Title: Detection of Cosmological 21cm Emission with CHIME

Speakers: Simon Foreman

Series: Cosmology & Gravitation

Date: March 08, 2022 - 11:00 AM

URL: https://pirsa.org/22030104

Abstract: Intensity mapping of redshifted 21cm emission from neutral hydrogen holds great promise for learning about cosmology, as it provides an efficient way to map large volumes of the universe without the need to characterize individual luminous sources. The Canadian Hydrogen Intensity Mapping Experiment (CHIME) is a cylinder telescope located in Western Canada that was custom-built for this purpose, with additional science targets including fast radio bursts, pulsars, and Galactic radio emission. In this talk, I will provide an overview of the design and operational status of the telescope (in the context of the cosmology science case), and then present its first 21cm science results: detection of a cross-correlation between CHIME sky maps and galaxy/quasar catalogs from the extended Baryon Oscillation Spectroscopic Survey (eBOSS). In particular, I will discuss our data processing pipeline and how we model the measured signal, as well as the physical implications and prospects for more precise future measurements.

Detection of Cosmological 21cm Emission with CHIME

Simon Foreman

Perimeter Institute for Theoretical Physics
/ Dominion Radio Astrophysical Observatory

PERIMETER INSTITUTE

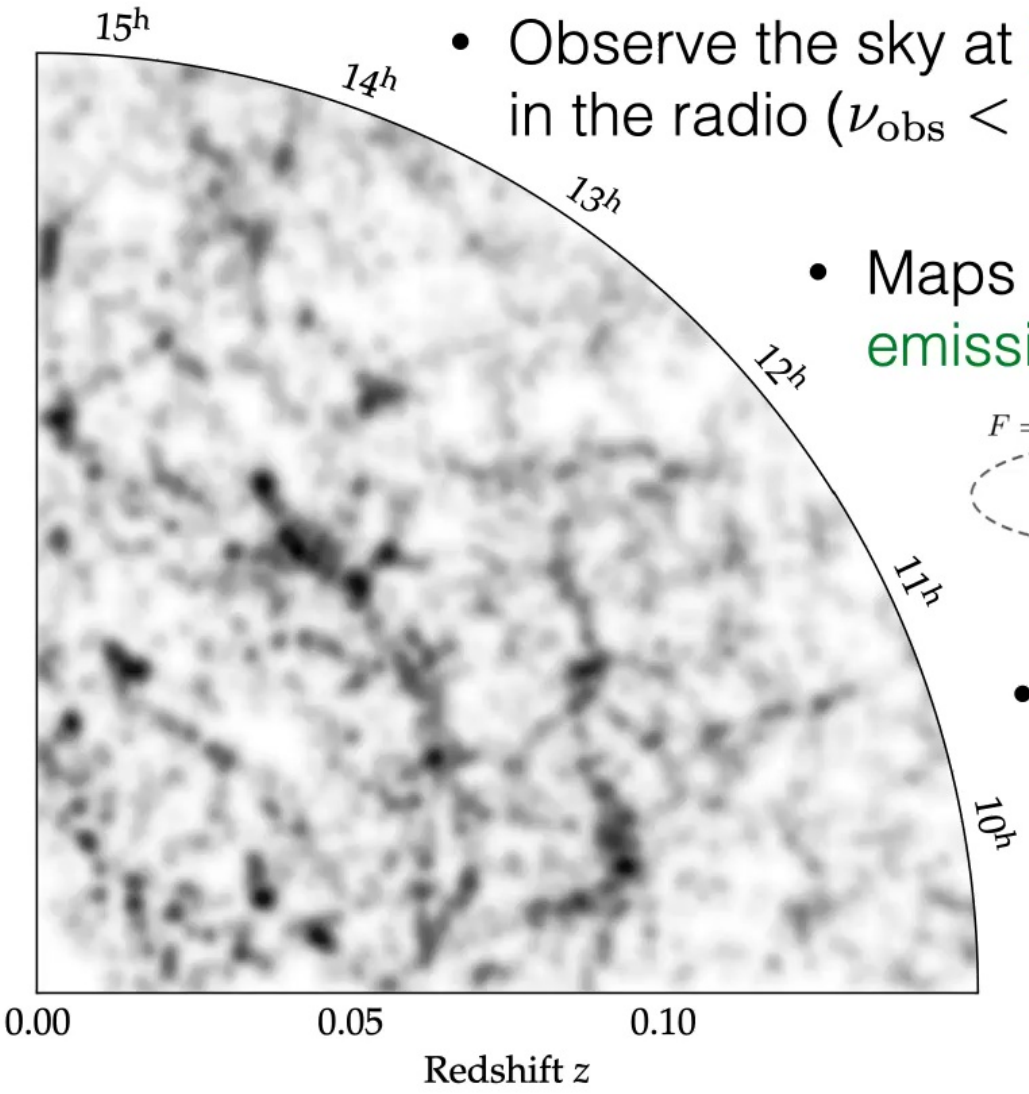
PI cosmology seminar
March 8, 2022

DRAO
NRC · CNRC

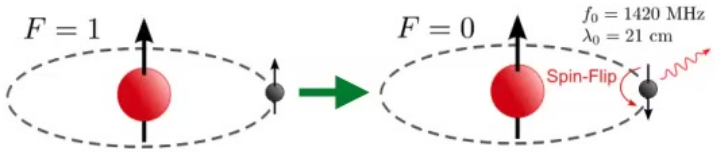
Outline

1. Review: 21cm intensity mapping
2. CHIME instrument overview and status
3. Cross-correlation analysis: data processing
4. Cross-correlation analysis: physical interpretation

Large-scale structure with 21cm intensity mapping



- Observe the sky at low resolution in the radio ($\nu_{\rm obs} < 1420.4\,{\rm MHz}$)
- Maps contain 21cm line emission from spin flips in HI

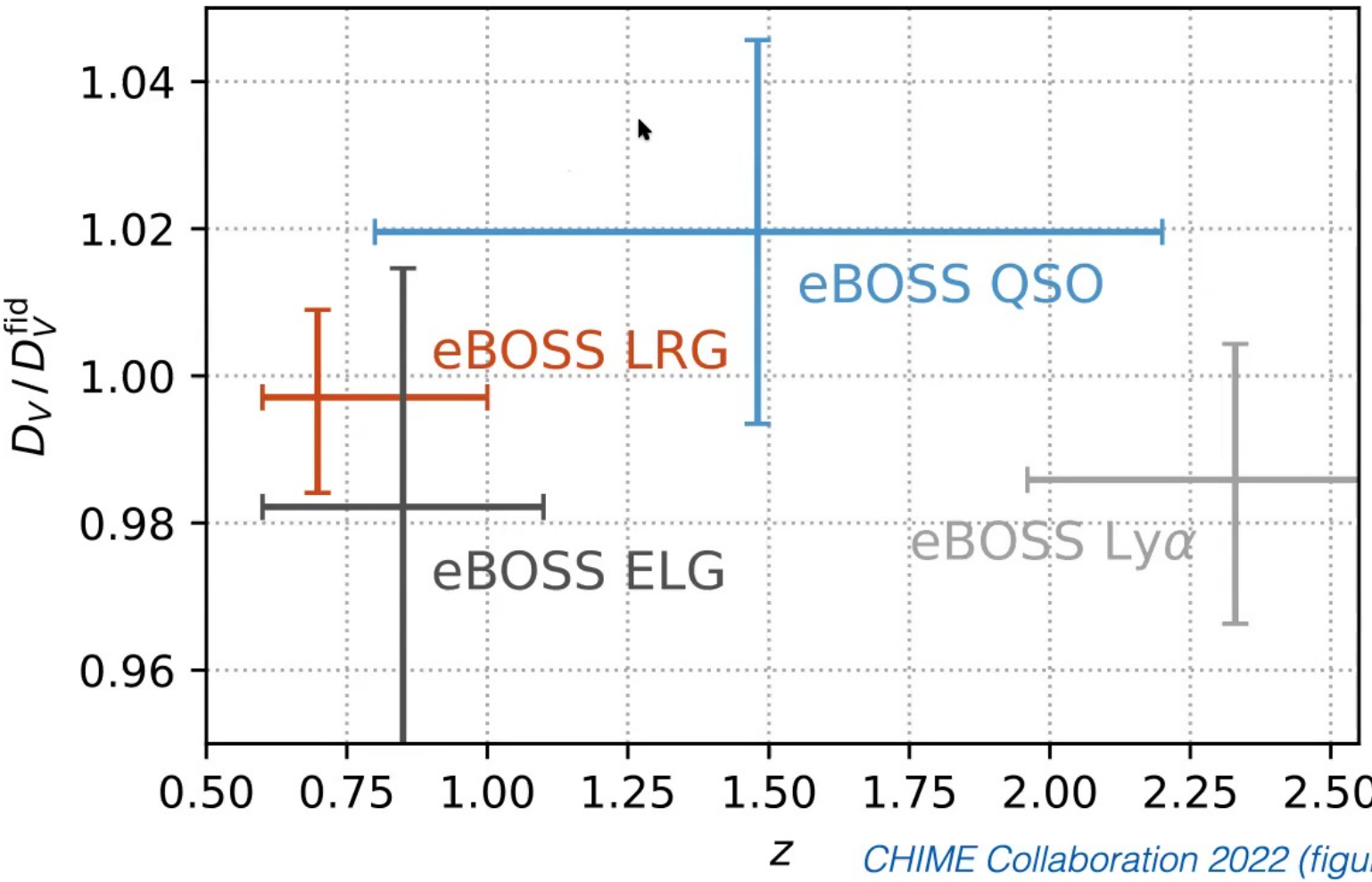


- Observing frequency → redshift:

$$z = \frac{1420.4\,{\rm MHz}}{\nu_{\rm obs}} - 1$$

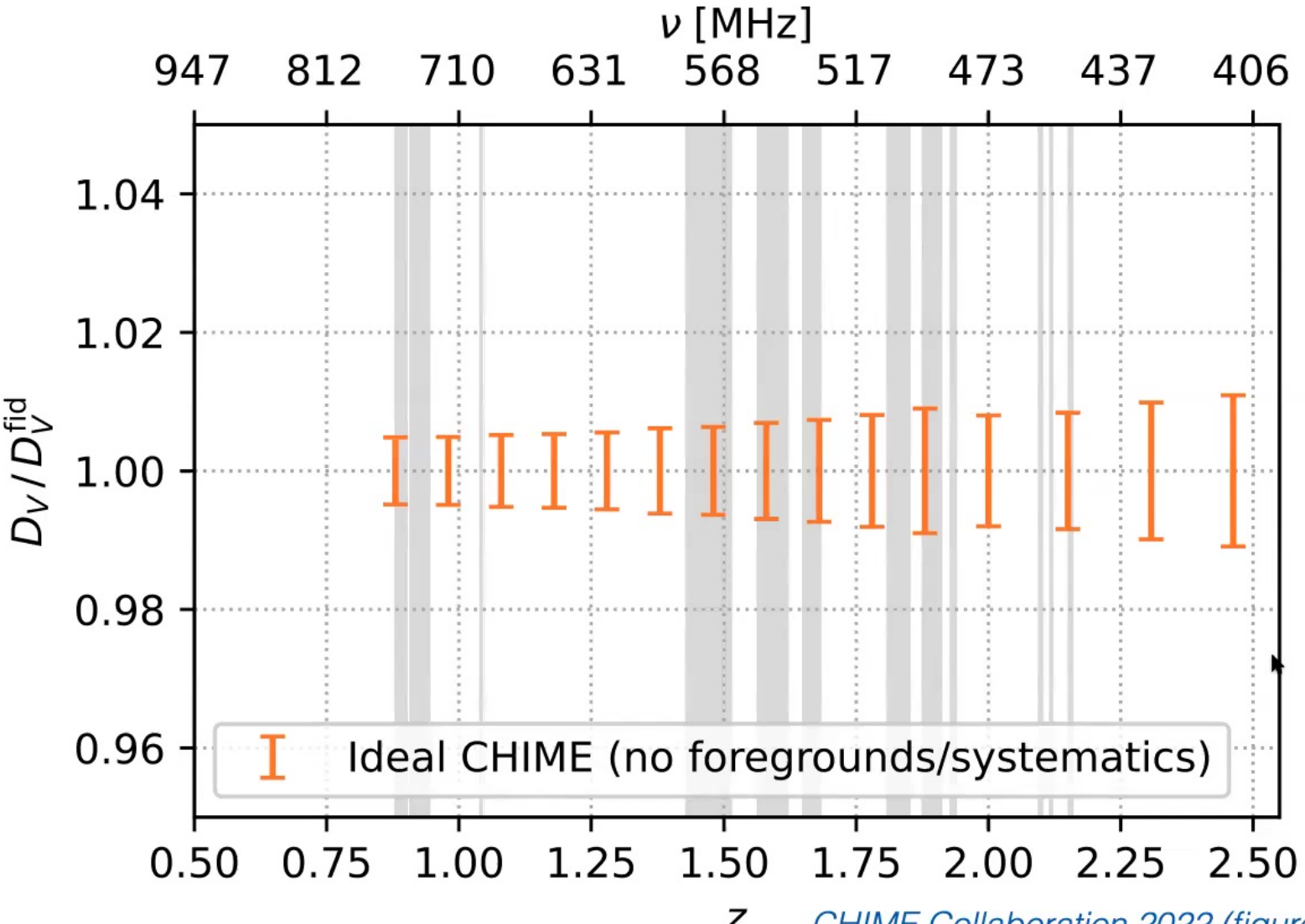
figure: Richard Shaw

Expansion history: state of the art



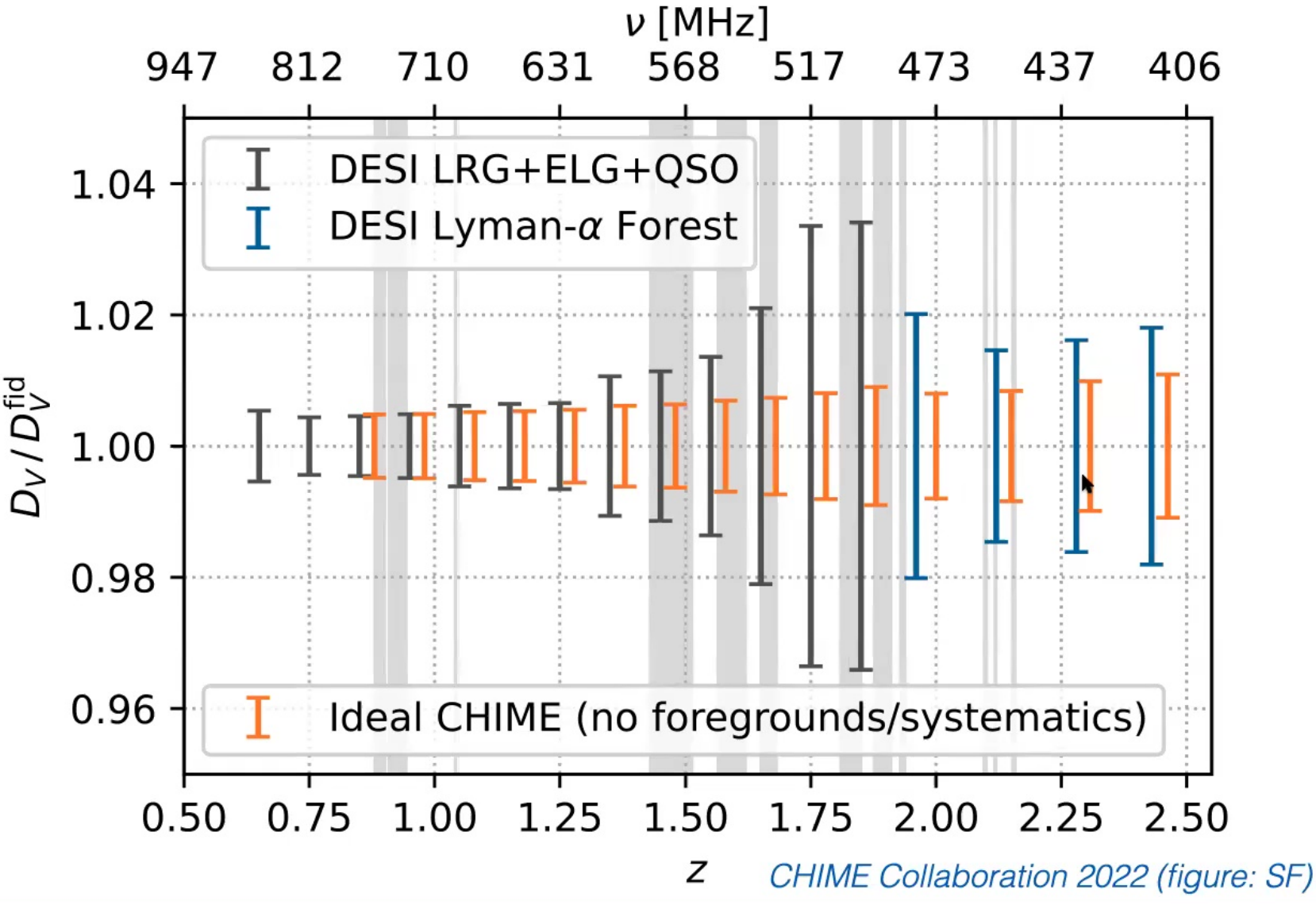
CHIME Collaboration 2022 (figure: SF)

