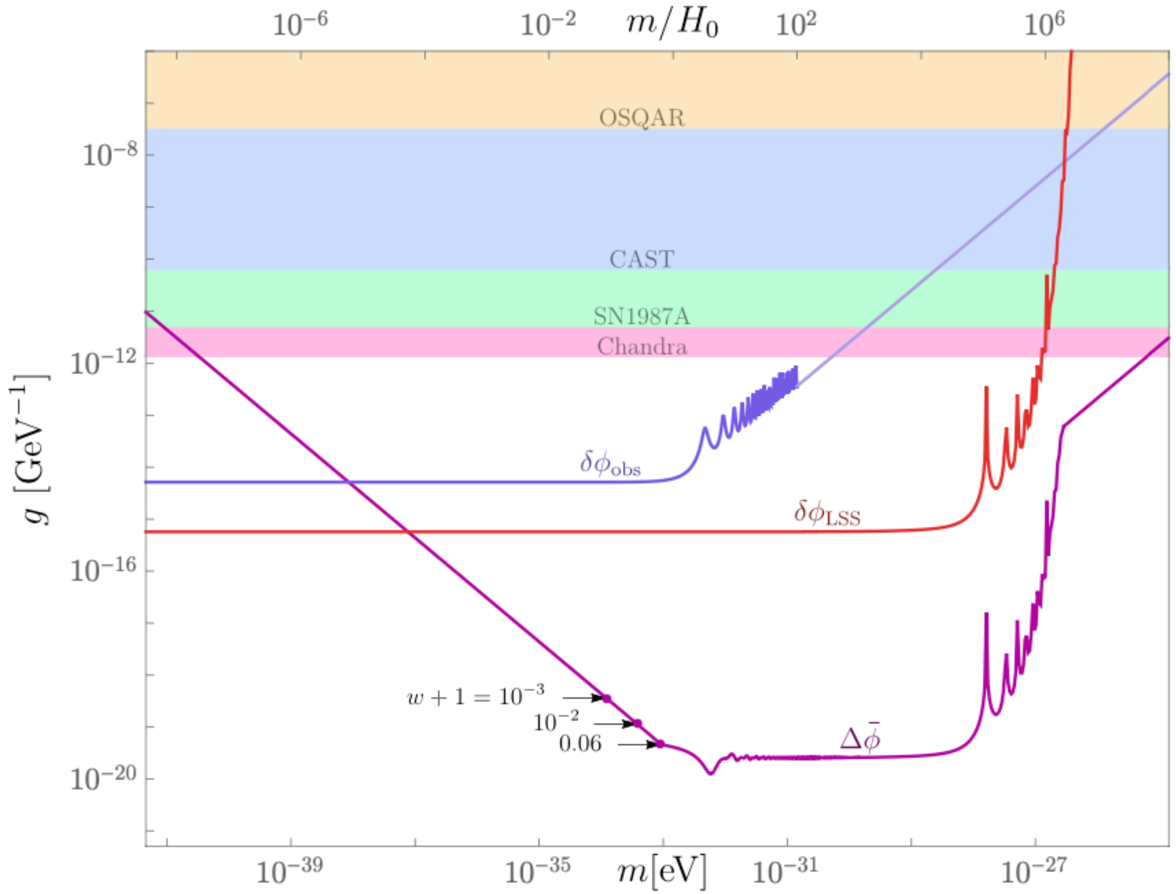
Probing Axion-like Particles via CMB Polarization



Collaborators: Tomohiro Fujita, Yuto Minami, Kai Murai,

arxiv:2008.02473

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PPP,2020-09-03

Axion

QCD axion

- Strong CP problem:

C. A. Baker, et al. (2006)

$$\mathcal{L}_{\theta_{QCD}} = \frac{\theta_{QCD}}{32\pi^2}\mathrm{Tr}G_{\mu\nu}\tilde{G}^{\mu\nu} \quad , \quad \theta_{QCD} \lesssim 10^{-10}$$

by the electric dipole moment of neutron

- One of solutions is QCD axion:

$$\mathcal{L}_{\theta_{QCD}} \to \left(\theta_{QCD} + \frac{\phi}{f}\right)\frac{1}{32\pi^2}\mathrm{Tr}G_{\mu\nu}\tilde{G}^{\mu\nu}$$

Axion-like particles by String Axiverse

A. Arvanitaki, et al. (2009)

“String theory suggests the simultaneous presence of many ultralight axions”

- Axions have mass nonperturbatively, which is exponentially suppressed:

$$m_\phi^2 \propto \left(\frac{\mu^4}{f^2}\right)e^{-S_{\mathrm{inst}}}$$

David J. E. Marsh (2015)

- Axion as Dark Matter: $10^{-22}\mathrm{eV} \lesssim m$
- Axion as Dark Energy: $m \lesssim H_0 \sim 10^{-33}\mathrm{eV}$

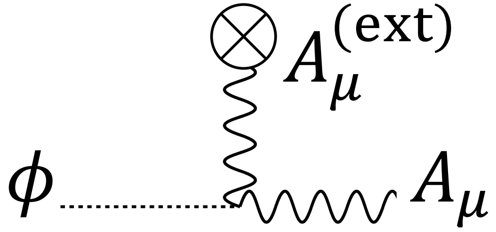
Axion-like Particles

Axion-Photon coupling

$$\mathcal{L} = -\frac{1}{2}\partial^{\mu}\phi\partial_{\mu}\phi - V(\phi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{4}g\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$

, ϕ:axion(ALP)

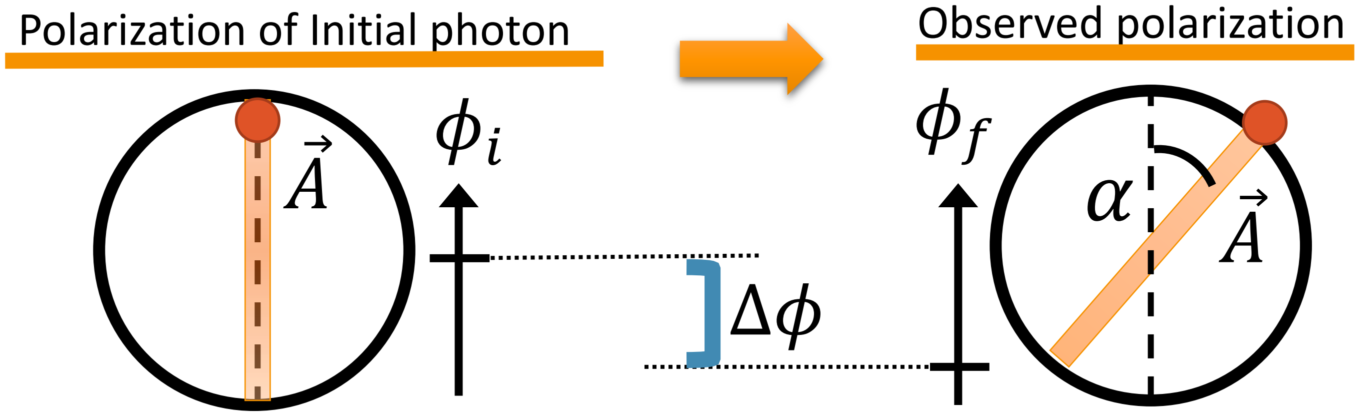
- Axion-photon conversion
  By background B field:



- Rotation of polarization angle

$$\alpha = \frac{g}{2}\Delta\phi = \frac{g}{2}(\phi_f - \phi_i)$$

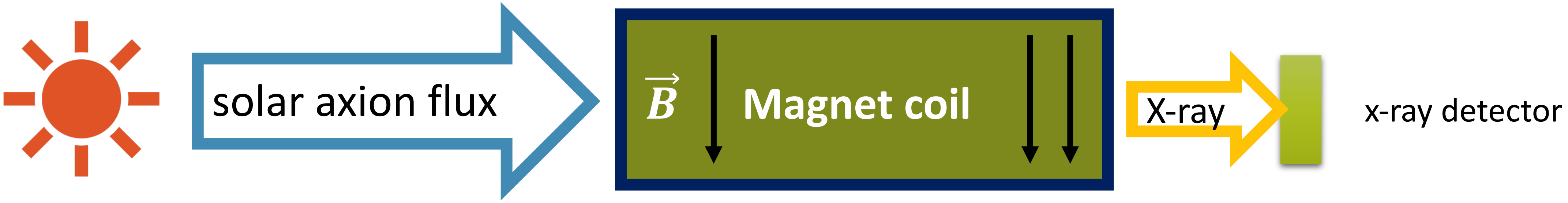
D.Harari&P.Sikivie (1992)


