21-cm Cosmology

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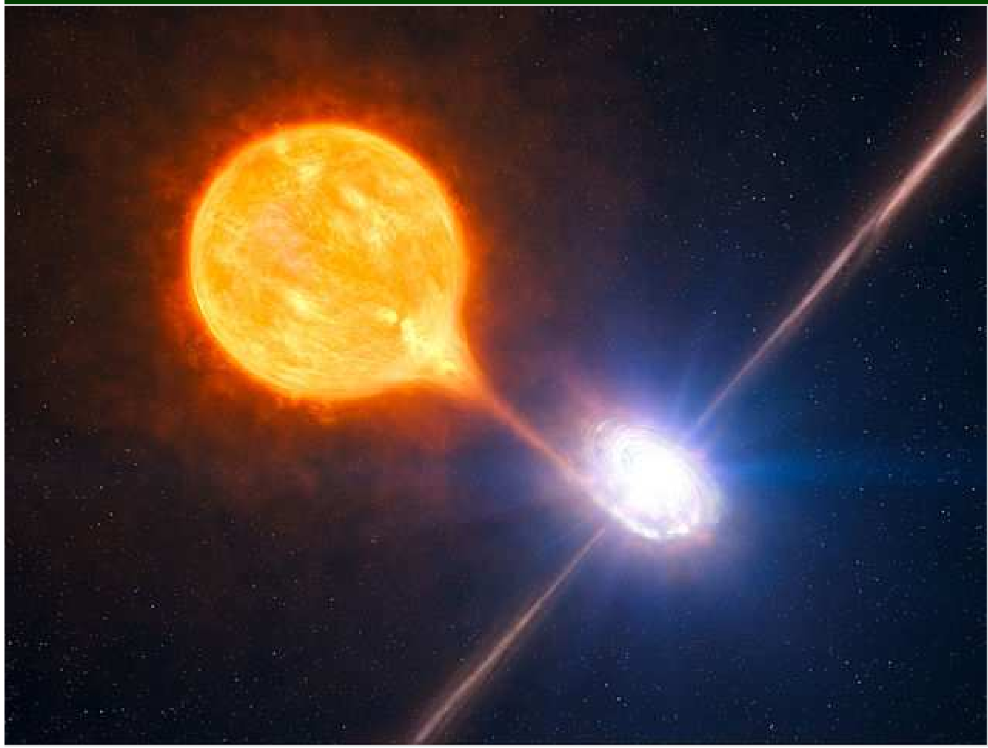
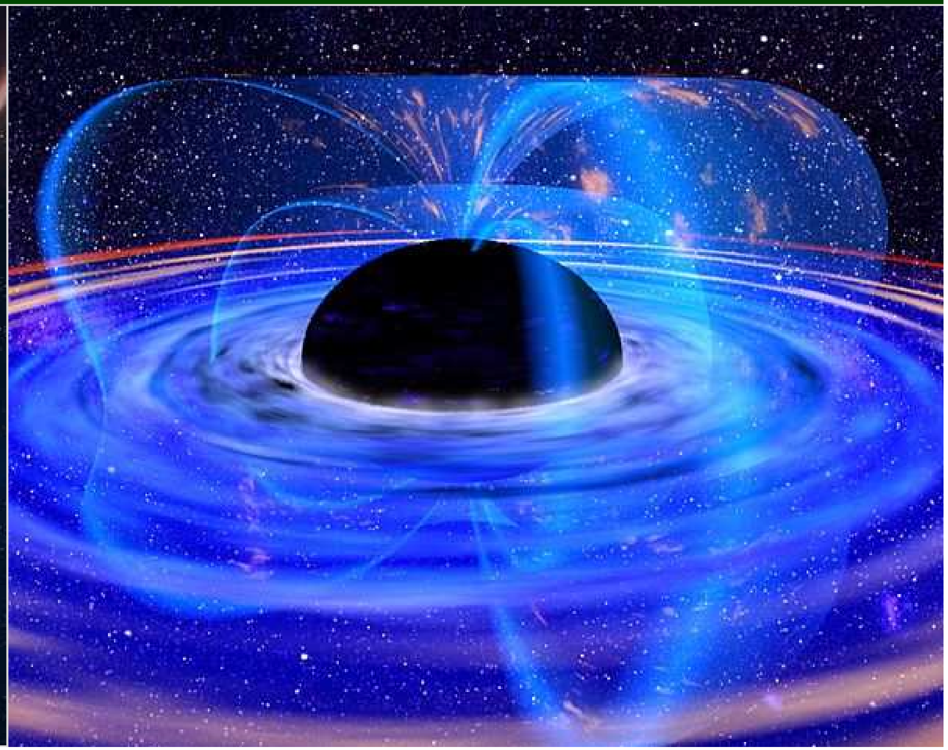




Cosmology

Robertson-Walker metric:

(R, θ, ϕ) Scale factor: $a(t)$

$$ds^2 = dt^2 - a^2(t)\left[\frac{dR^2}{1-kR^2} + R^2\left(d\theta^2 + \sin^2\theta\, d\phi^2\right)\right]$$

Friedmann equation:

$$H^2(t) = \frac{8\pi G}{3}\rho - \frac{k}{a^2}$$

$$H(t) = d\ln a(t)/dt$$

Energy conservation:

$$d(\rho R^3) = -pd(R^3)$$

Critical density:

$$\rho_C(t) \equiv \frac{3H^2(t)}{8\pi G}$$

$$\Omega \equiv \frac{\rho}{\rho_C}$$

Friedmann equation:

$$\frac{H(t)}{H_0} = \left[\frac{\Omega_m}{a^3} + \Omega_\Lambda + \frac{\Omega_r}{a^4} + \frac{\Omega_k}{a^2}\right]^{1/2}$$

$$\Omega_0 = \Omega_m + \Omega_\Lambda + \Omega_r$$

$$\Omega_k \equiv -\frac{k}{H_0^2} = 1 - \Omega_0$$

Cosmology

$$\frac{H(t)}{H_0} = \left[\frac{\Omega_m}{a^3} + \Omega_\Lambda + \frac{\Omega_r}{a^4} + \frac{\Omega_k}{a^2}\right]^{1/2}$$

Einstein-de Sitter (EdS) model ($\Omega_m = 1, \Omega_\Lambda = \Omega_r = \Omega_k = 0$)

High z (first stars): $$H(z) \approx H_0 \frac{\sqrt{\Omega_m}}{a^{3/2}}$$

Planck (1-yr): $h = 0.678$ $\Omega_m = 0.307$ $\Omega_b = 0.0482$

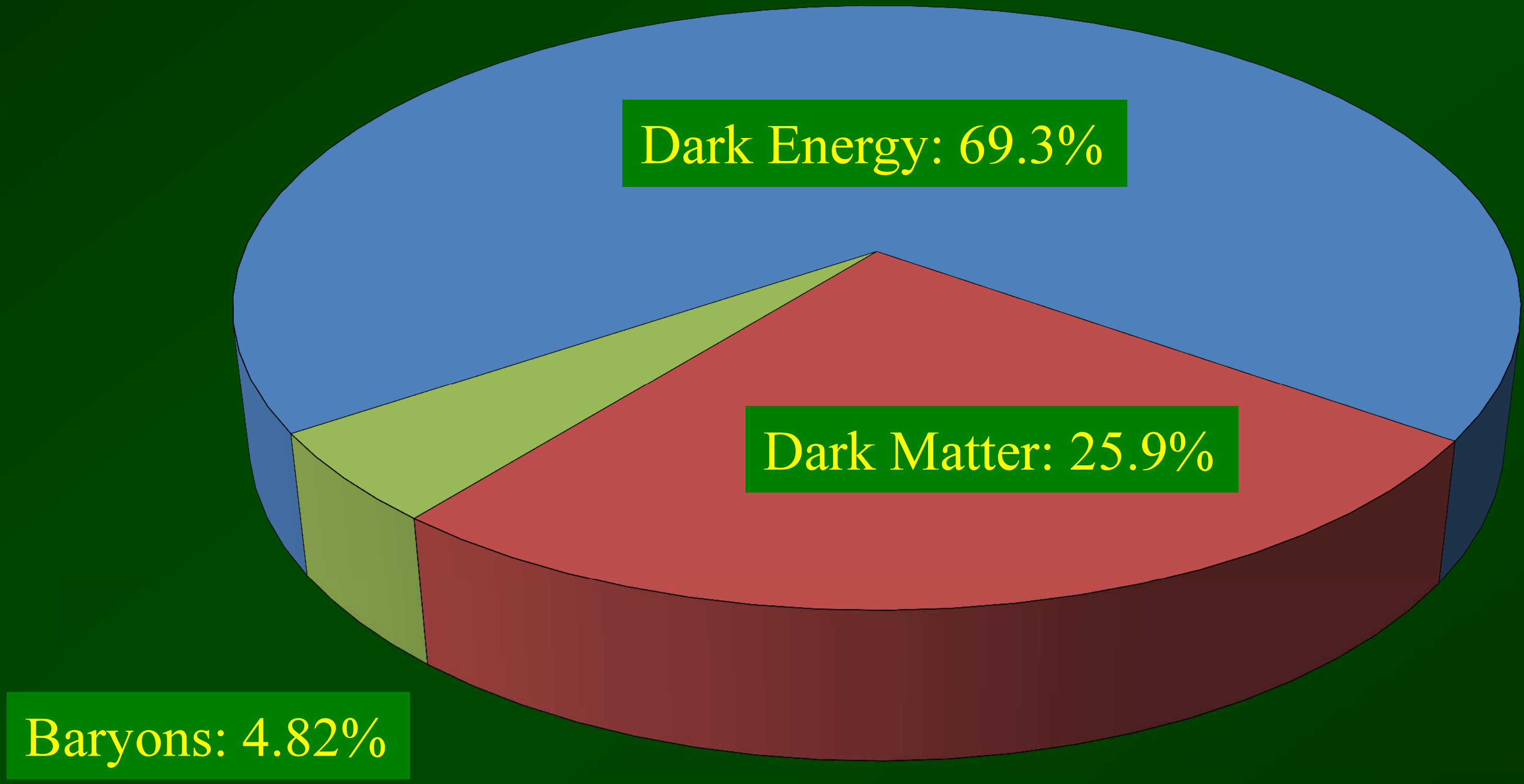
$H_0 = 100\,h$ km s^{-1} Mpc^{-1}

Redshift: $$a = \frac{1}{1+z}$$

Hubble expansion: $v = Hr$

Cosmic age: $$t \approx \frac{2}{3\,H_0\,\sqrt{\Omega_m}}(1+z)^{-3/2} = 5.49 \times 10^8 \left(\frac{\Omega_m h^2}{0.141}\right)^{-1/2} \left(\frac{1+z}{10}\right)^{-3/2} \text{ yr}$$

Cosmological Pie



Linear Perturbation Theory

Density perturbation: $\delta(\mathbf{x}) \equiv \frac{\rho(\mathbf{r})}{\bar{\rho}} - 1$

$\mathbf{x} = \mathbf{r}/a$

Comoving coordinates

Peculiar velocity: $\mathbf{u} \equiv \mathbf{v} - H\mathbf{r}$

Linearized fluid eq's => $\frac{\partial^2 \delta}{\partial t^2} + 2H\frac{\partial \delta}{\partial t} = 4\pi G\bar{\rho}\delta$

Growing mode: $D(a) = a$ (EdS) $D(a) \approx 1.28a$ (High z)

$D(z = 0) = 1$

Fourier space: $\delta_{\mathbf{k}} = \int d^3x\, \delta(x) e^{-i\mathbf{k}\cdot\mathbf{x}}$ $k = \frac{2\pi}{\lambda}$

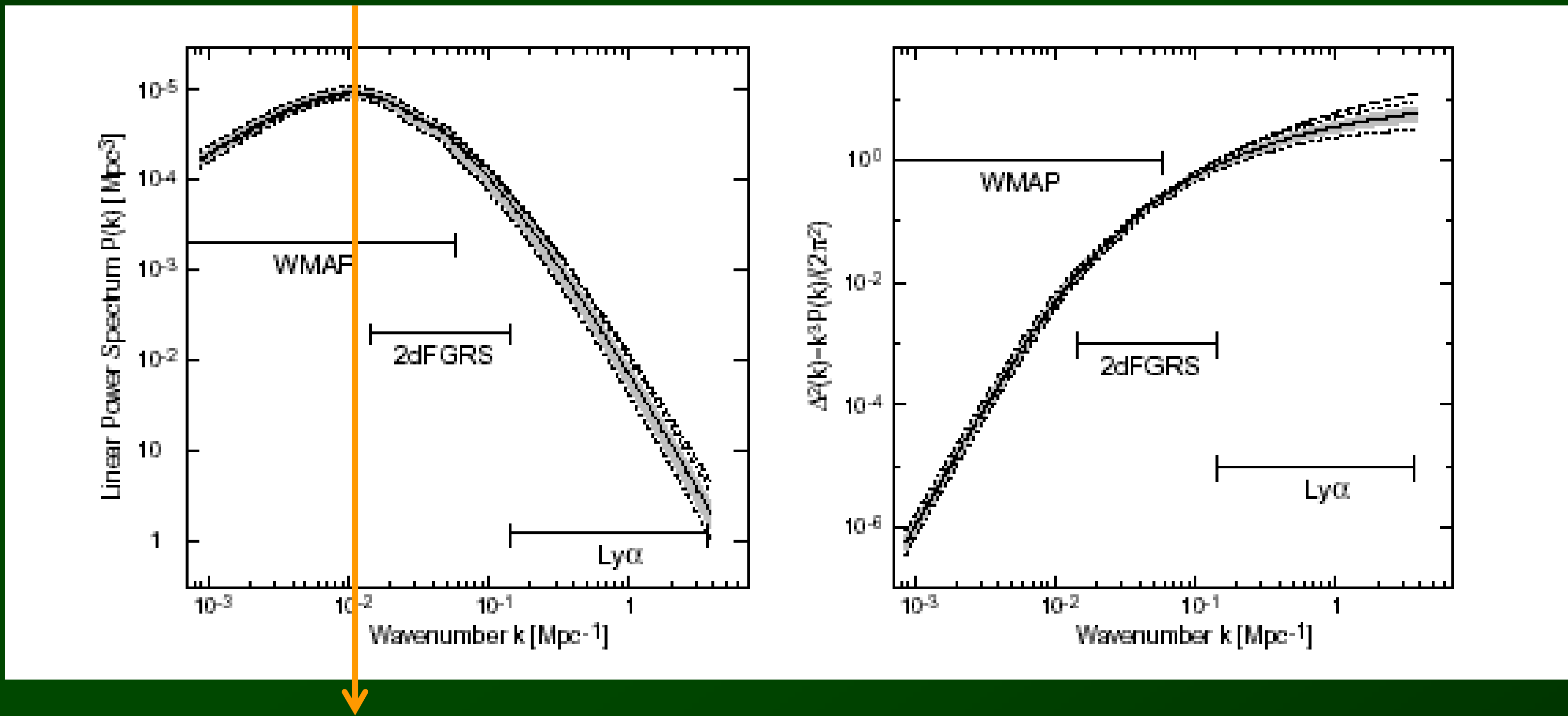
Power spectrum: $\langle \delta_{\mathbf{k}} \delta^*_{\mathbf{k}'} \rangle = (2\pi)^3 P(k)\, \delta_D^{(3)}(\mathbf{k} - \mathbf{k}')$

Linear Power Spectrum

Inflation: Gaussian random field

$$\sigma^2 = \int_0^\infty \frac{dk}{2\pi^2} k^2 P(k)$$

$P(k) \propto k^n$ $n \sim 1$ $P(k) \propto k^{n-4}$



horizon cH^{-1} at matter-radiation equality

Non-linear Collapse

Mass scale:

$$M = \frac{4}{3}\pi\bar{\rho}_0 R^3 = 1.64 \times 10^8 \left(\frac{\Omega_m h^2}{0.141}\right)\left(\frac{R}{100\ \text{kpc}}\right)^3 M_\odot$$

Variance:

$$S(M) = \sigma^2(M) = \sigma^2(R) = \int_0^\infty \frac{dk}{2\pi^2} k^2 P(k) \left[\frac{3 j_1(kR)}{kR}\right]^2$$

$$j_1(x) = (\sin x - x\cos x)/x^2$$

$$\sigma_8 \equiv \sigma(R = 8h^{-1}\text{Mpc})$$

Spherical collapse: (EdS)

$$\delta_{\text{crit}}(z) = \frac{1.686}{D(z)}$$

Virial density:

$$\Delta_c = 18\pi^2 \simeq 178$$

$$U = -2K$$

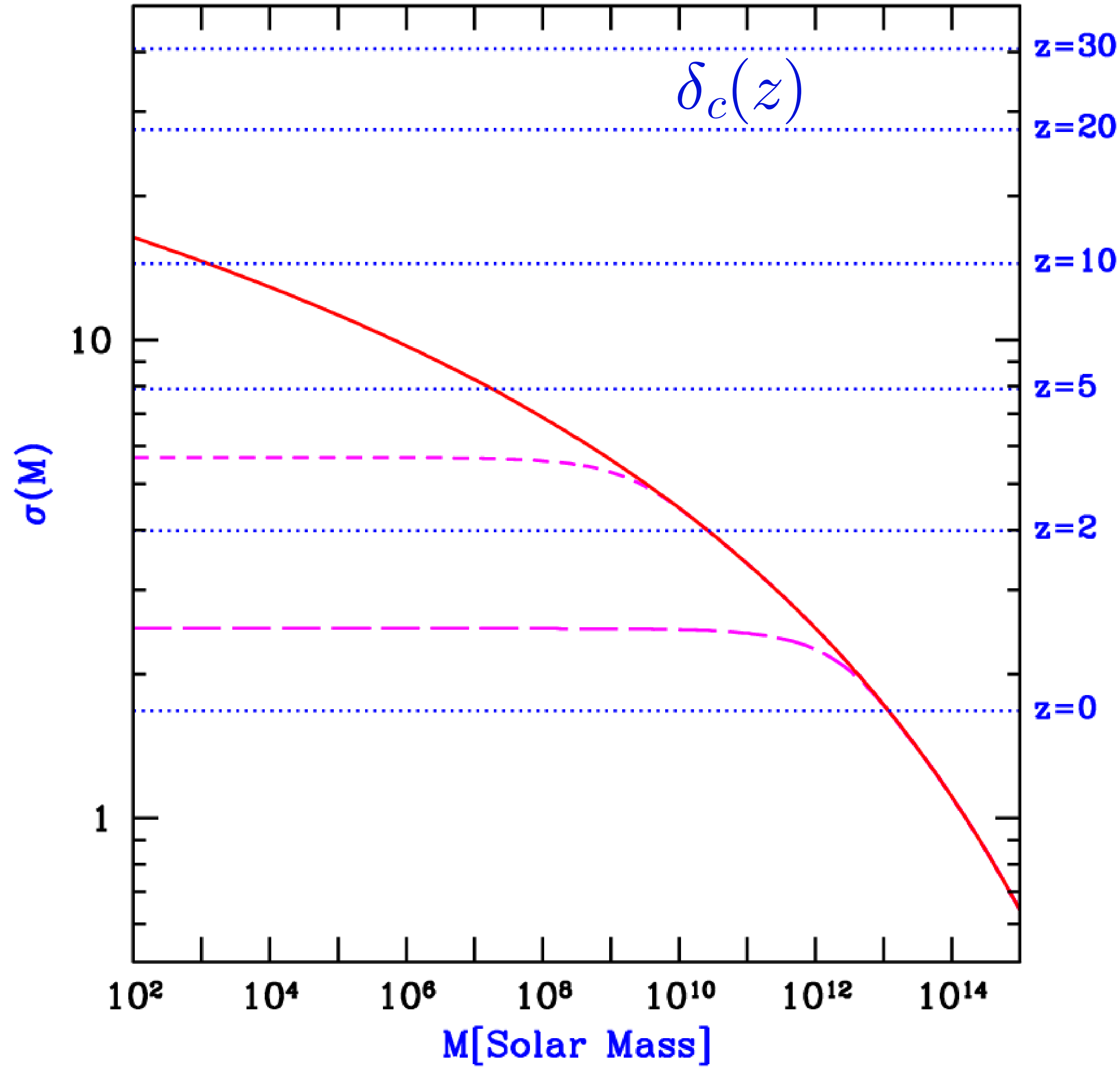
Circular velocity:

$$V_c = \left(\frac{GM}{r_{\text{vir}}}\right)^{1/2} = 16.9 \left(\frac{\Omega_m h^2}{0.141}\right)^{1/6} \left(\frac{M}{10^8\ M_\odot}\right)^{1/3} \left(\frac{\Delta_c}{18\pi^2}\right)^{1/6} \left(\frac{1+z}{10}\right)^{1/2} \text{km s}^{-1}$$

Virial temperature:

