The Cosmic History of the 21-cm Line Signal from the Recombination Epoch to the First Stars

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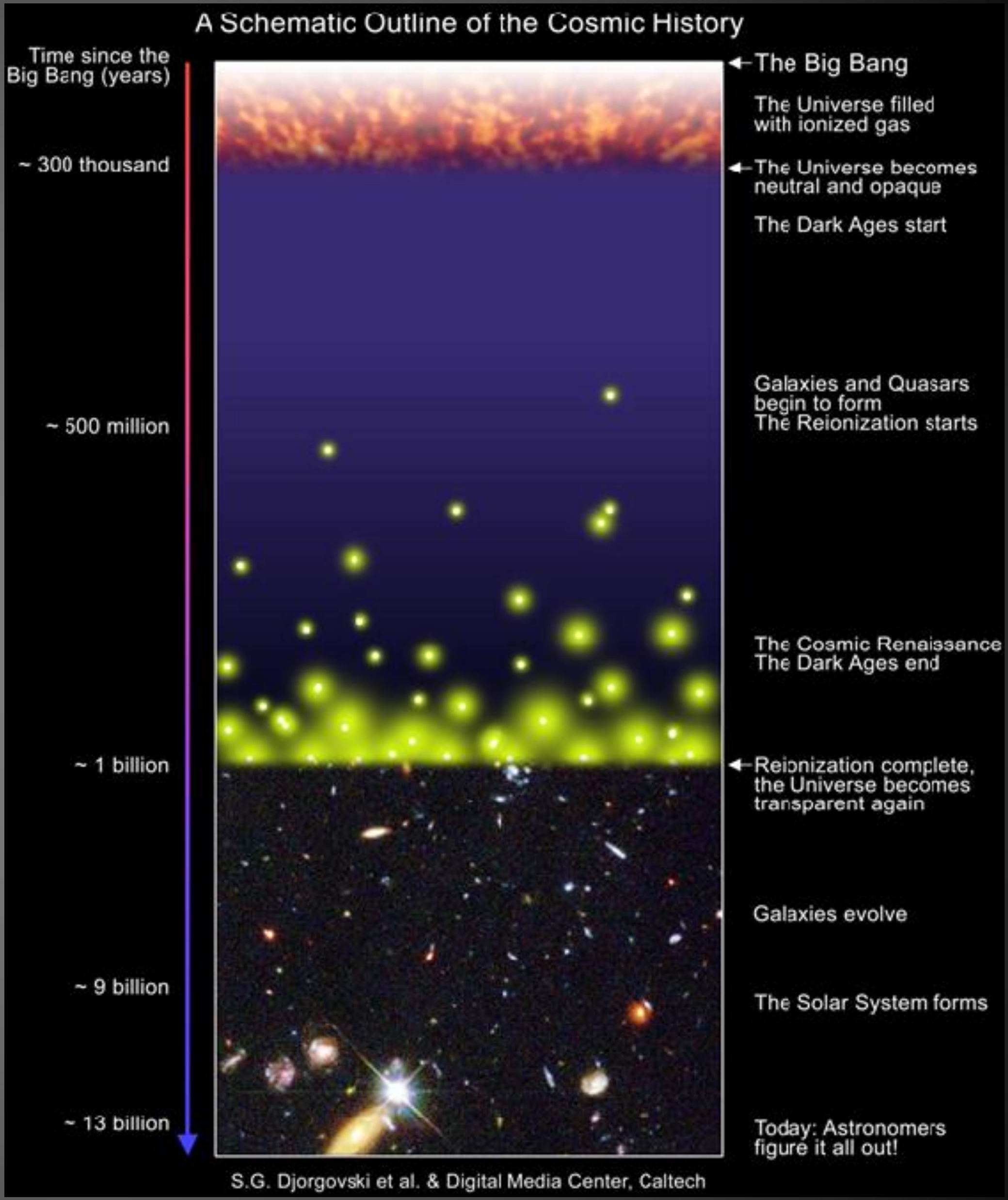
Ecole Normale Superieure

Chalonge Meudon Workshop 2014

Cosmic History

- CMB
- Dark Ages
- First Stars and Galaxies
- Reionization
- Large scale structure

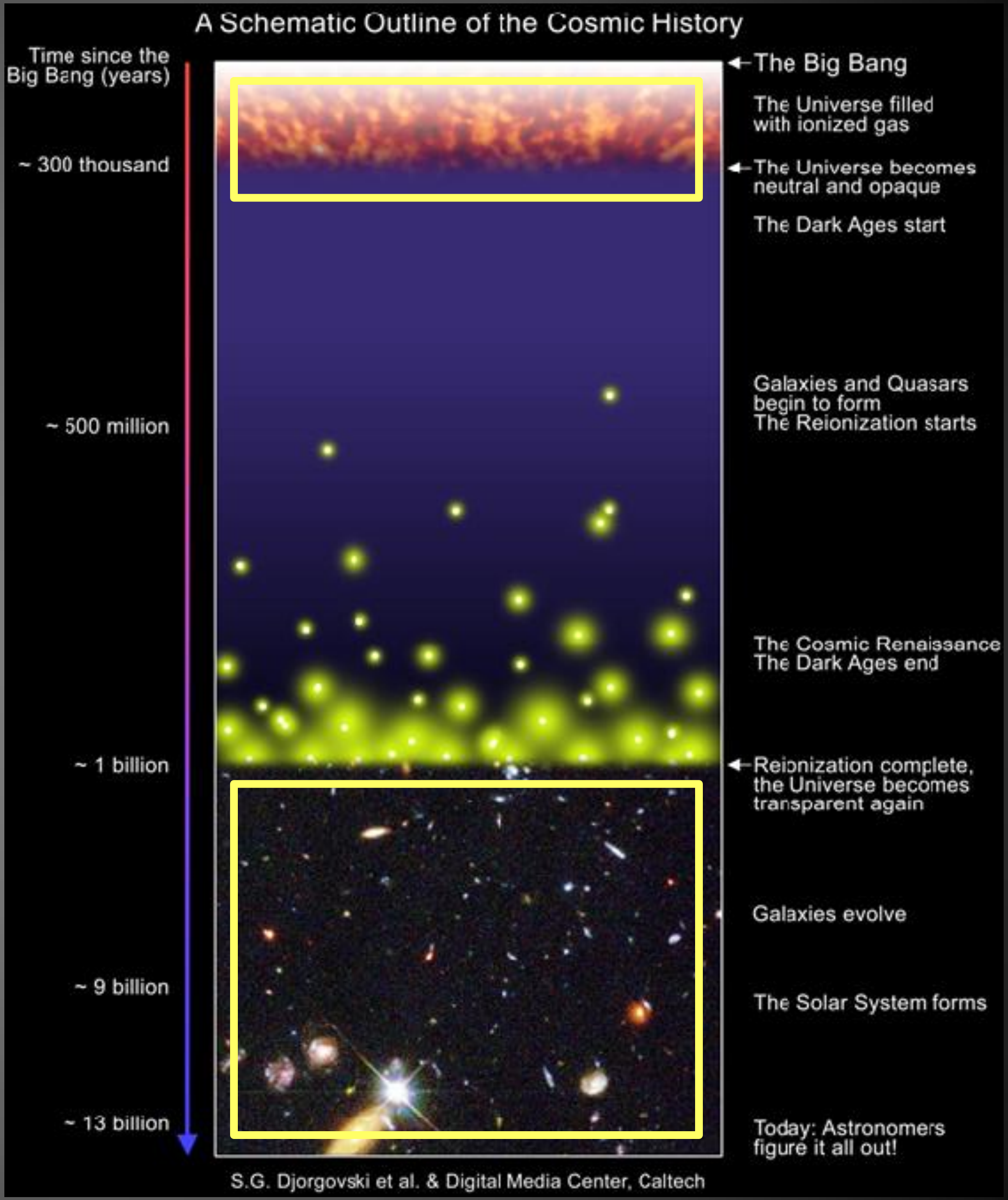


A Schematic Outline of the Cosmic History

S.G. Djorgovski et al. & Digital Media Center, Caltech

Observed

- CMB
- Dark Ages
- First Stars and Galaxies
- Reionization
- Large scale structure



S.G. Djorgovski et al. & Digital Media Center, Caltech

Unobserved

- CMB
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- First Stars and Galaxies
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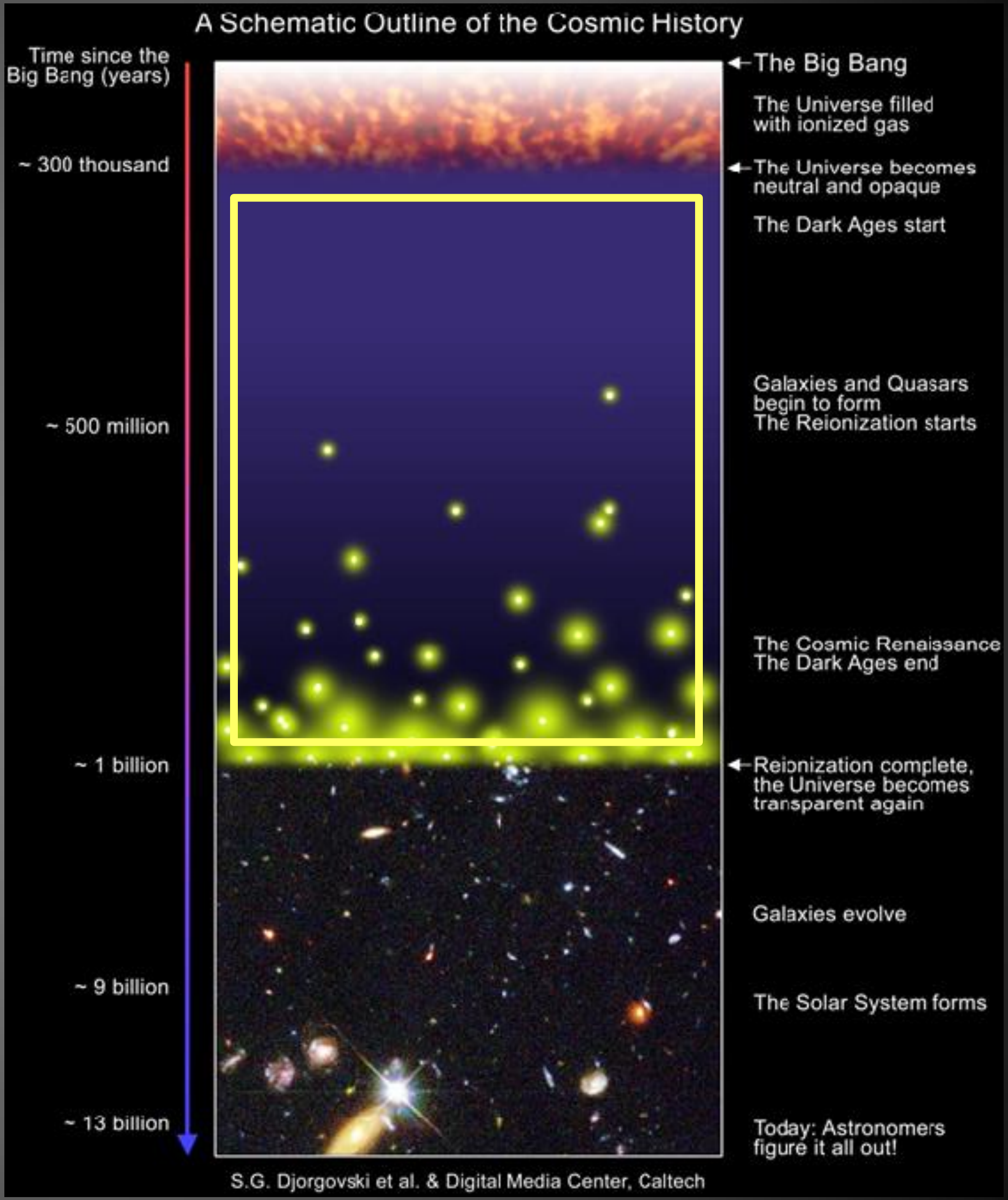
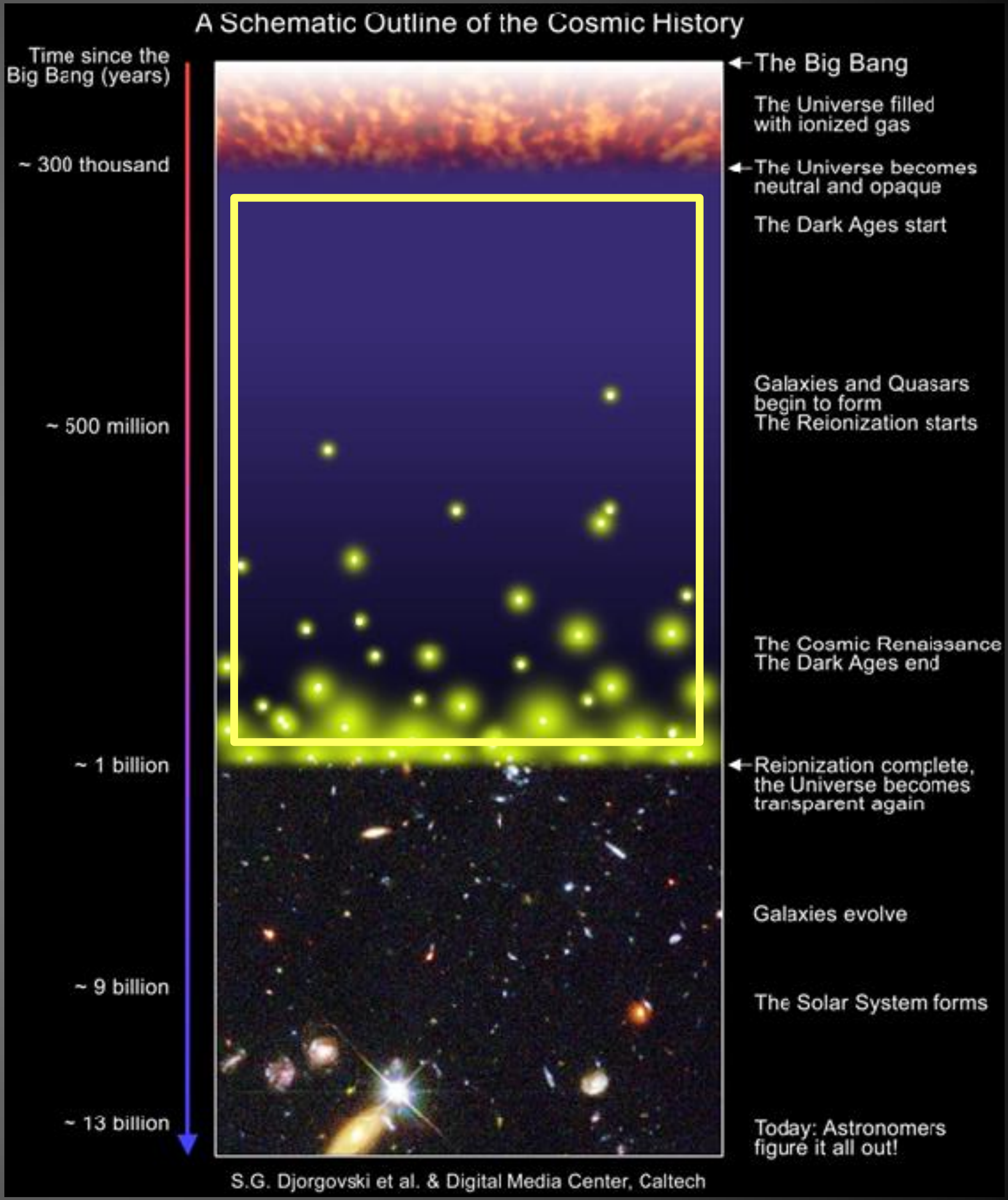