Polarization of Initial photon

Observed polarization

Axion-photon conversion

- Axion Helioscope (e.g., CAST, CAST Collaboration (2005))



solar axion flux

$\vec{B}$ **Magnet coil**

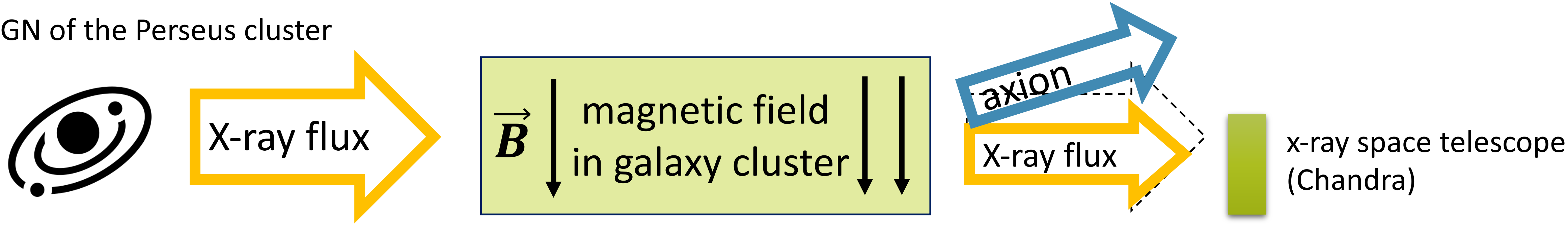
X-ray

x-ray detector

- Axion Dark Matter eXperiment (ADMX) for Axion DM S.J. Asztalos, et al. (2009)
  - The microwave cavity for resonant conversion

- X-ray space telescope: Chandra observatory M. Berg, et al. (2016)

AGN of the Perseus cluster



X-ray flux

$\vec{B}$ magnetic field in galaxy cluster

axion

X-ray flux

x-ray space telescope (Chandra)

Polarization rotation

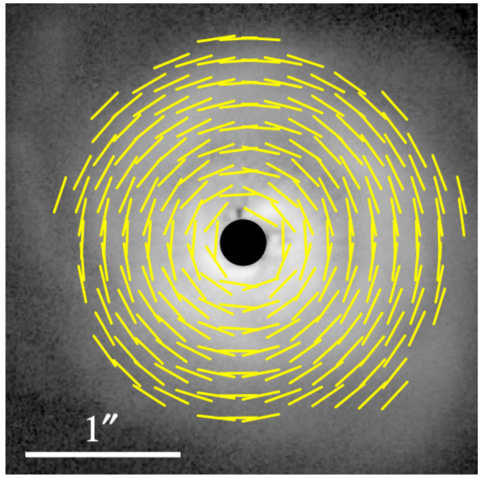
- Ground-based experiment: Laser technique
  - The background axion DM rotates the polarization angle of laser.
  - Laser cavity can detect the small rotation angle.

  H. Liu, et al. (2018), I. Obata, et al. (2018), K. Nagano, et al. (2019)

- Astronomical source (e.g. proto-planetary disc)
  - Flattened gaseous object surrounding a young star
  - The background axion DM rotates the direction of scattering polarization.

