Cosmic Birefringence

and its Implications for Axion Phenomenology

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Outline

1. What is the cosmic birefringence and how it has been measured?
2. What are the current constraints for the usual parameter space of axion-like particles?
3. New implications for axion quintessence in string theory?

Cosmic Birefringence

The Universe filled with a "Birefringence Material" :
If the Universe is filled with a pseudo-scalar field (e.g., an axion field) coupled to the electromagnetic tensor via a Chern-Simons coupling:

Turner & Widrow (1988)

the effective Lagrangian for axion electrodynamics is

Chern-Simons term

$$\mathcal{L} = -\tfrac{1}{2}\partial_\mu\theta\partial^\mu\theta - \tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} + \boxed{g_a\theta F_{\mu\nu}\tilde{F}^{\mu\nu}}, \qquad (3.7)$$

$$\tilde{F}^{\mu\nu} = \sum_{\alpha\beta}\frac{\epsilon^{\mu\nu\alpha\beta}}{2\sqrt{-g}}F_{\alpha\beta}$$

where g_a is a coupling constant of the order α, and the vacuum angle $\theta = \phi_a/f_a$ (ϕ_a = axion field). The equations

- $\phi F_{\mu\nu}\tilde{F}^{\mu\nu} = -(\partial_\mu\phi)2A_\mu\tilde{F}^{\mu\nu}$ **Derivative coupling**
- $F_{\mu\nu}F^{\mu\nu} = 2(\vec{B}\cdot\vec{B} - \vec{E}\cdot\vec{E})$ **Parity even**
- $F_{\mu\nu}\tilde{F}^{\mu\nu} = 4\vec{E}\cdot\vec{B}$ **Parity odd**

Modified Electrodynamics

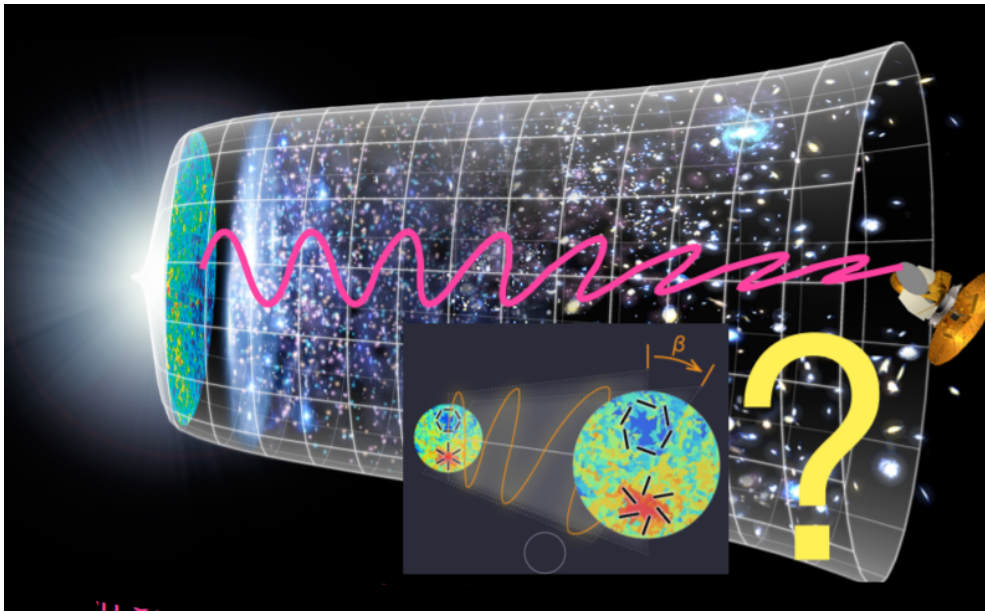
How does the propagation of EM wave is affected?

E.O.M for the vector potential, with homogeneous scalar field $\phi = \phi(\eta)$, in Fourier space:

$$A''_{\pm}(\eta,k) + \underbrace{k^2\left(1 \pm \frac{g_{\phi\gamma}\phi'}{k}\right)}_{\omega_{\pm}^2} A_{\pm}(\eta,k) = 0$$

left- and right- handed waves travel at **different speed**. The modification is **frequency independent**!

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

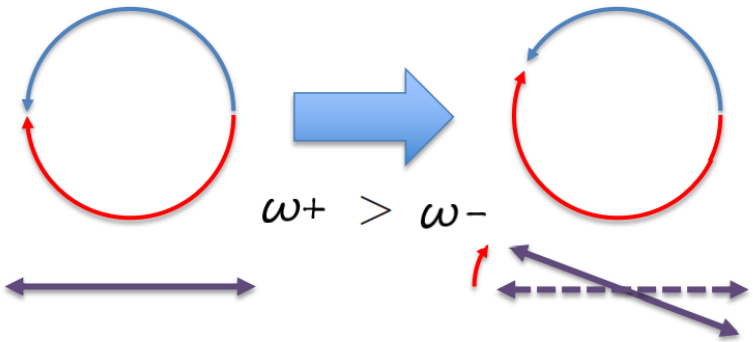


Rotation of the polarization plane as the EM wave propagates
Credit: Y. Minami and E. Komatsu

Detectable effect

Polarization direction rotates:

$$\beta = \frac{g_{\phi\gamma}}{2}\int_{t_{em}}^{t_{obs}} \mathrm{d}t\dot{\phi} = \\ = \frac{g_{\phi\gamma}}{2}(\phi_{obs} - \phi_{em})(\hat{n})$$



Left-handed component arrives before than righ-handed one.