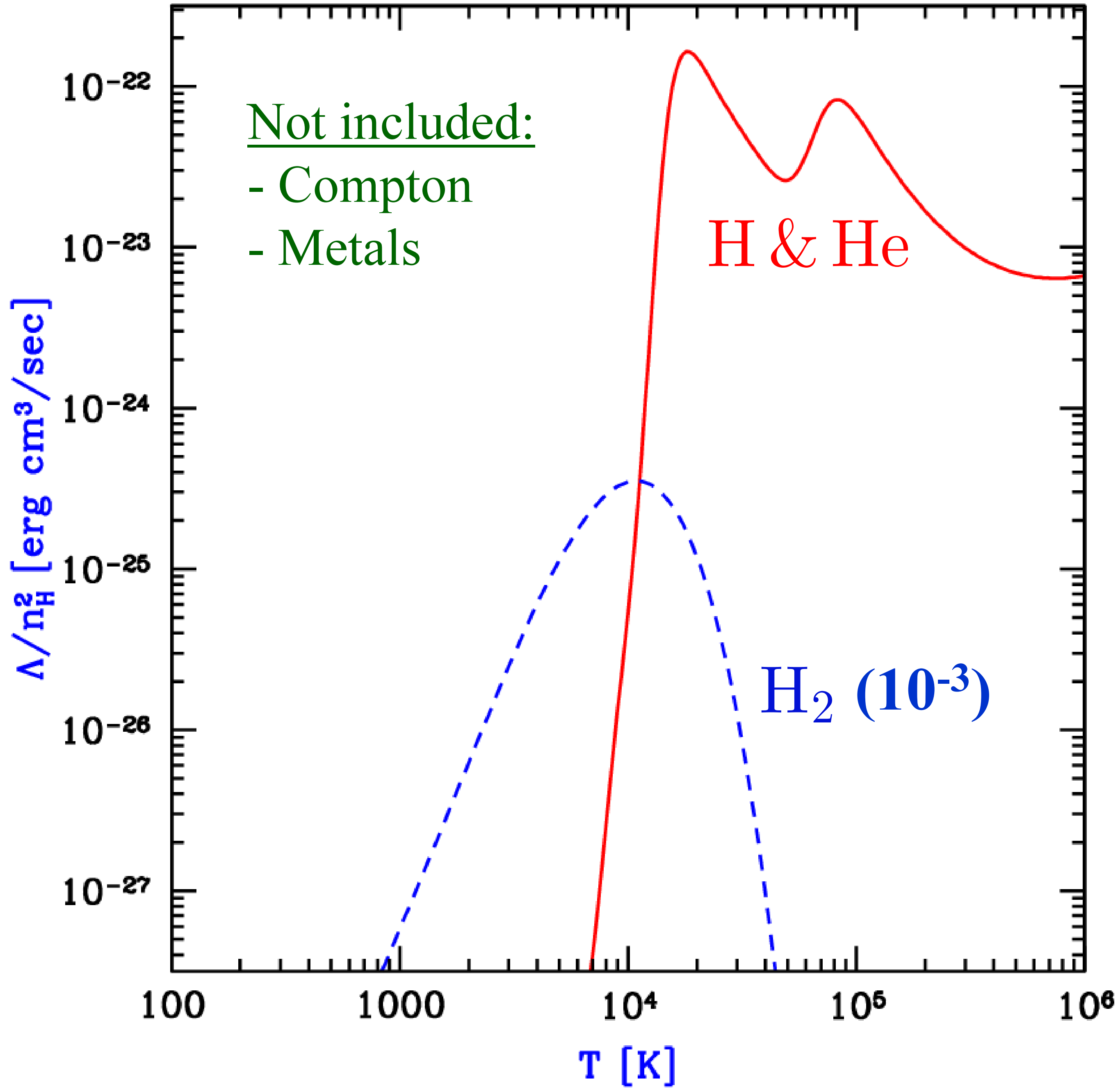
$$T_{\text{vir}} = \frac{\mu m_p V_c^2}{2k_B} = 1.03 \times 10^4 \left(\frac{\Omega_m h^2}{0.141}\right)^{1/3} \left(\frac{\mu}{0.6}\right) \left(\frac{M}{10^8\ M_\odot}\right)^{2/3} \left(\frac{\Delta_c}{18\pi^2}\right)^{1/3} \left(\frac{1+z}{10}\right) \text{K}$$

Mean molecular weight: $\mu = 1.22$ (neutral), 0.61 (ionized H), 0.59 (fully ionized He)



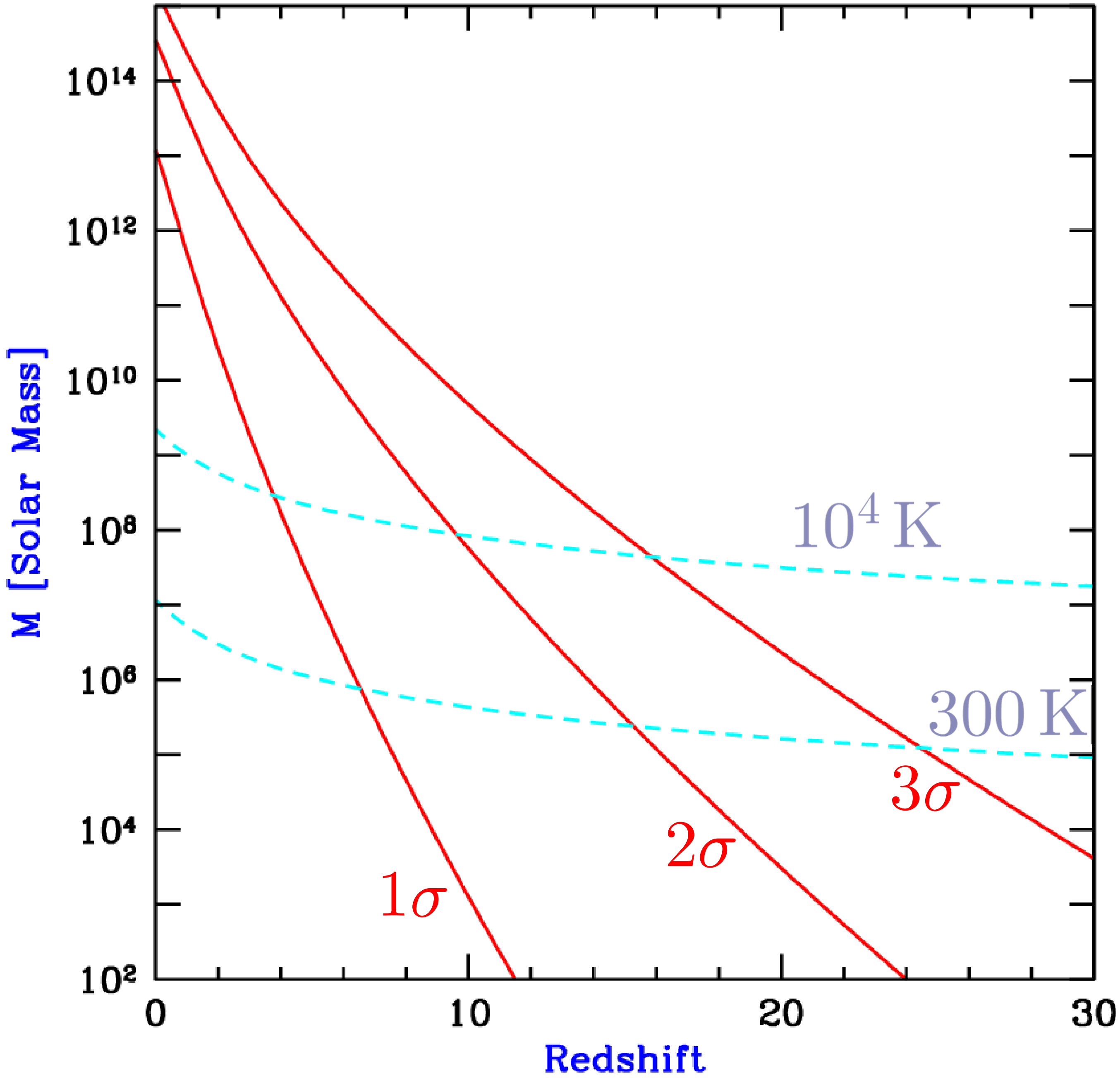
Typical fluctuations compared with the critical value

Barkana & Loeb 2001



Cooling rate of a primordial cosmic gas

Barkana & Loeb 2001



Galactic halos

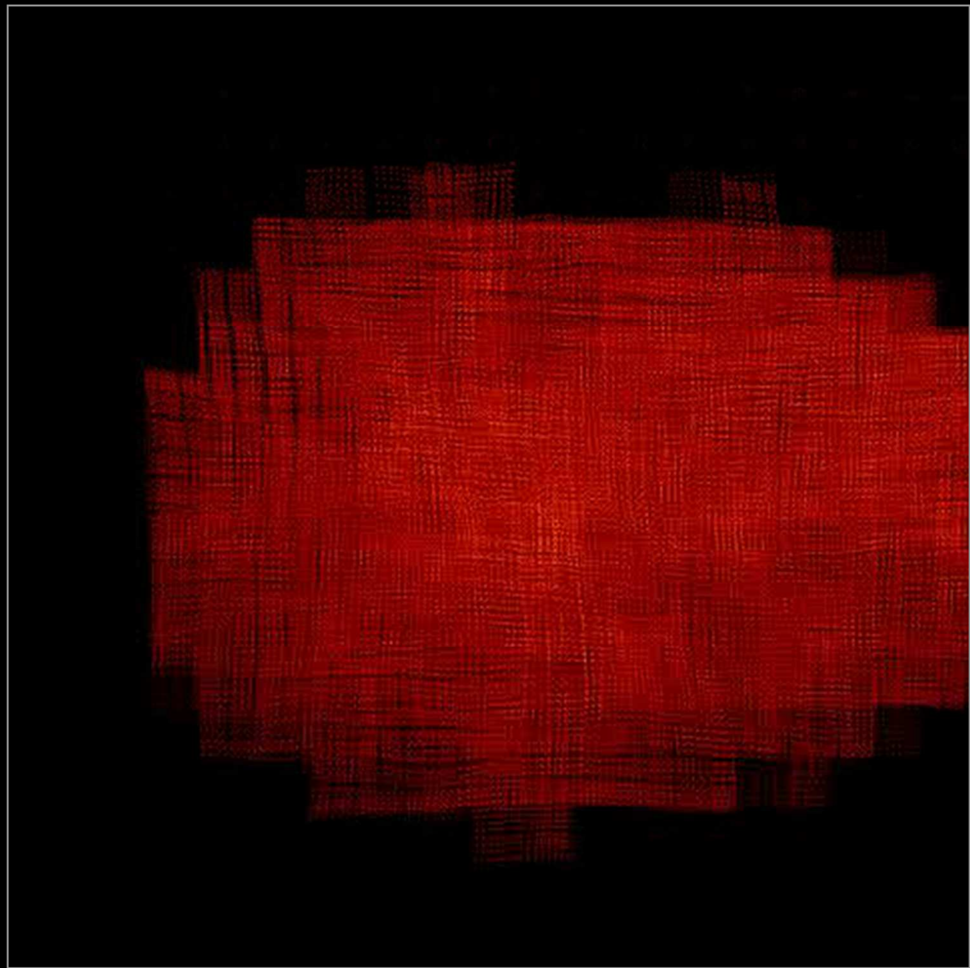
Barkana & Loeb 2001

Hierarchical Galaxy Formation:

CDM

$P(k) \propto$ CDM

20 kpc box



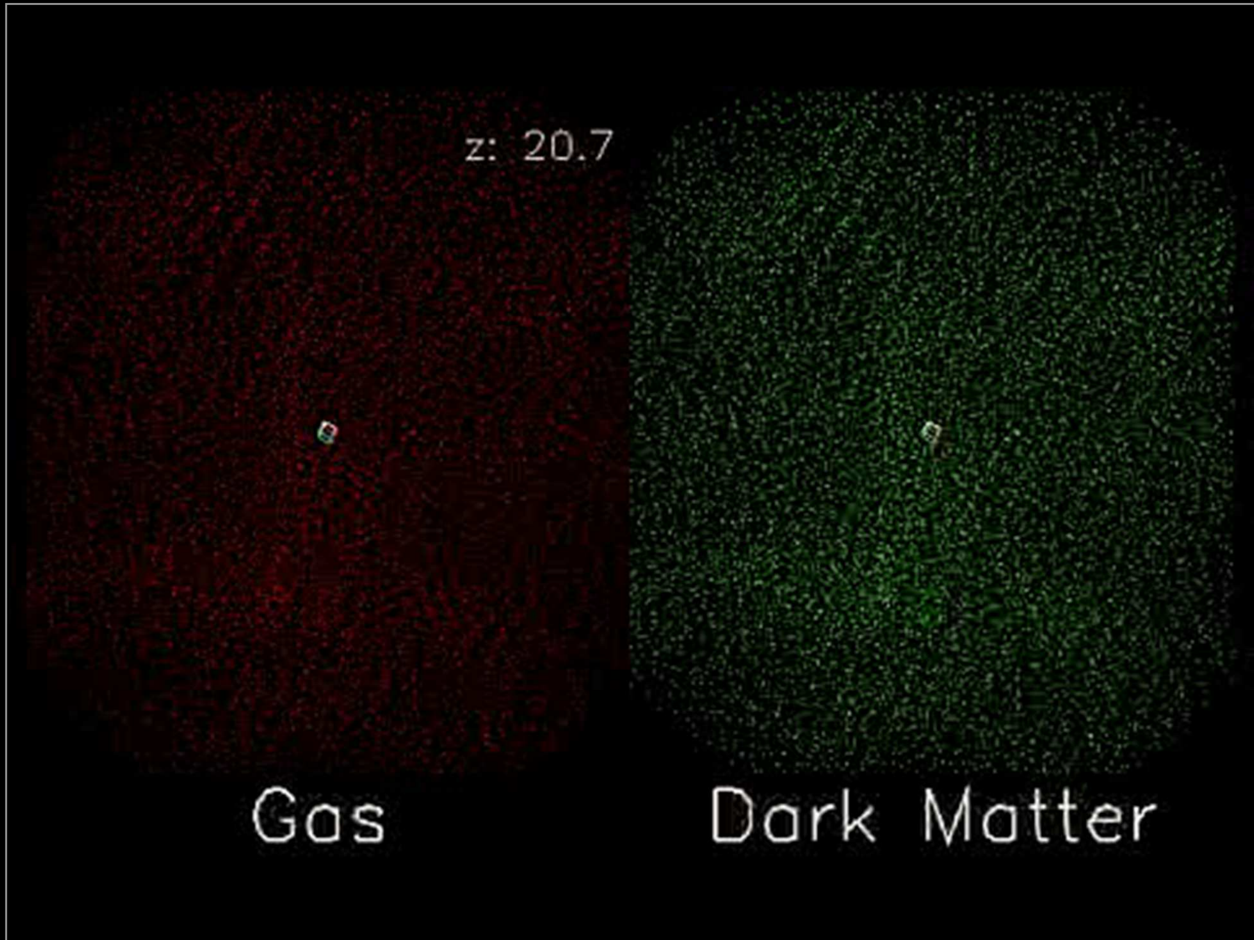
Credits: Matthias Steinmetz

http://www.aip.de/People/MSteinmetz/E/movies.html

Hierarchical Galaxy Formation:

CDM

$P(k) \propto$ CDM



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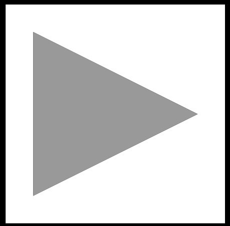
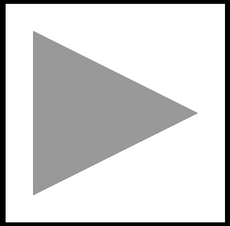
The universe today: 

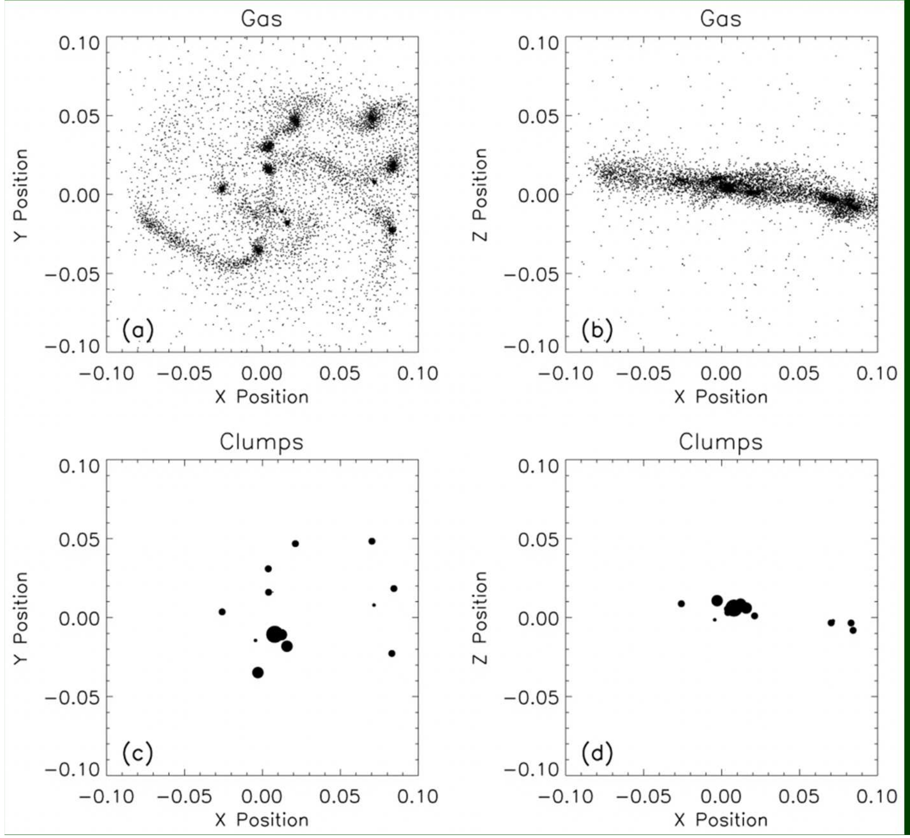
http://www.mpa-garching.mpg.de/galform/millennium/

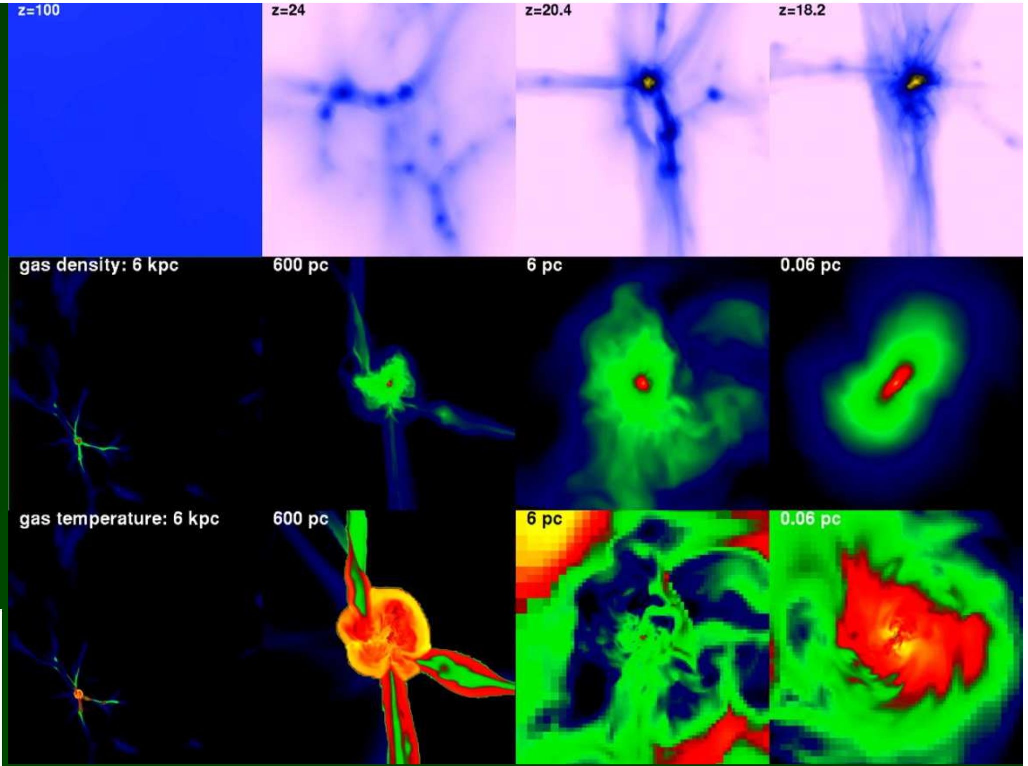
Formation of a galaxy cluster: 

http://www.mpa-garching.mpg.de/galform/data_vis/

The First Star (simulations)

Bromm et al. (1999)



