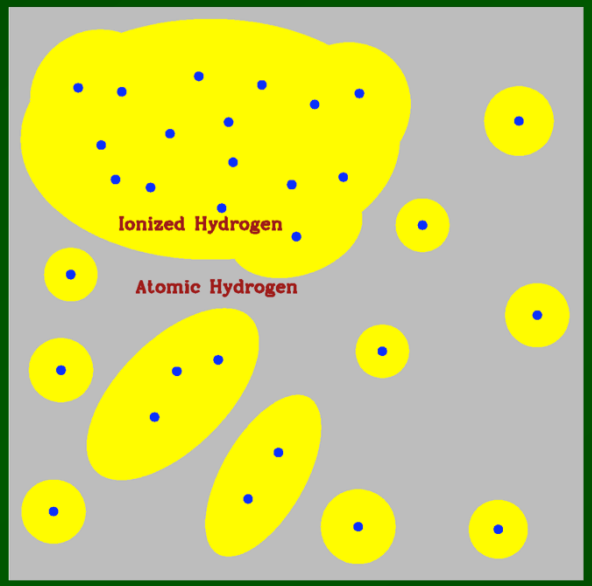
Studying Galaxies and Reionization with 21-cm Cosmology

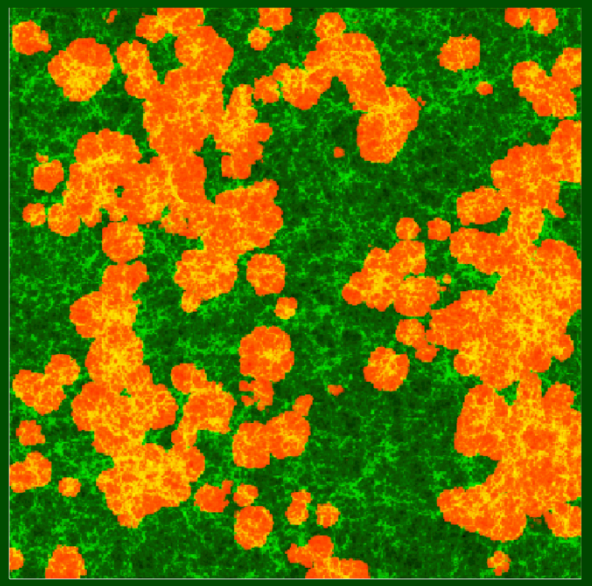
Rennan Barkana

רנן ברקנא

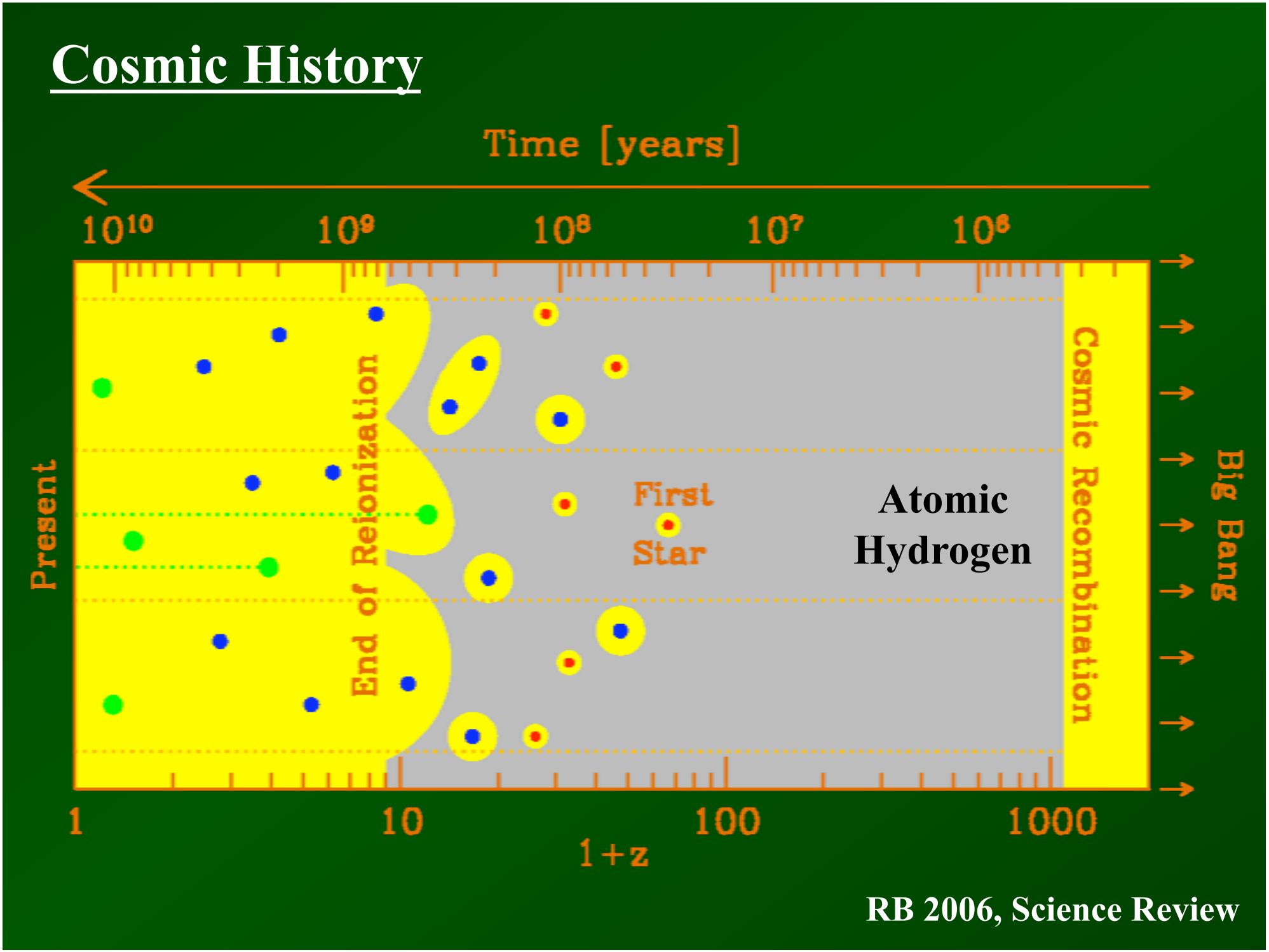
TEL AVIV UNIVERSITY

אוניברסיטת תל-אביב





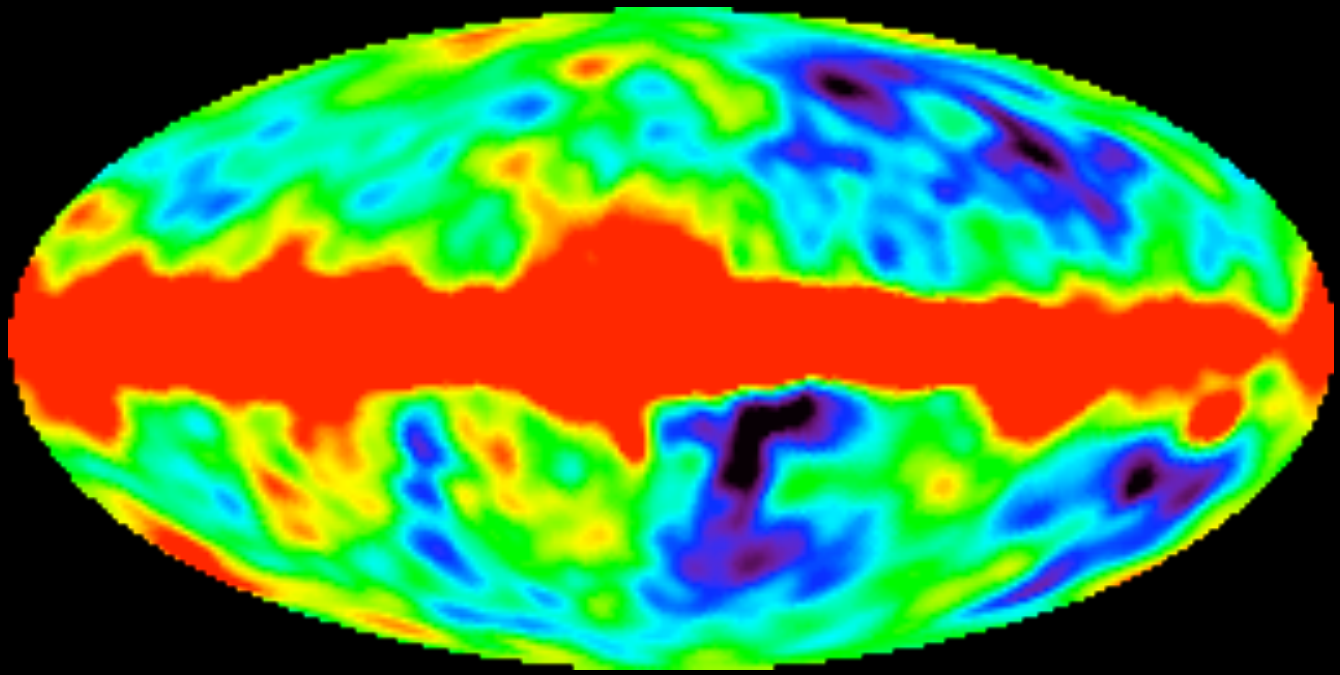
Cosmic History



RB 2006, Science Review

CMB: 2D temperature map, 10^{-5} fluctuations

COBE
1992



CMB: 2D temperature map, 10^{-5} fluctuations

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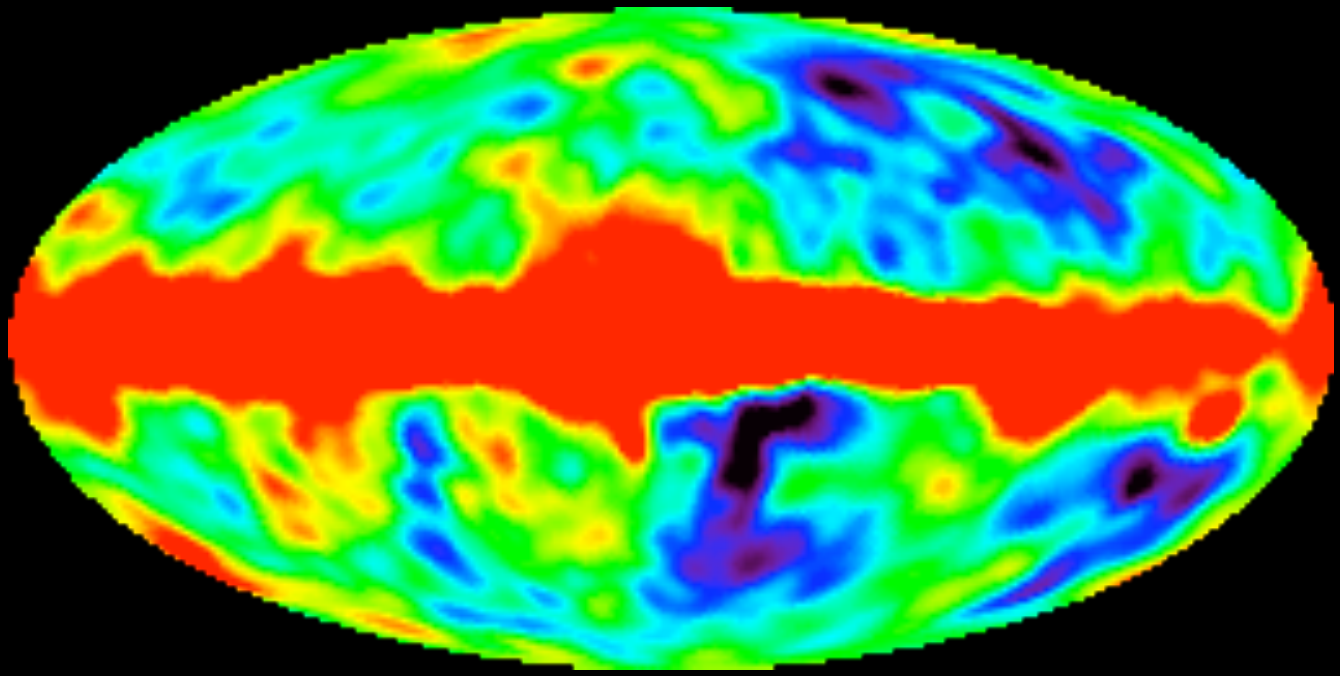
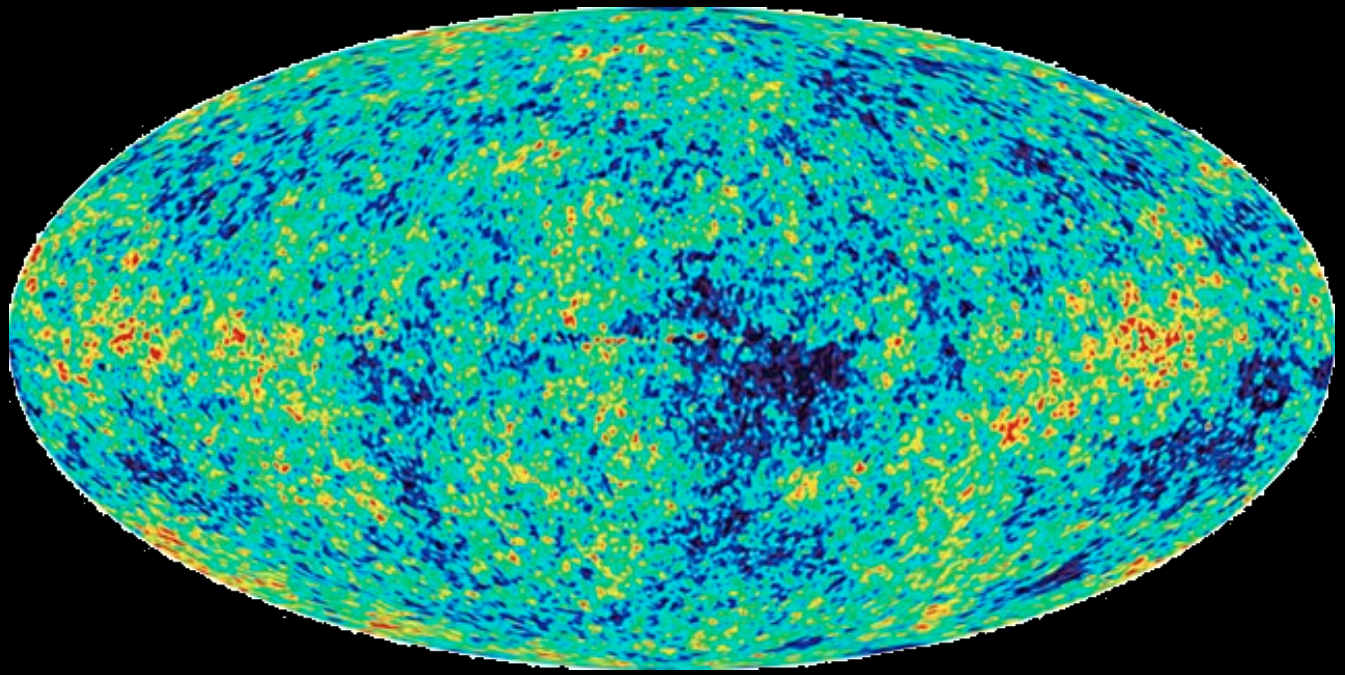
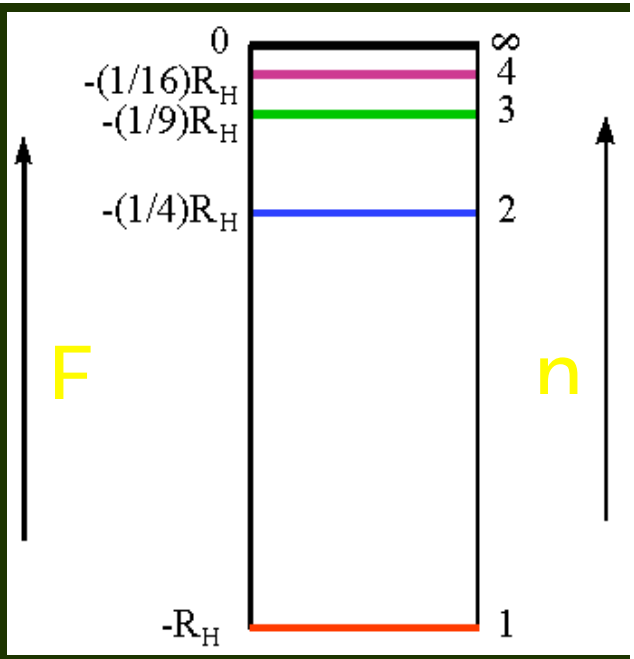
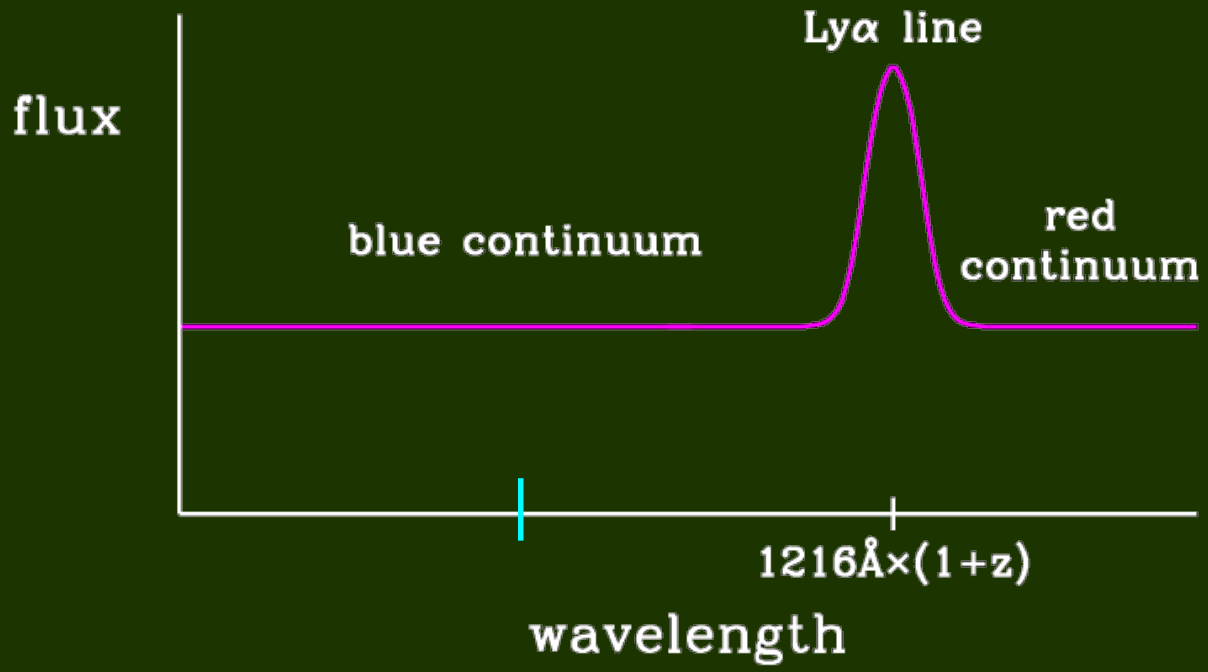


