# B-mode signal from Patchy Reionization

Anirban Roy,
PhD Student, SISSA,
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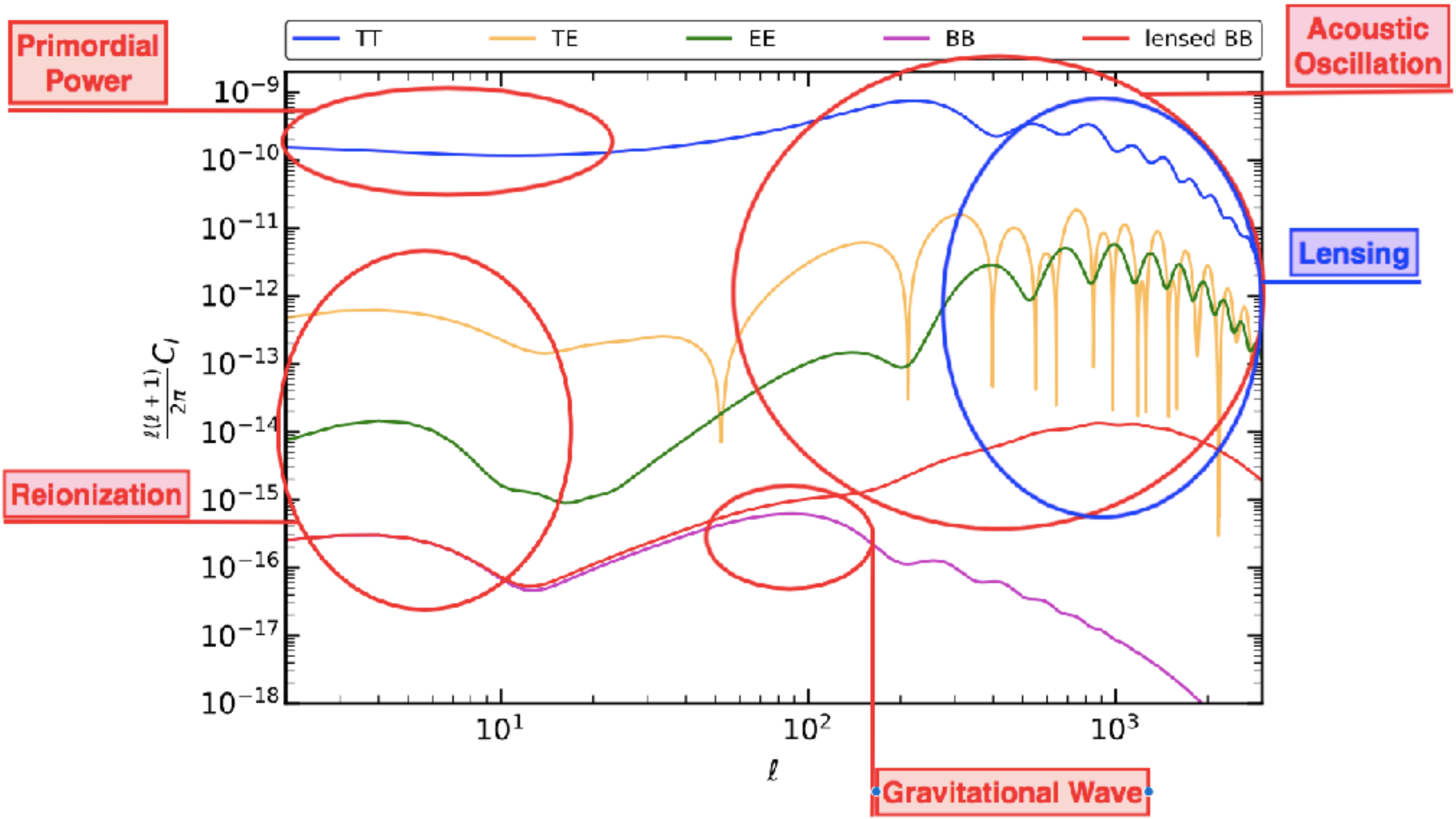
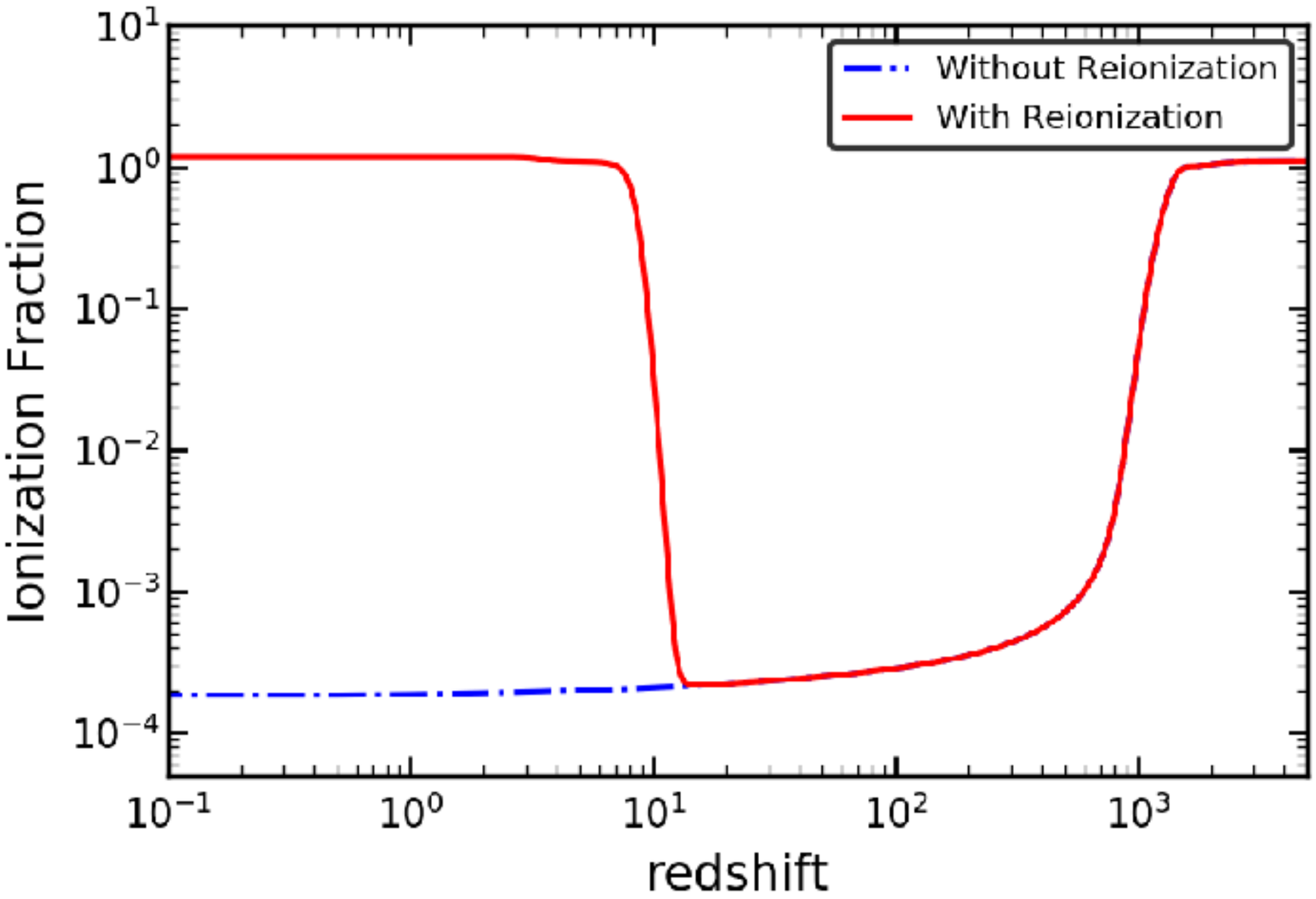
Based on: arxiv:1801.02393

