21cm cosmology
Ue-Li Pen

T. Chang, UP, J. Peterson, P. McDonald
PRL 100, 091303 (2008)
K. Masui, F. Schmidt, UP, P. McDonald,
PRD 81,062001 (2010)

21cm: HI hyperfine transition

- Hydrogen is the most abundant element in the universe
- 21cm line optically thin over most lines of sight to very high z
- Hyperfine transition when electron and proton spins flip: change in magnetic moment
- $h\,\nu = \alpha^4 m_e c^2 (m_e/m_p)$
- ν=1420.40575 MHz

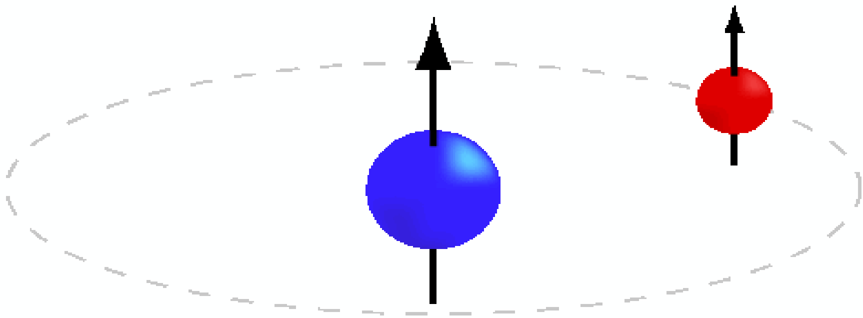
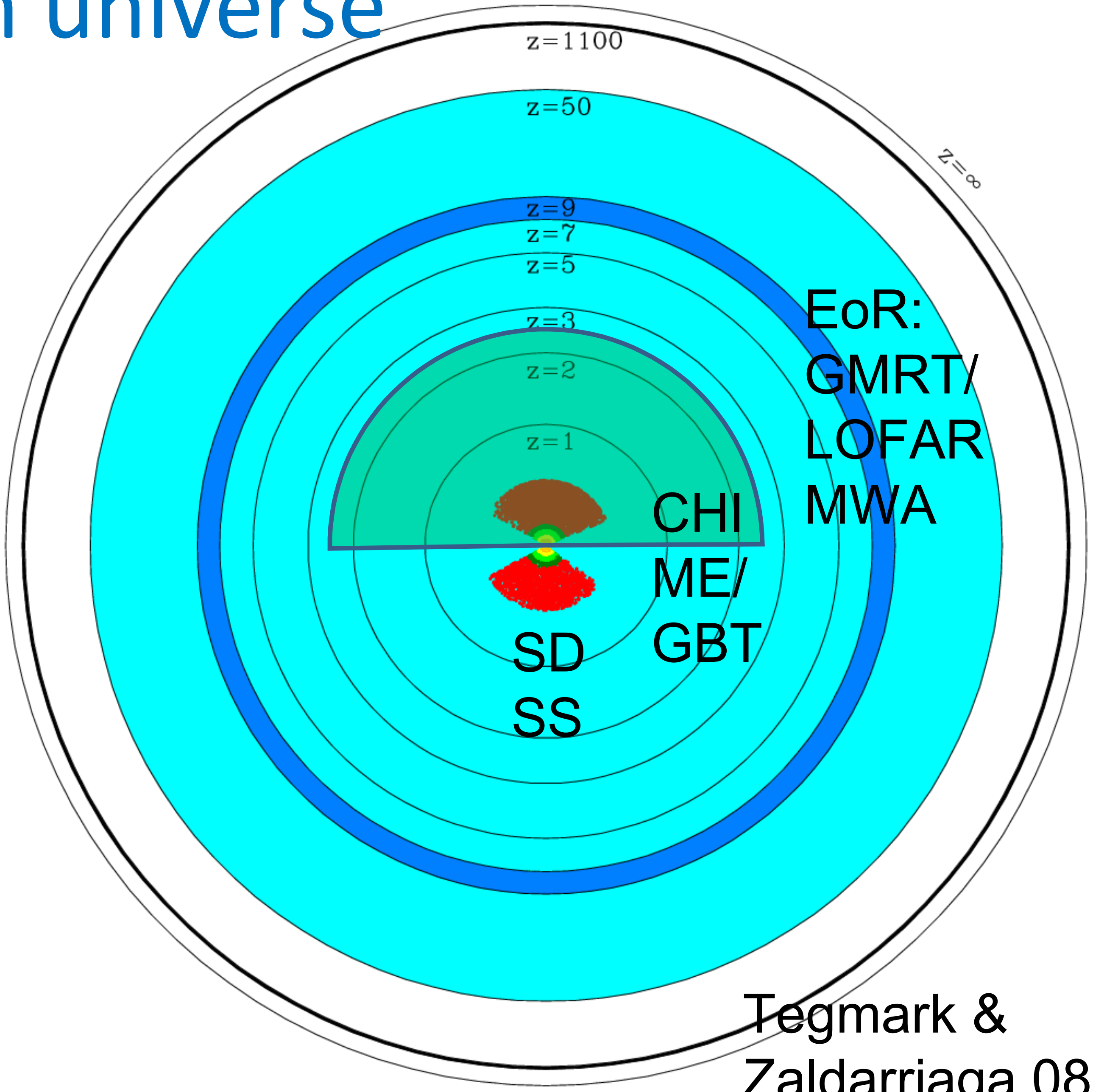


Image courtesy of NRAO/AUI and Chung et al.,

The 21 cm universe

- Cosmological LSS treasure grove (UP04, Loeb&Zaldarriaga 04, Lewis&Challinor 07, etc)
- Up to 10^{18} modes: (Jeans/Hubble)^3
- Physics: Lensing, gravity waves, primordial NG, BAO, AP
- GW to r ~ 10^{-8}
- f_{NL}~ 10^{-4}
- Astrophysics: EoR, galaxy evolution
- Experiments NOW



Tegmark & Zaldarriaga 08

Fundamental Physics

- $0<z<2$: BAO: w-w'
- $z>2$: Large angle lensing: modified gravity
- $z>10$: gravitational waves

