Probing Axionic Instabilities in the late Universe via CMB-B mode

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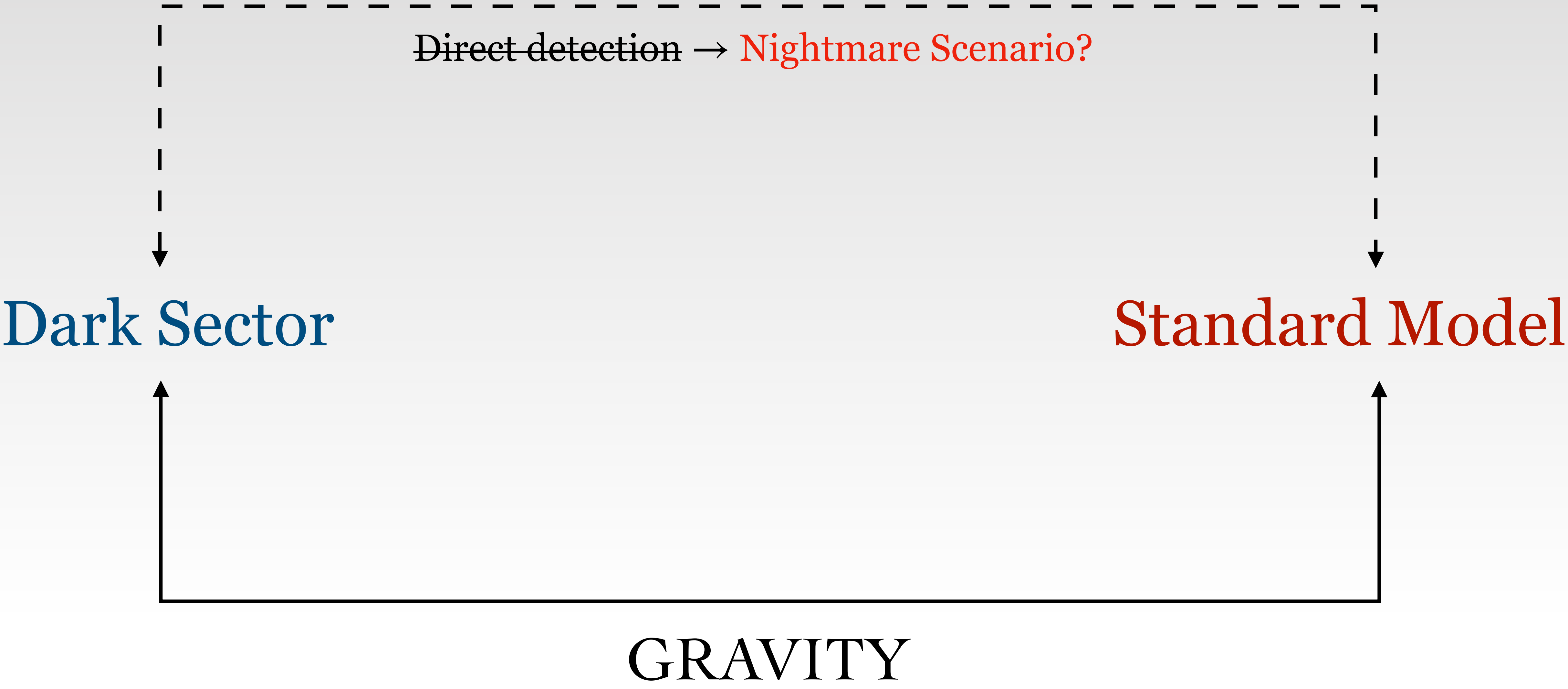
Introduction



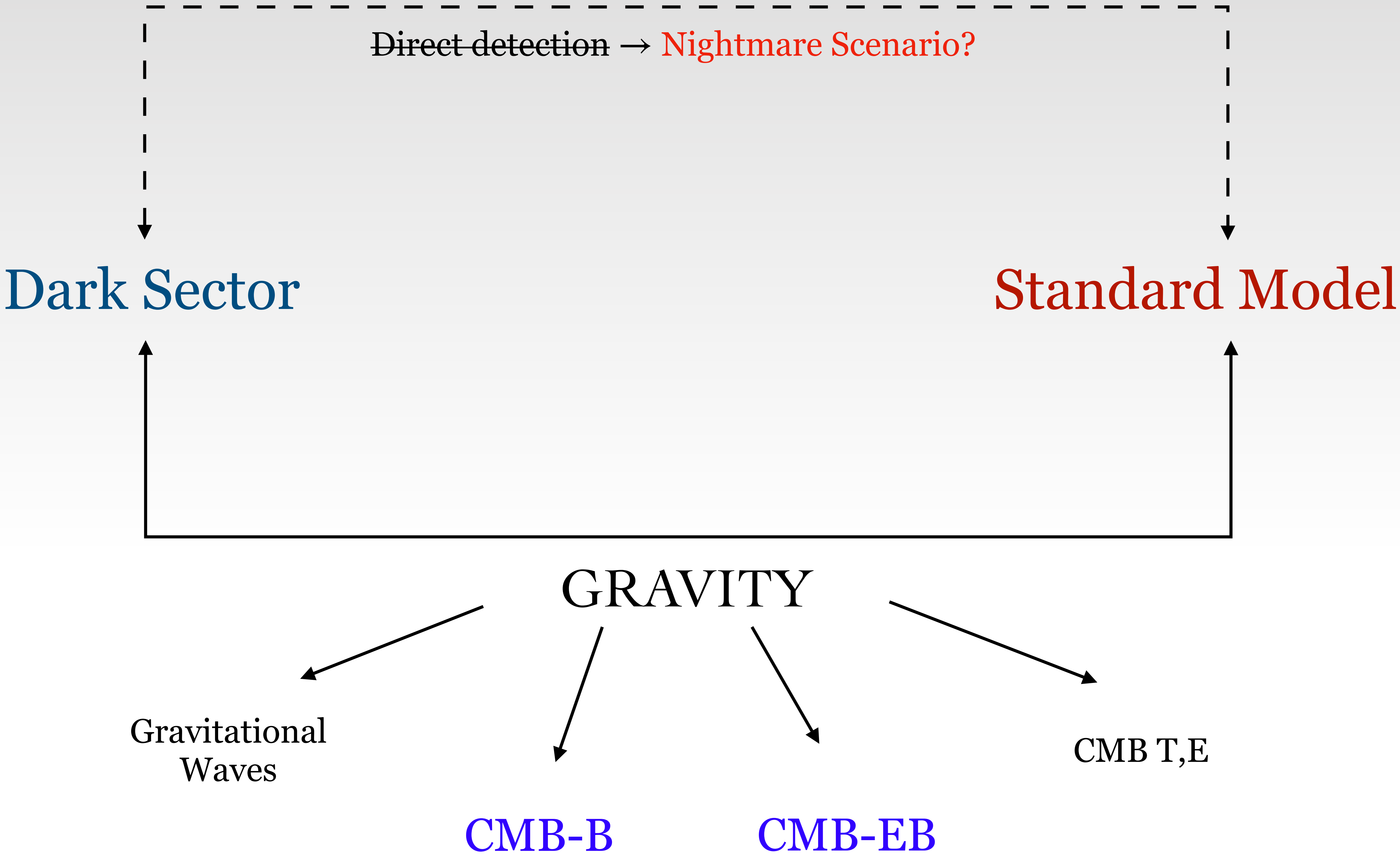
~~Direct detection~~ → Nightmare Scenario?

