The First Generations of Galaxies and 21cm Fluctuations

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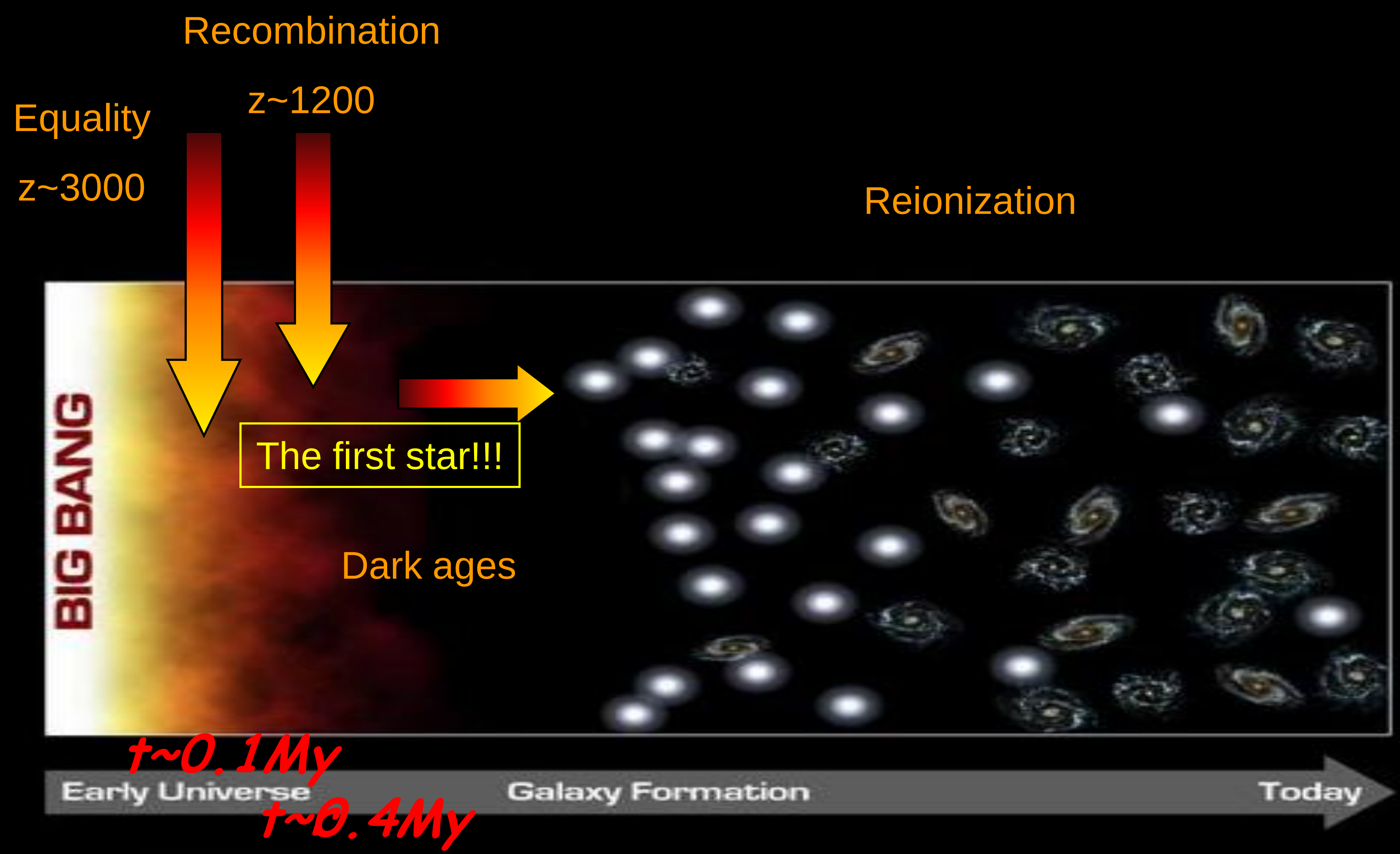
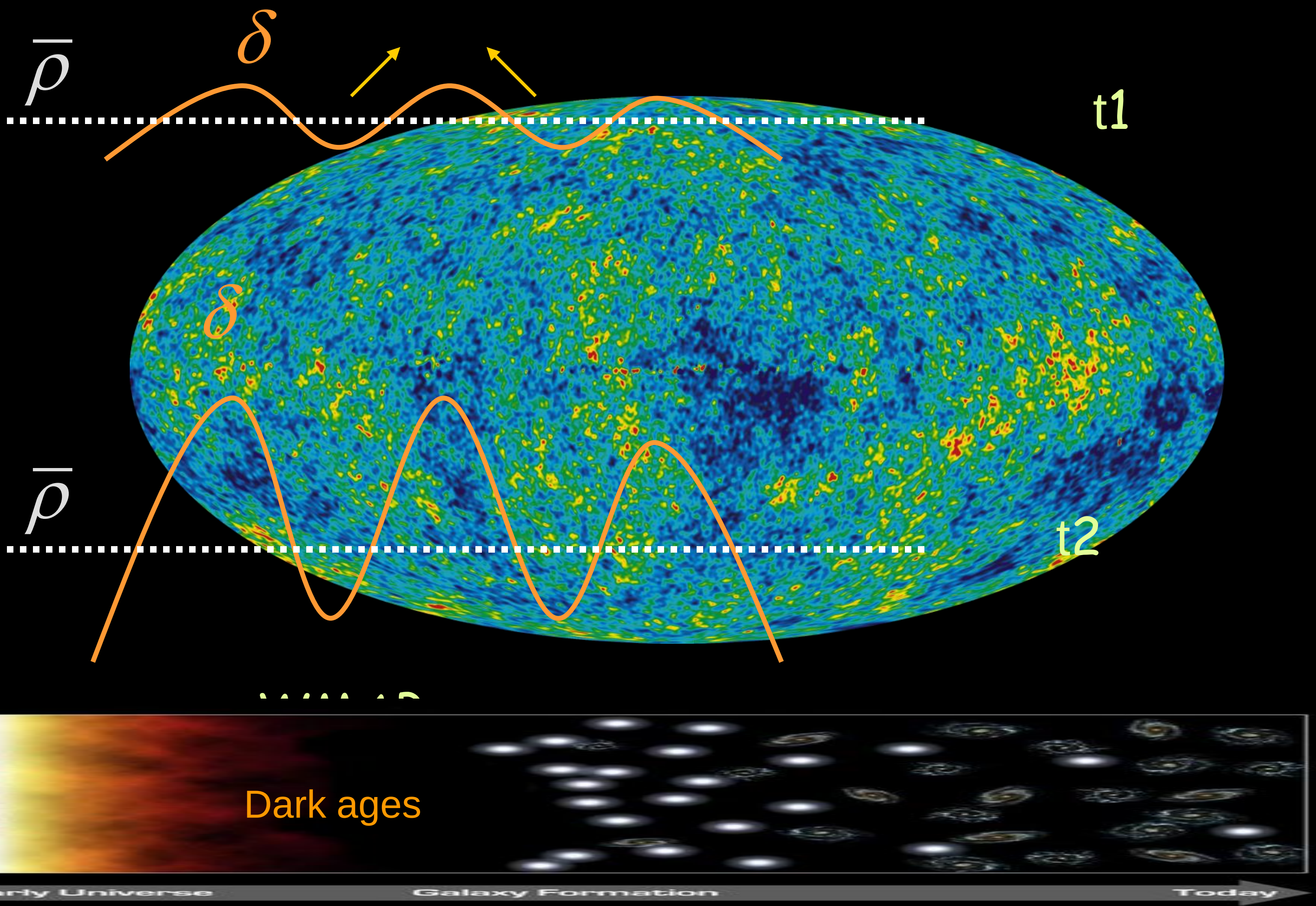
Outline

- Introduction
- Structure formation:
  - Linear behavior
  - Non-linear behavior
  - Pressure and simulated gas in early objects
- The first GRBs
- Cosmic Reionization:
  - Lyman series scattering
  - 21cm power spectrum

