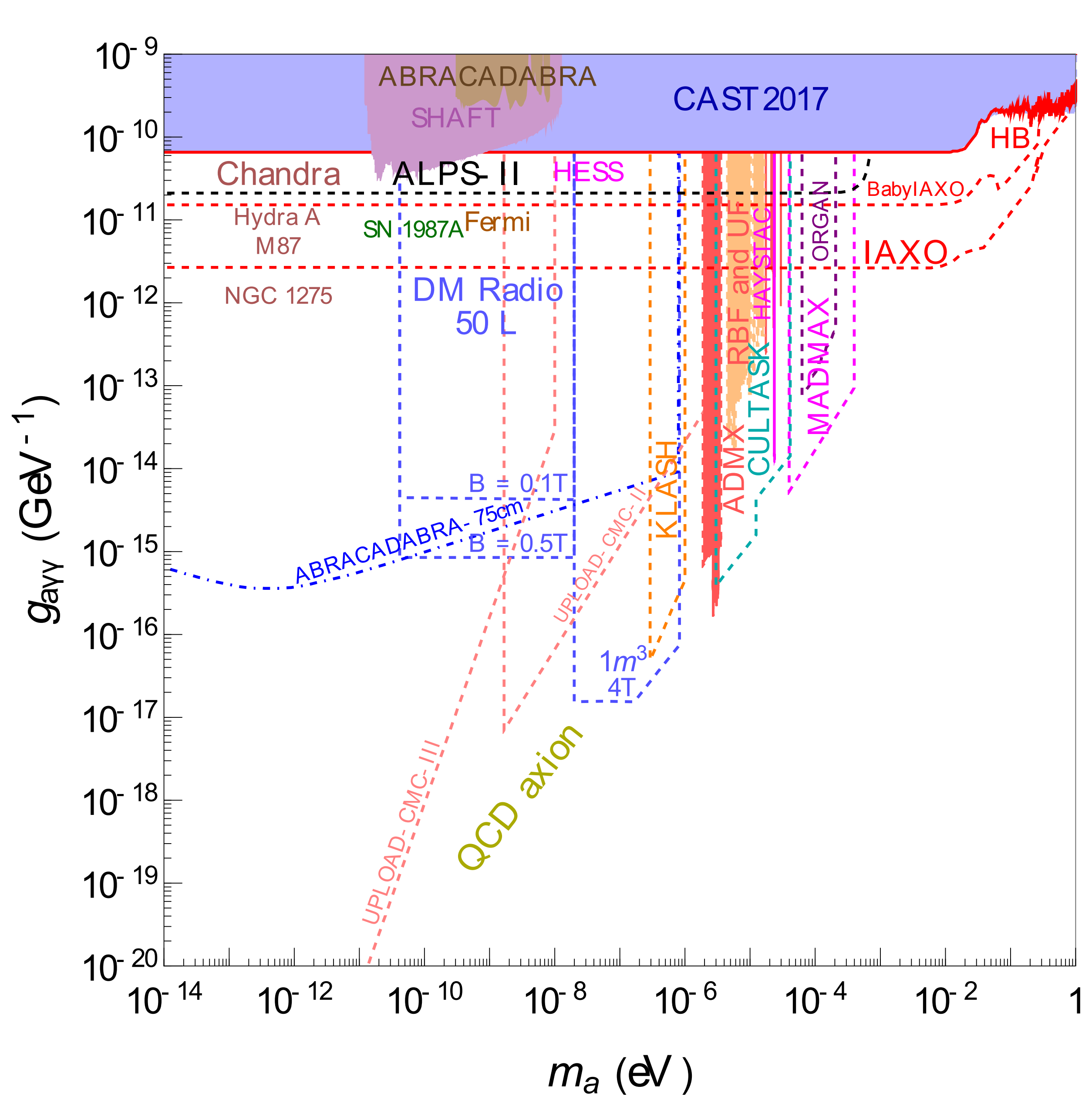
Status of Axion Dark Matter

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)

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"
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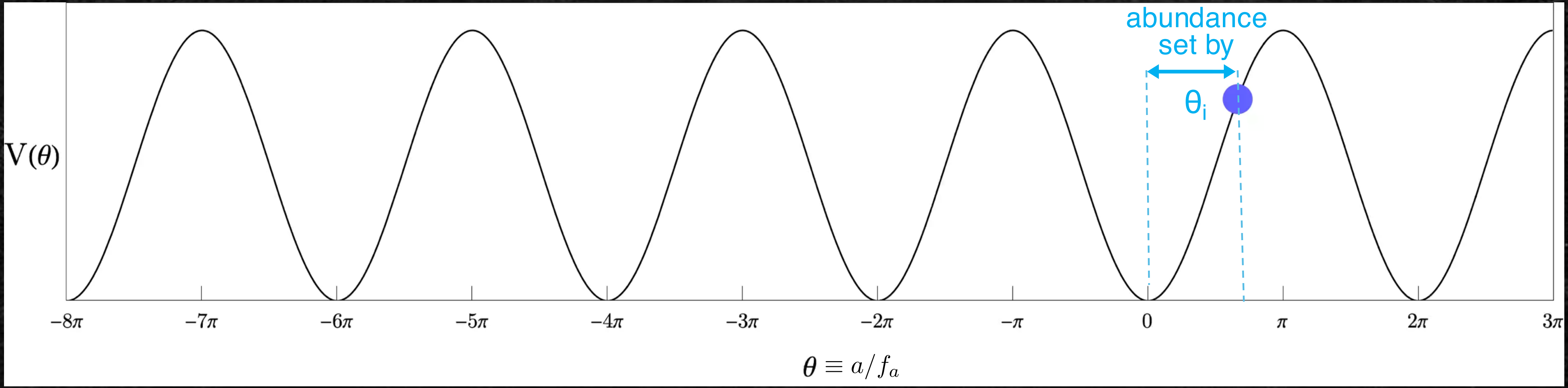
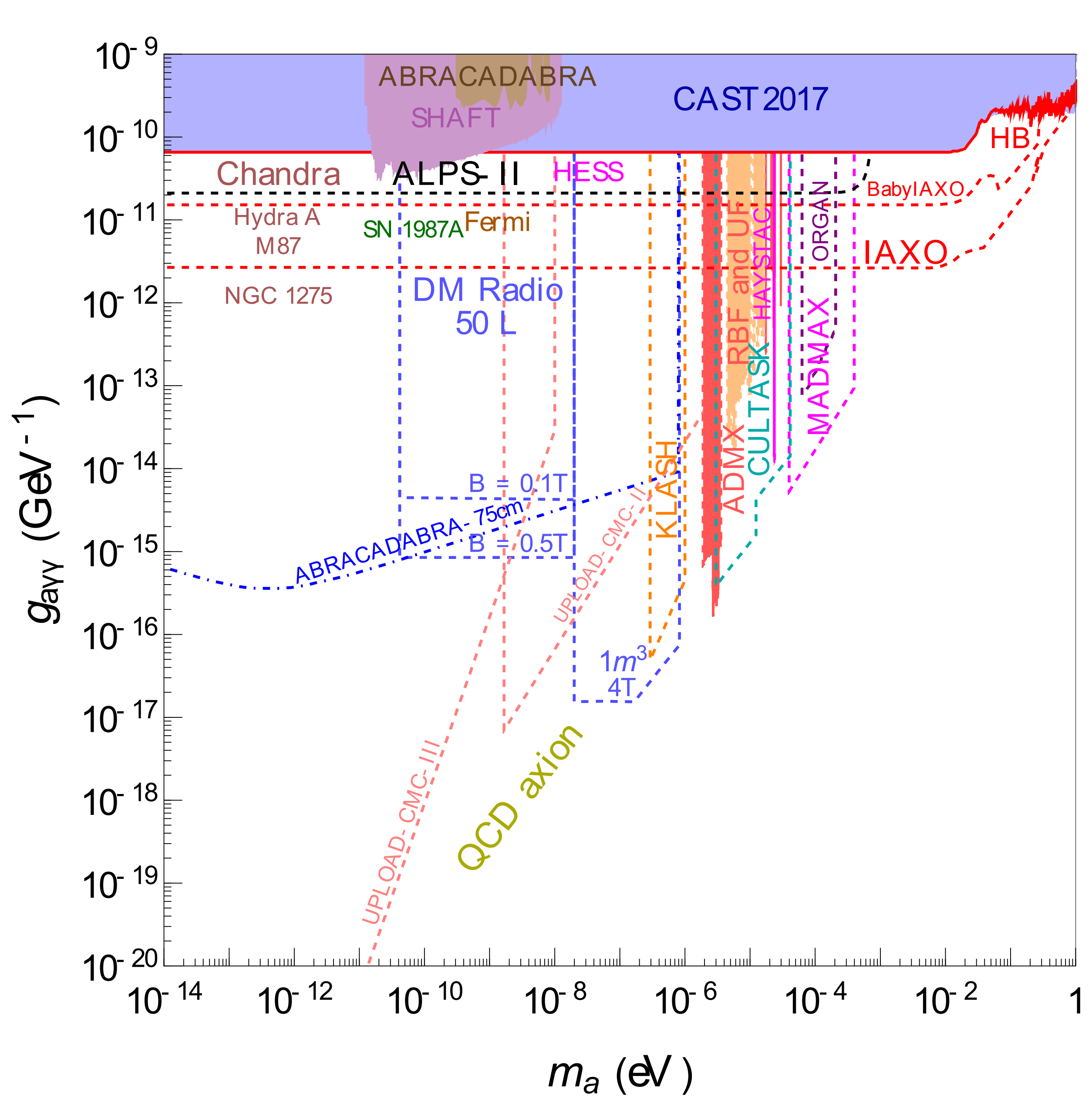
Misalignment Mechanism

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

oscillations start when
$H \lesssim m_a$

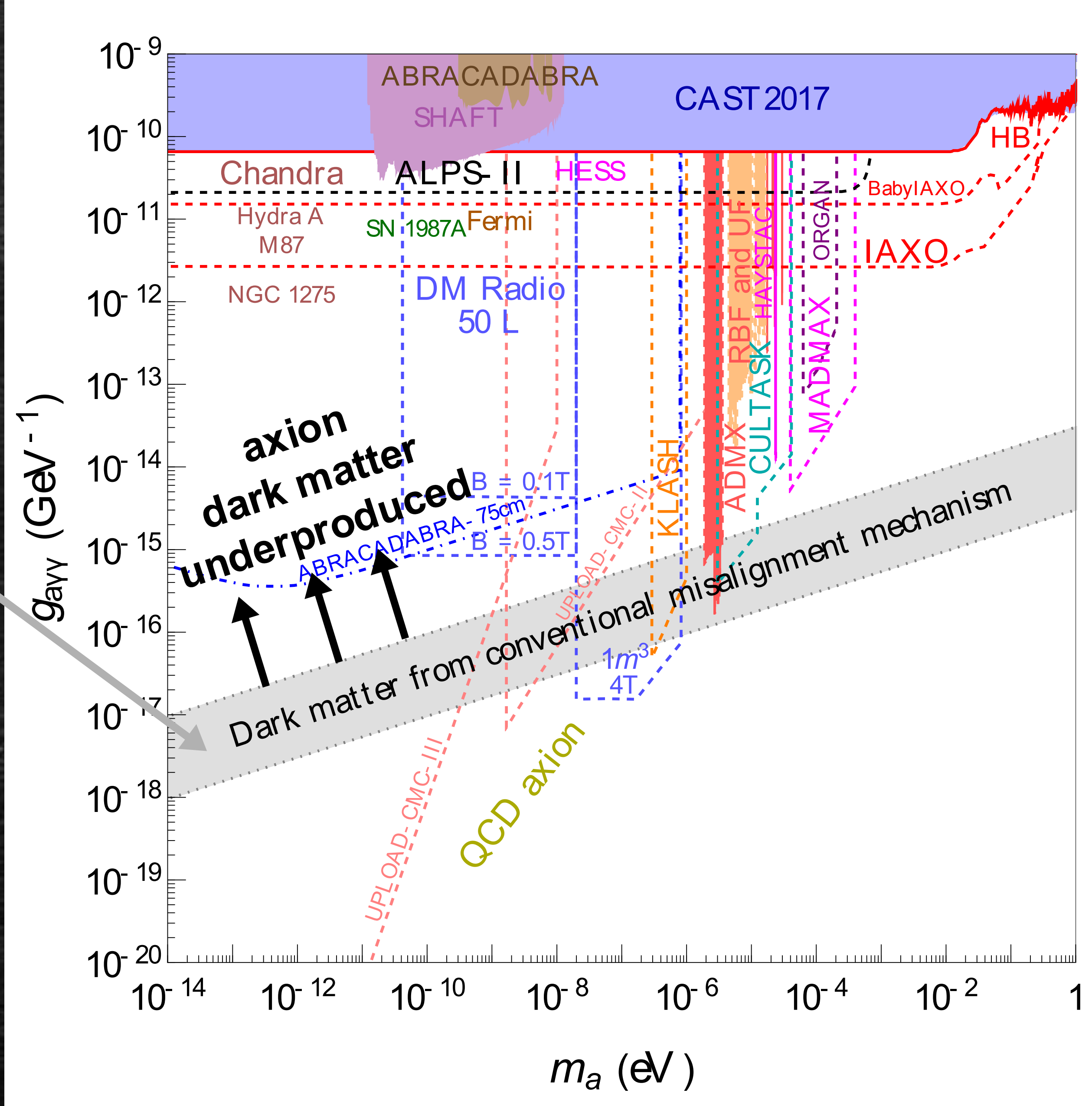


Axion Dark Matter Abundance



Axion Dark Matter Abundance

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

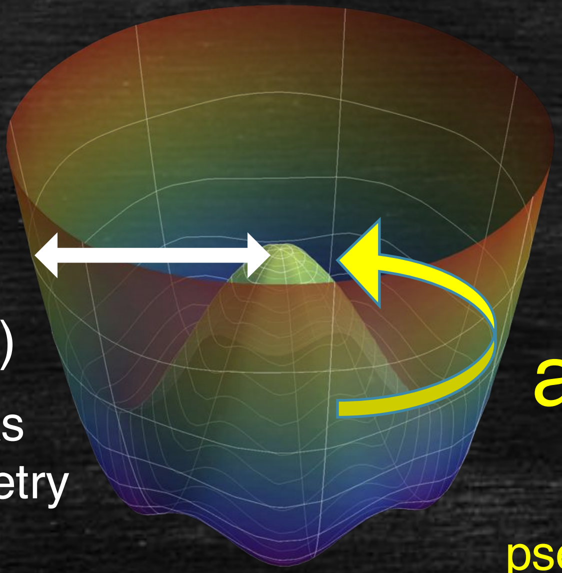


Axion Dynamics

Axion UV Completion

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

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



Axion Dynamics

- ✓ Parametric Resonance
- ✓ Axion Rotations

Parametric Resonance

Pedagogical example:

(Non-expanding Universe)

Quartic potential:

$$V = \lambda^2 |P|^4$$

$$= \frac{\lambda^2}{4}\left(S^2 + \chi^2\right)^2$$

radial mode

"axion"

$$P = \frac{S + i\chi}{\sqrt{2}}$$

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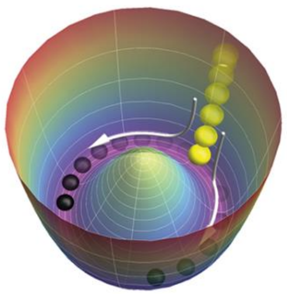


EDITORS' SUGGESTION

QCD Axion Dark Matter with a Small Decay Constant

A proposed new cosmological production mechanism for QCD axion dark matter that involves parametric resonance in field oscillation predicts larger axion masses than the conventional misalignment mechanism.

Raymond T. Co, Lawrence J. Hall, and Keisuke Harigaya
Phys. Rev. Lett. **120**, 211602 (2018)

Equation of motions:

$$\ddot{\chi} - \nabla^2\chi + V''(\chi)\,\chi = 0$$

$$V''(\chi) = \lambda^2 S^2 = \lambda^2 S_0^2 \cos^2(\lambda S_0 t)$$

$$S \sim S_0 \cos(\lambda S_0 t)$$

PRL 120, 211602 (2018) RC, L. Hall, and K. Harigaya

Parametric Resonance

Oscillation frequency
of the field
in absence of
the driving force

Oscillation frequency of
the driving force

$$\ddot{\chi} - \underline{\nabla^2} \chi + V''(\chi)\ \chi = 0 \qquad V''(\chi) = \underline{\lambda^2 S^2} = \lambda^2 S_0^2 \cos^2(\lambda S_0 t)$$

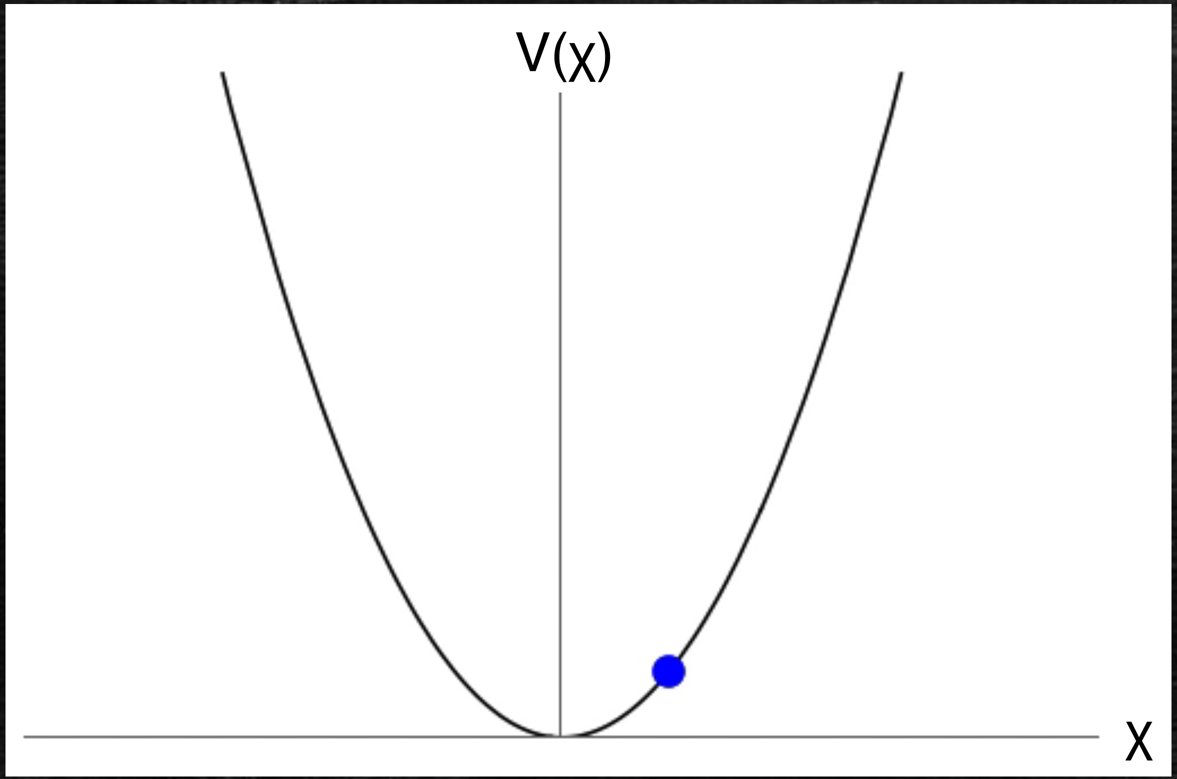
Resonance occurs for some specific frequencies: warm dark matter.

