Hydrogen 21cm Cosmology

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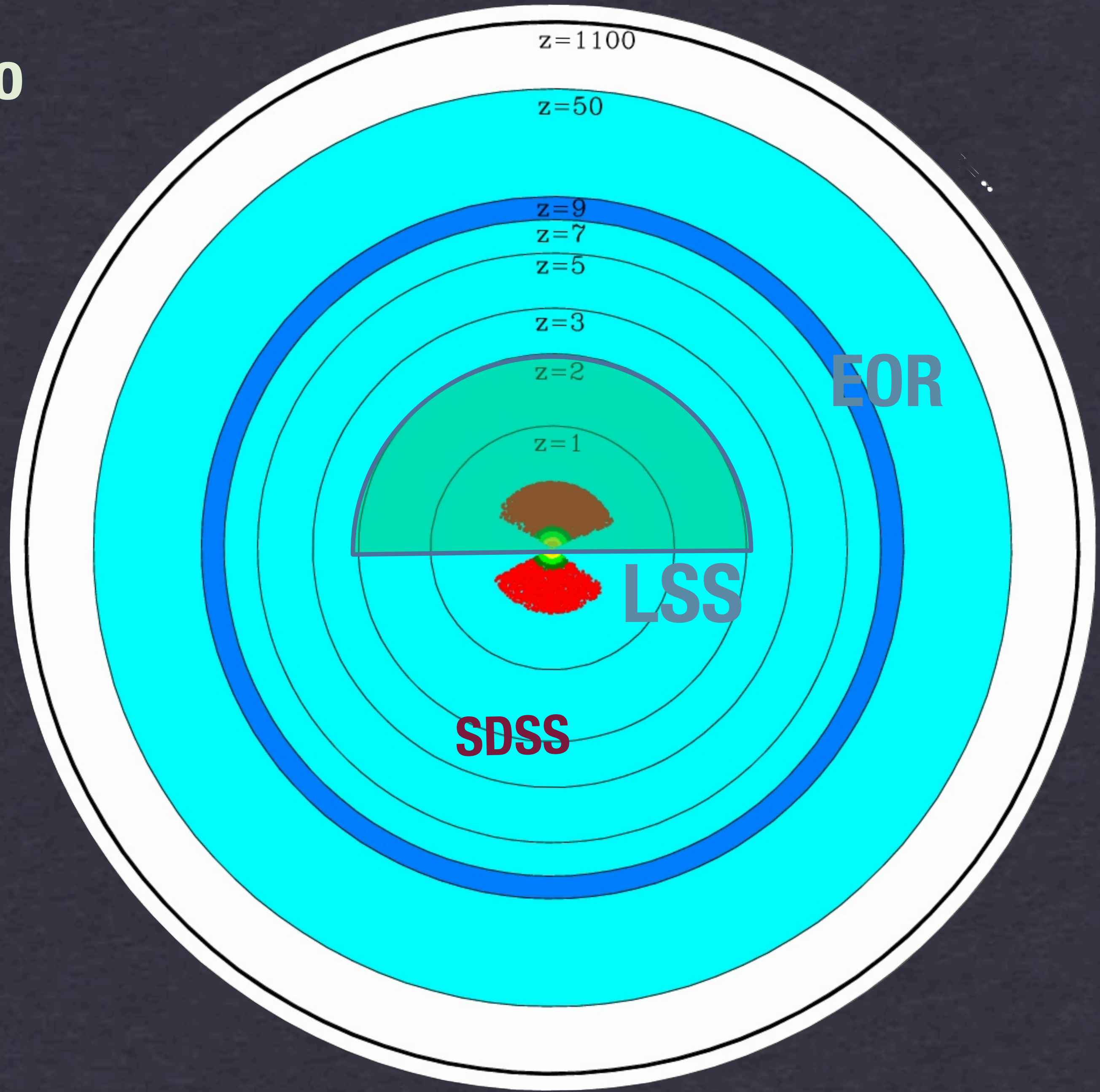
Chris Hirata (Caltech), Kris Sigurdson (UBC)

The 21cm universe

- HI 21cm radiation observable up to z~150
- Up to 10^{16} modes to z~50(Hubble/Jeans)^3
- Physics: Lensing, gravity waves, primordial NG, BAO, AP (Pen 04, Loeb & Zaldarriaga 04, Lewis & Challinor 07, etc.)
- Astrophysics: EoR, galaxy formation & evolution
- Experiment Now
  - EoR: GMRT-EoR, PAPER, LOFAR, MWA, 21CMA, EDGES, DARE
  - BAO: GBT, CRT, CHIME

(also talks by Thijs, Roy and Ray)

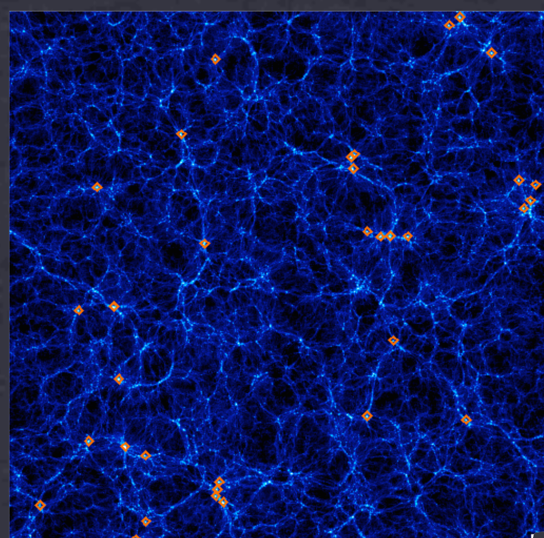


TEGMARK & ZALDARRIAGA 08

21cm Large-Scale Structure

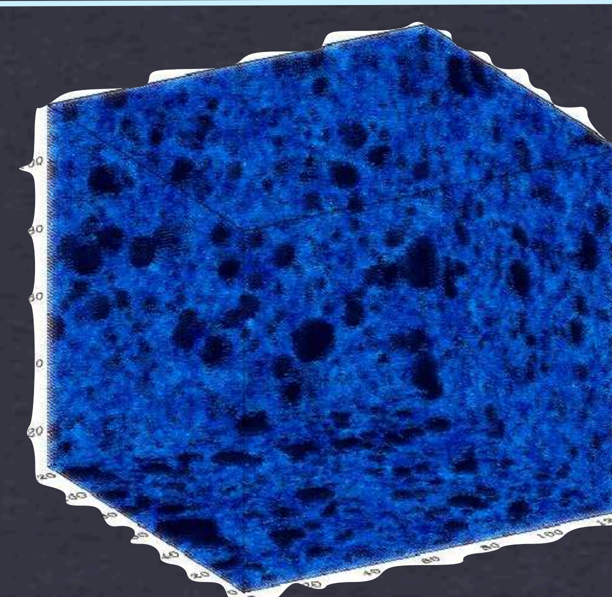
- Large-scale HI temperature fluctuation intensity mapping; CMB-like, in 3D

1 — 10 — z



M. White

LSS; BAO



EOR

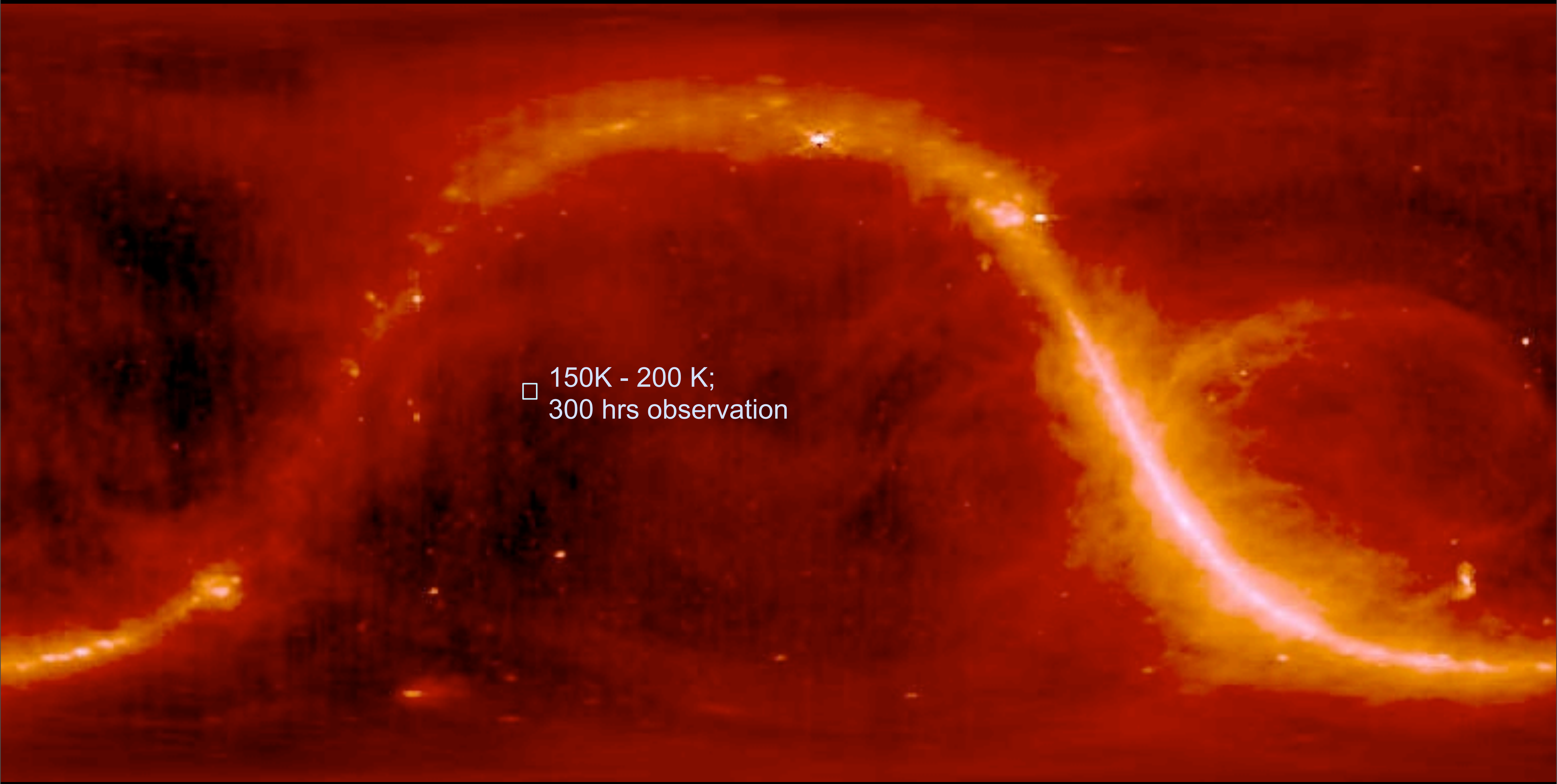
- 0.5<z<2.5, HI traces underlying matter distribution, can be used to measure Baryon Acoustic Oscillations (BAO), 109 h^{-1} Mpc scale => dark energy

- 6<z<10, Epoch of Reionization (EoR), HI shows tomographic history of reionization, ~20-50 Mpc scale => astrophysics

21cm Intensity Mapping

- Due to small emissivity, HI in emission is difficult to detect.
- Previously, HI direct detection at z~0.2 (Verheijen et al 2007), stacking at z~0.37 (Lah et al. 2007); both on galaxy scales.
- "Intensity Mapping" (Chang et al 2008, Wyithe & Loeb 2008):
  - instead of HI associated with galaxies, interested in HI associated with large-scale structure
  - measure the collective HI emission from a large region, more massive and luminous, without spatially resolving down to galaxy scales.
- Measurement of spatially diffused spectral line, in the confusion-limited regime
- Brightness temperature fluctuations on the sky: just like CMB temperature field, but in 3D
- Low-angular resolution redshift surveys: LSS science, economical

