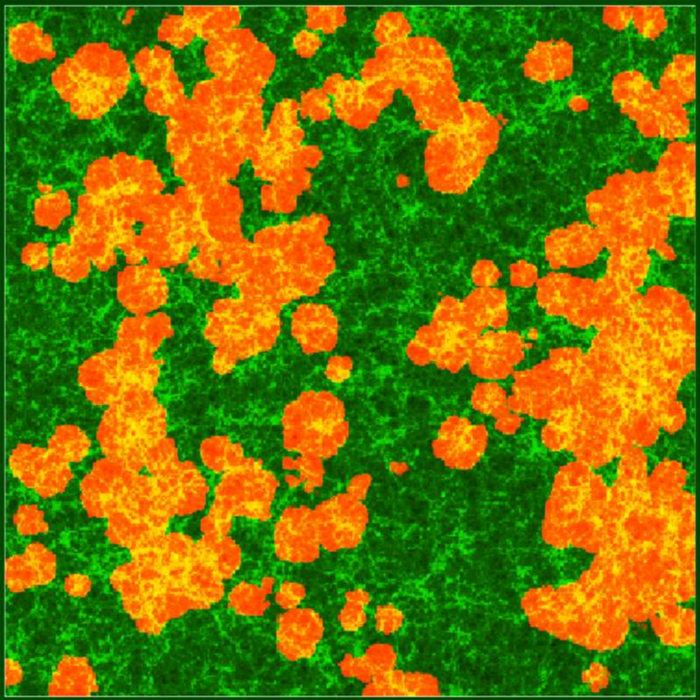
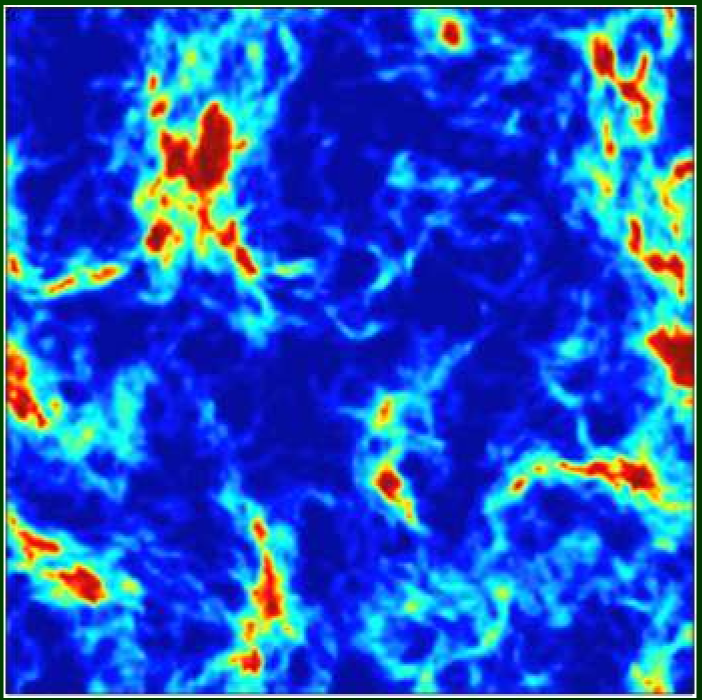
Reionization +
Galaxy Formation; First Stars; 21-cm Cosmology

Rennan Barkana רנן ברקנא

TEL AVIV UNIVERSITY אוניברסיטת תל-אביב





Cosmology

Robertson-Walker metric:

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

(R, θ, ϕ) Scale factor: $a(t)$

Friedmann equation:

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

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

Energy conservation:

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

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 2018:

h=0.677, Ω_m=0.311, Ω_b=0.0490

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

Redshift:

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

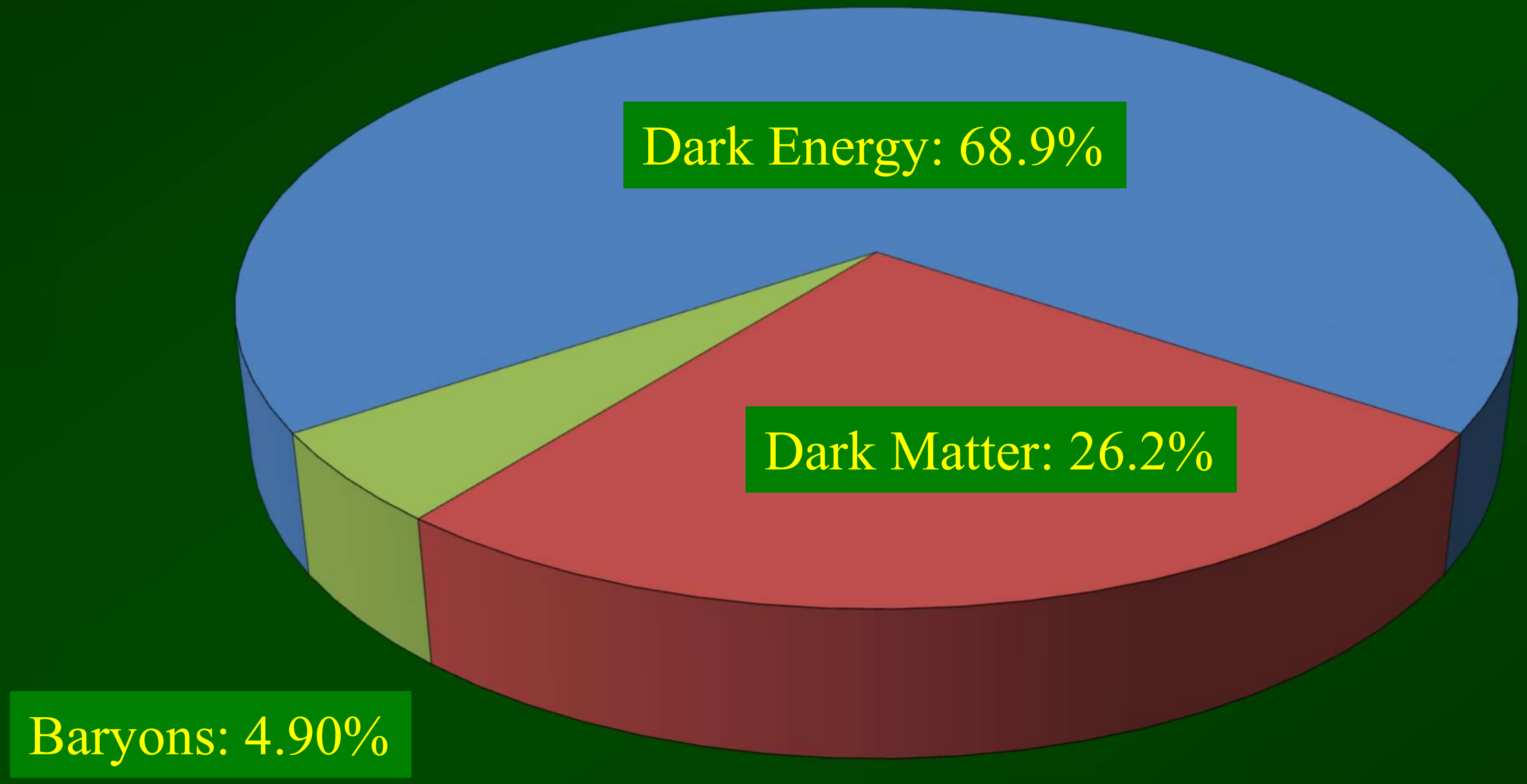
Hubble expansion:

$$v = Hr$$

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)

$D(z=0) = 1$

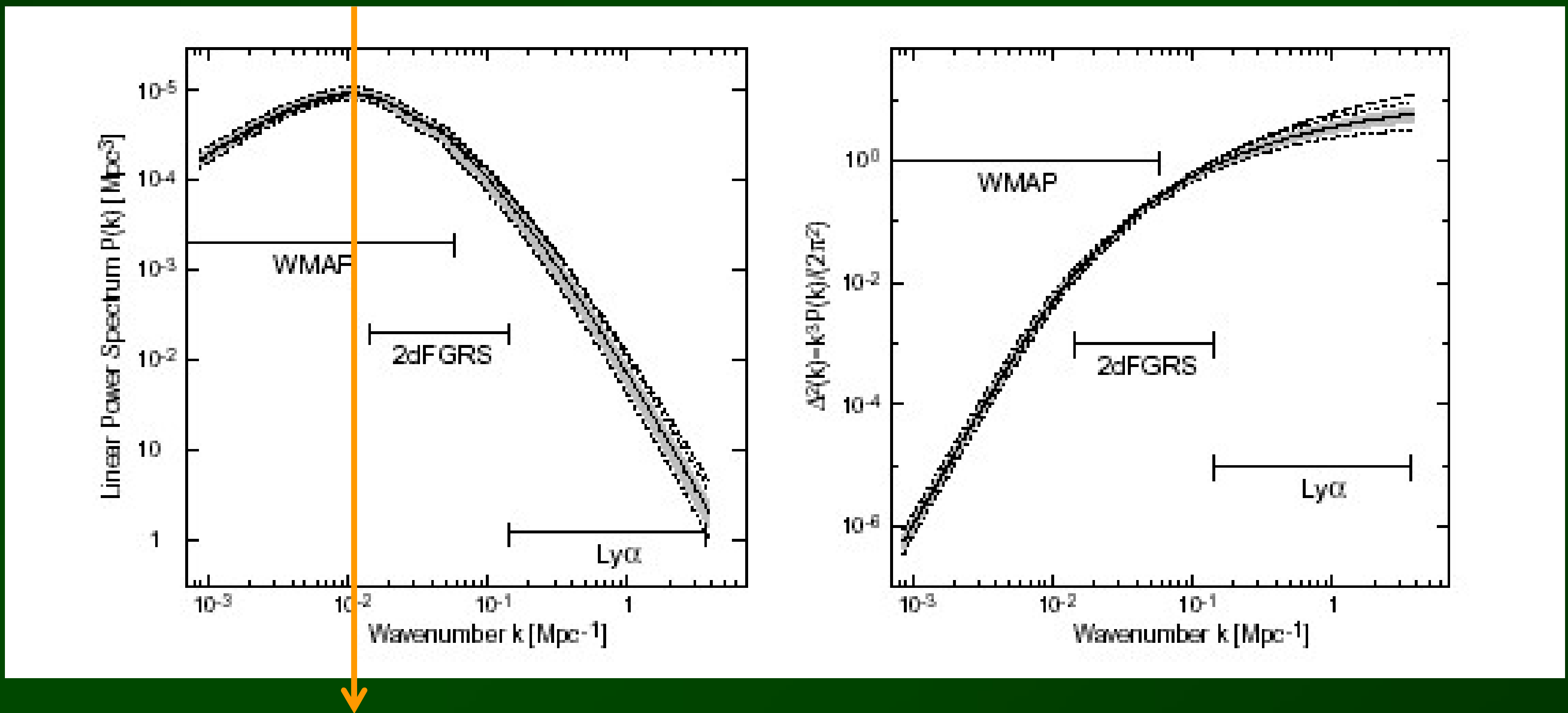
Fourier space: $\delta_{\mathbf{k}} = \int d^3x\, \delta(x) e^{-i\mathbf{k}\cdot\mathbf{x}}$ $k = \frac{2\pi}{\lambda}$

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

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



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

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

Non-linear Collapse

Mass scale:

$$M = \frac{4}{3}\pi\bar{\rho}_0 R^3 = 1.64\times10^8\left(\frac{\Omega_m h^2}{0.141}\right)\left(\frac{R}{100\text{ kpc}}\right)^3 M_\odot$$

Variance:

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

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

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

Spherical collapse:
(EdS)

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

Virial density:

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

$$U = -2K$$

Circular velocity:

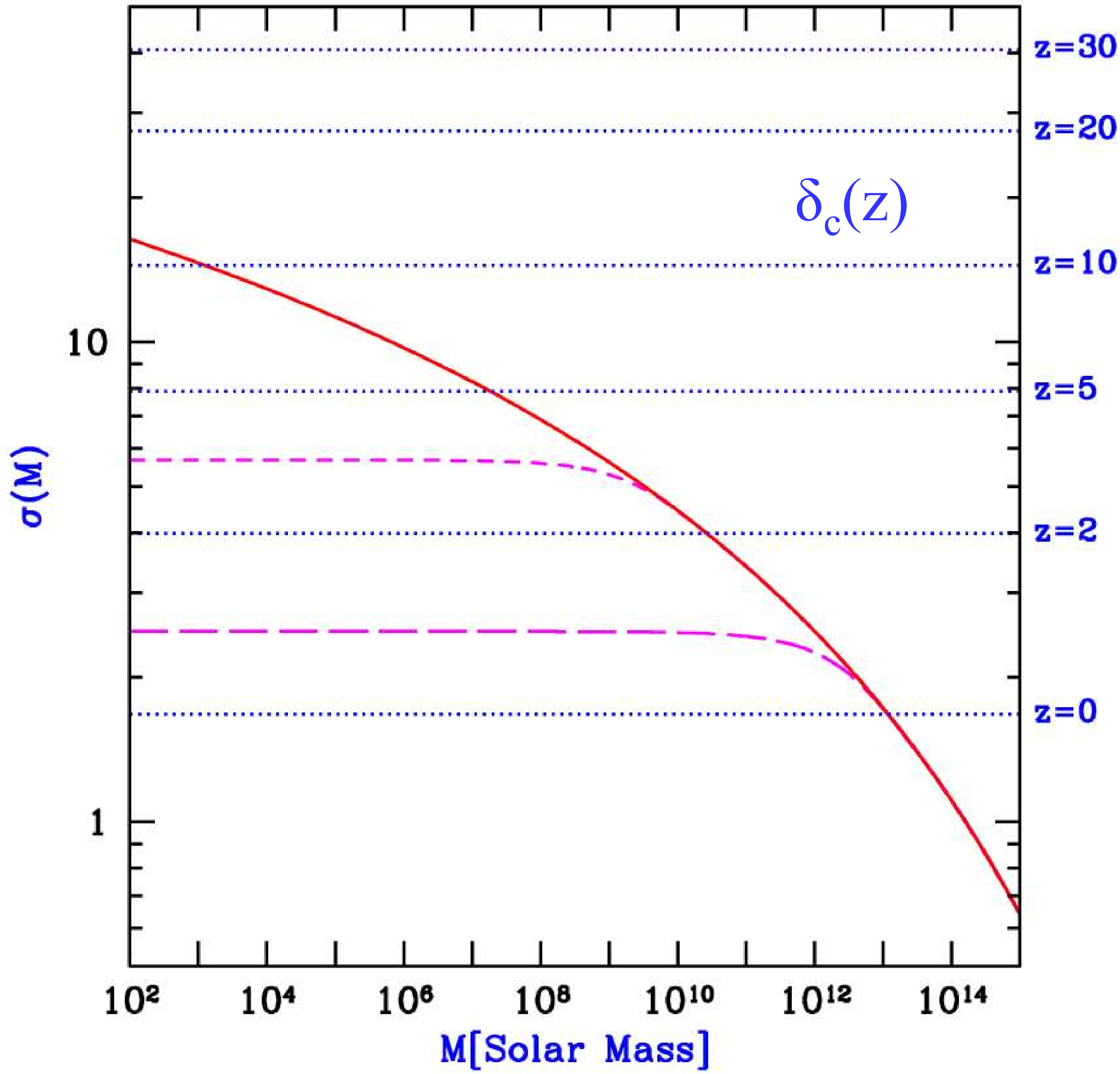
$$V_c = \left(\frac{GM}{r_{\rm vir}}\right)^{1/2} = 16.9\left(\frac{\Omega_m h^2}{0.141}\right)^{1/6}\left(\frac{M}{10^8 M_\odot}\right)^{1/3}\left(\frac{\Delta_c}{18\pi^2}\right)^{1/6}\left(\frac{1+z}{10}\right)^{1/2}\text{ km s}^{-1}$$

Virial temperature:

$$T_{\rm vir} = \frac{\mu m_p V_c^2}{2k_{\rm B}} = 1.03\times10^4\left(\frac{\Omega_m h^2}{0.141}\right)^{1/3}\left(\frac{\mu}{0.6}\right)\left(\frac{M}{10^8 M_\odot}\right)^{2/3}\left(\frac{\Delta_c}{18\pi^2}\right)^{1/3}\left(\frac{1+z}{10}\right)\text{ K}$$

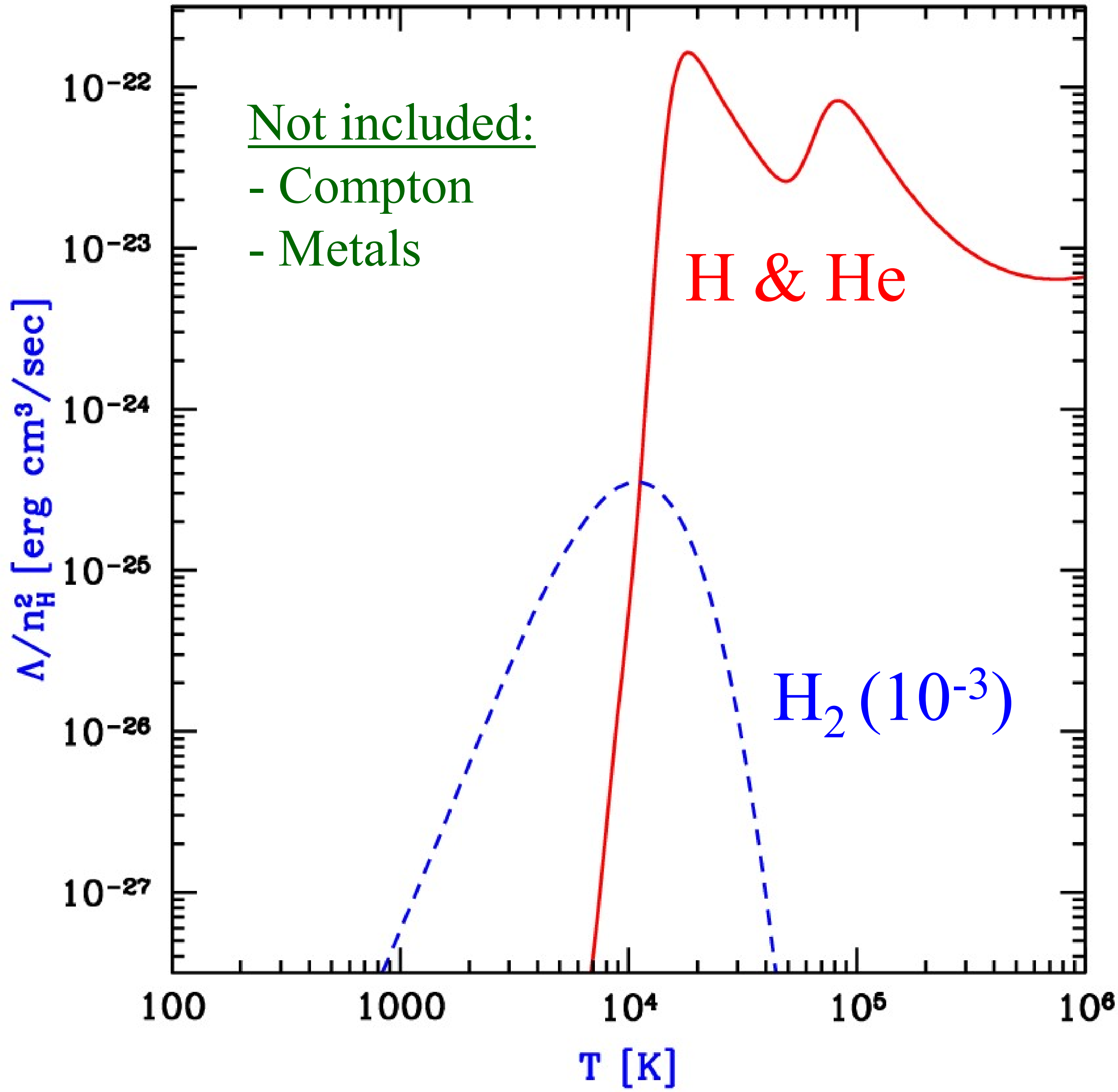
Mean molecular weight:

$\mu = 1.22$ (neutral), 0.61 (ionized H), 0.59 (fully ionized He)



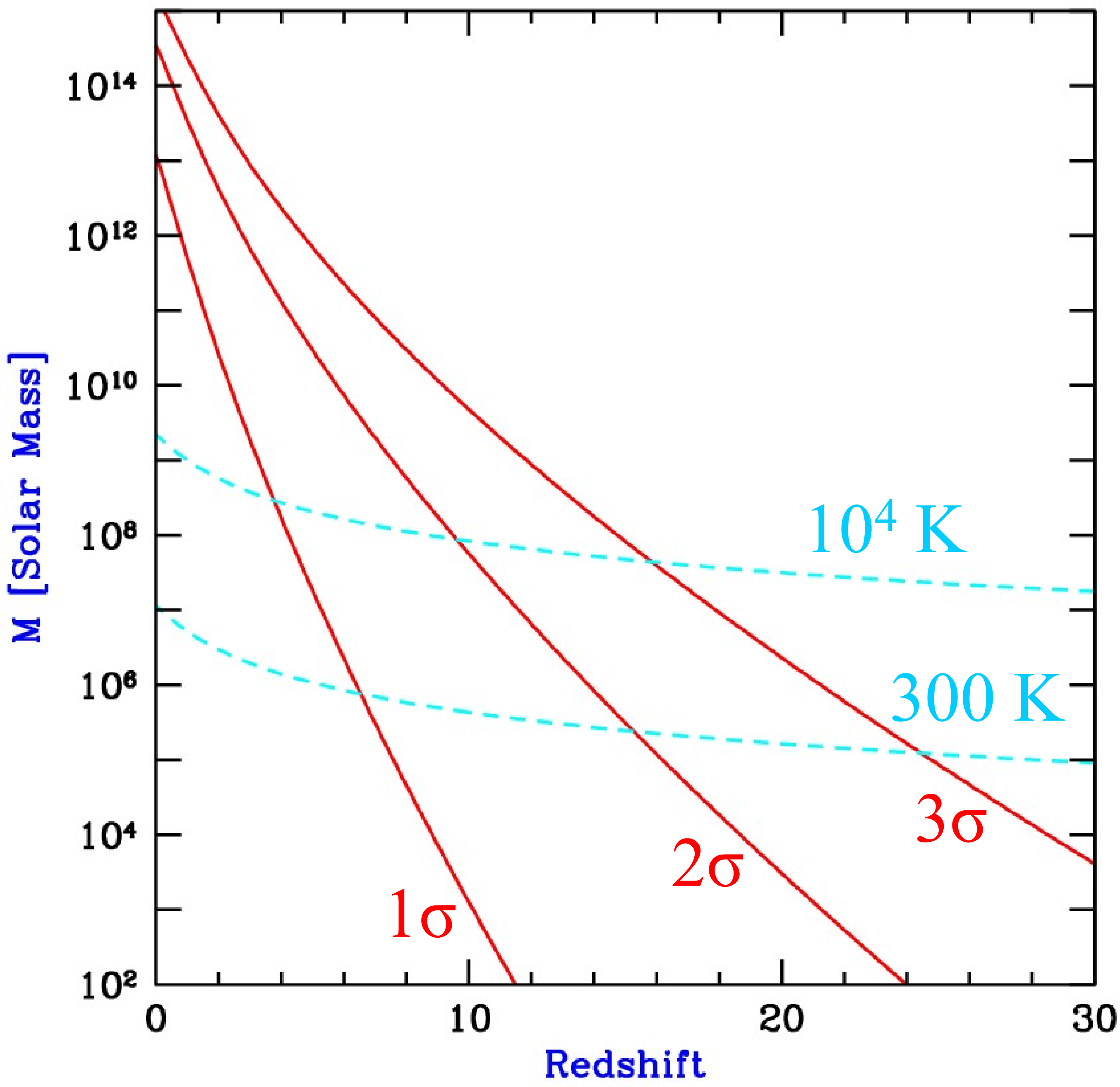
Typical fluctuations compared with the critical value

Barkana & Loeb 2001



Cooling rate of a primordial cosmic gas

Barkana & Loeb 2001



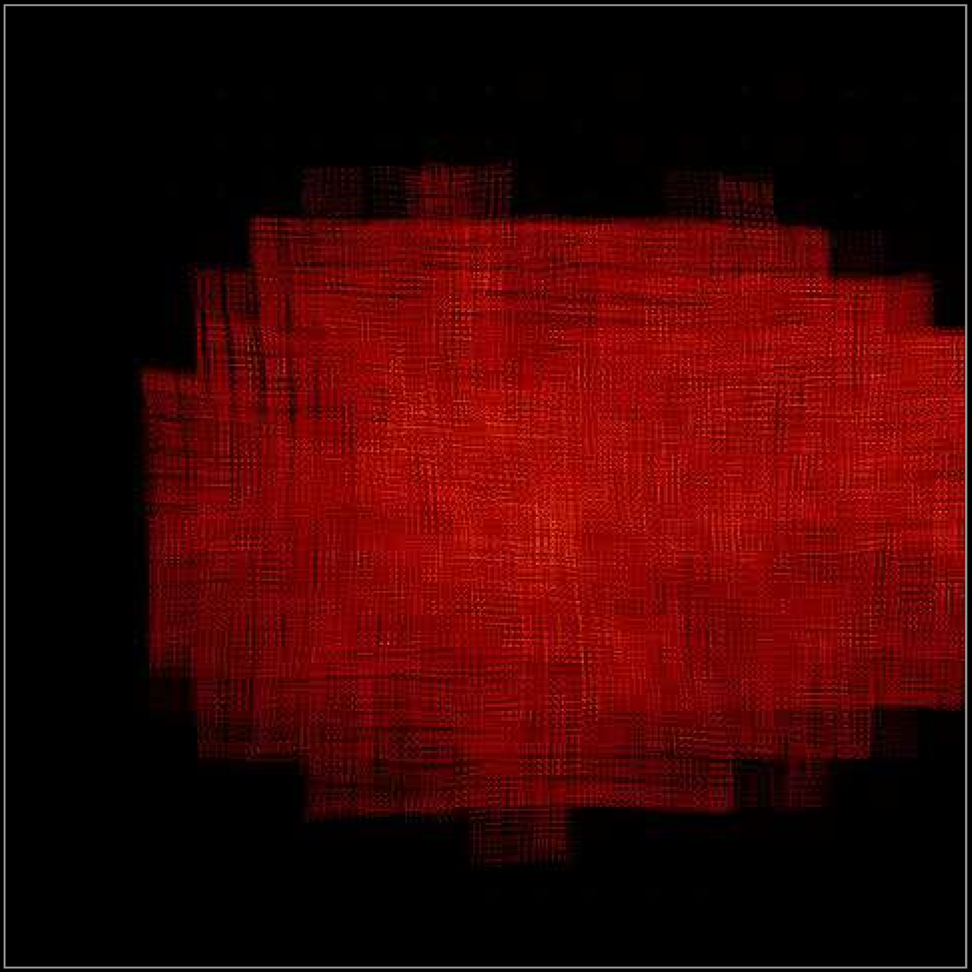
Galactic halos

Barkana & Loeb 2001

Hierarchical Galaxy Formation:

CDM

20 kpc box

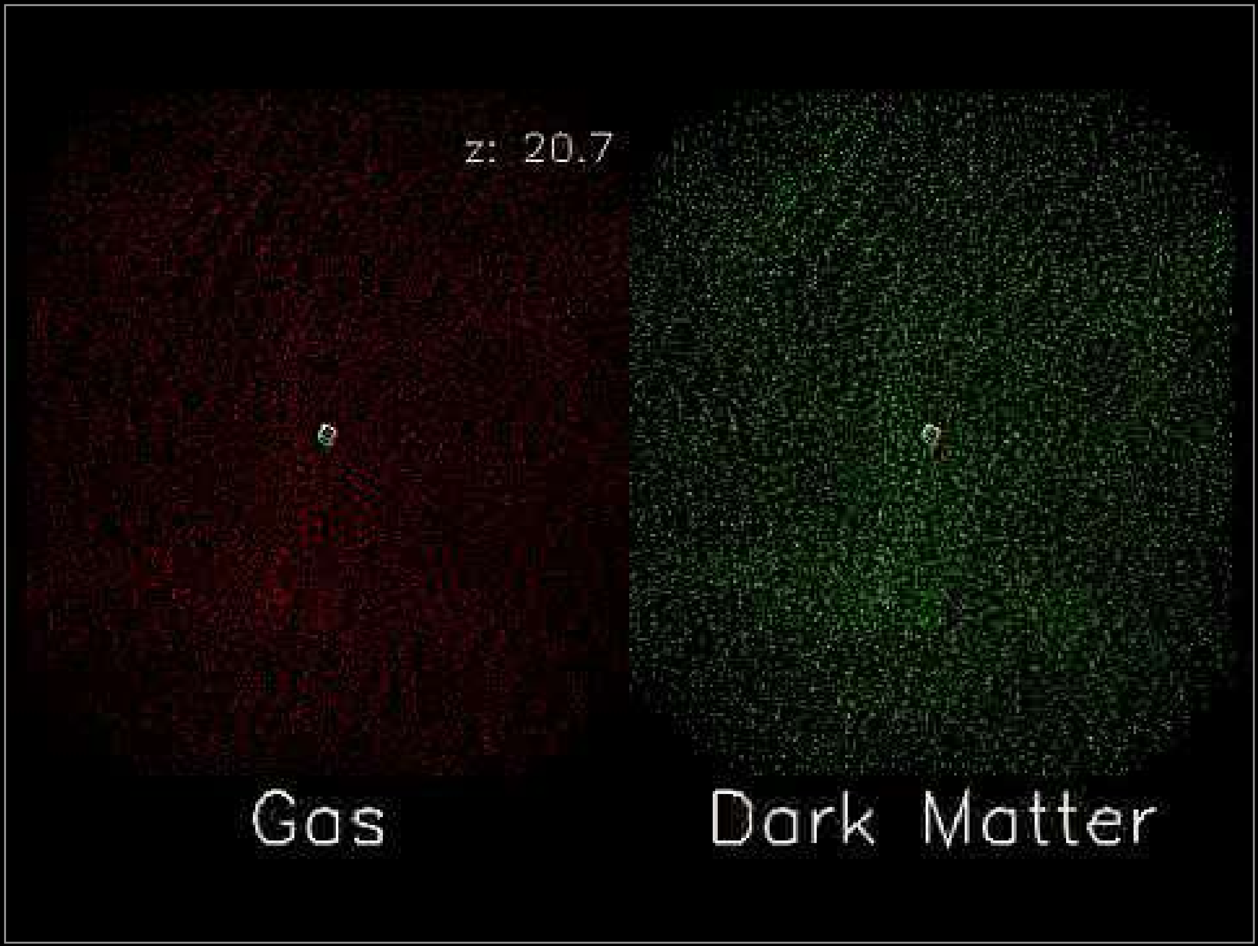


Credits: Matthias Steinmetz

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

Hierarchical Galaxy Formation:

CDM



Credits: Matthias Steinmetz

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

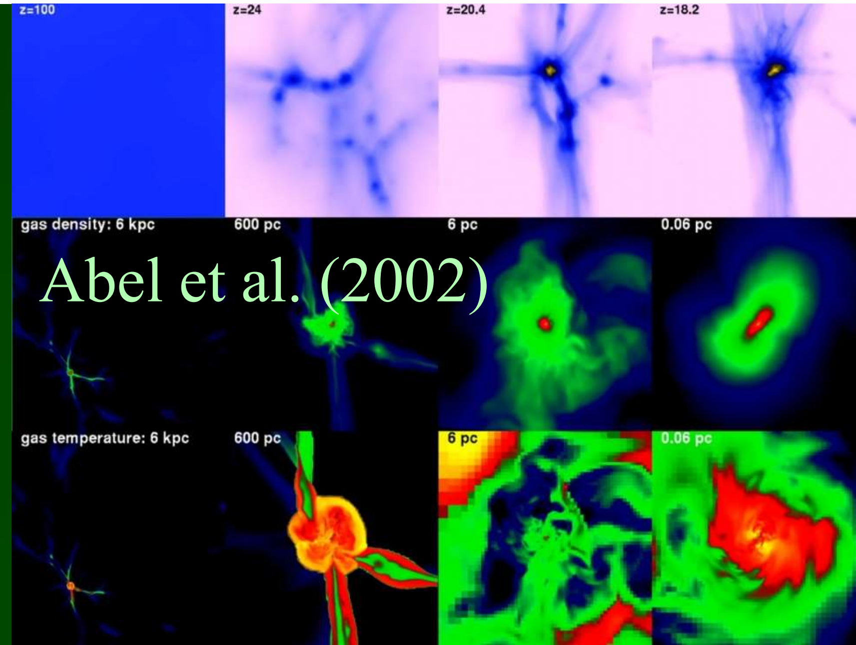
The universe today:

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

Formation of a
galaxy cluster:

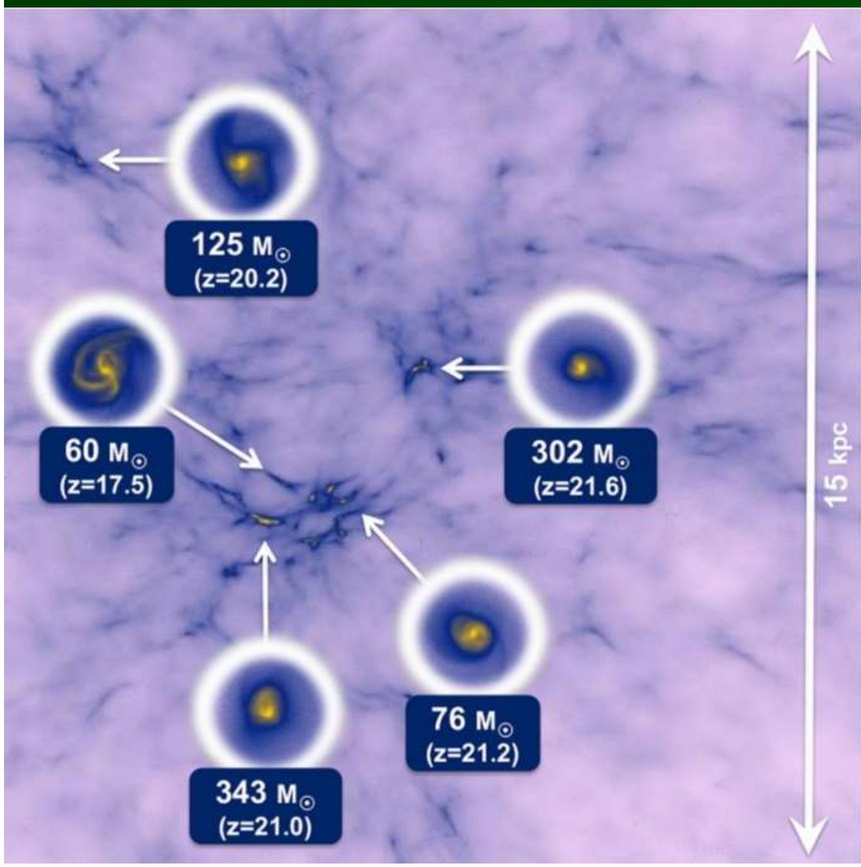
http://www.mpa-garching.mpg.de/galform/data_vis/

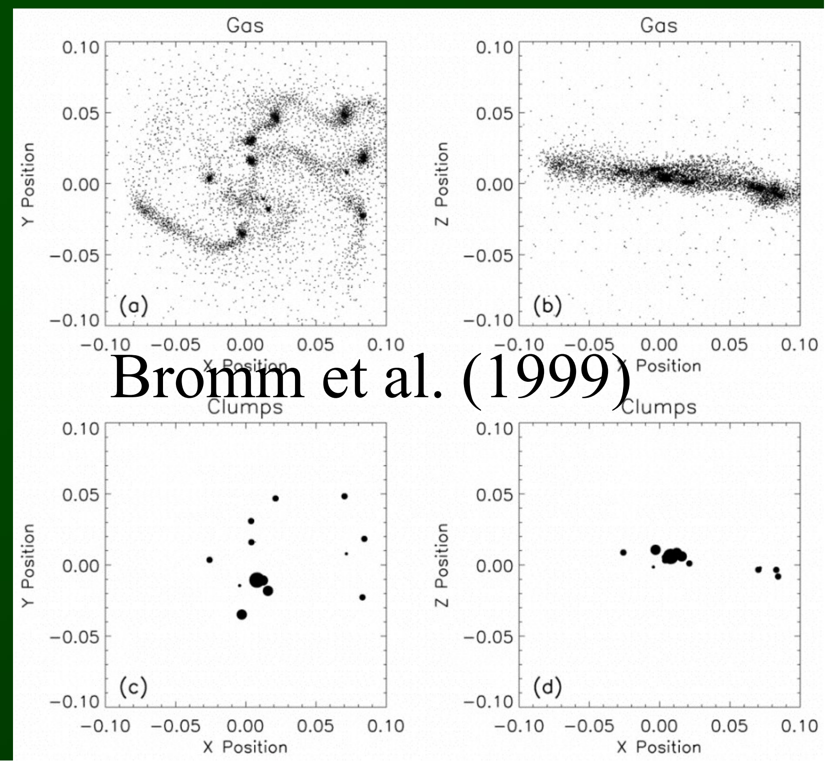
The First Star (simulations)



Abel et al. (2002)

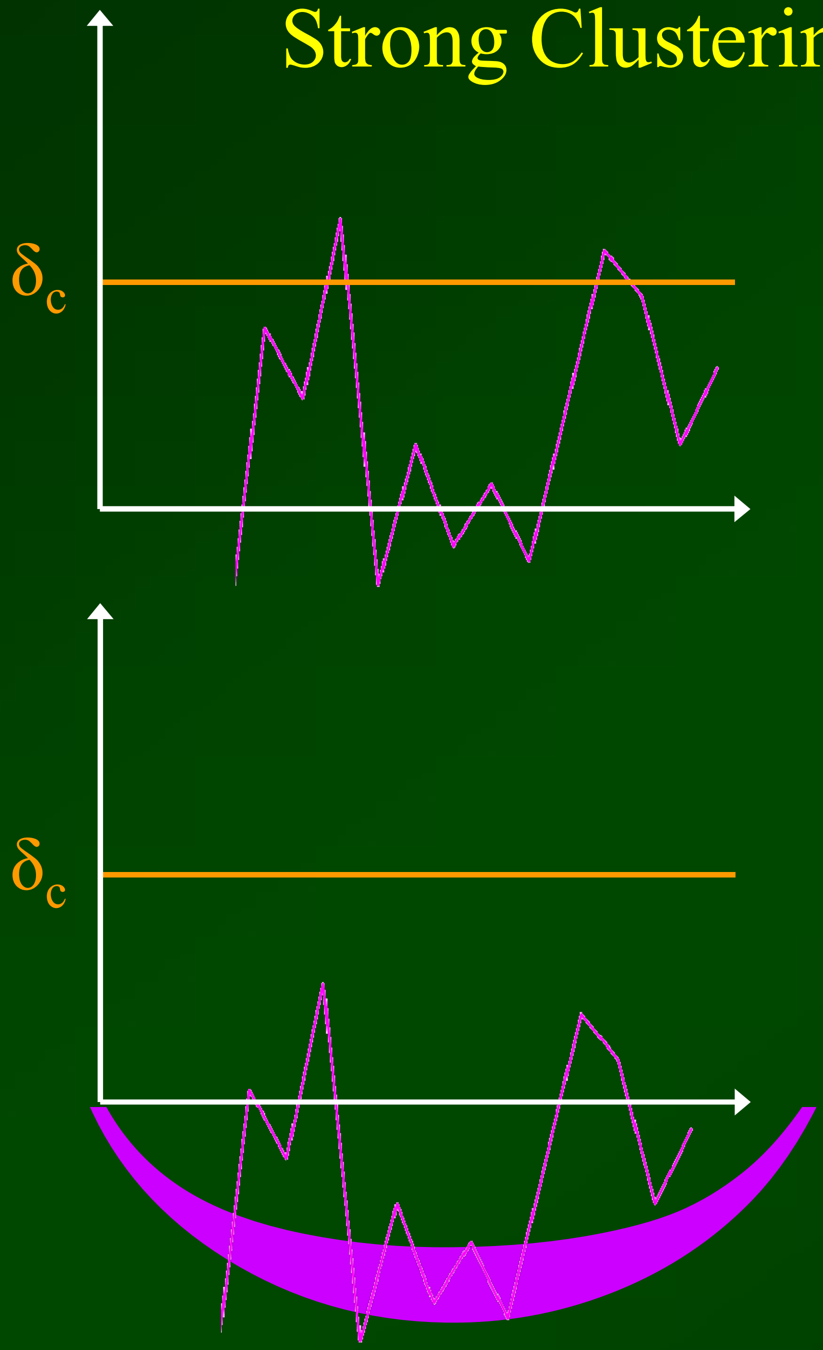
Hirano et al. (2014)





Bromm et al. (1999)

Strong Clustering of Early Galaxies



Extended Press-Schechter
Peak-Background Split

Press & Schechter 1974

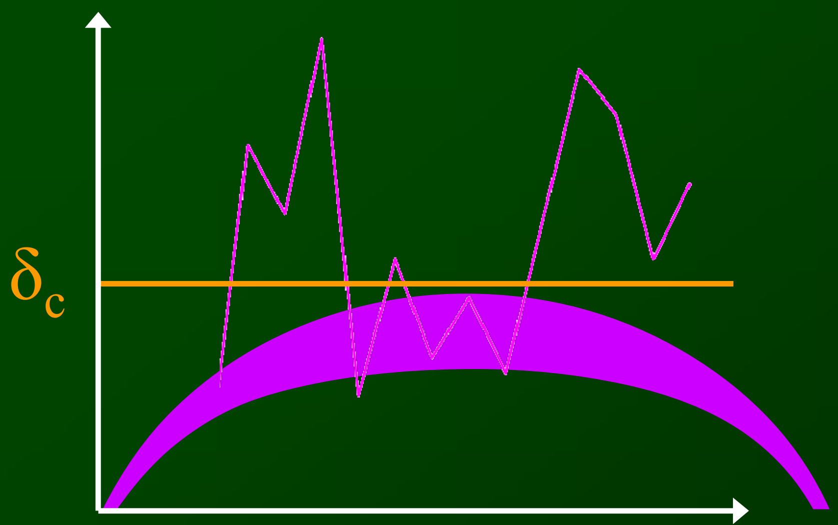
Bardeen, Bond, Kaiser, & Szalay 1986

Kaiser 1984

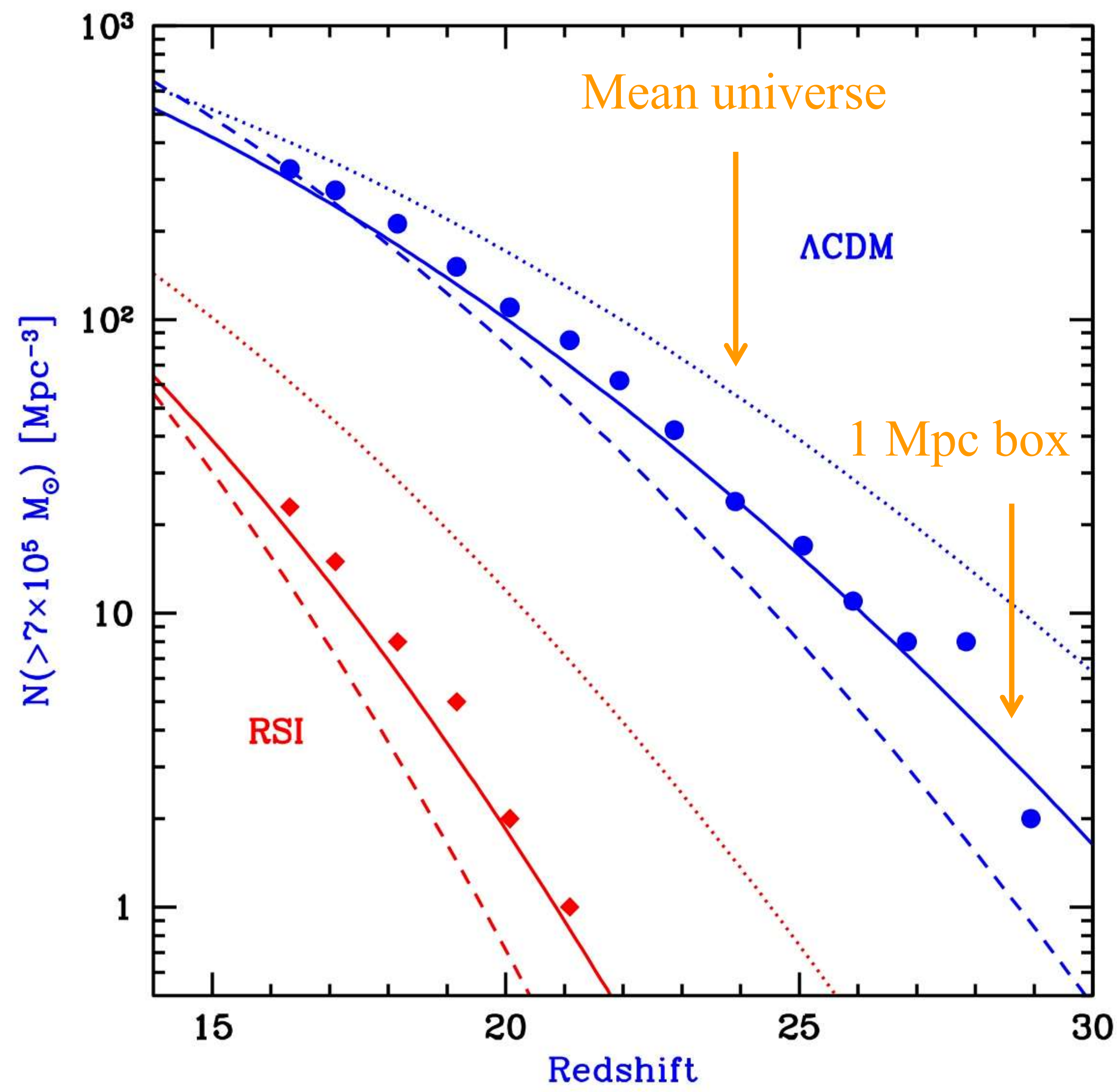
Bond, Cole, Efstathiou, & Kaiser 1991

Cole & Kaiser 1989

Mo & White 1996



The First Star (theory)

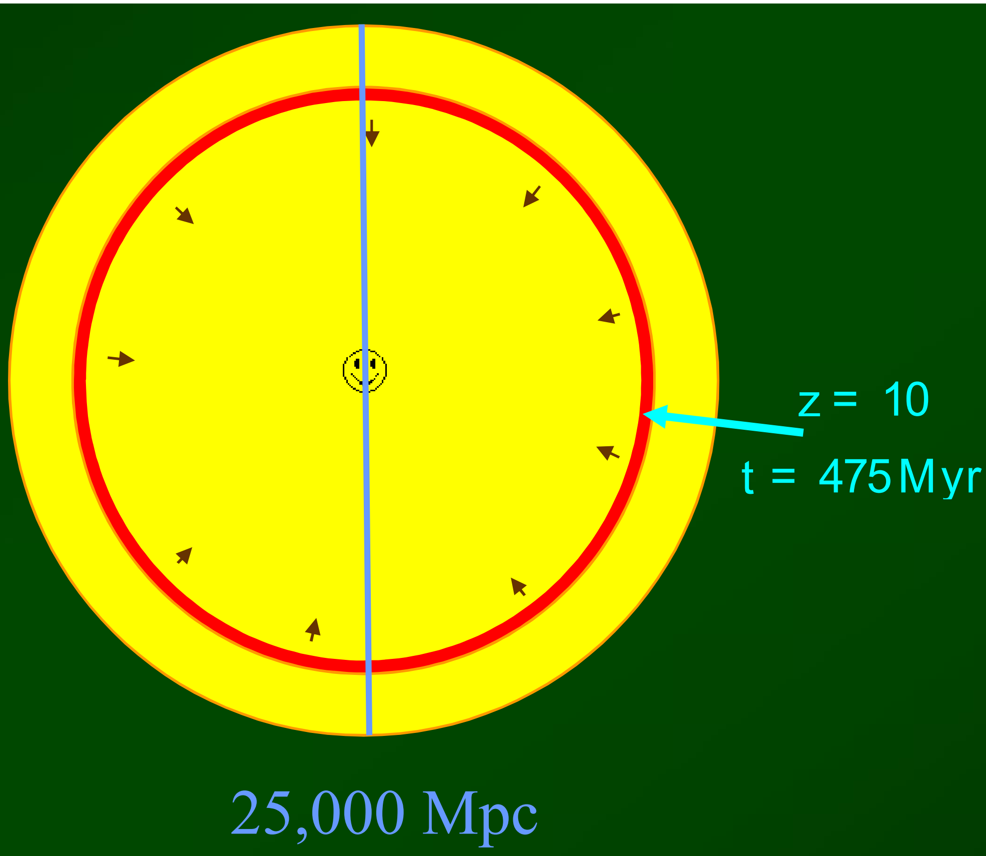


Simulations:
Yoshida et al. (2003)

RB & Loeb (2004)

The First Star (theory)

Naoz, Noter, & RB (2006)



z ~ 65 (t ~ 30 Myr)

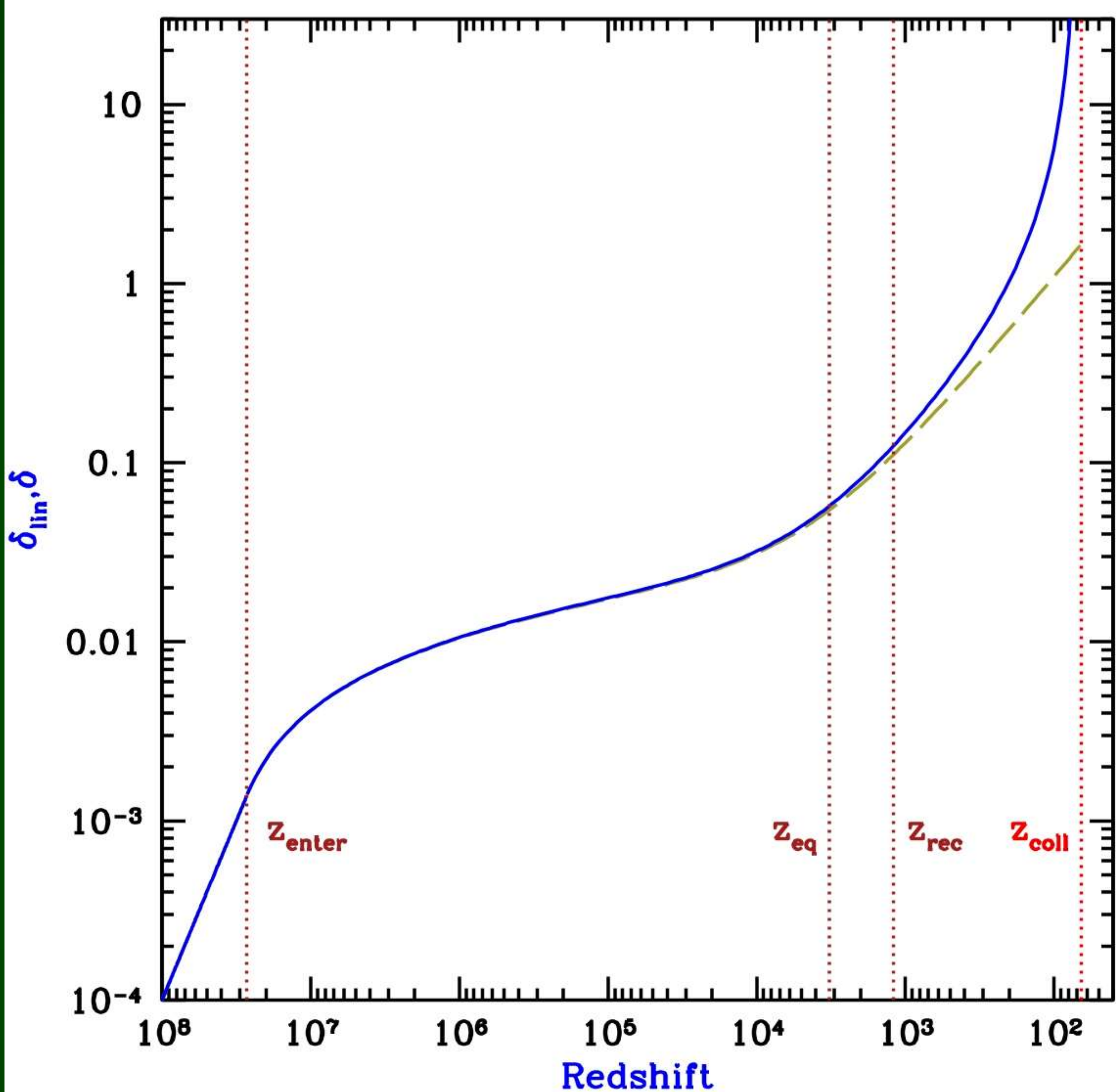
Compare:

z ~ 30 (t ~ 100 Myr)

Small galaxies ↔ Large scales

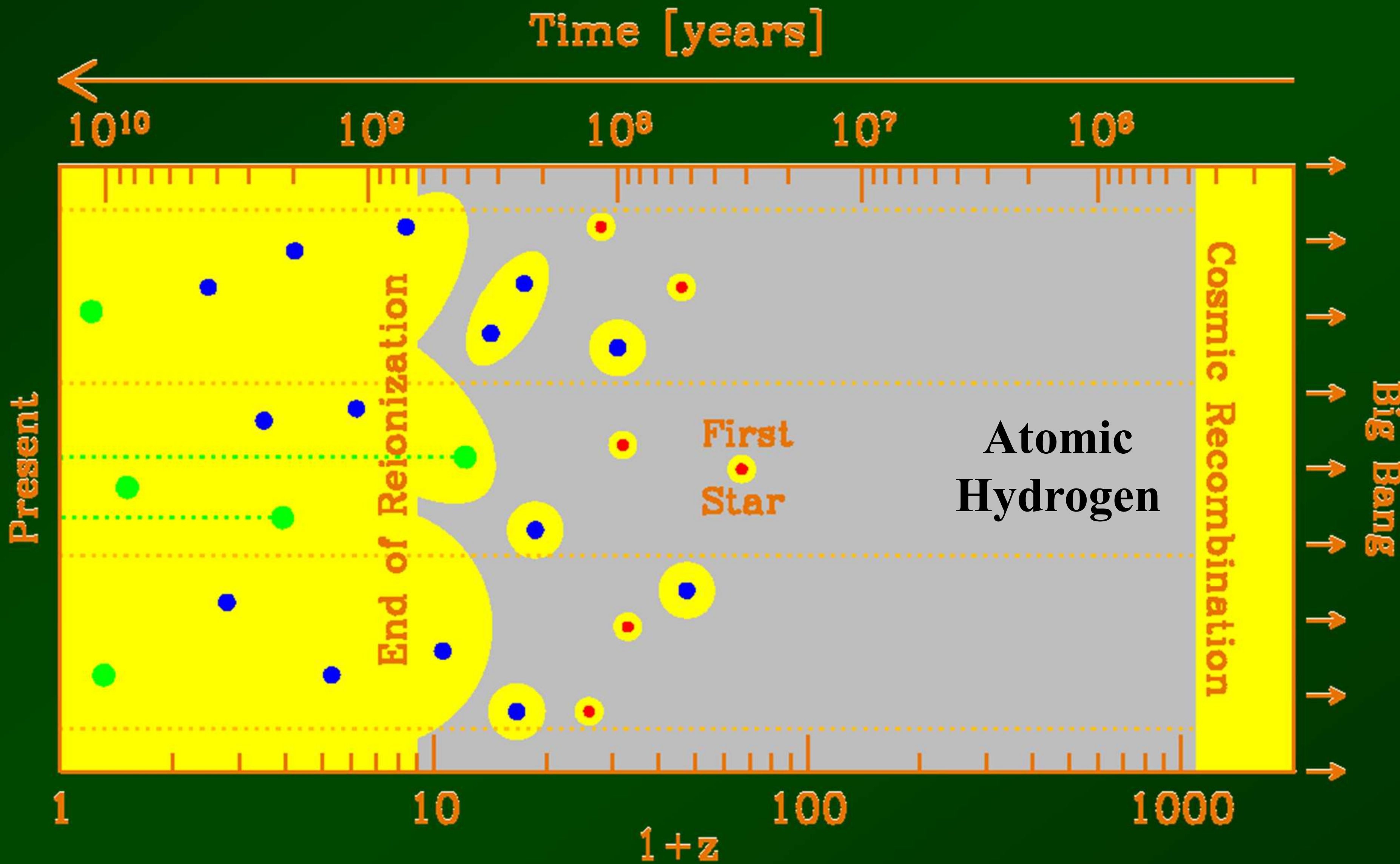
The First Star (theory)

The second star: feedback



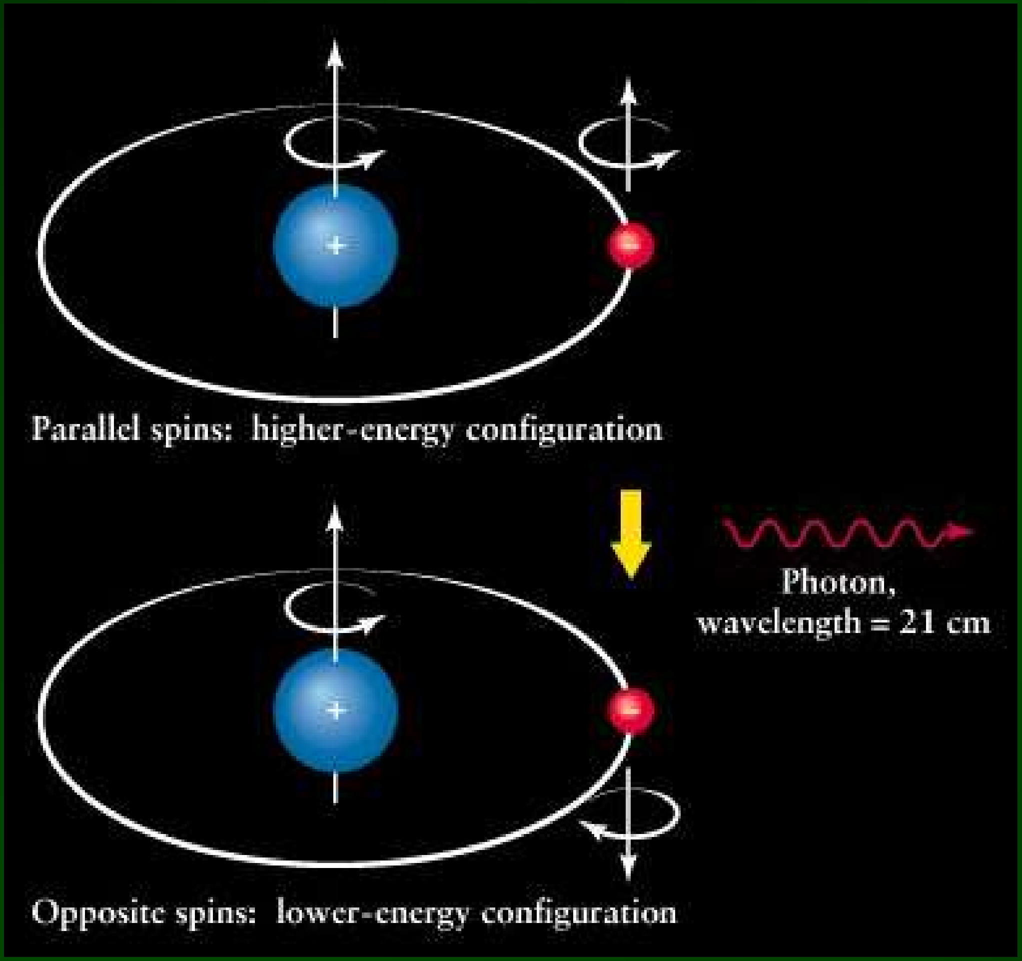
Naoz, Noter, & RB (2006)

Cosmic History



RB 2006, Science

21-cm Cosmology: The Spin Temperature



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

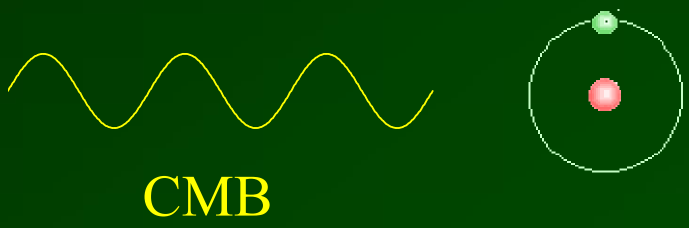
$\nu = 1420\ \mathrm{MHz}$

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

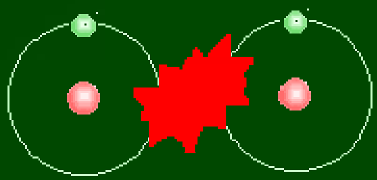
$\frac{E}{k_B} = T_* = 0.068\ \mathrm{K}$

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

What determines T_S?