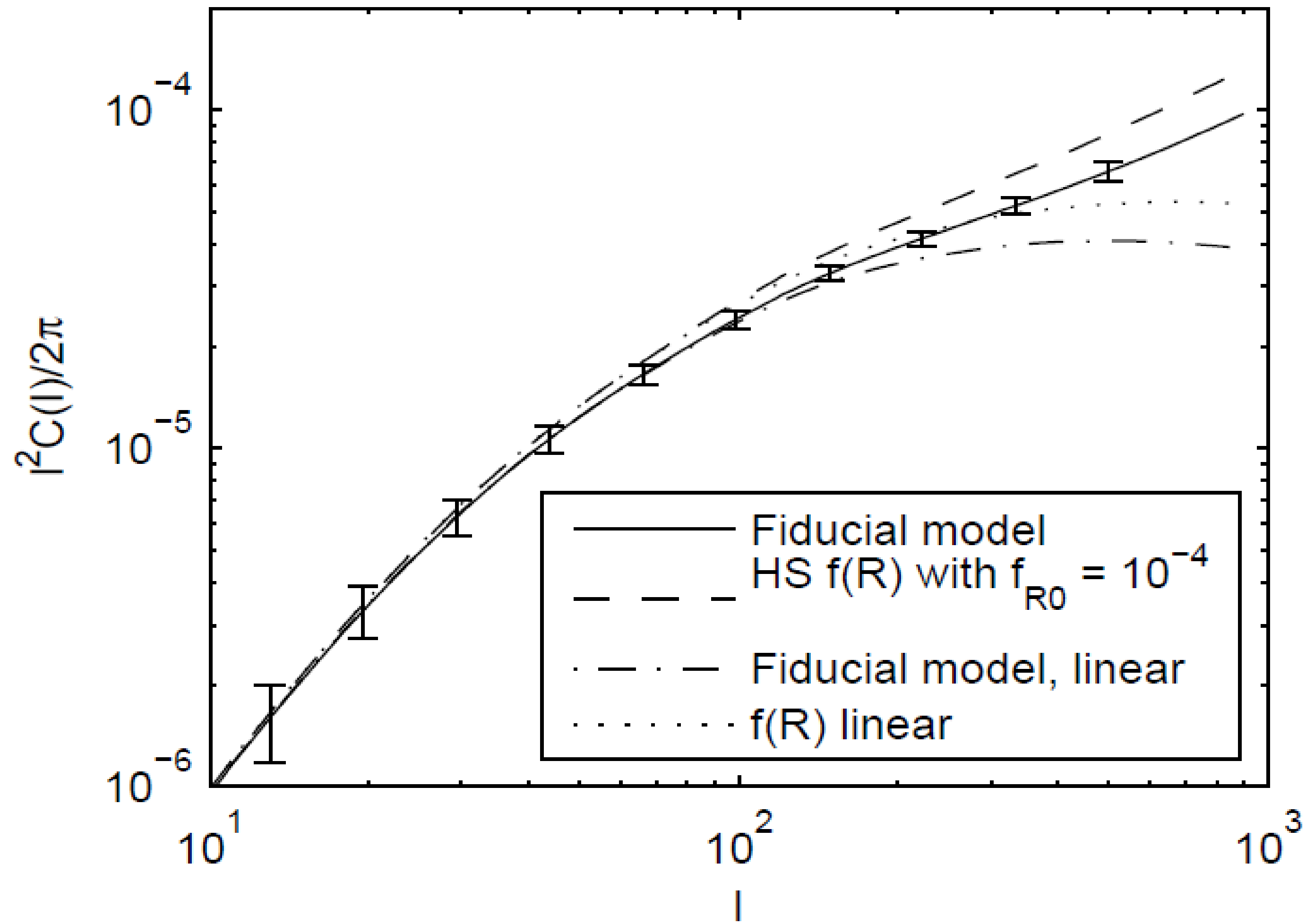


FIG. 1: The Weak lensing convergence power spectra for ΛCDM and the HS $f(R)$ model with $n = 1$ and $f_{R0} = 10^{-4}$. Galaxy distribution function is flat between z = 1 and z = 2.5.

Masui, Schmidt, Pen, McDonald 2010

Gravity Waves

- K. Masui, to appear this week
- Analogous to lensing: shearing of cosmic structure.
- Fossil memory effect: $h \sim 10^{-6}$ (inflation)
- Measure r, n_T at $z \sim 15$
- Requires $1/h^2$ modes
- Separates from lensing: tranverse traceless
- Structures available to $k \sim 10^{-3}$-10^3:horizon to Jeans scale, $\sim 10^{18}$ modes, peaks at $z \sim 15$

