Title: Physical modelling of patchy reionization

Speakers: Suvodip Mukherjee

Series: Cosmology & Gravitation

Date: September 07, 2021 - 1:00 PM

URL: https://pirsa.org/21090008

Abstract: The epoch of cosmic reionization can be probed using the secondary anisotropies imprinted on the cosmic microwave background (CMB) temperature and polarization field. I will discuss the imprints of patchy reionization on the kSZ power spectrum and CMB B-mode polarization. I will introduce two new scaling relations to connect the kSZ and secondary B-mode power spectrum with the physics of reionization. I will discuss the advantage of a joint study of the kSZ signal and secondary B-mode polarization from the ongoing/upcoming CMB experiments to get a better understanding of the epoch of reionization.

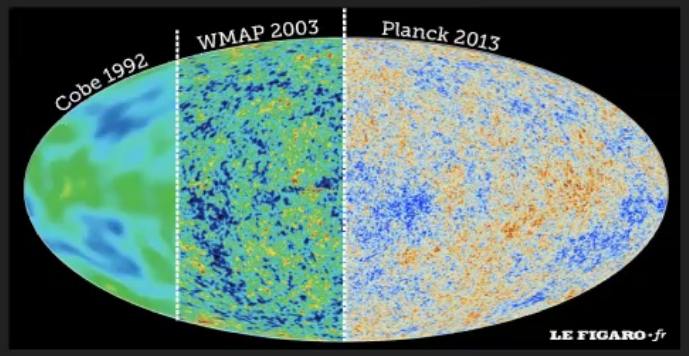
PERIMETER INSTITUTE

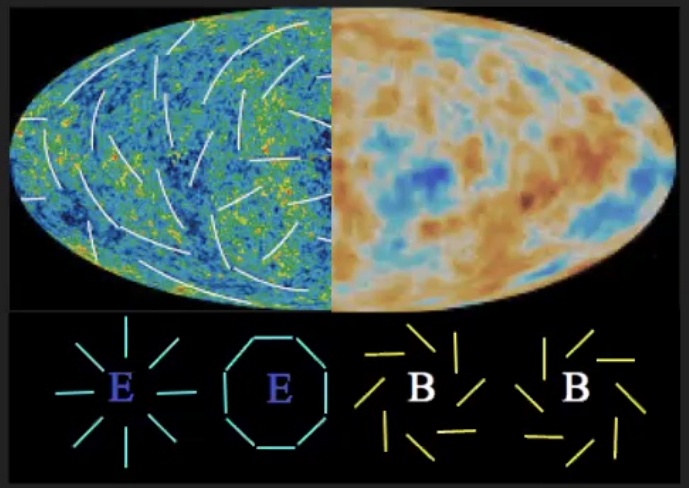
SUVODIP MUKHERJEE

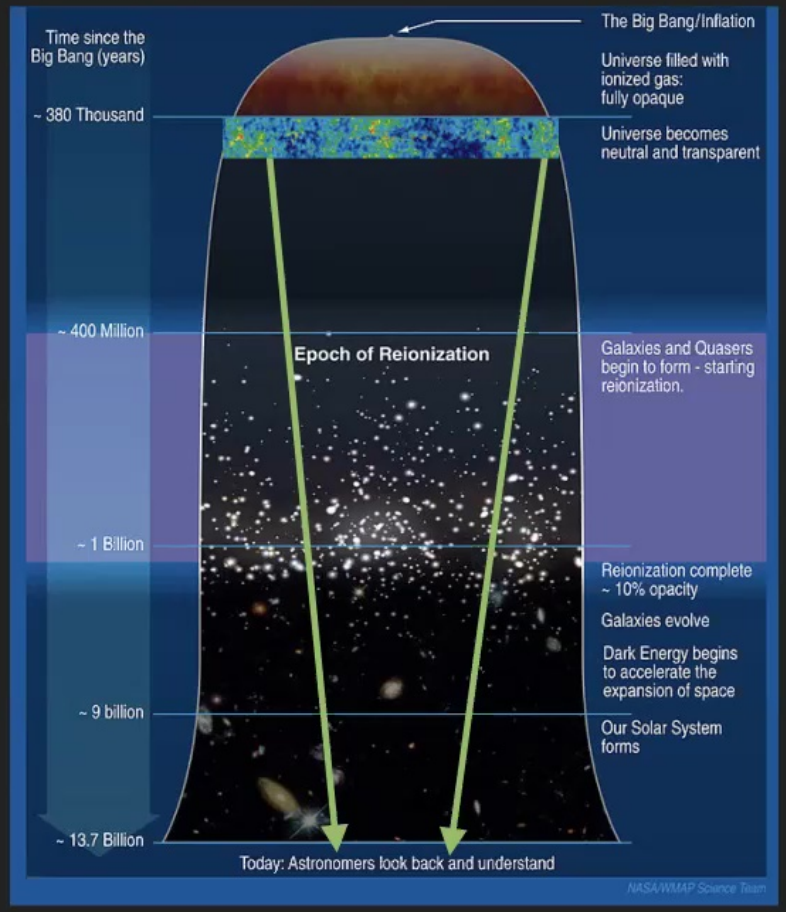
PHYSICAL MODELLING OF PATCHY REIONIZATION

PI Cosmology Seminar, September 7th 2021

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







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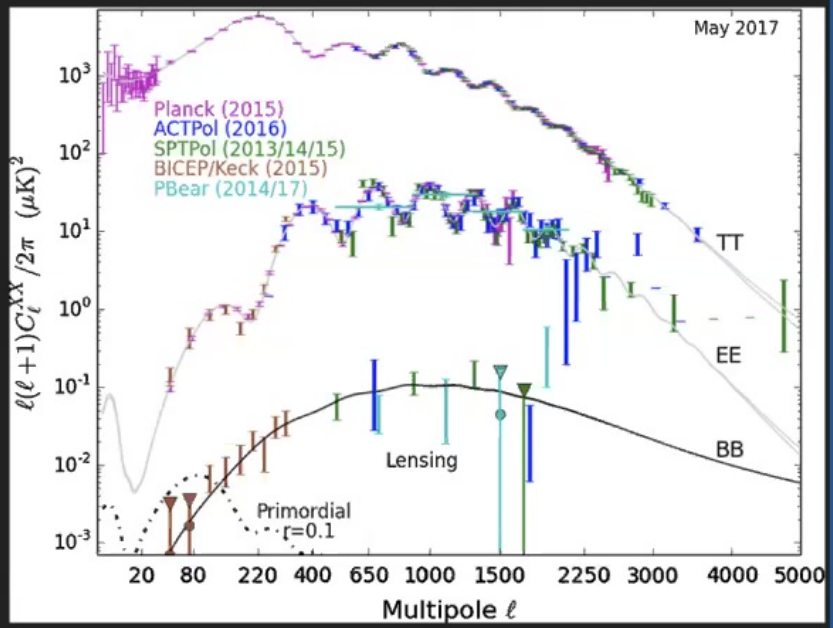

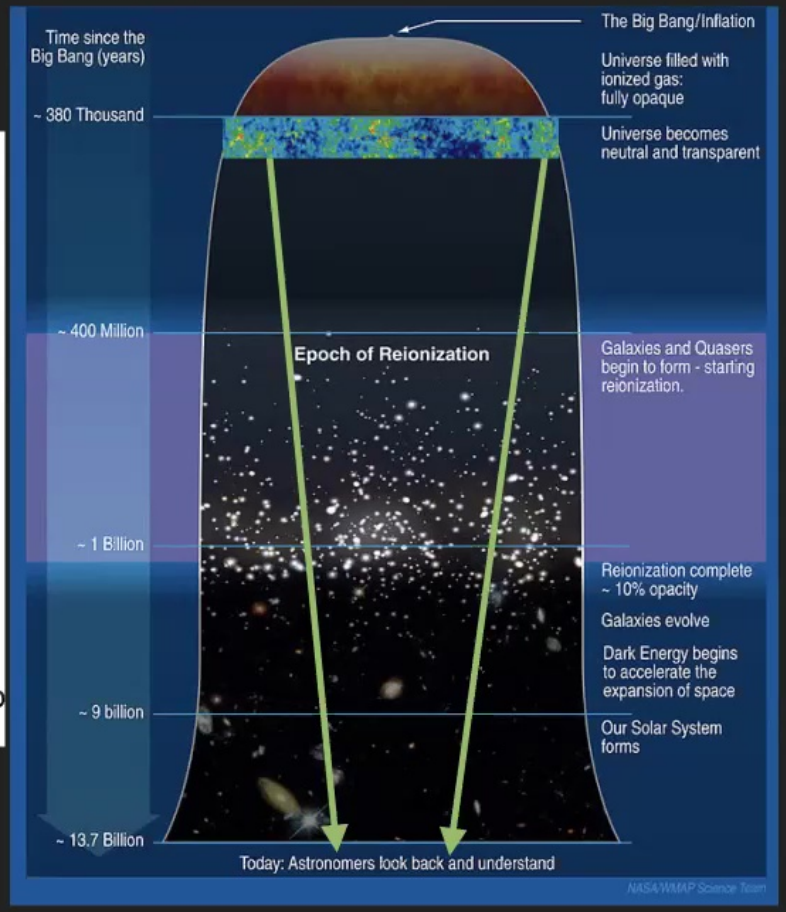

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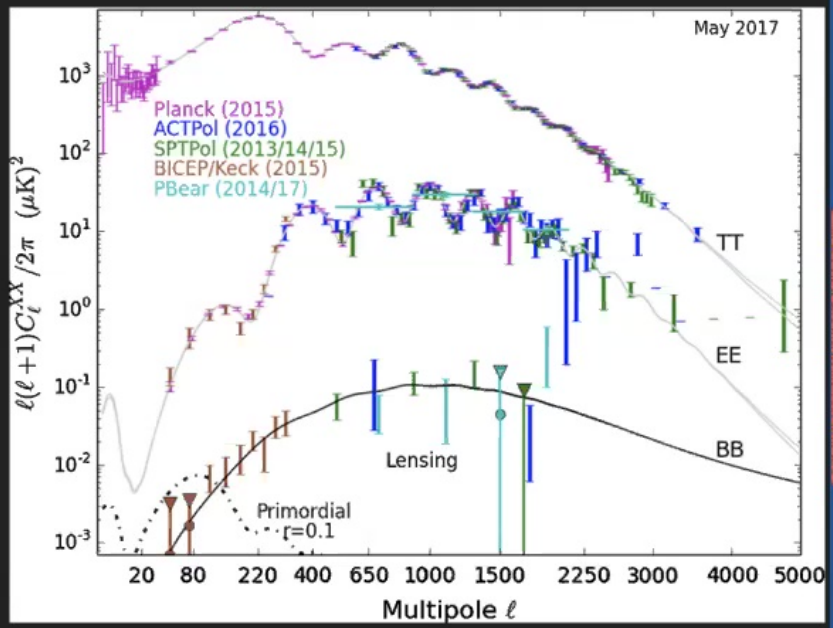
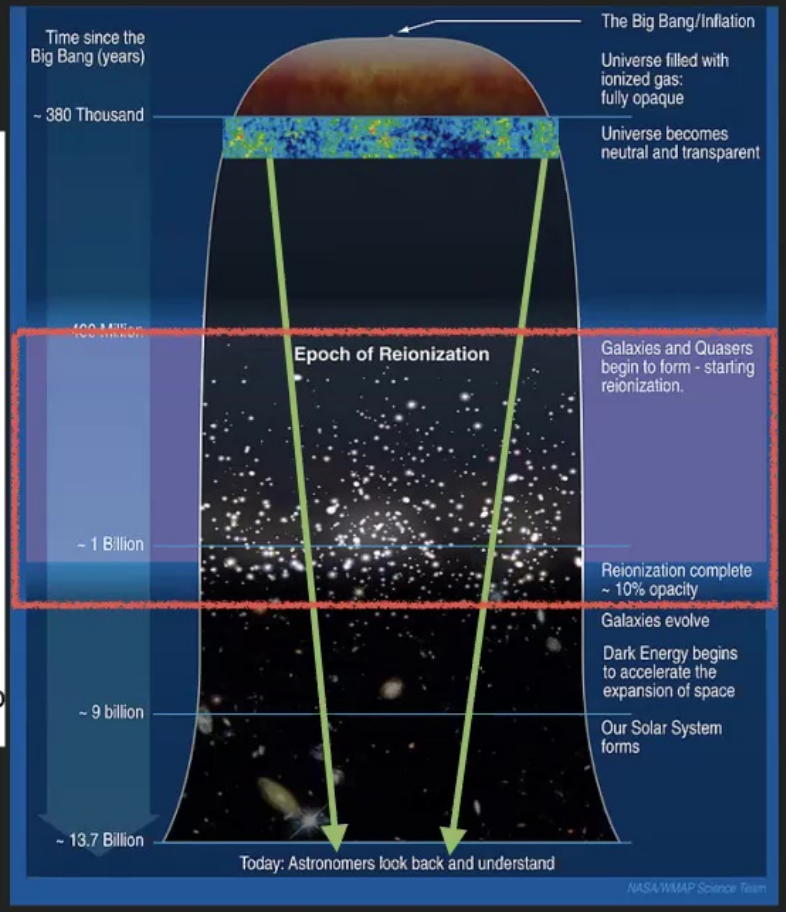
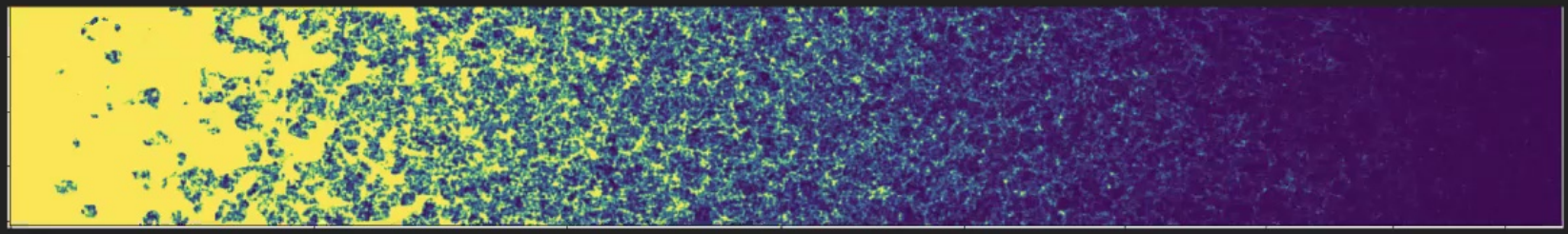




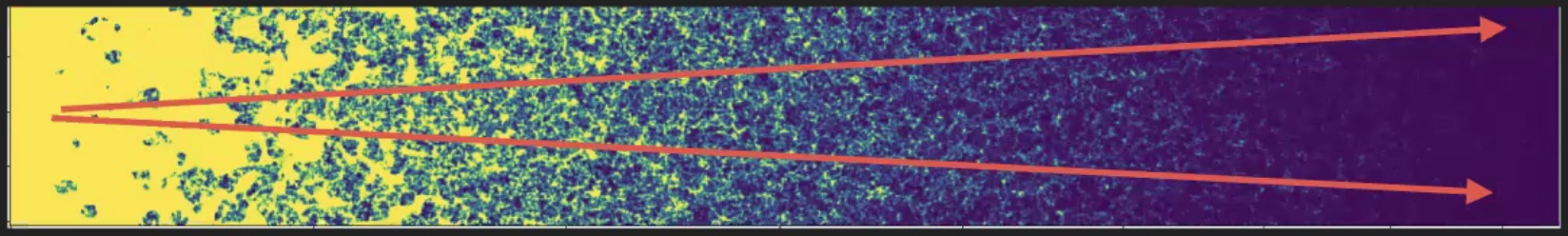
OPEN QUESTIONS ABOUT COSMIC REIONIZATION



- 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?
- How inhomogeneous is the reionization process?
- ....
- ....

