Cosmology and Future Radio Telescopes

Steve Furlanetto

Yale University

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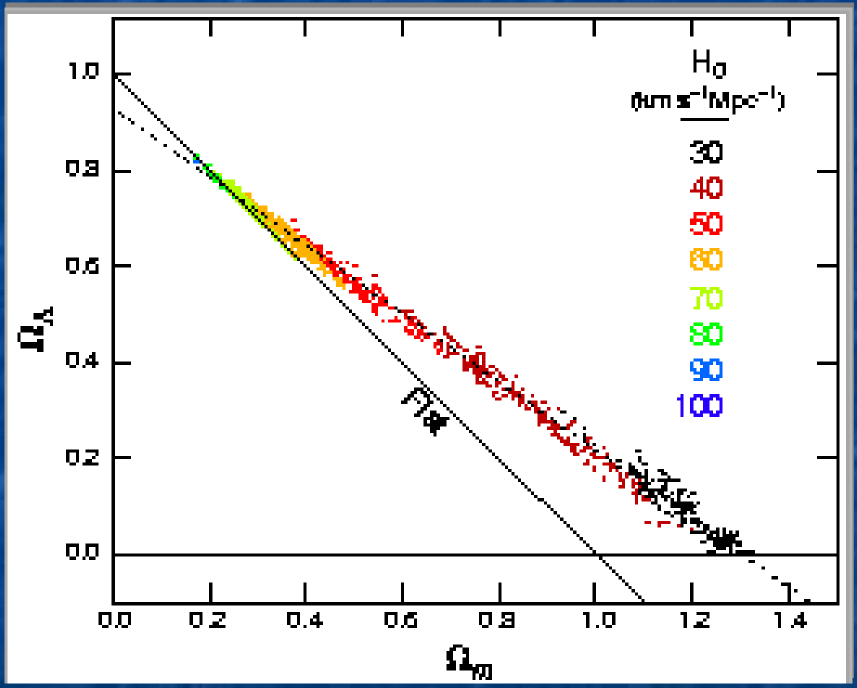
What is Cosmology?

- Fundamental Cosmology
  - Measuring global parameters (Ω_Λ, w, H_0, etc.)
- Astrophysical Cosmology
  - The history of structure formation (galaxy evolution, reionization, etc.)

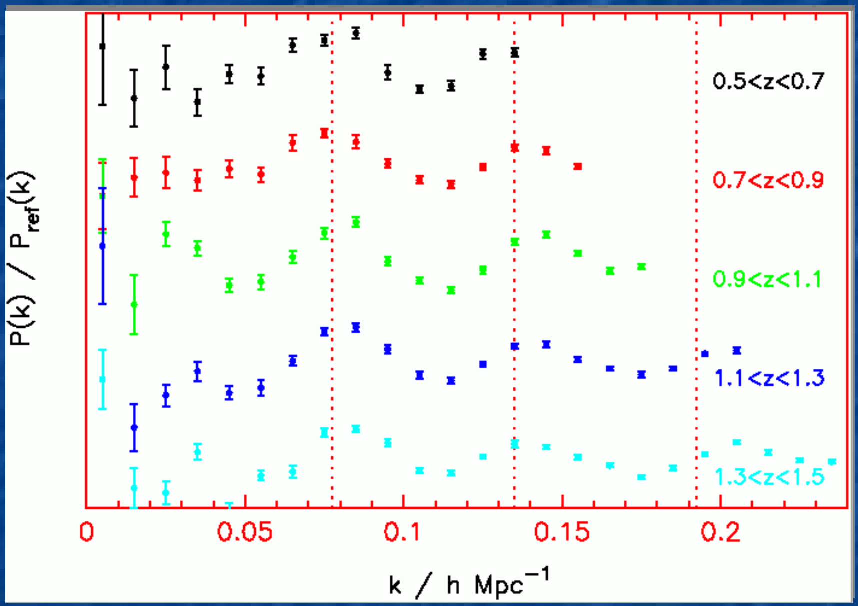
Fundamental Cosmology I: The Hubble Constant

- Underpins many of the improvements over CMB
- Current state of the art: HST key project
  - Systematic-limited at ~10% level
- The future: geometric distances from masers (Greenhill 2004)
  - Measure accelerations and proper motions in accretion disks
  - Hundreds of sources reduce to ~1% errors
  - Requires high frequencies (23 GHz) and long baselines (mapping structure)



Spergel et al. 2006

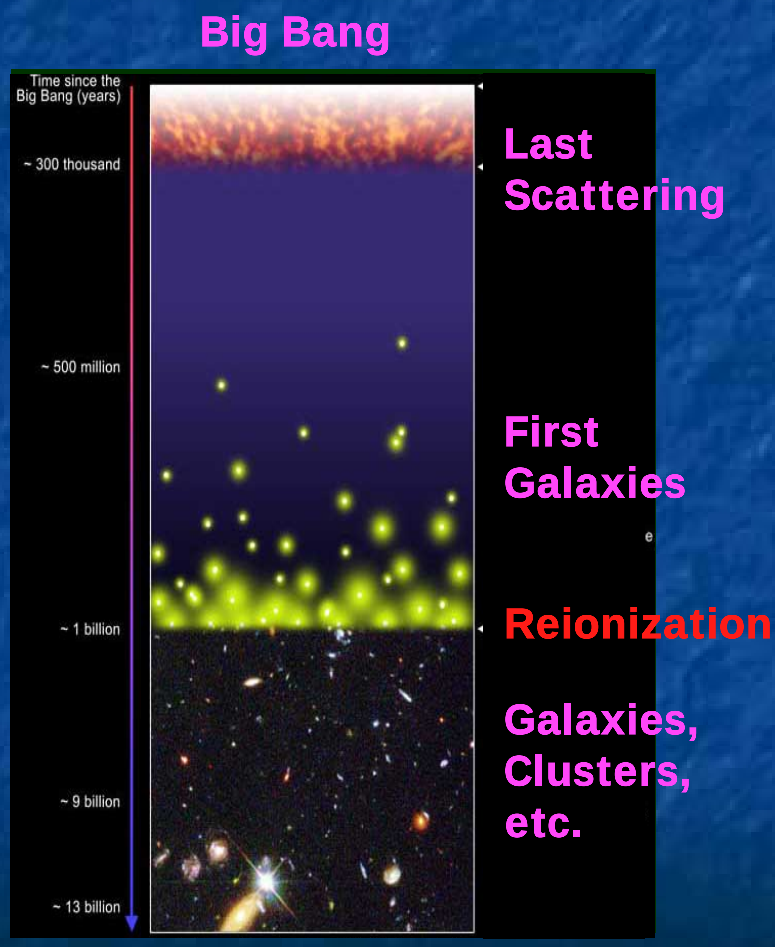
Fundamental Cosmology II: HI Surveys



Blake et al. 2004

- Advantages of SKA
  - Rapid survey speed
  - Spectroscopic redshifts
- Half-sky survey to z=1.5
  - 10^9 galaxies
  - 500 times volume of 2dF
- Also weak lensing
  - Requires 0.1” resolution
- SKA surveys could provide <5% errors on (w_0, w_1)
- Can be done in other ways, but not over such large volumes

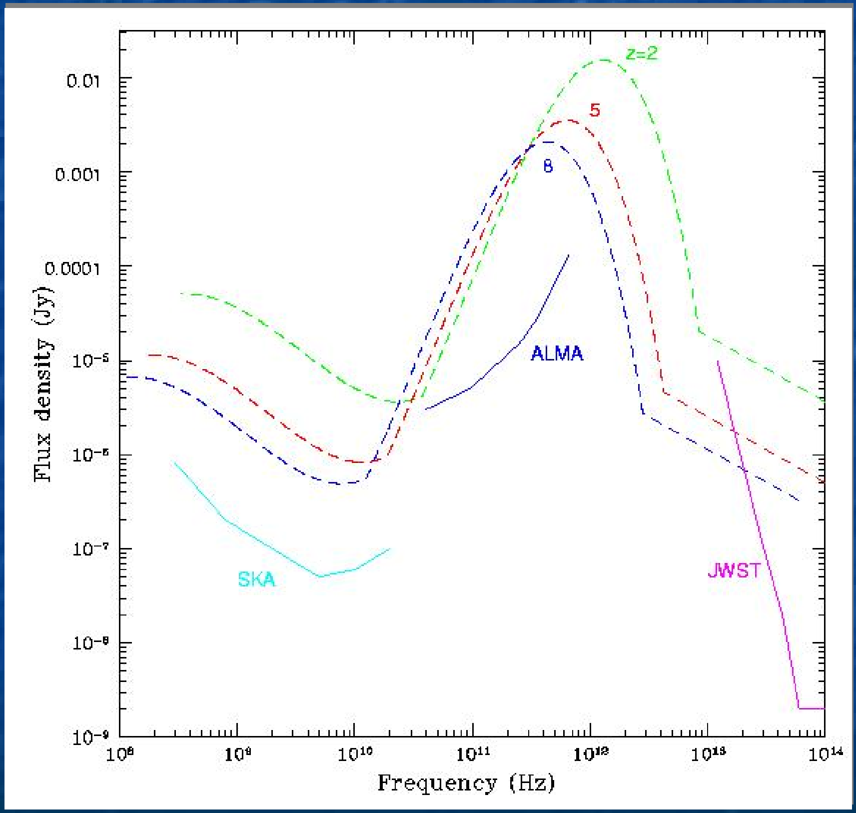
Astrophysical Cosmology



G. Djorgovski

- Last scattering: z=1089, t=379,000 yr
- Today: z=0, t=13.7 Gyr
- Reionization: z=6-20, t=0.2-1 Gyr
- First galaxies: ?

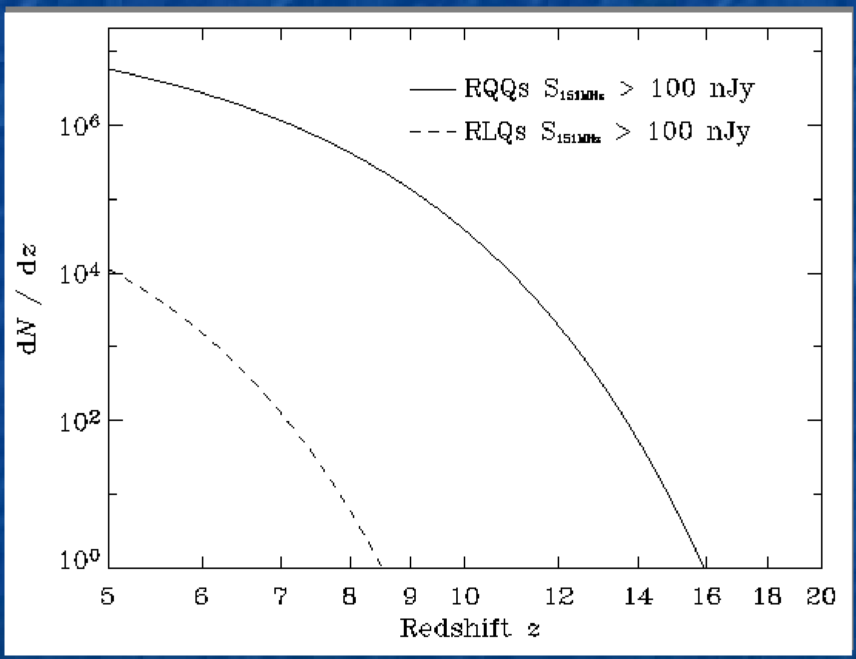
High-Redshift Galaxies



Carilli et al. (2004)

- Arp 220, at z=2, 5, and 8 (L_{IR}~10^{12} Lsun)
- Assumes 1 hr integrations
- Understanding sources will require multiwavelength campaigns

High-Redshift Quasars



Carilli et al. (2004)

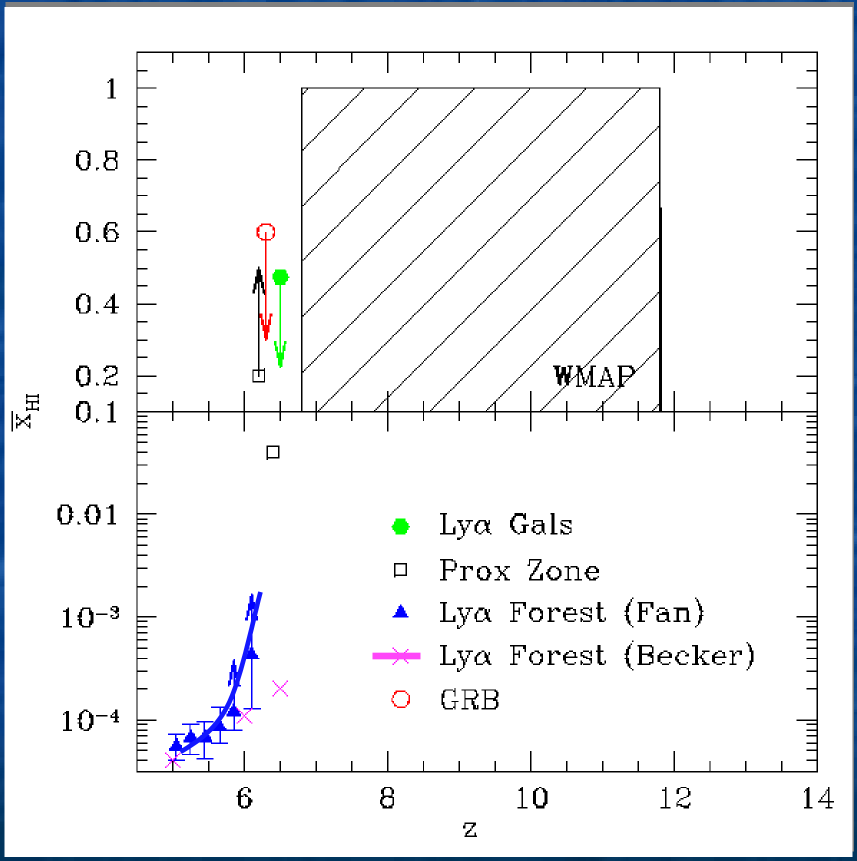
- 1 yr SKA survey at 150 MHz, half-sky, with model luminosity function
- RLQs above break detected at >1 mJy
- Also detects all RQQs above break in X-ray luminosity function
- Other models predict even longer tail to high-z (Haiman et al. 2004)

