Cosmology at Low Radio Frequencies

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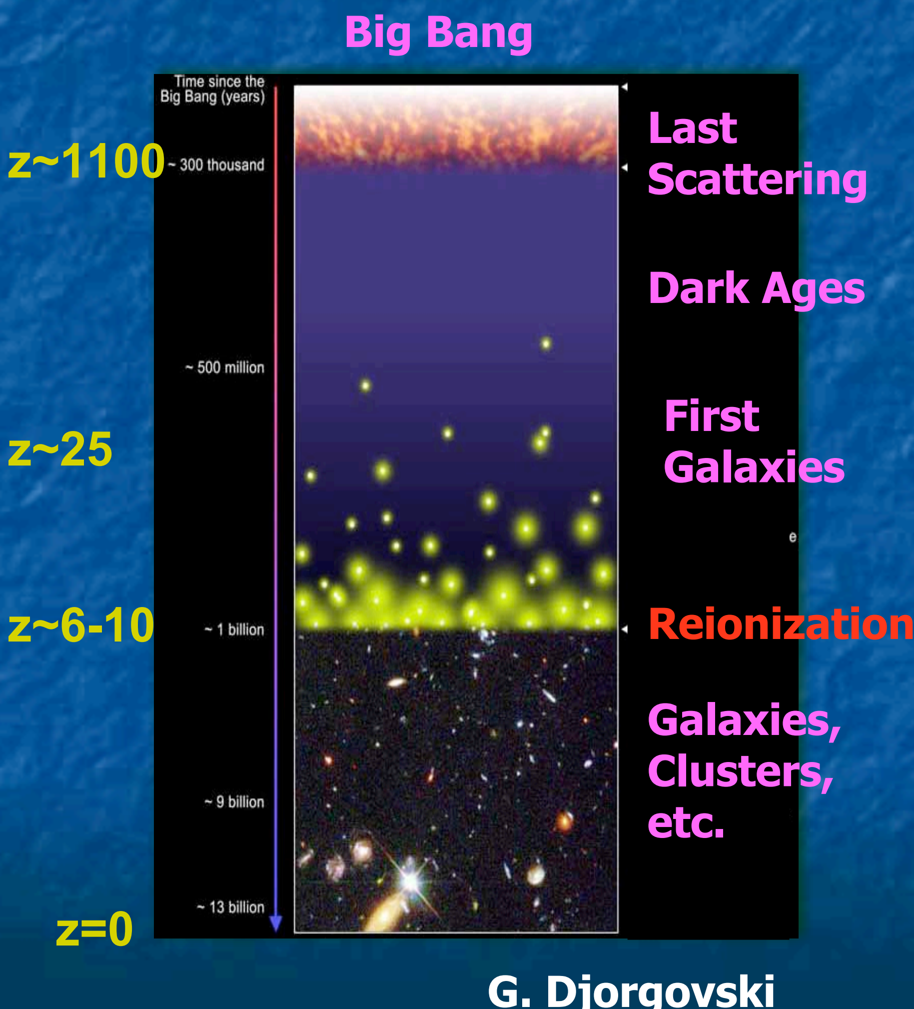
Yale University
January 22, 2007

Outline

- The Dark Ages and First Light
- The 21 cm Transition as a Cosmological Probe
  - Basic Physics
  - The Mean 21 cm Background
- Measurements and Instruments
  - Challenges
  - Sensitivity
  - Statistical Measurements
- The Fluctuating Sky
  - The Pre-reionization IGM
  - Reionization
- Conclusion

A Brief History of the Universe



- 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: ?

Why are they interesting?

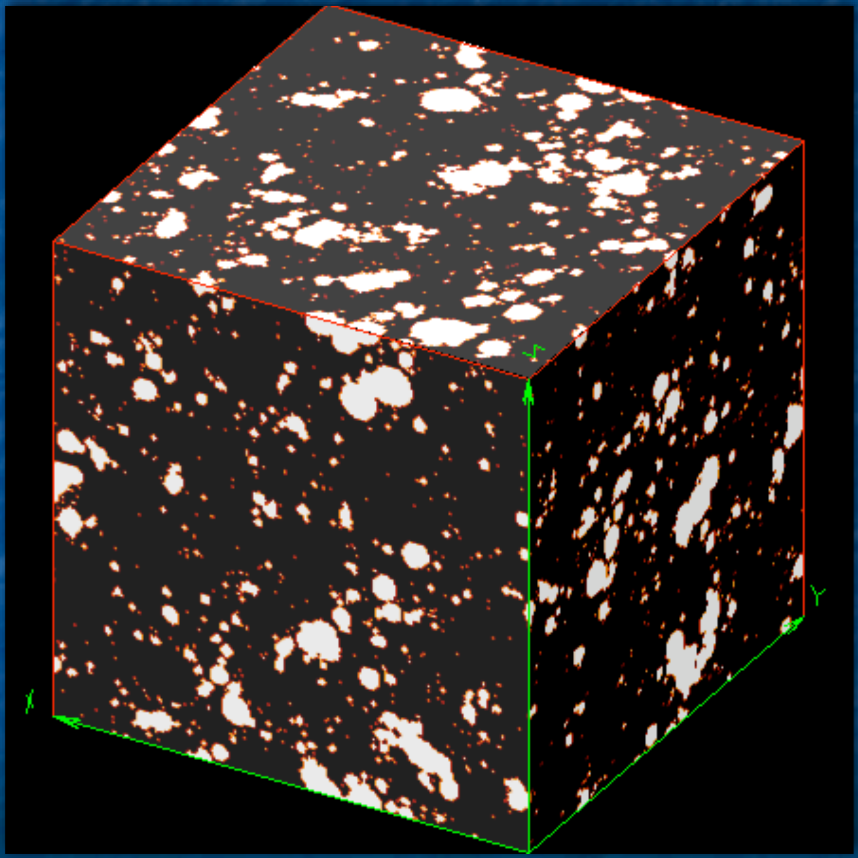
- From an astrophysical perspective…
  - Form seeds of modern galaxies and supermassive black holes
  - “Simple” laboratory for star formation
  - Feedback affects future generations
- From a fundamental physics perspective…
  - Study linear distribution of matter
  - Formation of first objects sensitive to details of matter power spectrum
  - “Cleaner” tests of fundamental physics
  - New source screen for “secondary” measurements

What do we know about the first galaxies?

- Distant, faint, and IR
- Hierarchical structure formation implies intrinsically small galaxies (~10^8-10^9 Msun)
- Most distant confirmed galaxies observed at z=6.6 (~1 billion years after Big Bang)
- Six recent candidates at z=8.7-10.2 (Stark et al. 2007), using ~150 ksec on Keck!
- “Great Leap Forward” will require JWST/JDEM and/or 30 m

Reionization

- First stars and galaxies produce ionizing photons
- Ionized bubbles grow and merge
- Affects all baryons in the universe
- Important feedback mechanism for later generations of structure



Mesinger & Furlanetto

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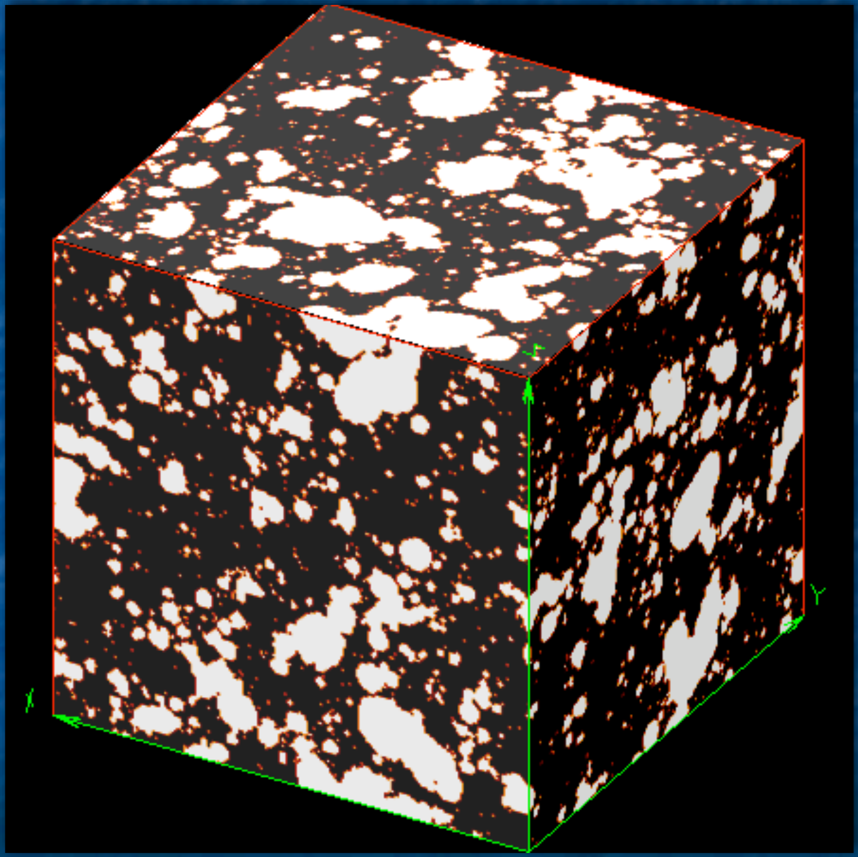

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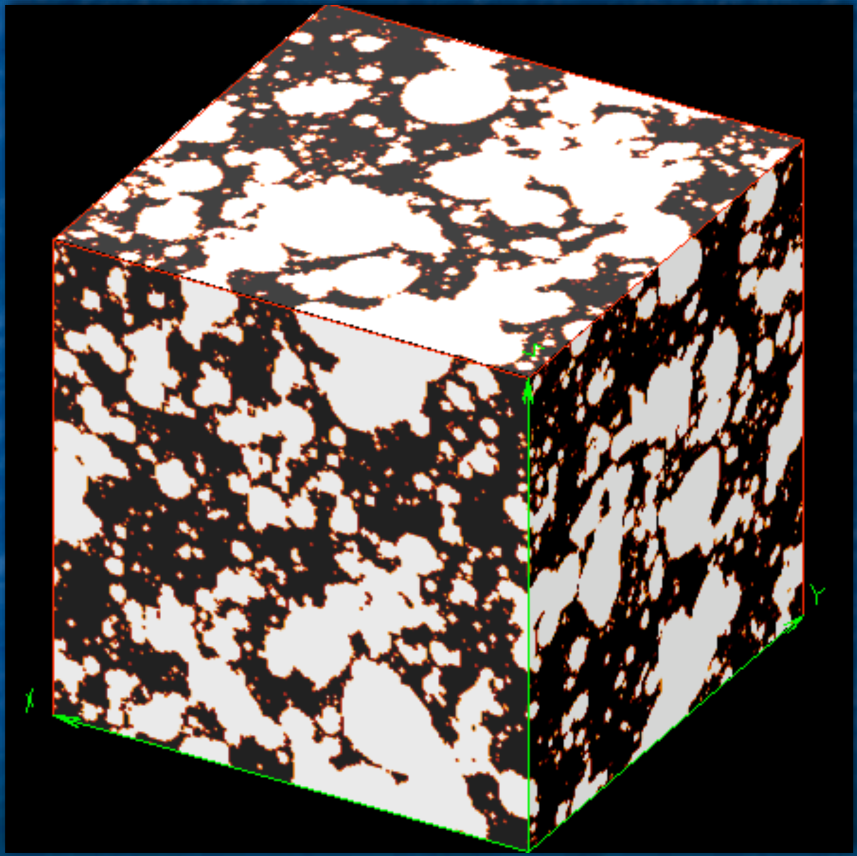

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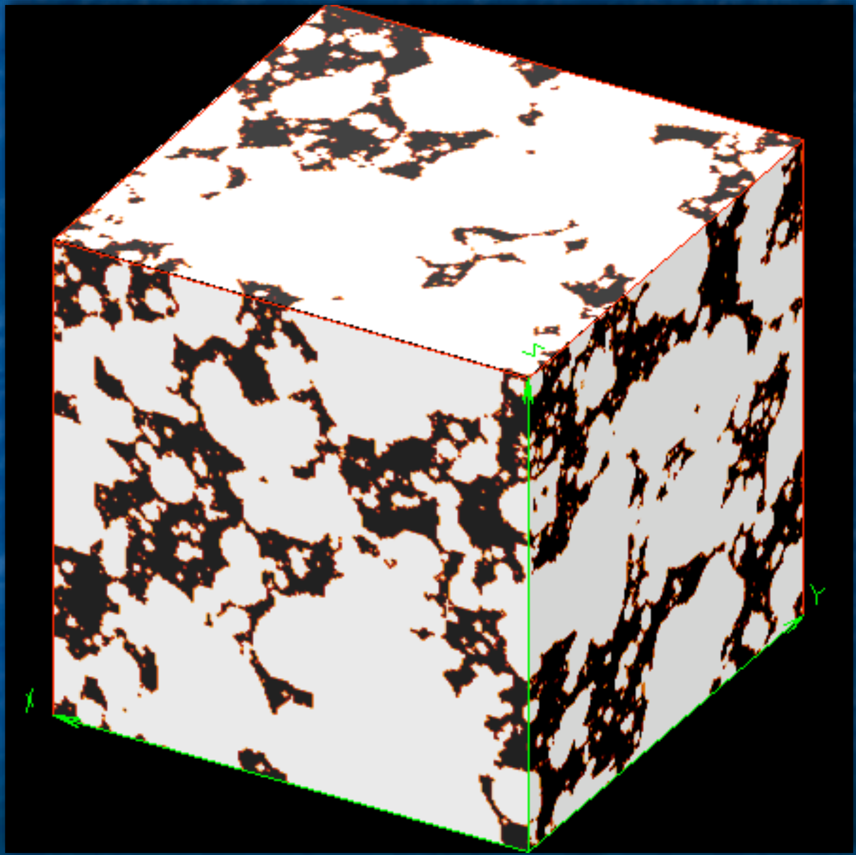
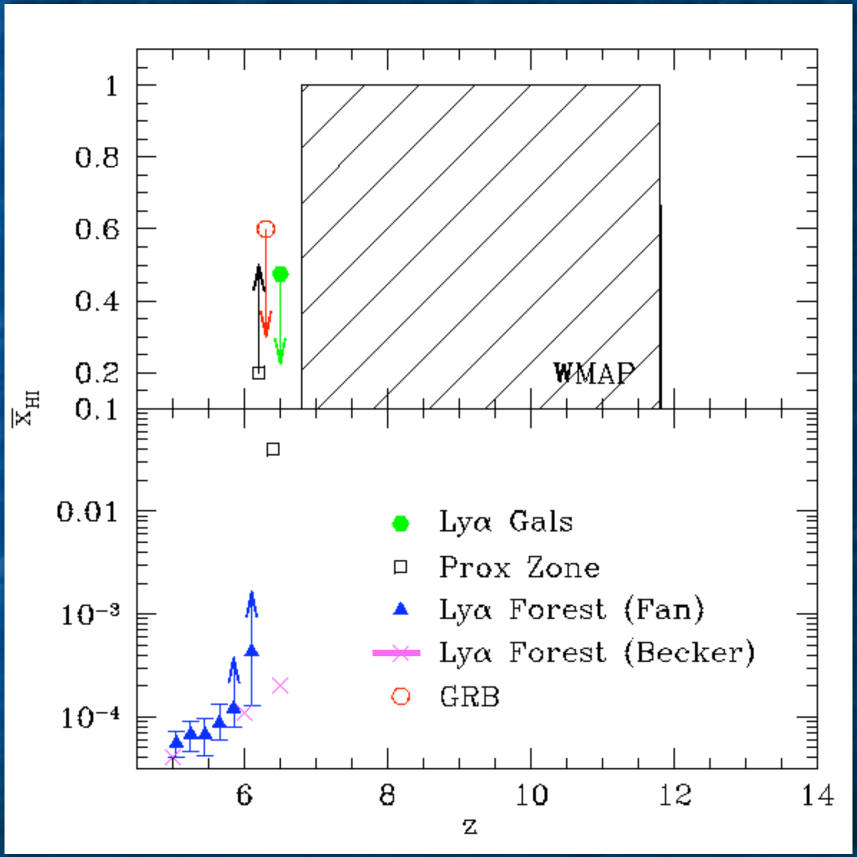