PRL 120, 211602 (2018) RC, L. Hall, and K. Harigaya

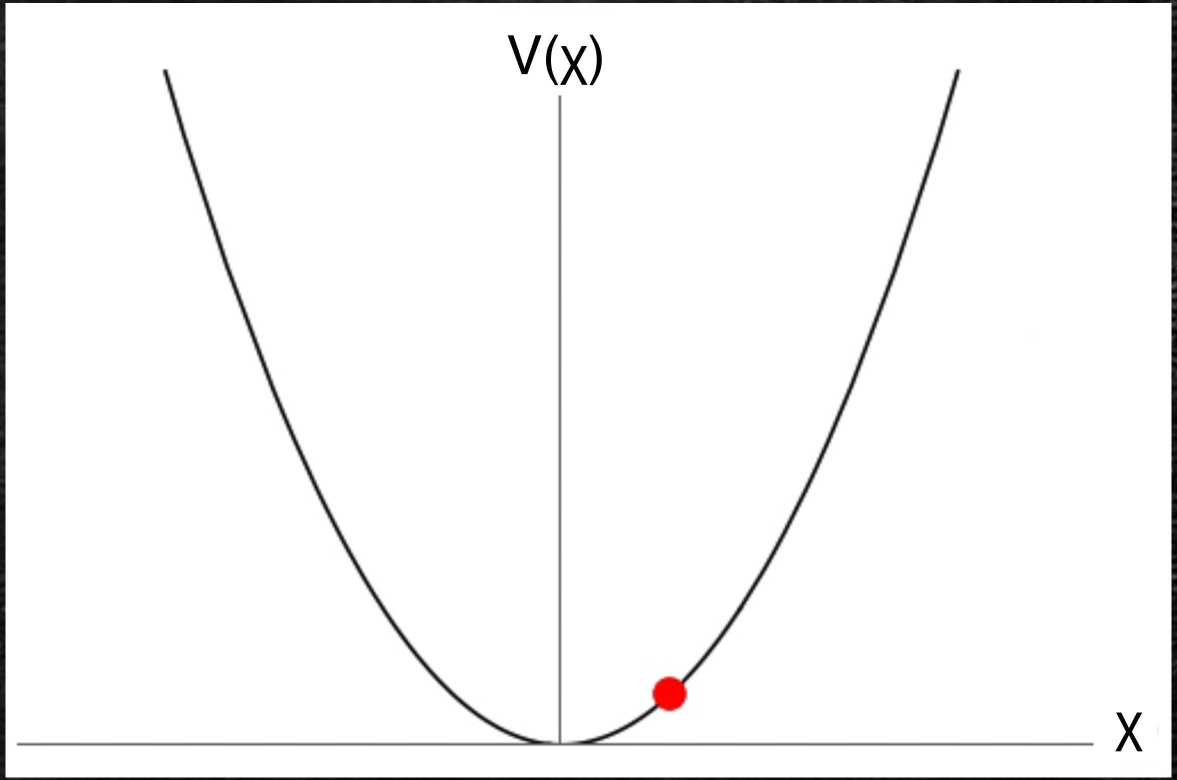
Parametric Resonance

Graphical understanding

No Enhancement



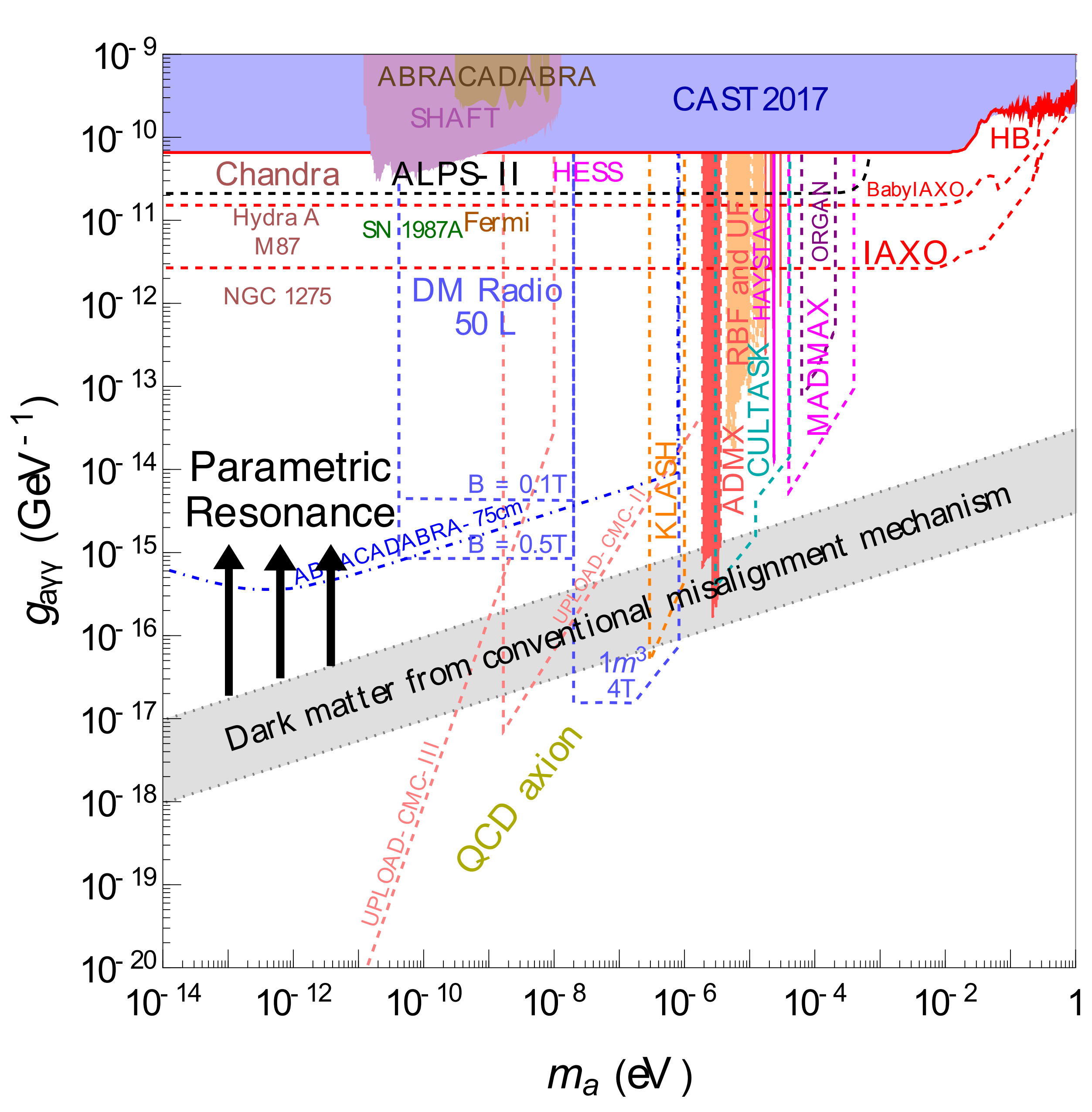
Parametric Resonance



PRL 120, 211602 (2018) RC, L. Hall, and K. Harigaya

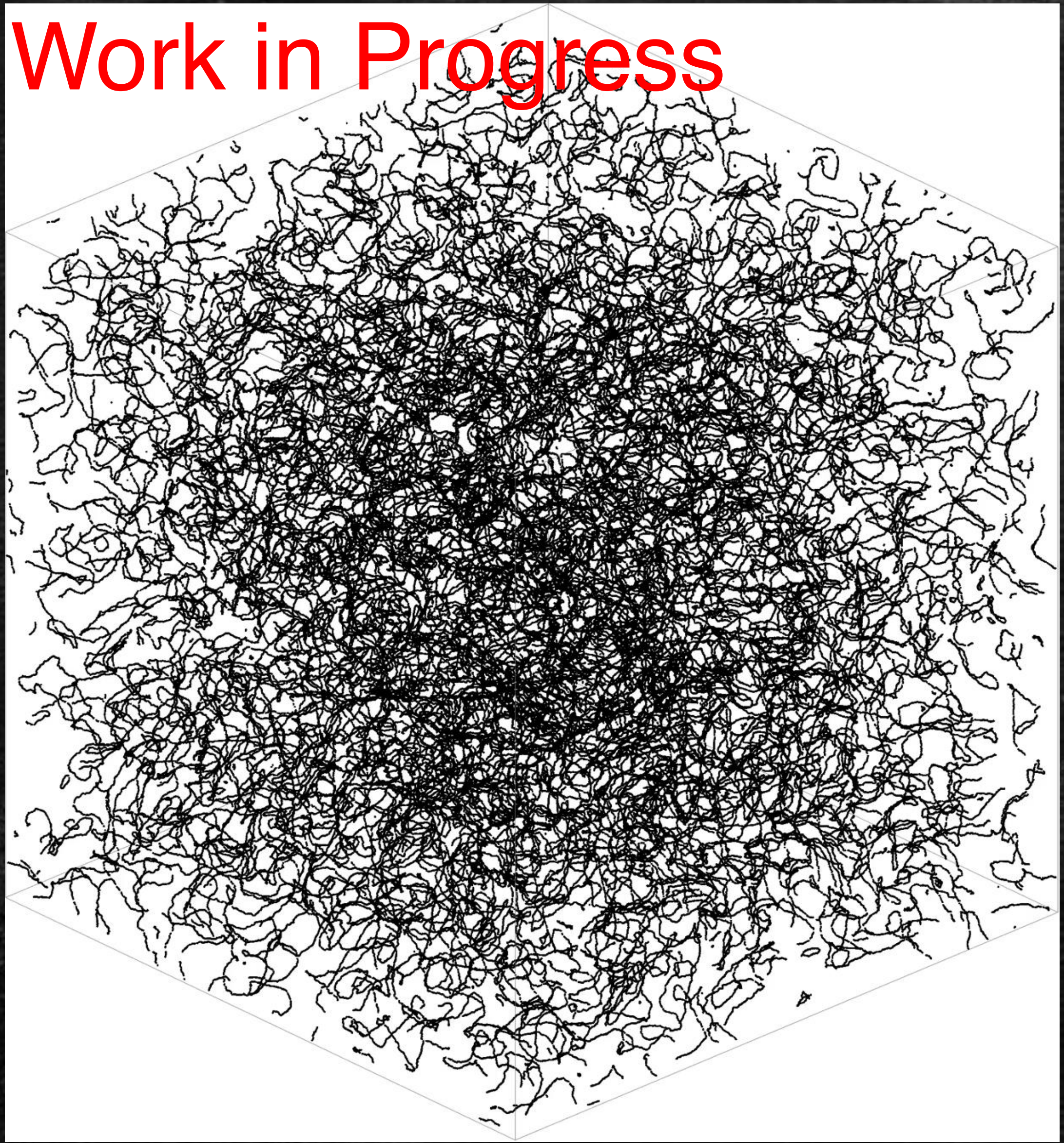
Parametric Resonance

giving a strong motivation for axion dark matter experiment



PRL 120, 211602 (2018) RC, L. Hall, and K. Harigaya

Non-thermal PQ Symmetry Restoration



Animation for illustration purposes only.
Caution: string core ~ 0.5 lattice spacing

parametric resonance when P oscillates

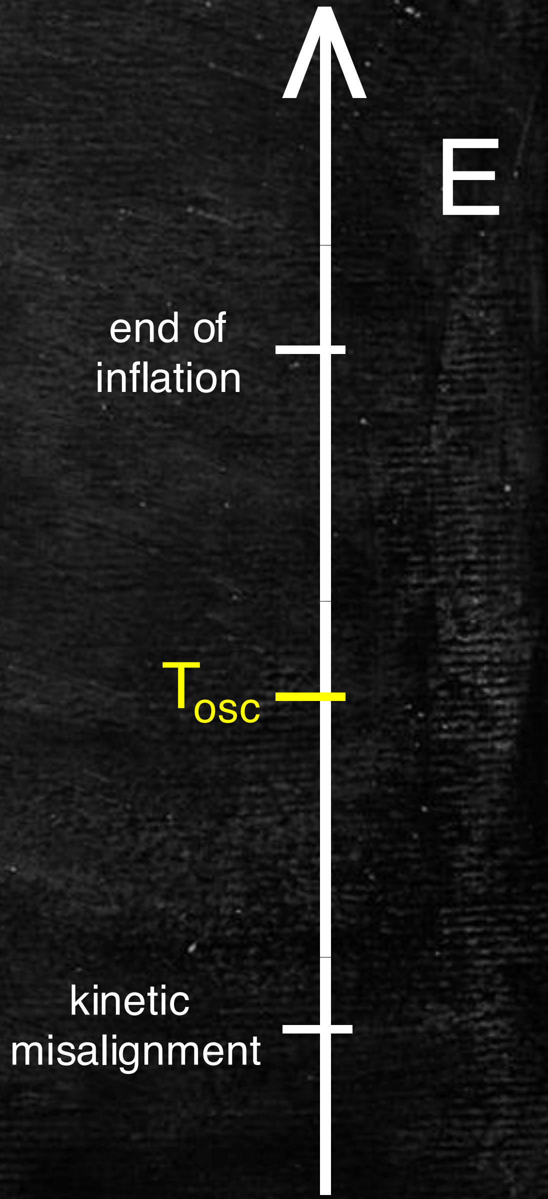
↓

fluctuations create effective mass term

↓

PQ symmetry restored
cosmic strings created

Grad student: Taegyu Lee



RC, K. Harigaya, T. Lee, A. Pierce

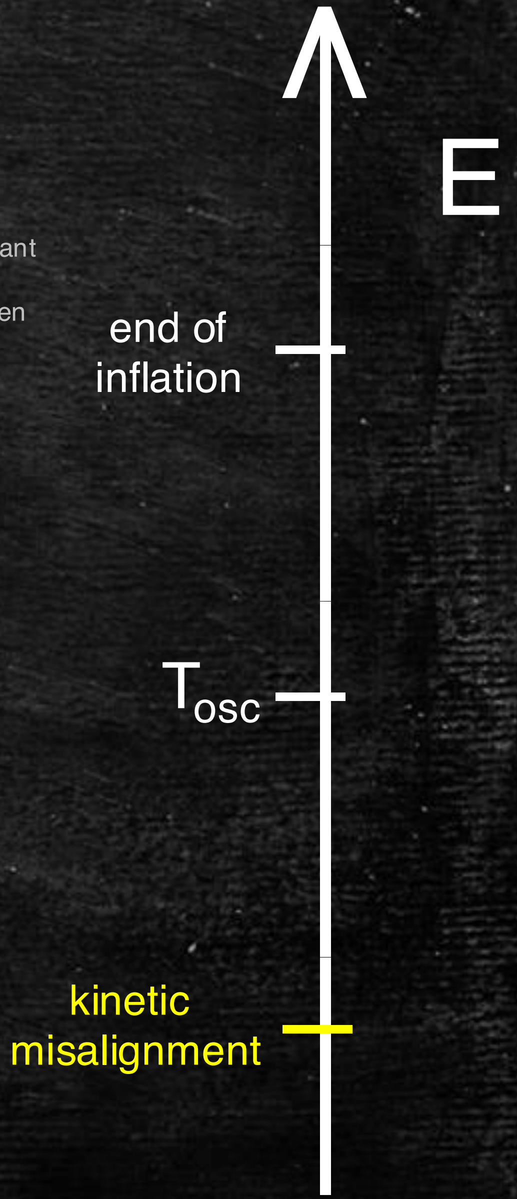
Axion Parametric Resonance

Parametric resonance from hilltop/trapped misalignment

PRD 101 (2020) 8, 083014 A. Arvanitaki, S. Dimopoulos, M. Galanis, L. Lehner, J. Thompson, K. Van Tilburg
JCAP 10 (2021) 001 L. Luzio, B. Gavela, P. Quilez, A. Ringwald
JHEP 09 (2024) 145 RC, T. Gherghetta, Z. Liu, K. Lyu
2408.04623 L. Luzio, P. Sørensen

