21-cm emission from the era of the first galaxies

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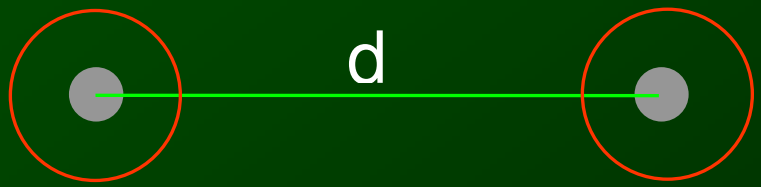
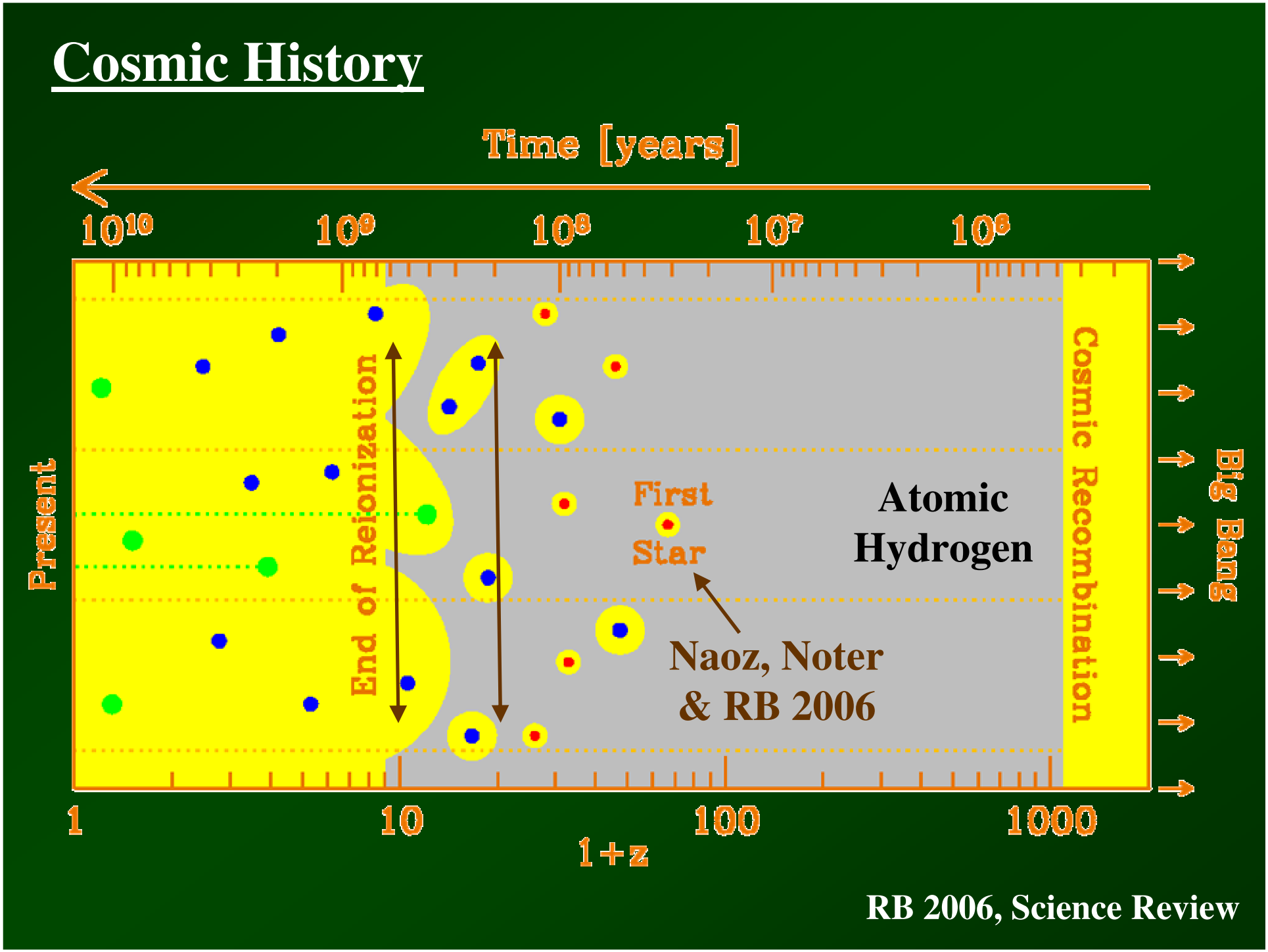
רנן ברקנא

TEL AVIV UNIVERSITY

אוניברסיטת תל-אביב

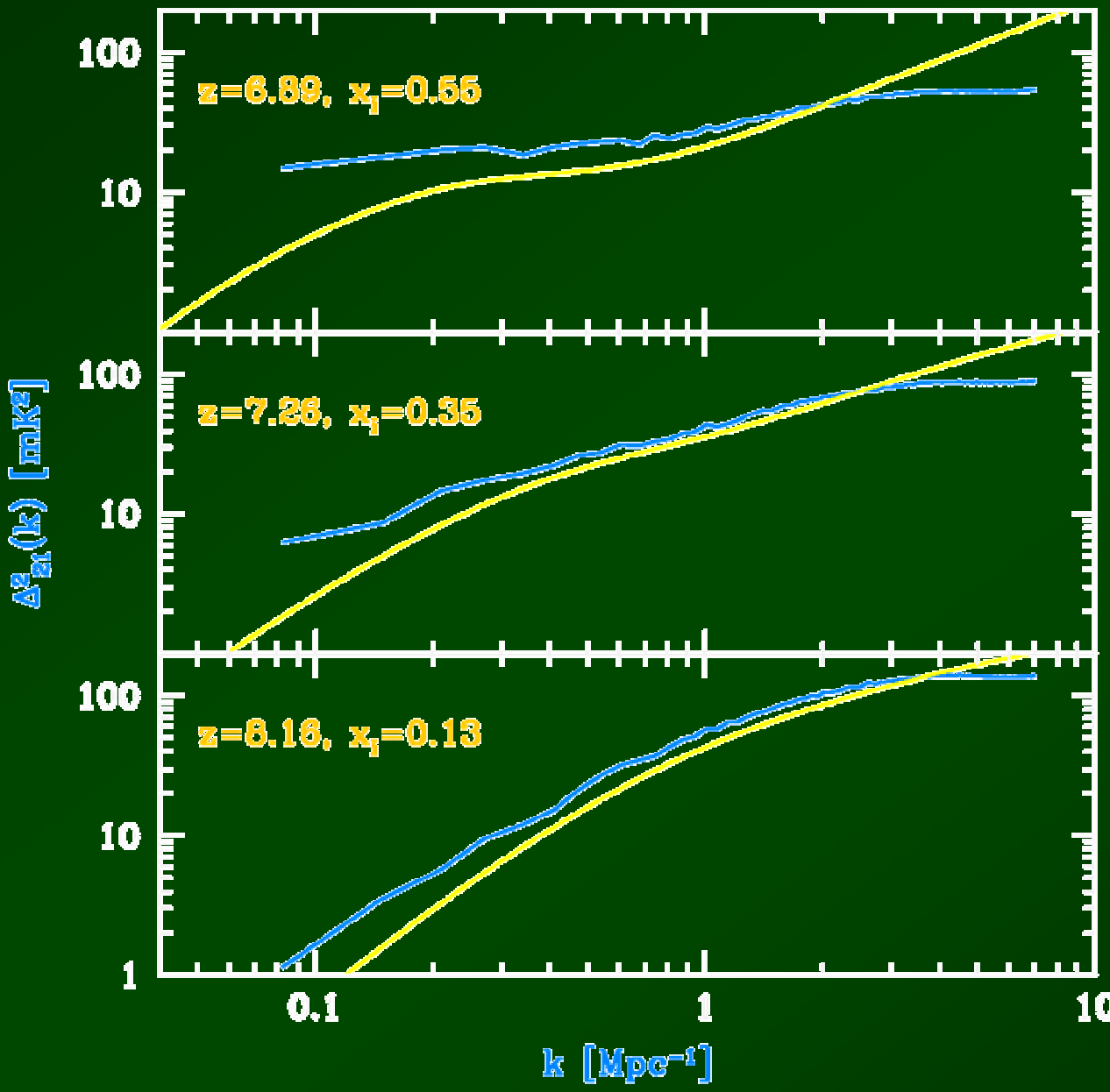


Cosmic History



RB 2006, Science Review

21-cm Correlation Function



$$T_b = 25\,\tilde{N}\,\sqrt{\frac{1+z}{8}}\ \text{mK}$$

$$\tilde{N} = x_H\,(1+\hat{\imath})$$

$$4\pi^2\Delta^2_{21}(k) = \frac{k^3P(k)}{2\pi^2}$$

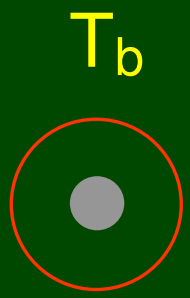
Zahn et al. 2006 simulation

RB 2007

(Furlanetto et al. 2004)

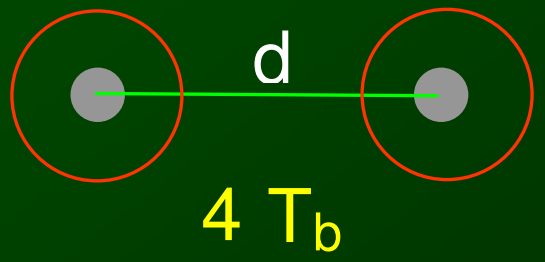
Non-Gaussianity:
Furlanetto et al. 2004
Bharadwaj & Ali 2005
Saiyad-Ali et al. 2006
Wyithe & Morales 2007

