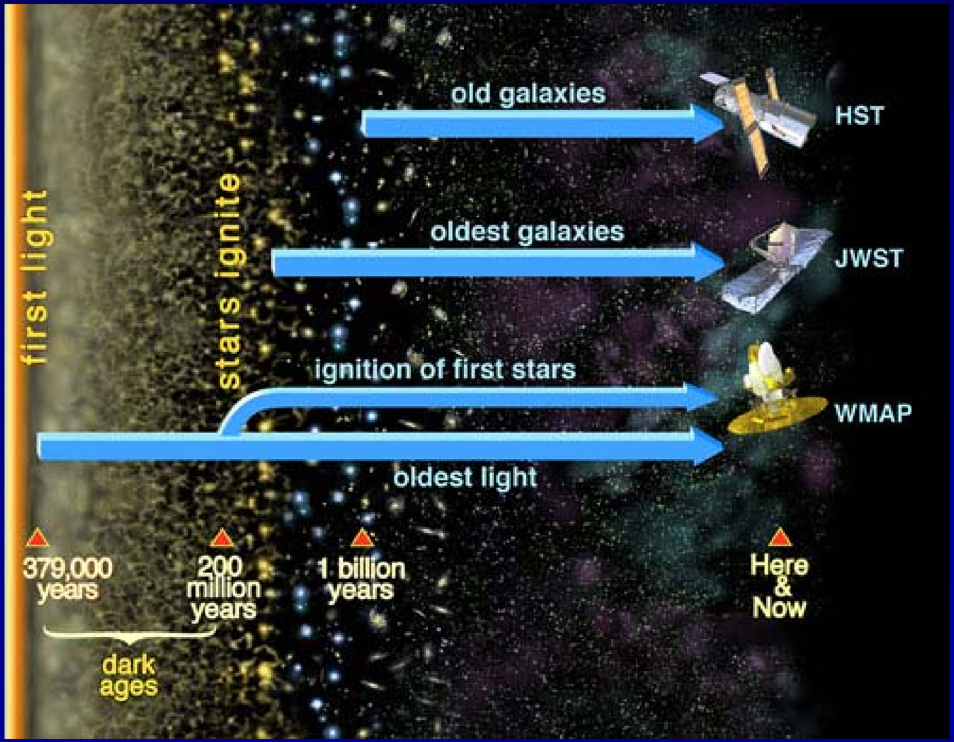
Studying Reionization with Redshifted 21 cm Radiation

Lars Hernquist
Institute for Theory and Computation
Harvard University

collaborators: S. Furlanetto, M. Zaldarriaga

Ionization History of Hydrogen



- From CMB & quasars:

ionized, $z > 1100$

↓

neutral: dark ages

↓

reionized, $z \sim 6 - 20$

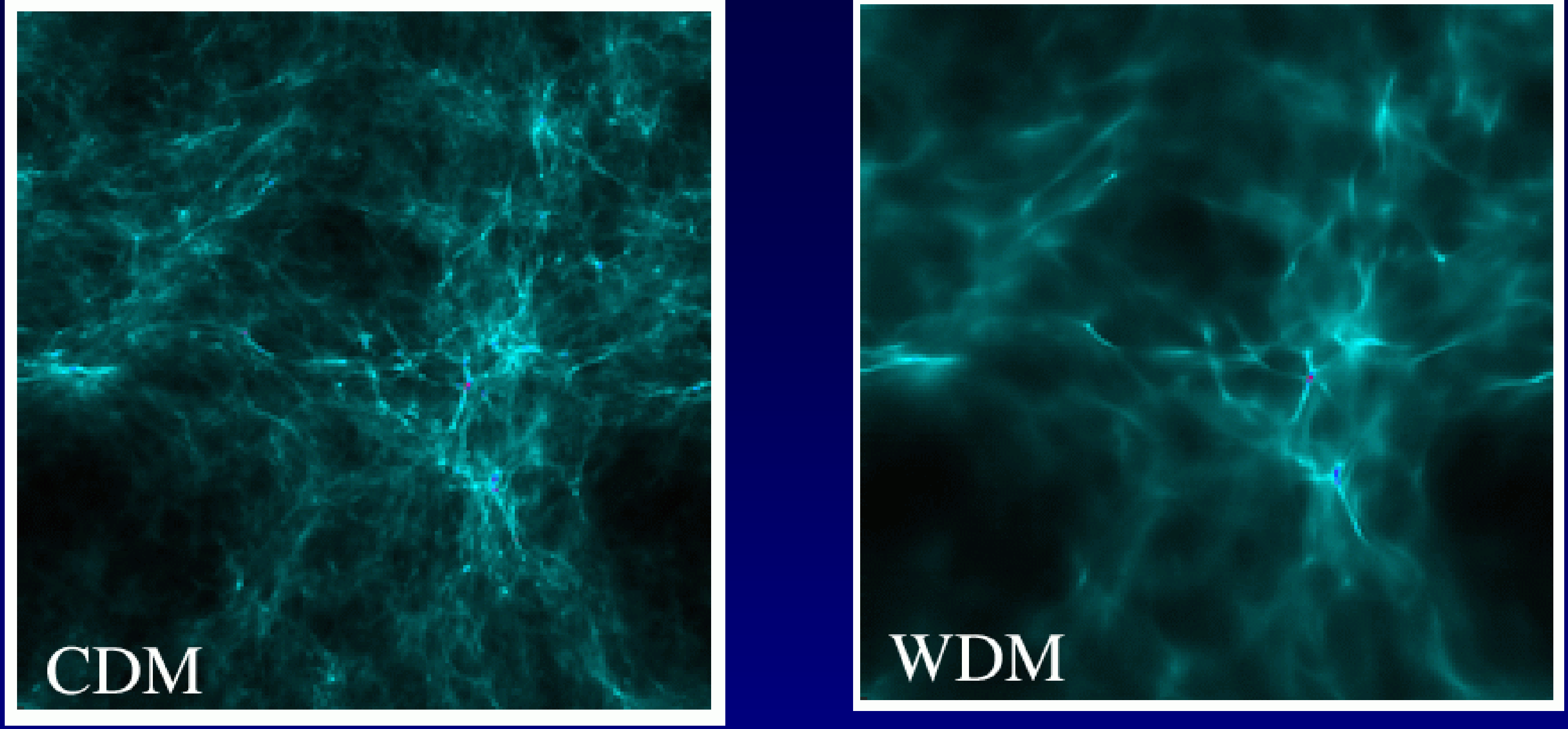
- How and when did reionization happen?

