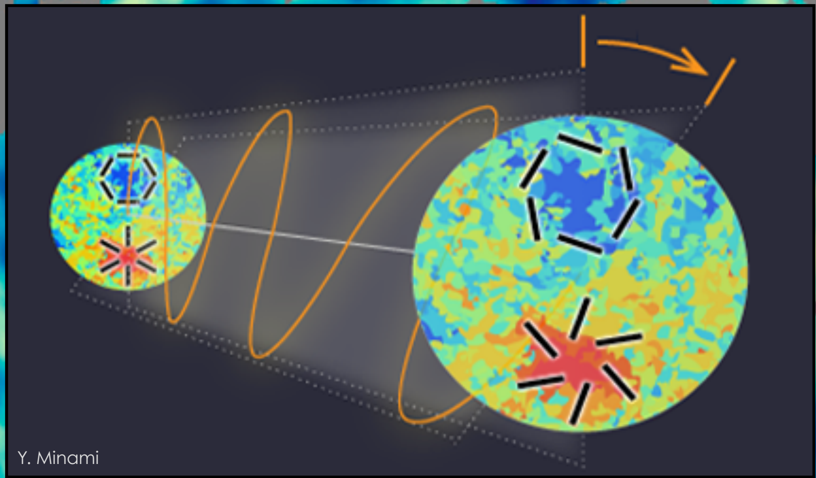
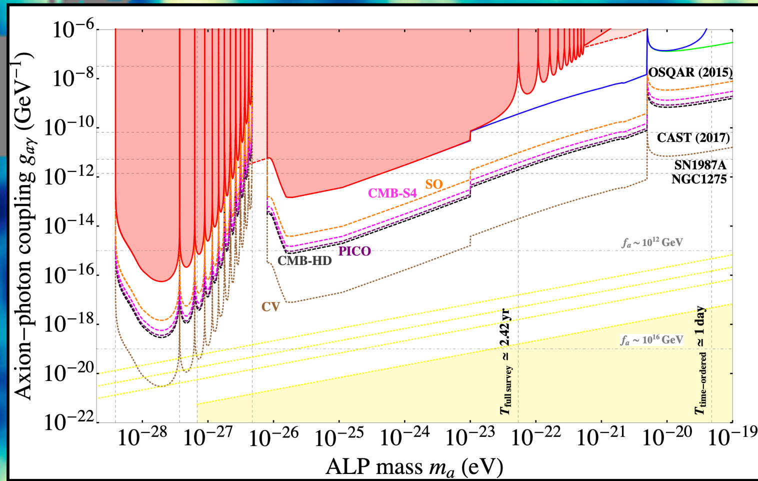
Cosmic Birefringence Signal from Axion-like Dark Matter





Planck ESA

hamburger sternwarte
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Universität Hamburg
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Pranjal Trivedi

University of Hamburg
Hamburg Observatory

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

in collaboration with **Günter Sigl** *(University of Hamburg, II. Institute for Theory)*

DESY Theory Workshop 2021 - Bright Ideas for a Dark Universe

Cosmological Birefringence from Axions

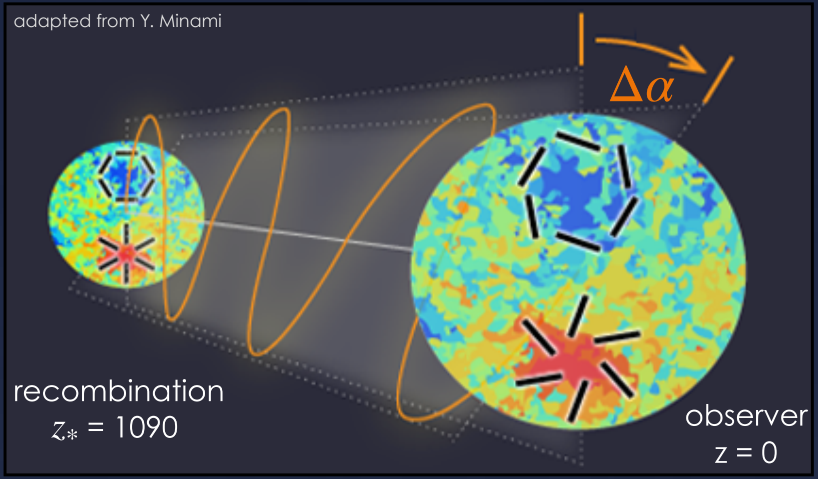
Inhomogeneous axion (or axion-like) field a

—> optically active medium

—> **rotation of polarization of light (birefringence)**

achromatic effect (cf. Faraday rotation $\propto 1/\lambda^2$)

[Carroll, Field & Jackiw 90, Carrol & Field 91, Harari & Sikivie 92, Carroll 98, Lue, Wang & Kamionkowski 99, Liu+ 06, Feng+ 06, Finelli & Galaverni 09, Arvanitaki+ 10, Galaverni+ 15, Fedderke, Graham & Rajendran 19, Fujita+ 20]



$$\Delta\alpha \simeq \frac{g_{a\gamma}}{2}\int_C d\eta\, n^\mu \partial_\mu a \simeq \frac{g_{a\gamma}}{2}\Delta a$$

$$g_{a\gamma} = \frac{s\alpha_{\mathrm{em}}}{2\pi f_a}$$

Earlier picture

$$\Delta a = [a(z_*) - a_{\mathrm{local}}]$$

$$\rho_a = (1/2)\, m_a^2\, a^2$$

$10^{-33}\,\mathrm{eV} \lesssim m_a \lesssim 10^{-28}\,\mathrm{eV}$: a —> cosmological birefringence. But a cannot be DM at CMB epoch

$m_a \gtrsim 10^{-28}\,\mathrm{eV}$: a can be DM - but birefringence considered suppressed $T_a(m_a) \ll \Delta\tau_{\mathrm{rec}}$