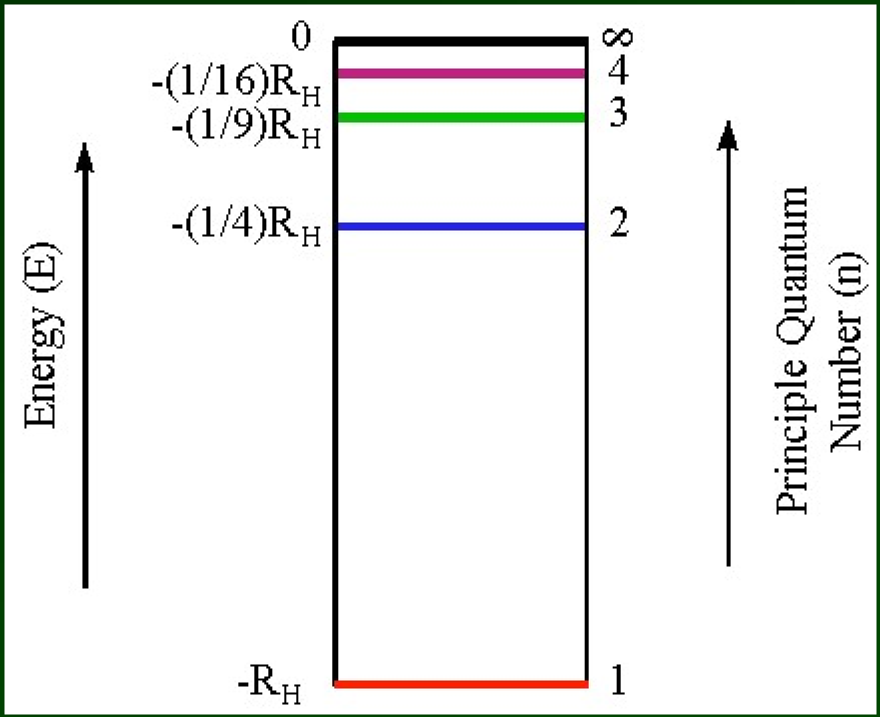


$$T_S \rightarrow T_{\mathrm{CMB}}$$

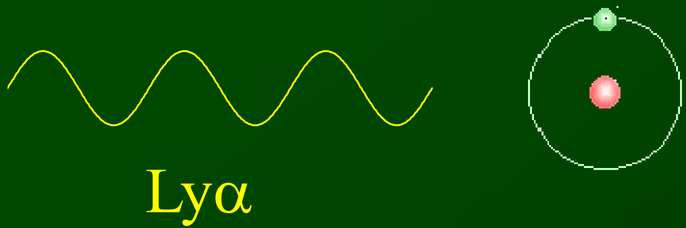


$$T_S \rightarrow T_{\mathrm{gas}}$$

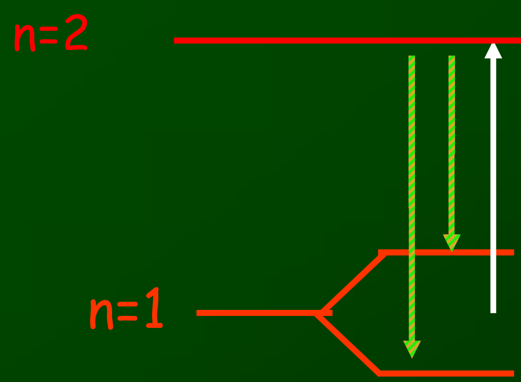
What determines T_S?



Ly-Limit: 13.6 eV
Lyα: ¾ LL = 10.2 eV

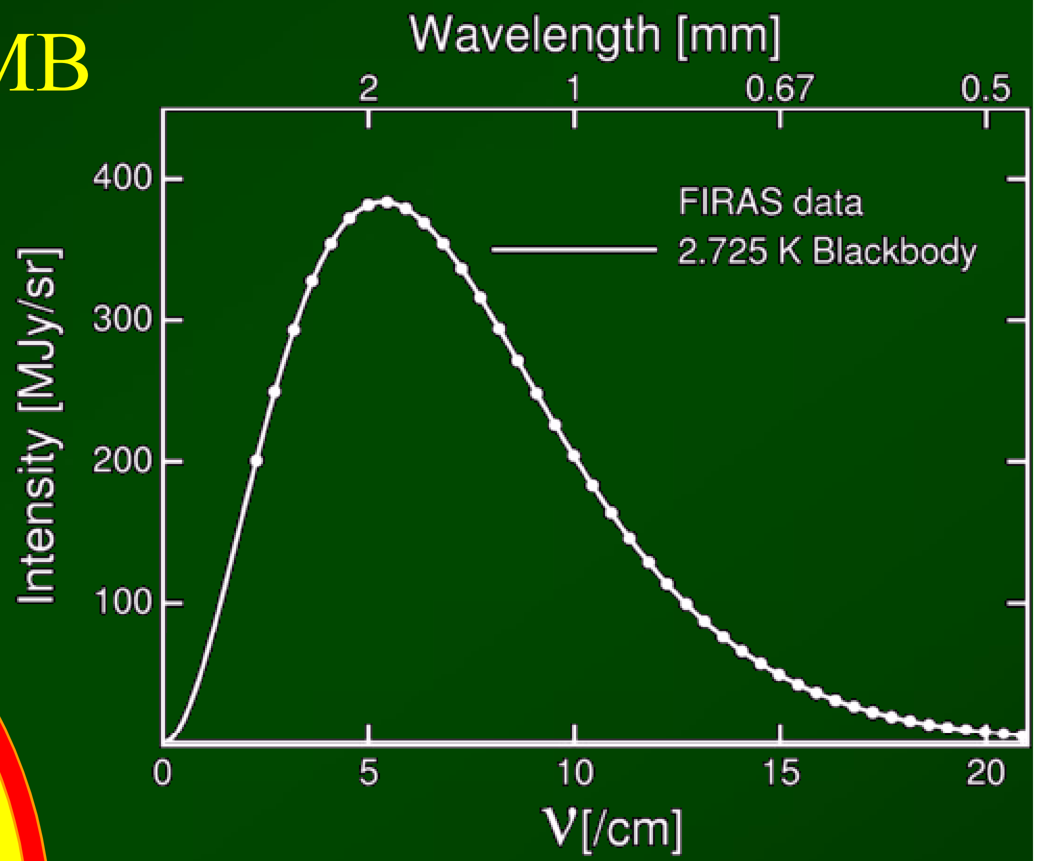


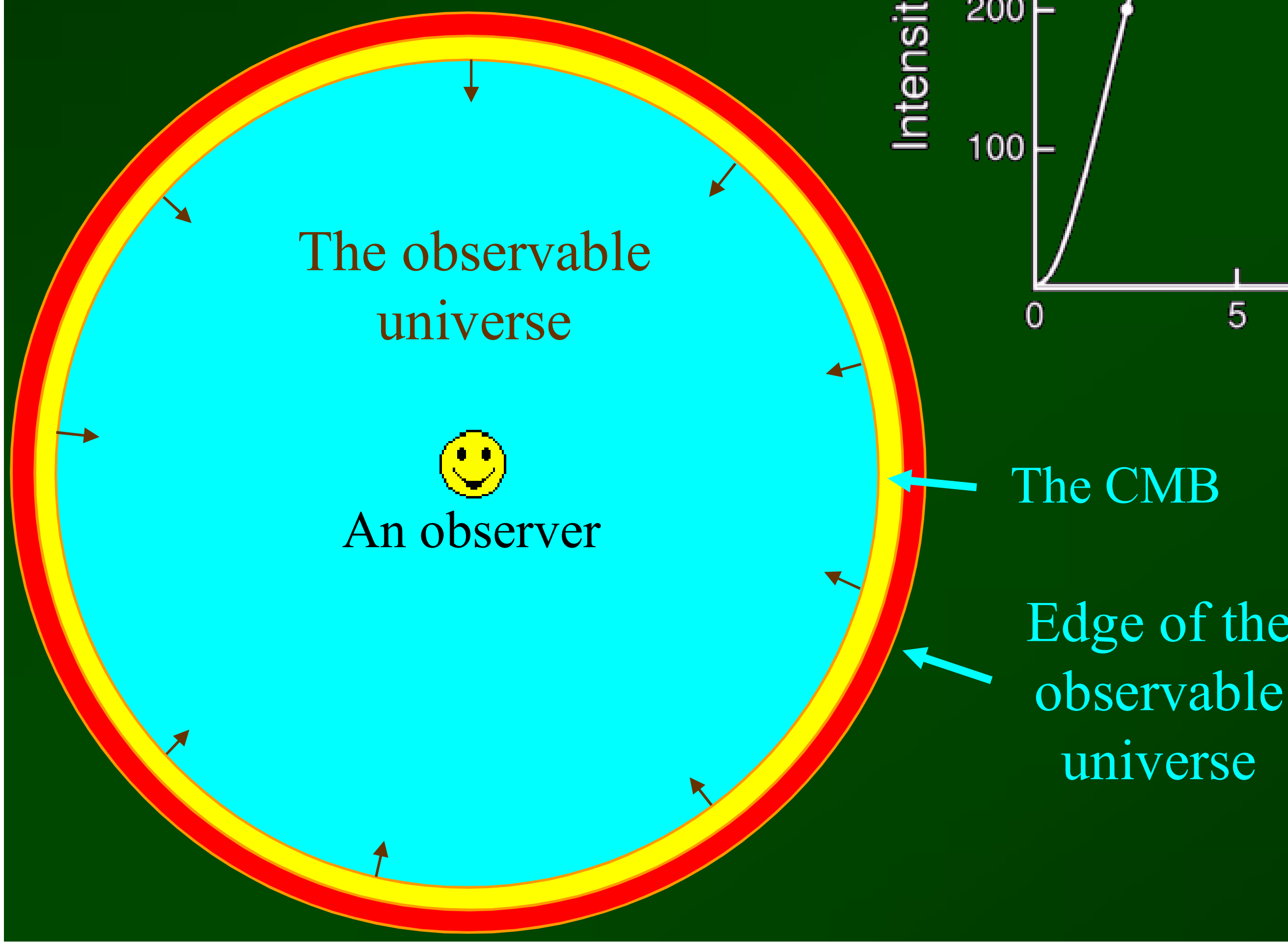
Wouthuysen 1952
Field 1958



$T_S \rightarrow T_{gas}$

Diffuse Source: The CMB

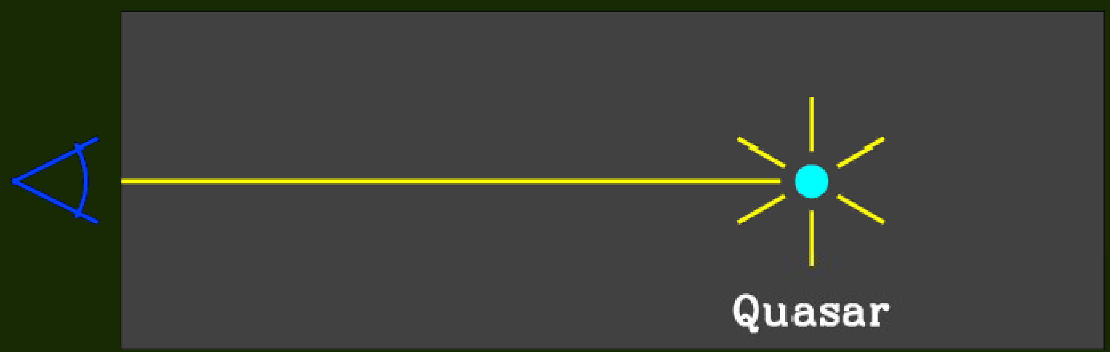


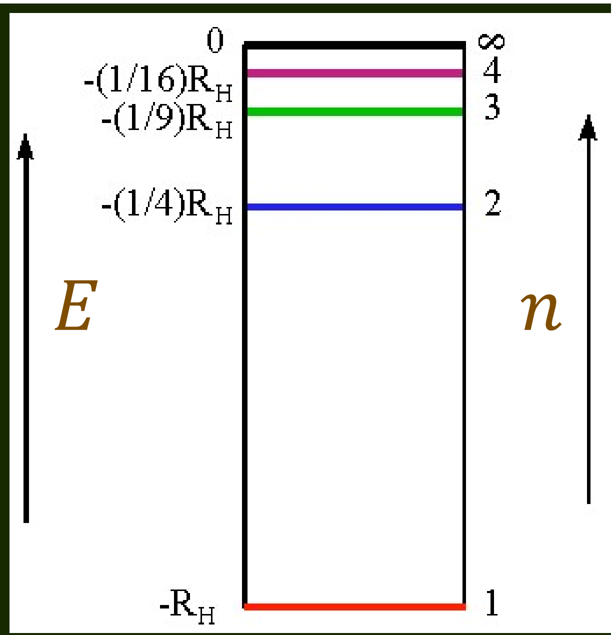


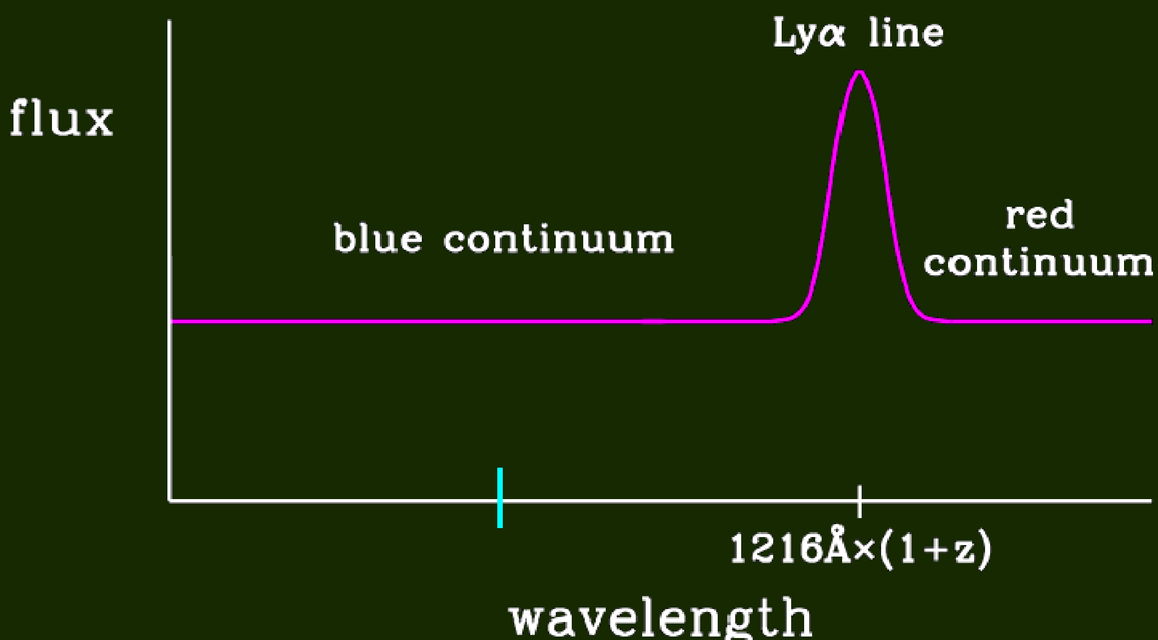
$$h\nu \ll k_B T$$

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

Lyα Spectra:



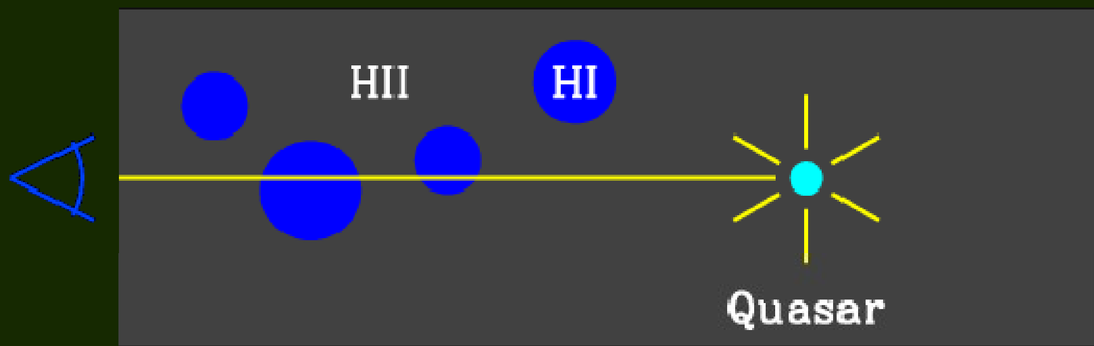


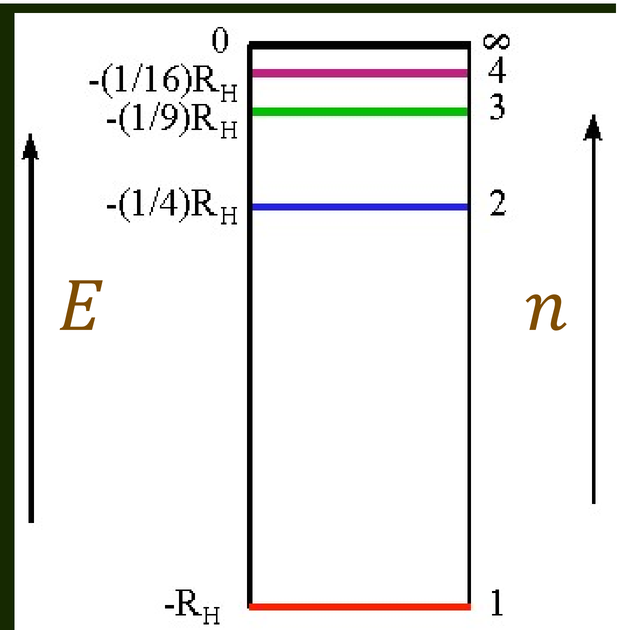


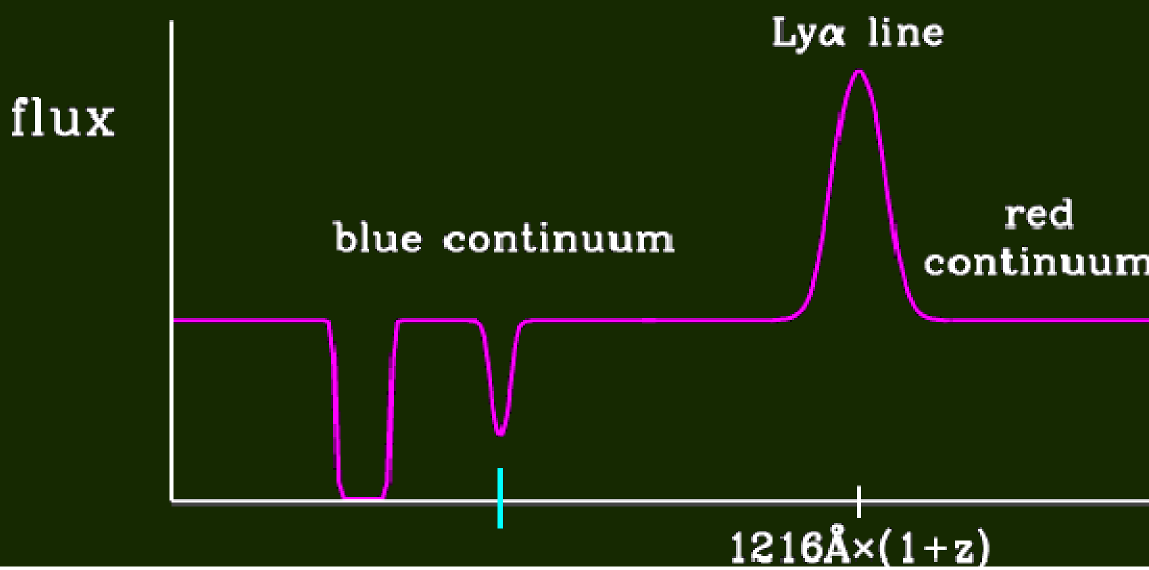
Resonance Line + Cosmological Redshift

$$1100\text{Å} \times (1 + z)$$

Lyα Spectra: 1D density distribution





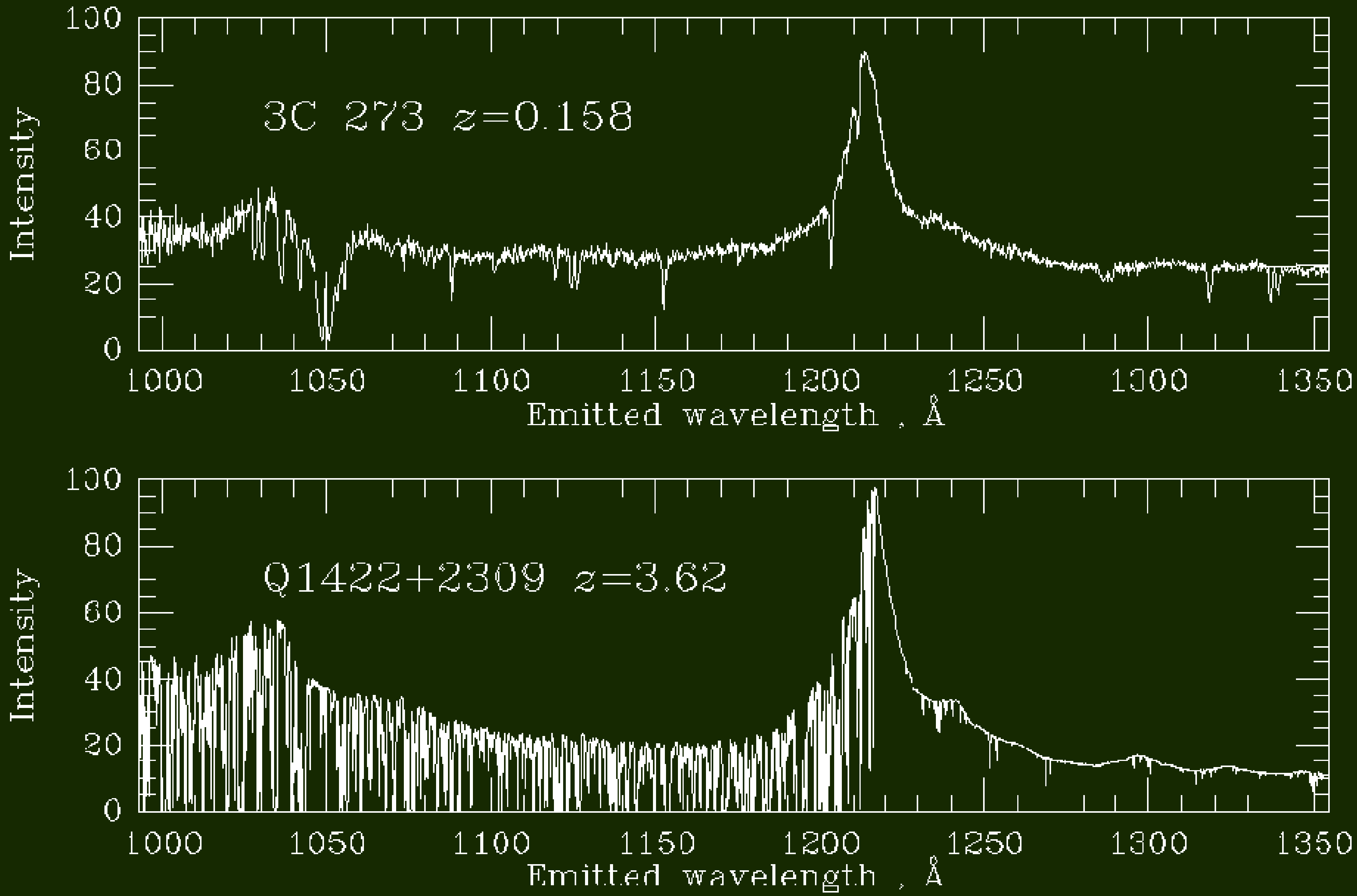


Resonance Line +
Cosmological Redshift

$$1100\text{Å} \times (1 + z)$$

$$= 1216\text{Å} \times (1 + z')$$

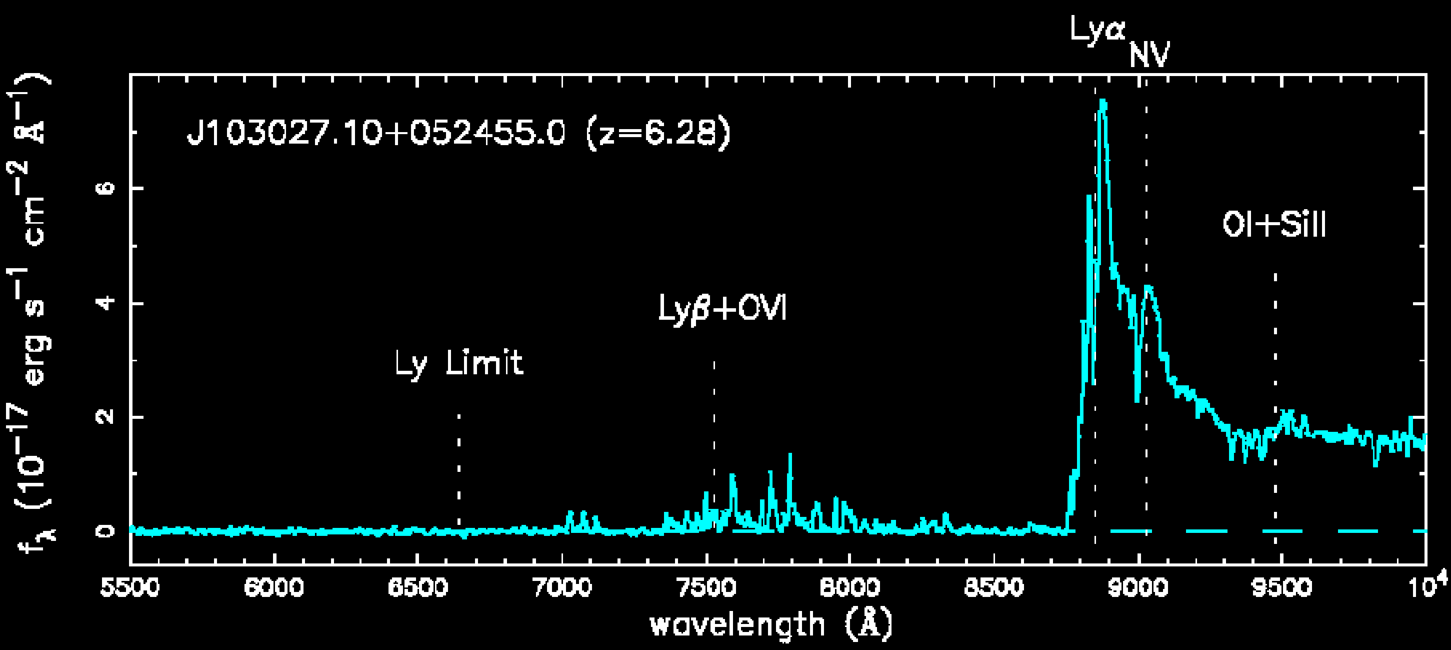
Gunn & Peterson 1965: $\tau_{\rm GP} = \dfrac{\pi e^2 f_\alpha \lambda_\alpha n_{\rm H\,I}}{m_e c H} = 6.62 \times 10^5 \left(\dfrac{\Omega_b h}{0.0327}\right)\left(\dfrac{\Omega_m}{0.307}\right)^{-1/2}\left(\dfrac{1+z}{10}\right)^{3/2}$