Mesinger & Furlanetto

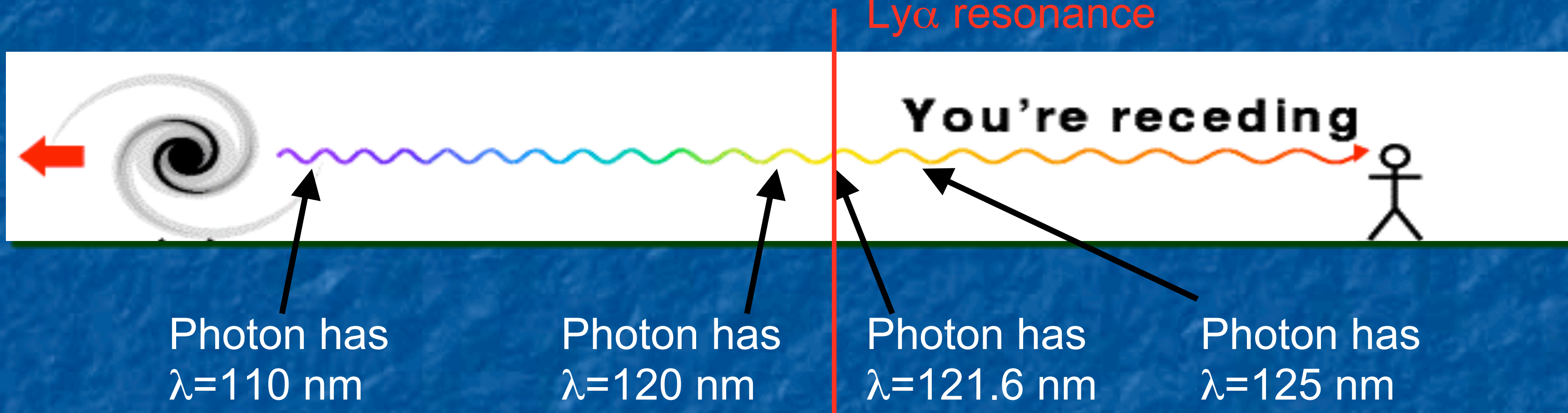
Reionization: Observational Constraints

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



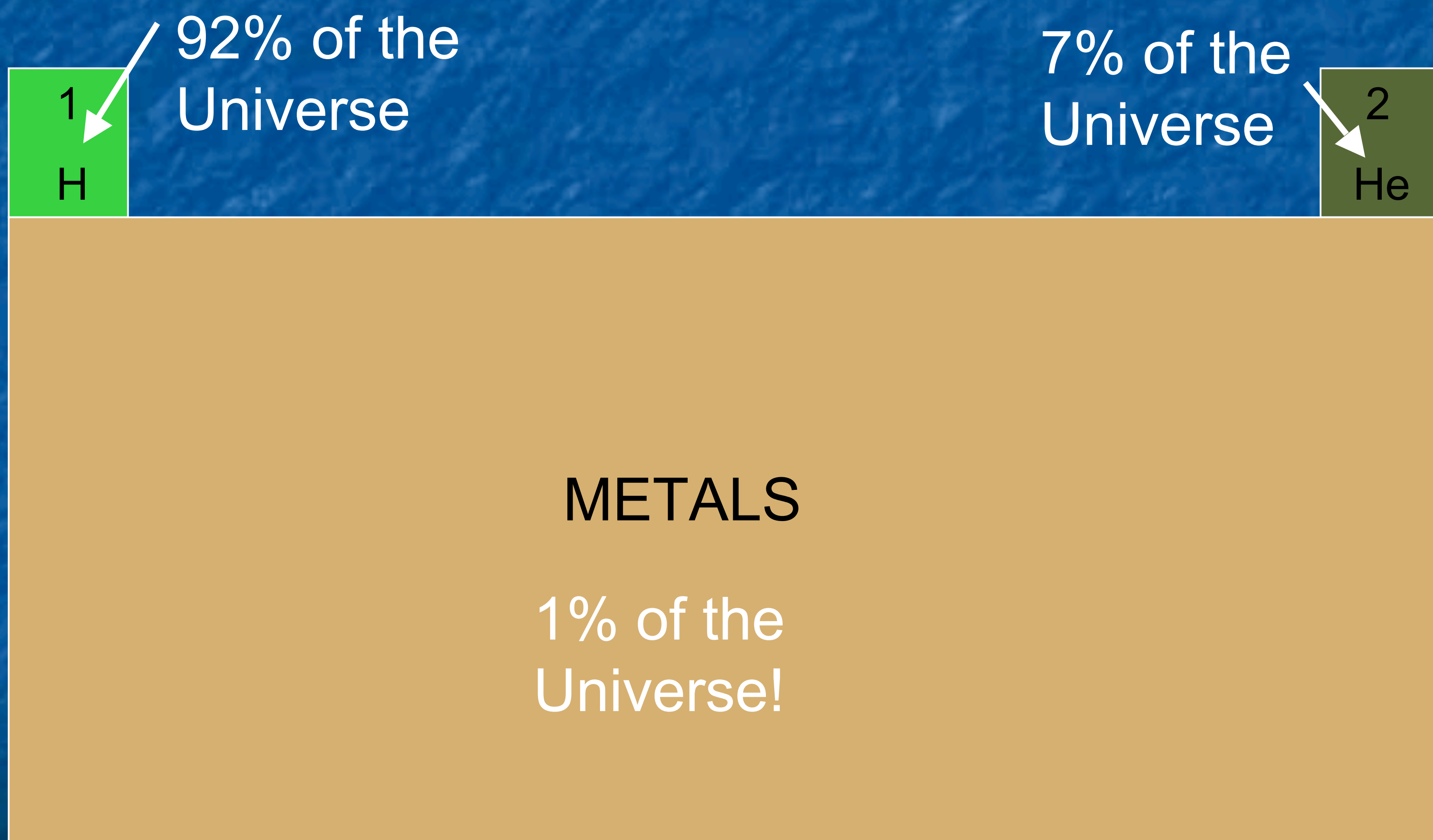
Furlanetto, Oh, & Briggs (2006)

Lyα Absorption



- Absorption occurs if frequency matches n=1-2 transition (at λ=121.6 nm)
- If there is neutral hydrogen when light passes through resonance, it gets absorbed!

The Astronomer's Periodic Table



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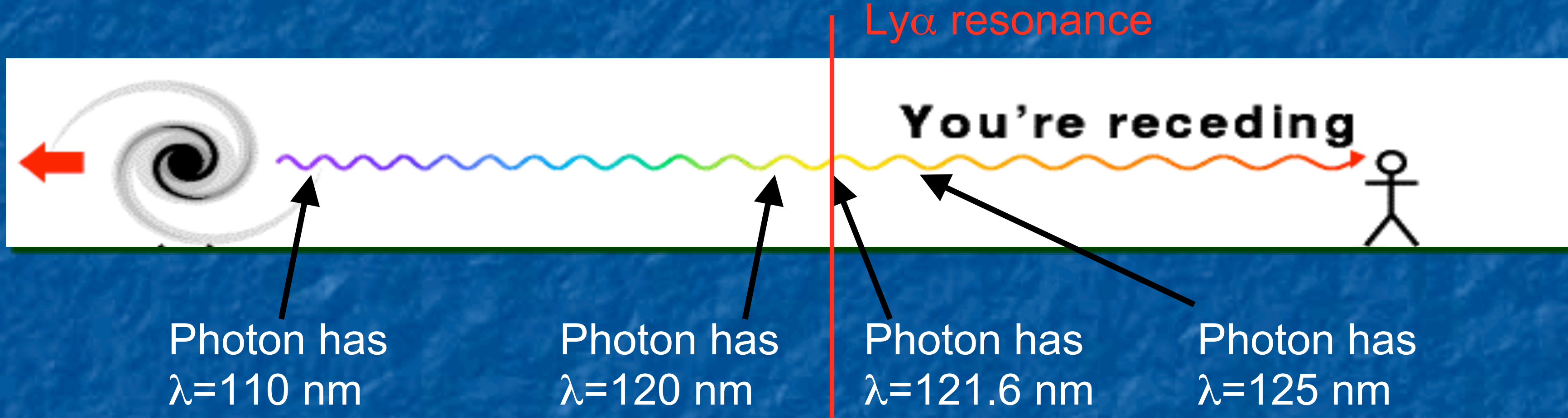

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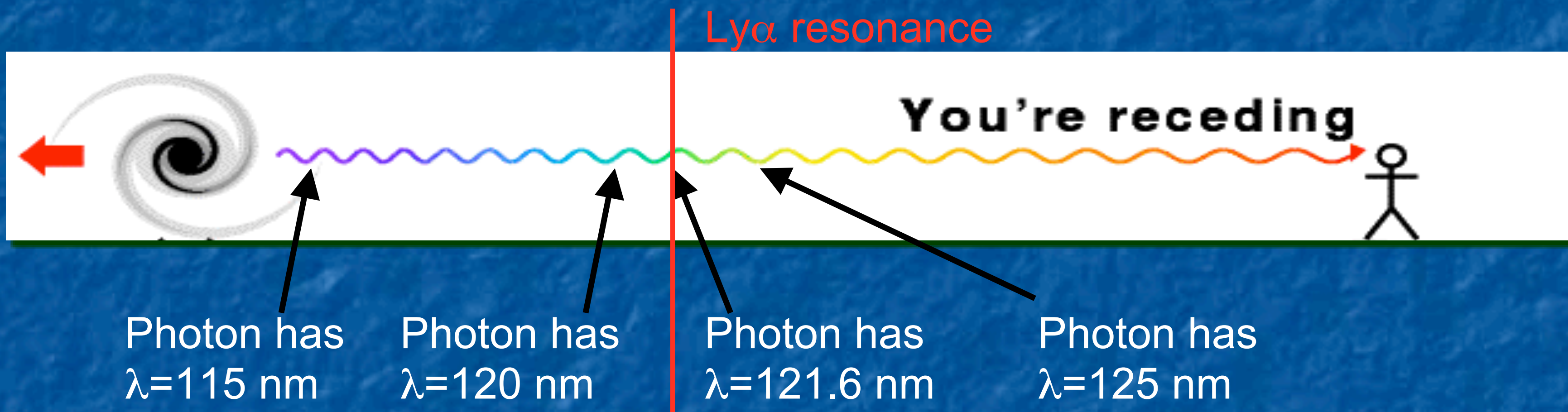
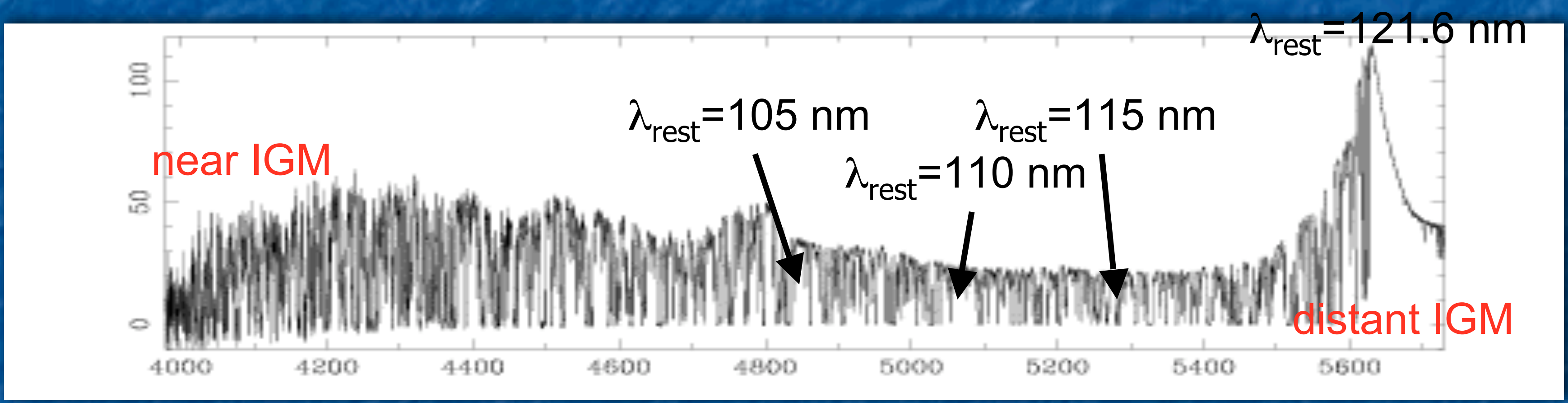


- Each wavelength reaches resonance at a different location in the IGM

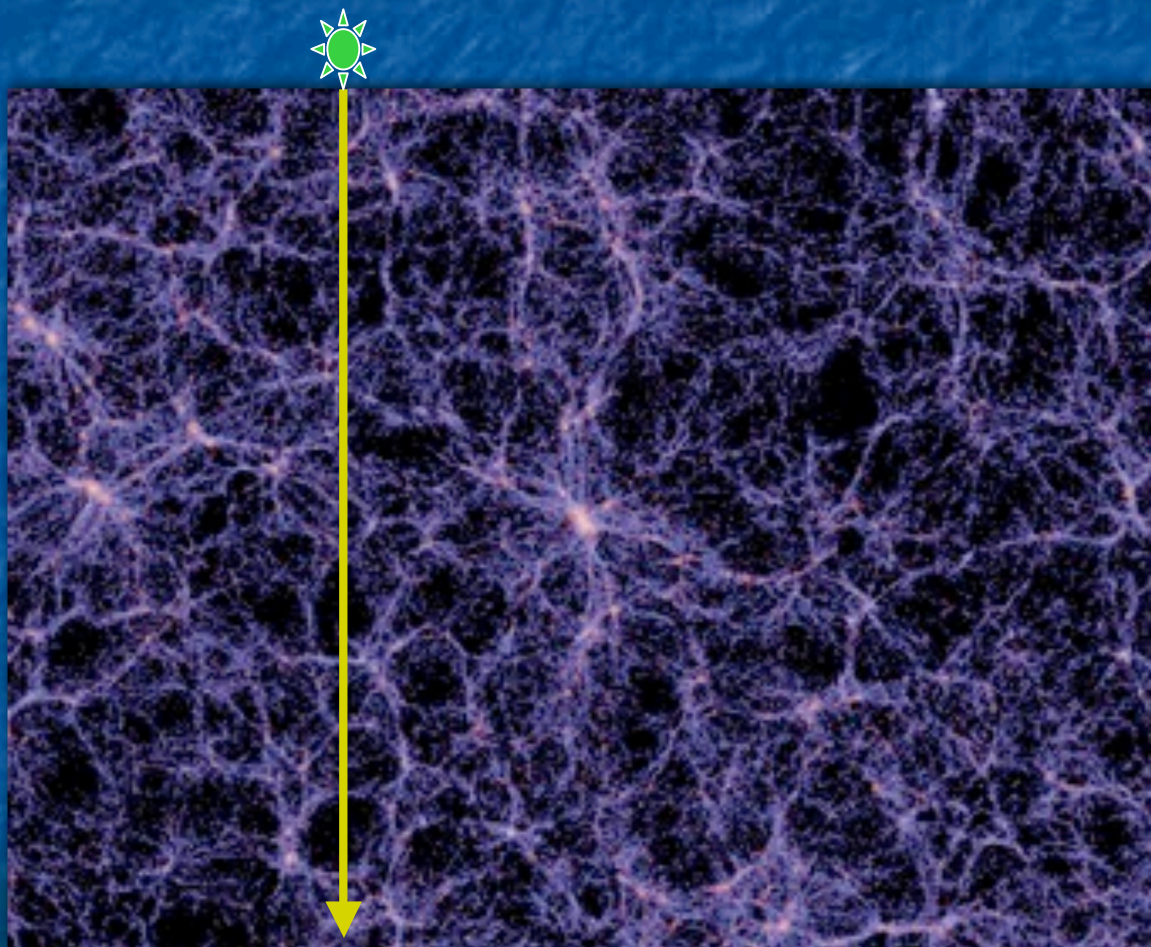
The Lyα Forest



Rauch (2001)

- Amount of absorption depends on local gas density → "forest" of absorption features between us and the object

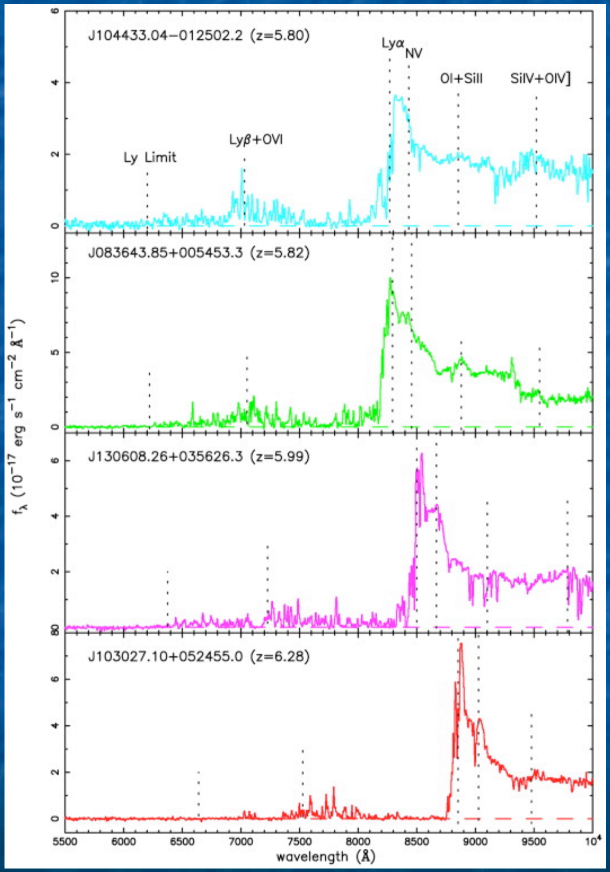
The Cosmic Web



V. Springel et al.

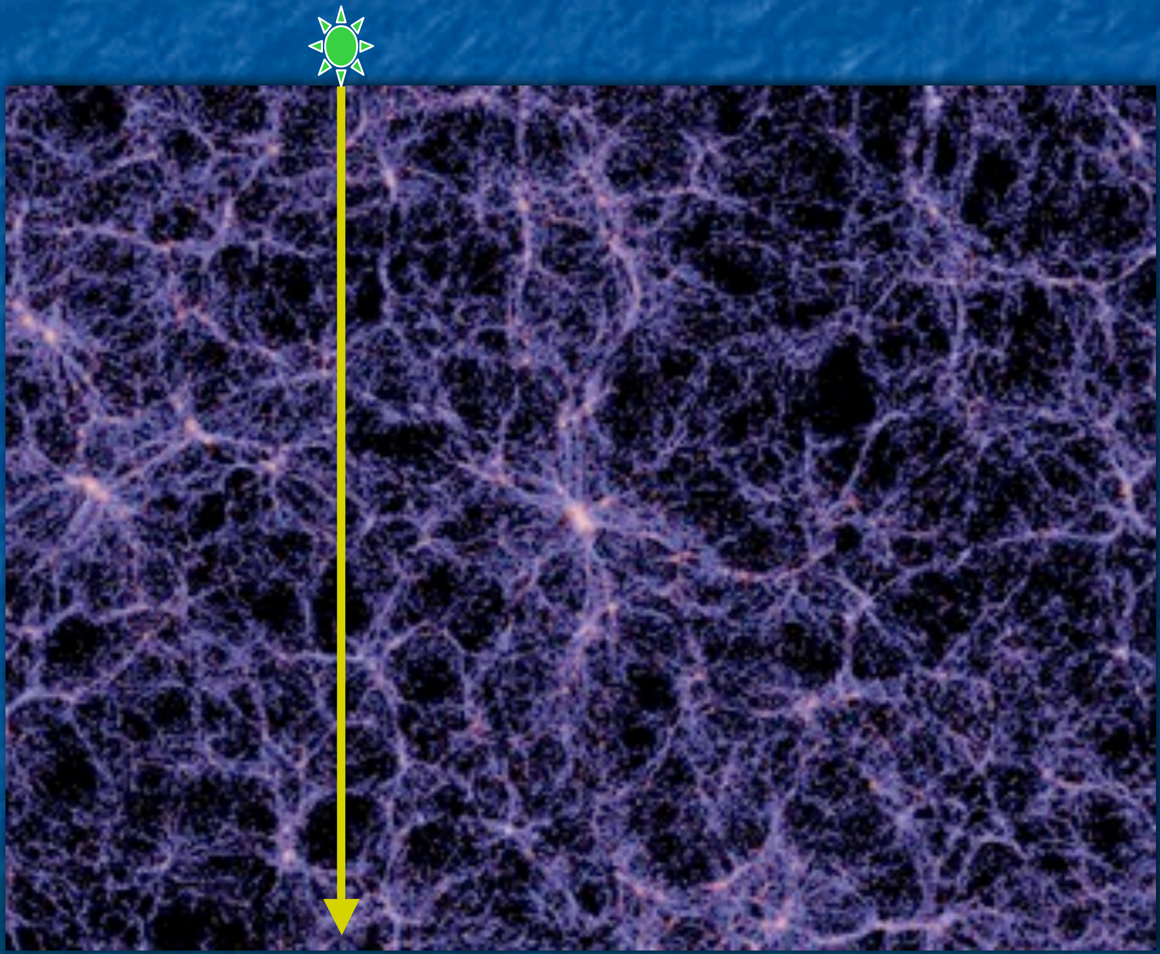
The Lyα Forest at High Redshifts

- Lyα forest gets deeper with redshift
- Universe becomes more neutral
- Complete absorption by z=6.3!
- What does this mean for neutral fraction, though?