The History of the Universe

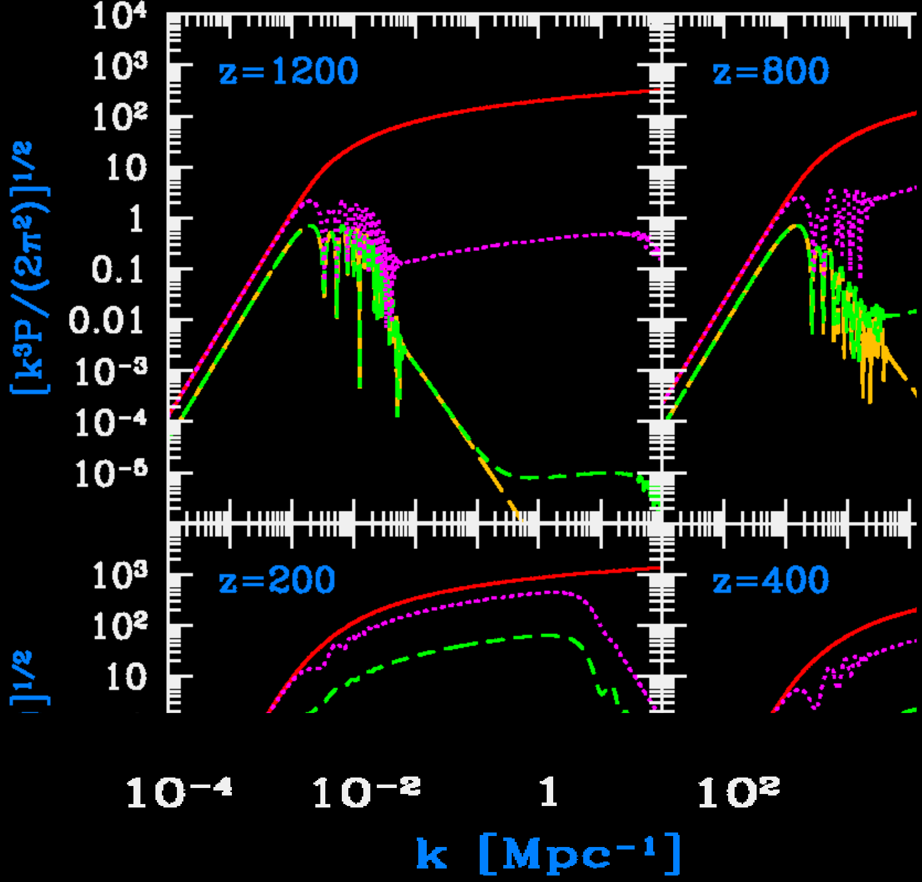


Structure formation



The Power Spectrum: linear behavior

$$|\delta| =$$



δ

Dark Matter

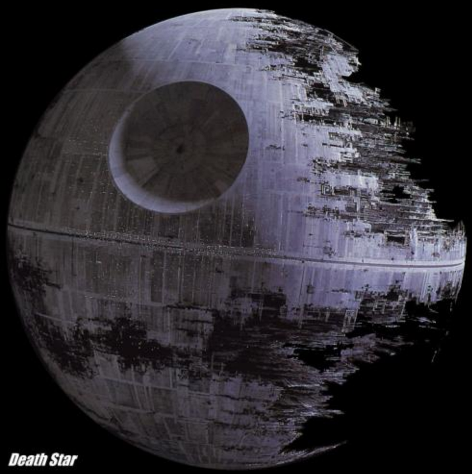
Gas

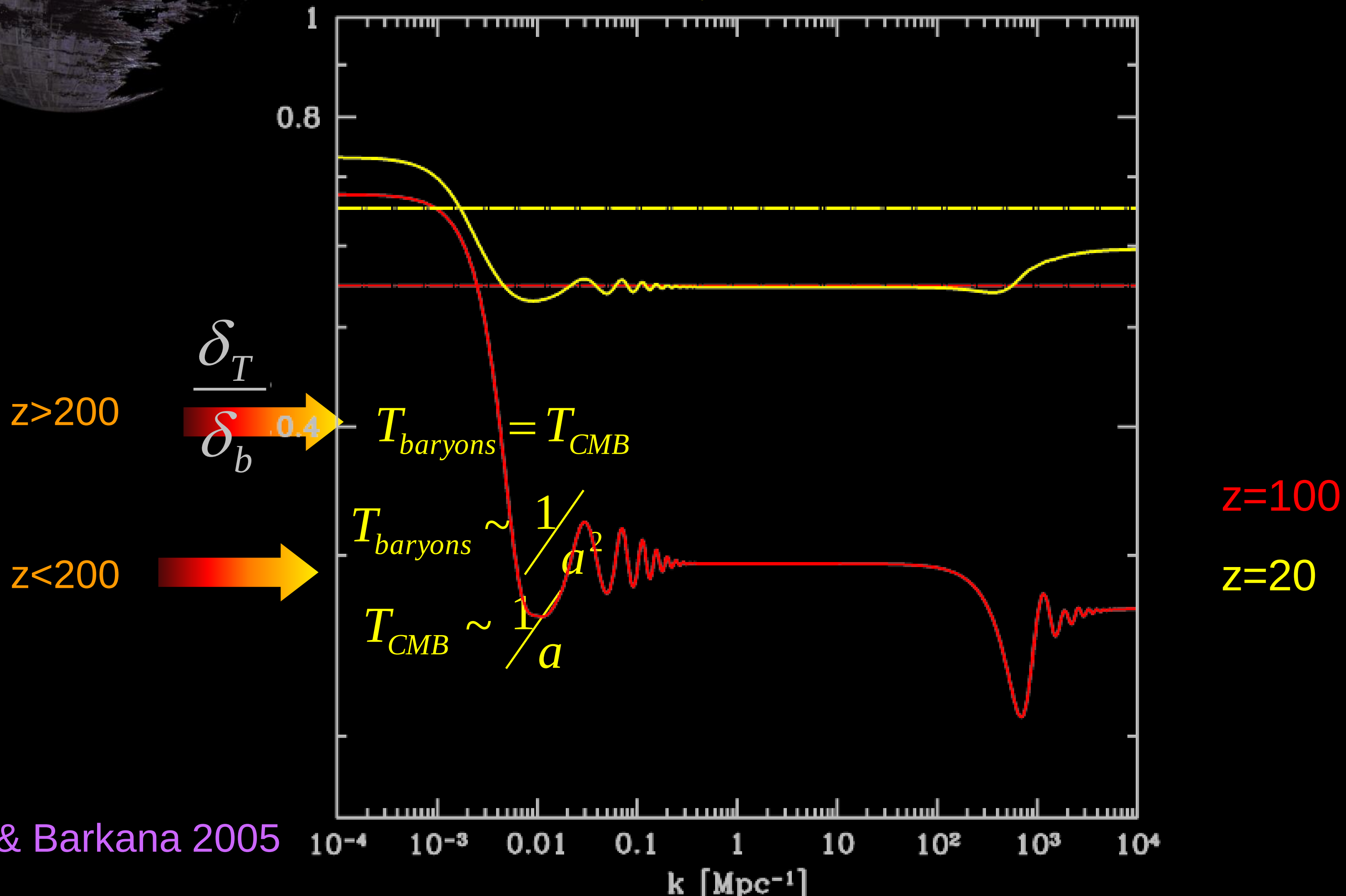
Gas temp

Radiation temp

Naoz & Barkana 2005

The Dark Ages,
linear behavior
our modification





Naoz & Barkana 2005

Non-linear behavior
Standard: Press & Schechter

Top – Hat: Dark Matter halo in **EdS** universe

The extrapolated linear fluctuation at the time of the collapse: $\delta_c = 1.686$

Dark matter halo in a matter dominated universe with a cosmological constant...

