



UNIVERSITY  
OF AMSTERDAM



SUVODIP MUKHERJEE

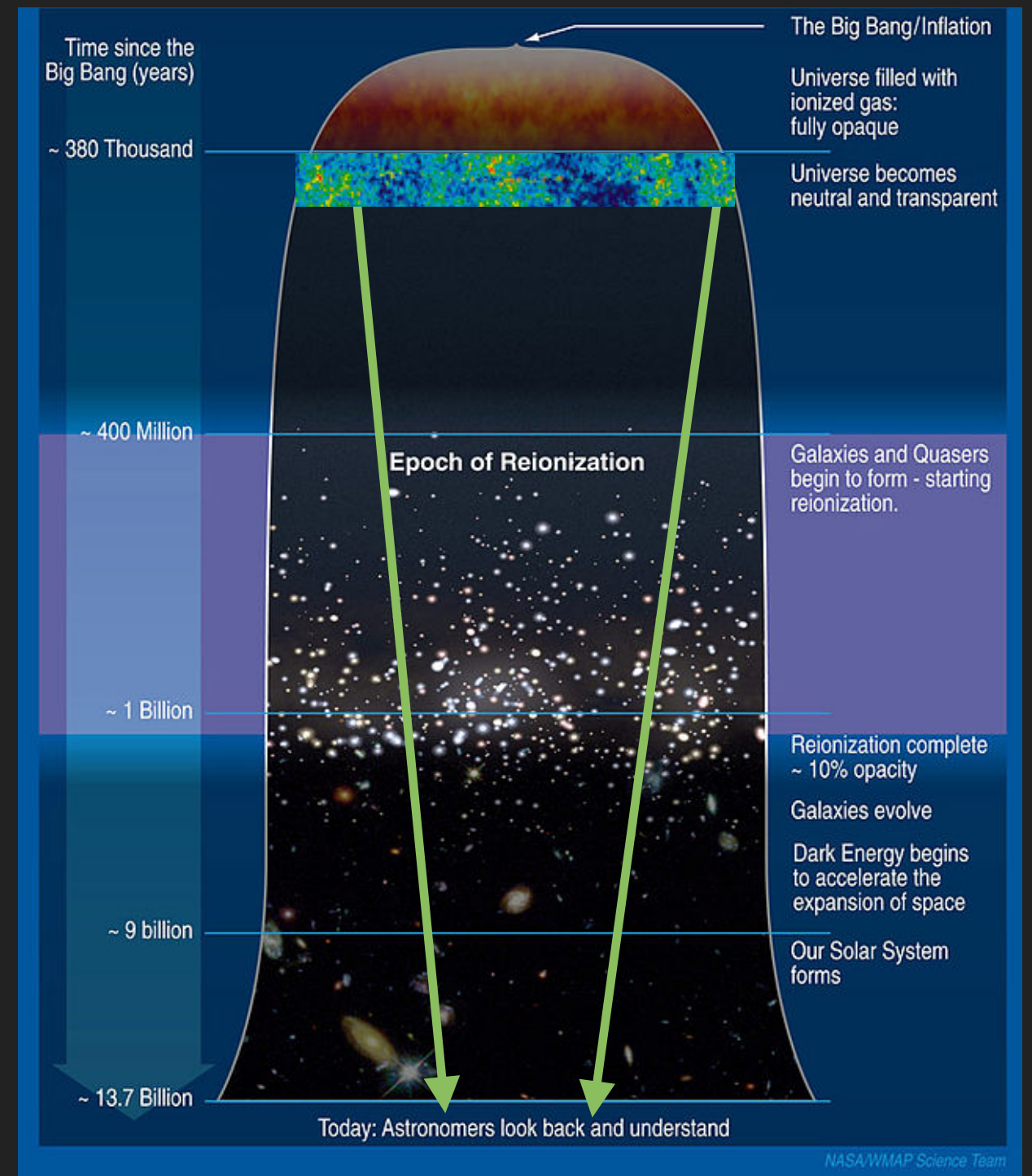
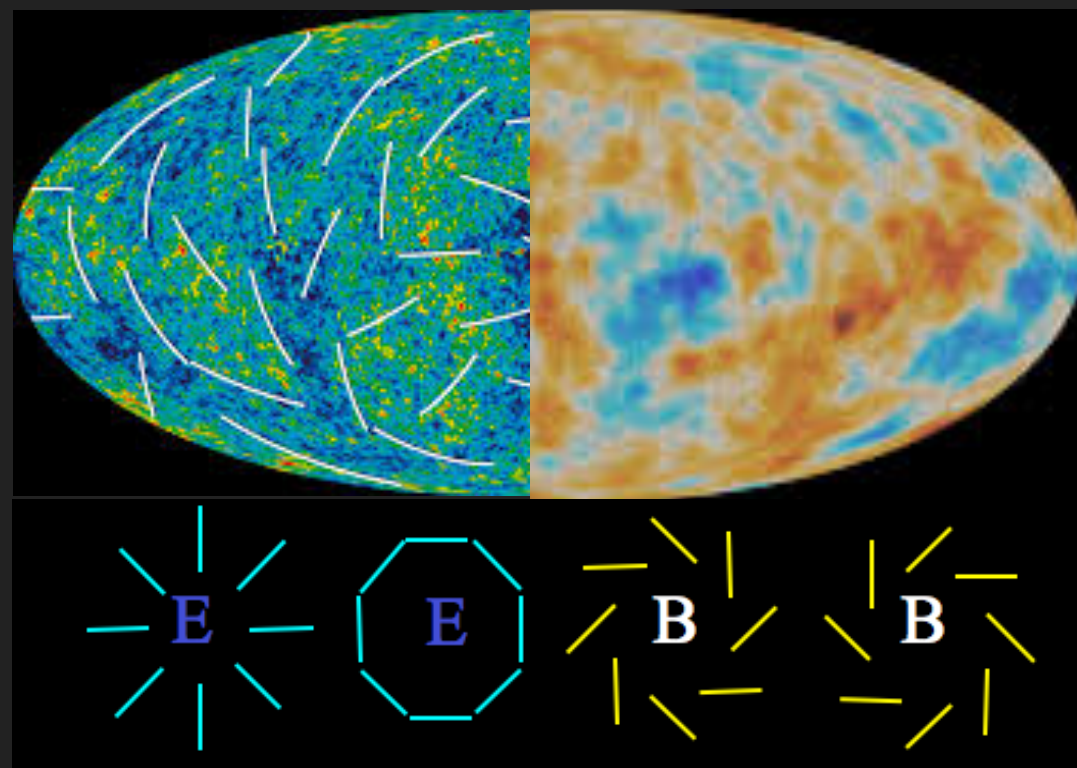
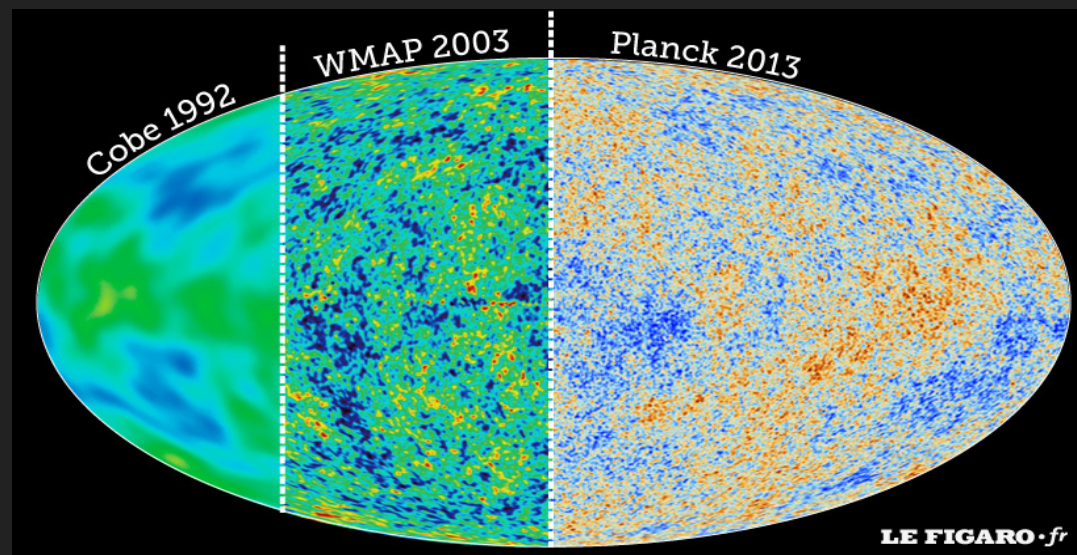
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# PHYSICAL MODELLING OF PATCHY REIONIZATION

