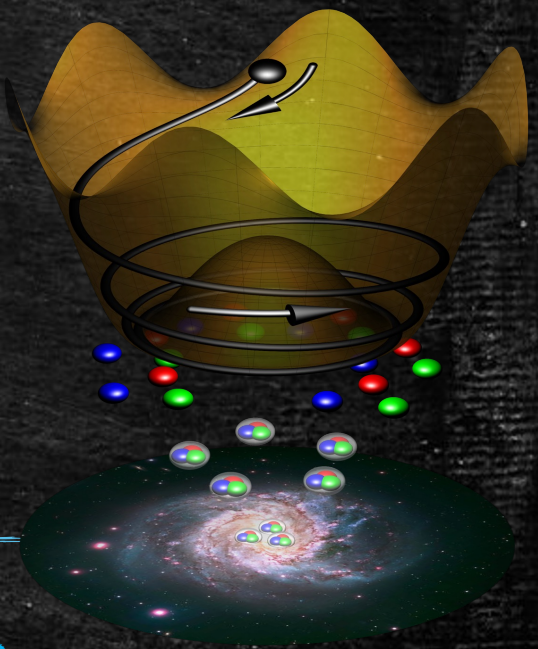
Novel Cosmological Roles and Experimental Searches of (QCD) Axions

Raymond Co

William I. Fine Theoretical Physics Institute
University of Minnesota

Fine Theoretical Physics Institute



Particle Avenues in the Dark Universe Arena (PADUA): Axions
September 13th 2022

Based on:

1910.02080	RC, Keisuke Harigaya	Phys. Rev. Lett. 124, 111602 (2020)
1910.14152	RC, Lawrence Hall, Keisuke Harigaya	Phys. Rev. Lett. 124, 251802 (2020)
2206.00678	RC, Tony Gherghetta, Keisuke Harigaya	JHEP accepted
2207.08448	RC et al. and ArgoNeuT collaboration	
2208.07878	Patrick Barnes, RC, Keisuke Harigaya, Aaron Pierce	
Soon.IHope	RC, Soubhik Kumar, Zhen Liu	

Today

Enrico Fermi Prize 2009

for the discovery of fundamental phenomenological properties of grand unification and superstring theories

Dimitri Nanopoulos

born on

September 13th 1948

https://en.sif.it/activities/fermi_award

Early Universe Dynamics

- **Axion**

(0) **Misalignment mechanism**
Preskill, Wise, Wilczek 1983, Abbott, Sikivie 1983, Dine, Fischler 1983

(1) **Parametric resonance**
RC, L. Hall, K. Harigaya 2017 K. Harigaya, J. Leedom 2019

(2) **- Kinetic misalignment mechanism**
RC, L. Hall, K. Harigaya 2019 + K. Olive, S. Verner 2020

- Axiogenesis
RC, K. Harigaya 2019

- ALP cogenesis
RC, L. Hall, K. Harigaya 2020

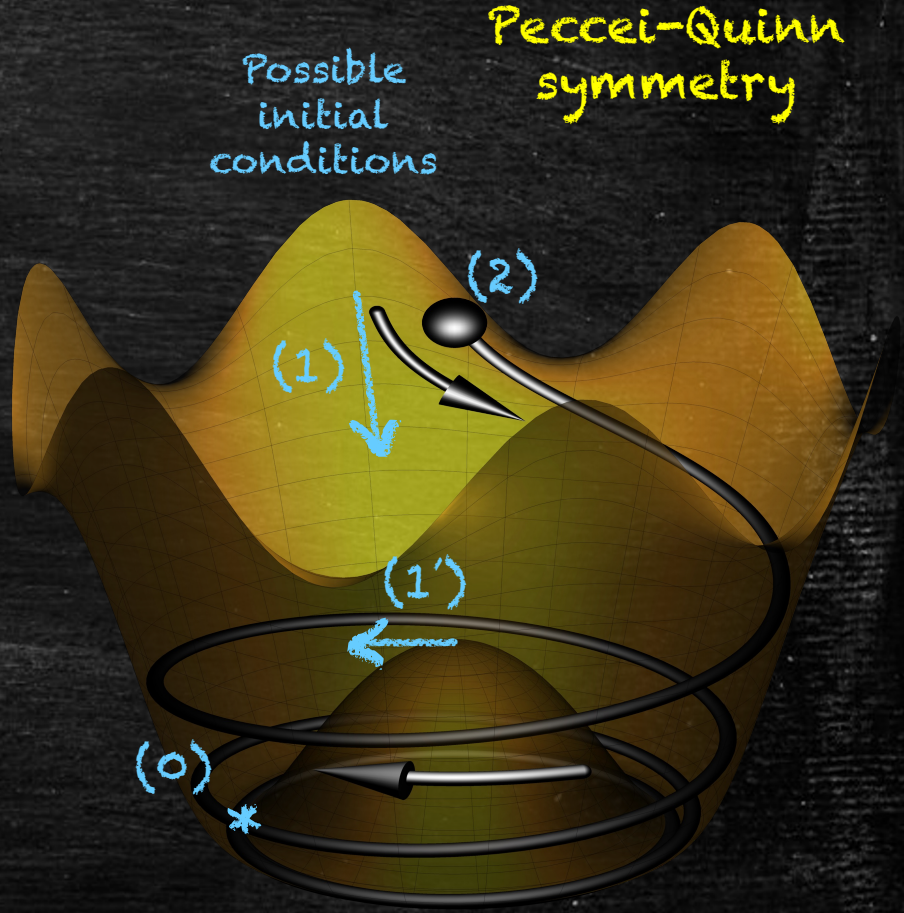
- Lepto-Axiogenesis
RC, N. Fernandez, A. Ghalsasi, L. Hall, K. Harigaya 2020

- Tachyonic instability
RC, K. Harigaya, A. Pierce 2020

} Dark Matter

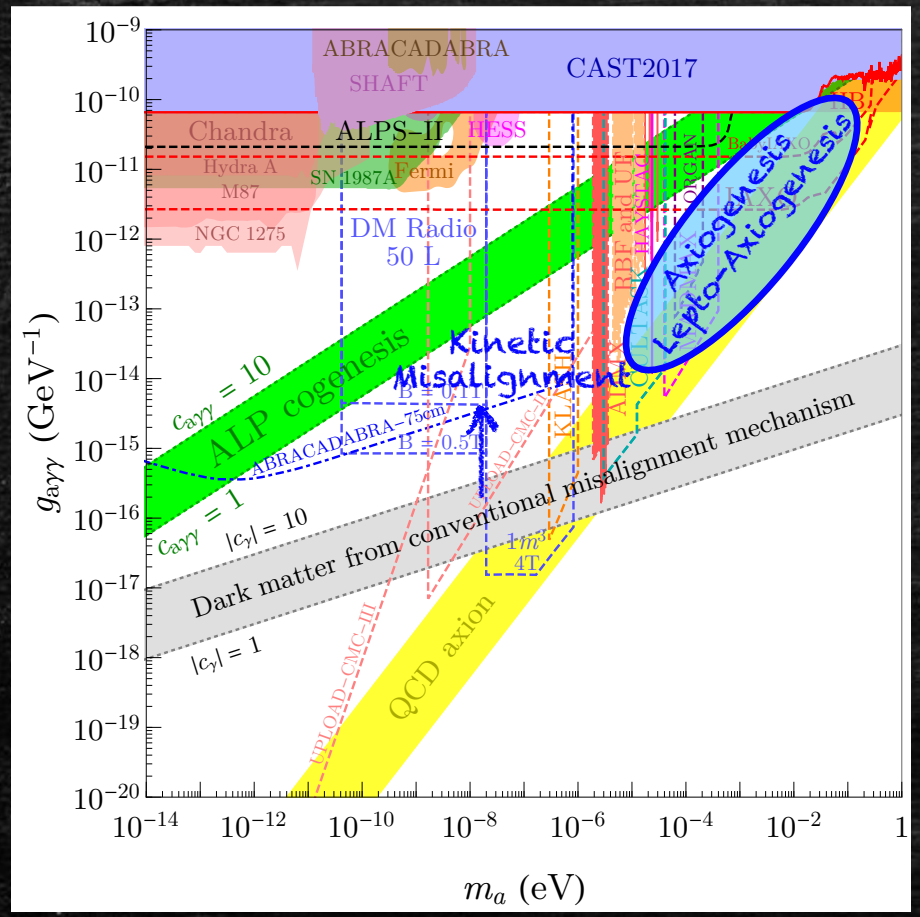
} Baryon Asymmetry

} Gravitational Waves



Predictions

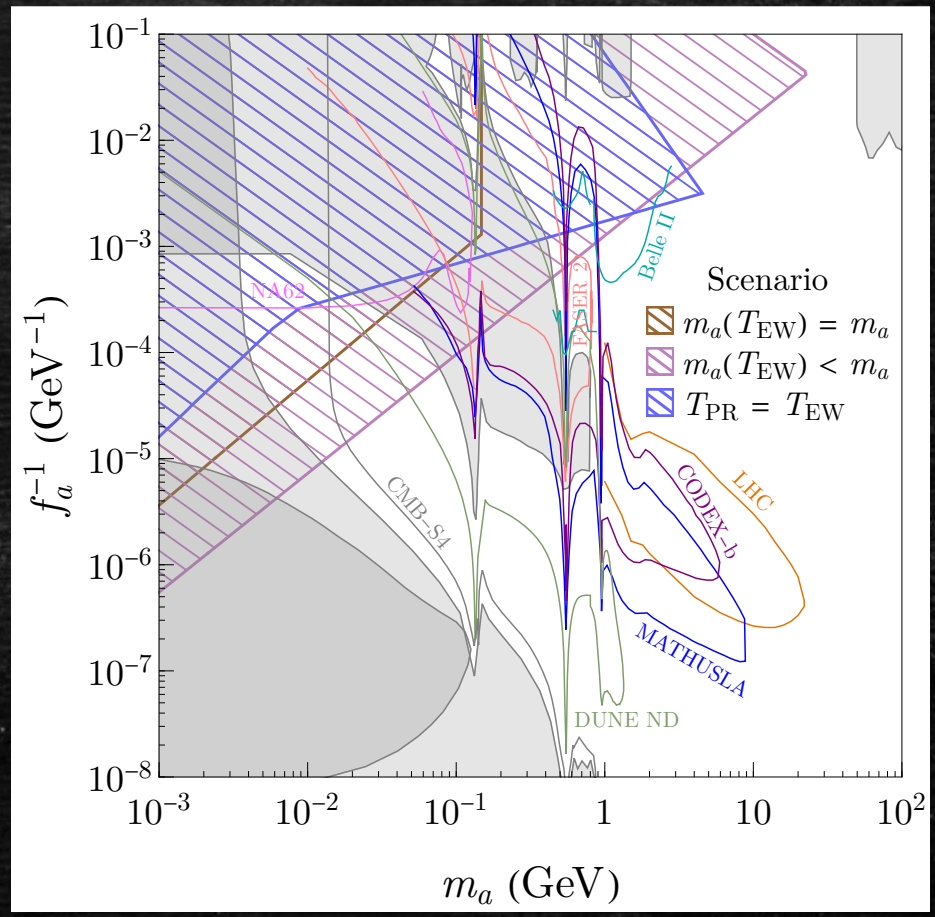
ultralight axions



R. Co Minnesota

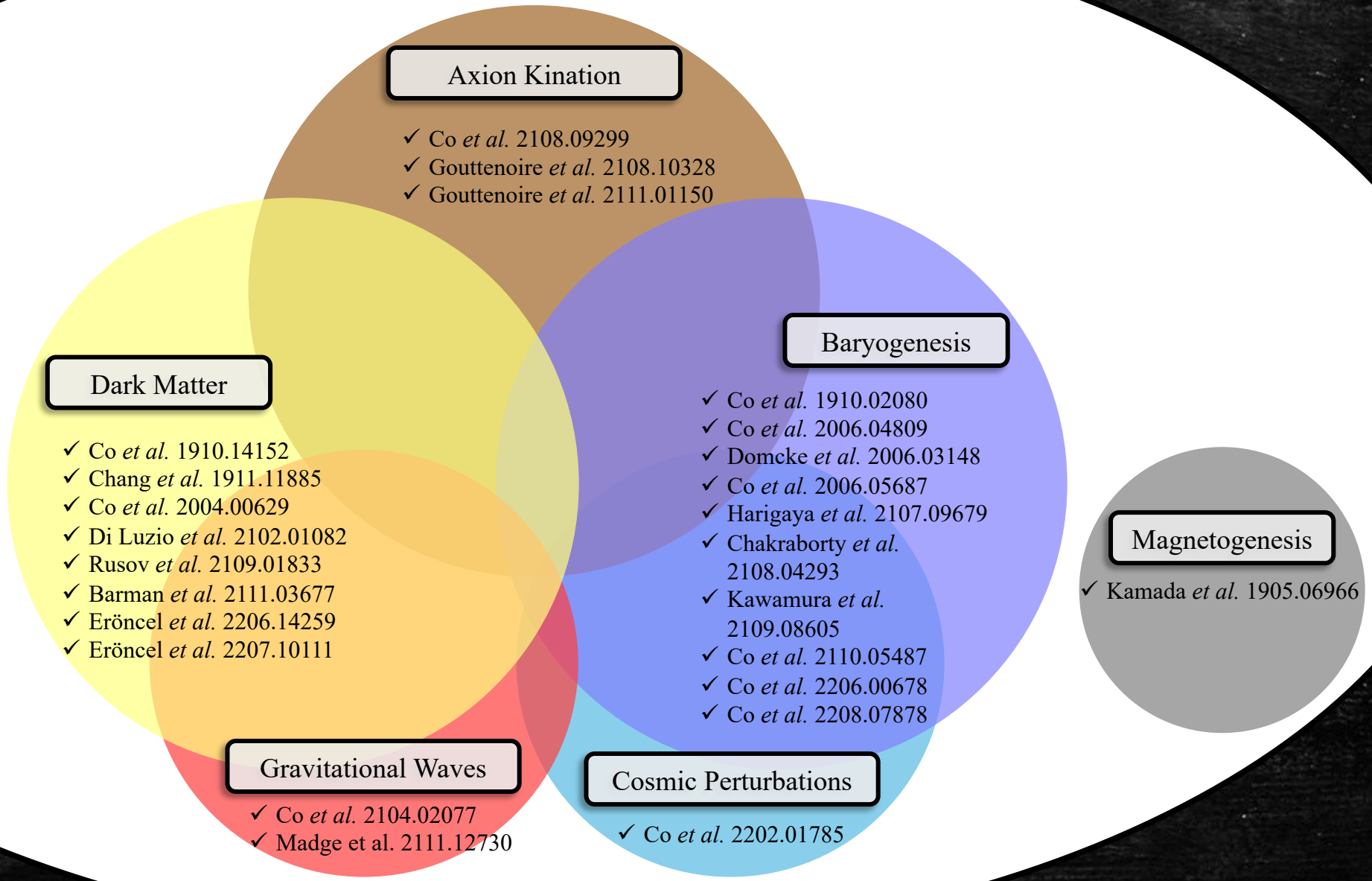
2006.04809 RC, L. Hall, K. Harigaya

heavy axions



2206.00678 RC, T. Gherghetta, K. Harigaya

Axion Rotations



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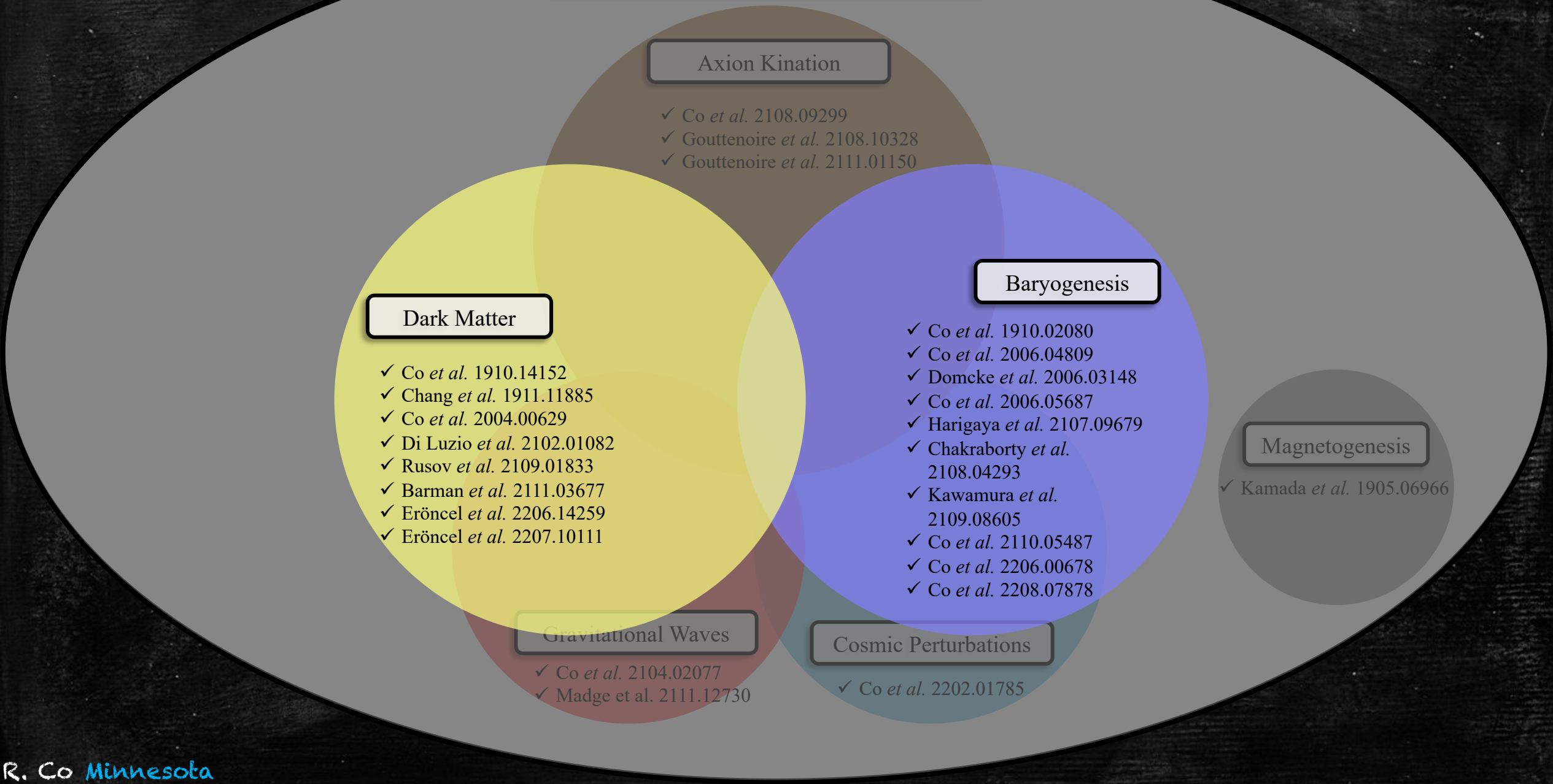
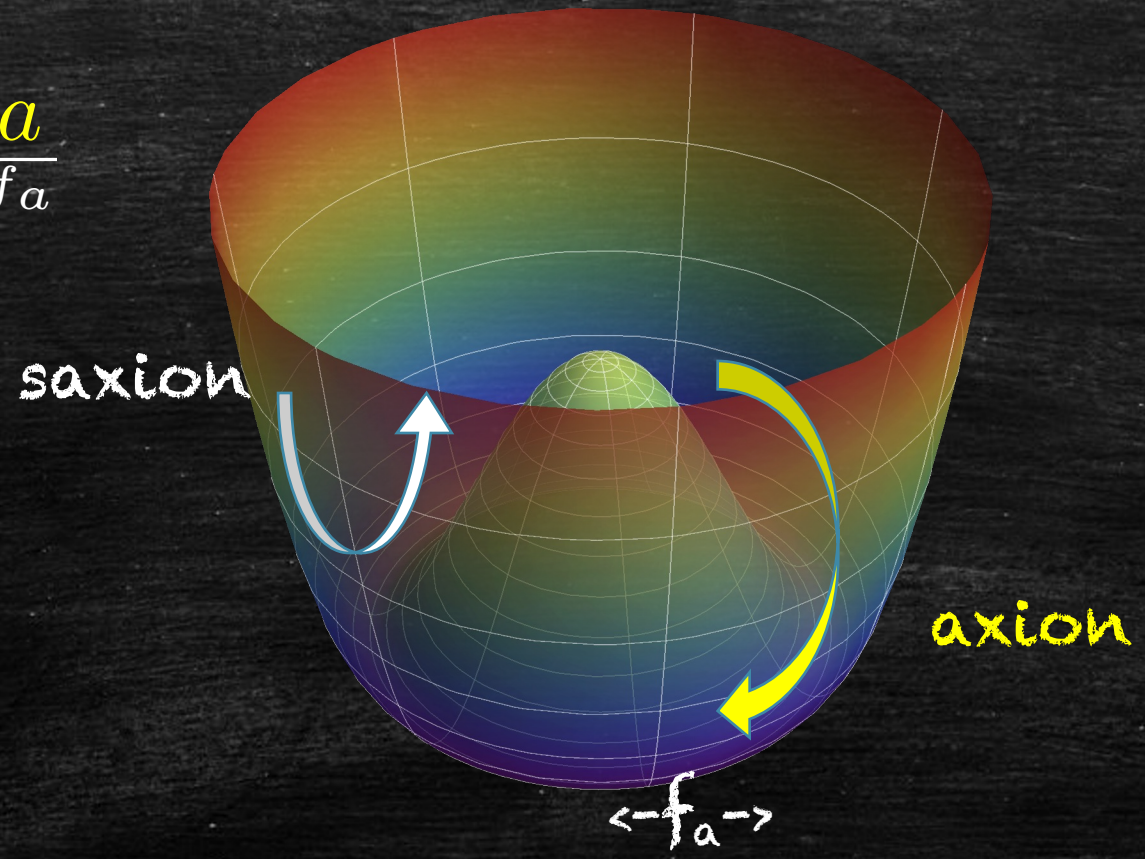


