Title: Mapping the Universe at 21 cm

Speakers: Seth Siegel

Series: Cosmology & Gravitation

Date: October 03, 2022 - 12:00 PM

URL: https://pirsa.org/22100094

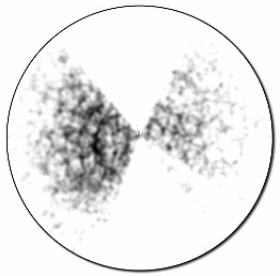
Abstract: Mapping the intensity of the 21 cm emission line from neutral hydrogen (HI) is a promising technique for characterizing the 3D matter distribution over large volumes of the Universe and out to high redshifts. The Canadian Hydrogen Intensity Mapping Experiment (CHIME) is a radio interferometer specifically designed for this purpose. CHIME recently reported the detection of 21 cm emission from large-scale structure between redshifts 0.8 and 1.4. This was achieved by stacking maps of the radio sky, constructed from 102 nights of CHIME data, on the angular and spectral locations of galaxies and quasars from the eBOSS clustering catalogs. In this talk, I will introduce the experiment and provide an overview of the detection. I will describe key aspects of both the data processing pipeline and the simulation pipeline used to model the stacked signal. I will discuss the implications of the detection. Finally, I will evaluate the prospects for using CHIME -- and it's successor, the Canadian Hydrogen Observatory and Radio-transient Detector (CHORD) -- to measure the power spectrum of 21 cm emission, identify the signature of baryon acoustic oscillations, and constrain dark energy.

Zoom link: https://pitp.zoom.us/j/94362295704?pwd=NnQxa1pteWJVTzVBTVFYUmlsWnlVUT09

Mapping the Universe at 21 cm

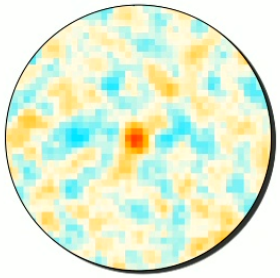
Seth Siegel
Research Associate
McGill University

Outline

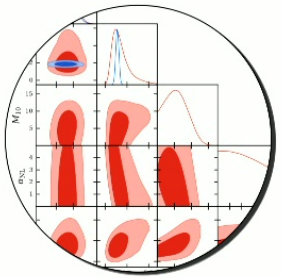


Motivation

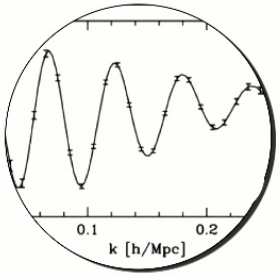
CHIME



Detection

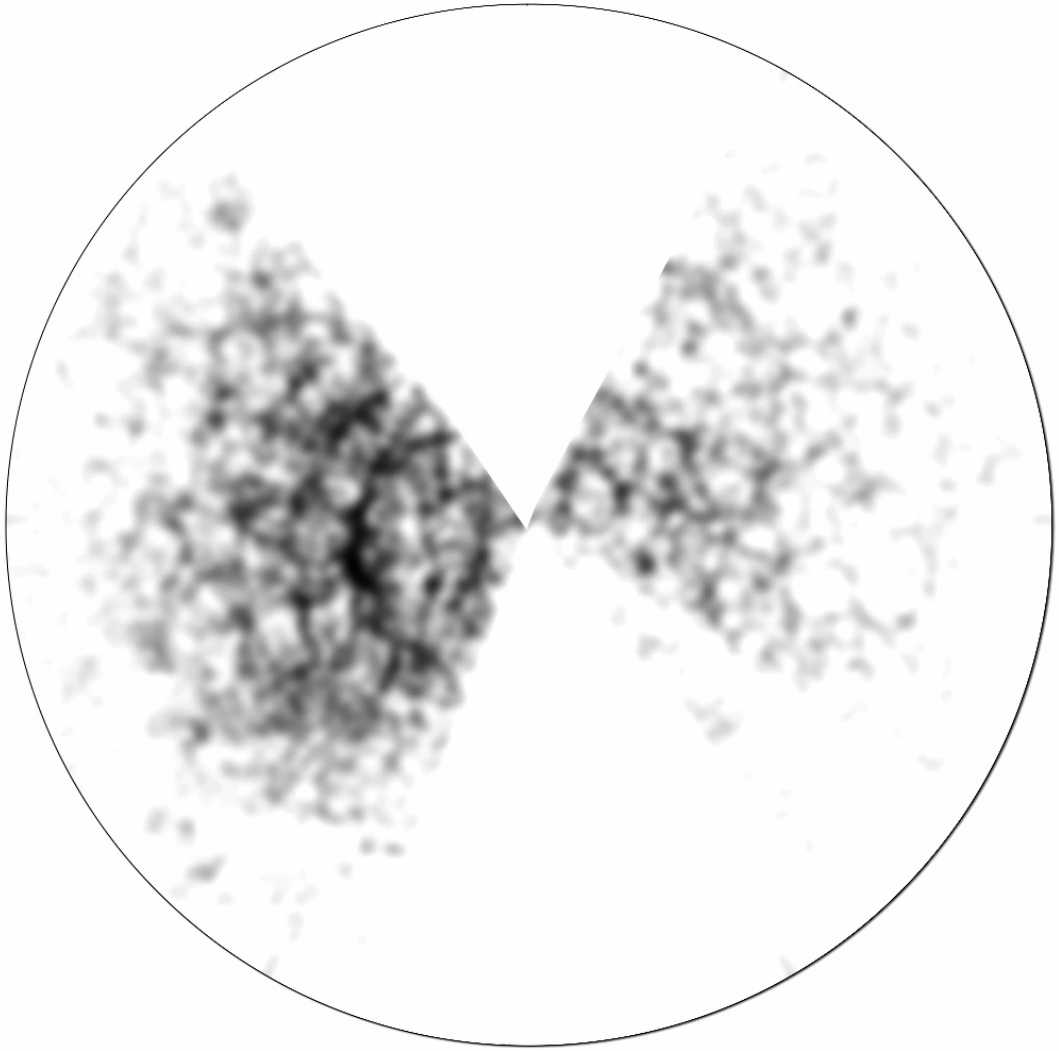


Interpretation



Outlook

21 cm Intensity Mapping: A Promising Probe of Cosmology



Outstanding Questions in Cosmology

Is General Relativity a complete description of gravity?

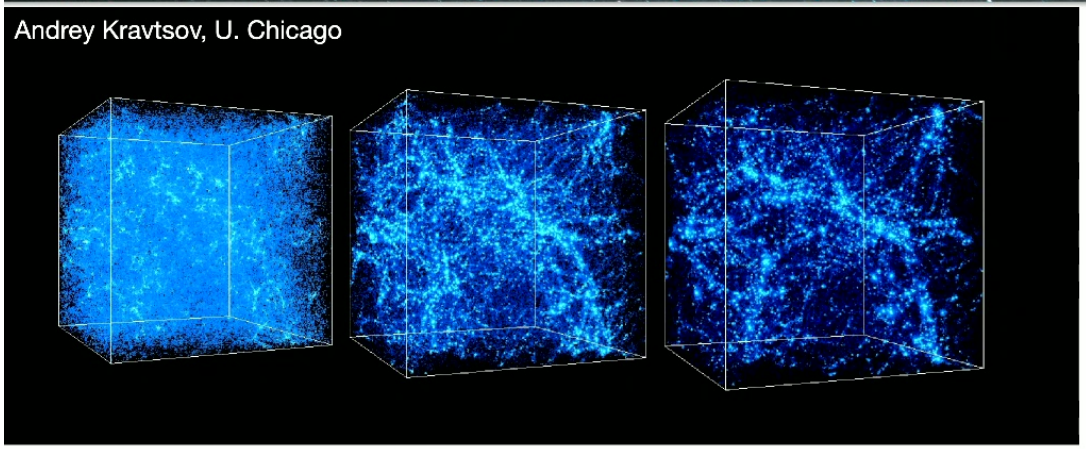
Is inflation the correct description of the early Universe?

What is the nature of dark matter?

What is causing the accelerated expansion of the Universe?

Significant progress can be made on all fronts by mapping the large-scale structure (LSS) of the Universe out to redshifts $z \approx 6$.

Outstanding Questions in Cosmology



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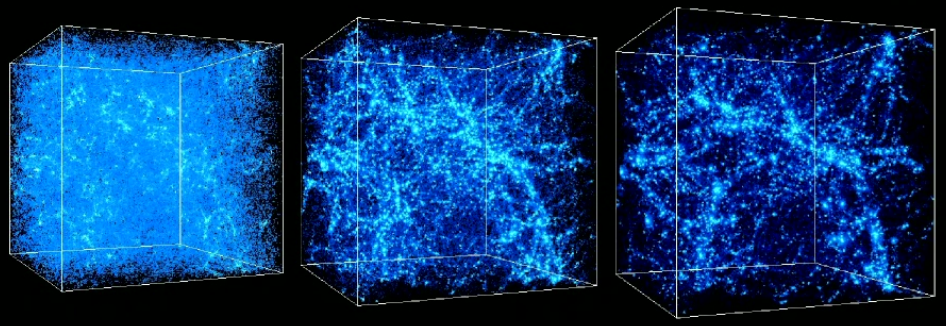
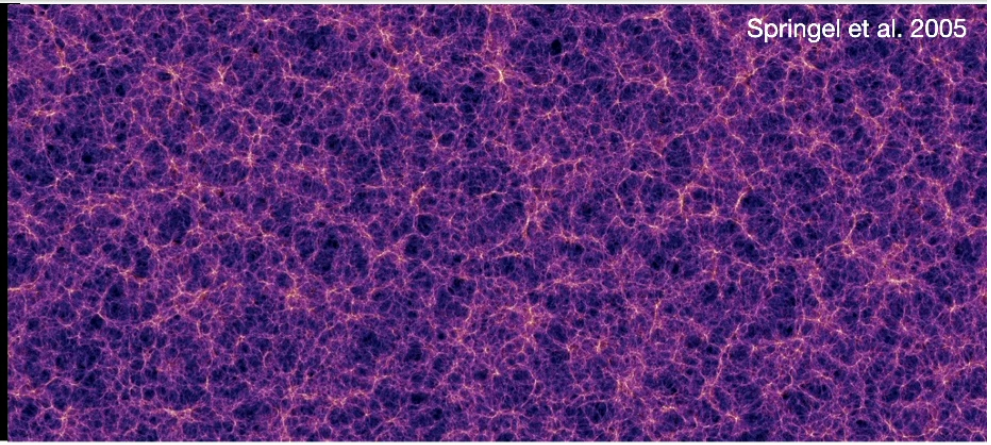
Outstanding Questions in Cosmology

Andrey Kravtsov, U. Chicago





Springel et al. 2005

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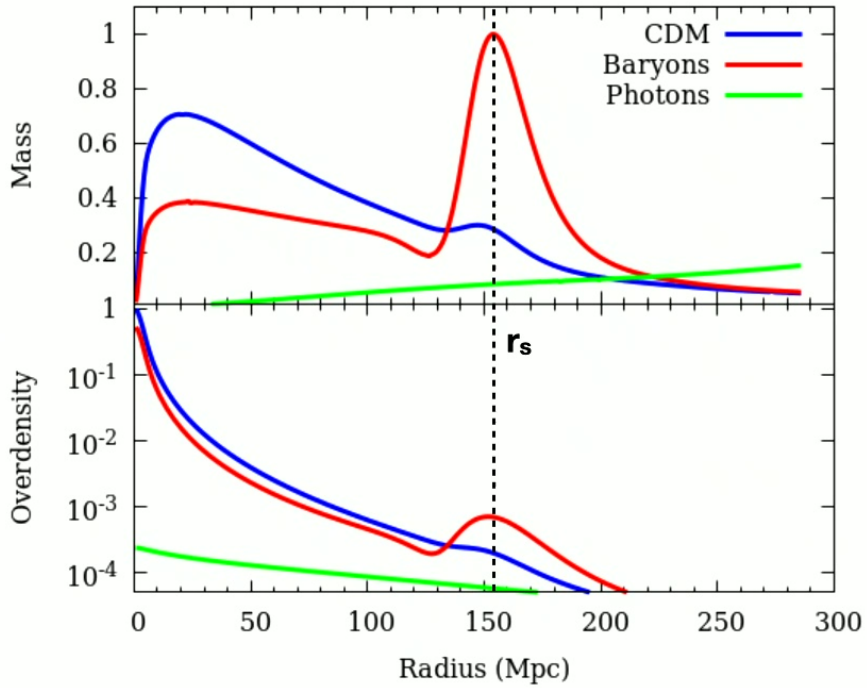
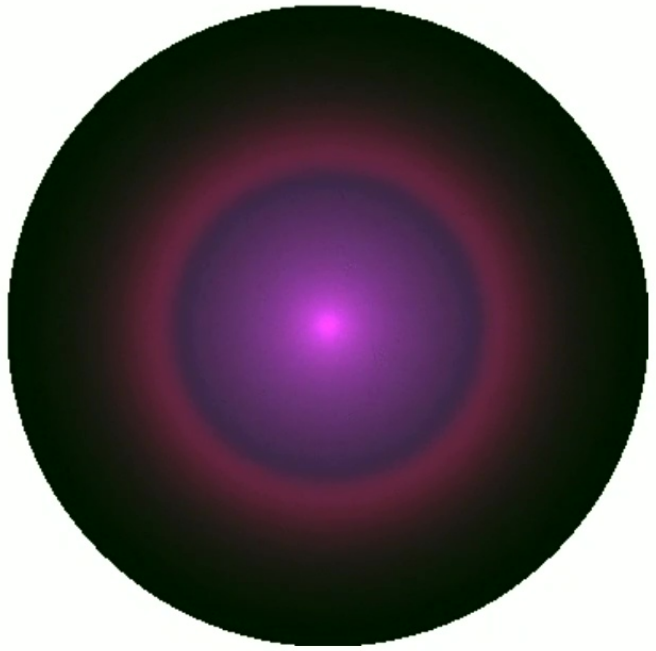
Baryon Acoustic Oscillations (BAO)

Initial density perturbations result in sound waves that propagate in the baryon-photon fluid of the early universe. These are “frozen in” at recombination, leaving acoustic peaks in the CMB and matter power spectrum.

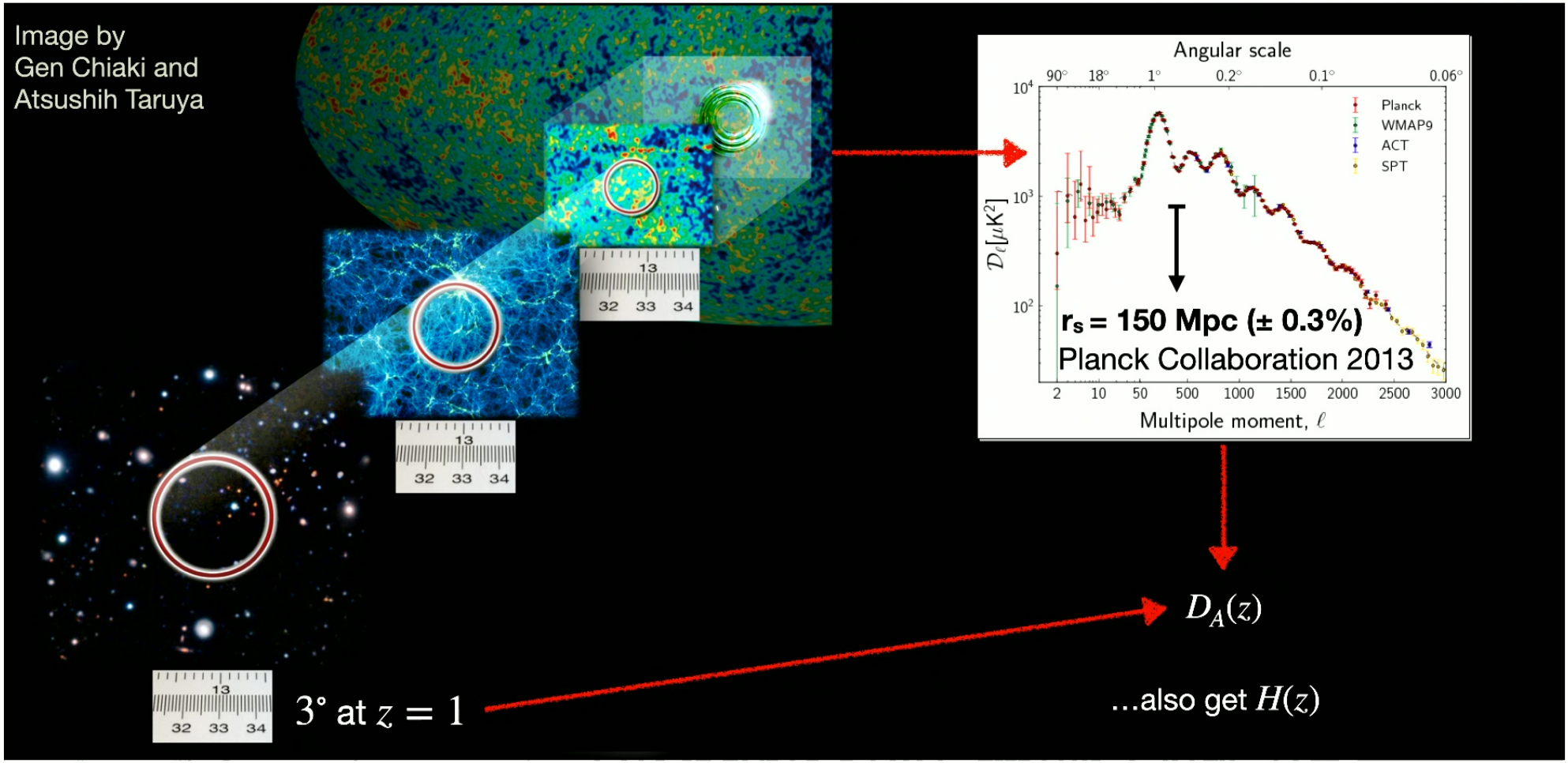
Evolution of a primordial density perturbation





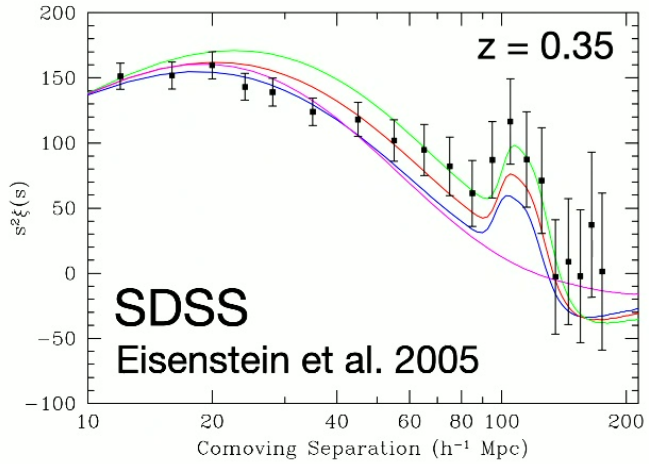
Movies by Adam Hincks: http://adh-sj.info/bao_cmb.php

