Probing the Epoch of Reionization with line-intensity mapping

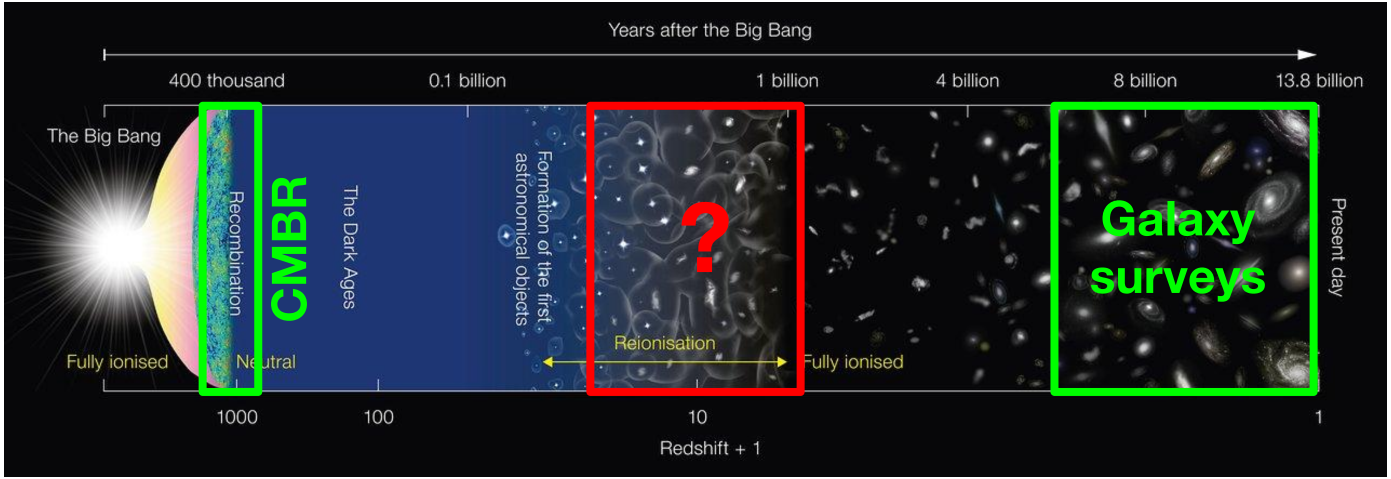
Chandra Shekhar Murmu (IIT Indore)

Collaborators: **Suman Majumdar (IIT Indore), Kanan K. Datta (Jadavpur University)**, **Thomas R. Greve (Cosmic Dawn Center)**, Karen P. Olsen (University of Arizona), Bryan R. Scott (University of California, Riverside), T. K. Daisy Leung (Flatiron Institute), Romeel Dave (University of Edinburgh), Gergö Popping (ESO), Raul O. Ochoa (Cosmic Dawn Center), David Vizgan (University of Illinois), Desika Narayanan (University of Florida), Bharat K. Gehlot (University of Groningen), Garrelt Mellema (Stockholm University), L. V. E. Koopmans (University of Groningen)

Background

- I work on simulations of cosmic reionization and line-intensity mapping (LIM)
- I investigate models of reionization and work on forecasting and interpretation of observable LIM summary statistics
- Soon to submit my PhD thesis

The Epoch of Reionization (EoR)



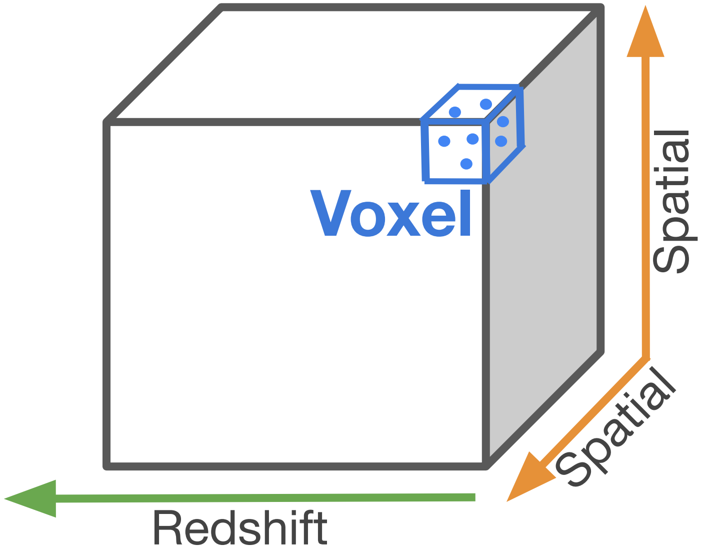
Credit: NAOJ

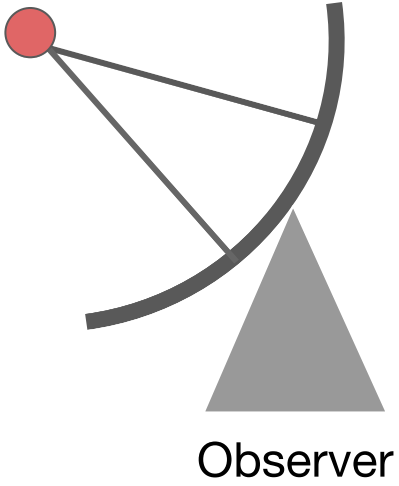
- First luminous sources (galaxies) were formed
- Ionizing radiation from the luminous sources reionized the neutral IGM

How to probe the EoR universe?

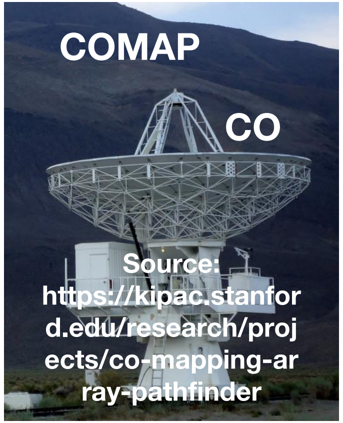
Line-intensity mapping

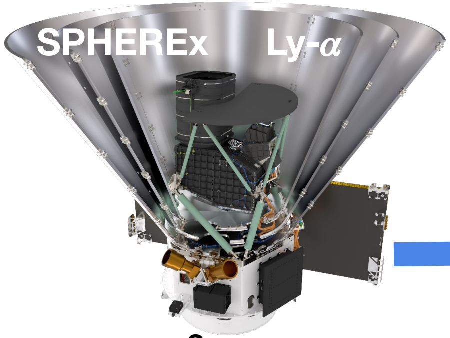
Accumulate the cumulative flux of numerous sources from a comparatively small region (Voxel)



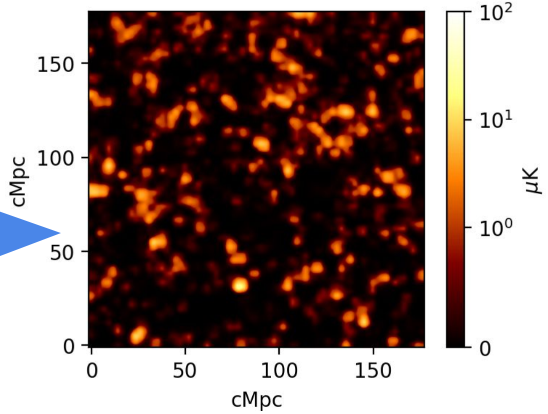


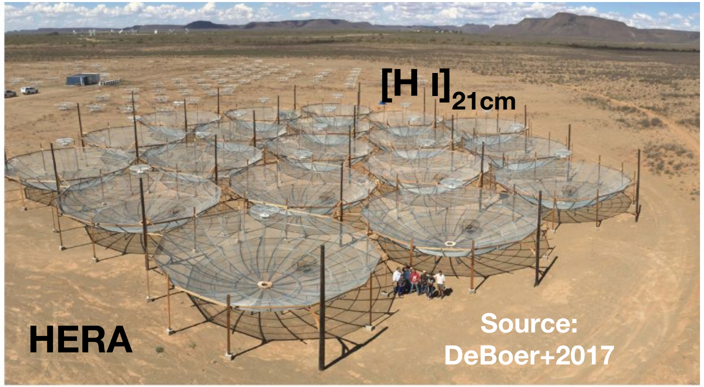
Probing the EoR with Intensity Mapping: galaxies and IGM