Numerical PDF:
Ciardi & Madau 2003
Mellema et al. 2006



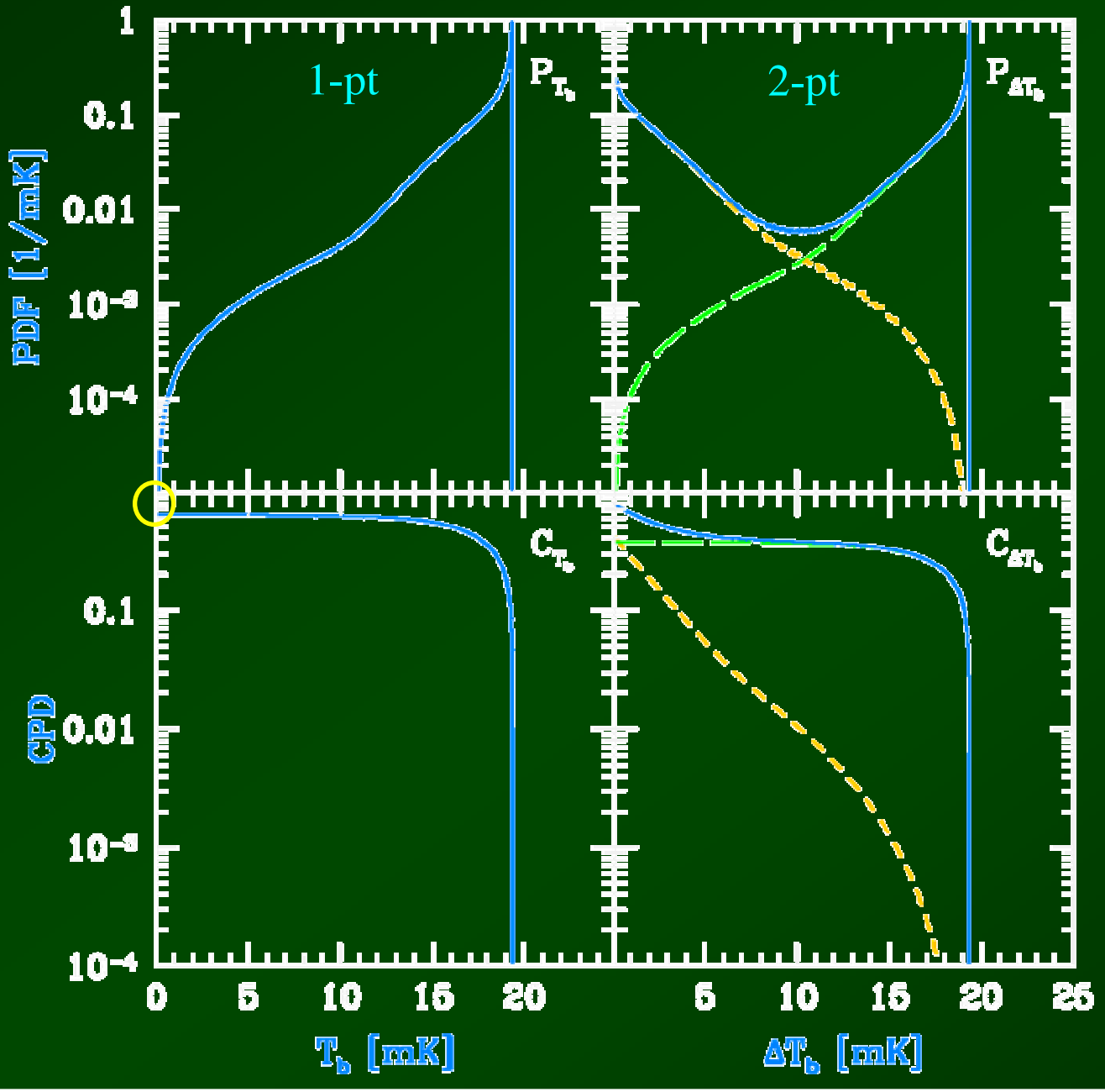
The Difference PDF

RB & Loeb 2007



Variance => Correlation Fn

The Difference PDF



$\tilde{N} = x_H (1 + \hat{\imath})$

$\tilde{N}_{max}$

$P(x_i = 1)$

Both neutral

One neutral

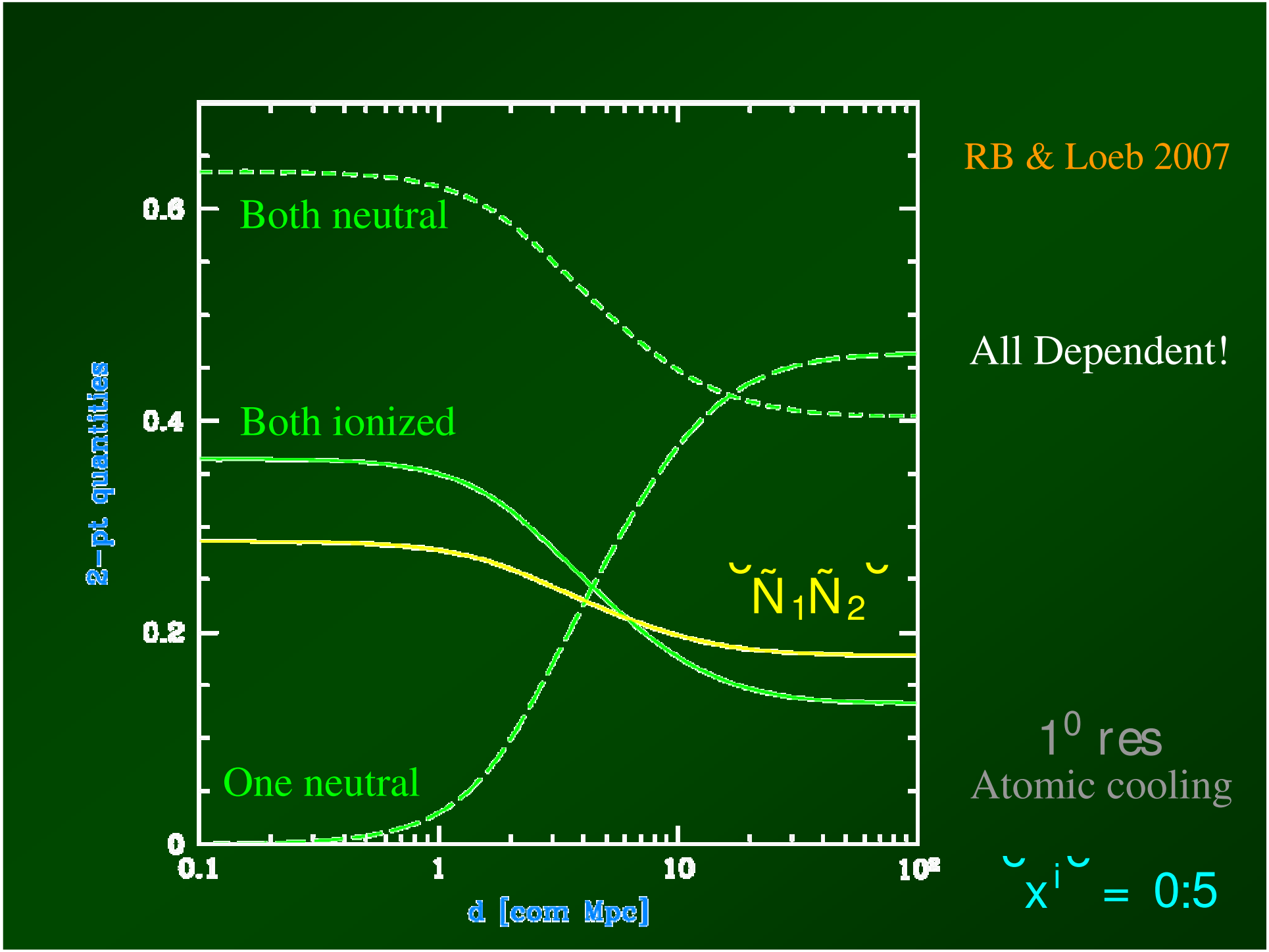
Both ionized

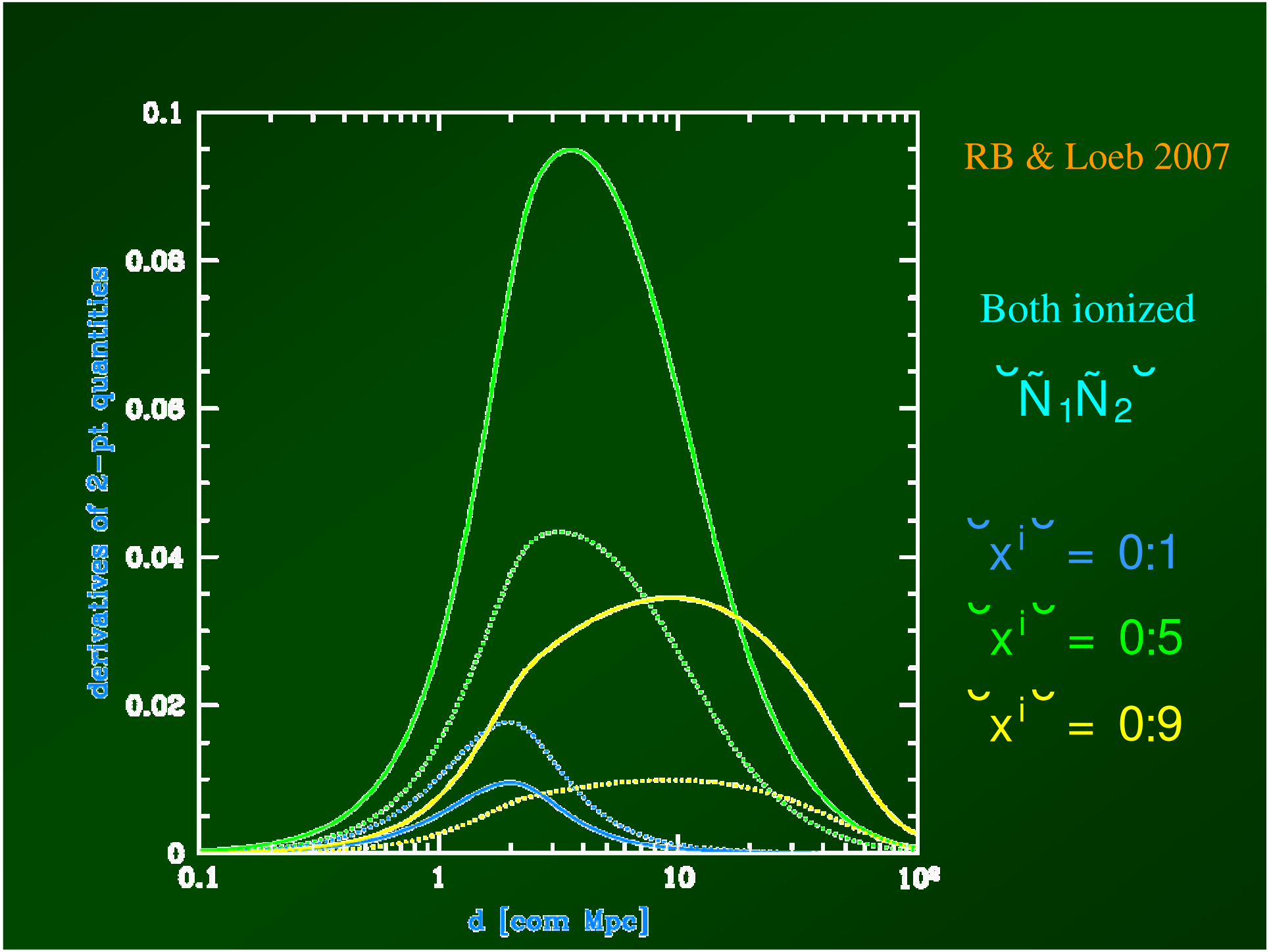
1^0 res

Atomic cooling

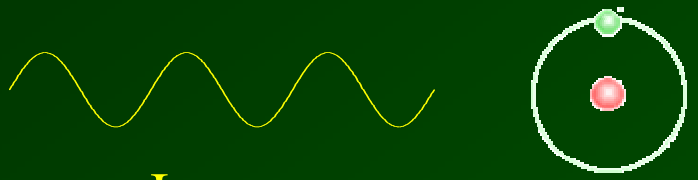
d = 10 Mpc

$\overset{\circ}{x}_i \overset{\circ}{} = 0{:}5$


RB & Loeb 2007
Both neutral
Both ionized
One neutral
$\tilde{N}_1\tilde{N}_2$
All Dependent!
1^0 res
Atomic cooling
$x^i = 0{:}5$
2−pt quantities
0
0.2
0.4
0.6
0.1
1
10
10^2
d [com Mpc]

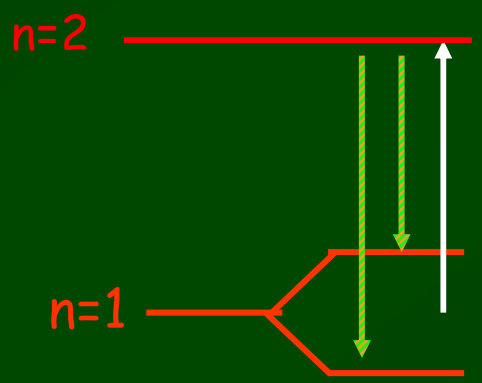

0.1
0.08
0.06
0.04
0.02
0
derivatives of 2−pt quantities
0.1
1
10
10^2
d [com Mpc]
RB & Loeb 2007
Both ionized
⟨Ñ1Ñ2⟩
⟨x^i⟩ = 0:1
⟨x^i⟩ = 0:5
⟨x^i⟩ = 0:9