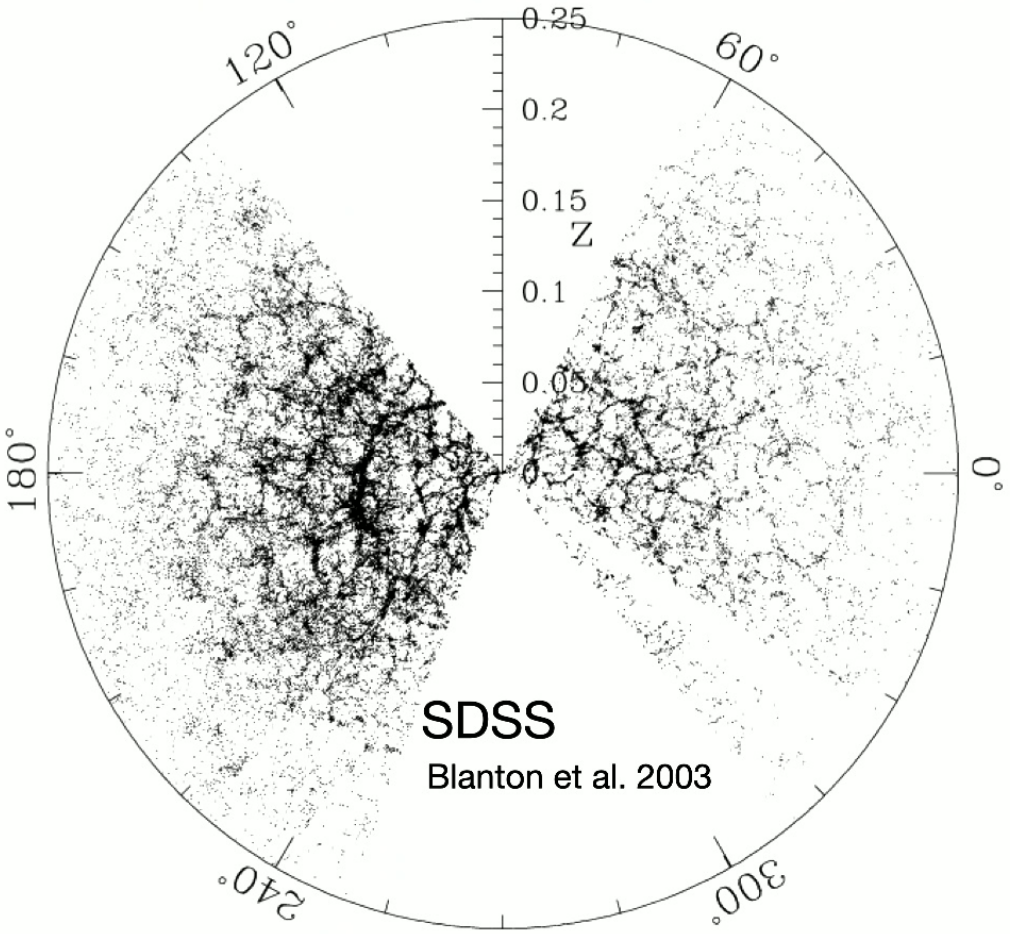
BAO as Cosmological Ruler



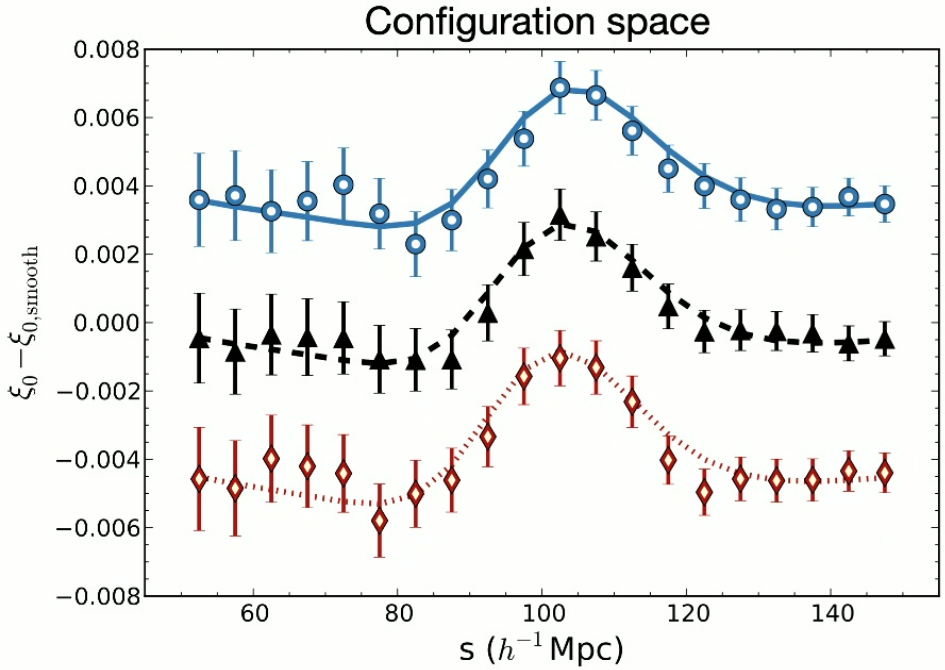
Spectroscopic Galaxy Surveys

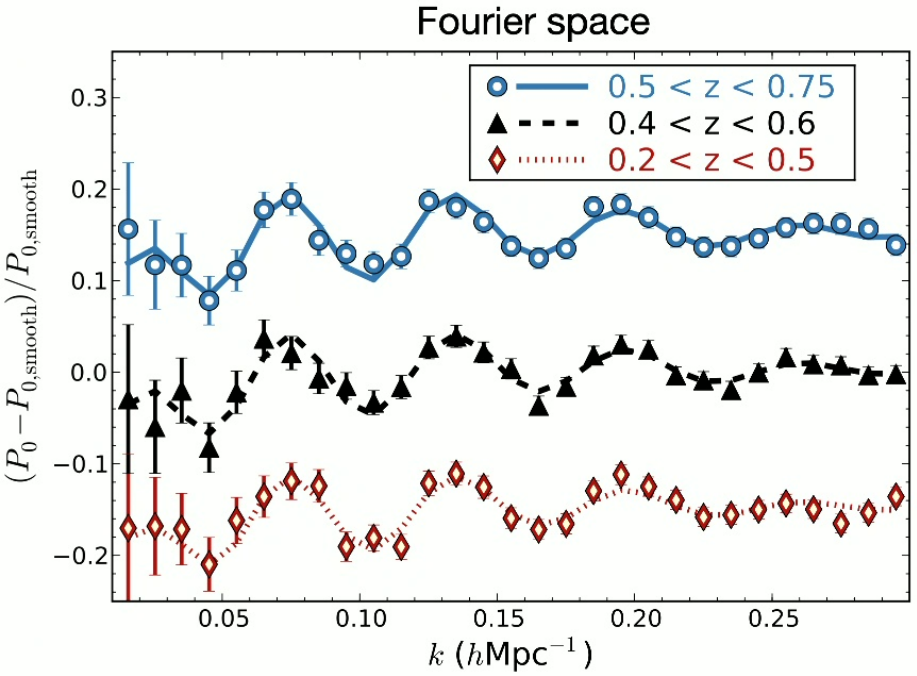
- Carry out an imaging survey
- Select targets for follow up
- Perform spectroscopic follow up of each object to obtain redshift





BAO in the Galaxy Correlation Function / Power Spectrum



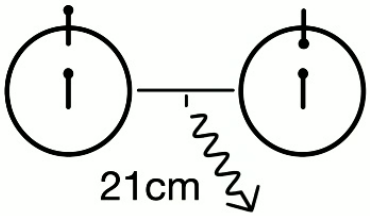


BOSS

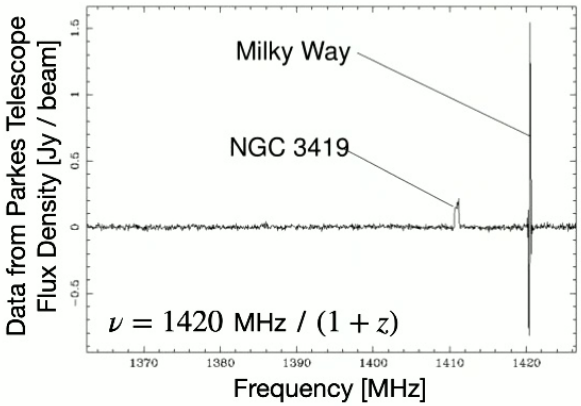
Alam et al. 2017

21 cm Intensity Mapping

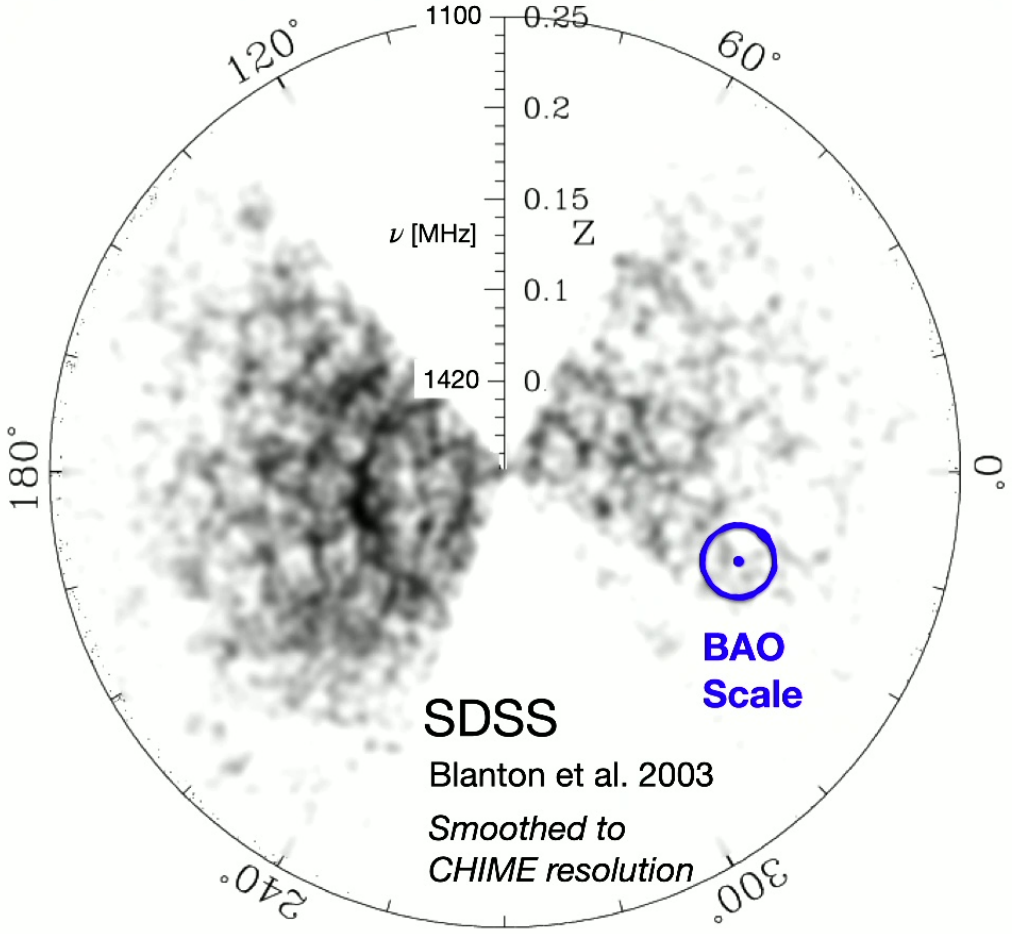
- Use the hyperfine transition of neutral hydrogen (HI)



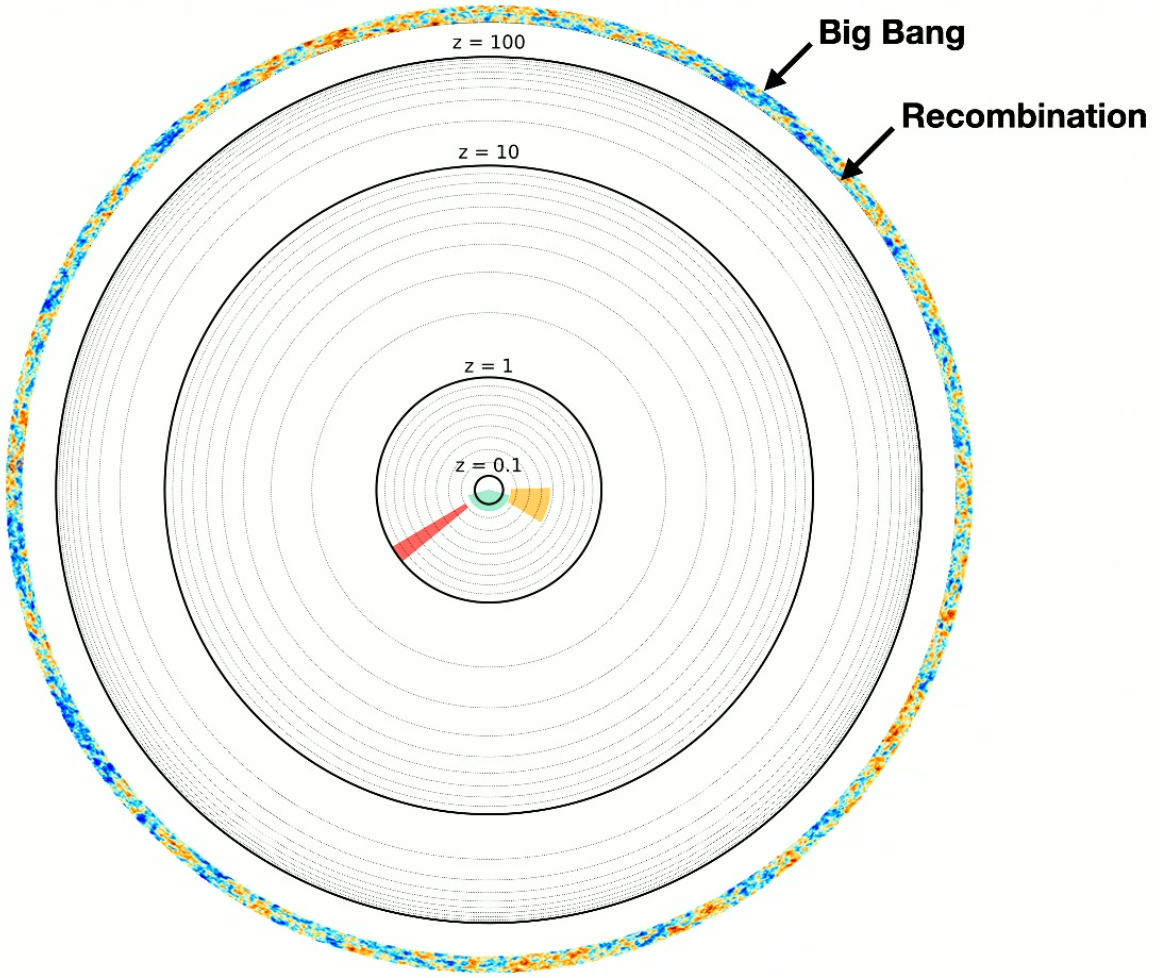
- Make low-res maps of radio sky over large bandwidth
  - Radio frequency maps to redshift:



- Efficient way to map large-scale structure

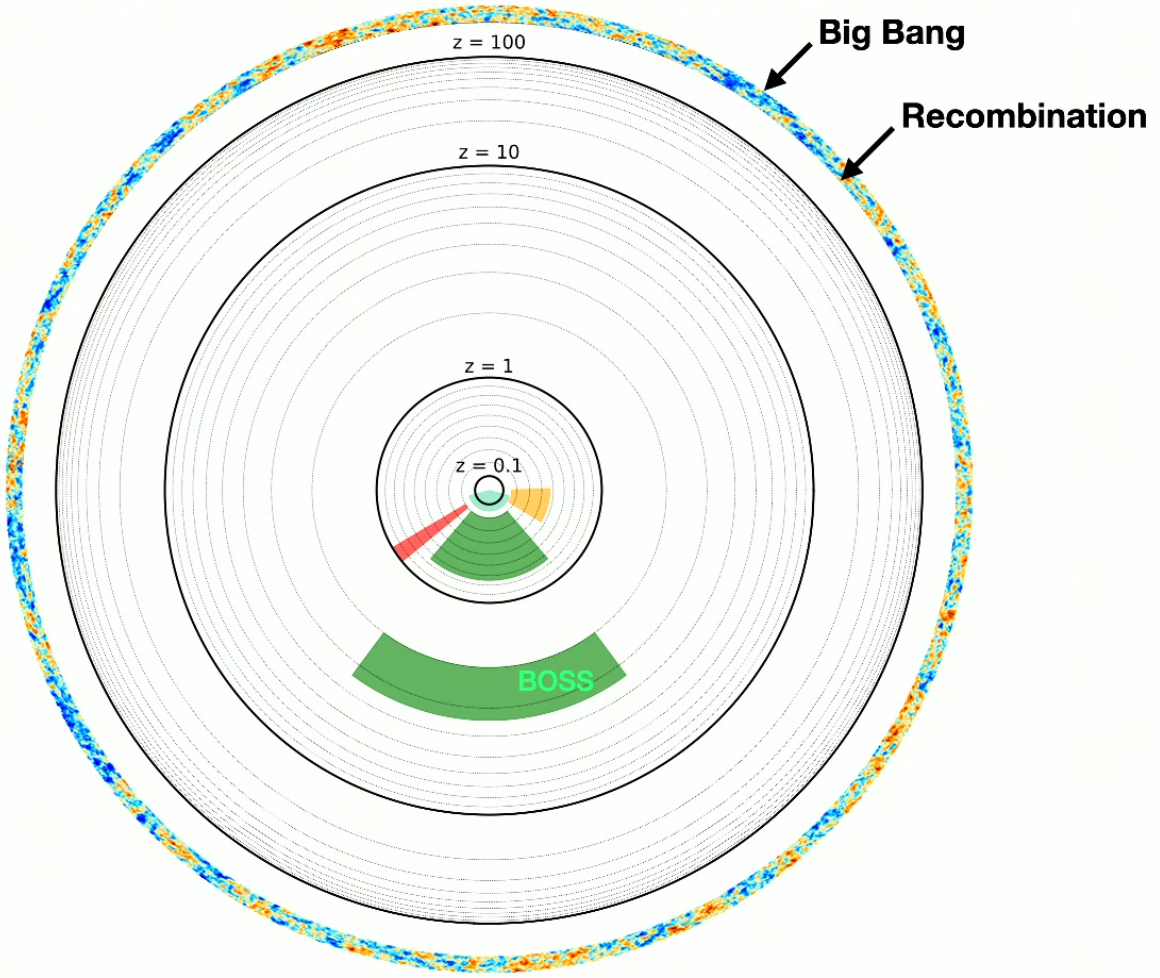


Survey Volume



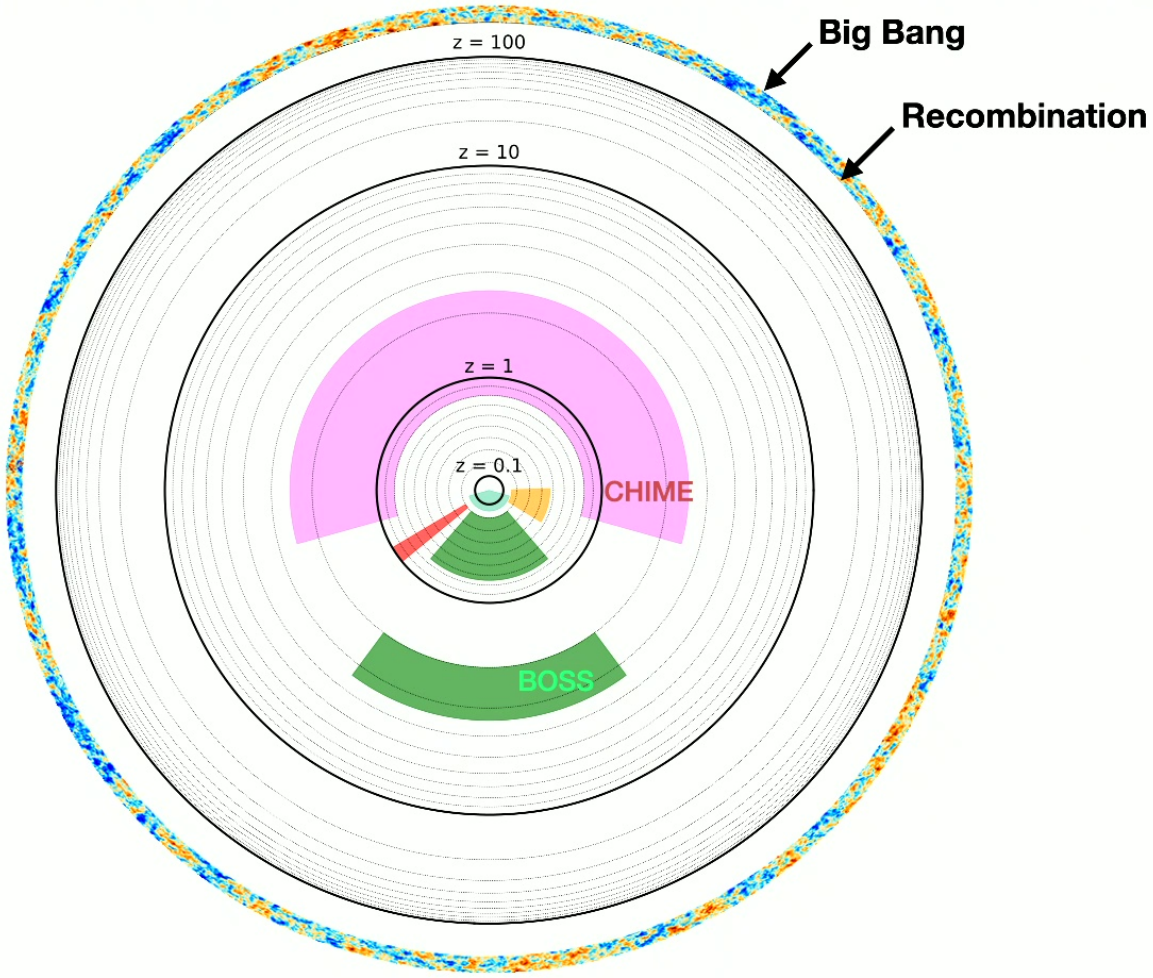
Scaled such that
Area = Survey Volume

Survey Volume



Scaled such that
Area = Survey Volume

Survey Volume



Scaled such that
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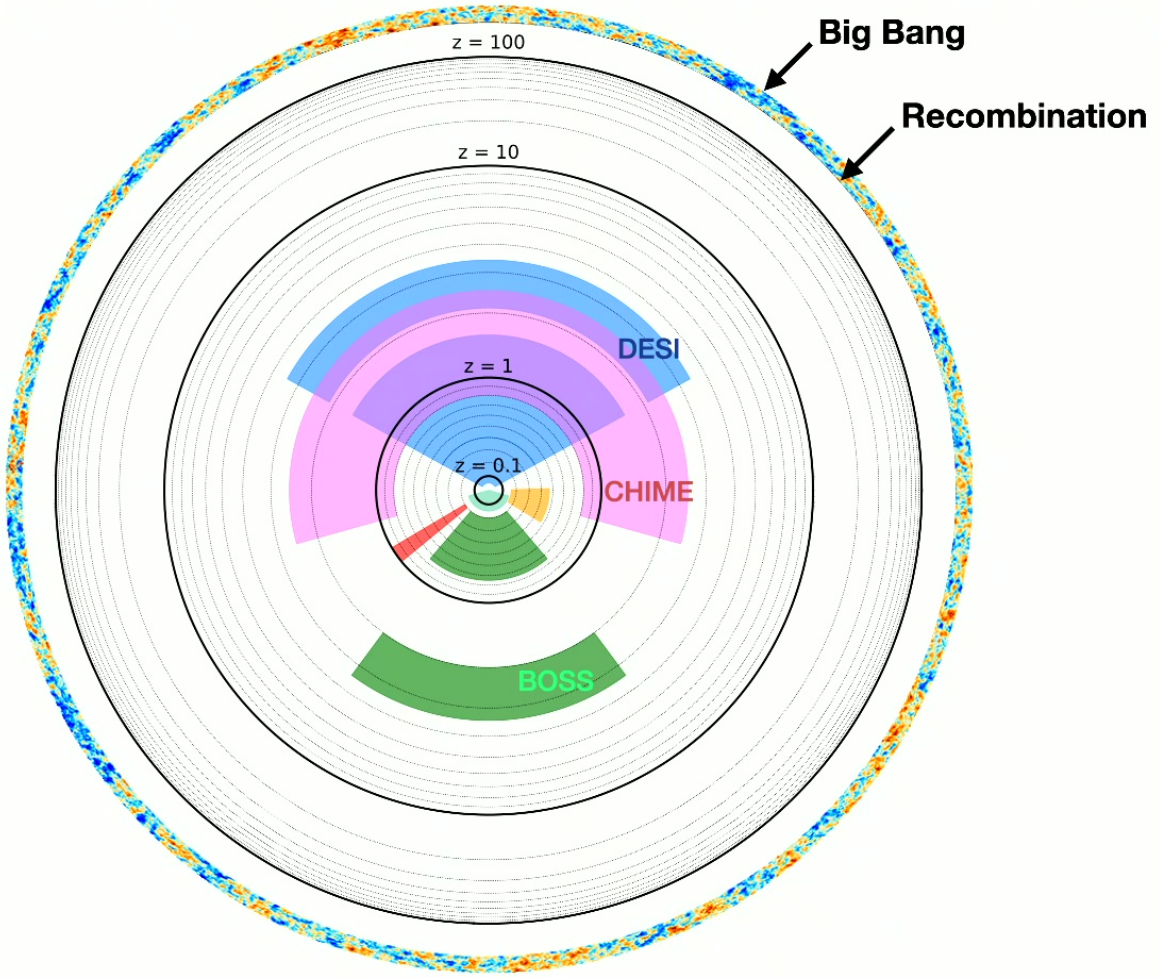
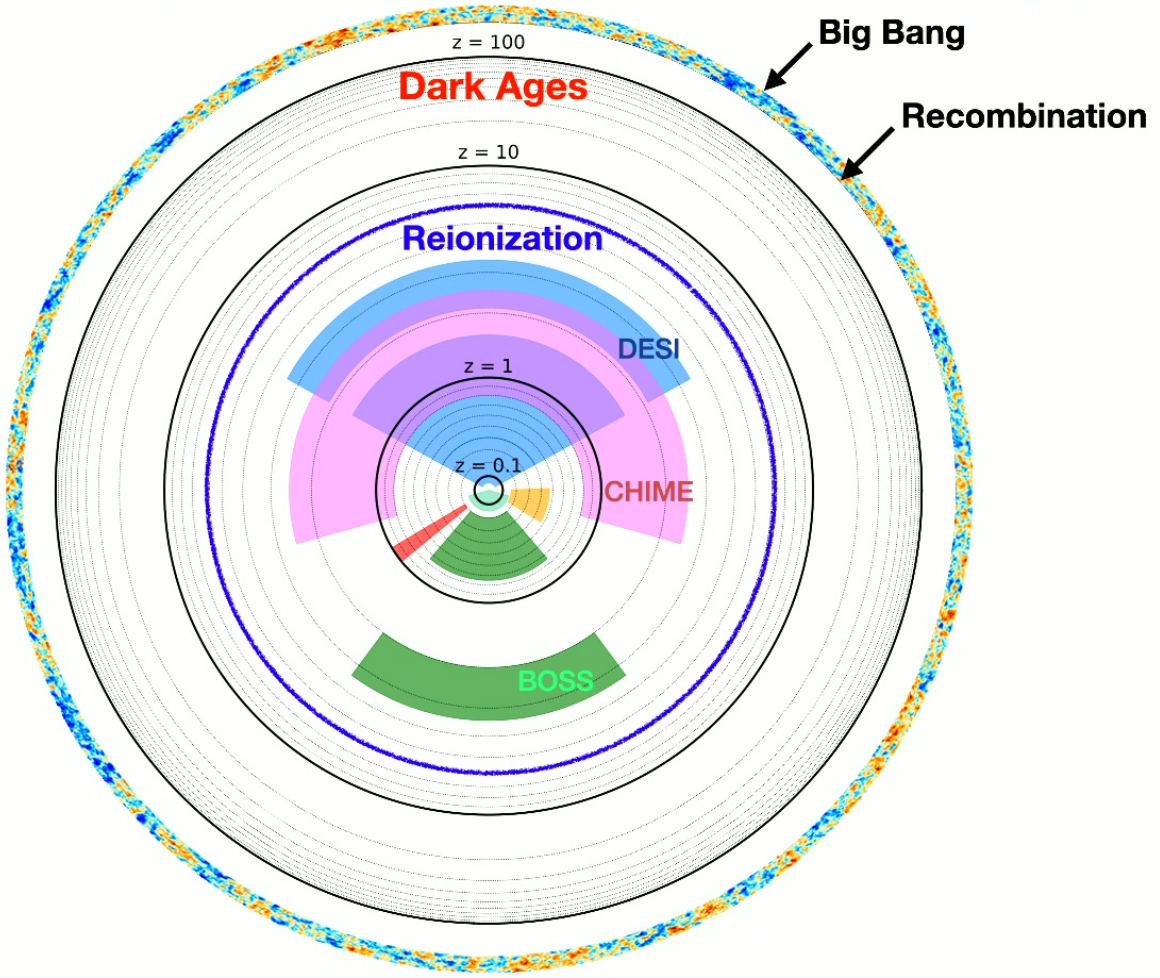
Survey Volume



Scaled such that
Area = Survey Volume

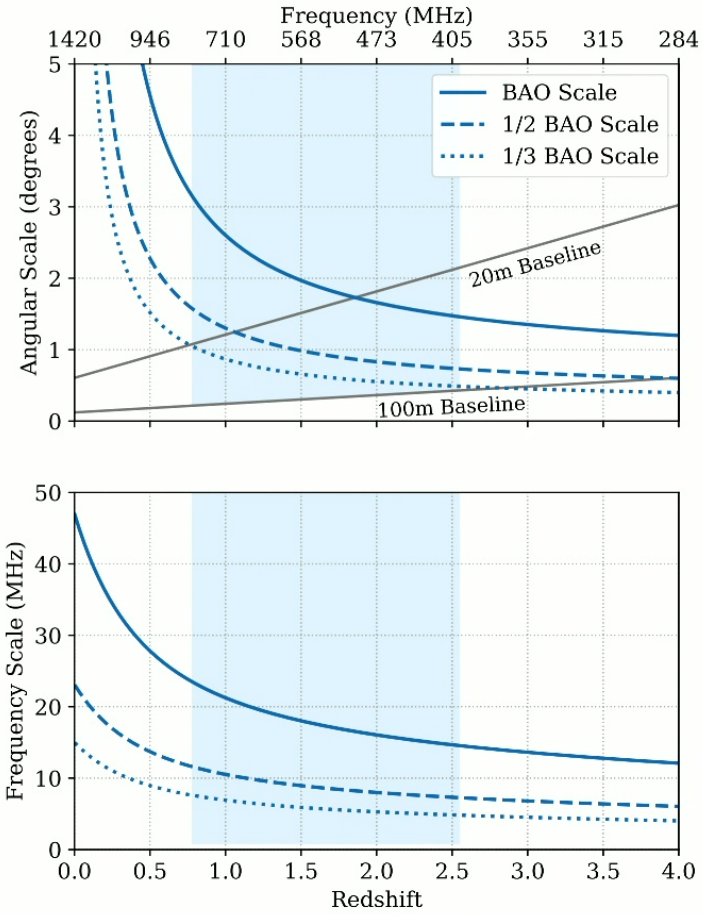
Survey Volume



Scaled such that
Area = Survey Volume

Instrument Considerations

- Map a large volume
- Choose angular and frequency resolution to measure third BAO peak
- Maximize sensitivity to these scales
- Limit cost



from arXiv:2201.07869


CHIME:
the Canadian Hydrogen Intensity Mapping Experiment

a collaboration between


THE UNIVERSITY OF BRITISH COLUMBIA


UNIVERSITY OF TORONTO


McGill


Dominion Radio Astrophysical Observatory

with partners at


Yale University

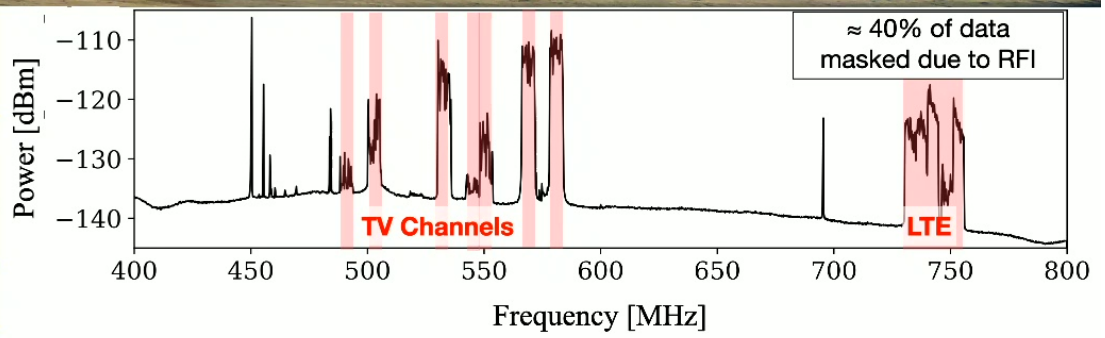

WestVirginiaUniversity


PERIMETER INSTITUTE


Massachusetts Institute of Technology


NRAO

Dominion Radio Astrophysical Observatory (DRAO)



Seth Siegel

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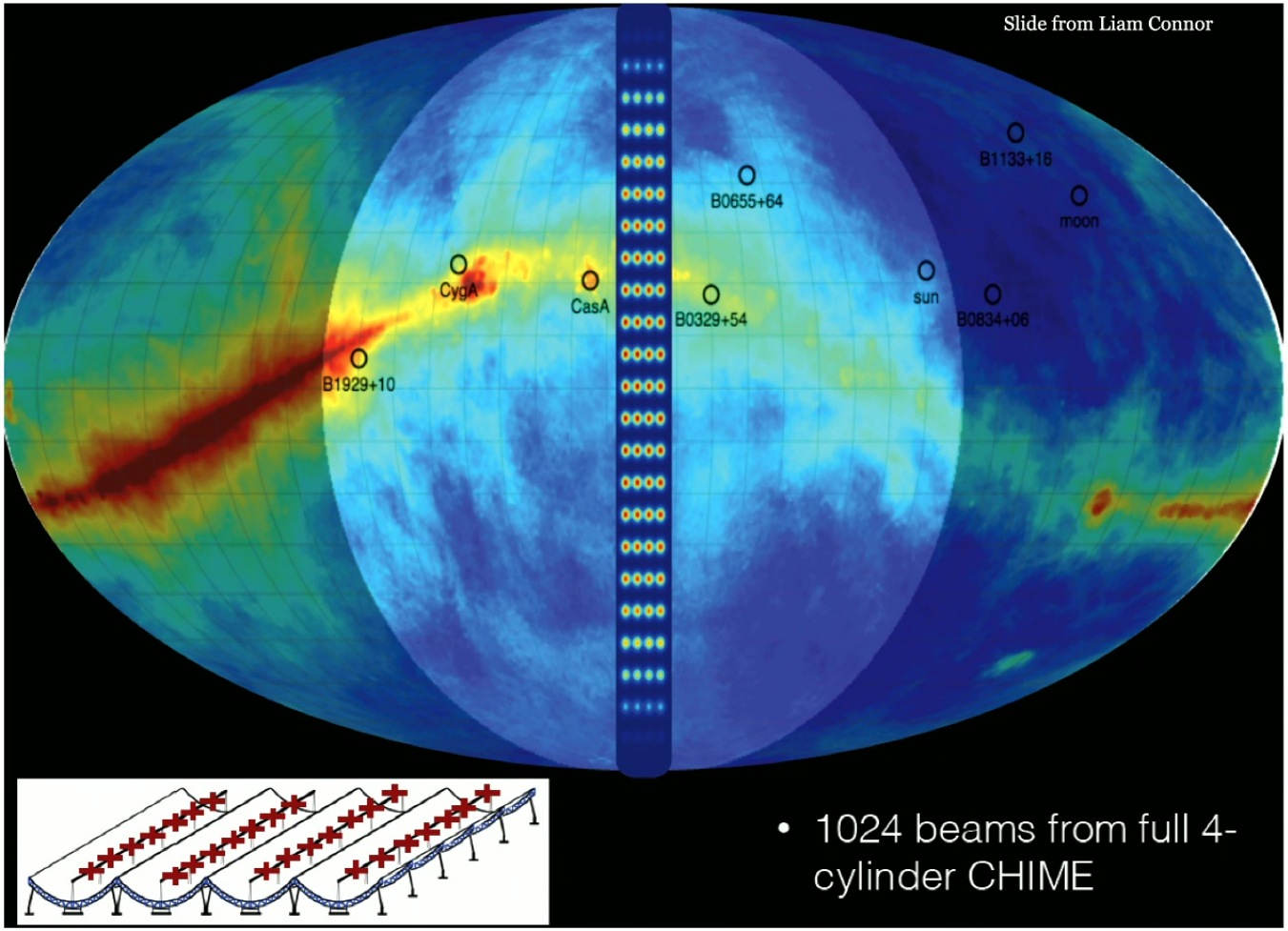
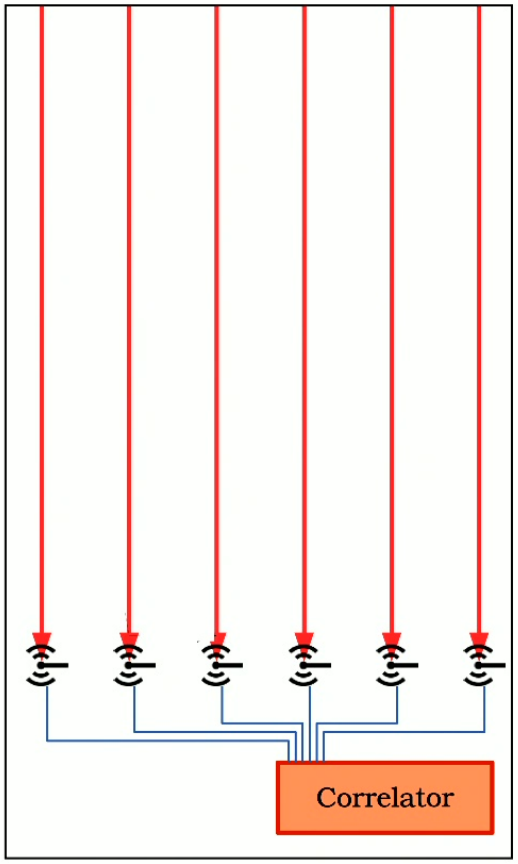
Cylindrical Transit Interferometer

