ASTR 6000 Wk 14:
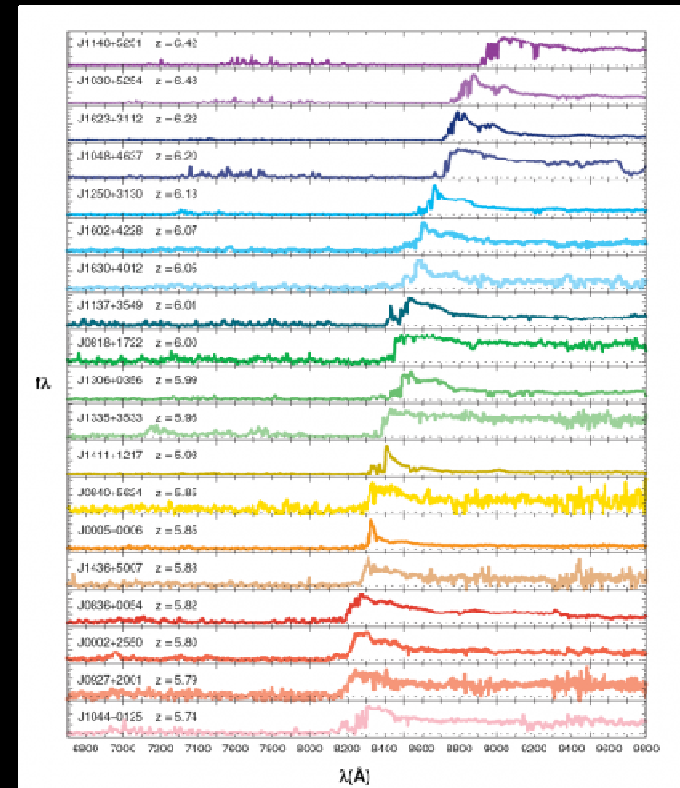## "Statistical Probes of Reionization with 21 cm Tomography"

