“What we want to know about the sources of Reionization”

Peng Oh
UCSB

Connections between Lensing and Reionization

- Early Reionization --> Small Scale Structure (see Madau's talk)
- Lensing of 21cm maps (Futuristic)
- Gravitational Telescopes ---> Probe Sources of Reionization

What do we want to know?

- When did it happen?
- How fast was reionization?
- What was the topology of reionization?
- What were the sources responsible?

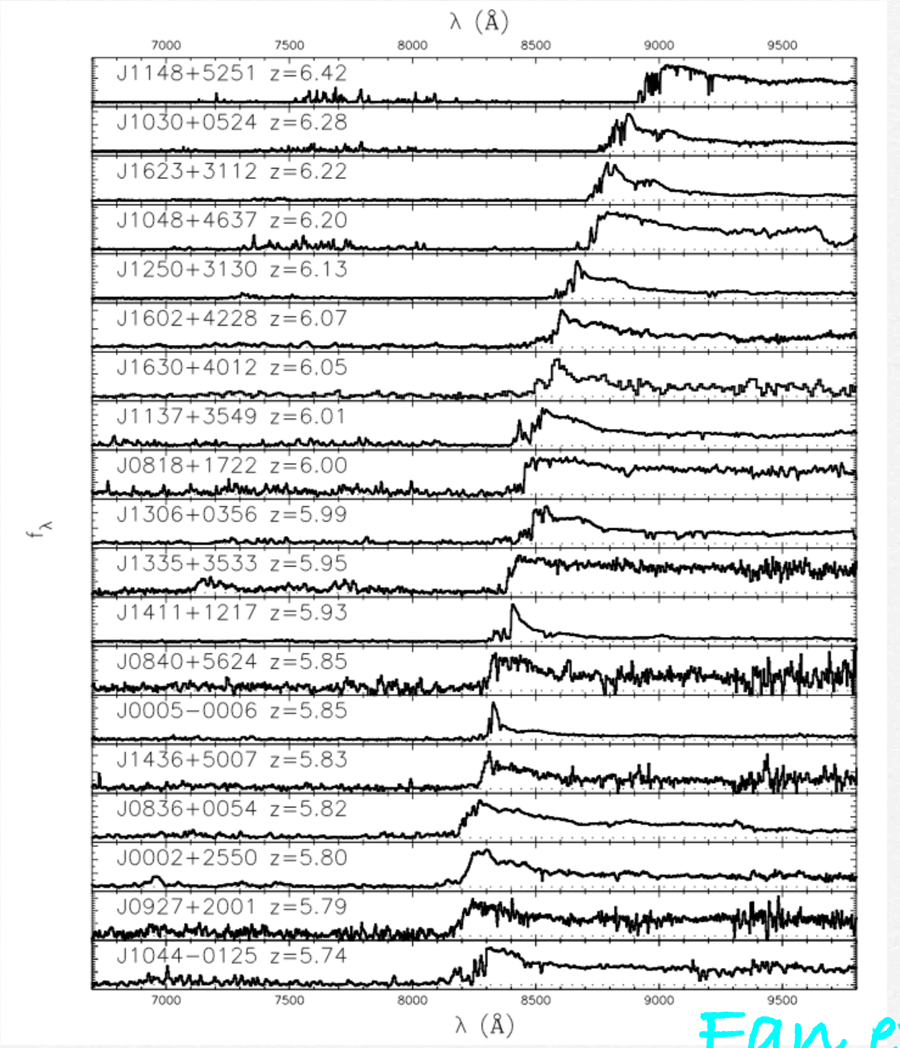
Field is driven primarily by observations

Talk Outline

- What do we already know about the z~6 IGM?
- Some Theoretical Priors for Source Detection
- The future: 21cm observations

What do we already know about the z~6 IGM?

How neutral is the Universe at z~6?

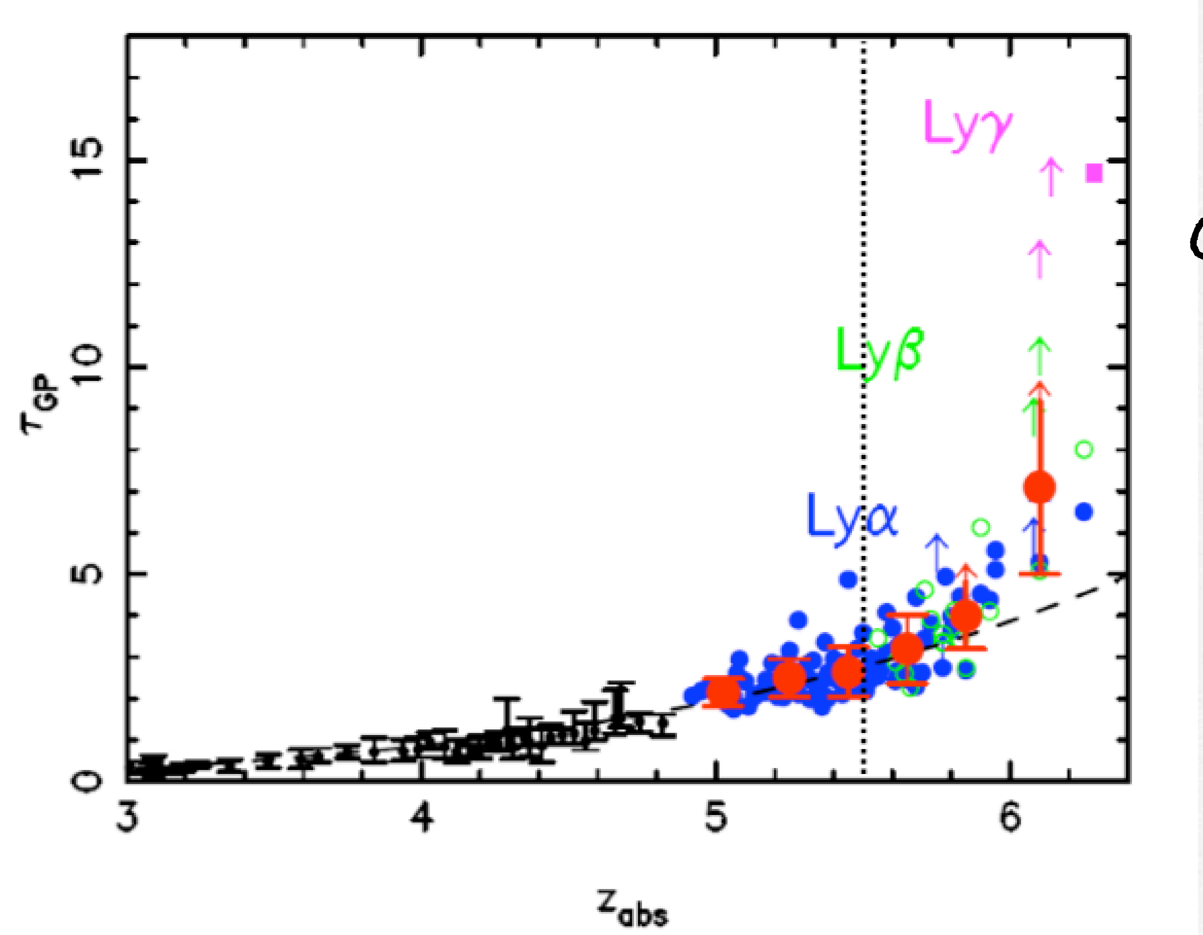


Best probe: Ly series absorption seen in 19 SDSS QSOs with $5.74 < z < 6.42$

Saturated absorper: can only probe tail end of reionization

Fan et al 2006

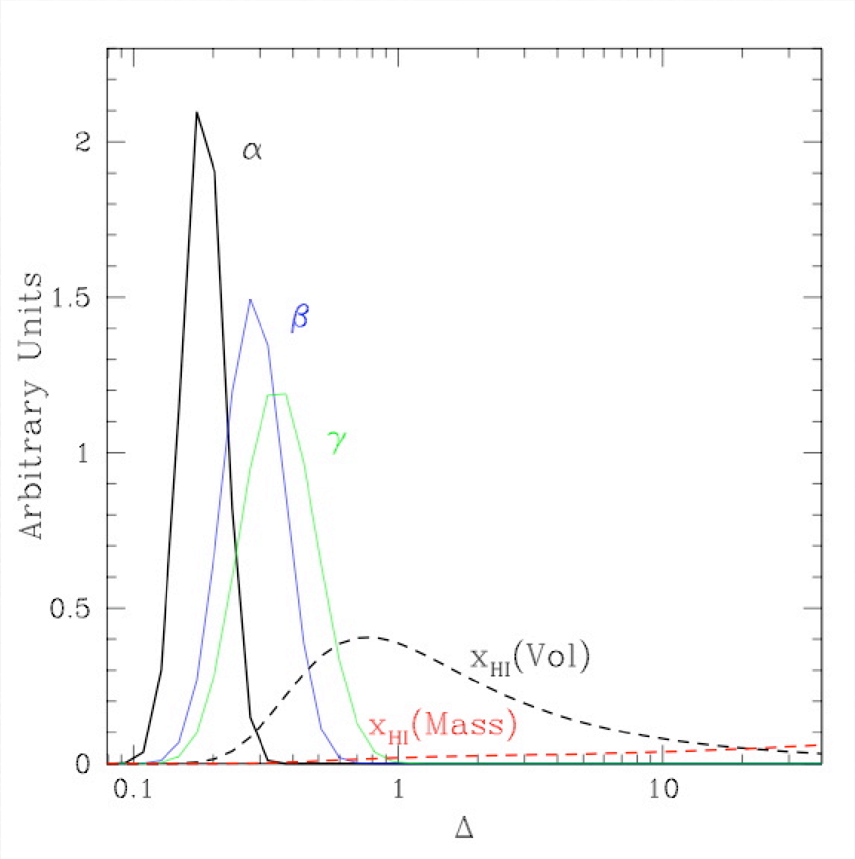
End of reionization?



Claimed sharp increase in optical depth and scatter

Fan et al 06

...but it's really hard to infer neutral fraction...



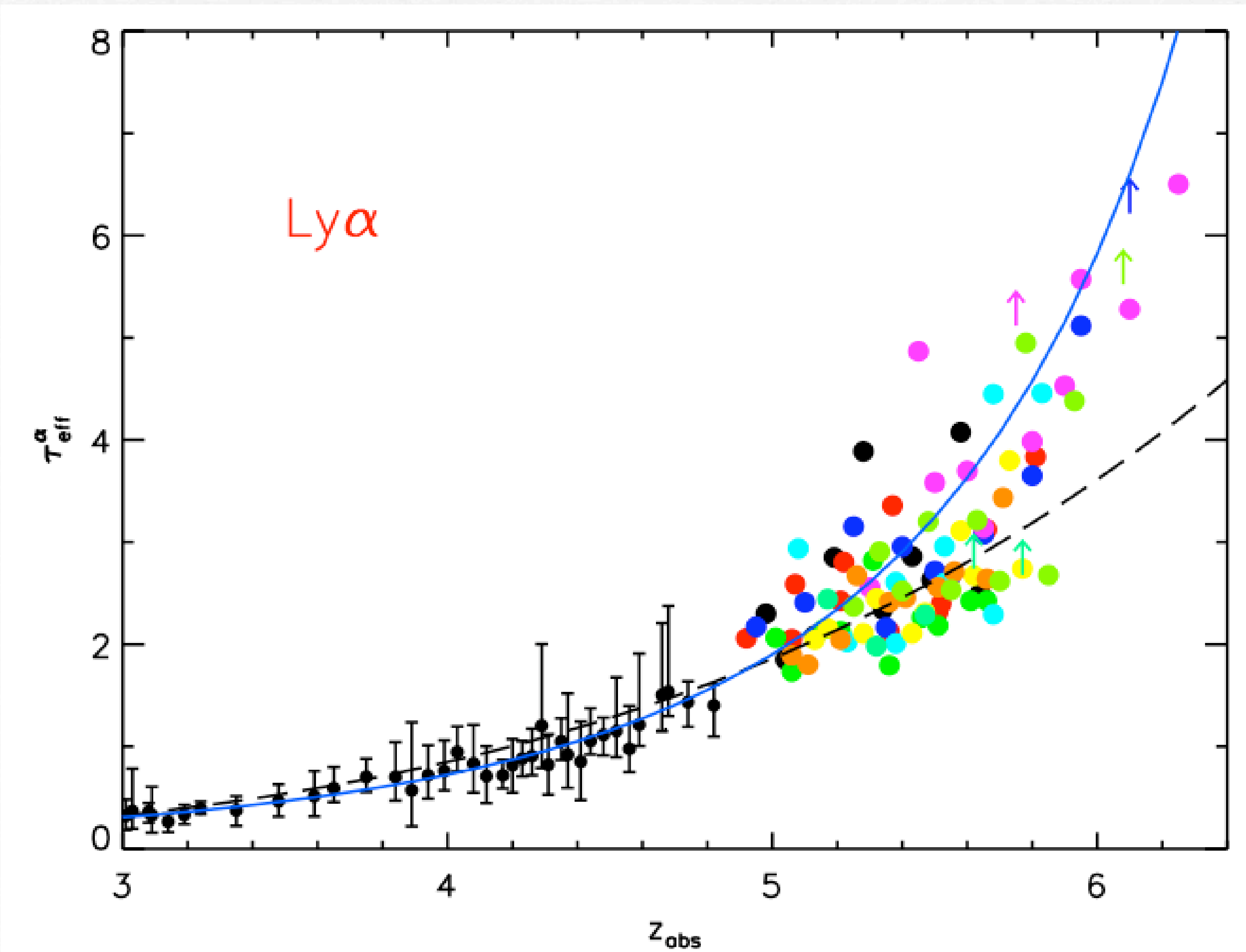
Oh & Furlanetto 2005

Transmission mainly due to rare voids

Most HI at higher overdensities

Caution: comparing different Lyman series on absolute scale is hard

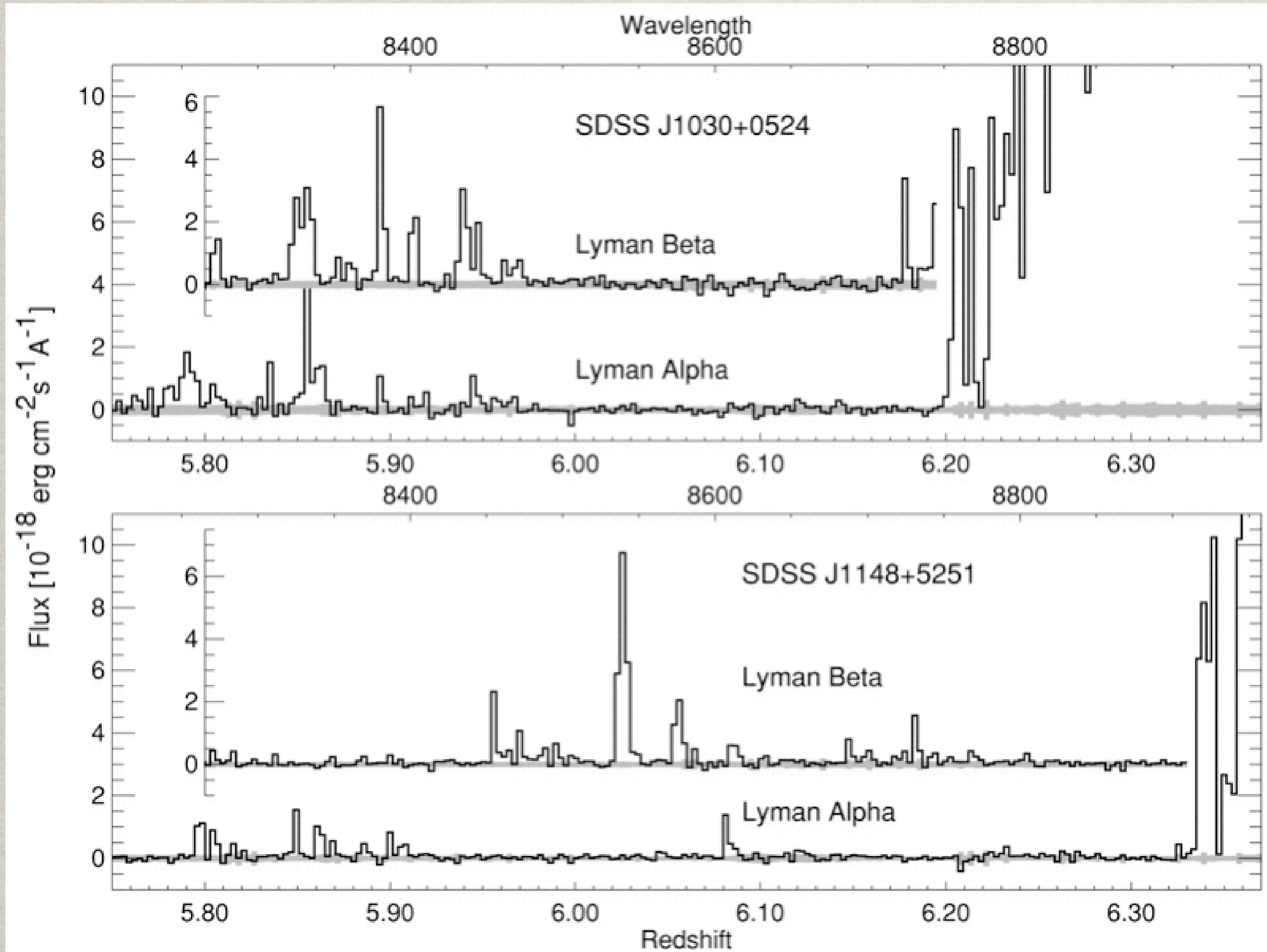
...and highly dependent on assumed density PDF



Becker, Rauch & Sargent 2006

Evolution can be explained if assume lognormal PDF

Have We Seen Patchy Reionization?



