Novel Cosmological Roles and Experimental Searches of (QCD) Axions

Raymond Co

Fine Theoretical Physics Institute

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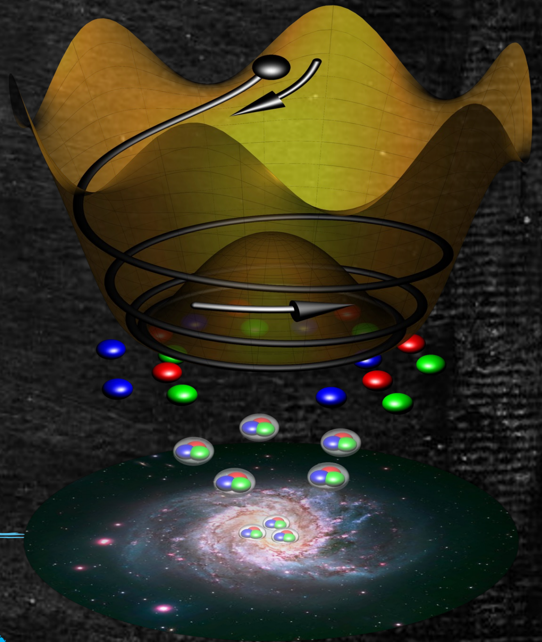


Baryon and Lepton Number Violation 2022
September 5th 2022

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
2206.00678	RC, Yann Mambrini, Keith Olive	PRD accepted
2207.08448	RC et al. and ArgoNeuT collaboration	
Soon.IHope	RC, Soubhik Kumar, Zhen Liu	

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

} Dark Matter

(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

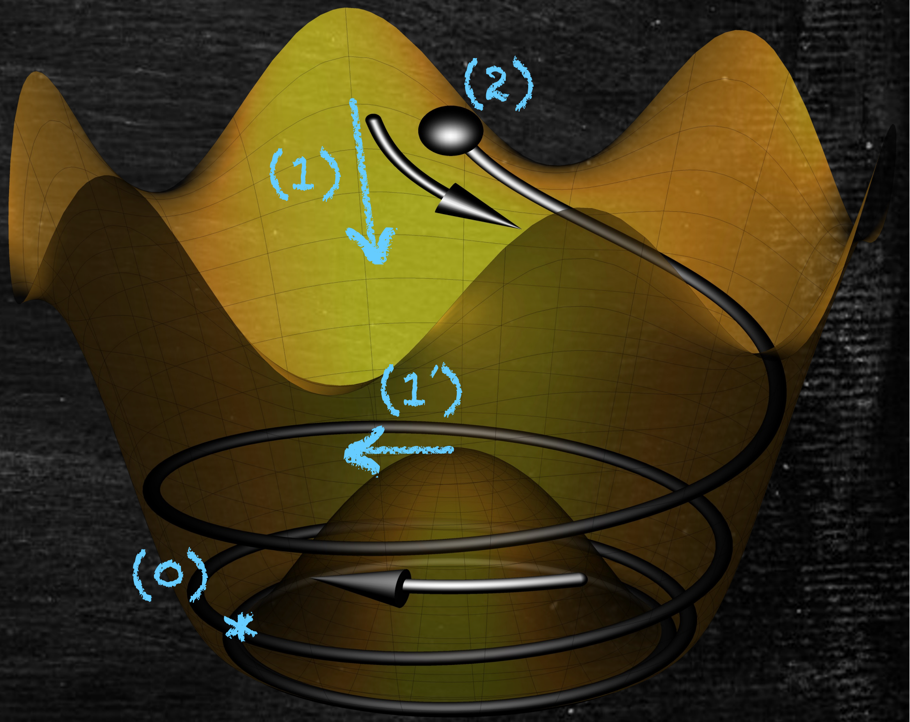
} Baryon Asymmetry

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

} Gravitational Waves

Possible initial conditions

Peccei-Quinn symmetry



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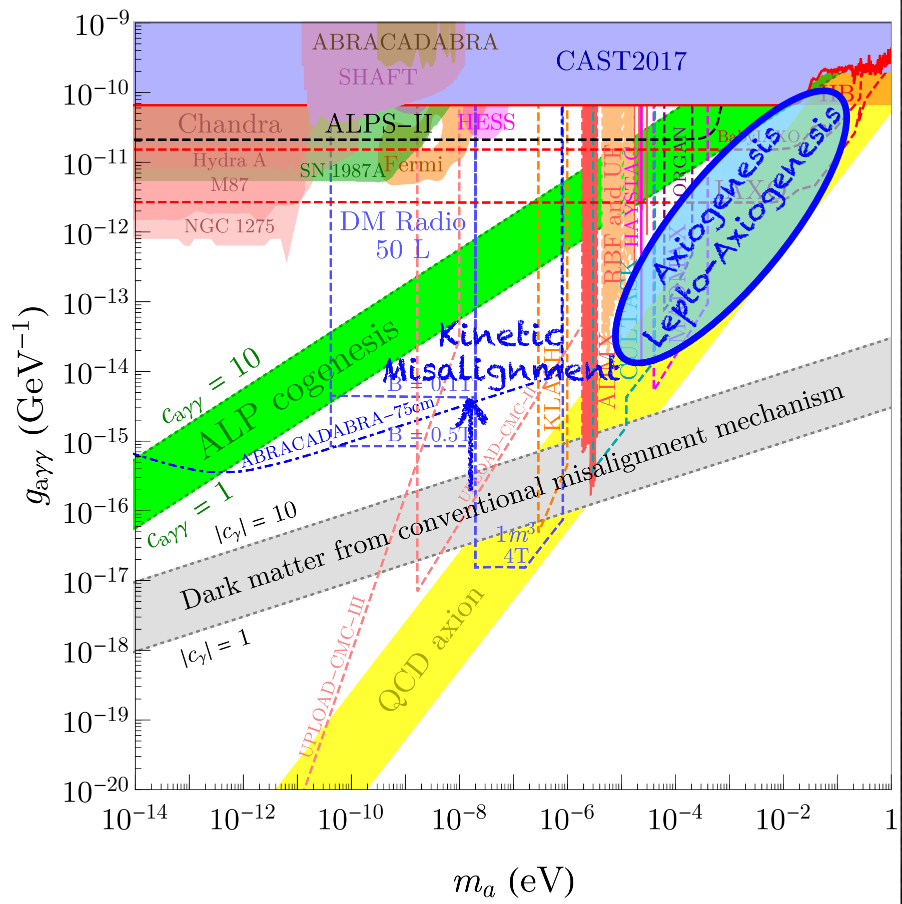
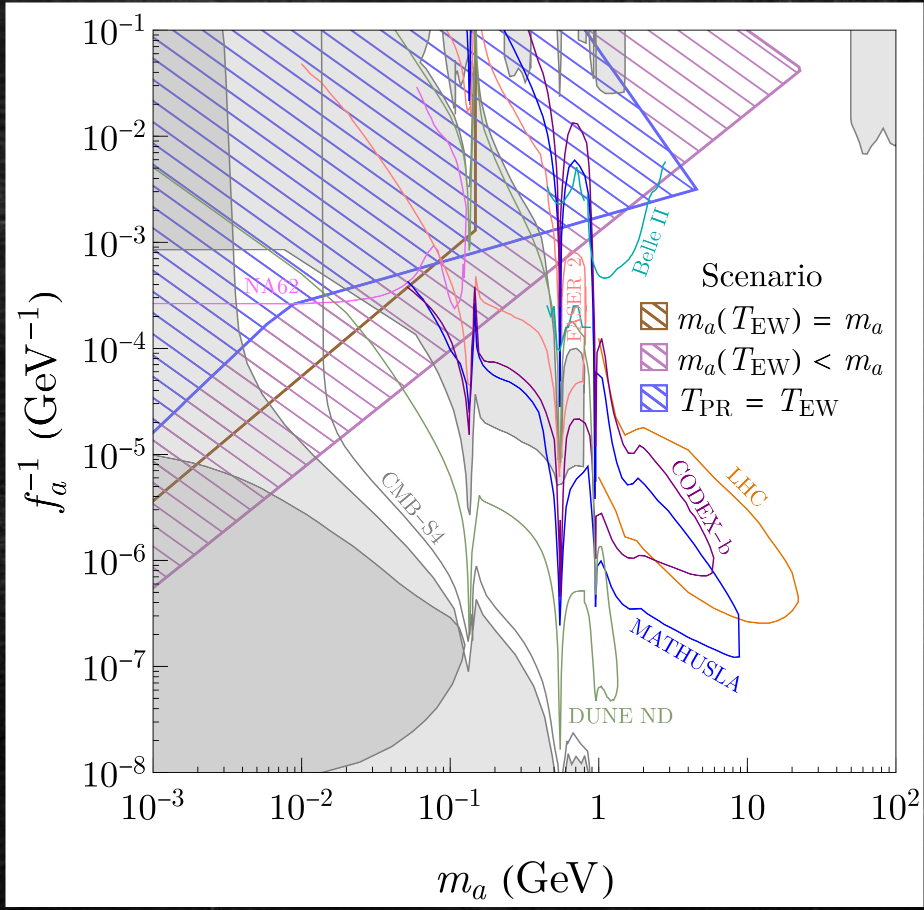
Predictions

ultralight axions



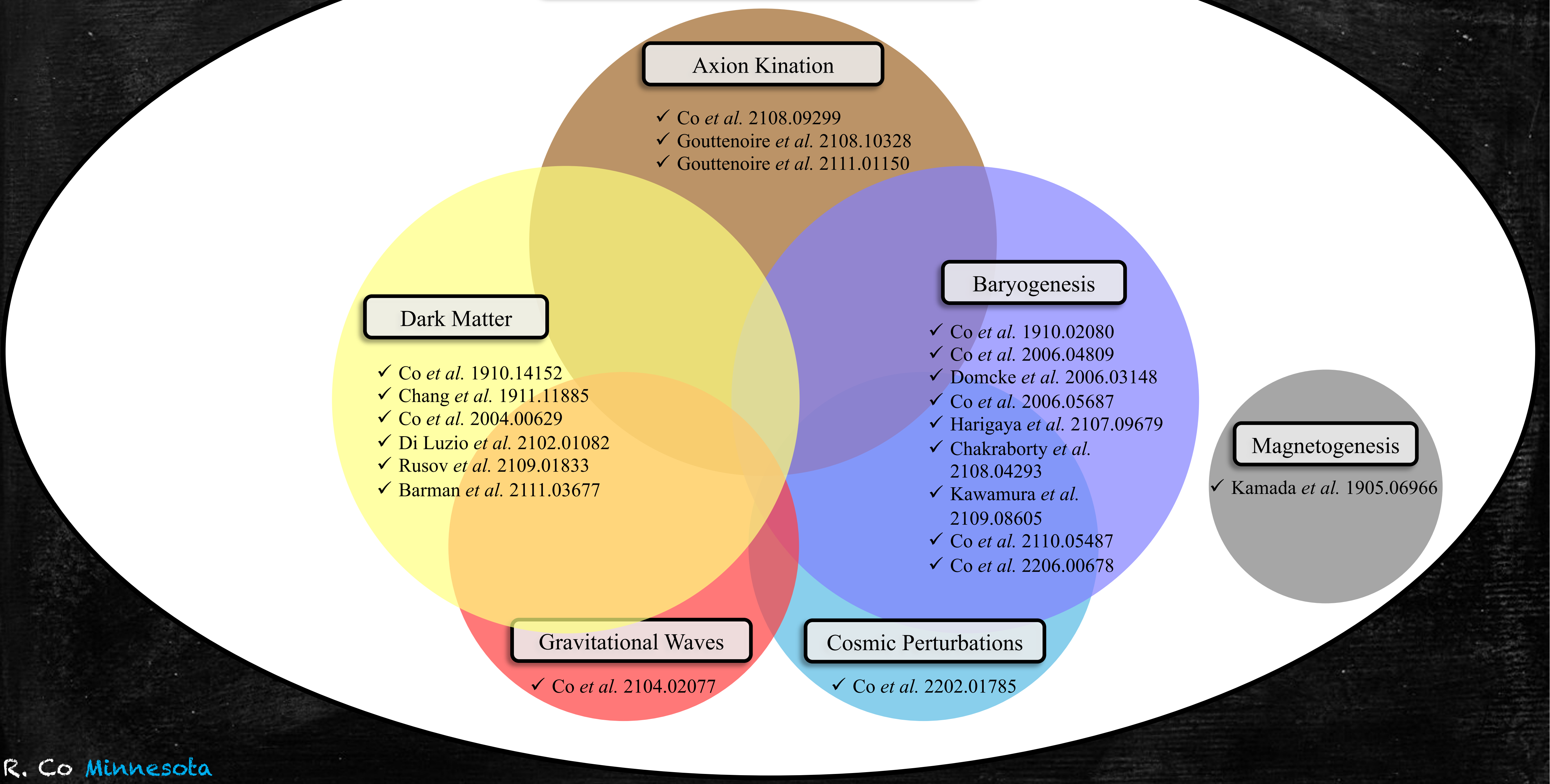
2006.04809 RC, L. Hall, K. Harigaya

heavy axions



2206.00678 RC, T. Gherghetta, K. Harigaya

Axion Rotations



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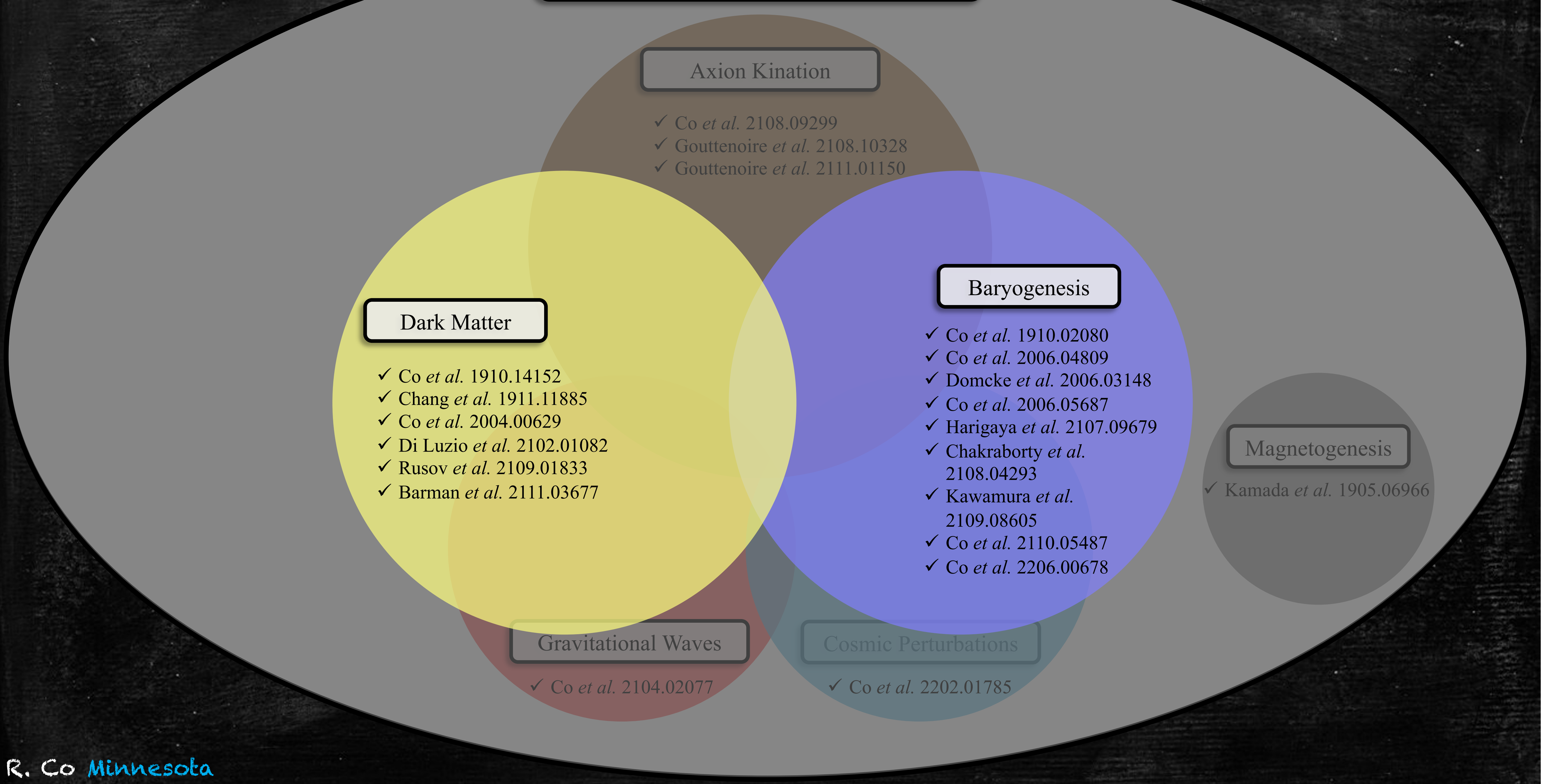
Axion Rotations



