Cosmic Birefringence Tomography

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EB power spectrum from axion-induced birefringence

- Planck data suggests a hint of cosmic birefringence

0.35 ± 0.14 deg	Minami & Komatsu (2020)
0.36 ± 0.11 deg	Diego-Palazuelos et al. (2022)

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Sherwin & TN (2021) Nakatsuka, TN, Komatsu (2022)

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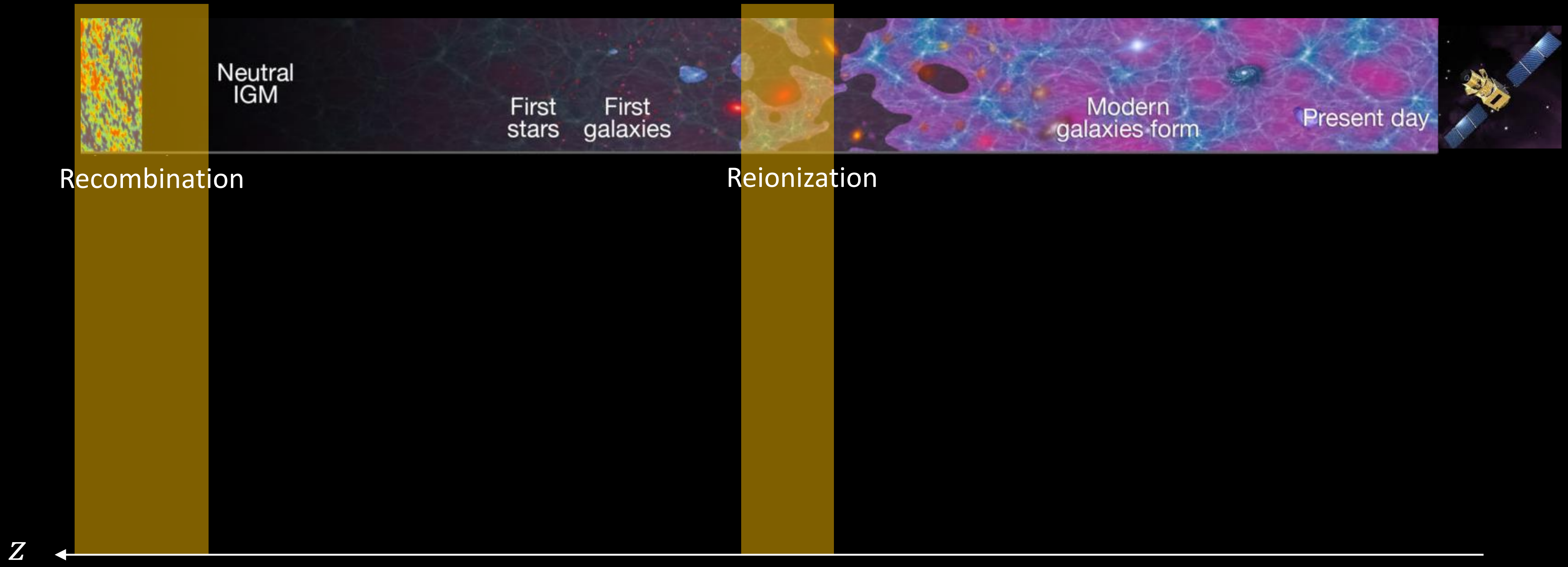
We can constrain m_ϕ from C_ℓ^{EB} to determine e.g. whether axions behave as DE or (a fraction of) DM

Generation of polarization

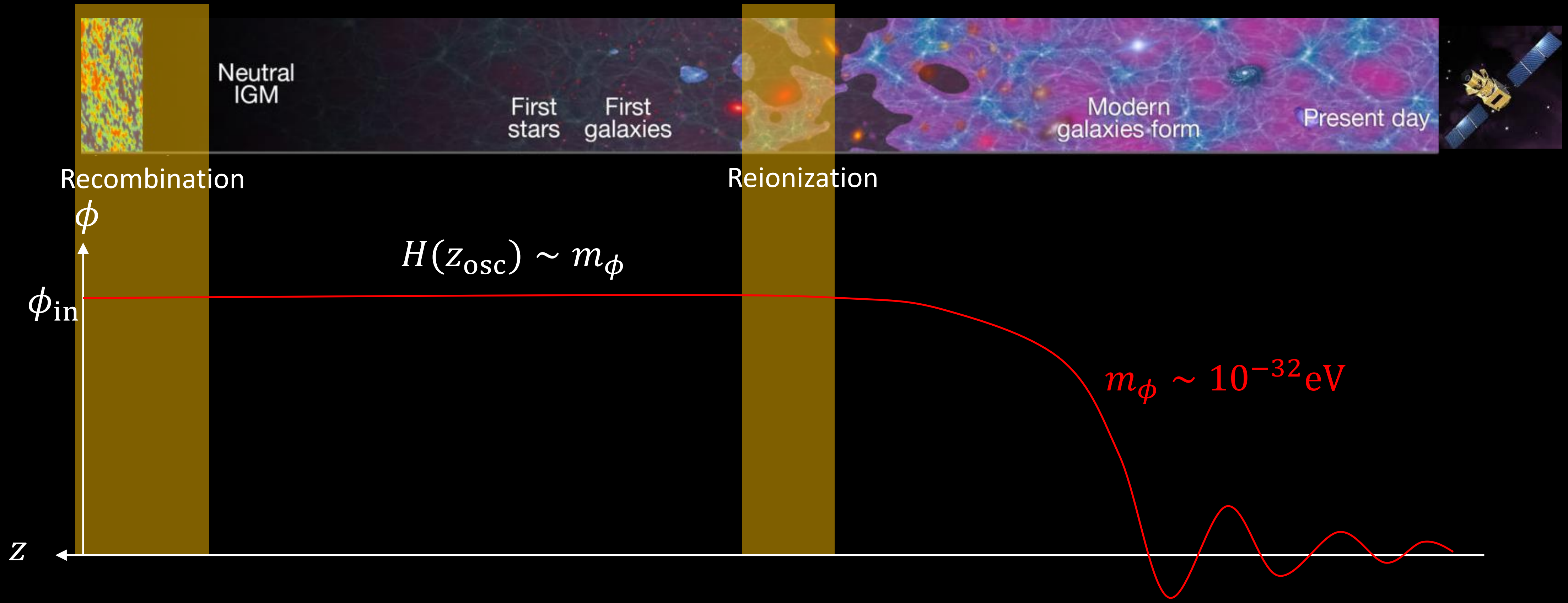


Recombination

Reionization

z

Dynamics of axions



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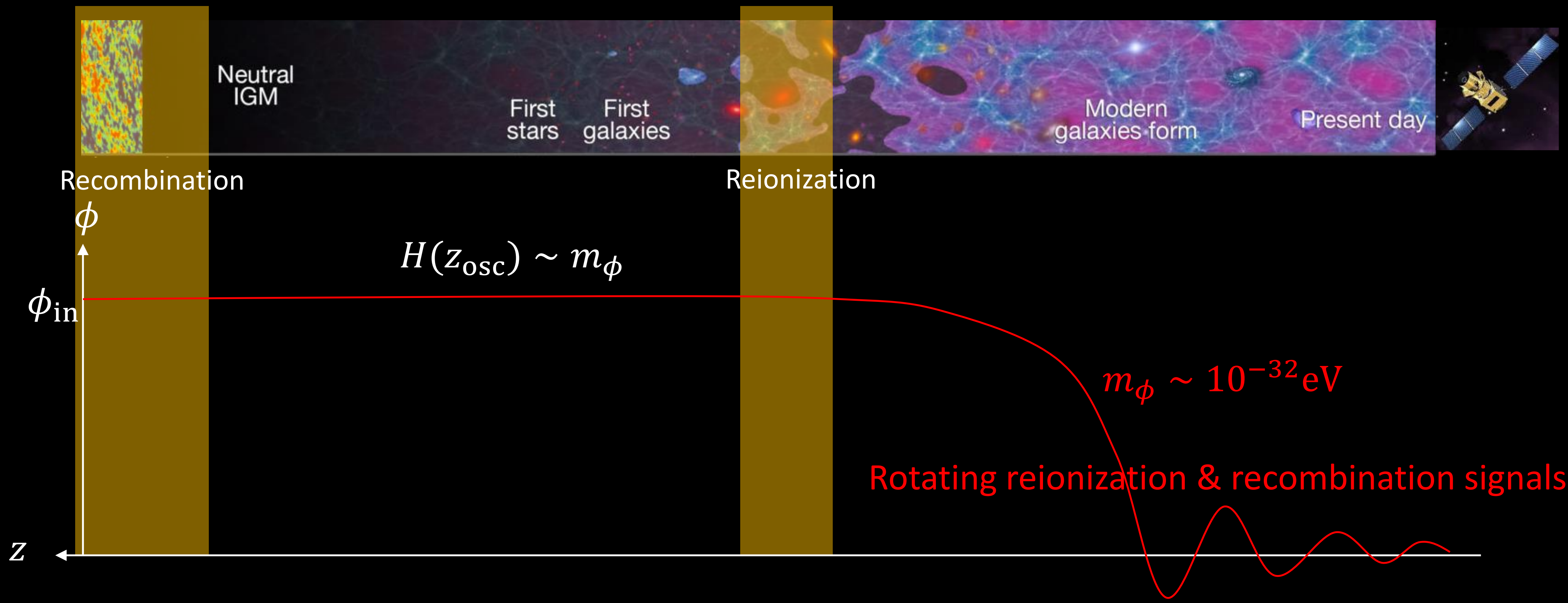