Foregrounds



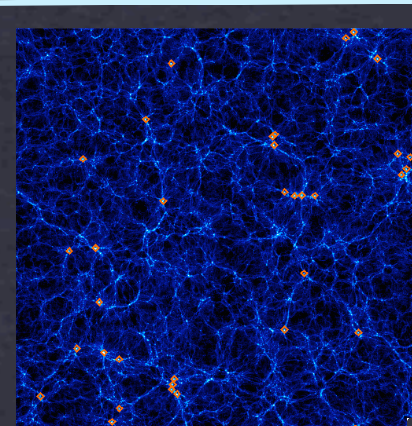
Haslam 408 MHz

Foregrounds: much brighter than signal, but no spectral structure

Observing 21cm Large-Scale Structure

1 10 Z

BAO



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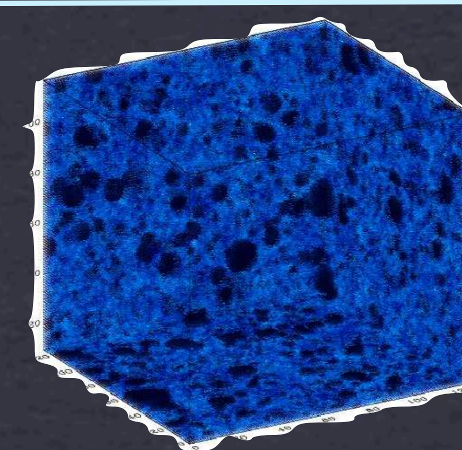


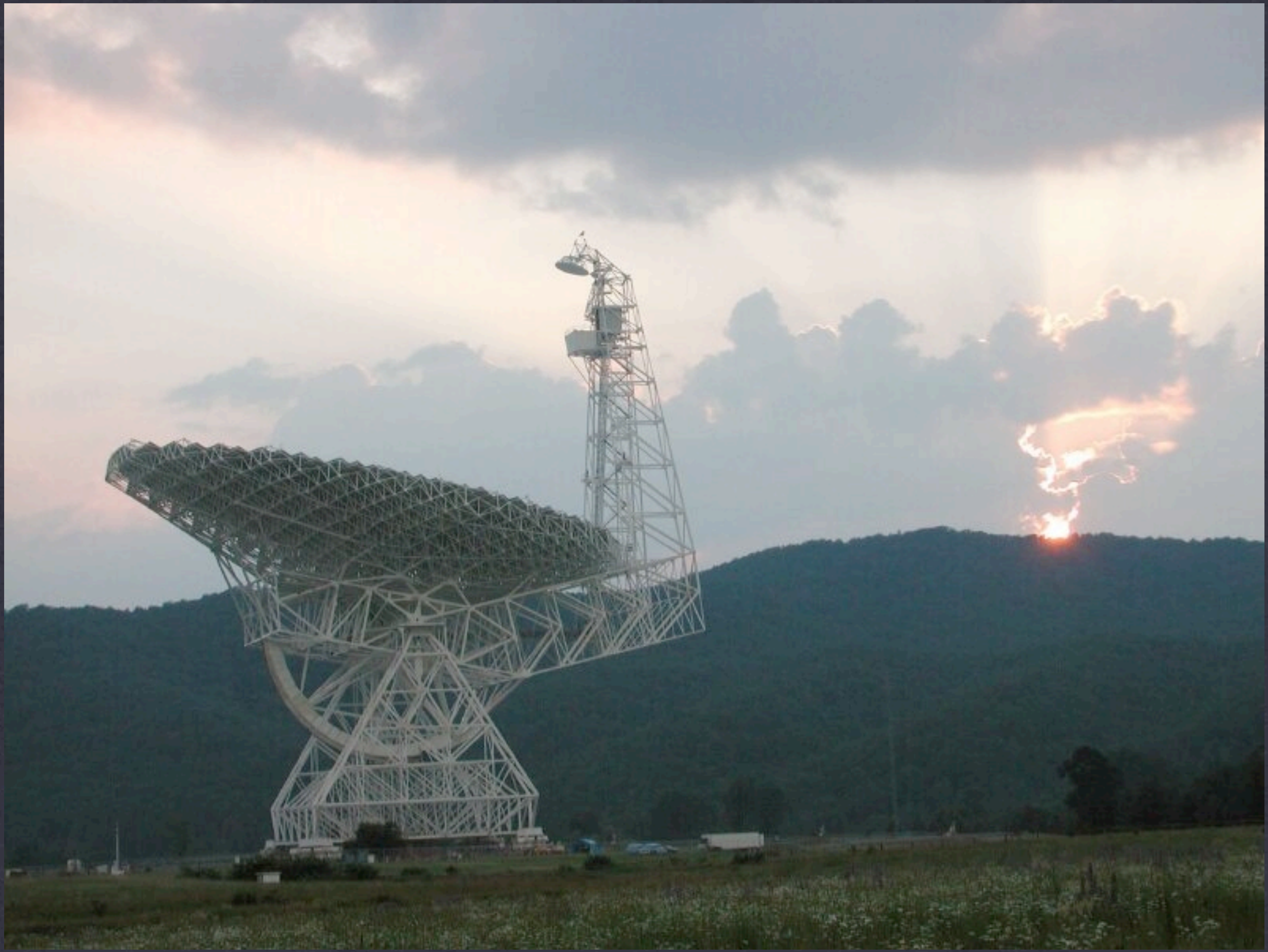
EOR

z	~1	~10
Science goal	BAO	EoR
Signal (mK)	0.1	10
Tsys (K)	30	300
Foreground spatial fluctuation (K)	0.1	10
Size scale	~10' – 1.4 deg; 109 h^{-1} Mpc (non-linear scale – first peak)	~10'-30'; 20-50 Mpc (bubble scale)
First proposed	2007	1970's?
First mesurement	2010; cross-correlation	>2011; upper limit
Strategy	single dish	Interferometers

Probing Large-Scale Structure

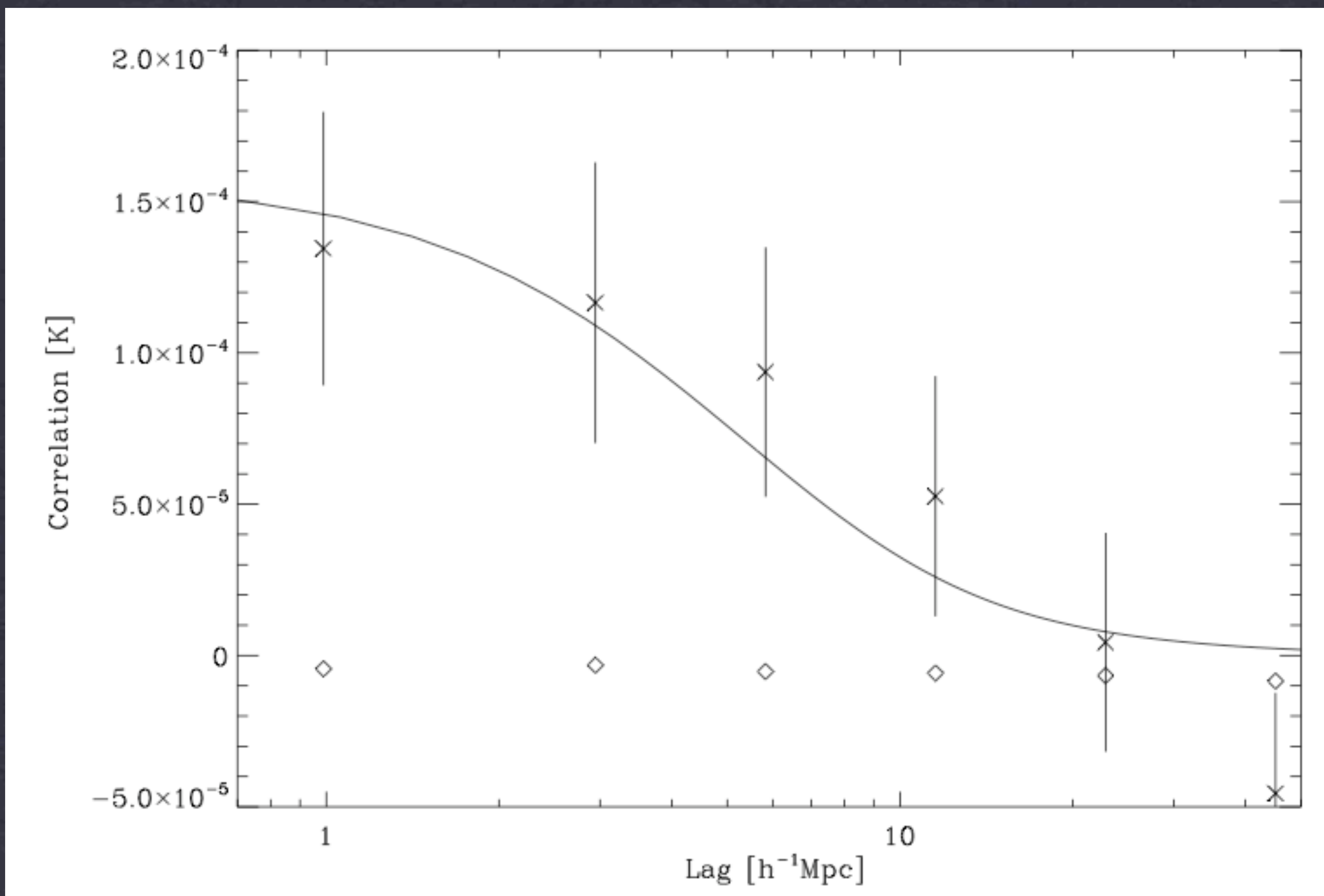
- Measuring Baryon Acoustic Oscillation with HI power spectrum at z~1

Green Bank Telescope



HI Intensity Mapping at z=0.8

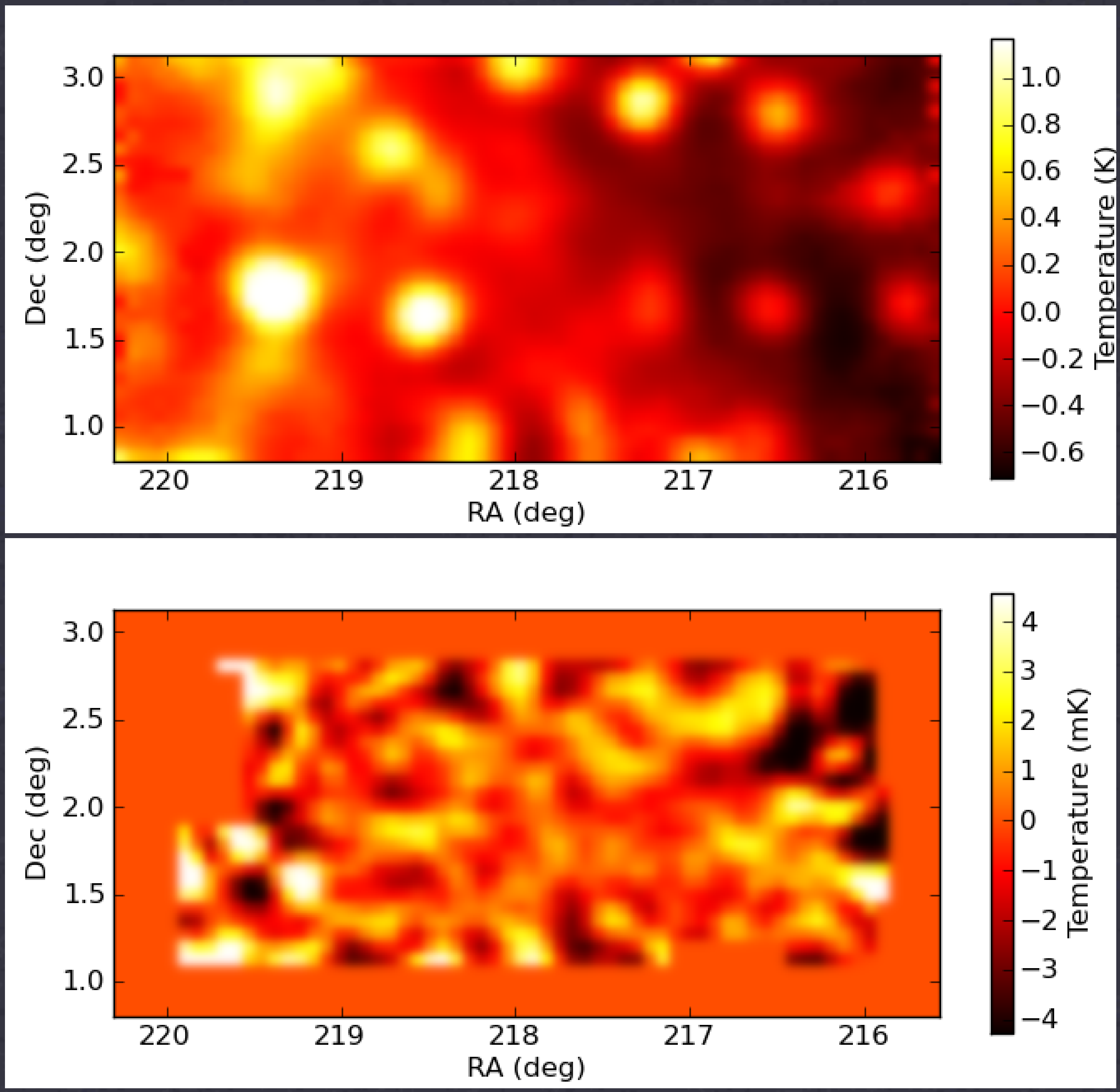
Cross-correlating GBT HI & DEEP2 optical galaxies at z ~ 0.7-1.1



Chang, Pen, Bandura, Peterson, in Nature 2010

- Measure HI & DEEP2 optical cross-correlation on 9 Mpc (spatial) x 2 Mpc (redshift) comoving scales
- HI brightness temperature on these scales at z=0.8:
- T = 157 ± 42 μK
- Ω_{HI} r b = (5.5 ± 1.5) x 10^{-4}
- Highest-redshift detection of HI in emission at 4-sigma statistical significance.