Parametric resonance from kinetic misalignment

JCAP 01 (2017) 036 J. Jaeckel, V. Mehta, L. Witkowski
JCAP 08 (2019) 020 J. Berges, A. Chatrchyan, J.Jaeckel
JHEP 04 (2020) 010 N. Fonseca, E. Morgante, R. Sato, G. Servant
JHEP 12 (2021) 099 RC, K. Harigaya, A. Pierce
JCAP 10 (2022) 053 C. Eroncel, R. Sato, G. Servant, P. Sørensen
JCAP 01 (2023) 009 C. Eroncel, G. Servant

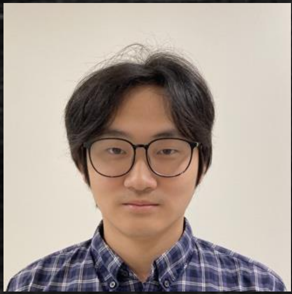


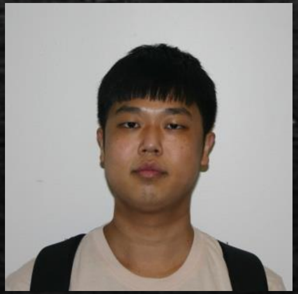
CosmoLattice 2102.01031

Work in Progress


High schooler: Ardashir Kocer


Undergrad: Owen Leonard

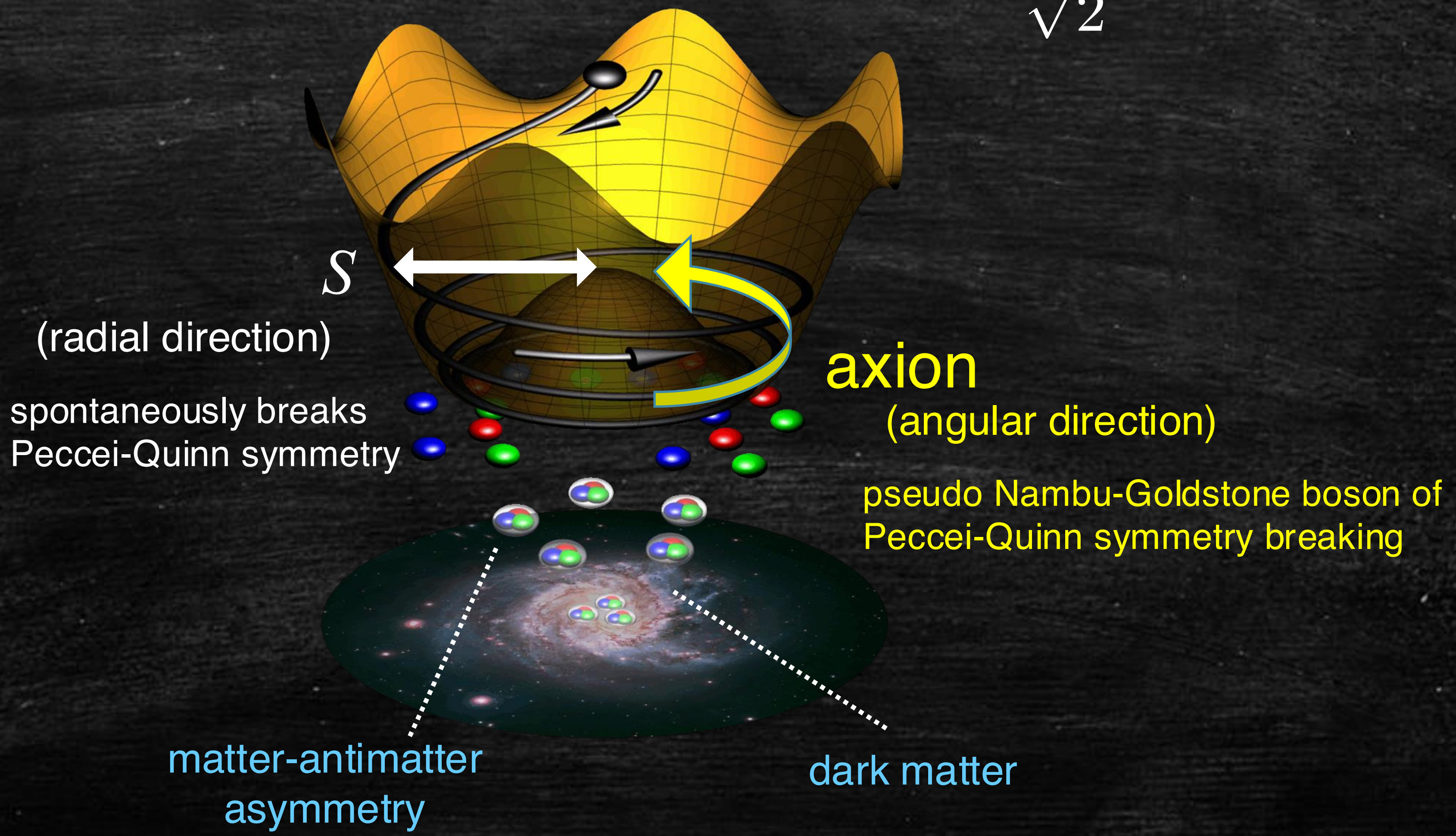

Undergrad: Bohao Wang


Grad student: Taegyu Lee

Axion Rotation

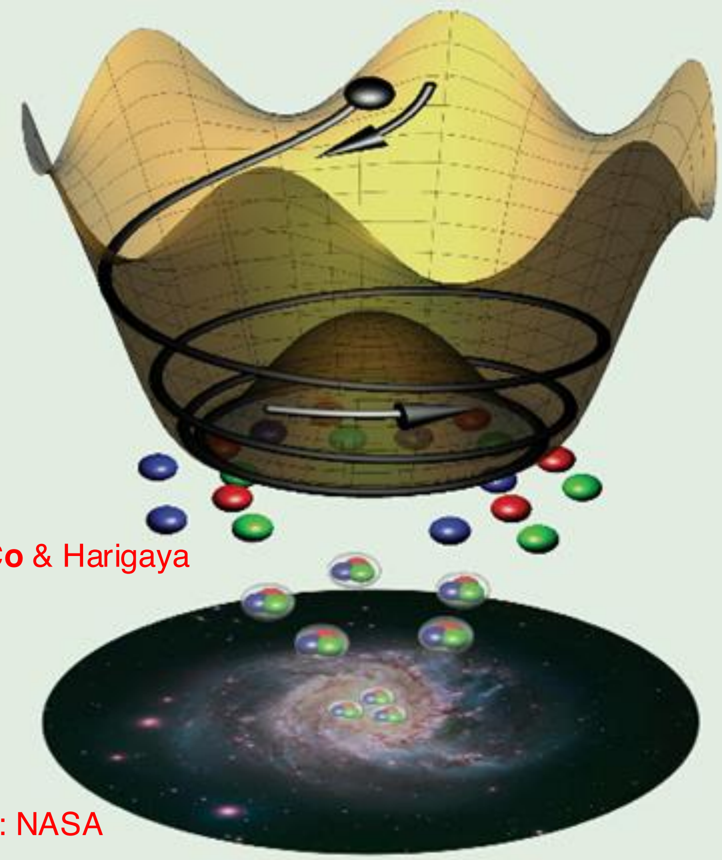
$$\mathcal{L} \supset \frac{\alpha_s}{8\pi} \frac{a}{f_a} G_b^{\mu\nu} \widetilde{G}_{b\mu\nu}$$

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



PHYSICAL REVIEW LETTERS

Articles published week ending 20 MARCH 2020



Graphic: **Co** & Harigaya

Photo: NASA

Published by American Physical Society

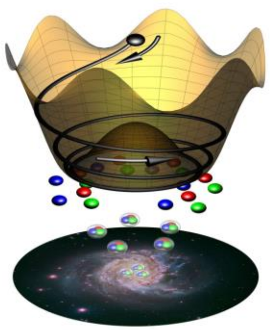
APS physics

Volume 124, Number 11

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

Quantamagazine Physics Mathematics Bio

ABSTRACTIONS BLOG

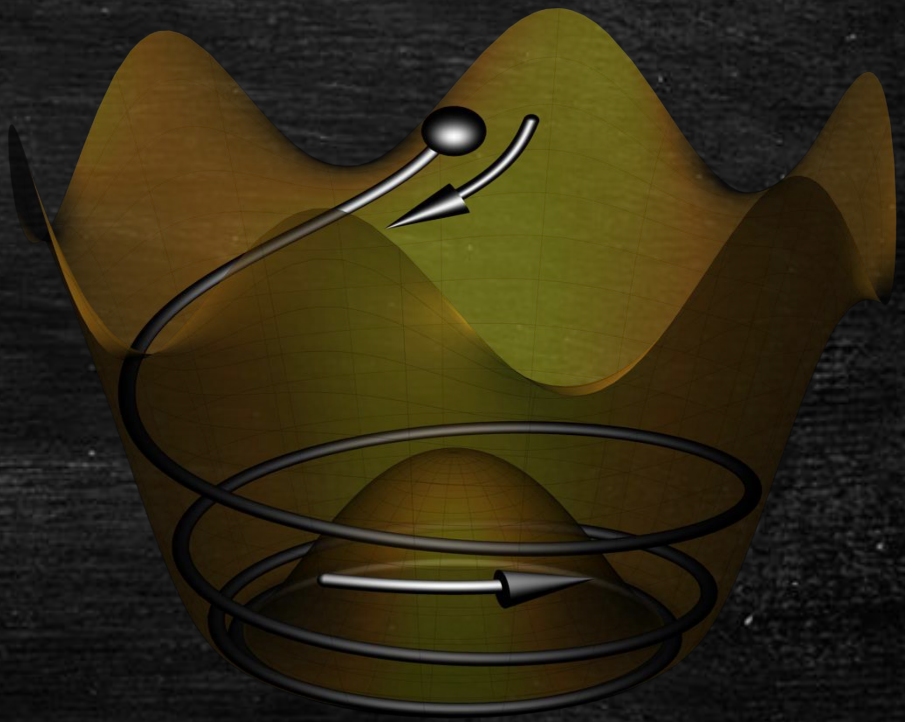
Axions Would Solve Another Major Problem in Physics

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?

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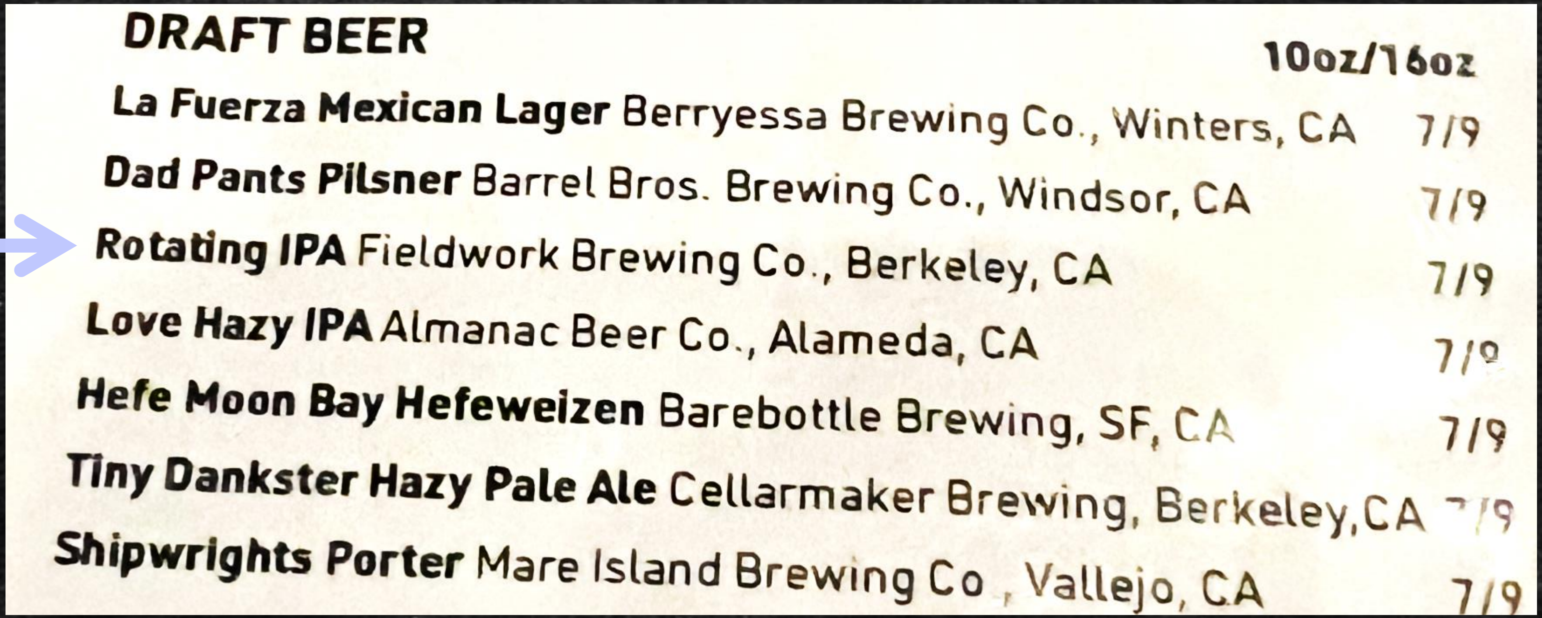


DRAFT BEER 10oz/16oz

La Fuerza Mexican Lager Berryessa Brewing Co., Winters, CA 7/9

Dad Pants Pilsner Barrel Bros. Brewing Co., Windsor, CA 7/9

Rotating IPA Fieldwork Brewing Co., Berkeley, CA 7/9

Love Hazy IPA Almanac Beer Co., Alameda, CA 7/9

Hefe Moon Bay Hefeweizen Barebottle Brewing, SF, CA 7/9

Tiny Dankster Hazy Pale Ale Cellarmaker Brewing, Berkeley, CA 7/9

Shipwrights Porter Mare Island Brewing Co., Vallejo, CA 7/9

Why Rotation?

Wiggles :

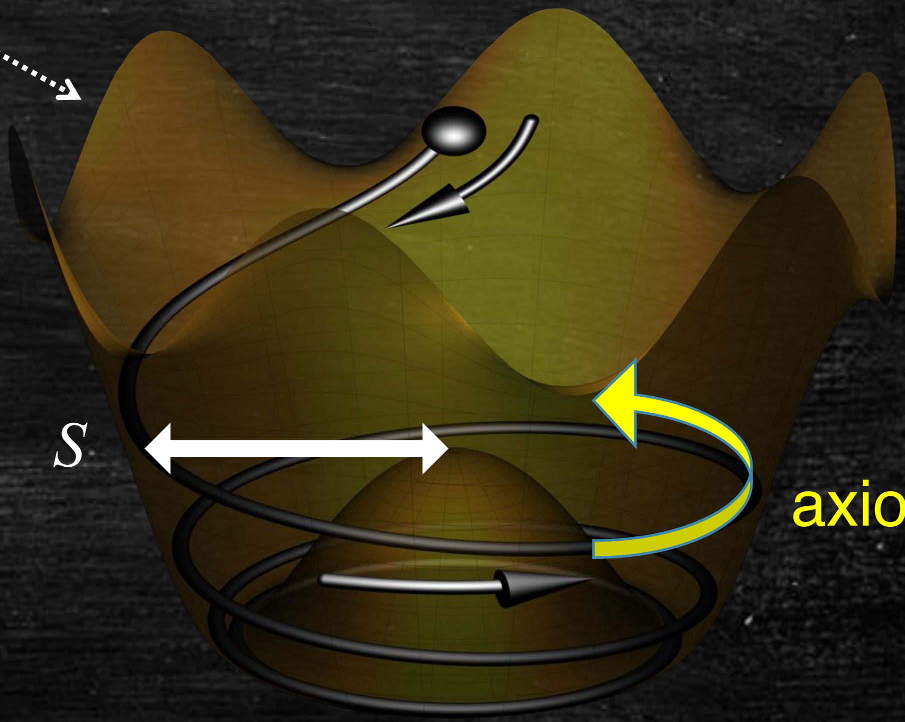
$$V(P) \sim \frac{P^n}{M^{n-4}} e^{i\varphi} + \text{h.c.} \sim \frac{|P|^n}{M^{n-4}} \cos\left(n\frac{a}{f_a} + \varphi\right)$$

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

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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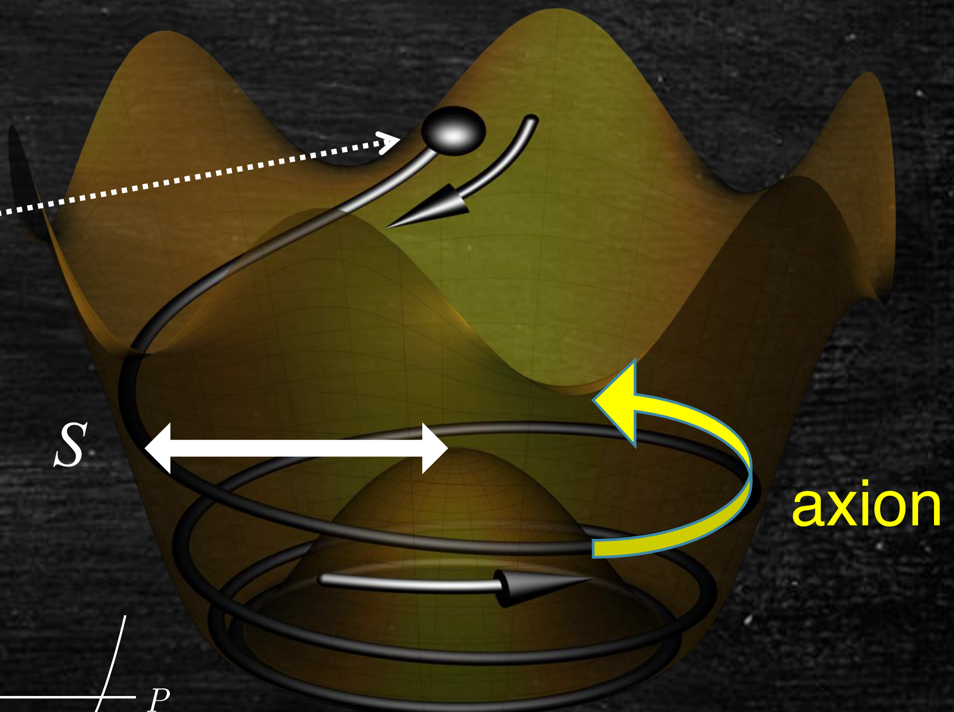
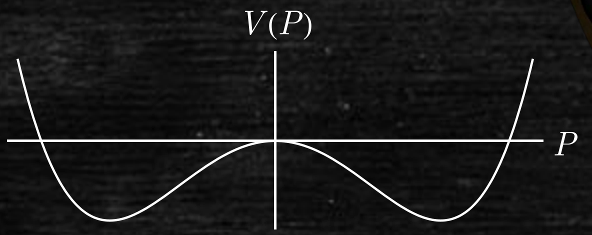