WMAP



Lyα Spectra:

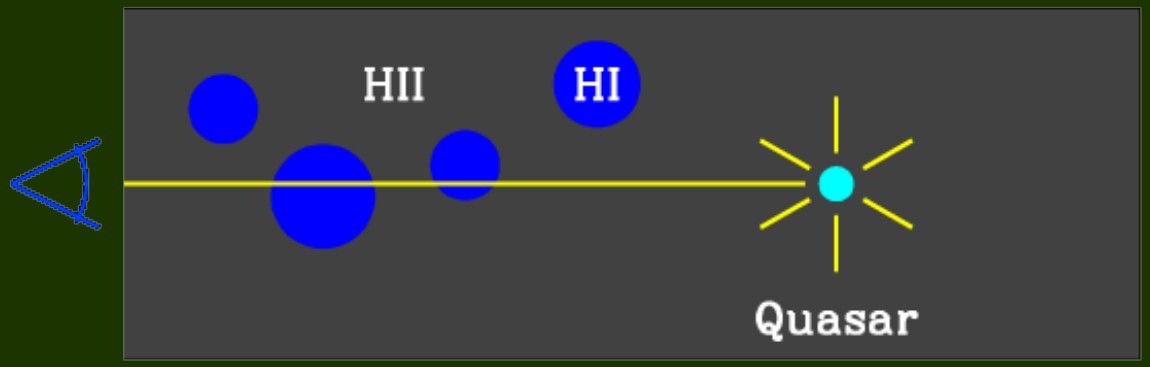


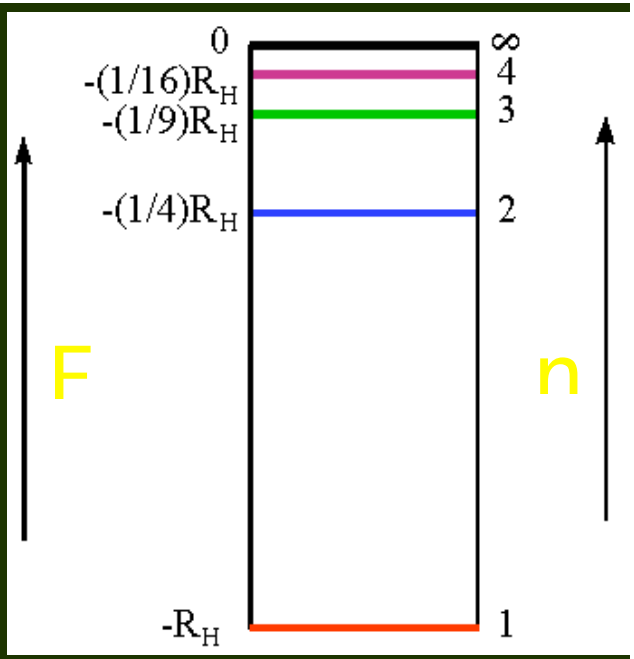


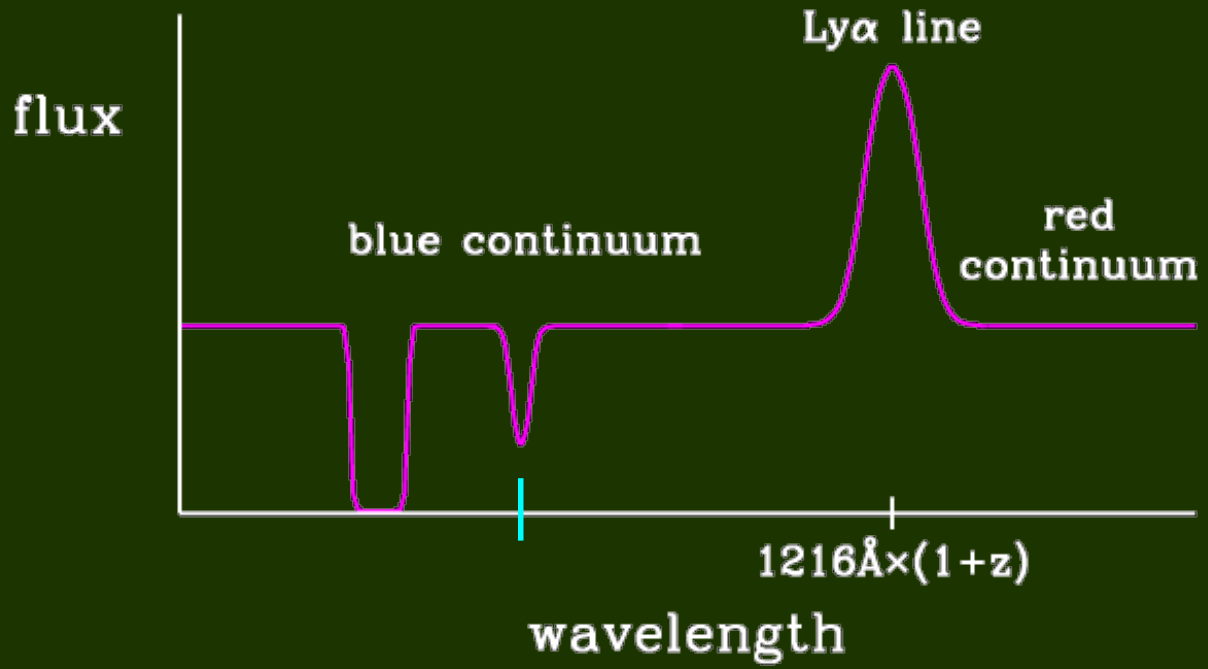
Resonance Line + Cosmological Redshift

1100Å â (1 + z)