(rapid oscillations of a during $\Delta\tau_{\mathrm{rec},99\%} \sim 0.5\,\mathrm{Myr}$)

$$T_a = 2\pi/m_a \simeq (1\ \mathrm{year})(1.22\ \times 10^{-22}\ \mathrm{eV})/m_a$$

Birefringence from oscillating Axion DM

Inhomogeneous axion (or axion-like) field a

—> optically active medium

—> **<u>rotation of polarization</u> of light (<u>birefringence</u>)**

<u>achromatic</u> effect (cf. Faraday rotation ∝ $1/\lambda^2$)

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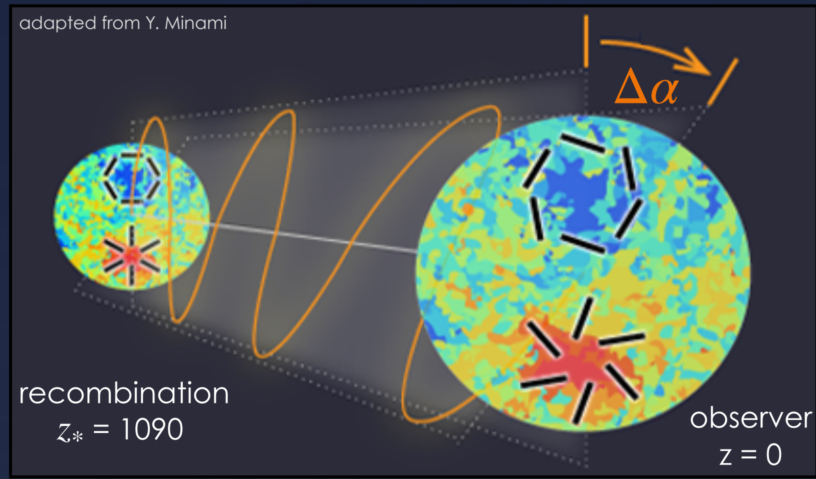


$$\Delta\alpha \simeq \frac{g_{a\gamma}}{2}\int_C d\eta\; n^\mu \partial_\mu a \simeq \frac{g_{a\gamma}}{2}\Delta a$$

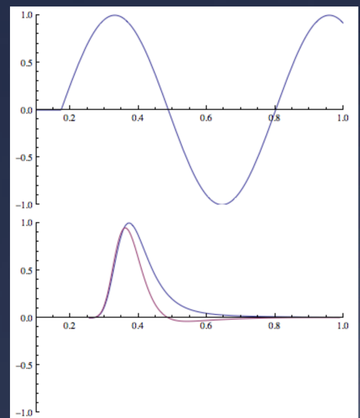
$$g_{a\gamma} = \frac{s\alpha_{\rm em}}{2\pi f_a}$$

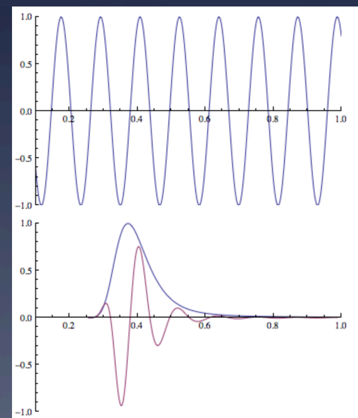
$$\Delta a = [a(z_*) - a_{\rm local}]$$

$$\rho_a = (1/2)\, m_a^2\, a^2$$

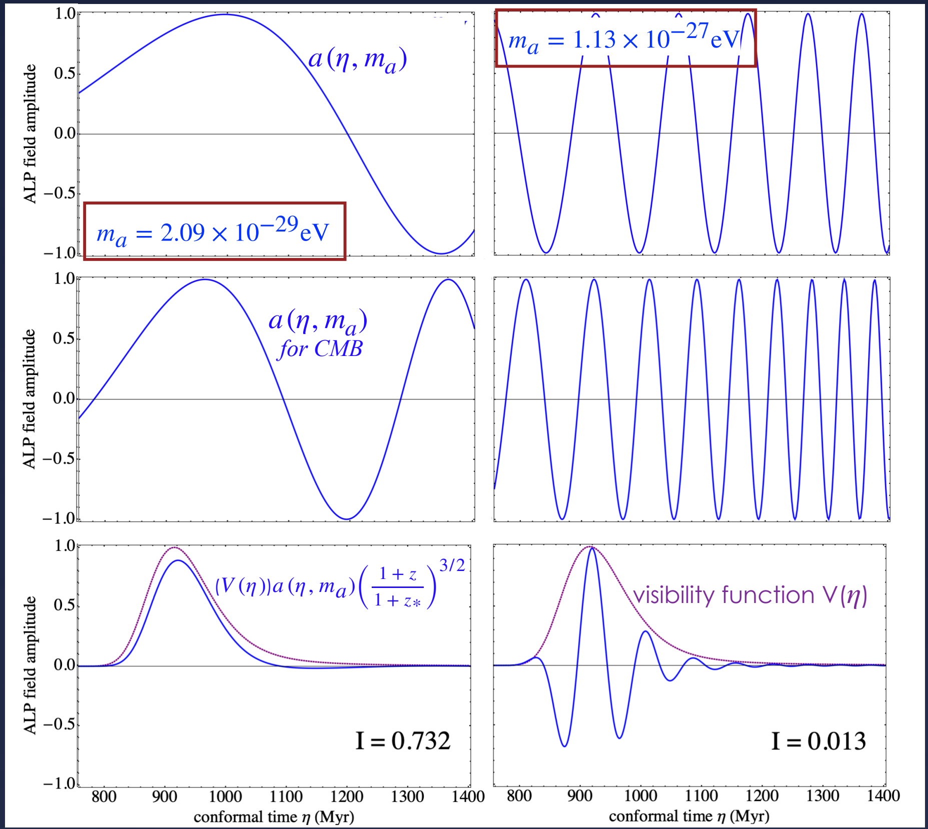
• **<u>This work:</u>**

- Consider **oscillating** $a(t)$, $\omega_a = m_a$, phase, start of oscillation
- Recombination Visibility fn. $V(\eta)$ from Planck, local obs. Window $W(t)$
- Difference of recombination & local signals
- Obs. CMB are photons arriving together from across $V(\eta)$





