Approaches to Constraining Reionization

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Journal Club

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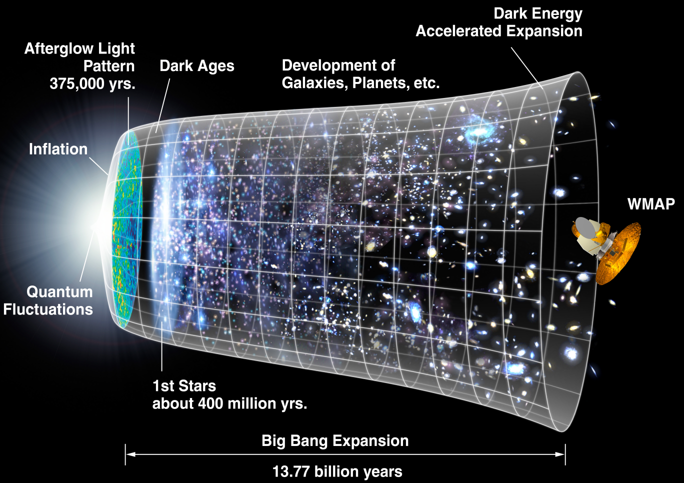
Outline

- Background and current state of the field
- Past work
- Future work

What is reionization?



Phases of hydrogen record several important milestones in the history of the evolution of the Universe. [Image from NASA]

Importance of Reionization?

- Marks time when of order 1 ionizing photon was emitted per baryon in the Universe
  - → Hence when radiation became dominant influence on the IGM
- Star and galaxy formation is affected by the temperature and ionization state of the IGM.
- Reionization affects both the temperature and ionization state of the IGM and therefore plays a regulatory role in formation of stars and galaxies.
- In order to understand the history of large-scale structure formation, you must also understand the Epoch of Reionization (EoR).

What do we want to know?

- The timing of reionization.
  - $\rightarrow$ When did it occur?
  - $\rightarrow$ How long did it last?
- What caused it? What were the sources of ionizing photons?
  - $\rightarrow$ Quasars?
  - $\rightarrow$ Dwarf galaxies?
  - $\rightarrow$ Other X-ray sources?
- How did these sources impact their environments?

What do we want to know?

With Jargon

- Neutral fraction of the Universe as a function of redshift ($Q_{\mathrm{HI}}(z)$)
  - $\rightarrow$ Direct progress bar for the EoR
- Size distribution of ionized regions as a function of redshift
  - $\rightarrow$ Provides evidence for sources of reionization
- Ionizing emissivity, escape fraction, galaxy UV luminosity function along with respective redshift dependencies
  - $\rightarrow$ Important, yet highly uncertain, parameters to reionization models.
- and others

Approaches to Constraining Reionization

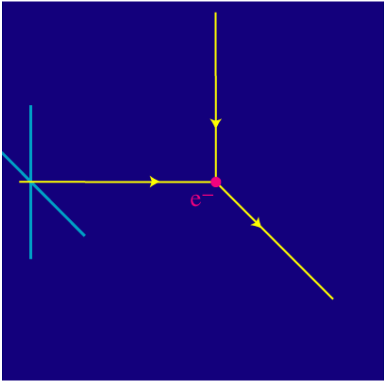
- Quasar spectra
  - → Presence/absence of Gunn-Peterson trough.
  - → Damping wings.
  - → Absorption redward of Lyman-α.
  - → Evolution of Lyman-α line profile.
  - → Proximity zone sizes.
  - → IGM temperature measurements.
- 21cm line
  - → Mapping/power spectra of 21cm fluctuations.
  - → Evolution of global 21cm signal.
  - → 21cm forest (analogous to Lyman-α forest).
- Thompson scattering of CMB photons
  - → Optical depth to Thompson scattering
  - → Kinetic Sunyaev-Zel'Dovich effect

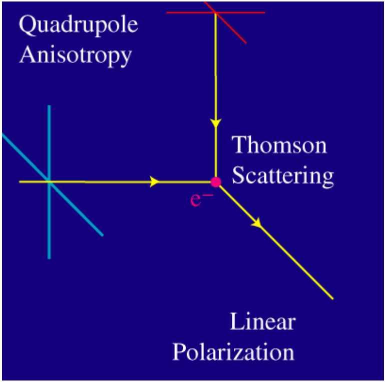
What do we already know?