Lyα Spectra: 1D density distribution



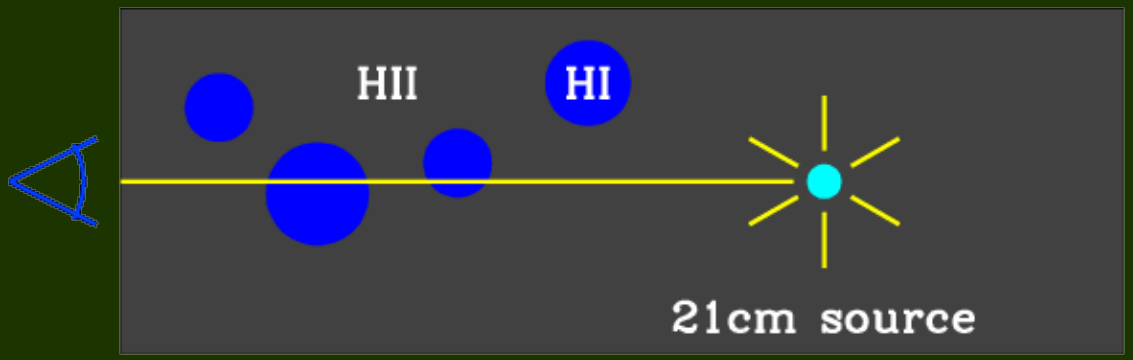


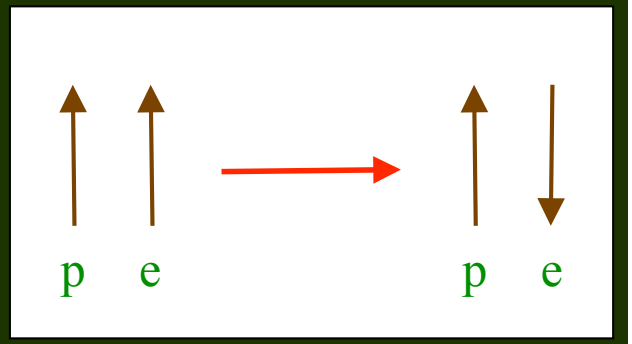


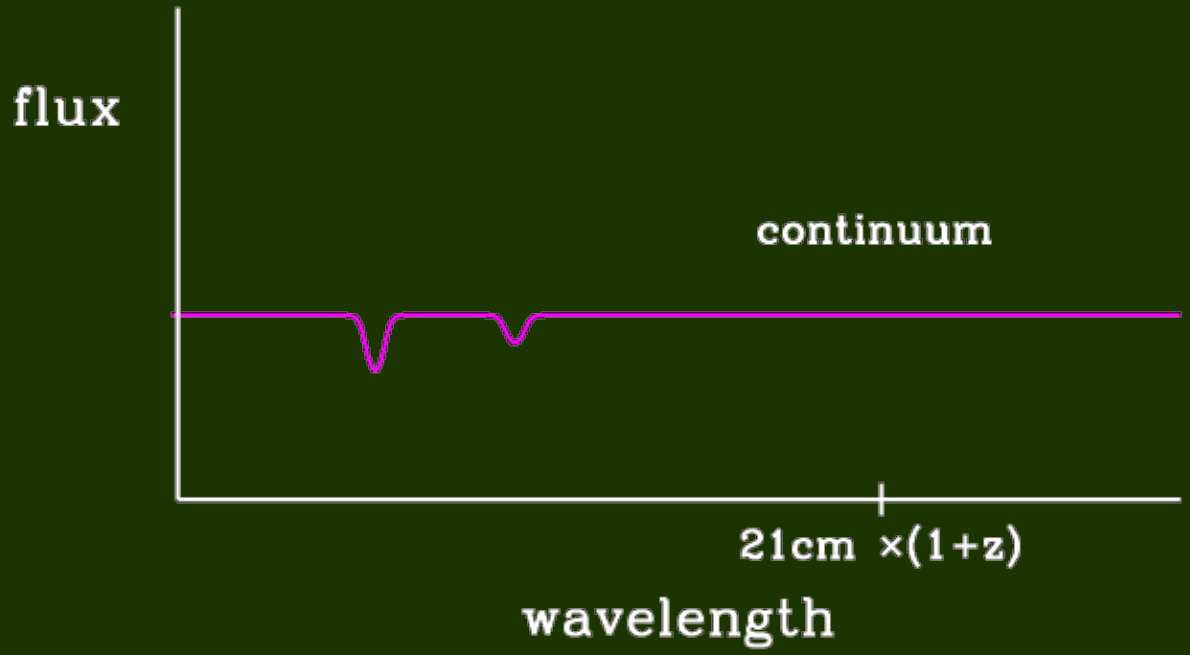
Resonance Line + Cosmological Redshift

$$1100\text{Å} \hat{a} (1+z) = 1216\text{Å} \hat{a} (1+z^0)$$

21-cm Spectra



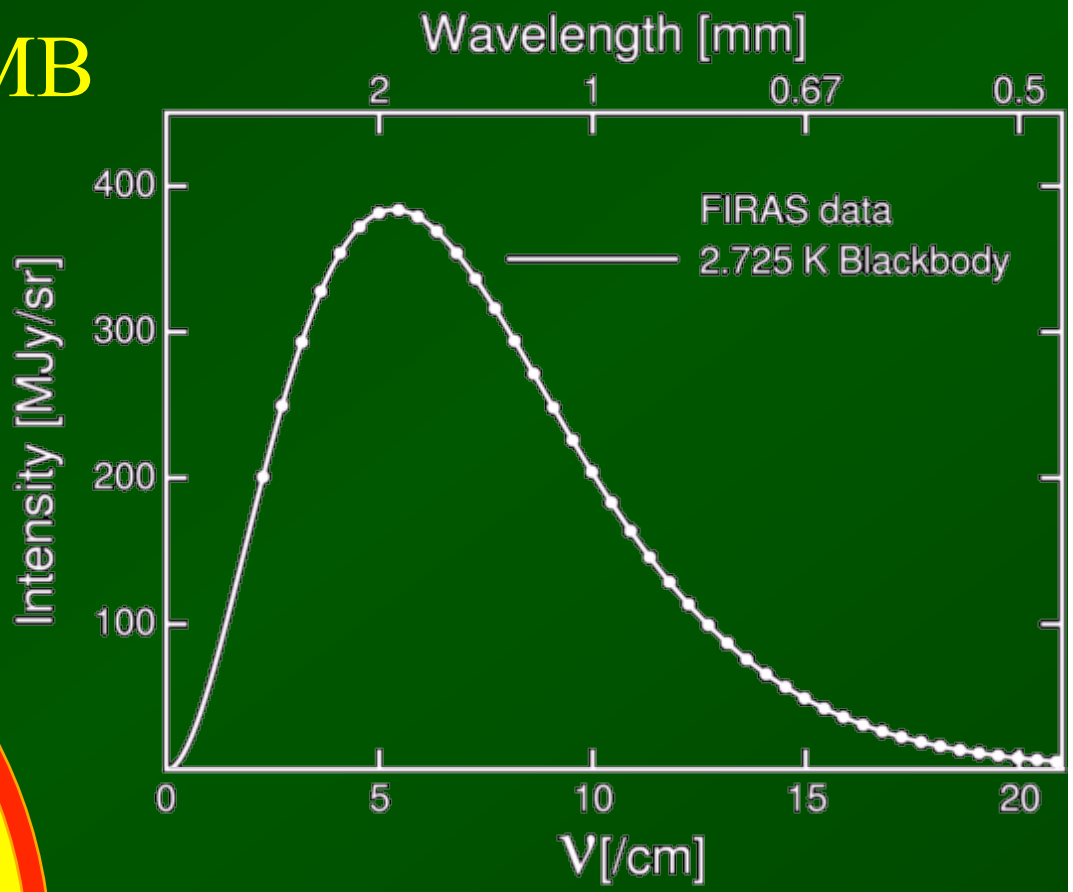




Resonance Line +
Cosmological Redshift

Mean T: no flux

Diffuse Source: The CMB



The CMB

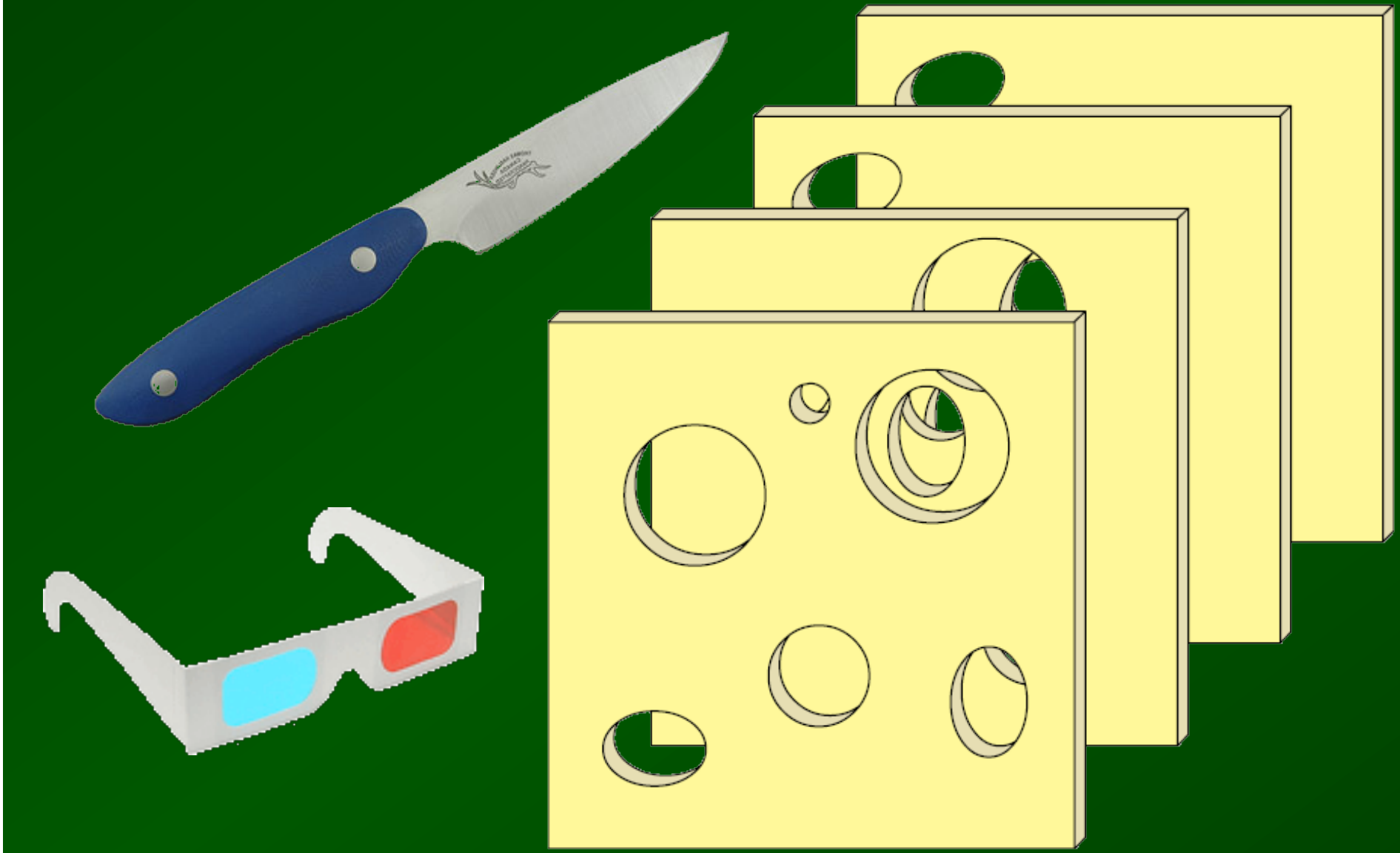
Edge of the observable universe

$h\nu \quad k_B T$

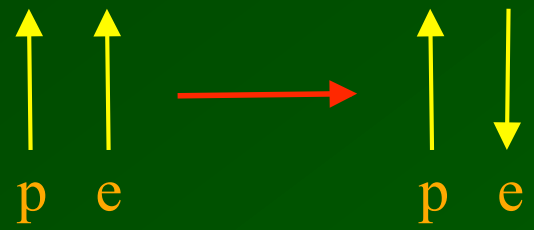
$I_\nu = 2k_B T \nu^2/c^2$

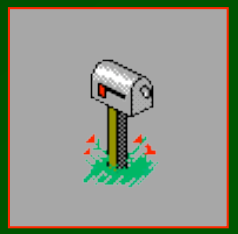
Mean T: no flux

Redshift Slices of the Universe



The Spin Temperature





$$\lambda = 21\,\mathrm{cm}$$

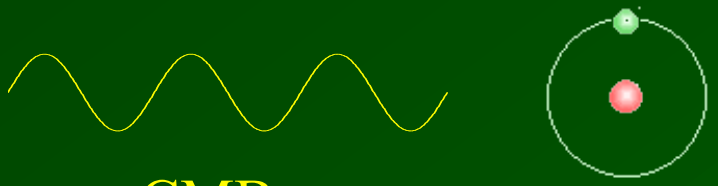
$$\nu = 1420\,\mathrm{MHz}$$

$$E = 5.9 \times 10^{-6}\,\mathrm{eV}$$

$$\frac{E}{k_B} = T_* = 0.068\,\mathrm{K}$$

$$\frac{n_1}{n_0} = 3 \exp\left[-\frac{T_*}{T_S}\right]$$

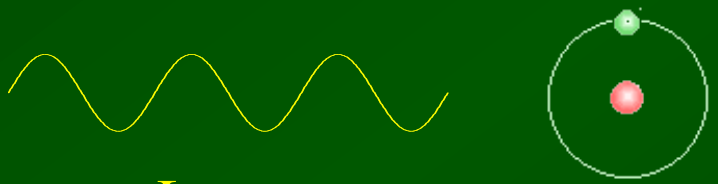
What determines T_S?



