Forecasting the CO-21cm cross-correlation signal from the EoR using line-intensity mapping surveys

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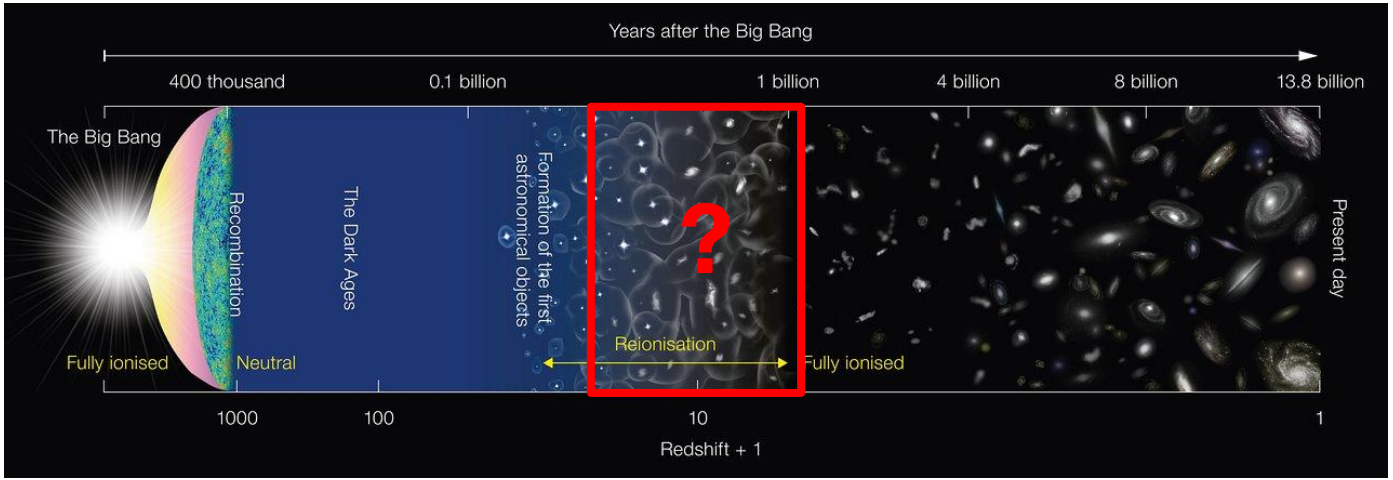
The Epoch of Reionization (EoR)

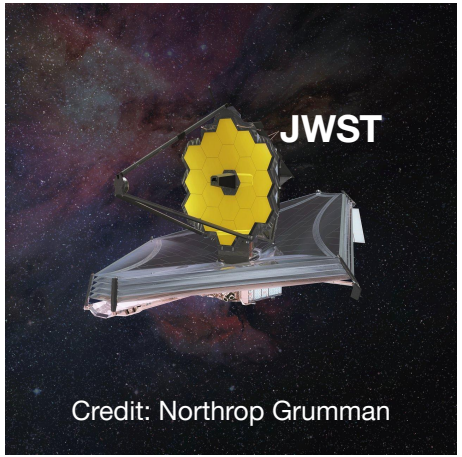


Credit: NAOJ

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

How to probe the EoR universe?