Large field value : Flat potential

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

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S. Coleman 1988
G. Gilbert 1988

Work in Progress: Axion Non-Gaussianity

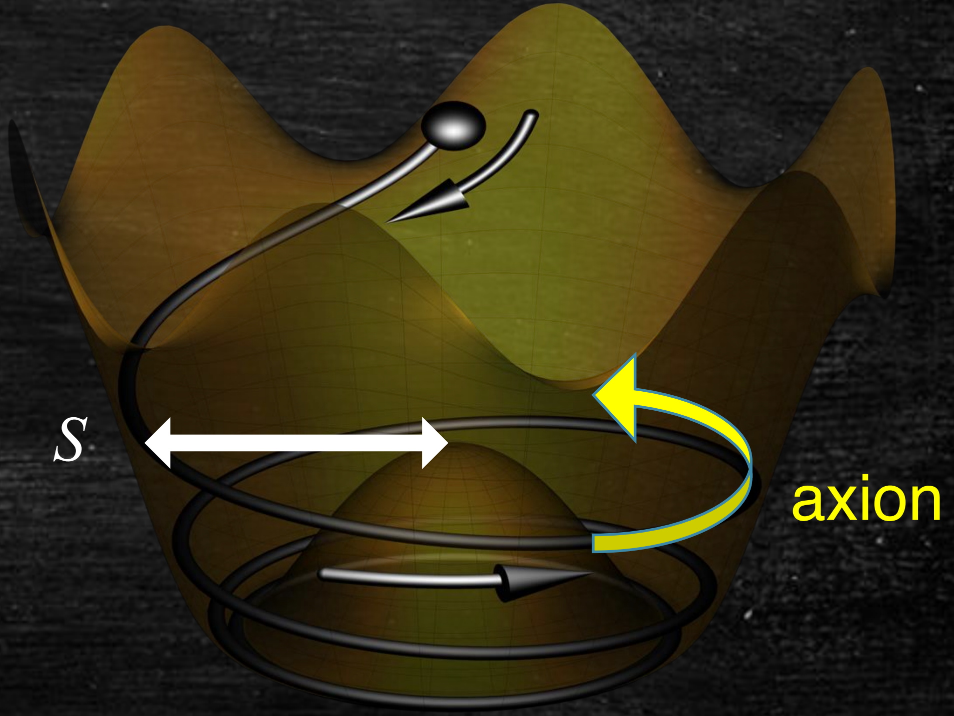
PQ field and inflaton interaction

Higher dimensional $U(1)_{PQ}$ breaking

JHEP 12 (2023) 197 X. Chen, J. Fan, L. Li

Postdoc: Sai Chaitanya Tadepalli

Grad student: Taegyu Lee



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Asymmetry of PQ Charge

Noether charge associated with the shift symmetry

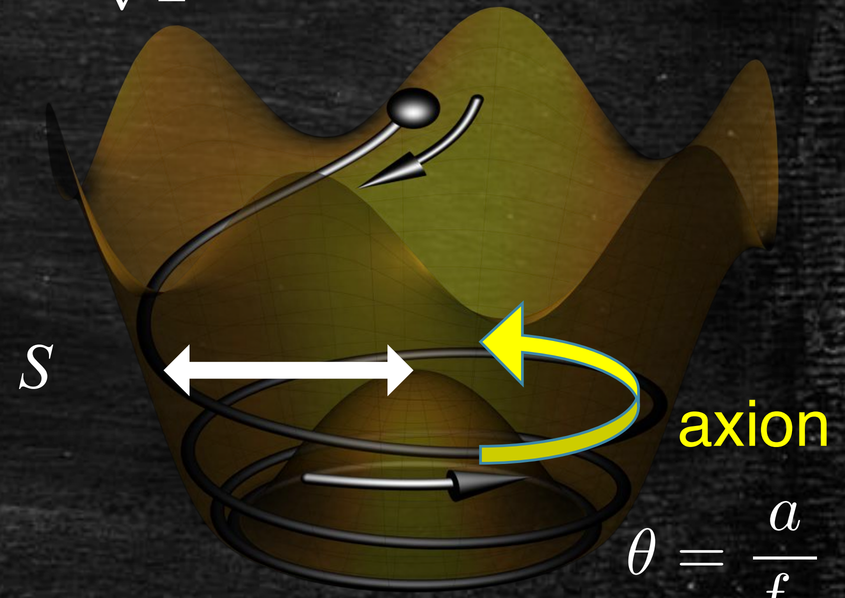
$$n_\theta = S^2\dot{\theta}$$

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

PQ asymmetry
PQ charge density = Rotation of PQ field

This is conserved soon after the initial kick.

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



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

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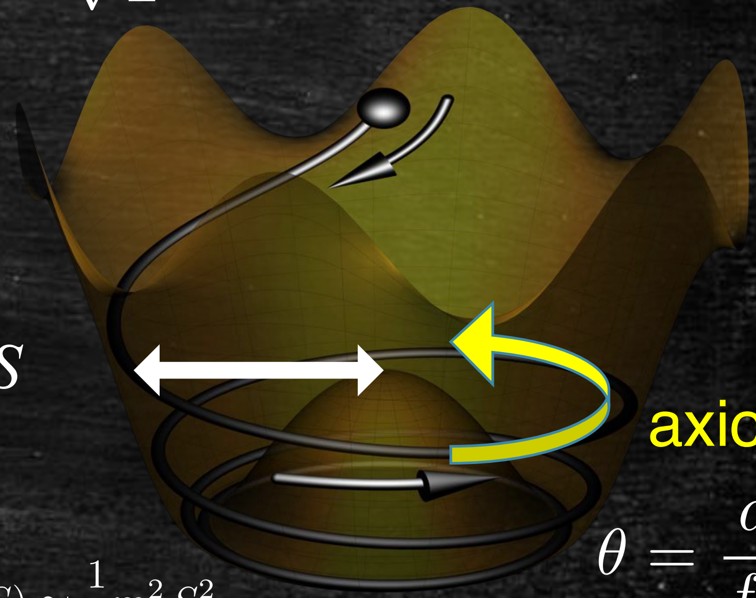


$$\theta = \frac{a}{f_a}$$

PQ asymmetry
PQ charge density **=** Rotation of PQ field

This is conserved soon after the initial kick.

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

$$F_c = m a_c$$

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

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

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

from supersymmetry

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

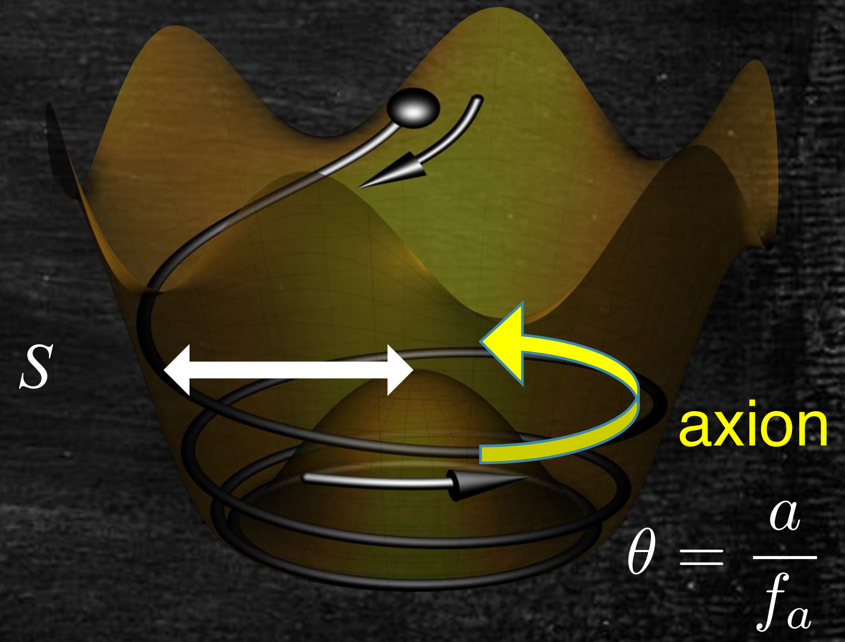
PQ Charge Evolution

Charge conservation:

scale factor of the universe

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

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 ($S \gg f_a$):

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

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

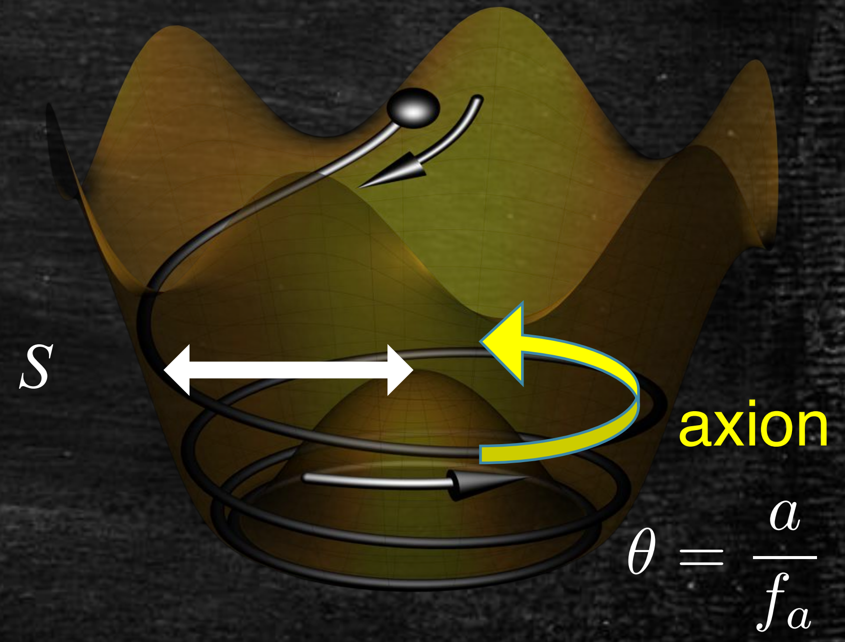
At the minimum:

$$S^2 = f_a^2$$

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

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

kination



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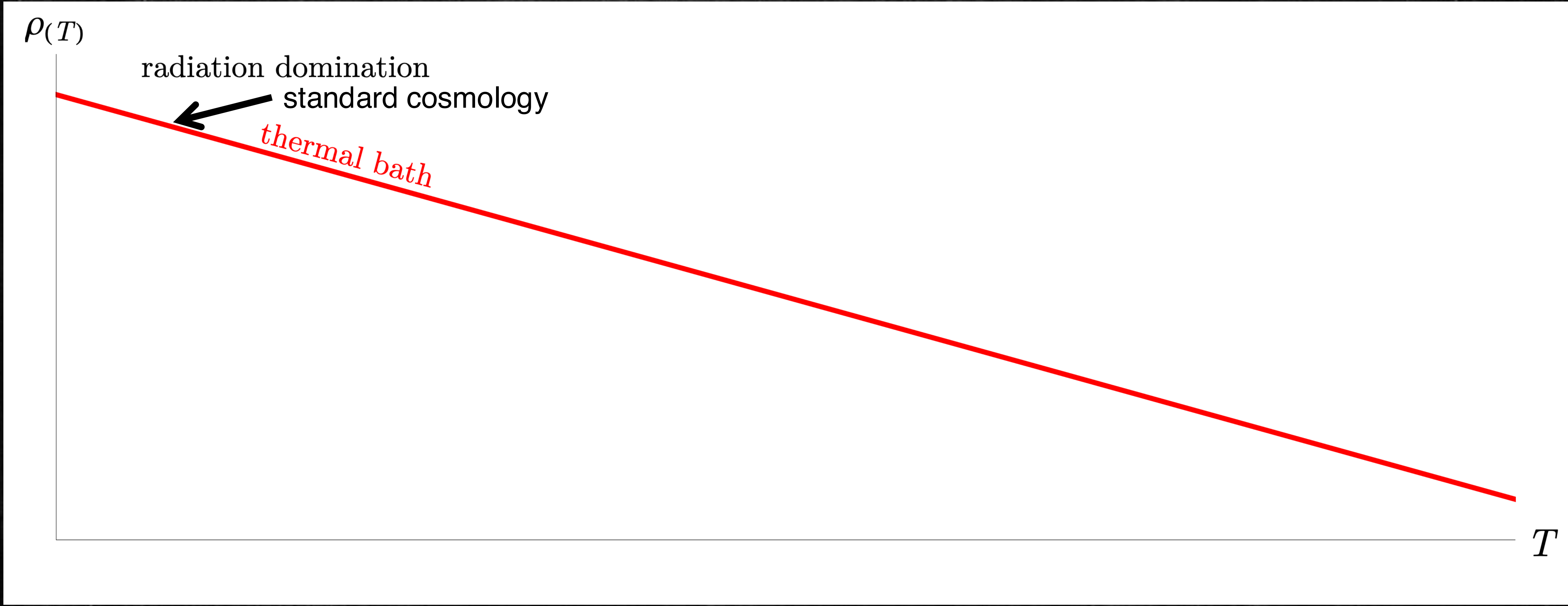
Gravitational Wave Signatures

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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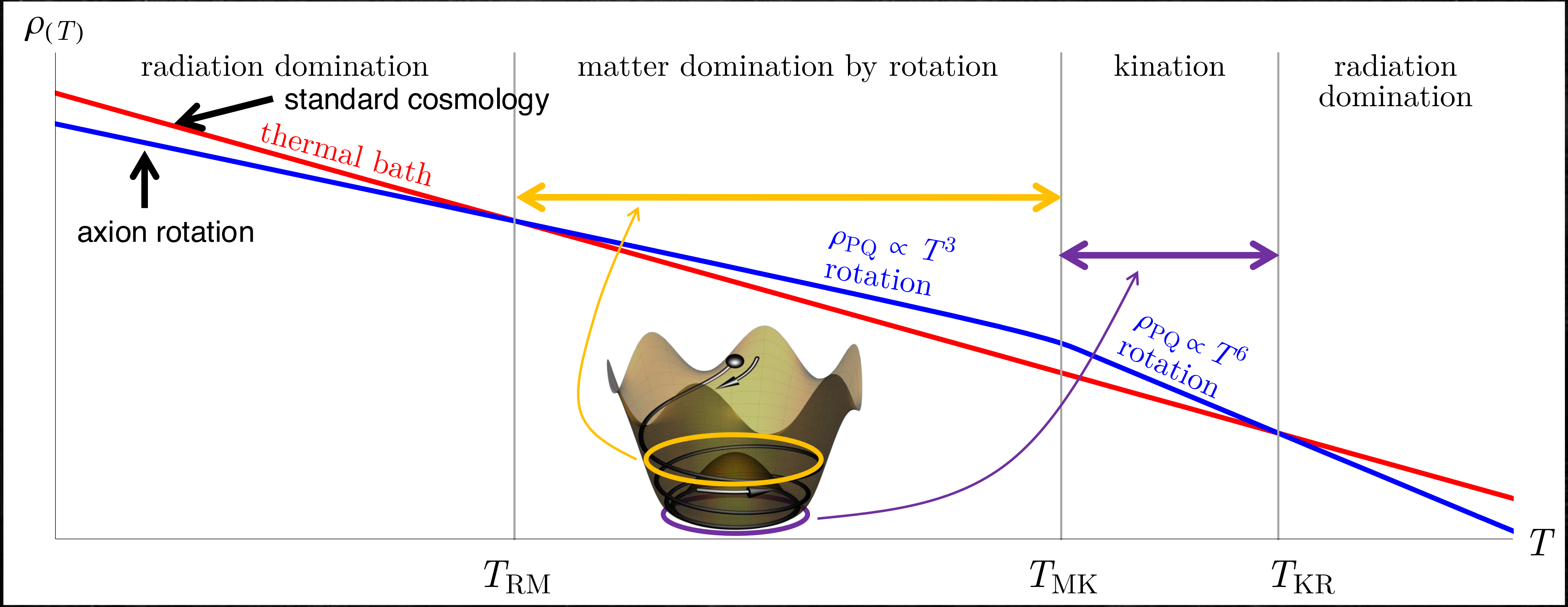