$\delta_c(z)$

Gunn & Gott 1972
Press & Schechter 1974
Bond, Cole, Efstathiou, &

Kaiser 1991

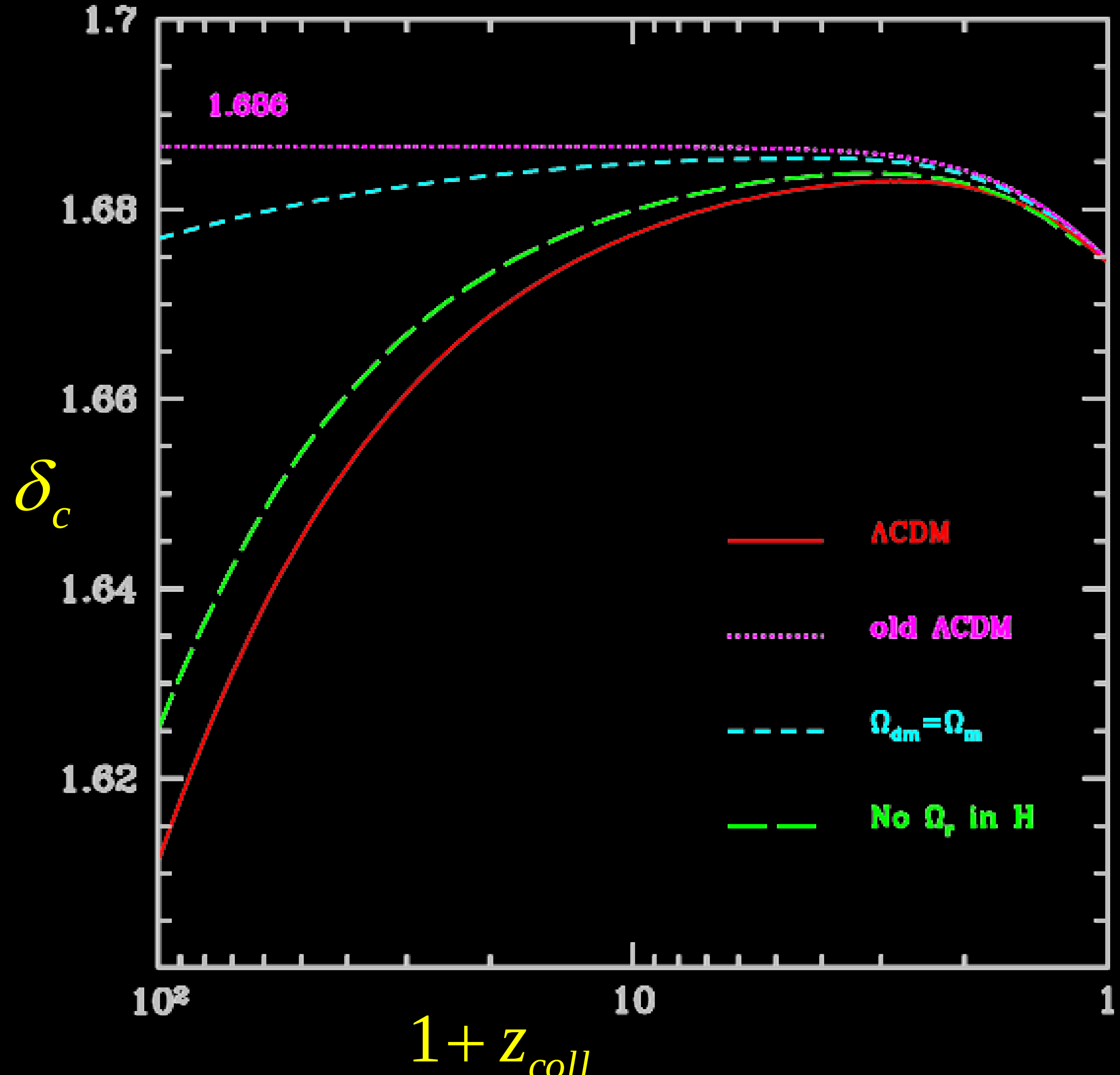
Our Modification

Non-linear behavior

Non-linear behavior

The extrapolated linear fluctuation

$$\delta = \frac{\rho - \bar{\rho}}{\bar{\rho}}$$



"old"

ΛCDM

ΛCDM

including early cosmic history

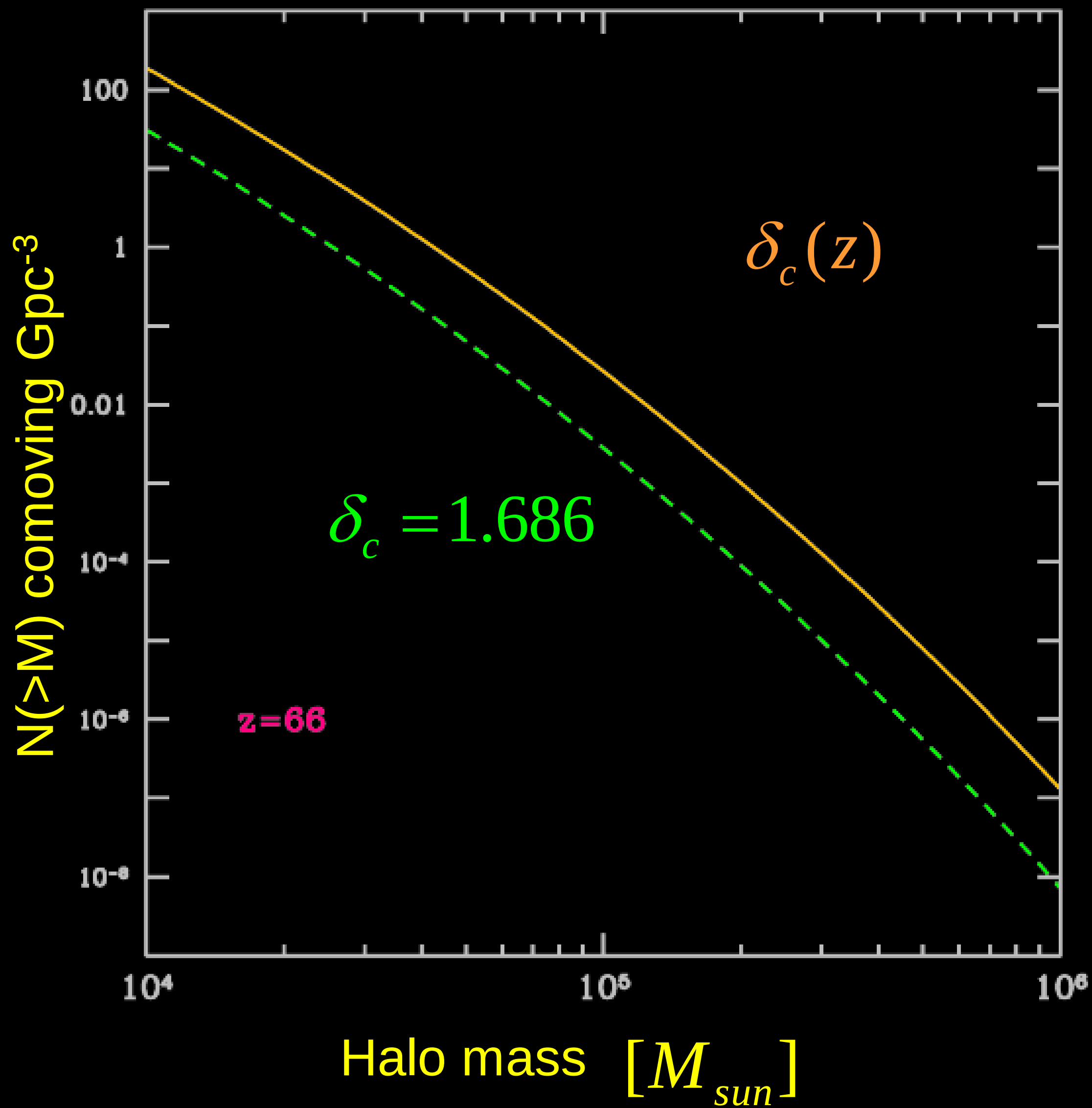
Gunn & Gott 1972

Naoz, Noter & Barkana 2006

Lahav et al. 1991

Eke et al. 1996

Our Modification
Non-linear behavior



Remainder:

$$N \sim \exp\left(\delta_c^2 / \sigma^2 \right)$$

5% ⟶ order of magnitude

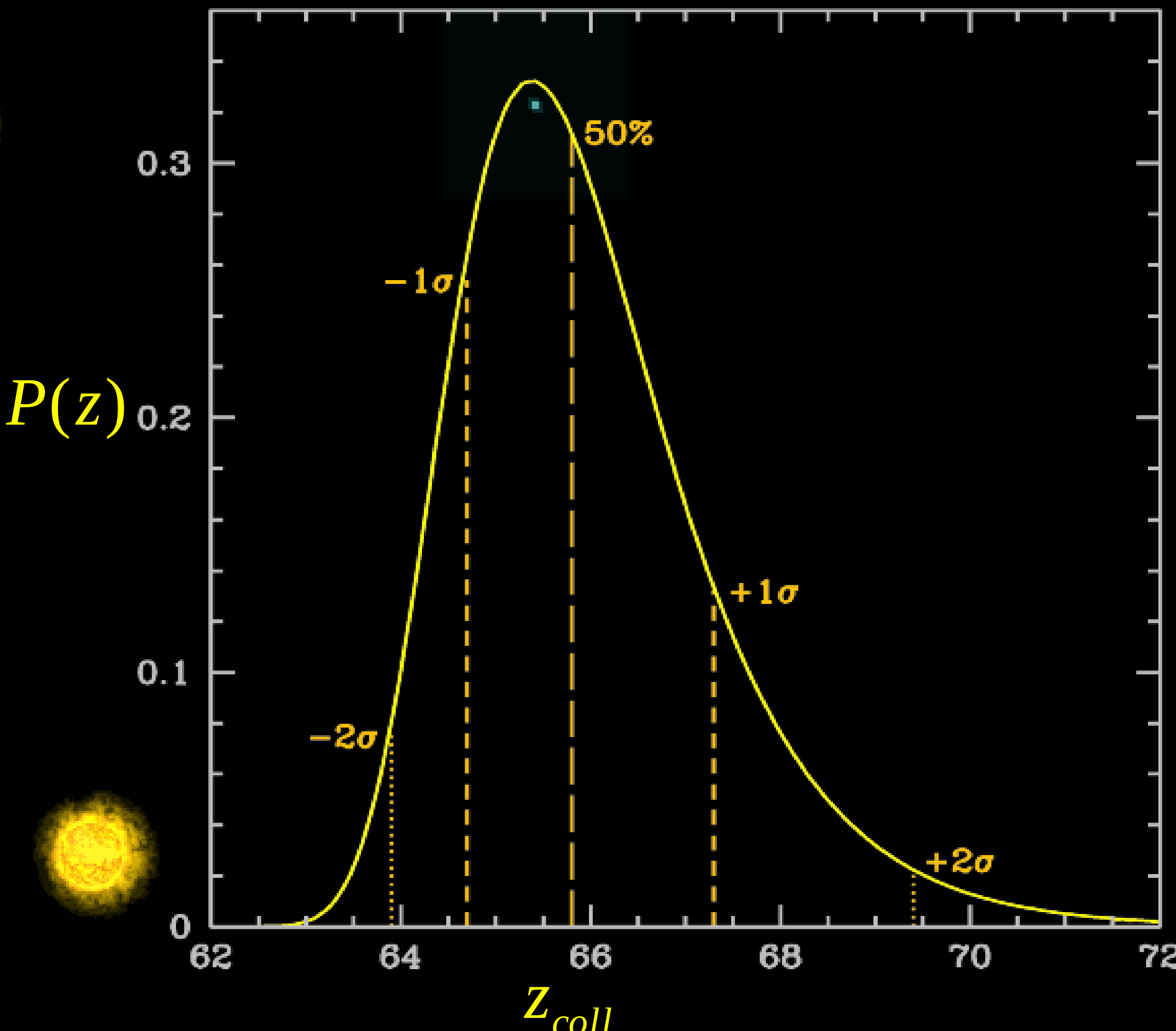
$z \approx 66$

ΛCDM

including early cosmic history

Naoz, Noter & Barkana 2006

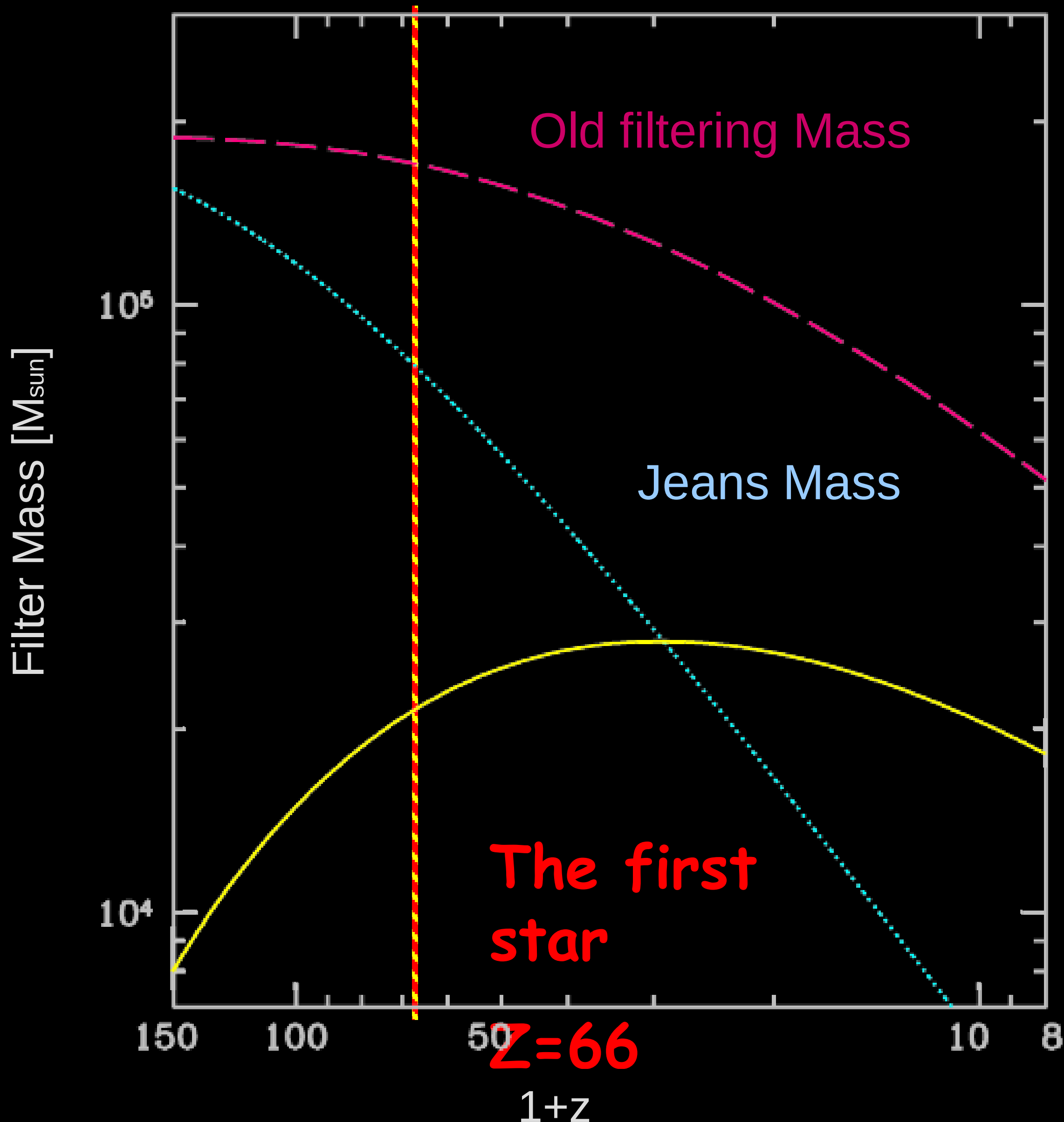
Let there be light!