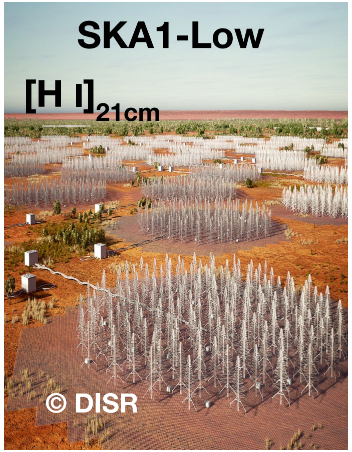


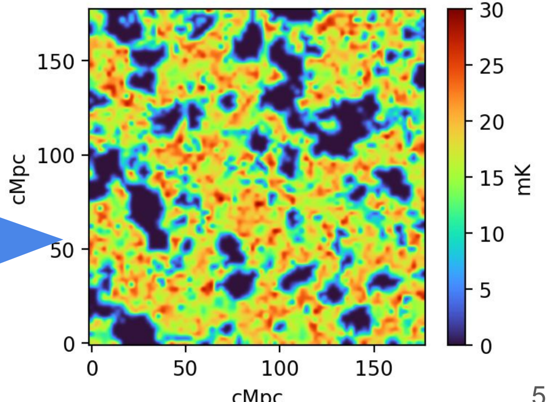


Source: https://spherex.caltech.edu/page/instrument









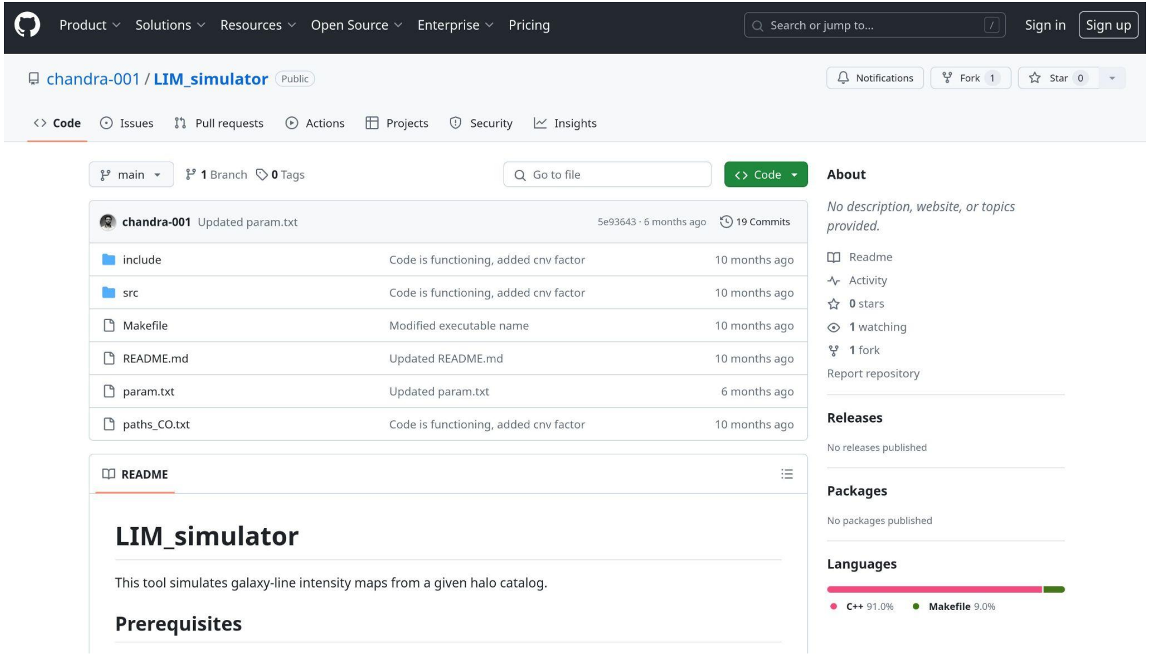
Murmu et al. 2021, MNRAS, 507(2), 2500

Observable summary statistics

Modelling (analytical/numerical) of observable summary statistics (e.g. power spectrum) is essential to interpret line-intensity mapping (LIM) observations

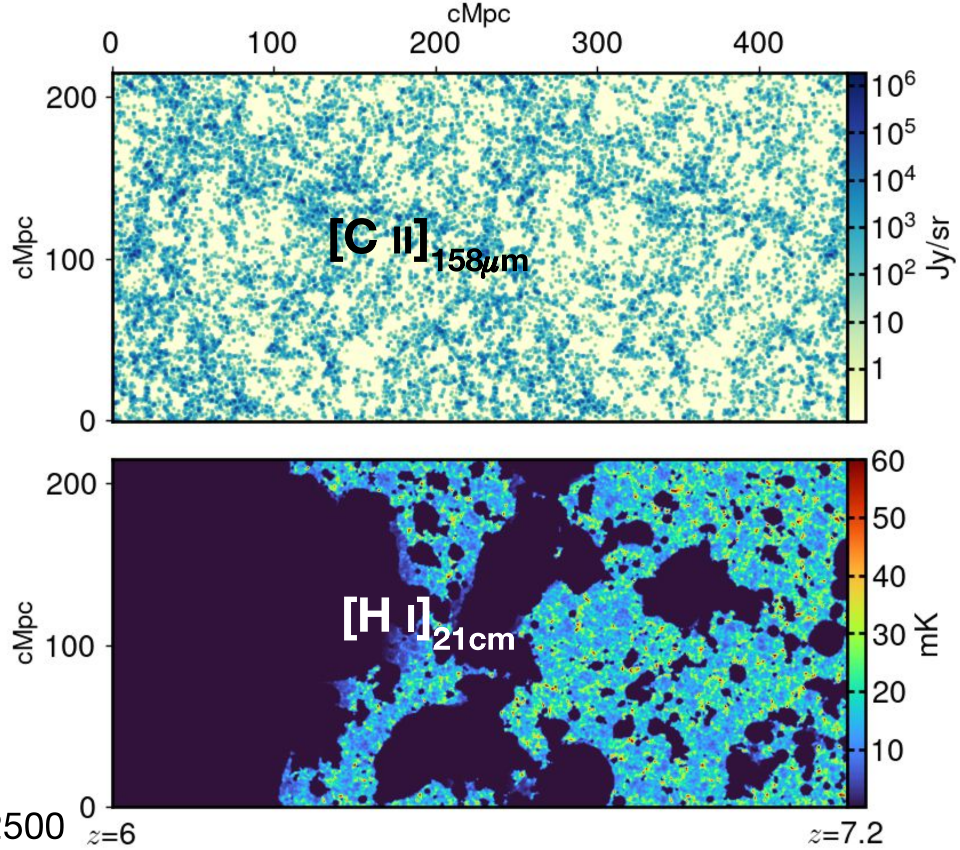
Simulations of LIM signals

https://github.com/chandra-001/LIM_simulator



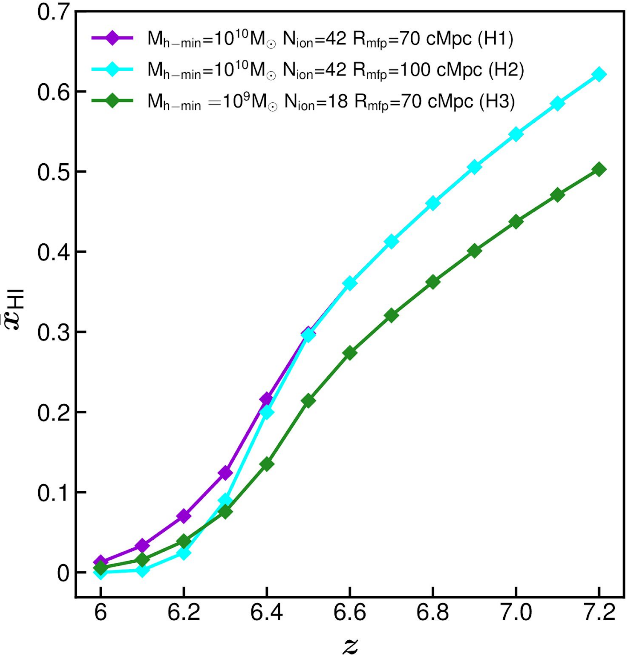
Scan here!

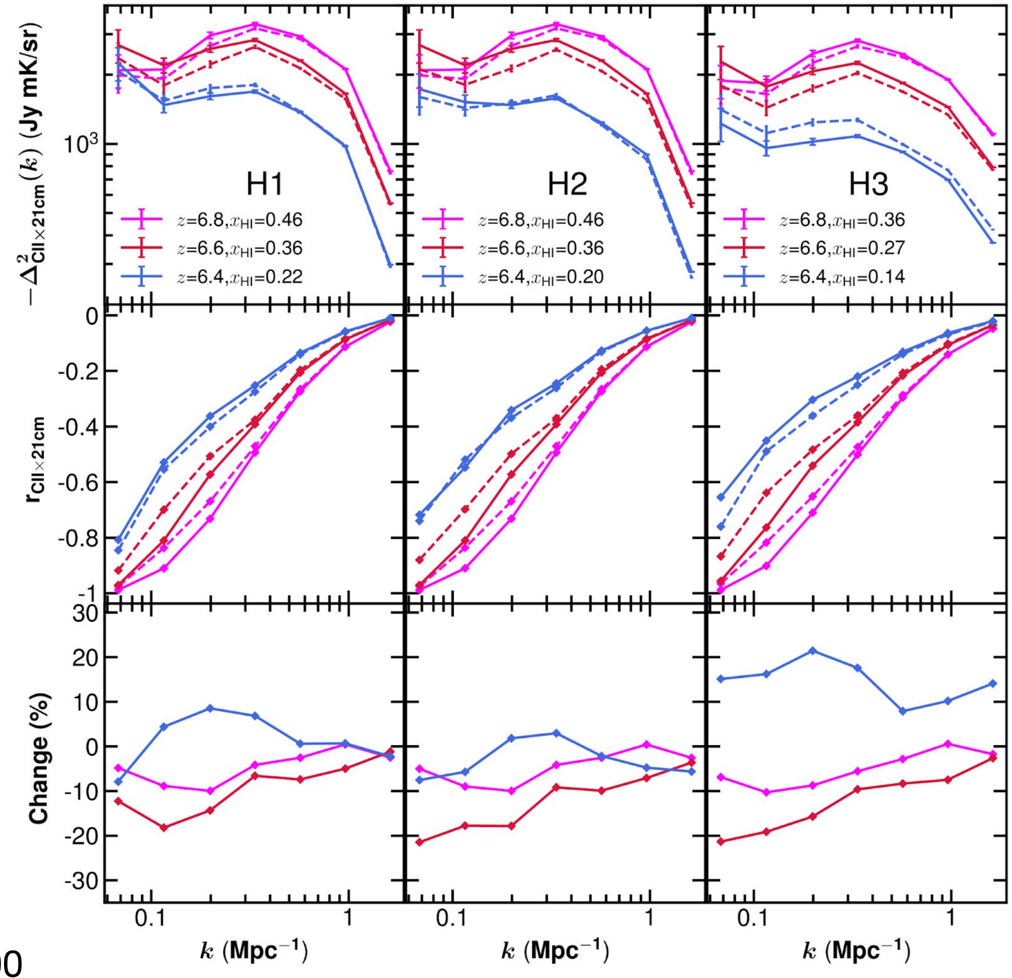
Line-of-sight anisotropies: Light cone effect