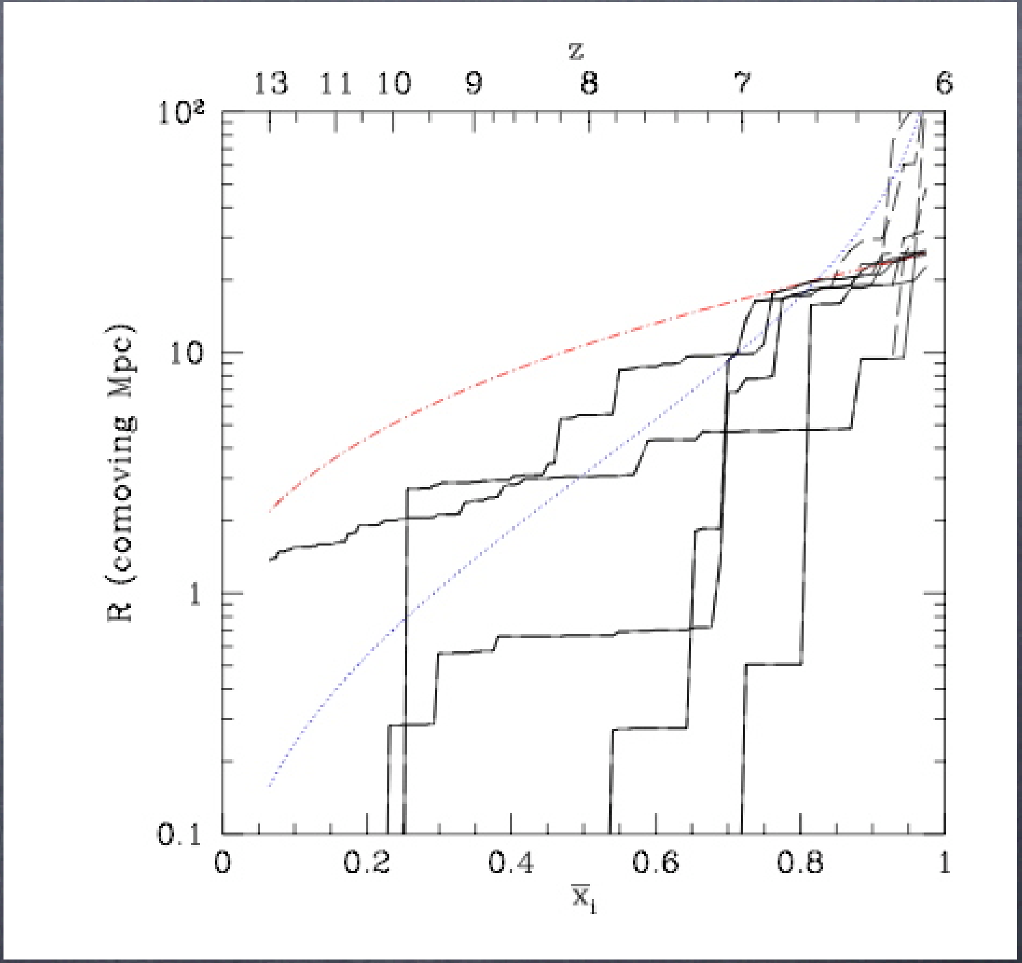
White et al 2003

There's a lot of sight-line to sight-line scatter in QSO absorption spectra. Order unity fluctuations on LARGE (50-100 Mpc comoving) scales

Might be expected at during overlap...

Overlap is a local rather than global process..

Naturally expect large cosmic variance along different lines of sight...



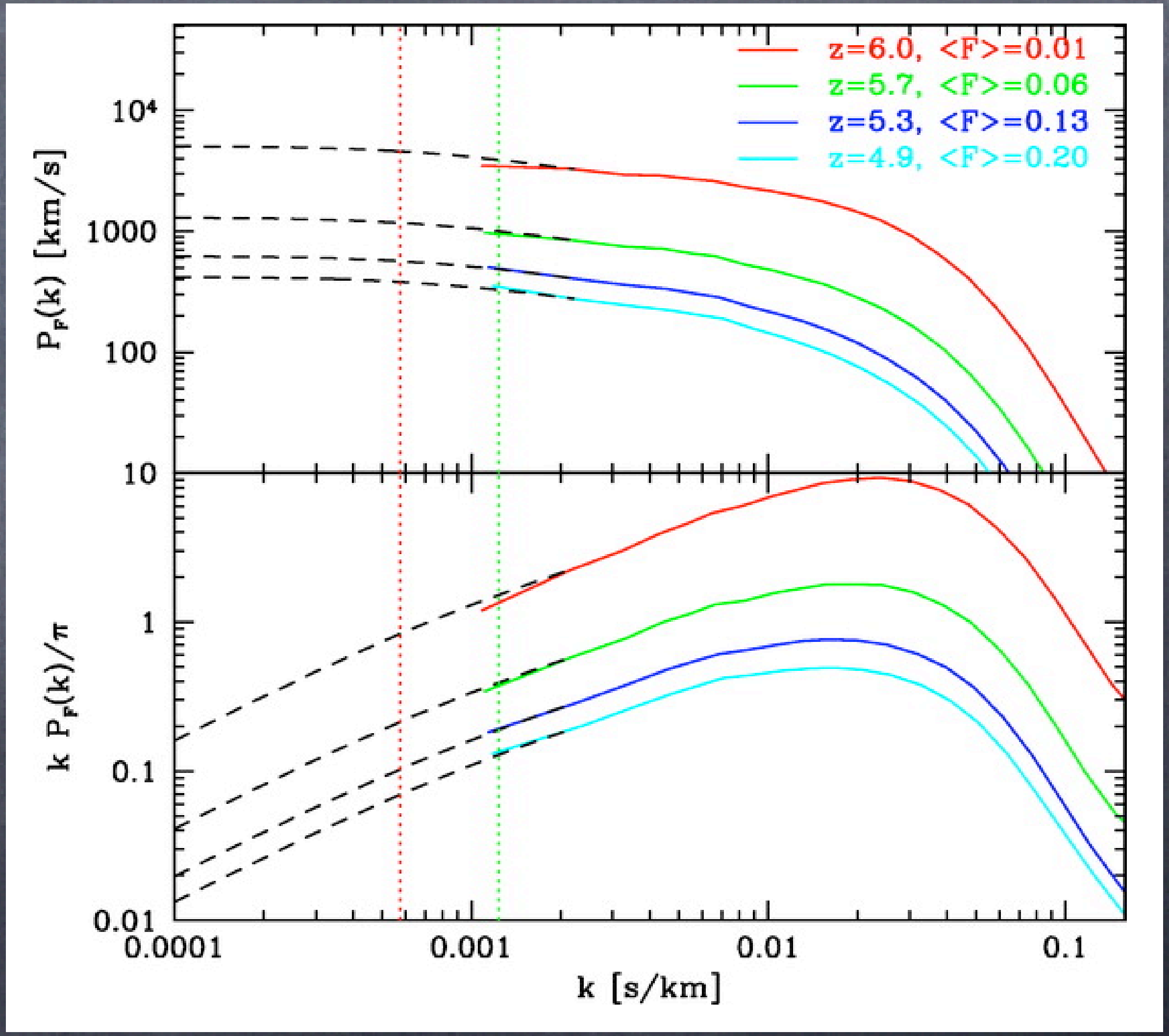
Furlanetto & Oh 2005

But it is VERY hard to see patchy reionization...

Lidz, Oh & Furlanetto 2006

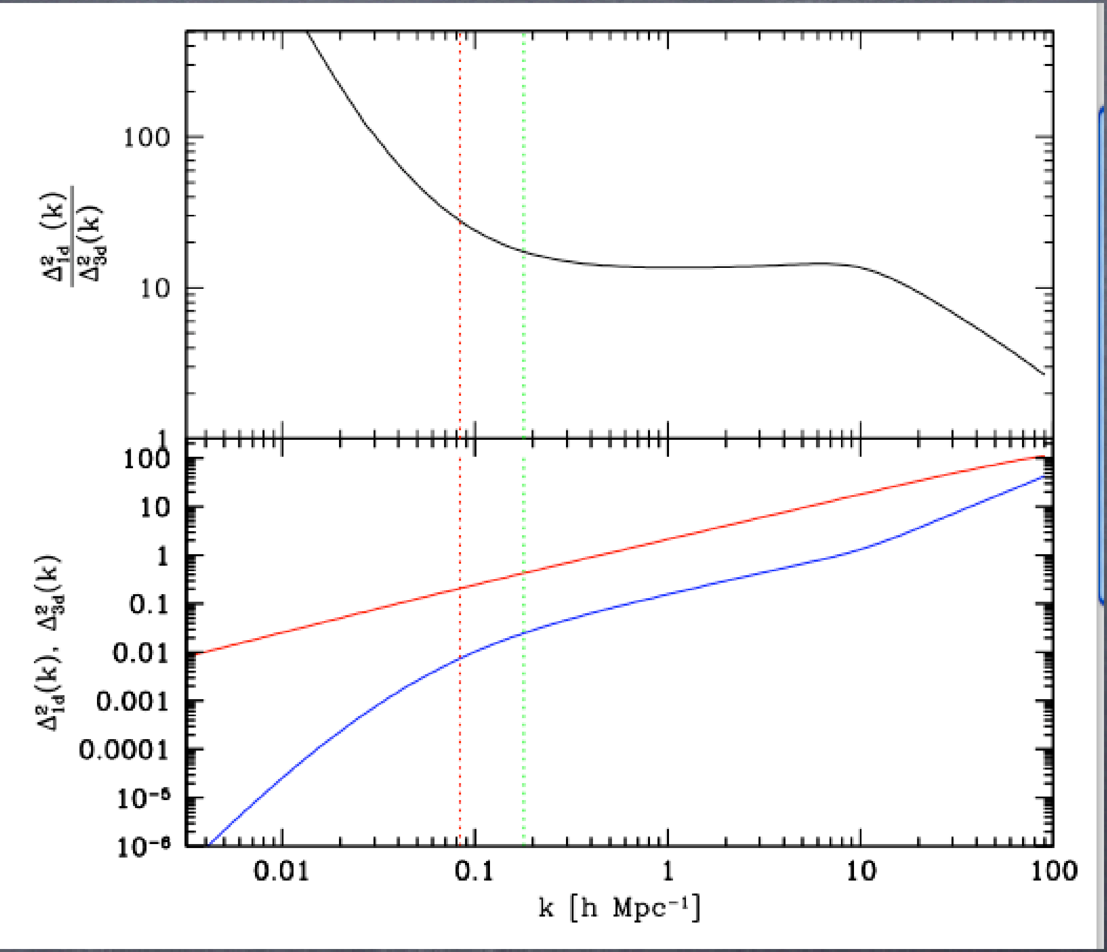
Simulate 40 Mpc h^-1 box

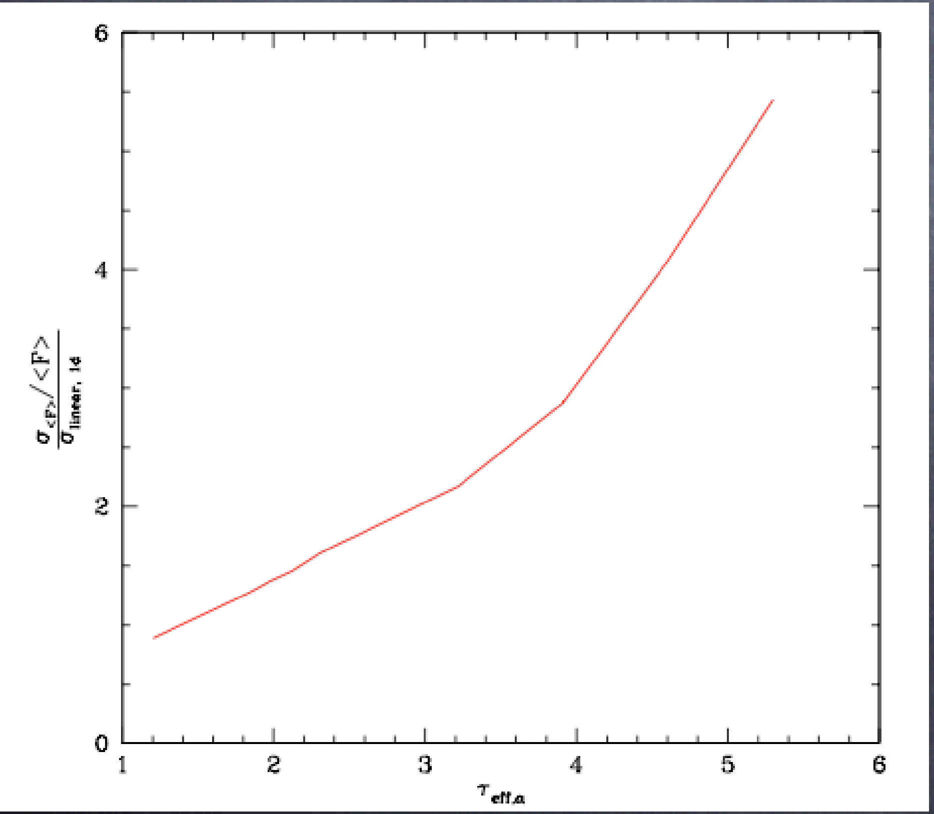
Flux power spectrum declines slowly with scale



