

Title: Probing reionization and structure formation with CMB and multi-line intensity mapping

Speakers: Anirban Roy

Series: Cosmology & Gravitation

Date: January 09, 2023 - 12:00 PM

URL: <https://pirsa.org/23010094>

Abstract: The observation of the Cosmic Microwave Background (CMB) is a powerful probe to unravel many mysteries of the late-time Universe. During the first half of the talk, I will discuss how future low-noise and high-resolution CMB experiments can be used to probe the detailed physics of reionization, constraining the morphology, shape, and temperature of ionized bubbles. Furthermore, I will talk about the prospects of LSS x CMB to understand the thermodynamic properties of gas in the halos. In the second part of my talk, I will also talk about "line intensity mapping", a novel technique that will provide us with new information from the star formation in galaxies to the expansion of our Universe. Mentioning the viable challenges, I will discuss the estimators to extract the signal in the presence of interlopers and instrumental noise. I will also describe how the MLIM could help us to perform cross-correlations with complementary probes such as CMB lensing and galaxy field. In the end, I will present the constraints on astrophysical and cosmological parameters that we hope to achieve from future intensity mapping observations.

Zoom link: <https://pitp.zoom.us/j/93308659447?pwd=VVM2czBWc0NTeTA5eTRWdzVFRUtdz09>

CIB

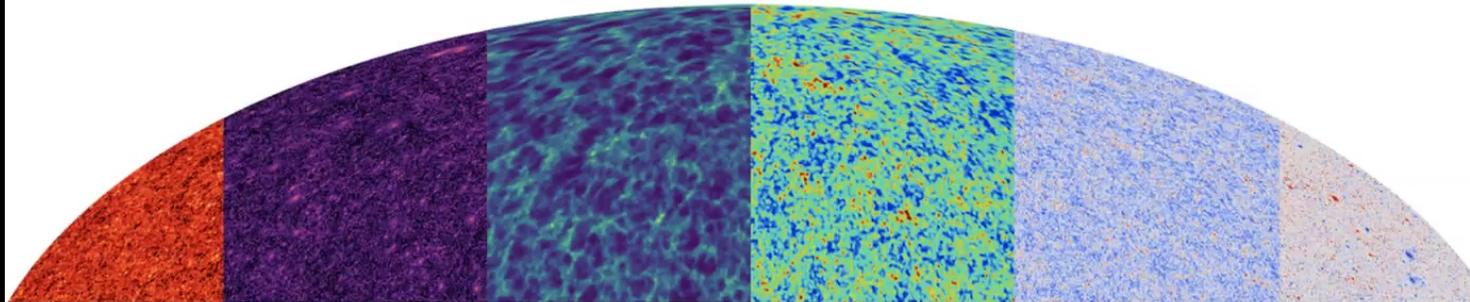
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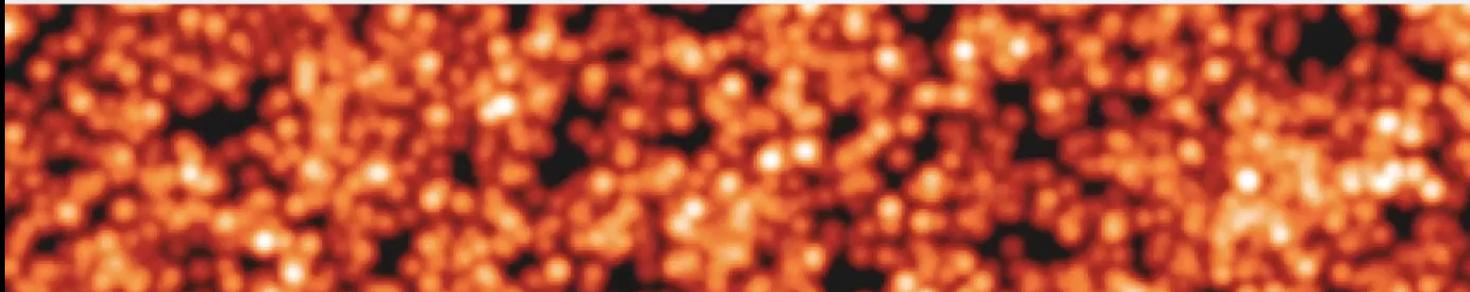
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**Probing reionization and structure formation
with CMB and multi-line intensity mapping**

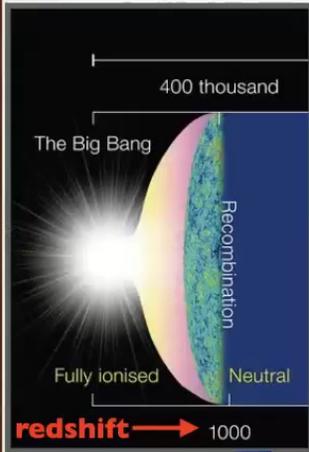
Anirban Roy

Research Associate
Cornell University



Probing the Universe

2



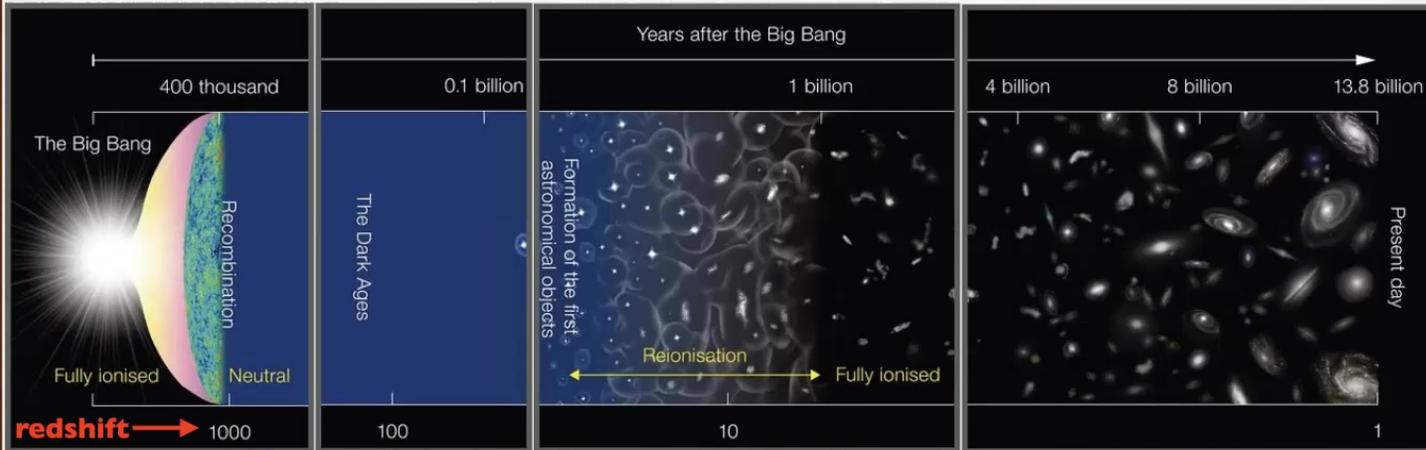
Cosmic Microwave Background



Observer

Probing the Universe

2



How could CMB be used to probe the late-time Universe?

Cosmic Microwave Background

21 cm, Ly-alpha

Galaxy surveys



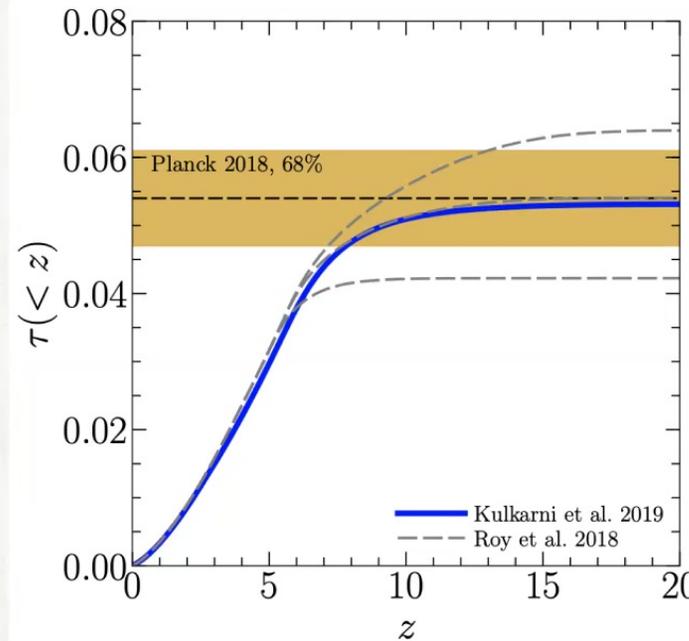
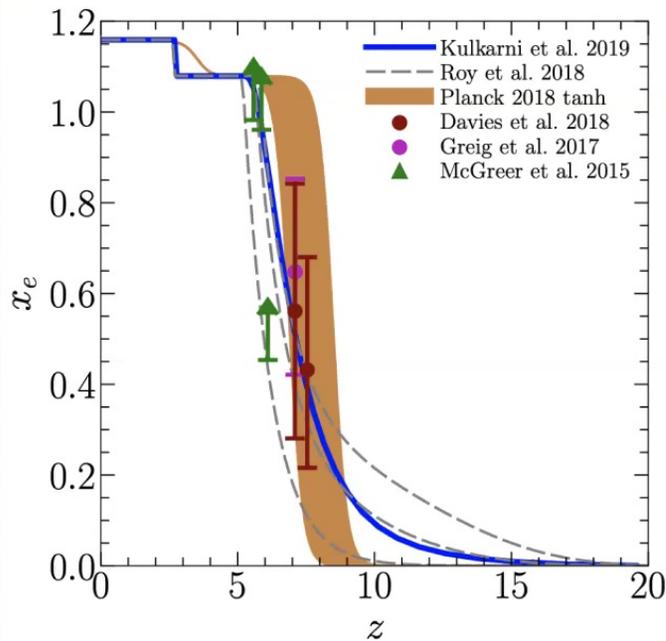
Observer

Ionization history

3



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A variety of observations (Lyman alpha, tau constraints from CMB, QSO near-zones...) suggests reionization is delayed.

Roy et al. 2021, Kulkarni et al. 2019

Probing reionization inside and out

4

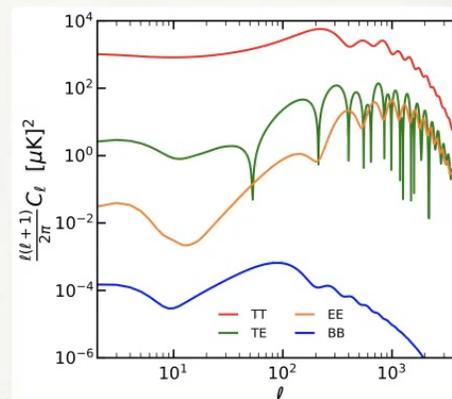
Potential of high resolution CMB

Sources of reionization

Number density of ionized bubbles

Temperature of IGM during EoR

Small-scale CMB fluctuations can unveil more about the reionization



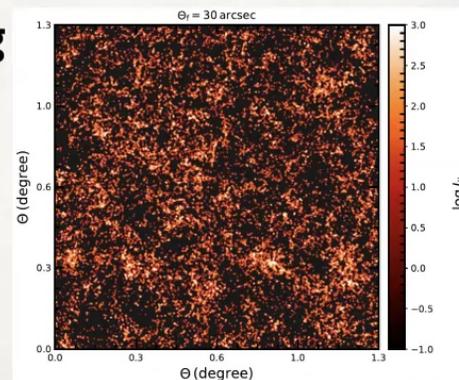
Potential of multi-line intensity mapping

ISM physics at high redshift

How does an intensity map trace LSS?

Morphology of reionization

Tomography using MLIM and a robust analysis of MLIM can shed light on these topics

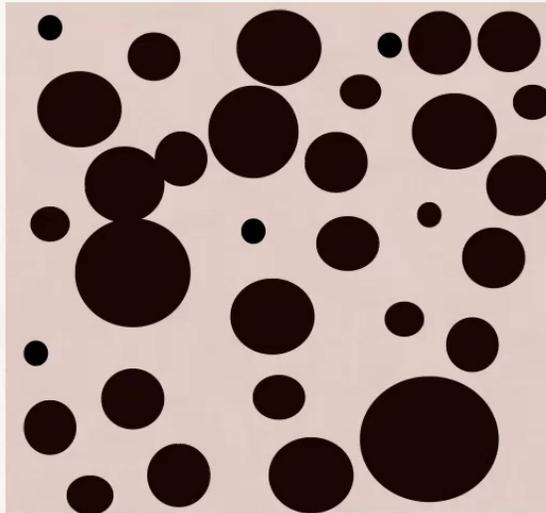


Patchy reionization

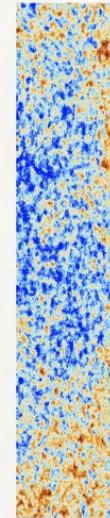
5



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$z \sim 7$



$z \sim 1100$

Imprints of reionization on CMB

screening

scattering

kinetic SZ

$$\tau(\hat{\mathbf{n}}, \chi) = \sigma_T \bar{n}_{p,0} \int_0^\chi \frac{d\chi'}{a^2} [\bar{x}_e(\chi') + \Delta x_e(\hat{\mathbf{n}}, \chi')]$$

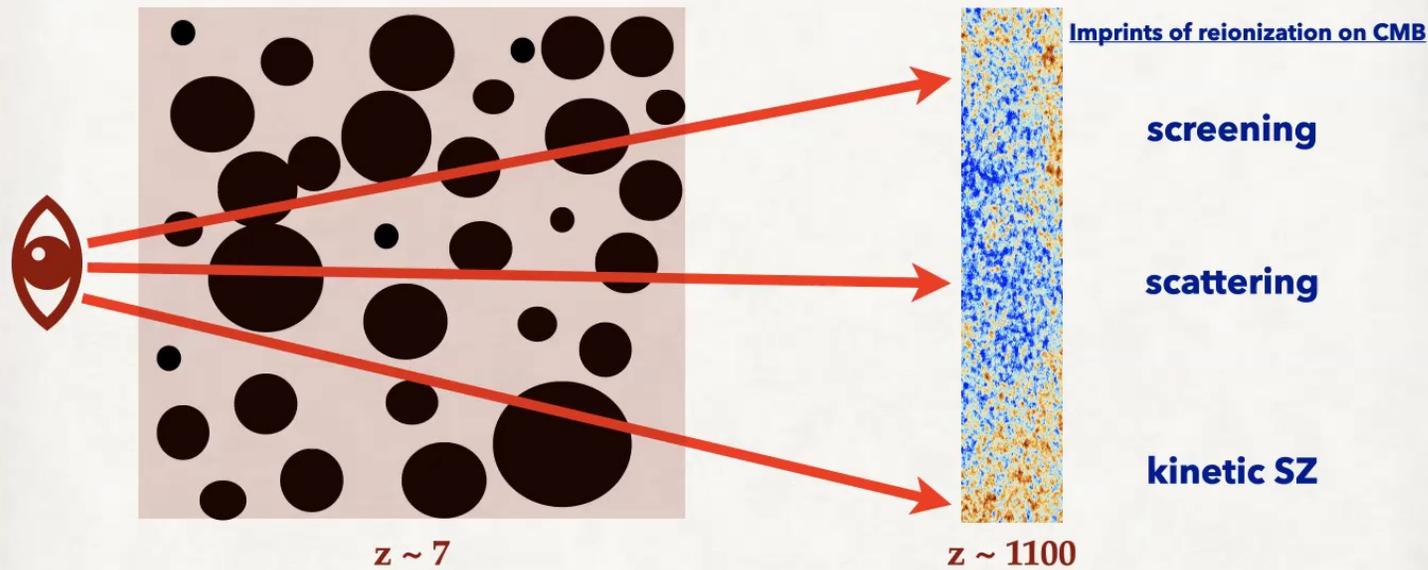
Roy et al. 2018, Namikawa 2018,
Ferraro & Smith 2017, Dvorkin & Smith 2009