R. Co Minnesota

Axions

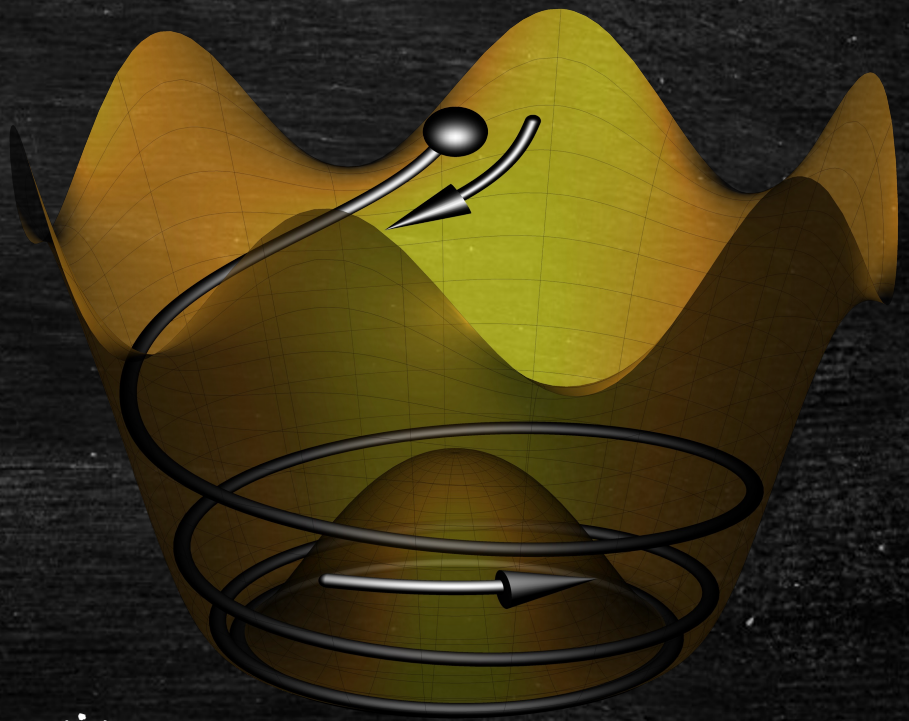
$$P = \frac{S + f_a}{\sqrt{2}} e^{i \frac{a}{f_a}}$$



Why Rotation?

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

Initial condition



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?

Angular motion : Explicit PQ breaking

$$V(P) \sim \frac{P^n}{M^{n-4}} + \text{h.c.}$$

expected from quantum gravity
or PQ as an accidental symmetry

S. Giddings et al. 1988, S. Coleman 1988, G. Gilbert 1988, D. Harlow et al. 2019
R. Holman 1992, S. Barr 1992, M. Kamiokowski 1992, M. Dine 1992

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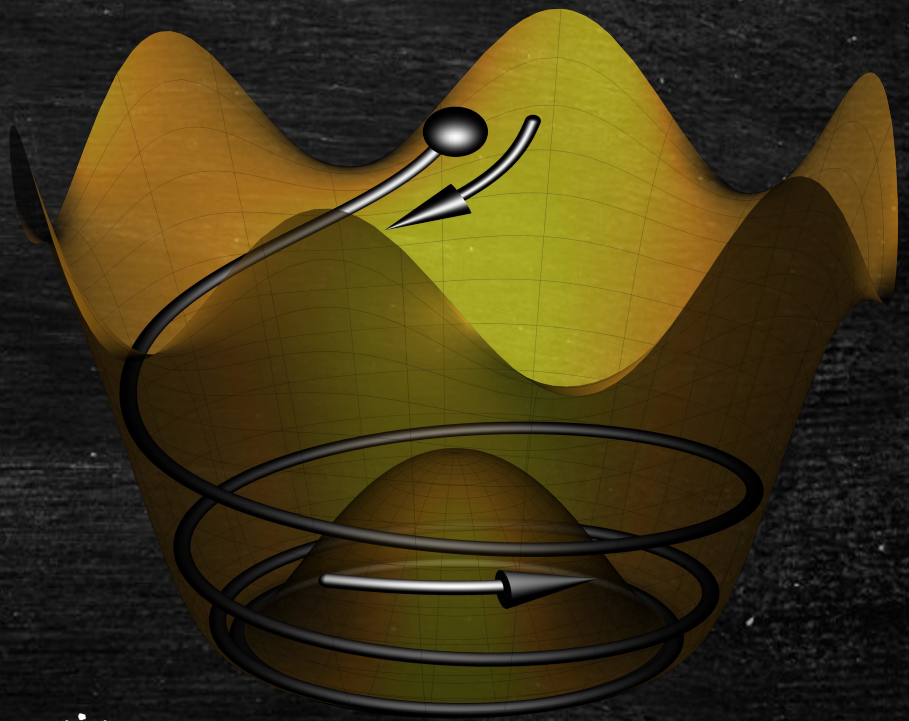

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R. Holman 1992, S. Barr 1992, M. Kamiokowski 1992, M. Dine 1992

Large field value : **Flat potential**

For example, as an initial condition or
set dynamically by the Hubble-induced mass

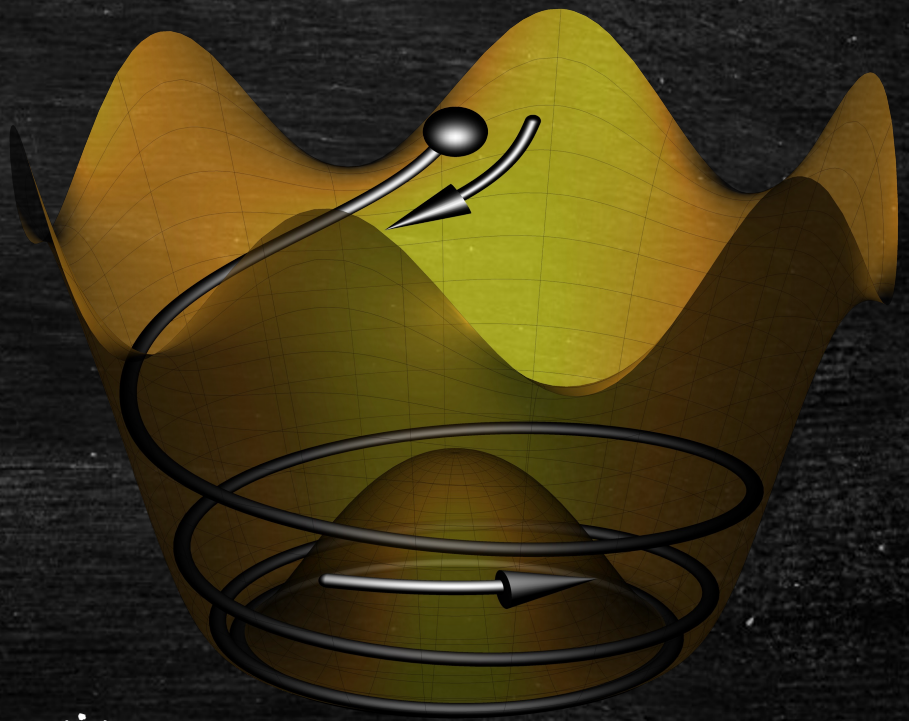
$$V(|P|) \sim -H_I^2 |P|^2 + \frac{|P|^{2d}}{M^{2d-4}}$$

Dynamics analogous to that in Affleck-Dine baryogenesis

I. Affleck and M. Dine 1991

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

Initial condition



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

Asymmetry of PQ Charge

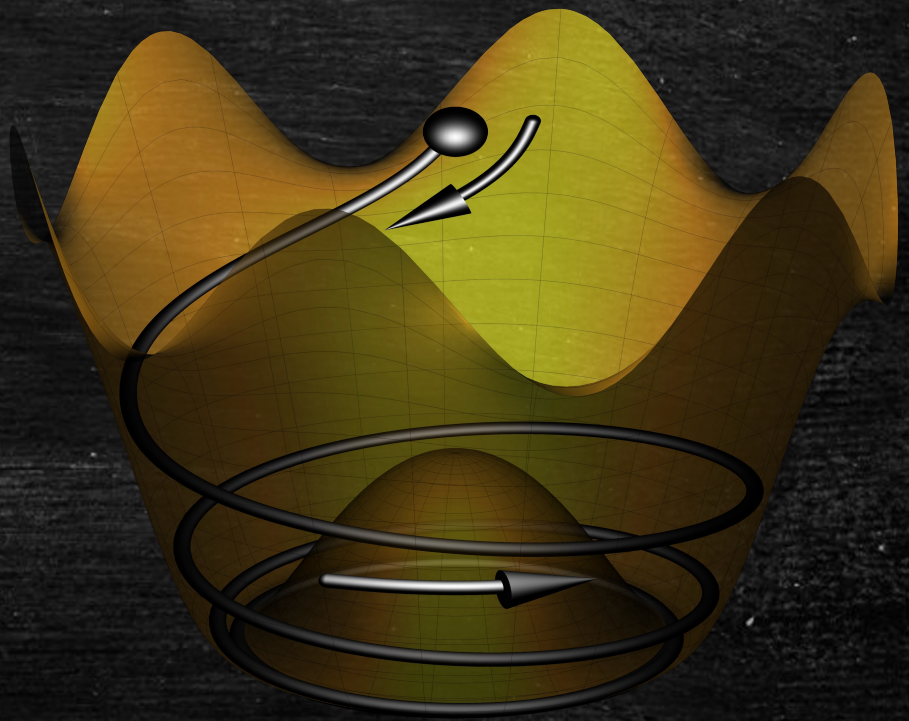
$$P = \frac{S + f_a}{\sqrt{2}} e^{i\frac{a}{f_a}}$$

Noether charge associated with the shift symmetry

$$n_{\rm PQ} = iP\dot{P}^* - iP^*\dot{P}$$

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

PQ asymmetry
PQ charge density = Rotation of PQ field



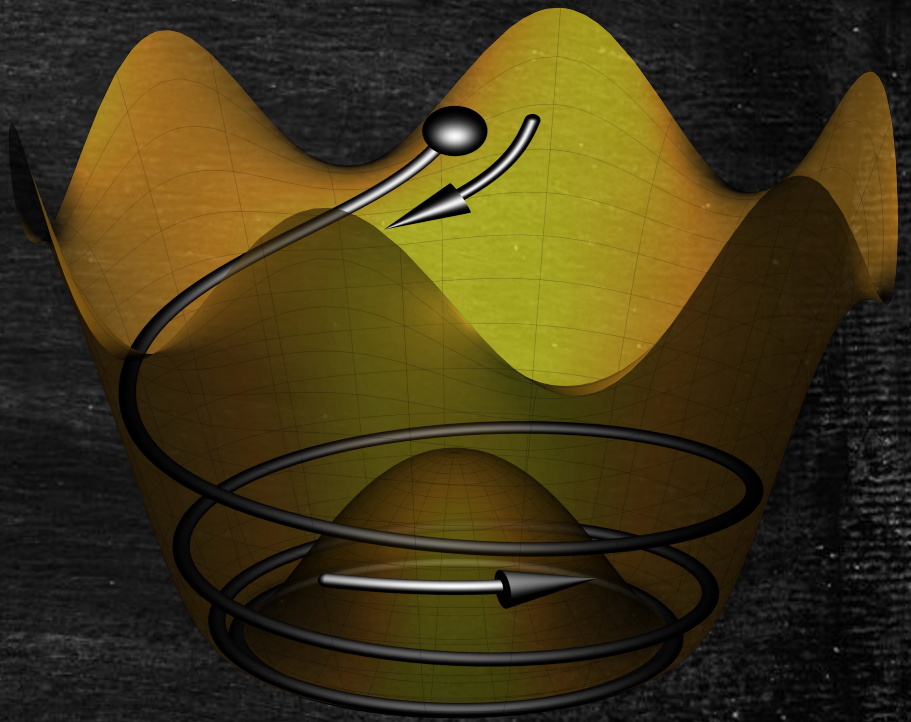
PQ charge is conserved soon after the onset.

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

PQ Charge Evolution

Reason:

$$n_{\rm PQ} = S^2\dot{\theta} \qquad n_{\rm PQ}R^3 = \text{conserved charge}$$



At the minimum:

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

Large field ($S \gg f_a$):

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

kination!

- quartic: $S^2 \propto R^{-2}$, $\dot{\theta} \propto R^{-1}$, $\rho_{\rm PQ} \propto R^{-4}$
- quadratic: $S^2 \propto R^{-3}$, $\dot{\theta} = \text{constant}$, $\rho_{\rm PQ} \propto R^{-3}$ ← necessary to achieve kination domination

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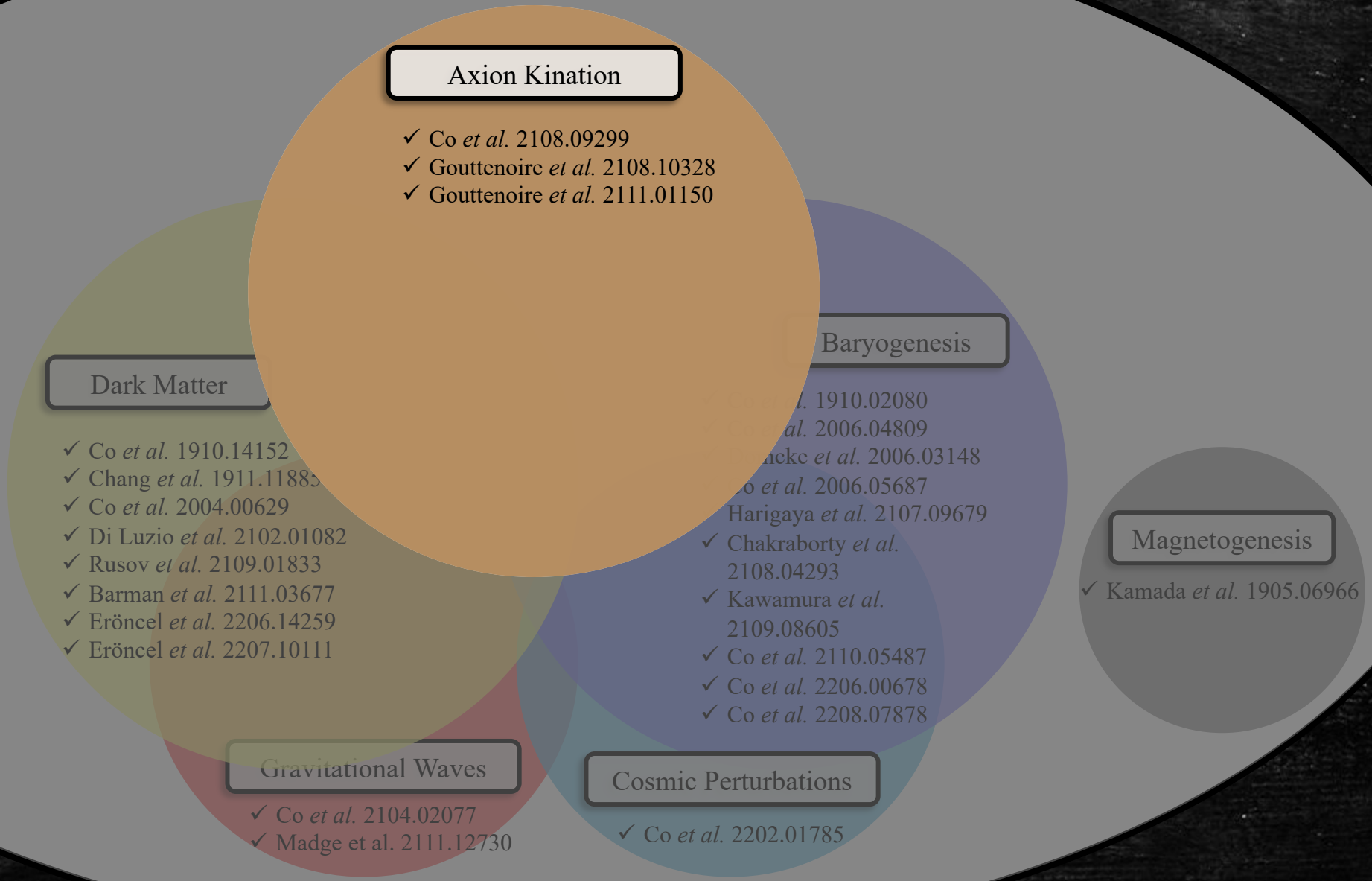
Axion Rotations



What is kination?