[Steven Furlanetto, Matias Zaldarriaga, and Lars Hernquist (2004)]
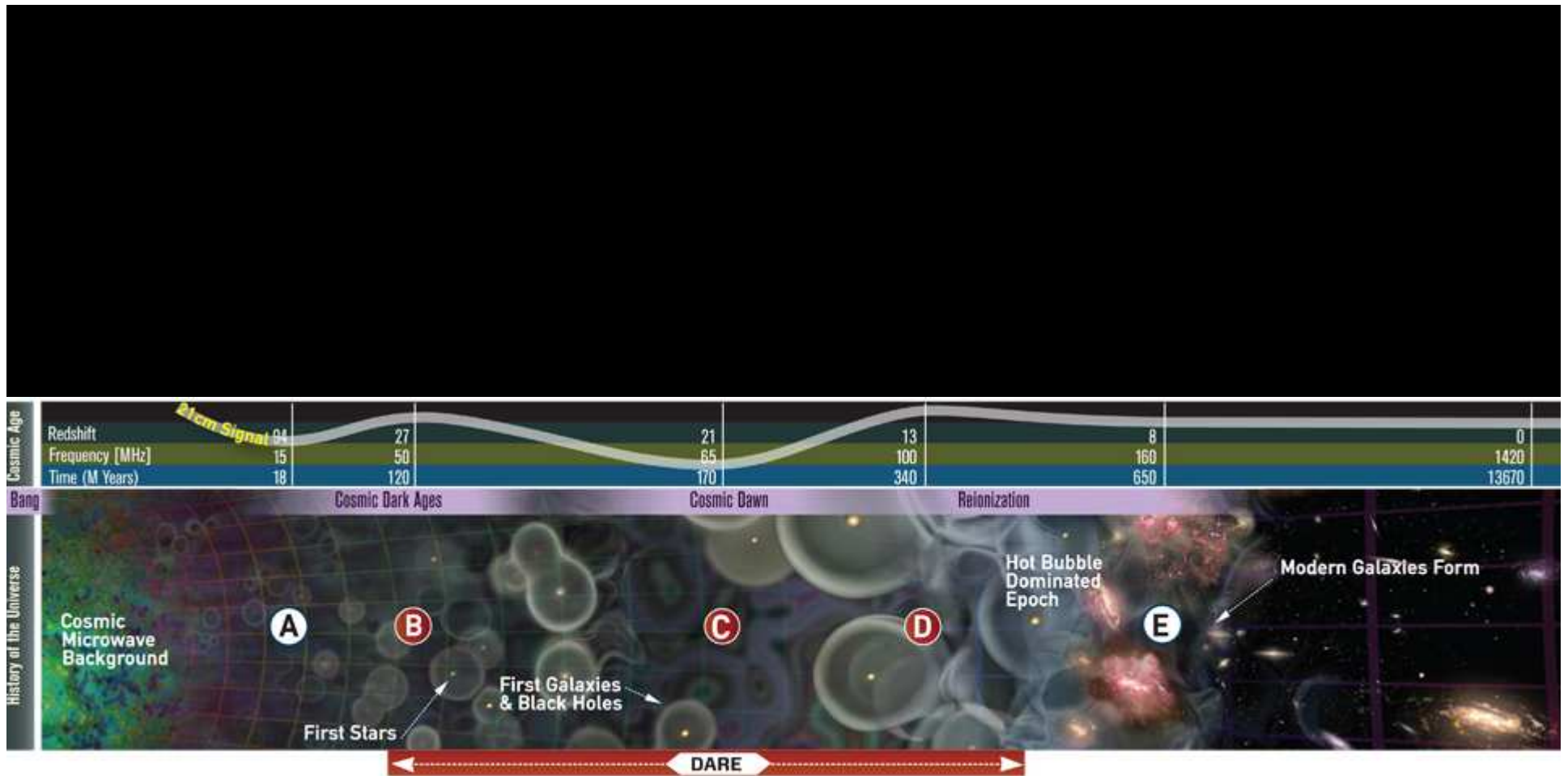
Bang Nhan
(Spring 2012)

Review: High z Detection Methods

- Gunn – Peterson trough/ Drop-out Technique ($z \leq 6.5$)
- CMB polarization (small x_H @ $z \geq 14$)
- Lyα forest ($O(1)$ change in x_H @ $z \leq 10$)
- HI 21 cm emission: free from saturation

BREAKING NEWS: $z \sim 9.6 \pm 0.2$ candidate detected via gravitational lensing [Wei Zhang, Marc Postman, et al. (2012)] http://arxiv.org/abs/1204.2305