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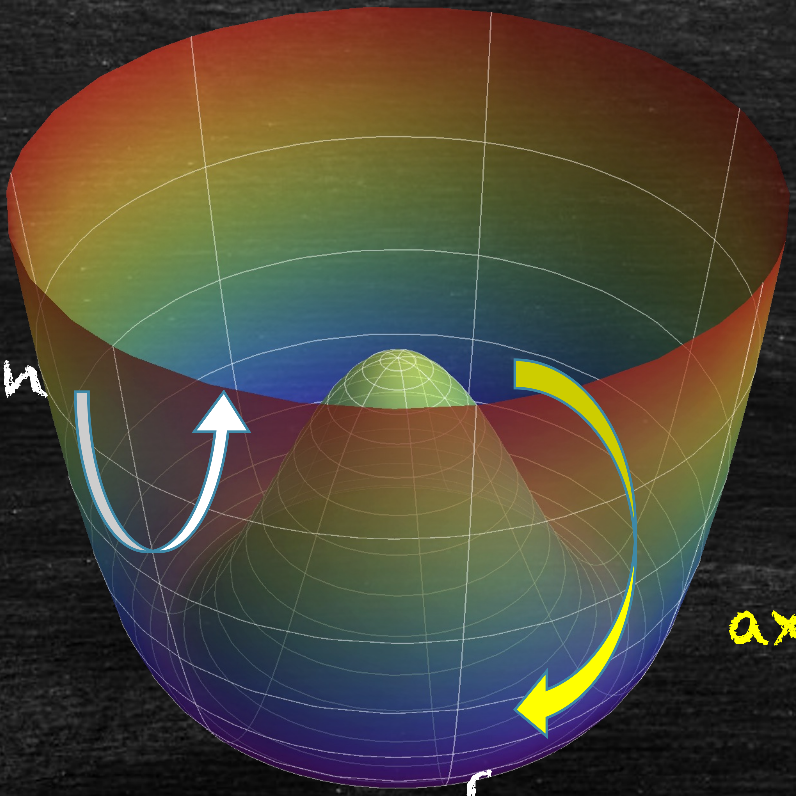
Axions

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



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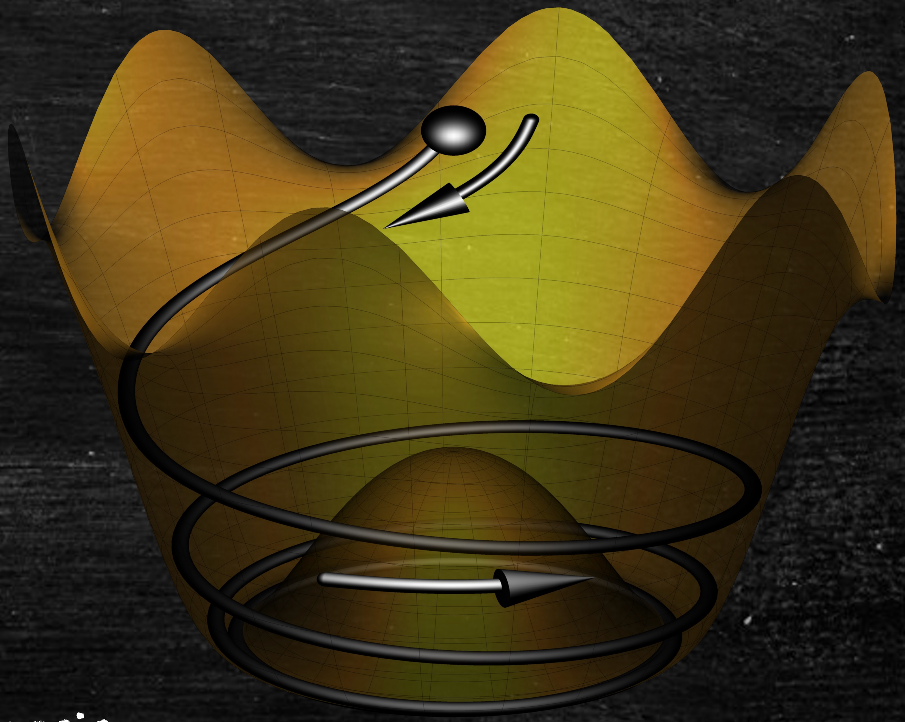
Why Rotation?

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

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

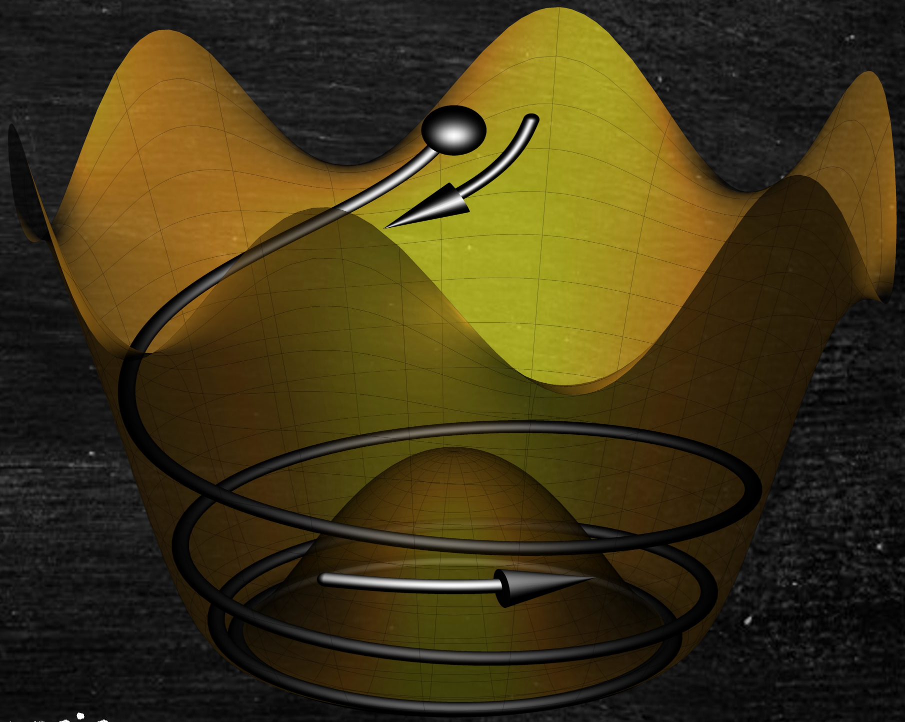
$$V(P) \sim \frac{P^n}{M^{n-4}} + \text{h.c.}$$

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

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

Initial condition



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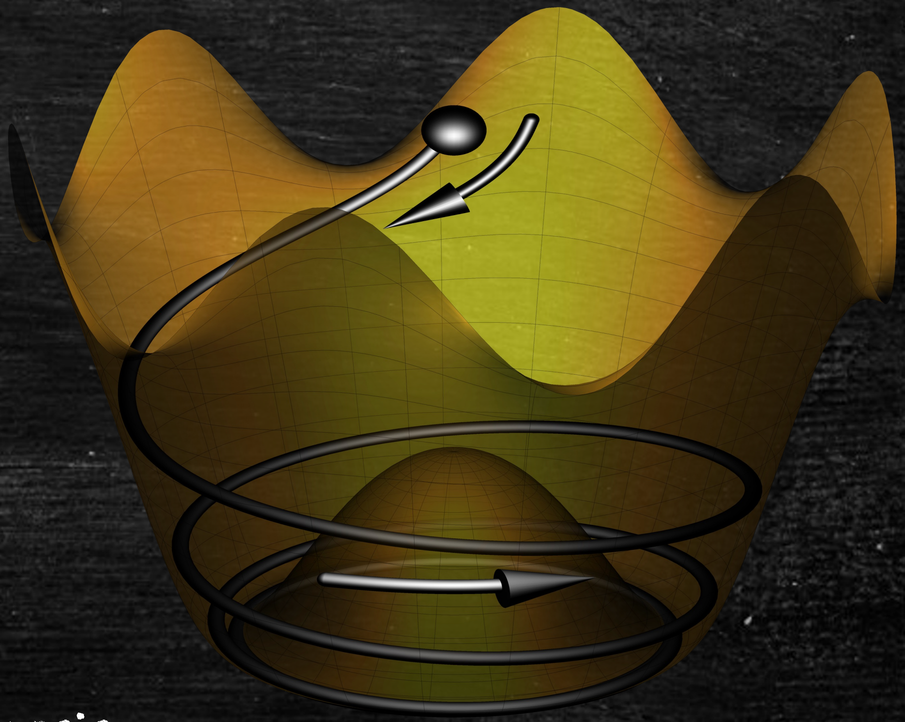

Large field value : Flat potential

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

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

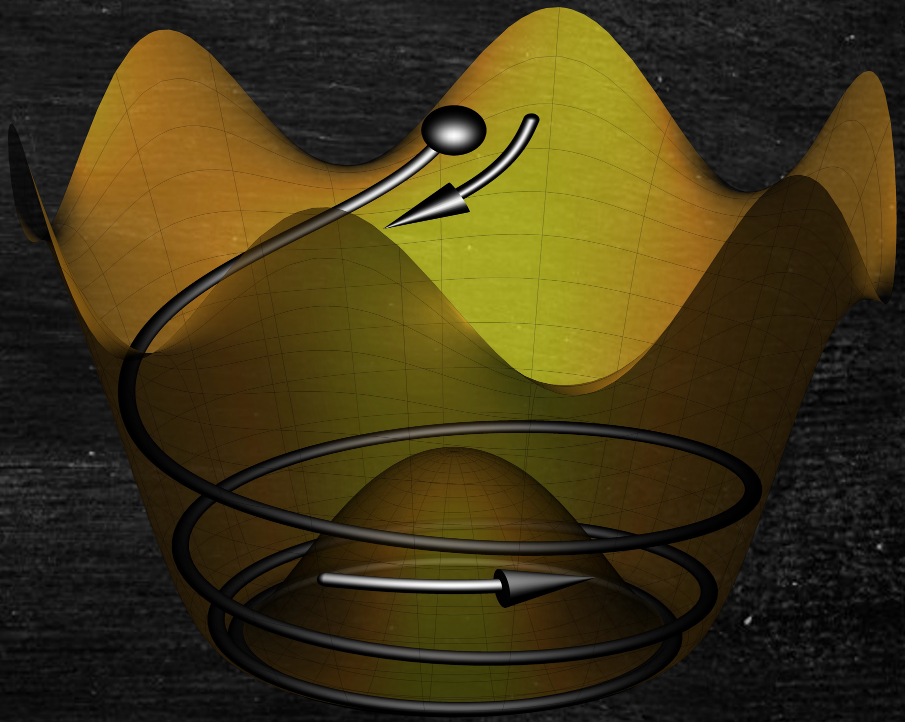
Asymmetry of PQ Charge

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

Noether charge associated with the shift symmetry

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

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



PQ asymmetry
PQ charge density = Rotation of PQ field

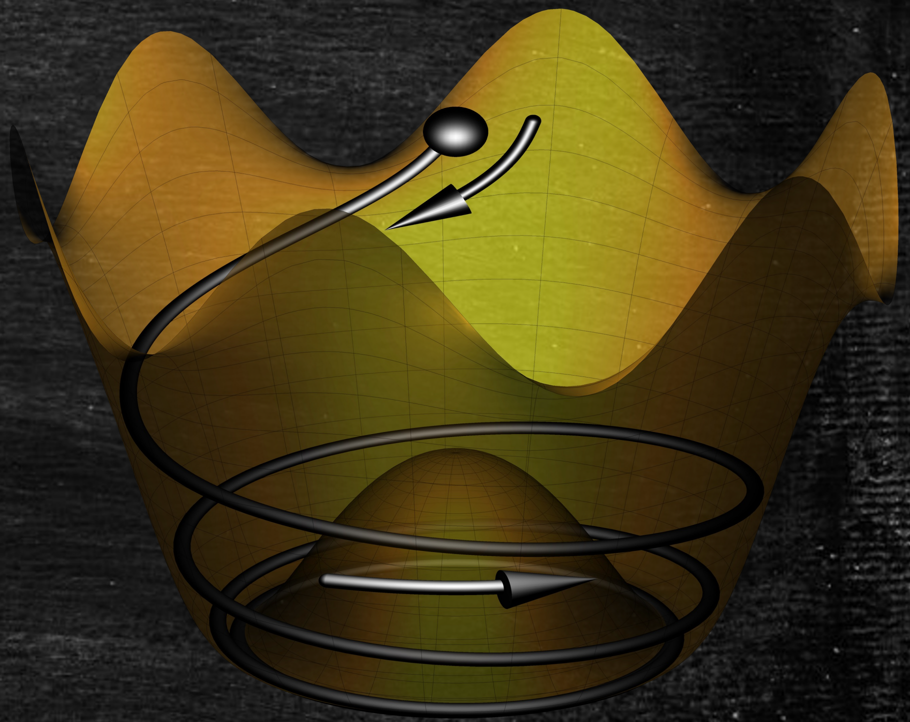
PQ charge is conserved soon after the onset.

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 = $ 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} = $ constant	$\rho_{\rm PQ} \propto R^{-3}$ ⟵ necessary to achieve kination domination

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

What is kination?

