Implications of the cosmic birefringence measurements for the axion monodromy

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JCAP 08 (2022) 08, 025 [arXiv:2203.09409[astro-ph.CO]]

In collaboration with **Silvia Gasparotto** (corresponding author)

科研費 KAKENHI

ダークマターの正体は何か？
広大なディスカバリースペースの網羅的研究
What is dark matter? - Comprehensive study of the huge discovery space in dark matter
文部科学省
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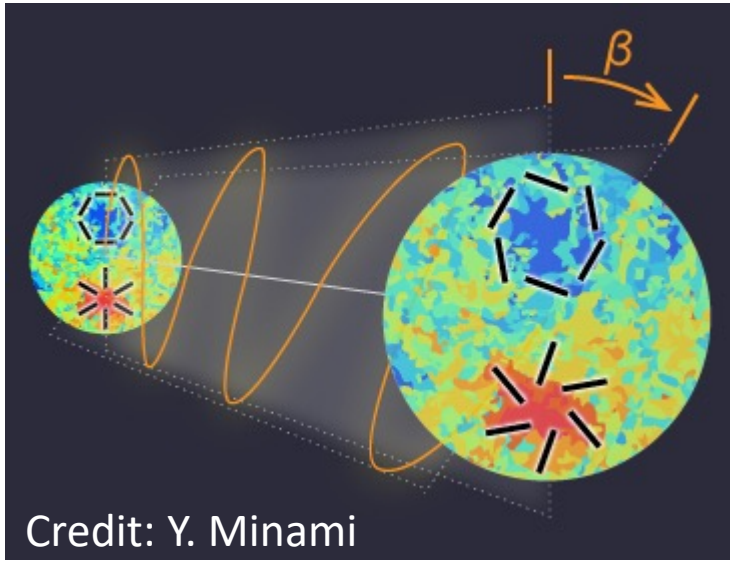
Isotropic cosmic birefringence (ICB)



Minami, Komatsu (2020); (*Planck* PR3)

$$\beta = 0.35 \pm 0.14 \text{ deg } (2.4\sigma)$$

(upgrade!)

Eskilt & Komatsu (2022); (*Planck*/WMAP)

$$\beta = 0.34 \pm 0.09 \text{ deg } (3.6\sigma)$$

- Linear polarization rotation is potentially caused by the axion-photon interaction

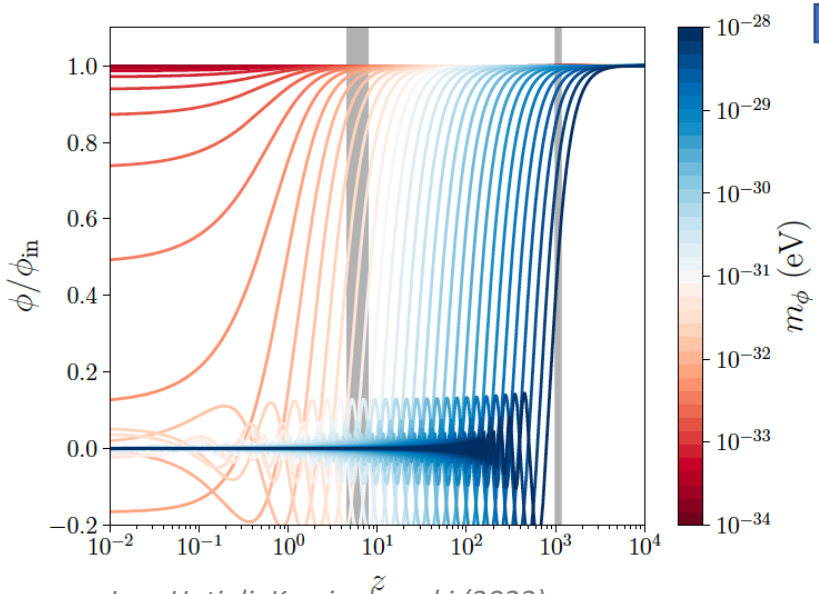
$$\mathcal{L}_{\rm int} = \frac{1}{4} g_{\phi\gamma} \phi F_{\mu\nu} \tilde{F}^{\mu\nu} \rightarrow \omega_{\rm L/R} = k\sqrt{1 \pm \frac{g_{\phi\gamma}\dot{\phi}}{k}} \simeq k \pm \frac{g_{\phi\gamma}}{2}\dot{\phi}$$