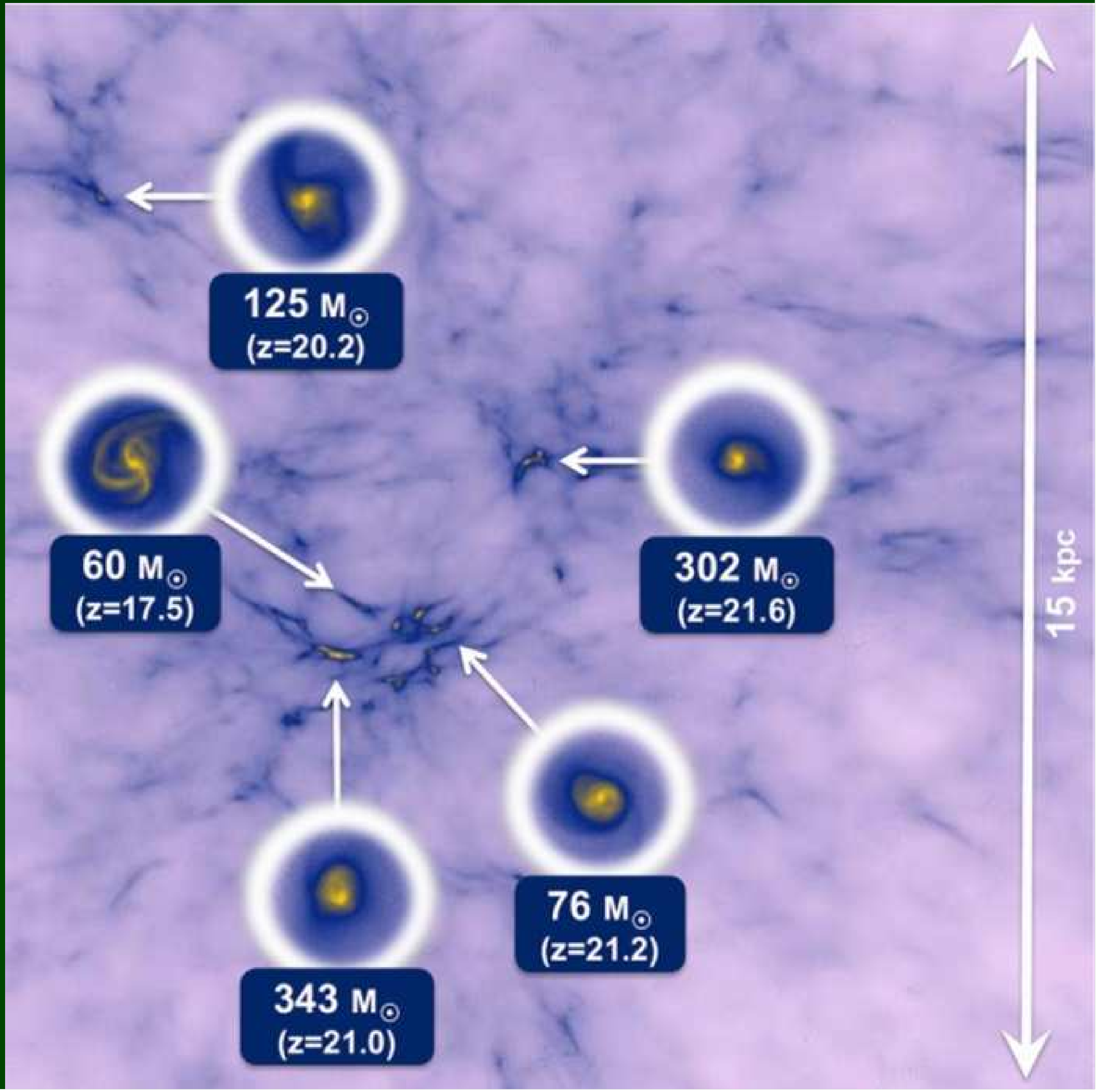


Abel et al. (2002)

$z = 18.2$;   128 kpc (AMR)

$z = 28$;   150 pc (artificial)

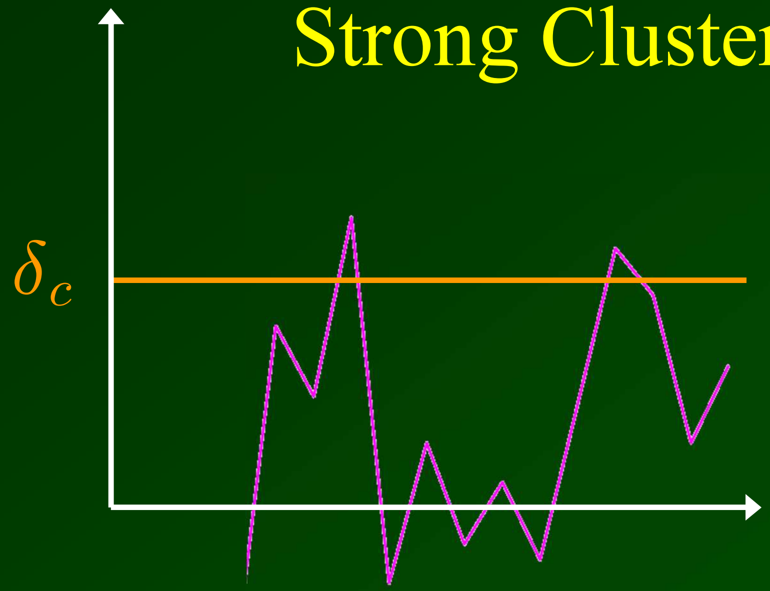
The First Star (simulations)



Hirano et al. (2014)

2 / *h* Mpc

Strong Clustering of Early Galaxies



Extended Press-Schechter

Peak-Background Split

Press & Schechter 1974

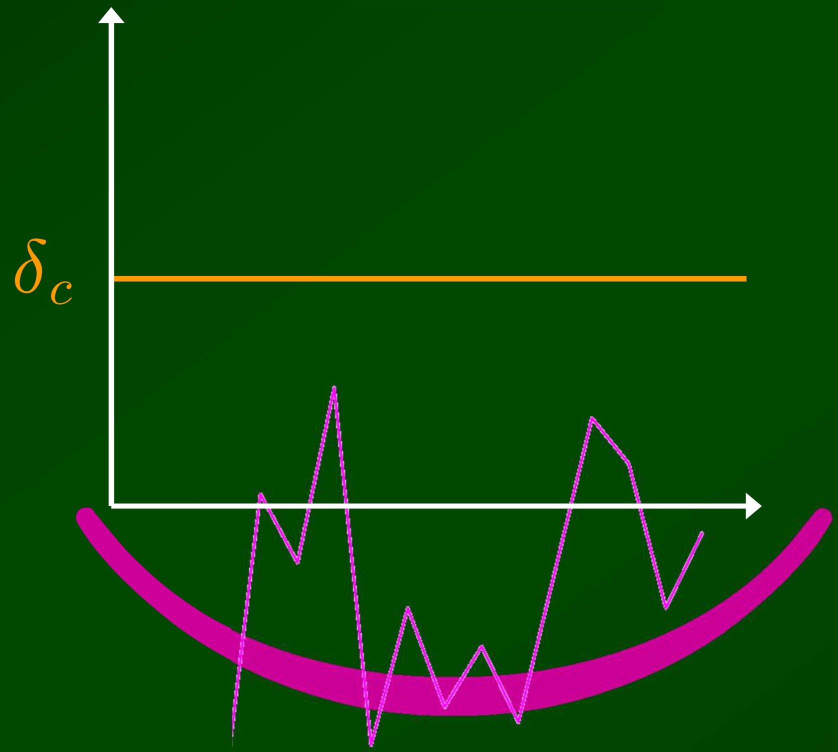
Bardeen, Bond, Kaiser, & Szalay 1986

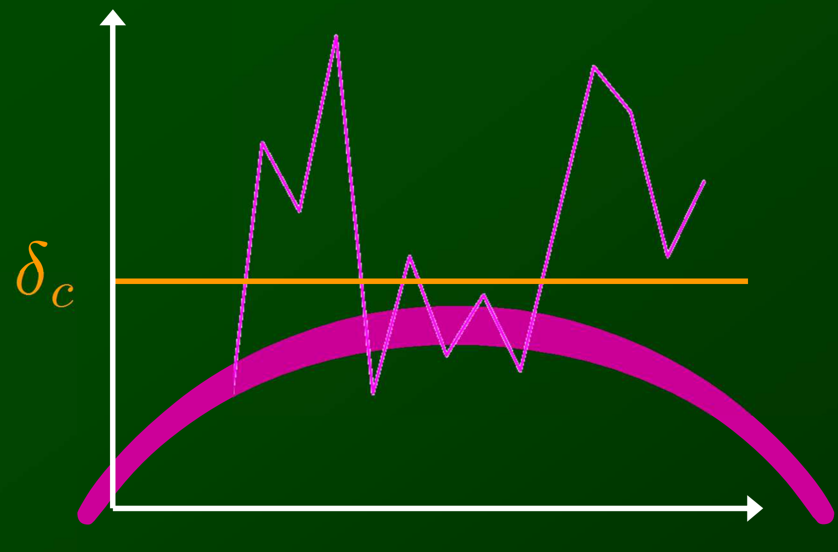
Kaiser 1984

Bond, Cole, Efstathiou, & Kaiser 1991

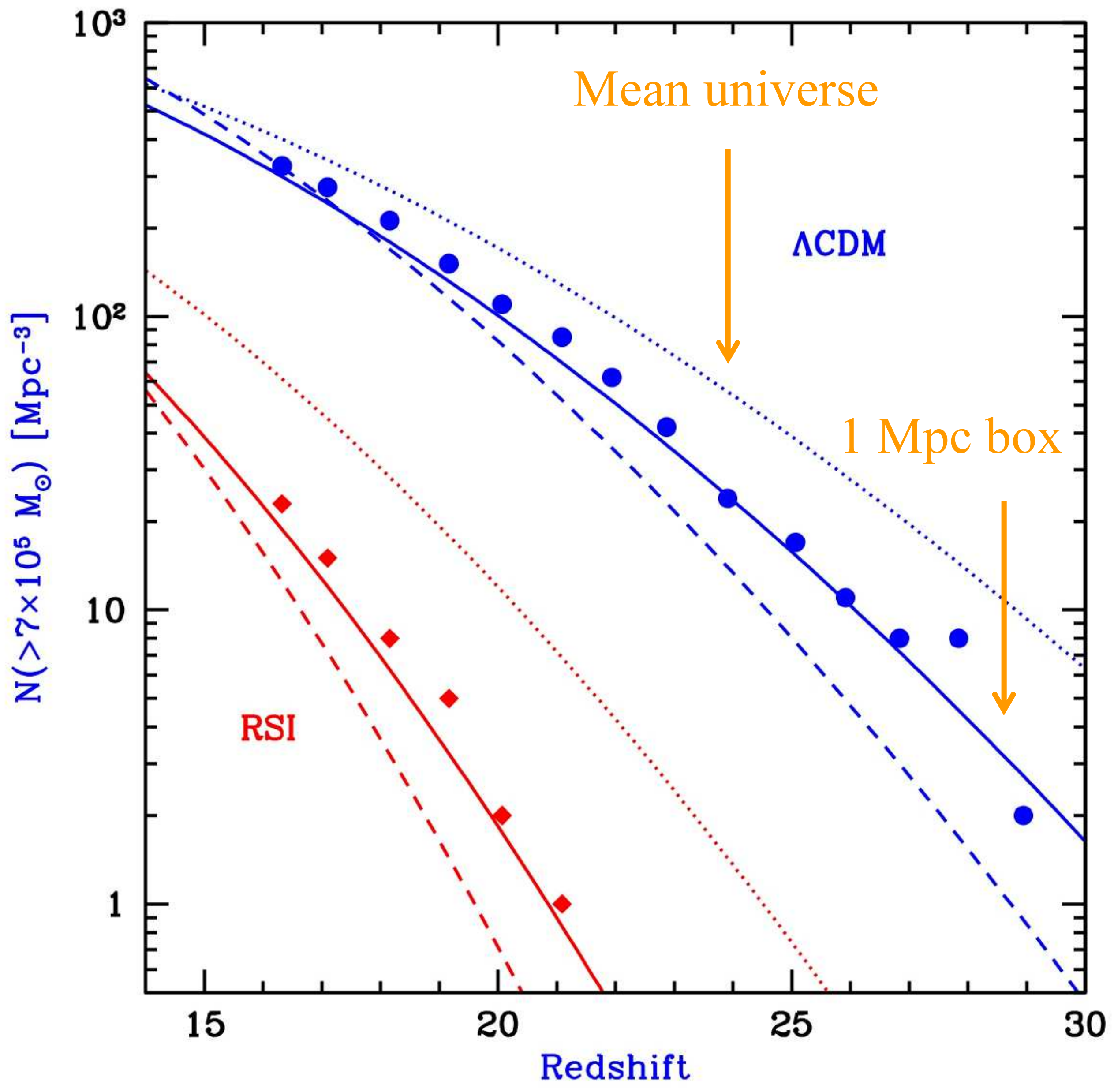
Cole & Kaiser 1989

Mo & White 1996





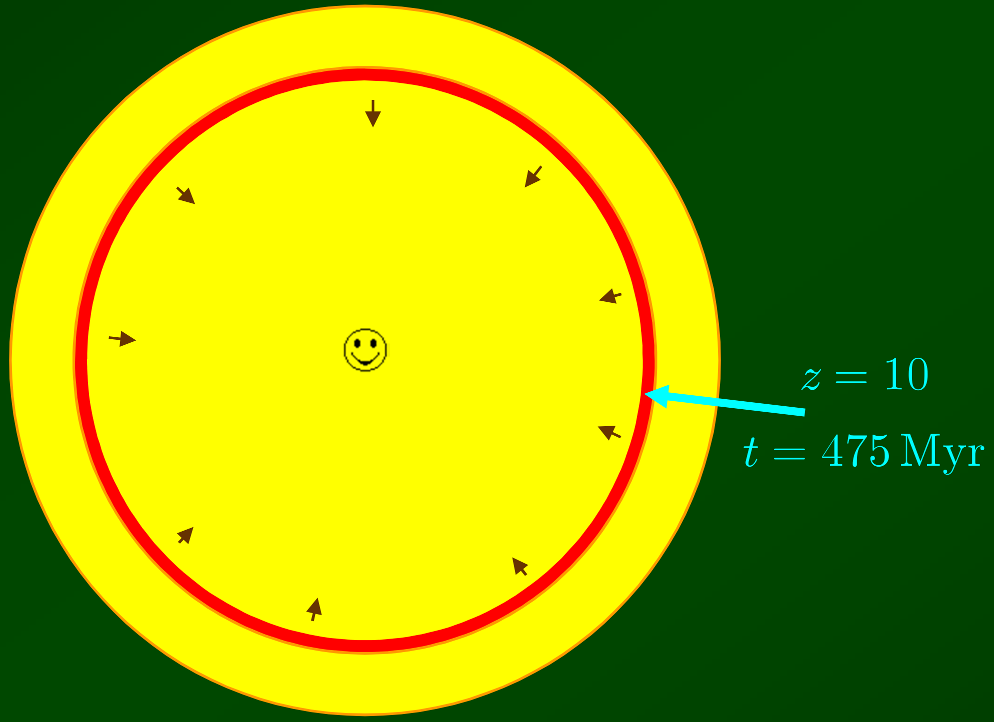
The First Star (theory)



Simulations:
Yoshida et al. (2003)

RB & Loeb (2004)

The First Star (theory)



Naoz, Noter, & RB (2006)

$z \sim 65 \quad (t \sim 30\ \mathrm{Myr})$

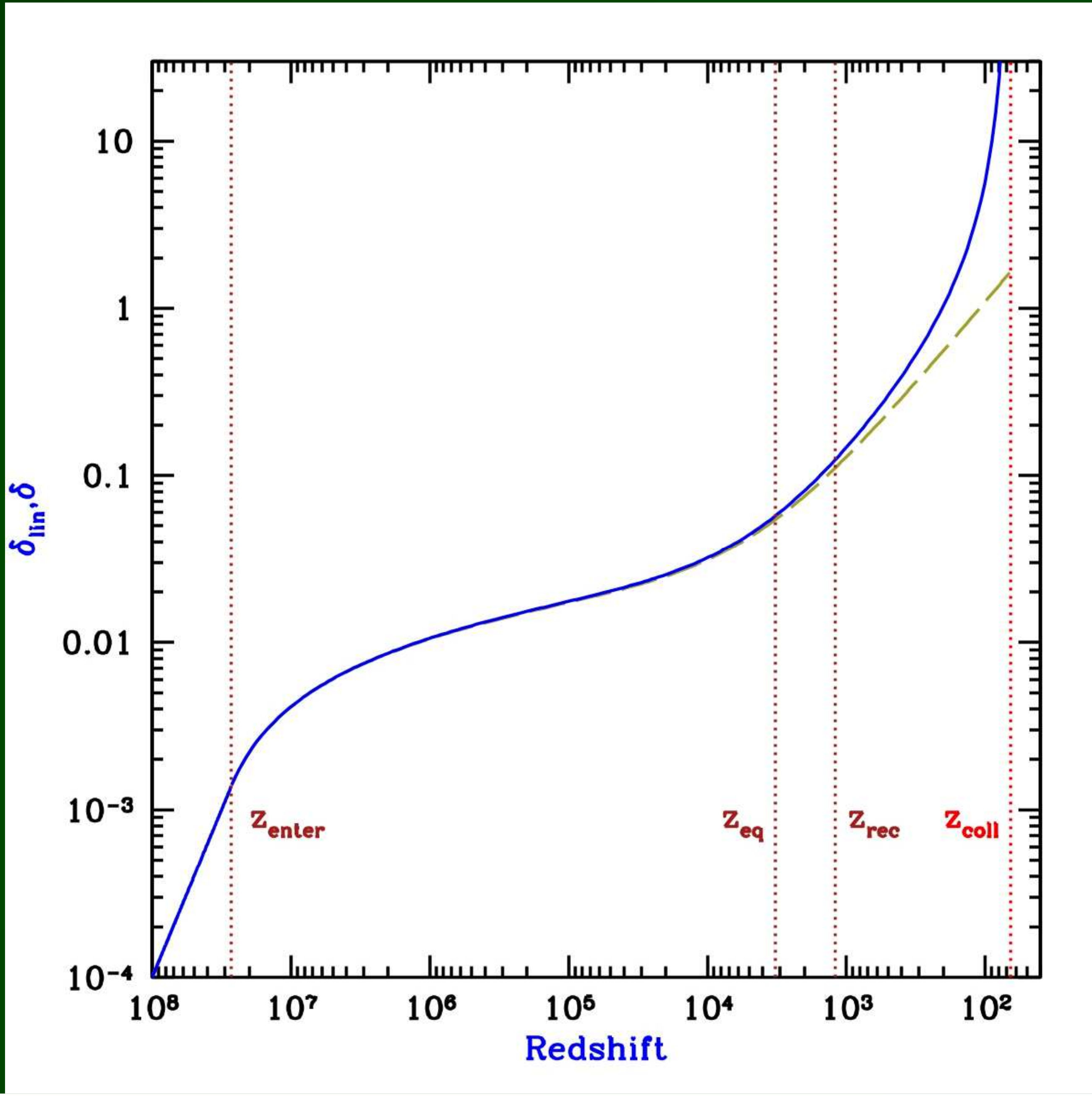
Compare:

$z \sim 30 \quad (t \sim 100\ \mathrm{Myr})$

Small galaxies ⟷ Large scales

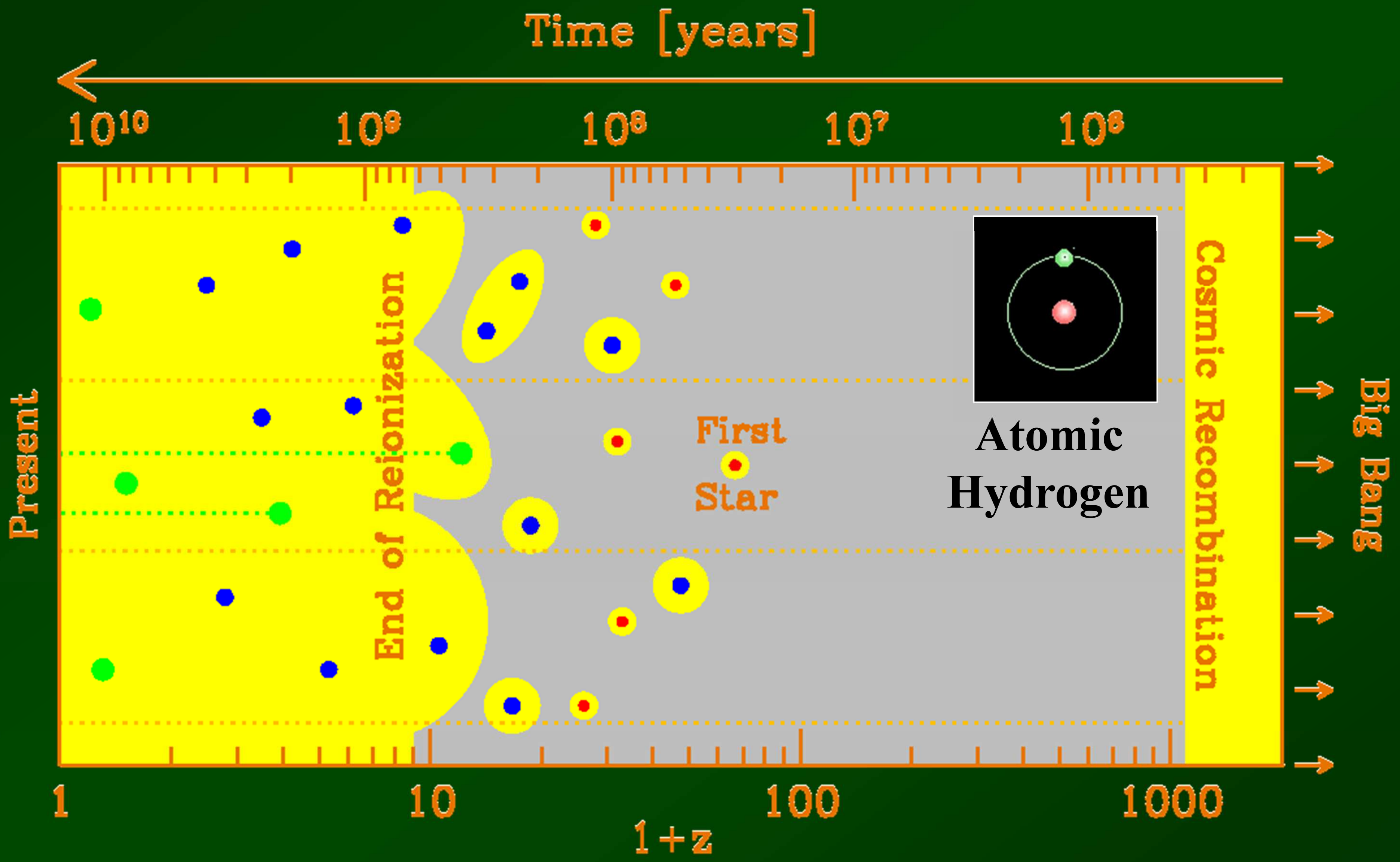
The First Star (theory)