Dark Sector

Standard Model

GRAVITY

Introduction



~~Direct detection~~ → Nightmare Scenario?

Dark Sector

Standard Model

GRAVITY

Gravitational Waves

CMB-B

CMB-EB

CMB T,E

Secluded Dark Sector: Axion

$$\frac{1}{2}\partial_\mu\phi\,\partial^\mu\phi - V(\phi) - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{\alpha}{4f}\phi X_{\mu\nu}\widetilde{X}^{\mu\nu}$$ → Dark photon

Initial condition:
$\Omega_\phi \neq 0$
$\Omega_F = 0$

$$\Lambda^4 \cos\left(\frac{\phi}{f}\right) \rightarrow \boxed{m = \frac{\Lambda^2}{\sqrt{2}f}}$$

Axion E.O.M →

$$\phi'' + 2aH\phi' + a^2\frac{\partial V}{\partial\phi} = \frac{\alpha}{f}a^2\mathbf{E}\cdot\mathbf{B}$$

Hubble friction

$m^2\phi$

$m > H(z)$ at Matter Domination ⟶ $m \lesssim 10^{-28}$ eV

Caution: $\phi \neq$ DM

Tachyonic instability: Exponential production of Dark photon

$$\hat{X}^i(\mathbf{x},\tau) = \int \frac{d^3k}{(2\pi)^3} \hat{X}^i(\mathbf{k},\tau) e^{i\mathbf{k}\cdot\mathbf{x}} = \sum_{\lambda=\pm} \int \frac{d^3k}{(2\pi)^3} v_\lambda(k,\tau)\, \varepsilon^i_\lambda(\mathbf{k})\, \hat{a}_\lambda(\mathbf{k})\, e^{i\mathbf{k}\cdot\mathbf{x}} + \text{h.c.}$$

Dark Photon E.O.M →

$$v''_\pm(k,\tau) + \omega^2_\pm(k,\tau)\, v_\pm(k,\tau) = 0$$

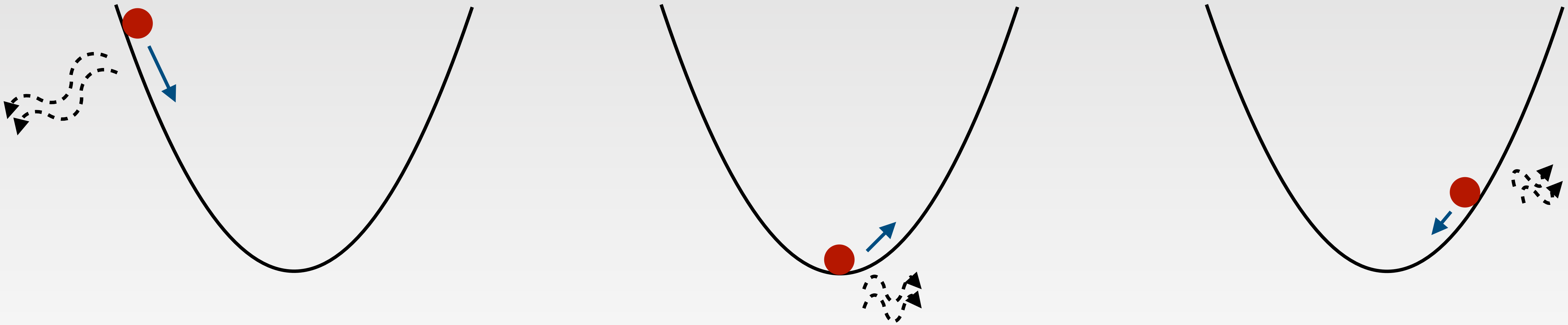
Time dependent frequency →

$$\omega^2_\pm(k,\tau) = k^2 \mp k\frac{\alpha}{f}\phi'$$

$$0 < k < \frac{\alpha\,|\,\phi'\,|}{f} \longrightarrow \omega^2_\pm < 0 \longrightarrow \boxed{v_\pm \sim e^{|\omega_\pm|\tau}}$$