S.G. Djorgovski et al. & Digital Media Center, Caltech

Unobserved

- CMB
- Dark Ages
- First Stars and Galaxies
- Reionization
- Large scale structure

21-cm Signal: Probe of the Early Universe



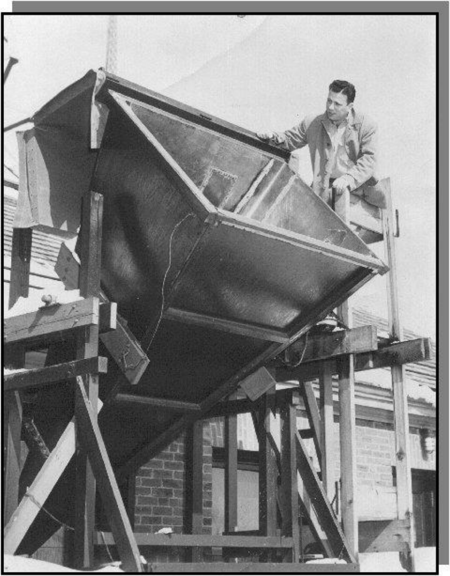
S.G. Djorgovski et al. & Digital Media Center, Caltech

21-cm as a Space Probe. Since 1942

1942 – Van de Hulst predicted 21-cm line from interstellar HI

1952 – HI in the Milky Way
First detection by Ewen and Purcell

Van de Hulst



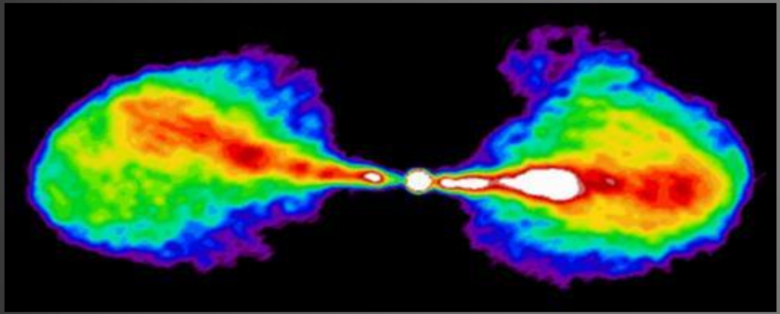
First Detector

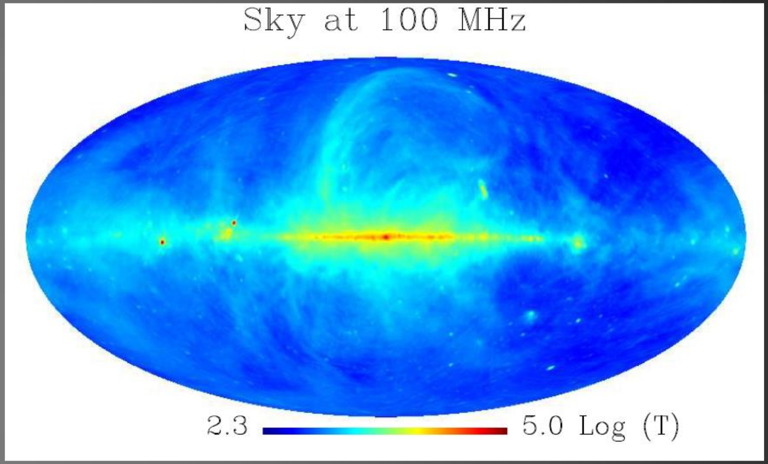
Future – Probe the epoch of first stars

Observations are Challenging! Foregrounds ≈ $(10^5 - 10^9) \times$ Signal

Astrophysical Foregrounds

- Galactic Synchrotron Emission
- Extragalactic Radio Sources

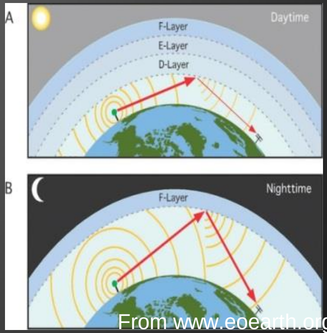




Synchrotron
De Oliveira-Costa *et al* 2008

Terrestrial

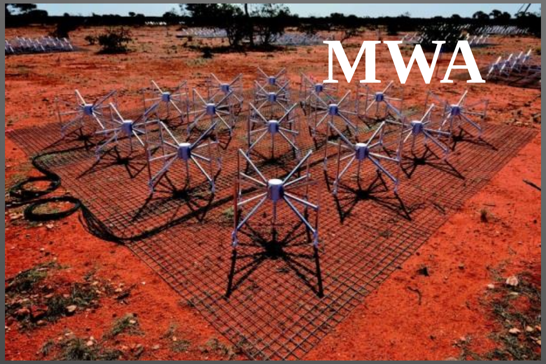
- Radio Frequency Interference
- Ionosphere Distortions



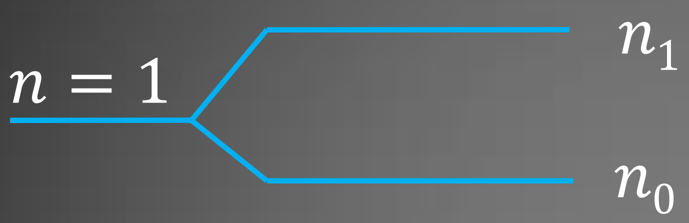
From www.eoearth.org

Current and Future Observational Effort:

Global spectrum and power spectrum from Epoch of Reionization and Cosmic Dawn



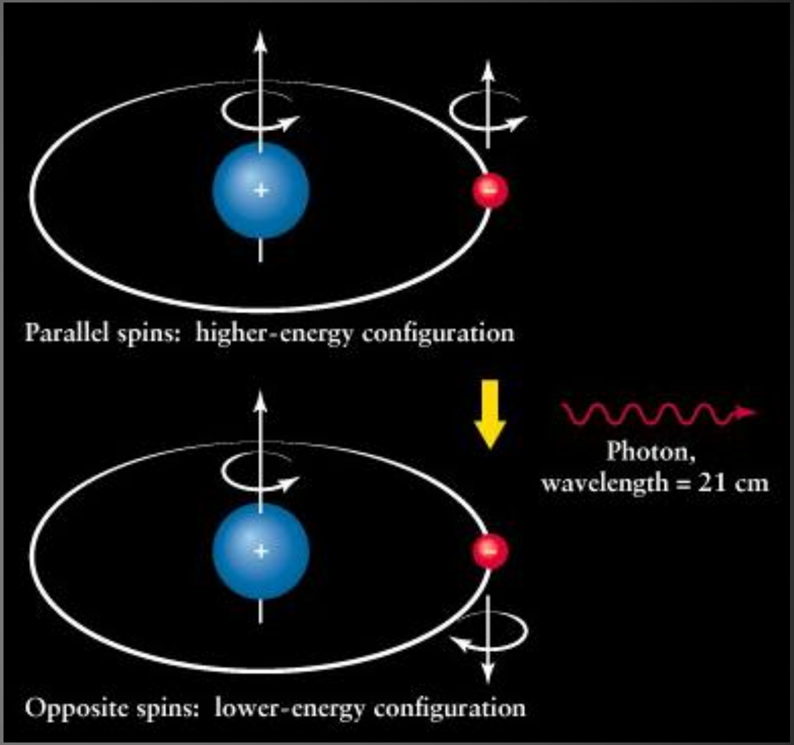
21-cm Line: Spin-Flip Transition of HI



$n = 1$

n_1

n_0



λ = 21 cm

ν = 1420 MHz (Radio)

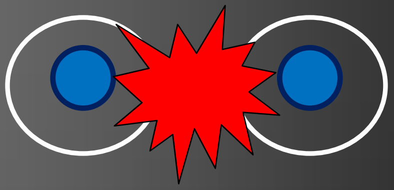
Spin Temperature

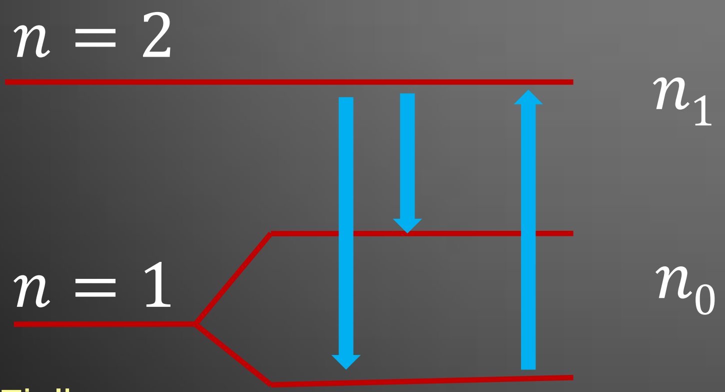
$n_1/n_0 \equiv 3\exp(-T_*/\mathbf{T_S})$, $T_* = 0.068$ K