Recombination

Reionization

$H(z_{\mathrm{osc}}) \sim m_\phi$

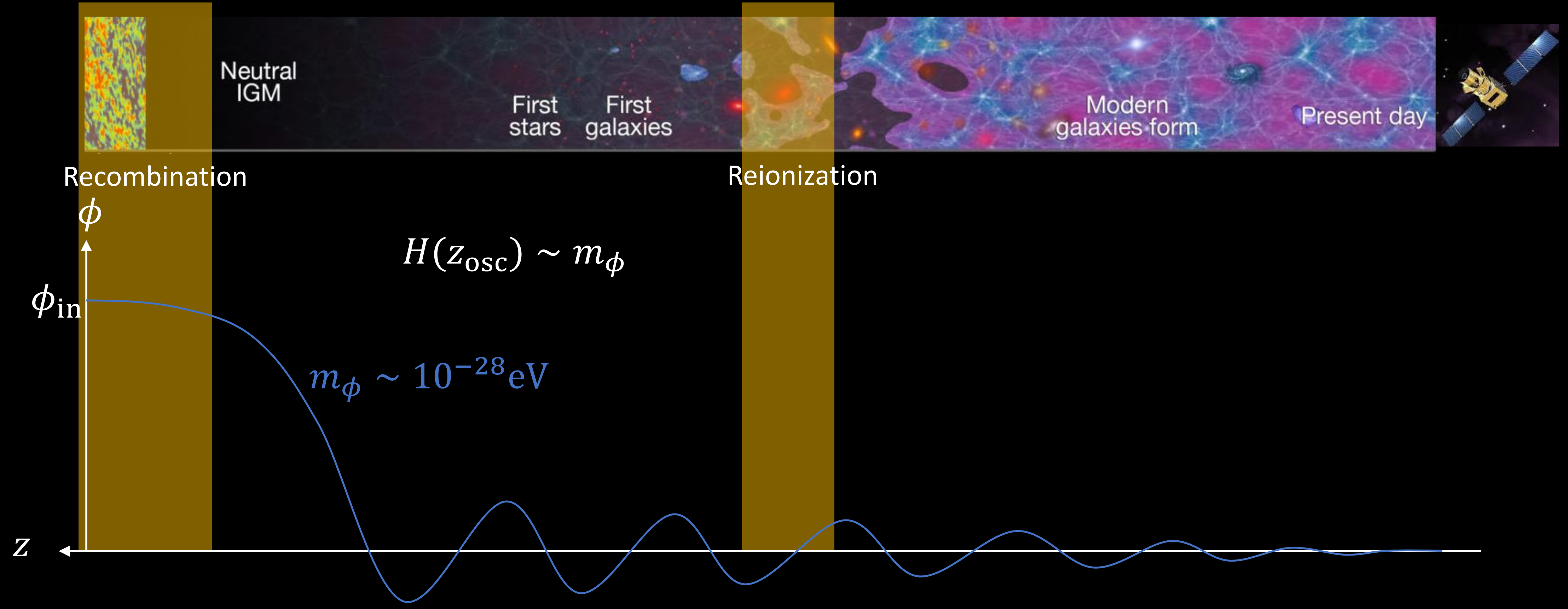
$m_\phi \sim 10^{-32}\mathrm{eV}$

Rotating reionization & recombination signals

$\beta_{\mathrm{rec}} \simeq \frac{g}{2}\phi_{\mathrm{in}}$

$\beta_{\mathrm{rei}} \simeq \frac{g}{2}\phi_{\mathrm{in}}$

Dynamics of axions



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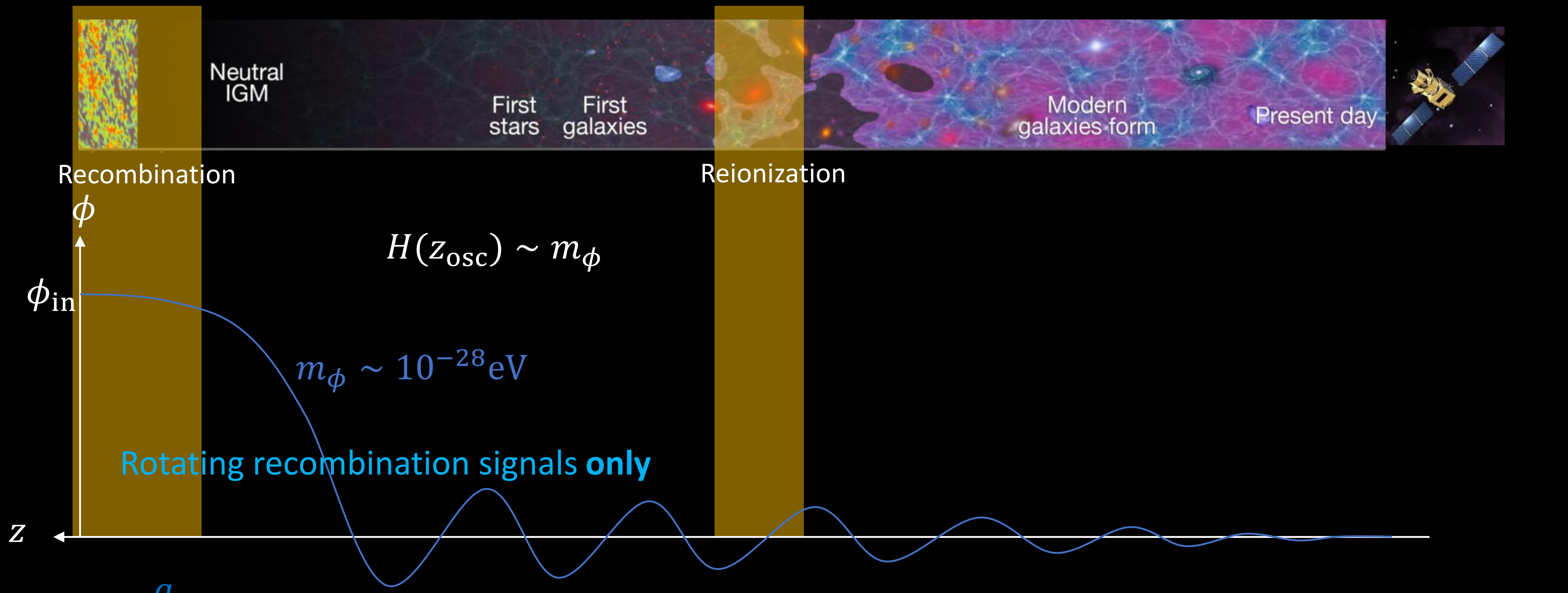

$H(z_{\text{osc}}) \sim m_\phi$

$m_\phi \sim 10^{-28}\text{eV}$

Rotating recombination signals **only**

$\beta_{\text{rec}} \simeq \frac{g}{2}\phi_{\text{in}}$

$\beta_{\text{rei}} \simeq 0$

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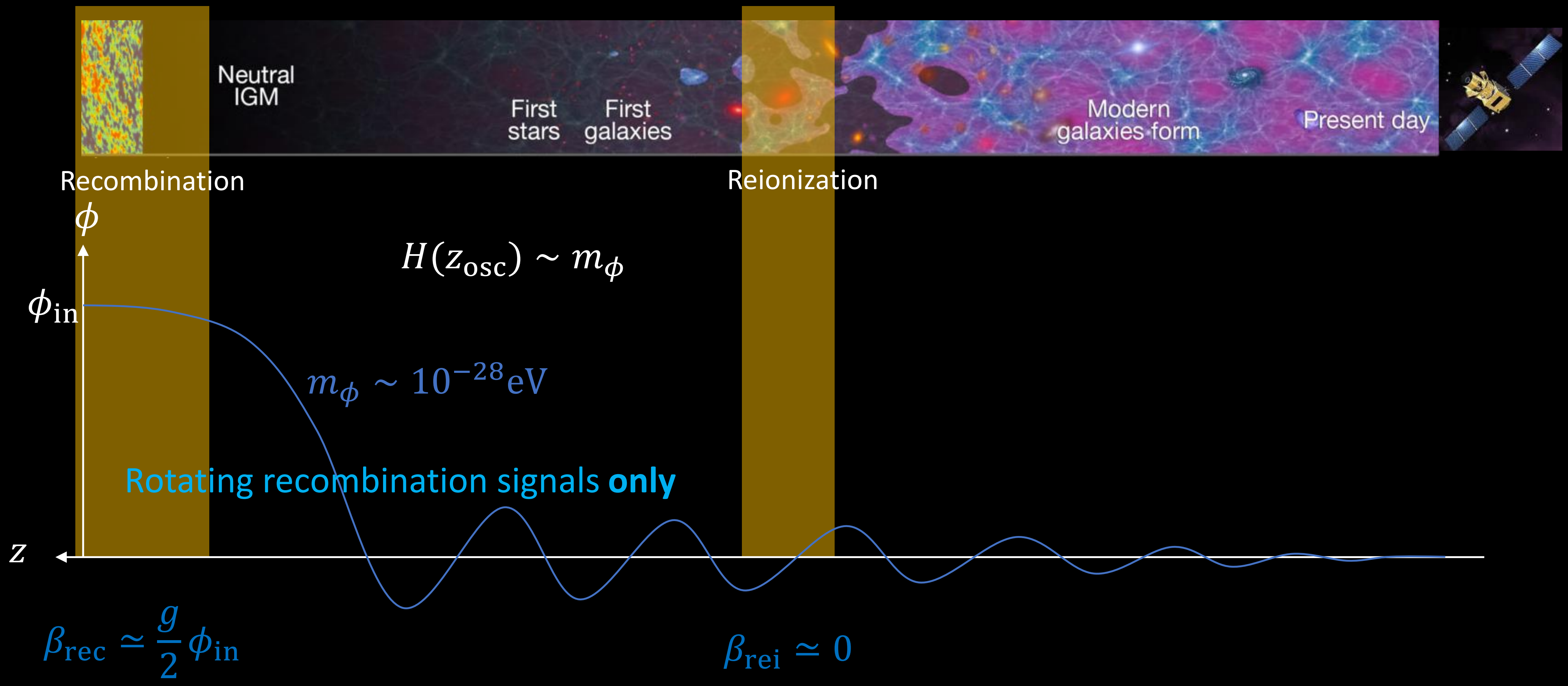

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$\beta_{\rm rec} \simeq \frac{g}{2}\phi_{\rm in}$

