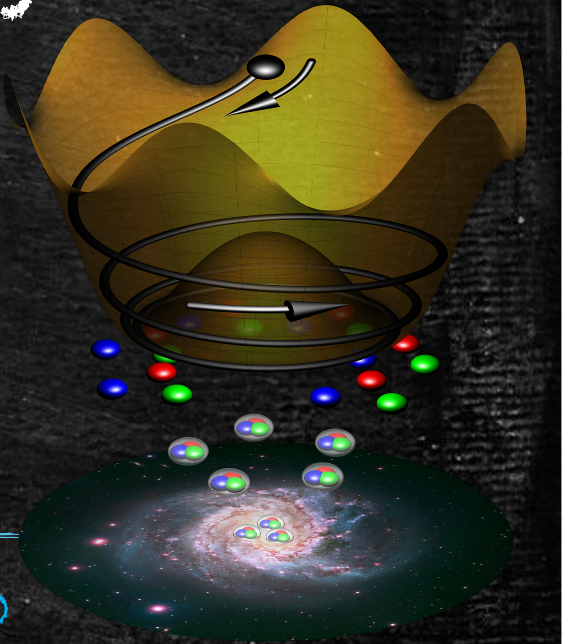
Gravitational Wave Probes of Axion Rotations Responsible for Dark Matter and Baryon Asymmetry



Raymond Co

Fine Theoretical Physics Institute

William I. Fine Theoretical Physics Institute
University of Minnesota

QMAP Particles/Cosmology seminar, UC Davis
May 23rd 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)
2006.04809	RC, Lawrence Hall, Keisuke Harigaya	JHEP 01 (2021) 172
2006.05687	RC, Nicolas Fernandez, Akshay Ghalsasi, Lawrence Hall, Keisuke Harigaya	JHEP 03 (2021) 017
2108.09299	RC, David Dunsky, Nicolas Fernandez, Akshay Ghalsasi, Lawrence Hall, Keisuke Harigaya, Jessie Shelton	JHEP
2110.05487	RC, Keisuke Harigaya, Aaron Pierce	JHEP 11 (2021) 210
2202.01785	RC, Keisuke Harigaya, Aaron Pierce	JCAP

Today

Nobel Prize in Physics 1972

for their jointly developed theory of superconductivity, usually called the BCS-theory

Nobel Prize in Physics 1956

for their researches on semiconductors and their discovery of the transistor effect

John Bardeen

born on

May 23rd 1908

R. Co Minnesota

https://www.nobelprize.org/prizes/physics/1972/bardeen/facts/

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

} Dark Matter

- 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

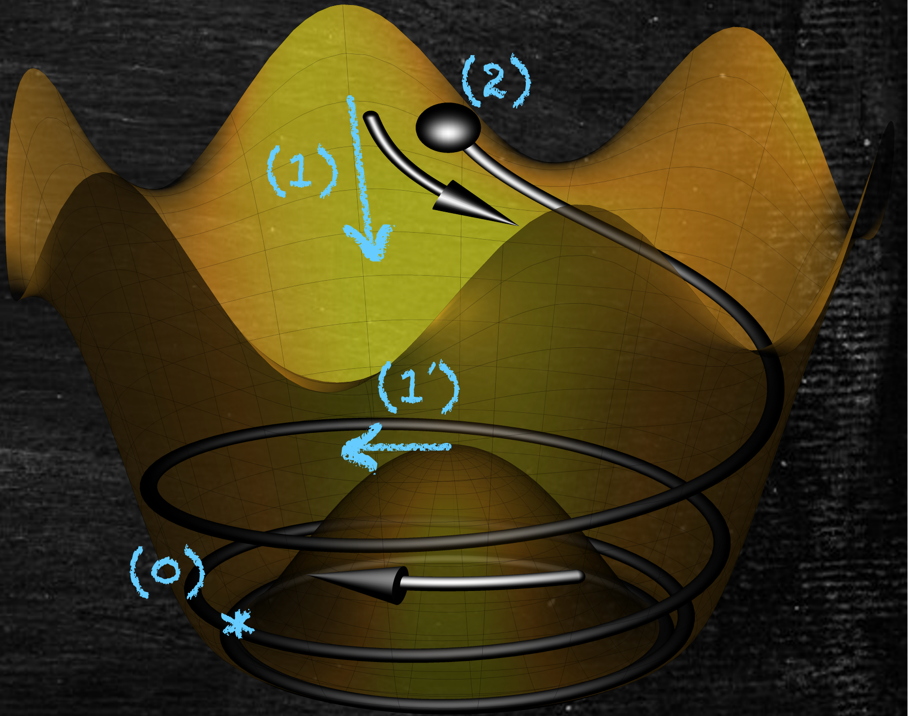
- Tachyonic instability

RC, K. Harigaya, A. Pierce 2020

} Gravitational Waves

Possible initial conditions

Peccei-Quinn symmetry



Axion Rotations

- Axion

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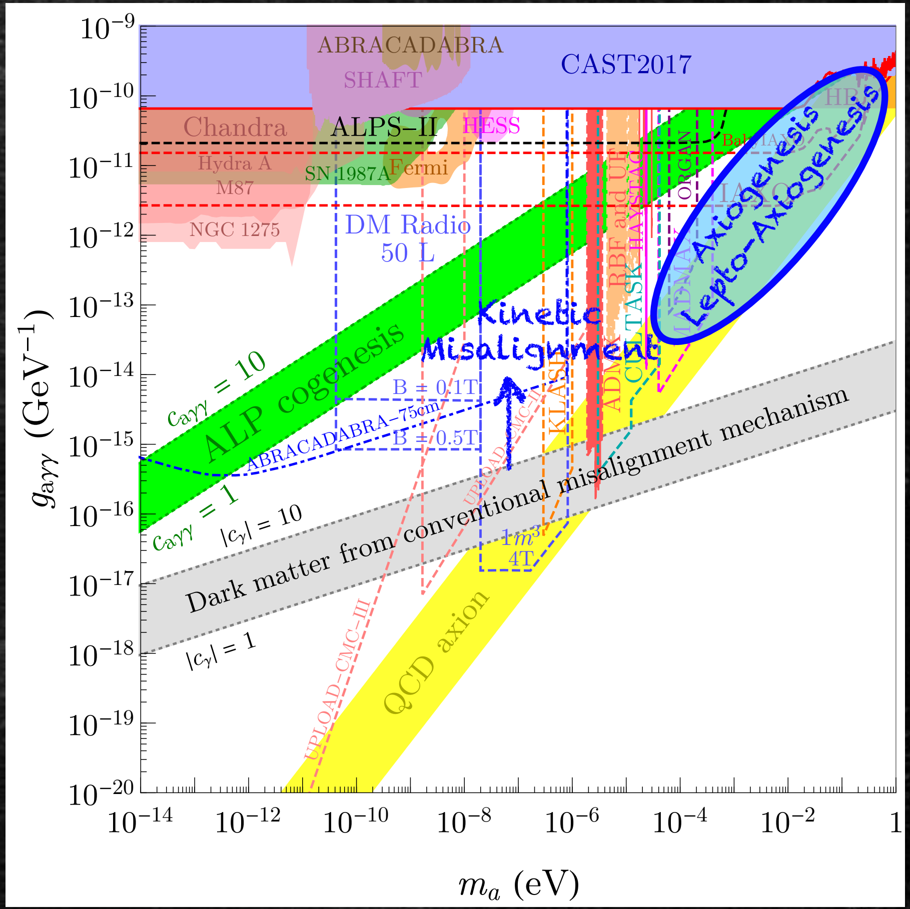
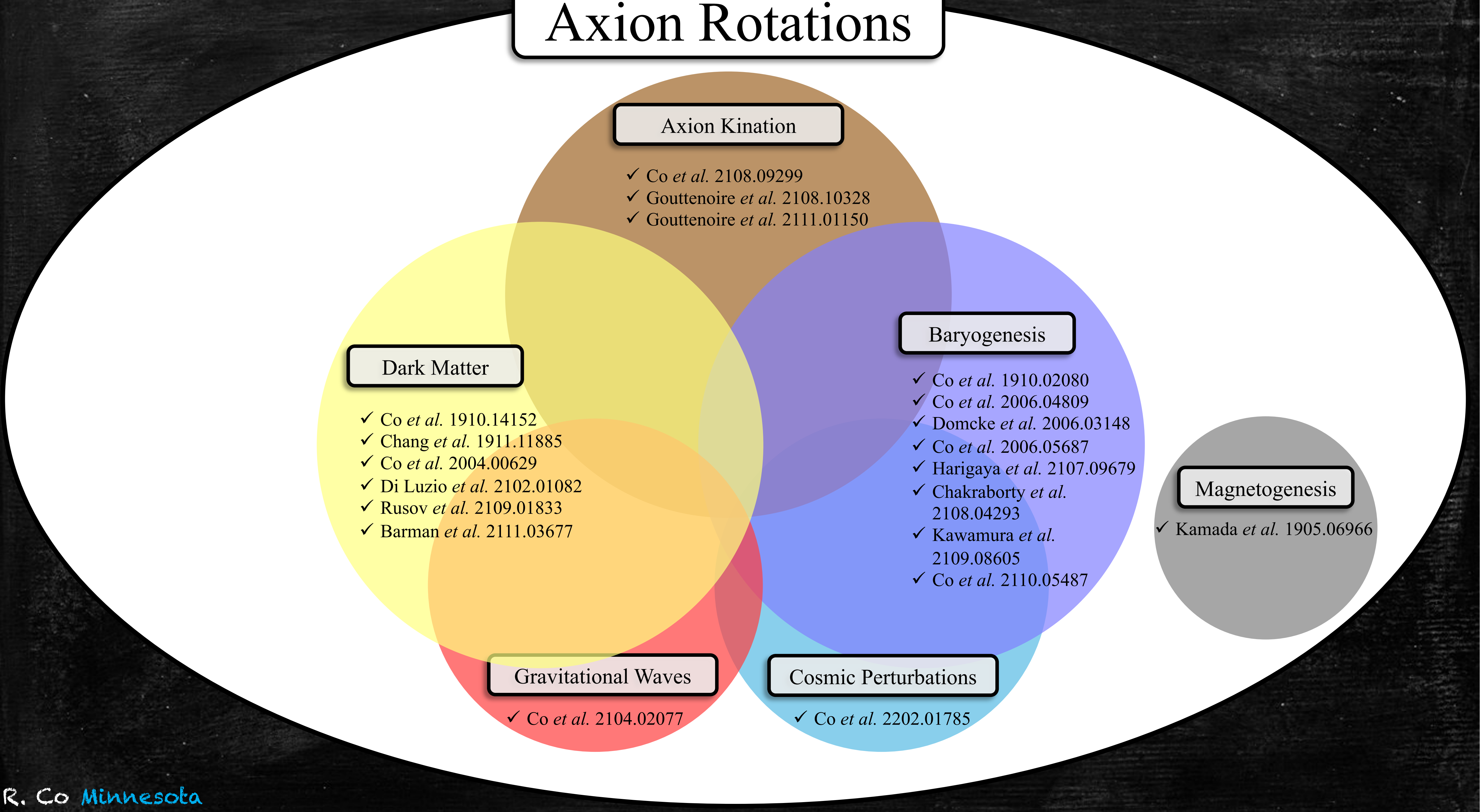


Axion Rotations



Axion Kination

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- ✓ Gouttenoire *et al.* 2108.10328
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Magnetogenesis

- ✓ Kamada *et al.* 1905.06966

Gravitational Waves

- ✓ Co *et al.* 2104.02077

Cosmic Perturbations

- ✓ Co *et al.* 2202.01785

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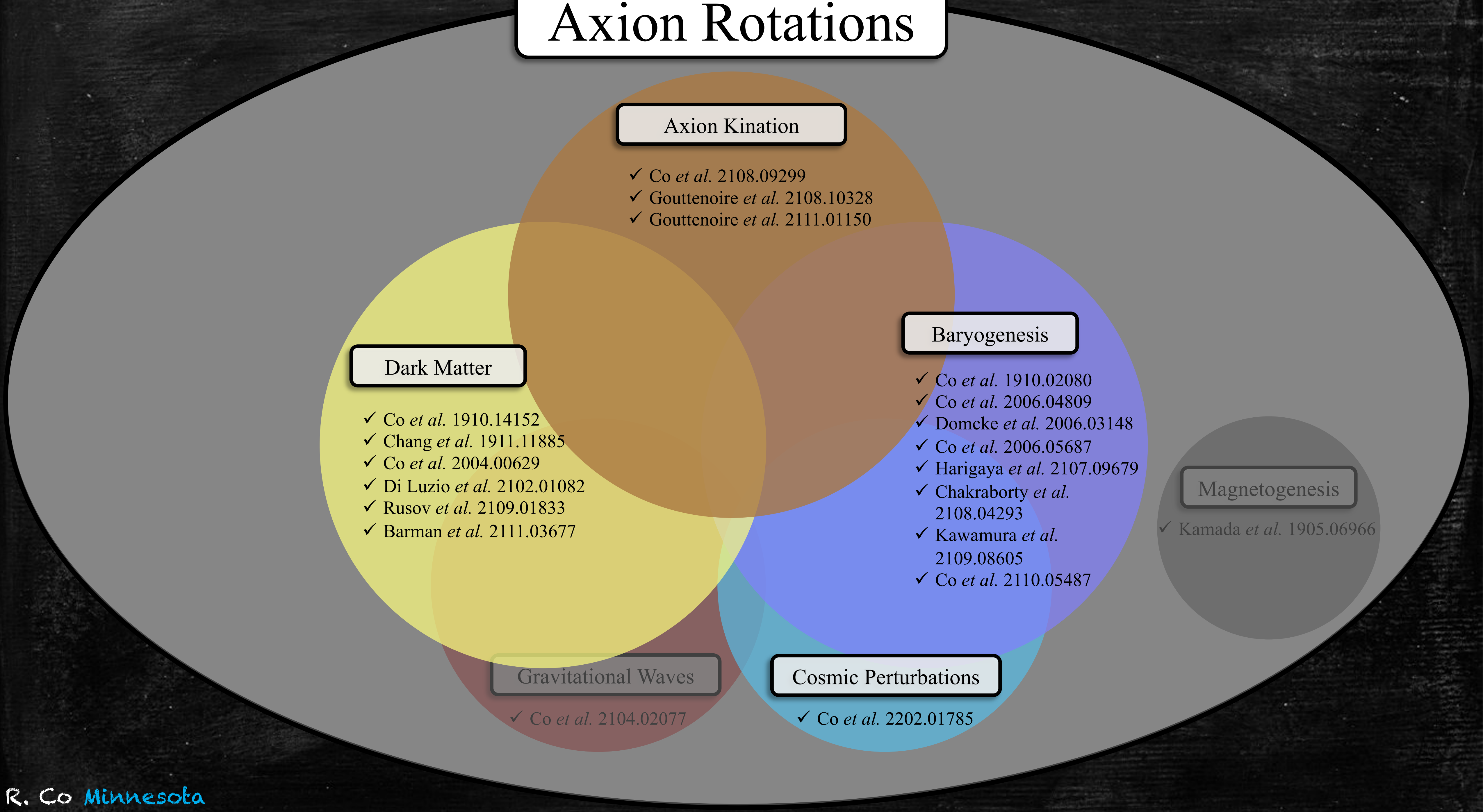

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What is kination?

9306008 Boris Spokoiny
9606223 Michael Joyce

"One simple alternative - 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

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

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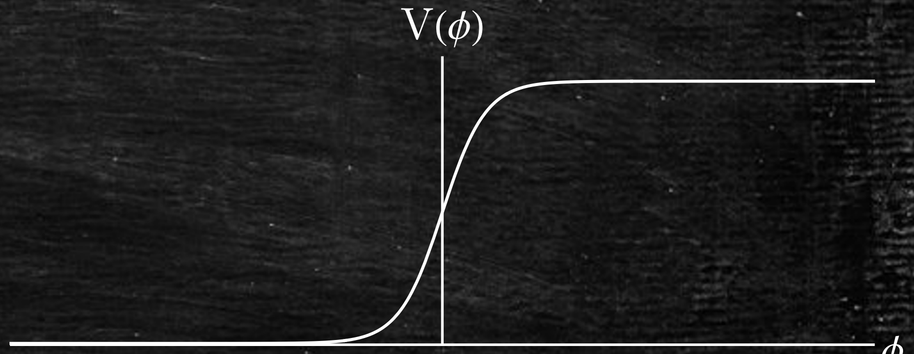


An unnatural example

Equation of state

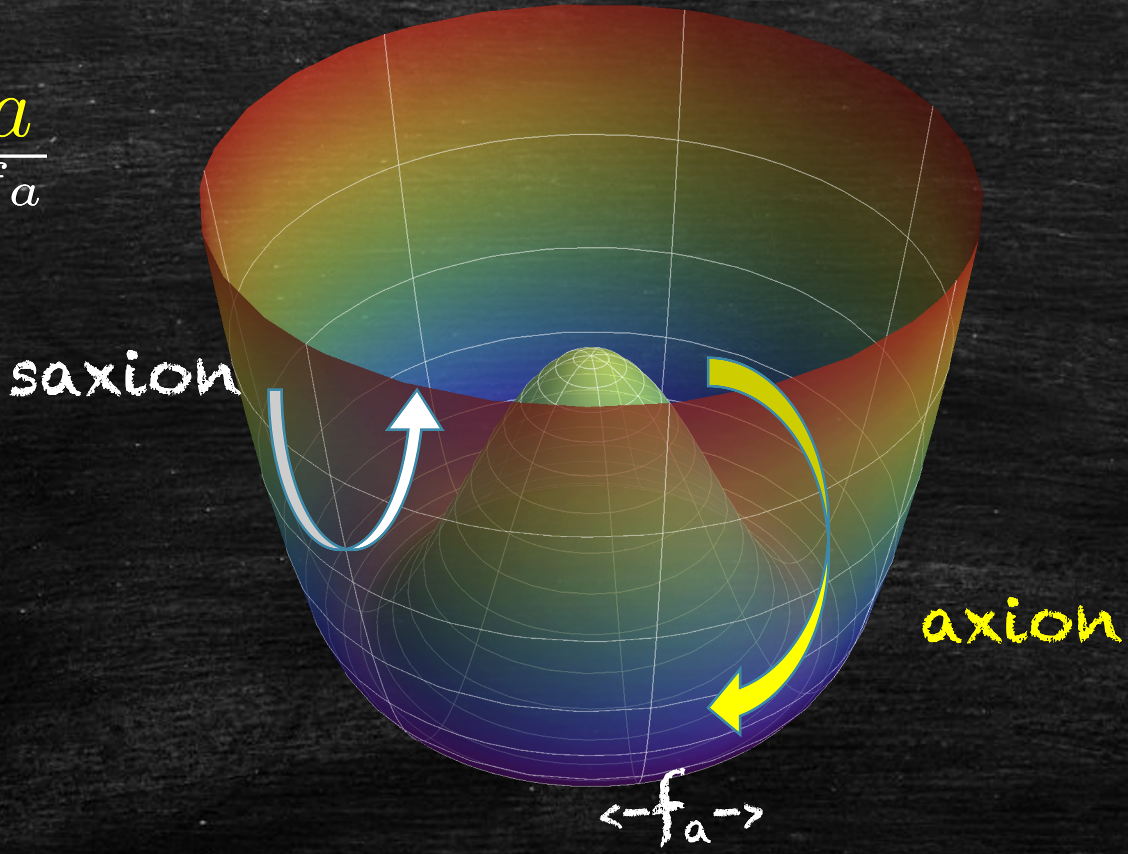
$$w = \frac{p}{\rho} = \frac{K - V}{K + V} \simeq 1$$