  J. Hashimoto, et al. (2011), T. Fujita, et al. (2018), S. Chigusa et al. (2019)

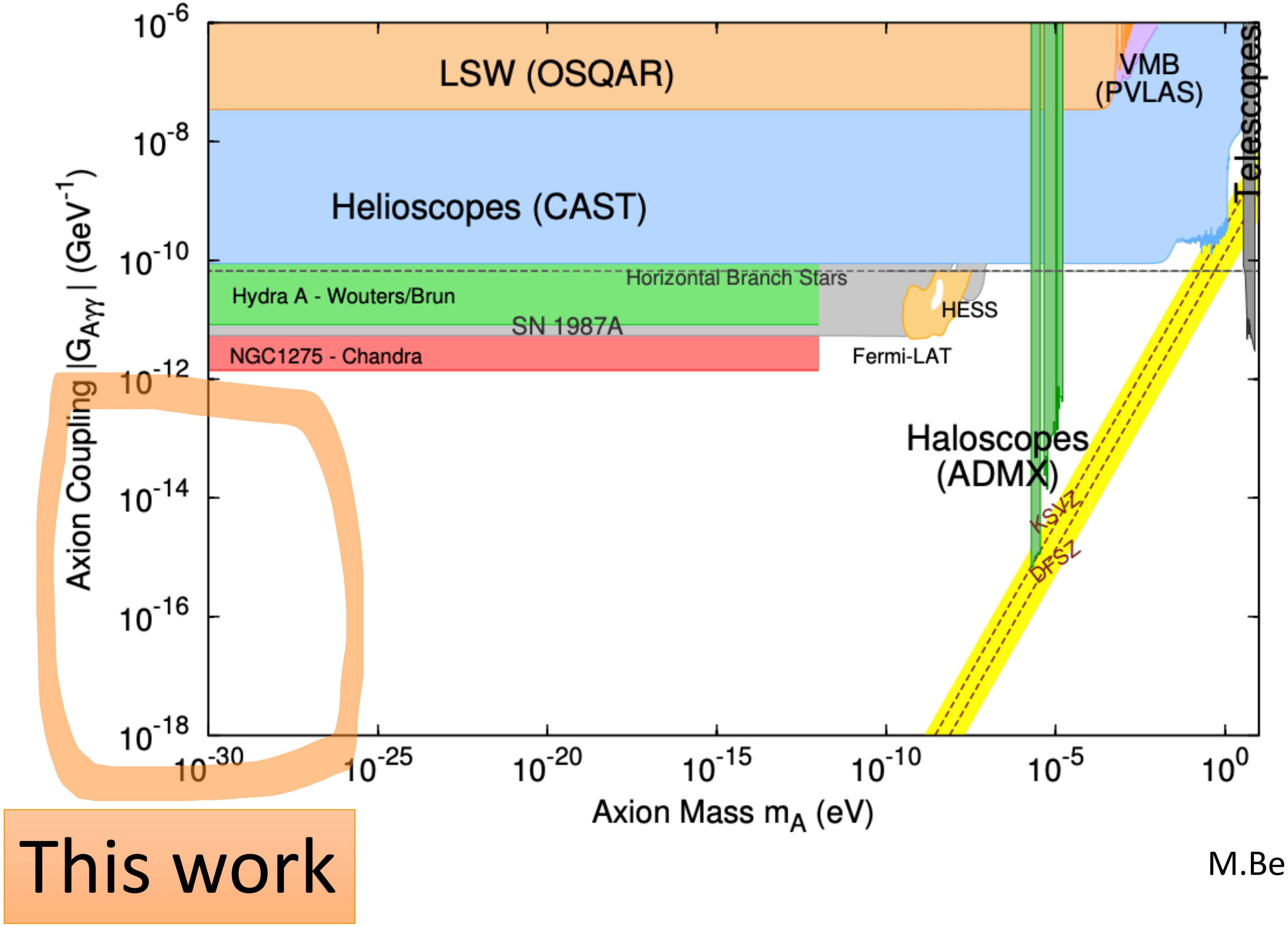
J.Hashimoto, et al. (2011),



- Cosmological source: CMB

  S. M. Carroll (1998), A. Lue, et al. (1999), M. A. Fedderke, et al. (2019), G. Sigl&P. Trivedi (2018)
  - and This work

The constraints of axion-photon coupling

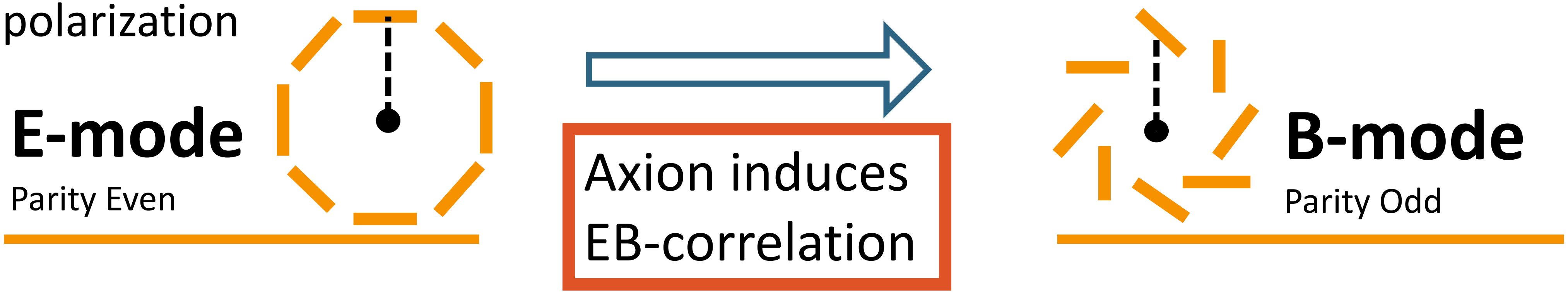


This work

M.Berg, et.al. (2016)

Cosmic Birefringence

- CMB polarization



E-mode

Parity Even

Axion induces EB-correlation

B-mode

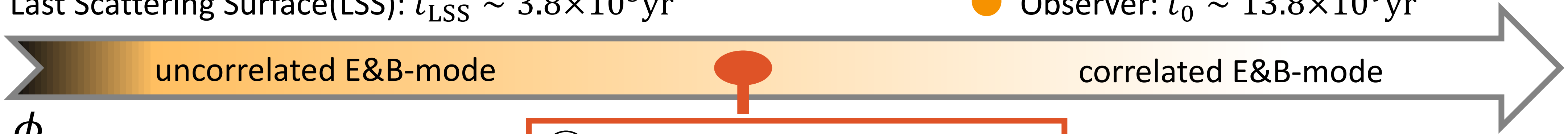
Parity Odd

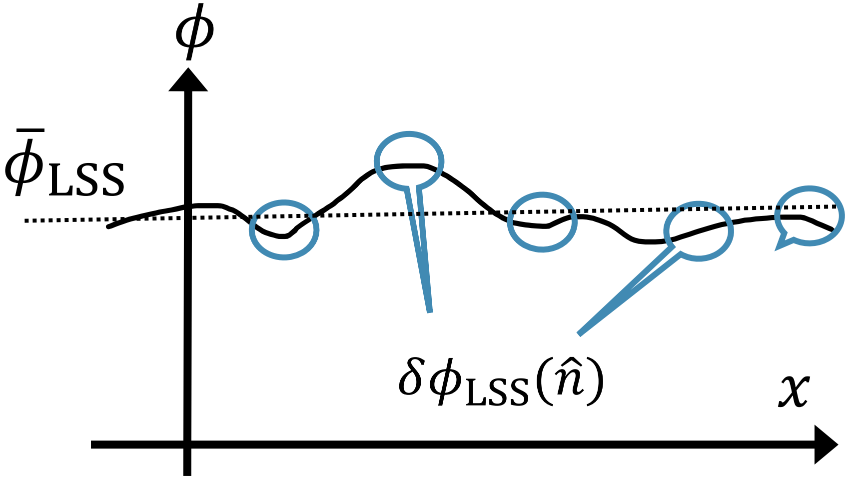
- Cosmic Birefringence

S.M.Carroll (1998), A. Lue, et.al. (1999)

● Last Scattering Surface(LSS): $t_{\rm LSS} \sim 3.8\times10^{5}{\rm yr}$

● Observer: $t_0 \sim 13.8\times10^{9}{\rm yr}$



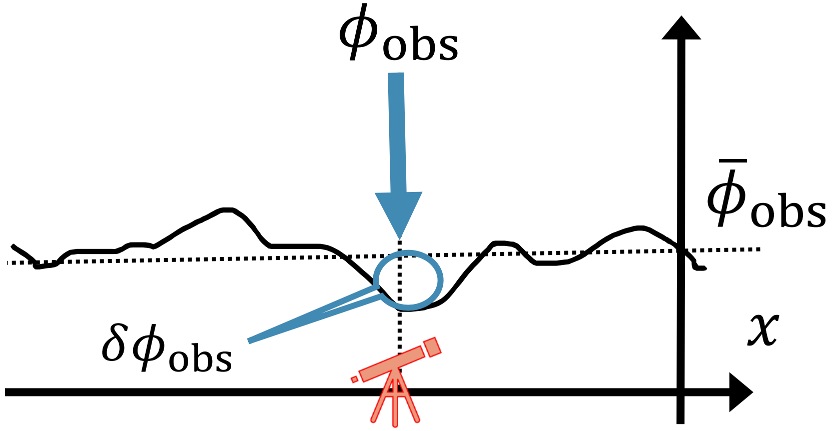


① anisotropic rotation (direction dependent)

$$\alpha(\hat{n}) \equiv -\frac{g}{2}\delta\phi_{\rm LSS}(\hat{n})$$

② isotropic rotation

$$\bar{\alpha} \equiv \frac{g}{2}(\bar{\phi}_{\rm obs} - \bar{\phi}_{\rm LSS} + \delta\phi_{\rm obs})$$



Field Dynamics

Birefringence by $\Delta\bar{\phi}$, $\delta\phi_{\rm obs}$ and $\delta\phi_{\rm LSS}$

- $\begin{cases}\phi_{\rm LSS} = \bar{\phi}(t_{\rm LSS}) + \delta\phi_{\rm LSS}(t_{\rm LSS},\hat{n}) \\ \phi_{\rm obs} = \bar{\phi}(t_0) \quad + \delta\phi_{\rm obs}(t_0, x=0)\end{cases}$
- H_0: (current Hubble parameter)

- Potential term : $V(\phi) = \frac{1}{2}m^2\phi^2$
- Background motion : $\Delta\bar{\phi} \equiv \bar{\phi}(t_0) - \bar{\phi}(t_{\rm LSS})$,
  - Dynamics : $\bar{\phi}(t) \propto \begin{cases}\text{constant} & (m < H(t)\,) \\ a(t)^{-\frac{3}{2}}\sin(mt) & (H(t) < m)\end{cases}$
  - Amplitude : $|\bar{\phi}| \propto \Omega_\phi^{1/2}$, $\Omega_\phi \sim \begin{cases}0.7\ (\mathrm{m} \lesssim H_0) \\ 0.01\ (H_0 \lesssim \mathrm{m} \lesssim 10^{-25}\mathrm{eV})\end{cases}$ R.Hlozek, et.al.(2015)
- Perturbation: $\delta\phi_{\rm obs}$ & $\delta\phi_{\rm LSS}$
  - $\mathcal{P}_\phi^{\rm inf} = \left(\frac{H_I}{2\pi}\right)^2 = \frac{M_{\rm pl}{}^2}{8\pi}\mathcal{P}_\zeta \times r$, $\mathcal{P}_\zeta \simeq 2\times10^{-9}$, r: tensor to scalar ratio, we use $r = 0.06$