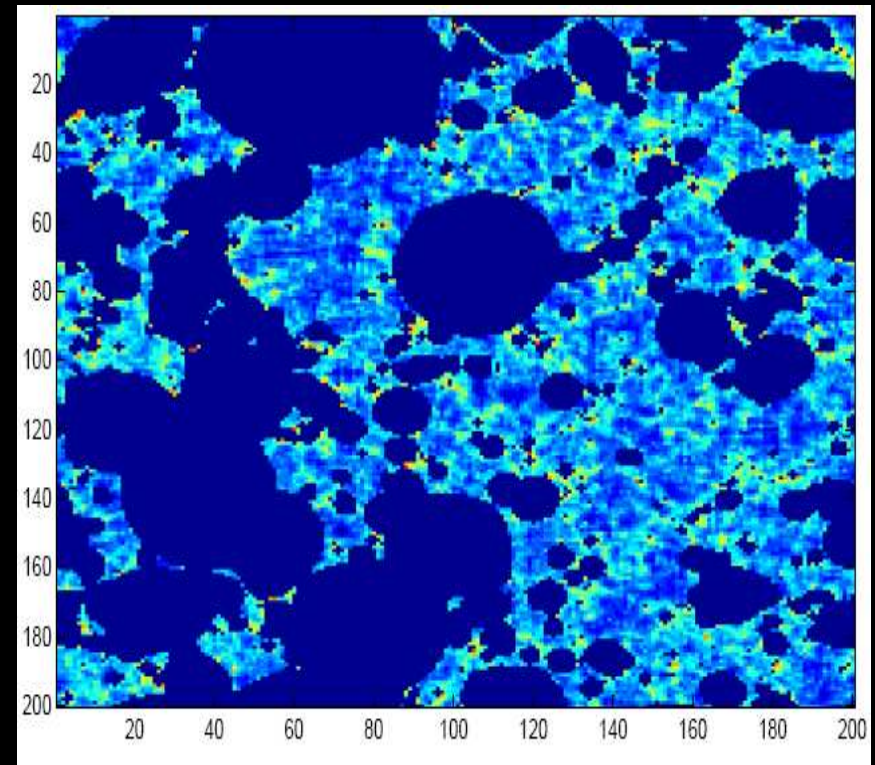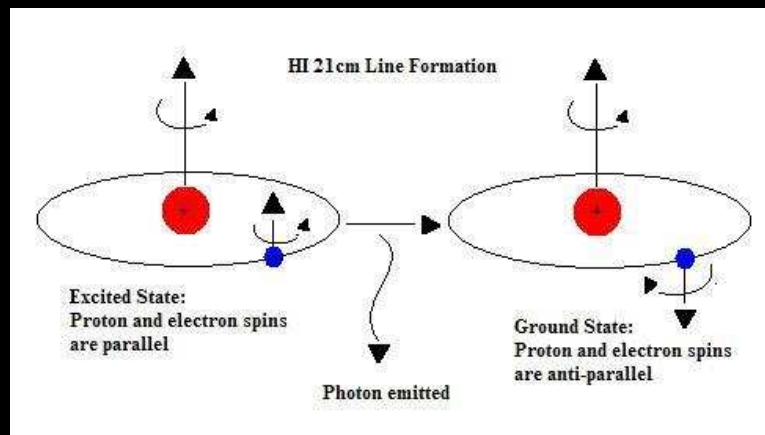|									
Redshift	*21cm Signal*	94	27		21	13	8		0
Frequency [MHz]		15	50		65	100	160		1420
Time (M Years)		18	120		170	340	650		13670

Cosmic Age

Bang — Cosmic Dark Ages — Cosmic Dawn — Reionization

History of the Universe

Cosmic Microwave Background

A   **B**   **C**   **D**   **E**

Hot Bubble Dominated Epoch

Modern Galaxies Form

First Stars

First Galaxies & Black Holes

DARE

Courtesy of the DARE Science Team

What's 21 cm Tomography?

21 cm Emission Signal

- ## What caused it?

z=8 via DexM
[Mesinger et al. 2010]

$$\nu_{10} = \frac{8}{3} g_I \left(\frac{m_e}{m_p} \right) \alpha^2 (R_M c) \approx 1420.405751 \text{ MHz}$$

Detection Estimation

$$D_A(z) = r_{\text{com}}/(1 + z)$$

$$\frac{\mathrm{d}r_{\text{com}}}{\mathrm{d}z} = \frac{c}{H(z)}$$

- z = 9
- H_0 = 70 km s^{-1} Mpc^{-1}
- Ω_m = 0.3, Ω_{vac} = 0.7
- bubble sz ~ 1 Mpc
- Ned Wright's calculator:
  - D_A ~ 920.6 Mpc