9306008 Boris Spokoiny
9606223 Michael Joyce

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

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

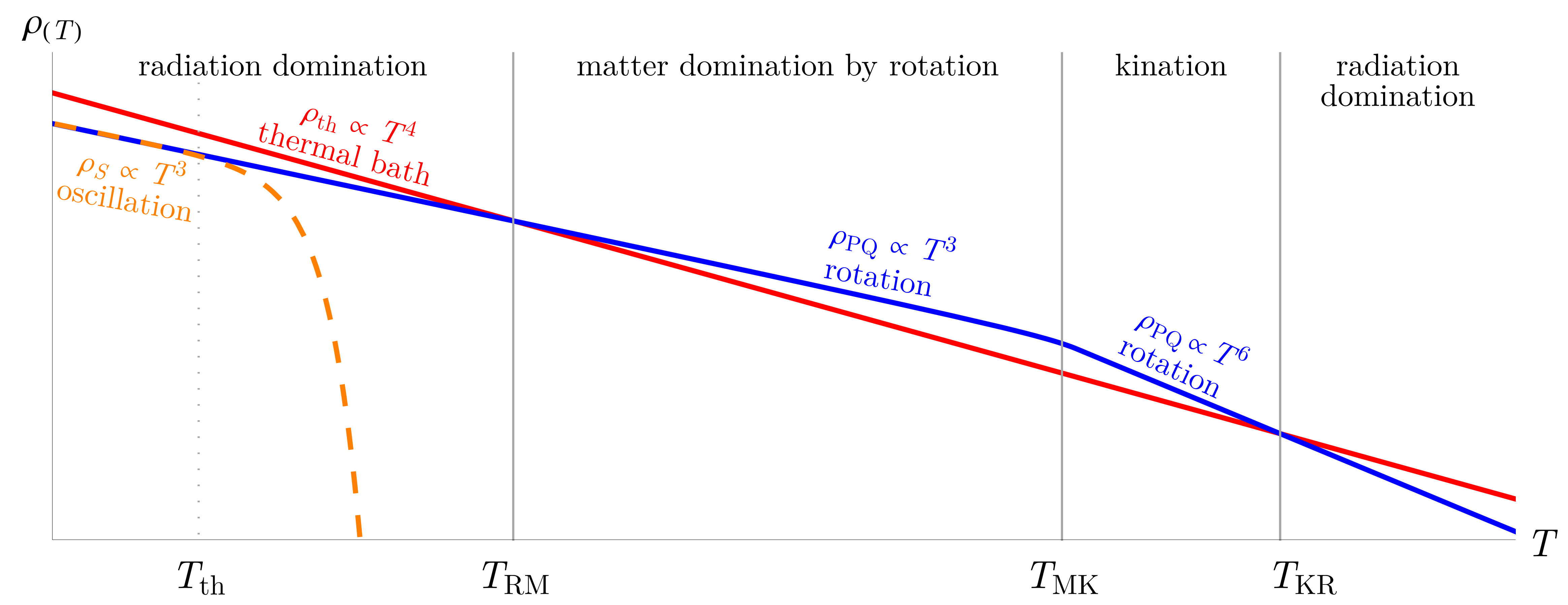
Equation of state

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

Evolution

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

Evolution of Energy Densities



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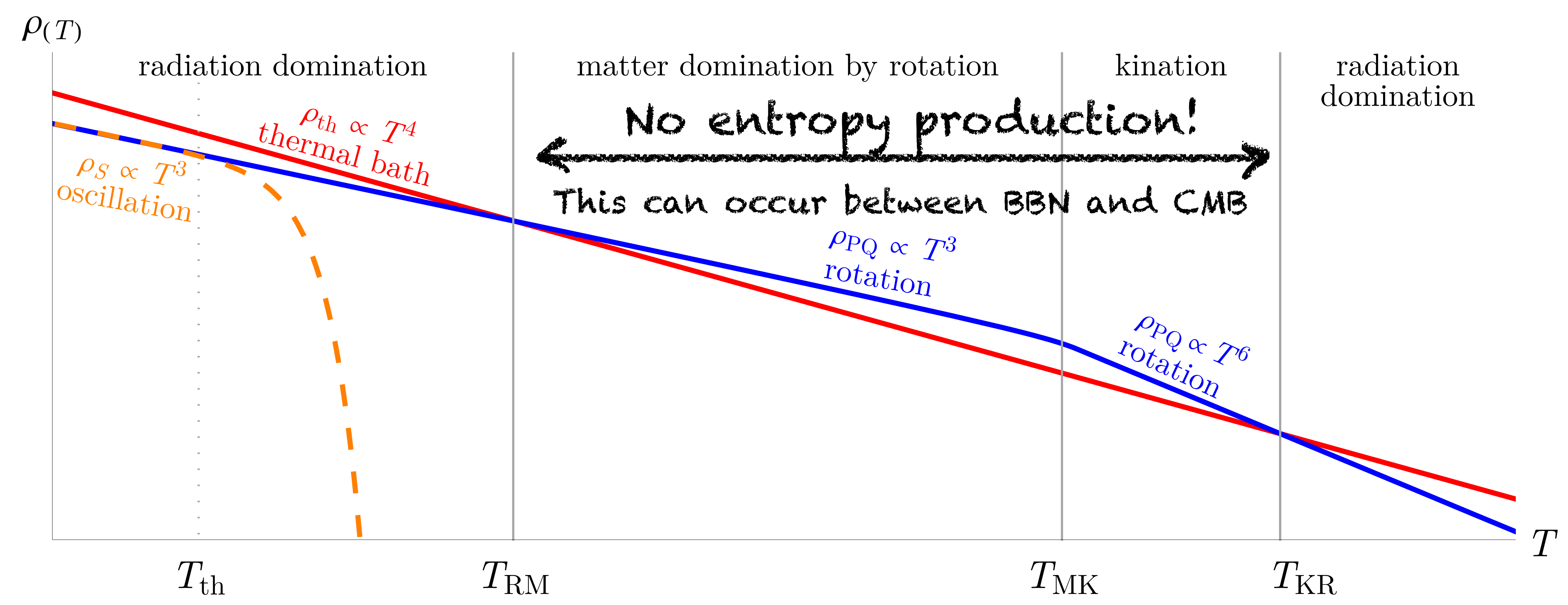
Evolution of Energy Densities



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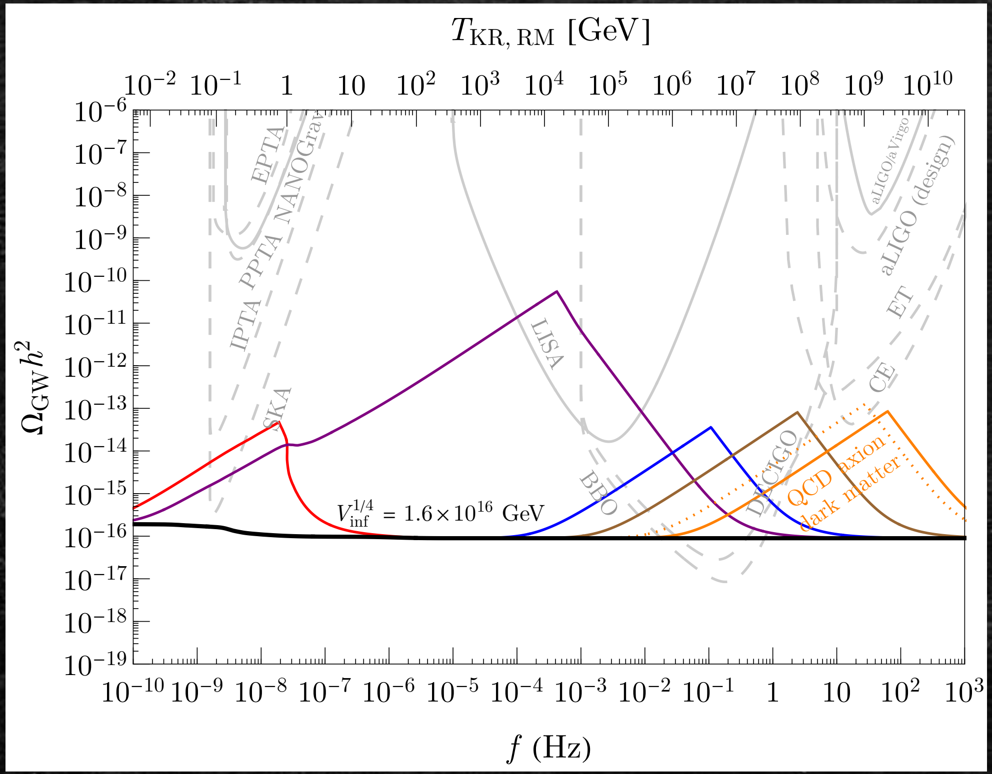
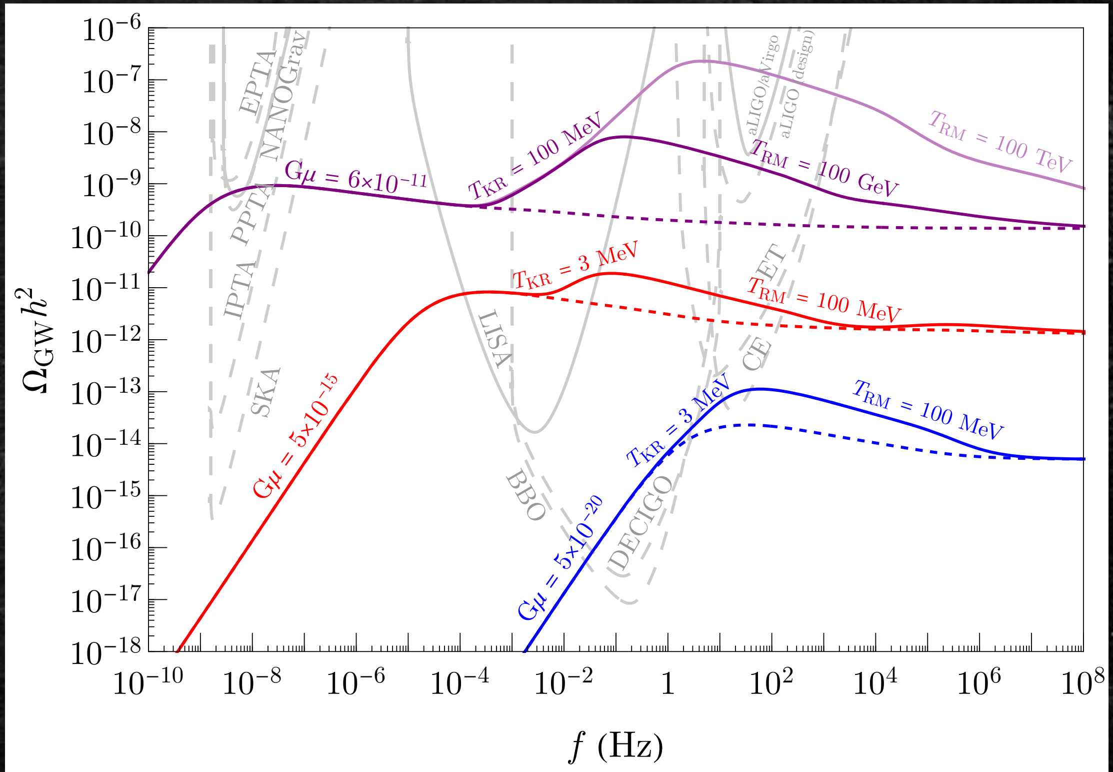
Triangular peak GW spectra from kination

from inflation



from cosmic strings



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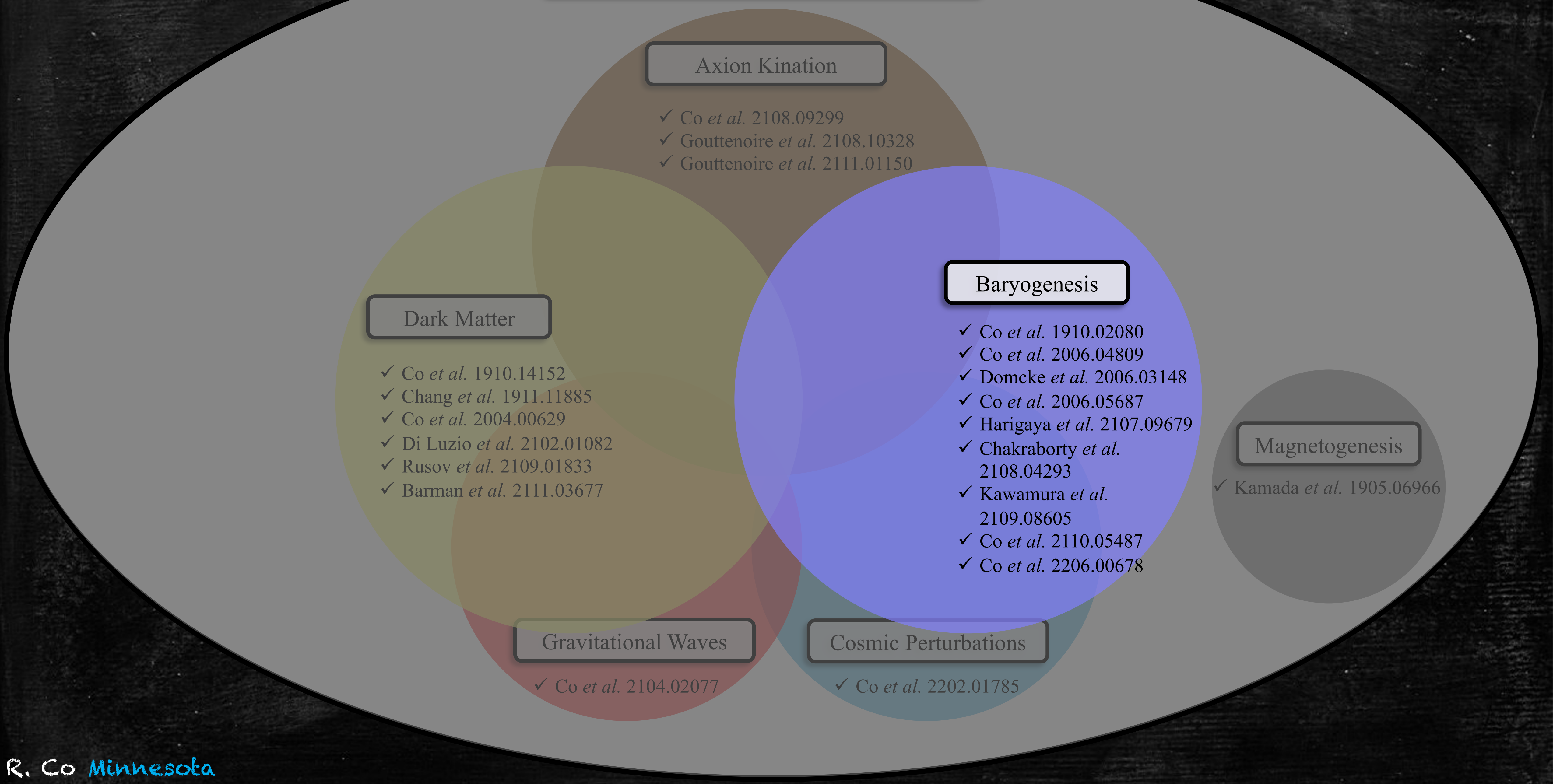
Axion Rotations



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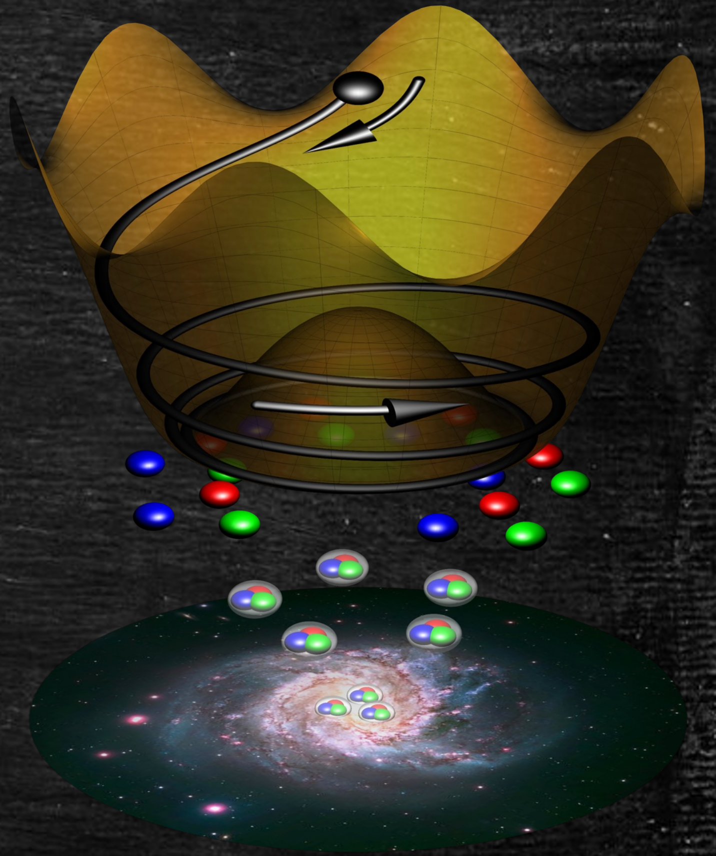
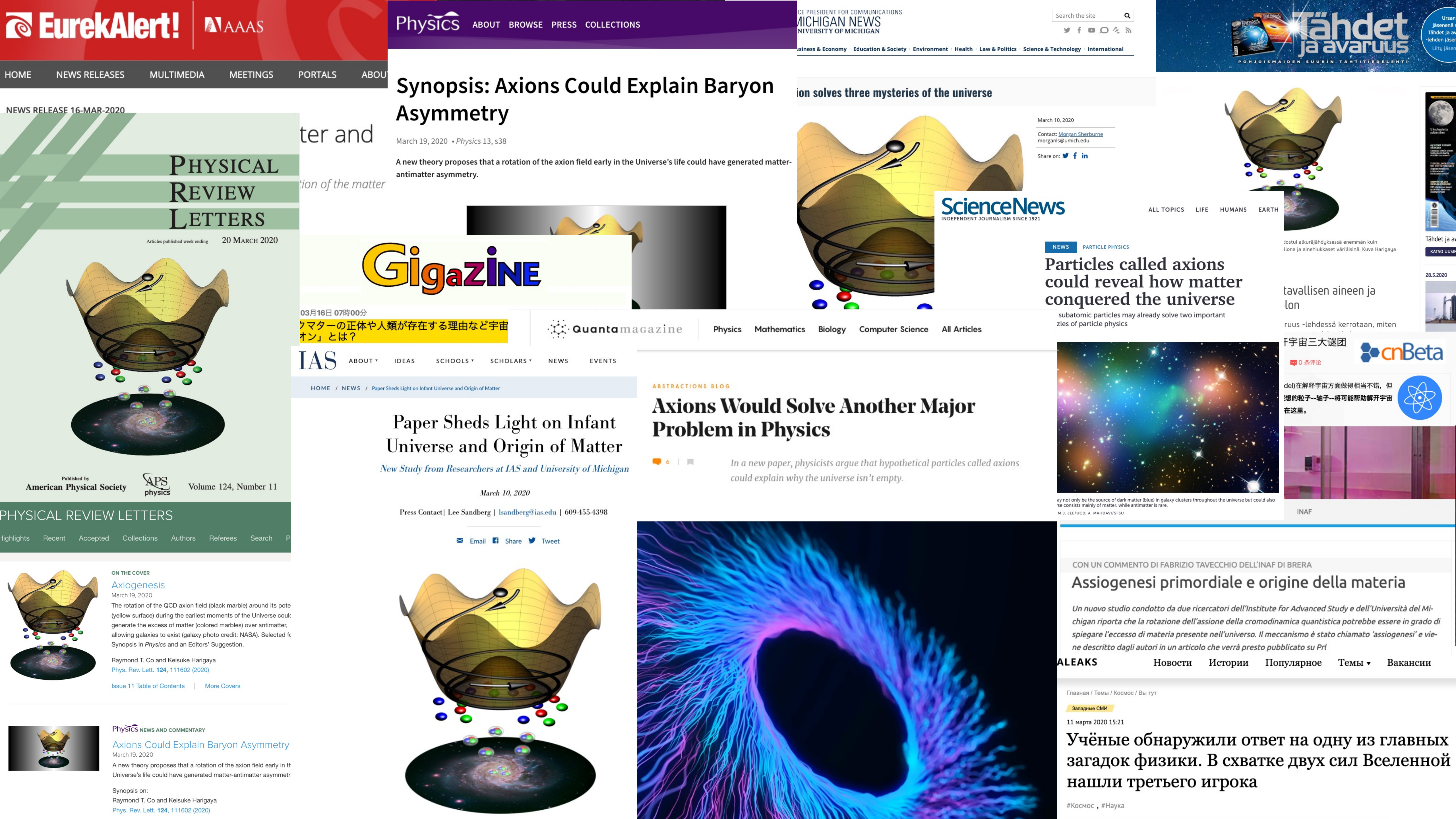