Becker et al. (2001)

The Cosmic Web



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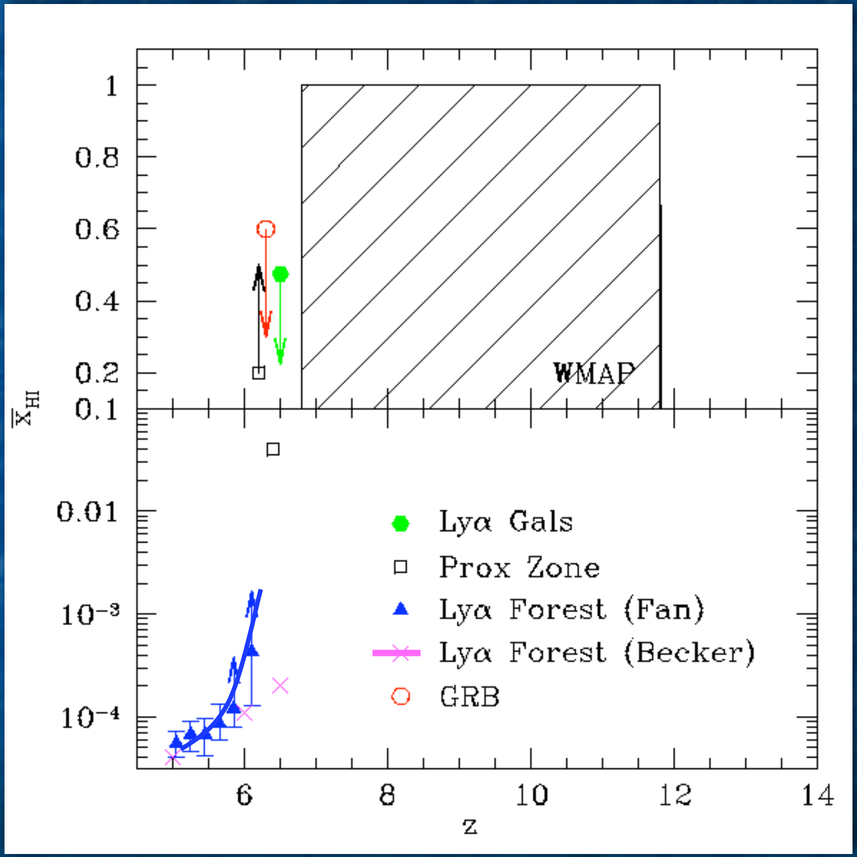

Furlanetto, Oh, & Briggs (2006)

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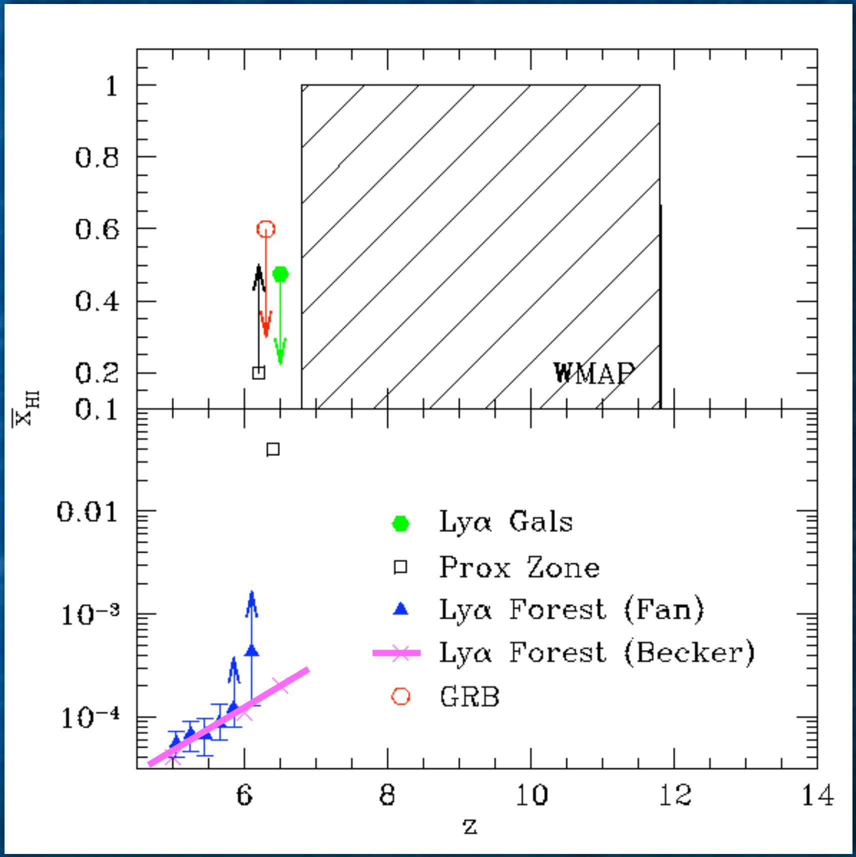
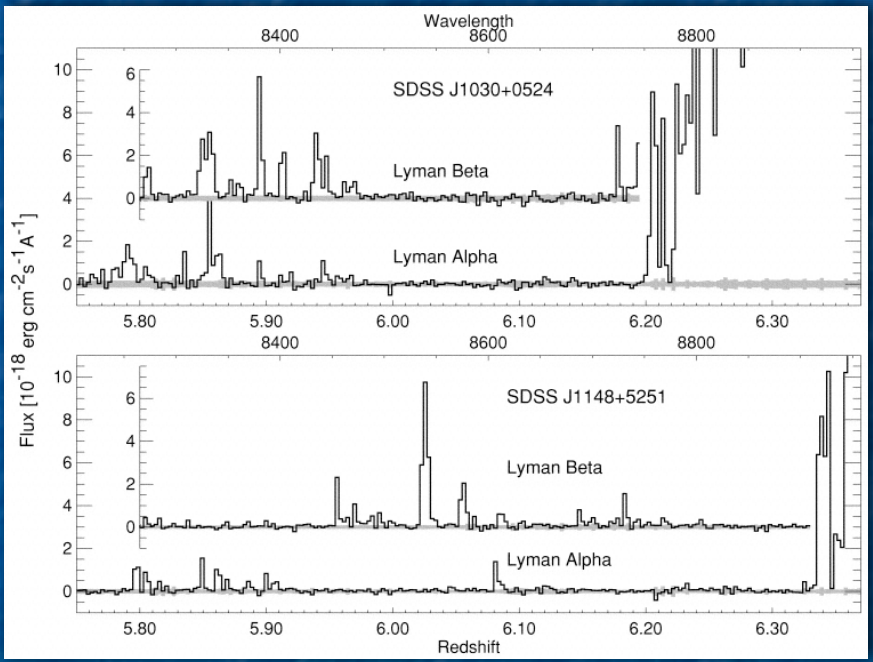


Furlanetto, Oh, & Briggs (2006)

SDSS Quasars: Line of Sight Variations

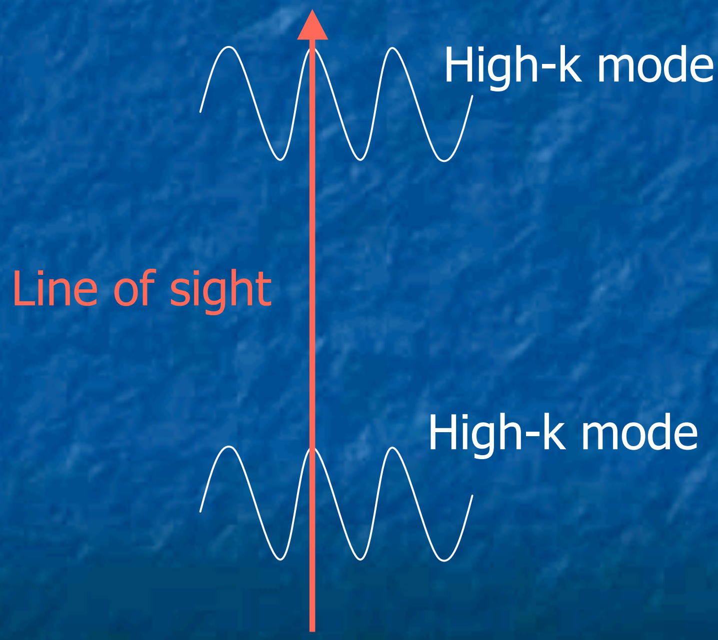


White et al. (2003)

- 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)



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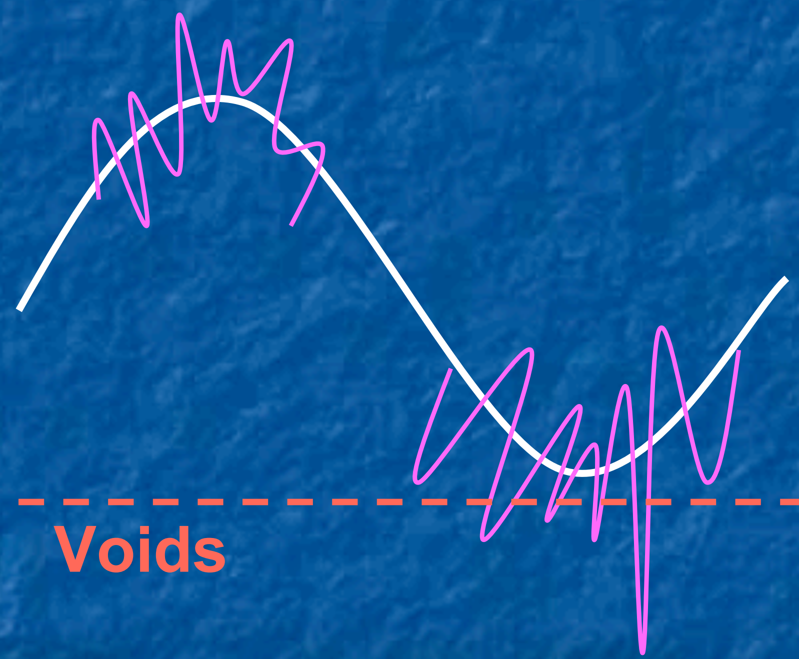
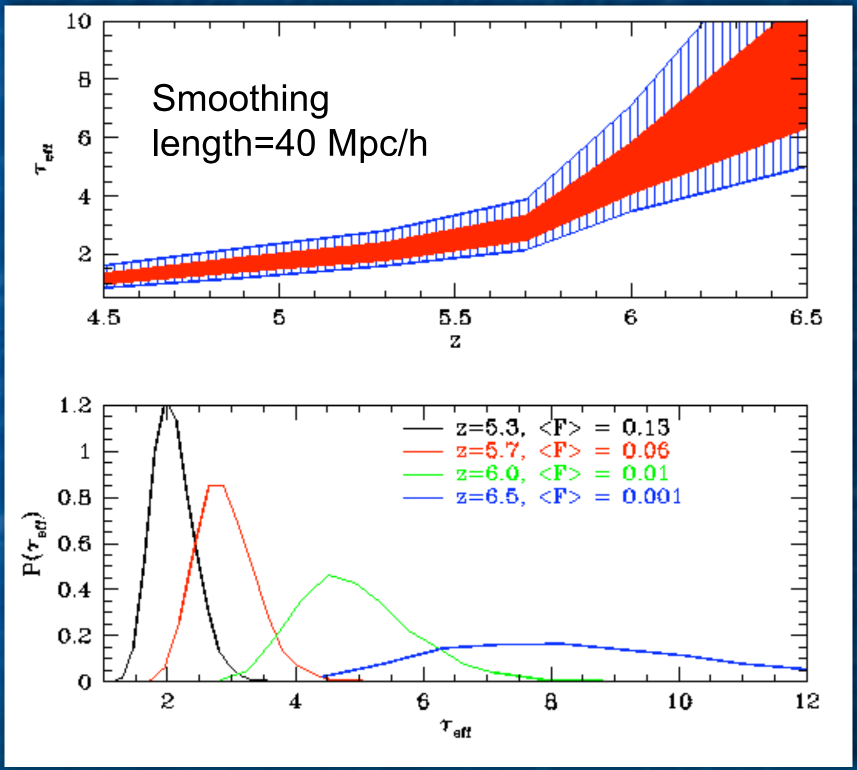


SDSS Quasars: Line of Sight Variations

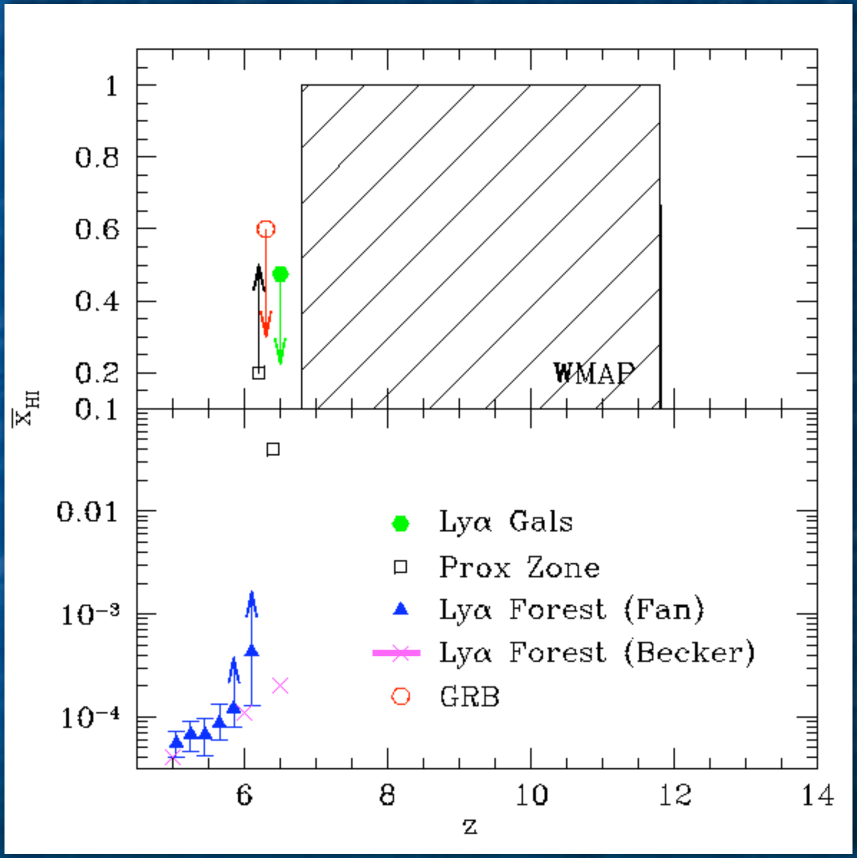
- But complications!
  - Aliasing (Kaiser & Peacock 1991)
  - Transmission bias because only see through rare voids
- Observed variance slightly more than expected from uniform ionizing background
  - Structure in intrinsic quasar spectra is likely another significant contributor



Lidz, Oh, & Furlanetto (2006)

Reionization: Observational Constraints

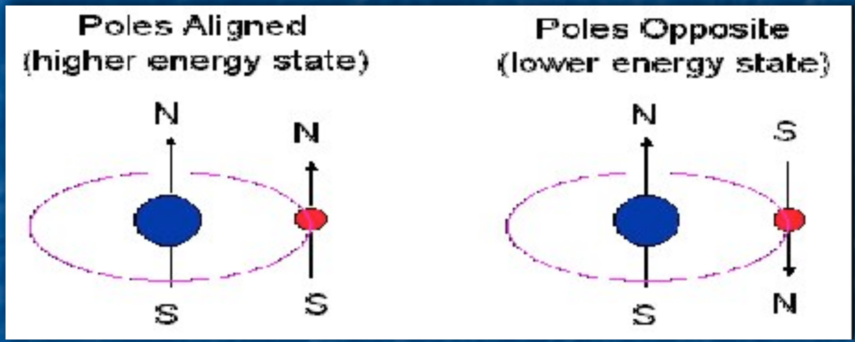
- Quasars/GRBs
  - Nearly saturated absorption
  - Sparse background lights
- CMB optical depth
  - Essentially integral constraint
- Lyα-selected galaxies
  - Uncertain source populations
  - Small volumes



Furlanetto, Oh, & Briggs (2006)

The Spin-Flip Transition

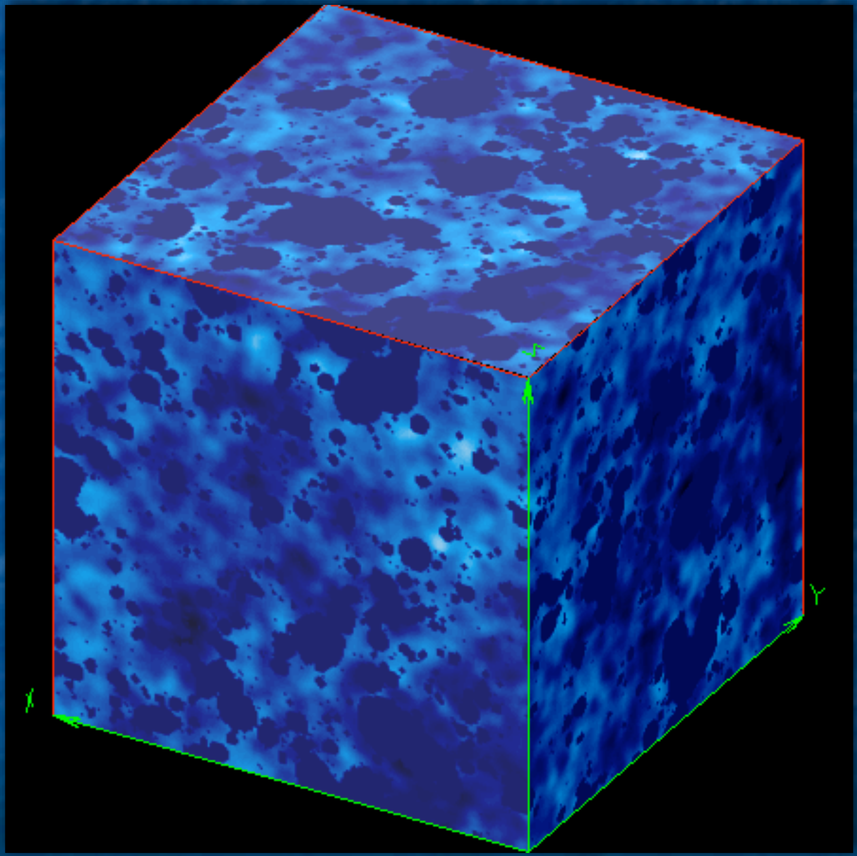
- Proton and electron both have spin ➜ magnetic fields
- Produces 21 cm radiation (ν =1420 MHz)
- Extremely weak transition
  - Mean lifetime ~10^7 yr
  - Optical depth ~1% in fully neutral IGM



The 21 cm Transition

- Map emission (or absorption) from IGM gas
  - Spectral line: measure entire history
  - Direct measurement of IGM properties
  - Can use CMB as a backlight
  - No saturation!