Keck, HST; Mike Rauch

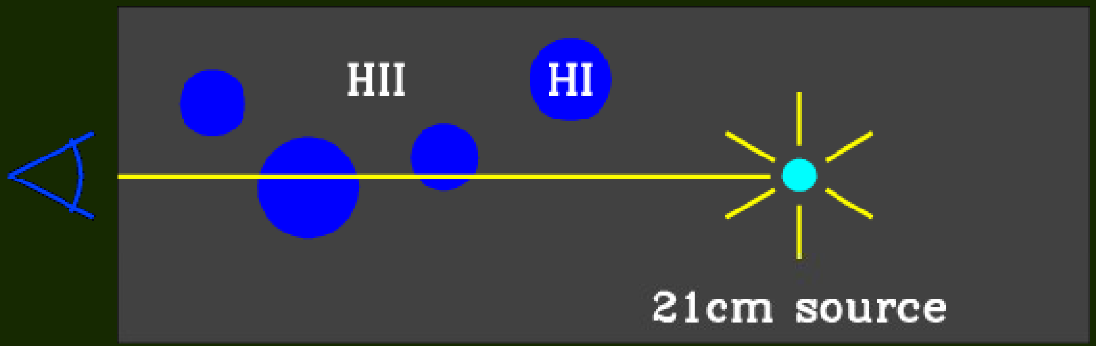
http://www.astr.ua.edu/keel/agn/forest.html

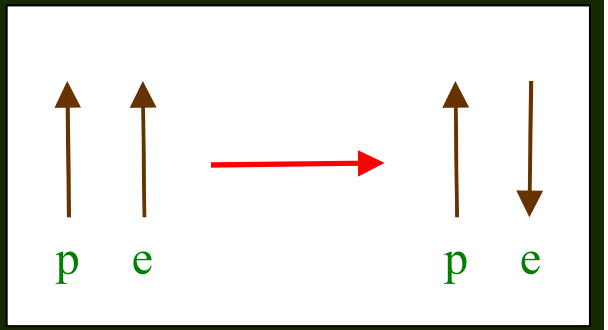
Quasar at z=6.3

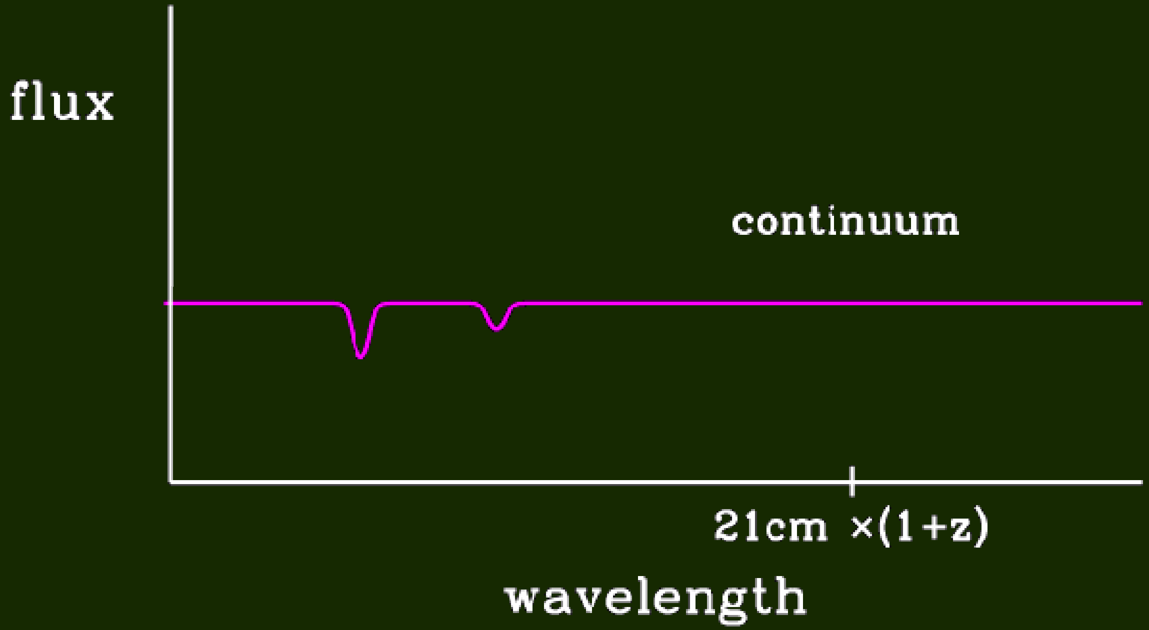


Becker et al. 2001

21-cm Spectra

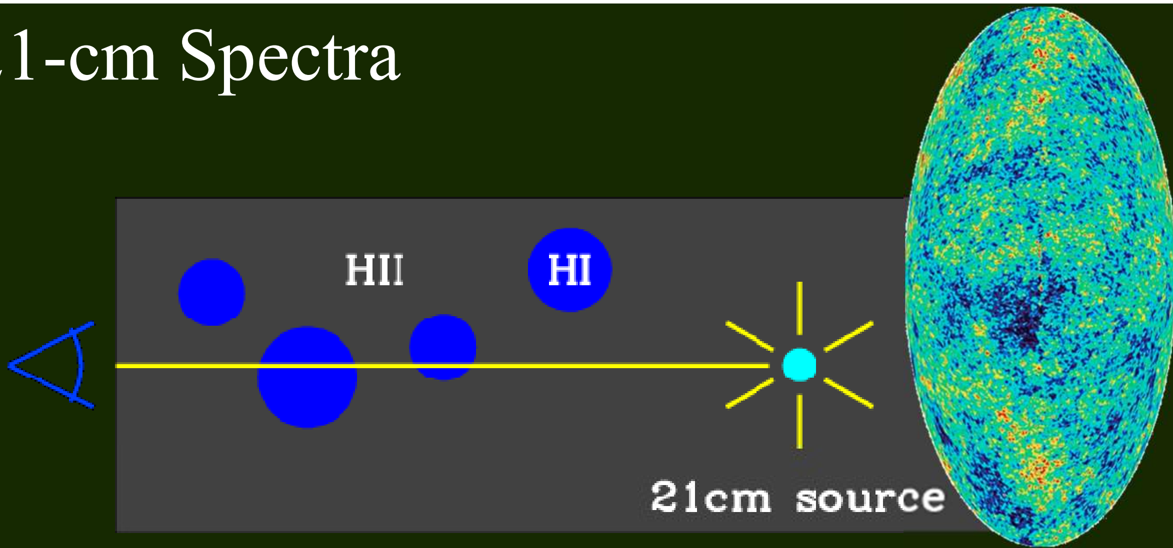


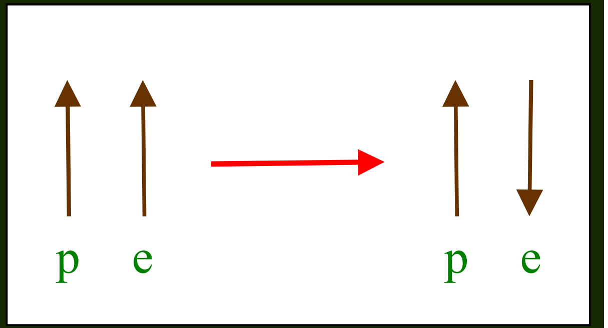


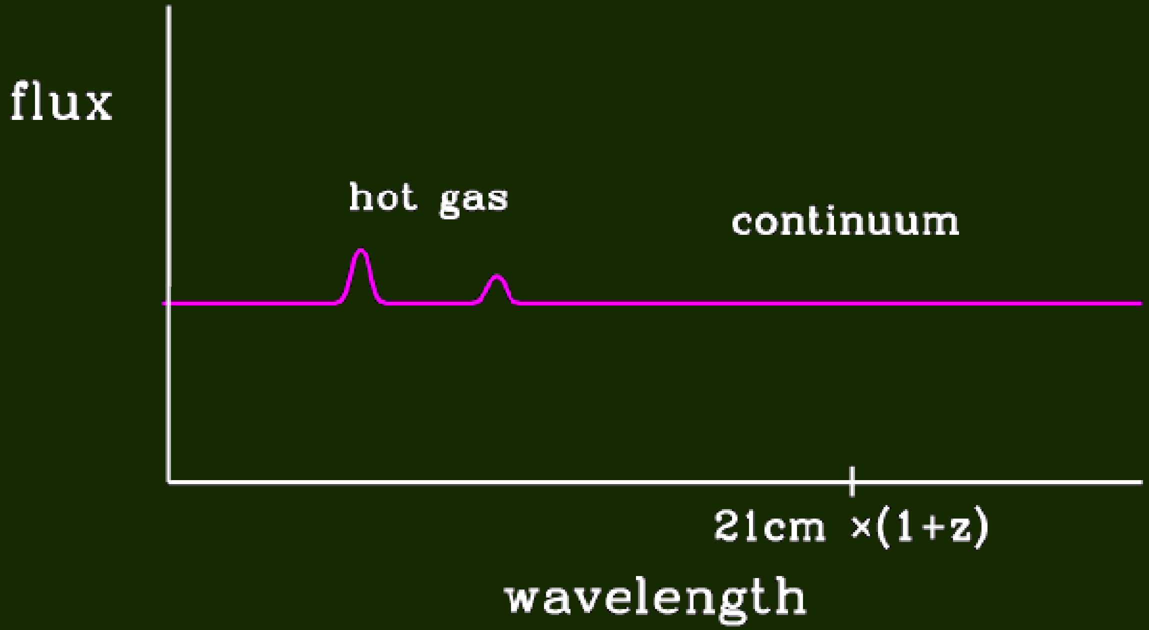


Resonance Line +
Cosmological Redshift

21-cm Spectra



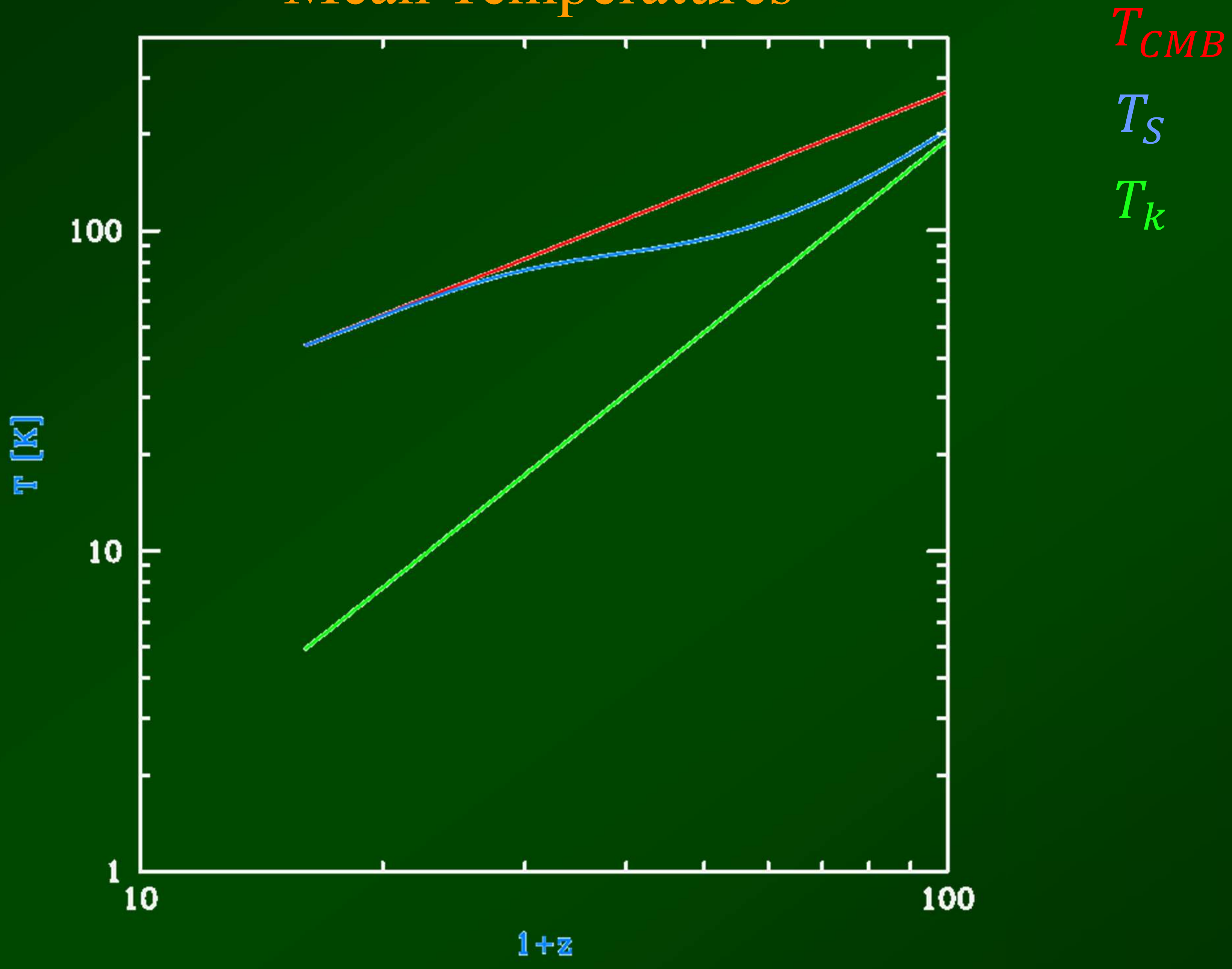




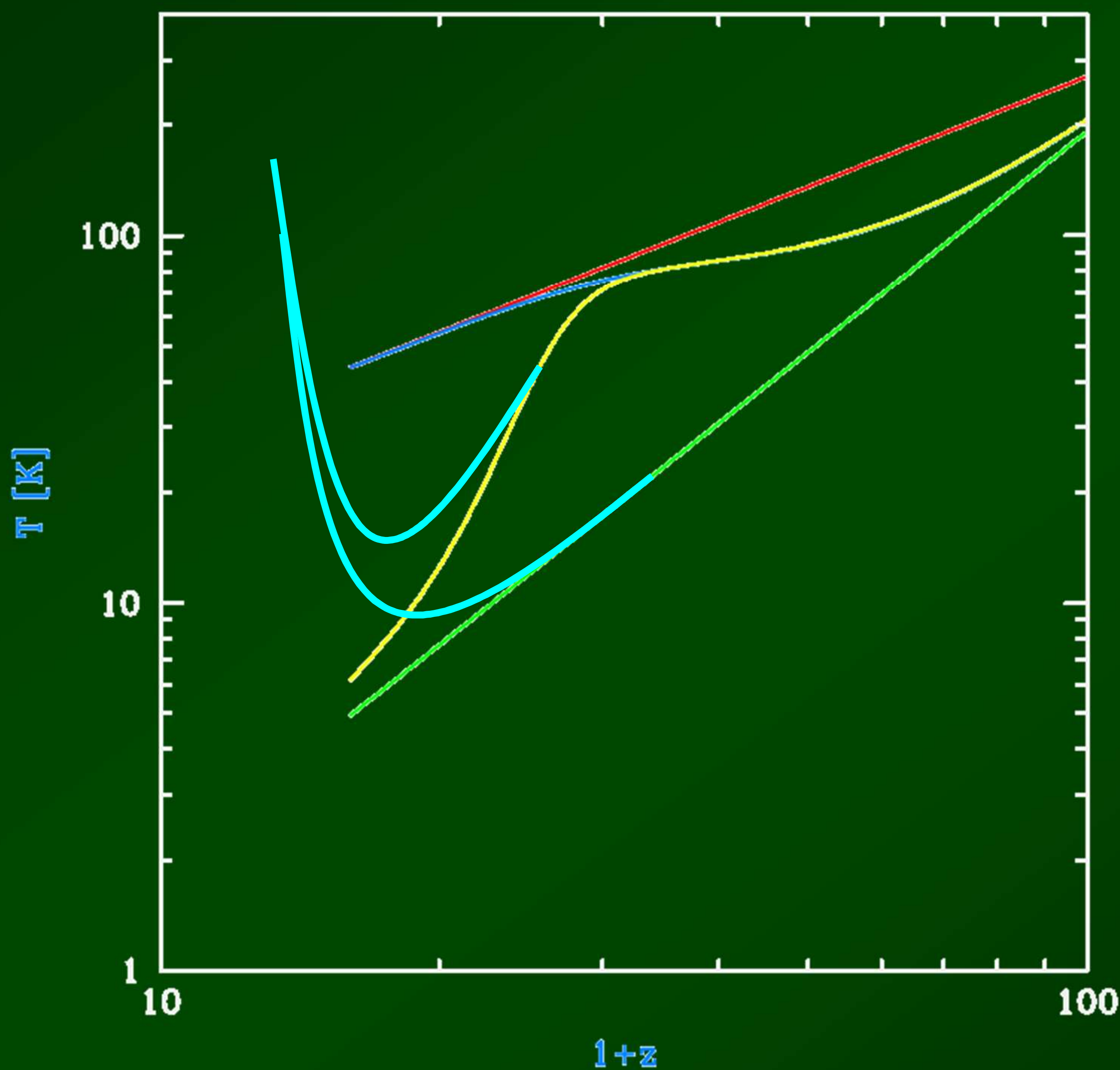
Resonance Line +
Cosmological Redshift


3D CINEMA
ILLUSION

Mean Temperatures



Mean Temperatures



T_{CMB}

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:

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

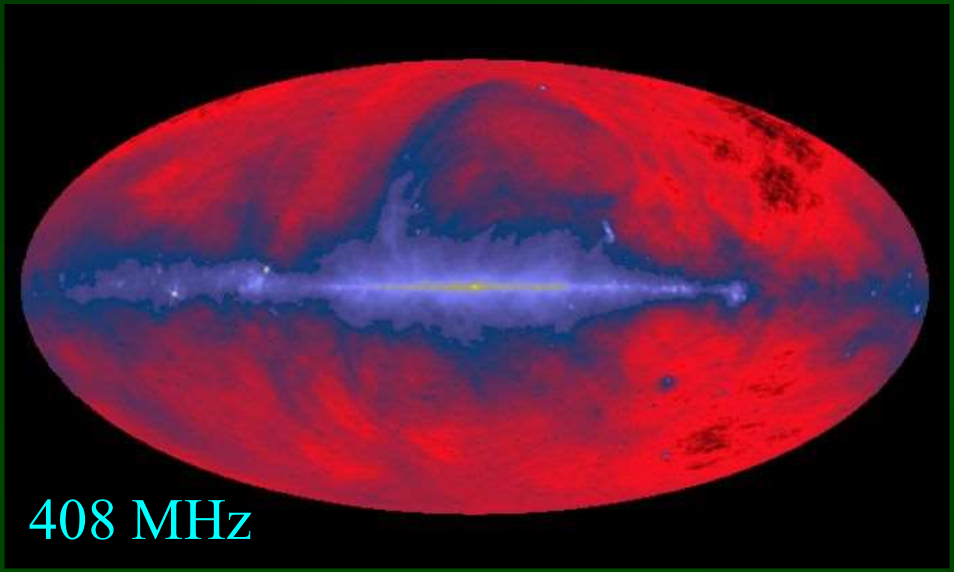
$$\tau(z) = 9.85 \times 10^{-3} \left(\frac{T_{\rm CMB}}{T_S}\right)\left(\frac{\Omega_b h}{0.0327}\right)\left(\frac{\Omega_m}{0.307}\right)^{-1/2}\left(\frac{1+z}{10}\right)^{1/2}$$

Brightness temperature:

$$I_\nu = 2k_B T_{\rm b}\frac{\nu^2}{c^2} \qquad T_{\rm b}^z = T_{\rm CMB}e^{-\tau} + T_S(1-e^{-\tau})$$

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

Foregrounds



$T_{sky} \sim 200$ K
(ν=170 MHz)