Naoz, Noter & Barkana 2006

Baryons: the Filtering Mass

Pressure has only a moderate effect !!!



Naoz, Noter & Barkana 2006

Naoz & Barkana 2007 + 2005

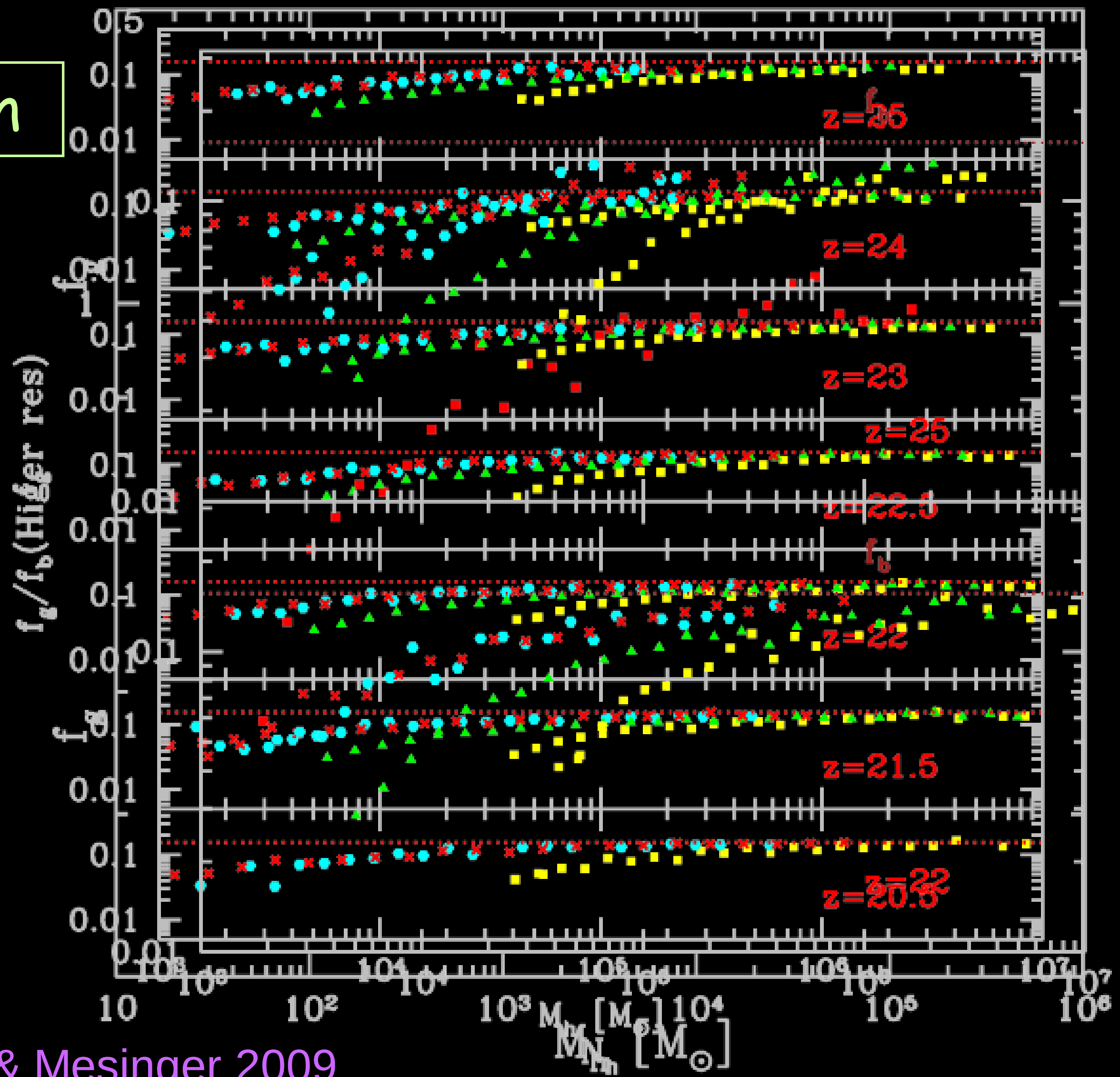
Gnedin & Hui 1998

Gnedin 2000

Gas content - in simulations

The condition

The Gas fraction over f_g in higher res

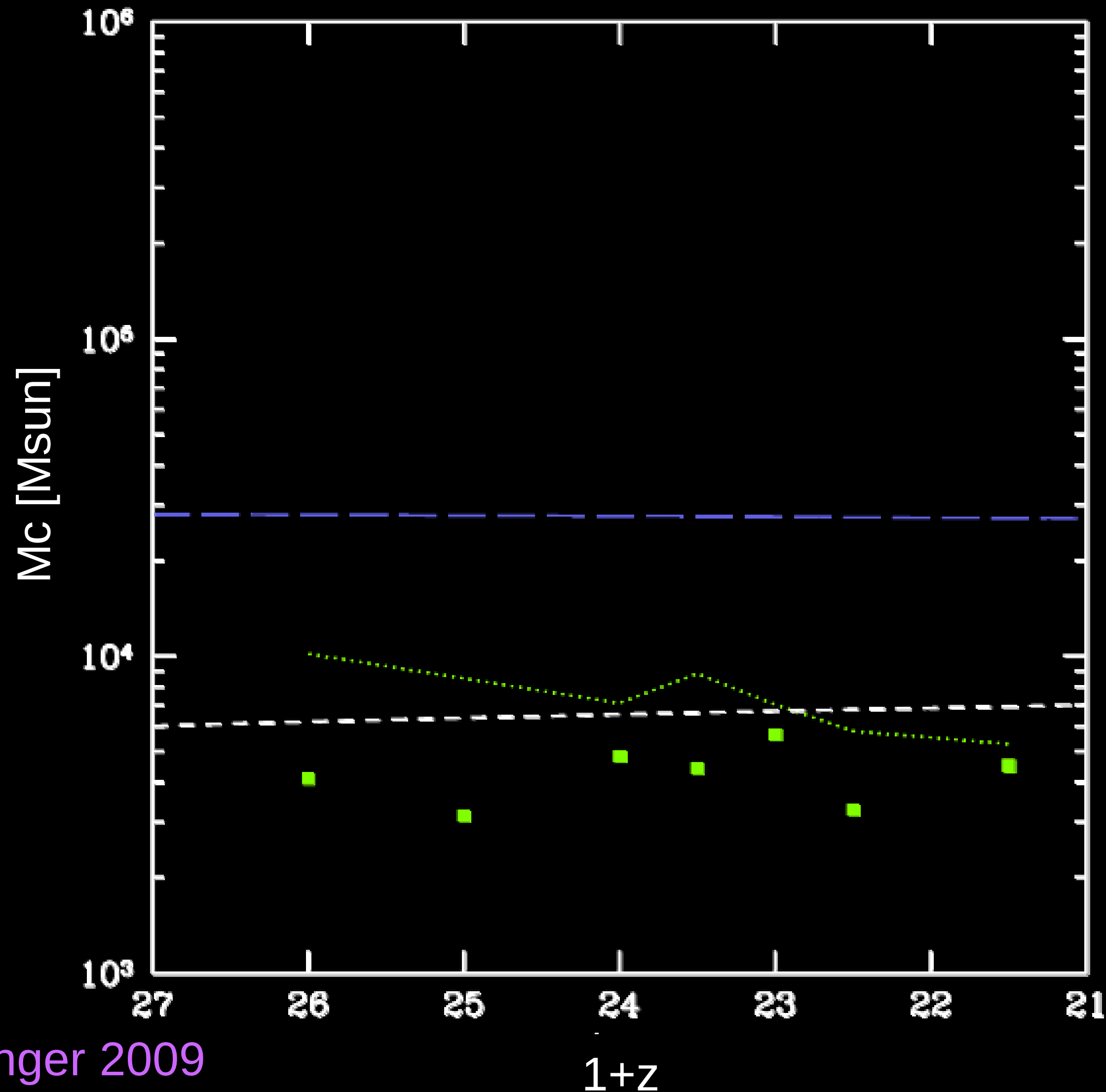


Naoz, Barkana & Mesinger 2009

Characteristic mass – in simulations

Min mass for a halo to keep most of it's baryons during formation, before heating:

$$\sim 3\times10^{4} M_{sun}$$



Naoz, Barkana & Mesinger 2009

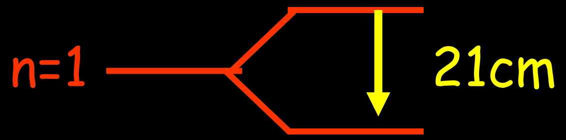
Until now….