Two effects

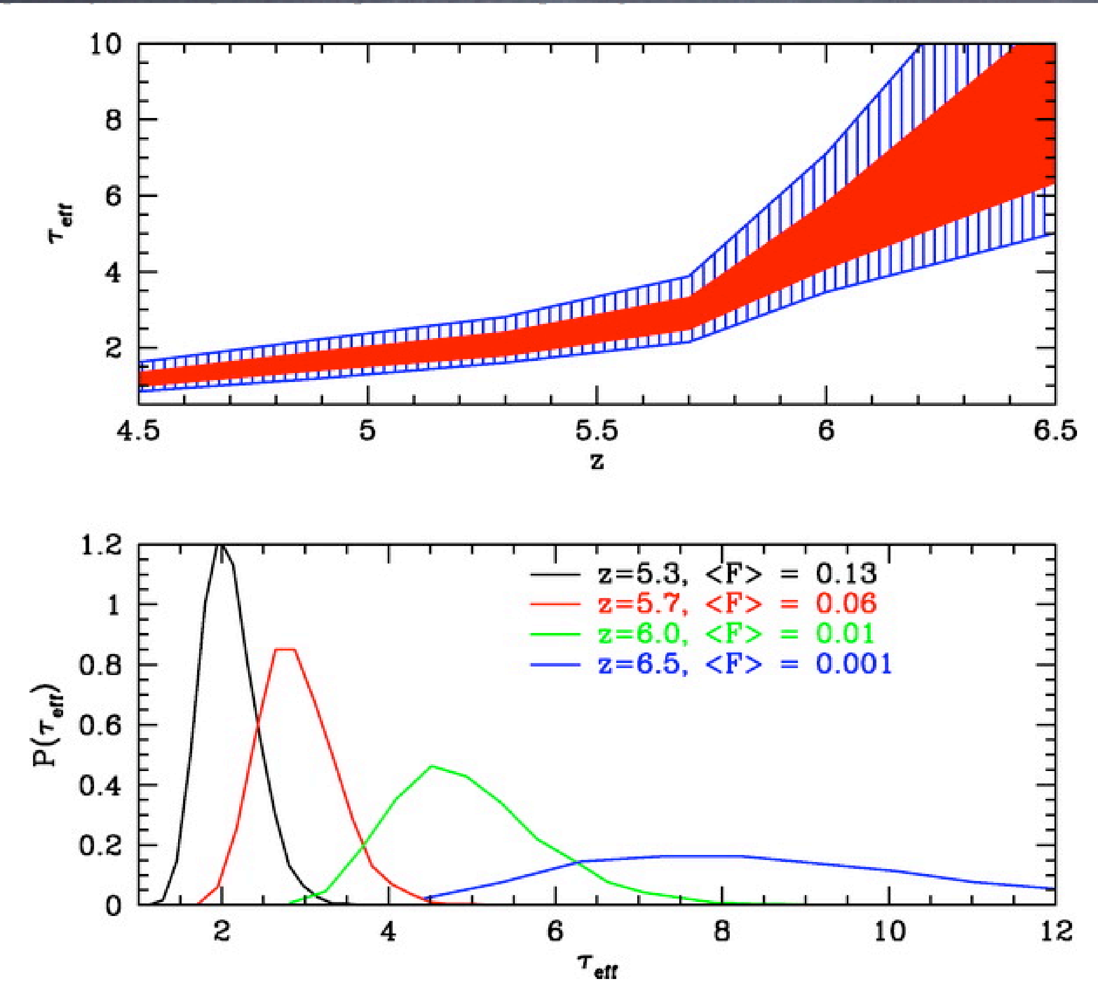
Aliasing boosts power on large scales

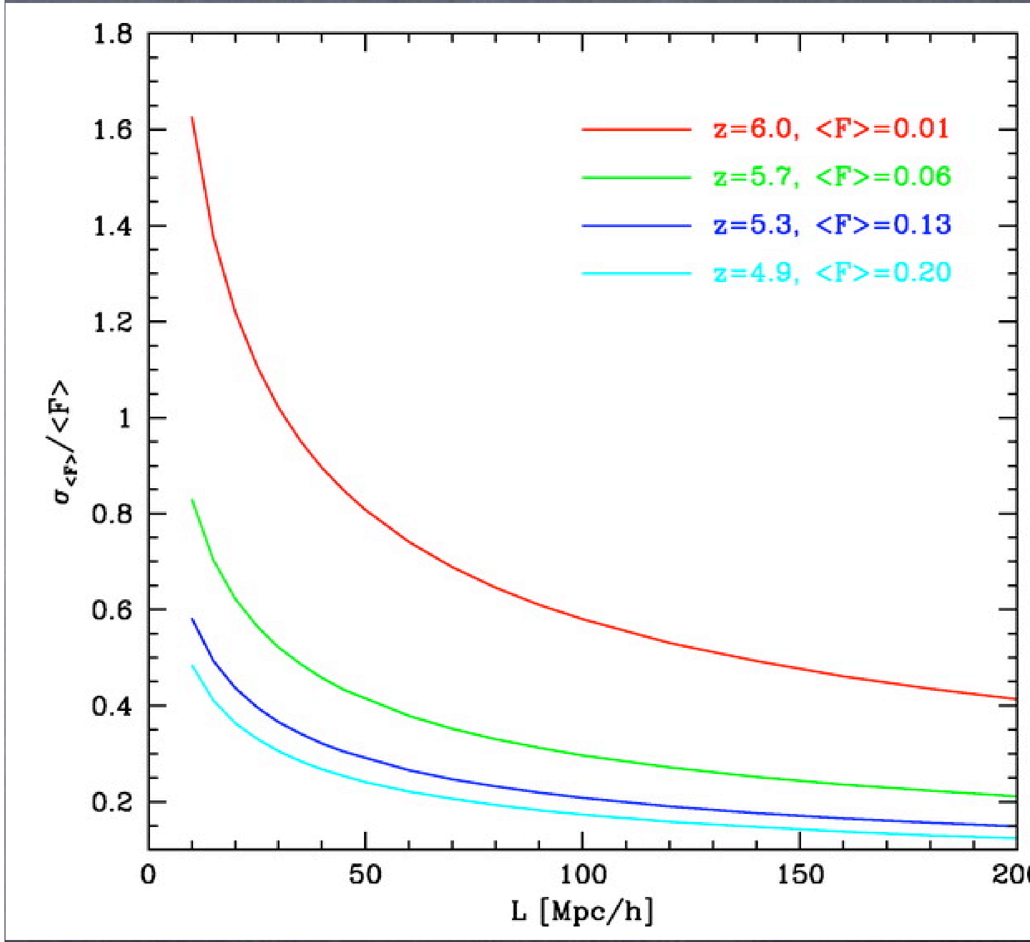




Bias increases amplitude of fluctuations

Uniform Radiation Field is consistent w/ observed scatter...





OI absorption: a scorecard

Oh 2002

What you want

1. Unsaturated absorption when universe is fully neutral.

2. Absorption redward of HI Lyα at 1216 Angstroms

3. Ionization Potential close to that of HI

What you get

1. Abundance lower by ~10^{-6}

$\tau = 0.15\, x_{HI}\, (Z/10\text{–}2.5\, Z)$

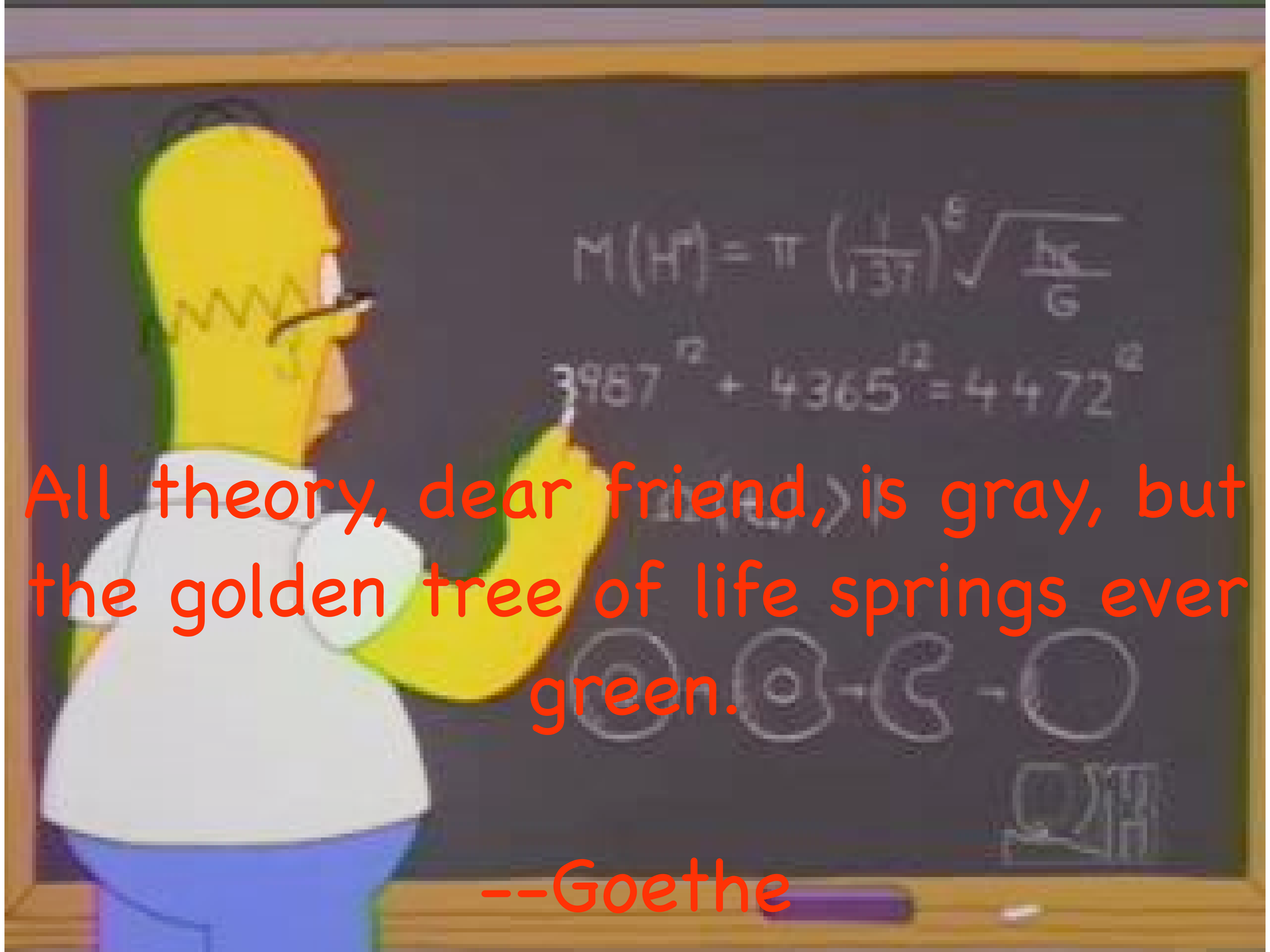
$[(1+z)/7]^{3/2}$ for uniform IGM

2. Strongest line at 1302 Angstroms

3. Ionization Potential 13.6 eV !

$x_{OI} \approx x_{HI}$ Charge exchange equilibrium

$O+H^{o} \rightarrow O+H^{+}$; $O^{+}+H^{o} \rightarrow O+H^{+}$


$3987^{12} + 4365^{12} = 4472^{12}$
All theory, dear friend, is gray, but the golden tree of life springs ever green.
--Goethe

OI absorption in IGM has been seen!

O I search: Results

Name	z_{QSO}	Max $\Delta z_{O\,I}$	# O I systems
SDSS 2225-0014	4.87	0.39	0
SDSS J1204-0021	5.09	0.40	0
SDSS J0915+4244	5.20	0.41	0
SDSS J0231-0728	5.42	0.43	1
SDSS J0836+0054	5.80	0.45	0
SDSS J0002+2550	5.82	0.45	0
SDSS J1623+3112	6.25	0.48	1
SDSS J1030+0524	6.30	0.49	0
SDSS J1148+5251	6.42	0.49	4

Becker, Sargent, Rauch, Simcoe 2006,

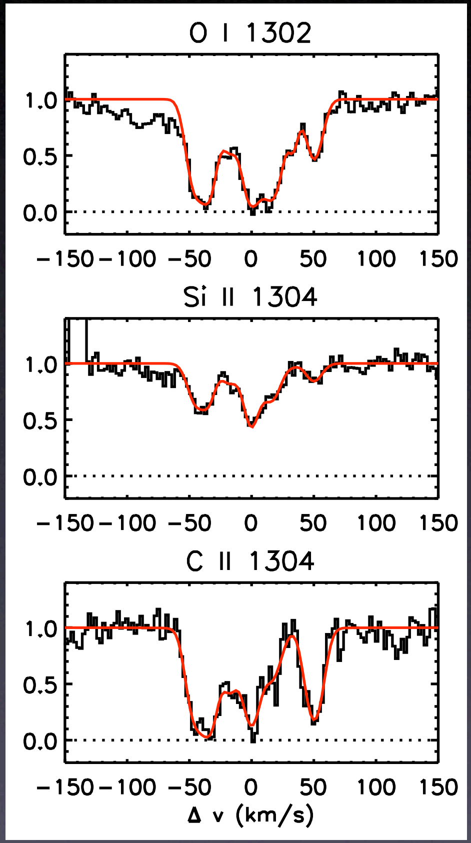
Confirmed with CII, SiII lines

Appearance to be a genuine excess of lines

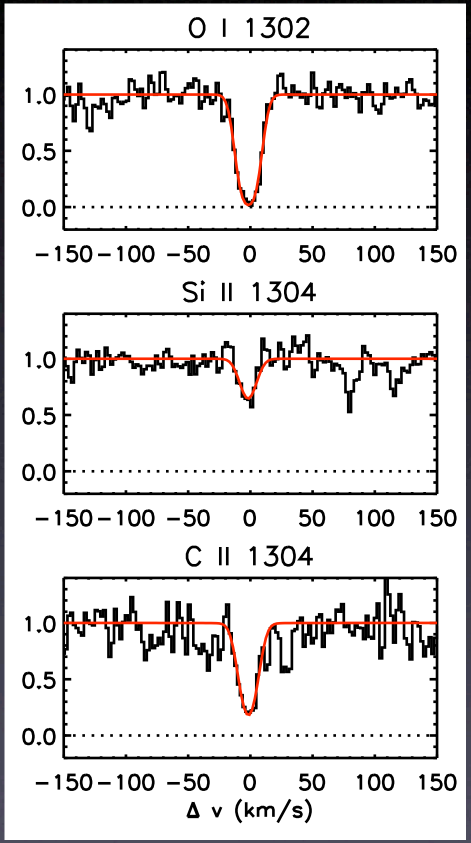
But most lines appear along highly ionized sightline???

Kinematic Differences

SDSS 1623+3112 (z_{abs} = 5.841)



SDSS 1148+5251 (z_{abs} = 6.129)



- 3/4 SDSS1148+5251 systems have a single component
- 2 other O I systems have multiple components (like DLAs)

courtesy of george becker

A New Class of Absorber??

Other probes

Dark Gap distribution

Size of HII regions

Gamma-ray bursts

But still mostly unsatisfactory....

Theoretical Prejudices for Source Detection

"A foolish consistency is the hobglobin of little minds." -- R.W. Emerson

Clumping factors could be small

Many observational papers quote clumping factors of ~30 at z=6

More recent estimates give clumping factors ~few.

Minihalos unlikely to boost photon budget needed for reionization.

Reionization could be local, rather than global

Before: reionization thought to be sudden, phase change like

Now: expect significant cosmic variance in percolation

Inferring IGM state from Ly-alpha emitter abundances is hard

Before: sharp decrease in abundance of Ly-alpha emitters--->pre-ionization epoch

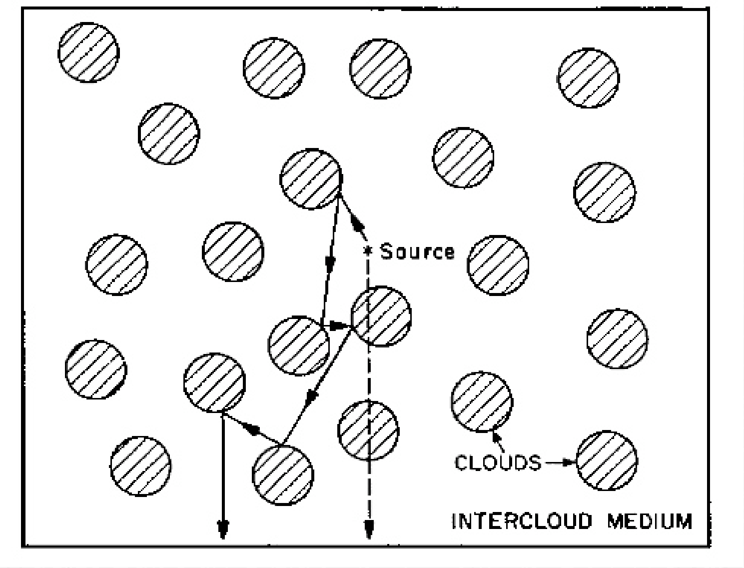
But: most sources are clustered and live in big HII bubbles

Still: fact that you see emitters lets you place lower limit on Q_HII (Malhotra & Rhoads 2006)

Ly-alpha EWs are messy

Some Ly-alpha surveys have v. high EWs (e.g. LALA)

This does not necessarily indicate exotic stellar populations...



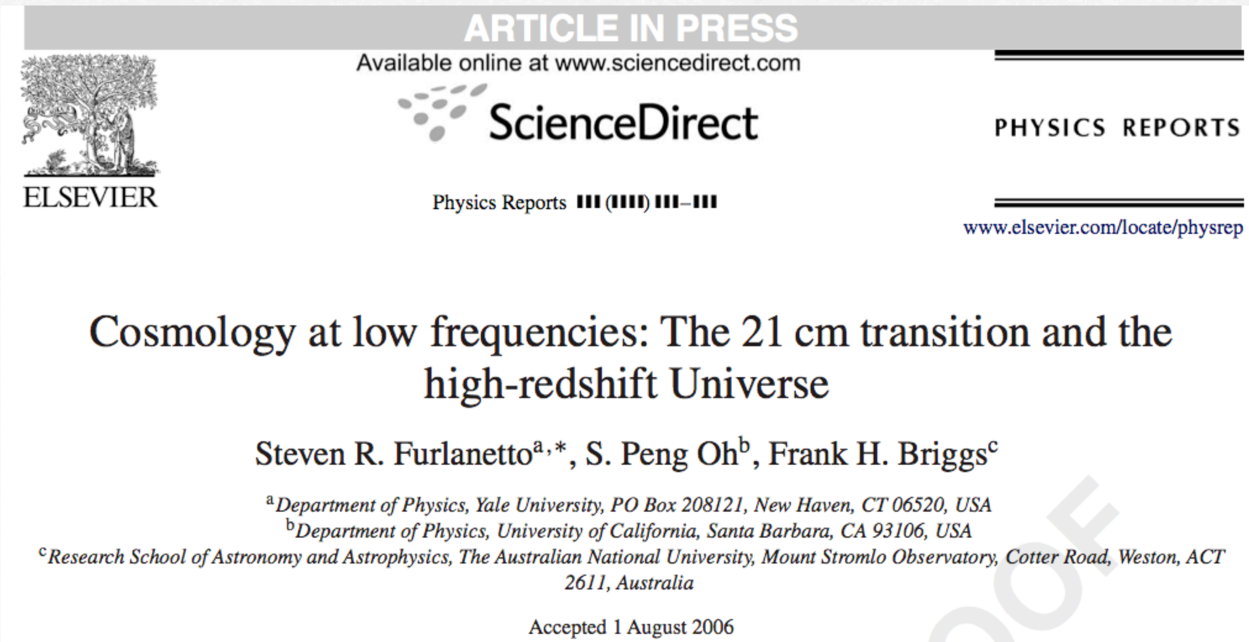
e.g., preferential escape of Ly-alpha photons possible in clumpy, dusty medium (Hansen & Oh 06)

The future: 21cm observations

"There are more things in heaven and earth, Horatio, Than are dreamt of in your philosophy."