Exponential growth

Tachyonic instability: Exponential production of Dark photon



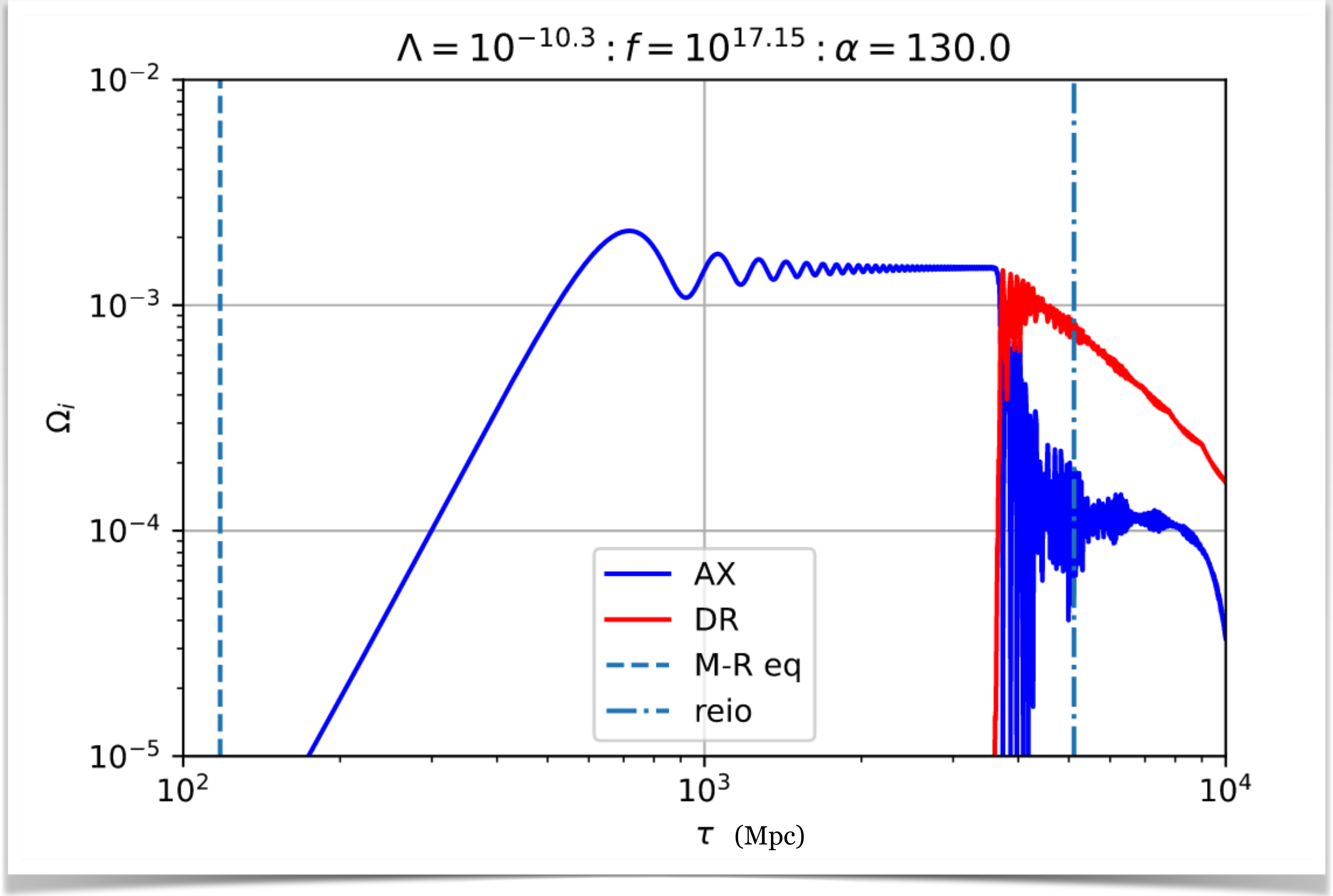
$v_+ \sim e^{\omega_+ \tau}$ $v_+ \sim e^{\omega_+ \tau}$ $v_- \sim e^{\omega_- \tau}$

$$|v_+| \gg |v_-|$$

In our numerical calculation we only consider one helicity for simplicity

Did not include back-reaction of Dark photon gauge modes on Axion (requires lattice study)

Axion Energy gets transferred to DR



Λ, f in GeV

$m = 1.25 \times 10^{-29}$ eV

Dark photon sources metric fluctuations

The density perturbation in Dark Photon is very high → sources metric fluctuation in Matter Domination

$$\langle \delta\rho_e^2 \rangle^{1/2} \sim 10^{-5} \rho_m$$

Scalar Mode

$$\delta'_m + \theta_m = 3\Phi' \,,$$
$$\theta'_m + \frac{a'}{a}\theta_m = -\Phi \,,$$
$$k^2\Phi + 3\frac{a'}{a}\Phi' + 3\left(\frac{a'}{a}\right)^2 \Phi = -4\pi G_N\, a^2(\delta\rho_e + \delta\rho_m)$$

ISW Effect

$$\Theta_0(\mathbf{n}) = \sum_l i^l\,(2l+1) \int \mathcal{D}k\,\tilde{\Theta}_l(\mathbf{k}) P_l\left(\frac{\mathbf{k}\cdot\mathbf{n}}{k}\right)$$
$$\tilde{\Theta}_l(\mathbf{k}) = 2\int_{\tau_{rec}}^{\tau_0} d\tau\,\Phi'(\mathbf{k},\tau) j_l[k(\tau_0-\tau)] \,,$$

$$C_l^{TT} = \frac{1}{4\pi}\int d\mathbf{n}' d\mathbf{n}'' \Theta_0(\mathbf{n}')\Theta_0(\mathbf{n}'') P_l(\mathbf{n}'\cdot\mathbf{n}'')$$