The Lyman-α flux: effect on T_S



Lyα

Wouthuysen 1952
Field 1958



T_S ! T_k

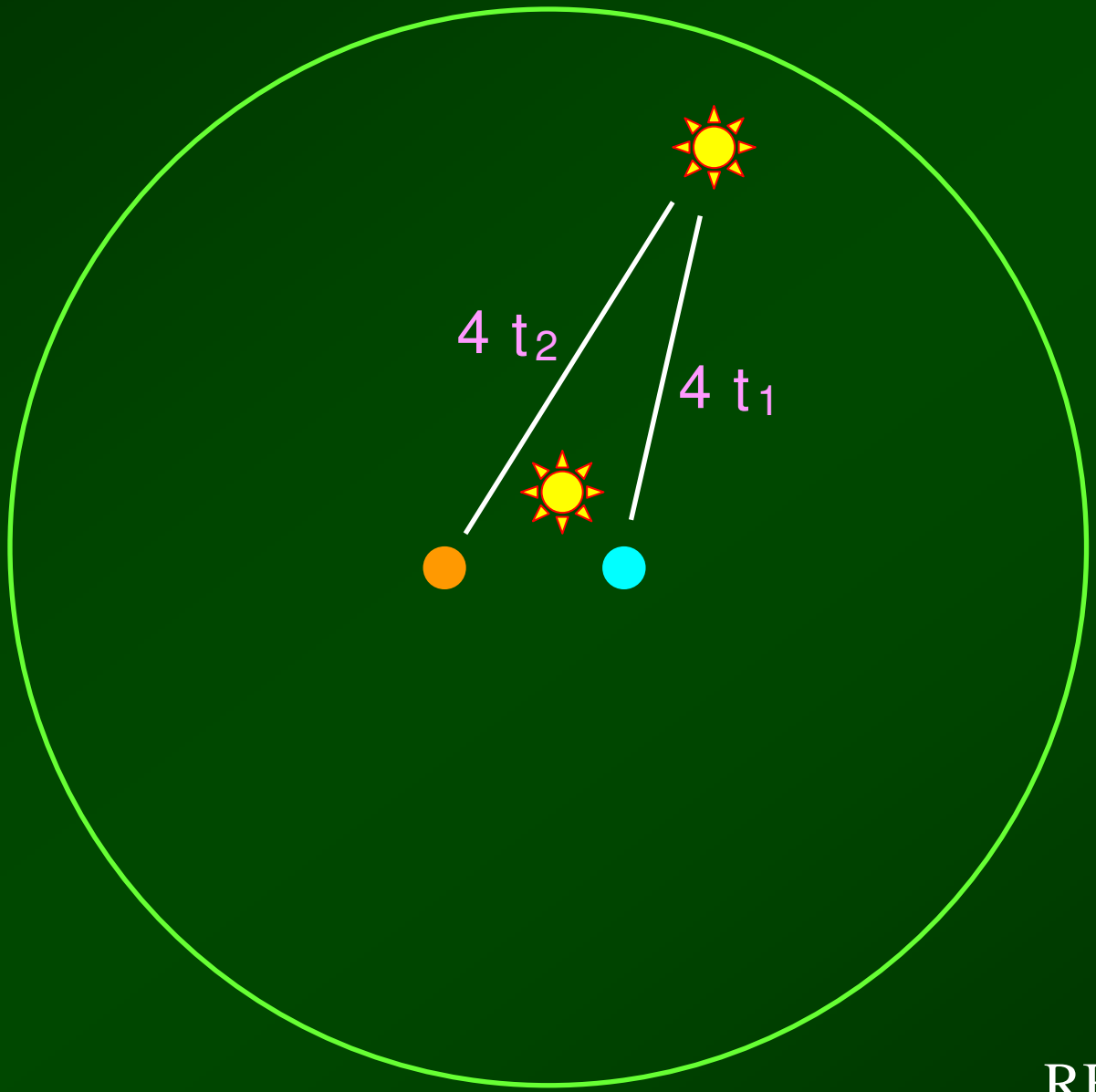
Lyë = 10:2 eV

11 eV ⟩ 10:2 eV

Biased Density Fluctuations

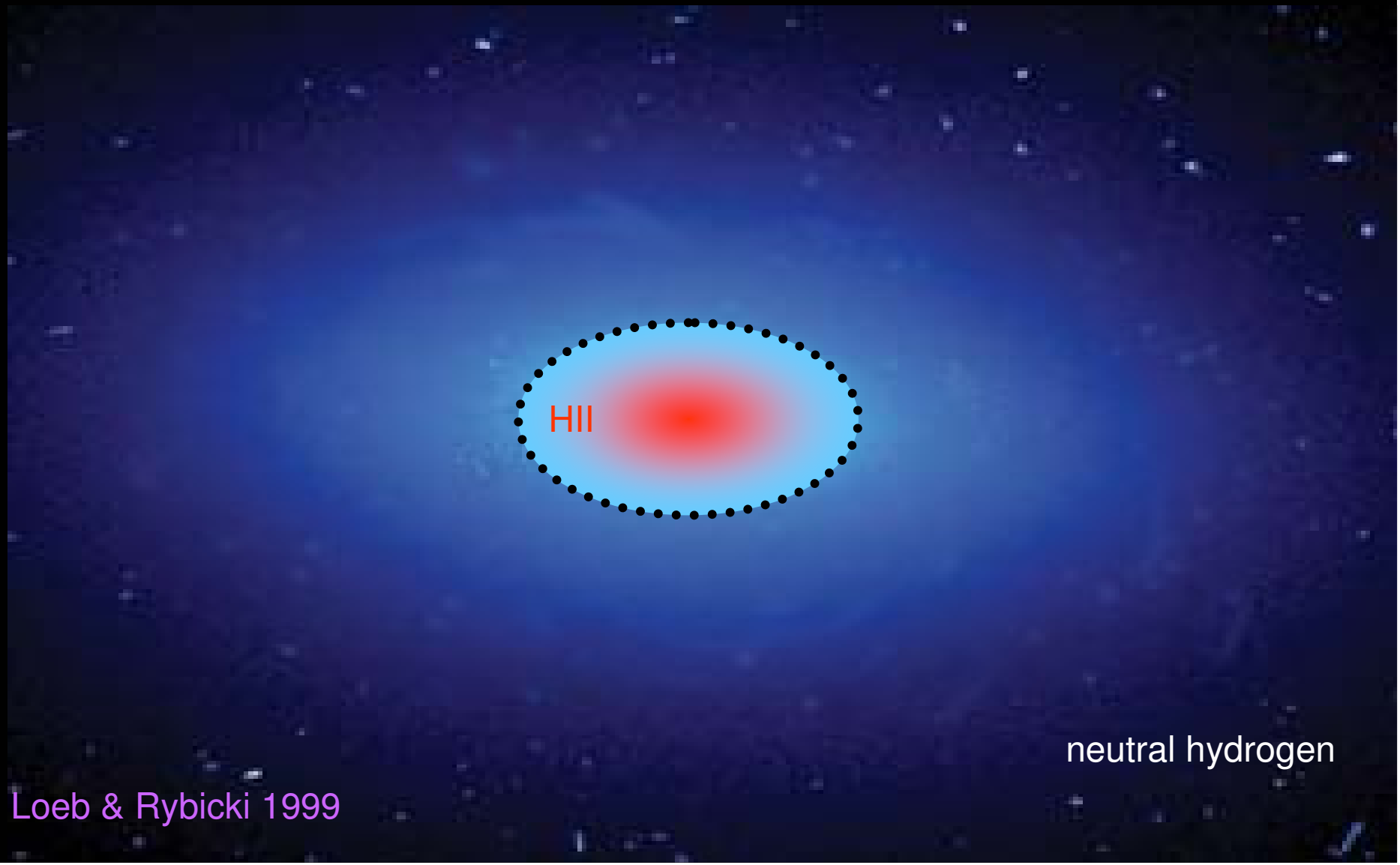
RB & Loeb 2005

Correlated Poisson Fluctuations



RB & Loeb 2005

Ly-α Scattering



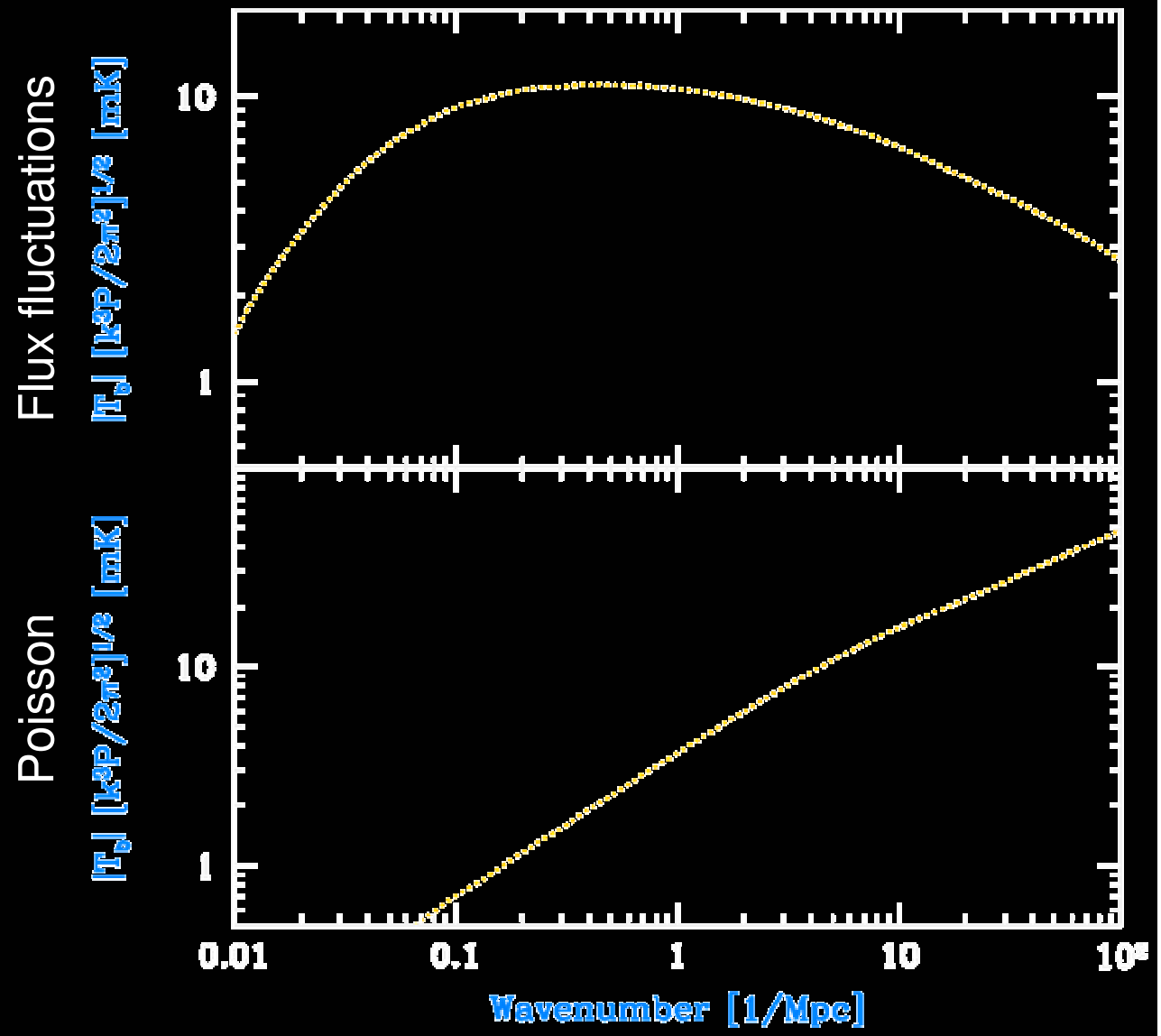
Loeb & Rybicki 1999

21-cm power spectrum

RB & Loeb 2004

z=20

Minimum mass for
Atomic cooling



Naoz & RB 2007

