Constraining reionization with the CMB optical depth fluctuation - Compton-y cross-correlation

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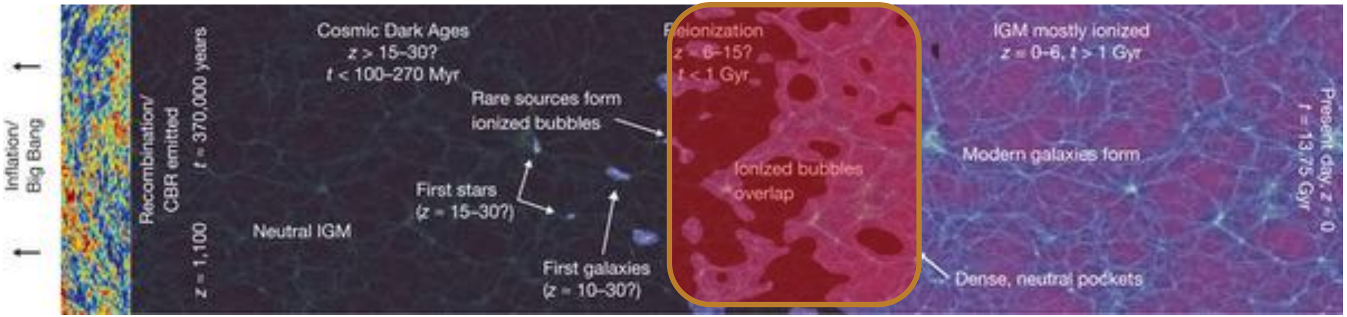
Motivation



(Robertson et al. 2010)

- Radiation from the first star-forming galaxies should reionize the intergalactic medium, highly inhomogeneous process (e.g. Kamionkowski, Spergel & Sugiyama 1994, Fukugita & Kawasaki 1994, Shapiro, Giroux & Babul 1994, Tegmarkm Silk & Blanchard 1994, Barkana & Loeb 2001)

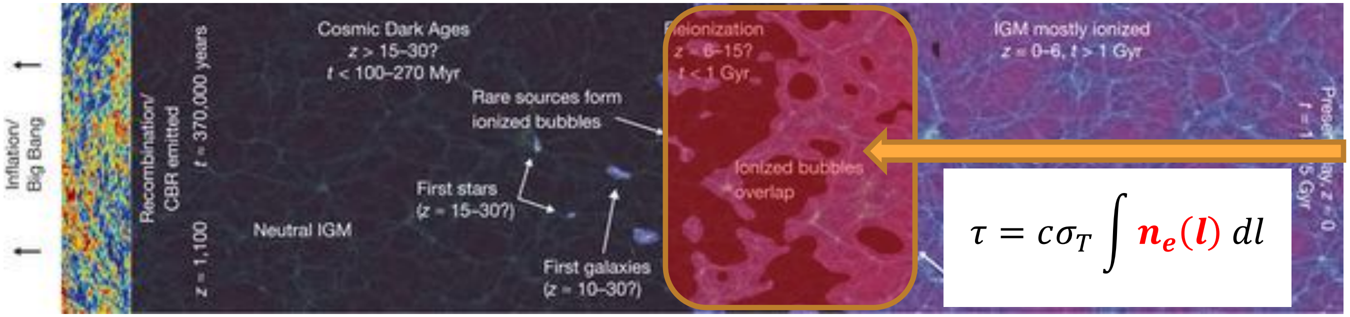
- Several observational implications for the reionization epoch (e.g. SDSS collaboration 2001, Planck collaboration 2016, Bowman et al. 2018)

    Quasar spectrum, CMB power spectrum, EDGES 21cm

Details of the reionization epoch are, however, still unclear

We propose a new method for exploring reionization from CMB observations

Direction-dependent CMB optical depth



$$\tau = c\sigma_T \int \boldsymbol{n_e(l)}\, dl$$

(Robertson et al. 2010)

- (Isotropic) CMB optical depth, τ, is often used for cosmological parameter constraints

- However, τ could be anisotropic (originated from fluctuations of $\boldsymbol{n_e}$)

Direction-dependent CMB optical depth

- $\delta\tau$ can be reconstructed by correlating different modes

CMB fluctuations are suppressed by the screening: $T \to e^{-\tau}T = T'$

$\delta\tau$ must be direction-dependent: $T^{\rm obs}(n) = e^{-\delta\tau(n)}T'(n) \sim T'(n) - \delta\tau(n)T'(n)$

