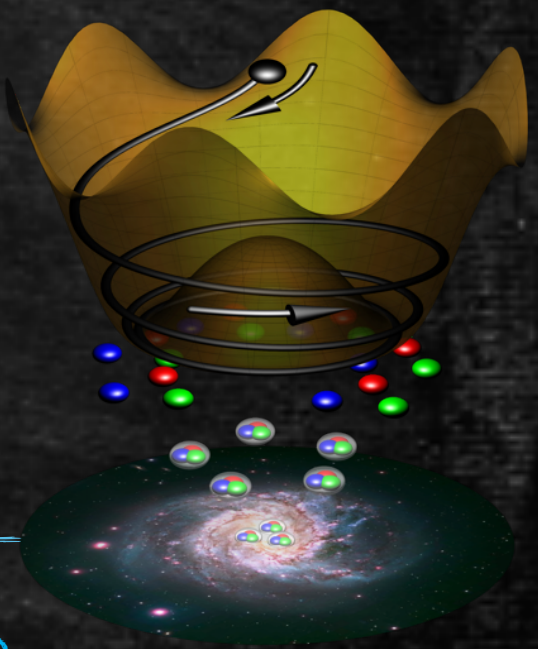
Gravitational Wave Probes of Axion Kination

Raymond Co

William I. Fine Theoretical Physics Institute
University of Minnesota



Brookhaven Forum November 4th 2021

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

Today

Nobel Prize in Physics 1989

for the invention of the separated oscillatory fields method and its use in the hydrogen maser and other atomic clocks

Norman F. Ramsey

died on November 4th 2011

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https://www.nobelprize.org/prizes/physics/1989/ramsey/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

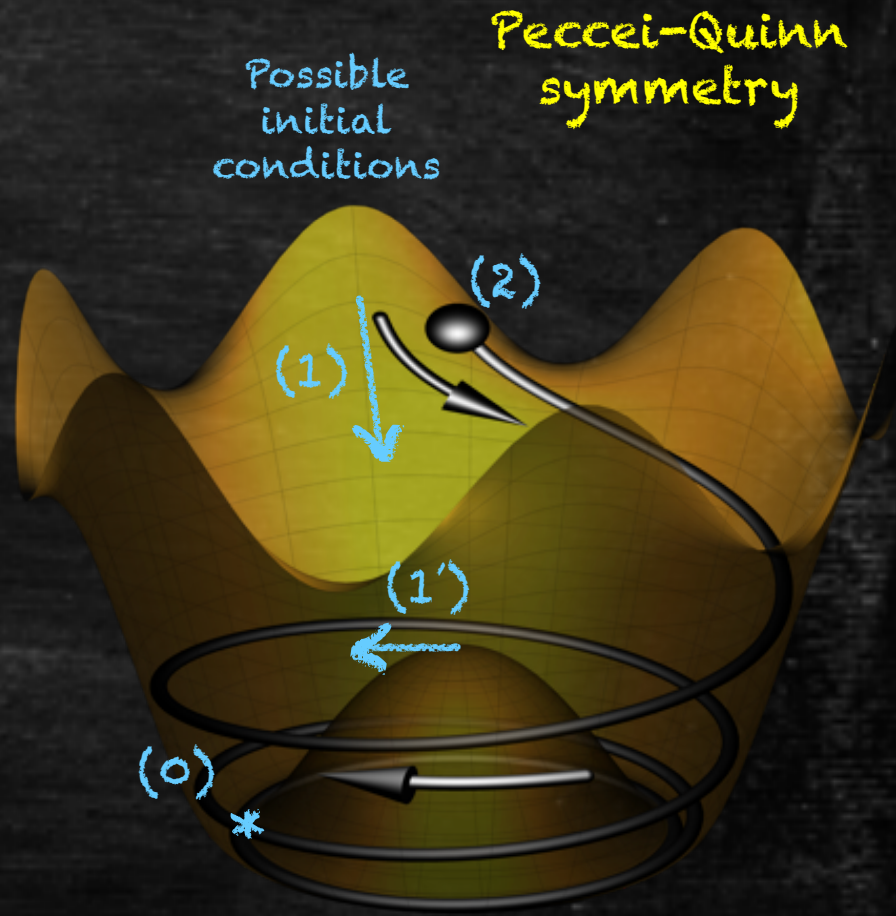
- ALP cogenesis
RC, L. Hall, K. Harigaya 2020

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

} Baryon Asymmetry

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

} Gravitational Waves



Axion Rotations

- **Axion**

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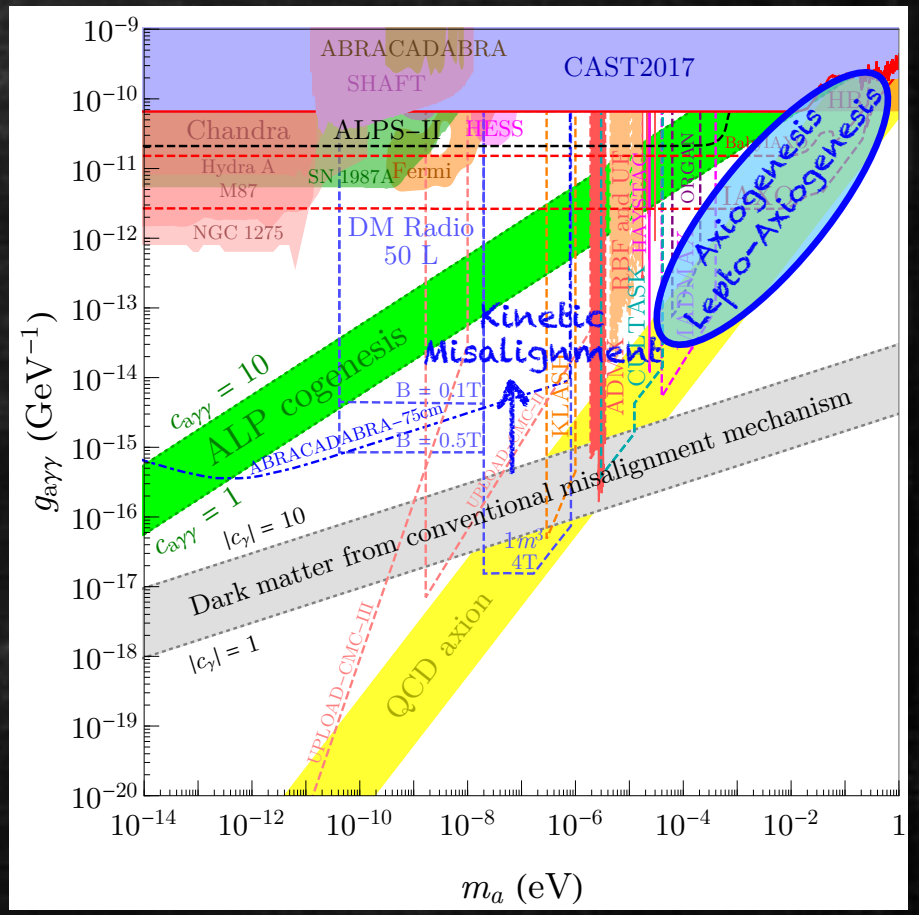
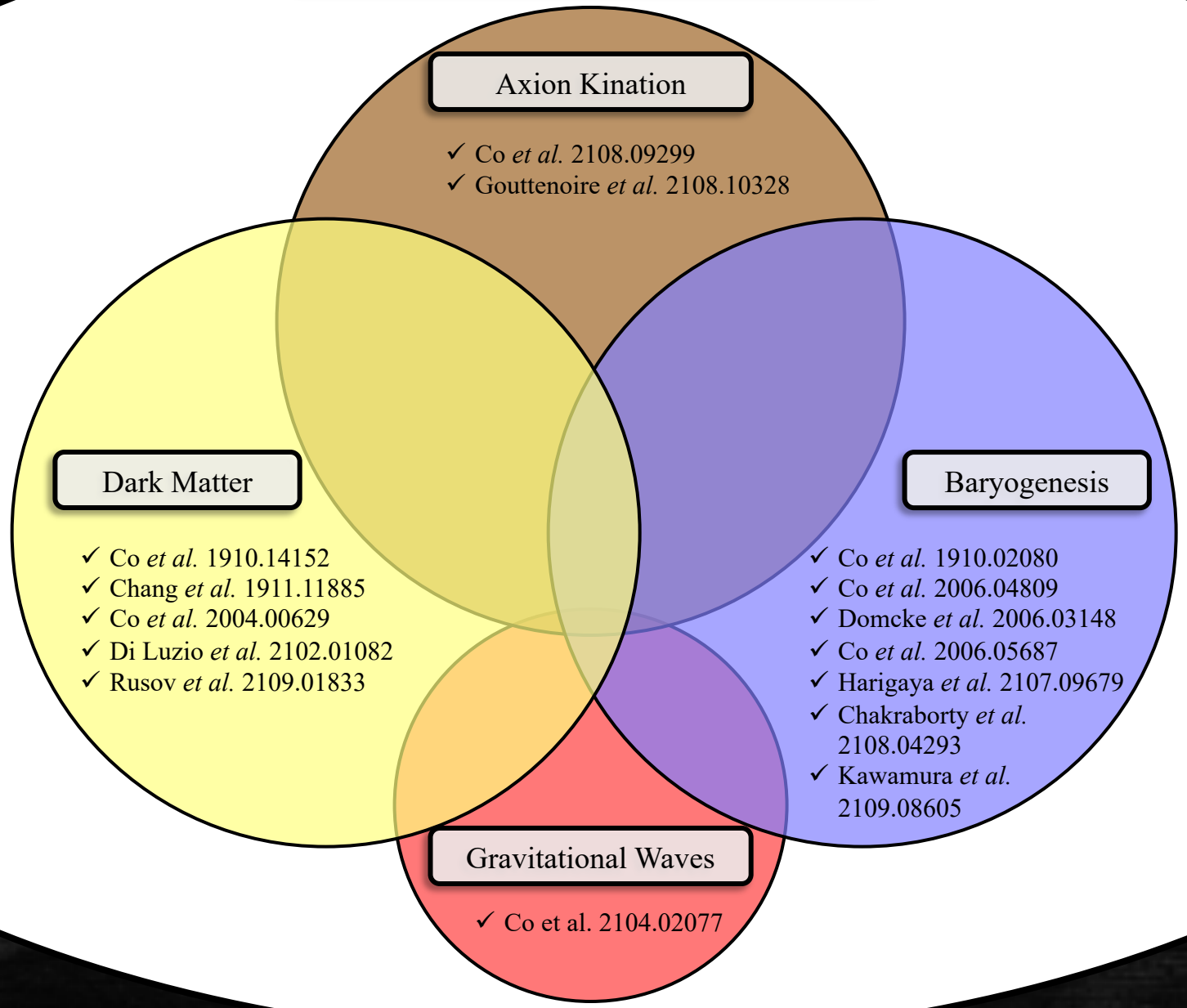
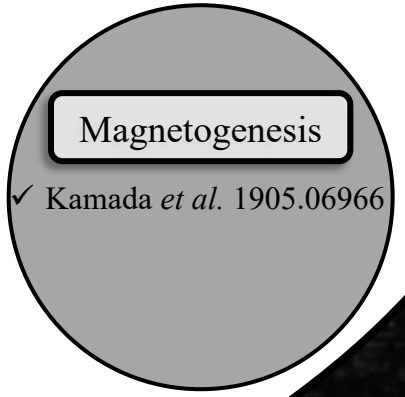