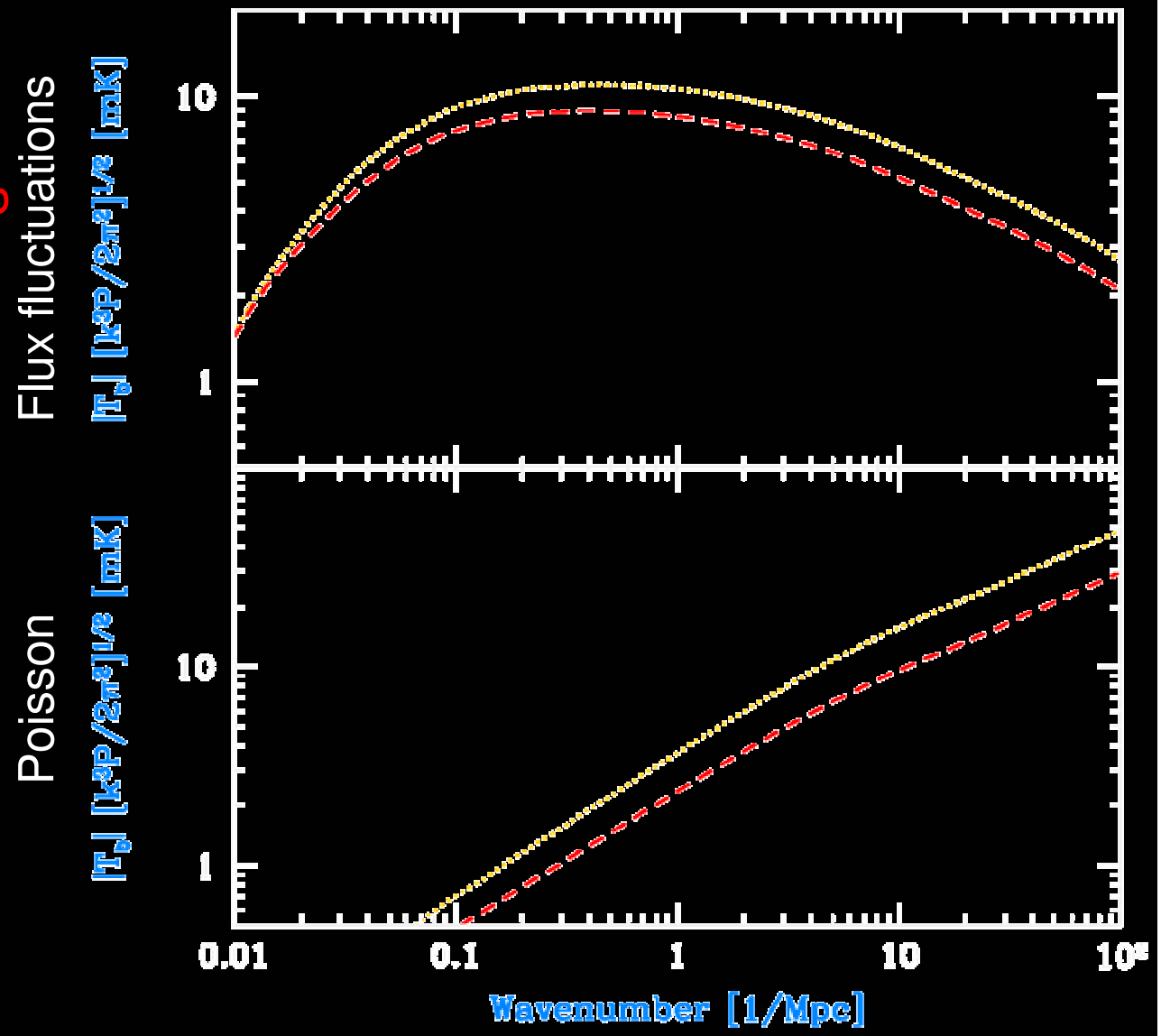
21-cm power spectrum

RB & Loeb 2004

+ Pritchard & Furlanetto 2006; Hirata 2006

z=20

Minimum mass for Atomic cooling



Naoz & RB 2007

21-cm power spectrum

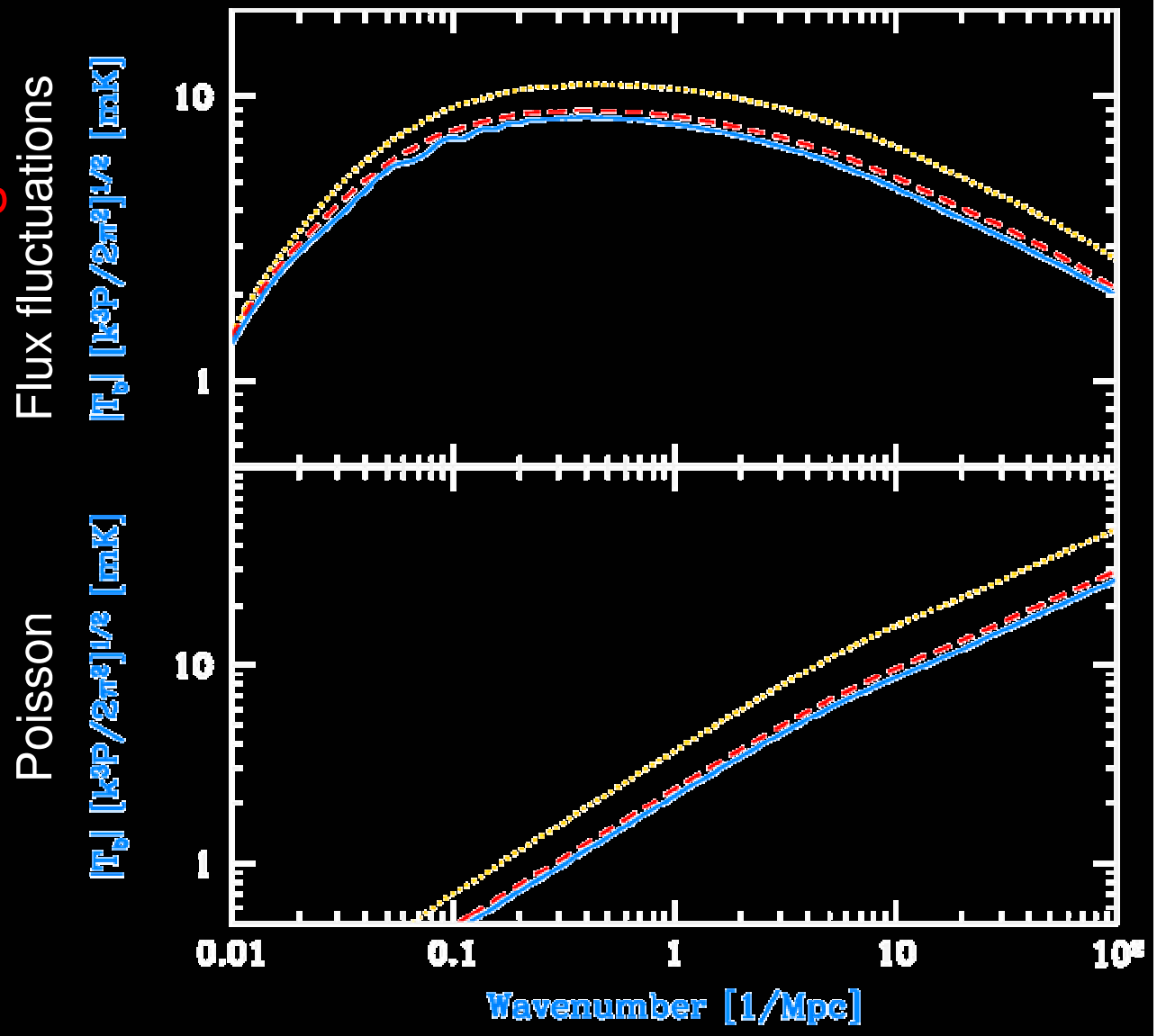
RB & Loeb 2004

+ Pritchard & Furlanetto 2006; Hirata 2006

+ Naoz & RB 2005

z=20

Minimum mass for Atomic cooling



Naoz & RB 2007

21-cm power spectrum

RB & Loeb 2004

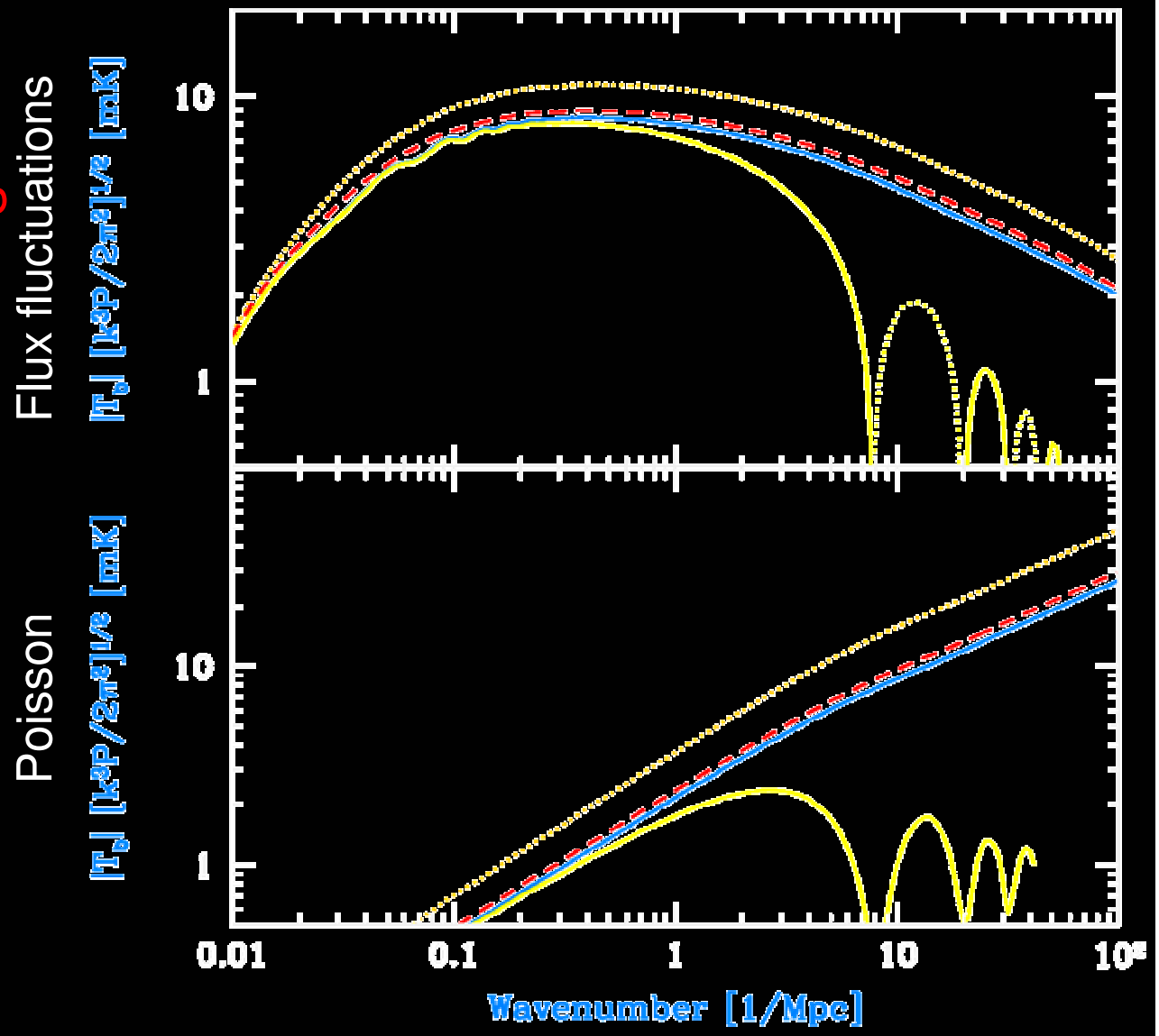
+ Pritchard & Furlanetto 2006; Hirata 2006

