21cm Cosmology

Tzu-Ching Chang

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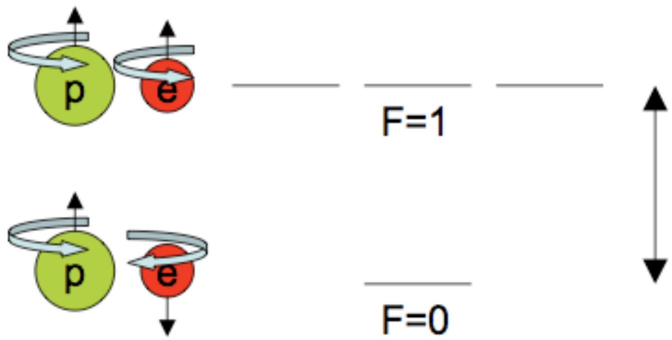
21cm Line



$$\Delta E = \frac{4}{3}\alpha^4 g_p \frac{m_e}{m_p} m_e c^2 = 5.9\mu\mathrm{eV} = h(1420\mathrm{MHz})$$

$$\lambda = 21\,\mathrm{cm}$$

Picture from C. Hirata

-- Hyperfine transition of neutral hydrogen
-- Hydrogen: most abundant element, optically thin
-- Line transition: Probe 3D structure of the Universe
-- can be seen in absorption or emission against the CMB, depending on the spin temperature:

Ts > Tcmb: emission (z < 10)
Ts < Tcmb: absorption (30 < z < 150)

$$\frac{n_{F=1}}{n_{F=0}} = 3e^{-\Delta E / kT_s}$$

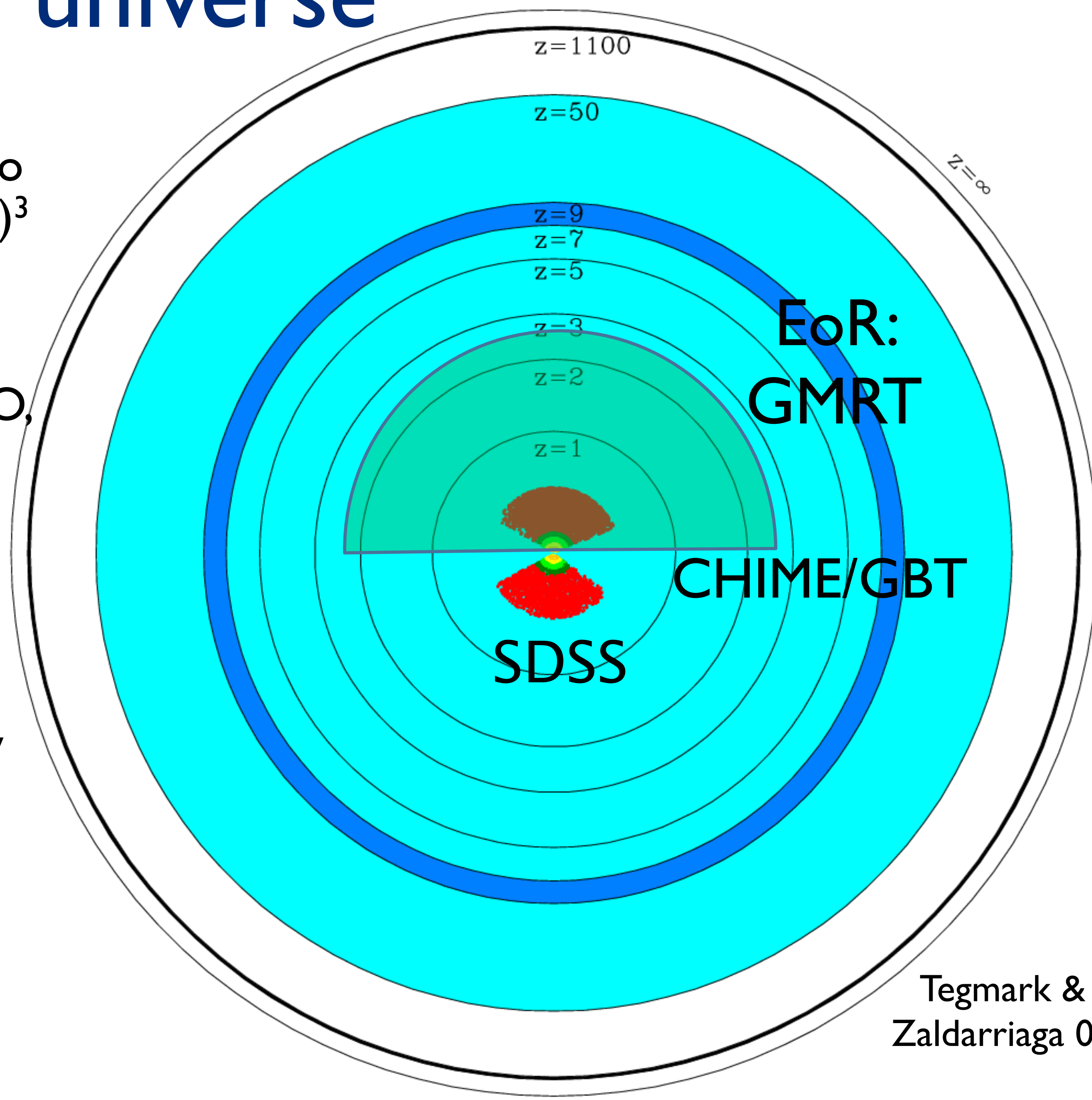
-- Brightness Temperature

$$\Delta T = \frac{3 n_{\mathrm{HI}} \lambda^3 T_*}{32\pi H \tau_{1\to 0}(1+z)}\left(1 - \frac{T_{cmb}}{T_s}\right)$$

$$= 300\,(1+\delta)\left(\frac{\Omega_{HI}}{10^{-3}}\right)\left(\frac{h}{0.73}\right)\left(\frac{\Omega_m + (1+z)^{-3}\Omega_\Lambda}{0.35}\right)^{-0.5}\left(\frac{1+z}{1.9}\right)^{0.5}\mu\mathrm{K}$$

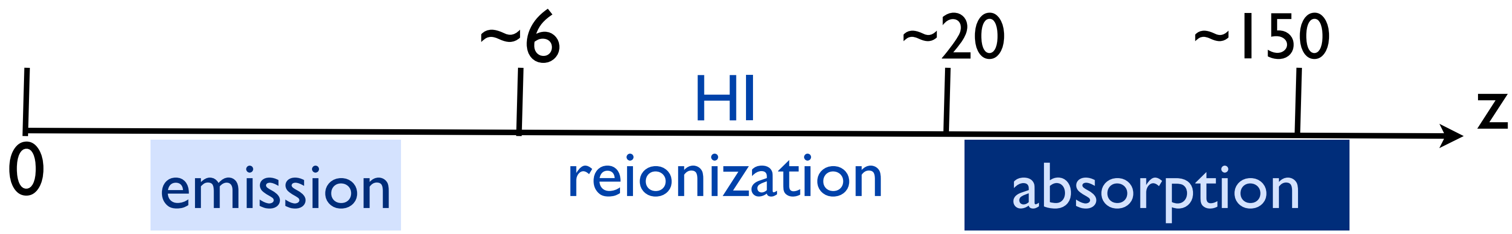
The 21cm universe

- 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 evolution
- Experiments NOW
  - EoR : GMRT, LOFAR, MWA, PAPER, 21CMA
  - BAO : GBT/ CHIME



Tegmark & Zaldarriaga 08

21cm Cosmology



- Astrophysical -- probing the Epoch of Reionization (EoR):
  - Traditional observation can't see anything before there were luminous matter
  - Can probe full ionization structure (Ly-alpha saturates except at the end of reionization)
- Precision cosmology -- measuring cosmological parameters:
  - at high z, pre-reionization: linear, 10^{16} modes; much more than the CMB (10^7), LSS (10^7 at $z<1$)
  - at low z, "ionized": use HI intensity mapping to make an efficient redshift survey: Baryon Acoustic Oscillation measurements; Lensing (O. Dore, T. Lu, U. Pen, 2009)