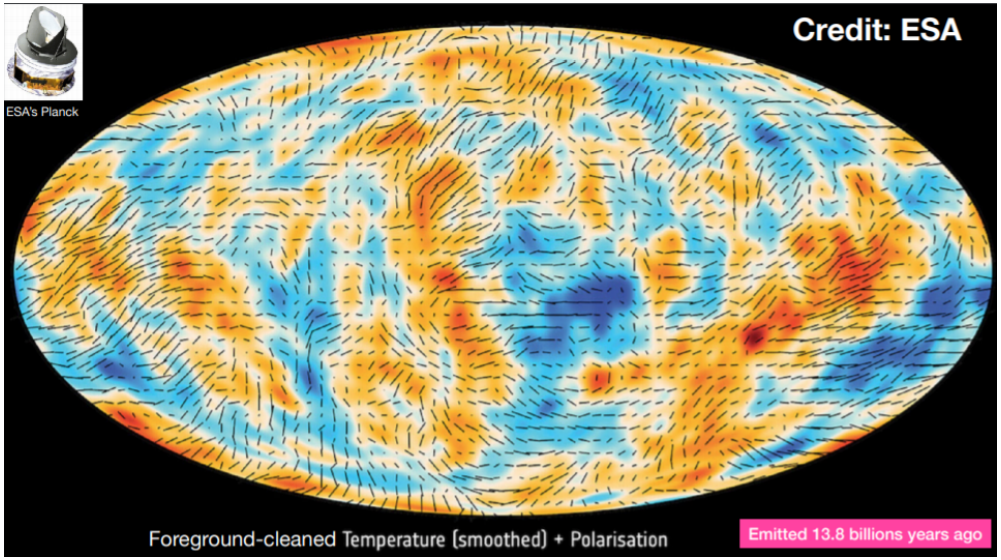
What do we need to detect the signal?

- Linearly polarized light;
- Relation between the polarization at the emission and detection time.

At first: Radio galaxies and quasars

Carroll, Field & Jackiw(1990); Harari & Sikivie (1992); Carroll (1998)

Using CMB Polarization



CMB is a perfect target:

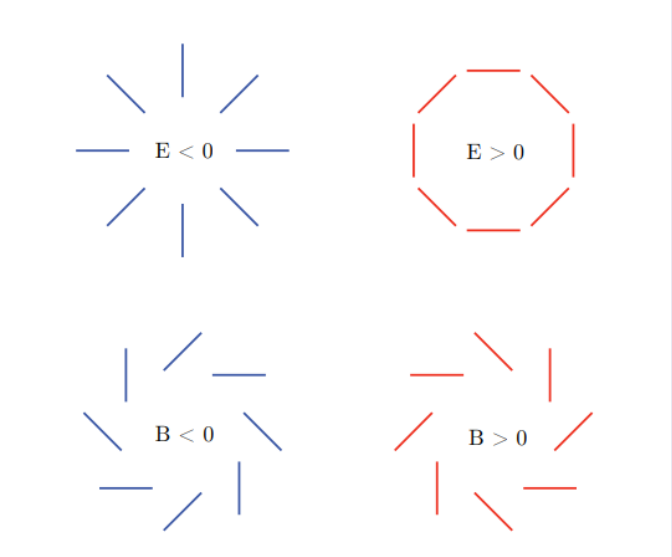
- Polarization pattern decomposed into:
  - *E-mode*: sound waves
  - *B-mode*: gravitational lensing and gravitational waves

  Seljak & Zaldarriaga (1997); Kamionisky, Kosowsky & Stebbins (1997)
- Photons emitted 13.8 billion years ago $\Longrightarrow$ bigger birefringence effect (axion quintessence)

  Lue, Wang & Kamioniski (1997); Feng et al. (2005,2006); Liu, Lee & Ng (2006)

E- and B-modes and cross correlations

Under Parity Flip:



- E-mode: parity even
- B-mode parity odd

- In the standard scenario only parity-even correlation functions are non zero $\Longrightarrow$ $C_l^{EE}, C_l^{BB}, C_l^{TE}$ power spectra;
- If polarization undergoes a rotation, the observed E- and B-modes are related to the intrinsic ones:

$$E^o_{l,m} = E_{l,m}\cos(2\beta) - B_{l,m}\sin(2\beta)$$
$$B^o_{l,m} = E_{l,m}\sin(2\beta) + B_{l,m}\cos(2\beta)$$

- This leads to a non-zero parity-odd cross-correlations $\langle EB \rangle$ and $\langle TB \rangle$ $\Longrightarrow$ hint of **parity-violating physics**

Seljak & Zaldarriaga (1997); Kamionisky, Kosowsky & Stebbins (1997)

General birefringence angle

$$\beta(\hat{n}) = \frac{g_{\phi\gamma}}{2}(\Delta\bar{\phi} + \Delta\delta\phi(\hat{n}))$$

$$\Delta\bar{\phi} = \bar{\phi}_{obs} - \bar{\phi}_{lss} \qquad \Delta\delta\phi(\hat{n}) = \delta\phi_{obs} - \delta\phi_{lss}(\hat{n})$$

- **Background evolution** $\Delta\bar{\phi}$: homogeneous and isotropic rotation (Dark Matter or Dark Energy)
- **Fluctuations** $\Delta\delta\phi(\hat{n})$: spatial dependence (e.g. isocurvature fluactations)

Homogeneous rotation leads to:

$$C_l^{EB,obs} = \frac{1}{2}\sin(4\beta)(C_l^{EE} - C_l^{BB}) + C_l^{EB}\cos(4\beta)$$

Lue, Wang & Kamioniski (1997); Feng et al. (2005,2006); Liu, Lee & Ng (2006)

Key Idea of the Recent Measurement

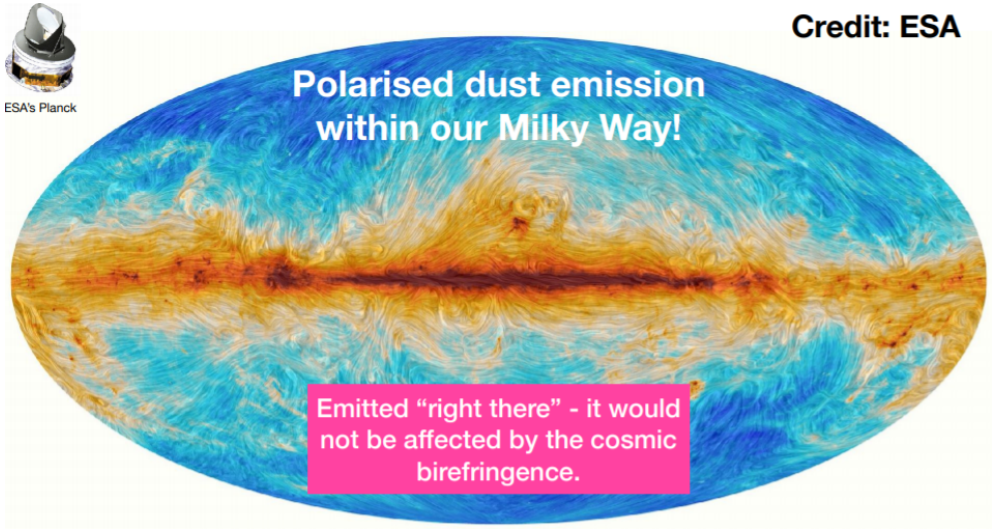
Credit: Y. Minami and E. Komatsu

Is the potential signal cosmic or instrumental?