With Andrea Lapi, David Spergel and Carlo Baccigalupi

# CMB Power Spectra

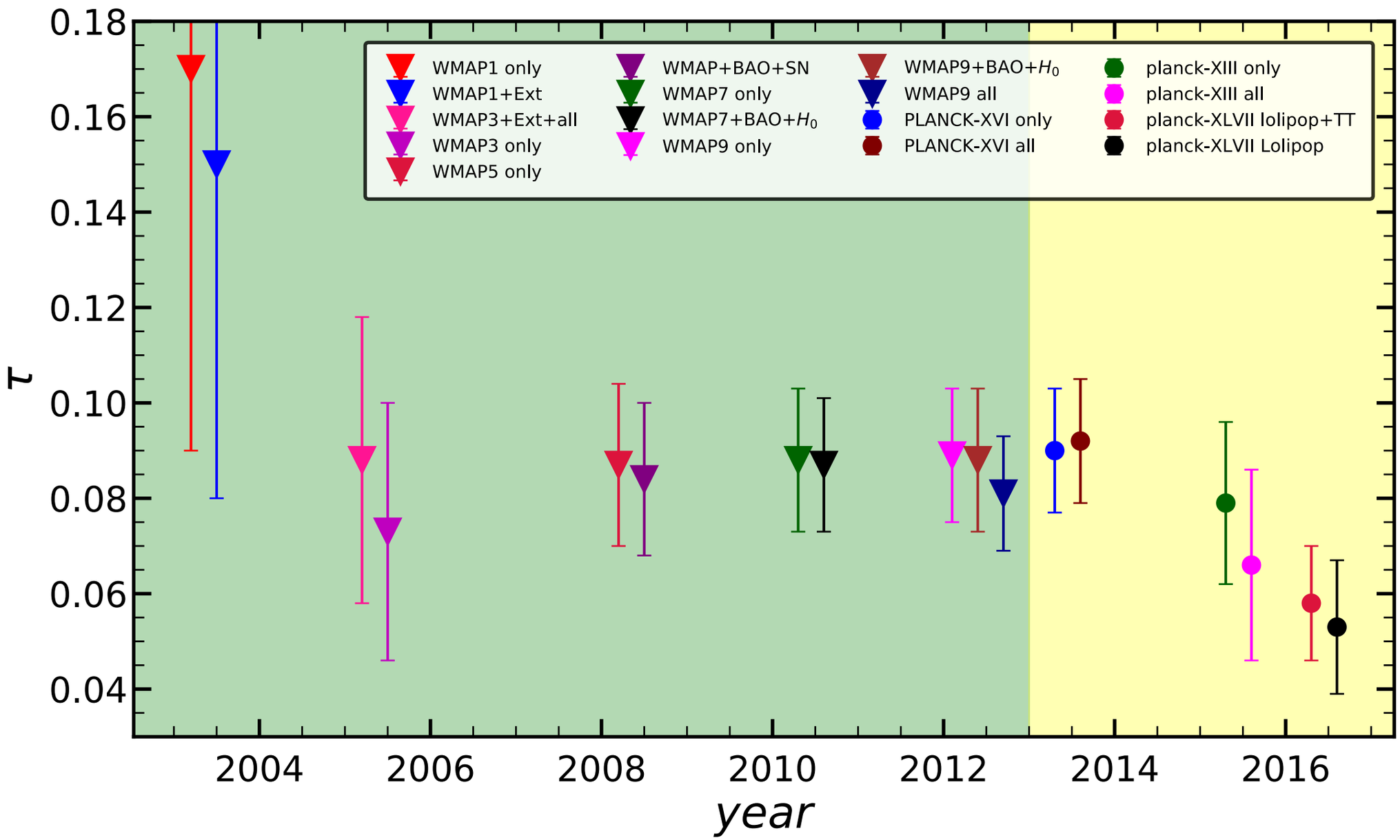


# Thermal History




$$\overline{X}_e = \frac{1}{2}\left[1 - \tanh\left(\frac{y(z) - y(z_{re})}{\Delta y}\right)\right]$$