Patchy reionization

5



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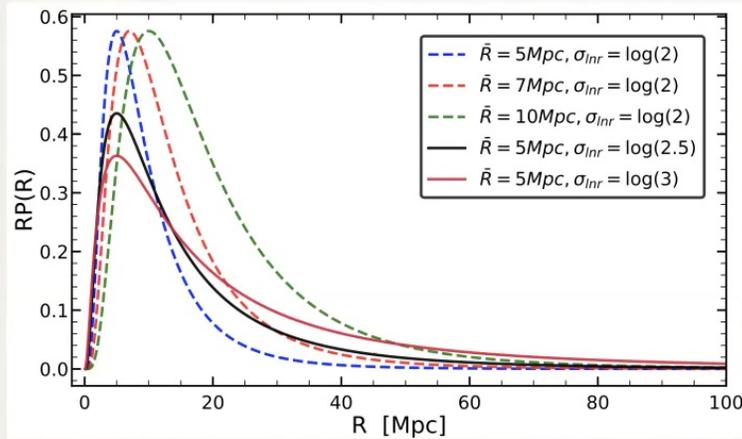
Roy et al. 2018, Namikawa 2018,
Ferraro & Smith 2017, Dvorkin & Smith 2009

Modeling patchy reionization

6



Toy Model

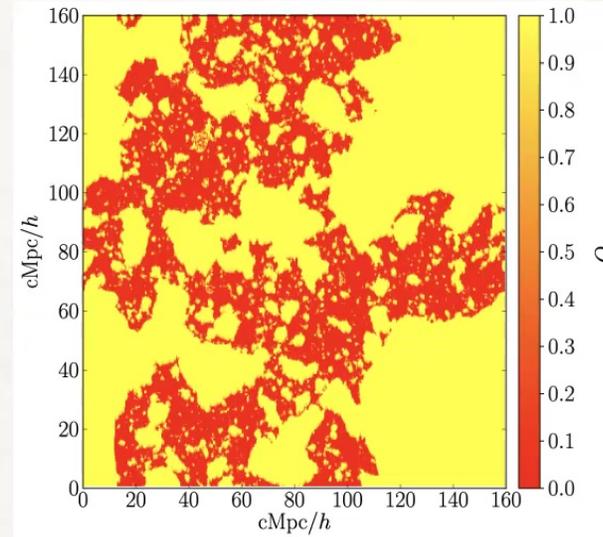


$$P(R) = \frac{1}{R} \frac{1}{\sqrt{2\pi\sigma_{lnr}^2}} \exp\left[-\frac{\{\ln(R/\bar{R})\}^2}{2\sigma_{lnr}^2}\right]$$

Spread in the bubble distribution

Characteristic bubble size

Numerical



Excursion set

Inferring the statistics of ionized bubbles from radiative transfer simulations is **not** straightforward.

Wang & Hu 2006, Furlanetto et al. 2004

Tau fluctuations

8



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

Reconstructed signal

Astrophysical aspects
of Reionization

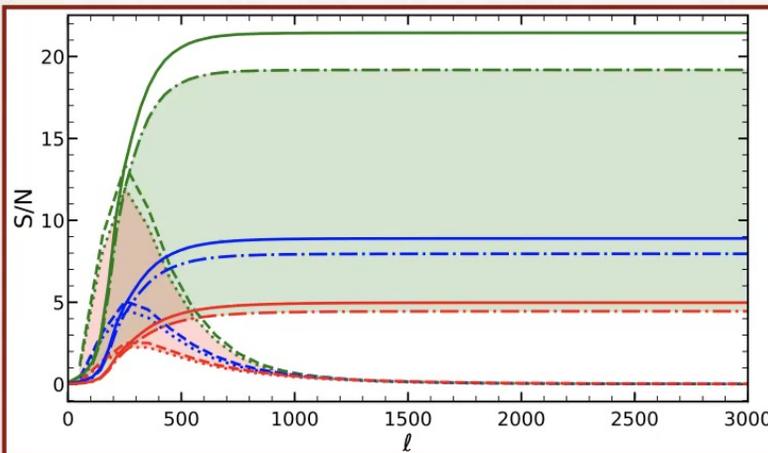
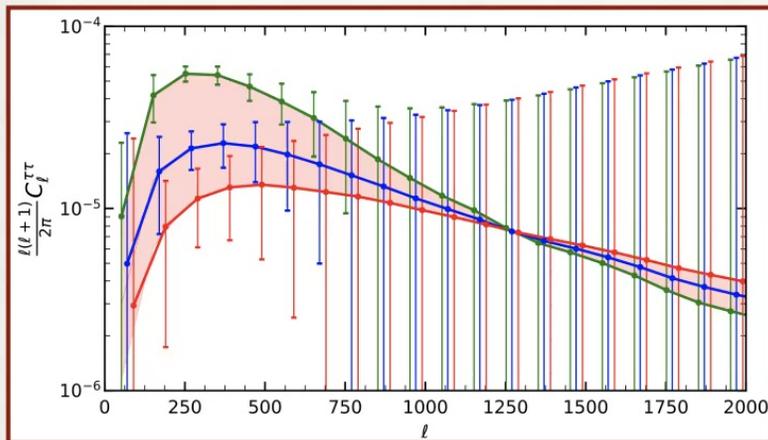
Cosmological Signal

$$C_{\ell}^{\text{BB}} = \frac{3}{100} \int \left[\frac{g(\chi)}{x_e(\chi)} \right]^2 Q_{\text{rms}(\chi)}^2 P_{x_e x_e}(k, \chi) d\chi$$