Probing the EoR: galaxies

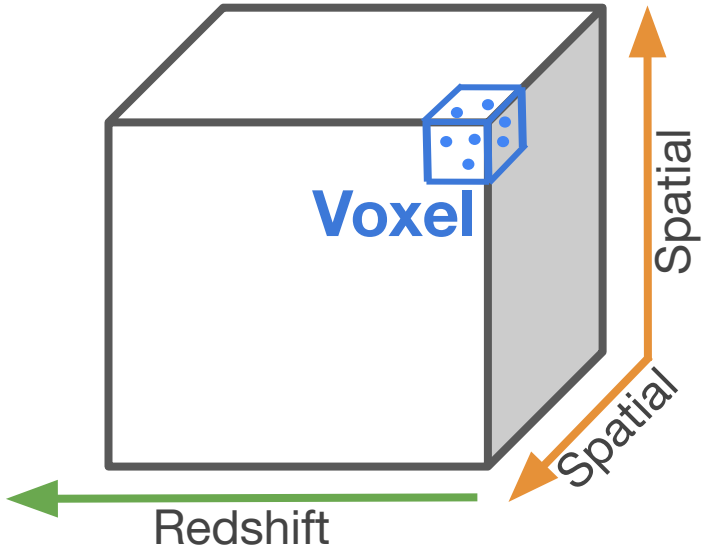


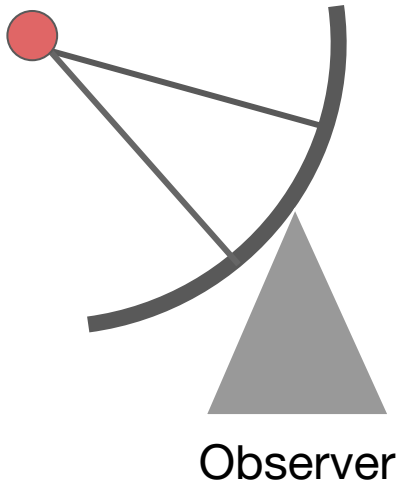
Challenges!

- Demanding sensitivity limits and angular resolutions
- Expensive to operate, therefore it becomes impractical to map large galaxy samples

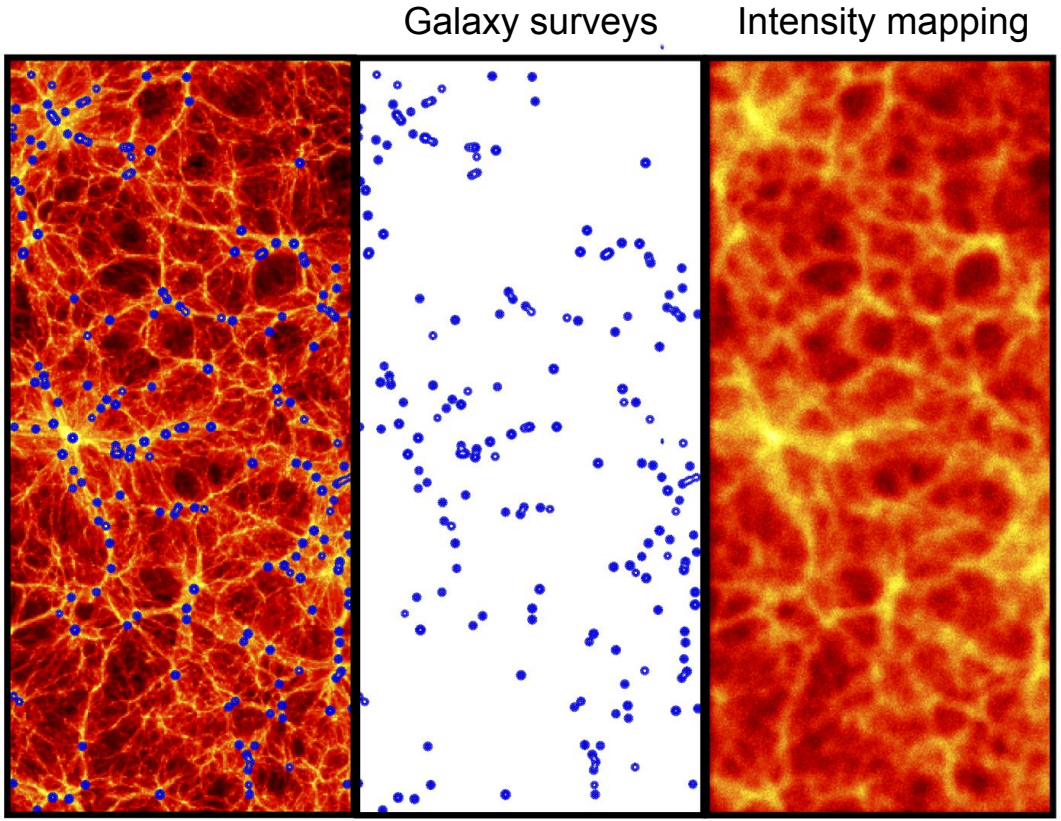
Line-intensity mapping (LIM)

LIM can probe the large-scale structures by detecting the integrated flux of numerous sources from a comparatively small region (Voxel)