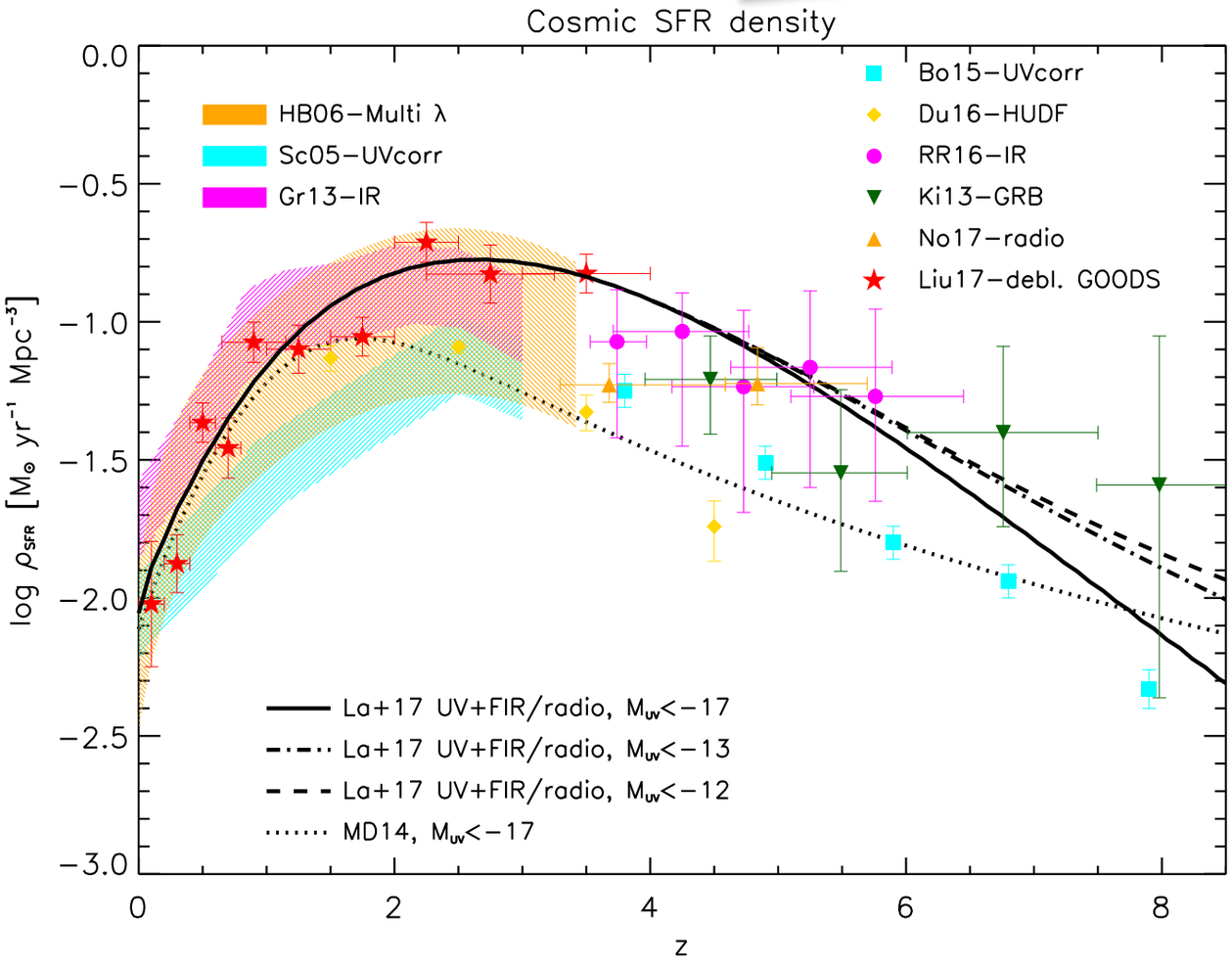
# Tau Observation

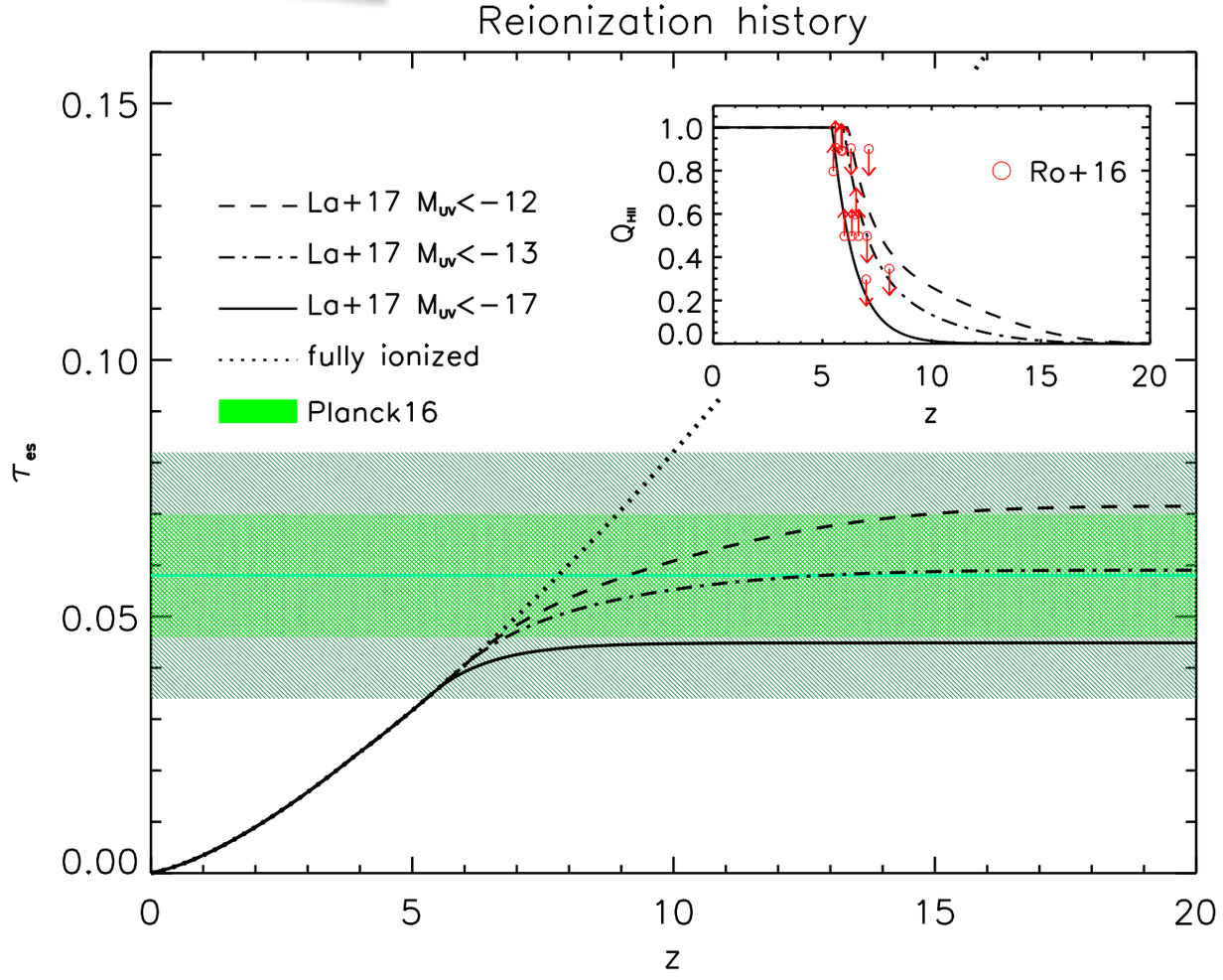



$$\tau(z) = \sigma_T n_{p0} \int_0^z dz' \frac{(1+z')^2}{H(z')} \overline{X}_e(z')$$