Murmu et al. 2021, MNRAS, 507(2), 2500

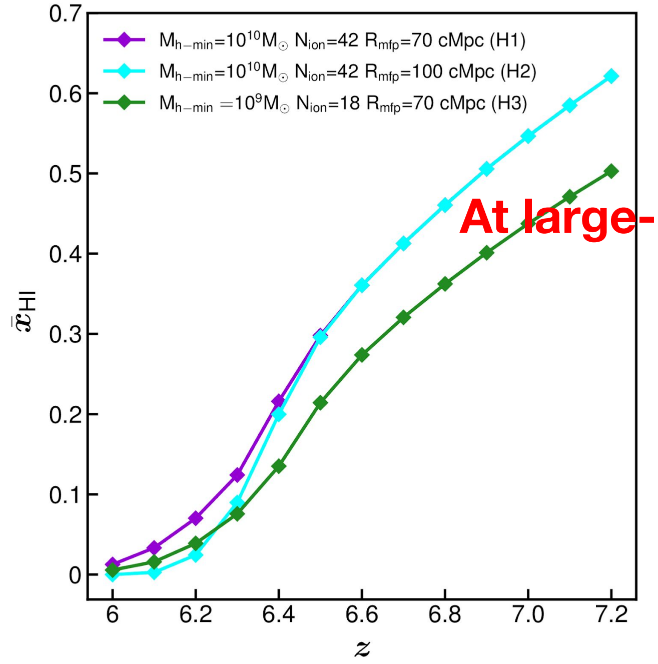
Light cone effect: Impact on CII x 21cm cross-power spectrum