Axion Rotations





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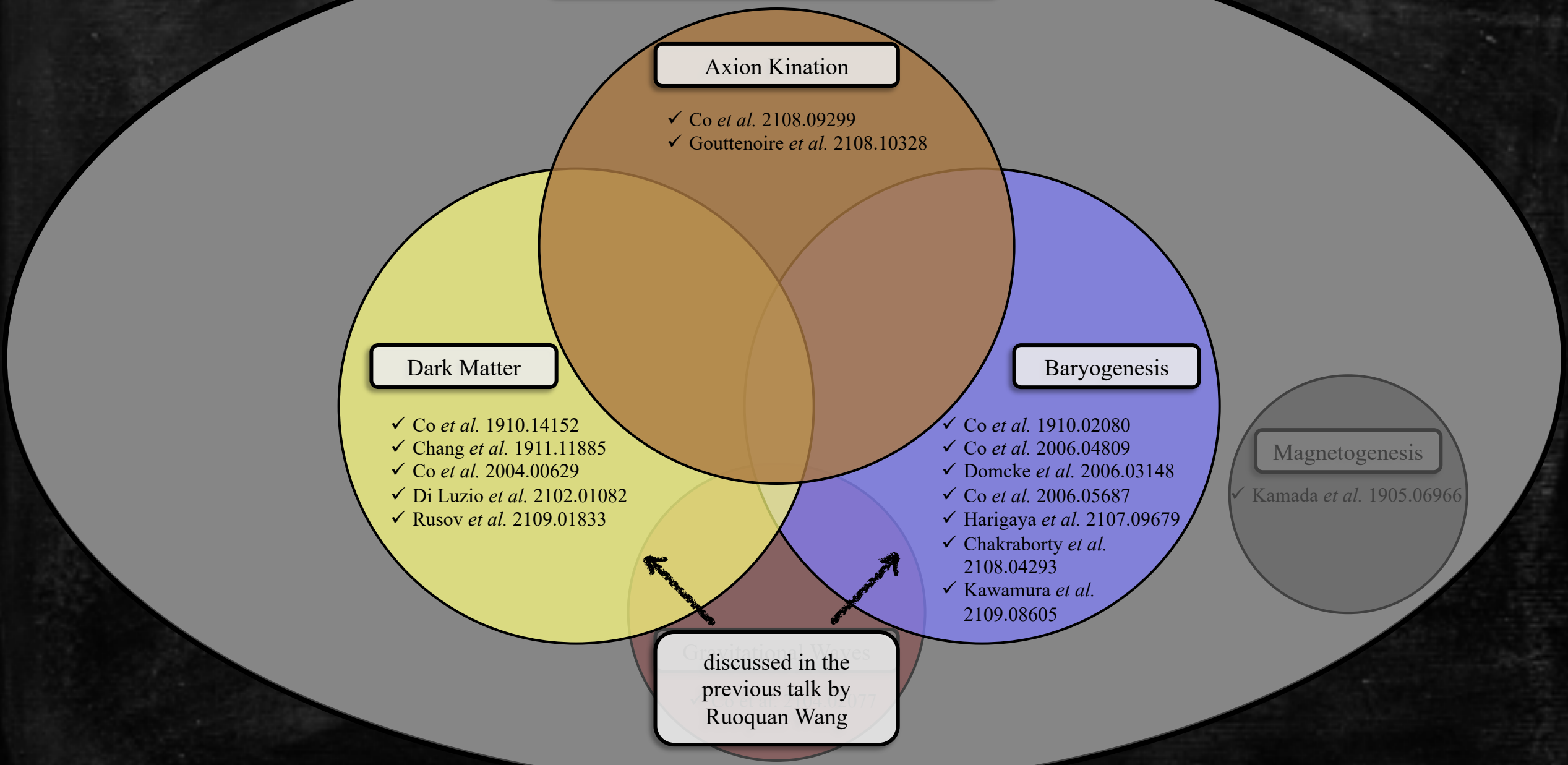
Axion Rotations



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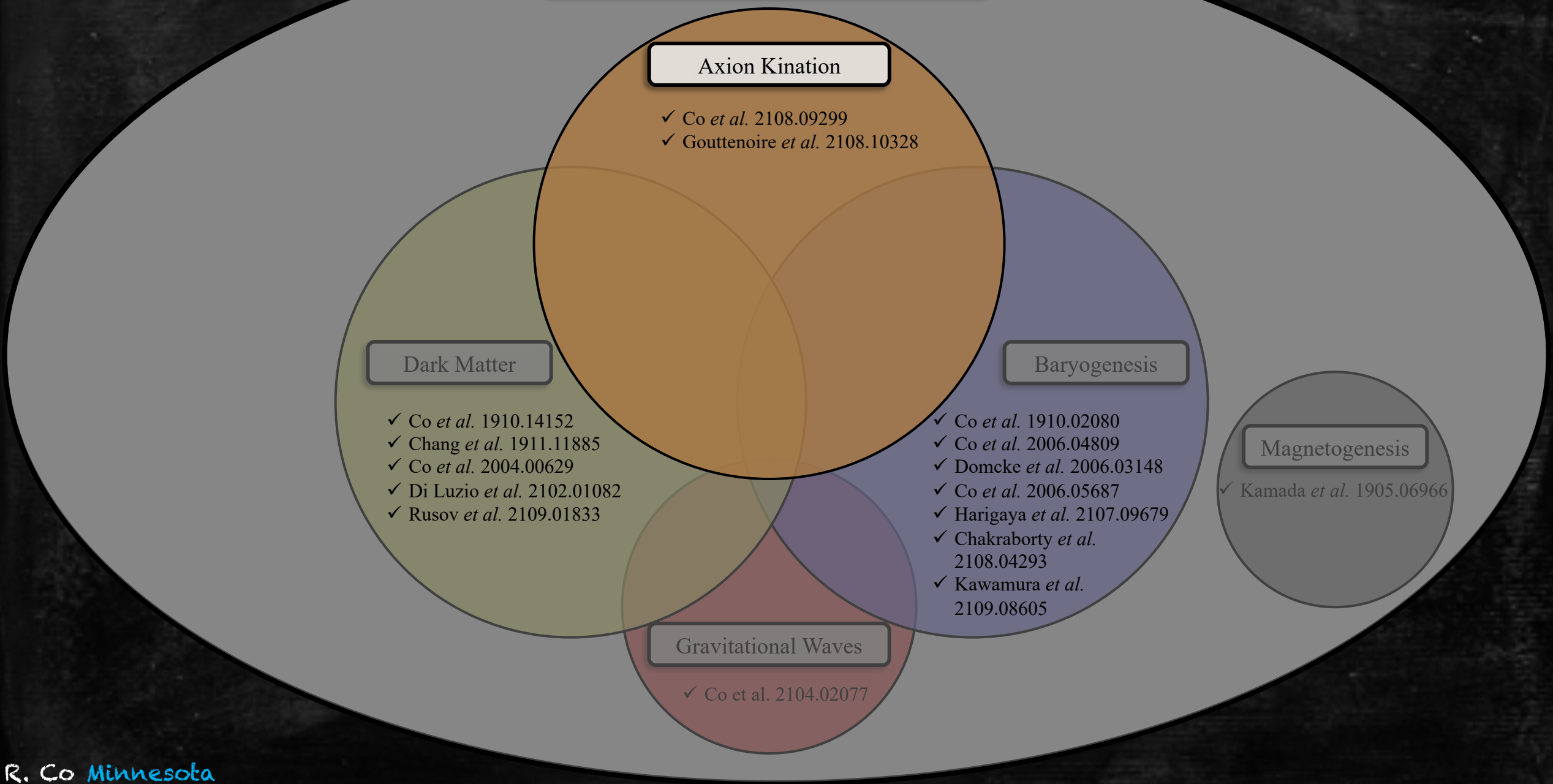

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What is kination?

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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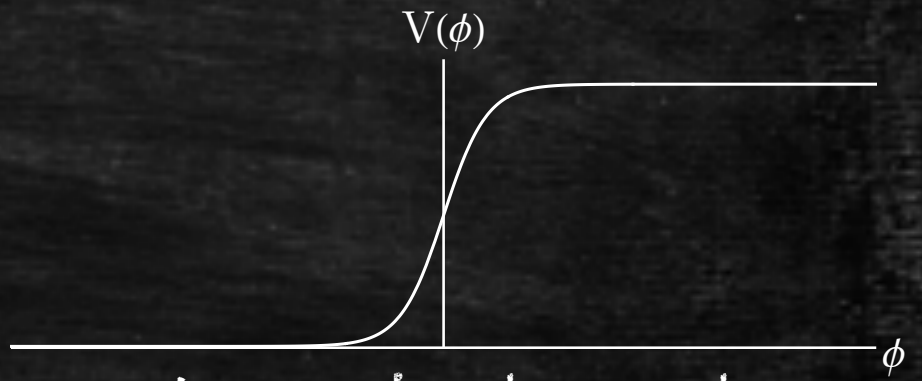


An unnatural example

Equation of state

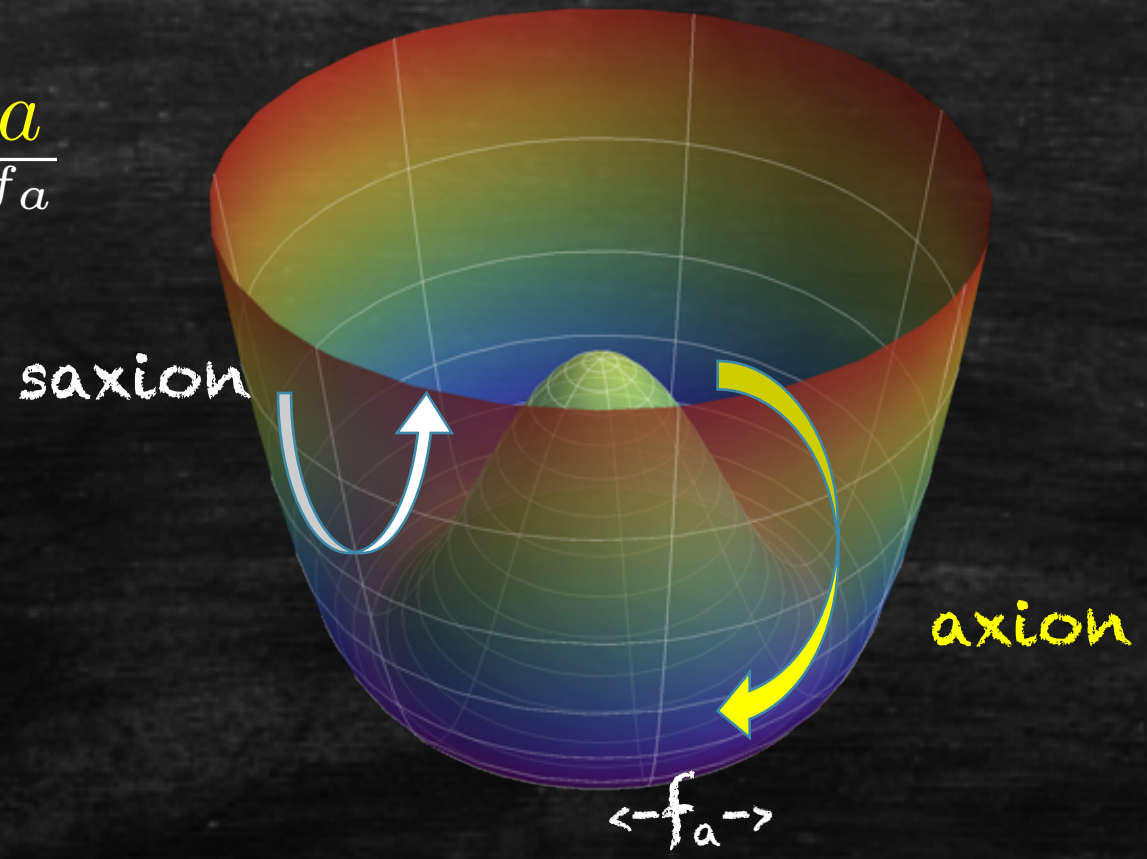
$$w = \frac{p}{\rho} = \frac{K - V}{K + V} \simeq 1$$