Linear gravity wave memory

- GW in initial condition, then redshifts away

$$ds^2 = a(\eta)^2 \left[-d\eta^2 + (h_{ij} + \delta_{ij})dx^i dx^j\right].$$

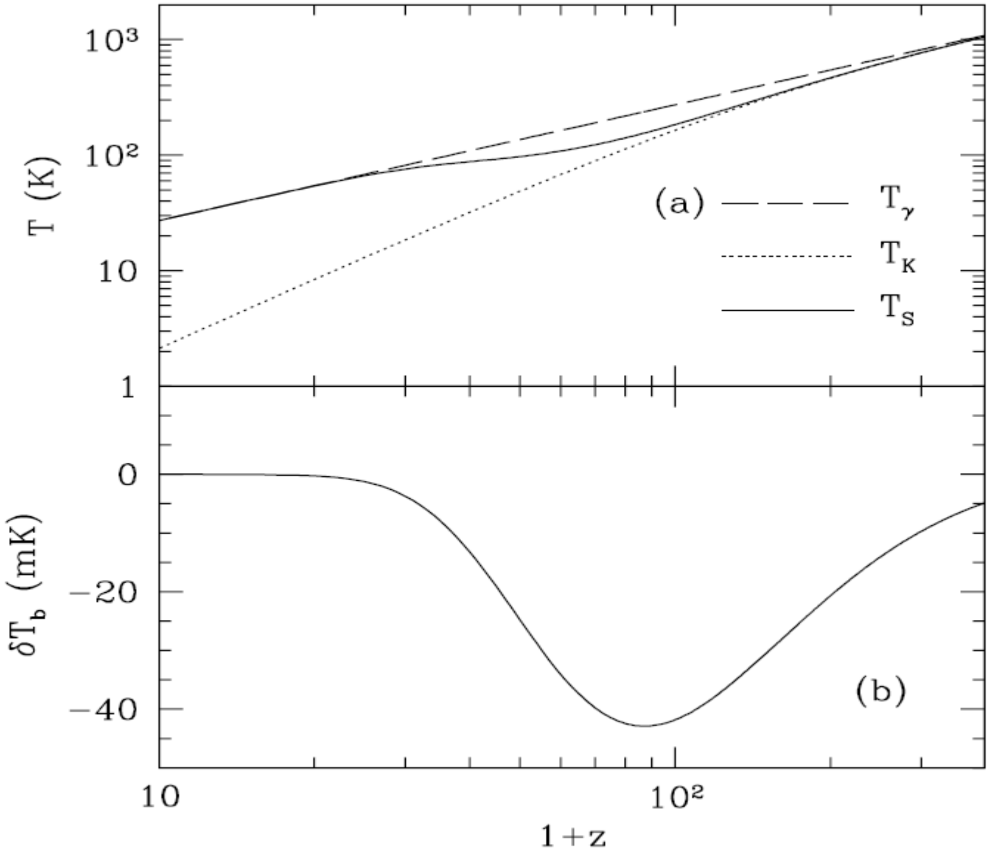
$$\tilde{x}^\alpha = (x^\alpha - \frac{1}{2} h_{\alpha\beta} x^\beta),$$

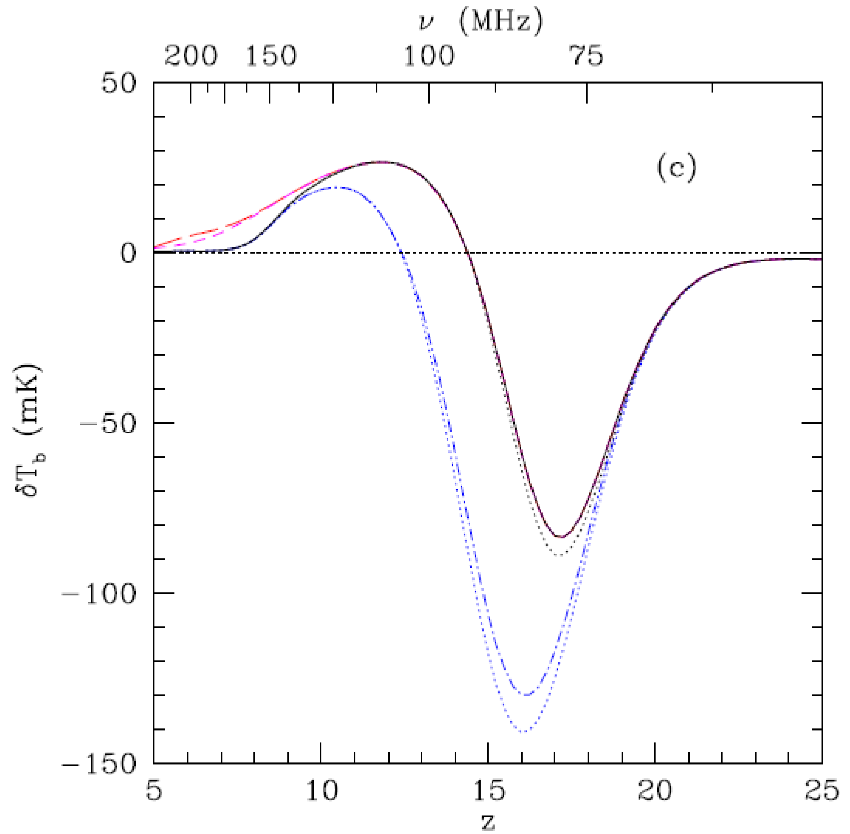
$$P(\overrightarrow{k}) = \tilde{P}(k) - \frac{k_i k_j h_{ij}}{2k} \frac{d\tilde{P}}{dk} + O(\frac{k_T}{k} h_{ij}) + O({h_{ij}}^2)$$

$$h_{ij} \propto \langle \partial_i \delta \partial_j \delta \rangle$$

$$r_{\rm min} = 2.7 \times 10^{-4} \left(\frac{50h/{\rm Mpc}}{k_{\rm max}}\right)^3 \left(\frac{44({\rm Gpc/h})^3}{V}\right)^{1/2}$$