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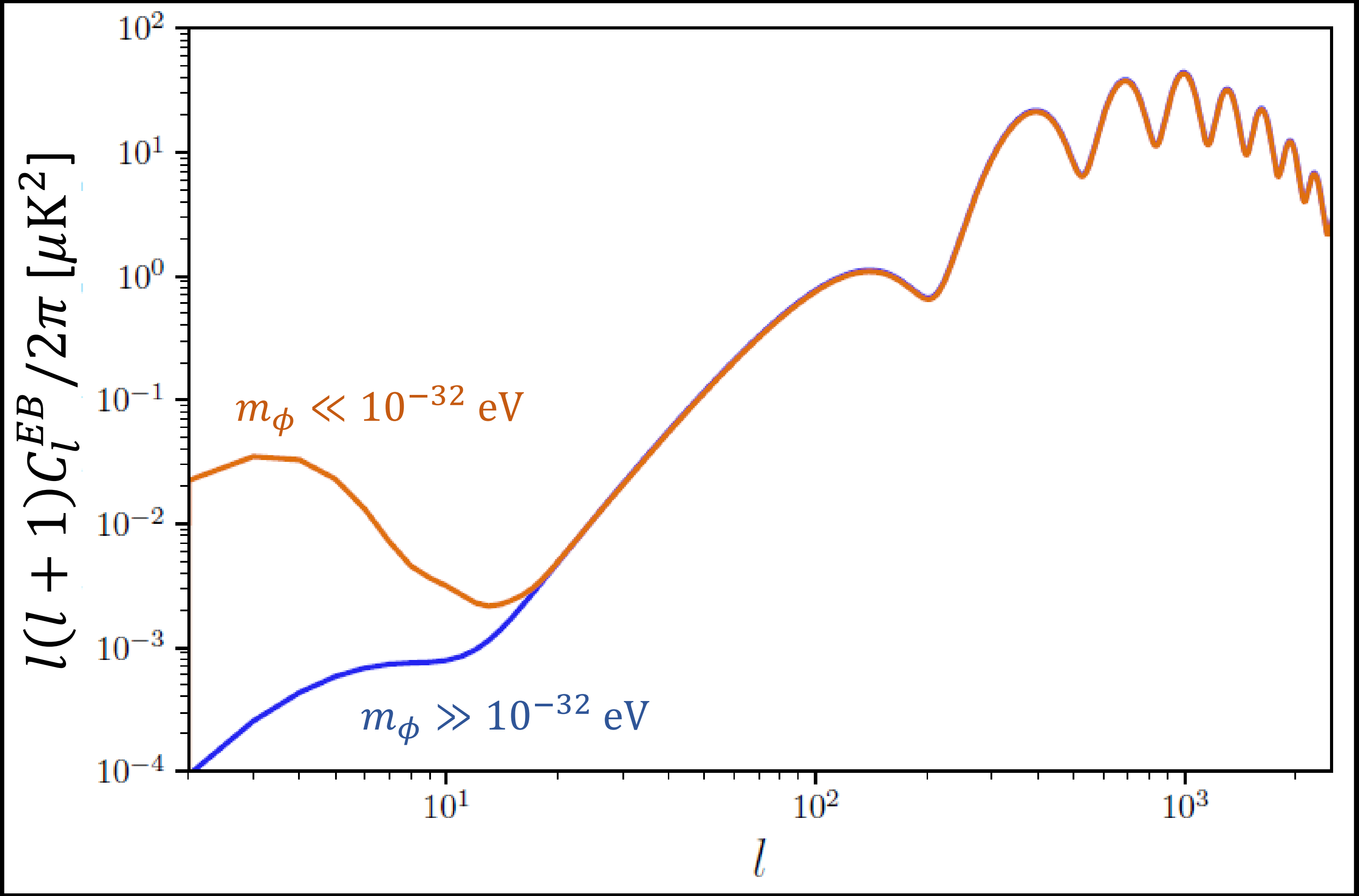
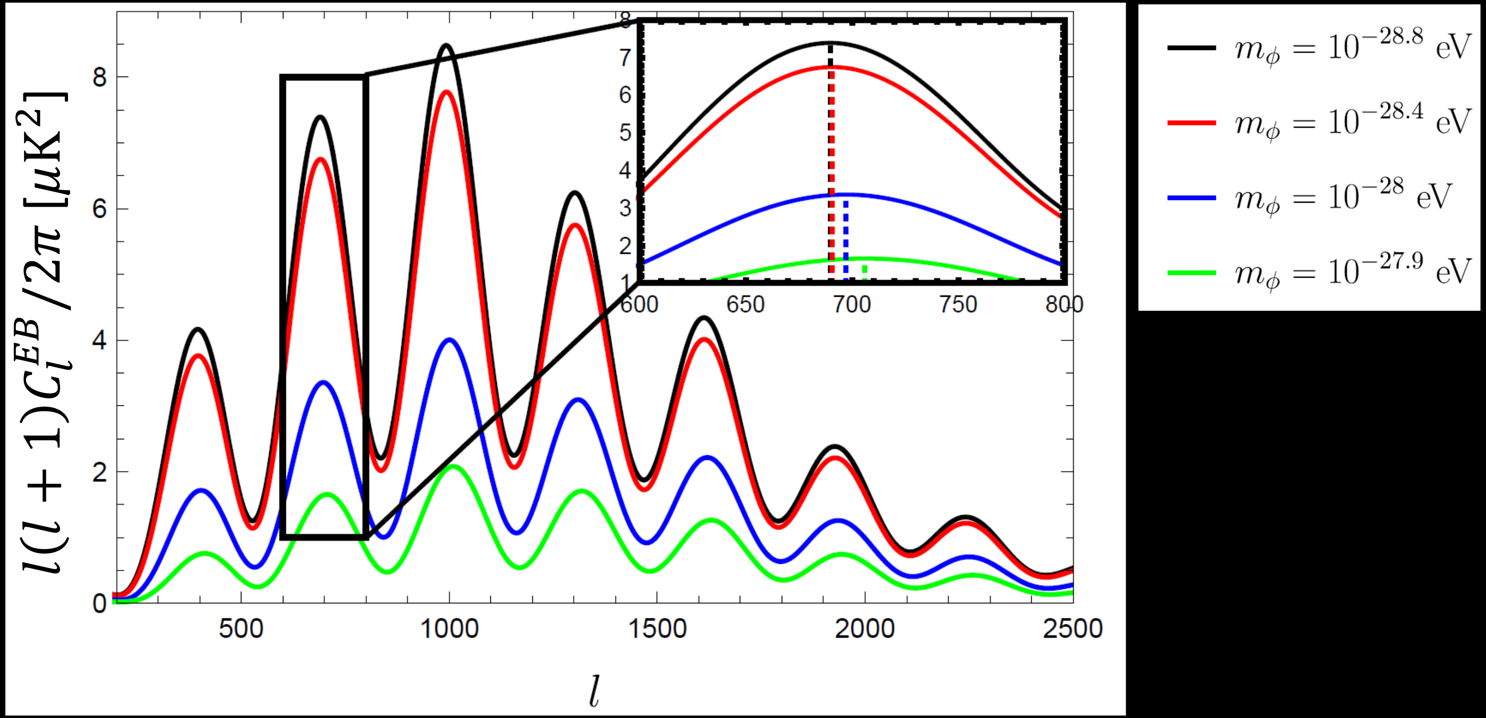
Polarization from reionization and recombination could be differently rotated depending on m_ϕ

Mass dependence of C_ℓ^{EB} $10^{-32}\mathrm{eV} \ll m_\phi \ll 10^{-28}\mathrm{eV}$



Reionization bump depends on axion mass

Mass dependence of C_ℓ^{EB} $m_\phi \sim 10^{-28}\mathrm{eV}$



- Shifting scales of acoustic peaks
- Suppressing C_l^{EB} amplitude

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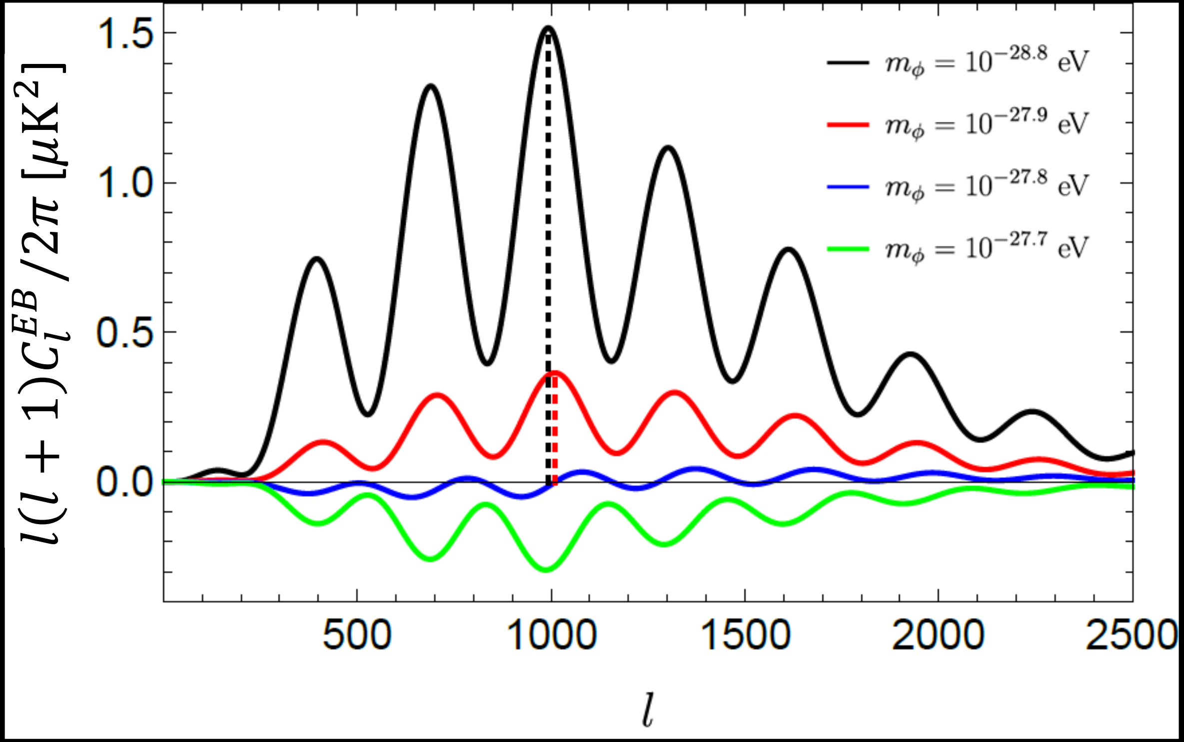

- Shifting scales of acoustic peaks
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- Sign of C_l^{EB} becomes negative as m_ϕ increases