- **Biggest problem:** miscalibration of polarization-sensitive detectors respects the sky coordinates $\Longrightarrow$ only $\alpha + \beta$ can be measured.
- **New Idea**: Use the foreground emission of the Milky way as calibrator at different frequencies. Minami et al. 2019, Minami & Komatsu (2020)

Motivation:

- α_ν affects both CMB and Milky Way;
- β affects only CMB and is frequency independent.



$$E^o_{l,m} = E^{\rm fg}_{l,m}\cos(2\alpha) - B^{\rm fg}_{l,m}\sin(2\alpha) + E^{\rm CMB}_{l,m}\cos(2\alpha+2\beta) - B^{\rm CMB}_{l,m}\sin(2\alpha+2\beta)$$

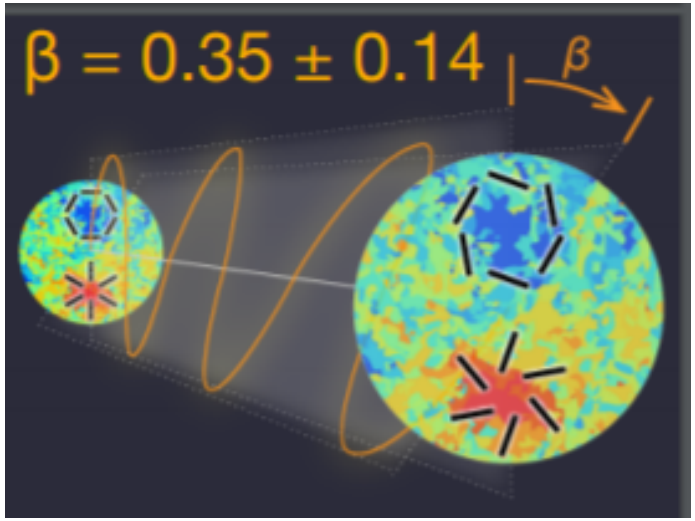
$$B^o_{l,m} = E^{\rm fg}_{l,m}\sin(2\alpha) + B^{\rm fg}_{l,m}\cos(2\alpha) + E^{\rm CMB}_{l,m}\sin(2\alpha+2\beta) + B^{\rm CMB}_{l,m}\cos(2\alpha+2\beta)$$

α_ν and β can be estimated simultaneously from Planck data using a multi-frequency likelihood, for the single frequency and full sky data case:

$$-2\ln\mathcal{L} = \sum_{l=2}^{l_{max}} \frac{\left[C_l^{EB,o} - \frac{1}{2}\tan(4\alpha)(C_l^{EE,o} - C_l^{BB,o}) - \frac{\sin 4\beta}{2\cos 4\alpha}(C_l^{EE,\rm CMB} - C_l^{BB,\rm CMB})\right]^2}{\mathrm{Var}\left(C_l^{EB,o} - \frac{1}{2}\tan(4\alpha)(C_l^{EE,o} - C_l^{BB,o})\right)}$$

Minami et al. 2019, Minami & Komatsu (2020)

Final Result



Credit:Y.Minami (KEK)

Conclusion:

$\beta = 0.35 \pm 0.14 \quad$ deg (68 % CL)

Excluded null result at 99.2%

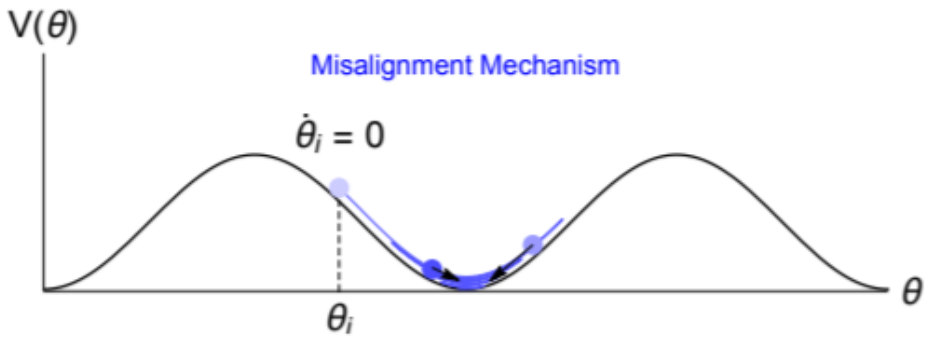
Implications for axion models of dark matter or dark energy, using the result that β is originated by:

$$\beta = \frac{g_{\phi\gamma}}{2}(\bar{\phi}_{obs} - \bar{\phi}_{lss})$$

It depends on the evolution of the background field!

Standard Scenario of Cosmological Axion

What are the initial conditions for the cosmological axion field?



Credit: R. T. Co, L.J. Hall

- Instantons give a periodic potential to the axion field

$$V = m_a^2 f_a^2 \left[\cos\left(\frac{\phi}{f_a}\right) - 1 \right]$$

- Axion takes a random initial value within $\frac{\phi_i}{f_a} = \theta_i \subseteq [-\pi, \pi]$.