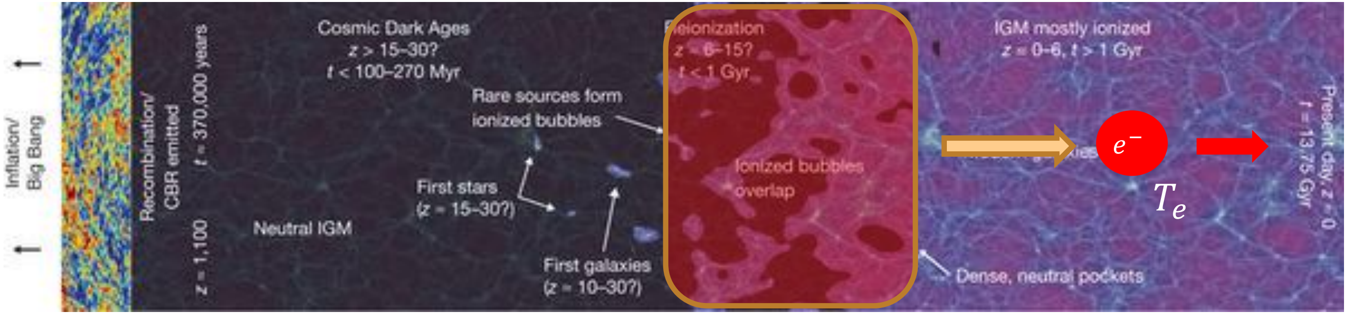
This leads to mode coupling between Fourier modes

$$T^{\rm obs}_{\vec{L}_1}T^{\rm obs}_{\vec{L}_2} \propto \delta\tau_{\vec{L}_1-\vec{L}_2} \qquad (\vec{L}_1 \neq \vec{L}_2)$$

We estimate $\delta\tau$ by correlating different modes with an optimal weighting

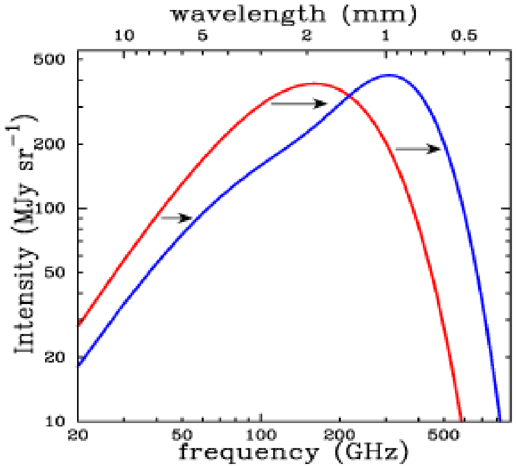
$$\widehat{\delta\tau}_{\vec{L}} = \int \mathrm{d}^2\vec{\ell}\ w^{\tau}_{\vec{\ell},\vec{L}}\, T^{\rm obs}_{\vec{\ell}}T^{\rm obs}_{\vec{L}-\vec{\ell}}$$

Thermal Sunyaev Zel'dovich (SZ) effect



(Robertson et al. 2010)

- CMB photons are scattered to higher energies by hot electron gas and the black body spectrum is shifted



The temperature change is characterized by

$$\frac{\Delta T_\nu(n)}{T_{\mathrm{CMB}}} = g(\nu)y(n)$$

where the Compton y-parameter is defined as

$$y = \int \frac{k_B T_e(l)}{m_e c^2} n_e(l) \sigma_T c \, \mathrm{d}l$$

(integrated electron pressure)

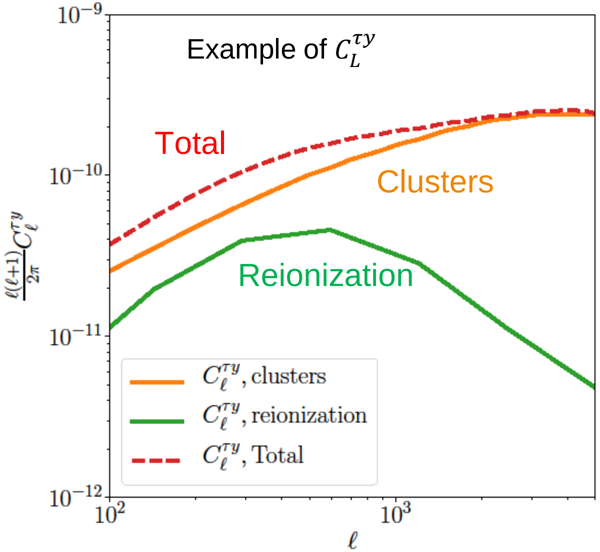
y is generated at both late-time and reionization