The second star: feedback



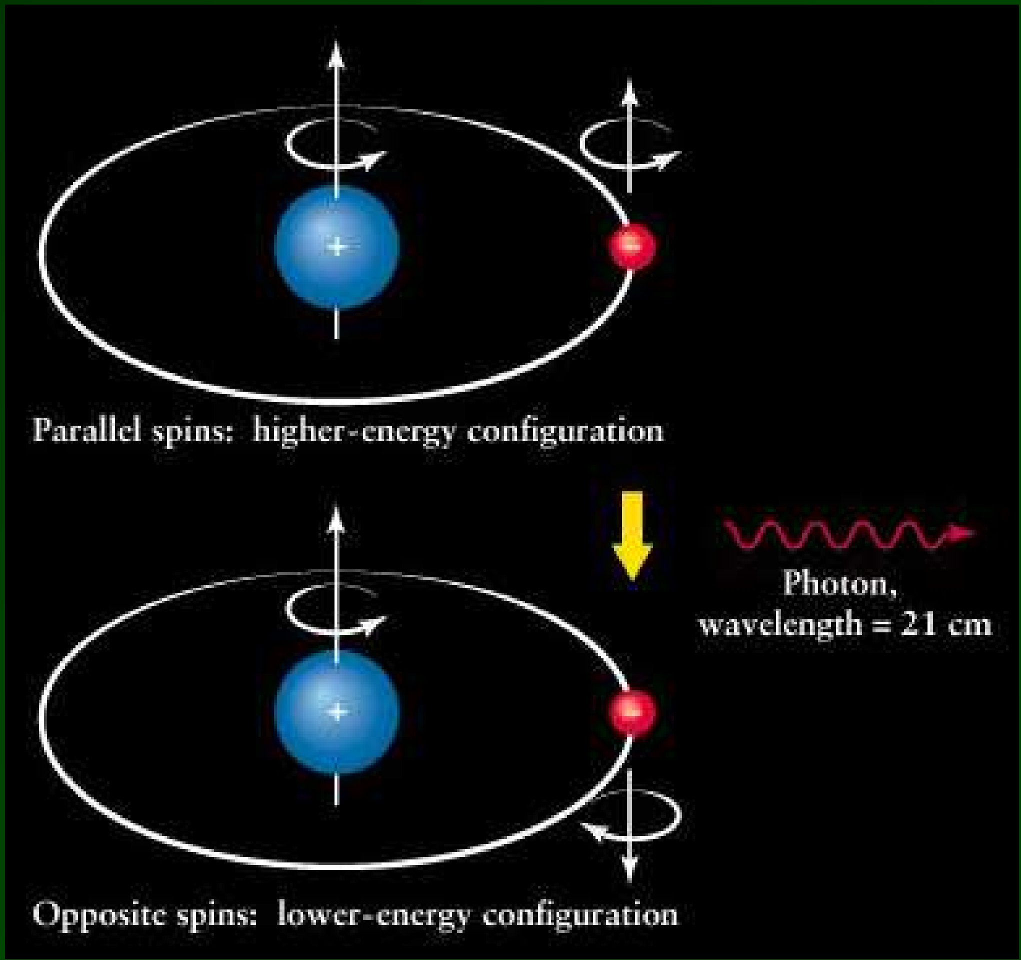
Naoz, Noter, & RB (2006)

Cosmic History



RB 2006, Science

Atomic Physics : The Spin Temperature



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

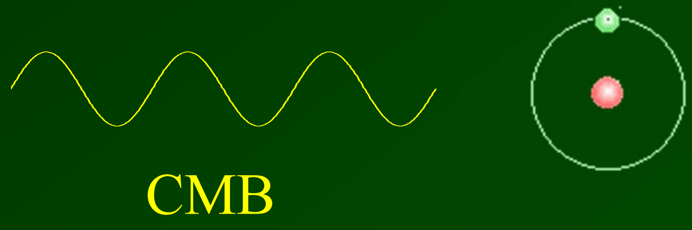
$$\nu = 1420\,\mathrm{MHz}$$

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

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

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

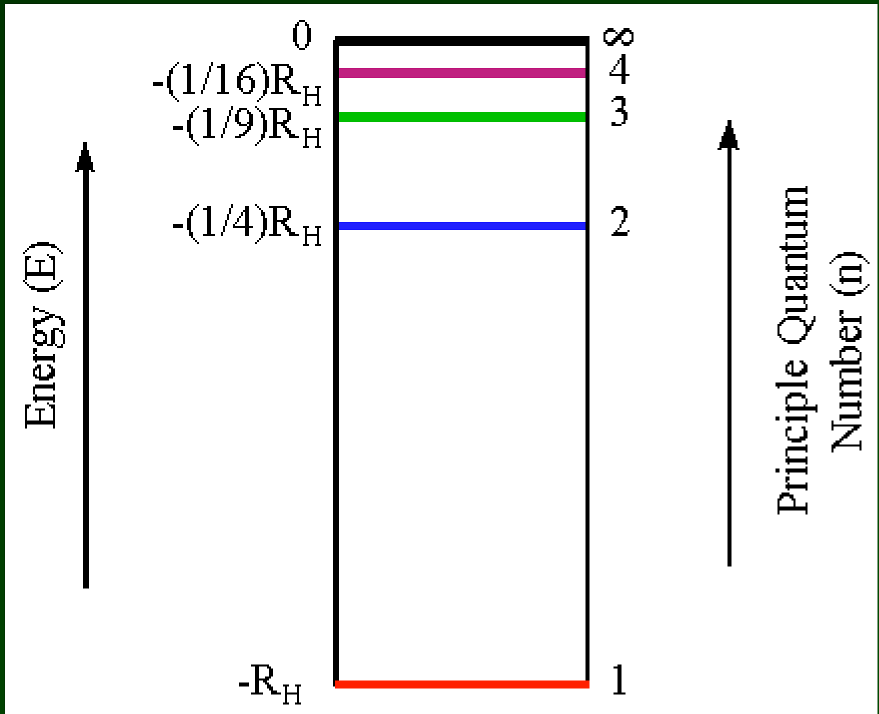
What determines T_S?



$$T_S \rightarrow T_{\mathrm{CMB}}$$

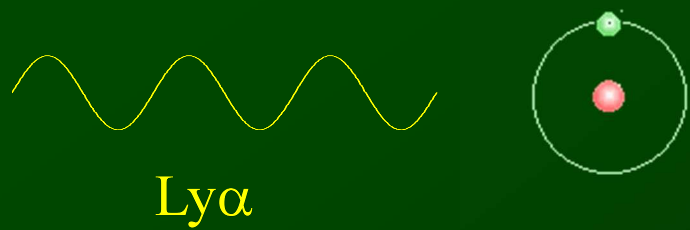
$$T_S \rightarrow T_{\mathrm{gas}}$$

What determines T_S?

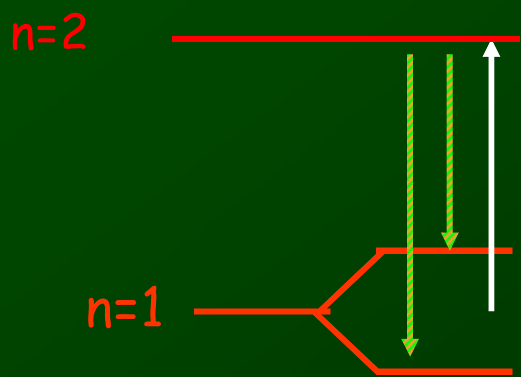


$$\mathrm{LLimit}: \quad 13.6 \ \ \mathrm{eV}$$

$$\mathrm{Ly}\alpha: \quad \tfrac{3}{4}\mathrm{LL} = 10.2 \ \ \mathrm{eV}$$

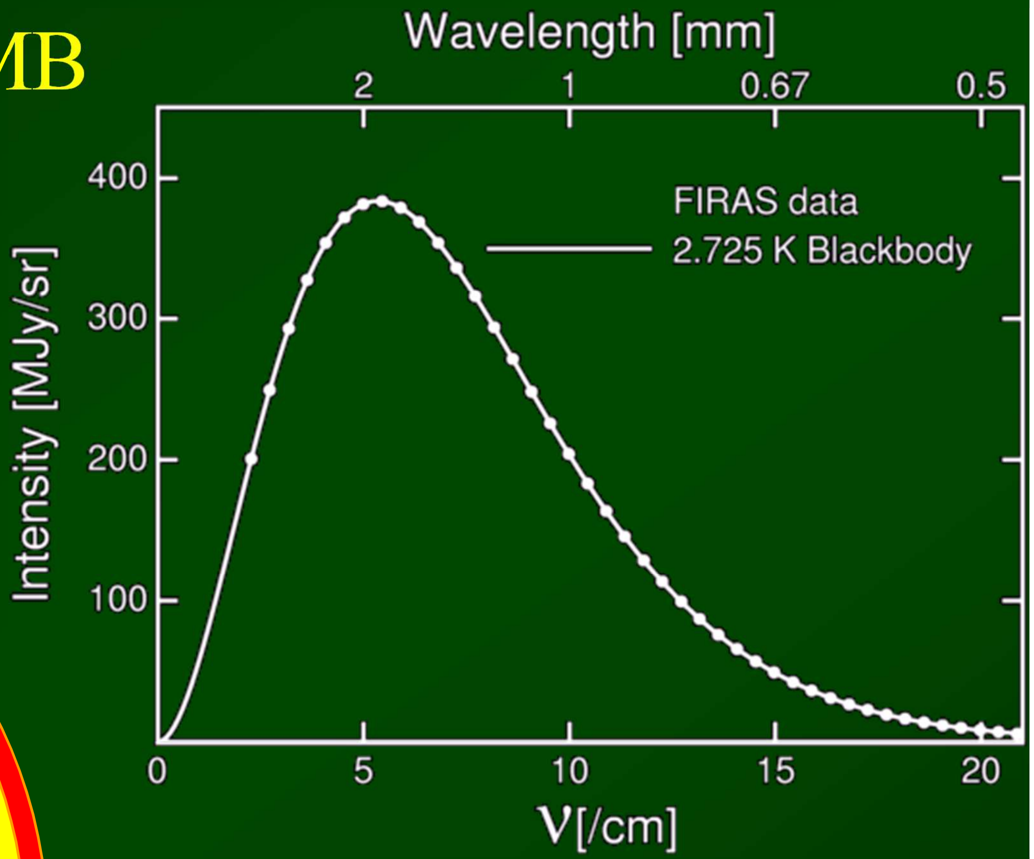


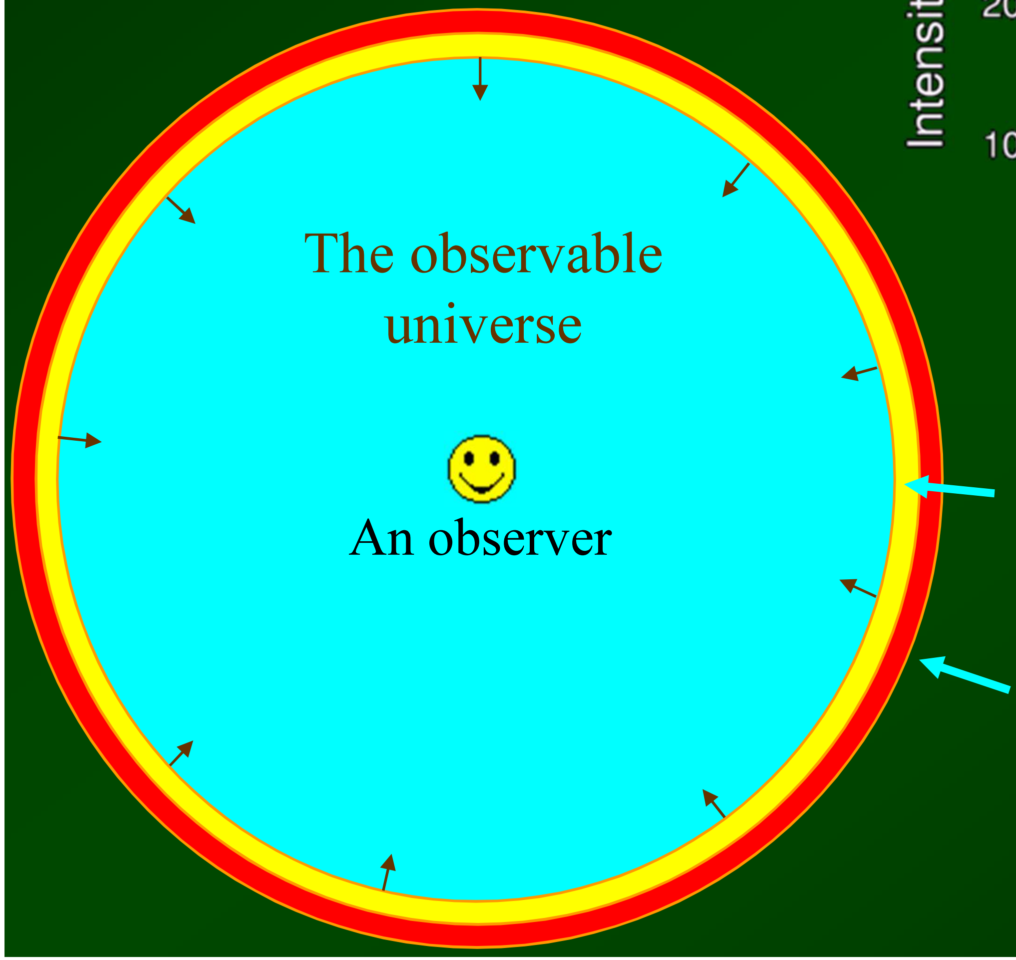
Wouthuysen 1952
Field 1958



$$T_S \rightarrow T_{\mathrm{gas}}$$

Diffuse Source: The CMB

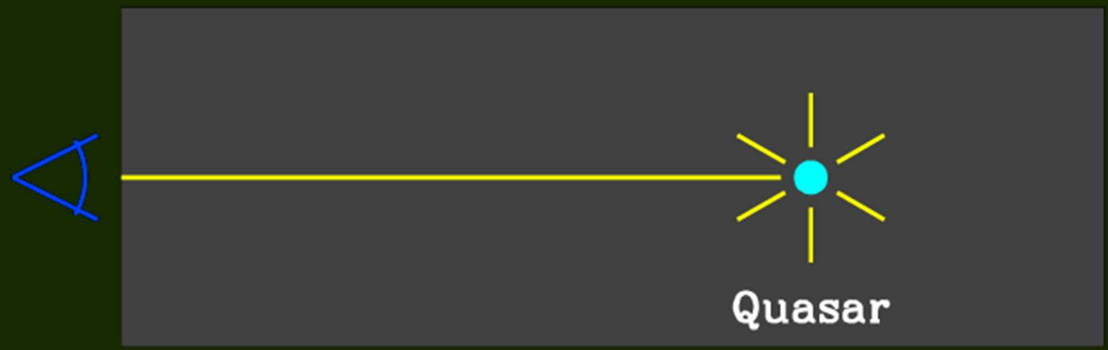


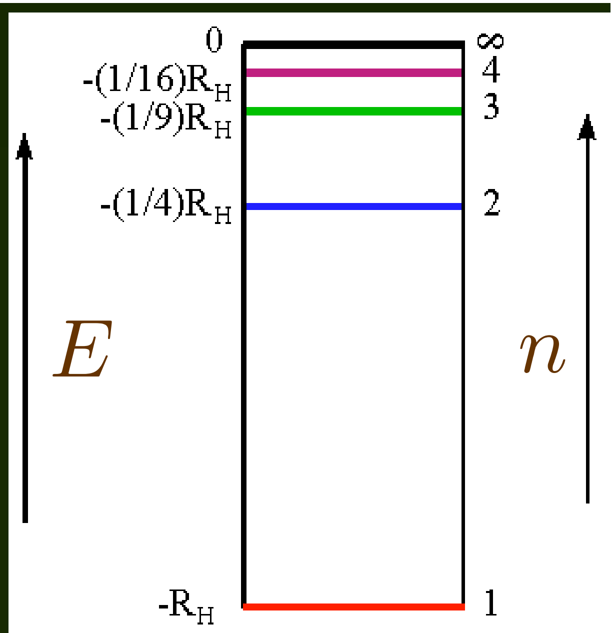


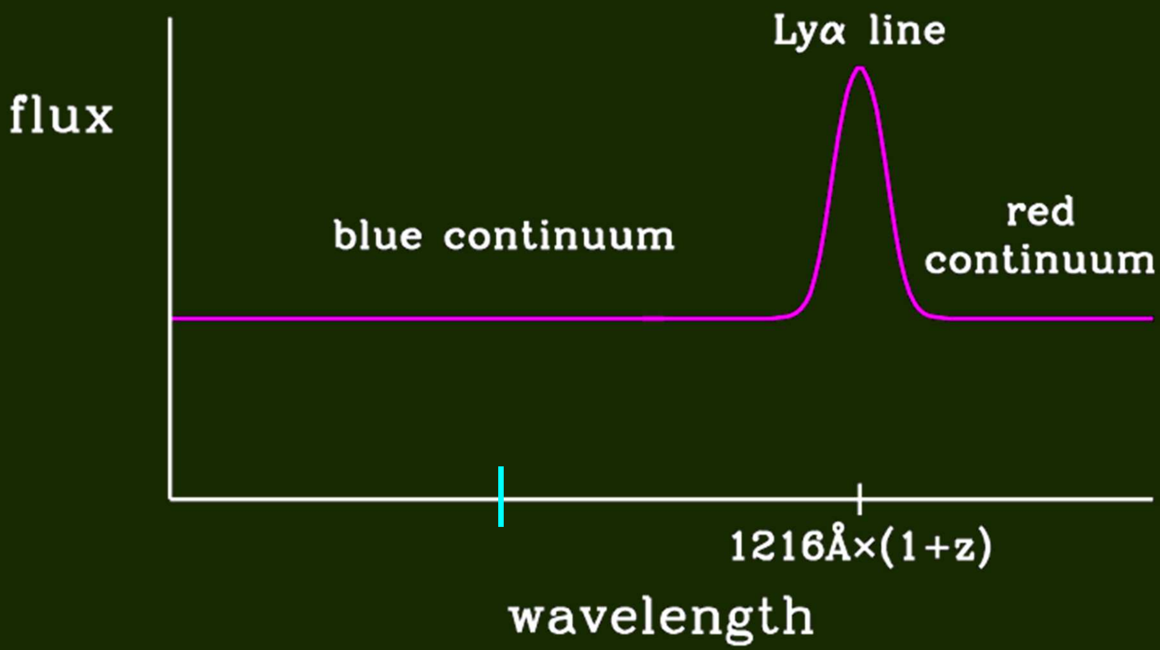
$$h\nu \ll k_B T$$

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

Lyα Spectra:



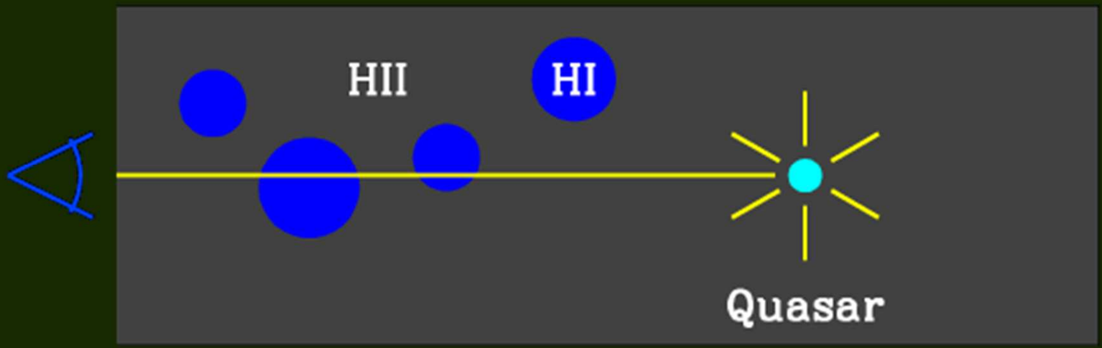


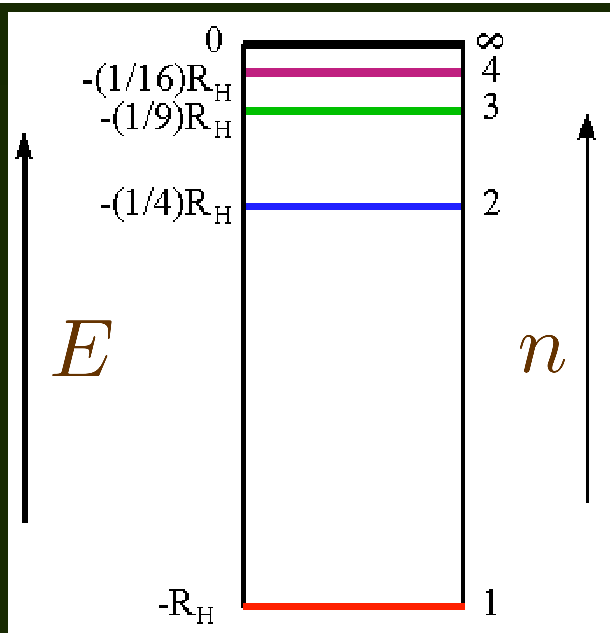


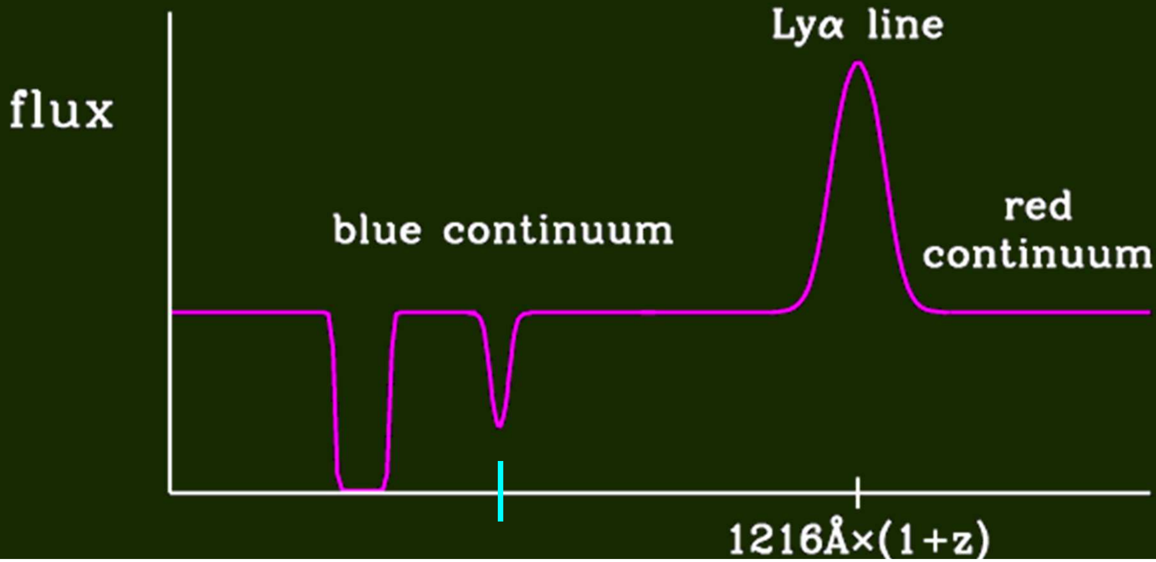
Resonance Line + Cosmological Redshift

$$1100\text{Å} \times (1+z)$$

Lyα Spectra: 1D density distribution



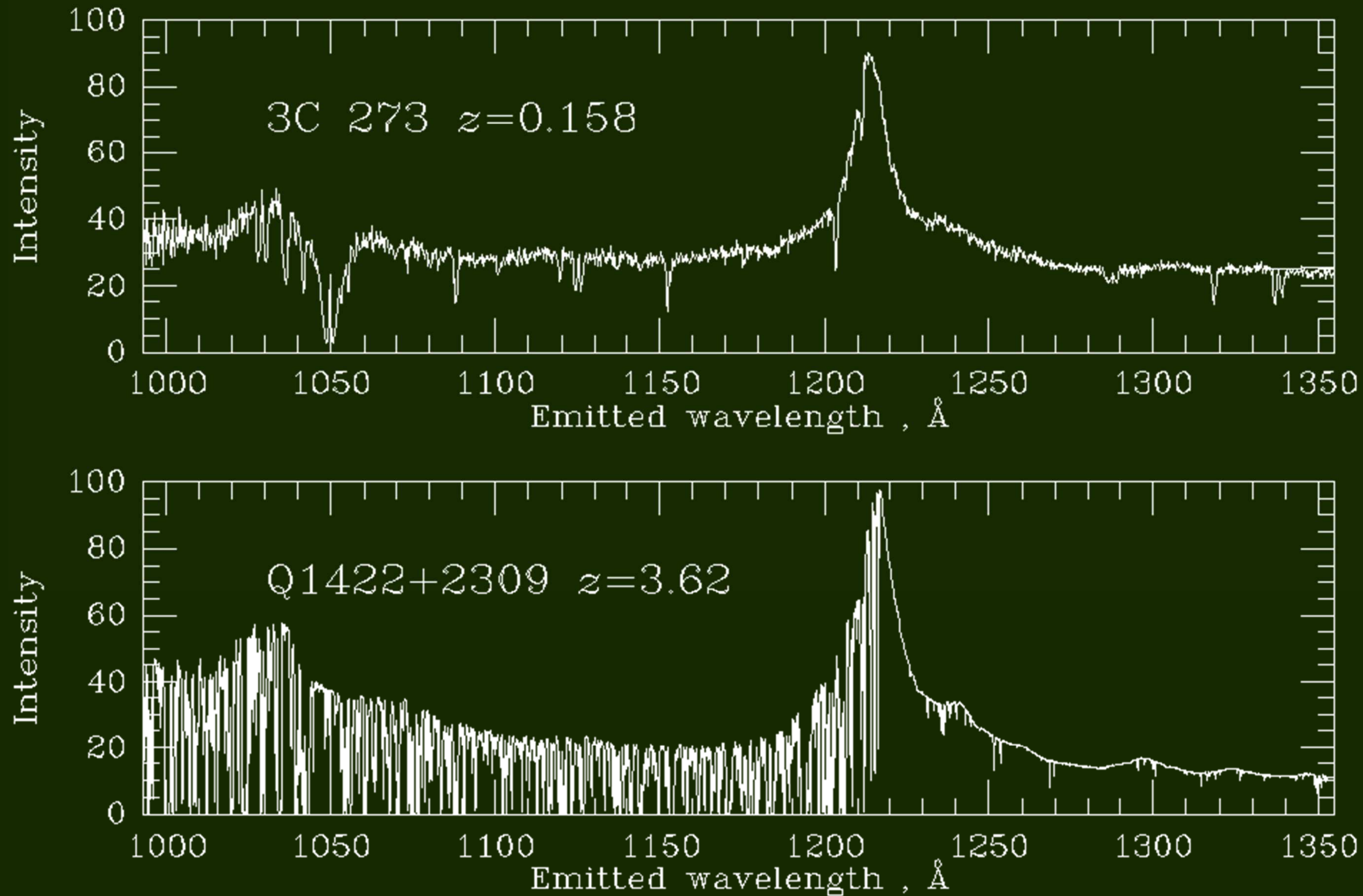




Resonance Line + Cosmological Redshift

$$1100\text{Å} \times (1+z)$$
$$= 1216\text{Å} \times (1+z')$$

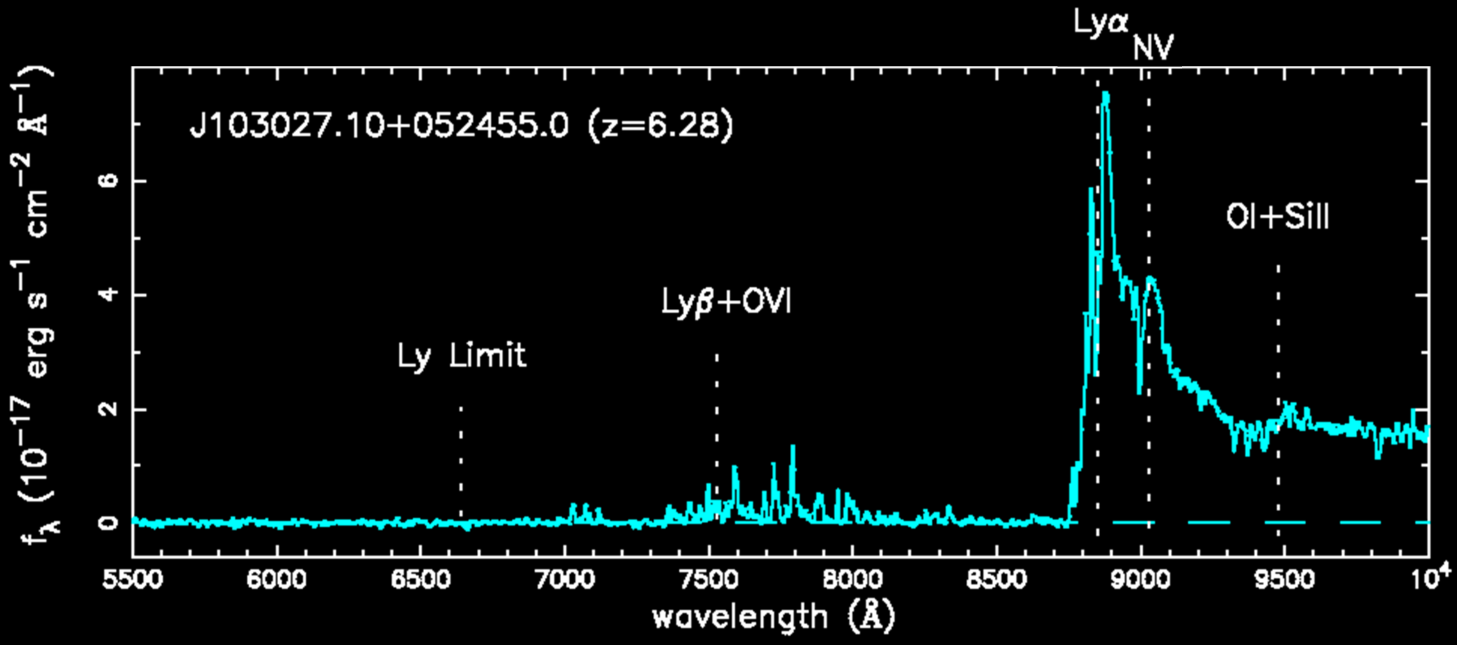
Gunn & Peterson 1965: $\tau_{\rm GP} = \dfrac{\pi e^2 f_\alpha \lambda_\alpha n_{\rm H\,I}}{m_e c H} = 6.62 \times 10^5 \left(\dfrac{\Omega_b h}{0.0327}\right)\left(\dfrac{\Omega_m}{0.307}\right)^{-1/2}\left(\dfrac{1+z}{10}\right)^{3/2}$



Keck, HST; Mike Rauch

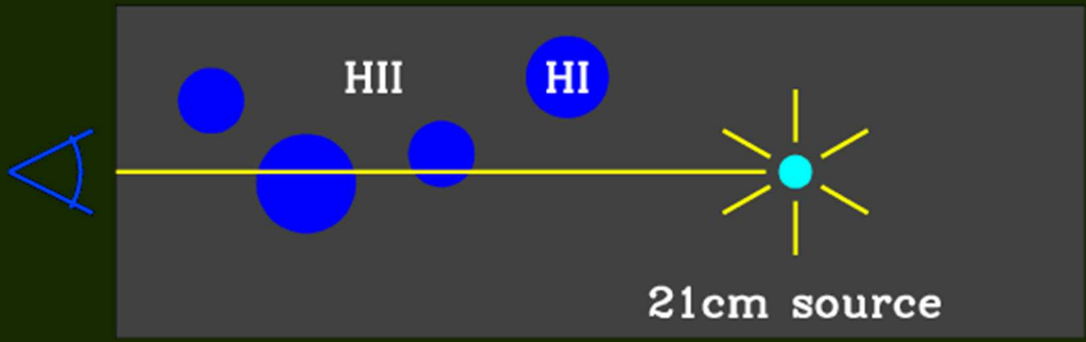
http://www.astr.ua.edu/keel/agn/forest.html