Evolution

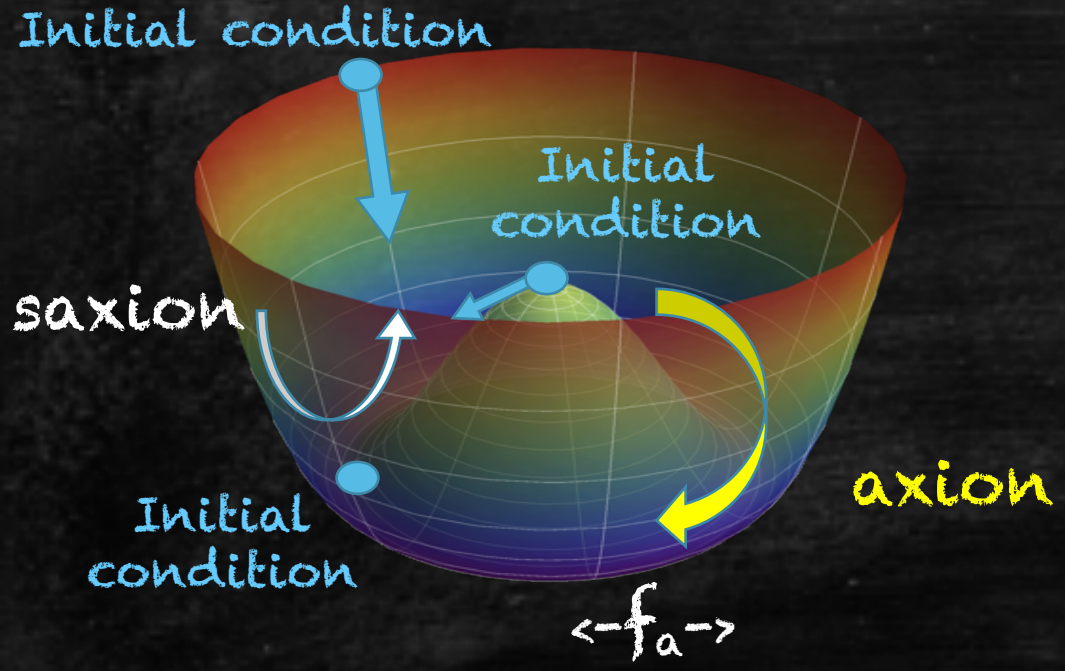
$$\rho_\phi \propto R^{-3(1+w)} = R^{-6}$$

Axions

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



Rotation


Initial condition
Initial condition
saxion
Initial condition
axion
<-f_a->
Initial condition
<-f_a->
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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

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

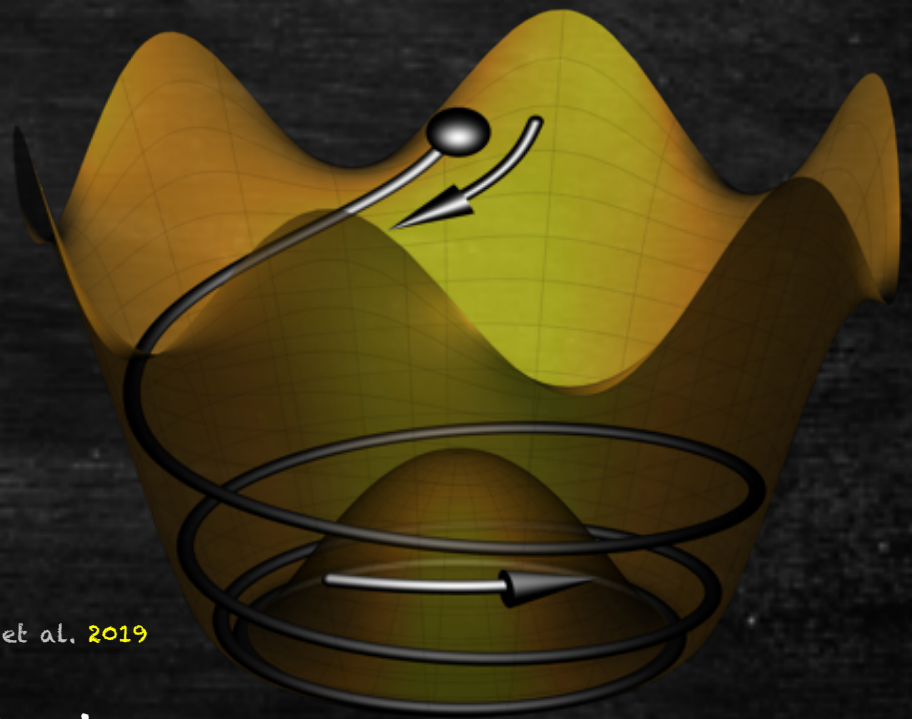
Angular motion : **Explicit PQ breaking**

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

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

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

Asymmetry of PQ Charge

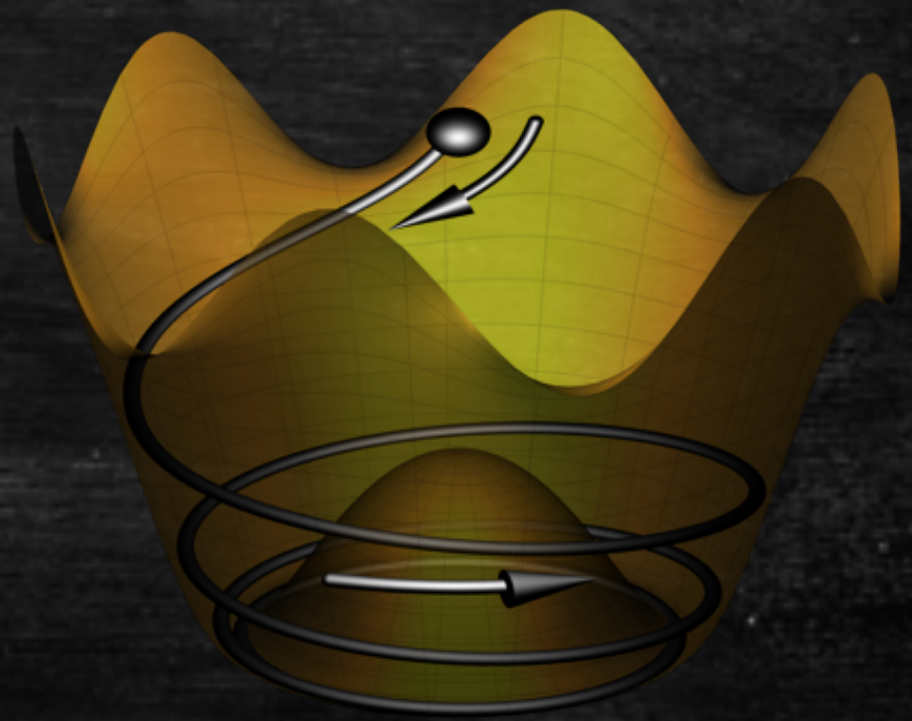
$$P = \frac{S + f_a}{\sqrt{2}} e^{i\frac{a}{f_a}}$$

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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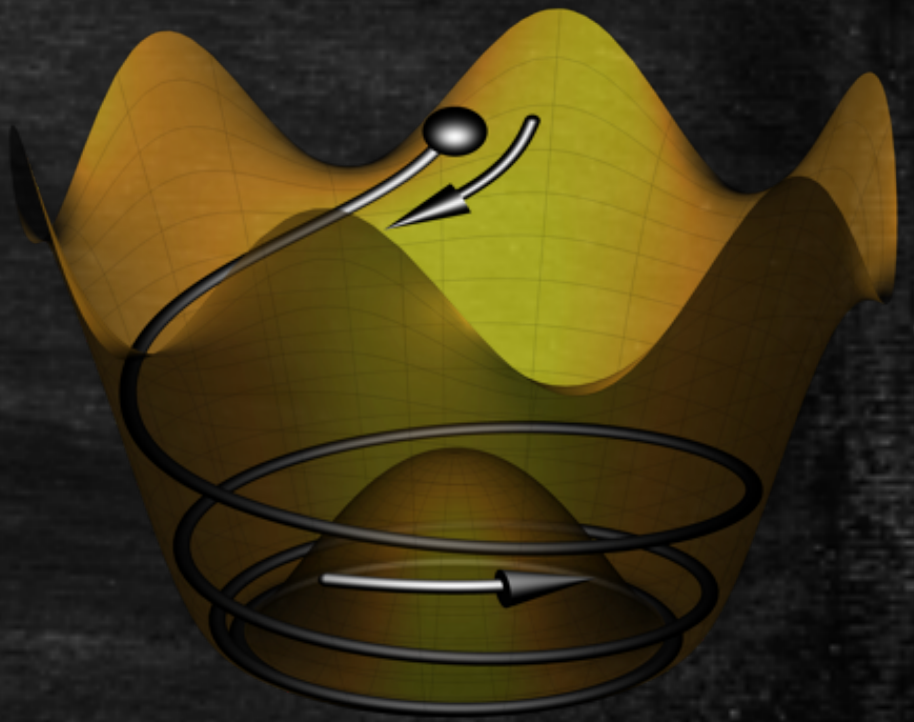
PQ Charge Evolution

Reason:

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



Conventional:

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

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

Our scenario ($S \gg f_a$):