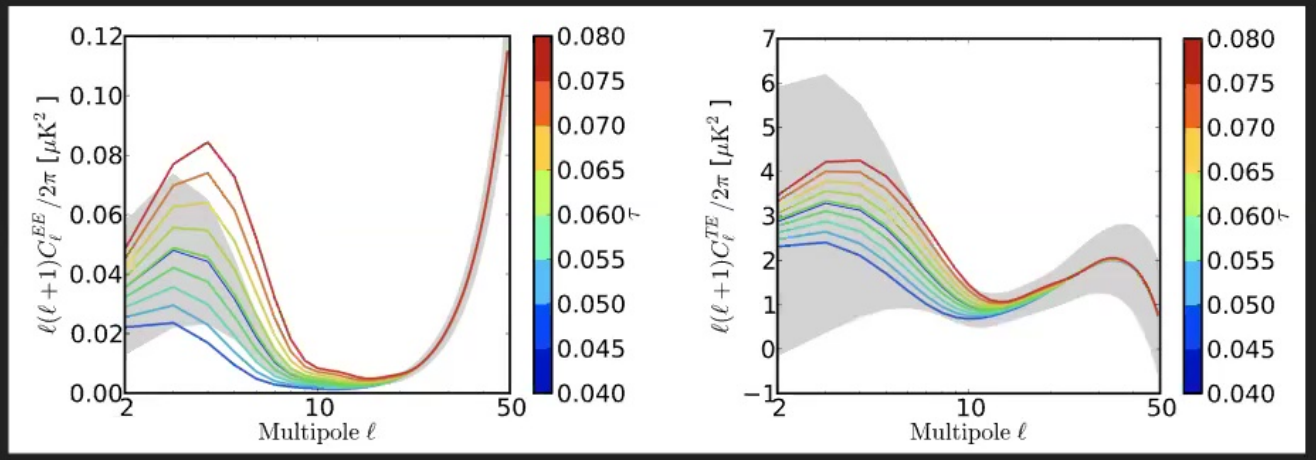
IMPRINTS OF REIONIZATION ON CMB

OPTICAL DEPTH



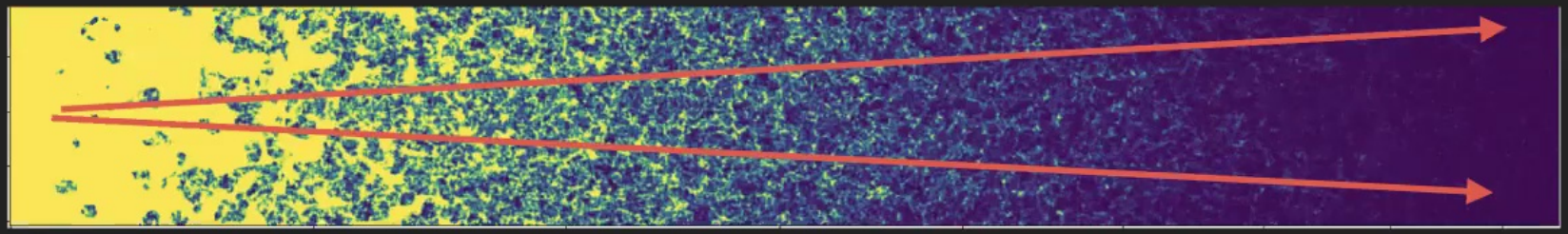
$$\tau(\chi) = \sigma_T \int_0^{\chi} (1+z')^2 n_e(\chi') d\chi'$$

TEMPERATURE AND E-MODE POLARIZATION FLUCTUATIONS

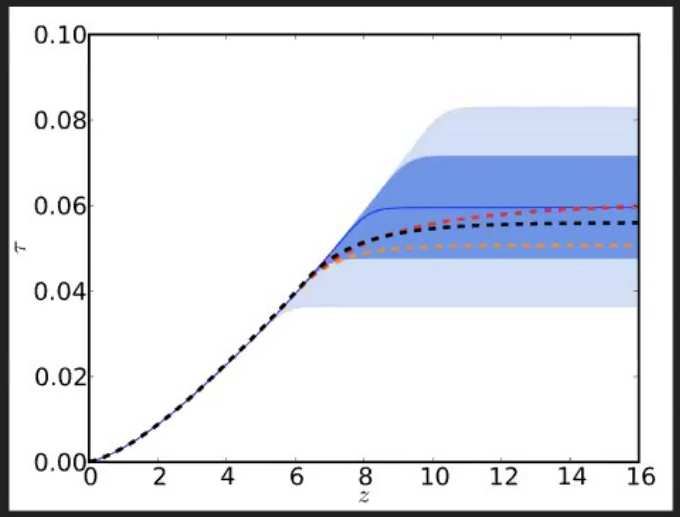


Planck collaboration (2018)

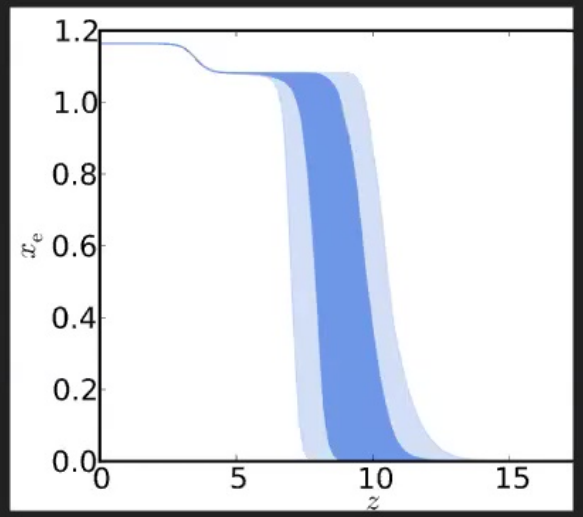
OPTICAL DEPTH: CONSTRAINTS FROM PLANCK SATELLITE



$$\tau = 0.058 \pm 0.012 \,(\text{low-l EE} + \text{TT})$$



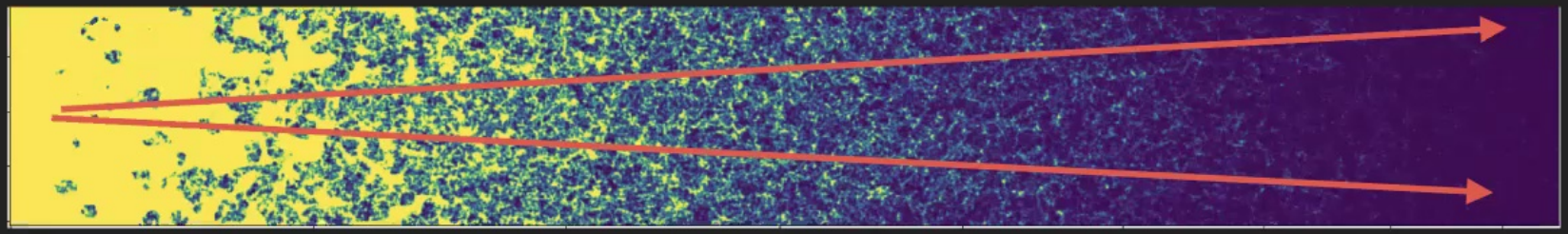
Planck collaboration (2018)

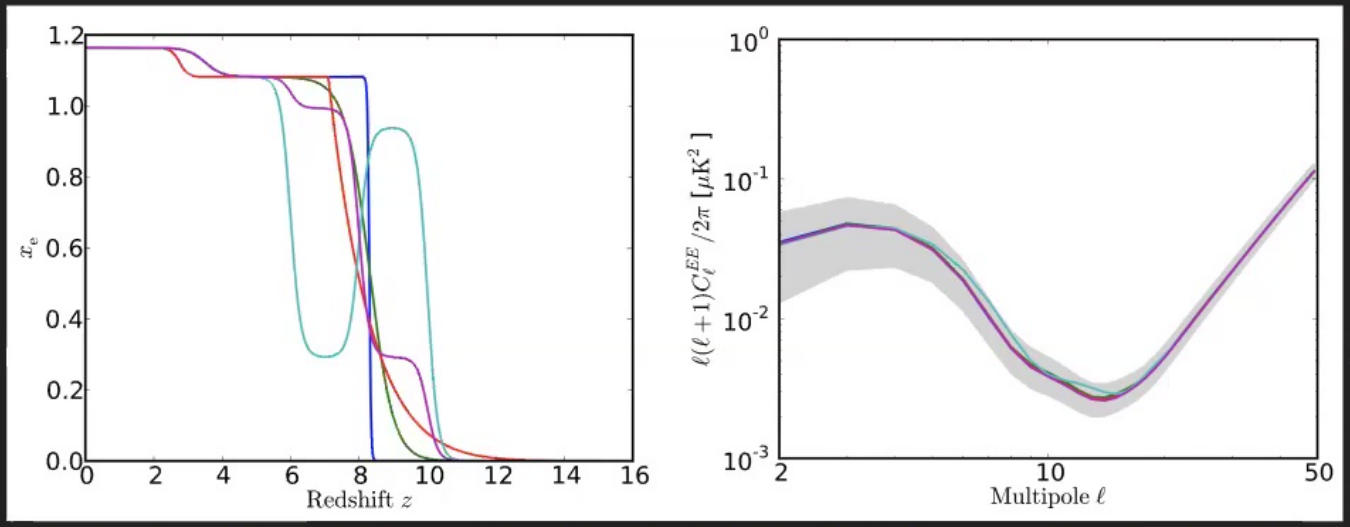


Planck collaboration (2018)

A TOO SIMPLE PARAMETRIZATION TO CAPTURE THE DETAIL PHYSICS

OPTICAL DEPTH: CONSTRAINTS FROM PLANCK SATELLITE



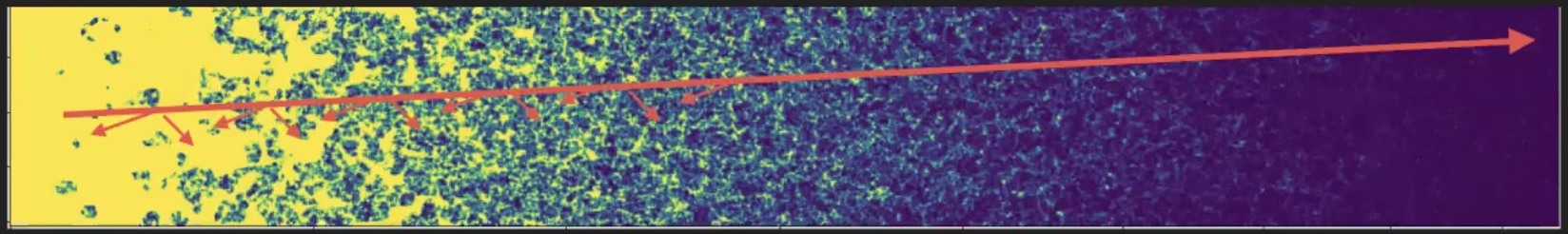


Planck collaboration (2018)

LESS SUSCEPTIBLE TO THE DETAILS OF THE REIONIZATION HISTORY

PROBES TO COSMIC REIONIZATION USING THE MILLIMETER WAVE SKY

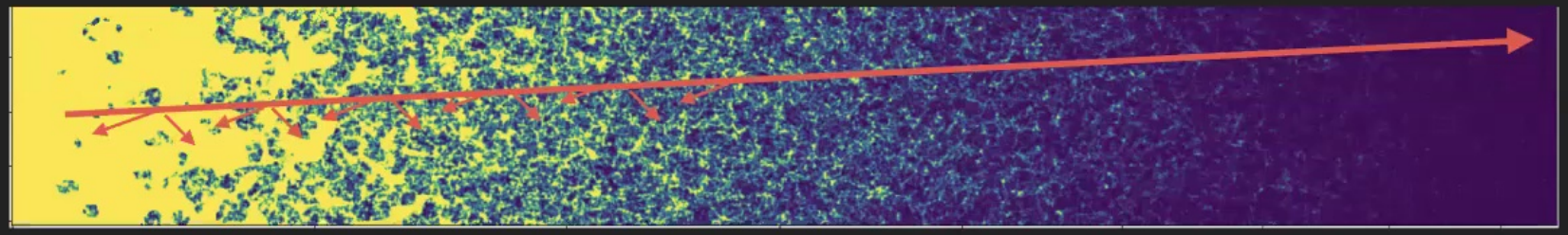
KINETIC SUNYAEV-ZELDOVICH EFFECT



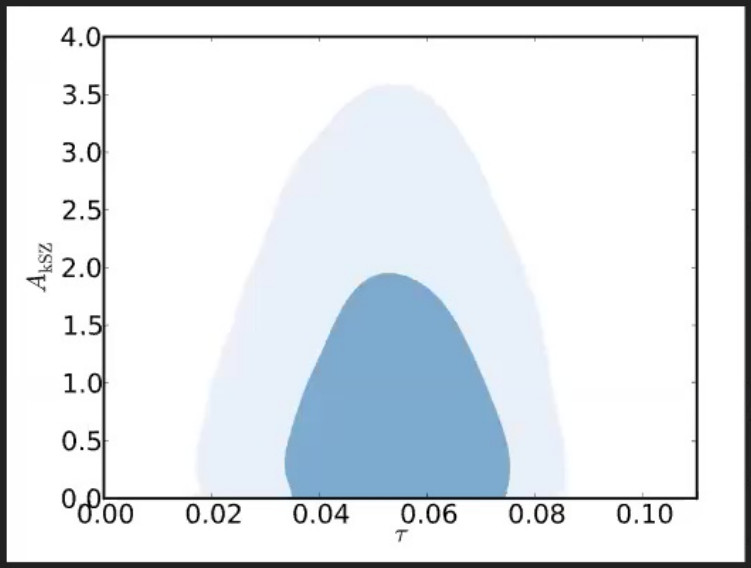
$$\Delta T_{kSZ}(\hat{n}) = \frac{\sigma_T}{c} \int_{l_0}^{l} e^{-\tau(l,\hat{n})} n_e(l,\hat{n}) \hat{n}.\vec{v} dl$$