Axiogenesis

(QCD axion + baryogenesis)

PRL 124, 111602 (2020) RC and K. Harigaya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Volume 124, Number 11
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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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Axions Would Solve Another Major Problem in Physics
In a new paper, physicists argue that hypothetical particles called axions could explain why the universe isn't empty.
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ion solves three mysteries of the universe
March 10, 2020
Contact: Morgan Sherburne
morganls@umich.edu
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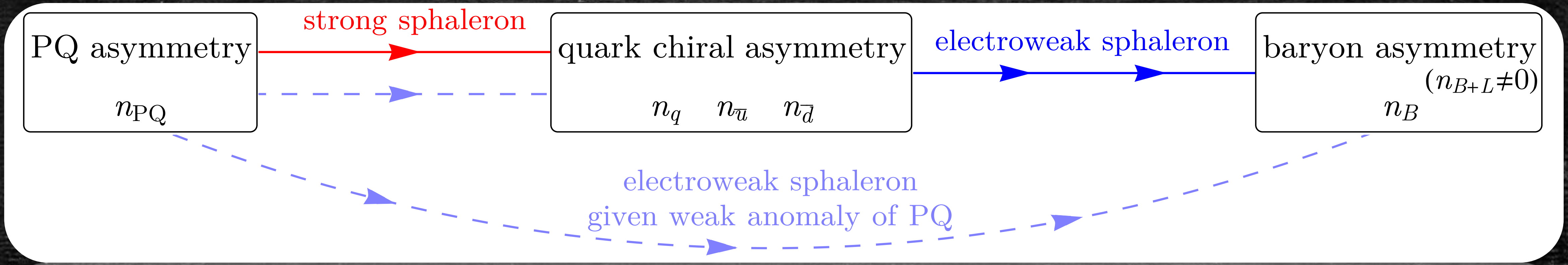
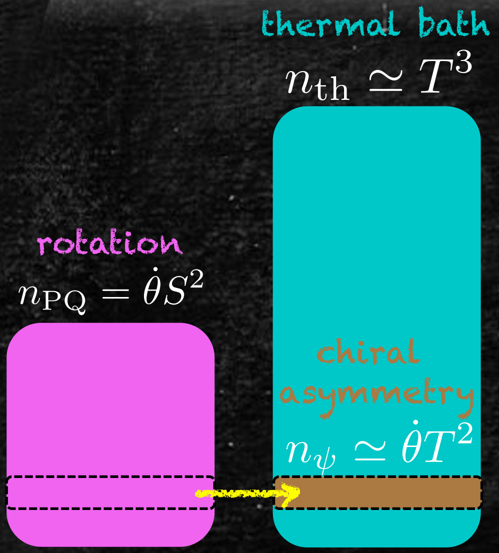
Particles called axions could reveal how matter conquered the universe
subatomic particles may already solve two important
zles of particle physics
ay not only be the source of dark matter (blue) in galaxy clusters throughout the universe but could also
se consists mainly of matter, while antimatter is rare.
M.J. JEE/UCD, A. MAHDAVI/SFSU
Tähdet ja avaruus
POHJOISMAIDEN SUURIN TÄHTITIEDELEHTI
tavallisen aineen ja
lon
ruus -lehdessä kerrotaan, miten
28.5.2020
宇宙三大谜团
cnBeta
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。
INAF
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
ALEAKS
Новости Истории Популярное Темы Вакансии
Главная / Темы / Космос / Вы тут
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

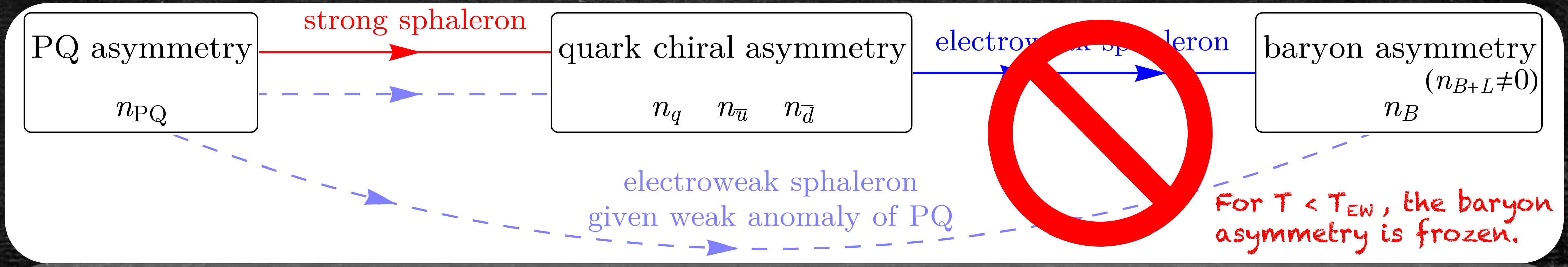


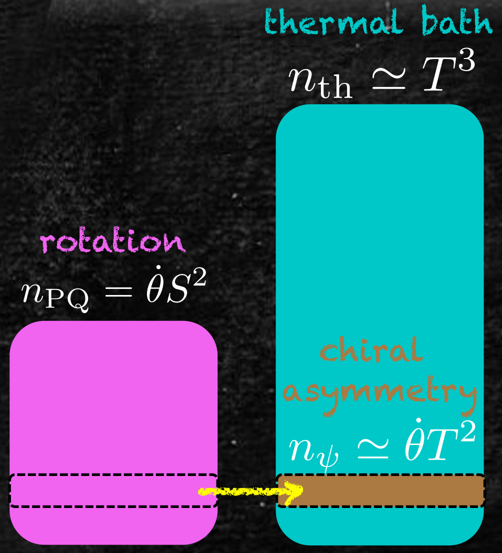


$$Y_B \equiv \frac{n_B}{s} = \frac{c_B \dot{\theta} T^2}{s}$$

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

Axiogenesis



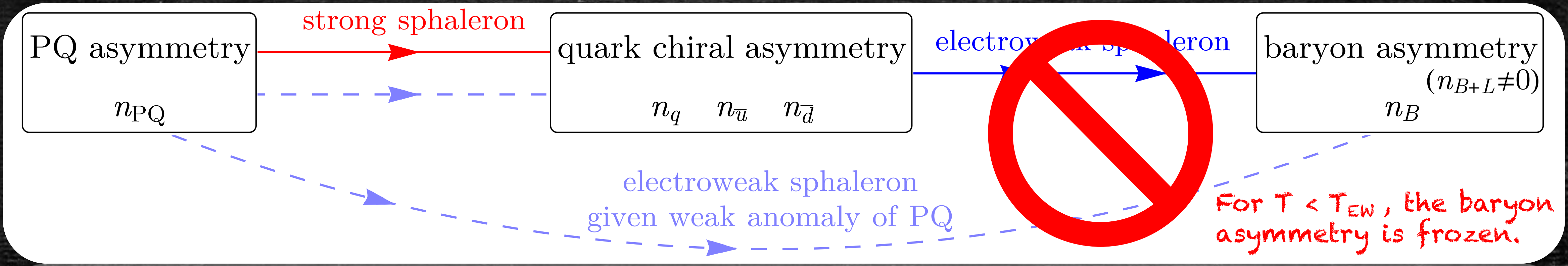


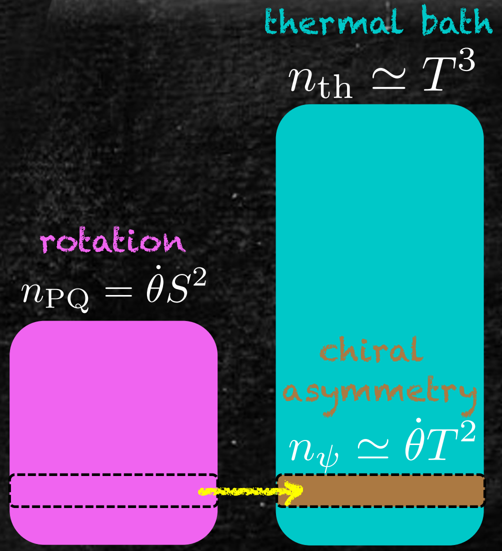
$$Y_B \equiv \frac{n_B}{s} = \frac{c_B \dot\theta T^2}{s}\Bigg|_{T = T_{\rm EW}} = c_B Y_{\rm PQ} \left(\frac{T_{\rm EW}}{f_a}\right)^2$$

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

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

Axiogenesis



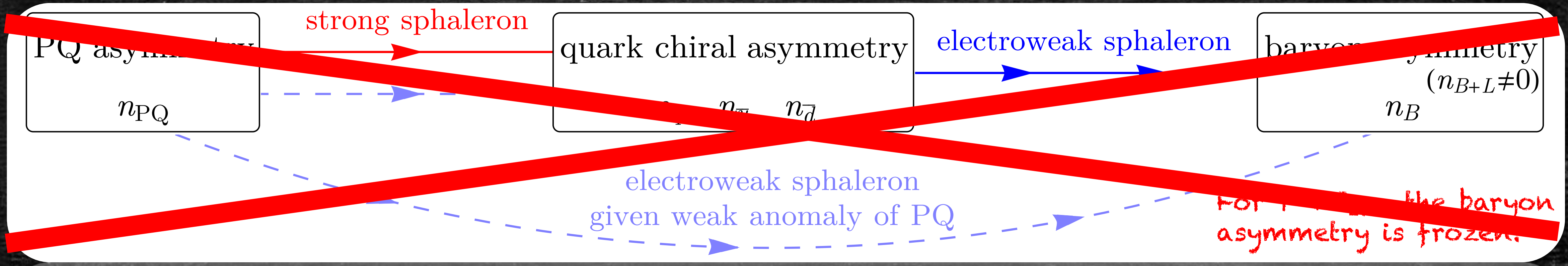


$$Y_B \simeq 10^{-10} \left(\frac{c_B}{0.1}\right) \left(\frac{T_{\rm EW}}{130\ {\rm GeV}}\right)^2 \left(\frac{10^8\ {\rm GeV}}{f_a}\right)^2 \left(\frac{Y_{\rm PQ}}{500}\right)$$

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

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

Extensions of Axiogenesis



Lepto-Axiogenesis

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

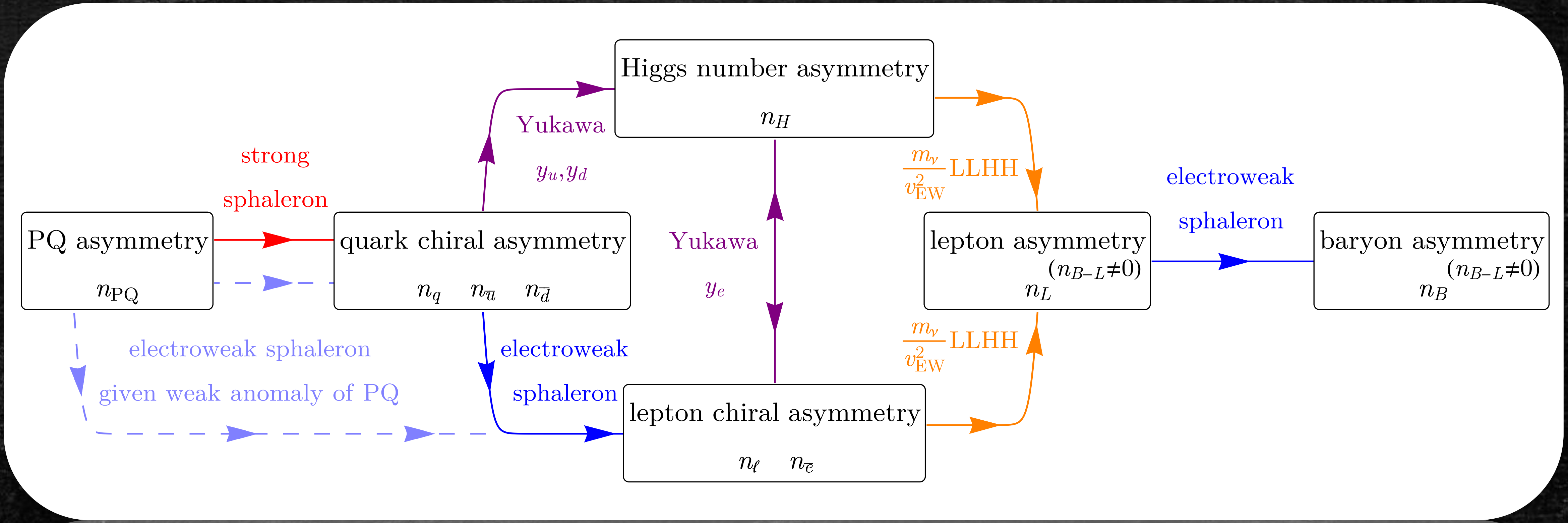
2006.05687 RC, N. Fernandez, A. Ghalsasi, L. Hall, K. Harigaya