Axion DM Birefringence



Instead of $\Delta a = [a(z_*) - a_{\rm local}]$

eg. Fedderke, Graham & Rajendran 19; Fujita+ 20]

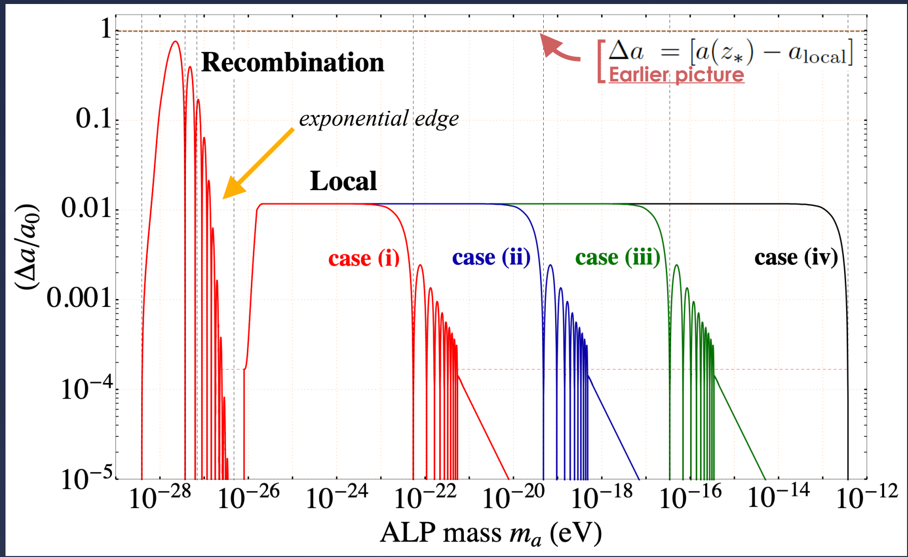
We find

$$\Delta a = \left| \frac{\int_{\rm rec.} V(\eta)\, a(\eta, m_a) \left(\frac{1+z}{1+z_*}\right)^{3/2} d\eta}{\int_{\rm rec.} V(\eta)\, d\eta} \right| - \left| \frac{\int_{\rm loc.} W(t)\, a(t)\, dt}{\int_{\rm loc.} W(t)\, dt} \right| .$$

where

$$a(\eta, m_a) = \Theta\left[\eta - \eta_{\rm osc}(m_a)\right] \times a_0 \cos\left[m_a\{\eta - \eta_{\rm osc}(m_a) - (\eta_{\rm peak} - \eta)\} + \delta_0\right],$$

$$a_0 = \int_{\rm rec.} \delta(\eta - \eta_*)\, a(\eta) d\eta$$



- **Our recent work:**
  - Consider **oscillating** $a(t)$, $\omega_a = m_a$, phase, start of oscillation
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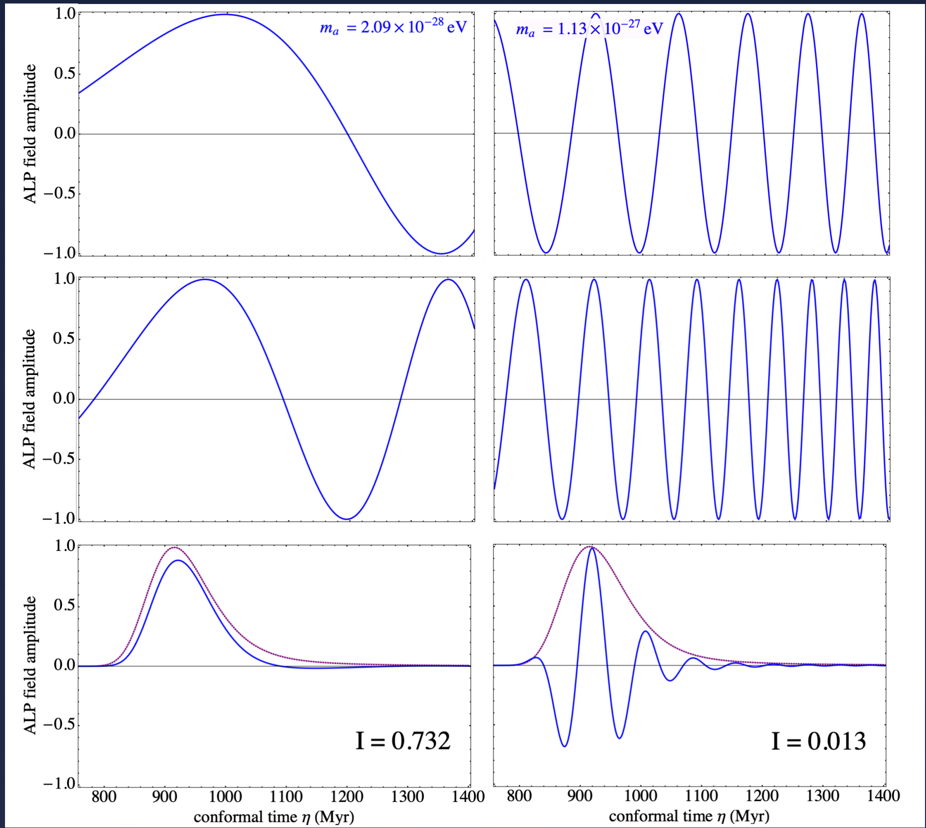
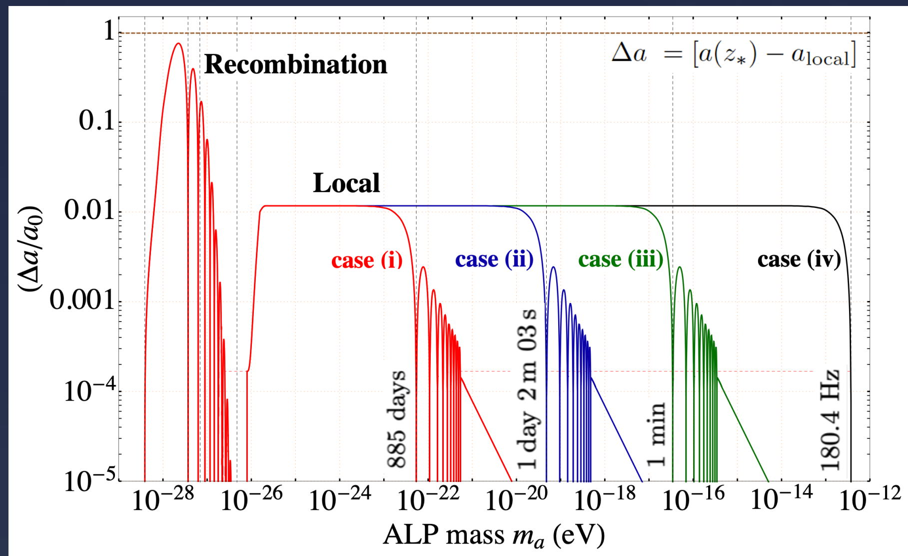
  - **Difference** of recombination & local signals: birefringence