+ Naoz & RB 2005

+ HII Cutoff

z=20

Minimum mass for Atomic cooling



Naoz & RB 2007

21-cm power spectrum

RB & Loeb 2004

+ Pritchard & Furlanetto 2006; Hirata 2006

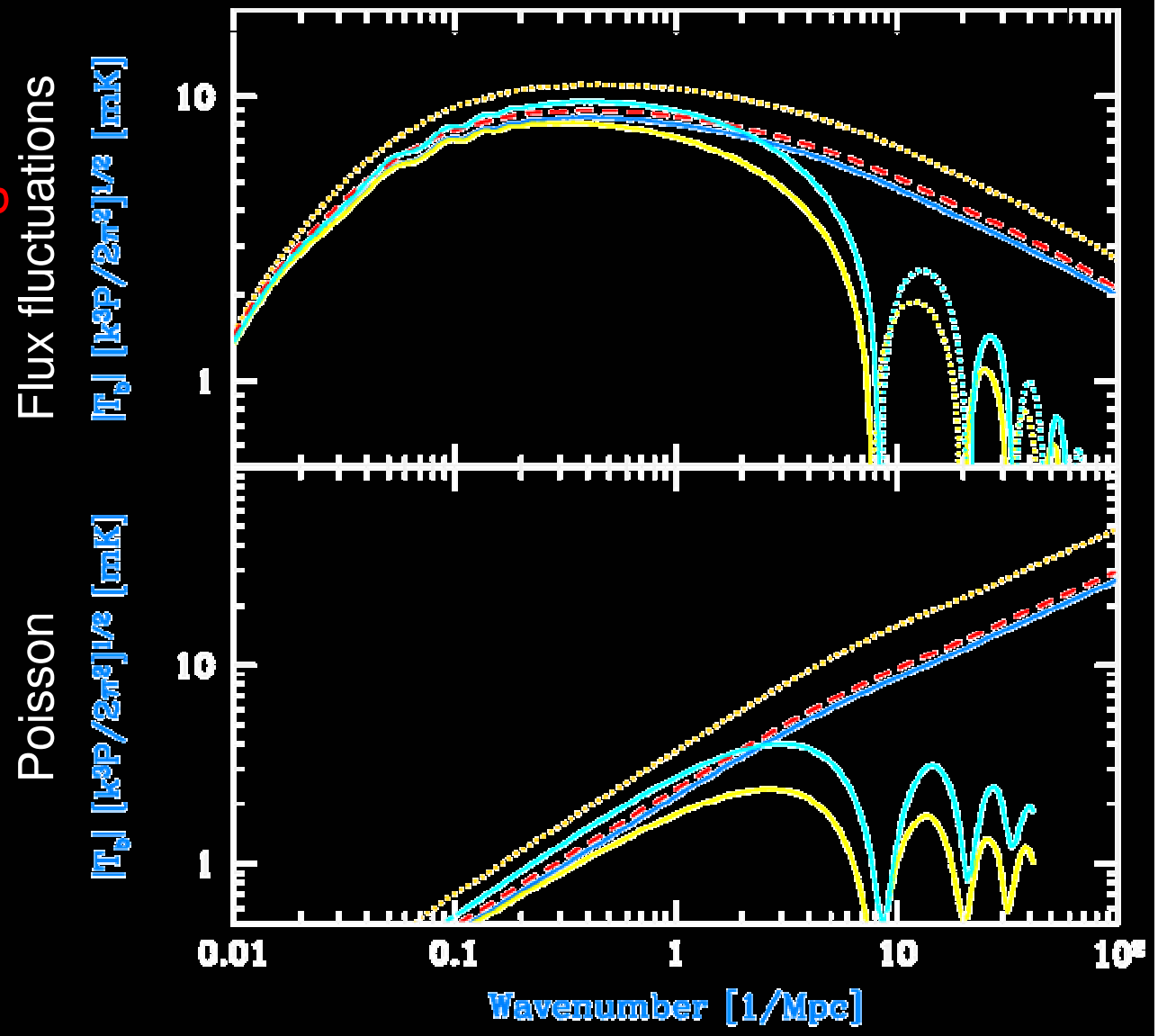
+ Naoz & RB 2005

+ HII Cutoff

+ scattering

z=20

Minimum mass for Atomic cooling



Naoz & RB 2007

21-cm power spectrum

RB & Loeb 2004

+ Pritchard & Furlanetto 2006; Hirata 2006

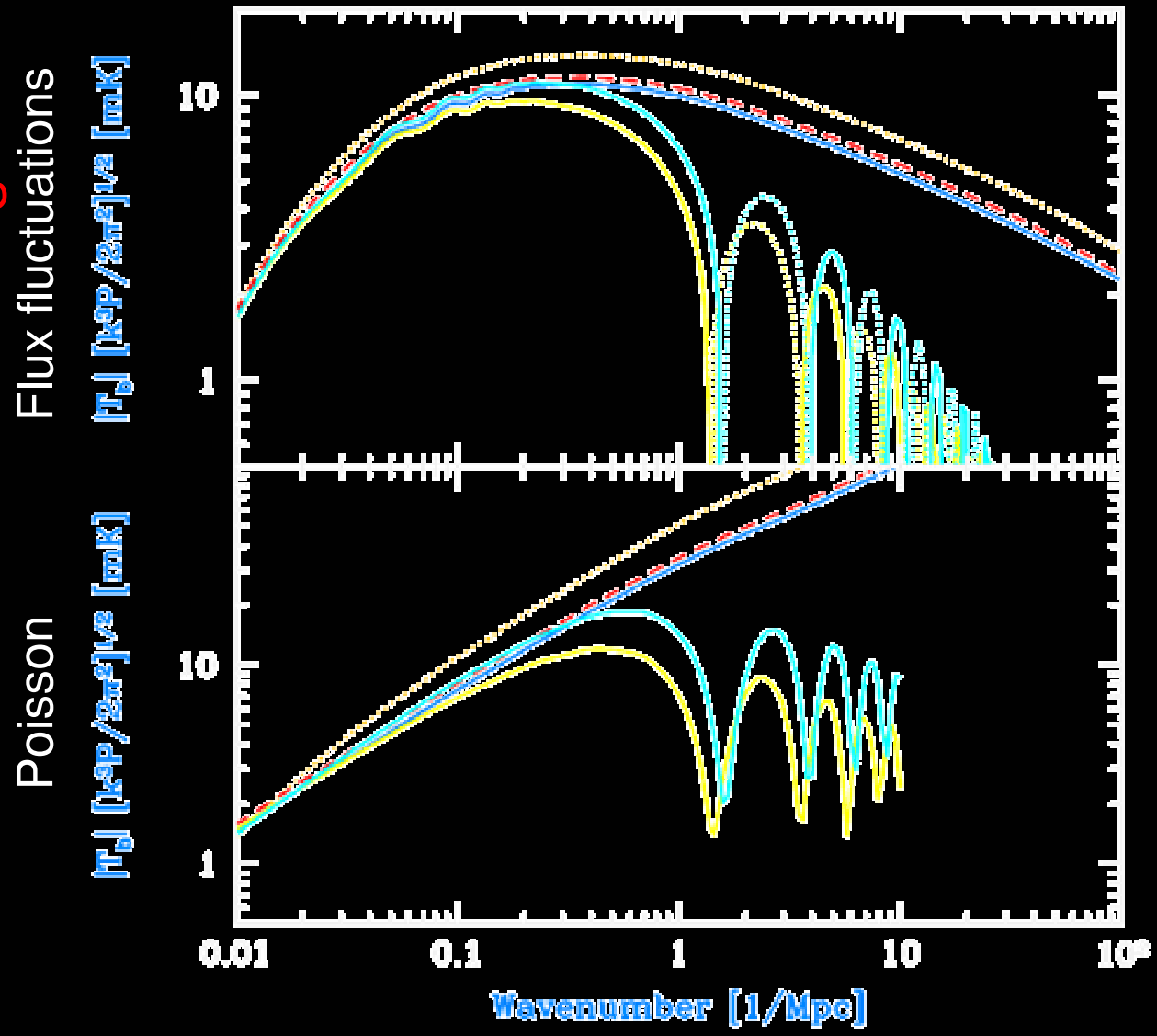
+ Naoz & RB 2005

+ HII Cutoff

+ scattering

z=20

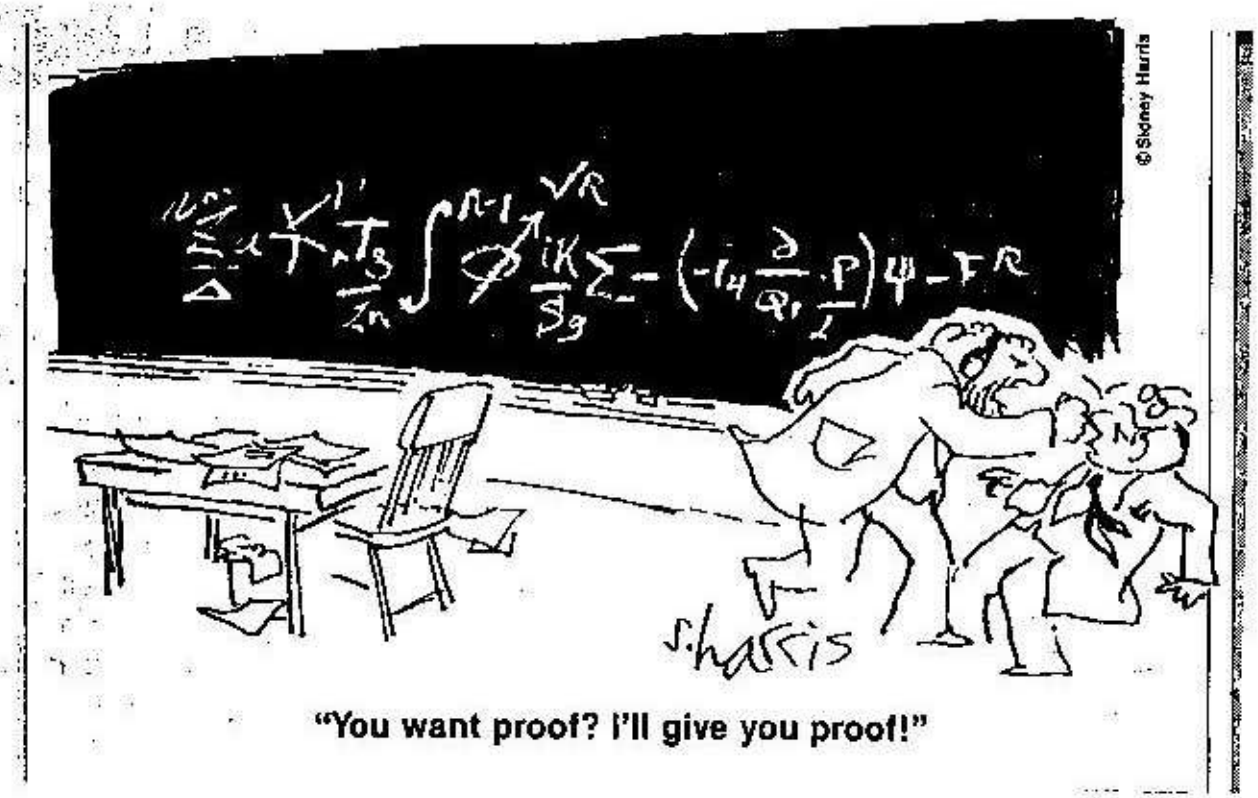
10 x Minimum mass for Atomic cooling