9306008 Boris Spokoiny
9606223 Michael Joyce

"domination by the energy in a kinetic mode of a scalar field which scales as $1/R^6$. "

$$\rho_\phi = \frac{1}{2}\left(\dot{\phi}^2 + m_\phi^2\phi^2\right) \simeq \frac{1}{2}\dot{\phi}^2$$

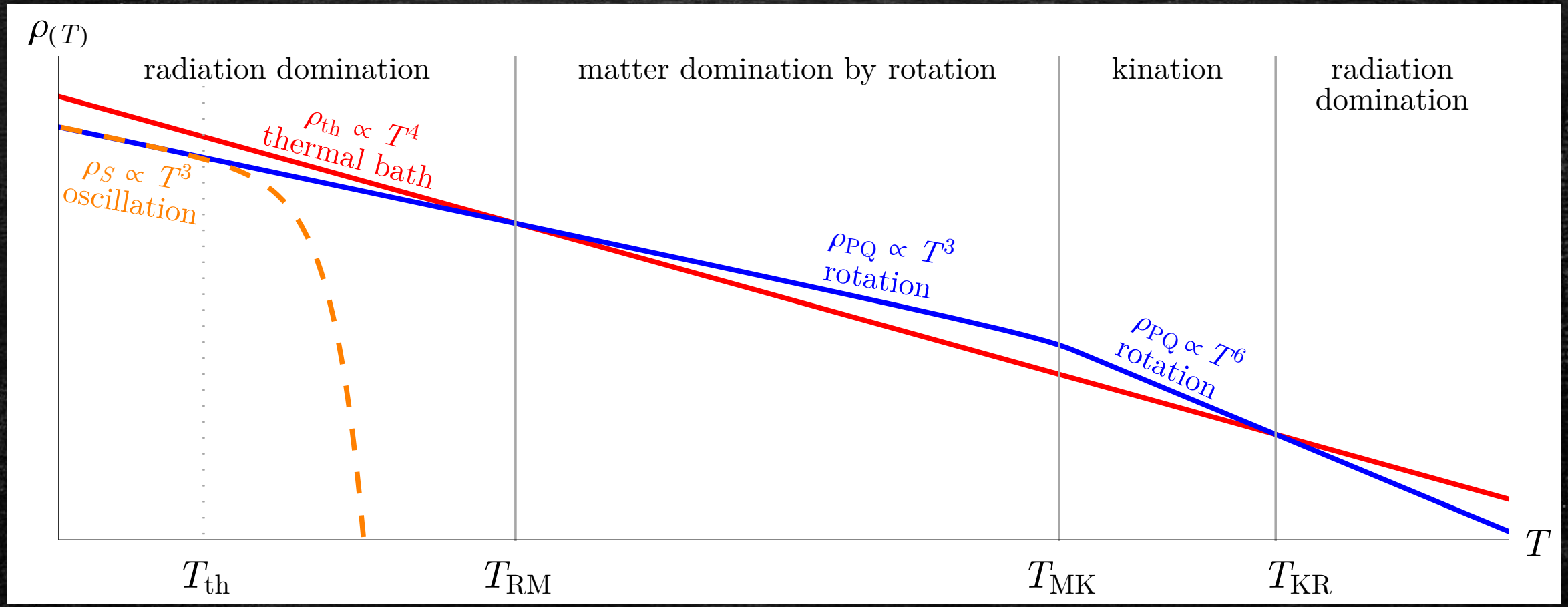
Equation of state

$$w = \frac{p}{\rho} = \frac{K-V}{K+V} \simeq 1$$

Evolution

$$\rho_\phi \propto R^{-3(1+w)} = R^{-6}$$

Evolution of Energy Densities



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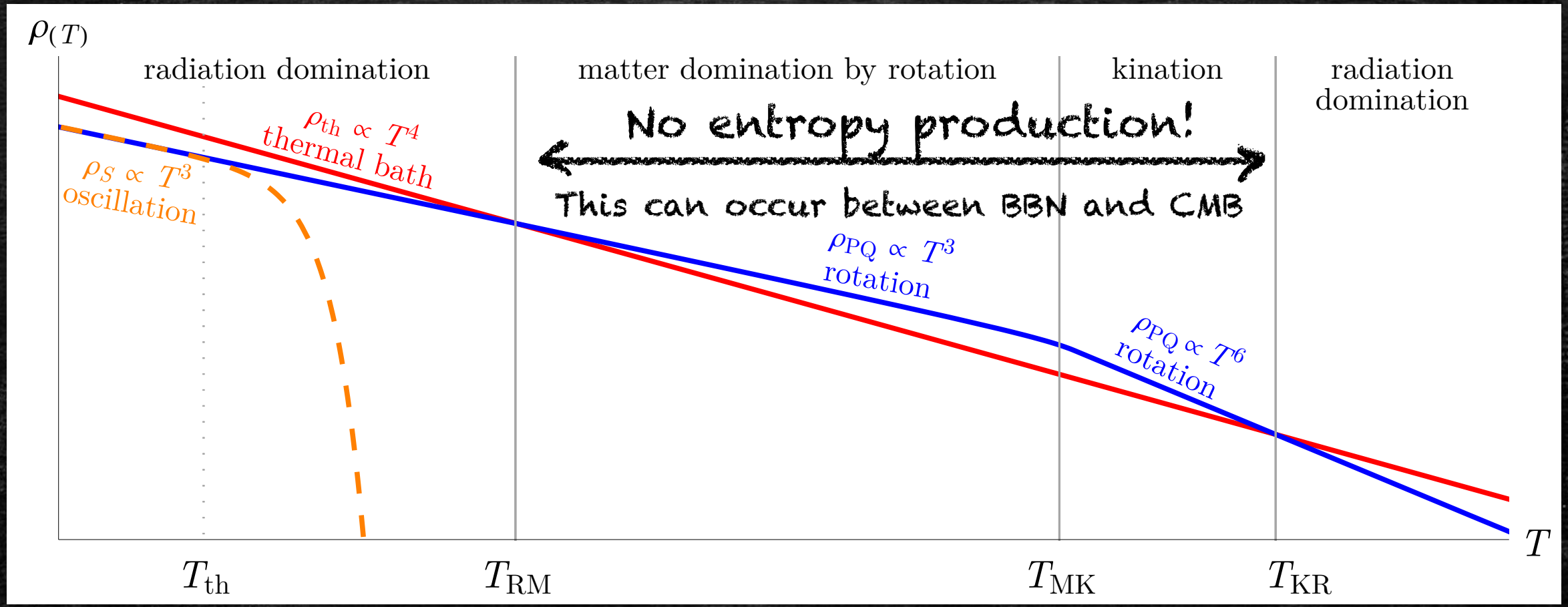
Evolution of Energy Densities



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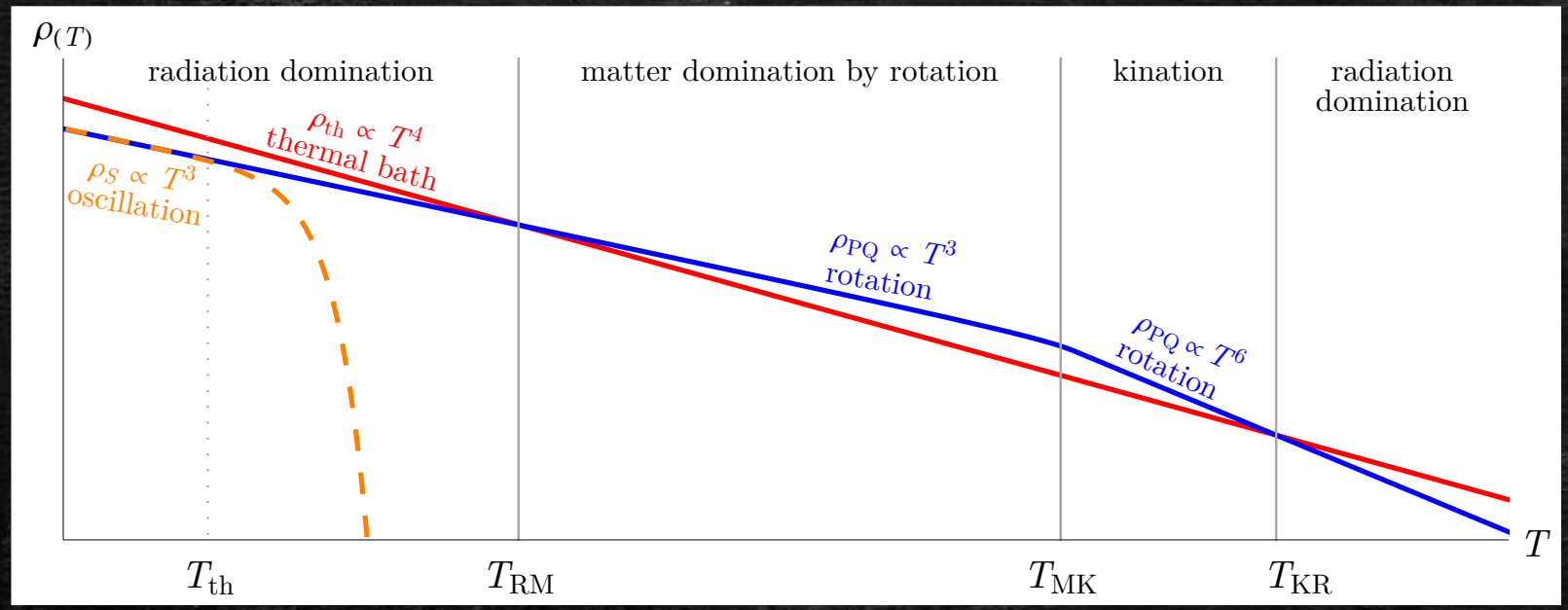
Relevant Temperatures



$$T_{\rm RM} = \frac{4}{3} m_S Y_{\rm PQ}$$

$$T_{\rm MK} = \left(\frac{45}{2\pi^2 g_*} \frac{m_S f_a^2}{Y_{\rm PQ}} \right)^{\frac{1}{3}}$$

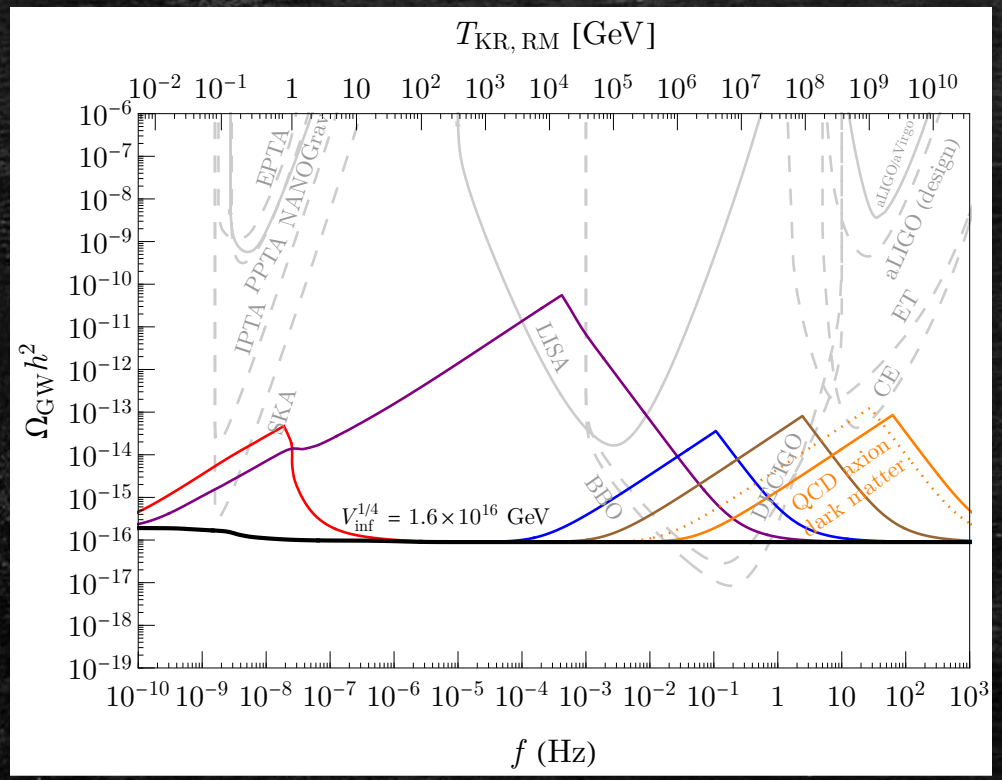
$$T_{\rm KR} = \frac{3\sqrt{15}}{2\sqrt{g_*}\pi} \frac{f_a}{Y_{\rm PQ}}$$

$$T_{\rm MK}^3 = T_{\rm KR}^2 T_{\rm RM}$$

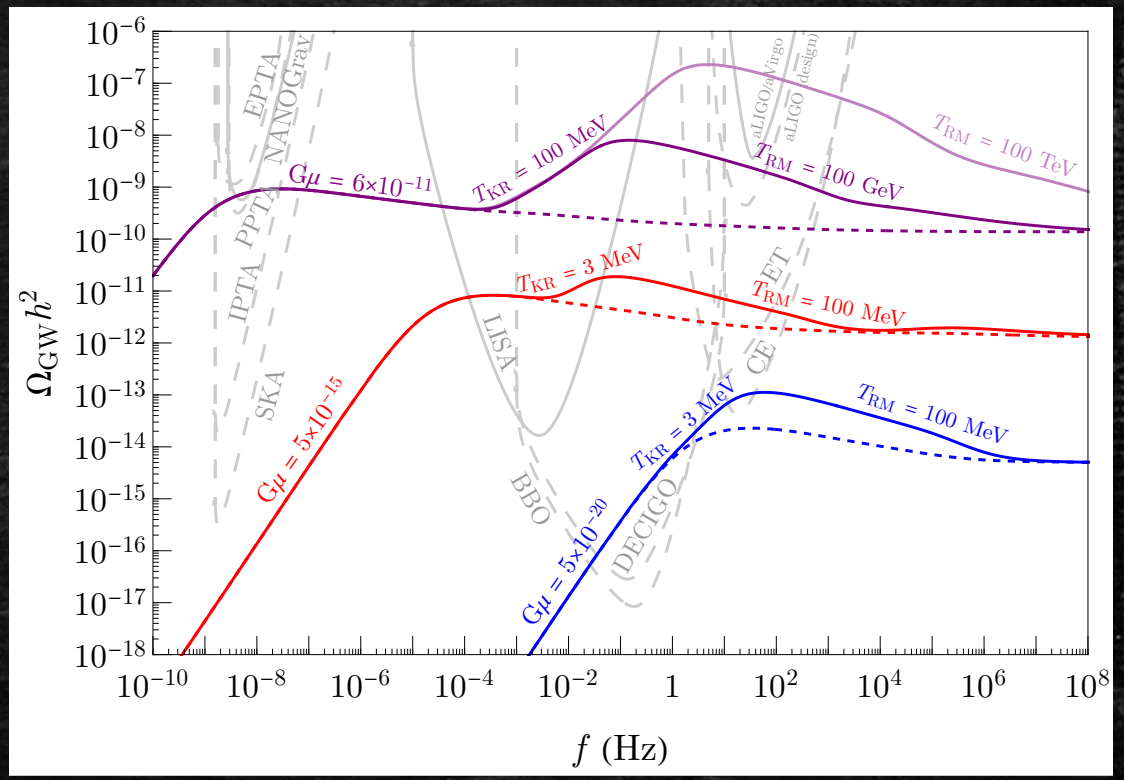
PRL 124, 111602 (2020) RC and K. Harigaya

Triangular peak GW spectra from kination

from inflation



from cosmic strings



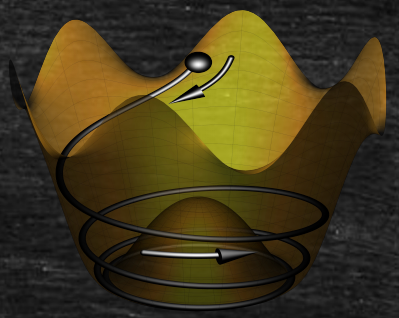
2108.09299 RC, D. Dunsky, N. Fernandez, A. Ghalsasi, L. Hall, K. Harigaya, J. Shelton

