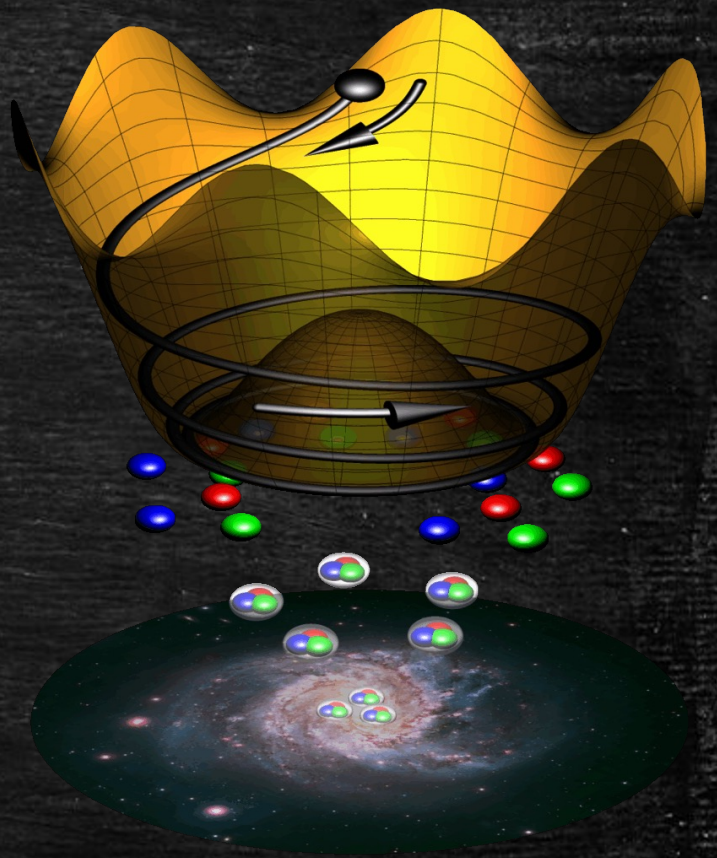
Cosmic Birefringence and Axiogenesis



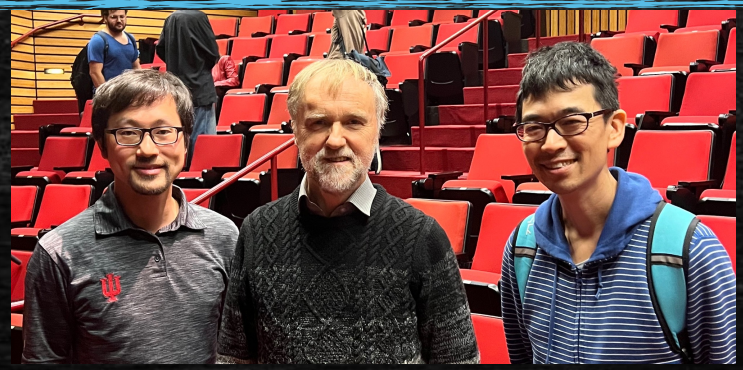
PIKIMO 21
University of Pittsburgh

November 7th, 2026

Raymond Co

Indiana University

my first grad student





2609.25202 RC, Lawrence Hall, Keisuke Harigaya, and Taegyu Lee

Today

These Nobel Laureates were born on November 7

- Marie Curie in recognition of the extraordinary services they have rendered by their joint researches on the radiation phenomena discovered by Professor Henri Becquerel.

- C. V. Raman for his work on the scattering of light and for the discovery of the effect named after him



Marie Curie
born in 1867



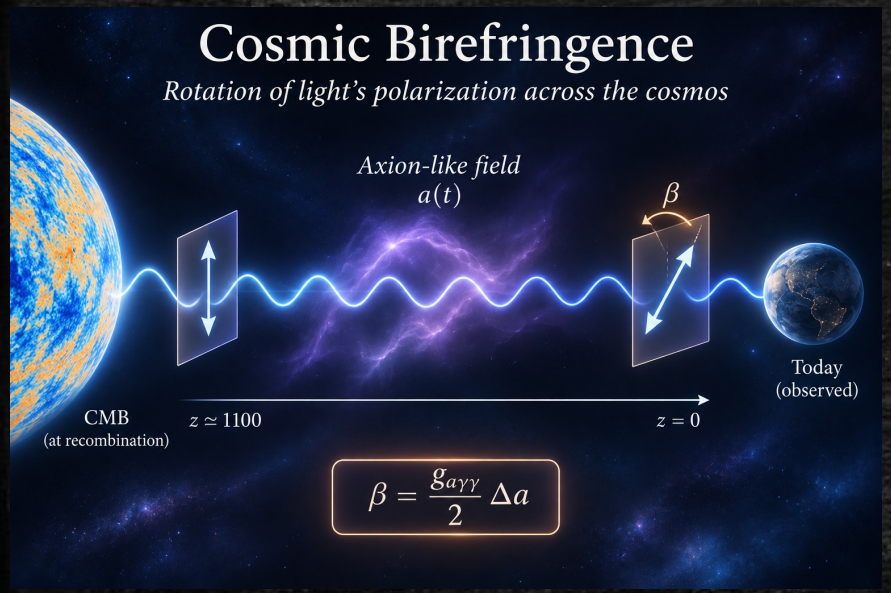
Chandrasekhara Venkata Raman
born in 1867

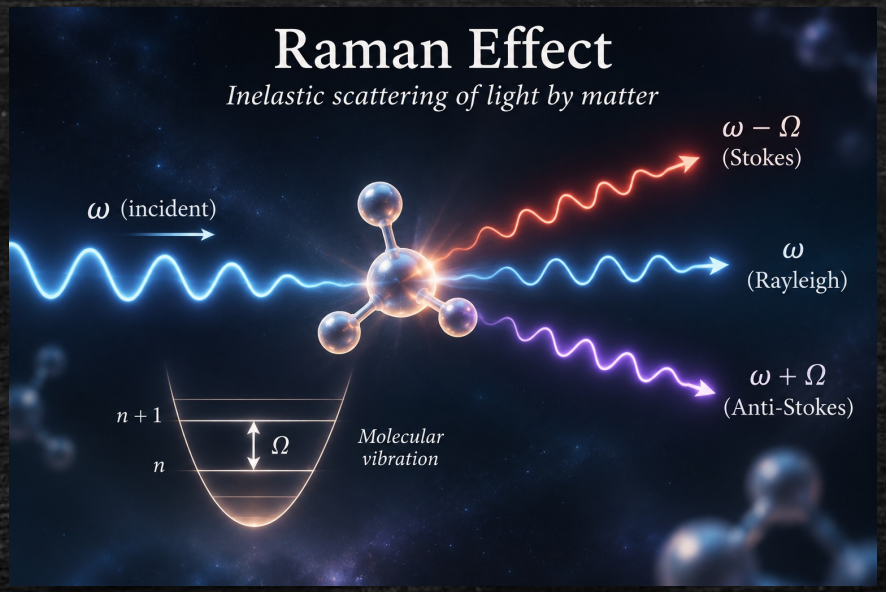
Today

These Nobel Laureates were born on November 7

- Marie Curie in recognition of the extraordinary services they have rendered by their joint researches on the radiation phenomena discovered by Professor Henri Becquerel.

- C. V. Raman for his work on the scattering of light and for the discovery of the effect named after him