21cm in Emission

- Astrophysical -- probing the EoR:
  - 6 < z < 11;   probing luminous structure formation.
  - Ionized regions (bubbles) are large: >20 Mpc, ~20' at z~9
  - Neutral fraction ~ 1, dominates T fluctuation
- Precision cosmology -- measuring BAO:
  - 0 < z <3;   HI in high-density clumps (DLA's, galaxies), probing properties of dark energy.
  - Baryon Acoustic Oscillation imprints on PS: Sound horizon scale at recombination: ~109 h^{-1} Mpc.
  - neutral fraction ~ 0.01; traces LSS

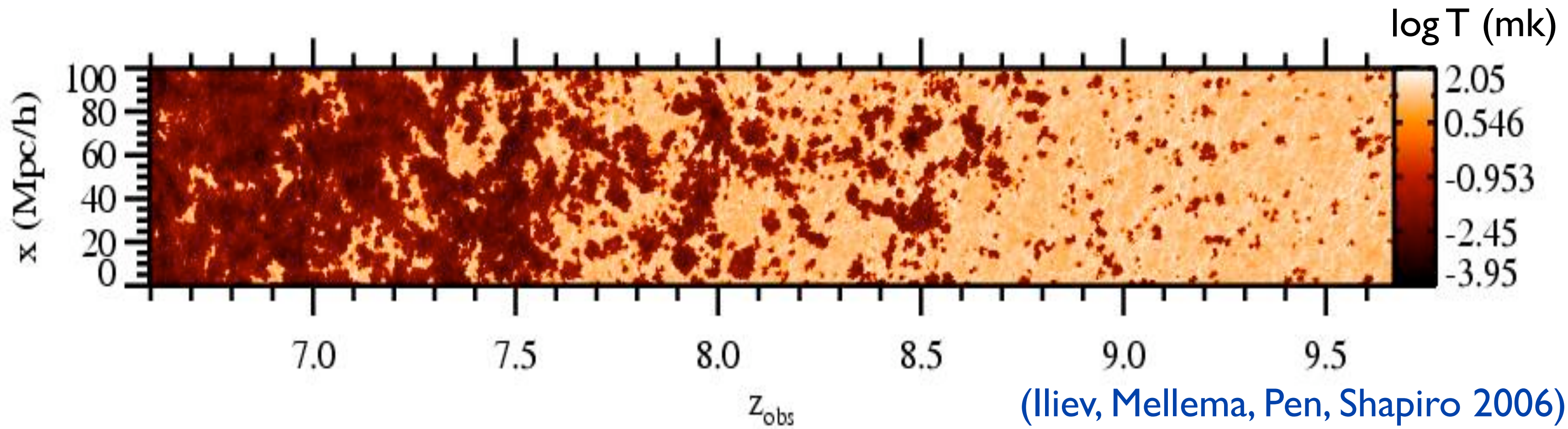
Observing 21cm

- Astrophysical -- probing the EoR:
  - at z ~ 8.5, wavelength ~ 2m, 150 MHz (...unexplored, RFI severe)
  - Signal: dT ~ 20 mK
  - Diffuse foregrounds: Galactic synchrotron $\sim \nu^{-2.6} \sim (1+z)^{2.6}$
    T ~ 200 K, dT ~ 2 K, but spectrally smooth
- Precision cosmology -- measuring BAO:
  - 0.5 < z <3, 350 - 900 MHz (...RFI an issue)
  - Signal: dT ~ 30-300 microK
  - Diffuse foregrounds: Galactic synchrotron $\sim \nu^{-2.6} \sim (1+z)^{2.6}$
    T ~ 3 K, dT ~ 30 mK, but spectrally smooth

Probing the Dark Ages

with neutral hydrogen 21cm emission
at z~8.5 with GMRT

Probing Reionization with 21 cm



(Iliev, Mellema, Pen, Shapiro 2006)

- Constraints from WMAP & SDSS quasar absorption lines:
  - 6 < z_reion < 11.
- Neutral hydrogen 21cm line: most direct probe of reionization
  - Visible through the reionization process
  - Brightness Temperature:

$$\Delta T = 22\ \chi_{\rm HI}(1+\delta_b)\left(\frac{1+z}{10}\right)^{0.5}\left(1-\frac{T_{cmb}}{T_s}\right)\ \mathrm{mK}$$

- At z=8.5, redshifted to 2m, 150MHz; Bubbles ~20 Mpc, 20’, 1MHz
- First PS Experiments: 21CMA, LOFAR, MWA, PAPER, GMRT

GMRT - Giant Meterwave Radio Telescope

30 antenna; 45-m diameter dish; 1km central core
collecting area ~4e4 m^2, 140-156 MHz, 8 < z < 9

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

GMRT forecast

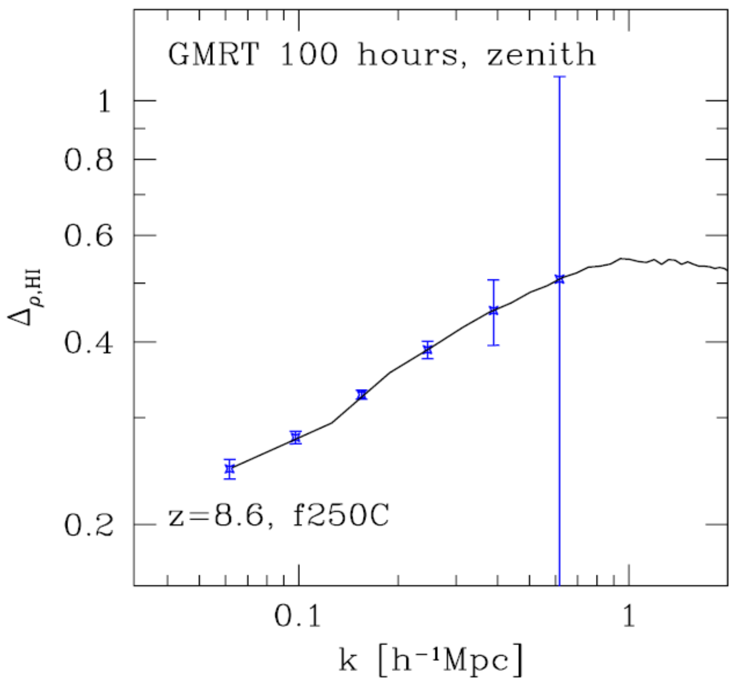
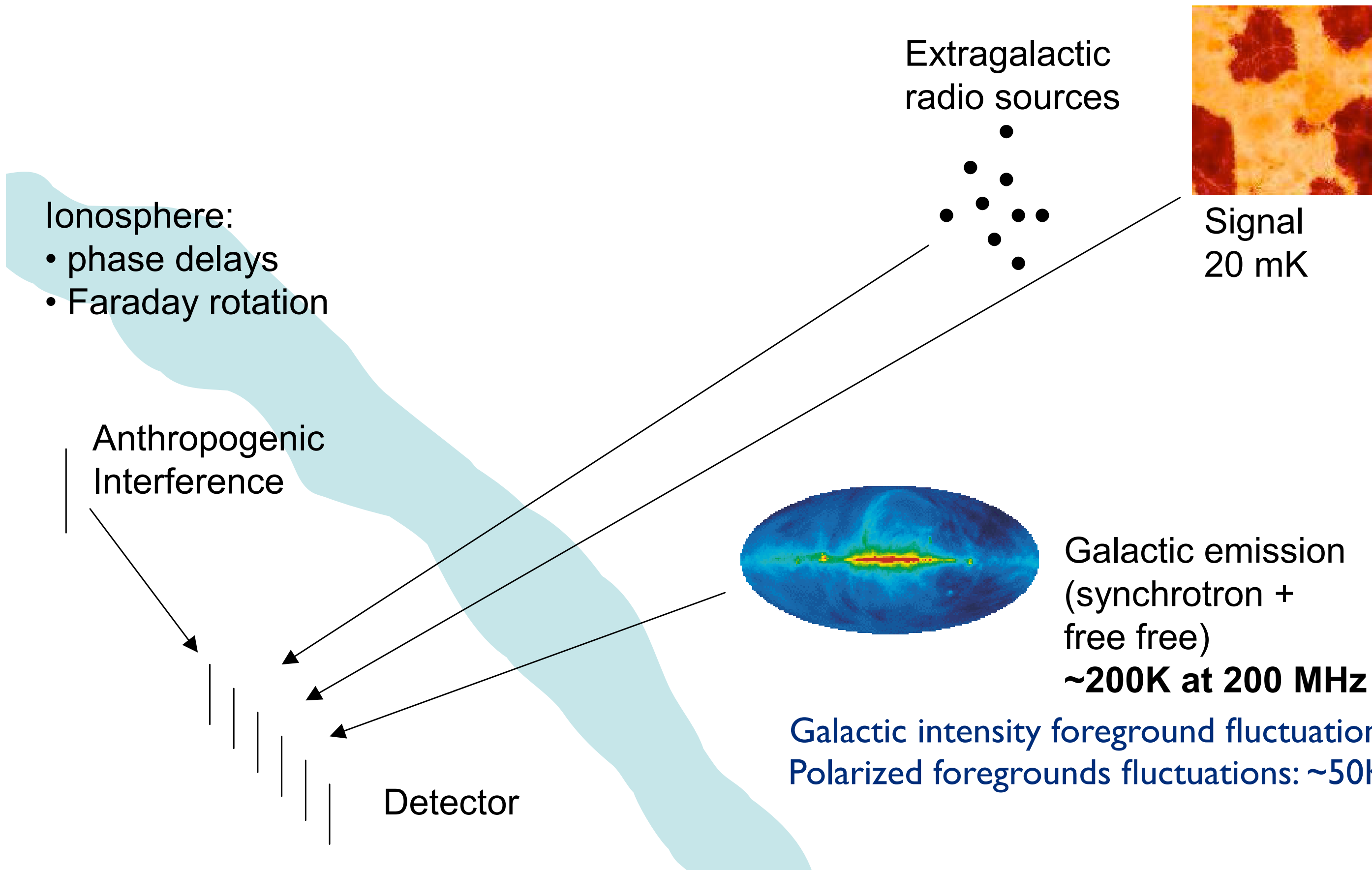