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

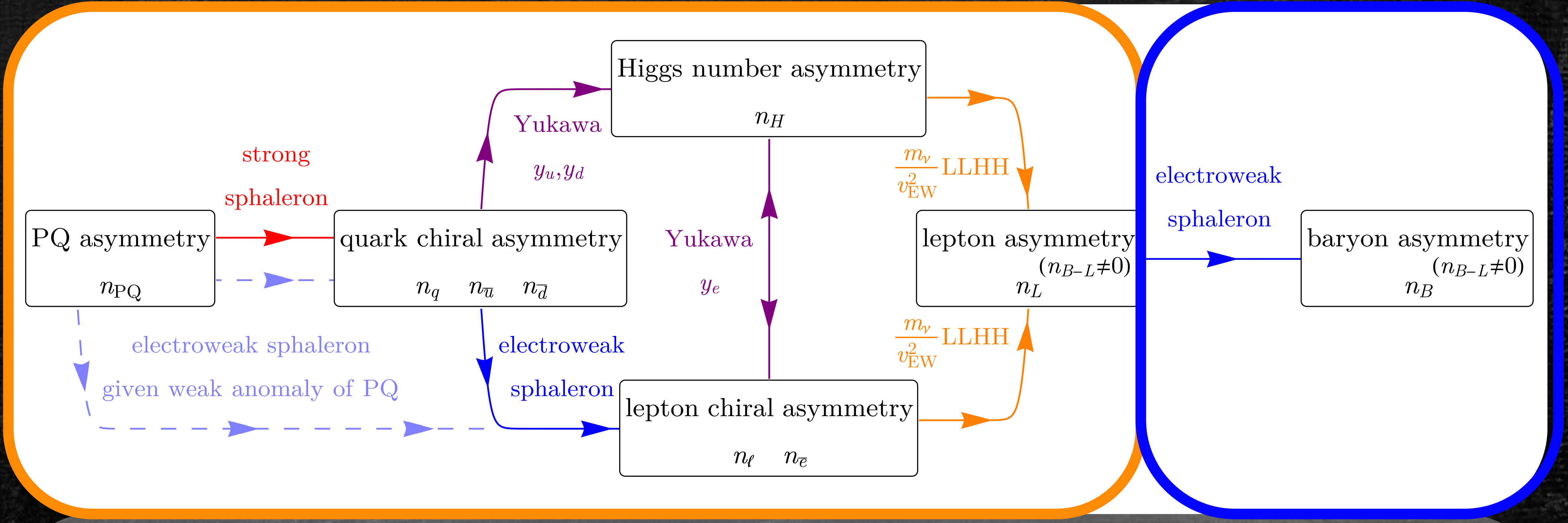


2006.05687 RC, N. Fernandez, A. Ghalsasi, L. Hall, K. Harigaya

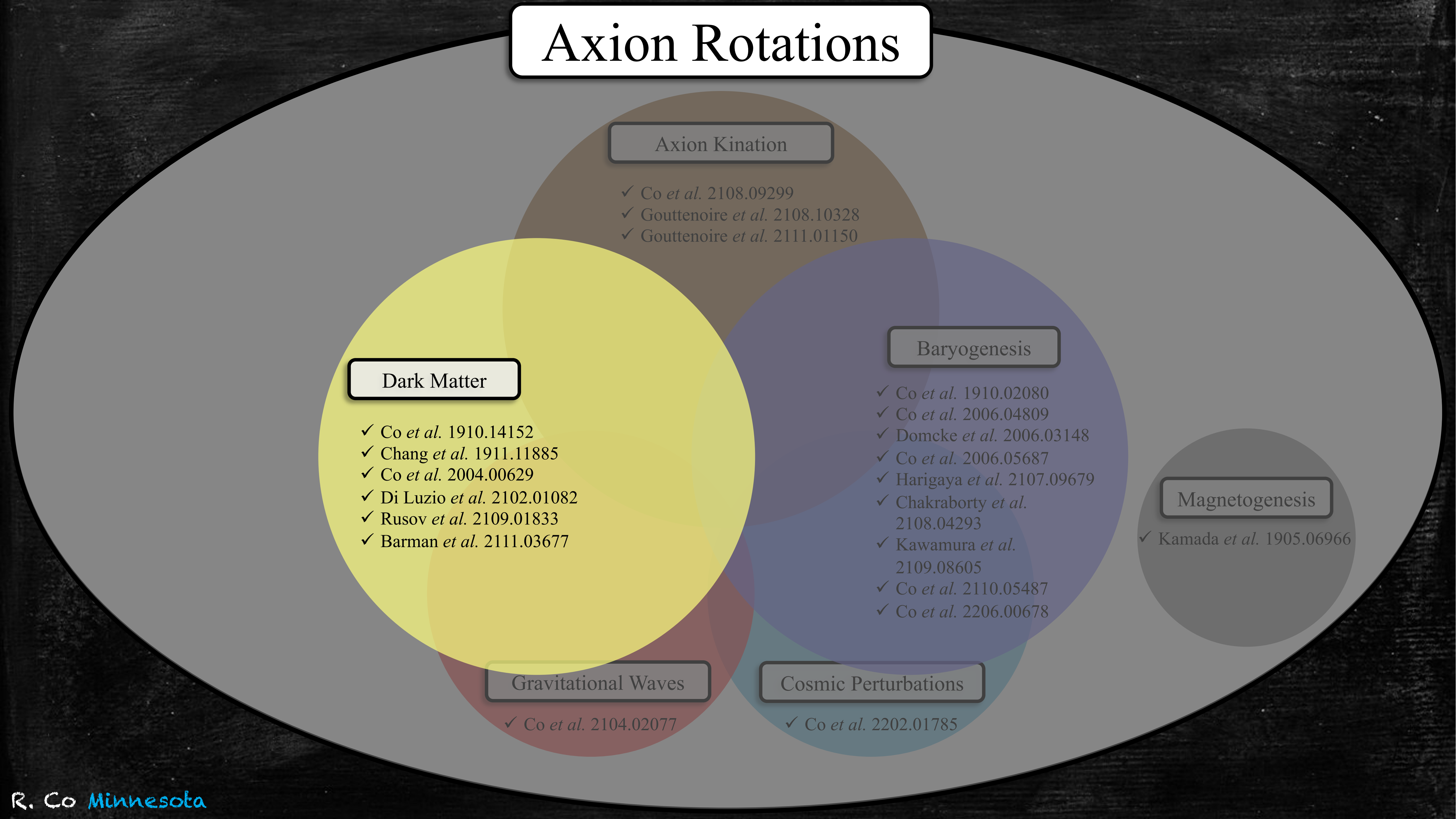
Lepto-Axiogenesis

Producing L at high temperatures

Converting to B at T_{EW}



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



Axion Rotations
Axion Kination
✓ Co et al. 2108.09299
✓ Gouttenoire et al. 2108.10328
✓ Gouttenoire et al. 2111.01150
Dark Matter
✓ Co et al. 1910.14152
✓ Chang et al. 1911.11885
✓ Co et al. 2004.00629
✓ Di Luzio et al. 2102.01082
✓ Rusov et al. 2109.01833
✓ Barman et al. 2111.03677
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✓ Domcke et al. 2006.03148
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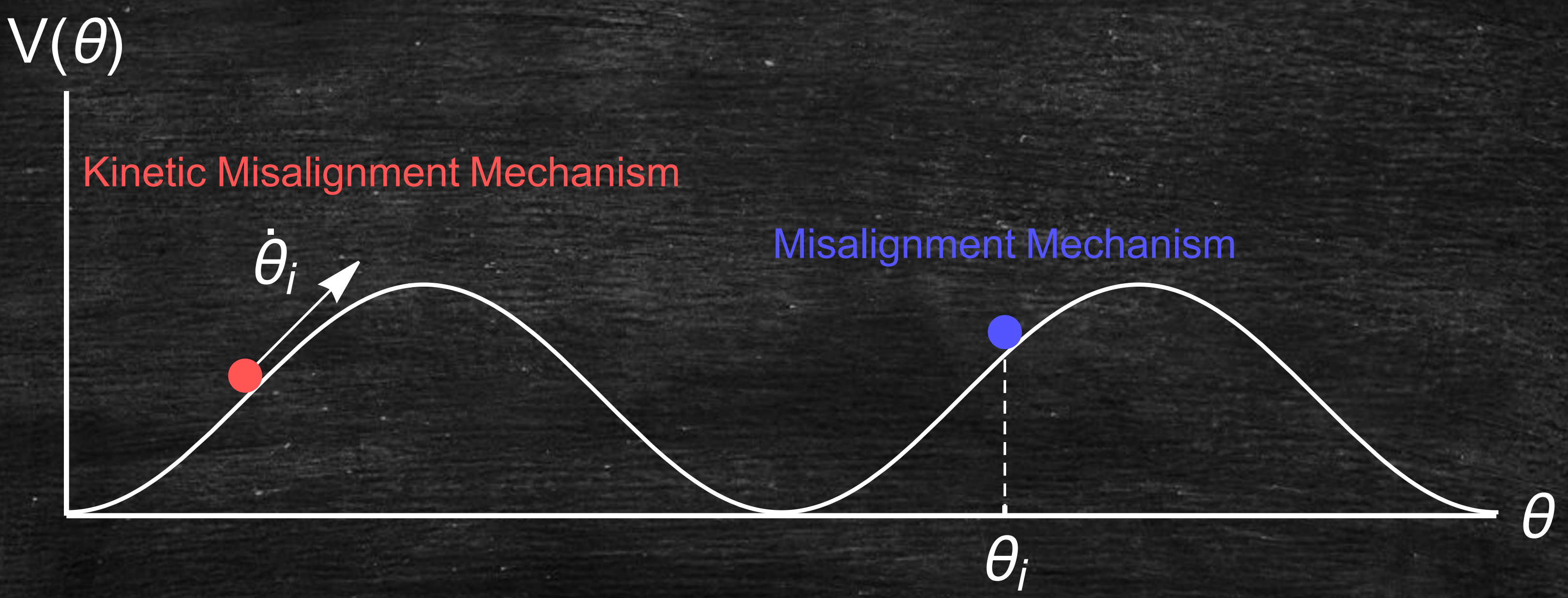
✓ Kawamura et al. 2109.08605
✓ Co et al. 2110.05487
✓ Co et al. 2206.00678
Magnetogenesis
✓ Kamada et al. 1905.06966
Gravitational Waves
✓ Co et al. 2104.02077
Cosmic Perturbations
✓ Co et al. 2202.01785
R. Co Minnesota



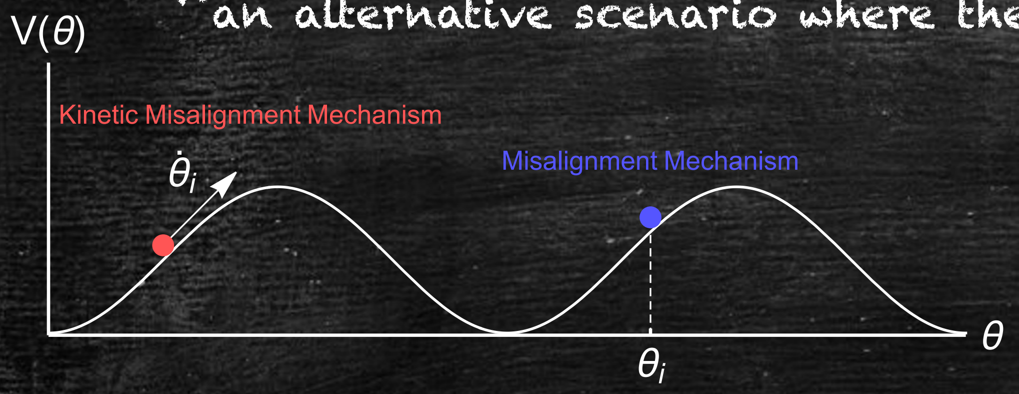
Kinetic Misalignment Mechanism

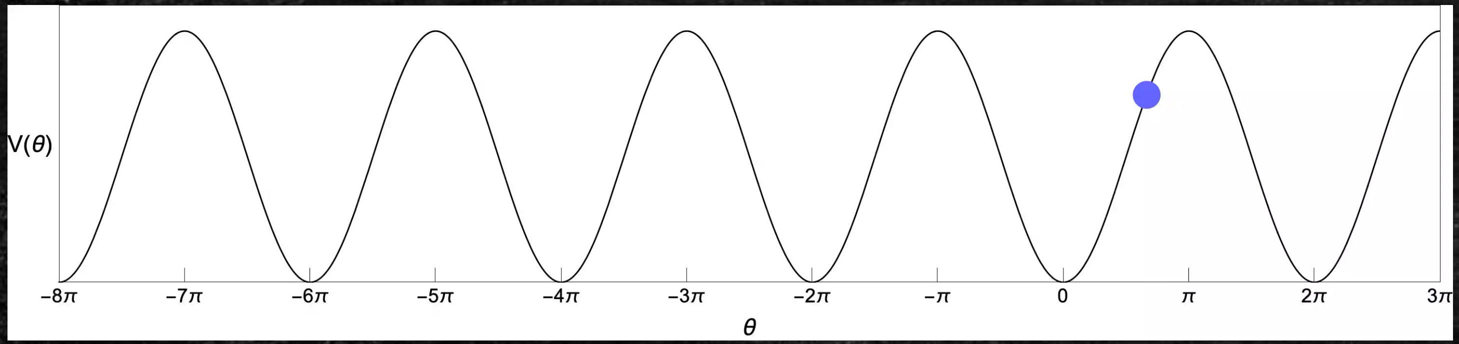
(Misalignment + non-zero kinetic energy)

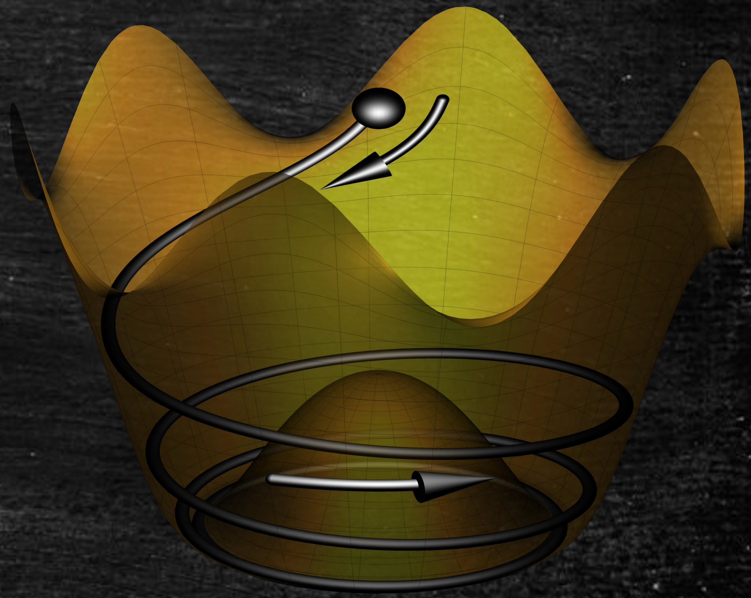
PRL 124, 251802 (2020) RC, L. Hall, K. Harigaya