Beyond Galaxy Surveys

- Another key component is the intergalactic medium (IGM)
  - Contains nearly all of the baryons
  - (More) directly traces matter distribution
  - First galaxies form out of it
  - Influenced by ALL galaxies
  - Affected by feedback from galaxies (radiative, mechanical, chemical)
  - Hallmark event: reionization

Reionization: Observational Constraints

- Quasars/GRBs
- CMB optical depth
- Lyα-selected galaxies



Furlanetto, Oh, & Briggs (2006)

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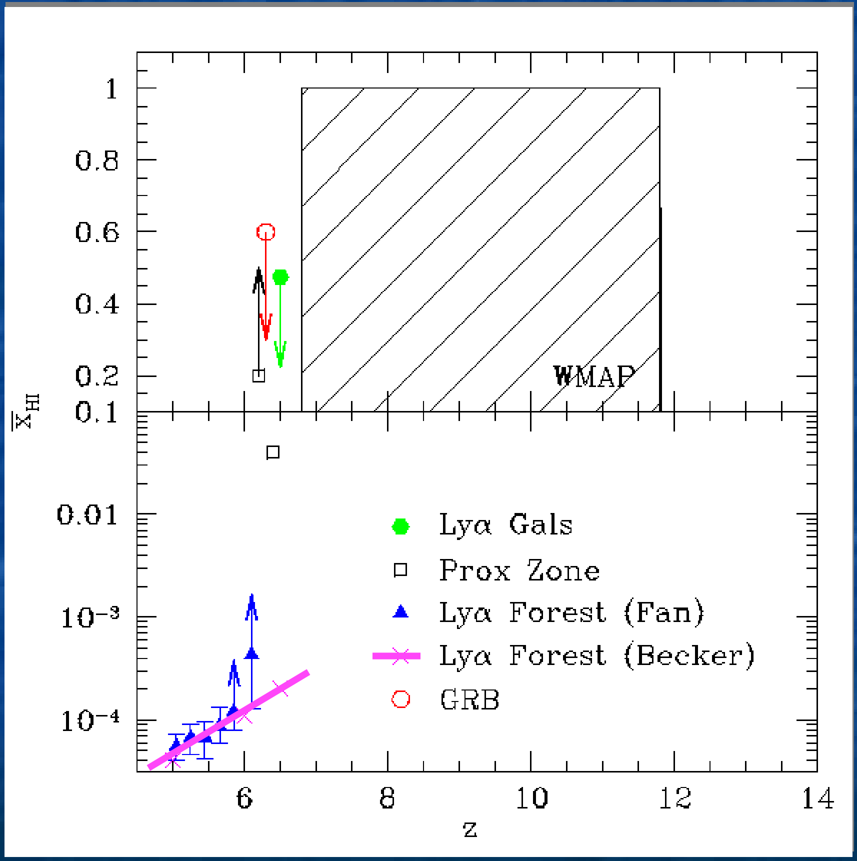
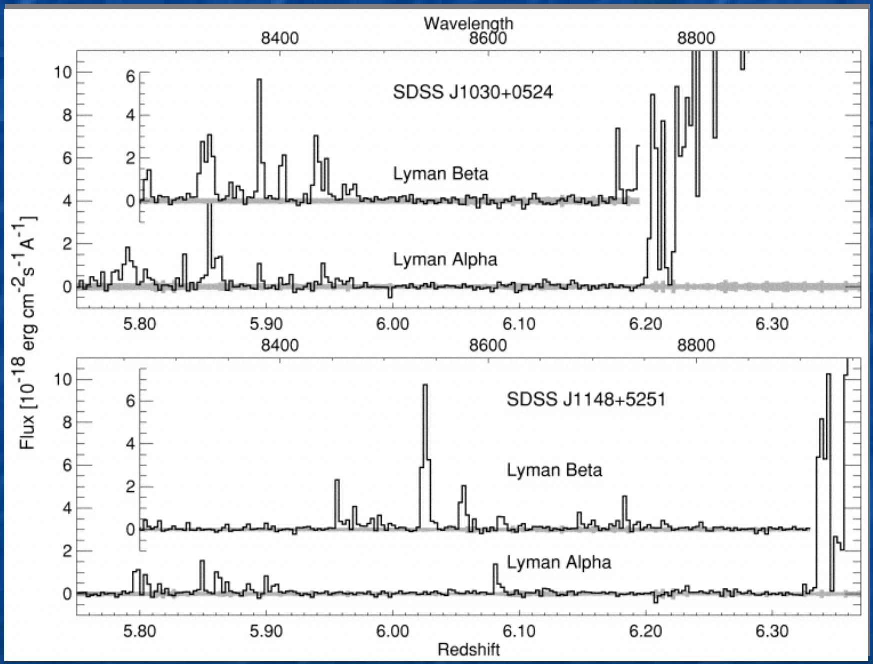


Furlanetto, Oh, & Briggs (2006)

SDSS Quasars: Line of Sight Variations

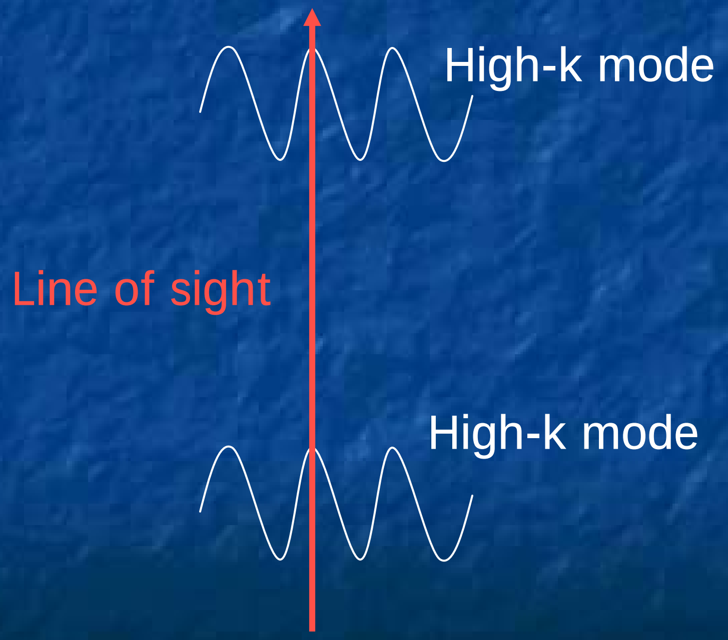


White et al. (2003)

- SDSS J1030 (z=6.28)
  - No flux for z=6.2-5.98
  - τ_α>10
- SDSS J1148 (z=6.42)
  - Transmission spikes and residual flux!
  - Lyγ trough: τ_α=7-11 (Oh & Furlanetto 2005)
- Attributed to reionization (Wyithe & Loeb 2005, Fan et al. 2006)

SDSS Quasars: Line of Sight Variations

- But complications!
  - Aliasing (Kaiser & Peacock 1991)

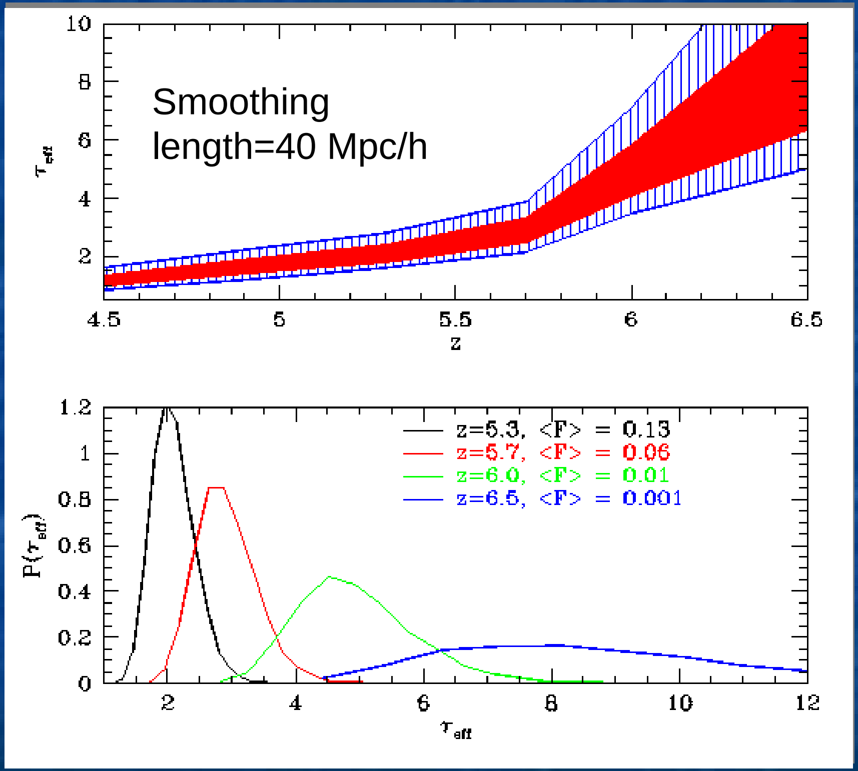


SDSS Quasars:
Line of Sight Variations

- But complications!
  - Aliasing (Kaiser & Peacock 1991)
  - Transmission bias because only see through rare voids

SDSS Quasars: Line of Sight Variations

- But complications!
  - Aliasing (Kaiser & Peacock 1991)
  - Transmission bias because only see through rare voids
- Observed variance slightly more than expected from uniform ionizing background
  - Structure in intrinsic quasar spectra is likely another significant contributor



Lidz, Oh, & Furlanetto (2006)

Reionization: Observational Constraints

- Quasars/GRBs
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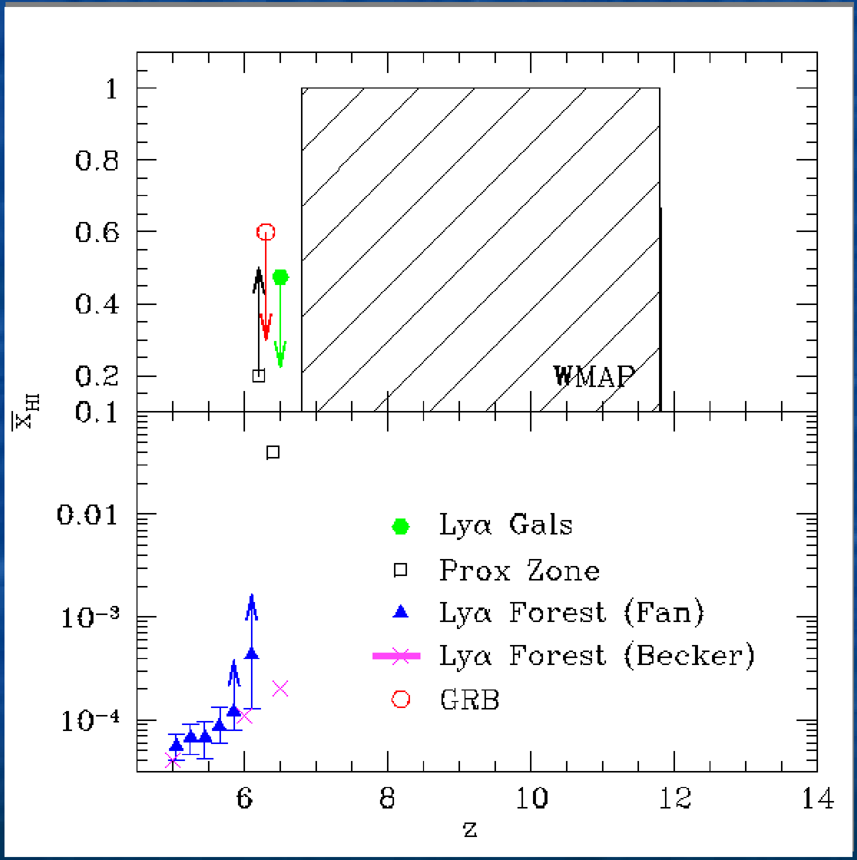
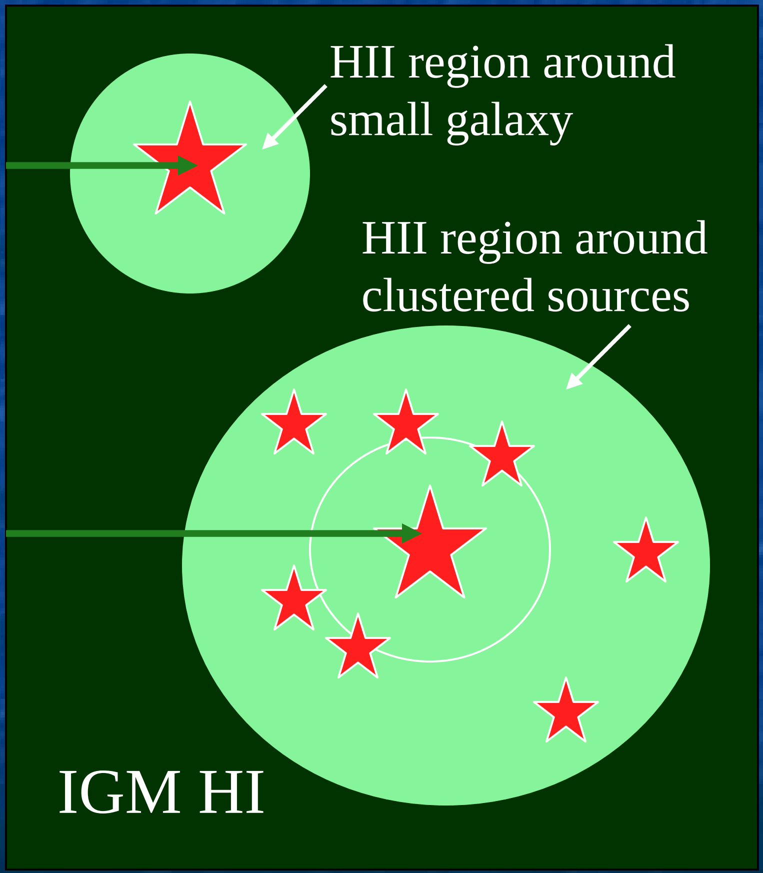