- Know for sure? Not a lot
- One popular constraint from WMAP CMB polarization measurements
- Another popular constraint from Lyman-α forest measurements
- Many tantalizing hints, but constraints are often model-dependent and hard to trust.

What do we already know?

WMAP CMB Polarization





gifs by Wayne Hu, strange artifacts are my own.

Knowing optical depth to Thomson scattering puts constraints on $x_{\mathrm{HI}}(z)$:

$$\tau = \int \frac{dz\ c}{H(z)(1+z)} \sigma_T n_{\mathrm{H}}(z) x_{\mathrm{HI}}(z) \tag{1}$$

What do we already know?

WMAP CMB Polarization

- Redshift of instantaneous reionization constrained to $z_{\rm reion} = 10.6 \pm 1.2$ [Komatsu et al.(2011)].
- Integral constraint, leaves flexibility in EoR history

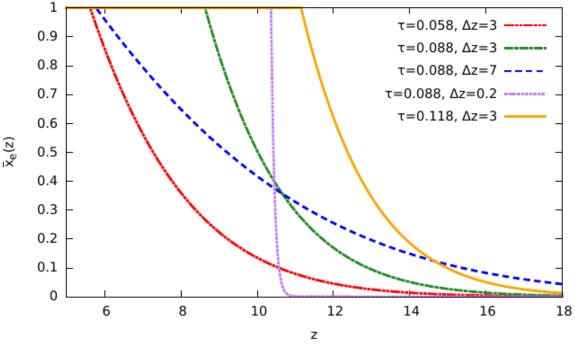


Figure: [Zahn et al.(2012)Zahn, Reichardt, Shaw, Lidz, Aird, et al.]

What do we already know?

Quasar Absorption Spectra

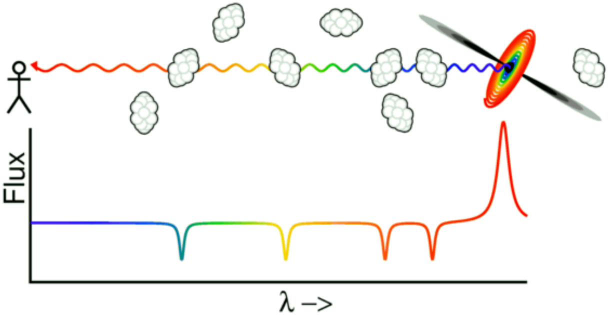
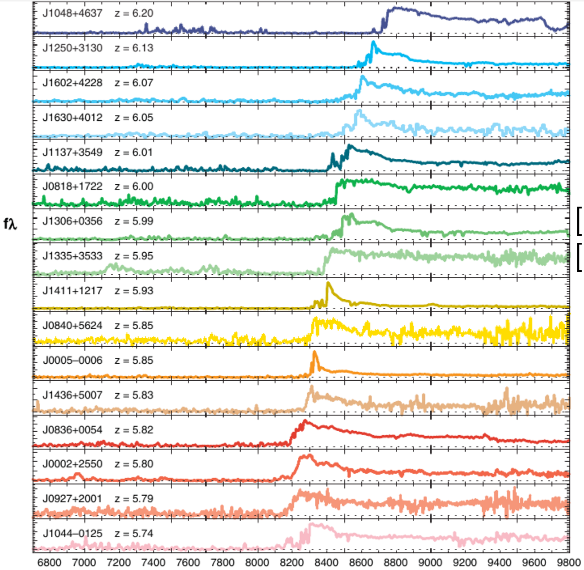


Figure: Image stolen from
http://www.astro.ucla.edu/∼wright/Lyman-alpha-forest.html

Lyman-α Forest Constraints

Gunn-Peterson Trough in High-z Quasar Spectra



[Fan et al.(2006a)Fan, Carilli,
[Fan et al.(2006b)Fan, Strauss

What We Know

Lyman-α Constraints

- At $z \sim 6$, Gunn-Peterson optical depth increases faster than expected solely due to cosmic expansion
- Suggests IGM is not entirely ionized
- Ionized fraction constrained to $3 \times 10^{-4} \lesssim x_{\mathrm{HI}} \lesssim 0.3$ at $z \approx 6$.