If this happens before or during inflation, the whole observable universe comes from a single domain $\implies$ axion field has the same value over all the sky

M. Dine & W.Fischler(1982), P. Arias et al. (2012),

Background Evolution

In quadratic approximation, the field evolves according to:

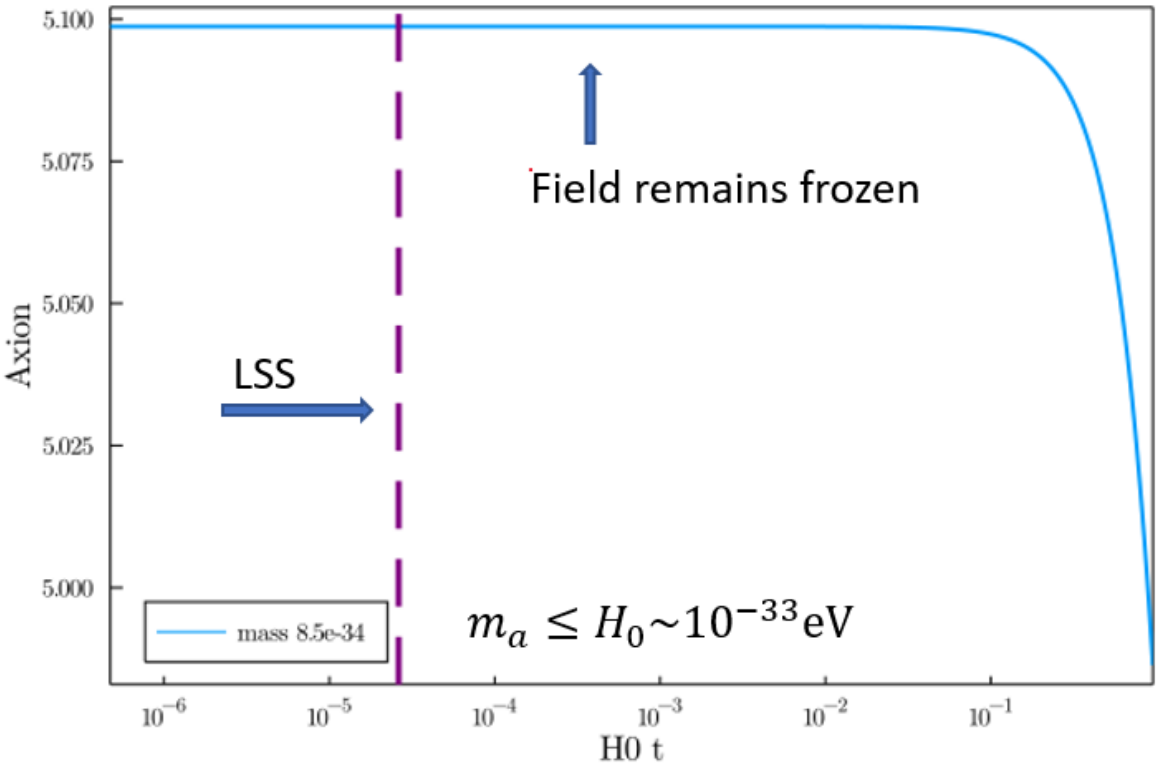
$$\ddot{\phi} + 3H\dot{\phi} + m_a^2\phi = 0$$

There are two main behaviors:

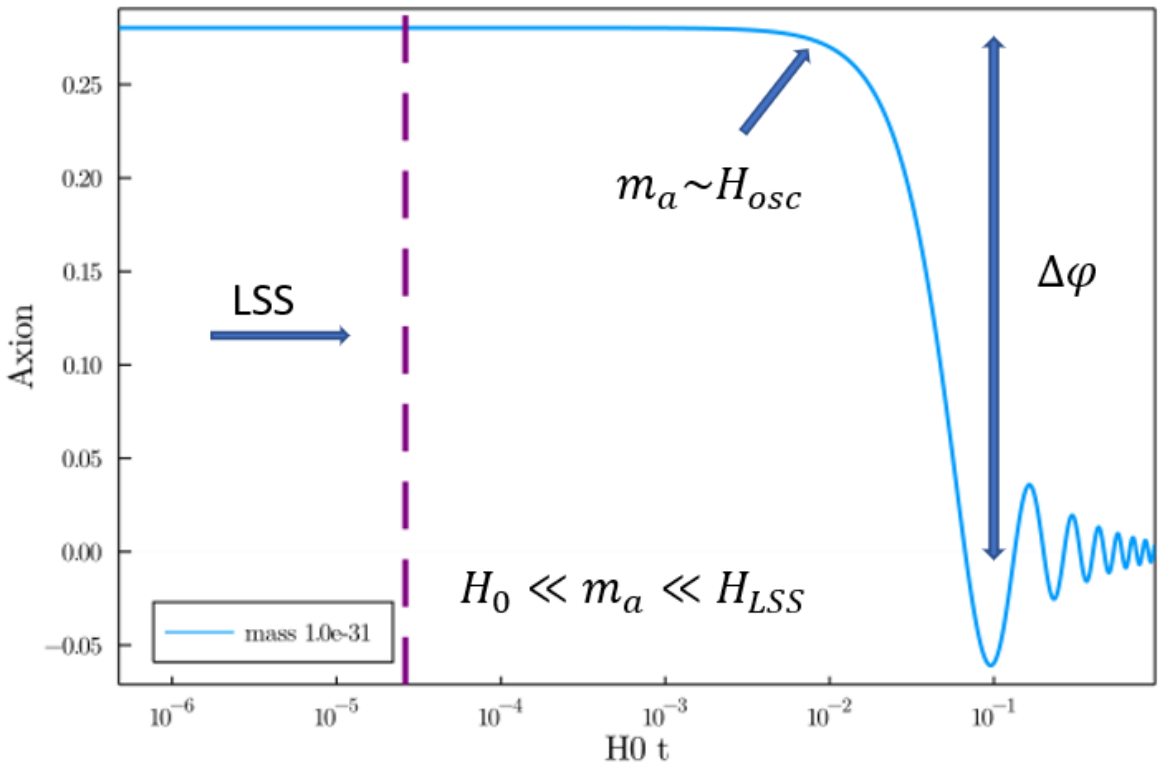
- **Dark energy**: the field is frozen by Hubble term;
- **Dark matter**: field starts oscillating around $m \sim H$ and later energy density dissipates as normal matter.

The field displacement $\Delta\phi = (\bar{\phi}_{obs} - \bar{\phi}_{lss})$ depends when the oscillation starts from LSS until now.

