Pioneering 21 cm intensity mapping at the Green Bank Telescope

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Berkeley, October 30, 2012

21 cm Intensity Mapping — What is it and why would we want it.

Green Bank Telescope — What we are working on now.

Future — Where I think we will be eventually.

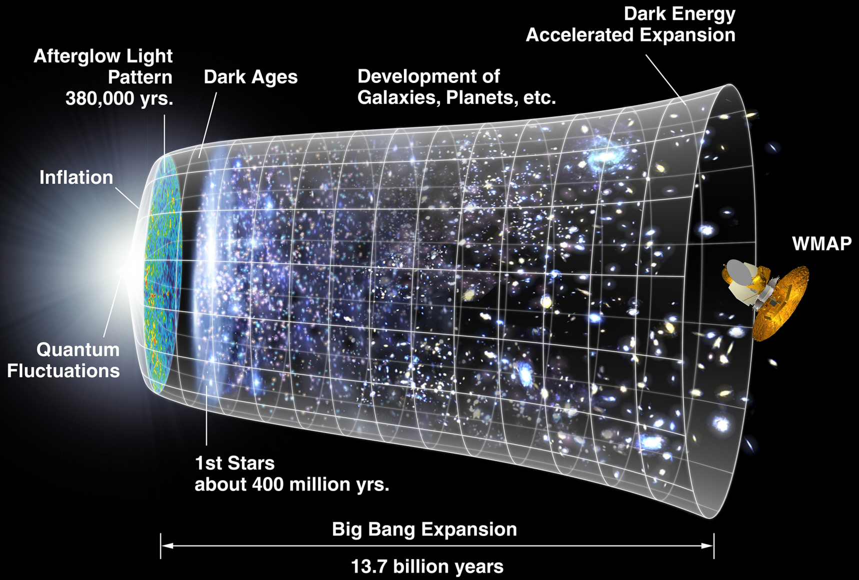
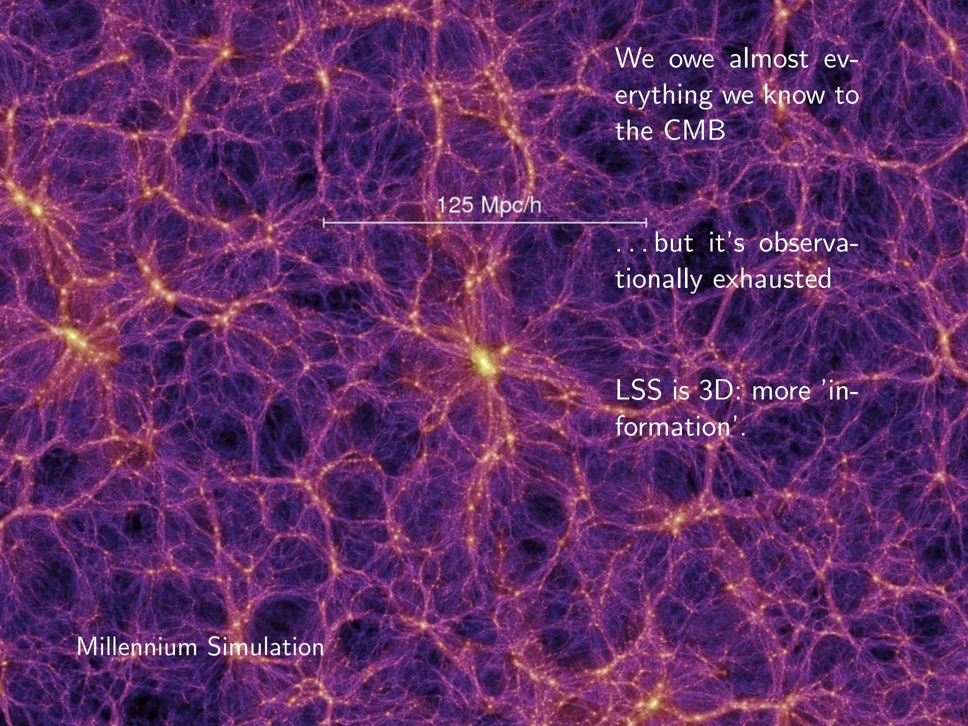