PROBES TO COSMIC REIONIZATION USING THE MILLIMETER WAVE SKY

KINETIC SUNYAEV-ZELDOVICH EFFECT: CONSTRAINTS FROM PLANCK+ ACT+ SPT

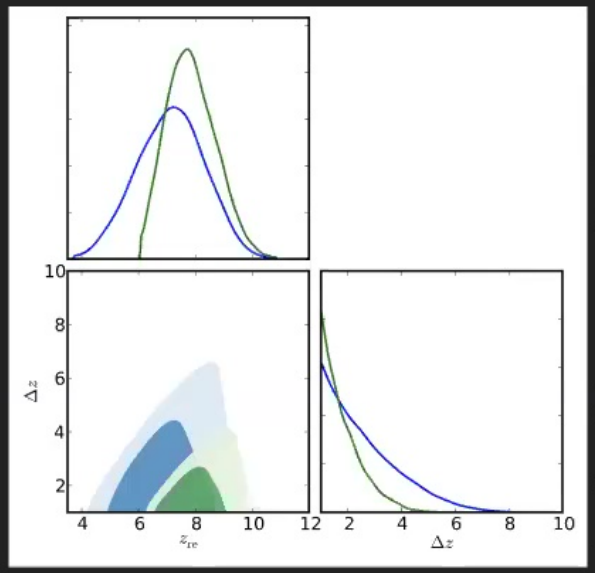


kSZ amplitude



Planck collaboration (2018)

Reionization History



Planck collaboration (2018)

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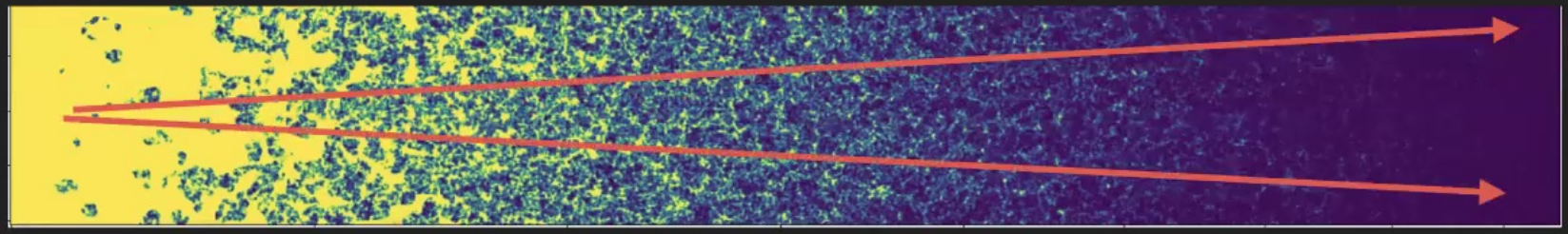
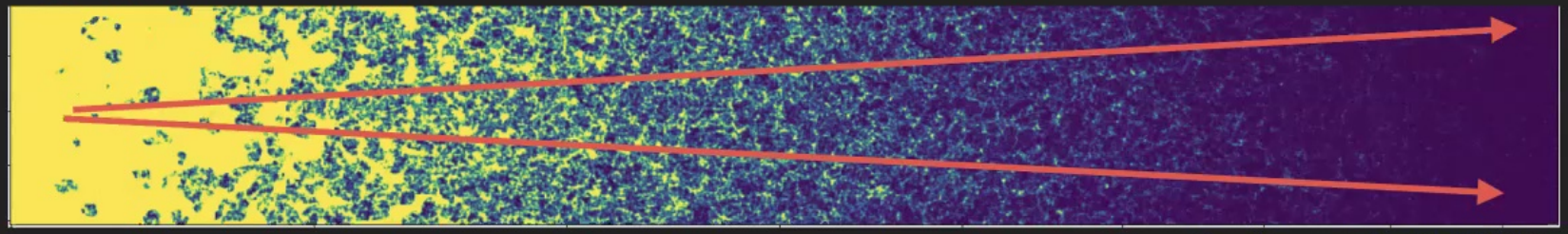
SECONDARY B-MODE POLARIZATION SIGNAL



Screening: Important at small angular scales

Scattering: Important at large angular scales

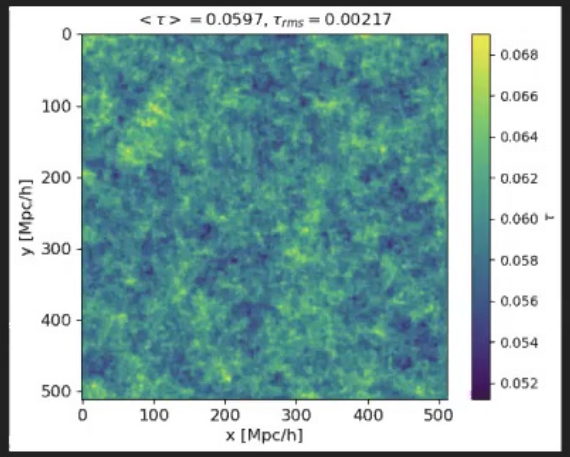
SECONDARY B-MODE POLARIZATION SIGNAL

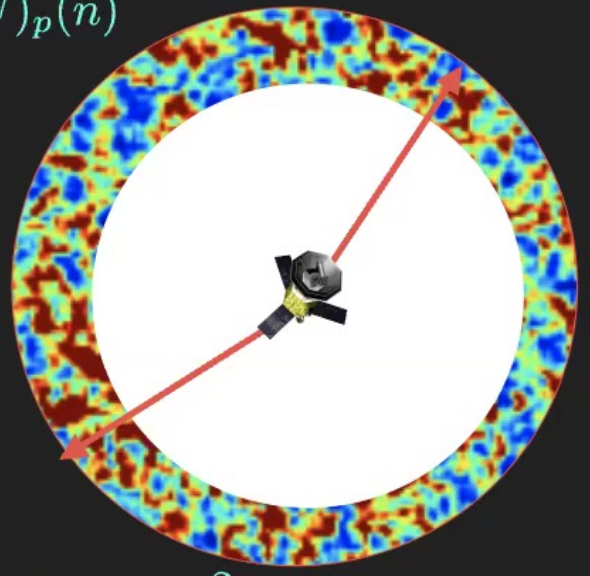


Dvorkin, Hu and Smith (2009)

Screening: Important at small angular scales

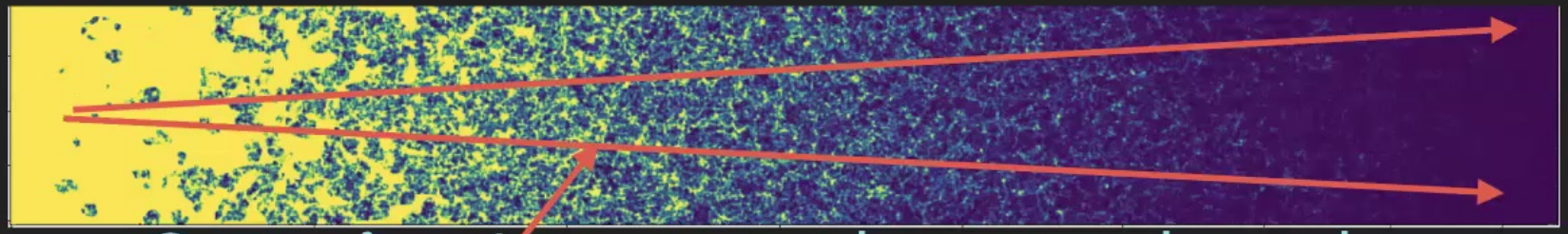
$$(Q \pm iU)(\hat{n}) = e^{-\tau(\hat{n})}(Q \pm iU)_p(\hat{n})$$





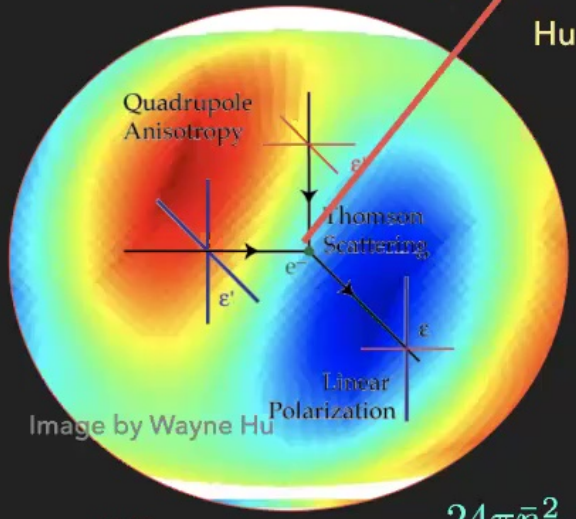
$$C_l^{BB} = e^{-2\bar{\tau}} \int \frac{d^2l'}{(2\pi)^2} C_{l'}^{EE,p} C_{|l-l'|}^{\tau\tau} \sin^2(2\phi_l')$$

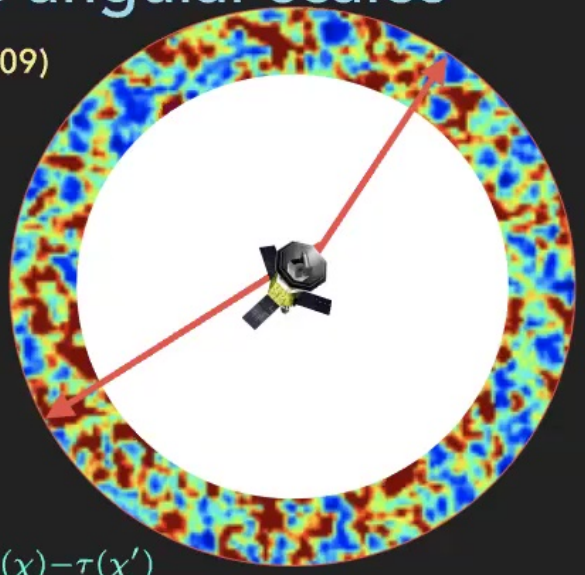
SECONDARY B-MODE POLARIZATION SIGNAL



Scattering: Important at large angular scales

Hu (2000), Dvorkin and Smith (2009)



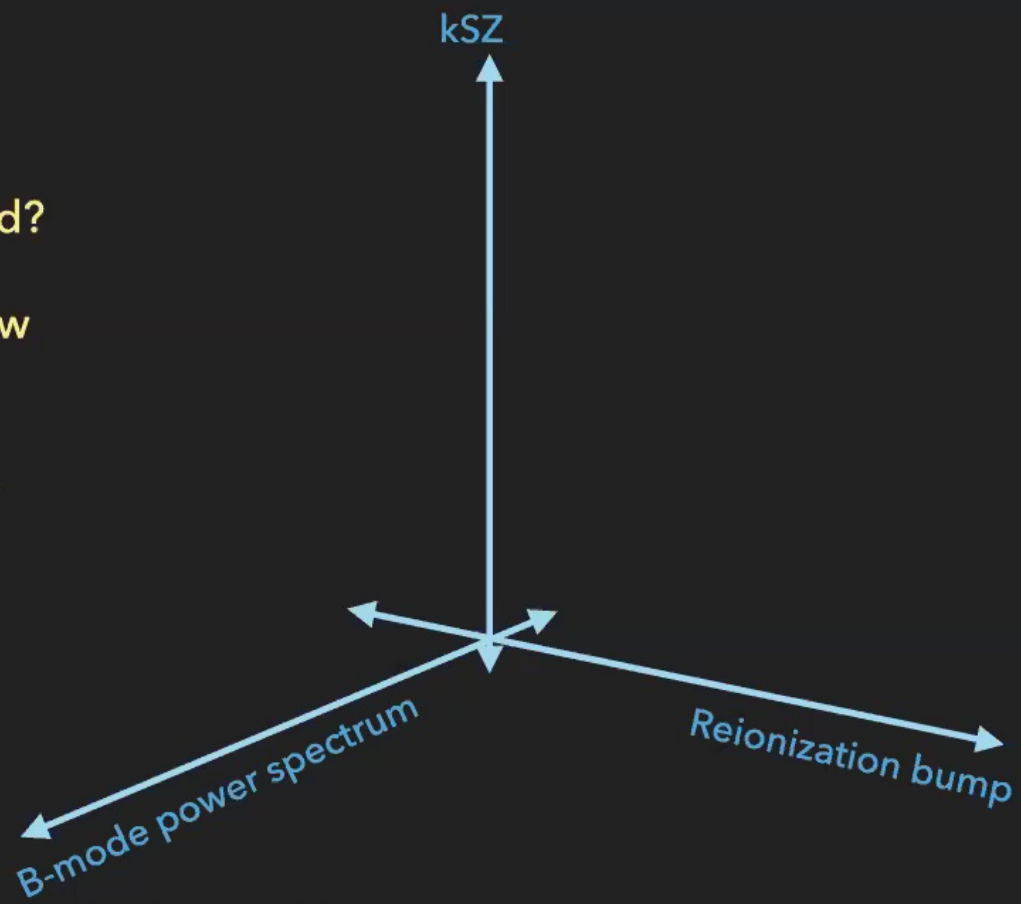


$$C_l^{BB} = \frac{24\pi\bar{n}_H^2\sigma_T^2}{100}\int d\chi\frac{1}{a^2}\int d\chi'\frac{1}{a'^2}e^{-\tau(\chi)-\tau(\chi')} \times \int dk\frac{k^2}{2\pi^2}P_{ee}(k,\chi,\chi')j_l(k\chi)j_l(k\chi')\frac{Q_{RMS}^2}{2}$$