GBT: Current limit on HI auto-correlation at z~1



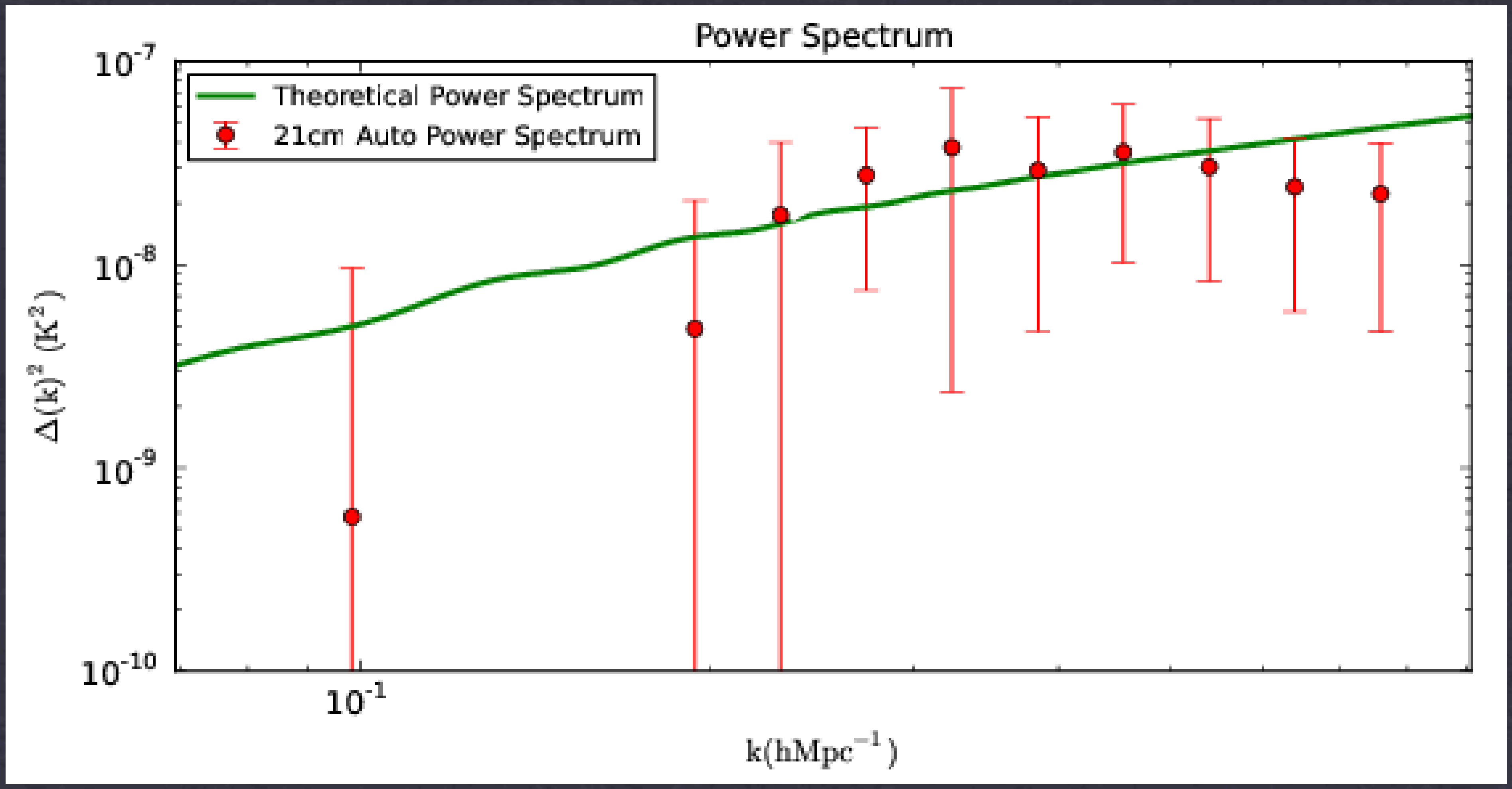
fluctuations: 200 mK v.s. 0.06 mK

- 300 hours, 50 deg^2 survey at the GBT
- Measuring the WiggleZ fields at 800 MHz band, 0.5 < z < 1.1
- Foreground subtraction using SVD, correcting for frequency dependent beam
- Foreground subtraction down to factor of 1000

- Continuum dynamic range ~10
- Spectral dynamic range ~1000
- Same requirement as EoR

The GBT HIM collaboration

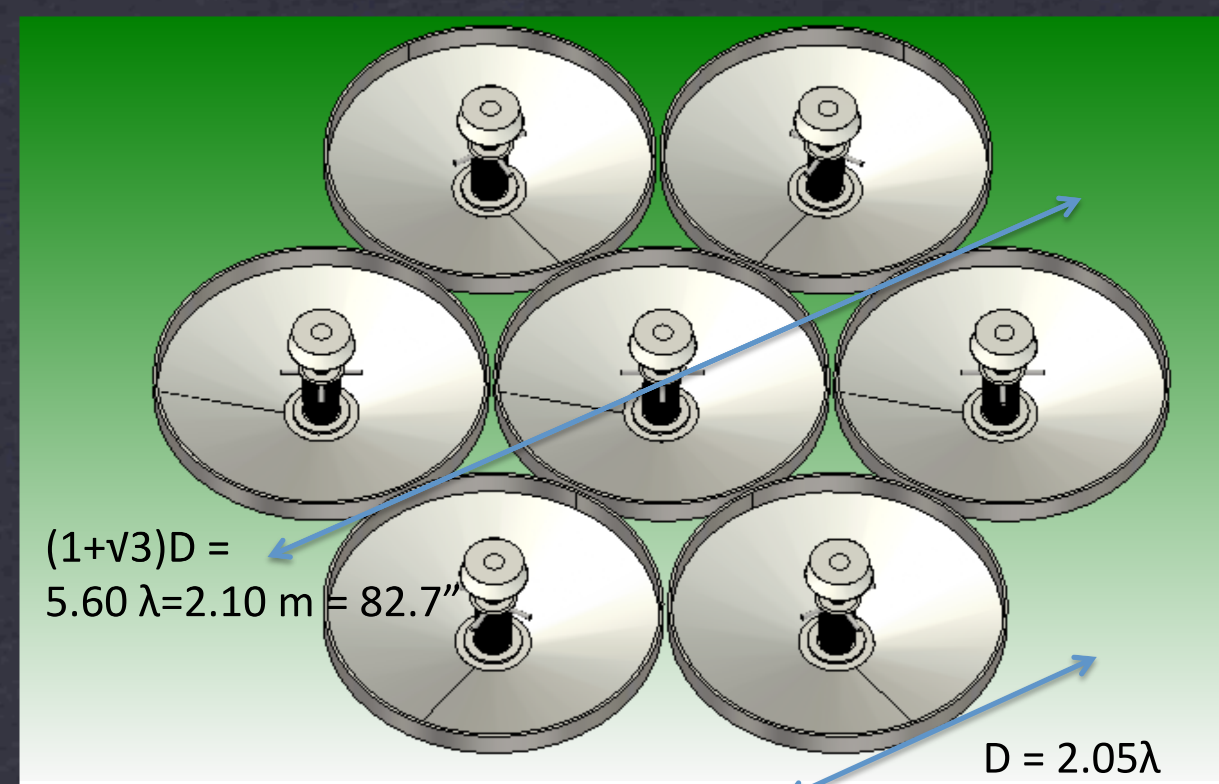
GBT: preliminary 3D HI power spectrum at z~1



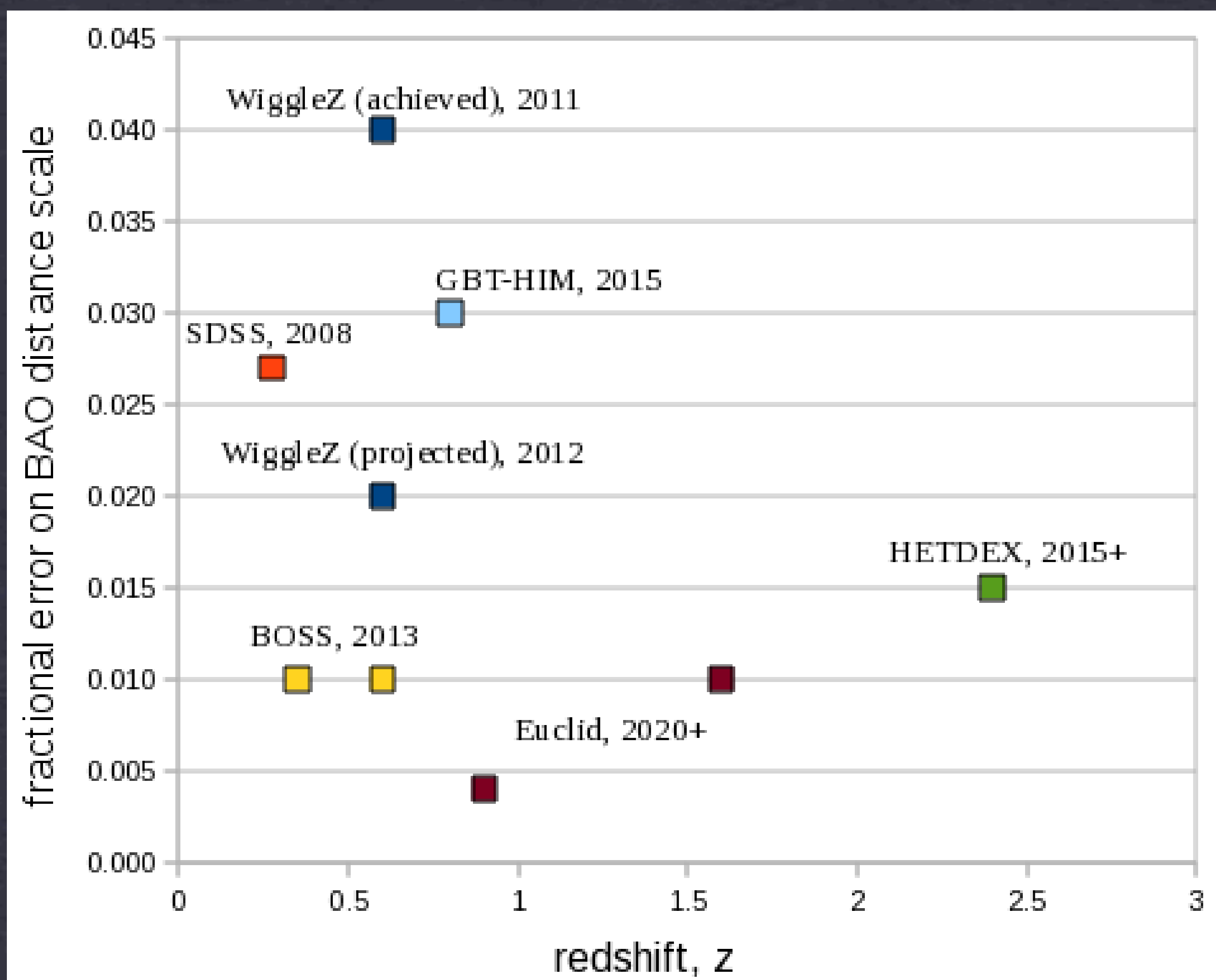
The GBT HIM collaboration

GBT 800 MHz multi-beam project

- Building a 7-9 beam receiver at 800 MHz for HI survey (and pulsar search)
- Use Short-backfire Antenna (SBA) with a edge-tapered reflector; with a cryogenic tube connecting to the dipole to reduce Tsys
- Prototyping underway; Yuh-Jing Hwang, Chi-Chang Lin+ (ASIAA)
- Members include: Sri Srikanth, Steve White, John Ford (NRAO), Jeff Peterson (CMU), Peter Timbie (U. Wisconsin), Chris Carilli (NRAO), Matt Dobbs (McGill), Dan Eisenstein (Harvard) + GBT-HIM team