Evolution

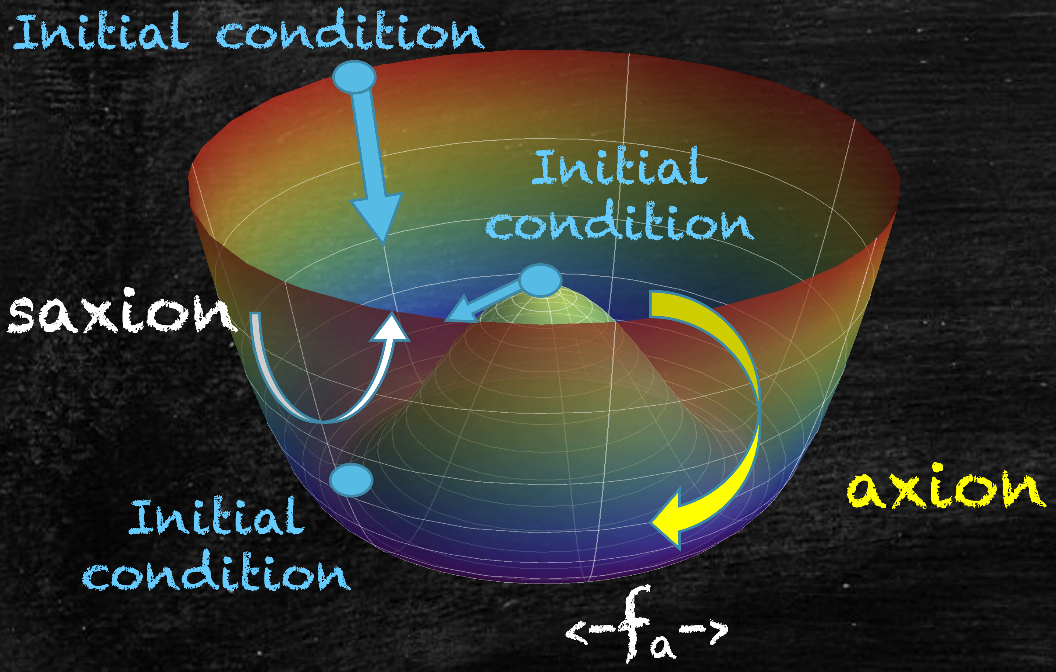
$$\rho_\phi \propto R^{-3(1+w)} = R^{-6}$$

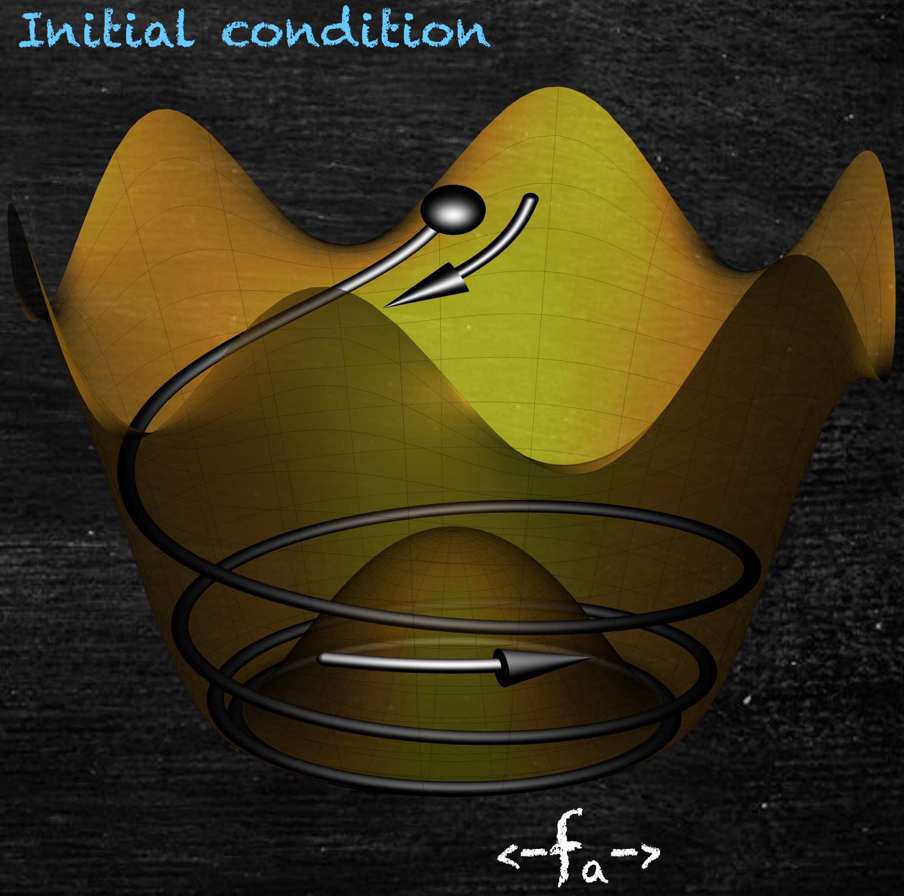
Axions

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



Rotation





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

Why Rotation?

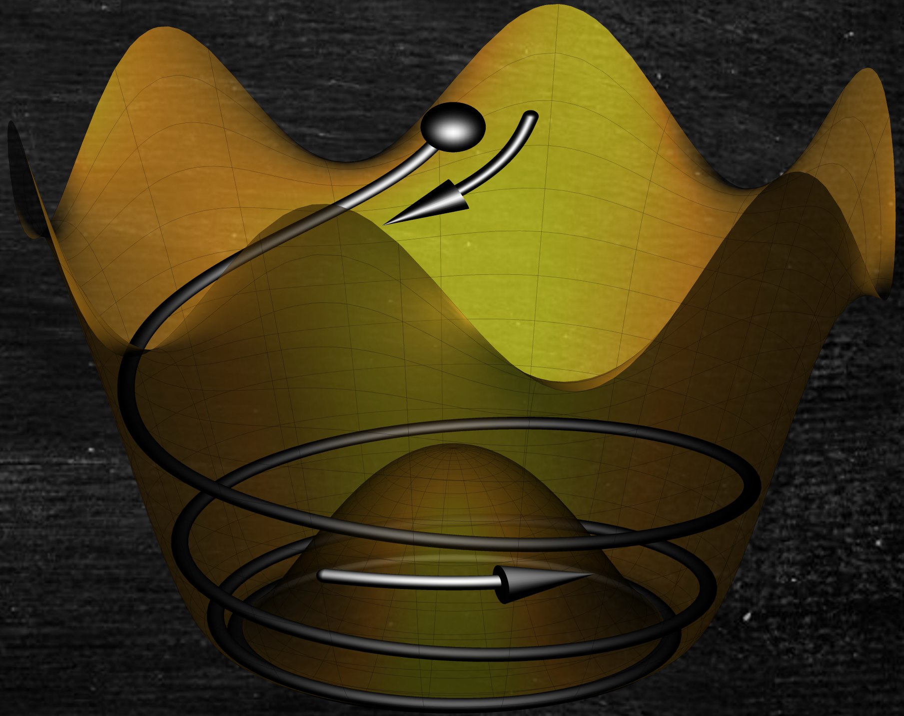
$$P = \frac{S + f_a}{\sqrt{2}} e^{i \frac{a}{f_a}}$$

Large field value : Flat potential

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

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

Initial condition



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

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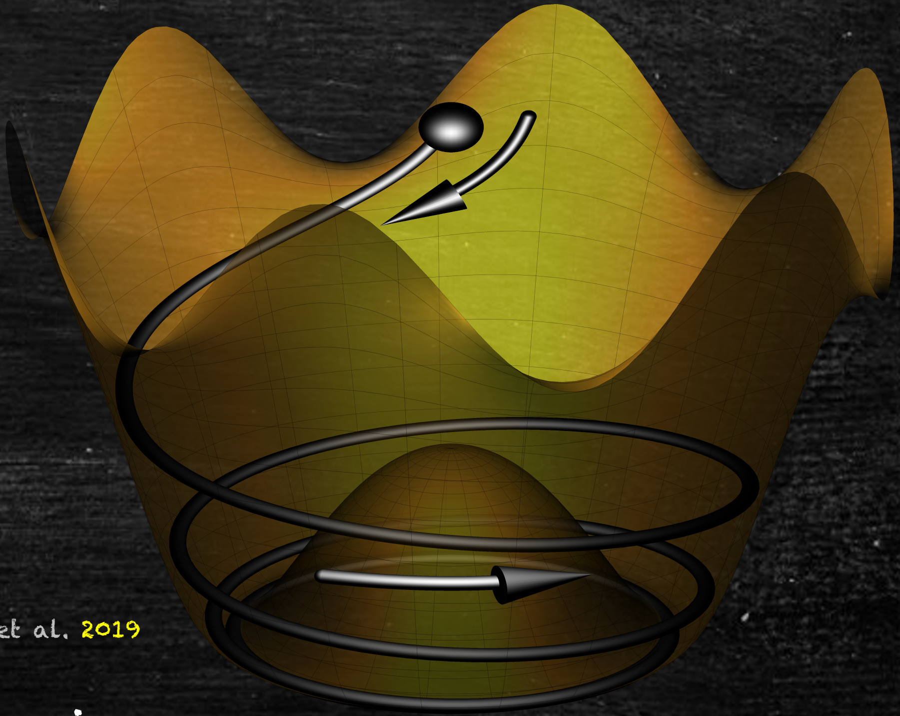
Angular motion : Explicit PQ breaking

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

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

Initial condition



Dynamics analogous to that in Affleck-Dine baryogenesis

I. Affleck and M. Dine 1991

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

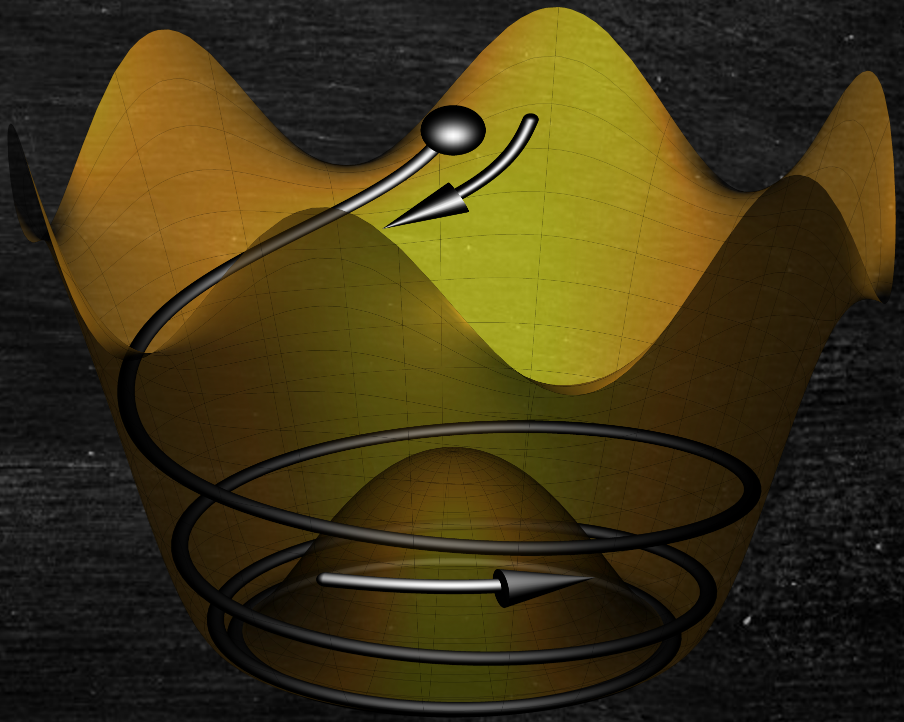
Asymmetry of PQ Charge

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

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.

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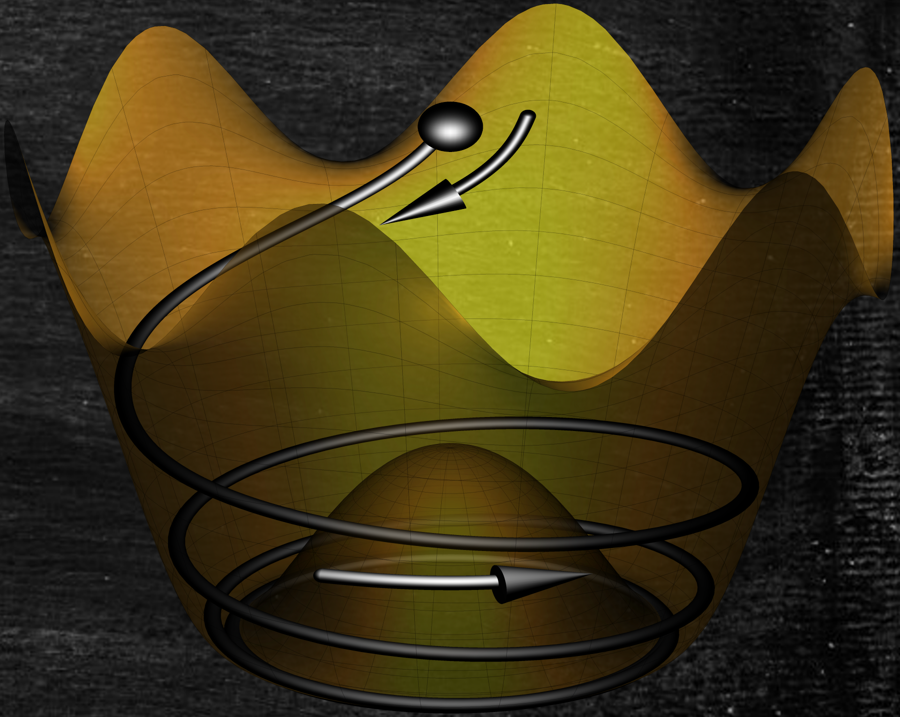
PQ Charge Evolution

Reason:

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



Conventional:

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

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

kination!

Our scenario ($S \gg f_a$):

quartic $S^2 \propto R^{-2}$ $\quad \dot{\theta} \propto R^{-1}$ $\quad \rho_{\rm PQ} \propto R^{-4}$

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

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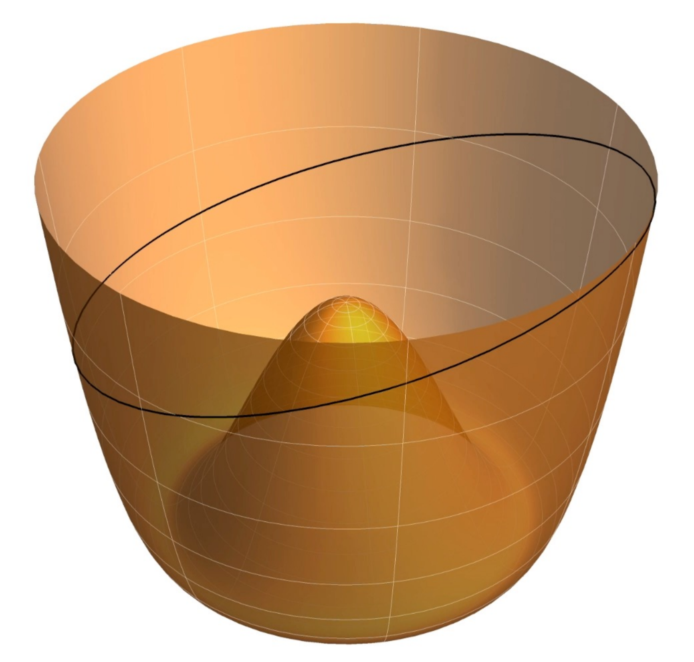
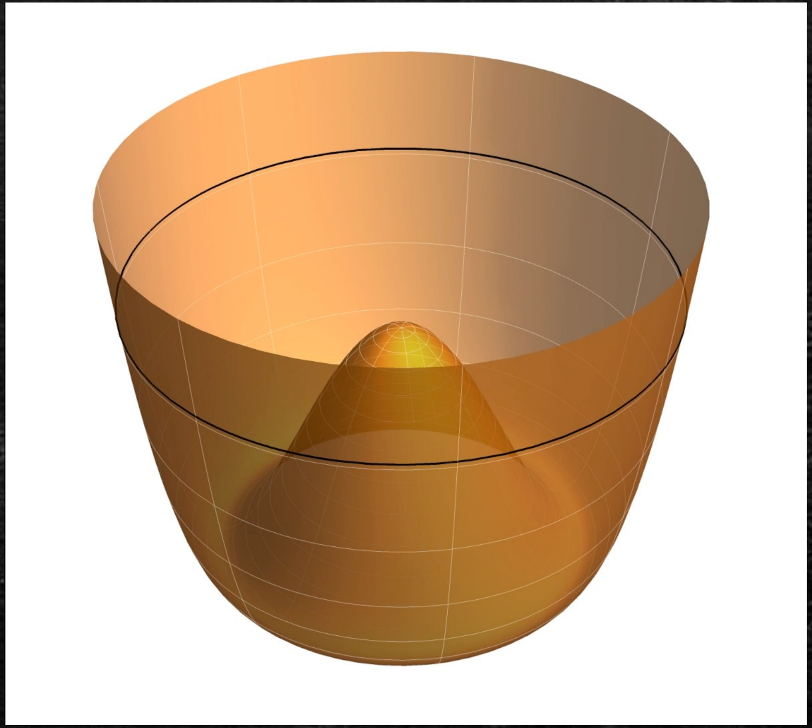
PQ Field Evolution

Thermalization

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

Redshift





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Asymmetries in Thermal Equilibrium

The free energy is minimized at equilibrium.

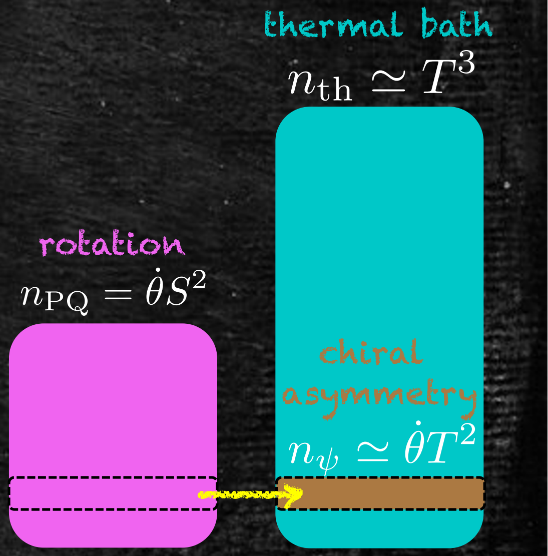
fermion asymmetry

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

Change of the free energy

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

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



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

Most of the PQ charge remains in the rotation!