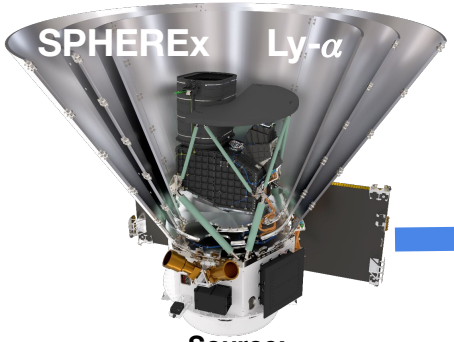


Line-intensity mapping (LIM)

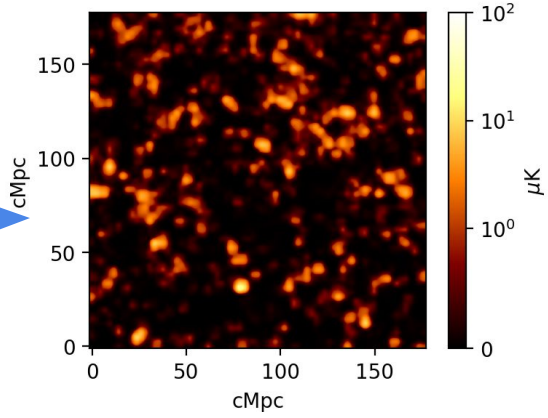


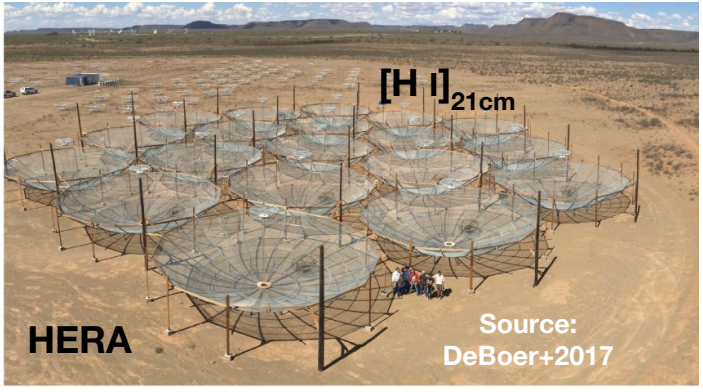
(Source: https://spherex.caltech.edu/page/the-origin-and-history-of-galaxies)

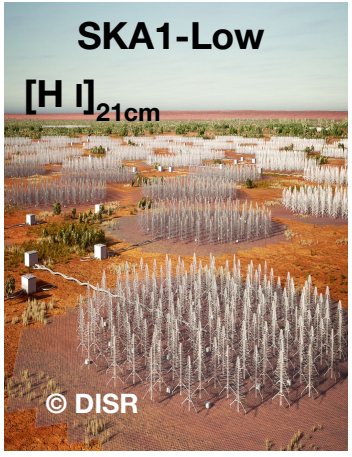
Probing the EoR with Intensity Mapping: galaxies and IGM

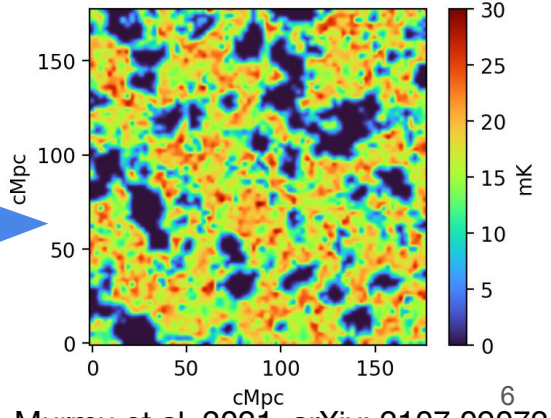


Source:
https://spherex.caltech.edu/page/instrument









Murmu et al. 2021, arXiv: 2107.09072

Observable summary statistics

Modelling (analytical/numerical) of observable summary statistics (e.g. power spectrum, cross-power spectrum etc.) is essential to interpret these LIM observations

Cross-correlation signal

$$\langle \tilde{A}(k)\tilde{B}^{*}(k')\rangle = V\delta_{k,k'}P_{AB}(k)$$

Cross-correlation can capture information about the relative phase difference between the two signals observed