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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PARAMETER SPACE OF EOR

- When did reionization start?
- When did reionization end?
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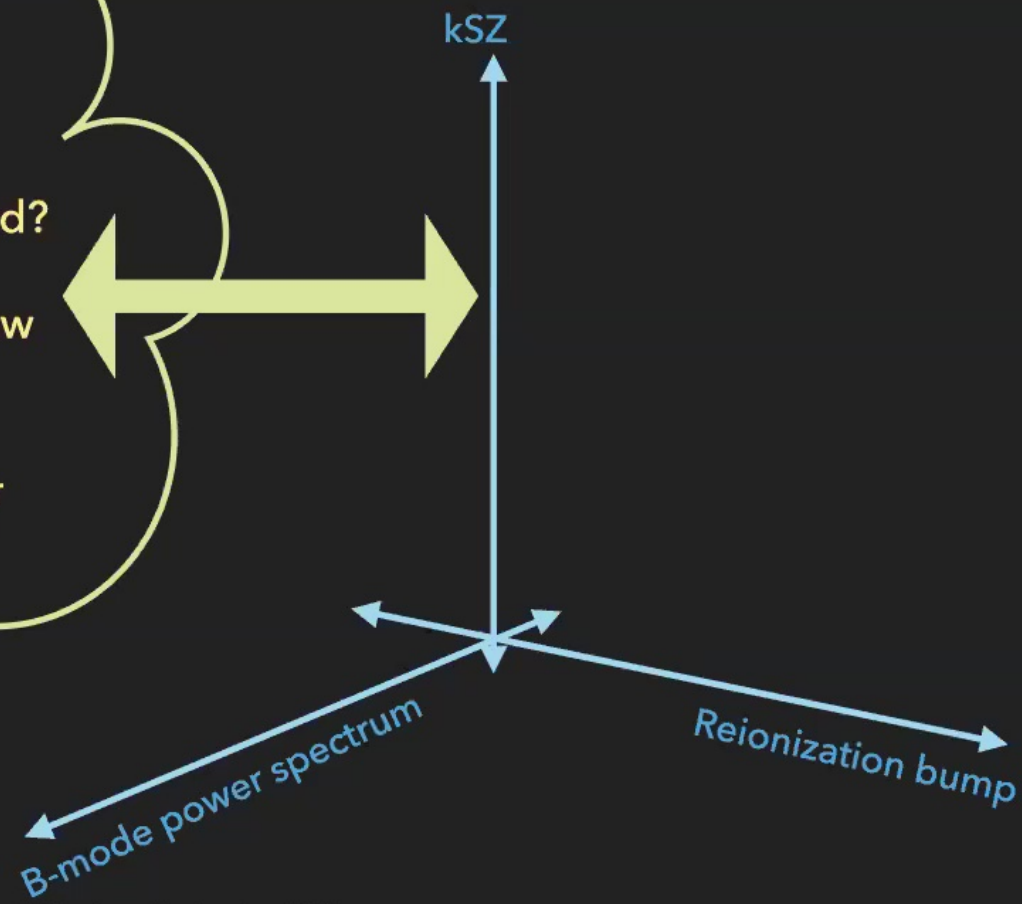
Latent parameters

PROBES AVAILABLE FROM CMB



CMB EXPERIMENTS WILL PLAY A KEY ROLE IN UNDERSTANDING REIONIZATION

Ground-based:
Adv ACTPol

Detector Array	Center Freq. [GHz]	Width [GHz]	# TES –	Projected Map Noise [μK-arcmin]	beam size [arcmin]
LF	28	6	88	80	7.1
LF	41	19	88	70	4.8
MF	90	39	1712	8	2.2
MF/HF	150	41	2718	7	1.4
HF	230	100	1006	25	0.9

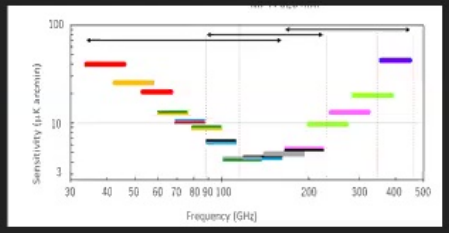
Ground-based:
SPT-3G

Experiment	N_{bolo}	NET_T ($\mu K\sqrt{s}$)	$Speed_T$	NET_P ($\mu K\sqrt{s}$)	$Speed_P$
SPT-SZ	960	22	1.0	-	-
SPT-POL	1,536	14	2.5	20	1.0
SPT-3G	**15,234**	**3.4**	**43**	**4.8**	**17**

Ground-based:
Simons
Observatory

	SATs ($f_{sky} = 0.1$)			LAT ($f_{sky} = 0.4$)		
Freq. [GHz]	FWHM (′)	Noise (baseline) [μK-arcmin]	Noise (goal) [μK-arcmin]	FWHM (′)	Noise (baseline) [μK-arcmin]	Noise (goal) [μK-arcmin]
27	91	35	25	7.4	71	52
39	63	21	17	5.1	36	27
93	30	2.6	1.9	2.2	8.0	5.8
145	17	3.3	2.1	1.4	10	6.3
225	11	6.3	4.2	1.0	22	15
280	9	16	10	0.9	54	37

Space-based:
LiteBIRD



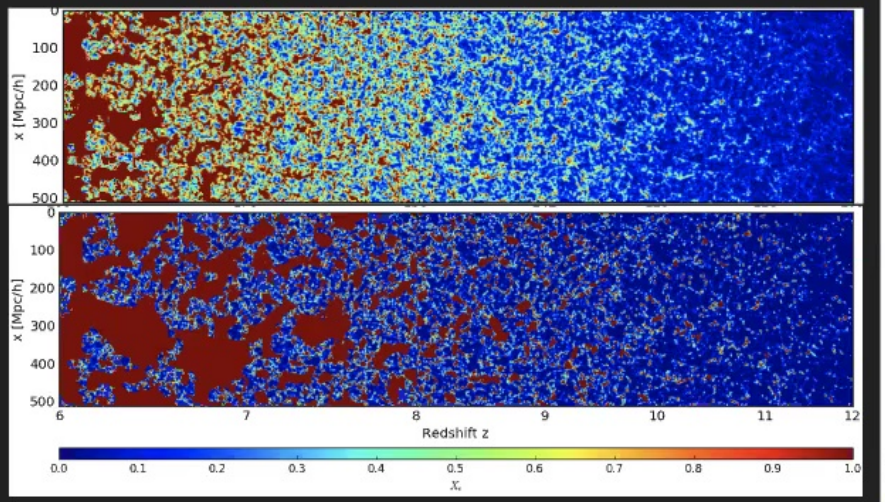
Ground-based:
CMB Stage-4

Frequency	20	30	40	85	95	145	155	220	270
Angular resolution (arcmin)	11.0	72.8	72.8	25.5	25.5	22.7	22.7	13.0	13.0
Total survey weight / 10^6 (μK^{-2})	0.12	0.69	0.43	11.0	14.1	5.7	4.8	0.71	0.24
Q/U rms (μK-arcmin)	8.4	3.5	4.5	0.88	0.78	1.2	1.3	3.5	6.0

MODELLING OF PATCHY REIONIZATION

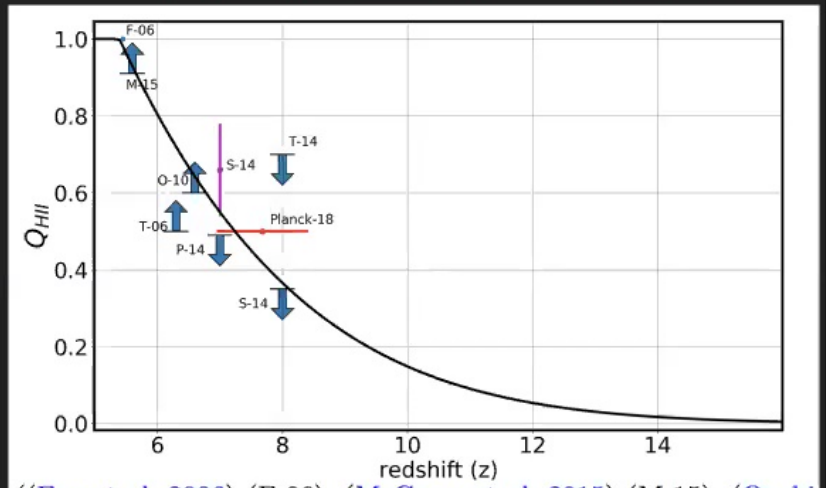
PROBING THE EPOCH OF REIONIZATION

For 10^8 M_{sun}



For 10^{10} M_{sun}

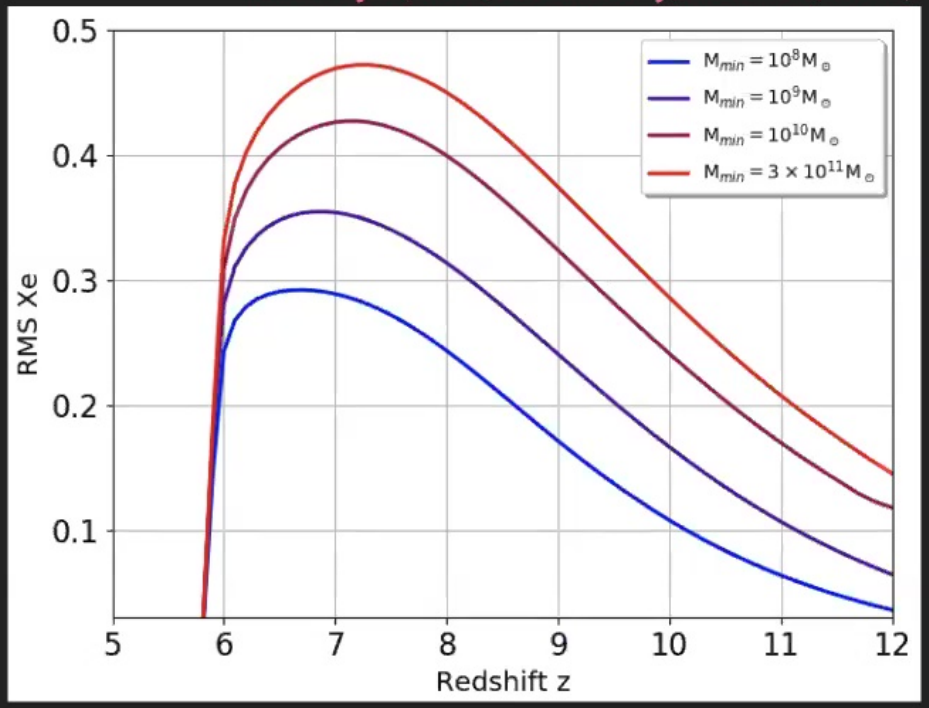
Mukherjee, Paul, Choudhury, MNRAS (2019)



((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)).

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

Mukherjee, Paul, Choudhury, MNRAS (2019)

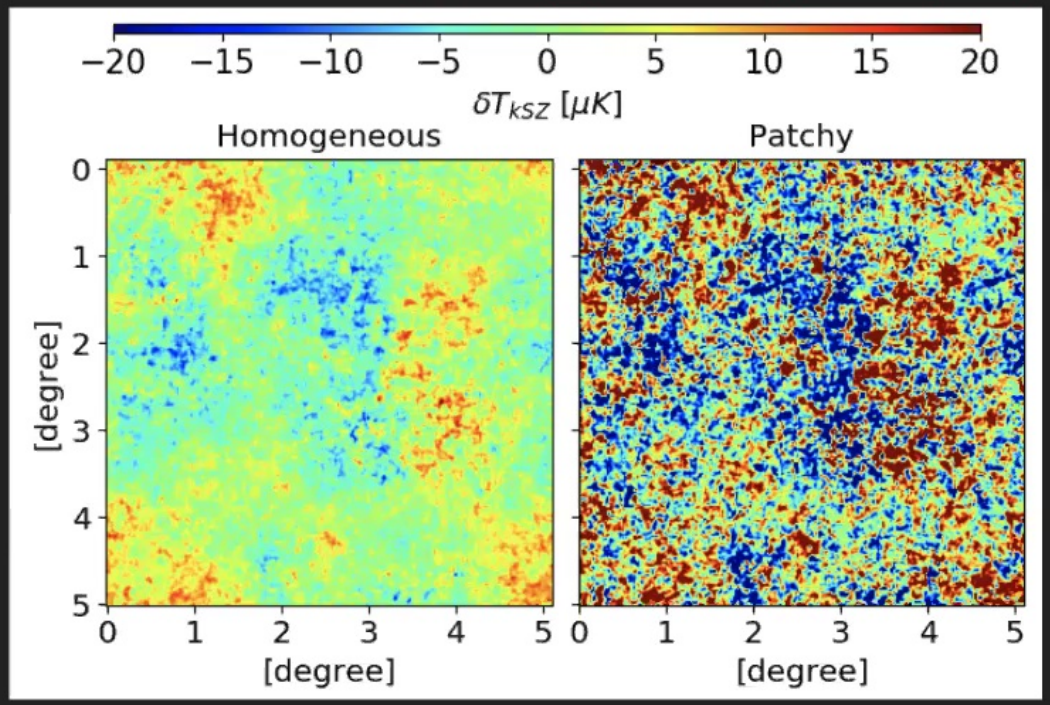


Reionization driven by big halos lead to large bubbles. Hence large fluctuations.