Structure formation:

- Early cosmic history is important!
- Non-linear behavior: lower threshold for collapse ⟹ Higher mass abundance
- Pressure plays only a moderate role
- Condition on the number of particles of simulated gas

Cosmic Reionization

Observation of 21cm emitted from neutral hydrogen compare to the CMB



Kamionkowski Spergel & Sugiyama 1994

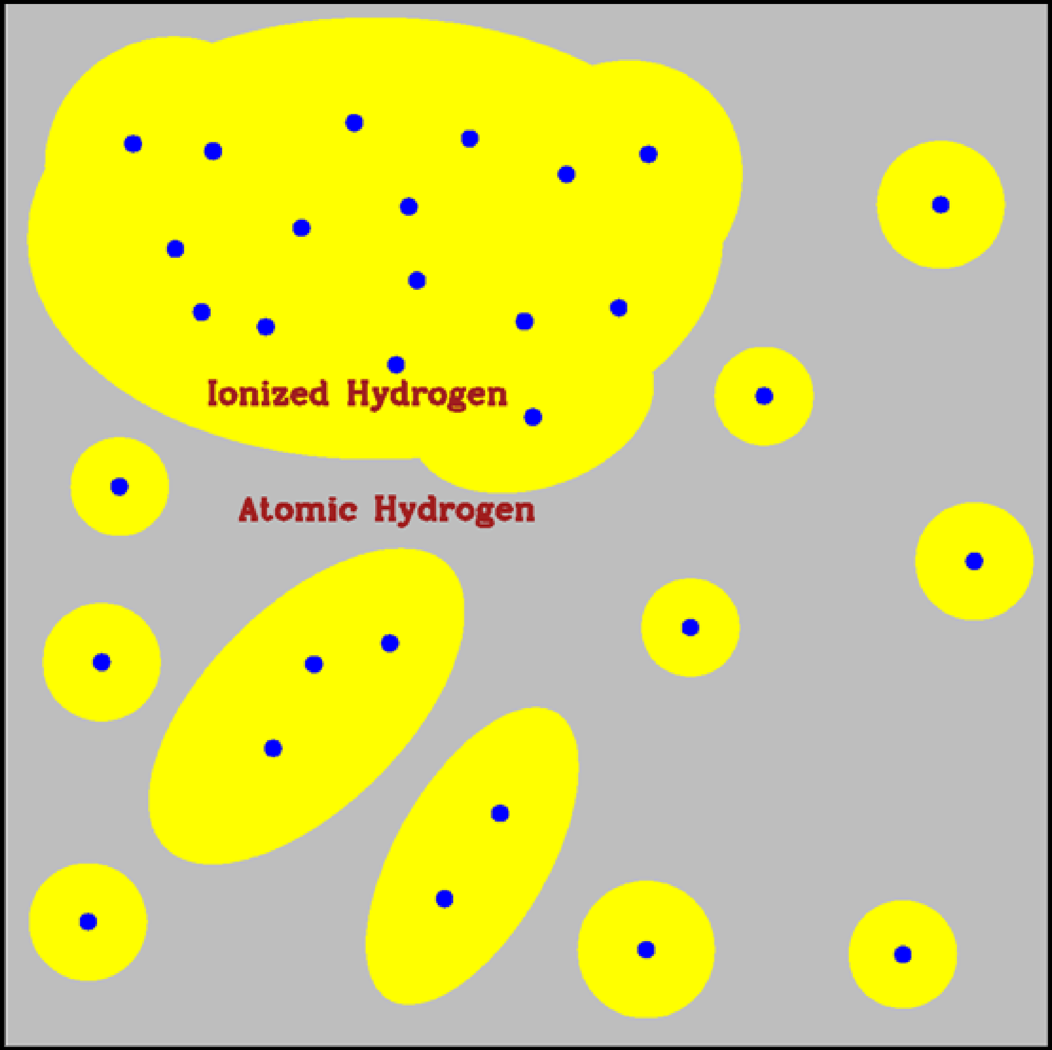
Loeb & Barkana 2001

Wyithe & Loeb 2003

Furlanetto, Zaldarriaga & Hernquist 2004

Loeb 2007

McQuinn, Lidz, Zahn, Suvendra, Hernquist & Zaldarriaga 2007

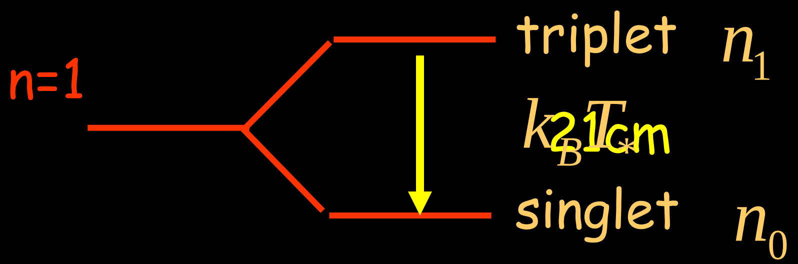


Barkana & Loeb 2004

Cosmic Reionization

The spin temperature:

$$\frac{n_1}{n_0} = 3\exp\left\{-\frac{T_*}{T_s}\right\}$$



Observation of 21cm compared to the CMB

The brightness temperature: $$T_b \approx 28mK\left(\frac{1+z}{10}\right)^{-1}\left(\frac{T_s - T_{CMB}}{T_s}\right)\bar{\chi}_{HI}$$

$T_s > T_{CMB}$ IGM observed in emission

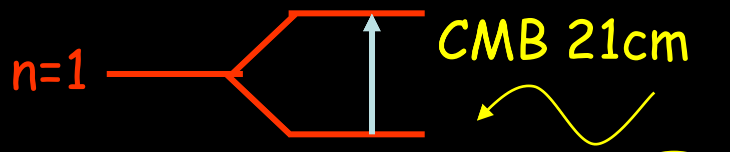
$T_s < T_{CMB}$ IGM observed in absorption

