

Probing the Epoch of Reionization with line-intensity mapping

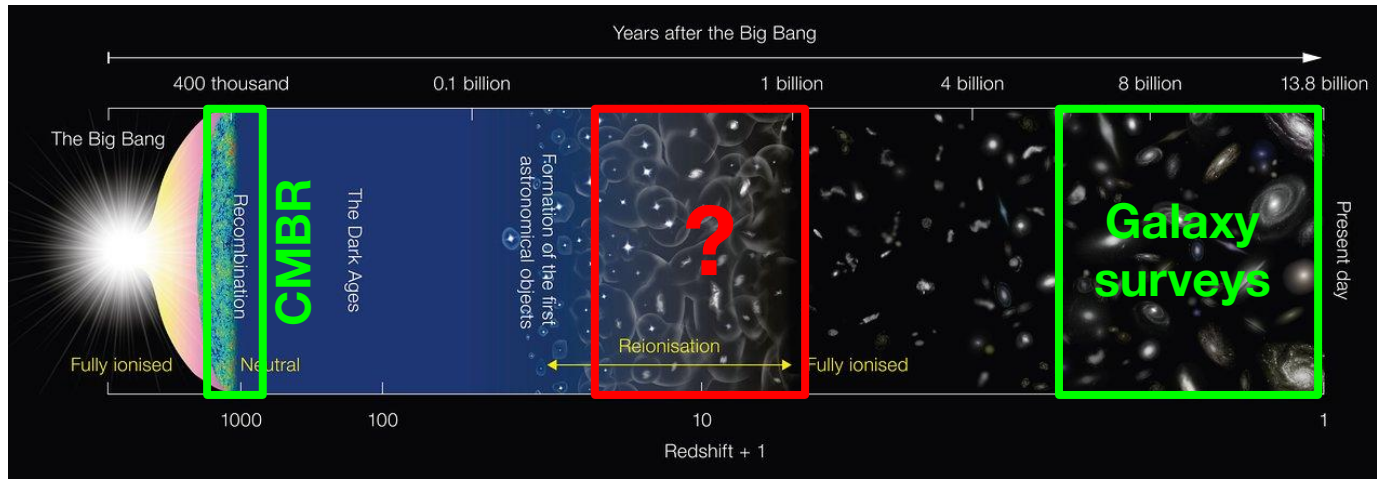
Chandra Shekhar Murmu (IIT Indore)

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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)



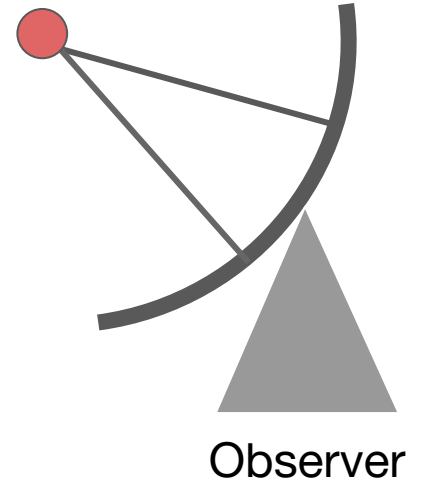
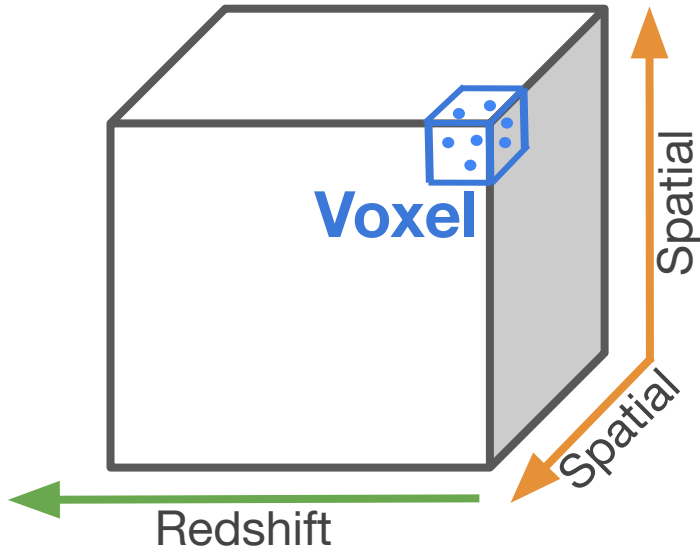
Credit: NAOJ

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

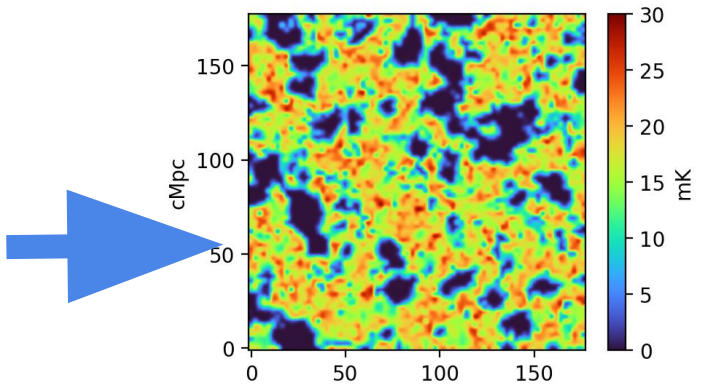
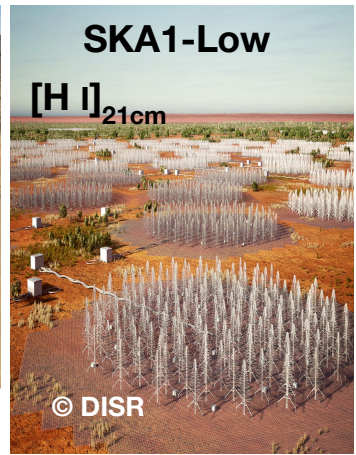
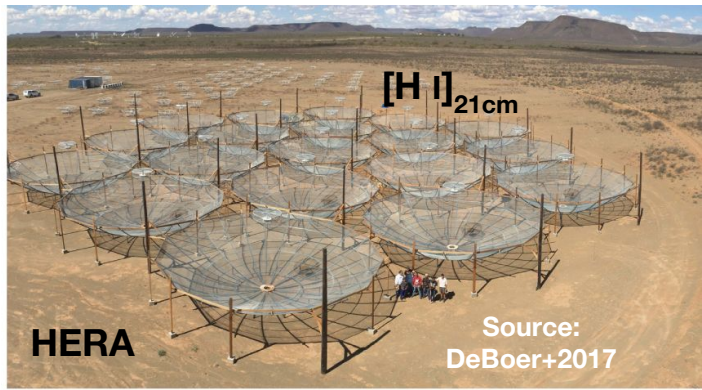
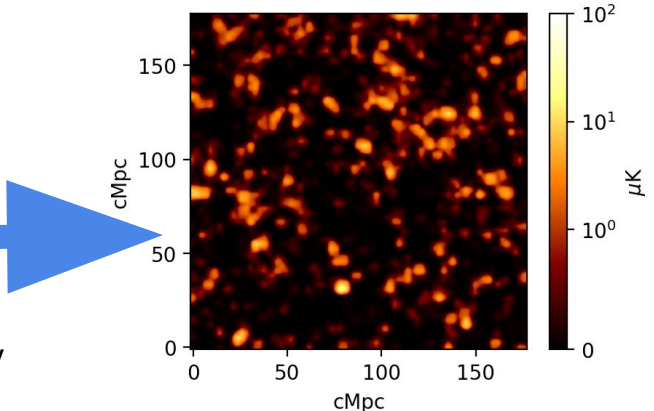
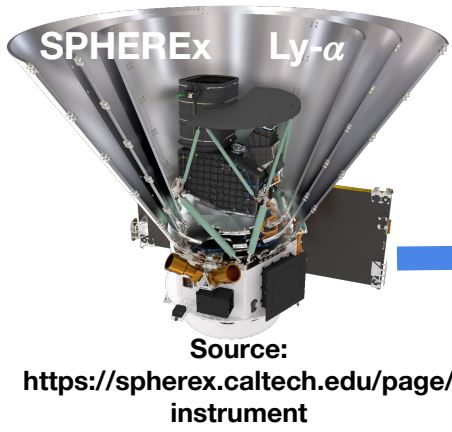
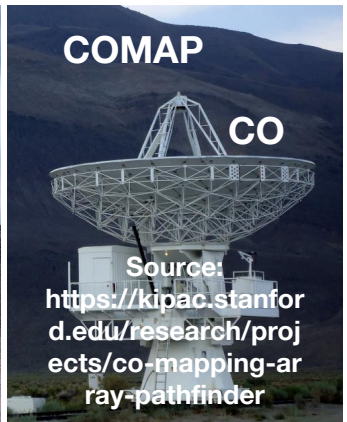
How to probe the EoR universe?