Hu 2000, Dvorkin & Smith 2009

Detectability

10



$$\tau = 0.058$$

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

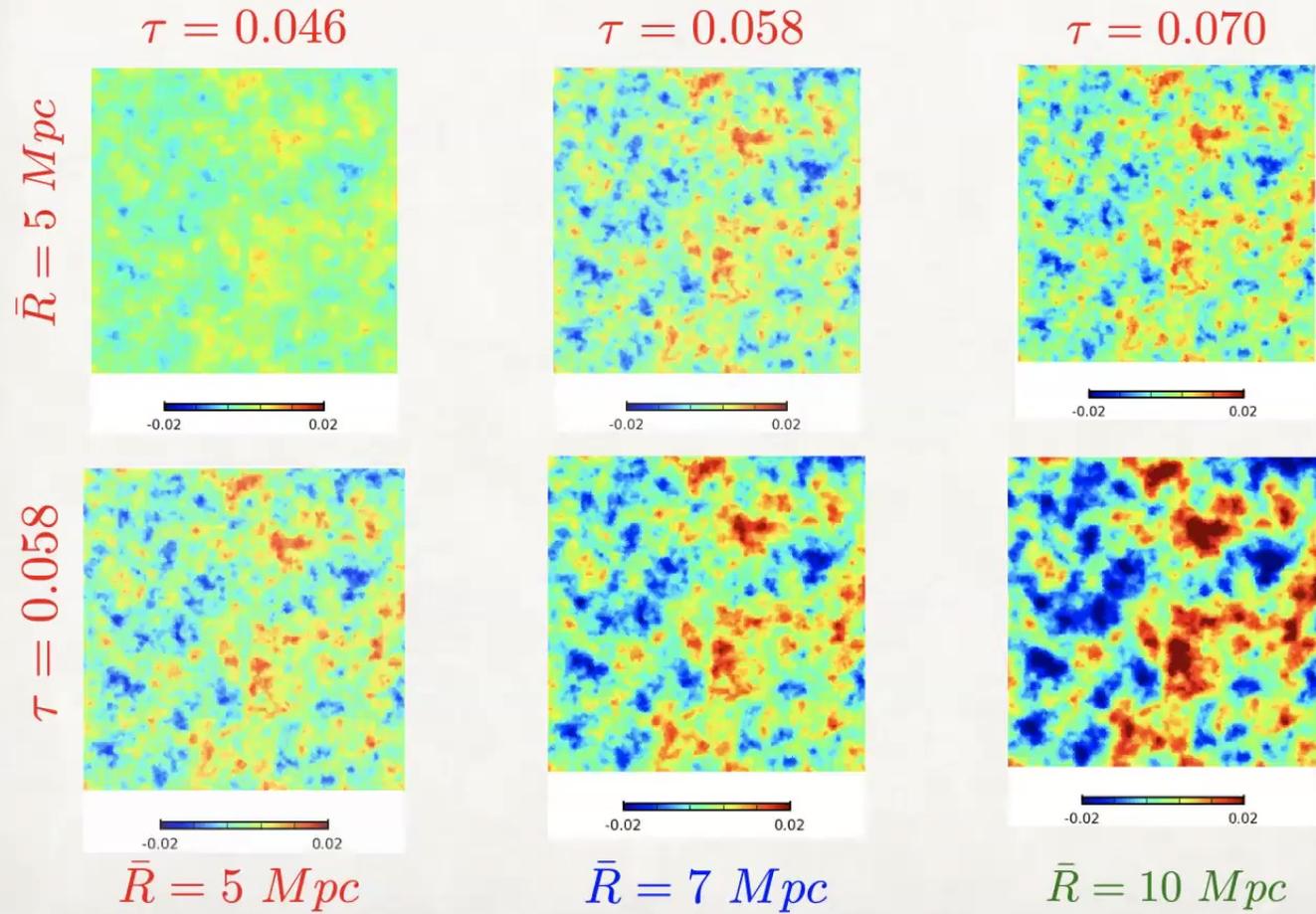
$$\bar{R} = 7 Mpc$$

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

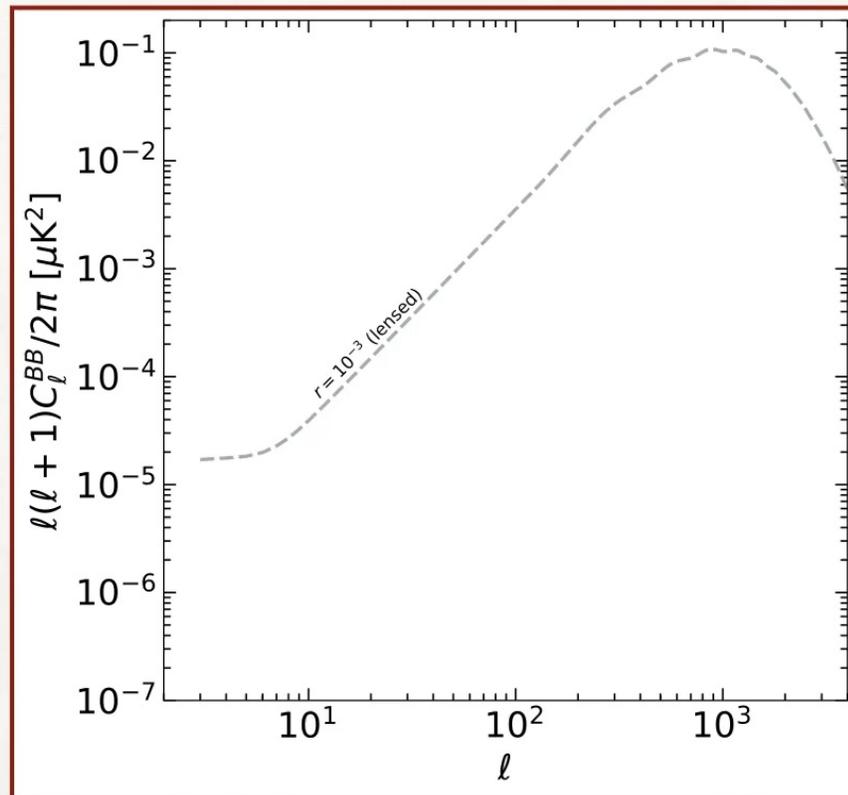
Roy et al. 2018

Maps of optical depth

11



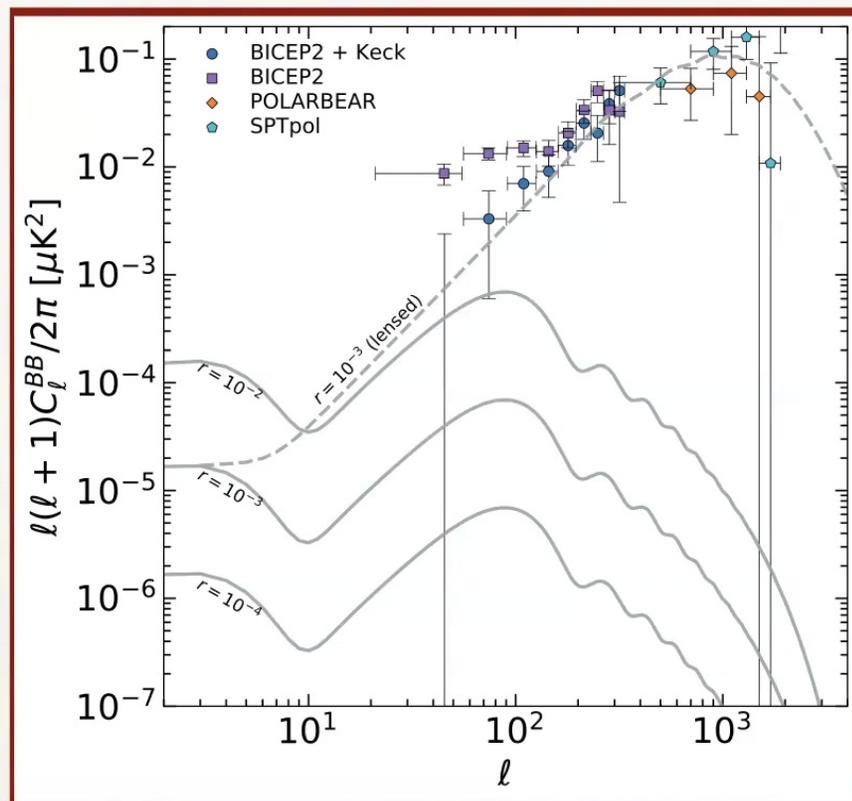
B modes in a nutshell



Roy, Kulkarni, Meerburg et al. 2021,
Mukherjee et al. 2019, Namikawa 2018



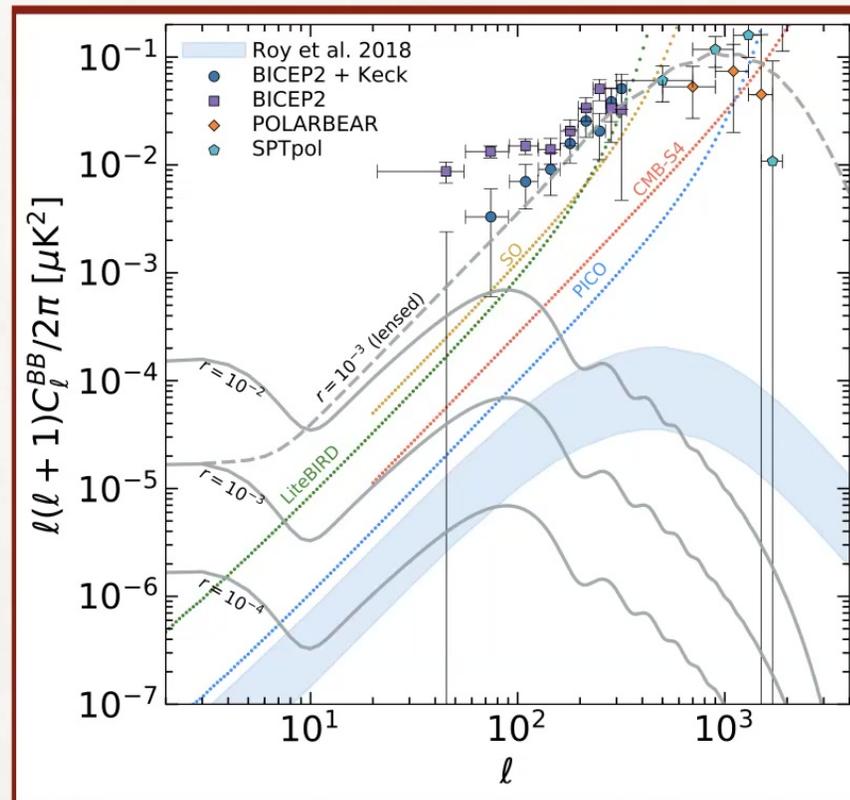
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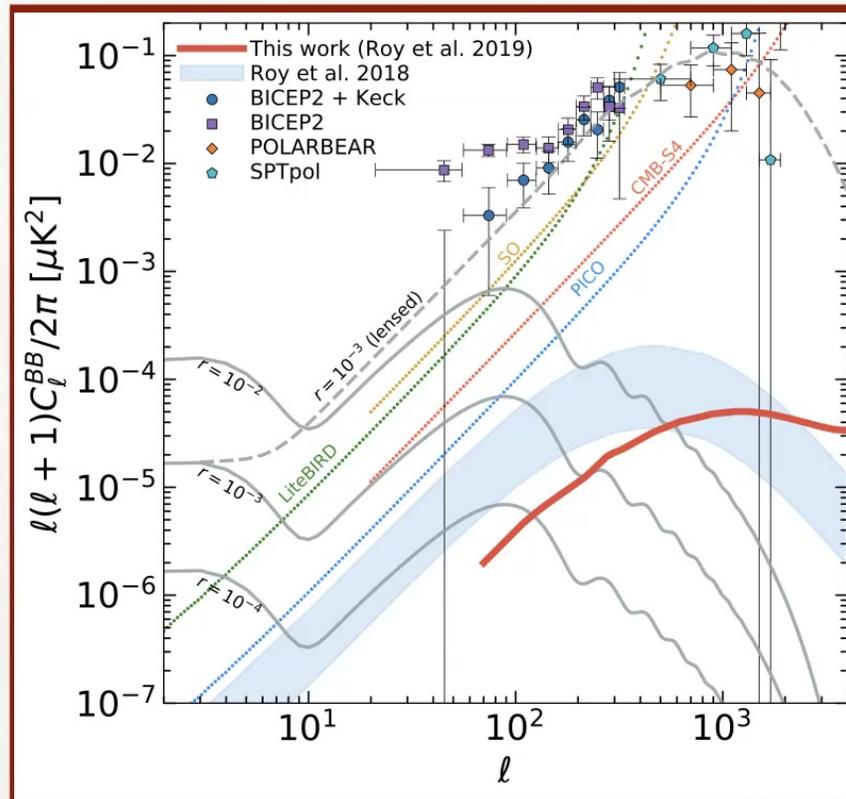
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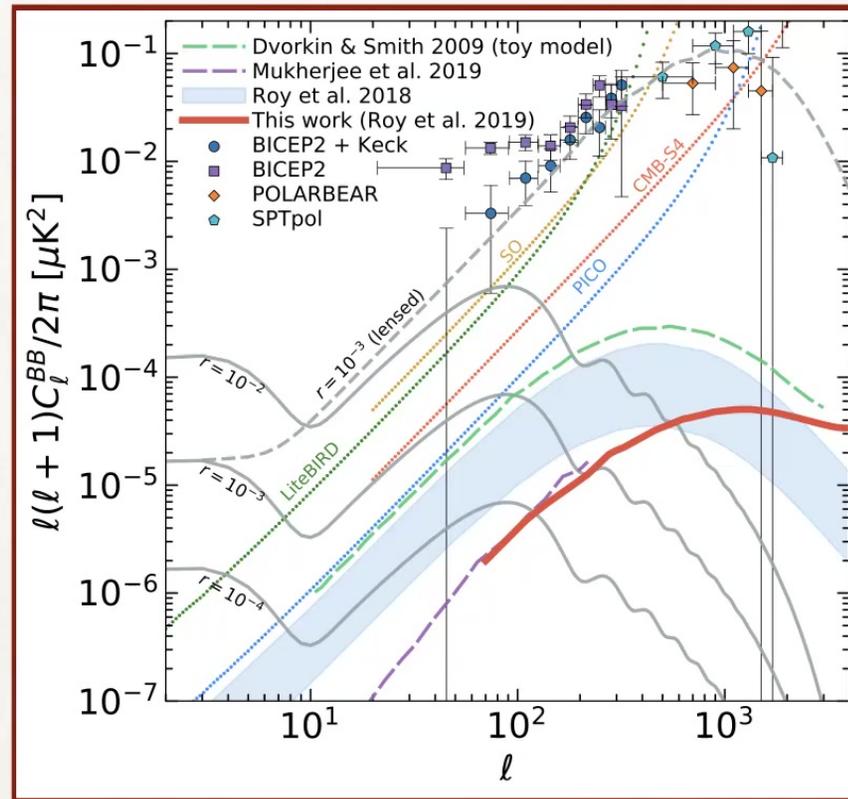
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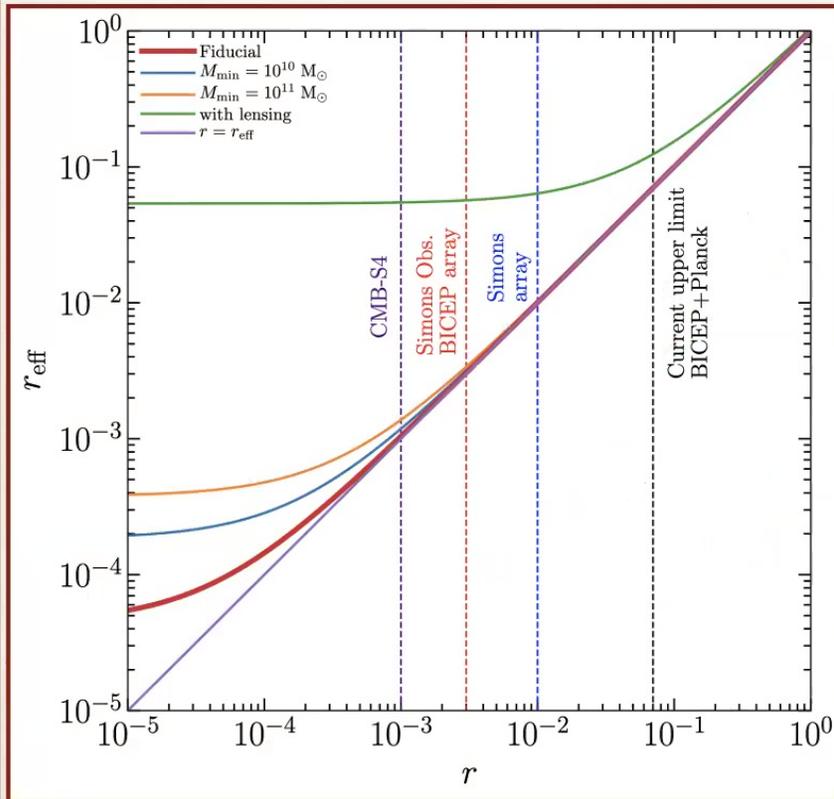
Roy, Kulkarni, Meerburg et al. 2021,
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Bias due to the patchy reionization



Anirban Roy



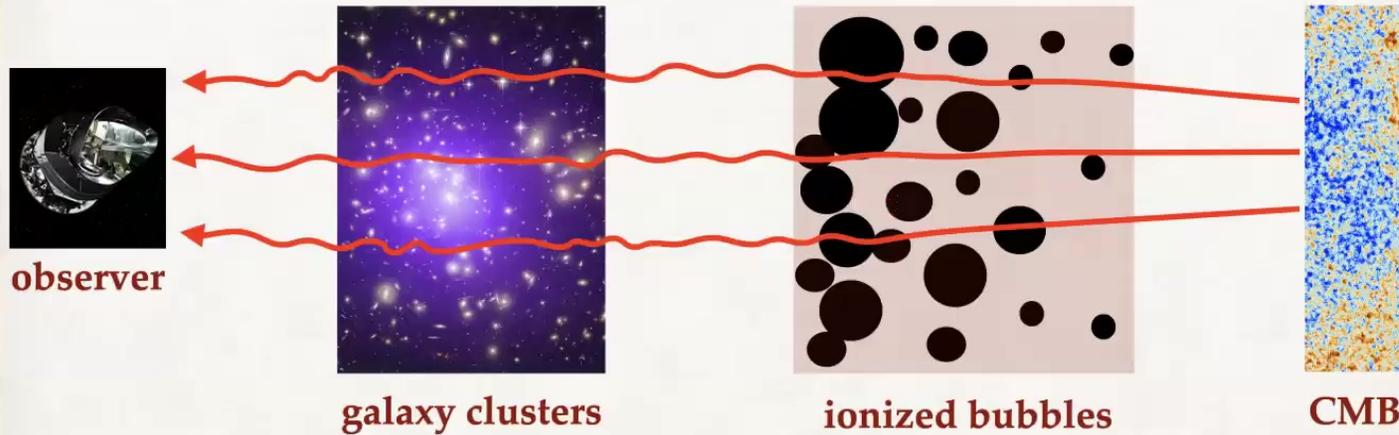
For which “r”, patchy B-mode signal can contaminate primordial B-mode signal?

$$\sum_{\ell'_{\min}}^{\ell'_{\max}} C_{\ell}^{BB}(r_{\text{eff}}) = \sum_{\ell'_{\min}}^{\ell'_{\max}} C_{\ell}^{BB}(r) + \sum_{\ell'_{\min}}^{\ell'_{\max}} C_{\ell}^{BB(\text{sec})}$$

Roy, Kulkarni, Meerburg et al. 2021

TSZ from reionization and halos

14



$$y(\hat{n}) = \frac{\sigma_T}{m_e c^2} \int a k_B T_b(\hat{n}, \chi) n_e(\hat{n}, \chi)$$

$$C_l^{\tau\tau}(\text{reionization}) > C_l^{\tau\tau}(\text{halos})$$

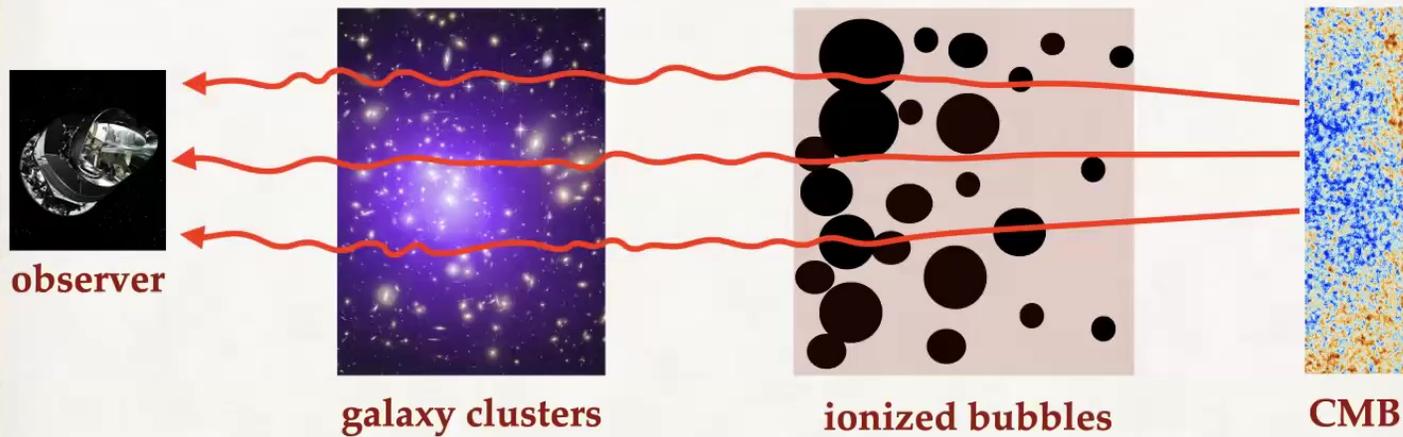
$$C_l^{yy}(\text{reionization}) \ll C_l^{yy}(\text{halos})$$

TSZ from reionization and halos

14



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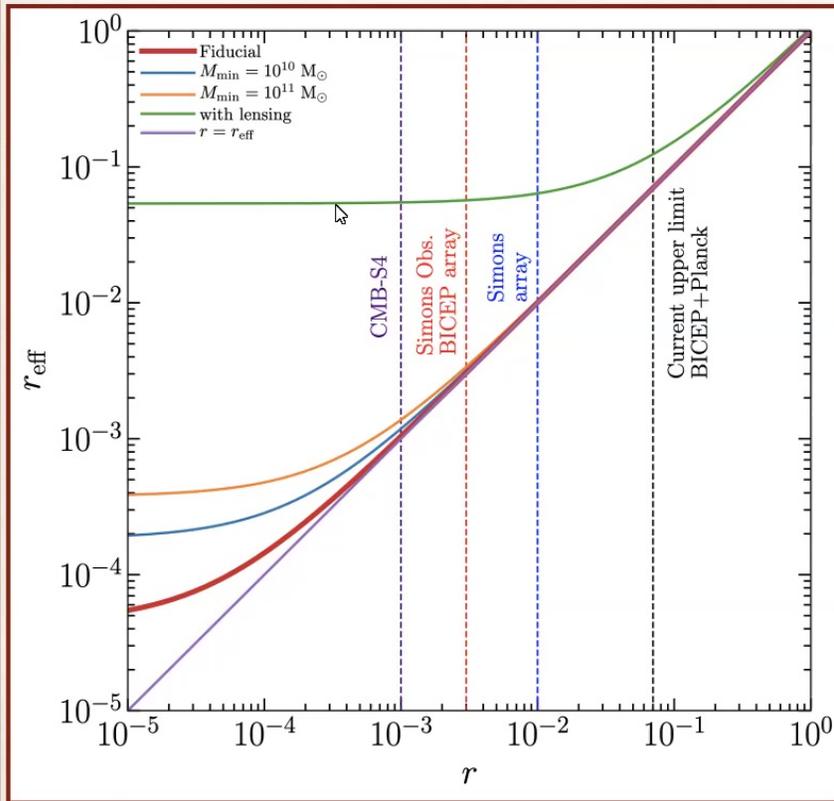
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Can we measure the tau-y cross-correlation?