Cross-correlation signal

Observed lines will consist of signal, instrumental noise and foregrounds

$$A \equiv s_a + n_a + f_a \qquad B \equiv s_b + n_b + f_b$$

Signal Noise Foreground

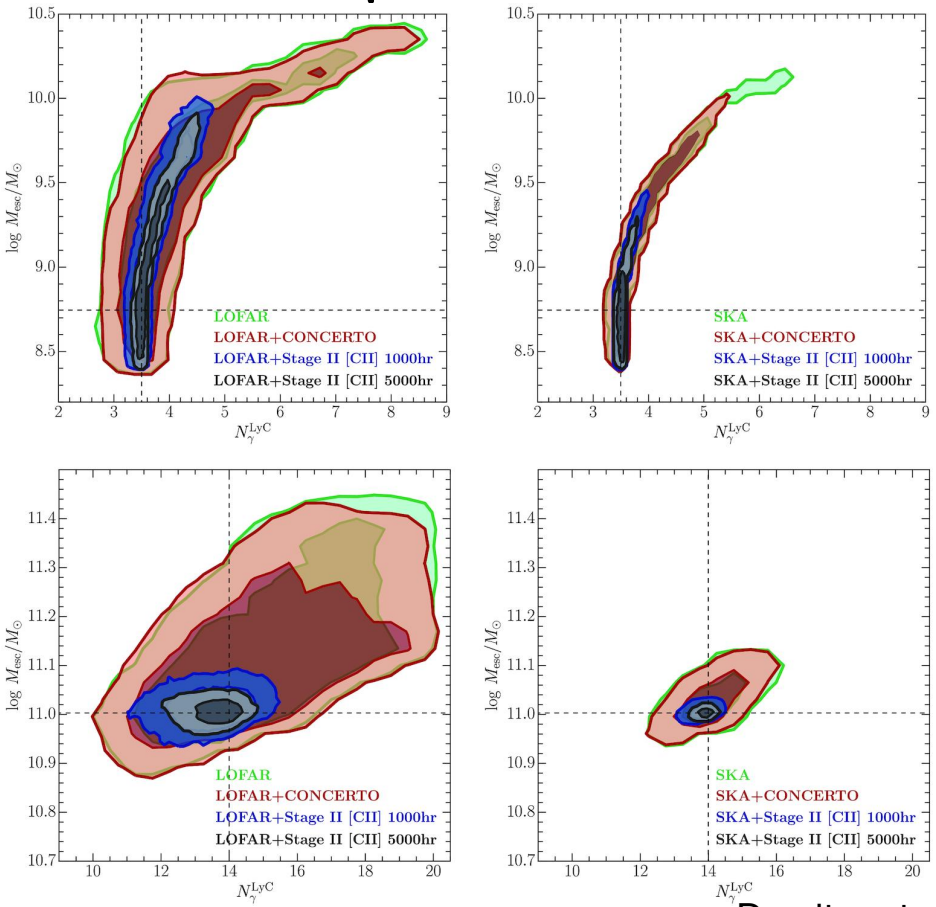
Cross-correlation signal

$$\langle \tilde{A}\tilde{B}^* \rangle = \langle \tilde{s}_a \tilde{s}_b^* \rangle + \langle \tilde{s}_a \tilde{n}_b^* \rangle + \langle \tilde{s}_a \tilde{f}_b^* \rangle + \langle \tilde{s}_b \tilde{n}_a^* \rangle + \langle \tilde{s}_b \tilde{f}_a^* \rangle + \langle \tilde{n}_a \tilde{n}_b^* \rangle + \langle \tilde{n}_a \tilde{f}_b^* \rangle + \langle \tilde{n}_b \tilde{f}_a^* \rangle + \langle \tilde{f}_a \tilde{f}_b^* \rangle$$

$$\simeq \langle \tilde{s}_a \tilde{s}_b^* \rangle$$

Fronenberg & Liu 2024 2024 *ApJ* 975 222

Constraints from [C II]$_{158\mu m}$ x [H I]$_{21cm}$ cross-power spectrum



M_{esc} = Minimum halo mass from which LyC photons escape

N_γ^{LyC} = Number of ionizing photons from halos

Dumitru et al 2019 MNRAS 485 3486-3498

CO LIM signal

- CO line emission traces molecular hydrogen (H_2) which fuels star formation in galaxies

- It is a potential candidate for probing the Universe with LIM instruments

- The CO Mapping Array Project (COMAP) has placed upper limits on the CO(1-0) power spectrum at z ~ 3 (Stutzer et al 2024 A&A 691 A336)