Spin Temperature Depends on Many Physical Processes

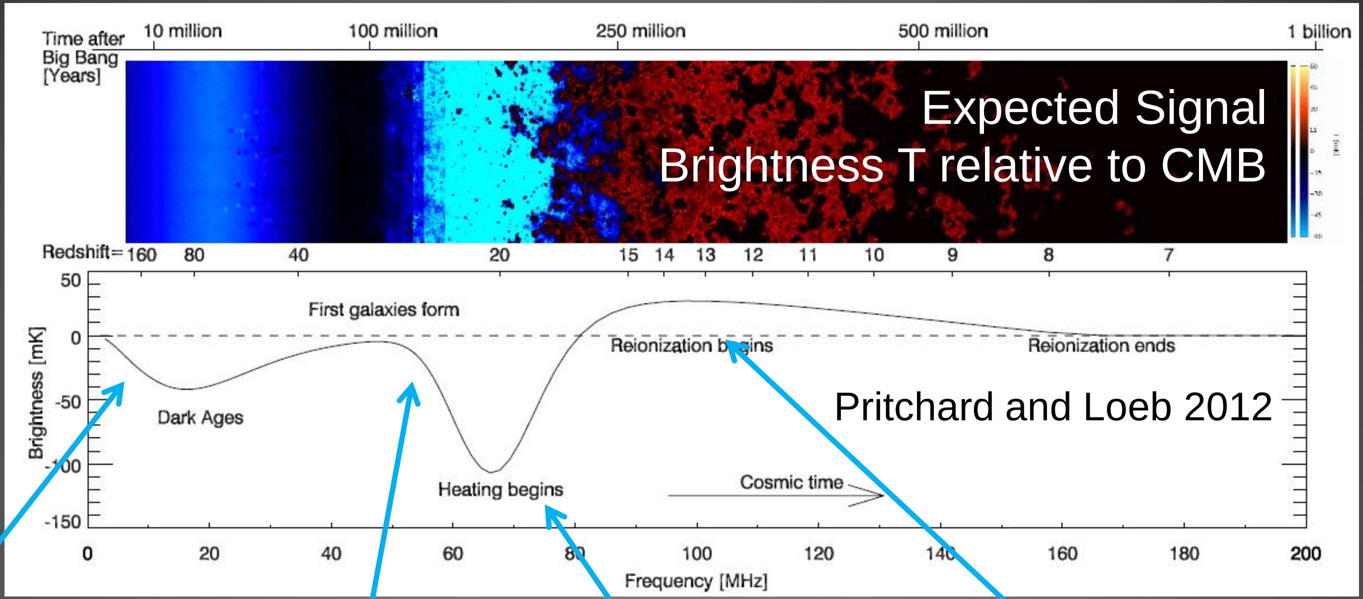
$$\frac{1}{T_s} = \frac{T_{\rm CMB}^{-1} + x_C T_K^{-1} + x_\alpha T_C^{-1}}{1 + x_C + x_\alpha}$$

- Absorption of CMB: $T_S \rightarrow T_{\rm CMB}$
- Collisions with other HI: x_C, $T_S \rightarrow T_{\rm gas}$
- Absorption and reemission of Lyα: x_α, $T_S \rightarrow T_{\rm gas}$ (Wouthuysen 1952, Field 1958)





Predicted 21-cm Signal in ΛCDM



Expected Signal
Brightness T relative to CMB

Pritchard and Loeb 2012

**Dark ages,
Collisional
coupling**

**Stars appear
Ly-a coupling**

Heating

Ionization

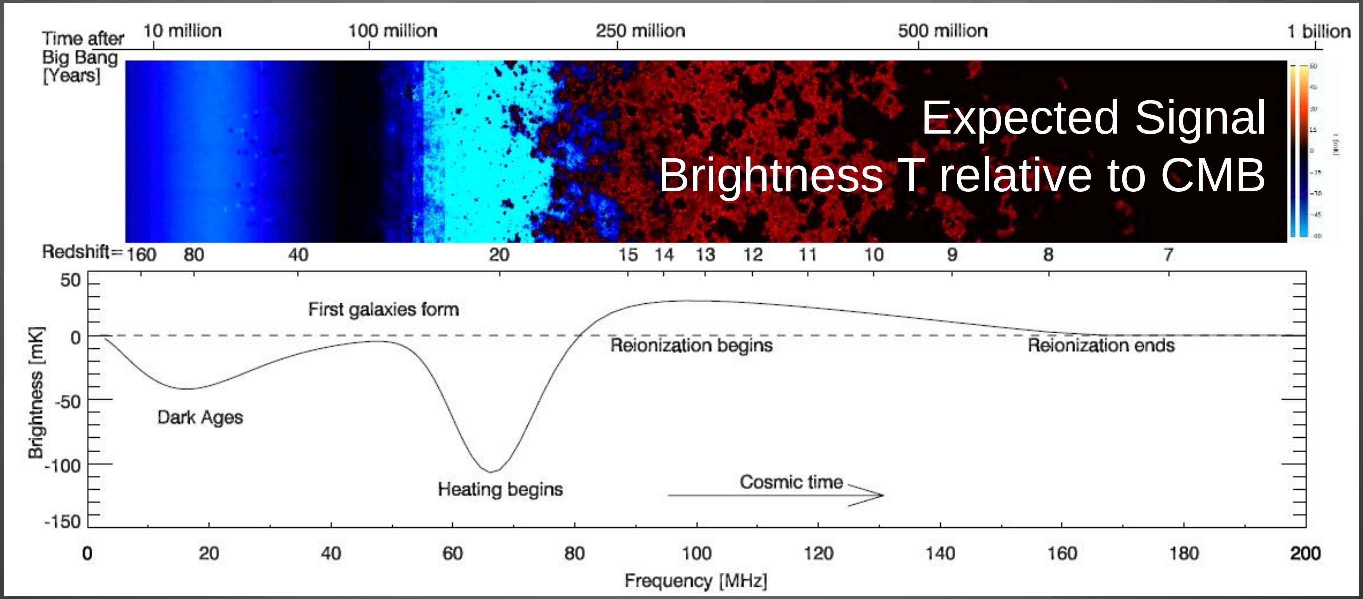
$$\delta T_b(\nu) = \frac{T_S - T_\gamma(z)}{1+z}\left(1 - e^{-\tau_{\nu0}}\right) \approx \frac{T_S - T_\gamma(z)}{1+z}\,\tau_{\nu0}$$
$$\approx 9\, x_{\rm HI}(1+\delta)\,(1+z)^{1/2}\left[1 - \frac{T_\gamma(z)}{T_S}\right]\left[\frac{H(z)/(1+z)}{{\rm d}v_{\parallel}/{\rm d}r_{\parallel}}\right]\ {\rm mK}$$

Furlanetto, Oh, Briggs 2006

21-cm Signal from High Redshifts is Science-rich

Sensitive to:

- Initial conditions δ, v_{bc} (cosmology)
- Gas temperature (heating mechanisms)
- Ly-a, LW, ionization fraction (radiative backgrounds)



Pritchard and Loeb 2012

In this Talk

1) 21-cm from the era of primordial star formation
2) Dark ages
3) Recombination

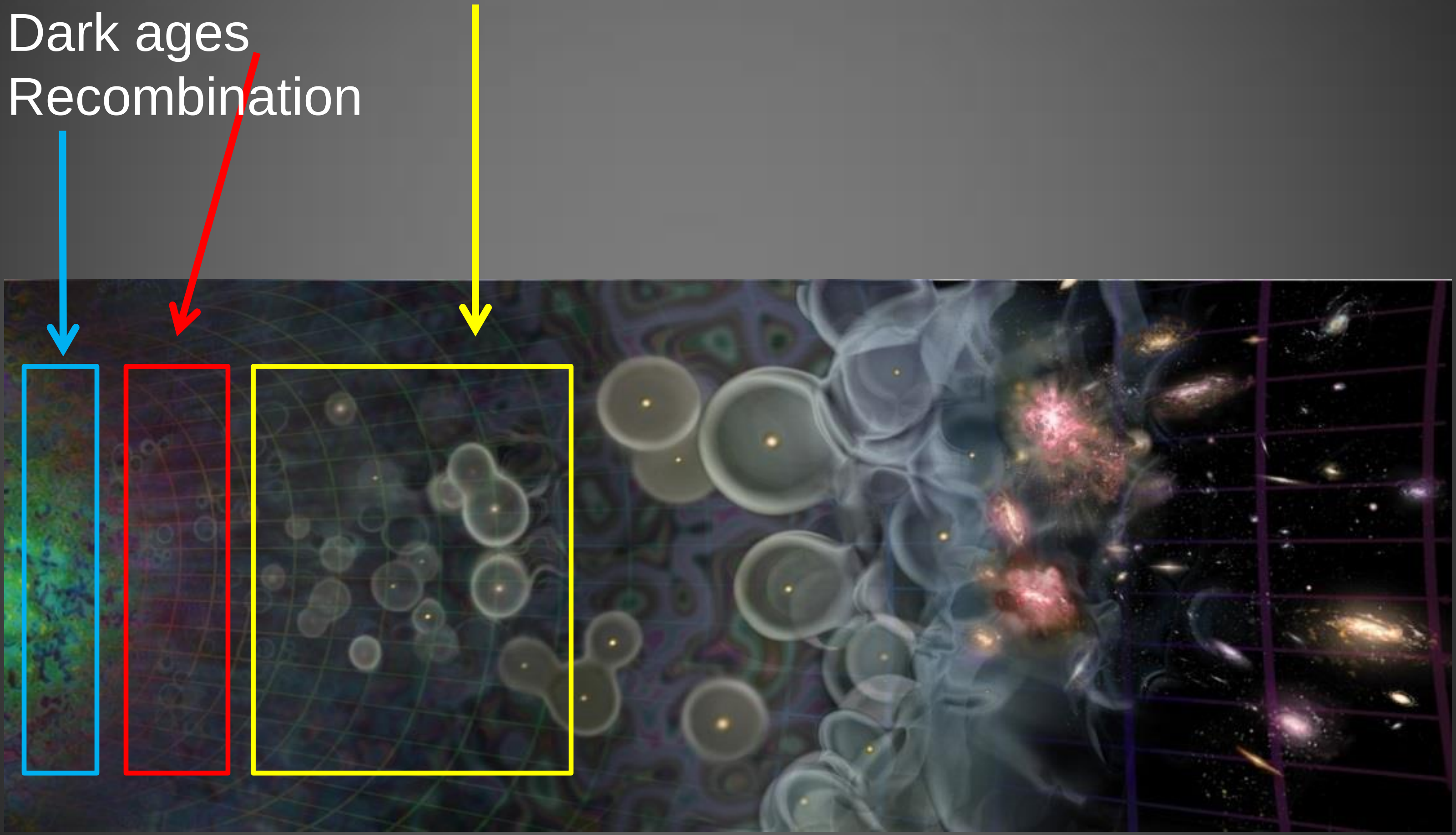
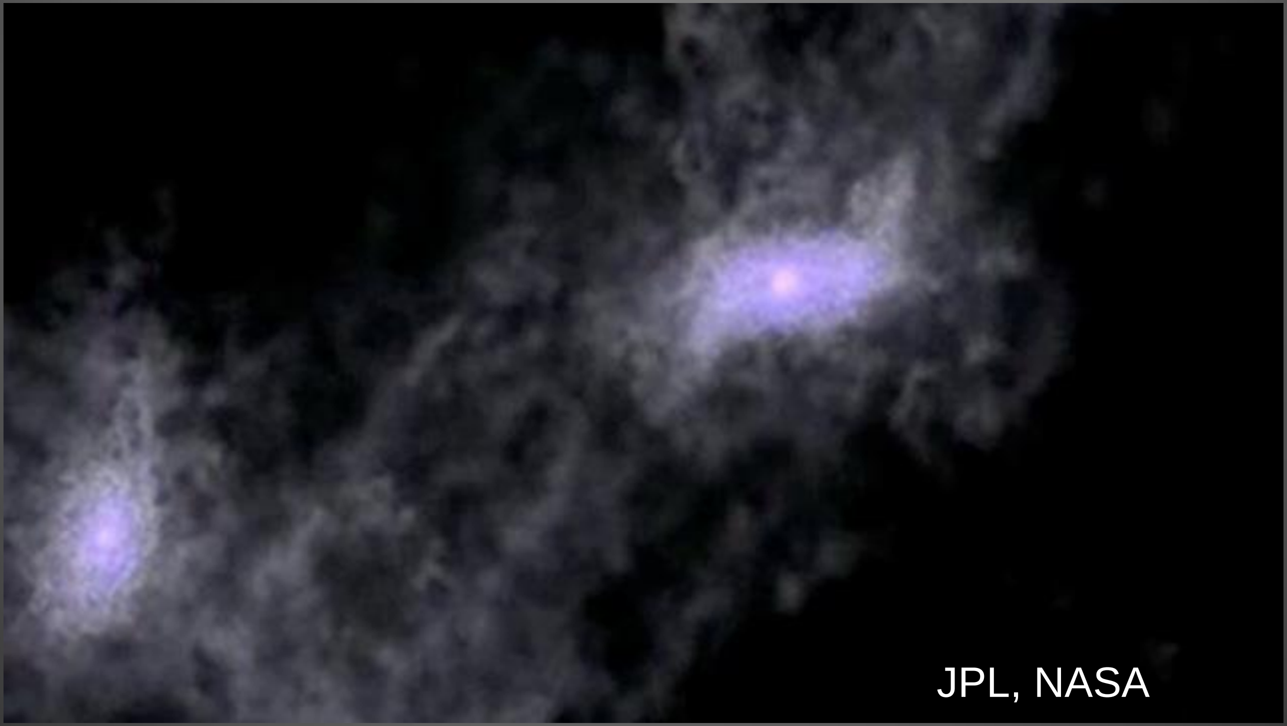