CMB

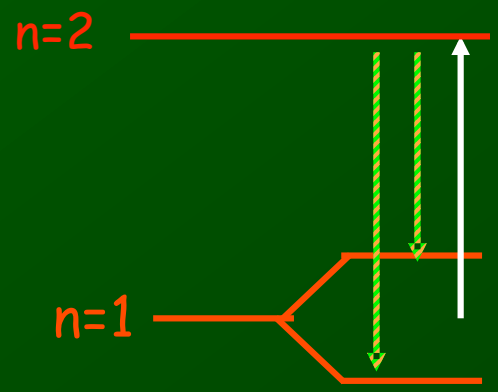
$T_S \neq T_\gamma$

$T_S \neq T_K$



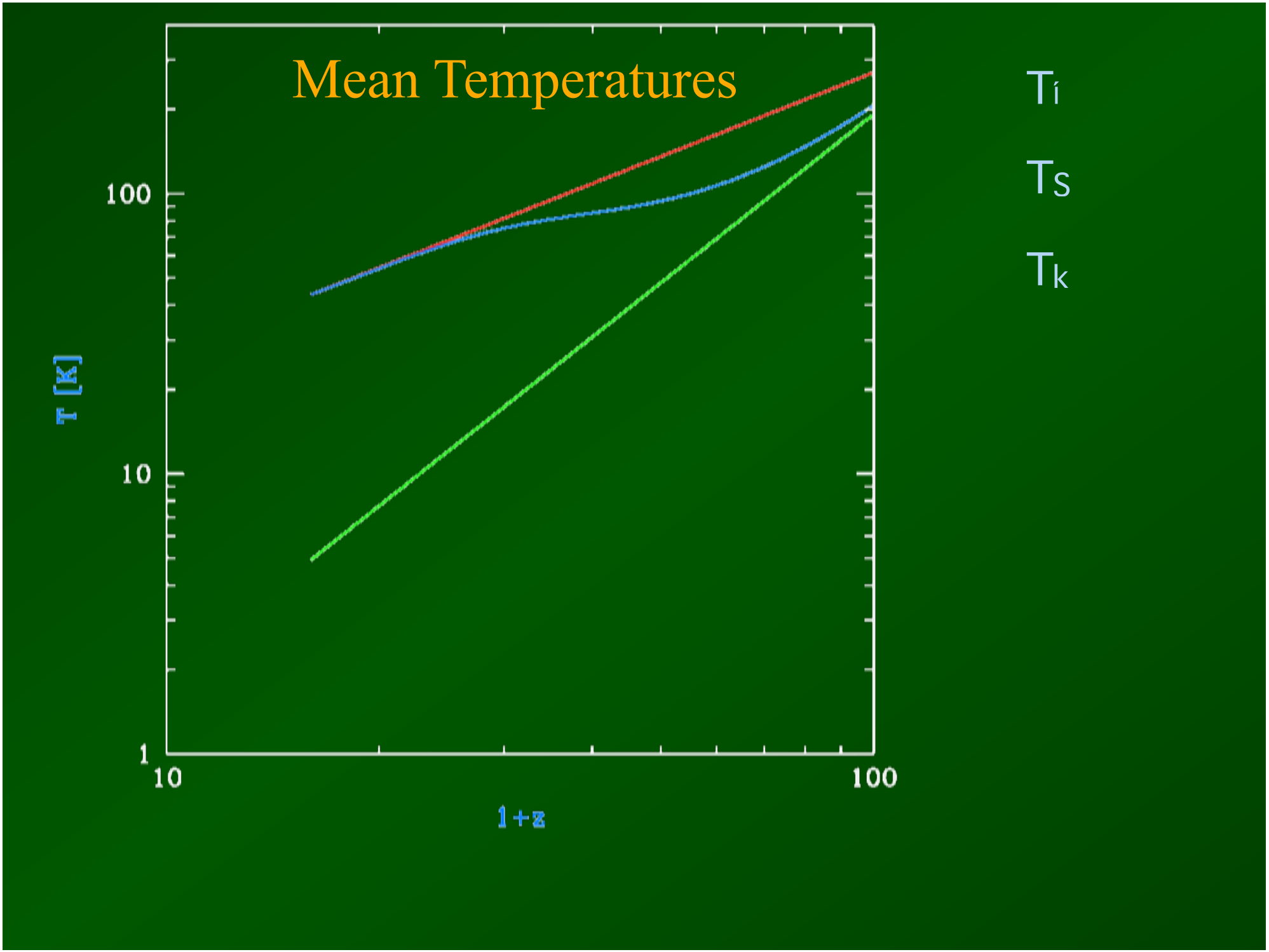
Lyα

Wouthuysen 1952
Field 1958

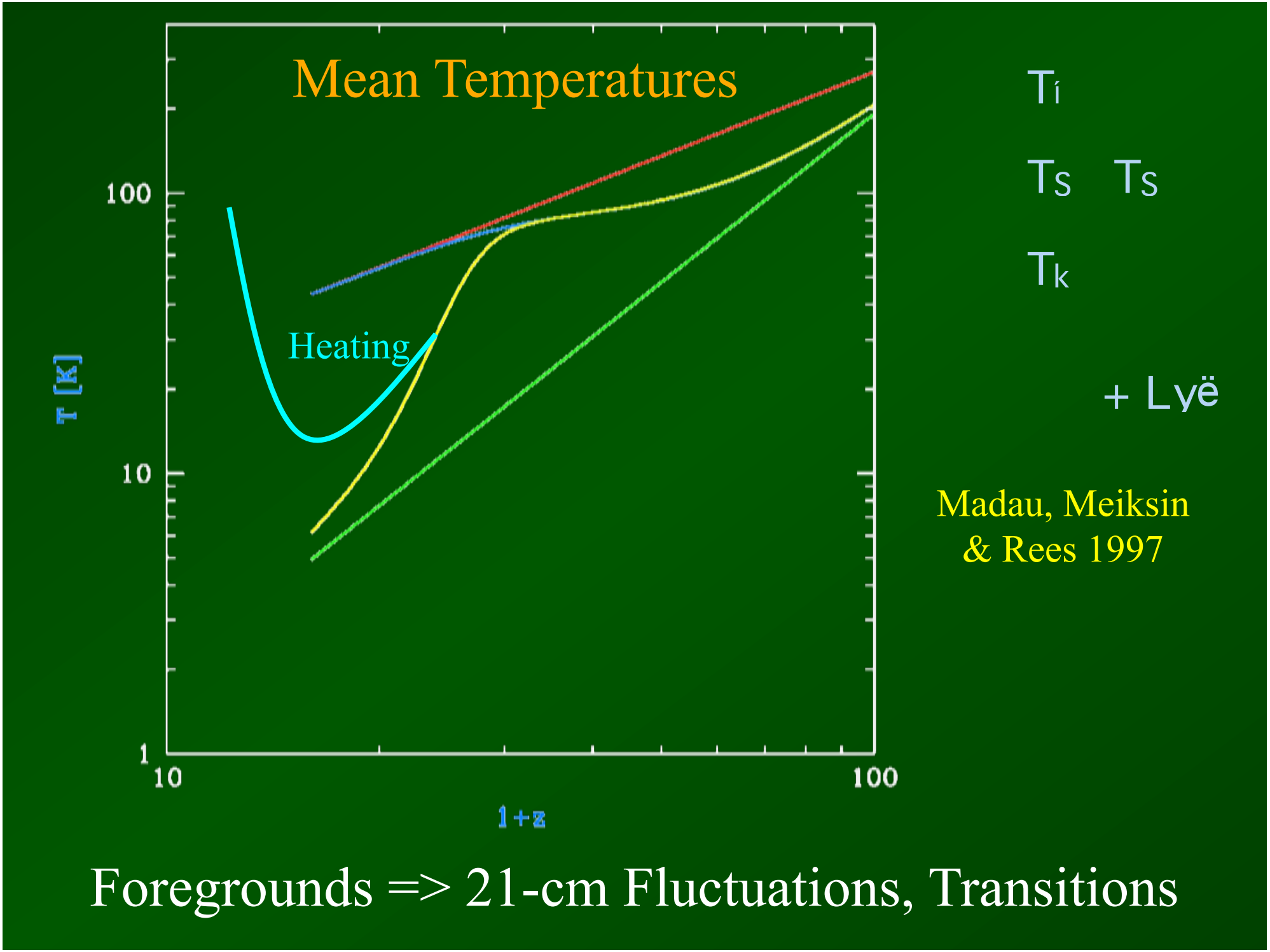


$T_S \neq T_K$

Mean T: no flux

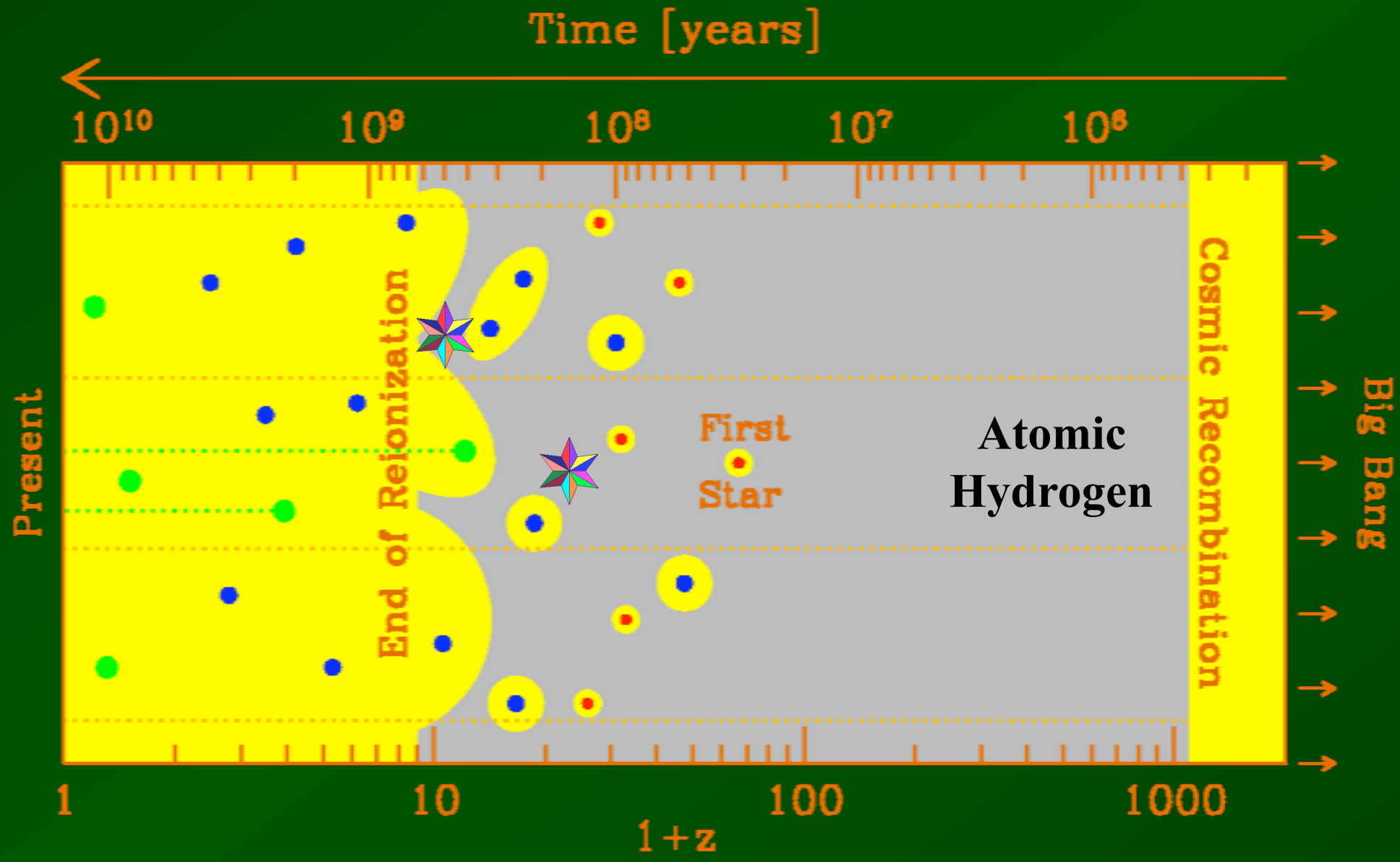


Mean T: with flux



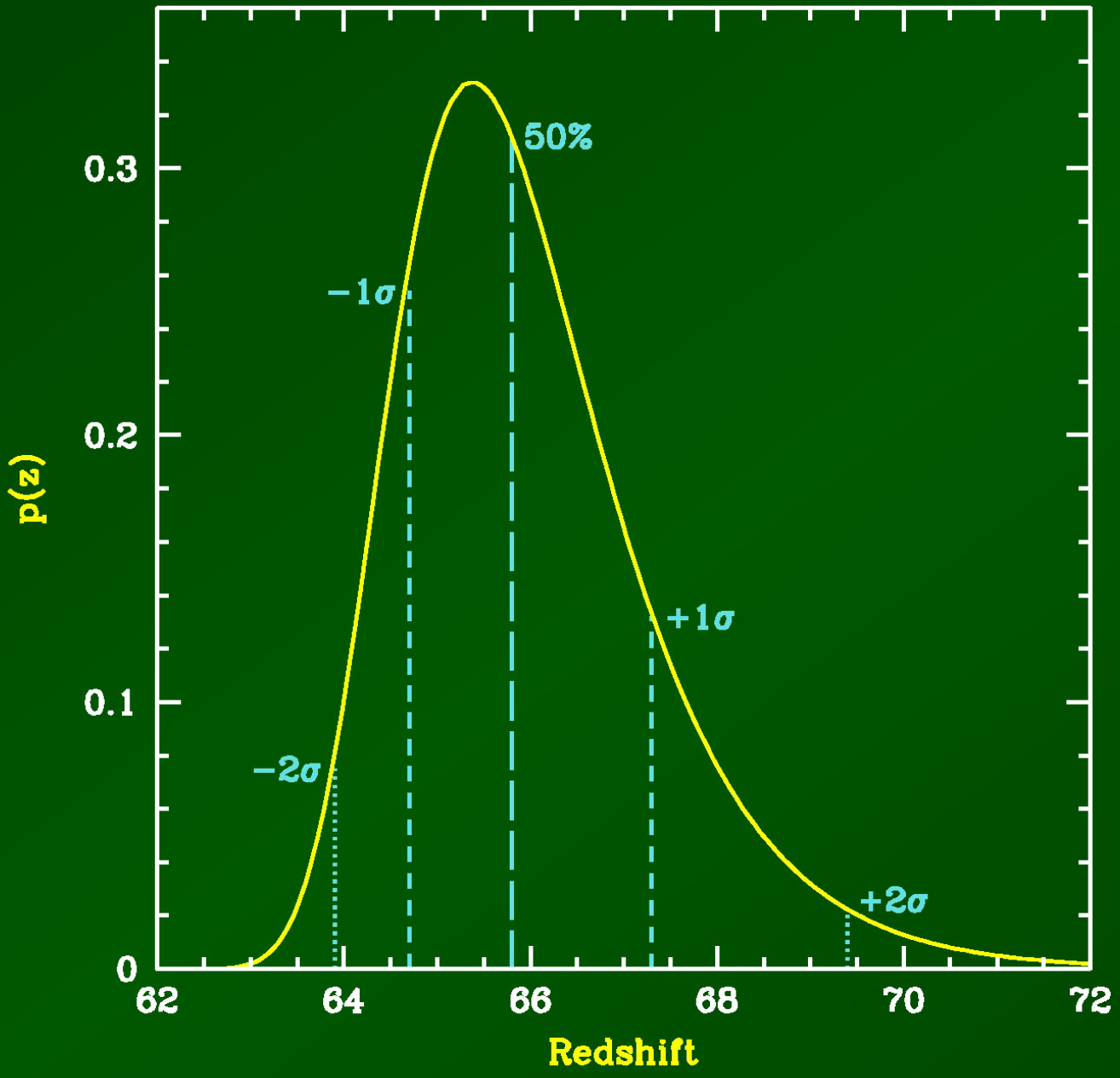
Foregrounds => 21-cm Fluctuations, Transitions

Cosmic History



RB 2006, Science Review

The First Star

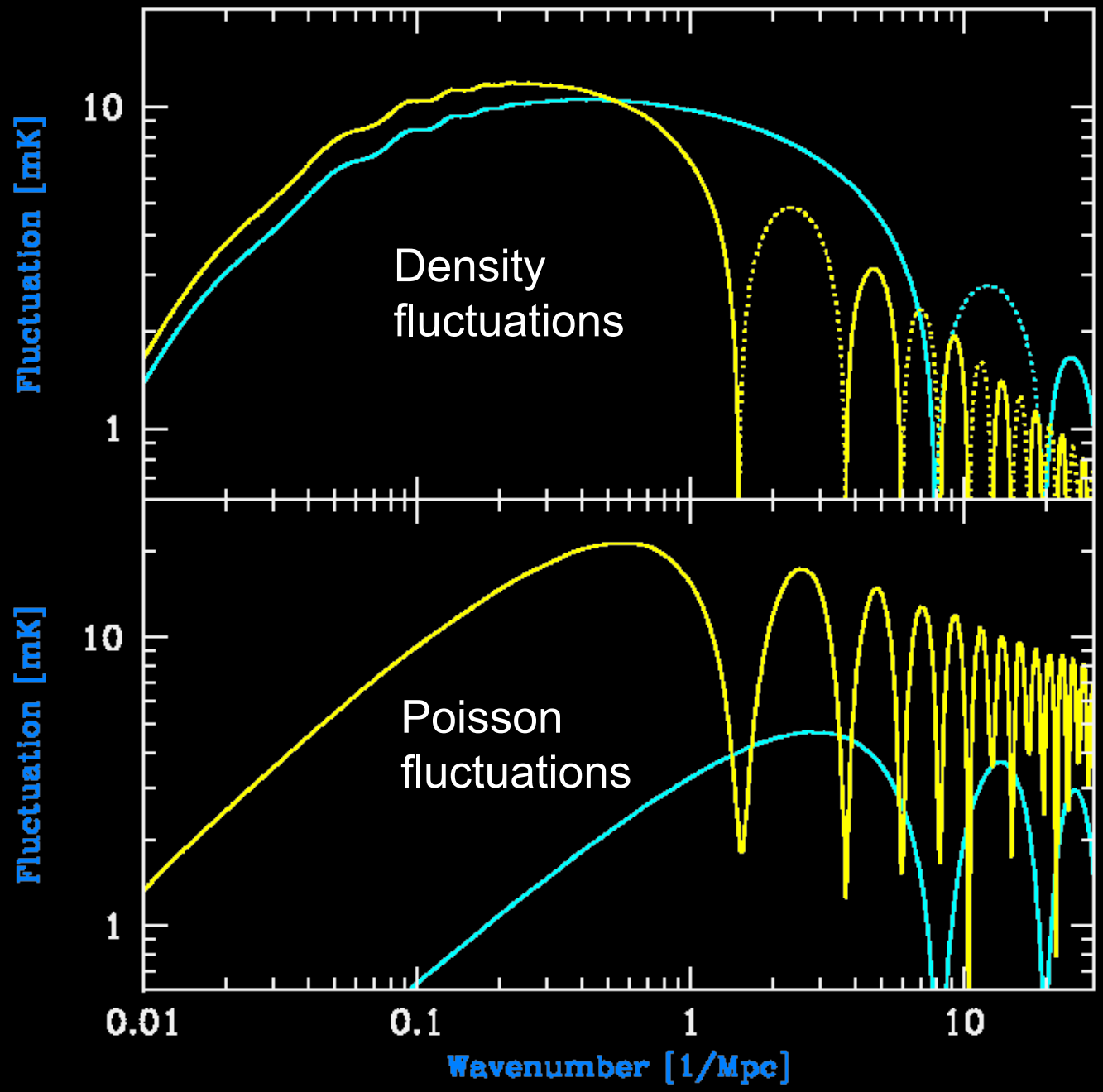


1û :