# Reionization Sources

$$\dot{N}_{ion} = f_{esc} k_{ion} \rho$$

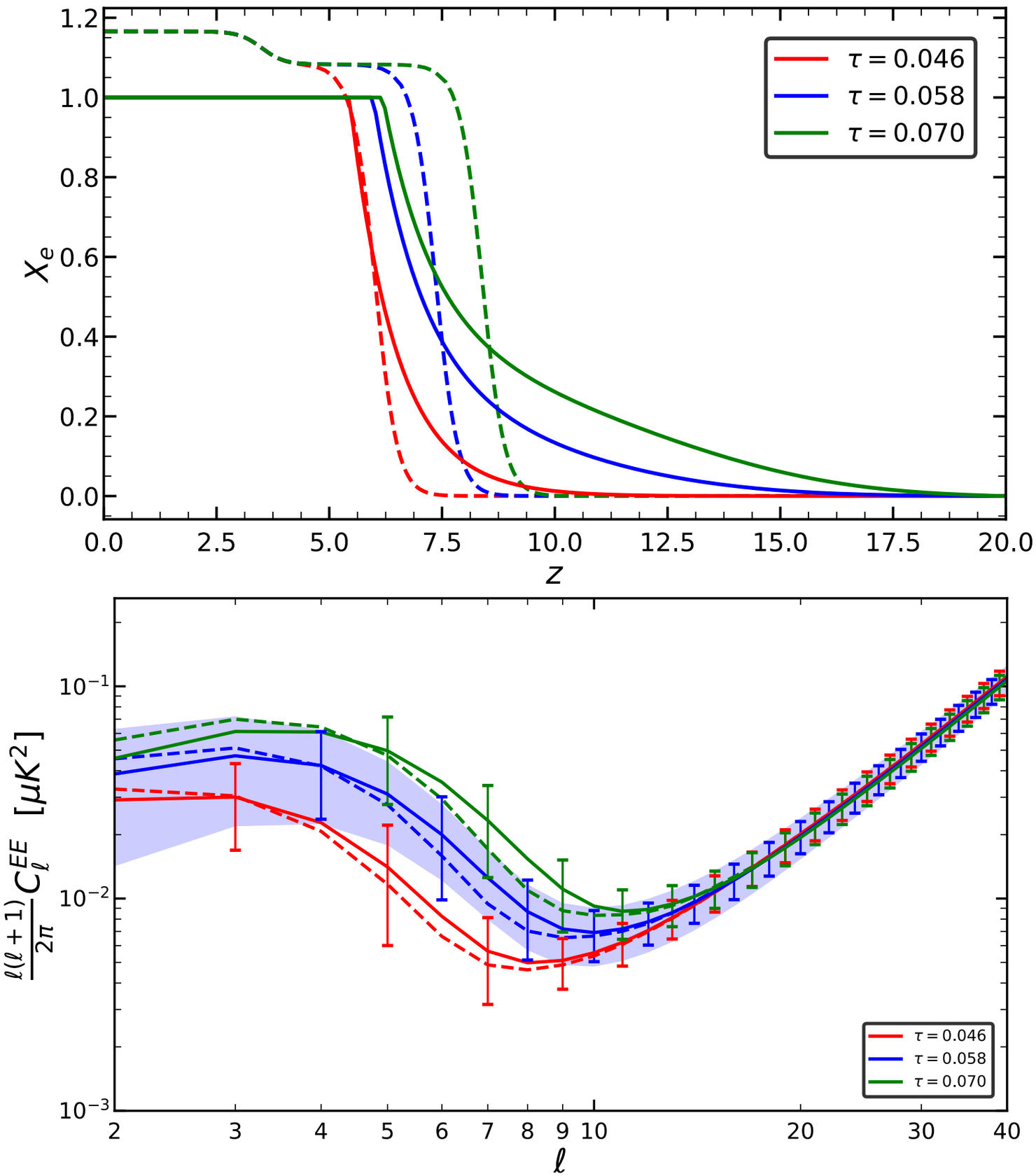


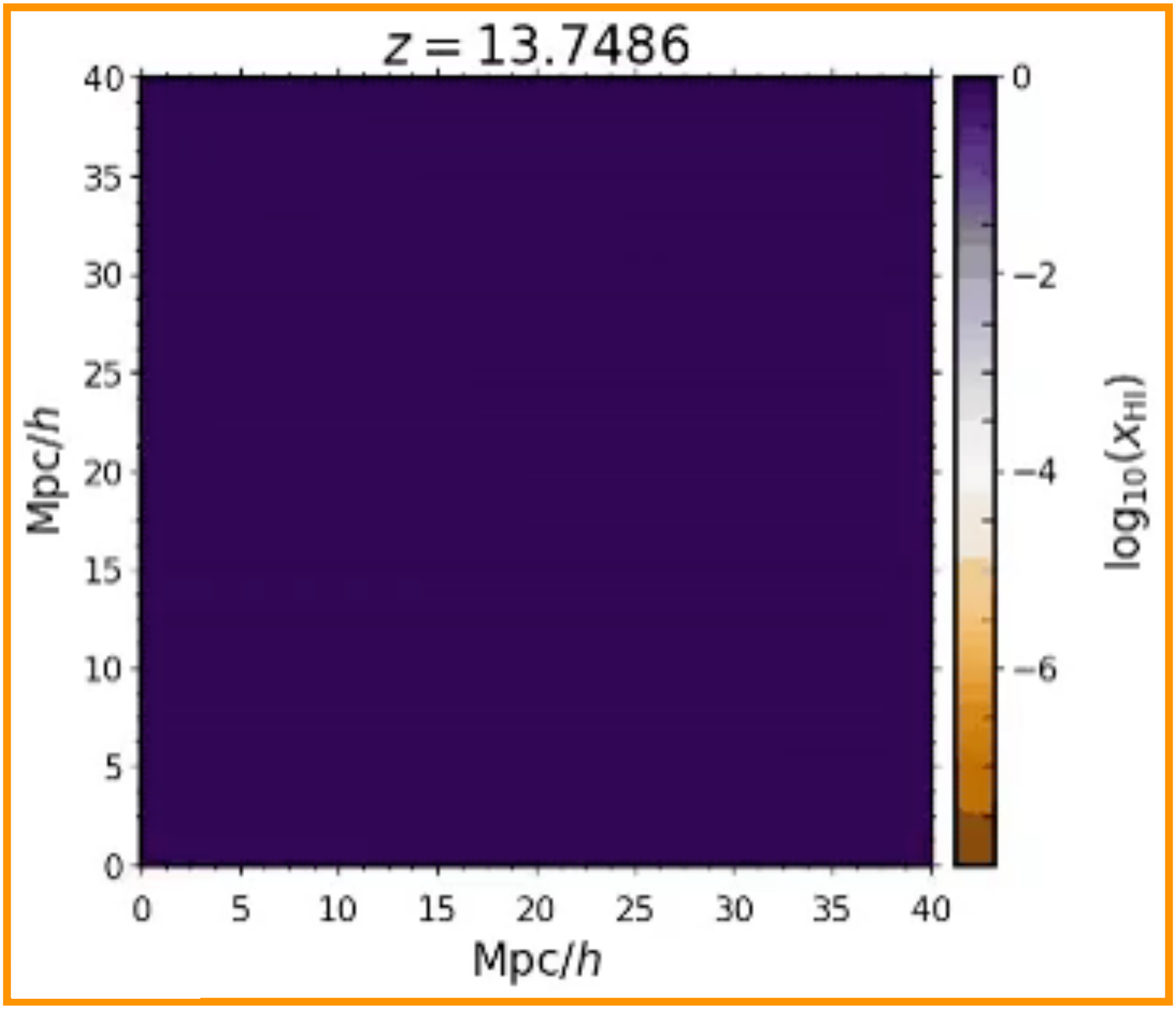

$$\dot{Q}_{HII} = \frac{\dot{N}_{ion}}{\bar{n}_H} - \frac{Q_{HII}}{t_{rec}}$$

**Lapi et al. 2017**

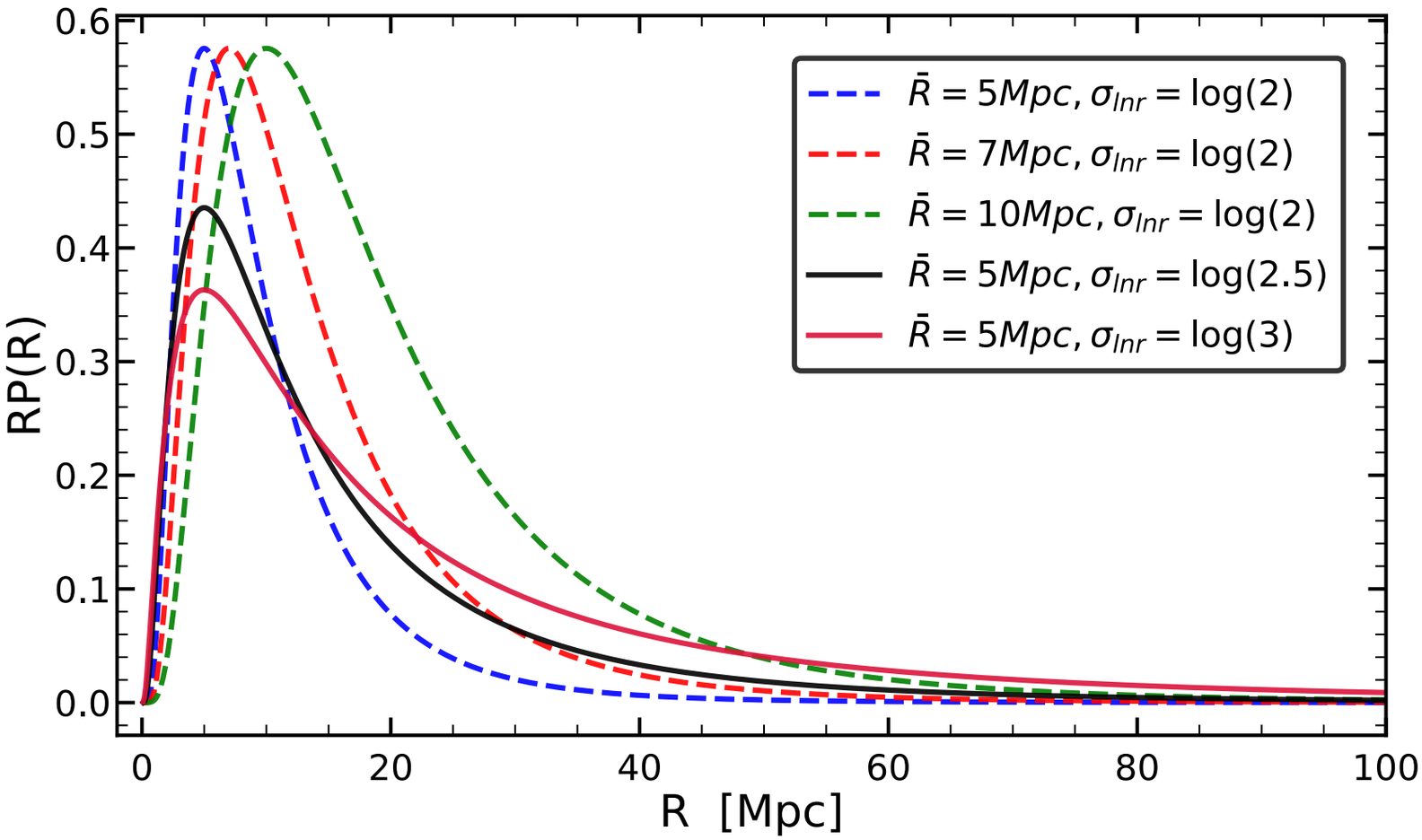
# Reionization and CMB



# Reionization Morphology



# Patchy Reionization




**Fluctuations in tau**

$$\tau(\hat{n}) = \bar{\tau} + \Delta\tau(\hat{n})$$

**Patchy KSZ Signal**

**Patchy screening by a factor** $e^{-\tau(\hat{n})}$

$$P(R) = \frac{1}{R}\frac{1}{\sqrt{2\pi\sigma_{lnr}^2}}\exp\left[-\frac{\ln(R/\bar{R})^2}{2\sigma_{lnr}^2}\right]$$

**Furlanetto et al. 2004**

# Patchy Reionization

**optical depth will be position depended quantity due to patchy reionization. So it is possible to construct tau power spectrum.**

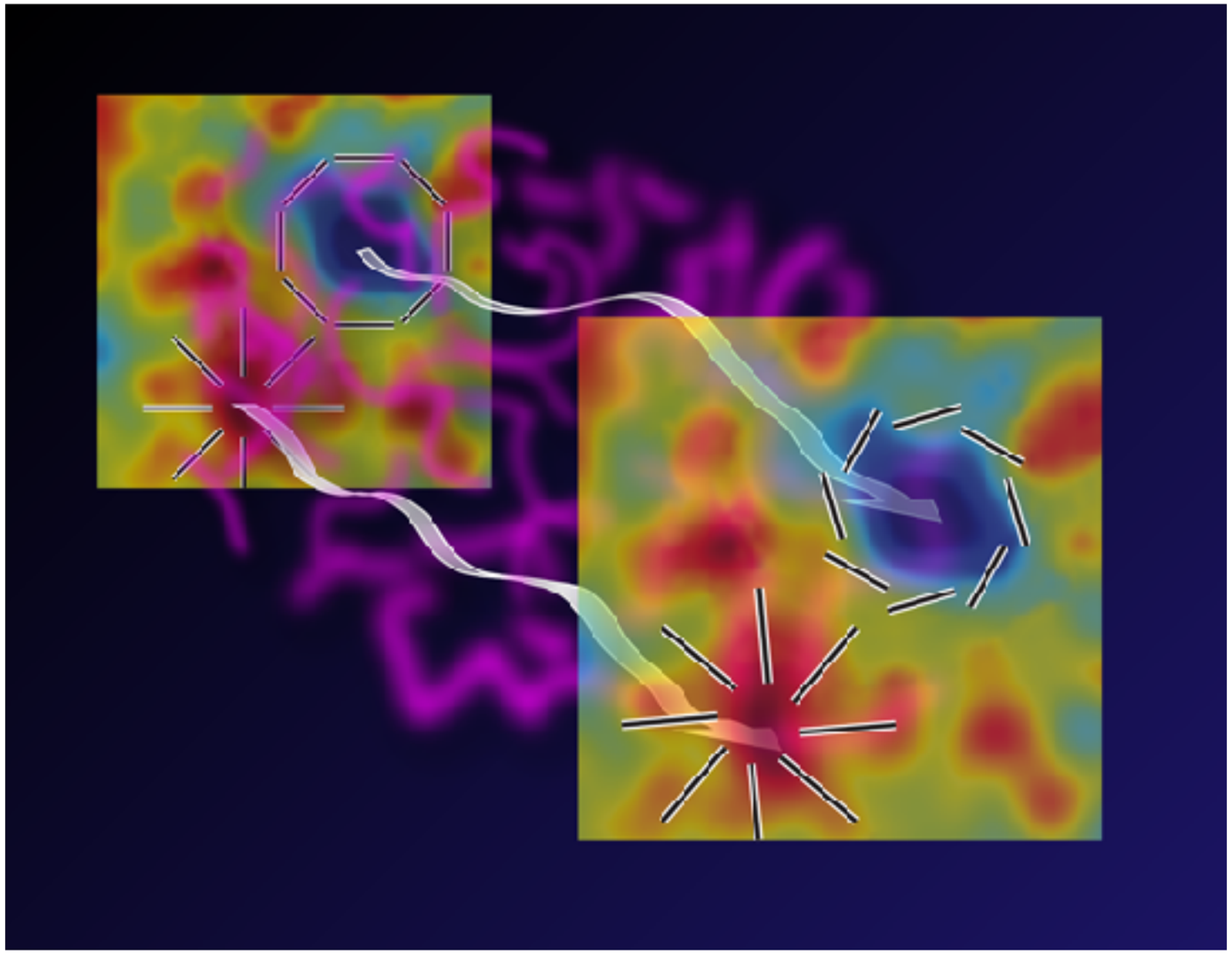