Image: Loeb, Scientific American 2006

21-cm Line Signal from Cosmic Dawn


JPL, NASA

Anastasia Fialkov

5 June, 2014

Early Universe is Very Unconstrained

Some of the Open Questions:

What were the masses of first stars and of halos in which they formed?
How efficient was star formation?
How first stars ended their lives?
What was the dominating heating mechanism?
How efficient were the stars in ionizing the gas?
How efficient were radiative and mechanical feedbacks?
How metal enrichment proceeded?
Were there any exotic processes (e.g., dark matter annihilation)?
…

Huge parameter space for 21-cm modeling!

21-cm Signal from High Redshifts is Science-rich but Hard to Model

$$\delta T_b(\nu) = \frac{T_S - T_\gamma(z)}{1+z}\left(1 - e^{-\tau_{\nu 0}}\right) \approx \frac{T_S - T_\gamma(z)}{1+z}\,\tau_{\nu 0}$$

$$\approx 9\, x_{\mathrm{HI}}(1+\delta)\,(1+z)^{1/2}\left[1 - \frac{T_\gamma(z)}{T_S}\right]\left[\frac{H(z)/(1+z)}{\mathrm{d}v_{\parallel}/\mathrm{d}r_{\parallel}}\right]\ \mathrm{mK}$$

Depends on:

- Initial conditions
- Star formation and thermal history
- Distribution of (rare) 1st stars
- Feedbacks
- Ionization fraction
- Exotic phenomena

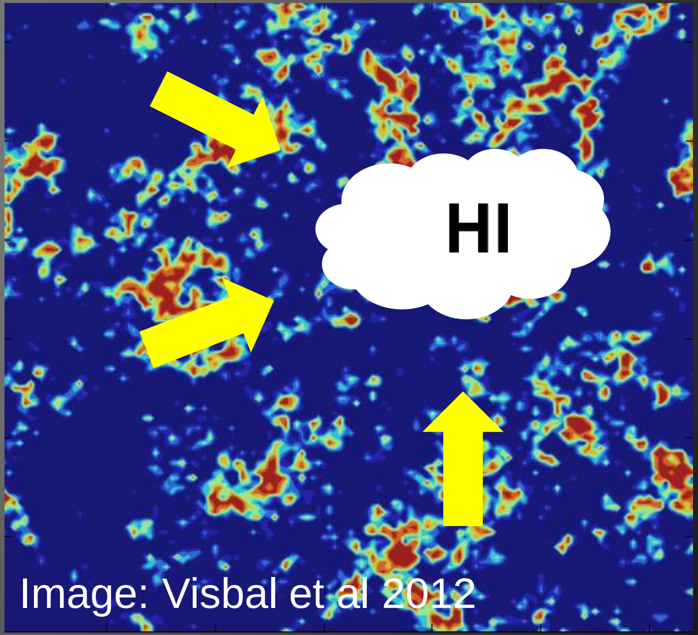


Image: Visbal et al 2012

References: works by Mesinger et al (2012, 2013), Christian and Loeb (2013), Visbal et al (2012), **Fialkov** et al. (2014, 2013) and others

21-cm Depends on Modeling of First Stars and Galaxies

First stars form in metal free environment

- H_2 cooling ~10^5 M_{sun} halos
- H cooling in ~10^7 M_{sun} halos

(e.g., Tegmark et al. 1997, Machacek, Bryan & Abel 2001)

Fragmentation (rotation, radiative feedback)

(e.g., Stacy, Greif, Klessen, Bromm, Loeb 2013; Stacy, Greif, Bromm 2010)

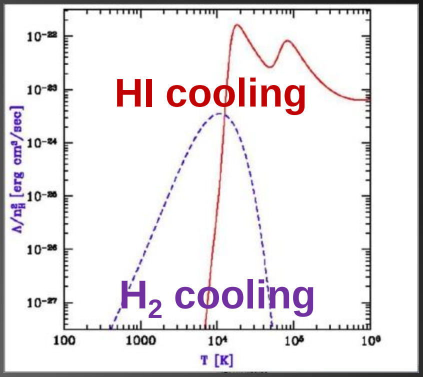
Start forming at z ~ 65

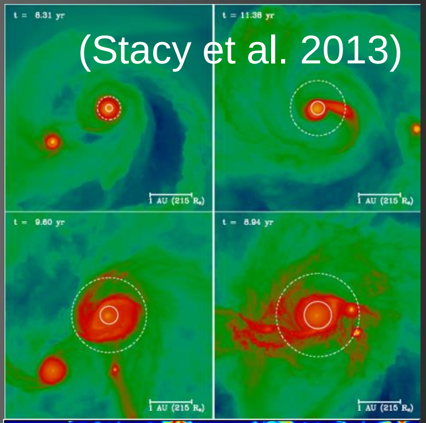
(Naoz et al. 2006, **Fialkov** et al. 2012)

Rare at high redshifts (biased by δ and v_{bc})

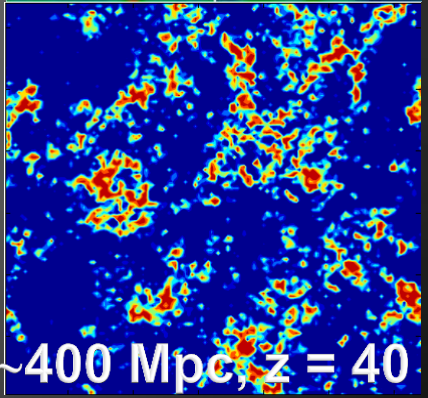
(e.g., Barkana & Loeb 2004; Tselikhovich & Hirata 2010)

Bromm (2012)





(Stacy et al. 2013)

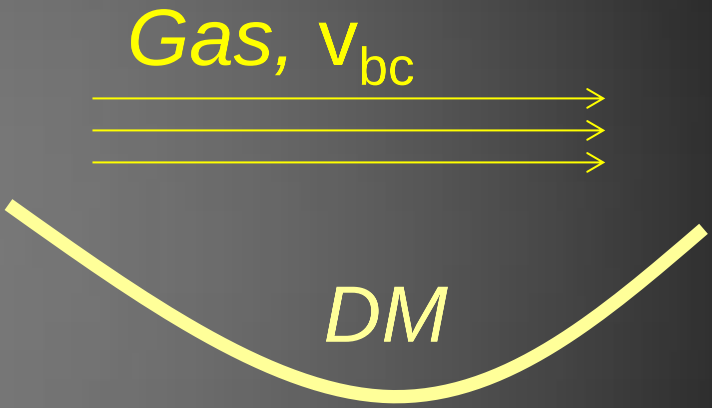


~400 Mpc, z = 40

Formation of First Stars is Biased

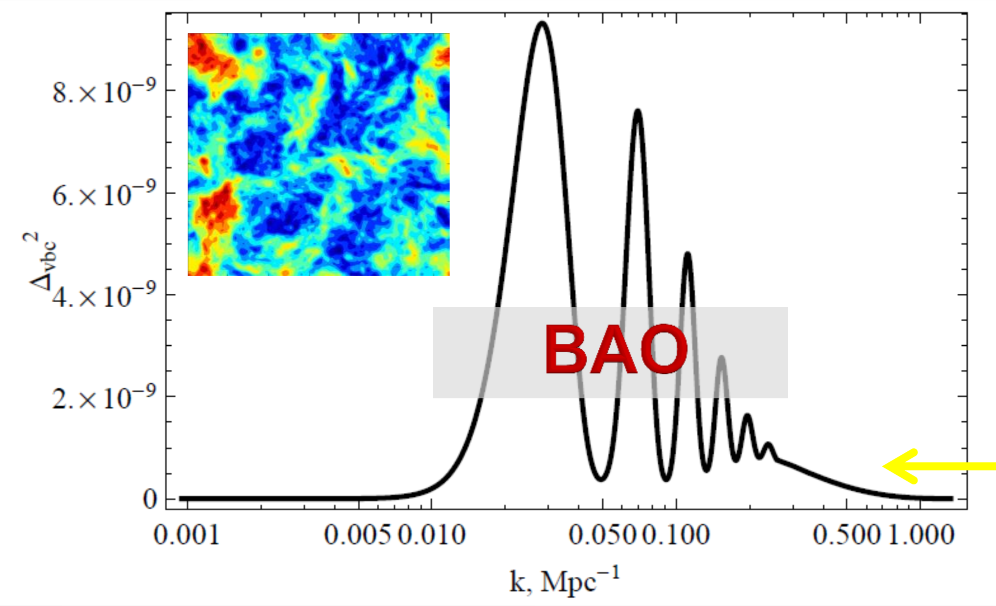
1. Relative supersonic motion between gas and dark matter affects **10^4-10^8 M_{sun}** halos (Tseliakhovich & Hirata, 2010)

- Supersonic: $\sigma_{vbc} \approx 30$ km/s $\approx 5c_s$
- Decays as (1+z)
- Random: MB distribution


Gas, v_{bc}

DM

Gas overshoots DM halos



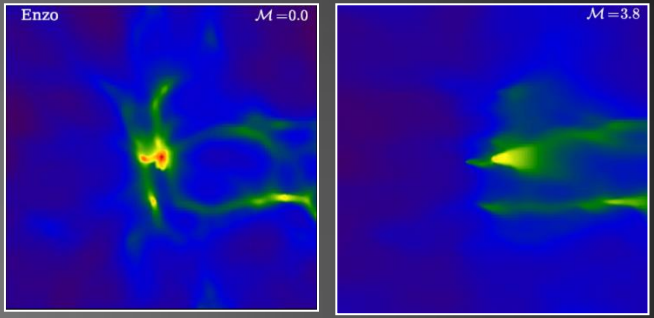
Silk damping:
Coherence scale
~ few Mpc

Formation of First Stars is Biased

1. Relative supersonic motion between gas and dark matter affects **10^4-10^8 M_{sun}** halos (Tseliakhovich & Hirata, 2010)