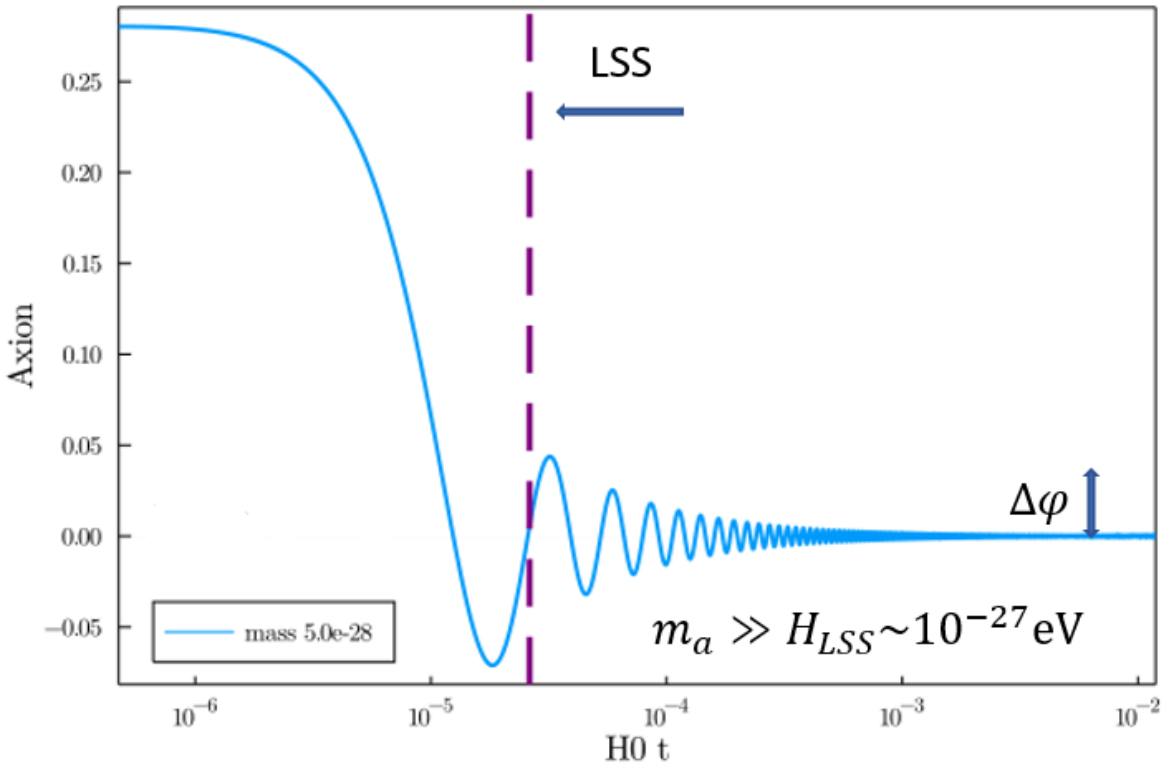
Background Evolution



Background Evolution

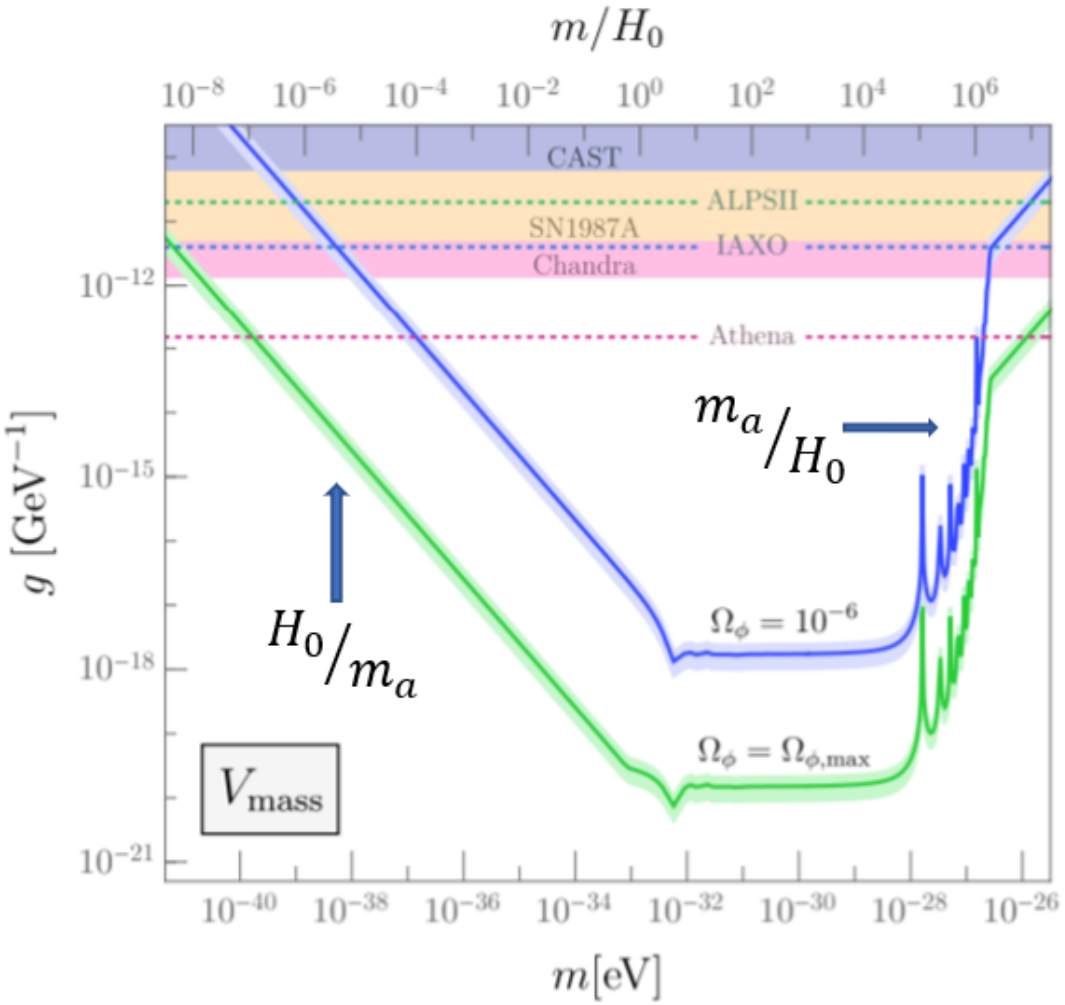


Background Evolution



Implications for Quadratic Potential

T. Fujita et al. (2020)



Axion Quintessence

Many models: J. E. Kim (1998), K.Choi(1999), Y.Nomura (2000),Kim & Nills(2002)...

