Cosmic Birefringence:

New Physics Explanations

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UNDARK Kick-Off 9/10/2924

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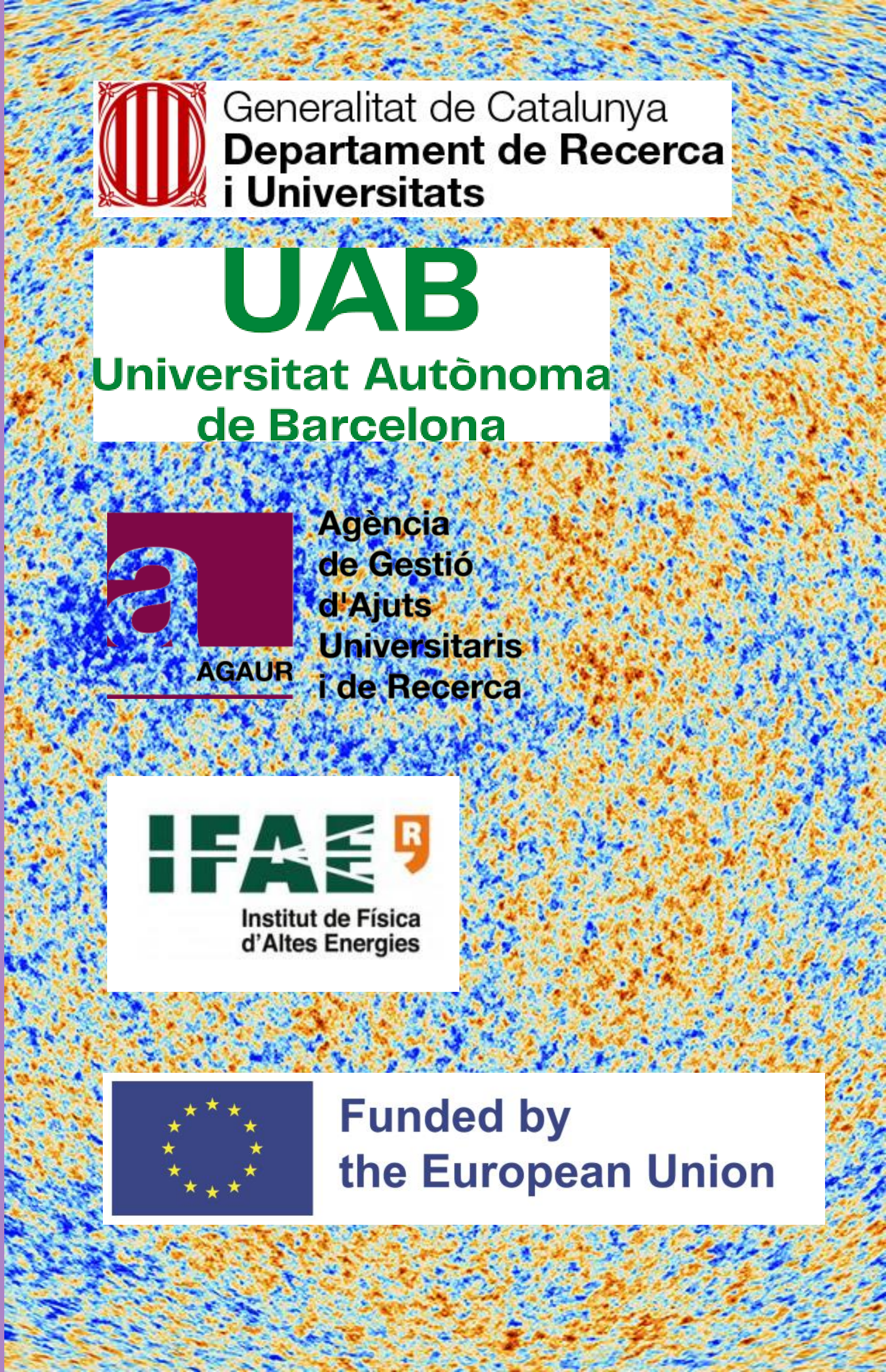
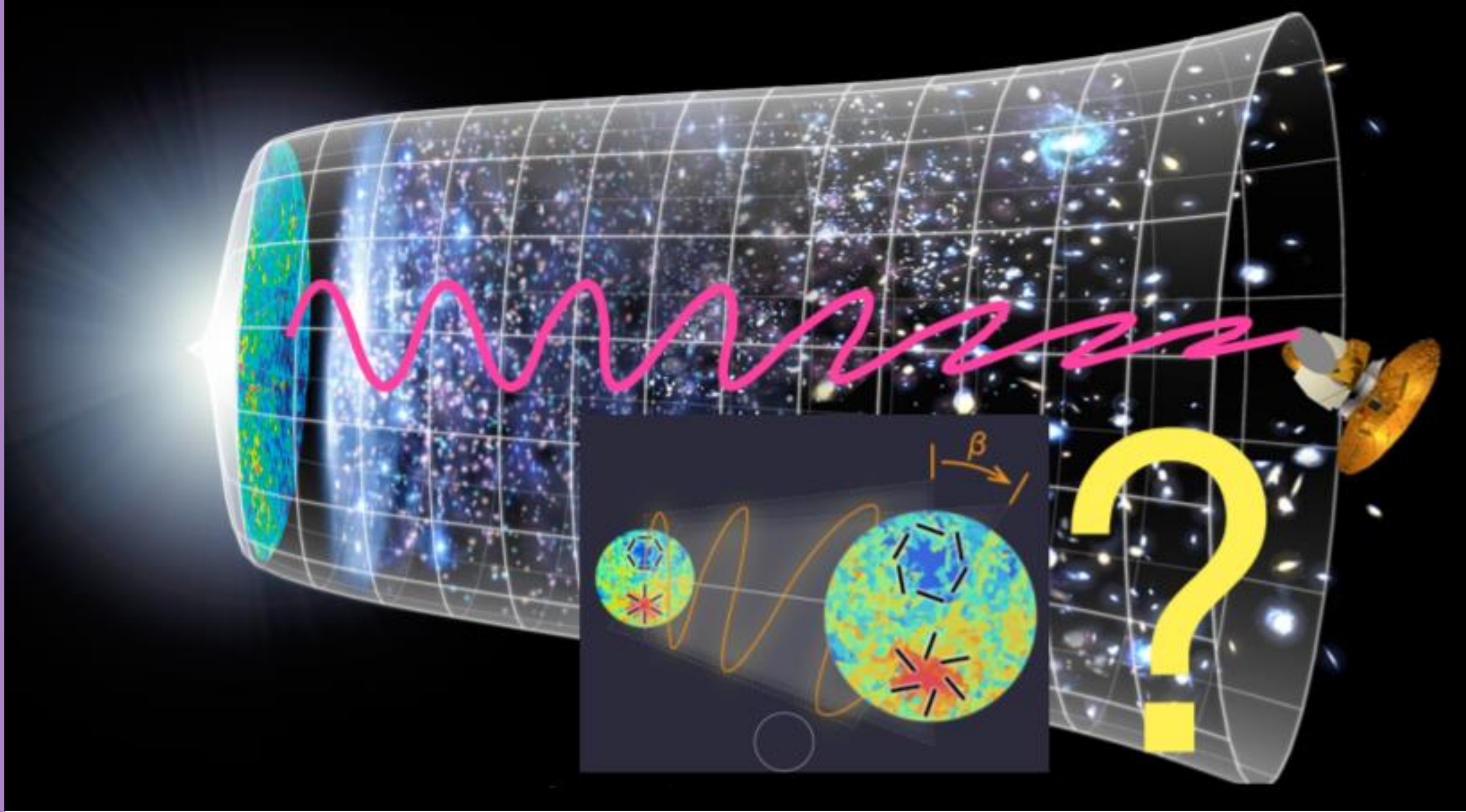