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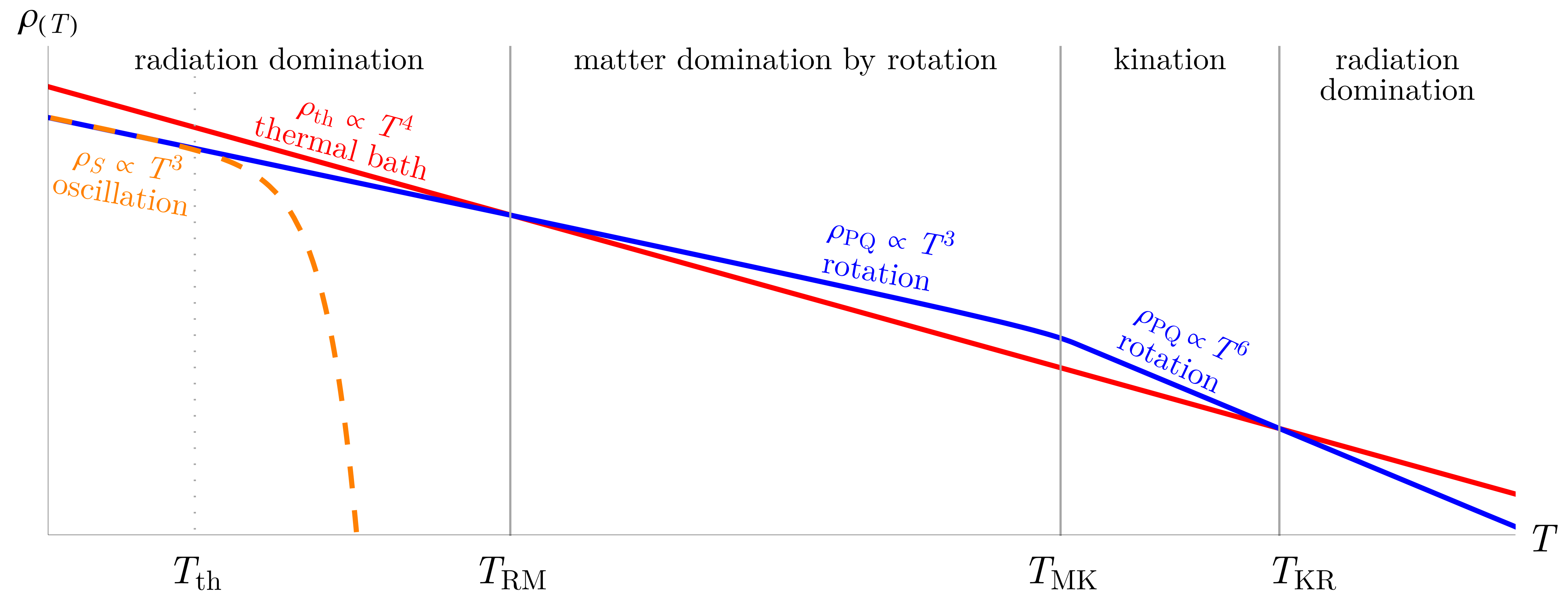
Evolution of Energy Densities



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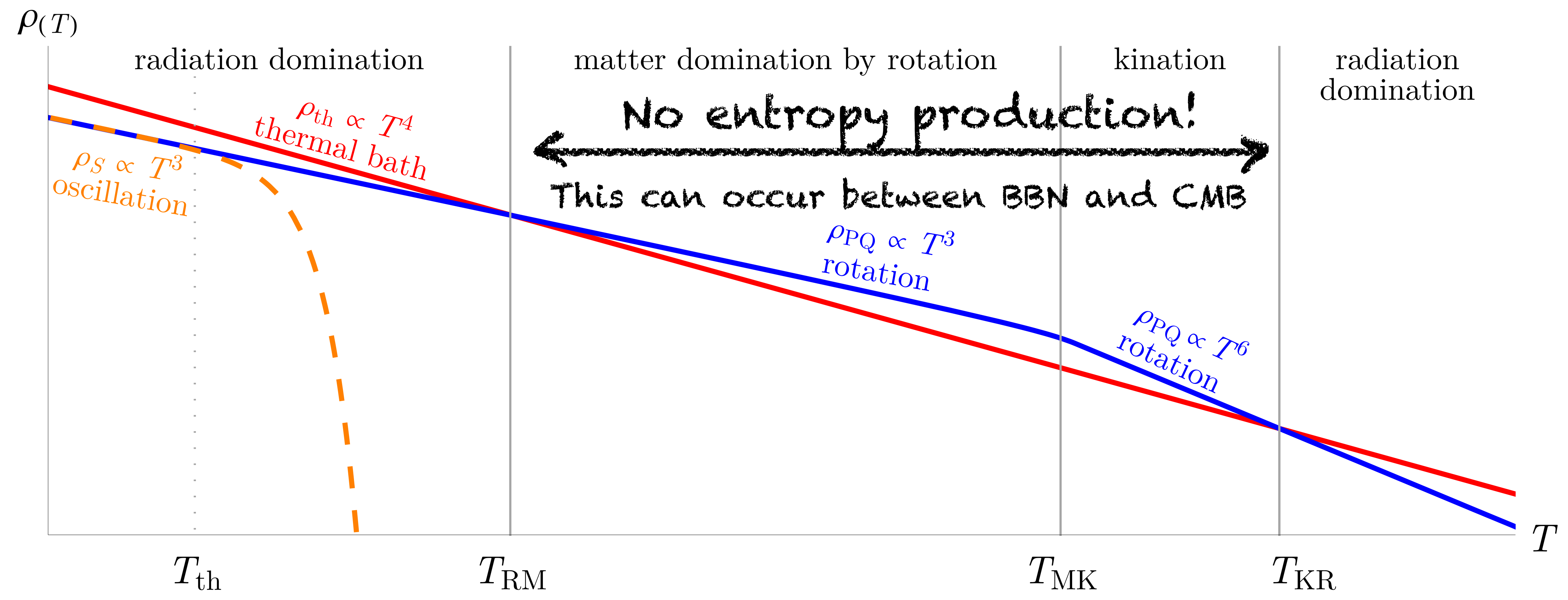

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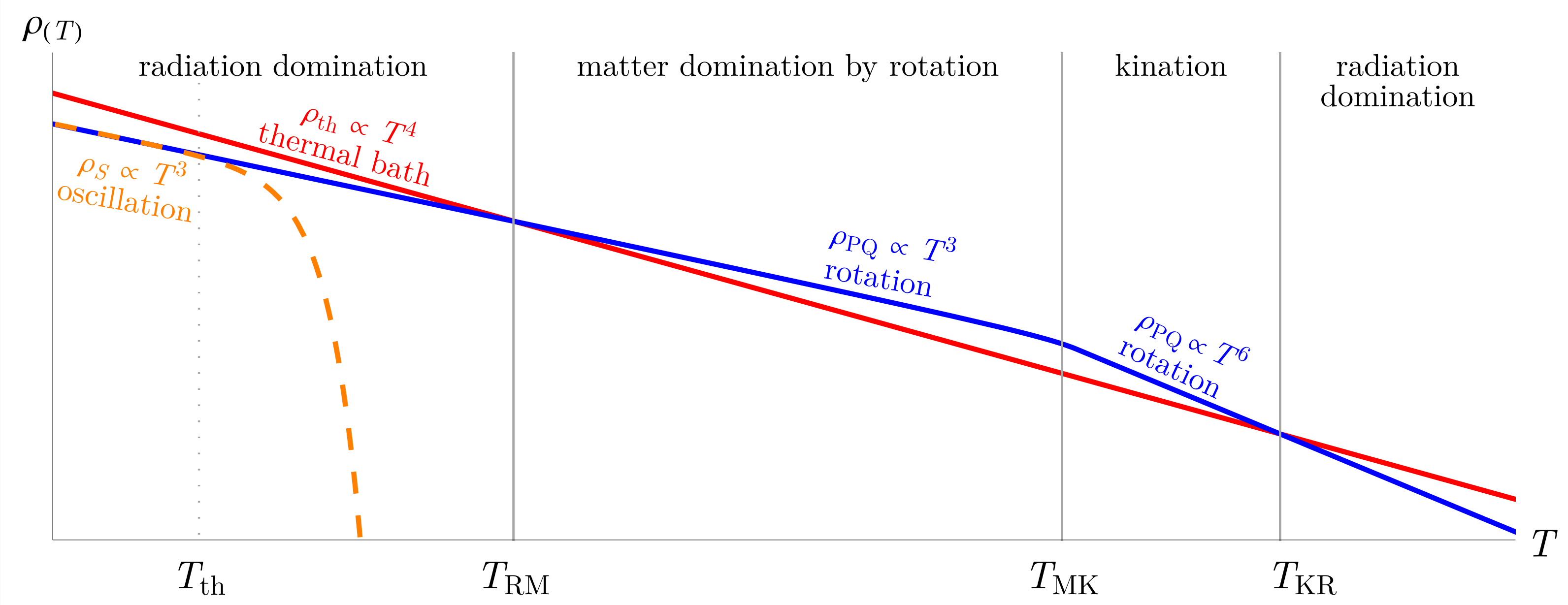
Relevant Temperatures



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

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

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

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

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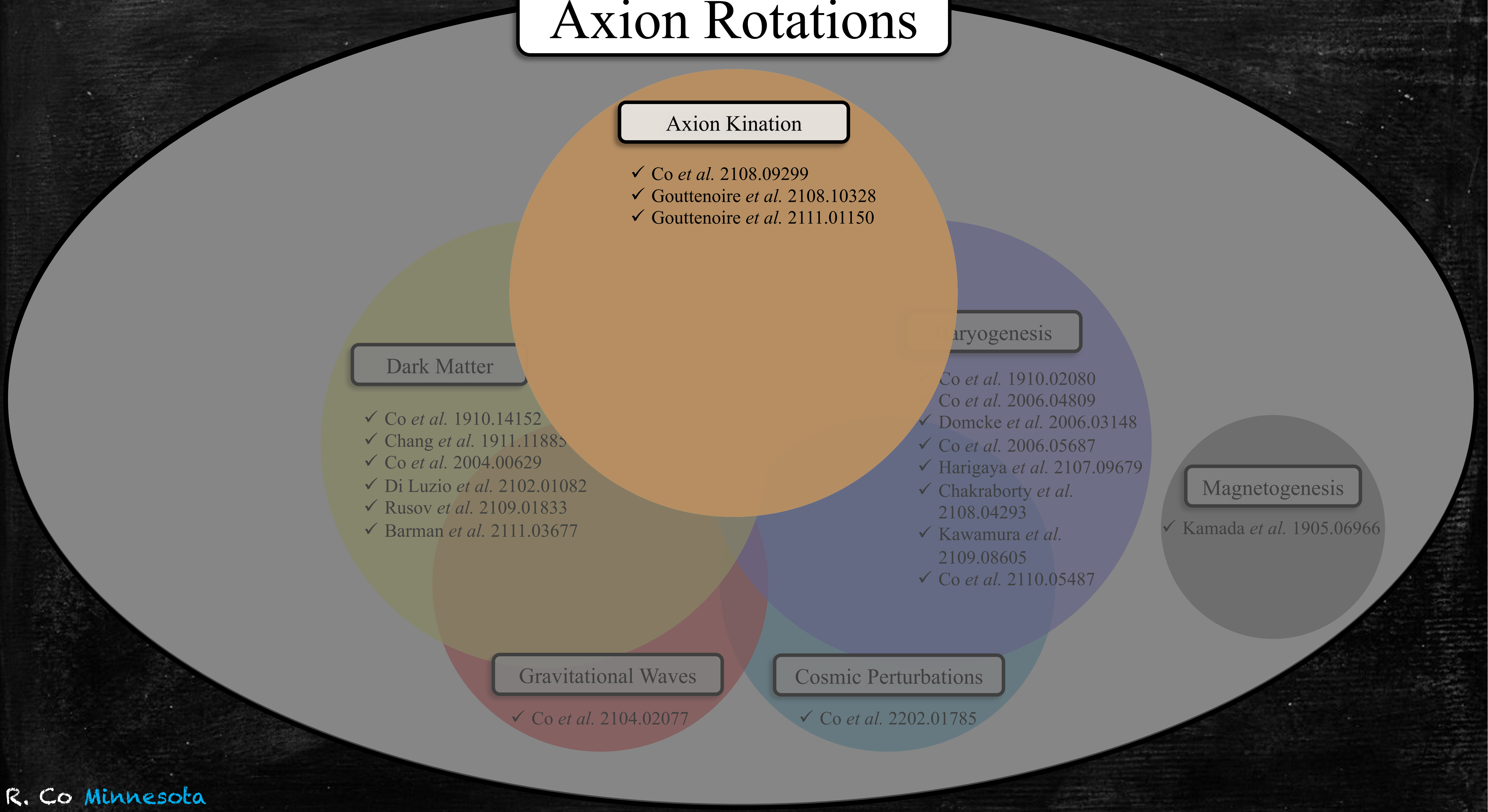
Axion Rotations



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Gravitational Waves from Inflation

The origin is the quantum fluctuations during inflation.

The horizon crossing, k = H, determines the onset of mode evolutions.

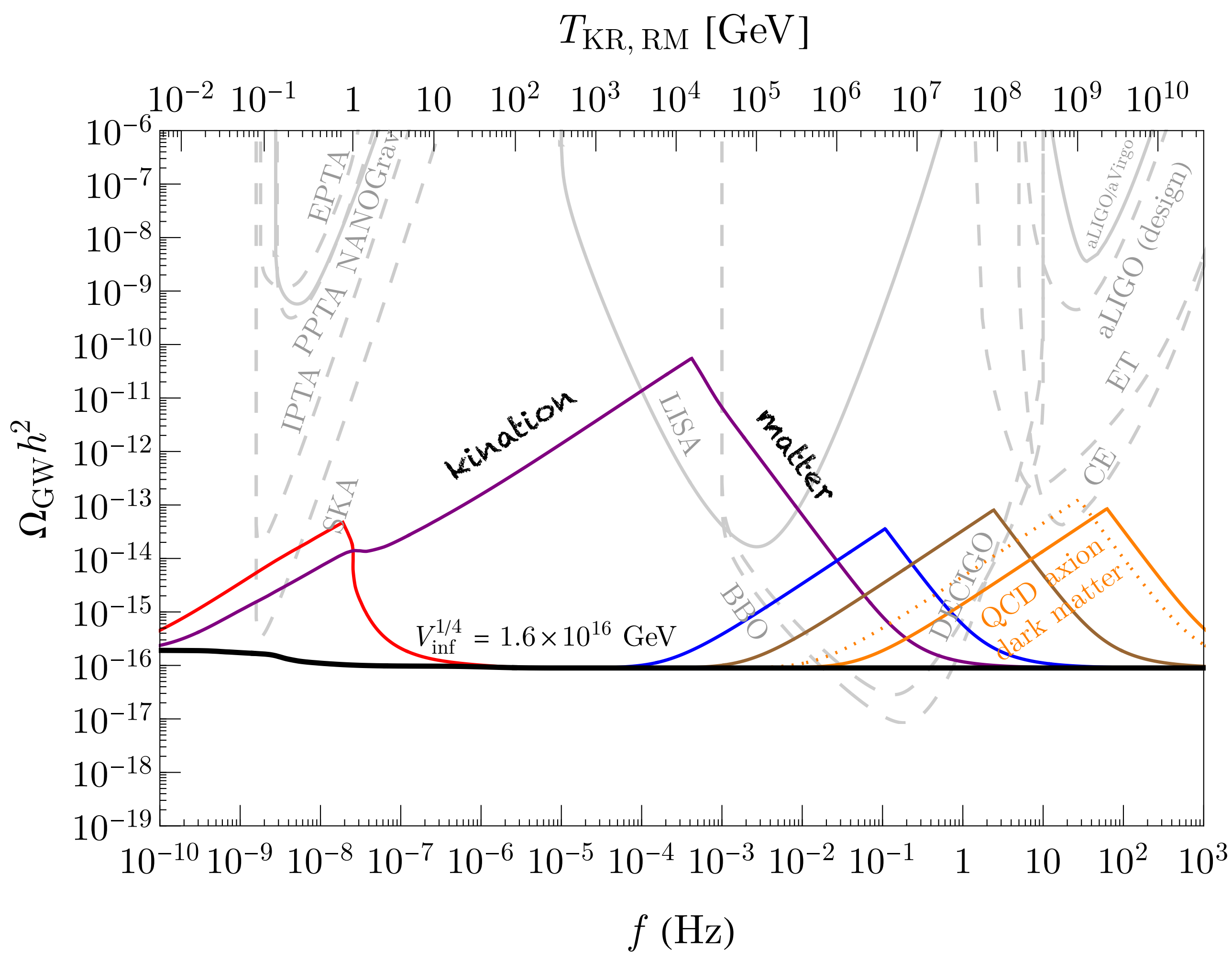
$$\Omega_{\rm GW} h^2 = \Omega_{r,0} h^2 \frac{1}{\rho_R(T_{\rm hc})} \frac{k^2}{64\pi G} \mathcal{P}_T(k) \qquad \mathcal{P}_T(k) = \frac{2H_I^2}{\pi^2 M_{\rm Pl}^2}$$

$$k = H(T_{\rm hc})$$

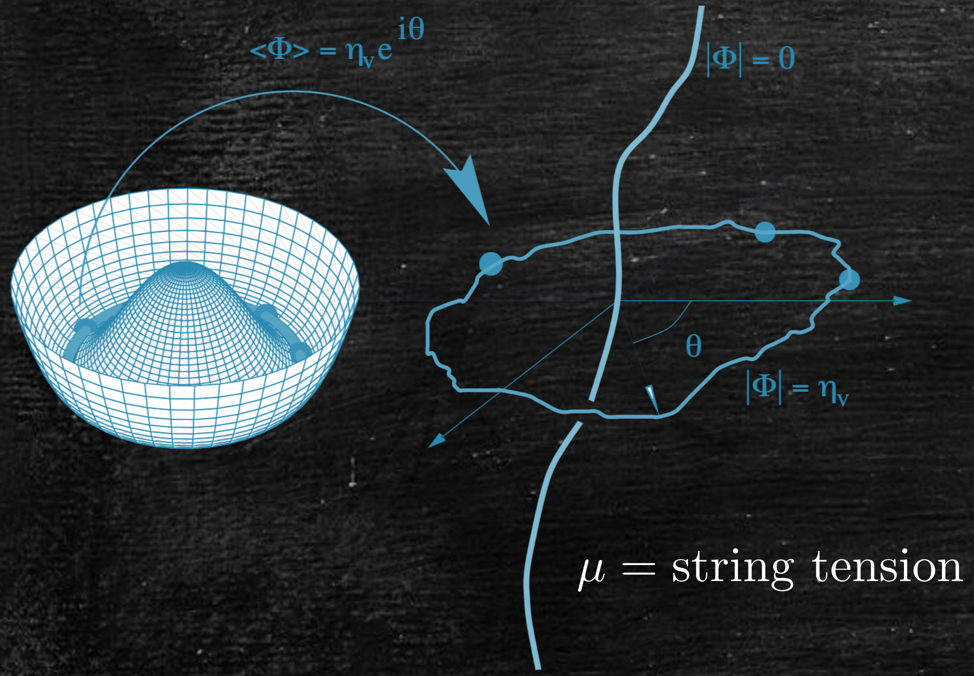
$$\Omega_{\rm GW} h^2 \simeq 1.4 \times 10^{-17} \left(\frac{V_{\rm inf}^{1/4}}{10^{16}\ {\rm GeV}} \right)^4 \left(\frac{g_{*,{\rm SM}}}{g_*(T_{\rm hc})} \right)^{\frac{1}{3}} \begin{cases} 1 & {\rm RD}: f_{\rm RM} < f \\ \left(\frac{f_{\rm RM}}{f} \right)^2 & {\rm MD}: f_{\rm MK} < f < f_{\rm RM} \\ \frac{f}{f_{\rm KR}} & {\rm KD}: f_{\rm KR} < f < f_{\rm MK} \\ 1 & {\rm RD}: f < f_{\rm KR} \end{cases}$$