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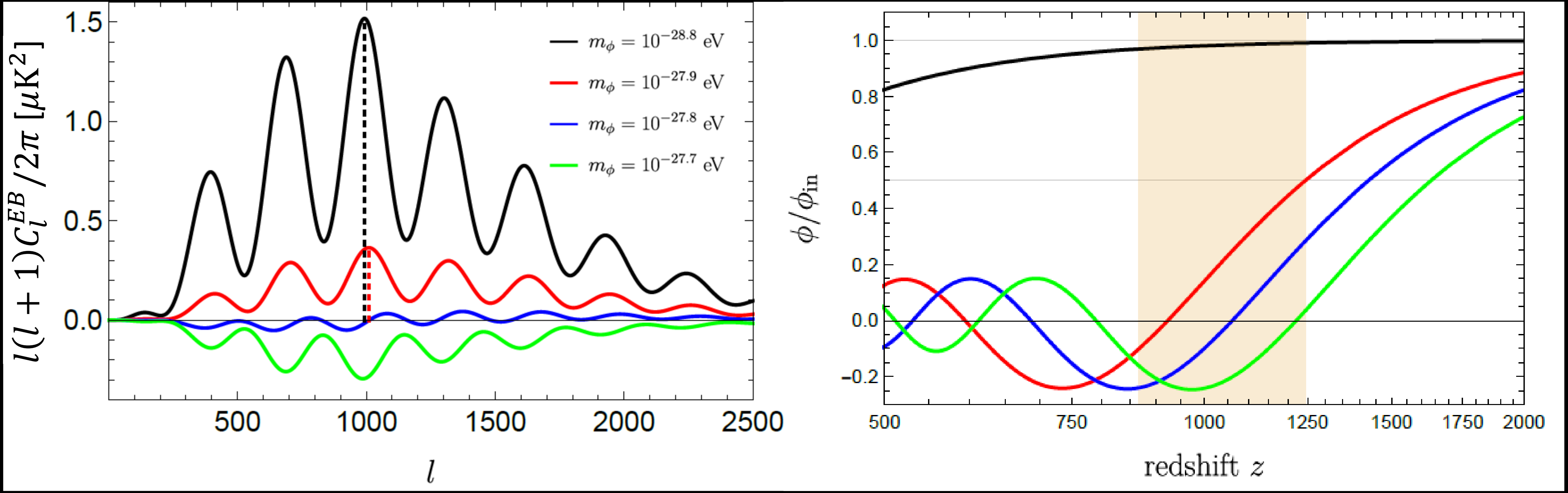

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Constraining axion by measuring C_ℓ^{EB}

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- C_l^{EB} is sensitive to m_ϕ

How significantly can we constraint axion parameters using ongoing and future experiments?

- We do not have to worry about the uncertainty of the instrumental miscalibration angle (α) $(C_\ell^{EB} = 2\alpha C_\ell^{EE})$

Using the full shape of C_l^{EB} , we can break degeneracy between axion parameters and miscalibration angle

Ongoing and Future Large CMB Projects

POLARBEAR

ACT

Simons Observatory (early 2020s)

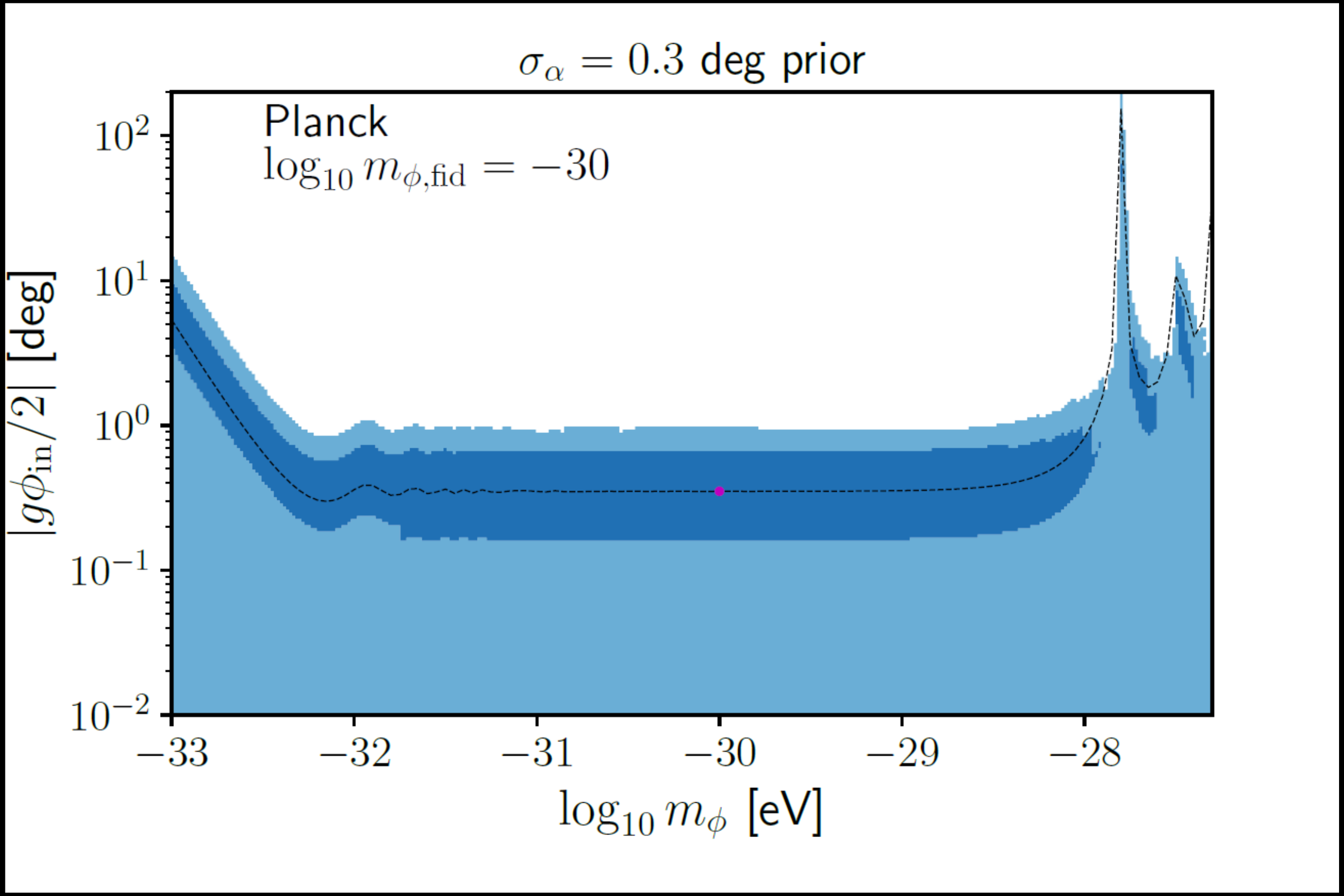
LiteBIRD (will be launched in 2028)

(2020s - 2035)

SPT/BICEP

2020s – 2030s is the very exciting era for cosmology using polarization

Space experiments ($m_\phi = 10^{-30}$eV)



$$\chi^2 = \sum_l \left| C_l^{EB,\mathrm{obs}} - \frac{g\phi_{\mathrm{in}}}{2} C_l^{EB}(m_\phi) - 2\alpha C_l^{EE} \right|^2 / \mathrm{Var}_l(C^{EB})$$

Use C_l^{EB} to simultaneously constrain m_ϕ ,amplitude and miscalibration angle (α)

Black dashed: approximate values of $|g\phi_{in}/2|$ for a given m_ϕ (to realize the Planck measurement: $\beta = 0.35$ deg)

Fiducial parameters are not ruled out by observations (Fujita, Murai, Nakatsuka & Tsujikawa 2021)

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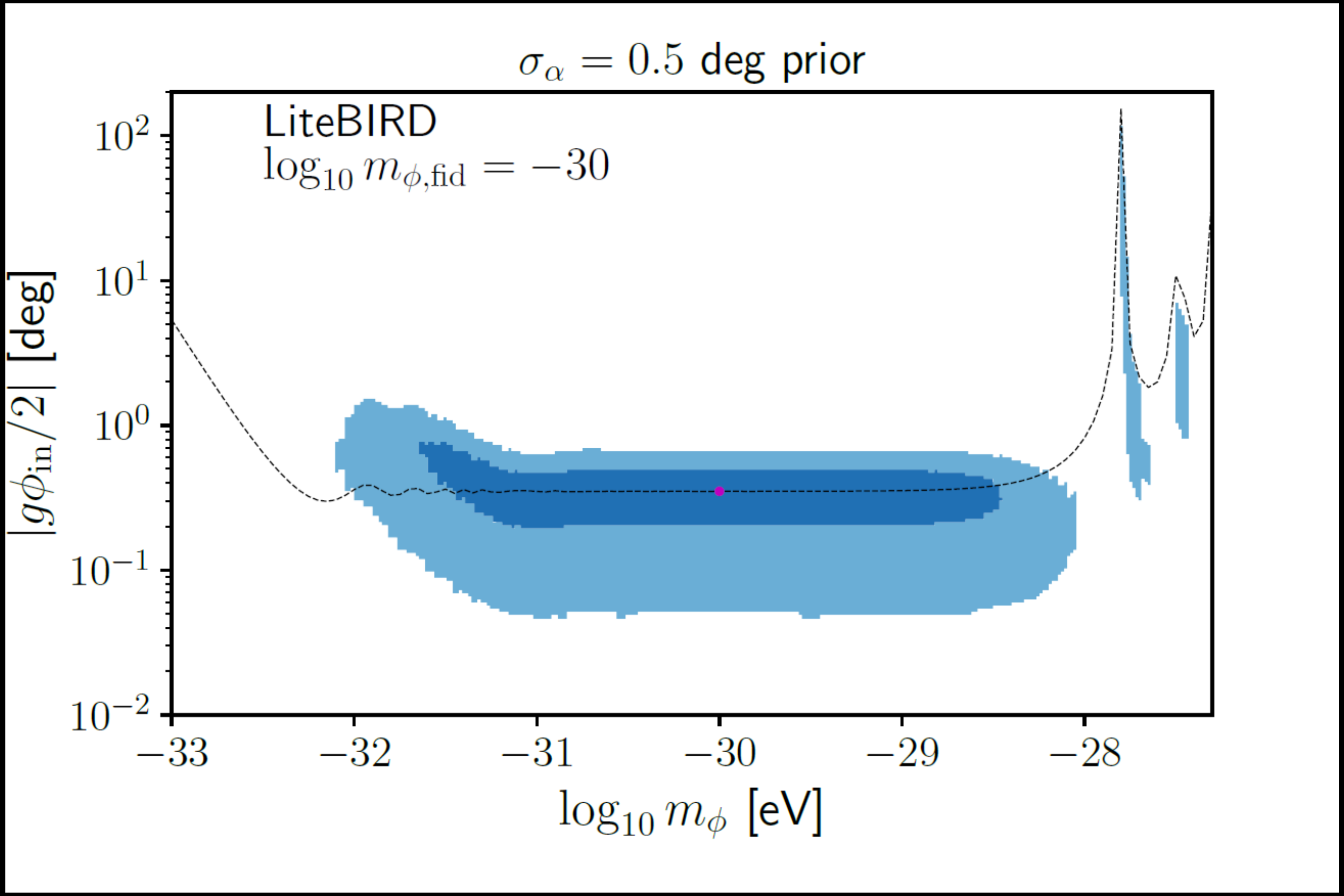