Expansion history: CHIME best-case scenario



CHIME Collaboration 2022 (figure: SF)

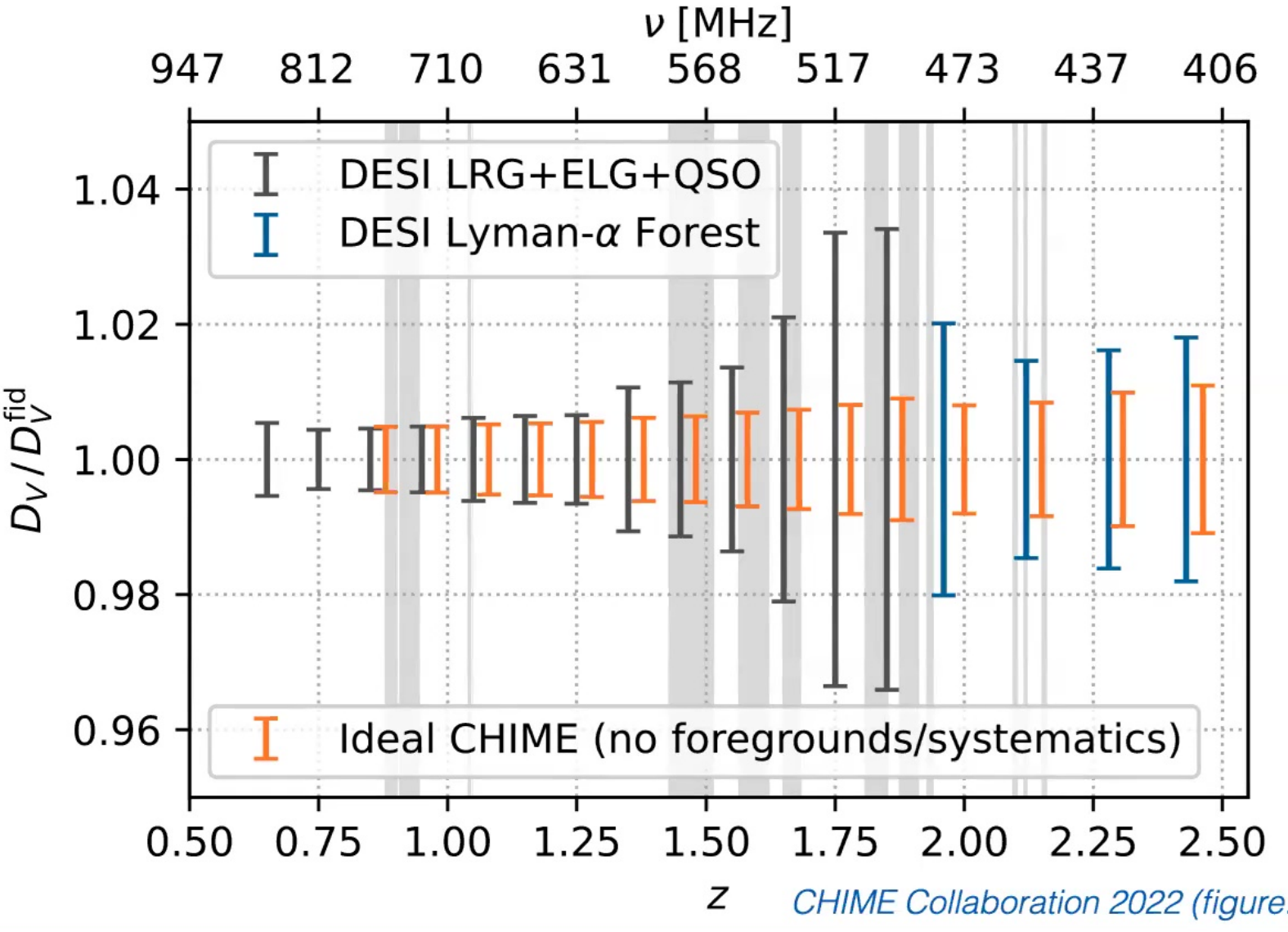
Expansion history: CHIME best-case scenario



CHIME Collaboration 2022 (figure: SF)

Instrument overview and status

Expansion history: CHIME best-case scenario



CHIME Collaboration 2022 (figure: SF)

Detection of Cosmological 21cm Emission with CHIME / Simon Foreman

The Canadian Hydrogen Intensity Mapping Experiment

Compact interferometer with redundant baselines

- 1024 antennas (2 polarized feeds each)
- 4 cylinders, 20m x 100m each

400 - 800 MHz ($2.5>z>0.8$), 1024 channels

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High redshift resolution ($\Delta\nu \approx 0.39\,\mathrm{MHz} \rightarrow \delta z \approx 10^{-3}$)

Location


CANADA
GREENLAND
(Denmark)
GROENLAND
(Danemark)
N
W
E
S
Arctic Ocean
Océan Arctique
Baffin Bay
Baie de Baffin
UNITED STATES OF AMERICA
ÉTATS-UNIS D'AMÉRIQUE
Yukon Territory
Territoire-du-Yukon
Whitehorse
Northwest Territories
Territoires-du-Nord-Ouest
Yellowknife
Nunavut
Iqaluit
Labrador sea
Mer du Labrador
Newfoundland and Labrador
Terre-Neuve et Labrador
Hudson Bay
Baie d'Hudson
St. John's
Pacific Ocean
Océan Pacifique
British Columbia
Colombie-Britannique
Alberta
Edmonton
Calgary
Saskatchewan
Regina
Manitoba
Winnipeg
Ontario
Quebec
Québec
Québec
Montréal
Ottawa
Toronto
Prince Edward Island
Île du Prince-Édouard
Charlottetown
Nova Scotia
Nouvelle-Écosse
Fredericton
Halifax
New Brunswick
Nouveau-Brunswick
chime
Victoria
Ingenio Canada Map Floor Puzzle

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Location, collaboration, and land acknowledgment

UBC THE UNIVERSITY OF BRITISH COLUMBIA

UNIVERSITY OF TORONTO

DRAO NRC·CNRC

McGill

with partners at

PERIMETER INSTITUTE

Yale University

SUN YAT-SEN UNIVERSITY

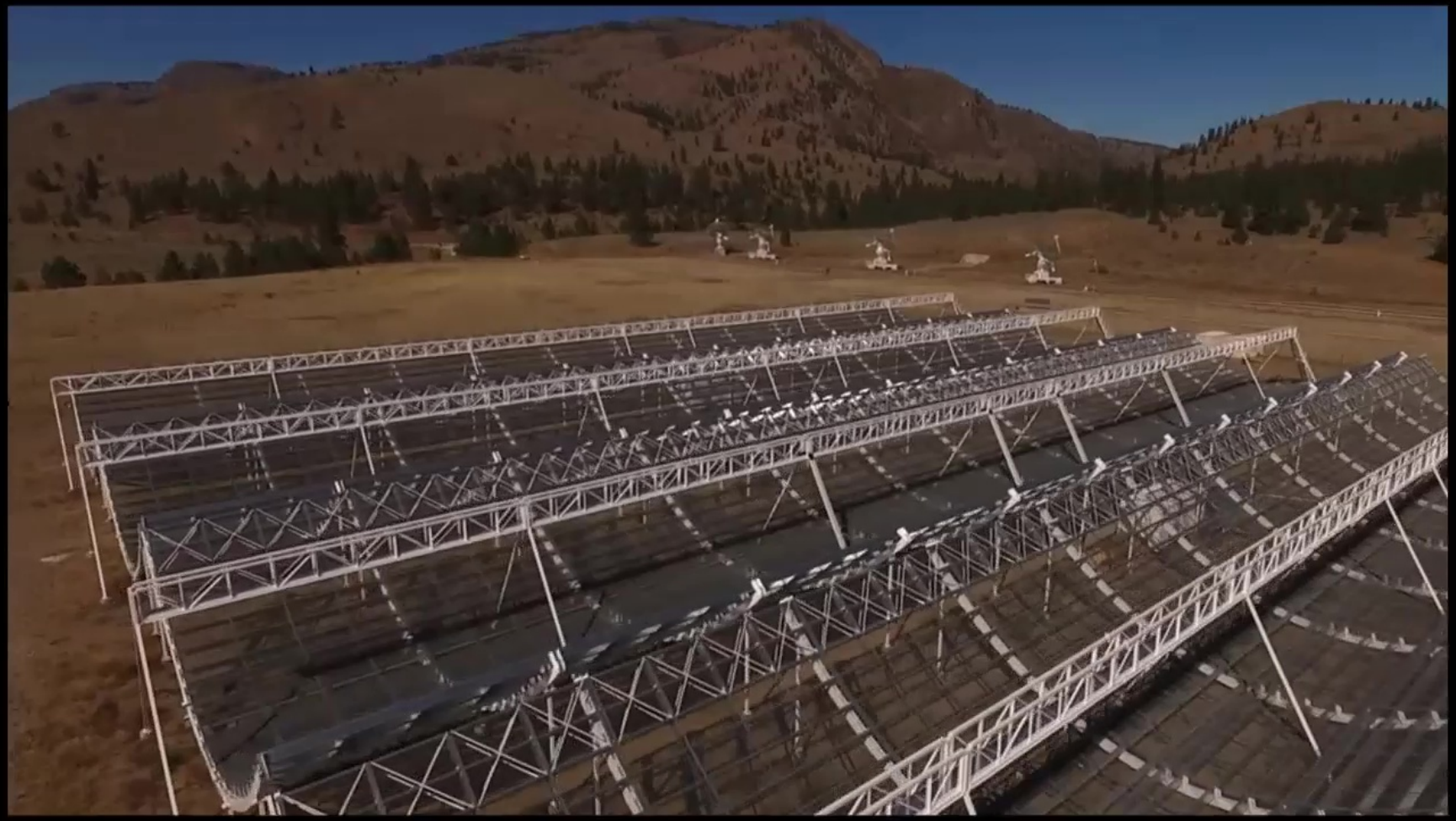
WestVirginiaUniversity

Massachusetts Institute of Technology

We acknowledge that CHIME is located on the traditional, ancestral, and unceded territory of the Syilx Okanagan people.

Detection of Cosmological 21cm Emission with CHIME / Simon Foreman

Flyover of site (from Sept. 15, 2016)



What CHIME measures

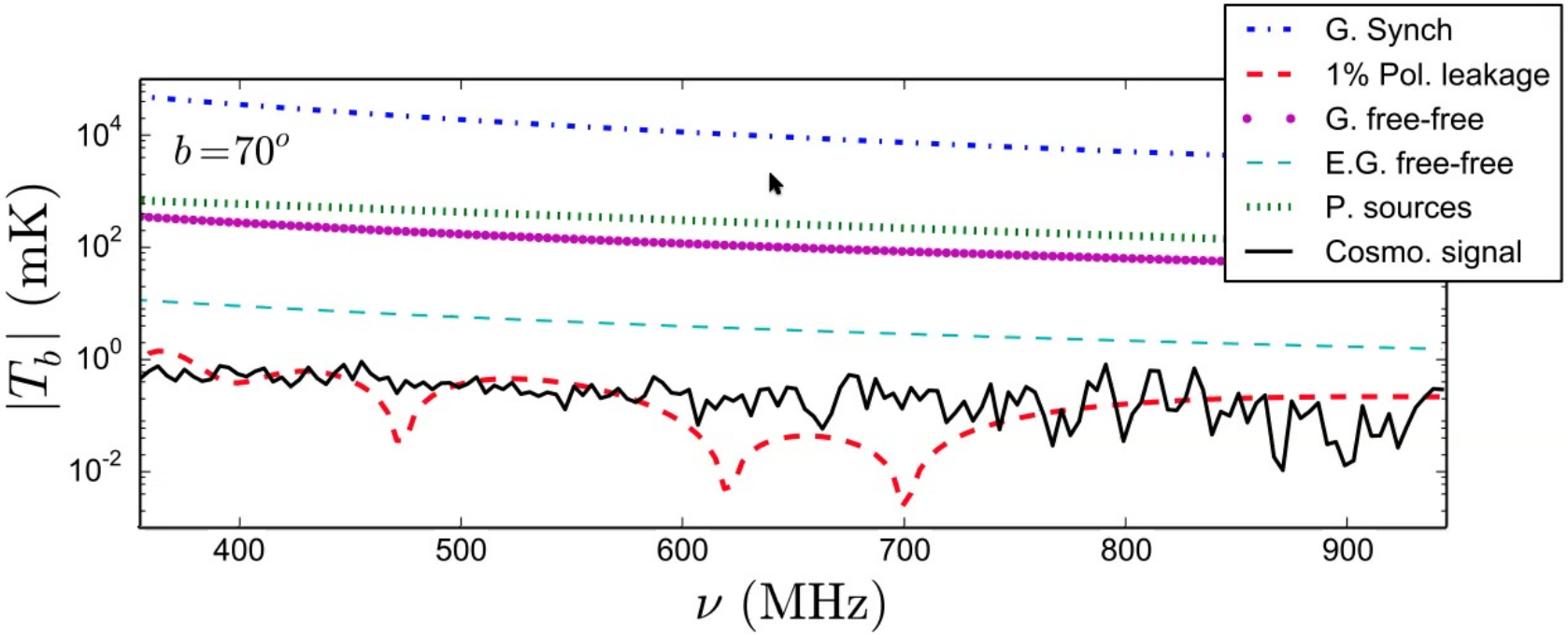
product of voltages at feeds a, b — *complex gains of feeds a, b* — *thermal noise*

$$\langle V_a V_b^* \rangle = g_a(t) g_b^*(t) \left\{ N_{ab}(\nu, t) + \int d^2\hat{n}\, A_a(\hat{n}, t) A_b^*(\hat{n}, t) e^{2\pi i \vec{d}_{ab} \cdot \hat{n} \nu / c} \left[\mathrm{RFI}(\hat{n}, \nu, t) + T_{\mathrm{fg}}(\hat{n}, \nu) + T_{21}(\hat{n}, \nu) \right] \right\}$$

product of beam responses of feeds a, b — *phase/delay factor* — *radio frequency interference* — *foregrounds* — *21cm signal*