Furlanetto, Oh, & Briggs (2006)

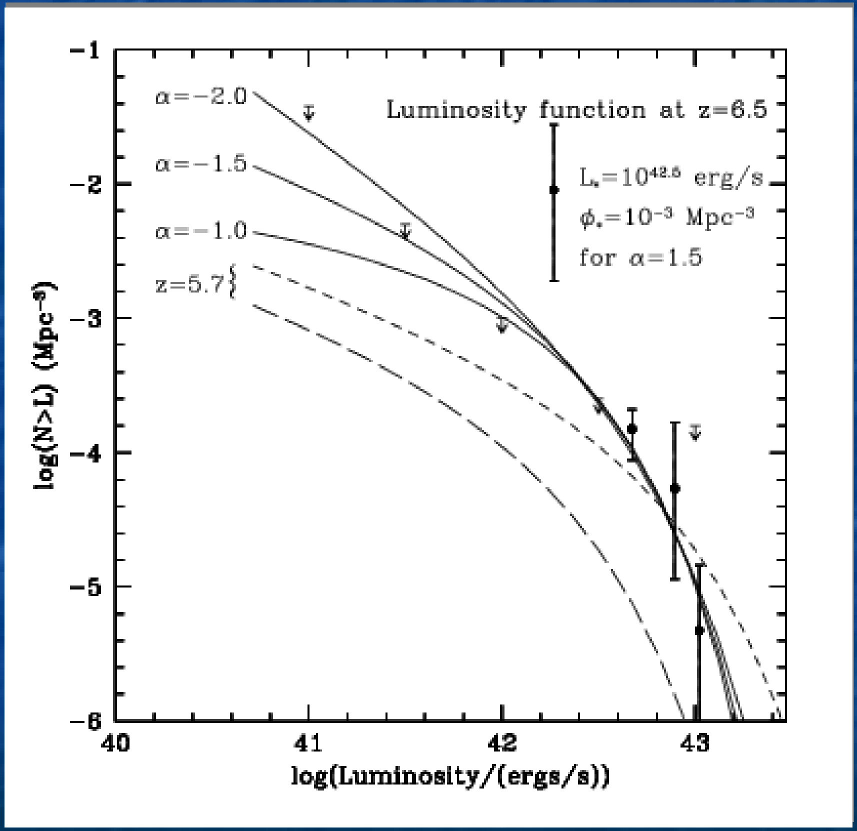
Lyα Emitters at High Redshifts

- Narrowband searches for Lyα lines are efficient way to target high-z galaxies
  - Already effective at z~6.5
  - Current efforts at z~8-10
- Also teaches us about reionization (Miralda-Escude & Rees 1998, Haiman 2002)
  - Damping wing absorption from IGM causes galaxy lines to vanish



Lyα Emitters

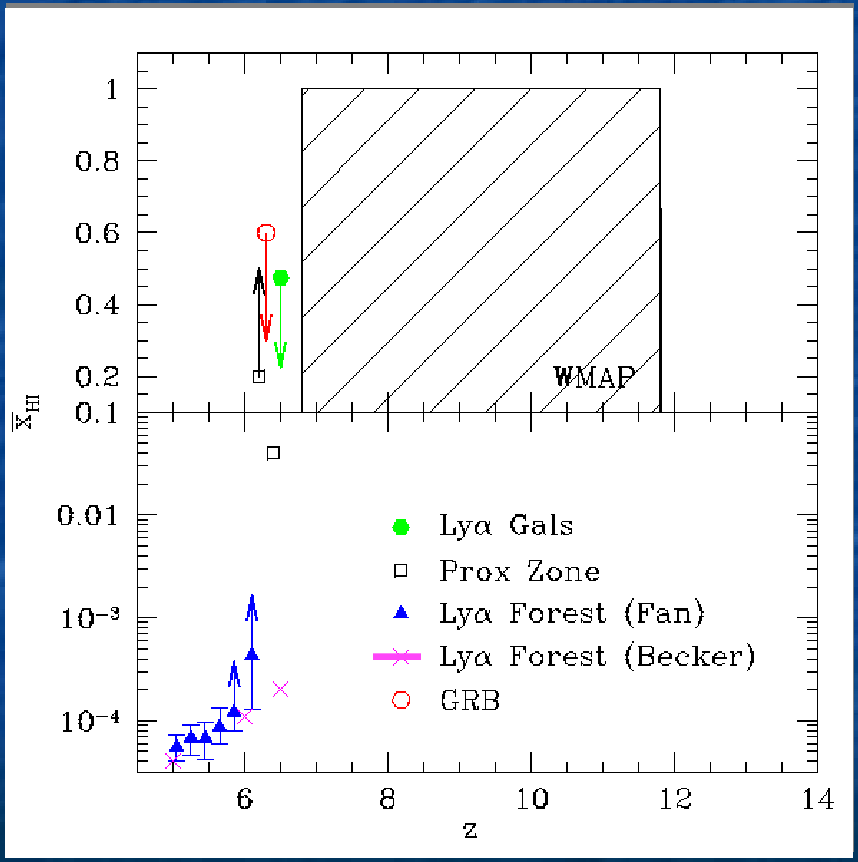
- Compare luminosity functions at z=5.7 and z=6.5
- Expect difference if substantially neutral IGM
  - In reality, statistically identical
- What are the implications for reionization?
  - Depends sensitively galaxy properties (Santos 2004)
  - Also on clustering (SF, LH, MZ 2004; Gnedin & Prada 2004, Wyithe & Loeb 2005, SF, MZ, LH 2006)



Malhotra & Rhoads (2004)

Reionization: Observational Constraints

- Quasars/GRBs
  - Nearly saturated absorption
  - Sparse background lights
- CMB optical depth
  - Essentially integral constraint
- Lyα-selected galaxies
  - Uncertain source populations
  - Small volumes

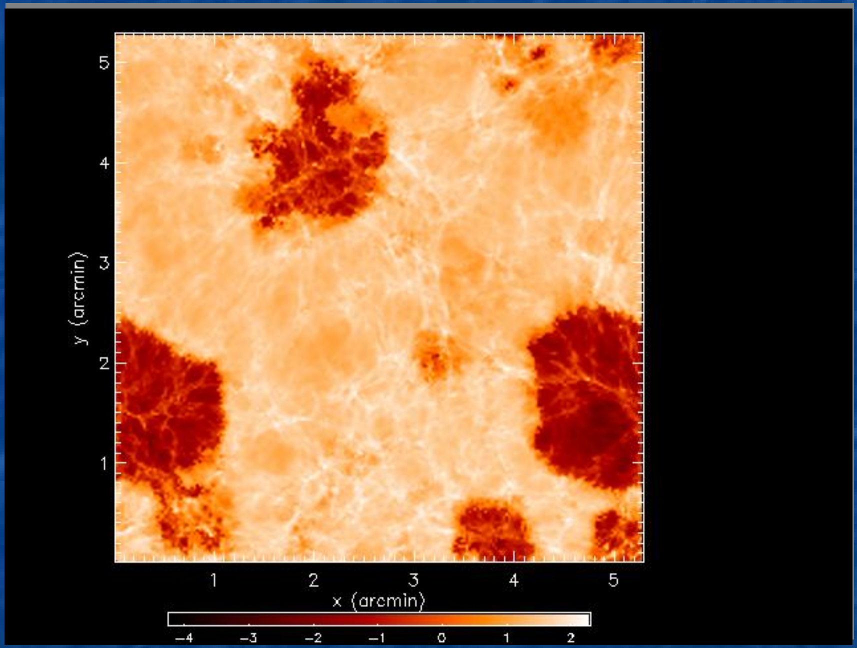


Furlanetto, Oh, & Briggs (2006)

The 21 cm Transition

- Map emission (or absorption) from IGM gas
  - Spectral line: measure entire history
  - Direct measurement of IGM properties
  - No saturation!

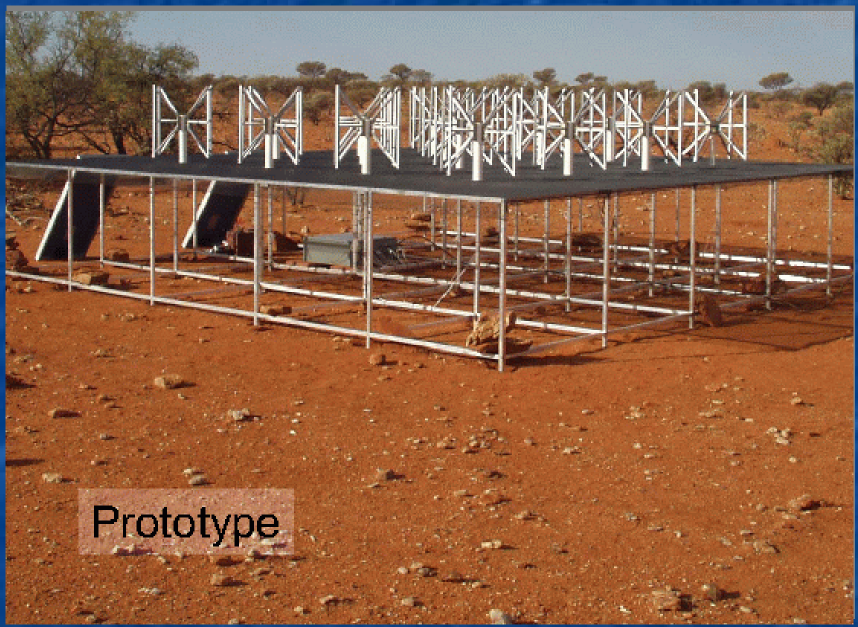
$$\delta T_b \approx 23 x_{HI} (1+\delta) \left(\frac{1+z}{10}\right)^{1/2} \left(\frac{T_S - T_{bkgd}}{T_S}\right) \left(\frac{H(z)/(1+z)}{\partial v_r / \partial r}\right) \text{ mK}$$



SF, AS, LH (2004)