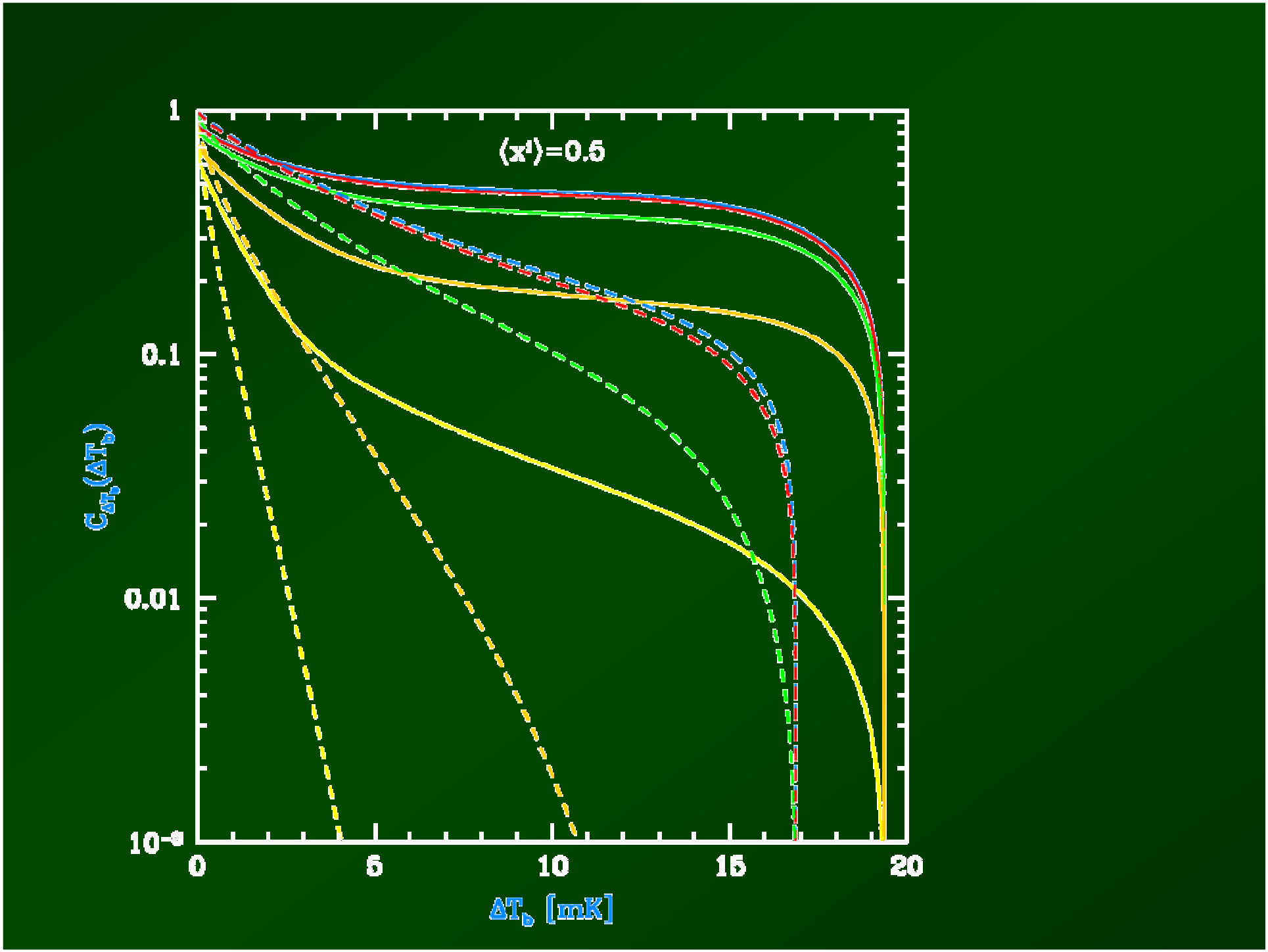
Naoz & RB 2007

Summary:

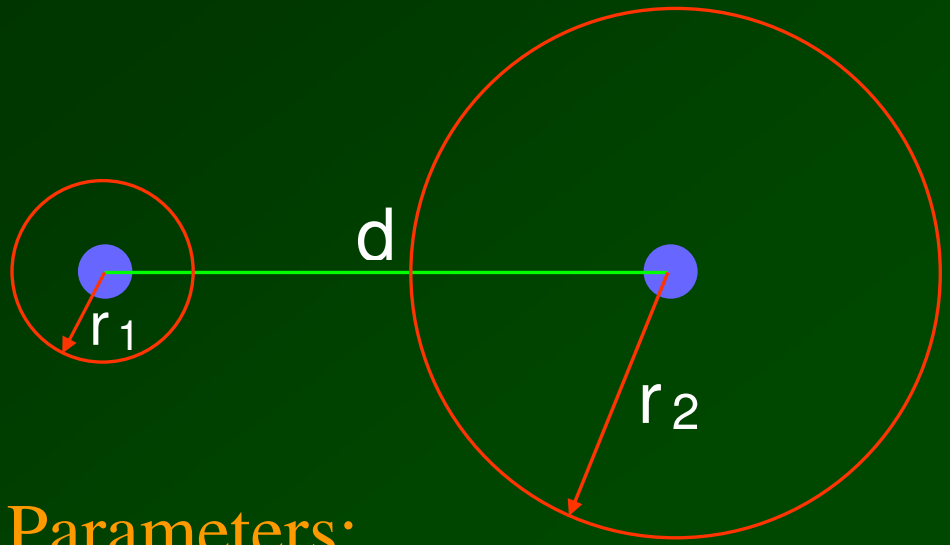
- Reionization: The Difference PDF of 21-cm fluctuations
  - Non-Gaussian => more information.
  - Separately measure ionization correlations.
- Ly-α coupling: 21-cm fluctuations:
  - HII region: cutoff
  - Ly-α scattering: enhancement
  - Observational signatures of early galaxies

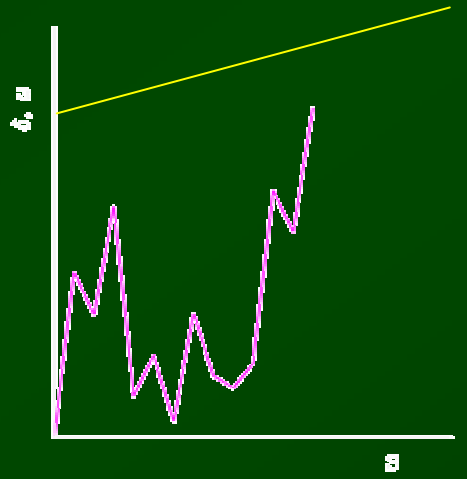


"You want proof? I'll give you proof!"


⟨x'⟩=0.5
1
0.1
0.01
10⁻³
0
5
10
15
20
ΔT_b [mK]
C_ΔT_b(ΔT_b)