Figure 9. Observability of the 21-cm signal: the 3D power spectrum of the neutral hydrogen density, $\Delta_{\rho,HI}$, at redshift $z = 8.59$ ($\overline{T_b} = 16.3$ mK) with the forecast error bars for 100 hours observation with GMRT vs. wavenumber k. We assumed 15 MHz observing bandwidth (the full instantaneous bandwidth of GMRT), $T_{\rm sys} = 480$ K and assuming $T_S \gg T_{\rm CMB}$. The array configuration is assumed pointed to the zenith, but the sensitivity is only weakly dependent on the pointing.

- Measure HI P(k) on sub-degree scales at z ~ 8
- 20-sigma on the power spectrum with 100 hours

Iliev et al. 2008

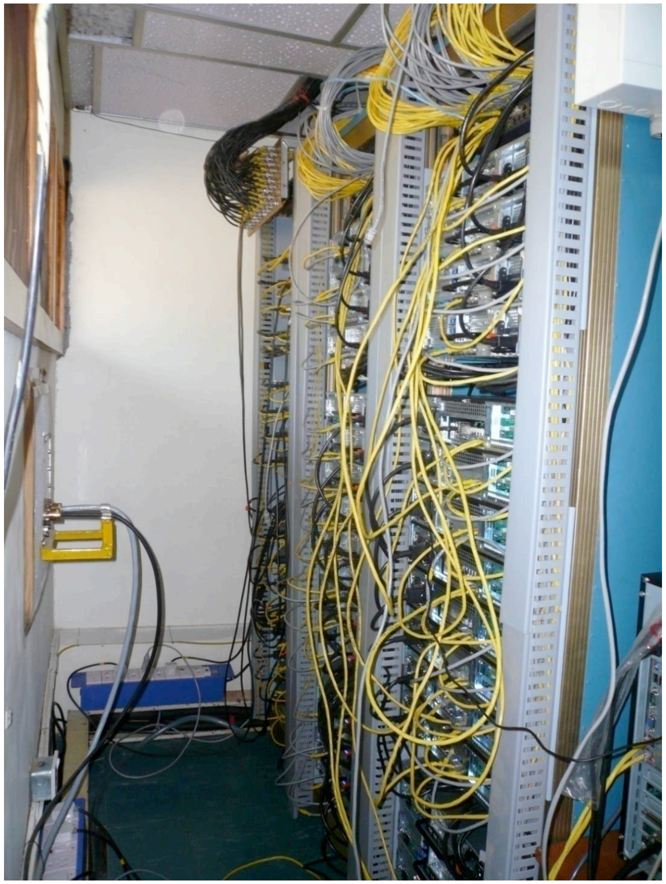
Observational challenges



Galactic intensity foreground fluctuations: ~1K at 150 MHz
Polarized foregrounds fluctuations: ~50K at 150 MHz?