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



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

The screenshot shows the GitHub repository page for 'chandra-001 / LIM_simulator'. The repository is public and has 19 commits, 1 fork, and 0 stars. The repository contains several files and folders: 'include', 'src', 'Makefile', 'README.md', 'param.txt', and 'paths_CO.txt'. The 'README.md' file is selected and its content is displayed below. The README content includes the title 'LIM_simulator', a description 'This tool simulates galaxy-line intensity maps from a given halo catalog.', and a section for 'Prerequisites'. On the right side of the repository page, there are sections for 'About', 'Releases', 'Packages', and 'Languages'. The 'About' section is currently empty. The 'Releases' and 'Packages' sections also show no published content. The 'Languages' section shows a bar chart with 'C++' at 91.0% and 'Makefile' at 9.0%.

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chandra-001 / LIM_simulator Public Notifications Fork 1 Star 0

Code Issues Pull requests Actions Projects Security Insights

main 1 Branch 0 Tags Go to file Code

chandra-001 Updated param.txt 5e93643 · 6 months ago 19 Commits

include	Code is functioning, added cnv factor	10 months ago
src	Code is functioning, added cnv factor	10 months ago
Makefile	Modified executable name	10 months ago
README.md	Updated README.md	10 months ago
param.txt	Updated param.txt	6 months ago
paths_CO.txt	Code is functioning, added cnv factor	10 months ago

README

LIM_simulator

This tool simulates galaxy-line intensity maps from a given halo catalog.

Prerequisites

About

No description, website, or topics provided.

- Readme
- Activity
- 0 stars
- 1 watching
- 1 fork

Report repository

Releases

No releases published

Packages

No packages published

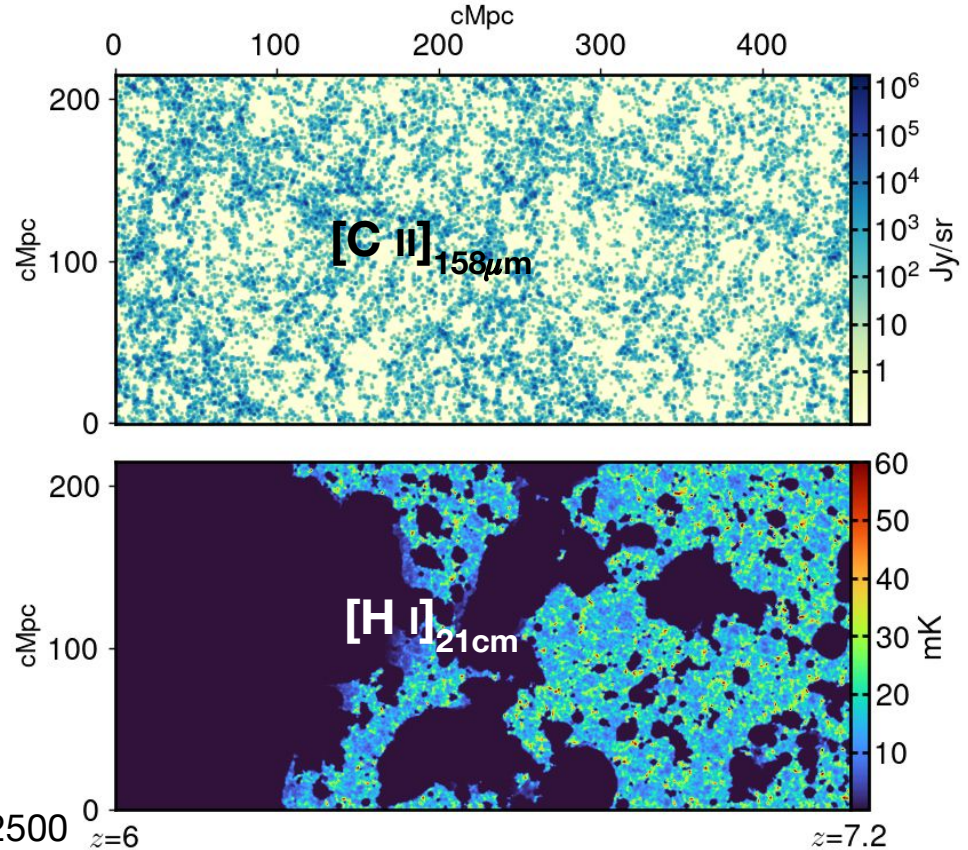
Languages

C++ 91.0% Makefile 9.0%

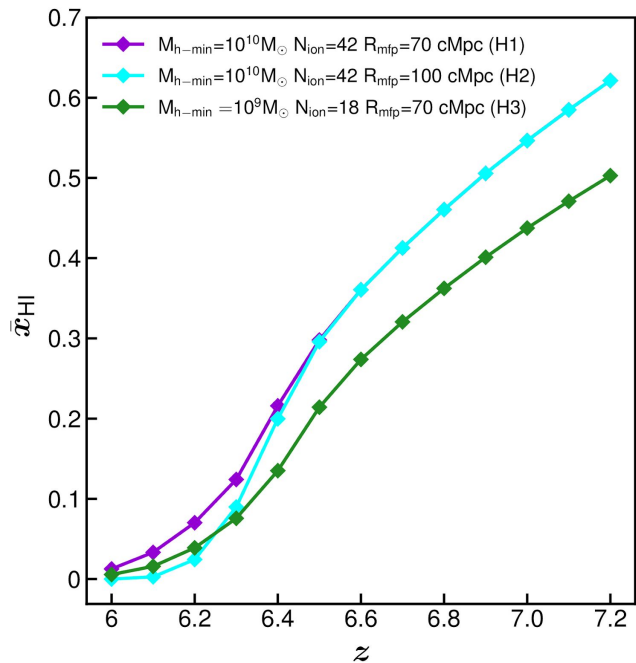
Scan here!