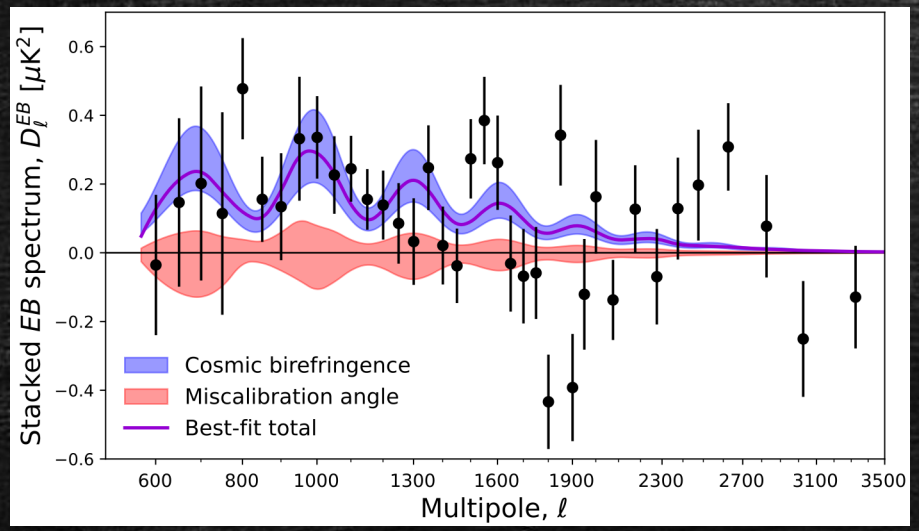




Chandrasekhara Venkata Raman
born in 1888

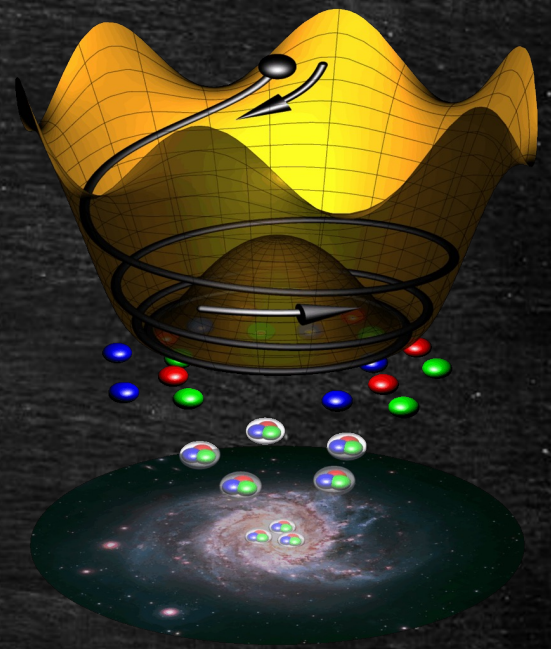
Outline of the Talk

1) Cosmic Birefringence

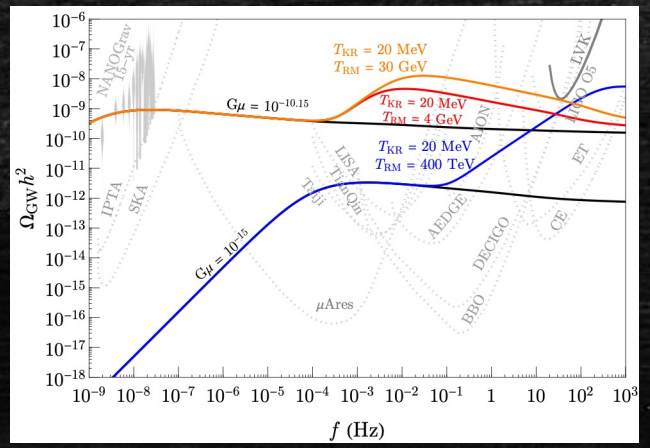


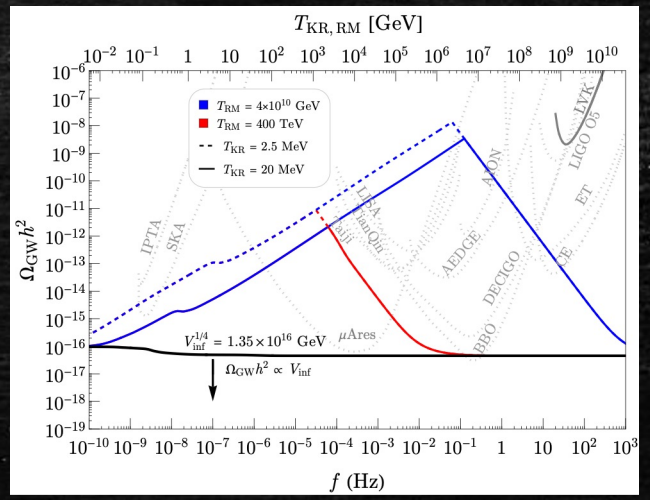
2) Axion Rotation
as an explanation

3) Axiogenesis



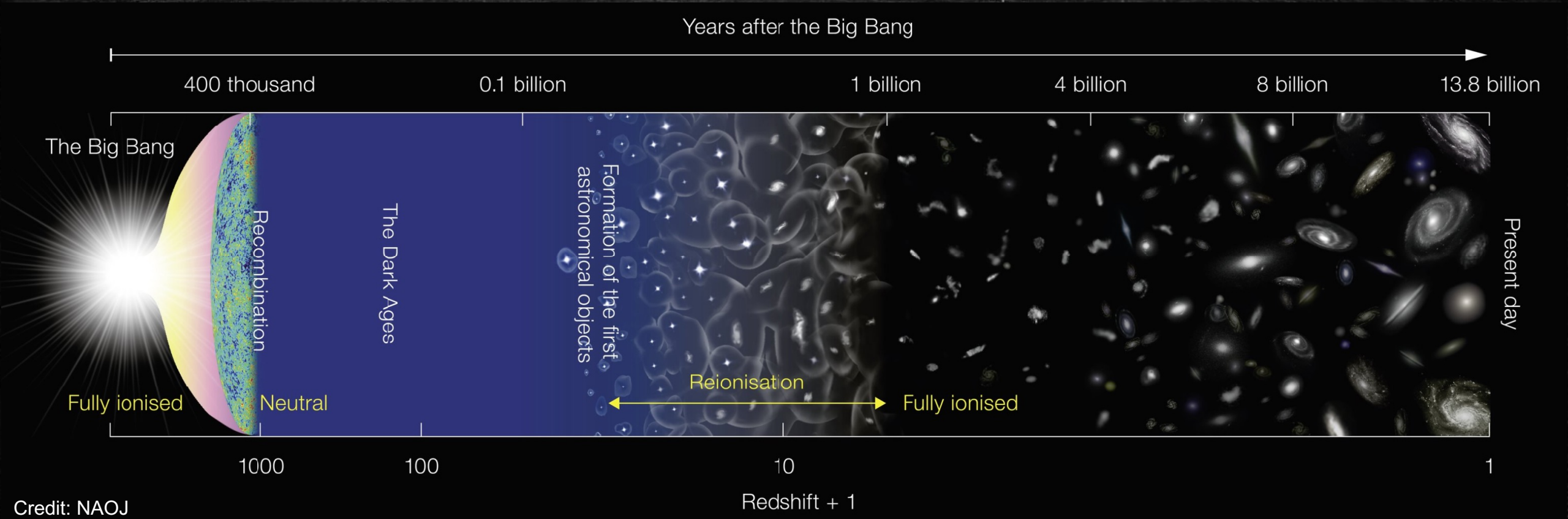
4) Enhanced gravitational waves





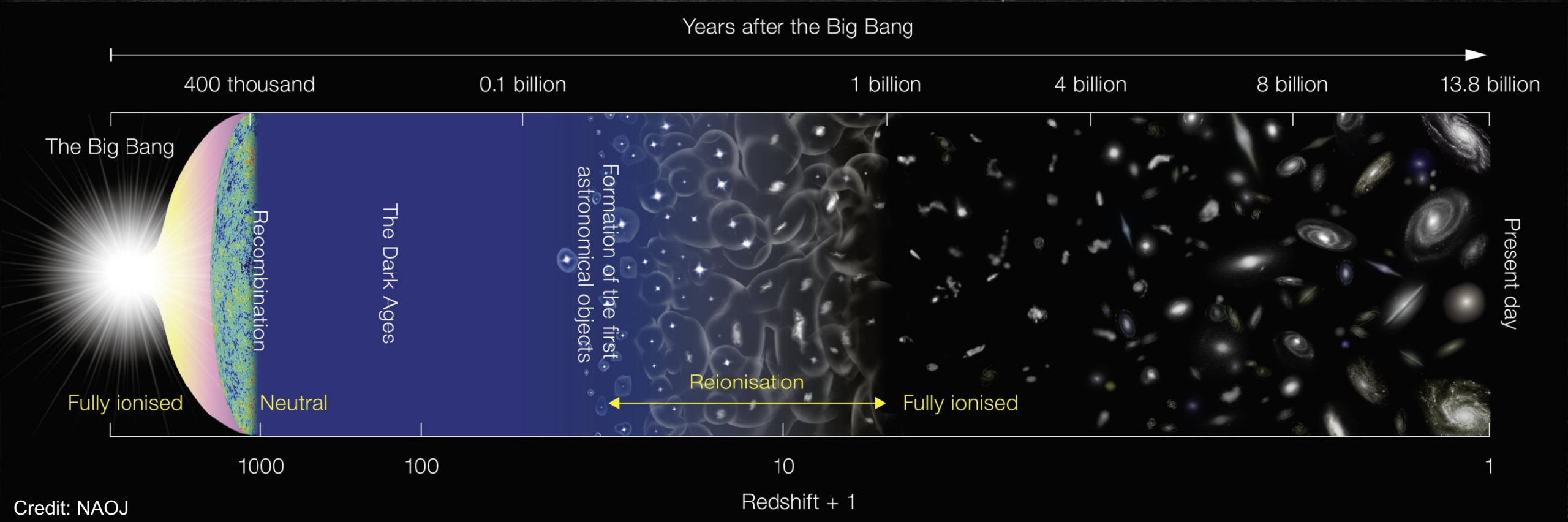
Standard Cosmology

Cosmology



Credit: NAOJ

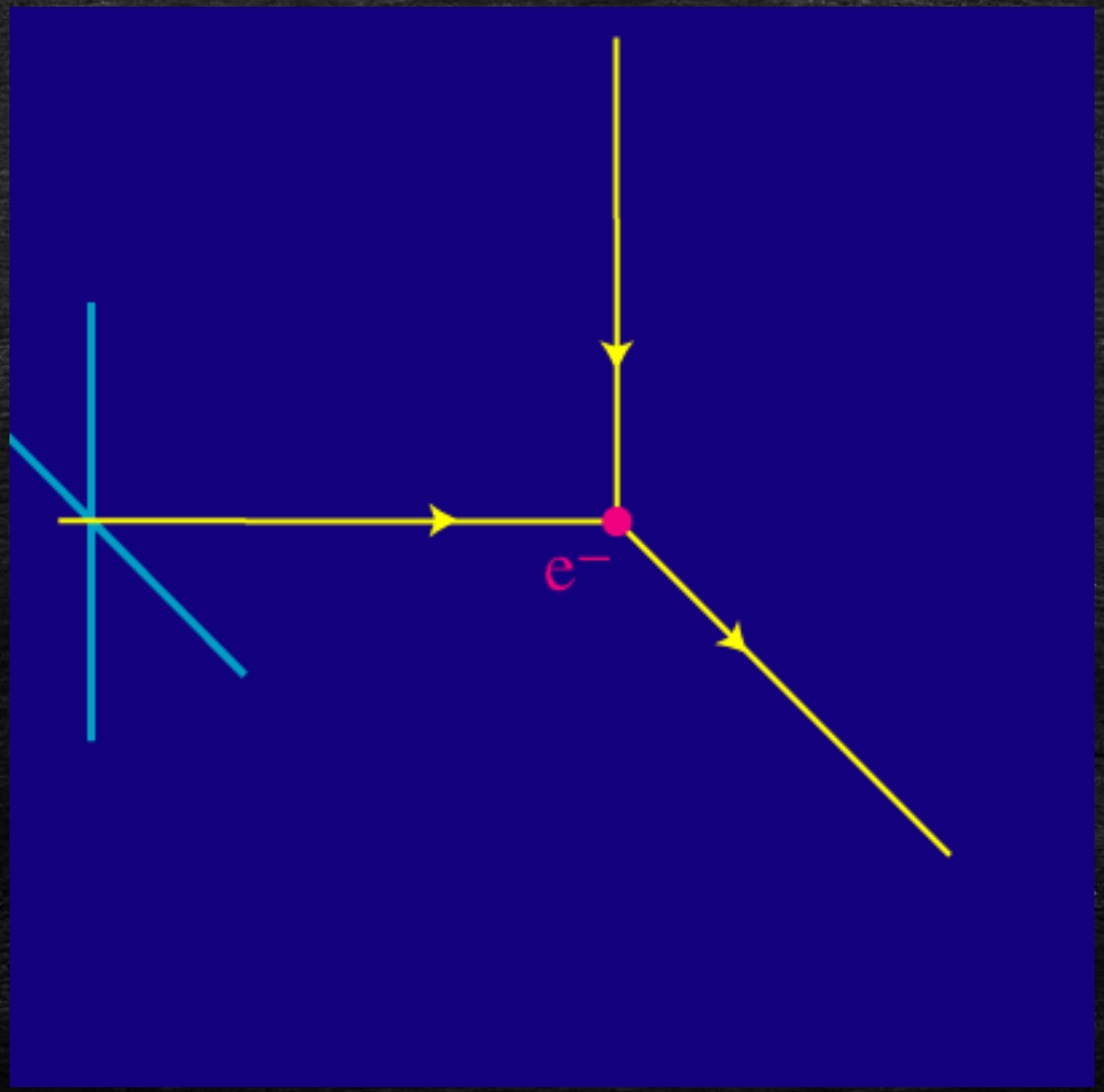
The Cosmic Microwave Background



Credit: NAOJ

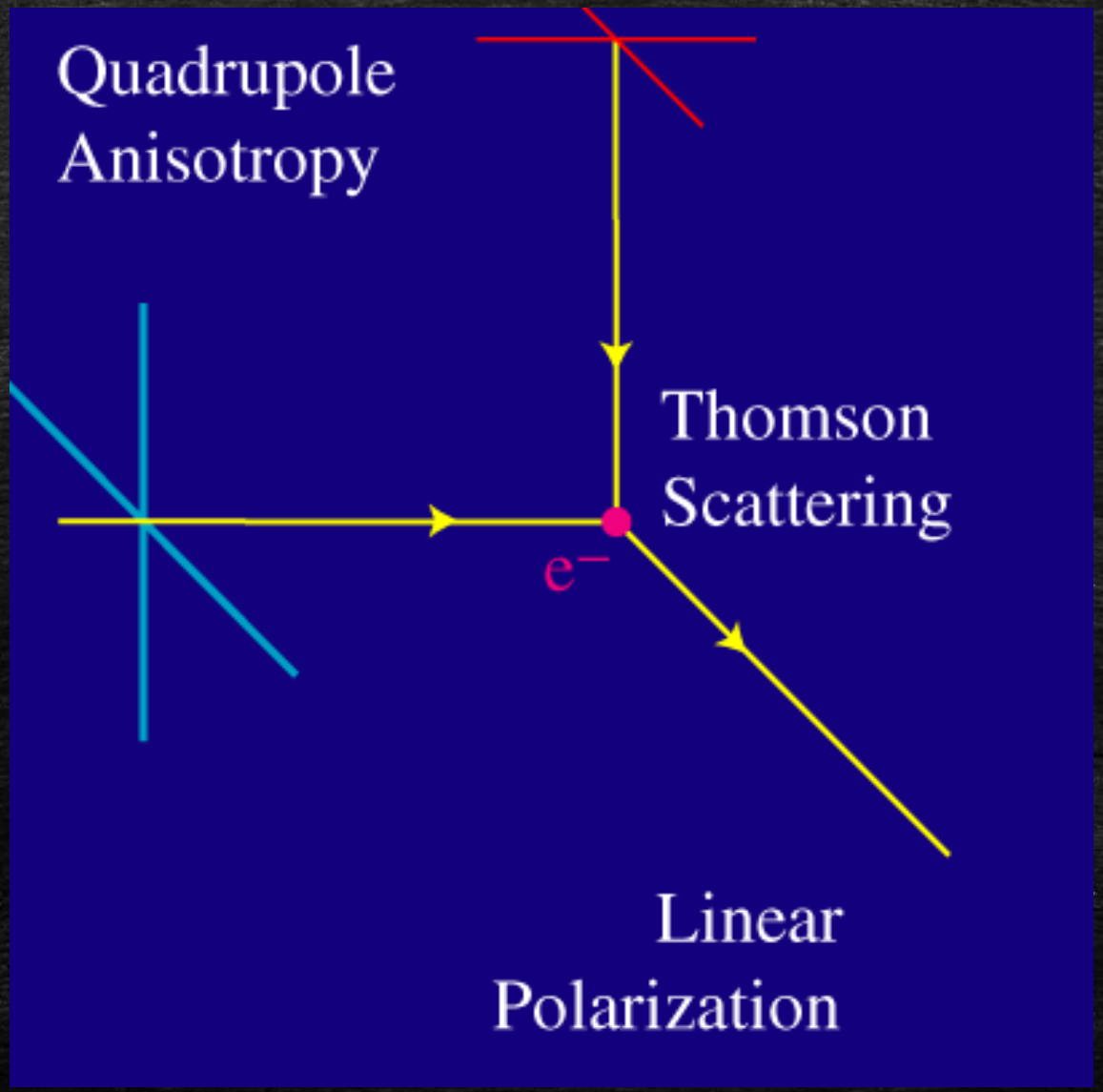
Photons freely propagate

The Cosmic Microwave Background



Credit: Wayne Hu

The Cosmic Microwave Background



Credit: Wayne Hu

The Cosmic Microwave Background

E-mode polarization



B-mode polarization



The Cosmic Microwave Background

Parity even

E-mode polarization



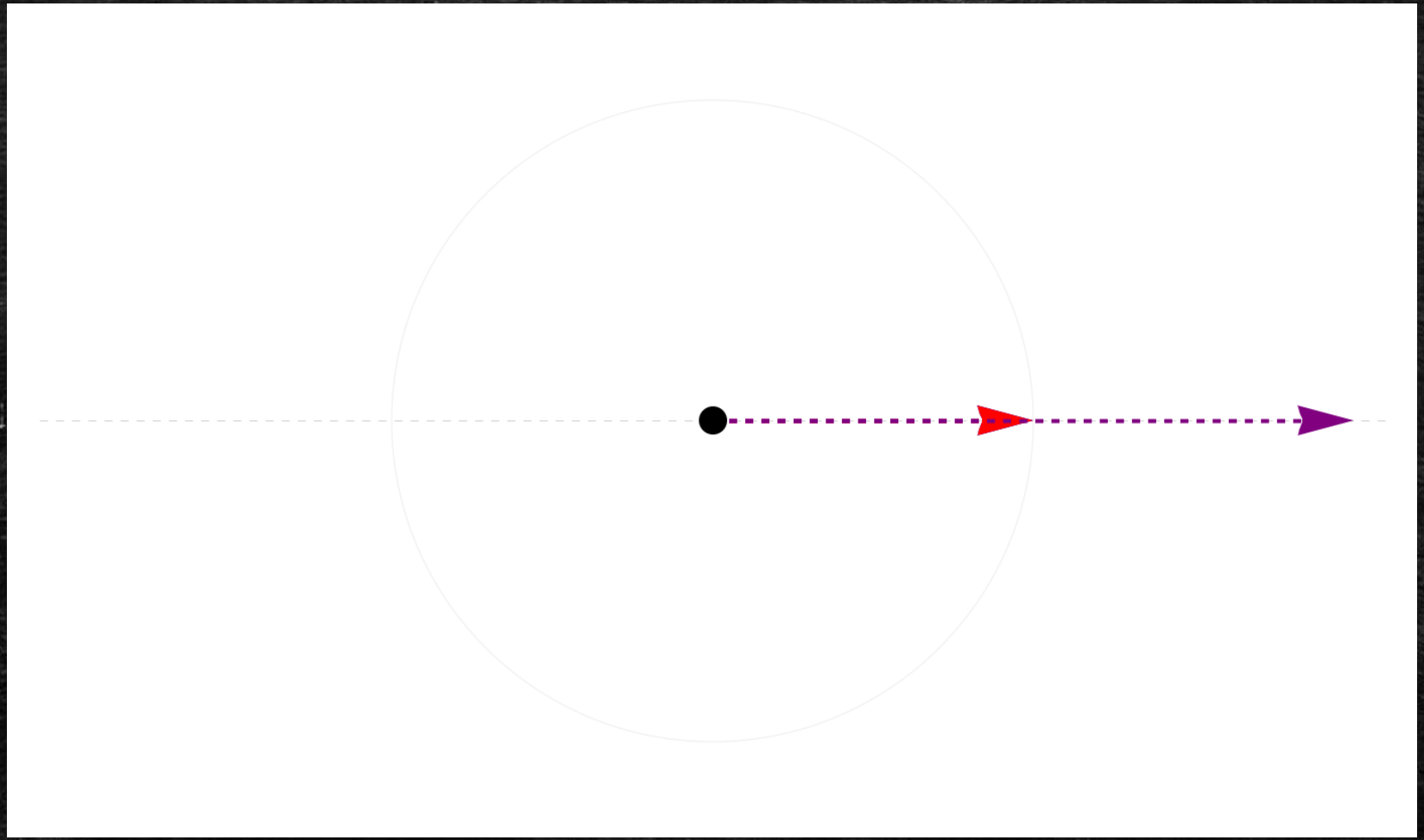
Parity odd

B-mode polarization

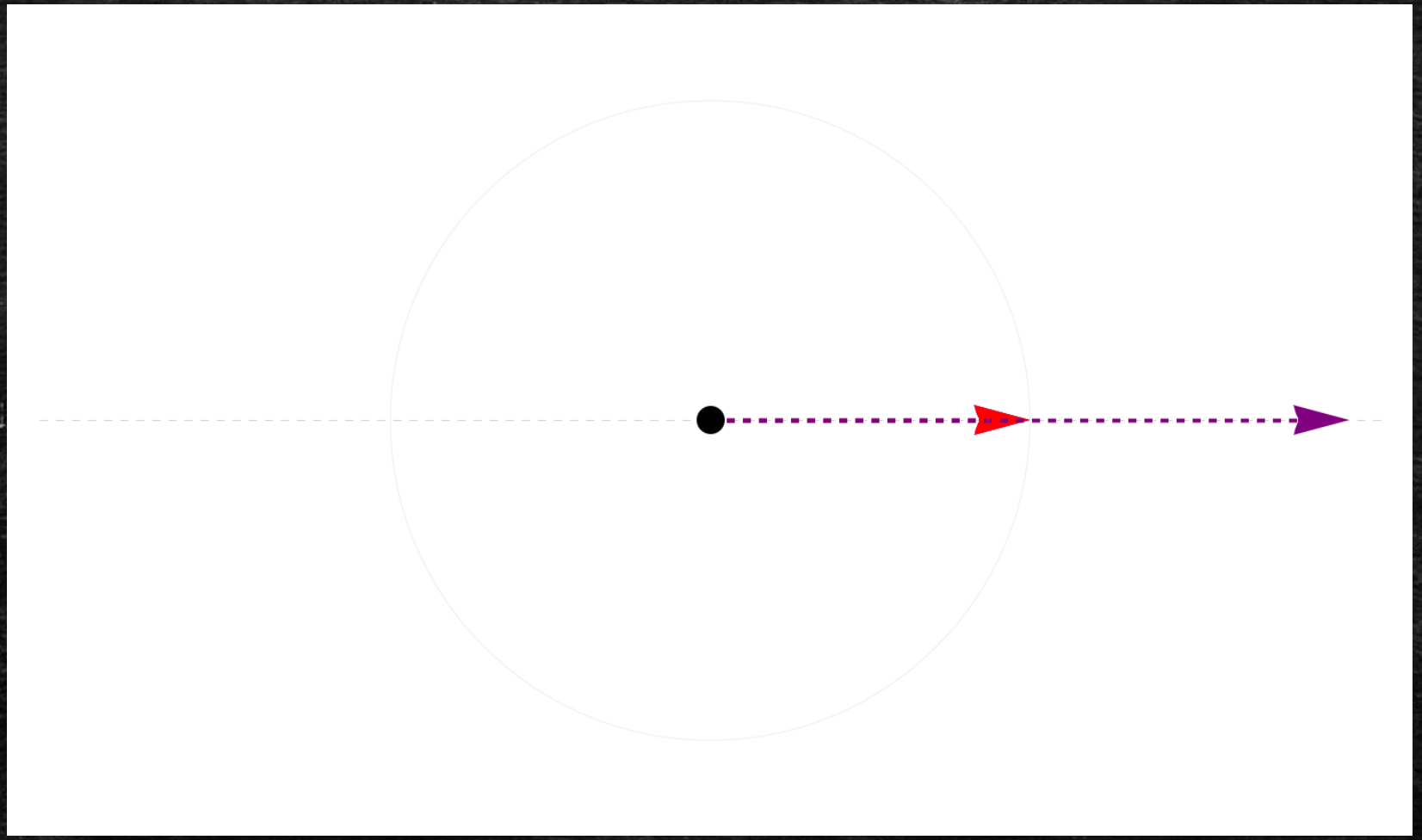


Cosmic Birefringence

Linear Polarization
= 2 opposite circular polarization



Rotation of Linear Polarization
= 2 opposite circular polarization
traveling at different phase velocity "birefringence"



The Cosmic Microwave Background
Cosmic Birefringence

With a polarization rotation of β, an E-mode is rotated into a B-mode

$$\begin{pmatrix} E_{\rm obs} \\ B_{\rm obs} \end{pmatrix} = \begin{pmatrix} \cos 2\beta & -\sin 2\beta \\ \sin 2\beta & \cos 2\beta \end{pmatrix} \begin{pmatrix} E_0 \\ B_0 \end{pmatrix} .$$