image: NASA / WMAP



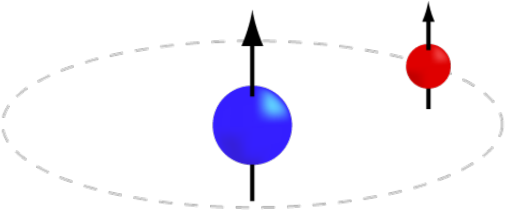
Millennium Simulation

We owe almost everything we know to the CMB

. . . but it's observationally exhausted

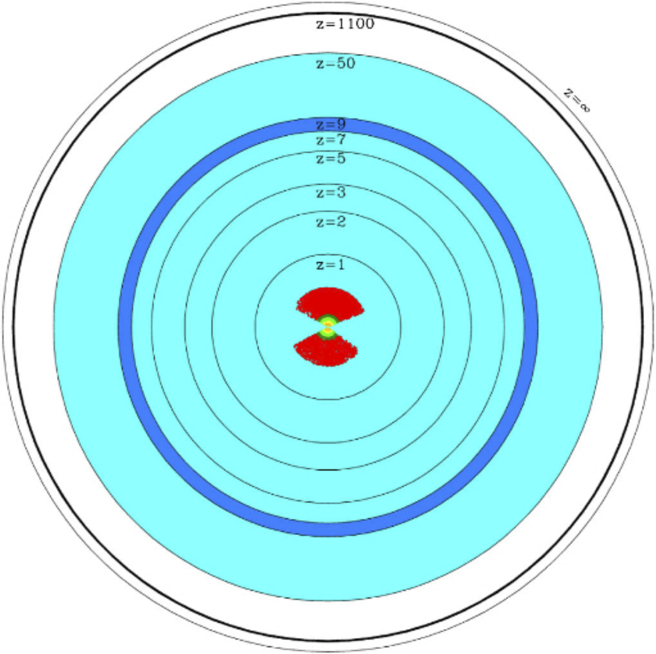
LSS is 3D: more 'information'.

The hydrogen atom



Hyperfine spin flip transition

$\lambda \approx 21\,\text{cm}$, $\nu \approx 1420\,\text{MHz}$



Tegmark and Zaldarriaga, 2009

We can measure . . .

At $z \sim 1$, Dark Energy:

baryon acoustic oscillations

redshift space distortions

weak lensing

We can measure ...

At $z \sim 8$, Reionization:

ionization power spectrum

duration

map of bubbles

We can measure ...

At $z > 10$, Inflation:

non-Gaussianity

n_s, α_s

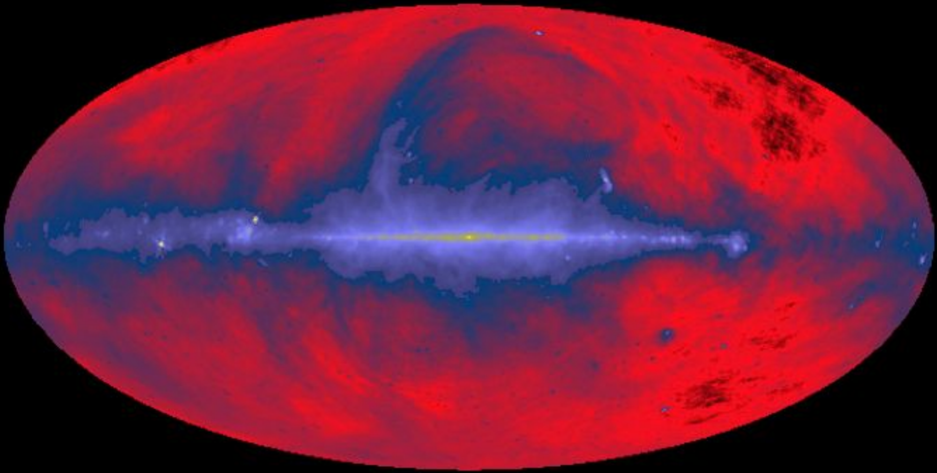
primordial gravity waves
(Masui and Pen, 2010)


12h
16h
8h
20h
4h
0h
0.02
0.04
0.06
0.08
0.10
0.12
0.14
Redshift z
SDSS

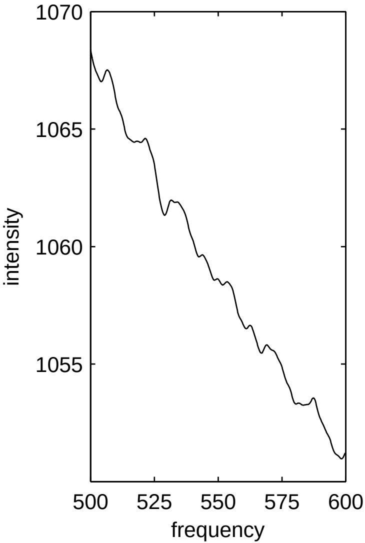
Intensity Mapping

"…21 centimeter observations, along with space-based gravity wave observations, are generally viewed as the next great frontier in observational cosmology, after the cosmic microwave background polarization."