Similar C_ℓ^{EE} expressions

Tensor Mode

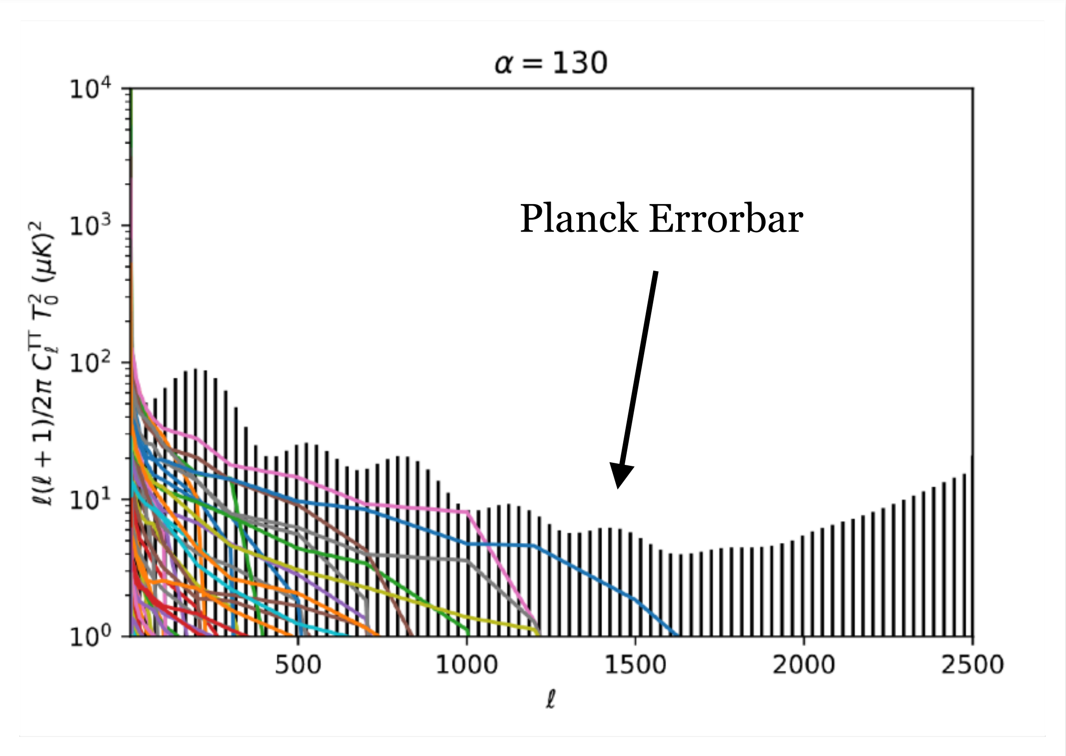
$$\bar{h}''_{ij} + \left(k^2 - \frac{a''}{a}\right)\bar{h}_{ij} = \frac{2}{M_{Pl}^2} a\,\Pi_{ij}(\mathbf{k},\tau)$$

$$C_l^{BB} = 36\pi\,\mathcal{T}_{\rm rei}^2 \int \mathcal{D}k\mathcal{D}k'\,\mathcal{J}_{l,B}^2(k) \cdot \langle \left\{ \int_{\tau_{\rm rec}}^{\tau_{\rm rei}} d\tau\, h'_{ij}(k,\tau) \frac{j_2[(\tau_{\rm rei}-\tau)\,k]}{(\tau_{\rm rei}-\tau)^2\,k^2} \right\}^2 \rangle$$

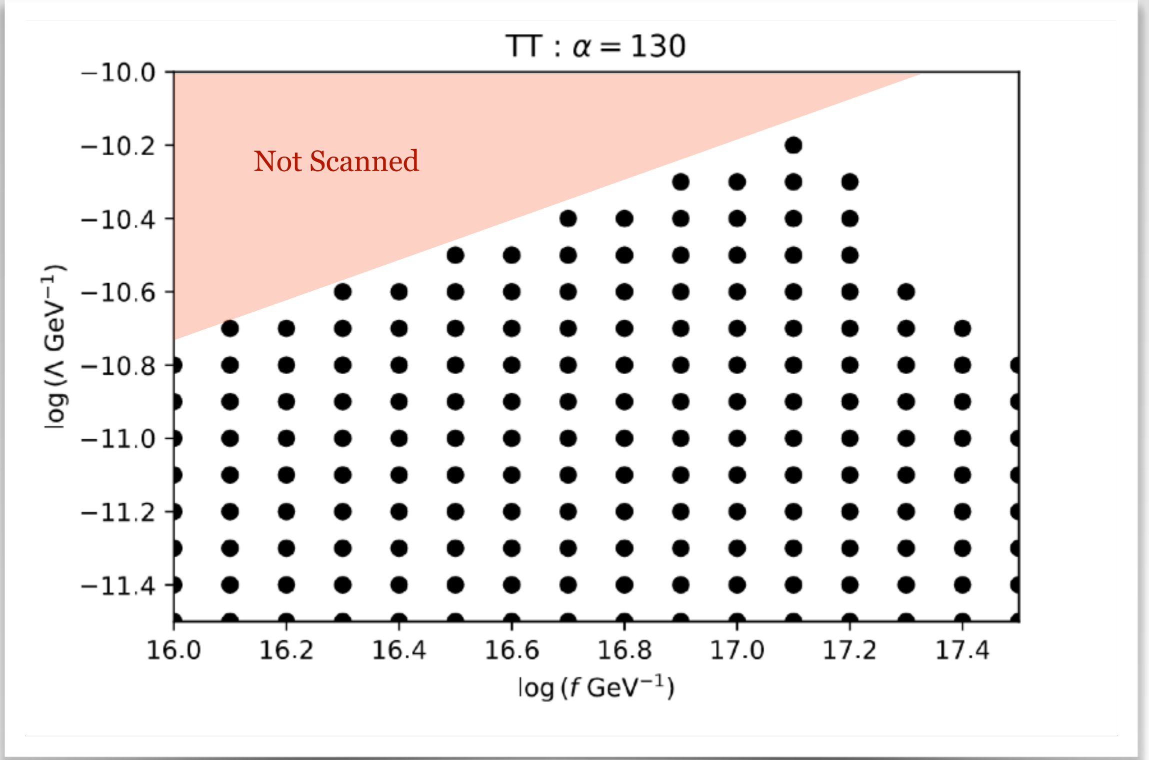
Similar C_ℓ^{TT} and C_ℓ^{EE} expressions