  Fan et al. (2006a)

  Lidz et al. (2002)

  Cen & McDonald (2002)

  Furlanetto et al. (2004)

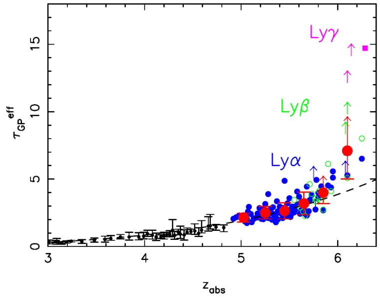


Figure: [Fan et al.(2006c)]

Additional Constraints

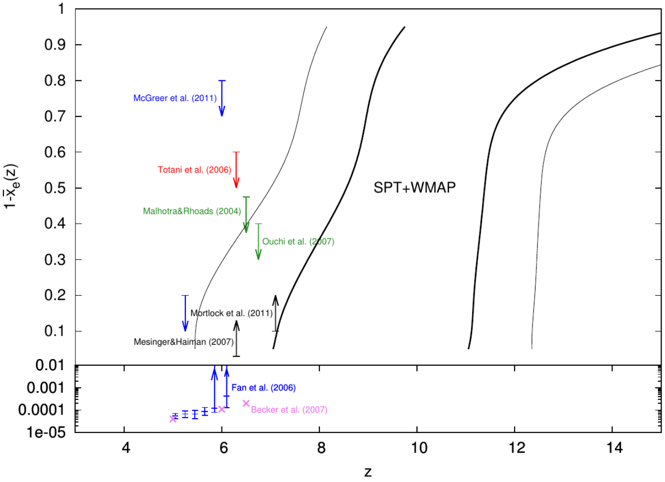
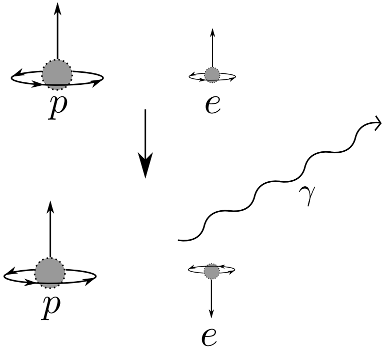


Figure: [Zahn et al.(2012)Zahn, Reichardt, Shaw, Lidz, Aird, et al.] (Pink/Blue/Black: quasar spectra, Red: GRB afterglow spectra, Green: Lyα Emitters)

The 21cm Line

Hydrogen Hyperfine Splitting

- 21cm emission line arises from the hyperfine splitting of the hydrogen atom
- The interaction of the magnetic moments of the electron and proton perturb the Hamiltonian
- The result is that the electron and proton reside in lower energy level with spins anti-aligned
- Spin flips can result in (from) emission (absorption) of photons with $\lambda = 21\text{cm}$



21cm Line as a Probe of Reionization

- Directly traces neutral hydrogen distribution
- All-sky signal, as opposed to absorption spectra, and doesn't require a background source
- Ability to probe higher neutral fractions than Lyman-α line
- Furthermore, it could, in principle, be used to study the "Dark Ages" prior to reionization

Precision Array for Probing the Epoch of Reionization

Statistical Detection of 21cm Signal

Figure: `eor.berkeley.edu`

Giant Metrewave Radio Telescope

Figure: Taken from www.mso.anu.edu.au/∼plah/, Philip Lah

Murchison Widefield Array

Figure: Photo found on `http://www.royalsociety.org.nz`, taken by Chris Thorne.

LOw Frequency ARray

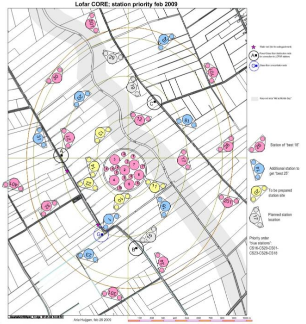


Figure: Configuration of antennae for LOFAR (`www.lofar.org`).

First Generation 21cm Arrays

Statistical Detection of 21cm Signal from EoR

- First generation arrays will have low signal-to-noise per resolution element
  - $\rightarrow$ As a result, the first detection of 21cm signal from EoR will likely be statistical, e.g. power spectrum measurements
  - $\rightarrow$ Bin together many noise modes
- Power spectrum measurements can provide very useful information about the neutral fraction and bubble size distribution
- However, the ionization field is very non-Gaussian, so the power spectrum is an incomplete description

Identifying Ionized Regions

Motivation

- Identifying individual ionized regions in noisy redshifted 21cm maps can help significantly to constrain reionization.
  - → Easier than making detailed maps
- Specifically, bubble identification can
  - → provide information to remove foregrounds more accurately
  - → allow targeted follow-up observations of galaxies inside/outside of ionized regions to compare/contrast their properties
  - → provide constraints on the neutral fraction through the average signal inside of ionized regions
  - → suggest likely sources of reionization through the measured bubble size distributions.