For a small β,

$$B_{\rm obs} \simeq B_{\rm em} + 2\beta E_{\rm em}$$

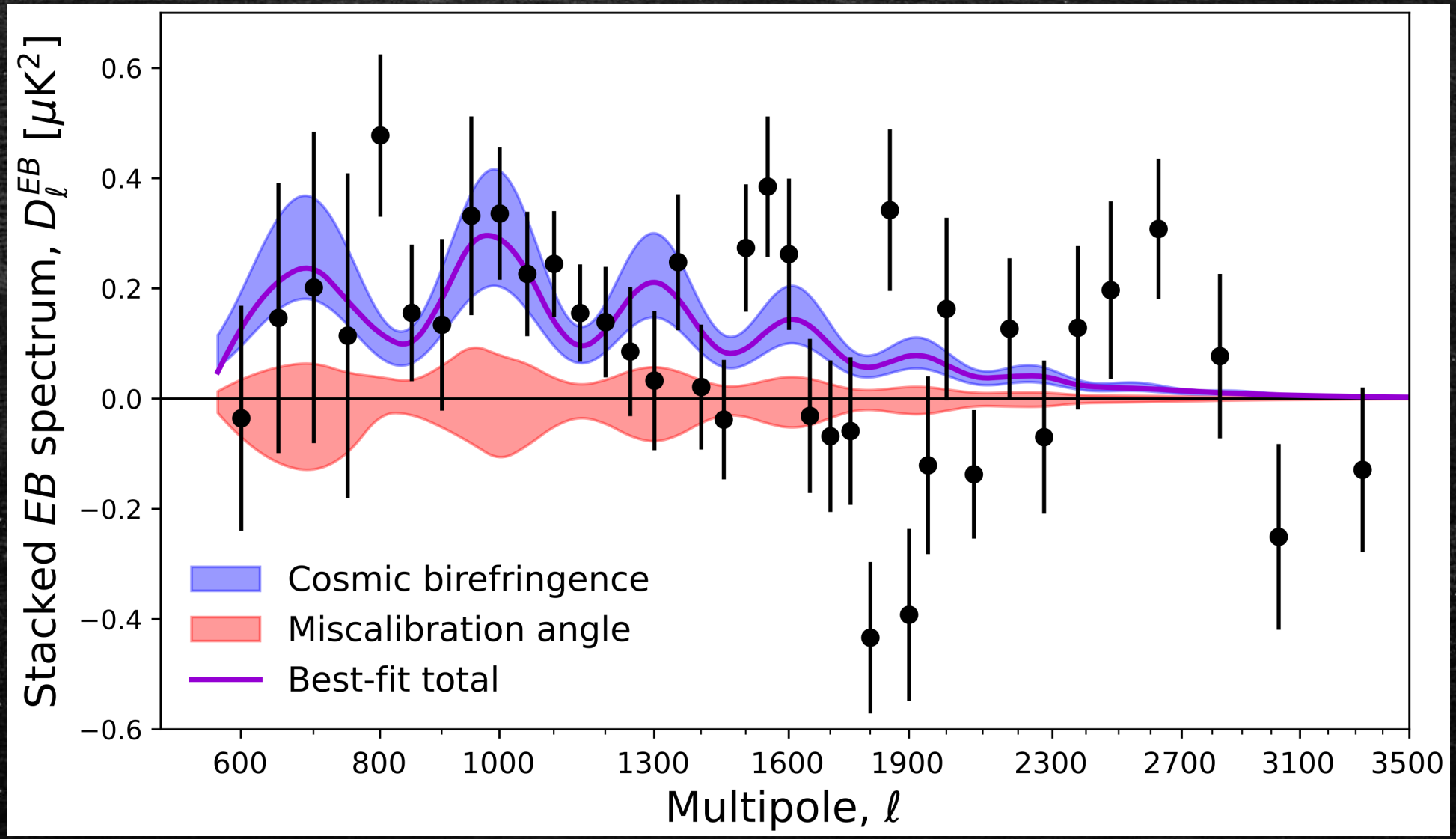
This generates a parity-odd EB cross-power spectrum

$$C_\ell^{EB} \simeq 2\beta (C_\ell^{EE} - C_\ell^{BB})$$

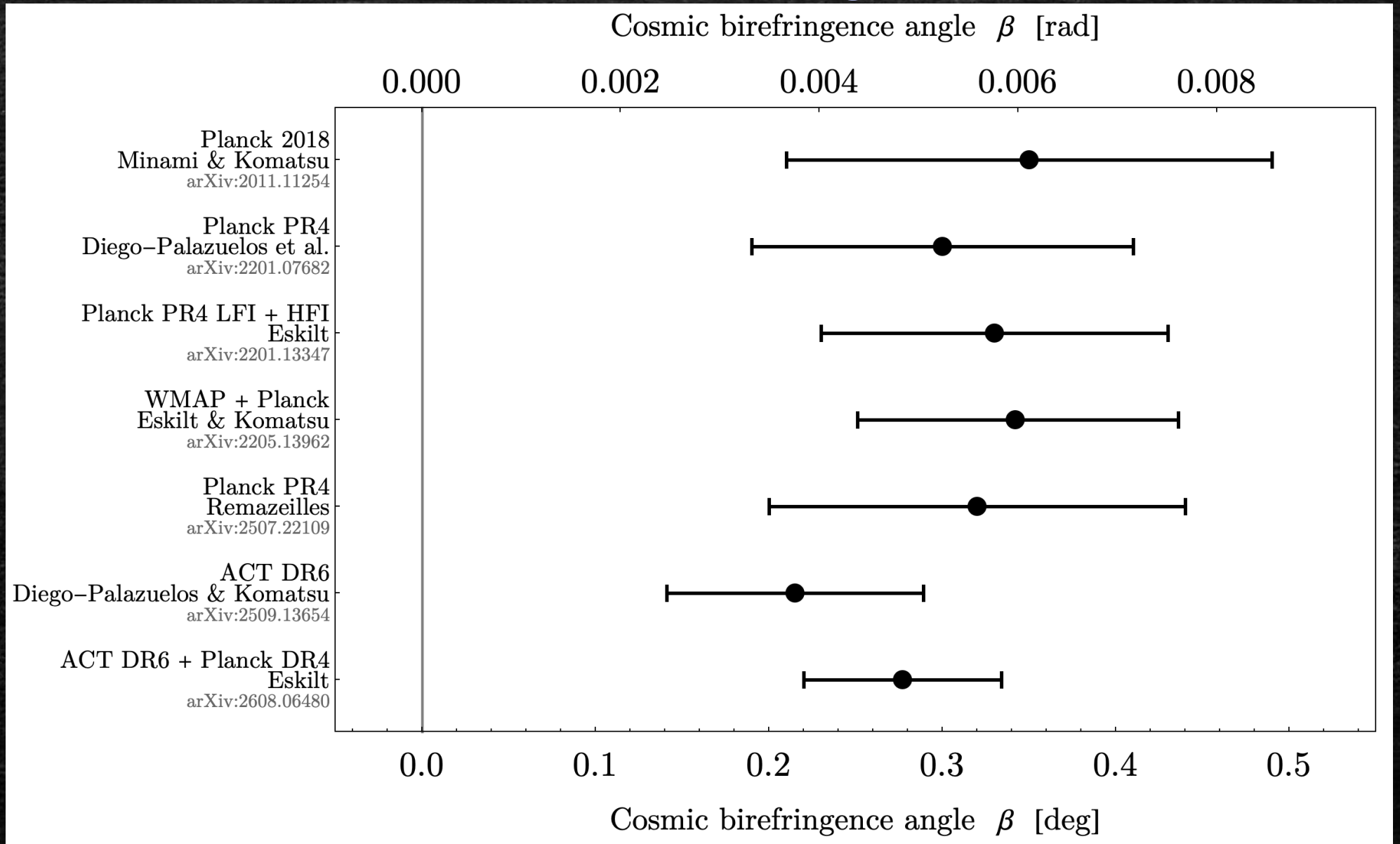
The Cosmic Microwave Background
Cosmic Birefringence

$$D_\ell^{EB} \equiv \frac{\ell(\ell+1)}{2\pi} C_\ell^{EB}$$

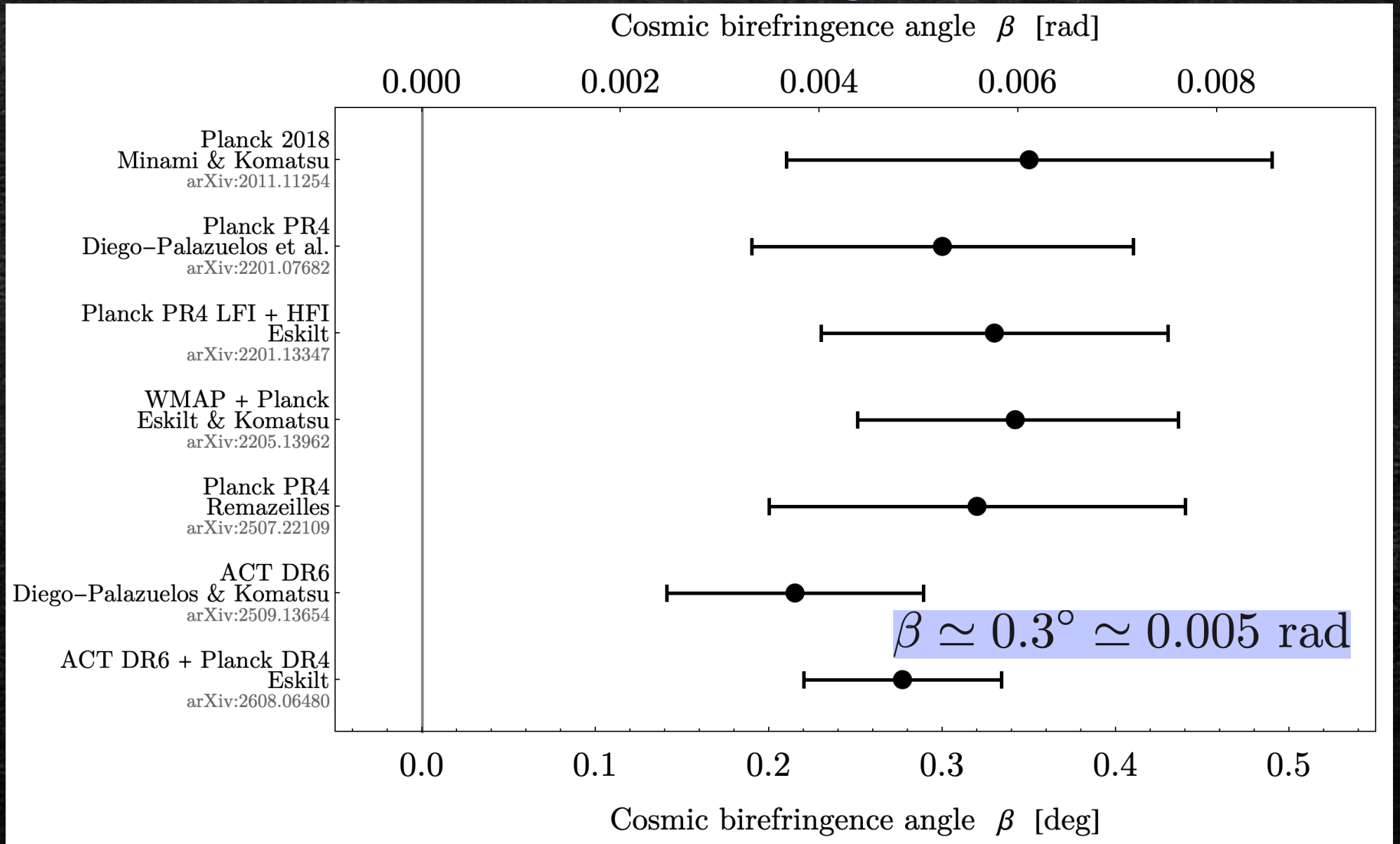
P. Diego-Palazuelos, E. Komatsu, 2509.13654



The Cosmic Microwave Background
Cosmic Birefringence



The Cosmic Microwave Background
Cosmic Birefringence



Cosmic Birefringence

Axion-Photon Coupling

We assume a massless axion-like particle ϕ that couples to photons

$$\mathcal{L} = \frac{\alpha_{\mathrm{EM}}}{8\pi} c_\gamma \frac{\phi}{f} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

$$= -\frac{\alpha_{\mathrm{EM}}}{2\pi} c_\gamma \frac{\phi}{f} \mathbf{E} \cdot \mathbf{B}$$

$$\equiv g_{\phi\gamma\gamma} \phi \mathbf{E} \cdot \mathbf{B} \qquad g_{\phi\gamma\gamma} \equiv \frac{\alpha_{\mathrm{EM}} c_\gamma}{2\pi f}$$

Modified Maxwell Equations

$$\nabla \cdot \mathbf{E} = \rho - g_{\phi\gamma\gamma} \nabla\phi \cdot \mathbf{B}$$

$$\nabla \times \mathbf{B} - \dot{\mathbf{E}} = \mathbf{J} + g_{\phi\gamma\gamma} \left(\dot{\phi}\mathbf{B} + \nabla\phi \times \mathbf{E} \right)$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} + \dot{\mathbf{B}} = 0$$

Birefringence

For a plane wave moving in the *z* direction, circular-polarization modes are

$$A_\pm = \frac{1}{\sqrt{2}} \left(A_x \pm i A_y \right) .$$

In a homogeneous axion background, the two helicities obey the equations of motion

$$A''_\pm + \left(k^2 \pm k \, g_{\phi\gamma\gamma} \phi' \right) A_\pm = 0$$

In the geometric-optics limit (photon wavelength ≪ axion coherence length),

$$\omega_\pm \simeq k \pm \frac{1}{2} g_{\phi\gamma\gamma} \phi'$$

Cosmic Birefringence

The two circular polarizations therefore accumulate different phases

$$\Delta\varphi_{+-} = \int d\eta\,(\omega_+ - \omega_-) \simeq -g_{\phi\gamma\gamma}\,(\phi_0 - \phi_{\rm em})$$

observation emission

Linear polarization is a superposition of the two circular helicities, and its rotation is half of their relative phase

$$\beta = \frac{1}{2}\Delta\varphi_{+-} = -\frac{g_{\phi\gamma\gamma}}{2}\,(\phi_0 - \phi_{\rm em})$$

today LSS

PLB 1991, Harari and Sikivie
PRD 2009, Finelli and Galaverni

Axion Interpretation

$$\beta = \frac{1}{2}\Delta\varphi_{+-} = -\frac{g_{\phi\gamma\gamma}}{2}(\phi_0 - \phi_{\rm em})$$

today LSS

The field value of the axion must change from last scattering to today

$$\beta = -\frac{\alpha_{\rm EM} c_\gamma}{4\pi}(\theta_0 - \langle\theta\rangle_{\rm LSS})$$

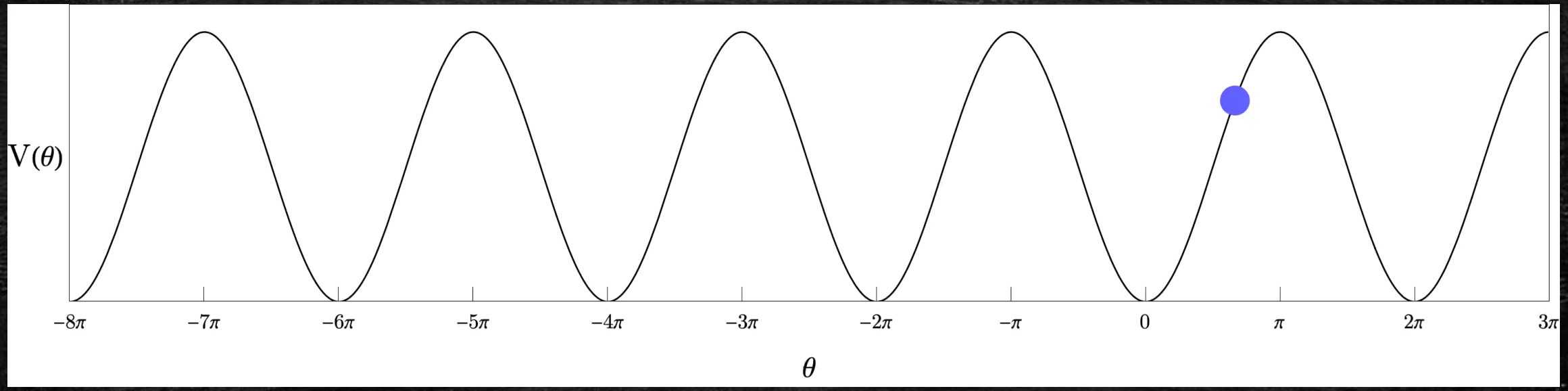
$$\simeq 0.005\, c_\gamma (\Delta\theta/8.6\ {\rm rad})$$

Existing Interpretations

Mechanism	References
General parity/CPT-violating electrodynamics	Carroll, Field & Jackiw (1990); Carroll & Field (1991); 9812088
Rolling pseudoscalar / ALP	Harari & Sikivie (1992); 9806099; 0606248; 0802.4210; 2008.02473
ALP dark energy	2011.11894; 2106.12602; 2203.09409
ALP dark matter / DM-triggered ALP	1903.02666; 2103.08153
Early dark energy	2209.07804
Cosmic strings	2608.24456
Rotating ALP	2609.25202 (**this work**)

Axion Interpretation

In the conventional axion dynamics, the axion oscillates in the potential



The oscillation amplitude redshifts, so oscillations should not occur long before the LSS to achieve

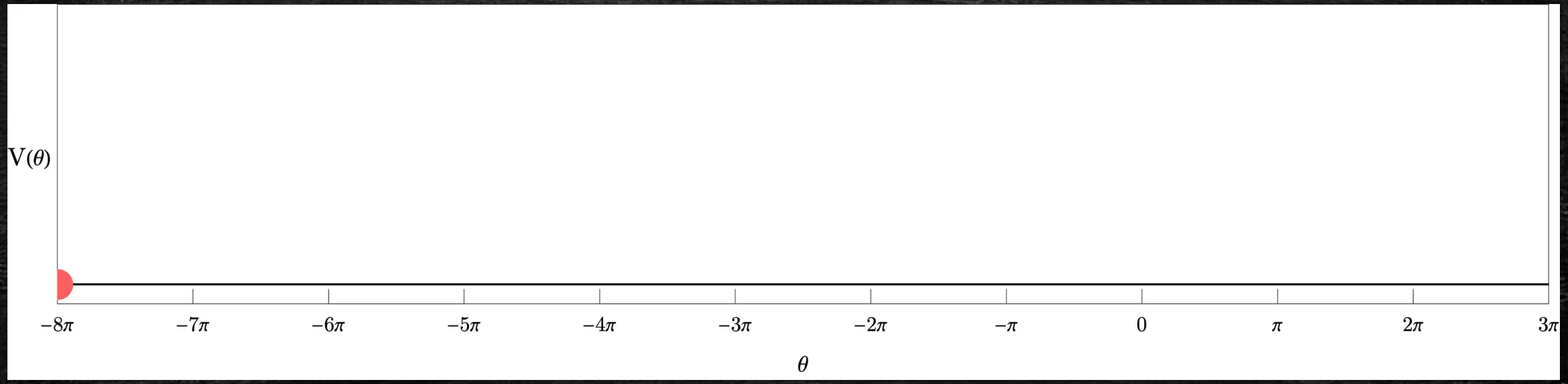
$$\Delta\theta \simeq 8.6 \text{ rad}/c_\gamma$$

This requires

$$\underset{10^{-33}\text{ eV}}{H_0} \lesssim m_\phi \lesssim \underset{10^{-29}\text{ eV}}{H_{\rm LSS}}$$

Axion Rotation

In our scenario, the axion rotates in the (vanishing) potential



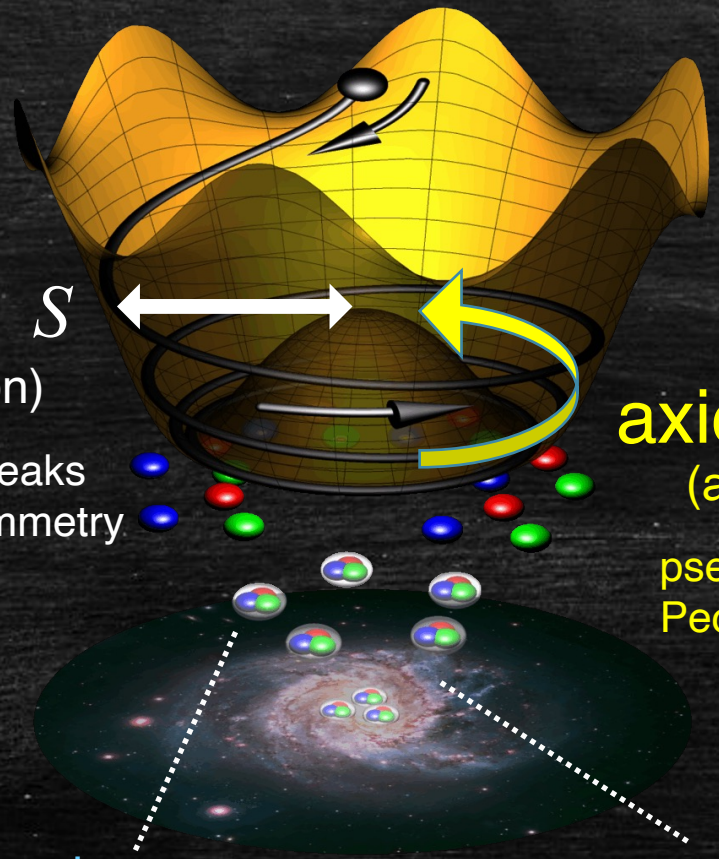
The rotational velocity around the last scattering surface is fixed by cosmic birefringence to achieve

$$\Delta\theta \simeq 8.6 \ \mathrm{rad}/c_\gamma$$

Axion Rotation

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

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



S

(radial direction)

spontaneously breaks
Peccei-Quinn symmetry

axion

(angular direction)

pseudo Nambu-Goldstone boson of
Peccei-Quinn symmetry breaking

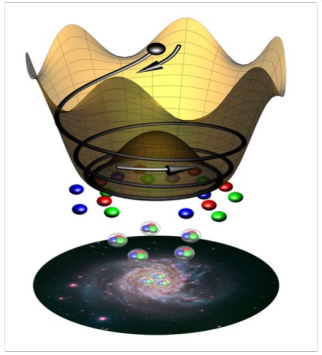
matter-antimatter
asymmetry

dark matter

PHYS.ORG

Paper sheds light on infant universe and origin of matter

10 March 2020



The rotation of the QCD axion (black ball) produces an excess of matter (colored balls) over antimatter, allowing galaxies and human beings to exist. Credit: Graphic: Harigaya and Co; Photo: NASA

A new study, conducted to better understand the origin of the universe, has provided insight into some of the most enduring questions in fundamental physics: How can the Standard Model of particle physics be extended to explain the cosmological excess of matter over antimatter? What is dark matter? And what is the theoretical origin of an unexpected but observed symmetry in the force that binds protons and neutrons together?