IMPACT OF PATCHINESS ON KSZ POWER SPECTRUM

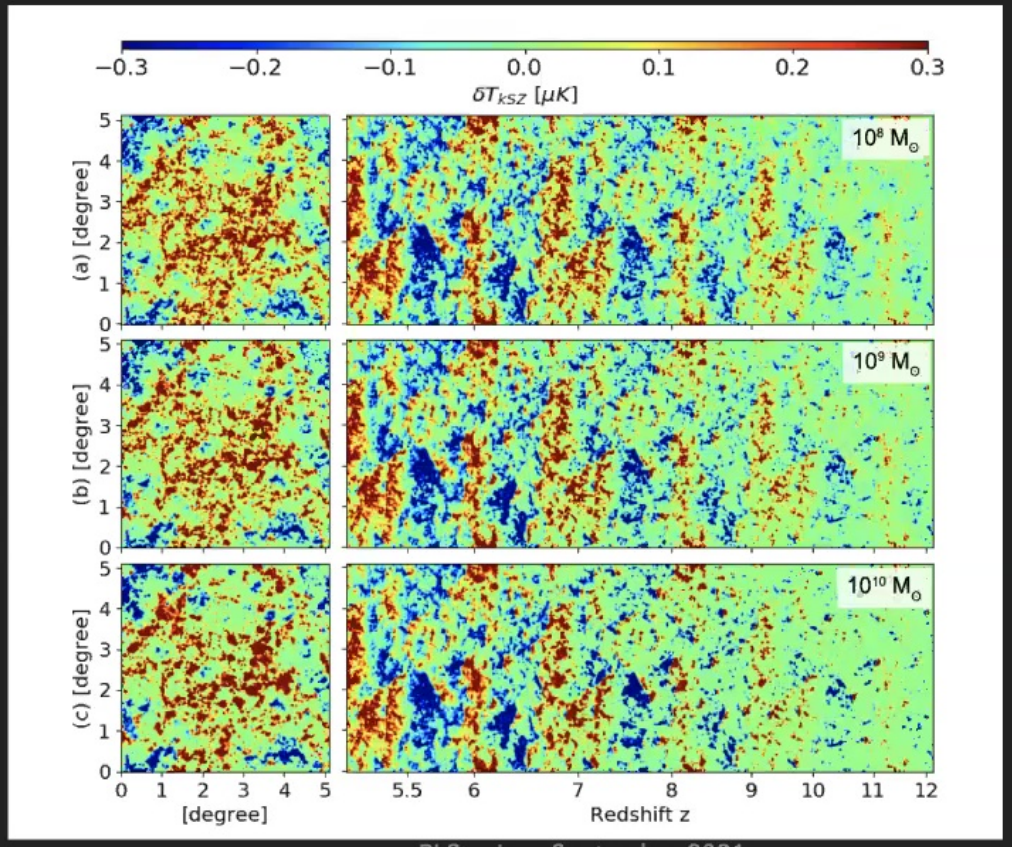
KSZ SIMULATED MAP: HOMOGENEOUS VS PATCHY REIONIZATION

Paul, Mukherjee, Choudhury, MNRAS (2020)



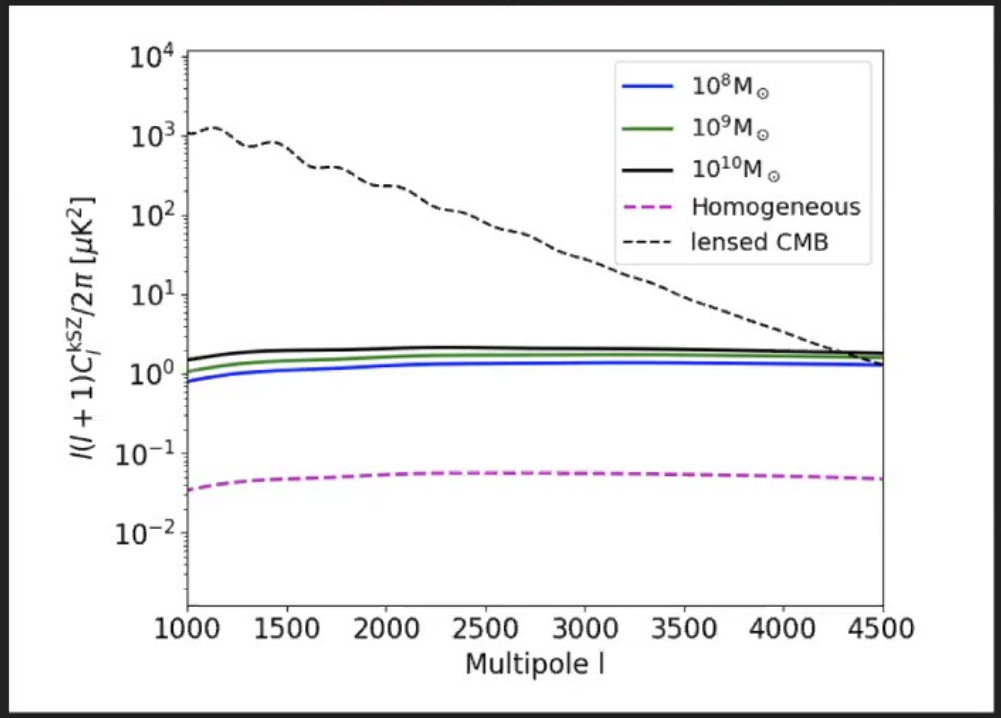
KSZ SIMULATED MAP FOR DIFFERENT MINIMUM HALO MASS

Paul, Mukherjee, Choudhury, MNRAS (2020)



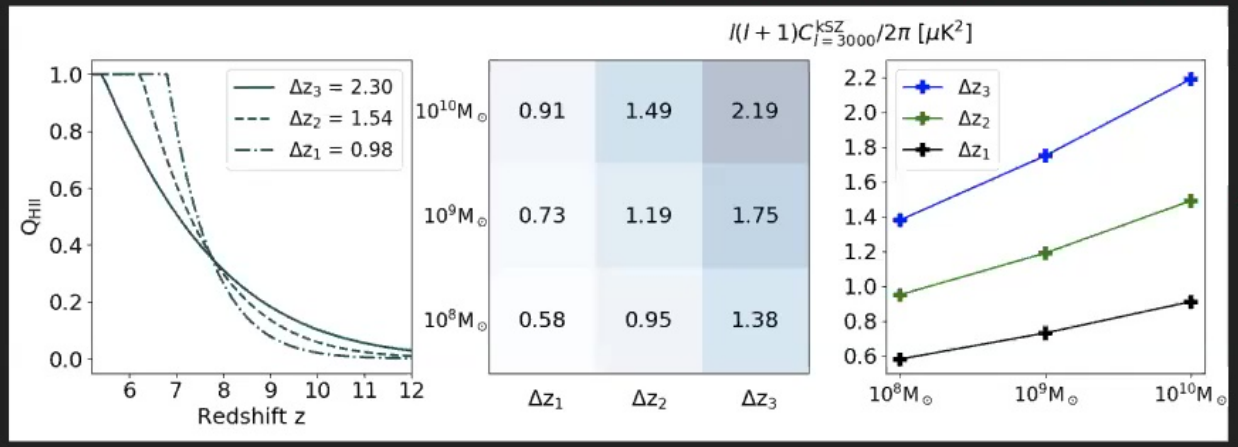
KSZ POWER SPECTRUM

Paul, Mukherjee, Choudhury, MNRAS (2020)

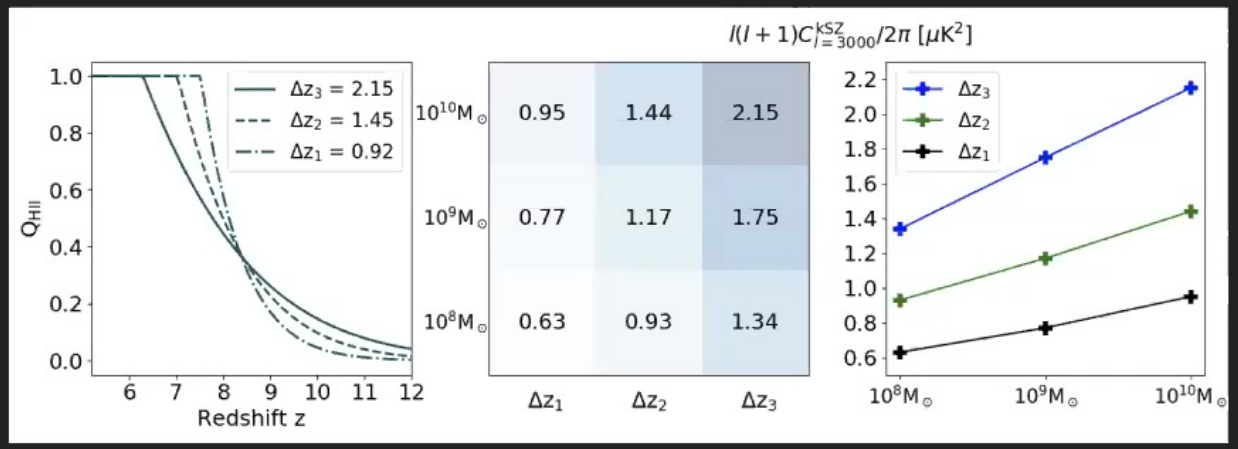


DEPENDENCE OF KSZ AMPLITUDE ON PATCHINESS

Paul, Mukherjee, Choudhury, MNRAS (2020)



$\tau = 0.054$

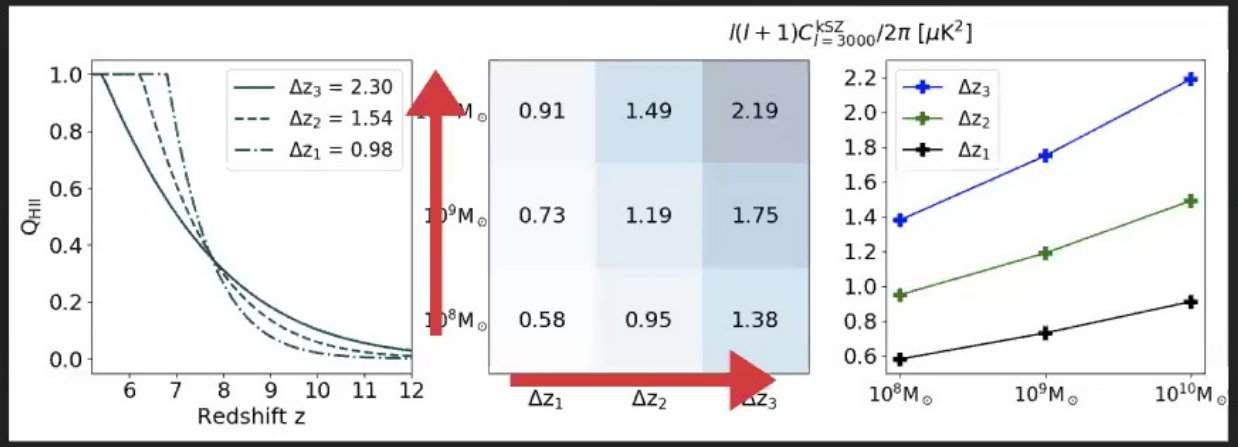


$\tau = 0.061$

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

DEPENDENCE OF KSZ AMPLITUDE ON PATCHINESS

Paul, Mukherjee, Choudhury, MNRAS (2020)



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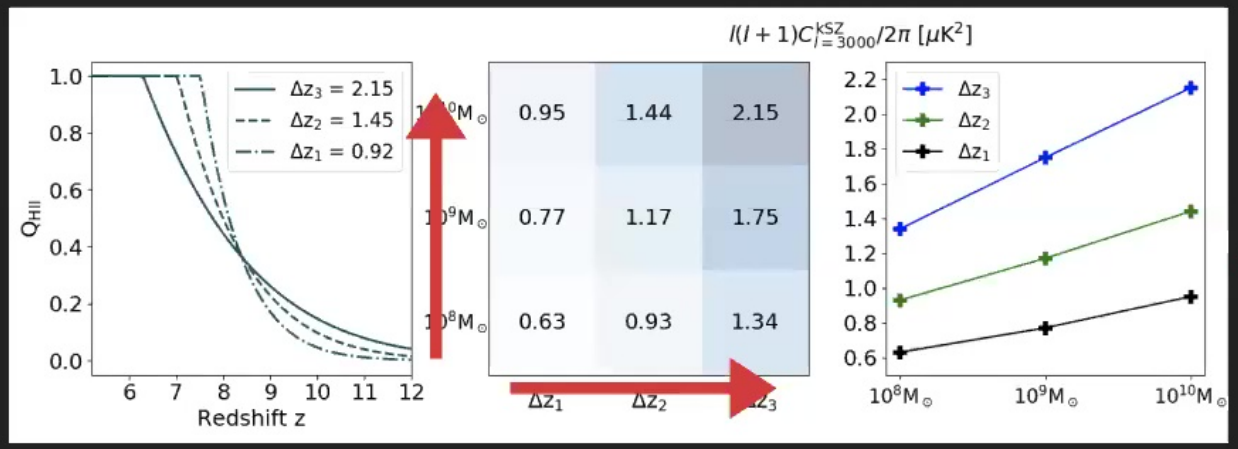


$\tau = 0.061$

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

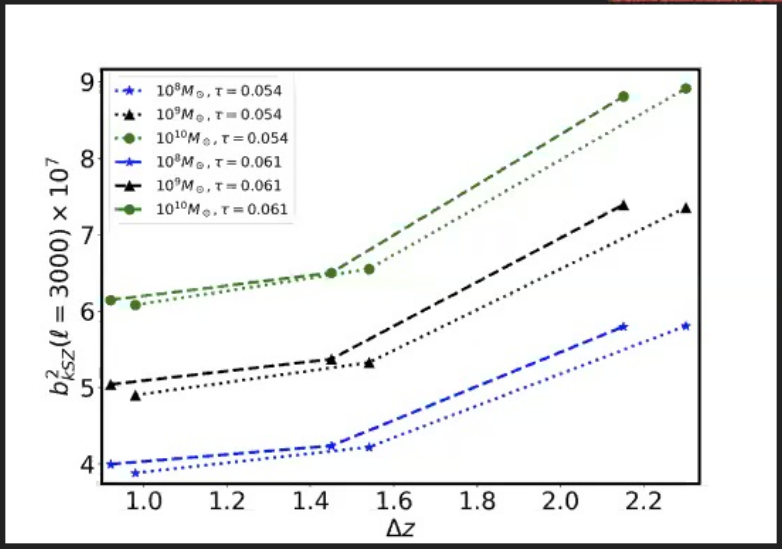
Commonly-used relation

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

Battaglia et al. (2013)

New relation

$$D^{\rm kSZ}_{l=3000} \approx 0.65\mu{\rm K}^2 \left(\frac{0.097+\tau}{0.151}\right) \left(\frac{\Delta z}{1.0}\right)^{0.54} \left(\frac{b^2_{\rm kSZ}(l=3000)}{4.0\times10^{-7}}\right)^{0.92}$$