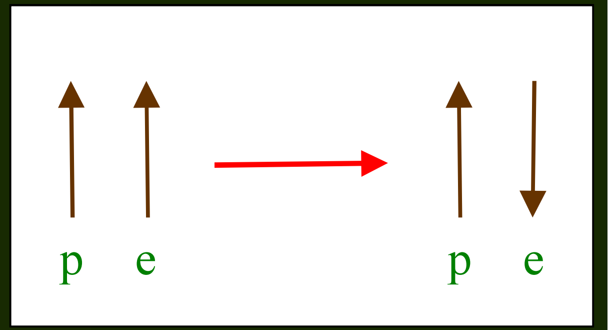
Quasar at $z = 6.3$

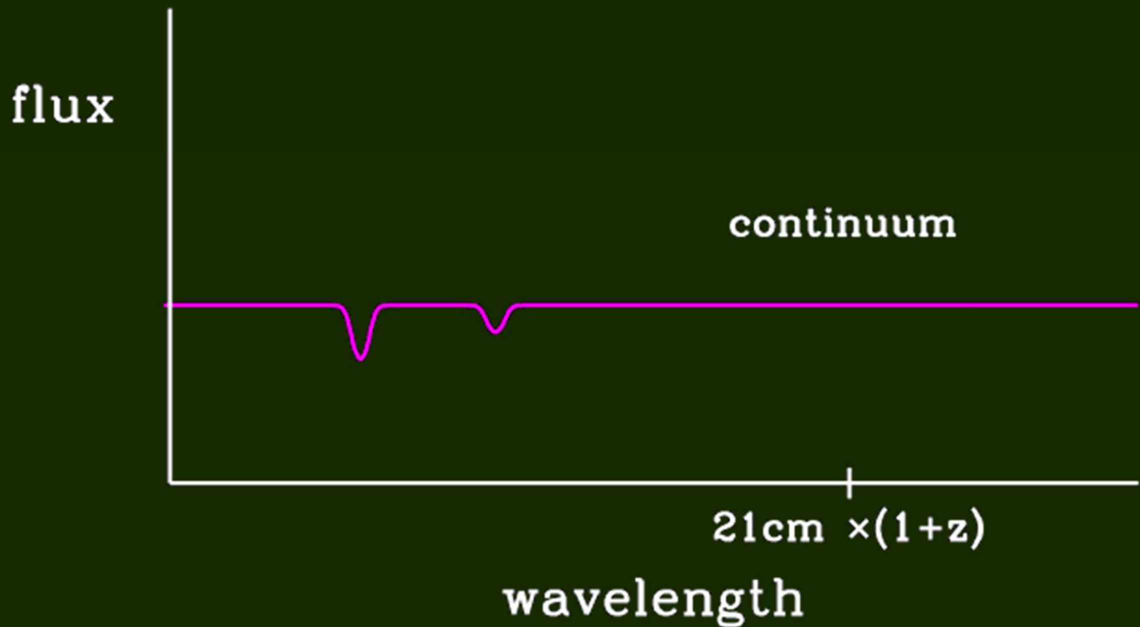


Becker et al. 2001

21-cm Spectra

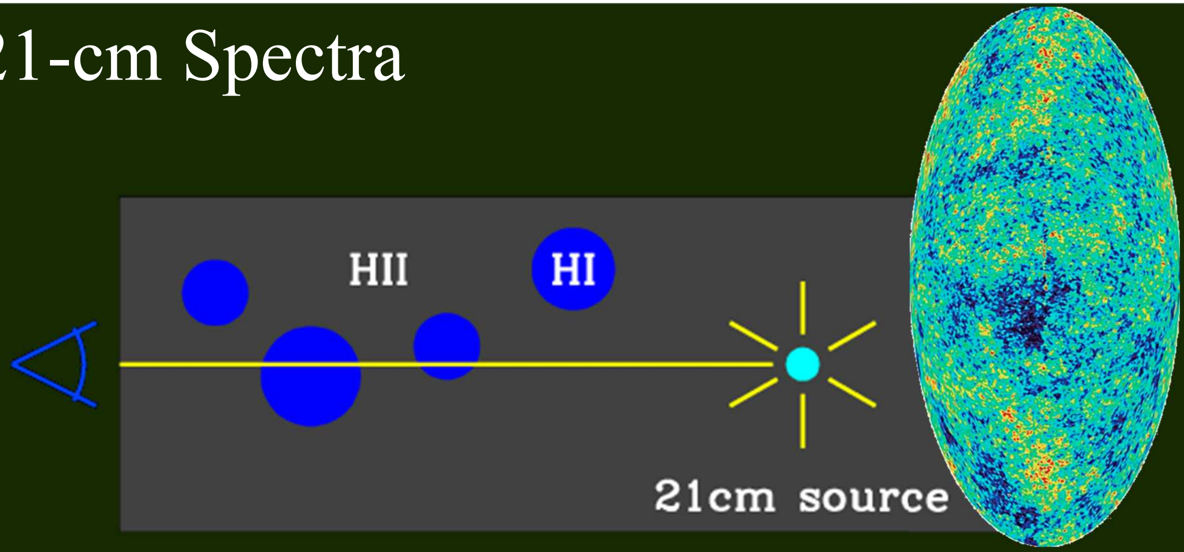


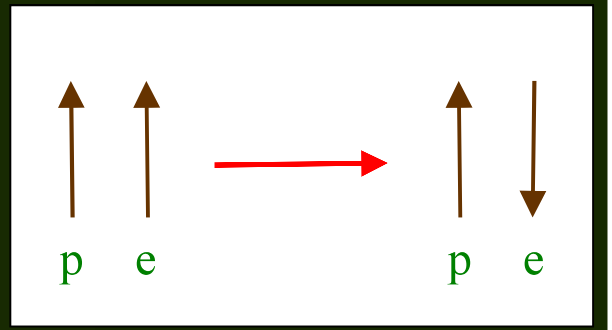


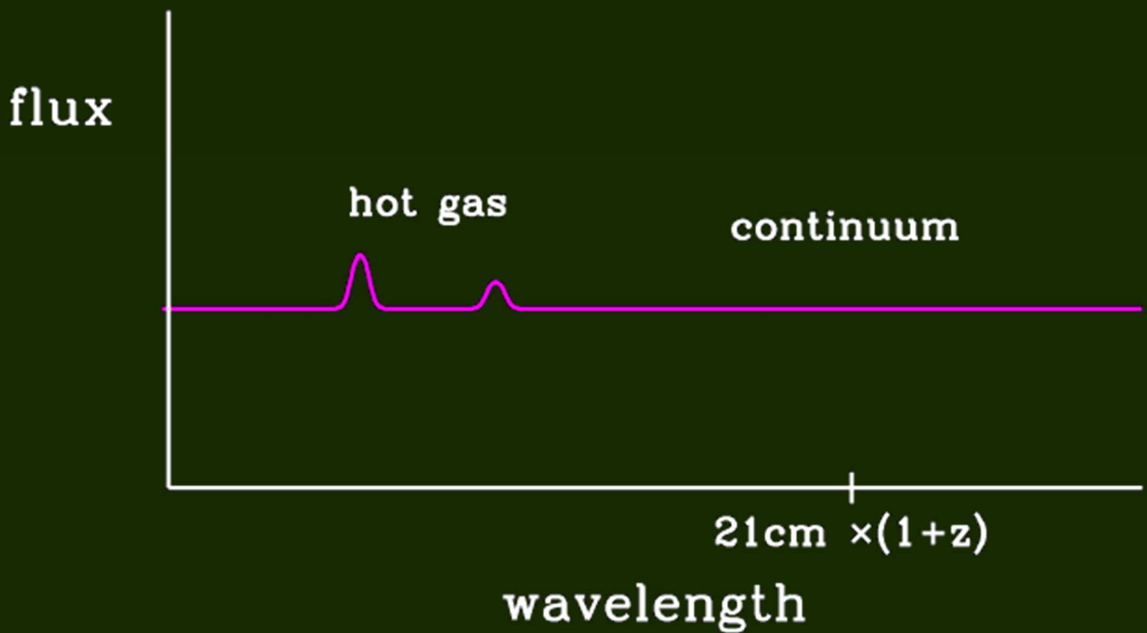


Resonance Line +
Cosmological Redshift

21-cm Spectra



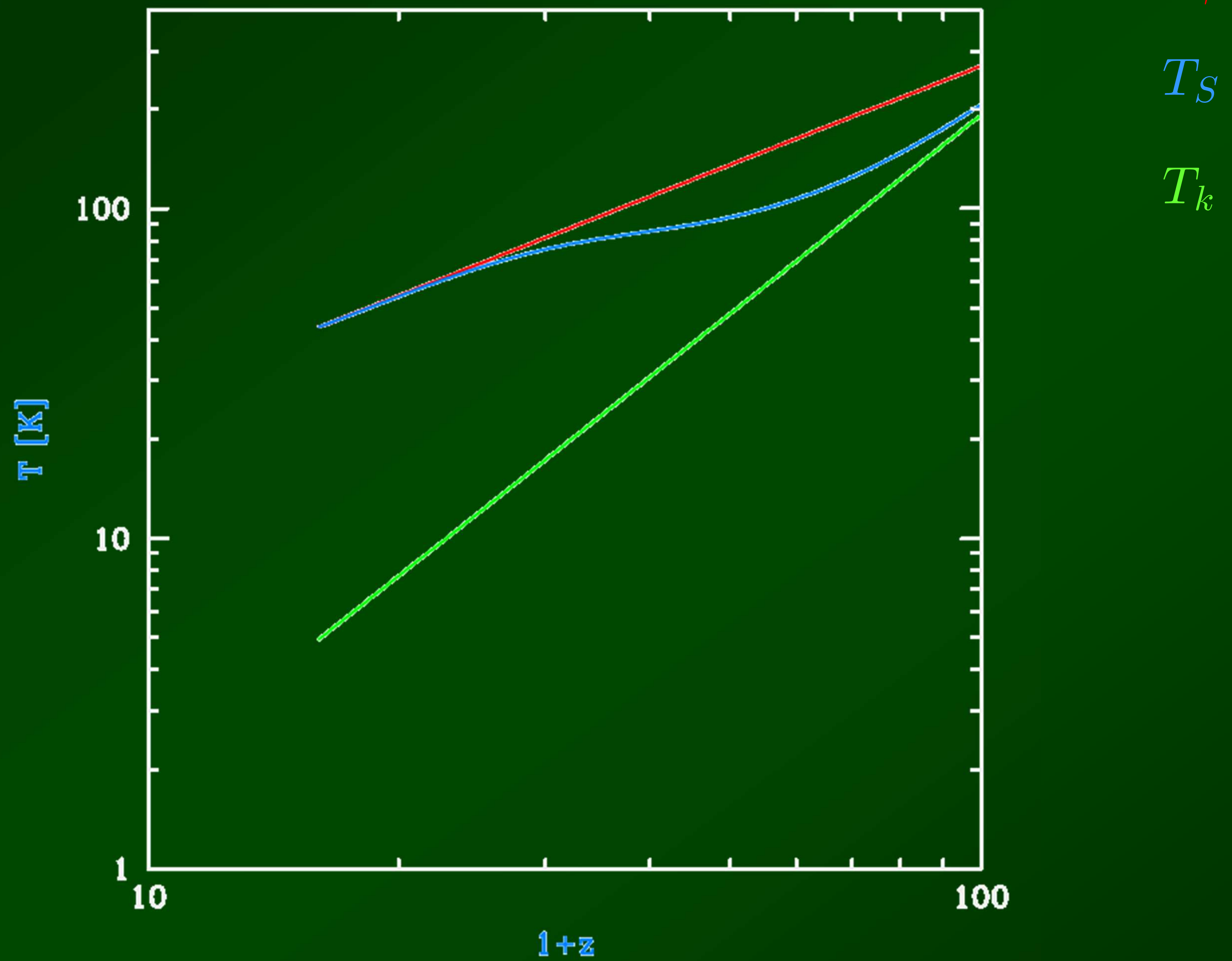




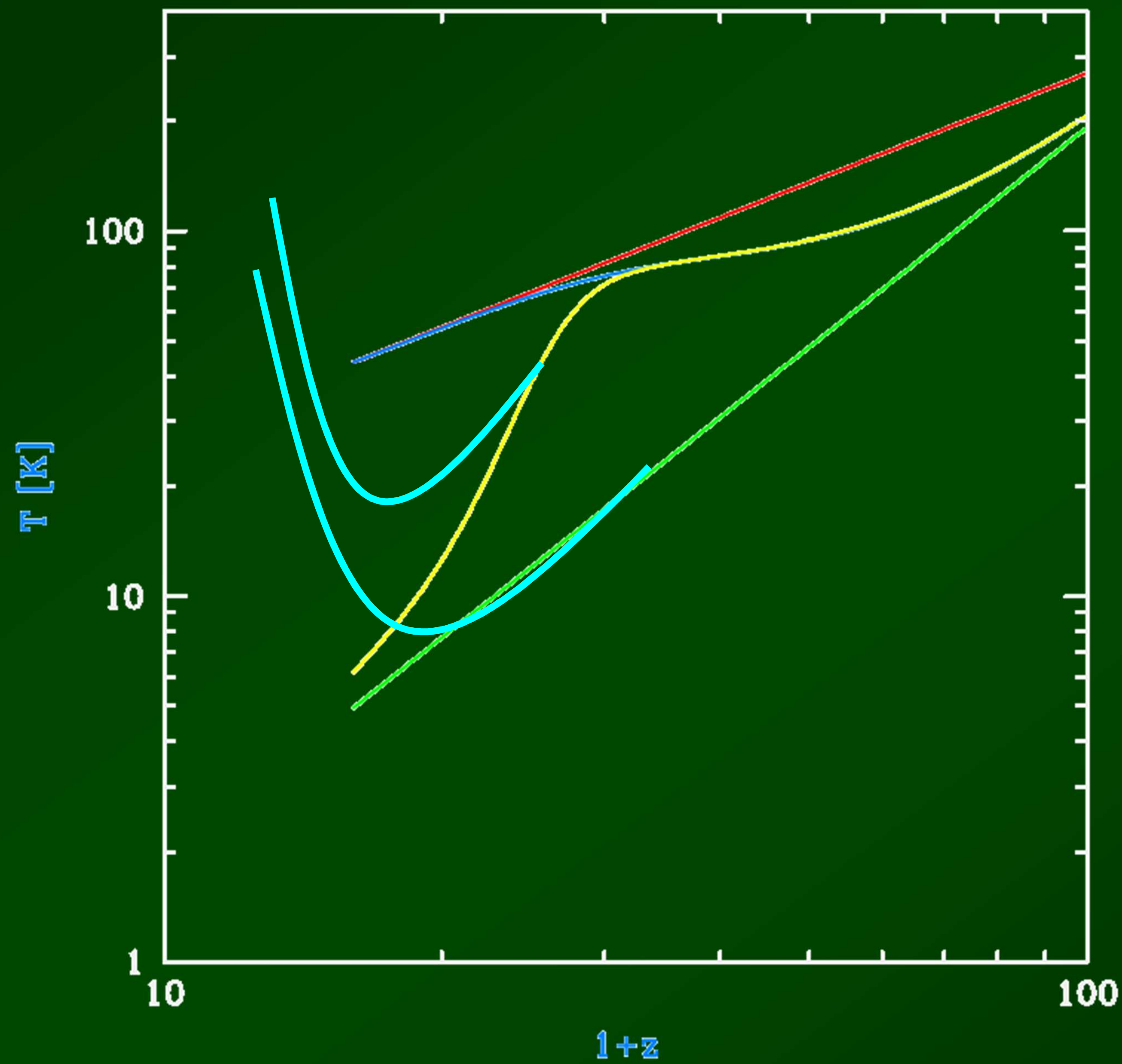
Resonance Line +
Cosmological Redshift


3D CINEMA
ILLUSION

Mean Temperatures



Mean Temperatures



T_γ

T_S

T_k

$+$ Lyα

Madau, Meiksin & Rees 1997

$+$ Heating

Atomic Physics: 21-cm Line

Spin temperature:

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

Optical depth:

$$\tau(z) = \frac{3c\lambda_{21}^2 h_P A_{10} n_{H\,I}}{32\pi k_B T_S (1+z)(dv_r/dr)}$$

$$\lambda_{21} = 21 \text{ cm} \qquad A_{10} = 2.85 \times 10^{-15} \text{ s}^{-1}$$

High z:

$$dv_r/dr = H(z)/(1+z)$$

$$\tau(z) = 9.85 \times 10^{-3} \left(\frac{T_{\rm CMB}}{T_S}\right)\left(\frac{\Omega_b h}{0.0327}\right)\left(\frac{\Omega_m}{0.307}\right)^{-1/2}\left(\frac{1+z}{10}\right)^{1/2}$$

Brightness temperature:

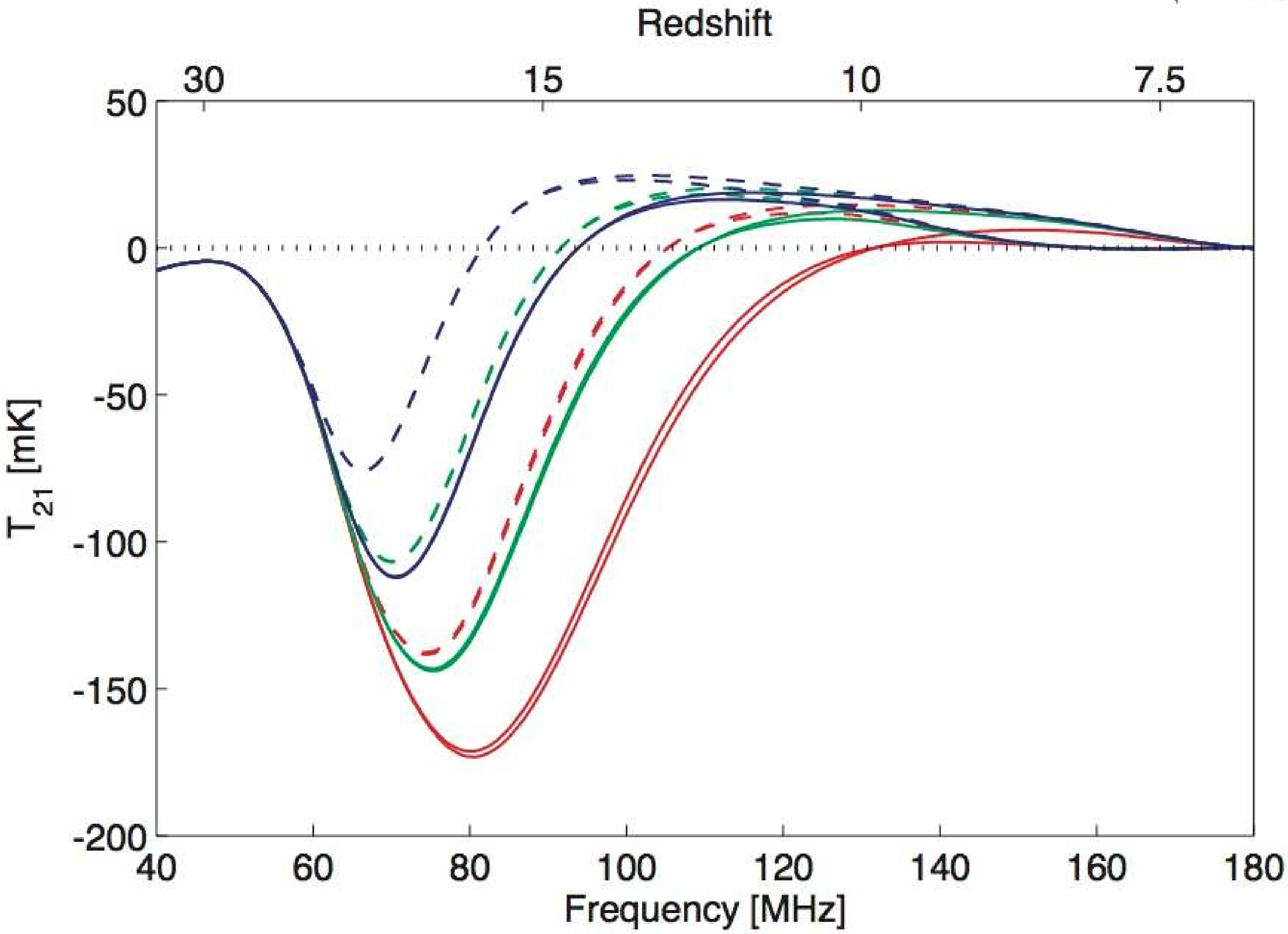
$$I_\nu = 2k_B T_{\rm b} \frac{\nu^2}{c^2}$$

$$T_{\rm b}^z = T_{\rm CMB} e^{-\tau} + T_S (1 - e^{-\tau})$$

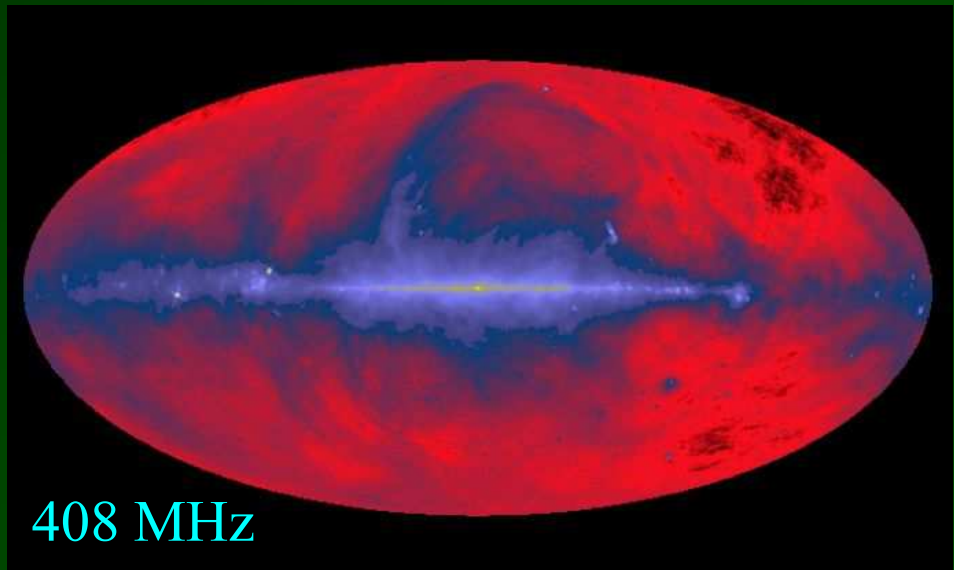
$$T_{\rm b} = (1+z)^{-1}(T_S - T_{\rm CMB})(1 - e^{-\tau}) \simeq 26.8\,{\rm mK}\left(\frac{\Omega_b h}{0.0327}\right)\left(\frac{\Omega_m}{0.307}\right)^{-1/2}\left(\frac{1+z}{10}\right)^{1/2}\left(\frac{T_S - T_{\rm CMB}}{T_S}\right)$$

Global 21-cm Spectrum

$$\left(\frac{T_S - T_{\rm CMB}}{T_S}\right)$$



Foregrounds



$T_{sky} \sim 200$ K

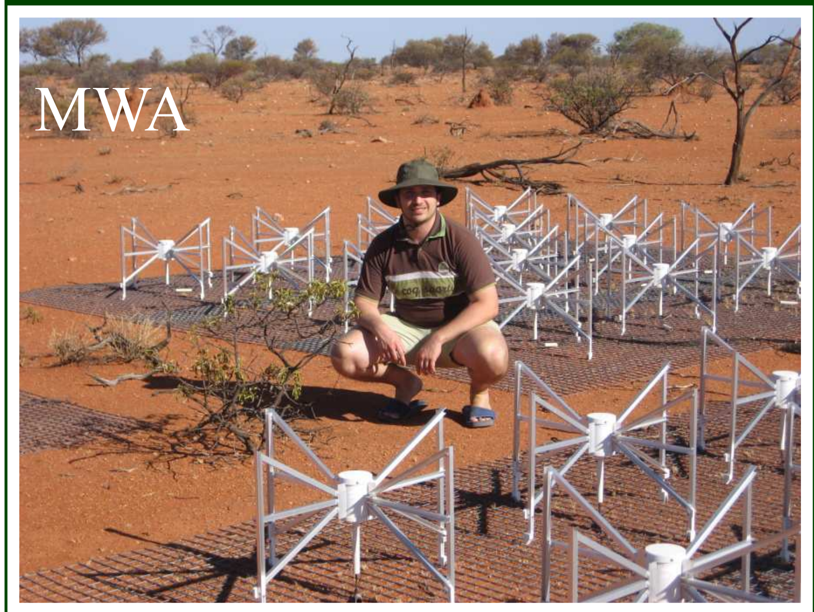
=> Large-Scale Fluctuations

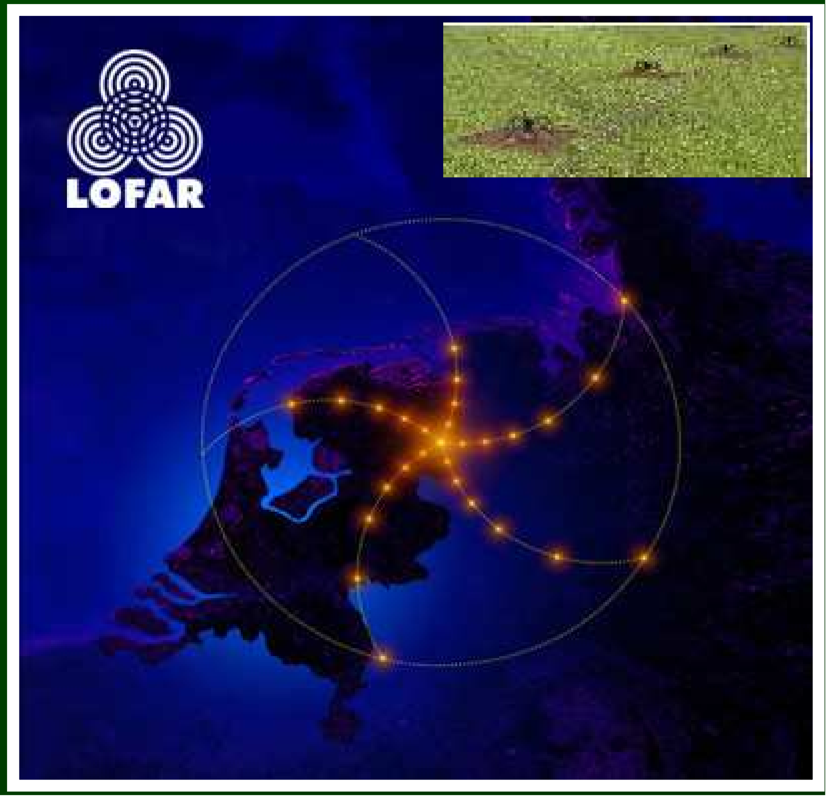
$$\delta T_b = \langle T_b \rangle \sqrt{\frac{k^3 P(k)}{2\pi^2}}$$