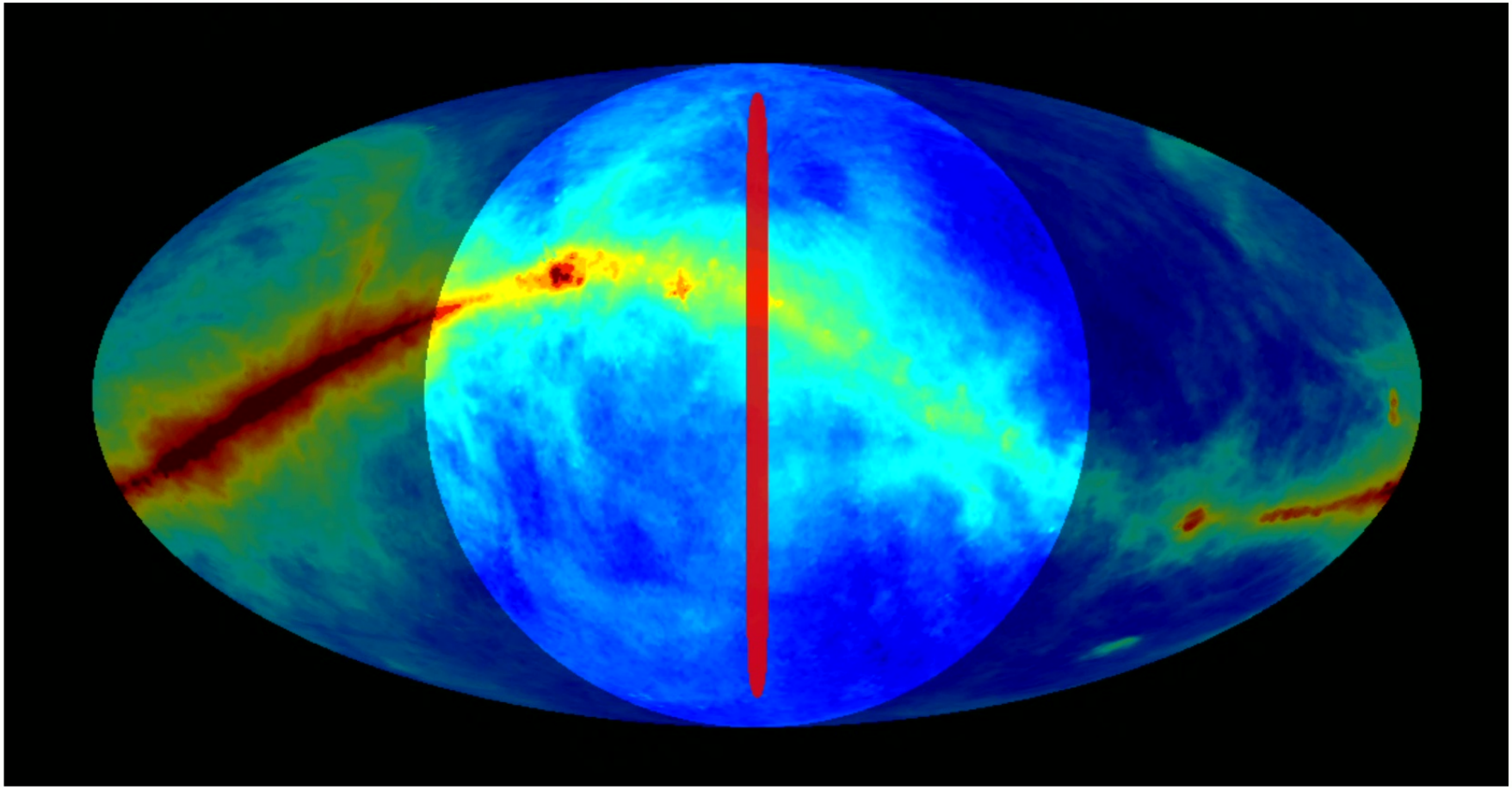
Movie by Peter Klagge

Cylindrical Transit Interferometer



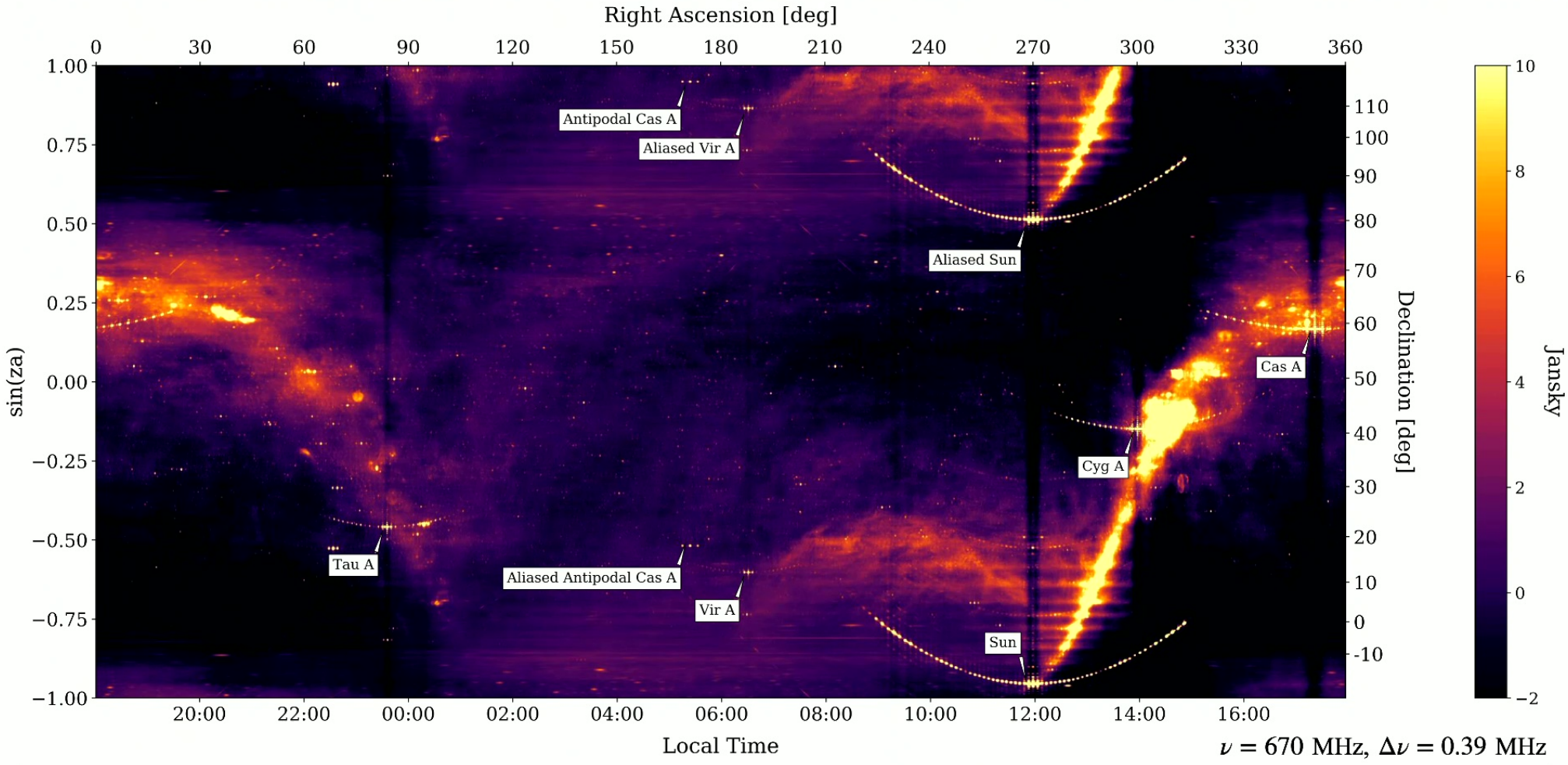


Cylindrical Transit Interferometer



Haslam 408 MHz Map

Radio Sky as Seen by CHIME



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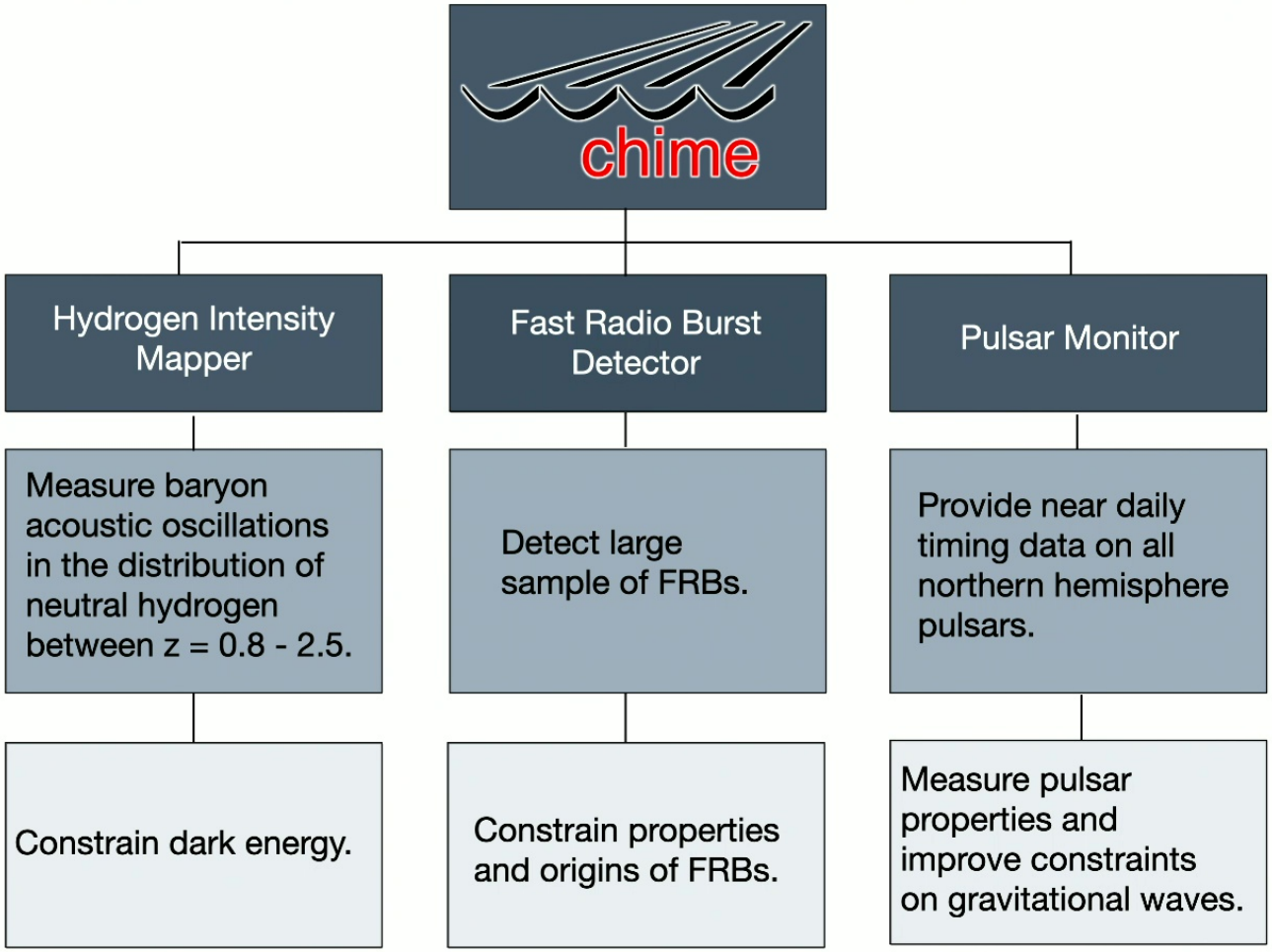
CHIME Science Objectives



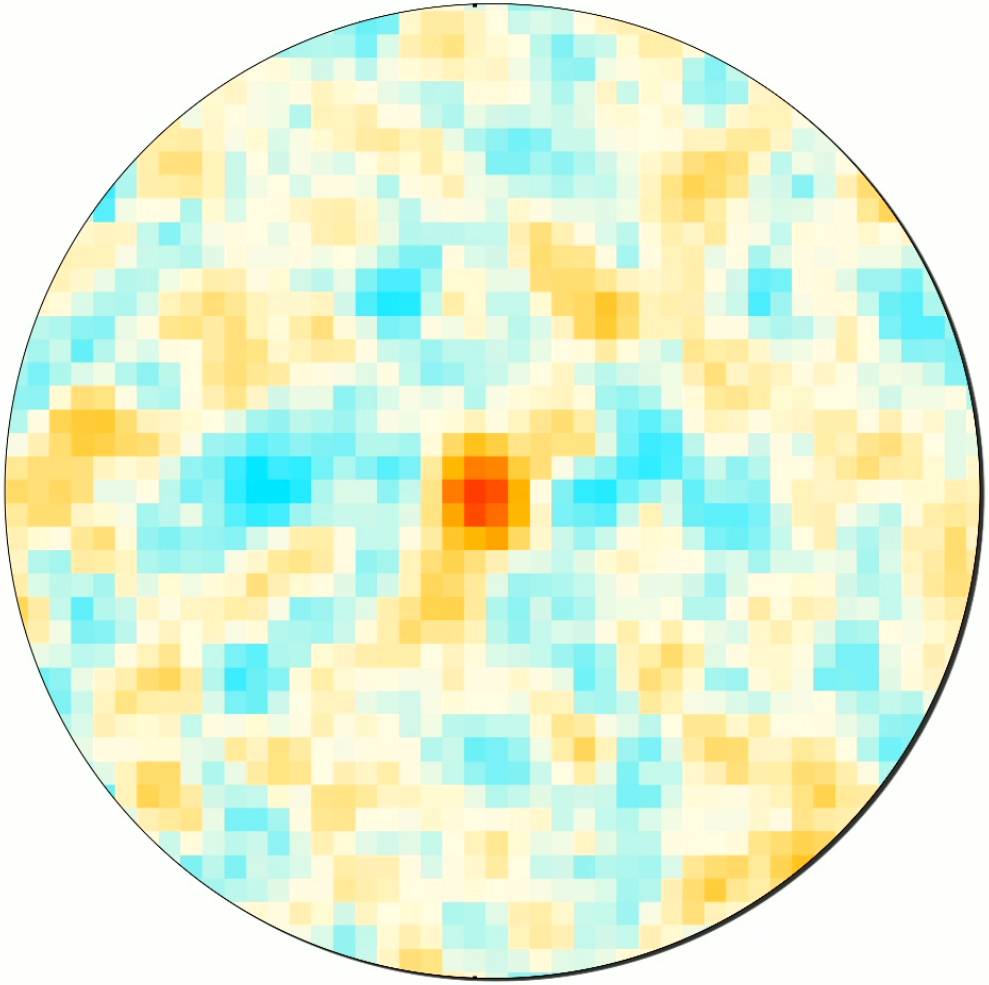
Current Status of CHIME 21 cm Intensity Mapping

- We have been acquiring data for 4 years.
  - Have ~450 days of total integration time (after flagging).
  - Data shown in this presentation has ~50 days of total integration time.

- Significant progress on instrument calibration over the past four years.
  - Full sky co-polar beam model at 5% level
  - Complex gain amplitude calibration < 1%, phase calibration < 0.015 rad.

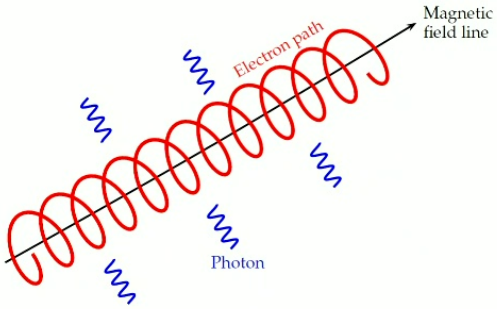
- Focusing efforts on:
  - Primary beam calibration
  - Foreground filtering
  - Cross-correlation with tracers of large-scale structure
  - Power spectrum estimation
  - Galactic science and “slow” radio transients

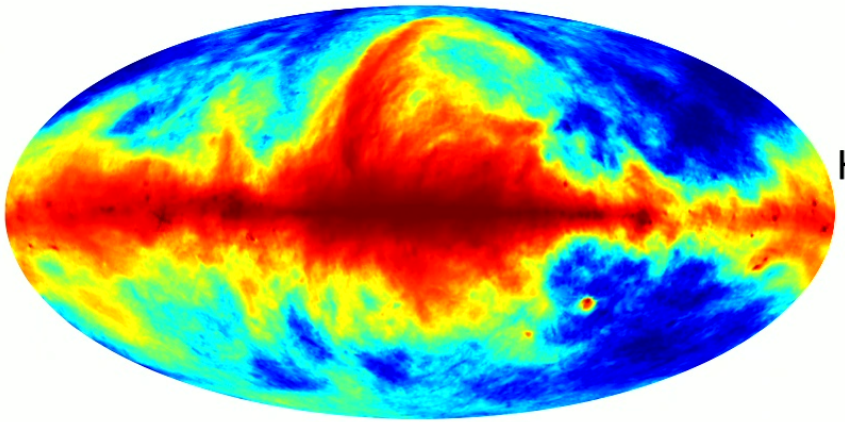
Detection of 21 cm Emission: Data Processing



Astrophysical Foregrounds

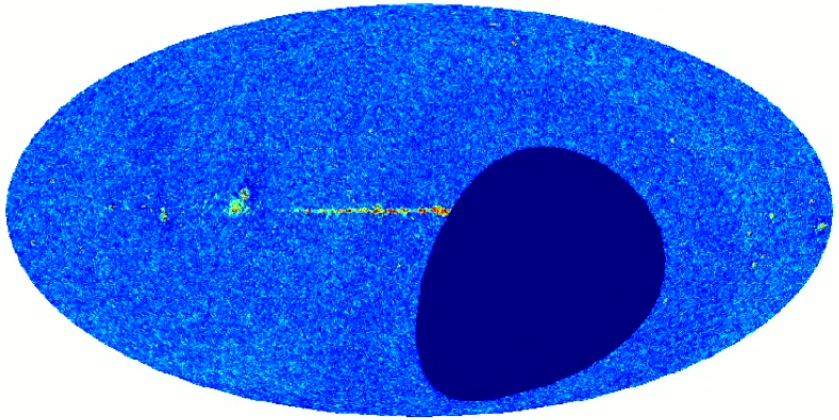
- **Galactic synchrotron**
  - Power law spectrum
    - $T_b(\nu) \propto \nu^{-\alpha}$ with $\alpha \approx 2.8$





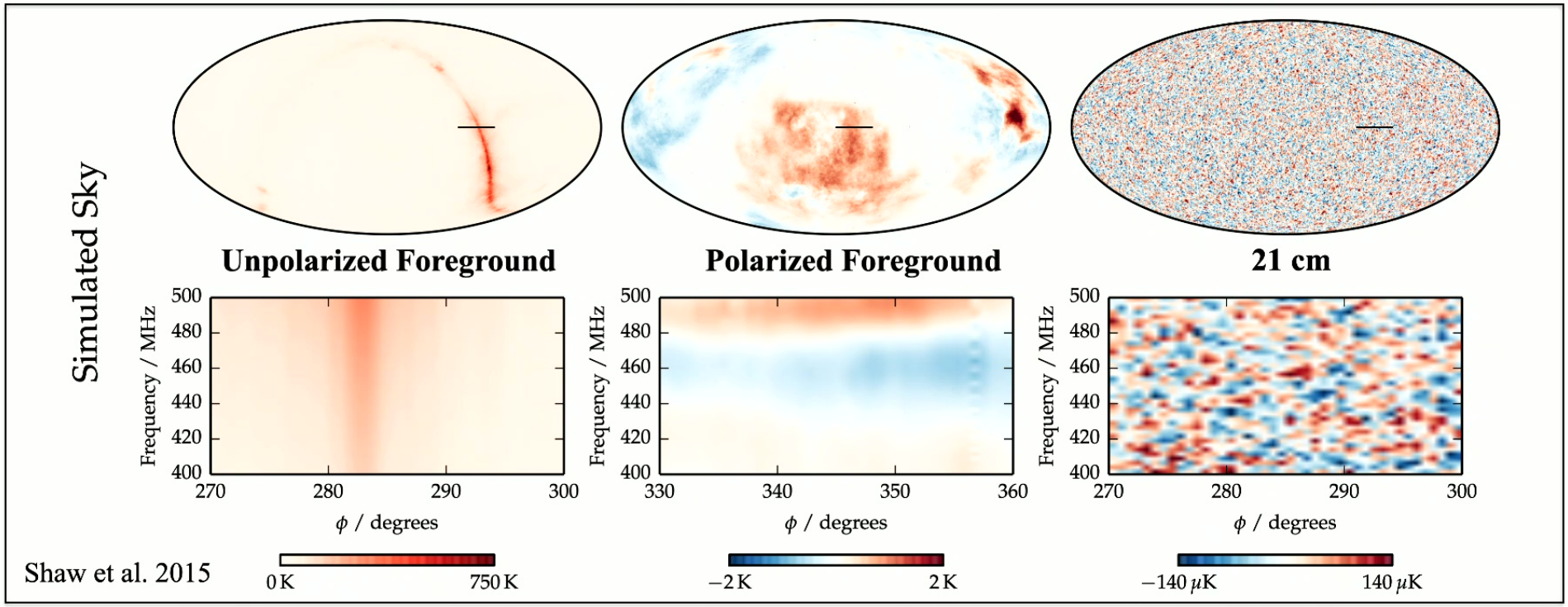
Haslam Map
408 MHz
log scale

- **Extra-galactic point sources**
  - Radio galaxies, AGN, supernovae remnants, …
    - Emission from synchrotron and free-free
    - Featureless spectra



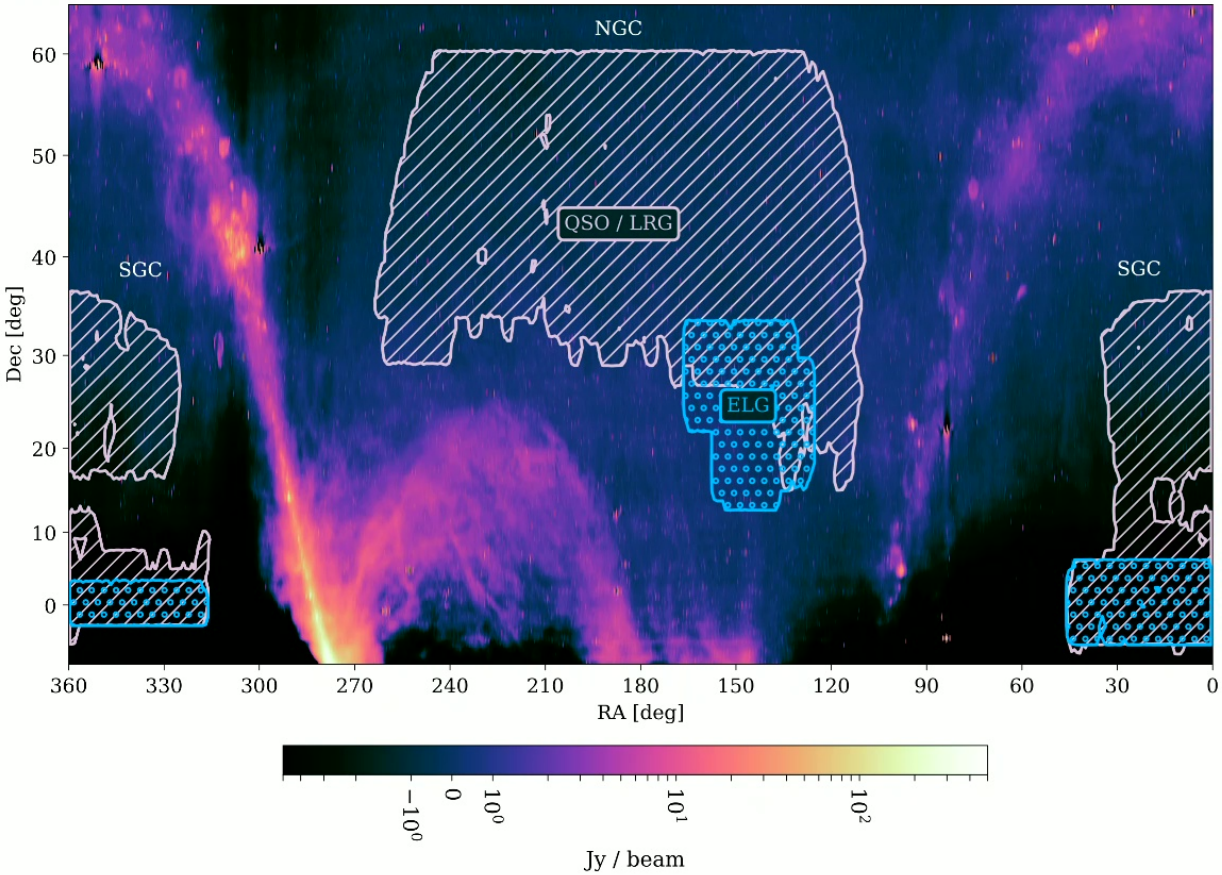
NVSS Map
1400 MHz

The Foreground Problem

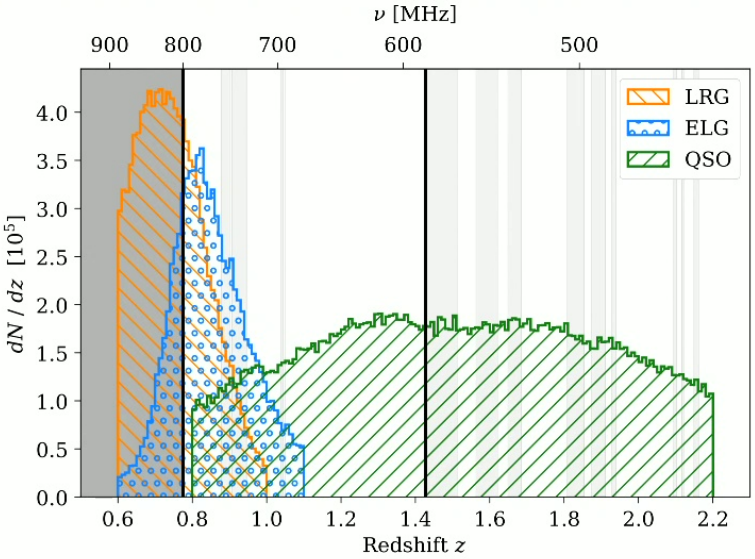


- Foregrounds due to galactic synchrotron and extragalactic point source emission are 10^5 times brighter than the 21 cm signal.
- Foregrounds have a smooth spectrum, whereas the 21 cm signal varies rapidly with frequency because it originates from distinct structure along the line-of-sight direction.