GBT high-z HI Survey v.s. Optical experiments



- 500 deg^2, 3000 hours, 700-900 MHz ($0.5 < z < 1$)
- HI provides a unique and large redshift window, at the onset of dark energy domination.
- HI provides a different measure than the optical surveys; different systematics, different astrophysical biases.
- HI surveys can be economical

HI BAO Experiment Prospects

- **HI Intensity Mapping Experiment: 10,000 m^2 collecting area (1% of SKA), 2000 hrs of observation - competitive to DETF stage III experiment: BOSS, DES**

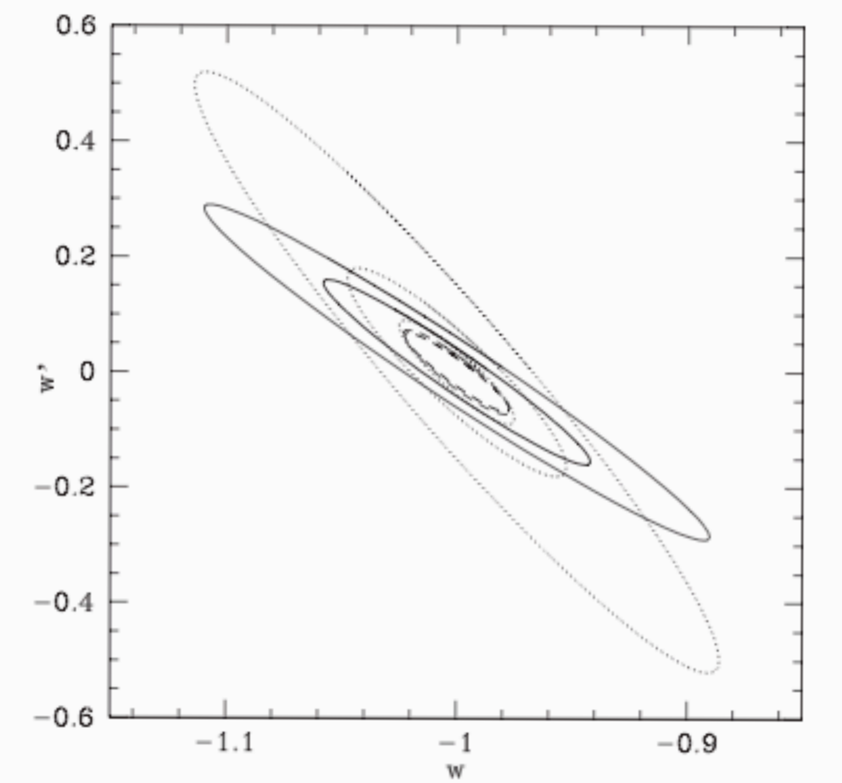


FIG. 4. The $1-\sigma$ contour for IM combined with Planck (inner thick solid for baseline model, outer thin solid for worst case), the Dark Energy Task Force stage I projects with Planck (outer dotted), the stage I and III projects with Planck (intermediate dotted), the stage I, III, and IV projects with Planck (inner dotted), and all above experiments combined (dashed, again thick for baseline, thin for worst case; the two contours are nearly indistinguishable).

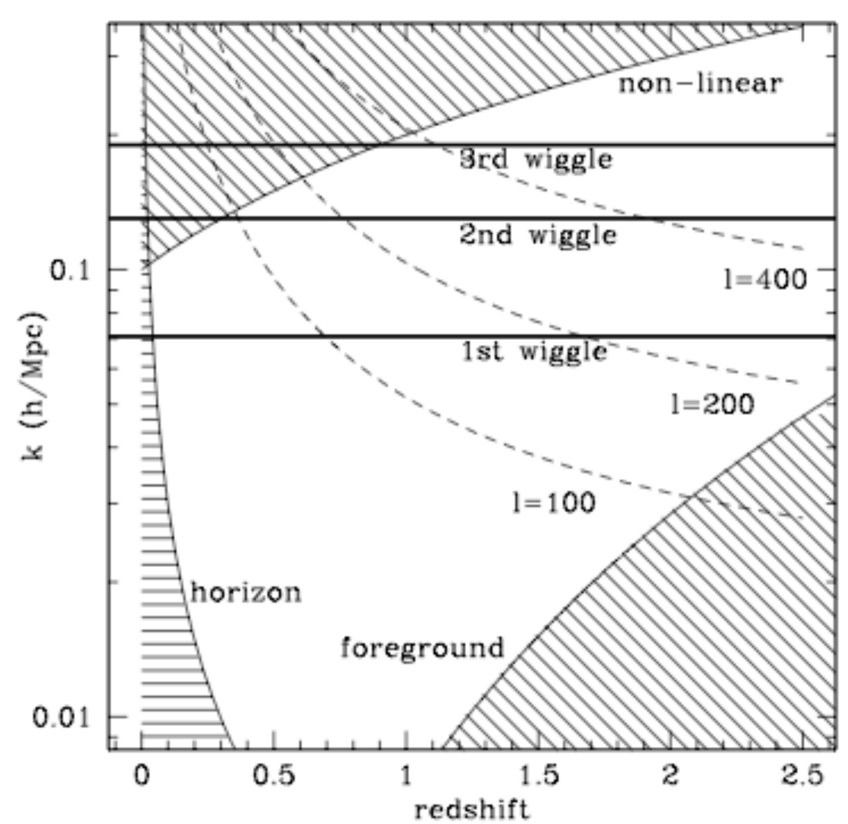


FIG. 3: The observable parameter space in redshift and in scale (k) for BAO. The shaded regions are observationally inaccessible (see text). The horizontal lines indicate the scale of the first three BAO wiggles, and the dashed lines show contours of constant spherical harmonic order ℓ.

Chang, Pen, Peterson, McDonald 2008

21cm at z~1: current status and outlook

- HI cross-correlation (with DEEP2 optical galaxies): measured at z~0.8: abundant HI at z~1; HI traces large-scale structure
- HI auto-correlation (power spectrum): 50 deg^2, 300 hrs at GBT, possible detection (caution: foreground, calibration issues..)
- GBT multi-beam focal-plane array at 800 MHz:
  - 500 deg^2, 3,000x4 hrs, measuring HI BAO distance scale to 3% accuracy.
- A >1% SKA survey instrument ideal for Baryon Acoustic Oscillation measurement (e.g., Chang et al. 08, Wyithe & Loeb 08, Seo et al. 10): Wide-field survey, large collecting area, compact configuration, (~10^4 m^2) covering $0.5<z<2.5$ (400-900 MHz, df~0.5 MHz), resolution ~10' (10 comoving Mpc);
- C.f. CHIME (Cosmic Hydrogen Intensity Mapping Experiment), CRT (Cosmic Radio Telescope).

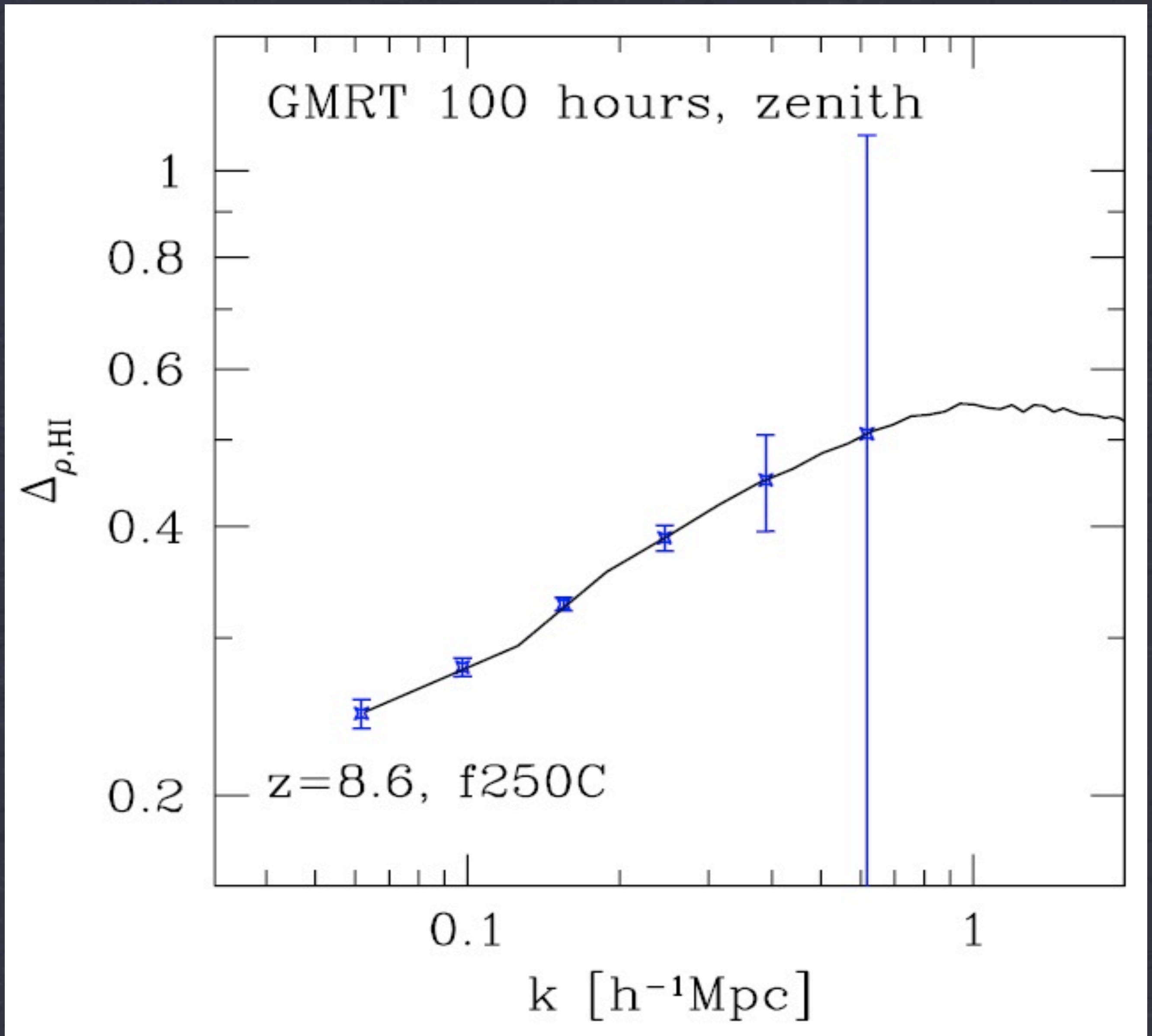
Probing Cosmic Reionization

- Measuring HI power spectrum from Epoch of Reionization (EoR) at z~8.5

GMRT - Giant Meterwave Radio Telescope

U.-L. Pen, T. Chang, G. Paciga, J. Peterson, J. Roy, Y. Gupta, J. Odegova, C. Hirata, K. Sidgurdson, J. Sievers, S. Meyers

GMRT-EoR forecast



Ilive et al. 2008

- GMRT: 30 antennae, D=45m diameter, 14 elements within 1km core; 3.3 deg FOV at 150 MHz
- 20000 m^2 collecting area (for EoR), 140-156 MHz, 8<z<9
- Traditional dish arrays, large collecting area, small field-of-view.
- EoR prediction: 20-sigma measurement on the HI power spectrum at k~0.1