Gravitational Waves from Inflation

kination before BBN



Gravitational Waves from Cosmic Strings



$\mu = \text{string tension}$

1005.4842 C. Ringeval

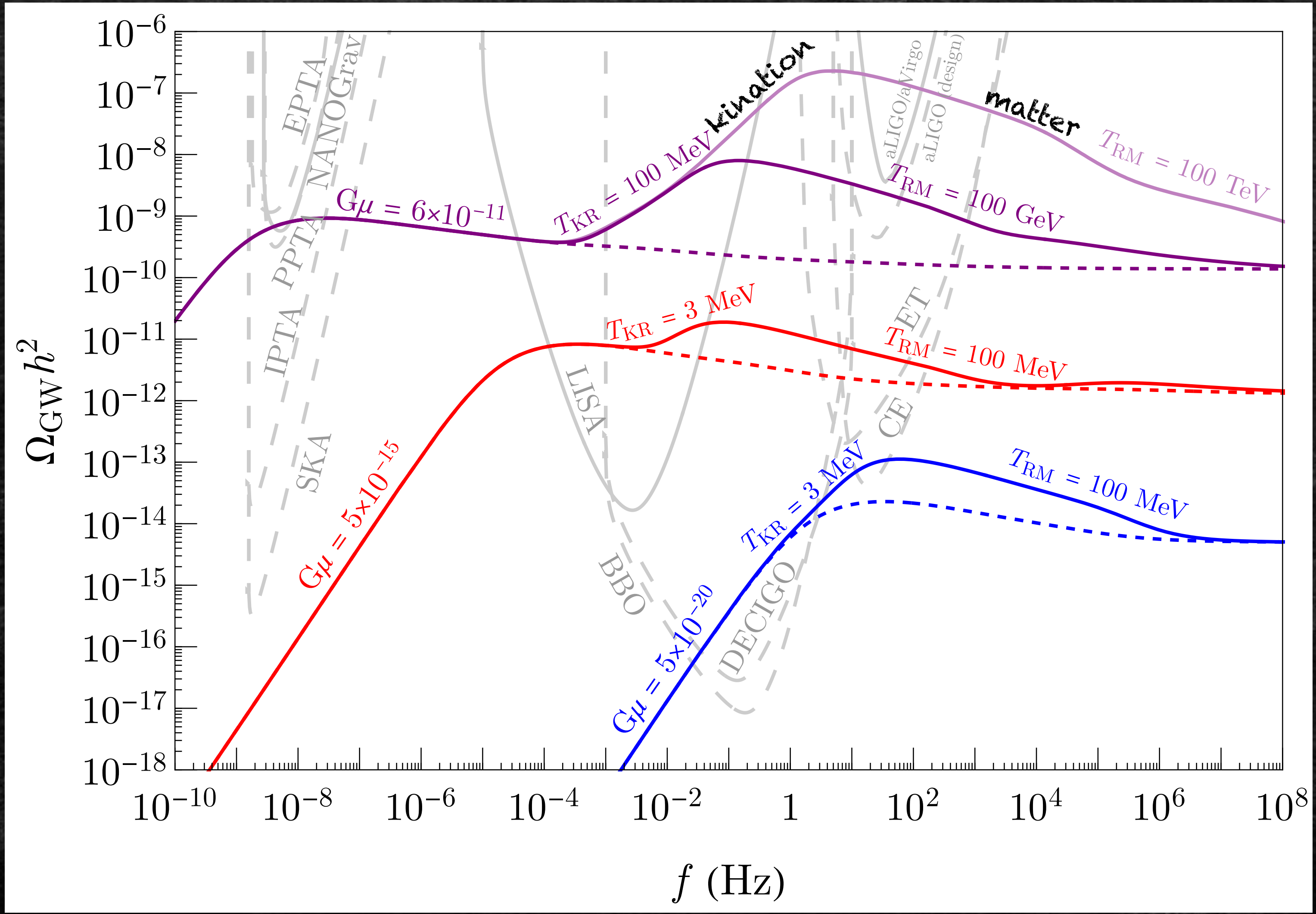
Daniel Dominguez/CERN

		Loop formation era		
		Radiation	Matter	Kination
Loop decay era	Radiation	f^0	f^{-1}	f^1
	Matter	$f^{-1/2}$	f^{-1}	f^1
	Kination	$f^{1/4}$	$f^{-1/2}$	f^1

1. Flat spectrum for radiation domination
2. An enhanced Hubble increases loop energy density.

Gravitational Waves from Cosmic Strings

kination before BBN



Gravitational Waves from Cosmic Strings

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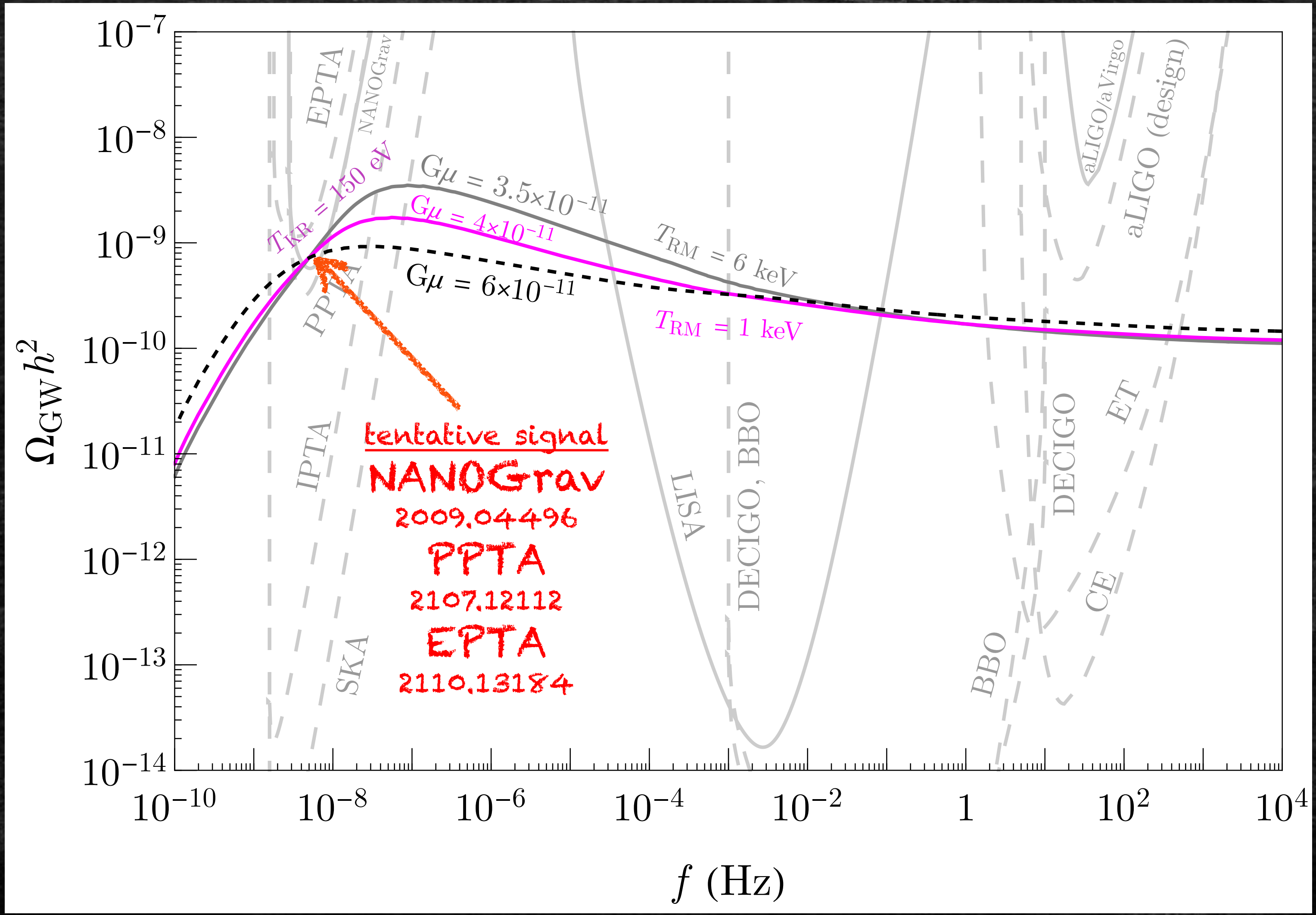


tentative signal

NANOGrav

2009.04496

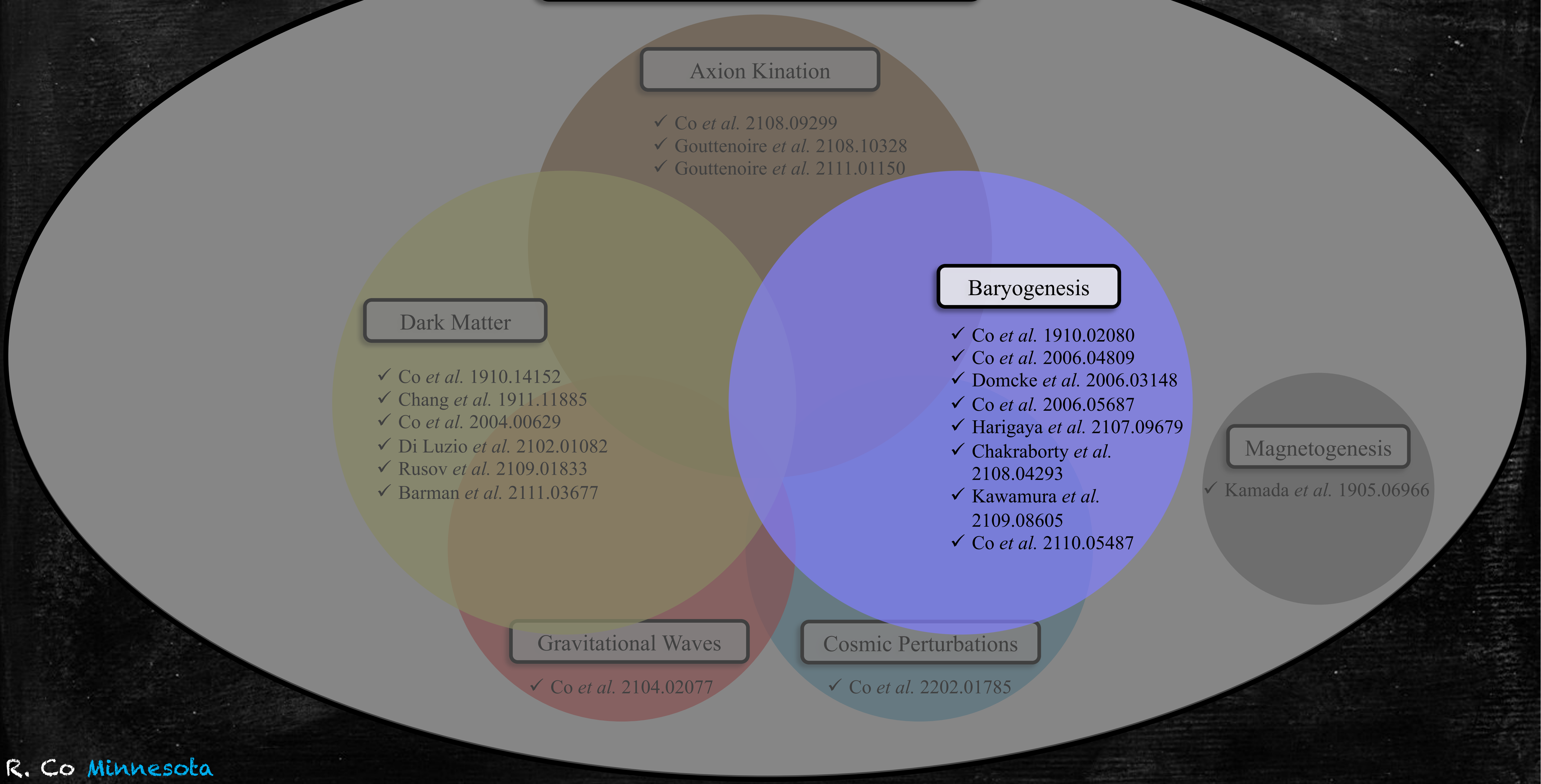
PPTA

2107.12112

EPTA

2110.13184

Axion Rotations



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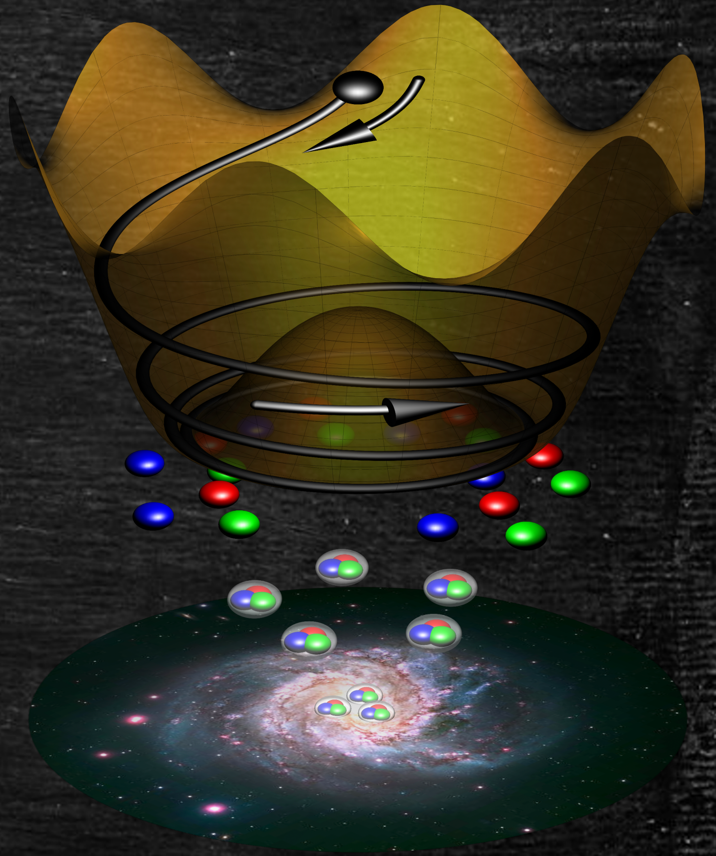

Axiogenesis

(QCD axion + baryogenesis)

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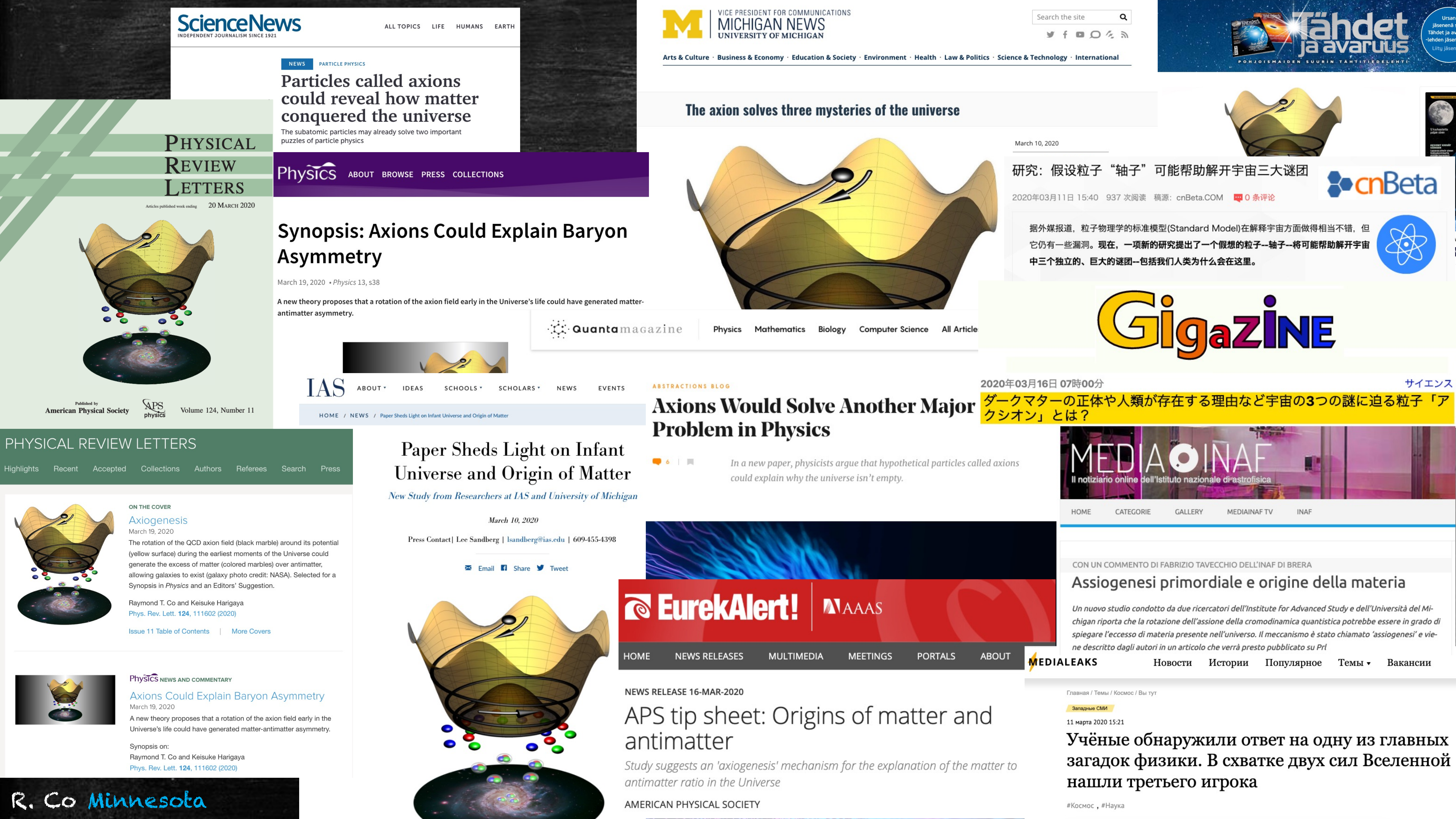

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NEWS PARTICLE PHYSICS

Particles called axions could reveal how matter conquered the universe

The subatomic particles may already solve two important puzzles of particle physics

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PHYSICAL REVIEW LETTERS
Articles published week ending 20 MARCH 2020
Published by American Physical Society APS physics Volume 124, Number 11

Physics ABOUT BROWSE PRESS COLLECTIONS

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.

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The axion solves three mysteries of the universe

March 10, 2020

Tähdet ja avaruus
POHJOISMAIDEN SUURIN TÄHTITIETEELEHTI

研究：假设粒子“轴子”可能帮助解开宇宙三大谜团

cnBeta

2020年03月11日 15:40 937 次阅读 稿源：cnBeta.COM 0 条评论

据外媒报道，粒子物理学的标准模型(Standard Model)在解释宇宙方面做得相当不错，但它仍有一些漏洞。**现在，一项新的研究提出了一个假想的粒子--轴子--将可能帮助解开宇宙中三个独立的、巨大的谜团--包括我们人类为什么会在这里。**

Quantamagazine Physics Mathematics Biology Computer Science All Article

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.

GigaziNE

2020年03月16日 07時00分 サイエンス

ダークマターの正体や人類が存在する理由など宇宙の3つの謎に迫る粒子「アクシオン」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

Press Contact| Lee Sandberg | lsandberg@ias.edu | 609-455-4398

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ON THE COVER

Axiogenesis

March 19, 2020

The rotation of the QCD axion field (black marble) around its potential (yellow surface) during the earliest moments of the Universe could generate the excess of matter (colored marbles) over antimatter, allowing galaxies to exist (galaxy photo credit: NASA). Selected for a 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 the Universe's life could have generated matter-antimatter asymmetry.