In the paper "Axiogenesis," scheduled to be published in *Physical Review Letters* on March 17, 2020, researchers Keisuke Harigaya, Member in the School of Natural Sciences at the Institute for Advanced Study, and Raymond T. Co of the University of Michigan, have presented a compelling case in which the quantum chromodynamics (QCD) axion, first theorized in 1977, provides several important answers to these questions.

"We revealed that the rotation of the QCD axion can account for the excess of matter found in the universe," stated Harigaya. "We named this mechanism axiogenesis."

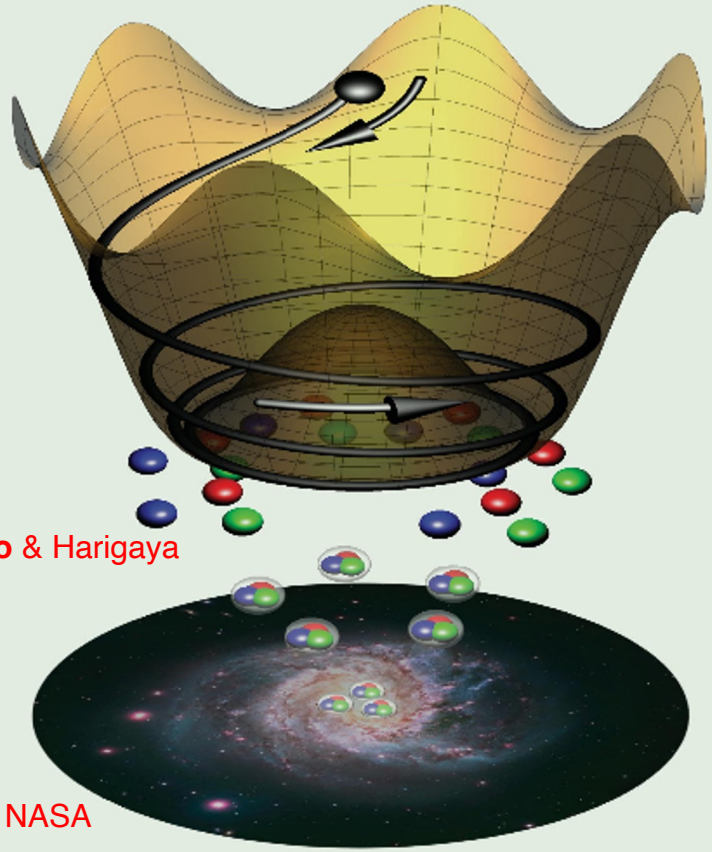
Infinitesimally light, the QCD axion—at least one billion times lighter than a proton—is nearly ghost-like. Millions of these particles pass through ordinary matter every second without notice. However, the subatomic level interaction of the QCD axion can still leave detectable signals in experiments with unprecedented sensitivities. While the QCD axion has never been directly detected, this study provides added fuel for experimentalists to hunt down the elusive particle.

"The versatility of the QCD axion in solving the mysteries of fundamental physics is truly amazing," stated Co. "We are thrilled about the unexplored theoretical possibilities that this new aspect of the QCD axion can bring. More importantly, experiments may soon tell us whether the mysteries of nature truly hint towards the QCD axion."

Harigaya and Co have reasoned that the QCD axion is capable of filling three missing pieces of the physics jigsaw puzzle simultaneously. First, the QCD axion was originally proposed to explain the so-called strong CP problem—why the strong force, which binds protons and neutrons together, unexpectedly preserves a symmetry called the Charge Parity (CP) symmetry. The CP symmetry is inferred from the observation that a neutron does not react with an electric field despite its charged constituents. Second, the QCD axion was found to

PHYSICAL REVIEW LETTERS

Articles published week ending 20 MARCH 2020



Graphic: **Co** & Harigaya

Photo: NASA

Published by
American Physical Society

APS physics

Volume 124, Number 11

Quanta magazine

Physics Mathematics Bio

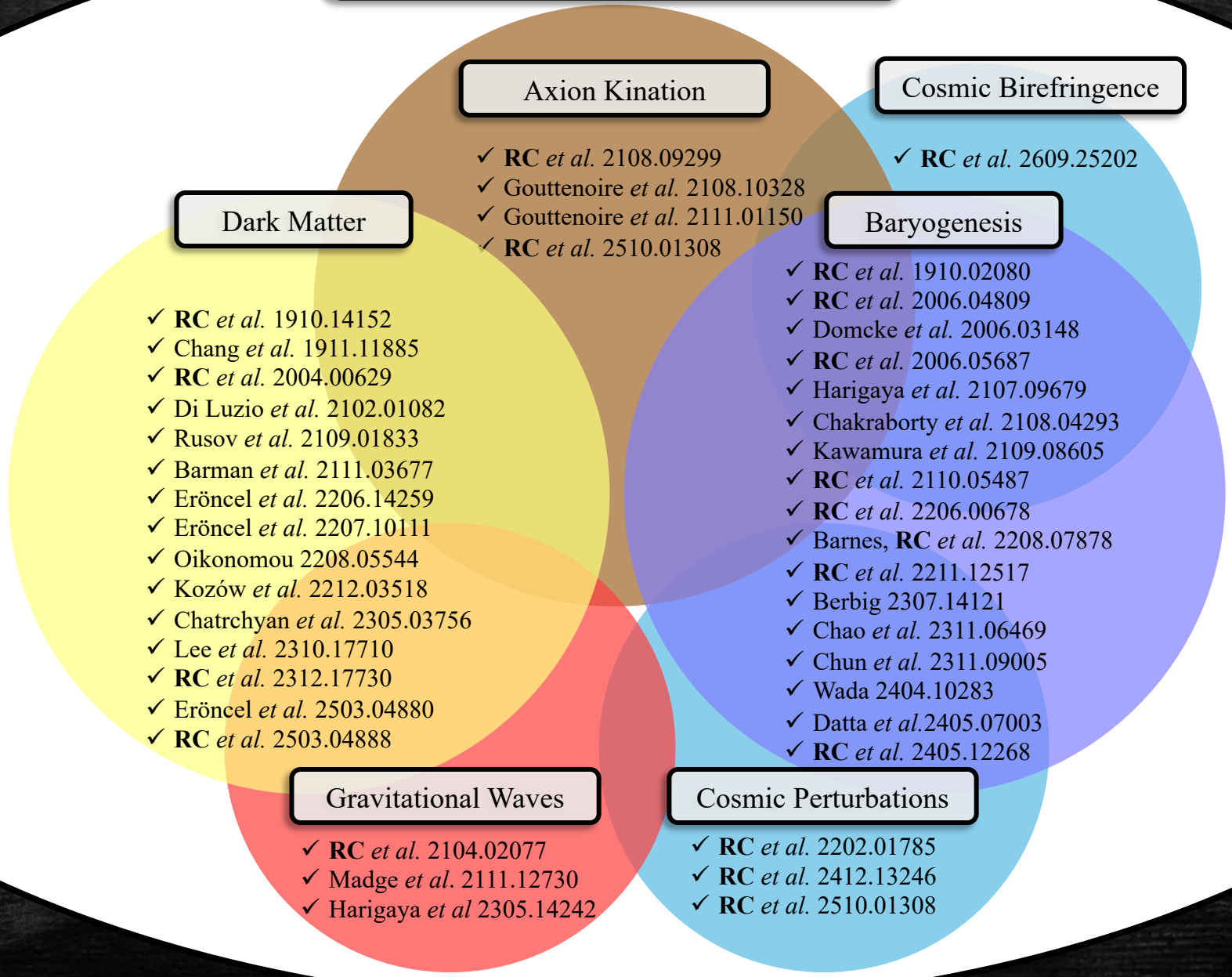
ABSTRACTIONS BLOG

Axions Would Solve Another Major Problem in Physics

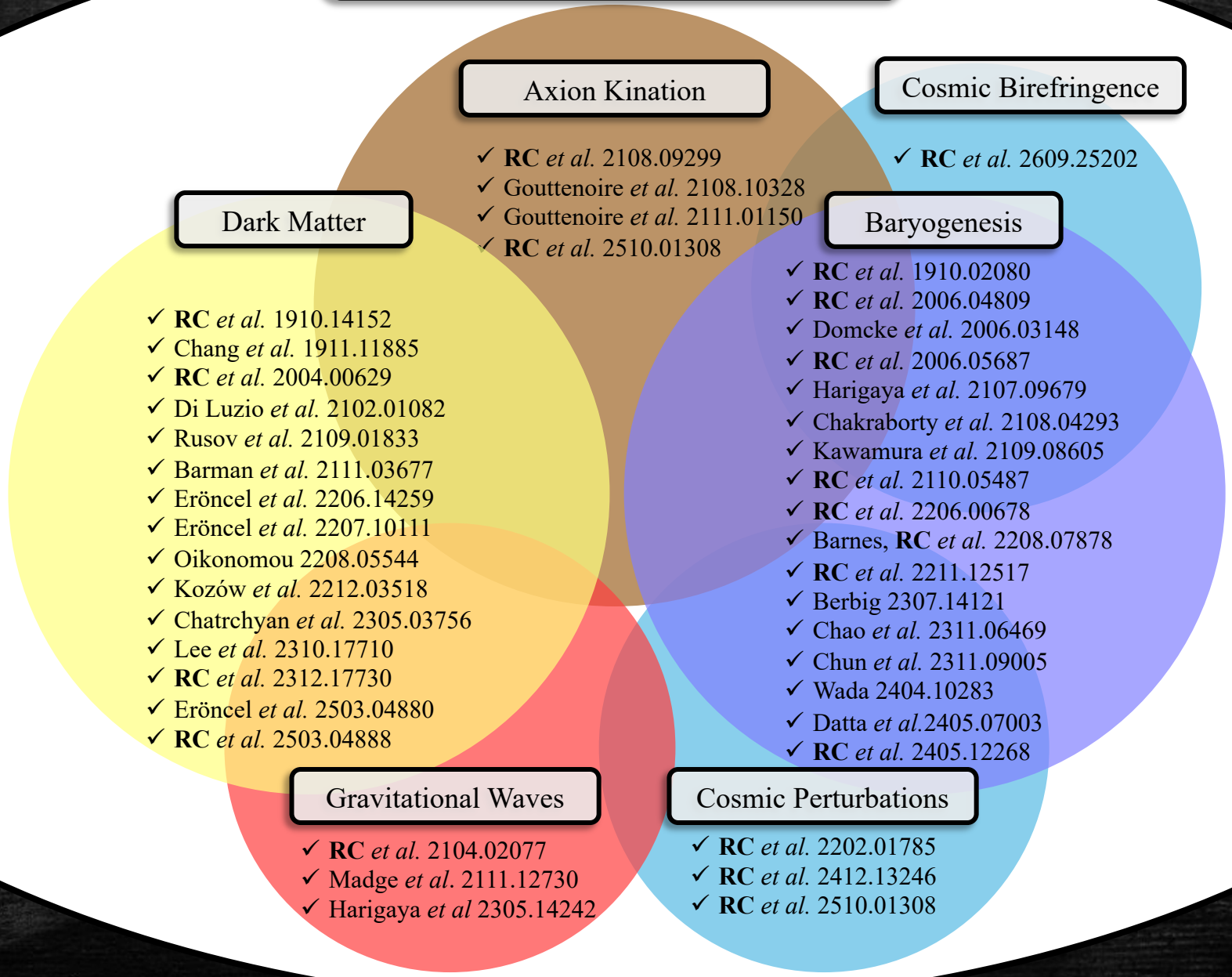
In a new paper, physicists argue that hypothetical particles called axions could explain why the universe isn't empty.



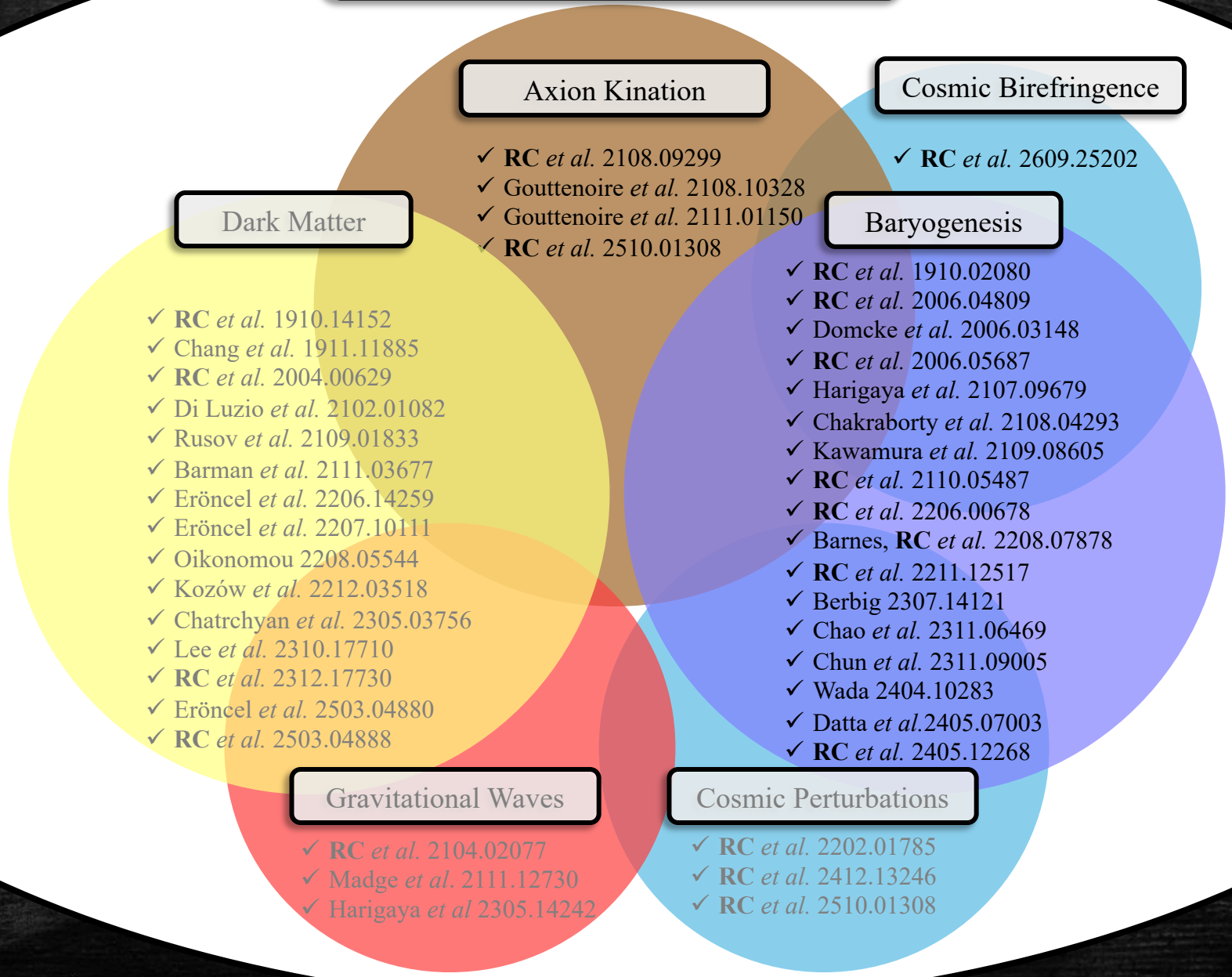
Axion Rotations



Axion Rotations

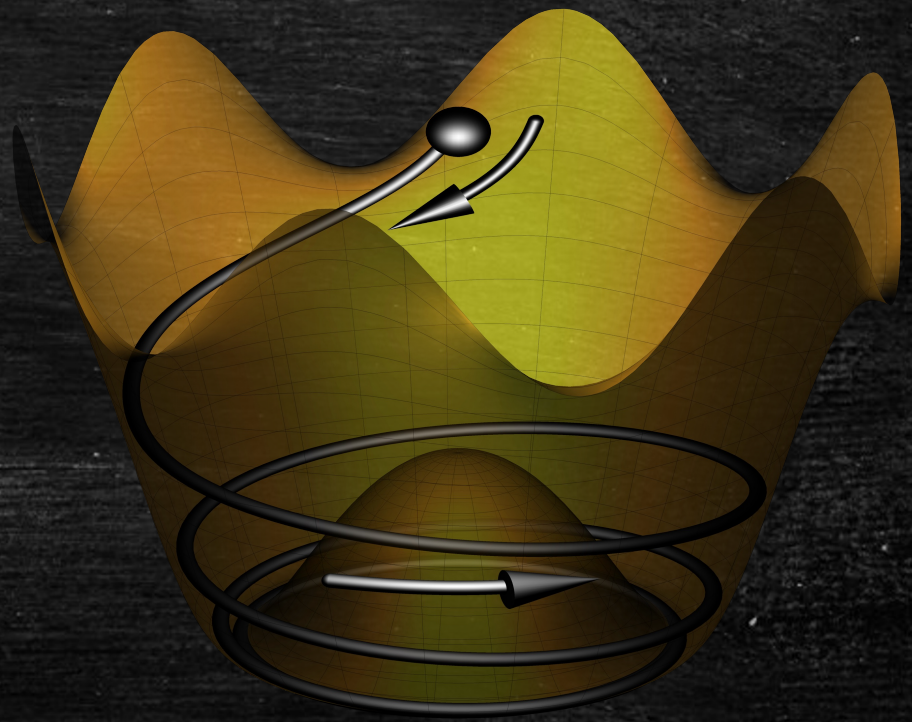


Axion Rotations



Why Rotation?