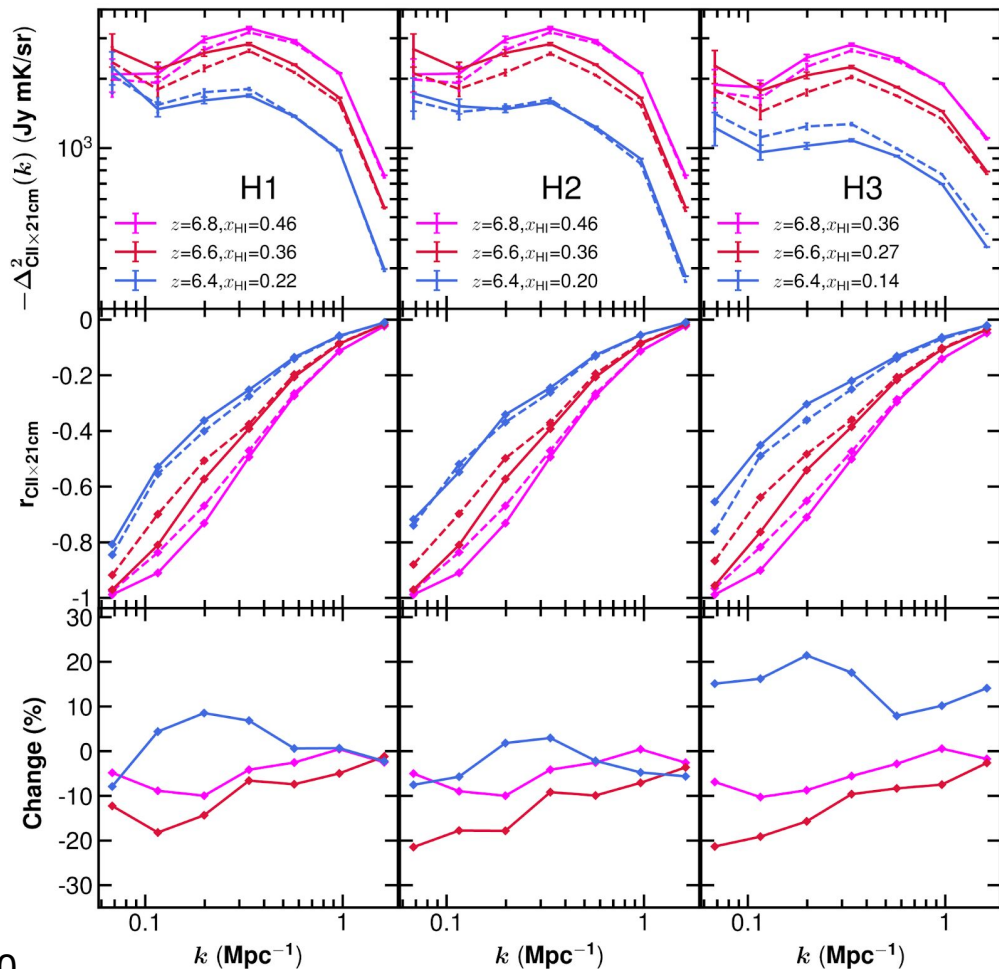
Line-of-sight anisotropies: Light cone effect



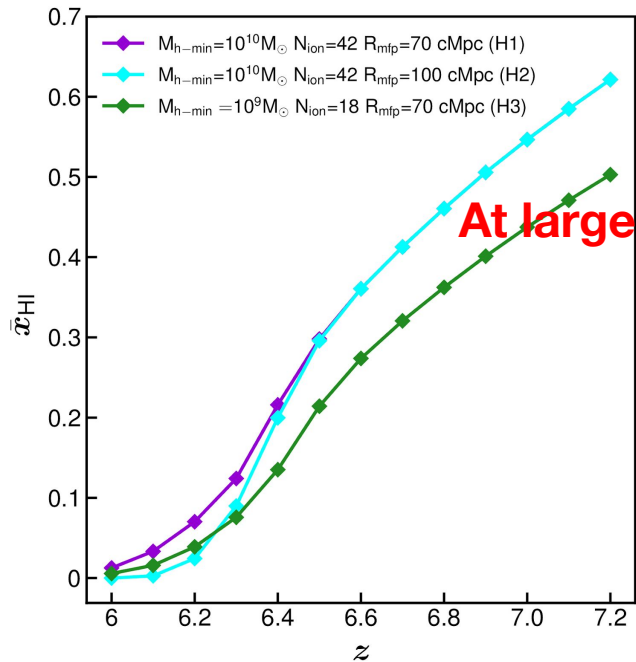
Light cone effect: Impact on CII x 21cm cross-power spectrum