Mode solution & Spectrum computed numerically from scratch → Huge Numerical Challenge

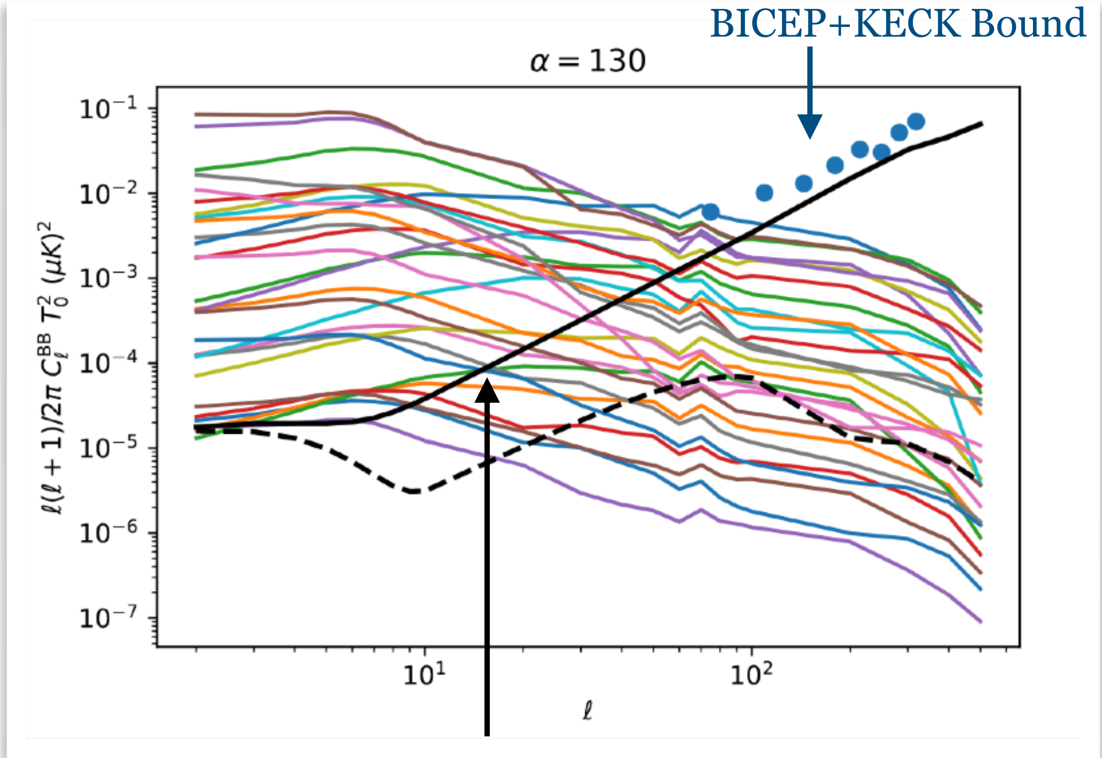
Constraints from CMB TT+EE+BB measurement