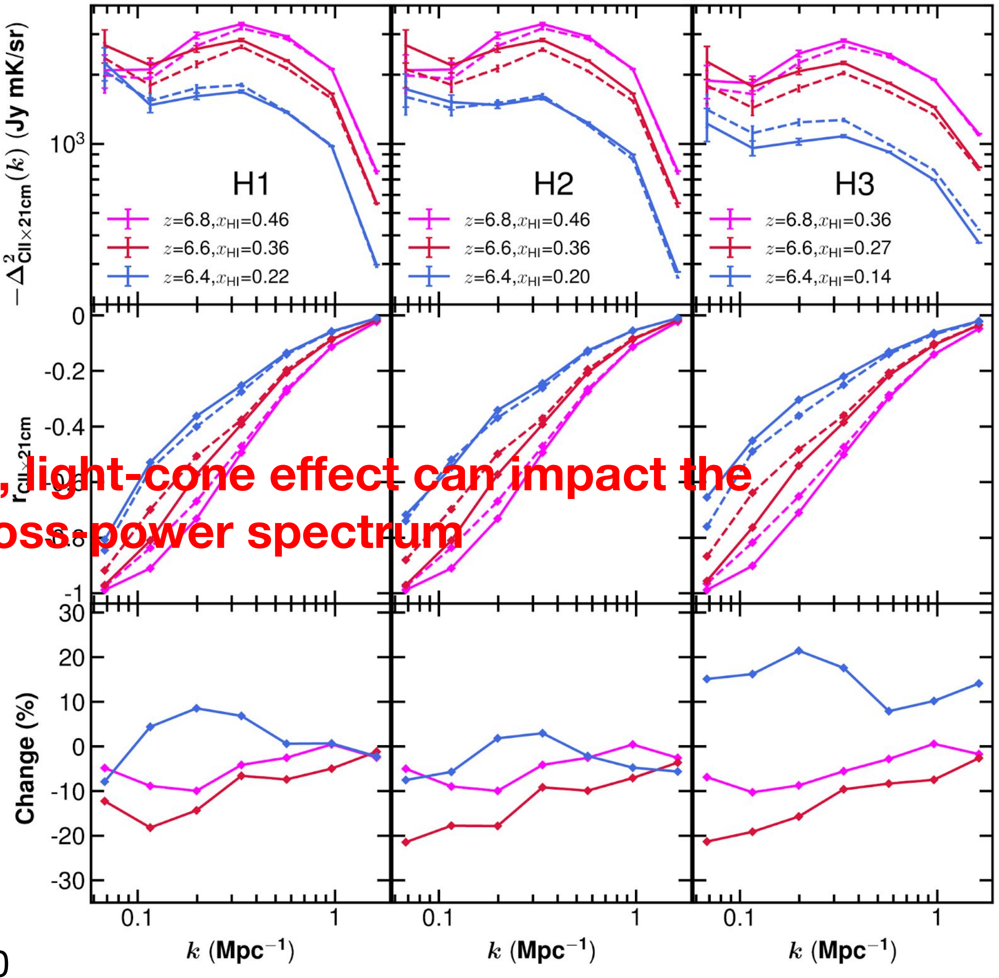




Murmu et al. 2021, MNRAS, 507(2), 2500

Light cone effect: Impact on CII x 21cm cross-power spectrum

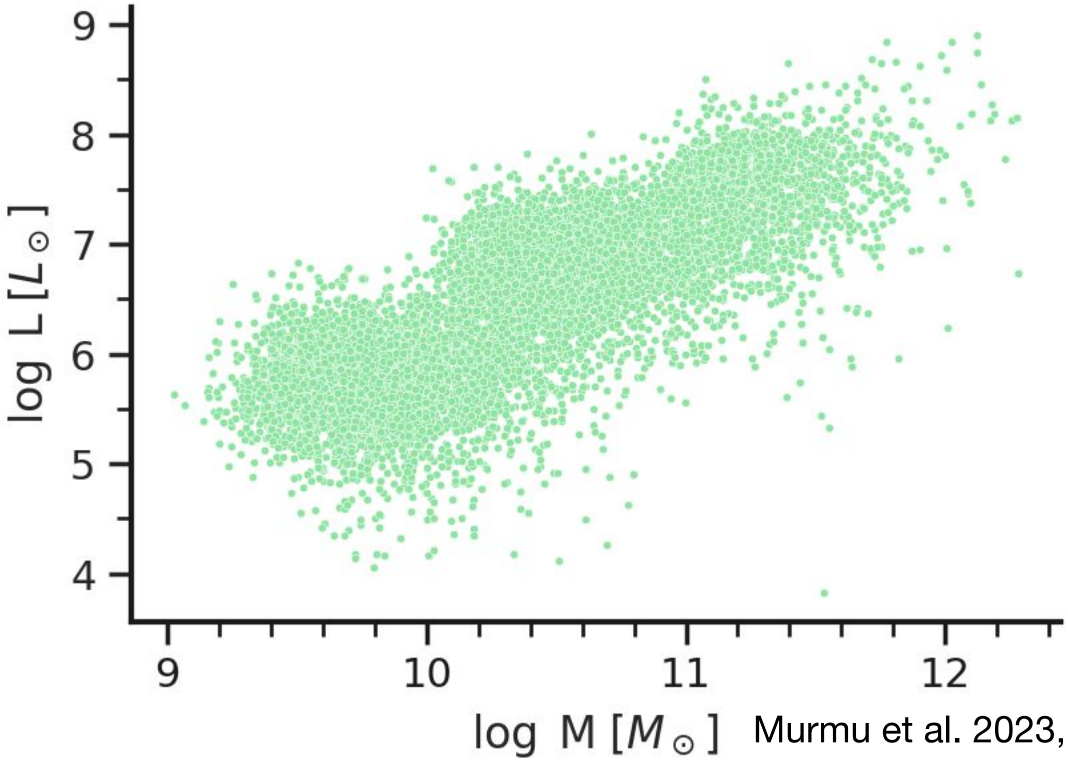




At large-scales, light-cone effect can impact the cross-power spectrum

Murmu et al. 2021, MNRAS, 507(2), 2500

[C II]$_{158\mu m}$ line-luminosity scatter: SIMBA + SIGAME

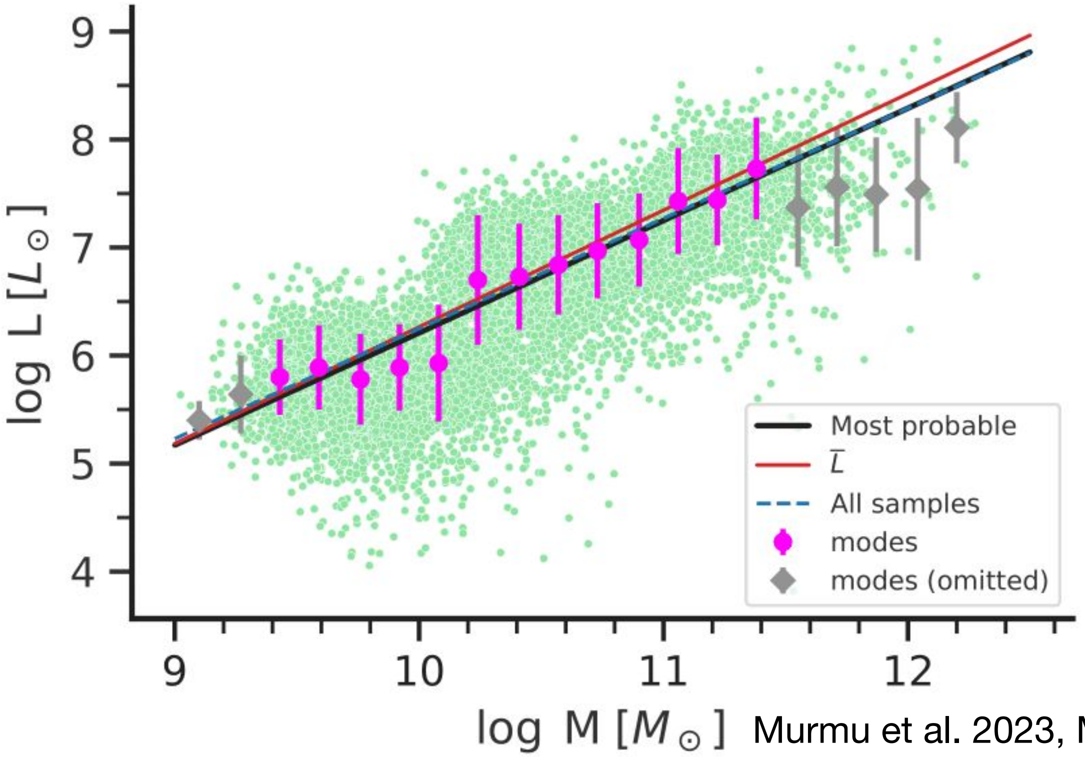


Murmu et al. 2023, MNRAS, 518(2), 3074

[C II]$_{158\mu m}$ line-emission exhibits scatter (refer to previous talk by Casavecchia)

Arises due to the multi-phase state of the ISM

[C II]$_{158\mu m}$ line-luminosity scatter: SIMBA + SIGAME



Murmu et al. 2023, MNRAS, 518(2), 3074

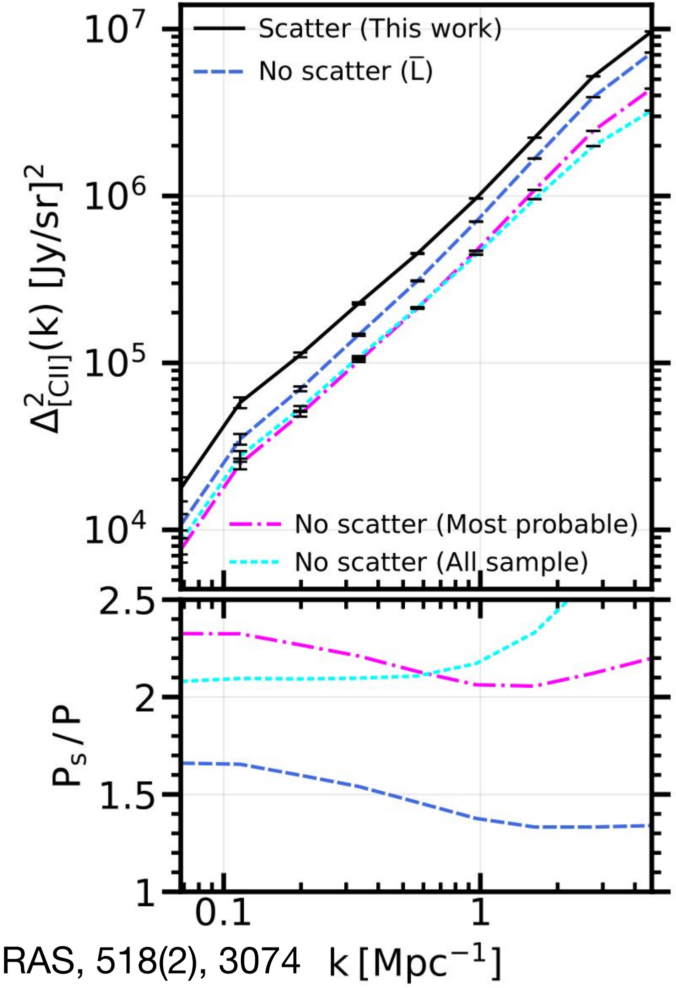
This is expected to impact the observable summary statistics (e.g. power spectrum)

Impact of line-luminosity scatter on the [C II]$_{158\mu m}$ power spectrum

The non-uniform scatter impacts the power spectrum regardless of the fit used for comparison

When compared against the most-probable fit, this impact can be modelled robustly, unlike the mean fit

Line-luminosity scatter can significantly affect the large-scale power spectrum

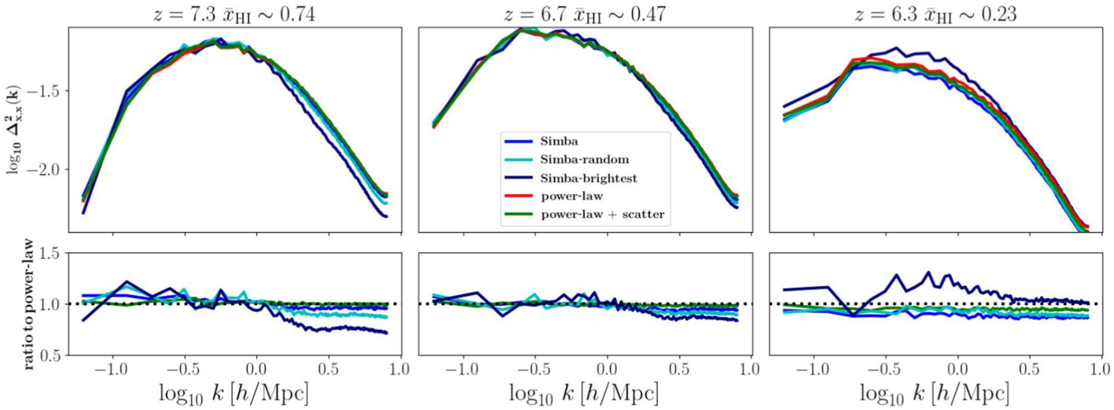


Murmu et al. 2023, MNRAS, 518(2), 3074

Star-formation can be stochastic in nature e.g. bursty star-formation
(refer to previous talks by Nikolić, Stark, Gelli and Bhagwat)

How variability in the star-formation rate (astrophysical scatter) affects reionization of the IGM?

Impact on power spectrum



Hassan et al. 2022, *ApJ*, 931, 62

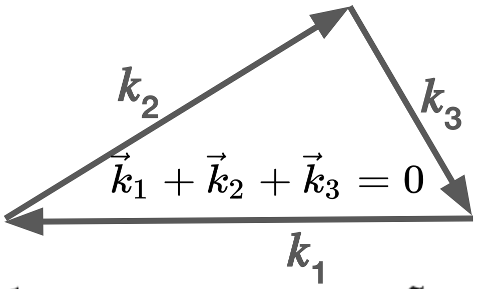
The ionization power spectrum is mostly unaffected, when astrophysical scatter is included in modelling reionization

- Ionization field is not directly observable, unlike the brightness temperature fluctuations of the $[\mathrm{H\ I}]_{21cm}$ signal
- $[\mathrm{H\ I}]_{21cm}$ signal is known to be highly non-Gaussian and astrophysical scatter might introduce additional non-Gaussianities

[H I]$_{21cm}$ bispectrum

[H I]$_{21cm}$ signal is known to be highly non-Gaussian and astrophysical scatter might introduce additional non-Gaussianities

Higher order statistics such as bispectrum can capture non-Gaussianities in the [H I]$_{21cm}$ signal



$$B_m(\vec{k}_1, \vec{k}_2, \vec{k}_3) = \frac{1}{N_{\rm tri} V} \sum_{[\vec{k}_1+\vec{k}_2+\vec{k}_3=0]\in m} \tilde{\Delta} T_b(\vec{k}_1)\tilde{\Delta} T_b(\vec{k}_2)\tilde{\Delta} T_b(\vec{k}_3)$$