$$C_\ell^{\tau\tau} = \int d\chi \frac{\sigma_T^2 n_{p0}^2}{a^4 \chi^2} P_{\Delta x_e \Delta x_e}\left(\chi, k = \frac{\ell}{\chi}\right)$$

**Like lensing, patchy reionization will also generate B mode signal which can be expressed as**

$$C_\ell^{BB-patchy} = \frac{3\sigma_T^2 n_{p0}^2}{100} \int \frac{d\chi}{a^4 \chi^2} e^{-2\tau(\chi)} Q_{rms}^2 P_{\Delta x_e \Delta x_e}\left(\chi, k = \frac{\ell}{\chi}\right)$$

**Dvorkin & Smith 2009, Roy et al. 2018**

# Lensing Approach



$$X^{len}(\hat{n}) = X^{Unl}\left(\hat{n} + \nabla\phi(\hat{n})\right)$$

$$\phi(\hat{n}) = -2\int dD \frac{D_s - D}{DD_s}\Psi(D\hat{n}, D)$$

# Tau Spectra Reconstruction

$$< E(\vec{\ell_1})B(\vec{\ell_1}) >= f^{\phi}(\vec{\ell_1},\vec{\ell_2})\phi(\vec{L})$$

$$< E(\vec{\ell_1})B(\vec{\ell_1}) >= f^{\tau}(\vec{\ell_1},\vec{\ell_2})\tau(\vec{L})$$