21CMA

MWA

LOFAR

SKA Central Region

Dense Aperture Arrays

Sparse Aperture Arrays

Dishes

5 km
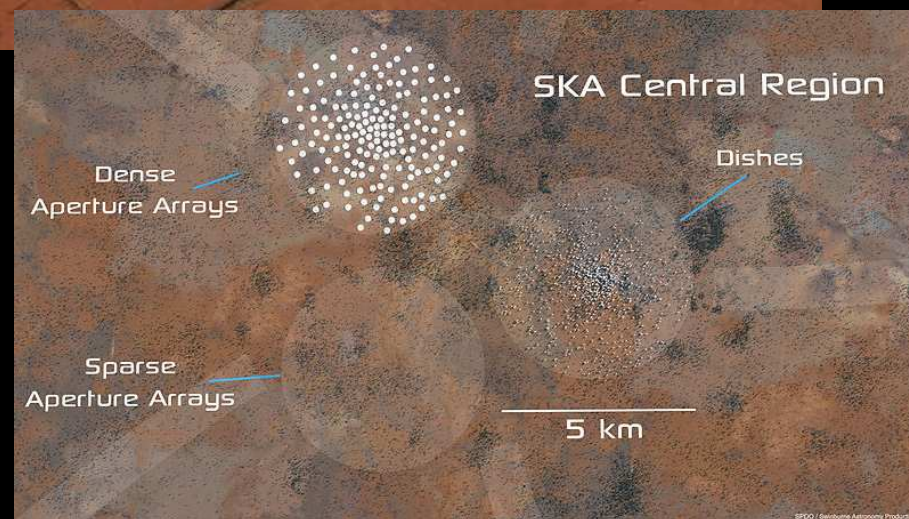
Array	N_a	A_{tot} (10^3 m^2)	ν (MHz)	FoV (deg^2)	D_{min} (m)	D_{max} (km)
21CMA	20	8.0	70–200	$\pi 15^2$	100	10
MWA	500	7.0	80–300	$\pi 16^2$	4	1.5
LOFAR	64	42	115–240	$4 \times \pi 2^2$	100	2c
SKA	5000	600	100–200	$\pi 5.6^2$	10	5c

Table 6

[Furlanetto; Oh; and Briggs (2006)]

21 cm Reionization Detection

- ## What are we detecting observationally?

  – Brightness temperature fluctuation

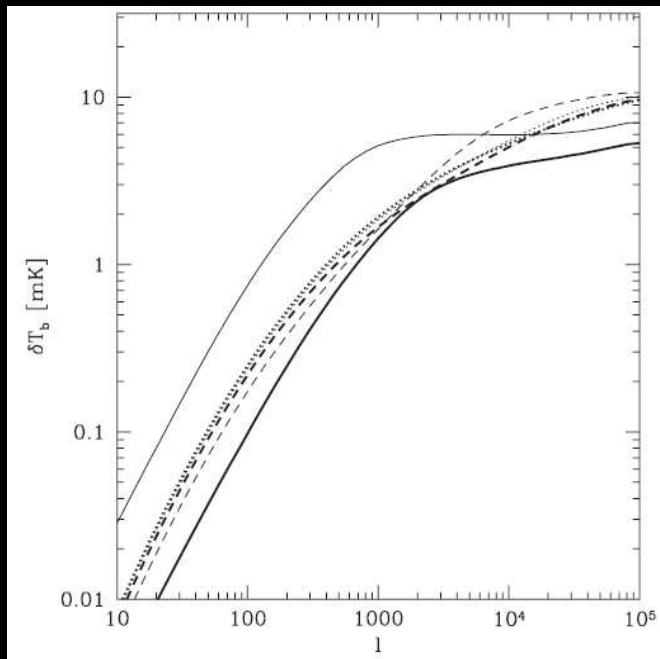$$\delta T(\nu) \approx \frac{T_S - T_{\rm CMB}}{1 + z} \tau$$

$$\frac{N_1}{N_0} \equiv \frac{g_1}{g_0} \exp\left(-\frac{h\nu_{10}}{kT_{\rm s}}\right)$$

$$\psi = x_{\rm H}(1 + \delta).$$

$$\delta T_b \approx 23\psi \left(\frac{T_S - T_{\rm CMB}}{T_S}\right)\left(\frac{\Omega_b h^2}{0.02}\right)\left[\left(\frac{0.15}{\Omega_m h^2}\right)\left(\frac{1+z}{10}\right)\right]^{1/2} \ {\rm mK}.$$