CMB-S4 summer meeting , August 12th 2021



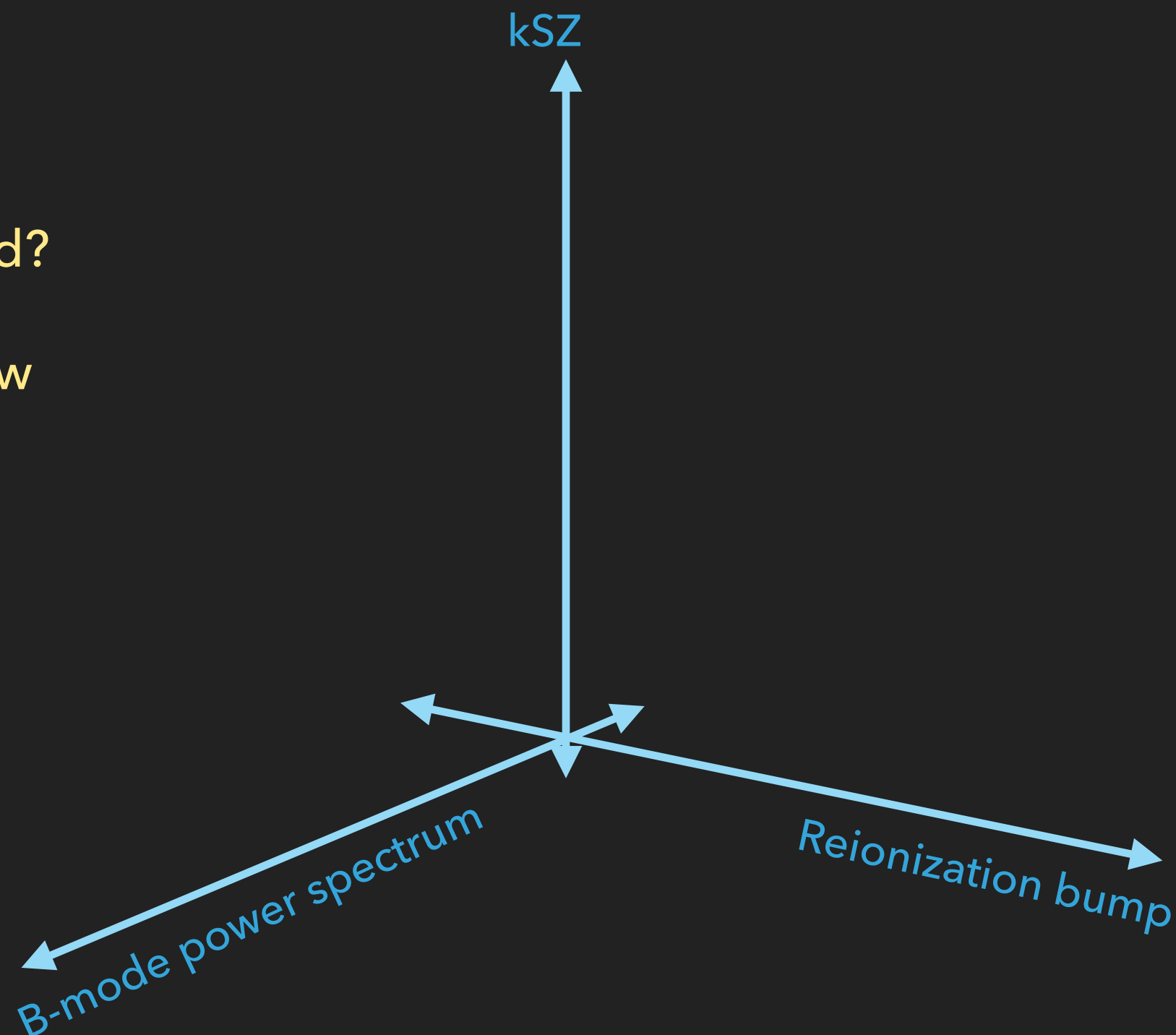
## CMB ANISOTROPIES PROBE THE COSMIC HISTORY FROM THE SURFACE OF LAST SCATTERING UNTIL NOW



## PARAMETER SPACE OF EOR

- ▶ When did reionization start?
- ▶ When did reionization end?
- ▶ Is it a fast process or a slow process?
- ▶ Are they driven by lighter halos or massive halos?

## PROBES AVAILABLE FROM CMB

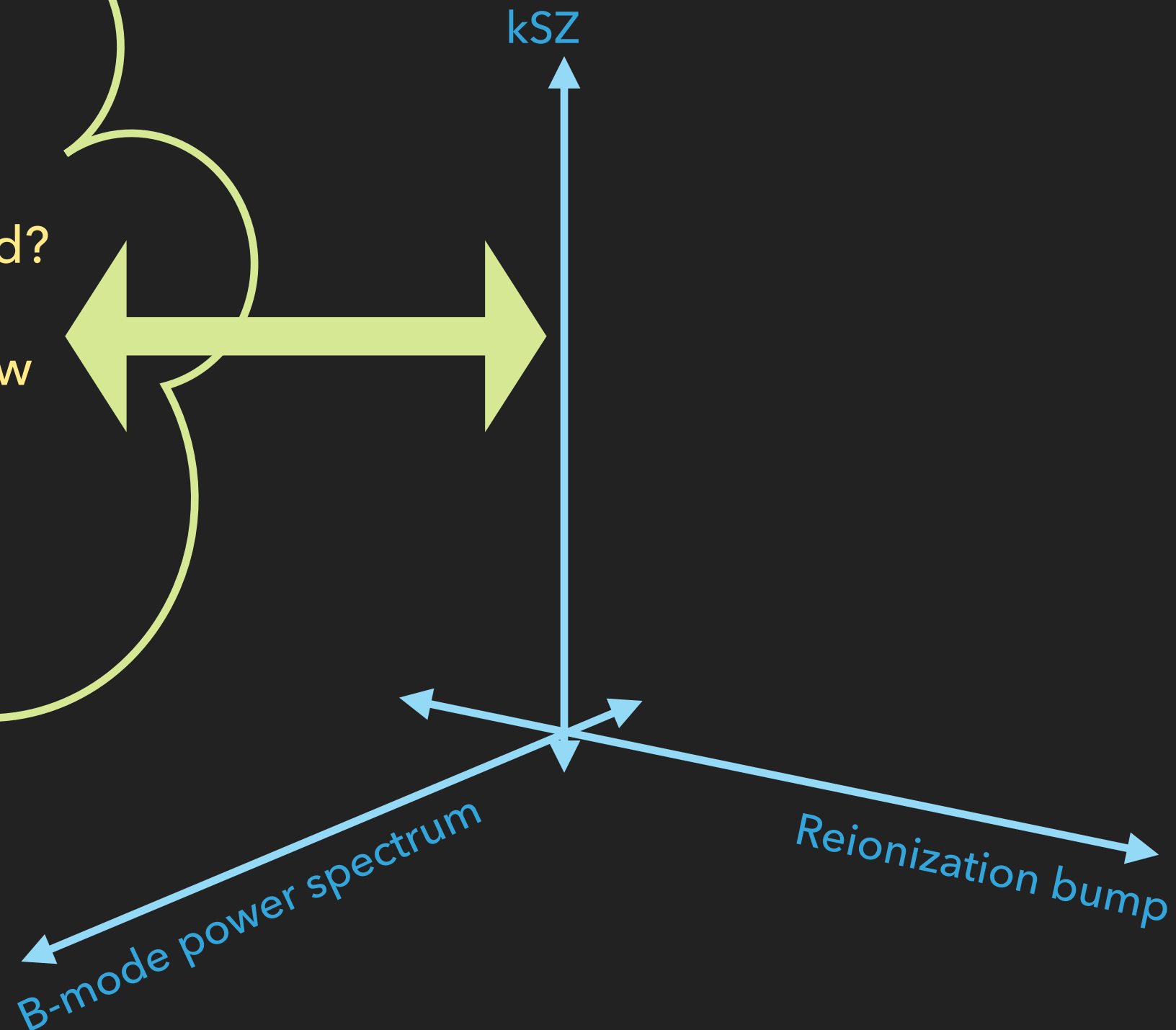


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Physical parameters

## PROBES AVAILABLE FROM CMB



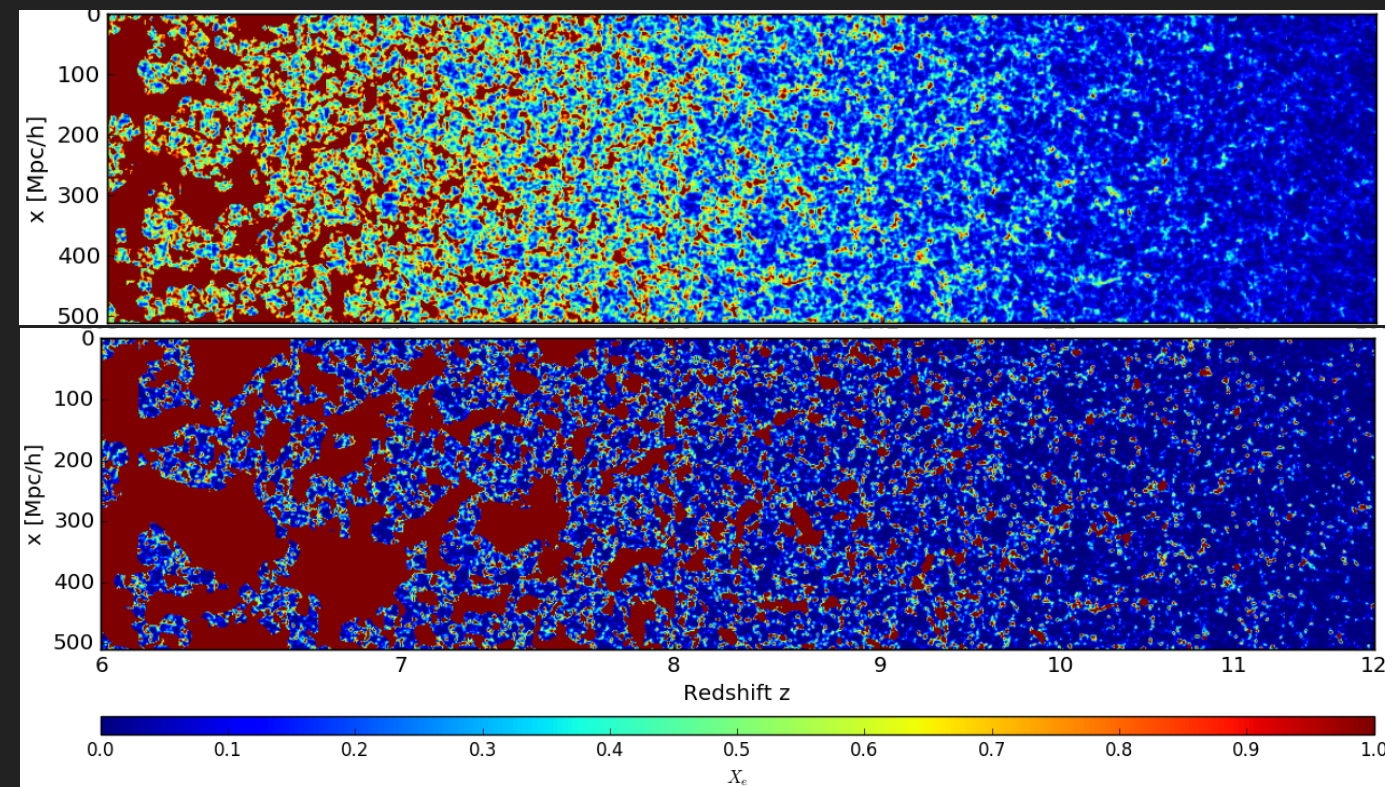
# IMPACT OF PATCHINESS ON KSZ POWER SPECTRUM