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

Probing PQ-breaking Potential

Piecewise approximation

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



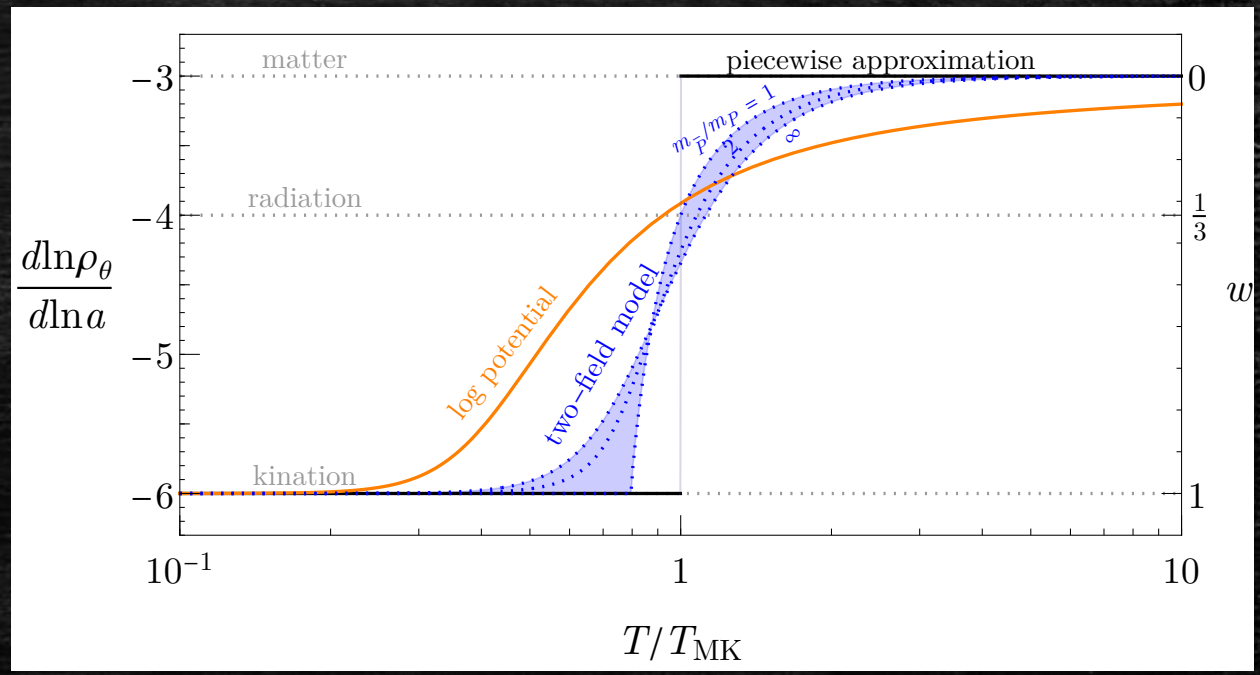
Log potential

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

Two-field model

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

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



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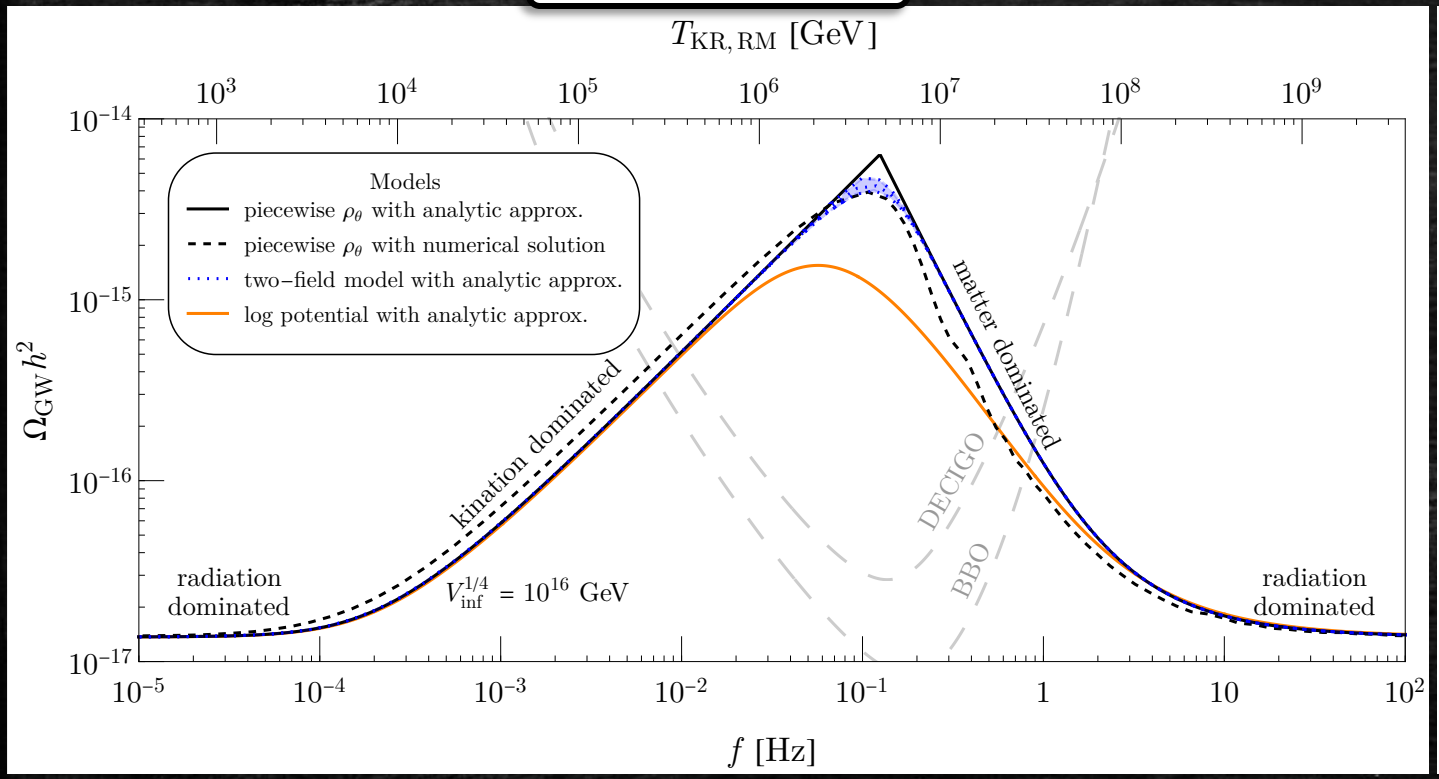
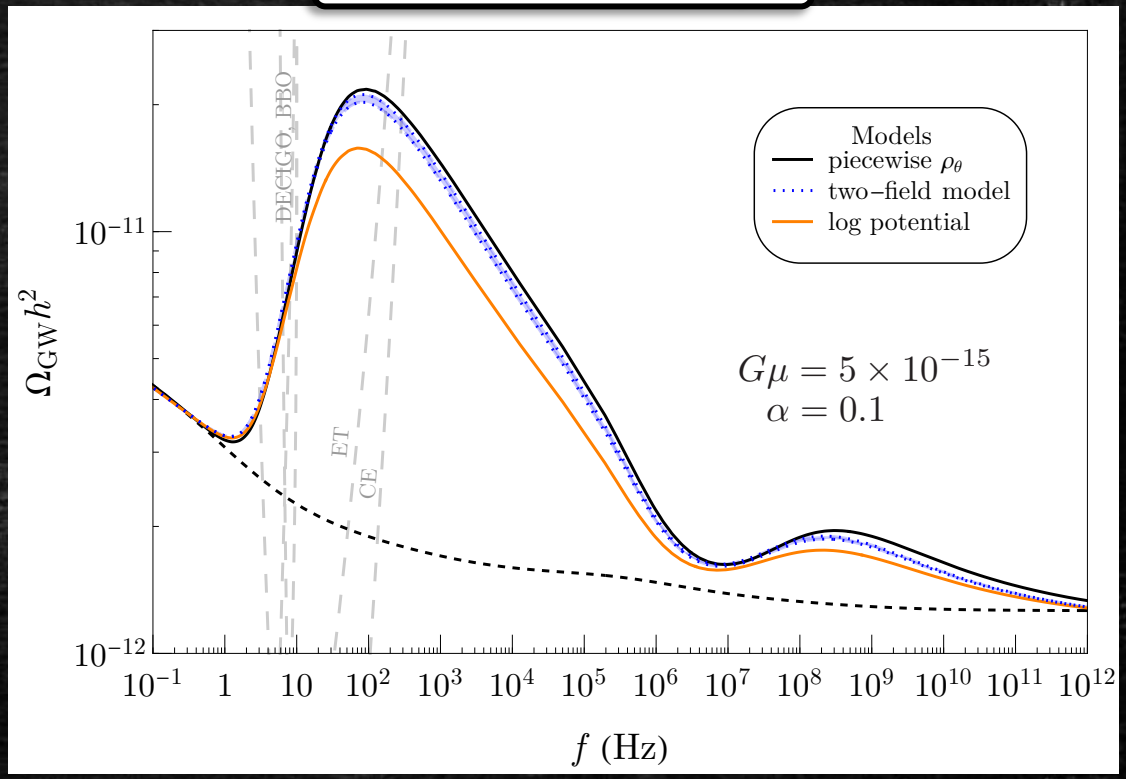
Probing PQ-breaking Potential

from inflation



from cosmic strings



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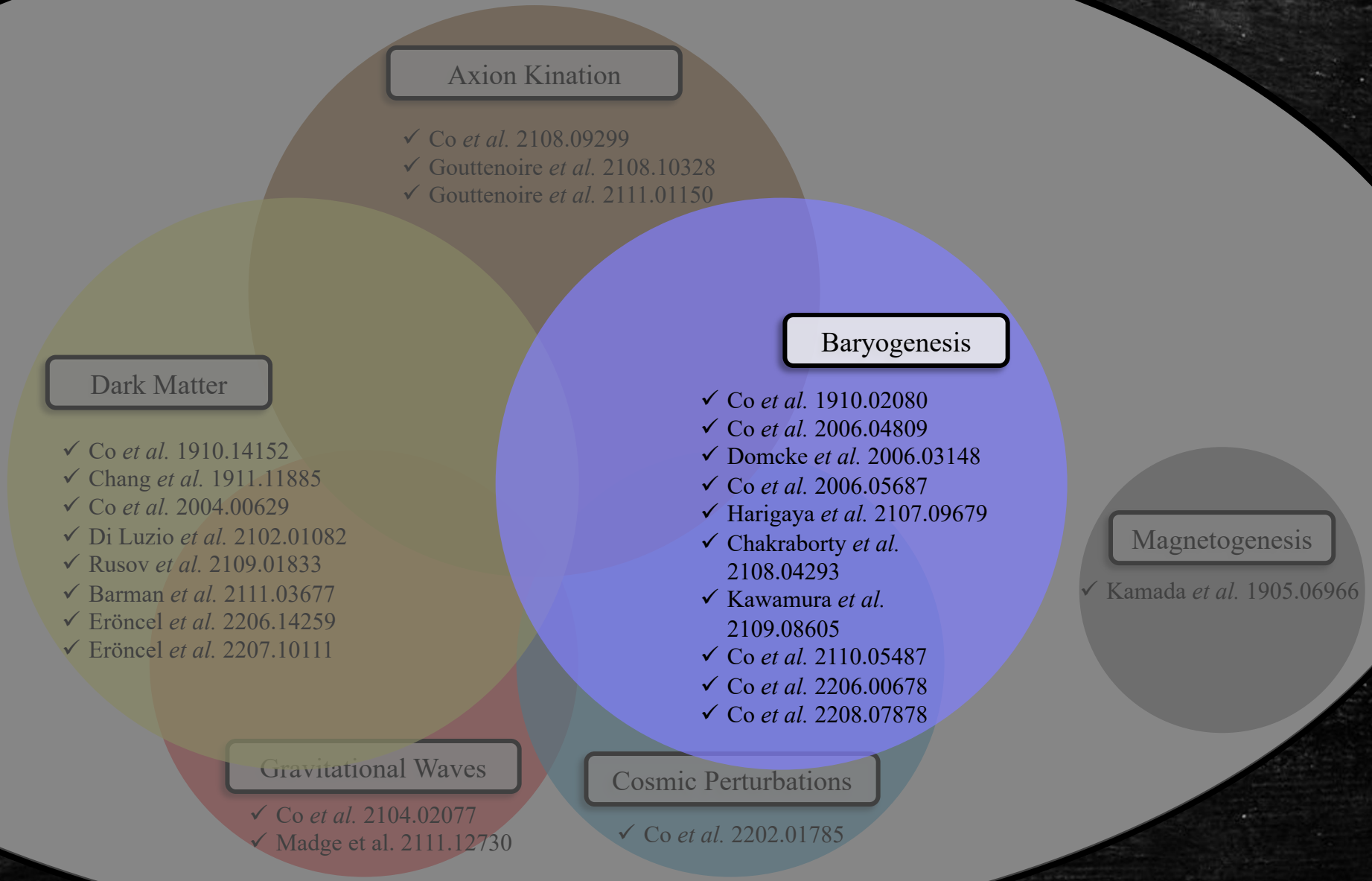
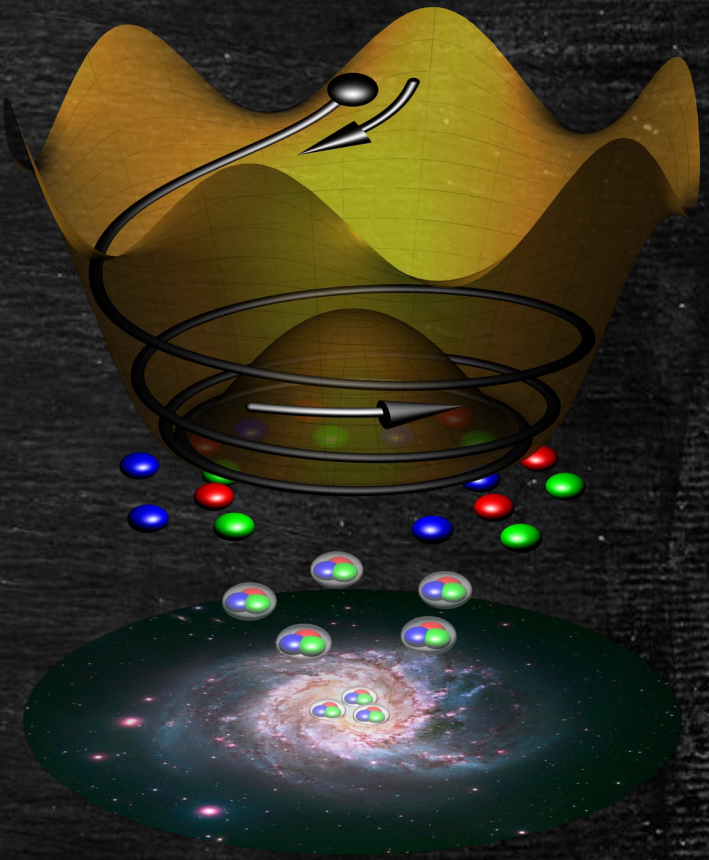
Axion Rotations





Axiogenesis

(QCD axion + baryogenesis)

R. Co Minnesota

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

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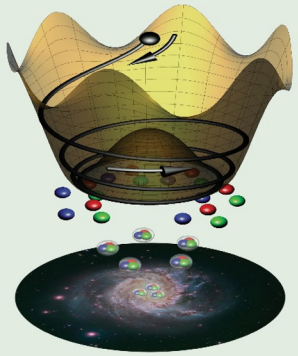

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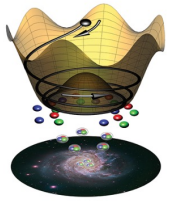

ON THE COVER

Axiogenesis

March 19, 2020

The rotation of the QCD axion field (black marble) around its pote
(yellow surface) during the earliest moments of the Universe coul
generate the excess of matter (colored marbles) over antimatter,
allowing galaxies to exist (galaxy photo credit: NASA). Selected fo
Synopsis in *Physics* and an Editors' Suggestion.

Raymond T. Co and Keisuke Harigaya

Phys. Rev. Lett. **124**, 111602 (2020)

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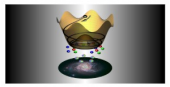

PHYSICS NEWS AND COMMENTARY

Axions Could Explain Baryon Asymmetry

March 19, 2020

A new theory proposes that a rotation of the axion field early in th
Universe's life could have generated matter-antimatter asymmetr

Synopsis on:

Raymond T. Co and Keisuke Harigaya

Phys. Rev. Lett. **124**, 111602 (2020)

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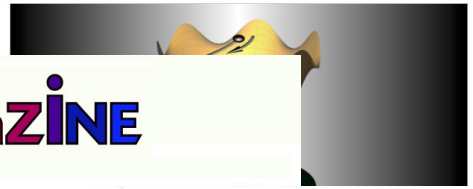
Synopsis: Axions Could Explain Baryon Asymmetry

March 19, 2020 • *Physics* 13, s38

A new theory proposes that a rotation of the axion field early in the Universe's life could have generated matter-antimatter asymmetry.



GIGAZINE

03月16日 07時00分

クマターの正体や人類が存在する理由など宇宙
オン」とは？

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Paper Sheds Light on Infant Universe and Origin of Matter

New Study from Researchers at IAS and University of Michigan

March 10, 2020

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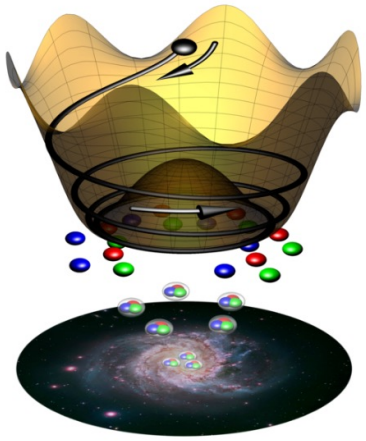

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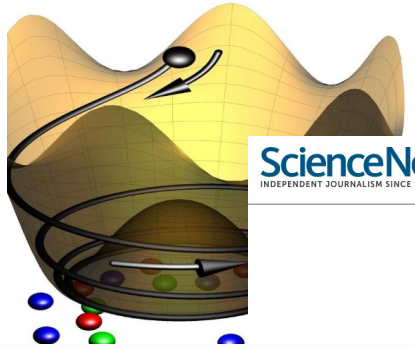
ion solves three mysteries of the universe



March 10, 2020

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morganls@umich.edu

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ABSTRACTIONS BLOG

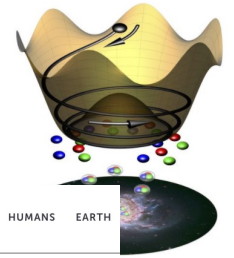
Axions Would Solve Another Major Problem in Physics

6

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

Tähdet ja avaruus

POHJOISMAIDEN SUURIN TÄHTITIEDELEHTI



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NEWS PARTICLE PHYSICS

Particles called axions could reveal how matter conquered the universe

subatomic particles may already solve two important
zles of particle physics

cnBeta

0 条评论

del)在解释宇宙方面做得相当不错，但
想的粒子--轴子--将可能帮助解开宇宙
在这里。

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CON UN COMMENTO DI FABRIZIO TAVECCHIO DELL'INAF DI BRERA

Assiogenesi primordiale e origine della materia

Un nuovo studio condotto da due ricercatori dell'Institute for Advanced Study e dell'Università del Michigan riporta che la rotazione dell'assione della cromodinamica quantistica potrebbe essere in grado di spiegare l'eccesso di materia presente nell'universo. Il meccanismo è stato chiamato 'assiogenesi' e viene descritto dagli autori in un articolo che verrà presto pubblicato su Prl

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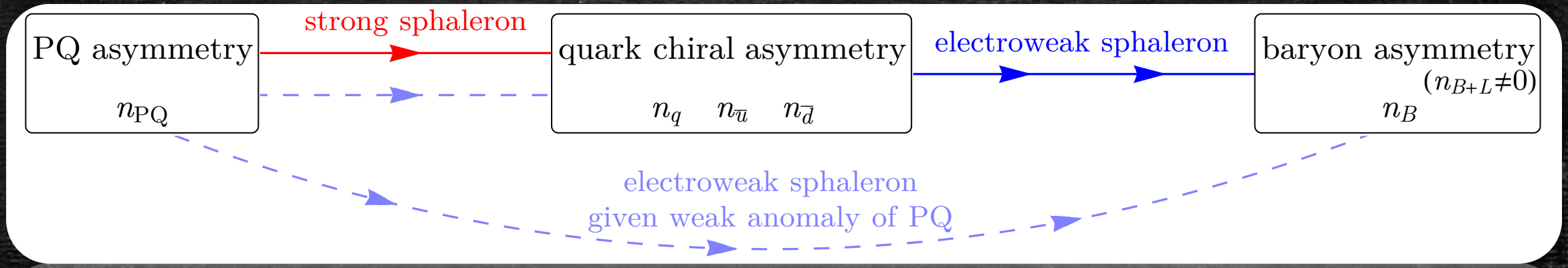
Западные СМИ

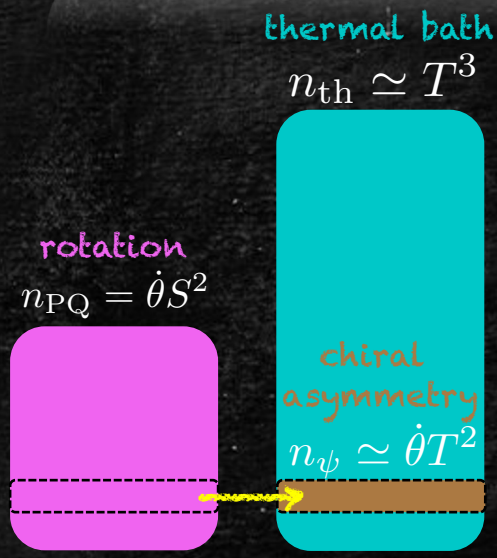
11 марта 2020 15:21

Учёные обнаружили ответ на одну из главных загадок физики. В схватке двух сил Вселенной нашли третьего игрока