Spin evolution

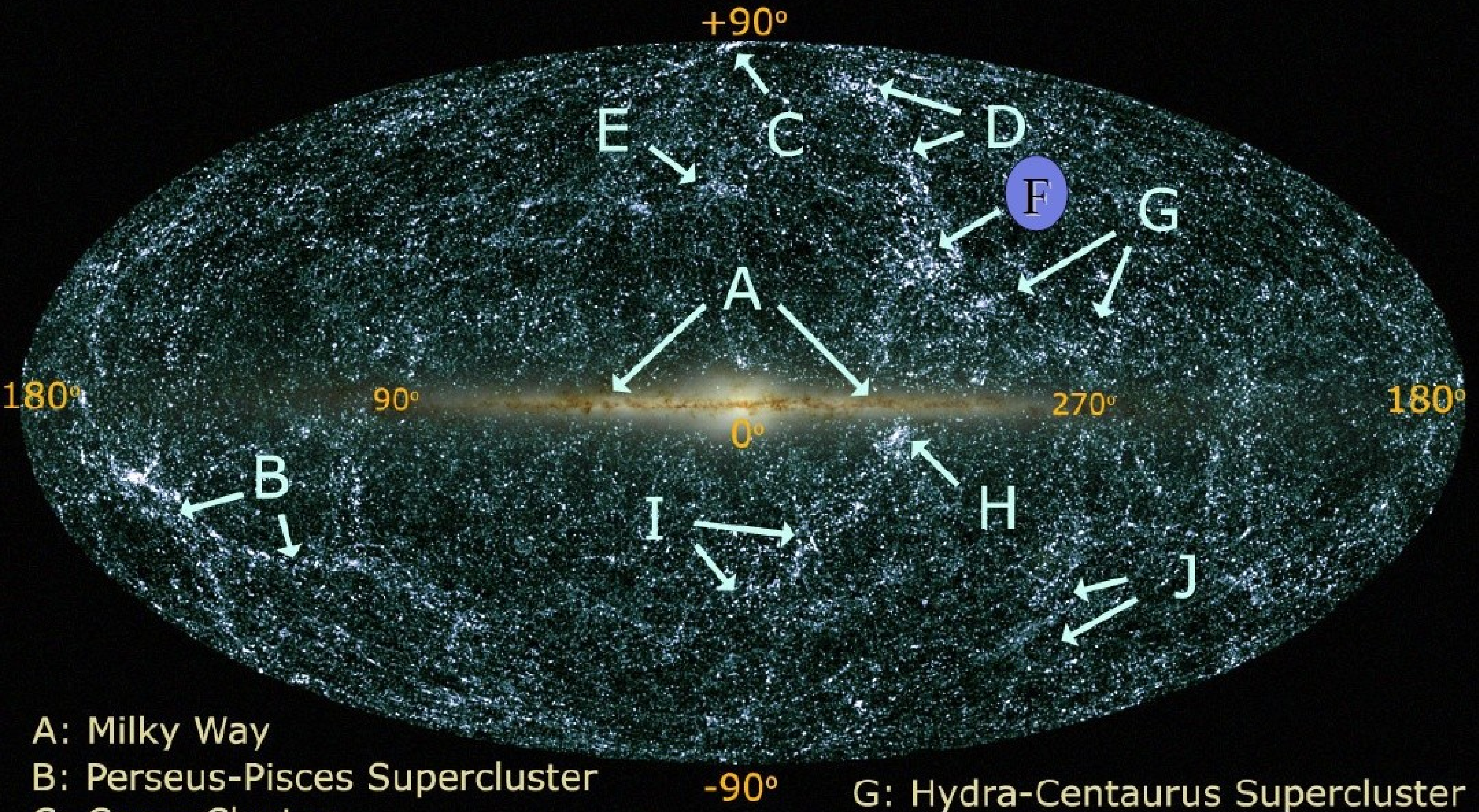




Furlanetto Oh & Briggs, 2006

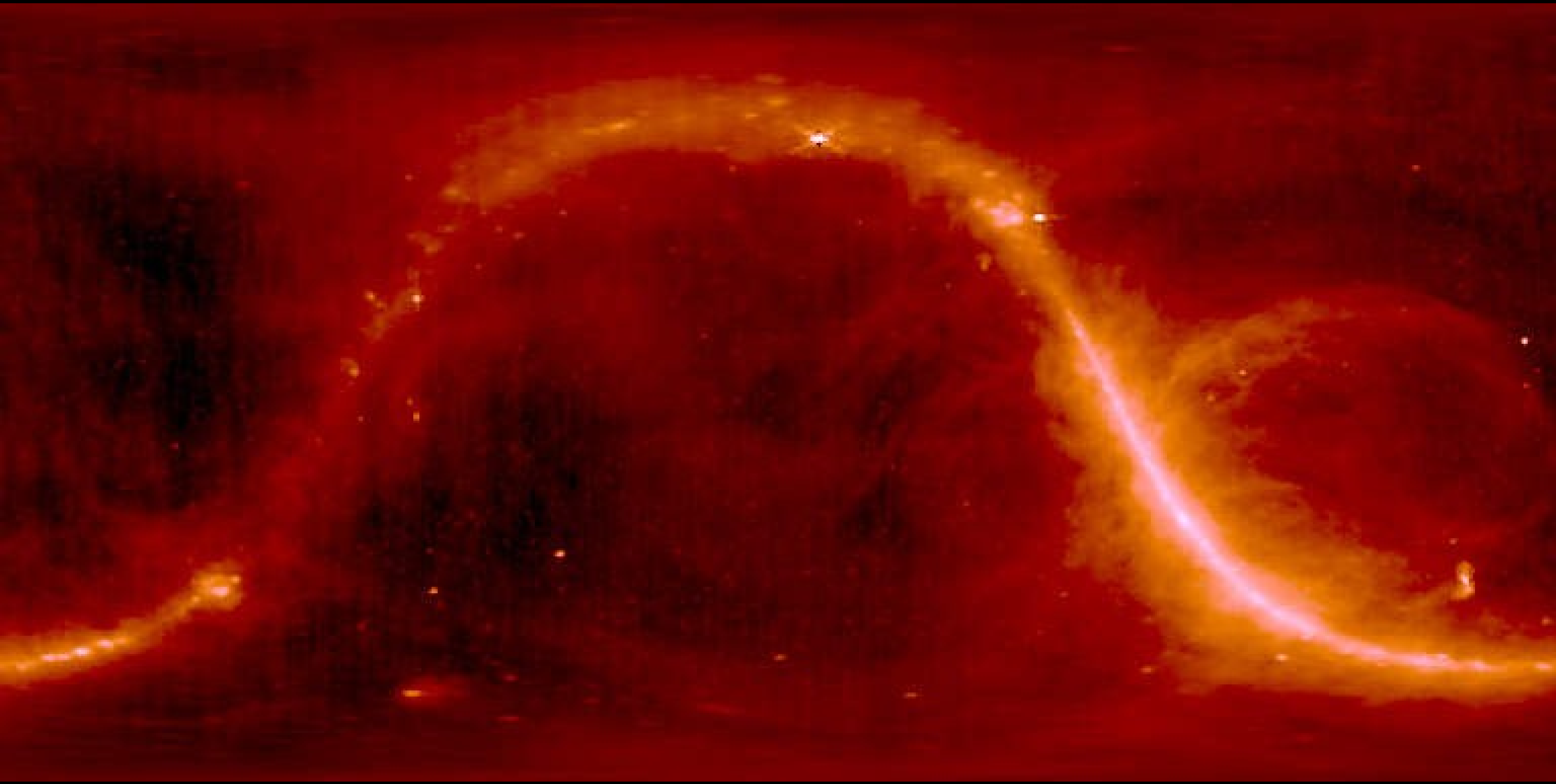
Intensity Mapping

- Stars get fainter with distance: hard to see individually at cosmological distance. Galaxies still visible.
- Galaxies get fainter with distance: hard to see in HI. Large scale structure still visible?
- Large scale structure is LARGE: degree scale. High resolution not needed.
- Modest size, monolithic radio telescopes needed. (CPPM 2008, Wyithe&Loeb 2008)



From: talk by O.