CHIME and SDSS Cross-correlation



Map of the northern radio sky as measured by CHIME.
Shown is the average spectral flux density over the 585 to 800 MHz band.



Use the SDSS DR16 eBOSS clustering catalogs.

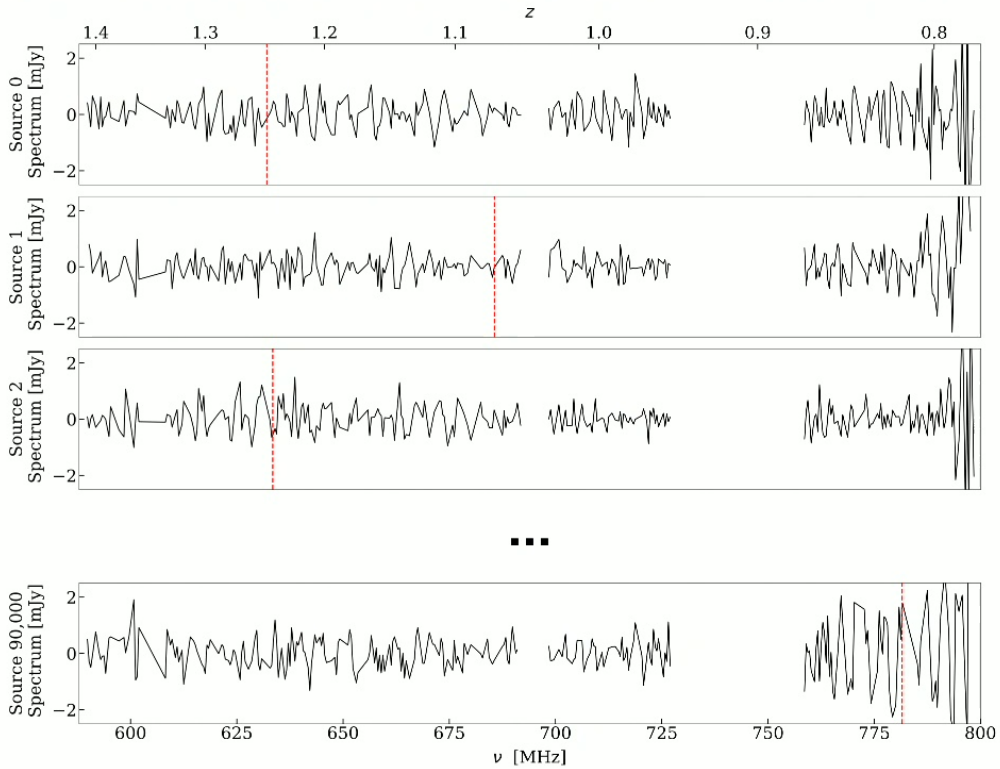
Three tracers of large-scale structure:

- Emission Line Galaxies (ELGs)
  - Blue, star forming
- Luminous Red Galaxies (LRGs)
  - Old, quiescent
- Quasars (QSOs)
  - Bright active galactic nuclei

Stacking on Tracers of Large-scale Structure

Procedure:

- Make map at each frequency.
- Apply a high-pass filter along frequency axis.
- Mask residual foregrounds and RFI.
- Extract spectral cube centered on each source.
- Take weighted average of the spectral cubes.



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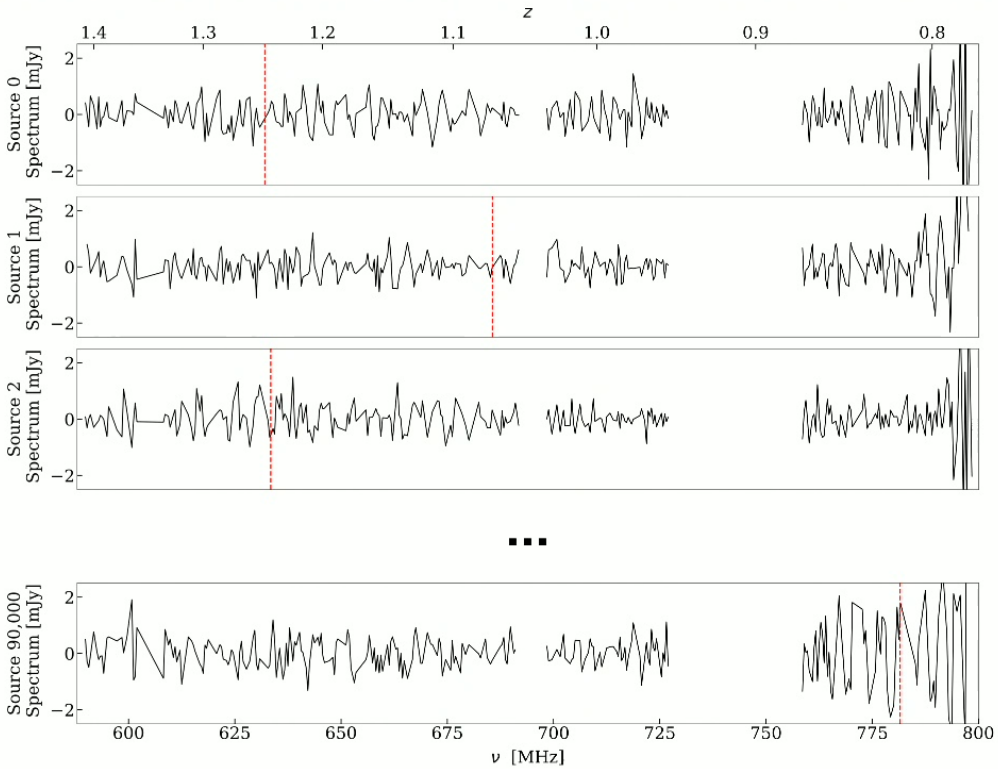

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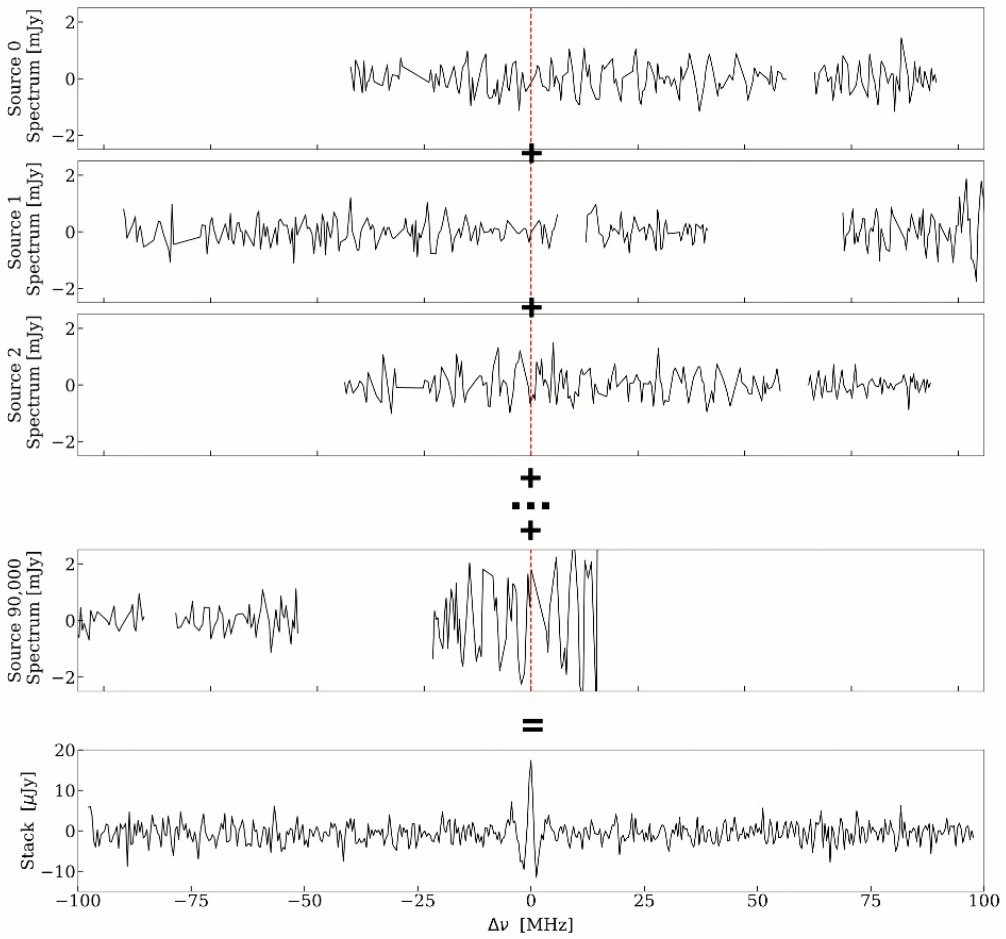
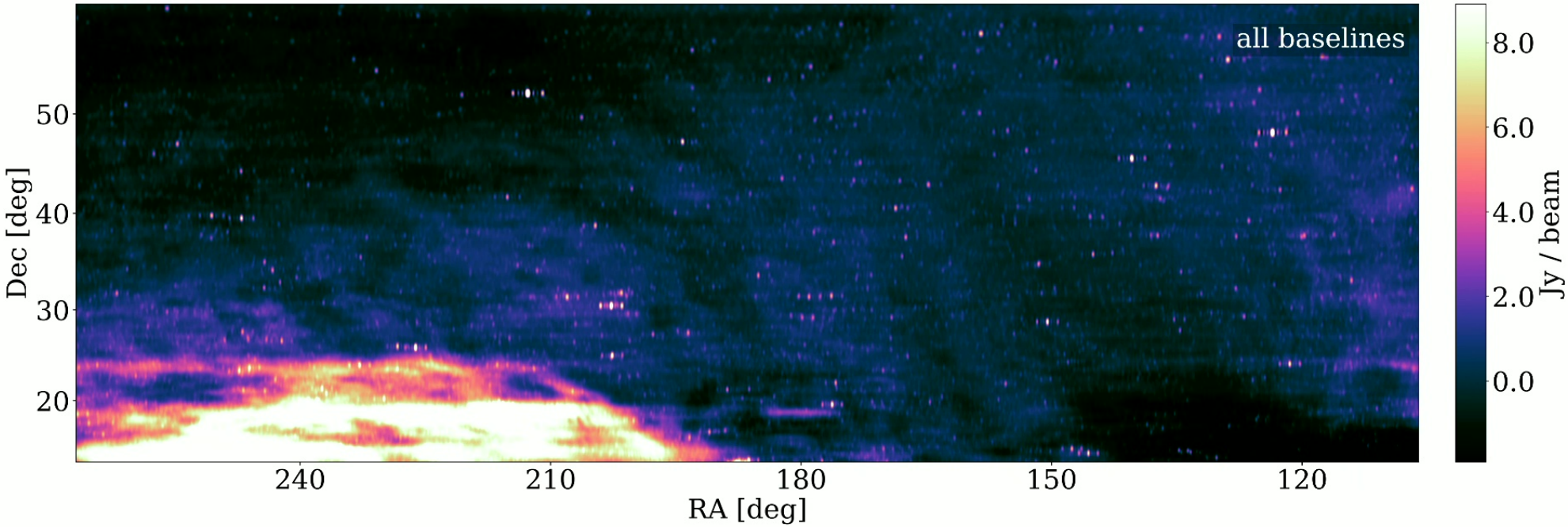
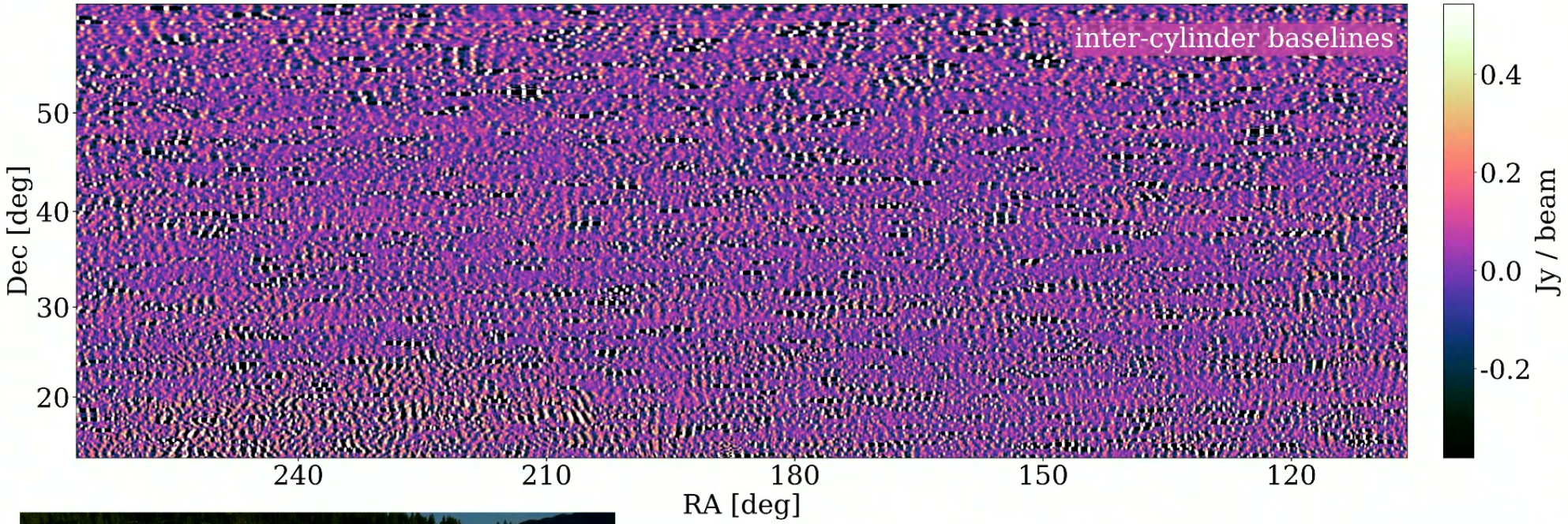


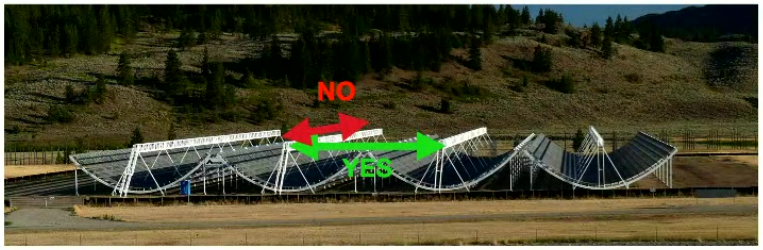
CHIME Map at 700 MHz for NGC Field



Map at 700 MHz covering the NGC field.
Constructed from visibilities averaged over 100 sidereal days.
Roughly 50 days of integration time on this field (we mask all day-time data).
Model for the primary beam pattern has been deconvolved.

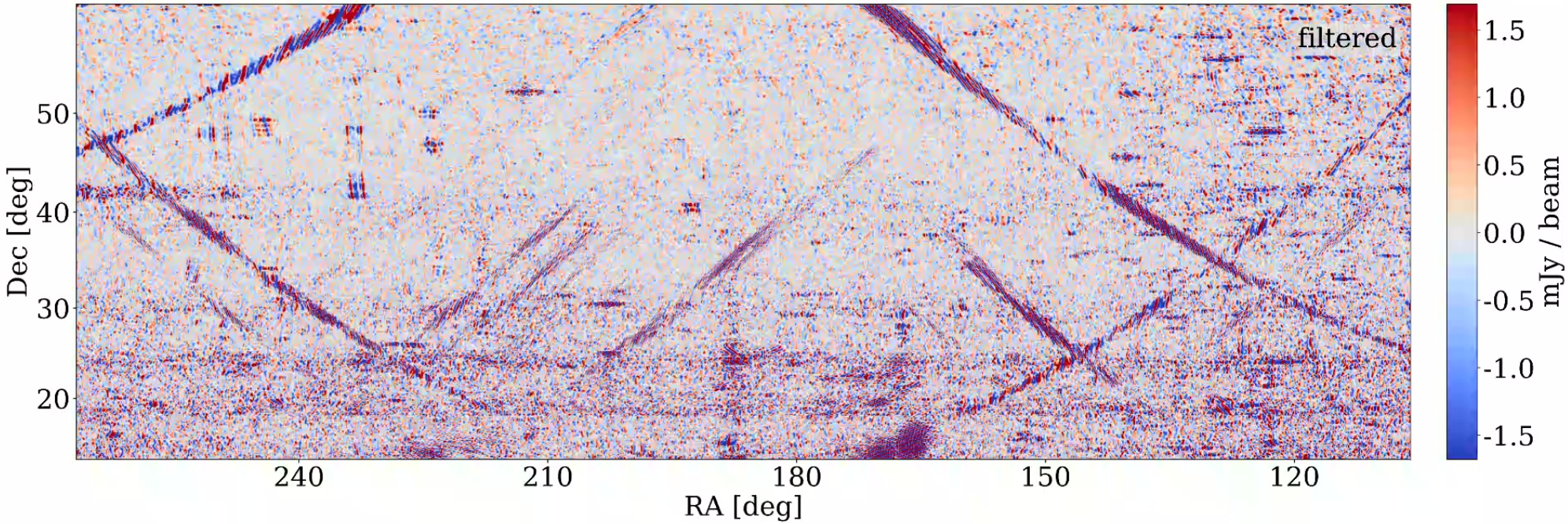
CHIME Map at 700 MHz (Inter-cylinder baselines)





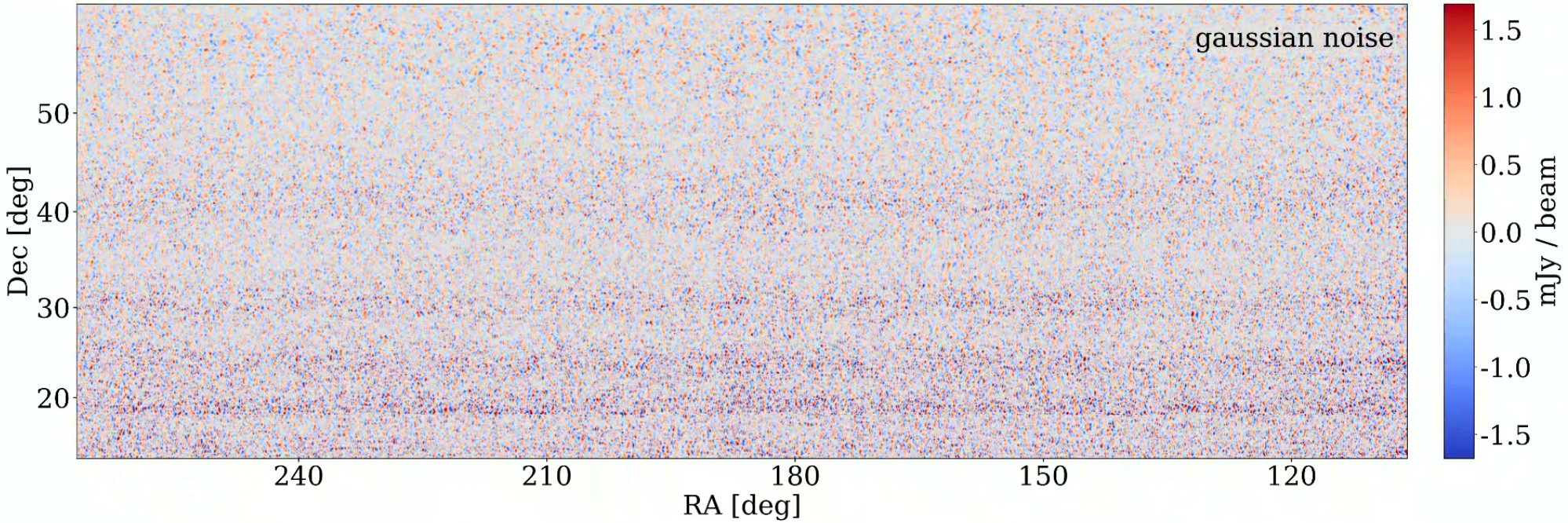
Map constructed from inter-cylinder baselines only.
Resolves out the diffuse galactic emission.
Dominated by emission from extra-galactic point sources.
Color scale has been compressed by a factor of 15.