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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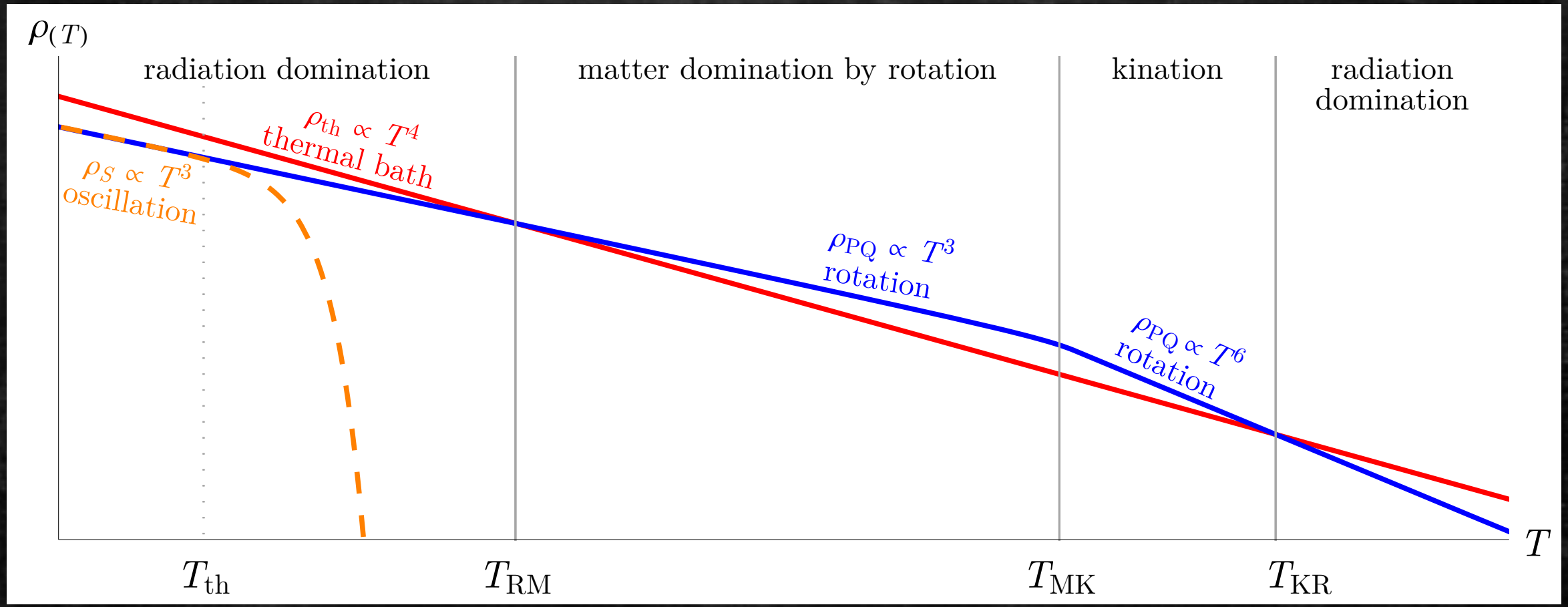
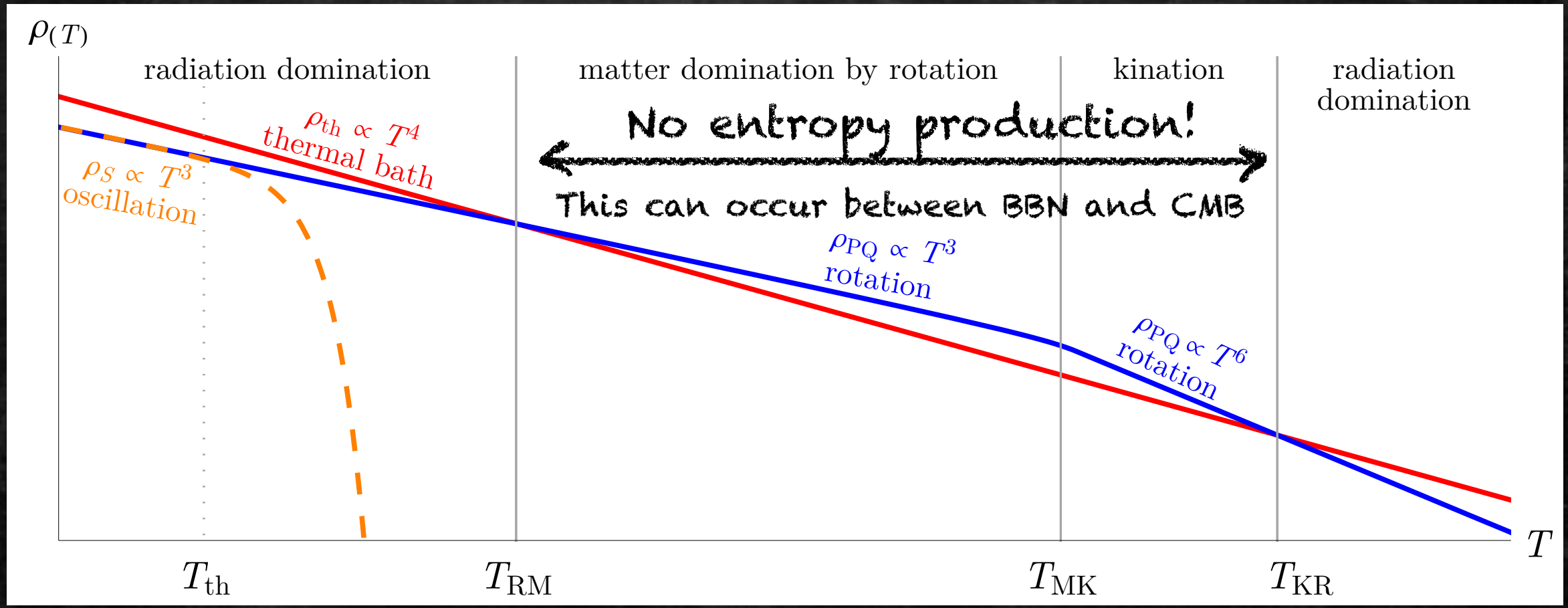
Evolution of Energy Densities



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

Evolution of Energy Densities



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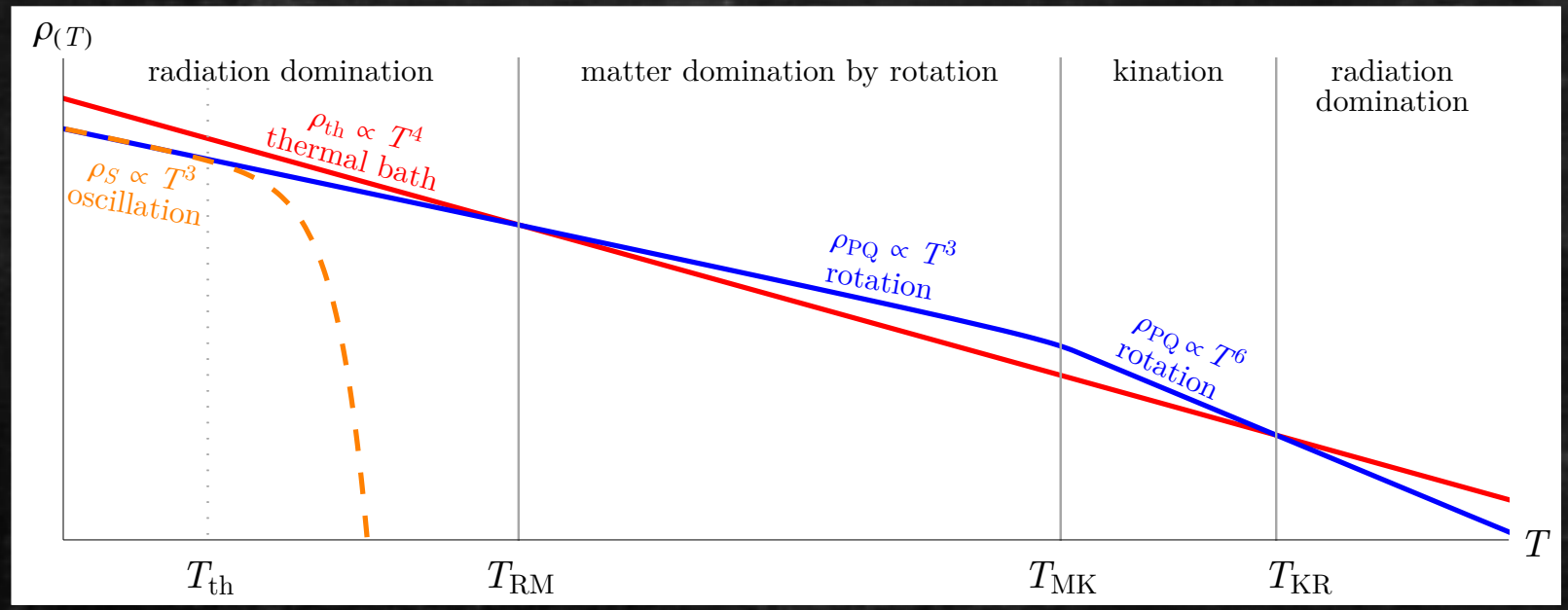
Relevant Temperatures



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

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

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

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

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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.

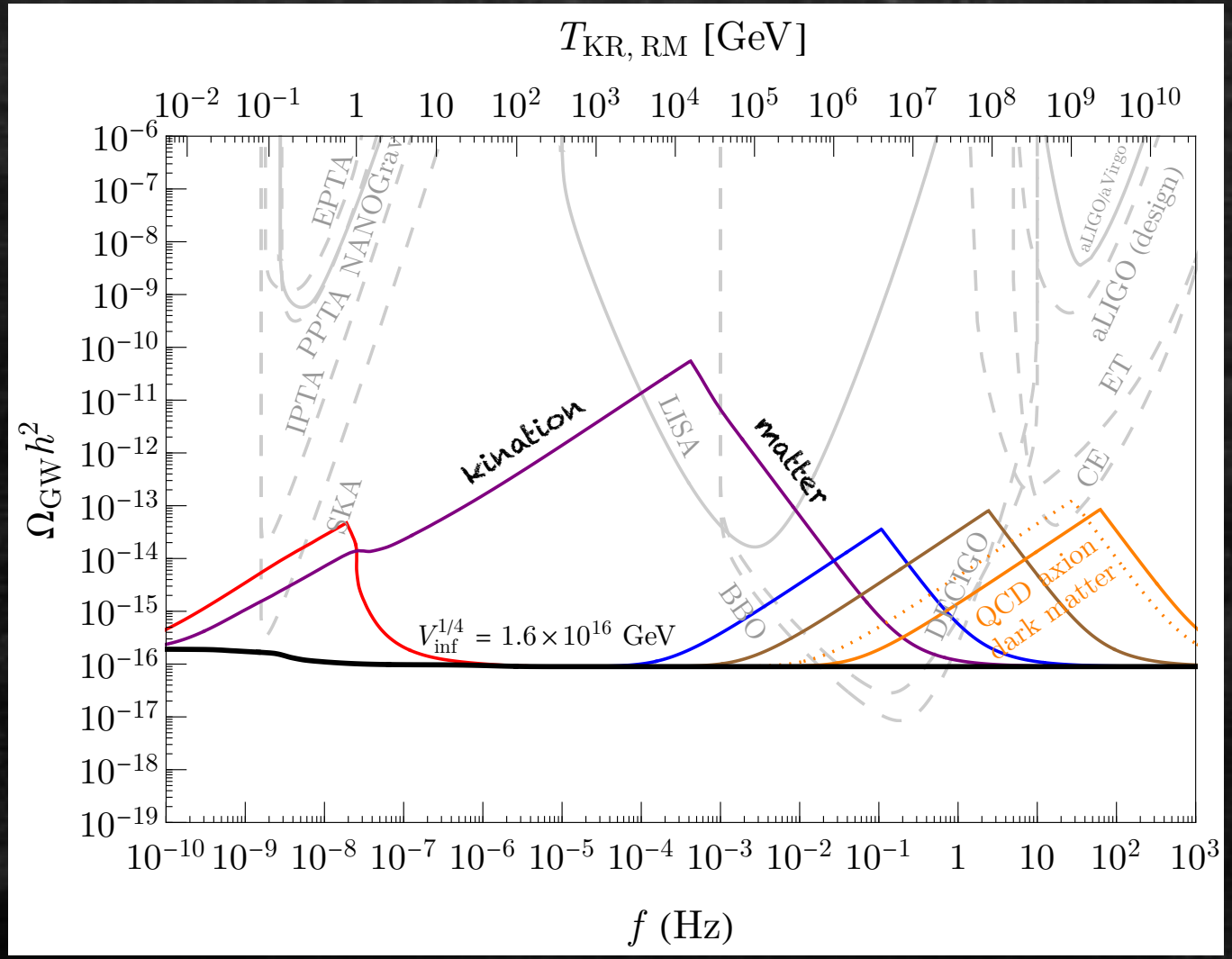
$$\Omega_{\rm GW}h^2 = \Omega_{r,0}h^2 \frac{1}{\rho_R(T_{\rm hc})} \frac{k^2}{64\pi G} \mathcal{P}_T(k) \qquad \mathcal{P}_T(k) = \frac{2H_I^2}{\pi^2 M_{\rm Pl}^2}$$

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

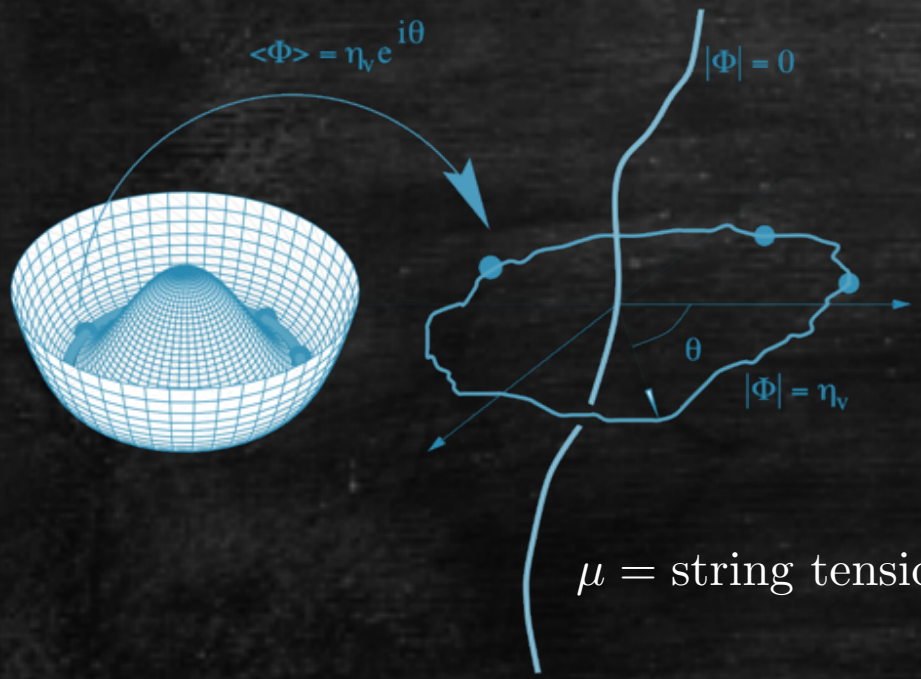
$$\Omega_{\rm GW}h^2 \simeq 1.4 \times 10^{-17} \left(\frac{V_{\rm inf}^{1/4}}{10^{16}\ {\rm GeV}}\right)^4 \left(\frac{g_{*,\rm SM}}{g_*(T_{\rm hc})}\right)^{\frac{1}{3}} \begin{cases} 1 & {\rm RD}: f_{\rm RM} < f \\ \left(\frac{f_{\rm RM}}{f}\right)^2 & {\rm MD}: f_{\rm MK} < f < f_{\rm RM} \\ \frac{f}{f_{\rm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

Gravitational Waves from Inflation

kination before BBN



Gravitational Waves from Cosmic Strings



$\mu =$ string tension

1005.4842 C. Ringeval

Daniel Dominguez/CERN

Loop decay era \ Loop formation era	Radiation	Matter	Kination
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.