=> Large-Scale Fluctuations

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

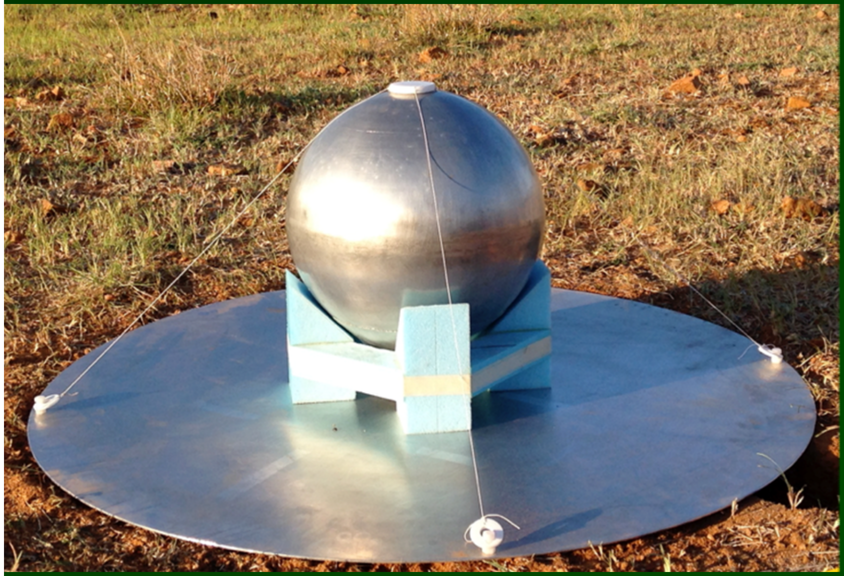
$T_{signal} \sim$ 1-10 mK

$T_{current} \sim$ 40 mK

Global 21-cm Experiments

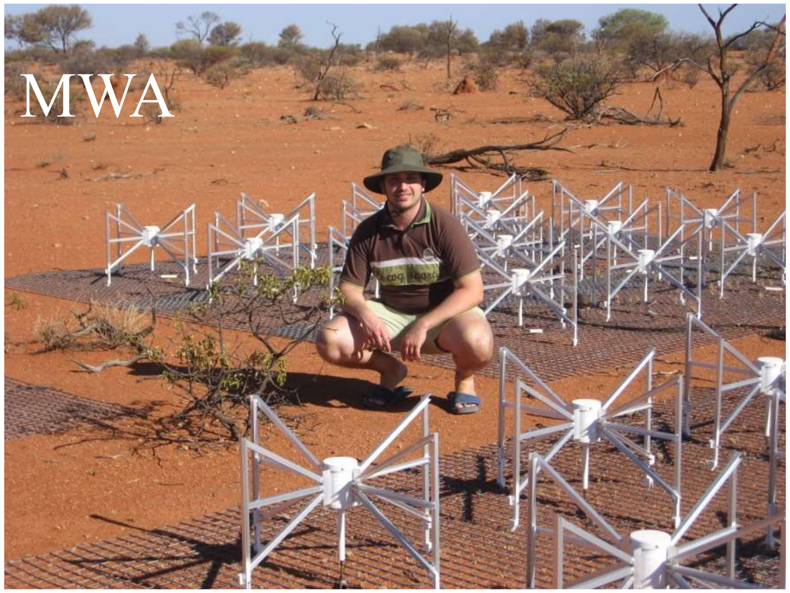
SARAS

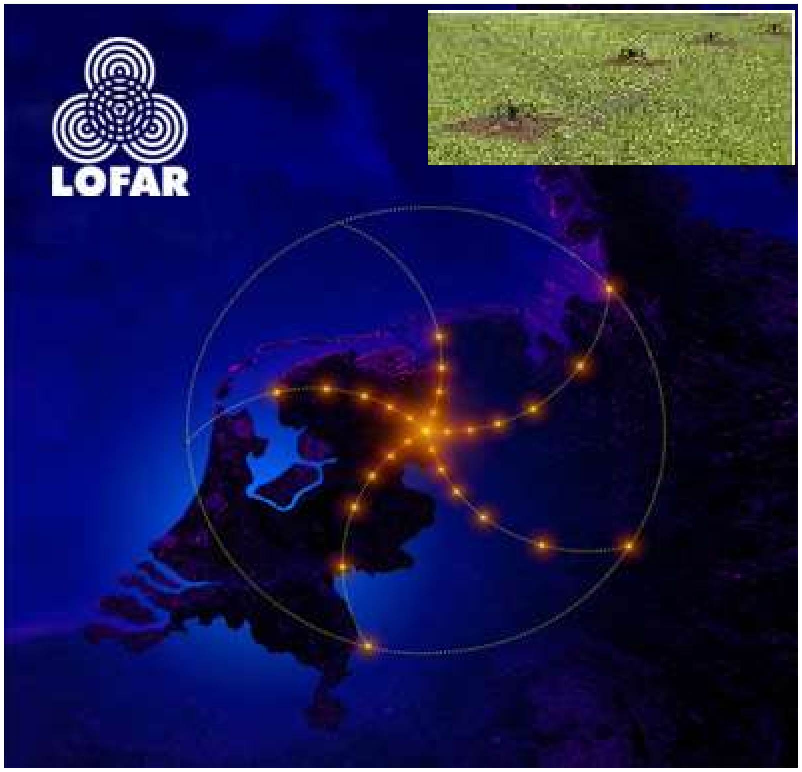
EDGES high

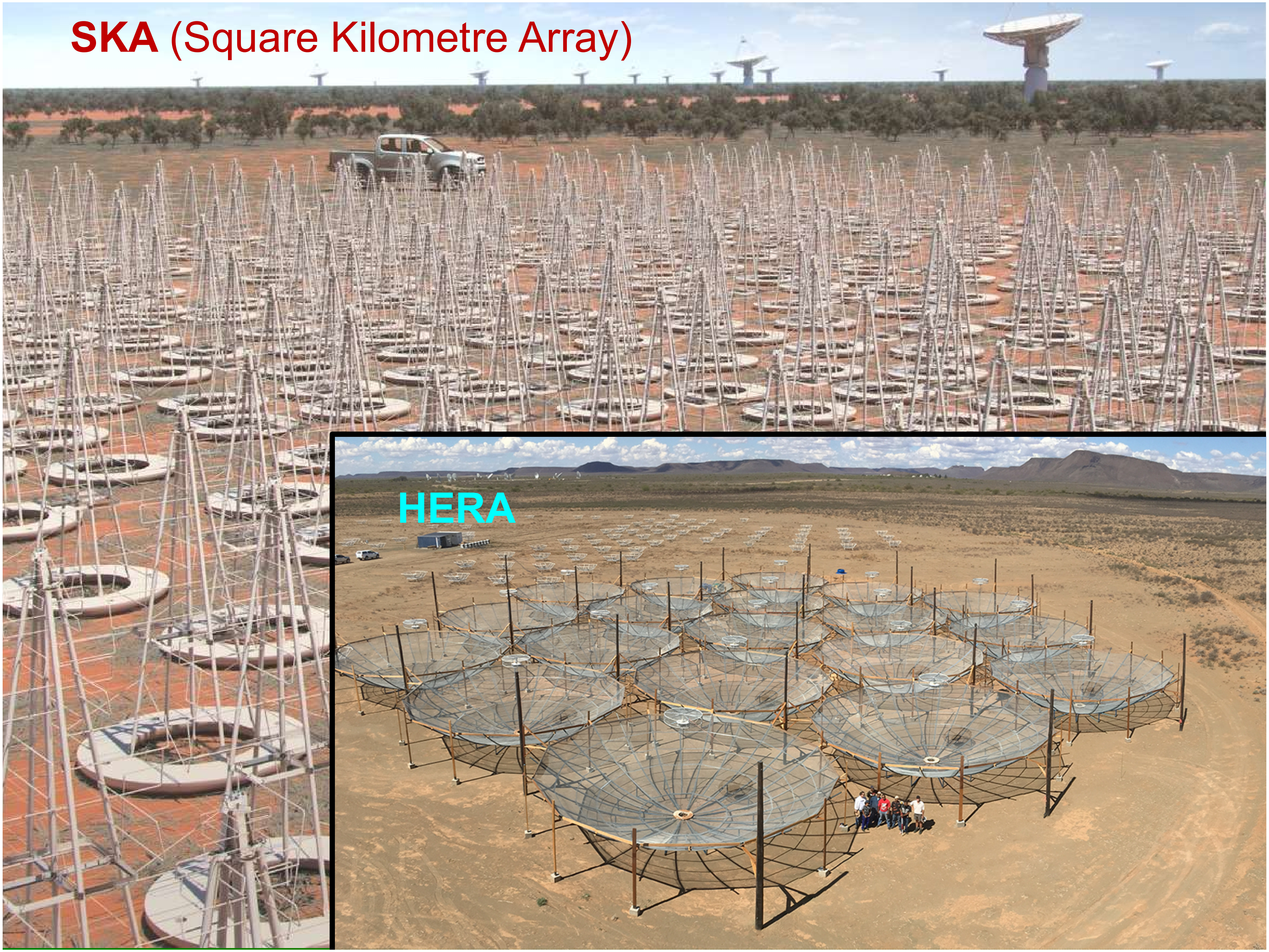


LEDA

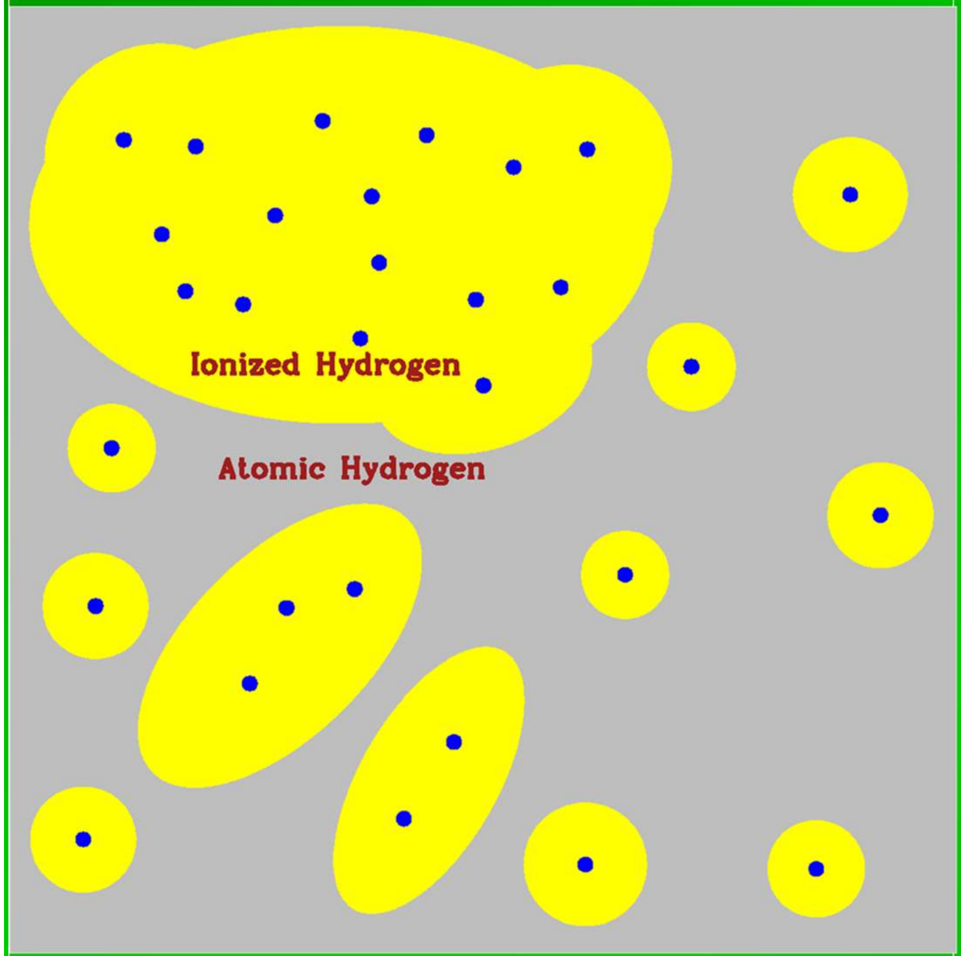
Interferometer Experiments

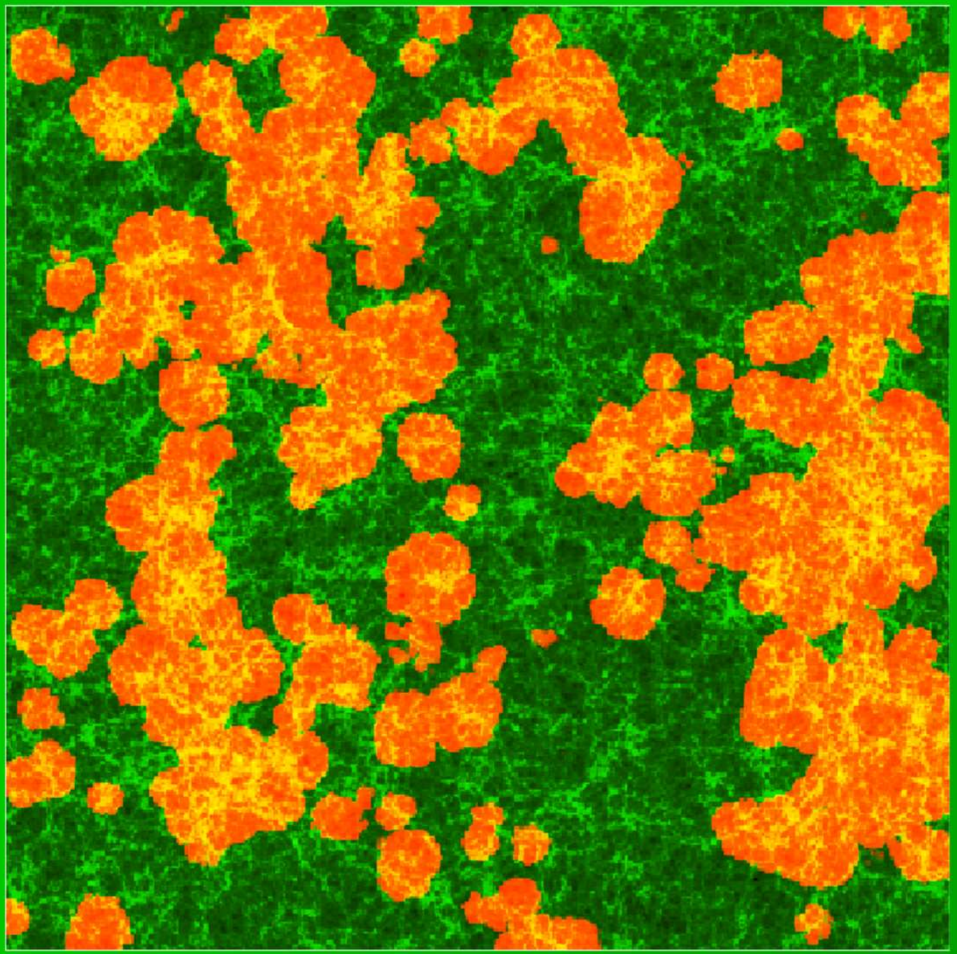





SKA (Square Kilometre Array)
HERA

Cosmic Reionization





← 100/h Mpc = 0.5° →

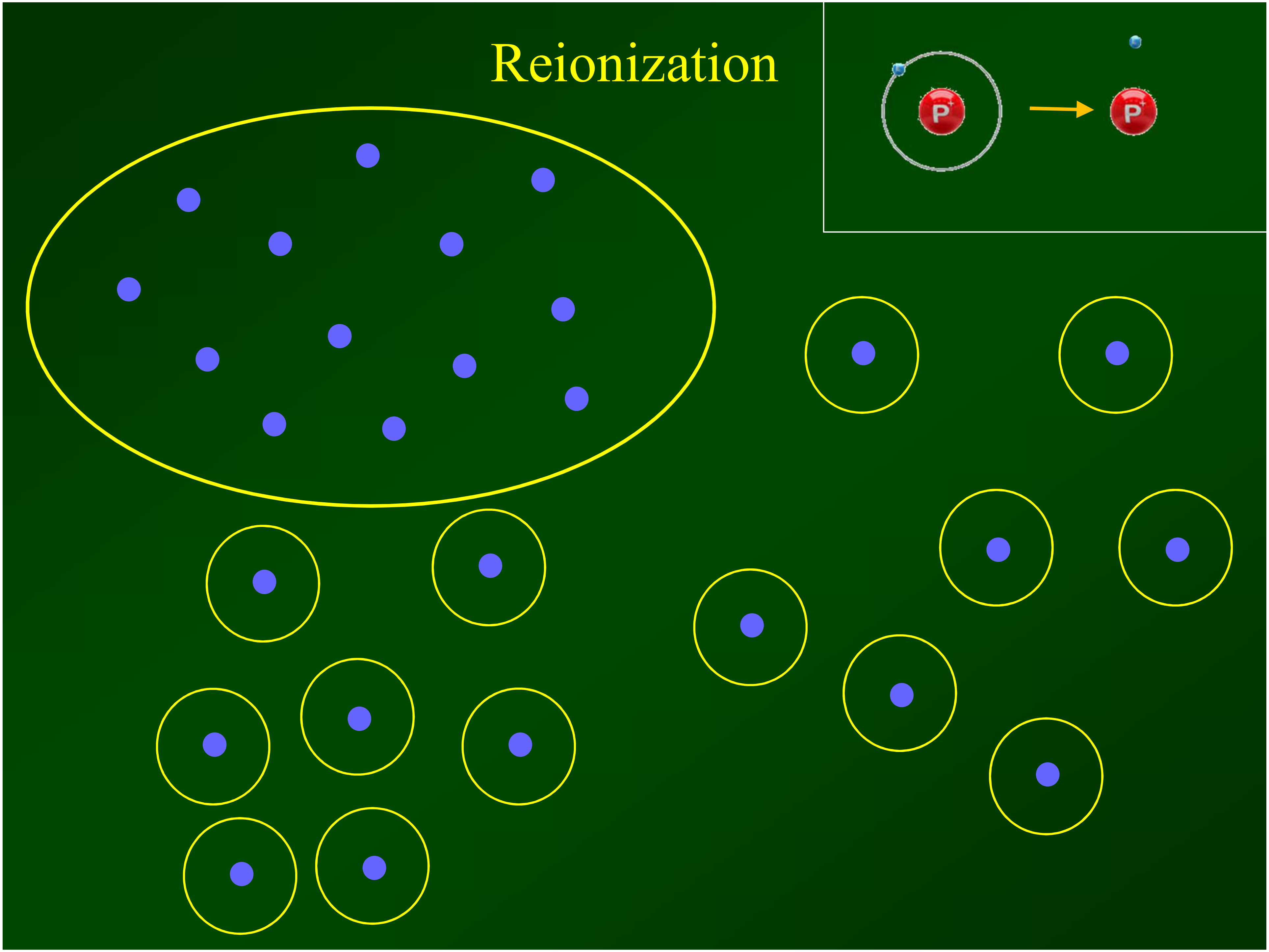
Mellema et al. 2006

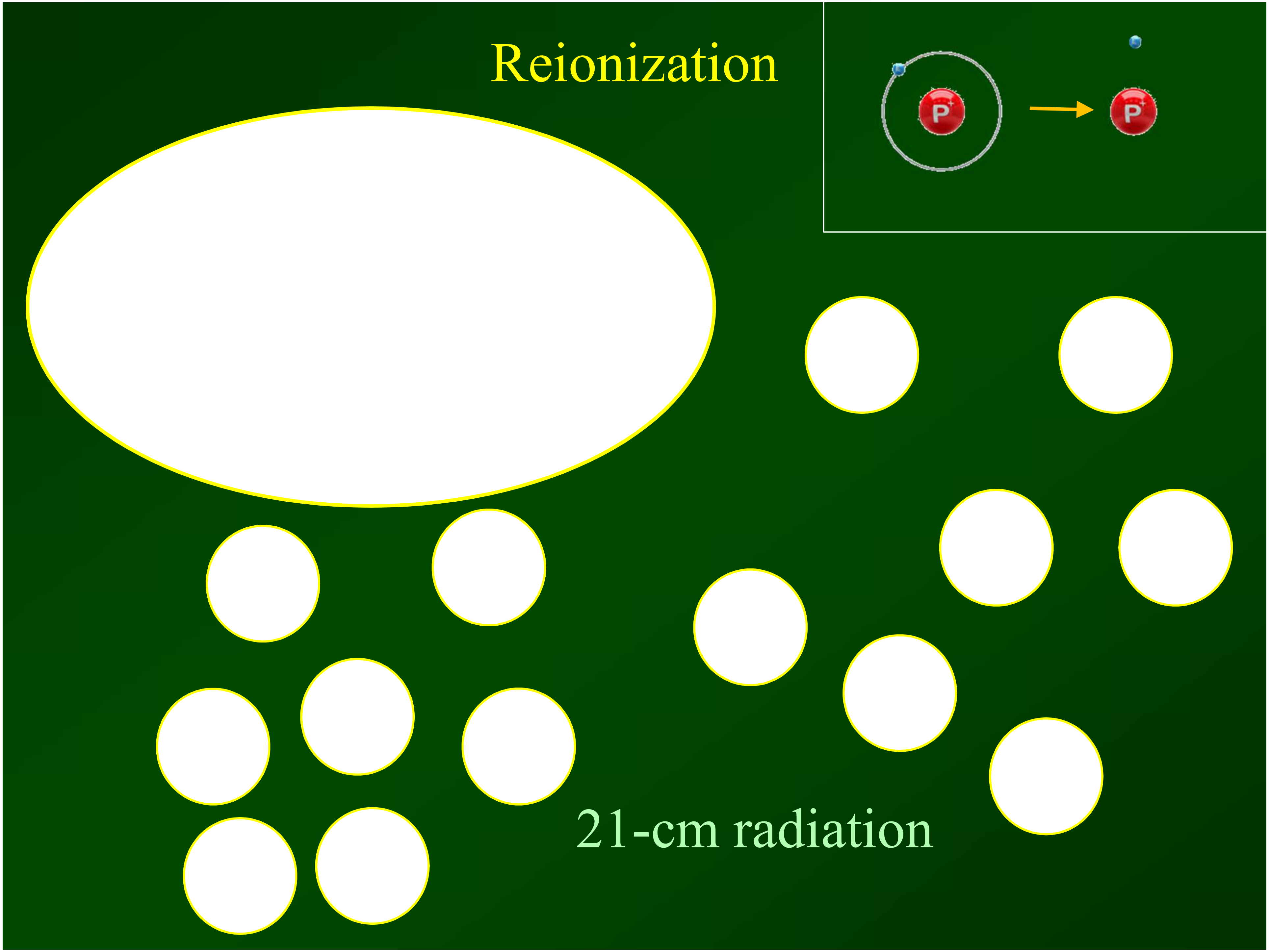
Furlanetto, Zaldariagga, Hernquist 2004

RB & Loeb 2004

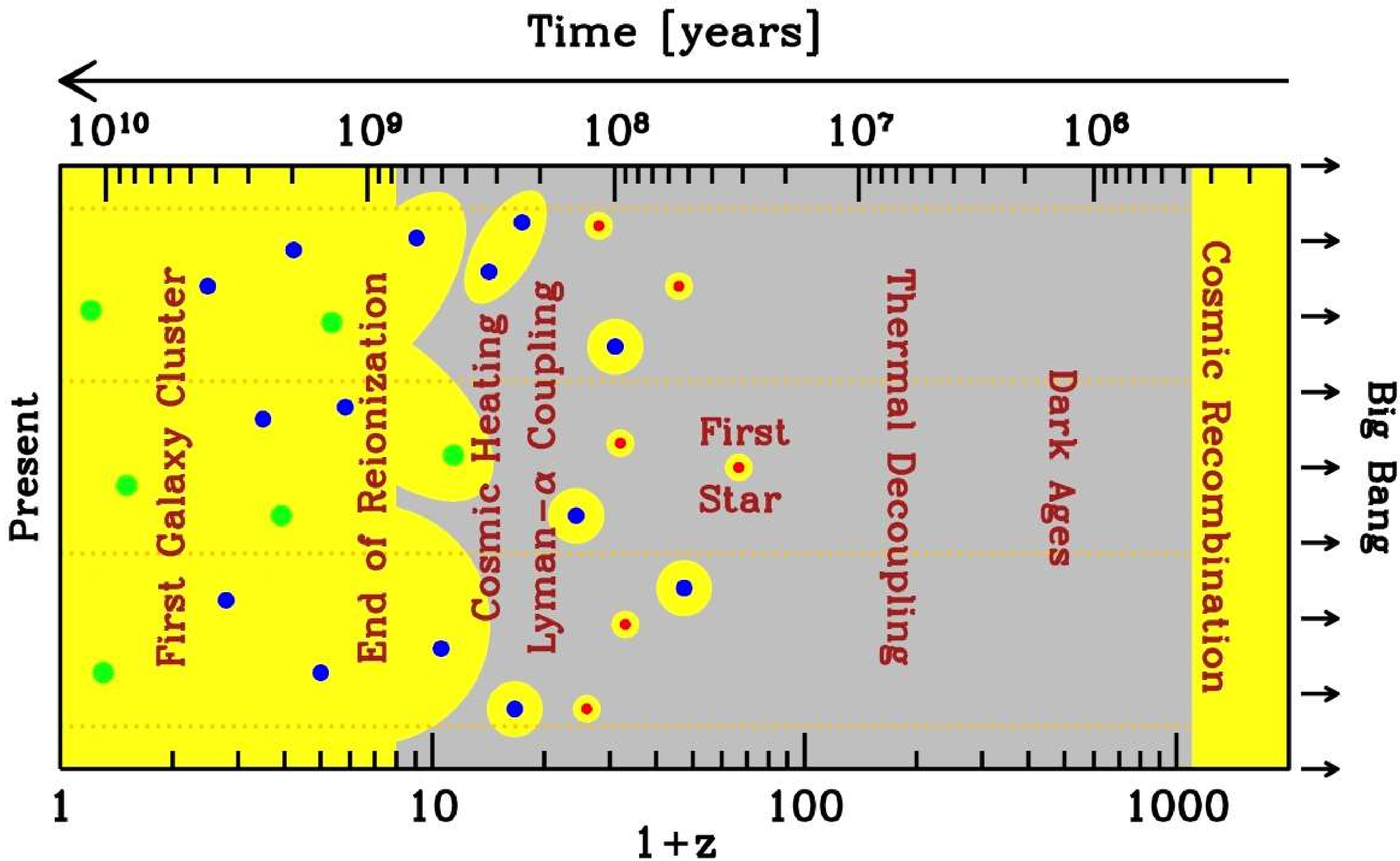
Inside-out reionization

Reionization




Reionization
P+
P+
21-cm radiation

Cosmic History



RB 2016, Physics Reports

21-cm Cosmology: Cosmic dawn

Madau, Meiksin & Rees 1997: Cosmic Dawn
(Ly-α and heating)

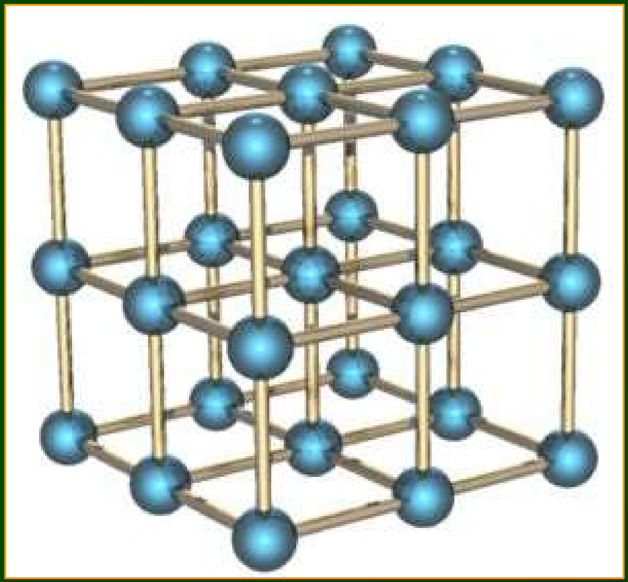
RB & Loeb 2005:
Ly-α fluctuations: z~20-30

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

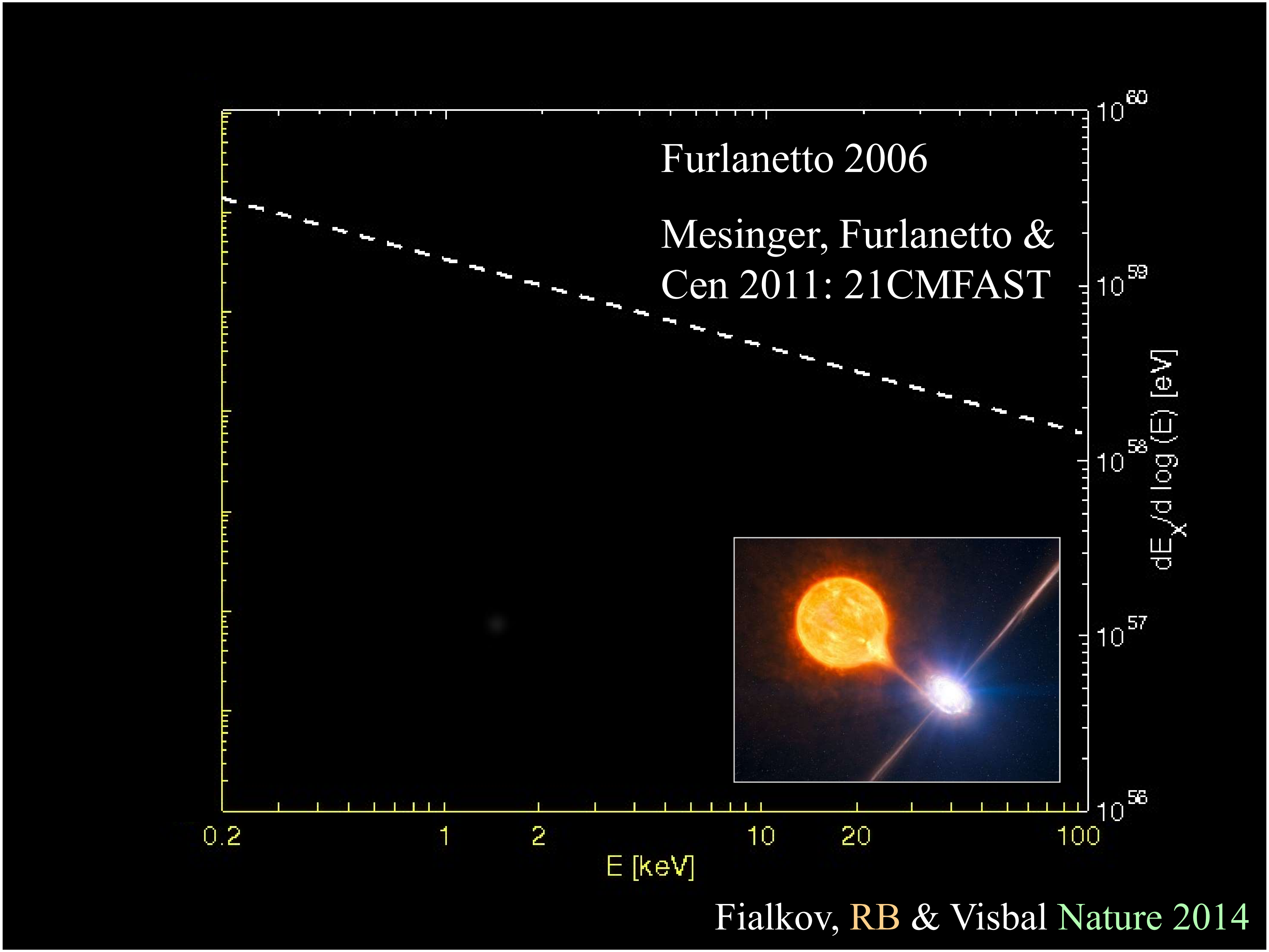
Semi-numerical Simulation

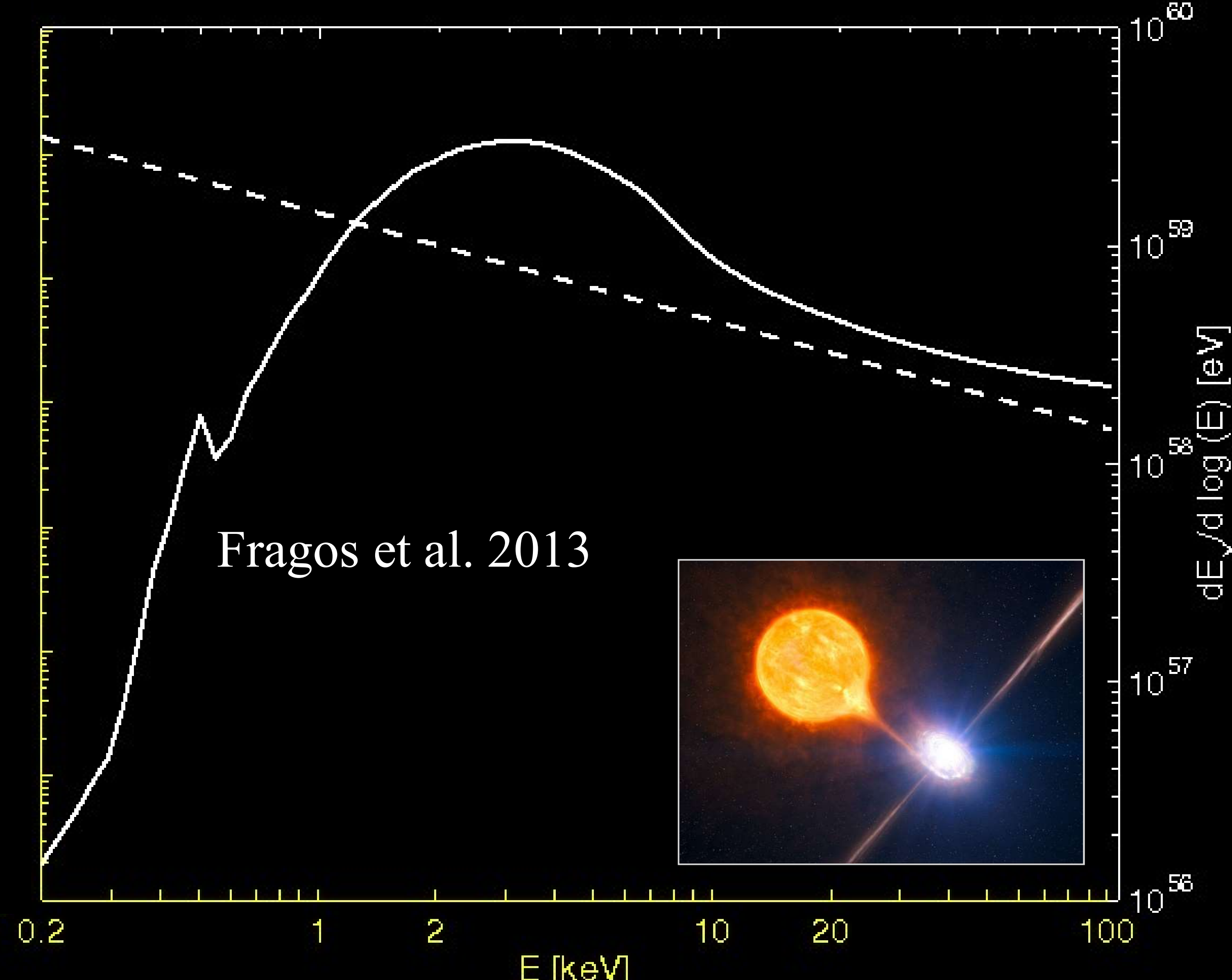
21cmfast, my group, …

(Itamar Reis)



- In each pixel:
  - Model + simulation results + free parameters
  - Halo abundance, cooling, star formation
  - Ly-α radiation, X-rays, UV
- Numerically:
  - Sum up Ly-α and X-ray intensity, reionization
  - 21-cm image, power spectrum, global signal

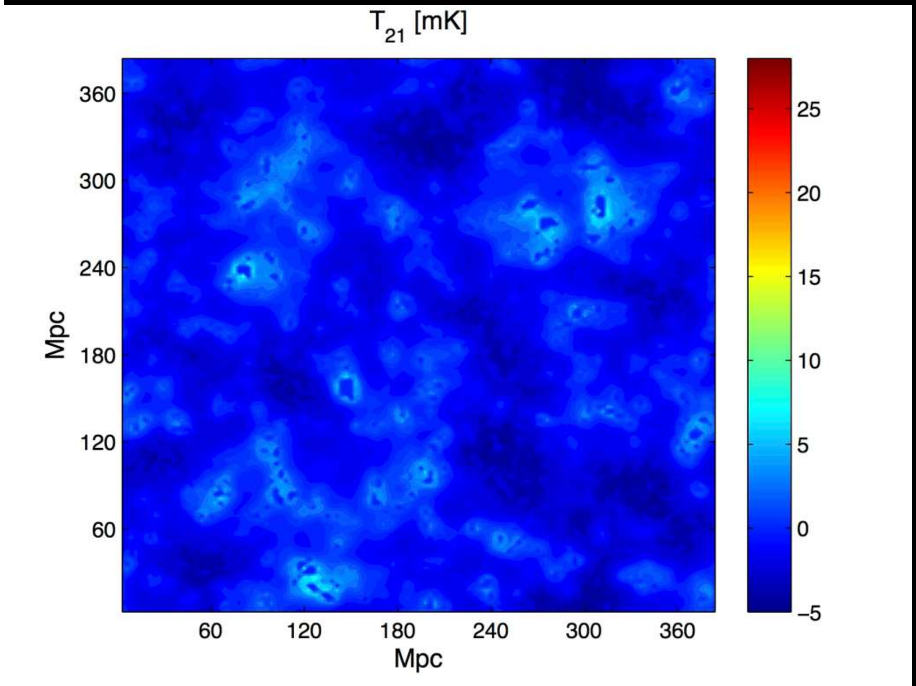

Furlanetto 2006
Mesinger, Furlanetto & Cen 2011: 21CMFAST
0.2
1
2
10
20
100
E [keV]
10^{60}
10^{59}
10^{58}
10^{57}
10^{56}
$dE_X/d\log(E)$ [eV]
Fialkov, RB & Visbal Nature 2014