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



Mesinger & Furlanetto

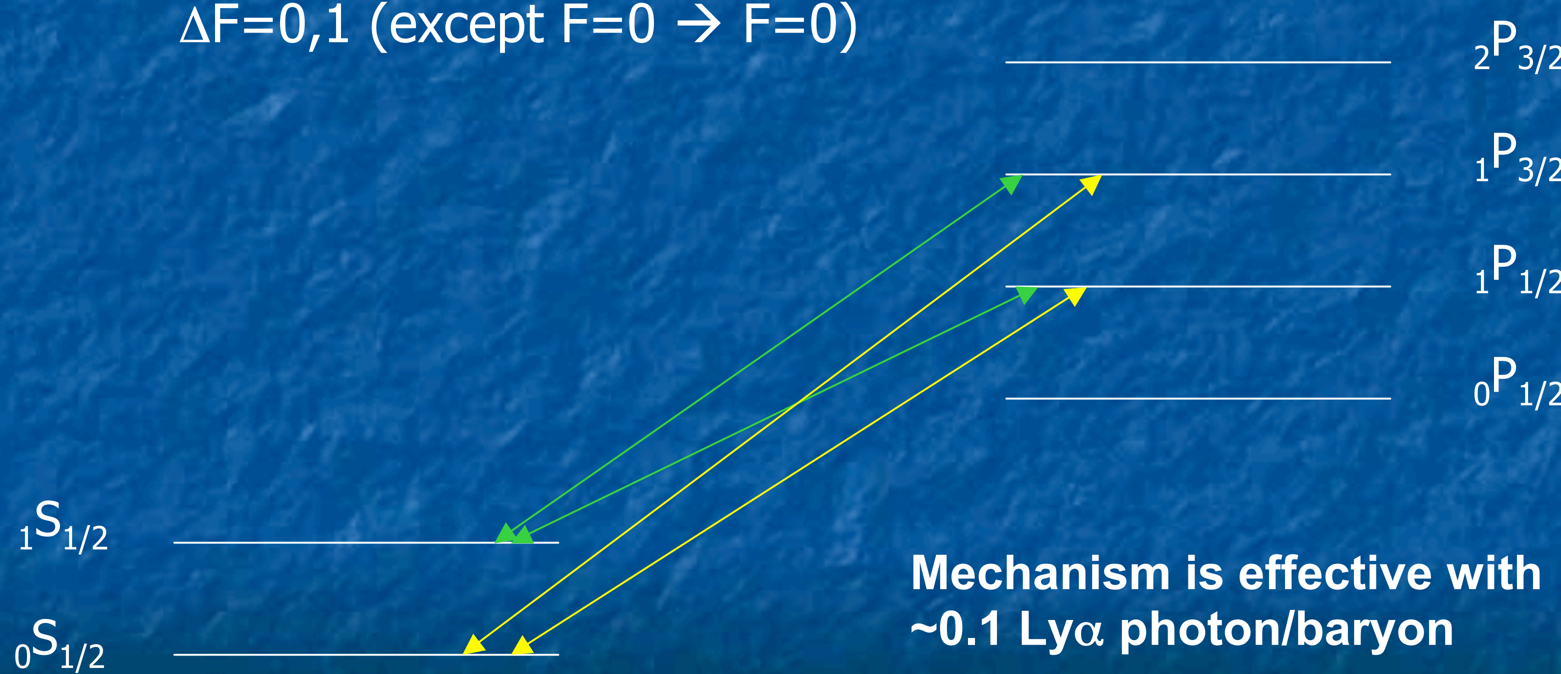
The Spin Temperature

- CMB photons drive toward invisibility: $T_S = T_{CMB}$
- Collisions couple T_S to T_K
  - Efficient when $\delta > 15\,[10/(1+z)]^2$ if relatively hot
  - Dominated by electron exchange in H-H collisions in neutral medium (Zygelman 2005)
  - Dominated by H-e^- collisions in partially ionized medium (Furlanetto & Furlanetto 2006), with some contribution from H-p collisions (Furlanetto & Furlanetto 2007)

The Wouthuysen-Field Mechanism I

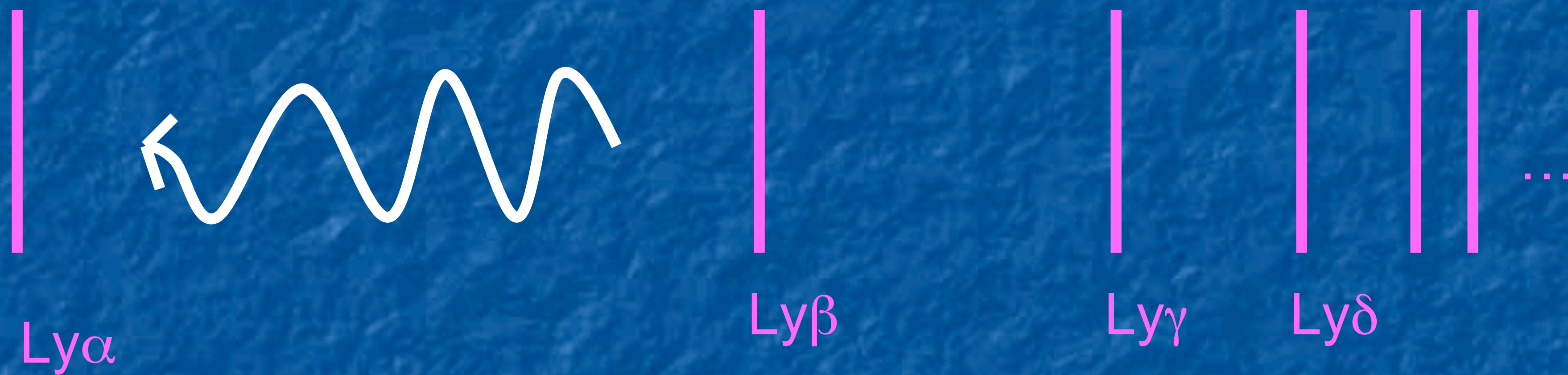
Selection Rules:

$\Delta F=0,1$ (except $F=0 \rightarrow F=0$)



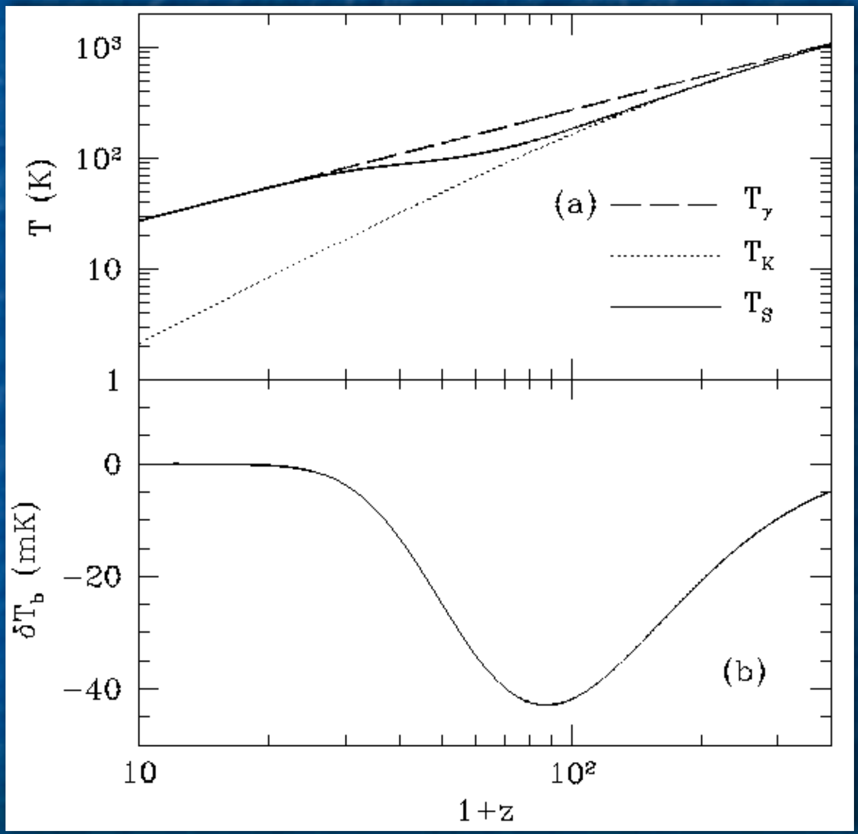
Mechanism is effective with ~0.1 Lyα photon/baryon

The Wouthuysen-Field Mechanism II



- Relevant photons are continuum photons that redshift into the Lyα resonance (or higher Lyman-series and cascade)
  - See Hirata (2006), Pritchard & Furlanetto (2006) for cascades
  - See Furlanetto & Pritchard (2006) for coupling strengths

The Global Signal: The Dark Ages

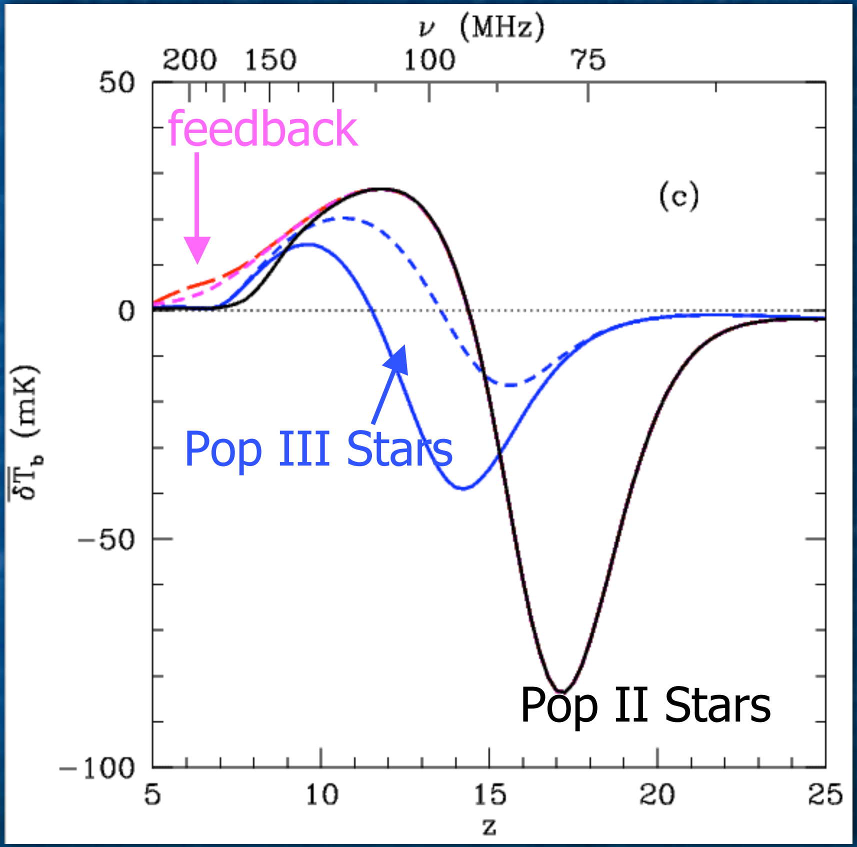


SF, PO, FB (2006)

- Straightforward physics
  - Expanding gas
  - Recombination
  - Compton scattering

The Global Signal: First Light

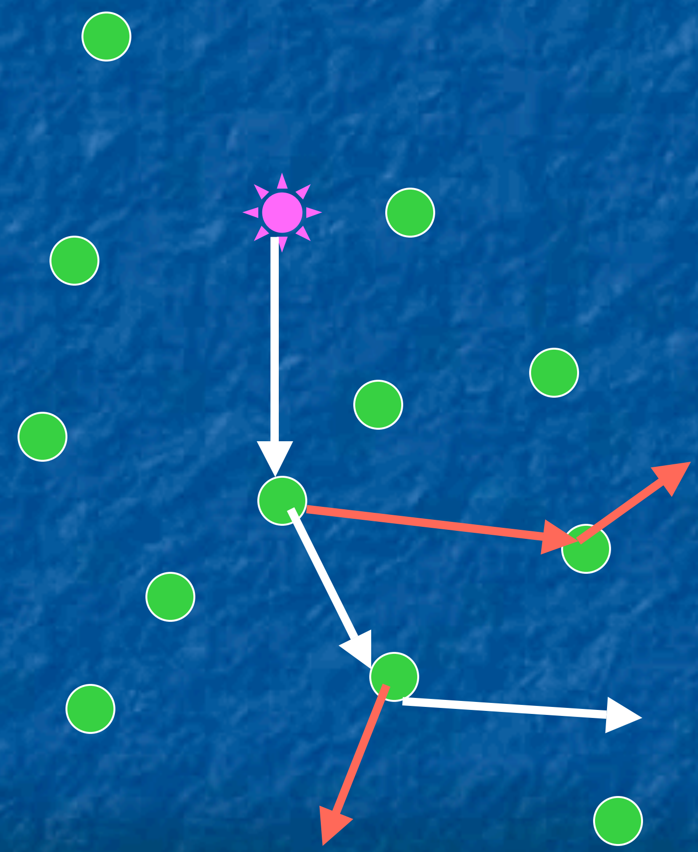
- First stars (quasars?) flood Universe with photons
  - Heating
  - W-F effect
  - Ionization
  - Timing depends on f_*, f_{esc}, f_X, stellar population



SF (2006)

X-ray Heating

- X-rays are highly penetrating in IGM
  - Mean free path >Mpc
  - Deposit energy as heat, ionization
- Produced by…
  - Stellar mass black holes
  - Quasars
  - Very massive stars (?)



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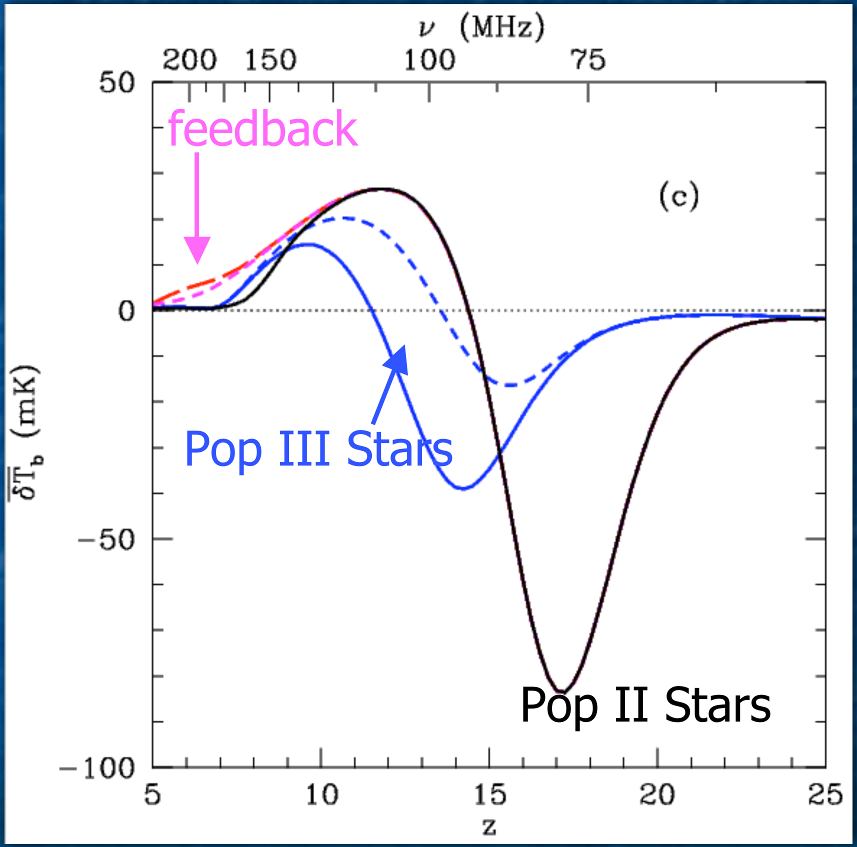