Simulations of the [H I]$_{21cm}$ signal

Usual reionization source model:

$$N_\gamma \propto \overline{\mathrm{SFR}}(M_h, z)$$

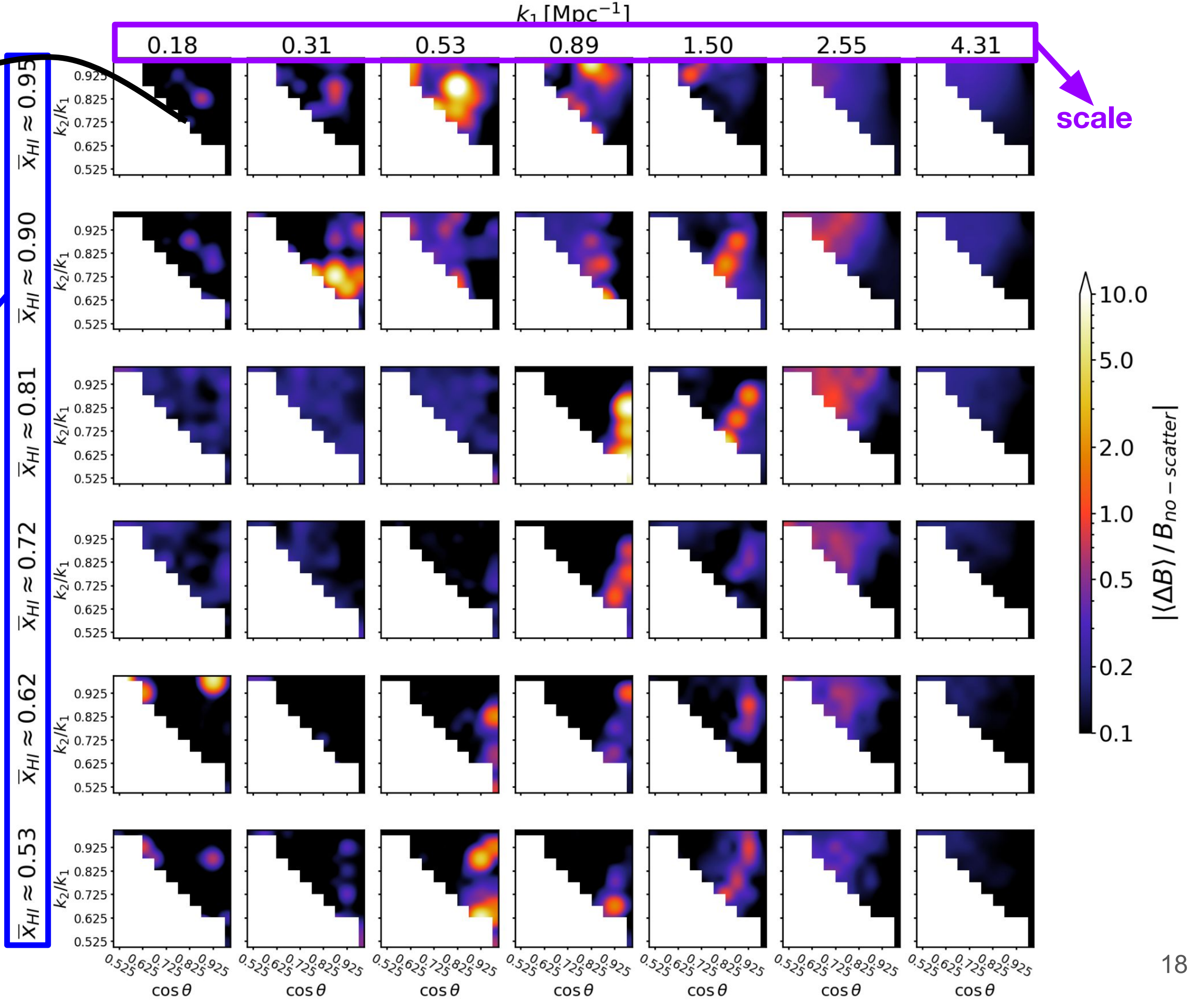
Simplistic model for astrophysical scatter:

$$N_\gamma \propto \overline{\mathrm{SFR}}(M_h, z) + \text{Log-normal scatter}$$

We generate 50 realizations of the [H I]$_{21cm}$ signal for each of six neutral fractions at z=7.4 that we considered (a total of 300 simulations were done)