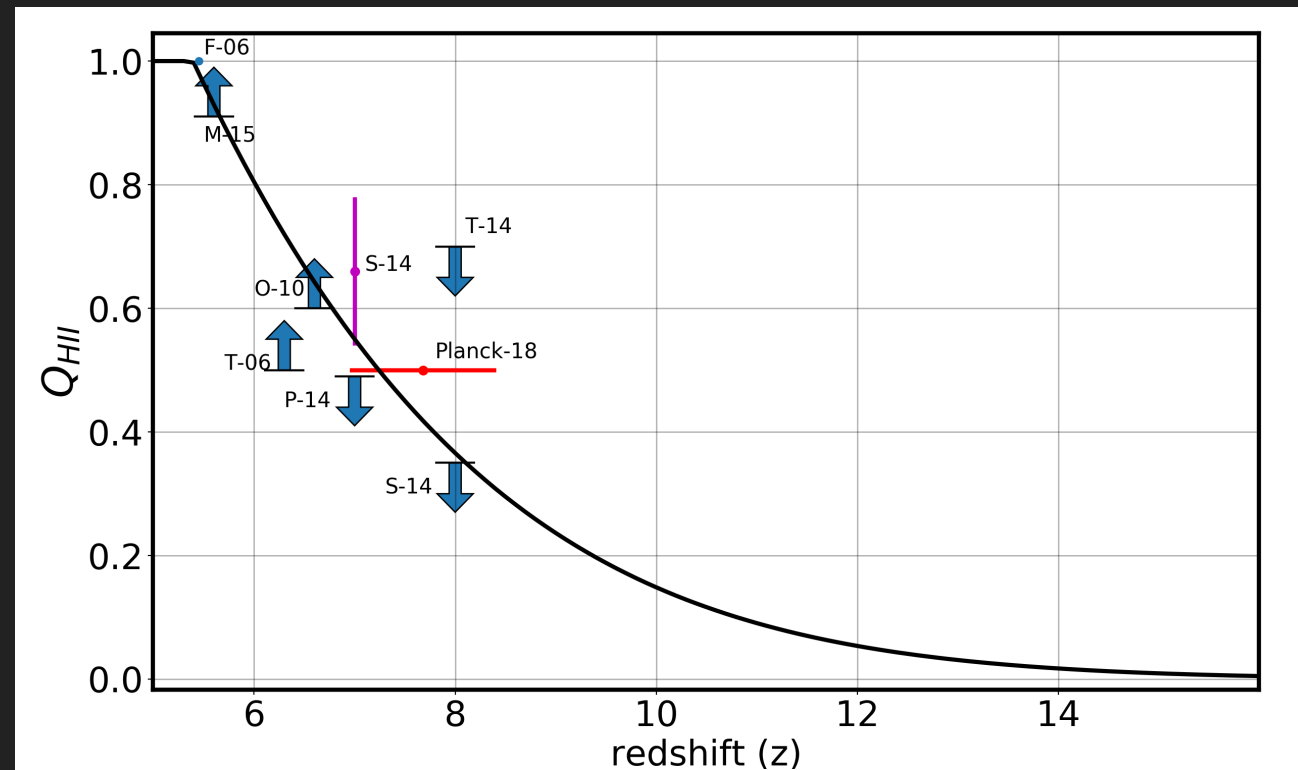
# PROBING THE EPOCH OF REIONIZATION

Mukherjee, Paul, Choudhury, MNRAS 486 (2019) 2, 2042-2049

For  $10^8 M_{\text{sun}}$



For  $10^{10} M_{\text{sun}}$

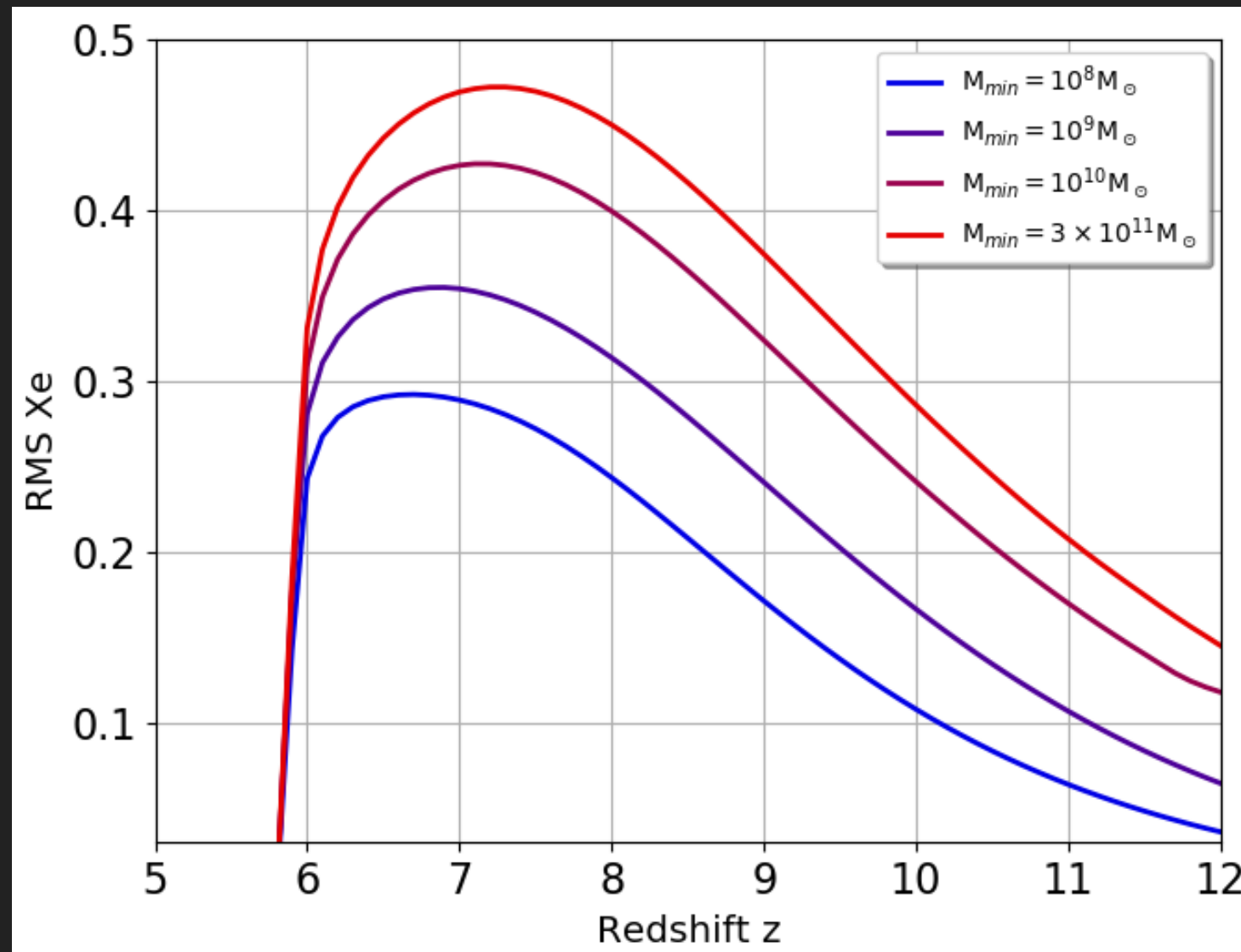


((Fan et al. 2006) (F-06), (McGreer et al. 2015) (M-15), (Ouchi et al. 2010) (O-10), (Pentericci et al. 2014) (P-14), (Planck Collaboration et al. 2018) (Planck-18), (Schenker et al. 2014) (S-14), (Tilvi et al. 2014) (T-14), (Totani et al. 2006) (T-06)).