$$\psi(\boldsymbol{x}) = \int \frac{d^3 k}{(2\pi)^3} \hat{\psi}(\boldsymbol{k}) e^{i\boldsymbol{k}\cdot\boldsymbol{x}}$$

$$= \int \frac{d^3 k}{(2\pi)^3} \hat{\psi}(\boldsymbol{k}) \sum_{lm} 4\pi i^l j_l(kr) Y_{lm}^*\left(\hat{\boldsymbol{k}}\right) Y_{lm}(\hat{\boldsymbol{n}}), \quad (11)$$

Power Spectrum and Detector

[Furlanetto et al. 2004, 613]

$$\langle \hat{\psi}(\boldsymbol{k}_1)\hat{\psi}(\boldsymbol{k}_2)\rangle = (2\pi)^3 \delta^{\mathrm{D}}(\boldsymbol{k}_1 + \boldsymbol{k}_2) P_\psi(k_1)$$

$$\xi(r) = \int \frac{dk}{k} \Delta_\rho^2(k) \frac{\sin kr}{kr}$$

$$\Delta^2(\mathbf{k}) = (k^3/2\pi^2)P(\mathbf{k})$$

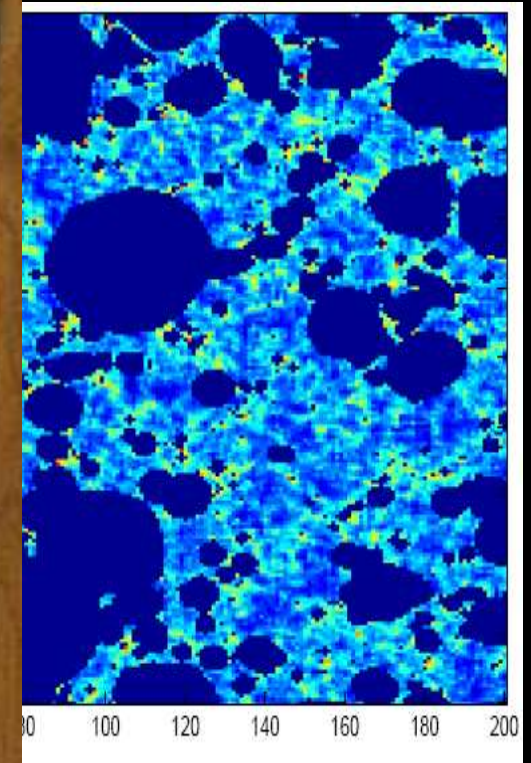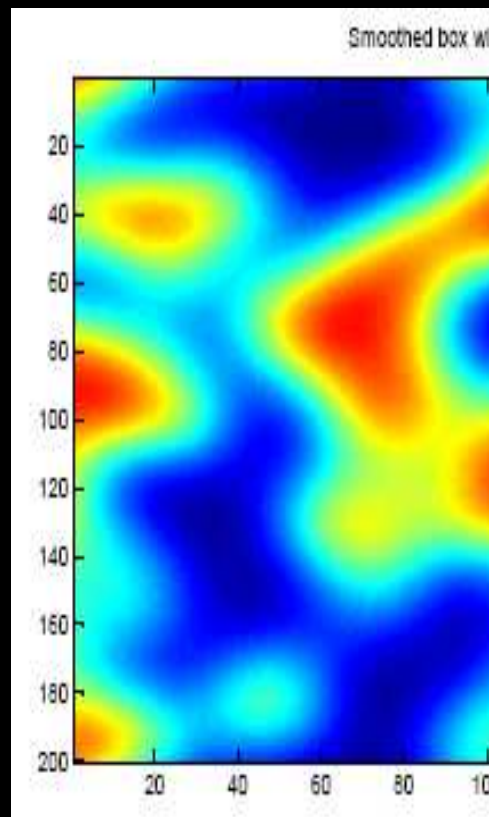- How the multipoles "l" relate to physical scale?

$$l \sim kD$$

$$D_A(z) = r_{\mathrm{com}}/(1+z)$$

$$\frac{\mathrm{d}r_{\mathrm{com}}}{\mathrm{d}z} = \frac{c}{H(z)}$$

Challenges

Smoothed box w...