#Космос , #Наука

Axiogenesis

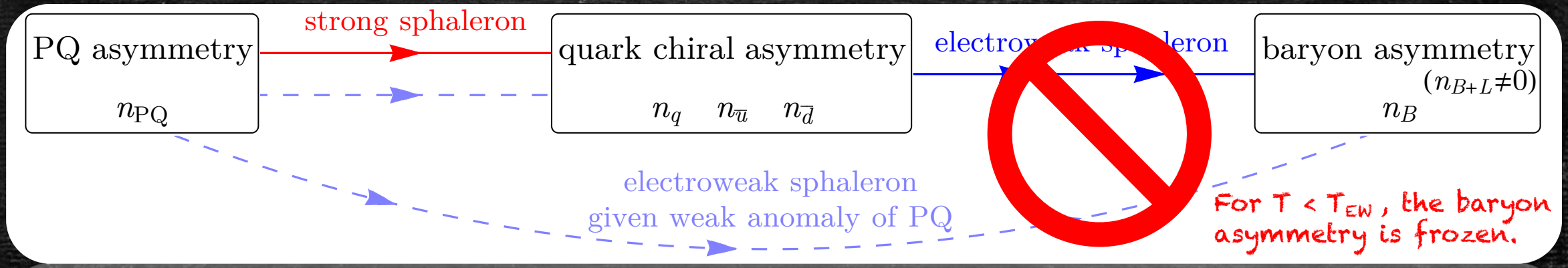


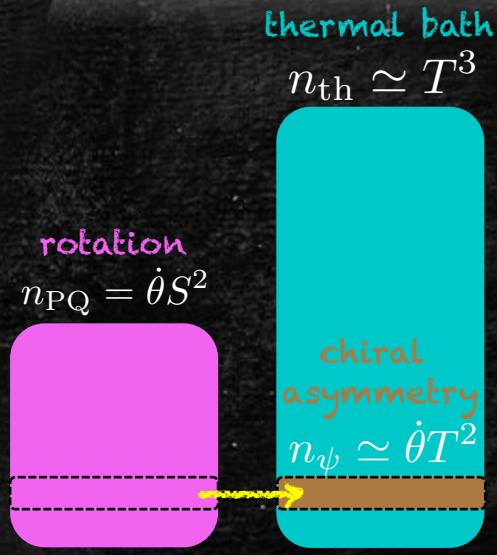


$$Y_B \equiv \frac{n_B}{s} = \frac{c_B \dot{\theta} T^2}{s}$$

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

Axiogenesis



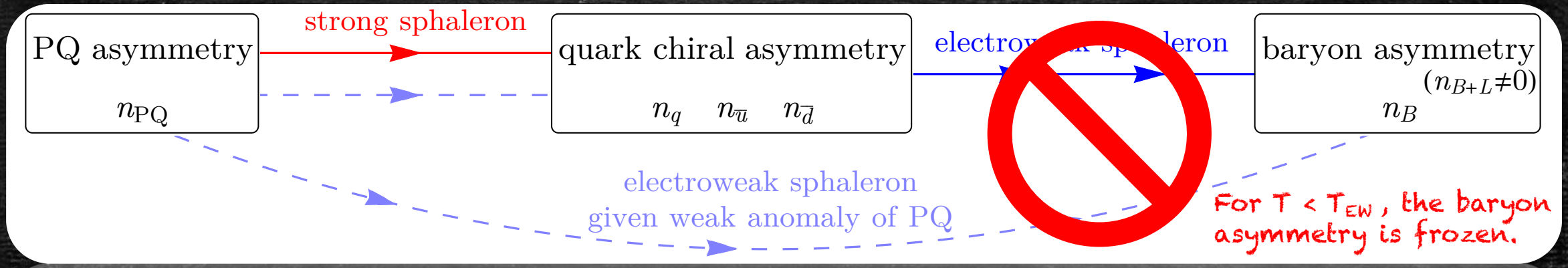


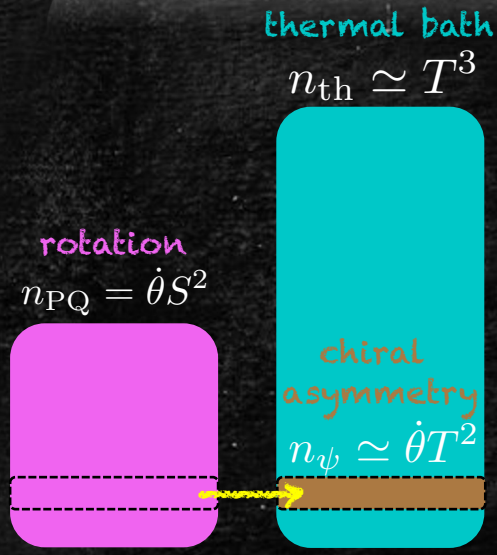
$$Y_B \equiv \frac{n_B}{s} = \frac{c_B \dot{\theta} T^2}{s} \Bigg|_{T = T_{\rm EW}} = c_B Y_{\rm PQ} \left(\frac{T_{\rm EW}}{f_a} \right)^2$$

Baryon asymmetry fixes rotational speed, equivalently $Y_{\rm PQ}$.

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

Axiogenesis



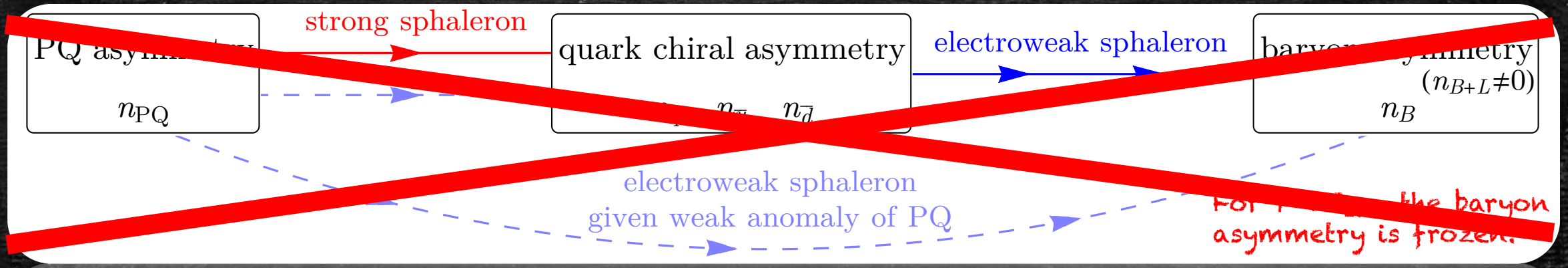


$$Y_B \simeq 10^{-10} \left(\frac{c_B}{0.1}\right) \left(\frac{T_{\rm EW}}{130\ {\rm GeV}}\right)^2 \left(\frac{10^8\ {\rm GeV}}{f_a}\right)^2 \left(\frac{Y_{\rm PQ}}{500}\right)$$

Baryon asymmetry fixes rotational speed, equivalently Y_{PQ}.

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

Extensions of Axiogenesis



Lepto-Axiogenesis

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

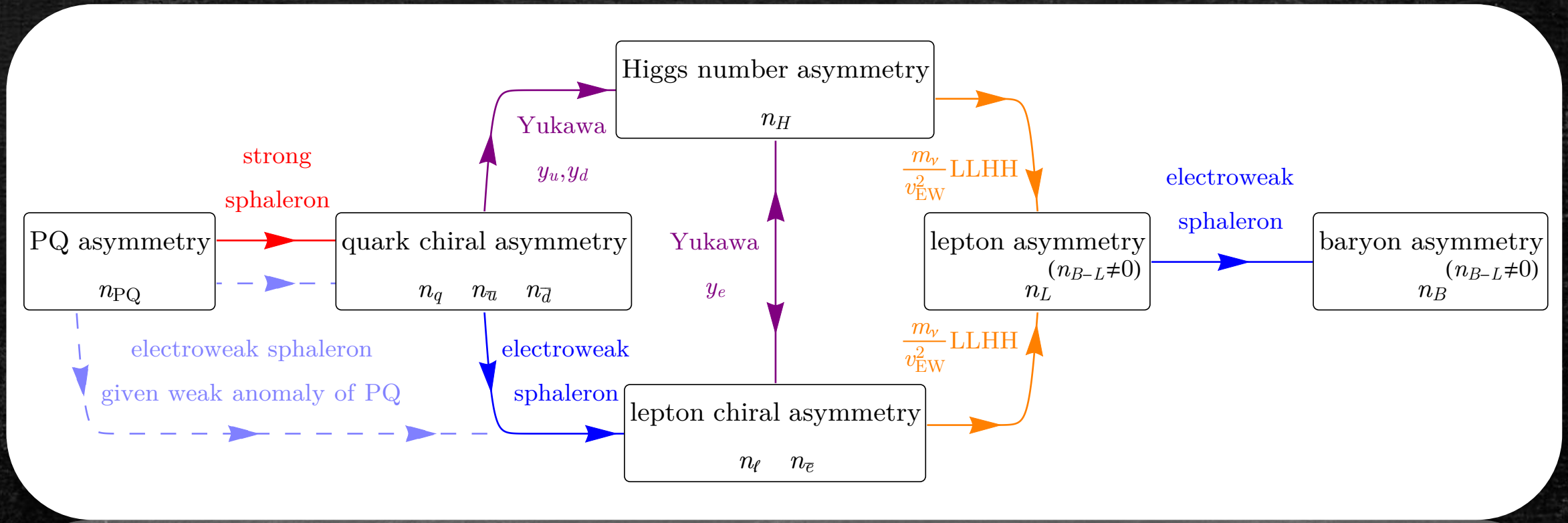
2006.05687 RC, N. Fernandez, A. Ghalsasi, L. Hall, K. Harigaya

R Parity Violation Axiogenesis

$$W = \frac{1}{2}\lambda\bar{e}LL + \lambda' QL\bar{d} + \frac{1}{2}\lambda''\bar{u}\bar{d}\bar{d}$$