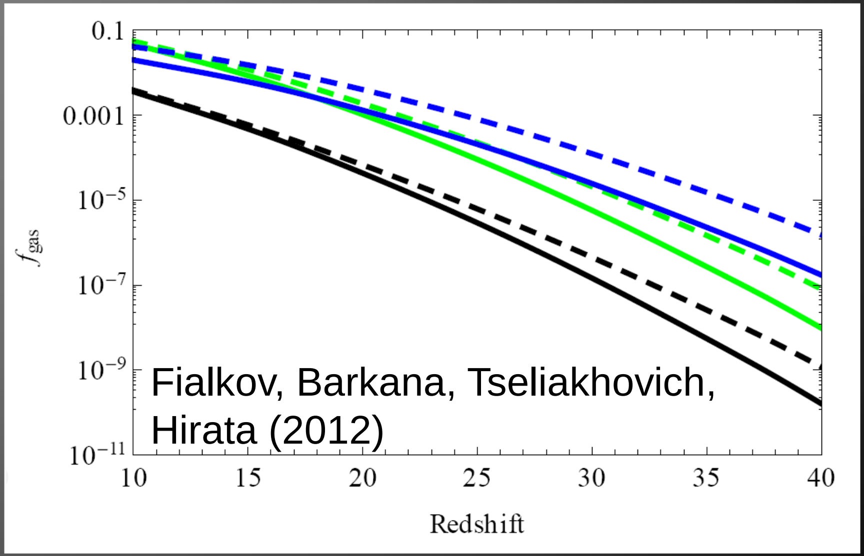
- Suppresses halo abundance
- Suppresses gas fraction
- Delays star formation
- First star is delayed by Δz ~ 5

Nonhomogeneous delay in star formation



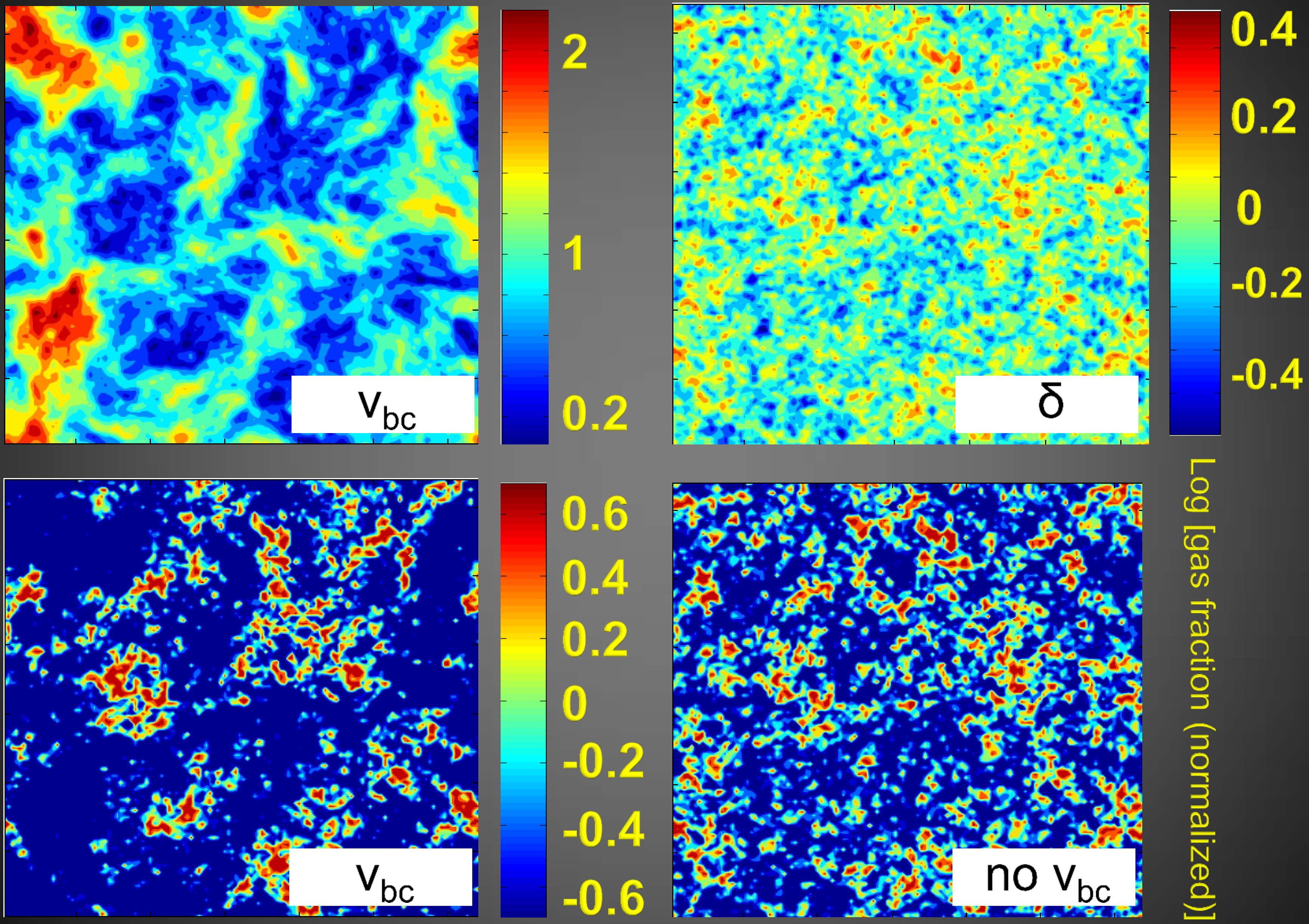
O’Leary & McQuinn (2012)

Tselikhovich & Hirata 2010; Naoz, Yoshida, Barkana 2011; Dalal, Pen & Seljak 2010; Tselikhovich, Barkana & Hirata 2011; Naoz, Yoshida, Gnedin 2012, 2013; **Fialkov,** Barkana, Tselikhovich & Hirata 2012; Maio, Koopmans & Ciardi 2011; Stacy, Bromm & Loeb 2011; Greif, White, Klessen & Springel 2011; Naoz, Yoshida & Gnedin 2011; O’Leary & McQuinn 2012; Bromm 2013; Yoo, Dalal, Seljak 2011 …



Fialkov, Barkana, Tseliakhovich, Hirata (2012)

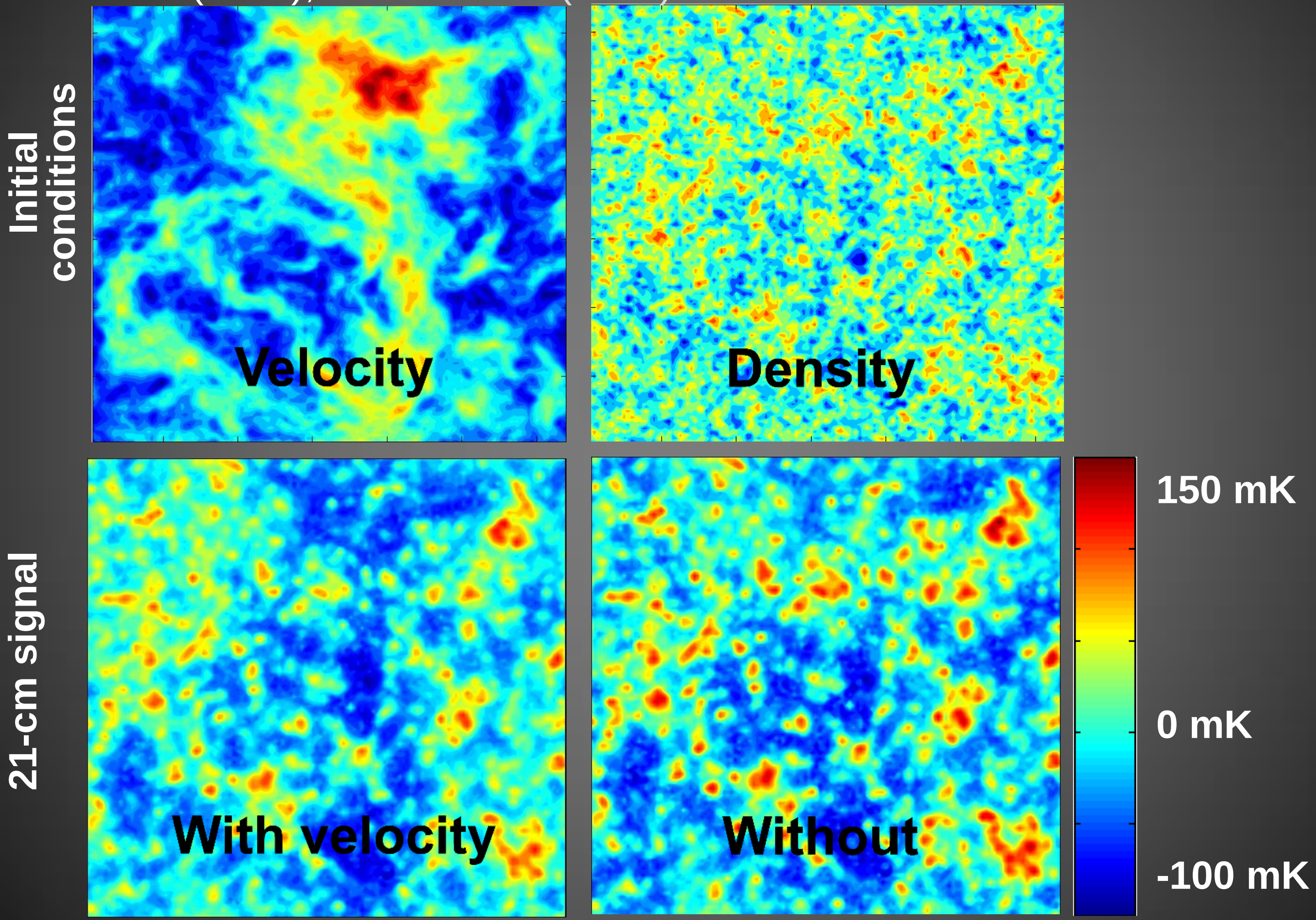
Example: Gas fraction in star-forming halos, z = 40



Visbal, Barkana, **Fialkov**, Tseliakhovich, Hirata 2012

Effect of the Motion on 21-cm Signal

Visbal et al (2012), **Fialkov** et al (2013)

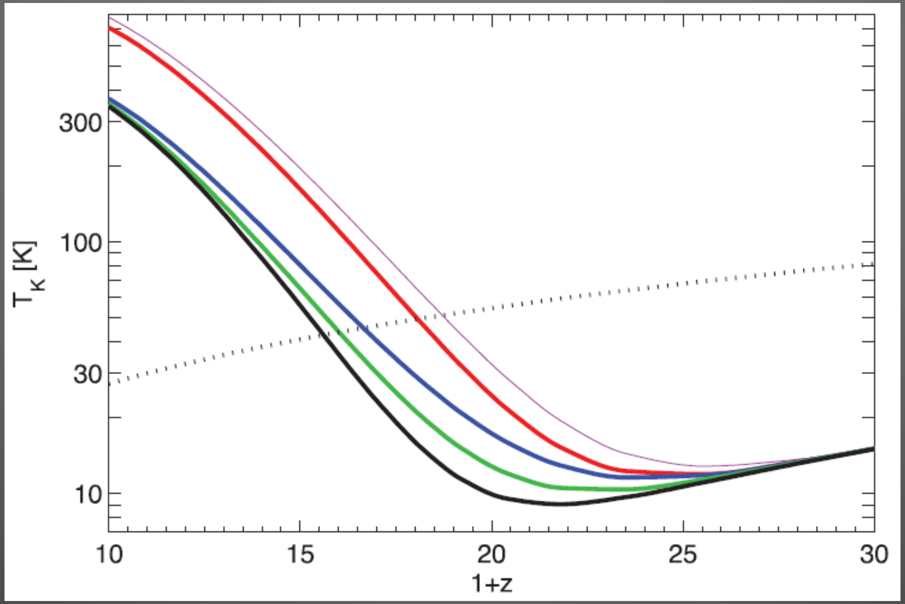


Formation of First Stars is Biased

2. Radiative feedbacks

- LW photons destroy H_2, suppress star formation
- Delay build-up of radiative backgrounds up to $\Delta z \sim 5$

Machacek et al. 2001; Wise & Abel 2007; O'Shea & Norman 2008, **Fialkov** et al. 2013; Visbal et al. 2014; Machacek, Bryan, Abel 2003….