CHIME Map at 700 MHz (Inter-cylinder, delay filtered)



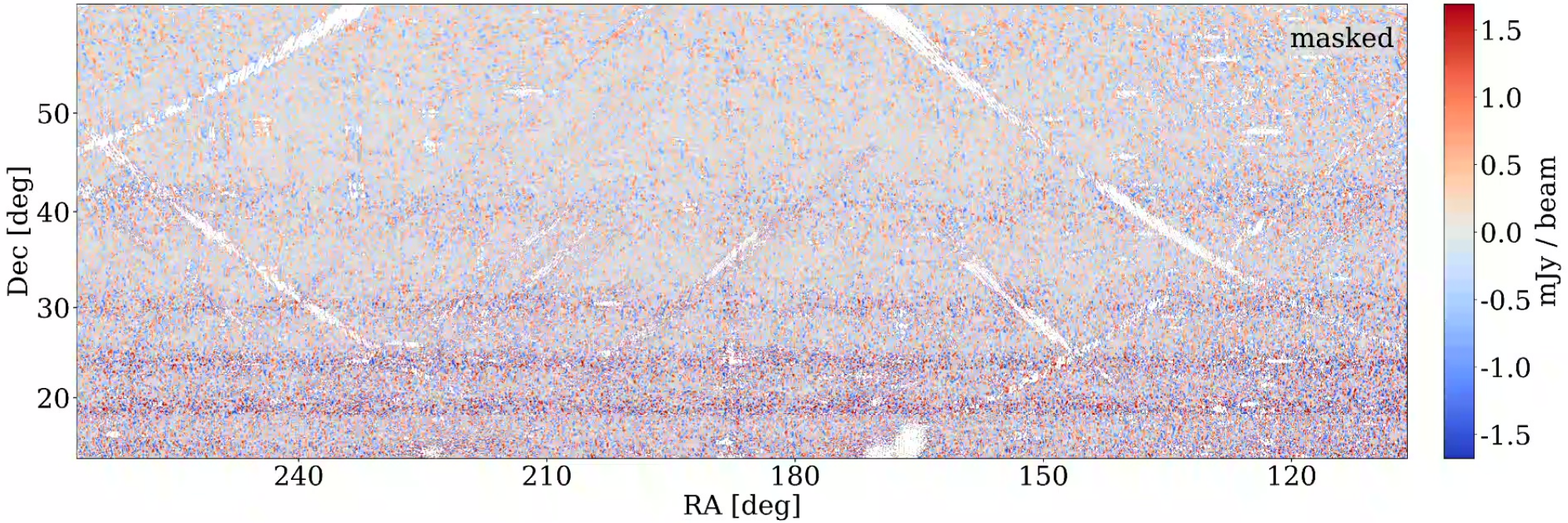
The inter-cylinder baseline map after applying the delay filter.
The color scale has been compressed by a factor of 300.
Residual foregrounds are evident, primarily due to very bright sources in the far sidelobes and bright sources in the main lobe.

Gaussian Noise Realization for Comparison



Create visibilities that are randomly drawn from a circularly symmetric complex Gaussian distribution with mean 0 and variance equal to the expected variance of the thermal noise, then apply the same map making and foreground filtering.

CHIME Map at 700 MHz (Inter-cylinder, filtered, masked)



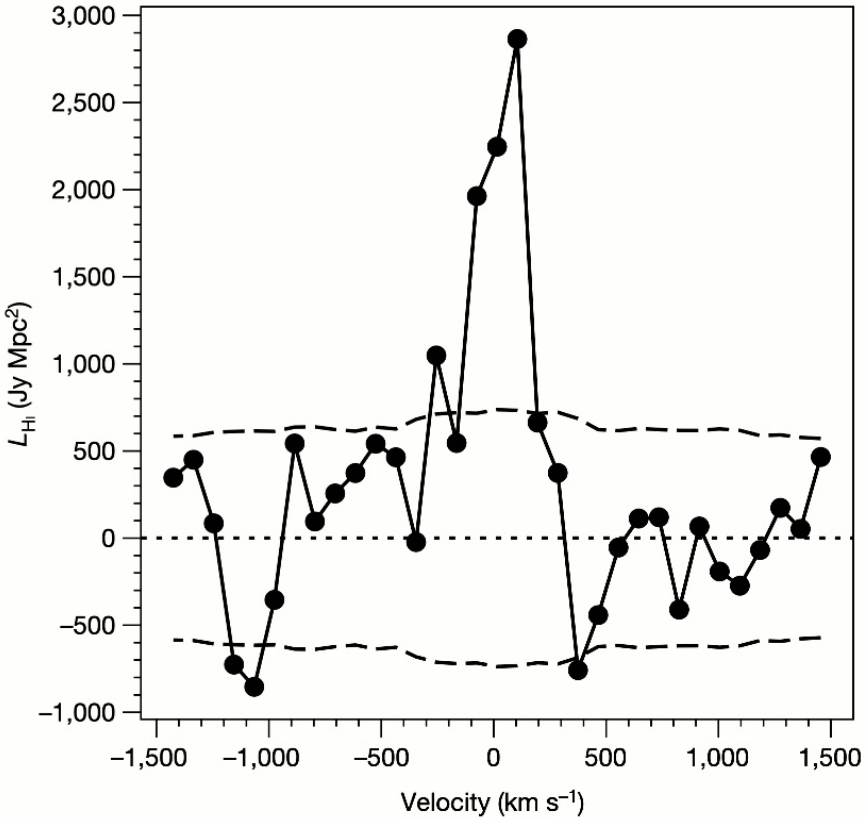
Inter-cylinder, delay filtered map after masking any pixel that is greater than 3σ,

where σ is the standard deviation of the expected radiometric noise.
Masks 6.1% of pixels in this field at this frequency.

Previous Stacking Analyses

- Interferometric observations
- No clustering information
- 4 - 13σ detection significance
- Derive mean HI mass of galaxy sample

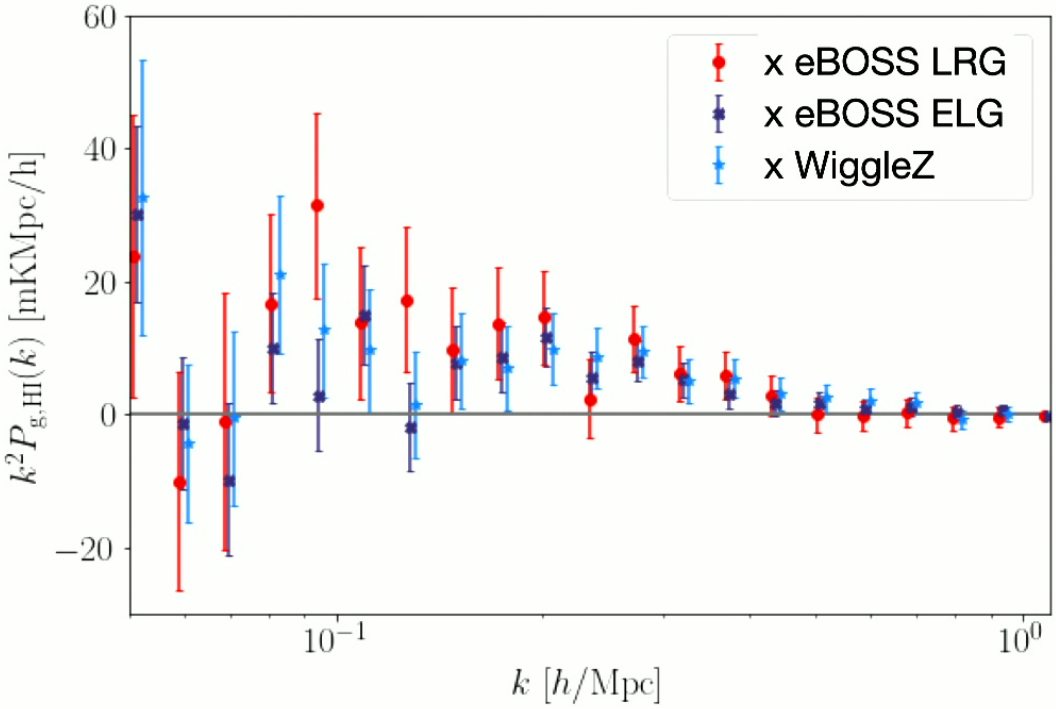
Chowdhury et al. 2021: GMRT
$0.74 < z < 1.45$



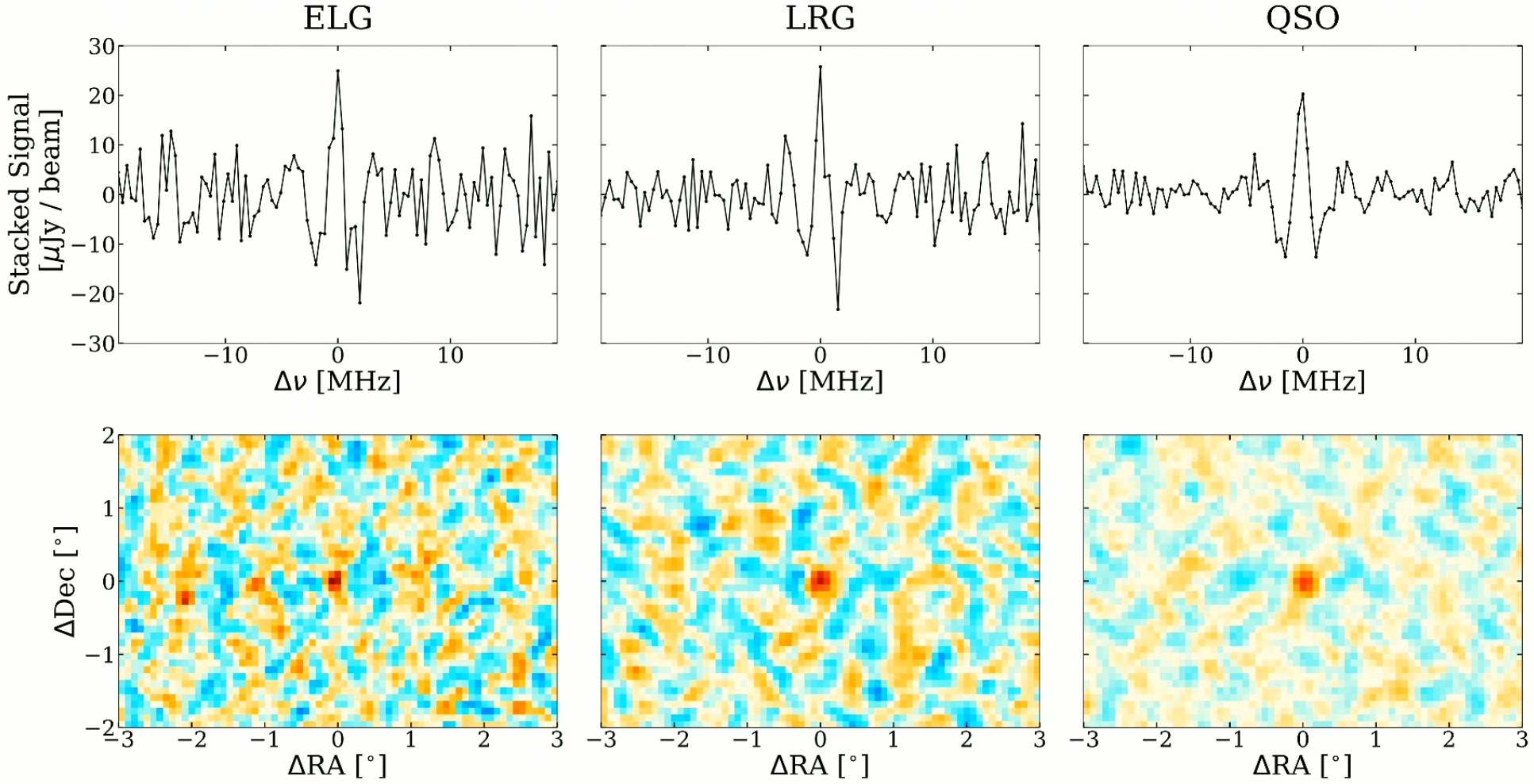
Previous Cross Power Spectrum Analyses

- Single-dish observations
- Mostly probe clustering
- 4 - 7σ detection significance
- Create template for scale-dependence of cross-correlation. Fit template to measured cross power spectrum to constrain overall amplitude.
- Constrain r $\Omega_{\rm HI}$ $b_{\rm HI}$.

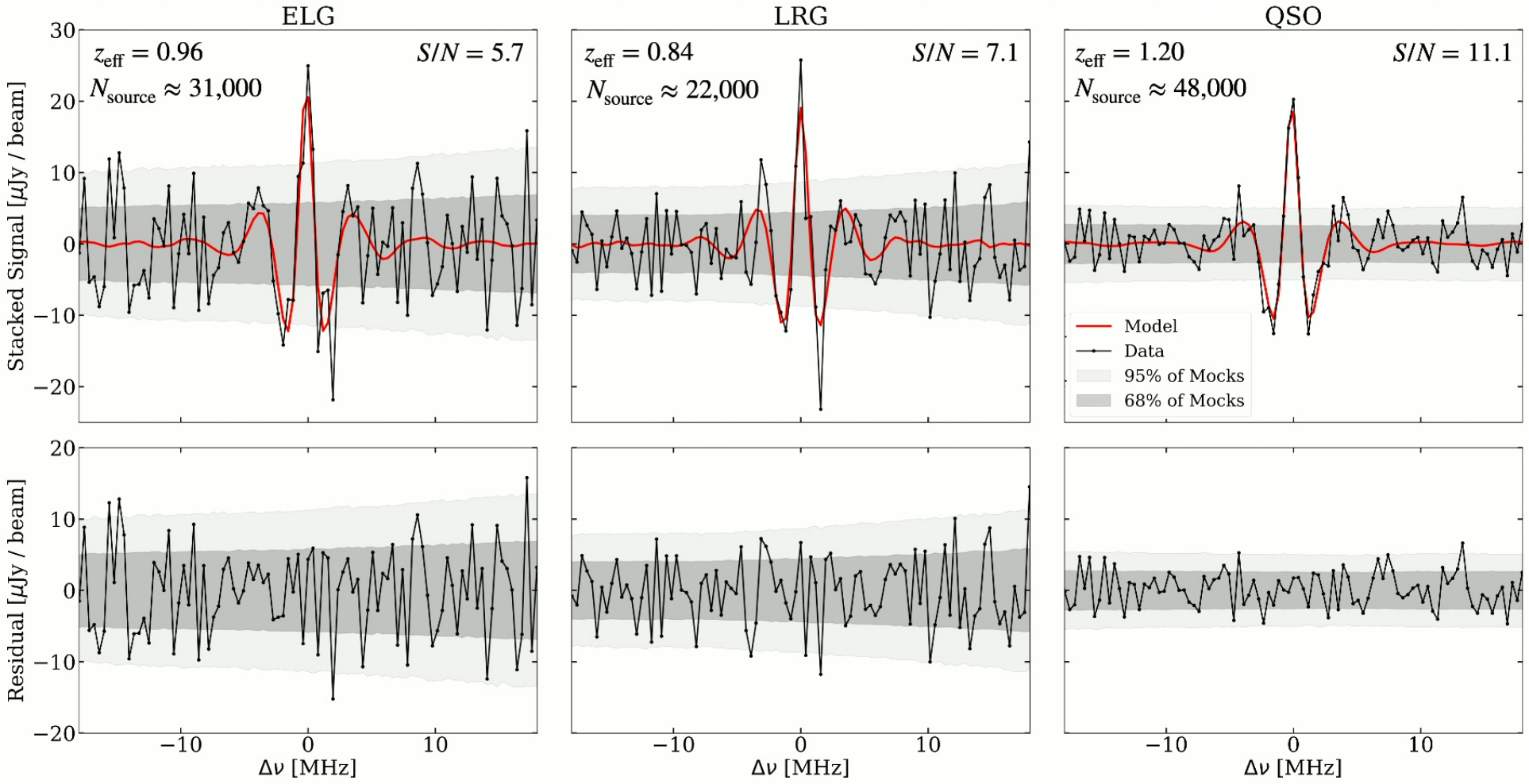
Wolz et al. 2021 : GBT
0.6 < z < 1.0



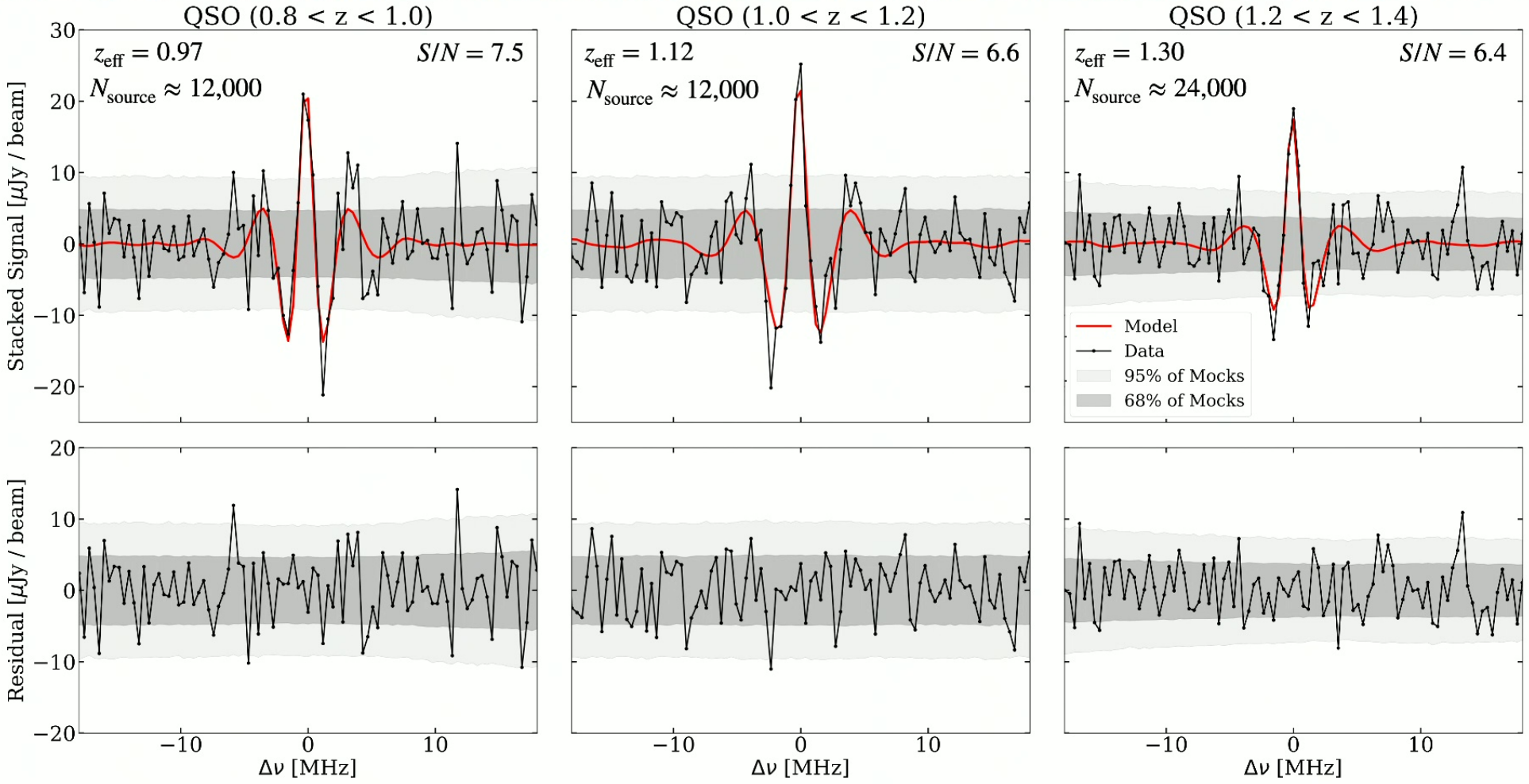
Stacked Signal for All Three eBOSS Tracers



Stacked Signal for All Three eBOSS Tracers

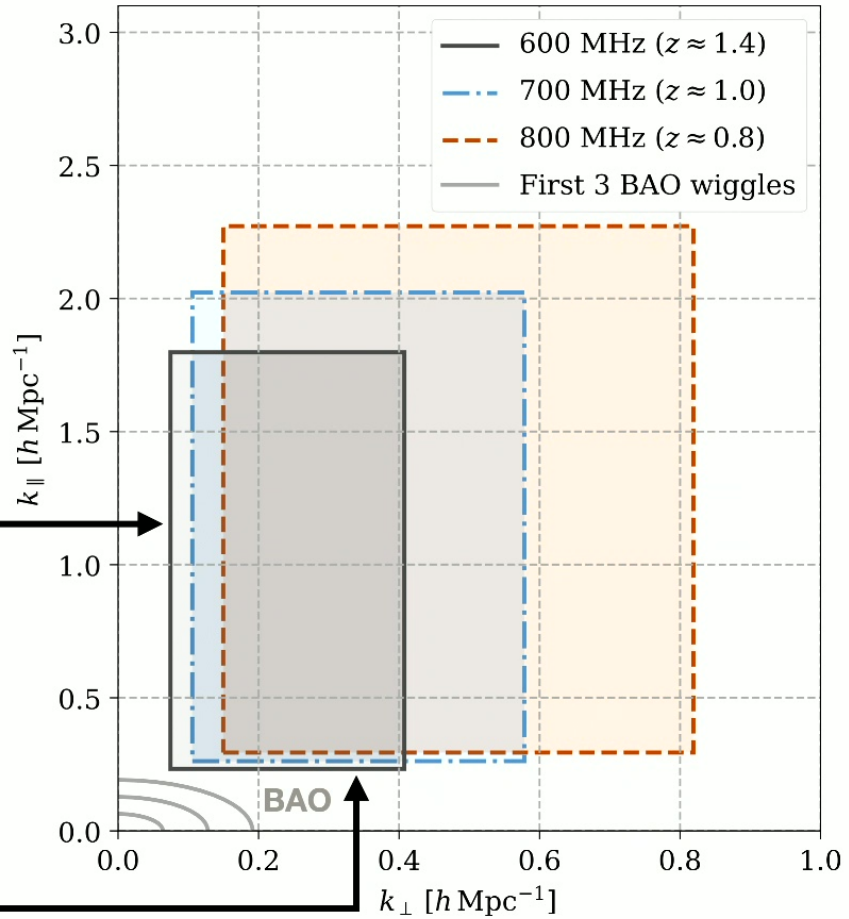


Stacked Signal for QSO Redshift Bins



Physical Scales Probed

Small Spectral Scales



Set by spatial + spectral foreground filter

Small Angular Scales

Modeling the Stacked Signal

Assume following model for the HI-galaxy cross-power spectrum:

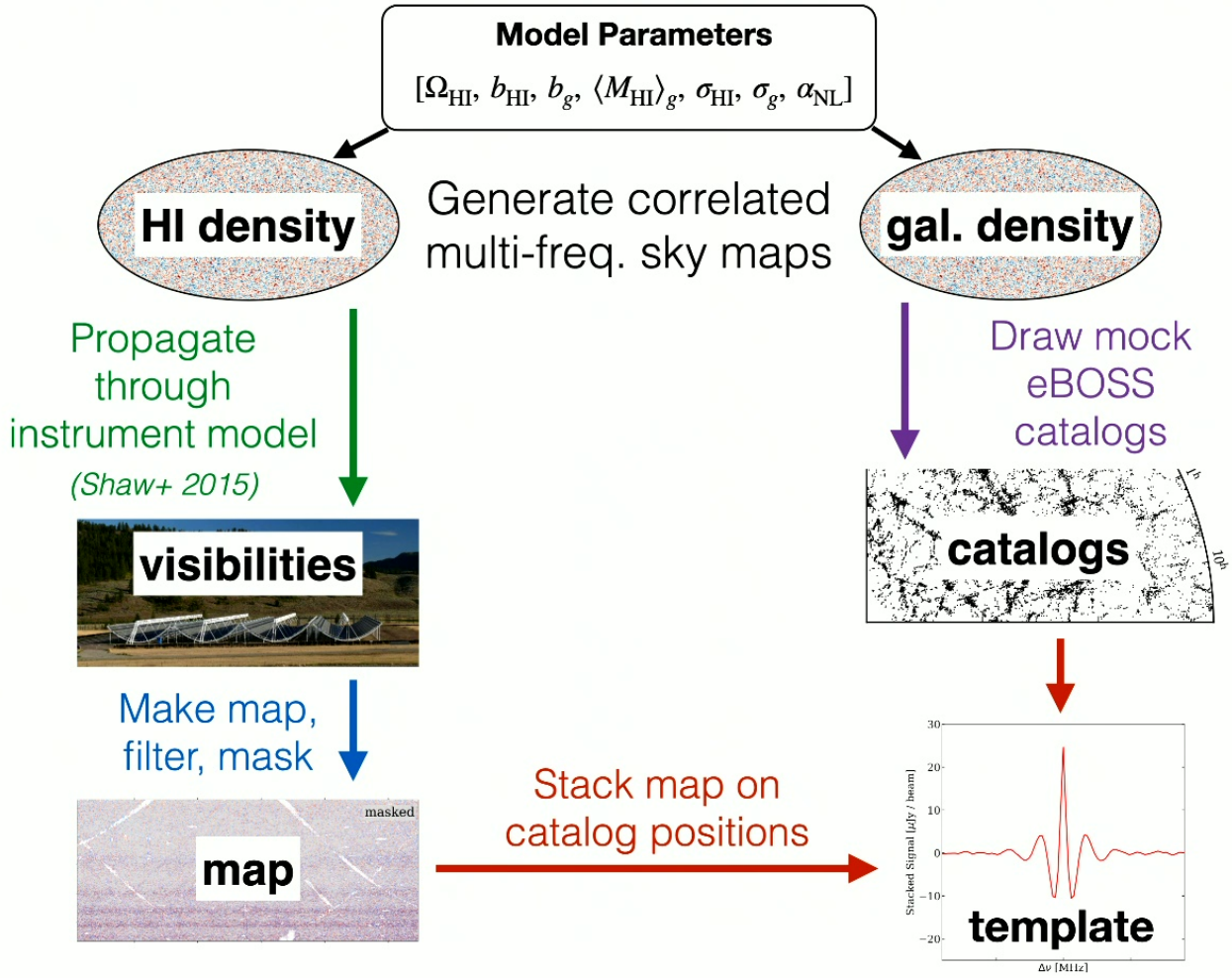
$$P_{\mathrm{HI,g}}(k,\mu;z_1,z_2) = T_b(z_1;\Omega_{\mathrm{HI}})\ [b_{\mathrm{HI}}(z_1)+f(z_1)\mu^2]\ [b_g(z_2)+f(z_2)\mu^2]$$
$$\times D(z_1)\ D(z_2)\ P_m(k;\alpha_{\mathrm{NL}})\ D_{\mathrm{FoG}}(k\mu,z_1;\sigma_{\mathrm{HI}})\ D_{\mathrm{FoG}}(k\mu,z_2;\sigma_g) + C(z_1)\langle M_{\mathrm{HI}}\rangle_g$$

with parameters:

Ω_{HI} :	mean HI density
b_{HI}, b_g :	linear bias (strength of clustering compared to total matter)
α_{NL} :	smoothly transition between the linear and non-linear total matter power spectrum
σ_{HI}, σ_g :	scale of “Finger of God” damping due to small-scale velocity dispersion
$\langle M_{\mathrm{HI}}\rangle_g$:	mean HI mass per object in catalog

Use simulation pipeline to predict the stacked signal observed by CHIME given the HI-galaxy cross-power spectrum.

Simulation-based Forward Modeling



Model Parameters

Parameters of Interest

Mean HI density $\Omega_{\rm HI}$

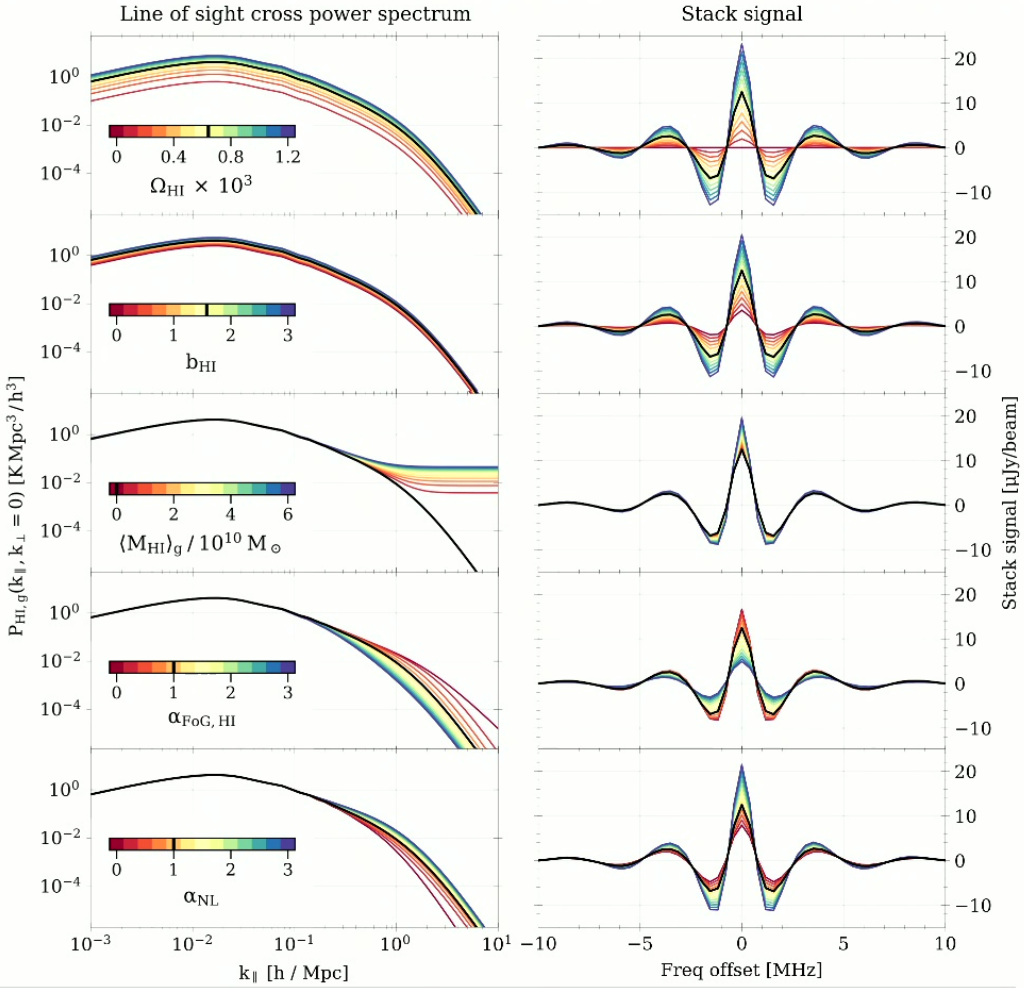
Linear bias $b_{\rm HI}$, b_g

Nuisance Parameters

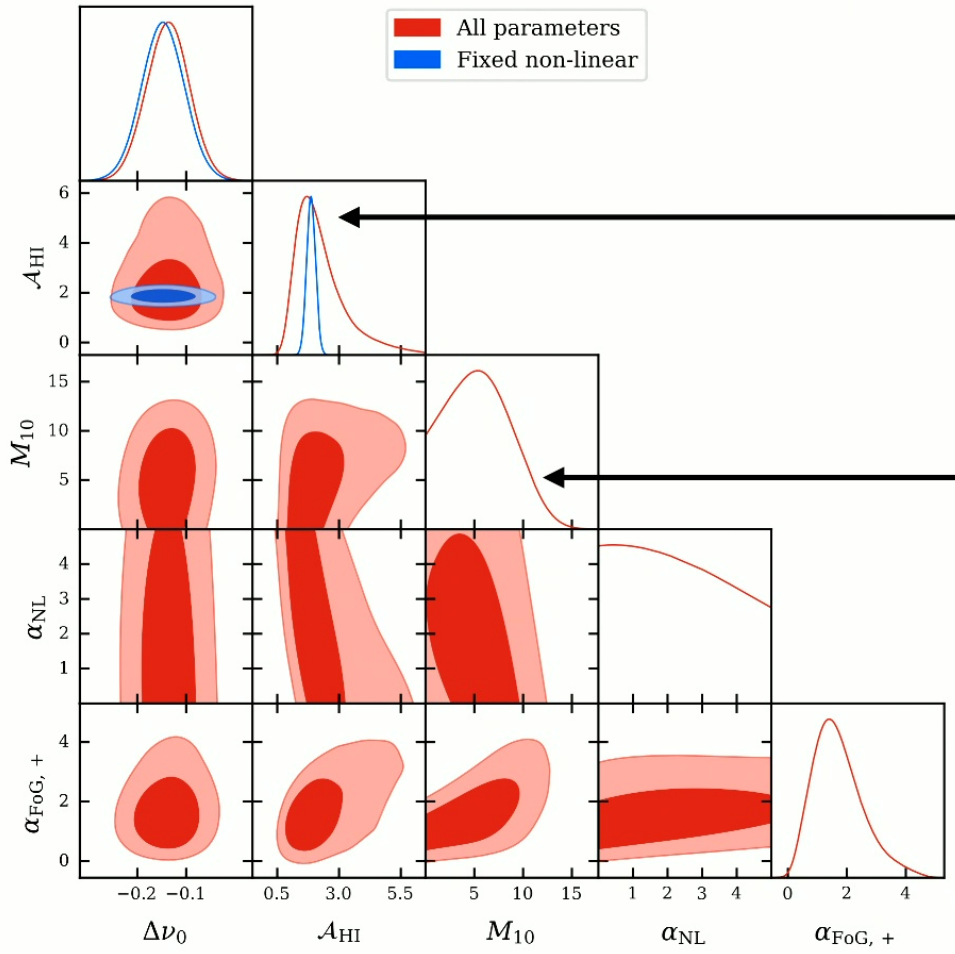
Mean HI mass per object in catalog, results in correlated shot noise $\langle M_{\rm HI}\rangle_g$

Small-scale velocity dispersion, results in “Finger of God” damping $\sigma_{\rm HI}$, σ_g

Controls shape of matter power spectrum, interpolating between linear spectrum and non-linear spectrum from Mead et al. 2020 $\alpha_{\rm NL}$



Parameter Constraints from QSOs



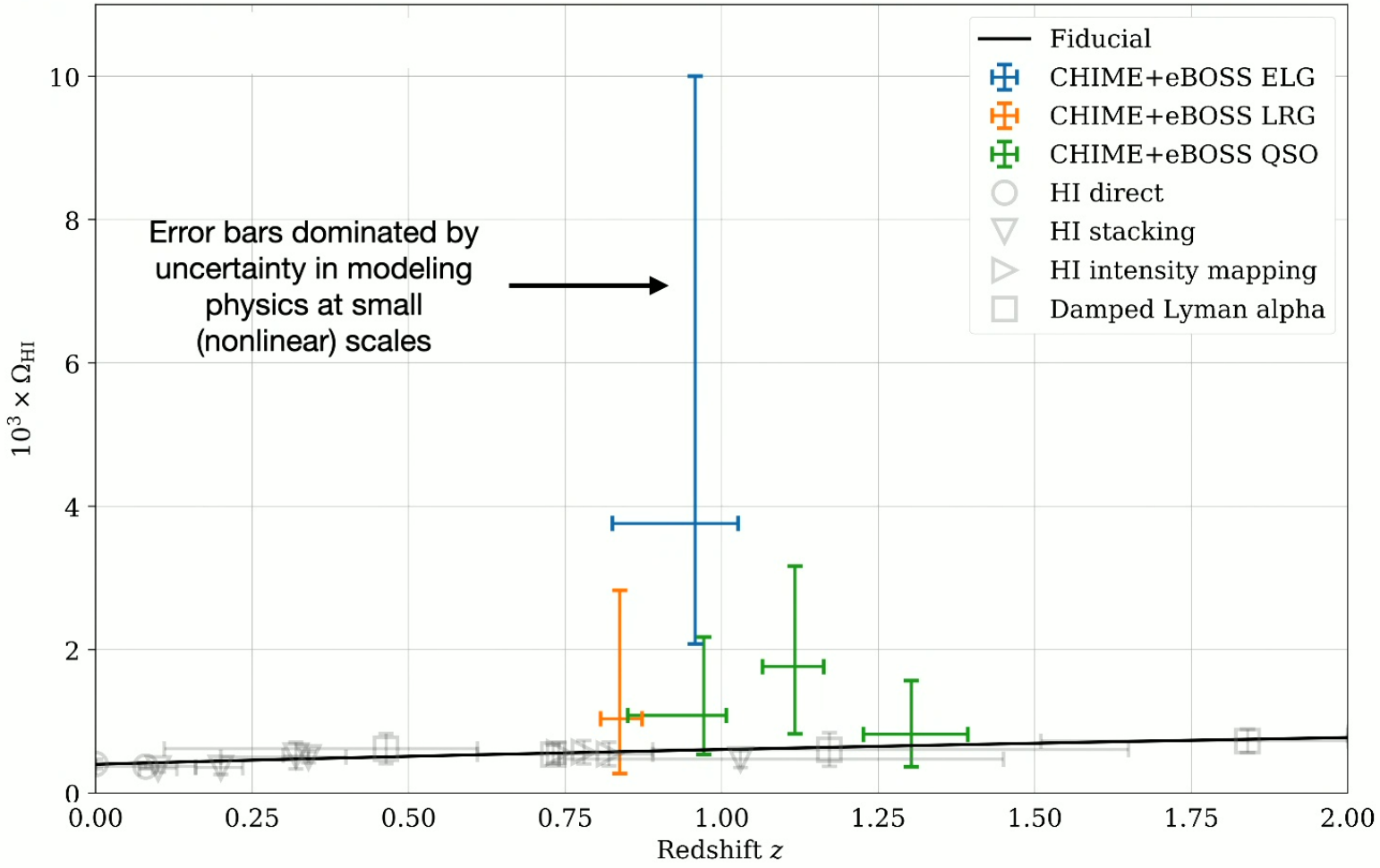
Use non-informative priors for all parameters except for b_g.

Our primary constraints are on the HI "clustering amplitude":

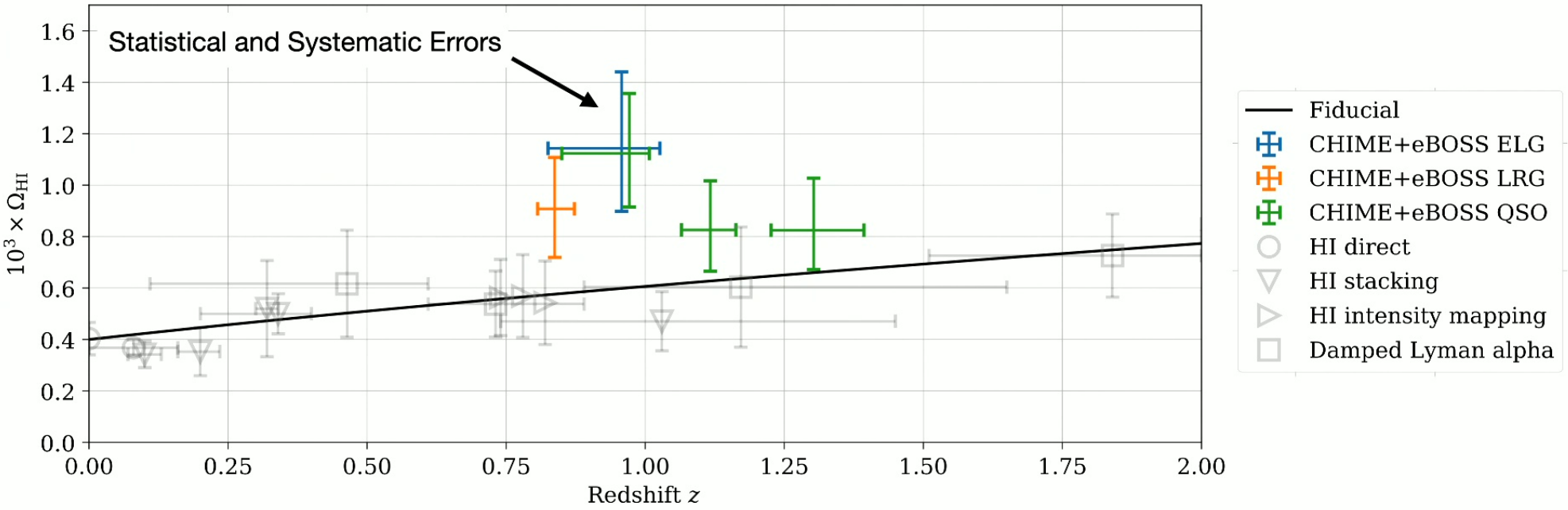
$$A_{\rm HI} \equiv 10^3\ \Omega_{\rm HI}\ (b_{\rm HI} + \langle f\mu^2 \rangle)$$

Starting to place interesting constraints on the average HI mass of each tracer.

Constraints on the Cosmic Density of Neutral Hydrogen



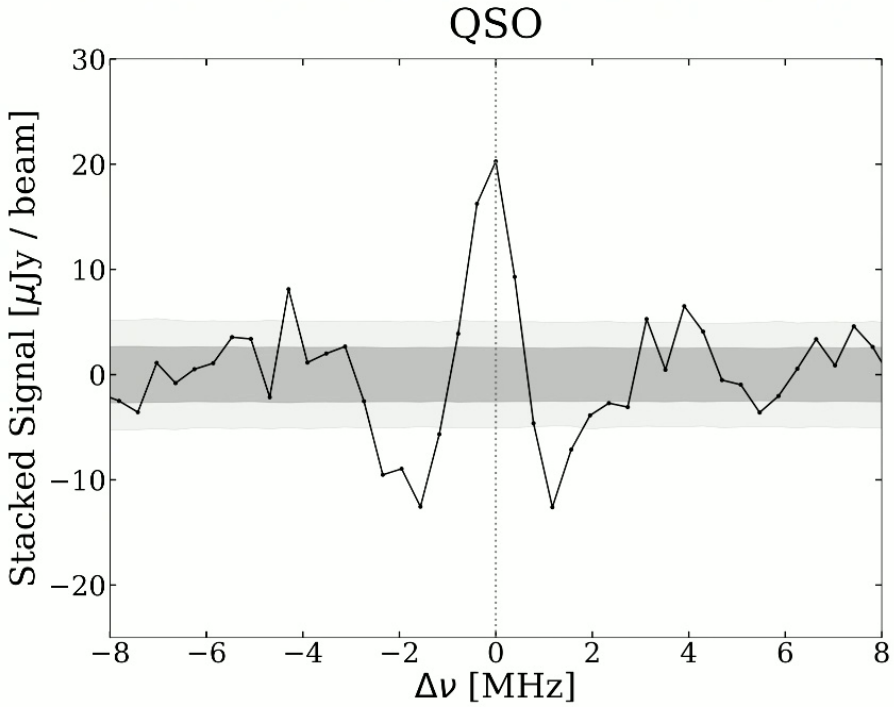
Constraints on the Cosmic Density of Neutral Hydrogen

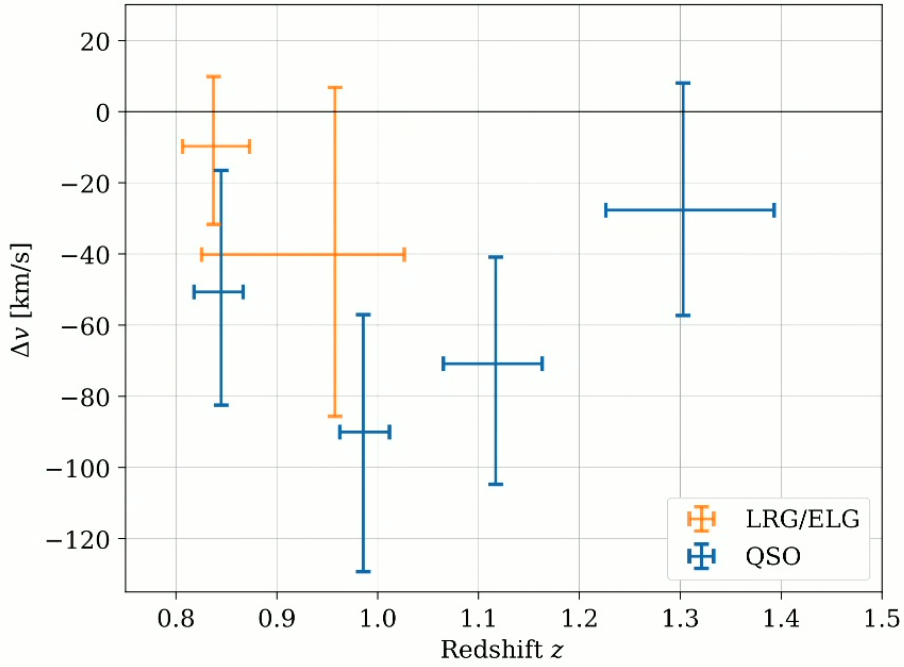


Fix the nonlinear parameters at their fiducial value.