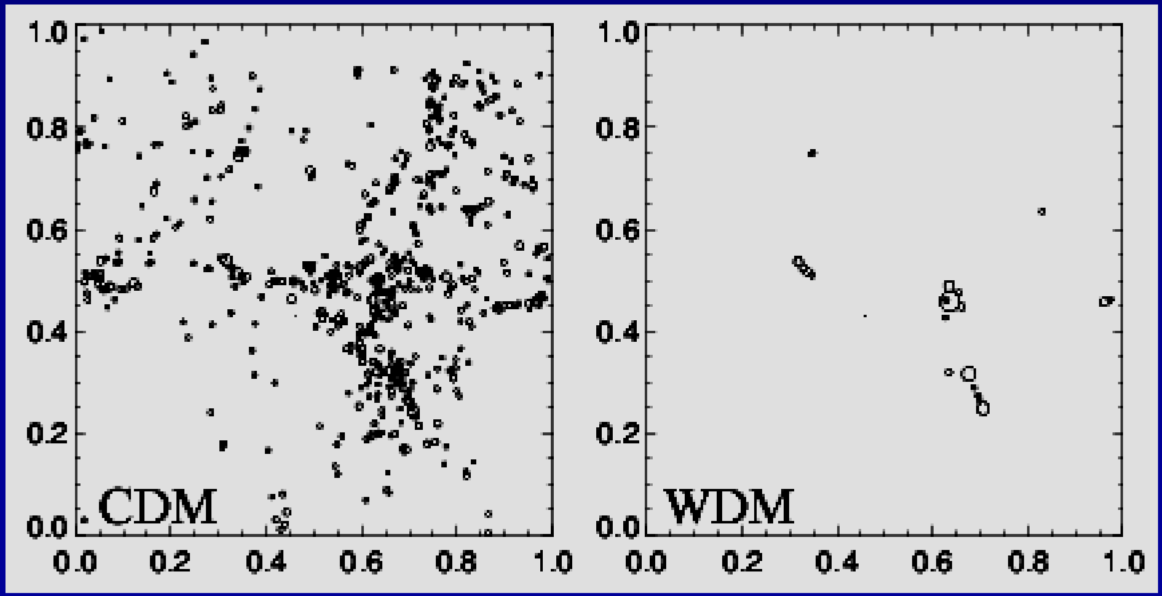
"Epoch of Reionization"

Why Interesting

- caused by first luminous sources
- sensitive to nature of first objects

  quasars? primeval galaxies? massive stars?
- feedback affects later generations of objects
- sensitive to cosmology, e.g. power spectrum, properties of dark matter