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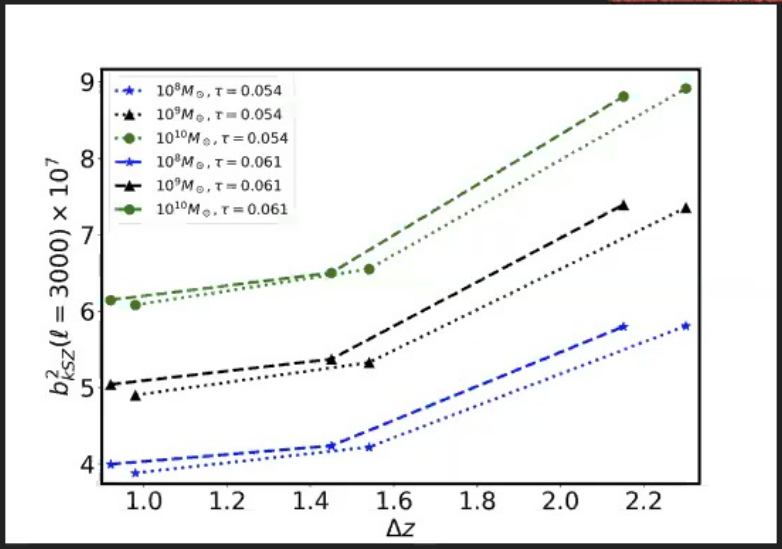
New relation

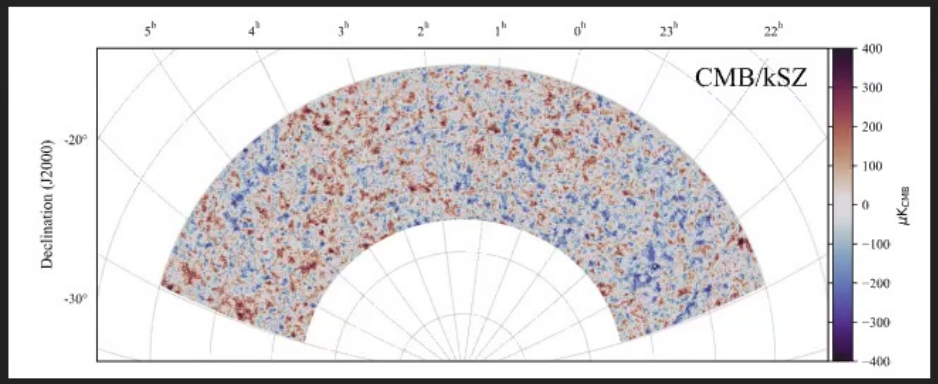
$$D^{\rm kSZ}_{l=3000} \approx 0.65\mu{\rm K}^2 \left(\frac{0.097+\tau}{0.151}\right) \left(\frac{\Delta z}{1.0}\right)^{0.54} \left(\frac{b^2_{\rm kSZ}(l=3000)}{4.0\times10^{-7}}\right)^{0.92}$$



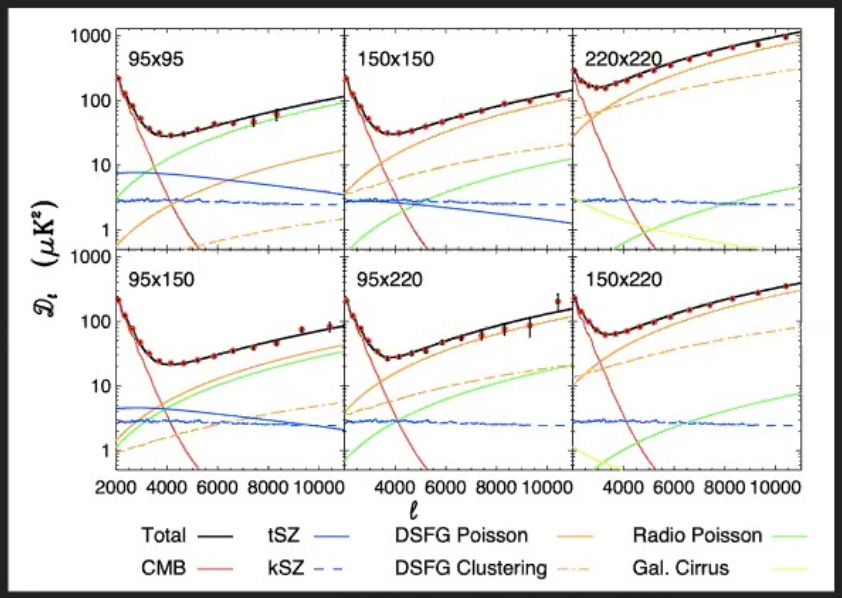
Paul, Mukherjee, Choudhury, MNRAS (2020)

CONSTRAINTS FROM THE CURRENT/FUTURE DATA

SPT DATA



Bleem et al. (2021)

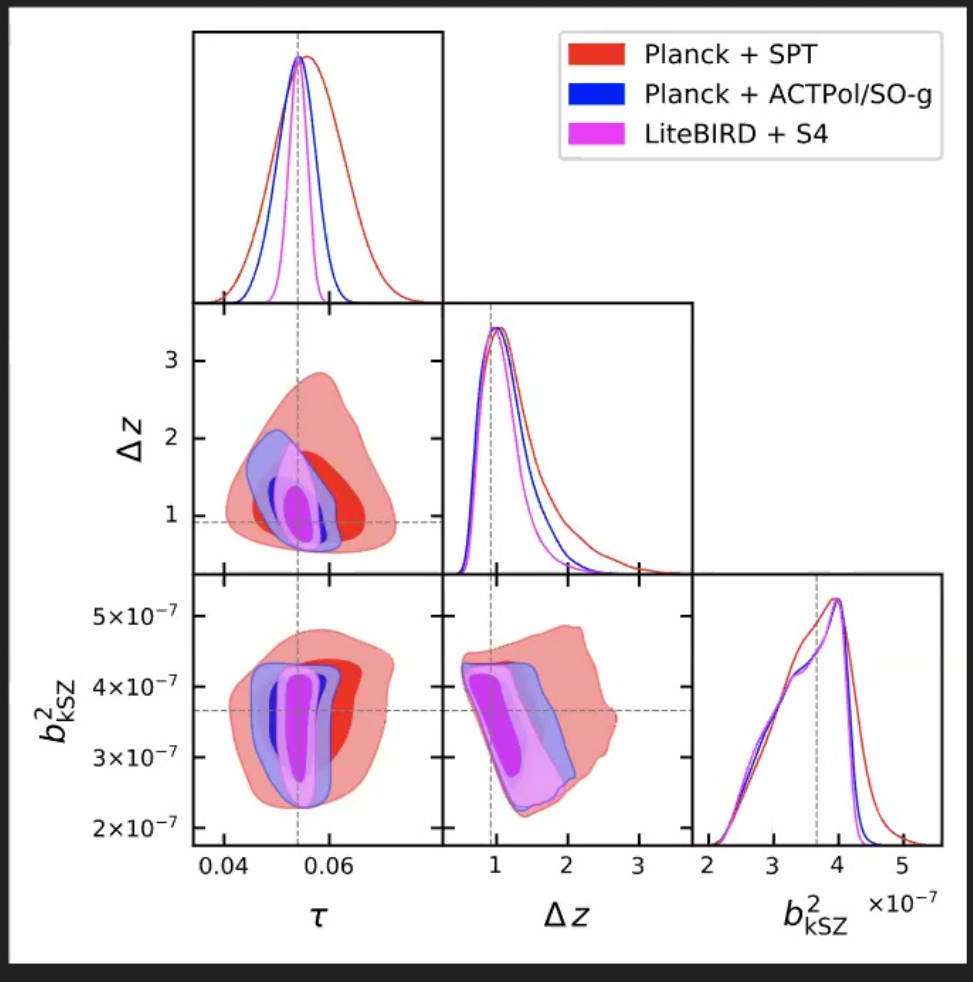


Reichardt et al. (2021)

PI Seminar, September-2021

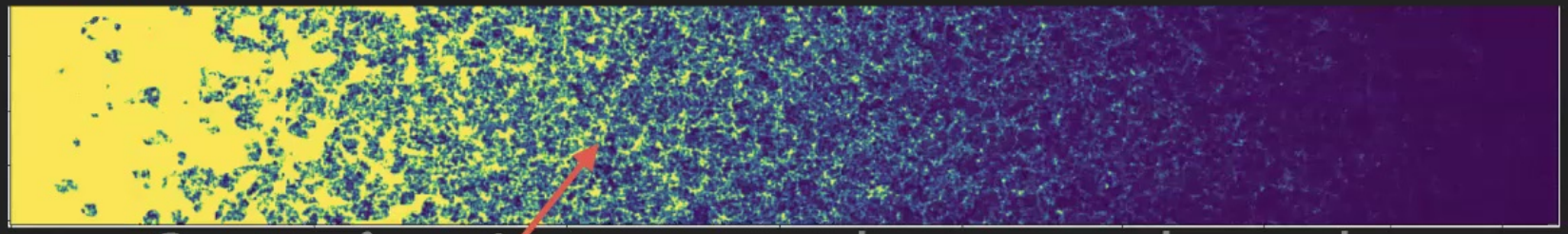
SPT+PLANCK AND FORECAST FOR THE UPCOMING CMB MISSIONS

Choudhury, Mukherjee, Paul, MNRAS-L (2020)



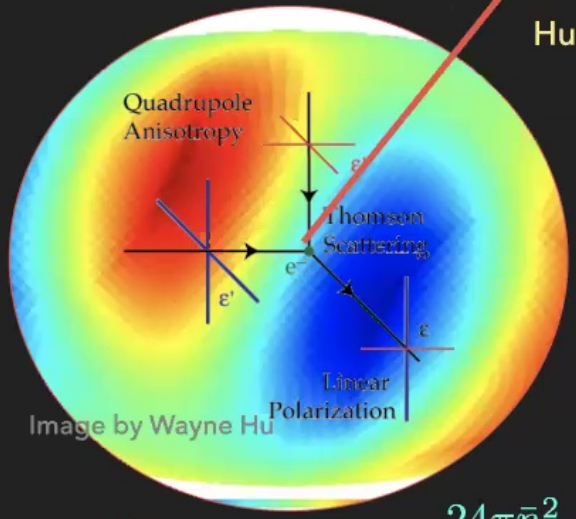
IMPACT OF PATCHY REIONIZATION ON B-MODE POLARIZATION

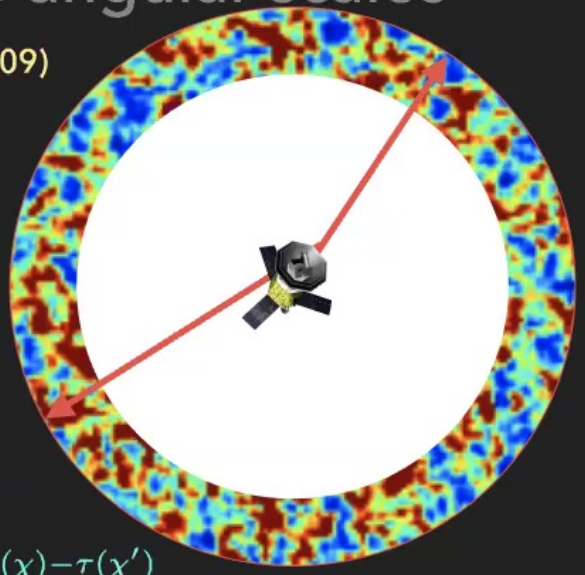
SECONDARY B-MODE POLARIZATION SIGNAL



Scattering: Important at large angular scales

Hu (2000), Dvorkin and Smith (2009)

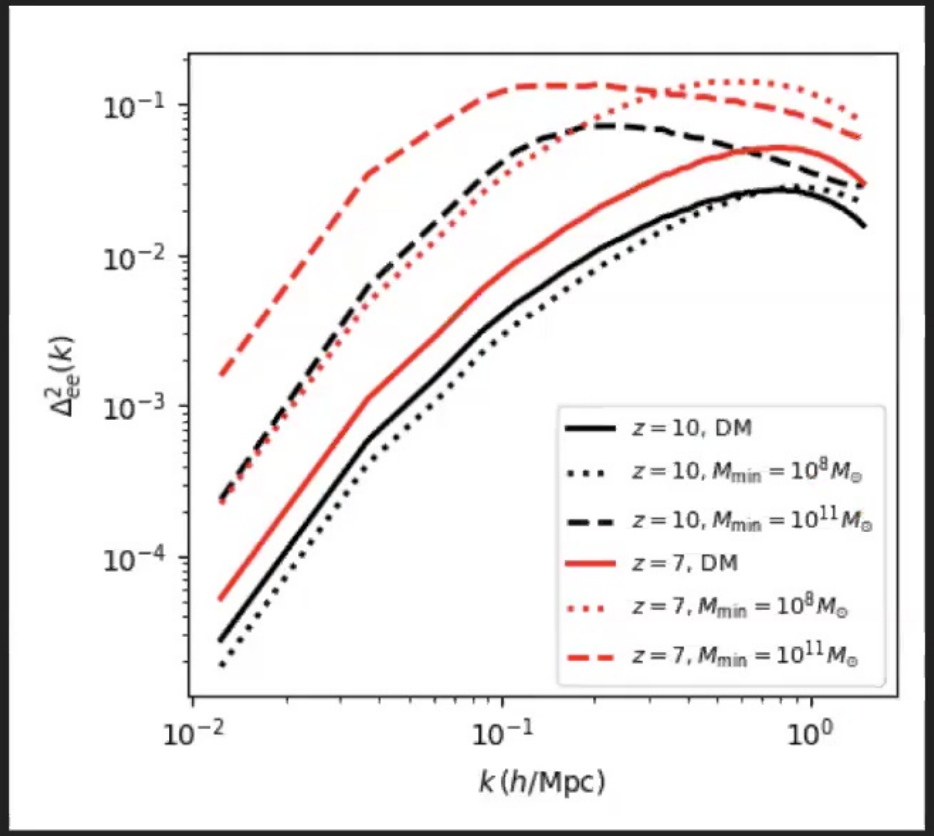




$$C_l^{BB} = \frac{24\pi\bar{n}_H^2\sigma_T^2}{100}\int d\chi\frac{1}{a^2}\int d\chi'\frac{1}{a'^2}e^{-\tau(\chi)-\tau(\chi')} \times \int dk\frac{k^2}{2\pi^2}P_{ee}(k,\chi,\chi')j_l(k\chi)j_l(k\chi')\frac{Q_{RMS}^2}{2}$$