Outlook

- Introduction: Axion Birefringence
- Signal from the Cosmic Microwave Background
- Possible explanations: different models
- Conclusion and future directions

Axion Birefringence

Turner & Widrow (1988)

the effective Lagrangian for axion electrodynamics is

Chern-Simons term

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

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

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

$g_{a\gamma}\phi\vec{E}\cdot\vec{B}$ Parity odd

Axion-photon interaction modifies the photon dispersion relation in a parity-violating way

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

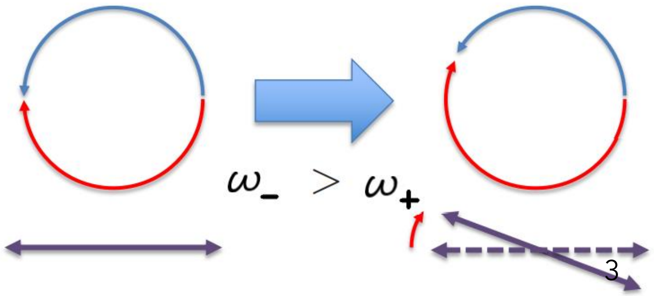
Left- and right handed photons propagate with a different speed

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

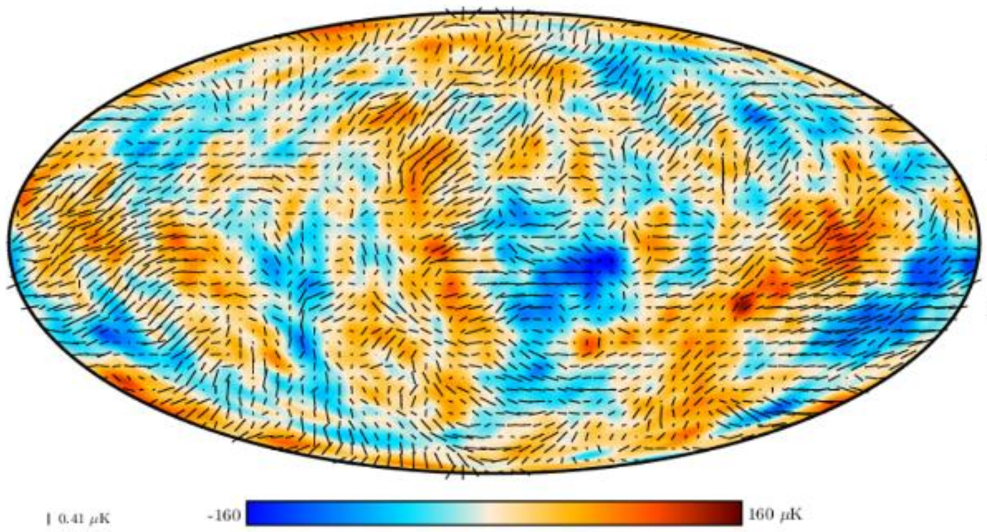
i. Frequency independent

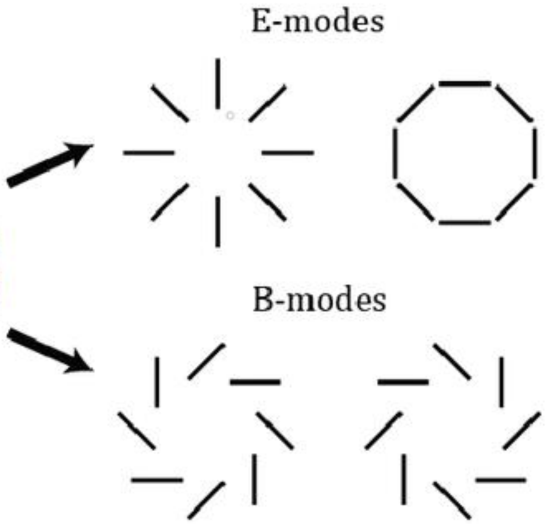
ii. Evolving field $\phi' \neq 0$

Rotation of the photon linear polarization



Cosmic Microwave Background as a perfect target





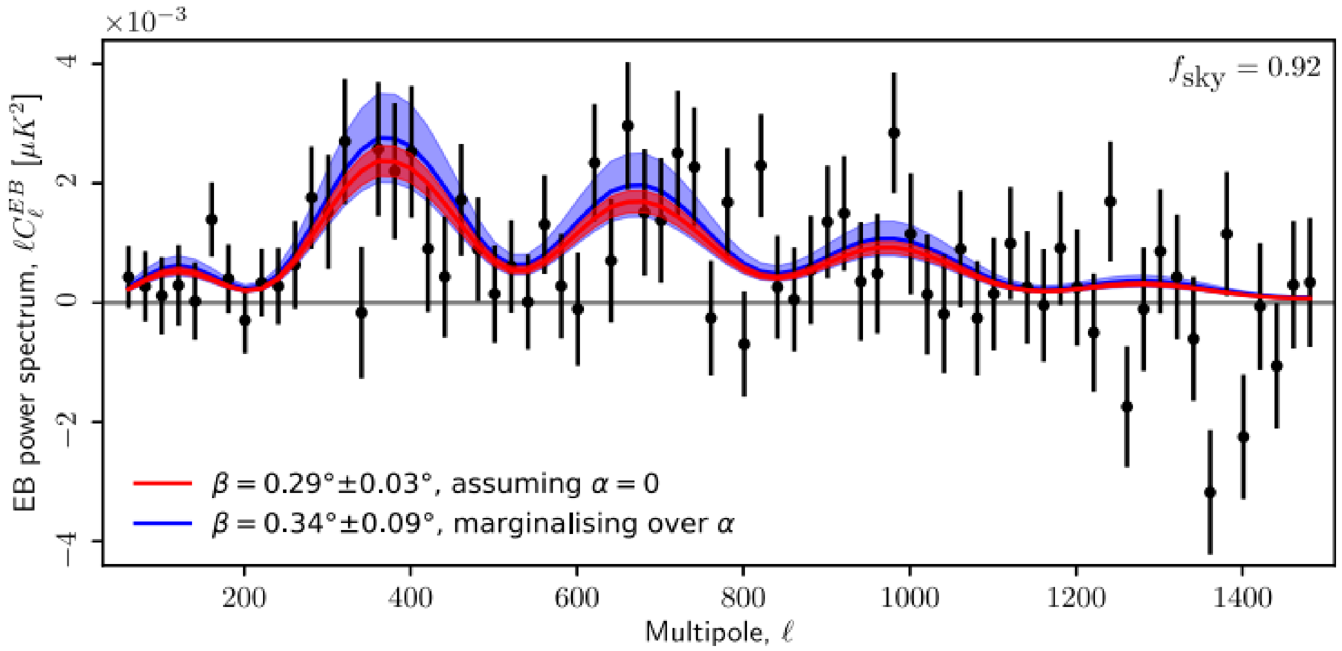
CMB photons emitted 13.8 billion years ago