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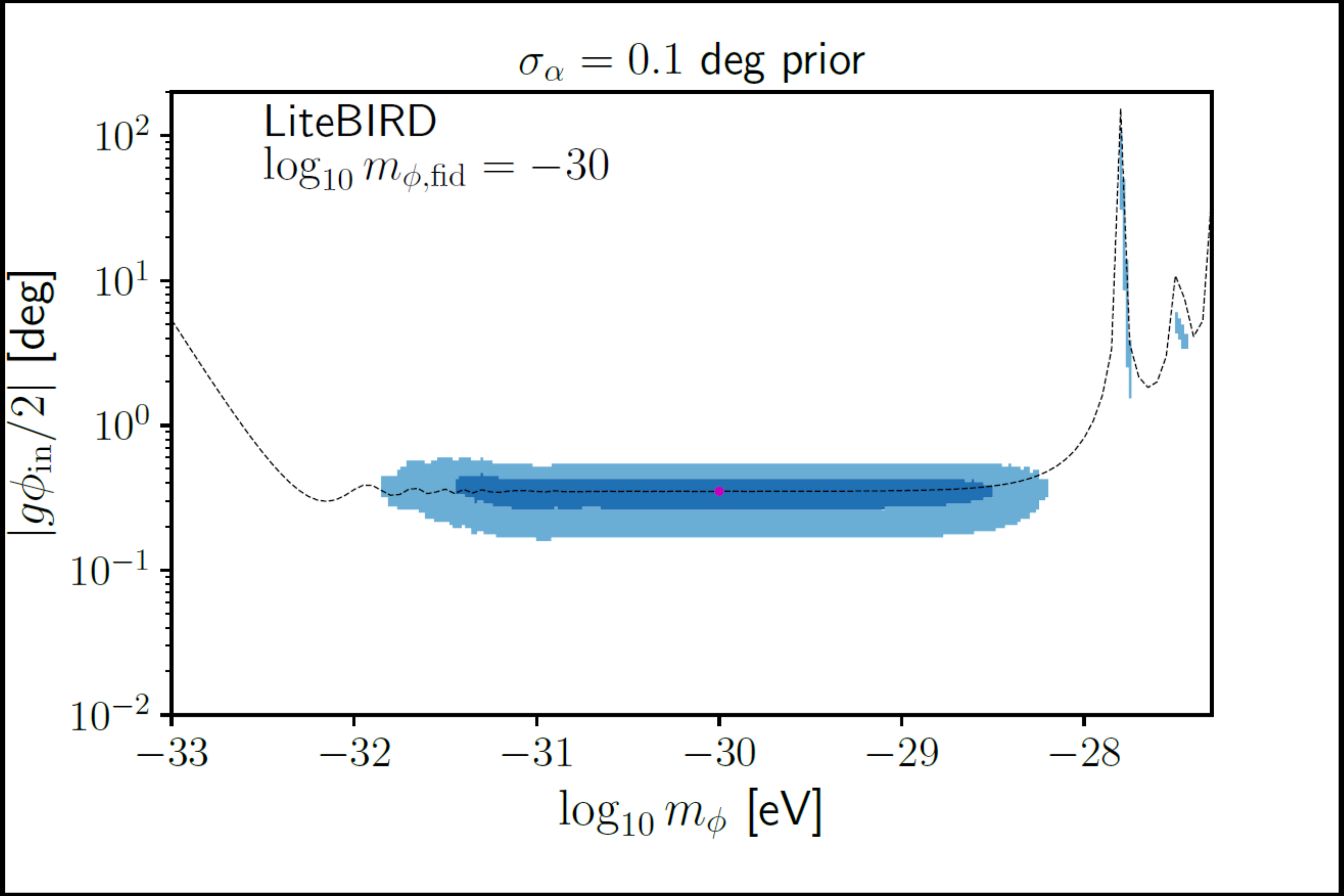

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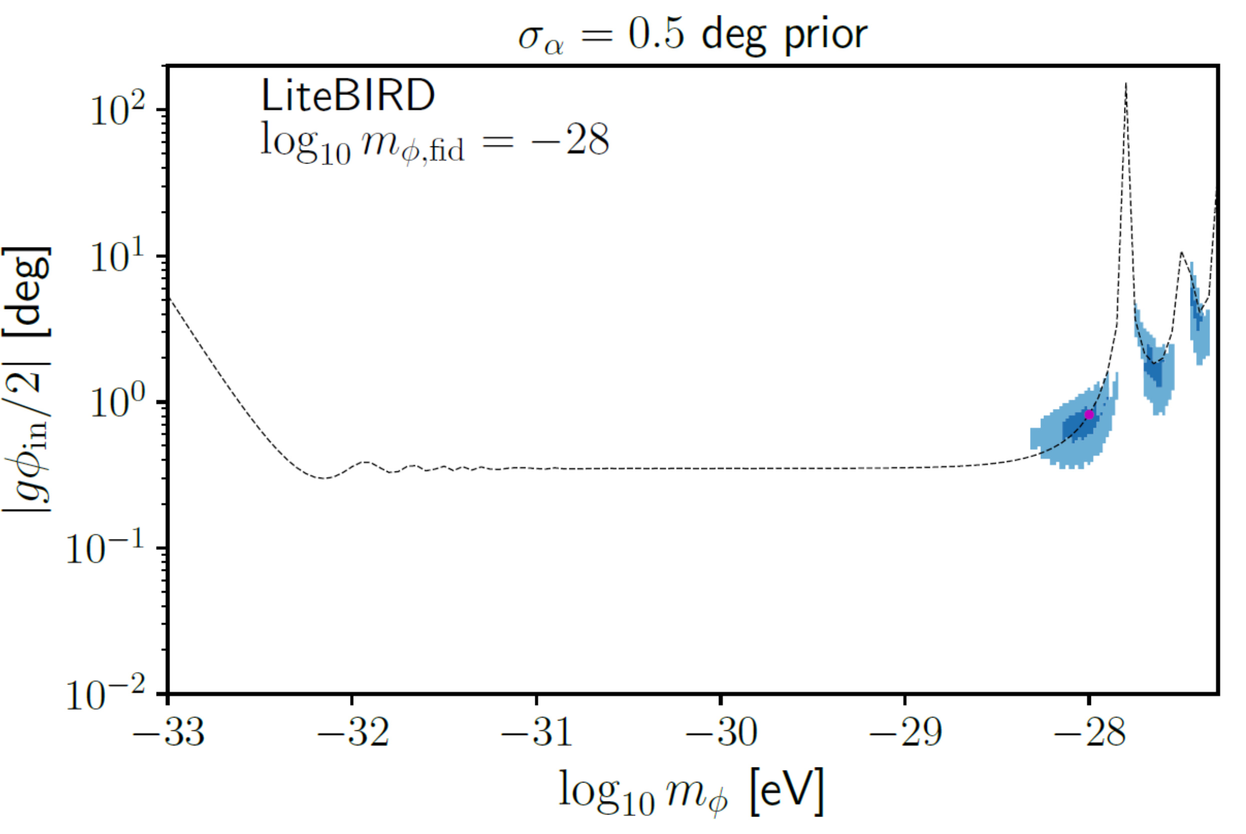

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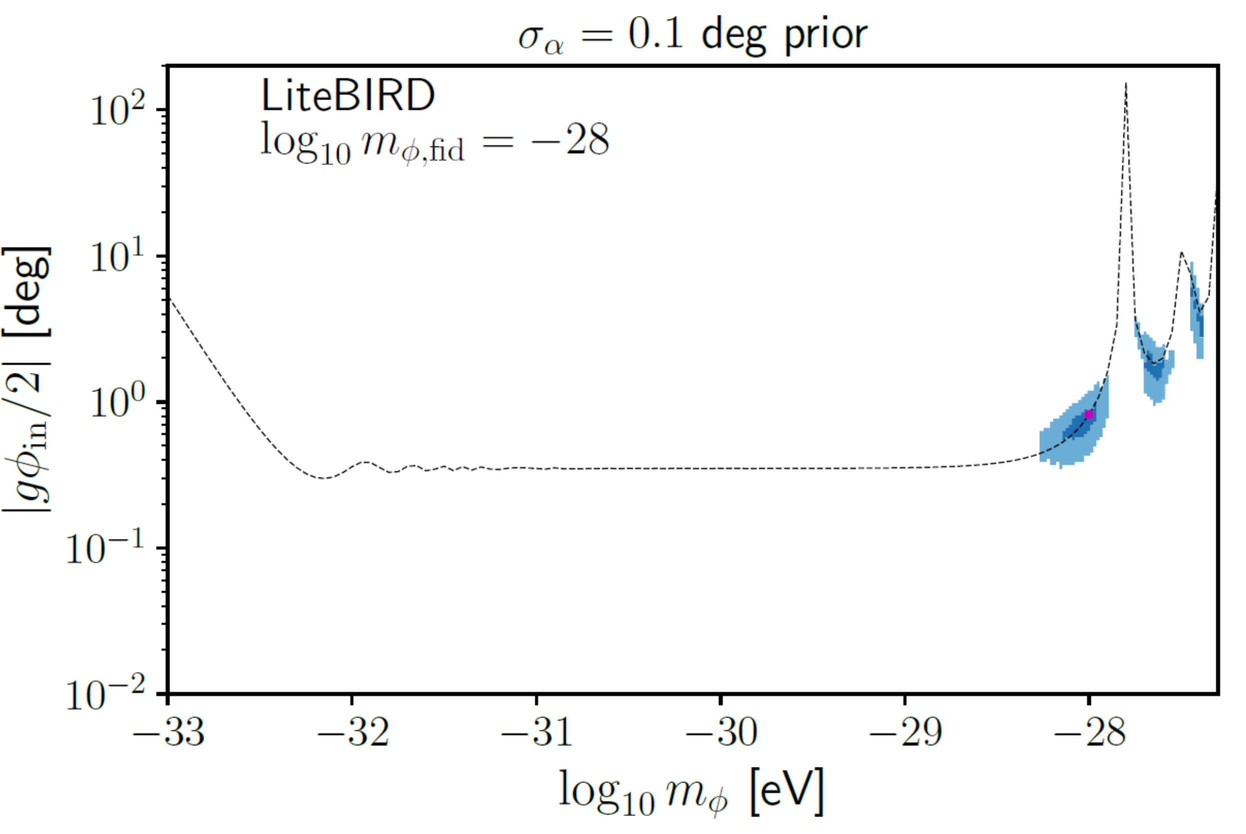