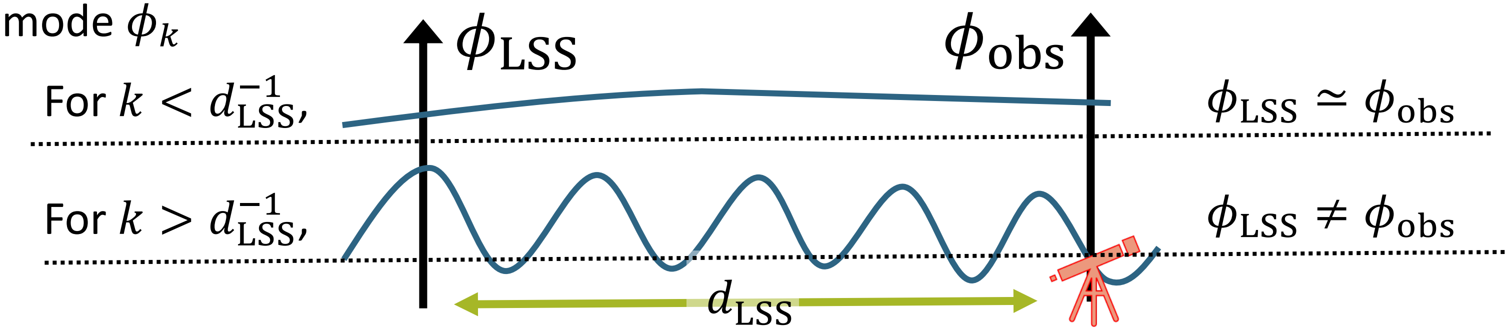
① anisotropic rotation (direction dependent) : $\alpha(\hat{n}) \equiv -\frac{g}{2}\delta\phi_{\rm LSS}(\hat{n})$

② isotropic rotation : $\bar{\alpha} \equiv \frac{g}{2}(\Delta\bar{\phi} + \delta\phi_{\rm obs})$

Field Dynamics

Fluctuation at observer: $\delta\phi_{\mathrm{obs}}$

- The Fourier mode $\tilde{\phi}_k$



For $k < d_{\mathrm{LSS}}^{-1}$, $\phi_{\mathrm{LSS}} \simeq \phi_{\mathrm{obs}}$

For $k > d_{\mathrm{LSS}}^{-1}$, $\phi_{\mathrm{LSS}} \neq \phi_{\mathrm{obs}}$

- $$\langle \delta\phi_{\mathrm{obs}}^2 \rangle = \int_{d_{\mathrm{LSS}}^{-1}}^{\infty} \int_{d_{\mathrm{LSS}}^{-1}}^{\infty} \frac{\mathrm{d}^3k\mathrm{d}^3p}{(2\pi)^6} \langle \phi_{\boldsymbol{k}}(\eta_0)\phi_{\boldsymbol{p}}(\eta_0) \rangle$$

Damping effect by the width of LSS

● Last Scattering Surface(LSS): $t_{\mathrm{LSS}} \sim 3.8{\times}10^5\mathrm{yr}$

● Observer: $t_0 \sim 13.8{\times}10^9\mathrm{yr}$

- For $m > 10^{-28}$eV, ϕ oscillates at LSS:

$$\langle \bar{\phi} \rangle_{\mathrm{LSS}} = \int \mathrm{d}T\, g(T)\bar{\phi}\,(t(T))$$

, visibility function: $g(T) \simeq \frac{1}{\sqrt{2\pi}\sigma_T} \exp\left[-\frac{(T-T_L)^2}{2\sigma_T^2}\right]$

Sensitivity

Current sensitivity from Planck, SPTpol & ACTPol

N. Aghanim, et al. (2016), F. Bianchini, et al. (2020), T. Namikawa, et al. (2020)

① anisotropic rotation (direction dependent) : $\alpha(\hat{n}) \equiv -\frac{g}{2}\delta\phi_{\mathrm{LSS}}(\hat{n})$

$$C_L^{\alpha\alpha} \equiv \frac{1}{2L+1}\sum_M a_{(\alpha)LM}a^*_{(\alpha)LM}, \quad a_{(\alpha)Lm} \equiv \int \mathrm{d}\Omega\, \alpha(\hat{n})\, Y_L^{m*}(\hat{n})$$

- For flat power spectrum,

$$A_\alpha \equiv \frac{L(1+L)C_L^{\alpha\alpha}}{2\pi}$$

- SPTpol & ACTPol 2020:

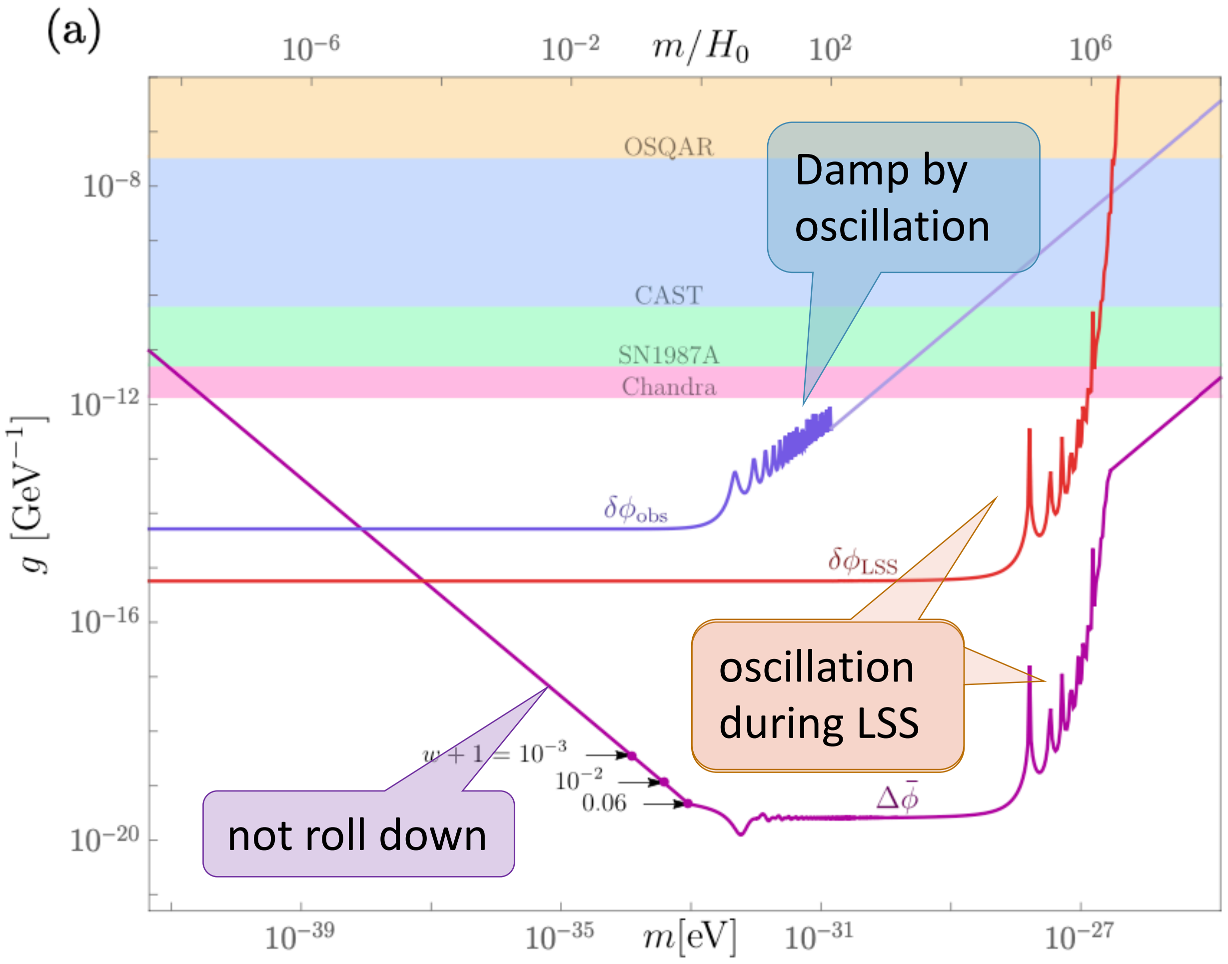
$$A_\alpha < 8.3\times10^{-3}\,\mathrm{deg}^2 \quad (68\%\mathrm{CL})$$

② isotropic rotation : $\bar{\alpha} \equiv \frac{g}{2}(\Delta\bar{\phi} + \delta\phi_{obs})$

- Planck2016: $|\bar{\alpha}| < 0.6\,°\quad(68\%\mathrm{CL})$

Sensitivity

H_0: (current Hubble parameter)



Damp by oscillation

oscillation during LSS

not roll down

- ■ Current sensitivity from Planck & SPTpol

  N. Aghanim et al. 2016, F. Bianchini et al.2020, T. Namikawa et al. 2020

- ● Red line by $\delta\phi_{\rm LSS}$

  For $10^{-28}\mathrm{eV} < m, \phi$ oscillates during LSS, and the averaged rotation angle damps.