$T_{signal} \sim 1\text{-}10$ mK

$T_{current} \sim 22$ mK

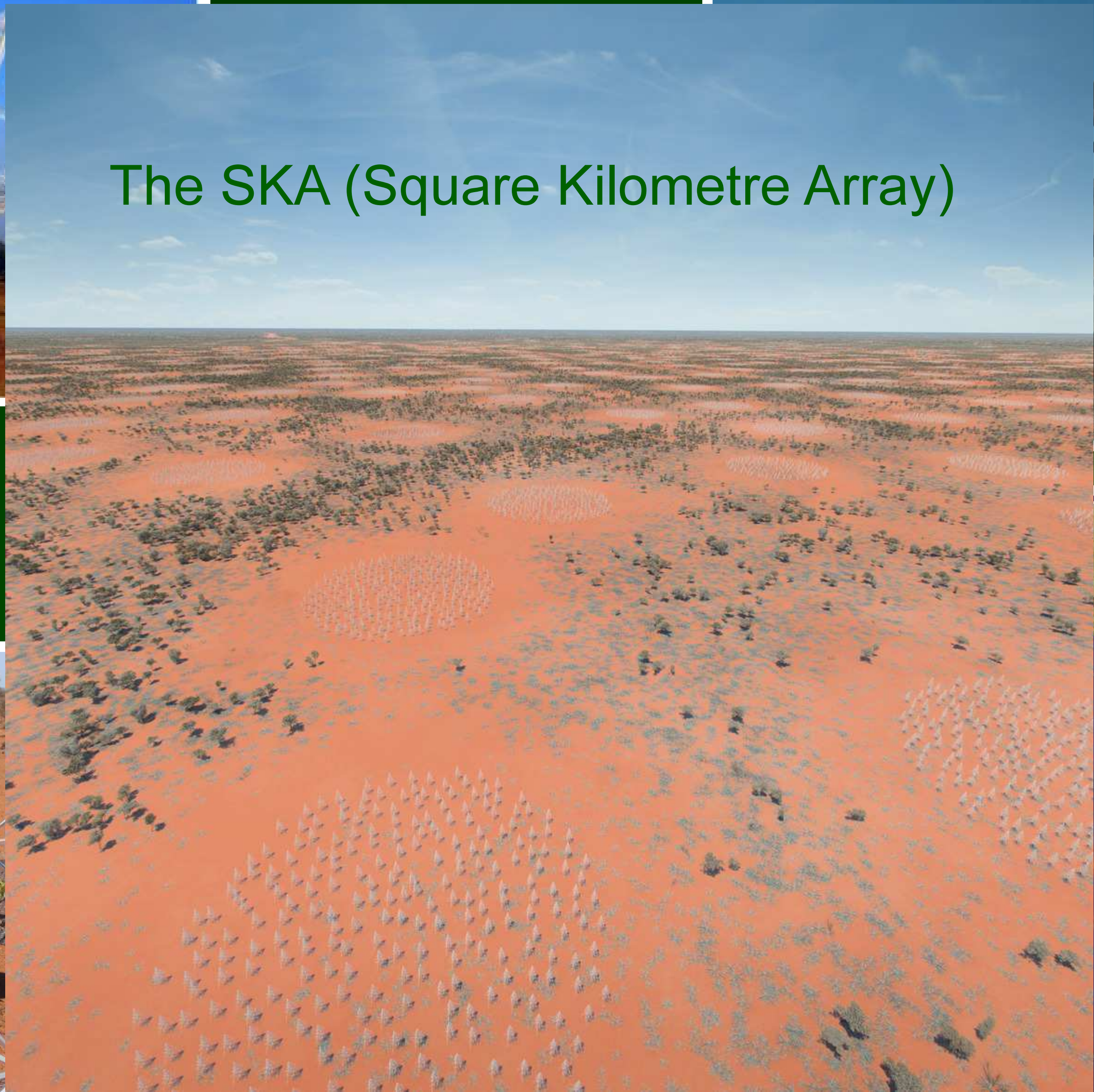
Experiments



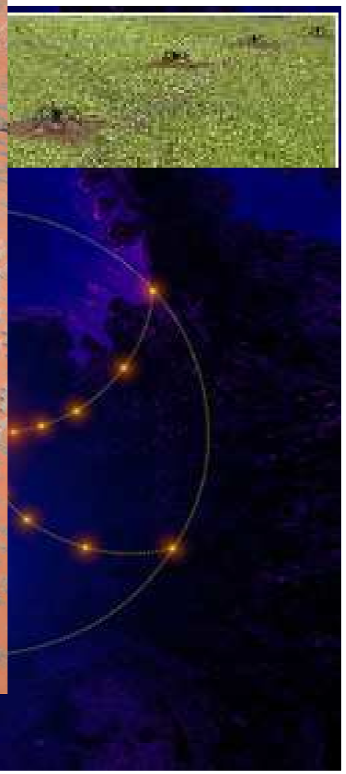



GMRT

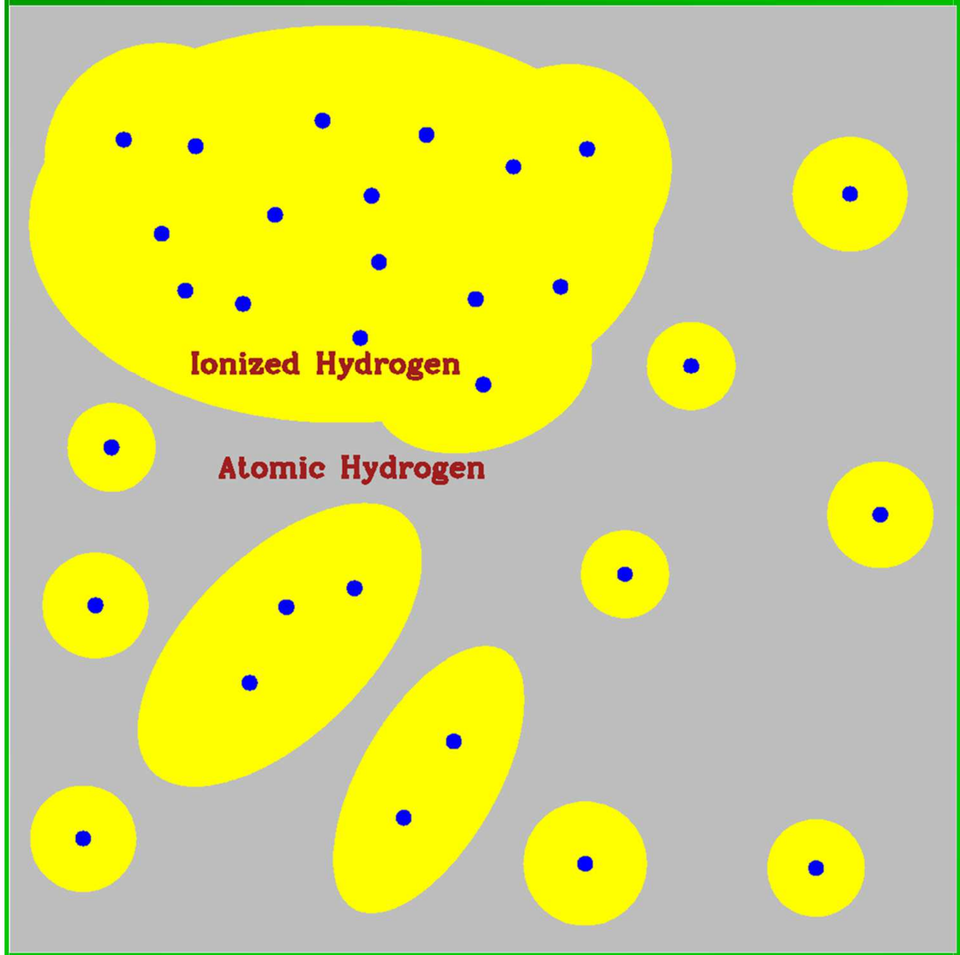

Paper

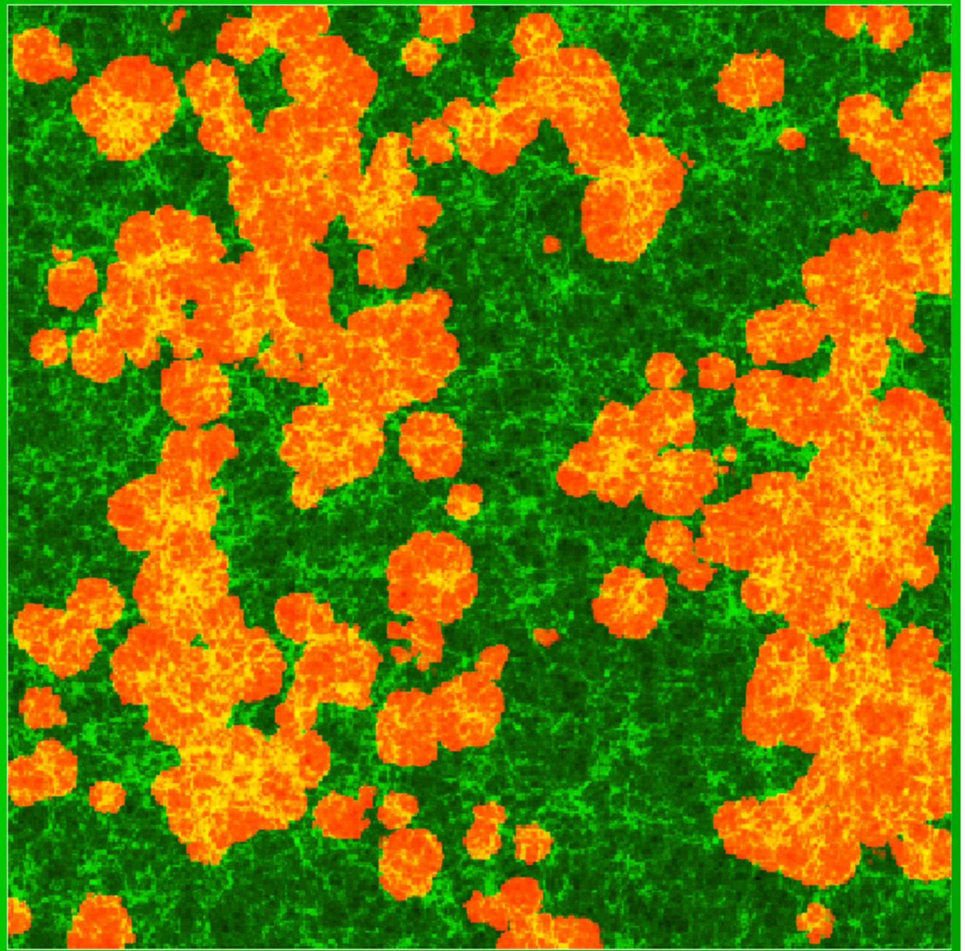

The SKA (Square Kilometre Array)


MWA



Cosmic Reionization





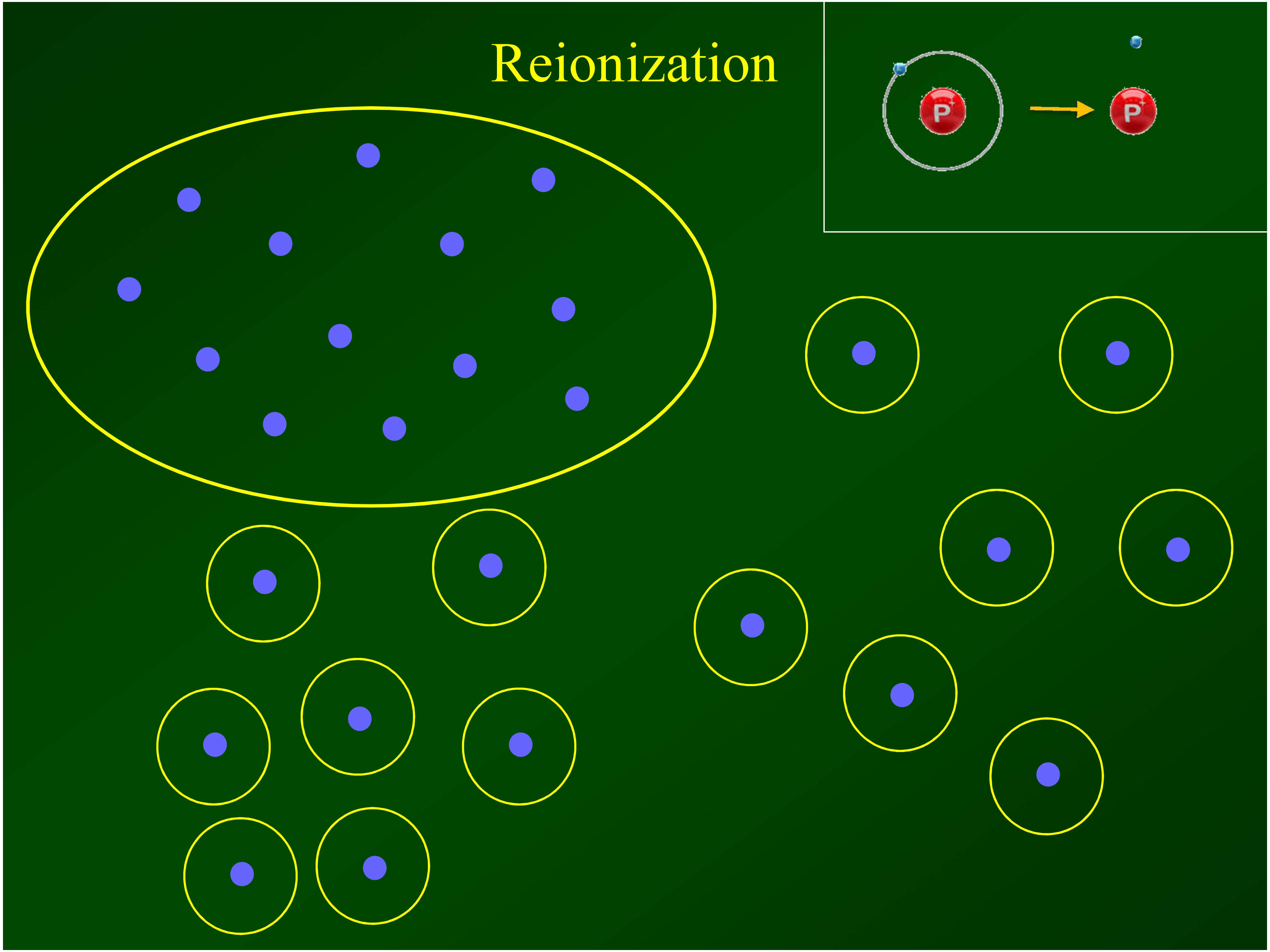
100/h Mpc = 0.5°

RB & Loeb 2004

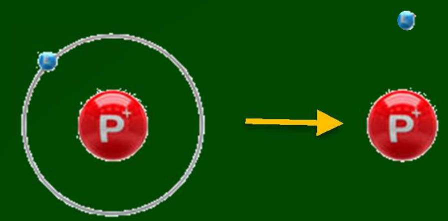
Mellema et al. 2006

Furlanetto, Zaldariagga, Hernquist 2004

Reionization

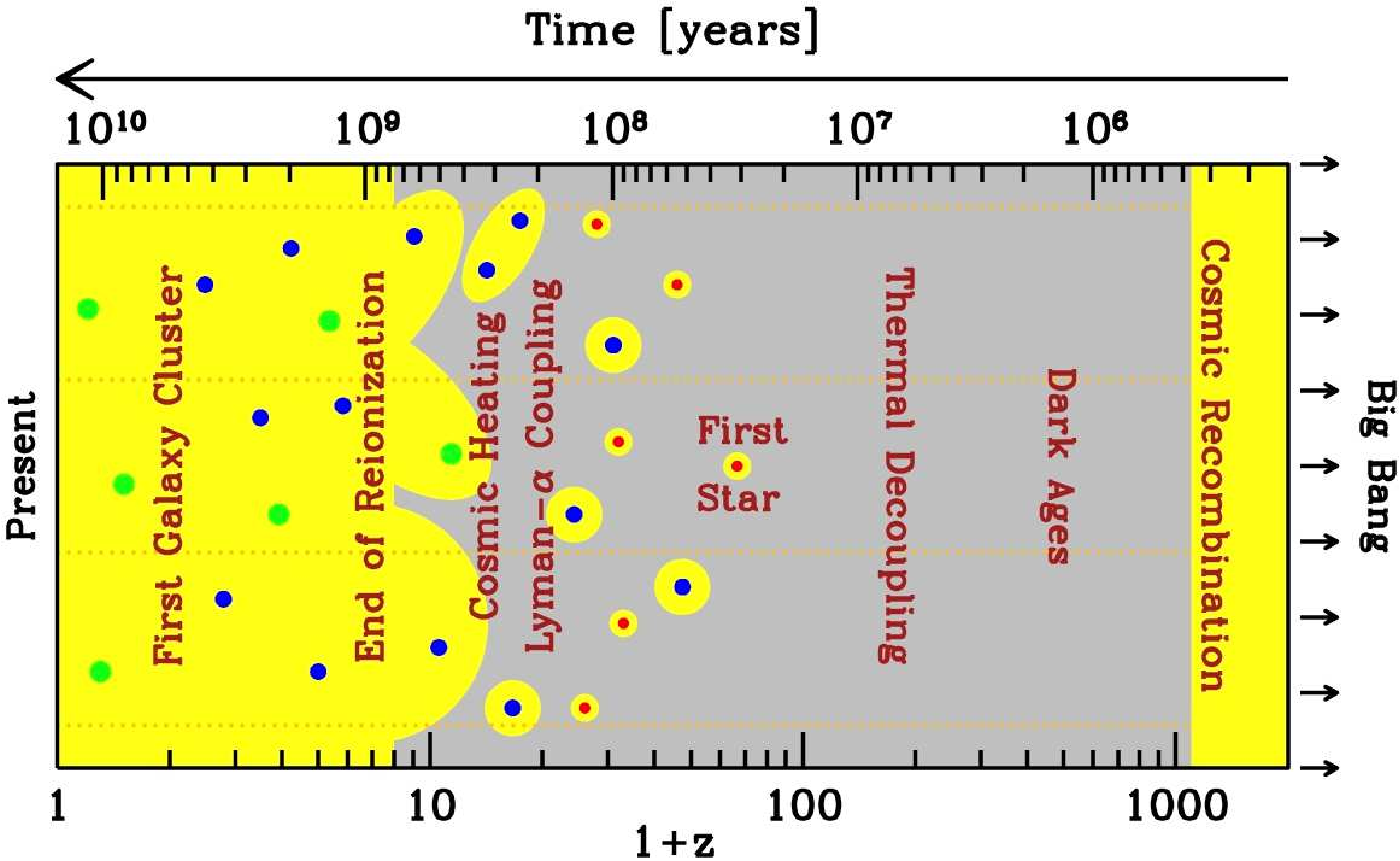


Reionization



21-cm radiation

Cosmic History



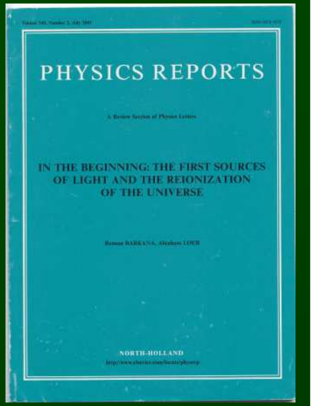
RB 2015, Physics Reports

21-cm Cosmology

Hogan & Rees 1979
Scott & Rees 1990

Madau, Meiksin & Rees 1997

RB & Loeb 2001 In the Beginning: the First Sources of Light and the Reionization of the Universe ?/114



Fialkov, **RB**, & Visbal Nature 2014

Early Radiative Feedback

Madau, Meiksin & Rees 1997:
Lyman-α (stars) and X-ray heating (XRBs)
=>Uniform<=

RB & Loeb 2005:
Ly-α fluctuations

Pritchard & Furlanetto 2007:
Temperature fluctuations (X-ray heating)

Early Radiative Feedback

Madau, Meiksin & Rees 1997:

$$T_b\,[\mathrm{mK}] \propto \rho_{\mathrm{H\,I}} \cdot \left(1 - \frac{T_{\mathrm{CMB}}}{T_{\mathrm{gas}}}\right)$$

THE ASTROPHYSICAL JOURNAL, 475:429–444, 1997 February 1

21 CENTIMETER TOMOGRAPHY OF THE INTERGALACTIC MEDIUM AT HIGH REDSHIFT

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ABSTRACT

We investigate the 21 cm signature that may arise from the intergalactic medium (IGM) prior to the epoch of full reionization ($z > 5$). In scenarios in which the IGM is reionized by discrete sources of photoionizing radiation, the neutral gas that has not yet been engulfed by an H II region may easily be preheated to temperatures well above that of the cosmic background radiation (CBR), rendering the IGM invisible in absorption against the CBR. We identify three possible preheating mechanisms: (1)

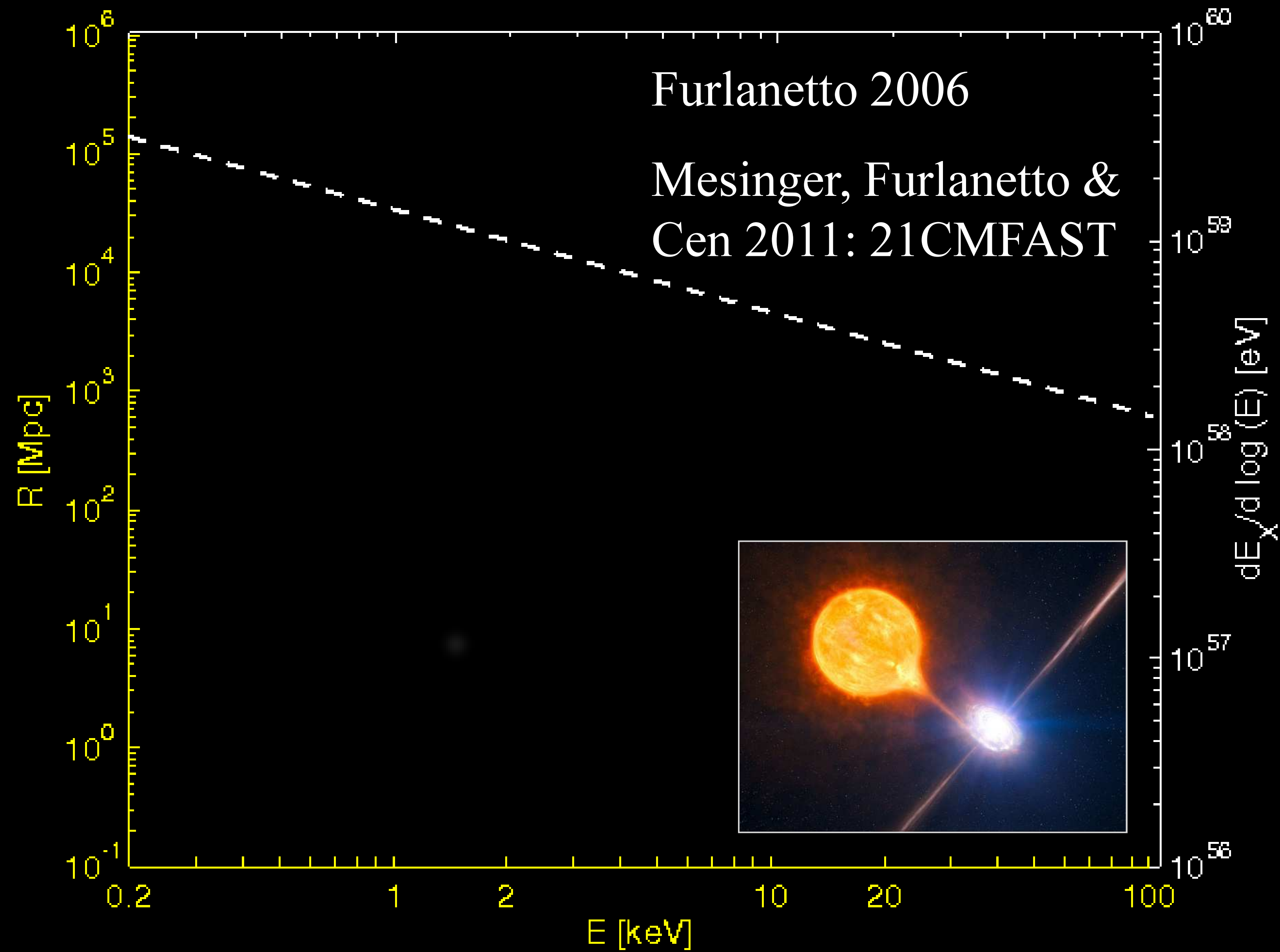
Early Radiative Feedback

Mon. Not. R. Astron. Soc. **000**, () Printed 20 January 2014 (MN LaTeX style file v2.2)

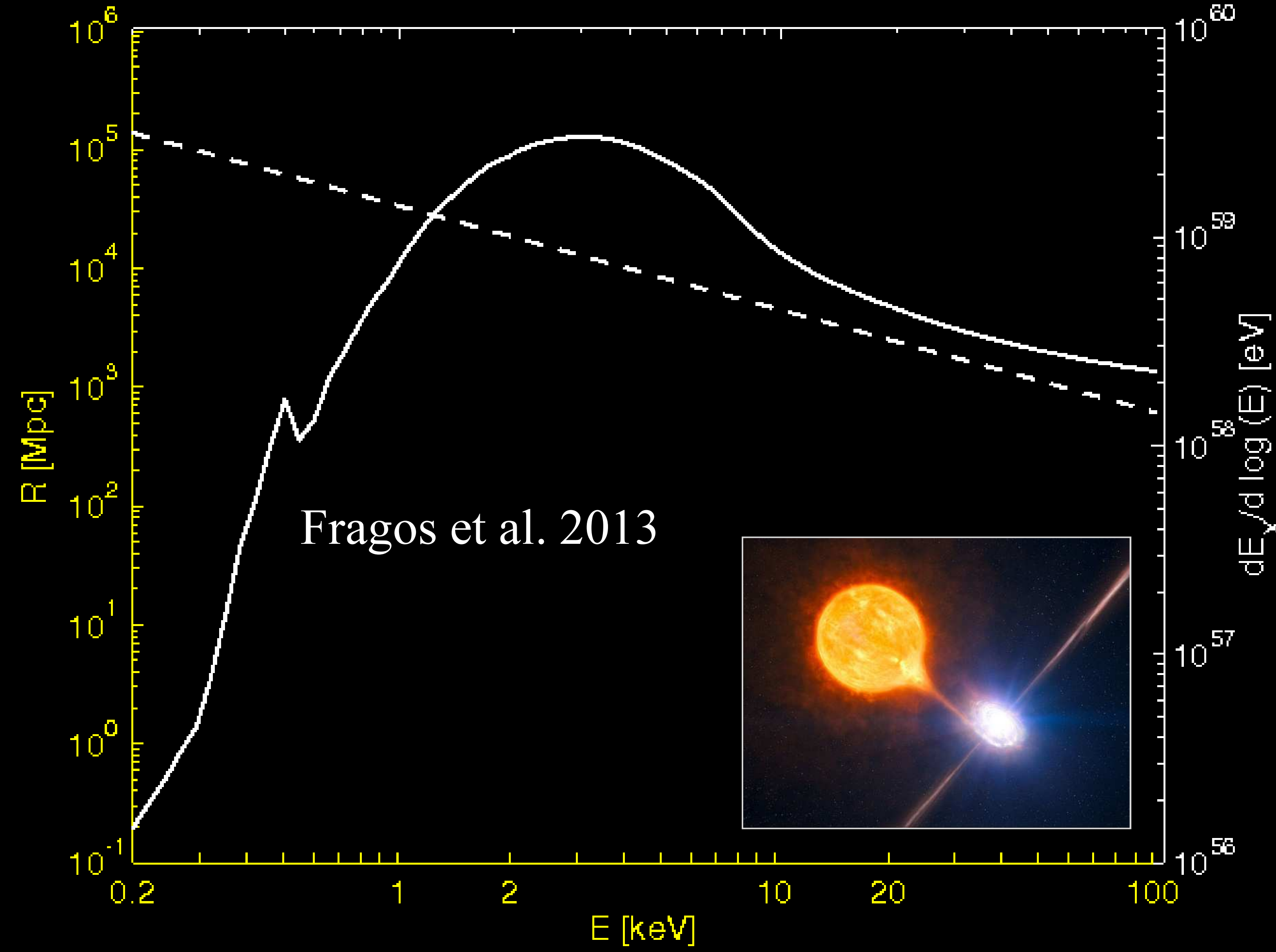
Constraining the epoch of reionization with the variance statistic: simulations of the LOFAR case