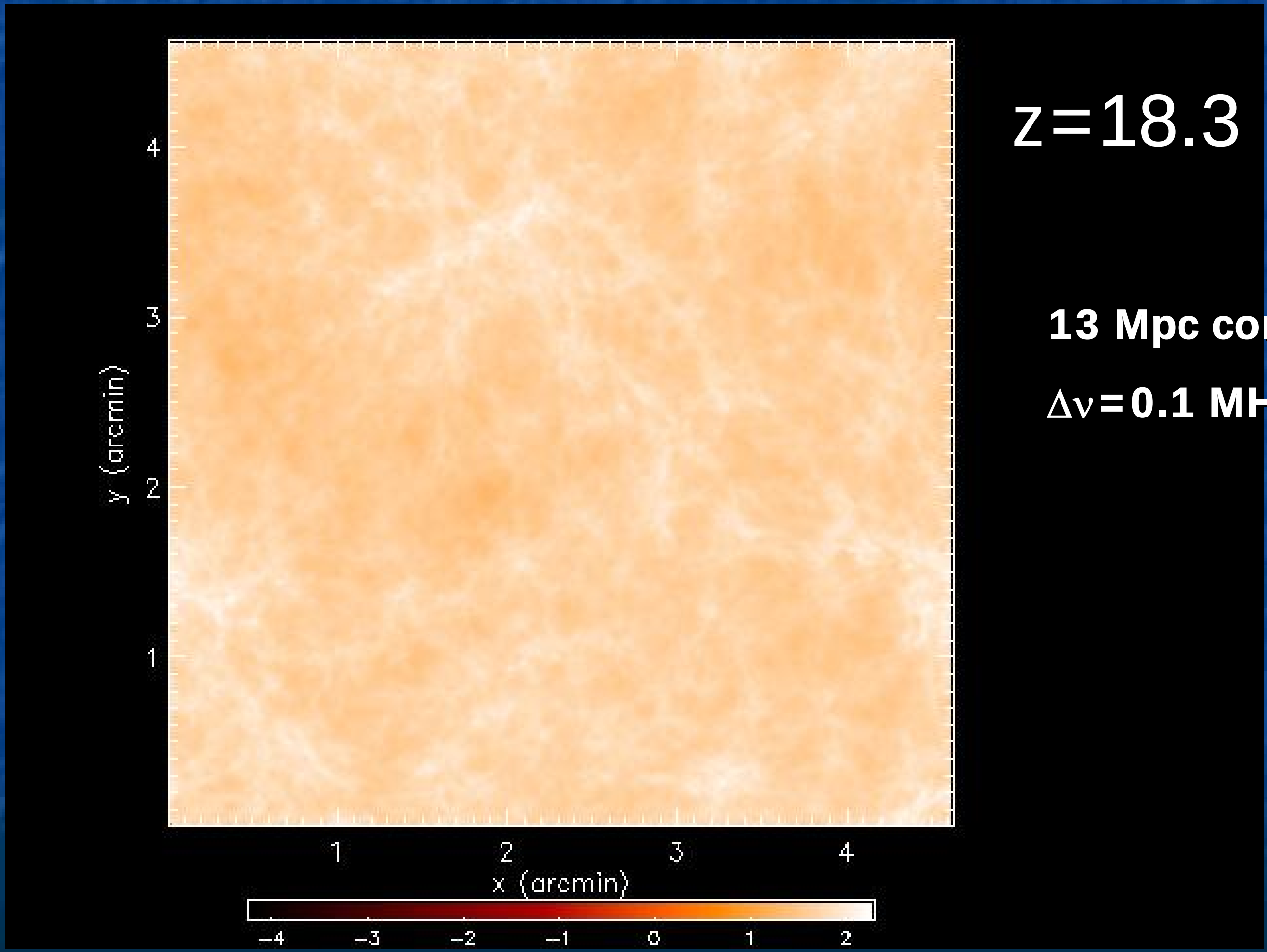
21 cm Observations

- Challenges
  - Terrestrial Interference
  - Ionosphere
  - Astronomical Foregrounds
    - T_b~200-2000 K
    - Galactic synchrotron
    - Extragalactic sources
    - Smooth spectra!
- Experiments
  - Global Signal: CoRE-ATNF
  - Fluctuations: 21CMA, LOFAR, MWA, PAPER, SKA
  - Imaging: SKA



MWA (from C. Lonsdale)

21 cm Observations: Reionization

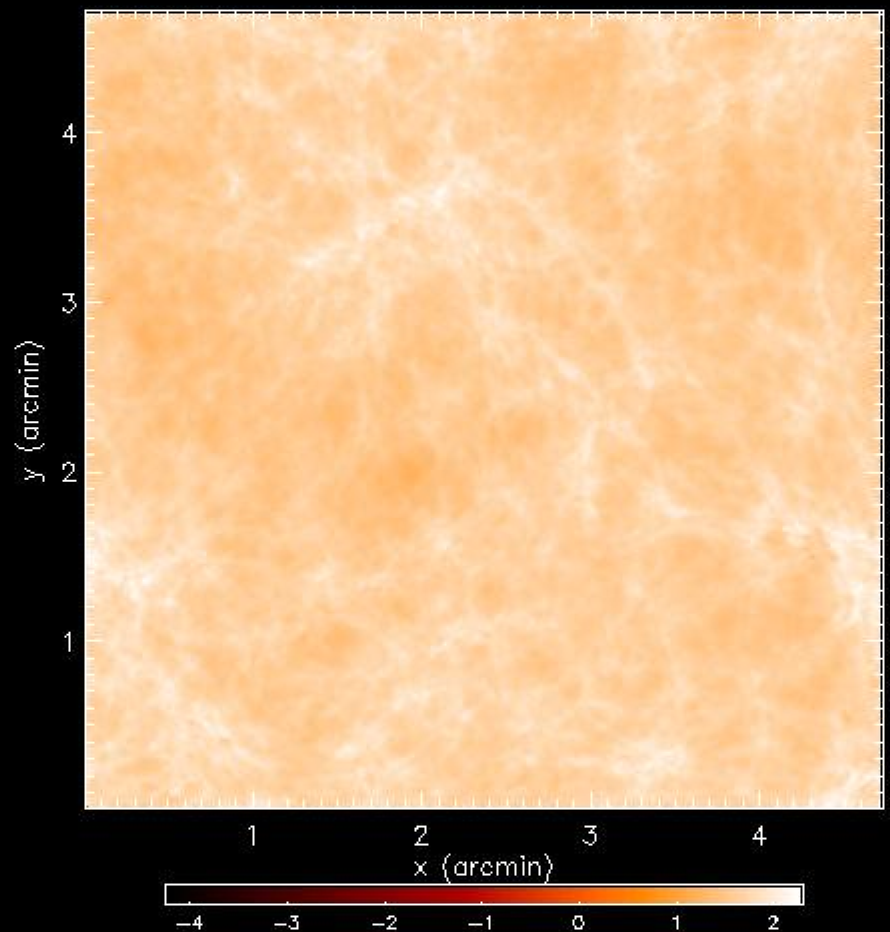


13 Mpc comoving

$\Delta\nu$=0.1 MHz

SF, AS, LH (2004)

21 cm Observations: Reionization



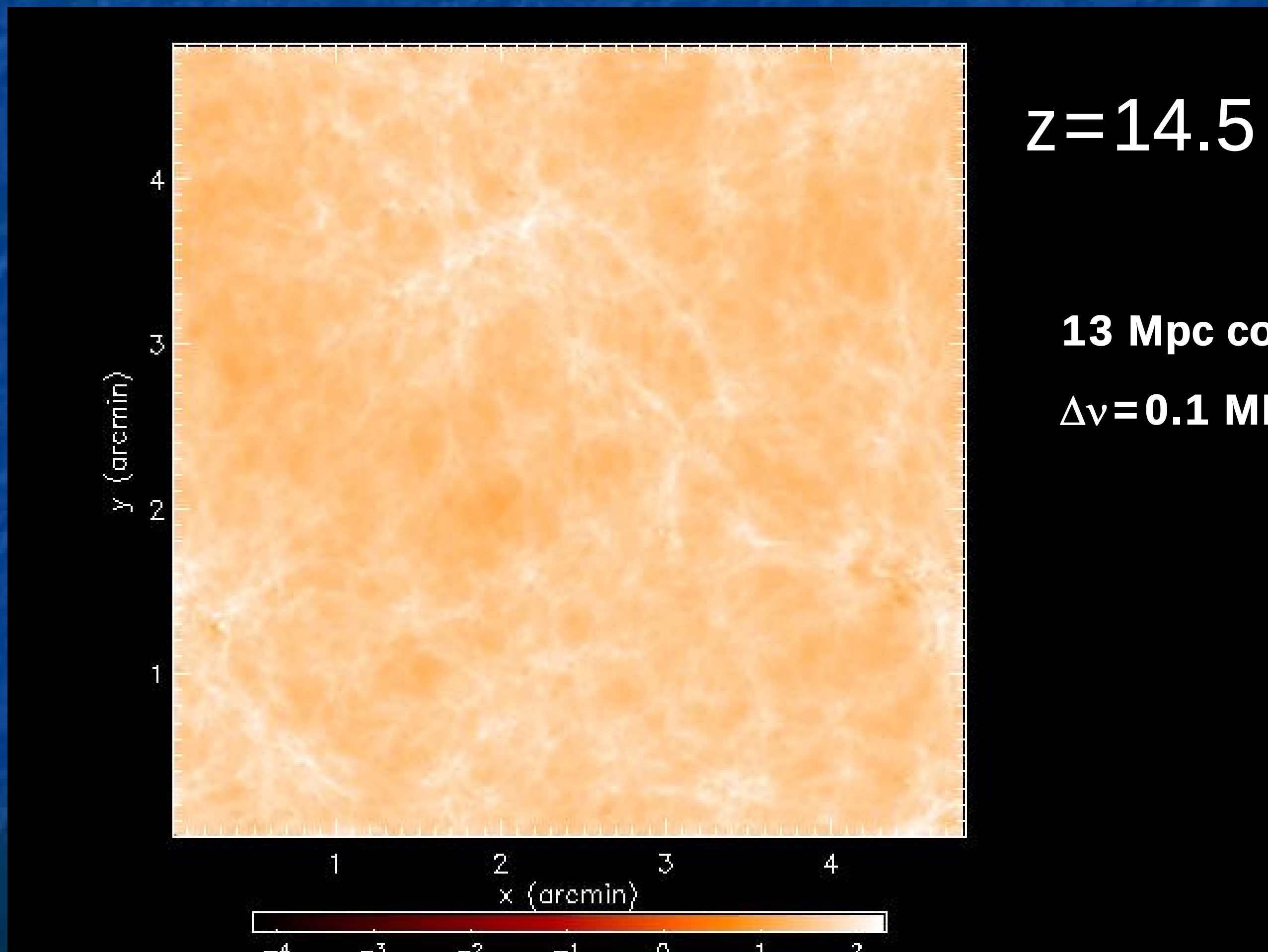
z=16.1

13 Mpc comoving

$\Delta\nu$=0.1 MHz

SF, AS, LH (2004)

21 cm Observations: Reionization

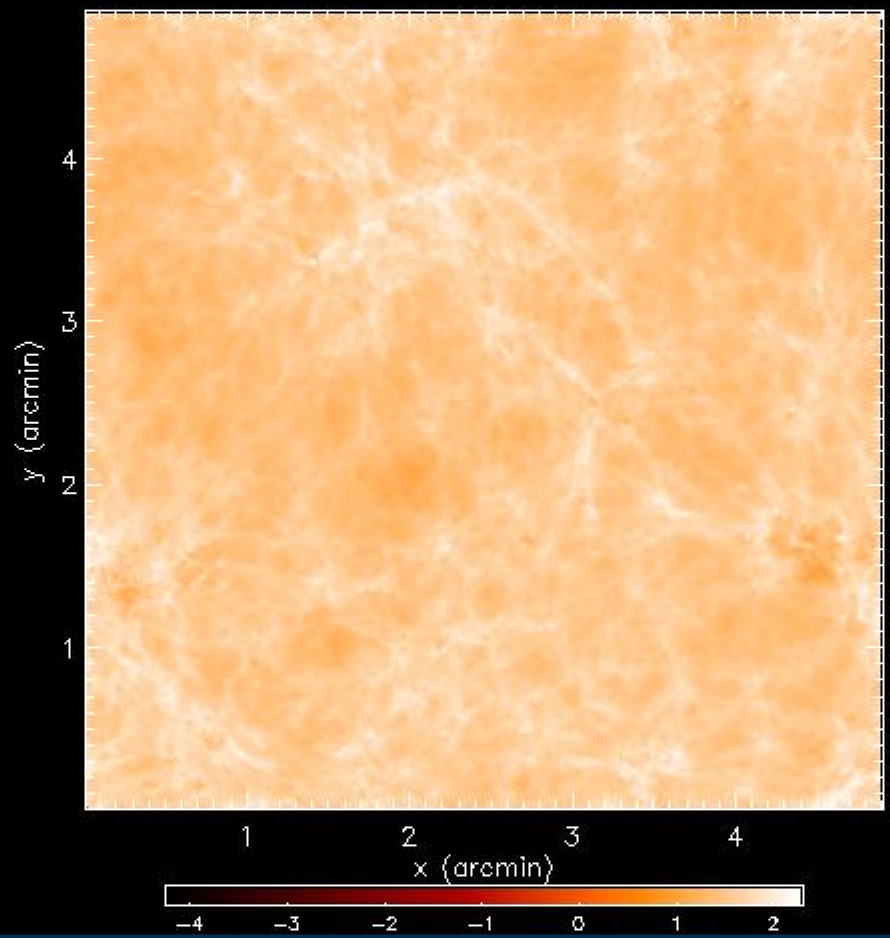


13 Mpc comoving

$\Delta\nu$=0.1 MHz

SF, AS, LH (2004)