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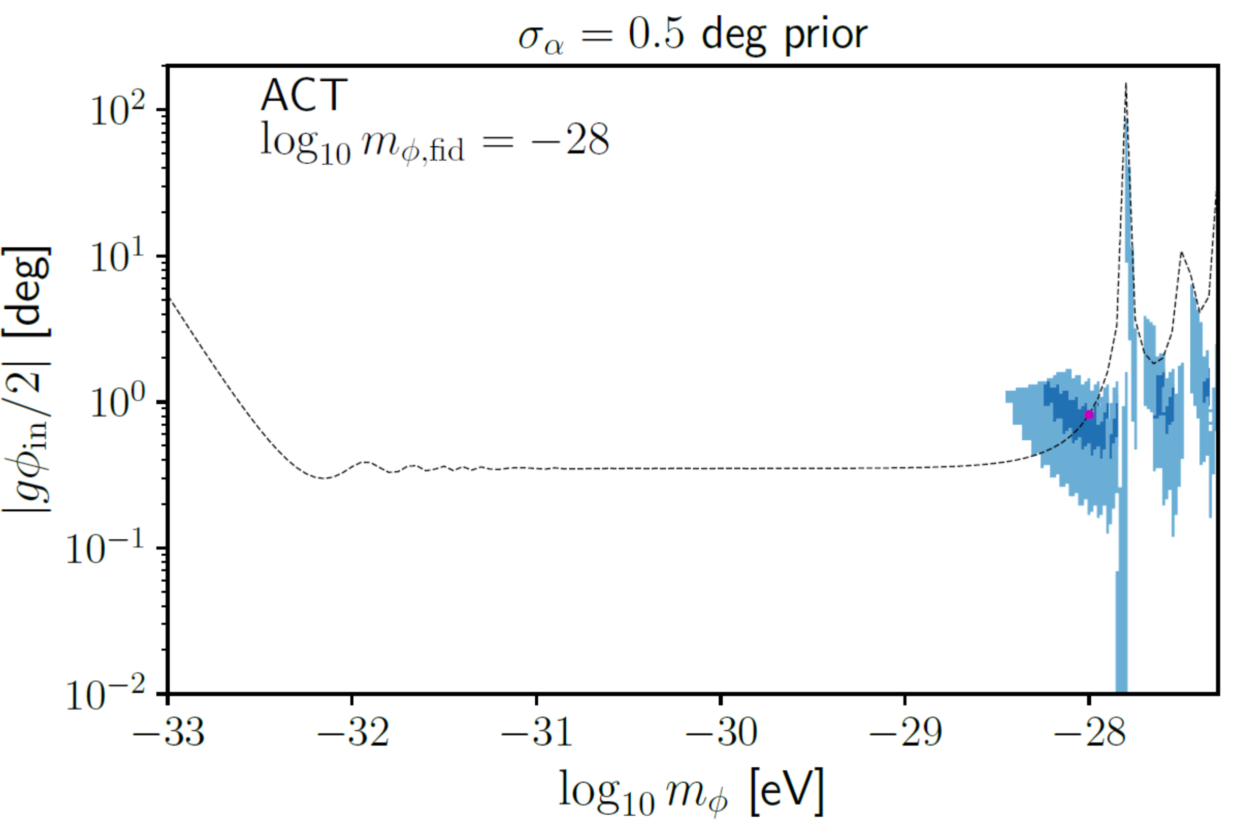
Ground-based experiments ($m_\phi = 10^{-28}$eV)



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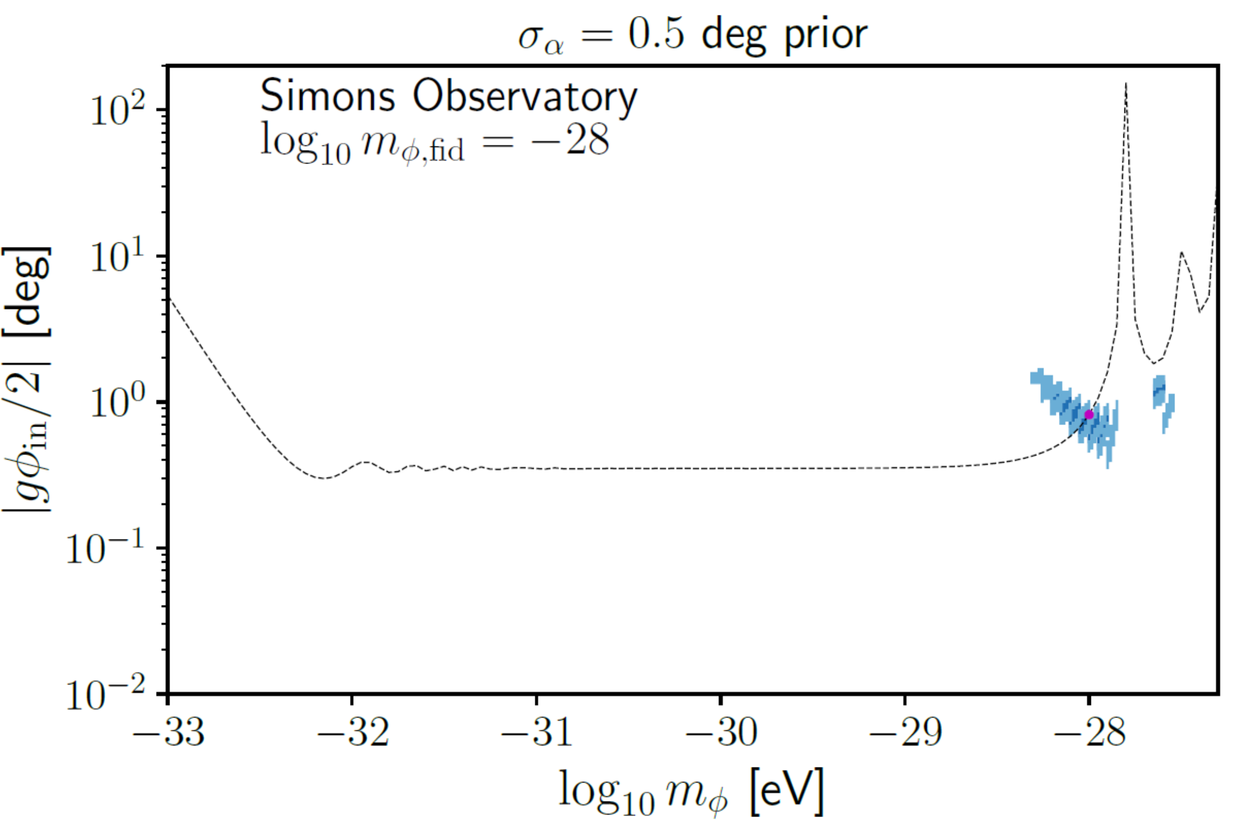

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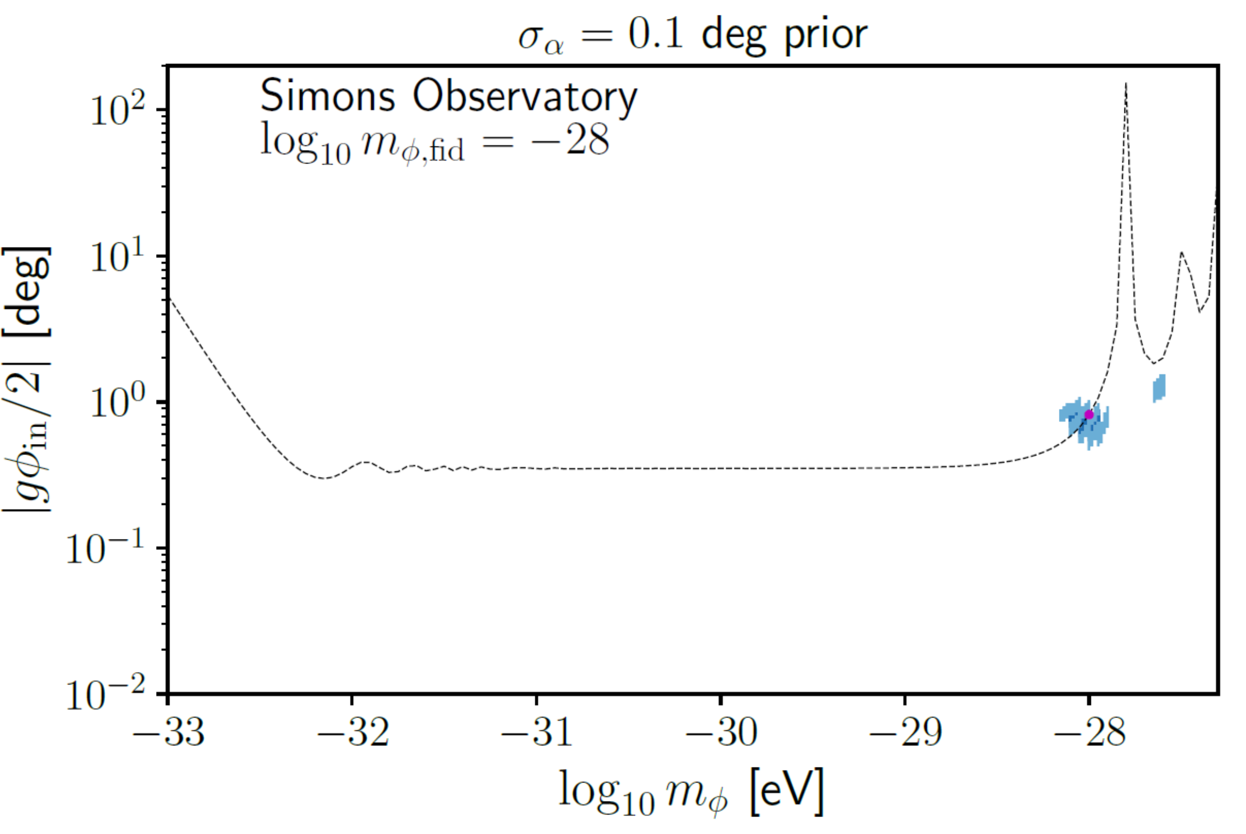