Synopsis on:
Raymond T. Co and Keisuke Harigaya
Phys. Rev. Lett. **124**, 111602 (2020)

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NEWS RELEASE 16-MAR-2020

APS tip sheet: Origins of matter and antimatter

Study suggests an 'axiogenesis' mechanism for the explanation of the matter to antimatter ratio in the Universe

AMERICAN PHYSICAL SOCIETY

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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

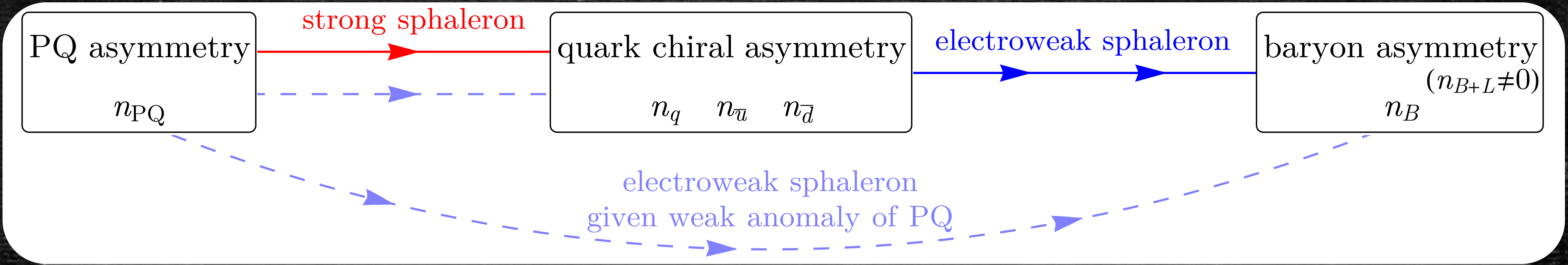
11 марта 2020 15:21

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

#Космос , #Наука

R. Co Minnesota

Axiogenesis



PQ asymmetry

$n_{\rm PQ}$

strong sphaleron

quark chiral asymmetry

$n_q \quad n_{\overline{u}} \quad n_{\overline{d}}$

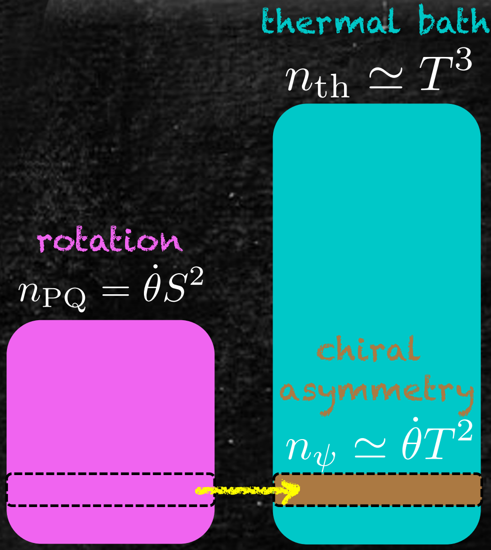
electroweak sphaleron

baryon asymmetry

$(n_{B+L}\neq 0)$

n_B

electroweak sphaleron
given weak anomaly of PQ



thermal bath

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

rotation

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

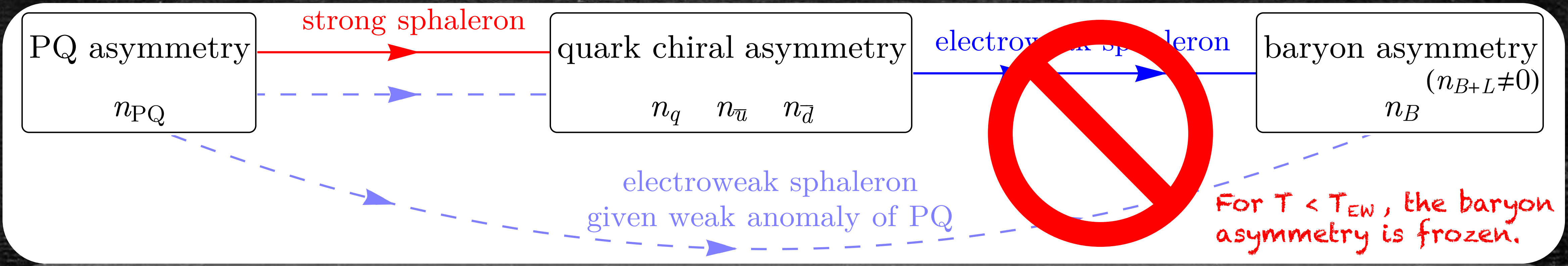
chiral asymmetry

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

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

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

Axiogenesis



PQ asymmetry $n_{\rm PQ}$

strong sphaleron

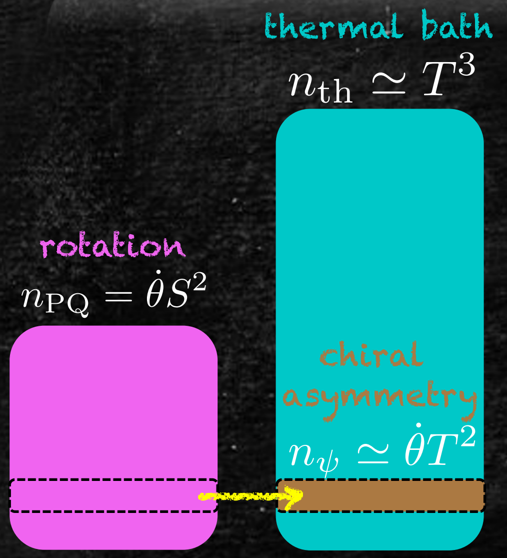
quark chiral asymmetry n_q $n_{\overline{u}}$ $n_{\overline{d}}$

electroweak sphaleron

baryon asymmetry $(n_{B+L}\neq 0)$ n_B

electroweak sphaleron given weak anomaly of PQ

For T < $T_{\rm EW}$, the baryon asymmetry is frozen.

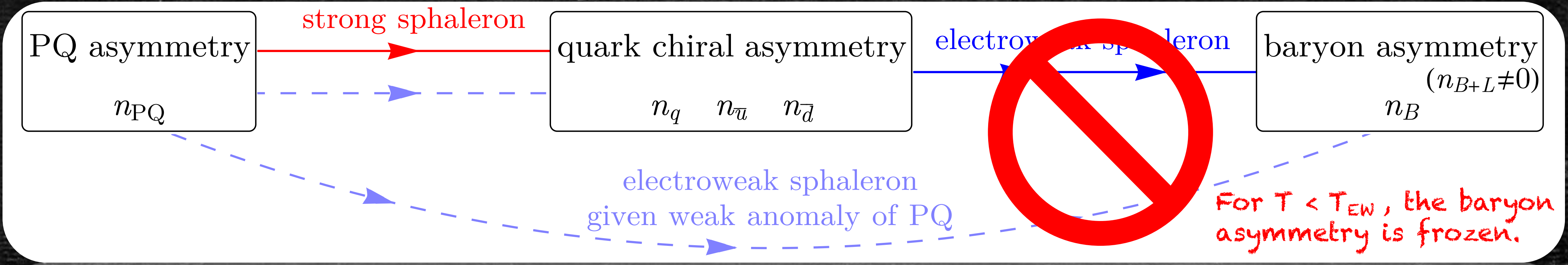


$$Y_B \equiv \frac{n_B}{s} = \frac{c_B \dot\theta T^2}{s}\bigg|_{T = T_{\rm EW}} = c_B Y_{\rm PQ}\left(\frac{T_{\rm EW}}{f_a}\right)^2$$

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

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

Axiogenesis



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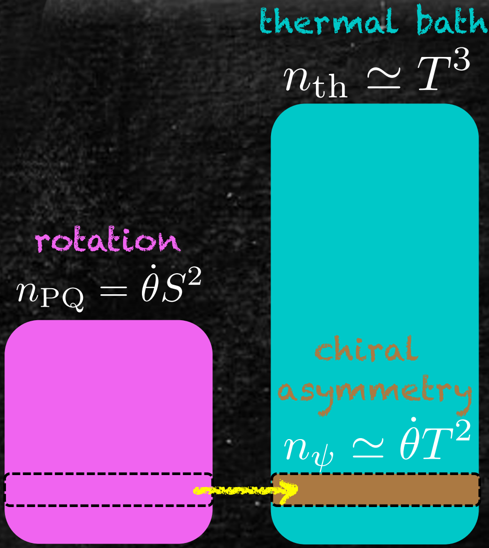


thermal bath

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

rotation

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

chiral asymmetry

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

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

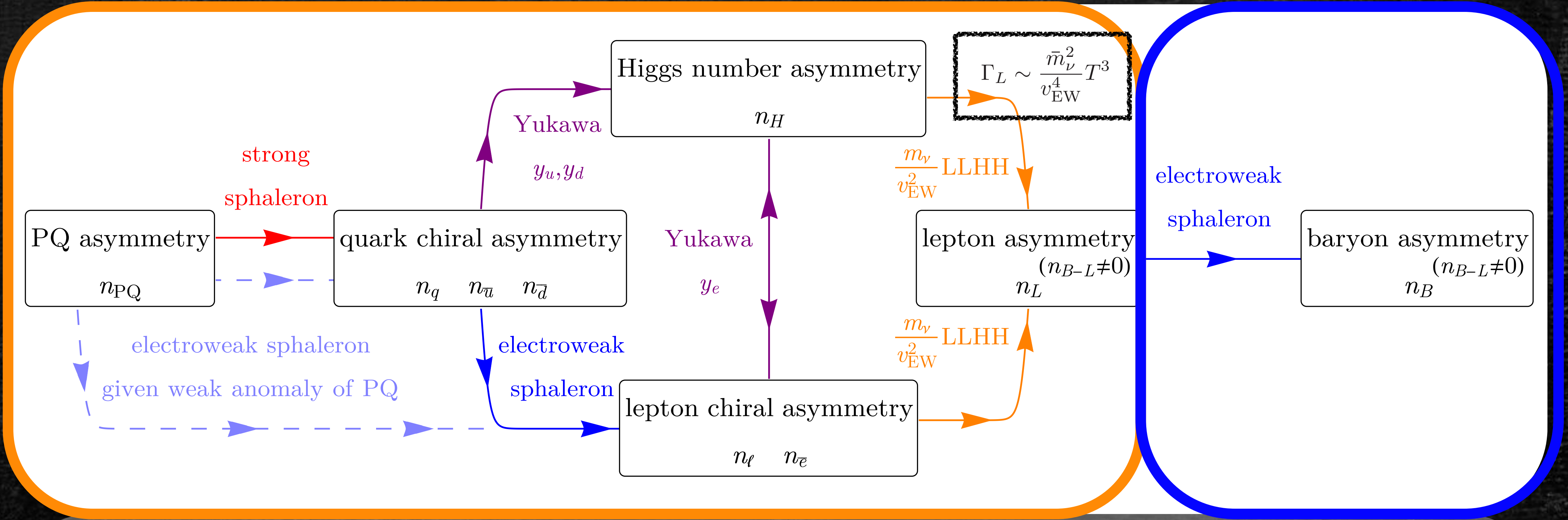
Baryon asymmetry fixes rotational speed, equivalently Y_{PQ}.

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

Lepto-Axiogenesis

Producing L at high temperatures

Converting to B at $T_{\rm EW}$



PQ asymmetry

$n_{\rm PQ}$

strong

sphaleron

quark chiral asymmetry

$n_q \quad n_{\overline{u}} \quad n_{\overline{d}}$

Yukawa

y_u, y_d

Higgs number asymmetry

n_H

$\Gamma_L \sim \frac{\bar{m}_\nu^2}{v_{\rm EW}^4} T^3$

$\frac{m_\nu}{v_{\rm EW}^2}$ LLHH

Yukawa

y_e

lepton asymmetry

$(n_{B-L} \neq 0)$

n_L

electroweak sphaleron

given weak anomaly of PQ

electroweak

sphaleron

lepton chiral asymmetry

$n_\ell \quad n_{\overline{e}}$

$\frac{m_\nu}{v_{\rm EW}^2}$ LLHH

electroweak

sphaleron

baryon asymmetry

$(n_{B-L} \neq 0)$

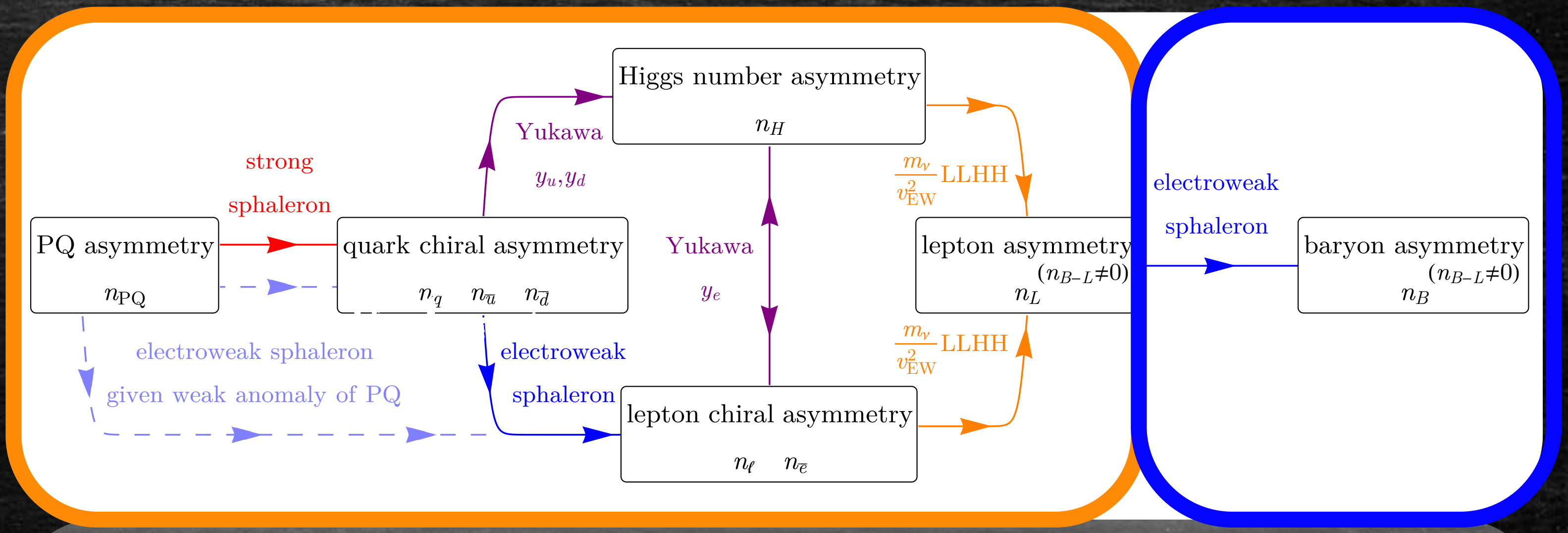
n_B

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

Lepto-Axiogenesis

Producing L at high temperatures

Converting to B at T_{EW}



Higgs number asymmetry n_H

Yukawa y_u, y_d

strong sphaleron

PQ asymmetry n_{PQ}

quark chiral asymmetry n_q $n_{\bar{u}}$ $n_{\bar{d}}$

Yukawa y_e

$\frac{m_\nu}{v_{\mathrm{EW}}^2}$ LLHH

lepton asymmetry $(n_{B-L}\neq 0)$ n_L

electroweak sphaleron

baryon asymmetry $(n_{B-L}\neq 0)$ n_B

electroweak sphaleron given weak anomaly of PQ

electroweak sphaleron

$\frac{m_\nu}{v_{\mathrm{EW}}^2}$ LLHH

lepton chiral asymmetry n_ℓ $n_{\bar{e}}$

Lepton number violating interaction rate

$$\Gamma_L \simeq \frac{1}{4\pi^3}\frac{\bar{m}^2}{v_{\mathrm{EW}}^4}T^3$$

$$\bar{m}^2 \equiv \sum m_\nu^2$$

Out of equilibrium when

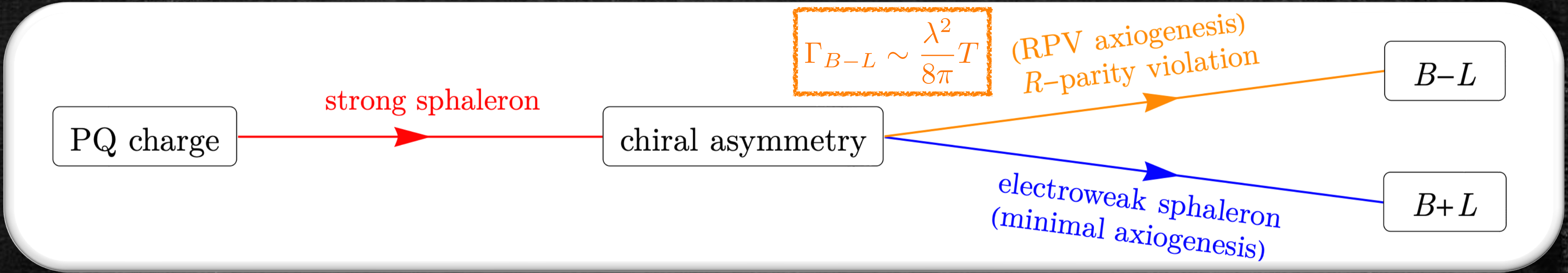
$$T \lesssim 5 \times 10^{12}\mathrm{GeV}\left(\frac{0.03\mathrm{eV}^2}{\bar{m}^2}\right)$$

$$Y_B = \frac{28}{79}Y_{B-L}$$

$$Y_{B-L} \equiv \frac{n_{B-L}}{s} = \frac{\Gamma_L}{H}\frac{c_{B-L}\dot{\theta}T^2}{s}$$

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

RPV Axiogenesis



PQ charge

strong sphaleron

chiral asymmetry

$\boxed{\Gamma_{B-L} \sim \frac{\lambda^2}{8\pi} T}$

(RPV axiogenesis)
R–parity violation

B–L

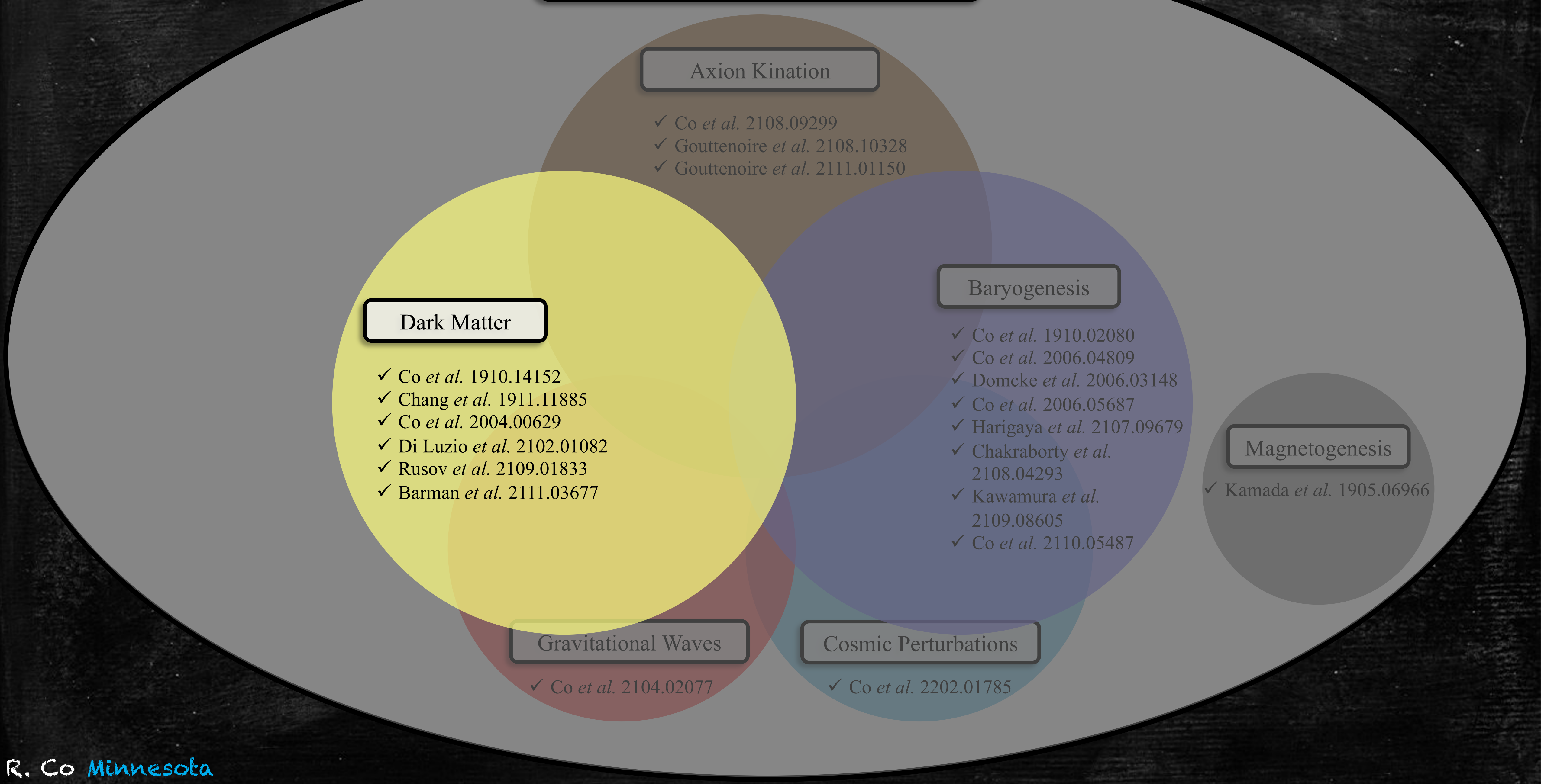
electroweak sphaleron
(minimal axiogenesis)