**Coupling Factor**

$$f^{\phi}(\vec{\ell_1},\vec{\ell_2}) = \left[(\vec{L}.\vec{\ell_1})C_{\ell_1}^{EE} - (\vec{L}.\vec{\ell_2})C_{\ell_2}^{BB}\right]\sin 2(\theta_{\ell_1}-\theta_{\ell_2})$$

$$f^{\tau}(\vec{\ell_1},\vec{\ell_2}) = \left[C_{\ell_1}^{EE} - C_{\ell_2}^{BB}\right]\sin 2(\theta_{\ell_1}-\theta_{\ell_2})$$

**Estimated Phi/ Tau**

$$d_{EB}(\vec{L}) = \frac{N_{EB}^{\phi}(\vec{L})}{\vec{L}}\int \frac{d^2\vec{\ell}_1}{2\pi^2}E(\vec{\ell_1})B(\vec{\ell_2})F_{EB}^{\phi}(\vec{\ell_1},\vec{\ell_2})$$

$$\tau_{EB}(\vec{L}) = \frac{N_{EB}^{\tau}(\vec{L})}{\vec{L}}\int \frac{d^2\vec{\ell}_1}{2\pi^2}E(\vec{\ell_1})B(\vec{\ell_2})F_{EB}^{\tau}(\vec{\ell_1},\vec{\ell_2})$$

**Hu & Okamato 2002, Su et al. 2013, Dvorkin & smith 2009**

# Tau Estimator Noise

## Filter

$$F^{\phi|\tau}_{EB}(\vec{\ell_1},\vec{\ell_2}) = \frac{f^{\phi|\tau}_{EB}(\vec{\ell_1},\vec{\ell_2})}{(C^{EE}_{\ell_1}+N^{EE}_{\ell_1})(C^{BB}_{\ell_2}+N^{BB}_{\ell_2})}$$

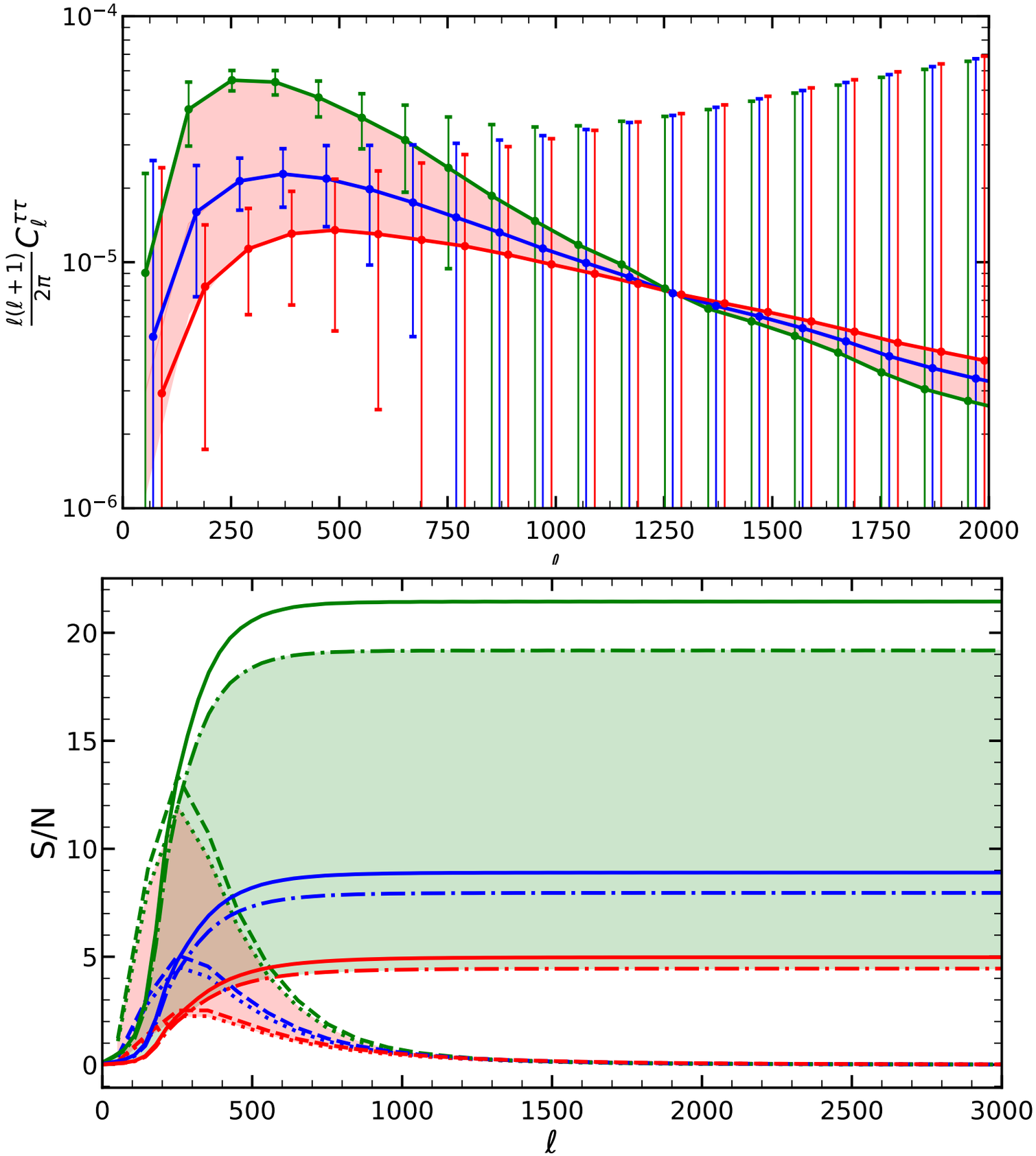
## Instrumental Noise

$$N^{EE}_{\ell} = N^{BB}_{\ell} = \Delta^2_P \exp\left[\frac{\ell^2\theta^2_{FWHM}}{8\ln 2}\right]$$

## Estimator Noise for Tau/ Phi

$$N^{EB}_{\phi|\tau}(\vec{L}) = L^2\left[\frac{d^2\ell_1}{2\pi^2} f^{\phi|\tau}_{EB}(\vec{\ell_1},\vec{\ell_2}) F^{\phi|\tau}_{EB}(\vec{\ell_1},\vec{\ell_2})\right]$$