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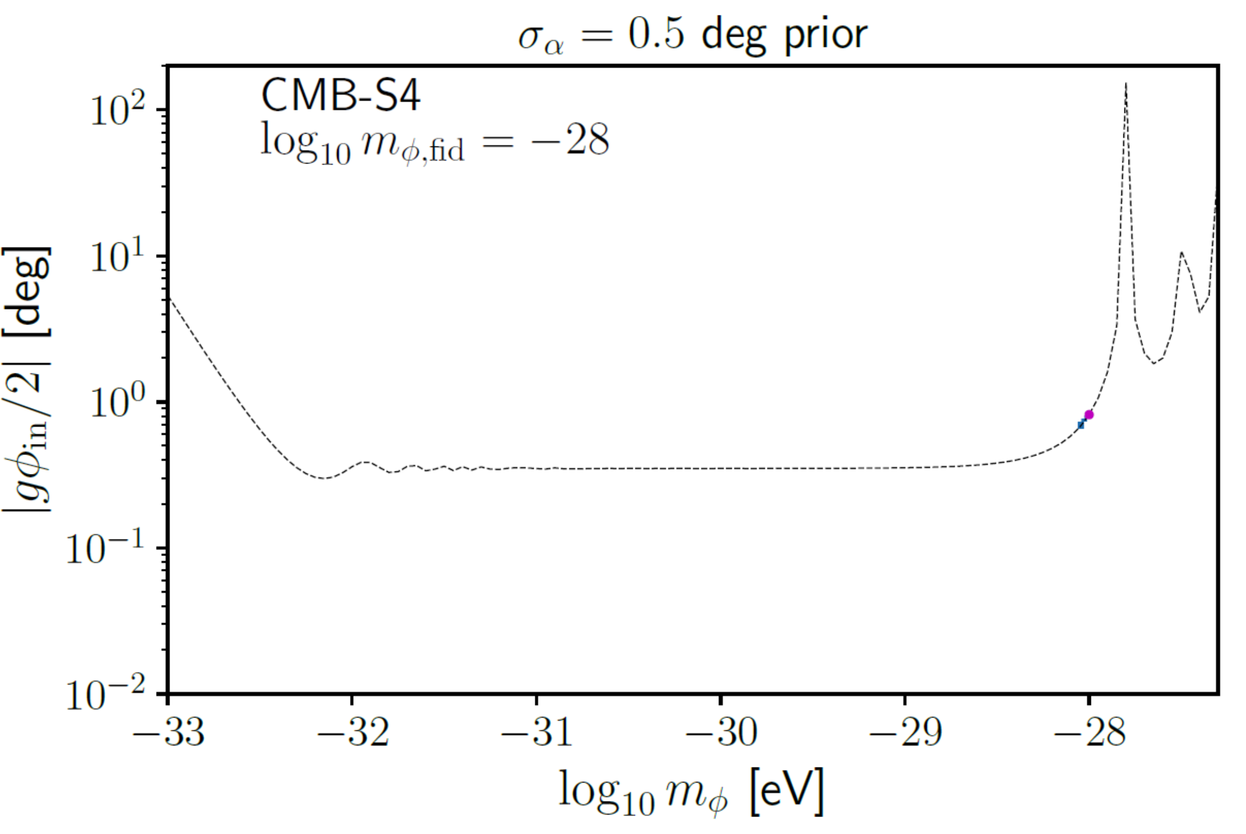

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Discussion

We simplified our calcuation by ignoring

- energy density of ϕ which affects the background evolution

DE-like: $m_\phi \ll 10^{-32}\ \mathrm{eV}$	considered as cosmological constant
DM-like: $10^{-32}\ \mathrm{eV} \ll m_\phi \ll 10^{-25}\ \mathrm{eV}$	$\Omega_\phi h^2 < 0.006$ is required (Hlozek et al. 2015)

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- gravitational lensing effect on EB

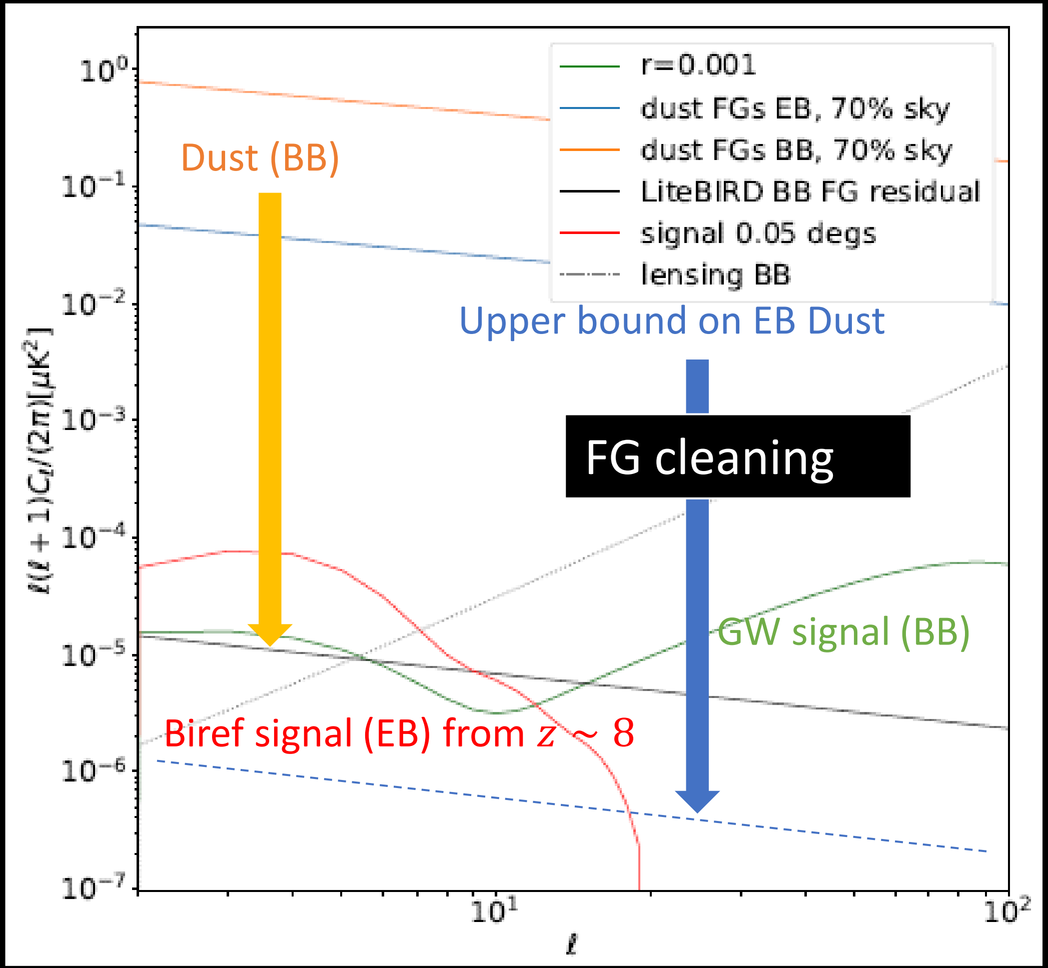
- anisotropic birefringence

$$\delta\ddot{\phi} + 2\mathcal{H}\delta\dot{\phi} + a^2 V''\delta\phi + k^2\delta\phi = \dot{\bar{\phi}}\left(3\dot{\Phi} + \dot{\Psi}\right) - 2a^2 V'\Psi$$

(Capparelli 2020)

Discussion

We need a foreground (FG) cleaning to accurately measure large scale C_l^{EB}



Dust (BB)

Upper bound on EB Dust

FG cleaning

GW signal (BB)

Biref signal (EB) from $z \sim 8$

- C_l^{EB} signal is much larger than C_l^{EB} dust FG after a FG cleaning method which realizes a detection of inflationary BB with r=0.001, a main goal of LiteBIRD
- Frequency dependence of mis-calibration angle can lead to e.g. anisotropic and/or ell-dependent α, depending on FG cleaning methods, more work needed.

However, FG is not important for high-ℓ C_l^{EB} (i.e., $m_\phi \gg 10^{-28}$ eV)

Discussion

Possible extensions

- including multiple axion fields (e.g. Obata 2022)? (Obata-kun’s talk)
- other possible sources of cosmic birefringence?
- remote quadrupole as a new tomographic information?

  providing low-z cosmic birefringence

Summary

We study in details the axion-induced cosmic birefringence effect on CMB polarization

We found that $C_\ell^{EB} \neq 2\beta C_\ell^{EE}$ and the shape significantly depends on m_ϕ

Especially, reionization bump and high-ℓ features in C_ℓ^{EB} can be used to constrain m_ϕ

Backup

Approximate birefringence angle

If the visibility function is $g_v(\eta) = \delta(\eta - \eta_{\mathrm{rec}})$:

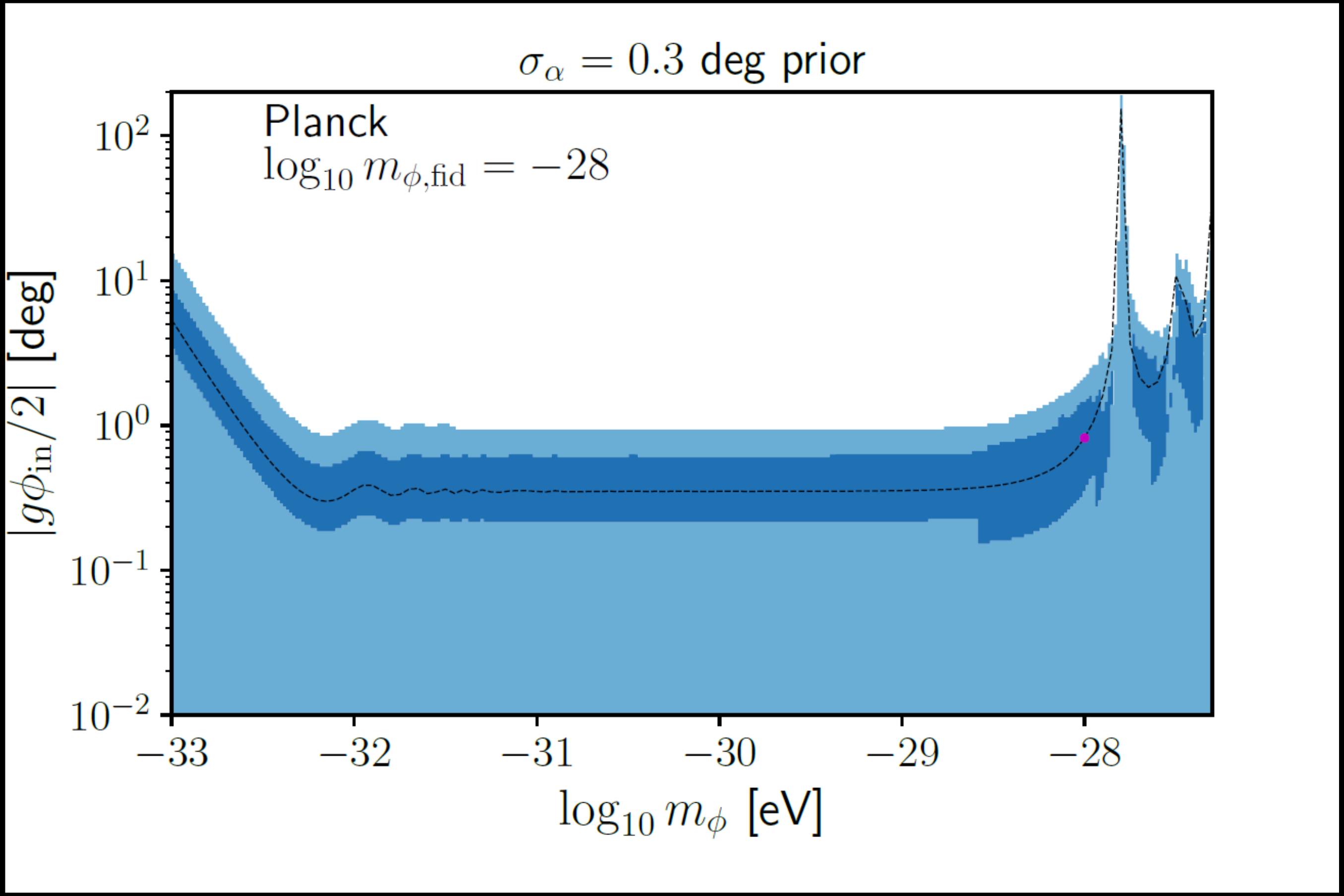
$$\beta = \frac{g}{2}(\phi(\eta_0) - \phi(\eta_{\mathrm{rec}}))$$