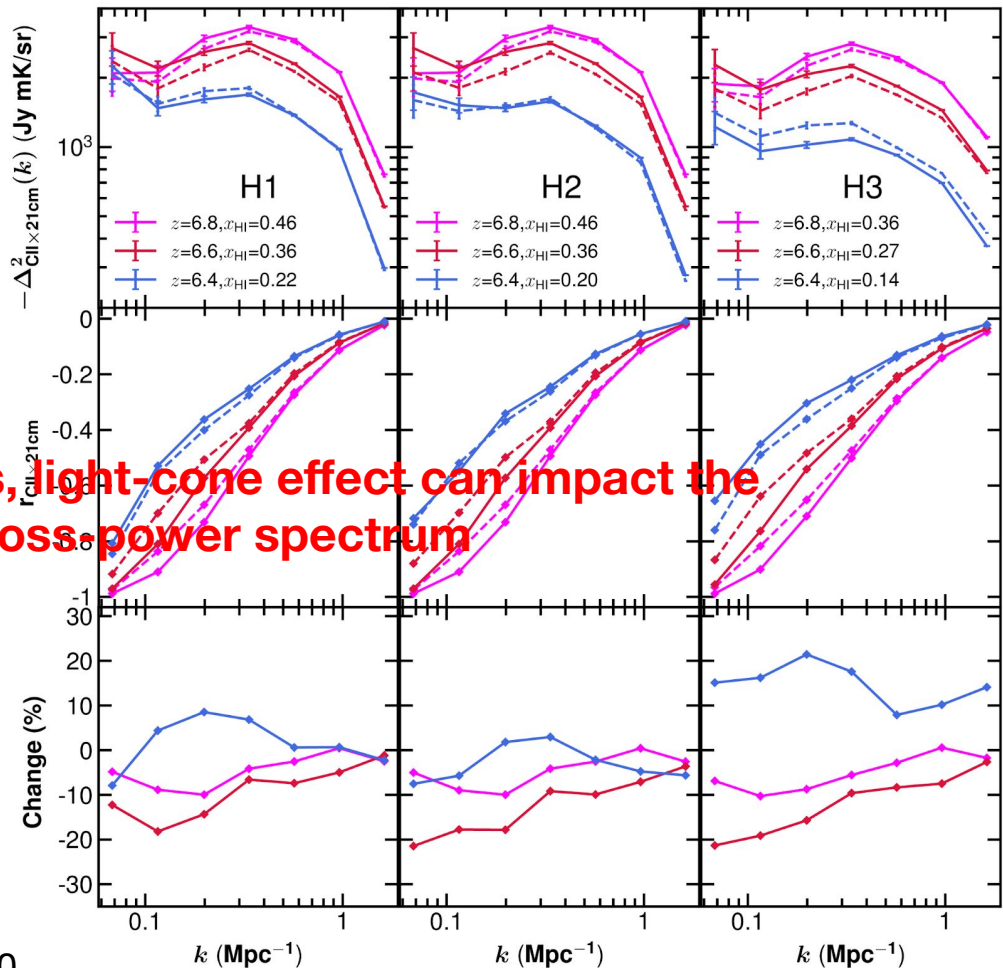
Murmu et al. 2021, MNRAS, 507(2), 2500



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

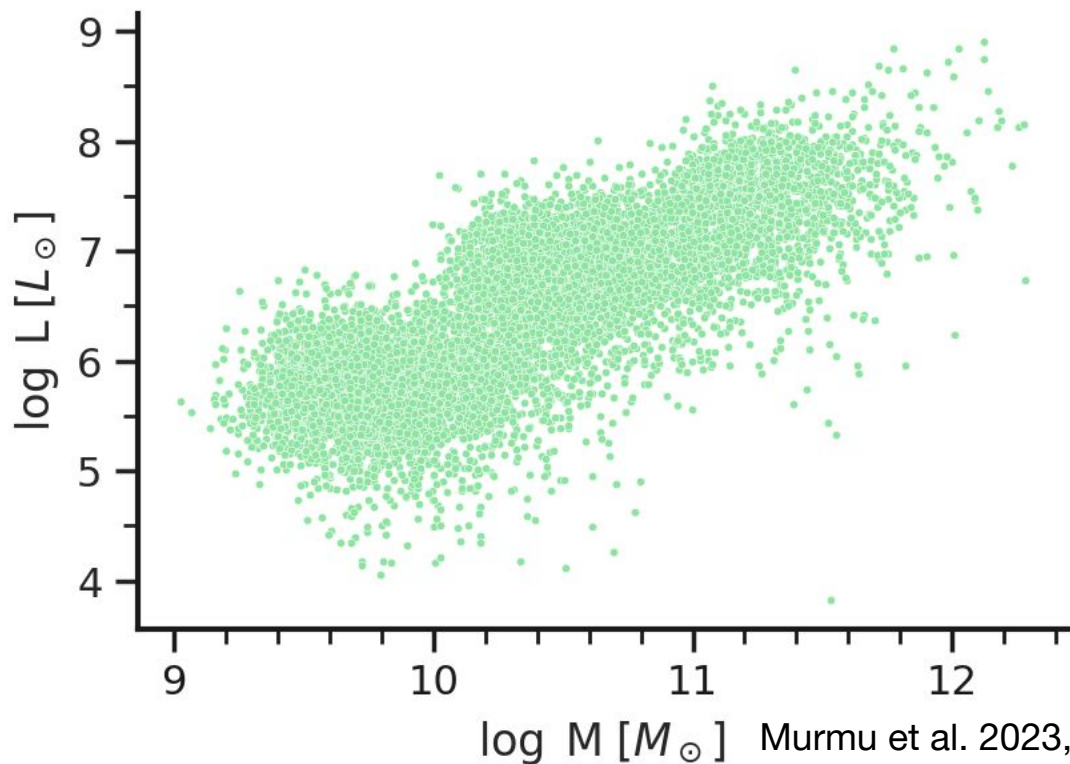


Murmu et al. 2021, MNRAS, 507(2), 2500



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

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

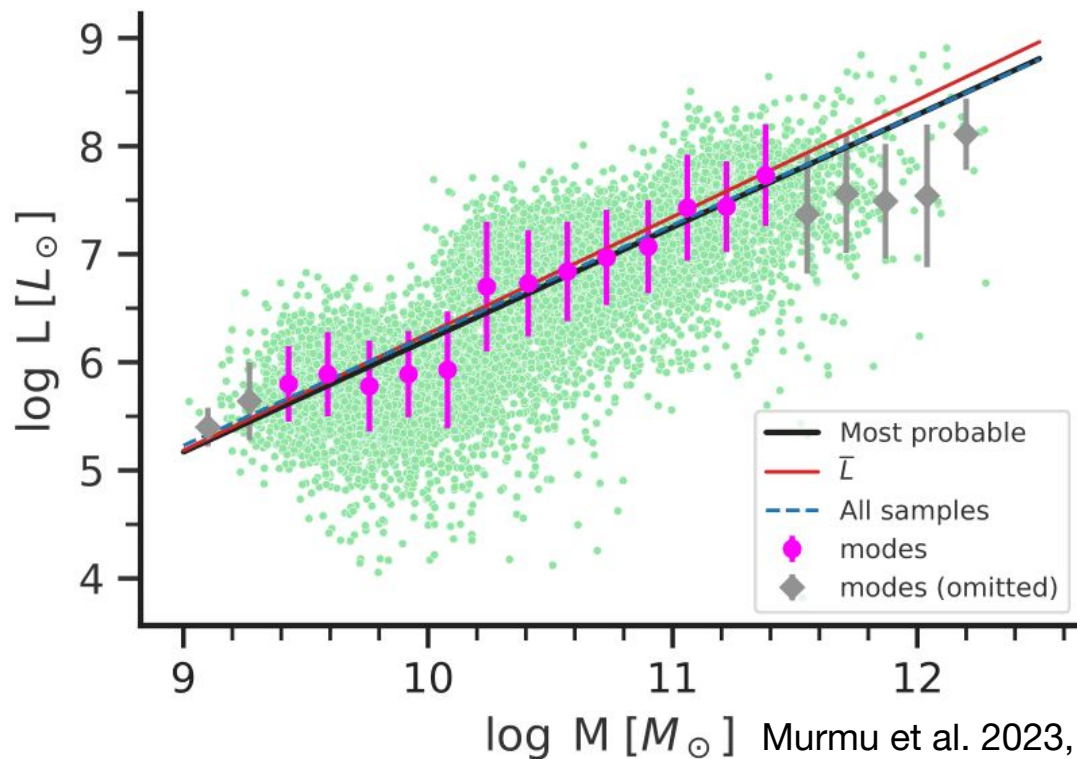


$[\text{C II}]_{158\mu\text{m}}$ line-emission exhibits scatter (refer to previous talk by Casavecchia)

Arises due to the multi-phase state of the ISM

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

[C II]_{158μm} line-luminosity scatter: SIMBA + SIGAME



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

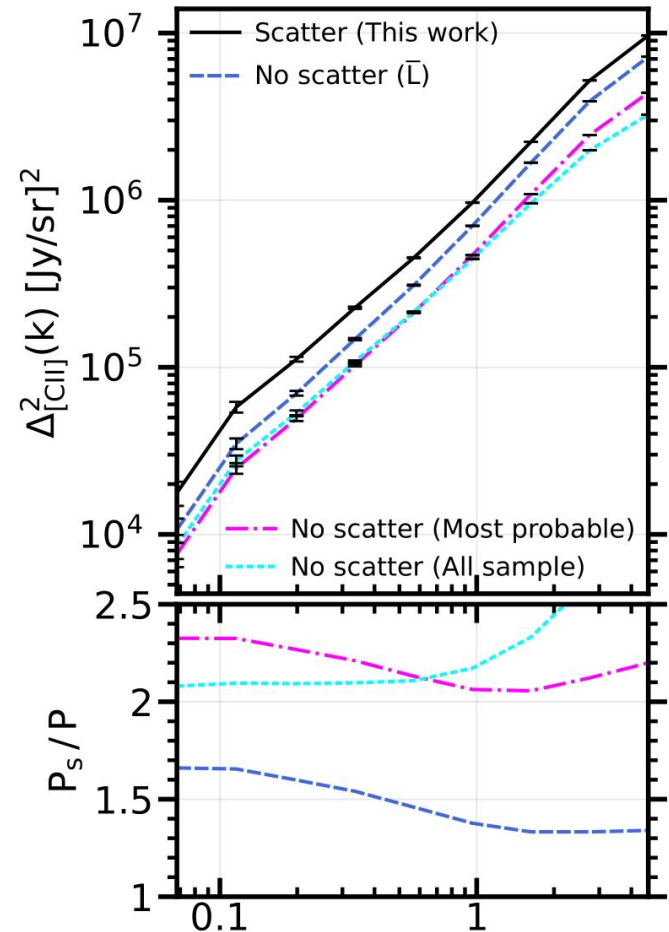
Murmu et al. 2023, MNRAS, 518(2), 3074

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

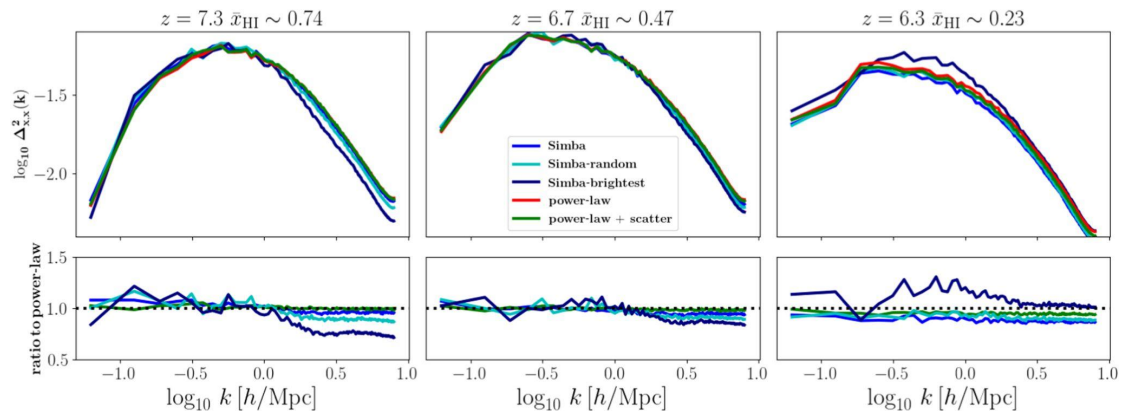
Line-luminosity scatter can significantly affect the large-scale power spectrum