- The CO signal from the EoR Universe is not well probed yet

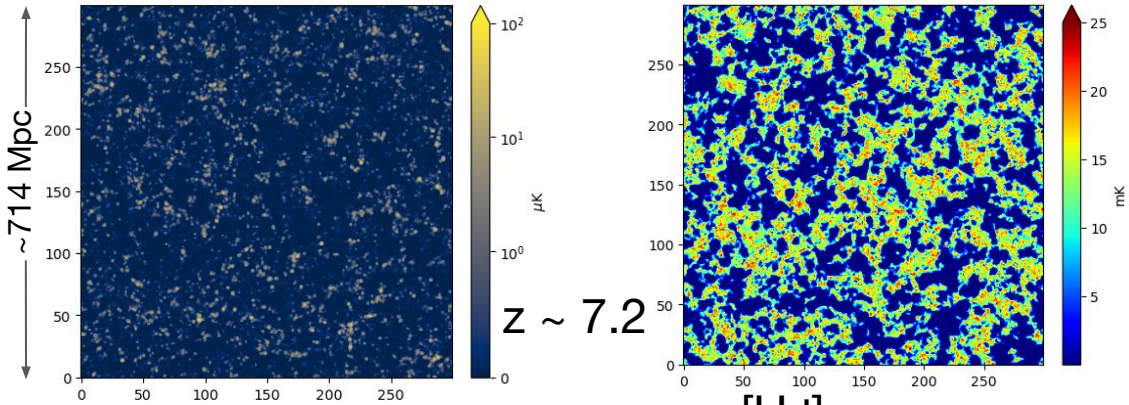
CO x [H I]$_{21cm}$ cross-power spectrum

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

- CO line luminosities are painted to the halos identified in the simulations using the following relations:

$$L_{\rm FIR} \propto {\rm SFR}(M_{\rm h}, z) \quad \text{and} \quad \log L_{\rm FIR} = \alpha \log L'_{\rm CO} + \beta$$

- $L_{\rm FIR}$ and $L_{\rm CO}$ are proxies for star-formation and presence of molecular gas (H_2) in galaxies



Uncertainty in cross-power spectrum

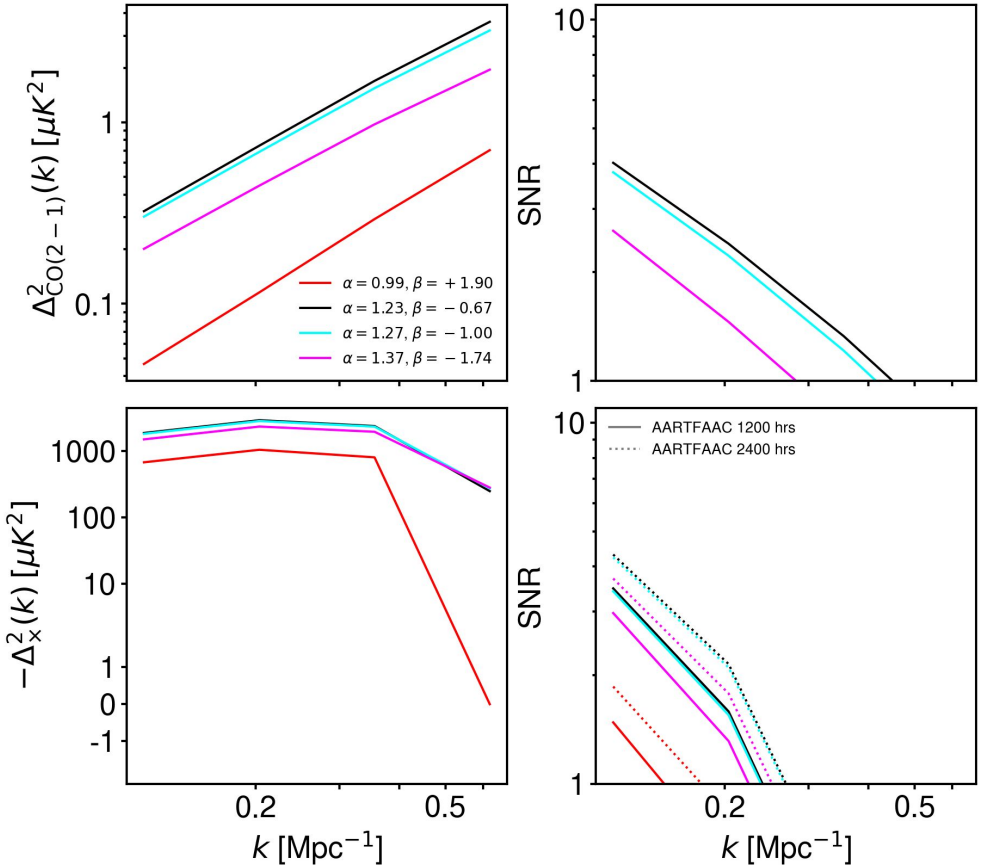
CO survey with COMAP and [H I]$_{21cm}$ survey with AARTFAAC is assumed with an overlap of 12 deg^2 survey area