For the visibility function deviates from the delta function, we define

$$\beta \equiv \frac{g}{2}(\phi(\eta_0) - \langle\phi\rangle)$$

$$\langle\phi\rangle \equiv \int d\eta\ g_v\phi / \int d\eta\ g_v$$

Forecast


$\sigma_\alpha = 0.3$ deg prior
Planck
$\log_{10} m_{\phi,\rm fid} = -28$
$|g\phi_{\rm in}/2|$ [deg]
10^2
10^1
10^0
10^{-1}
10^{-2}
-33
-32
-31
-30
-29
-28
$\log_{10} m_\phi$ [eV]

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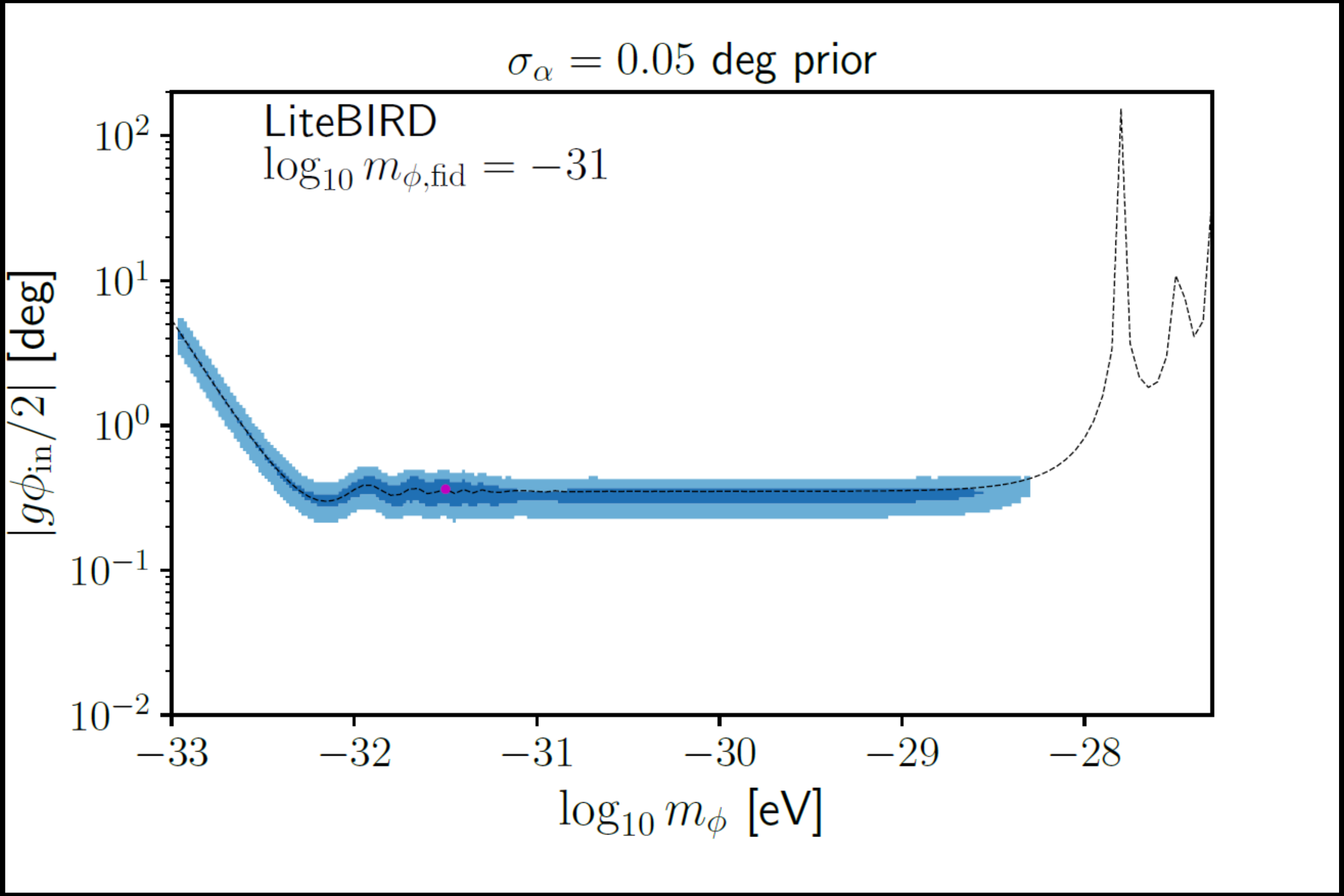
$\sigma_\alpha = 0.05$ deg prior
LiteBIRD
$\log_{10} m_{\phi,\mathrm{fid}} = -31$
$|g\phi_{\mathrm{in}}/2|$ [deg]
10^{2}
10^{1}
10^{0}
10^{-1}
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-33
-32
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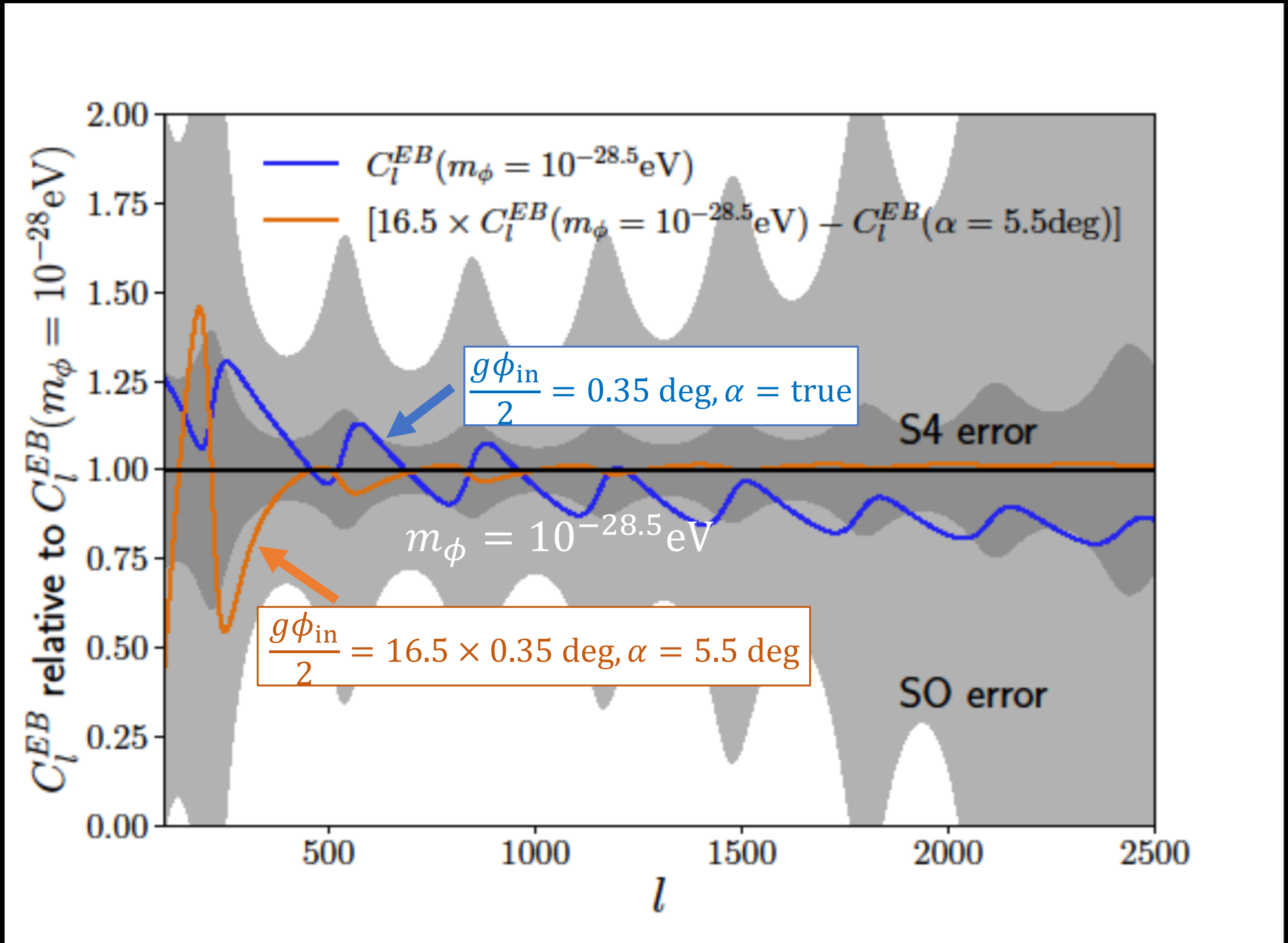

$\frac{g\phi_{\mathrm{in}}}{2} = 0.35$ deg, $\alpha =$ true

$m_\phi = 10^{-28.5}\mathrm{eV}$

$\frac{g\phi_{\mathrm{in}}}{2} = 16.5 \times 0.35$ deg, $\alpha = 5.5$ deg