– Wikipedia

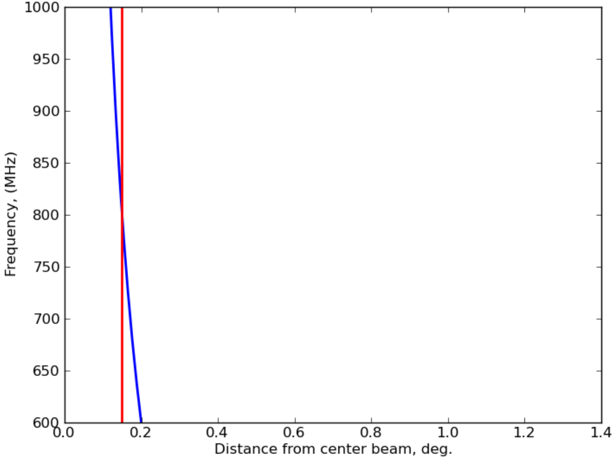


Haslam et. al., 1982



If we could measure a single line of sight perfectly, foreground subtraction would be easy.

Single dish complications

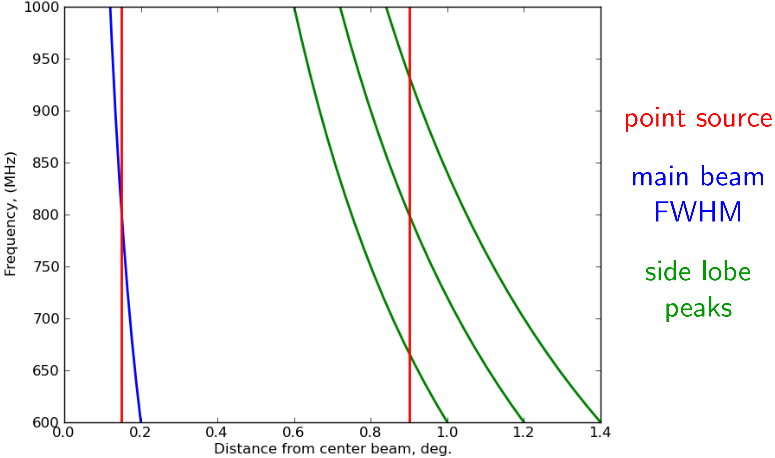


point source

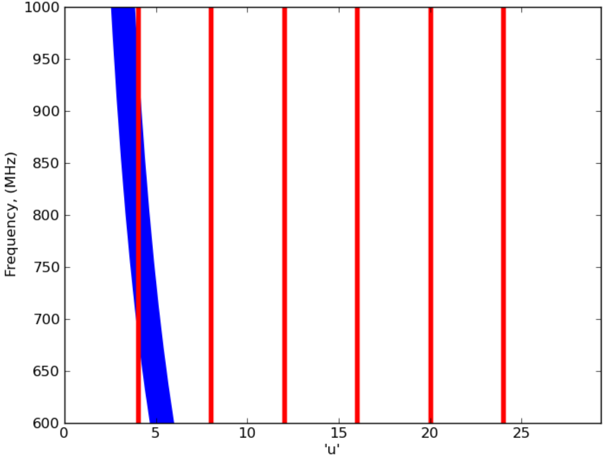
main beam FWHM

side lobe peaks

Single dish complications



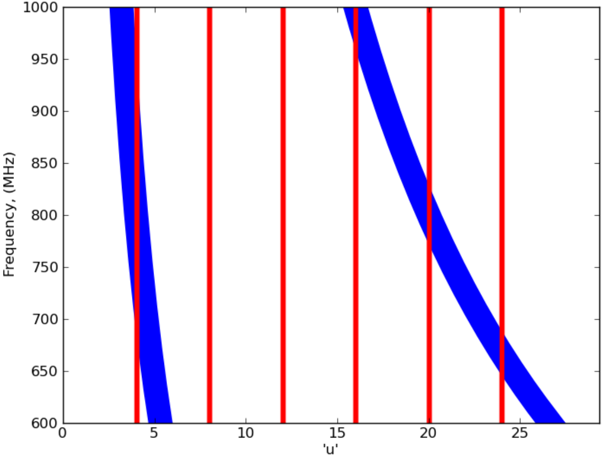
Interferometer complications



point source

base line
FWHM

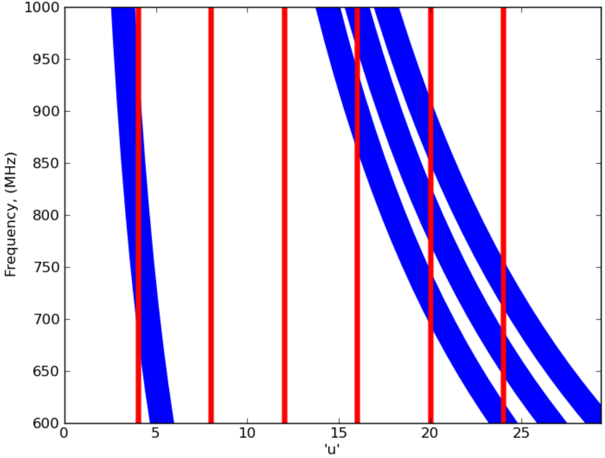