Axion DM Birefringence



Time scale or Frequency	*Planck* Mission value	Corresponding ALP mass m_a (eV)	Time Period $T_a(m_a) = 2\pi/m_a$ (yr)
$\mathcal{T}_{\text{full survey}}$	885 days	5.41×10^{-23}	2.423
$\mathcal{T}_{\text{time-ordered data}}$	1 day 2 m 03 s	4.78×10^{-20}	2.74×10^{-3}
$\mathcal{T}_{\text{rotation}}$	1 min	$3.45 \times 10^{-17\,\dagger}$	$3.80 \times 10^{-6\,\dagger}$
$\mathcal{F}_{\text{sampling}}$	180.4 Hz	$3.73 \times 10^{-13\,\dagger}$	$3.51 \times 10^{-10\,\dagger}$



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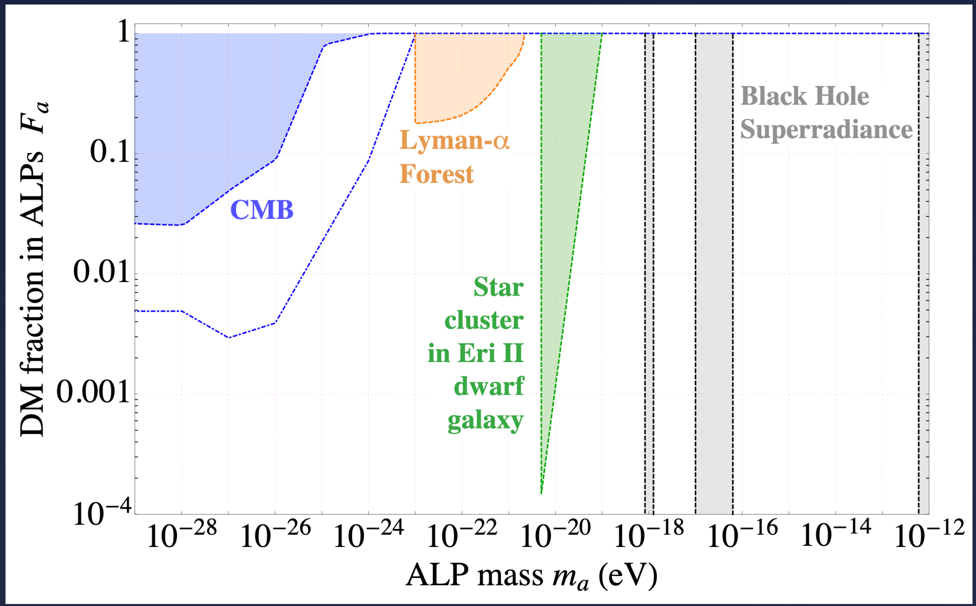
  - **Difference** of recombination & local signals: birefringence

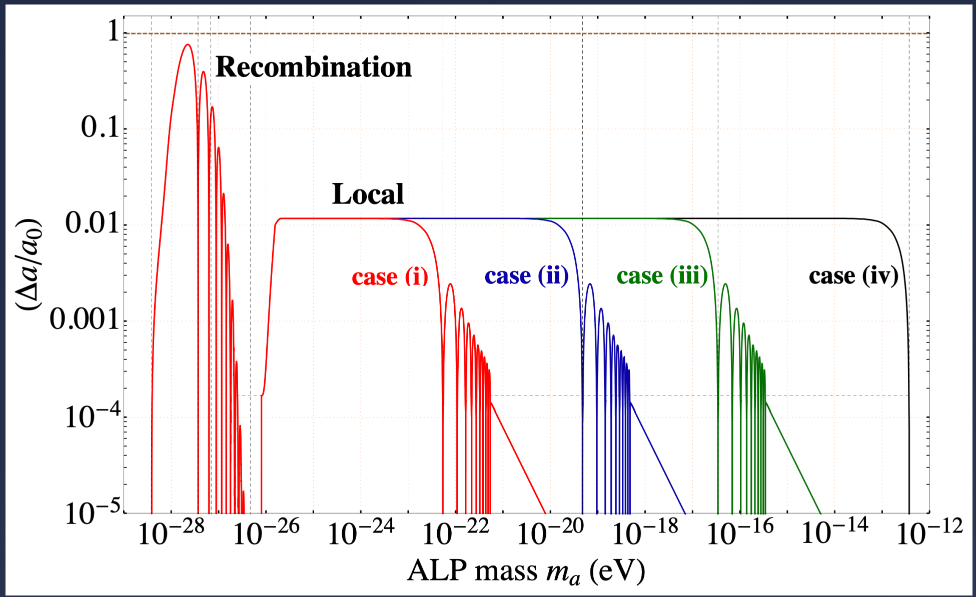
Constraints on the Fraction of ALP DM included