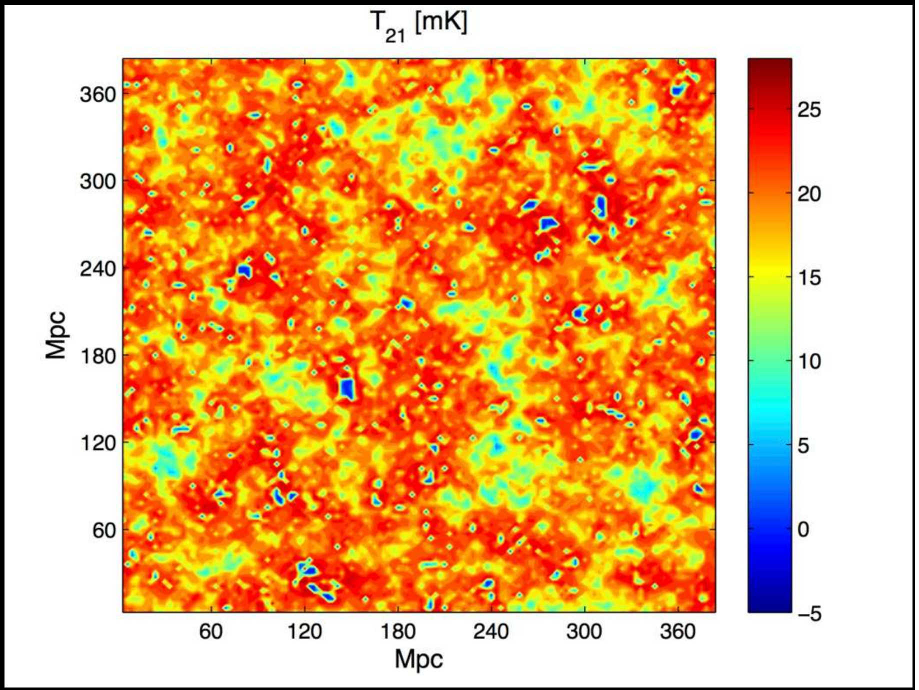


Fialkov, RB & Visbal Nature 2014

Hard X-rays

Soft X-rays



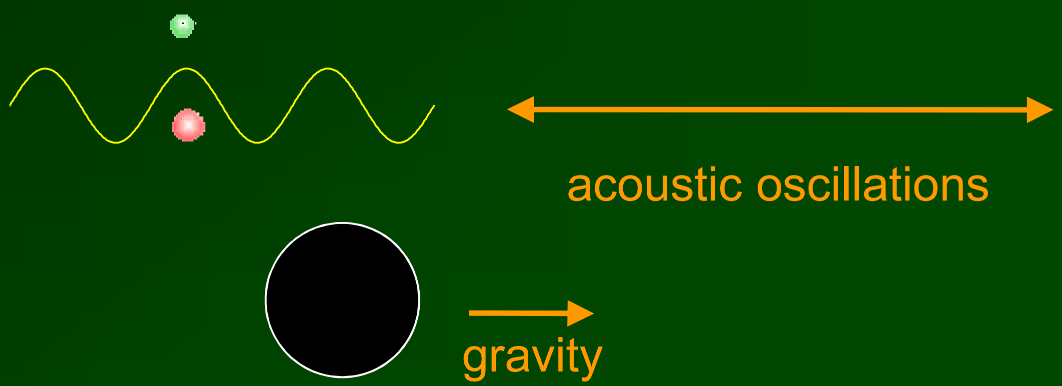


$z = 12.1$

Fialkov, RB & Visbal Nature 2014

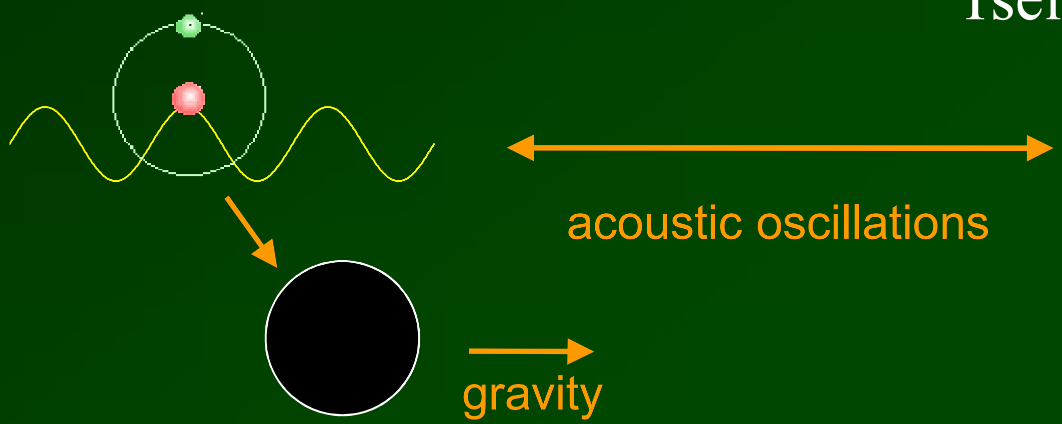
Baryon – Dark Matter Relative (Streaming) Velocity

Tseliakhovich & Hirata 2010

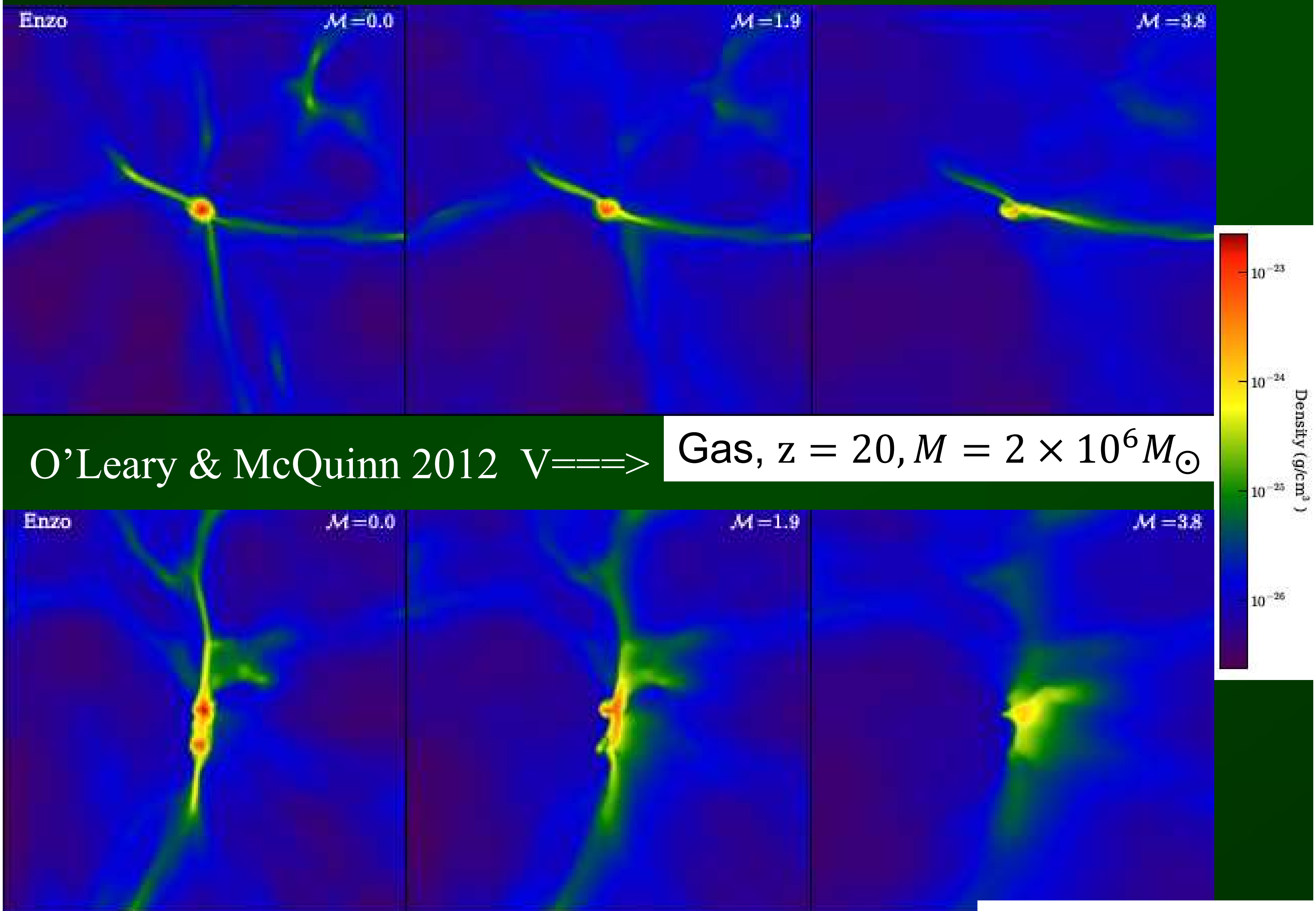


Baryon – Dark Matter Relative (Streaming) Velocity

Tseliakhovich & Hirata 2010



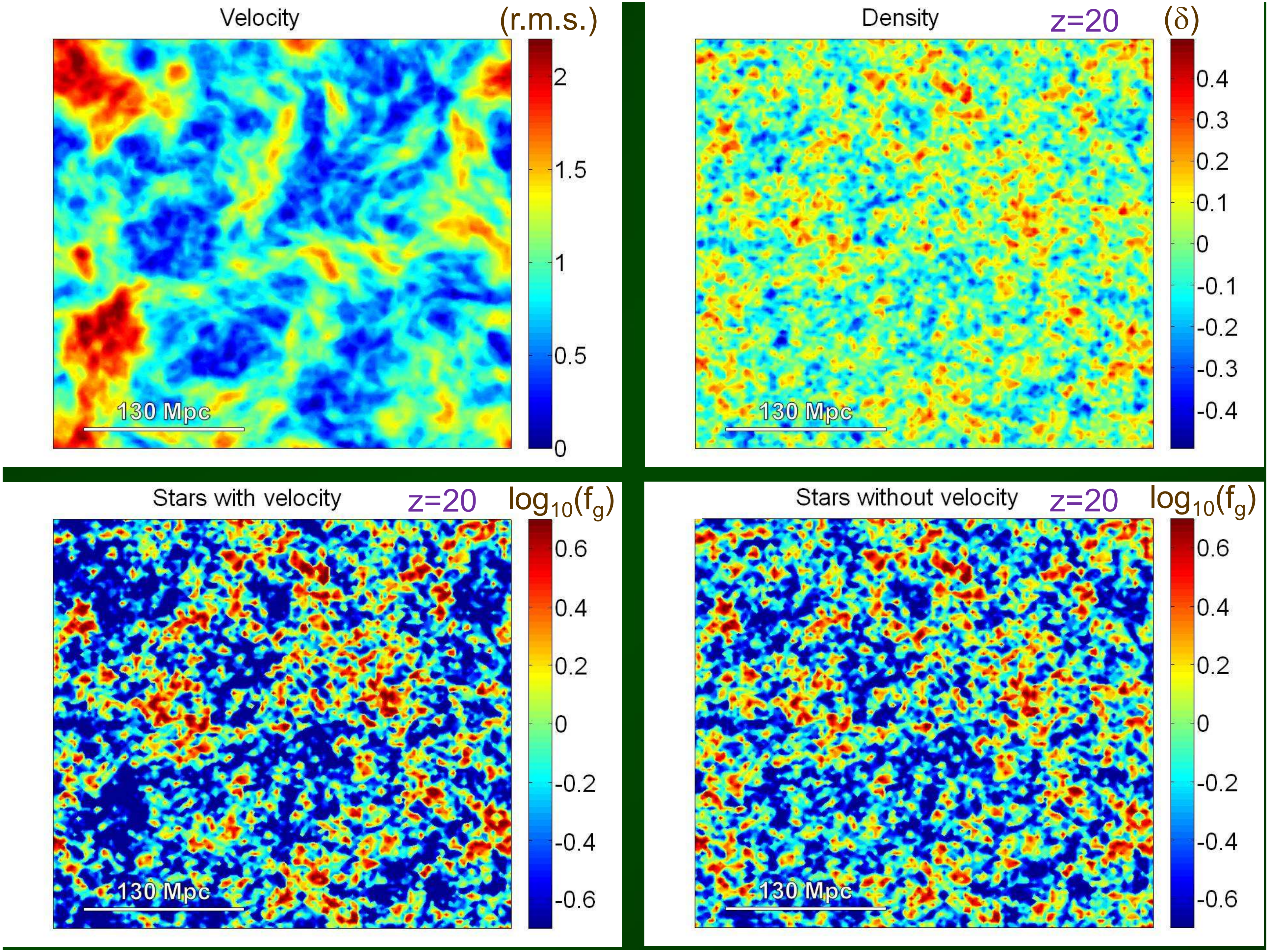
1. $|V_b - V_{cdm}|^{r.m.s.} \sim 30$ km/s at $z_{rec} \sim 5\ c_s$
2. Varies on large scales
3. BAOs

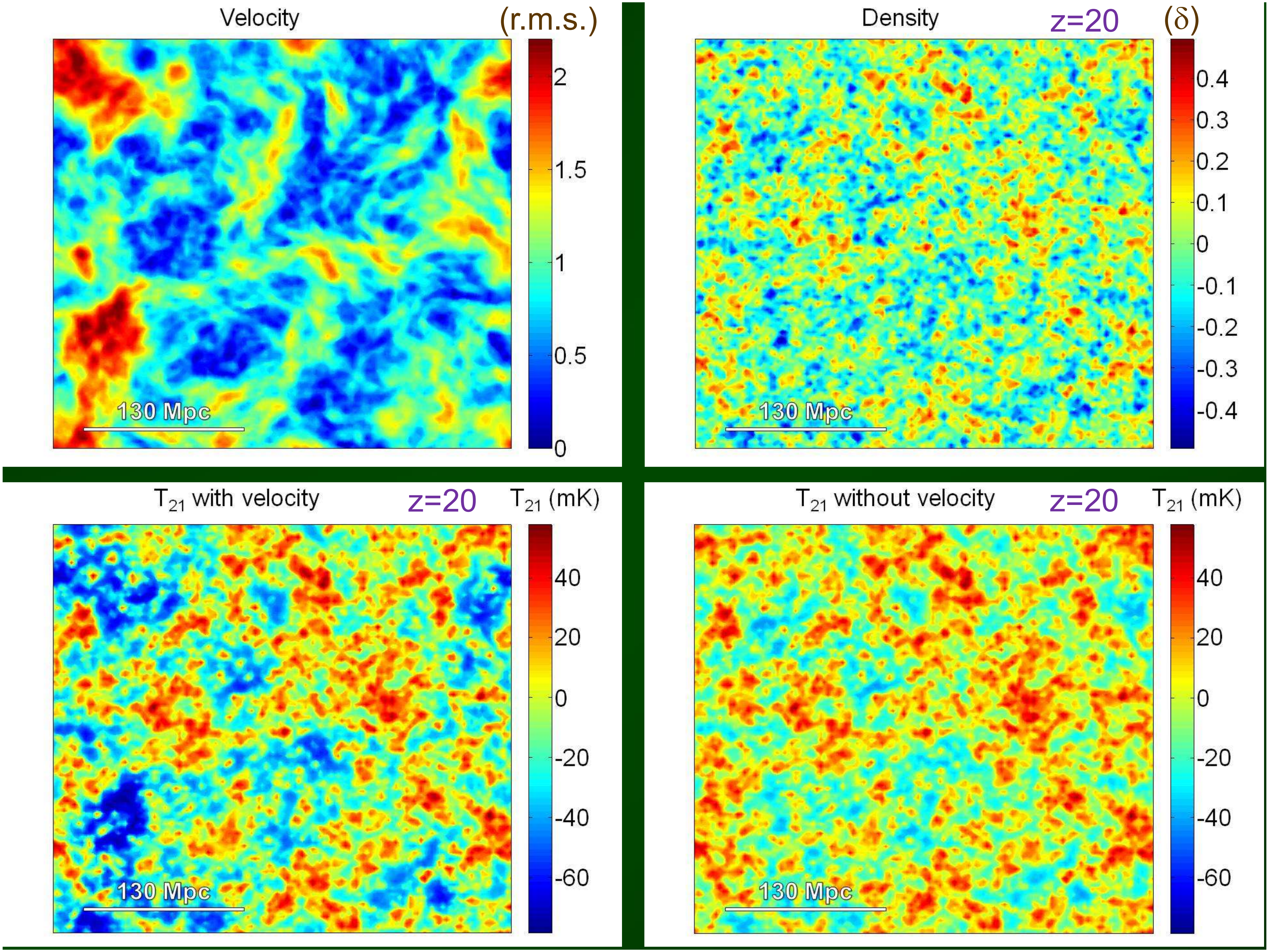


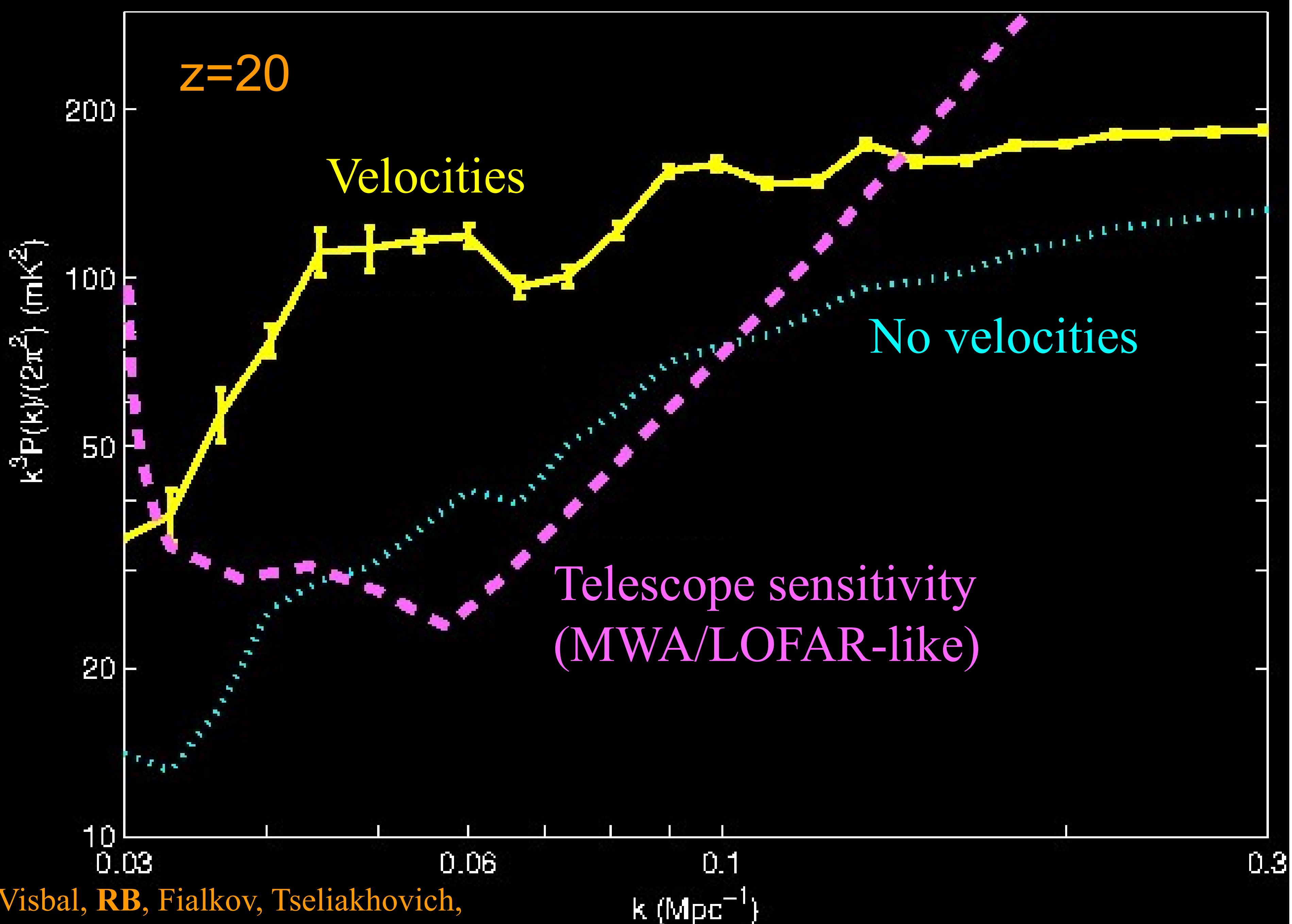
O'Leary & McQuinn 2012 V===>

Gas, $z = 20, M = 2 \times 10^6 M_\odot$

$M = 8 \times 10^5 M_\odot$

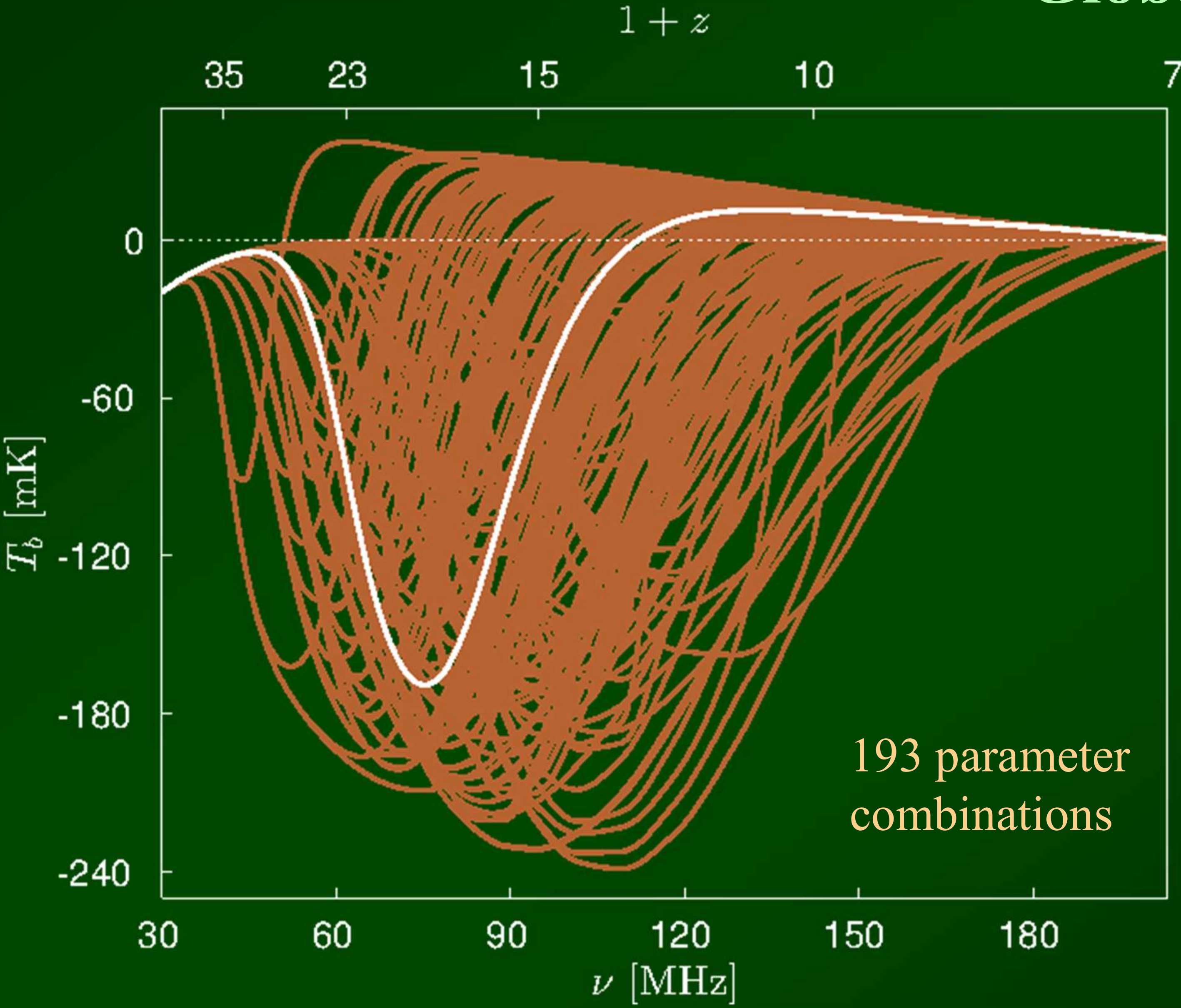

Velocity
(r.m.s.)
2
1.5
1
0.5
0
130 Mpc
Density
z=20
(δ)
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
130 Mpc
Stars with velocity
z=20
log10(fg)
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
130 Mpc
Stars without velocity
z=20
log10(fg)
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
130 Mpc


Velocity
(r.m.s.)
130 Mpc
2
1.5
1
0.5
0
Density
z=20
(δ)
130 Mpc
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
T21 with velocity
z=20
T21 (mK)
130 Mpc
40
20
0
-20
-40
-60
T21 without velocity
z=20
T21 (mK)
130 Mpc
40
20
0
-20
-40
-60



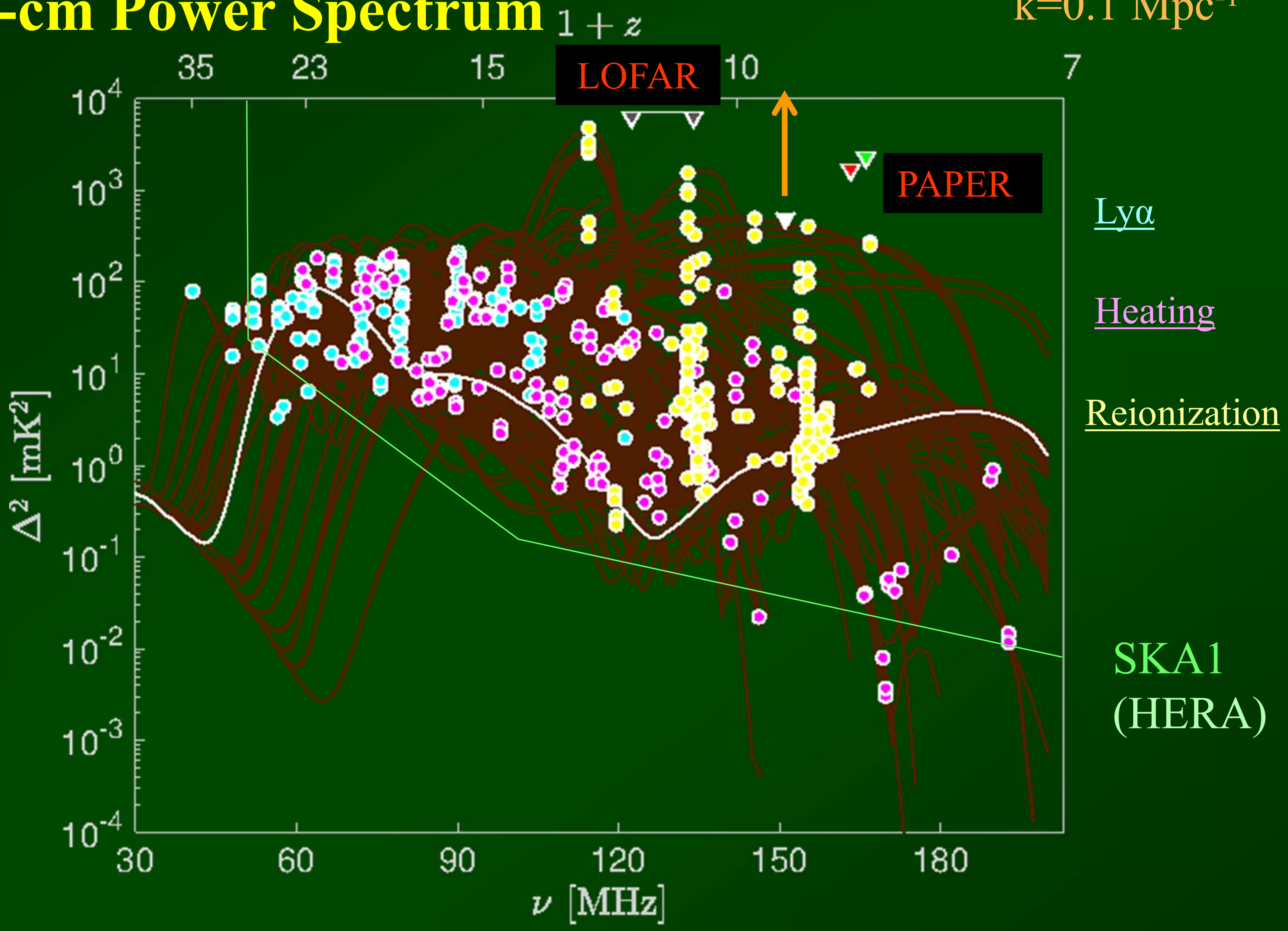
Visbal, **RB**, Fialkov, Tseliakhovich,
& Hirata Nature 2012