Challenge: understand or mitigate each item

The foreground problem



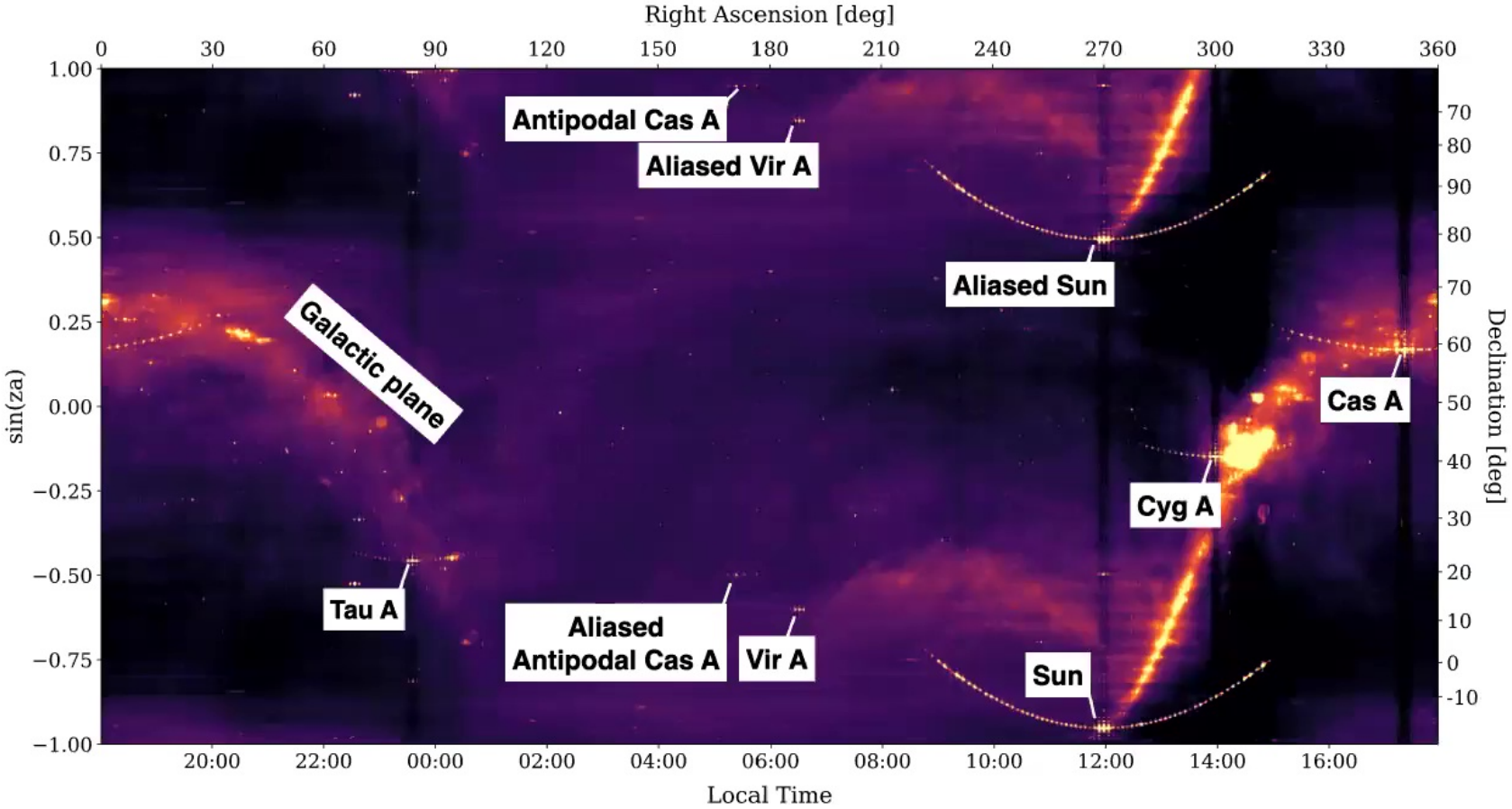
- Foregrounds: bright, but spectrally smooth
  → inhabit low-$k_{||}$ modes

- 21cm signal: low frequency-frequency correlation
  (frequency = source redshift)

figure: Alonso+ 2014

CHIME's view of the radio sky

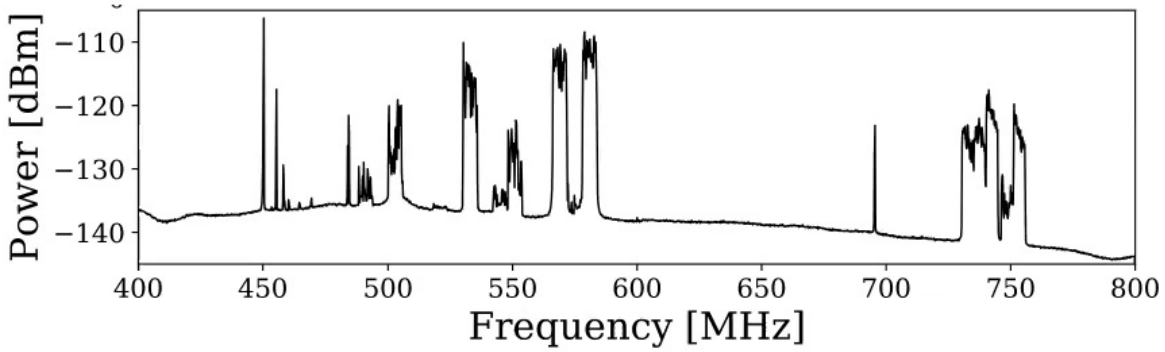
Map at 670MHz made from beams formed along meridian (minimal processing applied)



CHIME Collaboration 2022 (figure: S. Siegel)

Operational status

- Acquiring cosmology science data since Oct. 7, 2018
- 42% of band flagged due to RFI:



- Significant progress on instrument calibration since first light:
  - Complex gain calibration: <1%
  - Phase calibration: 0.015 rad

More details in instrument overview paper:
arXiv:2201.07869

Cross-correlation analysis

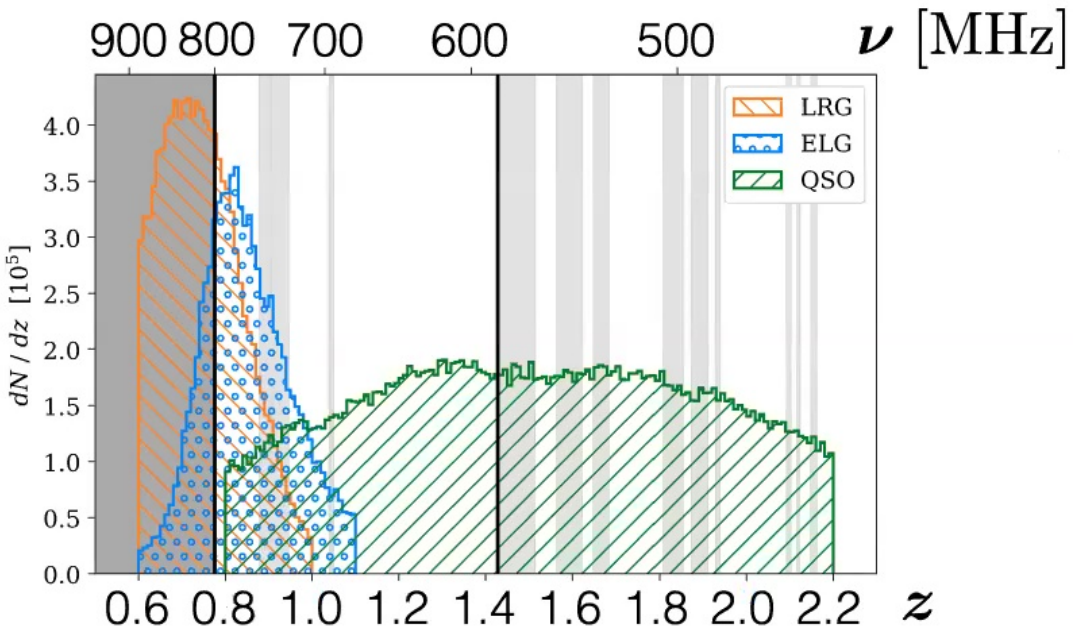
CHIME cross-correlation target: eBOSS survey

extended Baryon Oscillation Spectroscopic Survey (eBOSS):

4.5-year survey with Sloan Telescope *(e.g. Alam+ 2021)*

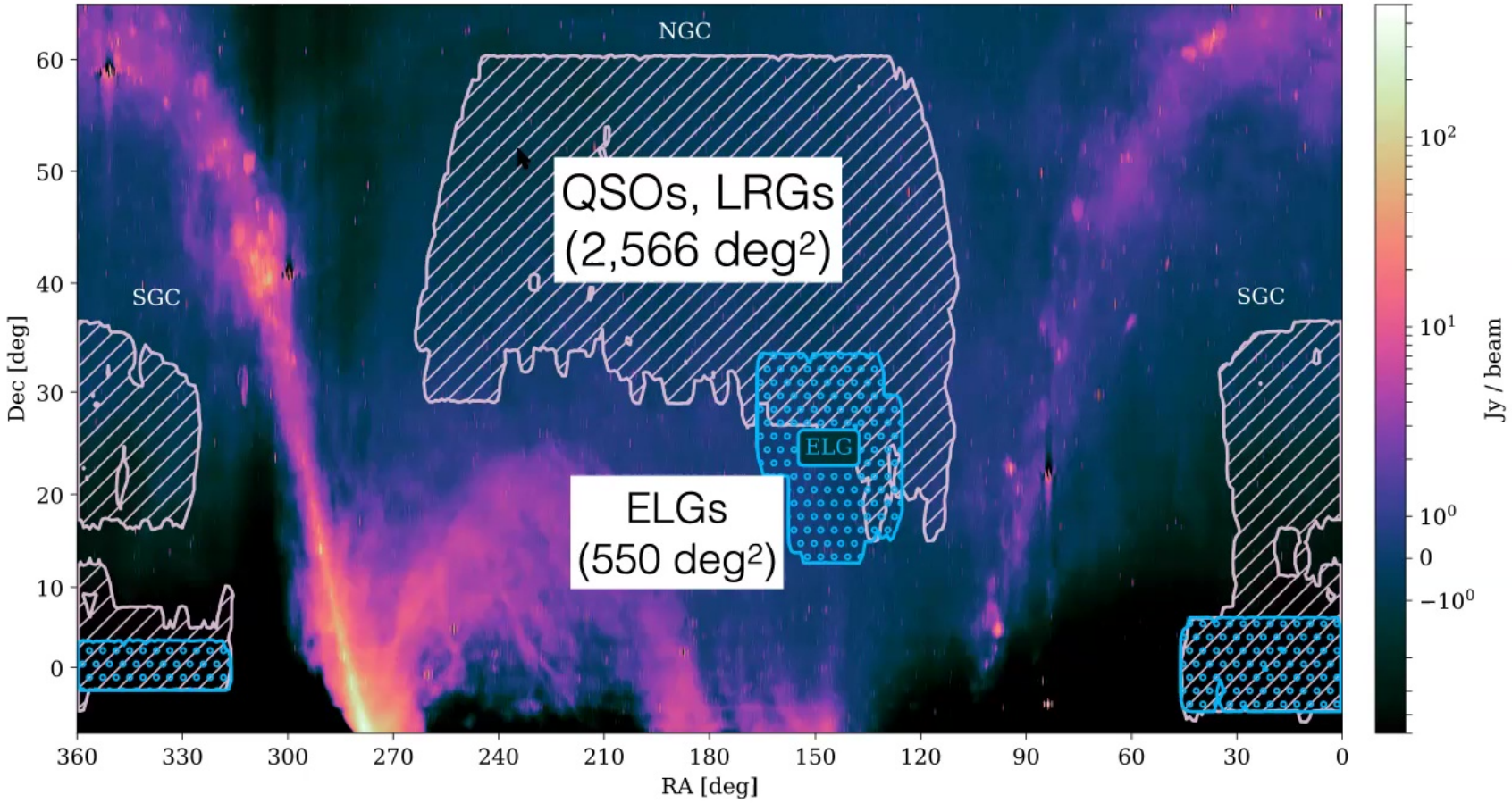
- Emission-line galaxies (ELGs): blue, star-forming **31,181**
- Luminous red galaxies (LRGs): old, quiescent **21,615**
- Quasars (QSOs): bright active galactic nuclei **48,046**

used in analysis



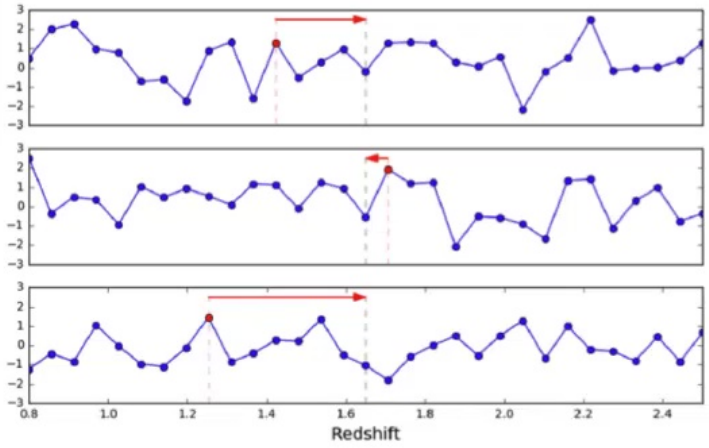
CHIME cross-correlation target: eBOSS survey

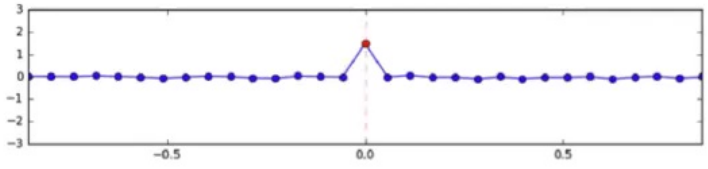
eBOSS footprints and example CHIME map

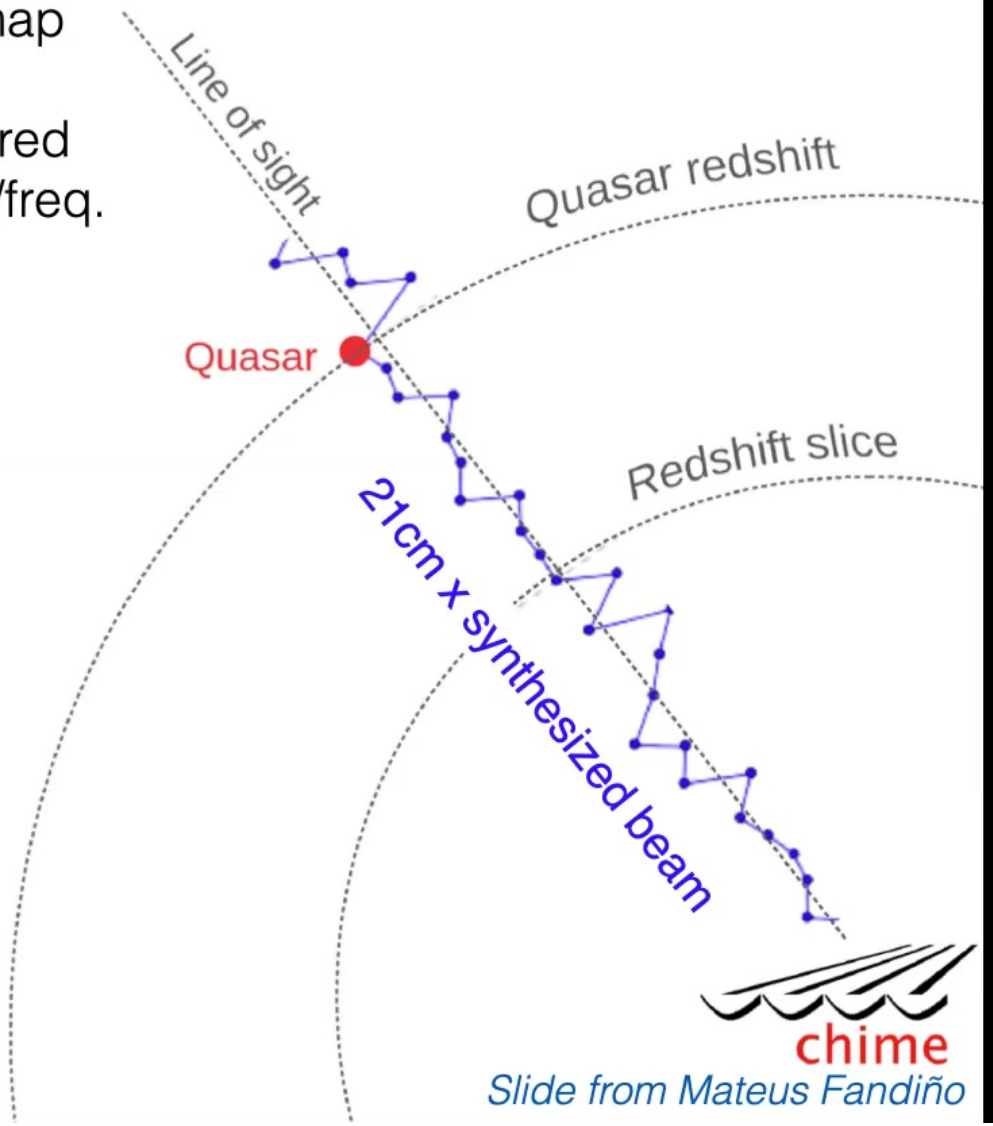


Cross correlations: method

- Make multi-frequency sky map
- Apply filtering and masking
- Extract spectral cube centered on each object's location/freq.
- Shift ν axis and stack