21 cm Observations: Reionization



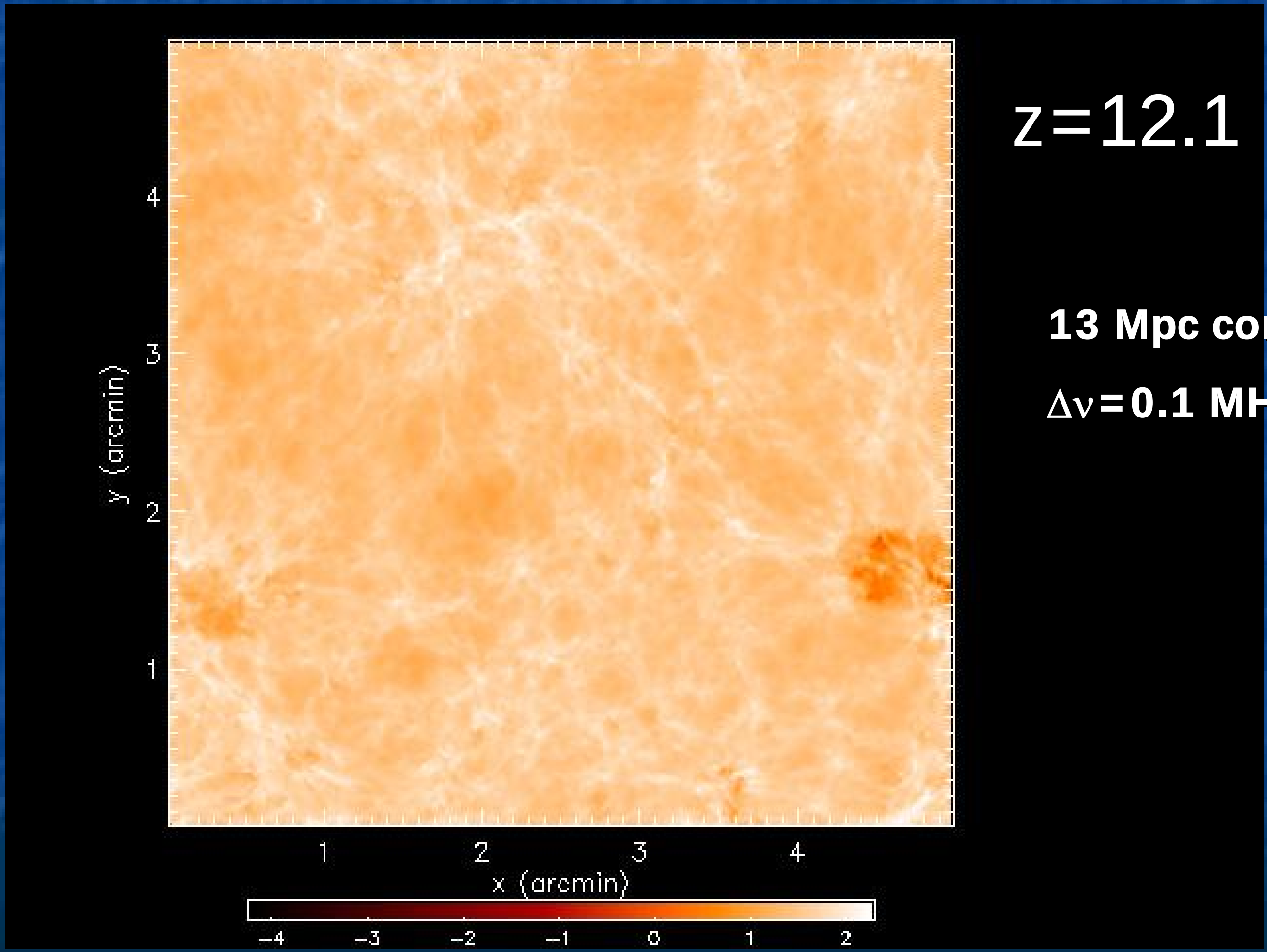
z=13.2

13 Mpc comoving

$\Delta\nu$=0.1 MHz

SF, AS, LH (2004)

21 cm Observations: Reionization

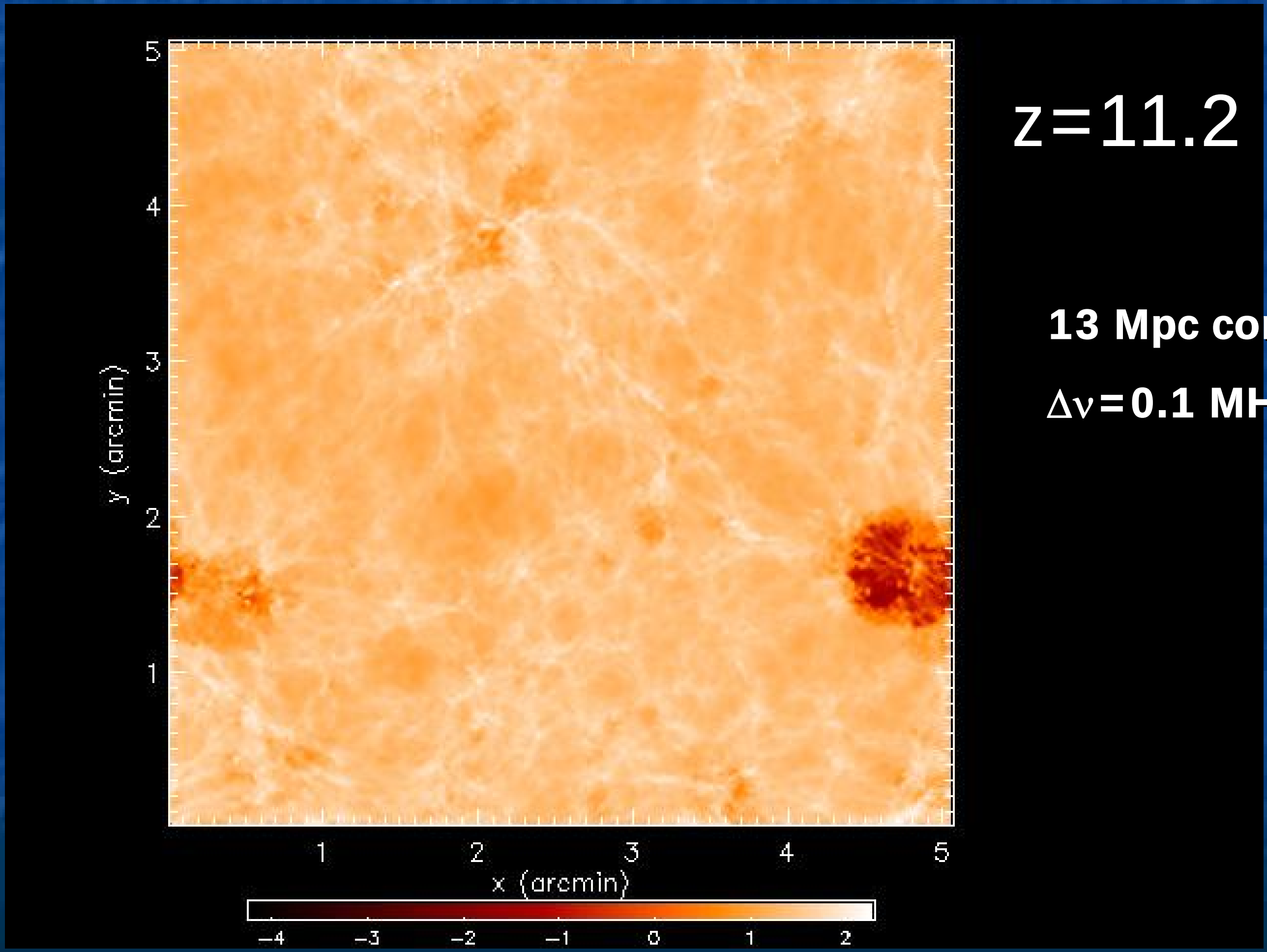


13 Mpc comoving

$\Delta\nu$=0.1 MHz

SF, AS, LH (2004)

21 cm Observations: Reionization



13 Mpc comoving

$\Delta\nu$=0.1 MHz

SF, AS, LH (2004)

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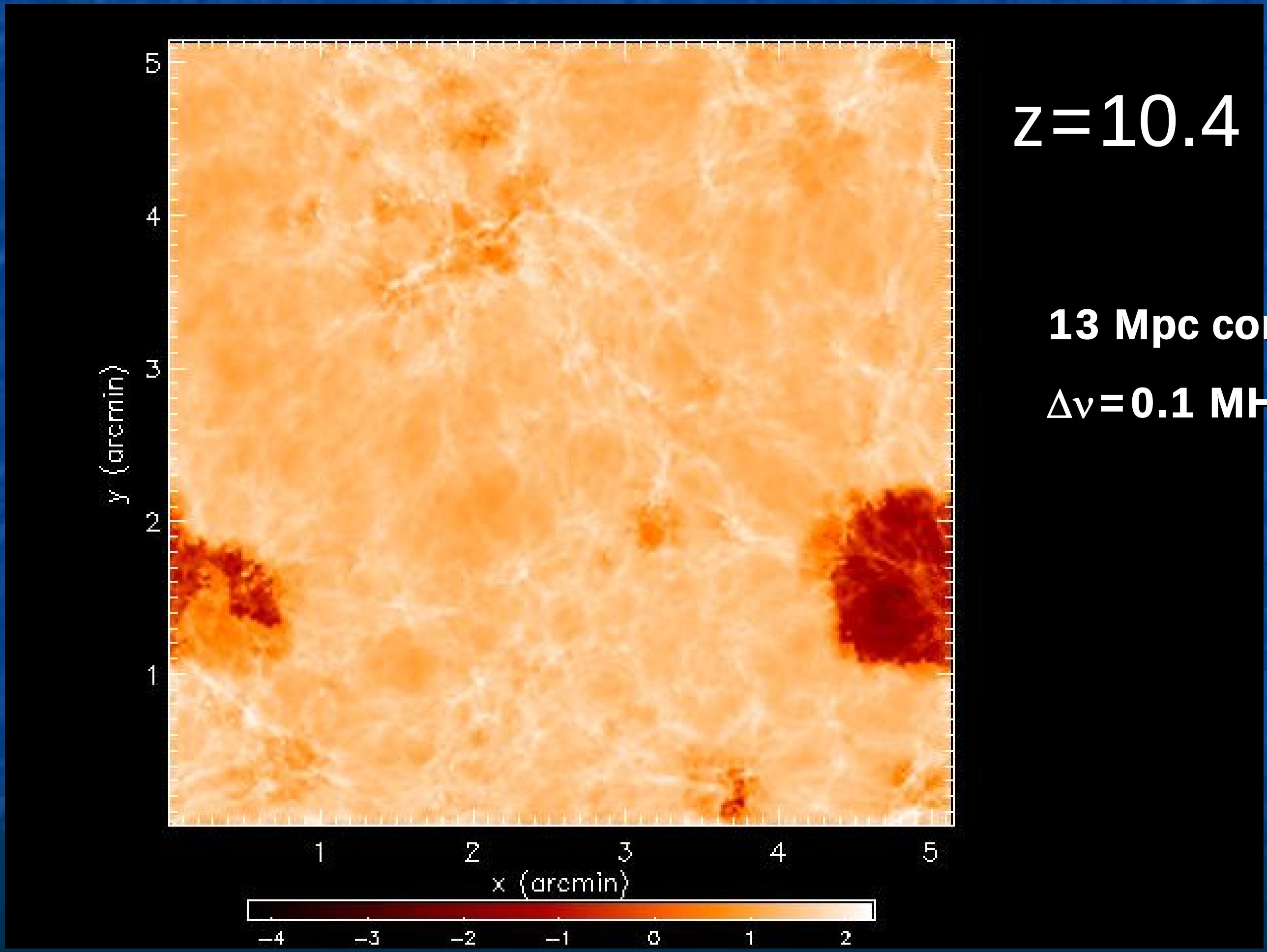


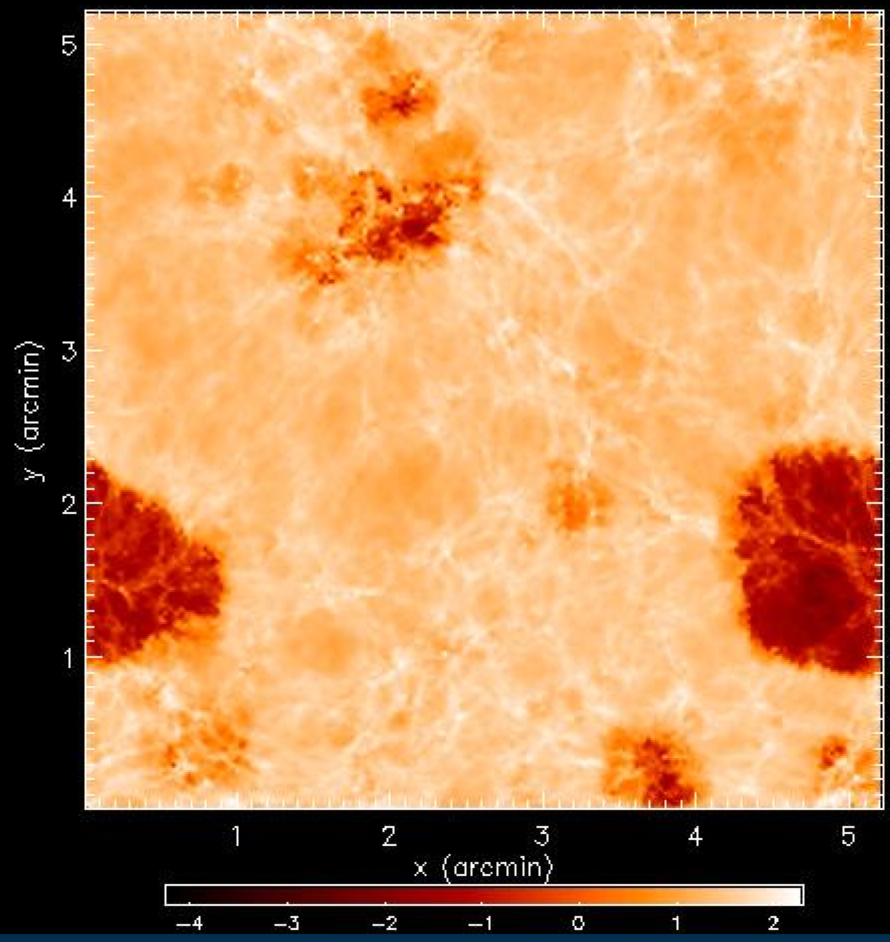
z=10.4

13 Mpc comoving

$\Delta\nu$=0.1 MHz

SF, AS, LH (2004)