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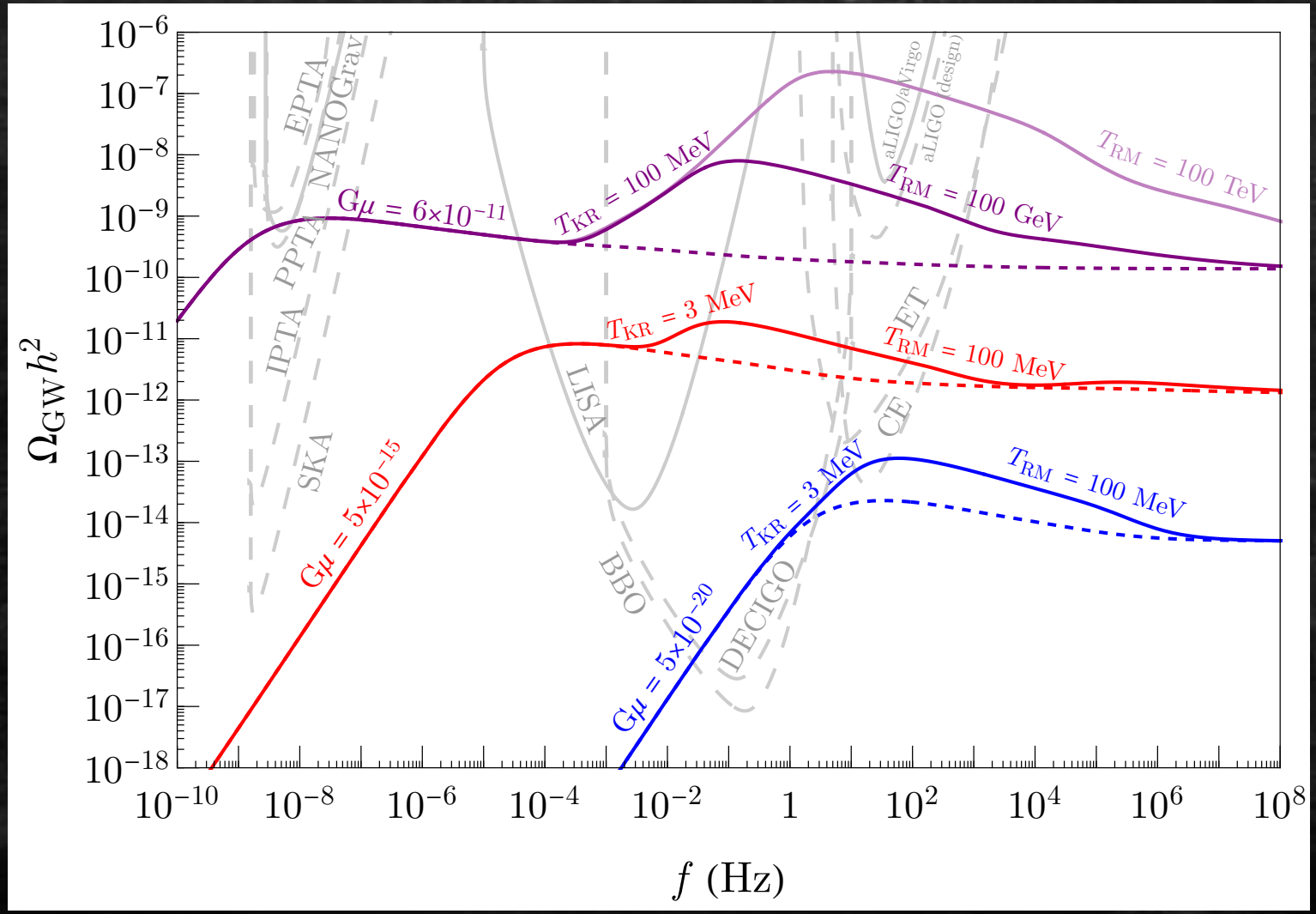
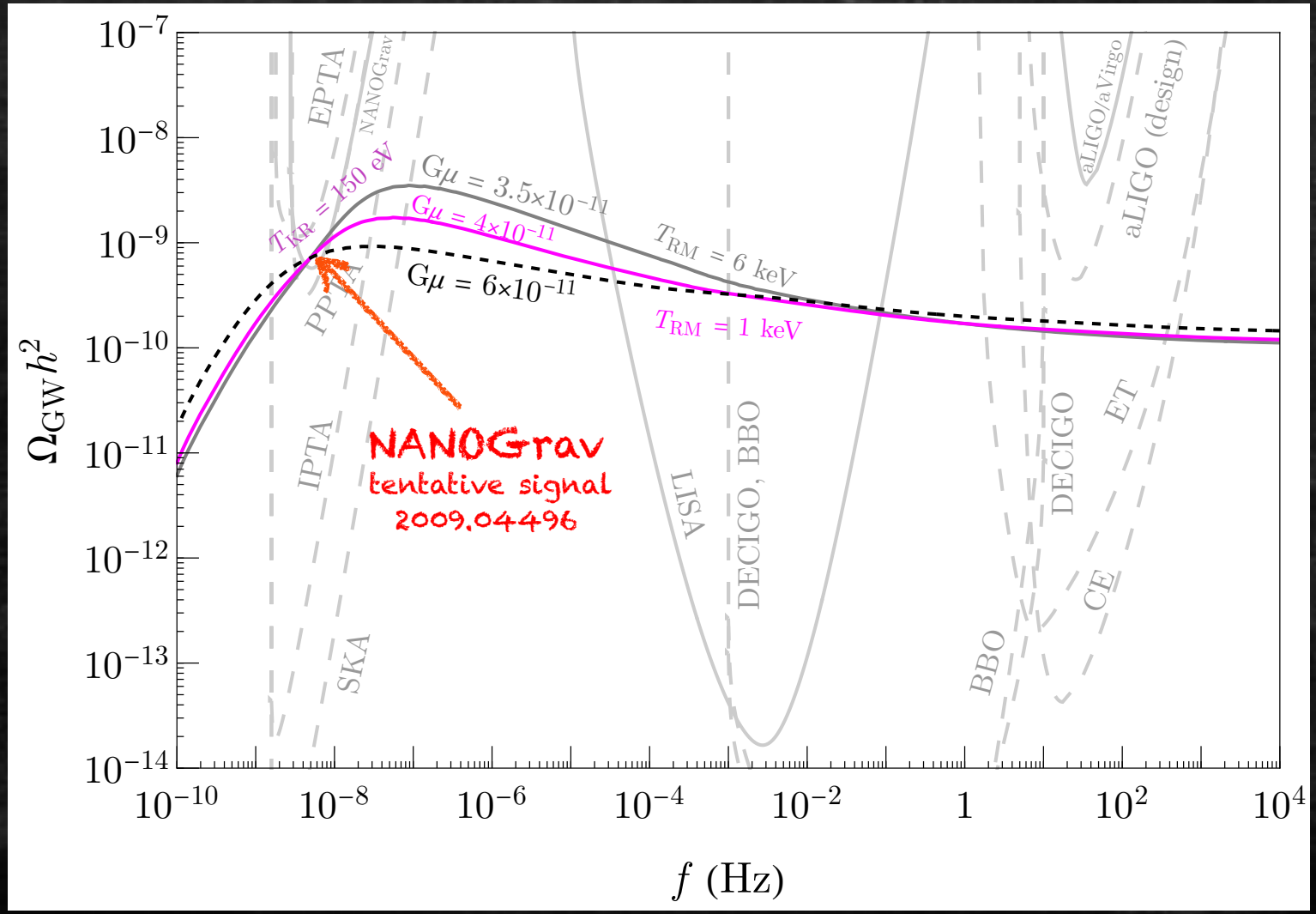
Gravitational Waves from Cosmic Strings