Fiducial Case

- Simulation
  - → $L = 1\text{Gpc}/h$
  - → $z_{\text{center}} = 6.9$
  - → $\bar{x}_{\text{HI}} = 0.21$
- Noise
  - → Generate mock thermal noise according to array configuration
  - → Mimic the degrading effects of foreground cleaning by removing running mean along line of sight ($B = 16\text{MHz}$, $L_{\text{fg}} = 185\text{Mpc}/h$).
- Array configurations
  - → Primarily consider scaled-up version of MWA-style instrument
  - → Also consider a scaled-up version of LOFAR-style instrument
  - → Representative of 2nd generation experiments

Obstacles

Life is Hard

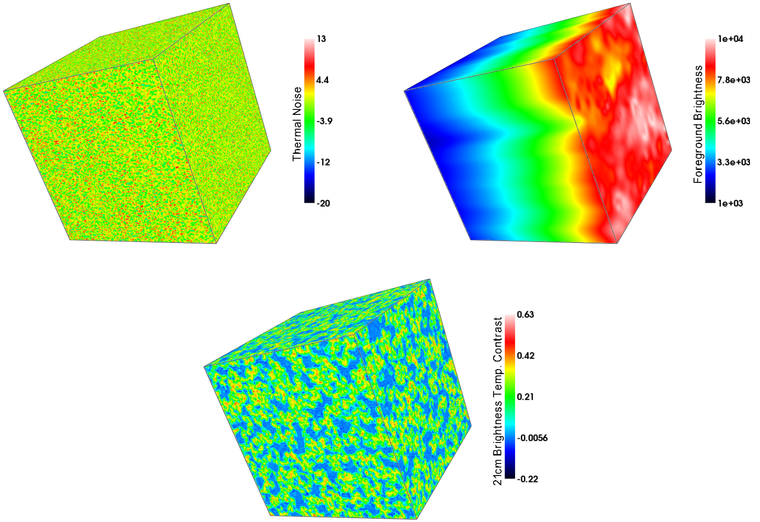
- The 21cm signal is not the only thing that contributes to measurements, there also are
  - → Foregrounds
  - → Thermal noise
  - → Ionospheric distortions
  - → Instrumental response
- Sources of noise can be orders of magnitude greater than the signal, for example

$$\delta T_{21} \approx 28\text{mK}\ x_{\text{HI}}(1+\delta_\rho)\left(\frac{T_{\text{S}}-T_{\text{CMB}}}{T_{\text{S}}}\right)\left(\frac{1+z}{10}\right)^{1/2}$$

$$T_{\text{fg}} \sim 180\text{K}\left(\frac{\nu}{180\text{MHz}}\right)^{-2.6} \qquad \text{(Cold FOV)}$$

Obstacles

Contributions to Observations



Identifying Ionized Regions

Optimal Matched Filter

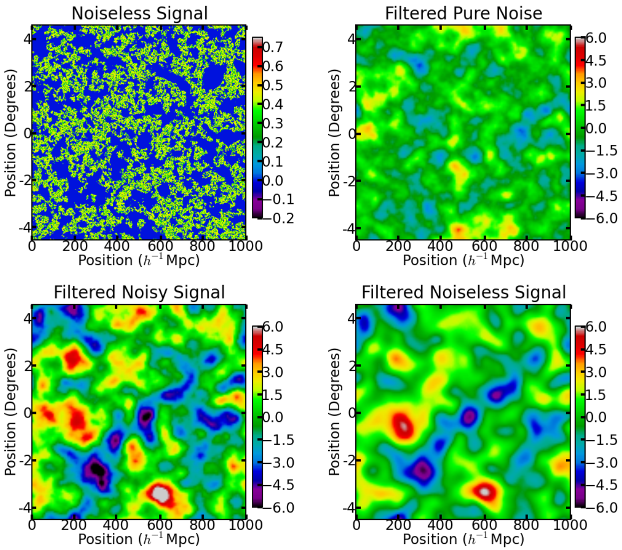
- In the case where you have a known feature embedded in noise, the filter that maximizes your signal-to-noise (SNR) when detecting the feature is the *optimal matched filter*.
- The filters acts by convolving the noisy signal with a template of the known feature and by downweighting noisy modes.

$$M(k,\mu) = \frac{T(k)}{P_{\rm N}(k,\mu)} \rightarrow \frac{T(k;R)}{P_{\rm N}(k,\mu)} \tag{2}$$

$\implies$ This implies constructing the filter involves specifying a template, $T(k)$, and approximately knowing the noise power, $P_{\rm N}(k,\mu)$.