Global 21-cm



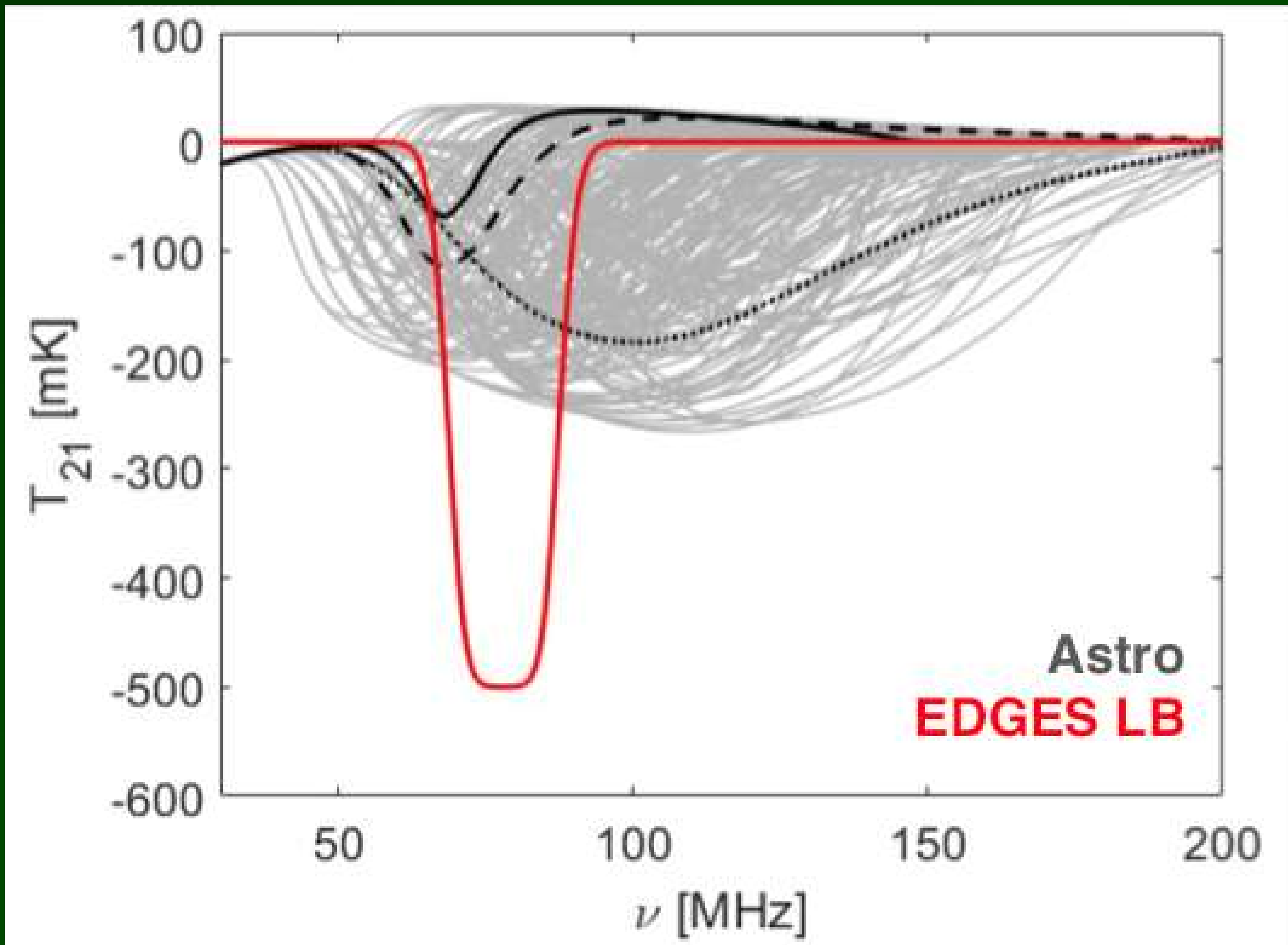
Cohen, Fialkov,
RB, & Lotem 2017

21-cm Power Spectrum



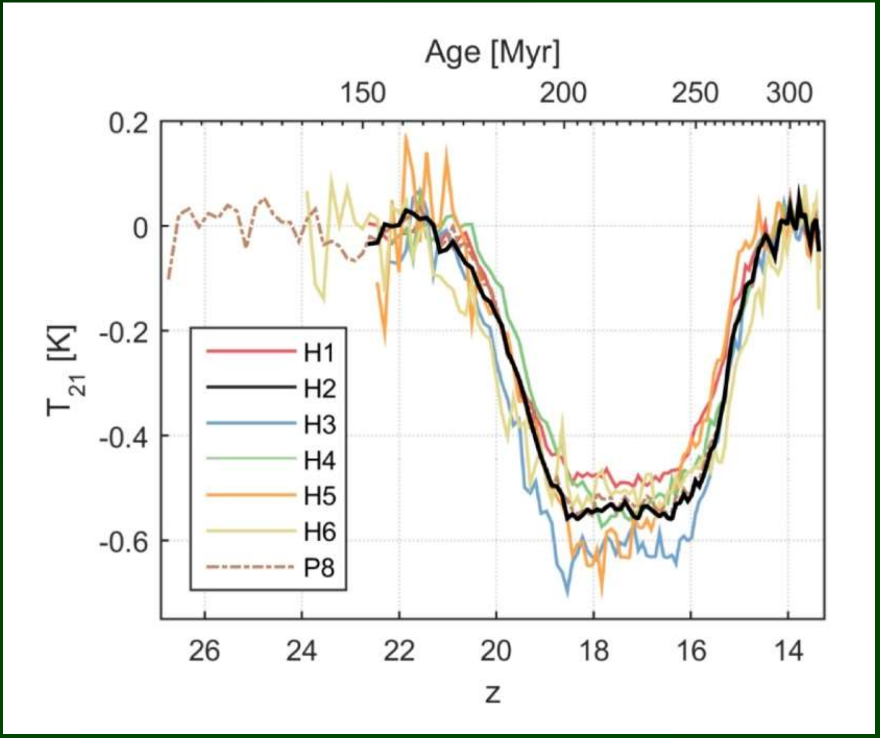
Cohen, Fialkov, RB 2017

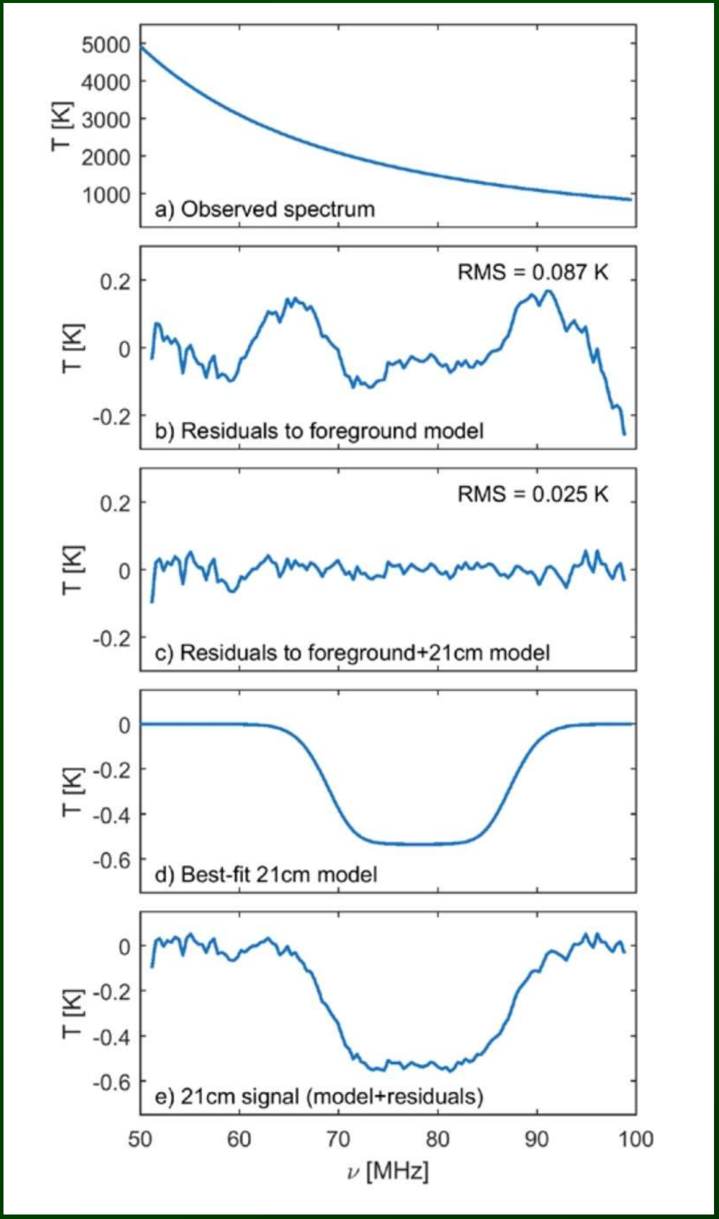
EDGES-Low


100
0
-100
-200
-300
-400
-500
-600
T_{21} [mK]
50
100
150
200
ν [MHz]
Astro
EDGES LB

Fialkov

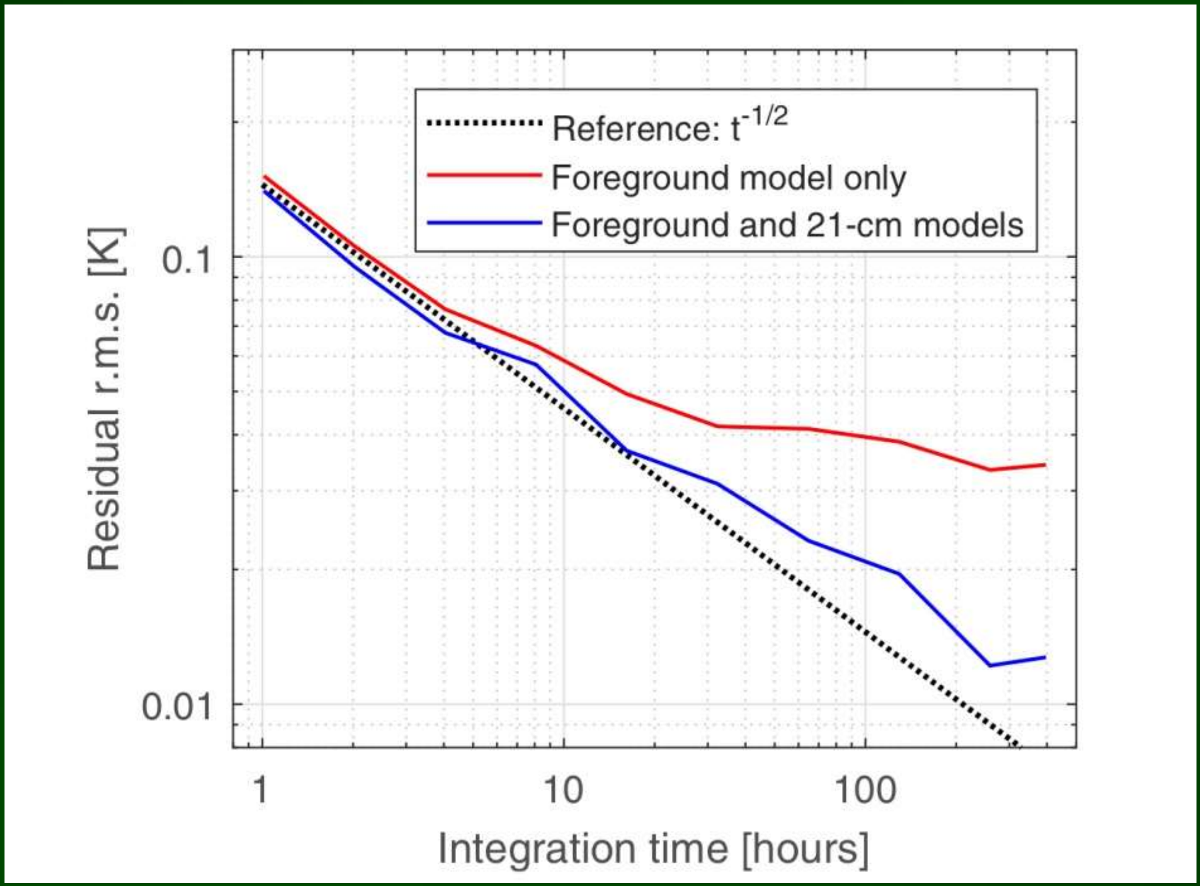
EDGES-Low





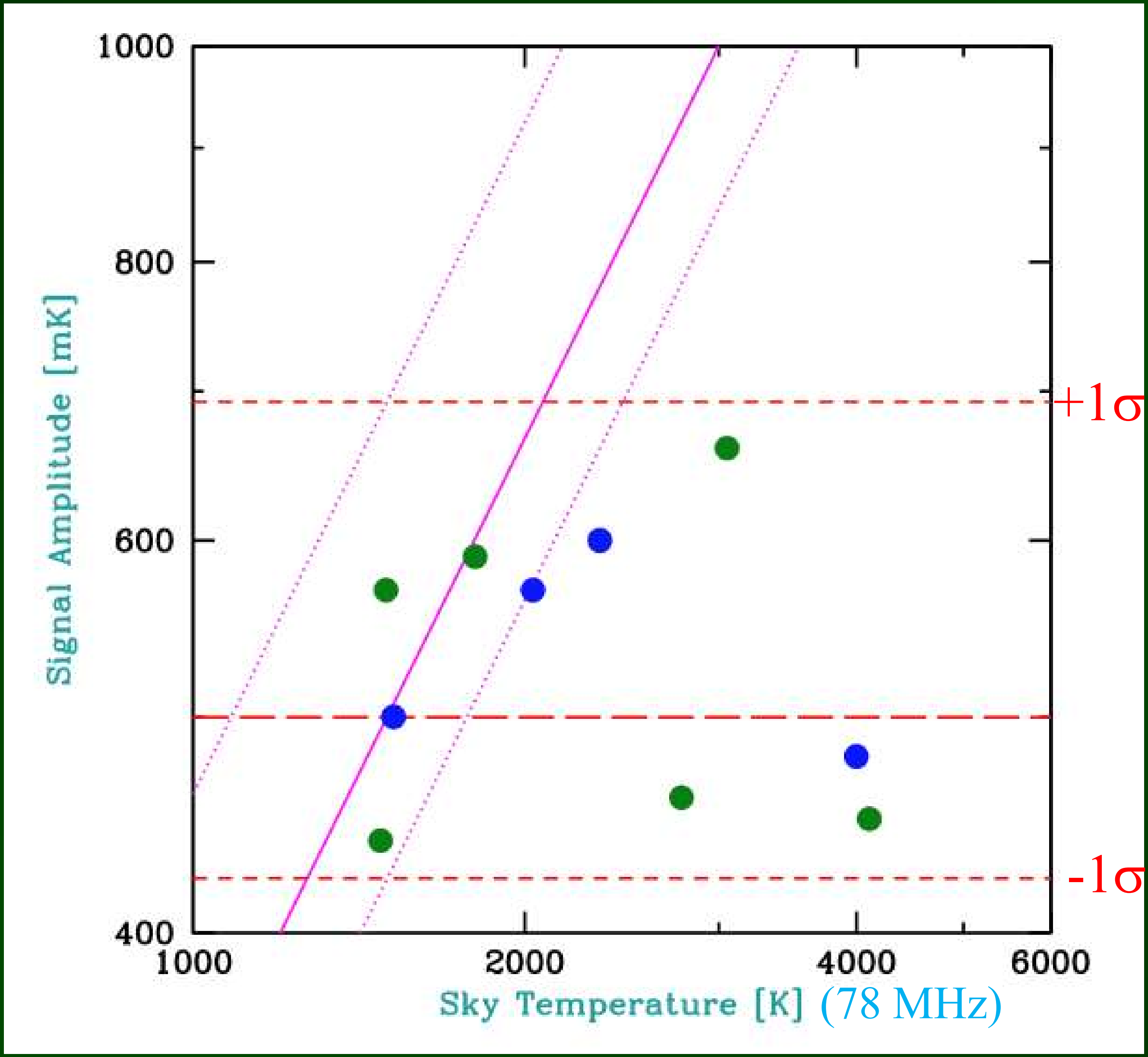
Bowman et al. 2018

EDGES-Low



Bowman et al. 2018

EDGES-Low

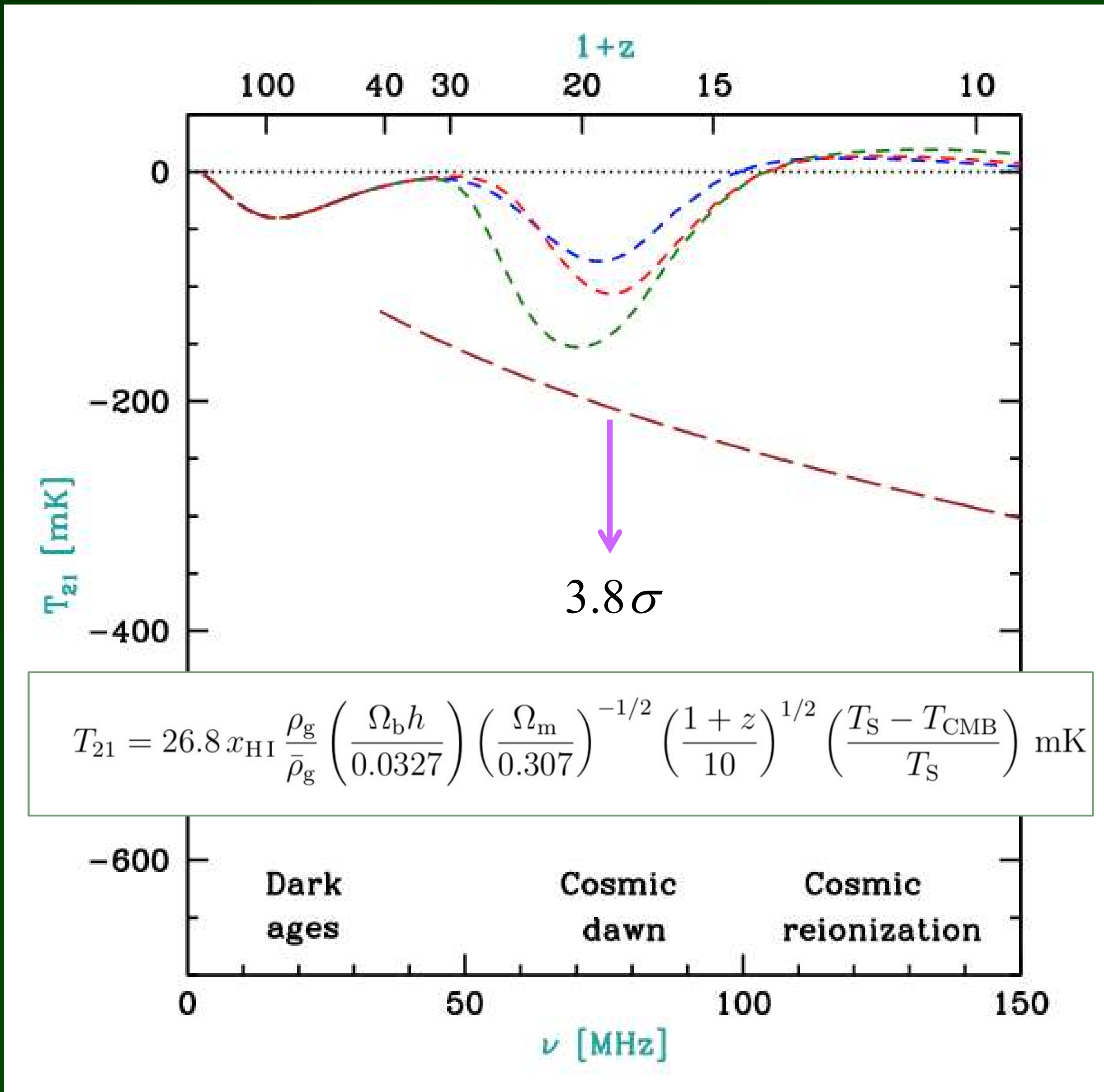


EDGES-Mid

(Nivedita Mahesh)

<u>Based on:</u>

Bowman et al. 2018



$$T_{21} = 26.8\, x_{\rm HI}\, \frac{\rho_{\rm g}}{\bar{\rho}_{\rm g}} \left(\frac{\Omega_{\rm b} h}{0.0327}\right) \left(\frac{\Omega_{\rm m}}{0.307}\right)^{-1/2} \left(\frac{1+z}{10}\right)^{1/2} \left(\frac{T_{\rm S} - T_{\rm CMB}}{T_{\rm S}}\right) \text{ mK}$$

Max absorption:

- No reionization.
- Saturated coupling.
- No heating.

RB, Nature 2018

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

Gas is colder than adiabatic cooling =>

Something cooled it down (heating is easy) =>

X must be even colder (than 5 K at z=17) =>

(Cold) dark matter

Dark matter interactions
(Cooling: Dark ages)

Cosmic dawn (WF coupling)

PHYSICAL REVIEW D **89,** 023519 (2014)

Constraining dark matter-baryon scattering with linear cosmology

Cora Dvorkin* and Kfir Blum†
Institute for Advanced Study, School of Natural Sciences, Einstein Drive, Princeton, New Jersey 08540, USA

Marc Kamionkowski‡
Department of Physics and Astronomy, Johns Hopkins University, Baltimore, Maryland 21218, USA
(Received 22 November 2013; published 27 January 2014)

PHYSICAL REVIEW D **90,** 083522 (2014)

Effects of dark matter-baryon scattering on redshifted 21 cm signals

Hiroyuki Tashiro,[1] Kenji Kadota,[2] and Joseph Silk[3,4,5]

PHYSICAL REVIEW D **92,** 083528 (2015)

Heating of baryons due to scattering with dark matter during the dark ages

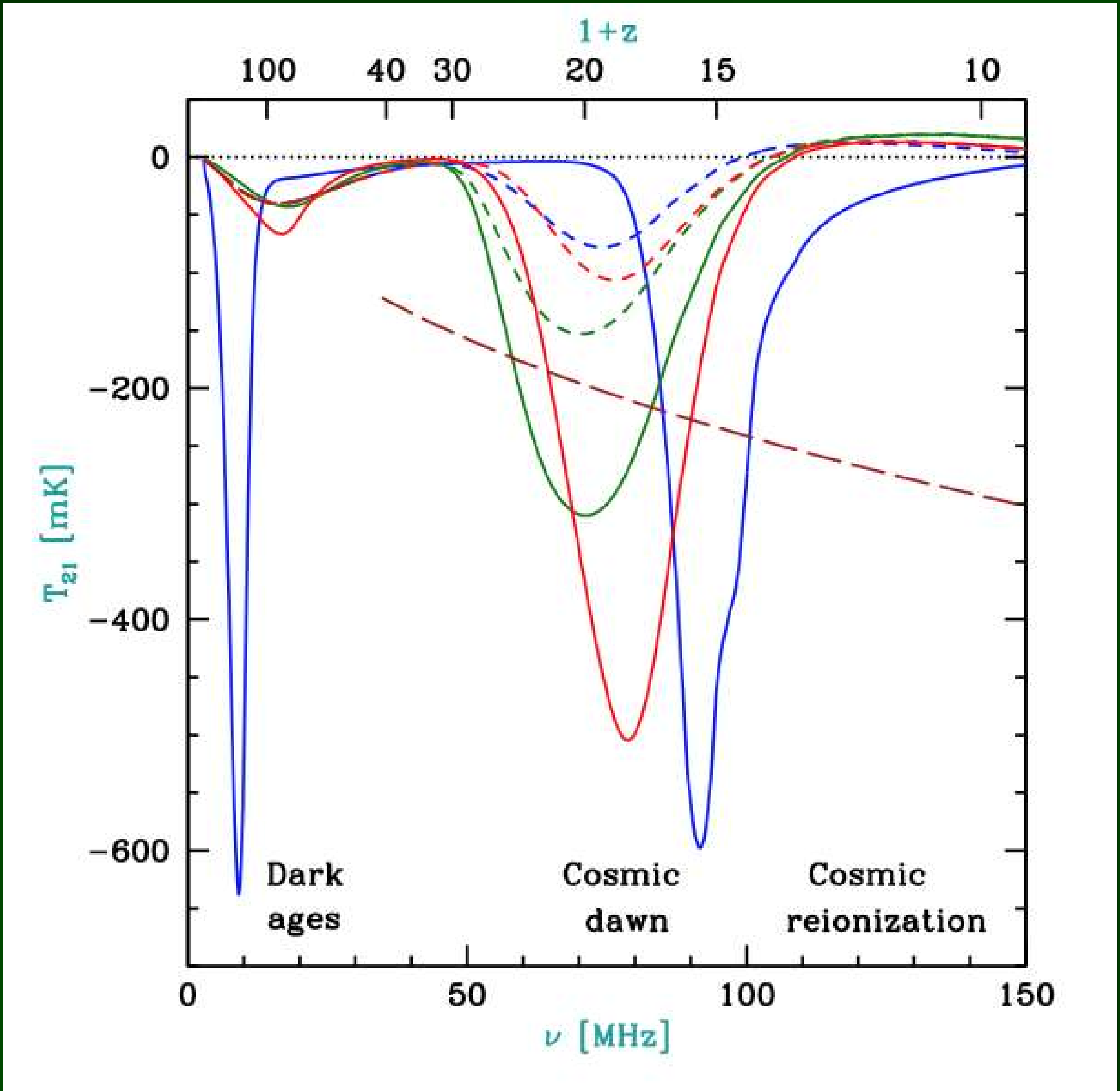
Julian B. Muñoz, Ely D. Kovetz, and Yacine Ali-Haïmoud

$$\sigma \propto v^n$$

Large at small v => n=-4
(Rutherford/Coulomb)

Cosmic dawn: min T/v

The streaming velocity!