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



Dynamics analogous to that in Affleck-Dine baryogenesis

I. Affleck and M. Dine 1991

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

Why Rotation?

Wiggles :

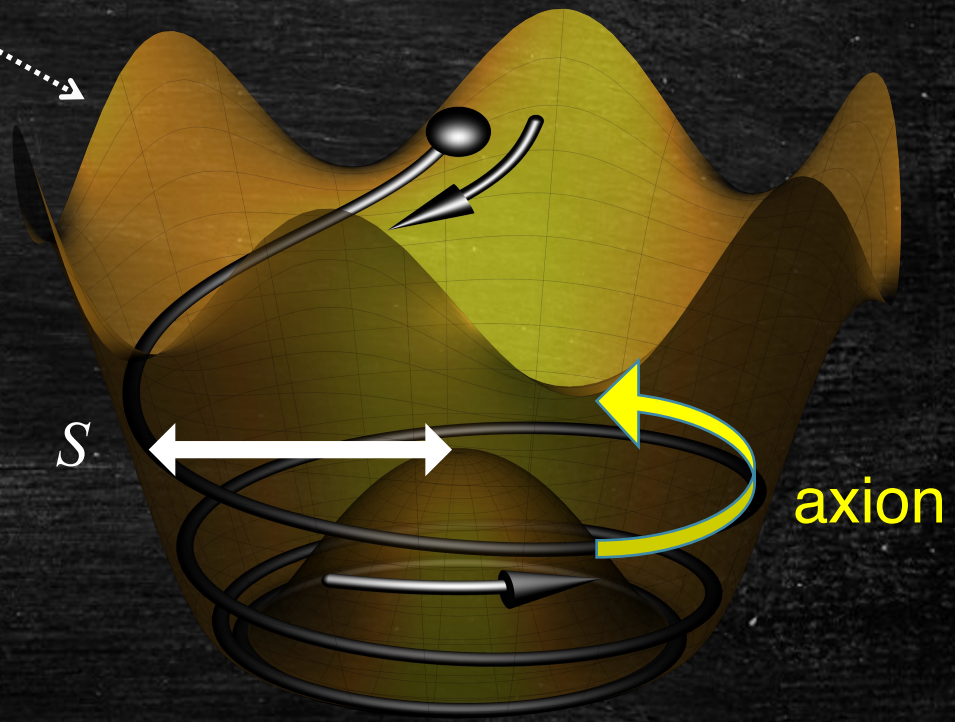
$$V(P) \sim \frac{P^n}{M^{n-4}} e^{i\varphi} + \text{h.c.} \sim \frac{|P|^n}{M^{n-4}} \cos\left(n\frac{a}{f_a} + \varphi\right)$$

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

Explicit PQ breaking

expected from quantum gravity
or PQ as an accidental symmetry

S. Giddings et al. 1988
S. Coleman 1988
G. Gilbert 1988



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?

Wiggles :

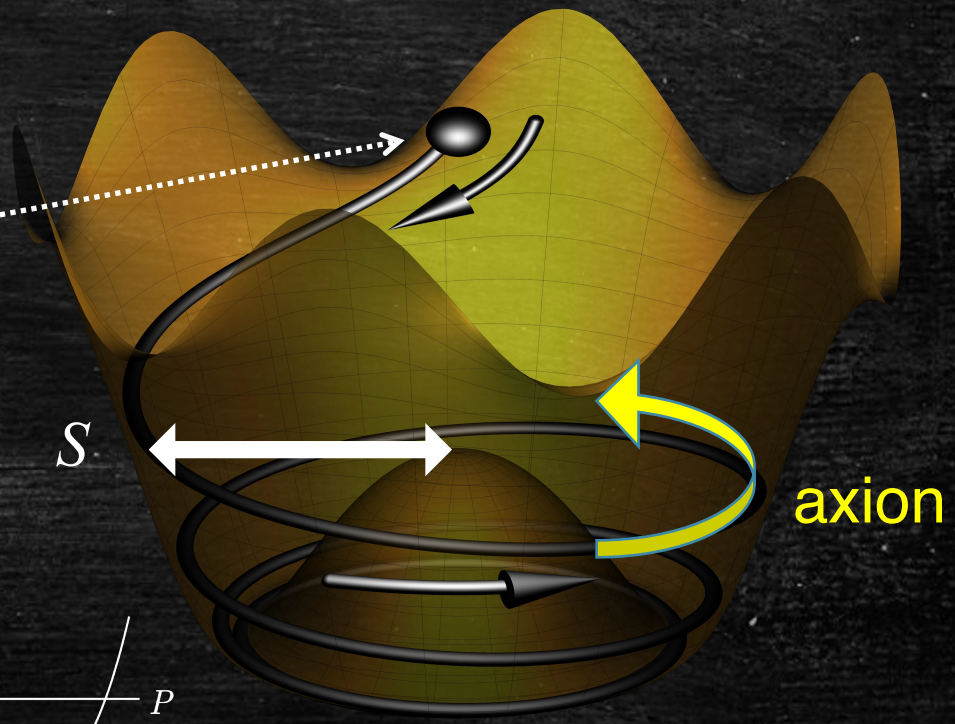
$$V(P) \sim \frac{P^n}{M^{n-4}} e^{i\varphi} + \text{h.c.} \sim \frac{|P|^n}{M^{n-4}} \cos\left(n\frac{a}{f_a} + \varphi\right)$$

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

Explicit PQ breaking

expected from quantum gravity
or PQ as an accidental symmetry

S. Giddings et al. 1988
S. Coleman 1988
G. Gilbert 1988



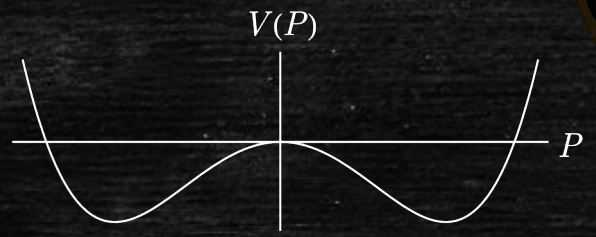
Large field value : Flat potential

For example, as an initial condition or
set dynamically by inflationary dynamics

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

Hubble-induced mass

M. Dine, L. Randall, and S. D. Thomas 1991



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

Noether charge associated with the shift symmetry

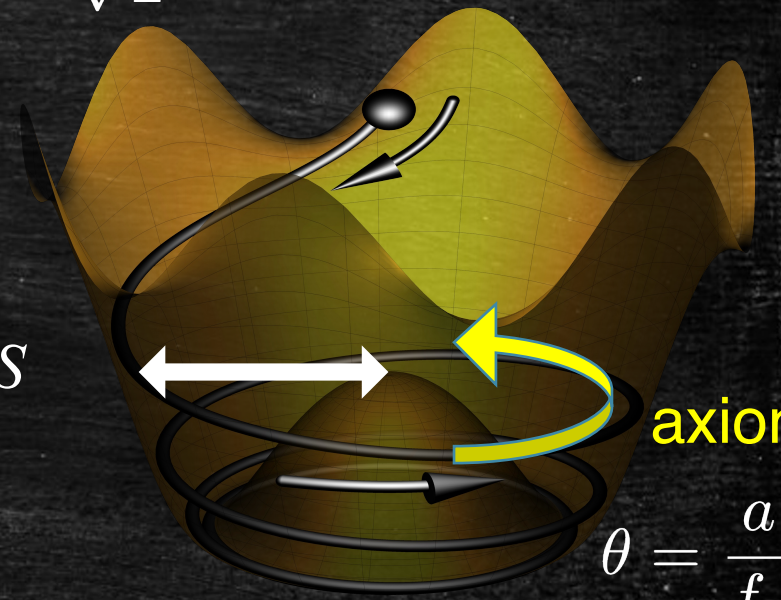
$$Y_\theta = \frac{n_\theta}{s} = \frac{S^2\dot{\theta}}{s}$$

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

PQ asymmetry
PQ charge density = Rotation of PQ field

This is conserved soon after the initial kick.

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



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

Cosmic Birefringence from Axion Rotation

The axion angle changes because of rotation

$$\theta_0 - \langle\theta\rangle_{\rm LSS} = \int_{t(T)}^{t_0} dt'\,\dot{\theta}(t')$$

This would be the correct formula if recombination occurs instantaneously.

2609.25202 RC, Lawrence Hall, Keisuke Harigaya, and Taegyu Lee

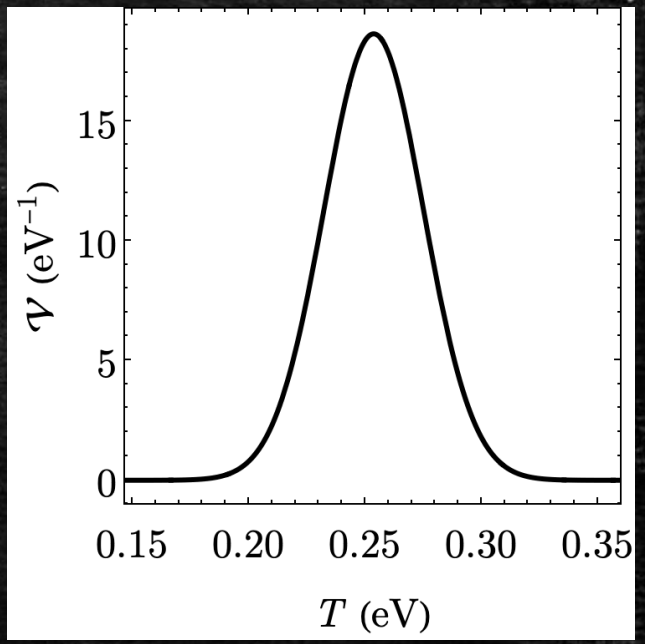
Cosmic Birefringence from Axion Rotation

The axion angle changes because of rotation

$$\theta_0 - \langle\theta\rangle_{\rm LSS} = \int_{t(T)}^{t_0} dt'\,\dot\theta(t')$$

This would be the correct formula if recombination occurs instantaneously. We account for the finite thickness of the LSS by defining a visibility-weighted effective field value,

$$\theta_0 - \langle\theta\rangle_{\rm LSS} = \int dT\,\mathcal{V}(T)\int_{t(T)}^{t_0} dt'\,\dot\theta(t')$$



S. Weinberg, Cosmology 2008

2609.25202 RC, Lawrence Hall, Keisuke Harigaya, and Taegyu Lee

Cosmic Birefringence from Axion Rotation

Cosmic birefringence is obtained from a finite PQ asymmetry

$$\beta = 0.003 \times c_\gamma \left(\frac{-Y_\theta / f_a^2}{8.7 \times 10^{-9}\ \mathrm{GeV}^{-2}} \right)$$

2609.25202 RC, Lawrence Hall, Keisuke Harigaya, and Taegyu Lee

Cosmic Birefringence from Axion Rotation

Cosmic birefringence is obtained from a finite PQ asymmetry

$$\beta = 0.003 \times c_\gamma \left(\frac{-Y_\theta / f_a^2}{8.7 \times 10^{-9}\ \mathrm{GeV}^{-2}} \right)$$

The required PQ asymmetry is then

$$Y_\theta = -5.7 \times 10^{10} c_\gamma \left(\frac{\beta}{0.005} \right) \left(\frac{f_a / c_\gamma}{2 \times 10^9\ \mathrm{GeV}} \right)^2$$

$$\dot{\theta}_{\mathrm{rec}} \simeq -\frac{4.0 \times 10^{-28}\ \mathrm{eV}}{c_\gamma} \left(\frac{\beta}{0.005} \right)$$

2609.25202 RC, Lawrence Hall, Keisuke Harigaya, and Taegyu Lee

Cosmic Birefringence from Axion Rotation

Cosmic birefringence is obtained from a finite PQ asymmetry

$$\beta = 0.003 \times c_\gamma \left(\frac{-Y_\theta / f_a^2}{8.7 \times 10^{-9}\ \mathrm{GeV}^{-2}} \right)$$

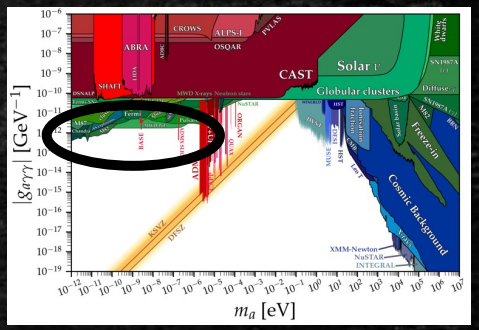
The required PQ asymmetry is then

$$Y_\theta = -5.7 \times 10^{10} c_\gamma \left(\frac{\beta}{0.005} \right) \left(\frac{f_a / c_\gamma}{2 \times 10^9\ \mathrm{GeV}} \right)^2$$

for experts

This benchmark value of f/c_γ comes from the astrophysical bound for $m_\phi < 10^{12}$ eV

$$g_{\phi\gamma\gamma} = \frac{\alpha_{\mathrm{EM}} c_\gamma}{2\pi f_a} < 6.3 \times 10^{-13}\ \mathrm{GeV}^{-1}$$



J.S. Reynés et al 2109.03261

from the absence of X-ray spectral irregularities from a bright quasar

Cosmic Birefringence from Axion Rotation

Cosmic birefringence is obtained from a finite PQ asymmetry

$$\beta = 0.003 \times c_\gamma \left(\frac{-Y_\theta / f_a^2}{8.7 \times 10^{-9}\ \mathrm{GeV}^{-2}} \right)$$

The required PQ asymmetry is then

$$Y_\theta = -5.7 \times 10^{10} c_\gamma \left(\frac{\beta}{0.005} \right) \left(\frac{f_a / c_\gamma}{2 \times 10^9\ \mathrm{GeV}} \right)^2$$

Namely, cosmic birefringence relates

$$\left(\frac{c_\gamma}{f_a^2} \right) \overset{\beta}{\longleftrightarrow} Y_\theta$$

2609.25202 RC, Lawrence Hall, Keisuke Harigaya, and Taegyu Lee

Baryon Asymmetry
Axiogenesis

Asymmetries in Thermal Equilibrium

The free energy is minimized at equilibrium.

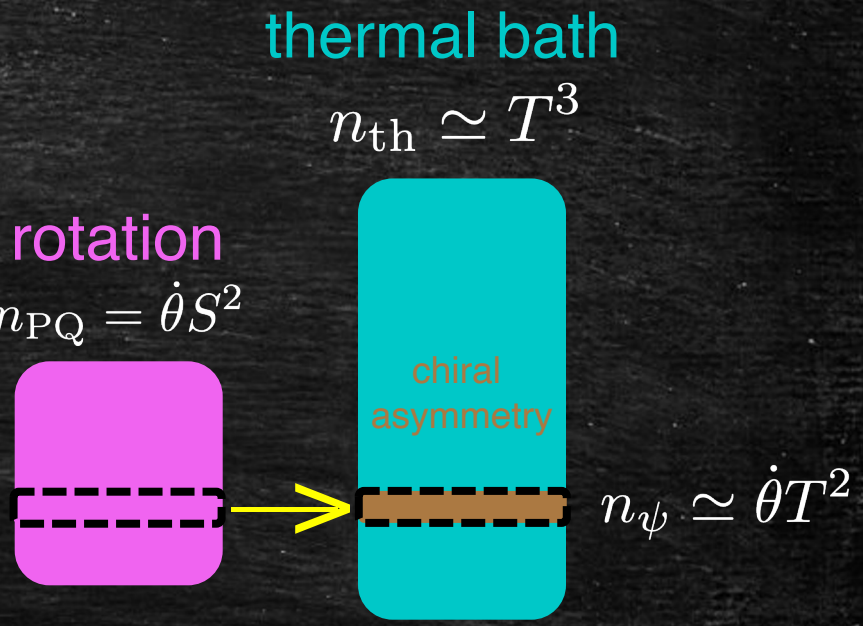
fermion asymmetry

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

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 $n_\psi \sim \dot\theta T^2 \ll \dot\theta S^2 = n_{\rm PQ}$

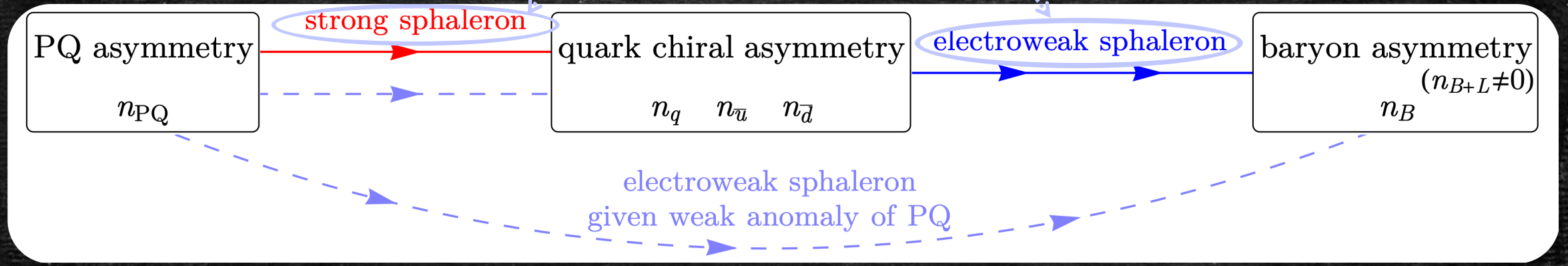
Most of the PQ charge remains in the rotation!