Fialkov, Barkana, Visbal, Tseliakhovich, Hirata (2013)

Formation of First Stars is Biased

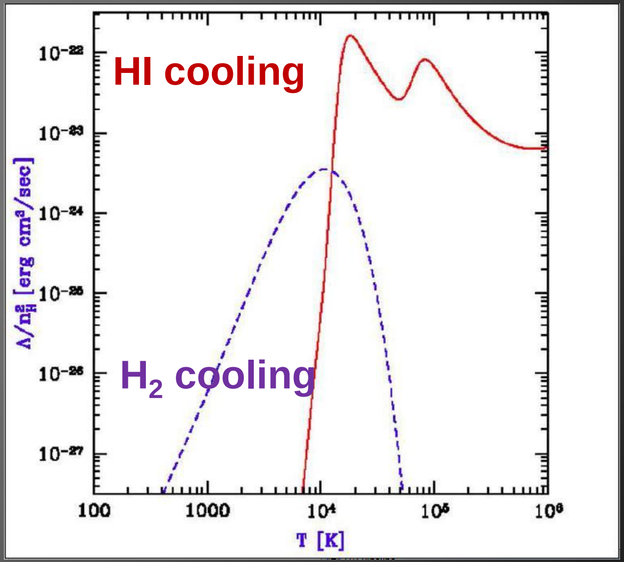
Relative velocities + Radiative feedbacks

- M_{cool} is boosted

$$M_{cool}(v_{bc}\,,\, J_{LW},\, z) = [1+6.96(4\,\pi\, J_{LW})^{0.47}]\times M_{cool,0}\,(v_{bc})$$

Fialkov, Barkana, Visbal, Tseliakhovich, Hirata (2013)

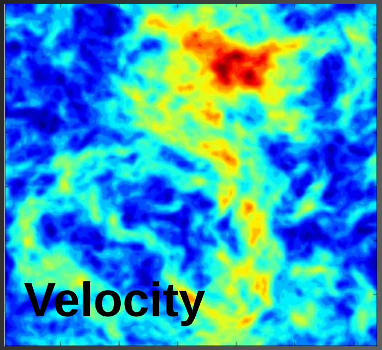
- Stars will form via H_2 cooling in ($M_{cool} < 10^7\ M_{sun}$, $T_{vir} < 1000$ K) or via HI cooling in ($M_{cool} \sim 10^7\ M_{sun}$, $T_{vir} < 1000$ K)

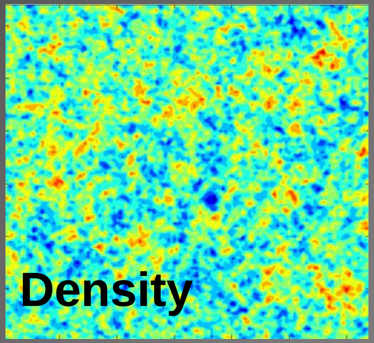


Barkana, Loeb (2001)

Effect of LW Feedback and Velocities

Initial conditions



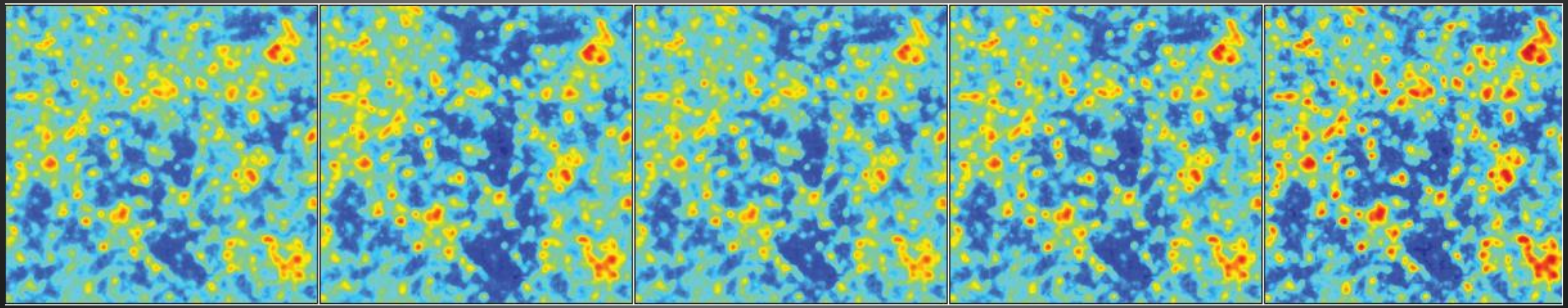


- H_2 cooling – sensitive to v_{bc} and LW feedback
- HI cooling – mildly sensitive to v_{bc}

21-cm brightness temperature

Molecular cooling

Atomic cooling



No feedback, No vbc

No feedback

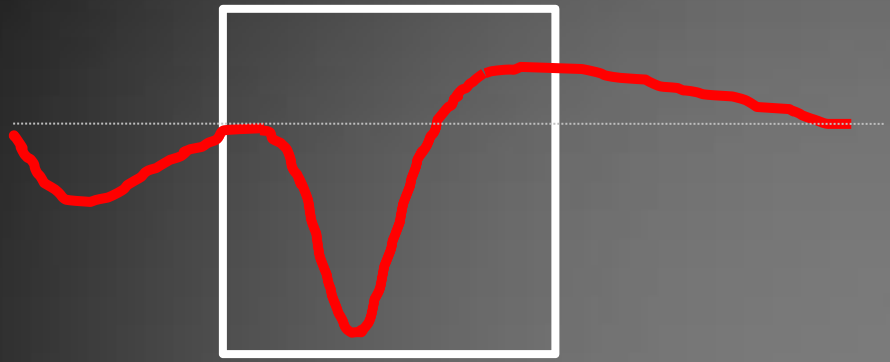
Weak feedback

Strong feedback

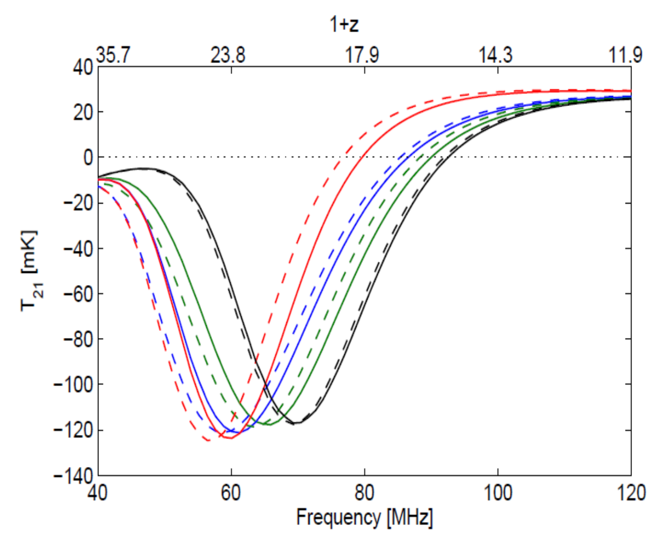
Saturated feedbback

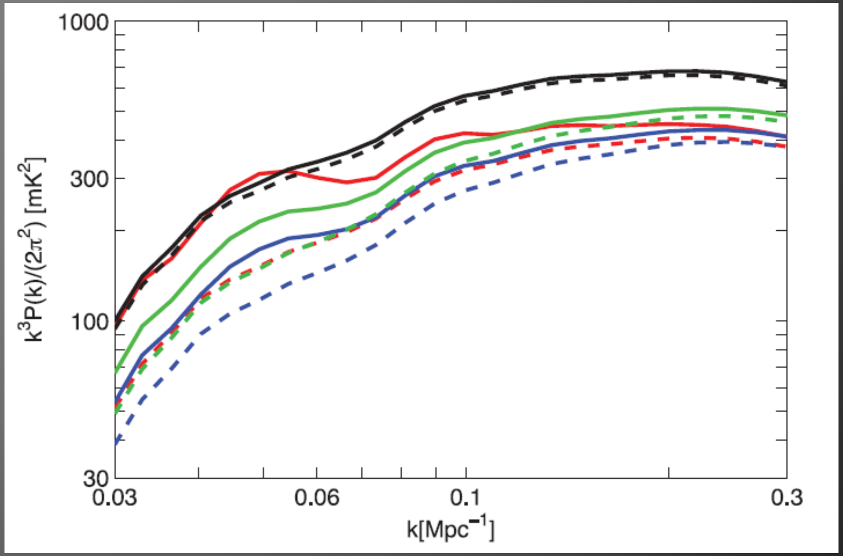
Fialkov, Barkana, Visbal, Tseliakhovich, Hirata (2013)

Uncertainty due to LW Feedback and Velocities



- Delay star formation and cosmic milestones by $\Delta z \sim 3.5$
- Impact on masses of star-forming halos
- BAO in power spectrum

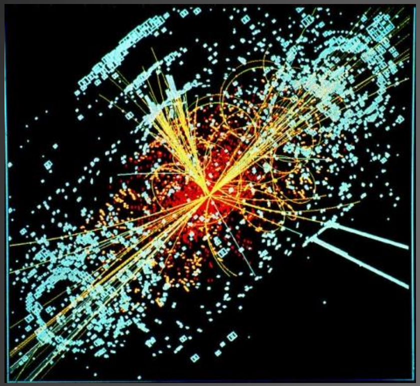


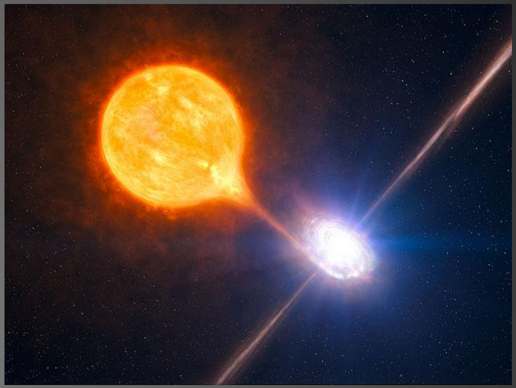


Fialkov, Barkana, Visbal, Tseliakhovich, Hirata (2013)

Heating Mechanisms at High Redshifts

T_{gas} is essential for understanding the 21-cm signal





Dark matter annihilation

A quasar

A black hole binary
(ESO image)

Possible heating sources:

X-ray binaries

Thermal emission from galaxies

Quasars, mini quasars

Dark matter annihilation

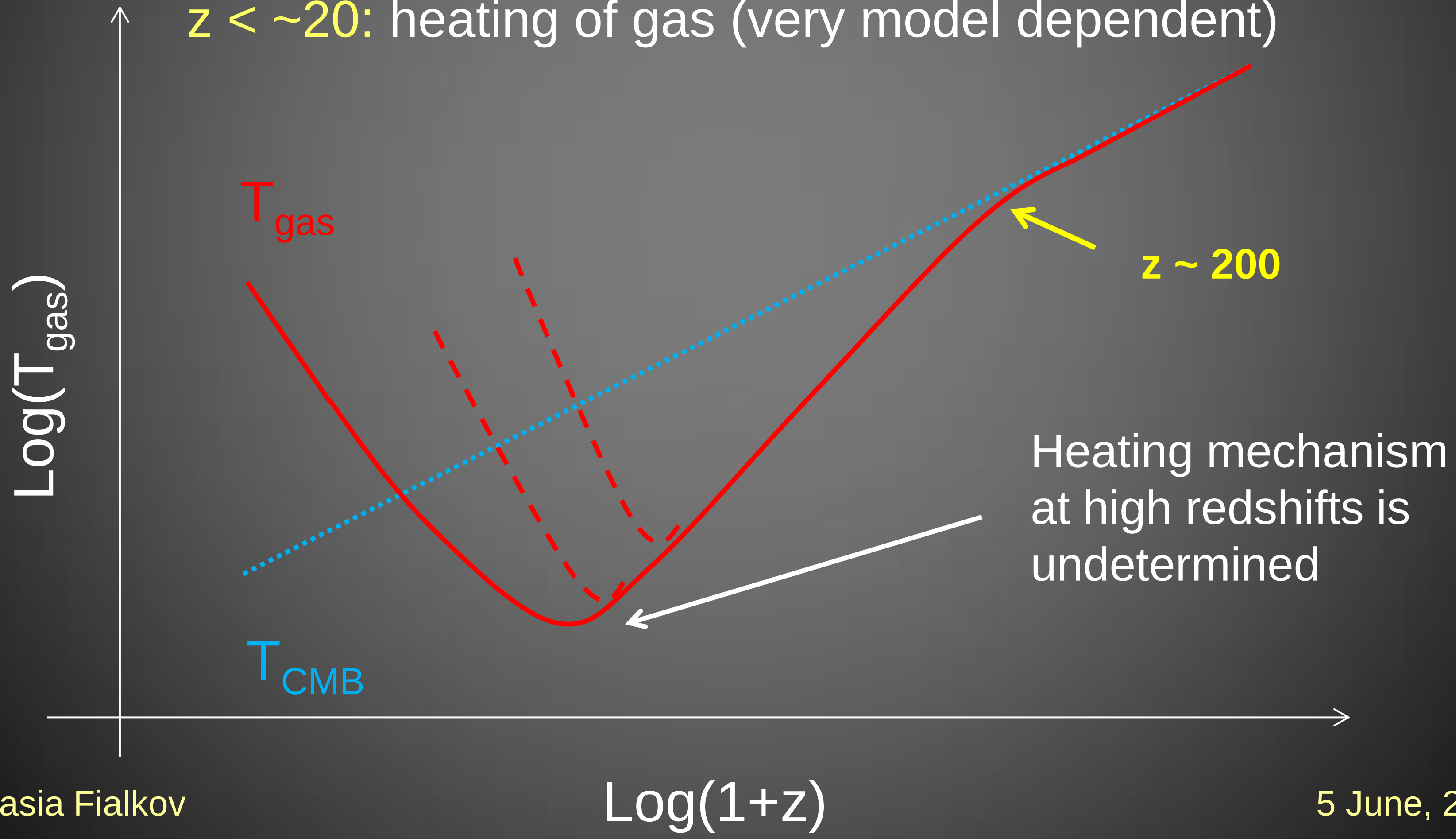
Etc.