- ● Purple line by $\Delta\bar{\phi}$

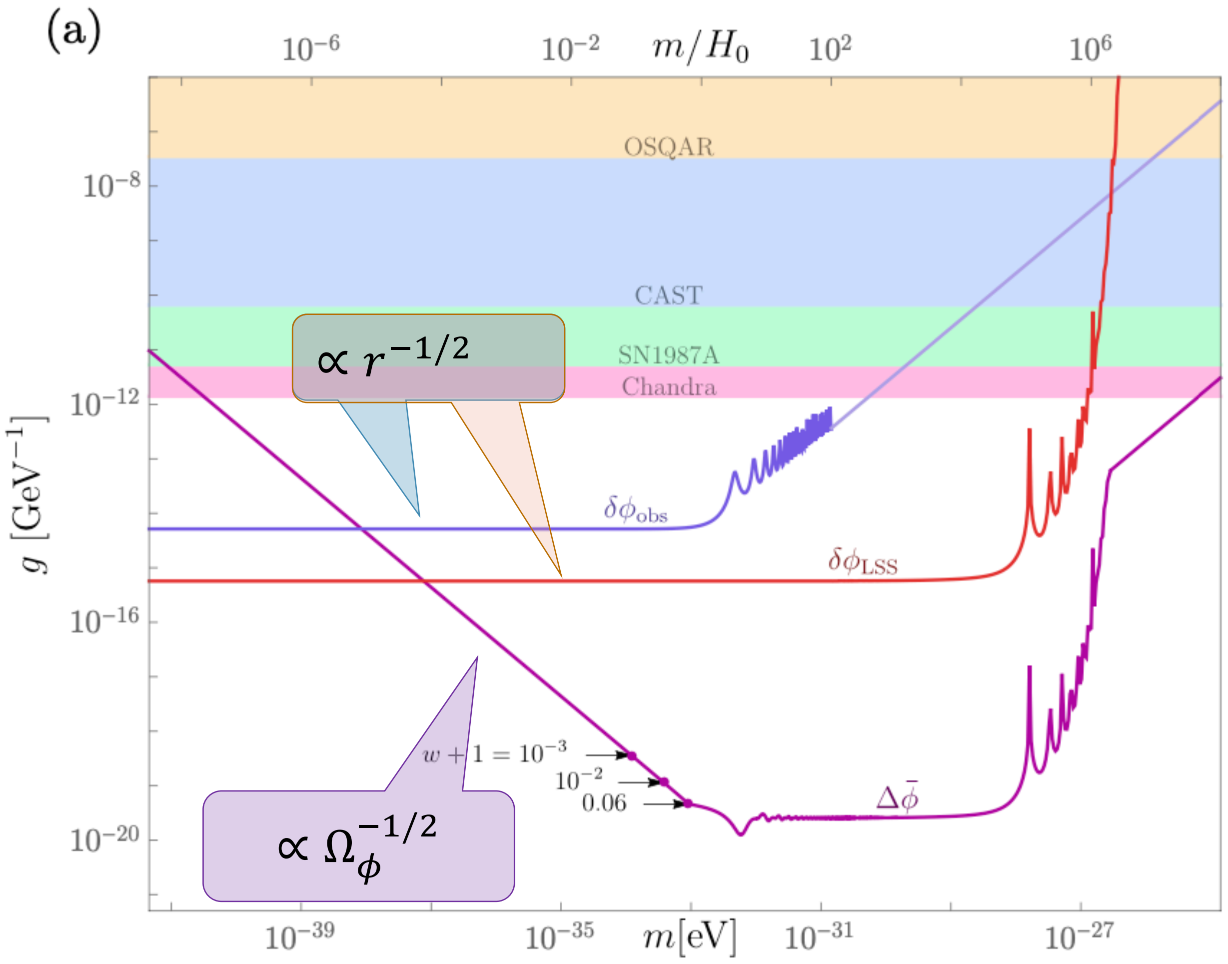
  For $m < H_0, \bar{\phi}$ does not roll down the potential, and $\Delta\bar{\phi} \propto (m/H_0)$

- ● Blue line by $\delta\phi_{\rm obs}$

  For $H_0 < m$, $\delta\phi_{\rm obs}$ starts oscillating and damps.

Sensitivity

H_0: (current Hubble parameter)



$\propto r^{-1/2}$

$\propto \Omega_{\phi}^{-1/2}$

- Current sensitivity from Planck & SPTpol

- Even if no BG axion $\Omega_{\phi} \to 0$, we ubiquitously have $\delta\phi_{\mathrm{LSS}}$& $\delta\phi_{\mathrm{obs}}$ from inflation.
  - $\delta\phi_{\mathrm{LSS}}$:anisotropic birefringence
  - $\delta\phi_{\mathrm{obs}}$:isotropic birefringence

Future sensitivity

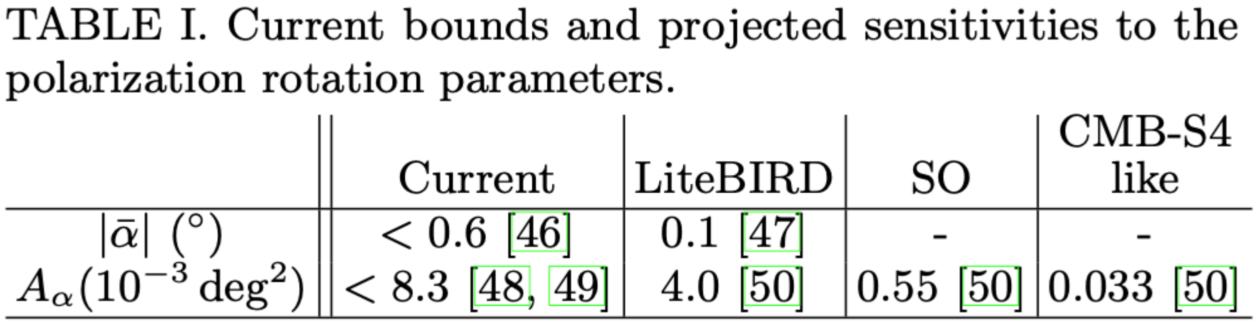
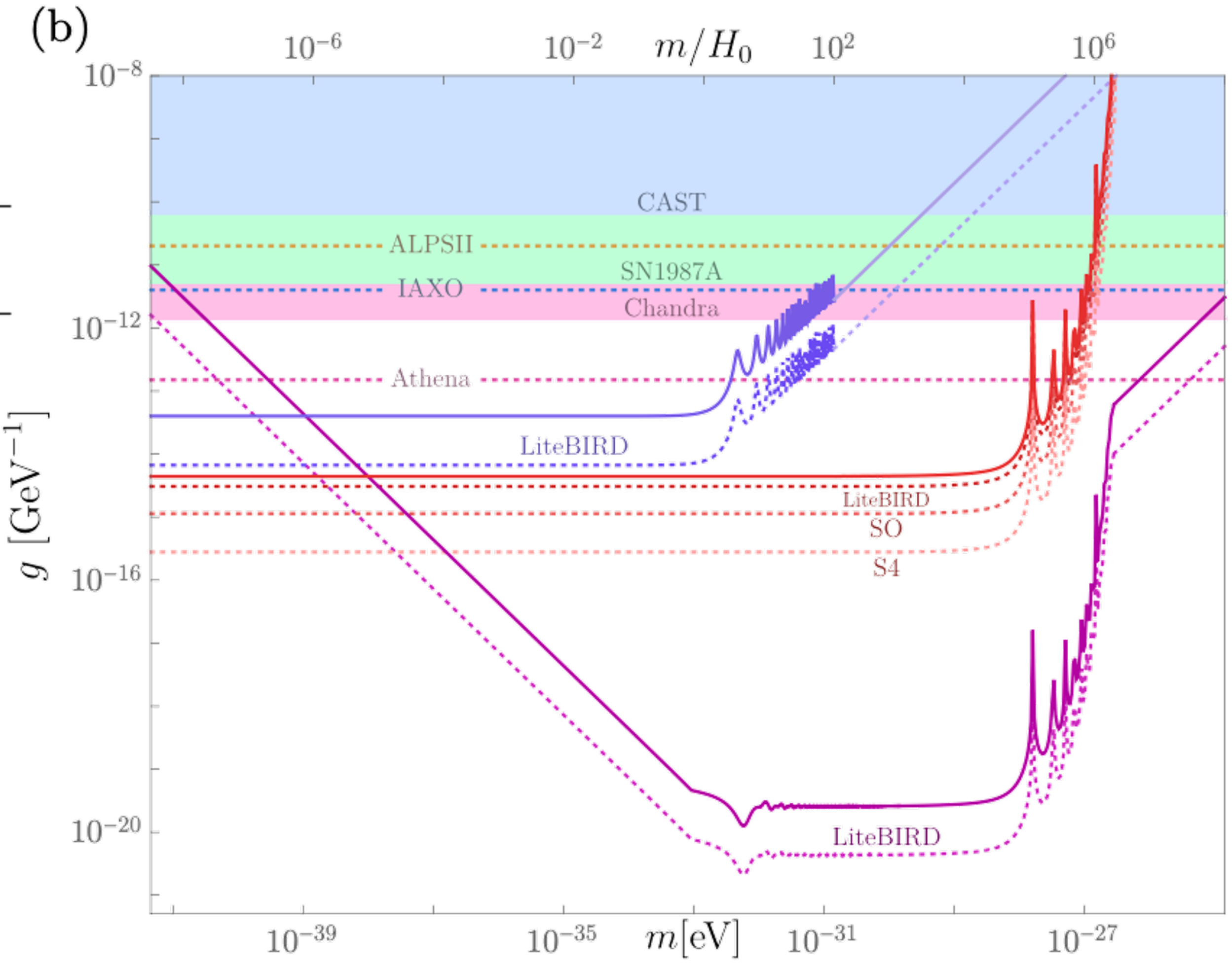