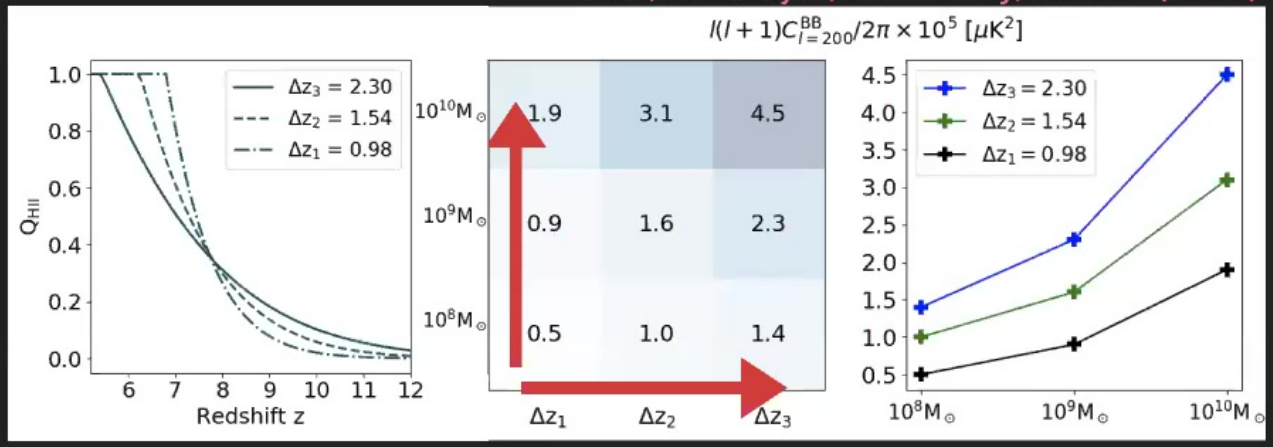
ELECTRON DENSITY POWER SPECTRUM FOR DIFFERENT REIONISATION SCENARIOS

Mukherjee, Paul, Choudhury, MNRAS (2019)

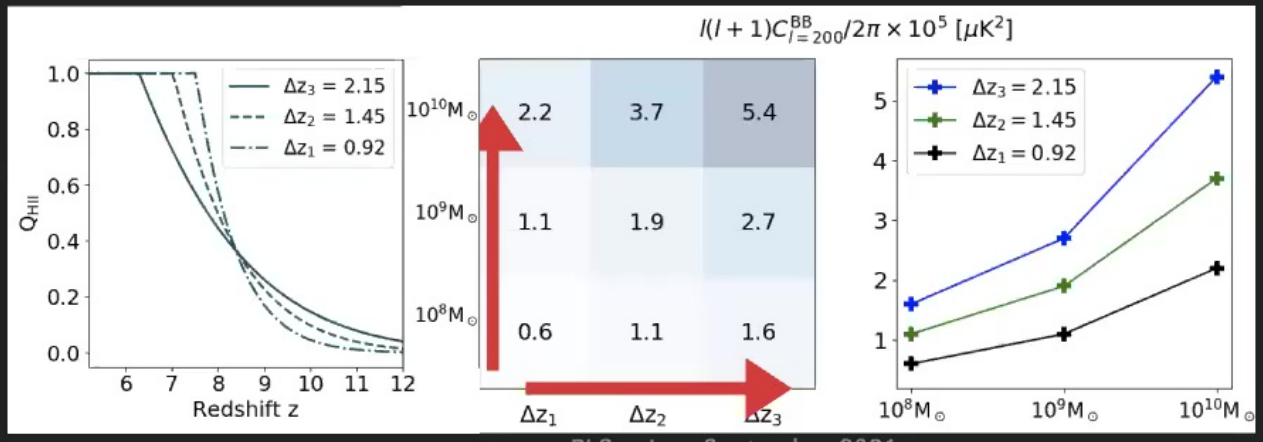


DEPENDENCE OF B-MODE POWER SPECTRUM ON PATCHY REIONIZATION

Paul, Mukherjee, Choudhury, MNRAS (2020)



$\tau = 0.054$

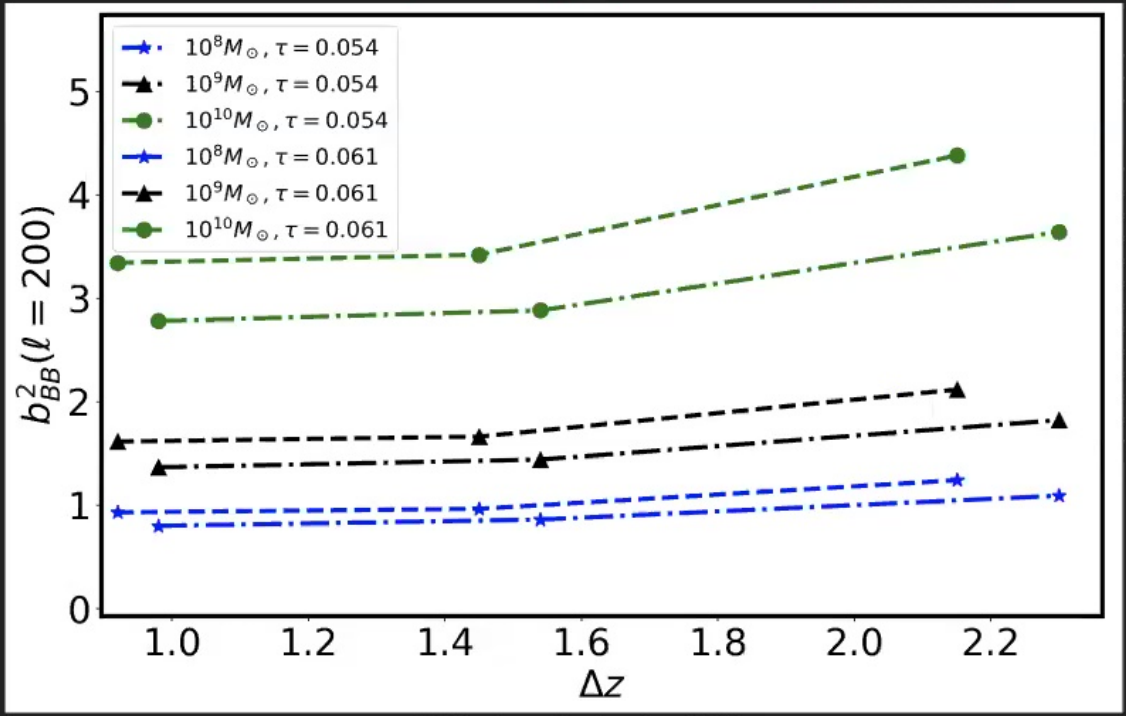


$\tau = 0.061$

A SCALING RELATION FOR B-MODE POLARIZATION

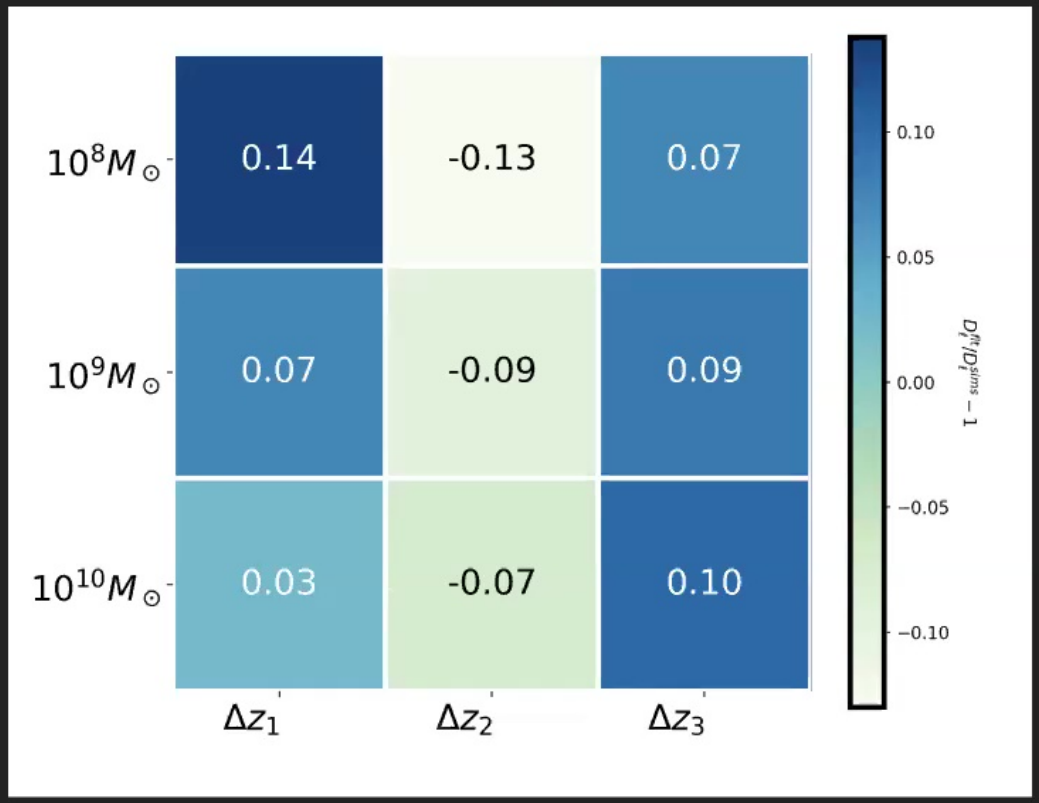
$$D^{BB}_{l=200} \approx 6.6\,\mathrm{nK}^2 \left(\frac{0.15+\tau}{0.204}\right)\left(\frac{\Delta z}{0.98}\right)^{0.78}\left(\frac{b^2_{\mathrm{BB}}(l=200)}{0.93}\right)^{0.99}$$

Paul, Mukherjee, Choudhury, MNRAS (2020)



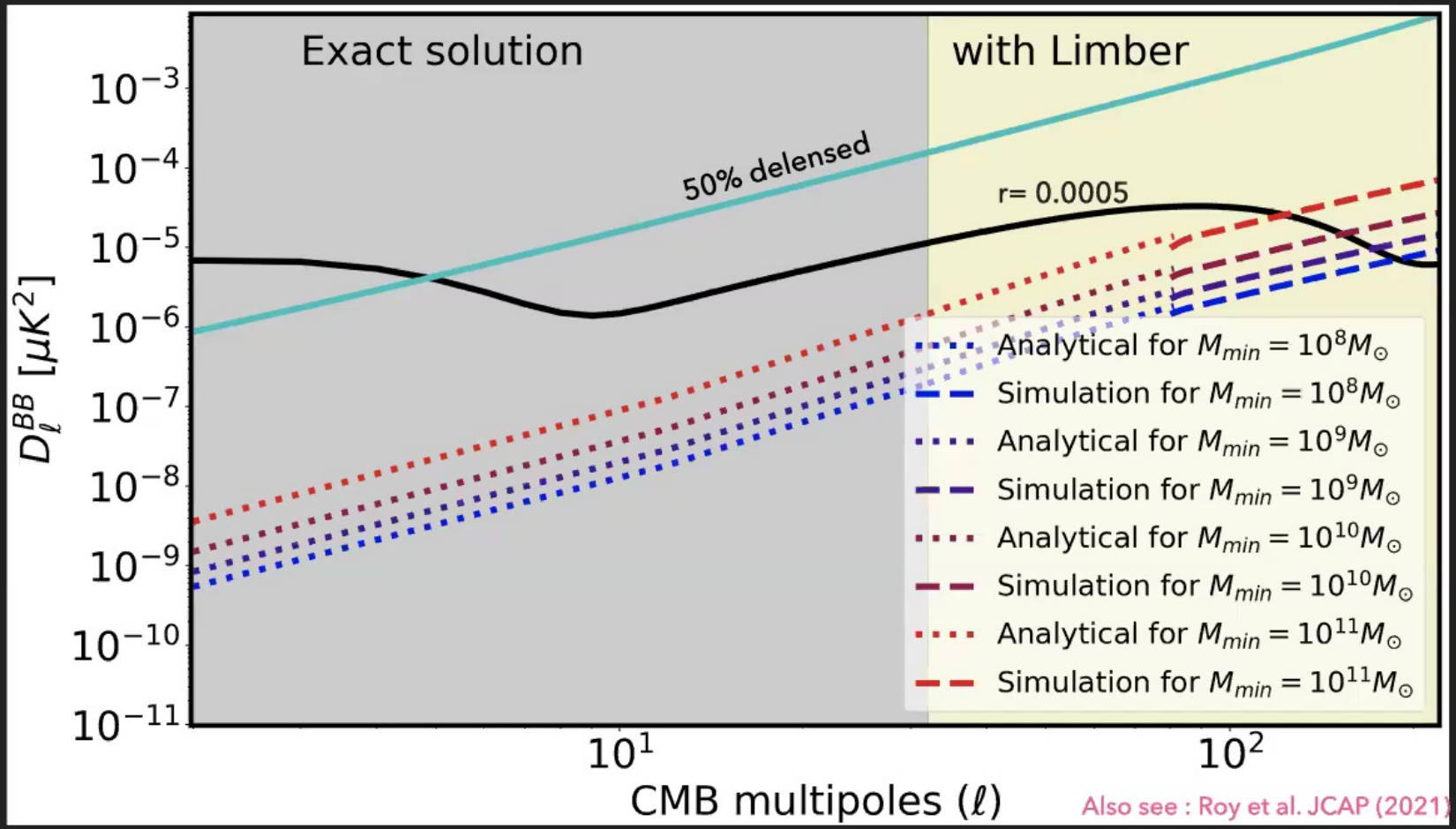
ACCURACY OF THE SCALING RELATION FOR B-MODE

Paul, Mukherjee, Choudhury, MNRAS (2020)