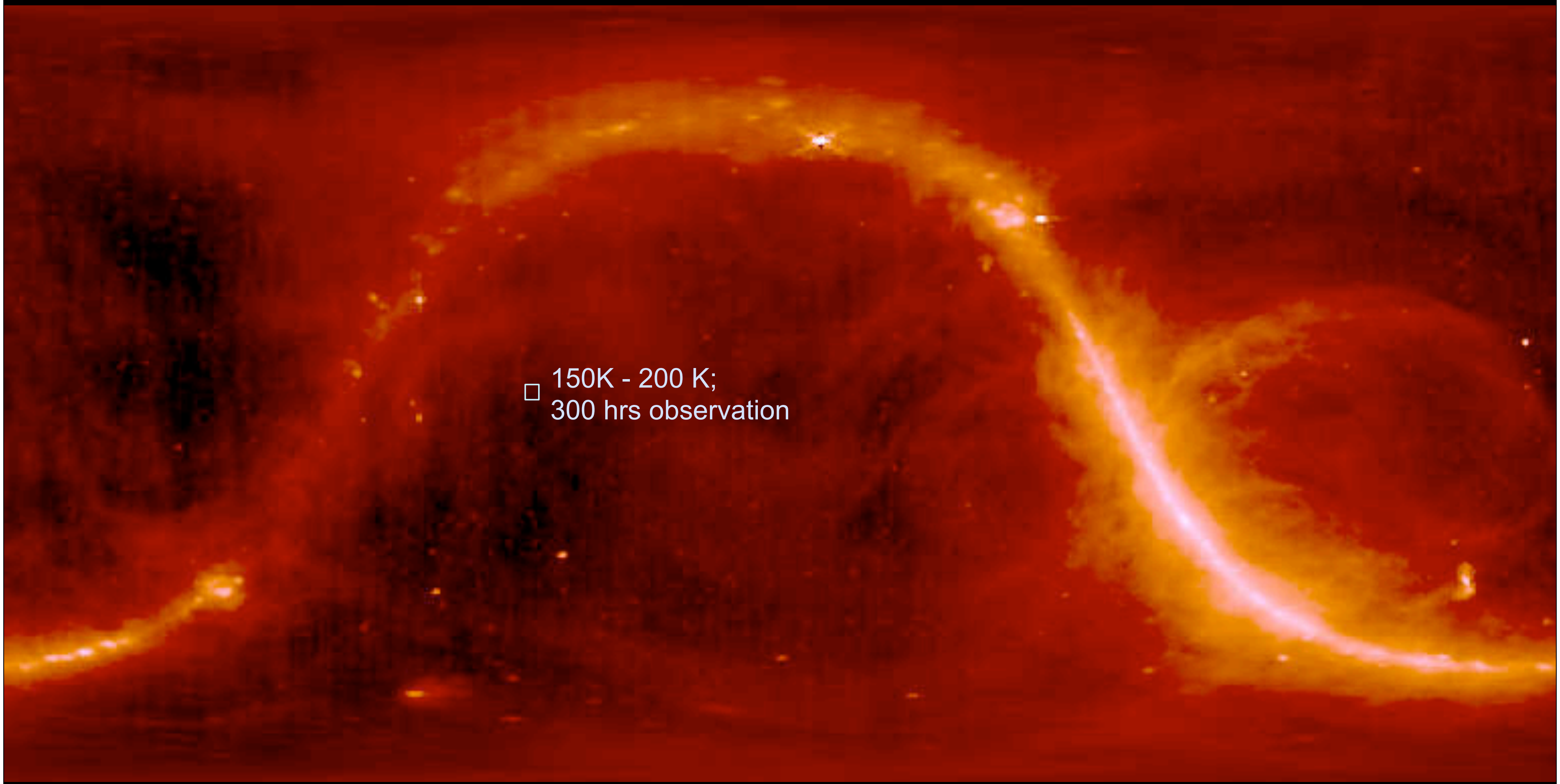
Courtesy of Chris Hirata

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

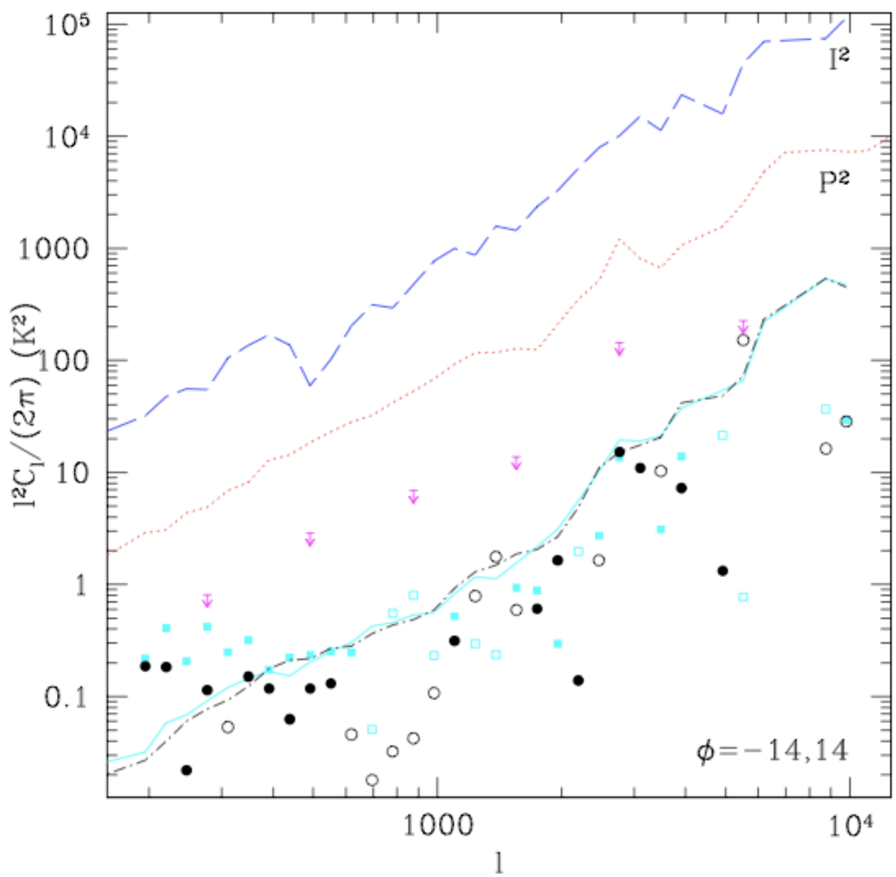
Foregrounds



Haslam 408 MHz

Foregrounds: much brighter than signal, but no spectral structure

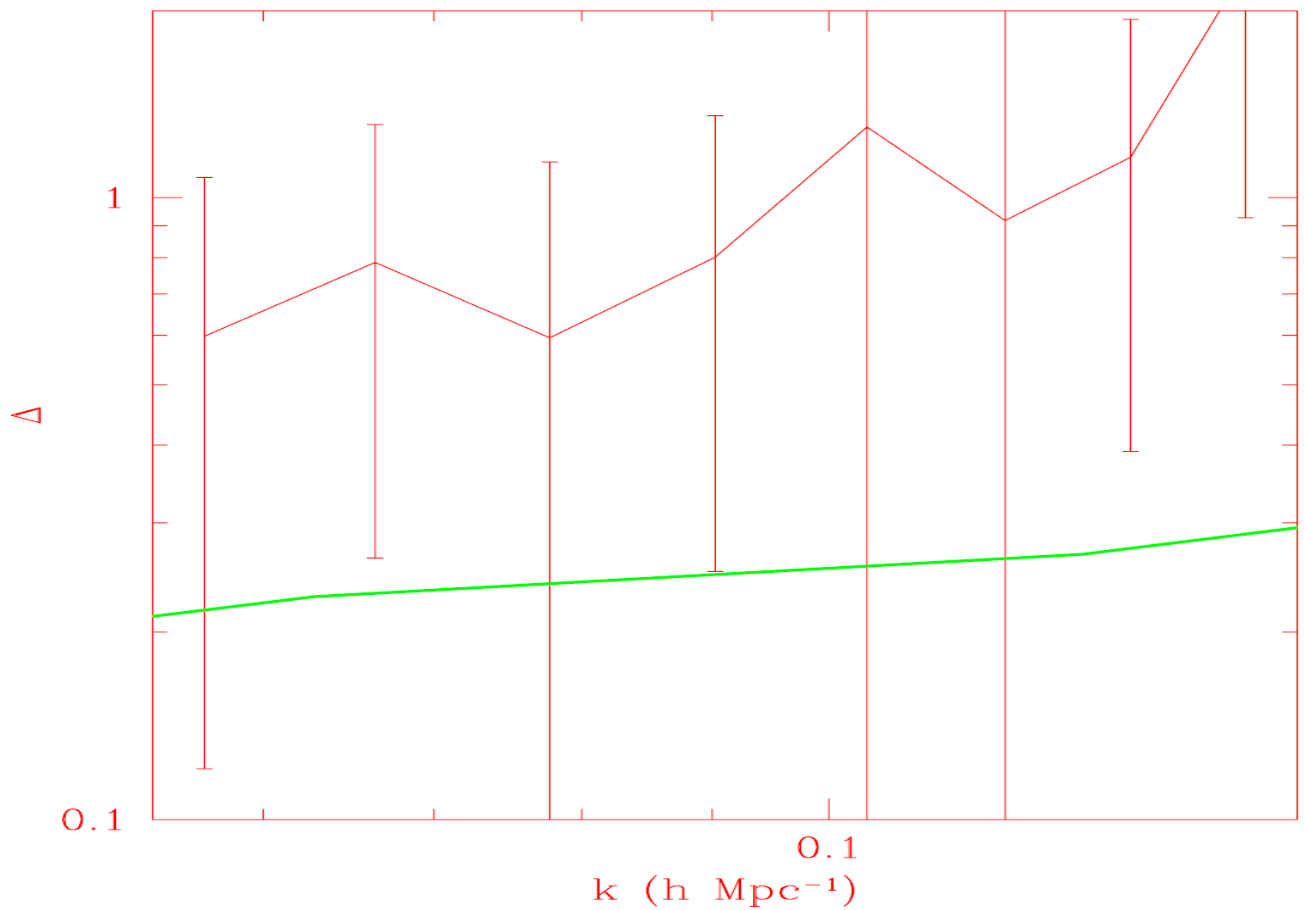
Upper limits on the Polarized Foregrounds from GMRT