Kinetic Misalignment Mechanism

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





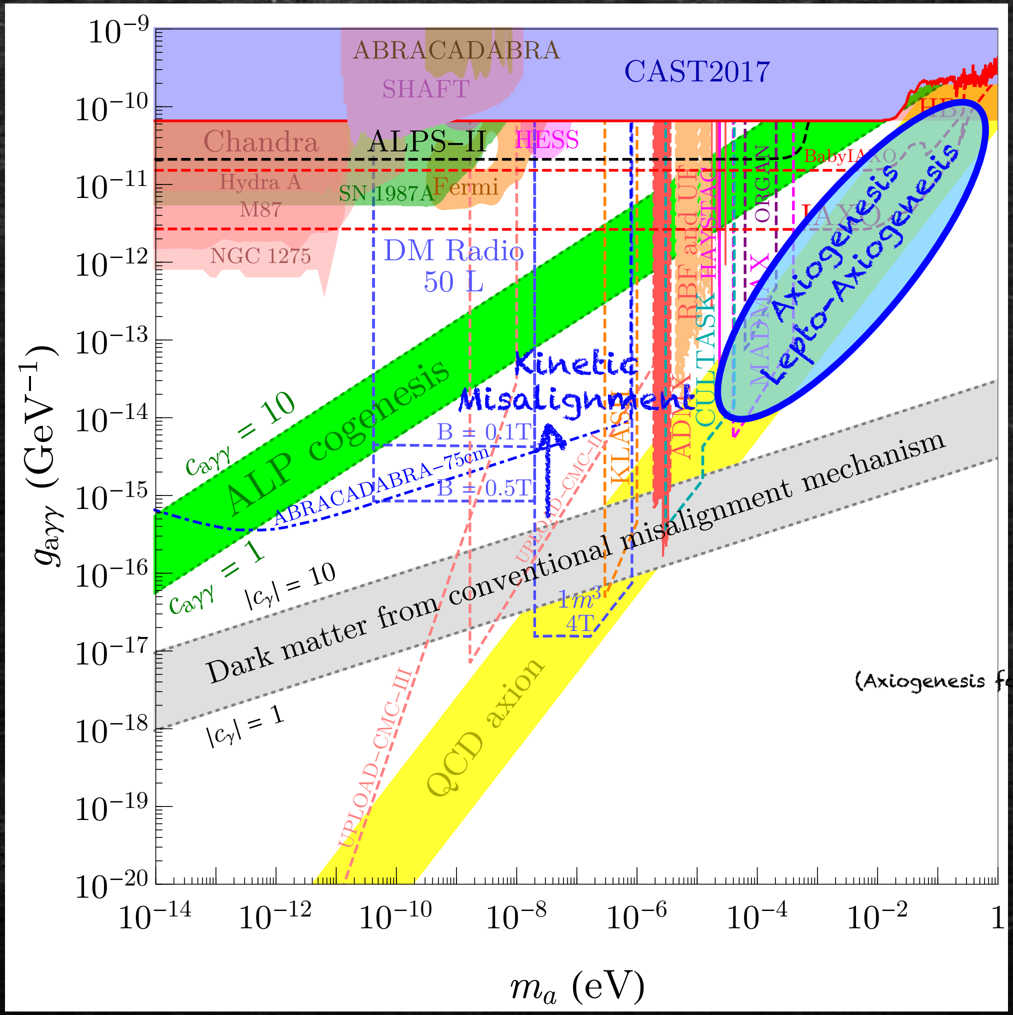


Abundance: $$\frac{\rho_a}{s} = C m_a Y_{\rm PQ}$$

$$\Omega_a h^2 \simeq \Omega_{\rm DM} h^2 \left(\frac{m_a}{\rm meV}\right)\left(\frac{Y_{\rm PQ}}{440}\right)$$

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

Predictions from Axiogenesis and Kinetic Misalignment



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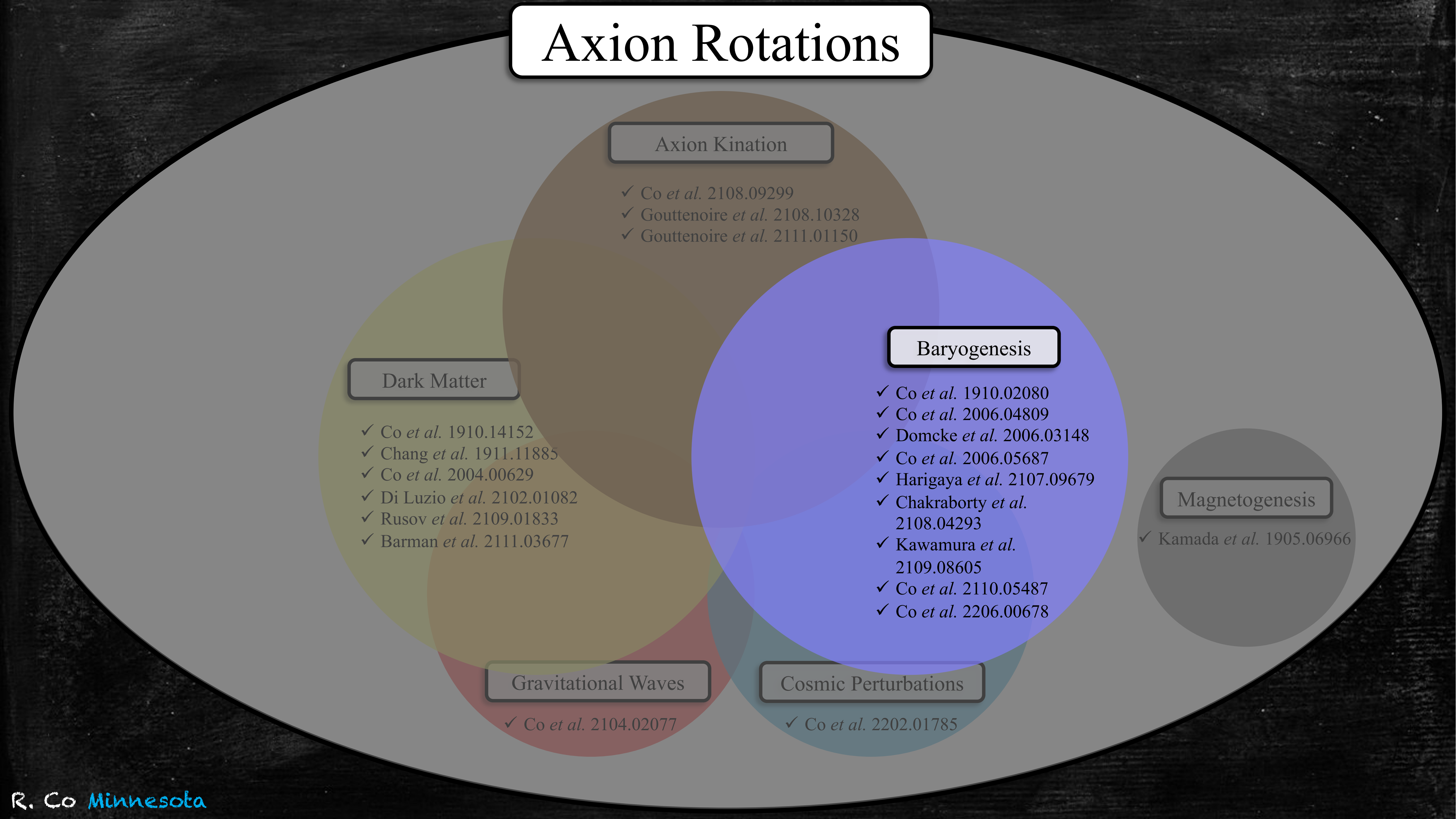
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Cosmic Perturbations
✓ Co et al. 2202.01785
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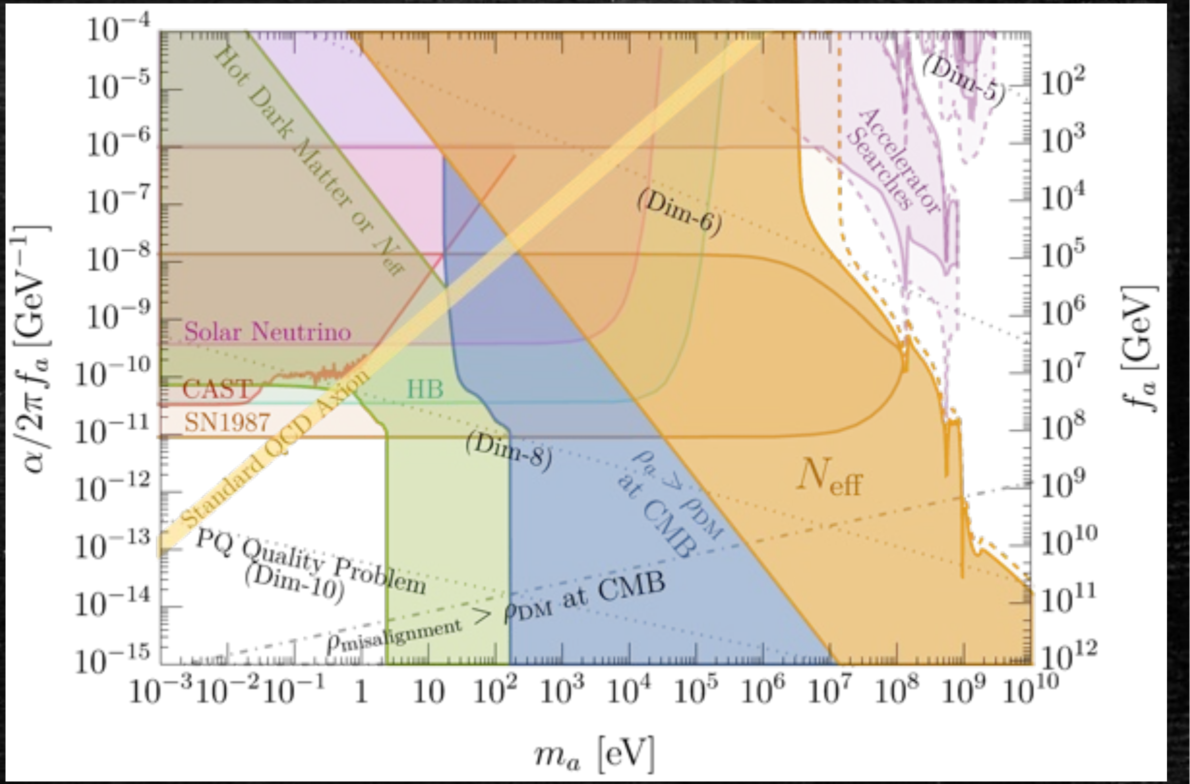
Heavy QCD Axion

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

- ✓ **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

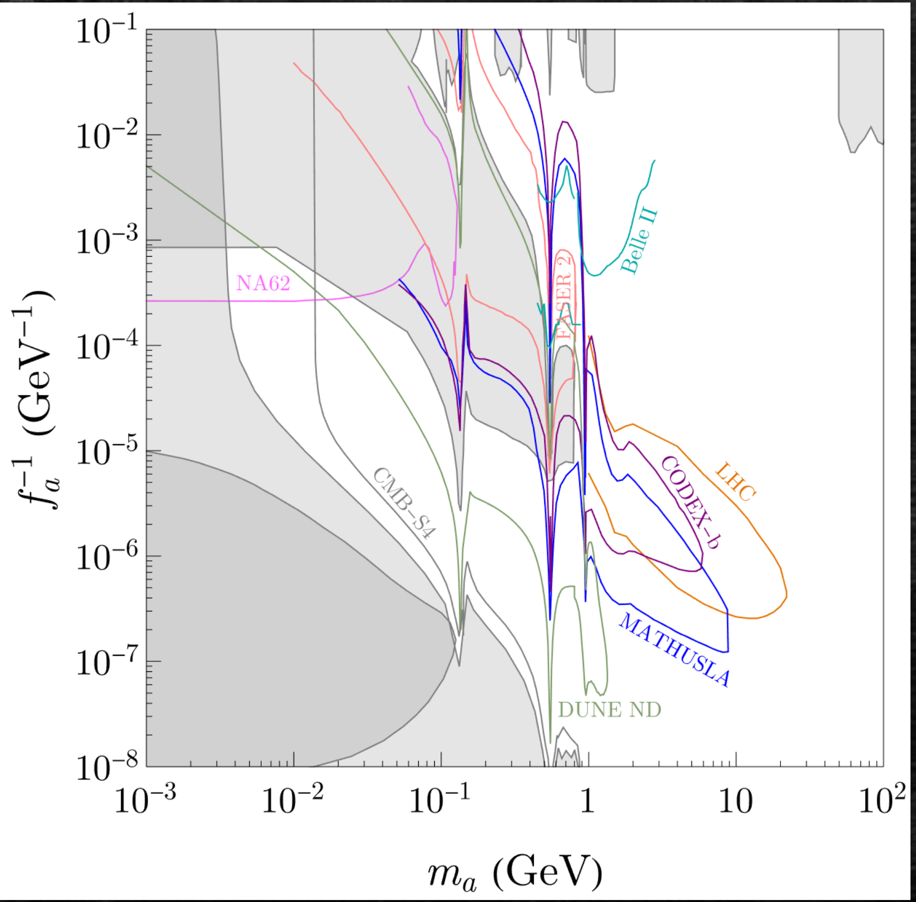
- ✓ **Model constructions**
  - ✓ 4D UV instantons — P. Agrawal et al. 2017, C. Csaki et al. 2019
  - ✓ 5D UV instantons — T. Gherghetta et al. 2020
  - ✓ Mirror QCD — V. Rubakov 1997, Z. Berezhiani et al. 2000, A. Hook 2014, H. Fukuda et al. 2015, A. Hook et al. 2019

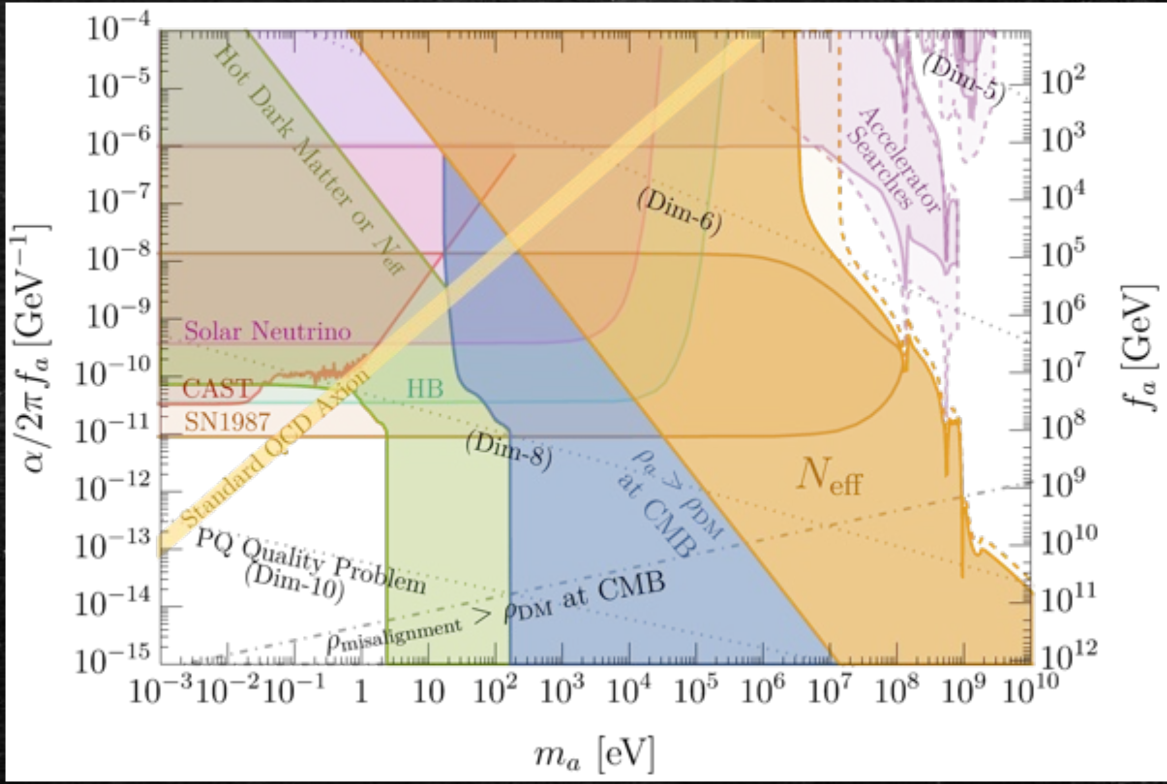


2205.11540 D. Dunsky, K. Harigaya, L. Hall

Heavy QCD Axion

✓ New theoretical and experimental opportunities





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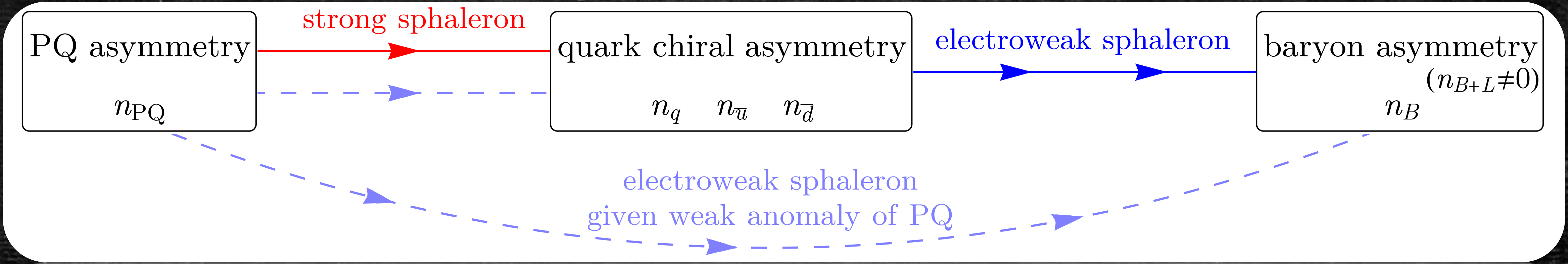
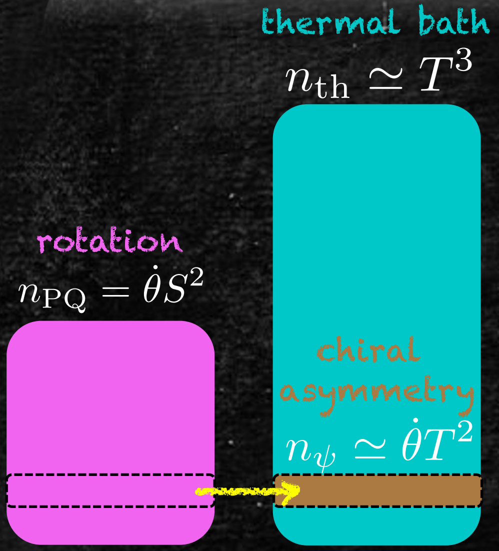
Axiogenesis with Heavy QCD Axion