--Hamlet (Act I, Scene V)

Advertising: New Review Article



ARTICLE IN PRESS

Available online at www.sciencedirect.com

ScienceDirect

ELSEVIER

Physics Reports ▮▮▮ (▮▮▮▮) ▮▮▮–▮▮▮

PHYSICS REPORTS

www.elsevier.com/locate/physrep

Cosmology at low frequencies: The 21 cm transition and the high-redshift Universe

Steven R. Furlanetto[a,*], S. Peng Oh[b], Frank H. Briggs[c]

[a] *Department of Physics, Yale University, PO Box 208121, New Haven, CT 06520, USA*
[b] *Department of Physics, University of California, Santa Barbara, CA 93106, USA*
[c] *Research School of Astronomy and Astrophysics, The Australian National University, Mount Stromlo Observatory, Cotter Road, Weston, ACT 2611, Australia*

Accepted 1 August 2006

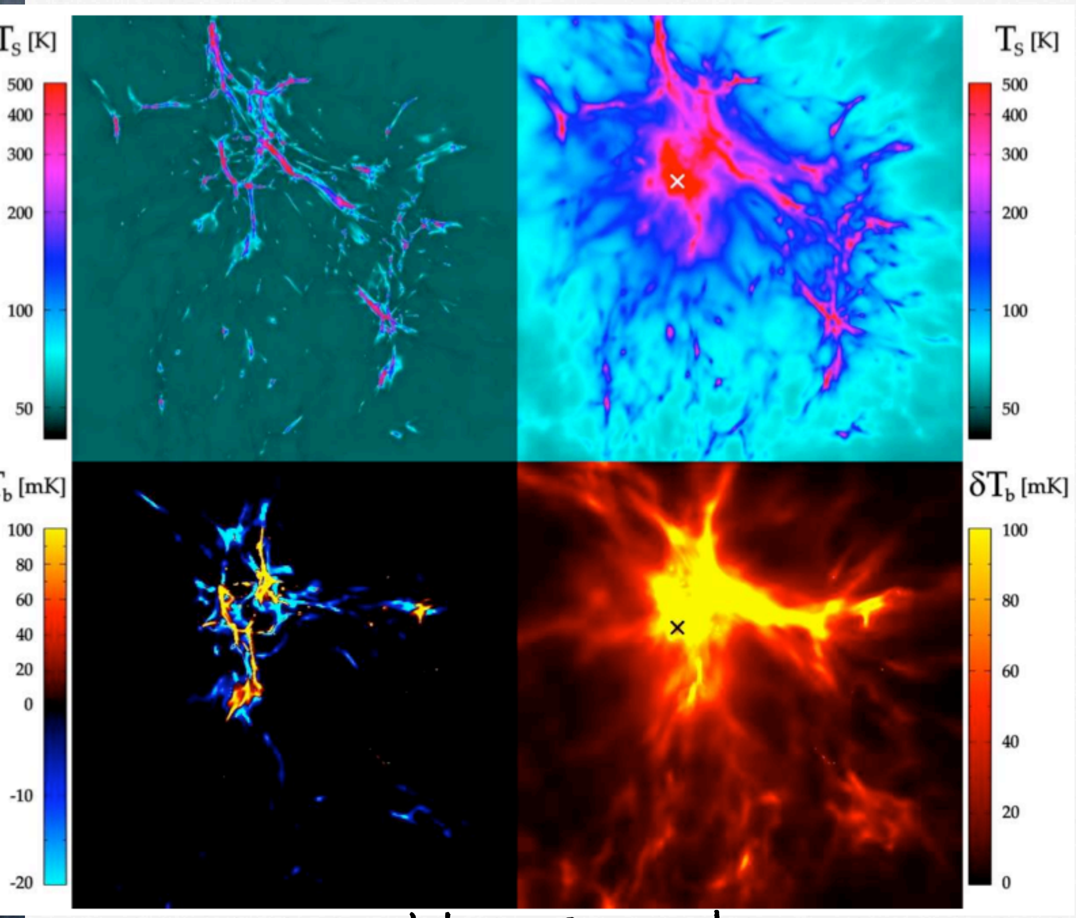
Furlanetto, Oh & Briggs 2006 (FOB06)

astro-ph/0608032

Top Google hit for '21cm transition'

But if you Google '21cm line' instead you get...

21cm observations will revolutionize the field



Kuhlen & Madau 06

See 21cm emission from IGM in absorption or emission against CMB

Couple spin and kinetic temperatures by collisions or Wouthuysen-Field effect

Probe both Dark Ages and First Light

MWA---Western Australia

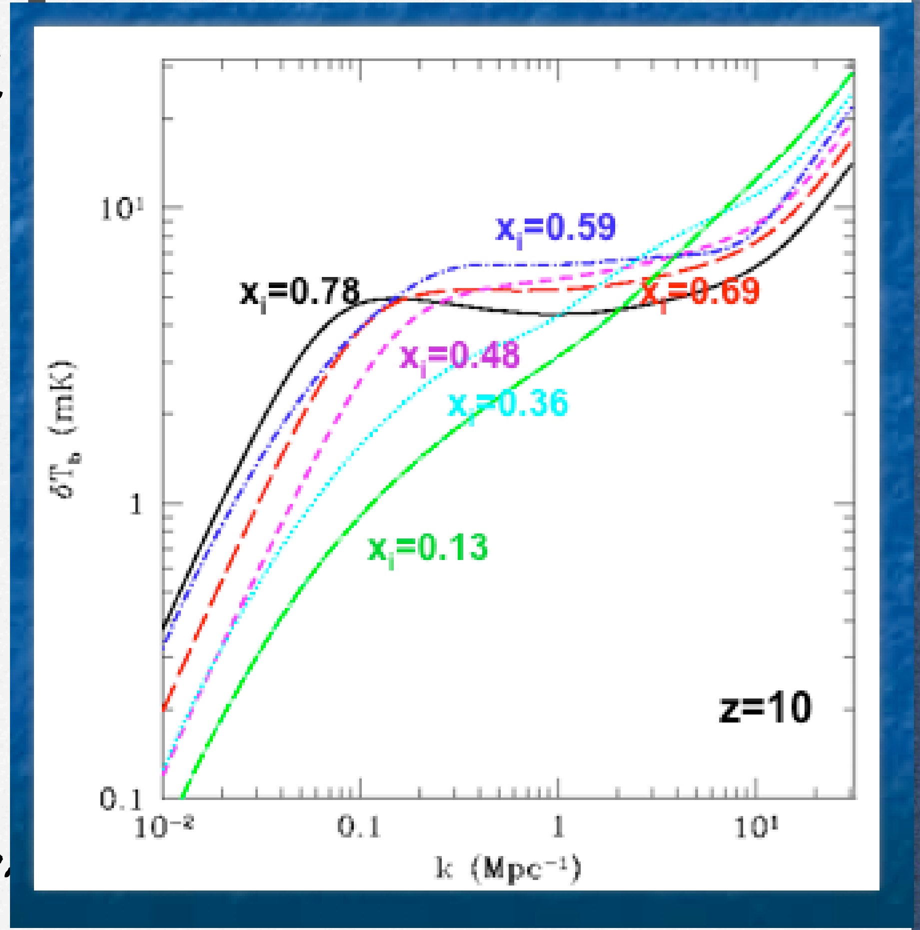
PAST---Northwest China

LOFAR--Netherlands

SKA--??

21cm Power Spectrum

- Language generally used for 21cm fluctuations
- Tools developed for CMB/ galaxy surveys
- Natural language for interferometer
- Good choice for Dark Ages, before ionizing sources turn on. But after that...

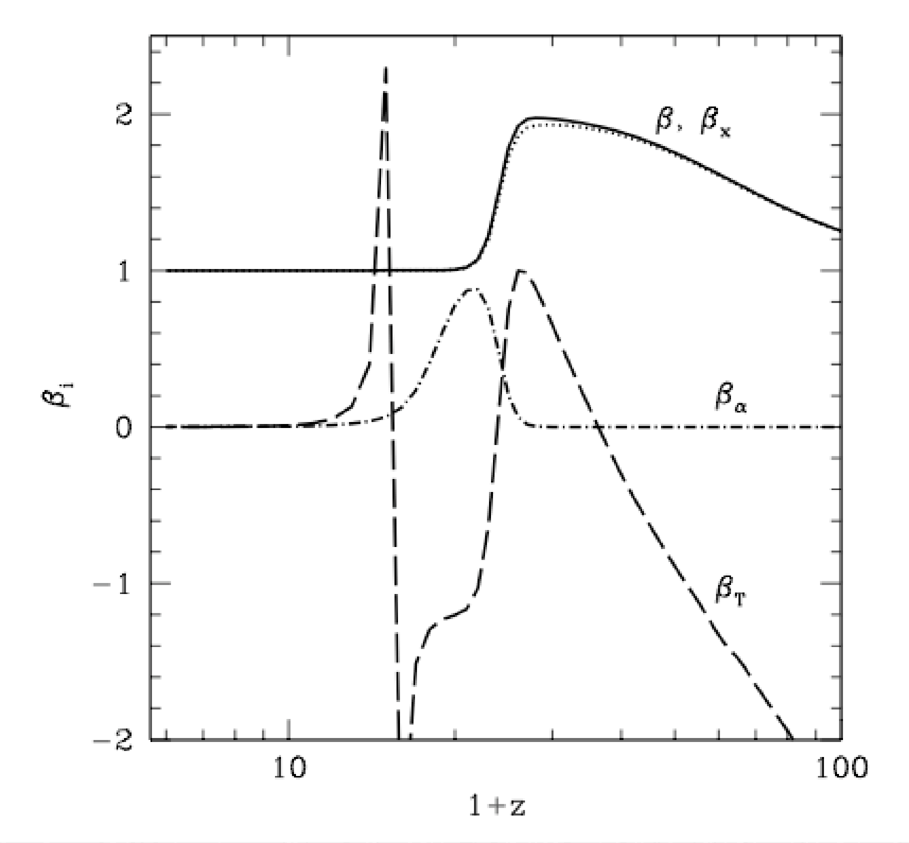


FOB06

...many effects contribute to 21cm fluctuations...

Fluctuations in...

- ☐ density (Gaussian)
- ☐ Ly-alpha flux
- ☐ ionization state
- ☐ temperature
- ☐ velocity gradients

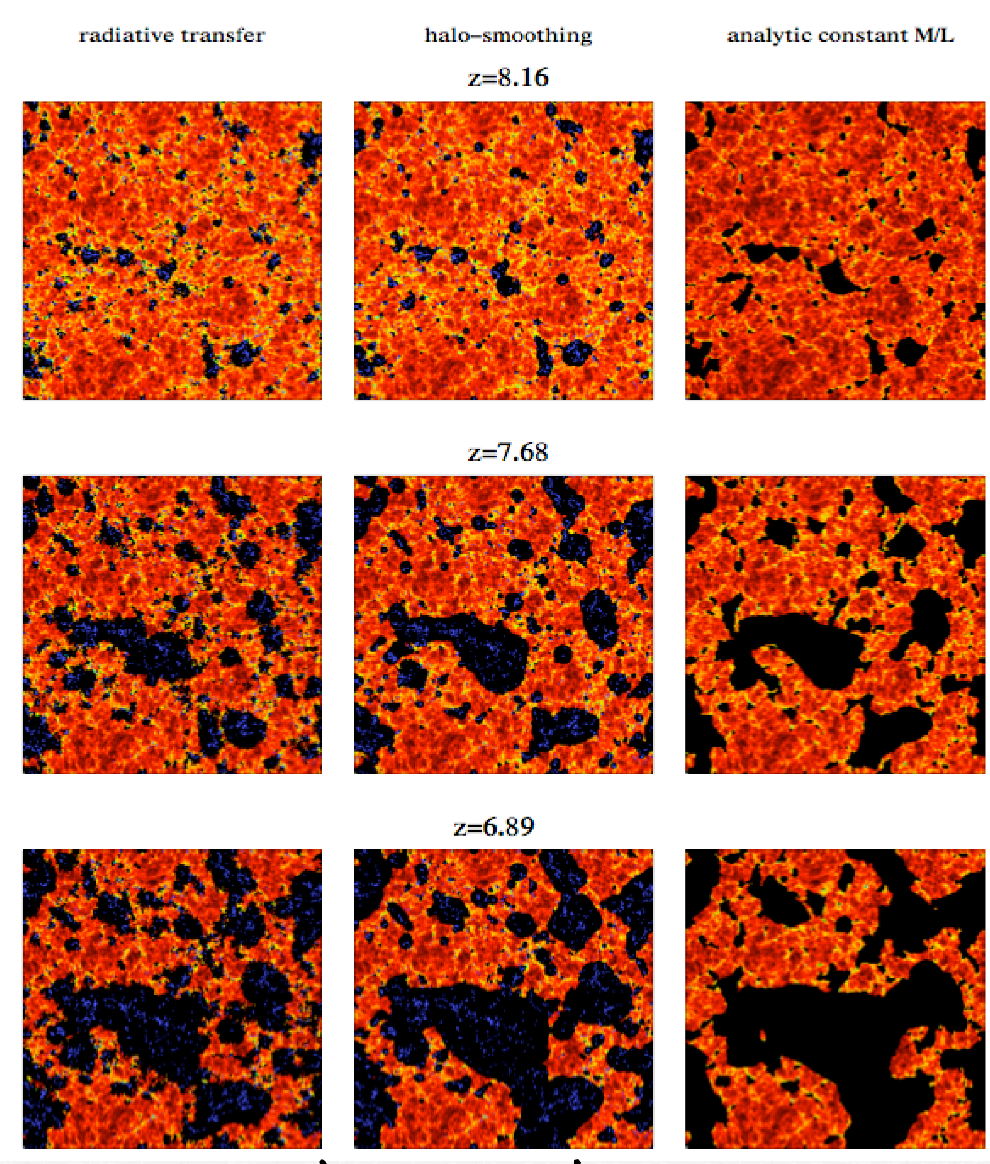


FOB06

Many likely to be correlated

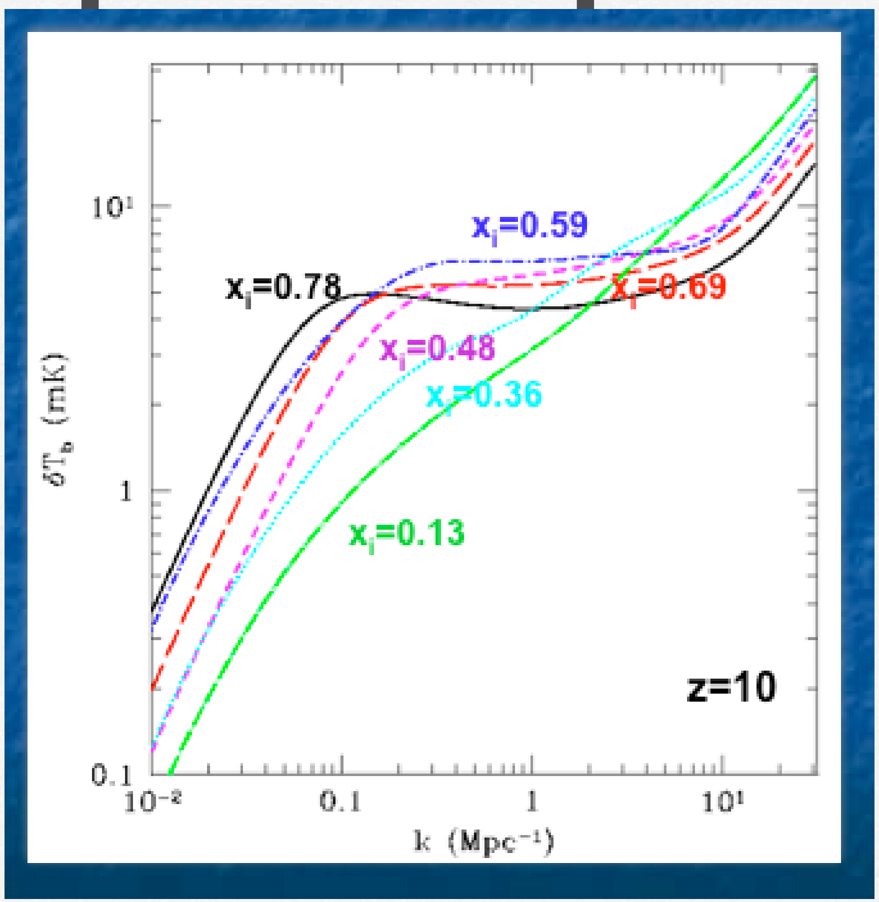
...it's a highly non-Gaussian field!