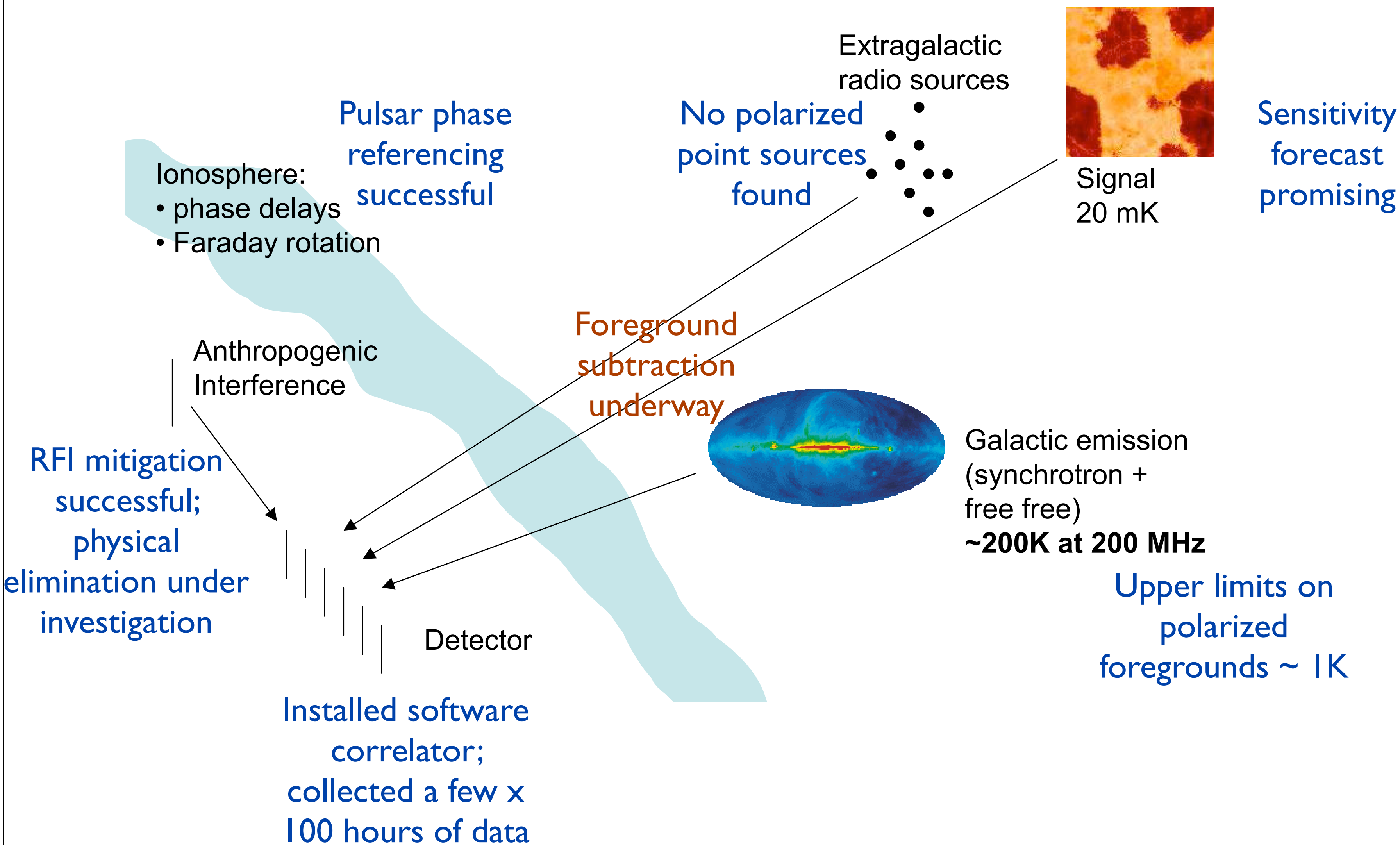
Pen, Chang, Hirata et al. 2008, arXiv: 0807.1056

- Polarized foregrounds at 150 MHz not known, expected to be large, potential worry for systematics
- We find no polarized point sources (except for pulsar) in our 3 deg field
- Upper limit on the polarized foregrounds is ~ 1 K
- Depolarization mechanism: beam/ depth depolarization;
- Good news for EoR, but P to I leakage correction is still important