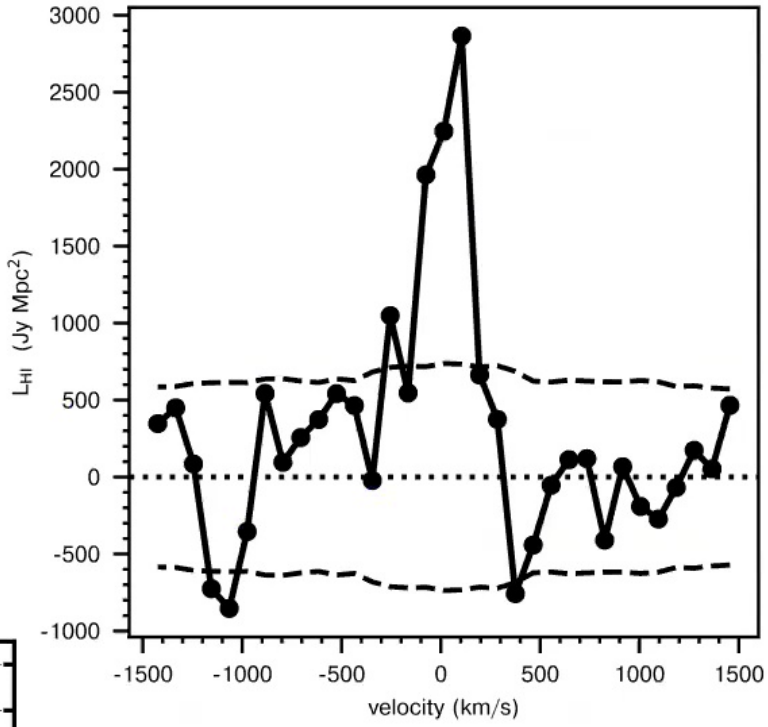


Slide from Mateus Fandiño

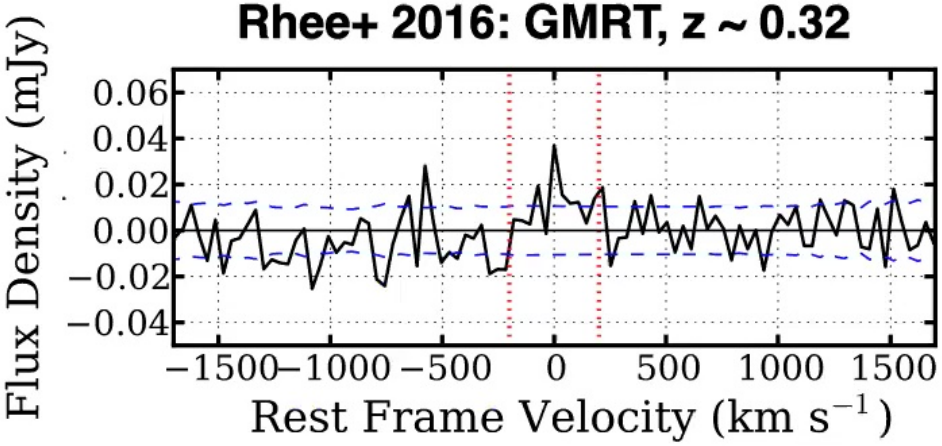
Previous work, part 1: spectral stacking

- Interferometric observations
- 4-30σ significance
- No clustering information
- Derive mean HI mass of galaxy sample

Chowdhury+ 2021: GMRT, 0.74 < z < 1.45

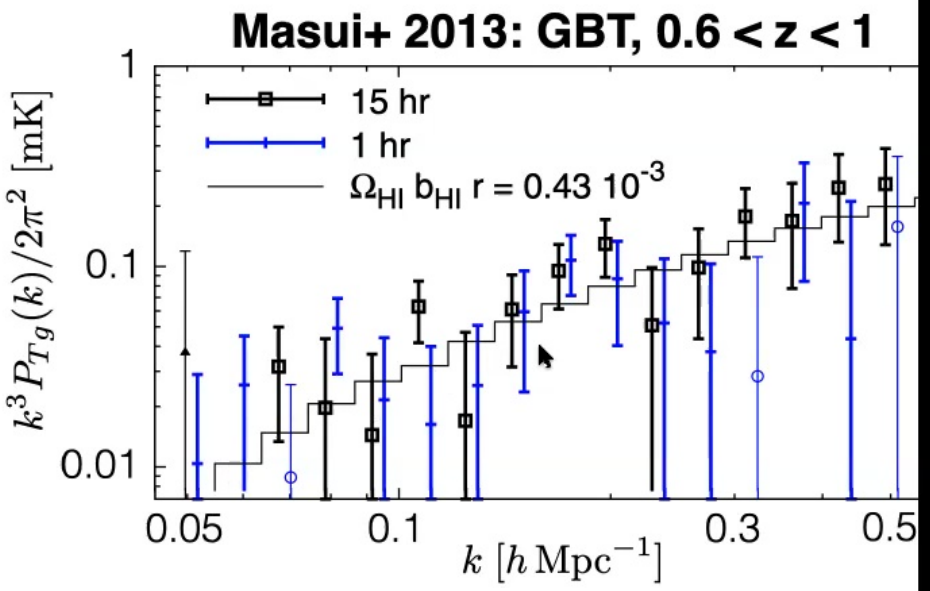


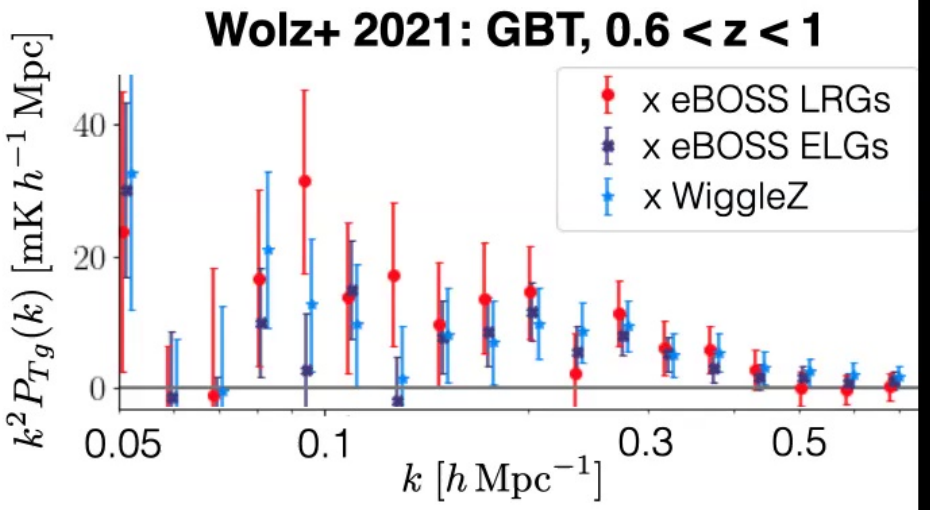
Rhee+ 2016: GMRT, z ~ 0.32



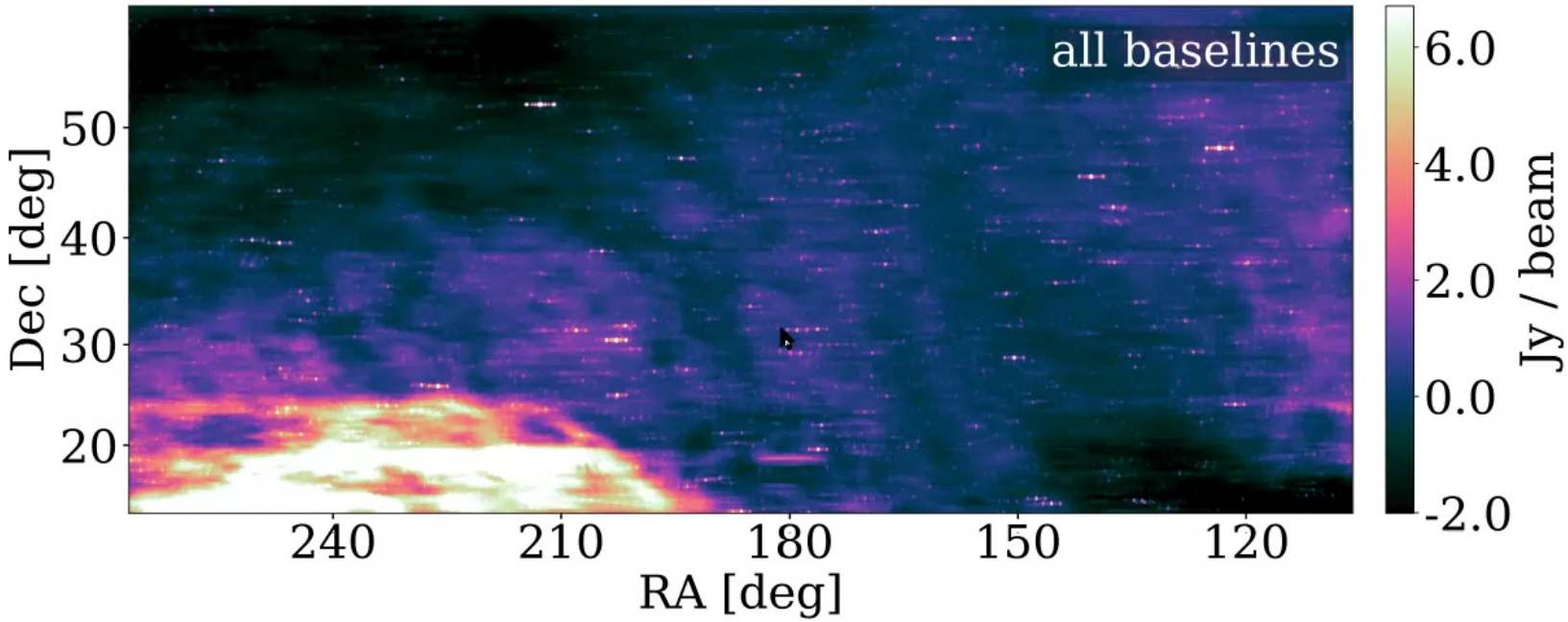
Previous work, part 2: cross power spectra of maps

- Single-dish observations
- 4-7σ significance
- Fixed template for scale-dependence of cross-correlation, with amplitude fit to data



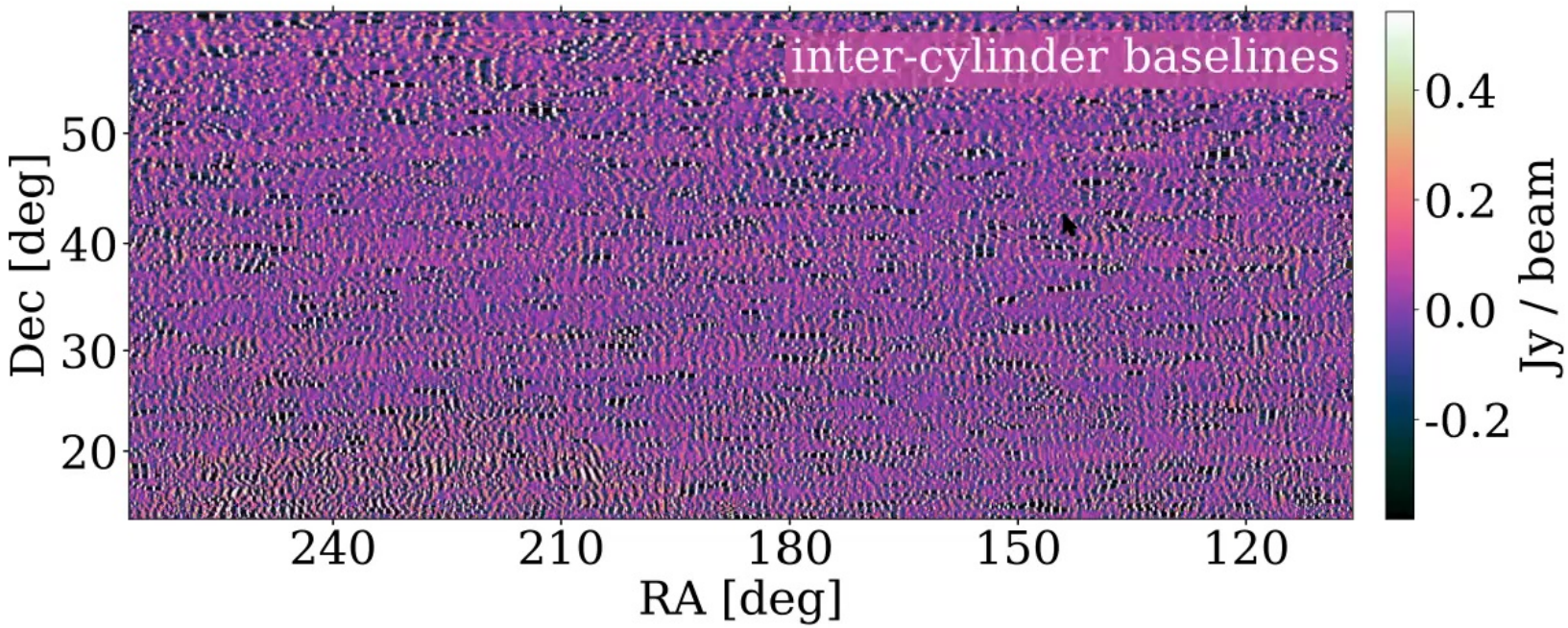


Map at 700MHz for NGC field



- Roughly 500 hours (~22 days) of integration time
- Primary beam model has been deconvolved

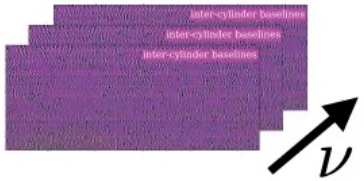
Map at 700MHz for NGC field

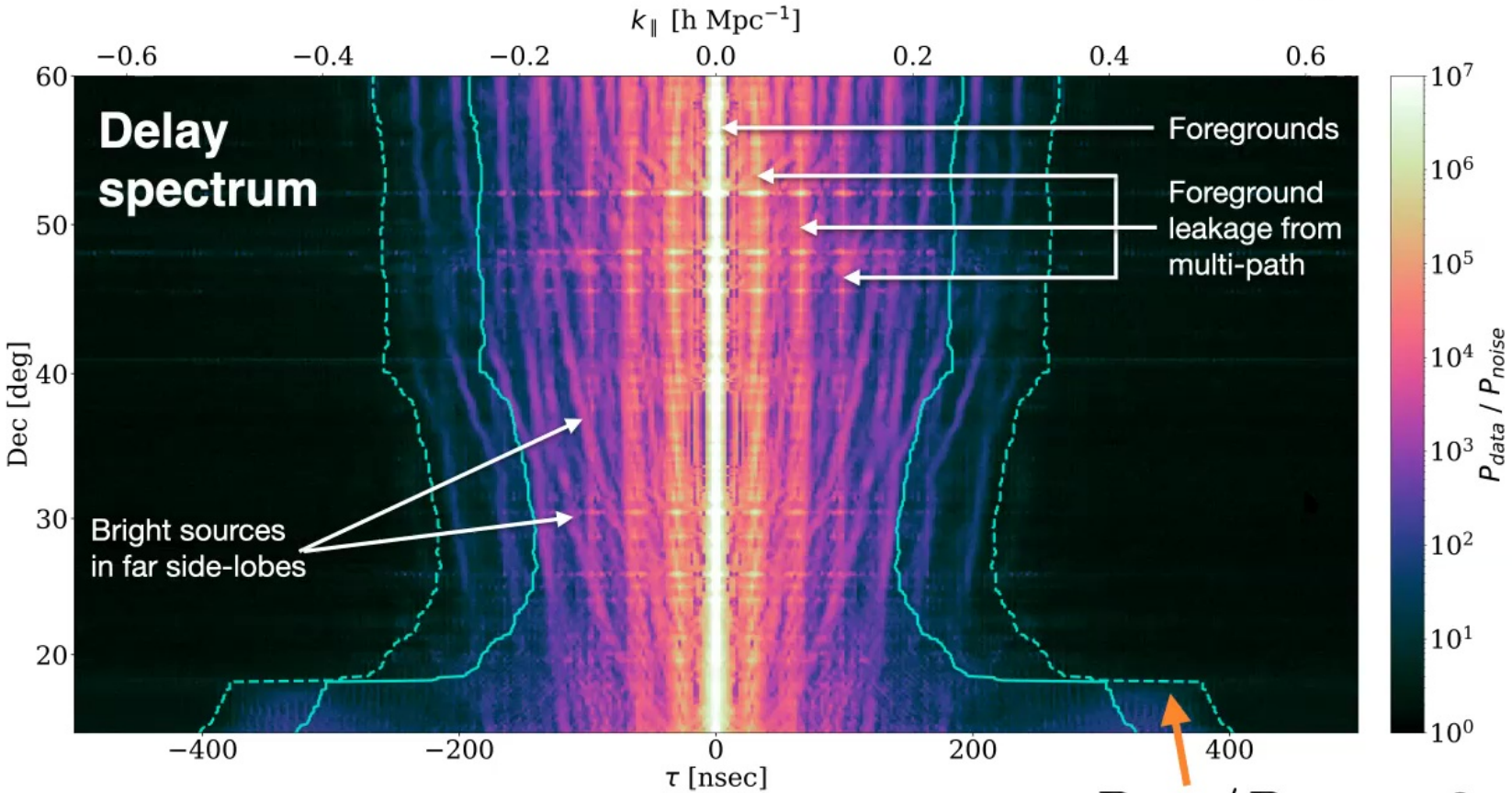


- Restrict to **inter-cylinder baselines**: resolve out diffuse fg

Delay space (Fourier conjugate of frequency)