Thermal History of Cosmic Gas

z > ~200: thermal coupling to CMB (Compton scattering), cooling as (1+z)

~20 < z < ~200: adiabatic cooling as $(1+z)^2$

z < ~20: heating of gas (very model dependent)



Heating mechanism at high redshifts is undetermined

Nature of Heating Sources is Reflected in 21-cm Signal

(Recent works e.g., Mirabel et al. (2011), **Fialkov** et al. (2014), **Fialkov** & Barkana (submitted), Mesinger et al. (2013, 2014), Pacucci et al. (2014))

T_{gas} couples to T_S,

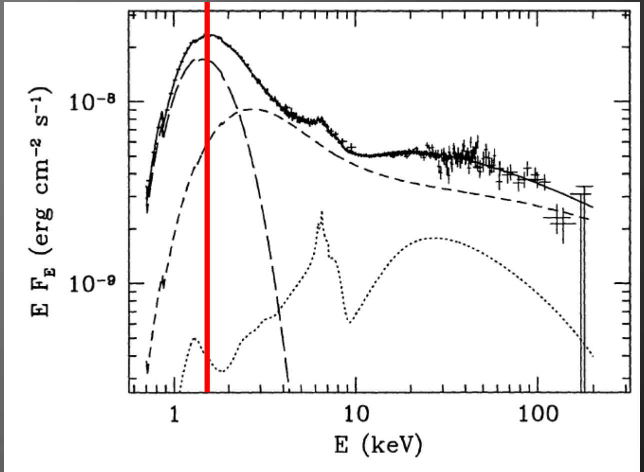
Fluctuations in T_{gas} are imprinted in 21-cm signal

Mean free path of X-ray photons seeds characteristic scale in 21-cm signal

$$\lambda_X \approx 4.9\,\bar{x}_{HI}^{1/3}\left(\frac{1+z}{15}\right)^{-2}\left(\frac{E}{300\text{ eV}}\right)^{3}\text{ Mpc}$$

Furlanetto et al. 2006


http://hubblesite.org/

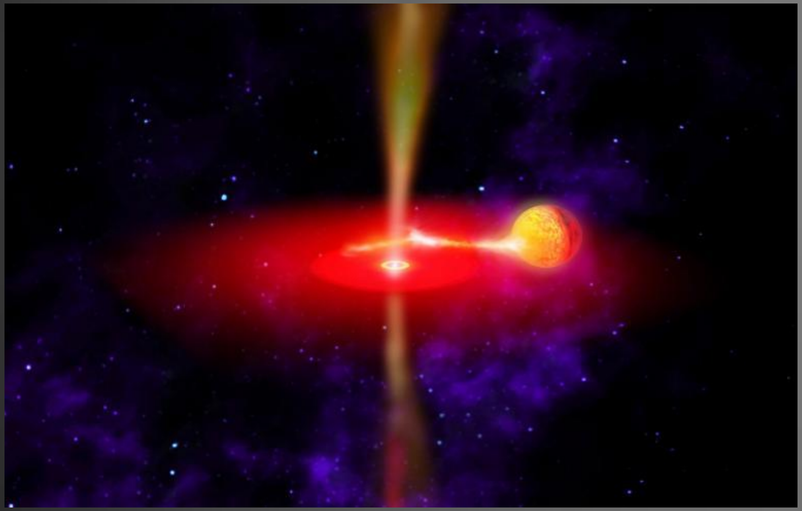


Gierlinski 1999, Cyg X-1 spectrum

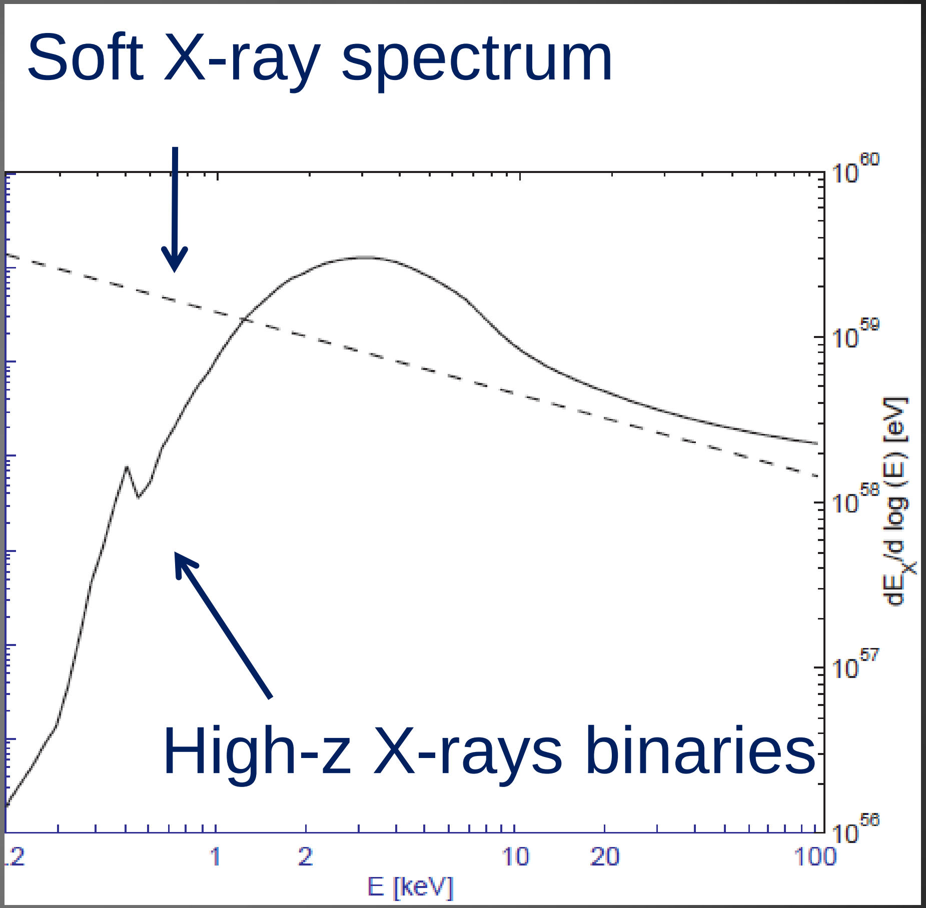
Compare: 21-cm History for Two Cases

- Heating by X-rays with power-law spectrum

- Realistic X-rays from HMXB



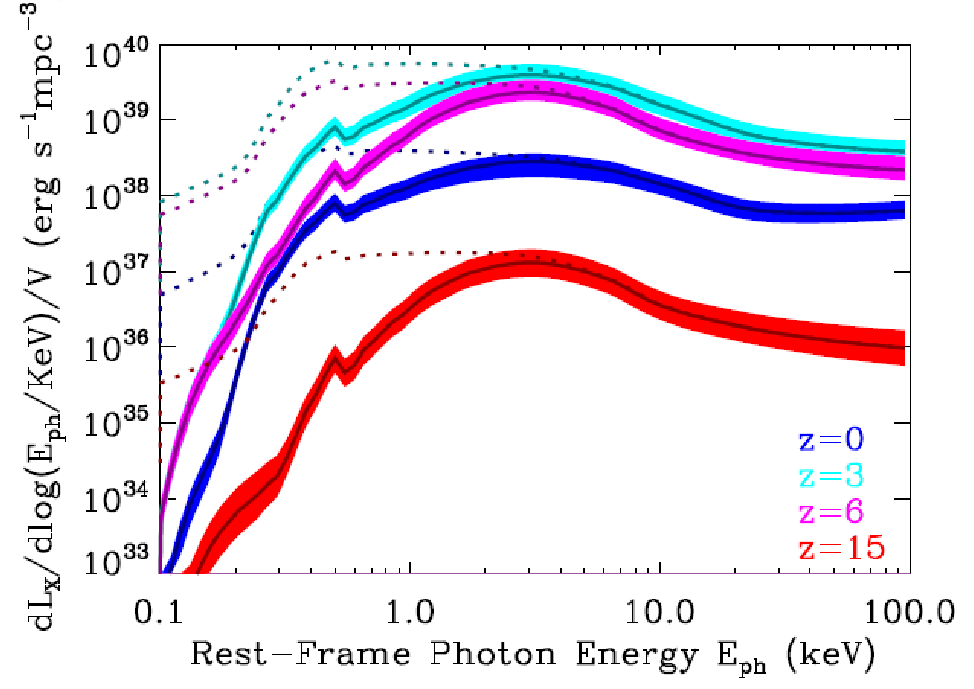
X-ray binary

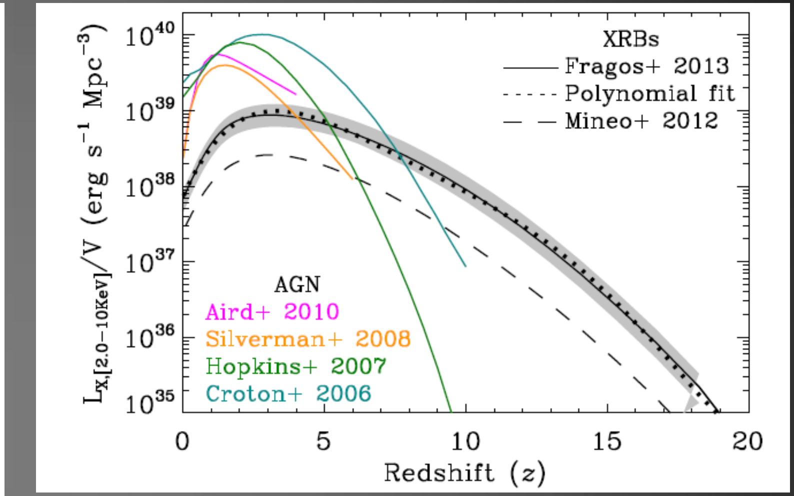


Fragos et al. (2013), **Fialkov**, Barkana, Visbal (2014)

Here: based on **Fialkov, Barkana, Visbal** (Nature 2014), but notice works by Mesinger et al. (2013, 2014), Pacucci et al. (2014).