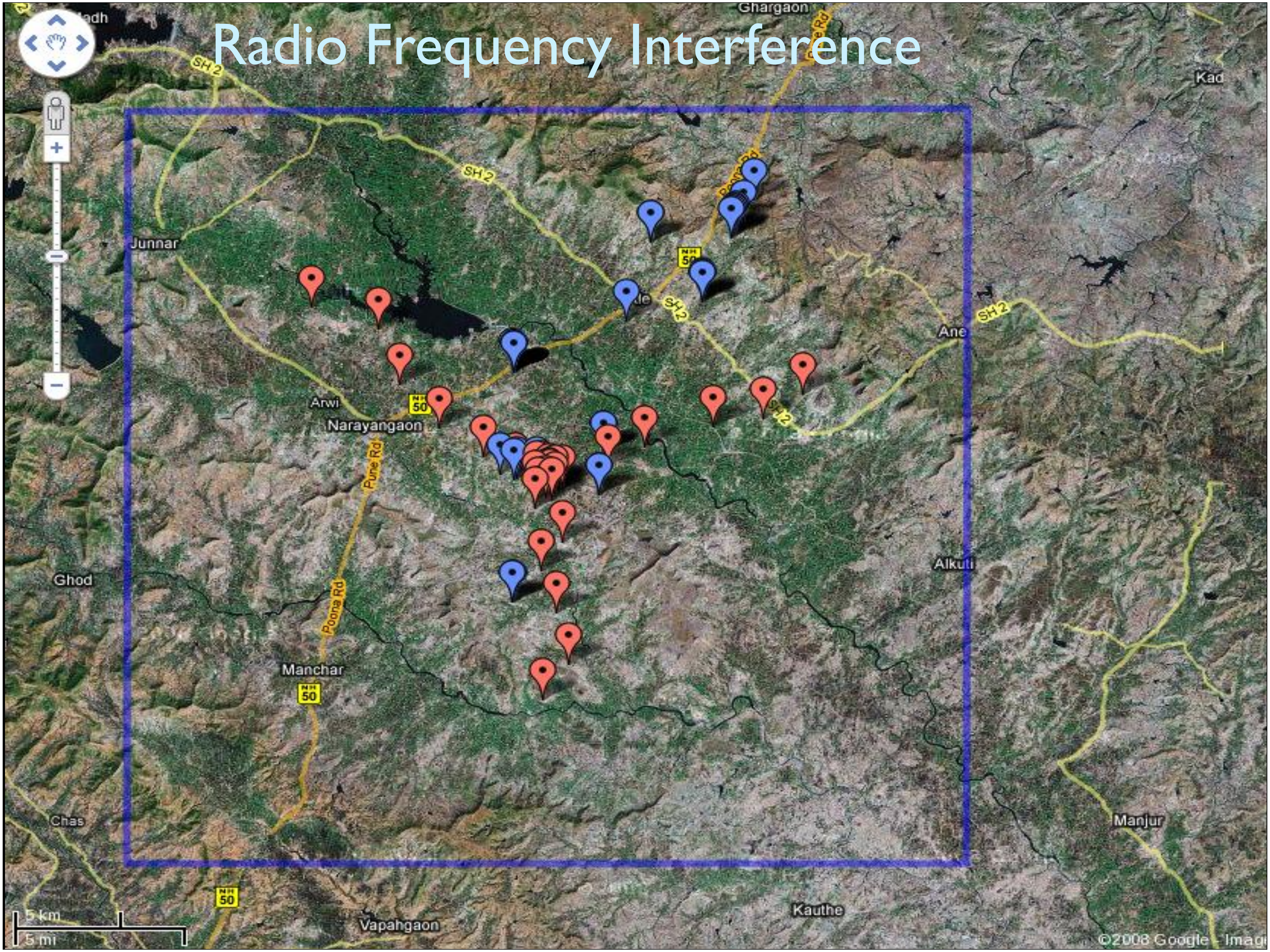
Preliminary Power Spectrum



GMRT Current Status



Radio Frequency Interference



Outlook

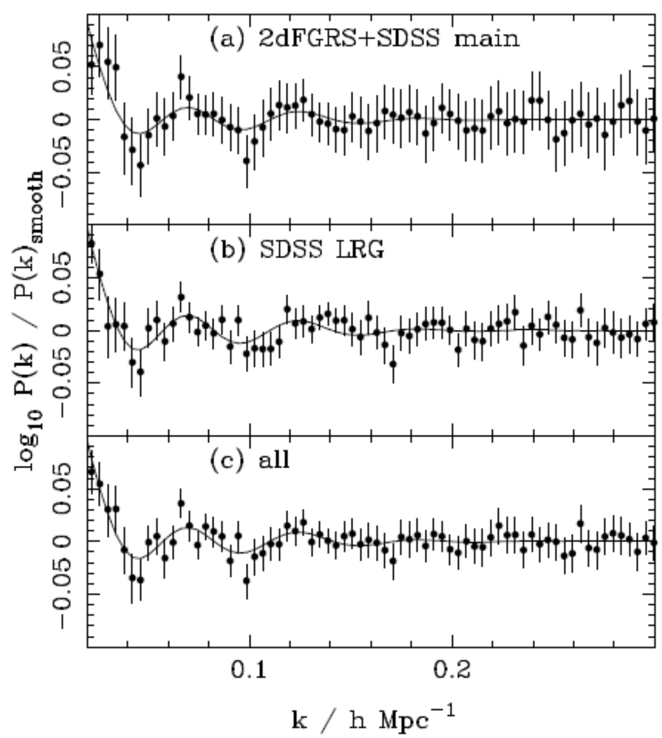
- Existing constraints: optical depth from WMAP (Pol'n), SDSS Quasars
- Theoretical Progress: simulations indicate power on large scales (~20')
- Current: large data set from GRMT, data analysis in progress. RFI mitigation and pulsar calibration successful; Set upper limits to polarized foregrounds to be ~ 1 K; Foreground subtraction main challenge.
- Outlook: several experiments to tap the next cosmic horizon: GMRT, LOFAR, MWA, PAPER, PAST/21CMA...
- Exciting new window on universe. Open field for theory and experiment.

21cm Intensity Mapping of Baryon Acoustic Oscillations

as a probe of dark energy at $0 < z < 3$

Baryon Acoustic Oscillations (BAO) – Dark Energy Probe

- CMB acoustic oscillations: imprinted standard ruler, 109 h^{-1} Mpc comoving.
- Present in current matter distribution
- Blake and Glazebrook, Seo & Eisenstein et al: standard ruler measures H(z) and D(z).
- Measures dark energy equation of state w, w'



Percival et al. 2008

BAO - Great Tool for Precision Cosmology

WMAP 5-year Cosmological Interpretation 15

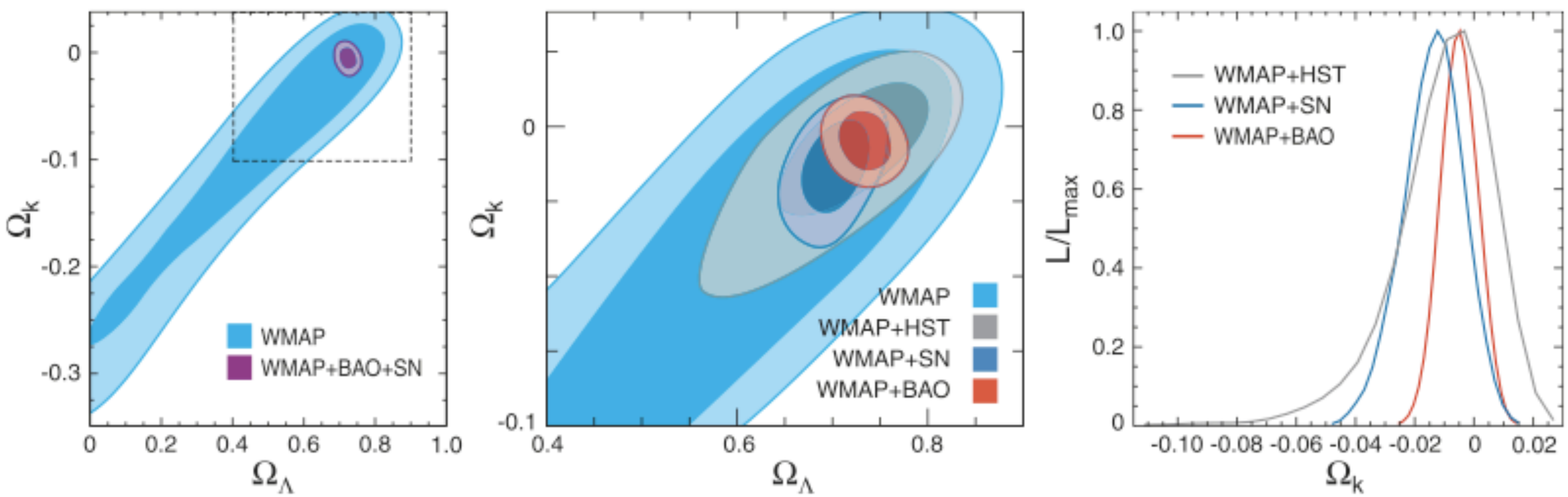


FIG. 6.— Joint two-dimensional marginalized constraint on the vacuum energy density, Ω_Λ, and the spatial curvature parameter, Ω_k (§ 3.4.3). The contours show the 68% and 95% CL. (*Left*) The WMAP-only constraint (light blue) compared with WMAP+BAO+SN (purple). Note that we have a prior on Ω_Λ, $\Omega_\Lambda > 0$. This figure shows how powerful the extra distance information is for constraining Ω_k. (*Middle*) A blow-up of the region within the dashed lines in the left panel, showing WMAP-only (light blue), WMAP+HST (gray), WMAP+SN (dark blue), and WMAP+BAO (red). The BAO provides the most stringent constraint on Ω_k. (*Right*) One-dimensional marginalized constraint on Ω_k from WMAP+HST, WMAP+SN, and WMAP+BAO. We find the best limit, $-0.0181 < \Omega_k < 0.0071$ (95% CL), from WMAP+BAO+SN, which is essentially the same as WMAP+BAO. See Fig. 12 for the constraints on Ω_k when dark energy is dynamical, i.e., $w \neq -1$, with time-independent w.

Komatsu et al. 2008

BAO- Mapping Large-scale Structure

- Current and proposed projects: measure individual galaxy redshifts - BOSS, AAO, HETDEX, WFMOS (optical spectra), KAOS, DES, LSST (photo-z), SKA (21cm), JDEM/ ADEPT (space), etc.

- Instead, measure collective large-scale structure traced by HI, without resolving individual objects - Hundreds of galaxies in each BAO pixel : Intensity Mapping (Chang et al. 2008; Wyithe & Loeb 2008).

- $\Delta T = 300\,(1+\delta)\left(\frac{\Omega_{HI}}{10^{-3}}\right)\left(\frac{h}{0.73}\right)\left(\frac{\Omega_m + (1+z)^{-3}\Omega_\Lambda}{0.35}\right)^{-0.5}\left(\frac{1+z}{1.9}\right)^{0.5}\mu\mathrm{K}$

HI Intensity Mapping (IM)

- Similar to CMB; large survey area, low surface brightness, but in 3D
- At $0.5 < z < 3$, 350 - 900 MHz:
  - HI signal: 30-300 microK
  - Diffuse foregrounds: T~3K, dT~30 mK (foreground removal a challenge!)
- IM allows access to much larger distance with existing technology; economical
- CHIME: Canadian Hydrogen Imaging Experiment. Radio Cylinder Telescope; 10,000 m^2, maps out BAO at $0.8<z<2.5$
  - Collaboration: M. Halpern, K. Sigurdson (UBC), M. Dobbs(McGill), U. Pen, J. R. Bond, T. Chang(CITA), J. Peterson(CMU) + others

HI BAO Experiment Prospects

- CHIME (Canadian Hydrogen Intensity Mapping Experiment); Cosmic Variance limited Hubble Survey