We consider a fixed reionization history and make semi-numerical simulations of cosmic reionization

# FOR A FIXED REIONIZATION HISTORY WITH DIFFERENT HALO MASSES $10^8$ TO $10^{11} M_{\text{SUN}}$ DRIVING THE REIONIZATION

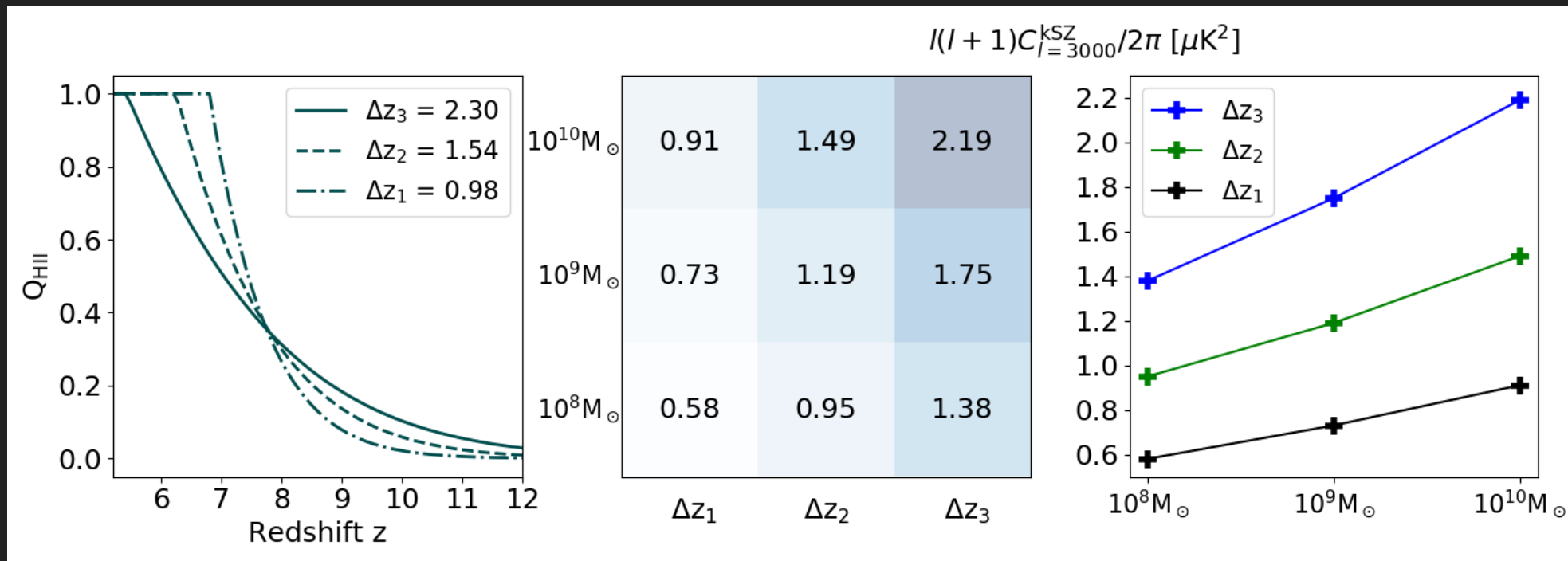
Mukherjee, Paul, Choudhury, MNRAS 486 (2019) 2, 2042-2049



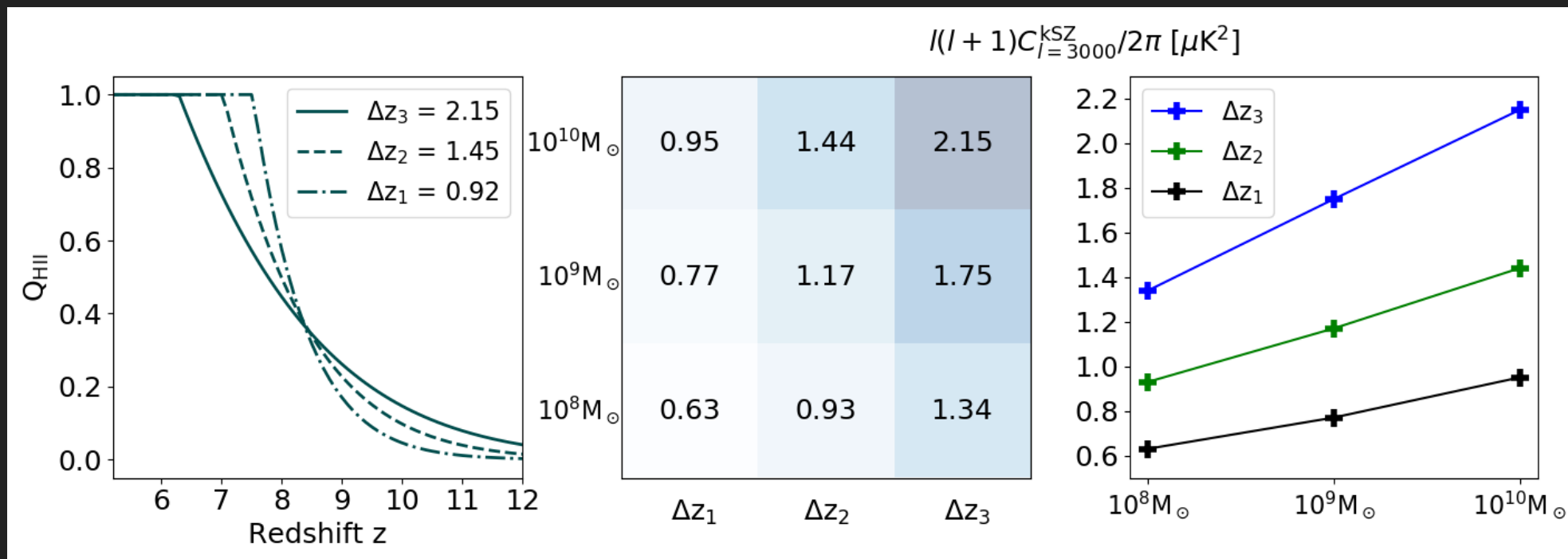
**Reionization driven by big halos lead to large bubbles hence large fluctuations**

# DEPENDENCE OF KSZ AMPLITUDE ON PATCHINESS

Paul, Mukherjee, Choudhury, MNRAS 500 (2020) 1, 232-246



$\tau = 0.054$



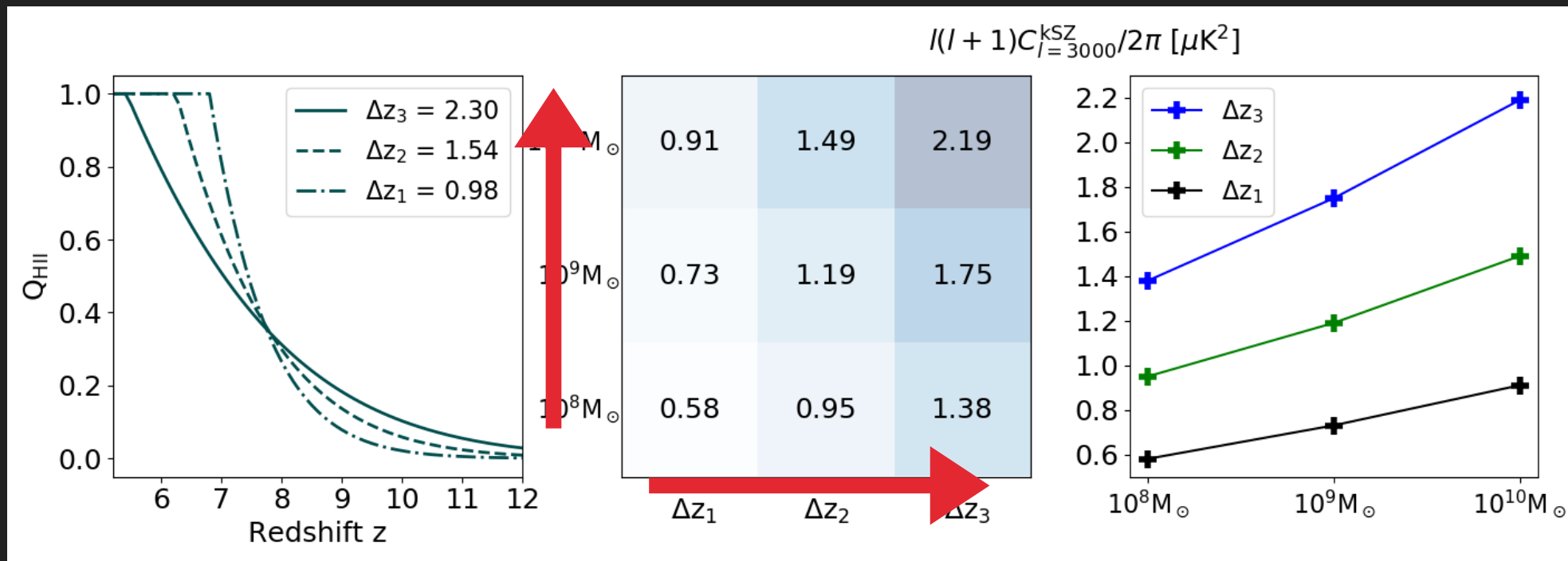
$\tau = 0.061$

Also see : Gorce et al. A&A (2020), Park et al. APJ (2013)

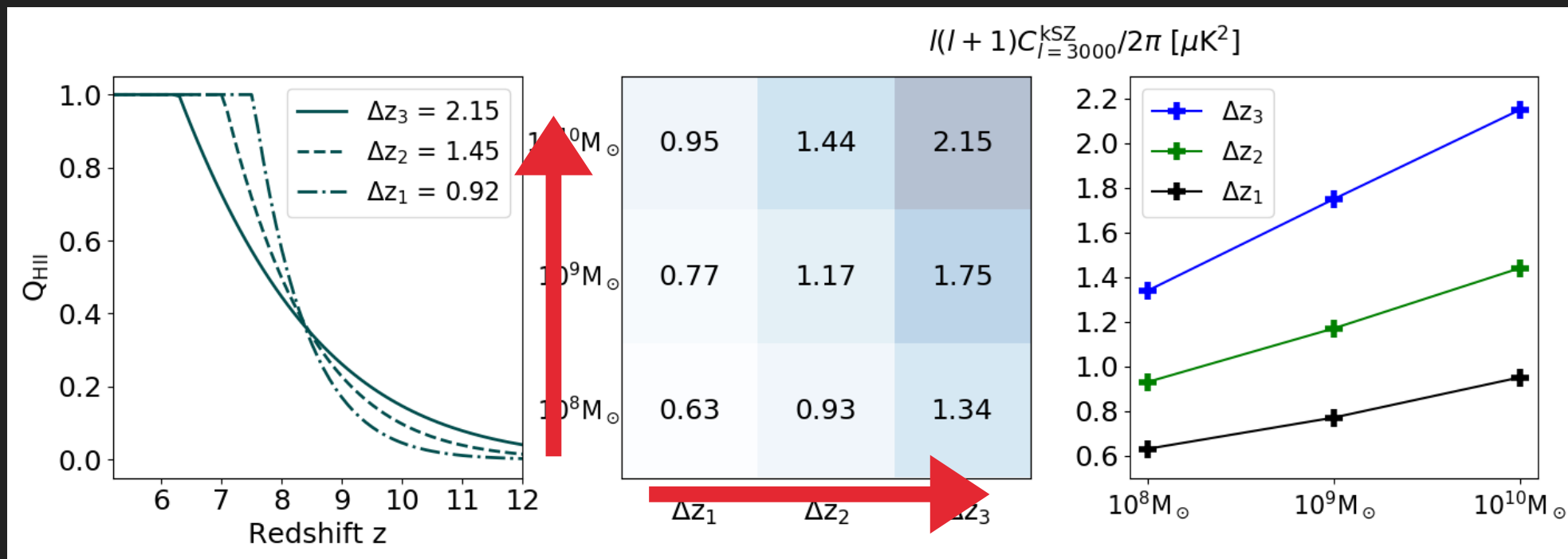


# DEPENDENCE OF KSZ AMPLITUDE ON PATCHINESS

Paul, Mukherjee, Choudhury, MNRAS 500 (2020) 1, 232-246



$$\tau = 0.054$$



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Also see : Gorce et al. A&A (2020), Park et al. APJ (2013)