$$\beta = \frac{1}{2}\int_{t_{\rm emit}}^{t_{\rm obs}} dt(\omega_L - \omega_R) = \frac{g_{\phi\gamma}}{2}\int_{t_{\rm emit}}^{t_{\rm obs}} dt\dot{\phi} = \frac{g_{\phi\gamma}}{2}\left[\phi(t_{\rm obs}) - \phi(t_{\rm emit})\right]$$

ICB from cosmological axion background

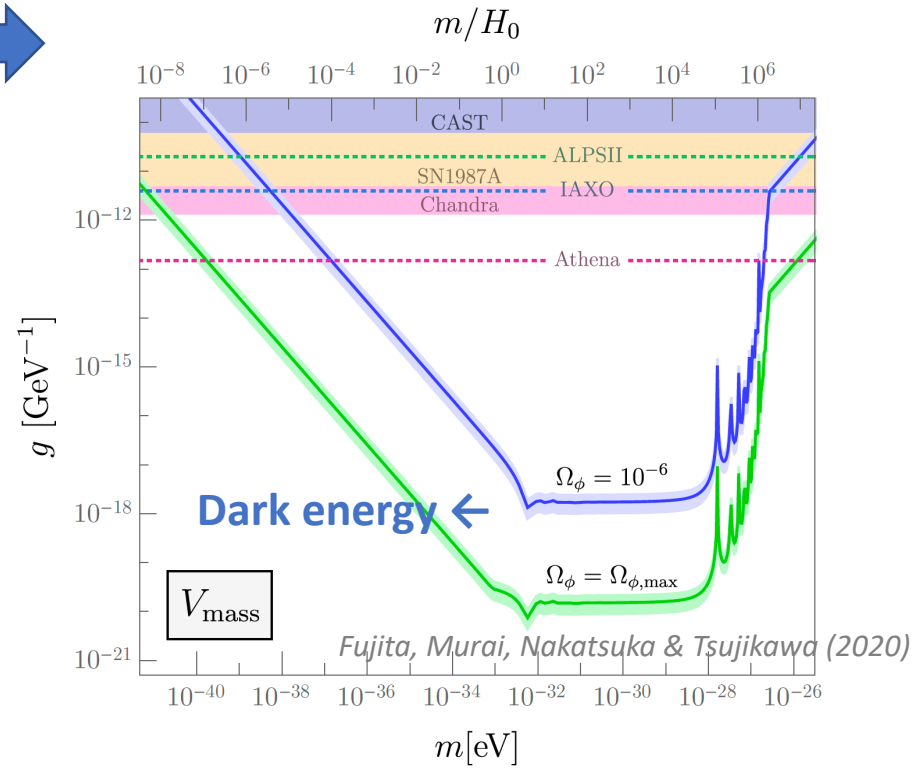
$$\beta = \frac{g_{a\phi}}{2}\Delta\phi$$

Time evolution of axion with different mass



Lee, Hotinli, Kamionkowski (2022)

Constraints on the axion-photon coupling



Fujita, Murai, Nakatsuka & Tsujikawa (2020)

EOM for cosmological axion field:

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

$$\Omega_{\phi,\rm max} \simeq \begin{cases} 0.69 & (m \lesssim 10^{-33}{\rm eV}) \\ 6\times 10^{-3}h^{-2} & (10^{-32}{\rm eV} \lesssim m \lesssim 10^{-25}{\rm eV}) \end{cases}$$