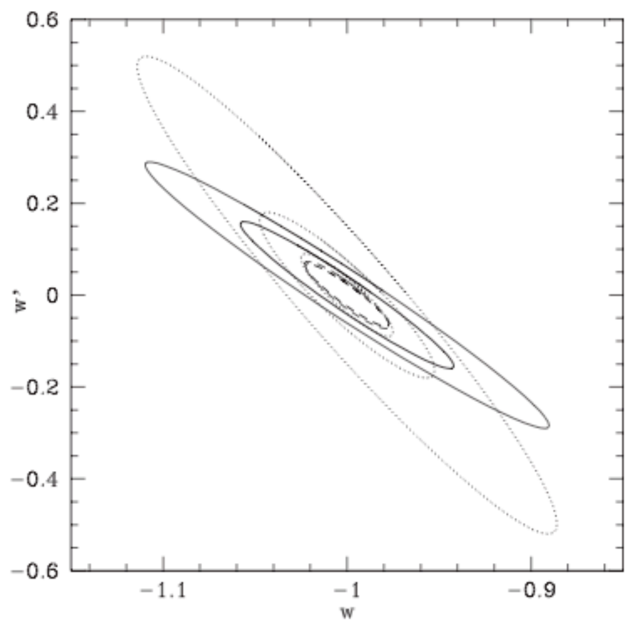


FIG. 4. The $1-\sigma$ contour for IM combined with Planck (inner thick solid for baseline model, outer thin solid for worst case), the Dark Energy Task Force stage I projects with Planck (outer dotted), the stage I and III projects with Planck (intermediate dotted), the stage I, III, and IV projects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

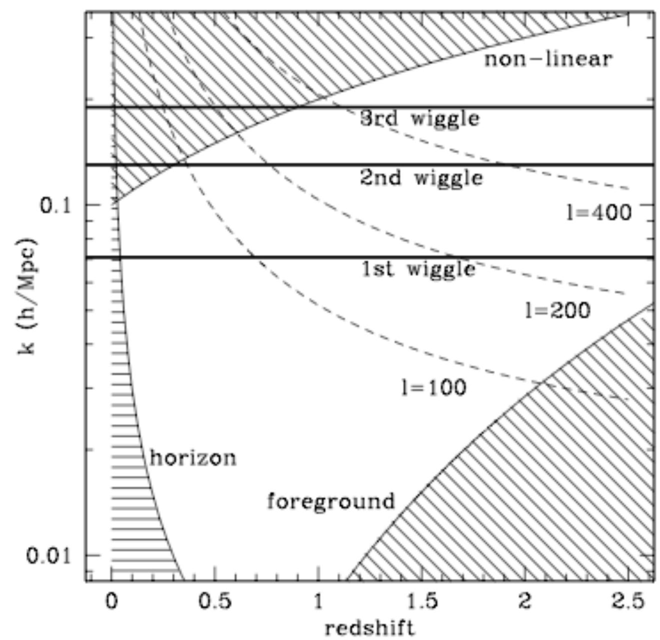


FIG. 3: The observable parameter space in redshift and in scale (k) for BAO. The shaded regions are observationally inaccessible (see text). The horizontal lines indicate the scale of the first three BAO wiggles, and the dashed lines show contours of constant spherical harmonic order ℓ.

Chang, Pen, Peterson, McDonald 2008


CMU cylinder under construction

CMU Radio Cylinder Prototype

- Testbed for CHIME
- Two 25mx10m cylinders
- J. Peterson, K. Bandura, U. Pen, U. Seljak, K. Sidgurdson, T. Chang, G. Vujanovic
- Technical challenges:
  - Foreground subtraction
  - Radio Frequency Interference

21cm universe at low-z

- Emitted by neutral hydrogen, ~ 2% of baryons
- Thought to be dominated by DLAs (damped Lyman alpha systems)
- Current highest-redshift detected HI emission: z~0.24
- Nature, mass, space density not known, but not important for IM
- Important issues:
  - Is HI really a good tracer of the Large-scale Structure?
  - How much HI there is at z ~1?

How well does HI trace Large-scale Structure?

Cross-correlating HIPASS & 6dFGS Large-scale Structure at z ~ 0.04

HIPASS HI Survey

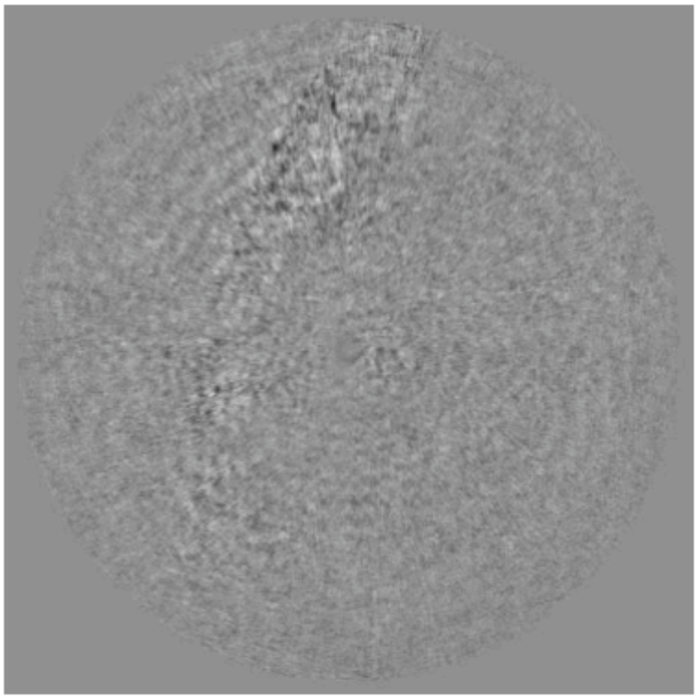


Figure 1. The HIPASS data cube $R < 127h^{-1}$ Mpc, projected in a cartesian coordinate system towards the south pole.

6dF Optical Galaxy Survey

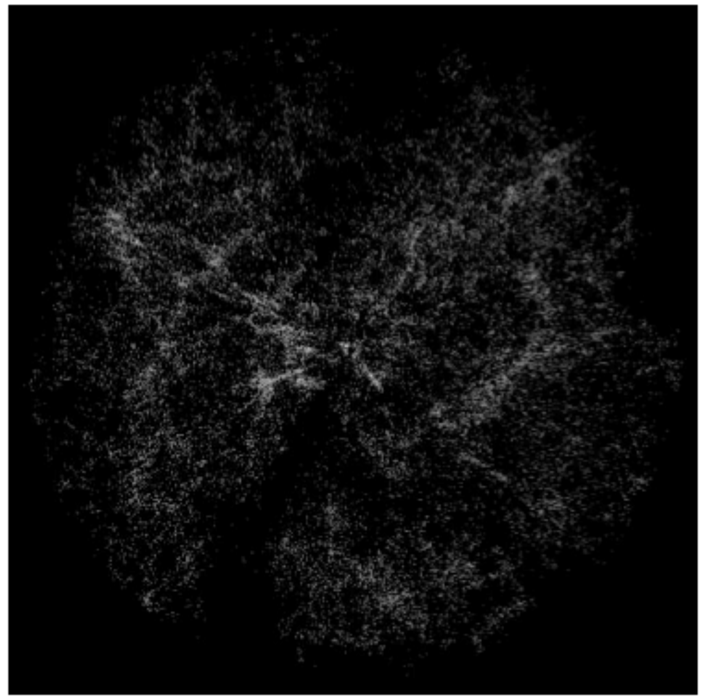


Figure 2. The 6dFGS catalog for $R < 127h^{-1}$ Mpc, also projected towards the south pole. The missing wedges are the galactic plane.