Planck Errorbar

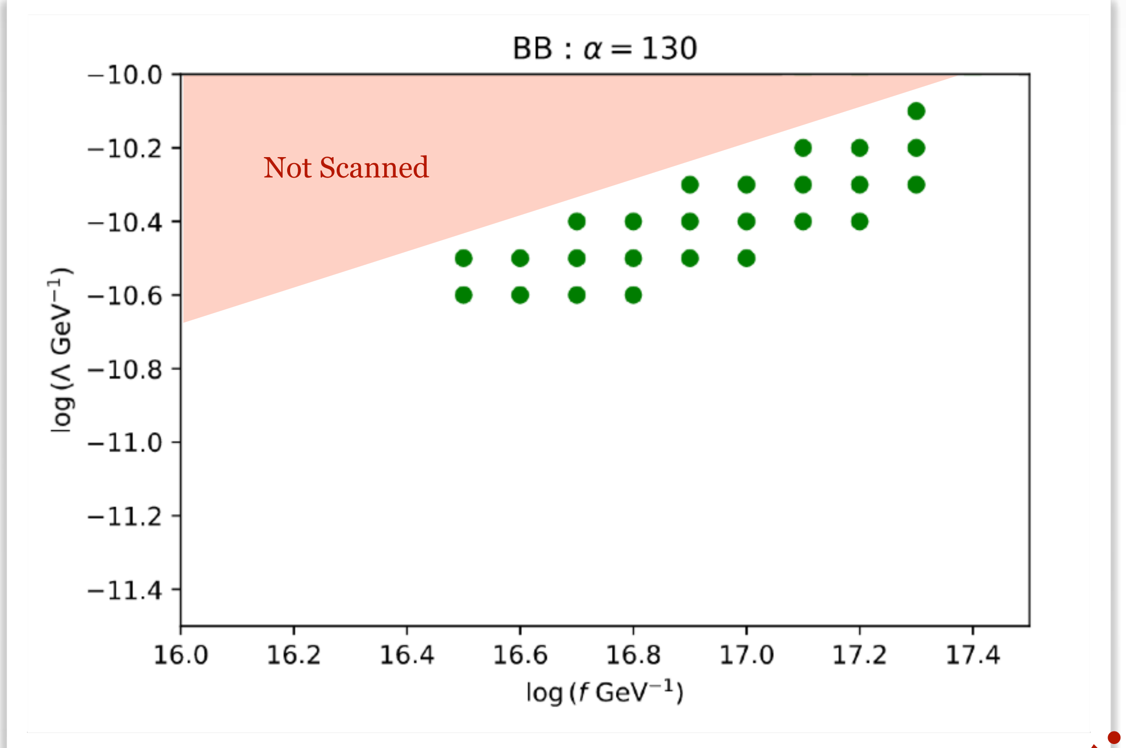


Similar plots for EE



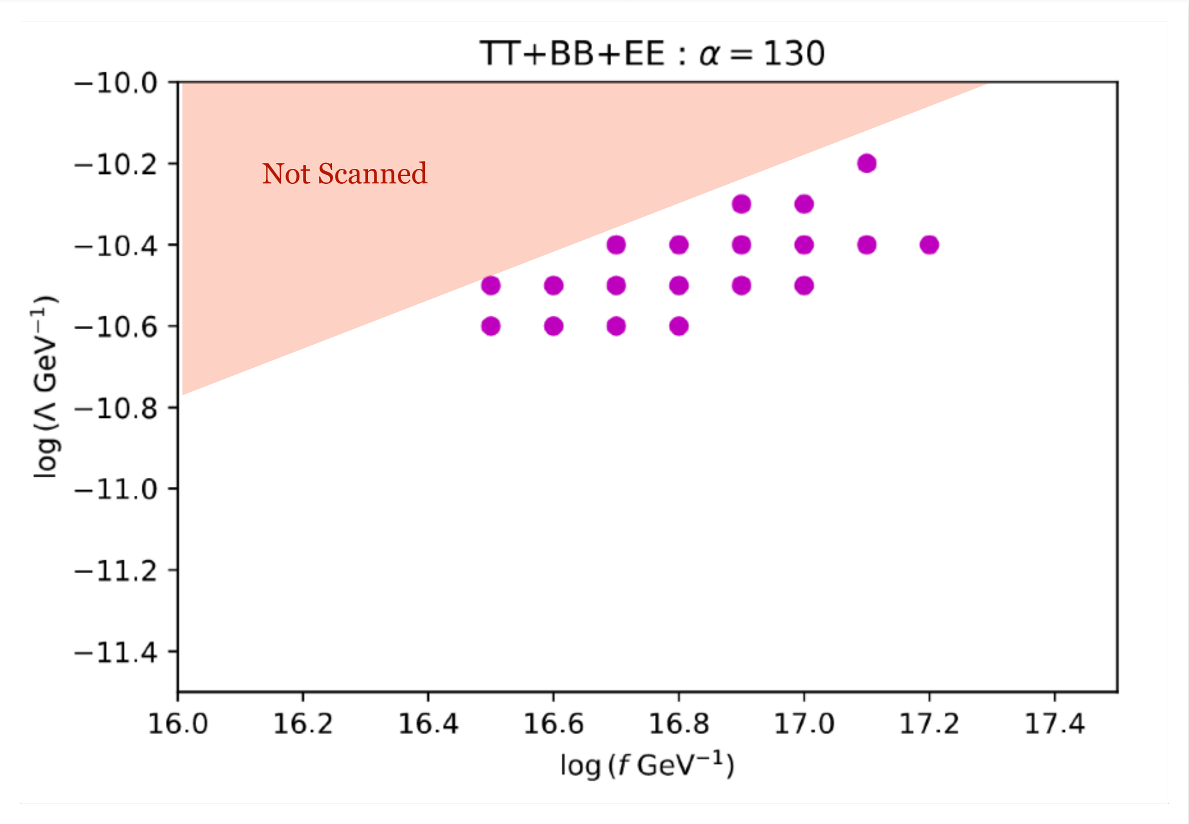
BICEP+KECK Bound

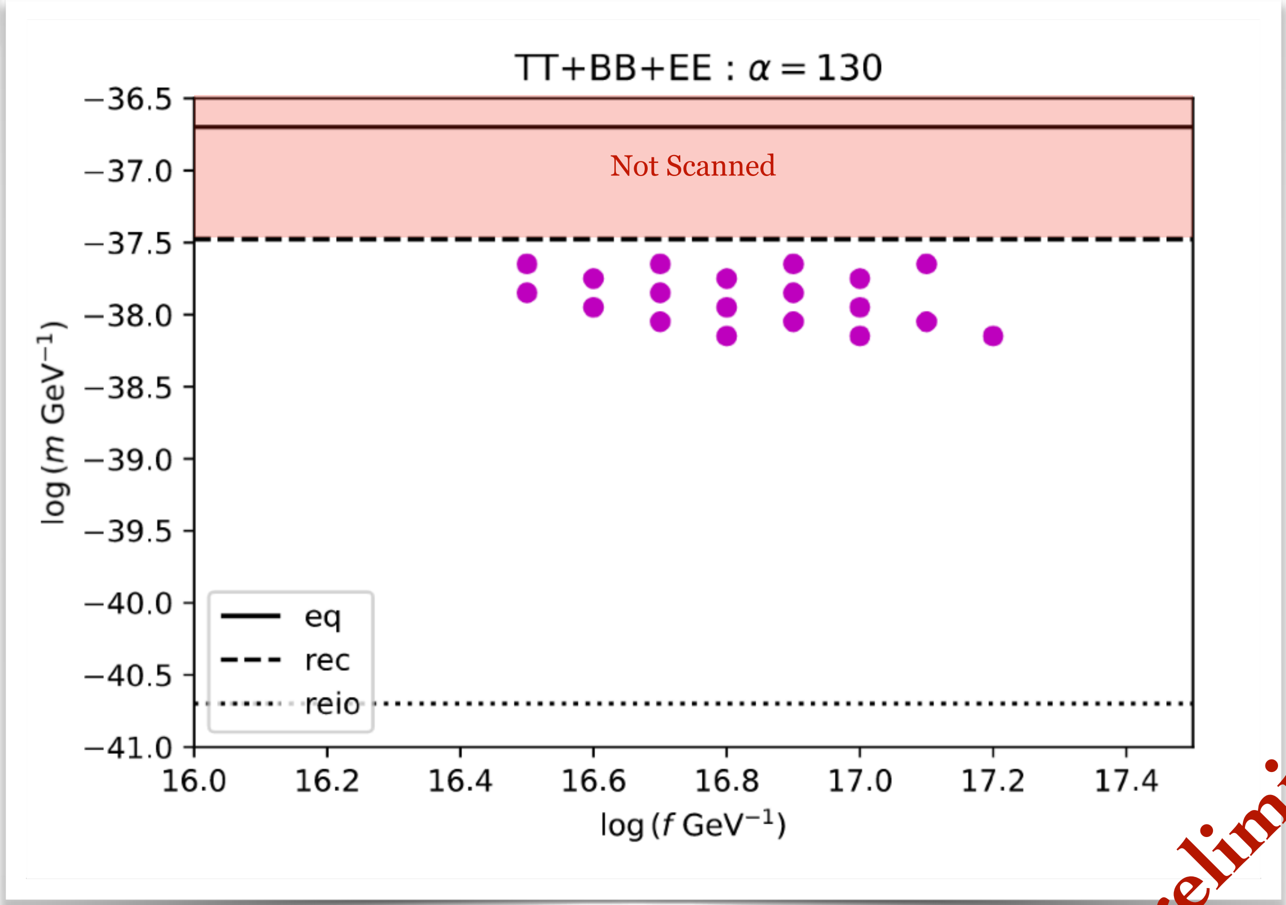
Primordial+Lensing for $r = 10^{-3}$
(Future B mode experiment sensitivity)



Preliminary

Combined CMB TT+EE+BB Constraint (preliminary)