Interferometer complications



point source

base line
FWHM

Interferometer complications



point source

base line
FWHM

Parsons, Pober, et. al. 2012	Liu and Tegmark, 2011
Minimal	Optimal
One baseline at a time	Assume array is well calibrated
Long baselines contaminated	Very little information lost

We are approaching the time where these can be tested.

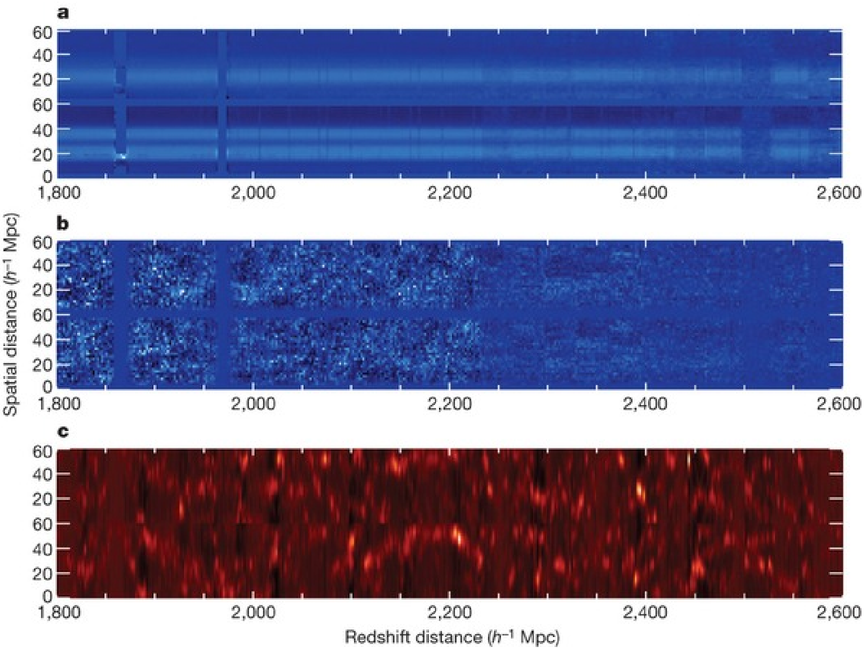
Systematics

Spectral calibration

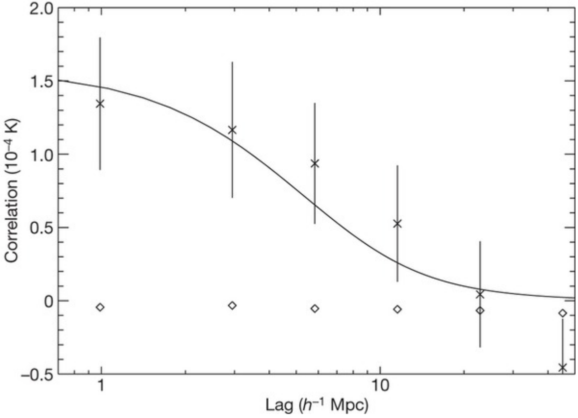
Polarization leakage

More on this latter . . .