Constraints already exist on the DM fraction possible as ALPs



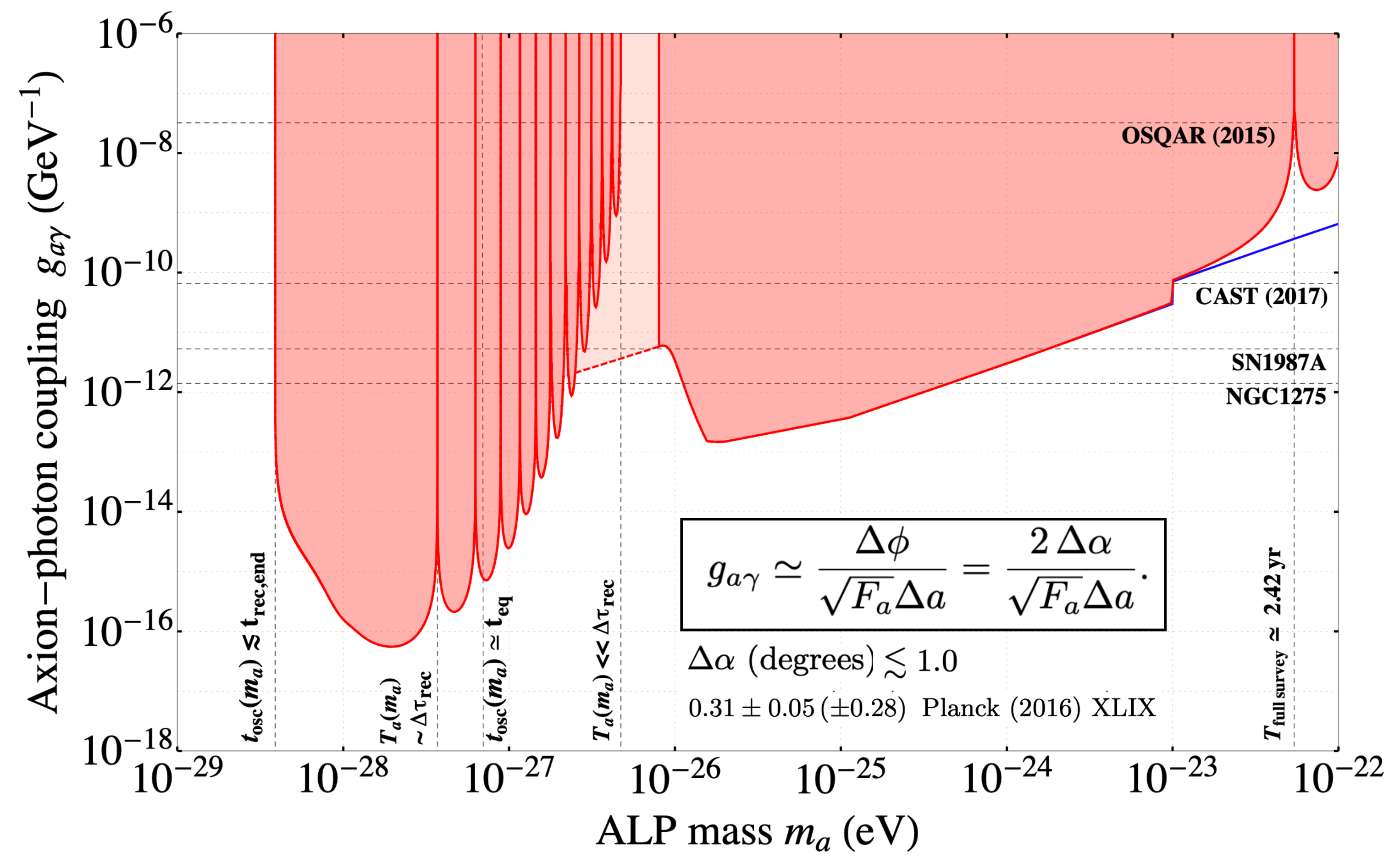
$F = \Omega_a / \Omega_c$ $\sqrt{F_a}$ multiplies $(\Delta a / a_0)$ below