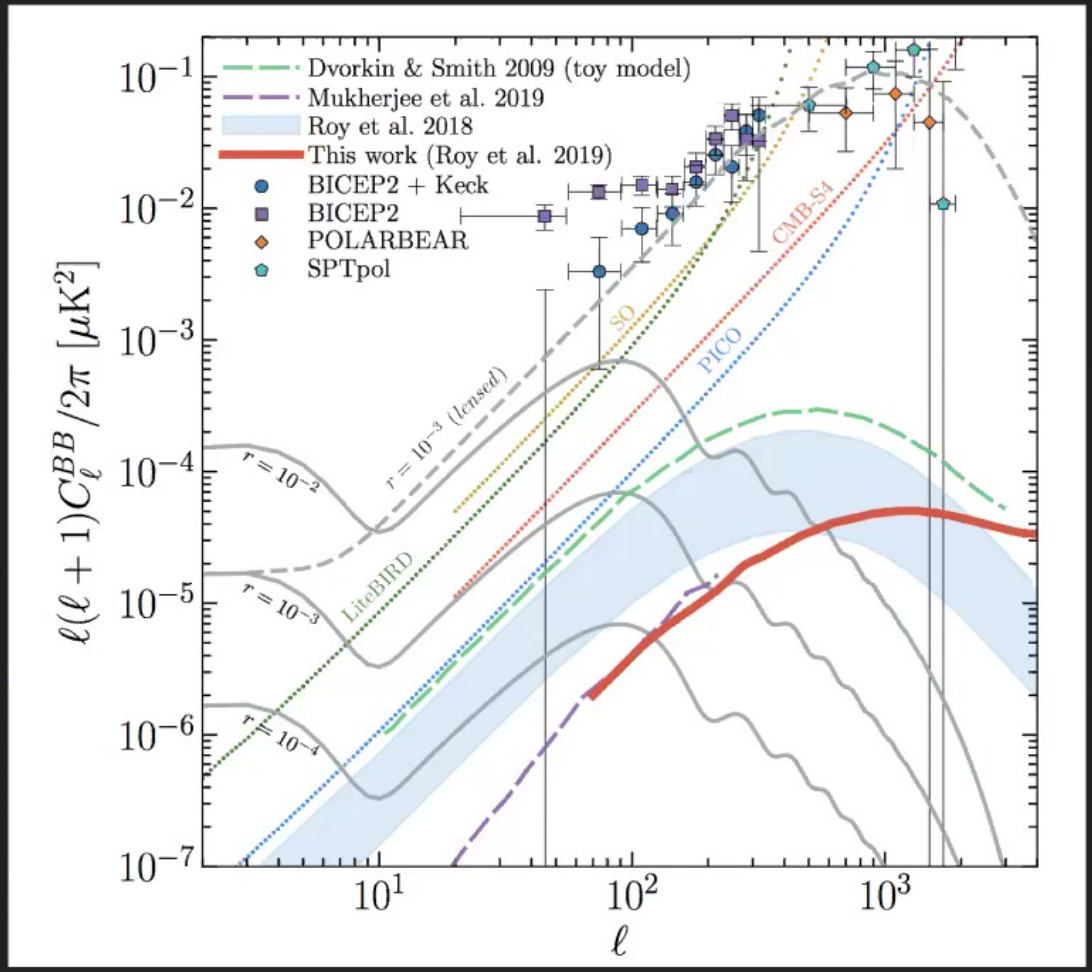


CMB B-MODE POWER SPECTRUM DUE TO PATCHY REIONIZATION

Mukherjee, Paul, Choudhury, MNRAS (2019)



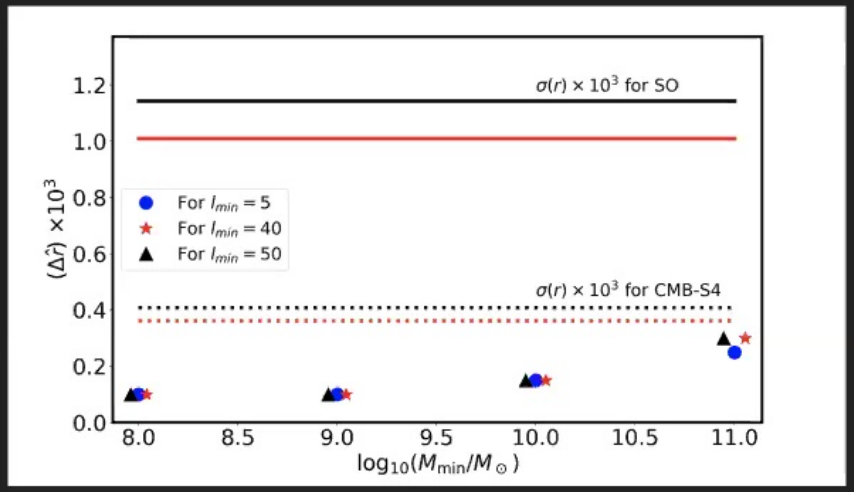
CMB B-MODE POWER SPECTRUM: COMPARISON OF DIFFERENT RESULTS

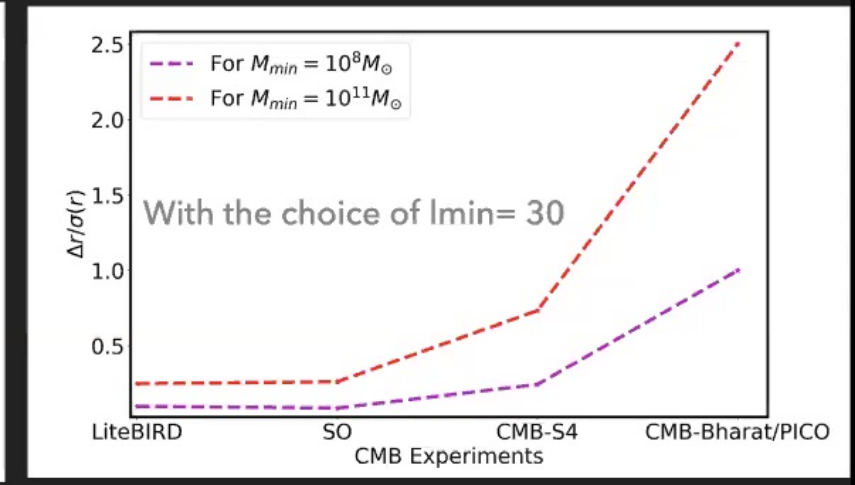


PhD Thesis, A. Roy (2019)

WILL IT BE AN OBSTRUCTION TO PRIMORDIAL GW SIGNAL

IMPACT OF THE CONTAMINATION ON TENSOR TO SCALAR RATIO: BIAS





Mukherjee, Paul, Choudhury MNRAS (2019)

$$-2\mathcal{L} \propto \sum_{l,l'=l_{min}}^{l_{max}} (\tilde{C}_l^{BB} - C_l^{BB}) \Sigma_{ll'}^{-1} (\tilde{C}_{l'}^{BB} - C_{l'}^{BB})$$

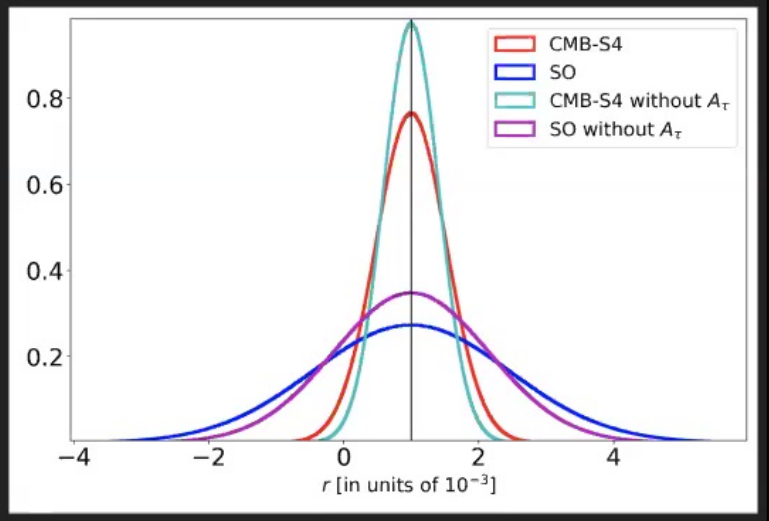
$$\tilde{C}_l^{BB} = C_l^{BB,prim} + A_\tau C_l^{BB,reion}(M_{min}) + A_{lens} C_l^{BB,lens}$$

$$\Sigma_{ll'} = \frac{2}{f_{sky}(2l+1)} \left(\tilde{C}_l^{BB} + N_l\right)^2 \delta_{ll'}$$

PI Seminar, September-2021

IMPACT OF THE CONTAMINATION ON TENSOR TO SCALAR RATIO: ERROR-BAR

- Reionization driven by larger halos creates more bias in the value of tensor to scalar ratio.
- The shape of the power spectrum of B-mode signal from primordial GW and patchy reionization differs and can be distinguished.



Mukherjee, Paul, Choudhury, MNRAS (2019)

PATCHY REIONIZATION IS NOT A SHOW-STOPPER TO DISCOVER PGW SIGNAL WHICH ARE ACCESSIBLE FROM THE UPCOMING CMB MISSIONS

PARAMETER SPACE OF EOR

- When reionization started ?
- When reionization ended ?
- Is it a fast process or a slow process?
- Are they driven by lighter halos or massive halos?

$$D^{\rm kSZ}_{l=3000} \approx 0.65\mu{\rm K}^2 \left(\frac{0.097+\tau}{0.151}\right)\left(\frac{\Delta z}{1.0}\right)^{0.54}\left(\frac{b^2_{\rm kSZ}(l=3000)}{4.0\times10^{-7}}\right)^{0.92}$$

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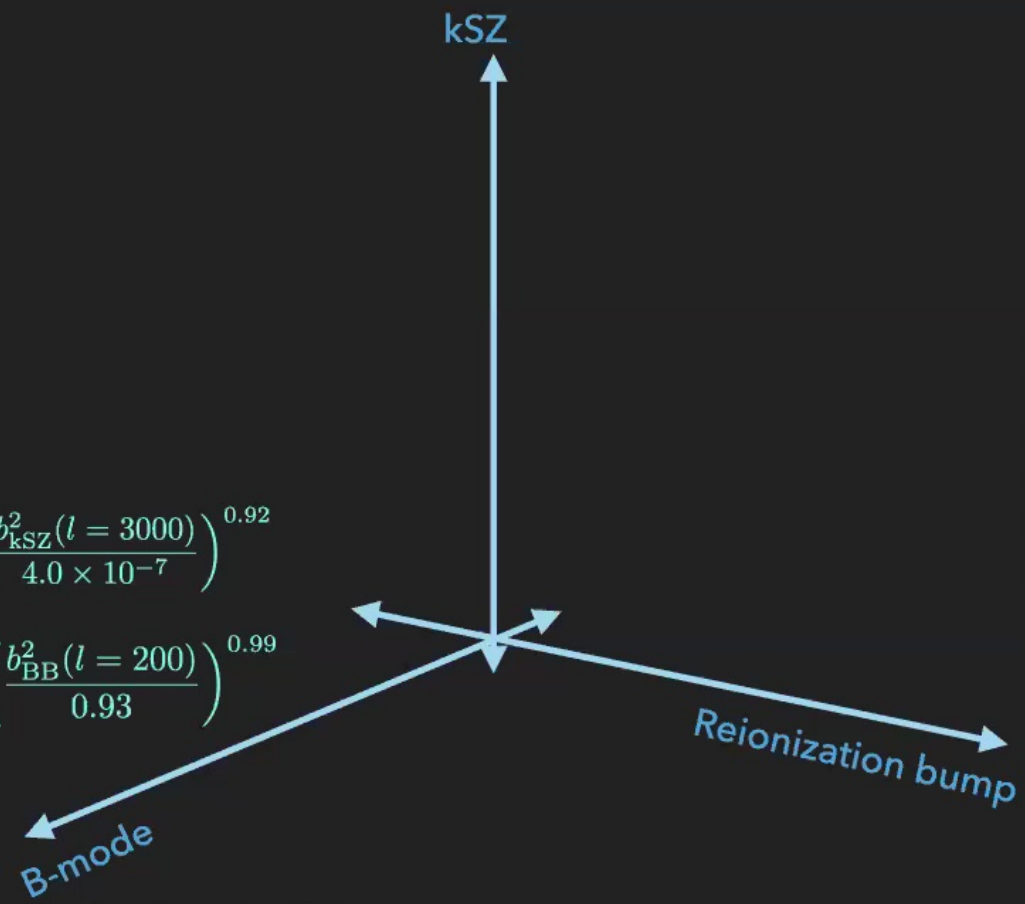
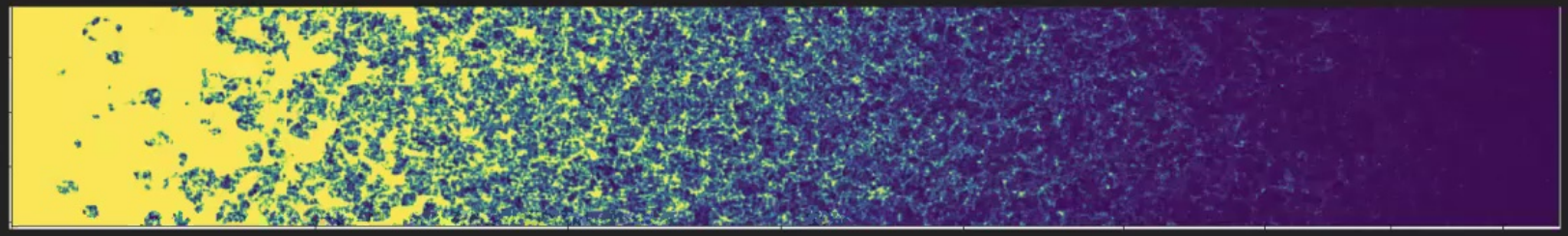
PROBES AVAILABLE FROM CMB



SUMMARY



- The EOR can be probed by E-mode polarization, patchy kSZ, and secondary B-mode polarization (and cross-correlation with other probes).
- The amplitude of kSZ and secondary B-mode polarization are related to the duration of reionization, optical depth, and patchiness in electron density.
- CMB missions can constrain reionization history and the patchiness during reionization.
- 21 cm signal will probe the typical bubble sizes. So cross-correlation with CMB observations will be a powerful tool.

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

SUMMARY

- The EOR can be probed by E-mode polarization, patchy kSZ, and secondary B-mode polarization (and cross-correlation with other probes).
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Thank you!

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