Impact of scatter

$$\langle \Delta B \rangle / B_{\text{no scatter}}$$

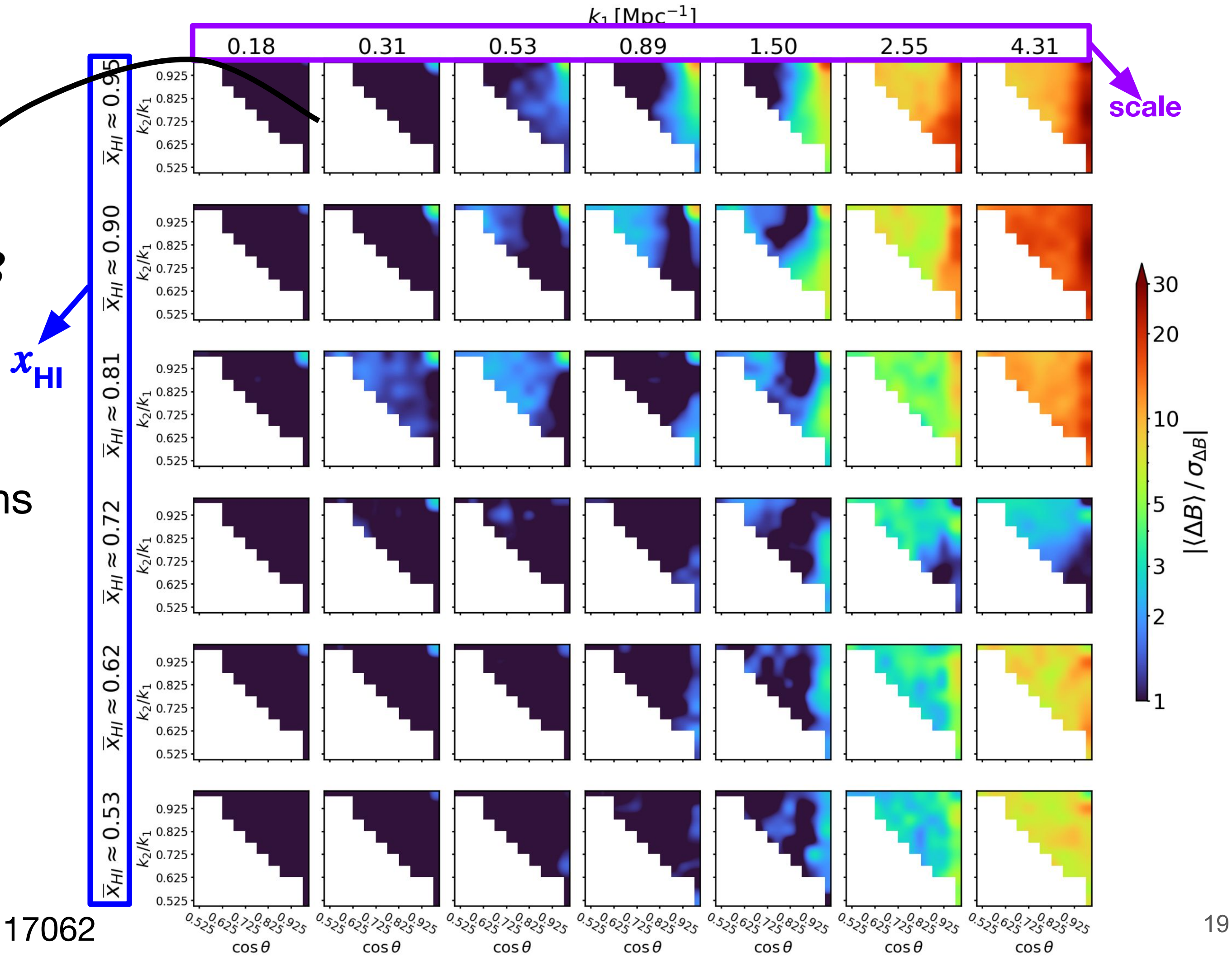


A total of 300 realizations were simulated

Murmu et al. 2023, arXiv: 2311.17062

Statistical significance

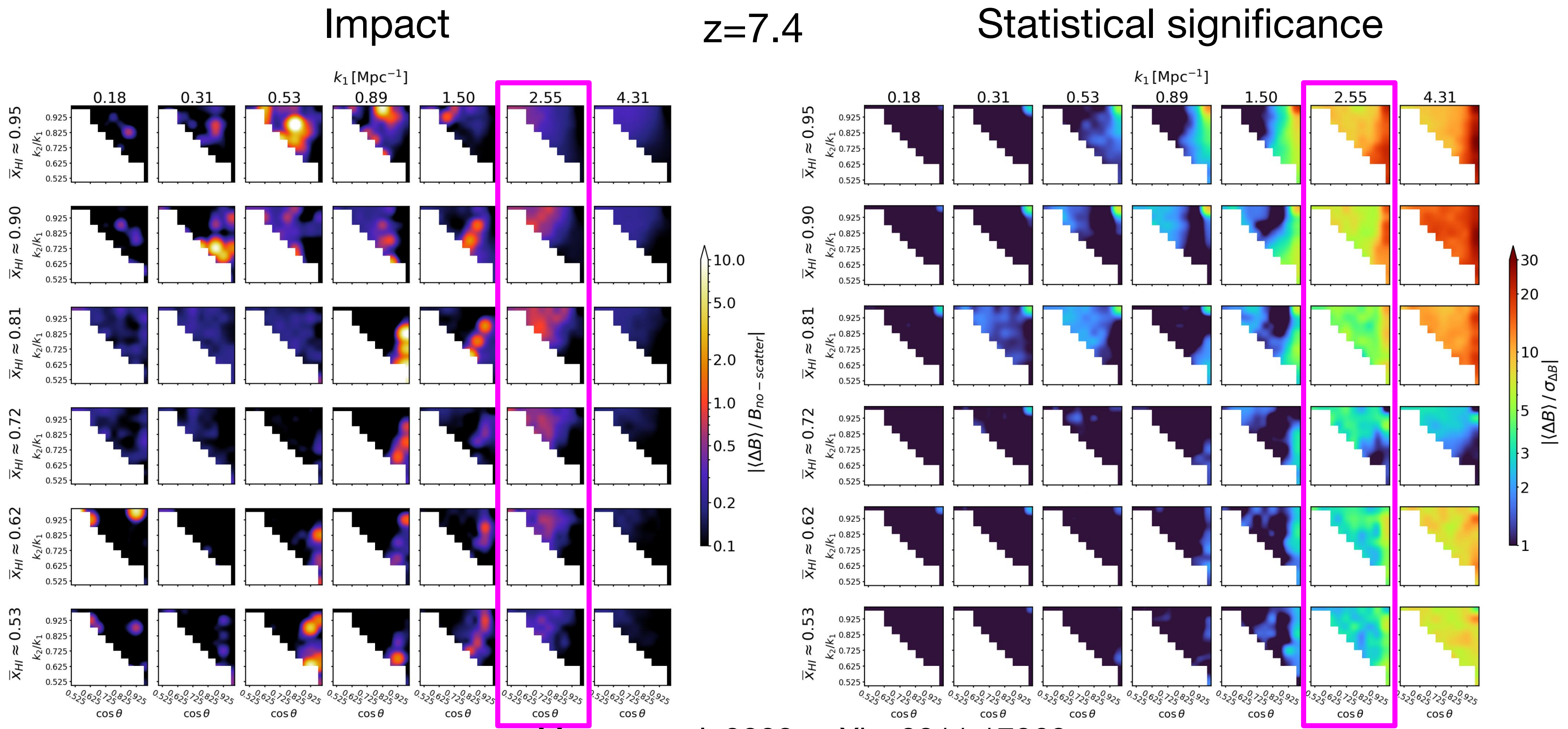
$$\langle \Delta B \rangle / \sigma_{\Delta B}$$



A total of 300 realizations were simulated

Murmu et al. 2023, arXiv: 2311.17062

Impact of scatter on the [H I]$_{21cm}$ bispectrum



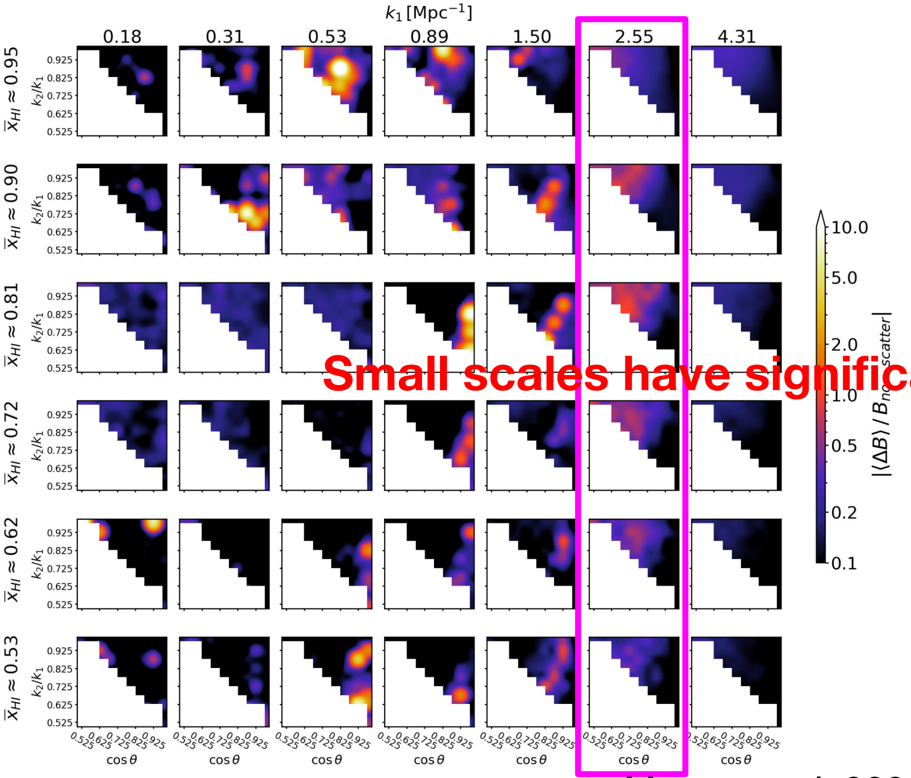
Murmu et al. 2023, arXiv: 2311.17062

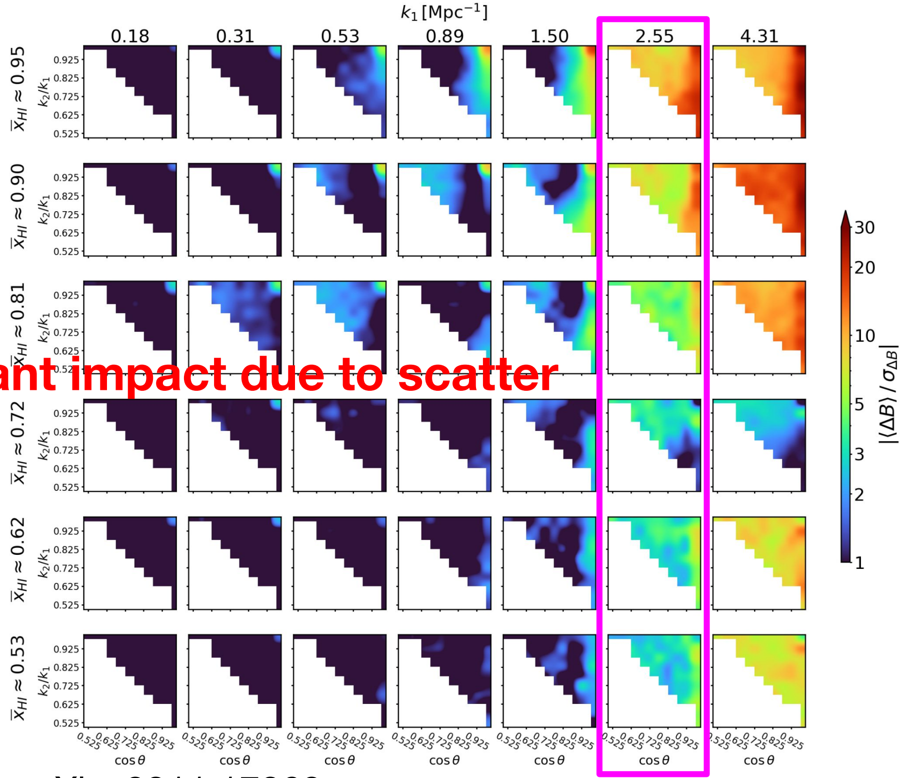
Impact of scatter on the [H ɪ]$_{21cm}$ bispectrum

Impact

z=7.4

Statistical significance





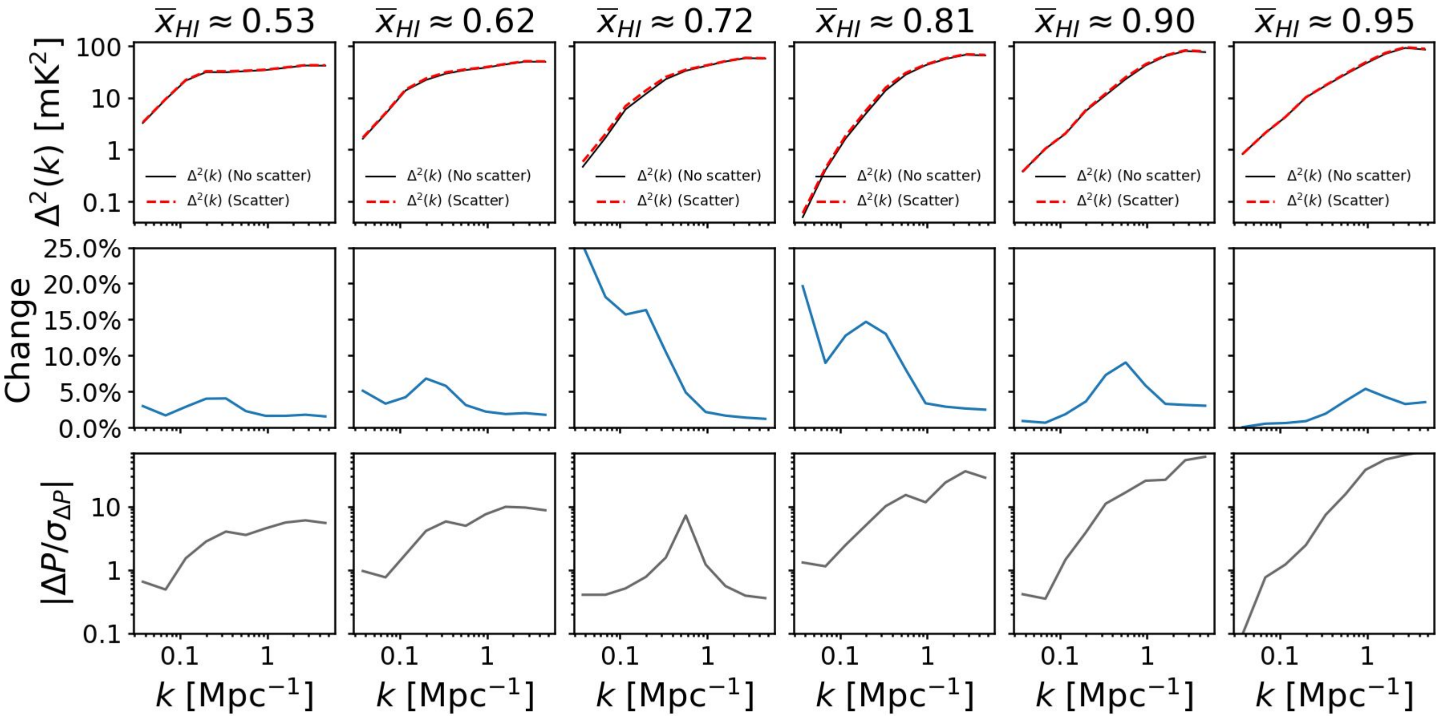
Small scales have significant impact due to scatter