Lowering DM fraction
—> only mild weakening of signal



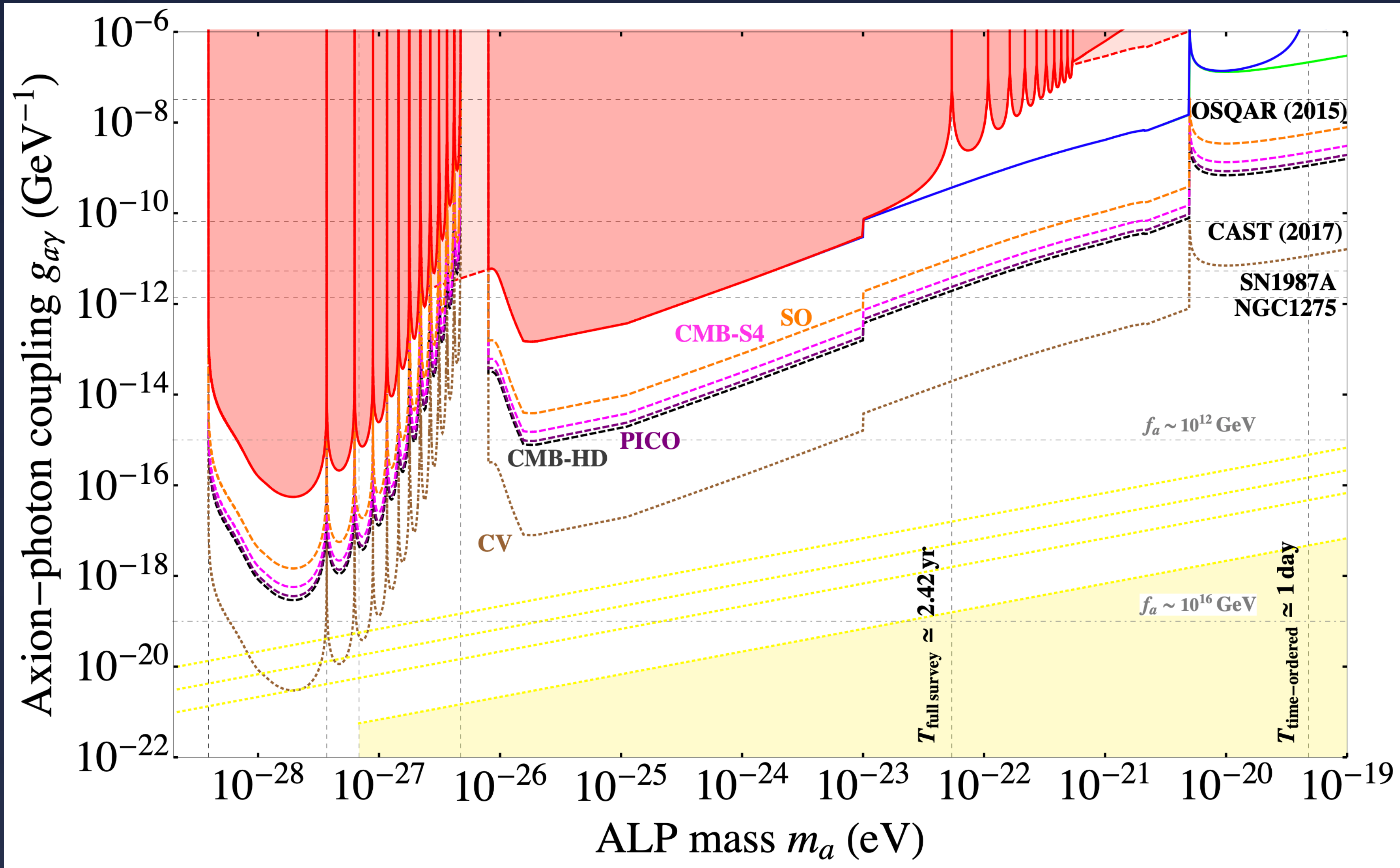
To give constraints on axion-photon coupling…..