RFI Reminders to Guests

- **Intentional Radiators:** Wireless Equipment (of all descriptions) is *Strictly Prohibited* everywhere on the Green Bank Site. Microwave Ovens are also Prohibited.

- **Please Power Off *ALL* Electronic Devices when you are not using them.**

- **Please take note of additional RFI precautions for the Radio Astronomy Instrument Zone; (See sheet in visitor's package.)**

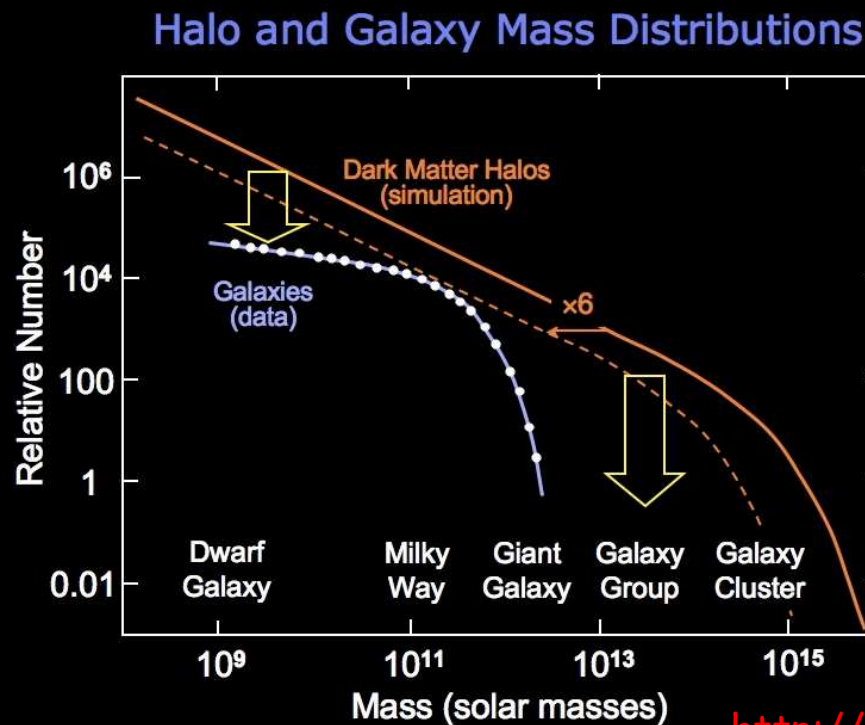# Press-Schechter Mass Function

Dark Matter Halo Mass Function:

$$n(m)\mathrm{d}m = \sqrt{\frac{2}{\pi}} \frac{\bar{\rho}}{m^2} \left| \frac{\mathrm{d}\ln\sigma}{\mathrm{d}\ln m} \right| \frac{\delta_c(z)}{\sigma(m)} \exp\left[-\frac{\delta_c^2(z)}{2\sigma^2(m)} \right] \mathrm{d}m$$

[Press & Schechter (1974)]

Halo and Galaxy Mass Distributions

Partially Ionized IGM

- ## Review: Possible ionizing sources?