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

Axiogenesis

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

matter-antimatter asymmetry



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

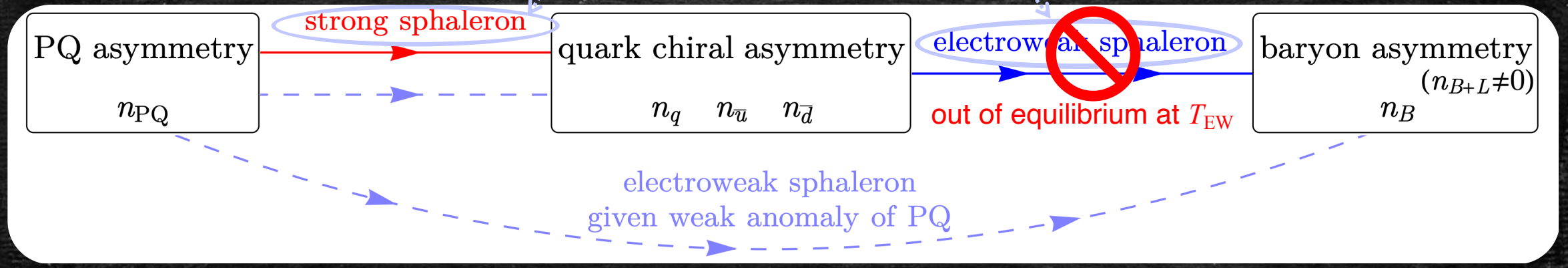
produced by axion rotations

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

Axiogenesis

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

matter-antimatter asymmetry



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

produced by axion rotations

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

experimentally measured value
(*Planck* 2018)

Namely, the baryon asymmetry relates

$$c_B \left(\frac{T_{\rm EW}}{S_{\rm EW}}\right)^2 \frac{Y_B}{\longleftrightarrow} Y_\theta$$

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

Cosmic Birefringence and Axiogenesis

cosmic birefringence relates

$$\left(\frac{c_\gamma}{f_a^2}\right) \overset{\beta}{\longleftrightarrow} Y_\theta$$

the baryon asymmetry relates

$$c_B \left(\frac{T_{\rm EW}}{S_{\rm EW}}\right)^2 \overset{Y_B}{\longleftrightarrow} Y_\theta$$

2609.25202 RC, Lawrence Hall, Keisuke Harigaya, and Taegyu Lee

Cosmic Birefringence and Axiogenesis

$$\beta = 1.8 \times 10^{-8} \frac{-0.1}{c_B/c_\gamma} \left(\frac{S_{\rm EW}}{f_a} \right)^2$$

cosmic birefringence relates

$$\left(\frac{c_\gamma}{f_a^2} \right) \overset{\beta}{\longleftrightarrow} Y_\theta$$

the baryon asymmetry relates

$$c_B \left(\frac{T_{\rm EW}}{S_{\rm EW}} \right)^2 \overset{Y_B}{\longleftrightarrow} Y_\theta$$

2609.25202 RC, Lawrence Hall, Keisuke Harigaya, and Taegyu Lee

Cosmic Birefringence and Axiogenesis

$$\beta = 1.8 \times 10^{-8} \frac{-0.1}{c_B/c_\gamma} \left(\frac{S_{\rm EW}}{f_a} \right)^2$$

CMB

$$\beta \simeq 0.005$$

cosmic birefringence relates $\left(\frac{c_\gamma}{f_a^2} \right) \overset{\beta}{\longleftrightarrow} Y_\theta$

the baryon asymmetry relates $c_B \left(\frac{T_{\rm EW}}{S_{\rm EW}} \right)^2 \overset{Y_B}{\longleftrightarrow} Y_\theta$

2609.25202 RC, Lawrence Hall, Keisuke Harigaya, and Taegyu Lee

Cosmic Birefringence and Axiogenesis

$$\beta = 1.8 \times 10^{-8} \frac{-0.1}{c_B/c_\gamma} \left(\frac{S_{\rm EW}}{f_a} \right)^2$$

CMB

$\beta \simeq 0.005$

very small, negative c_B is required

cosmic birefringence relates

$$\left(\frac{c_\gamma}{f_a^2} \right) \overset{\beta}{\longleftrightarrow} Y_\theta$$

the baryon asymmetry relates

$$c_B \left(\frac{T_{\rm EW}}{S_{\rm EW}} \right)^2 \overset{Y_B}{\longleftrightarrow} Y_\theta$$

2609.25202 RC, Lawrence Hall, Keisuke Harigaya, and Taegyu Lee

Minimal Model

The coefficient c_B depends on axion couplings to the Standard Model particles

$$c_B = \left(\frac{21}{158} - \delta\right) c_g - \frac{12}{79} c_W + \sum_i \left(\frac{18}{79} c_{q_i} - \frac{21}{158} c_{\bar{u}_i} - \frac{15}{158} c_{\bar{d}_i} + \frac{25}{237} c_{\ell_i} - \frac{11}{237} c_{\bar{e}_i}\right)$$

very small, negative c_B is required

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

2609.25202 RC, Lawrence Hall, Keisuke Harigaya, and Taegyu Lee

Minimal Model

The coefficient c_B depends on axion couplings to the Standard Model particles

$$c_B = \left(\frac{21}{158} - \delta\right) c_g - \frac{12}{79} c_W + \sum_i \left(\frac{18}{79} c_{q_i} - \frac{21}{158} c_{\bar{u}_i} - \frac{15}{158} c_{\bar{d}_i} + \frac{25}{237} c_{\ell_i} - \frac{11}{237} c_{\bar{e}_i}\right)$$

very small, negative c_B is required

If the ALP couples only to the hypercharge gauge field, $c_B = 0$ at the tree level. However, one-loop quantum corrections generate ALP-fermion couplings as

$$\mathcal{L} \supset 6 c_\gamma \left(\frac{\alpha_Y}{4\pi}\right)^2 \ln\left(\frac{\Lambda}{T_{\rm EW}}\right) \frac{\partial_\mu \phi}{f_a} \sum_\psi Y_\psi^2 \psi^\dagger \bar{\sigma}^\mu \psi$$

2609.25202 RC, Lawrence Hall, Keisuke Harigaya, and Taegyu Lee

Minimal Model

The coefficient c_B depends on axion couplings to the Standard Model particles

$$c_B = \left(\frac{21}{158} - \delta\right) c_g - \frac{12}{79} c_W + \sum_i \left(\frac{18}{79} c_{q_i} - \frac{21}{158} c_{\bar{u}_i} - \frac{15}{158} c_{\bar{d}_i} + \frac{25}{237} c_{\ell_i} - \frac{11}{237} c_{\bar{e}_i}\right)$$

very small, negative c_B is required

If the ALP couples only to the hypercharge gauge field, $c_B = 0$ at the tree level. However, one-loop quantum corrections generate ALP-fermion couplings as

$$\mathcal{L} \supset 6 c_\gamma \left(\frac{\alpha_Y}{4\pi}\right)^2 \ln\left(\frac{\Lambda}{T_{\rm EW}}\right) \frac{\partial_\mu \phi}{f_a} \sum_\psi Y_\psi^2 \psi^\dagger \bar{\sigma}^\mu \psi$$

The resultant c_B is $\dfrac{c_B}{c_\gamma} \simeq -9.7 \times 10^{-7} \ln\left(\dfrac{\Lambda}{T_{\rm EW}}\right)$ Correct sign!!!

2609.25202 RC, Lawrence Hall, Keisuke Harigaya, and Taegyu Lee

Minimal Model

The coefficient c_B depends on axion couplings to the Standard Model particles

$$c_B = \left(\frac{21}{158} - \delta\right) c_g - \frac{12}{79} c_W + \sum_i \left(\frac{18}{79} c_{q_i} - \frac{21}{158} c_{\bar{u}_i} - \frac{15}{158} c_{\bar{d}_i} + \frac{25}{237} c_{\ell_i} - \frac{11}{237} c_{\bar{e}_i}\right)$$

very small, negative c_B is required

If the ALP couples only to the hypercharge gauge field, $c_B = 0$ at the tree level. However, one-loop quantum corrections generate ALP-fermion couplings as

$$\mathcal{L} \supset 6 c_\gamma \left(\frac{\alpha_Y}{4\pi}\right)^2 \ln\left(\frac{\Lambda}{T_{\rm EW}}\right) \frac{\partial_\mu \phi}{f_a} \sum_\psi Y_\psi^2 \psi^\dagger \bar{\sigma}^\mu \psi$$

The resultant c_B is $\dfrac{c_B}{c_\gamma} \simeq -9.7 \times 10^{-7} \ln\left(\dfrac{\Lambda}{T_{\rm EW}}\right)$ Correct sign!!!

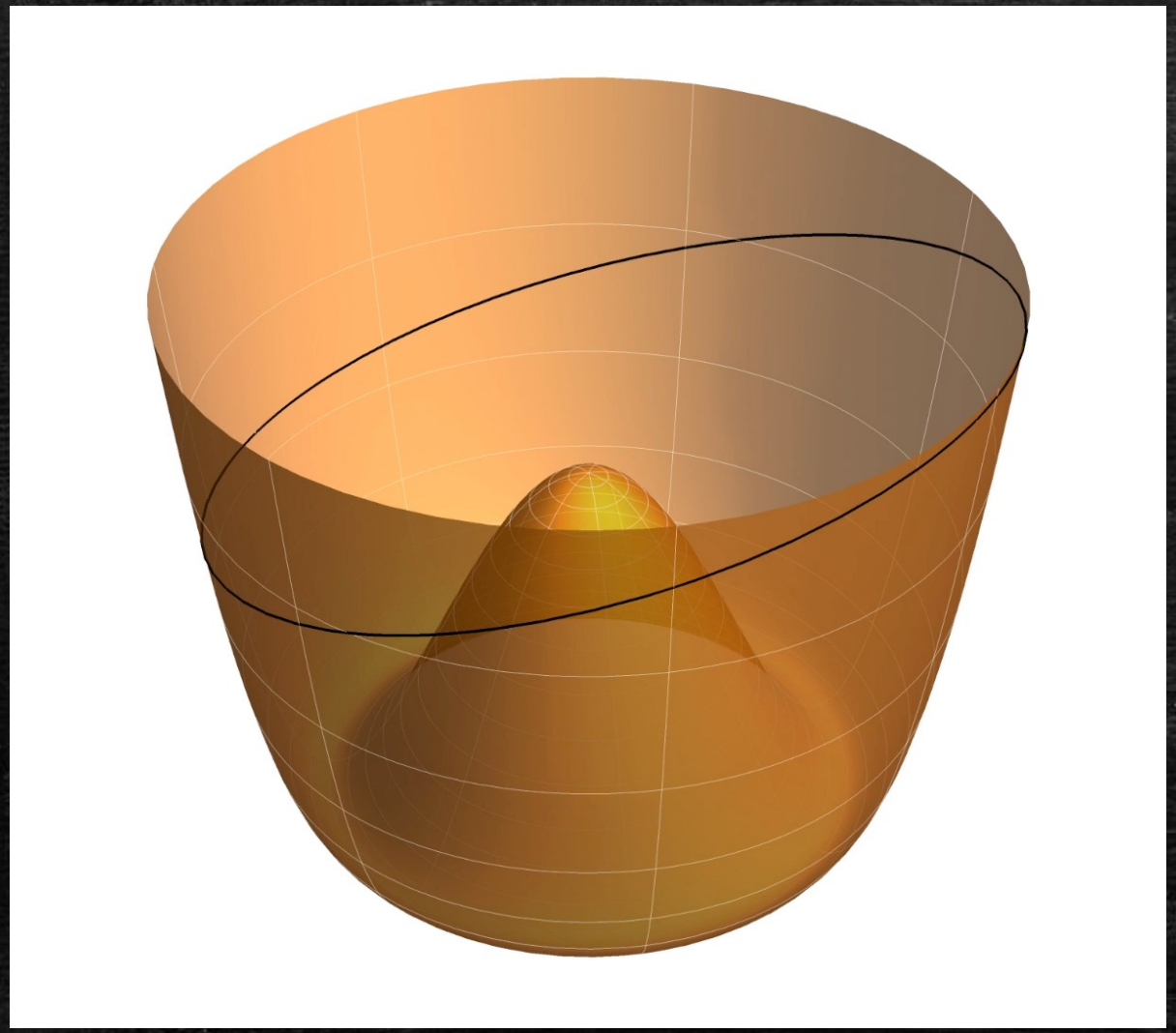
Cosmic birefringence is

$$\beta \simeq 0.0019 \frac{1}{\ln(\Lambda/T_{\rm EW})} \left(\frac{S_{\rm EW}}{f_a}\right)^2$$

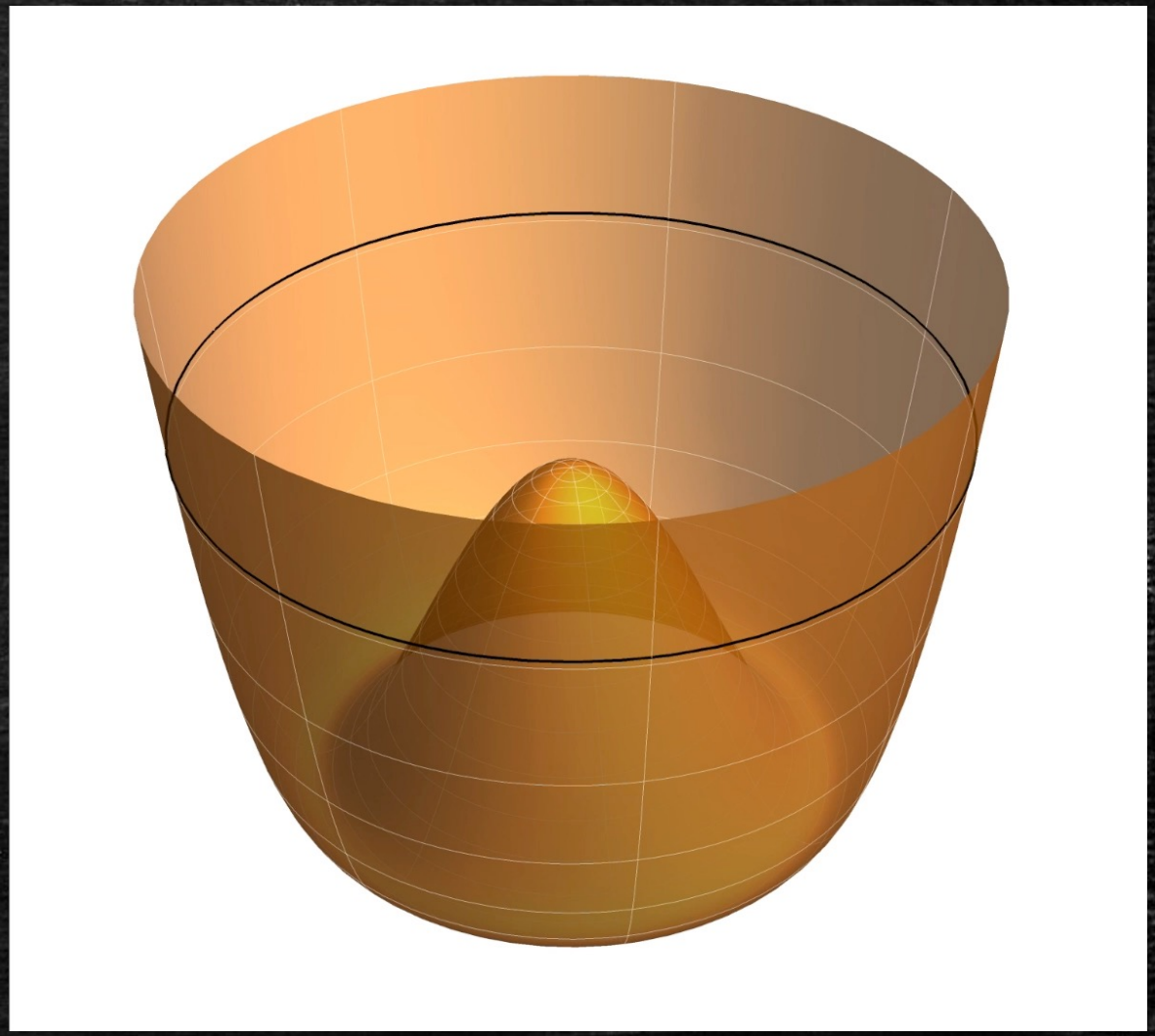
Technical Detail

Perfect circular motion from thermalization

Thermalization



Redshift



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

Technical Detail

Perfect circular motion from thermalization

Efficient thermalization

$$\Gamma_{\rm th} \simeq \frac{bT^3}{S^2} > H \quad \text{requires} \quad |Y_\theta| < 3 \times 10^5 \left(\frac{b}{0.1}\right)^{1/3} \left(\frac{10\ \text{MeV}}{m_P}\right)^{1/3}$$

However, the PQ asymmetry required by cosmic birefringence is

$$Y_\theta = -5.7 \times 10^{10} c_\gamma \left(\frac{\beta}{0.005}\right) \left(\frac{f_a/c_\gamma}{2 \times 10^9\ \text{GeV}}\right)^2$$

We can resolve this by the clockwork mechanism 0409138, 1404.3511, 1404.6209, 1404.6923, 1407.4893, 1511.00132, 1511.01827

$$Y_\theta = 3^k \frac{n_k}{s} \qquad V_{\rm clockwork} \supset \sum_{n=0}^{k-1} \left(\lambda_n P_n^3 P_{n+1}^\dagger + \text{h.c.}\right)$$

2609.25202 RC, Lawrence Hall, Keisuke Harigaya, and Taegyu Lee

Axion Kination

Asymmetry of PQ Charge

Noether charge associated with the shift symmetry

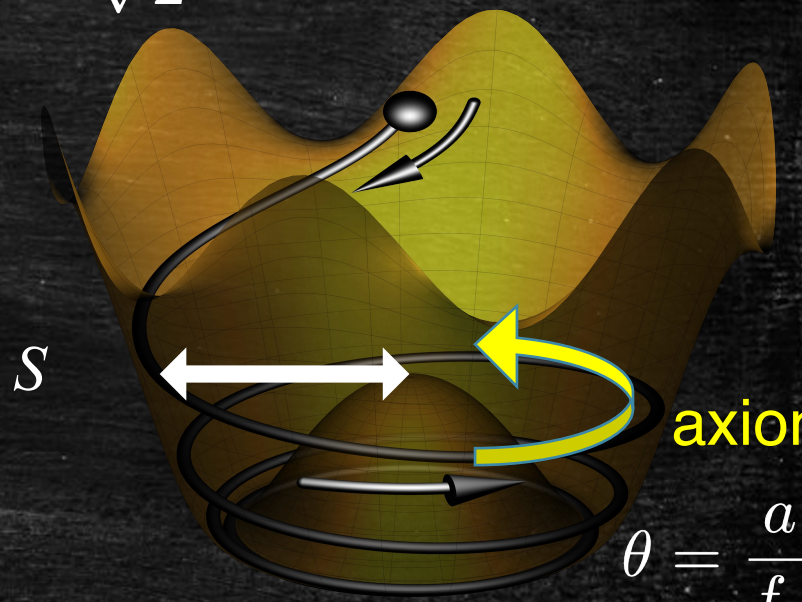
$$n_\theta = S^2\dot{\theta}$$

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

PQ asymmetry
PQ charge density = Rotation of PQ field

This is conserved soon after the initial kick.