kination before BBN

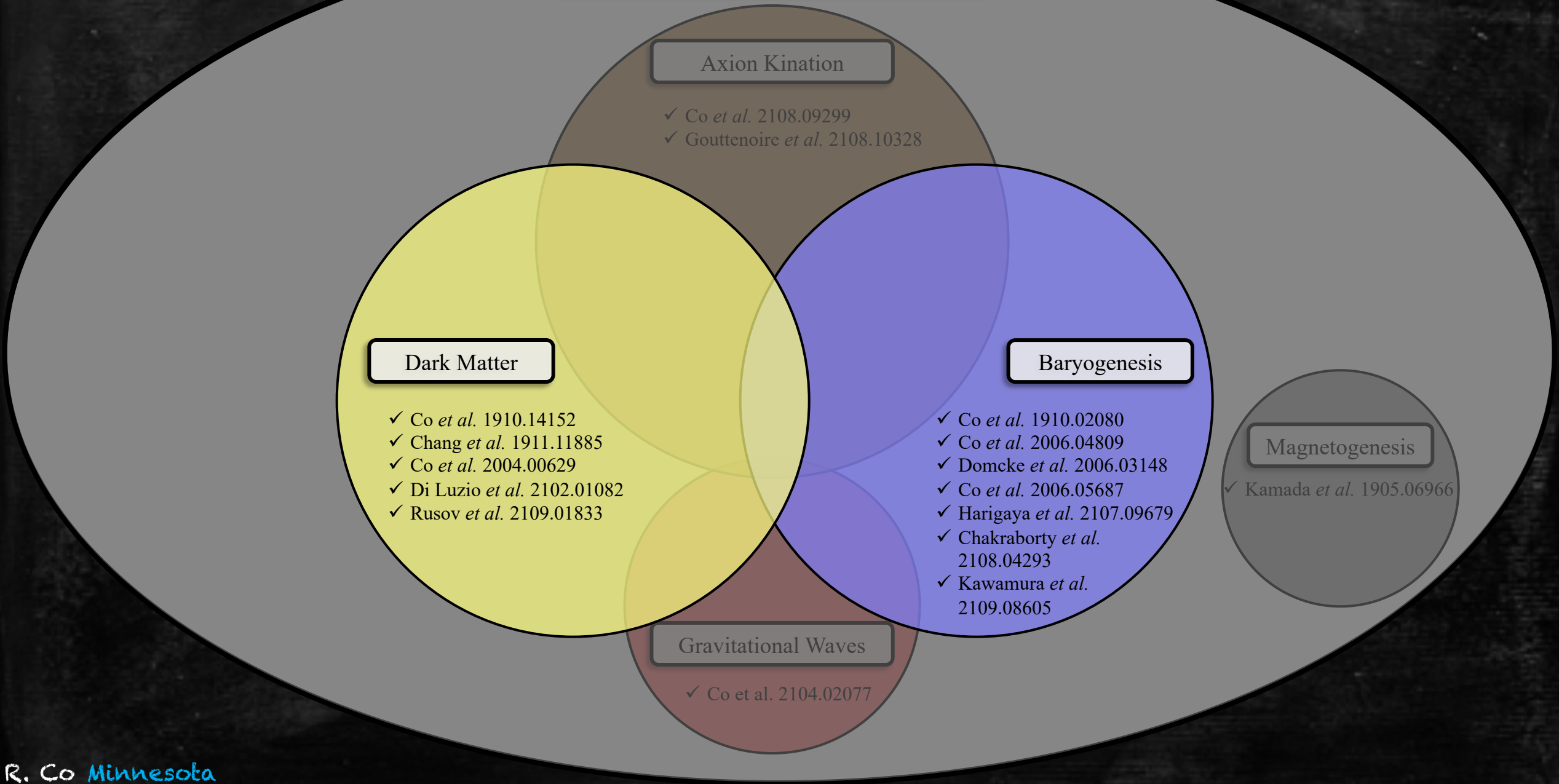


Gravitational Waves from Cosmic Strings

kination after BBN



Axion Rotations



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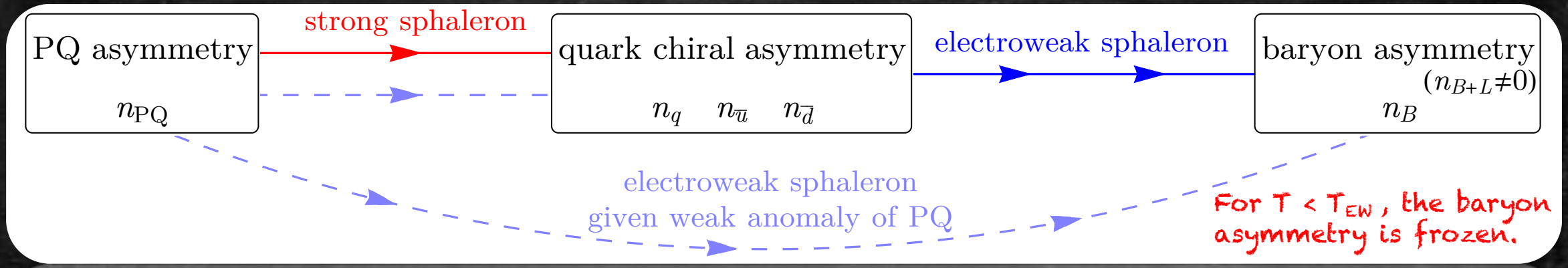
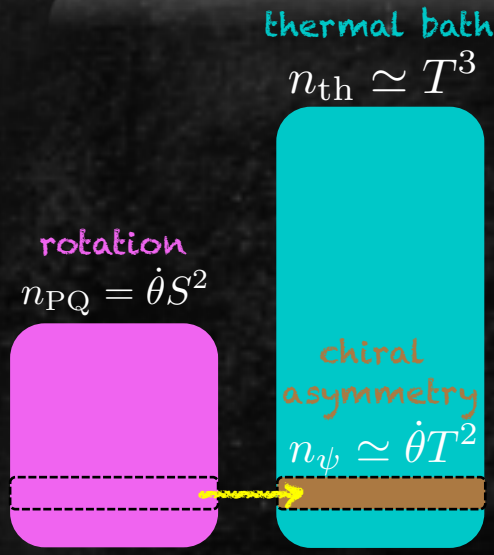
Axiogenesis





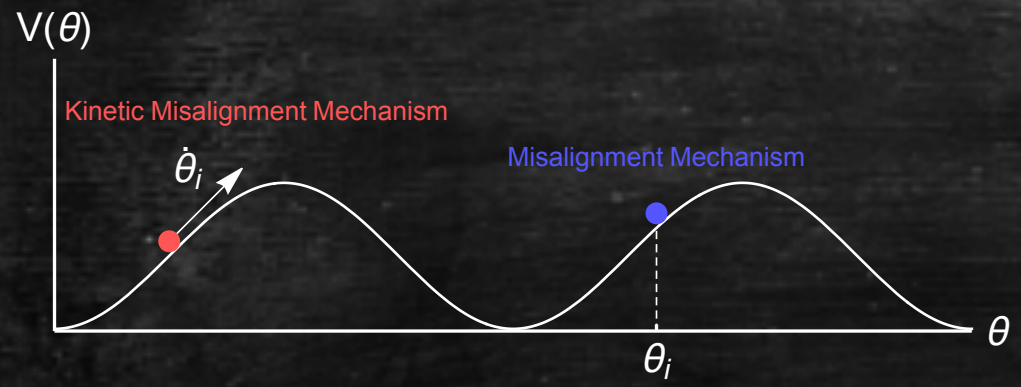
$$Y_B \equiv \frac{n_B}{s} = \left.\frac{c_B \dot{\theta} T^2}{s}\right|_{T=T_{\rm EW}} = c_B Y_{\rm PQ} \left(\frac{T_{\rm EW}}{f_a}\right)^2$$

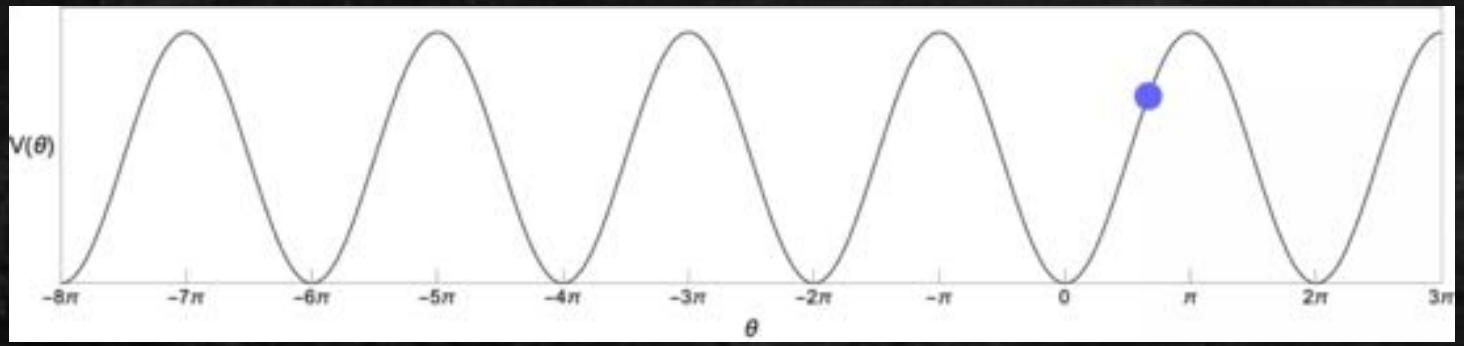
Baryon asymmetry fixes rotational speed, equivalently Y_{PQ}.

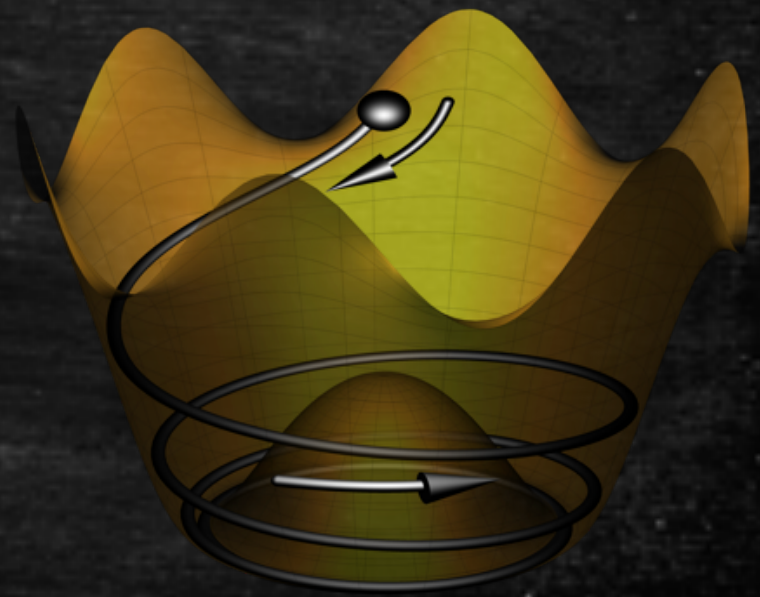
PRL 124, 111602 (2020) RC and K. Harigaya

Kinetic Misalignment Mechanism

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







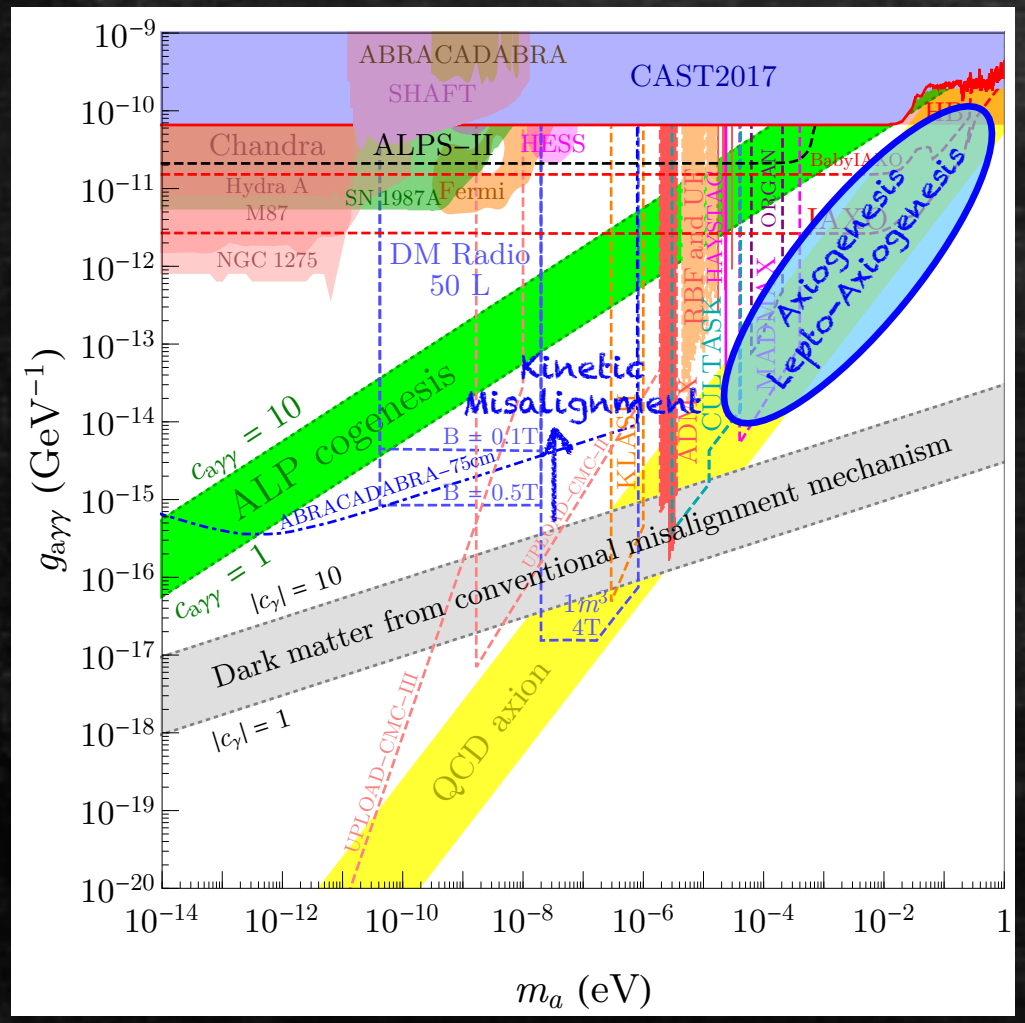
Consequence: delaying* usual T_{osc} until KE = PE, enhancing the dark matter abundance