- Although ionized regions are manifestly not spherical, we find a spherical top-hat with a variable radius ($T(k;R)$) is an effective choice.

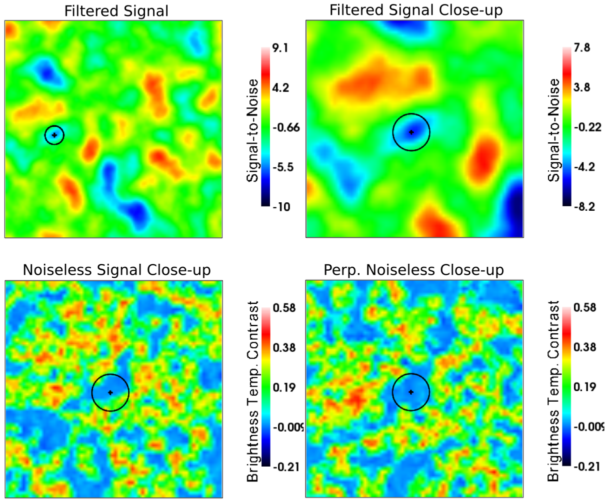
Optimal Matched Filter



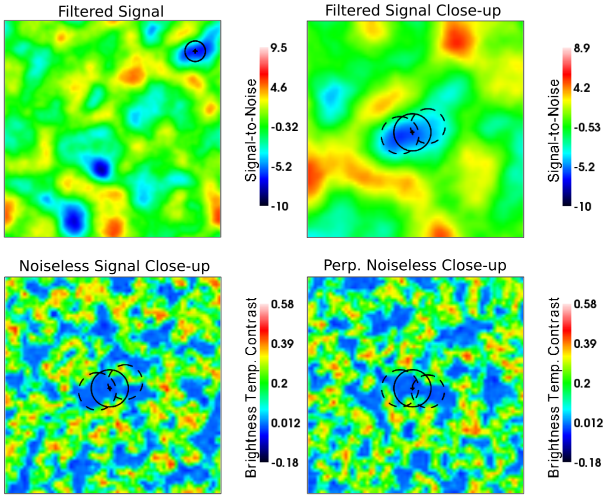
When $R_{\text{template}} = R_{\text{Bubble}}$, then SNR is maximized for isolated spherical bubbles. Using this, we:

1. Vary template radius over physically-relevant interval $R_{\min} \leq R_{\text{template}} \leq R_{\max}$.
2. Track maximum SNR value at *each* pixel.
3. Construct a new field where each pixel is given its corresponding maximum SNR value.
4. Local maxima in this field are the centers of candidate bubbles.
5. Candidate bubble's radius is the template radius that maximized the pixel's SNR.
6. Throw out all bubbles with $\text{SNR} < \text{SNR}_{\min}$.

Identified Bubble Example

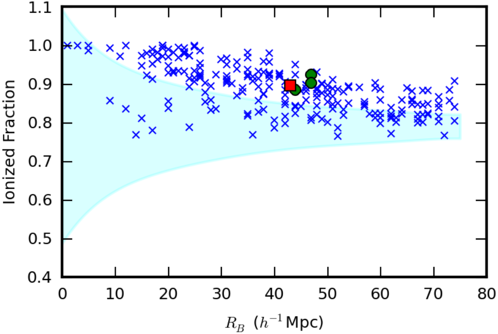


Detecting a Single Bubble as Multiple



Success of Detected Bubbles

- For our fiducial reionization simulation ($L = 1\text{Gpc}/h$, $x_{\rm HI} = 0.21$, $z = 6.90$) we detect ∼220 bubbles (∼ 140 when rescaled to MWA survey volume).
- ∼96% of bubbles are more ionized than the simulation box on average.
- ∼43% of bubbles are more than 90% ionized.



Summary

- Bubble detection should be successful with second generation arrays, provided systematic effects can be mitigated
- This would open up several interesting avenues for constraining neutral fraction
- (`arXiv:1212.2656`)

Future Work

More Realistic Bubble Detection

- Currently teaming up with Judd Bowman, Piyanat Kittiwisit, and Daniel Jacobs
- Working on applying bubble detection algorithm to 21cm signals corrupted by more realistic foregrounds and noise
  - → Are we still able to detect bubbles?
  - → Can we use the average signal in bubbles to accurately constrain x_{HI}?