t = 31 æ 1 M yr

Naoz, Noter
& RB 2006

21-cm fluctuations from Lyα



RB & Loeb 2005

Naoz & RB 2008

$$4_{21}(k) = \ddot{\Phi}_b \sqrt{\frac{k^3 P(k)}{2\pi^2}}$$

Many small galaxies

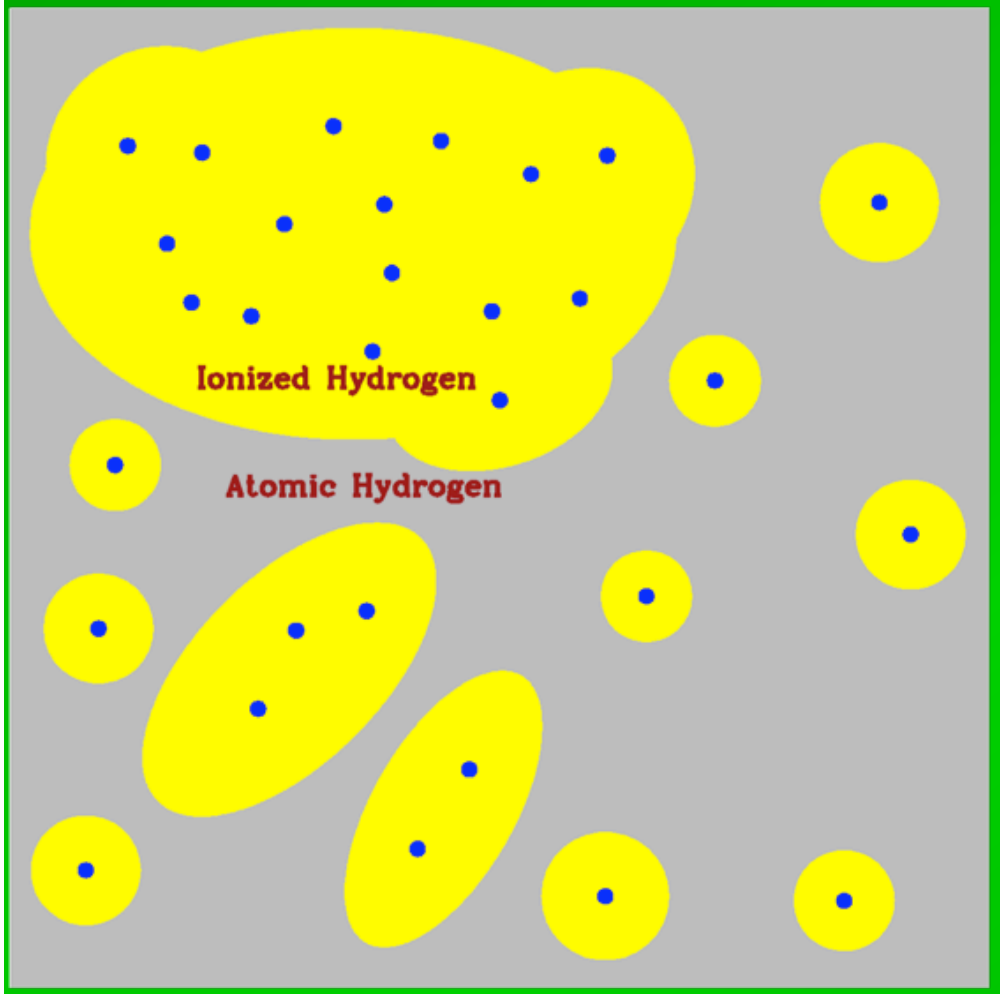
$V_c = 16.5$ km/s

A few large galaxies

$V_c = 35.5$ km/s

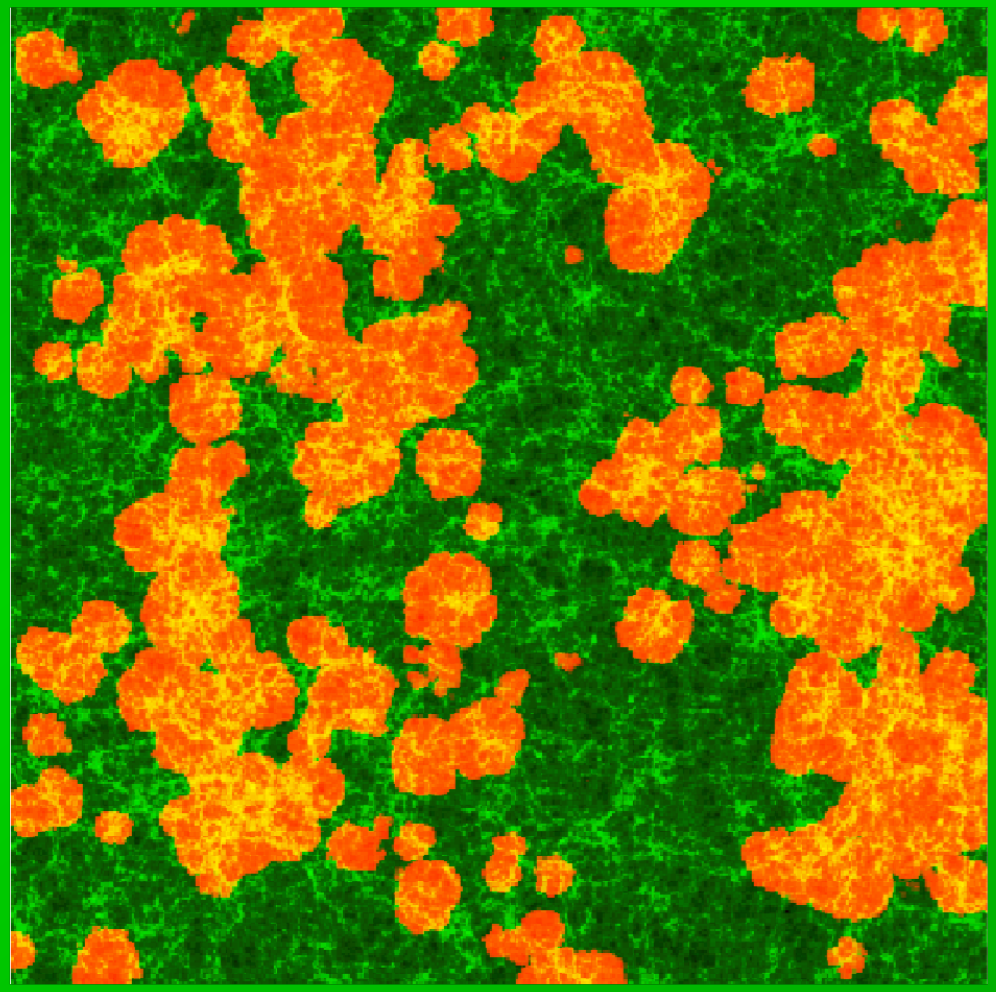
$$V_c = \sqrt{\frac{GM}{R}}$$

Cosmic Reionization:



RB & Loeb 2004

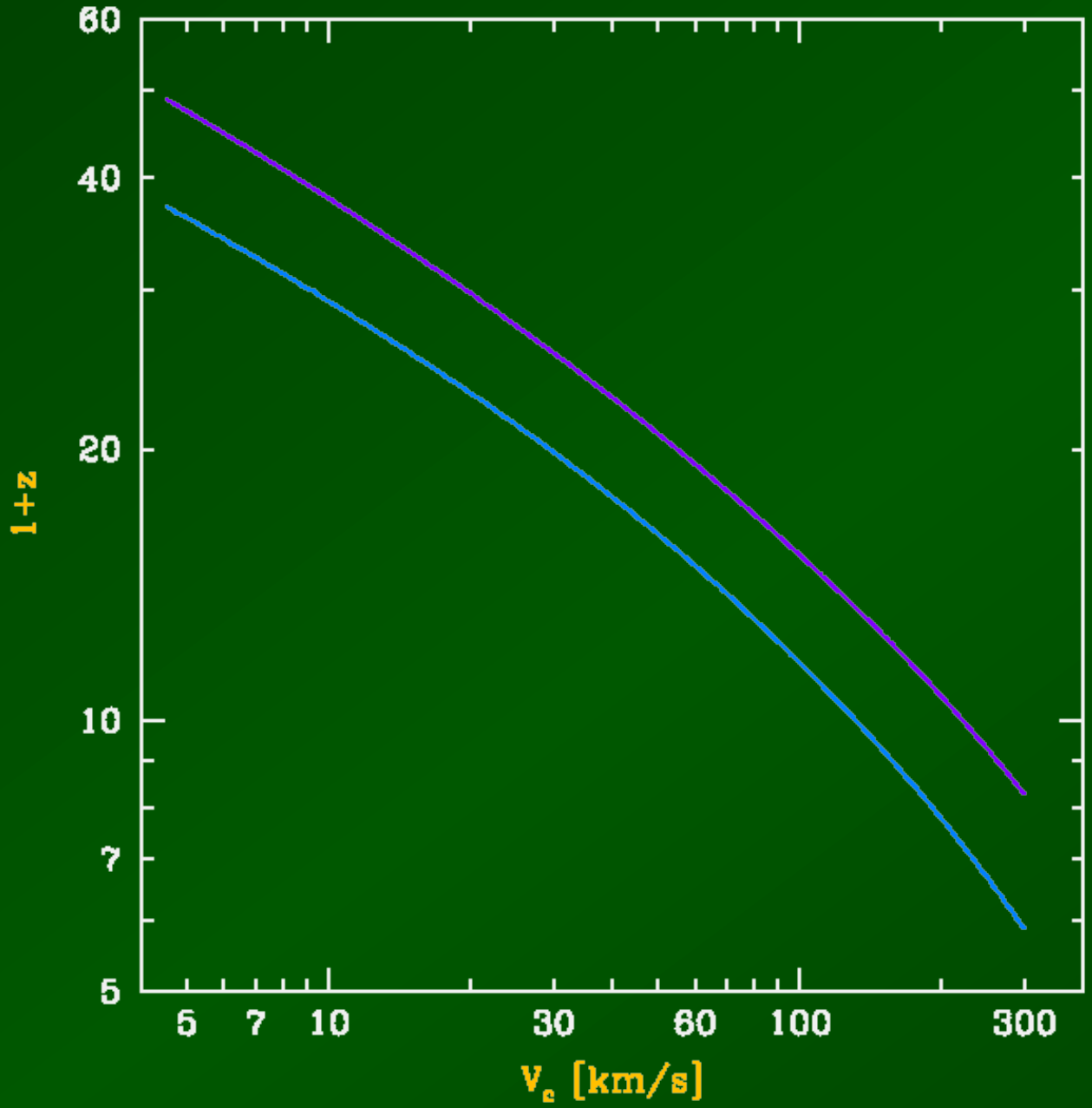
Furlanetto, Zaldariagga, Hernquist 2004



100/h Mpc = 0.5°

Mellema, Iliev, Pen, Shapiro 2006

The Infancy of Reionization



Galaxies:

Small and rare

Fluctuations:

Poisson & density

N=1 domination:

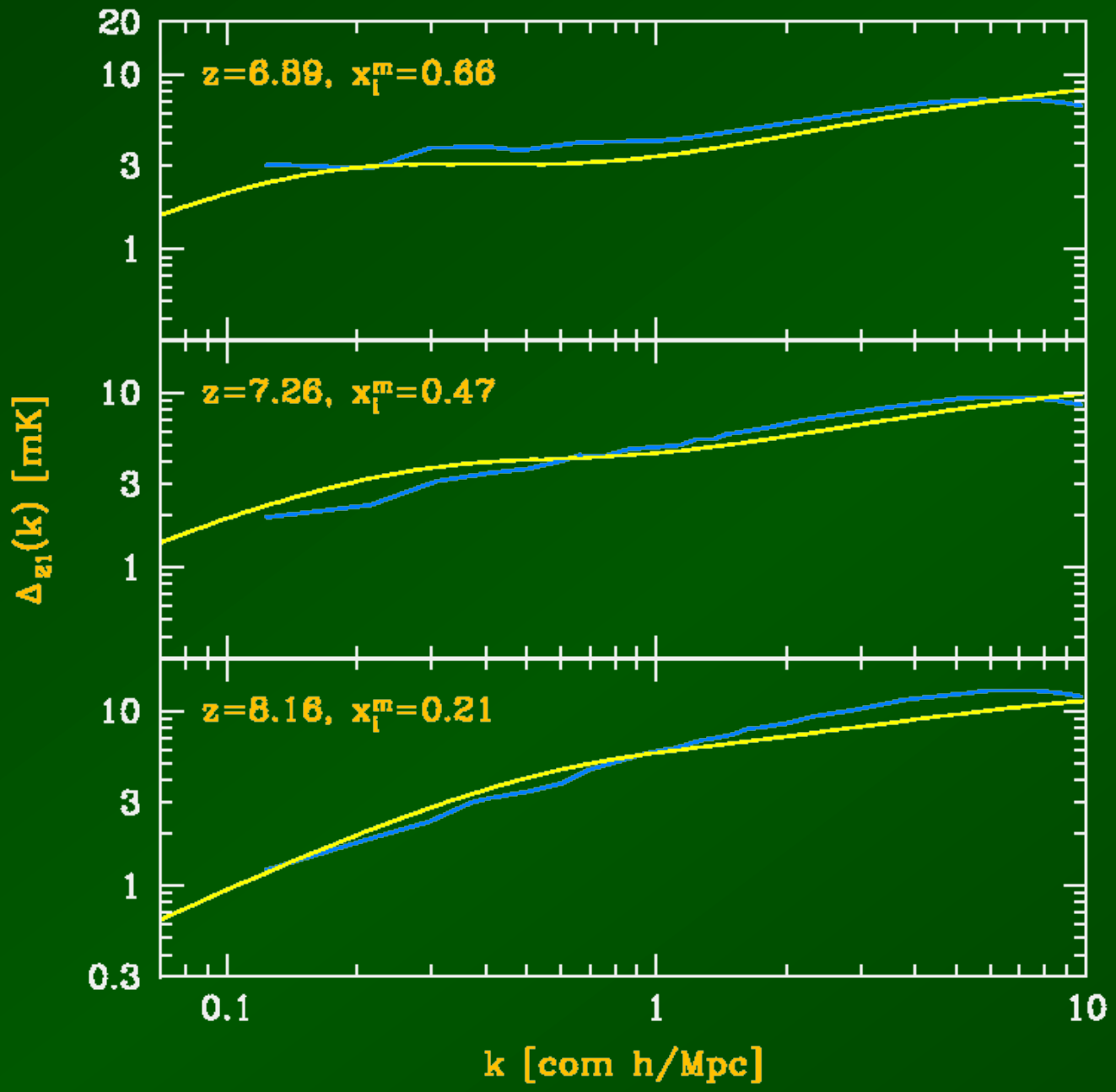
90%

50%

$$V_c = \sqrt{\frac{GM}{R}}$$

RB 2008

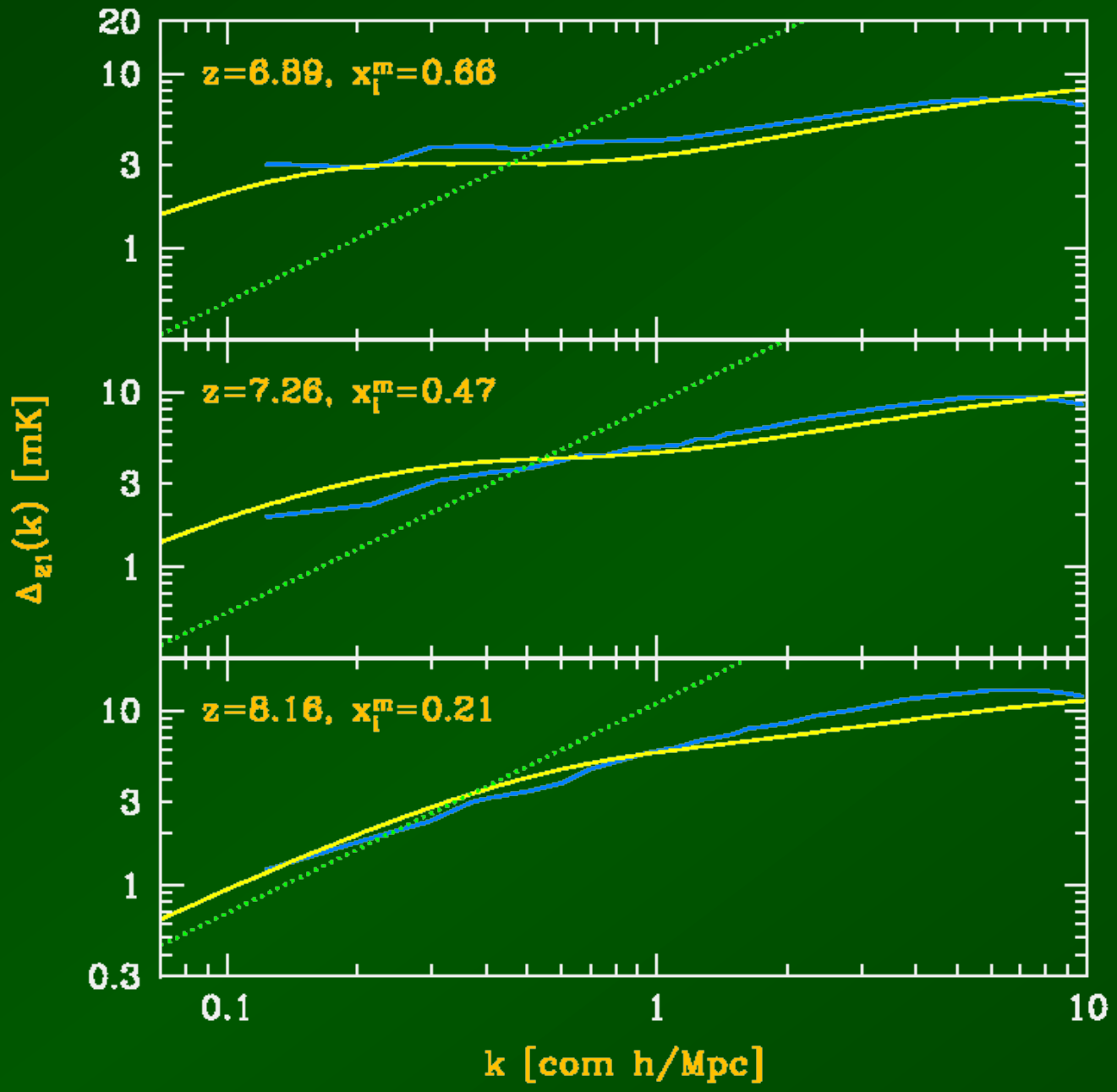
21-cm Power Spectrum



Zahn et al. 2007 simulation

RB 2007

21-cm Power Spectrum

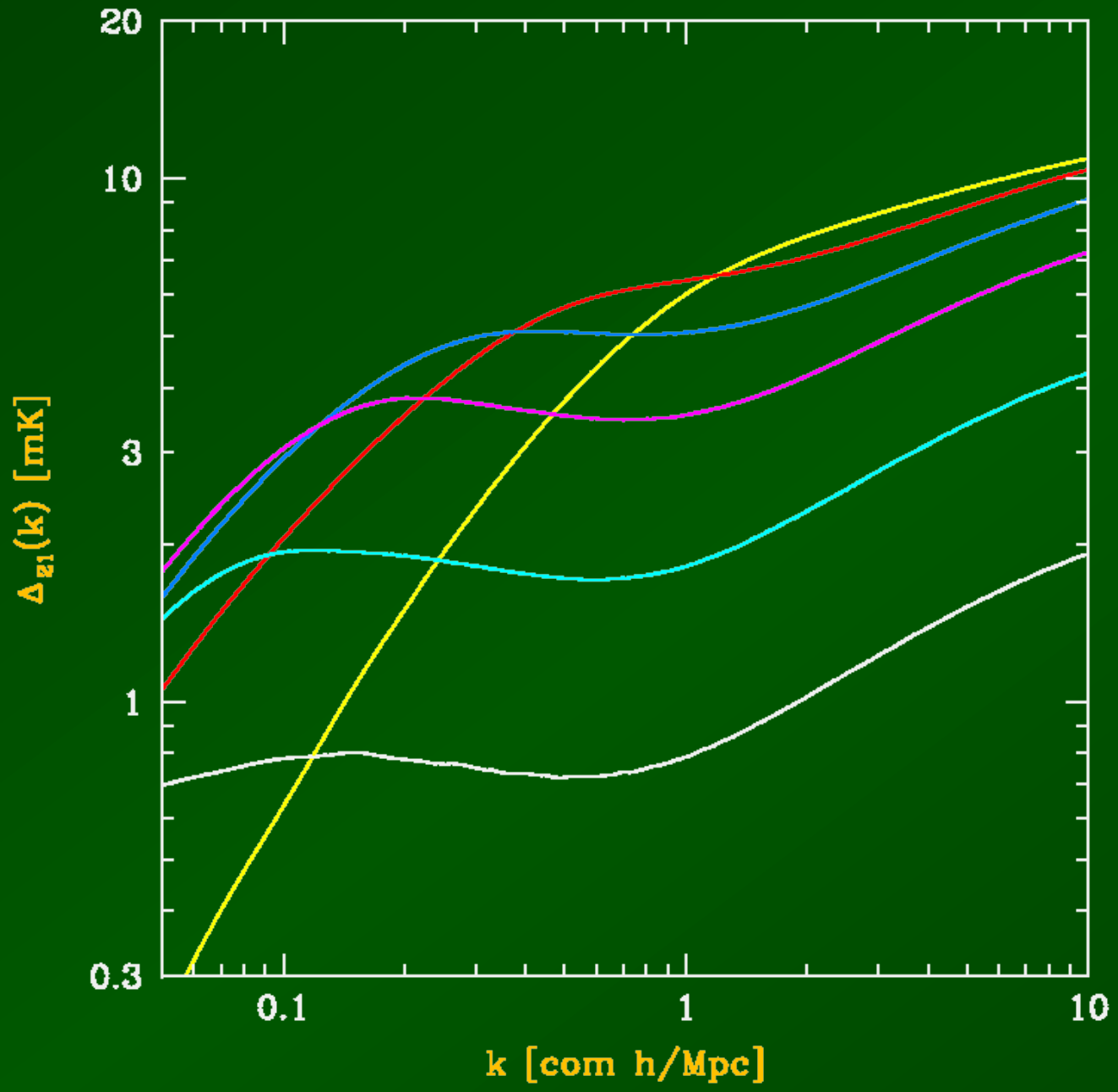


MWA, LOFAR

Zahn et al. 2007 simulation

RB 2007

21-cm Power Spectrum



$x_i = 0.1\,;\, z = 10.5$

$x_i = 0.3\,;\, z = 8.7$

$x_i = 0.5\,;\, z = 7.8$

$x_i = 0.7\,;\, z = 7.1$

$x_i = 0.9\,;\, z = 6.7$

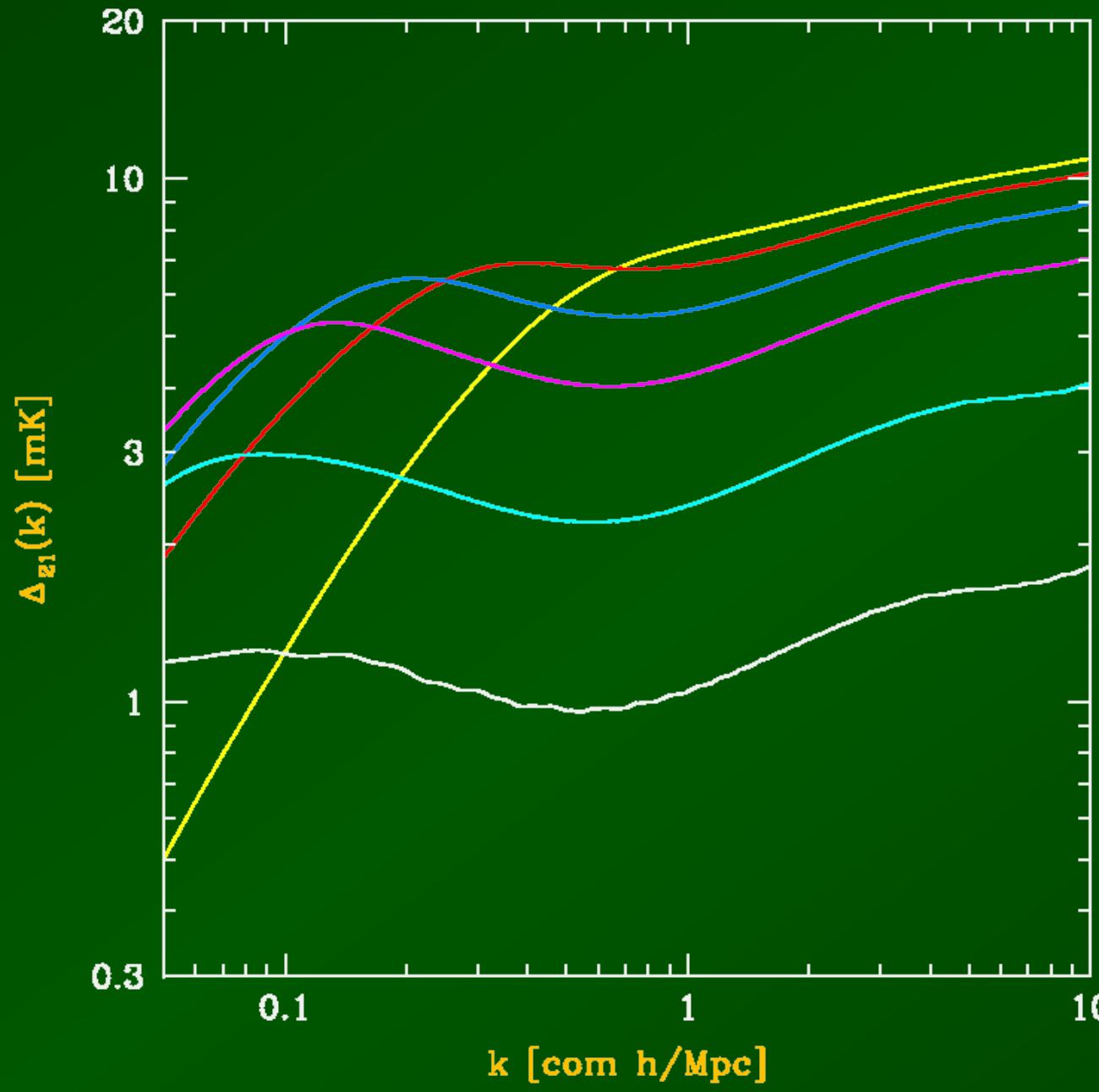
$x_i = 0.98\,;\, z = 6.5$

$V_c = 35$ km/s

$M_{\rm min} = 10^9\, M_\odot$

$\langle M \rangle = 3\times 10^9\, M_\odot$

21-cm Power Spectrum



$x_i = 0.1 \; ; \; z = 9.0$

$x_i = 0.3 \; ; \; z = 7.8$

$x_i = 0.5 \; ; \; z = 7.3$

$x_i = 0.7 \; ; \; z = 6.9$

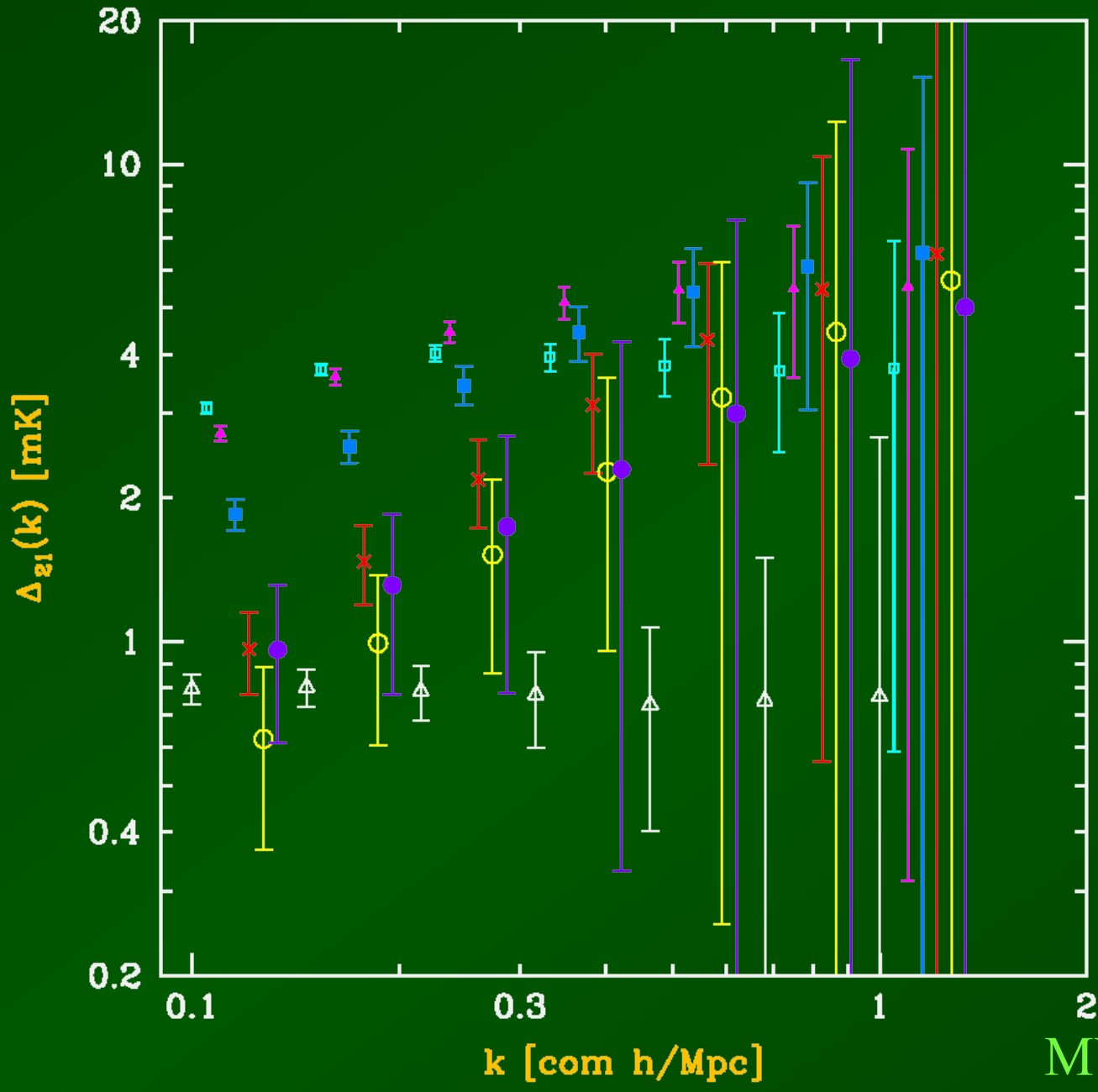
$x_i = 0.9 \; ; \; z = 6.6$

$x_i = 0.98 \; ; \; z = 6.5$

$V_c = 100$ km/s

$\zeta = \dfrac{\#\text{ ionizing photons}}{\text{hydrogen atom}}$

21-cm Power Spectrum



$V_c = 35$ km/s

$x_i = 0.04$; $z = 12.0$

$x_i = 0.08$; $z = 10.9$

$x_i = 0.15$; $z = 9.8$

$x_i = 0.27$; $z = 8.9$

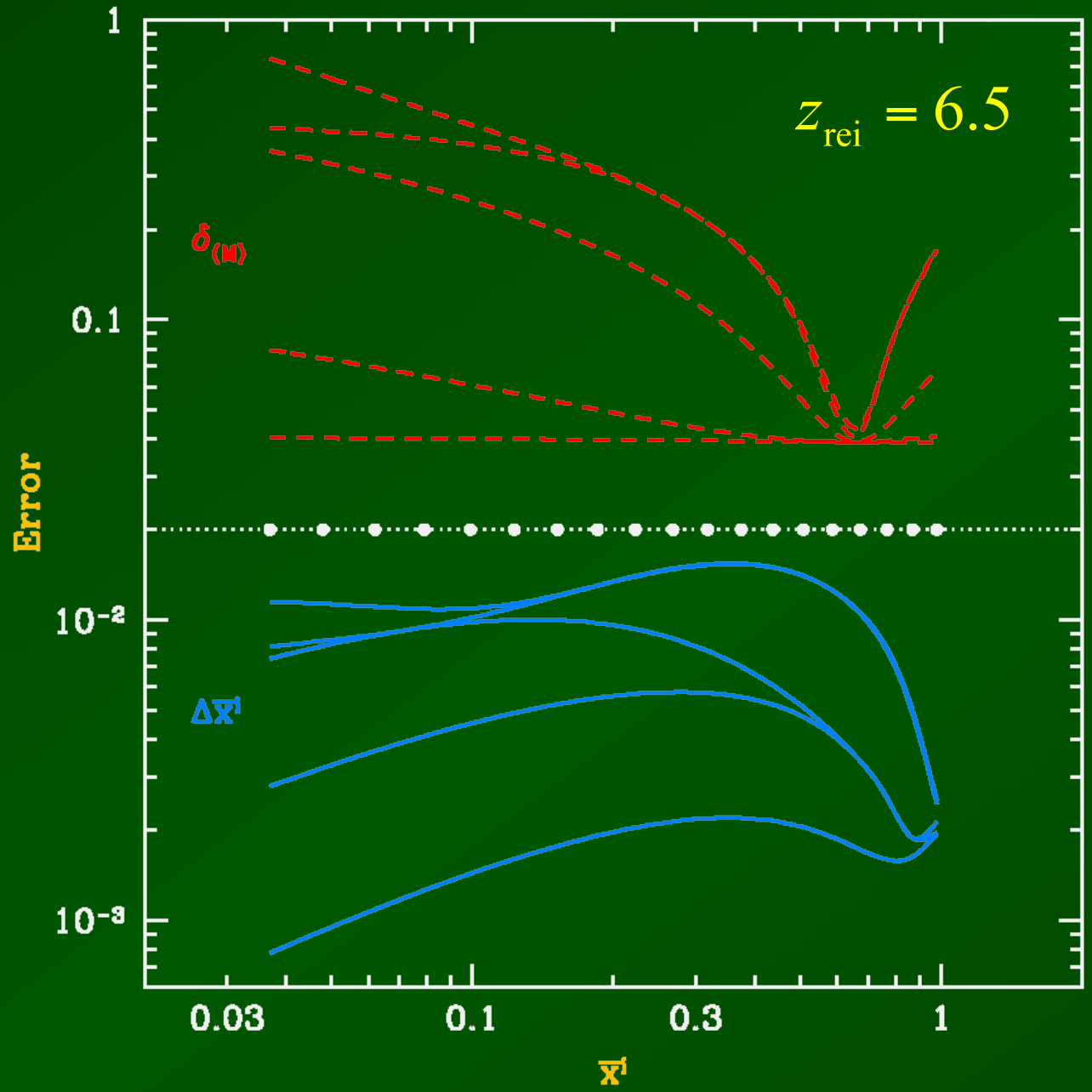
$x_i = 0.44$; $z = 8.0$

$x_i = 0.67$; $z = 7.3$

$x_i = 0.98$; $z = 6.5$

MWA (Lidz et al. 2008)