Rotation accumulates over distance

Birefringence of CMB is called COSMIC BIREFRINGENCE

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

Hint of parity violation



Uniform rotation of CMB polarization of an **angle β** generates an EB cross-correlation

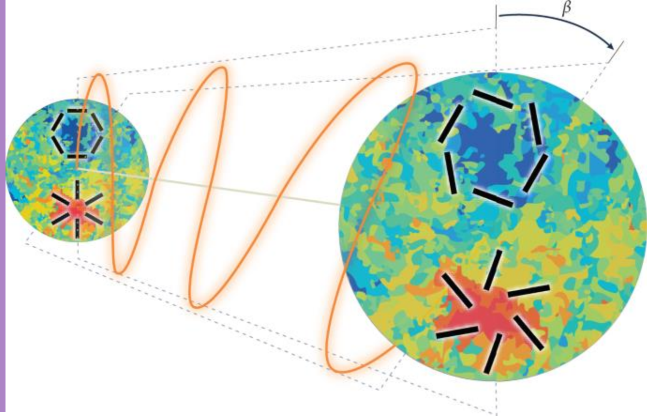
$$C_l^{EB,obs} = \frac{1}{2}\sin(4\beta)\left(C_l^{EE} - C_l^{BB}\right)$$

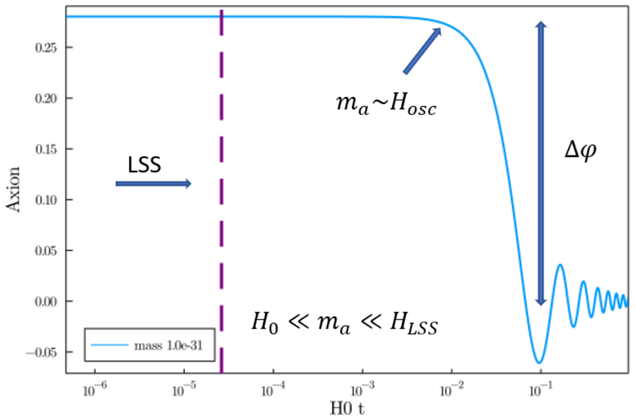
β is degenerate with a miscalibration angle → New method from Minami and Komatsu (2020) from reported β=0.35°±0.14° also Diego-Palazuelos et al. (2022), Eskilt (2022)

Current measure: $\beta = 0.342^{+0.094}_{-0.091}\text{deg}\ (3.6\sigma)$ Frequency independent!

Zero excluded at 99.987% C.L. *from* the joint analysis of Planck and WMAP data
Eskilt et al (2023)

Axion Explanation





$$\beta(\hat{n}) = \frac{1}{2}\int_{\eta_{em}}^{\eta_{obs}} d\eta(\omega_- - \omega_+) = \frac{g_{a\gamma}}{2}\int_{\eta_{em}}^{\eta_{obs}} d\eta \frac{d\phi}{d\eta} = \frac{g_{a\gamma}}{2}\left(\phi_{obs}(\hat{n}) - \phi_{em}(\hat{n})\right)$$

Axion field displacement from CMB and today

The field evolution is model-dependent

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$$

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

Different scenarios:

Uniform axion-like background

I. Pre-inflationary case ($f_a \gg H_I$)

II. (Early-)Dark Energy or percentage of Dark matter

III. Small fluctuations expected

Network of topological defects:

I. Post-inflationary case ($f_a \ll H_I$): cosmic strings and domain walls

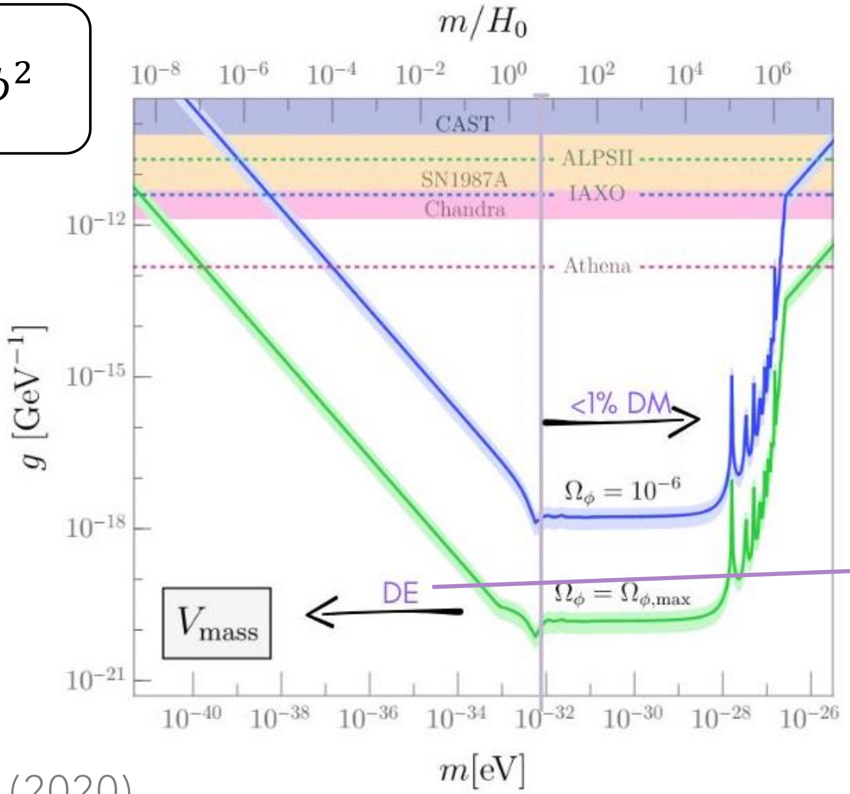
II. Large quantum diffusion ($\sigma_{a_{in}} \gg f_a$): domain walls