This work: Probing reionization using $\delta\tau$ and y

- $\delta\tau$ and y trance electron density fluctuations and are correlated

$$C_L^{\tau\tau} = \sigma_T^2 n_{p0}^2 \int \frac{\mathrm{d}\chi}{a^4\chi^2} P_{x_e x_e}(\chi, L)$$

$$C_L^{\tau y} = \sigma_T^2 n_{p0}^2 \int \frac{\mathrm{d}\chi}{a^4\chi^2} \frac{k_B T_e}{m_e c^2} P_{x_e x_e}(\chi, L)$$



- y-map has significant contribution from cluster at late time and yy is not sensitive to the reionization

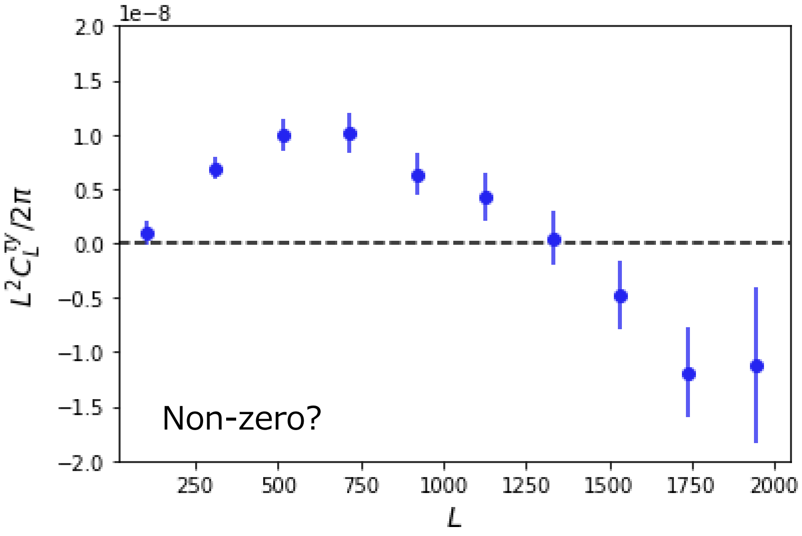
- Cross-correlation is much less sensitive to the individual systematics in each measurement

(next slides)

We use existing data (Planck) to measure the above quantities and constrain reionization model

Measurement of optical-depth power spectrum $C_L^{\tau y}$

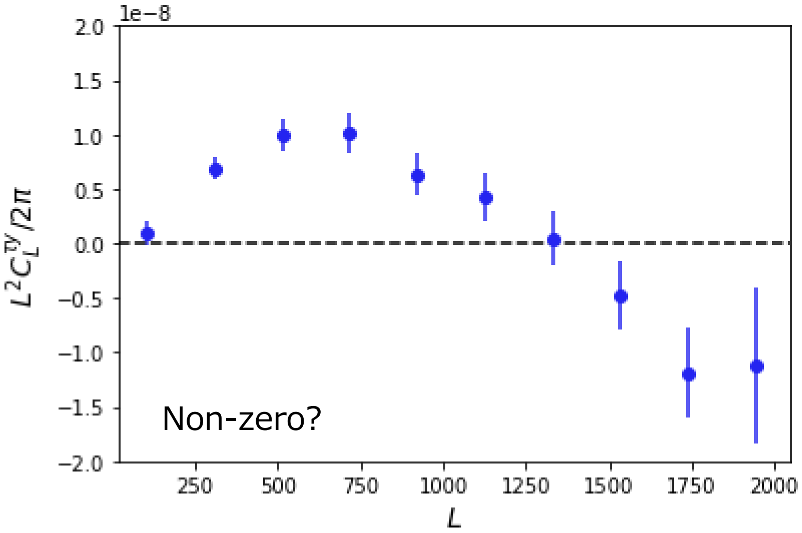
Planck 2015 data



(Namikawa et al. 2021)