2110.05487 RC, K. Harigaya, Z. Johnson, A. Pierce

Lepto-Axiogenesis

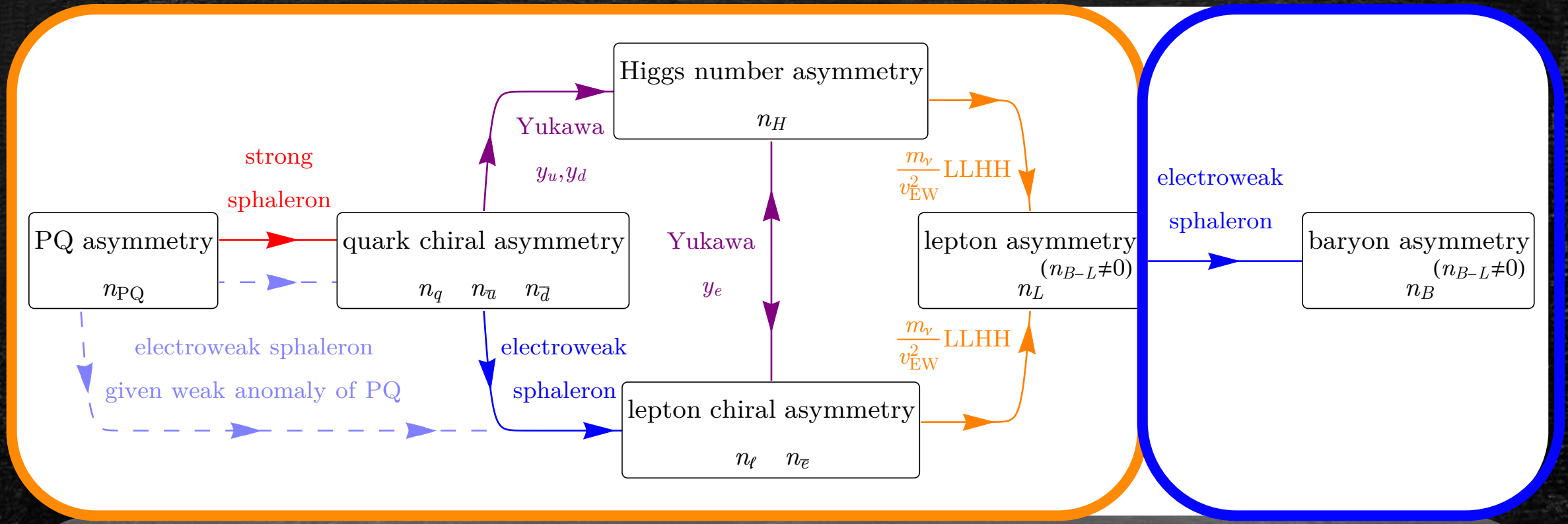


2006.05687 RC, N. Fernandez, A. Ghalsasi, L. Hall, K. Harigaya

Lepto-Axiogenesis

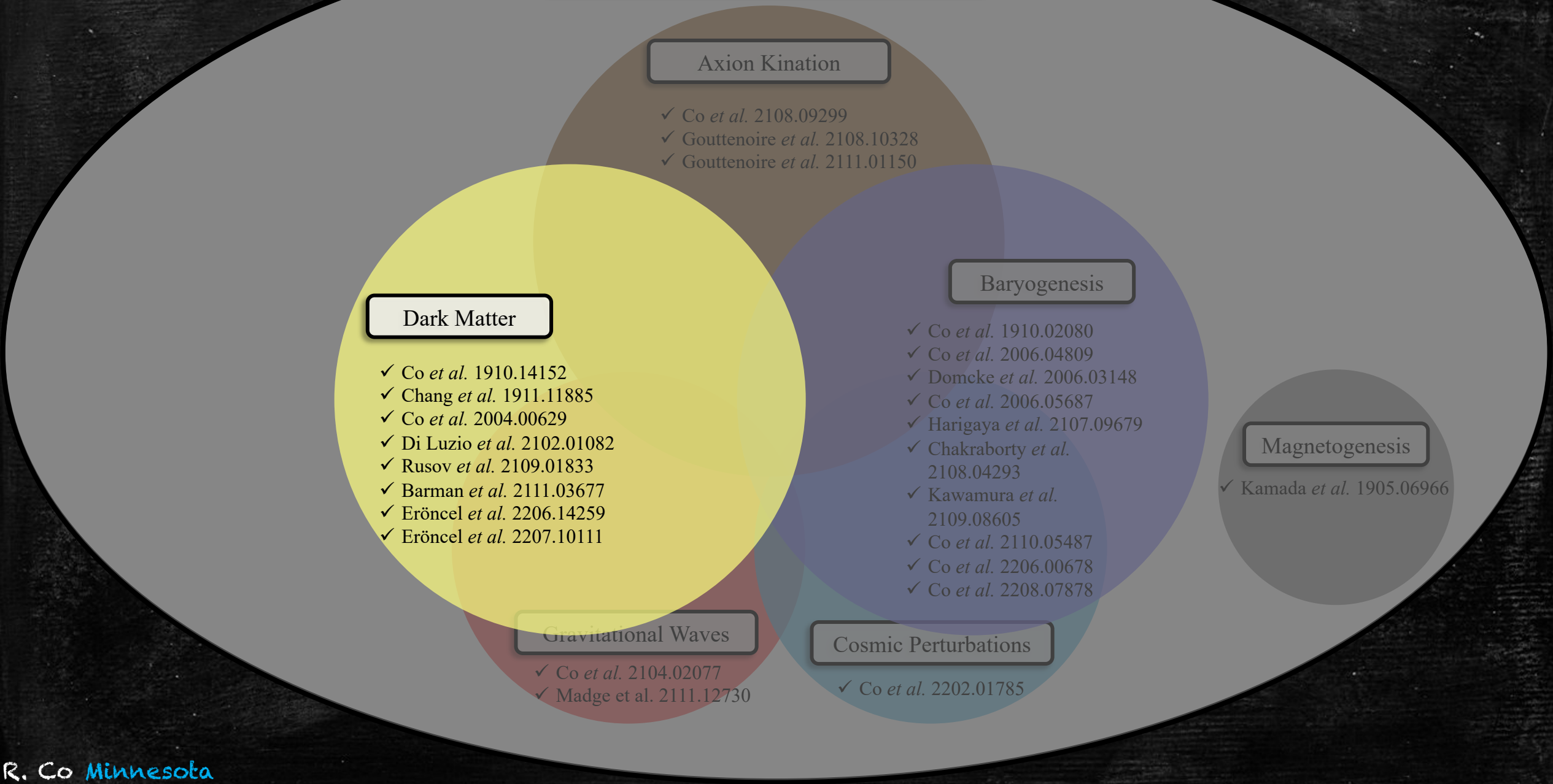
Producing L at high temperatures

Converting to B at T_{EW}

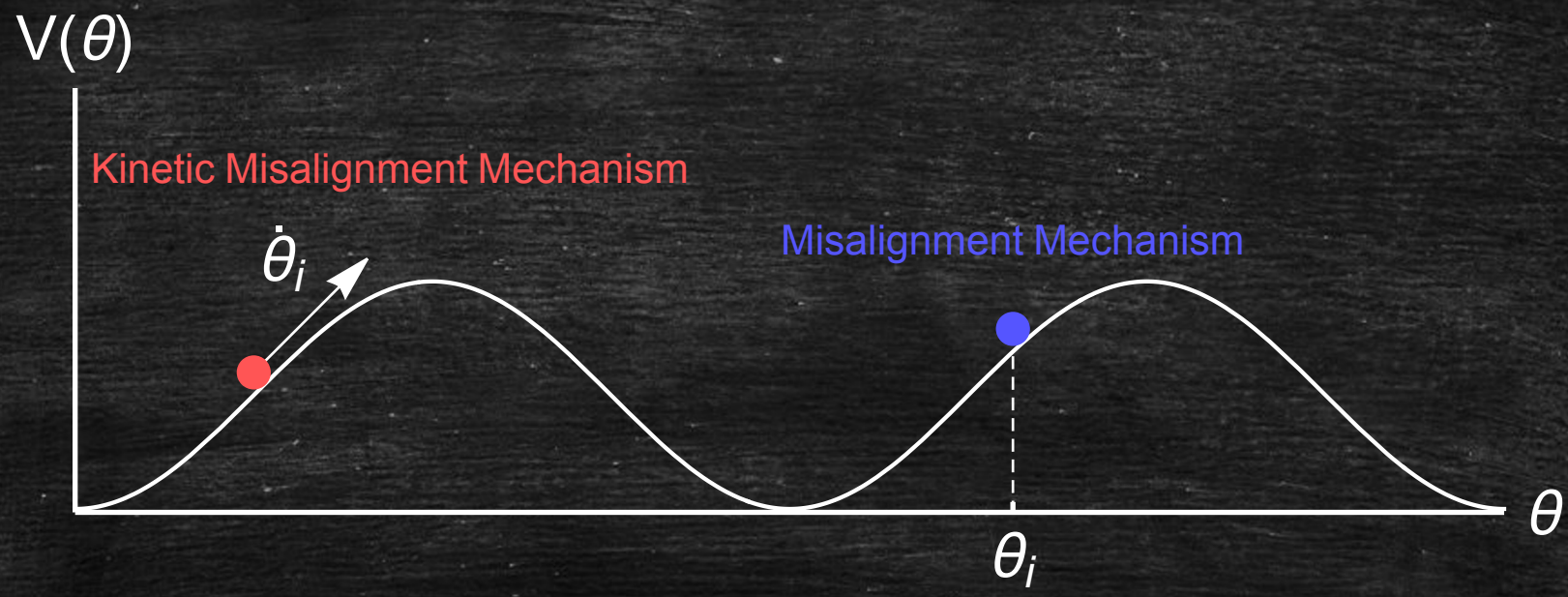


2006.05687 RC, N. Fernandez, A. Ghalsasi, L. Hall, K. Harigaya

Axion Rotations



R. Co Minnesota



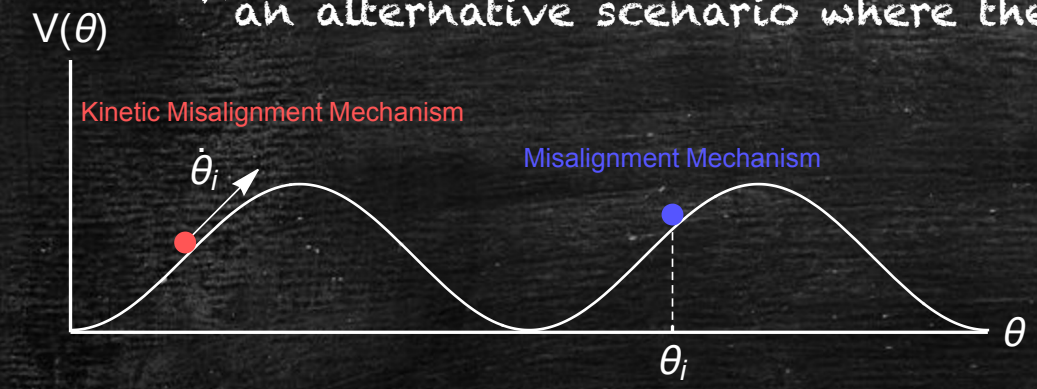
Kinetic Misalignment Mechanism

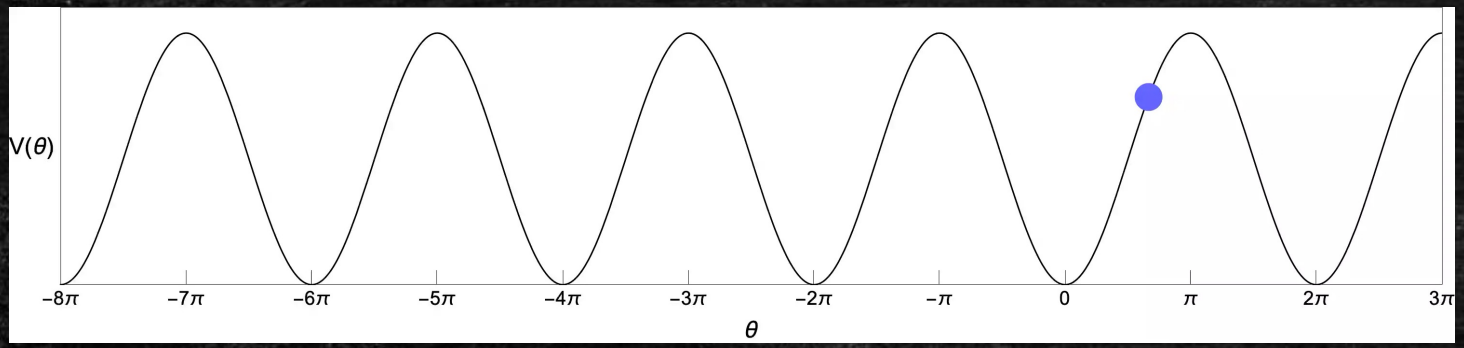
(Misalignment + non-zero kinetic energy)

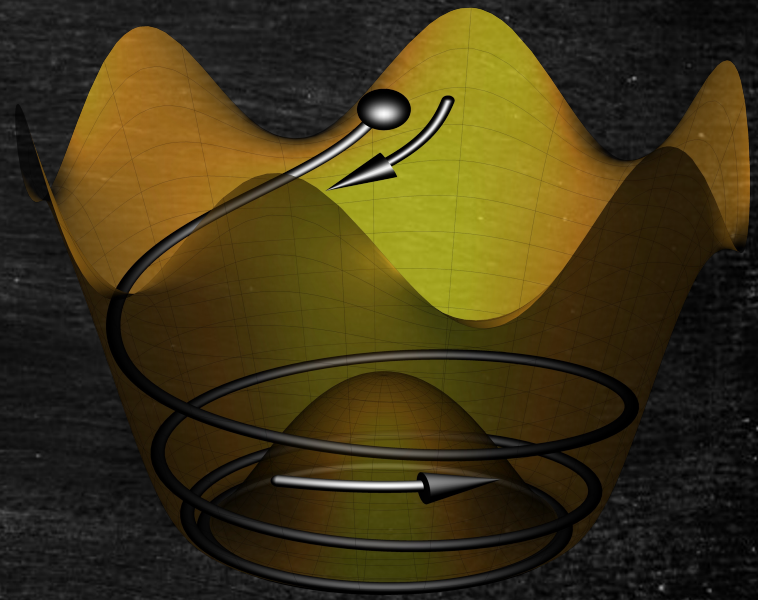
PRL 124, 251802 (2020) RC, L. Hall, K. Harigaya

Kinetic Misalignment Mechanism

"an alternative scenario where the axion field has a nonzero initial velocity"





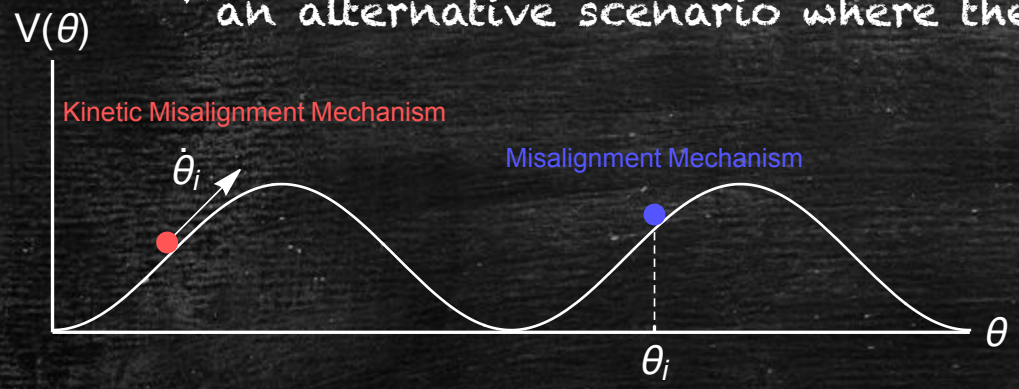


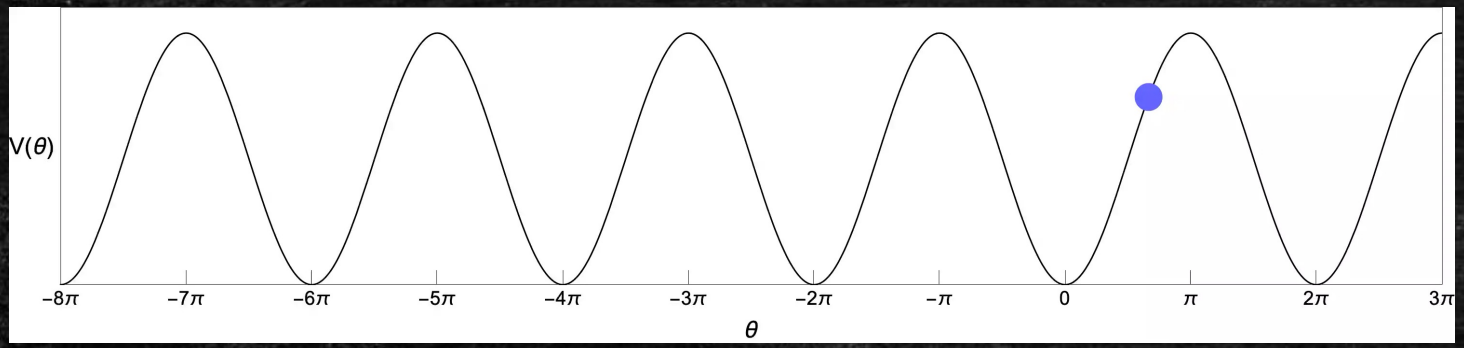
Abundance: $\frac{\rho_a}{s} = C m_a Y_{\rm PQ}$ $\Omega_a h^2 \simeq \Omega_{\rm DM} h^2 \left(\frac{m_a}{\rm meV}\right)\left(\frac{Y_{\rm PQ}}{440}\right)$

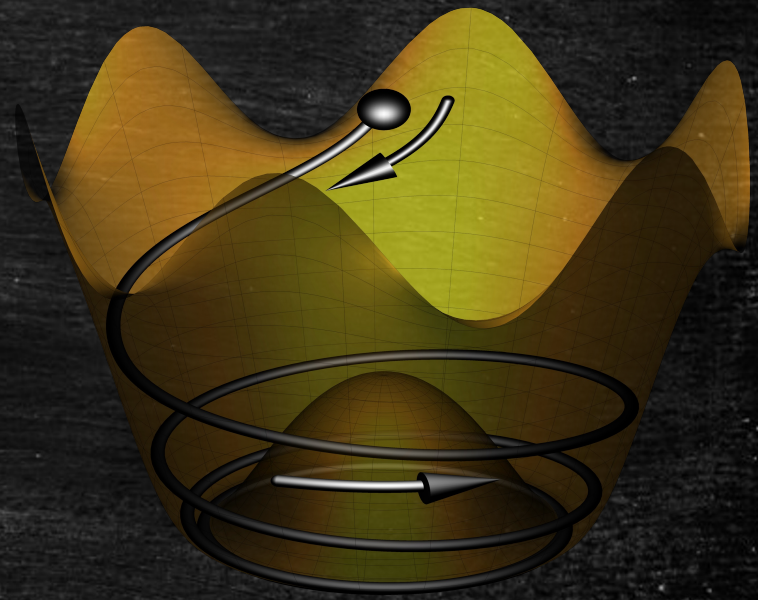
PRL 124, 251802 (2020) RC, L. Hall, K. Harigaya

Kinetic Misalignment Mechanism

"an alternative scenario where the axion field has a nonzero initial velocity"





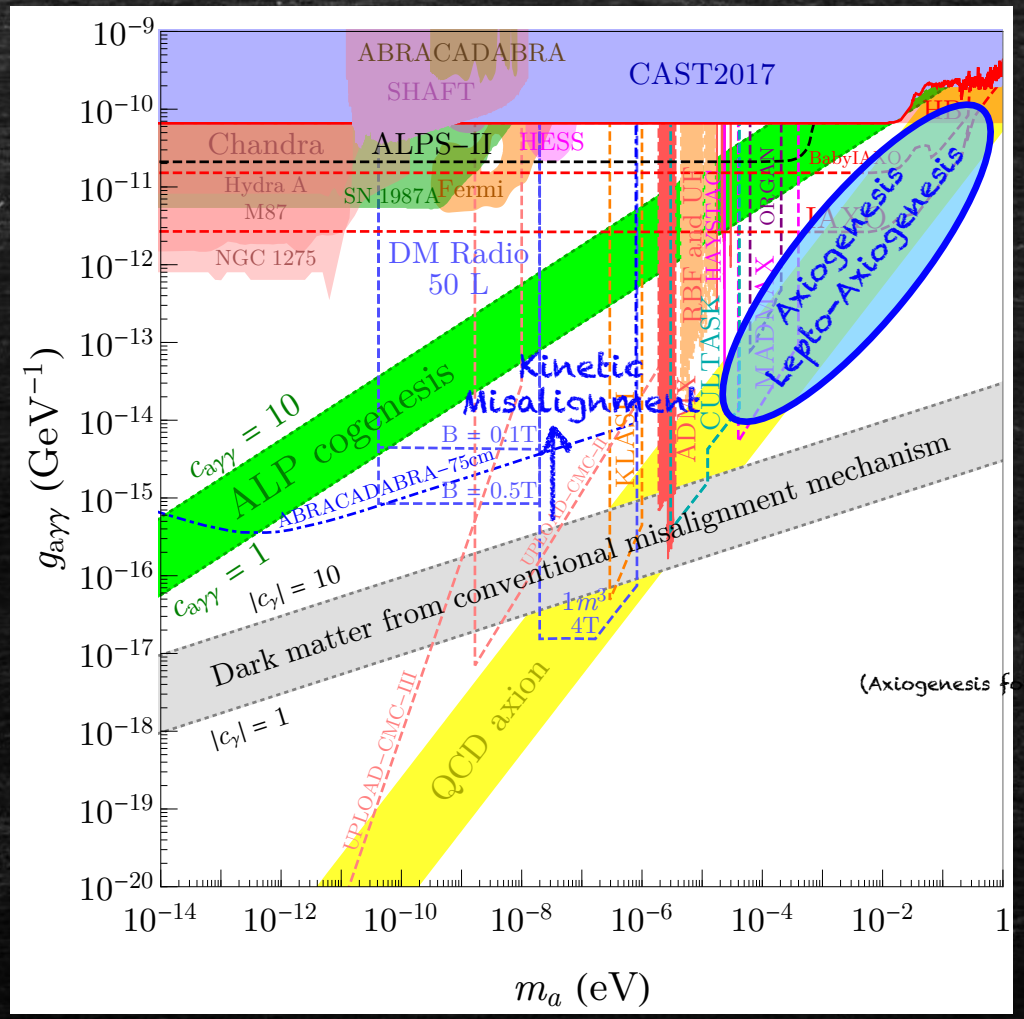


Abundance: $\frac{\rho_a}{s} = C m_a Y_{\rm PQ}$ $\Omega_a h^2 \simeq \Omega_{\rm DM} h^2 \left(\frac{m_a}{\rm meV}\right)\left(\frac{Y_{\rm PQ}}{440}\right)$

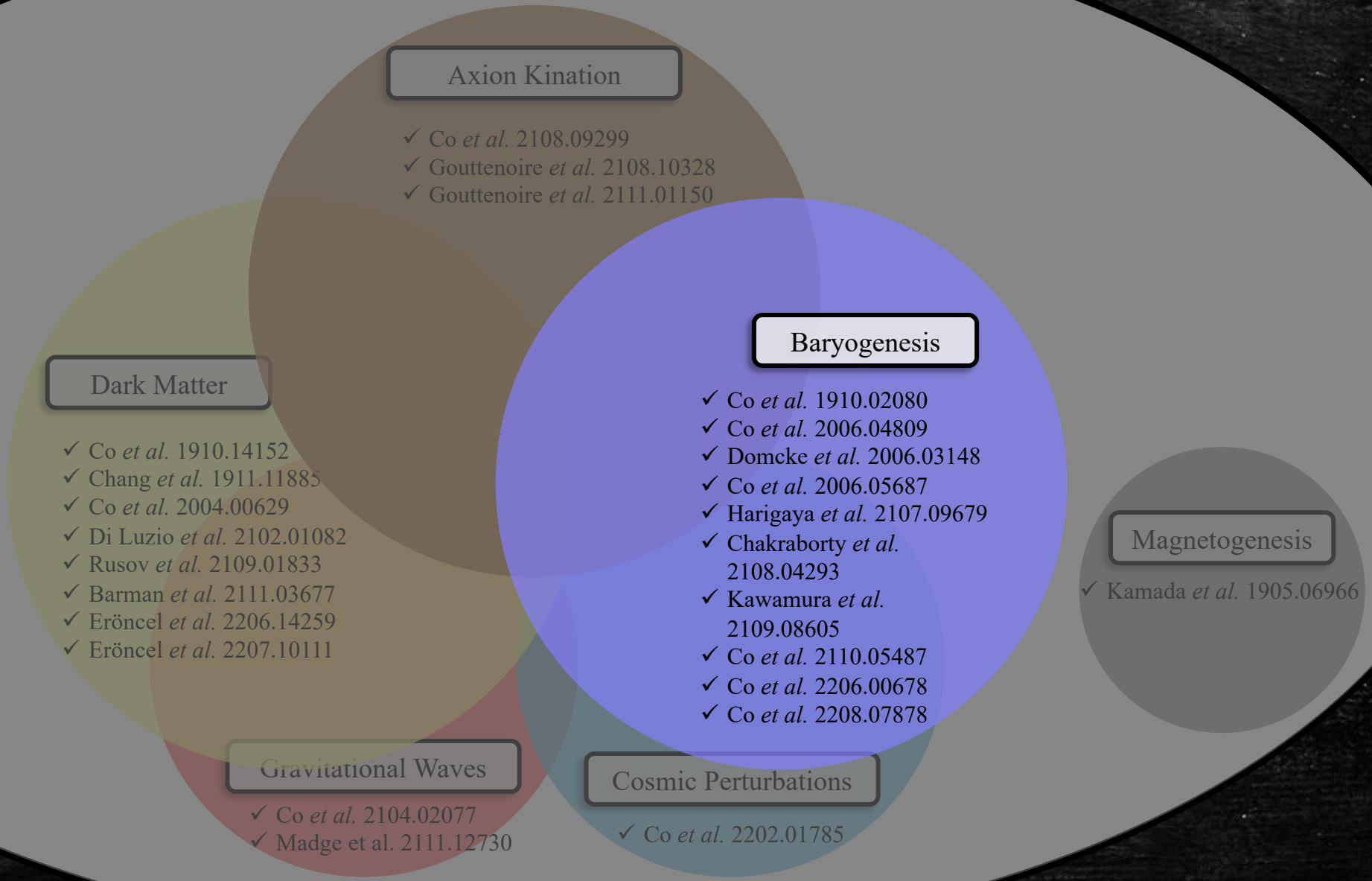
* Axion fragmentation in fact occurs before oscillations start. The abundance is modified by an O(1) factor but axion dark matter can be warm and can cluster. 1605.01367, 1903.03116, 1911.08472, 2104.02077, 2207.10111

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

Predictions from Axiogenesis and Kinetic Misalignment



Axion Rotations



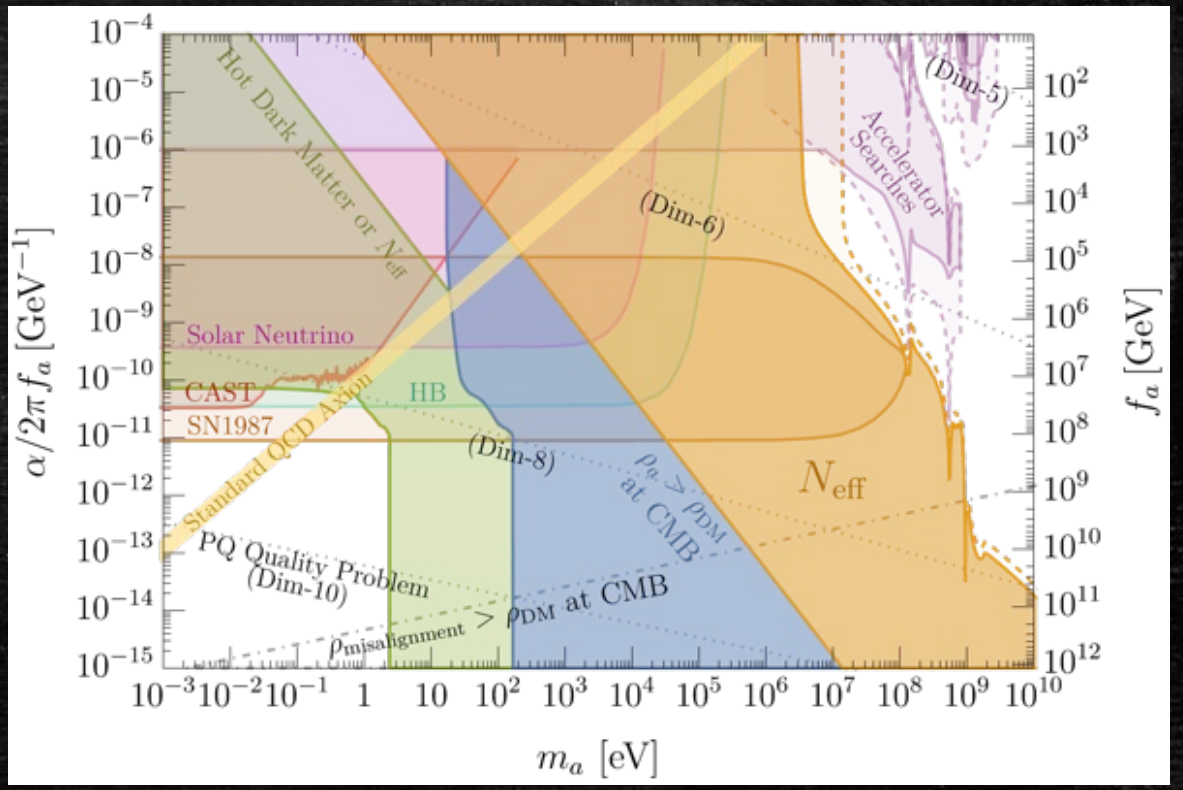
Heavy QCD Axion

- ✓ Axion quality problem
  - ✓ Neutron EDM $|d_n| \leq 1.8 \times 10^{-26}$ e cm
  - ✓ CP violation $\bar{\theta} \leq 10^{-10}$
  - ✓ Axion quality $V(P) \sim \frac{P^n}{M^{n-4}} + \text{h.c.}$