100 m unobstructed aperture
700 MHz to 900 MHz, $0.6 < z < 1$
$T_{sys} = 25K$



Chang, Pen, Bandura and Peterson, 2010



Cross-correlation with DEEP2

4.5σ detection of large-scale structure.

Chang, Pen, Bandura and Peterson, 2010

Going forward, want to measure the auto-correlation:

More data

More sky

Better calibration

Better analysis

The Survey

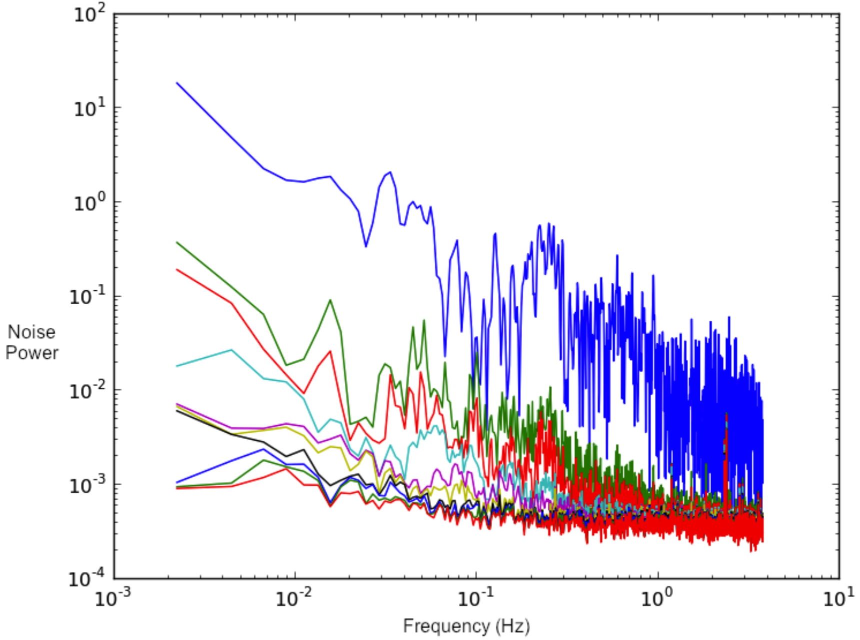
400 hours of telescope time

Survey the WiggleZ fields

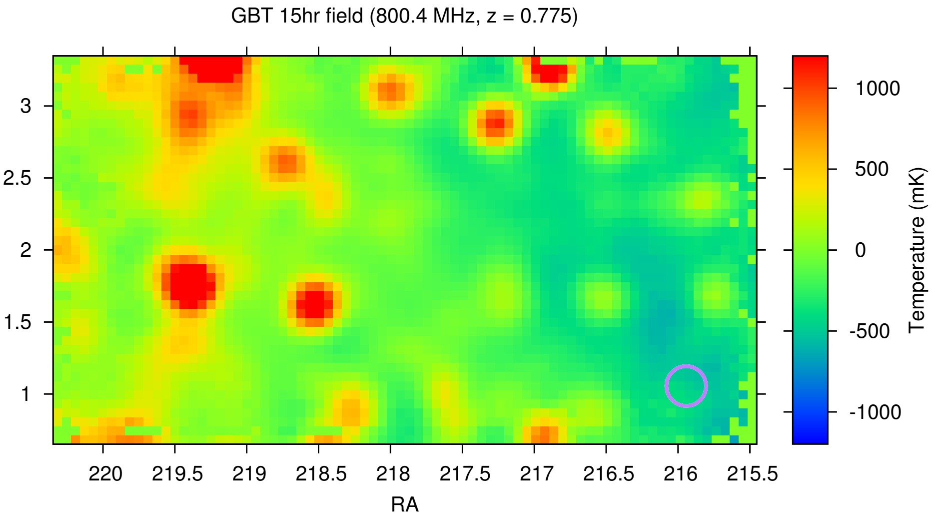
~ 60 sq. deg. of sky

Analysis

map-making foreground cleaning power spectra



10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Noise Power
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
Frequency (Hz)