B+L

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

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

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
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Baryogenesis

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Magnetogenesis

- ✓ Kamada *et al.* 1905.06966

Gravitational Waves

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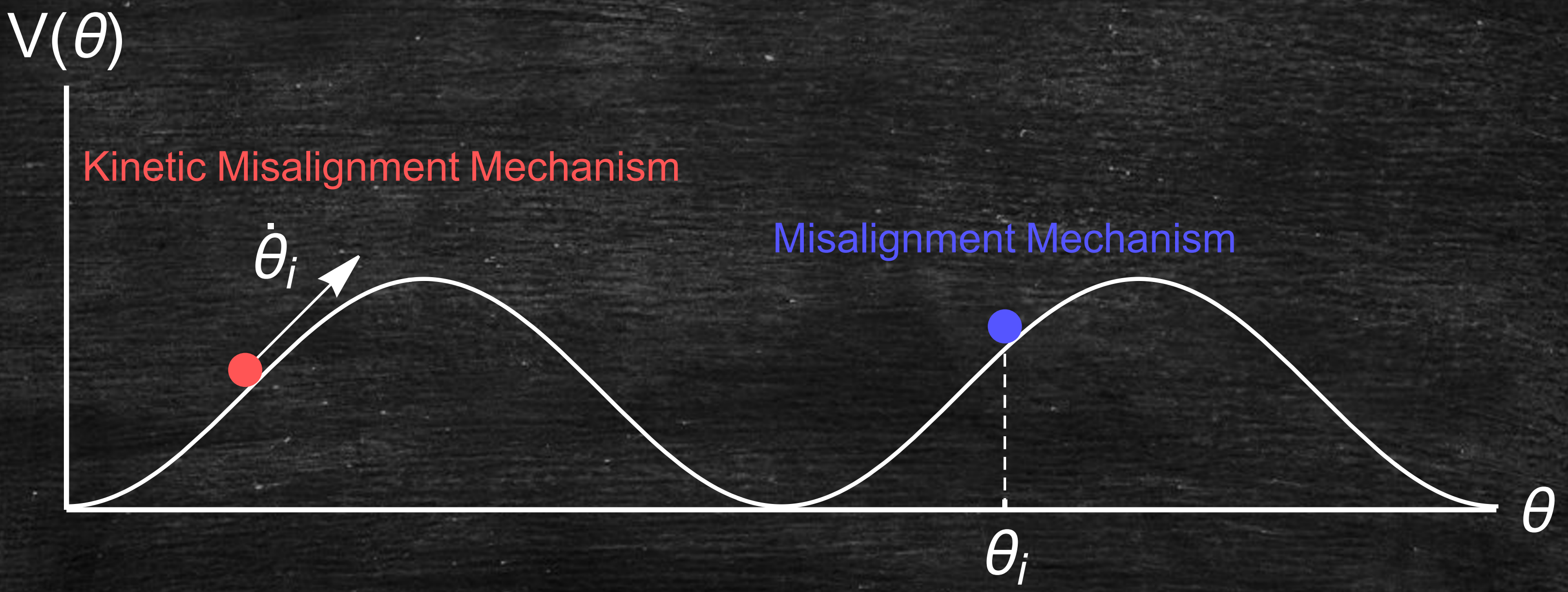
Cosmic Perturbations

- ✓ Co *et al.* 2202.01785



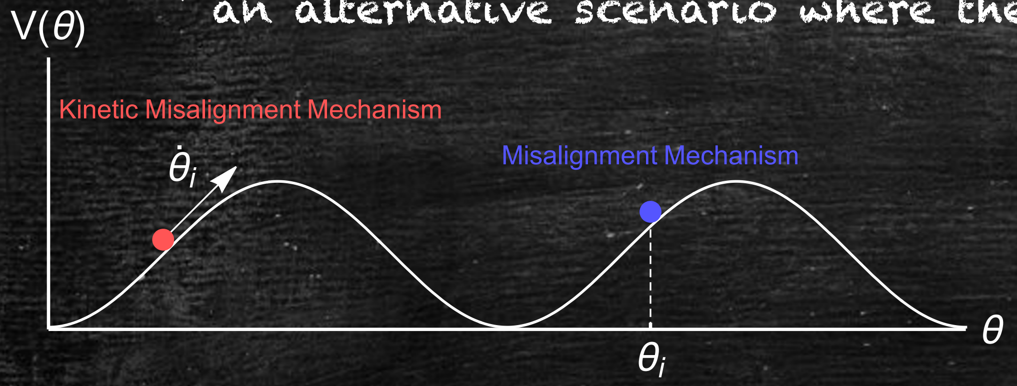
Kinetic Misalignment Mechanism

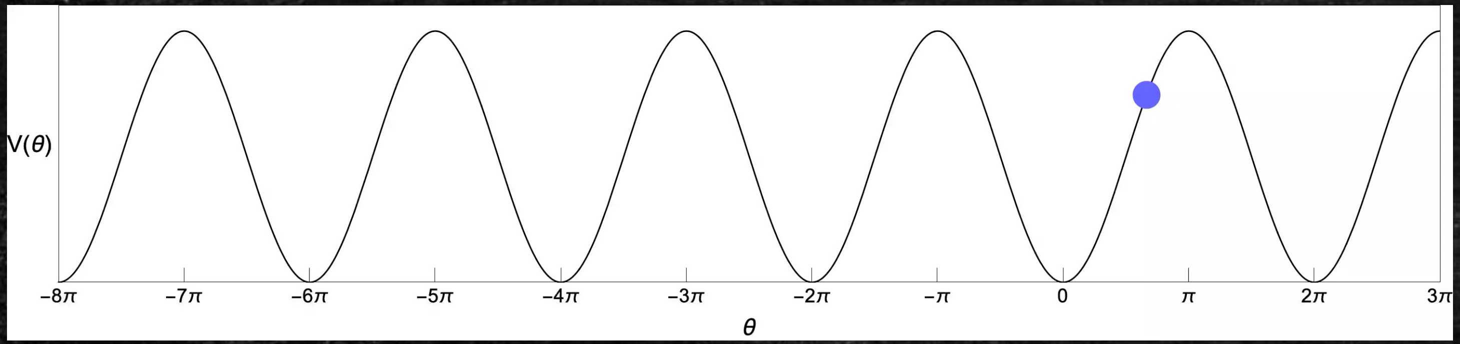
(Misalignment + non-zero kinetic energy)

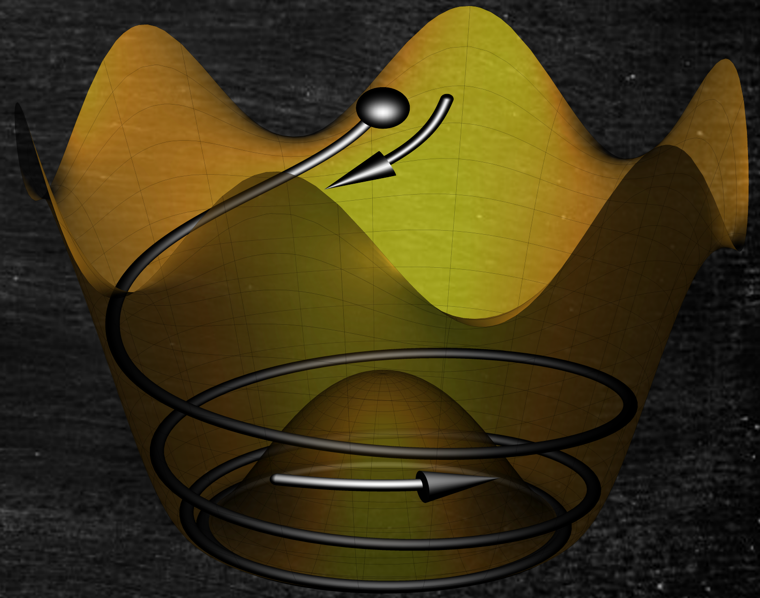
PRL 124, 251802 (2020) RC, L. Hall, K. Harigaya

Kinetic Misalignment Mechanism

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







Consequence: delaying* usual $T_{\rm osc}$ until KE = PE, enhancing the dark matter abundance

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

* Parametric resonance in fact occurs before oscillations start. The abundance is modified by an O(1) factor but axion dark matter can be warm.

1605.01367, 1903.03116, 1911.08472

2104.02077 RC, K. Harigaya, A. Pierce

R. Co Minnesota

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

Kinetic Misalignment Mechanism

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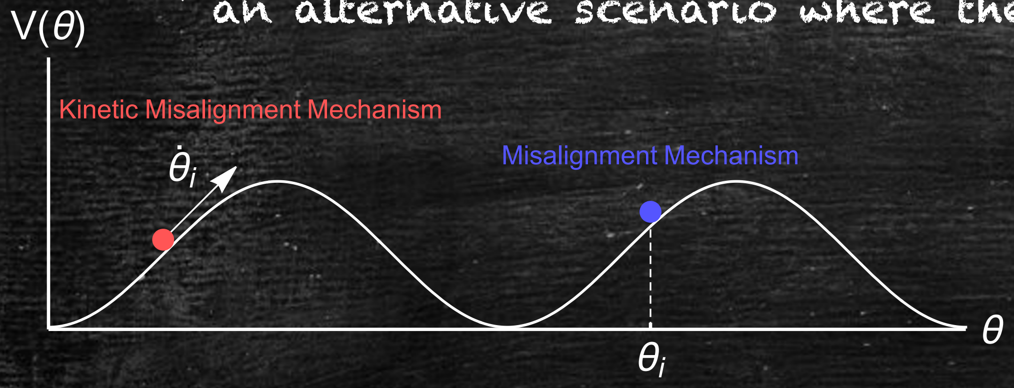
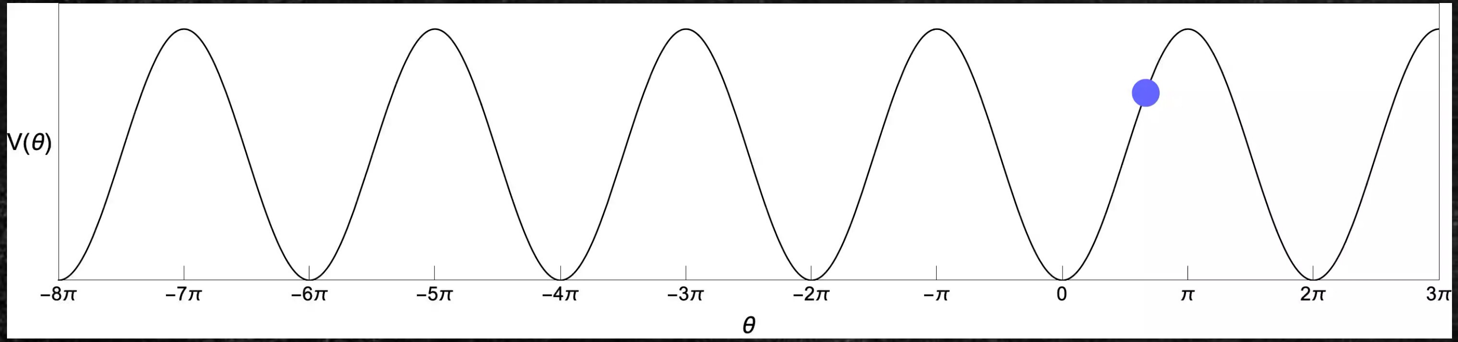
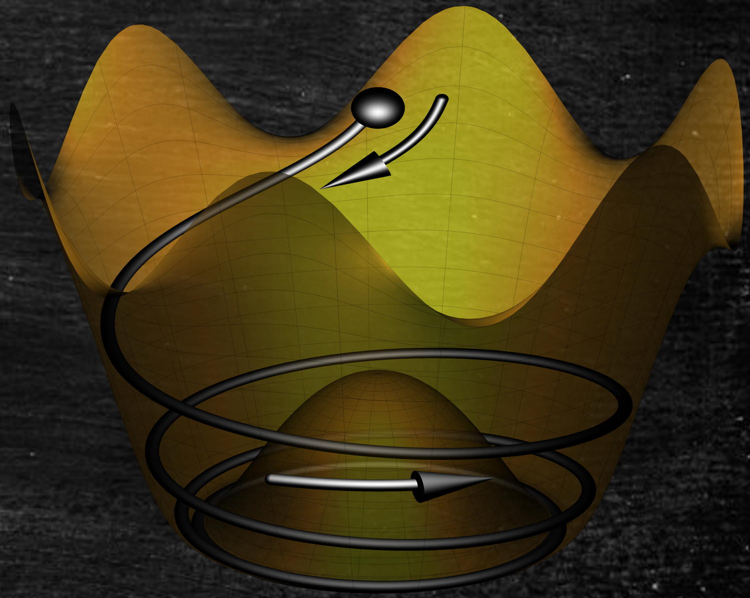






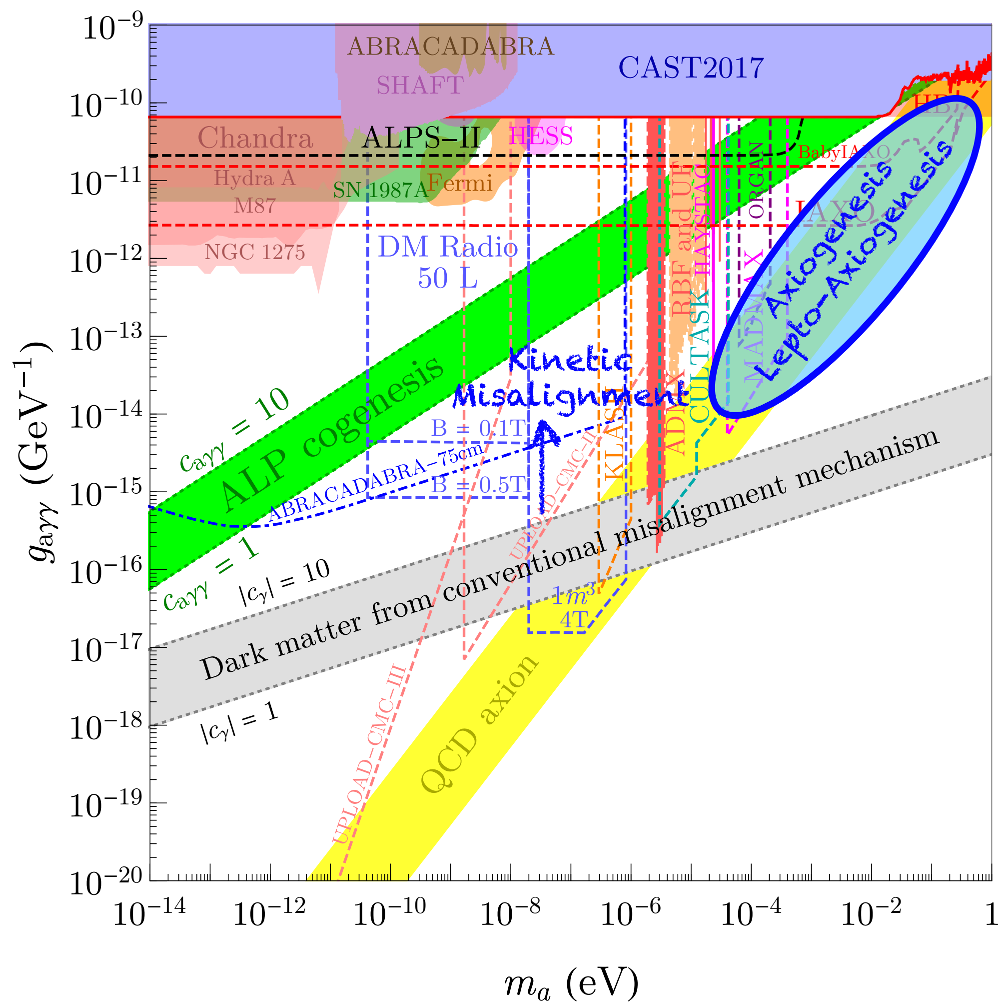
Abundance: $\frac{\rho_a}{s} = C m_a Y_{\rm PQ}$

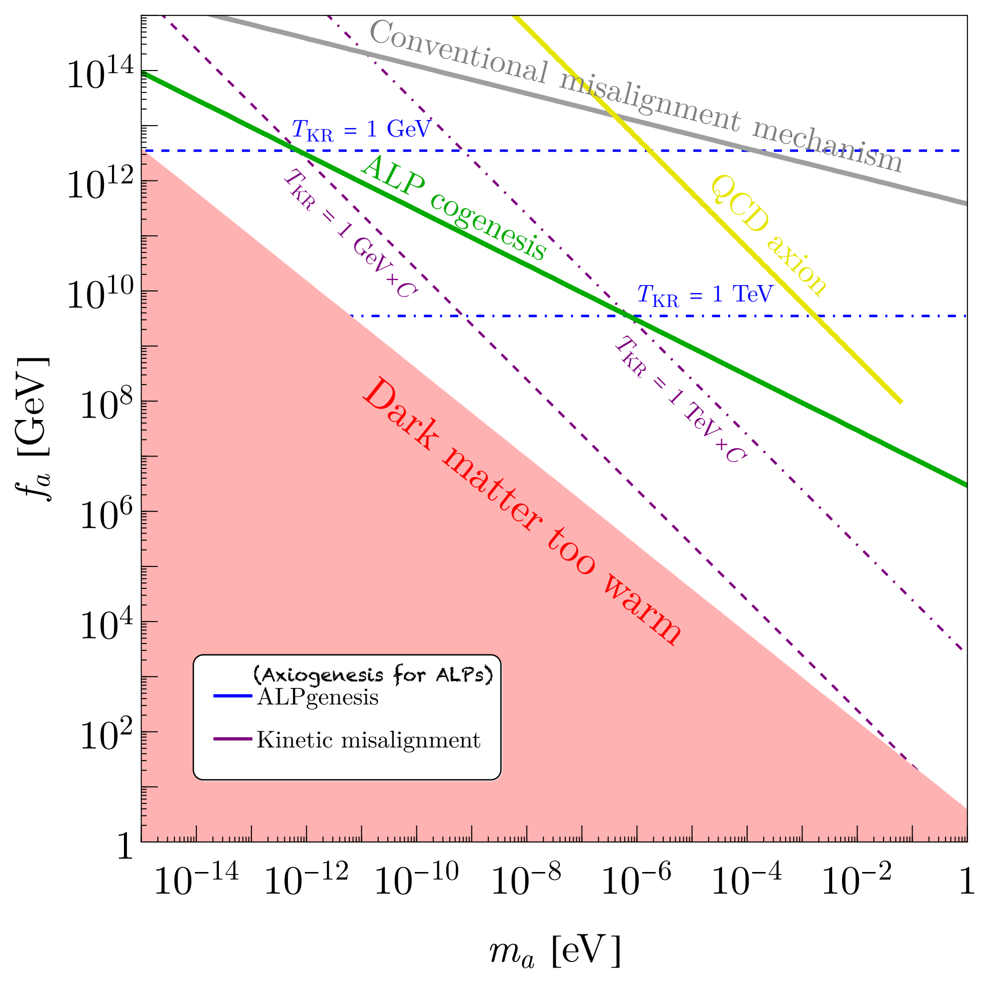
$$\Omega_a h^2 \simeq \Omega_{\rm DM} h^2 \left(\frac{m_a}{\rm meV}\right)\left(\frac{Y_{\rm PQ}}{440}\right)$$