  - UV photoionization
  - X-Ray
  - Decaying particles
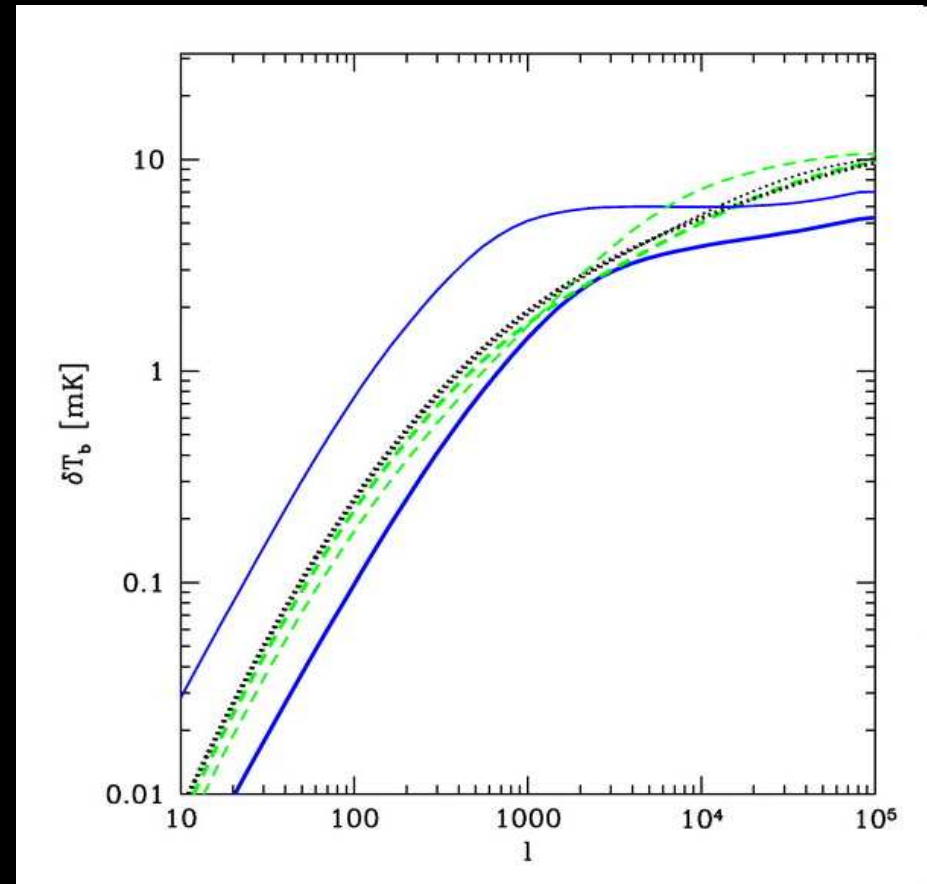
Fig 1 - [Furlanetto et al. 2004, 613]

	Solid	Dashed	Dotted
Thick (ζ = 12)	x_H = 0.26	x_H = 0.8	x_H = 0.96
Thin (ζ = 40)			

Double Reionization

- 1st generation ionize first
- 2nd generation HII will grow faster, why?
- What they ignore in this model?
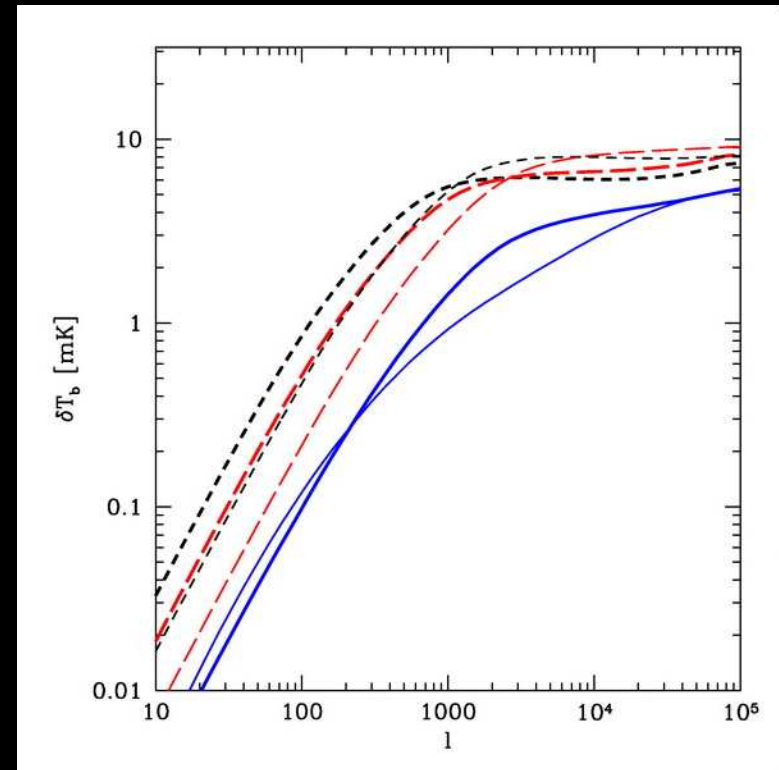- How to interpret the difference on the power spectrum?