Observational challenges

Extragalactic radio sources

Signal 20 mK

Upper limit at ~100 mK

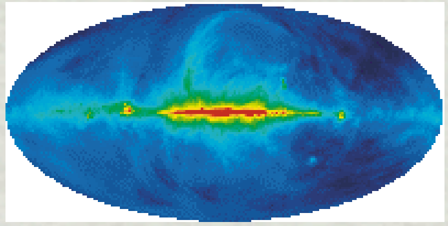
No polarized point sources found

Pulsar phase referencing successful

Ionosphere:
- phase delays
- Faraday rotation

"EoRgrider" Foreground subtraction underway

Anthropogenic Interference



Galactic emission (synchrotron + free free)
~200K at 200 MHz

RFI mitigation successful; physical elimination in progress

Detector

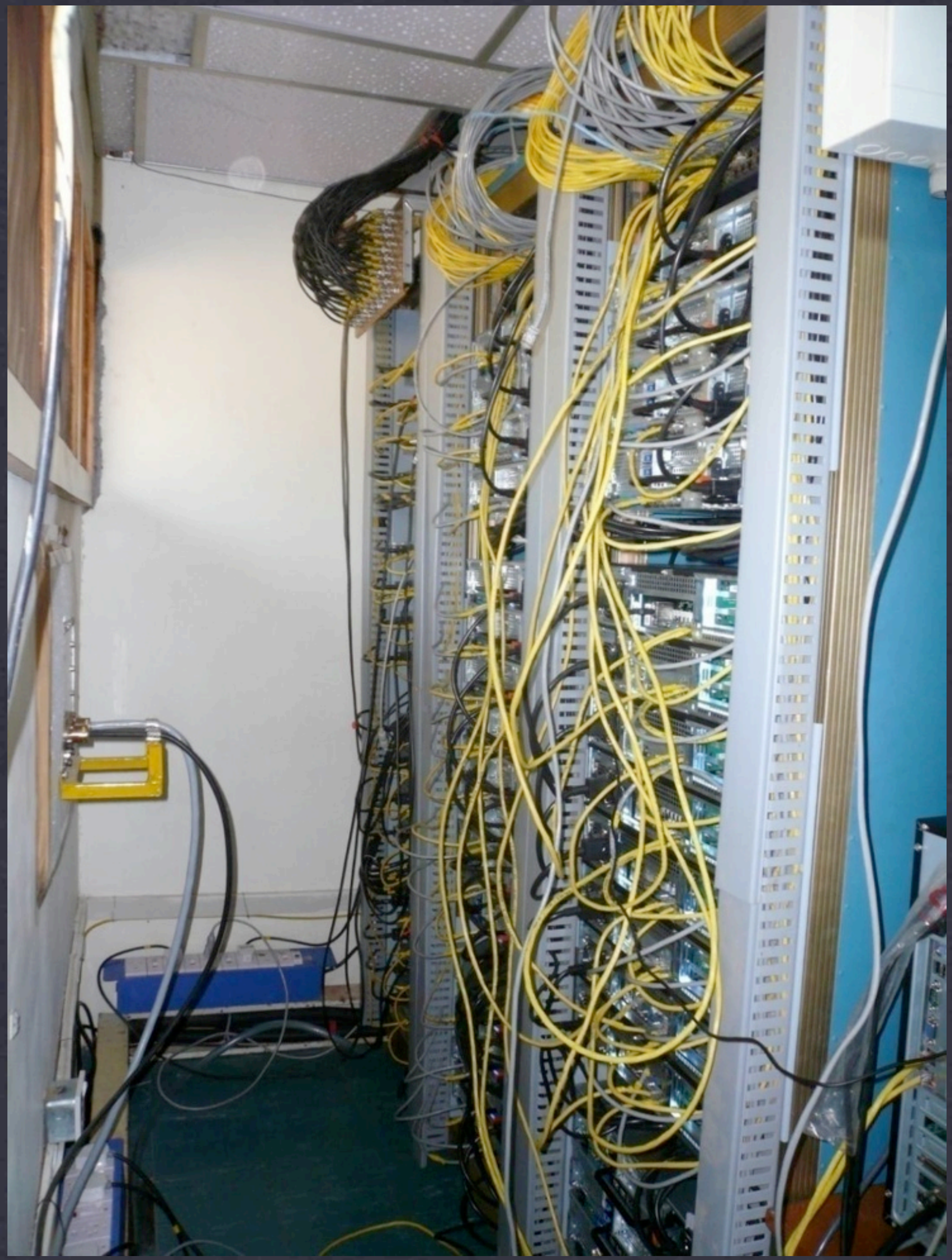
Galactic intensity foreground fluctuations: ~1K at 150 MHz

Upper limits on polarized diffuse foregrounds ~ 1K

Installed software correlator; collected a few x 100 hours of data

Courtesy of Chris Hirata

Software Correlator at GMRT



15 nodes taking data (30x2 inputs); 16 nodes perform real-time correlation (data rate ~1.6 TByte/hour), allowing high time & freq resolutions; collected more than 300 hrs of data

Phase calibration at 150 MHz

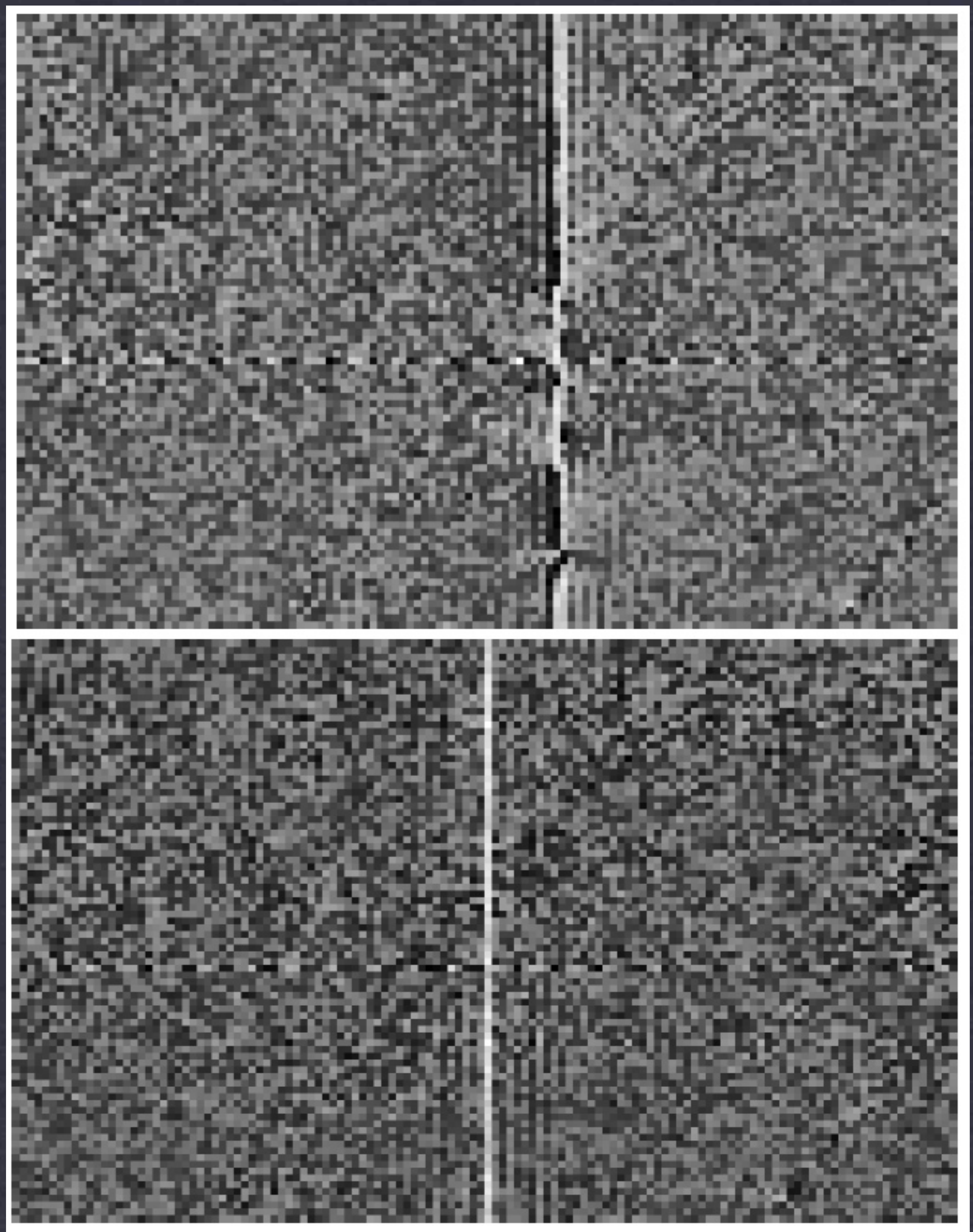
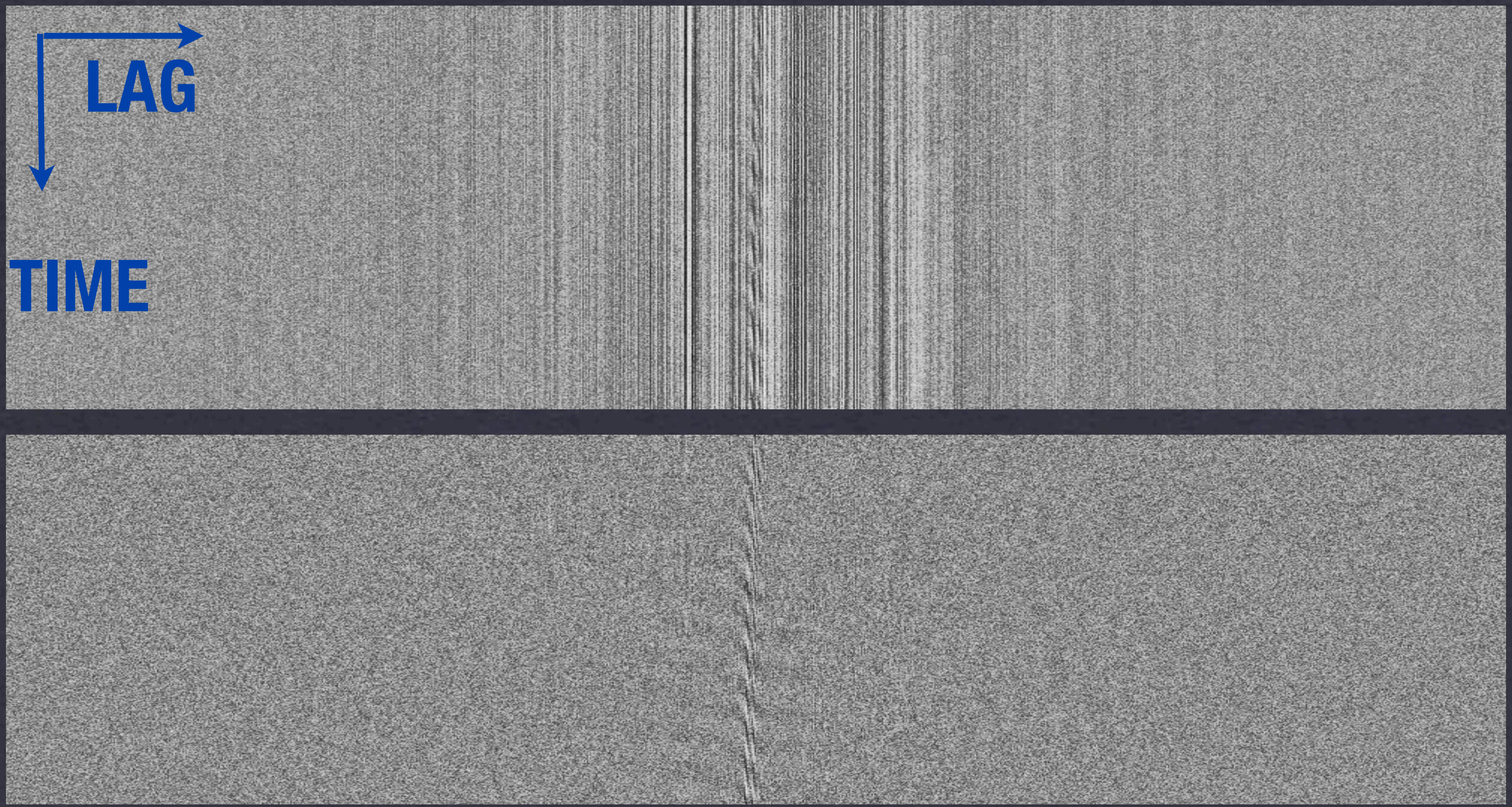


Figure 2: same baseline after phase corrections.