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

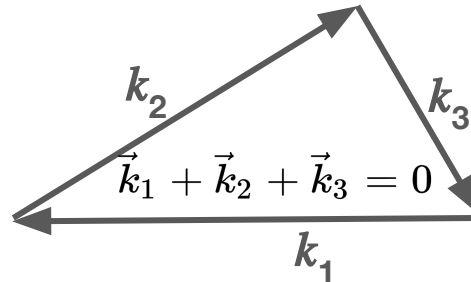
The ionization power spectrum is mostly unaffected, when astrophysical scatter is included in modelling reionization

- Ionization field is not directly observable, unlike the brightness temperature fluctuations of the $[\text{H I}]_{21\text{cm}}$ signal
- $[\text{H I}]_{21\text{cm}}$ 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



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

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

Usual reionization source model:

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

Simplistic model for astrophysical scatter:

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

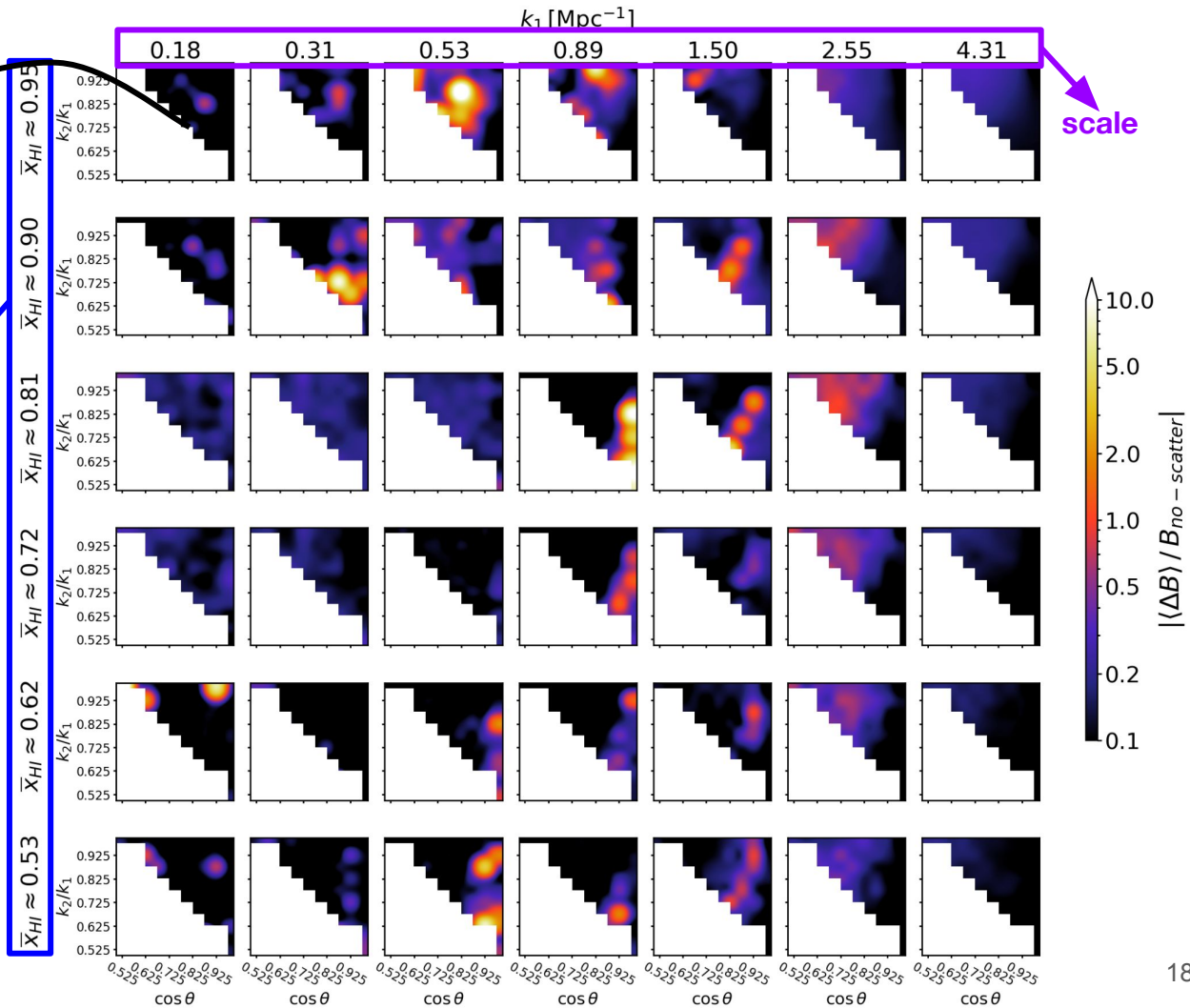
We generate 50 realizations of the $[\text{H I}]_{21\text{cm}}$ signal for each of six neutral fractions at $z=7.4$ that we considered (a total of 300 simulations were done)

Impact of scatter

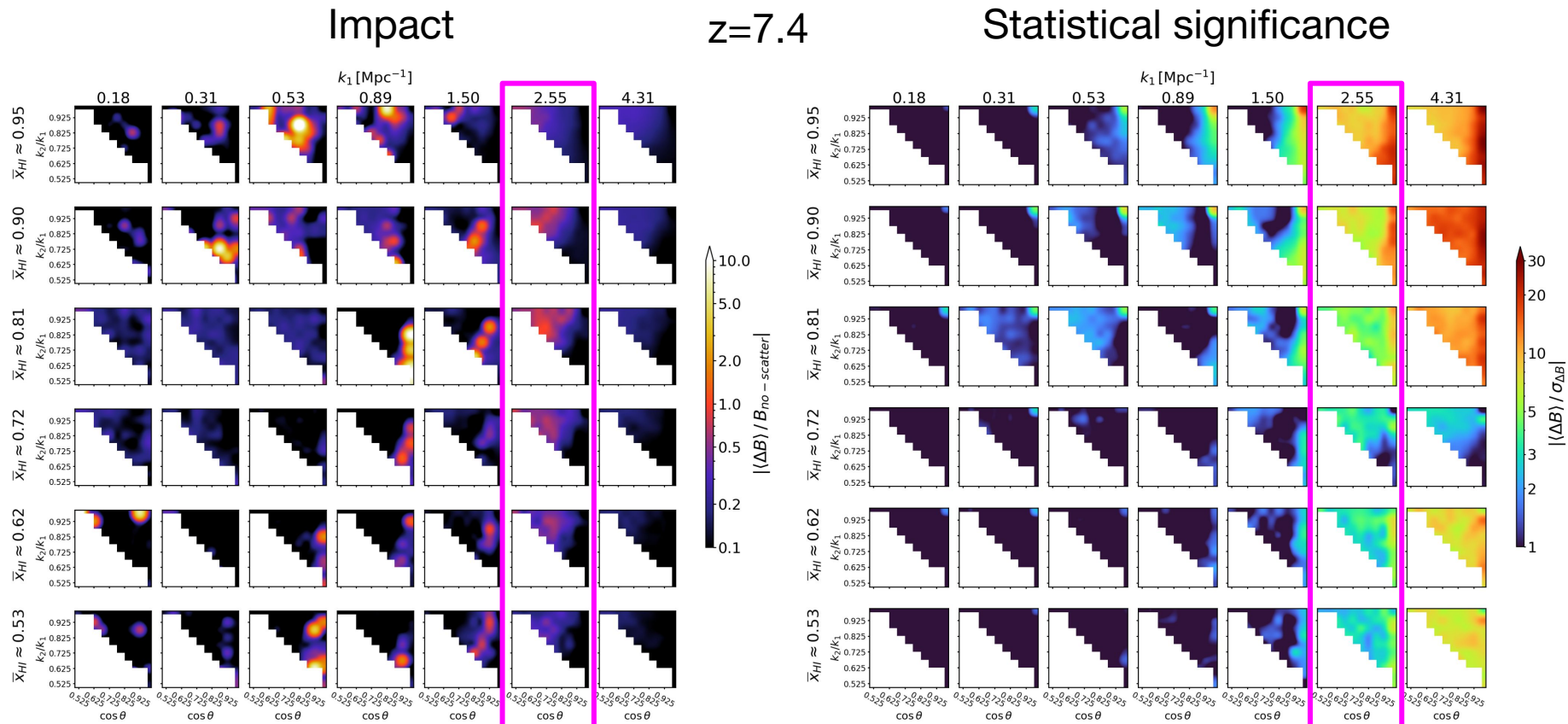
$$\langle \Delta B \rangle / B_{\text{no scatter}}$$