Isotropic Birefringence **Constraints**

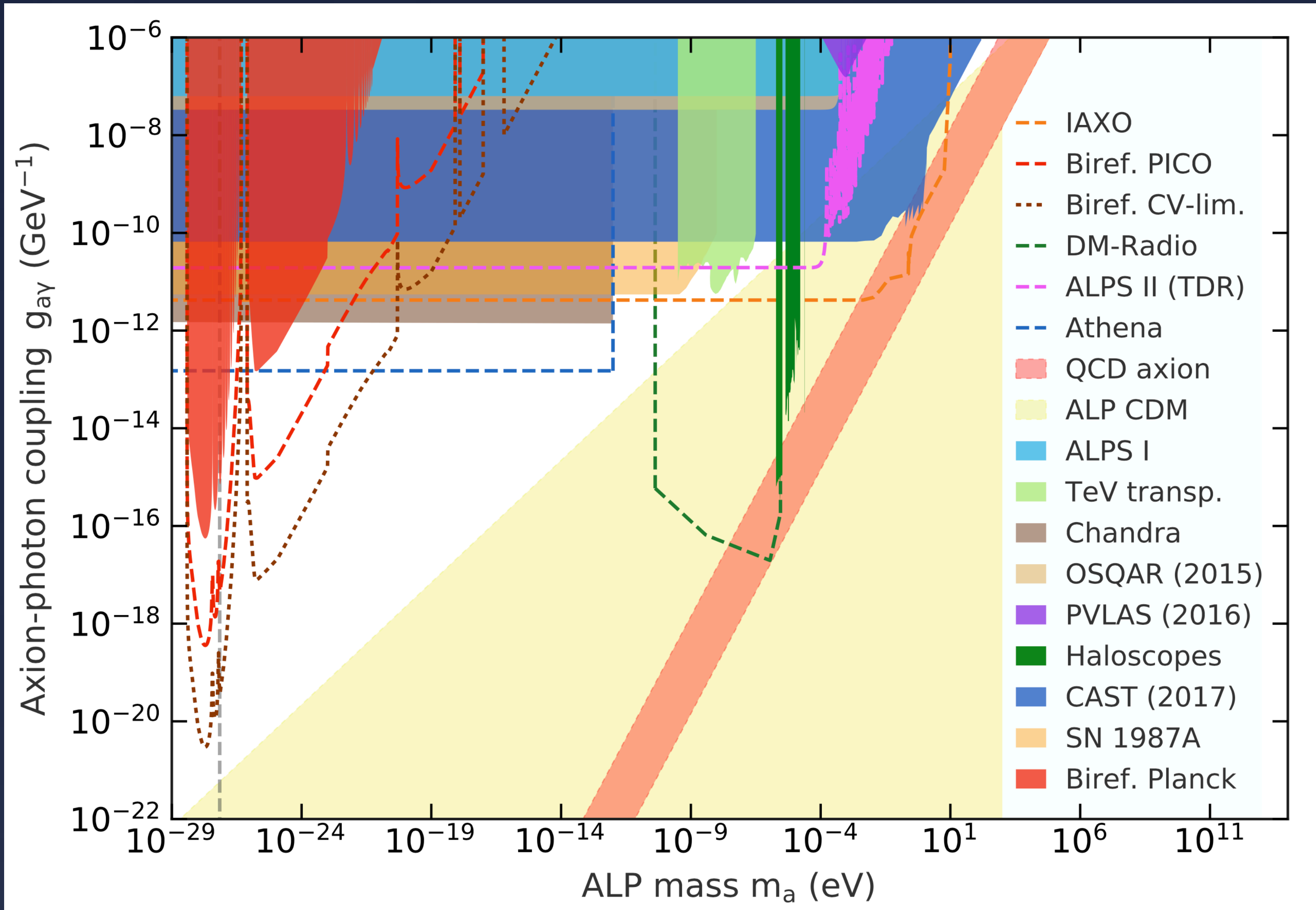


Cosmological Epoch t or Time scale τ	Corresponding ALP mass m_a (eV)	Time Period $T_a(m_a) = 2\pi/m_a$ (Myr)	Redshift of Oscillation z_{osc}	Oscillation Epoch $t_{osc} = \tau_{age}(z_{osc})$ (Myr)	Feature produced in the Birefringence Signal Δa from Recombination
$t_{osc}(m_a) \lesssim t_{rec,end}$	3.9×10^{-29}	3.4	600	0.99	a_{rec} signal rises above zero
$T_a(m_a)/2 \lesssim \Delta\tau_{rec}$	1.7×10^{-28}	0.75	1530	0.21	maximum a_{rec} signal at 1st peak
$T_a(m_a) \sim \Delta\tau_{rec}$	2.6×10^{-28}	0.50	1950	0.14	1st null of a_{rec} signal
$t_{osc}(m_a) = t_{eq}$	6.8×10^{-28}	0.19	3400	0.051	T-indep. m_a limit: std. ALP DM
$T_a(m_a) \ll \Delta\tau_{rec}$	2.9×10^{-27}	0.046	7570	0.012	exponential damping of a_{rec} signal

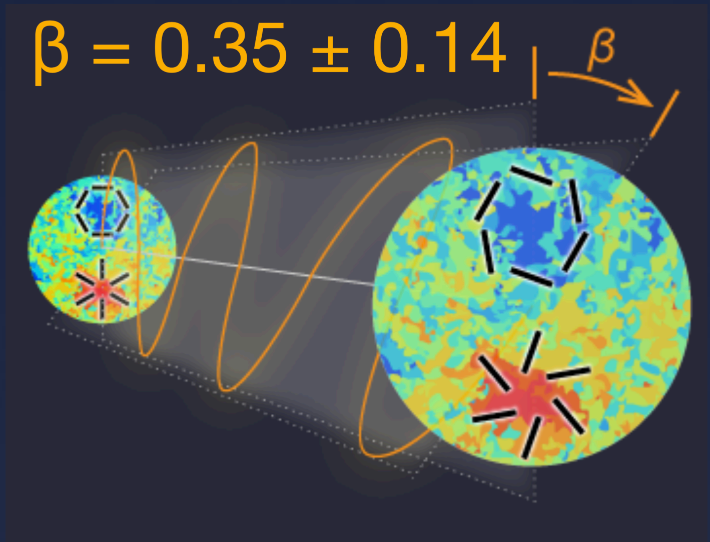
Isotropic Birefringence **Forecasts**



Isotropic Birefringence **Forecasts**



Hint!? of Cosmic Birefringence



Y. Minami

Breakthrough analysis
of Planck 2018 CMB polarization data

Compared Birefringence from
CMB ↔ Galactic CMB foreground

—> isolated detector (HFI) miscalibration angle uncertainty

—> reduced systematic error by x 2

cf.
$0.31 \pm 0.05\,(\pm 0.28)$
Planck Collaboration I. XLIX 2016

PHYSICAL REVIEW LETTERS **125,** 221301 (2020)

Editors' Suggestion | Featured in Physics

New Extraction of the Cosmic Birefringence from the Planck 2018 Polarization Data

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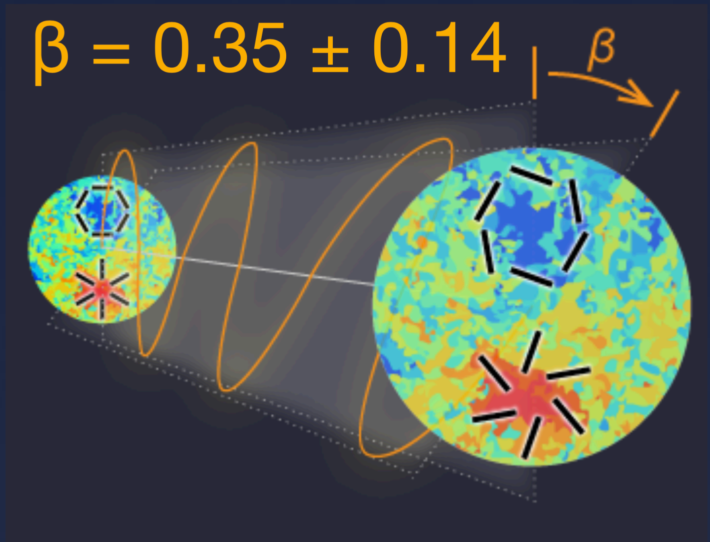
Eiichiro Komatsu†

We search for evidence of parity-violating physics in the Planck 2018 polarization data and report on a new measurement of the cosmic birefringence angle β. The previous measurements are limited by the systematic uncertainty in the absolute polarization angles of the Planck detectors. We mitigate this systematic uncertainty completely by simultaneously determining β and the angle miscalibration using the observed cross-correlation of the E- and B-mode polarization of the cosmic microwave background and the Galactic foreground emission. We show that the systematic errors are effectively mitigated and achieve a factor-of-2 smaller uncertainty than the previous measurement, finding $\beta = 0.35 \pm 0.14$ deg (68% C.L.), which excludes $\beta = 0$ at 99.2% C.L. This corresponds to the statistical significance of 2.4σ.