- Fourier transform $\nu \rightarrow \tau$
- Compute variance over RA





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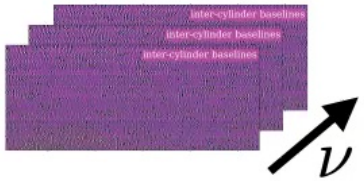
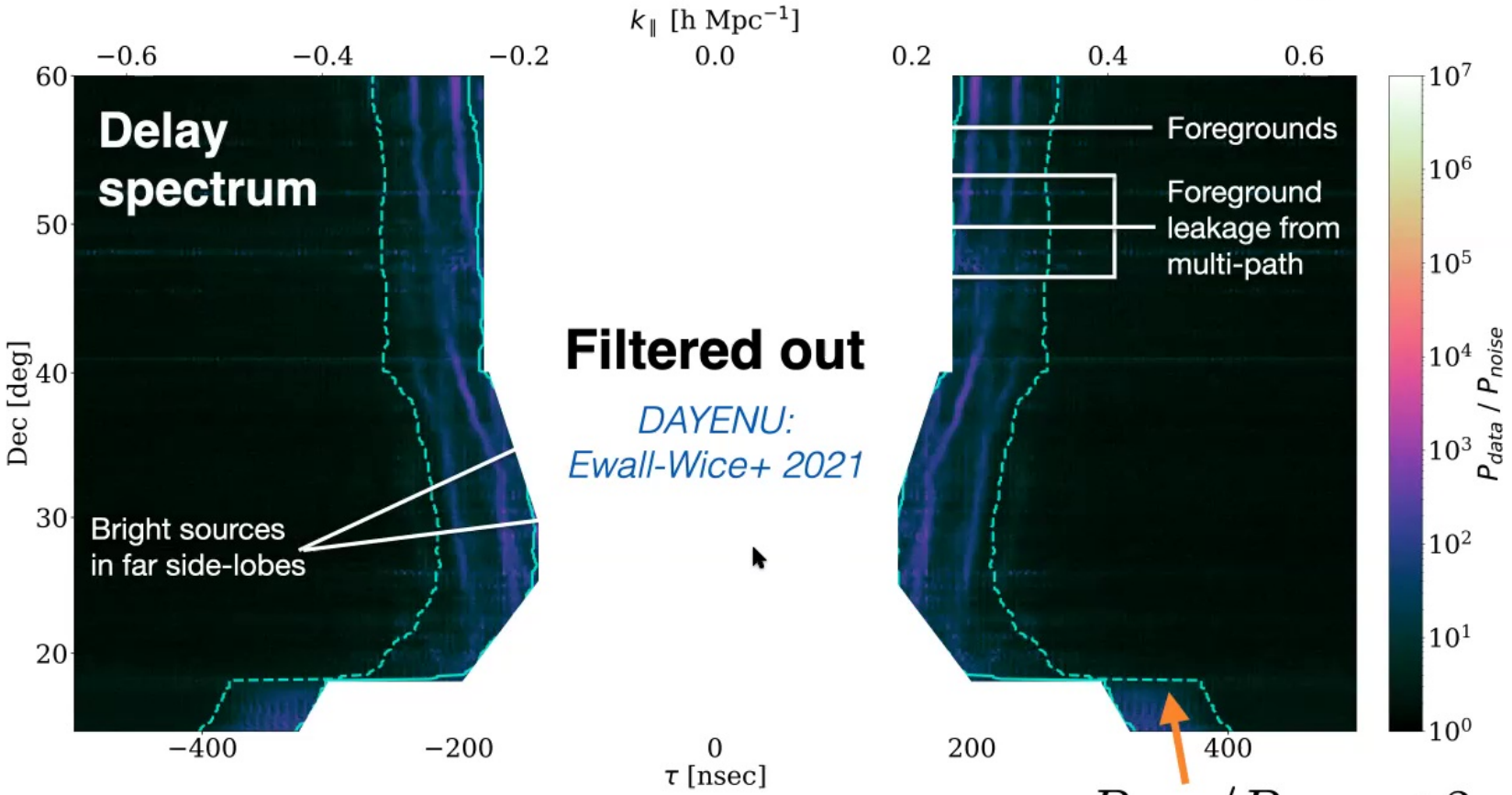
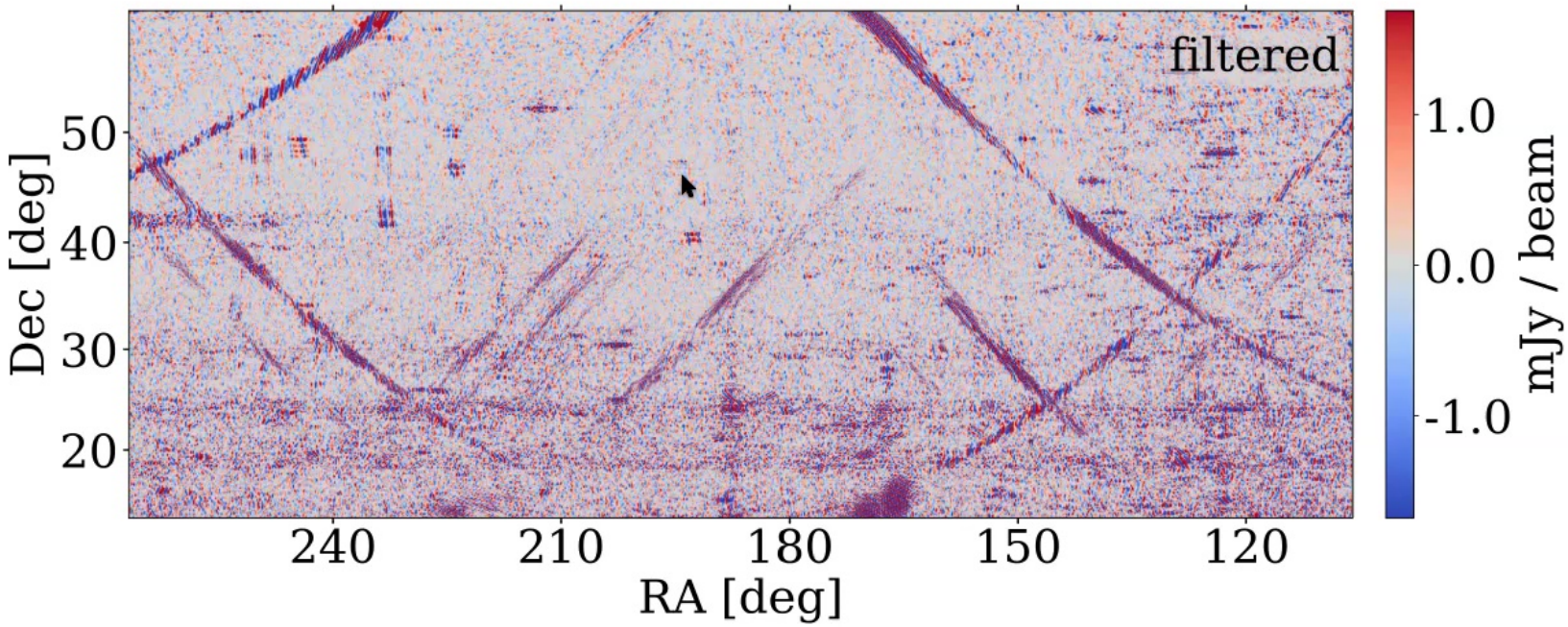


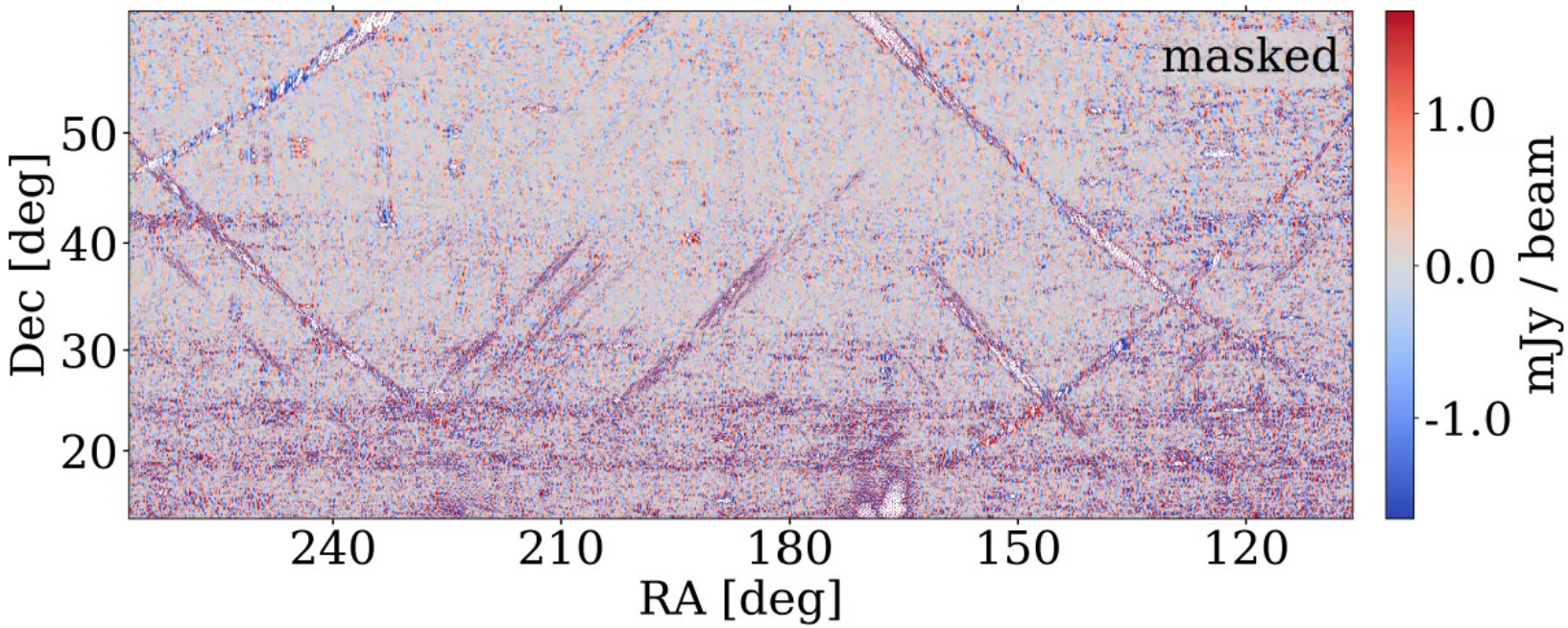


Map at 700MHz for NGC field



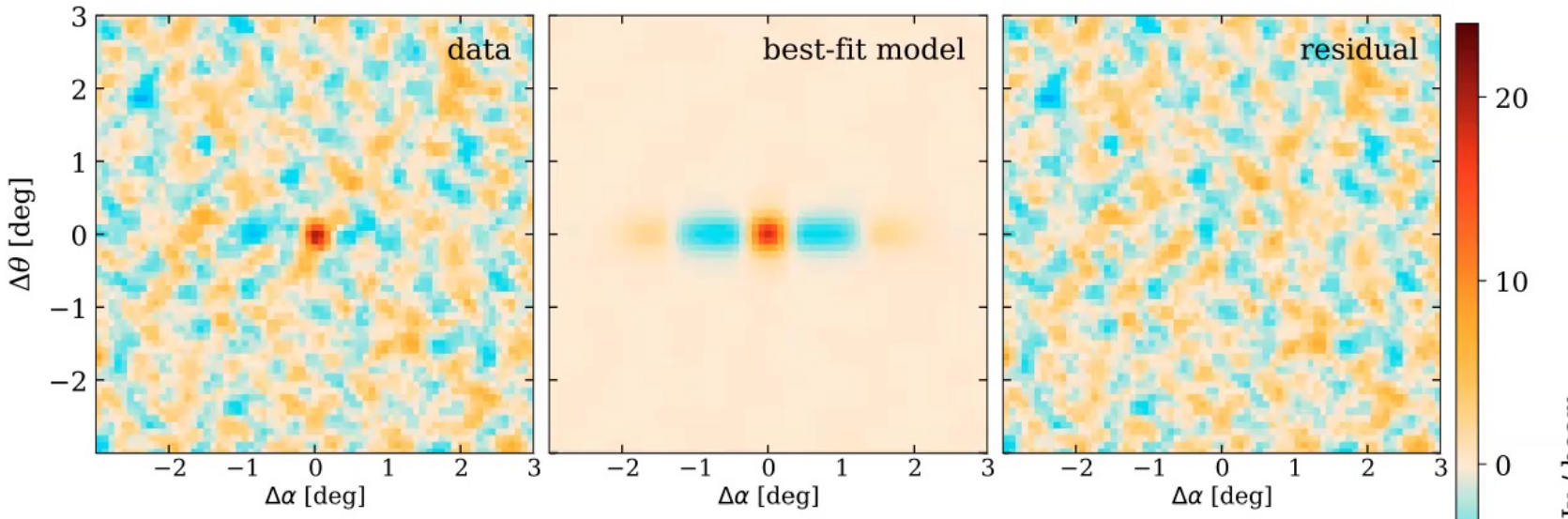
- Restrict to **inter-cylinder baselines**: resolve out diffuse fg
- Apply **high-pass delay filter**:
  remove spectrally-smooth modes

Map at 700MHz for NGC field

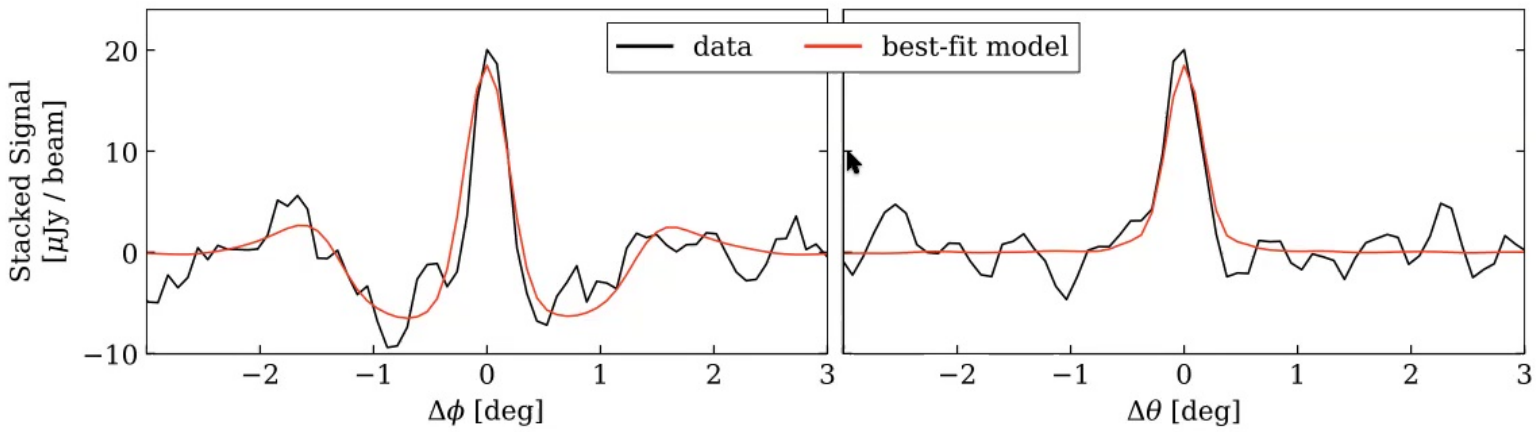


- Restrict to **inter-cylinder baselines**: resolve out diffuse fg
- Apply **high-pass delay filter**:
  remove spectrally-smooth modes
- **Mask pixels** >6 times expected noise level:
  mitigate artifacts from bright point sources