x_{HI}

A total of 300 realizations were simulated



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



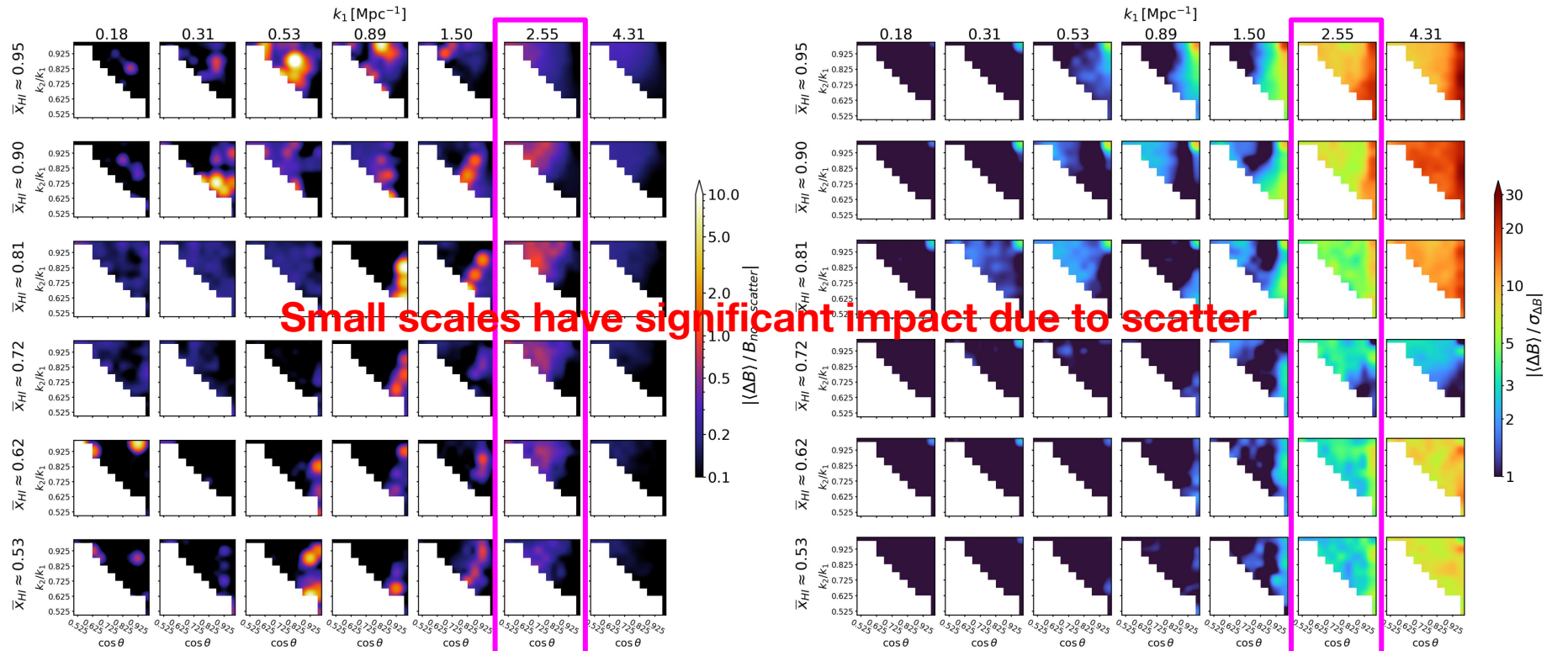
Murmu et al. 2023, arXiv: 2311.17062

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

Impact

$z=7.4$

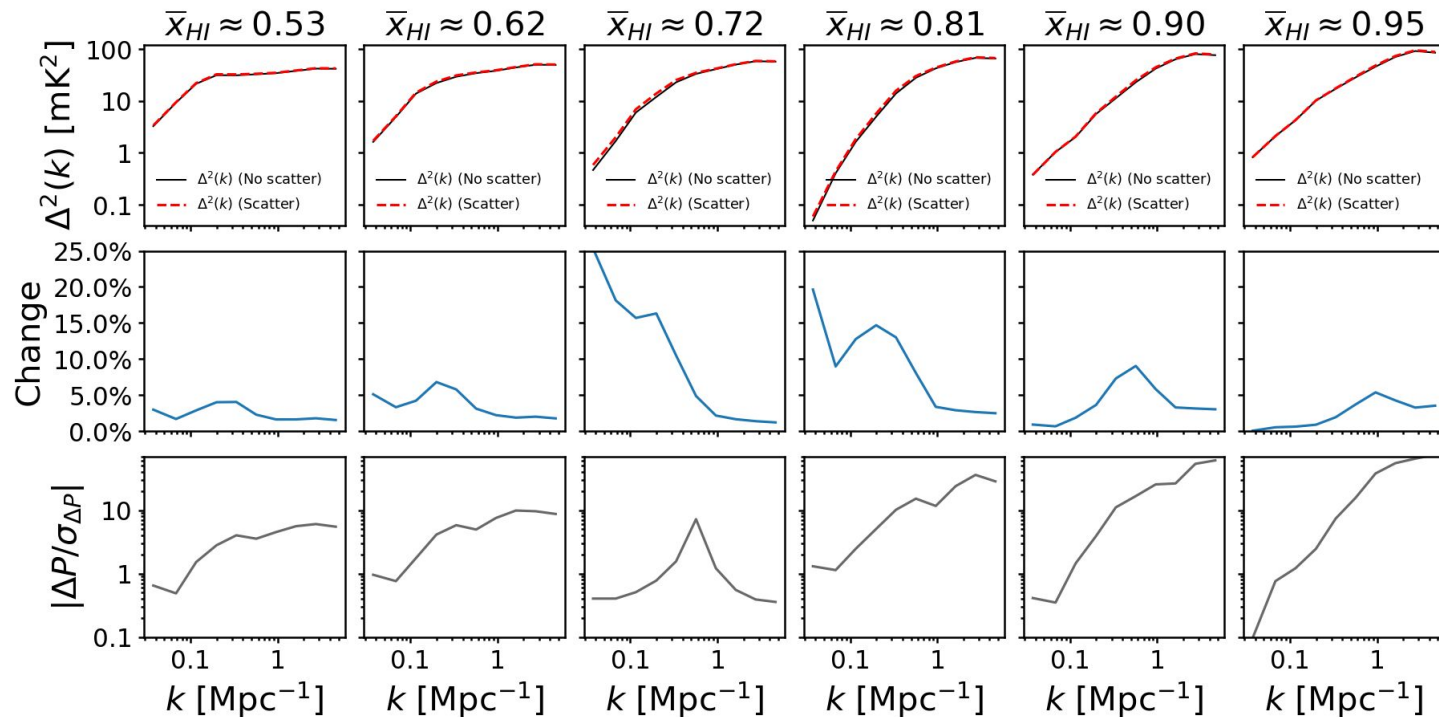
Statistical significance



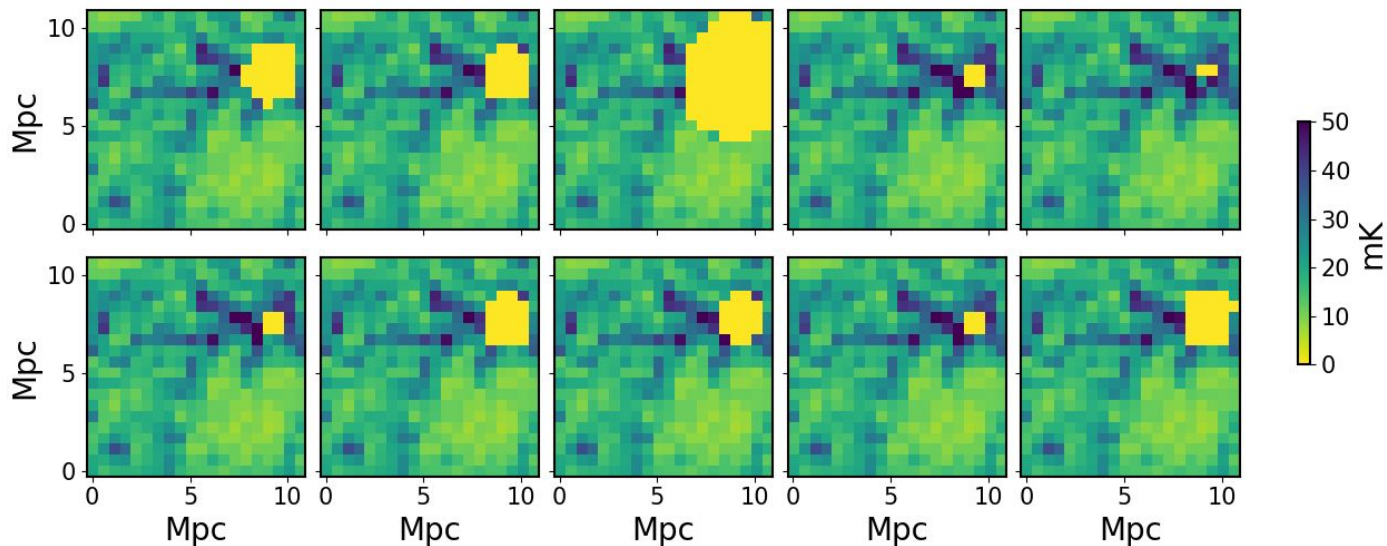
Murmu et al. 2023, arXiv: 2311.17062