Interpretation of Cosmic Birefringence



Y. Minami

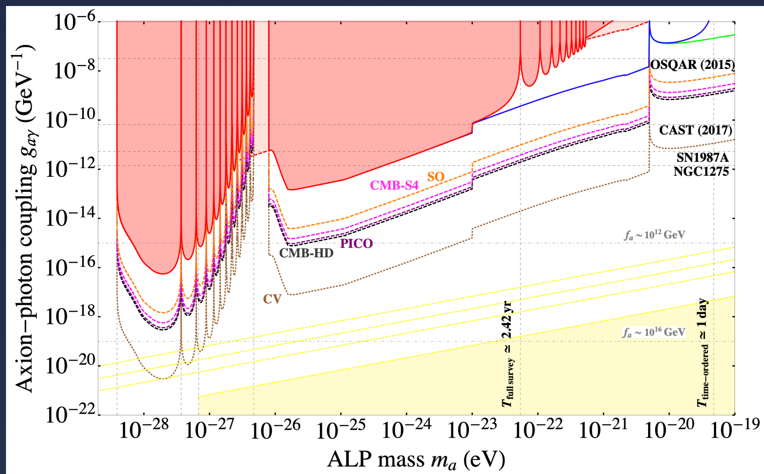
cf.
$0.31 \pm 0.05\,(\pm 0.28)$
Planck Collaboration I. XLIX 2016

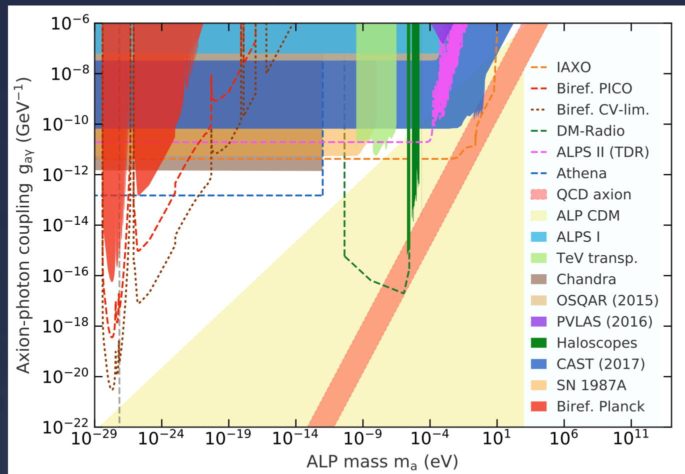
Critical Assessment

- ***Dust*** effects: full investigation (see recent Galactic dust EB - Clark+ 2105.00120)
- Foreground effects and EB
- Fresh look at systematics, instrument modelling
- Low significance 2.4σ : needs to be compared to other CMB data
- Independent Verification!

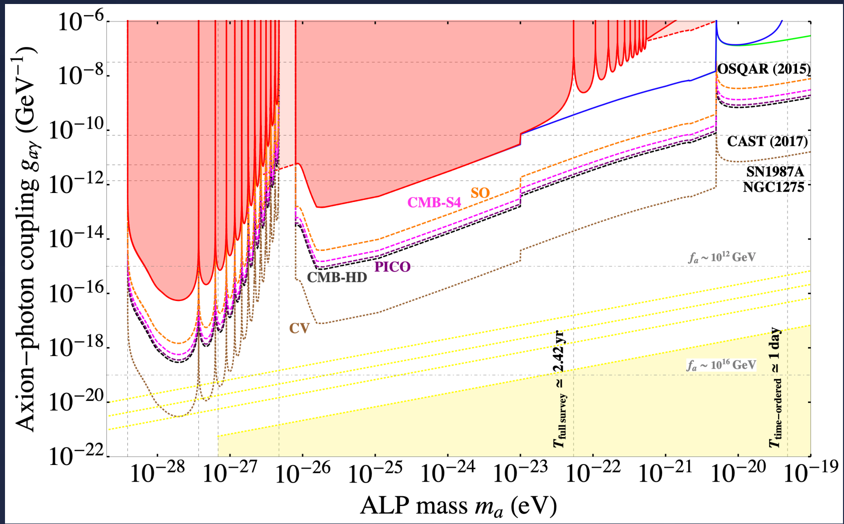
Future Observations: SO, BICEP Array, CMB-S4, CMB-HD, LiteBIRD, PICO

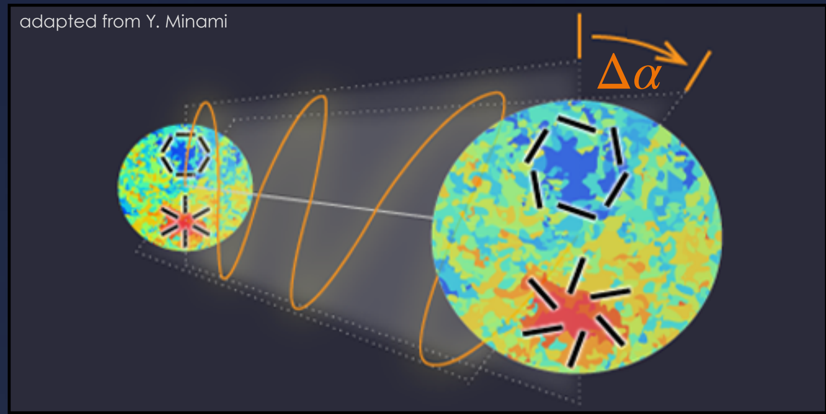
Our theory constraints & forecasts:





CMB Birefringence probe of Axion(-like) Dark Matter





- Cosmic birefringence constraints are <u>upto 4 orders stronger</u> than x-ray AGN in cluster constraints (Chandra).
- Mass scales probed by CMB in log (m_a/eV)
  -29 to -27 and -26 to -21 (upto FDM)
- CMB-S4, PICO, CMB-HD can all improve by 1-2 orders of mag. in axion-photon coupling
- Exciting obs. hint of 0.35 (0.14) isotropic birefringence —> if confirmed <u>could reveal axions contributing to dark matter</u>

CMB Birefrengence robust probe of aDM :

<u>Independent of</u>

- Astrophysical magnetic fields, unknown P_B (k)
- DM density assumptions/enhancements/spikes
- Astrophysical polarised source

Thank you