Ionization Correlation Function

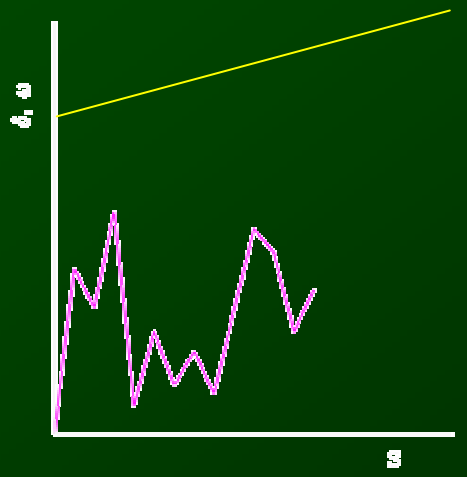


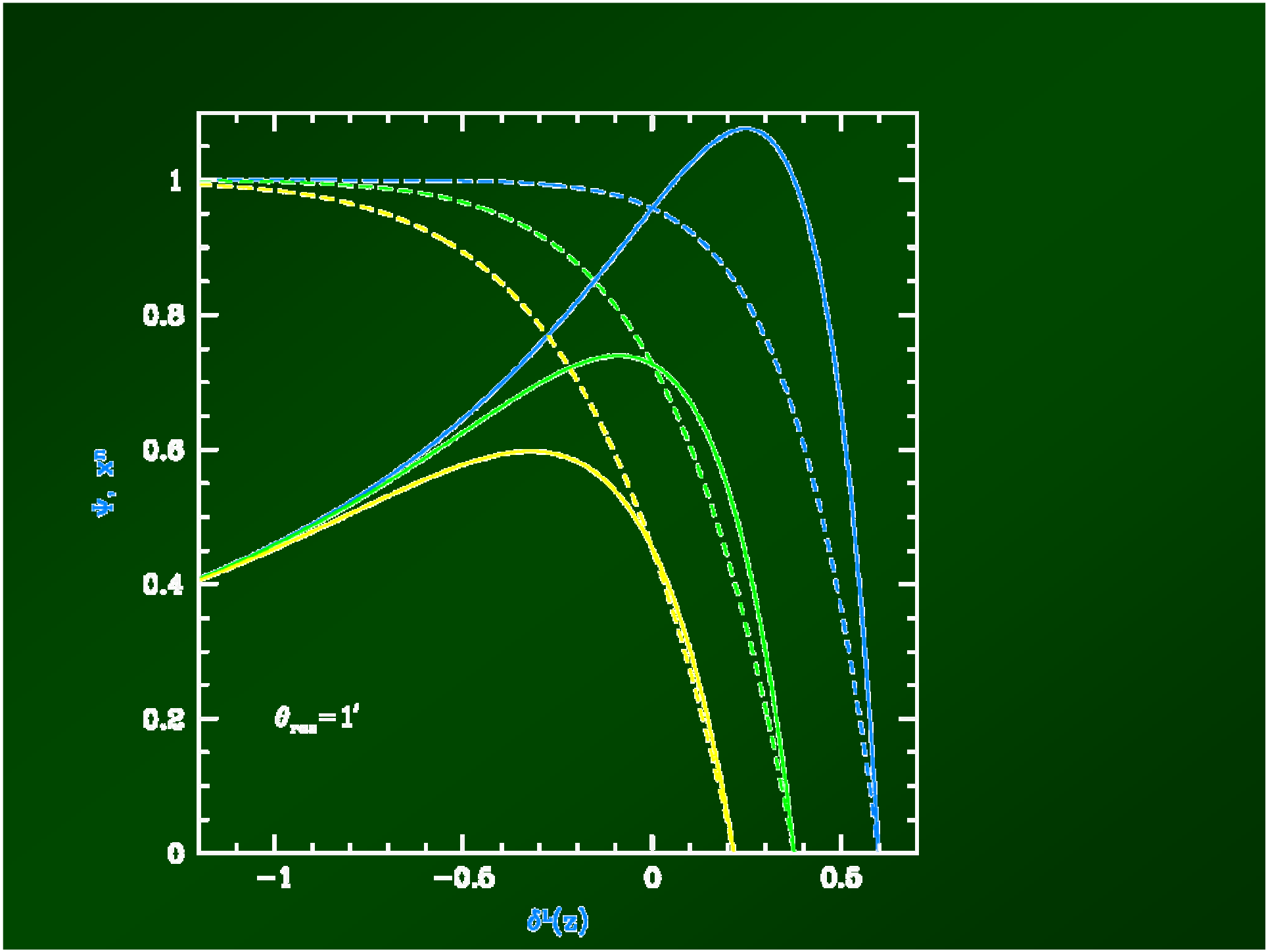


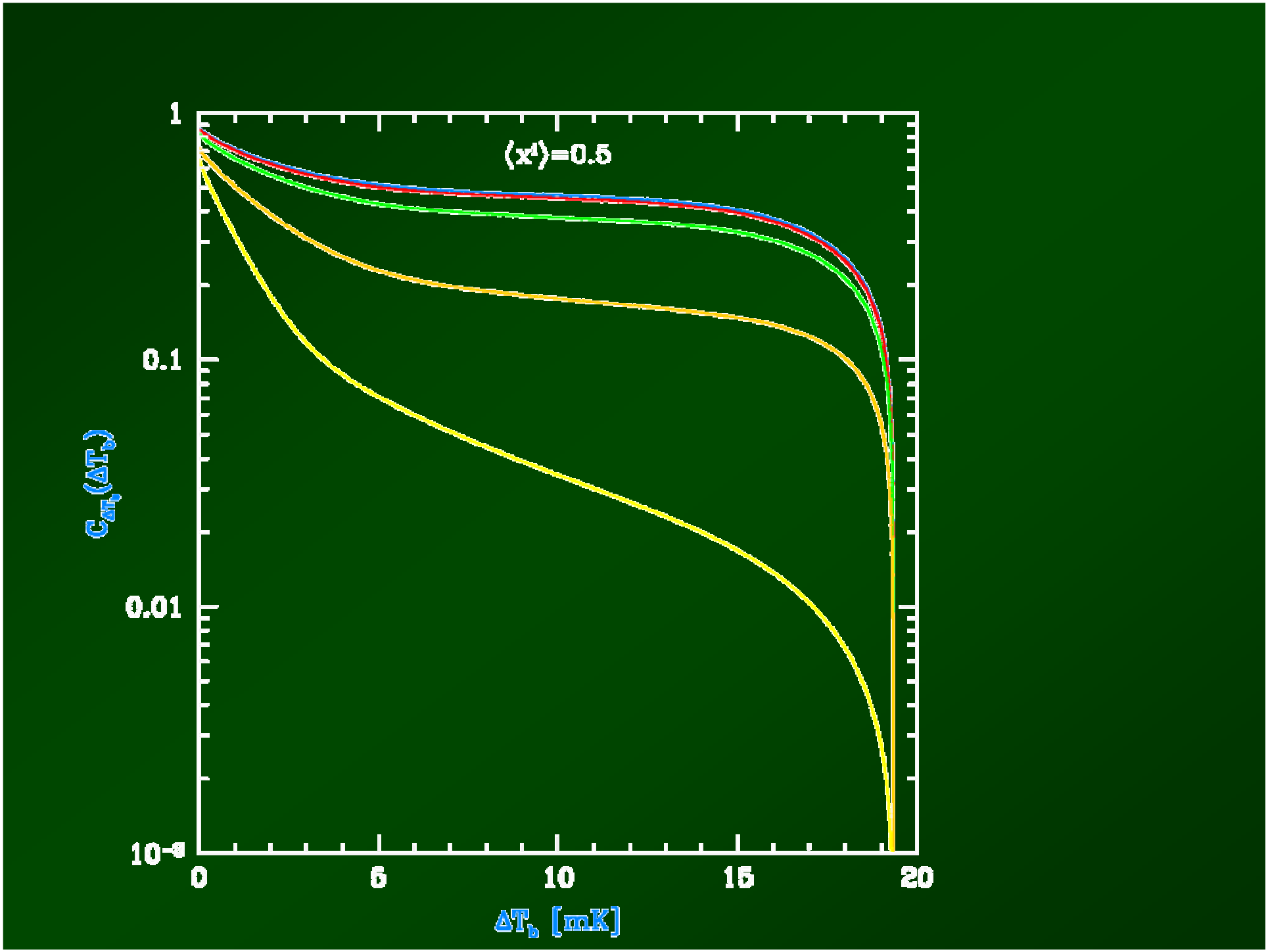
Parameters:

$r_1; r_2; z_1; z_2; d$

Furlanetto, Zaldariagga, Hernquist 2004

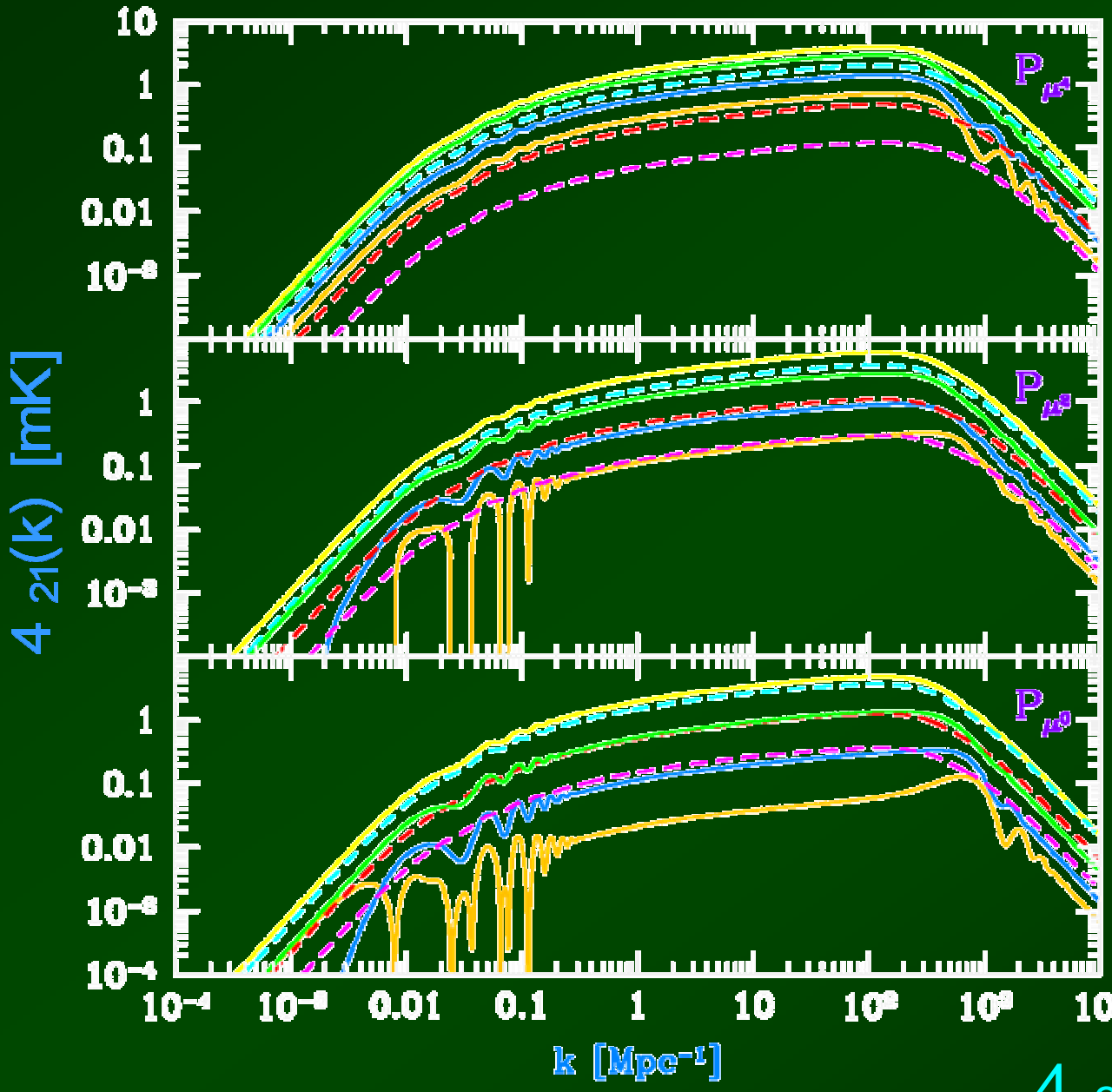



1
0.8
0.6
0.4
0.2
0
−1
−0.6
0
0.5
$\psi_c \times n$
$\theta_{min}=1'$
$\delta^L(z)$


1
0.1
0.01
10⁻³
0
5
10
15
20
⟨x⁴⟩=0.5
C_m(ΔT_b)
ΔT_b [mK]