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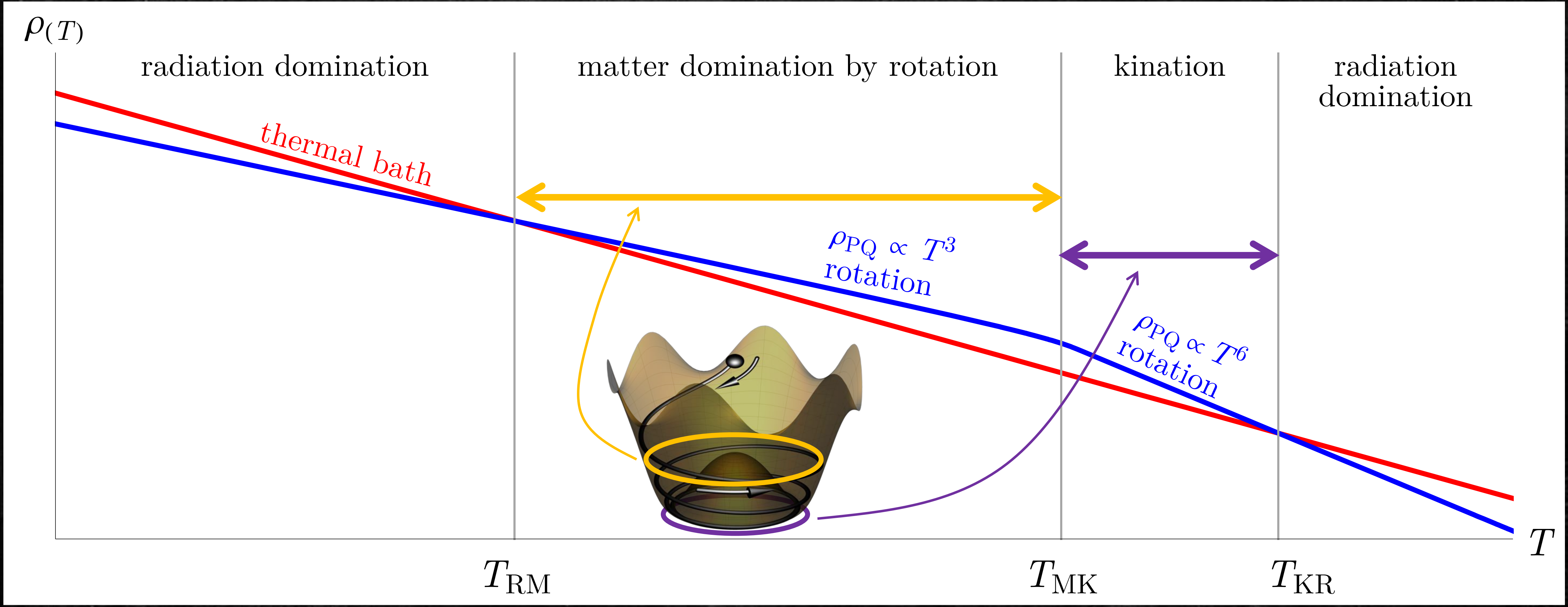
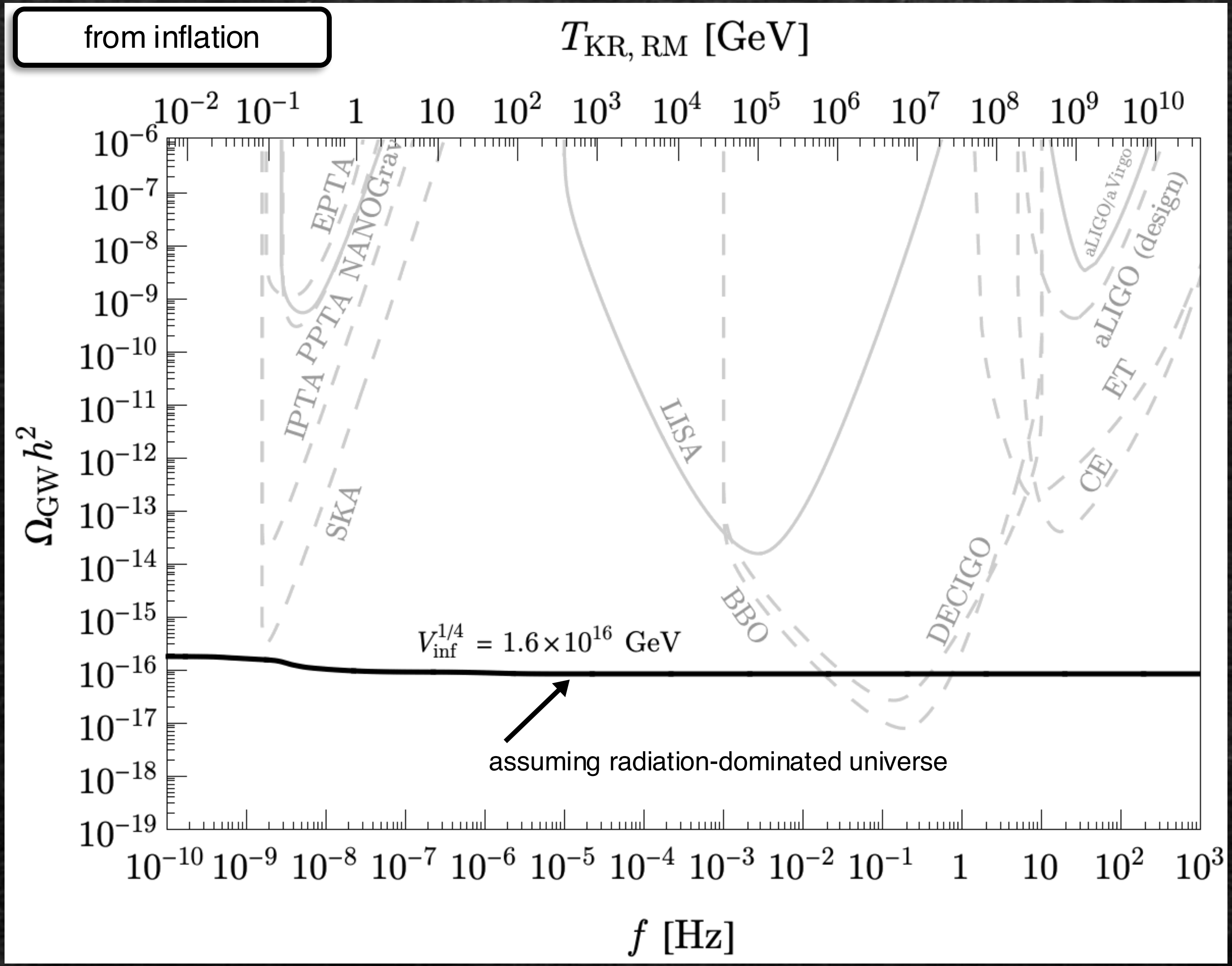


Smoking Gun: Triangular Peak in Gravitational Wave Spectra



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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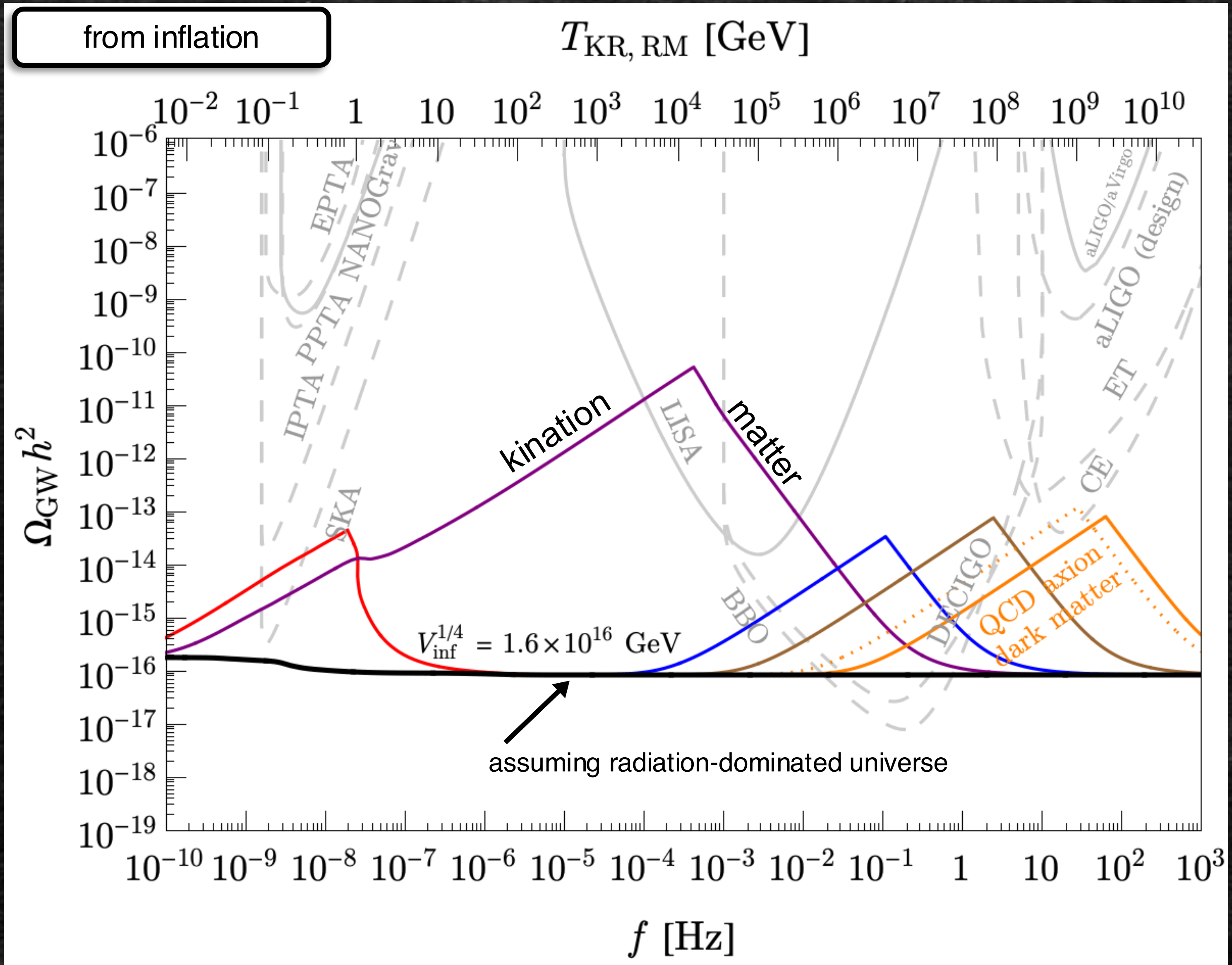

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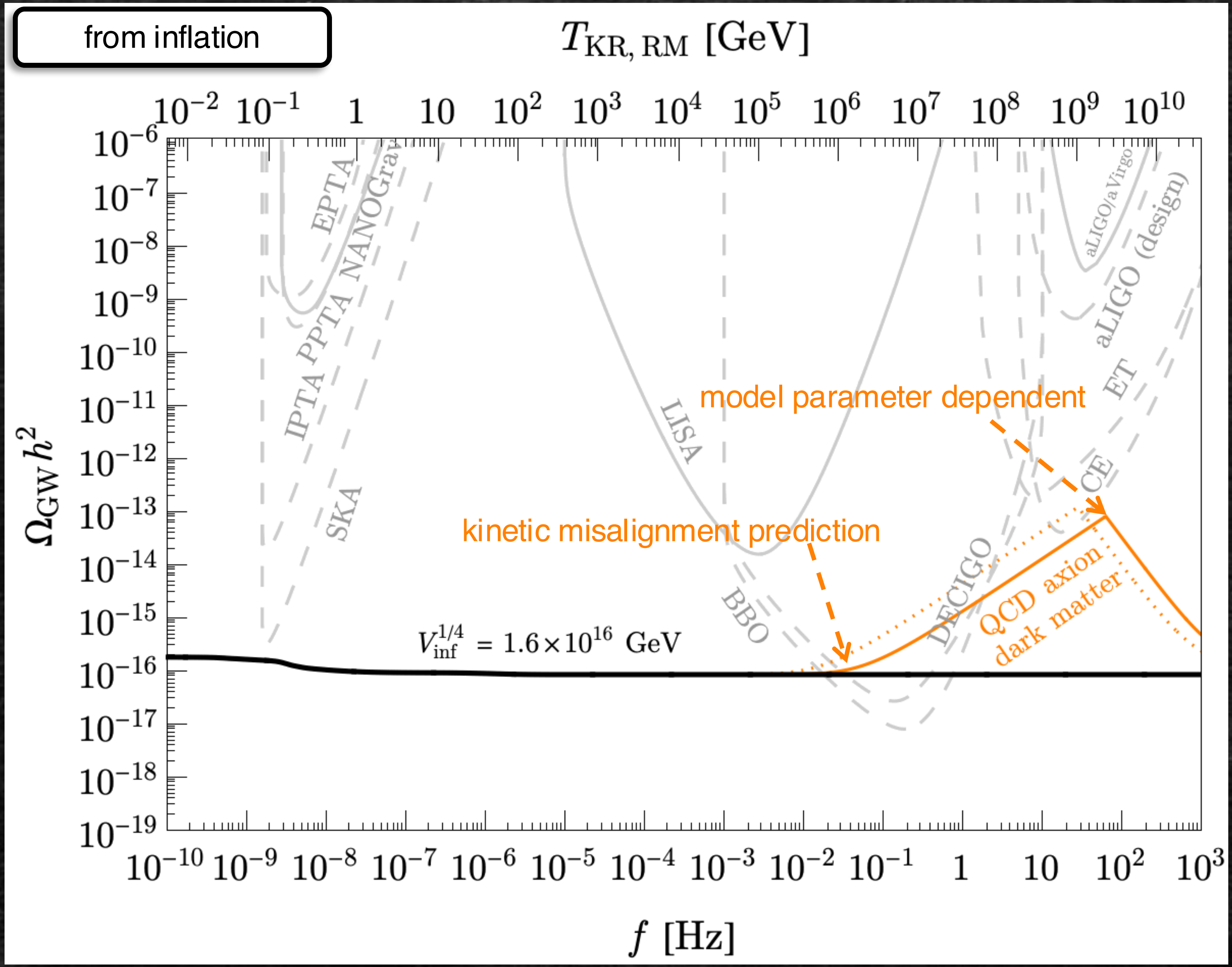

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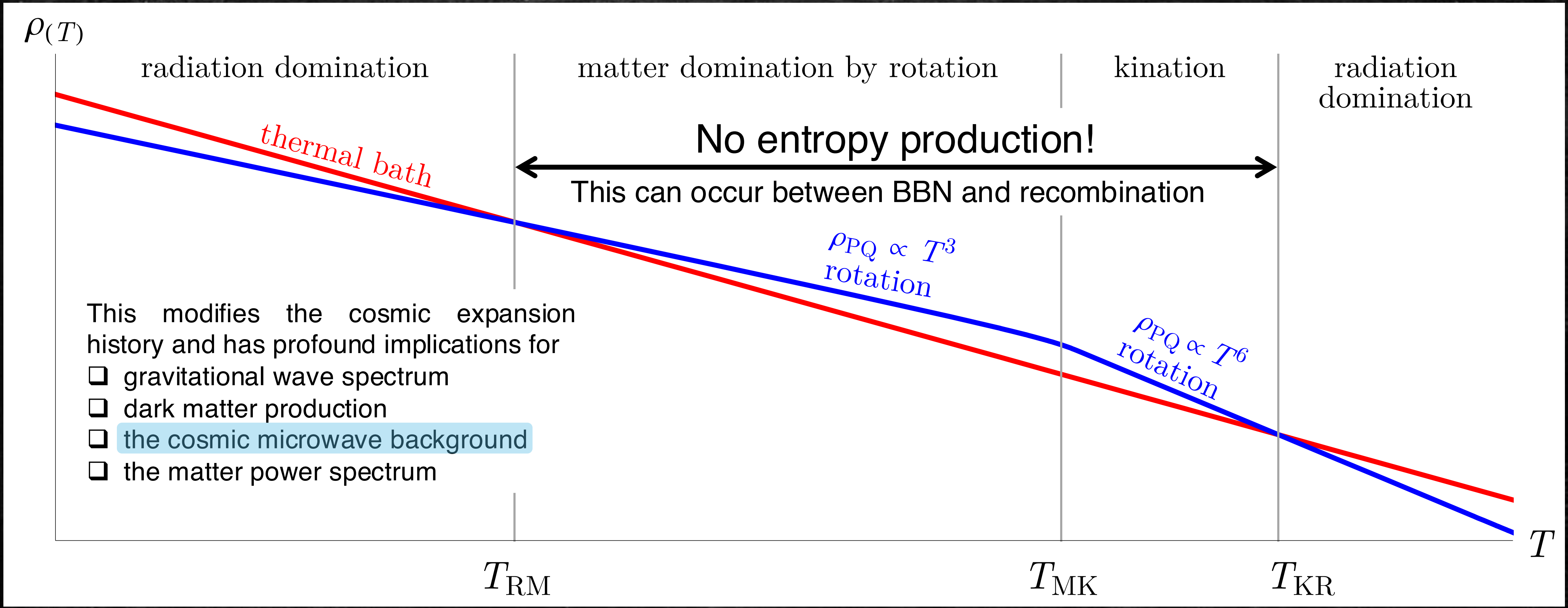
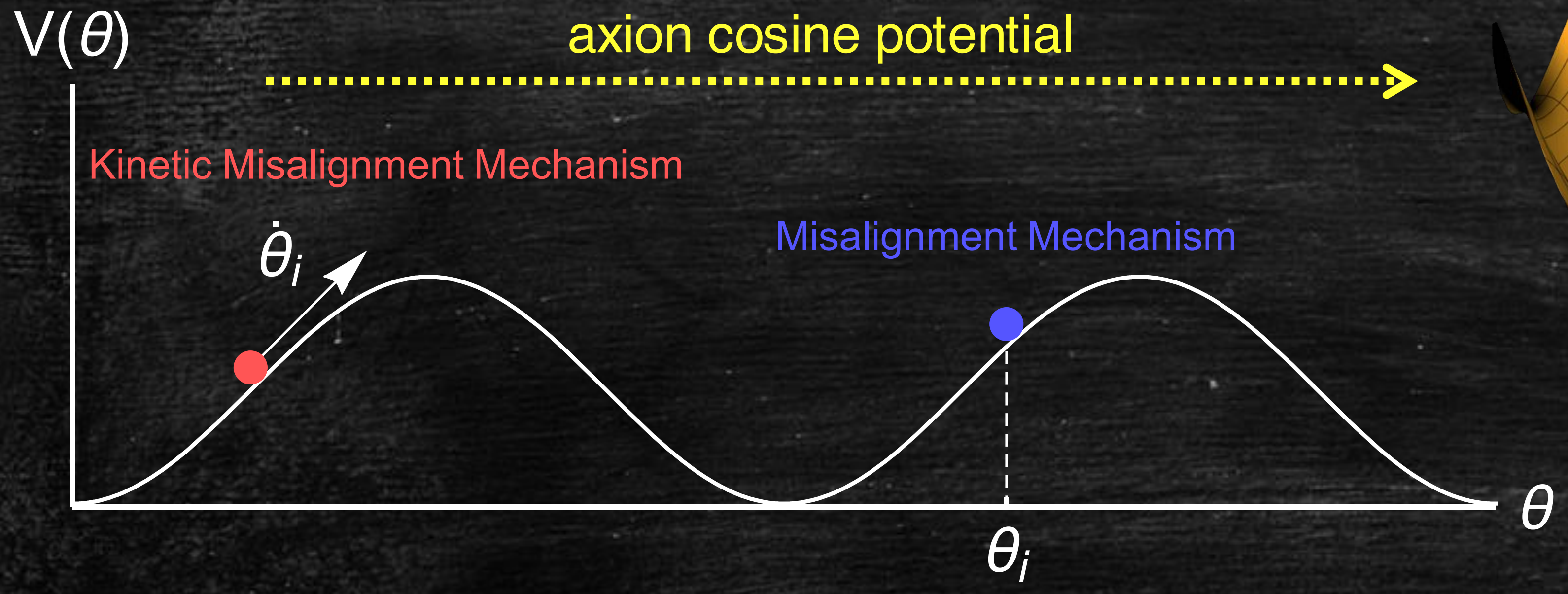