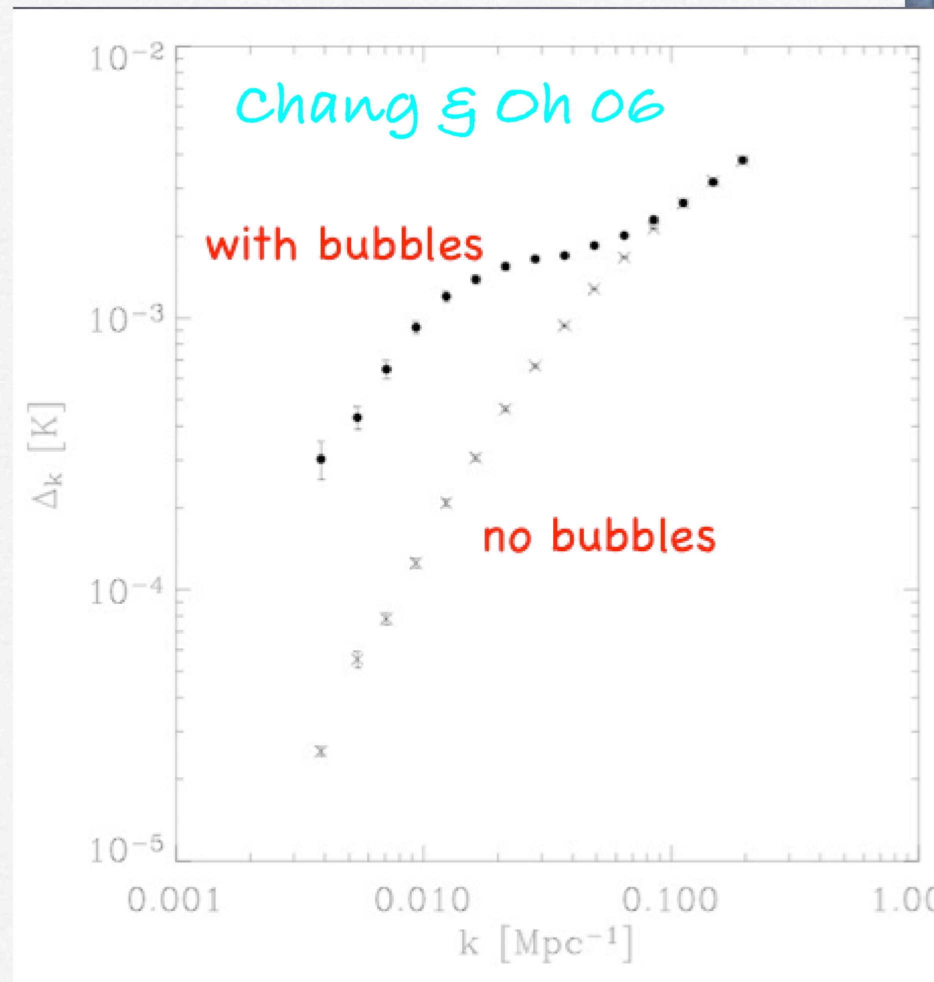
If we want to study growth and topology of reionization, we should focus on the bubbles



Zahn et al 2006

...bubbles DO strongly affect power spectrum

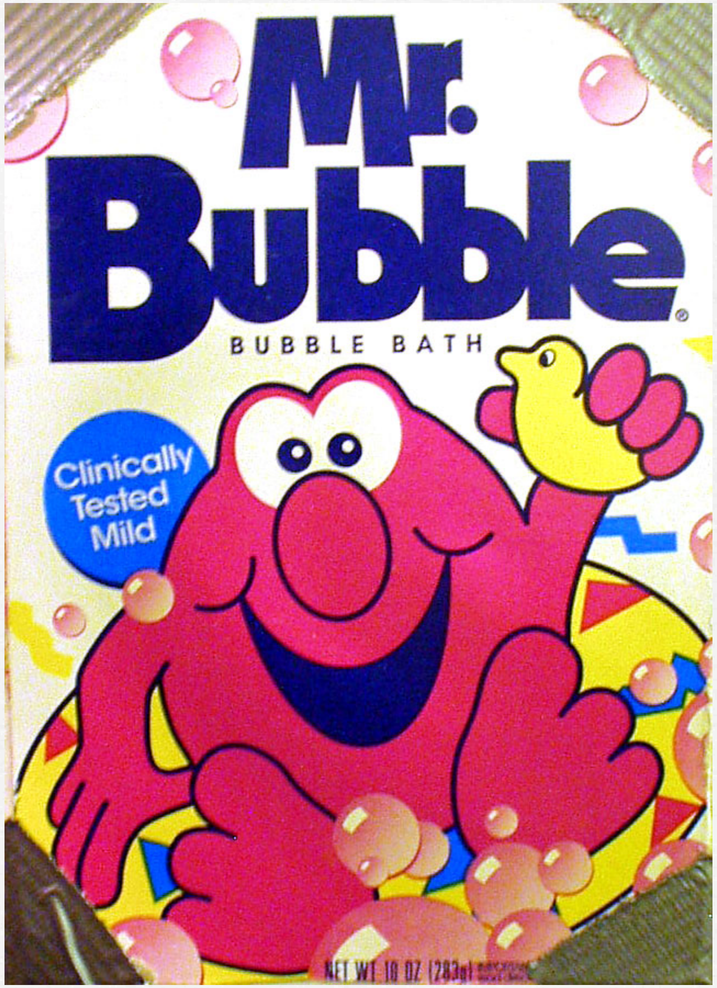




...but quantifying this will be model-dependent

Bubbles are your Friend

- Probe of ionizing source population (supposed to be big)
- Directly extract HII filling factor
- Foreground calibrator:
  - Measure mean temperature T(z)
  - Remove long wavelength artifacts from foreground removal



A few words about foregrounds...

Continuum foregrounds

Signal: ~10 mK

Noise: 1) Galactic foreground:

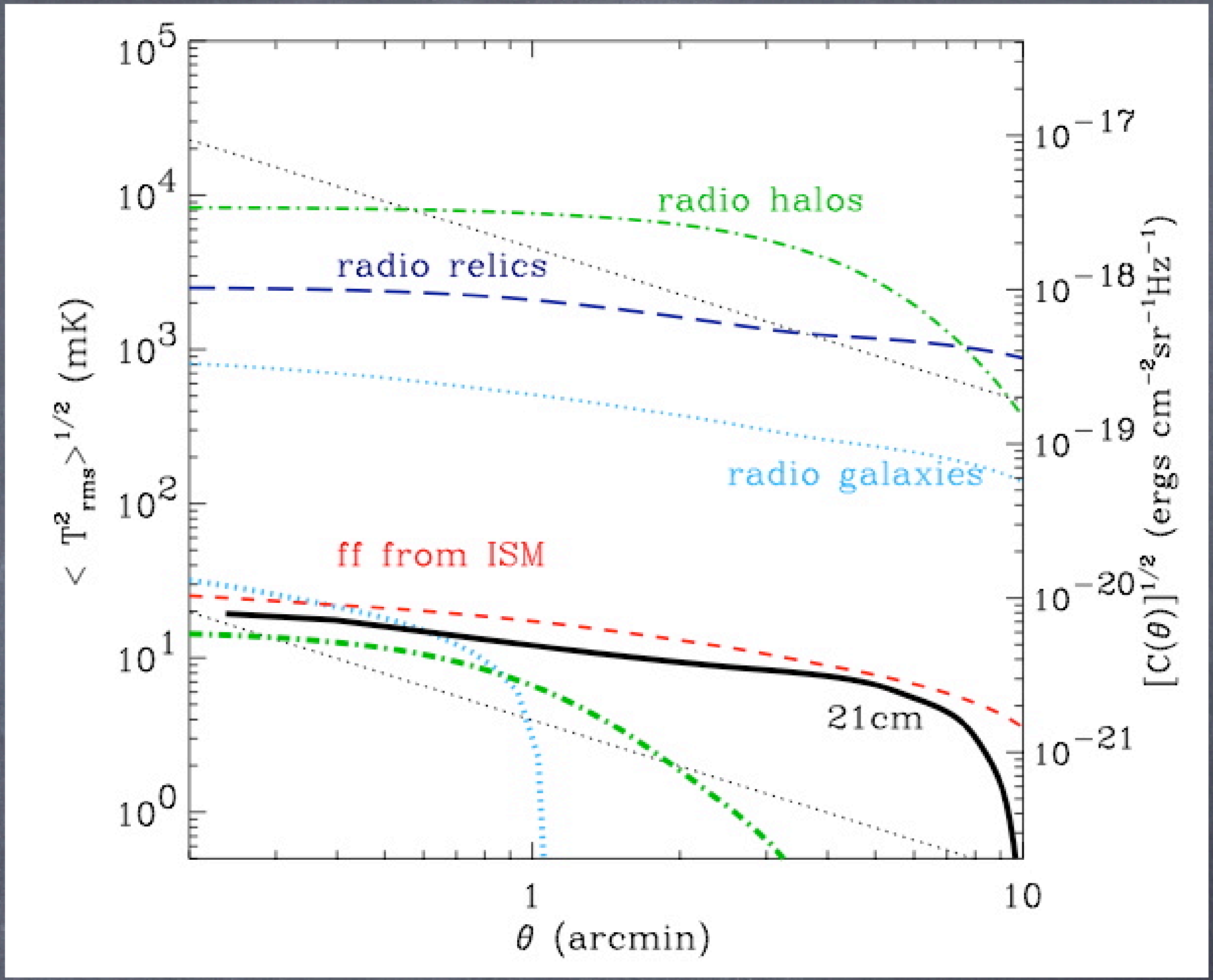
~250K at 150 MHz

2) Associated telescope noise:

$$\Delta T = 7.5 \left(\frac{1.97}{C_{\rm beam}}\right) {\rm mK} \left(\frac{A}{A_{\rm LFD}}\right)^{-1} \times \left(\frac{\Delta\nu}{1{\rm MHz}}\right)^{-1/2} \left(\frac{t_{\rm int}}{100{\rm hr}}\right)^{-1/2} \left(\frac{\Delta\theta_{\rm beam}}{5'}\right)^{-2}.$$

3) Extragalactic radio sources: DC noise~ 30K at 150 MHz

AC noise: Angular Brightness temperature fluctuations swamp 21cm signal

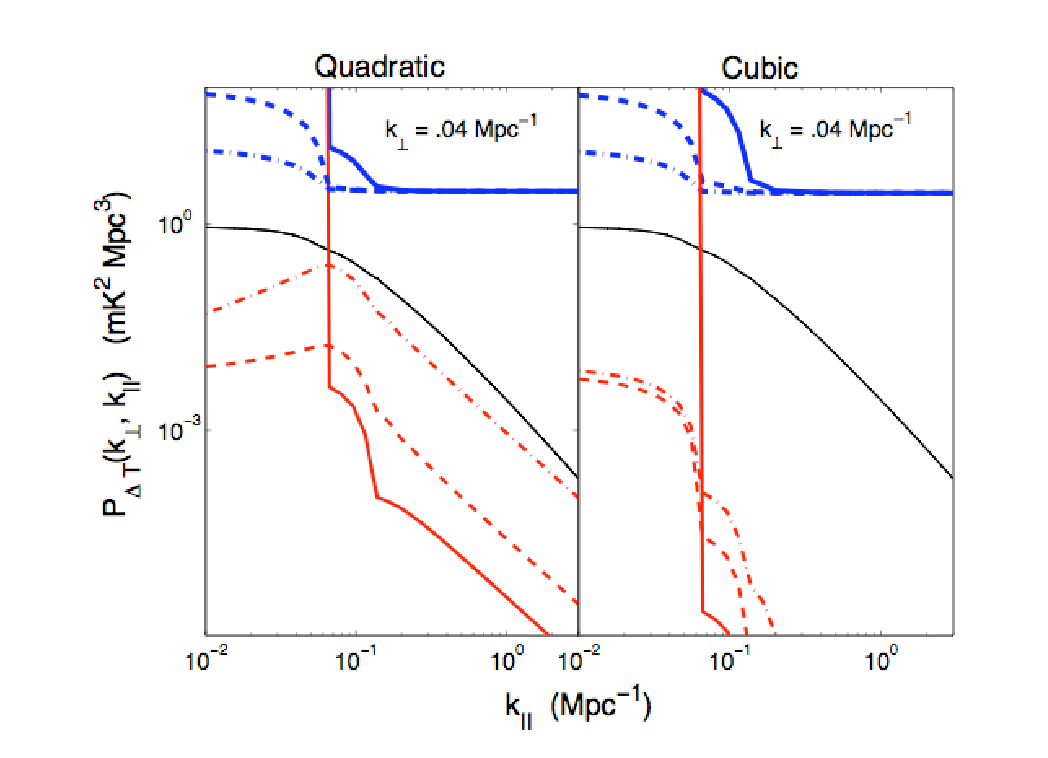


di Matteo et al (2004)

On large scales, dominated by clustering of sources
Try to reduce by point source removal....

Continuum is spectrally smooth...

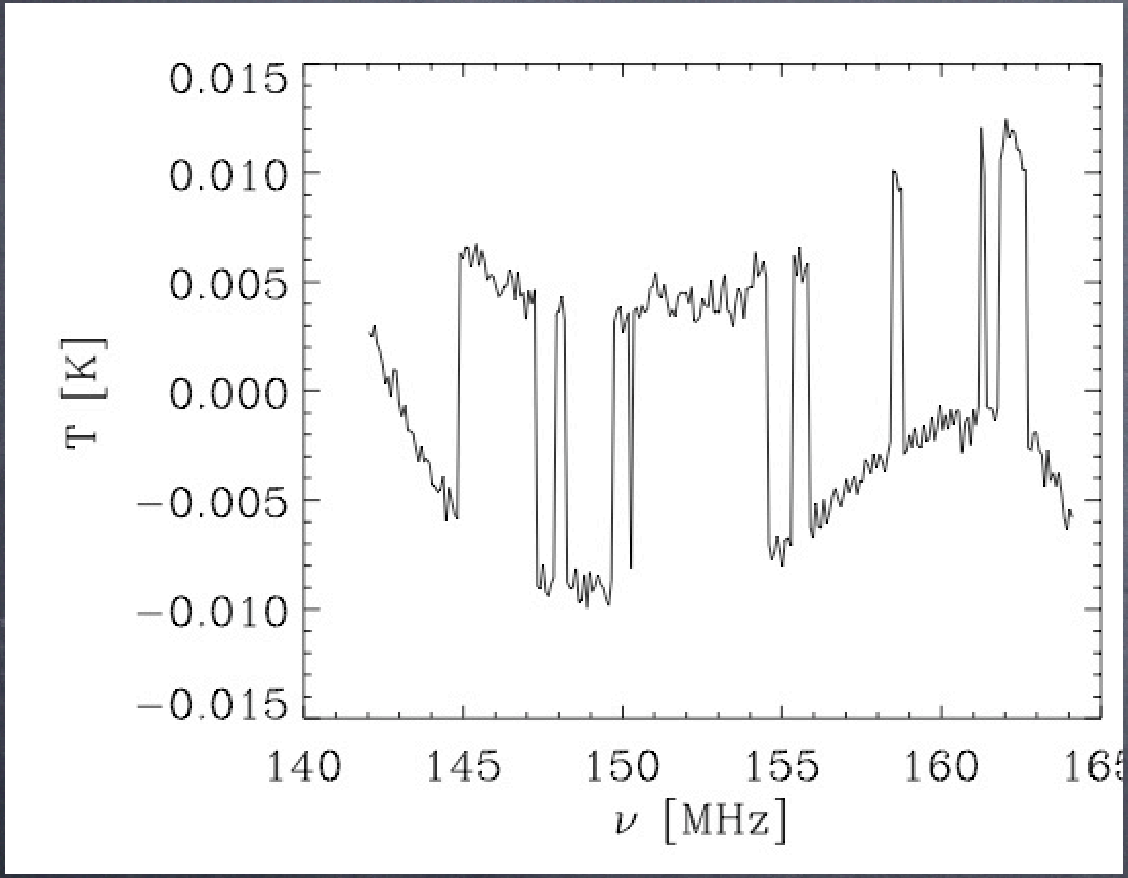
- frequency channels are highly correlated
- apply trend removal: fit and subtract smooth function to data



McQuinn et al 2006

But this also removes large scale power! (esp for high-order fit to small length)

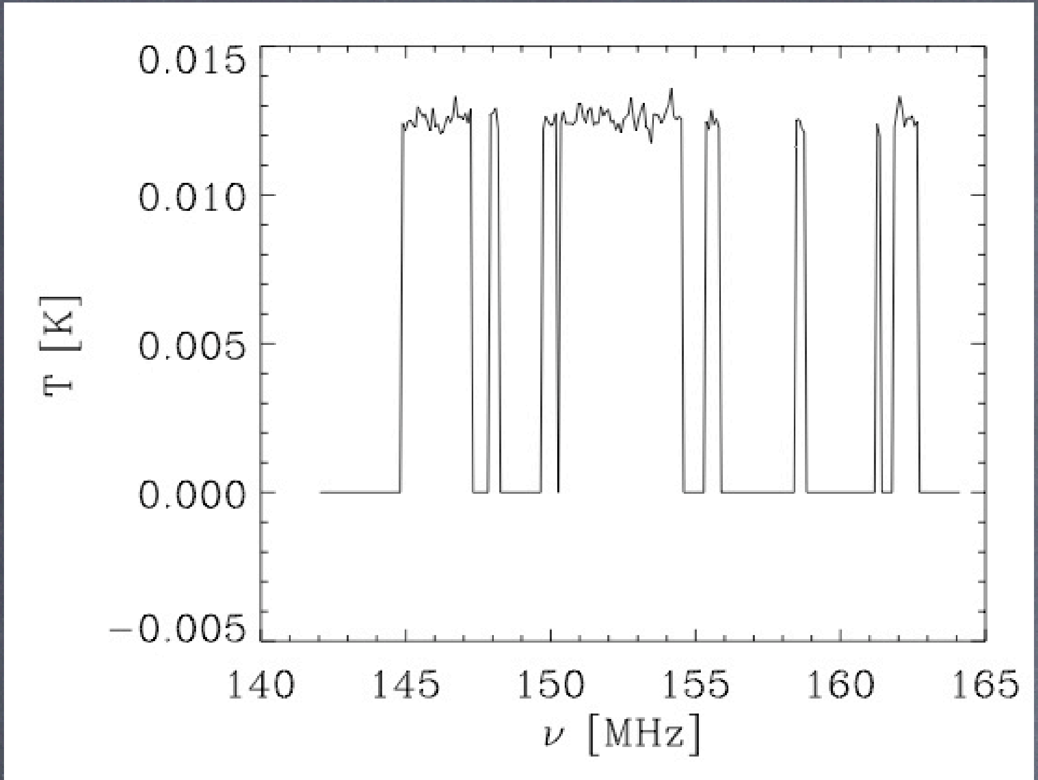
...a solution: Detrending with large bubbles