Foreground: Galactic Synchrotron



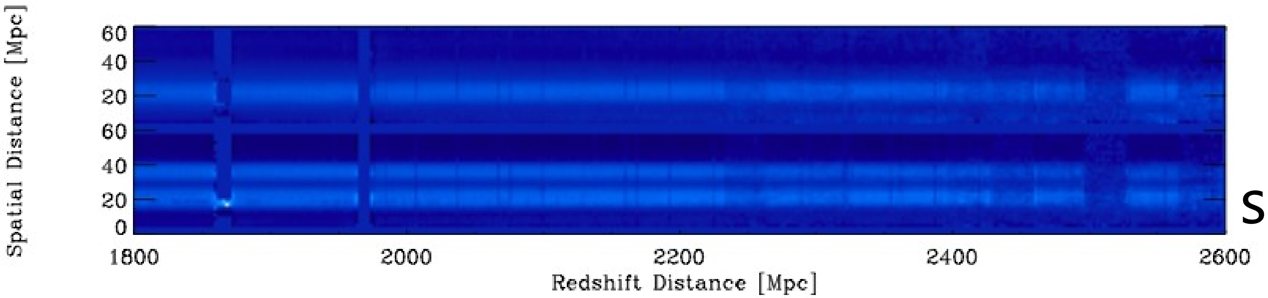
Haslam 408 MHz

Much brighter than signal, but no spectral

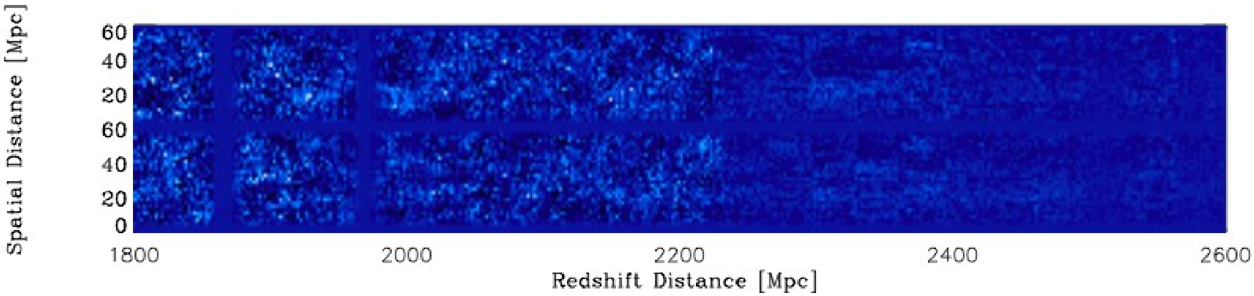
Robert C Byrd Telescope: 100m

HI content at z=0.8

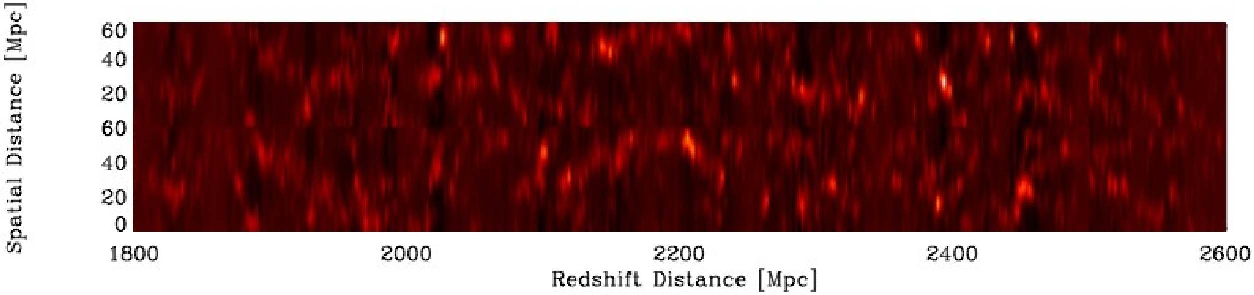
Cross-correlating GBT HI & DEEP2 optical galaxies at z ~ 0.7-1.1