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

$P_{\mathrm{N},21\mathrm{cm}}$ 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)

CO(2-1) x [H I]$_{21cm}$ cross-power spectrum

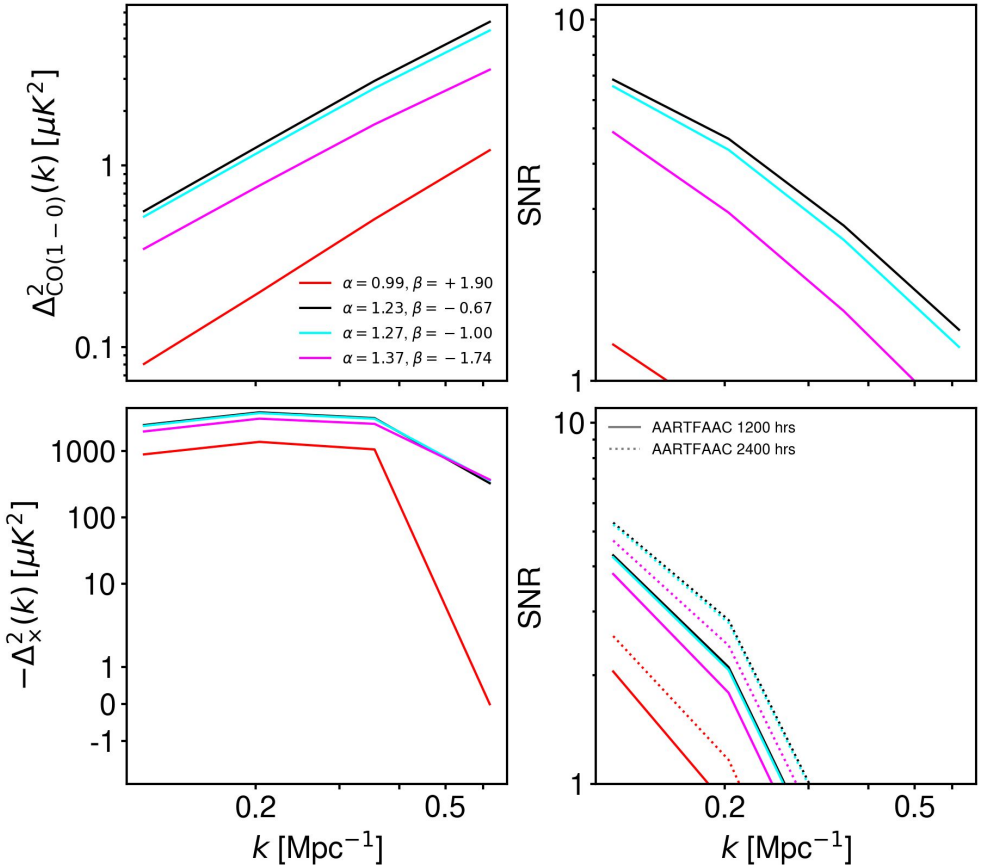


Murmu+2025 (In prep.)