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



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

Asymmetry of PQ Charge

Noether charge associated with the shift symmetry

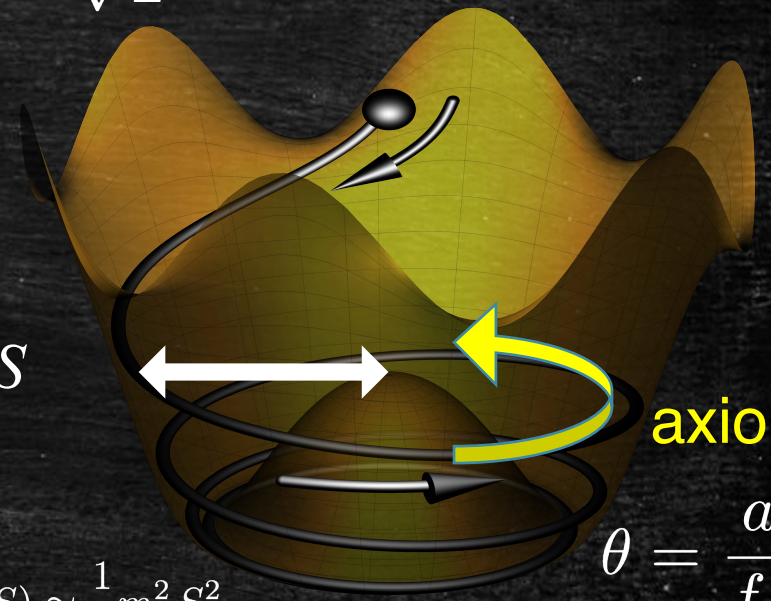
$$n_\theta = S^2\dot{\theta}$$

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

PQ asymmetry
PQ charge density = Rotation of PQ field

This is conserved soon after the initial kick.

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



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

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

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

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

which is in turn set by supersymmetry scale.

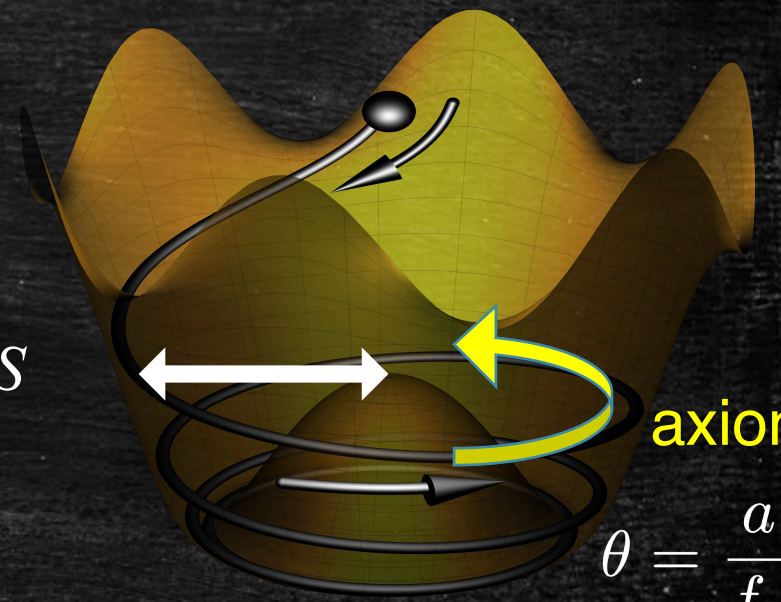
PQ Charge Evolution

Charge conservation:

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

scale factor of the universe

dilution due to cosmic expansion



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

PQ Charge Evolution

Charge conservation:

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

scale factor of the universe

dilution due to cosmic expansion

Large field ($S \gg f_a$):

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

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

$$\dot{\theta} = \text{constant}$$

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

matter

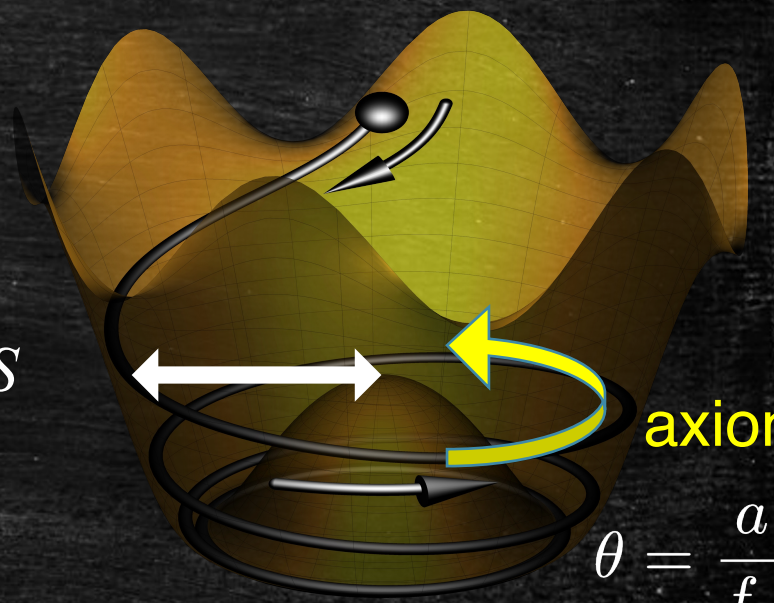
At the minimum:

$$S^2 = f_a^2$$

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

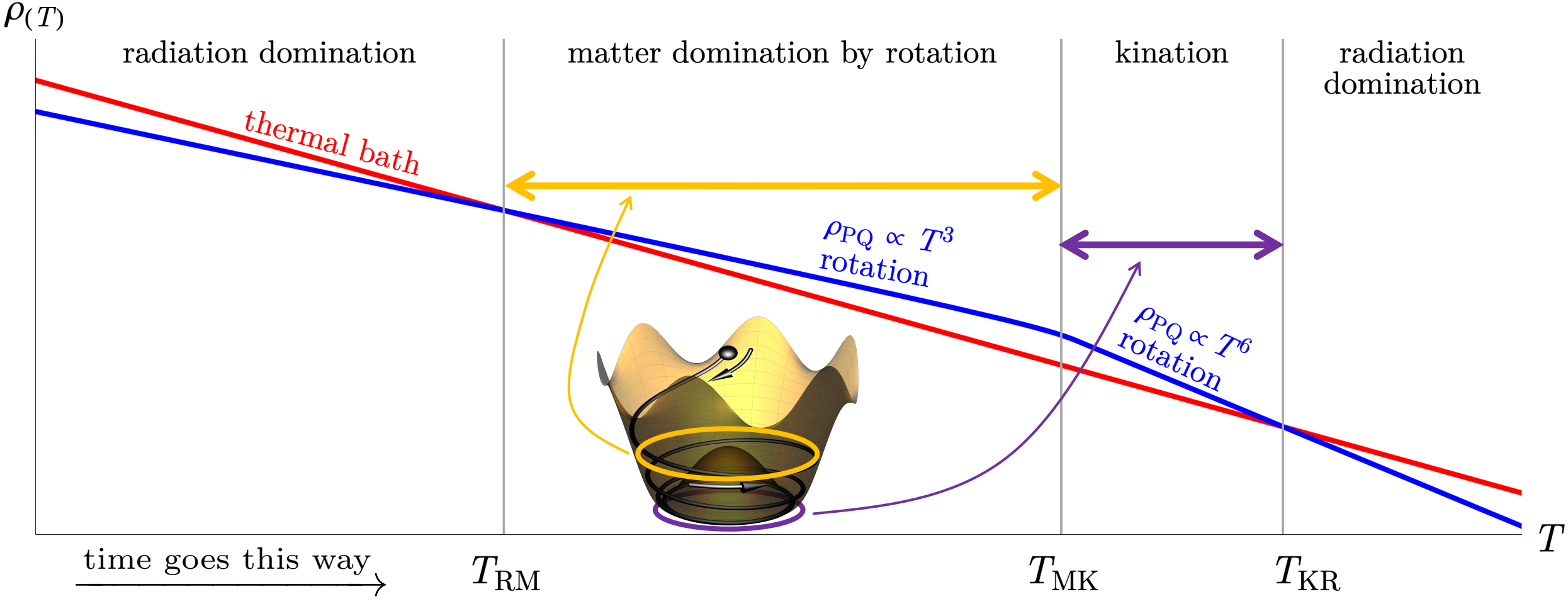
$$\rho_\theta = \dot{\theta}^2 f_a^2 \propto R^{-6}$$

kination



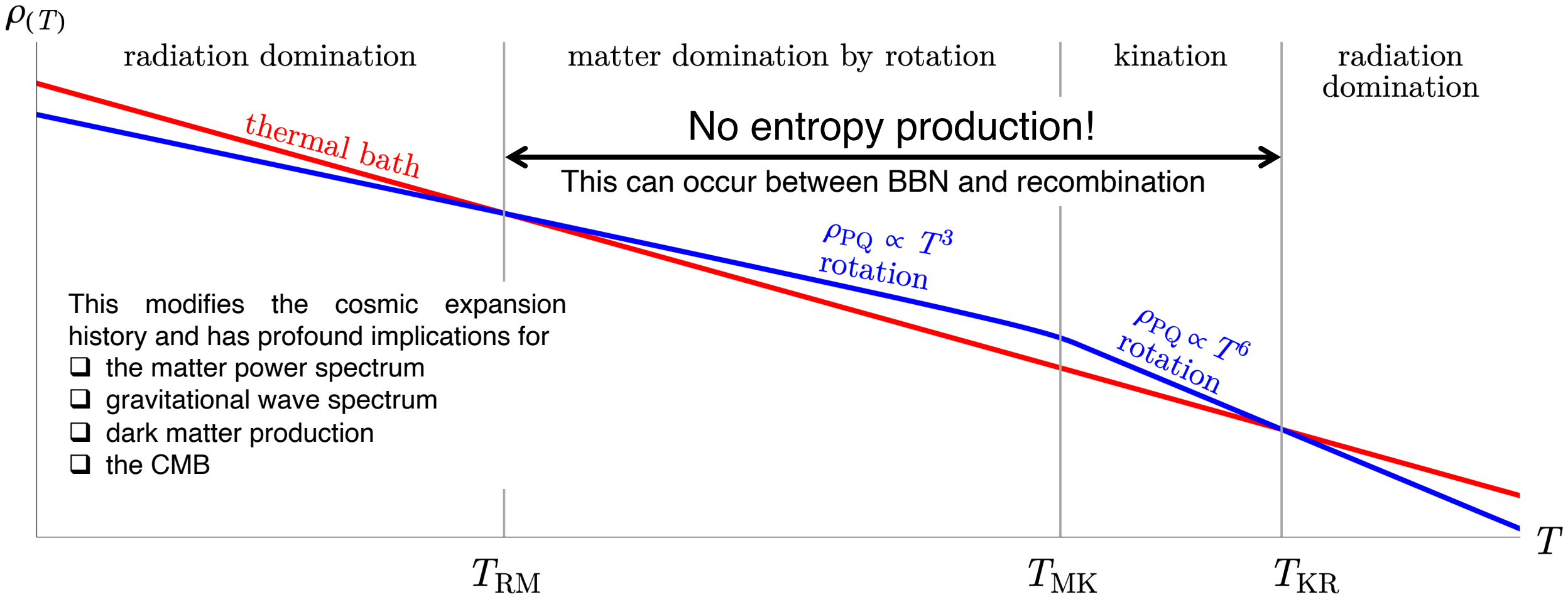
PRL 124, 111602 (2020) RC and K. Harigaya

Axion Rotations



2405.12268 RC, N. Fernandez, A. Ghalsasi, K. Harigaya, and J. Shelton

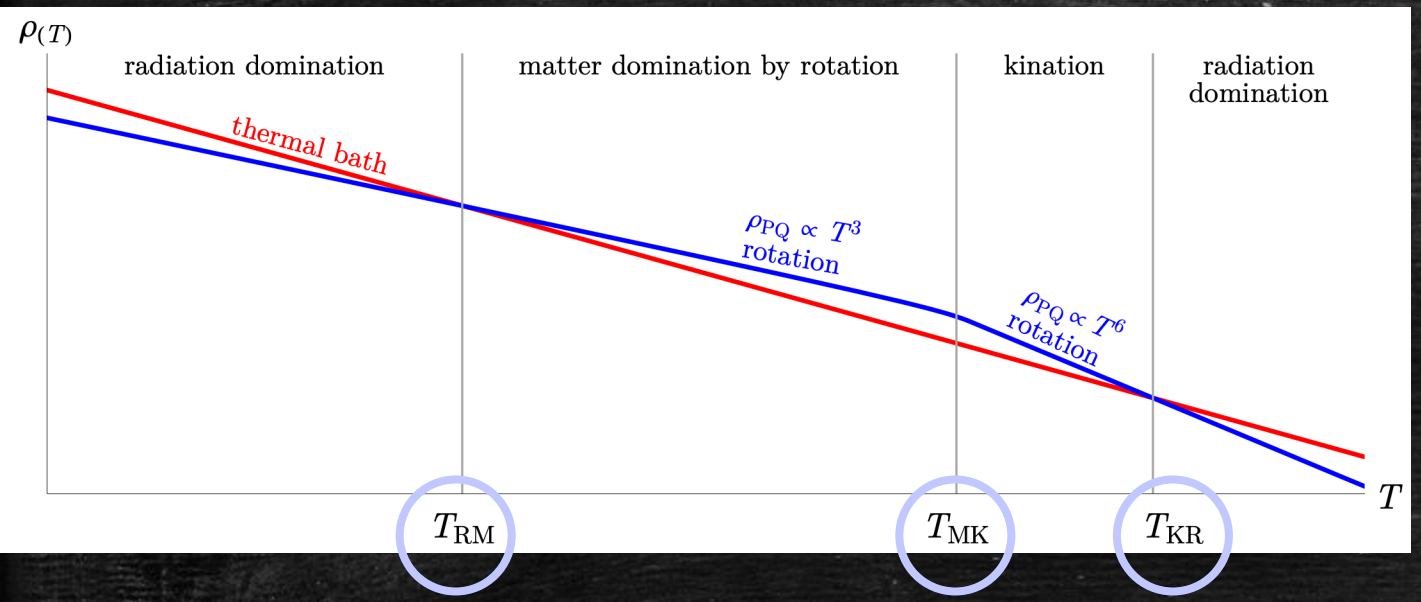
Evolution of Energy Densities



This modifies the cosmic expansion history and has profound implications for

- ❑ the matter power spectrum
- ❑ gravitational wave spectrum
- ❑ dark matter production
- ❑ the CMB