  $n > 8\text{-}36$ for $f_a = 10^{8\text{-}16}$ GeV

- ✓ Model constructions
  - ✓ 4D UV instantons — T. Gherghetta et al. 2016 P. Agrawal et al. 2017, M. K. Gaillard et al. 2018, C. Csaki et al. 2019
  - ✓ 5D UV instantons — T. Gherghetta et al. 2020
  - ✓ Mirror QCD — V. Rubakov 1997, Z. Berezhiani et al. 2000, A. Hook 2014, H. Fukuda et al. 2015, A. Hook et al. 2019

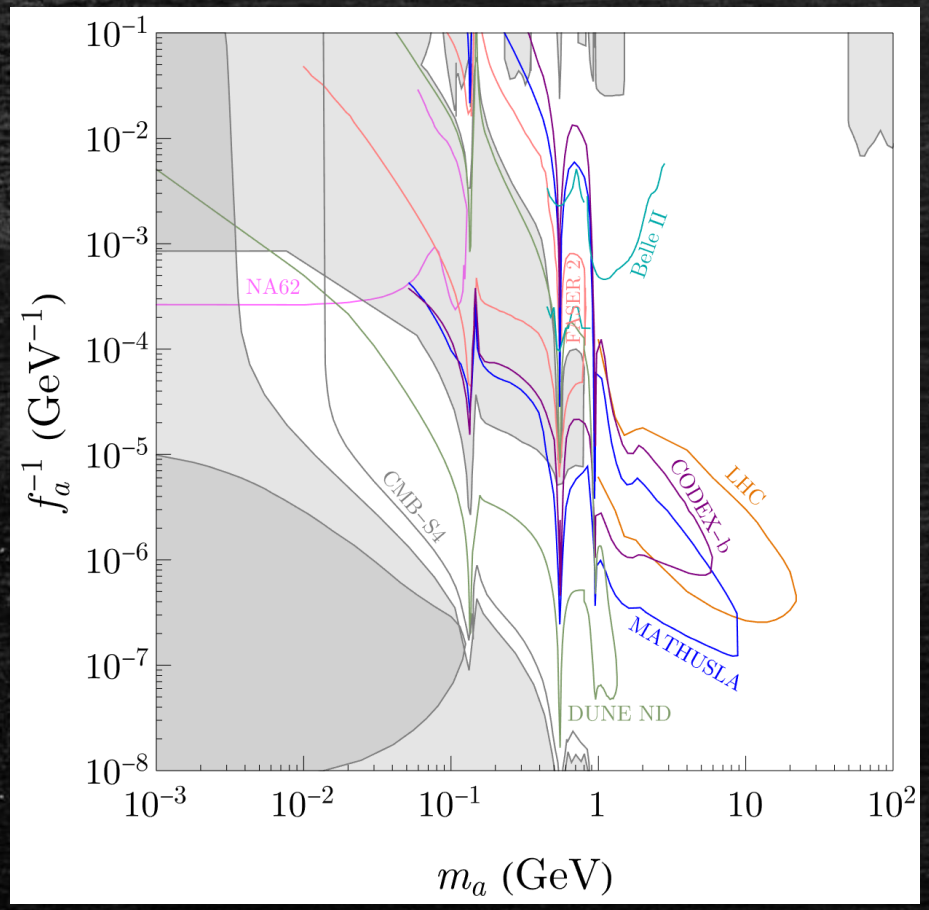
$$\mathcal{L} \supset \bar{\theta} \frac{g_s^2}{32\pi^2} G_b^{\mu\nu} \tilde{G}_{b\mu\nu}$$

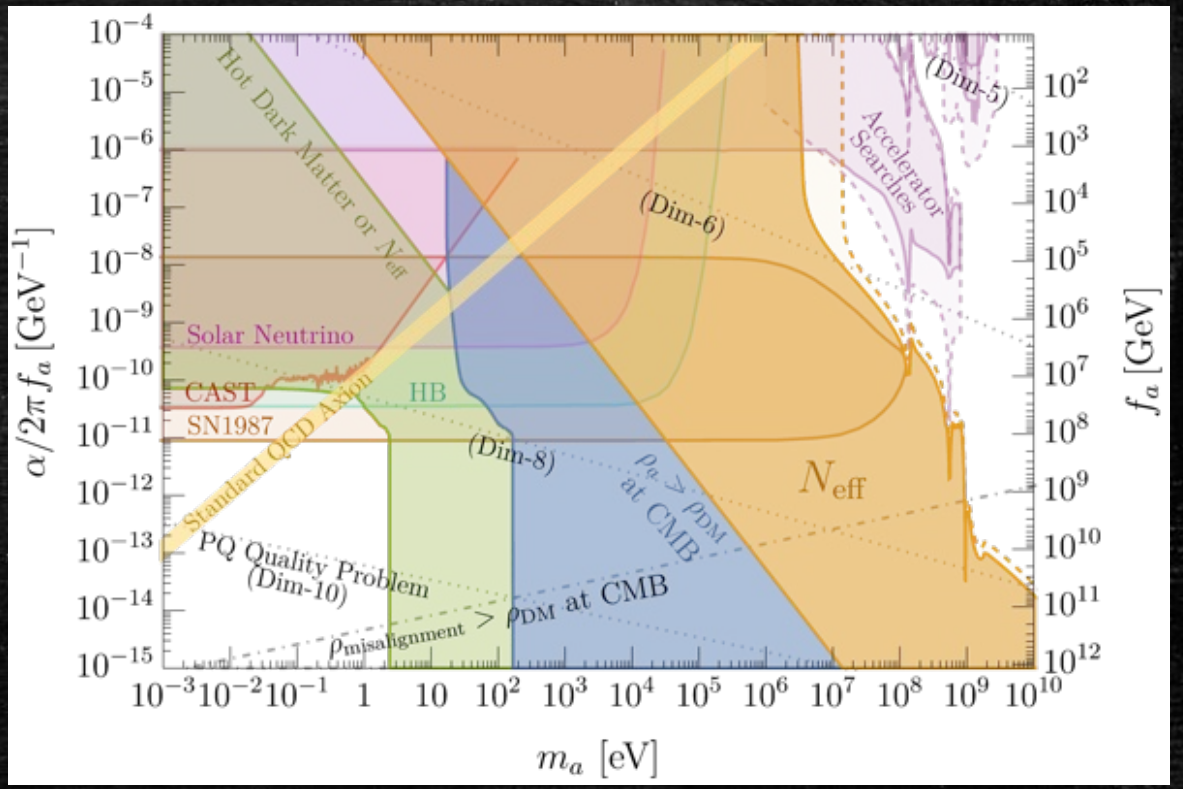


2205.11540 D. Dunsky, K. Harigaya, L. Hall

Heavy QCD Axion

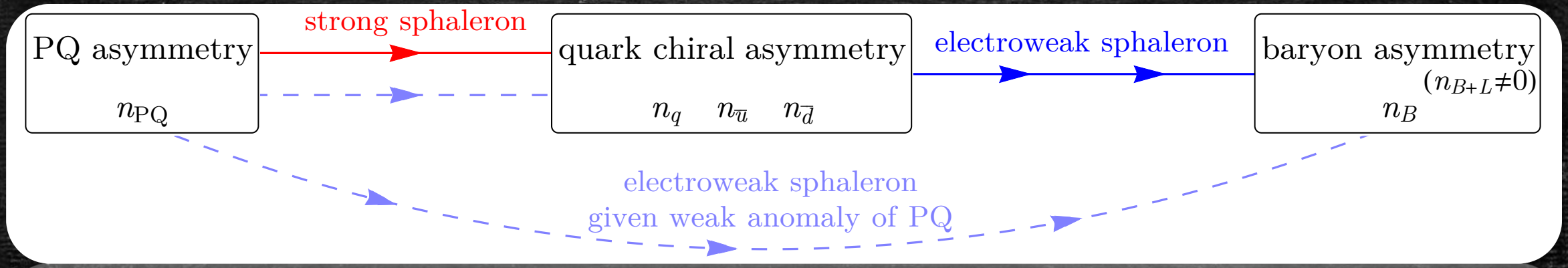
✓ New theoretical and experimental opportunities

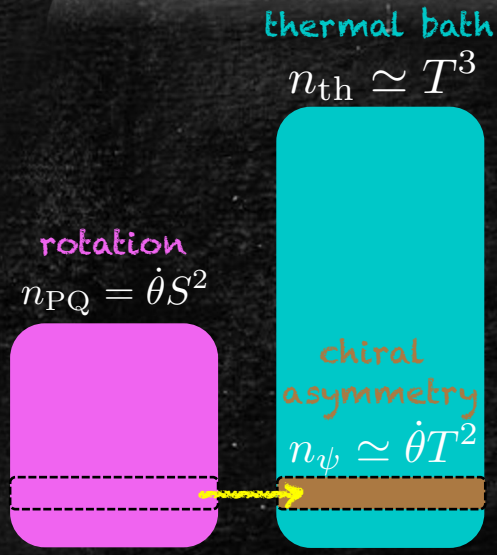




2205.11540 D. Dunsky, K. Harigaya, L. Hall

Axiogenesis with Heavy QCD Axion



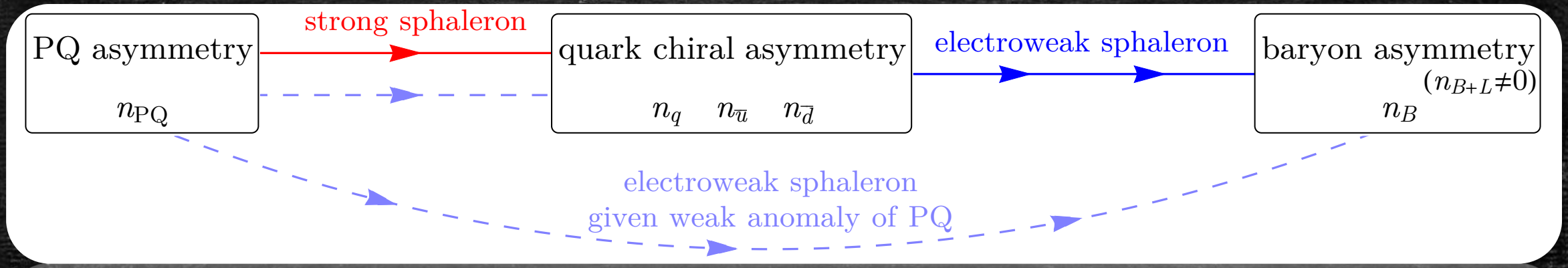


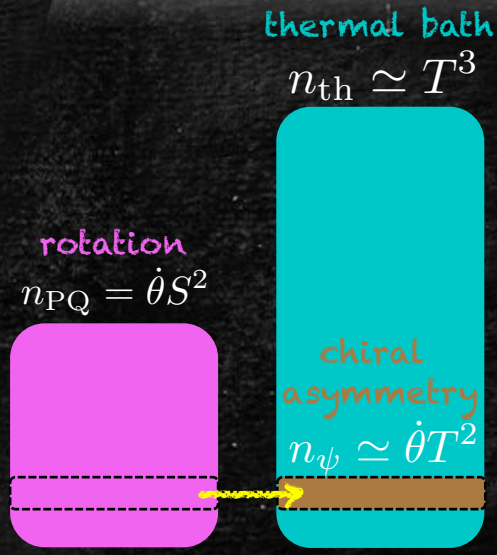
$$Y_B \equiv \frac{n_B}{s} = \frac{c_B \dot{\theta} T^2}{s}$$

R. Co Minnesota

2206.00678 RC, T. Gherghetta, and K. Harigaya

Axiogenesis with Heavy QCD Axion





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

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

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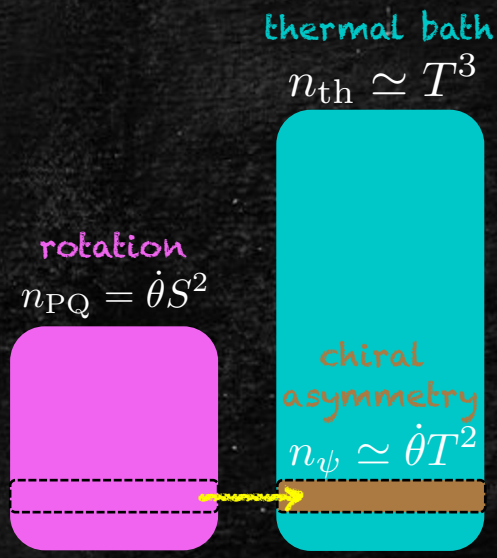
2206.00678 RC, T. Gherghetta, and K. Harigaya

Axiogenesis with Heavy QCD Axion



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

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

$\dot\theta > m_a$ is necessary to maintain the rotation

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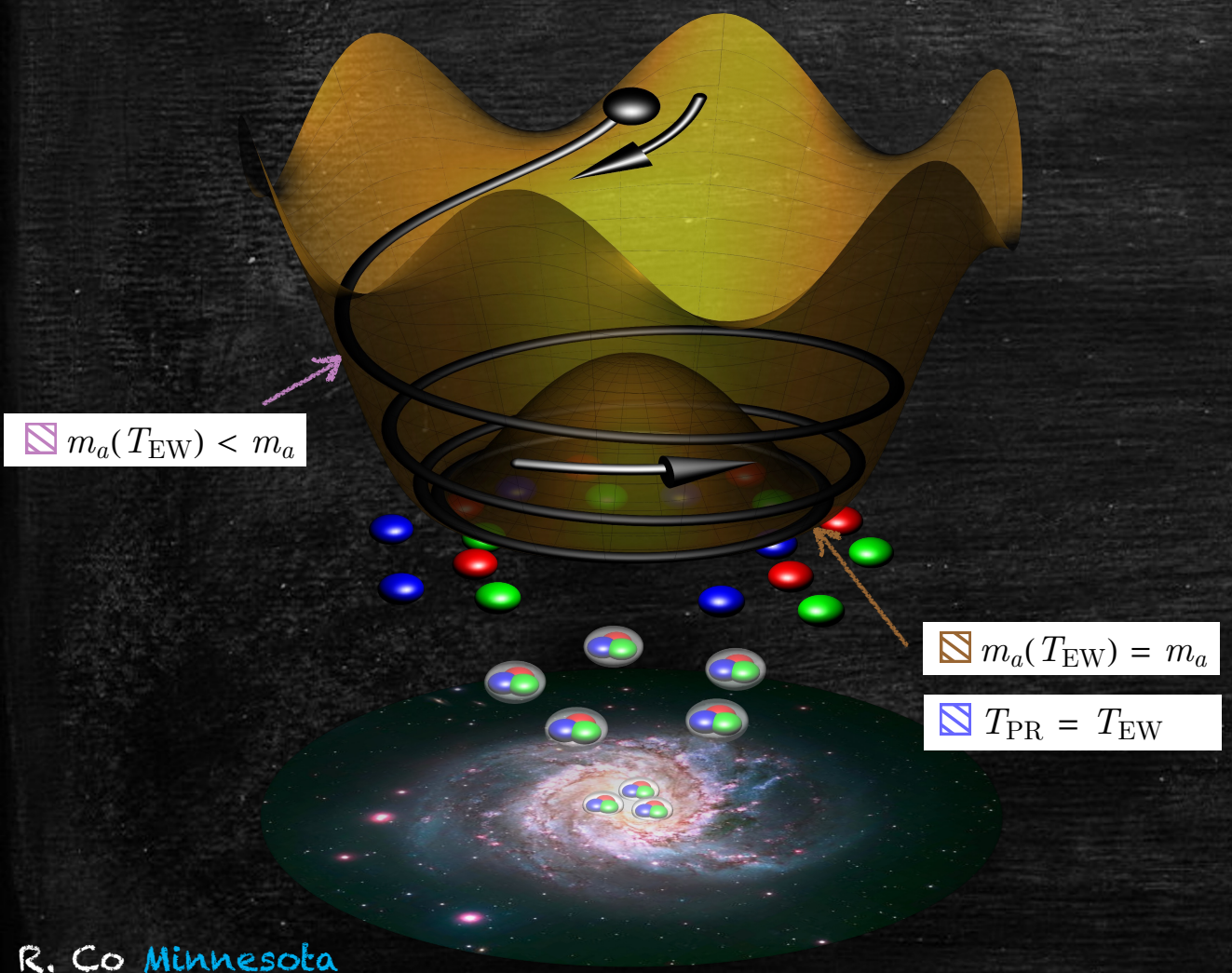
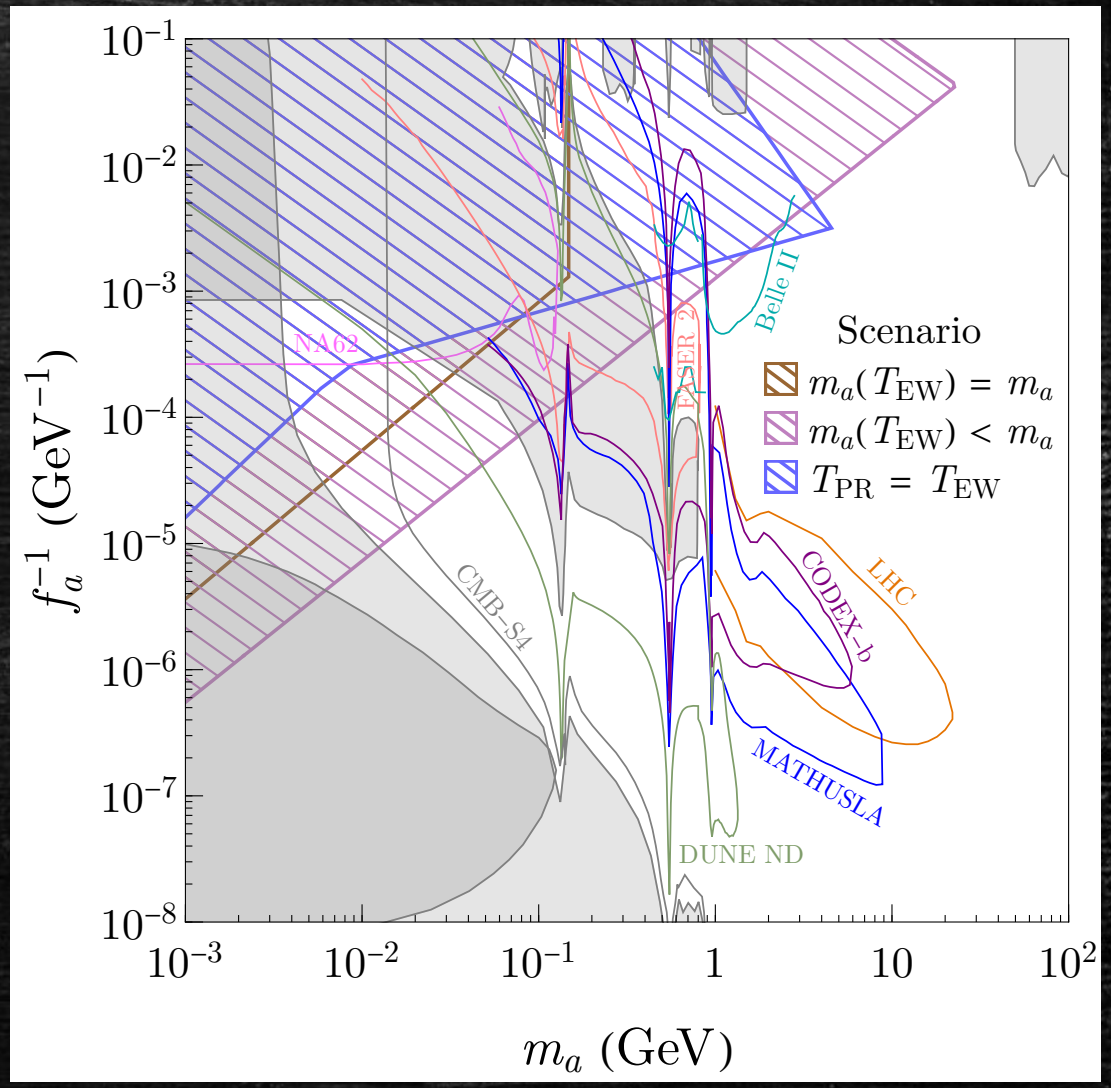
Predictions from Axiogenesis