# Reconstructed Tau Spectra




$$\tau = 0.058$$

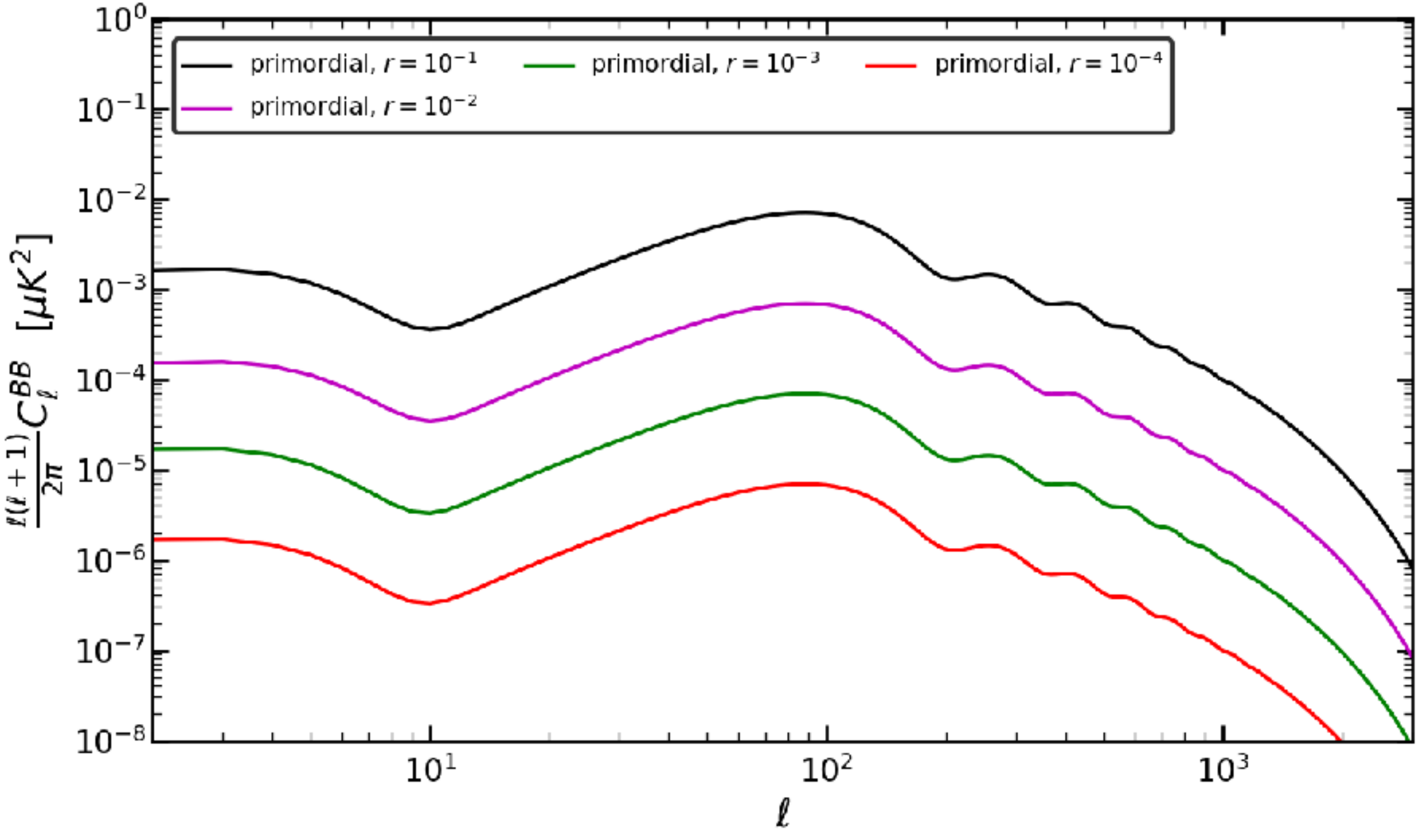
$$\bar{R} = 10Mpc$$

$$\bar{R} = 7Mpc$$

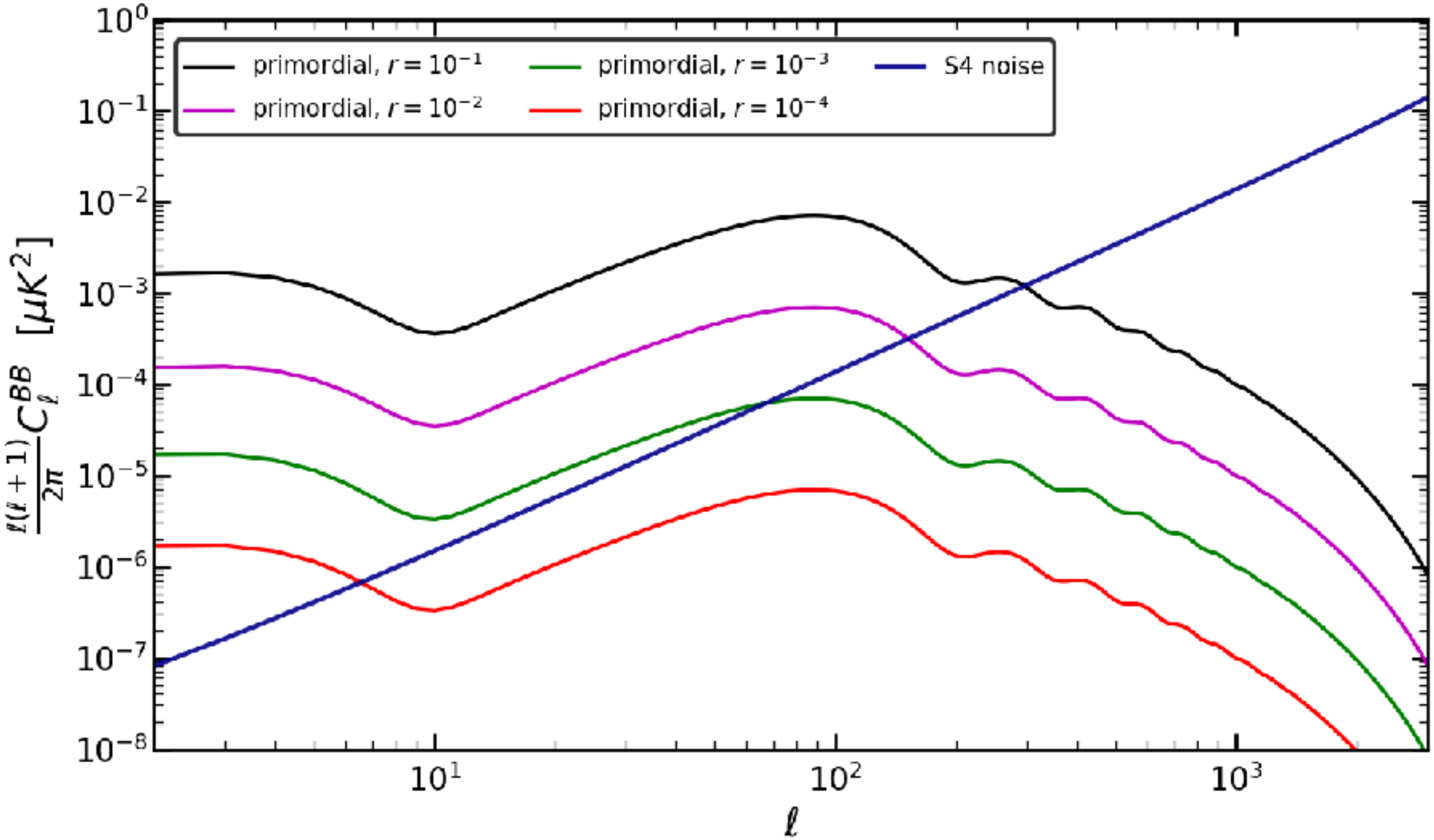
$$\bar{R} = 5Mpc$$

**Roy et. al 2018 (arxiv:1801.02393)**

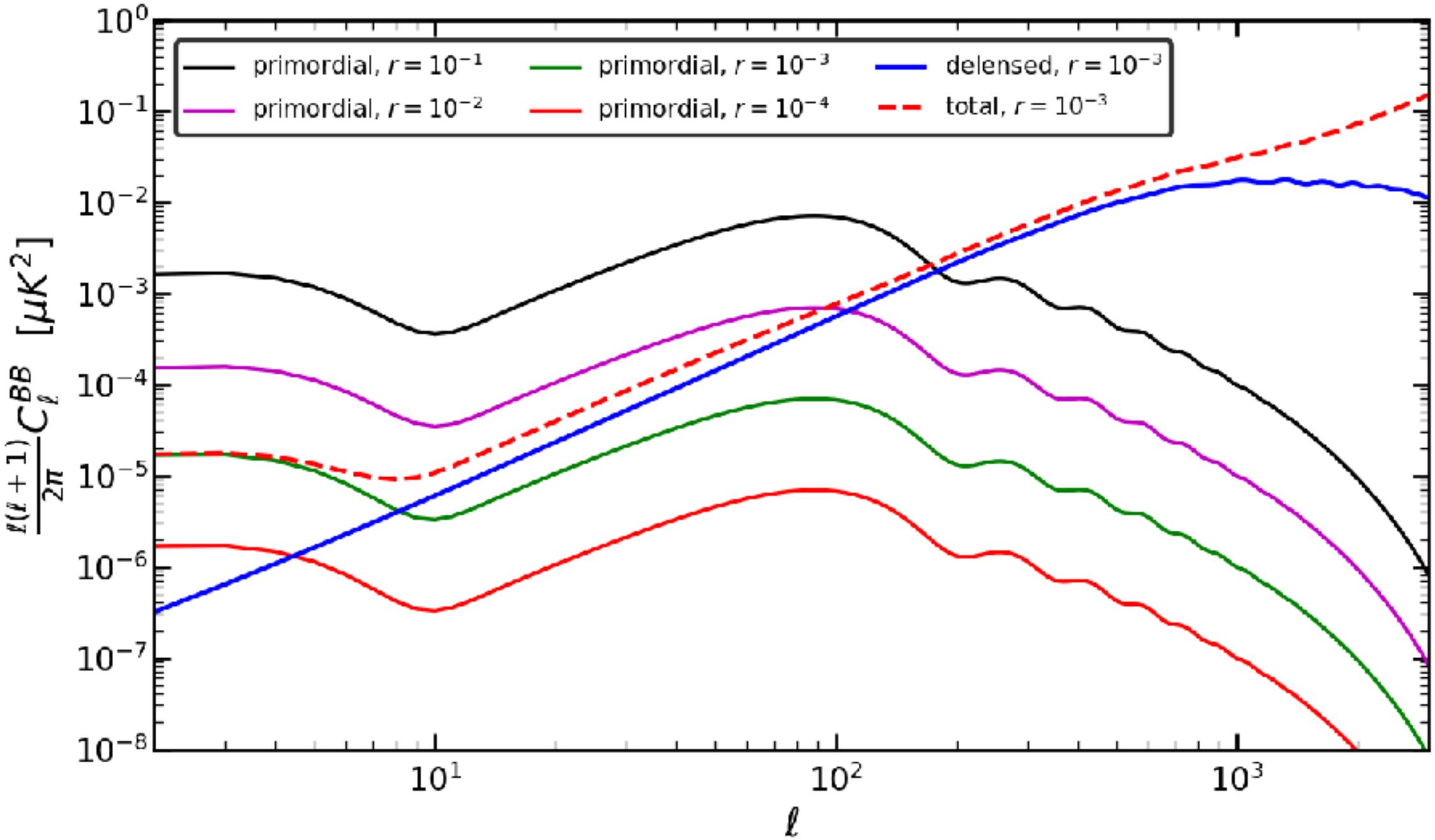
# B mode signal (Primordial)



# B mode signal (Primordial+Instrumental noise)

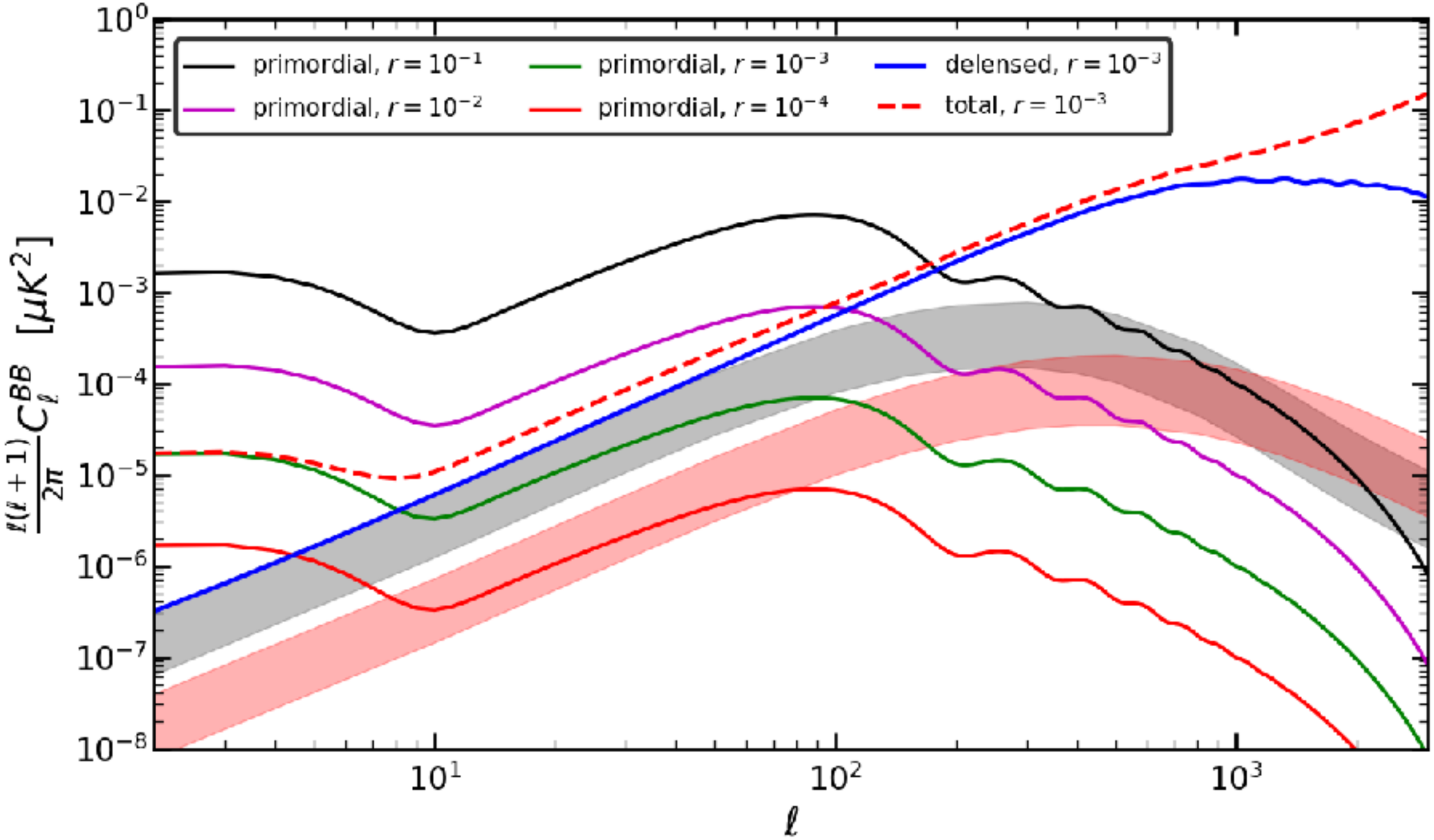


# B mode signal (Primordial+delensed)



# B mode signal (Primordial+delensed+patchy BB)

$\bar{R} = 10Mpc$ $\bar{R} = 5Mpc$



# Into the Future

**1) What is the effect of foregrounds on tau measurement? Can we measure tau with $\sigma(\tau) = 0.002$?**

**2) Need to study Reionization morphology in details to evaluate the amplitude of tau spectra correctly.**

**3) If r=0.001, our preliminary analysis shows that primordial B mode signal can be contaminated by patchy B mode signal. What to do then? Should we do "de-Patchy" analogous to delensing to recover the primordial B mode signal?**