TABLE I. Current bounds and projected sensitivities to the polarization rotation parameters.

	Current	LiteBIRD	SO	CMB-S4 like
$\lvert\bar{\alpha}\rvert$ (°)	< 0.6 [46]	0.1 [47]	-	-
$A_\alpha (10^{-3}\,\mathrm{deg}^2)$	< 8.3 [48, 49]	4.0 [50]	0.55 [50]	0.033 [50]

Table in our paper, arxiv:2008.02473

- Here, $r = 10^{-3}$ in the reach of LiteBIRD



Discussion

What if we detect … ?

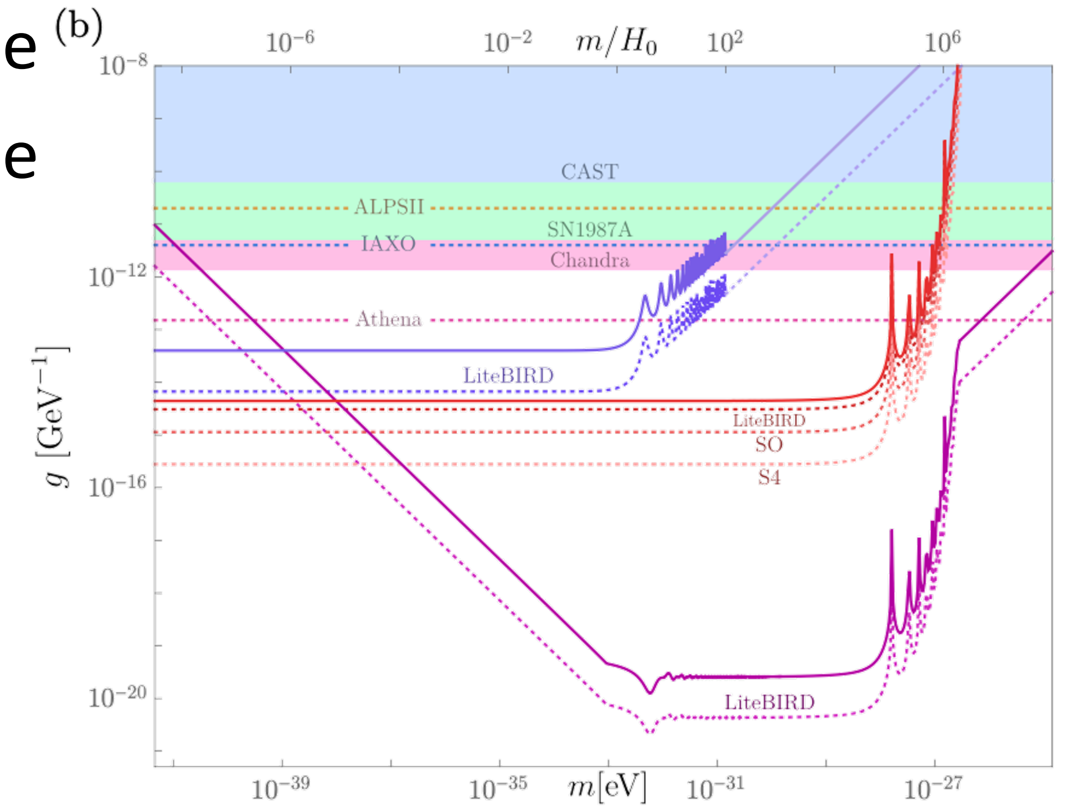
① anisotropic birefringence

② Only isotropic (no anisotropic) birefringence

③ Only anisotropic (no isotropic) birefringence

$$\alpha(\hat{n}) \equiv \boxed{-\frac{g}{2}\delta\phi_{\mathrm{LSS}}(\hat{n})}$$

$$\bar{\alpha} \equiv \frac{g}{2}\left(\boxed{\Delta\bar{\phi}} + \boxed{\delta\phi_{\mathrm{obs}}}\right)$$



Discussion

What if we detect … ?

① anisotropic birefringence by $\delta\phi_{\rm LSS} \propto \left(\frac{H_I}{2\pi}\right)$

- we can fix "$g^2 \times r$",

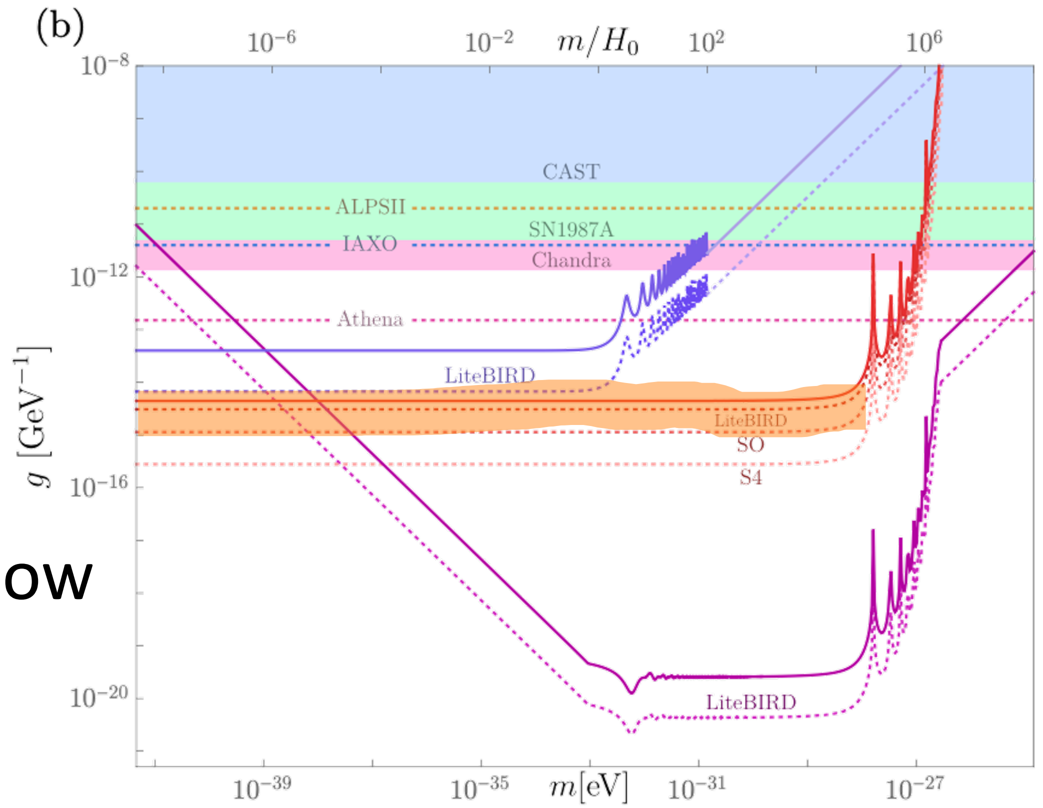
$$\underbrace{\left(\frac{A_\alpha^{\rm CMB}}{8.3\times10^{-3}\,{\rm deg}^2}\right)}_{\text{Observable}} = \underbrace{\left(\frac{g}{4.4\times10^{-15}\,{\rm GeV}^{-1}}\right)}_{\text{upper bound (e.g. Chandra)}}^2 \left(\frac{r}{10^{-3}}\right)$$