Pen et al. 2008

HI & Optical cross-correlation

Pen et al. 2008

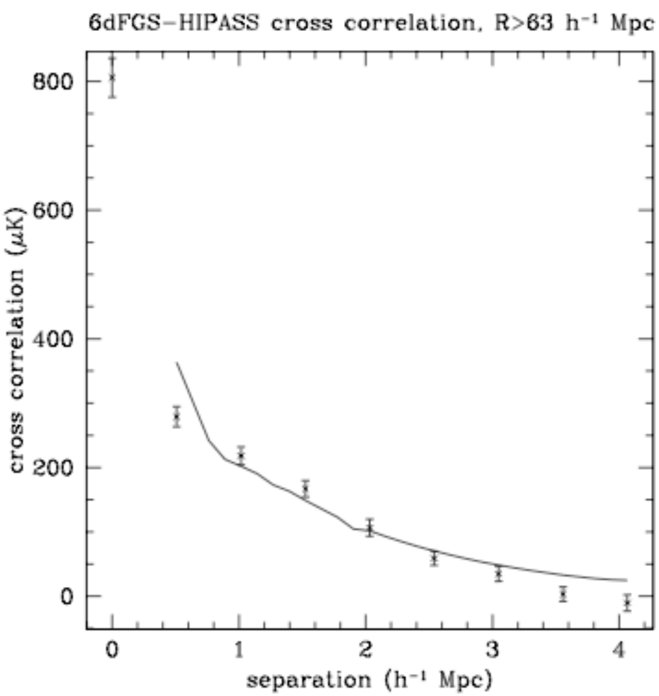


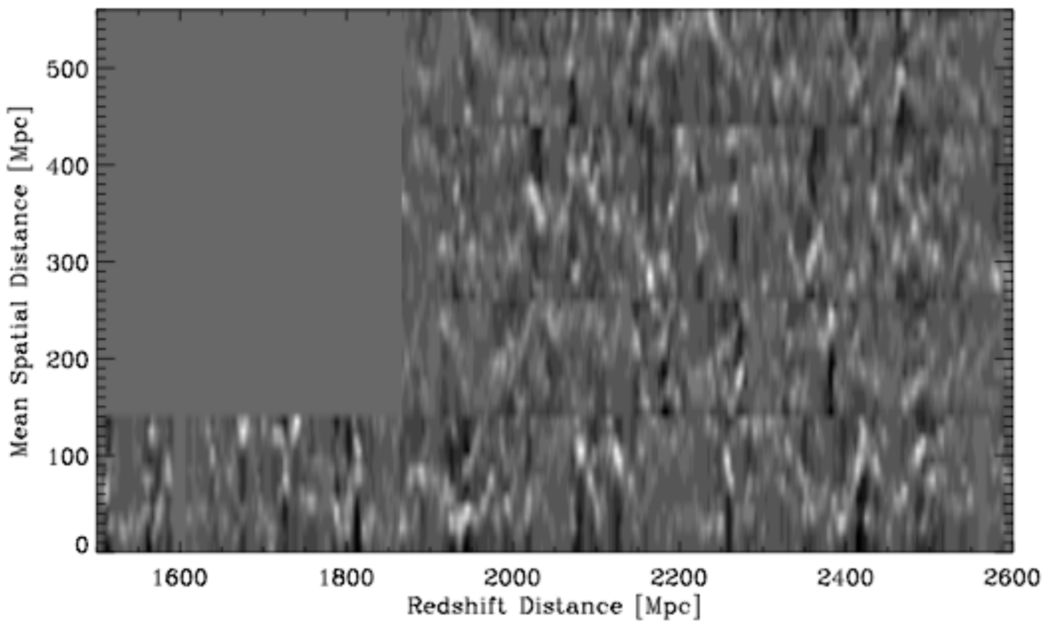
Figure 4. The correlation function of hydrogen 21 cm emission when stacked around optically selected galaxies from the 6dFGS. The solid line is a standard clustering model. The point at zero separation is the mean flux from 6dF galaxies, while points at larger separations measure the associated surrounding large scale structure. HI emission from the 6dF galaxies could spill up to 1 h^{-1} Mpc into neighboring bins at the $\sim 20\mu$K level.

- Show good correlation between Hydrogen and Optical galaxy surveys
- Neutral hydrogen traces Large-scale Structure well

What is Ω_{HI} at z=1?

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

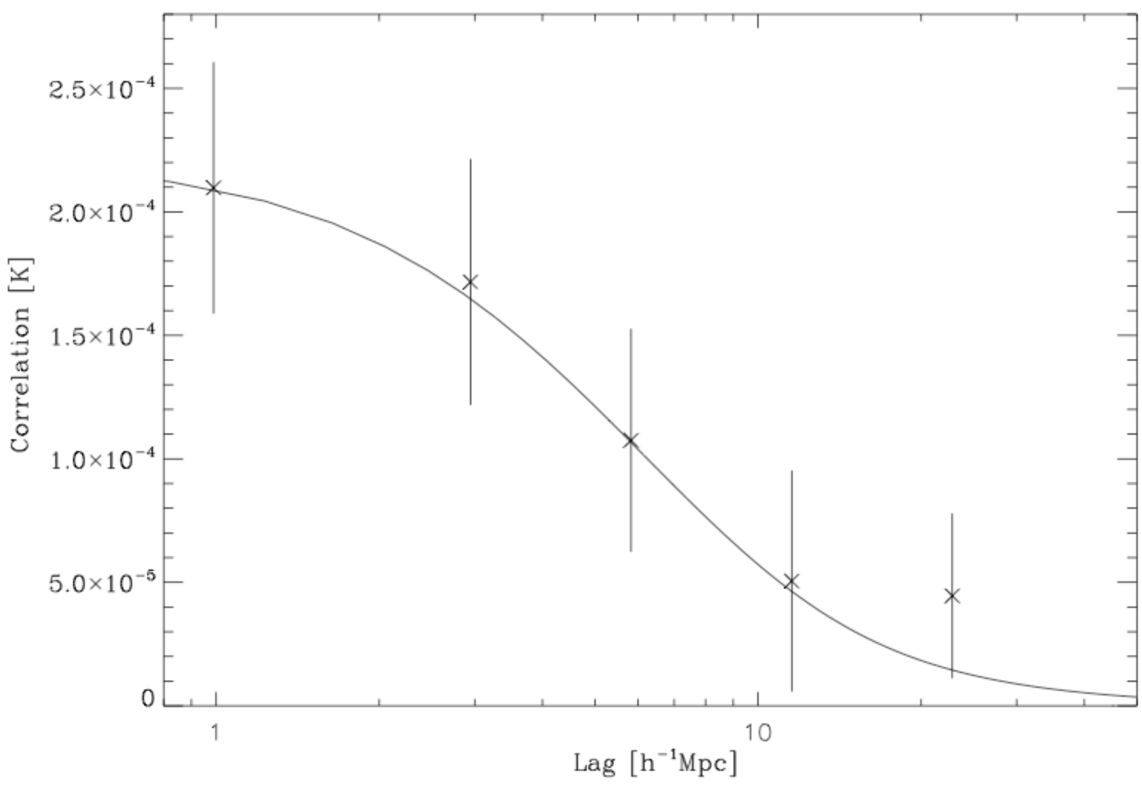
- Measure HI & optical cross-correlation on 10 Mpc (spatial) x 2 Mpc (radial) scales
  - Test of Intensity Mapping idea



Deep2 density field

Chang, Pen, Peterson, Bandura, submitted to Nature

HI & Optical cross-correlation at z~0.9



- Again shows good correlation between hydrogen and Deep2 optical galaxy surveys
- Moderate hydrogen content at z~1
- Highest-redshift HI detection
- Good news for IM.

Chang, Pen, Peterson, Bandura, submitted to Nature

Outlook

- 21cm line provides a good probe of cosmology
- HI Intensity Mapping: an efficient/economical way of measuring BAO/dark energy
  - Neutral hydrogen traces large-scale structure at low-z
    - HIPASS/6dF cross-correlation shows good correlation
  - Good amount of neutral hydrogen at z ~ 1
    - GBT/DEEP2 cross-correlation: $\Omega_{HI} \sim (7.0 \pm 1.7) \times 10^{-4}$
  - Issues of foregrounds, RFI removal, calibration, etc.
    - CMU radio cylinder prototype underway
- Prospects of measuring BAO with HI: CHIME