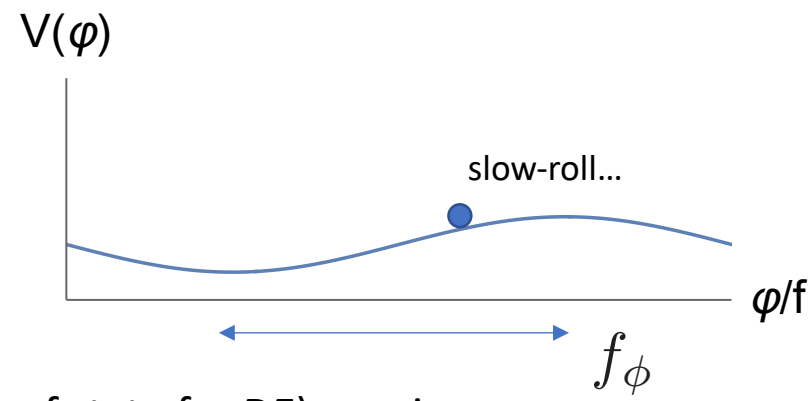
Hlozek+ (2015)

Conventional issue of axion DE model

Friemann+ (1995); …

- Consider a **nearly flat** axion cosine potential

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



- Slow-roll condition (constraint on the equation of state for DE) requires

$$f_\phi \simeq 14 M_{\rm Pl} \left(\frac{\Omega_\phi}{0.69}\right)^{1/2} \left(\frac{m_\phi/H_0}{0.1}\right)^{-1} > M_{\rm Pl}$$

(In controlled setup, $f_\phi \ll M_{\rm Pl}$) ***Banks+ (2003);***

Or we could avoid it by relying on a fine-tuning of initial axion displacement…

Potential solutions to this issue

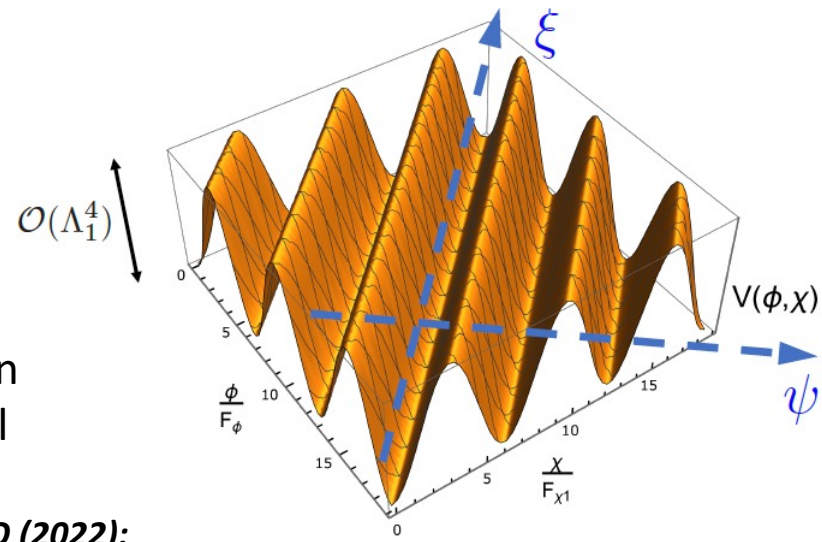
- Multiple-axion scenario

  Dark energy: ***Kim (1999)(2000), …***

  Inflation: ***Kim, Nilles & Peloso (2005), …***

  Nearly-flat direction can be realized by an alignment of the multiple axion potential

  - Implications of birefringence measurement: ***IO (2022);***



- **Monodromy** scenario

  Inflation: ***Silverstein, Westphal (2008); McAllister, Silverstein, Westphal (2008);…***