Cross-correlation can improve the detection prospects of the CO LIM signal from the EoR

z ~ 7.2

CO(1-0) x [H I]$_{21cm}$ cross-power spectrum



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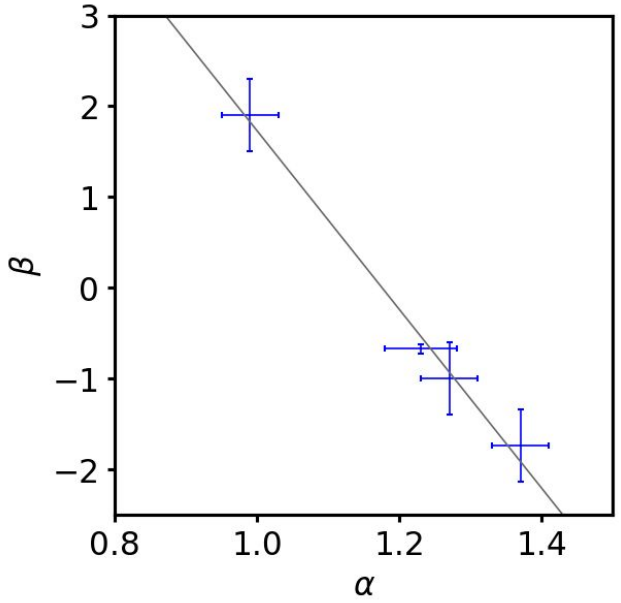

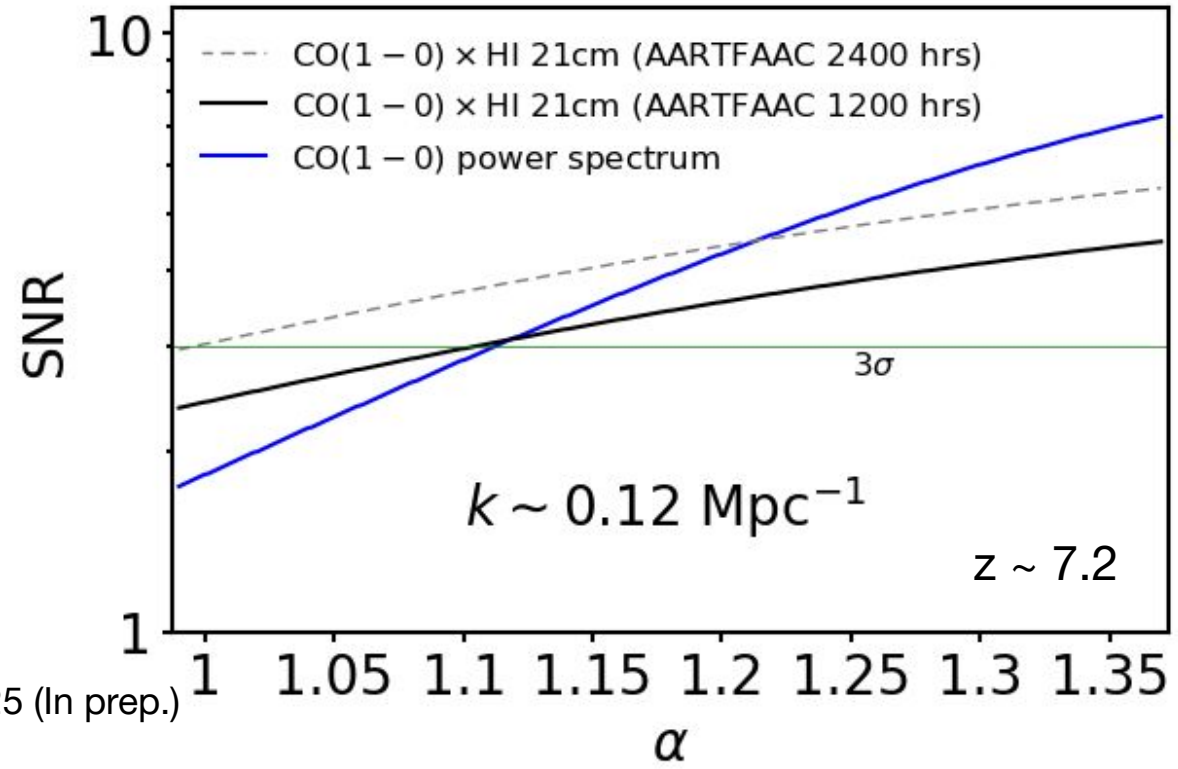

Murmu+2025 (In prep.)

Cross-correlation can improve detectability for the weak CO emission models

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

- The CO line emission is a potential candidate for LIM tracer for surveys such as COMAP

- Cross-correlations can boost the detectability of the CO LIM signal from the EoR

Future scope

- Constrain the CO emission models and galaxy populations considering various survey scenarios with power spectrum and cross-power spectrum

- Investigate these prospects further for various reionization histories

Thank you !