Ajinkya H. Patil,[1⋆] Saleem Zaroubi,[1] Emma Chapman,[2] Vibor Jelić,[1,3] Geraint Harker,[4] Filipe B. Abdalla,[2] Khan M. B. Asad,[1] Gianni Bernardi,[5] Michiel A. Brentjens,[3] A. G. de Bruyn,[1,3] Sander Bus,[1] Benedetta Ciardi,[6] Soobash Daiboo,[1] Elizabeth R. Fernandez,[1] Abhik Ghosh,[1] Hannes Jensen,[7] Sanaz Kazemi,[1] Léon V. E. Koopmans,[1] Panagiotis Labropoulos,[3] Maaijke Mevius,[1,3] Oscar Martinez,[1] Garrelt Mellema,[7] Andre. R. Offringa,[1,8] Vishhambhar N. Pandey,[1,3] Joop Schaye,[9] Rajat M. Thomas,[1] Harish K. Vedantham,[1] Vamsikrishna Veligatla,[1] Stefan J. Wijnholds[3] and Sarod Yatawatta[1,3]

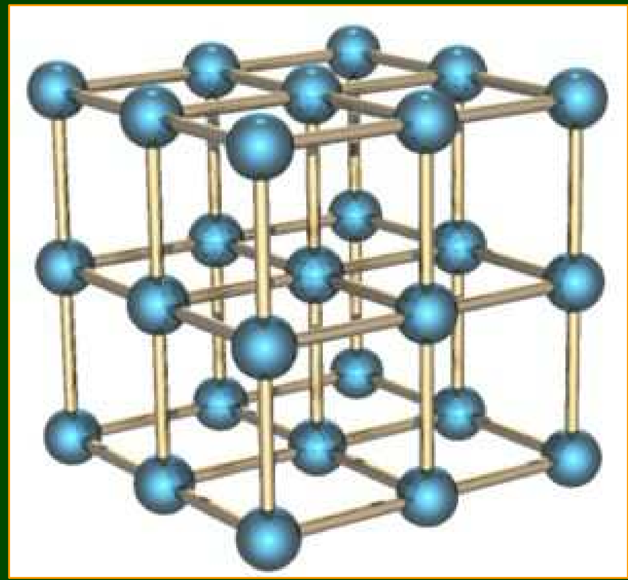
our run, but we neglected spin temperature fluctuations by assuming $T_S \gg T_{CMB}$, i.e. the neutral gas has been heated well above the CMB for redshifts 6 to 12 (Pritchard & Loeb 2008). We combined the δT_b boxes at different redshifts us-



Fialkov, Barkana & Visbal Nature 2014



Fialkov, Barkana & Visbal Nature 2014



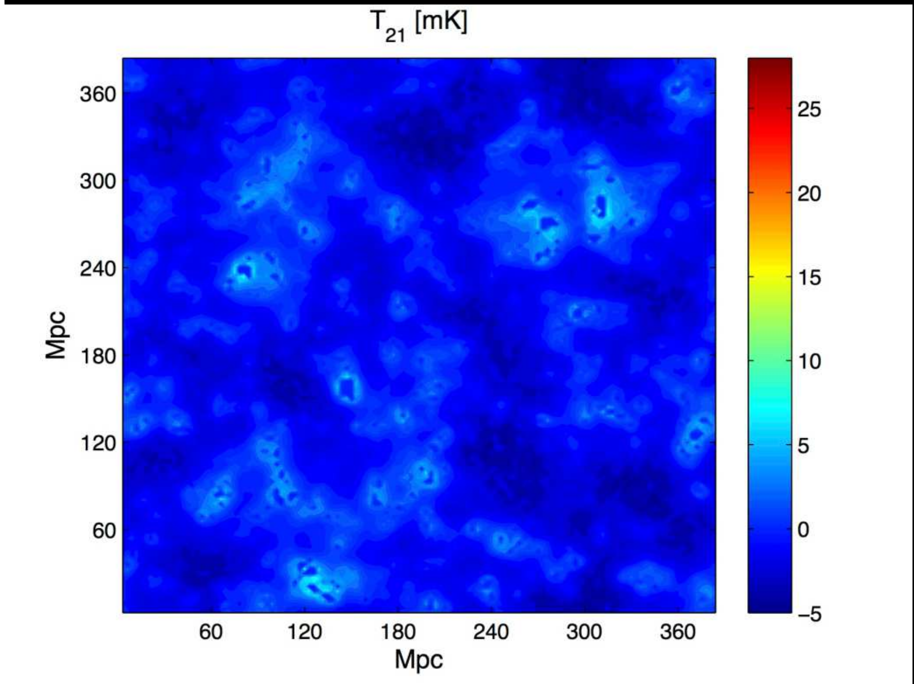
1) 400 Mpc box

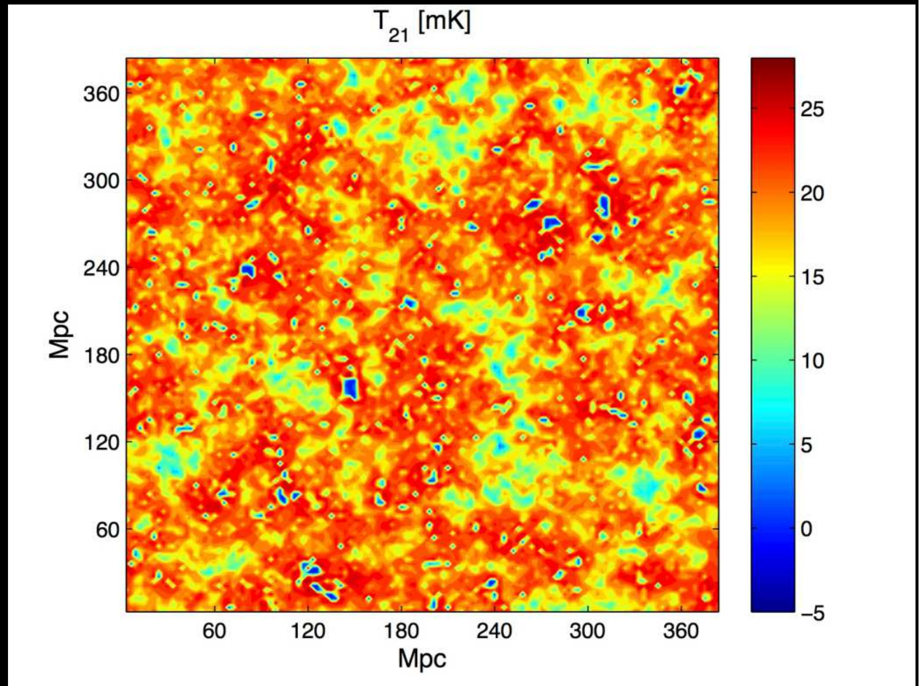
2) Semi-numerical:
   Hybrid simulation method

3) Halo abundance, cooling, star formation

4) Ly-α radiation, X-rays, reionization

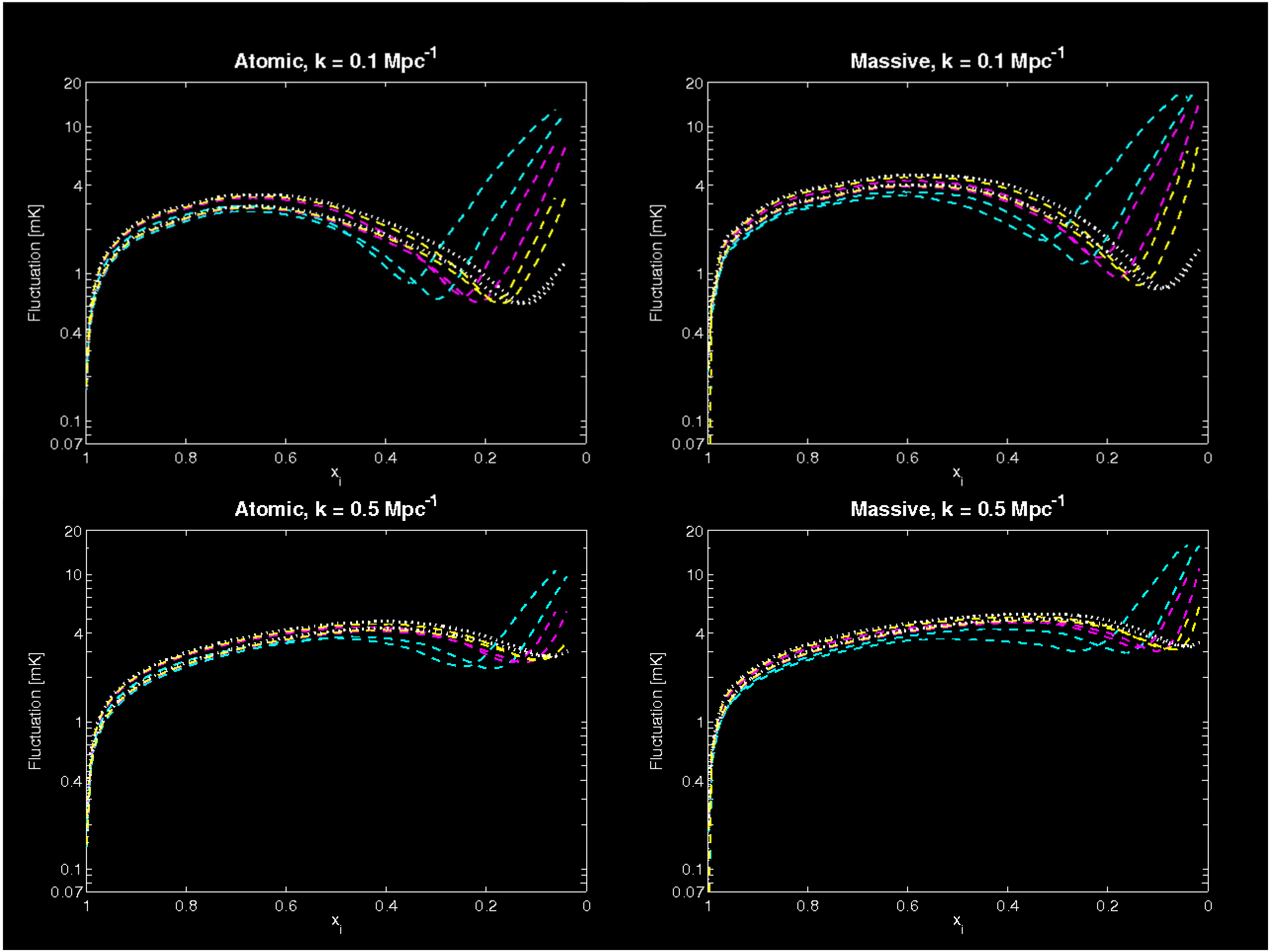
Fialkov, Barkana & Visbal Nature 2014

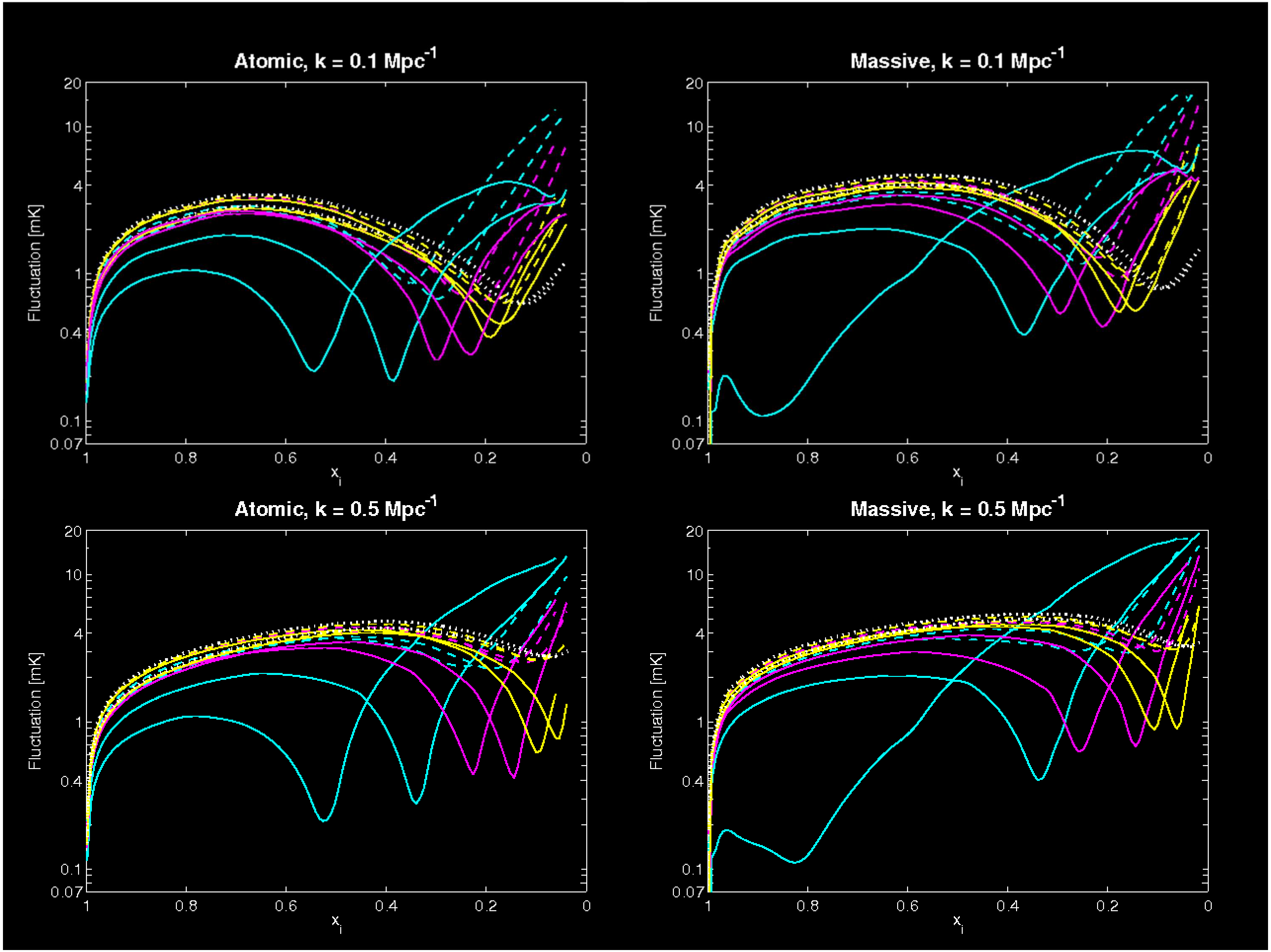




$z = 12.1$

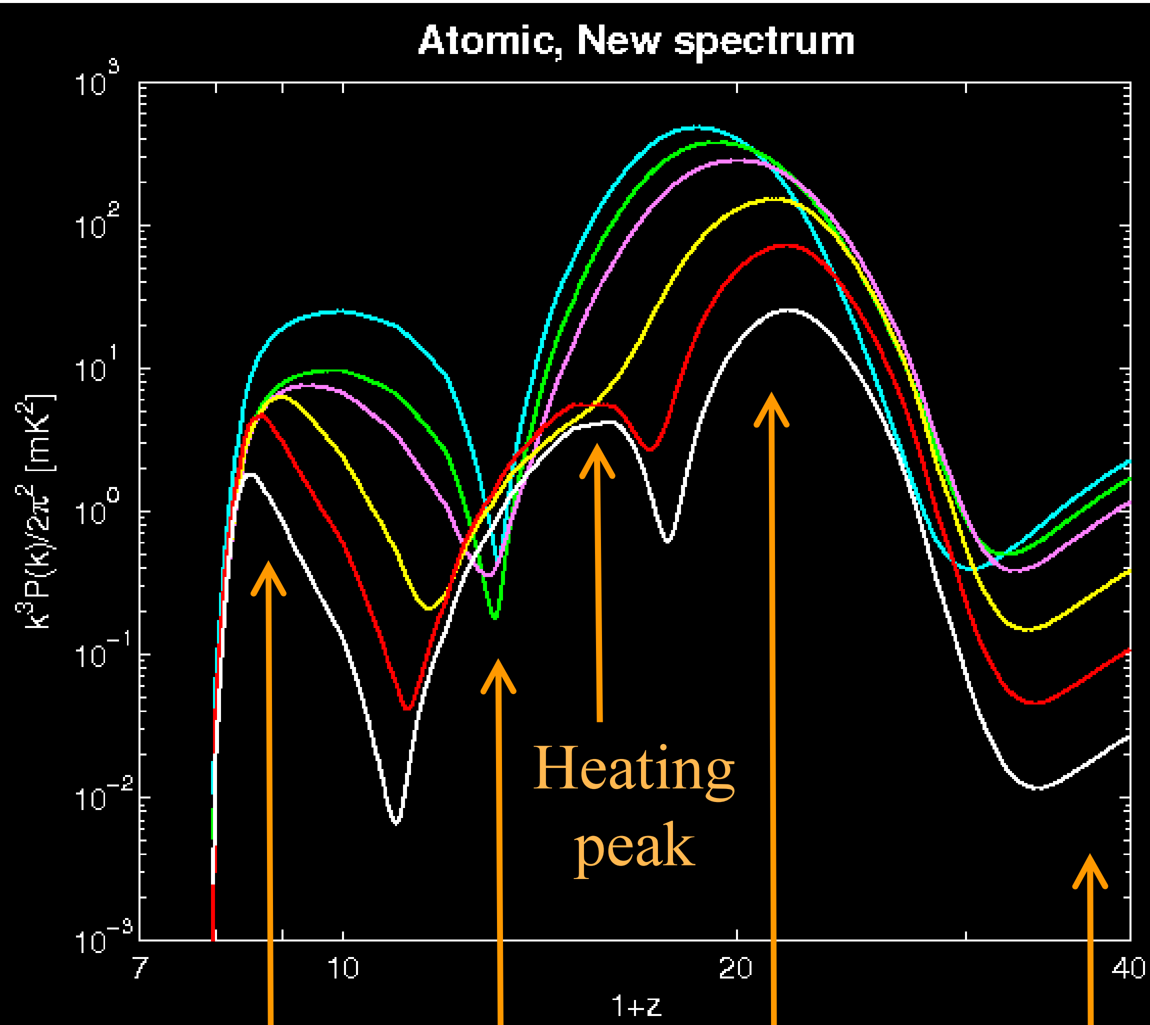
Fialkov, Barkana & Visbal Nature 2014


Atomic, k = 0.1 Mpc-1
Massive, k = 0.1 Mpc-1
Atomic, k = 0.5 Mpc-1
Massive, k = 0.5 Mpc-1
Fluctuation [mK]
xi
20
10
4
1
0.4
0.1
0.07
1
0.8
0.6
0.4
0.2
0



Atomic, k = 0.1 Mpc^{-1}
Massive, k = 0.1 Mpc^{-1}
Atomic, k = 0.5 Mpc^{-1}
Massive, k = 0.5 Mpc^{-1}
Fluctuation [mK]
x_i
20
10
4
1
0.4
0.1
0.07
1
0.8
0.6
0.4
0.2
0

Fluctuation^2 at k = 1 , 0.5 , 0.3 , 0.1 , 0.05 , 0.03 /Mpc



Reionization peak

Heating transition

Heating peak

Lyα peak

Dark ages

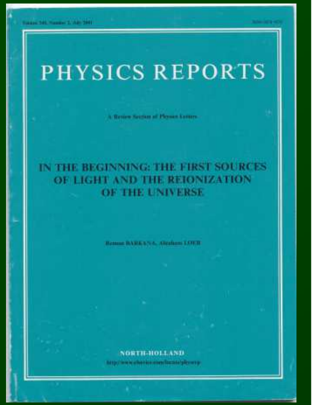
Fialkov & Barkana 2014

21-cm Cosmology

Hogan & Rees 1979
Scott & Rees 1990

Madau, Meiksin & Rees 1997

RB & Loeb 2001 — In the Beginning: the First Sources of Light and the Reionization of the Universe ?/114



Fialkov, **RB**, & Visbal — Nature 2014

RB 2015 — The Rise of the First Stars: Supersonic Streaming, Radiative Feedback, and 21-cm Cosmology