Murmu et al. 2023, arXiv: 2311.17062

Impact of scatter on the [H I]$_{21\mathrm{cm}}$ power spectrum

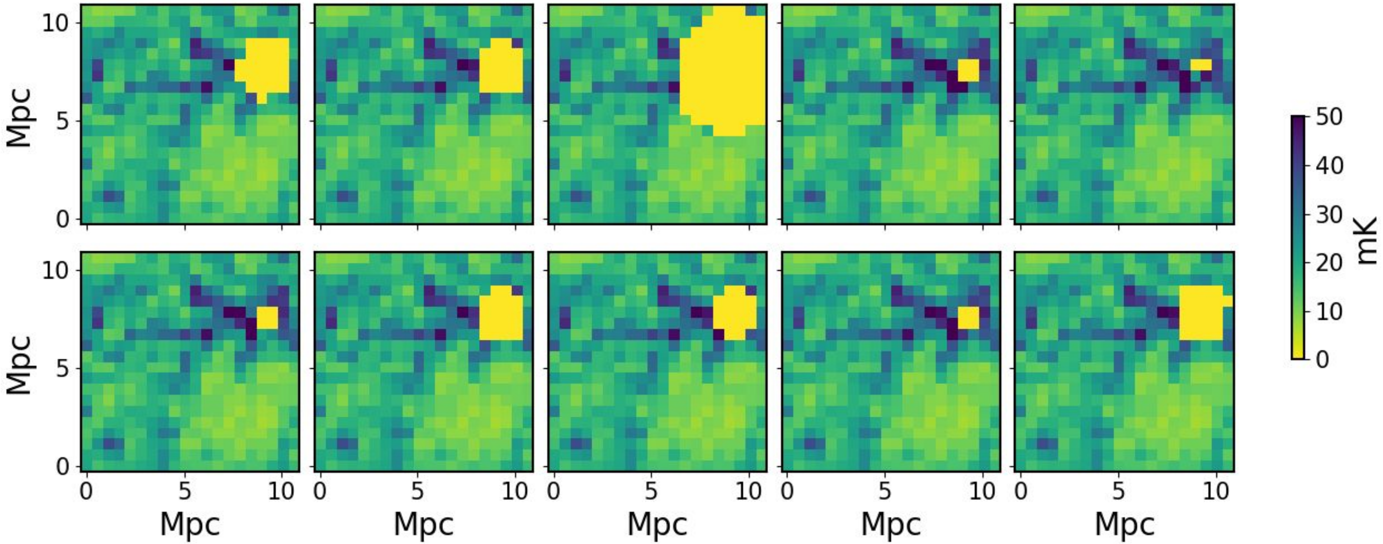
$$\langle \tilde{\delta}(\mathbf{k})\tilde{\delta}^*(\mathbf{k}')\rangle = V\delta_{k,k'}P(k)$$

$$\Delta^2(k) = \frac{k^3 P(k)}{2\pi^2}$$



Murmu et al. 2023, arXiv: 2311.17062

Small-scale ionized bubbles



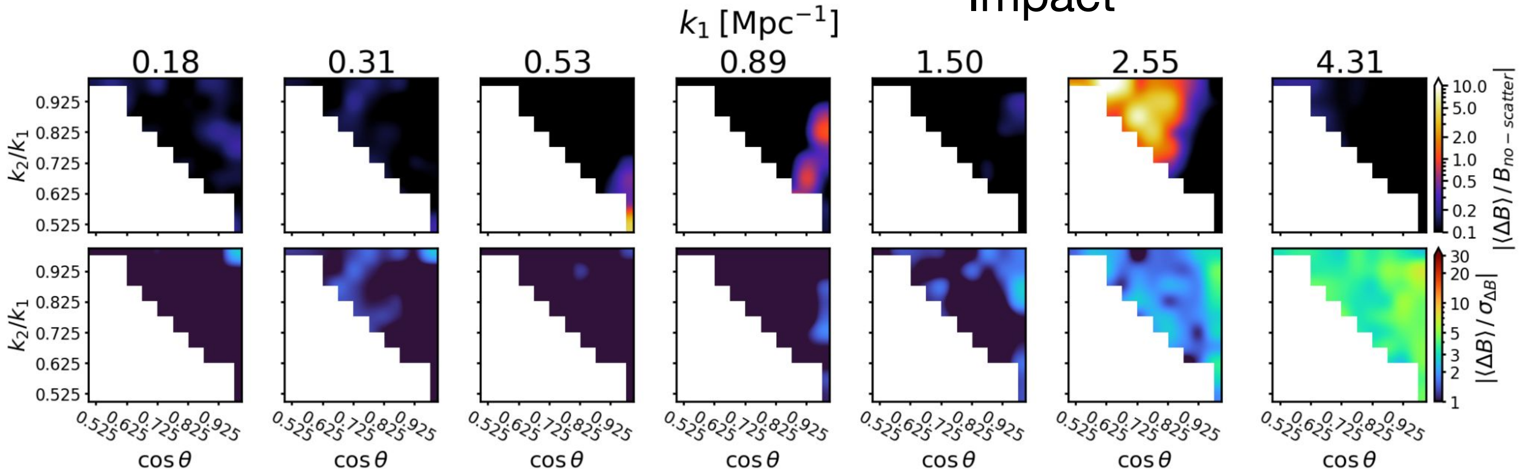
Murmu et al. 2023, arXiv: 2311.17062

The small-scale ionized bubbles vary across different realizations of the astrophysical scatter