Bias due to the patchy reionization



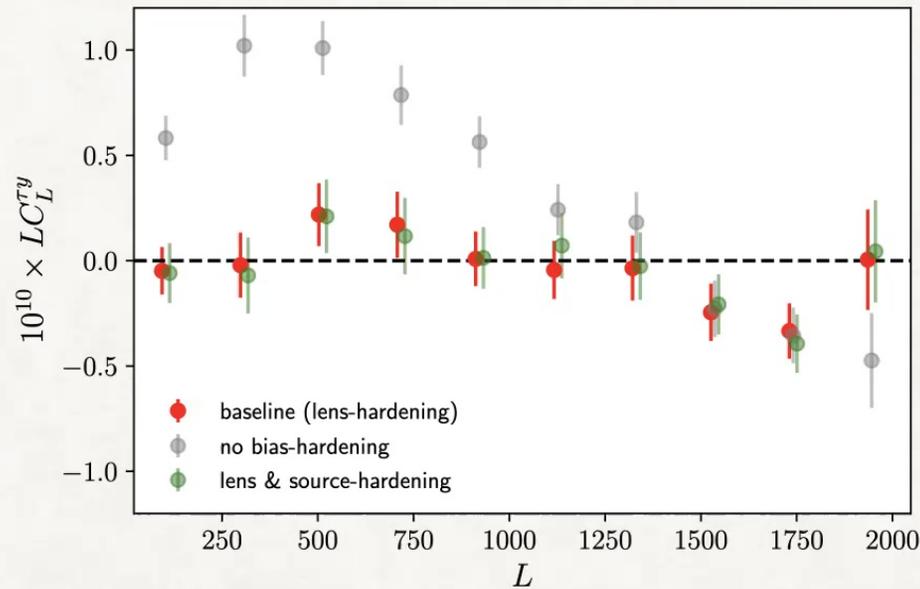
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Roy, Kulkarni, Meerburg et al. 2021

Measurements of tau-y

15



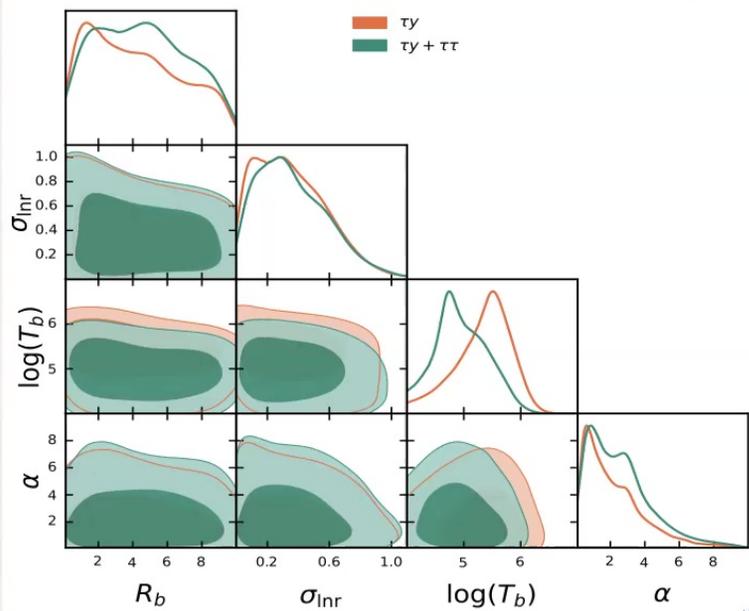
$$C_l^{\tau y} = \frac{k_B \sigma_T^2 n_{p0}^2}{m_e c^2} \int \frac{\chi}{a^4 \chi^2} \underbrace{T_e(\chi)} P_{x_e x_e} \left(k = \frac{L+1/2}{\chi}, \chi \right)$$

Temperature of ionized bubbles

Namikawa, Roy et al. 2021

Constraints on reionization parameters

16



Priors on R_b	[0.01, 10]	[0.01, 50]	
Parameters	$C_L^{\tau y}$	$C_L^{\tau y} + C_L^{\tau \tau}$	$C_L^{\tau y}$
R_b	9.4	9.5	23.1
σ_{Inr}	0.81	0.83	0.74
$\log(T_b)$	6.11	5.85	6.05
α	5.8	6.3	6.16

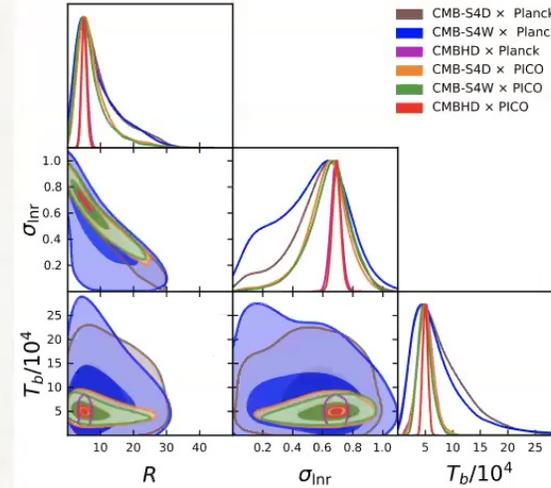
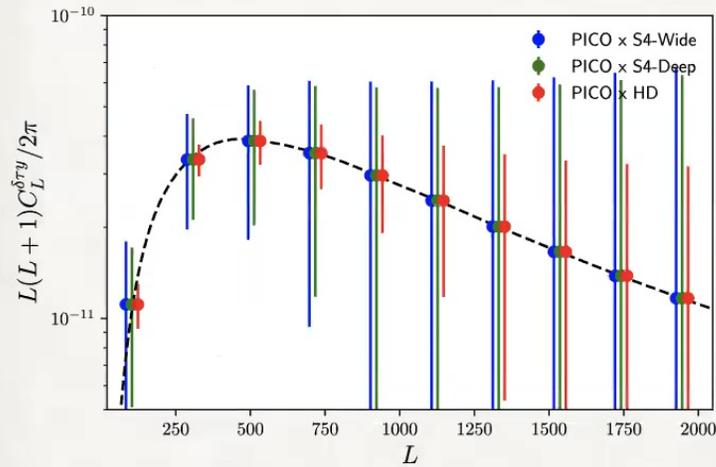
normalization

$$C_l^{\tau y(\text{total})} = C_l^{\tau y(\text{reio})} + \frac{1}{\alpha} \times C_l^{\tau y(\text{halos})}$$

Namikawa, Roy et al. 2021,
Battaglia 2016

Forecasts for future CMB experiments

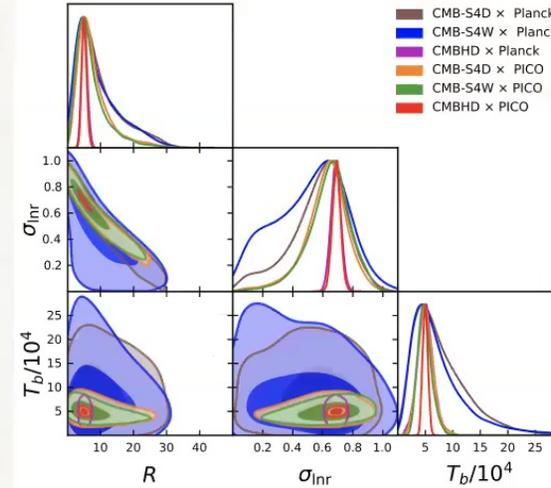
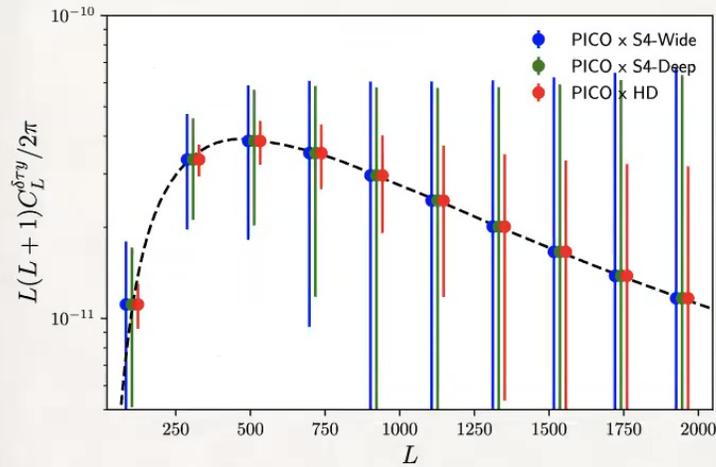
17



Experiments	R_b [Mpc]	σ_{lnr}	T_b [K]
S4-Deep × Planck	$9.5^{+2.4}_{-7.8}$	$0.57^{+0.22}_{-0.13}$	77000^{+23000}_{-60000}
S4-Wide × Planck	$9.0^{+2.7}_{-7.9}$	$0.51^{+0.29}_{-0.20}$	80000^{+13000}_{-63000}
HD × Planck	$5.19^{+0.77}_{-0.96}$	$0.688^{+0.034}_{-0.034}$	50800^{+14000}_{-13000}
S4-Deep × PICO	$7.9^{+1.7}_{-5.7}$	$0.62^{+0.15}_{-0.11}$	51000^{+12000}_{-16000}
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Forecasts for future CMB experiments

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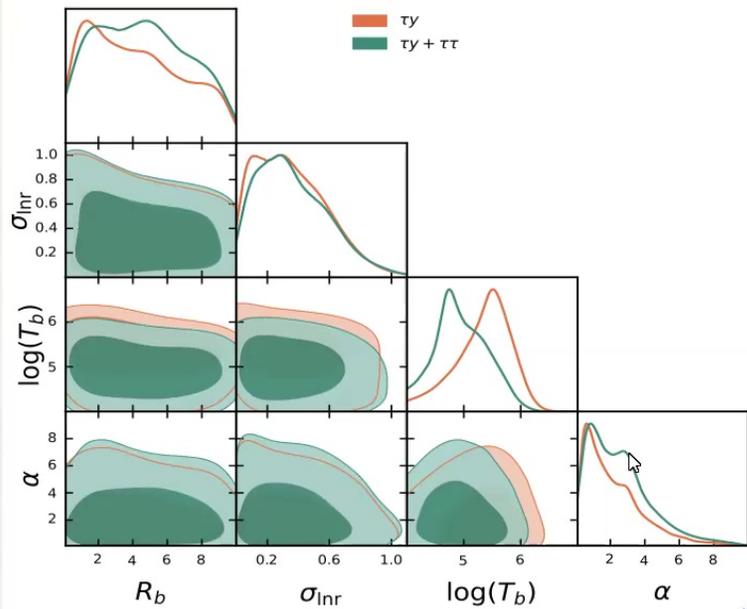
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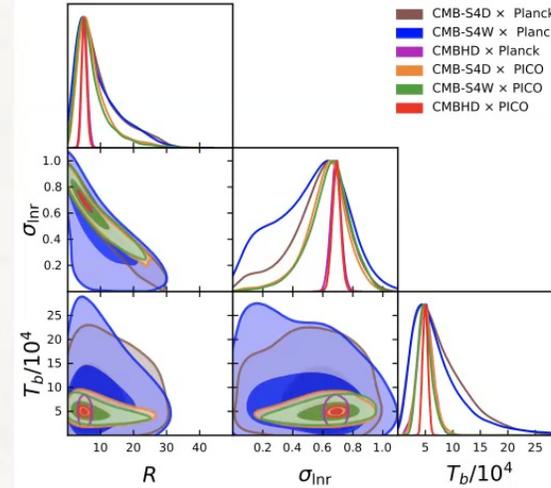
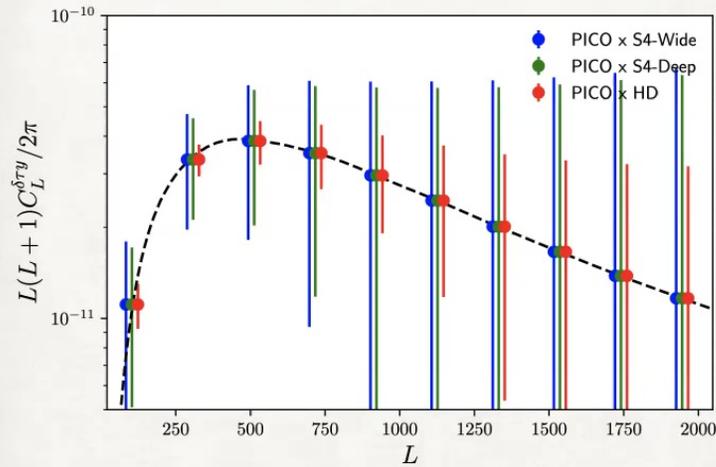
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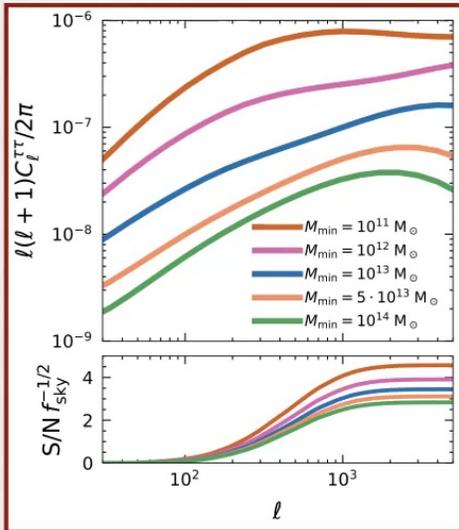
Cross-correlations