21-cm Power Spectrum



$z_{\rm rei} = 6.5$

$V_{\rm c}$ & ς

$V_{\rm c} = 35$ km/s

6-parameter model

5-parameter model

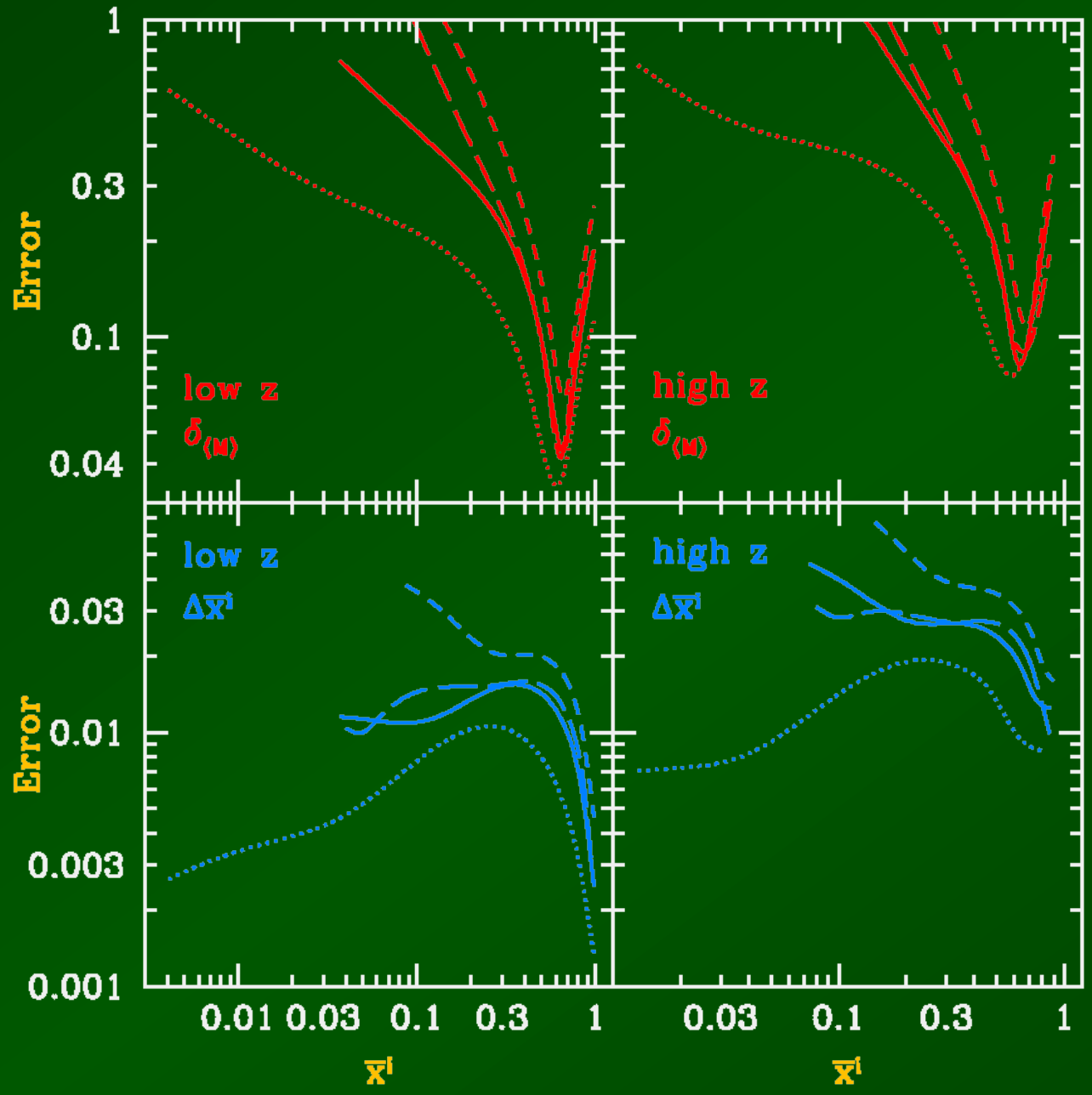
4-parameter model

3-parameter model

2-parameter model

RB 2008

21-cm Measurements



V_c & ς

$z_{rei} = 6.5$

$z_{rei} = 7.8$

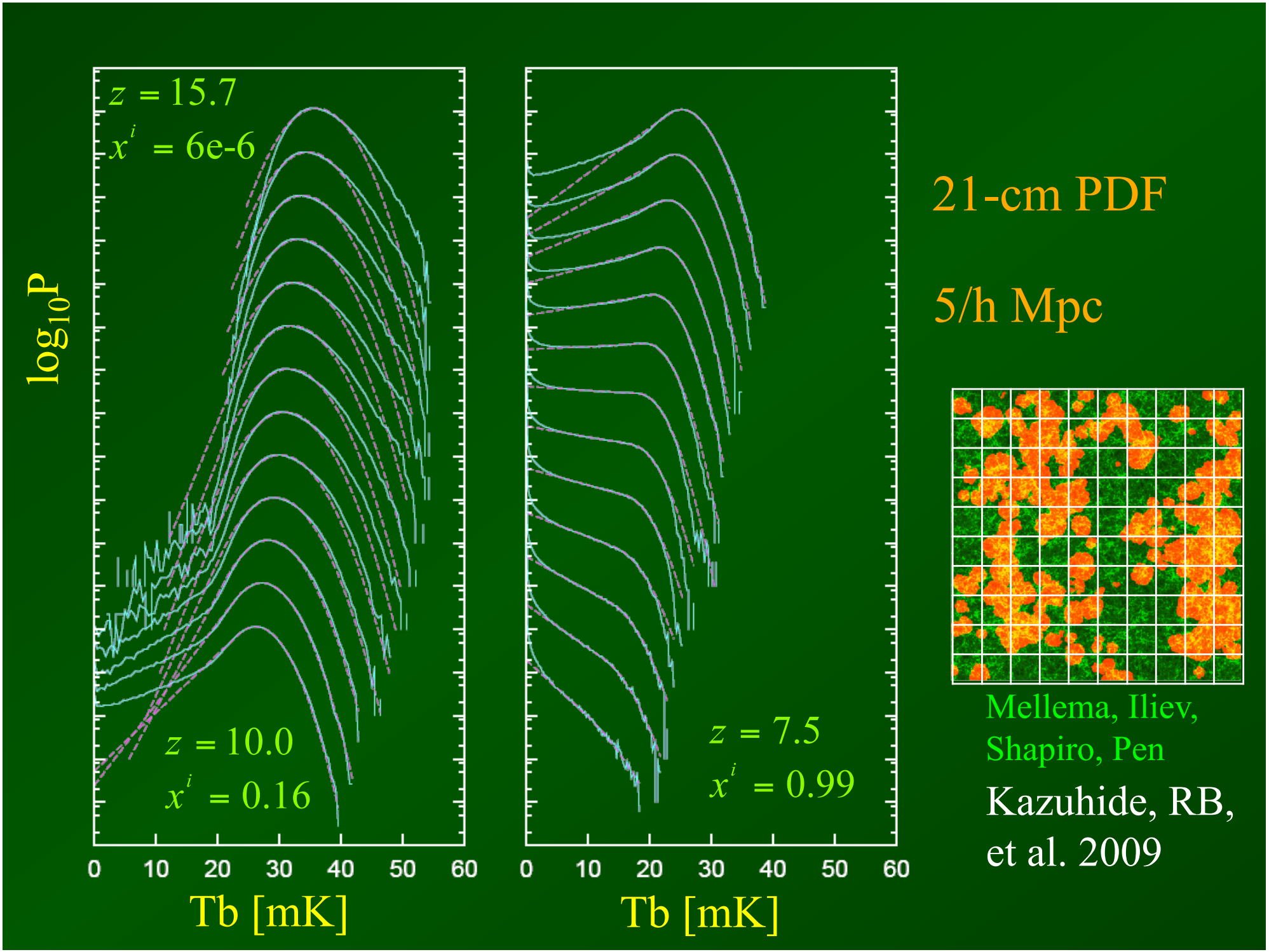
$V_c = 16.5$ km/s

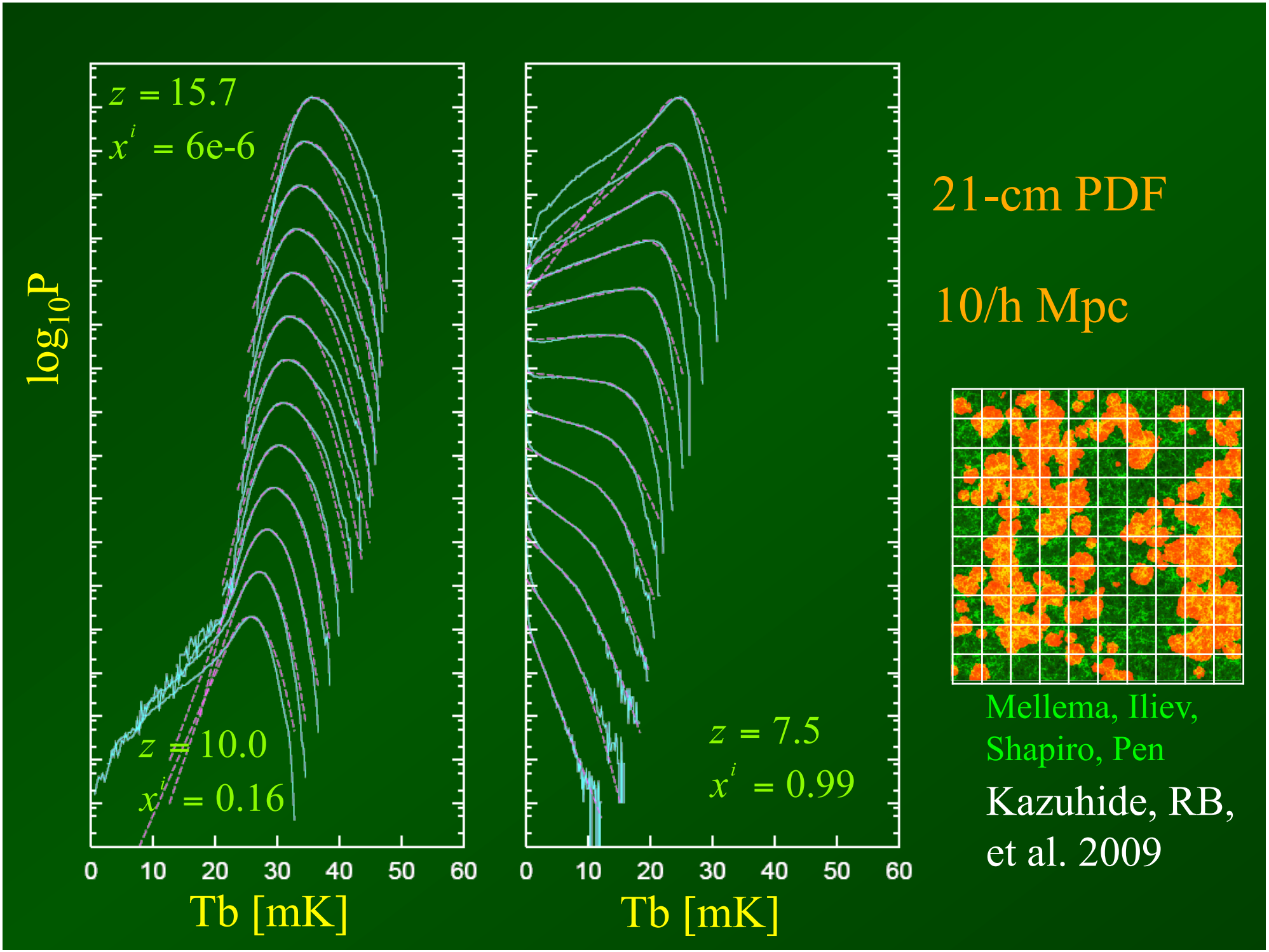
$V_c = 35$ km/s

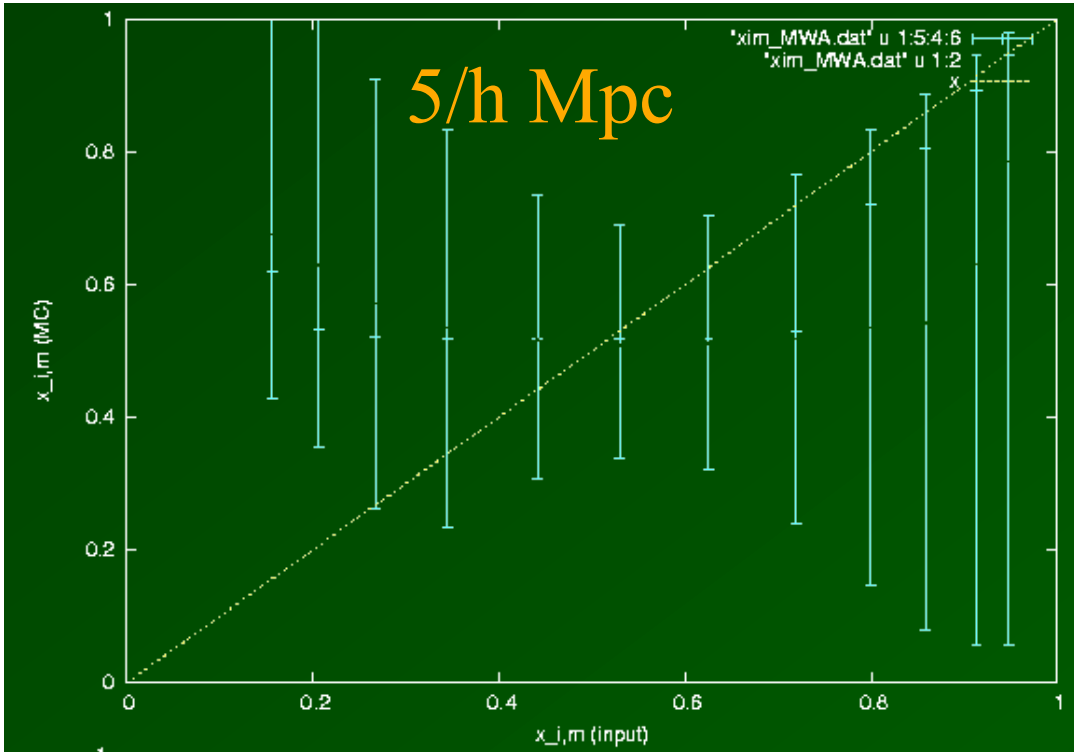
"Feedback"