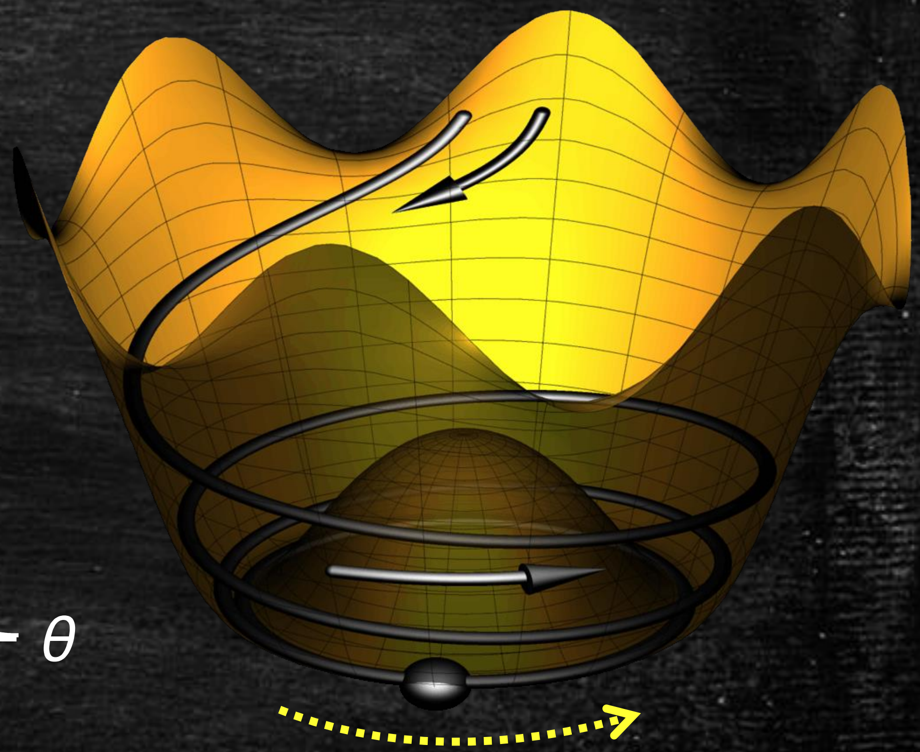
2108.09299 RC, N. Fernandez, A. Ghalsasi, K. Harigaya, J. Shelton

Axion Dark Matter

Kinetic Misalignment Mechanism

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



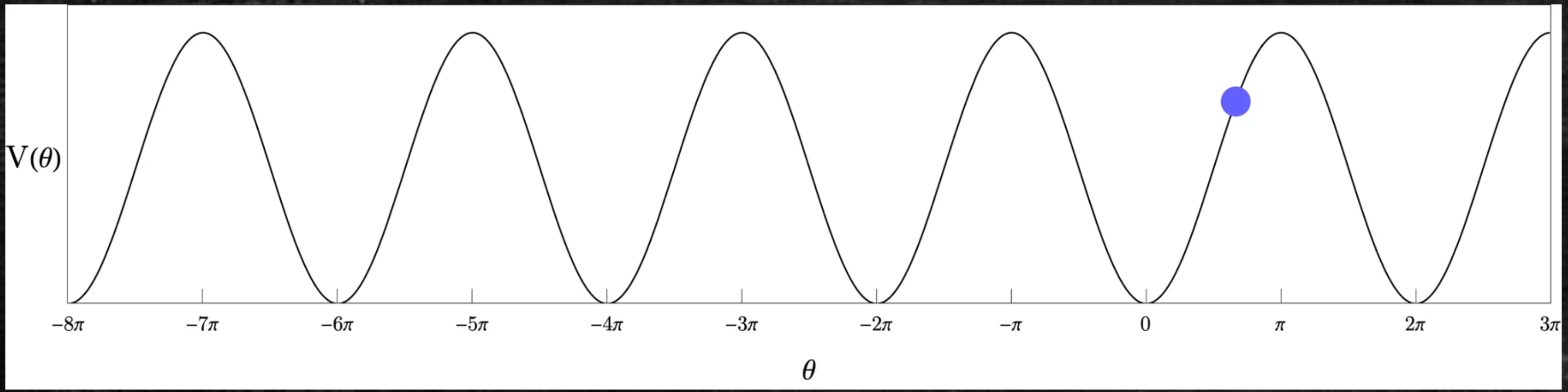


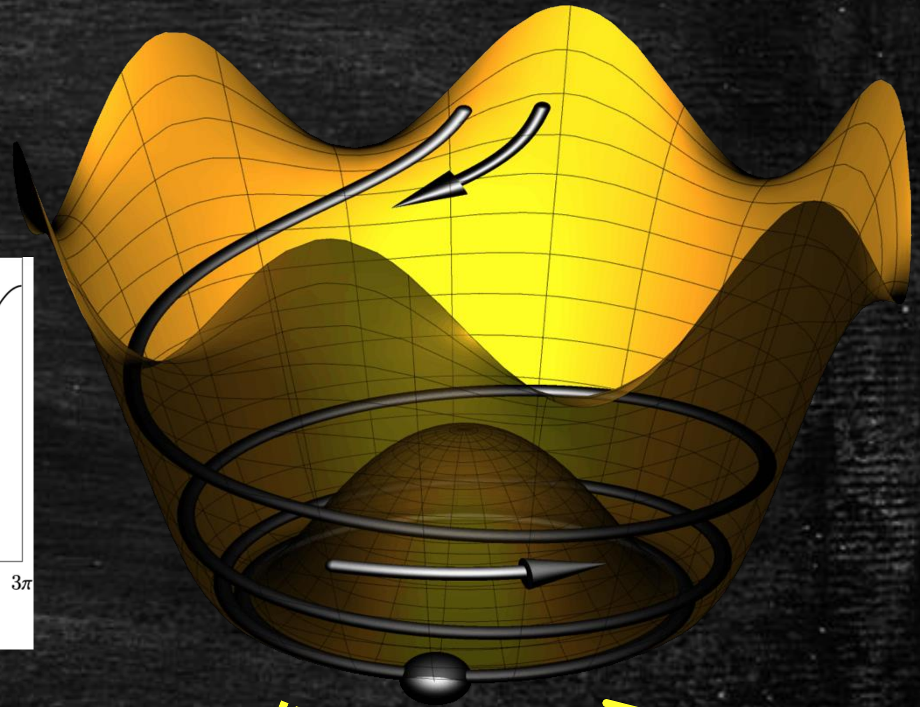
PRL 124, 251802 (2020) RC, L. Hall, K. Harigaya

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

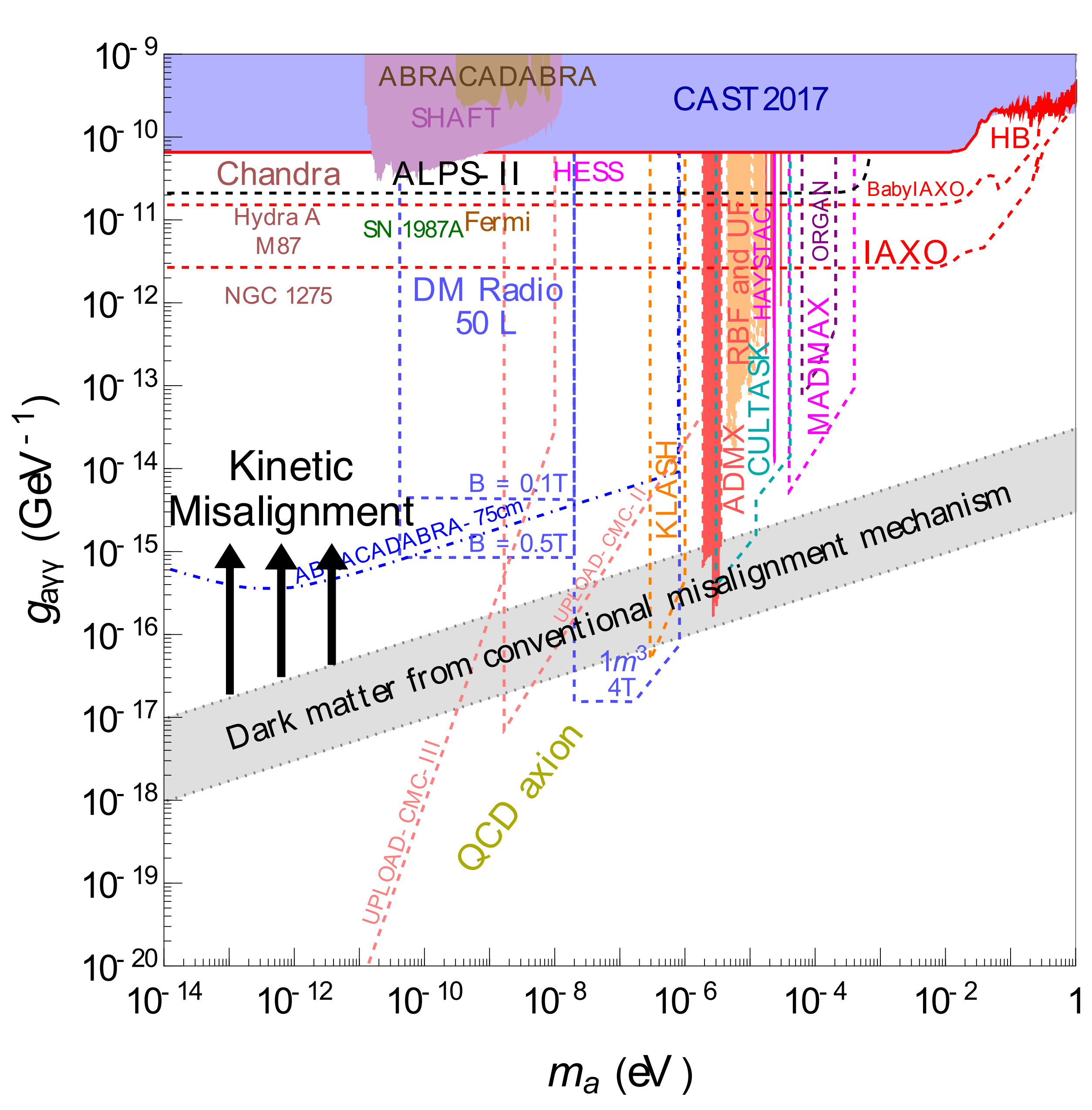
kinetic energy > potential energy

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

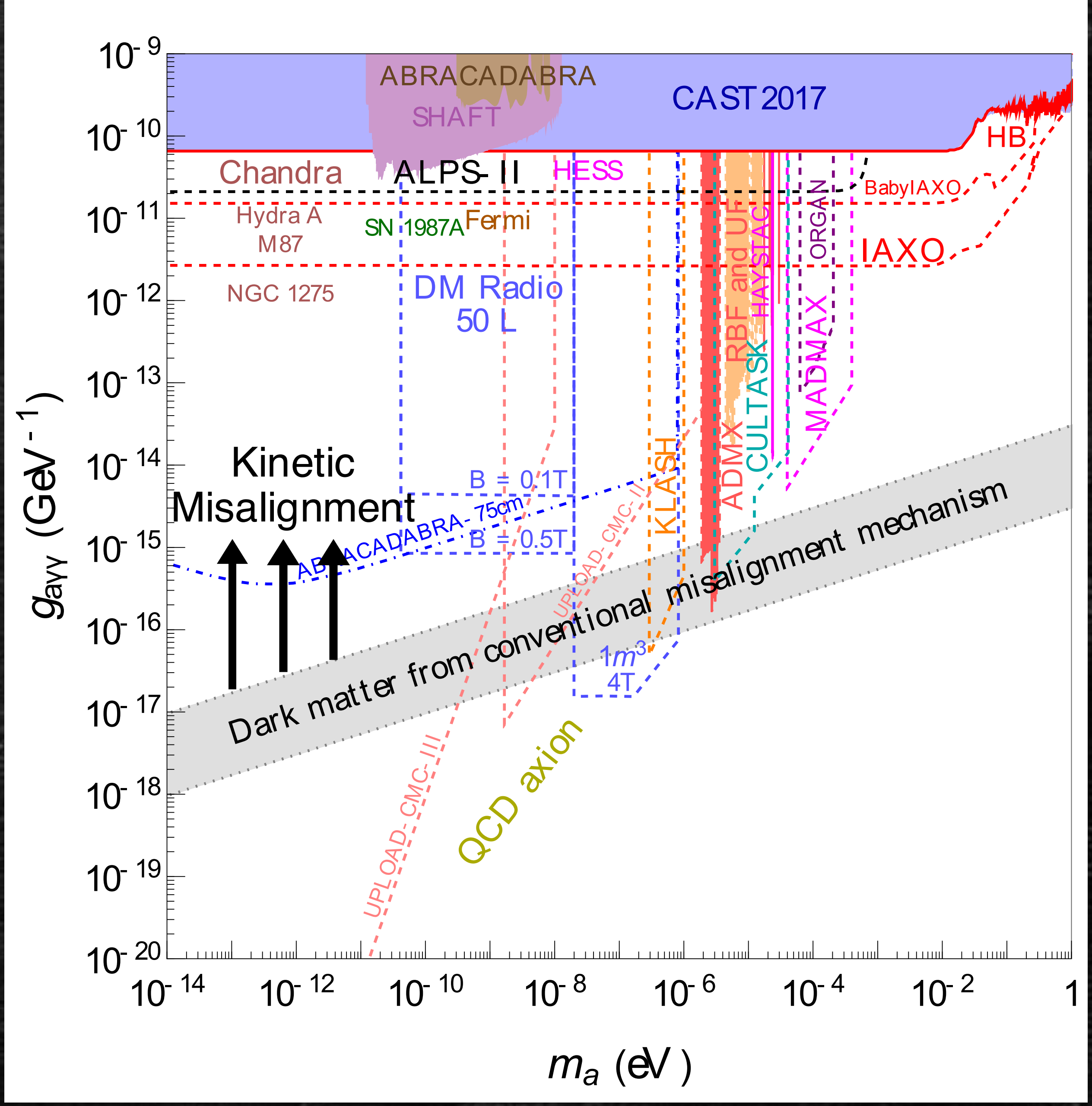
Observed dark matter abundance

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

(*Planck* 2018)

Thus, dark matter relates

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

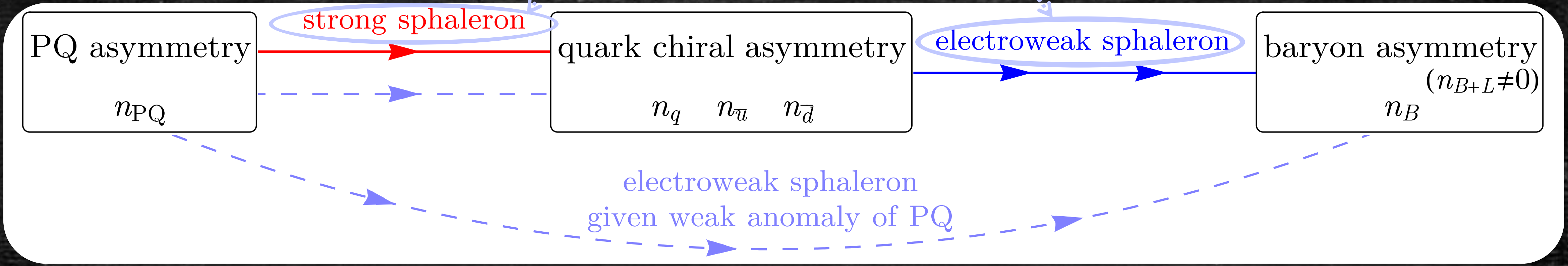


Baryon Asymmetry

Axiogenesis

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

matter-antimatter asymmetry



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

produced by axion rotations

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

experimentally measured value
(*Planck* 2018)