## A NEW SCALING RELATION FOR CORRECT INTERPRETATION OF THE KSZ POWER SPECTRUM

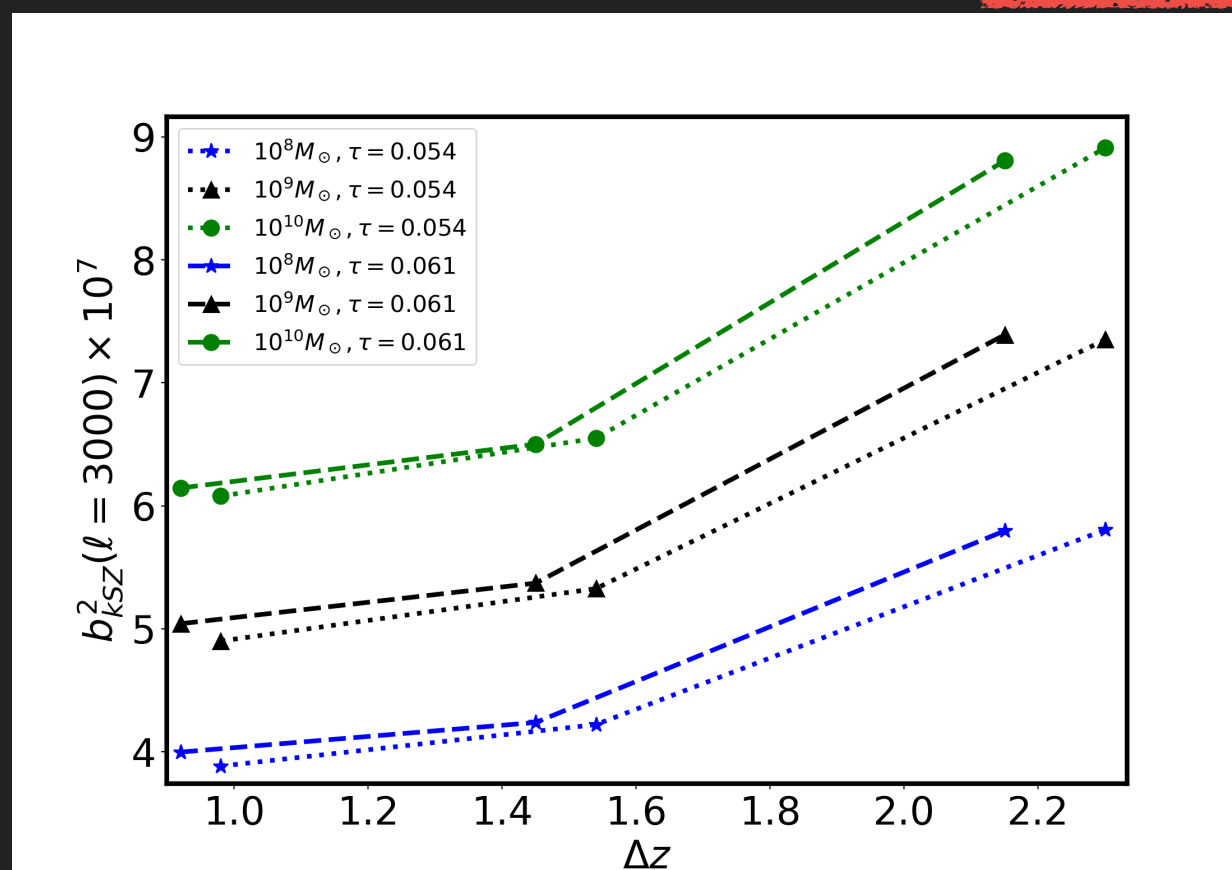
Commonly-used  
relation

$$D_{l=3000}^{\text{kSZ}} \approx 2.02 \mu\text{K}^2 \left[ \left( \frac{1 + \bar{z}}{11} \right) - 0.12 \right] \left( \frac{\Delta z}{1.05} \right)^{0.47}$$



$$D_{l=3000}^{\text{kSZ}} \approx 0.65 \mu\text{K}^2 \left( \frac{0.097 + \tau}{0.151} \right) \left( \frac{\Delta z}{1.0} \right)^{0.54} \left( \frac{b_{\text{kSZ}}^2(l=3000)}{4.0 \times 10^{-7}} \right)^{0.92}$$