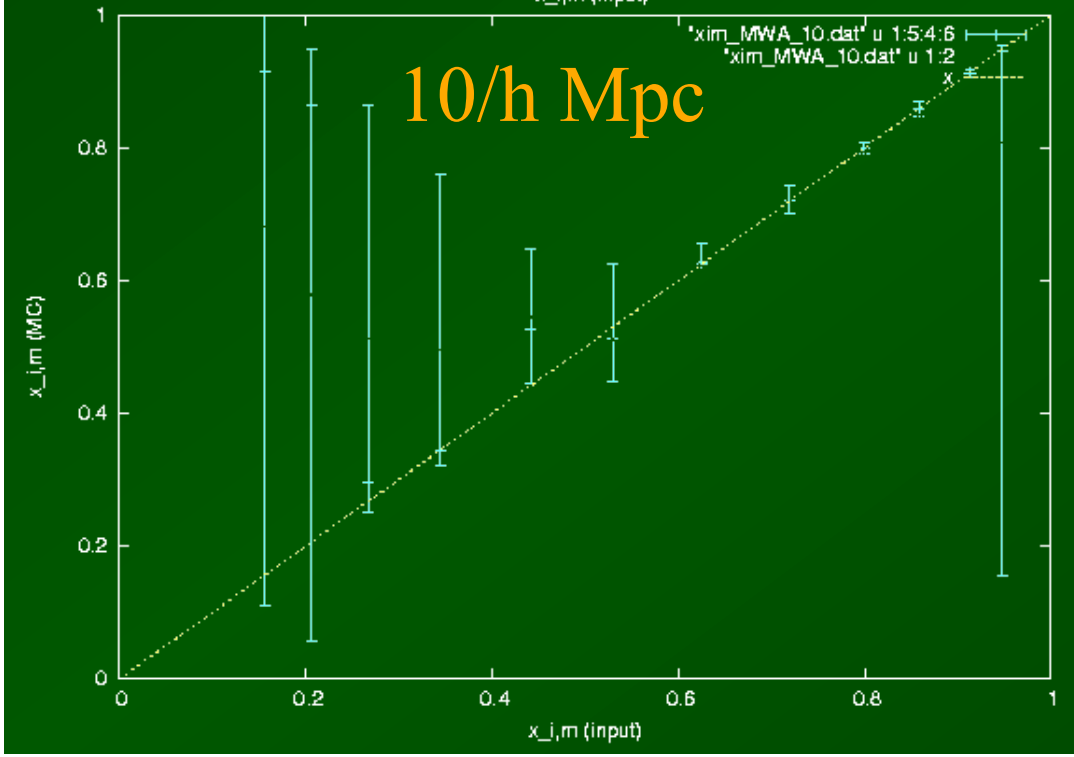
$V_c = 100$ km/s

RB 2008


z = 15.7
x^i = 6e-6
$\log_{10}$P
z = 10.0
x^i = 0.16
0 10 20 30 40 50 60
Tb [mK]
z = 7.5
x^i = 0.99
0 10 20 30 40 50 60
Tb [mK]
21-cm PDF
5/h Mpc
Mellema, Iliev,
Shapiro, Pen
Kazuhide, RB,
et al. 2009


z = 15.7
x^i = 6e-6
$\log_{10}$P
z = 10.0
x^i = 0.16
0 10 20 30 40 50 60
Tb [mK]
z = 7.5
x^i = 0.99
0 10 20 30 40 50 60
Tb [mK]
21-cm PDF
10/h Mpc
Mellema, Iliev, Shapiro, Pen
Kazuhide, RB, et al. 2009





Measured vs. Real

$x^i : 0 \rightarrow 1$

MWA, $z = 8,1 - \mathrm{yr}$:

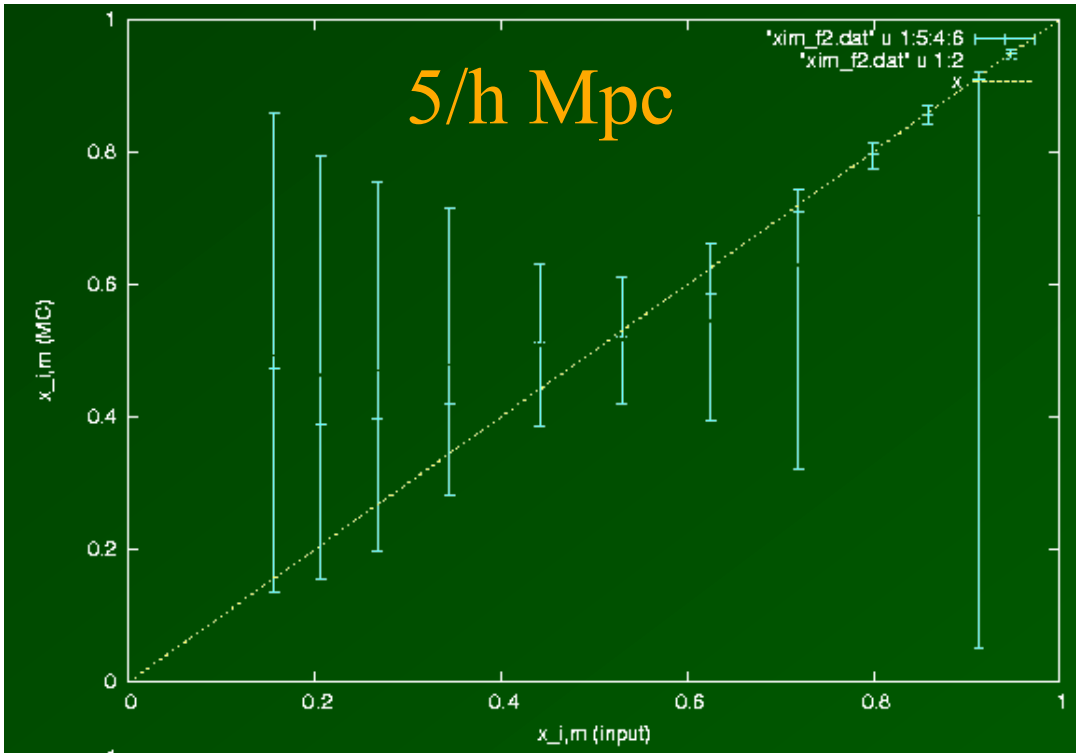
$5/h$:

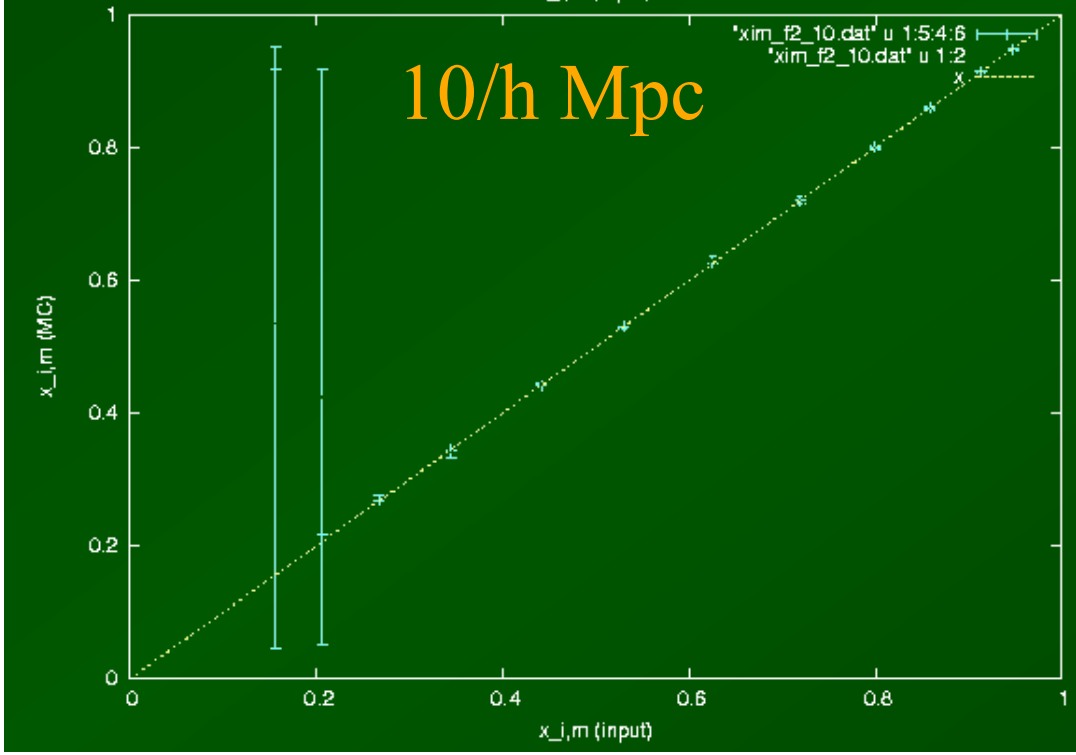
$\Delta T_N = 120\,\mathrm{mK}$, #=5.5e6

$10/h$:

$\Delta T_N = 20\,\mathrm{mK}$, #=7e5

Kazuhide, RB, et al. 2009





Measured vs. Real

$x^i : 0 \rightarrow 1$

MWA, $z = 8,4 - \mathrm{yr}$:

$5/h$:

$\Delta T_N = 60\,\mathrm{mK}$, #=5.5e6

$10/h$:

$\Delta T_N = 10\,\mathrm{mK}$, #=7e5

Kazuhide, RB, et al. 2009

Foregrounds

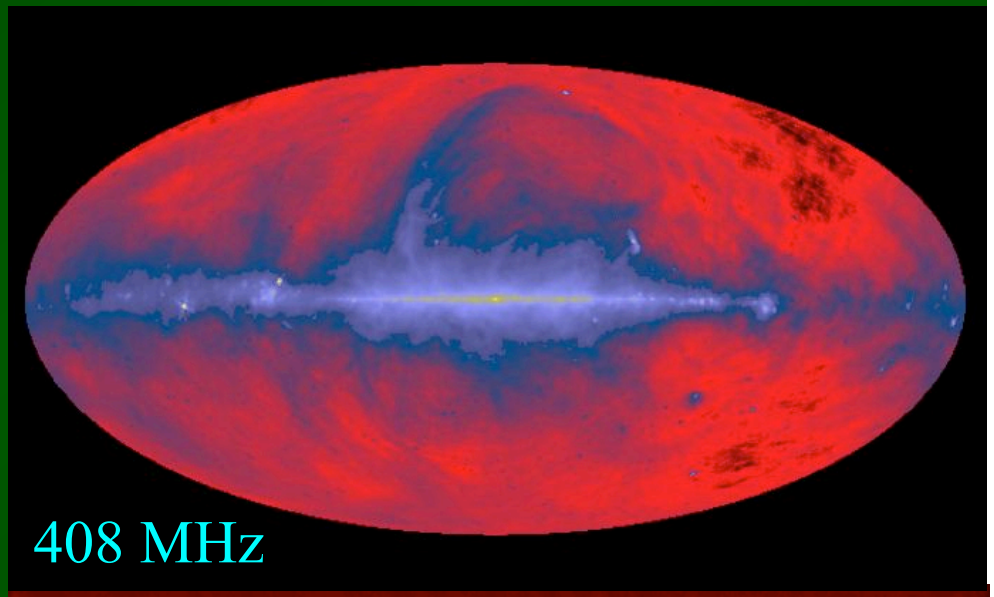
RFI: Radio Frequency Interference

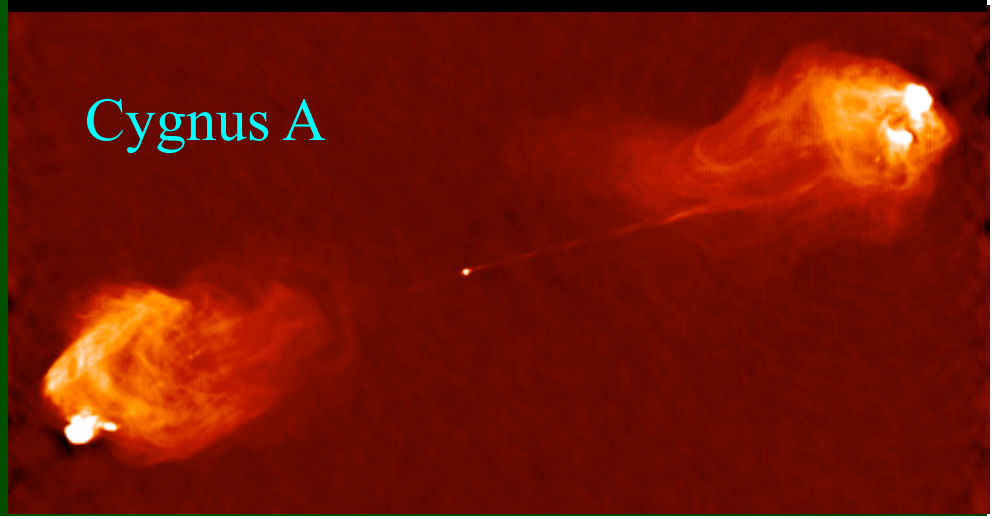
Ionosphere: Distortion

ø 80 à 200 km

Galactic Synchrotron Emission

$$T_{\text{sky}} \sim 180 \left(\frac{\nu}{180\,\text{MHz}} \right)^{-2.6} \text{K}$$





Extragalactic Radio Sources

Experiments

$t_{\rm int} \sim 100\,{\rm hr}, \Delta\nu \sim 1\,{\rm MHz} \Rightarrow 1\,{\rm mK}$

$D \sim 1\ {\rm km} \Rightarrow \Delta\theta \sim 4'$

GMRT 21CMA: 21 Centimeter Array

India China ~ 10,000 Antenna Interferometer

MWA: The Mileura Wide-field Array

Australia, MIT, Harvard

LOFAR: The Low Frequency Array

Holland + Europe

SKA: The Square Kilometer Array

Summary:

- Early Signals
  - The first galaxies (Lyα radiation: z=20)
  - Reionization complex early on
- Cosmic Reionization
  - x_i and <M> with 21-cm P(k)
  - x_i (late) with 21-cm PDF