18

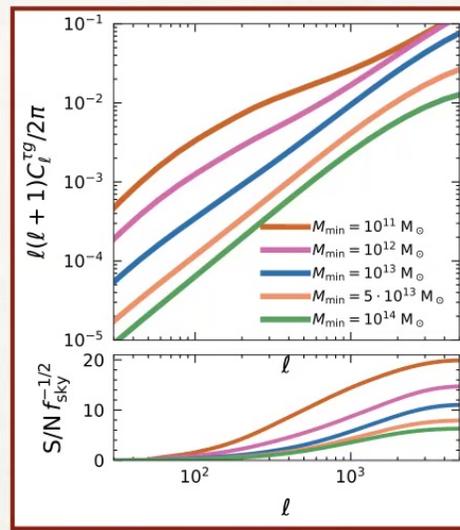


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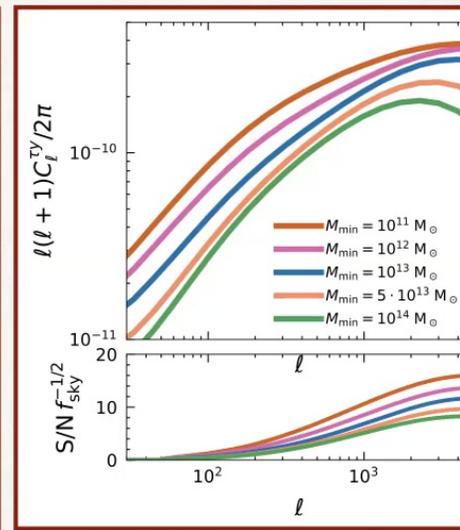
electron density



electron density - galaxies



electron density - pressure

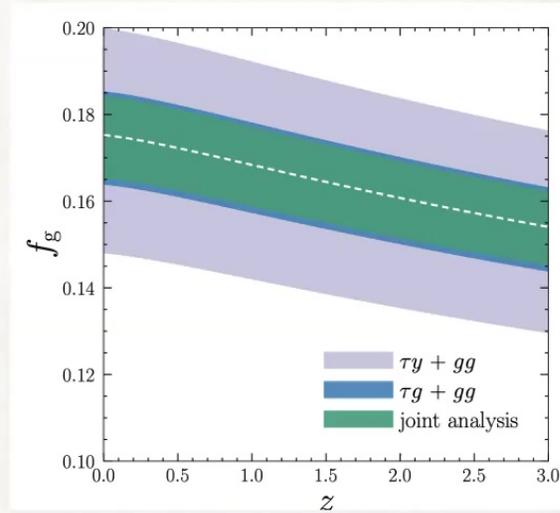
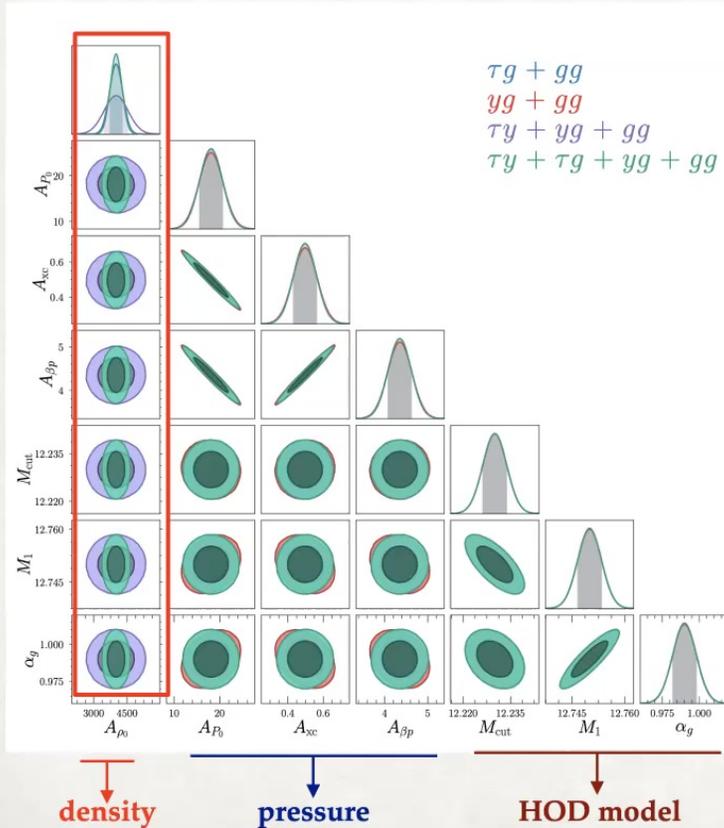


Can we measure the thermodynamic properties of galaxy clusters (and CGM) by the measurements of these cross-correlations?

Roy et al. 2022

Constraints on CGM

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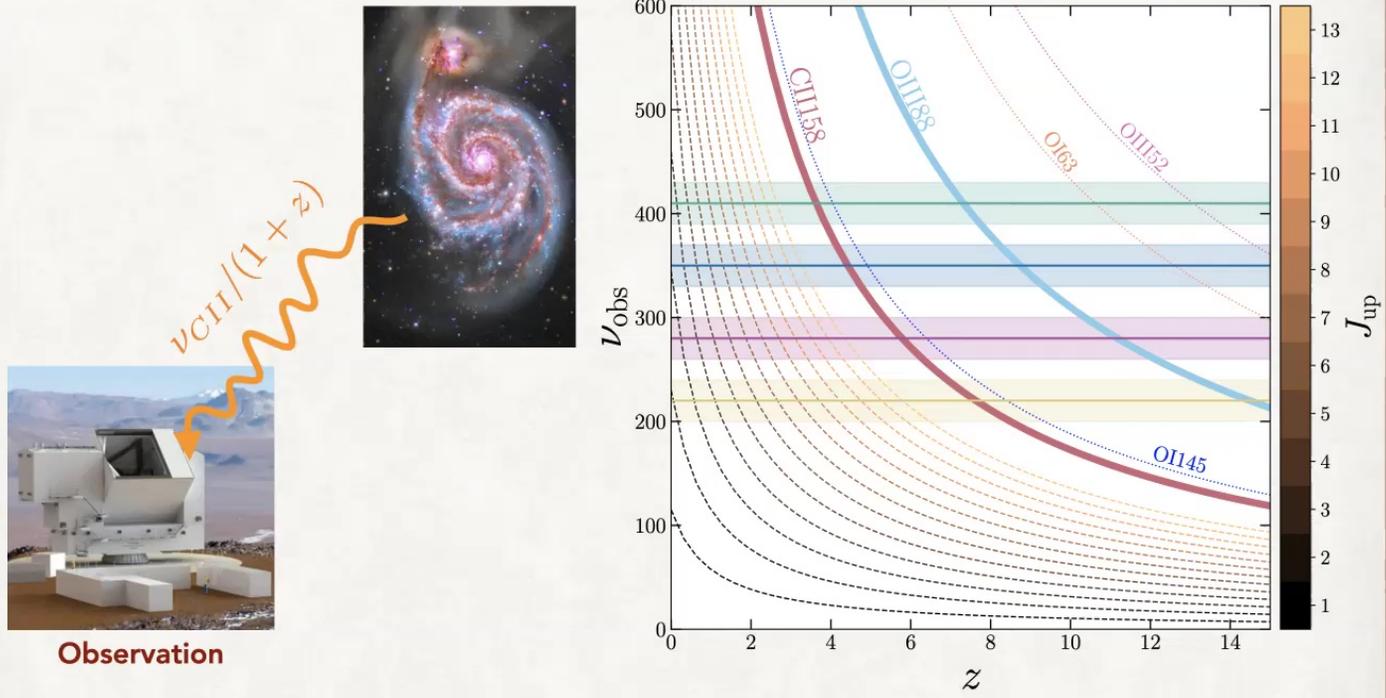


Constraints on the density and pressure profile translate into constraints on f_g (~ 7%).

Roy et al. 2022, Pandey et al. 2020

Multi-line intensity mapping

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Halos \longrightarrow star formation rate \longrightarrow Line luminosities

MLIM experiments

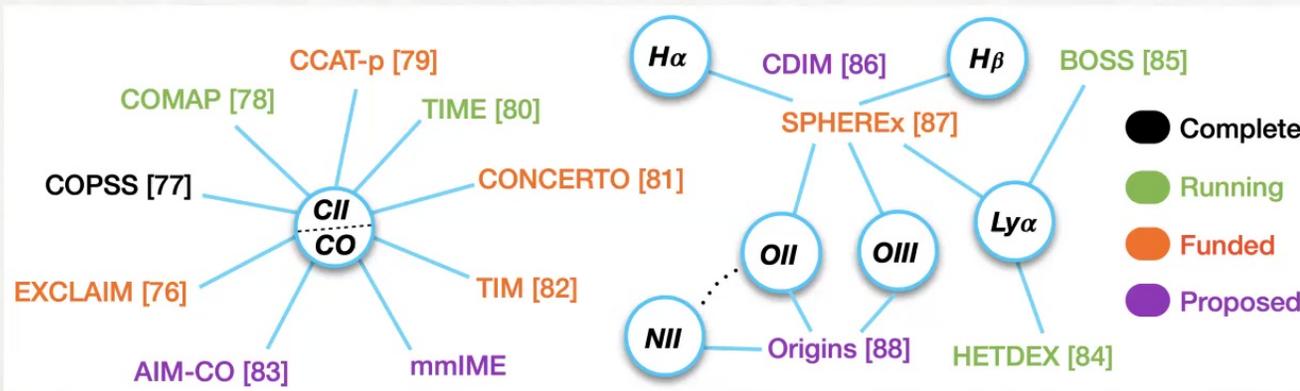
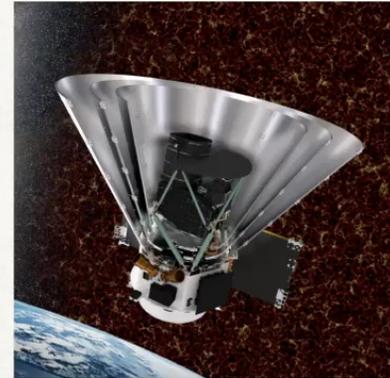
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CCAT-prime



SPHEREx



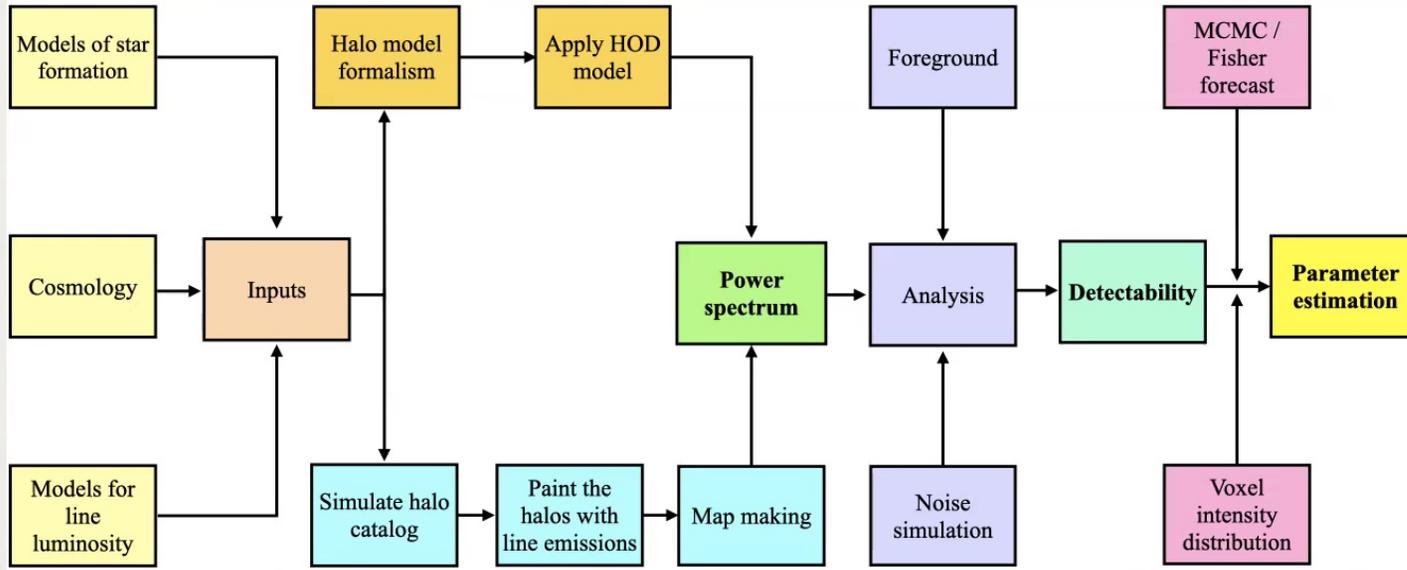
Kovetz et al. (2017)

Basic structure of LIMpy

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Modelling of all bright lines from $z \sim 0 - 10$.

Generate simulated intensity maps quickly for analysis.

Include varieties of model to study the foreground contamination.