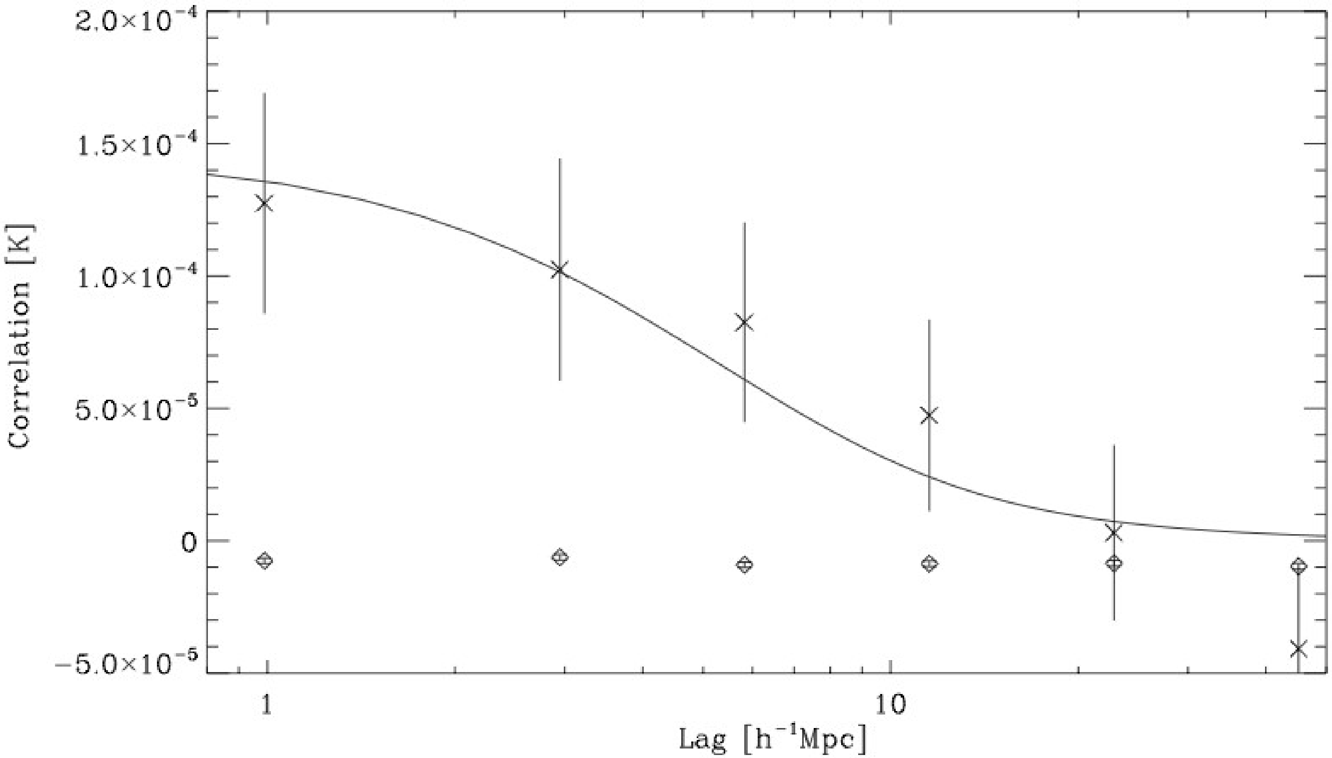
GBT radio continuum sources + HI



GBT HI



DEEP2 density



Chang, Pen, Bandura, Peterson, accepted by Nature

- Measure HI & optical cross-correlation on 9 Mpc (spatial) x 2 Mpc (redshift) comoving scales
- HI brightness temperature on these scales at z=0.8:
- $\Omega_{HI} = (4.5 \pm 1.0) \times 10^{-4}$ ×

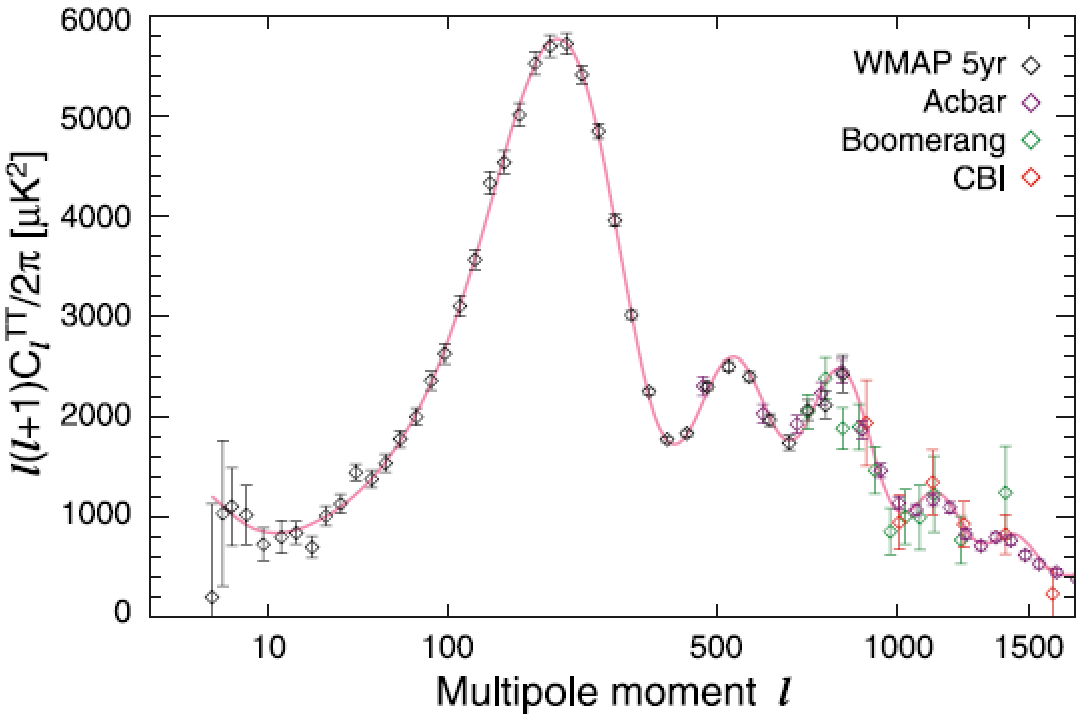
  $T = 127 \pm 29 \mu K$
- Highest-redshift detection of HI in emission at 4-sigma statistical significance.

Initial Intensity Mapping

- Detected collective large scale structure with 20h of GBT time: first demonstration of distant IM. No individual galaxies detected, many galaxies per resolution element
- 300 h allocated to measure z~1 power HI spectrum, redshift distortion, Ω_{HI}

Baryon Acoustic Oscillations – Dark Energy Probe

- CMB acoustic oscillations: imprinted standard ruler, 100 Mpc.
- Present in current matter distribution
- Kinematic metric of universe



WMAP5 and other, Nolta et al (2008)