Measurement of optical-depth power spectrum $C_L^{\tau y}$

Planck 2015 data

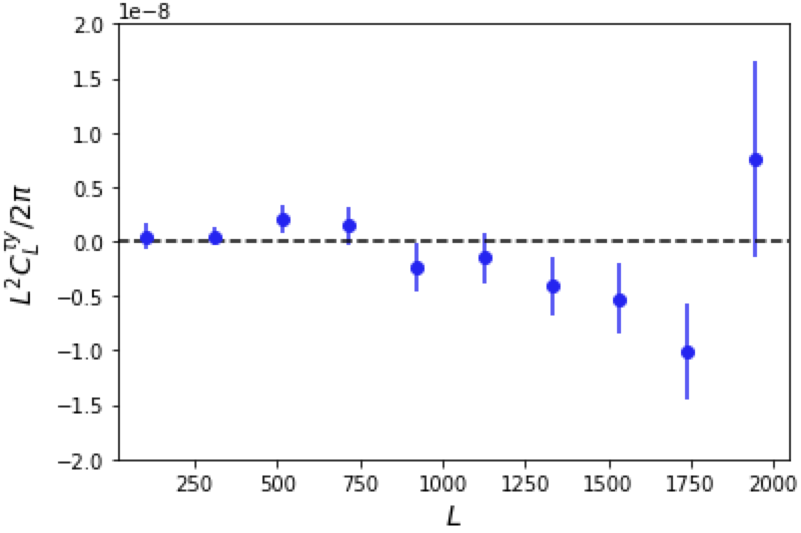


(Namikawa et al. 2021)

- Lensing also creates another type of mode-coupling which correlates with y-map and biases the measurement
- Bias-hardening can remove such bias

Measurement of optical-depth power spectrum $C_L^{\tau y}$

Planck 2015 data

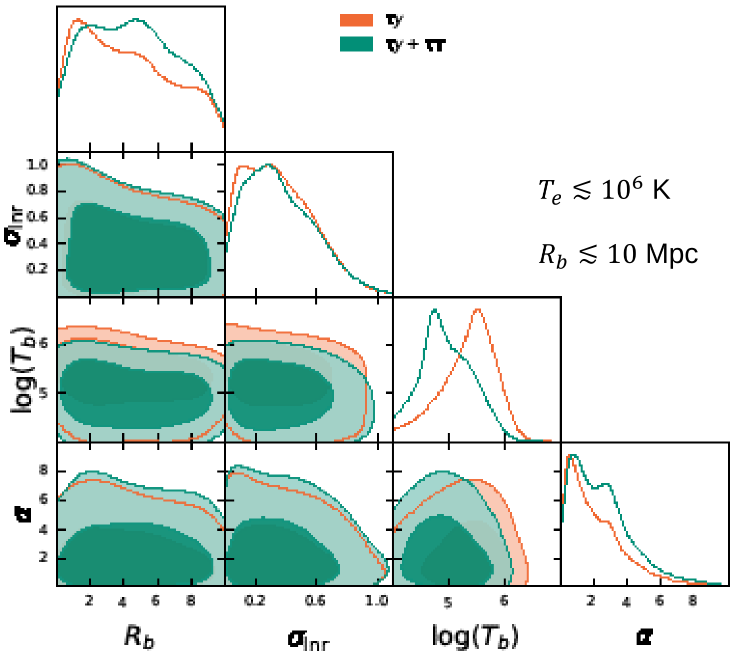


(Namikawa et al. 2021)

Extracting $\delta\tau$ alone, the measured spectrum becomes consistent with null

Constraints on the typical temperature of ionization bubble from $C_L^{\tau\tau}, C_L^{\tau y}$

- $C_L^{\tau y}$ is a novel probe of temperature of ionization bubble



$T_e \lesssim 10^6$ K

$R_b \lesssim 10$ Mpc

$$C_L^{\tau\tau} = \sigma_T^2 n_{p0}^2 \int \frac{d\chi}{a^4\chi^2} P_{x_e x_e}(\chi, L)$$

$$C_L^{\tau y} = \sigma_T^2 n_{p0}^2 \int \frac{d\chi}{a^4\chi^2} \frac{k_B \boldsymbol{T_e}}{m_e c^2} P_{x_e x_e}(\chi, L) + \alpha C_L^{\tau y,\mathrm{low}-z}$$

A theoretical model for $P_{x_e x_e}$: Wang & Hu (2006)

Model parameters :

Mean bubble size: R_b
Bubble size distribution: $\sigma_{\rm lnr}$
Bubble bias: b
Background ionization history: x_e