Consequences of shift symmetry:

- Couplings with matter fields are naturally suppressed $\beta_i \frac{\phi}{f_a} \mathcal{L}_{int}$;
- Potential from non-perturbative physics $V = \mu^4 \cos\left(\frac{\phi}{f_a}\right)$, $\rho_\Lambda \sim (10^{-3}\text{eV})^4$:
  - small breaking $\mu^4 \sim e^{-S_{ins}}$
  - symmetry can protect the flatness of the potential
    J. Frieman et al. (1995), C.Kolda & D.H. Lyth (1998)

Difficulties:

- Slow-roll conditions:

$$\left(\frac{V''}{V}\right) M_{PL}^2 \ll 1 \implies f_a \gg M_{PL} \text{ but } f_a \leq \frac{M_{Pl}}{S_{ins}}$$

P.Svreck & E. Witten (2006), N. Arkani-Hamed et al. (2006)

- Severe fine tuning on the top of the potential
  N. Kaloper & L. Sorbo(2005)

Axion Quintessence in String Theory

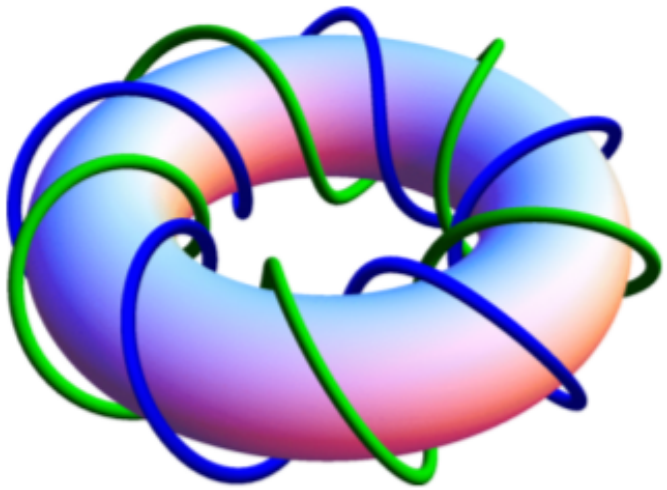
Ways out within String Theory:

- Multiple axions: $N \gtrsim 10^4 - 10^5$ — P. Svrecek (2006)
- Two axions model — J.Kim et al. (2004), I.Obata (2021)
- **MONODROMY**

Breaking of shift symmetry:
presence of **WRAPPED BRANES**

Monodromy effect studied in type II B String Theory, initially proposed for large field inflation

L. McAllister et al. (2008),E. Silverstein & A. Westphal (2008), R.Flauger et al. (2009)



Credit: Deanna C. Hooper

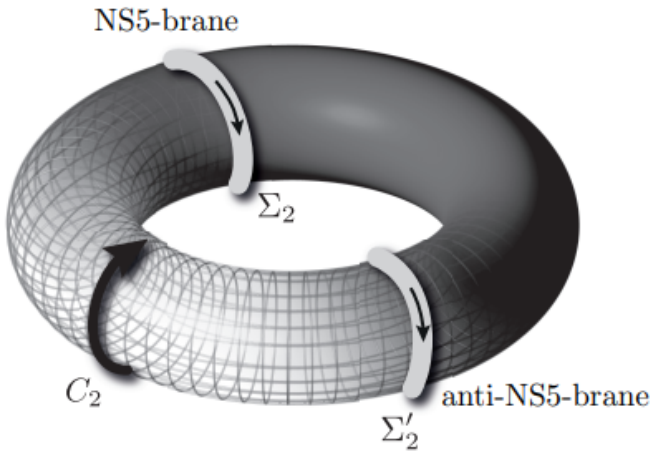
Axion Potential from Monodromy

Monodromic Quintessence S.Panda, Y.Sumitomo & S.Trivedi

We can use the idea of axion monodromy to construct a successful model for Quintessence.

Ingredients:

- Axion coming from zero-mode of C_2 RR field $a = \frac{1}{\alpha'} \int_{\Sigma_2} C_2$
- $NS5$ brane and anti-brane in a highly warped throats



Credit:D. Baumann and L. McAllister

The shift symmetry is broken by the interplay of axion and branes.
The potential comes from the DBI action of the wrapped brane:

$$V = \frac{2e^{4A_0}}{(2\pi)^5 g_s^2 \alpha'^2} \sqrt{L^4 + g_s^2 a^2} \xrightarrow{a \gg L^2/g_s} \boxed{V = \frac{\mu^4}{f_a}\phi}$$

$$\phi = f_a a \quad \text{with} \quad f_a/M_{Pl} = g_s/(\sqrt{6}L^2)$$

Quintessence Requirements

- **Slow-roll condition:**

$$\left(\frac{V''}{V}\right) M_p^2 \ll 1 \implies \boxed{\phi \gg M_{Pl}}$$

No problem: The field range is not bounded from above.

- **Energy scale:**

$$V = \mu^4 a \sim (10^{-3}\text{eV})^4$$
$$\implies \mu^4 \propto e^{4A_0} \sim 10^{-120}$$

e^{4A_0} is the warped factor at the bottom of the throat, it can be exponentially small.

M. C. Escher

Monodromy extends the allowed values of the field compared to the periodic potential!

Coupling with Electromagnetism

A potential interaction with electromagnetic field can arise from the coupling:

$$\int C_2 \wedge F \wedge F \rightarrow a \int F \wedge F \quad \text{Chern-Simons}$$

We are interested in studying the cosmic birefringence induced by axion monodromy quintessence.

Important points:

- There is NO MASS in the potential, therefore the dynamics only depends on the **first derivative**, e.g. **"s" for slope**.
- The field must respect the current bounds on the equation of state Planck 2018 data requires $\omega_\phi \leq -0.95$.