R. Co Minnesota

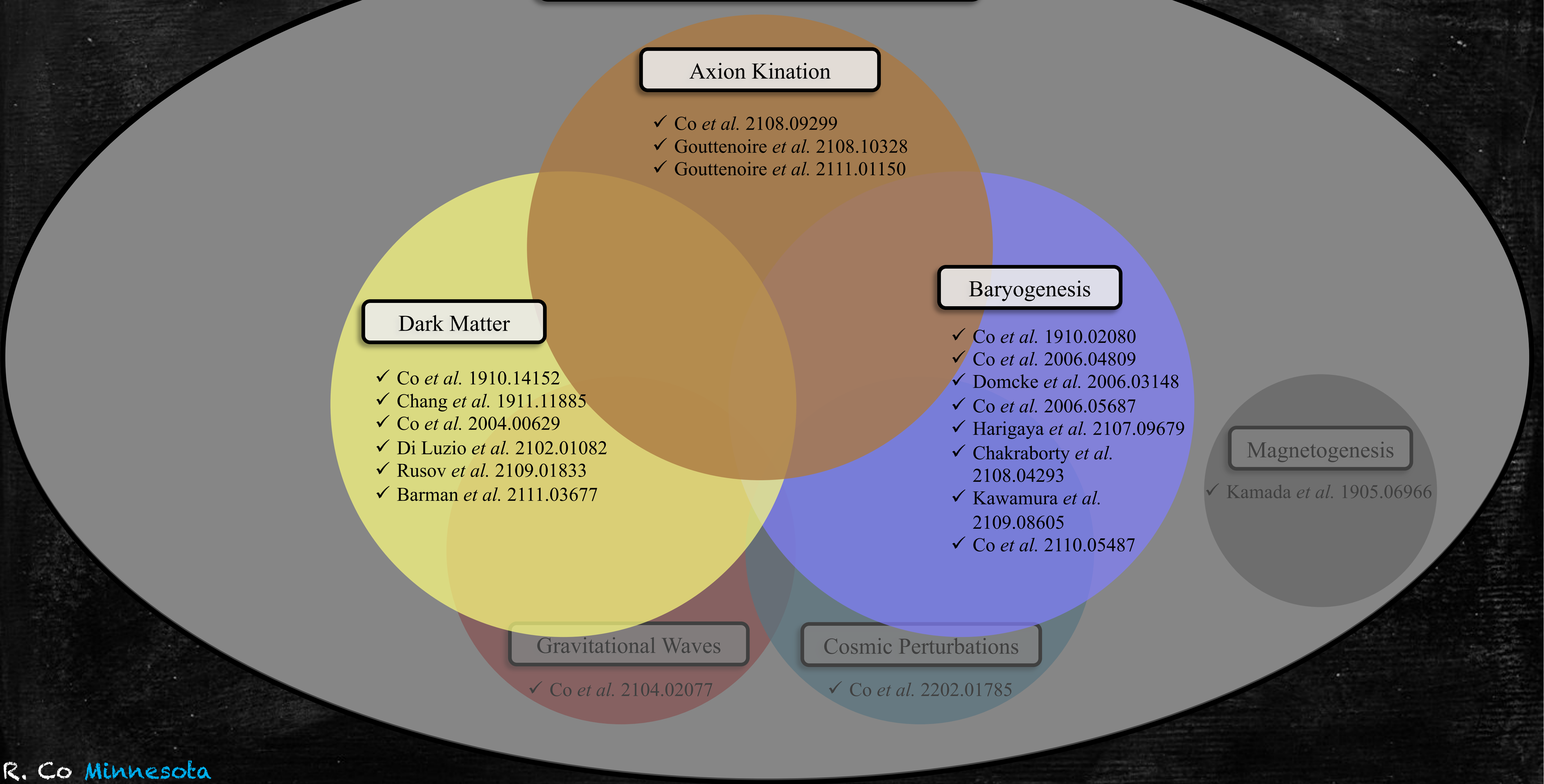
PRL 124, 251802 (2020) RC, L. Hall, K. Harigaya

Predictions from
Axiogenesis and Kinetic Misalignment





Axion Rotations



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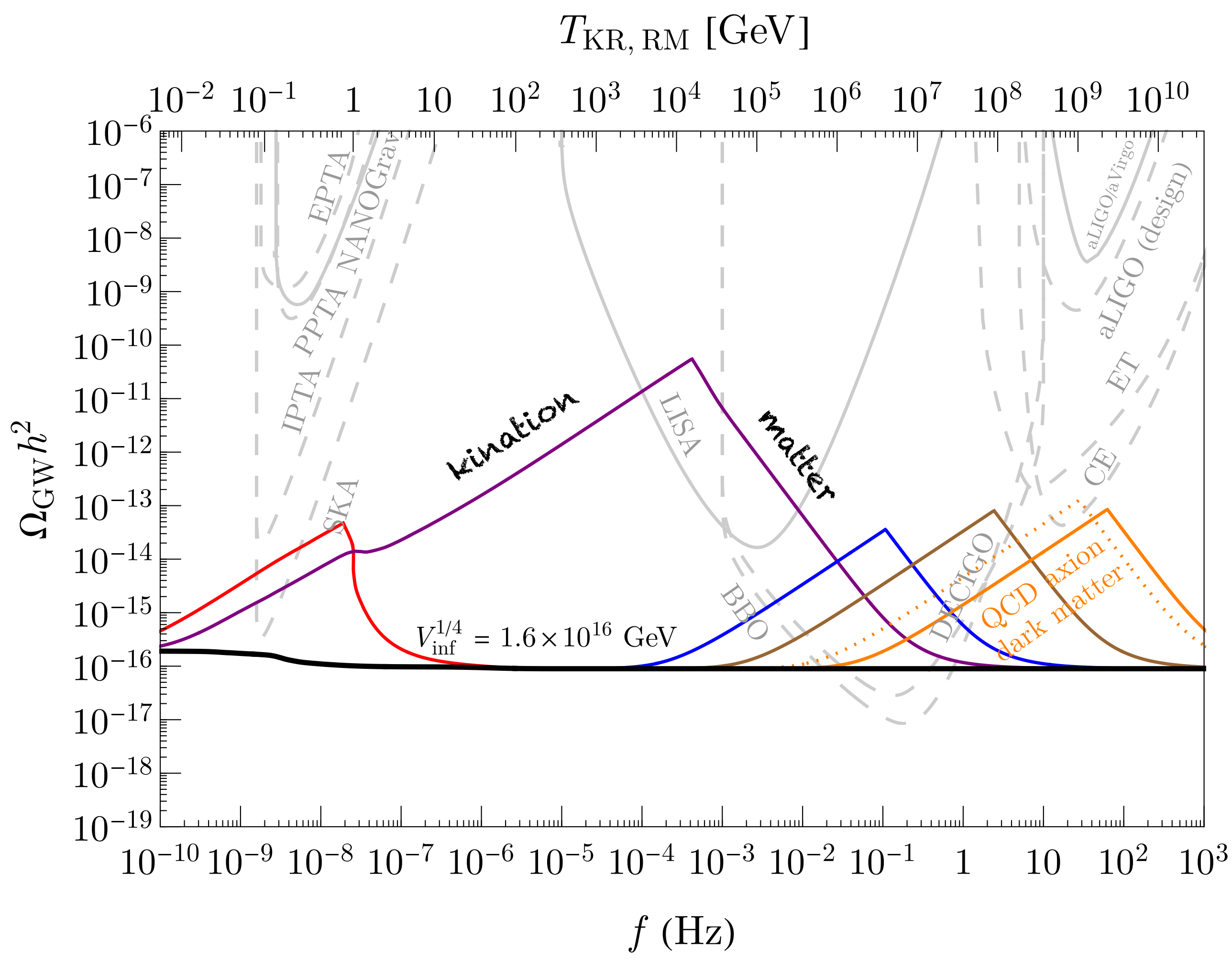
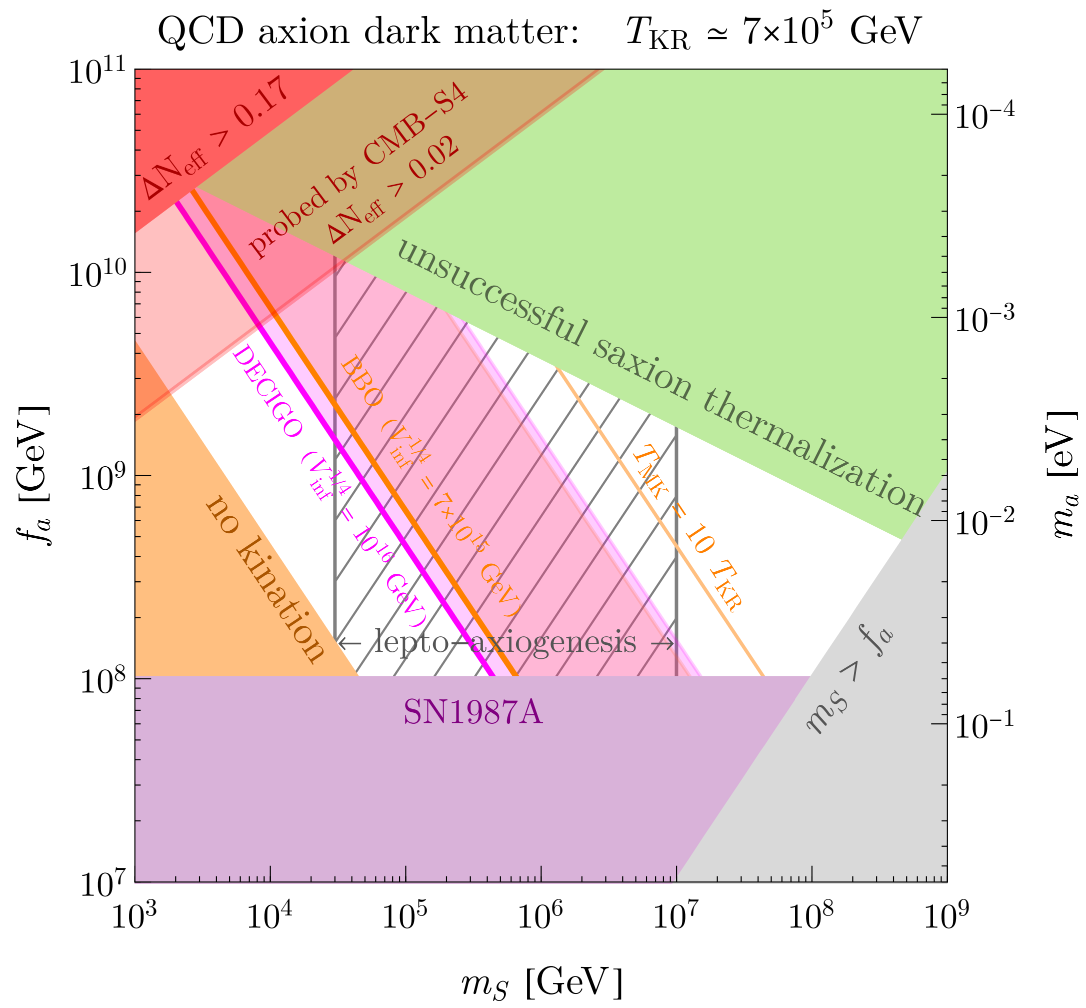
Gravitational Waves from Inflation

the QCD axion

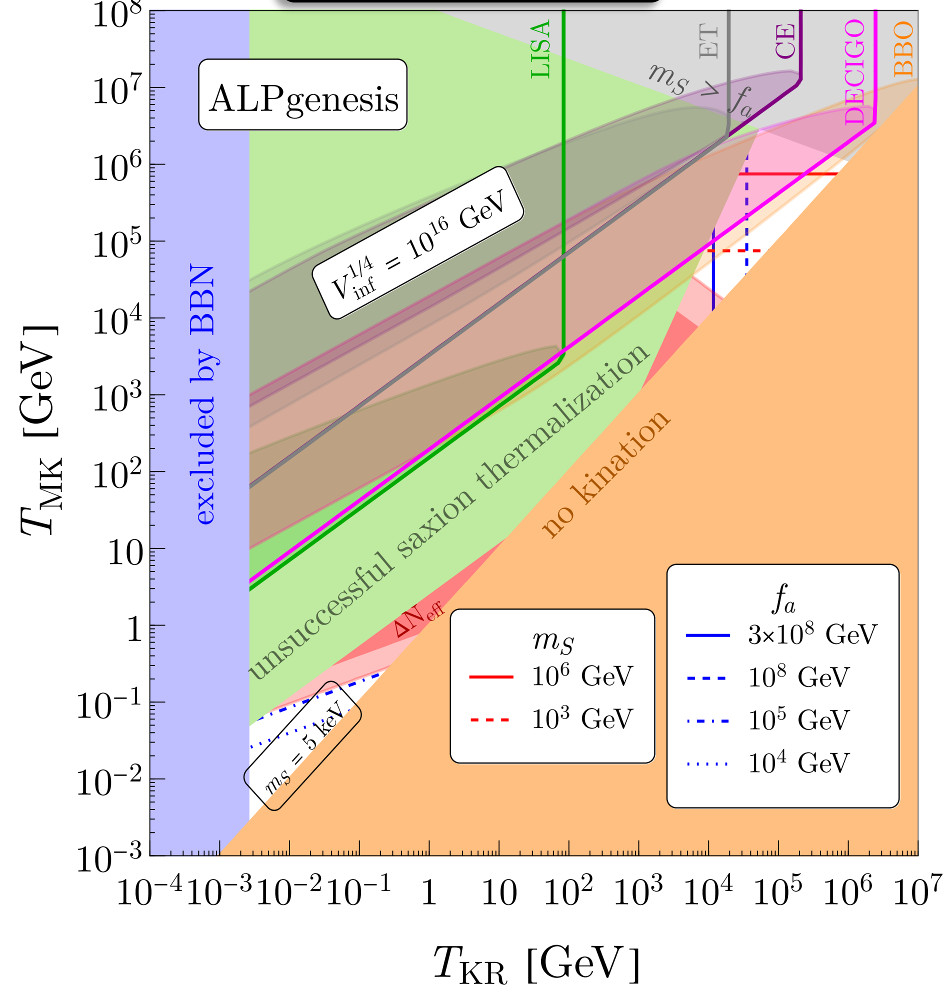




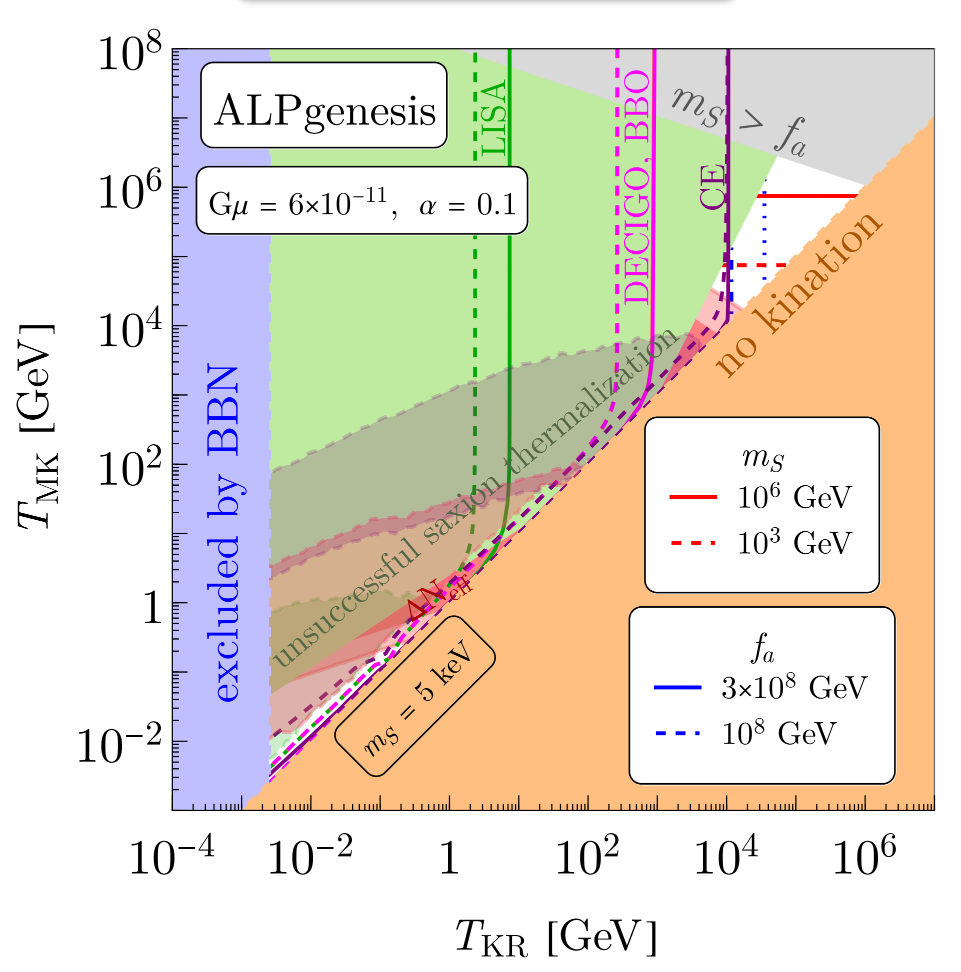
ALPgenesis

(Axiogenesis for ALPs)