  Dark energy: ***Panda, Sumitomo, Trivedi (2010);…***

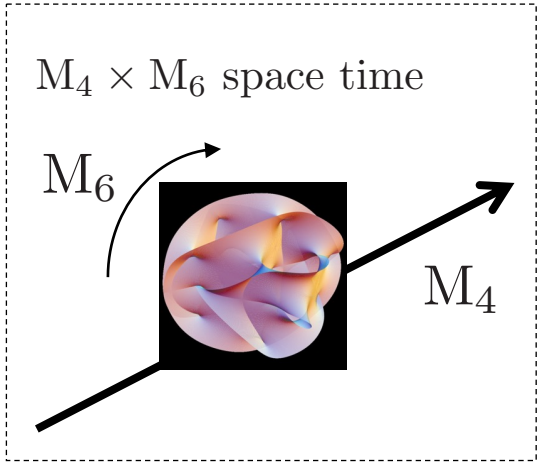
  The axion shift-symmetry is broken by the interplay of axion and branes

  → allows a field range to extend beyond a periodic scale!

Axions in string theory

Svrcek & Witen (2006);…

- Axion-like particles arises from the compactifications of form fields in extra dimensions



Ex: 10-dim. action in Type-IIB string theory

$$S = \frac{1}{(2\pi)^7 \alpha'^4} \int d^{10}x \sqrt{-g_{10}} \left[\frac{1}{g_s^2} R - \frac{1}{12} \partial_\mu C_{2,ab} \partial^\mu C_{2,a'b'} g^{aa'} g^{bb'} + \ldots \right]$$

$$(\mu = 0, 1, 2, 3 : \text{ four non-compact direction, } a, b, a', b' : \text{ six compact direction})$$

$$\ell_s = 2\pi\sqrt{\alpha'} : \text{string scale , } g_s : \text{string coupling}$$

$$\text{space time} : ds^2 = g_{10,mn} dx^m dx^n = g_{4,\mu\nu} dx^\mu dx^\nu + g_{6,ab} dx^a dx^b$$

C_2 : RR 2-form → its zero mode becomes axion field

Axions in string theory

Svrcek & Witen (2006);…

- We then reduce to get the 4-dim. action:

$$S = \frac{1}{(2\pi)^7 \alpha'^4} \int d^{10}x \sqrt{-g_{10}} \left[\frac{1}{g_s^2} R - \frac{1}{12} \partial_\mu C_{2,ab} \partial^\mu C_{2,a'b'} g^{aa'} g^{bb'} + \ldots \right]$$

(compactification) $V = L^6 (\alpha')^3$: volume of internal space

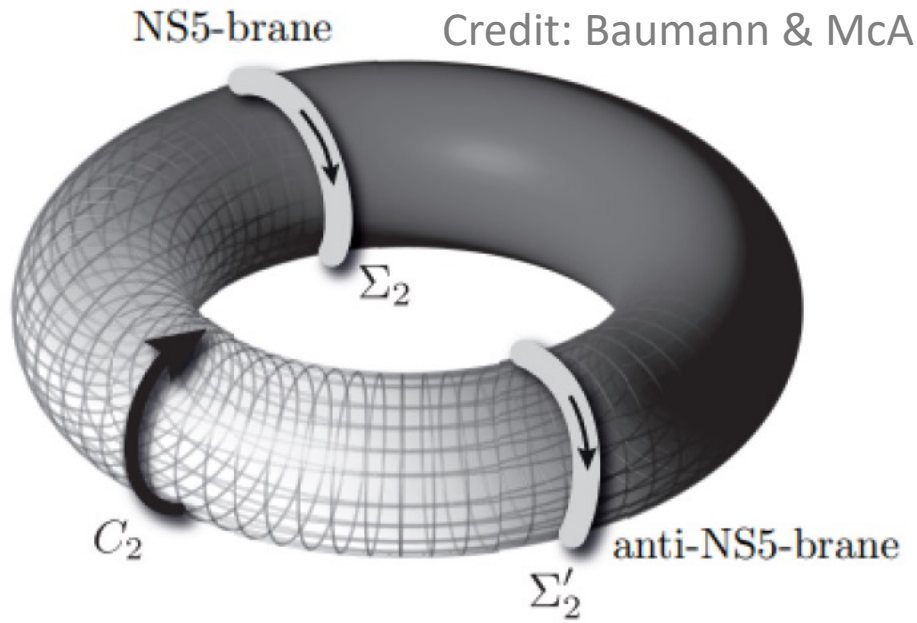
$$S = \int d^4x \sqrt{-g_4} \left[\frac{M_{\rm Pl}^2}{2} R - \frac{1}{2} f_a^2 (\partial a)^2 \right] \qquad f_a^2 \sim \frac{g_s^2 M_{\rm Pl}^2}{L^4} \qquad M_{\rm Pl}^2 = \frac{2L^6}{(2\pi)^7 g_s^2 \alpha'}$$