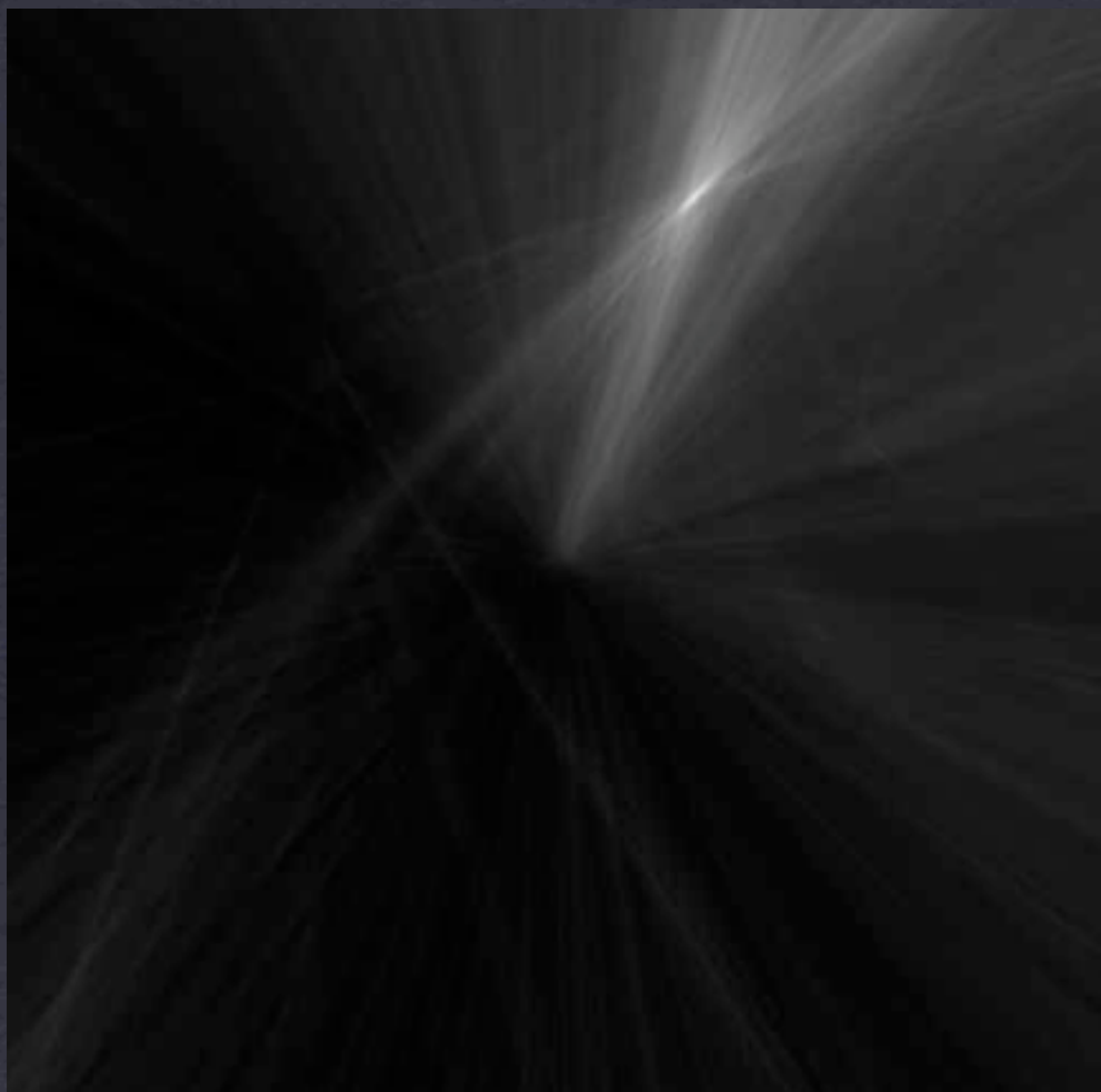
- Calibration at low frequency is non-trivial
- Use pulsar as phase calibrator
- Take gated data: 16 gates per pulsar period; (pulsar-on - pulsar-off) = clean, pulsar-only sky; solve for antenna gains
- Use parallatic angle rotation to separate sky polarization and leakage

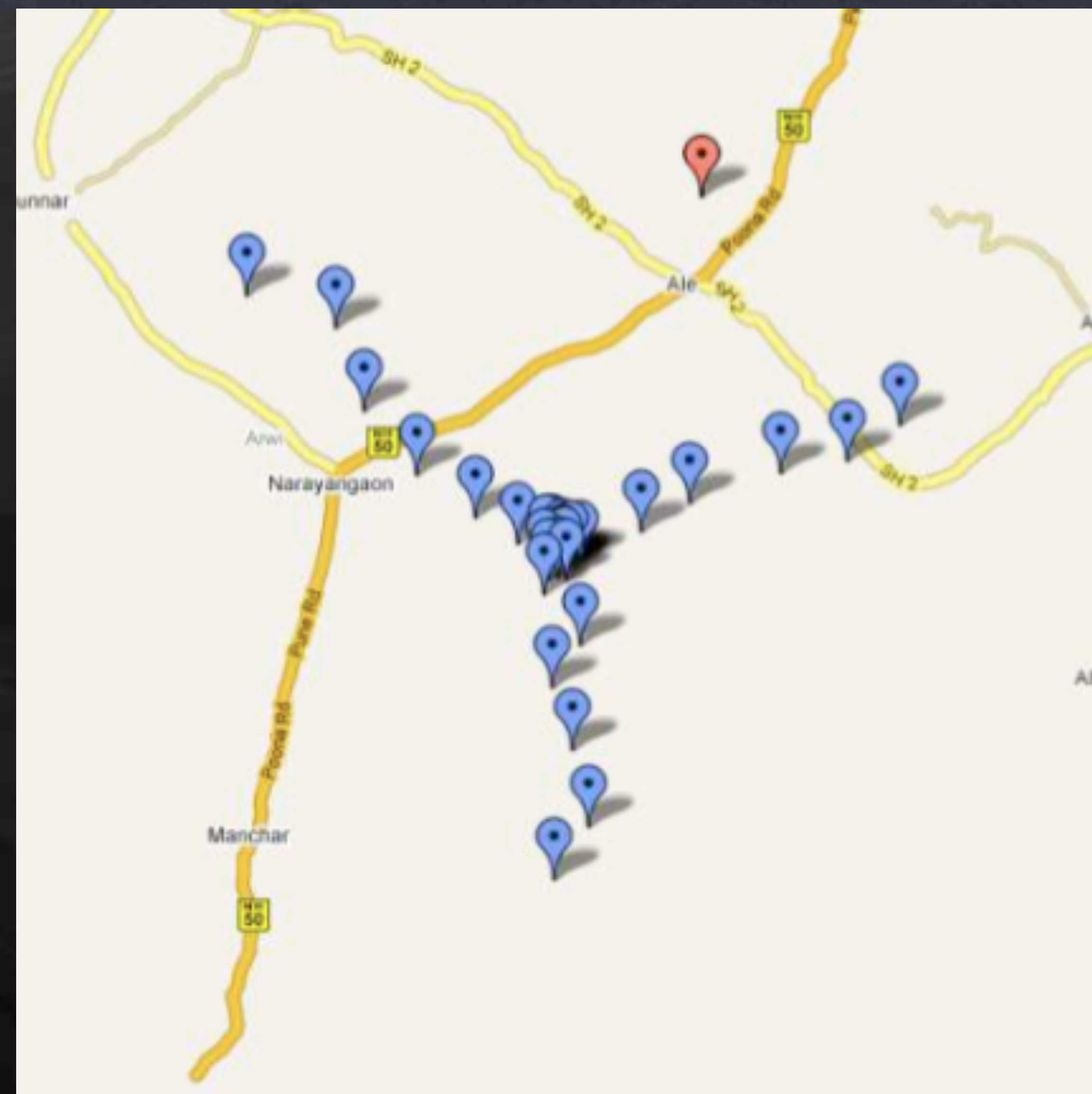
Broadband RFI Mitigation - software

- Sky fringe-rotates but RFI's don't
- Use SVD-based technique to filter out largest few eigen modes
- Successful RFI removal (reduced >1 orders of magnitude in temperature)



Broadband RFI Mitigation: near-field imaging





Solving for hyperbolic functions (constant delays)

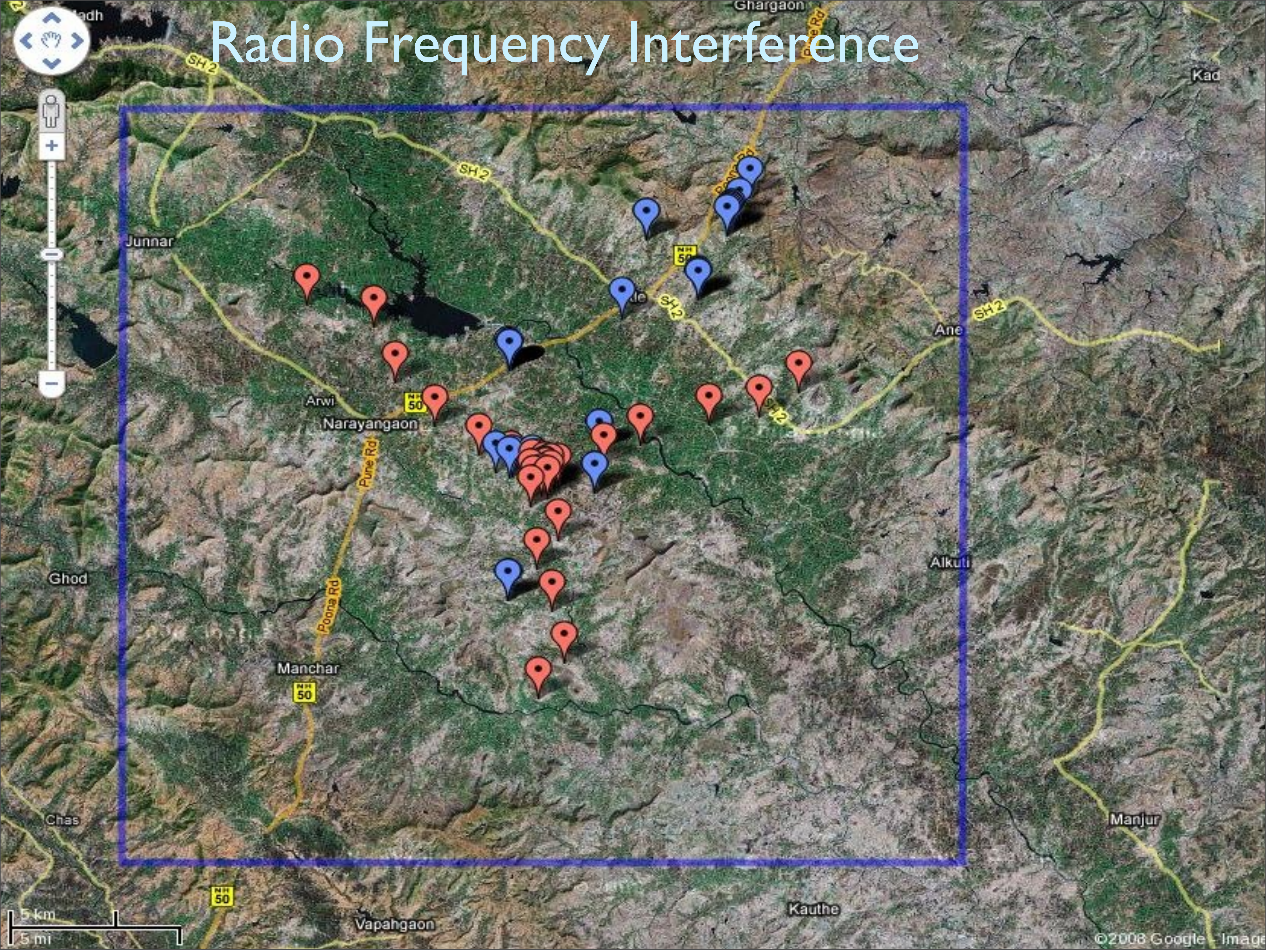
Broadband RFI hungting at GMRT

- Use noise source as calibrator for position
- Use Yaggi antenna to localize RFI