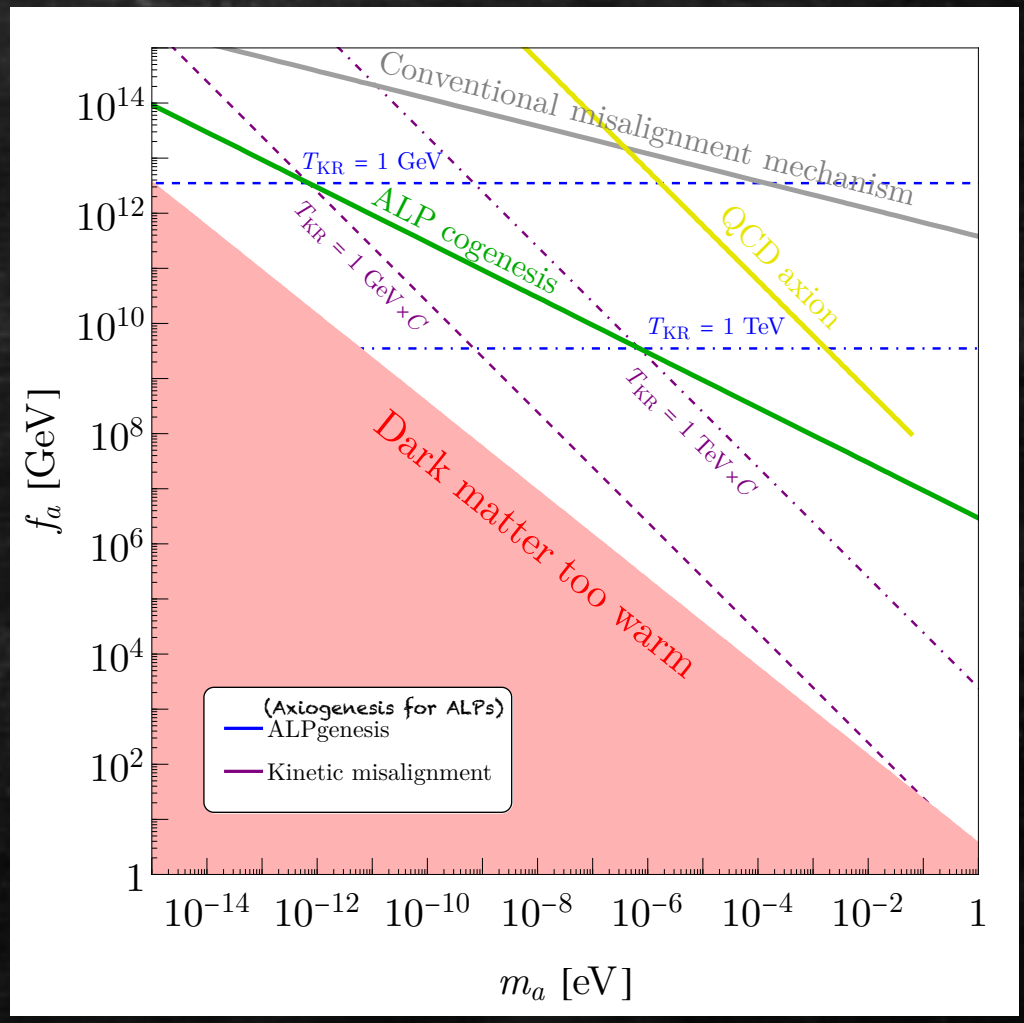
Abundance: $\frac{\rho_a}{s} = C m_a Y_{\rm PQ}$

* Parametric resonance in fact occurs before oscillations start. The abundance is modified by an O(1) factor but axion dark matter can be warm.
arXiv:2104.02077 RC, K. Harigaya, A. Pierce

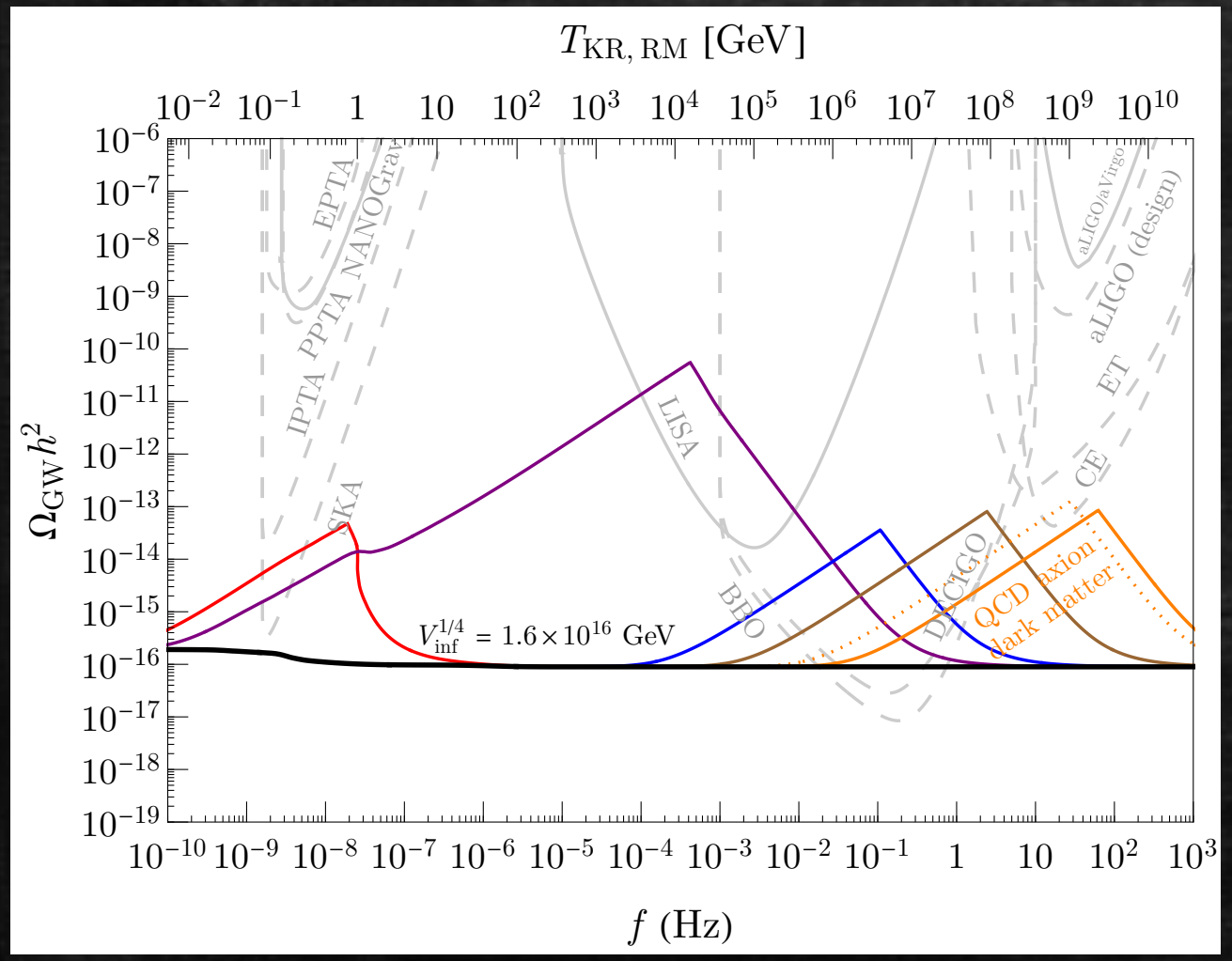
PRL 124, 251802 (2020) RC, L. Hall, K. Harigaya

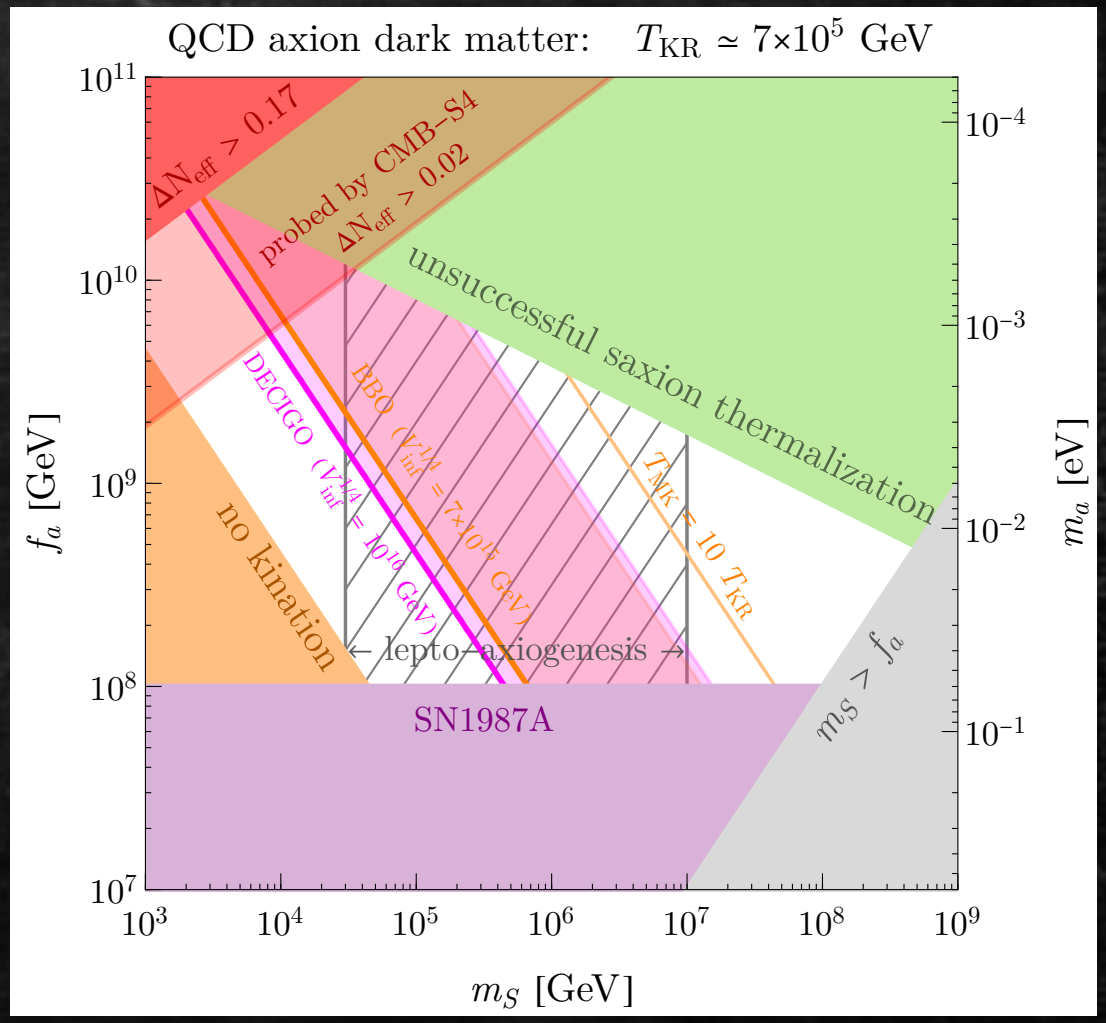
Predictions from Kinetic Misalignment and Axiogenesis