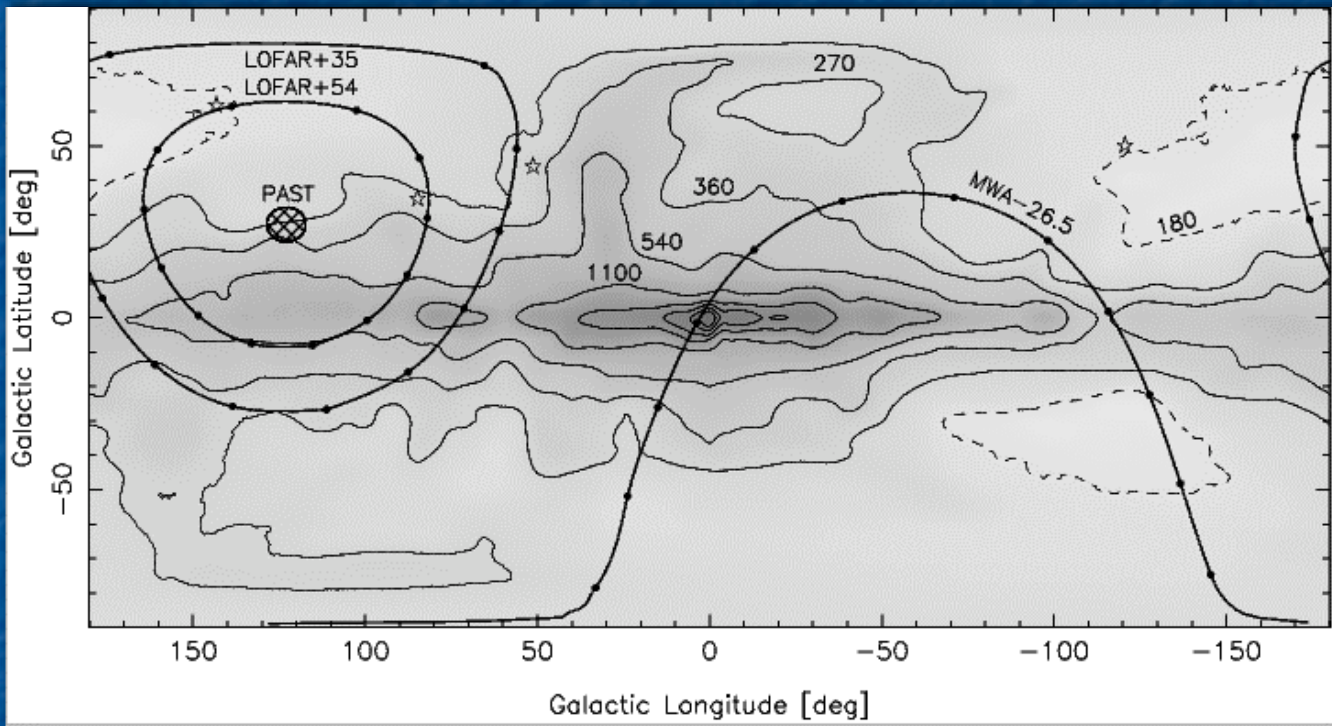
SF (2006)

21 cm Observations

- Experiments
  - Global Signal: CoRE-ATNF
  - Fluctuations: 21CMA, LOFAR, MWA, PAPER, SKA
  - Imaging: SKA
- Challenges
  - Terrestrial Interference:
    - Distance, Excision
  - Ionosphere
    - “Adaptive optics”
  - Foregrounds

MWA

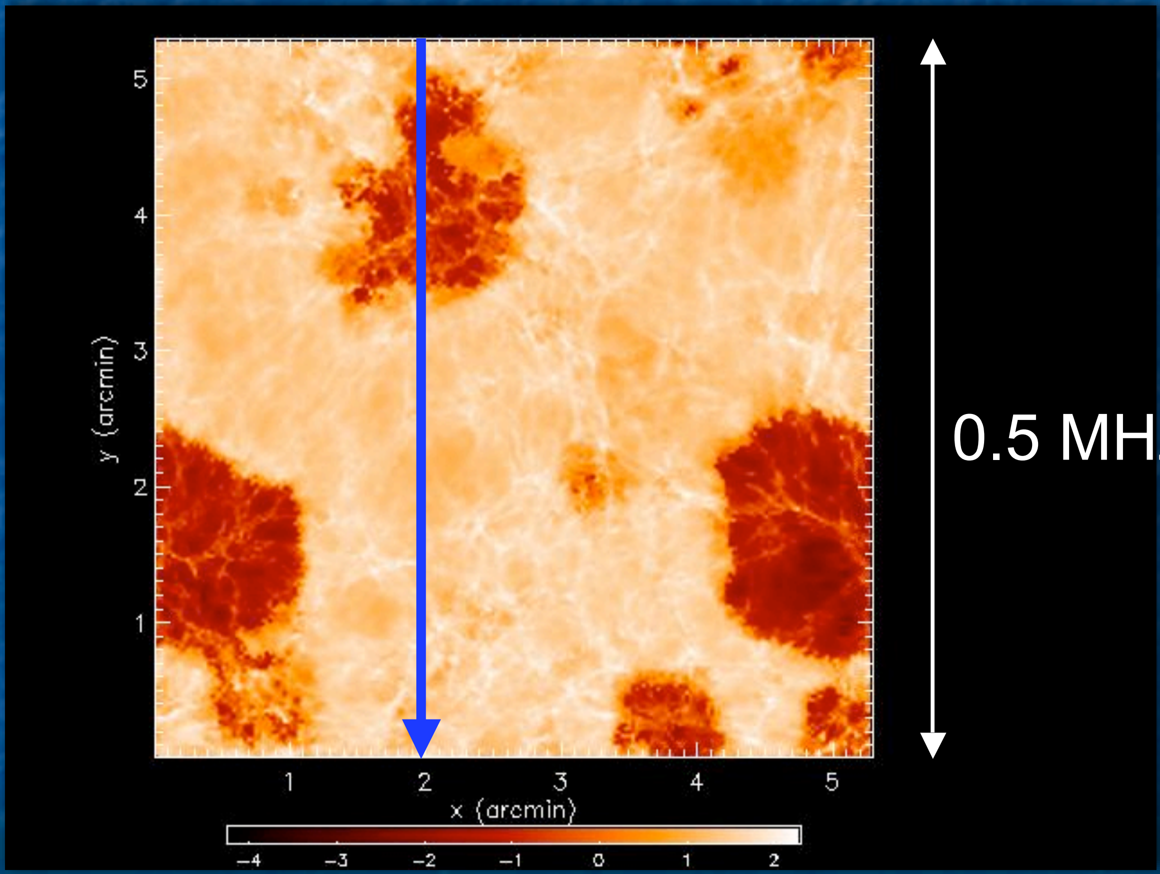
Astronomical Foregrounds



- Map at 150 MHz
- Contours are in Kelvin

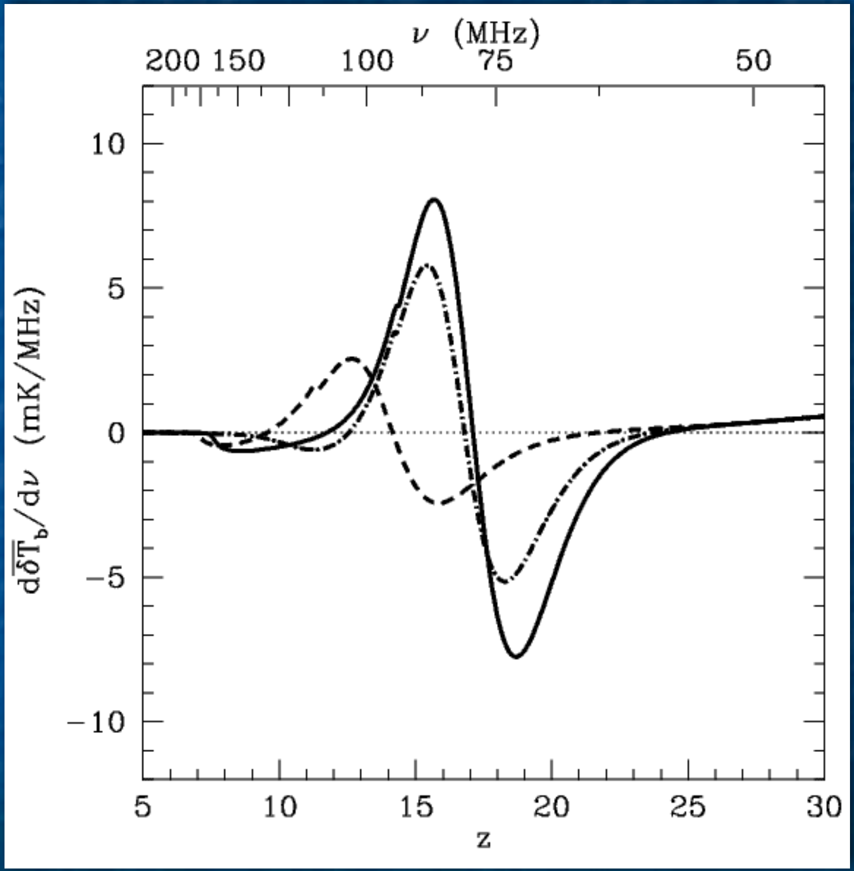
Landecker et al. (1969)

Foregrounds on Small Scales



Removal algorithms: Zaldarriaga, Furlanetto, & Hernquist (2004); Morales & Hewitt (2004); Santos et al. (2005), McQuinn et al. (2006)

Measuring the Global Signal?



SF (2006)

- Gradient is few mK/MHz
- Foregrounds vary as (near) power law
  - Synchrotron, free-free
  - Gradient is few K/MHz
- CoRE-ATNF experiment will try (PI: Ekers)

Foreground Noise

- Thermal noise is NOT smooth: varies between each channel
- For first generation instruments, 1000 hr observations still have S/N<1 per pixel
- Imaging is not possible until SKA!

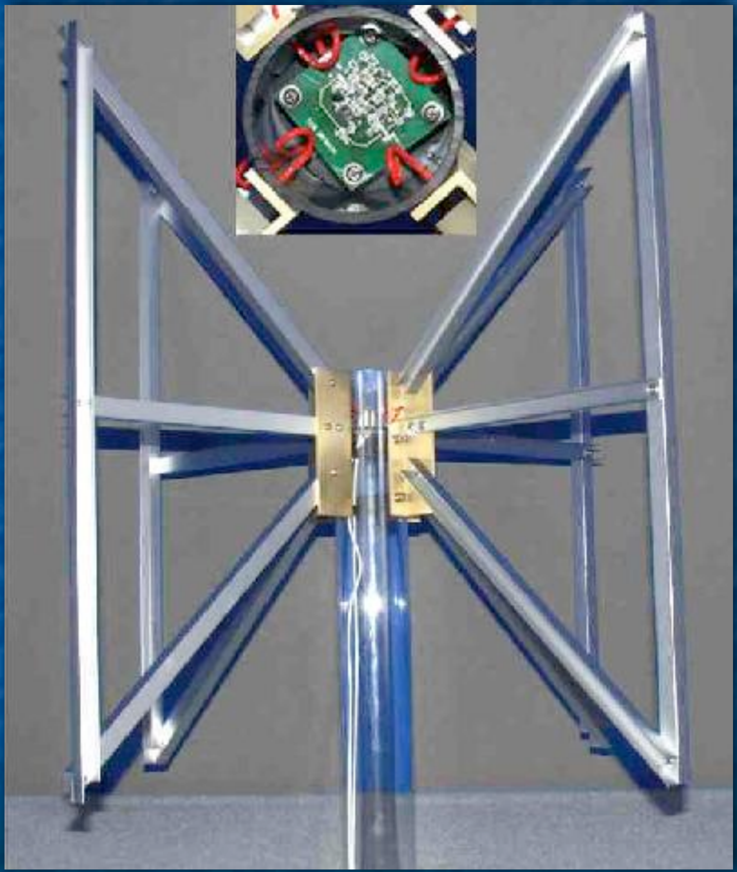
$$\delta T_b \approx 23 x_{HI} (1+\delta) \left(\frac{1+z}{10}\right)^{1/2} \left(\frac{T_S - T_{bkgd}}{T_S}\right) \left(\frac{H(z)/(1+z)}{\partial \mathrm{v}_{\mathrm{r}} / \partial r}\right) \mathrm{mK}$$

The Mileura Widefield Array

Bowman et al. (2007)

- Low Frequency Demonstrator under construction (fully funded, first light ~2008)
- Located on sheep ranch in Western Australia

The Mileura Widefield Array



Bowman et al. (2007)

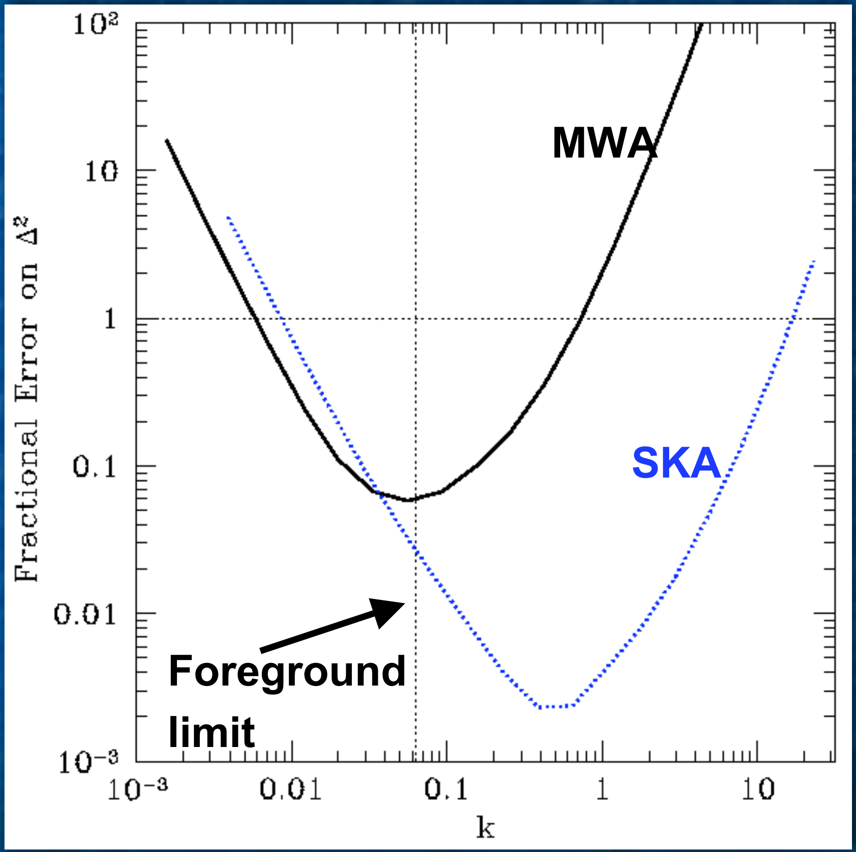
- Bowtie antennae grouped in tiles of 16
  - Broad frequency response
  - Large field of view

Mileura Widefield Array: Low Frequency Demonstrator

- Instrument characteristics
  - Radio-quiet site
  - 500 16-element antennae in 1.5 km distribution
  - 10^4 m^2 total collecting area
  - Full cross-correlation of all 500 antennae
  - 80-300 MHz
  - 32 MHz instantaneous bandwidth at 8 kHz resolution
  - 20-30 degree field of view

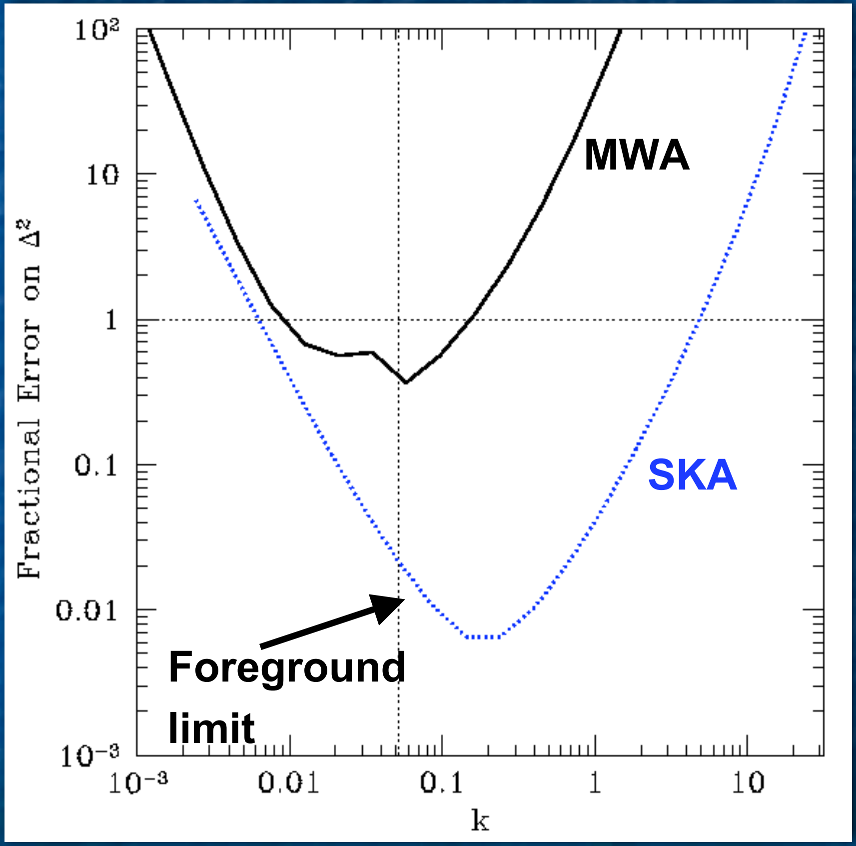
Bowman et al. (2007)

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
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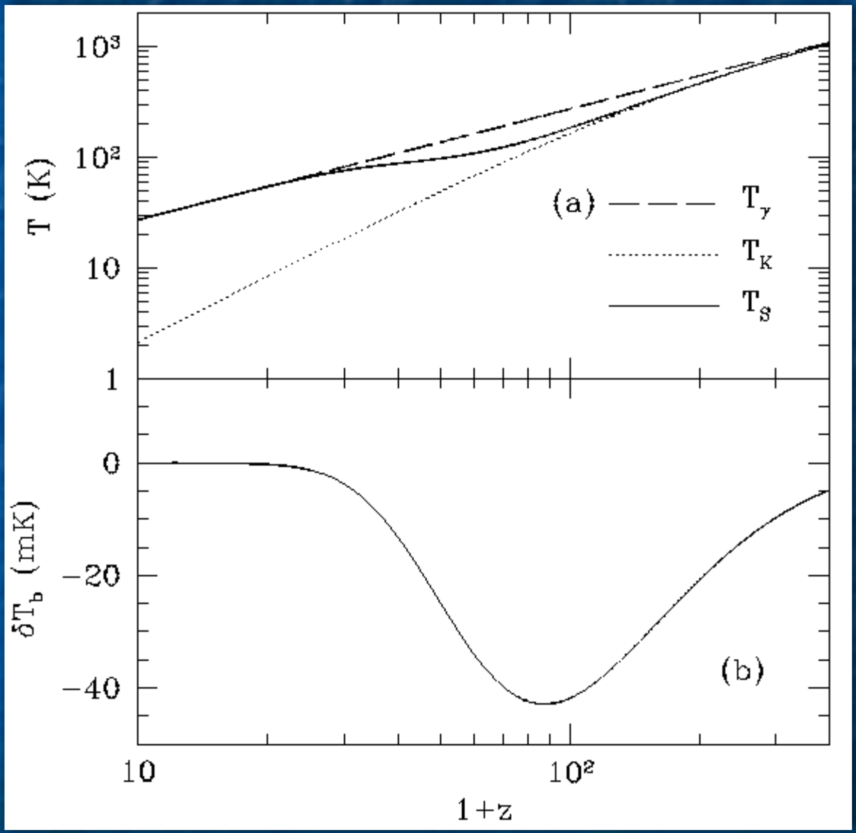
The Global Signal: The Dark Ages