GBT 15hr field (800.4 MHz, z = 0.775)
3
2.5
2
1.5
1
220
219.5
219
218.5
218
217.5
217
216.5
216
215.5
RA
1000
500
0
-500
-1000
Temperature (mK)

Foreground subtraction

Spectral calibration is not smooth

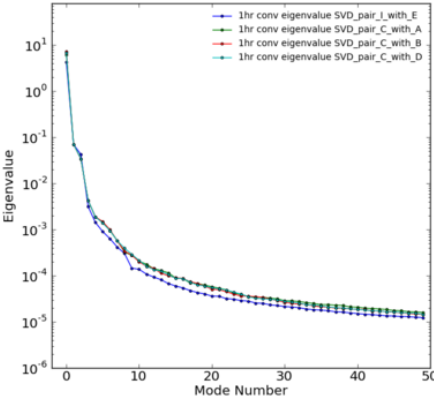
Polarization leakage

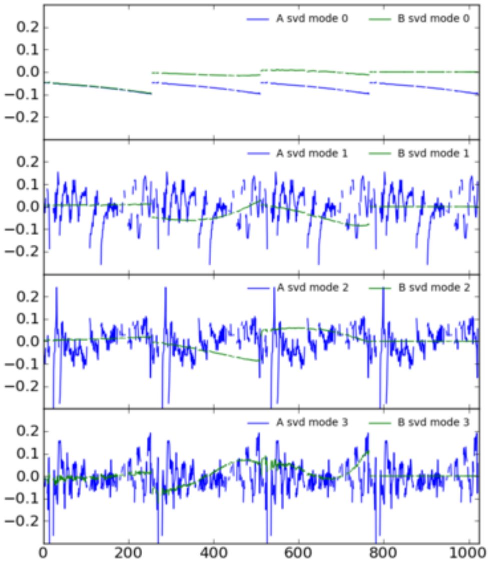
Foreground Subtraction

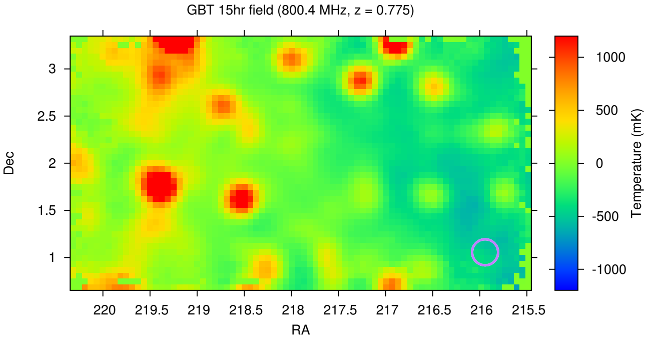
$$C_{\nu I,\nu' p} = \langle m_{I,i\nu} m_{p,i\nu'} \rangle_i$$

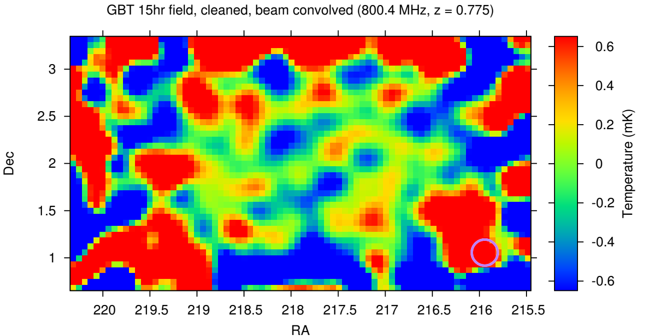
$$C_{\nu I,\nu' p} = \sum_j v_\nu^j \sigma^j u_{\nu p}^j$$

Index i runs over angular pixels and p over polarizations $\{I, Q, U, V\}$.


1hr conv eigenvalue SVD_pair_I_with_E
1hr conv eigenvalue SVD_pair_C_with_A
1hr conv eigenvalue SVD_pair_C_with_B
1hr conv eigenvalue SVD_pair_C_with_D
Eigenvalue
Mode Number


A svd mode 0
B svd mode 0
A svd mode 1
B svd mode 1
A svd mode 2
B svd mode 2
A svd mode 3
B svd mode 3


GBT 15hr field (800.4 MHz, z = 0.775)
Dec
3
2.5
2
1.5
1
220
219.5
219
218.5
218
217.5
217
216.5
216
215.5
RA
1000
500
0
-500
-1000
Temperature (mK)


GBT 15hr field, cleaned, beam convolved (800.4 MHz, z = 0.775)
Dec
3
2.5
2
1.5
1
220
219.5
219
218.5
218
217.5
217
216.5
216
215.5
RA
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
Temperature (mK)

Cleaned maps are noise dominated.