$$g < g_{\rm max}$$

$$\Rightarrow \quad r > 5\times10^{-9}\left(\frac{A_\alpha^{\rm CMB}}{4\times10^{-3}\,{\rm deg}^2}\right)$$

$$\alpha(\hat{n}) \equiv \boxed{-\frac{g}{2}\delta\phi_{\rm LSS}(\hat{n})}$$

$$\bar{\alpha} \equiv \frac{g}{2}(\Delta\bar{\phi} + \delta\phi_{\rm obs})$$



✓ CMB experiments can investigate r from below by Birefringence!

(and from above by the primordial GW)

Discussion

What if we detect ... ?

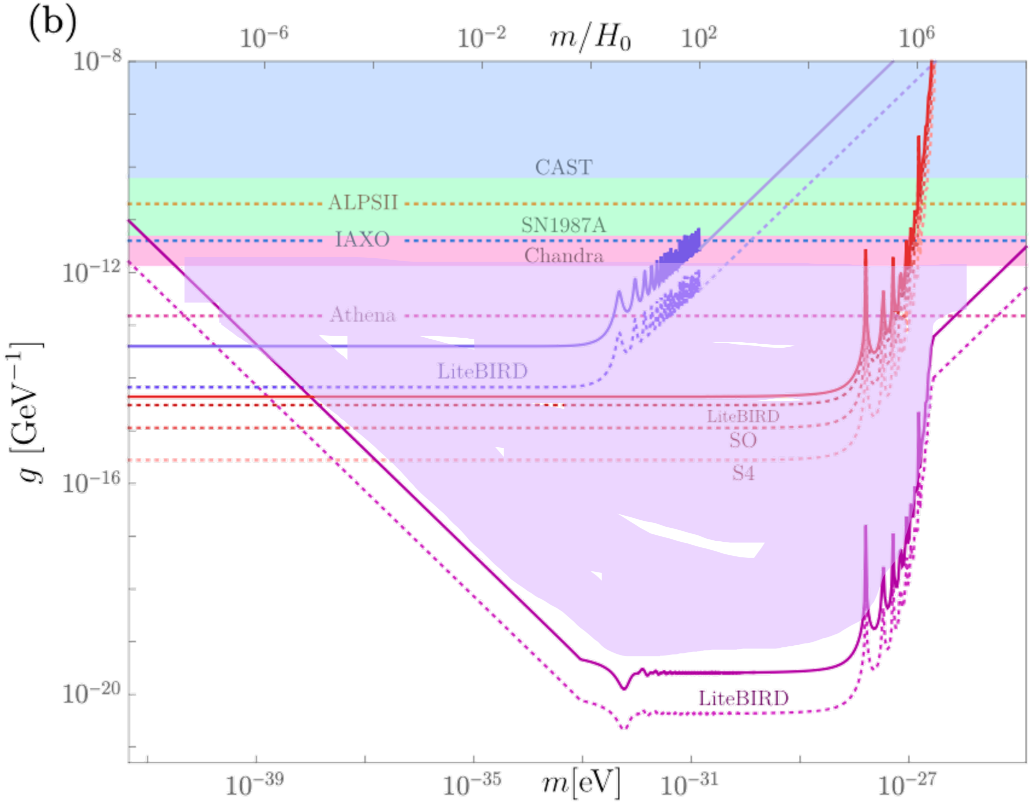
② Only isotropic birefringence by $\delta\phi_{\rm obs}$ or $\Delta\bar{\phi}$

$$\alpha(\hat{n}) \equiv -\xcancel{\frac{g}{2}\delta\phi_{\rm LSS}}(\hat{n})$$

$$\bar{\alpha} \equiv \frac{g}{2}\left(\boxed{\Delta\bar{\phi}} + \boxed{\delta\phi_{\rm obs}}\right)$$

- Non-detection of $\delta\phi_{\rm LSS}$ means $\Delta\bar{\phi}$, not $\delta\phi_{\rm obs}$
- g has upper bound, then

$$10^{-8}\left(\frac{|\bar{\alpha}|}{0.3^\circ}\right) < \frac{m}{H_0} < 10^{8}\left(\frac{|\bar{\alpha}|}{0.3^\circ}\right)$$



✓ We can investigate the mass of axion DE, including very small Equation of State w !

Discussion

What if we detect … ?

③ Only anisotropic birefringence

- Non-detection of $\delta\phi_{\mathrm{obs}}$ means

$$1 \lesssim \frac{m}{H_0}$$

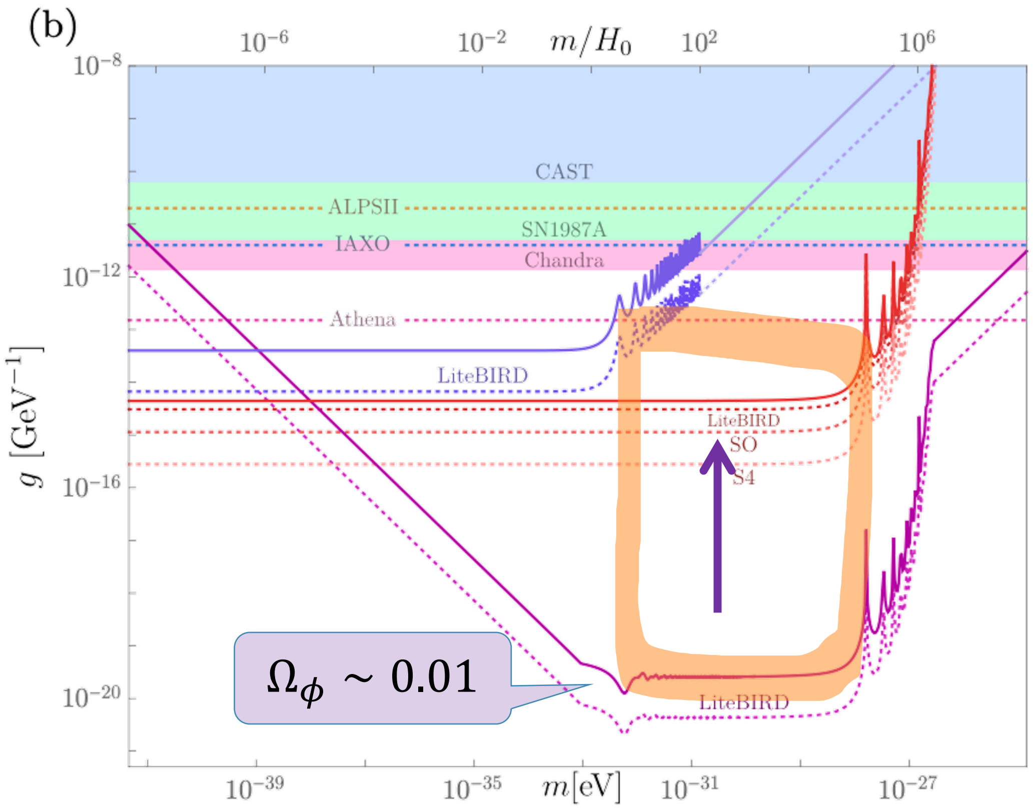
- Non-detection of $\Delta\bar{\phi}$ means

$$\Omega_\phi h^2 \lesssim 2{\times}10^{-13}\left(\frac{|\bar{\alpha}|}{0.05^\circ}\right)^2\left(\frac{A_\alpha^{\mathrm{CMB}}}{4{\times}10^{-3}\mathrm{deg}^2}\right)^{-1}\left(\frac{r}{0.06}\right)$$