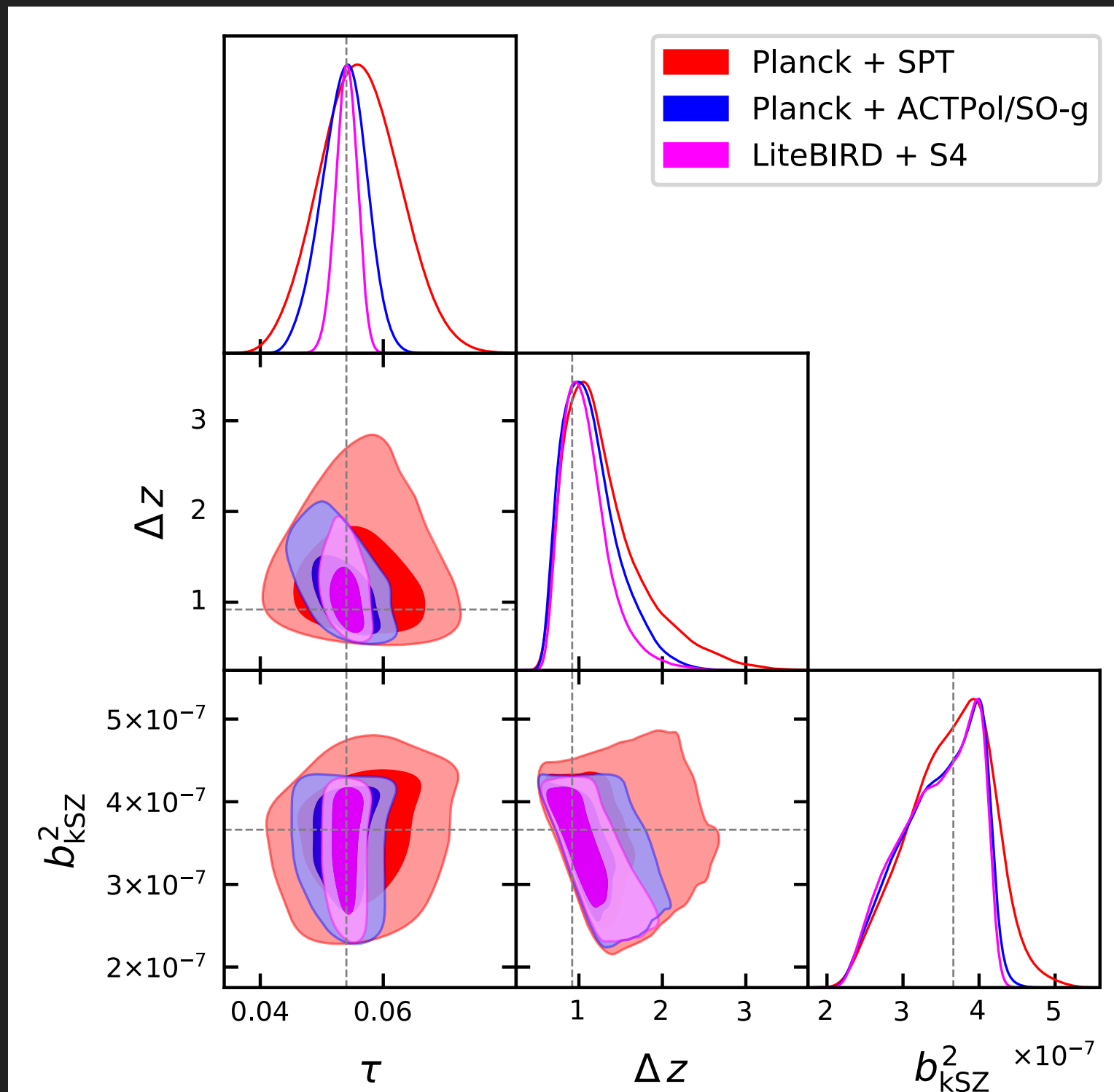
New relation



Paul, Mukherjee, Choudhury,  
MNRAS 500 (2020) 1,  
232-246

# SPT+PLANCK AND FORECAST FOR THE UPCOMING CMB MISSIONS

Choudhury, Mukherjee, Paul, MNRAS-L 501 (2021) 1, L7-L11

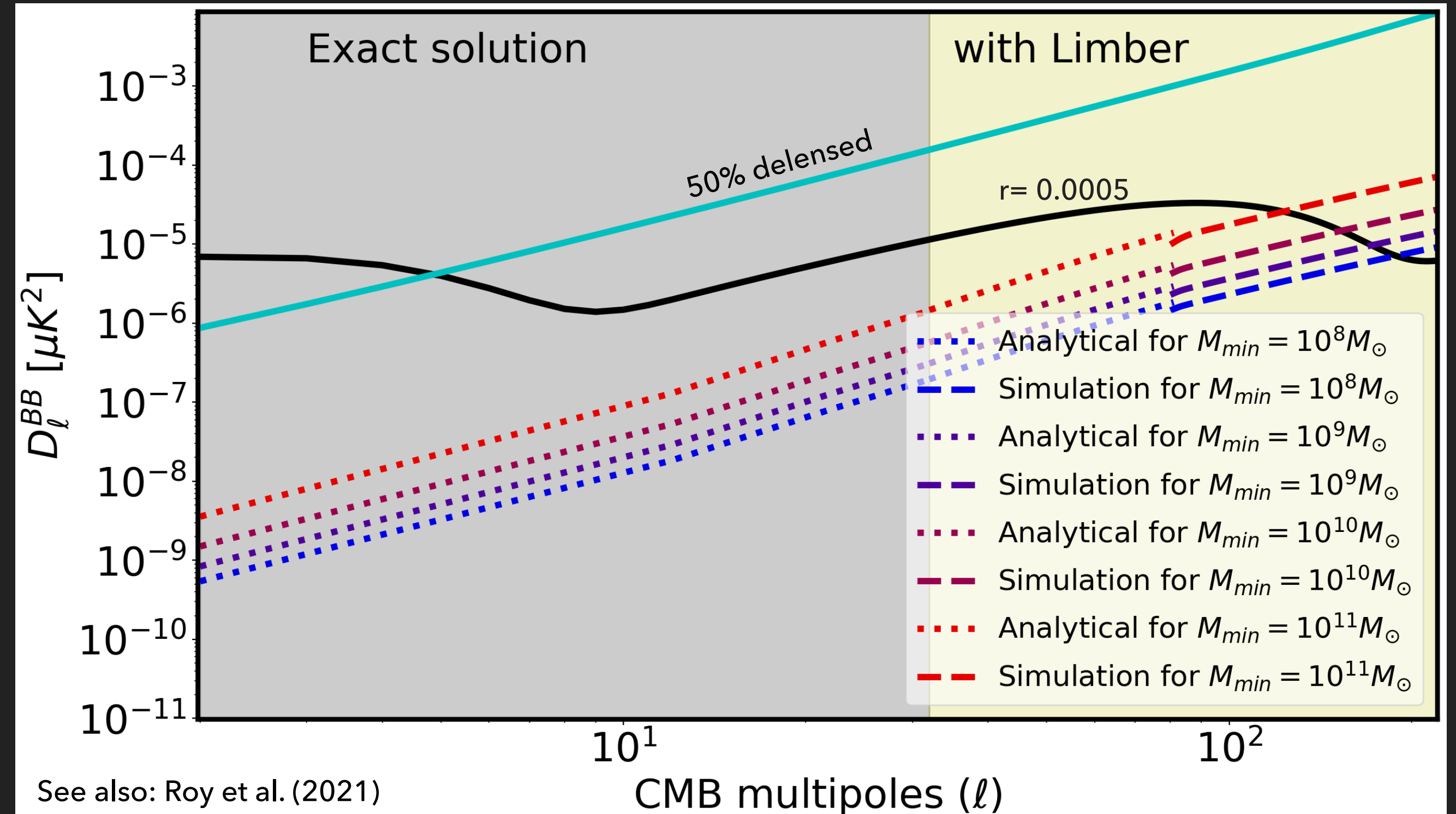




# IMPACT OF PATCHY REIONIZATION ON B-MODE POLARIZATION

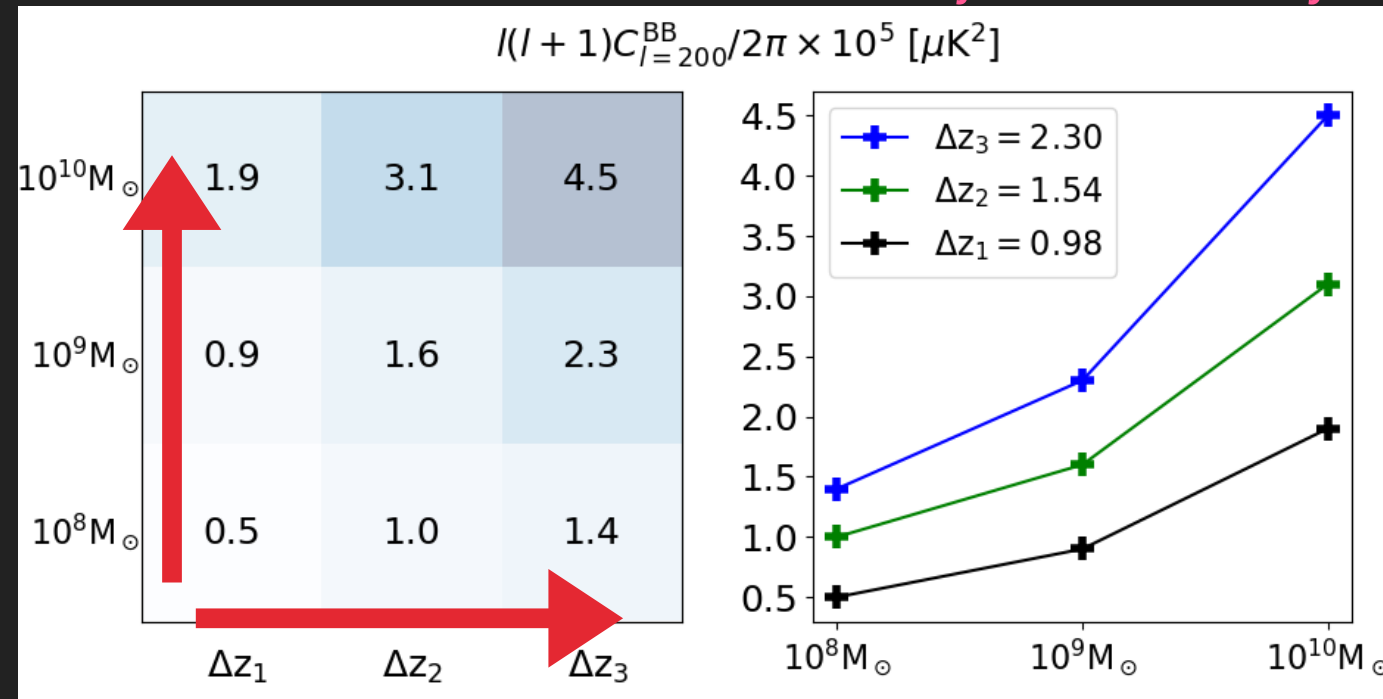
# CMB B-MODE POWER SPECTRUM DUE TO PATCHY REIONIZATION

Mukherjee, Paul, Choudhury, MNRAS 486 (2019) 2, 2042-2049

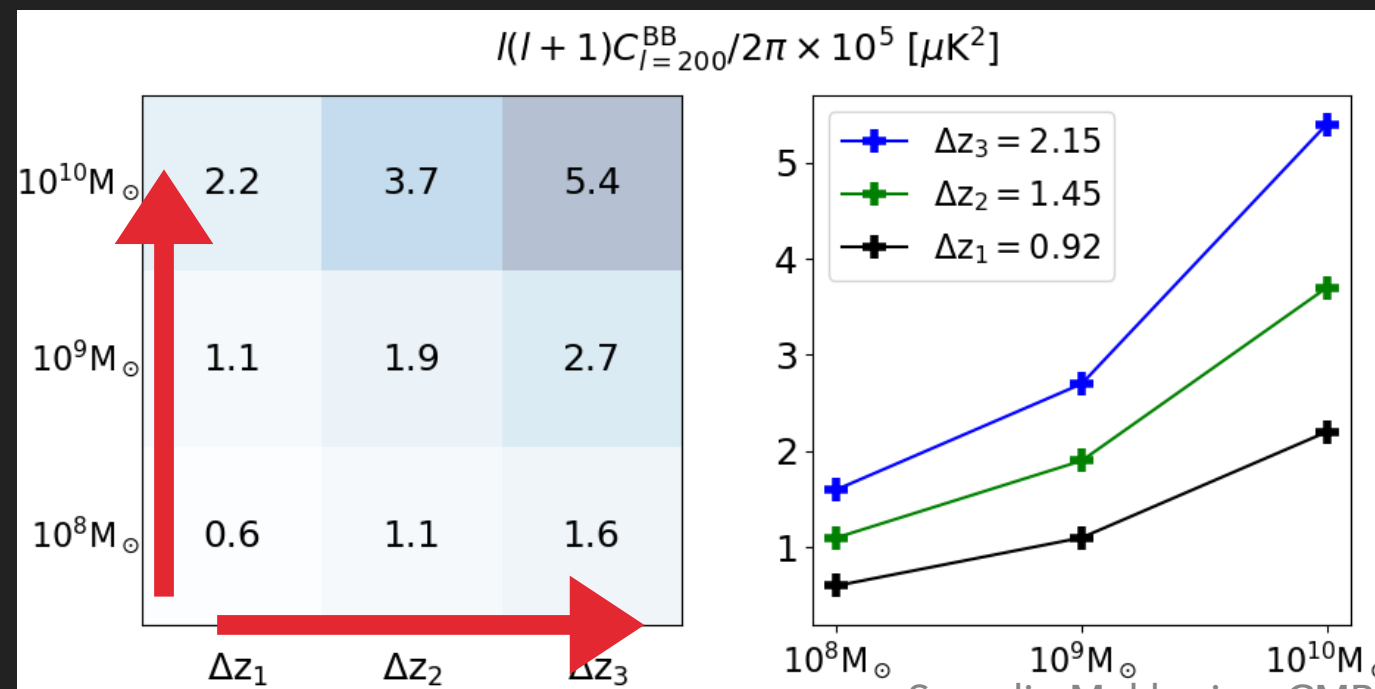


# DEPENDENCE OF B-MODE POWER SPECTRUM ON PATCHY REIONIZATION

Paul, Mukherjee, Choudhury, MNRAS 500 (2020) 1, 232-246



$$\tau = 0.054$$



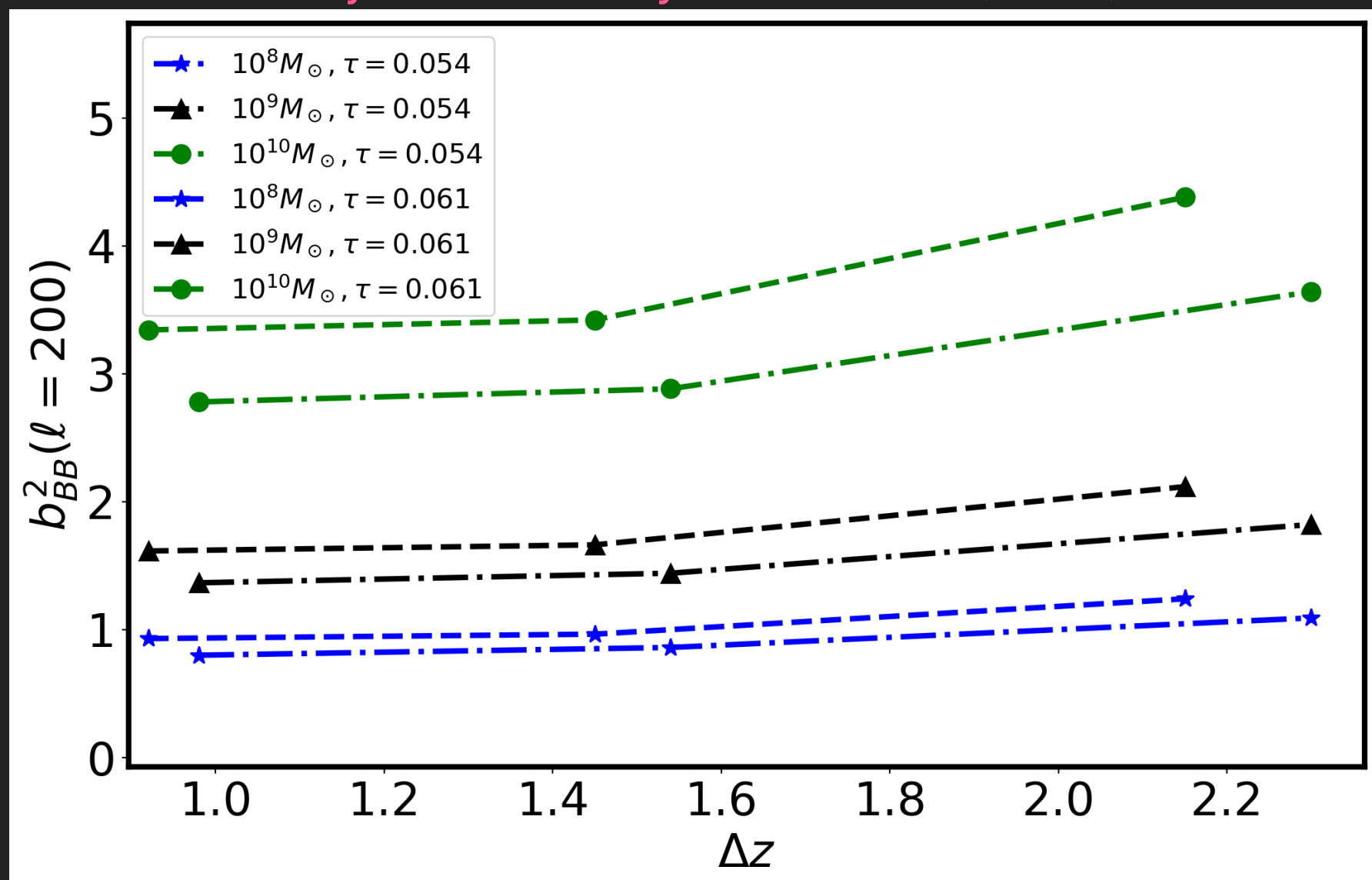