Future Work

Global 21cm Signal and Matched Filtering

Global 21cm signal also contains much information about structure formation and reionization.

$$\delta T_{21} = 28 x_{\rm HI}(1+\delta)\left(\frac{T_{\rm S}-T_{\rm CMB}}{T_{\rm S}}\right)\left(\frac{1+z}{10}\right)^{1/2}\,\mathrm{mK}$$

A: Collisions become inefficient at coupling $T_{\rm S} \to T_K$.
B: First stars turn on
C: First X-ray sources turn on
D: 21cm signal saturates, reionization begins
E: EoR completes, $\delta T_{21} \to 0$

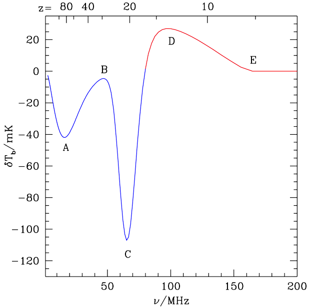


Figure:

[Harker et al.(2011)Harker, Pritchard, Burns, & Bowman]

Future Work

Global 21cm Signal and Matched Filtering

Global 21cm signal also contains much information about structure formation and reionization.

$\delta T_{21} = 28 x_{\mathrm{HI}} (1+\delta) \left(\frac{T_S - T_{CMB}}{T_S} \right) \left(\frac{1+z}{10} \right)^{1/2} \mathrm{mK}$

- Seems easier since you only need the *sky-averaged* signal
- However, this signal will be buried in foregrounds
- Global signal evolves much more smoothly along line of sight than fluctuation signal
  - → Foreground subtraction becomes a bigger problem

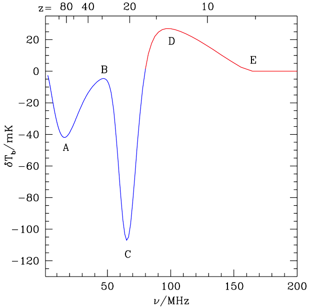


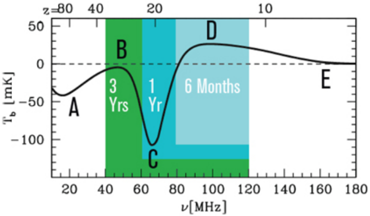
Figure:

[Harker et al.(2011)Harker, Pritchard, Burns, & Bowman]

Future Work

Global 21cm Signal and Matched Filtering

- Model of structure formation predicts a certain $\delta T_{21}(z)$ curve.
  - $\rightarrow$ Ideal application for a matched filter.
  - $\rightarrow$ Can using an array of template functions allow us to estimate the most likely $\delta T_{21}(z)$ curve? Constrain timing of turning points $A - E$?
- One experiment being proposed is Dark Ages Radio Explorer (DARE).



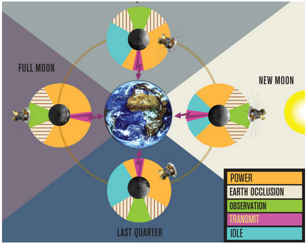
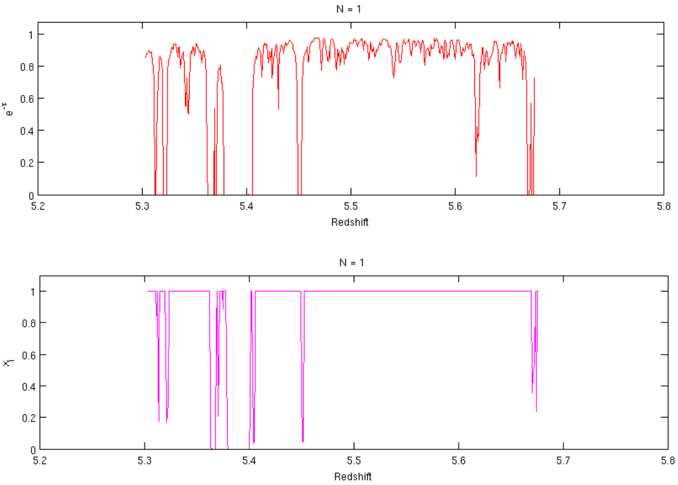