21 cm Observations: Reionization



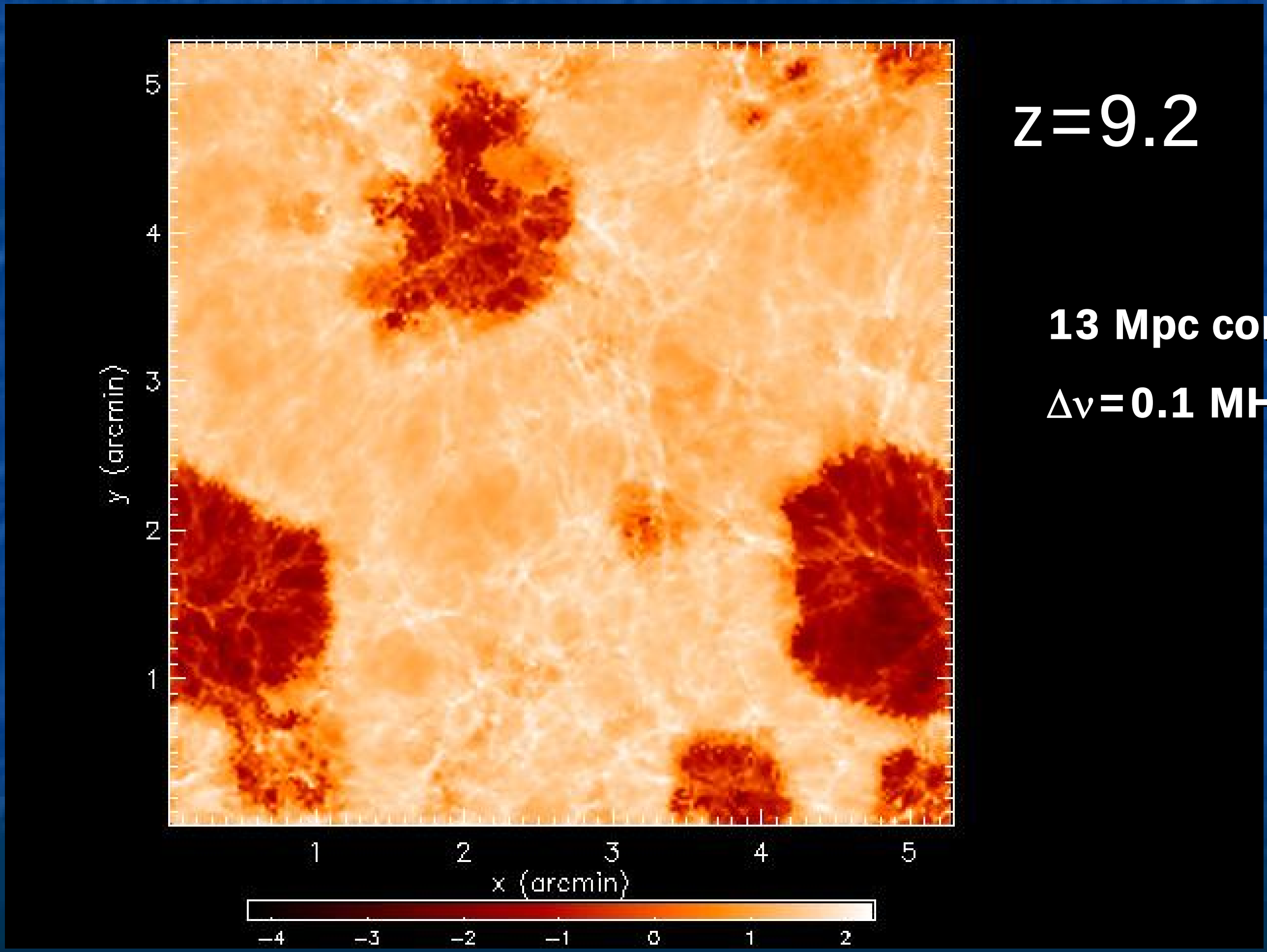
z=9.8

13 Mpc comoving

$\Delta\nu$=0.1 MHz

SF, AS, LH (2004)

21 cm Observations: Reionization



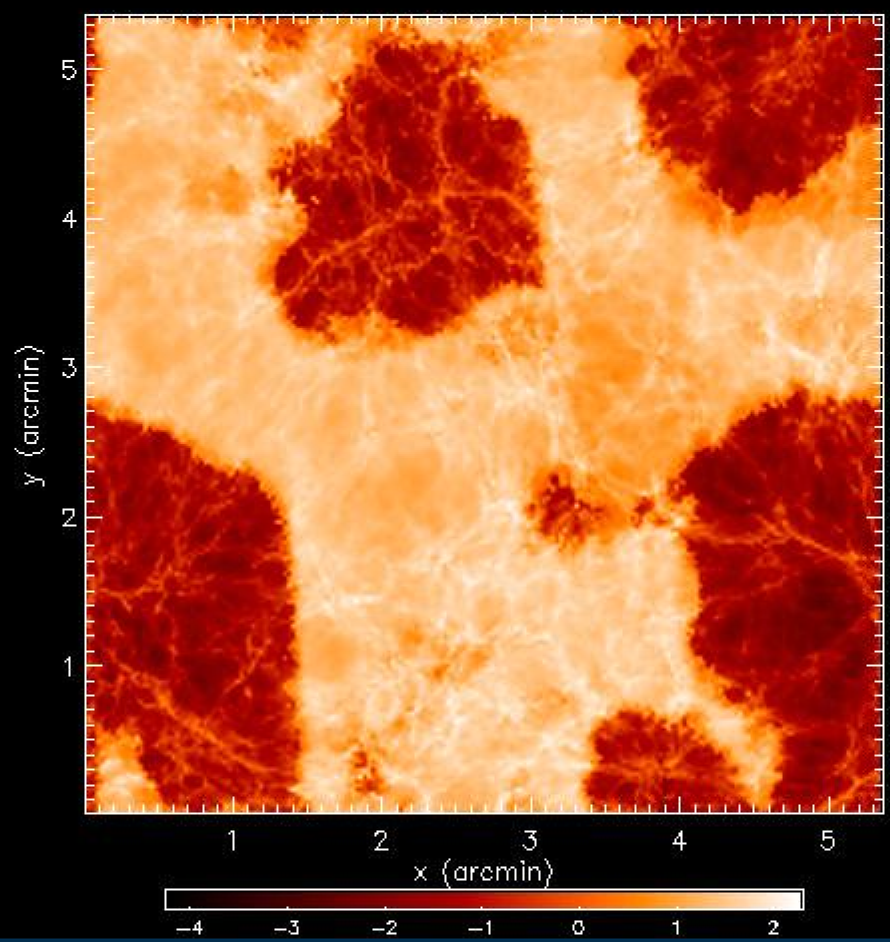
z=9.2

13 Mpc comoving

$\Delta\nu$=0.1 MHz

SF, AS, LH (2004)

21 cm Observations: Reionization



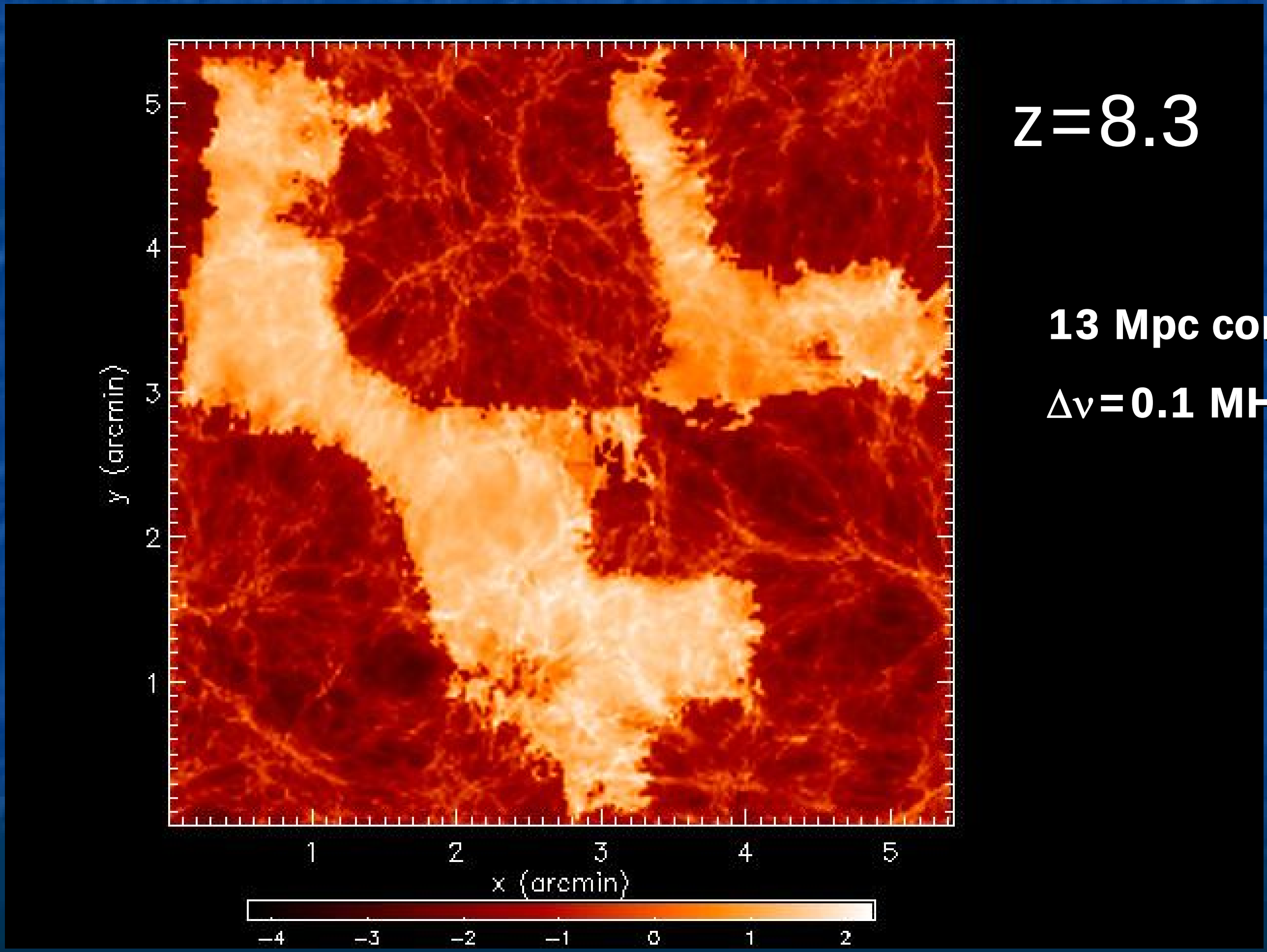
z=8.7

13 Mpc comoving

$\Delta\nu$=0.1 MHz

SF, AS, LH (2004)

21 cm Observations: Reionization



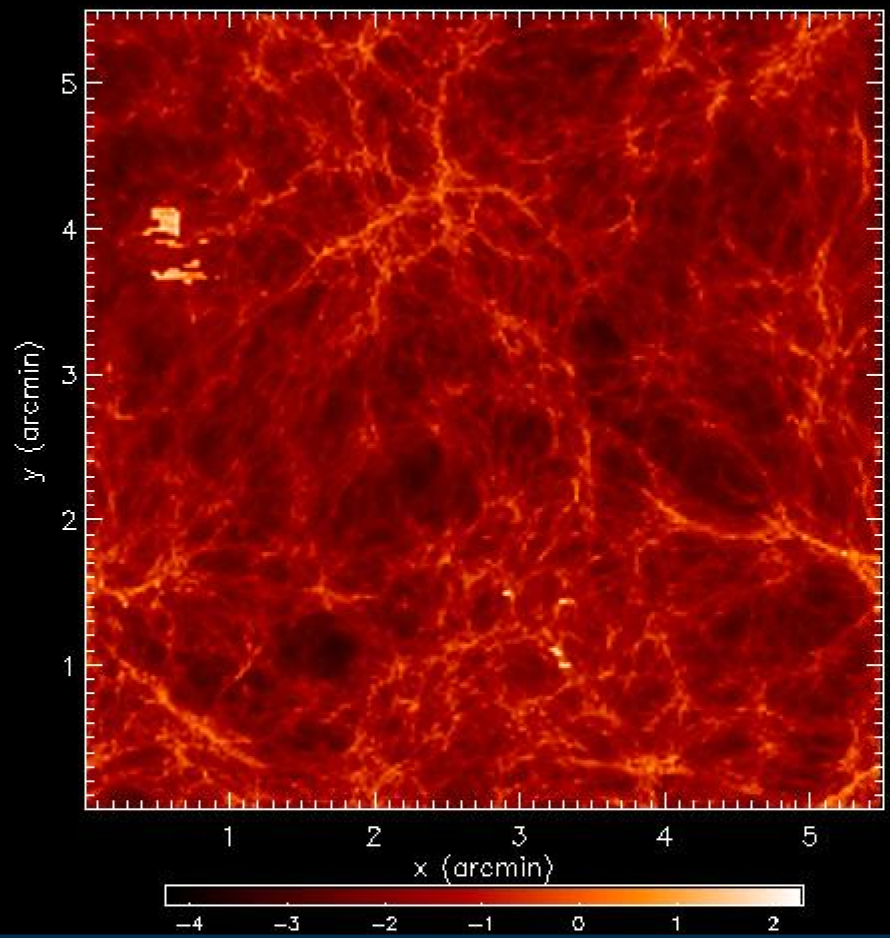
z=8.3

13 Mpc comoving

$\Delta\nu$=0.1 MHz

SF, AS, LH (2004)