III. Large anisotropies, isotropic rotation on average

Implication for single-field

Parameter space explaining the CMB signal $\beta \sim 0.3$ deg

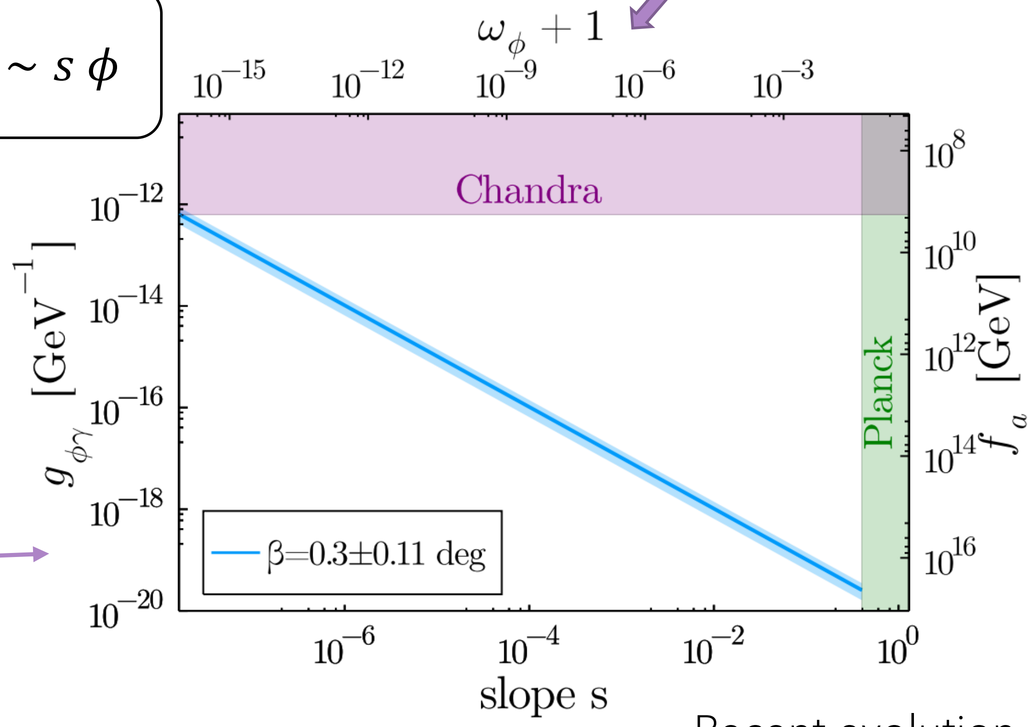
$$V(\phi) = \frac{1}{2} m_a \phi^2$$



T. Fujita et al. (2020)

$$V(\phi) \sim s\,\phi$$

Dark energy equation of state



SG & I. Obata (2022)

Recent evolution of the field

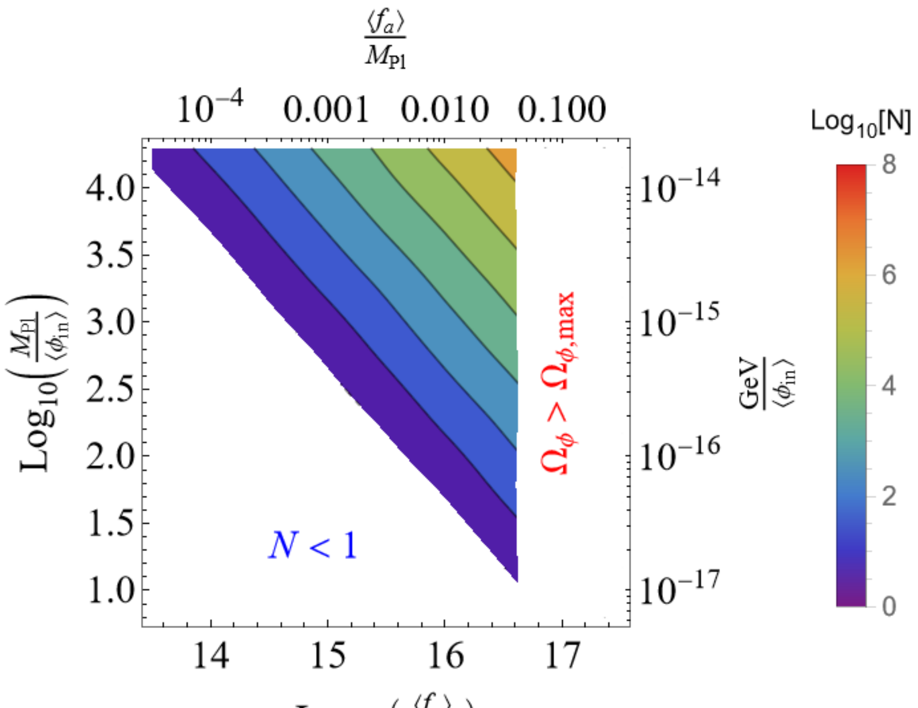
Multi- fields and the Axiverse

Axions within 15 orders of magnitude in mass could generate the signal even with a small energy density

→ AXIVERSE Arvanitaki et al (2009) …

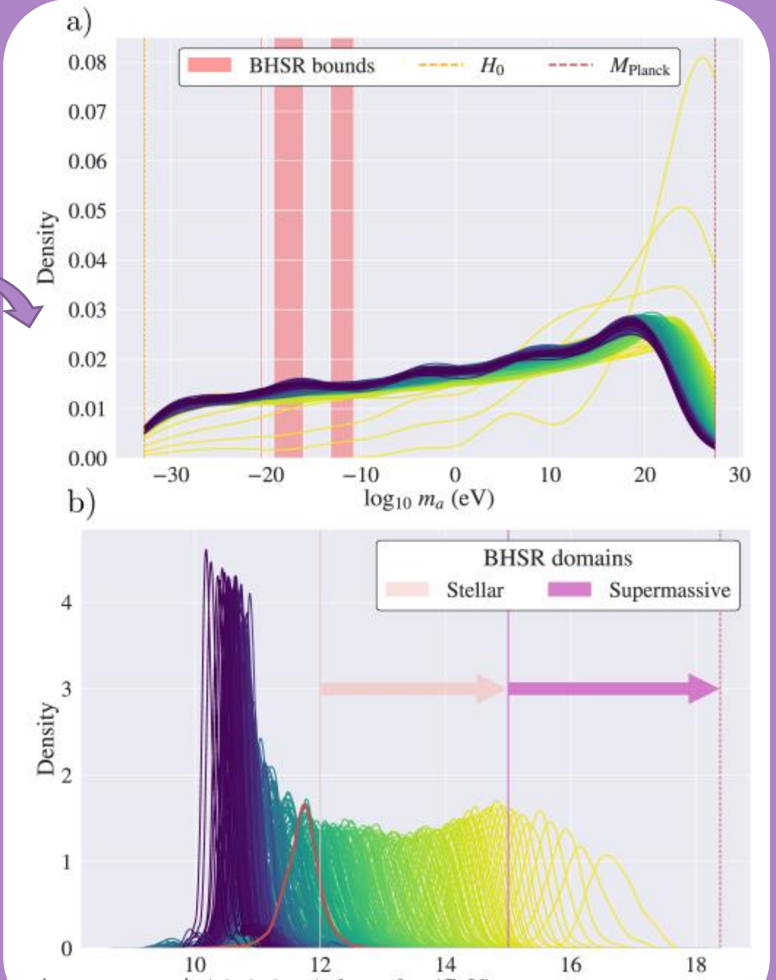
The total birefringence signal is given by the variance

$$\beta = \sum_{i=0}^{N} \frac{\alpha_{em}}{2\pi f_{a,i}} \frac{\phi_{in,i}}{2} \quad \Rightarrow \sqrt{\langle \beta^2 \rangle} = \frac{\alpha_{em}}{4\pi} \sqrt{\sum_{i=1}^{N} \left(\frac{\phi_{in,i}}{f_{a,i}}\right)^2} \propto \sqrt{N}$$