Figure: `lunar.colorado.edu`

Future Work

High-z Quasar Spectra and Matched Filtering



Conclusions

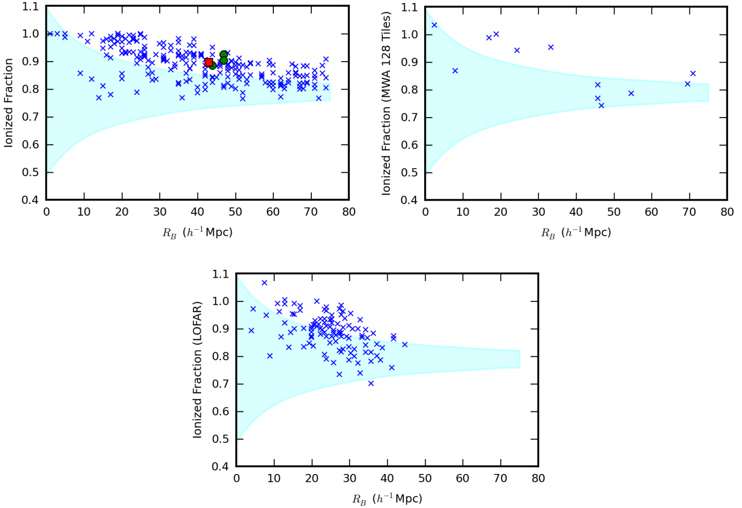
- Reionization is an important, yet only loosely-constrained, process in Universe's history
- A wide variety of strategies exist for putting constraints on the process, yet many await future data
- While some data and constraints already exist, several hotly-anticipated reionization experiments are gearing up to collect data over the next decade

Conclusions

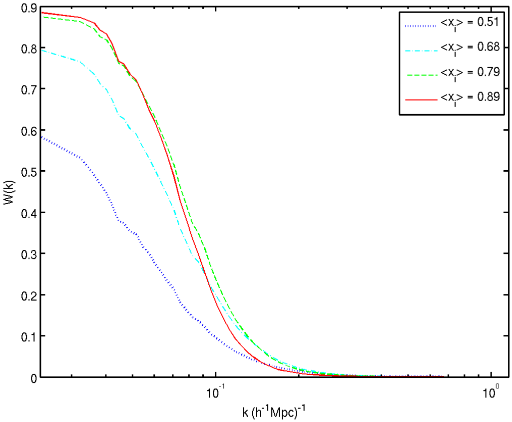
- Reionization is an important, yet only loosely-constrained, process in Universe's history
- A wide variety of strategies exist for putting constraints on the process, yet many await future data
- While some data and constraints already exist, several hotly-anticipated reionization experiments are gearing up to collect data over the next decade

Thank you!

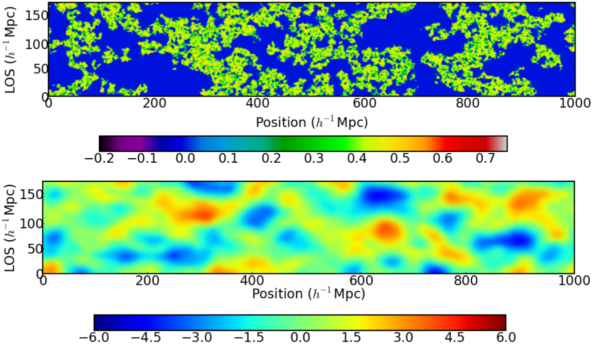
Comparing Arrays



Wiener Filter Fourier Profile (Back-up Slides Begin Here)