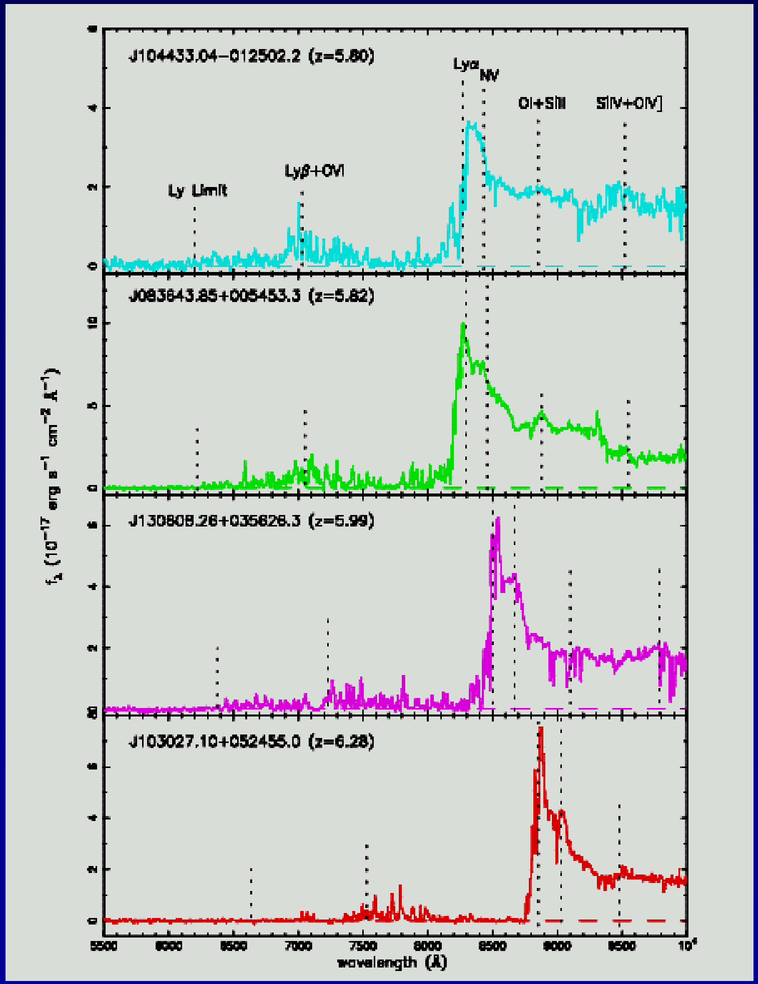


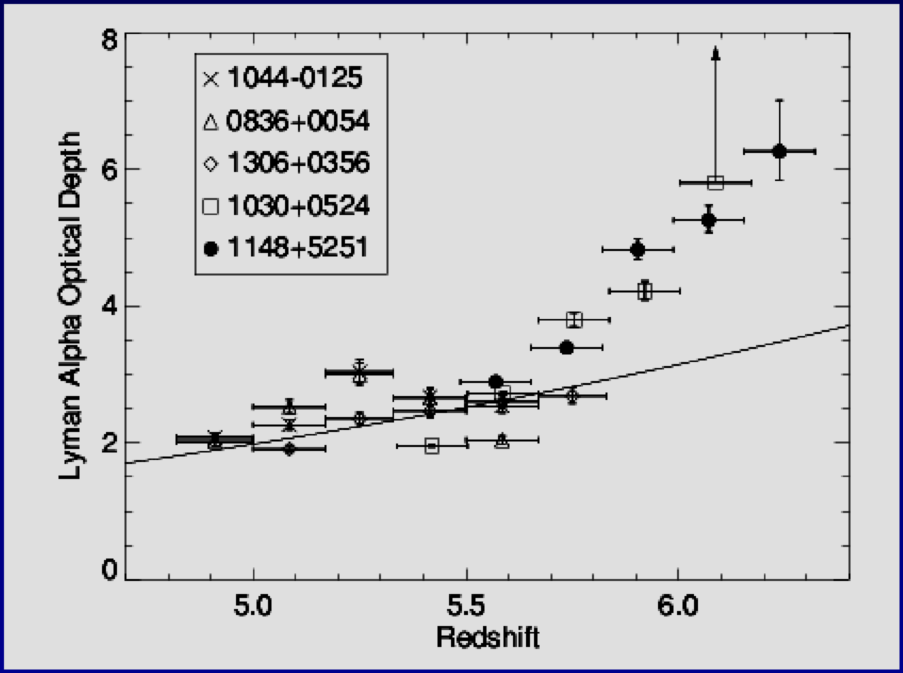
Yoshida et al. (2003)

1 Mpc, z = 20
10 keV particle

halos > 10^5 M_{sun}

Constraints: SDSS Quasars





Becker et al. (2001, 2003)

reionization complete by z ~ 6

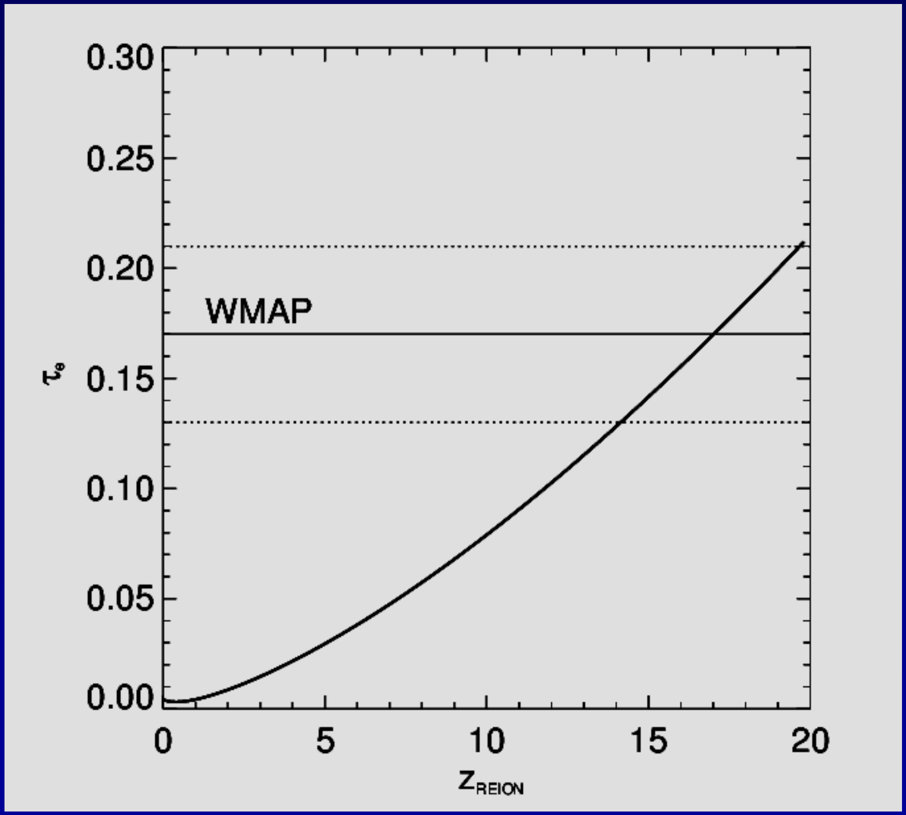
Constraints: WMAP

Thomson optical depth

$\tau \approx 0.17 \pm 0.4$

Spergel et al. (2003)

$z_r \approx 17 \pm 3$



Theoretical Models

- Conflicting views:

  * “late,” fast reionization:

    $z \sim 6 - 10$

  * “complex,” extended reionization:

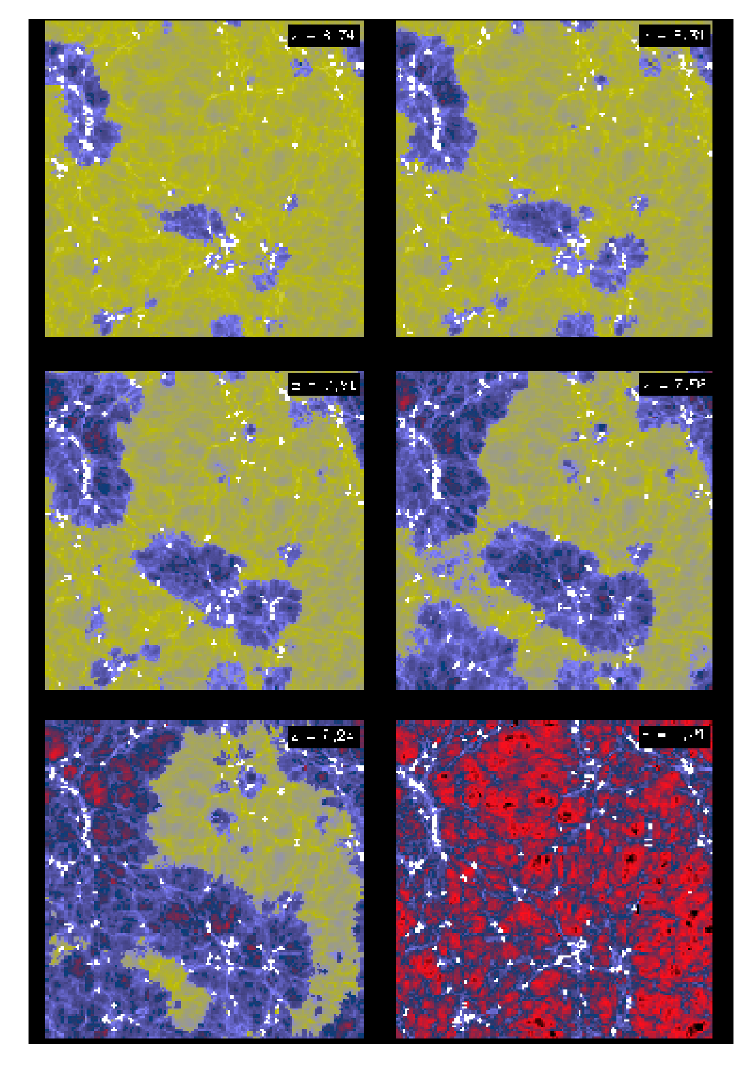
    $z \sim 6 - 20$

Late Reionization

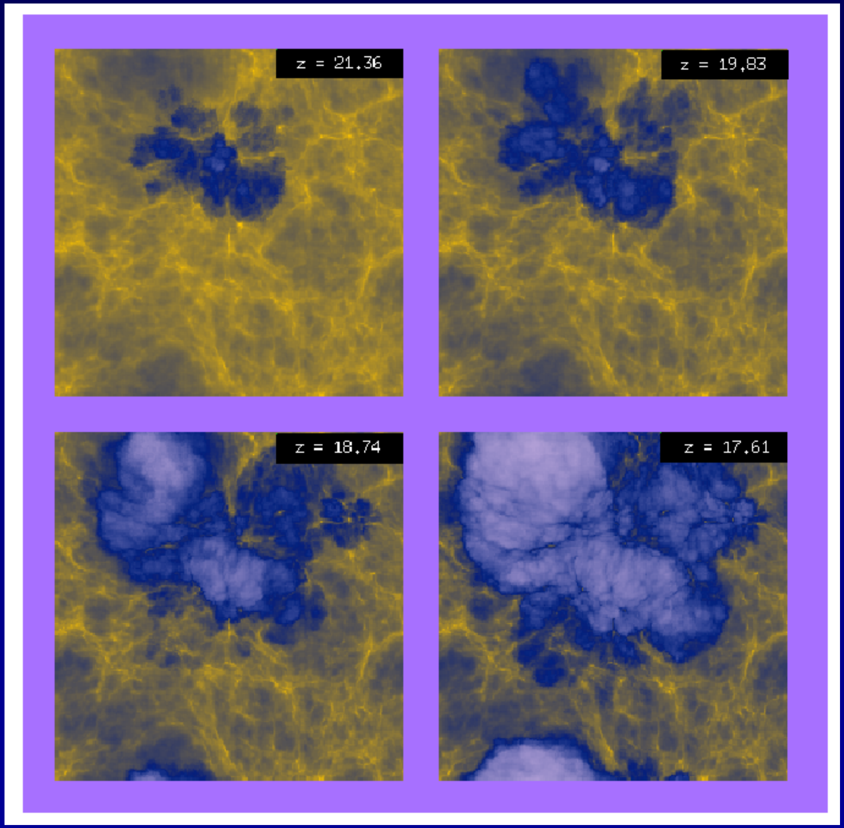
z = 8.7 - 6.2

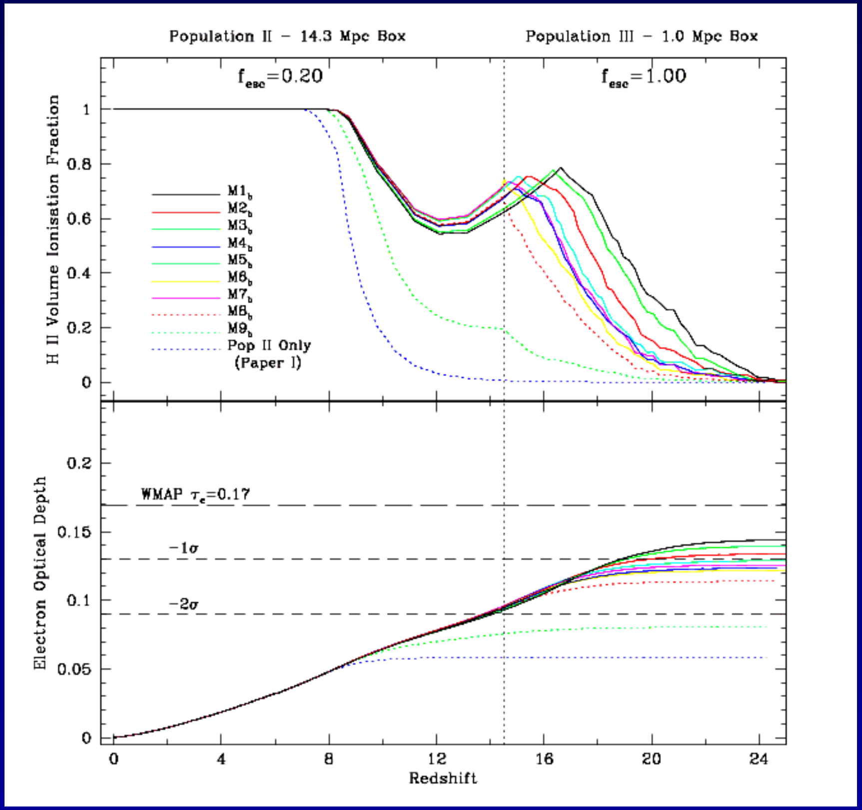
Sokasian, Abel et al. (2003)