We define:

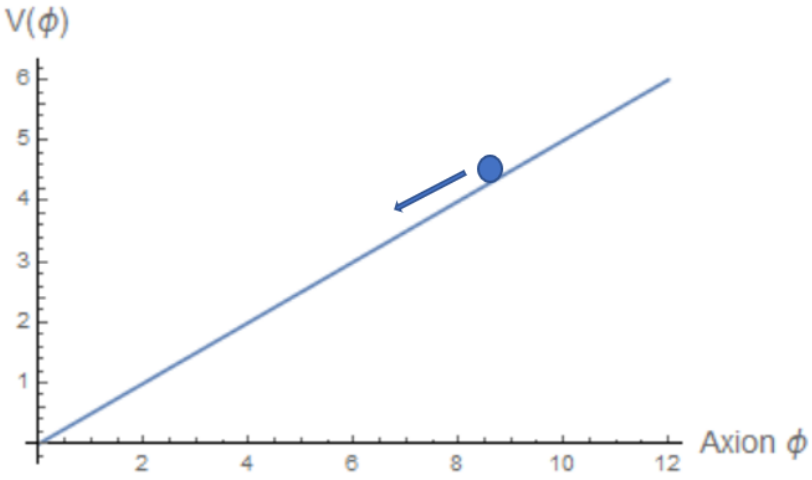
$$\Omega_\phi \simeq s\phi \text{ where } s = \frac{\mu^4/f_a}{3M_{Pl}H_0^2} = \frac{\mu^4 M_{Pl}/f_a}{\rho_c}$$

Field Displacement

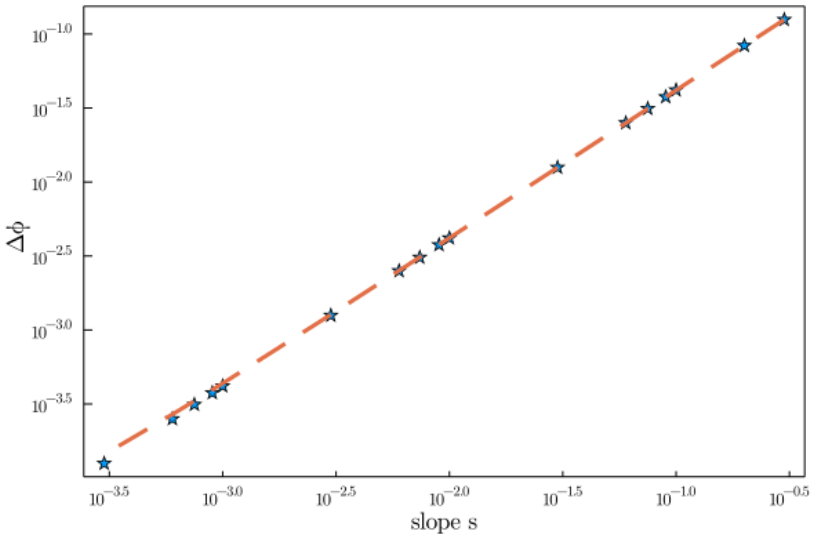
Field evolves according to :

$$\phi_n'' + 3\mathcal{H}\phi_n' + 3s = 0$$

with $\tau = H_0 t$
$\phi_n = \phi/M_{Pl}$, $\mathcal{H} = H/H_0$



Rolling of axion in a linear potential



Field displacement vs slope s

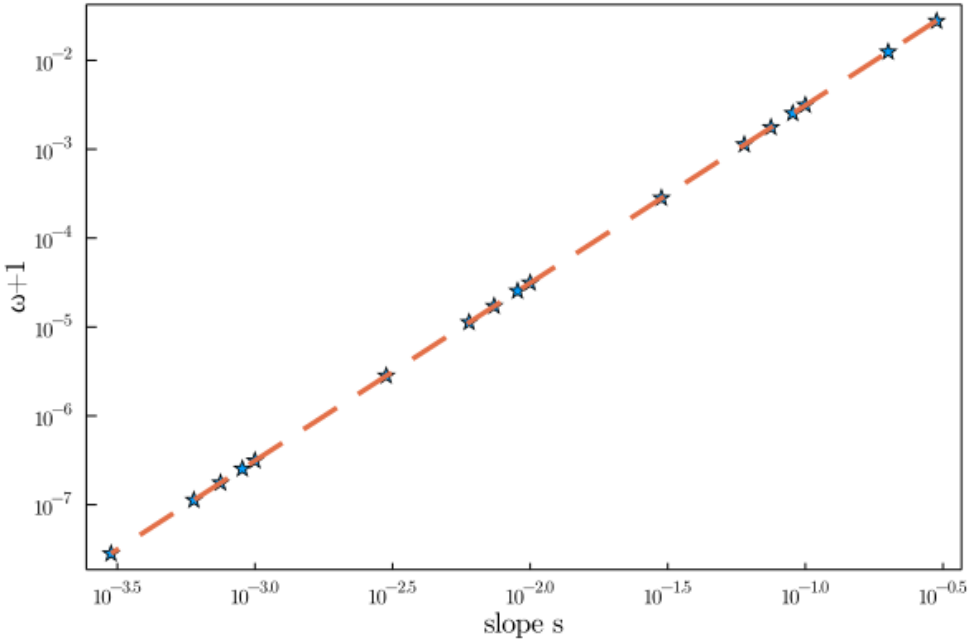
The field displacement depends linearly on s, e.g. the flatness of the potential.

$$\Delta\phi = (\phi_{lss} - \phi_0) = 0.416s$$

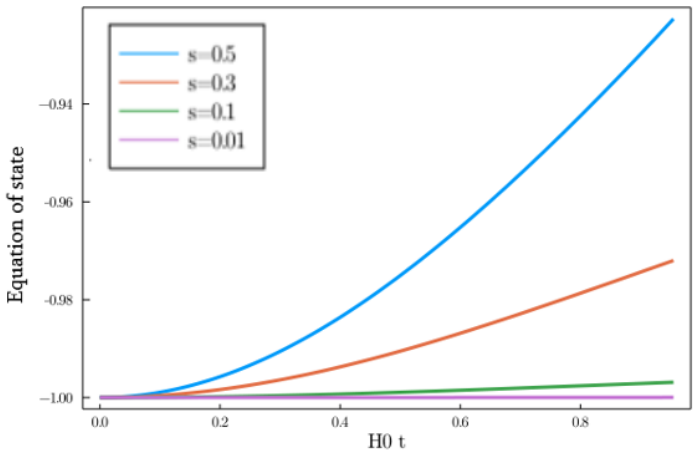
Equation of State

The e.o.s. is initially frozen at $\omega_\phi = -1$ and then it goes off with a rate that depends on s^2