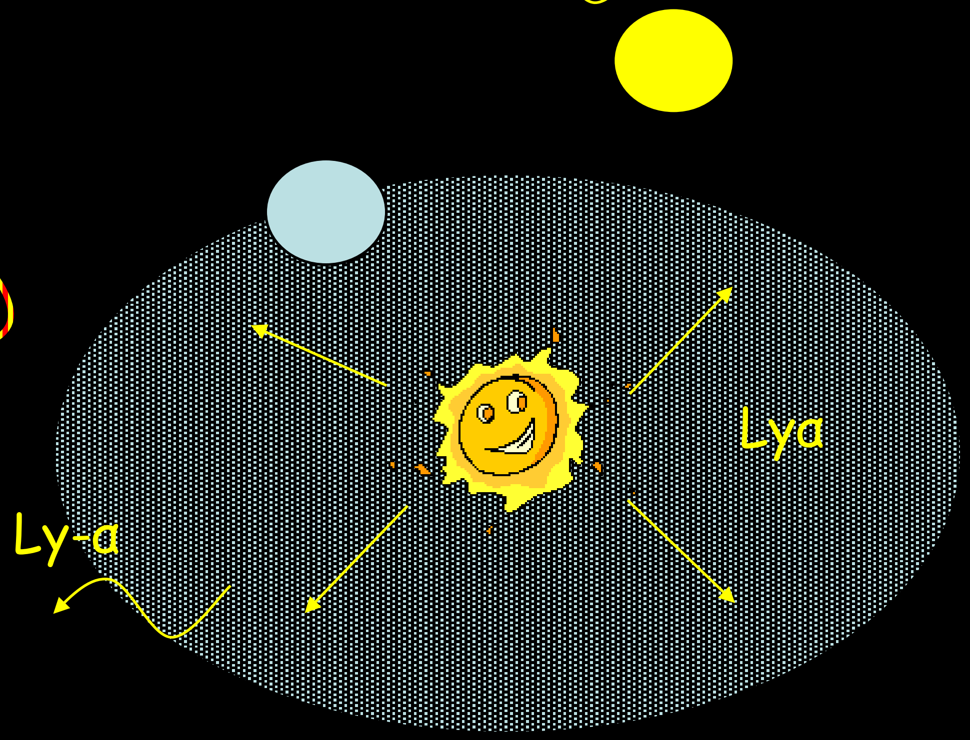
Cosmic Reionization

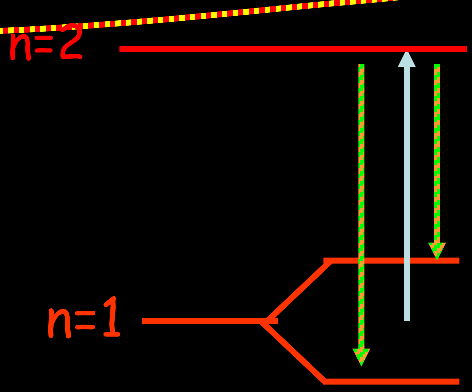
Fluctuations in the brightness temperature

Effects on the spin temperature:

- CMB absorption
- Collisions
- Ly-a interactions, the Wouthuysen-Field effect







Cosmic Reionization

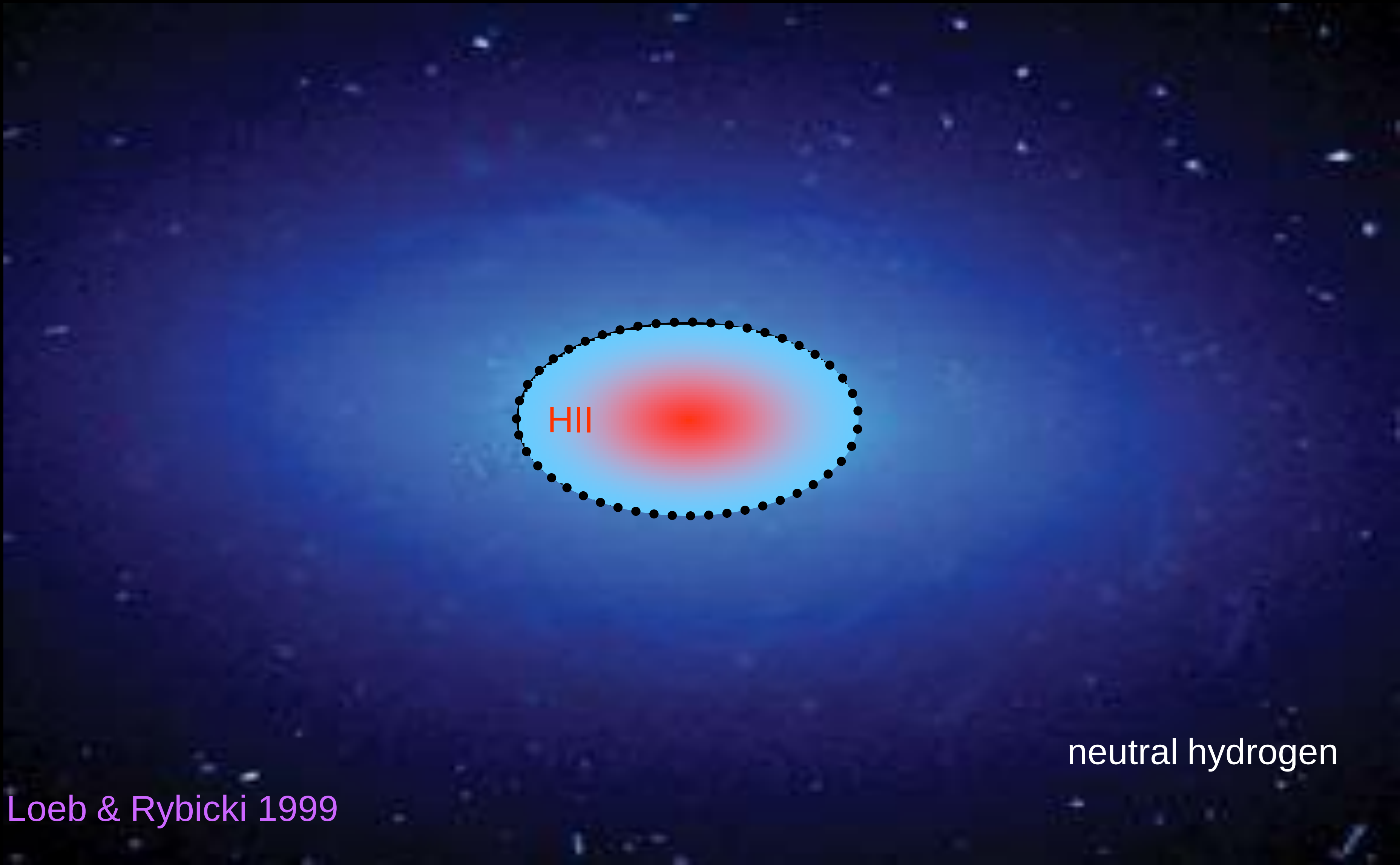
Fluctuations in the brightness temperature