Preliminary

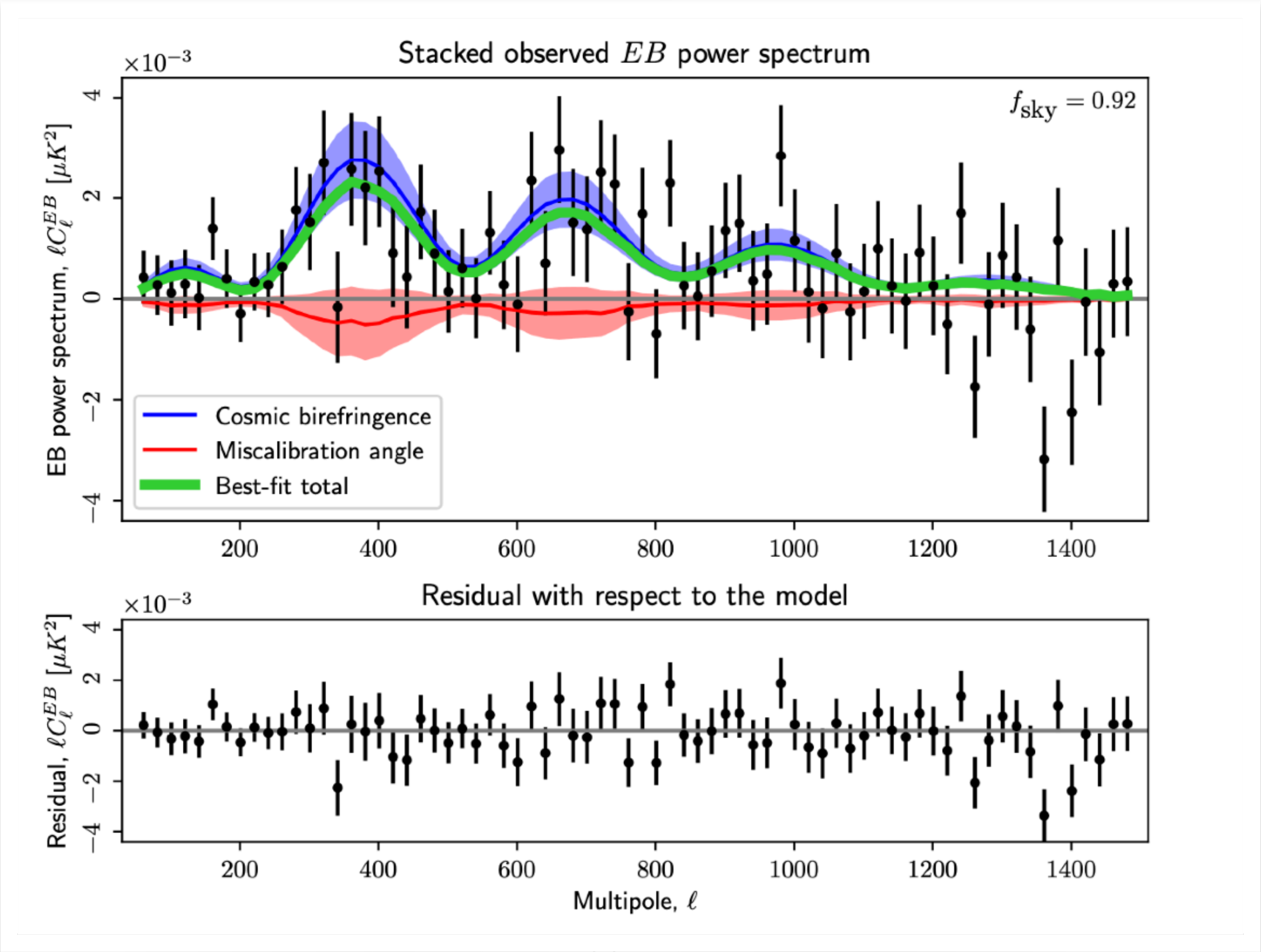
CP Violation: Non-zero EB correlation

$$\frac{\alpha}{4f}\phi X_{\mu\nu}\widetilde{X}^{\mu\nu}$$

Breaks CP as ϕ takes a background value

↓

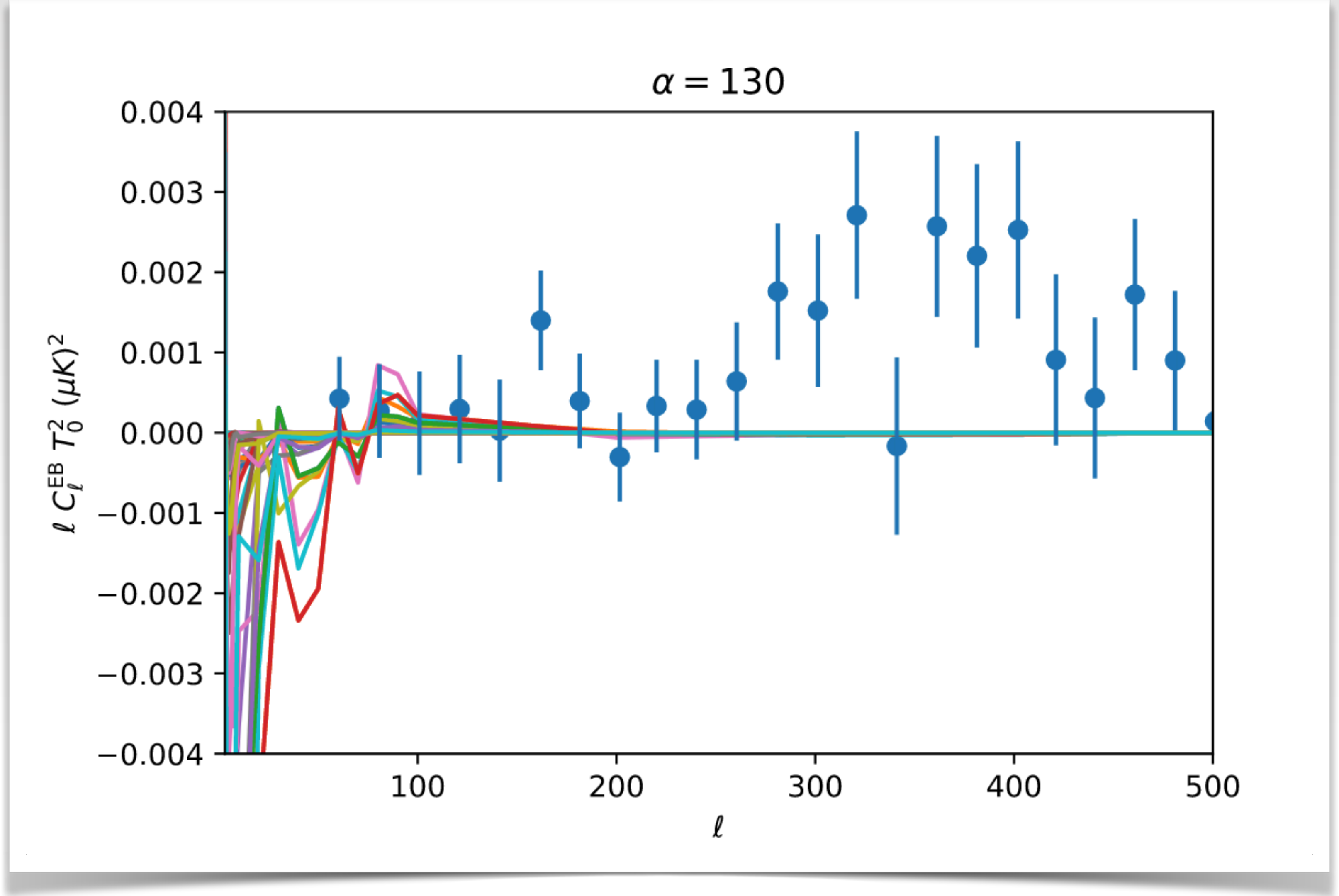
One helicity is enhanced compared to other ≡ CP Violation



Recent measurement of CP violation from CMB in terms of birefringence angle
CP violation seen at 3.6σ

Eskilt et. al.,
arXiv: 2205.13962

Non-zero EB correlation from Axion



The signal does not have large support at small scale (unable to explain the CP violation)

Predicts very large CP violation at large scale

Preliminary

Conclusion

- Completely secluded dark sectors can be probed via gravitational effects
- Tachyonic instability generates exponential growth for dark photon
- Preliminary studies show the signal is not strongly affected by back-reaction
- Axion - Dark photon system generates sizable B mode signal for future B mode experiments
- Produces CP violating EB signal at large scale

Stay tuned for the complete analysis (arXiv: 2212.xxxxx)

THANK YOU