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

$$\langle \tilde{\delta}(\mathbf{k}) \tilde{\delta}^*(\mathbf{k}') \rangle = V \delta_{k,k'} P(k) \quad \Delta^2(k) = \frac{k^3 P(k)}{2\pi^2}$$



Small-scale ionized bubbles

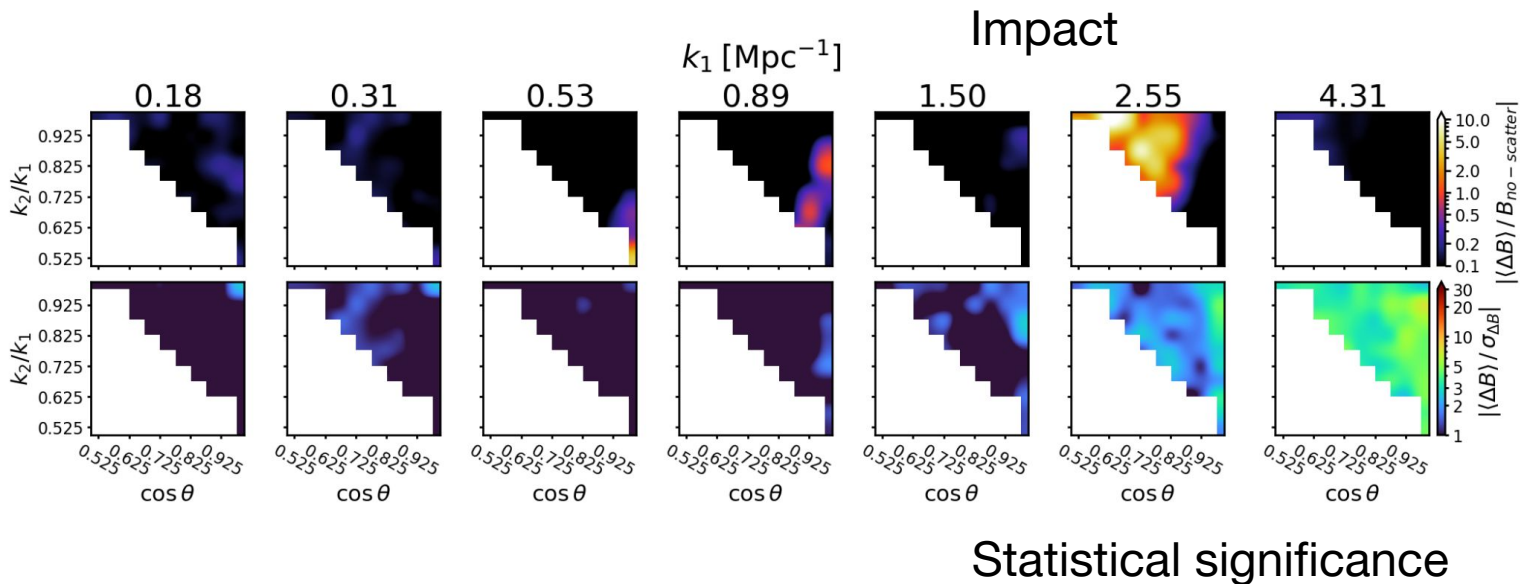


Murmu et al. 2023, arXiv: 2311.17062

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

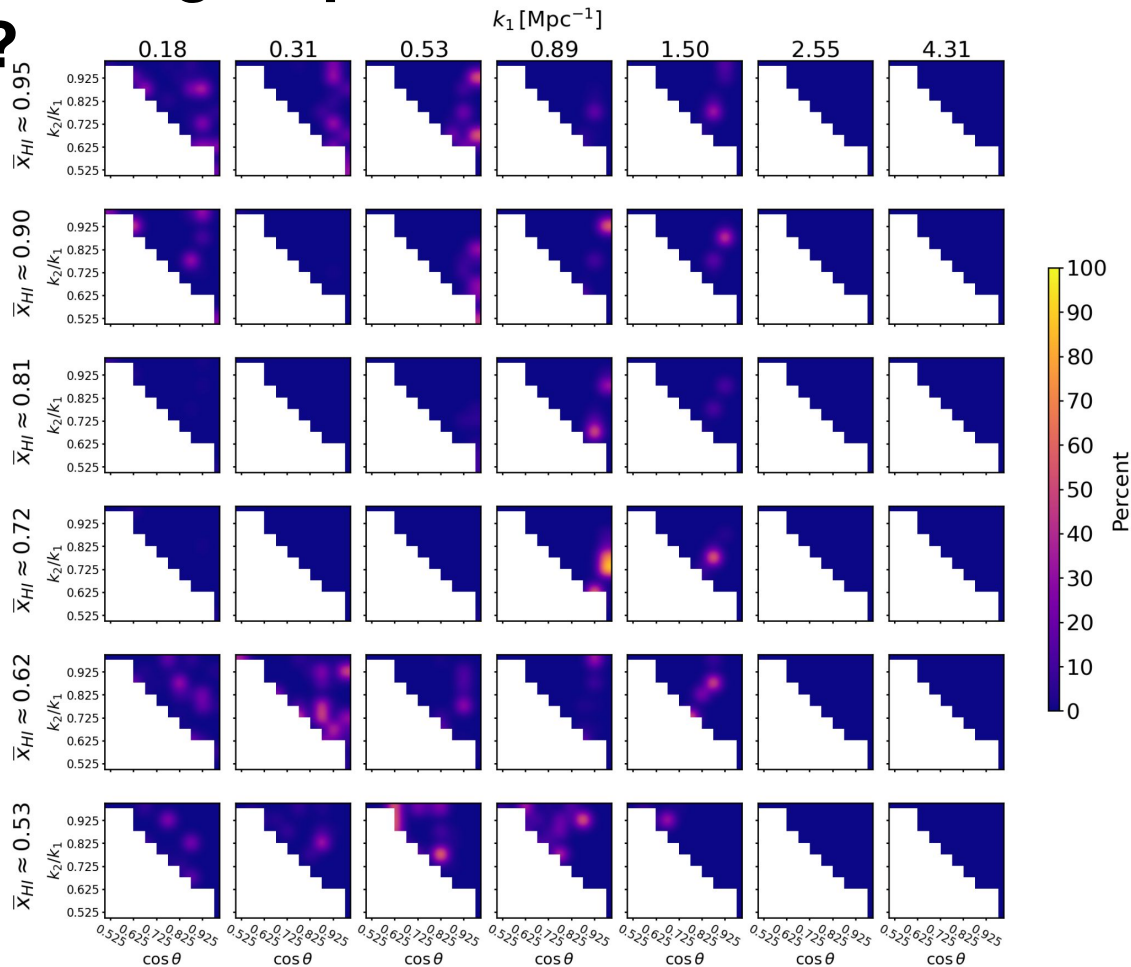
Impact of scatter at $z=10$, $x_{\text{HI}} \sim 0.8$