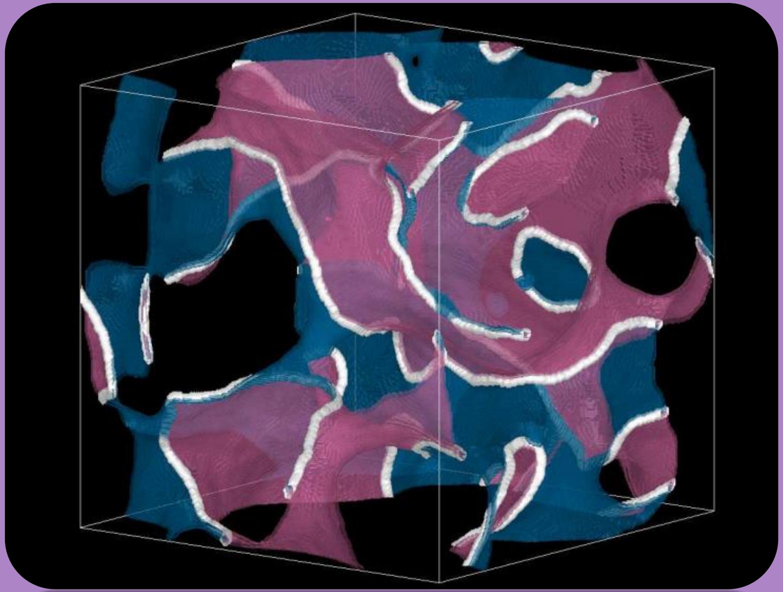
SG & E. Sfakianakis (2023)

The model depends on the probabilistic distribution of the model parameter (m_a, f_a)



Mehta et al (2021)

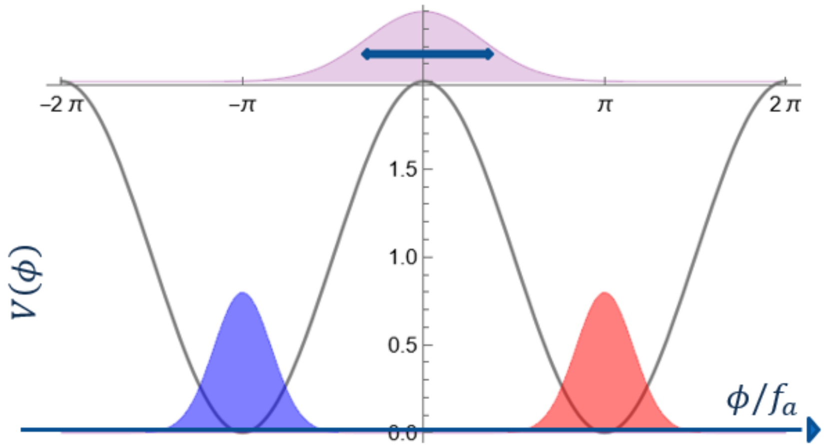
Topological defects: Domain Wall



Isotropic rotation

$$\langle \beta \rangle = \frac{\alpha_{em} c}{4\pi}(\theta_0 - \langle \theta_{LS}(\hat{n}) \rangle)$$

Symmetry breaking broken by the field local value

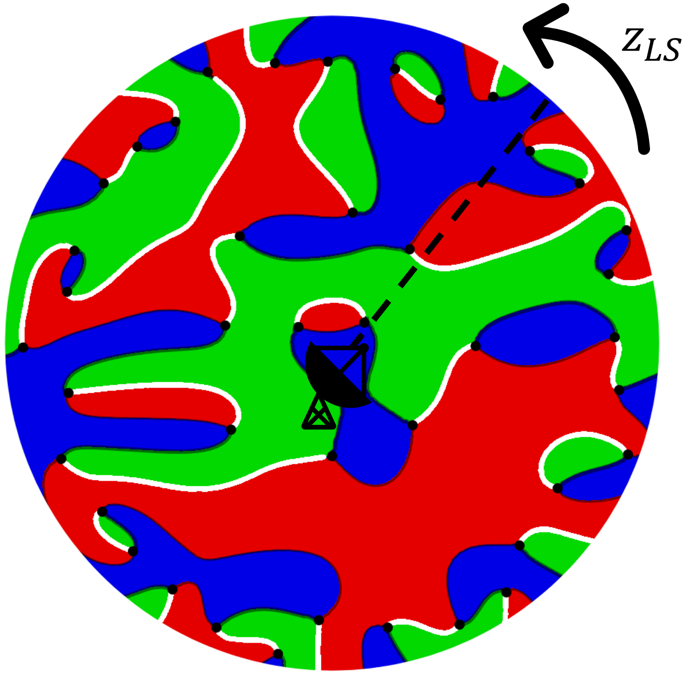


Anisotropic rotation

Anisotropic power spectrum

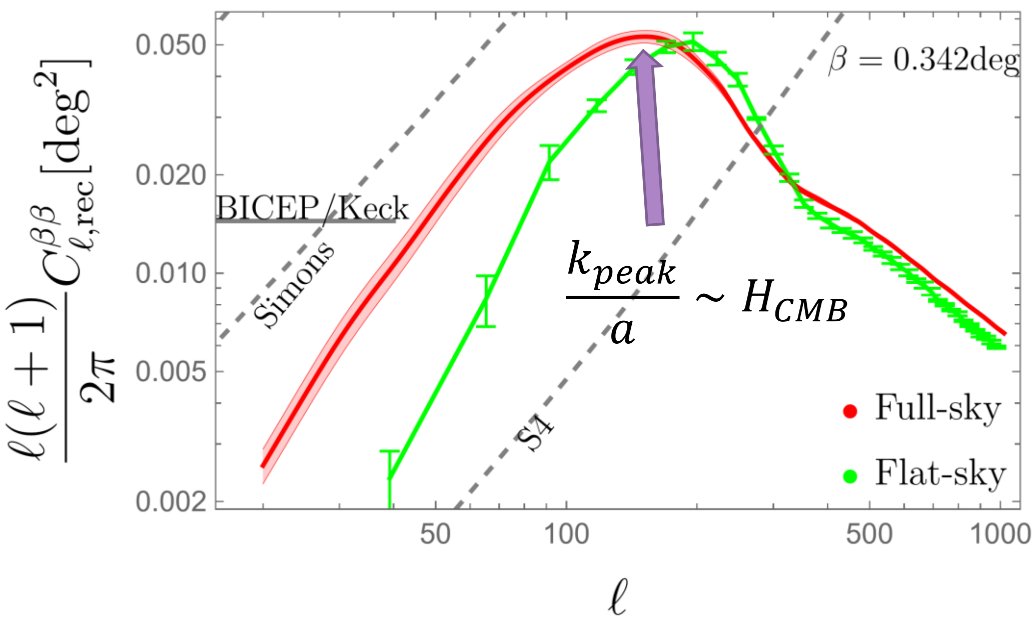
$$C_\ell^{\beta\beta}(\eta) = \frac{4}{\pi}\beta_{iso}^2 \int \frac{dk}{k} J_\ell^2(k\Delta\eta) P_\theta(k)$$