- Axion-U(1) coupling potentially arises from the Chern-Simons term in D-brane:

$$(2\pi\alpha')^2 T_5 \frac{1}{2} \int C_2 \wedge F \wedge F \xrightarrow[\text{(compact)}]{} (2\pi\alpha')^3 T_5 \frac{1}{2} a \int F \wedge F$$

Axion potential from wrapped branes

McAllister, Silverstein, Westphal (2008);…



Credit: Baumann & McAllister

- Consider the axion induced on the (anti) NS5-branes:

$$a = \frac{1}{\alpha'} \int_{\Sigma_2} C_2$$

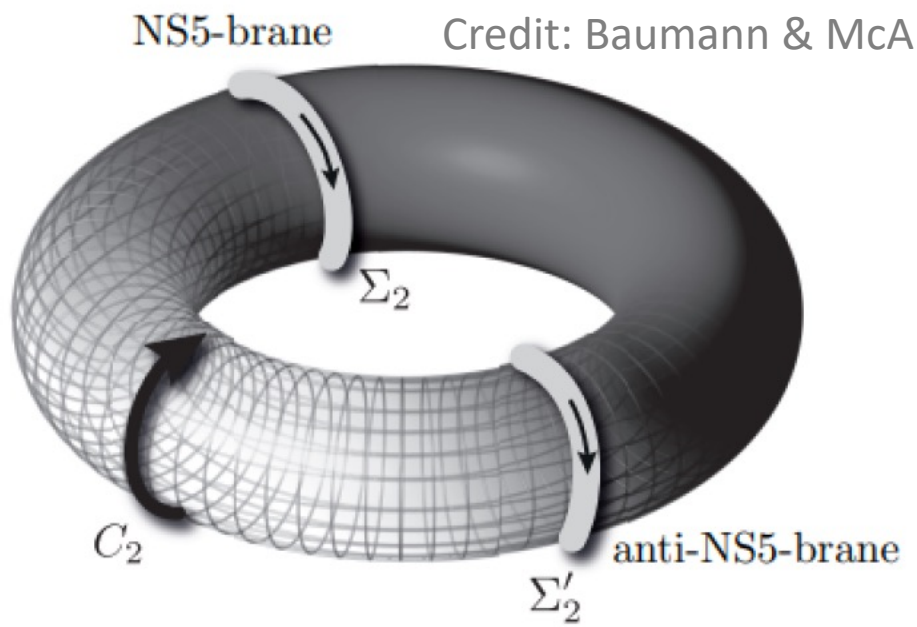
Σ_2 : 2-cycle

- DBI action from NS5 brane:

$$S_{NS5} = -\frac{1}{(2\pi)^5 g_s^2 \alpha'^3} \int_{\mathcal{M}_4 \times \Sigma_2} d^6x \sqrt{-\det(g_{10} + g_s C_2)}$$

Axion potential from wrapped branes

McAllister, Silverstein, Westphal (2008);…



Credit: Baumann & McAllister

- Metric & 2-form configuration

$$g_{10,mn} = \begin{pmatrix} e^{2A(y)} g_{\mu\nu} & 0 \\ 0 & g_{ab}(y) \end{pmatrix} ,$$

$$C_{2,mn} = \begin{pmatrix} 0 & 0 \\ 0 & a\alpha' \end{pmatrix}$$

leads to the 4-dim. DBI action:

$$S_{NS5} = -\frac{1}{(2\pi)^5 g_s^2 \alpha'^2} \int_{\mathcal{M}_4} d^4x \sqrt{-g} e^{4A_0} \sqrt{L^4 + g_s^2 a^2}$$