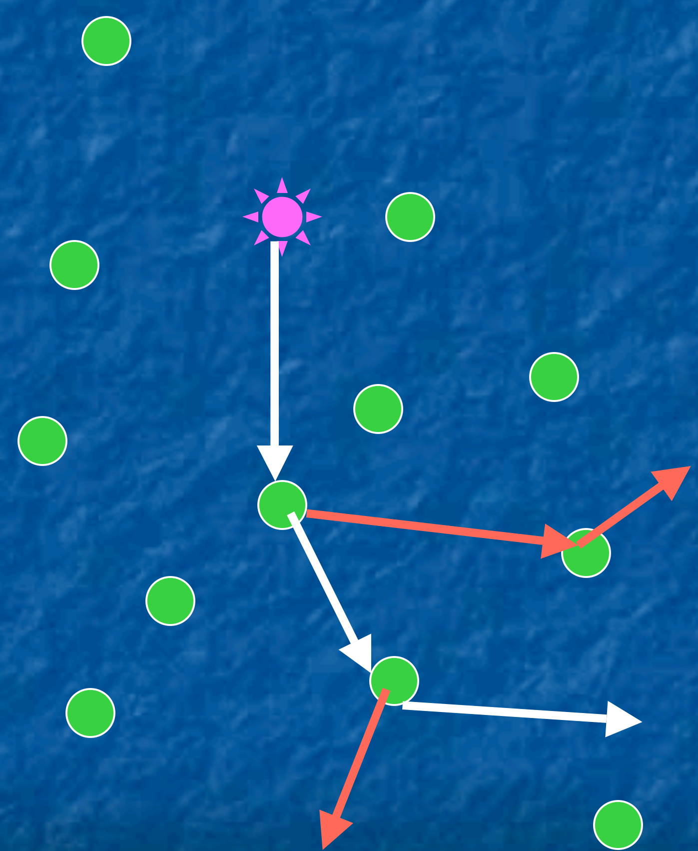


SF, PO, FB (2006)

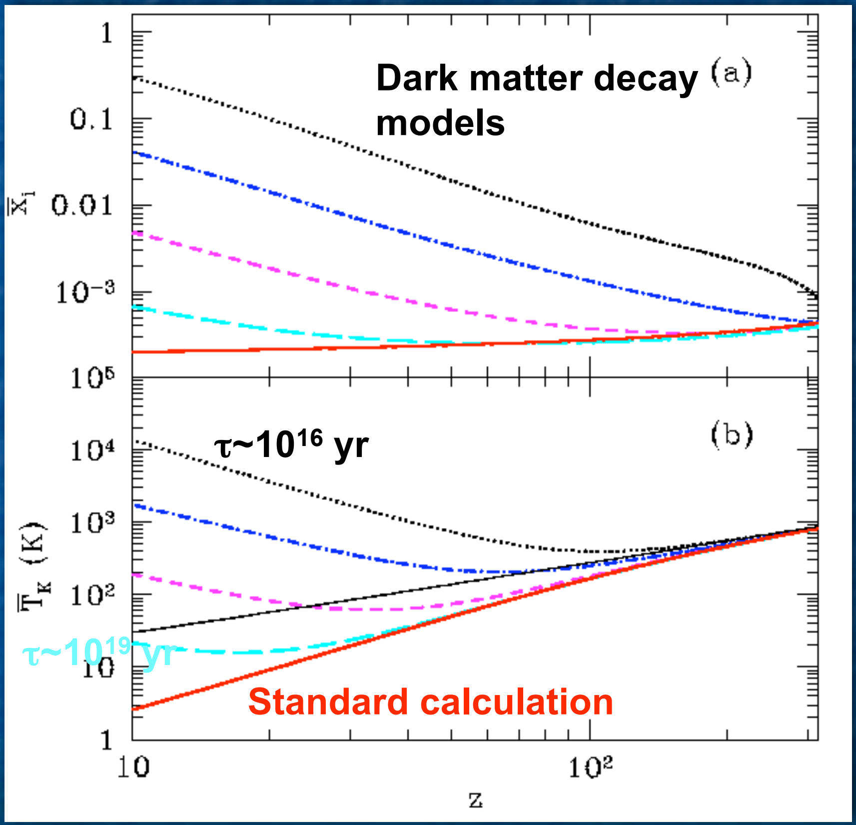
- Straightforward physics
- Fluctuations directly trace matter power spectrum (Loeb & Zaldarriaga 2004)
  - 3D dataset
  - Small-scale power

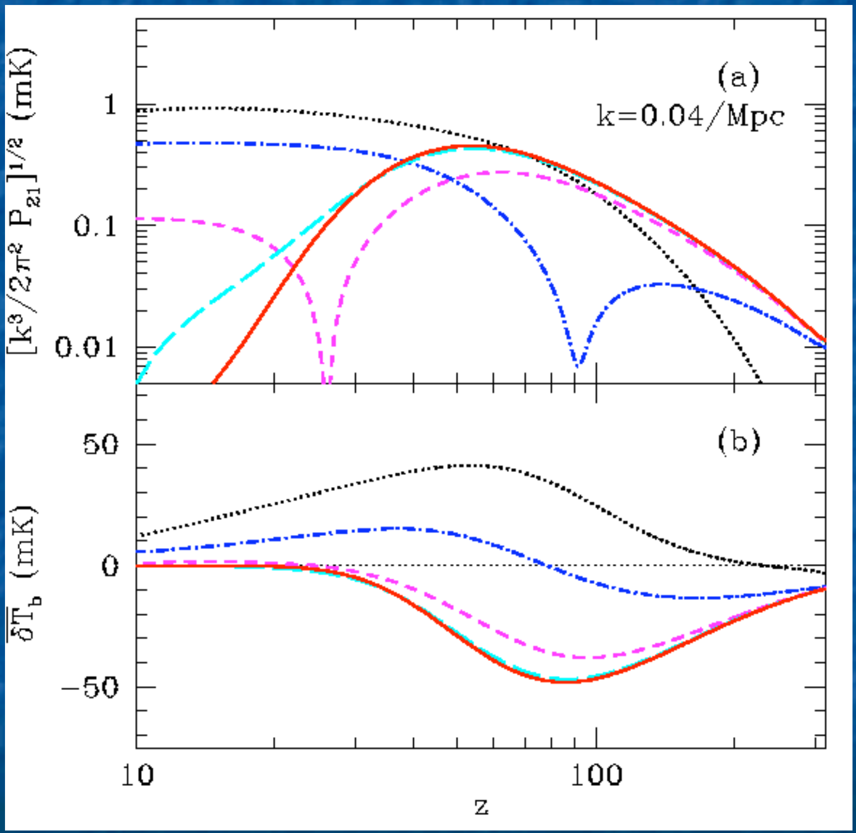
Dark Matter Decay?

- Dark matter MAY be an unstable particle on long timescales ($\gg H_0^{-1}$)
  - Sterile neutrinos
  - Light dark matter
  - Ultraheavy WIMPs
  - …
- Annihilation also possible



The Dark Ages: Dark Matter Decay





SF, PO, EP (2006)

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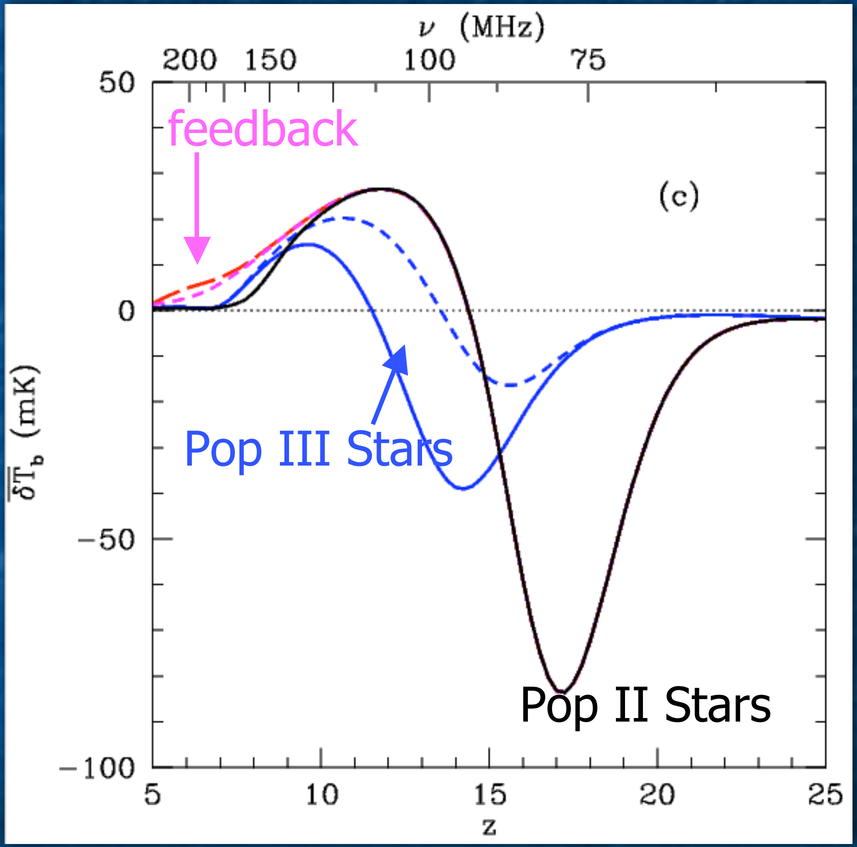
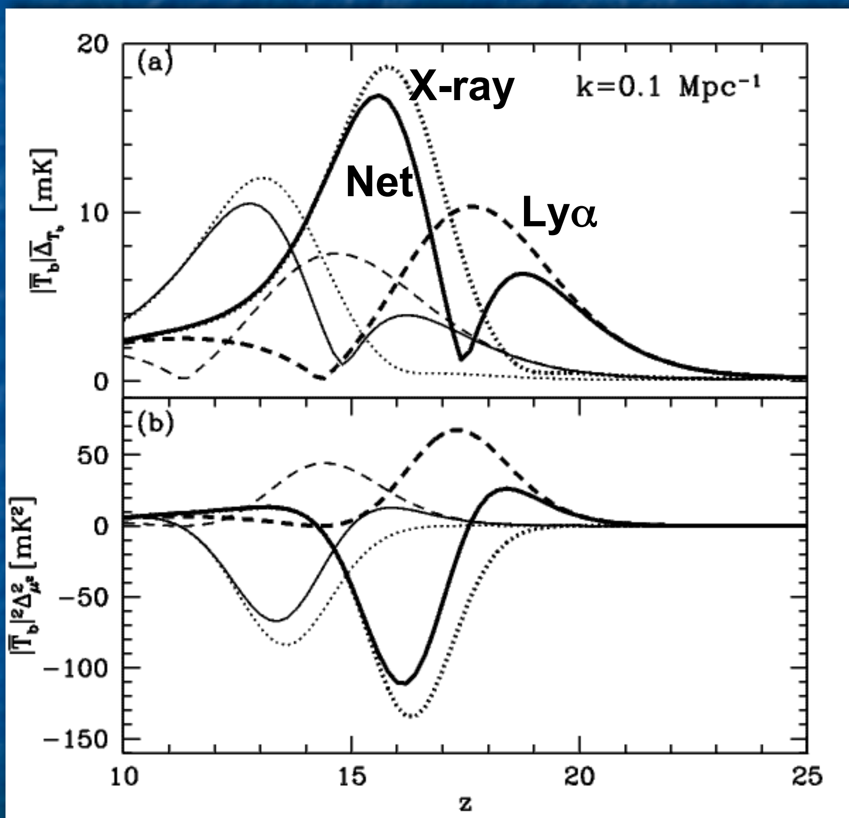


SF (2006)

The Pre-Reionization Era



Pritchard & Furlanetto (2007)

- Thick lines: Pop II model, z_r=7
- Thin lines: Pop III model, z_r=7
- Dashed: Lyα fluctuations
- Dotted: Heating fluctuations
- Solid: Net signal

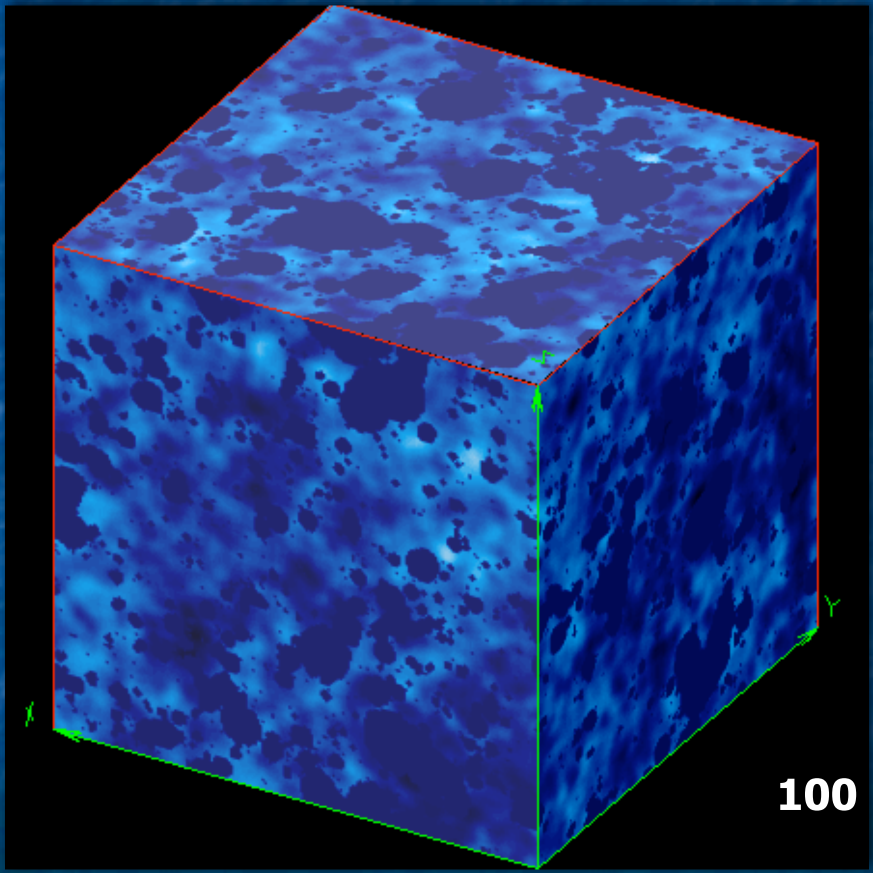
The “Quiet” Era

- IF Lyα, heating fluctuations damp out well before reionization, density/velocity dominates

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

- Can then constrain cosmology (McQuinn et al. 2006, Bowman et al. 2006, Santos & Cooray 2006)
  - Angular structure extremely useful
- SKA gives marginal improvements in tilt, neutrino mass, running

21 cm Observations: Reionization

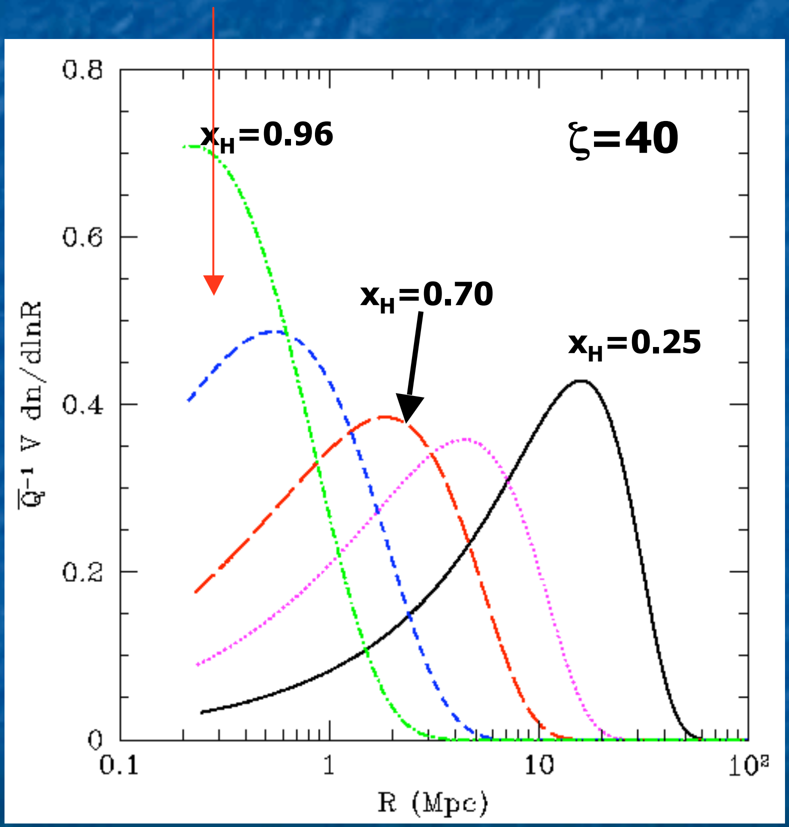


100 Mpc comoving

Mesinger & Furlanetto

Bubble Sizes

Typical galaxy bubble

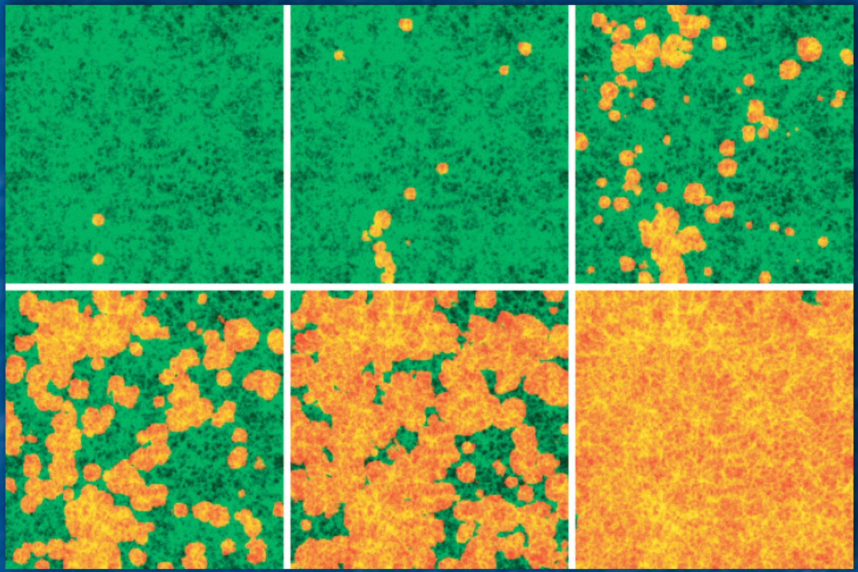


SF, MZ, LH (2004a)