U. Toronto summer students 2011

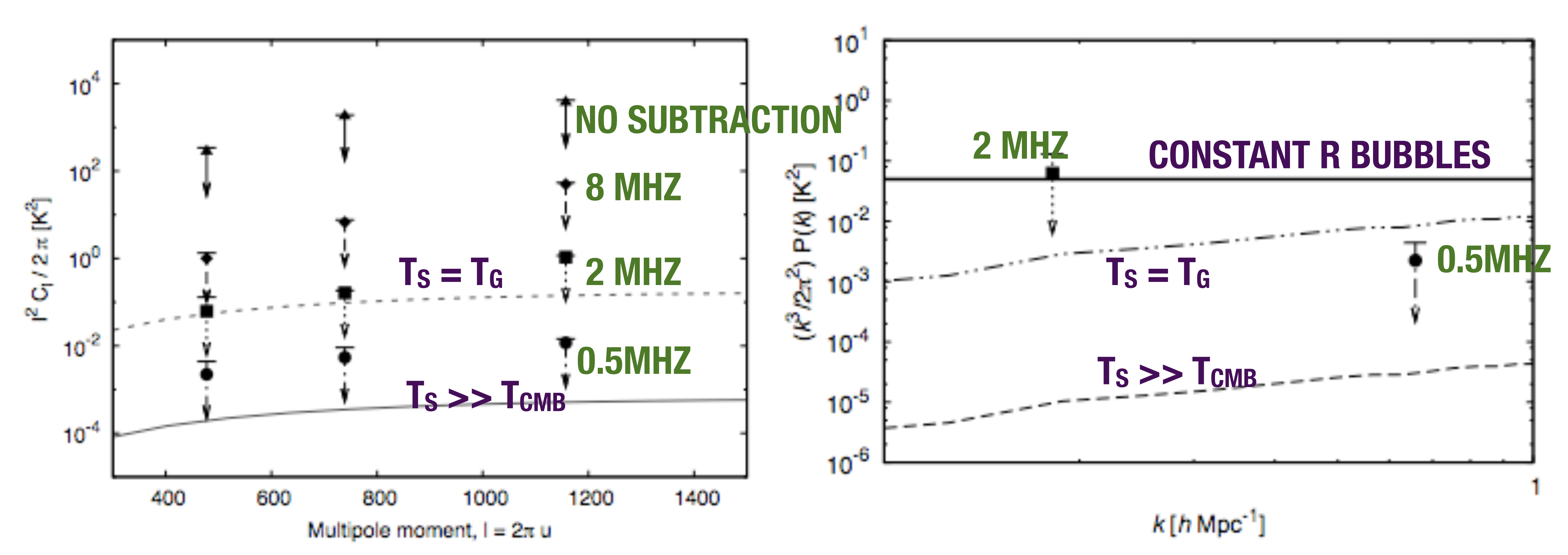
RFI: near-field imaging

Radio Frequency Interference



GMRT current upper limits:

- Straight forward foreground subtraction: subtract mean of (8, 2, 0.5) MHz, 60 < |U| < 200



JELIC 08 MODELS

ILIEV 08 MODELS

- T~70 mK, for the 0.5 MHz case
- Cross-day HI auto power spectrum

Paciga et al., 2011

GMRT work in progress: EoRgridr

- expand the CBIgridr (Myers et al. 2003) for 2D CMB to 3D EoR purpose
- added w-projection effect in the gridder

$$\tilde{v} = \tilde{A}\tilde{s} + \tilde{n}$$

$$\tilde{d} = \tilde{R}\tilde{s} + \tilde{n_d}$$

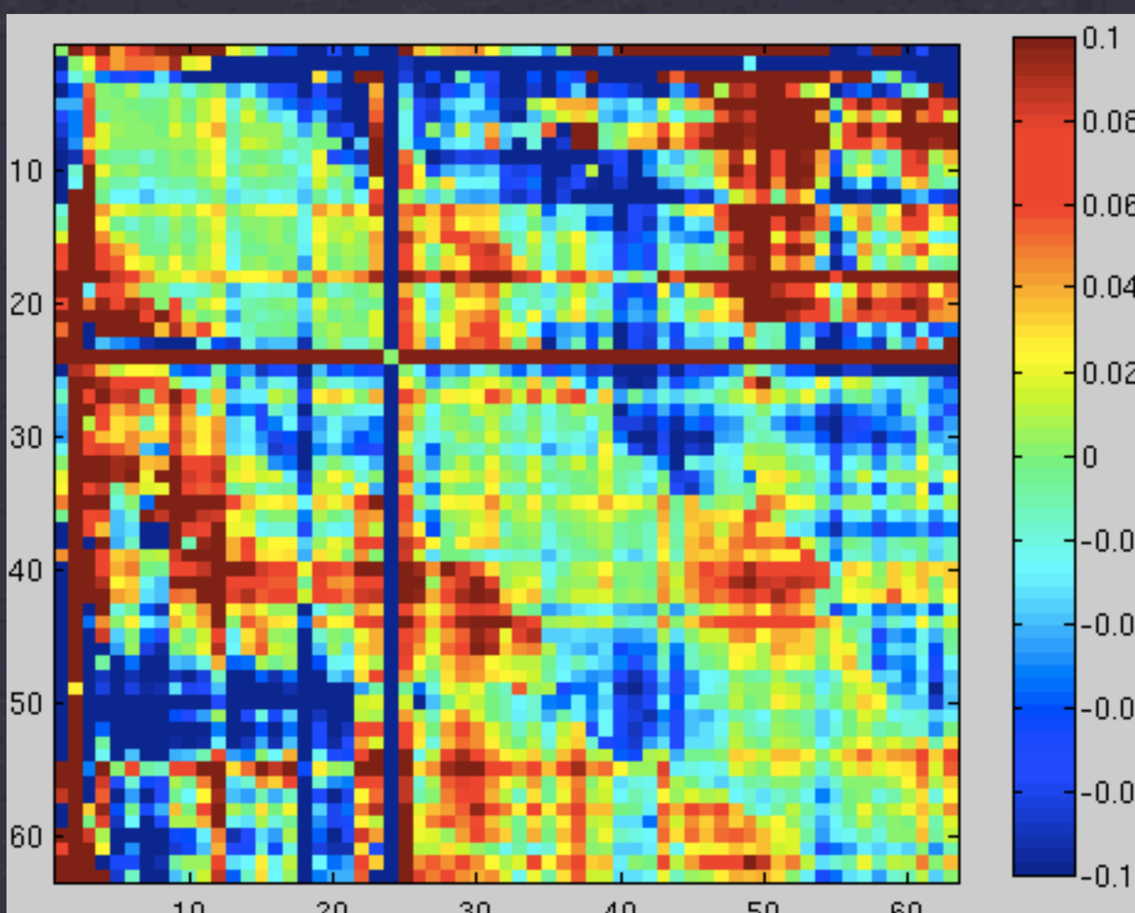
EoRGridr

$$\tilde{R} = \tilde{H}\tilde{A}\tilde{W}, \tilde{n_d} = \tilde{H}\tilde{n}$$

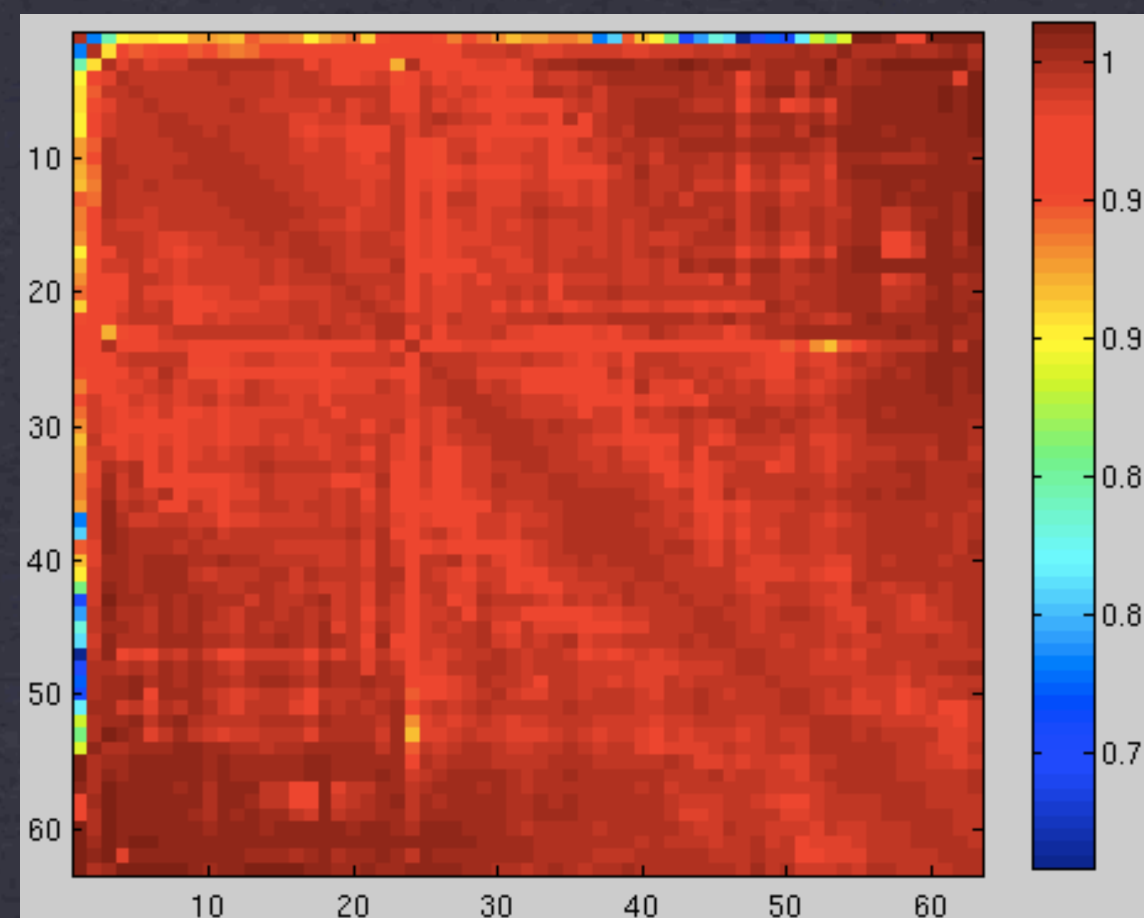
$$\tilde{\Delta} = (\tilde{R}^T N^{-1}\tilde{R})^{-1}\tilde{R}^T N^{-1}\tilde{d}\,, N = < \tilde{n_d}\tilde{n_d}^T >$$

$$\tilde{\Delta} = \tilde{R}^{-1}\tilde{d}$$

$$\left\langle \tilde{\Delta_\nu}\tilde{\Delta_\nu^T} \right\rangle = \tilde{S} + \tilde{F}$$