$$\tau = 0.061$$



# FIRST SCALING RELATION FOR B-MODE POLARIZATION

$$D_{l=200}^{BB} \approx 6.6 \text{ nK}^2 \left( \frac{0.15 + \tau}{0.204} \right) \left( \frac{\Delta z}{0.98} \right)^{0.78} \left( \frac{b_{BB}^2(l=200)}{0.93} \right)^{0.99}$$

Paul, Mukherjee, Choudhury, MNRAS 500 (2020) 1, 232-246



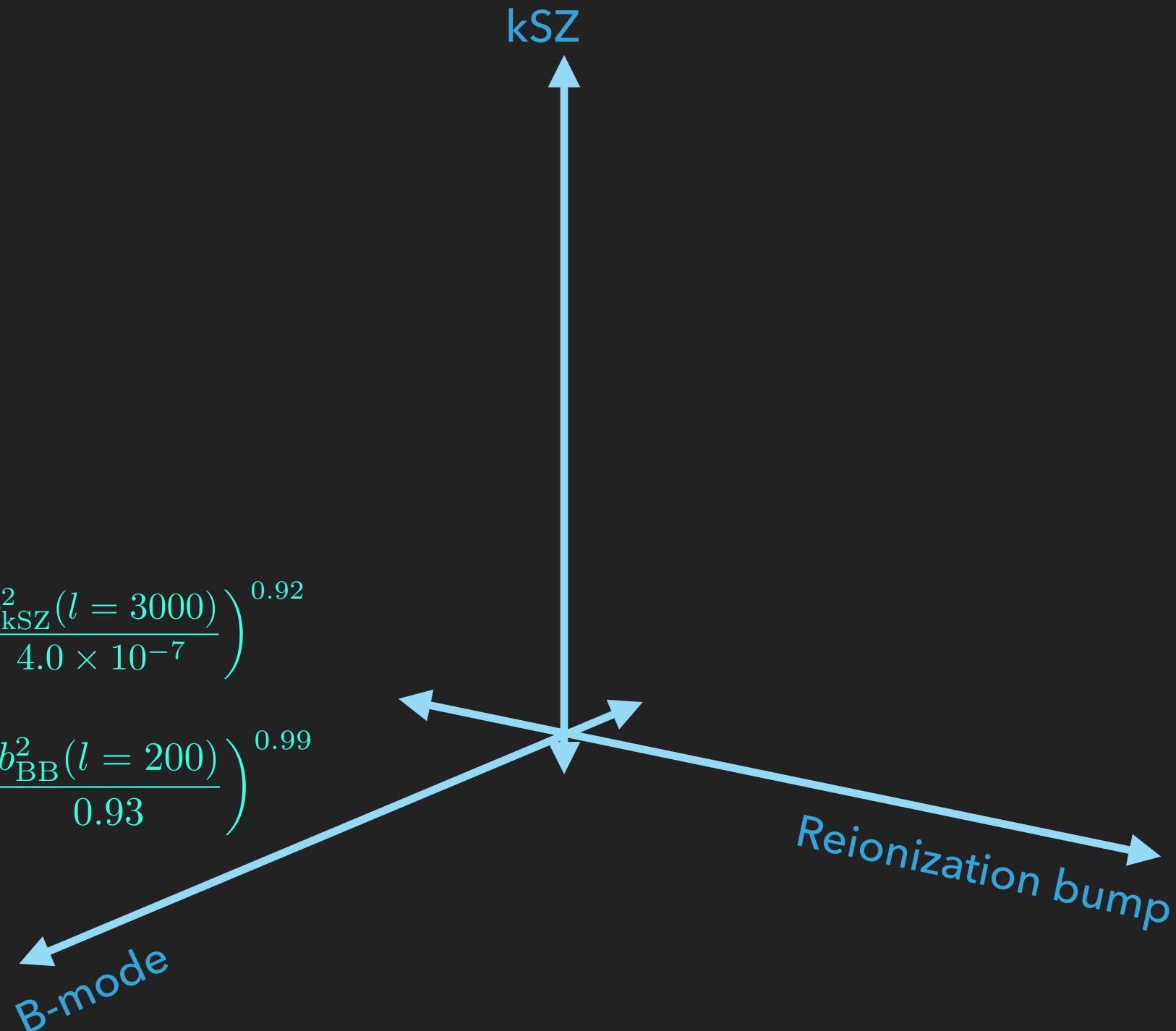
## PARAMETER SPACE OF EOR

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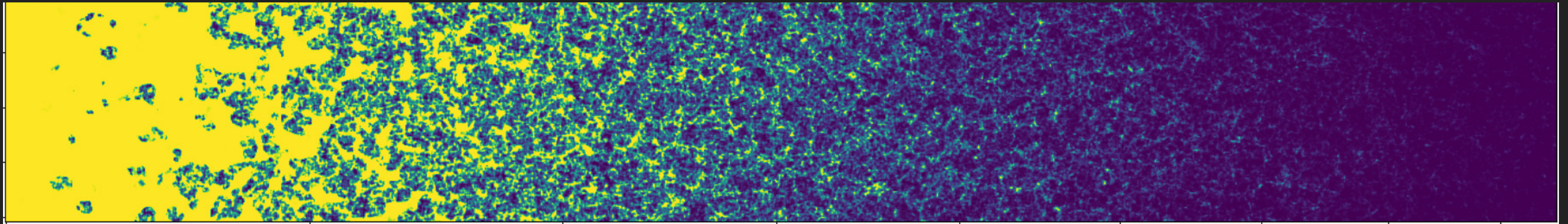
$$D_{l=3000}^{\text{kSZ}} \approx 0.65 \mu\text{K}^2 \left( \frac{0.097 + \tau}{0.151} \right) \left( \frac{\Delta z}{1.0} \right)^{0.54} \left( \frac{b_{\text{kSZ}}^2(l=3000)}{4.0 \times 10^{-7}} \right)^{0.92}$$