Relevant Temperatures



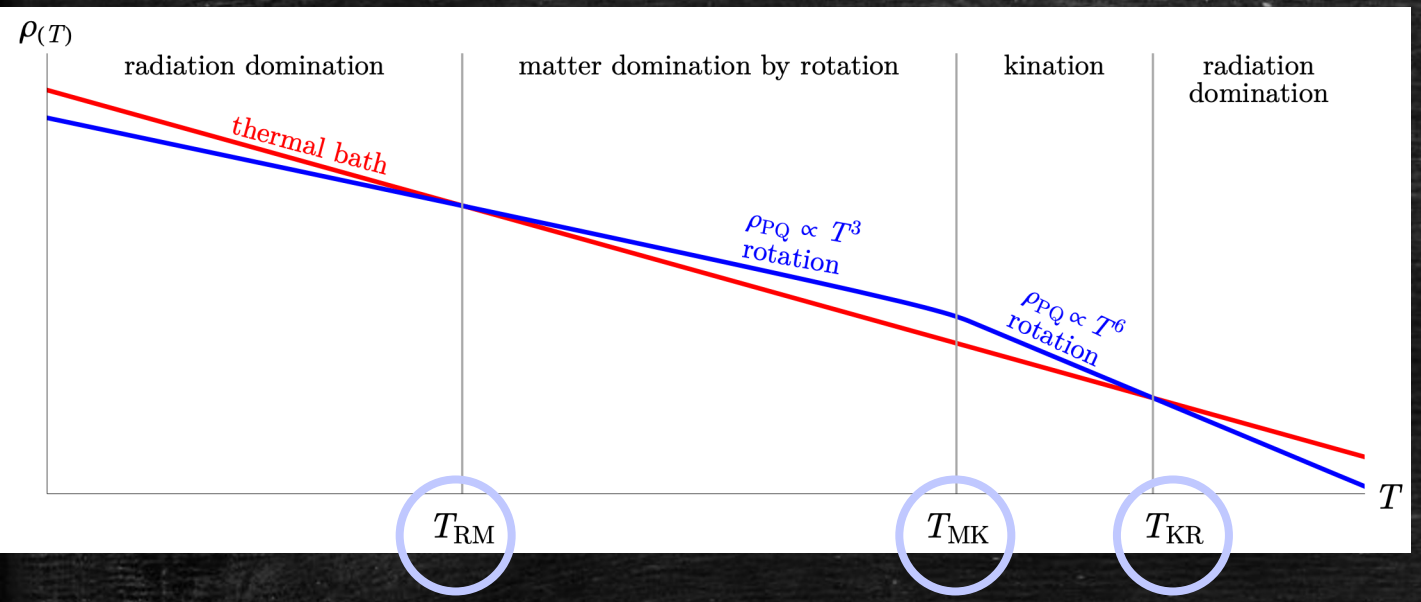
$$T_{\rm RM} = 400\ {\rm TeV}\ \frac{\beta}{0.005}\left(\frac{f_a/c_\gamma}{2\times 10^9\ {\rm GeV}}\right)^2 \frac{0.1}{|c_B/c_\gamma|}$$

$$T_{\rm MK} = 2.2\ {\rm GeV}\left(\frac{0.005}{\beta}\right)^{1/3}\left(\frac{0.1}{|c_B/c_\gamma|}\right)^{1/3}\left(\frac{80}{g_*}\right)^{1/3}$$

$$T_{\rm KR} = 20\ {\rm MeV}\ \frac{0.005}{\beta}\ \frac{2\times 10^9\ {\rm GeV}}{f_a/c_\gamma}\left(\frac{10}{g_*}\right)^{1/2}$$

2609.25202 RC, Lawrence Hall, Keisuke Harigaya, and Taegyu Lee

Relevant Temperatures



This model on f_a is falsifiable by future astrophysical probes 2211.05136

$$g_{\phi\gamma\gamma} > 7.3 \times 10^{-14}\ \text{GeV}^{-1}$$

$$T_{\rm KR} > T_{\rm BBN} \simeq 2.5\ \text{MeV}$$

2108.09299 JHEP 09 (2022) 116 RC, D. Dunsky, N. Fernandez, A. Ghalsasi, L. Hall, K. Harigaya, J. Shelton

$$T_{\rm KR} = 20\ \text{MeV}\ \frac{0.005}{\beta}\ \frac{2 \times 10^9\ \text{GeV}}{f_a/c_\gamma}\left(\frac{10}{g_*}\right)^{1/2}$$

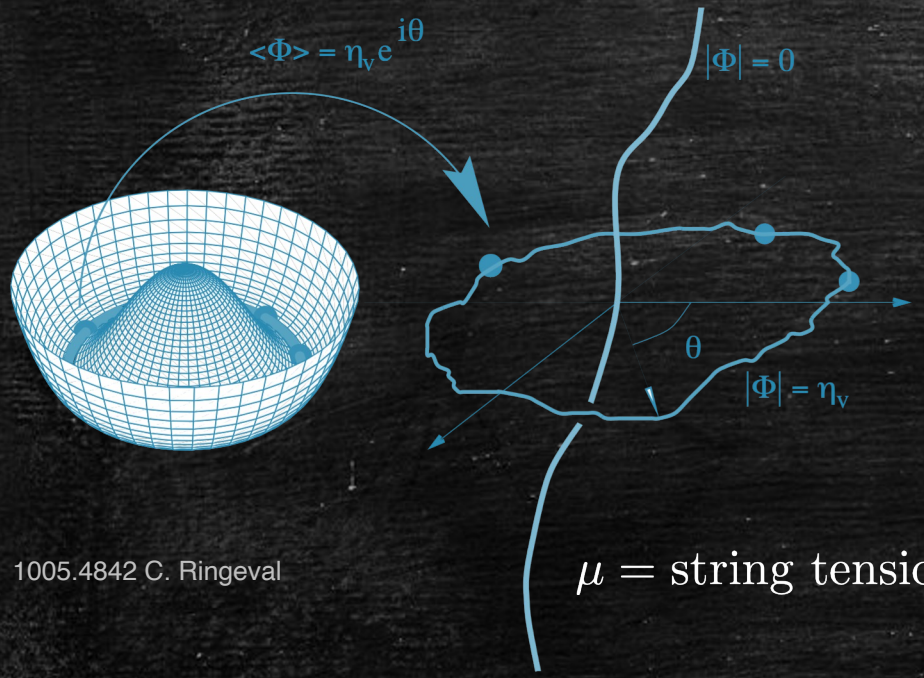
2609.25202 RC, Lawrence Hall, Keisuke Harigaya, and Taegyu Lee

Axion Kination

Gravitational Waves

Gravitational Waves from Cosmic Strings

Gauge symmetry breaking



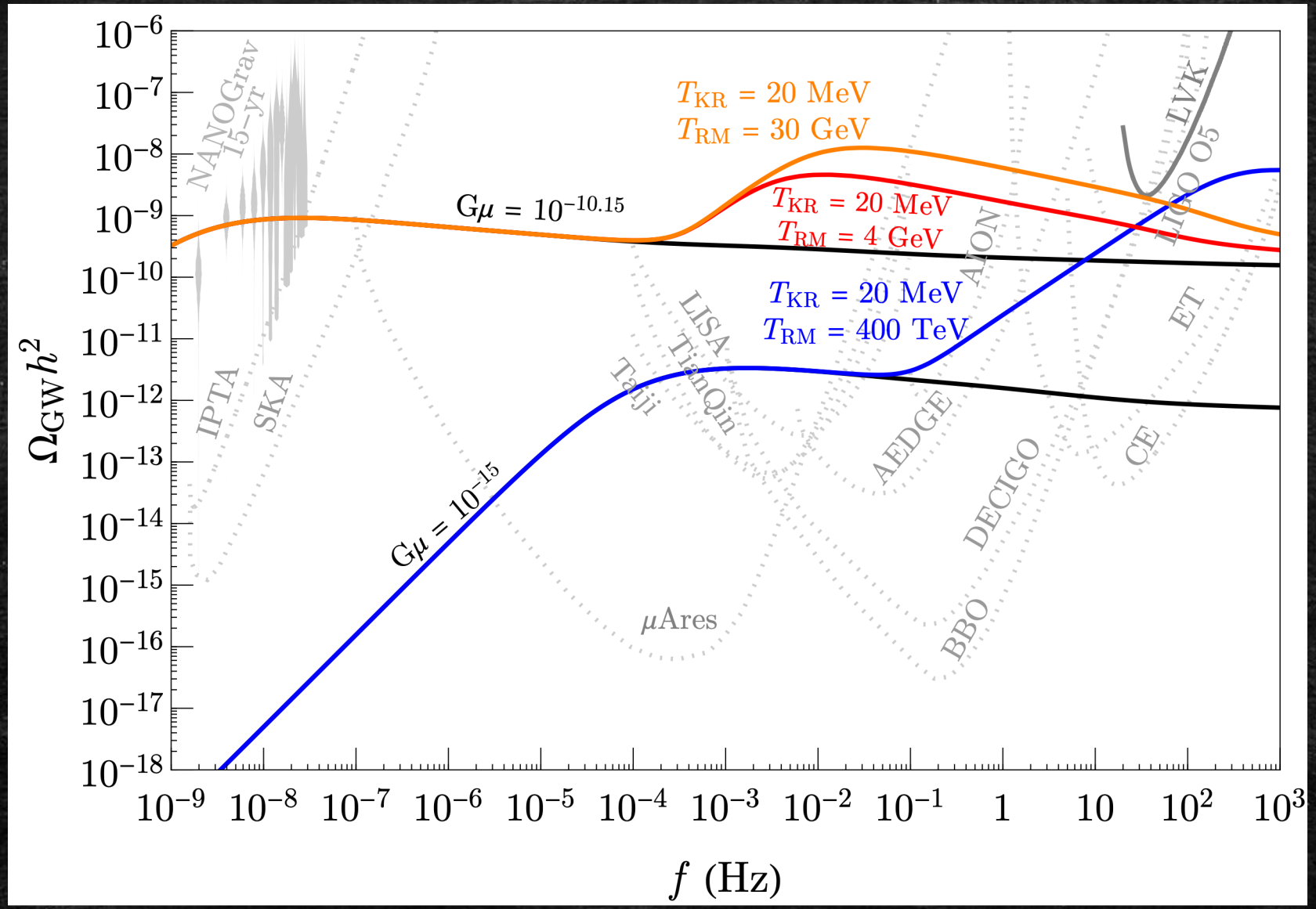
1005.4842 C. Ringeval

$\mu =$ string tension

Loop formation era

Loop decay 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

Gravitational Waves from Cosmic Strings



Gravitational Waves from Inflation

The origin is the quantum fluctuations during inflation.

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

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

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

Gravitational Waves from Inflation

The origin is the quantum fluctuations during inflation.

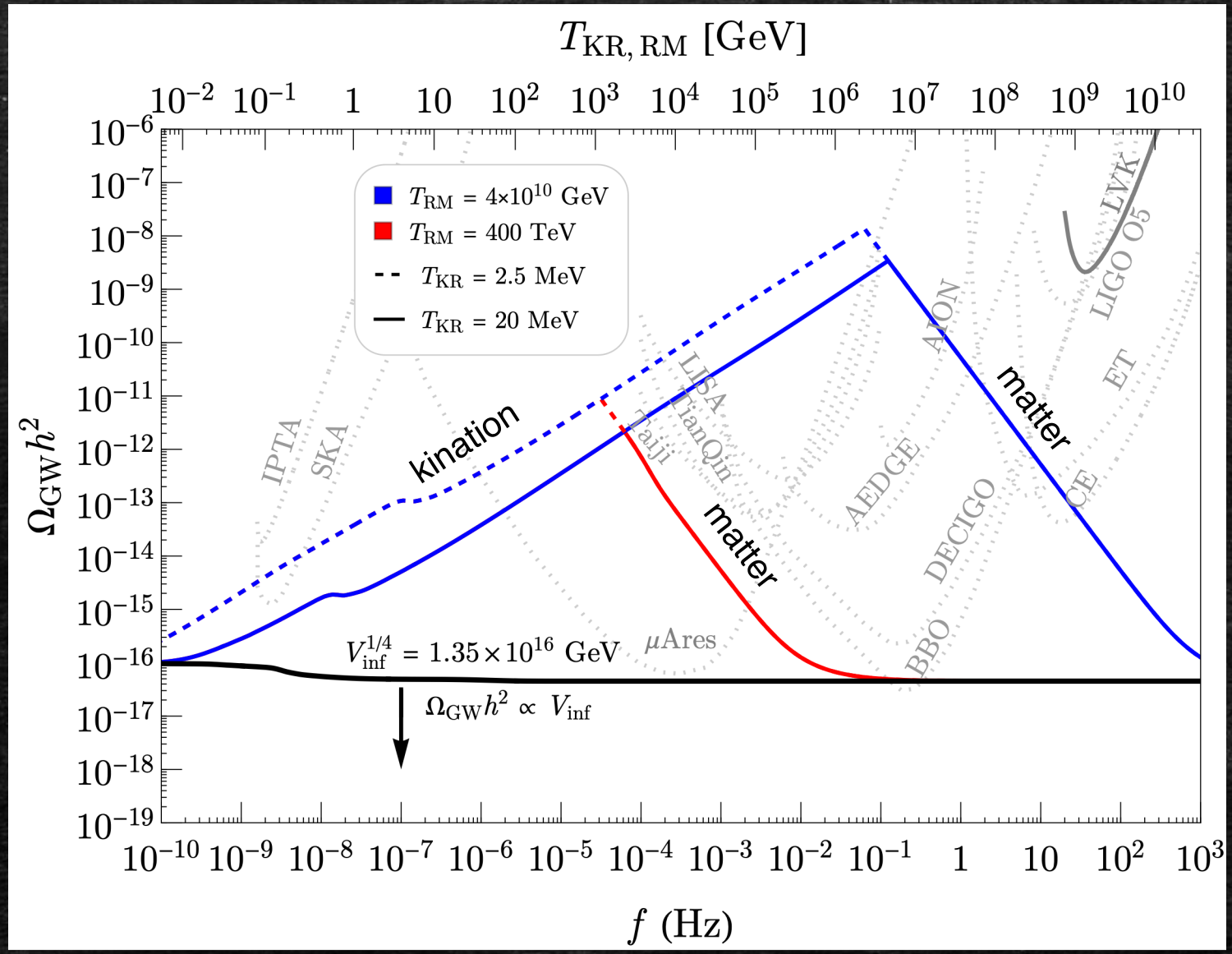
The horizon crossing, $k = H$, determines the onset of mode evolutions.

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

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

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

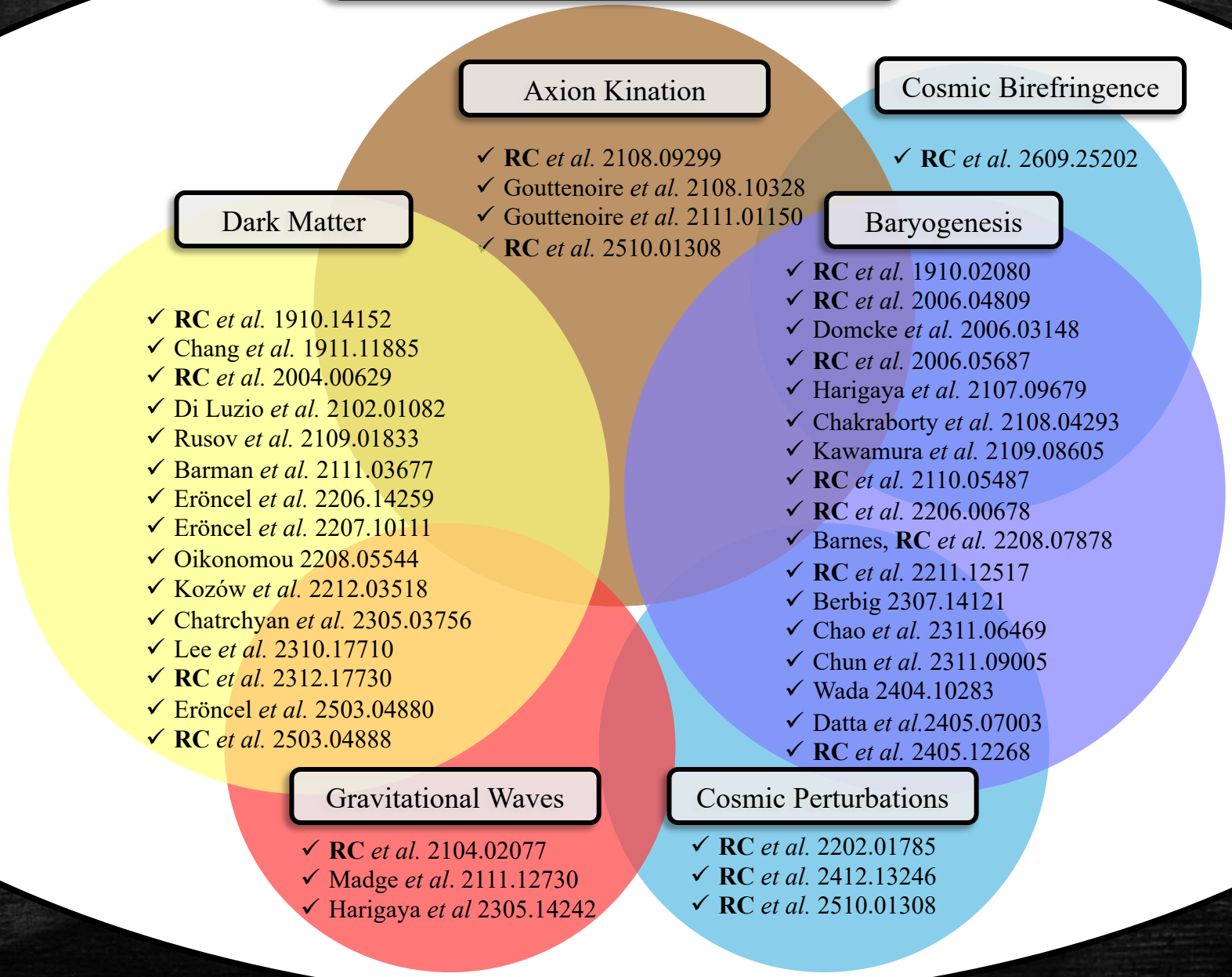
Smoking Gun: Triangular Peak in Gravitational Wave Spectra



2108.09299 JHEP 09 (2022) 116 RC, D. Dunsky, N. Fernandez, A. Ghalsasi, L. Hall, K. Harigaya, J. Shelton

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

Axion Rotations



2027 Particle Physics and Cosmology Conference

5/17-5/21

Indiana University Bloomington



PPC 2027: XX International Conference on Interconnections between Particle Physics and Cosmology

https://indico.global/event/18862/

Conclusions

- ✓ Axion rotation can explain
  - cosmic birefringence
  - baryon asymmetry
- ✓ Axion kination enhances Hubble rate and predicts
  - ✓ a minimum falsifiable axion-photon coupling
  - ✓ enhanced gravitational wave spectra
- ✓ The same axion dynamics may also explain
  - ✓ dark matter
- ✓ Other possible signatures include
  - ✓ anisotropic cosmic birefringence
  - ✓ ℓ-dependent cosmic birefringence angle
  - ✓ enhanced matter power spectrum
- ✓ New model building opportunities
  - ✓ other open questions across disciplines