Depends on the field power spectrum at CMB



Birefringence and gravitational waves

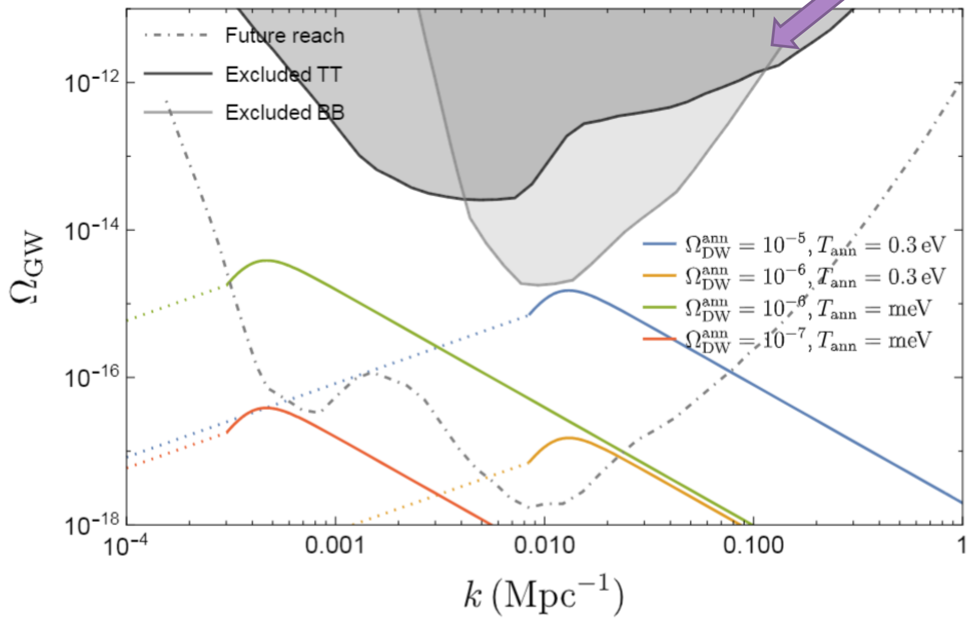
Anisotropic Birefringence:
(still undetected)



Assuming ``*scaling regime*'' (1 domain wall per Hubble volume), the spectrum peaks at CMB horizon scale.
Birefringence does not depend on the field energy density

Stochastic Gravitational-wave background:

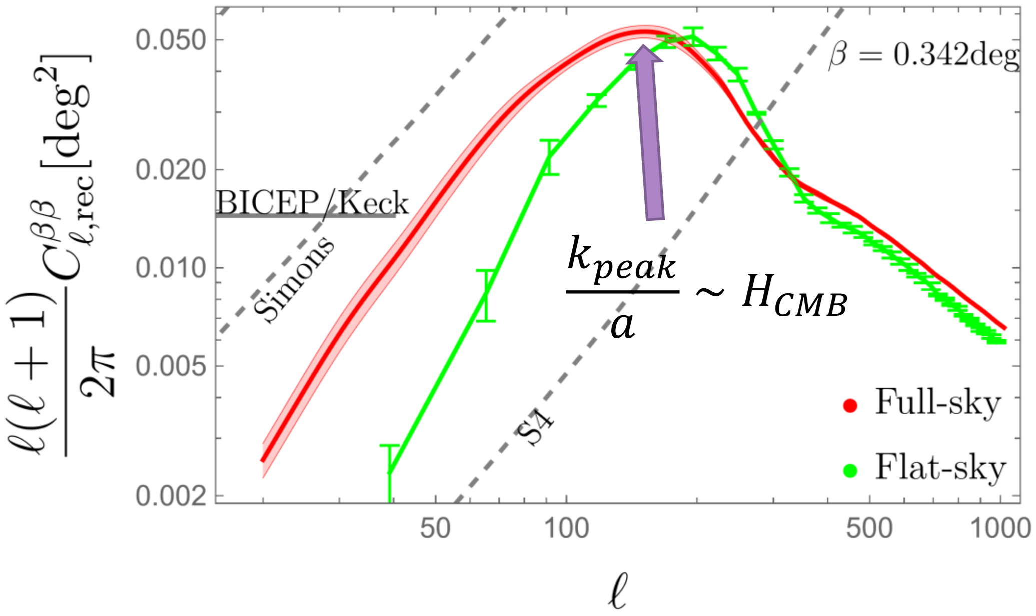
Current and future CMB constraint on the stochastic GW background from Namikawa et al (2019)



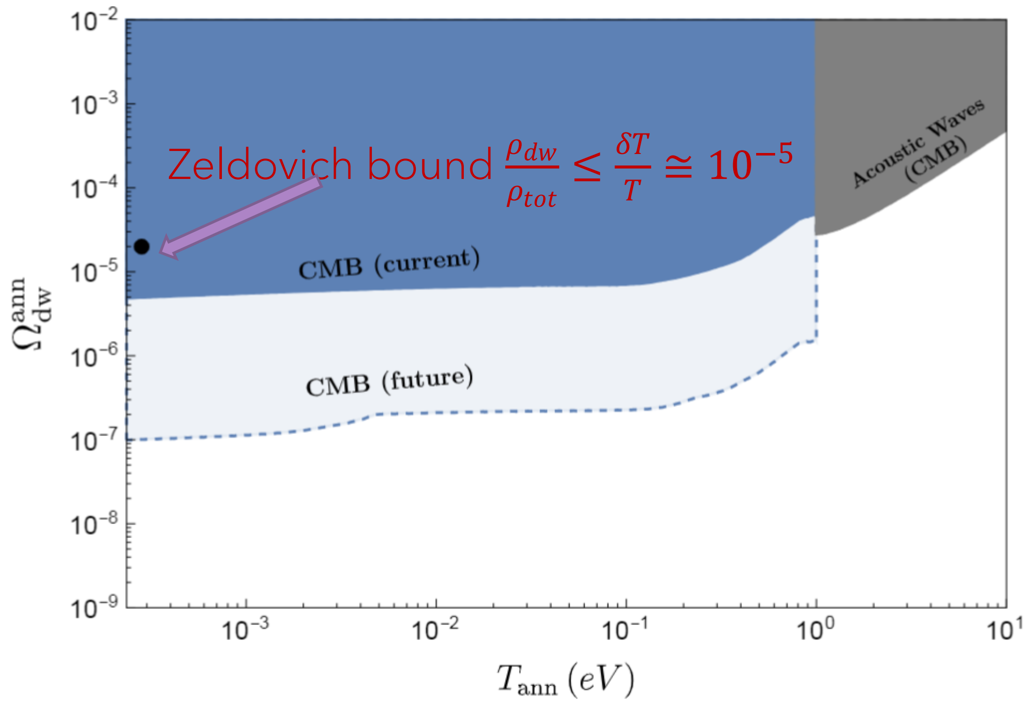
Bound on the GW energy density from domain wall network still **present or annihilated after CMB**

Birefringence and gravitational waves

Anisotropic Birefringence:
(still undetected)