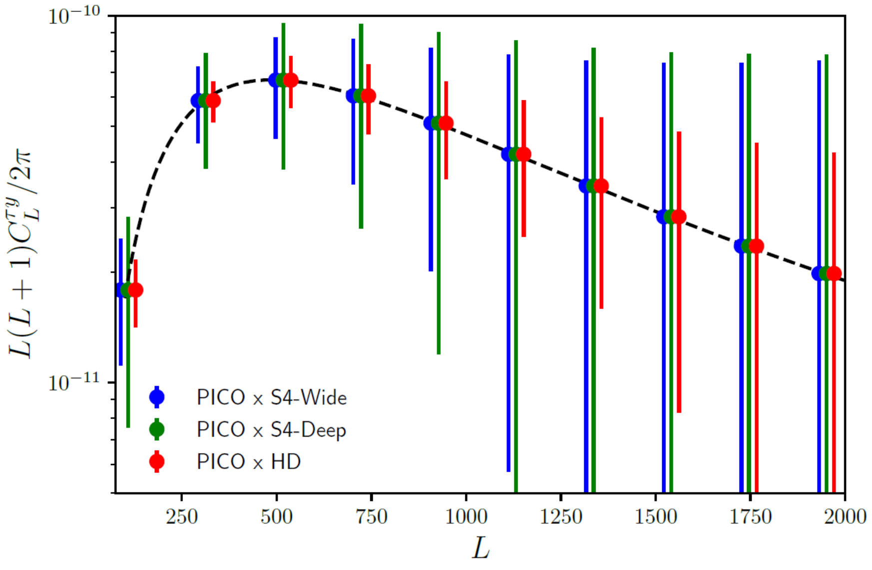
Usually $T_e \simeq 10^4$K inferred from Lyman-α

Radiative transfer simulations suggest $R_b \sim O(1)$ Mpc

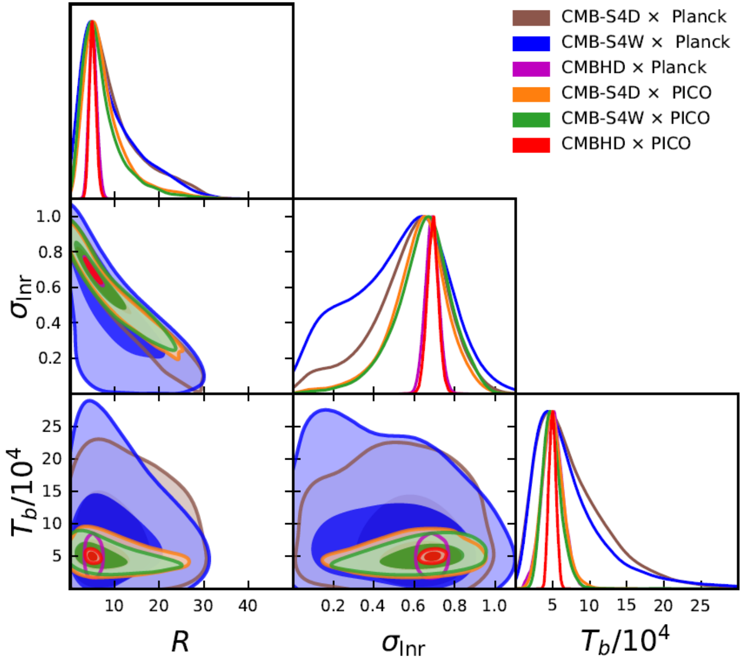
- The first constraint on the global temperature of the ionization bubble from CMB

Forecast

Future CMB experiments can improve the signal-to-noise by 2-3 orders of magnitudes, and provide much better constraints on reionization parameters



CMB experiment	$f_{\rm sky}$	θ [arcmin]	$\sigma_{\rm P}$ [μK-arcmin]	$\alpha_{\rm del}$
S4-Wide	0.4	2.0	1.4	0.2
S4-Deep	0.04	2.0	0.42	0.07
HD	0.5	0.2	0.7	0.1



Summary

- We can probe imhomogeneities of reionization via the mode-mixing effect in CMB induced by the direction-dependent CMB optical depth

- I showed no positive signals in the current Planck data, placing upper bounds on the reionization bubble size and providing the first bound on global reionization temperature with CMB

- Future polarization data will improve this constraint (CMBS4xPICO, CMBS4xLiteBIRD)