The QCD Axion
probed by gravitational waves from inflation





Probing PQ-breaking Potential

Piecewise approximation

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

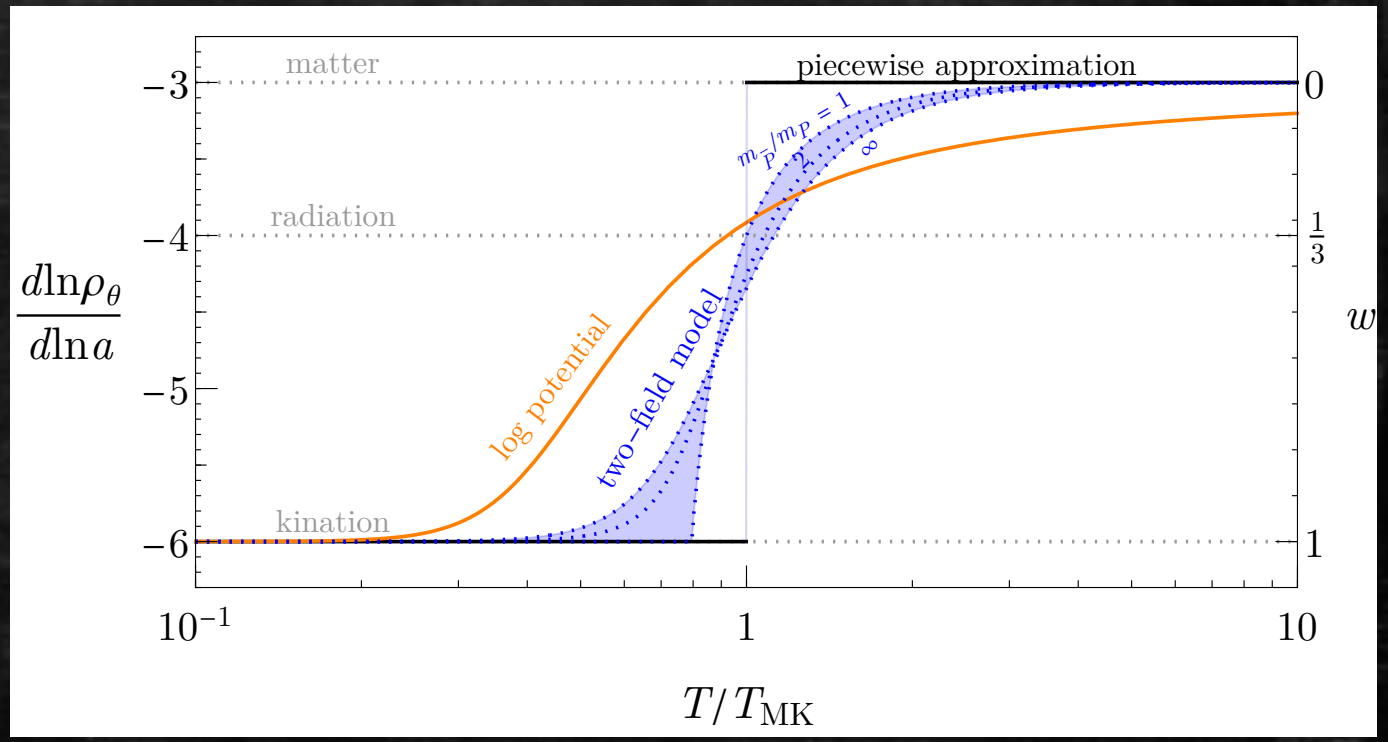
Log potential

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

Two-field model

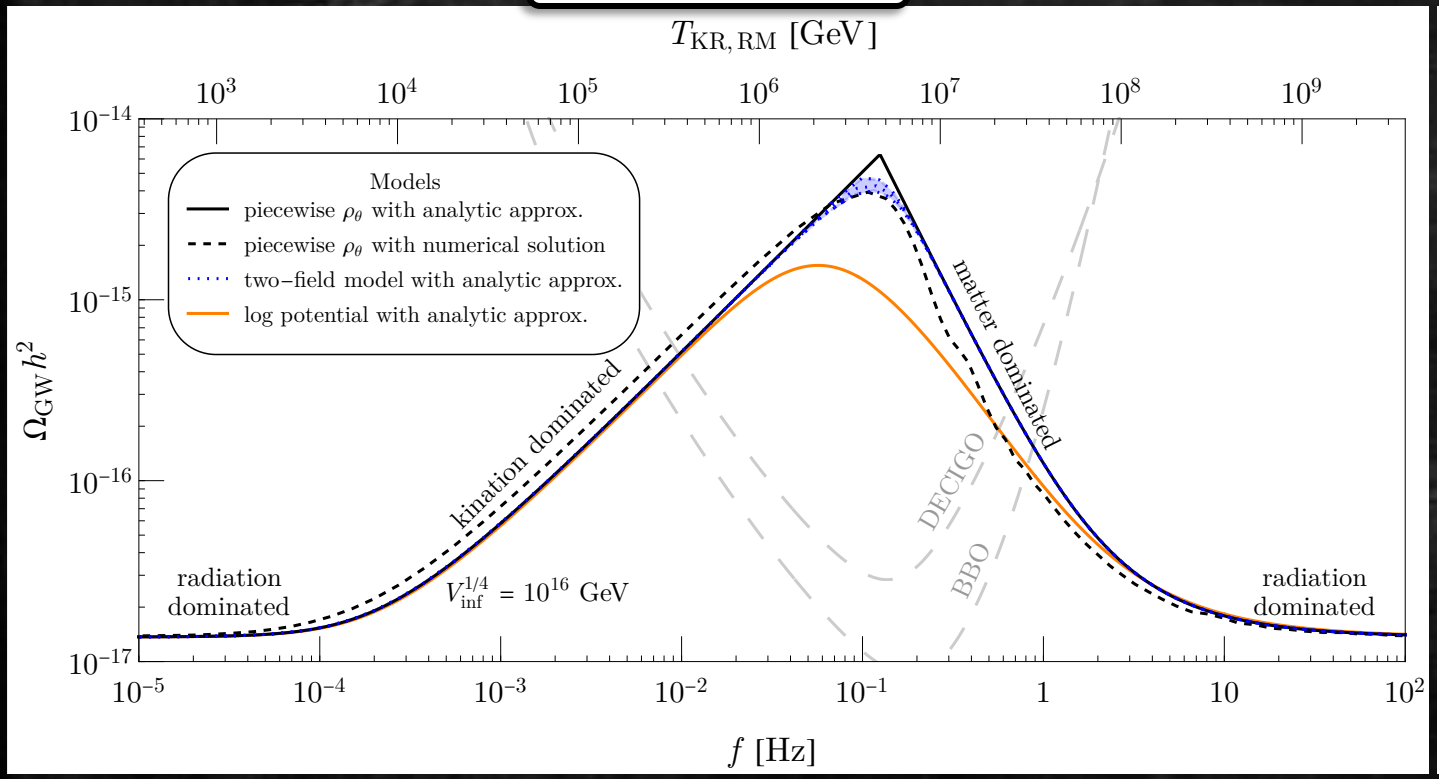
$$W = X(P\bar{P} - v_P^2)$$

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

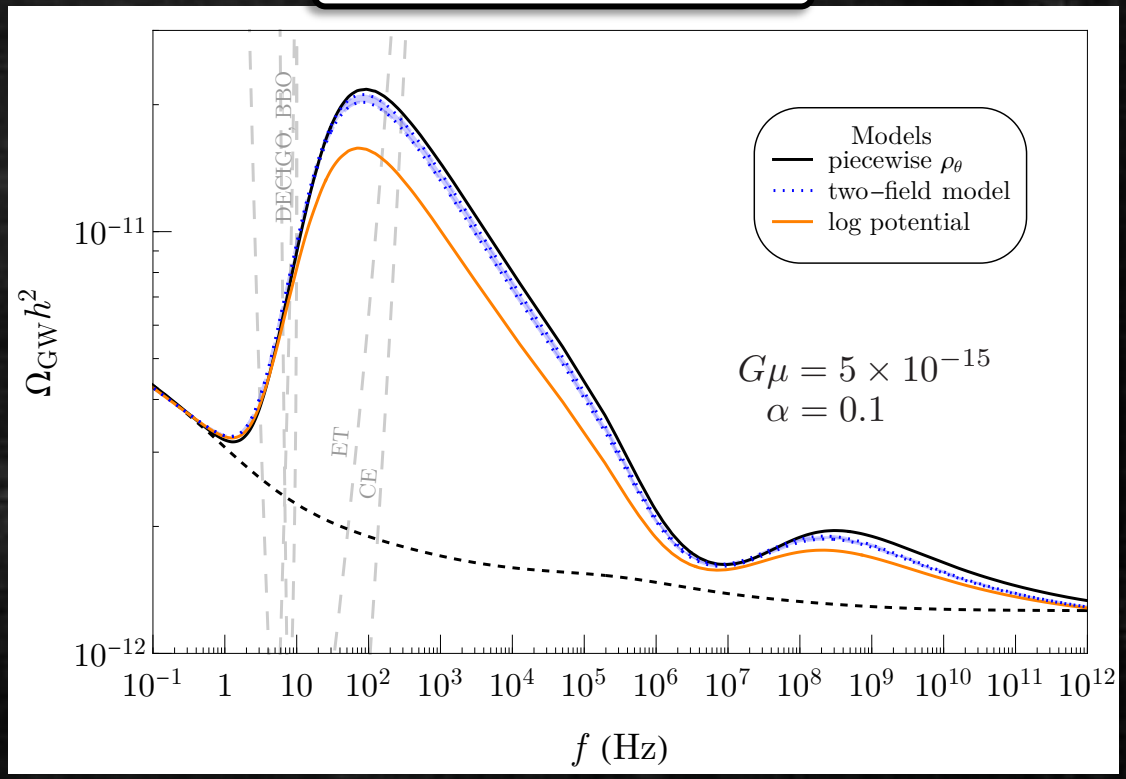


Probing PQ-breaking Potential

from inflation

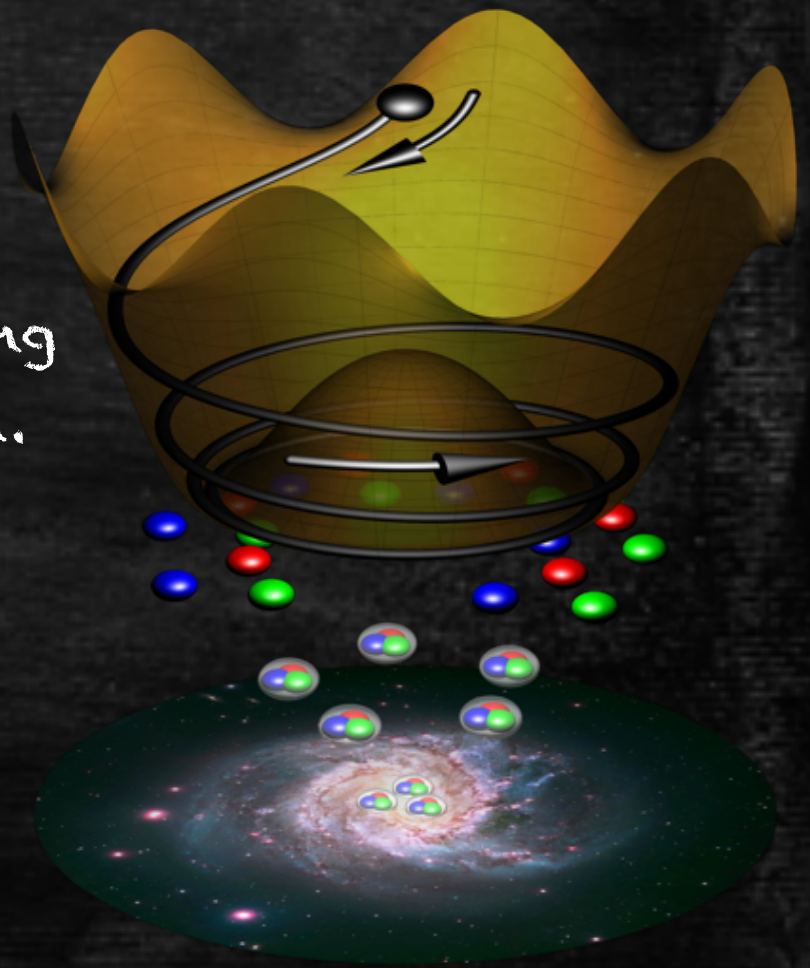


from cosmic strings



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!

RIP, Norman.