from inflation



from cosmic strings



R. Co Minnesota

Probing PQ-breaking Potential

Piecewise approximation

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

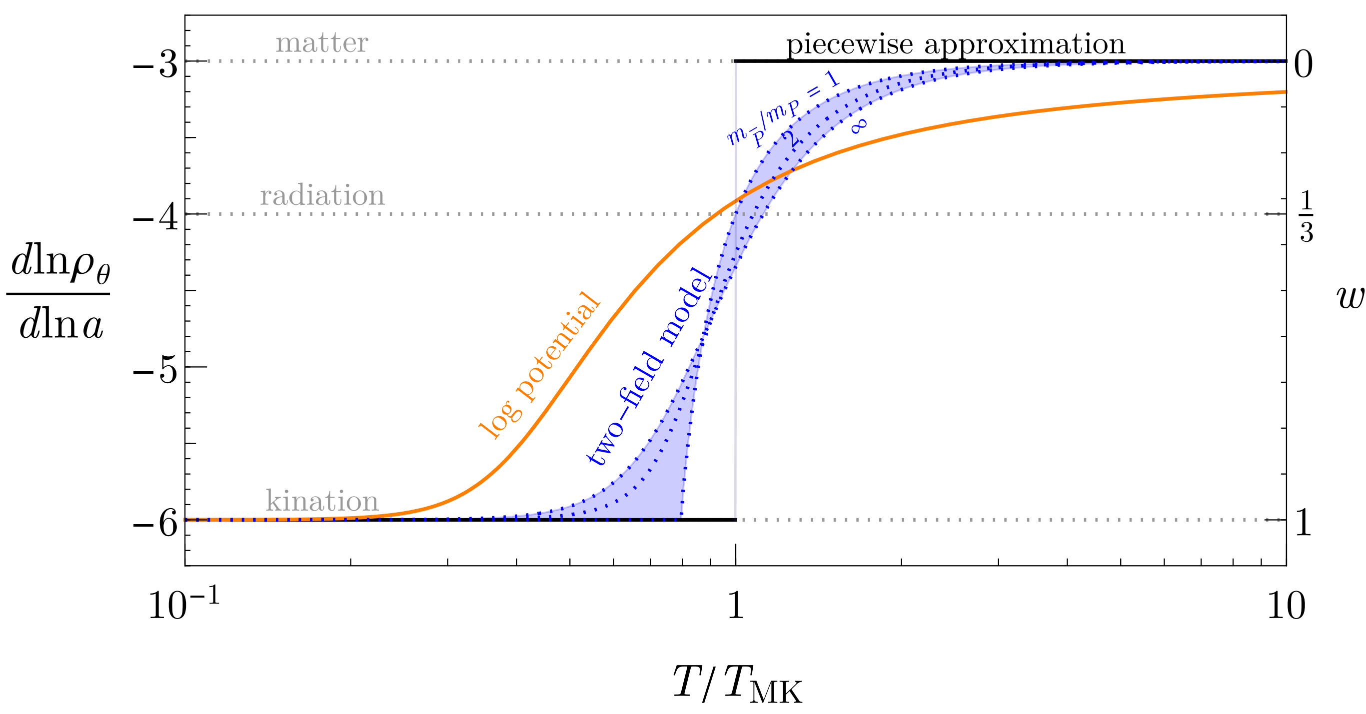
log potential

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

Two-field model

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

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



Probing PQ-breaking Potential

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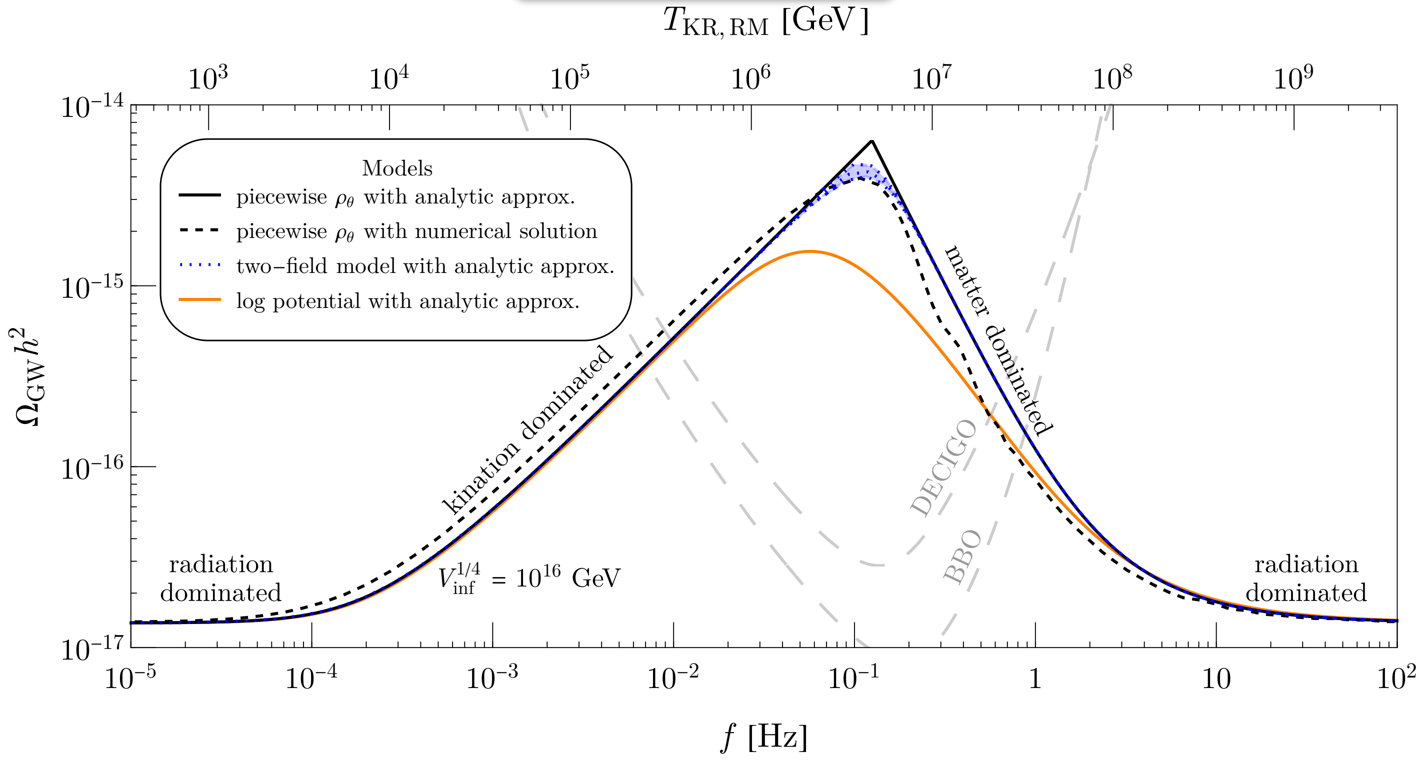

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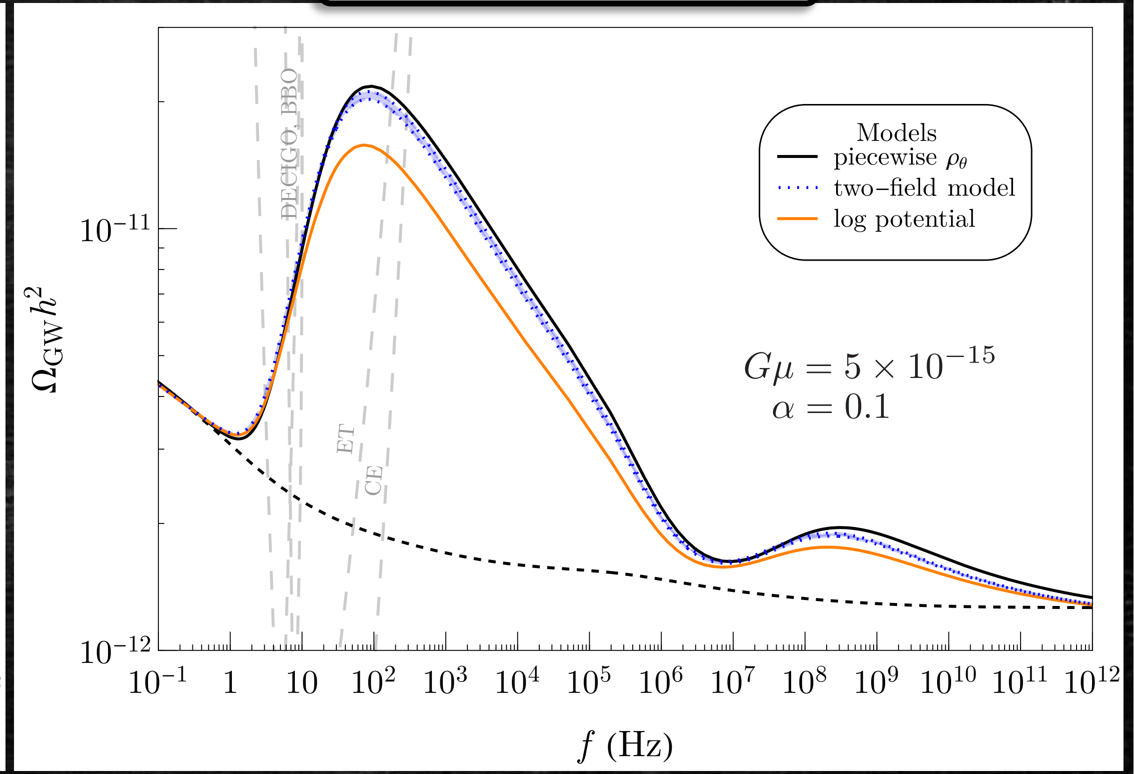
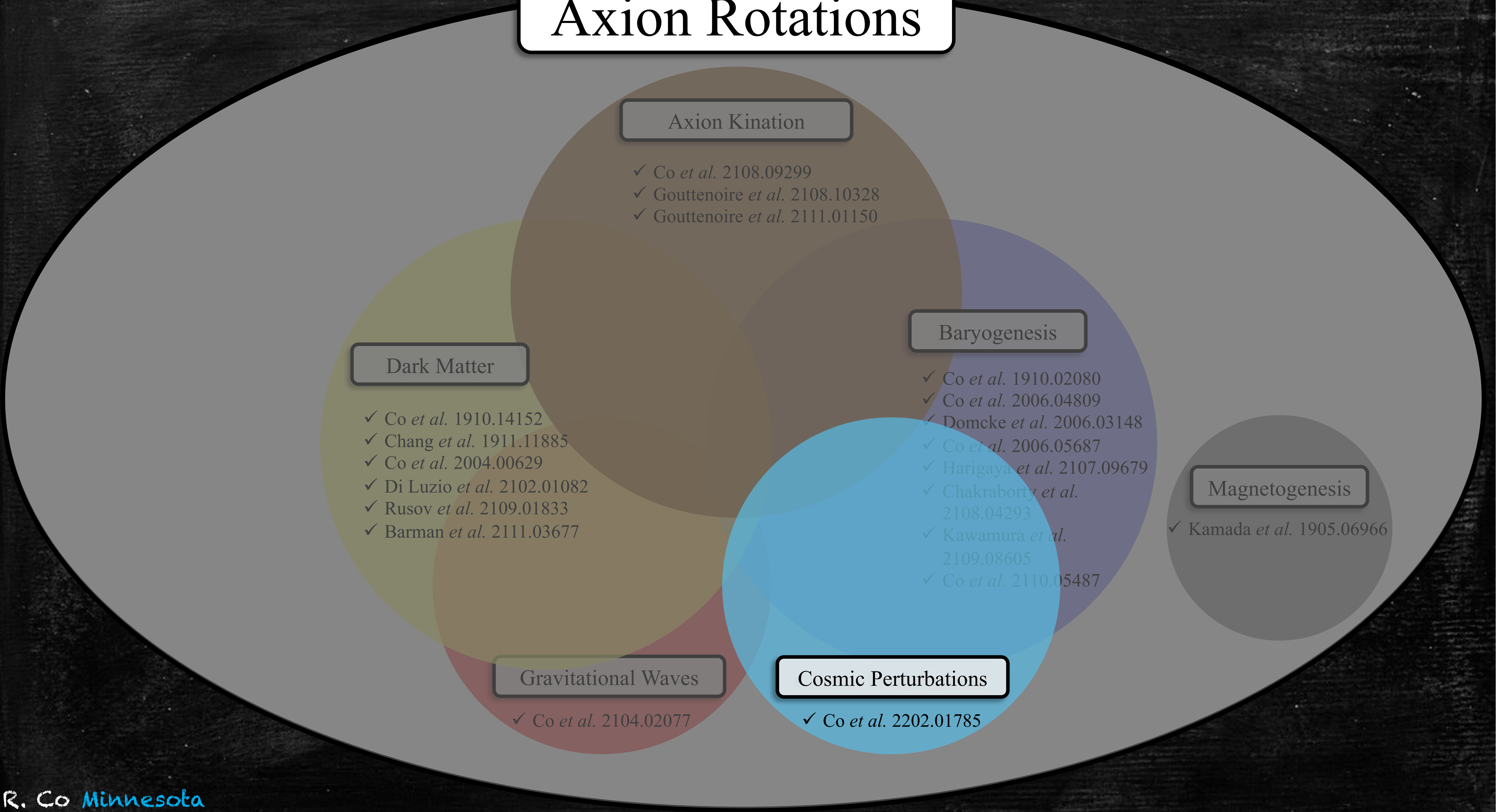


Axion Rotations



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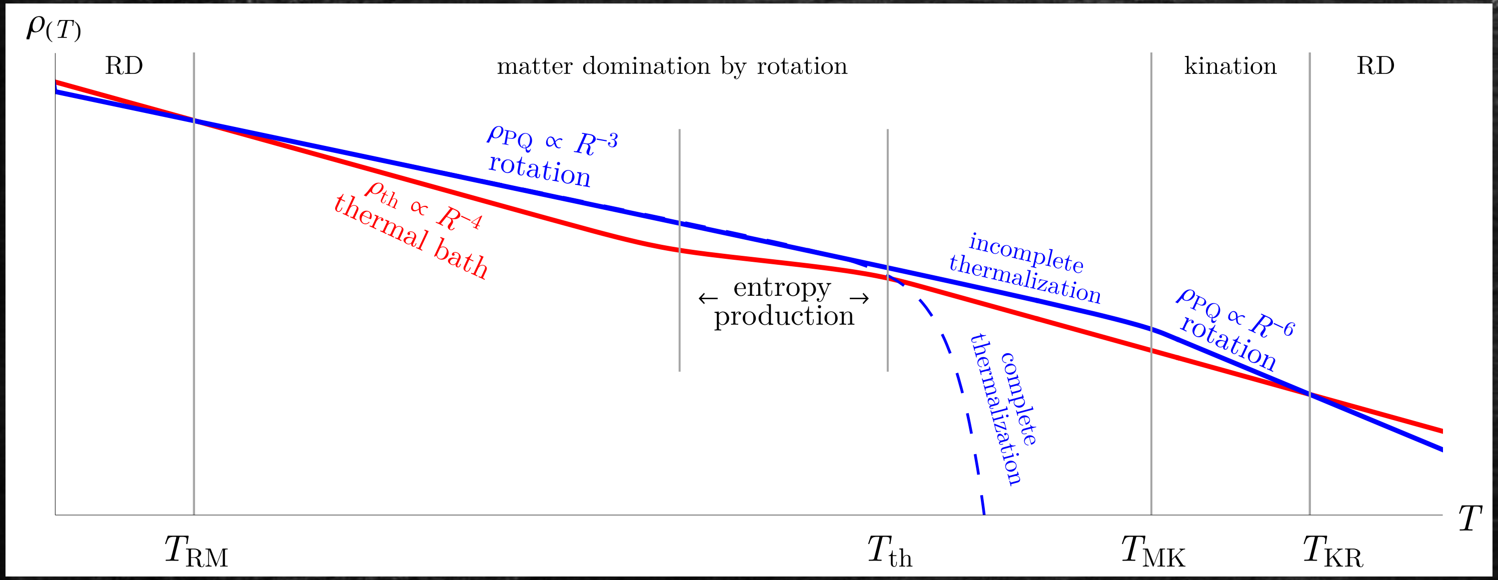
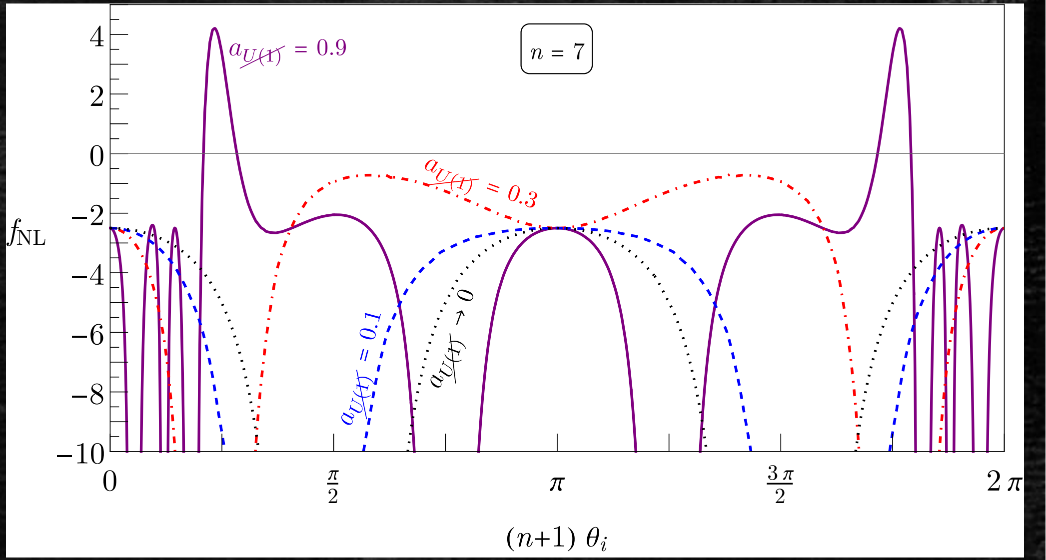
R. Co Minnesota

A Rotating Curvaton



observable non-Gaussianity



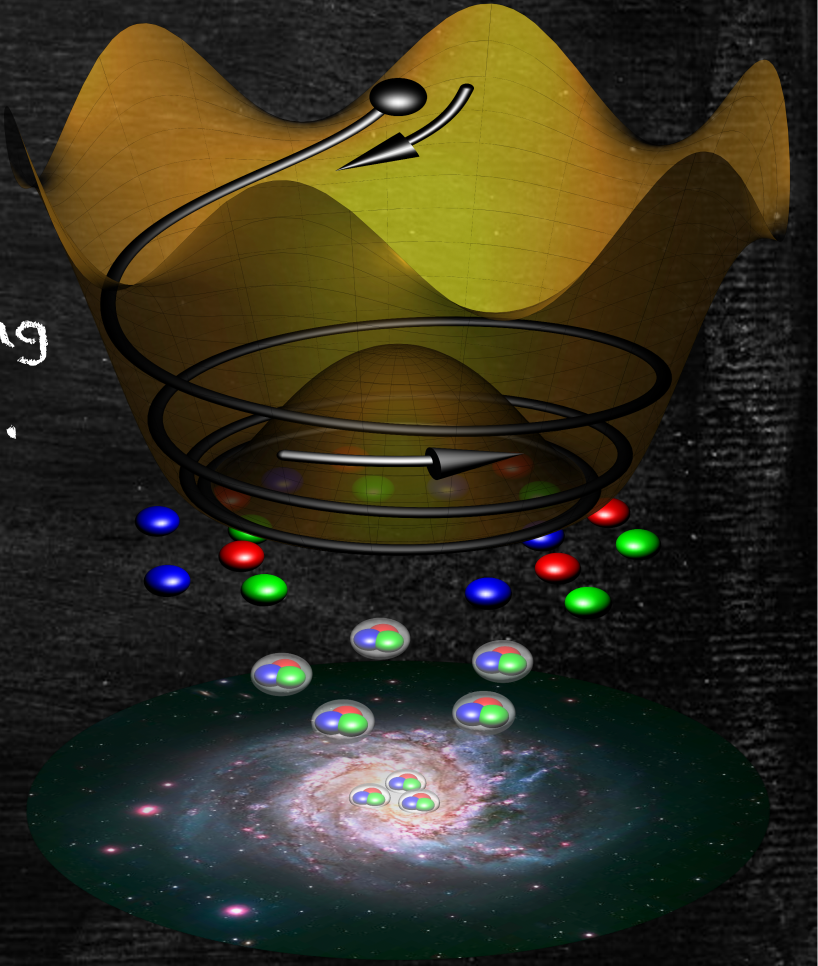
Conclusions

- ✓ 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:
  - ✓ (QCD) axion searches
  - ✓ Warm axion dark matter
  - ✓ Matter power spectrum

- ✓ New model building opportunities



Thank you!

Happy Birthday, John.