- Bubbles are BIG!!!
  - Many times the size of each galaxy's HII region
  - The good news…2 Mpc = 1 arcmin

Big Bubbles: The Bad News

- Numerical simulations require…
  - Initial conditions (trivial)
  - N-body for dark matter (weeks, large cluster)
  - Hydrodynamics (more weeks, large cluster!)
  - Radiative transfer (days)
- Not possible with required dynamic range: big bubbles, small galaxies
- Hard to survey parameter space

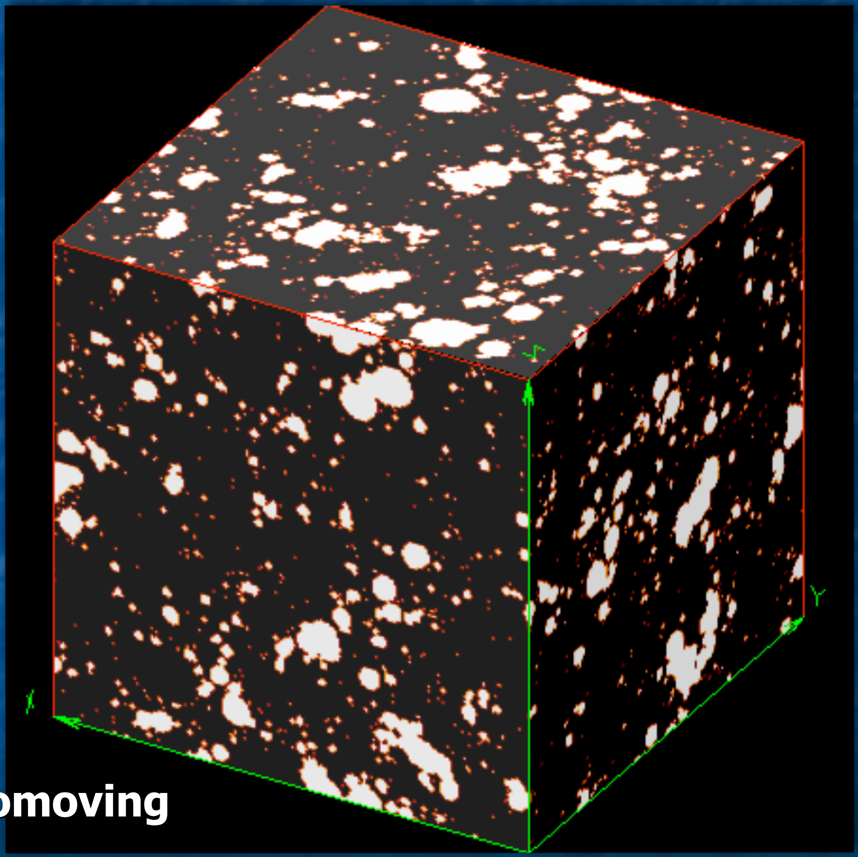


Iliev et al. (2006)

Reionization "Simulations"

- Model easy to implement in numerical simulation boxes

z=9.75, x_i=0.2



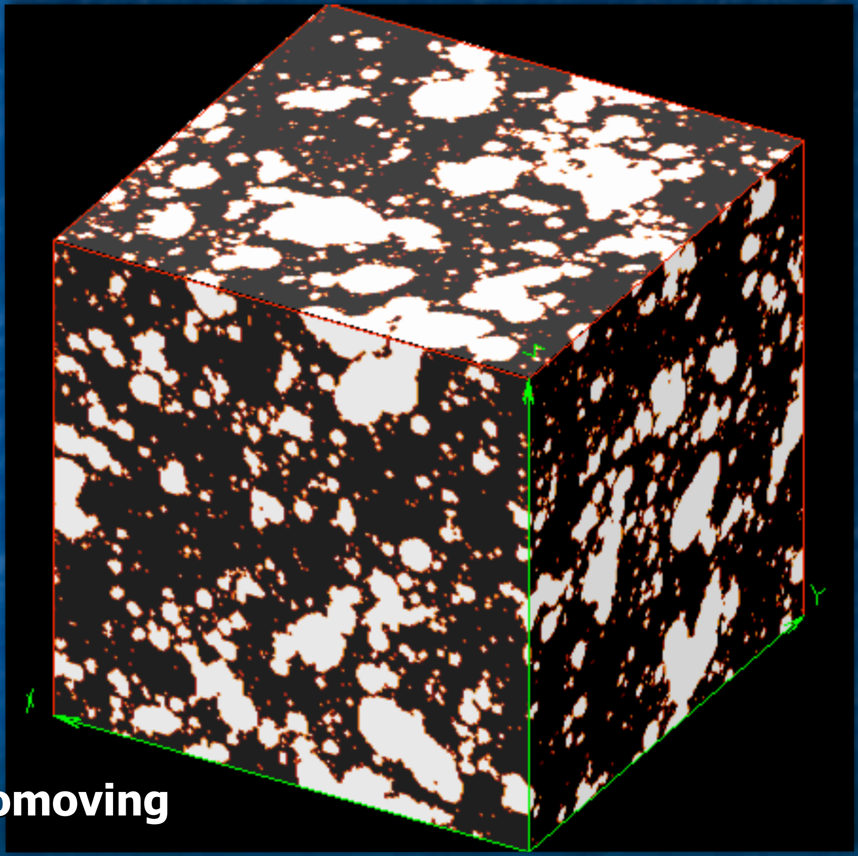
100 Mpc comoving

Mesinger & Furlanetto

Reionization “Simulations”

- Model easy to implement in numerical simulation boxes

$z=8.75$, $x_i=0.4$



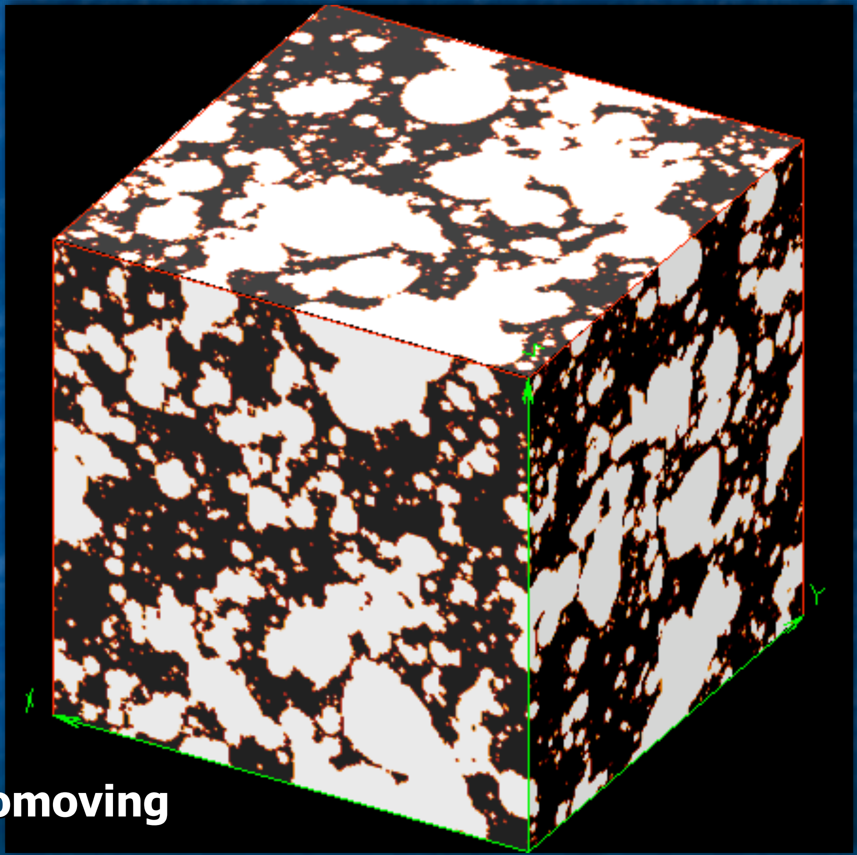
100 Mpc comoving

Mesinger & Furlanetto

Reionization "Simulations"

- Model easy to implement in numerical simulation boxes

$z=8$, $x_i=0.6$



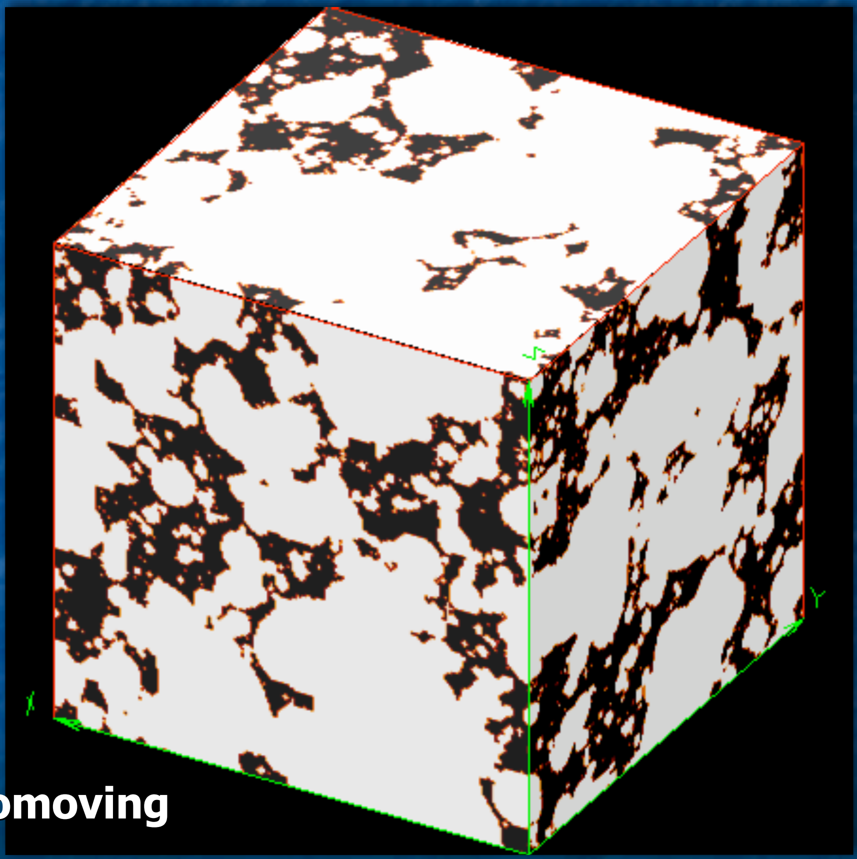
100 Mpc comoving

Mesinger & Furlanetto

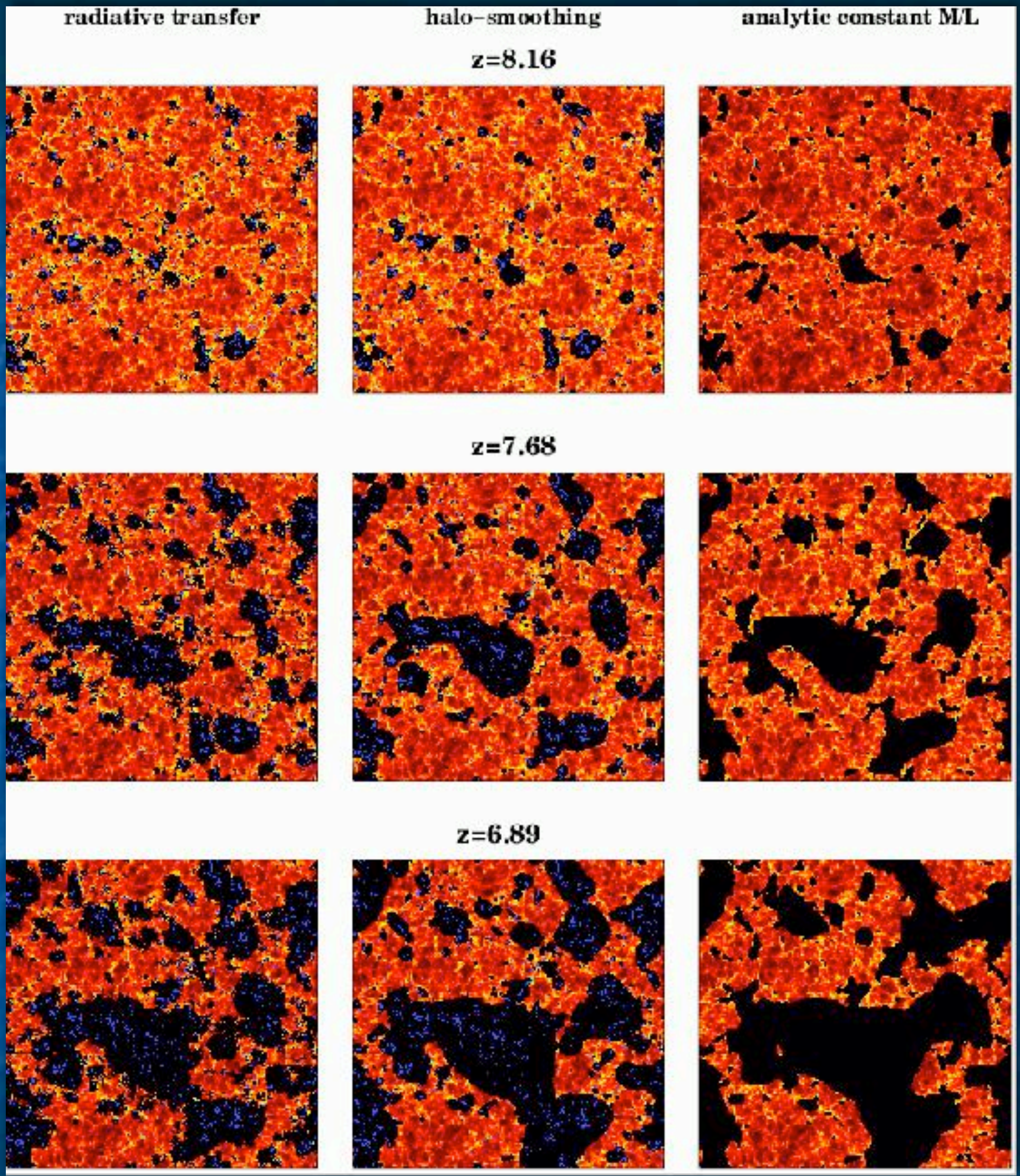
Reionization “Simulations”

- Model easy to implement in numerical simulation boxes
- Five hours on desktop!

z=7.25, x_i=0.8



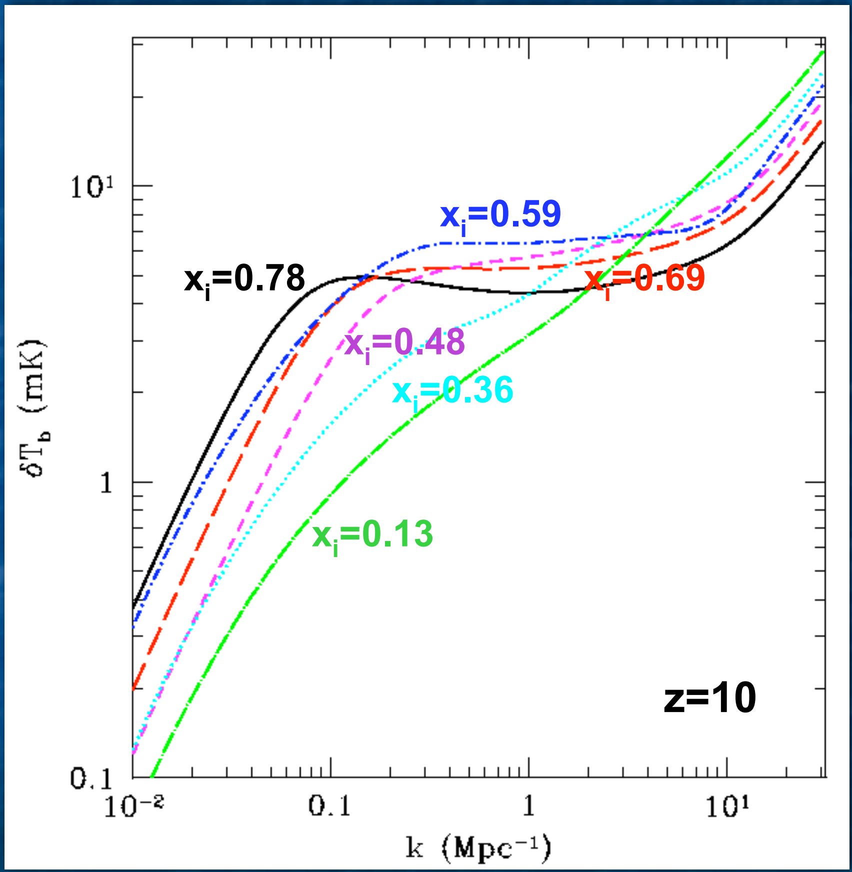
Mesinger & Furlanetto



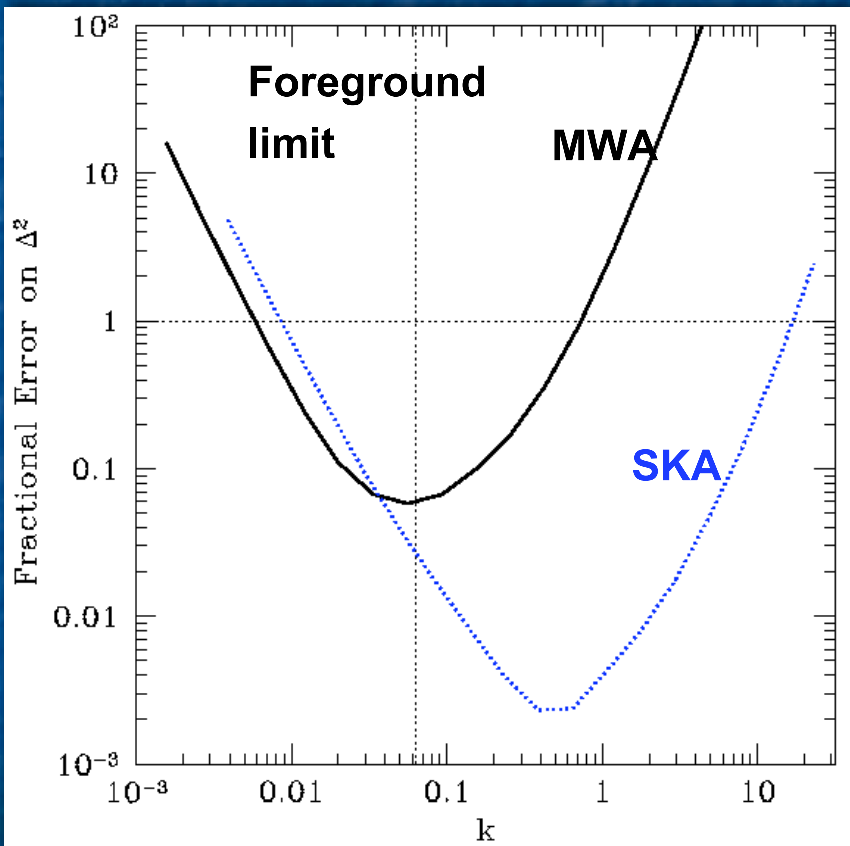
Zahn et al. (2006)