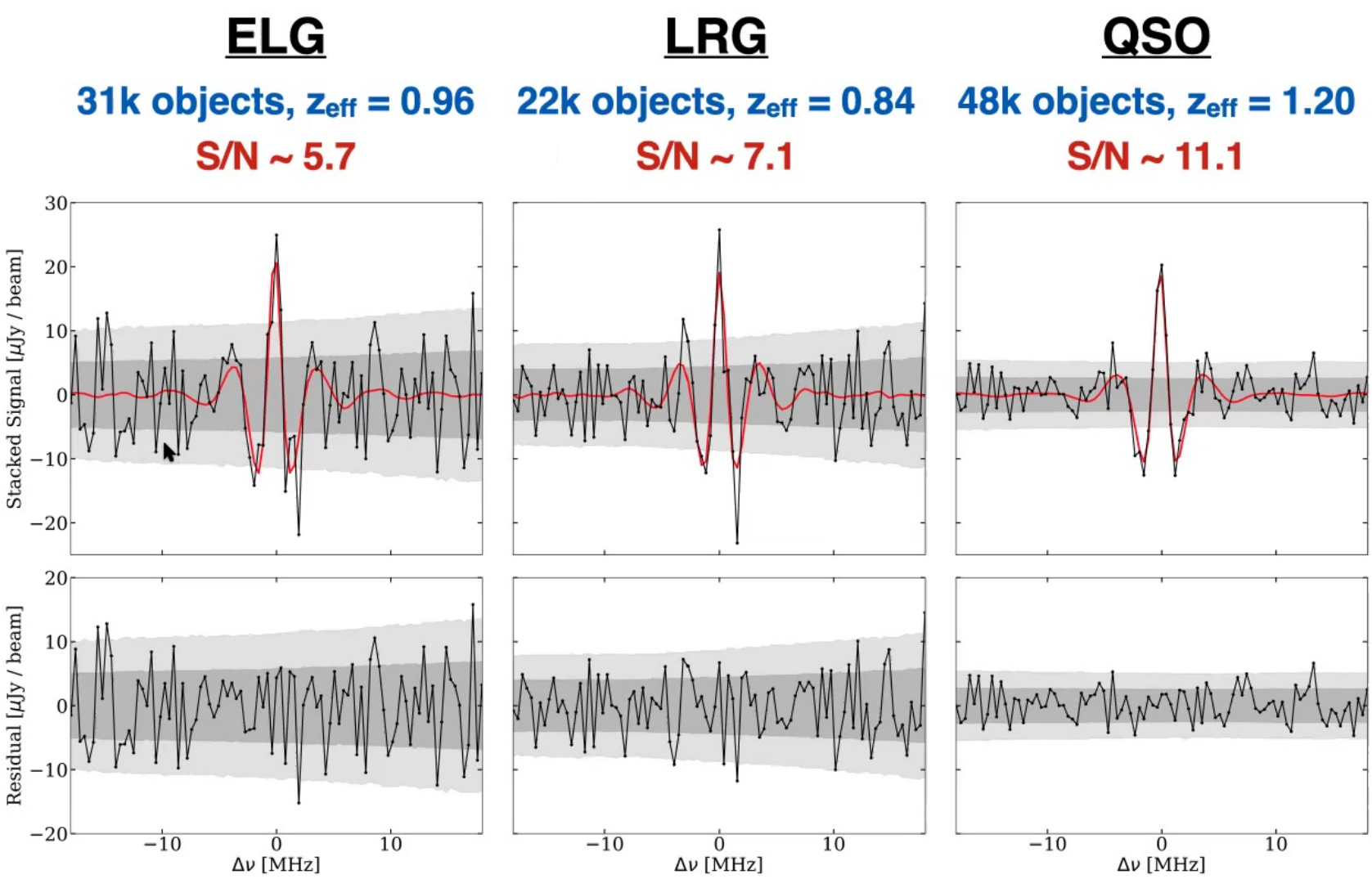
CHIME maps stacked on eBOSS QSO catalog



Consistent with unresolved point source



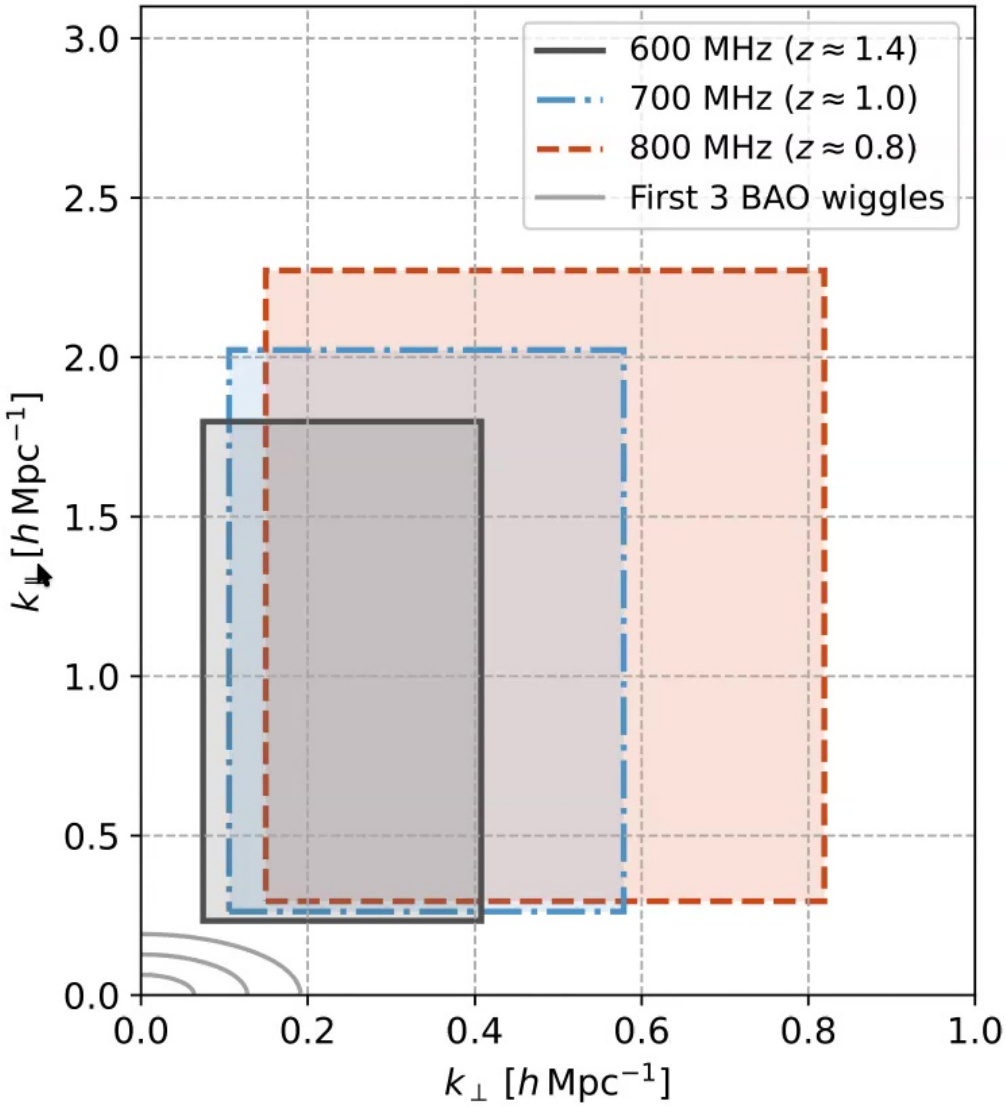
Stacking signal for all eBOSS catalogs



Physical interpretation

Cosmological scales probed

Small spectral scales

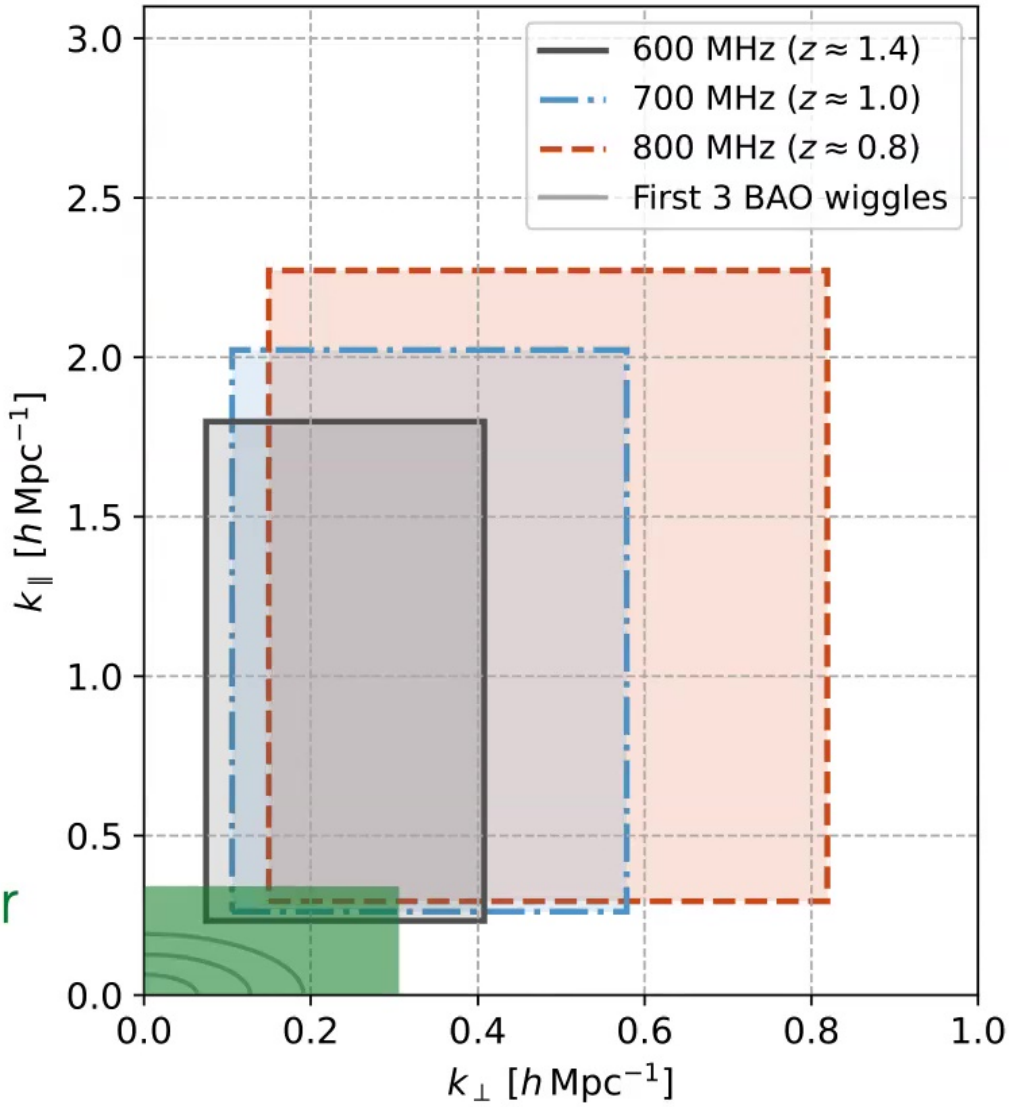


Small angular scales

Cosmological scales probed

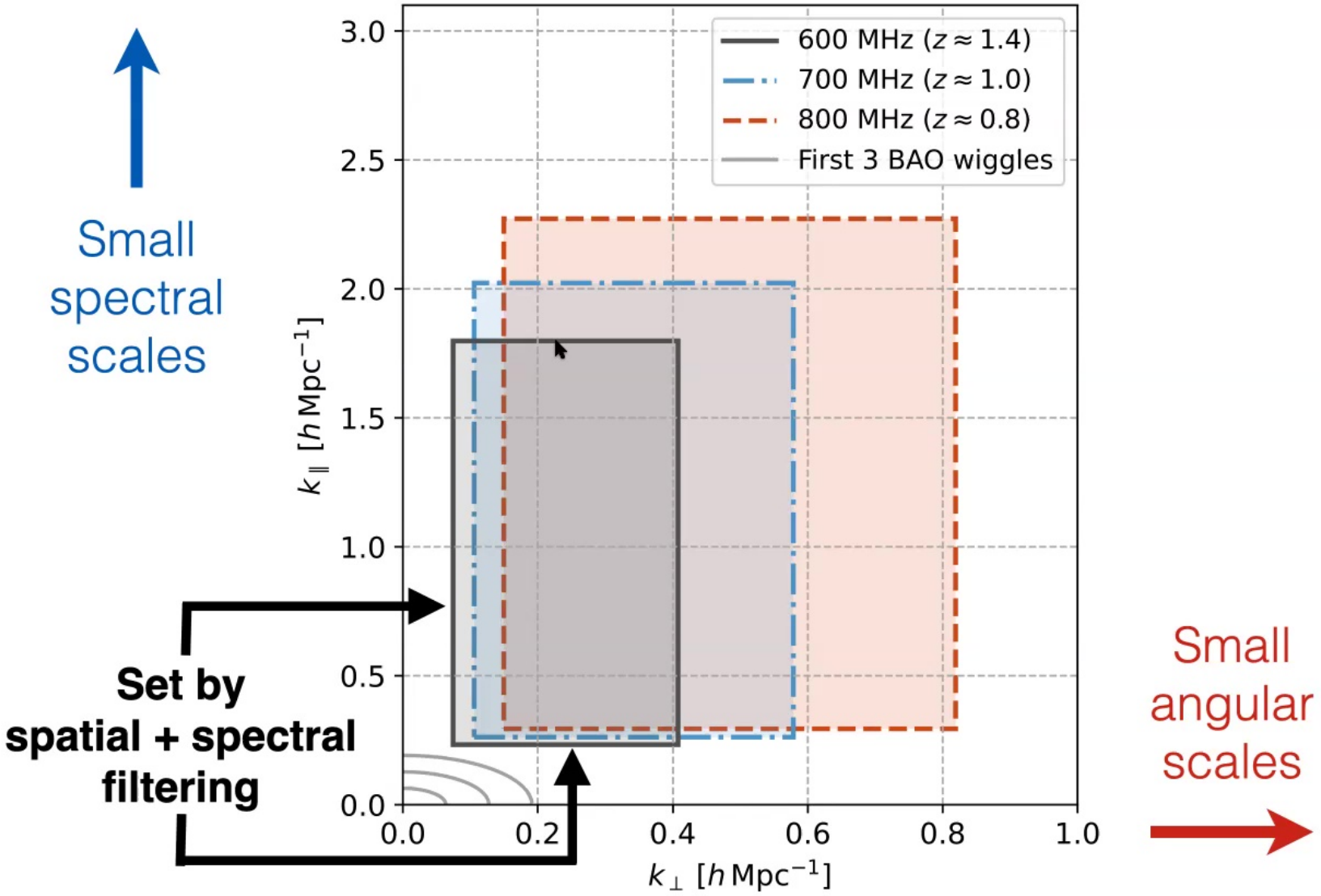
Small spectral scales

Quasi-linear regime

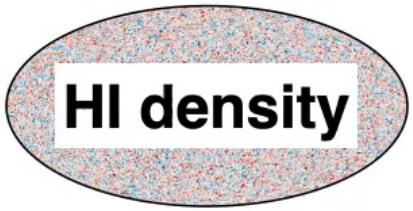


Small angular scales

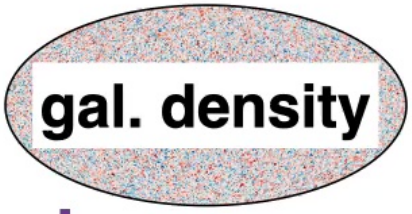
Cosmological scales probed



Simulation-based modelling



Generate correlated multi-freq. sky maps

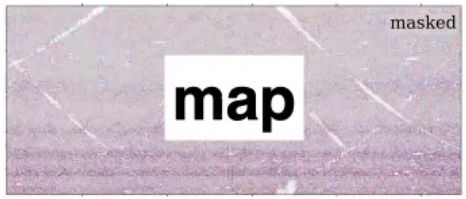


Propagate through instrument model

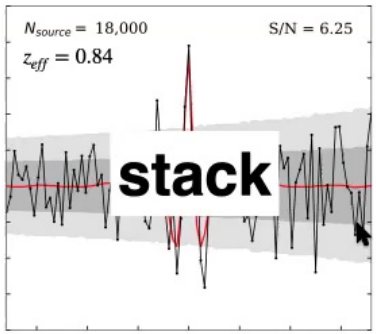
(Shaw+ 2015)

Draw mock eBOSS catalogs

Make map, filter, mask



Stack map on catalog positions



Simulation-based modelling

$$P_{\mathrm{g,HI}}(k,\mu;z_1,z_2) = T_{\mathrm{b}}(z_1;\Omega_{\mathrm{HI}})\left[b_{\mathrm{HI}}(z_1)+f(z_1)\mu^2\right]\left[b_{\mathrm{g}}(z_2)+f(z_2)\mu^2\right]$$
$$\times D(z_1)D(z_2)P_{\mathrm{m}}(k;\alpha_{\mathrm{NL}})D_{\mathrm{FoG}}(k\mu,z_1;\sigma_{\mathrm{HI}})D_{\mathrm{FoG}}(k\mu,z_2;\sigma_{\mathrm{g}}) + C(z)\,\langle M_{\mathrm{HI}}\rangle_{\mathrm{g}}$$