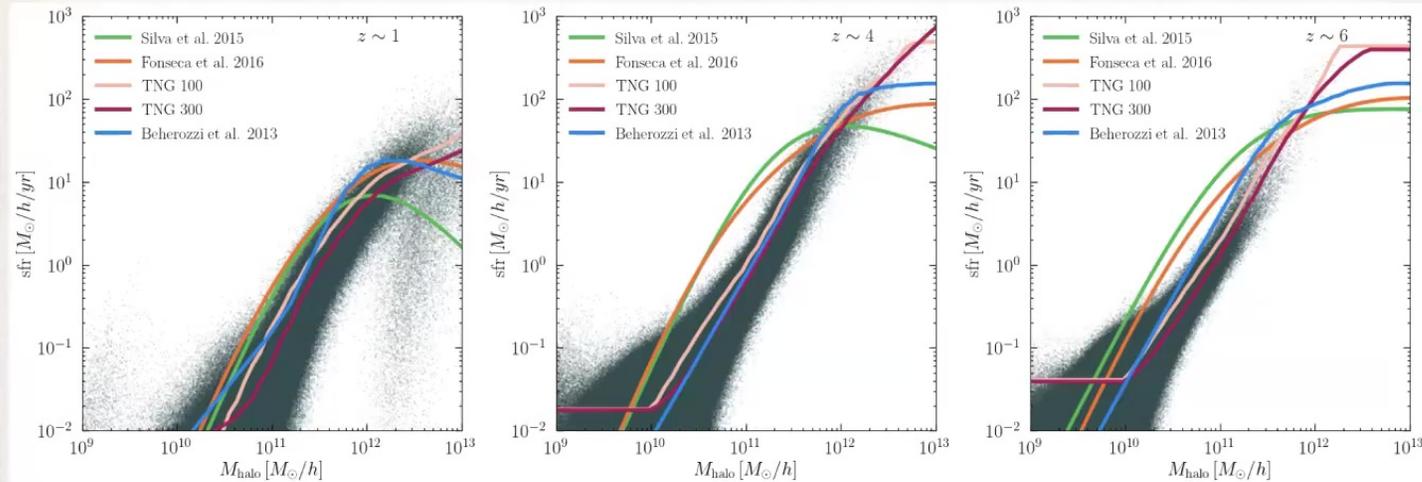
Roy et al. in preparation

Modelling of star formation rate

23



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$$SFR(M_{\text{halo}}, z)$$

Empirical

Simulation

Modelling of line luminosities

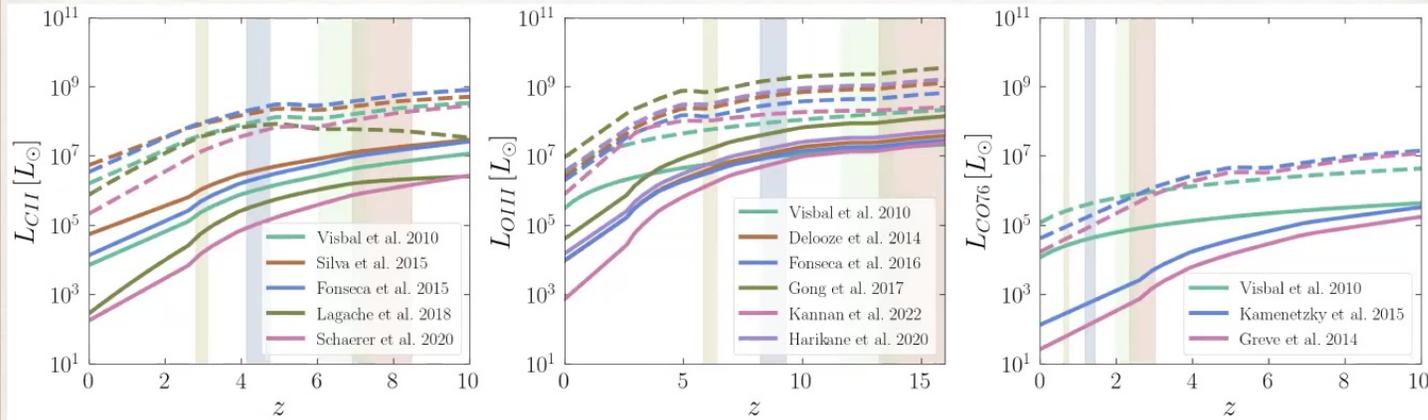
24



$$\log L_{CII\ 158} = \alpha \log \frac{sfr}{(M_{\odot}/yr)} + \beta$$

Solid: $M_{\text{halo}} = 10^{10} M_{\odot}/h$

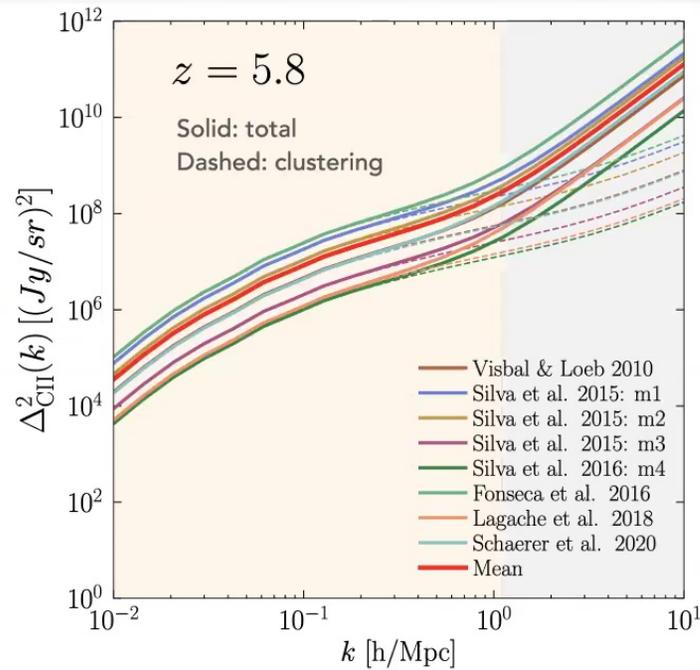
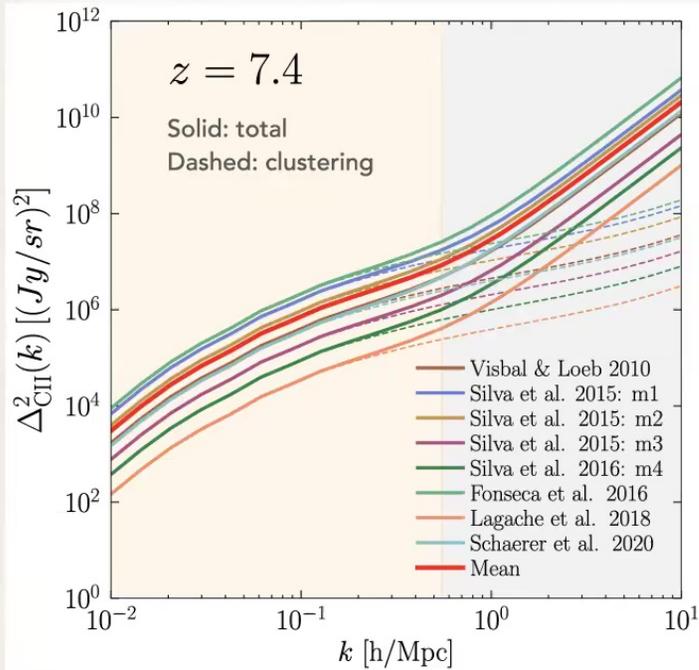
Dashed: $M_{\text{halo}} = 10^{11} M_{\odot}/h$



$$I_{\text{line}}(z) = \frac{c}{4\pi \nu_{\text{rest}} H(z_{\text{em}})} \int_{M_{\text{min}}}^{M_{\text{max}}} L_{\text{line}}(M, z) \frac{dn}{dM} dM$$

CII Power spectrum

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$$P^{\text{line}}(k, z) = A(z) + B(z) \times P_{\text{m}}(k, z)$$

↓
↓
↓
Shot noise **Clustering** **Matter PS**

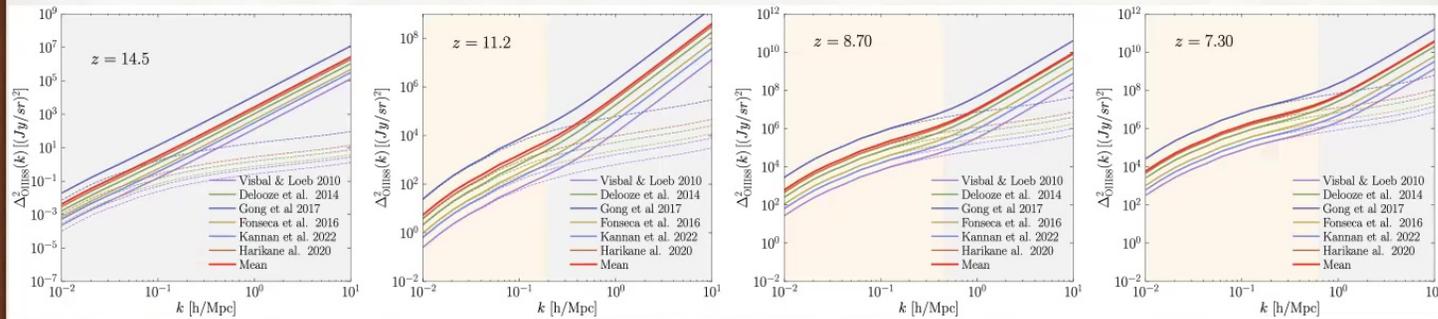
Power spectra (analytic)

26

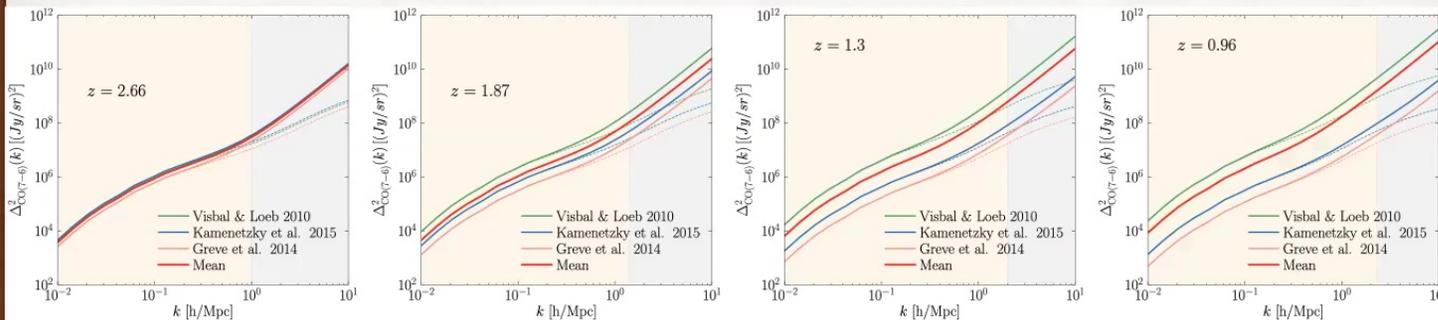


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[OIII]

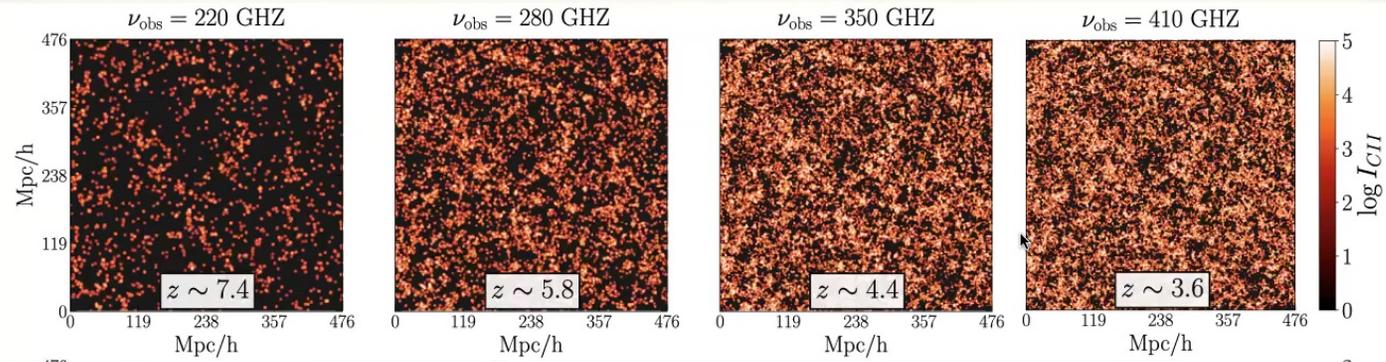


CO (7-6)