Noise level agrees with thermal.

Our foreground filter is non-linear.

Must carefully simulate signal loss.

MEASUREMENT OF 21 CM BRIGHTNESS FLUCTUATIONS AT $z \sim 0.8$ IN CROSS-CORRELATION

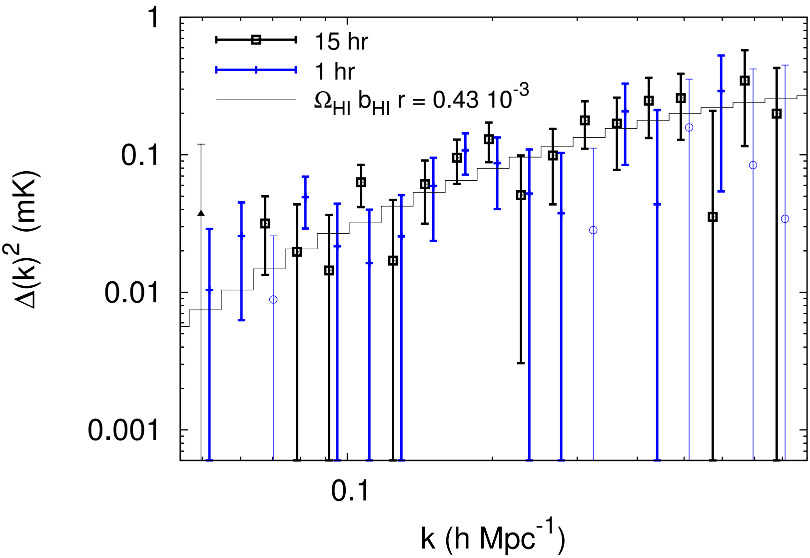
K. W. MASUI[1,2], E. R. SWITZER[1,3], N. BANAVAR[4], K. BANDURA[5], C. BLAKE[6], L.-M. CALIN[1], T.-C. CHANG[7], X. CHEN[8,9], Y.-C. LI[8], Y.-W. LIAO[7], A. NATARAJAN[10], U.-L. PEN[1], J. B. PETERSON[10], J. R. SHAW[1], T. C. VOYTEK[10]

Draft version August 2, 2012

ABSTRACT

In this letter, 21 cm intensity maps acquired at the Green Bank Telescope are cross-correlated with large-scale structure traced by galaxies in the WiggleZ Dark Energy Survey. The data span the redshift range $0.6 < z < 1$ over two fields totaling ~ 41 deg. sq. and 190 hours of radio integration time. The cross-correlation constrains $\Omega_{\rm HI} b_{\rm HI} r = [0.43 \pm 0.07({\rm stat.}) \pm 0.04({\rm sys.})] \times 10^{-3}$, where $\Omega_{\rm HI}$ is the neutral hydrogen (H I) fraction, r is the galaxy-hydrogen correlation coefficient, and $b_{\rm HI}$ is the H I bias parameter. This is the most precise constraint on neutral hydrogen density fluctuations in a challenging redshift range. Our measurement improves the previous 21 cm cross-correlation at $z \sim 0.8$ both in its precision and in the range of scales probed.

Subject headings: galaxies: evolution — large-scale structure of universe — radio lines: galaxies