→ provides a **non-periodic** potential:

$$V = \frac{2\epsilon}{(2\pi)^5 g_s^2 \alpha'^2} \sqrt{L^4 + g_s^2 a^2}$$

$$\epsilon \equiv e^{4A_0}$$

Monodromic axion dark energy

Panda, Sumitomo, Trivedi (2010);…

- For a limit of large axion field value, the potential form becomes **linear**:

$$V \longrightarrow \boxed{\mu^4 \frac{\phi}{f_a}} \quad (a \gg L^2/g_s) \qquad \boxed{\begin{array}{l} \mu^4 \equiv \dfrac{2\epsilon}{(2\pi)^5 g_s \alpha'^2} \\ \phi \equiv f_a a \end{array}}$$

The potential energy is not bounded from above, but experiences a *monodromy* - not coming back to itself as it moves around a circle in the manifold

→ extends axion field value to the periodic scale:

$$\boxed{\phi \gg M_{\rm Pl} \text{ with } f_a \ll M_{\rm Pl}}$$

(potentially explains the cosmic birefringence?)


Photo: Butler Cain (Loretto Chapel)

ICB from monodromic axion DE

Gasparotto & IO (2022);

- Consider a linear potential $V(\phi) = \mu^4 \dfrac{\phi}{f_a}$

  and define its dimensionless **slope parameter**: $s \equiv \dfrac{dV/d\phi}{3M_{\rm Pl}^2 H_0^2} = \dfrac{\mu^4/f_a}{3M_{\rm Pl}^2 H_0^2}$

- Dimensionless EOM for axion field:

$$\phi_n'' + 3\mathcal{H}\phi_n' + 3s = 0 \qquad \text{w.r.t.} \qquad \tau \equiv H_0 t$$

$\mathcal{H} \equiv H/H_0$

$\phi_n \equiv \phi/M_{\rm Pl}$

- Assuming matter-dominant era: $\mathcal{H} = 2/(3\tau)$

  we obtain an exact solution and the corresponding field displacement

$$\boxed{\phi_n(\tau) = \phi_{i,n} - \frac{s\tau^2}{2} \quad \longrightarrow \quad \Delta\phi_n = -\frac{s}{2}(\tau_0^2 - \tau_{\rm LSS}^2) \simeq \frac{s}{2}\tau_0^2}$$

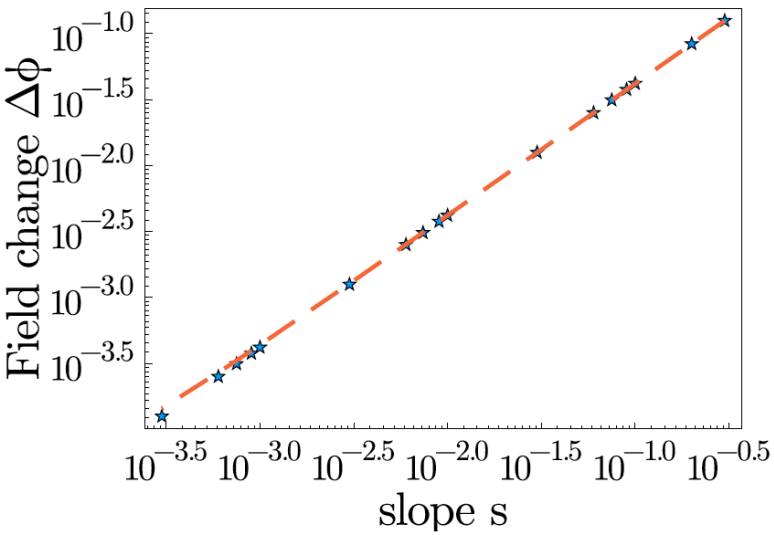
ICB from monodromic axion DE

Gasparotto & IO (2022);