21 cm Observations: Reionization



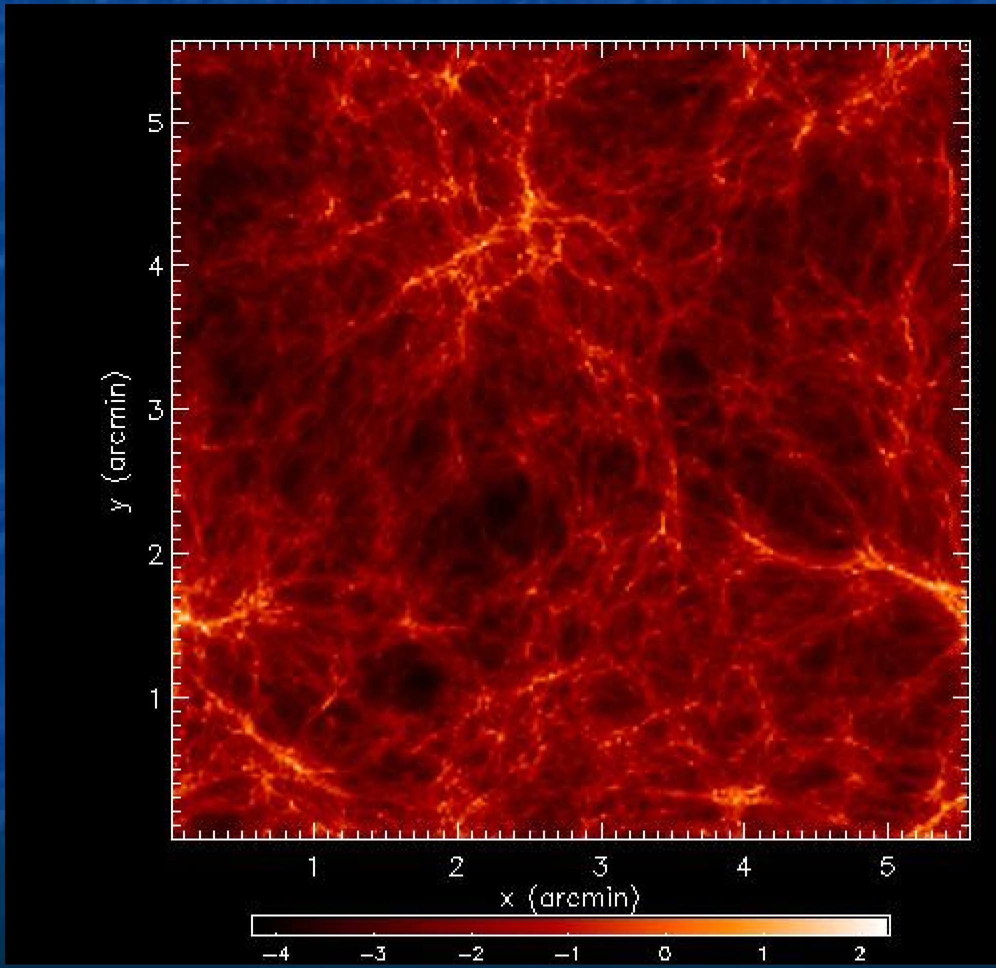
z=7.9

13 Mpc comoving

$\Delta\nu$=0.1 MHz

SF, AS, LH (2004)

21 cm Observations: Reionization



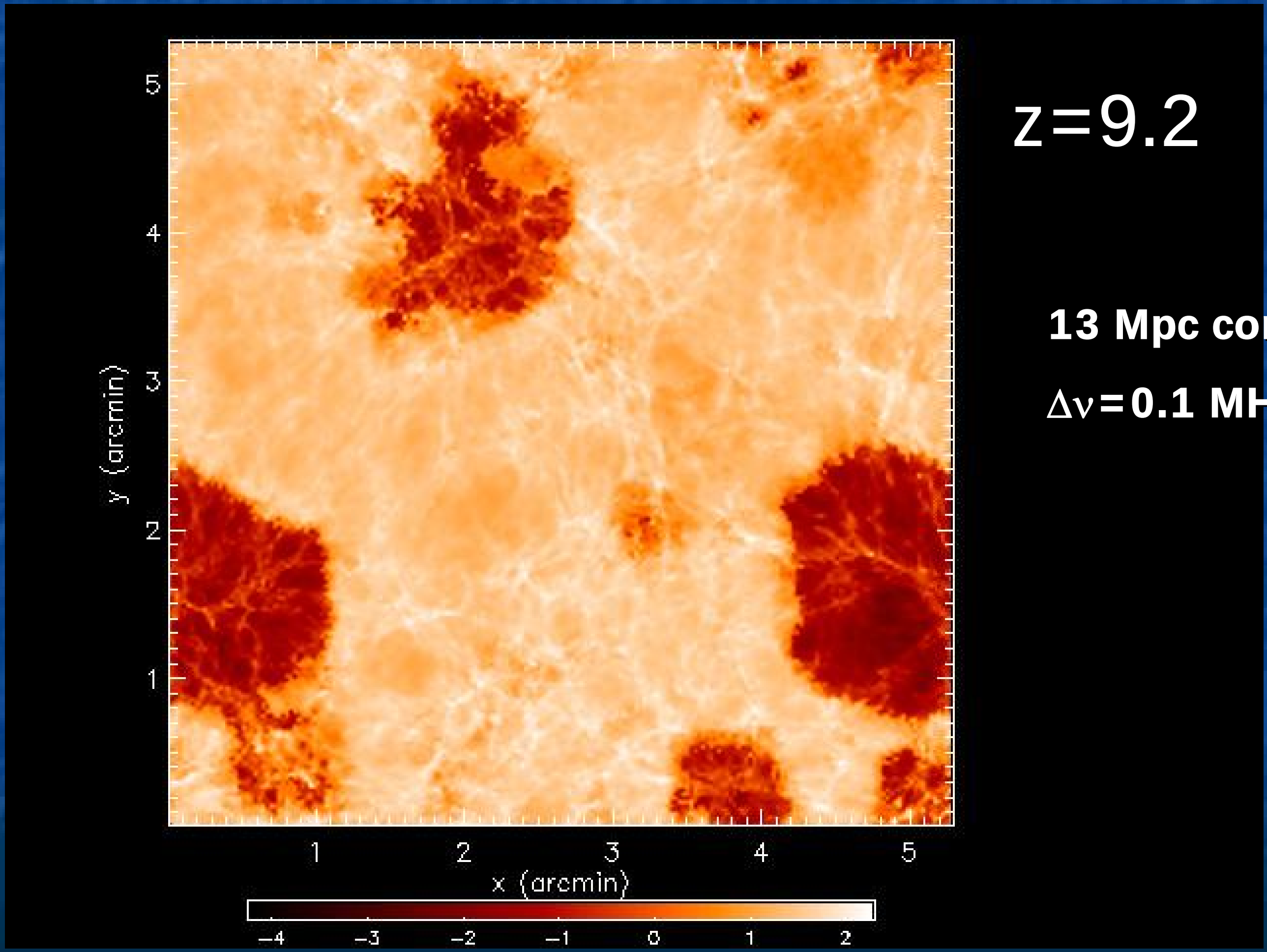
z=7.5

13 Mpc comoving

$\Delta\nu$=0.1 MHz

SF, AS, LH (2004)

21 cm Observations: Reionization



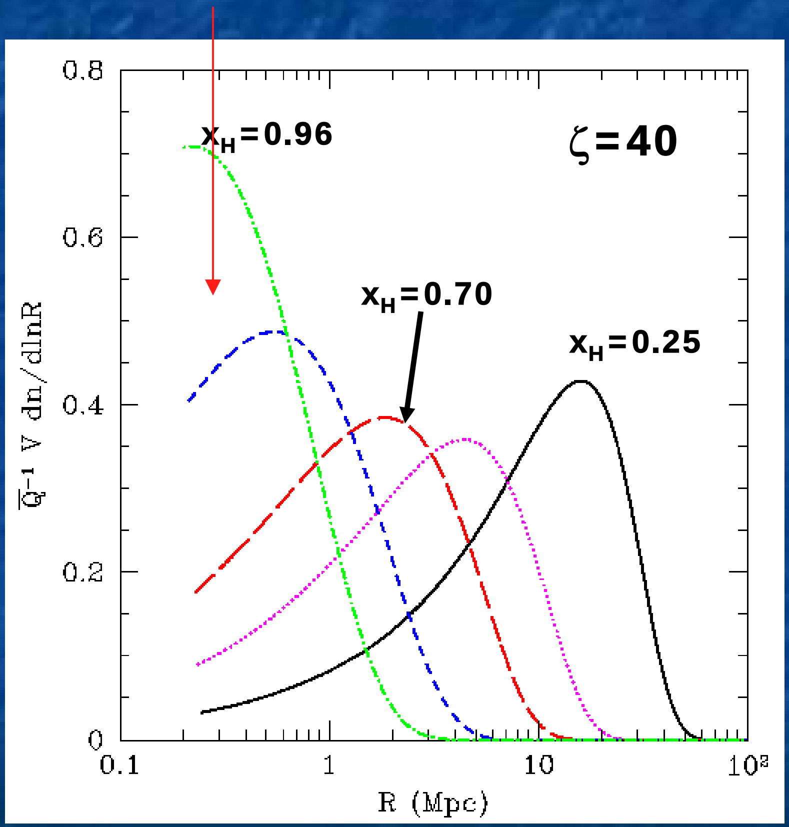
13 Mpc comoving

$\Delta\nu$=0.1 MHz

SF, AS, LH (2004)

Bubble Sizes

Typical galaxy bubble

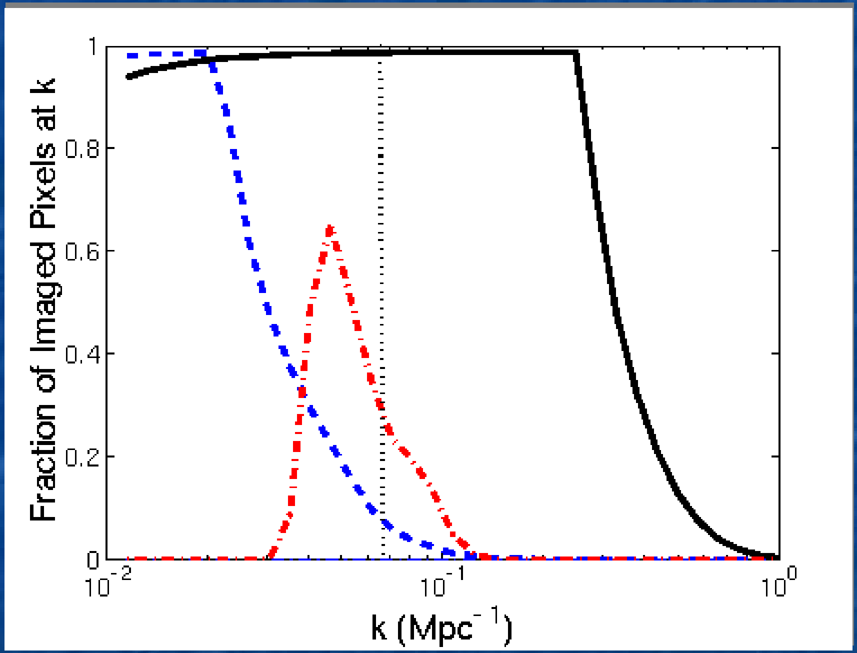


SF, MZ, LH (2004a)

- Bubbles are BIG!!!
  - 2 Mpc = 1 arcmin
- Well-defined characteristic size
- Robust to uncertainties in reionization redshift