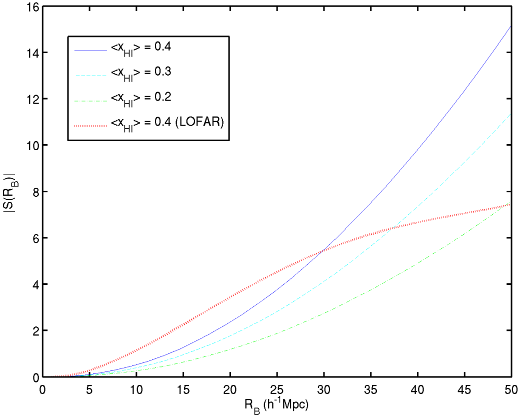


Effects of Foreground Cleaning on Imaging



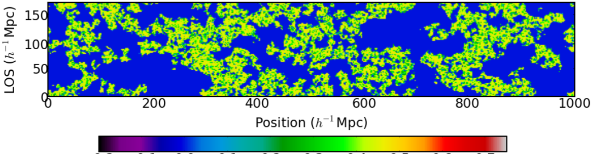
Toy Model for Detecting Ionized Regions

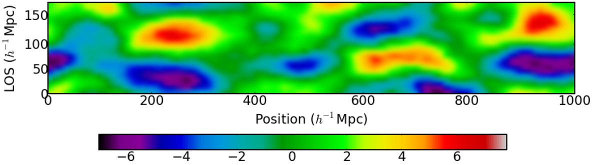
Isolated, Spherical Bubbles



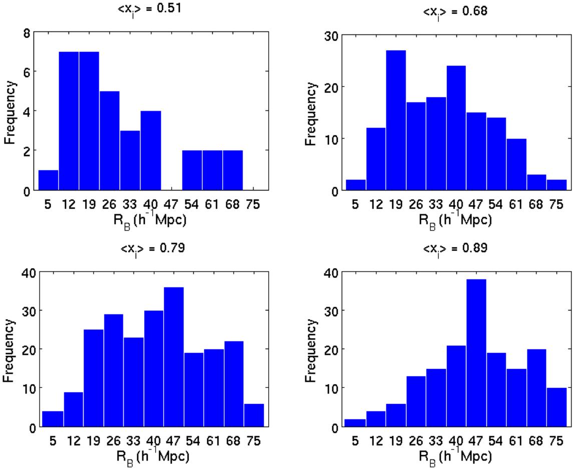
Effects of Foregrounds

Matched Filter

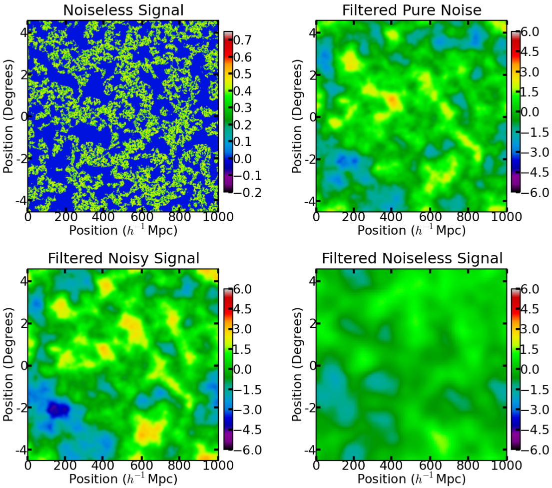




Detected Bubble Size Distributions

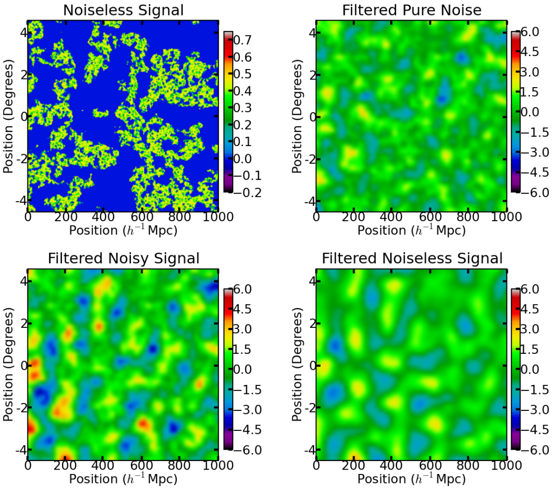


128-Tile MWA



Noiseless Signal
Filtered Pure Noise
Filtered Noisy Signal
Filtered Noiseless Signal
Position (Degrees)
Position (h^{-1} Mpc)

LOFAR


Noiseless Signal
Filtered Pure Noise
Filtered Noisy Signal
Filtered Noiseless Signal
Position (Degrees)
Position (h^{-1} Mpc)
0 200 400 600 800 1000
4 2 0 -2 -4
0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.0 −0.1 −0.2
6.0 4.5 3.0 1.5 0.0 −1.5 −3.0 −4.5 −6.0

- [Fan et al.(2006a)Fan, Carilli, & Keating], [Lidz et al.(2002)Lidz, Hui, Zaldarriaga, & Scoccimarro], Cen & McDonald (2002), [Furlanetto et al.(2004)Furlanetto, Hernquist, & Zaldarriaga]. Fan et al. (2006a)

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