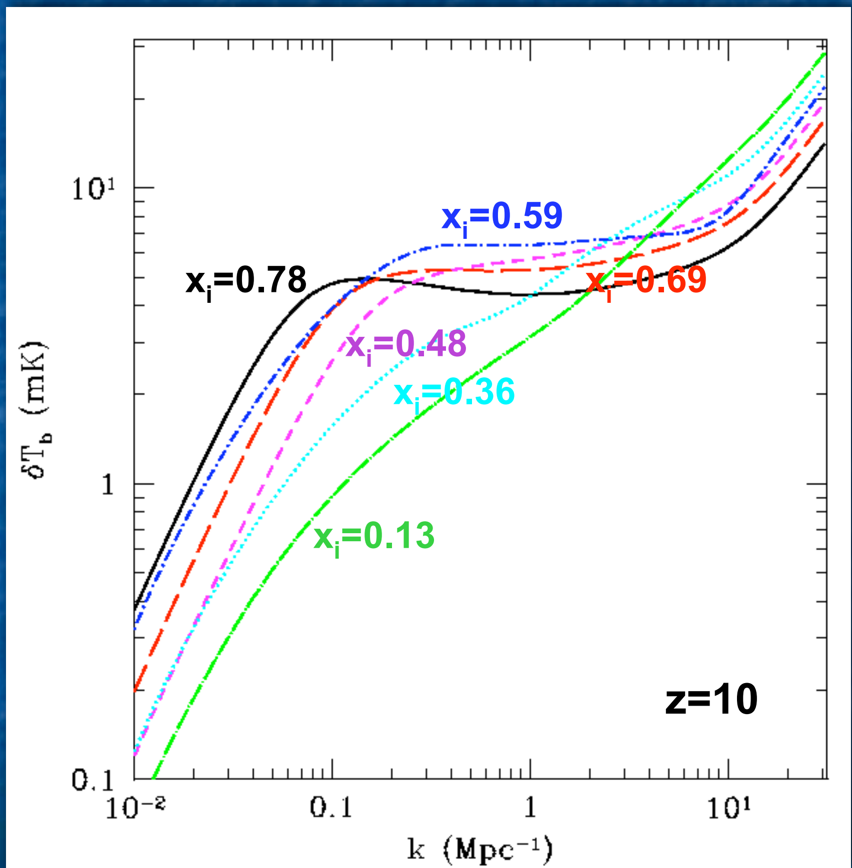
The Power Spectrum

- 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)



Error Estimates and the Power Spectrum

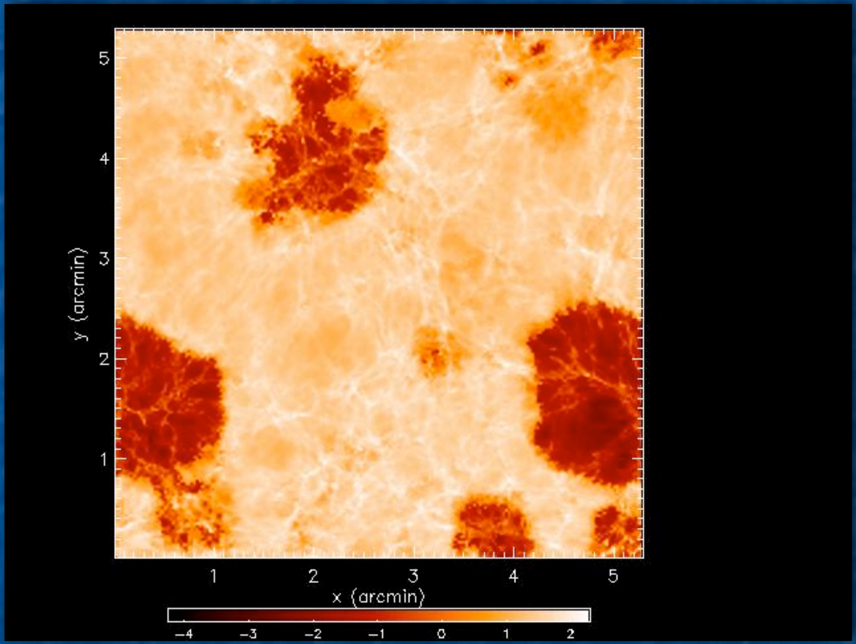




Smoking Guns?

- The power spectrum has only coarse features, and their interpretation is model-dependent
- Other signatures?
  - Cross-correlation
  - Other statistics

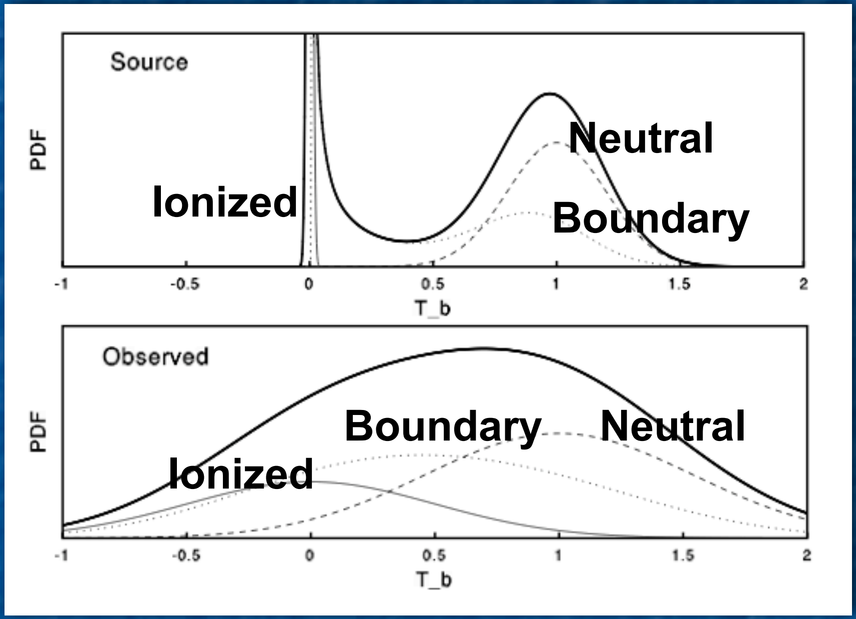
Signatures of Reionization



SF, AS, LH (2004)

- HII regions fundamentally alter distribution of fluxes
- Empty (ionized) pixels
- Neutral pixels (gaussian-ish)
- Overlap pixels

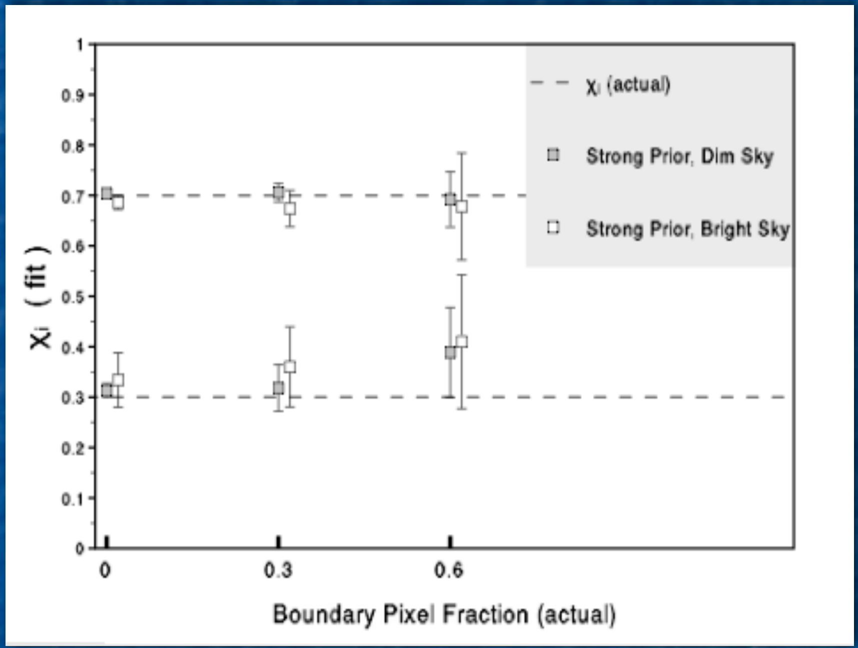
Signatures of Reionization



Hansen, Oh, and Furlanetto (2007)

- HII regions fundamentally alter distribution of fluxes
- Remains non-gaussian even in the presence of noise
- Use maximum likelihood methods to test for bimodality

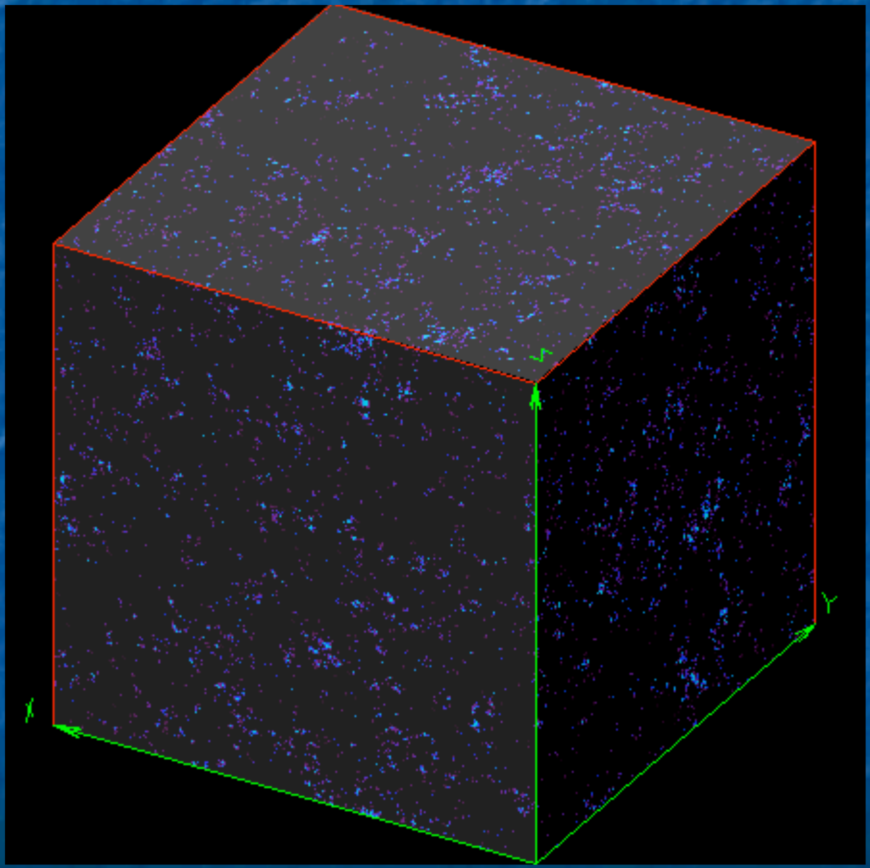
Tests for Bimodality

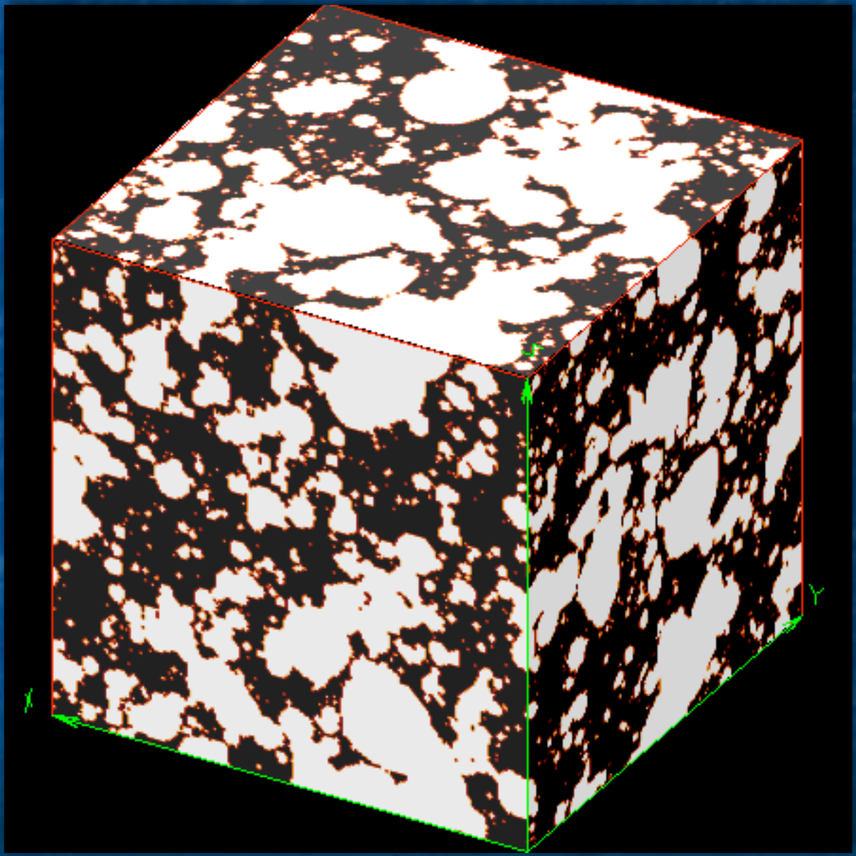


z=8, 500 hrs, 3.5 arcmin resolution

- LOFAR can recover ionized fraction quite well for simple toy model
- MWA less good because larger noise

21 cm-Galaxy Cross-Correlation





$z=8$, $x_i=0.6$

Mesinger & Furlanetto

21 cm-Galaxy Cross-Correlation

- Key advantages
  - Unambiguous confirmation of cosmological signal

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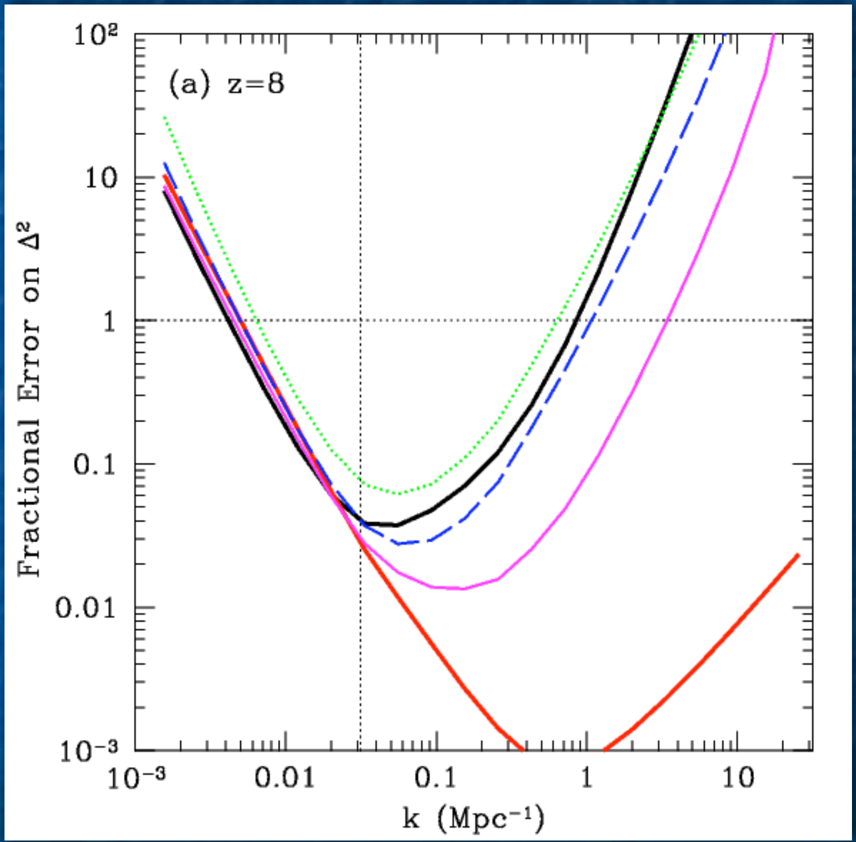

Furlanetto & Lidz (2007)

- Black solid: 21 cm (fiducial survey)
- Red solid: galaxy survey (10^{10} Msun)
- Magenta solid: Cross, $M>10^{10}$ Msun
- Blue dashed: Cross, $M>10^{11}$ Msun
- Green dotted: Cross, $M>2\times10^{11}$ Msun
- Errors scale like (overlap volume)$^{1/2}$
  - Detection possible with MWA + Subaru Deep Field (see also Wyithe & Loeb 2007)

21 cm-Galaxy Cross-Correlation

- Key advantages
  - Unambiguous confirmation of cosmological signal
  - Vastly reduces difficulty of foreground cleaning
    - Only emission from sources in survey slice contributes
  - Increase sensitivity and dynamic range
    - Helps with angular structure
  - Science! (stay tuned)

Conclusions

- New probes of high-z universe needed!
- The 21 cm transition best of these
  - Pre-reionization: fundamental physics, properties of first sources, cosmology
  - Reionization: morphology and growth of bubbles
  - Basics of models now in place
- First generation experiments will begin in ~2 years
  - Experimental challenges are large!
  - Interpretation will require improved theoretical tools

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