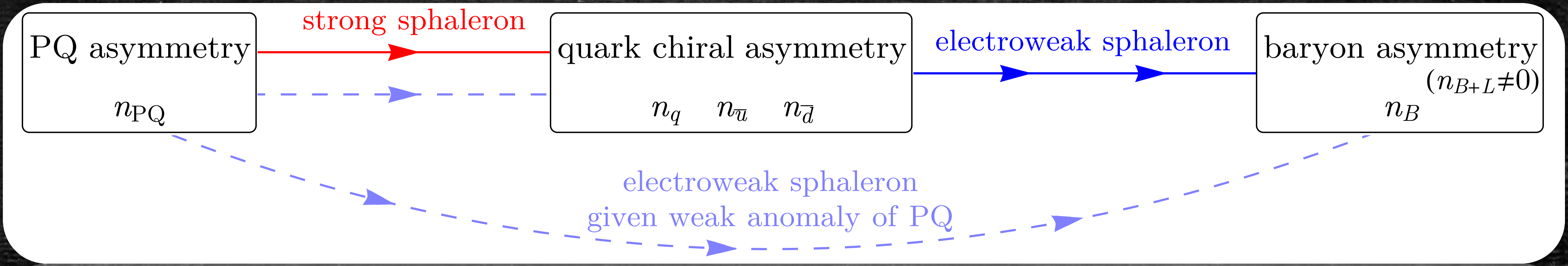


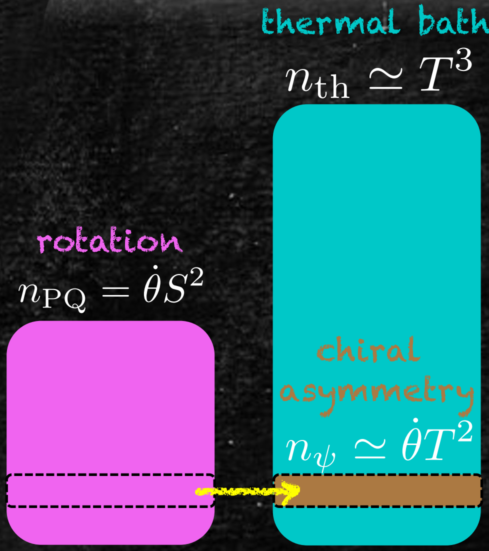


$$Y_B \equiv \frac{n_B}{s} = \frac{c_B \dot{\theta} T^2}{s}$$

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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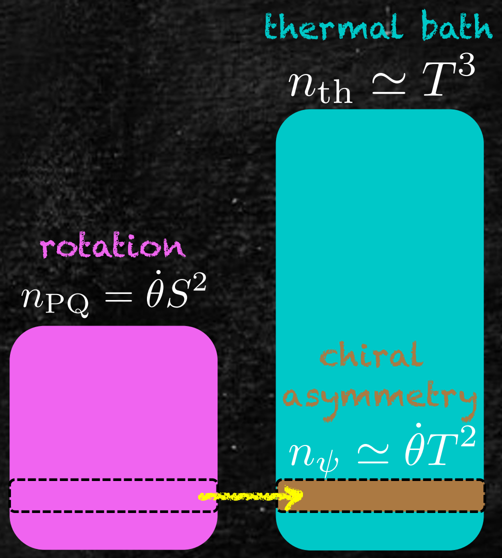
Axiogenesis with Heavy QCD Axion

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

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

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



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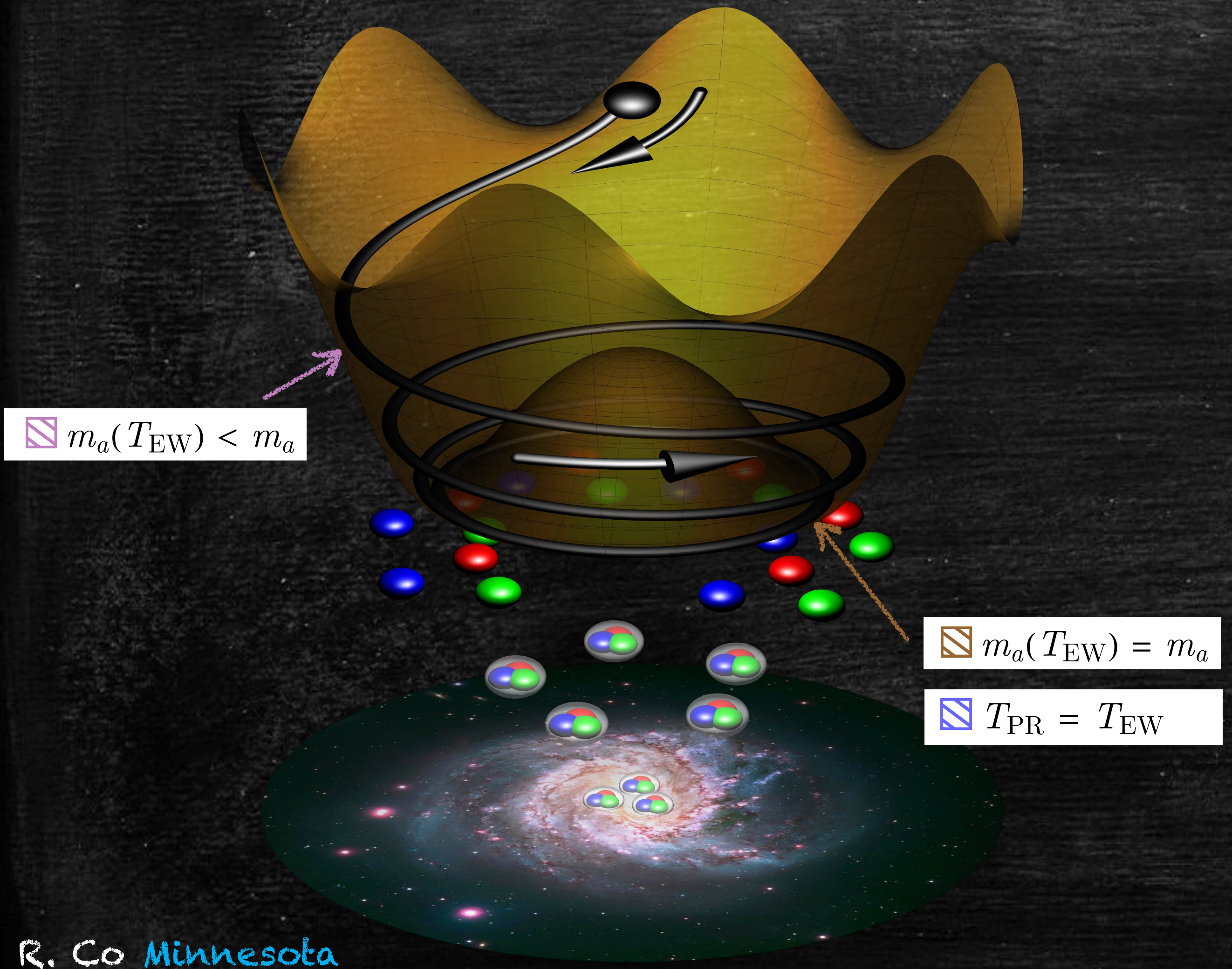
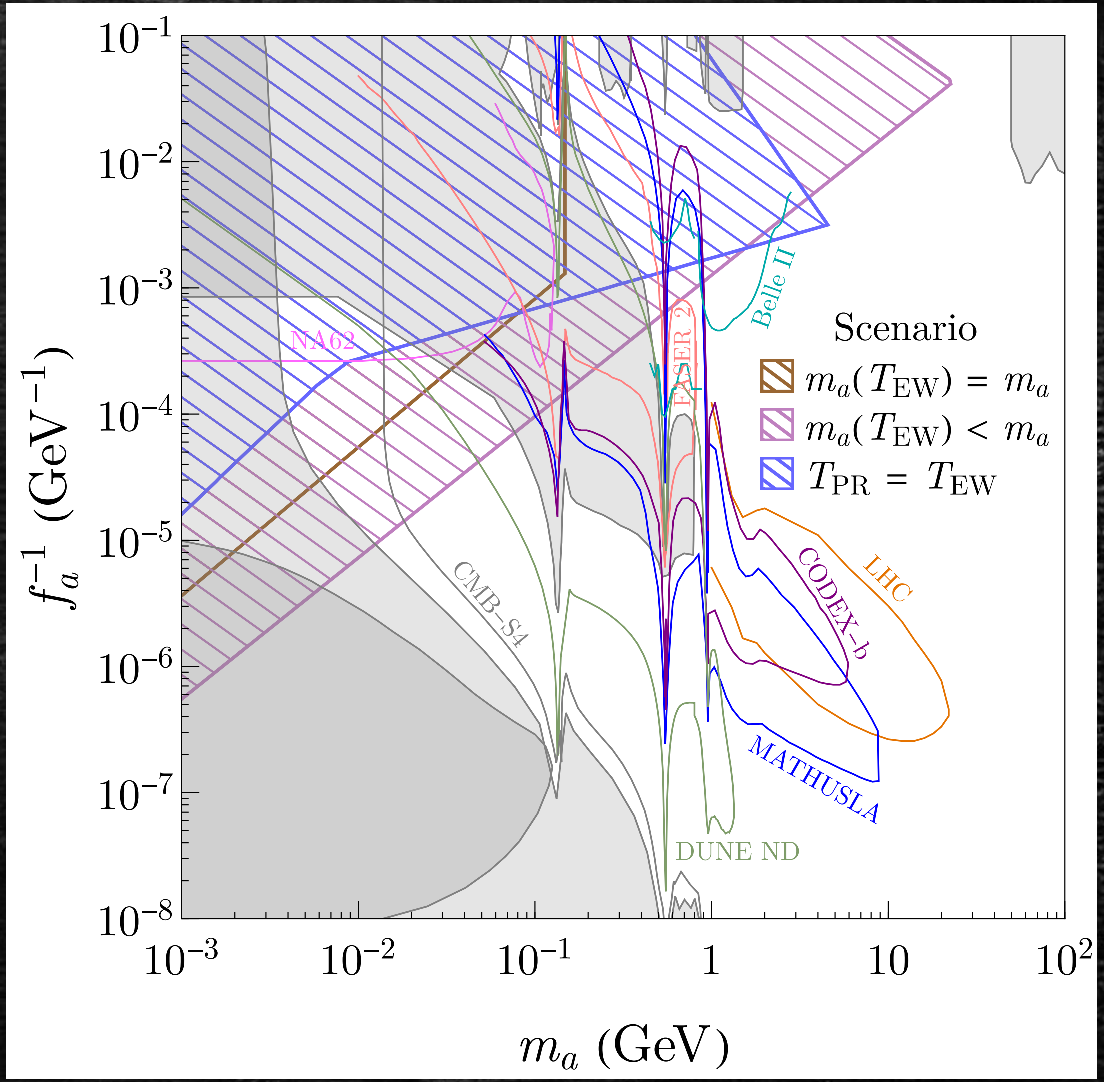
Predictions from Axiogenesis