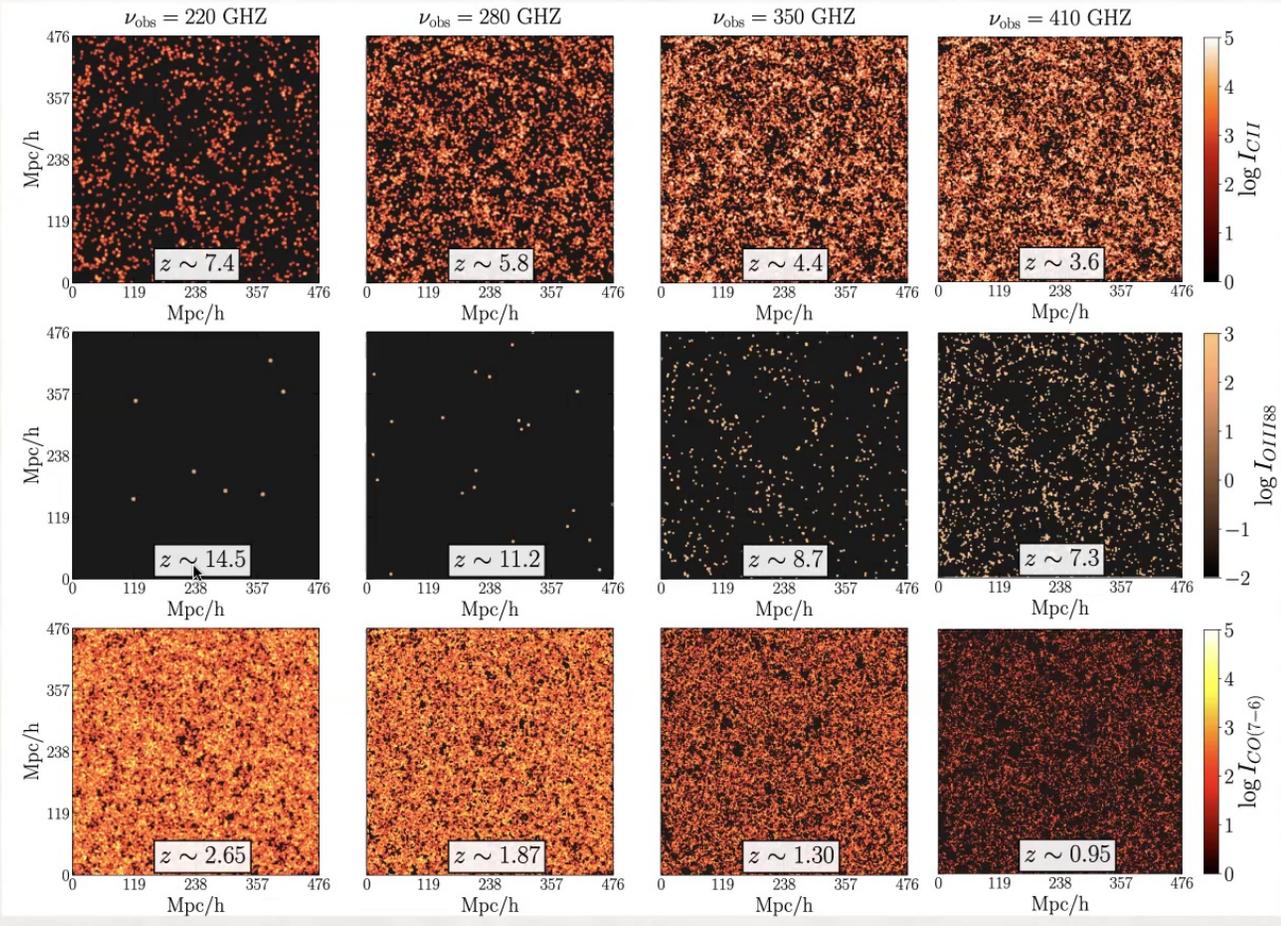
Simulations of MLIM

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Simulations of MLIM

28

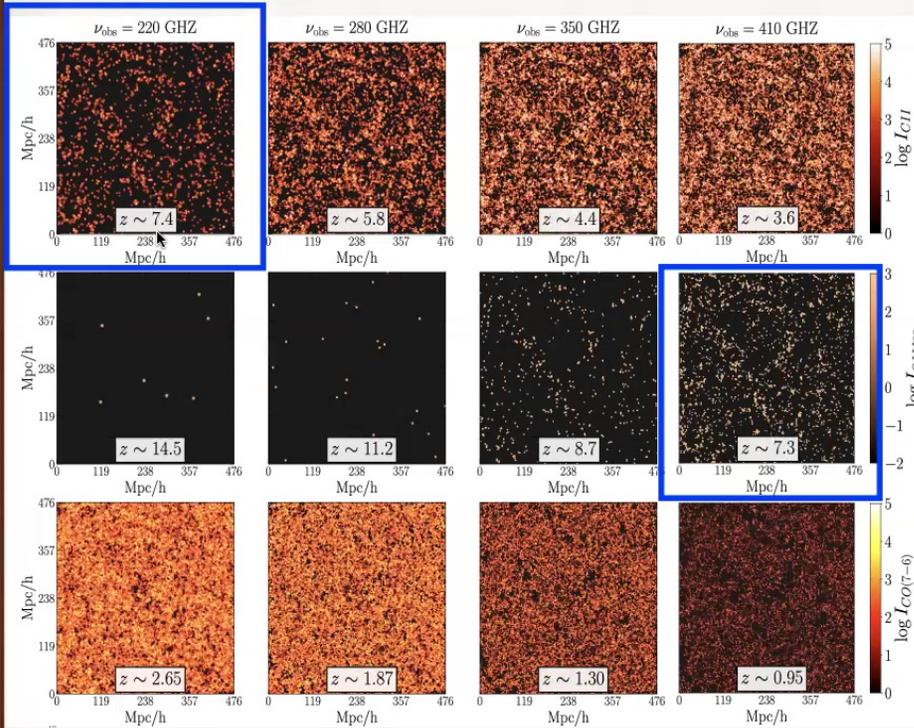


Cross-correlation studies

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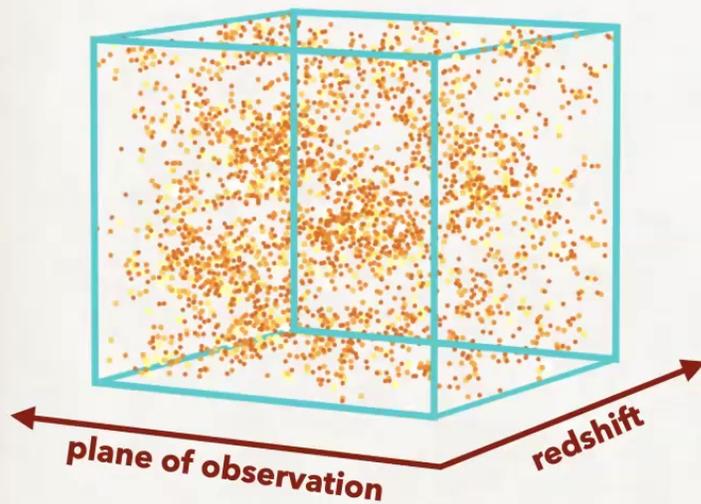
LIM -LIM cross-correlation
Helpful for removing interlopers
Estimation of cosmological parameters

LIM -CMB cross-correlation
Can break parameter degeneracies
Leads to multi-probe cosmology

LIM - galaxy cross-correlation
Useful for component separation
Explores ISM physics over a broad redshift range

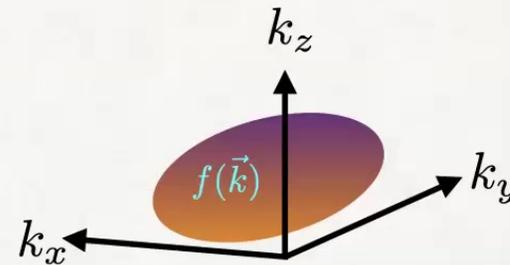


Simulations

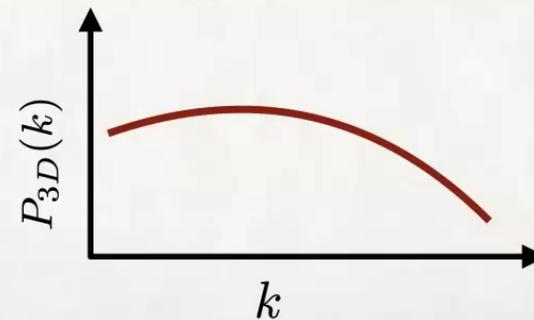


$L = 80 Mpc$
 $\nu_{\text{obs}} = 280 GHz$
 $z_{\text{obs}} = 5.8$
 $M_{\text{min}} = 10^{11} M_{\odot}$

Statistical properties



$$k = \sqrt{k_x^2 + k_y^2 + k_z^2}$$

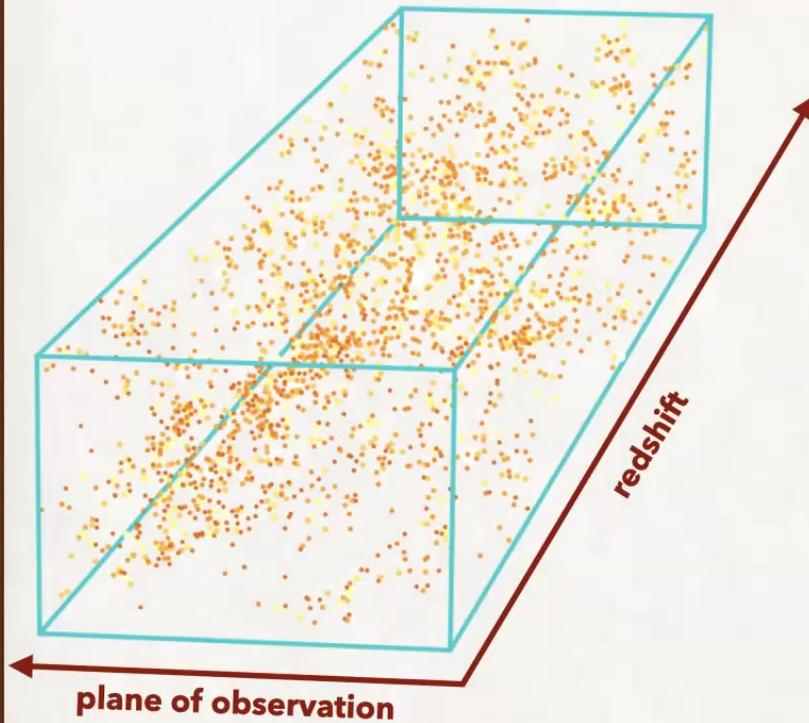


LIM observations

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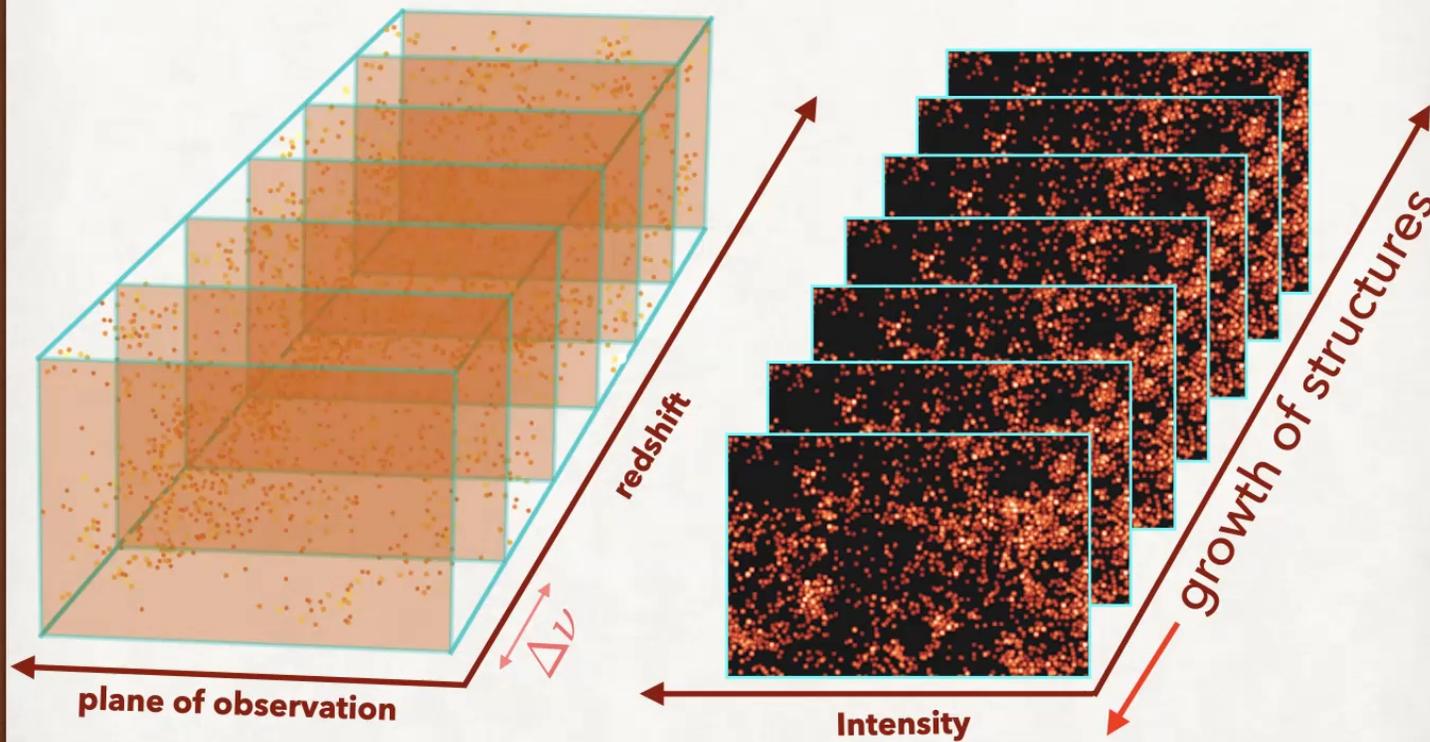
Simulations are done using LIMpy (Roy, Battaglia et al. in prep)

LIM observations

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How to analyze the LIM dataset to extract maximum information encoded in it?

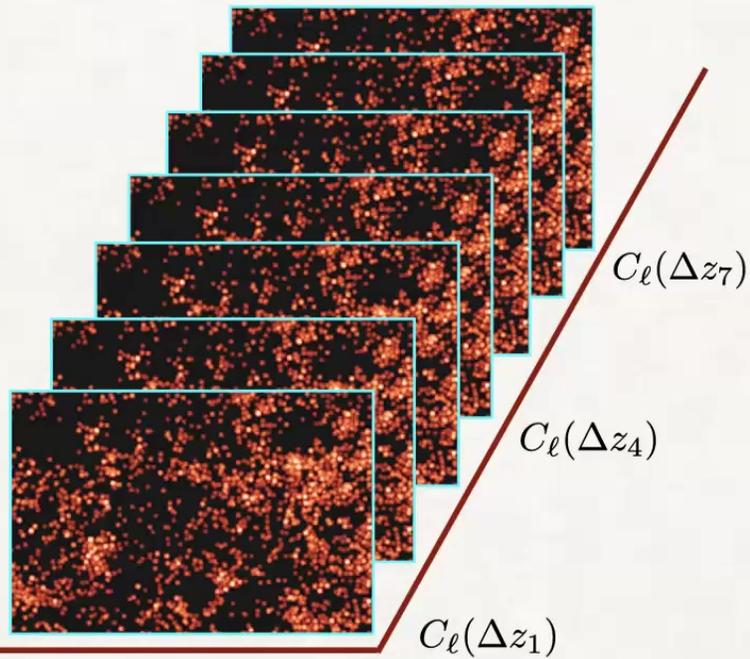
LIM observations

33



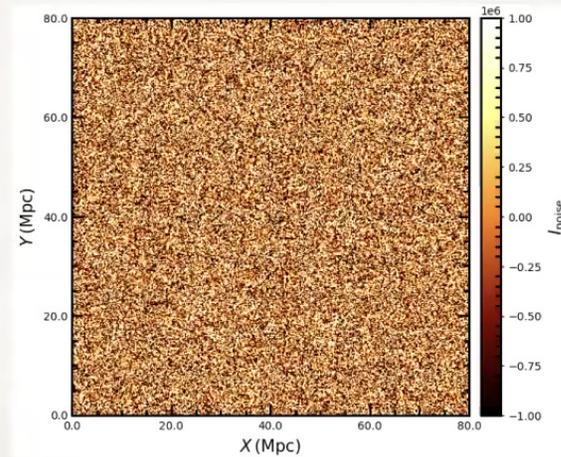
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signal



white noise

3D Gaussian
noise sims



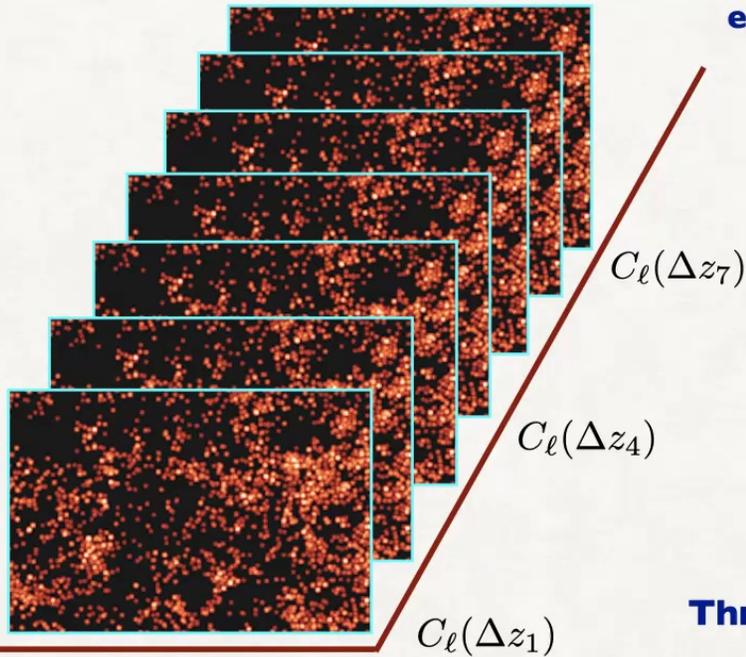
$$C_\ell(\Delta z_i) = \frac{P_{2D}(k_{2D}, \Delta z_i)}{\chi_i^2}$$

LIM observations

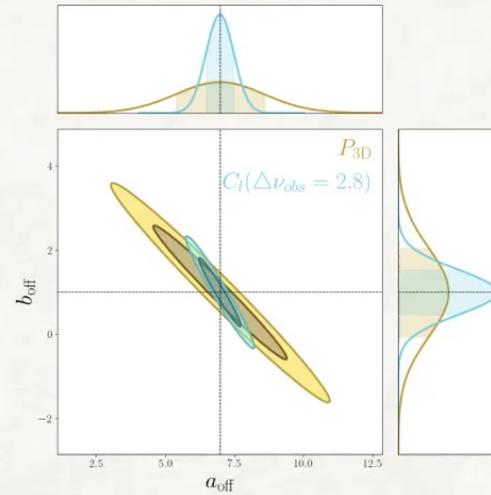
34



signal



How to analyze the LIM dataset to extract maximum information encoded in it?