- Linear dependence

From the numerical interpolation, we find

$$\boxed{|\Delta\phi_n| = 0.417s}$$



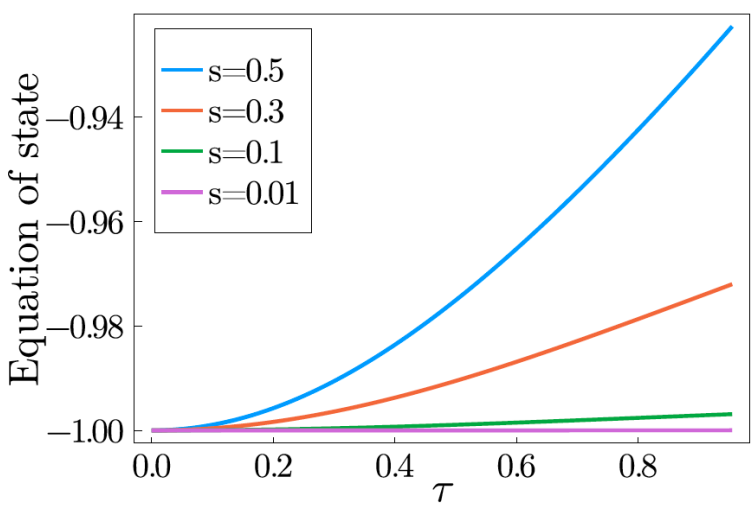
- Equation of state for axion DE:

$$\omega_\phi + 1 \simeq \frac{\dot{\phi}_0^2}{V} \simeq \frac{s^2\tau_0^2}{3\Omega_\phi}$$

Planck 2018: $\omega_\phi + 1 \leq 0.05$

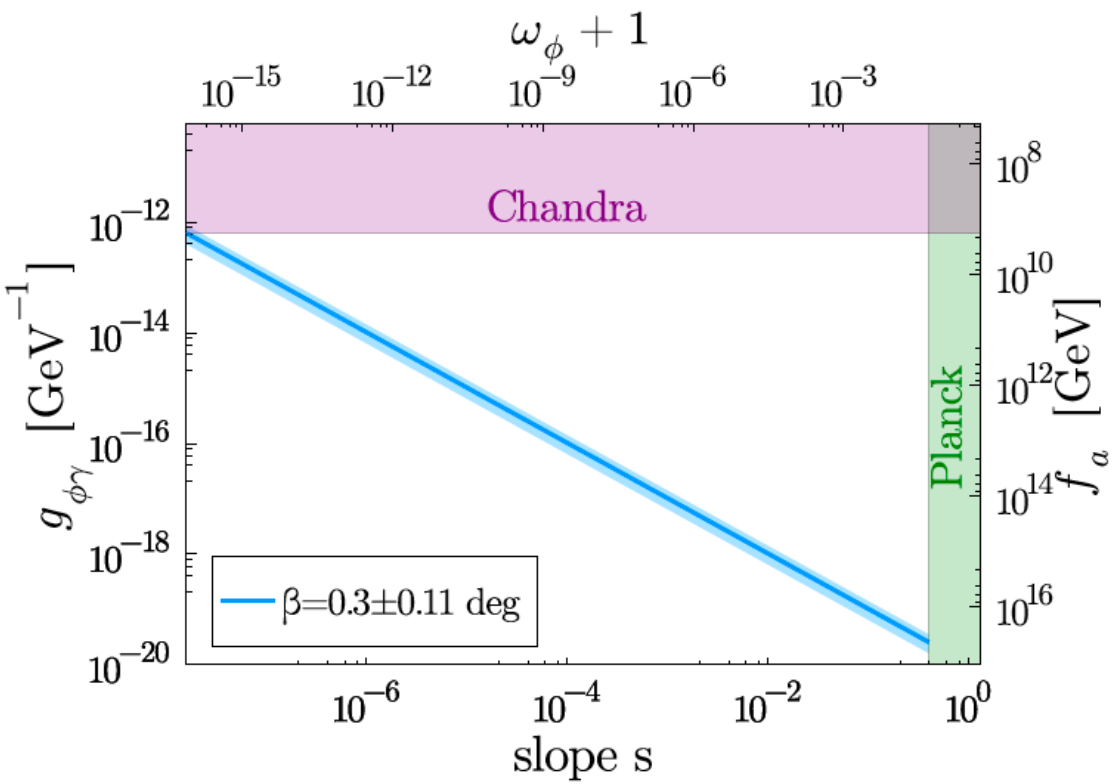
puts an upper bound on the slope:

$$\boxed{s \lesssim 0.4}$$



ICB from monodromic axion DE

Gasparotto & IO (2022);



Constraint on the coupling constant

$$g_{\phi\gamma} = \frac{\alpha_{em} c_{\gamma\phi}}{2\pi f_a}$$

w.r.t. potential slope (not mass!)

- ✓ Upper bound from EoS constraint
- ✓ Lower bound from X-ray search

$$\frac{f_a}{c_{\gamma\phi}} = 4.52 \times 10^{16}\,\mathrm{GeV}\left(\frac{0.30\mathrm{deg}}{|\beta|}\right)\left(\frac{s}{0.4}\right)$$

← sub-Planckian (GUT) scale!

Some other implications

Gasparotto & IO (2022);

- General monomial potential: $V = \mu^{4-n}\phi^n$

  We numerically found the following relation: $\lambda_0 = M_{\rm Pl}\partial_\phi V/V = n/\phi_{n,0}$

$$\omega_\phi + 1 = 0.149\lambda_0^2, \quad \Delta\phi_n = 0.29\lambda_0 = 0.75\sqrt{\omega_\phi + 1}$$

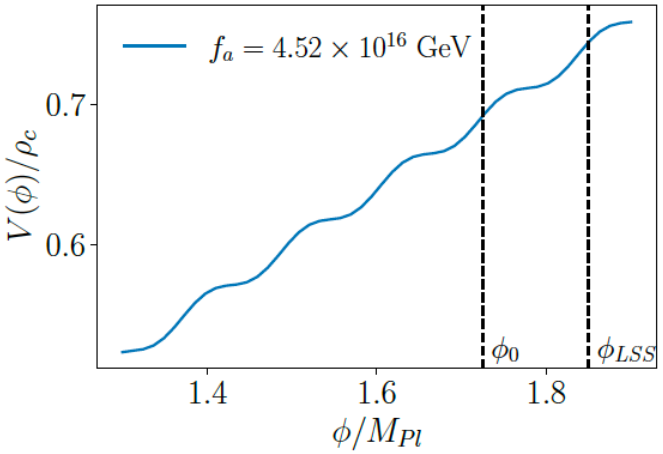
  and realized the ICB angle similar with the linear potential

- Oscillating dark energy model:

$$V(\phi) = \frac{\mu^4}{f_a}\left(\phi + b f_a \cos\left(\frac{\phi}{f_a}\right)\right)$$

  We found a relationship between the number of oscillation periods and ICB angle:

$$N_{osc} = \frac{\Delta\phi}{2\pi f_a} = \frac{2\beta}{\alpha_{em} c_{\phi\gamma}} = \frac{1.43}{c_{\phi\gamma}}\left(\frac{\beta}{0.30\ \text{deg}}\right)$$



Summary & Outlook

- A recent measurement of cosmic birefringence gives us a tantalizing hint for the axion physics, such as an ultralight axion as dark energy.

- We studied the implications of the ICB angle for axion dark energy with monodromy potential, where the potential is a linear form and hence its slope becomes a central role of determining the ICB angle instead of the axion mass.

- Upon using the birefringence measurement and the constraint on the equation of state for dark energy, we found an upper bound on the axion decay constant less than GUT scale, which is also consistent with the condition of sub-Planckian decay constant.

- More implications for Swampland conjectures, oscillatory potentials…