Present LSS BAO Detections

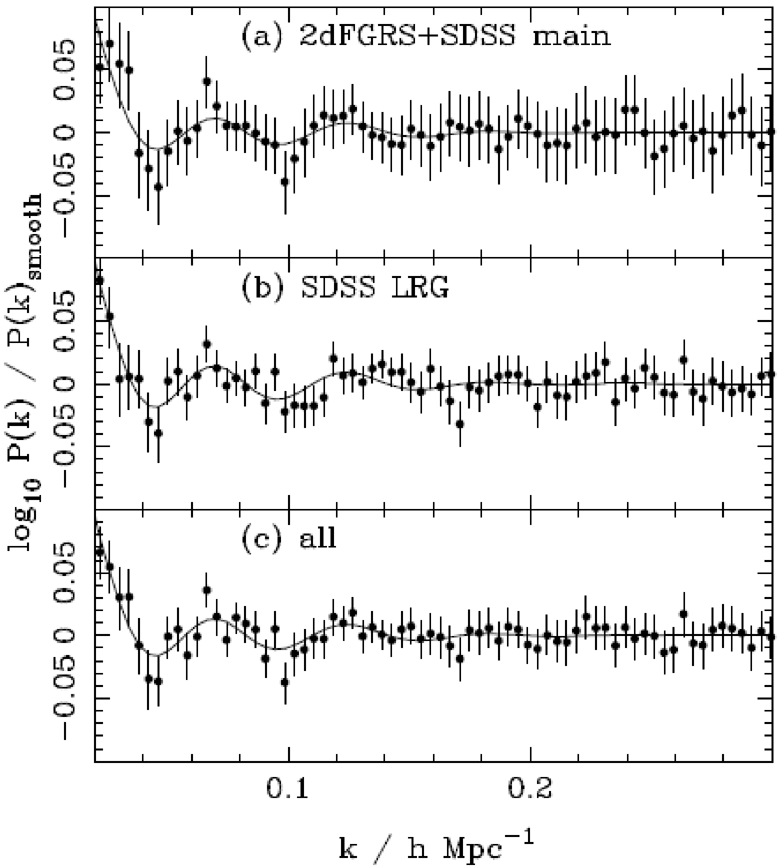
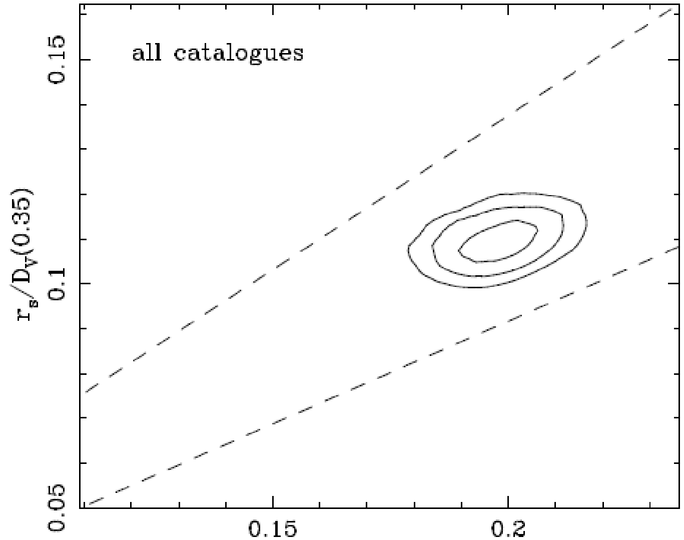
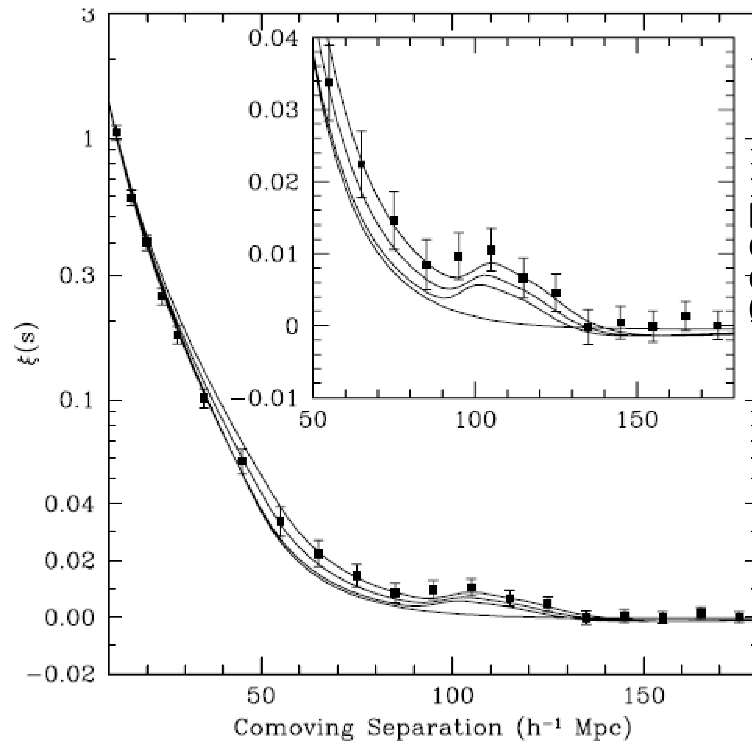


Figure 2. BAO in power spectra calculated from (a) the combined SDSS and 2dFGRS main galaxies, (b) the SDSS DR5 LRG sample, and (c) the combination of these two samples (solid symbols with 1σ errors). The data are correlated and the errors are calculated from the diagonal terms in the covariance matrix. A Standard ΛCDM distance–redshift relation was assumed to calculate the power spectra with $\Omega_m = 0.25$, $\Omega_\Lambda = 0.75$. The power spectra were then fitted with a cubic spline × BAO model, assuming our fiducial BAO model calculated using CAMB, as described in Section (3). The BAO component of the fit is shown by the solid line in each panel.