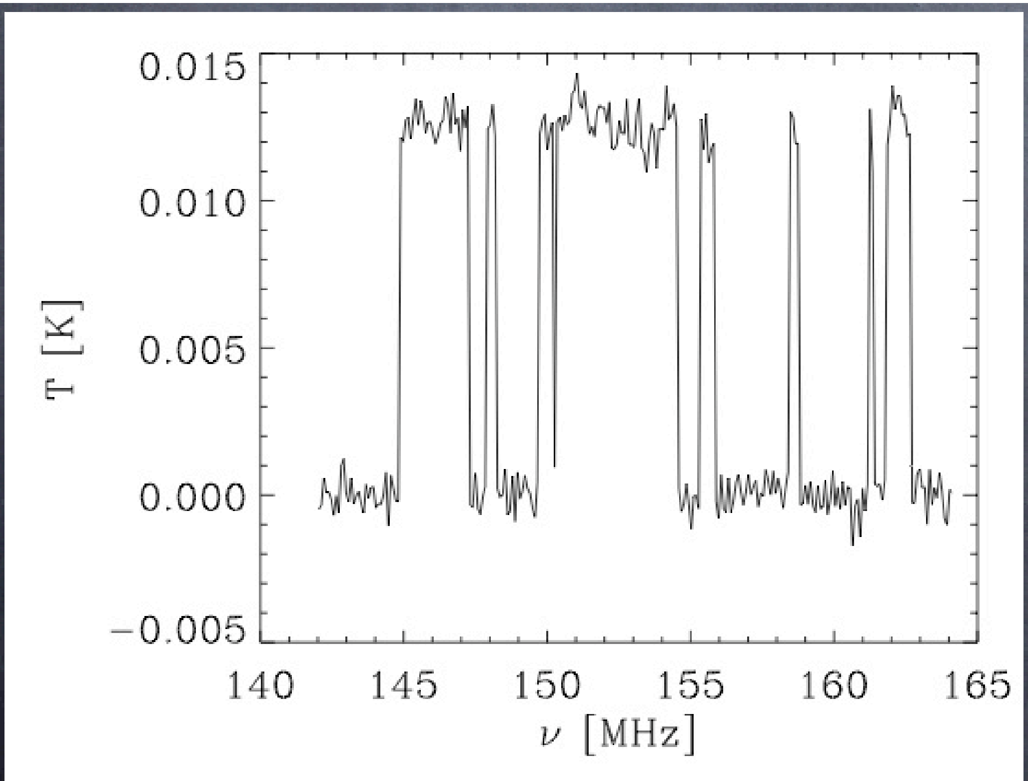
Recovered after continuum subtraction

Chang & Oh 06

Bubbles are foreground only....so use the minima of recovered spectra to normalize no 21cm baseline

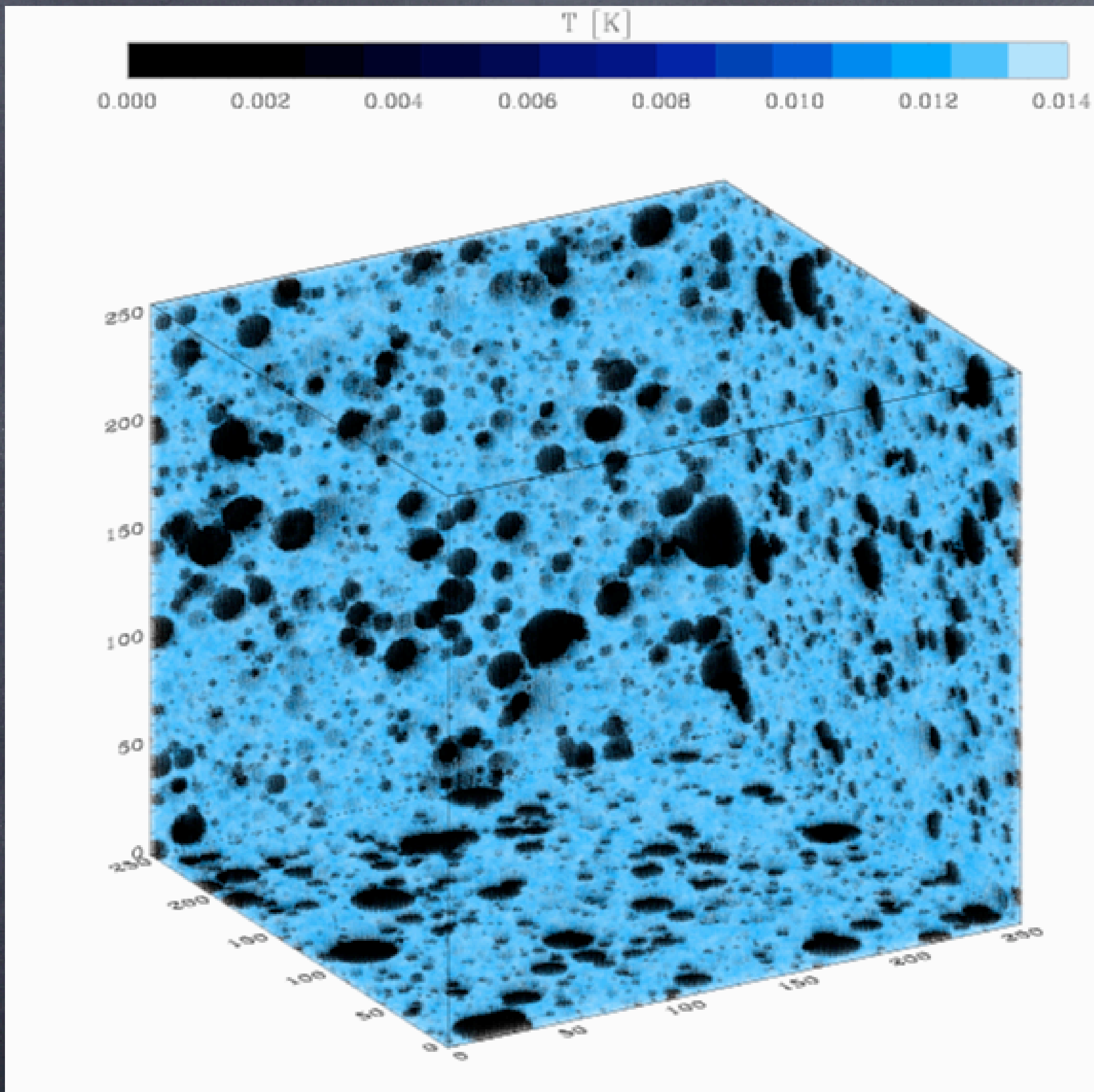


True (input) spectrum

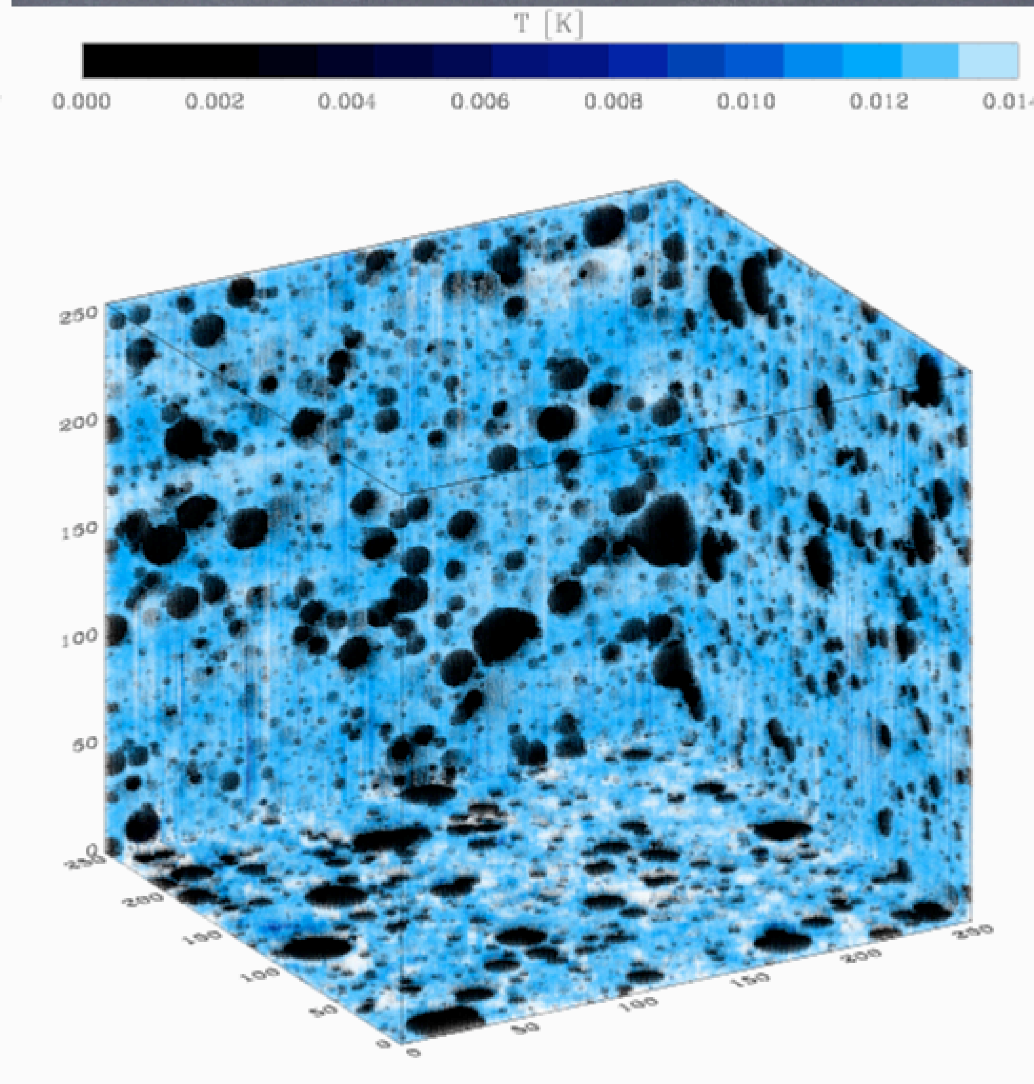


Bubble Detrended spectrum

For an SKA type instrument...



Input

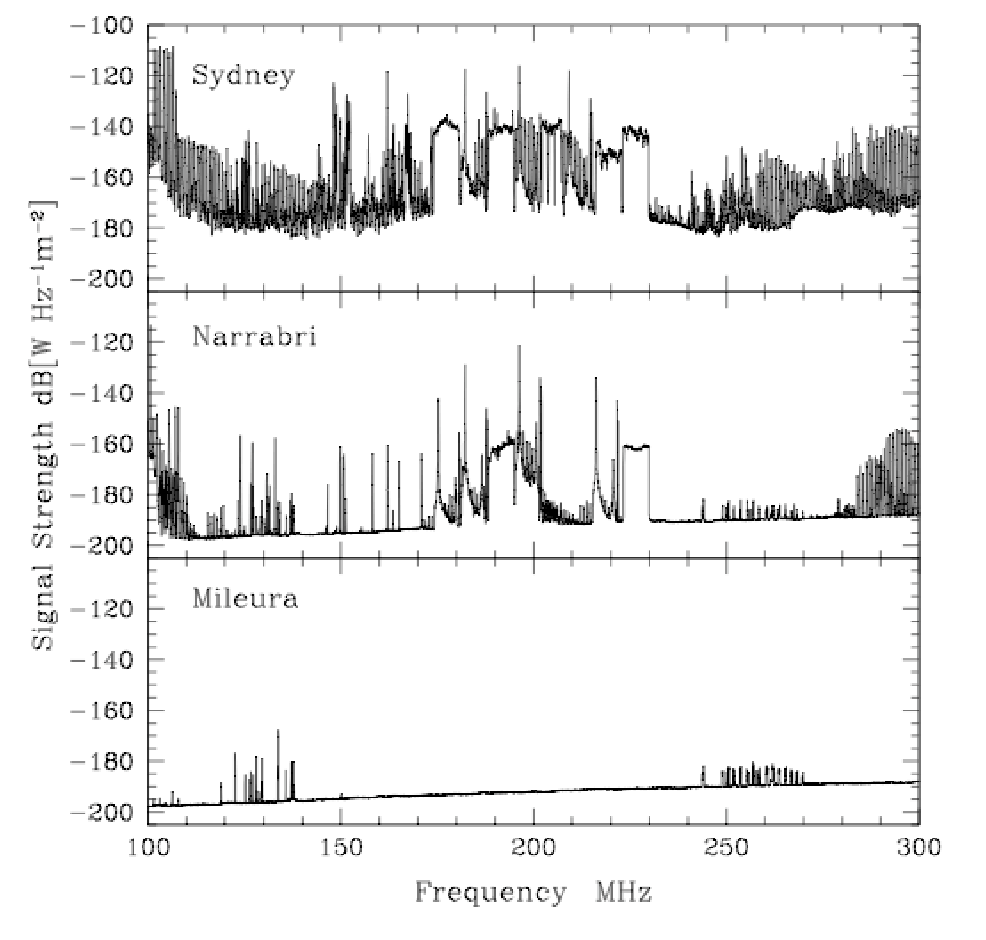


Recovered

...extremely good imaging is feasible!

Much scarier: spectral foregrounds

- Man-made interference
- Ionosphere
- Radio recombination lines
- Polarization/Faraday rotation
- Frequency-dependent side-lobes



FOB06

Back to Bubbles

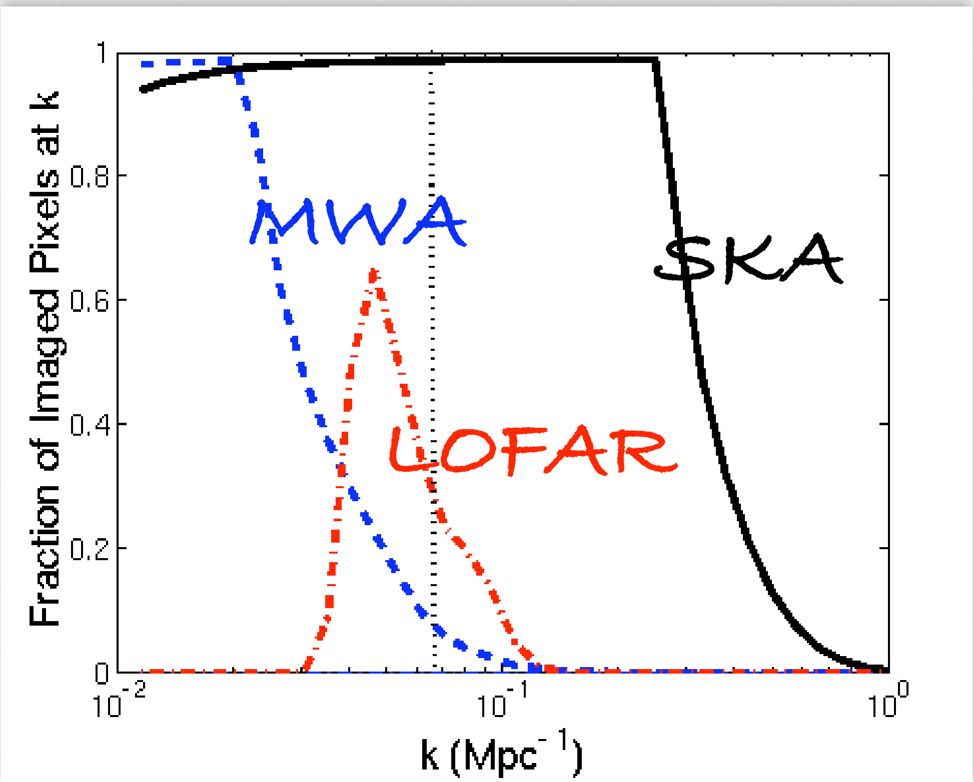
Direct Imaging

S/N high only on largest scales, need R~20 Mpc

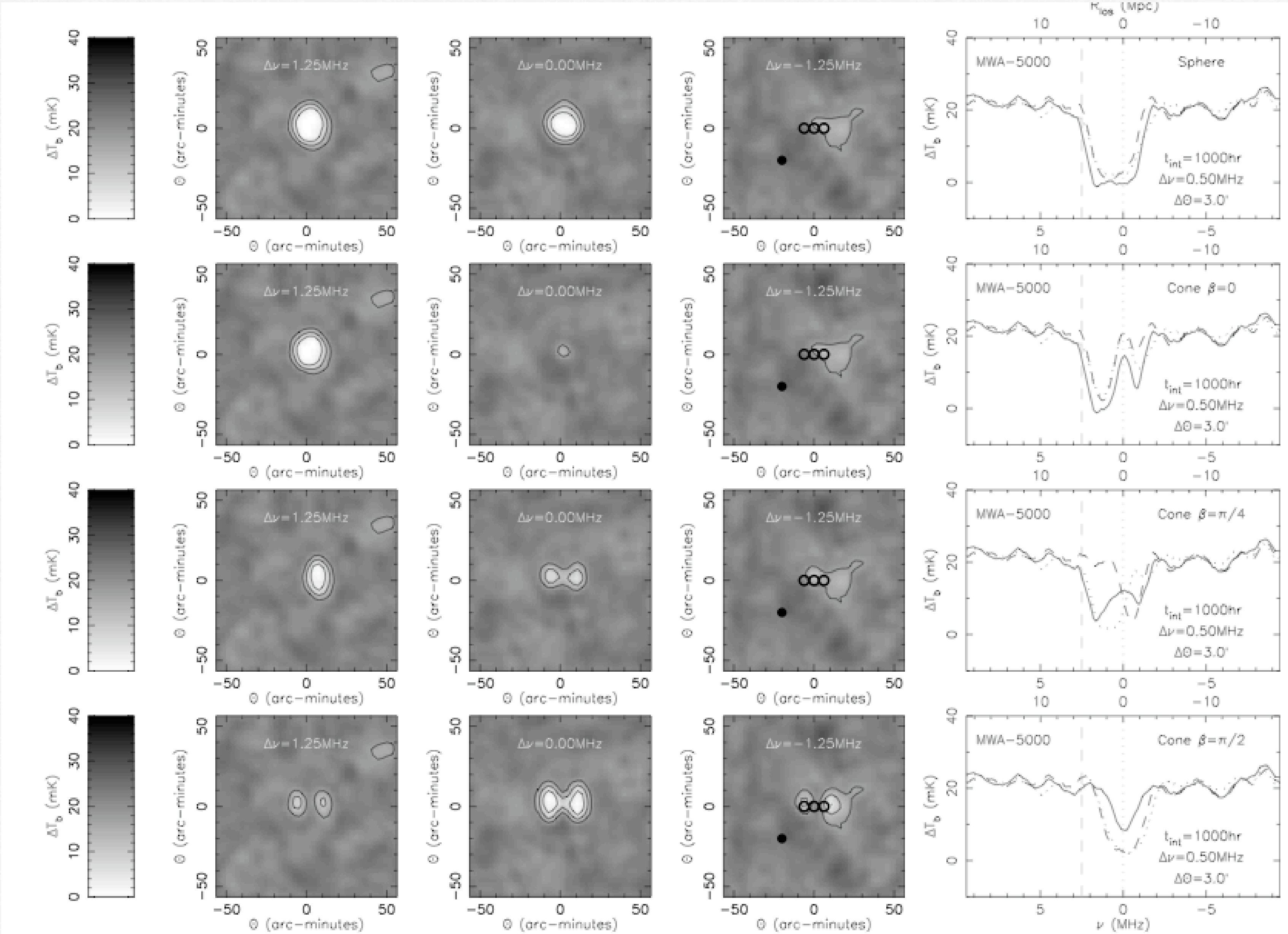
Rare bright quasars (or clustered galaxies)

BUT: survey volume is HUGE!