Observation of 21cm compared to the CMB

LOFAR

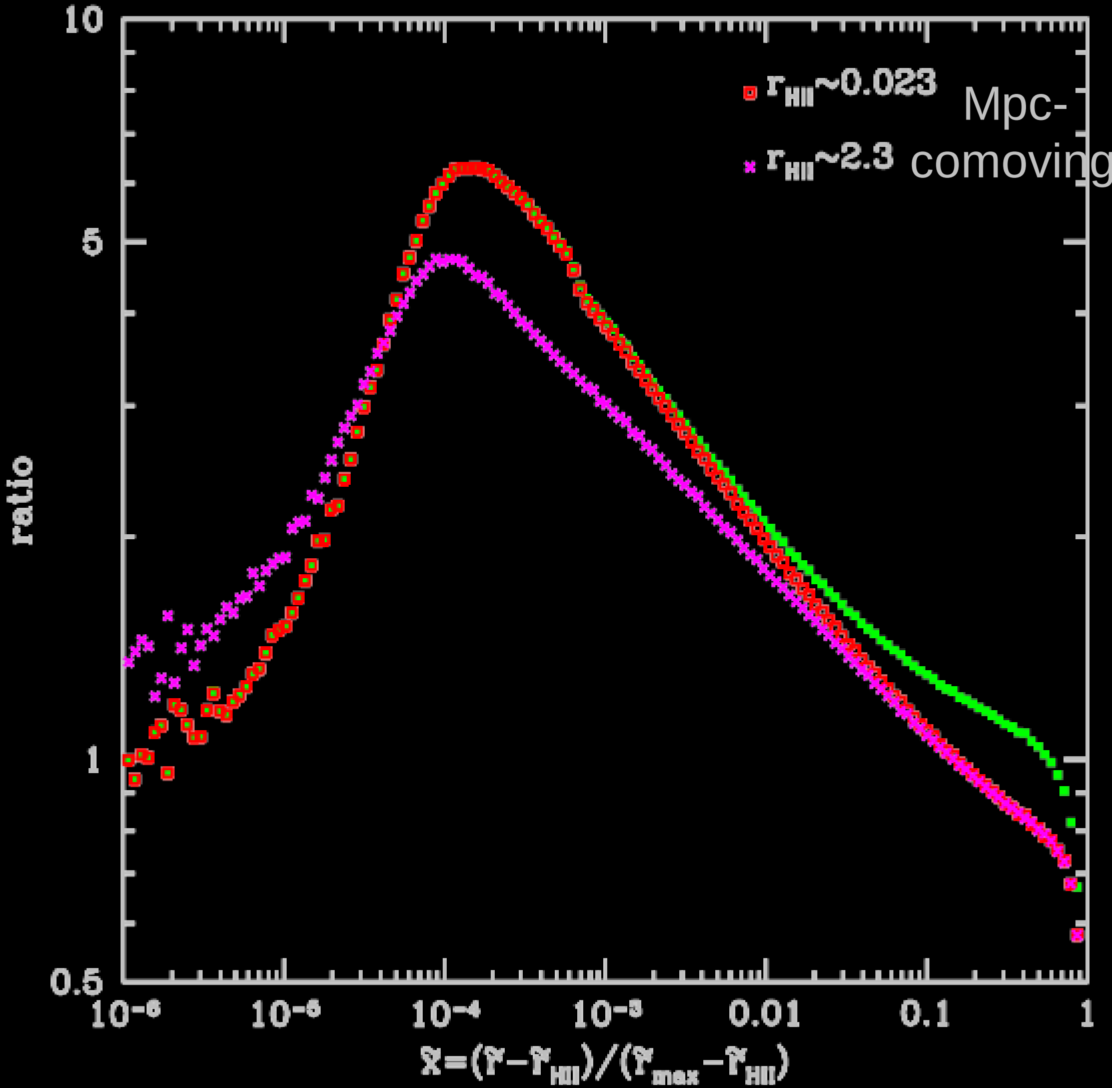
MWA

Ly-a Scattering



Ly-a Scattering

$$ratio = \frac{flux(scatt.)}{flux(no-scatt.)}$$



Naoz & Barkana 2008

21cm power spectrum

21cm power spectrum:
Barkana & Loeb 2004

+ *Atomic - Lyn->Lya :*
Pritchard & Furlanetto 2006; Hirata 2006

+ *Compton scattering:*
Naoz & Barkana 2005

+ HII Cutoff

+ scattering

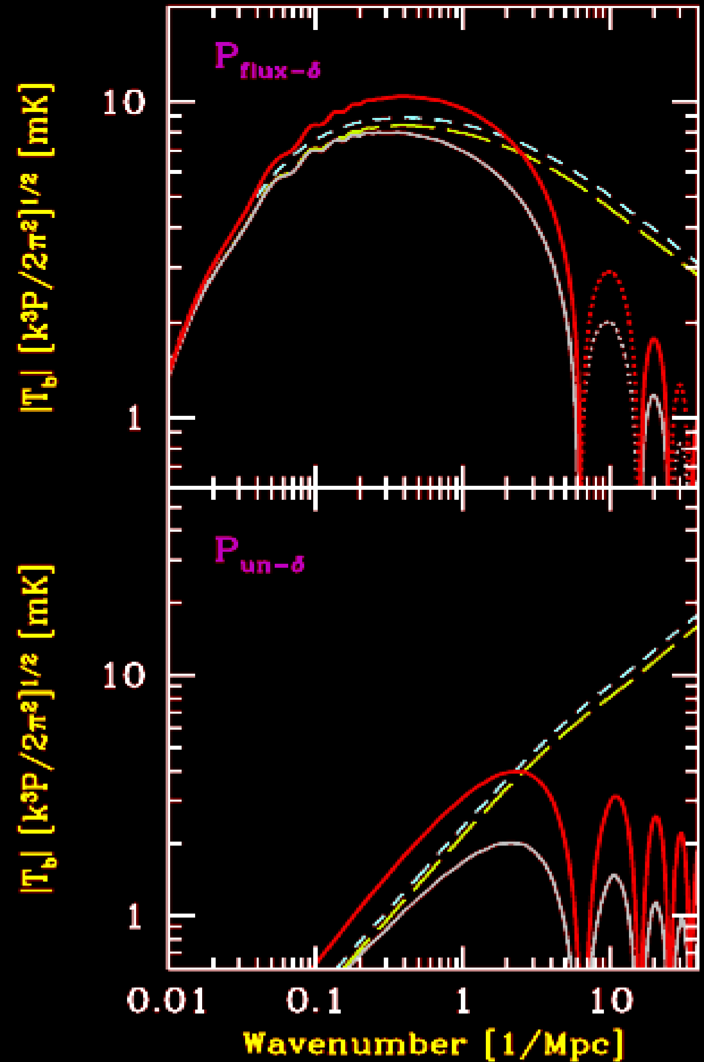
Minimum mass for Atomic cooling

Z=20

Naoz & Barkana 2008

Density fluctuations

Poisson



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10 x Minimum mass for Atomic cooling

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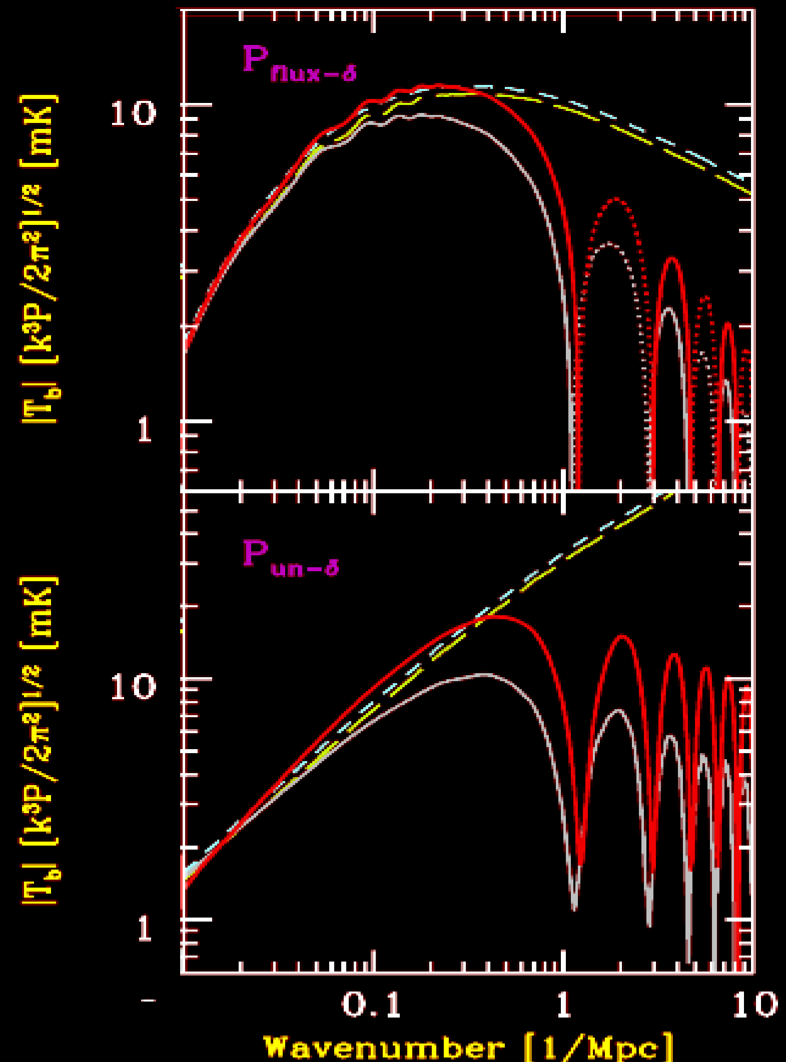
Naoz & Barkana 2008

Density fluctuations

Poisson



Summary

- **Early cosmic history is important!**
- The critical density is lower which affects the halo statistics (*higher mass abundance*)

- **Detecting the early generation of galaxies**
- HII regions around galaxies produce cutoff in the 21-cm power spectrum
- Lya scattering enhances the signal