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## PROBES AVAILABLE FROM CMB



## TAKE HOME MESSAGES

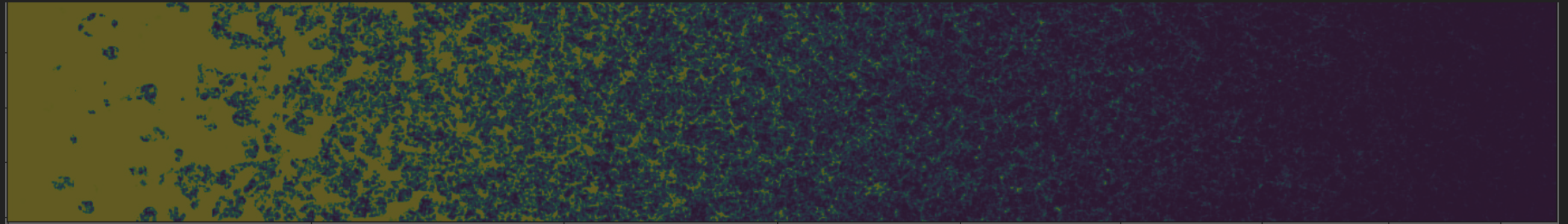


- ▶ It is not only the duration of reionization, but also the patchiness in electron density that drives amplitude of the KSZ and B-mode anisotropy.
- ▶ Using the modified-scaling relation, measurement of the patchiness in electron density and duration of reionization is possible.
- ▶ Joint study of kSZ and B-mode polarization is useful to constrain the parameter space.
- ▶ 21 cm signal will probe the typical bubble sizes. So cross-correlation with CMB observations will be a useful tool.

**WE ARE GOING TO LEARN ABOUT THE PHYSICAL PROCESSES DURING EOR FROM THE UPCOMING CMB EXPERIMENTS**



# SUMMARY



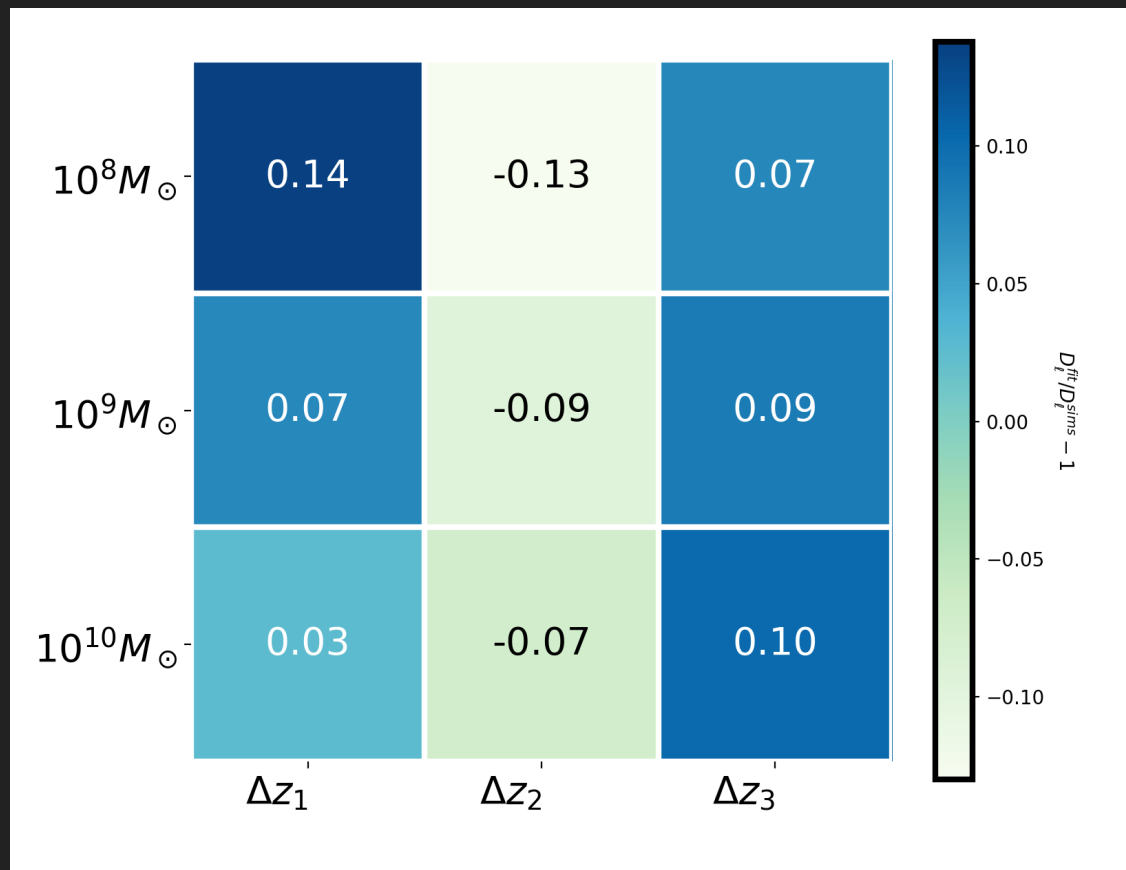
- ▶ The amplitude of kSZ and secondary B-mode polarization are related to the duration of reionization, optical depth, and patchiness in electron density.
- ▶ Using the modified-scaling relation, measurement of the patchiness in electron density and duration of reionization can be measured.
- ▶ Joint study of kSZ and B-mode polarization is useful to constrain the parameter space..
- ▶ 21 cm signal will probe the typical bubble sizes. So cross-correlation with CMB observations will be a useful tool.

Thank you!

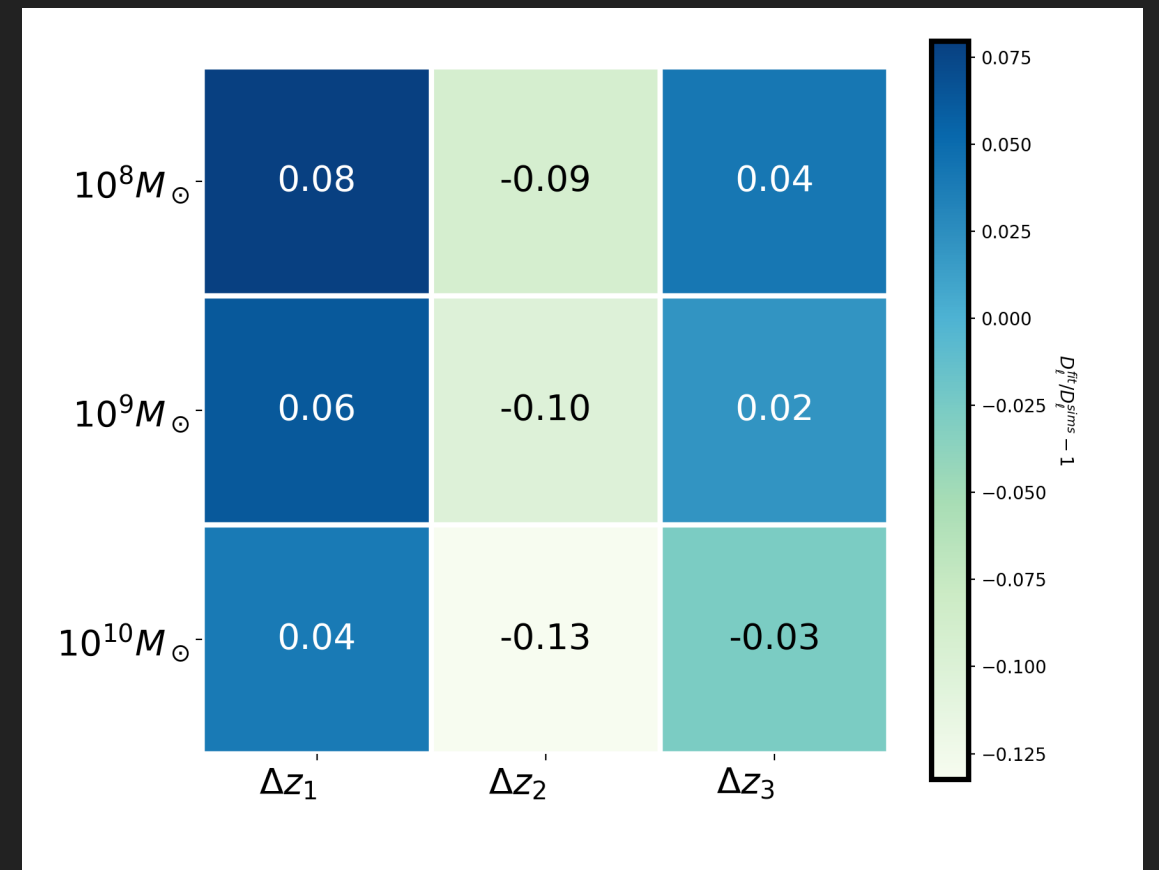
WE ARE GOING TO LEARN ABOUT THE PHYSICAL PROCESSES DURING EOR FROM THE UPCOMING CMB EXPERIMENTS

**EXTRA SLIDES**

# ACCURACY OF THE SCALING RELATION FOR KSZ AND B-MODE POLARIZATION



For B-mode polarization



For kSZ