Imaging Power

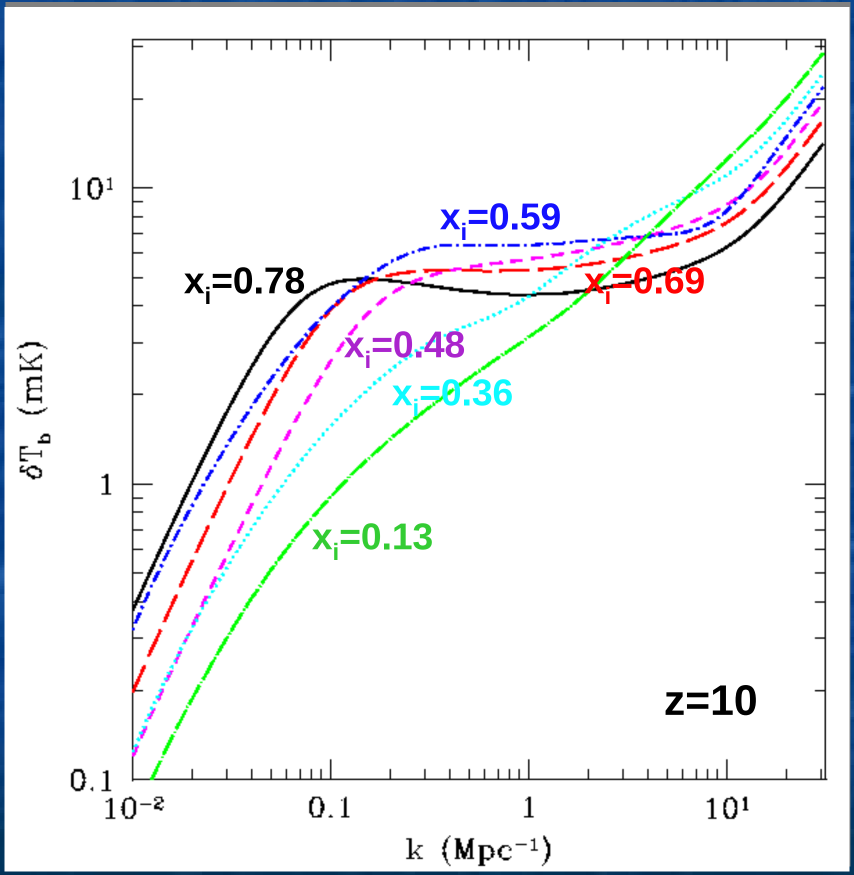
- Figure shows fraction of Fourier-space pixels with S/N>1 (1000 hr observation, z=8)
  - Blue: MWA
  - Red: LOFAR
  - Black: SKA



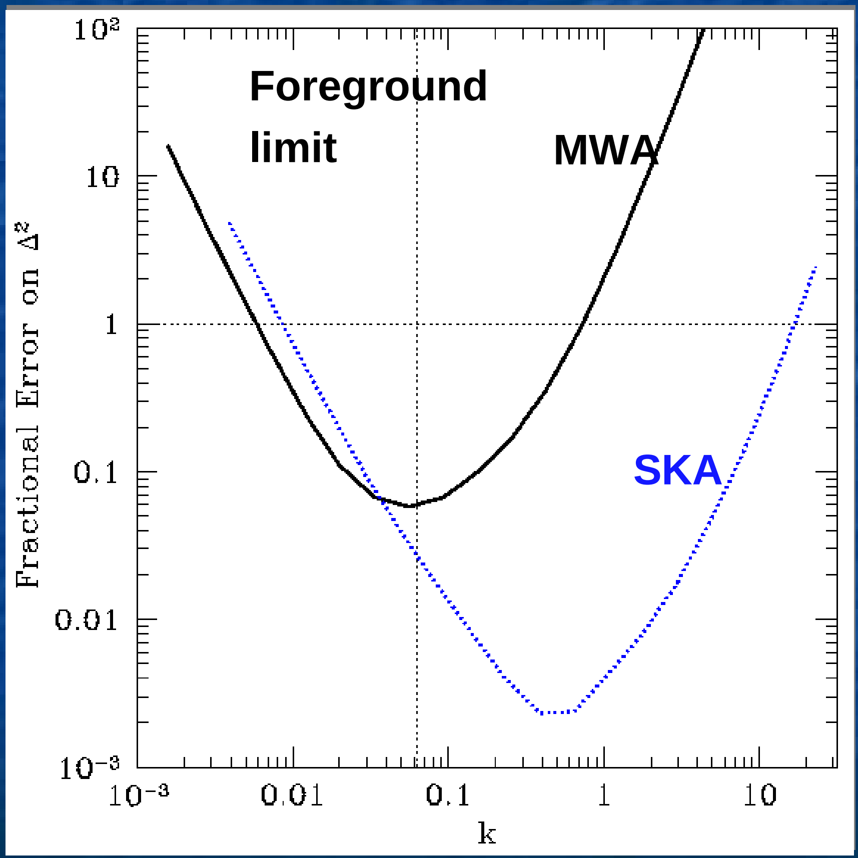
McQuinn et al. (2006)

The Power Spectrum

- Model allows us to compute statistical properties of signal
- Rich set of information from bubble distribution:
  - Timing: growth of structure
  - Underlying source population (SF, MM, LH 2005)
  - Uniform ionizing component (SF, MZ, LH 2004b)
  - Feedback (SF, MZ, LH 2004b)
  - Correlation with density field (SF, MZ, LH 2004b)
- Also must consider higher-order statistics!

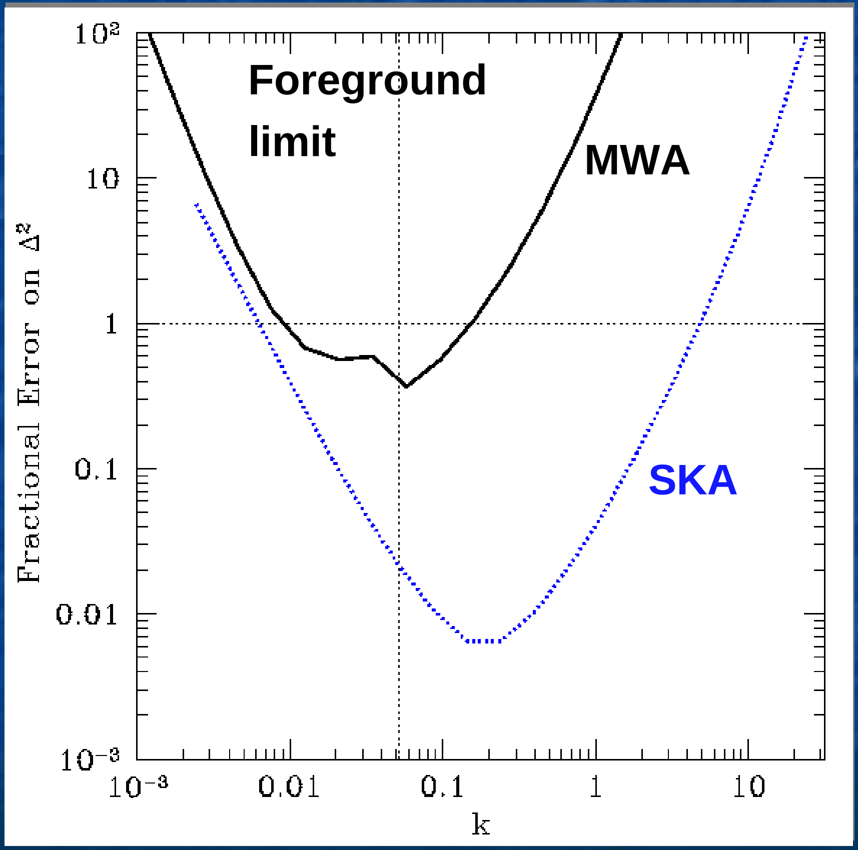


Error Estimates: z=8



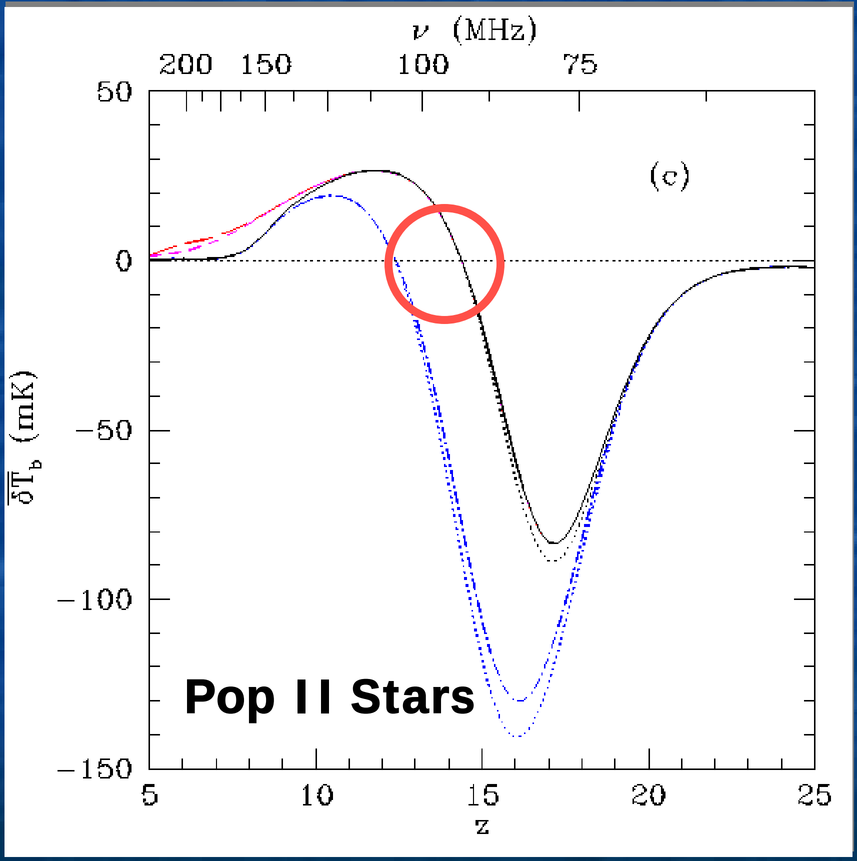
- Survey parameters
  - z=8
  - T_{sys}=440 K
  - t_{int}=1000 hr
  - B=6 MHz
  - No systematics!
- MWA (solid black)
  - A_{eff}=7000 m^2
  - 1.5 km core
- SKA (dotted blue)
  - A_{eff}=1 km^2
  - 5 km core

Error Estimates: z=12



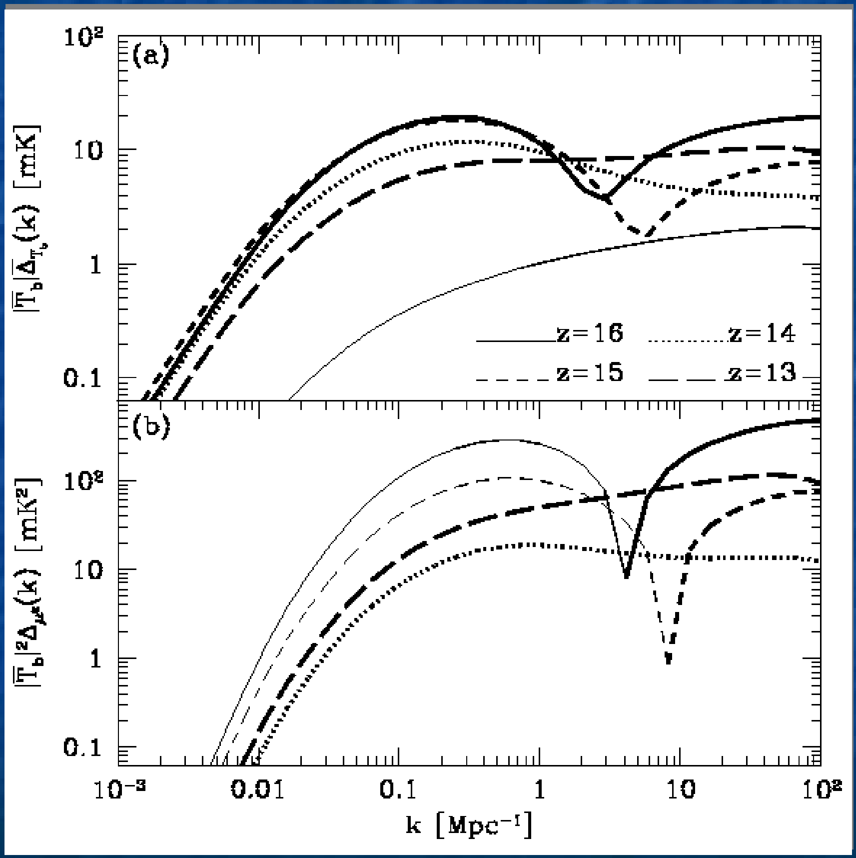
- Survey parameters
  - z=12
  - T_{sys}=1000 K
  - t_{int}=1000 hr
  - B=6 MHz
  - No systematics!
- MWA (solid black)
  - A_{eff}=9000 m^2
  - 1.5 km core
- SKA (dotted blue)
  - A_{eff}=1 km^2
  - 5 km core

Before Reionization



SF (2006)

The Heating Era



Pritchard & Furlanetto (2006)

- X-rays seed fluctuations in T_S (and hence δT_b)
  - Discrete (biased) sources and $1/r^2$ flux
  - Soft X-rays have shorter mean free paths
  - Rapid structure formation
- Also imprints features on power spectrum

The 21 cm Line and Fundamental Cosmology

- Matter power spectrum at z<20
  - Additional information on small-scale power spectrum (McQuinn et al. 2006, Bowman et al. 2006)
- The REAL "dark ages" (z>50)
  - Clean power spectrum (Loeb & Zaldarriaga 2004)
  - Sensitive to exotic physics (Furlanetto, Oh, & Pierpaoli 2006)
- Weak Lensing
  - Multiple source screens! (Mandel & Zaldarriaga 2006, Zahn & Zaldarriaga 2006)
  - Small-scale structure

Conclusions

- Fundamental Cosmology
  - True precision measurements of H_0 (high frequency, long baselines)
  - HI surveys and weak lensing: dark energy (large field of view)
  - 21 cm tomography as well, but need huge collecting area
- Astrophysical Cosmology
  - High-redshift galaxy surveys
  - 21 cm tomography (low frequencies, large field of view)

See our *Physics Reports* review (Furlanetto, Oh, & Briggs 2006, astro-ph/0608032) for more information on 21 cm possibilities!