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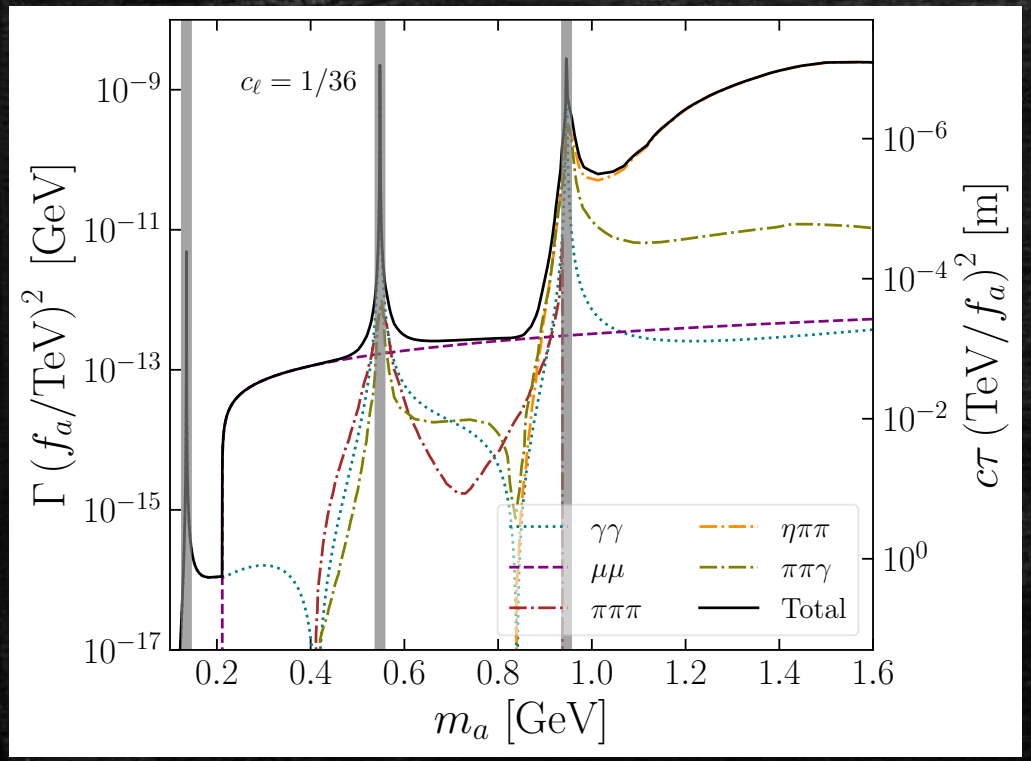
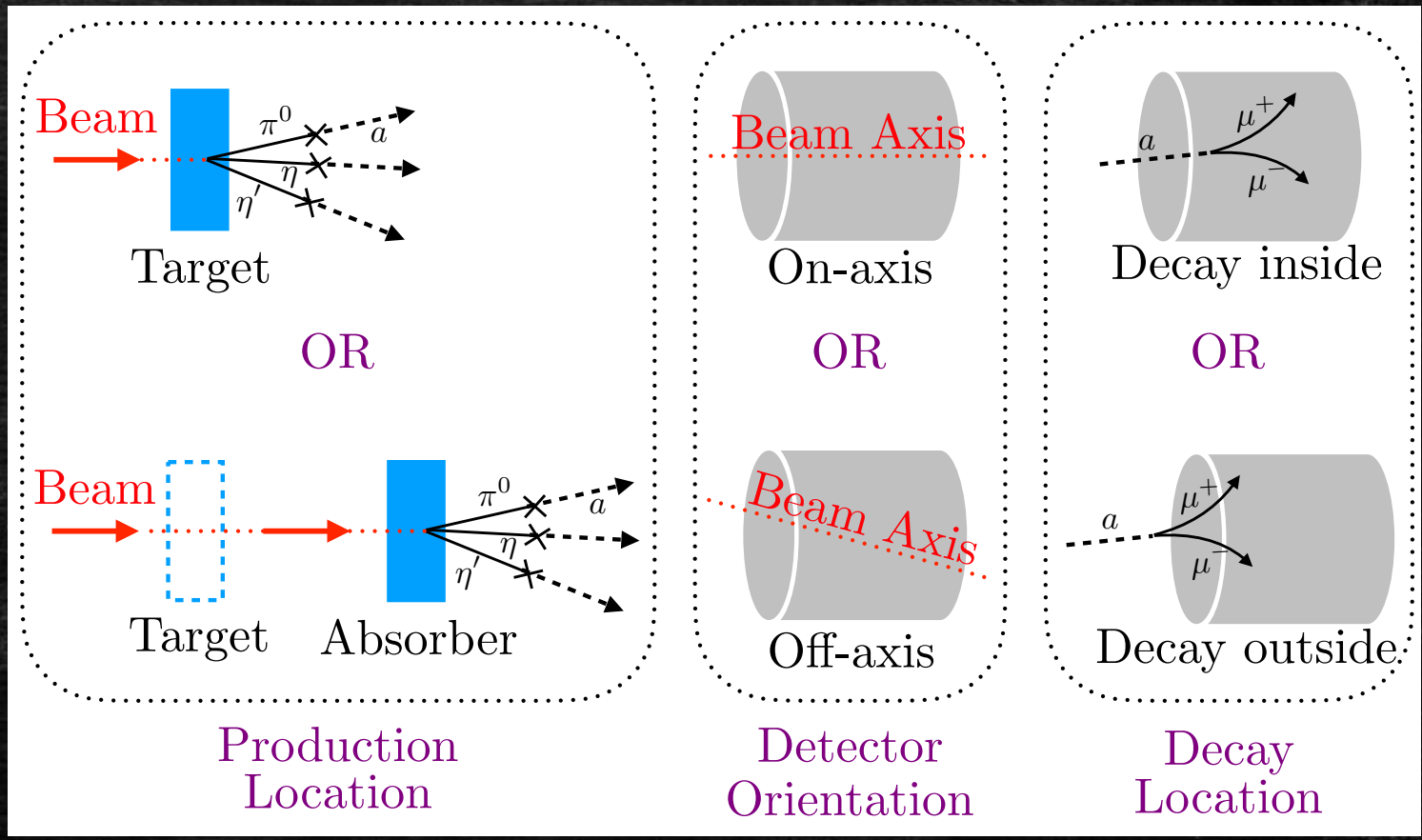
Heavy QCD Axion

✓ New theoretical and experimental opportunities

$$\mathcal{L}_{\text{lepton}} \supset \sum_{\ell=e,\mu,\tau} \frac{\partial_\mu a}{2f_a} \left(c_{V\ell}\bar{\ell}\gamma^\mu\ell + c_{A\ell}\bar{\ell}\gamma^\mu\gamma_5\ell\right)$$

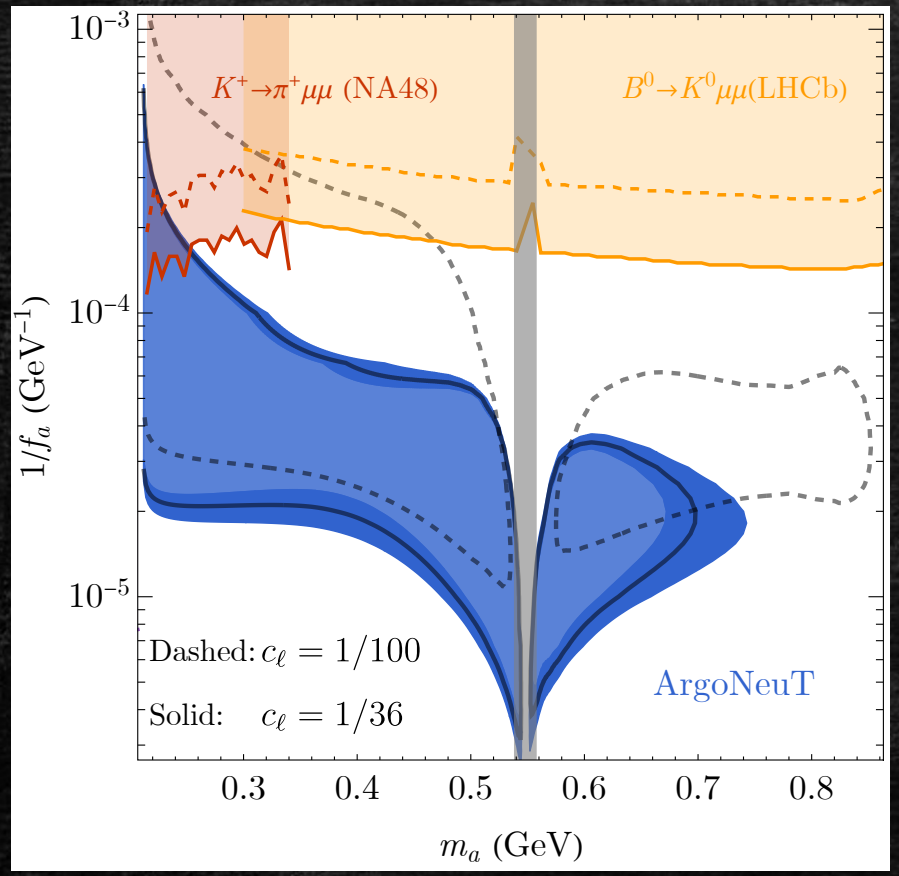


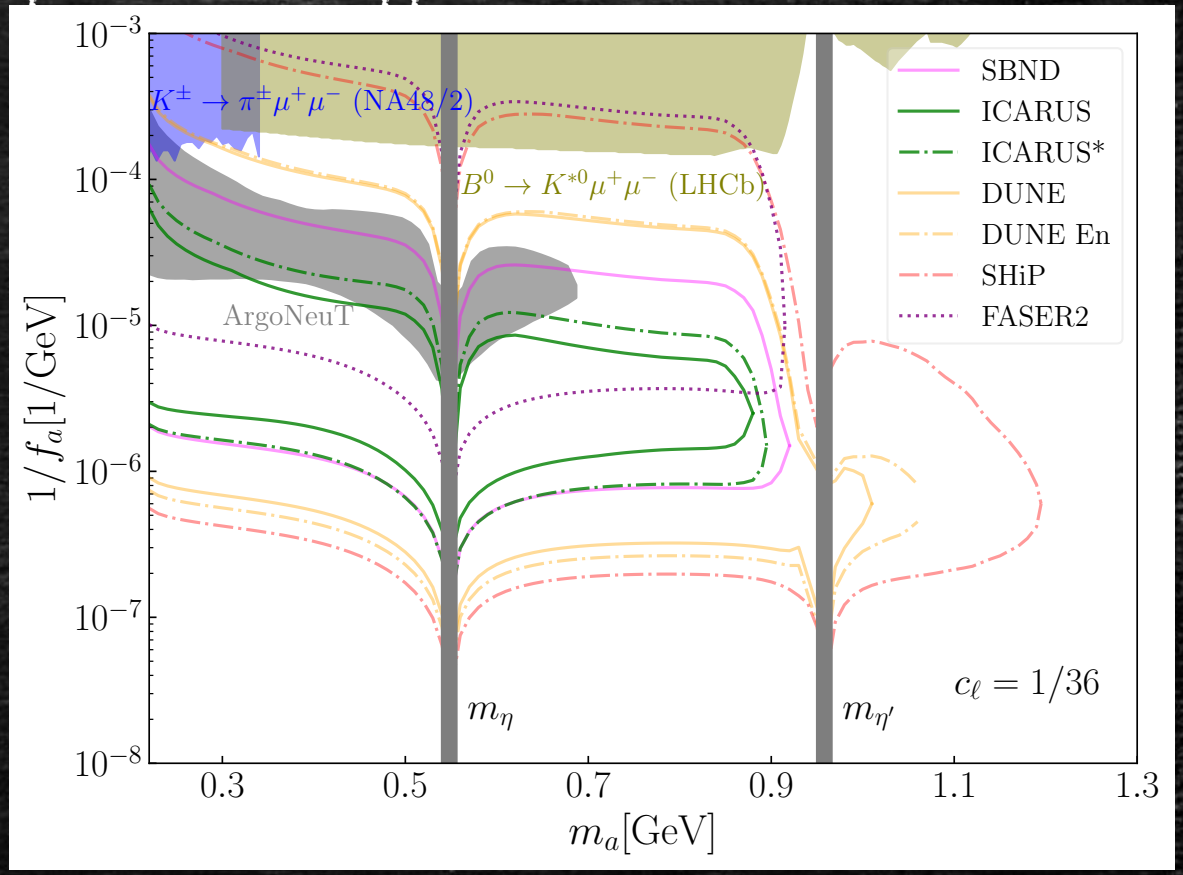


R. Co Minnesota Soon.IHope RC, Soubhik Kumar, Zhen Liu

Heavy QCD Axion

✓ New theoretical and experimental opportunities





2207.08448 RC et al. and ArgoNeuT collaboration

Soon.IHope RC, Soubhik Kumar, Zhen Liu

Heavy QCD Axion

		E_p (GeV)	$N_{\rm POT}$	d (m)	L (m)	$w \times h$ (m×m)
DUNE [79, 80]		120	1.47×10^{22}	574	$5 + 5$	7×3 $(r_{\rm eff} = 2.6$ m)
SBND [81]	BNB	8	6.6×10^{20}	110	5	4×4 $(r_{\rm eff} = 2.3$ m)
	NuMI	120	3×10^{21}	410		
MicroBooNE [81, 82]	BNB	8	1.32×10^{21}	470	10.4	2.6×2.3 $(r_{\rm eff} = 1.4$ m)
	NuMI	120	3×10^{21}	685		
ICARUS [81]	BNB	8	6.6×10^{20}	600	19.9	$(3.9 \times 3.6) \times 2$ $(r_{\rm eff} = 2.1$ m)
	NuMI	120	2.5×10^{21}	790		
SHiP [83]		400	2×10^{20}	70	50	5×10 $(r_{\rm eff} = 4.0$ m)
FASER 2 [84]		14000	1.1×10^{16} (LHC Run 3) 2.2×10^{17} (HL-LHC)	480	5	$r = 1$ m

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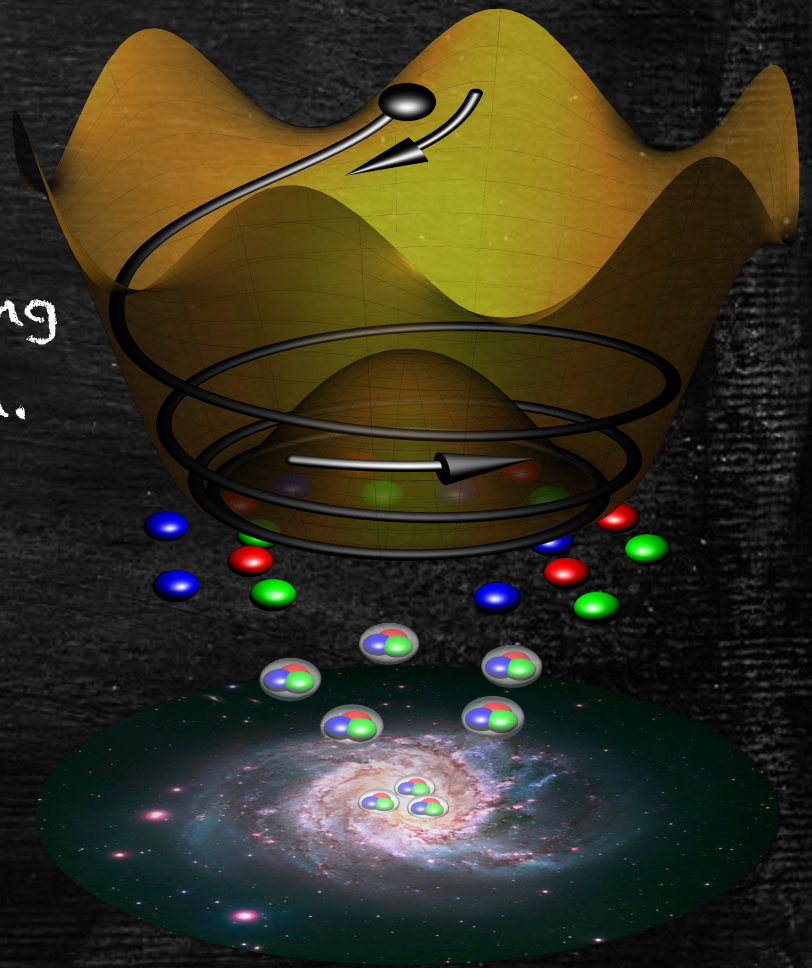
Conclusions

- ✓ New axion dynamics allows the QCD axion to simultaneously explain
  - ✓ the Strong CP problem
  - ✓ the dark matter abundance
  - ✓ the baryon asymmetry
- ✓ This paradigm predicts axion kination, featuring a triangular peak in gravitational wave spectra.
- ✓ Other possible signatures:
  - ✓ Warm axion dark matter
  - ✓ Matter power spectrum
- ✓ Heavy QCD axions are well motivated both theoretically and experimentally.



Thank you!

Happy birthday to Dimitri Nanopoulos!