Impact of scatter at z=10, x_{HI} ~ 0.8

Additional 50 realizations were simulated

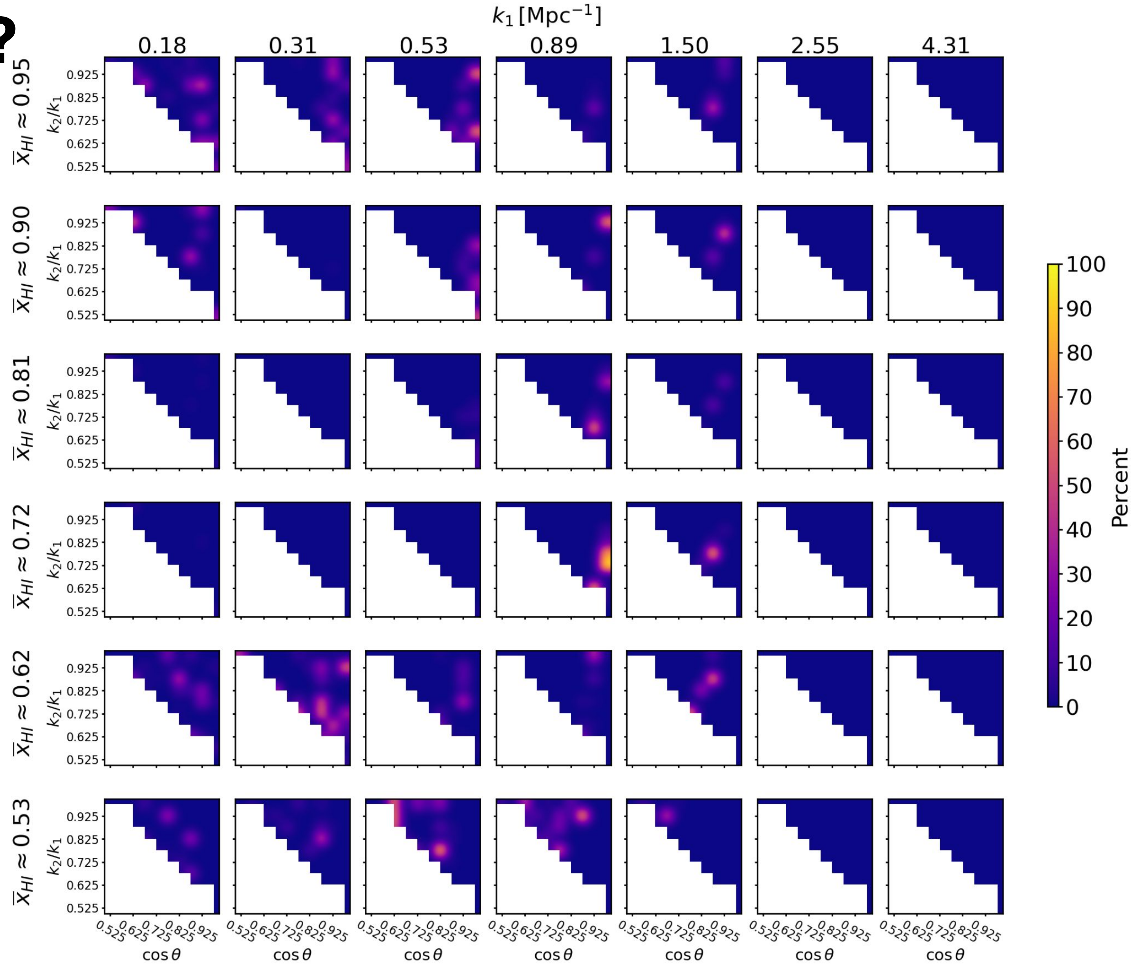
Impact



Statistical significance

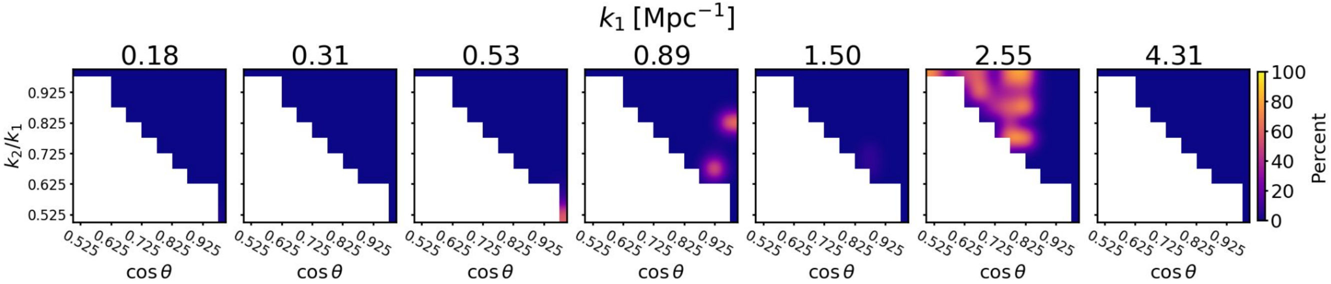
Can scatter in SFR induce sign flip in [H I]$_{21cm}$ bispectrum?

Frequency of sign flip at z=7.4



Can scatter in SFR induce sign flip in [H I]$_{21cm}$ bispectrum?

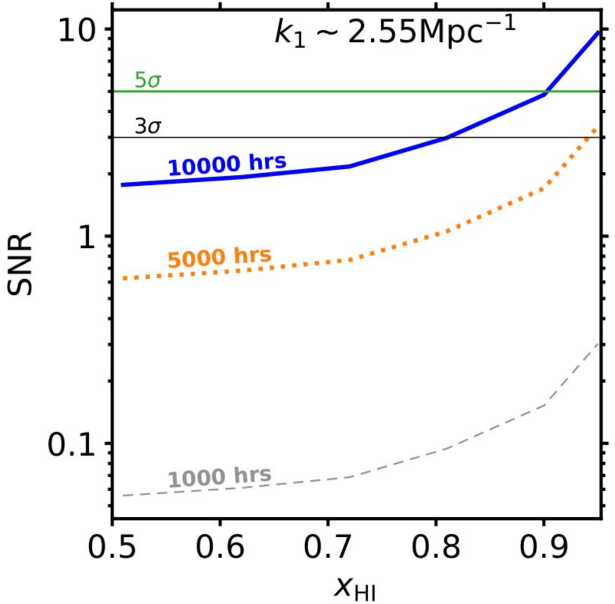
Frequency of sign flip at z=10, x_{HI} ~ 0.8



At small-scales frequency of sign flip can be significant

Detectability

z=7.4



Murmu et al. 2023, arXiv: 2311.17062

Optimistic scenarios can be adopted which observes for a fixed duration per year (e.g. 1000 hrs/year)

This can be extended for a couple of years after SKA1-Low is operational

[H I]$_{21cm}$ × CO cross-correlation signal from the EoR

Gridded density fields from N-body simulation outputs (CUBEP3M) and ionization fields from C2Ray radiative transfer simulations are used to generate [H I]$_{21cm}$ maps

CO(2-1) line luminosities are painted to the halos identified in the simulations

We assume overlap between the AARTFAAC ([H I]$_{21cm}$) and COMAP (CO) surveys

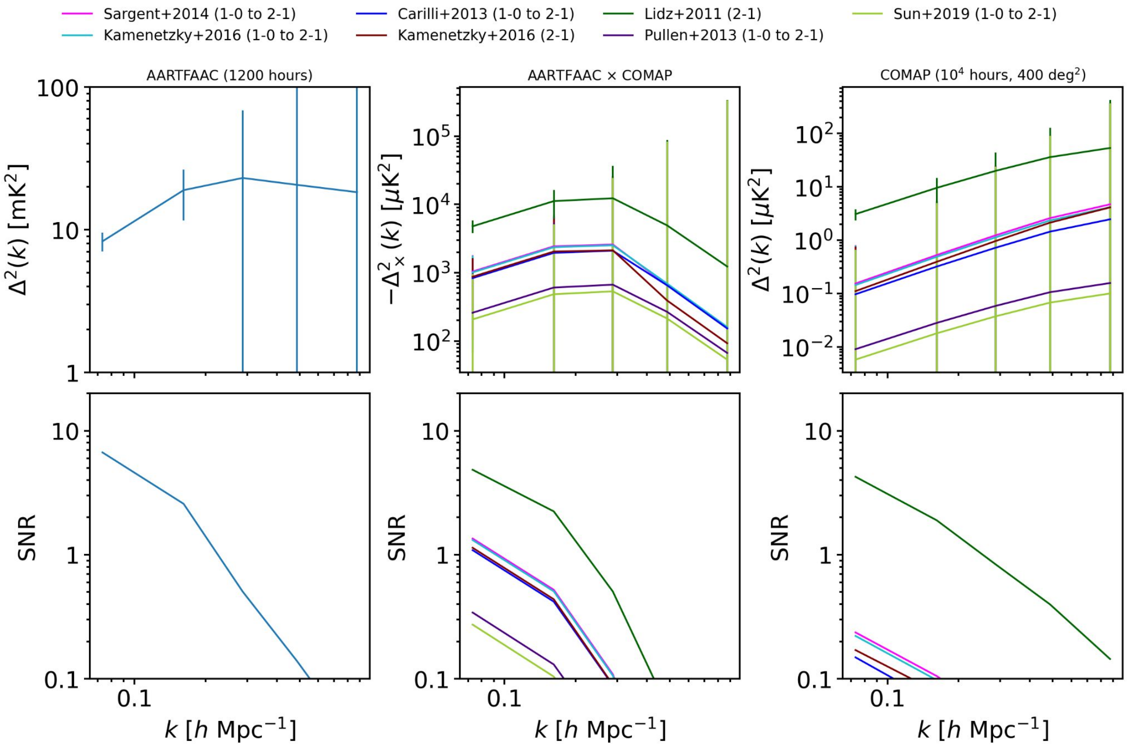
Uncertainty in the cross-power spectrum

$$\mathrm{var}[P_\times] = \frac{1}{2}\left(\frac{P_\times^2 + (P_{21\mathrm{cm}} + P_{\mathrm{N,21cm}})(P_{\mathrm{CO}} + P_{\mathrm{N,CO}})}{N_{\mathrm{modes}}}\right)$$

$P_{\mathrm{N,21cm}}$ is estimated using “ps_eor” (https://gitlab.com/flomertens/ps_eor)

$P_{\mathrm{N,CO}}$ is estimated using analytic formalisms (Breyesse et al. 2022, ApJ, 933, 188)

Detectability of the cross-power spectrum



z ~ 7.2

AARTFAAC ~ 1200 hrs
COMAP ~ 10000 hrs, 400 deg^2

- Constrain astrophysical parameters
- Extend this for lower redshifts

Summary

- Line intensity mapping is novel technique to probe the large-scale structures of the Universe, which provides a unique way to peer into the Epoch of Reionization

- Light-cone effect can significantly affect the large-scale cross-power spectrum

- Line-luminosity scatter significantly affects the large-scale galaxy LIM power spectrum

- At the small scales, the $[\mathrm{H\ I}]_{21cm}$ bispectrum can capture non-Gaussian signatures induced by scatter in SFR

- Cross-correlations can boost the detectability of the EoR LIM signals

Once again…

- I am interested to explore further avenues in LIM

- Soon to submit my PhD thesis (currently looking for Postdoctoral positions)

My publications are available here: https://arxiv.org/a/murmu_c_1.html

Scan here!

Thank you