Fig 2 - [Furlanetto et al. 2004, 613]

Both (ζ_2=12)	Solid	Long Dashed	Short Dashed
Thick: z=12, x_H=0.27	x_H = 0.5	z_1 = 18	z_1 = 18
Thin : z=16, x_H=0.46		ζ_1 = 500	ζ_1 = 105

Inside-Out vs Outside-In

Inside-Out

- Ionized in the dense filaments first
- Washes out large scale power

Outside-In

- Ionized in the void into the filaments
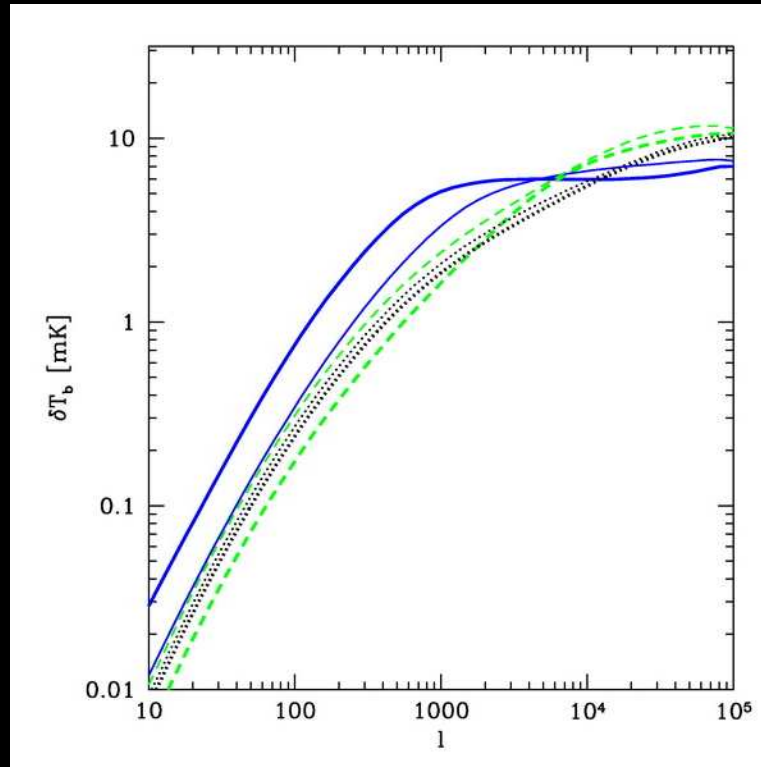- Amplifies large scale power

How 21 cm signal help?

Both ($\zeta = 40$)	Solid	Dashed	Dotted
Thick: Inside-out	z =12	z = 15	z = 18
Thin : Outside-in	x_H = 0.5	x_H = 0.8	x_H = 0.96

- [21 cm Brightness Temperature Fluctuation Evolution [by Andrei Mesinger]](#)

Upshot!

- Detect the Temperature Fluctuation
- Fourier transform it to power spectra
- Use the Power Spectra to constrain ionization fluxes, bubble size and redshifts
- Eventually, perhaps, to map the early universe