14 Mpc box, comoving; slices 0.4 Mpc thick



Complex, Extended Reionization





z = 21 - 18; 1 Mpc box, comoving; 0.25 Mpc slices

Sokasian, Abel et al. (2003)

Limitations of Current Probes

- Quasars probe only tail-end of reionization:
  $\tau_{Ly\text{-}\alpha} \approx 6 \times 10^5\, x_{HI}\, [(1+z) / 10]^{3/2}$
  $\Rightarrow$ spectrum black for $x_{HI} > 10^{-3}$
- WMAP: τ_{es} an integrated quantity
  $\Rightarrow$ many histories consistent with same τ_{es}

- Want a probe that maps reionization with z …

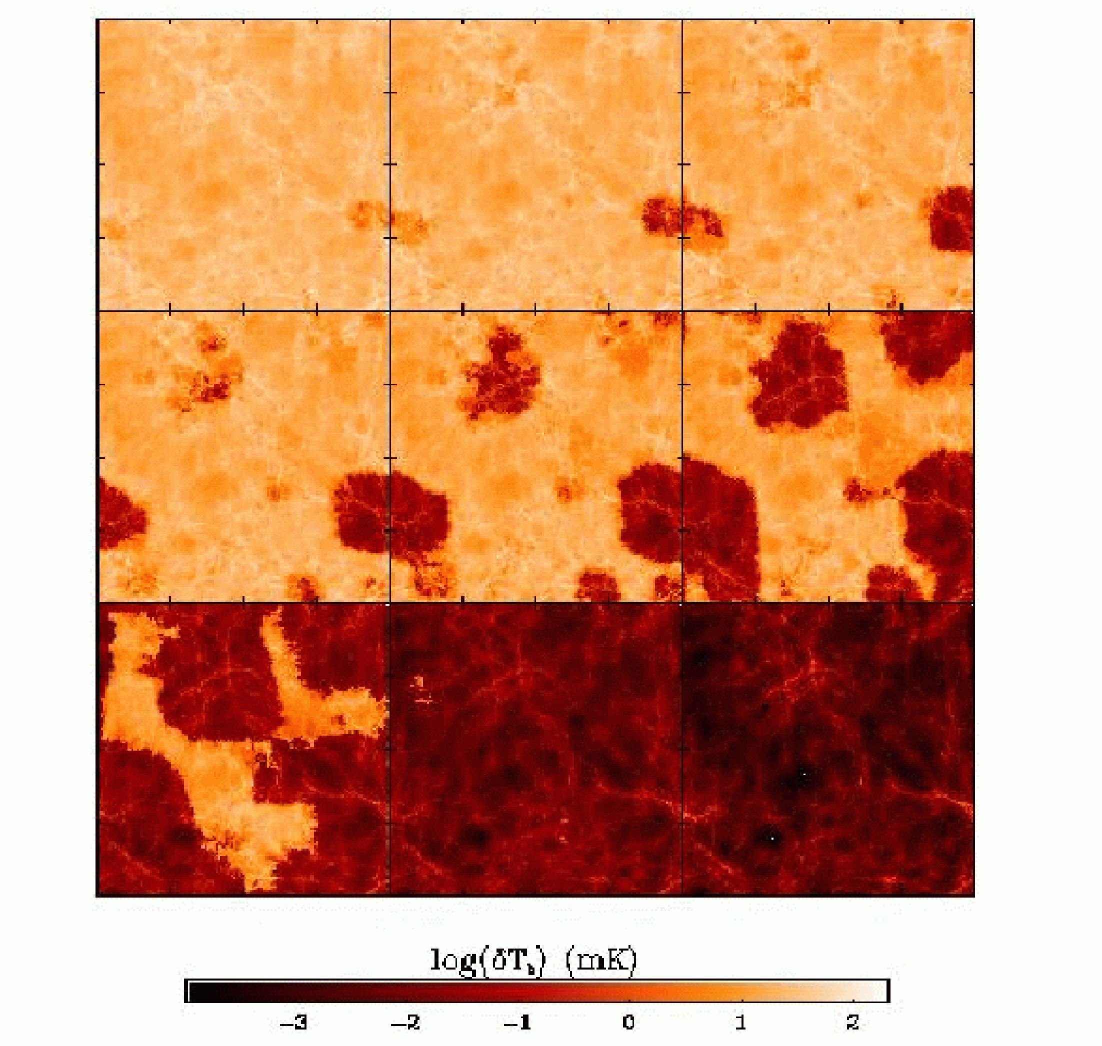
Redshifted 21 cm Radiation

21 cm brightness T,

z = 12 - 7.5

14 Mpc comoving
$\Delta\nu$ = 0.1 MHz

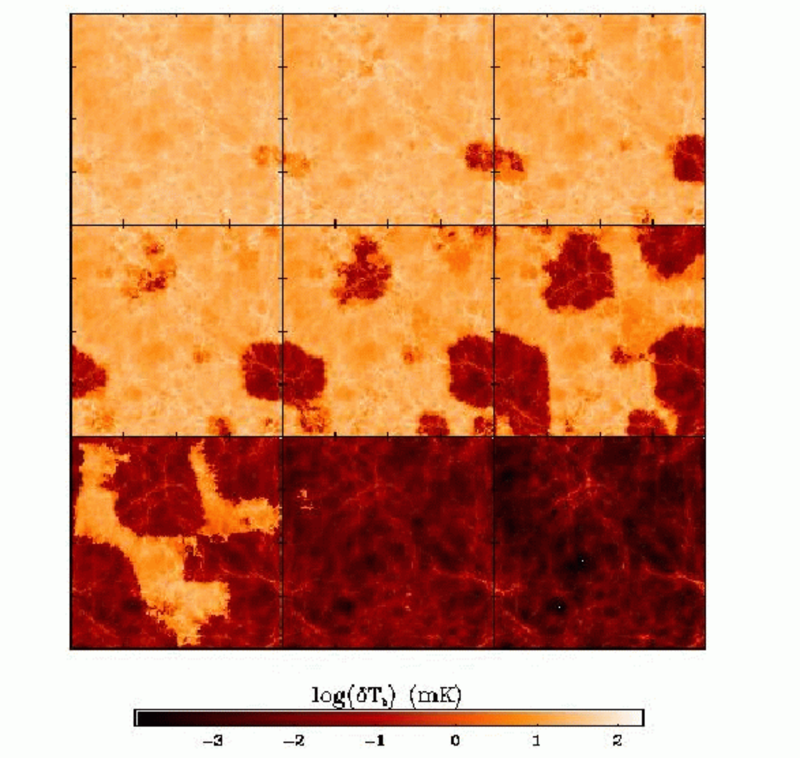
Furlanetto et al. (2004)



21 cm Radiation

- BIG advantage: line radiation, z maps to ν