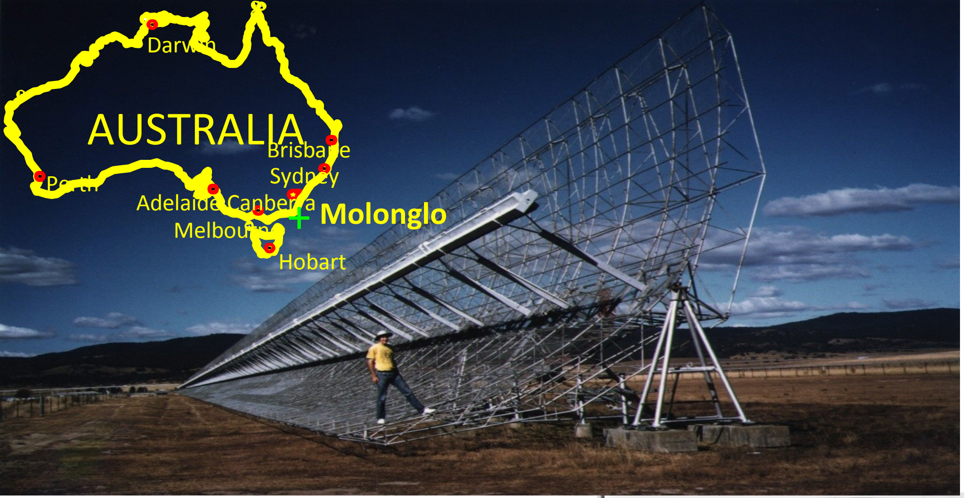
Percival et al 2007



Eisenstein et al 2005

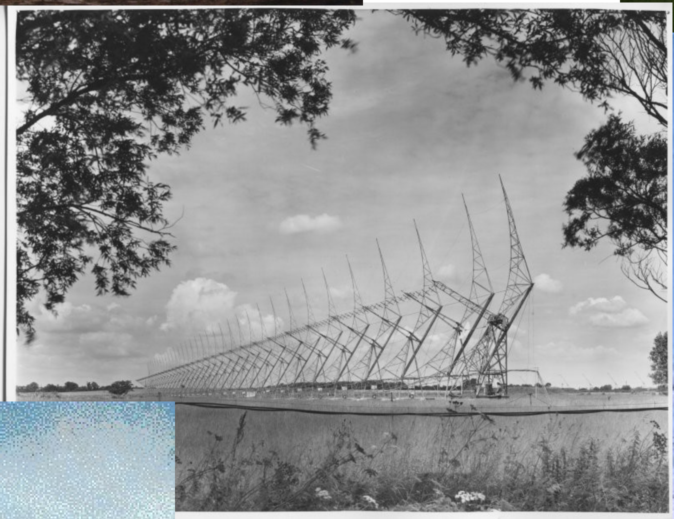
Dedicated Survey Experiment

- Low frequency technology cheap, modest size: $(100\ \text{m})^2$ to $z<2$
- Large field of view: receiver arrays
- High surface brightness sensitivity: compact arrays
- Stable, reliable: no moving parts
- Technologies: aperture arrays (Wyithe, Loeb, Geil 2008), cylinders (Peterson et al)



Northern Cross

Molonglo



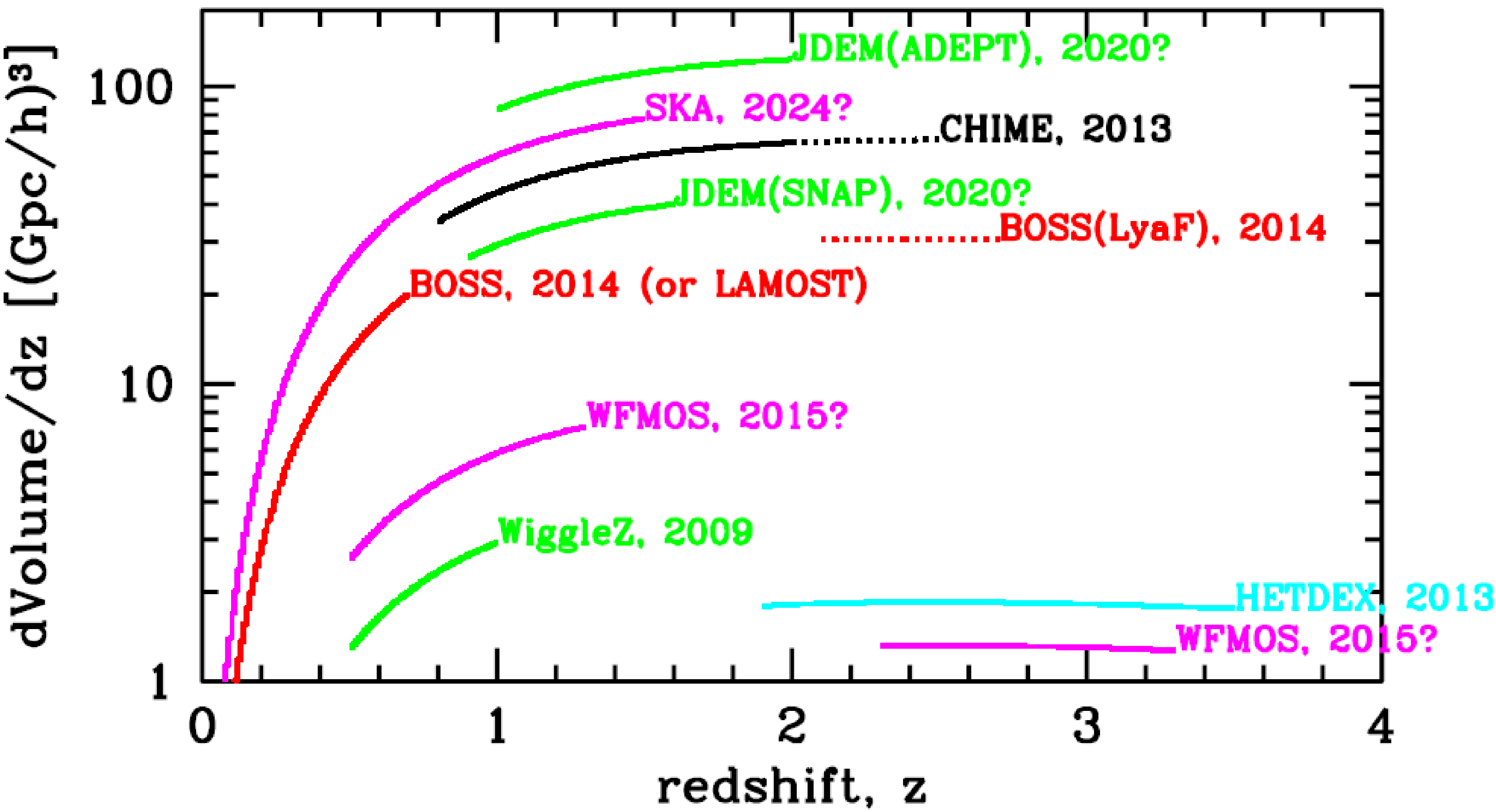
Ooty

Cambridge

Pushchin


CMU cylinder under construction:
U. Seljak, J. Peterson, K. Bandura, K. Sigurdson

BAO survey volumes



Conclusions

- 21cm cosmology: probes of dark energy (BAO), modified gravity (lensing), Inflation (tensor modes)
- Lack of substantial low frequency telescope investment in 30 years.
- Intensity Mapping: 21cm unresolved galaxies, accessible in redshift desert z=1-3.
- Initial HI detection with GBT at z~1
- Prototypes and observations under way. Cylinder telescopes a promising technology.