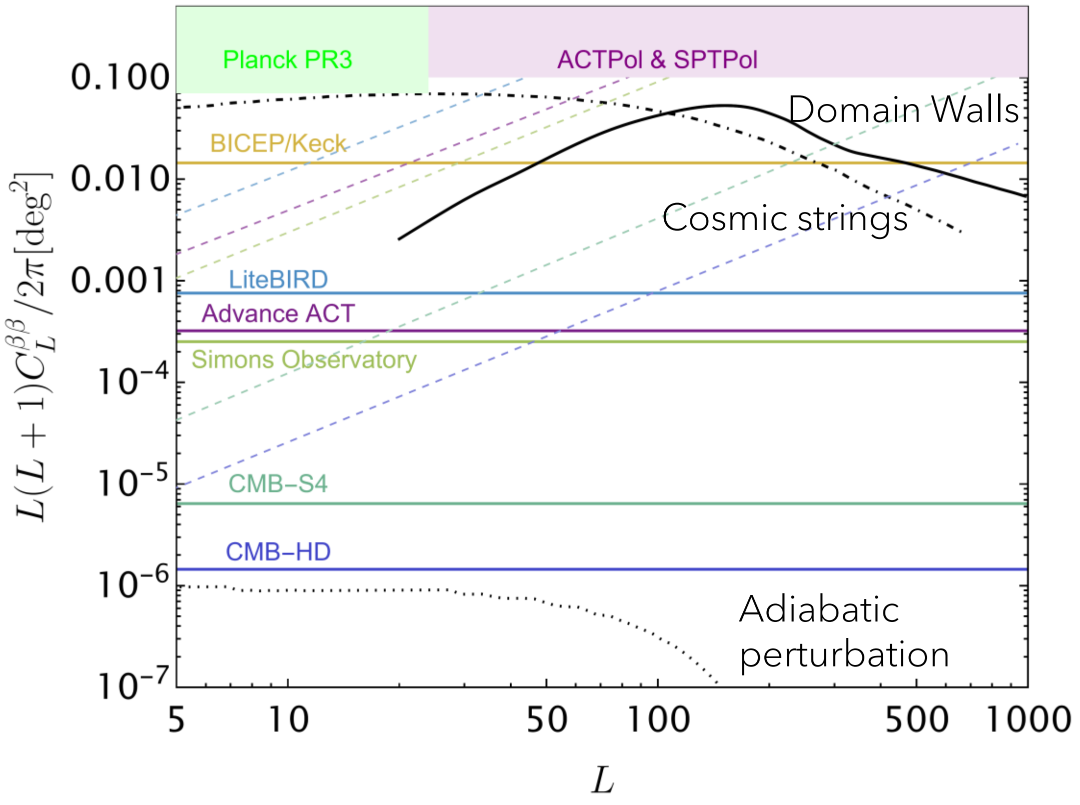
Stochastic Gravitational-wave background:



Assuming ``*scaling regime*'' (1 domain wall per Hubble volume), the spectrum peaks at CMB horizon scale.
Birefringence does not depend on the field energy density

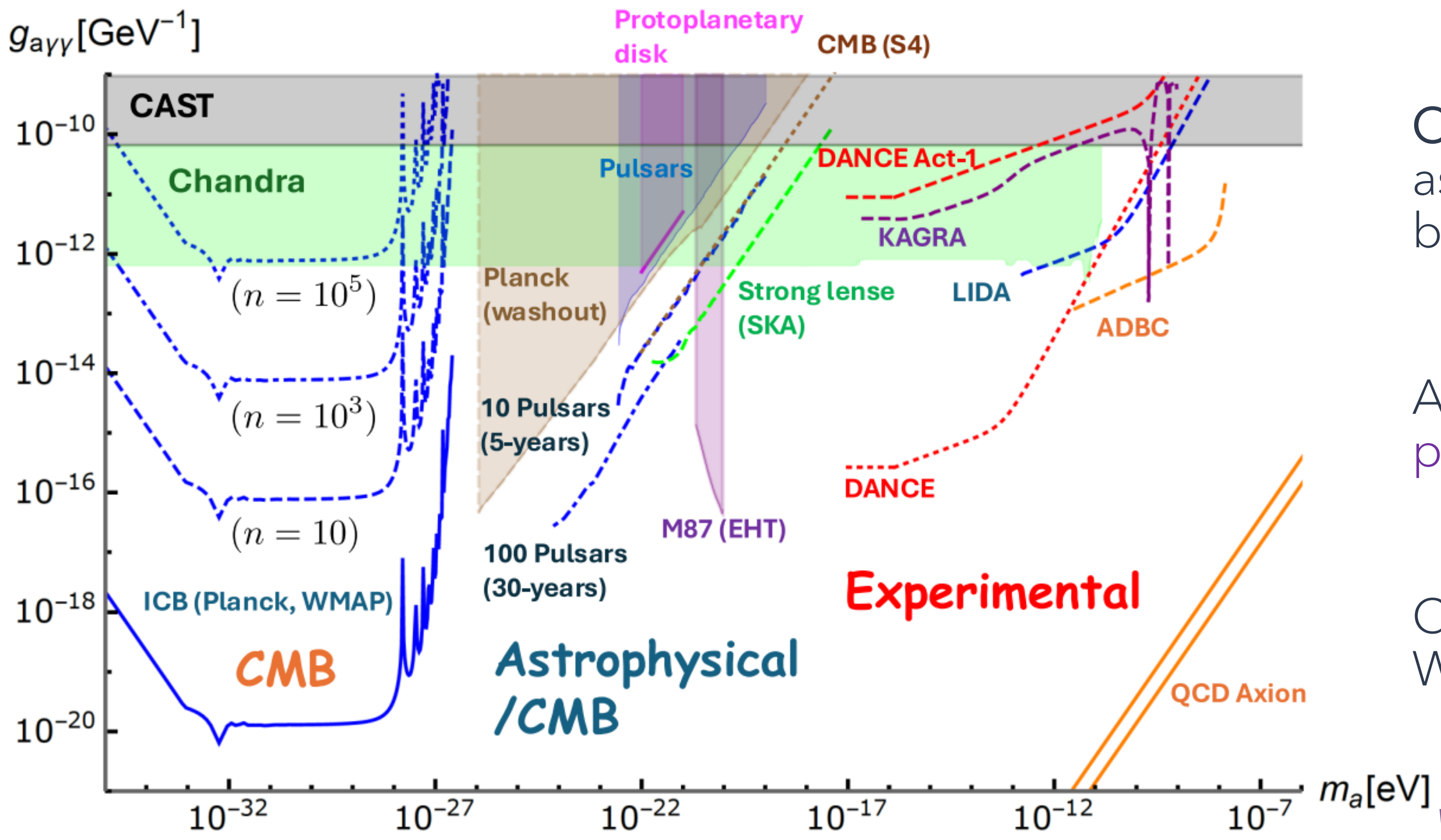
If the CMB signal is confirmed, how do we distinguish between models? The isotropic signal is very degenerate!

I. Anisotropic counterpart
II. Tomography to study its evolution (ask me)
III. Looking for other polarized sources (from local universe)



Dark energy & defects

Current and future prospects



Overview of constraints and forecast from astrophysical and laboratory searches of birefringence

At higher axion masses the signal would be periodic with frequency $\omega = m_a$

Contribution to White Paper of Cosmic WISPer COST action (in preparation)

Conclusions

Thank you!

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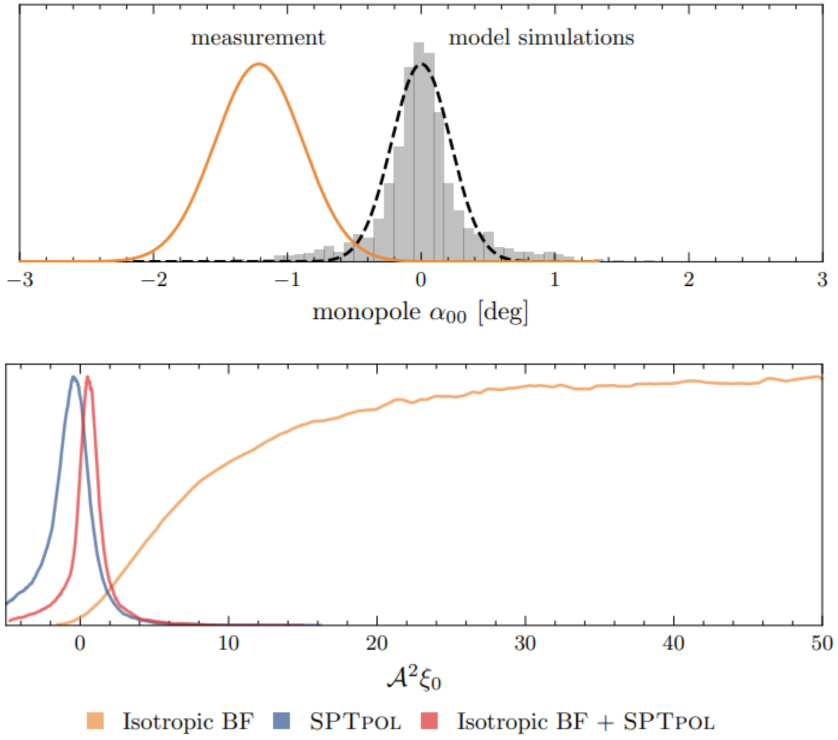
String-wall and String network case