Statistical and systematic errors at ~20%.

Bias in QSO Redshifts





- We measure an offset in the centroid of the QSO stack, likely due to bias in QSO redshifts.
- Demonstrates use of cross-correlations to calibrate systematic errors in individual surveys.

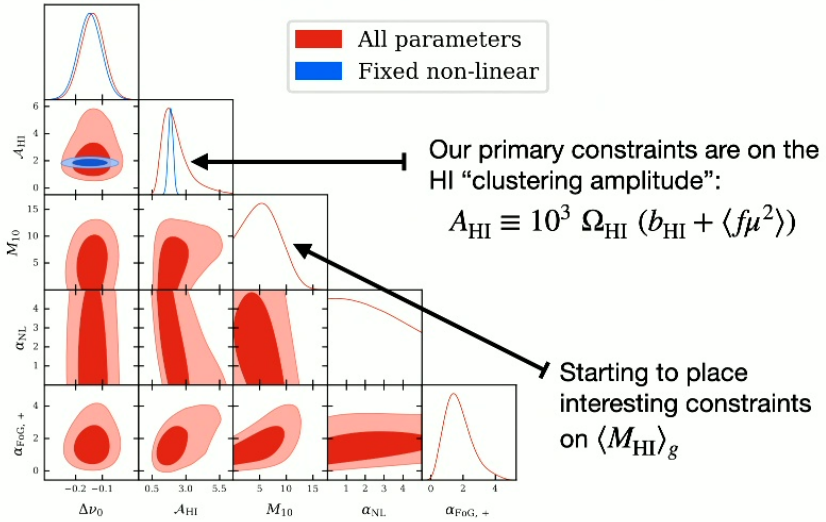
Additional Cross-correlation Studies

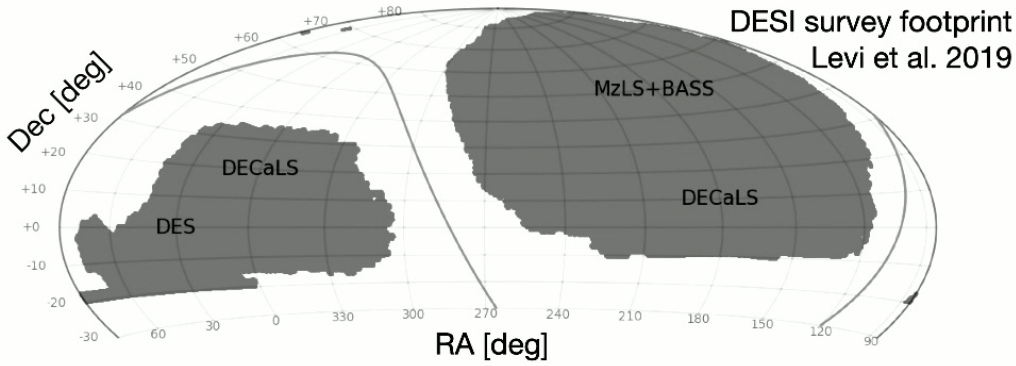
- Improve S/N and measure $\langle M_{\rm HI} \rangle_g$ – average HI mass of each eBOSS tracer

- eBOSS QSO at higher redshift ($1.4 < z < 2.2$)

- eBOSS Lyman-alpha forest

- DESI
  - 4 million LRGs ($0.4 < z < 1.0$)
  - 17 million ELGs ($0.6 < z < 1.6$)
  - 2 million QSOs ($z < 2.1$)

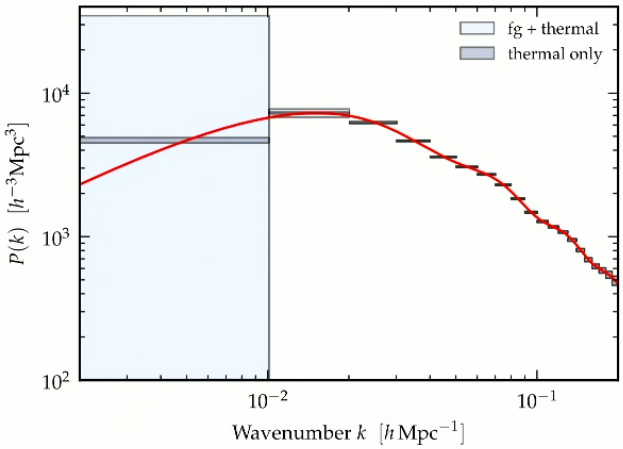




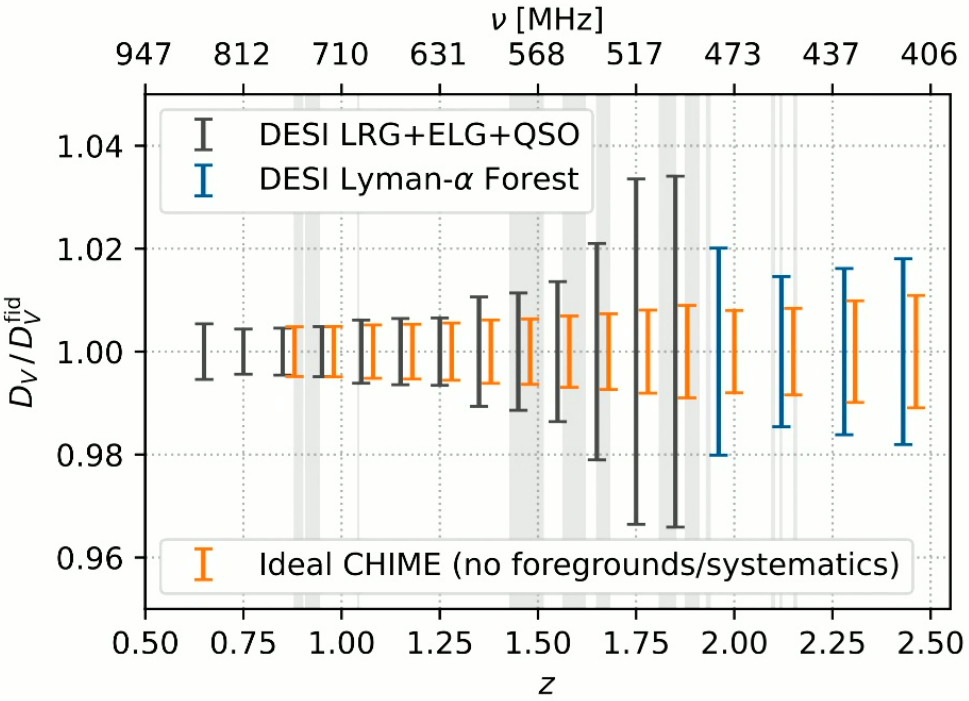
21 cm Power Spectrum Measurements with CHIME

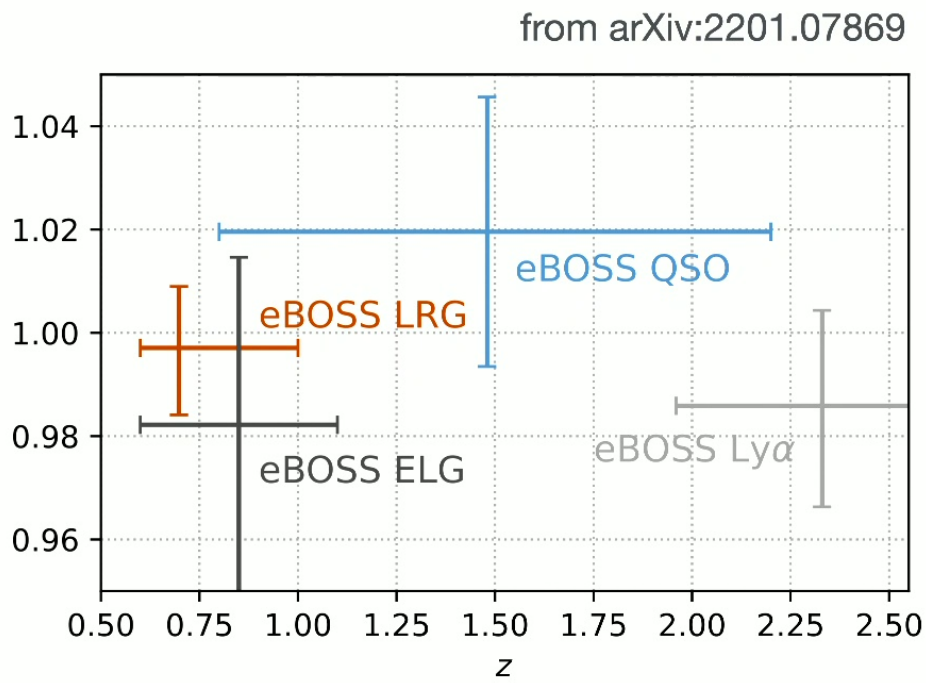
- Measure 21cm power spectrum using CHIME data only (i.e., in auto-correlation)

Simulations from Shaw et al. 2014



Cosmology Forecast





CHIME error bars assume 1 year of integration and no residual foregrounds or systematics.

Comparison to Existing Instruments

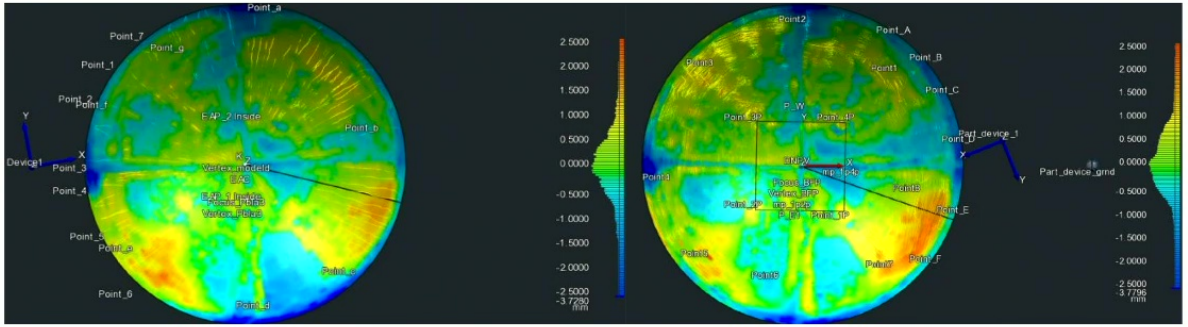
	CHORD	CHIME	GBT
T_{Sys}	30 K	55 K	20 K
z_{21cm}	0–3.7	0.8–2.5	0–3.9
A_{Eff}	8,640 m^2	4,800 m^2	7,850 m^2
FWHM	6' / *f* GHz	10' / *f* GHz	13' / *f* GHz
N_{Beam}	512	1024	1
σ_{RMS} *	12 mJy	41 mJy	9 mJy
FOM**	13	1.0	0.048

* For a 1 second integration and 600 kHz resolution (180 km/s @ 1 GHz)
** FOM = $\Delta z\, N / \sigma^2$ ~ survey volume per time

Table courtesy of Dallas Wulf

CHORD Front End Design

- Parabolic dishes
- Deep dish geometry (f / 0.21)
  - Reduced ground spill and cross-talk
- High precision (sub-mm) manufacturing and assembly tolerances.
- Repeatable manufacturing process
  - Same beam for different elements of the array.



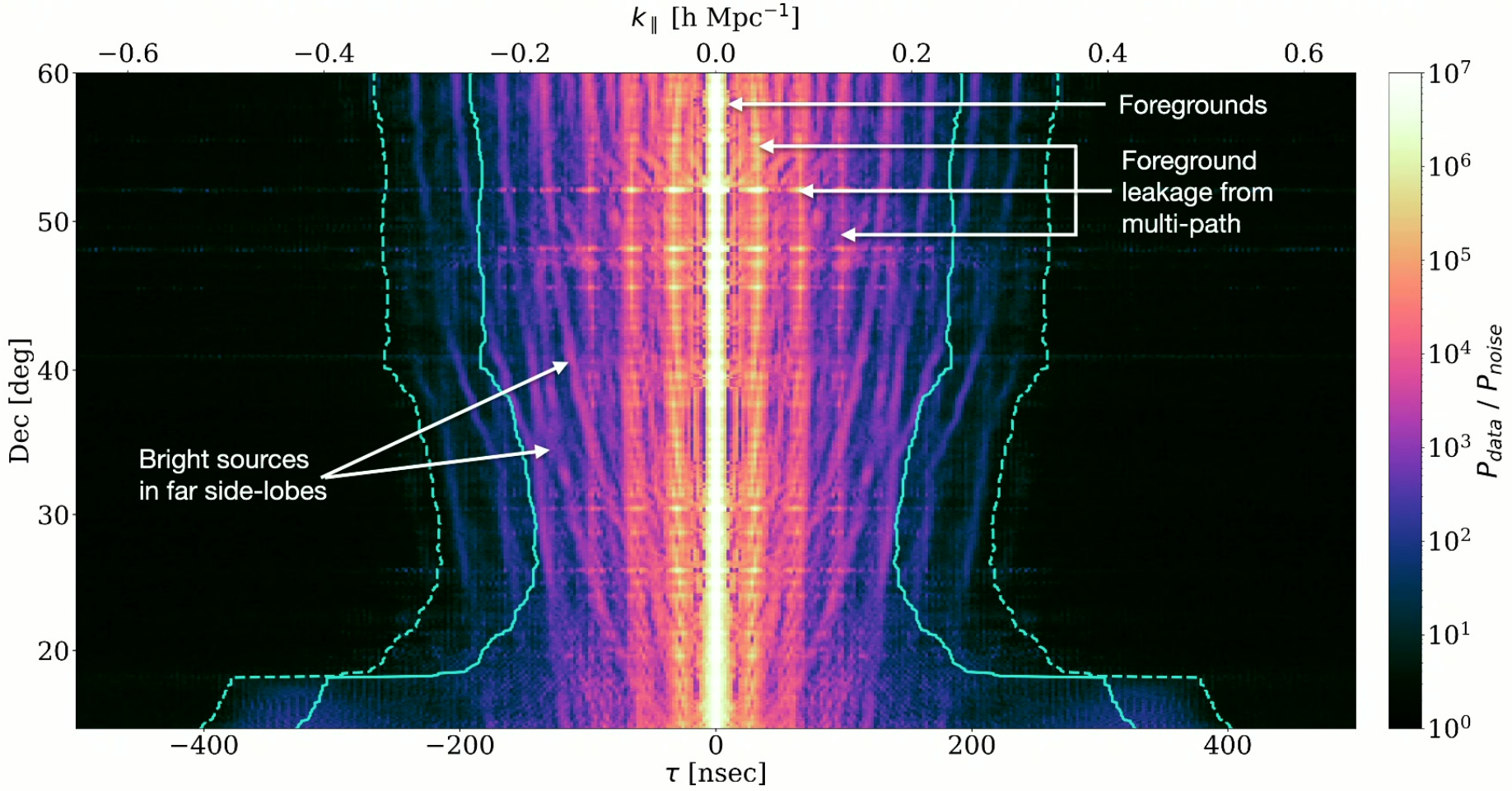
Summary

- Decisive detection of 21cm emission when stacking CHIME data (521 hours) on the LRG, ELG, and QSO clustering catalogs from eBOSS.
  - Constraints currently limited by modeling uncertainties on non-linear scales. Require:
    - Better modeling.
    - Mitigate systematic errors at linear scales.

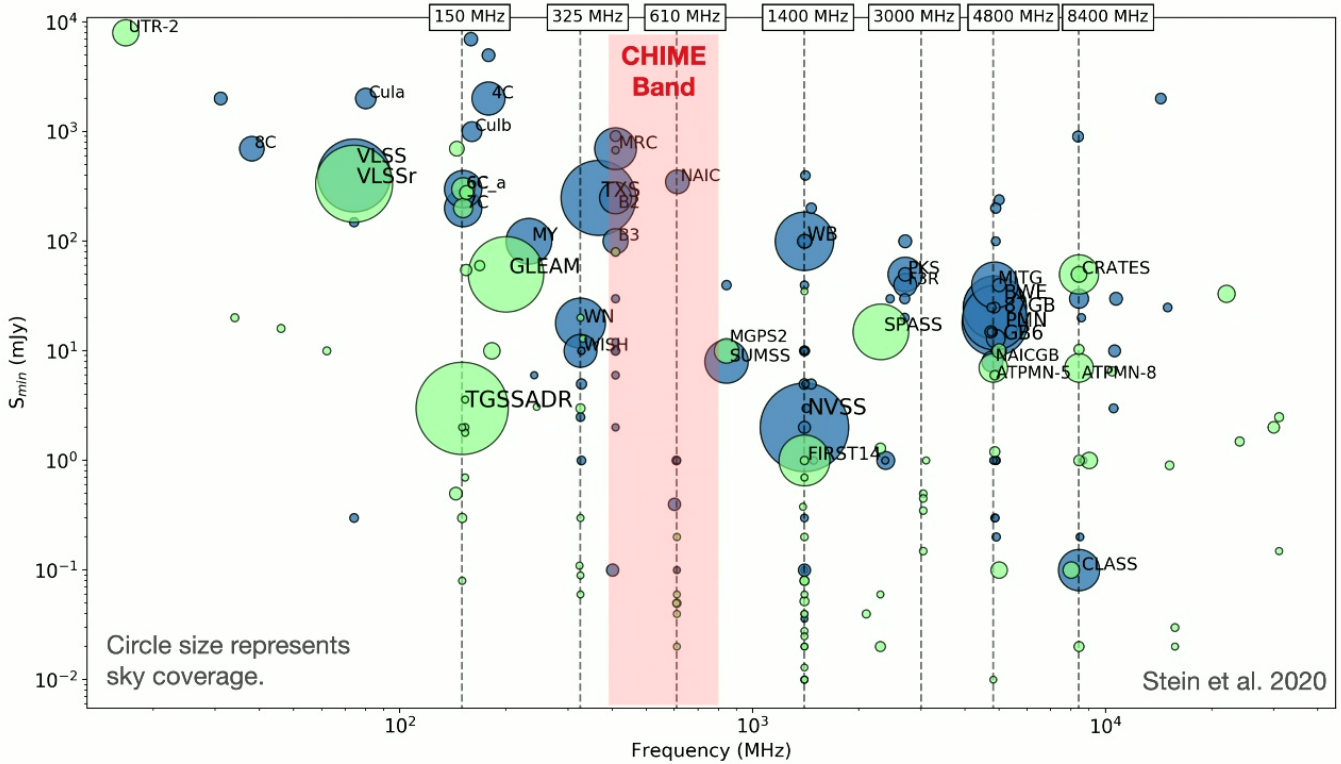
- Next goal: measure the power spectrum of the 21cm emission in auto-correlation.
  - In order to recover scales sensitive to BAO have to incorporate:
    - Shorter baselines.
    - Smaller delays. Requires better beam modelling / deconvolution.

- CHORD fully funded
  - 64 element array in 2023/2024. 512 element array in 2025/2026.
  - Front end designed to mitigate systematic errors currently preventing CHIME from accessing linear scales.

Delay Power Spectrum



Beam Calibration via Extragalactic Point Sources



Construct a model for the radio sky that consists only of extra-galactic point sources.

Interpolate flux measurements made by high-resolution, large-area sky surveys at radio/mm wavelengths to CHIME band (red).

Use ~300,000 sources between -40 deg < Dec < 90 deg. All sources have at least one measurement on either side of the CHIME band.