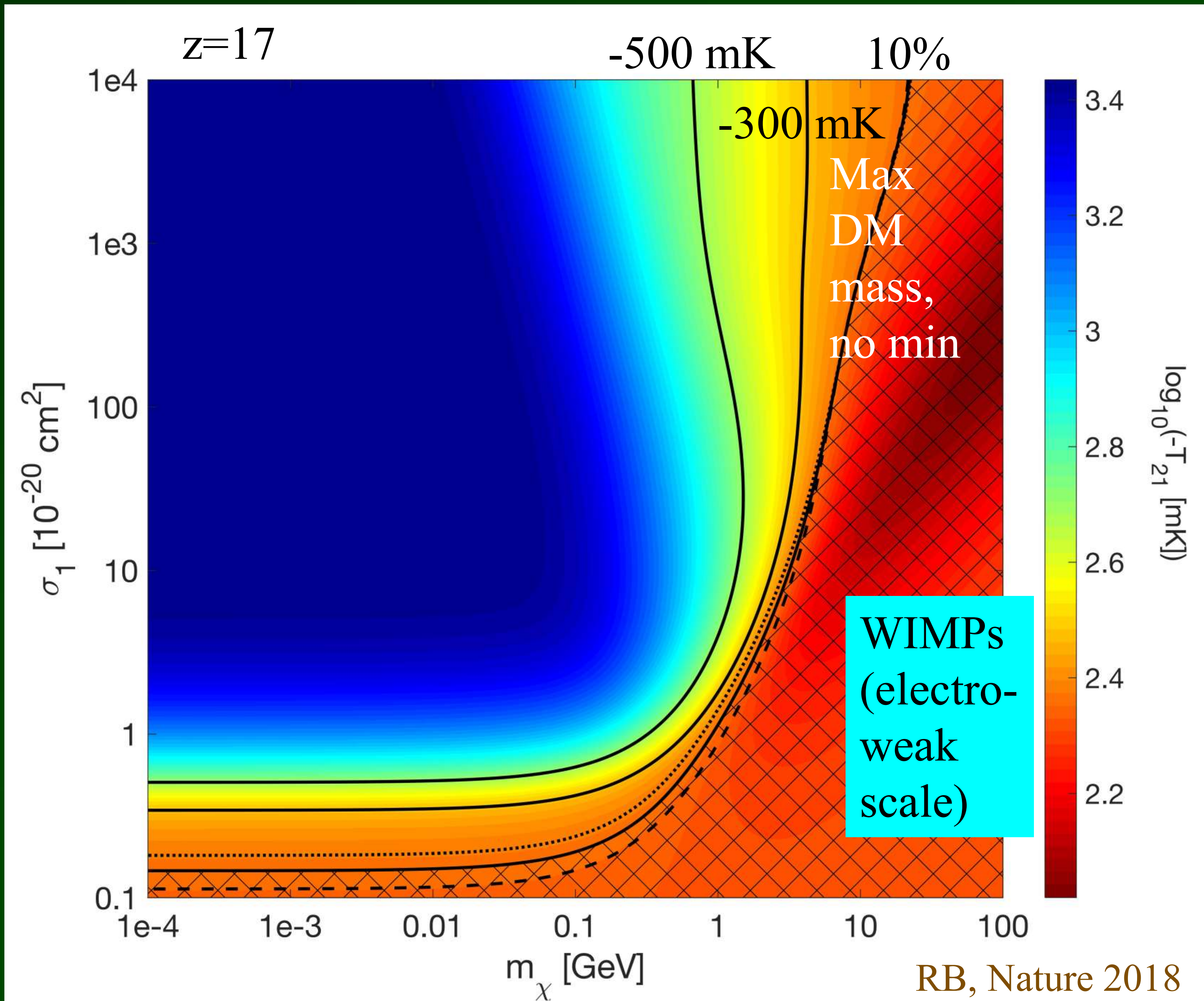


m_χ=0.3 GeV

m_χ=3 GeV

m_χ=0.01 GeV

RB, Nature 2018


z=17
-500 mK
10%
-300 mK
Max DM mass, no min
WIMPs (electro-weak scale)
1e4
1e3
100
10
1
0.1
1e-4
1e-3
0.01
0.1
1
10
100
σ_1 [10^{-20} cm^2]
m_χ [GeV]
3.4
3.2
3
2.8
2.6
2.4
2.2
$\log_{10}(-T_{21}$ [mK])
RB, Nature 2018

Alternative explanation

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

Bowman et al. 2018
Feng & Holder 2018

↓

10% of extragalactic radio excess
ARCADE-2: 2006 NASA balloon, 3-90 GHz
Residual with $\nu^{-2.6}$

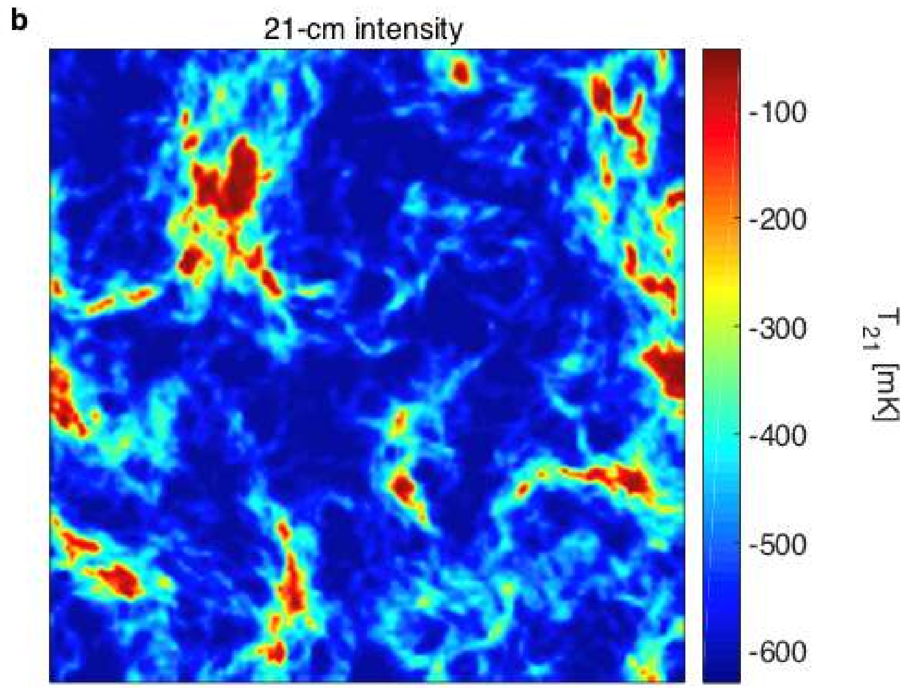
Subrahmanyan & Cowsik 2013

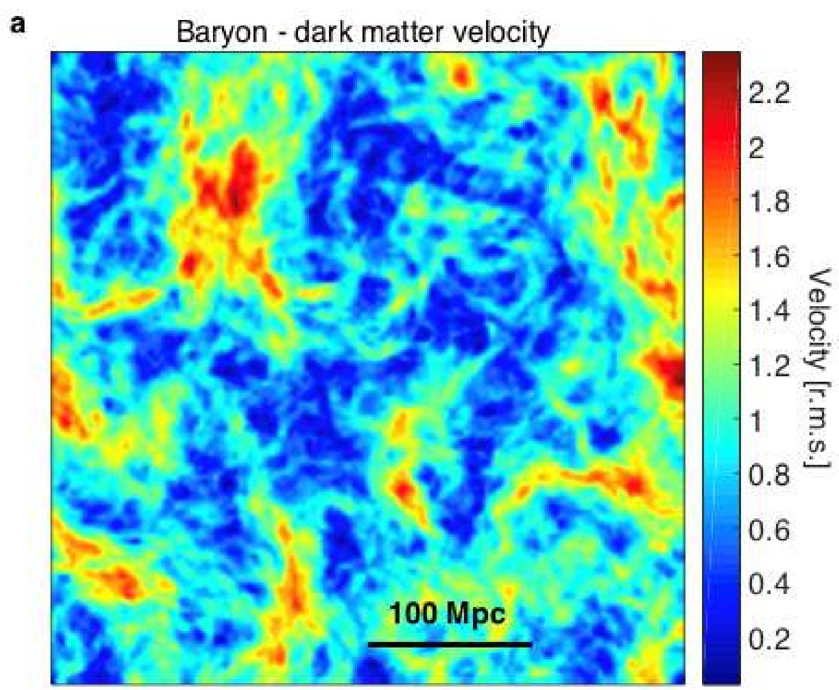
Realistic Galactic modeling => no excess.

Need z=20 radio background at MW level, without X-rays.
Mirocha & Furlanetto 2018: $\varepsilon \times 10^3$

RMS fluctuation ~ 140 mK
100 Mpc at z=17: 30’

DM cooling fluctuations only

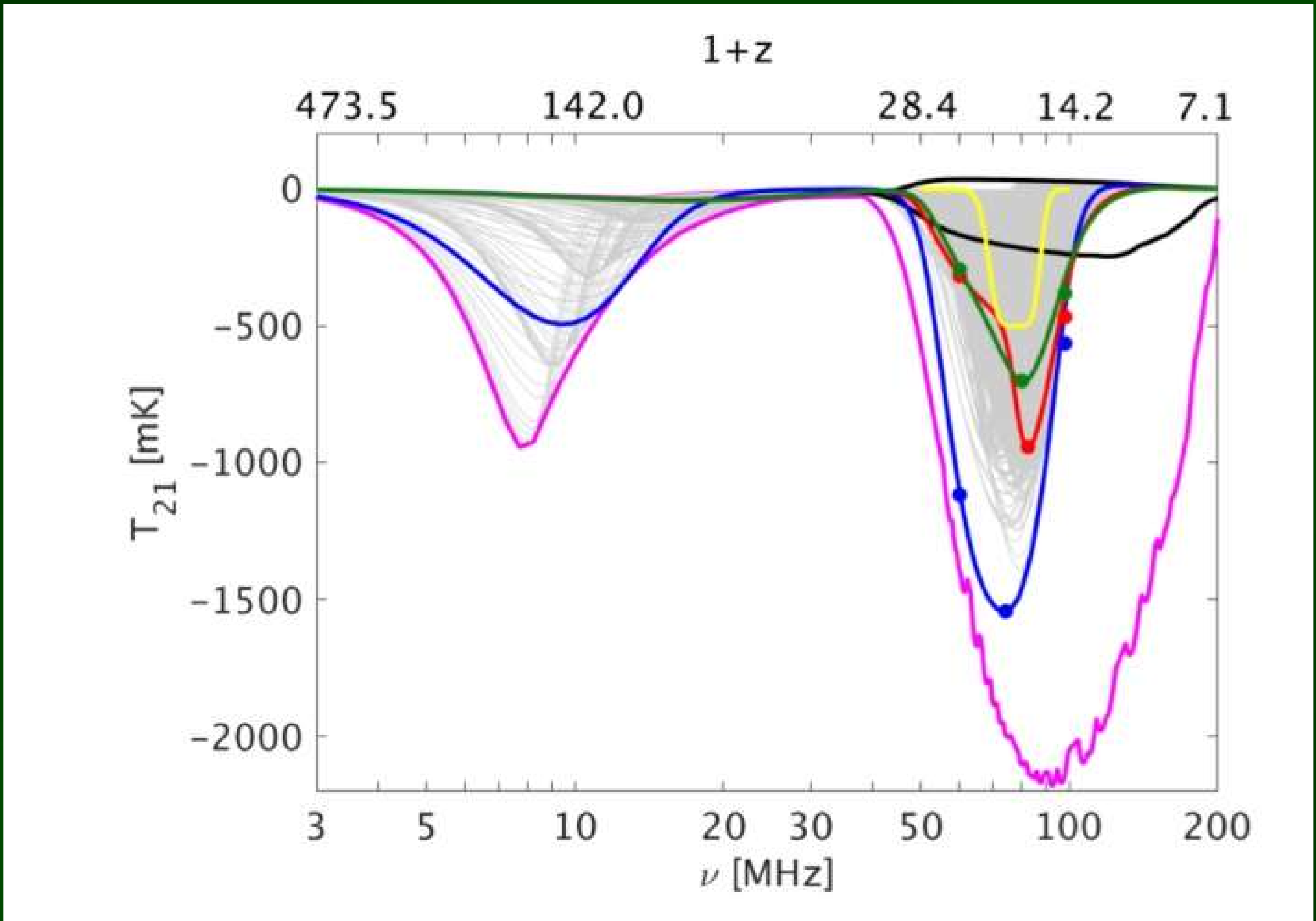




BAOs

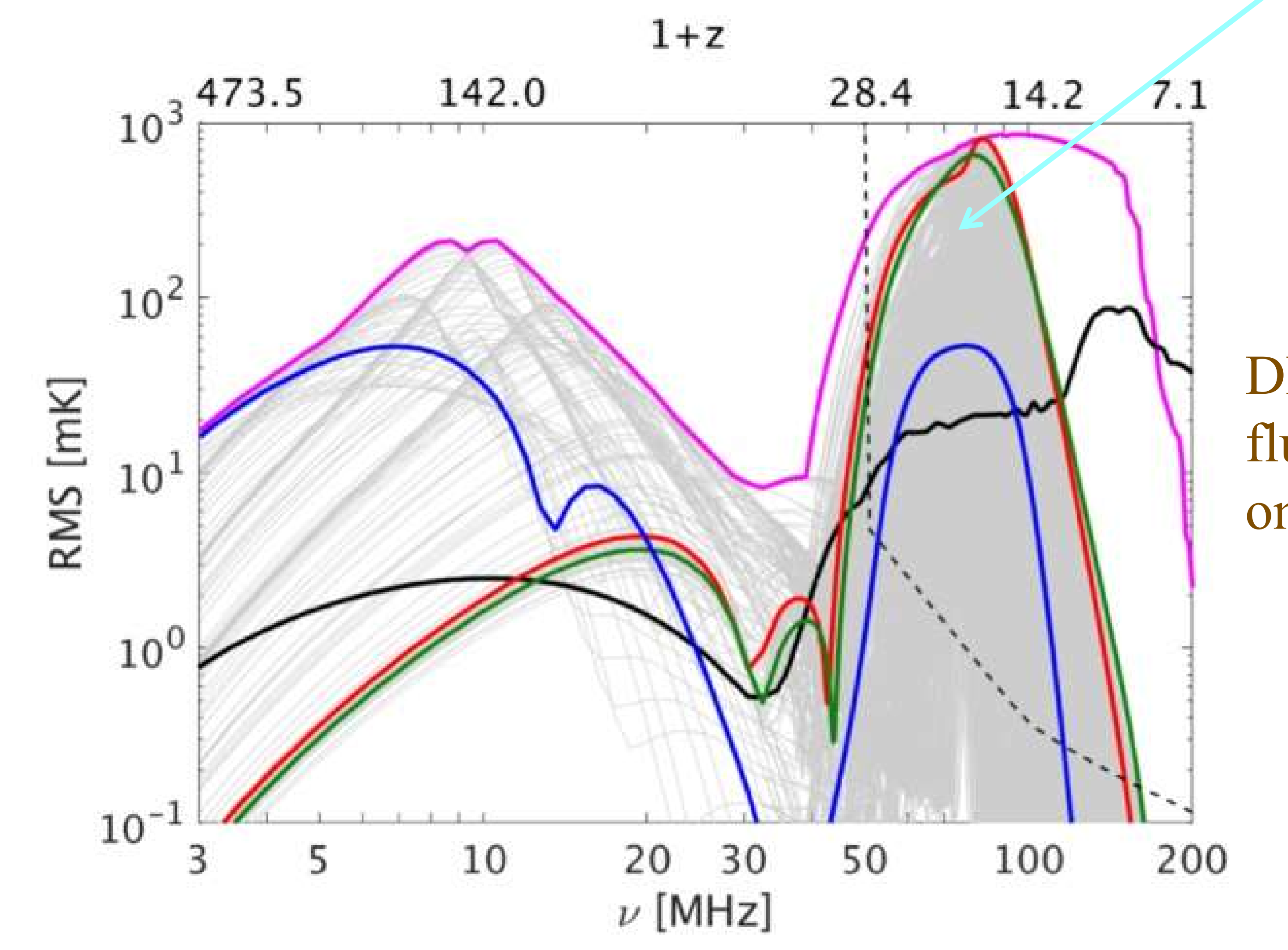
RB, Nature 2018

Range (Global)



Fialkov, RB, Cohen, PRL 2018

Range (Fluctuation)

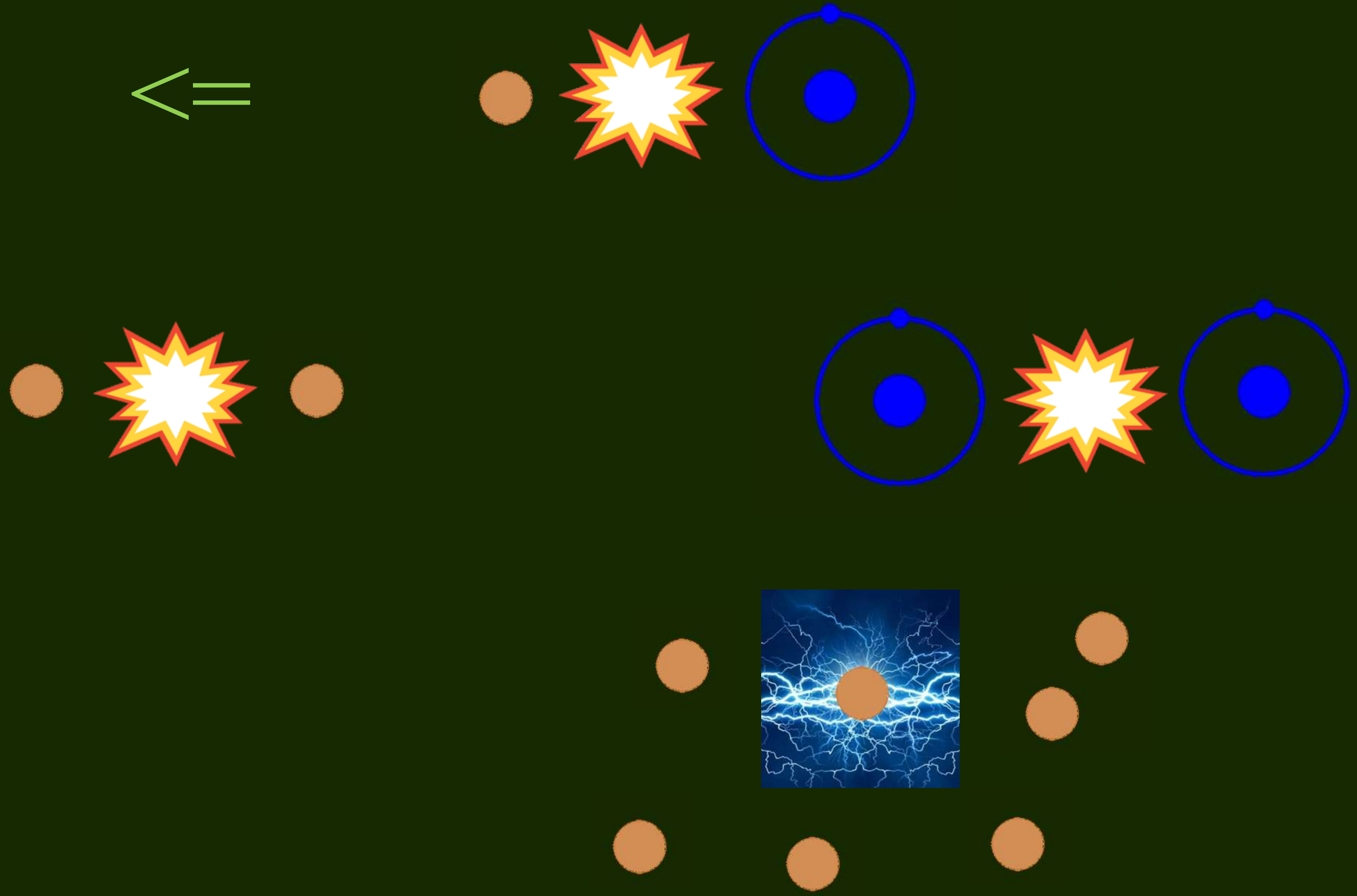


ACE
Nenufar

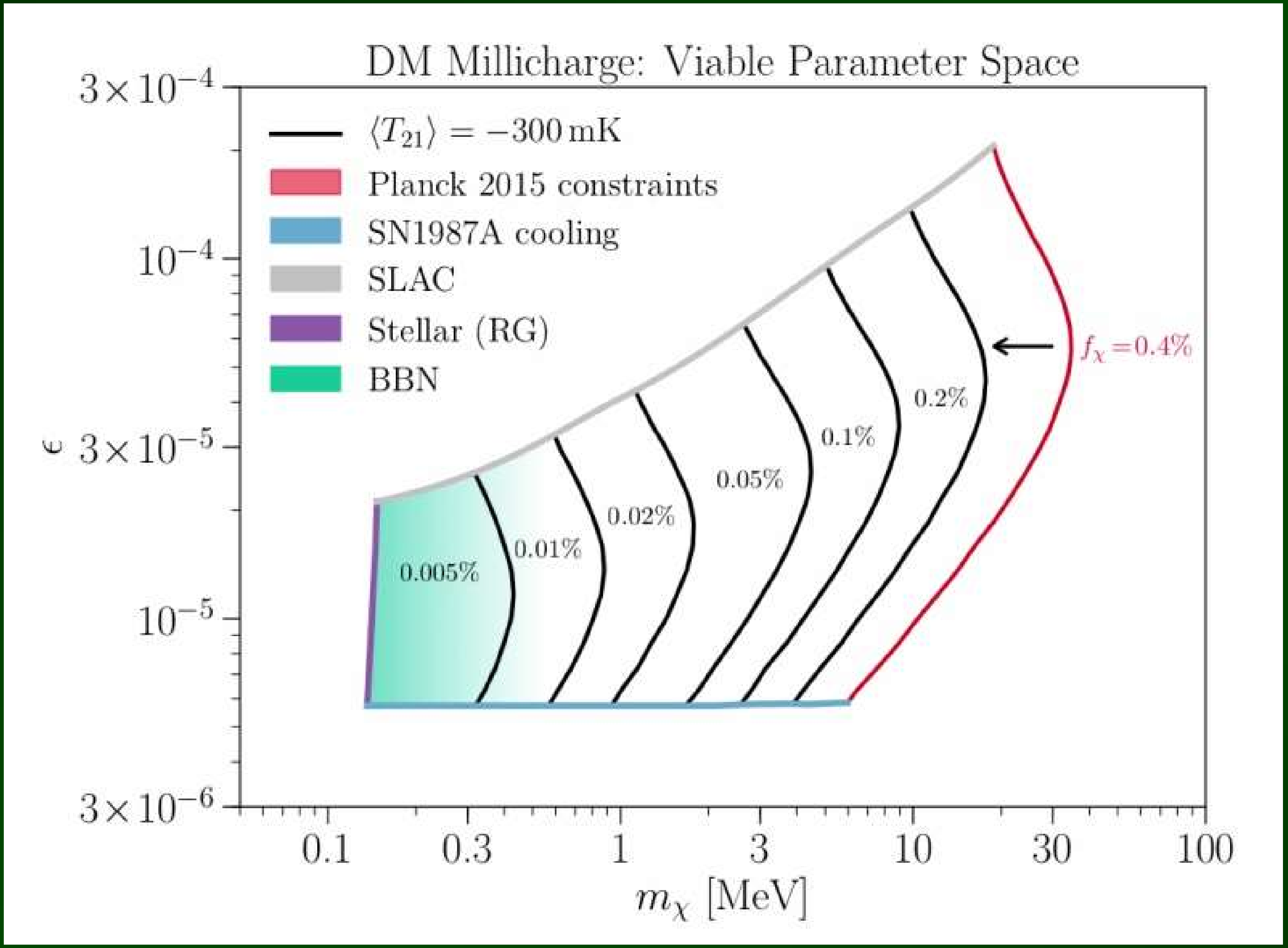
DM cooling fluctuations only

Fialkov, RB, Cohen, PRL 2018

Particle physics models



Munoz & Loeb 2018

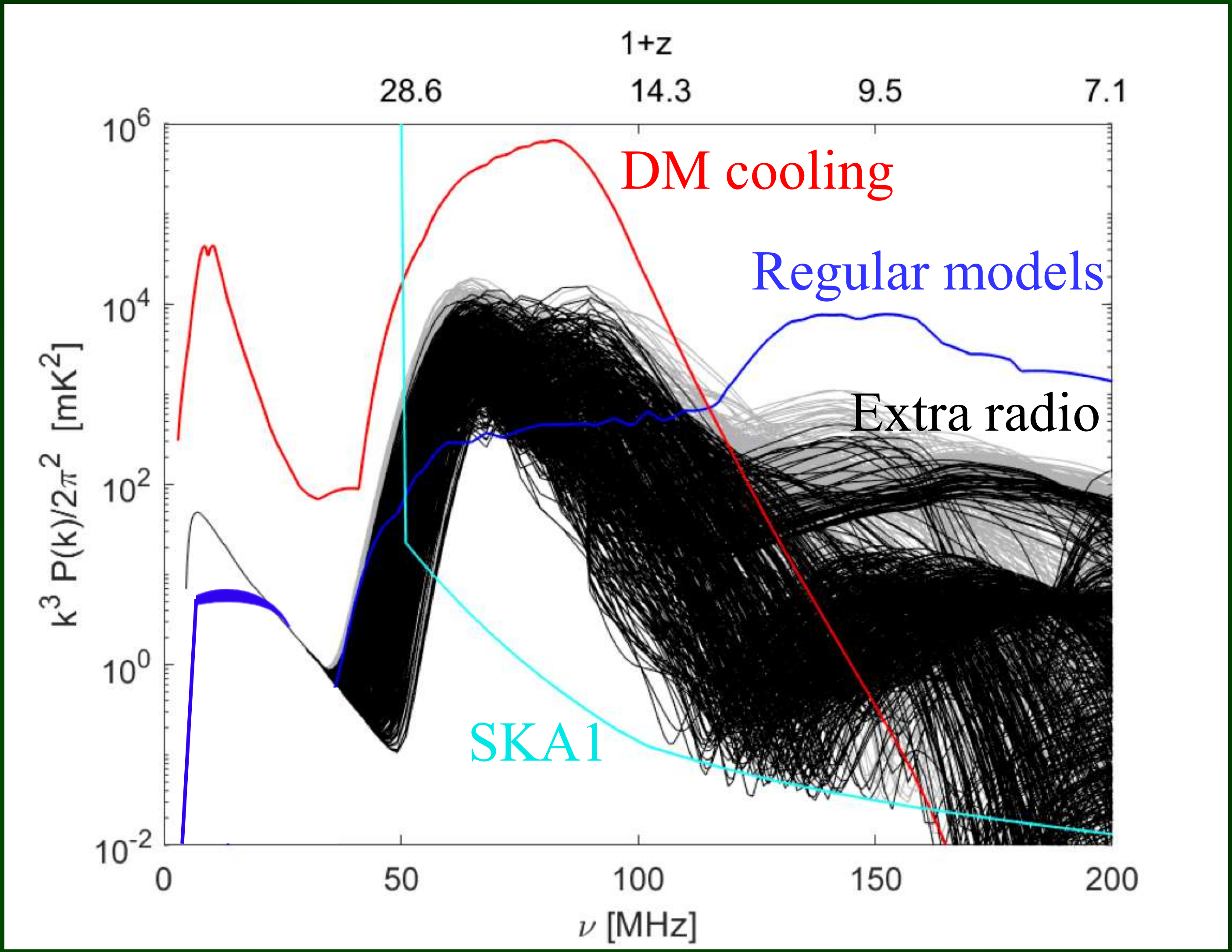


$\Omega_b h^2 = 0.0224 \pm 0.0001$ (Planck 2018) $\Omega_b h^2 \simeq 0.02170 \pm 0.00026$ (BBN)

Kovetz, Poulin, Gluscevic, Boddy, RB, Kamionkowski 2018

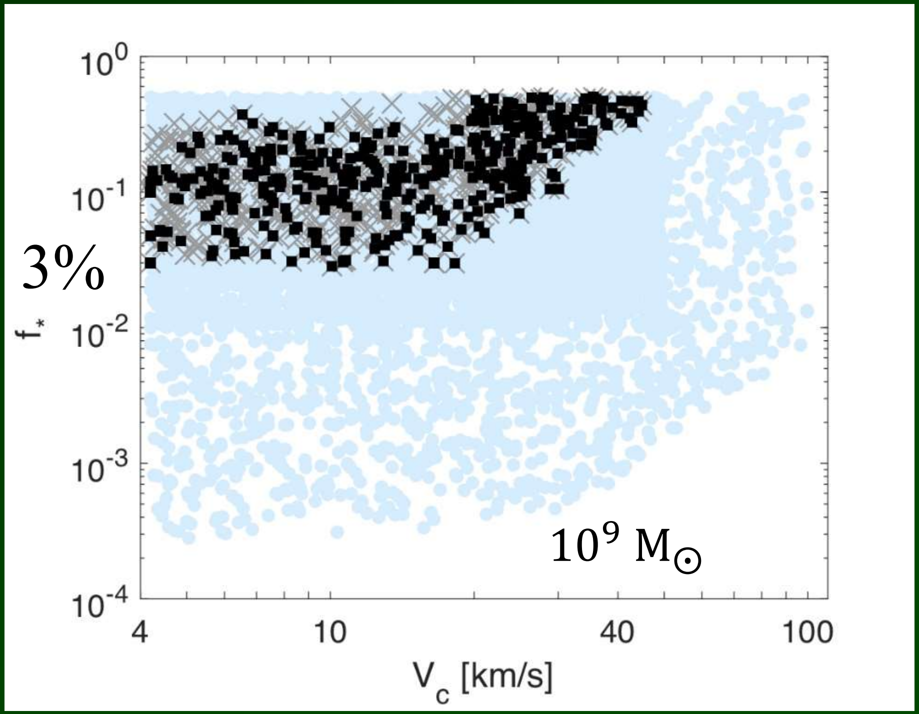
Alternative explanation

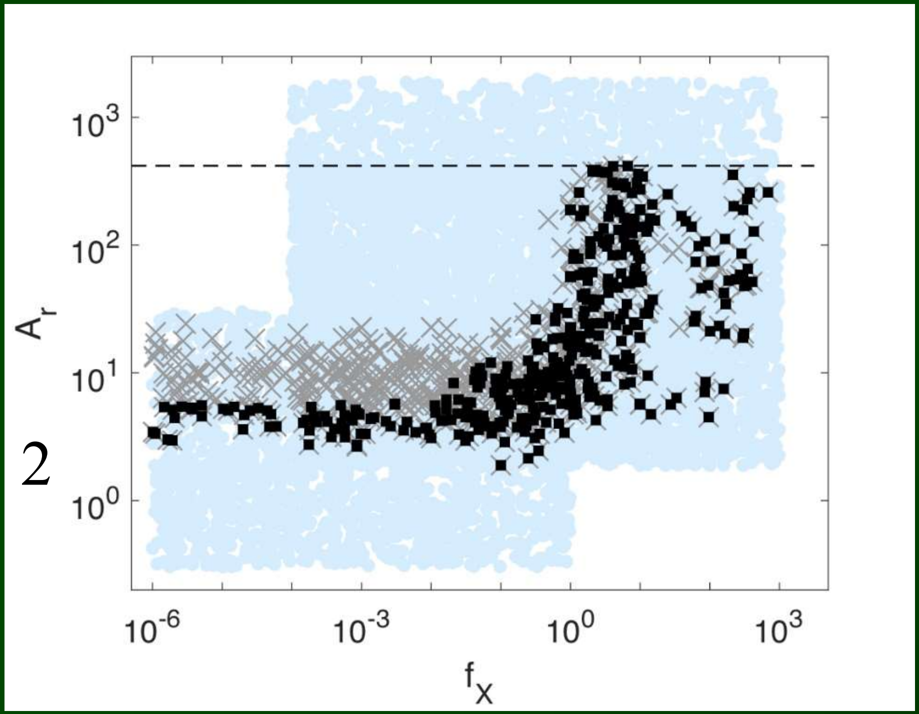
k=0.1 Mpc^{-1}



Fialkov & RB 2019

Alternative explanation





Fialkov & RB 2019