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

Axiogenesis

Baryogenesis is automatic, thanks to Standard Model processes
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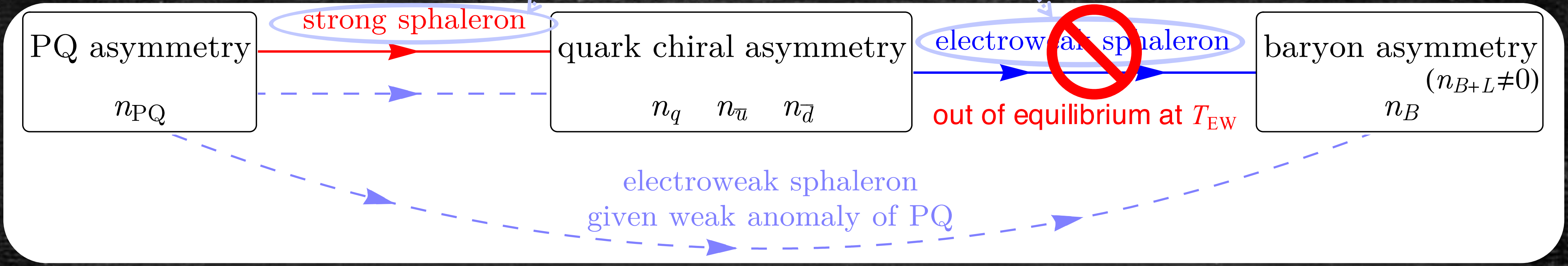
matter-antimatter asymmetry



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

experimentally measured value
(*Planck* 2018)

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

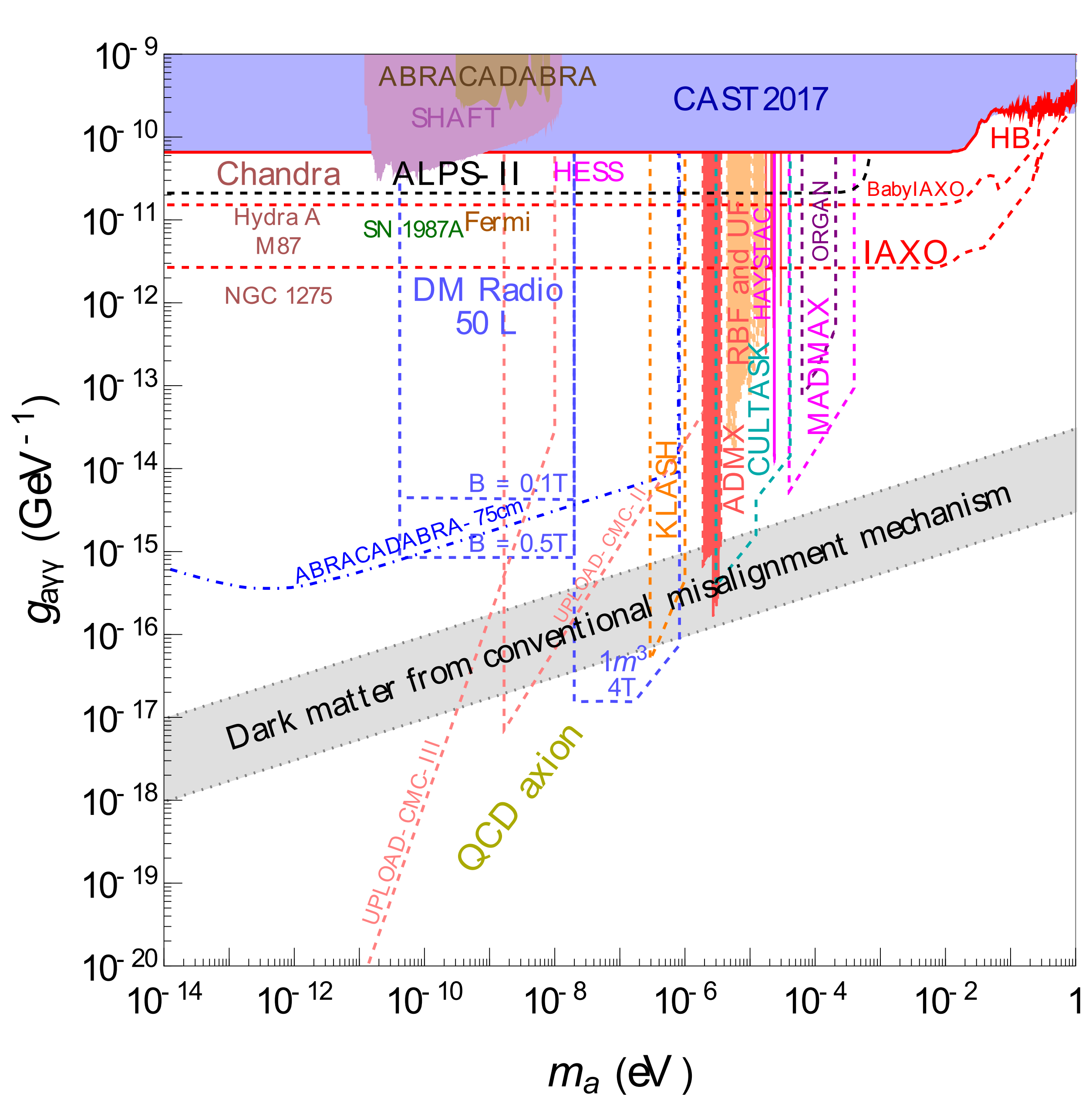
PRL 124, 111602 (2020) RC and K. Harigaya

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:

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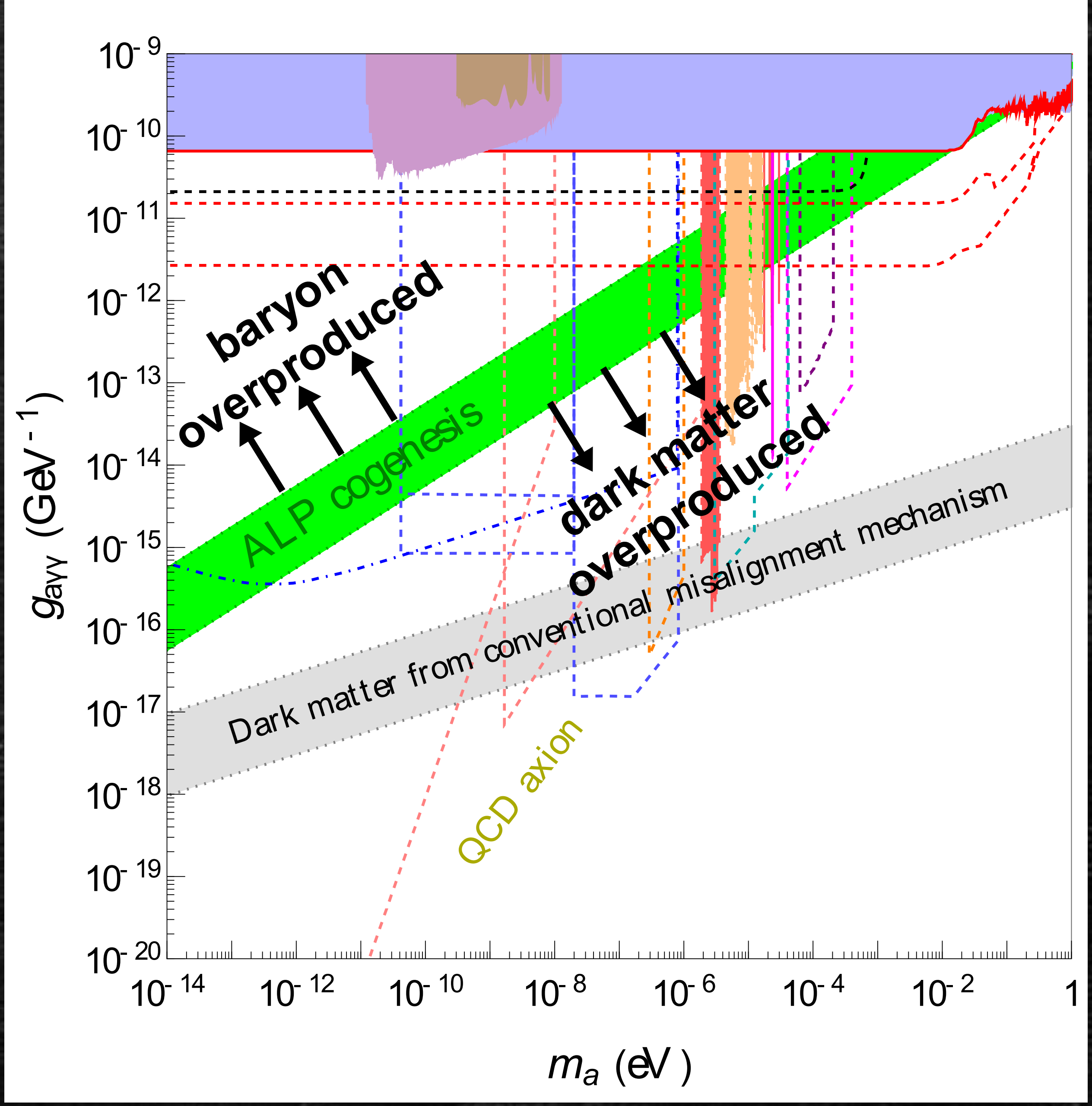
ALP cogenesis :

ALP = axion-like particle
(no gluon coupling)

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

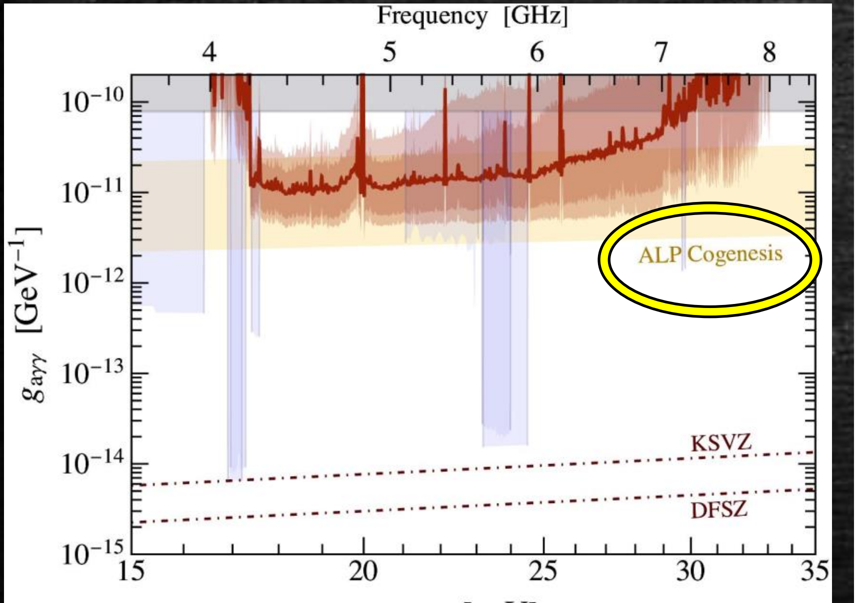
We assume $T_{\text{EW}} = 130$ GeV.



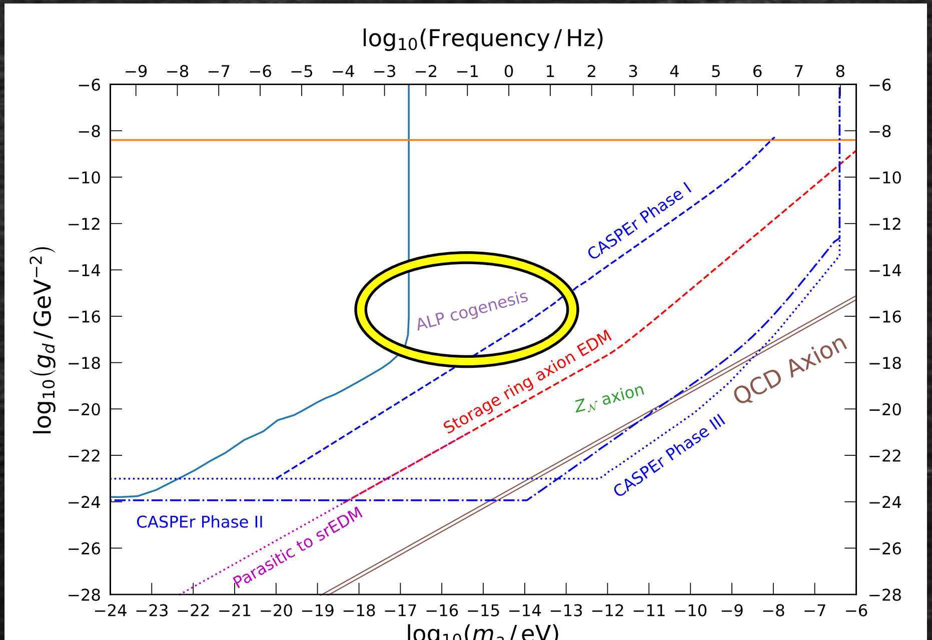
JHEP 01 (2021) 172 RC, L. Hall, K. Harigaya

ALP Cogenesis

Experimental probes are happening!



PRL 129, 251102 (2022)



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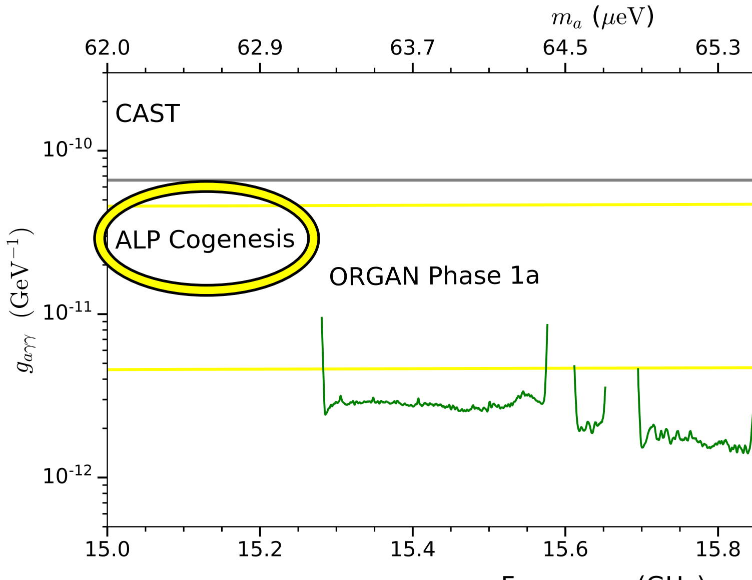
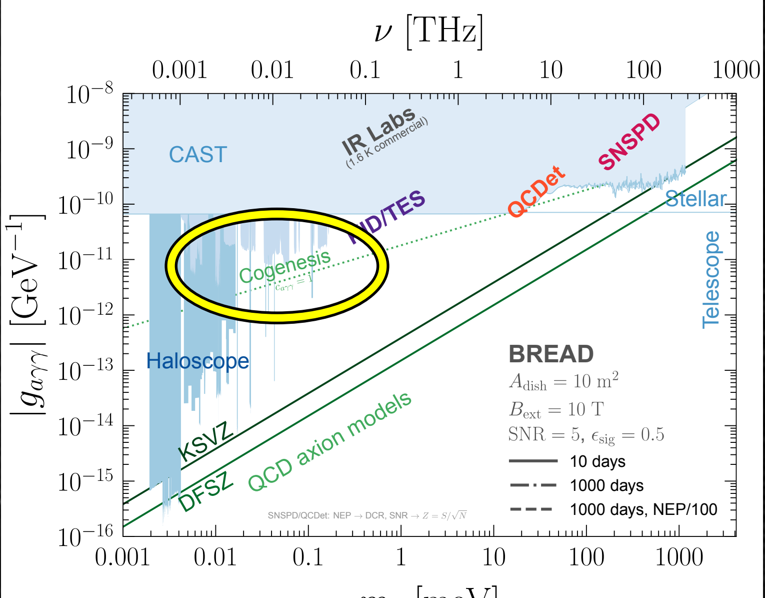
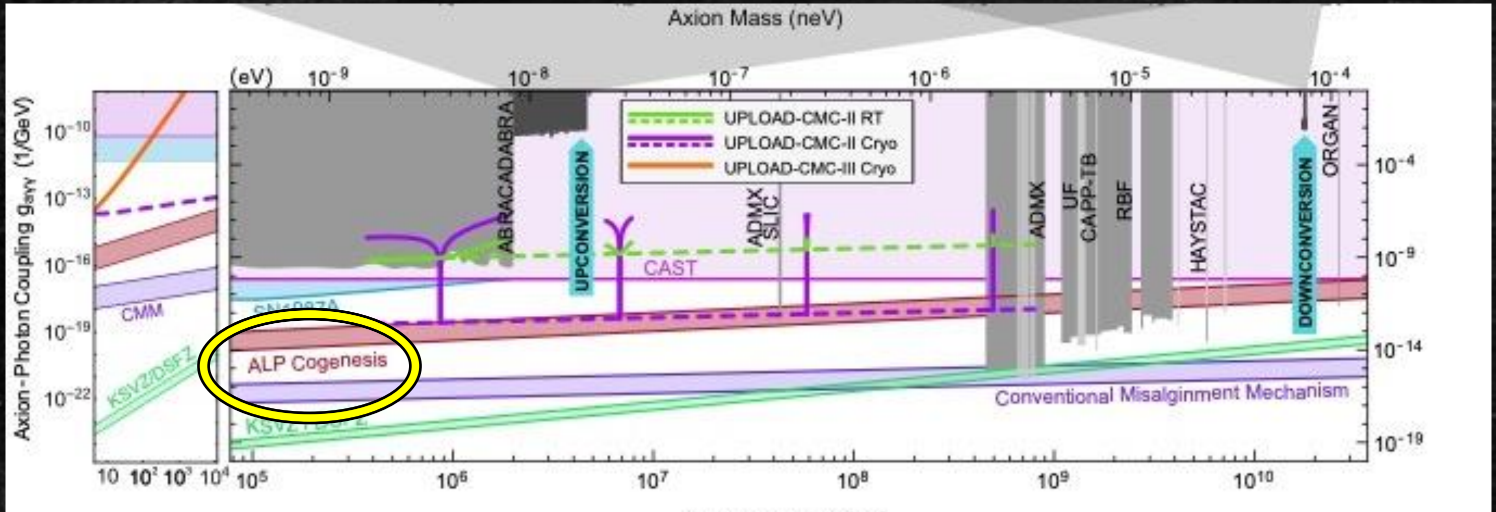