Expect 1 active/fossil HII region in every MWA FOV with R > (24,40) Mpc at z=7 (Wyithe & Loeb 2004)



McQuinn et al 2006



Wyithe, Loeb & Barnes 2004

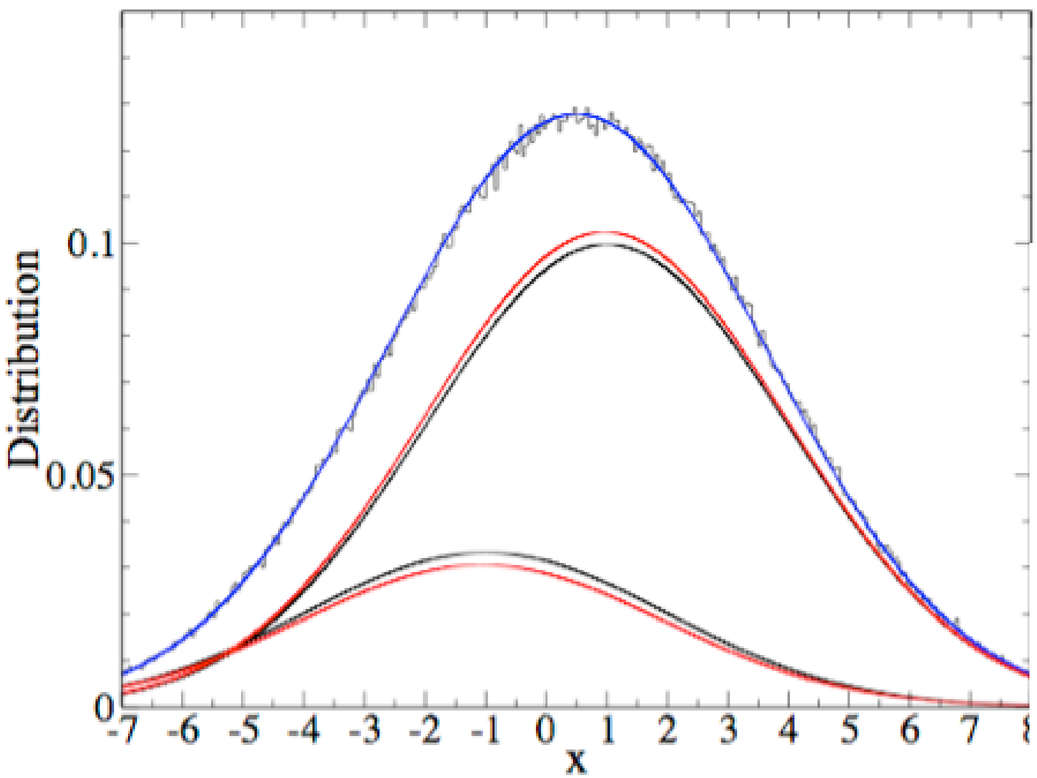
...what do we get?

- -- $\delta T_b(z)$ X-rays, fossil HII
- Foreground calibrator
- Size, shape of HII region--> QSO properties
- Discover QSOs? (though mostly their fossils)
- Try to cross-correlate with galaxy population

But can we see the smaller bubbles and get Q_HII(z)?

One Point Statistics

Bubbles create bimodality in the PDF



Can we pick it out?

DETECTING BIMODALITY IN ASTRONOMICAL DATASETS

KEITH M. ASHMAN AND CHRISTINA M. BIRD
Department of Physics and Astronomy, University of Kansas, Lawrence, Kansas 66045-2151
Electronic mail: ashman@kusmos.phsx.ukans.edu, tbird@kula.phsx.ukans.edu

STEPHEN E. ZEPF[1]
Department of Astronomy, University of California, Berkeley, California 94720
Electronic mail: zepf@astron.berkeley.edu

Received 1994 April 13; revised 1994 July 29

ABSTRACT

We discuss statistical techniques for detecting and quantifying bimodality in astronomical datasets. We concentrate on the KMM algorithm, which estimates the statistical significance of bimodality in such datasets and objectively partitions data into subpopulations. By simulating bimodal distributions with a range of properties we investigate the sensitivity of KMM to datasets with varying characteristics. Our results facilitate the planning of optimal observing strategies for systems where bimodality is suspected. Mixture-modeling algorithms similar to the KMM algorithm have been used in previous studies to partition the stellar population of the Milky Way into subsystems. We illustrate the broad applicability of KMM by analyzing published data on globular cluster metallicity distributions, velocity distributions of galaxies in clusters, and burst durations of gamma-ray sources. FORTRAN code for the KMM algorithm and directions for its use are available from the authors upon request.

Directly tells us Q_HII(z)!!!

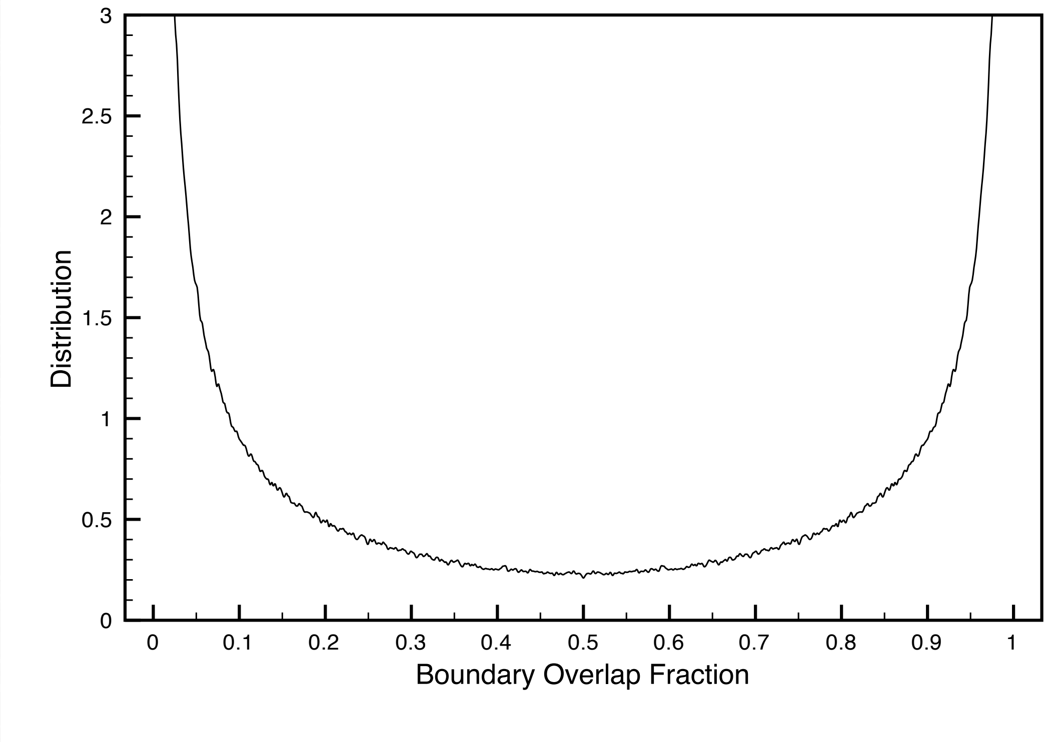
Hansen, Oh & Furlanetto (2006, in prep)

...partially ionized boundary pixels create complications

$$f_{bd} \approx 3\frac{r_{pix}}{R_{bub}} Q_{\rm HII}$$

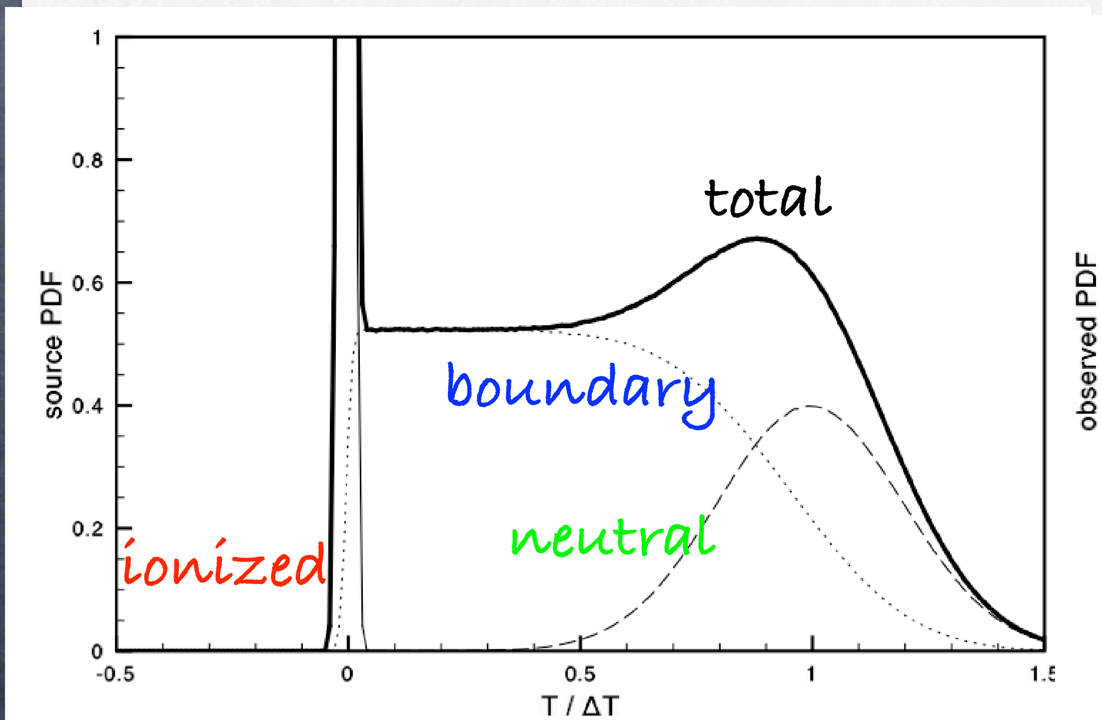
Can be ~10-70% of pixels

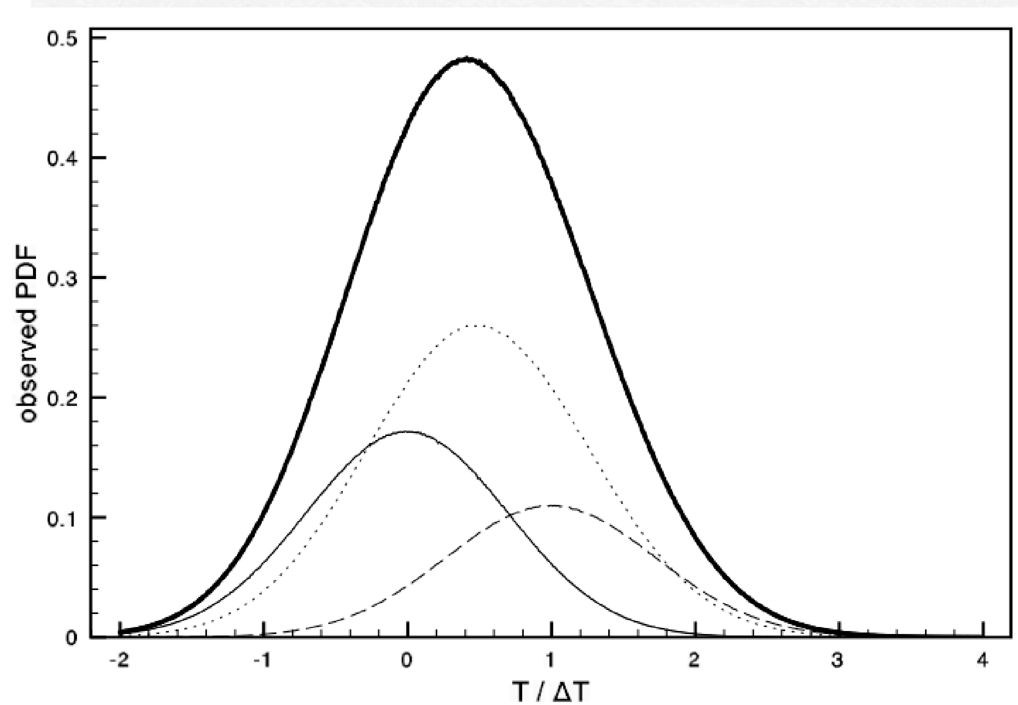
Dependent on telescope resolution+bubble size



By symmetry, tend to be ~1/2 ionized

...here's a more realistic PDF



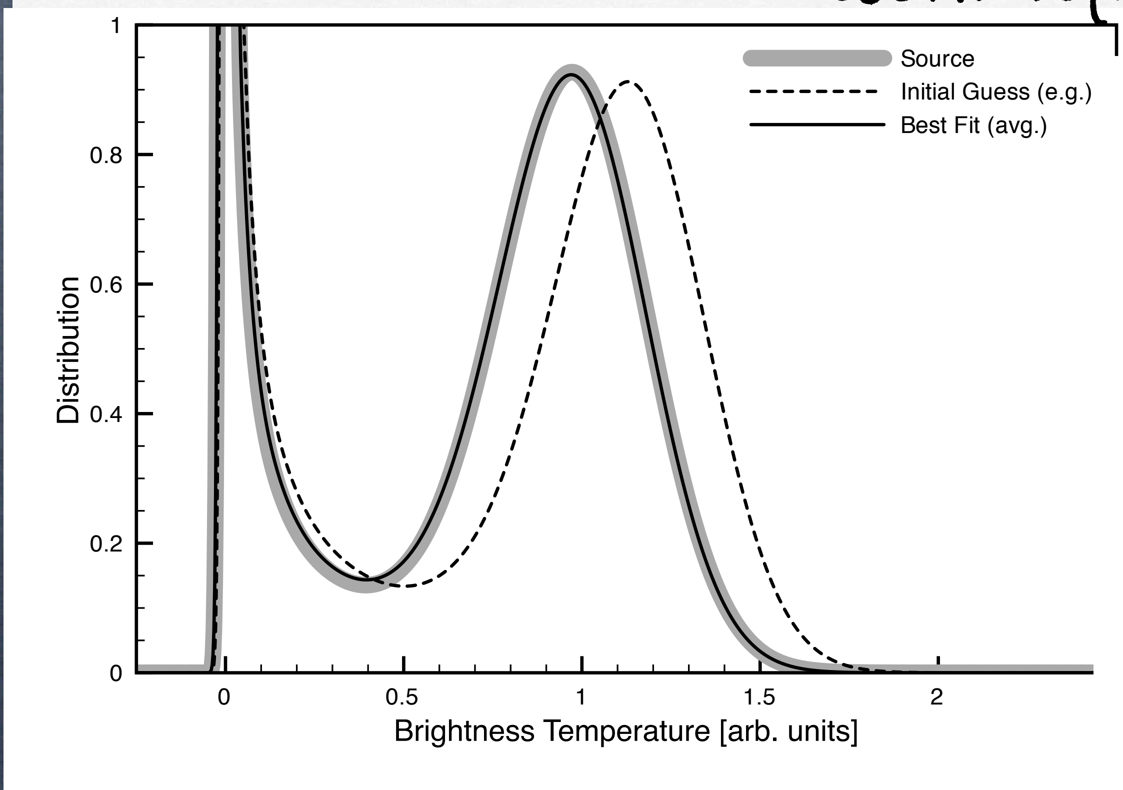


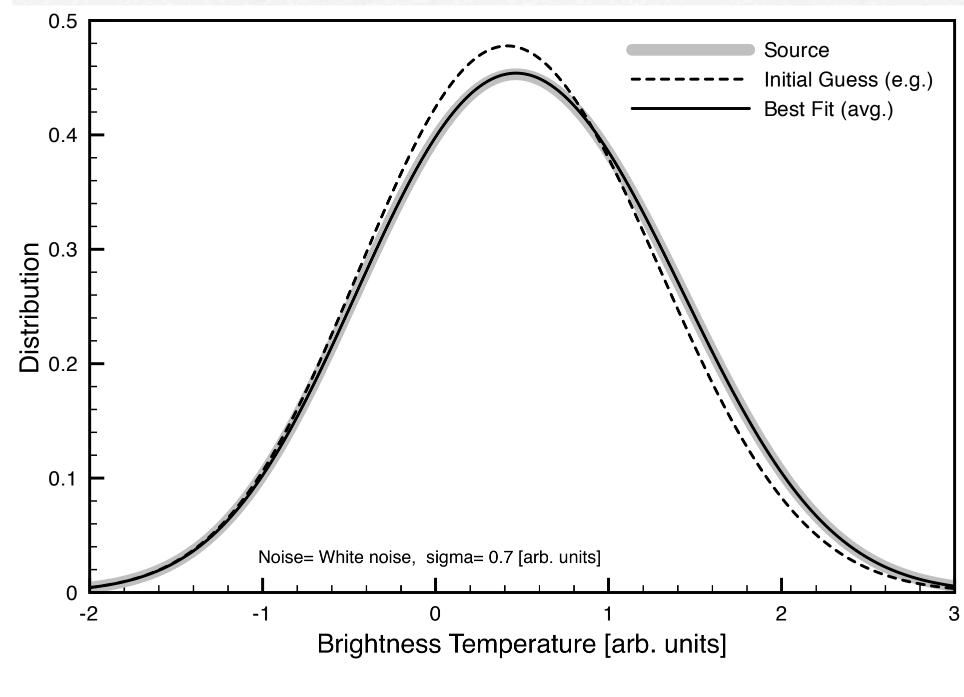
no noise

with noise

It works!