$$\Omega_{HI} b_{HI} r = 0.43 \pm 0.07(\text{stat.}) \pm 0.04(\text{sys.})$$

Auto-power progress

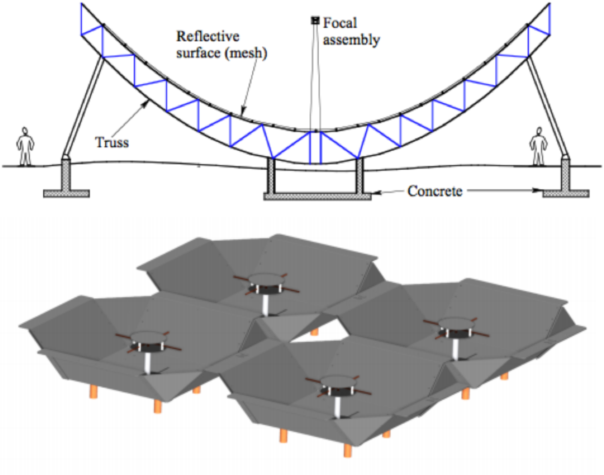
Future

multi-pixel

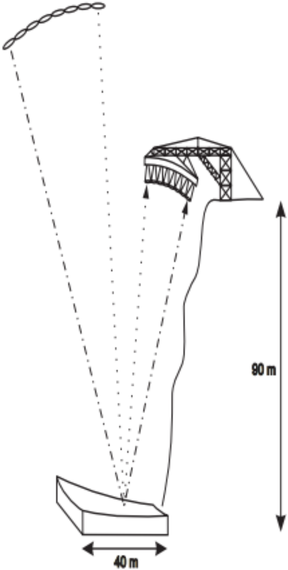
dedicated telescopes

omniscopes

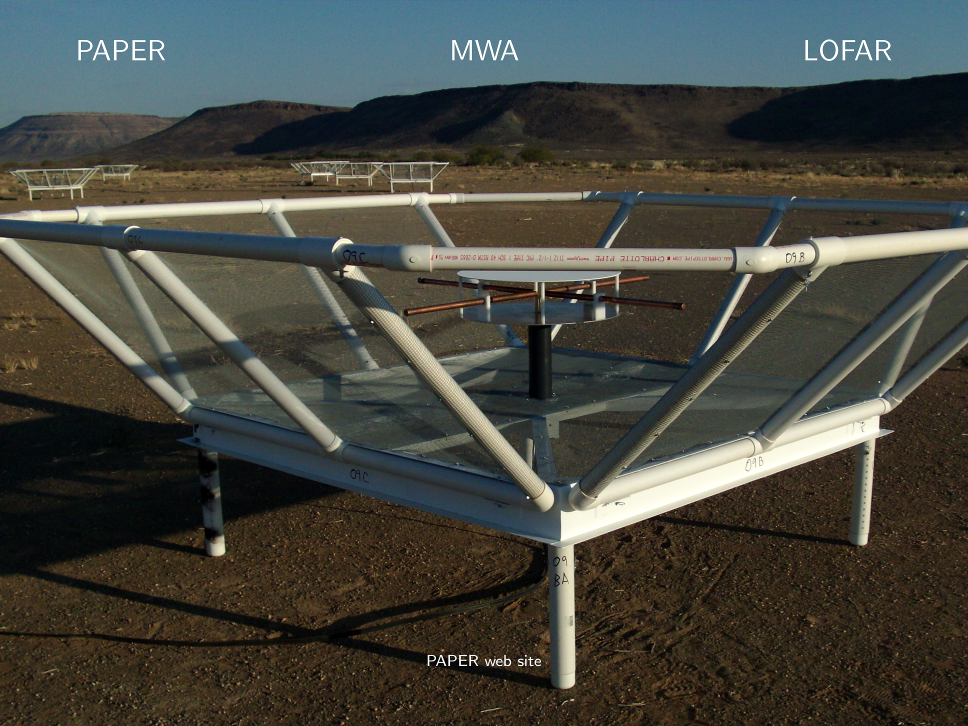
Multibeam for GBT
Parkes multi-beam
PAF on Westerbork
Effelsberg
ASKAP



Pober et. al., 2012

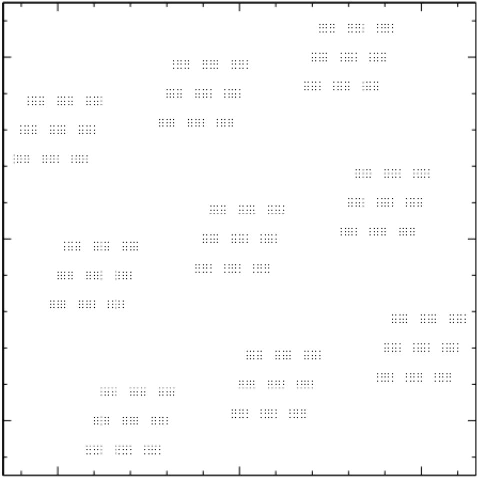


Battye et. al., 2012



PAPER web site

Omniscopes



Tegmark and Zaldarriaga 2010

On the back of the moon?

The End