Sci.Adv. 8 (2022) 27, abq3765



PRL 128 (2022) 13, 131801



PRL 126 (2021) 8, 081803

Kinetic Misalignment + Axiogenesis

Prediction:

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ALP cogenesis :

ALP = axion-like particle (no gluon coupling)

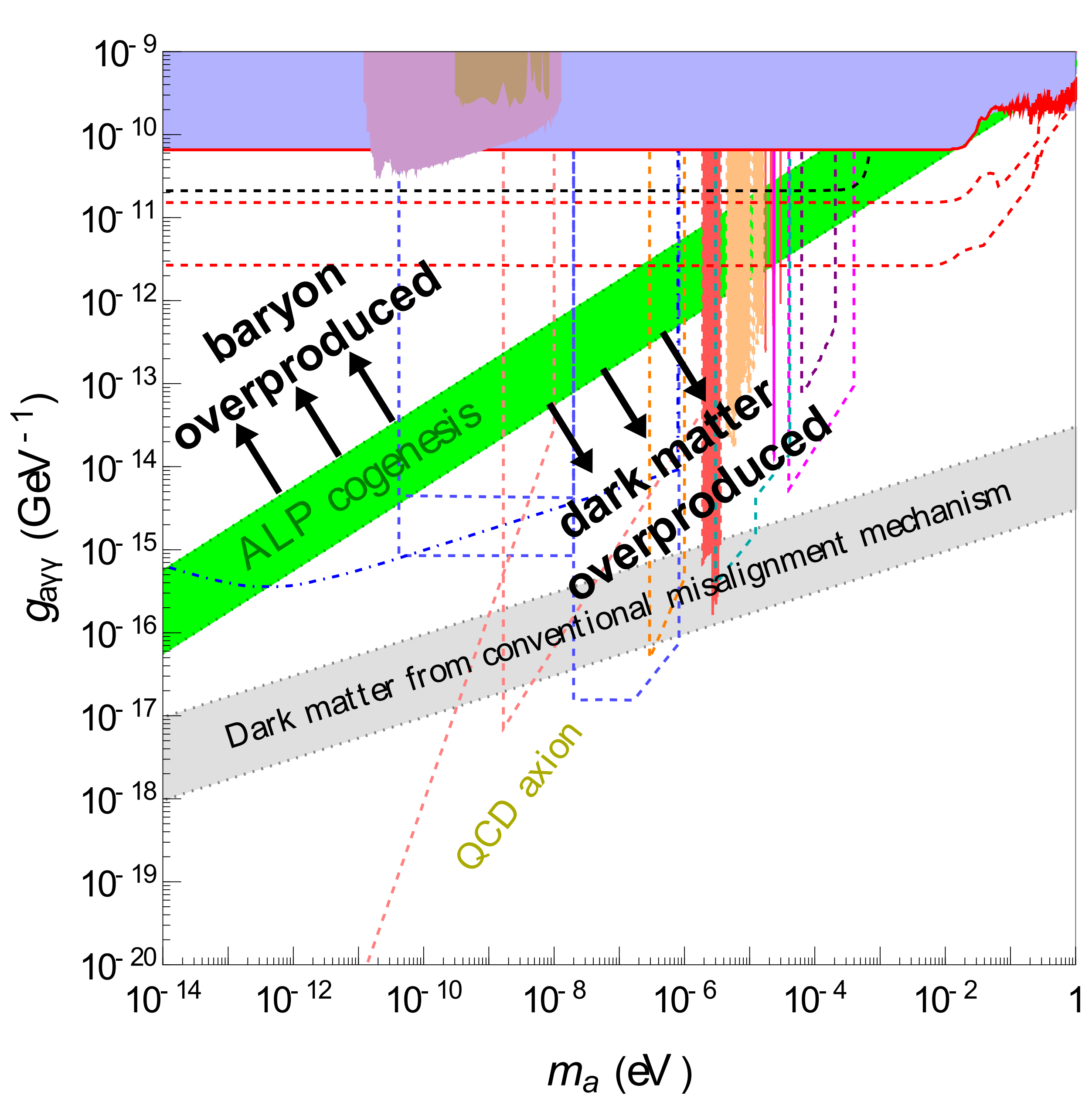
cogenesis = production of both dark matter & matter-antimatter asymmetry

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

QCD axion cogenesis?

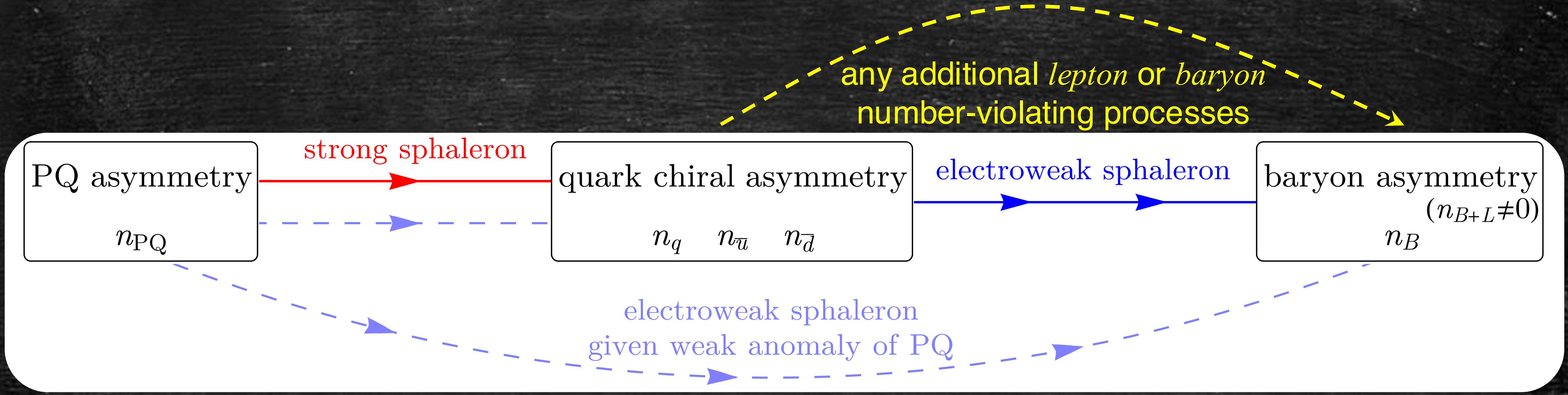
Can the QCD axion be compatible with cogenesis from axion rotations?

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

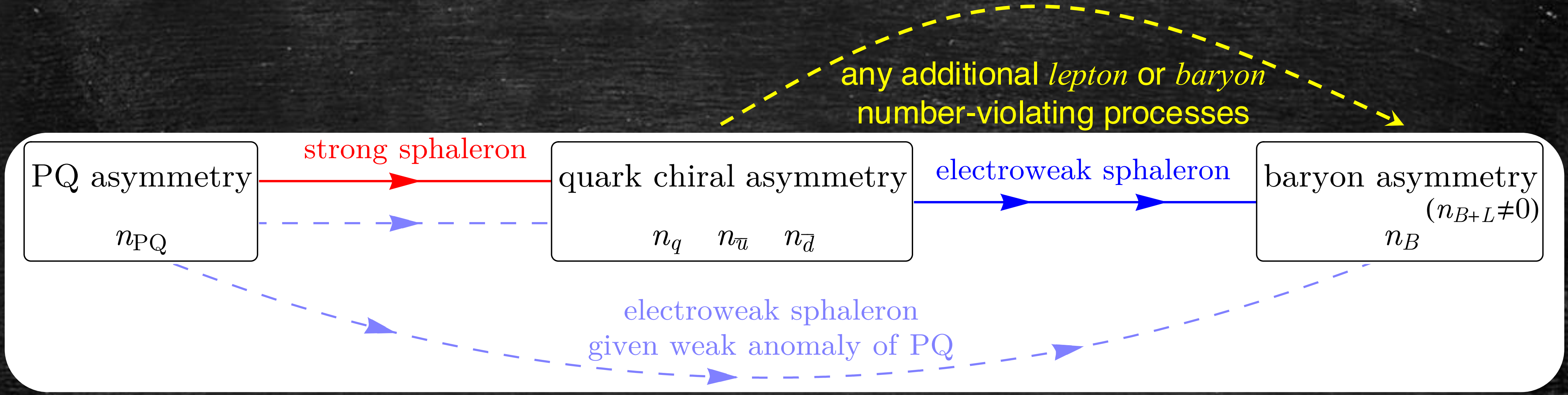


JHEP 01 (2021) 172 RC, L. Hall, K. Harigaya

Extensions of Axiogenesis



Extensions of Axiogenesis



Lepto-Axiogenesis

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

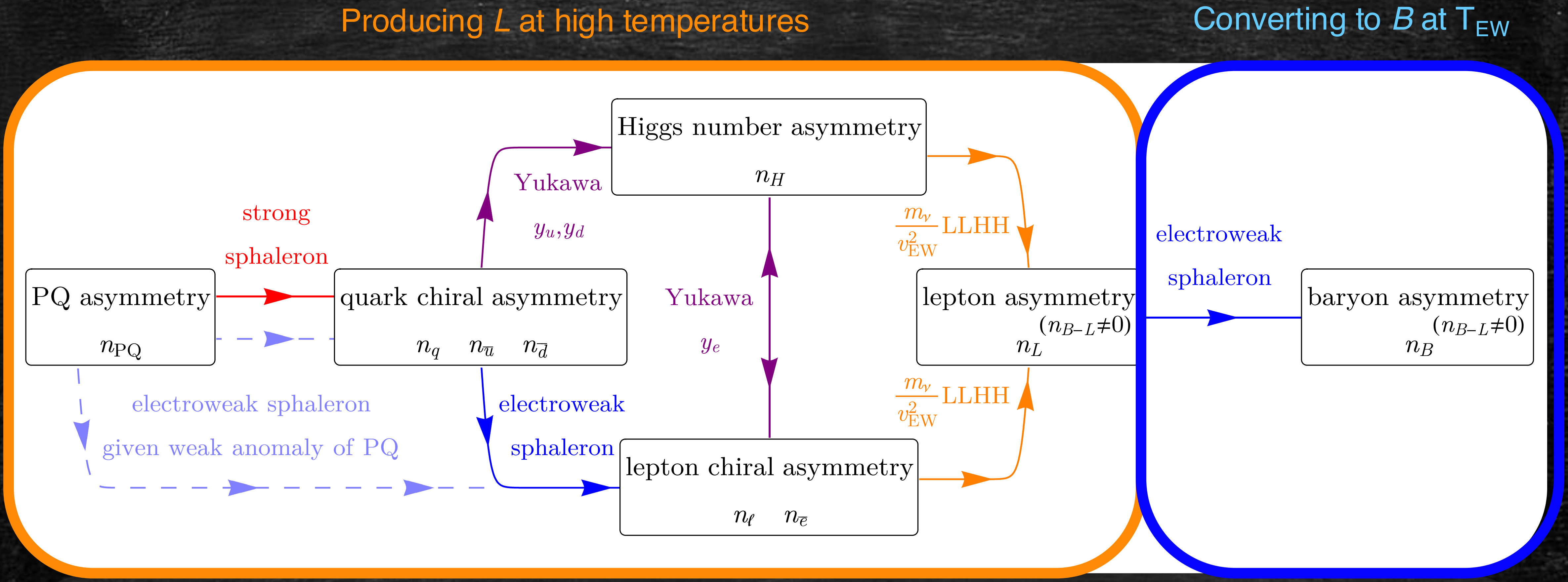
This Weinberg operator gives Majorana neutrino masses, breaks lepton number, and thus affects the charge transfer.

other extensions

- ✓ RC, K. Harigaya 1910.02080
- ✓ K. Harigaya, I. Wang 2107.09679
- ✓ S. Chakraborty, T. Jung, T. Okui 2108.04293
- ✓ J. Kawamura, S. Raby 2109.08605
- ✓ RC, K. Harigaya, Z. Johnson, A. Pierce 2110.05487
- ✓ RC, T. Gherghetta, K. Harigaya 2206.00678
- ✓ P. Barnes, RC, K. Harigaya, A. Pierce 2208.07878
- ✓ RC, V. Domcke, K. Harigaya 2211.12517
- ✓ P. Barnes, RC, K. Harigaya, A. Pierce 2402.10263
- ✓ RC, N. Fernandez, A. Ghalsasi, K. Harigaya, J. Shelton 2405.12268

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

Lepto-Axiogenesis



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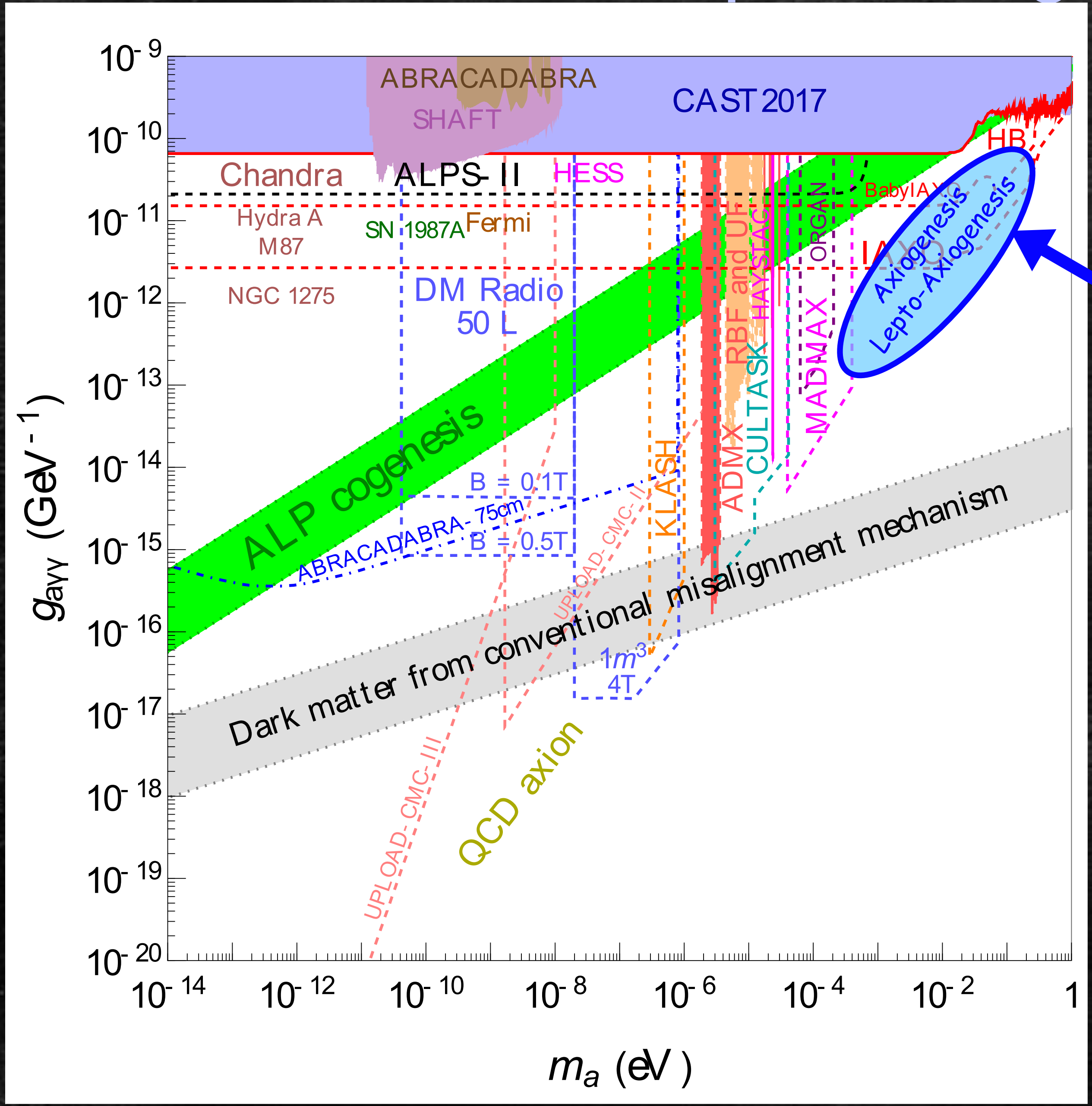
Lepto-Axiogenesis



Lepto-Axiogenesis achievement:

simultaneous production of
- dark matter
- matter-antimatter asymmetry

in the framework with
- QCD axion
- Majorana neutrinos

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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

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

Gravitational Waves

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

Cosmology

- ✓ **RC** *et al.* 2202.01785
- ✓ **RC** *et al.* 2405.12268

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
- ✓ New model building opportunities
  - ✓ other open questions across disciplines