- $\delta T(\nu) \approx 23\ x_{HI}\ (1 + \delta)\ [(1+z)/10]^{1/2}$ mK (for $T_s >> T_{CMB}$) depends on overdensity (δ) and neutral fraction (x_{HI})
- absolute signal swamped by foregrounds; e.g. Galactic synchrotron ~ 200 K …
- strategy?

21 cm Fluctuations



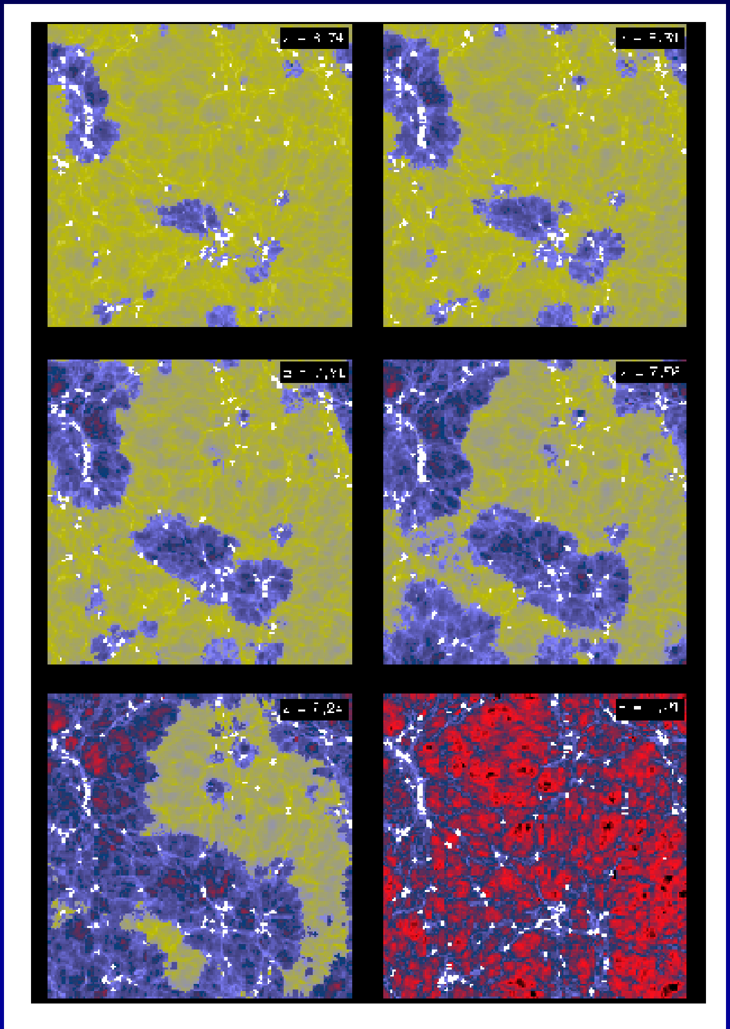
- like CMB, measure angular fluctuations:

  $R \approx 1.9\ (\theta\ /\ 1')\ ((1+z)/10)^{0.2}$ Mpc

- different slices in z uncorrelated: fluctuations with frequency

  $L \approx 1.7\ (\Delta\nu\ /\ 0.1\ \mathrm{MHz})\ ((1+z)/10)^{1/2}$ Mpc

Semianalytical Model



- ultimately, simulations
- simple model (FZH 2004a): distribution function of HII regions: size, evolution
- explore reionization scenarios
- idea: HII regions surround clustered sources in high density regions

Semianalytical Model

- Simple ansatz:

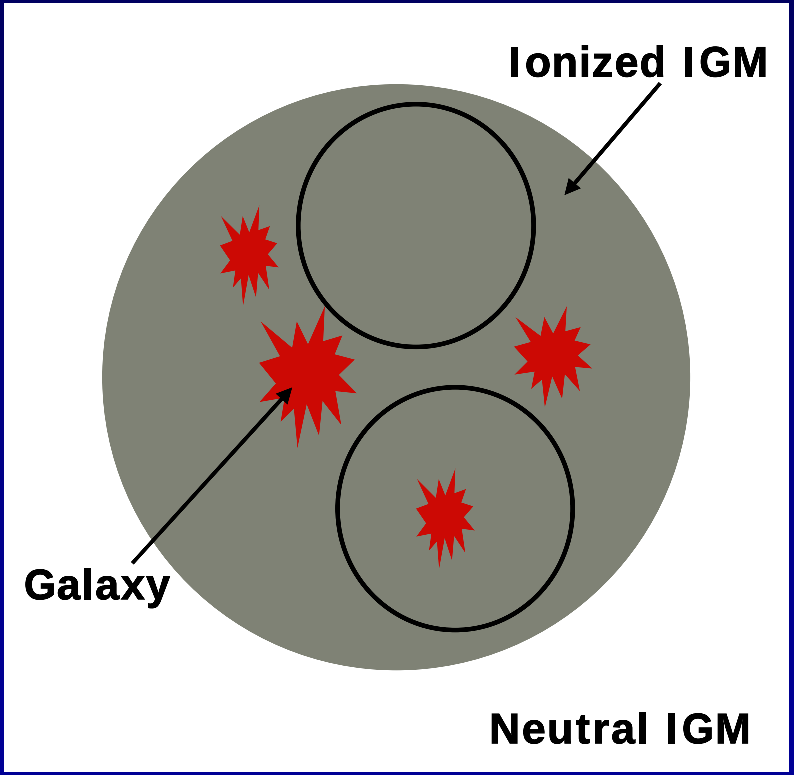
$$m_{ion} = \zeta\, m_{gal}$$

$$\zeta = f_* \, f_{esc} \, N_{\gamma/b} \, / \, n_{rec}$$

- Then condition for a region to be fully ionized is

$$f_{coll} > \zeta^{-1}$$

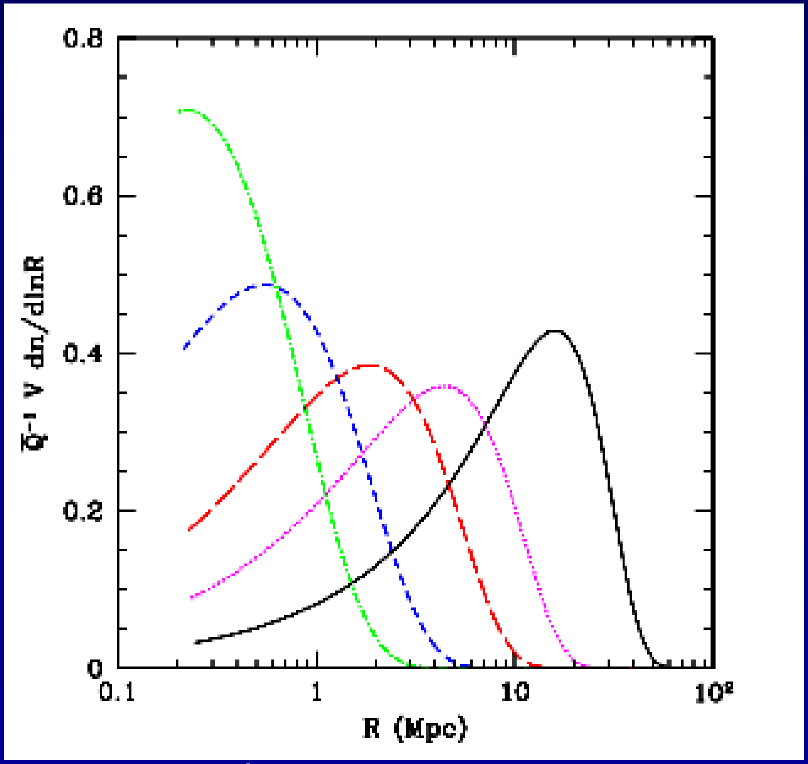
- Can construct an analog of Press-Schechter mass function = mass function of *ionized* regions
- use excursion set formalism



Semianalytical Model

- captures growth, coalescence of HII regions around clustered sources
- good match to simulations
- free from limitations of simulation box size
- but, neglects small-scale features: not precise on small angular scales

The Sizes of HII Regions



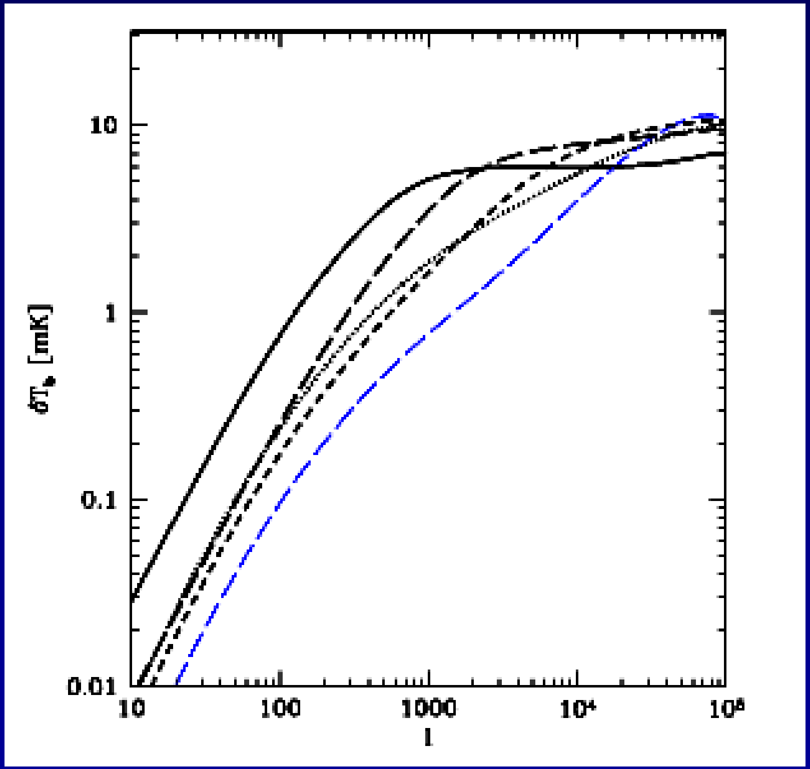
- green: $x_H = 0.96$
- red: $x_H = 0.70$
- black: $x_H = 0.25$

- predicts large HII regions
- evolves rapidly late
- good for 21 cm!