It was considered by Agrawal et al 2020, Jain et al 2021 & 2022 → in the presence of strings the signal can be enhanced at small angles because after each loop-crossing birefringence gets a $\Delta\theta = \pm\alpha_{em}c$ → it seemed that the non-detection of anisotropies is incompatible with the isotropic signal.



Jain et al 2022

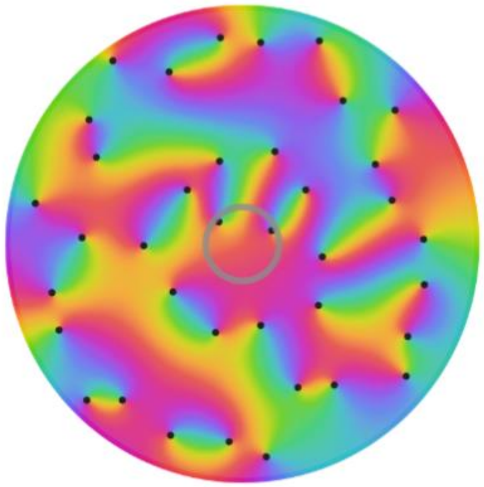
BUT the local gradient/value of the network which differs from the average value at recombination also contributes to the monopole which is not captured in the loop-crossing model

$$\langle\beta\rangle = \frac{0.21c}{2\pi}\left(\frac{\phi_{loc}}{f_a} - \langle\theta_S(\hat{n})\rangle\right)$$

Environmental birefringence

↓

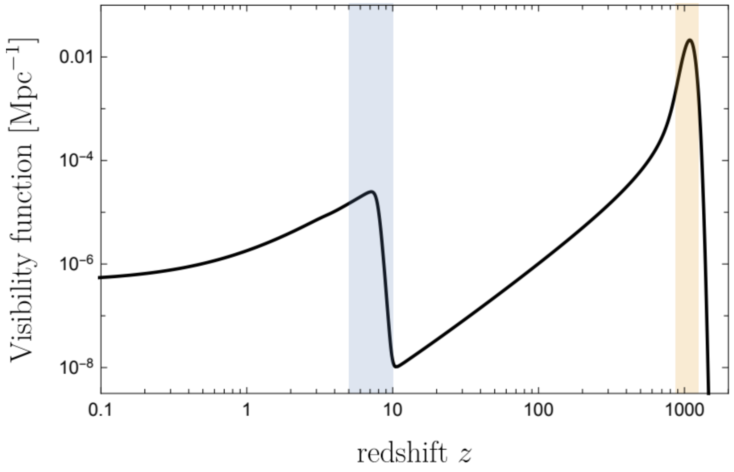
It seems that the isotropic birefringence naturally arises in every axionic network

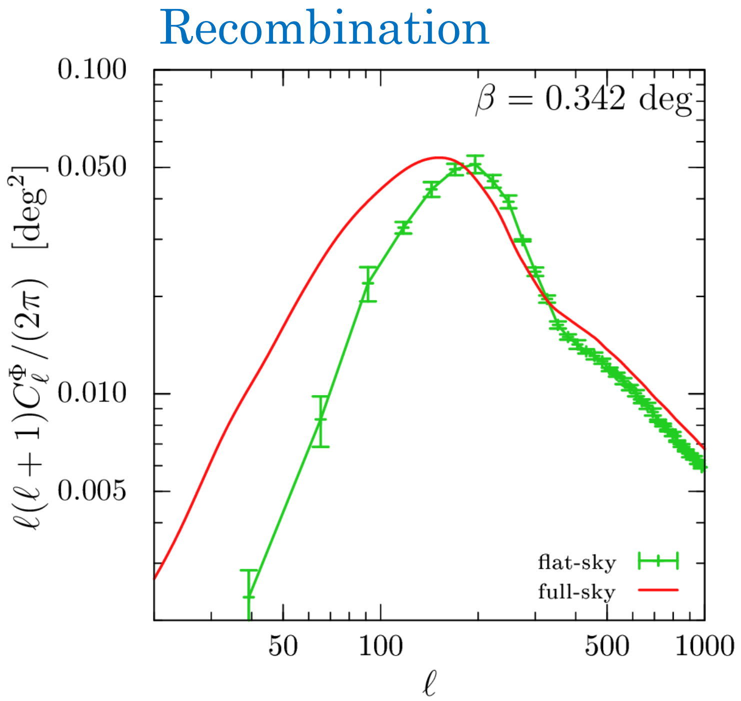


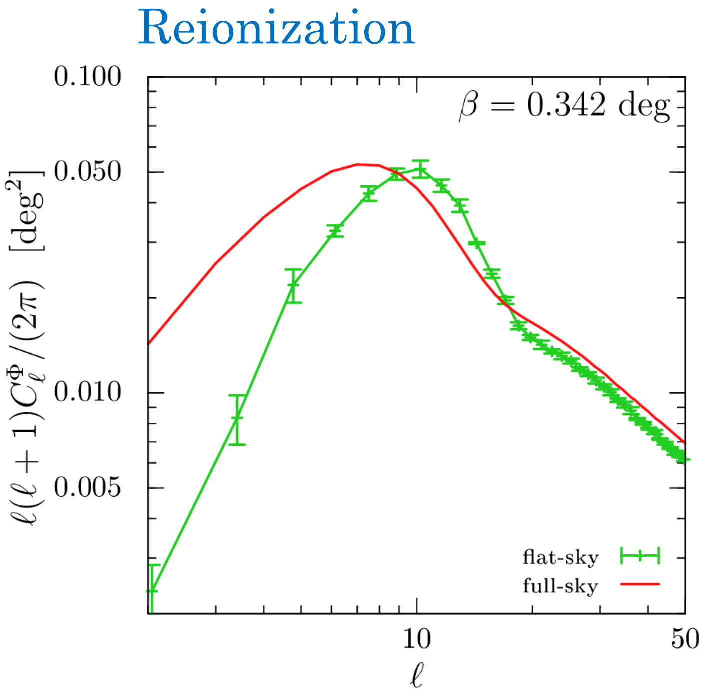
DWs at recombination and reionization

Anisotropies in the scalar power spectrum translate into anisotropies in the cosmic birefringence,

$$C_\ell^{\beta\beta}(\eta) = \frac{4}{\pi}\beta_{iso}^2 \int \frac{dk}{k} J_\ell^2(k\Delta\eta) P_\theta(k)$$







Contributions coming from the DW network at recombination and reionization which peak at different scales
→ birefringence tomography can be used to distinguish different formation/annihilation scenarios