21cm Power Spectra

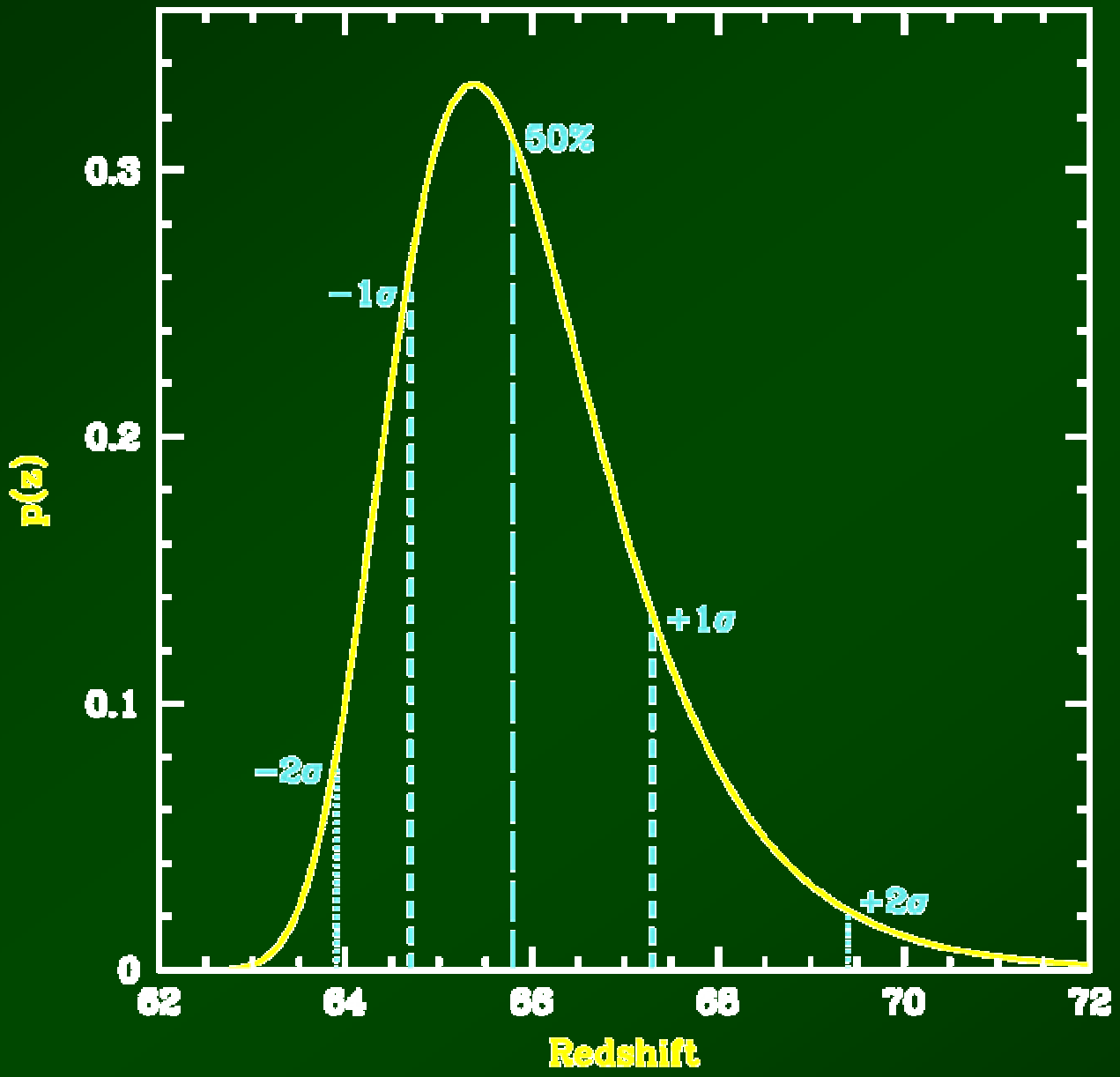
Naoz & RB 2005



z = 200
z = 150
z = 100
z = 50
z = 35
z = 25
z = 20

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

The First Star

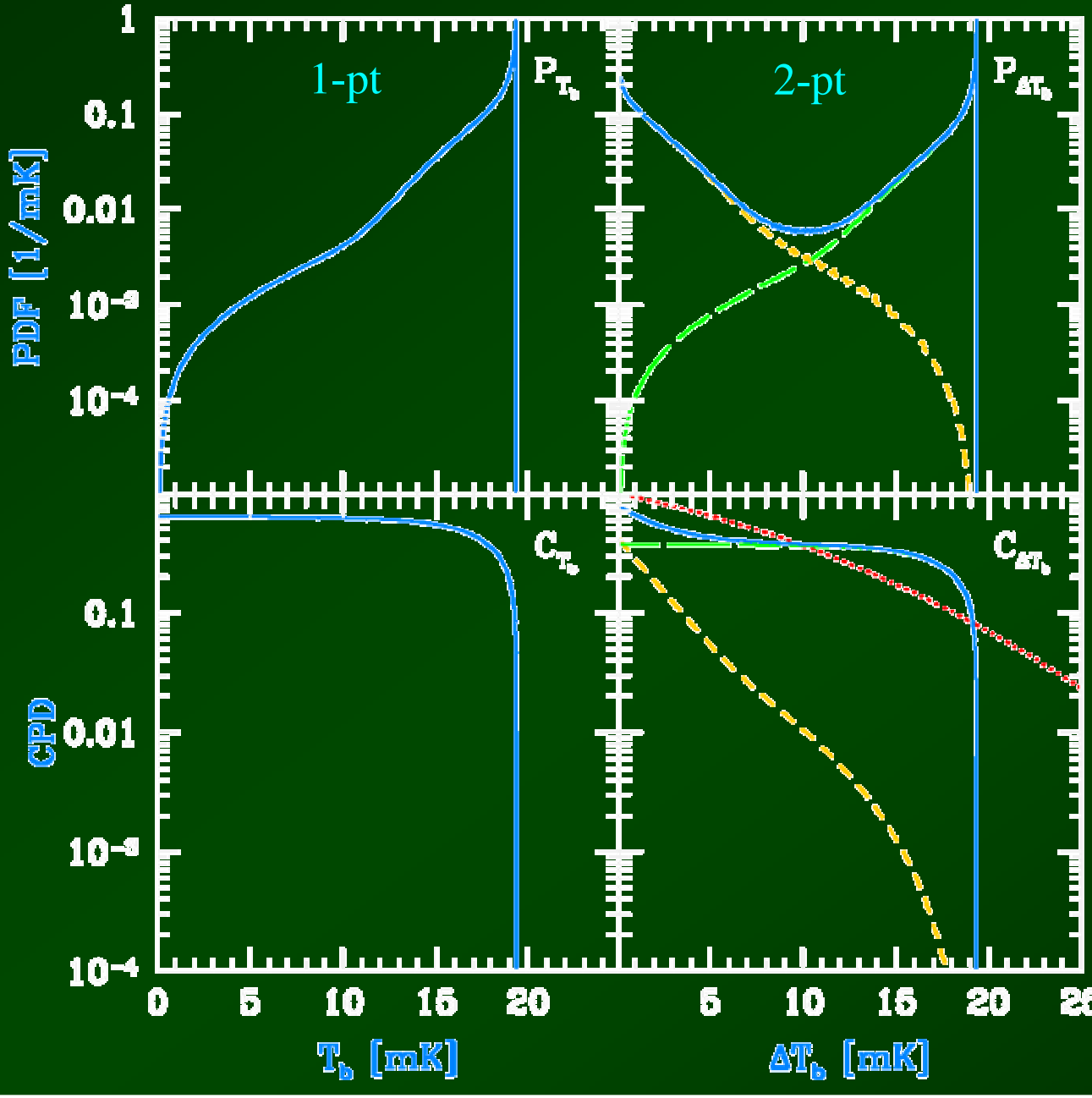


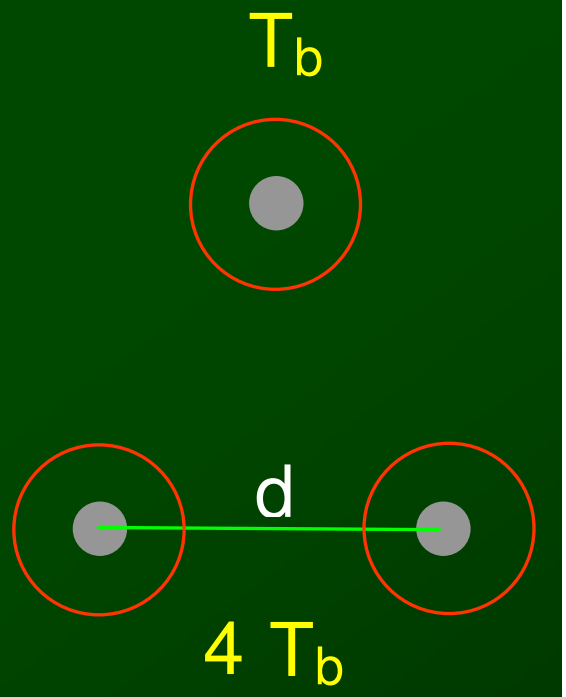
1û :

t = 31 æ 1 Myr

Naoz, Noter
& RB 2006

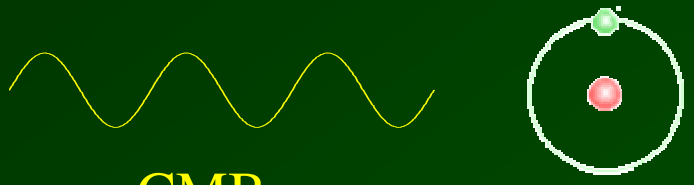
The Difference PDF





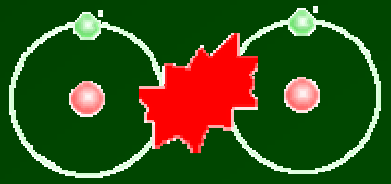
$$\overset{c}{x}_i \overset{c}{} = 0{:}5$$

What determines T_S?

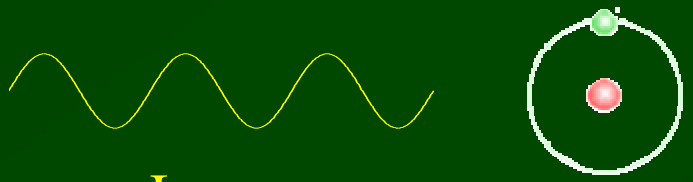


CMB

$T_S \sim T_\gamma$

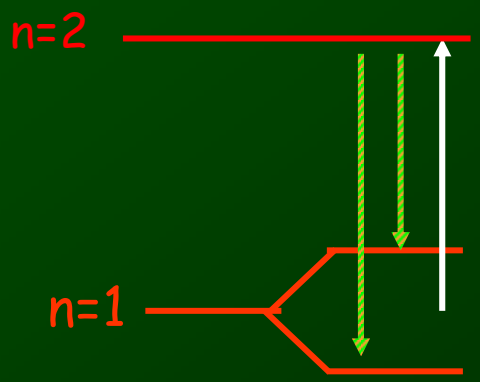


$T_S \sim T_K$



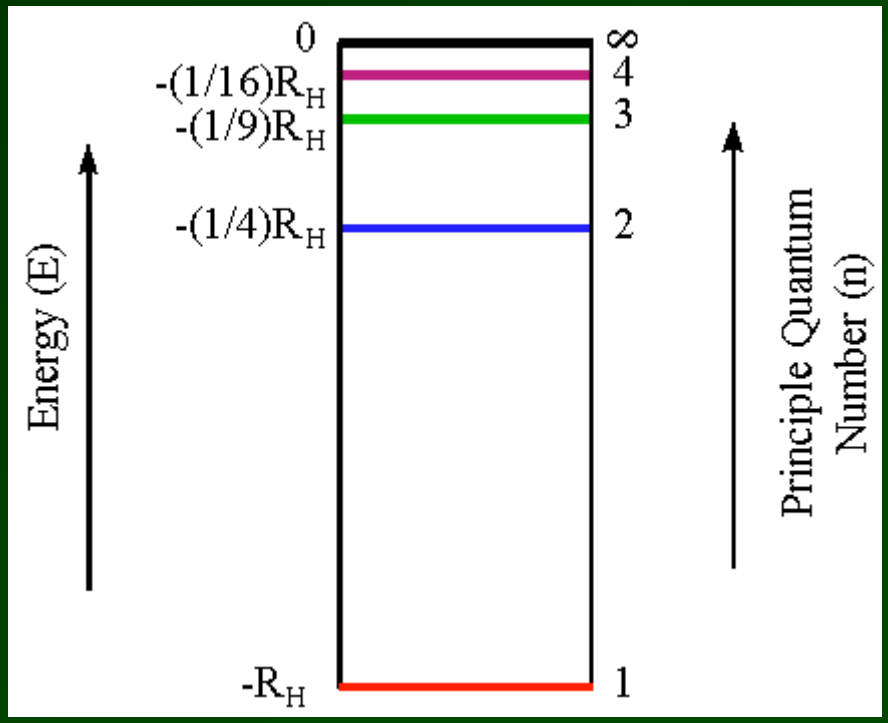
Lyα

Wouthuysen 1952
Field 1958



$T_S \sim T_K$

The Lyman-α flux



Lyë = 10:2 eV

11 eV) 10:2 eV

Biased Density Fluctuations

RB & Loeb 2005