Solve for populations via iterative Max-likelihood technique



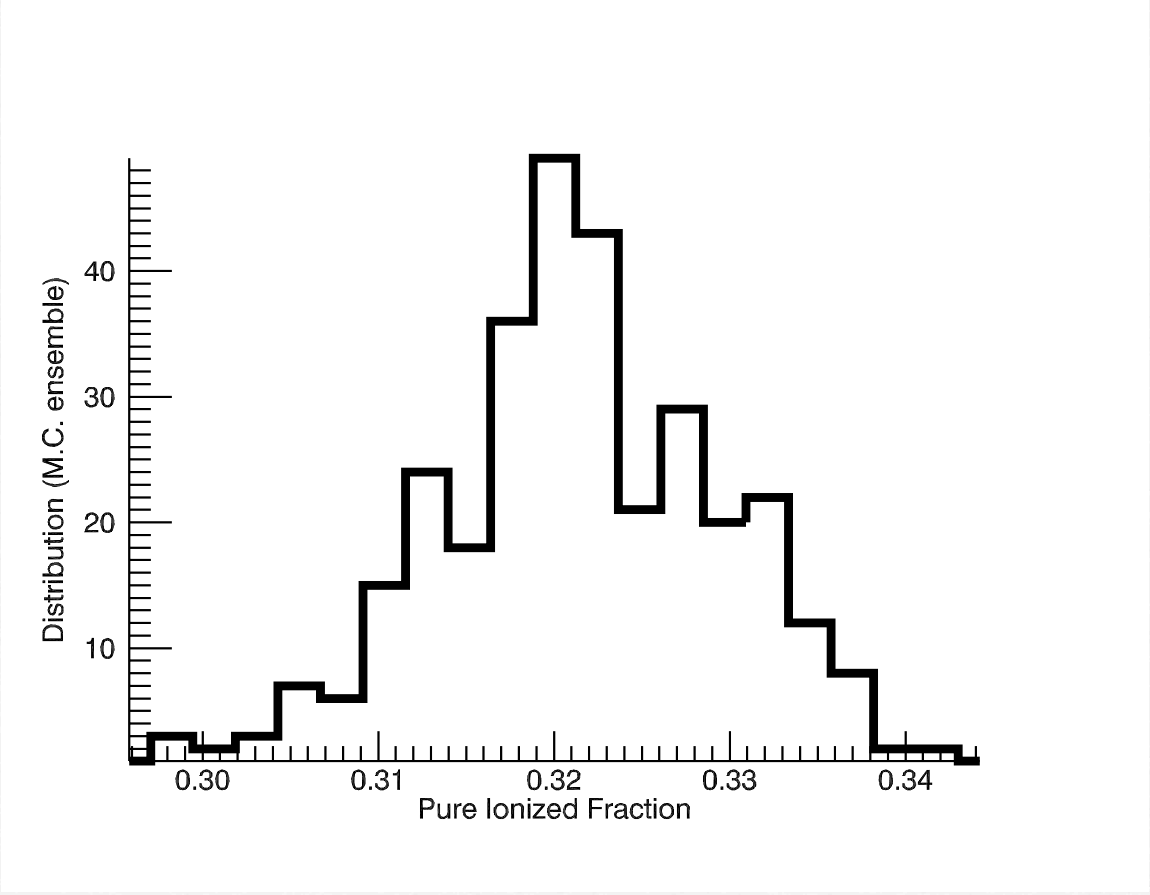


original distribution

with noise

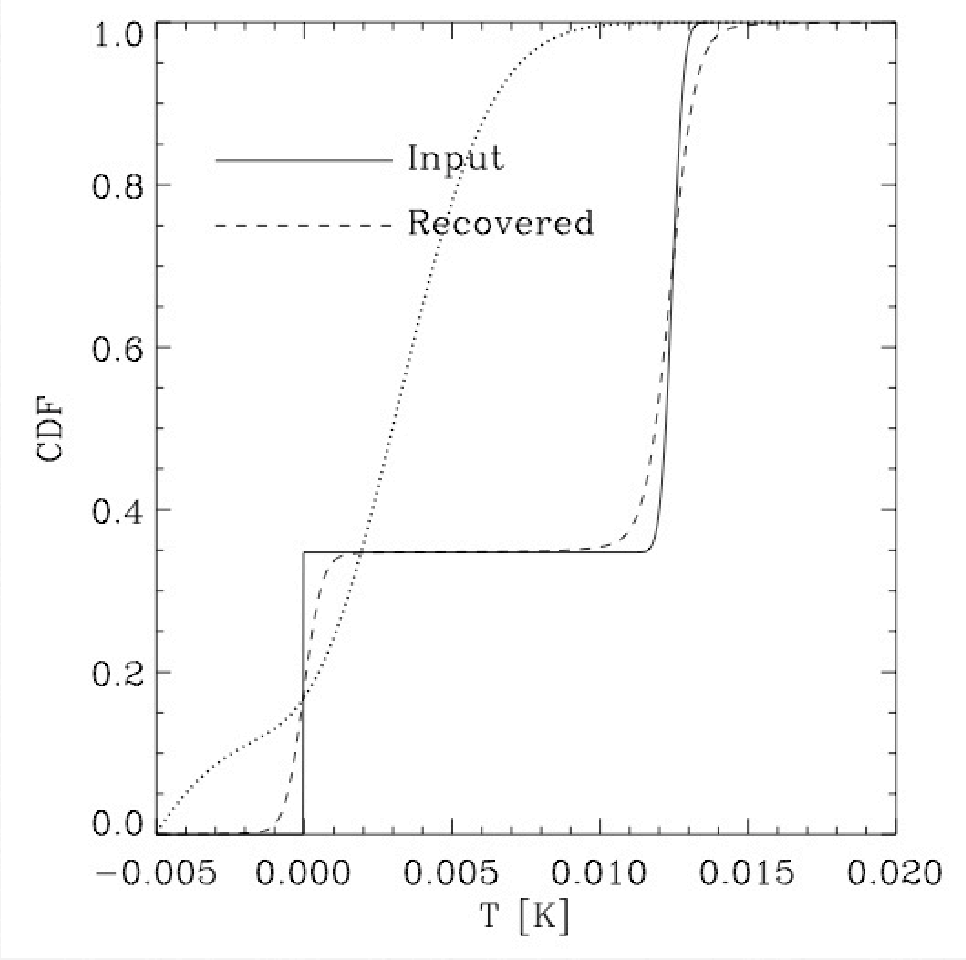
Leverage comes from having many pixels

Monte Carlo Errors agree with Fisher Matrix estimates



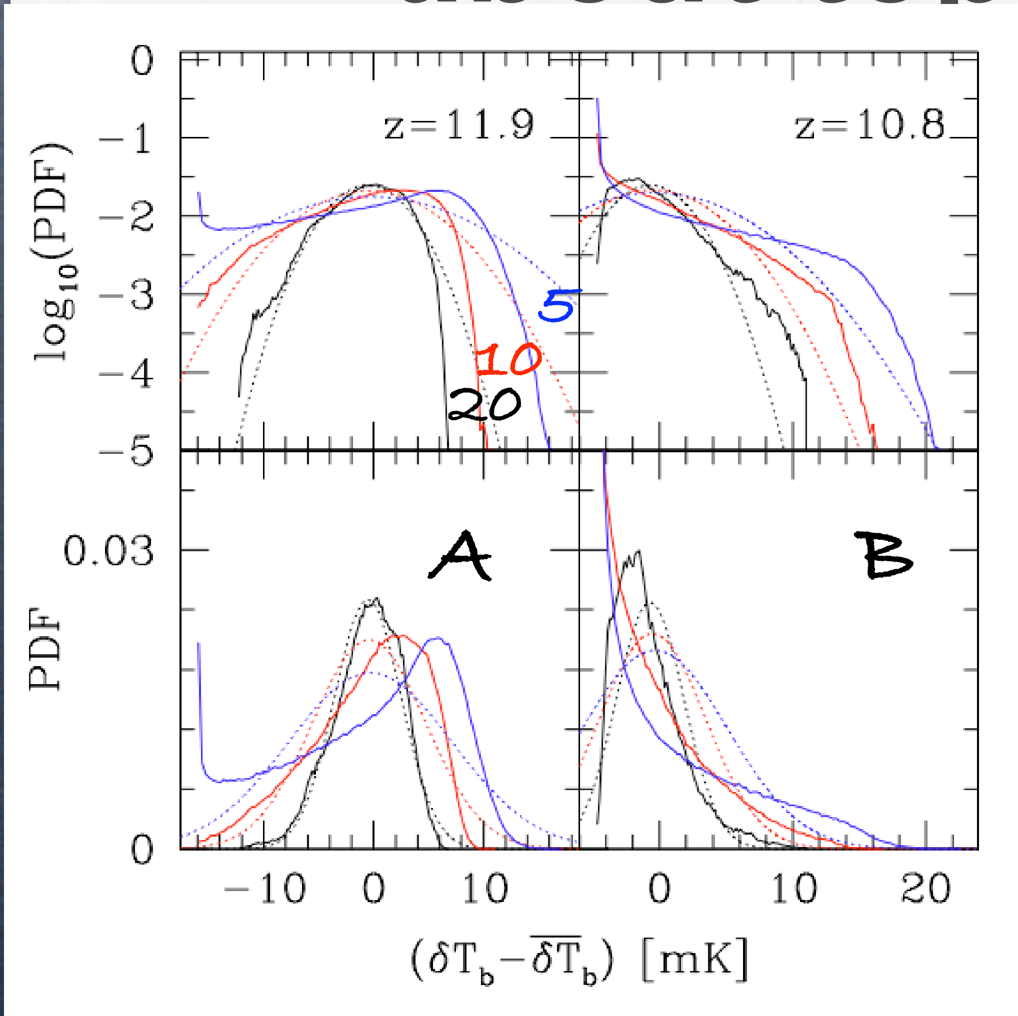
An idealized case, but results are very encouraging...

Still have to tackle Foregrounds



Though definitely works in high S/N case

In principle, PDF has info about topology too



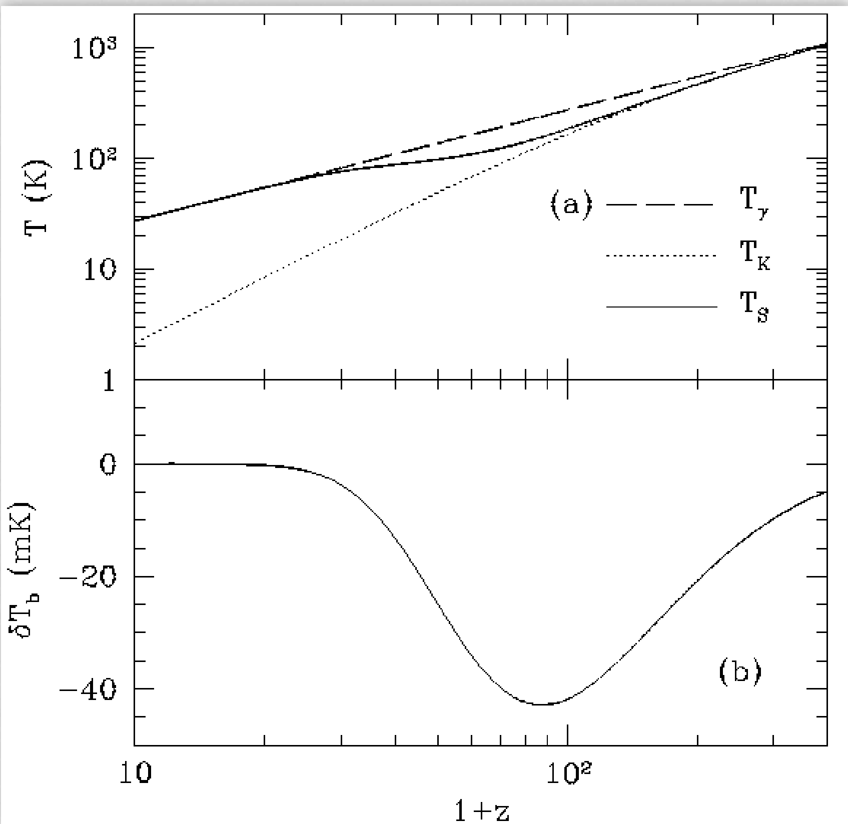
Mellema et al 2006

A: Cutoff at high Tb-- inside-out reionization

B: Tail at high Tb-- islands of neutral gas inside HII regions

Note: distribution narrows as smoothing scale increases

Dark Ages



Trace matter power spectrum (Loeb & Zaldarriaga 2004)

---fully 3D

--get small scale power

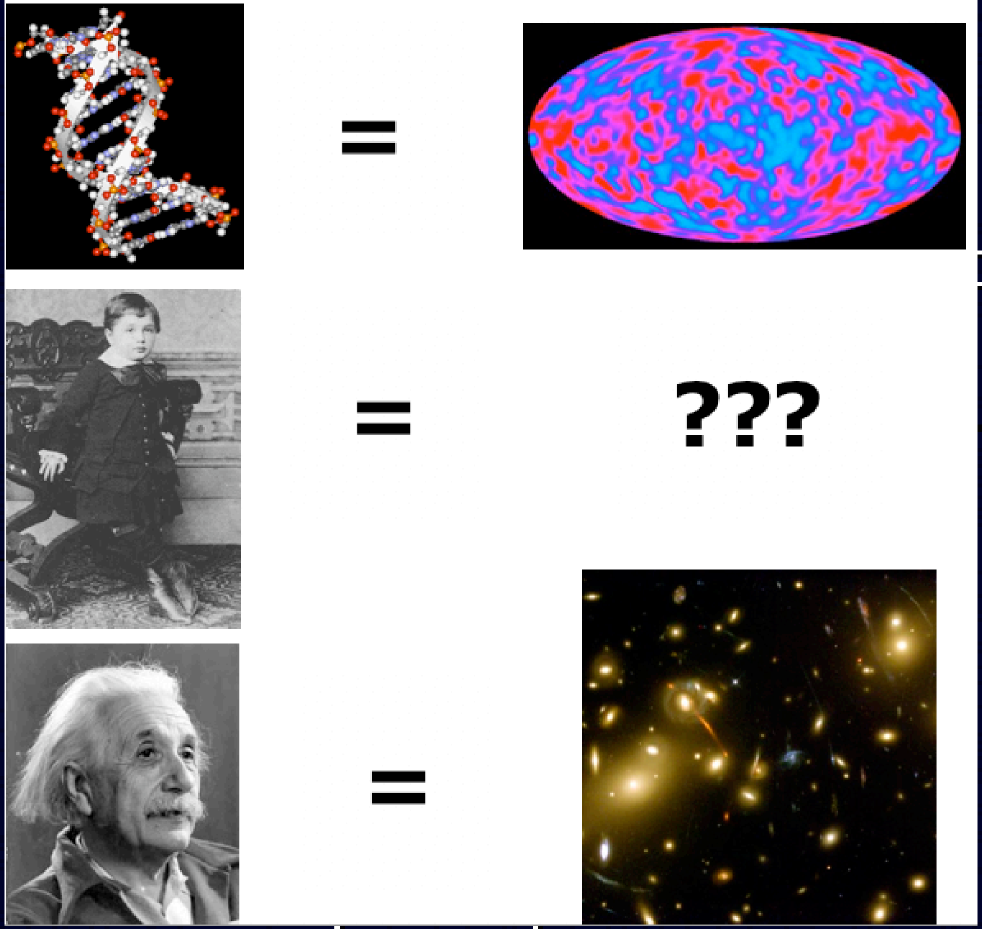
--can be used for lensing

--trace DM decay/ annhilation (Furlanetto, Oh & Pierpaoli 2006)

Bottom Line

- HII Bubbles are main feature (holes in 21cm emission) after first sources light up
- Much needed foreground calibrators
- Can only directly image biggest ones
- If can detect statistically, obtain Q_HII(z)
- More work needed!

Stay tuned...



"The childhood shows the man,
As morning shows the day."

John Milton, Paradise Regained