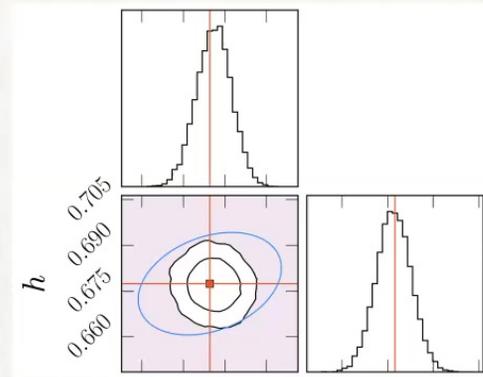
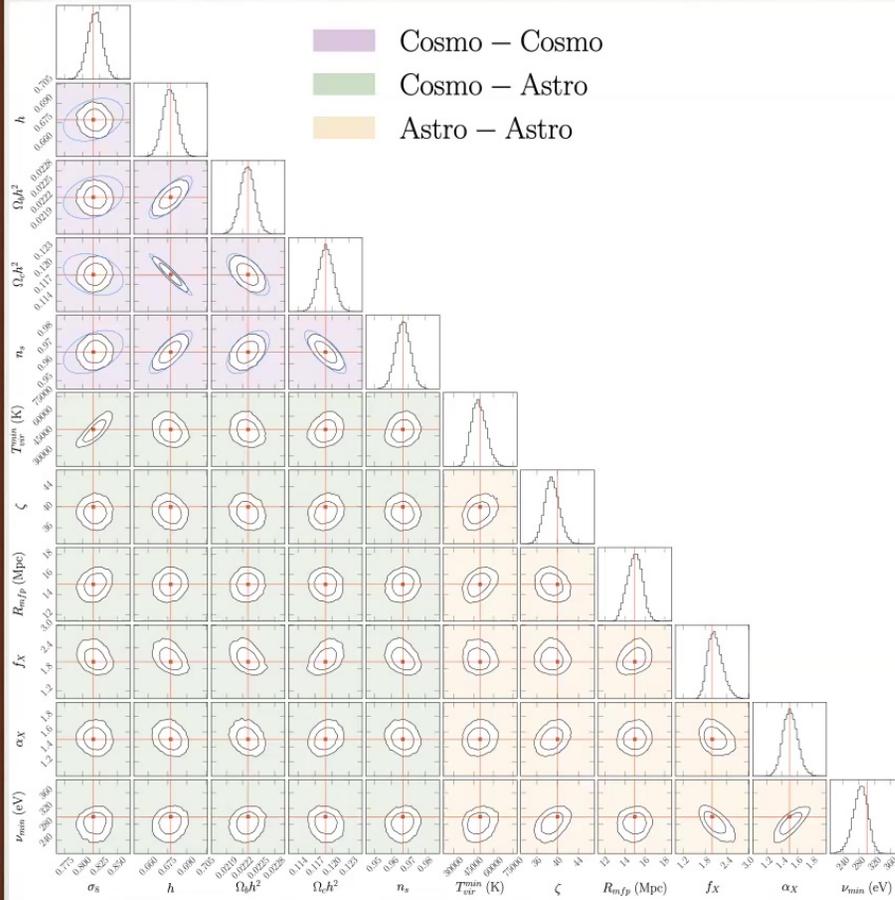


Three dimensional power spectrum
 Angular power spectrum
 Voxel Intensity distribution
 Likelihood free inference
 Nearest k-neighbor

$$C_\ell(\Delta z_i) = \frac{P_{2D}(k_{2D}, \Delta z_i)}{\chi_i^2}$$

What do we learn?

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Adding LIM data will improve the constraints on cosmological parameters

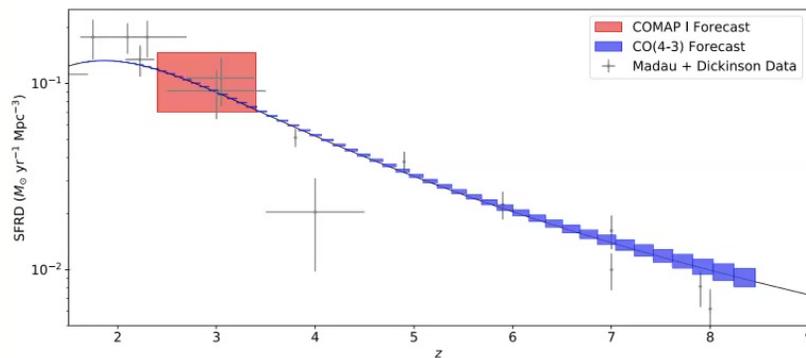
Kovetz et al. (2017)

What do we learn?

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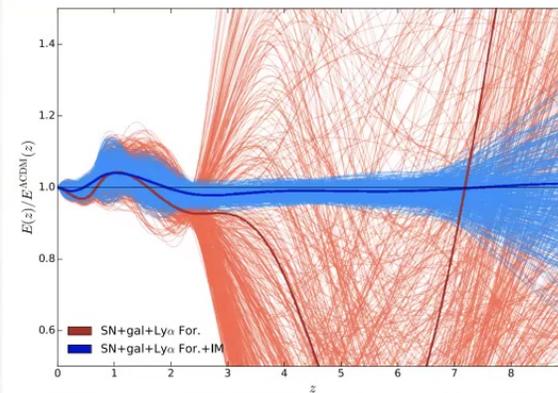


Astrophysics



Sources of reionization
ISM physics
Star formation history

Cosmology



Cross-correlations
Delensing
(early) Dark energy
Structure formation

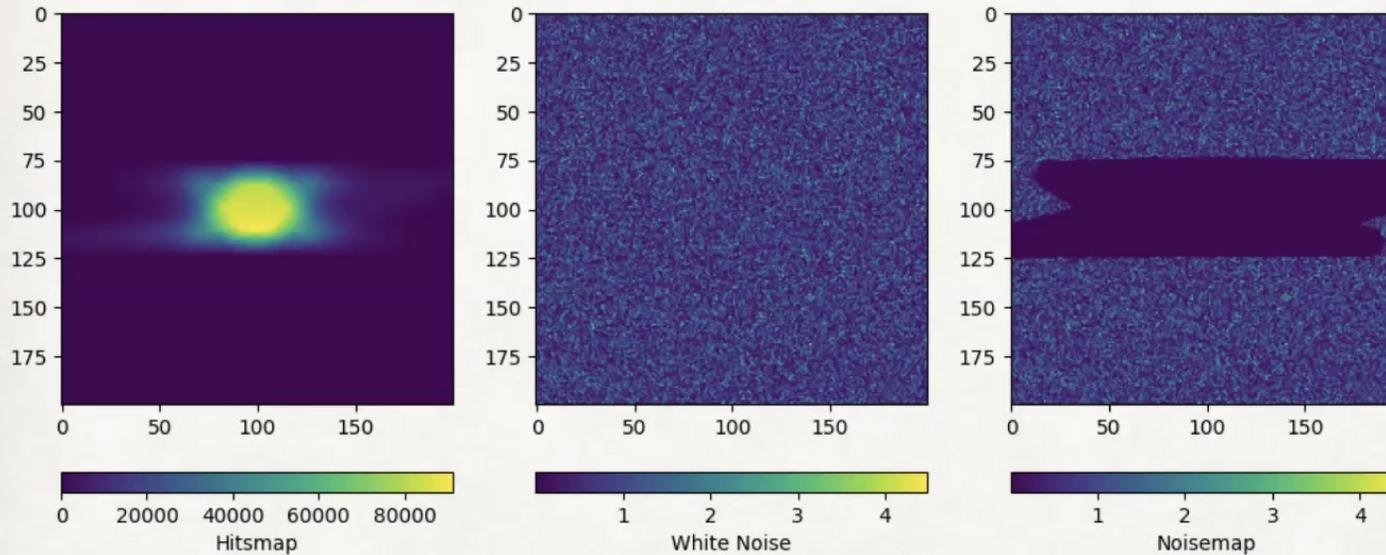
Silva et al. 2020

Noise simulations

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Preliminary result



Generate a noise map based on a fixed telescope scanning strategy and atmospheric noise

Use this noise map for detectability forecasts and parameter constraints

Summary and outlook

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Can we measure the radius and number density of ionized bubbles solely using the CMB dataset? A joint analysis using kSZ, fluctuations in optical depth, and tSZ.

Can we make an electron density template of the Universe by constructing an optical depth map? Forecasts show a CMB-S4-like experiment is capable of making a map of optical depth fluctuations (> 5 sigma).

What are the physical parameters of our interest that we can constrain from CMB measurements? $\tau, z_{\text{re}}, T_e, M_{\text{min}}, \zeta, R_b, \sigma_{\text{lnr}}$

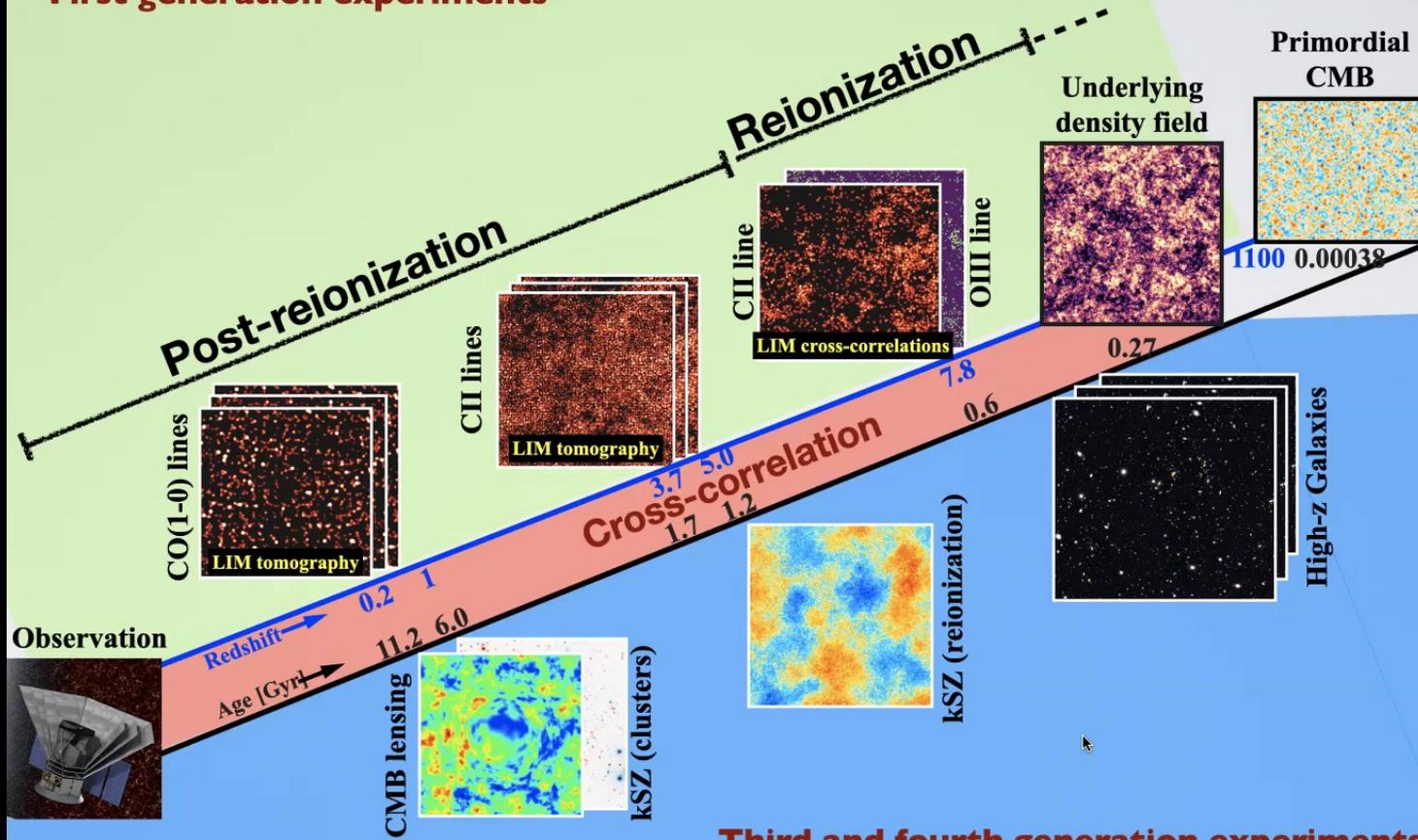
How do we separate small-scale CMB anisotropies induced by reionization from the low redshift contribution? Cross-correlations with galaxy samples and probing higher order statistics might be useful.

How the small-scale CMB measurements complement the other probes? Foreground removal is a major challenge but cross-correlations with LIM, galaxies, and other CMB anisotropies are important.



Line Intensity Mapping

First generation experiments



Third and fourth generation experiments
CMB (and galaxy survey)



Anirban Roy