Each galaxy

FZH (2004a)

21 cm Angular Power Spectrum



- evolution:
  - dotted: z=18, x_H = 0.96
  - short-dashed: z=15, x_H=0.81
  - long-dashed: z=13, x_H=0.52
  - solid: z=12, x_H=0.26
- feature grows, moves during reionization
- l = 20,000 ~ θ = 1'
- l =2000 ~ θ = 10'
- blue: HII around sources

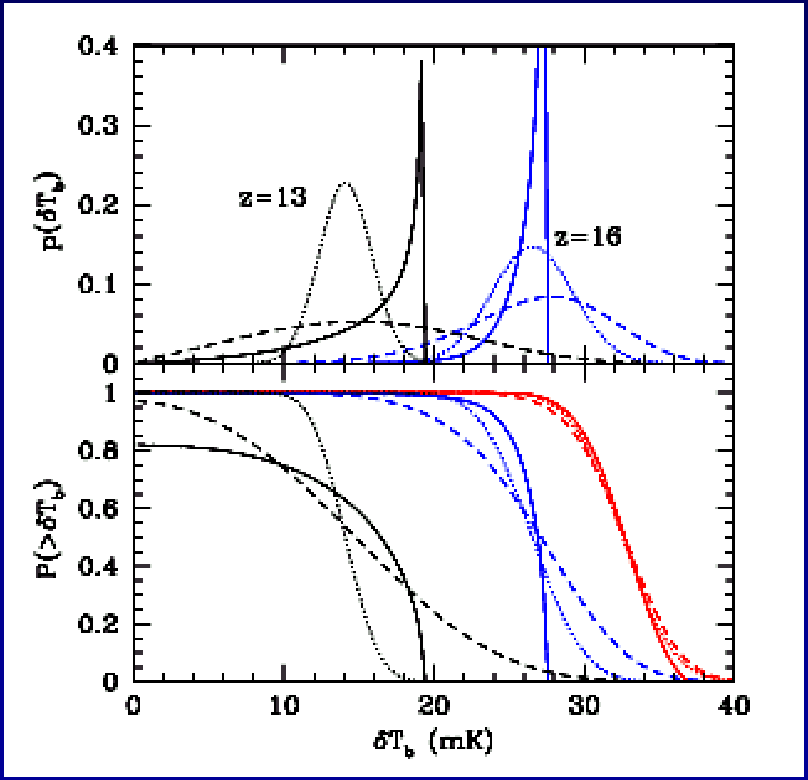
21 cm Tomography

- can distinguish different reionization models:

  e.g. late, fast vs. extended, complex

  e.g. “inside-out” vs. “outside-in”
- take advantage of non-Gaussian properties of signal

Other Statistical Measures



- x_H field non-Gaussian
- higher order statistics; e.g. pixel distribution function:
- dotted: uniform
- dashed: voids ionized first
- solid: overdense regions ionized first
- pixel size ~ 2.7’

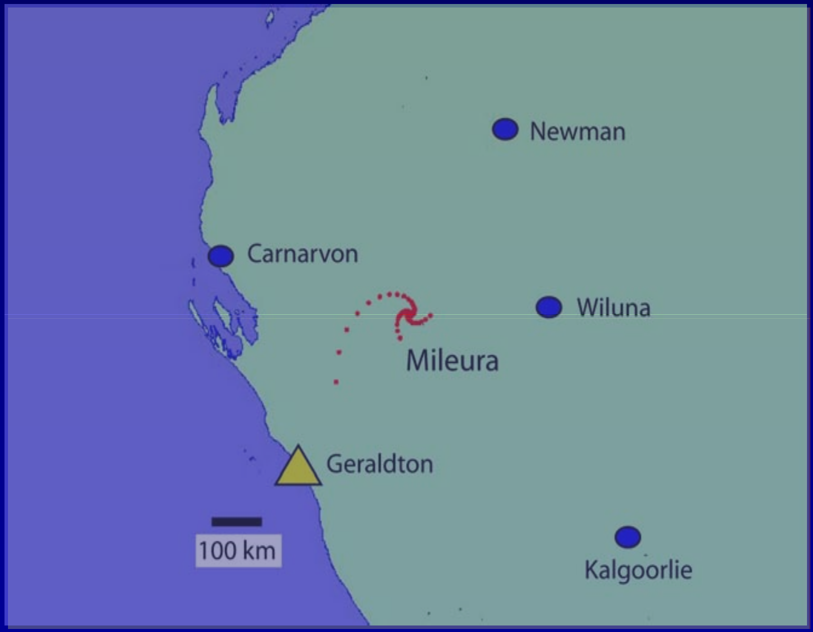
FZH (2004b)

Can It Be Done?

- foregrounds can be “subtracted” if spectra not fluctuating strongly with ν (ZFH 2004)
- radio noise: 1.42 GHz $\rightarrow$ 130 MHz for $z = 10$
- required sensitivities in ~ month long surveys
- various instruments now in design:
  - Primeval Structure Telescope (dedicated facility), full array ~ 2005
  - LOFAR: 30-240 MHz, first light ~ 2007
  - SKA: ~ 2020 (?)

Mileura Widefield Array

- Low-frequency radio telescope in Western Australia
- First observations planned for 2007
- Collaborators include MIT, Melbourne, CfA + others
- Also transients, heliosphere



Mileura Widefield Array

- Instrument characteristics
  - Radio-quiet site
  - 500 16-element antennae in 1.5 km distribution
  - 80-300 MHz
  - Many (4+) MHz instantaneous bandwidth at 8 kHz resolution
  - 20-30 degree field of view
  - Full cross-correlation of all 500 antennae

Mileura Widefield Array

- Instrument characteristics
  - Radio-quiet site
  - 500 16-element antennae in 1.5 km distribution
  - 80-300 MHz
  - Many (4+) MHz instantaneous bandwidth at 8 kHz resolution
  - 20-30 degree field of view
  - Full cross-correlation of all 500 antennae

Summary: 21 cm Measurements

- map how and when reionization occurred
- in principle, fluctuations can distinguish e.g.
  - fast, late vs. extended, complex reionization
  - inside-out vs. outside-in reionization
- probe of first luminous sources
- various observational efforts underway
- challenges: smoothness of backgrounds, radio frequency interference, optimal statistics …
- Potential to revolutionize understanding of epoch of reionization