" *Thawing model*"



Equation of state vs slope



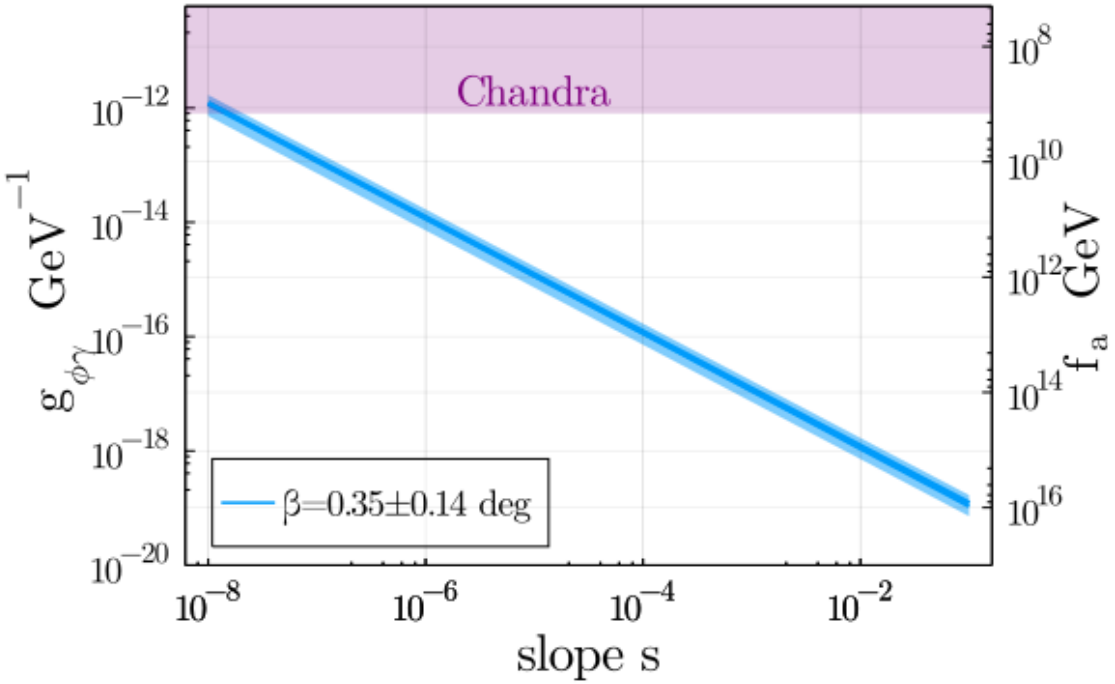
Evolution of the equation of state for different s

The final equation of state follows:

$$\omega_\phi + 1 = 0.31\left(\frac{\Omega_\Lambda}{\Omega_\phi}\right)s^2$$

$$\Longrightarrow \quad s \leq 0.4$$

Constraints from Cosmic Birefringence



$$g_{\phi\gamma} = 3 \times 10^{-20}\mathrm{GeV}^{-1}\left(\frac{|\beta|}{0.35\mathrm{deg}}\right)\left(\frac{0.4}{s}\right)$$

Bound on axion-photon coupling from Chandra X-ray observatories (C. S. Reynolds et al. (2020))

$$g_{\phi\gamma} \leq 6 - 8 \times 10^{-13}\mathrm{GeV}^{-1} \implies s \gtrsim 1.5 \times 10^{-8}$$

Implications from Cosmic Birefringence

Putting together:

- Relation between coupling and slope $g_{\phi\gamma} \propto s^{-1}$
- Relation between coupling and decay constant $g_{\phi\gamma} = \frac{\alpha_{em}}{2\pi} \frac{c_{\gamma\phi}}{f_a}$

The birefringence angle provides a link between the first derivative of the potential and the decay constant:

$$\frac{f_a}{c_{\gamma\phi}} = 3.8 \times 10^{16}\text{GeV}\left(\frac{0.35\text{deg}}{|\beta|}\right)\left(\frac{s}{0.4}\right).$$

Or, equivalently, between the DE equation of state and f_a:

$$\frac{f_a}{c_{\gamma\phi}} = 3.8 \times 10^{16}\text{GeV}\left(\frac{0.35\text{deg}}{|\beta|}\right)\left(\frac{\omega_\phi + 1}{0.05}\right)^{\frac{1}{2}}$$

Constraints from Cosmic Birefringence

Upper bound for the decay constant:

$$s \leq 0.4 \implies \boxed{\frac{f_a}{c_{\gamma\phi}} \leq 3.8 \times 10^{16}\text{GeV}}$$

Constraint on the equation of state bounds the decay constant to be smaller than the Planck mass. Superplanckian decay constant is avoided!

Lower bound on the e.o.s from Chandra:

$$\omega_\phi + 1 \geq 7 \times 10^{-17} \left(\frac{|\beta|}{0.35\text{deg}} \right)^2$$

It is extremely close to $\omega_\Lambda = -1$, it is degenerate with cosmological constant, therefore it cannot be ruled out by the traditional cosmological probes such as supernovae and the large-scale structure. But birefringence can see it!

Conclusions

Summary:

- We found a link between the slope and the e.o.s parameter.
- Cosmic birefringence is fundamentally determined by the slope of the potential, rather than by the mass!
  - $\Delta\phi$ depends ONLY on s, not on the initial condition or the axion field abundance.
- The relation between $g_{\phi\gamma}$ and s holds as a linear approximation for a generic thawing model.
- The expected decay constant is subplanckian!
- Cosmic birefringence serves as a link between cosmological and fundamental physics parameters.

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Thank you for the attention!