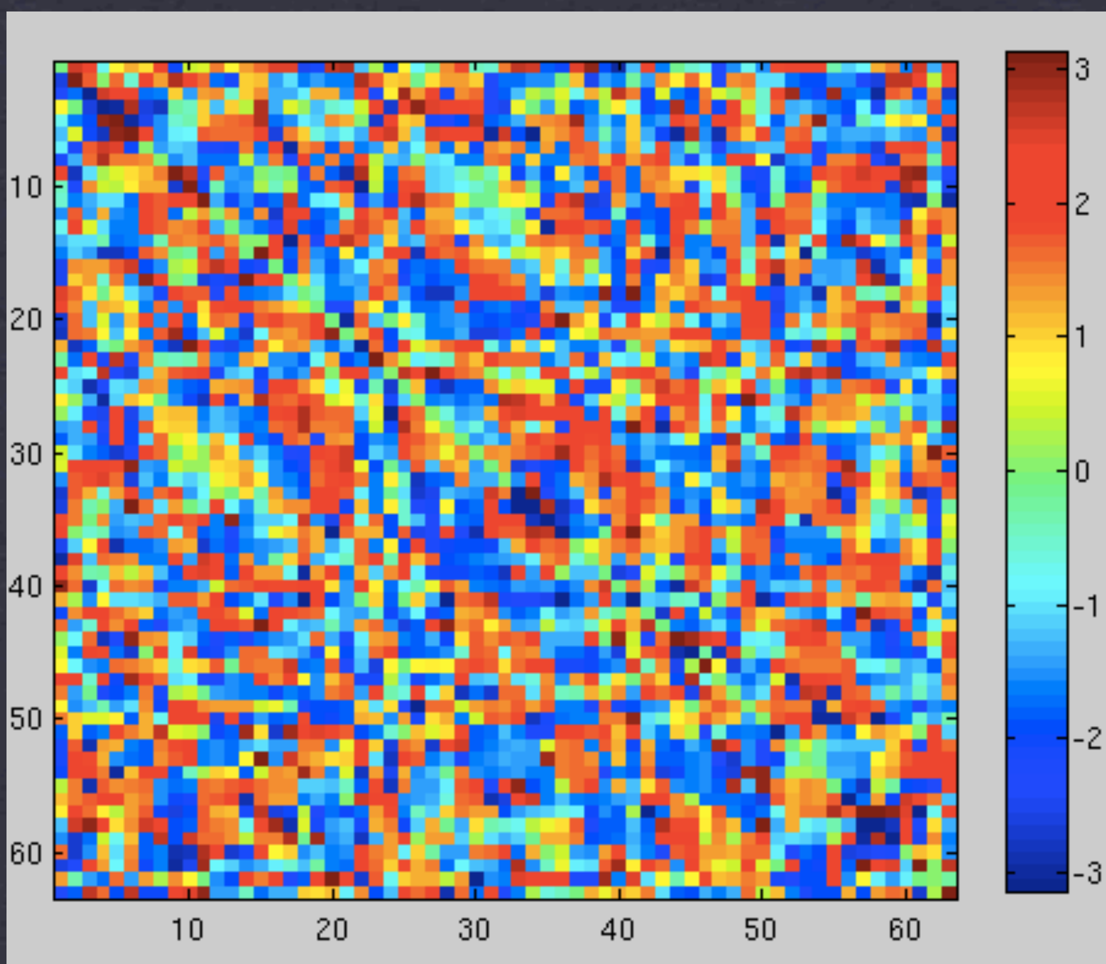
Phase



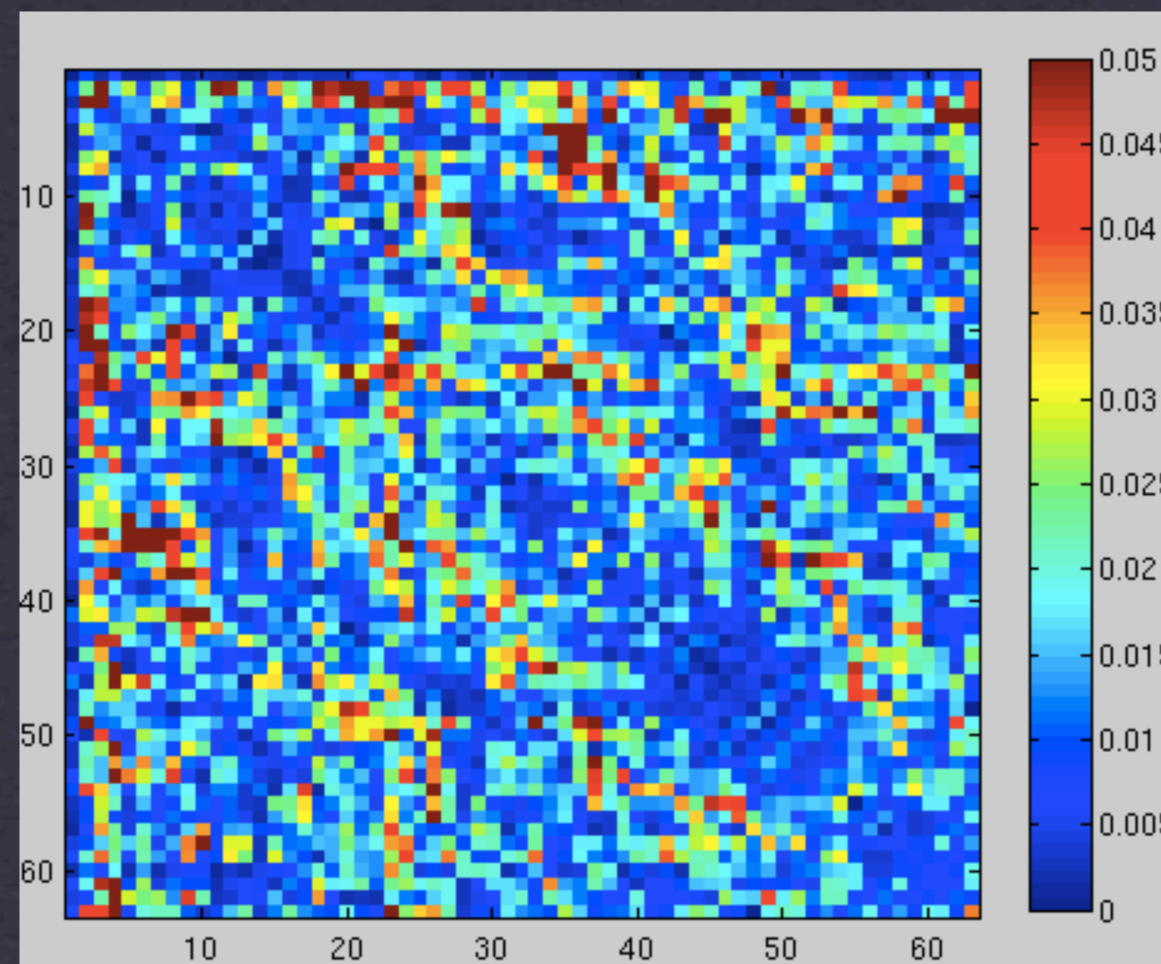
Amplitude

GMRT work in progress: EoRgridr

- SVD foreground-subtracted estimated (normalized) signal covariance $< \Delta_\nu \Delta_\nu^T > \sim S$
- After subtraction - no coherent phase structure
- Very preliminary!



Phase



Amplitude

Joining the PAPER team

PAPER SITE AT KAROO, SA

Pic: Nicole Gugliucci

Outlook

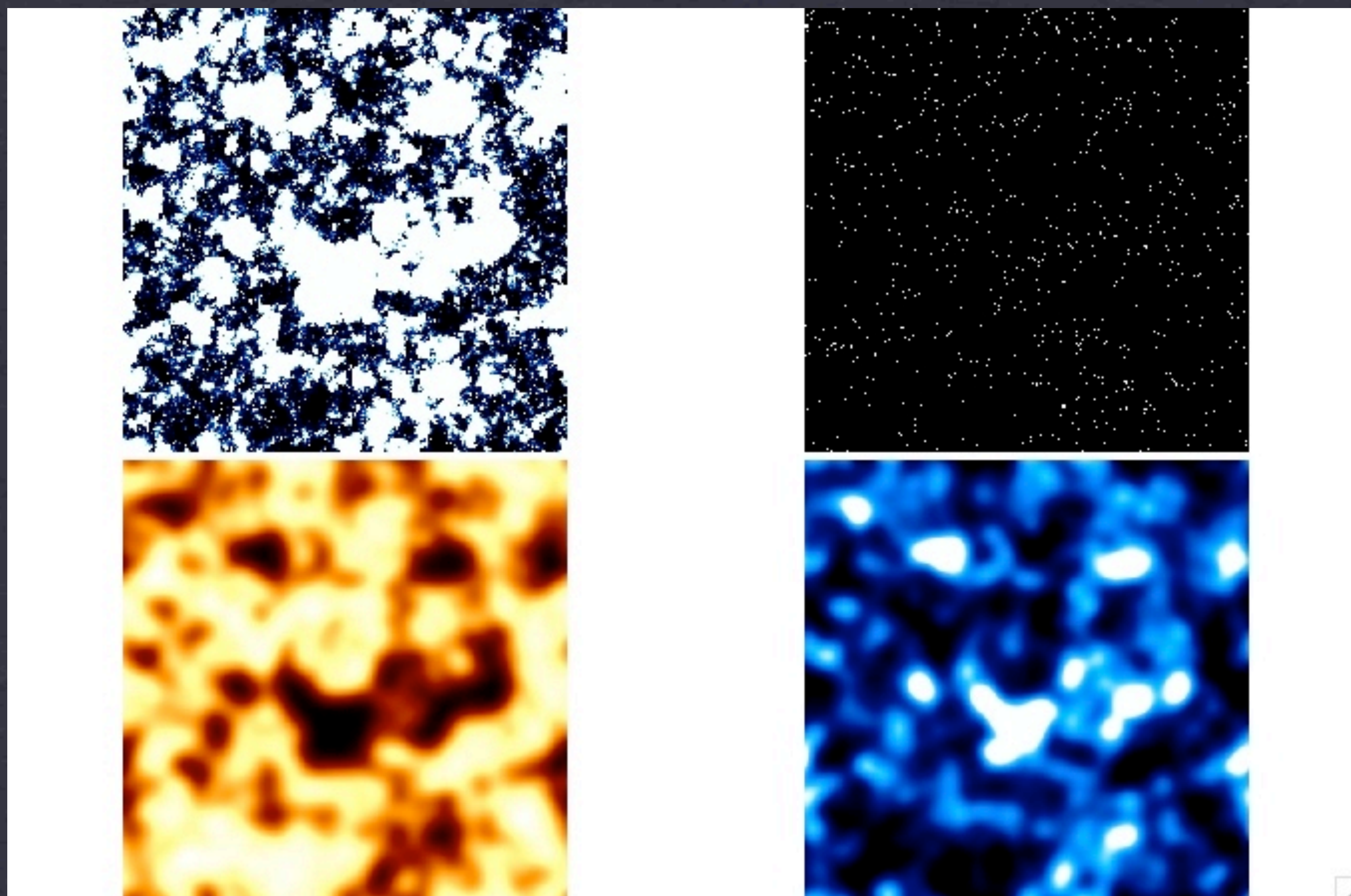
- On-going data analysis: EoRgridr
    - Extend to 3D for foreground/power spectra analysis
- More GMRT observations: drift scan, near-transit observations, mosaicking
- RFI mitigation this summer: team of summer students
- Current state-of-art spectral foreground subtraction limits on 10' scales :
    - GBT (single dish): 1000:1 -- foreground spectrally smooth!
    - GMRT (interferometric): 100:1
    - important metric for EoR measurements
- Current GMRT EoR power spectrum limit (~100 mK) c.f. Bebbington+ 1986 (~5K), Ali+ 2008 (~4K), Parsons+ 2010 (~5K; PAPER)
- LOFAR, MWA, PAPER in operation - more results soon!

CO Intensity Mapping

- CO large-scale structure 3D maps of the universe at around the redshifts of EoR

CO intensity mapping at EoR

LIDZ, FURLANATTO, OH, AGUIRRE, CHANG, DORE, PRITCHARD 2011



- CO (star formation) large-scale structure at high redshifts (T ~ 1 μK)
- HI-Co anti-correlates on large-scales, constraining size evolution of ionized regions at EoR (Lidz et al. 2009)
- Righi et al. 2008, Gong et al 2010, Carilli 2011, Lidz et al 2011

CO intensity mapping with AMiBA-DACOTA

- 1.2 m dish, 6 m baseline, currently operate at 83-102 GHz
- At 30-32 GHz, probes $6.19 < z < 6.67$ for CO[2-1], $2.59 < z < 2.83$ CO[1-0]
- At 31 GHz, resolution=6.7', FoV =28', probes >10 Mpc scales
- AMiBA team (ASIAA): Paul Ho, Kai-Yang Lin, Ming-Tang Chen, Homin Jiang+
- DACOTA team (Berkeley/Arizona): Geoff Bower, Dave Deboer, Dan Marrone+

Summary

- 21-cm cosmology is exciting and provides a unique view of a significant fraction of the Universe.
- HI “Intensity Mapping” proof of concept demonstrated at z~1
  - opens up 21-cm 3D large-scale structure studies (GBT 800 MHz focal-plane array; CHIME-like instrument)
  - may be interesting for the CO lines at high (and low) redshifts (CO AMiBA-DACOTA project)
- EoR 21-cm science is important. Initial results may come from several groups with different approaches in the next few years; paving the way to SKA.
- Novel use of radio astronomy tools can lead to unique cosmological and astrophysical insights.