Additional 50 realizations were simulated



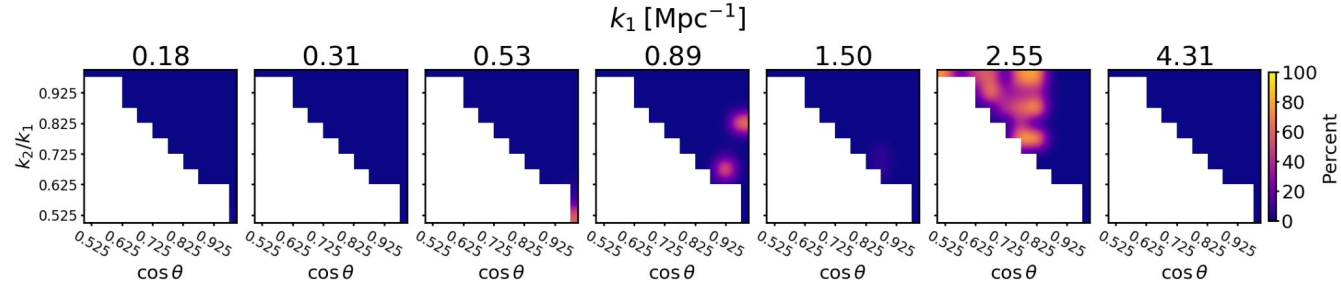
Can scatter in SFR induce sign flip in $[\text{H I}]_{21\text{cm}}$ bispectrum?

Frequency of sign flip at $z=7.4$



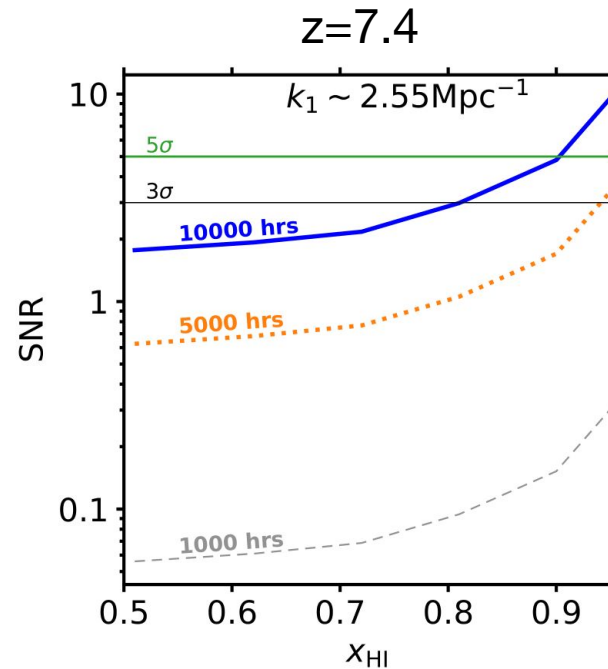
Can scatter in SFR induce sign flip in $[\text{H I}]_{21\text{cm}}$ bispectrum?

Frequency of sign flip at $z=10$, $x_{\text{HI}} \sim 0.8$



At small-scales frequency of sign flip can be significant

Detectability



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

$[\text{H I}]_{21\text{cm}}$ \times 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 $[\text{H I}]_{21\text{cm}}$ maps

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

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

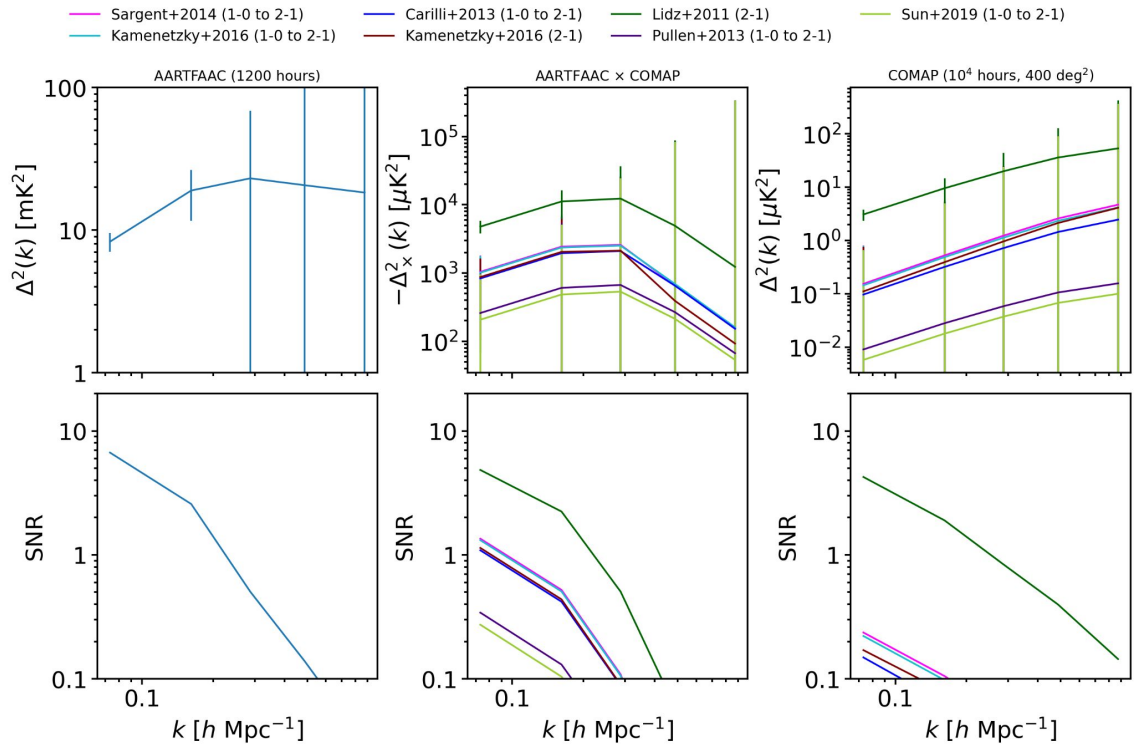
Uncertainty in the cross-power spectrum

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

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

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

Detectability of the cross-power spectrum



$z \sim 7.2$

AARTFAAC ~ 1200 hrs
 COMAP ~ 10000 hrs, 400 deg²

- Constrain astrophysical parameters
- Extend this for lower redshifts

Summary

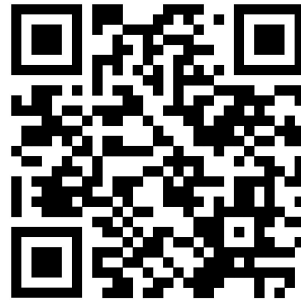
- Line intensity mapping is novel technique to probe the large-scale structures of the Universe, which provides a unique way to peer into the Epoch of Reionization
- Light-cone effect can significantly affect the large-scale cross-power spectrum
- Line-luminosity scatter significantly affects the large-scale galaxy LIM power spectrum
- At the small scales, the $[\text{H I}]_{21\text{cm}}$ 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