Ω_{HI} : mean HI density

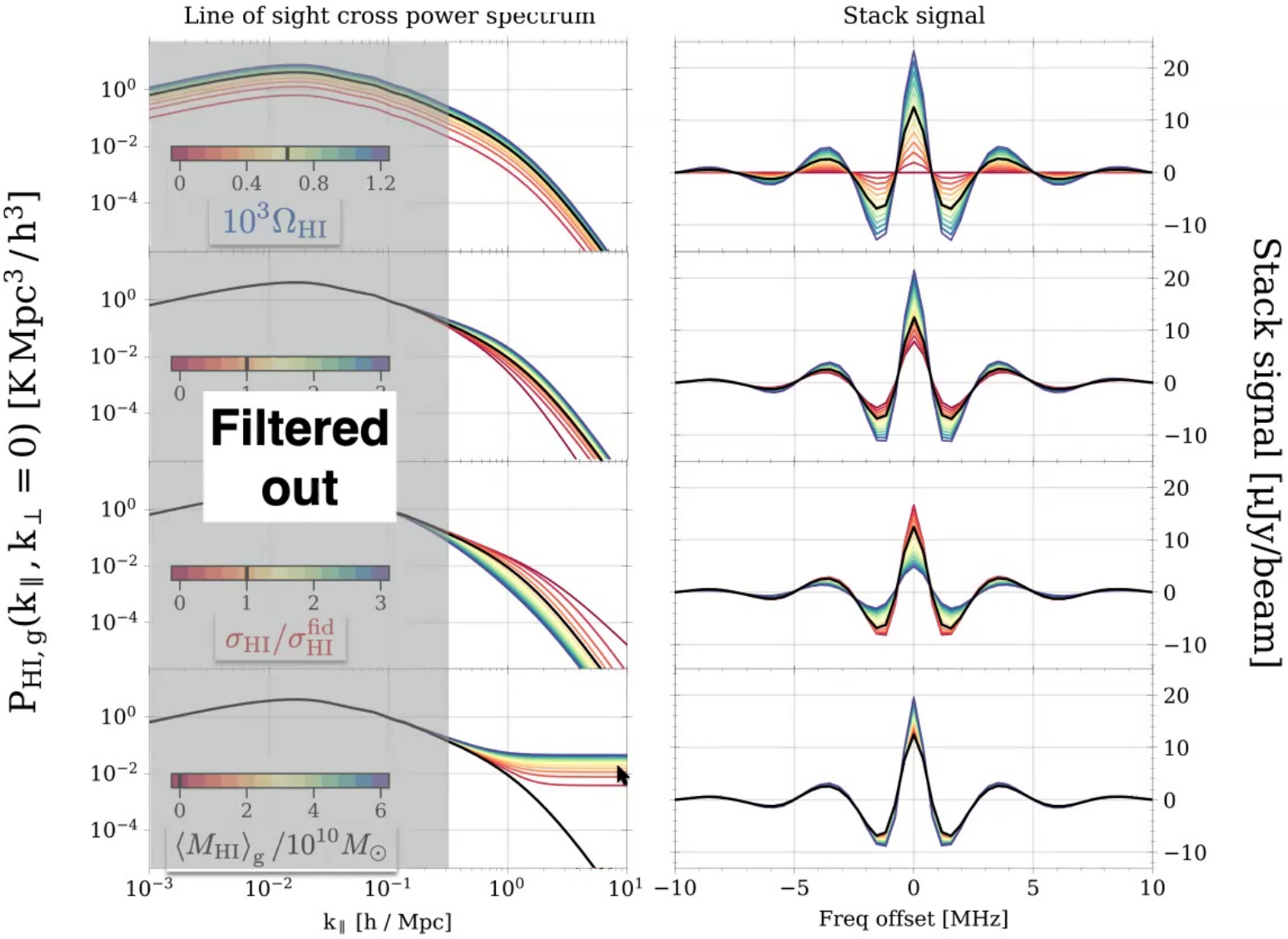
b_{HI}, b_{g} : linear bias of HI and galaxies/QSOs

α_{NL} : strength of nonlinear clustering

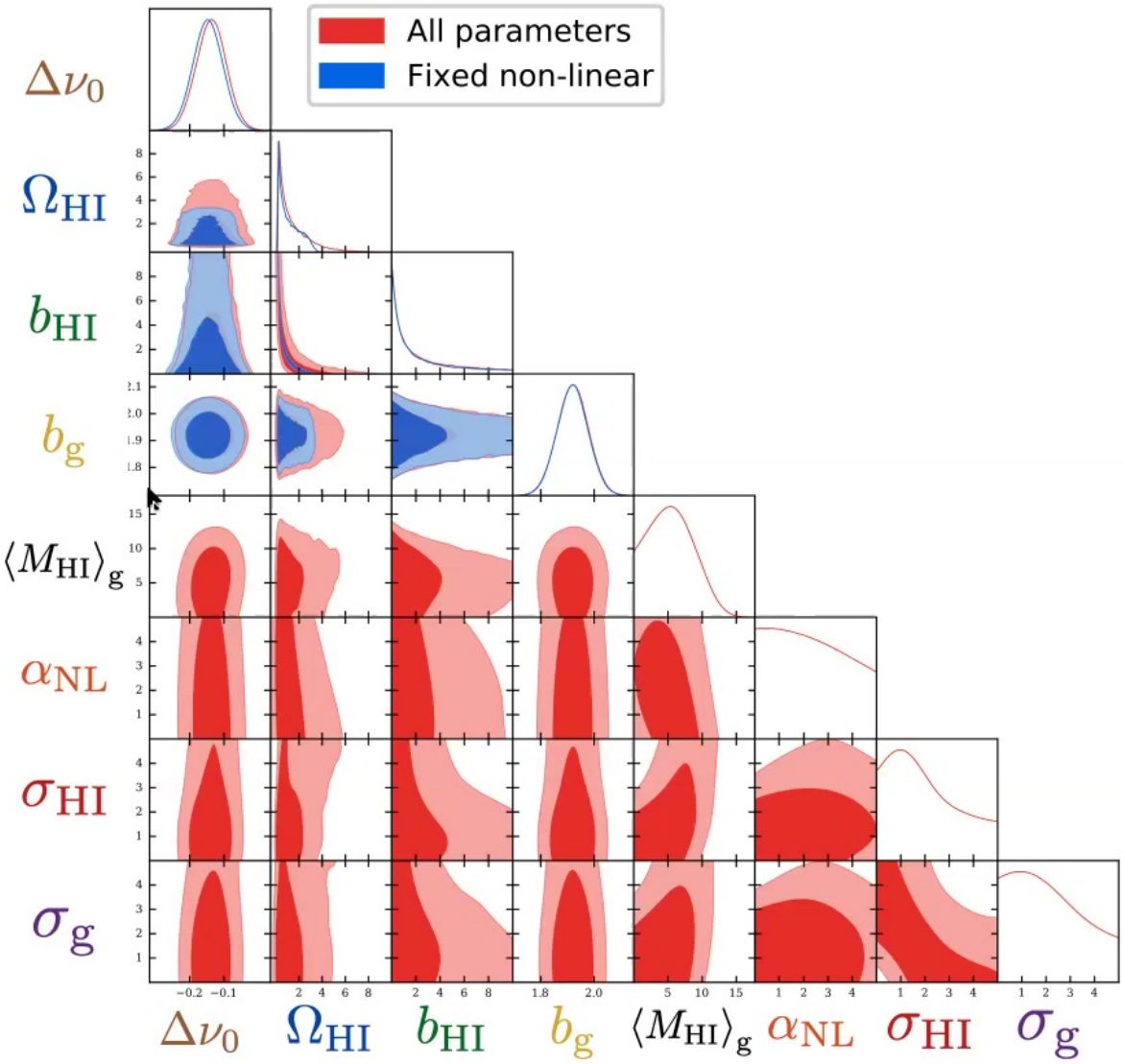
σ_{HI}, σ_{g} : scale of Finger of God damping due to small-scale velocity dispersion

$\langle M_{\mathrm{HI}}\rangle_{\mathrm{g}}$: mean HI mass per object in catalog

Effects of parameters on stacking model



Parameter constraints from QSOs



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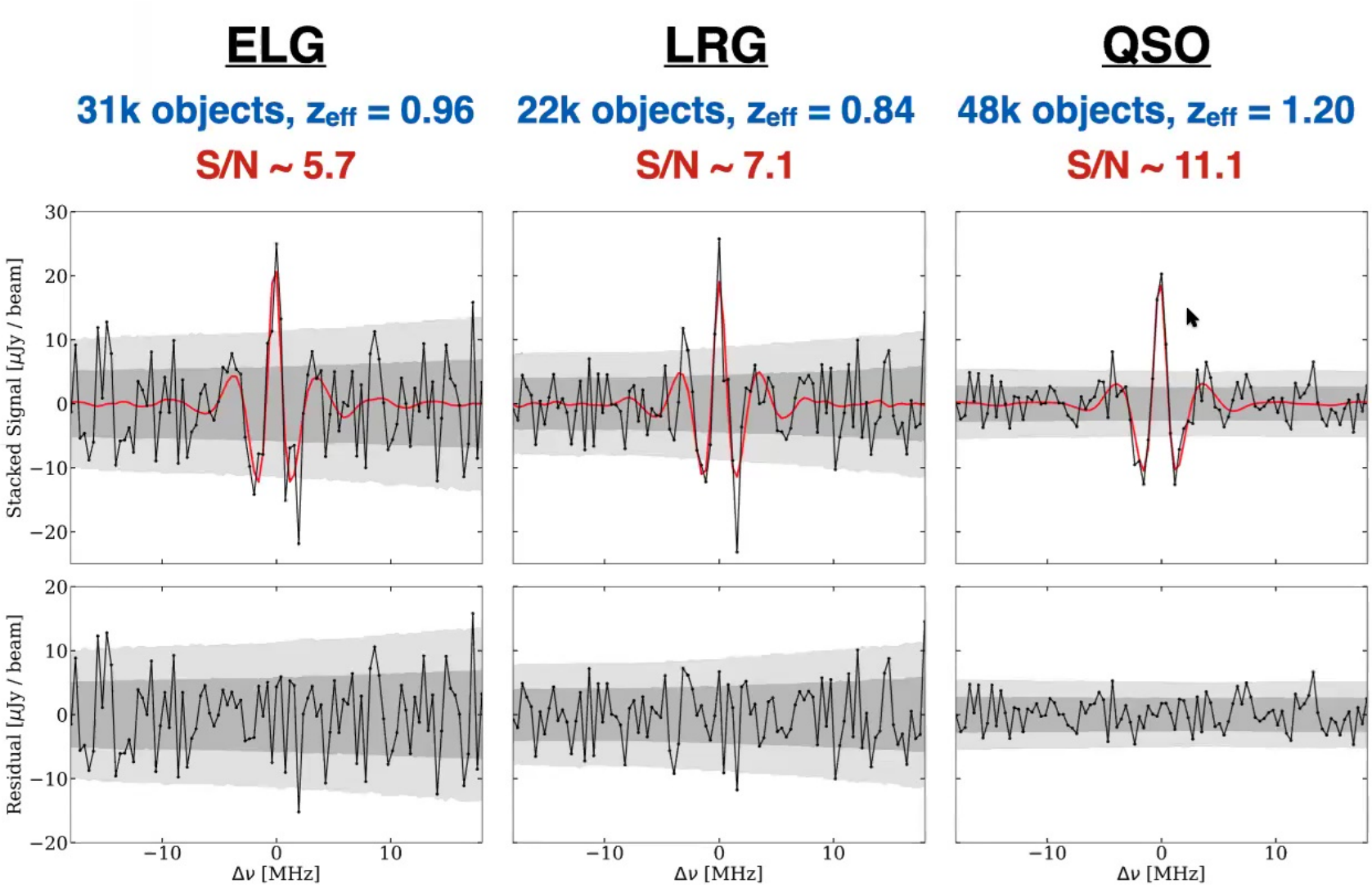
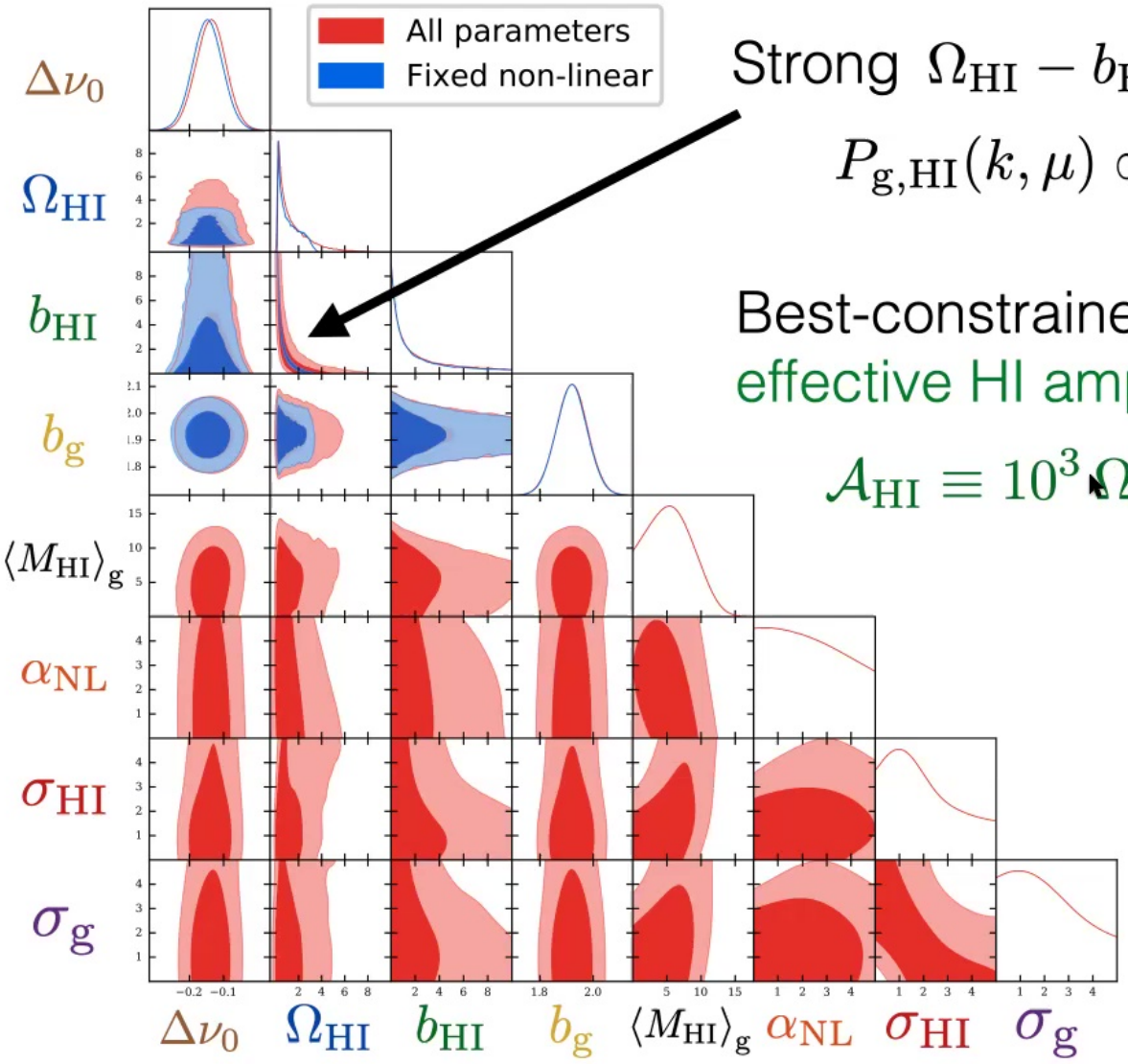


Parameter constraints from QSOs

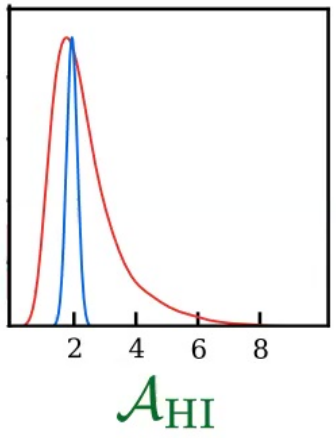


Strong $\Omega_{\rm HI} - b_{\rm HI}$ degeneracy:

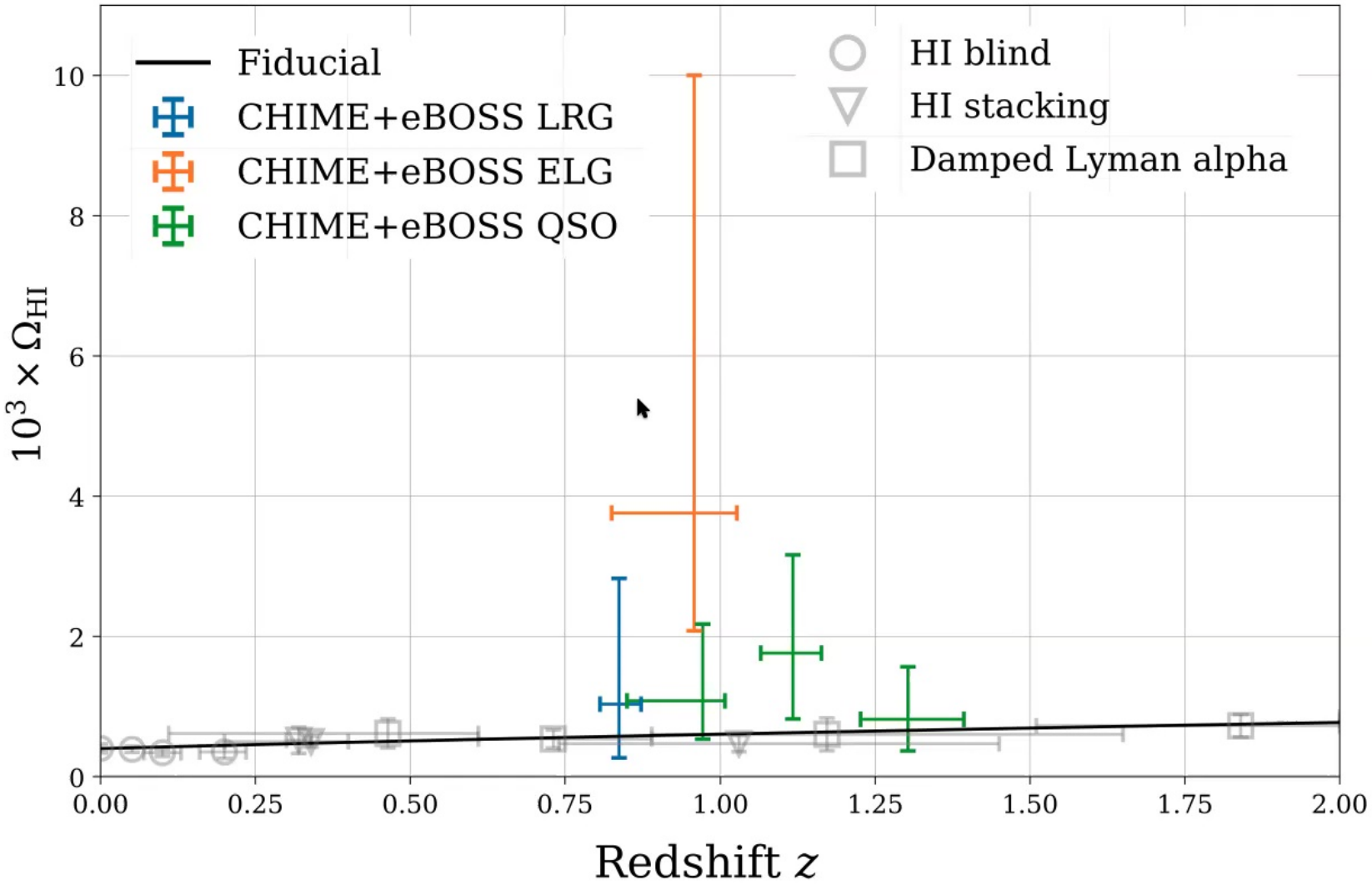
$$P_{\rm g,HI}(k,\mu) \propto \Omega_{\rm HI}\left(b_{\rm HI} + f\mu^2\right)$$

Best-constrained quantity:
effective HI amplitude

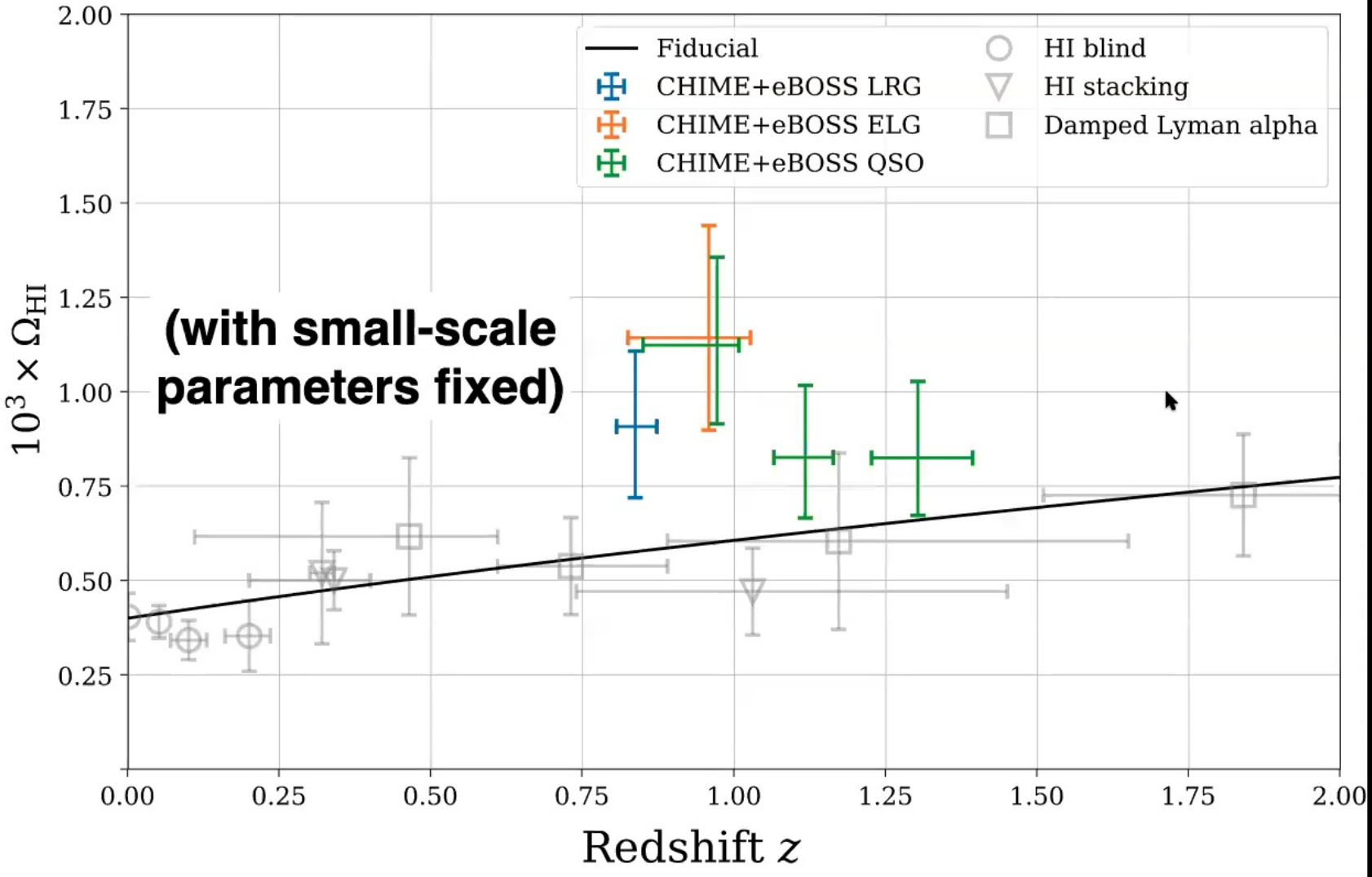
$$\mathcal{A}_{\rm HI} \equiv 10^3 \Omega_{\rm HI}(b_{\rm HI} + \langle f\mu^2\rangle)$$



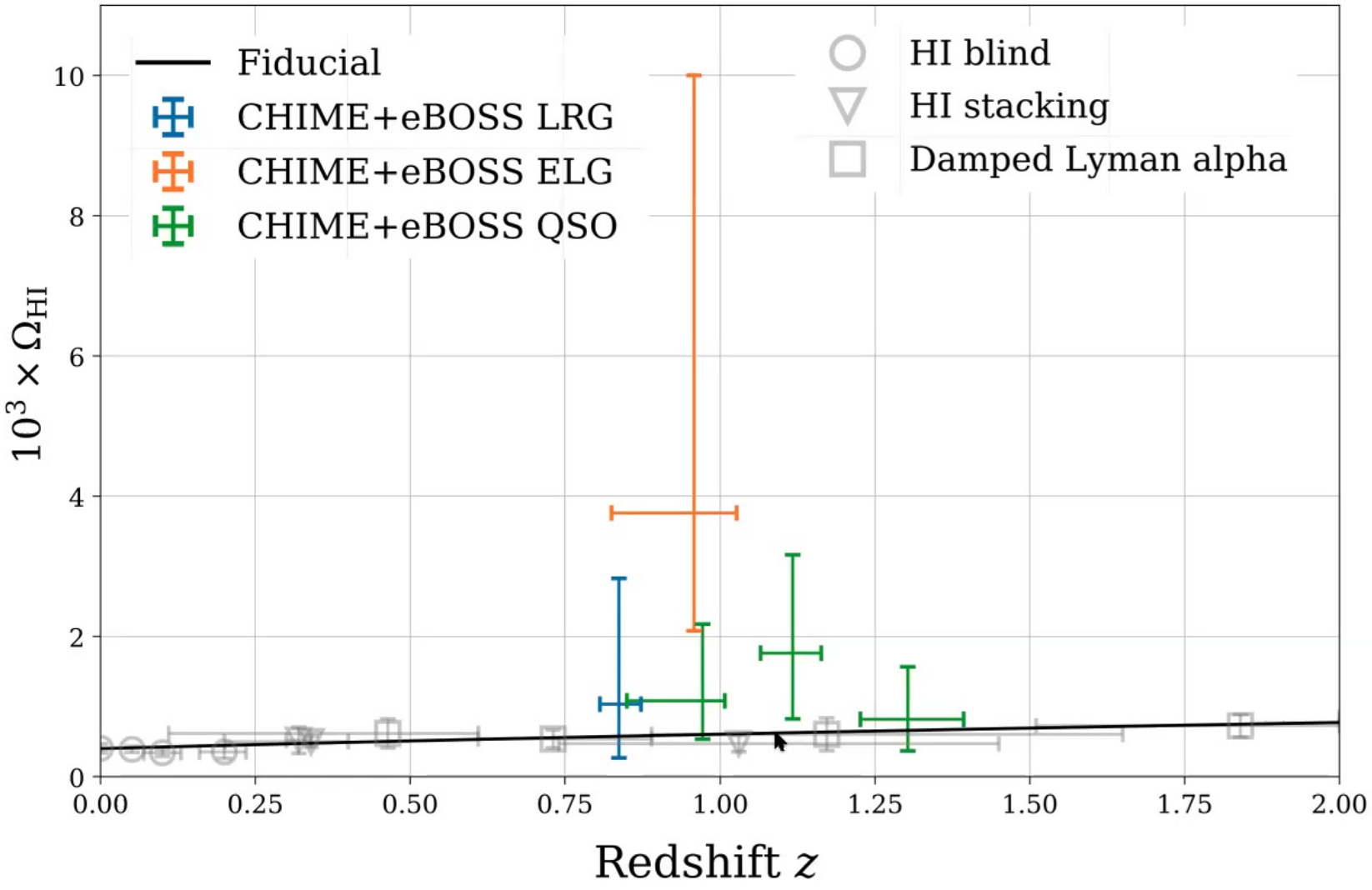
Constraints on mean HI density



Constraints on mean HI density



Constraints on mean HI density



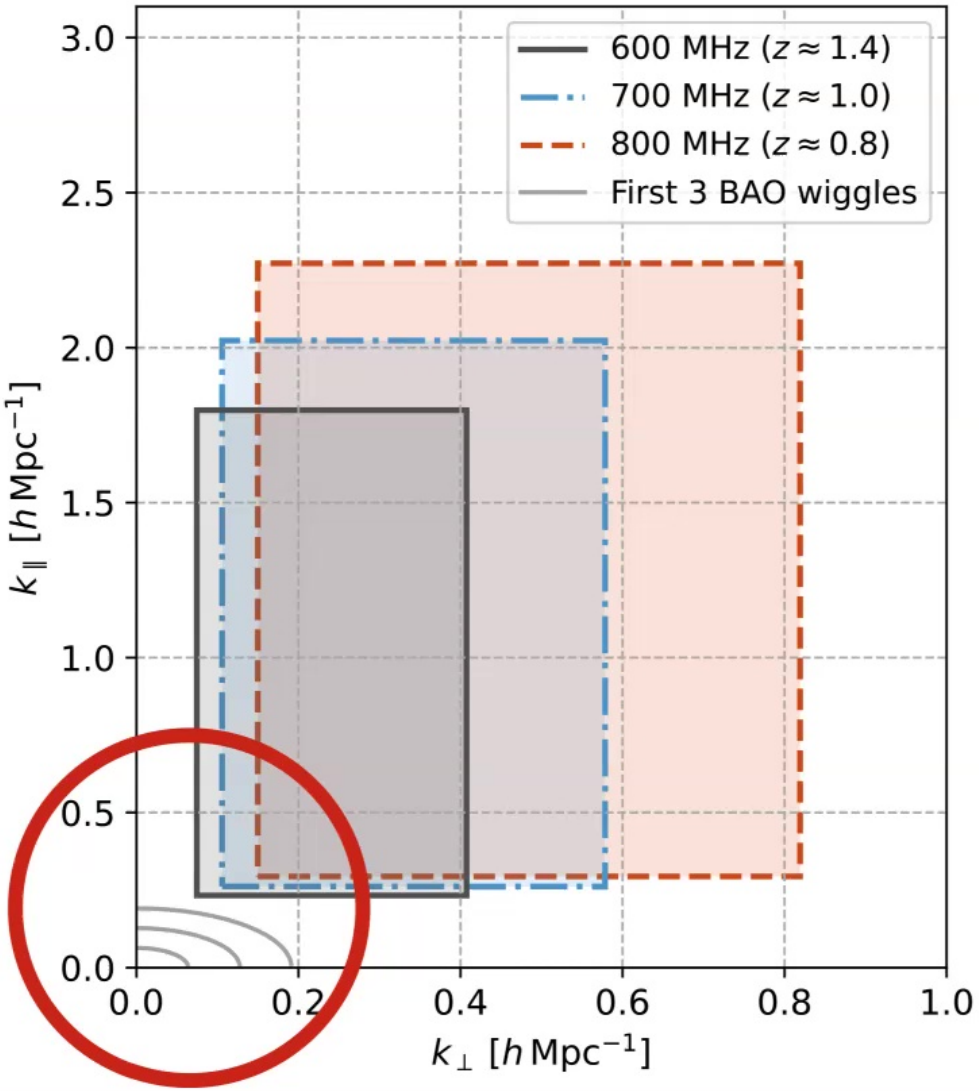
Next steps

Focus on recovering large scales:

- Beam characterization
  ➔ lower delay cut
- Removal of intracylinder noise crosstalk
- Other foreground removal strategies

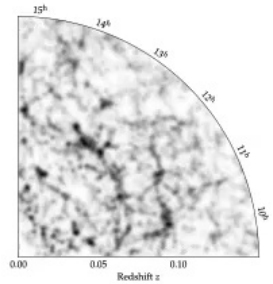
Inclusion of more data

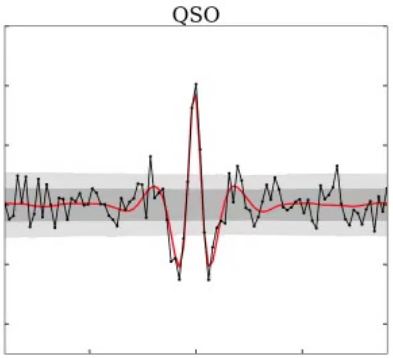
Other cross-correlations



Summary

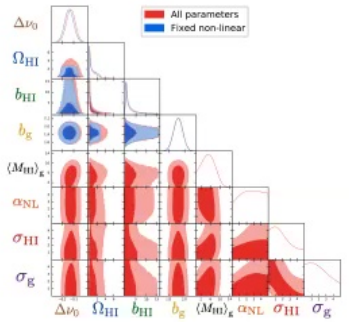
- CHIME is mapping large-scale structure from z = 0.8 to 2.5 using 21cm intensity mapping





- We have measured cross-correlations between CHIME sky maps and 3 galaxy/QSO catalogs from eBOSS, at >5σ

- Future analyses will push into regime where modelling is cleaner



CHIME overview paper: arXiv:2201.07869

Detection paper: arXiv:2202.01242