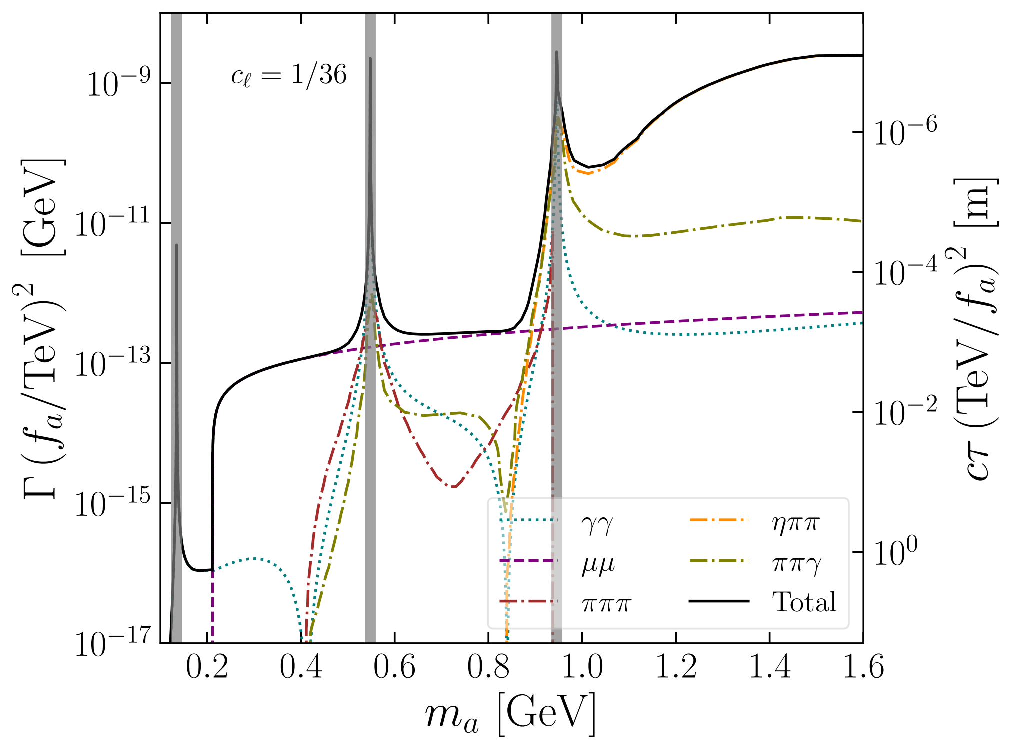


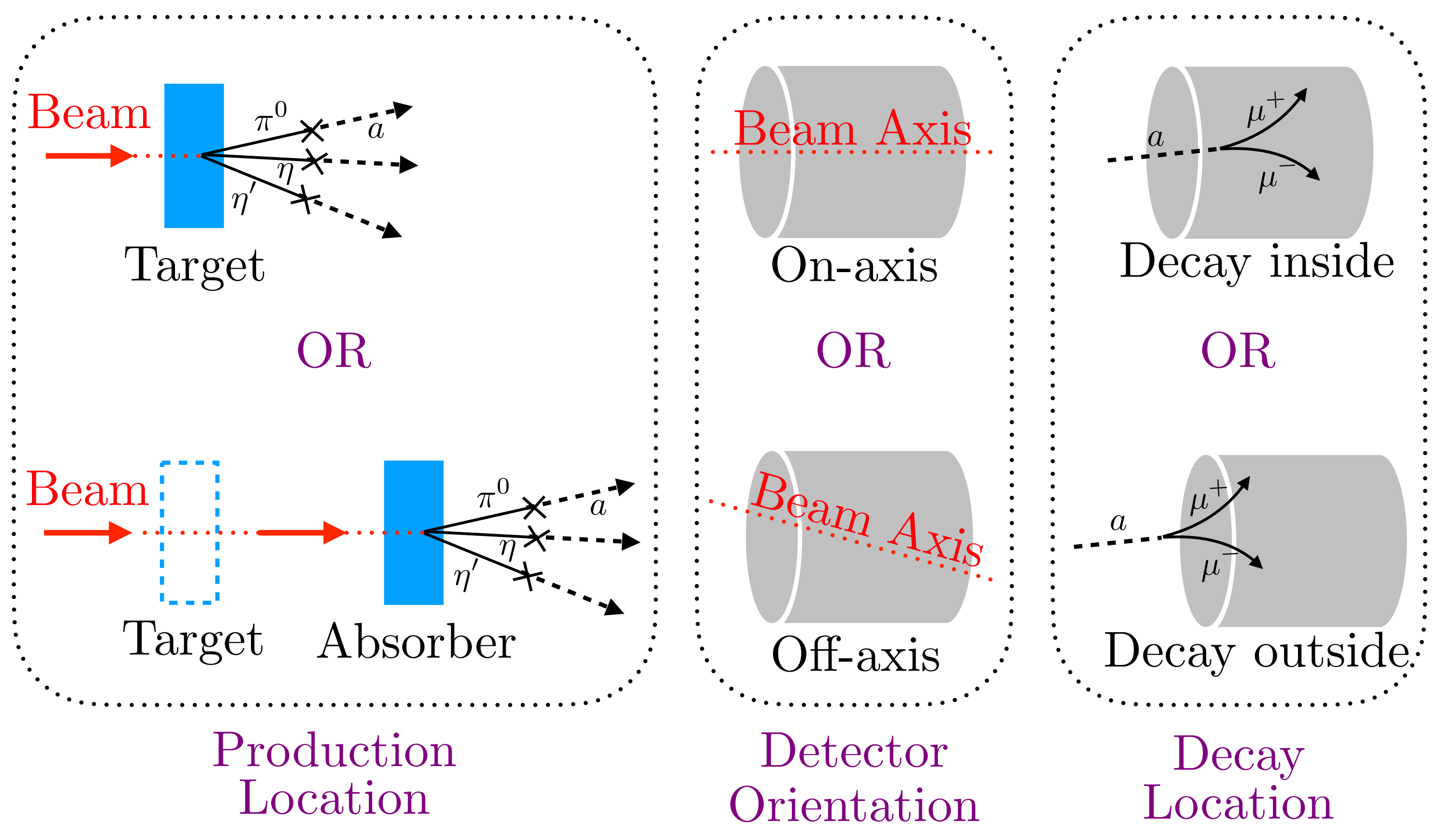


Heavy QCD Axion

✓ New theoretical and experimental opportunities

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

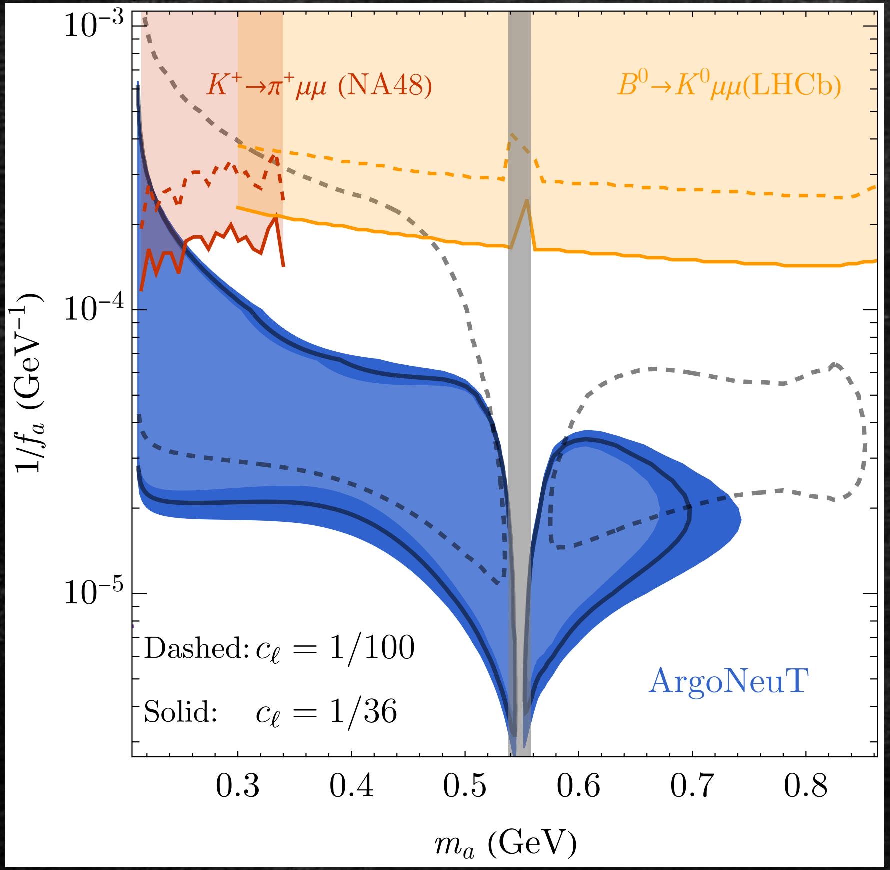


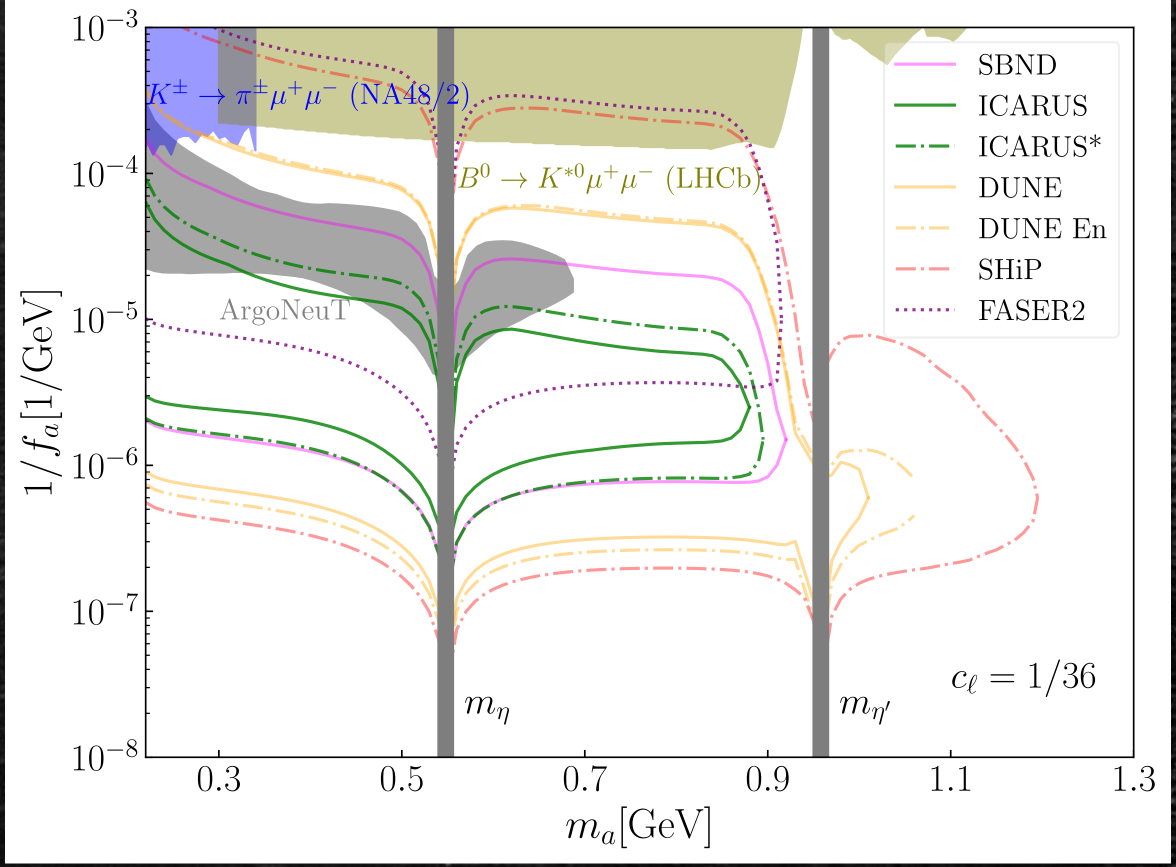


Soon.IHope RC, Soubhik Kumar, Zhen Liu

Heavy QCD Axion

✓ New theoretical and experimental opportunities





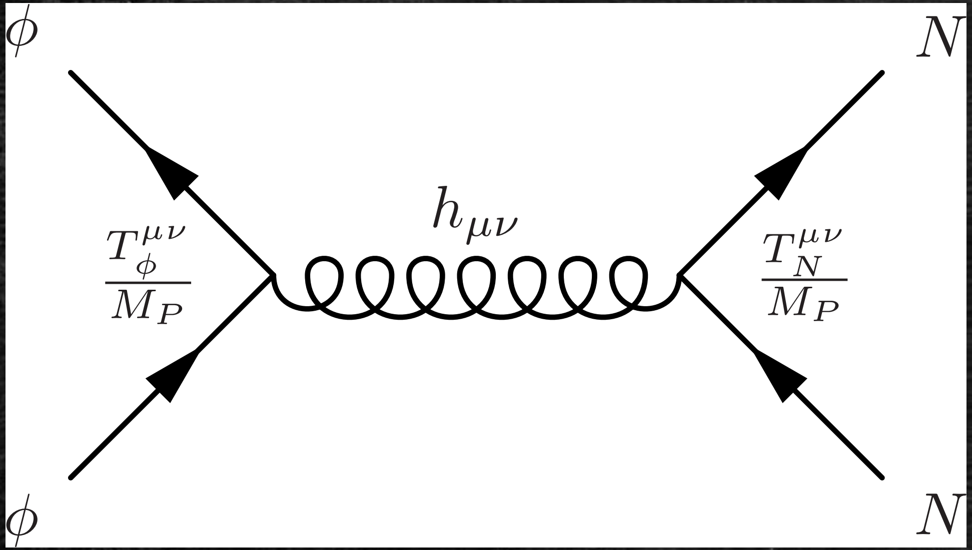
2207.08448 RC et al. and ArgoNeuT collaboration

Soon.IHope RC, Soubhik Kumar, Zhen Liu

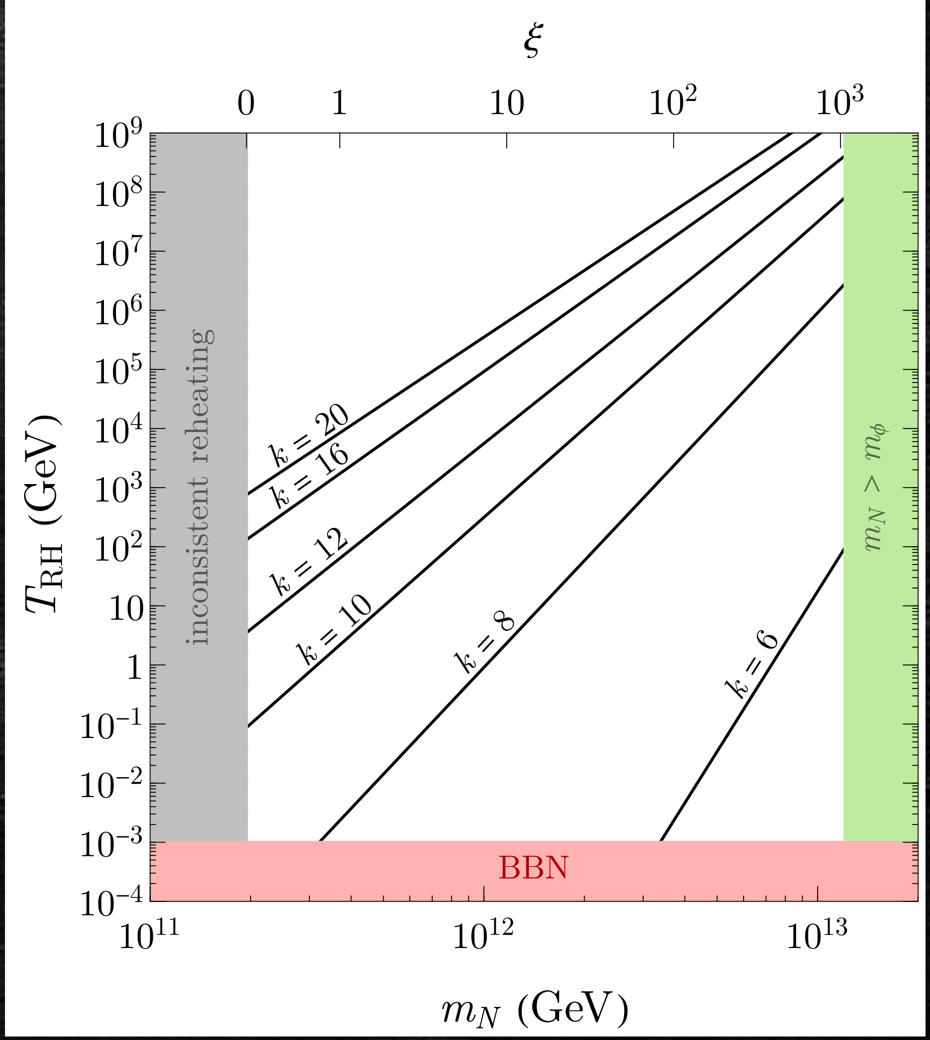
Inflationary Gravitational Leptogenesis

inflaton

right-handed neutrinos



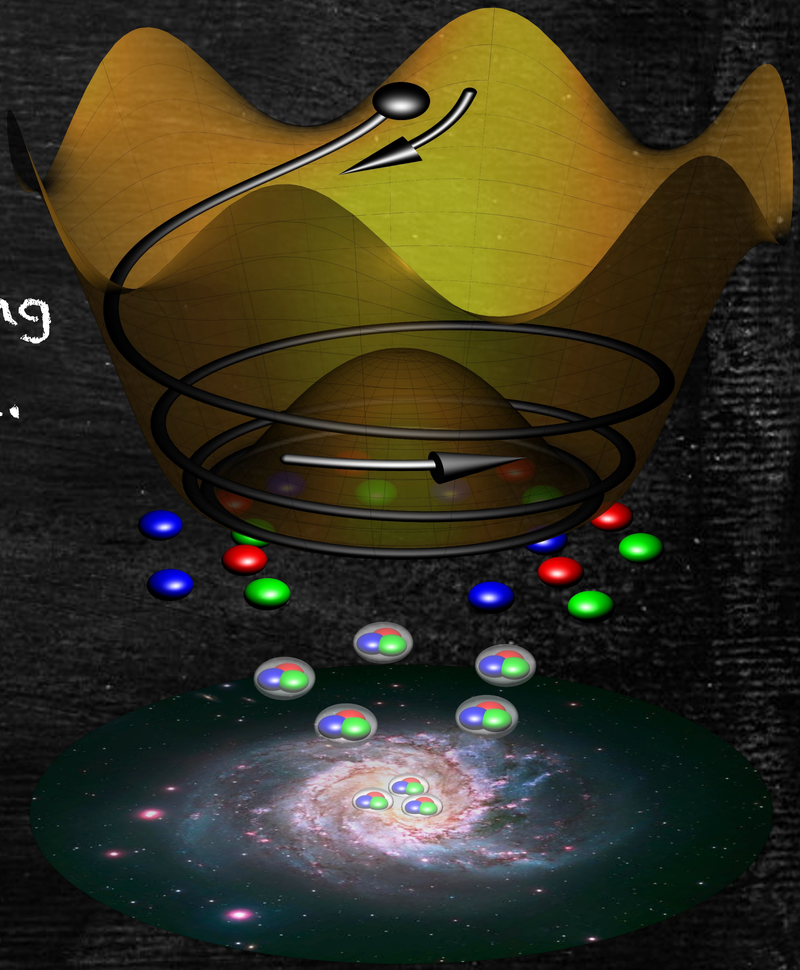
$$V(\phi) = \lambda \frac{\phi^k}{M_P^{k-4}}$$



R. Co Minnesota 2205.01689 RC, Yann Mambrini, and Keith Olive

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!