✓ We can put a stringent constraint on the energy fraction of the axion!

$$\alpha(\hat{n}) \equiv \boxed{-\frac{g}{2}\delta\phi_{\mathrm{LSS}}(\hat{n})}$$

$$\bar{\alpha} \equiv \frac{g}{2}\left(\cancel{\Delta\bar{\phi} + \delta\phi_{\mathrm{obs}}}\right)$$

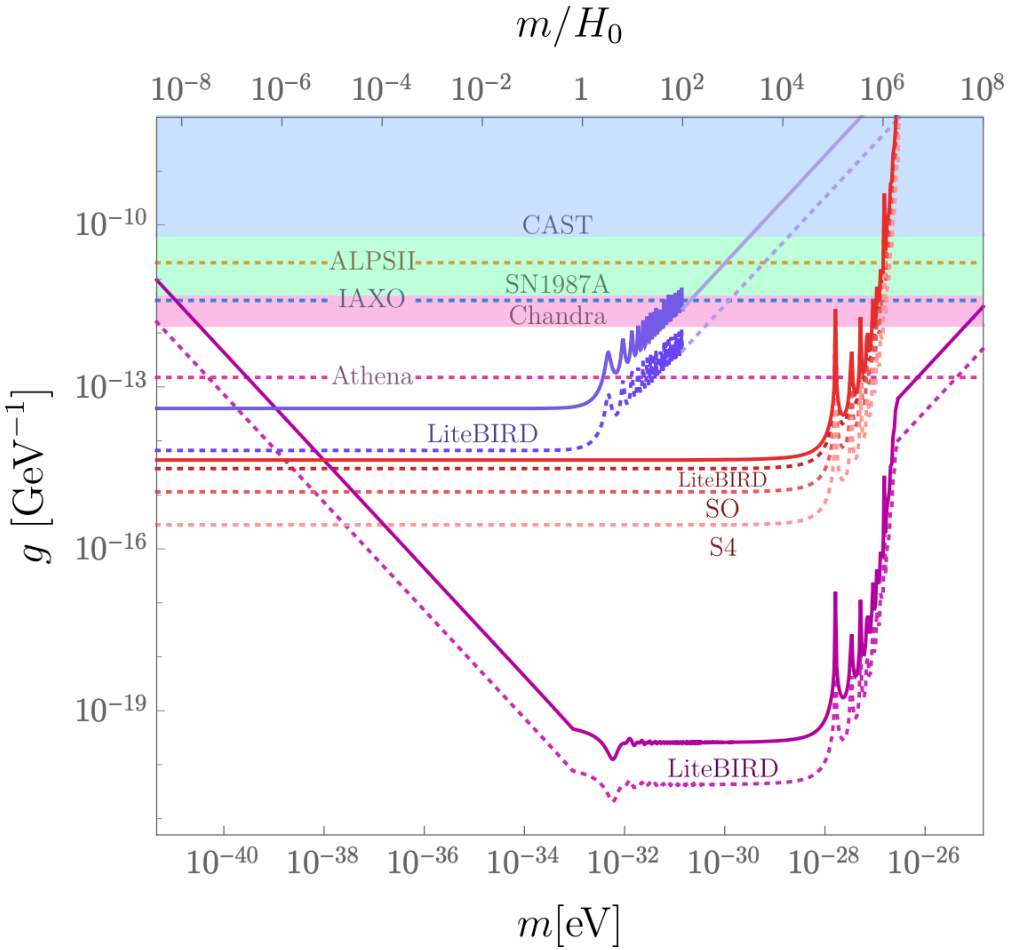


$\Omega_\phi \sim 0.01$

Conclusion

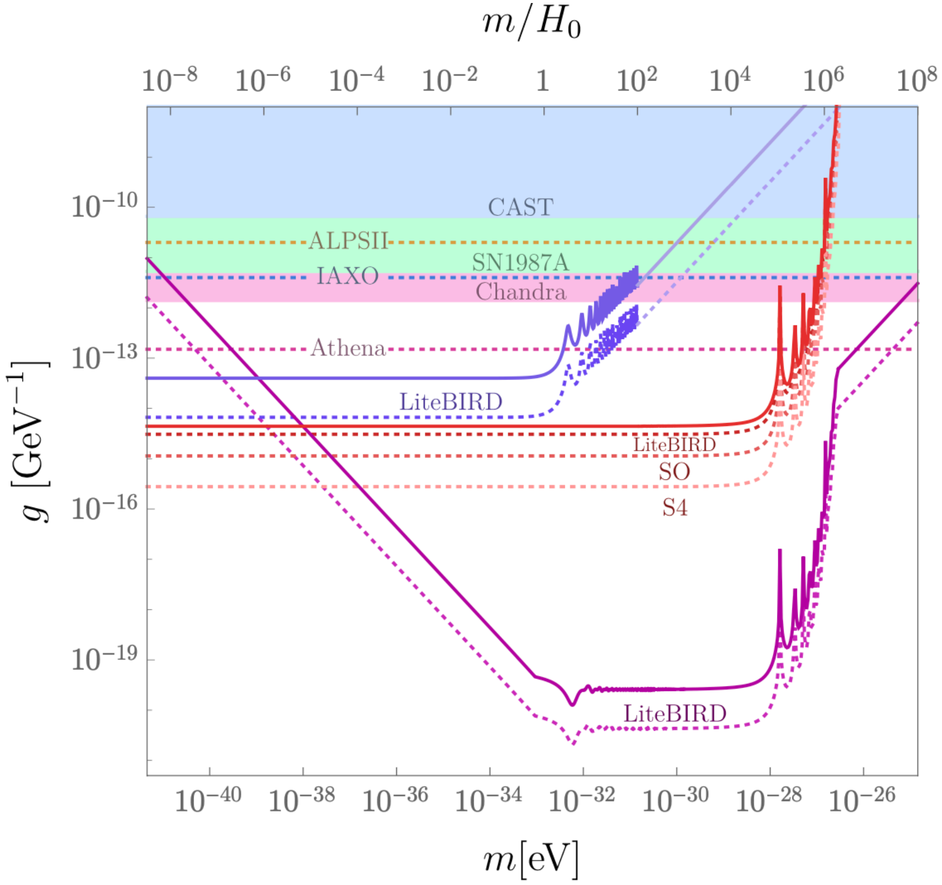
- Future CMB experiments investigates the broad range of axion-photon coupling, including
  - dark energy axion
  - axion with tiny energy fraction

- Detection of birefringence provides valuable information;
  - through anisotropic birefringence, we can search small-scale inflation with $r > 5{\times}10^{-9}$.
  - through isotropic rotation, we can search tiny energy fraction of axion with $\Omega_\phi h^2 \lesssim 2{\times}10^{-13}$.



Detailed calculations in arxiv:2008.02473

Backup


m/H_0
10^{-8}
10^{-6}
10^{-4}
10^{-2}
1
10^{2}
10^{4}
10^{6}
10^{8}
10^{-10}
10^{-13}
10^{-16}
10^{-19}
$g\ [\mathrm{GeV}^{-1}]$
CAST
ALPSII
SN1987A
IAXO
Chandra
Athena
LiteBIRD
LiteBIRD
SO
S4
LiteBIRD
10^{-40}
10^{-38}
10^{-36}
10^{-34}
10^{-32}
10^{-30}
10^{-28}
10^{-26}
$m[\mathrm{eV}]$

About CMB observation

$$\langle C^{EB,o}\rangle = \frac{\tan(4\alpha_s)}{2}(\langle C^{EE,o}\rangle - \langle C^{BB,o}\rangle) + \frac{\sin(4\alpha)}{2\cos(4\alpha_s)}\ (\langle C^{EE,CMB}\rangle - \langle C^{BB,CMB}\rangle)$$

α_s: rotation of polarization sensitive detector
α: cosmic birefringence

Y.Minami, et.al.(2019)