Realistic High Mass XRBs





Xray luminocity:
Xray binaries win over AGNs at high redshifts

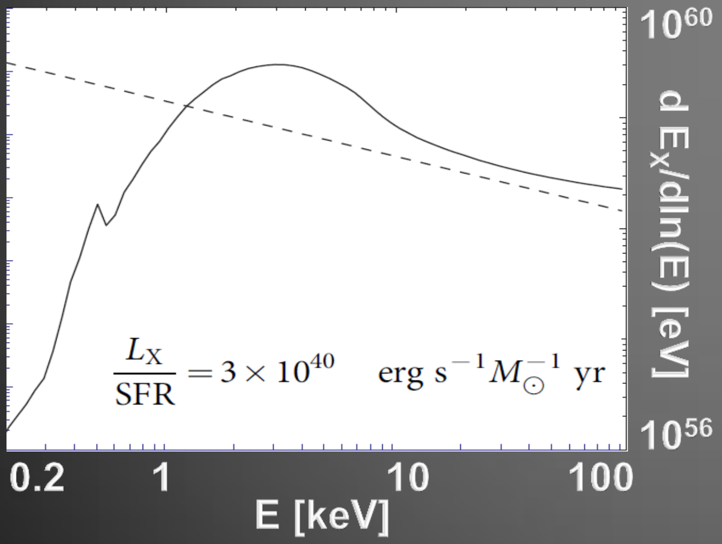
Results of a population synthesis simulations calibrated to all available observations of XRBs (Fragos et al. 2013)

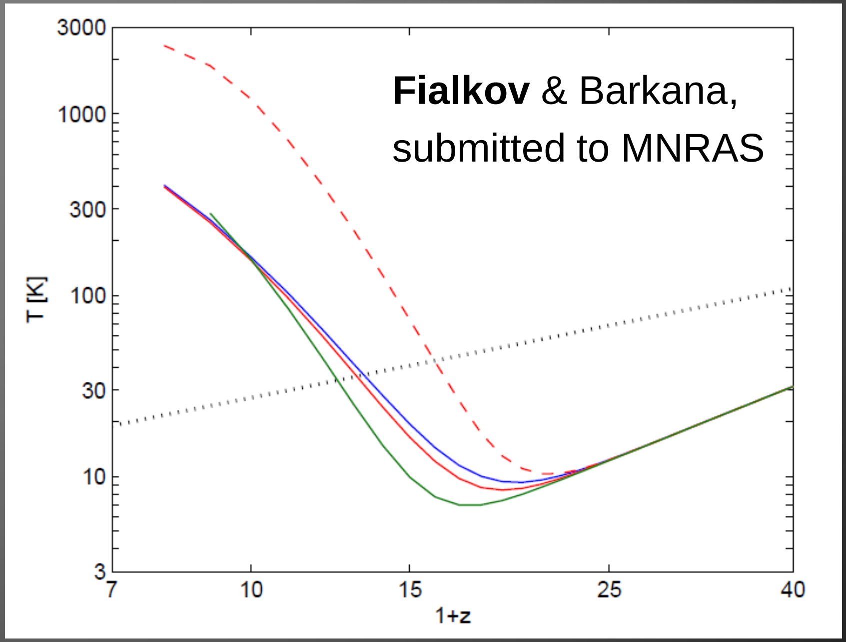
Hard vs Soft X-rays. Heating of IGM

- Harder X-rays → longer mean free pass (MFP)
- The energy absorbed by gas is reduced by factor **~ 5**

Unlike previously expected:

- Gas **can be cold** ($T_{gas} < T_{CMB}$) during the first half of EoR

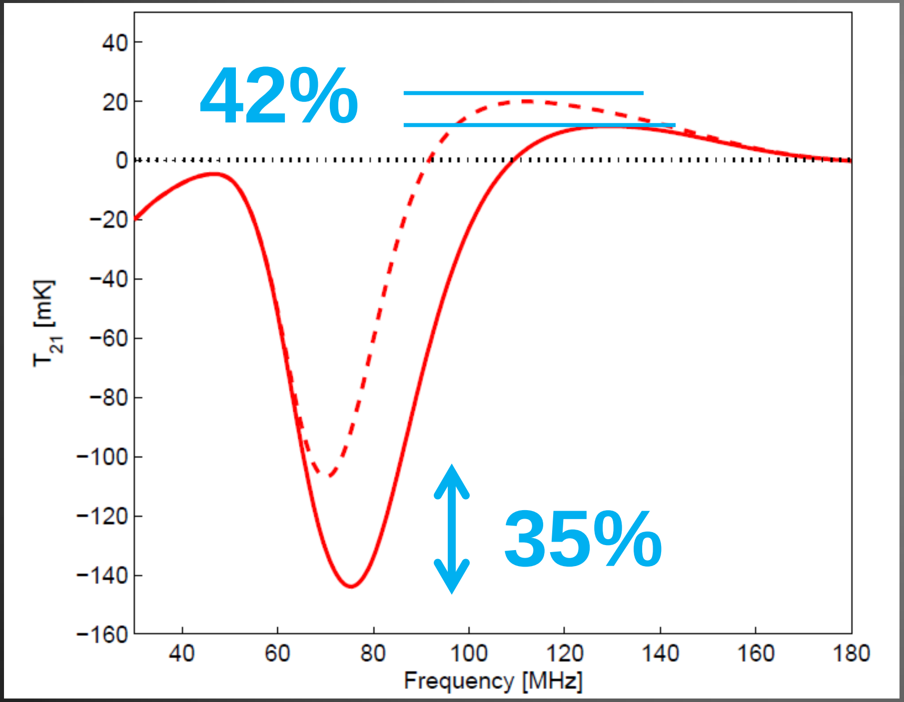



Fialkov & Barkana,
submitted to MNRAS

Effect on Global 21-cm Signal

Soft X-rays

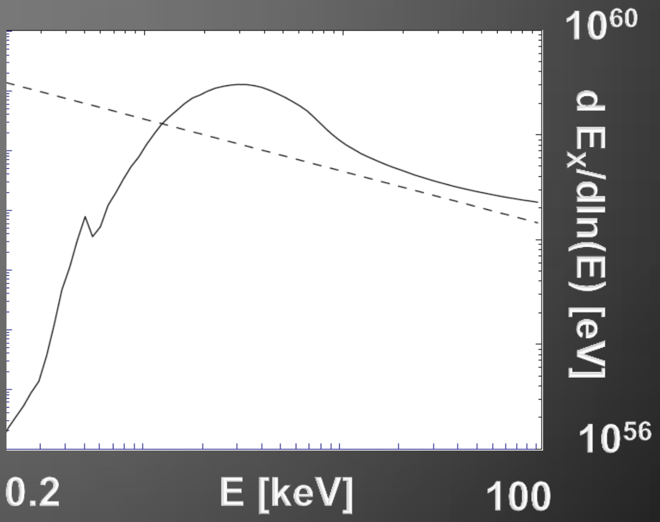
- Epochs of heating and reionization are separated in time



Fialkov, Barkana, Visbal (2014)

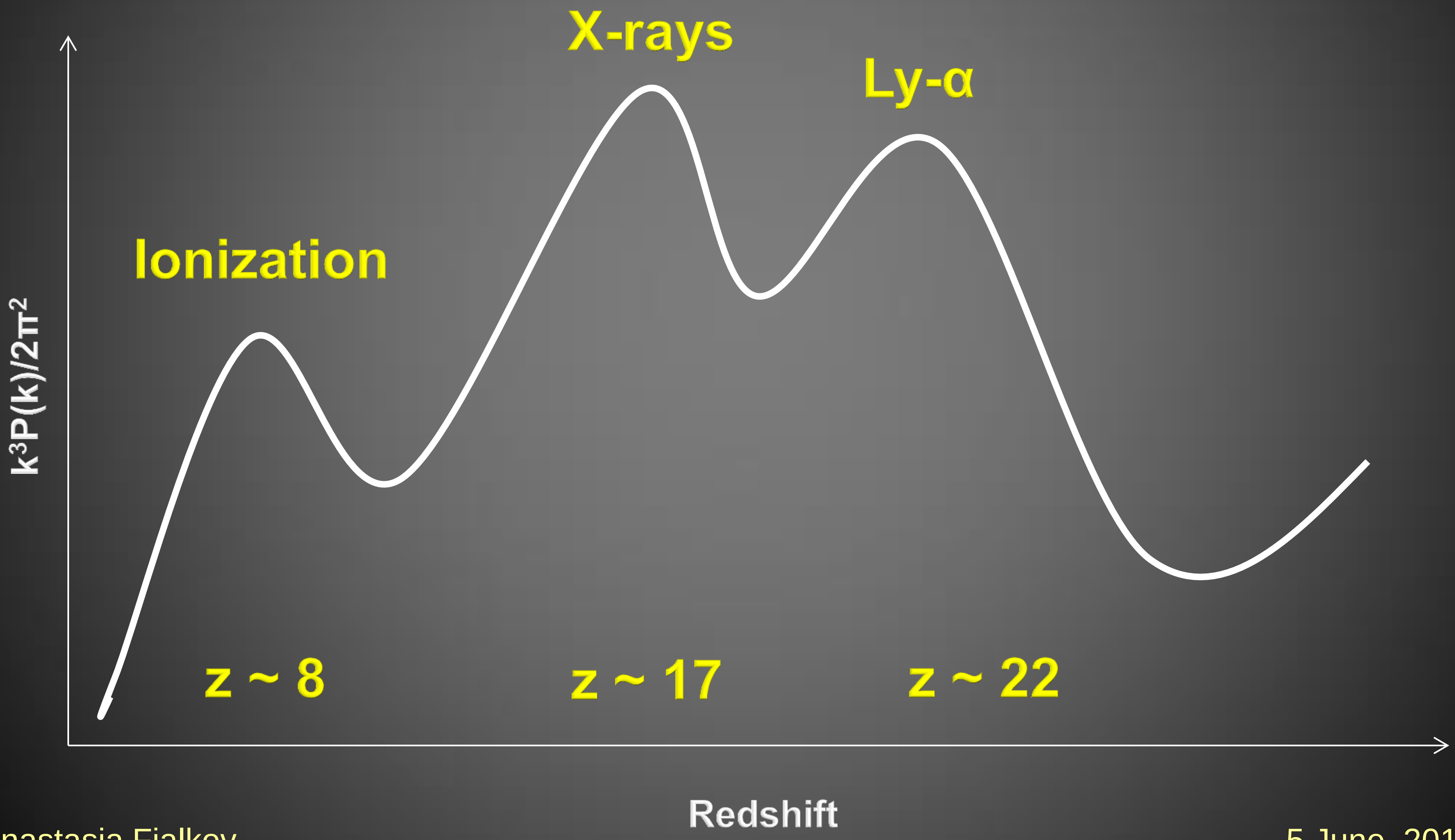
Hard X-rays

- Reionization and heating simultaneously
- Gas has more time to cool
- Maximal derivative is moved to higher frequencies. (Easier to observe!)



Effect on Fluctuations (vs Redshift)

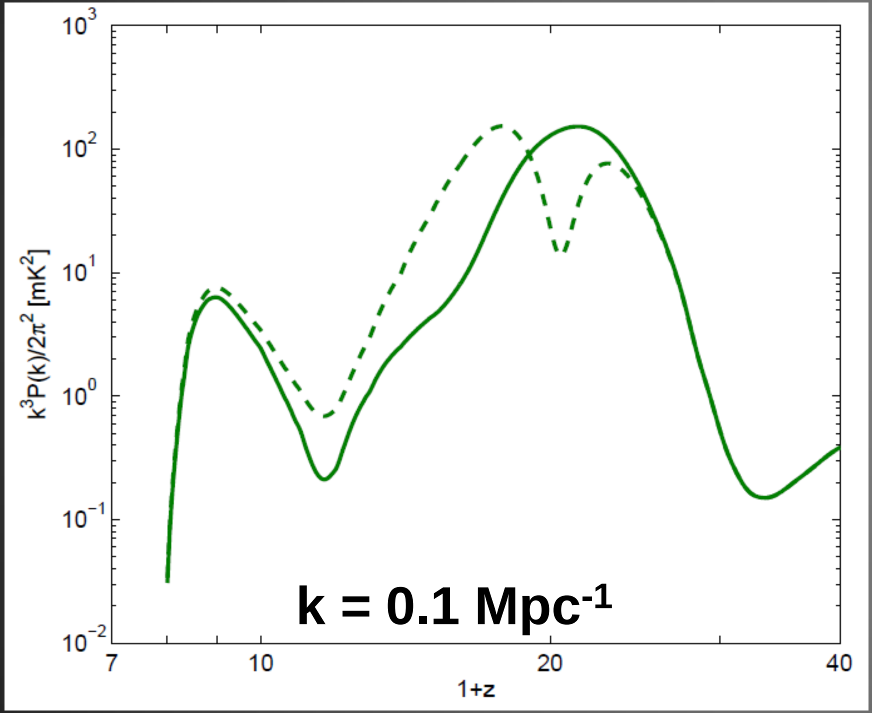
Generic expected dependence of power spectrum on redshift for a given k



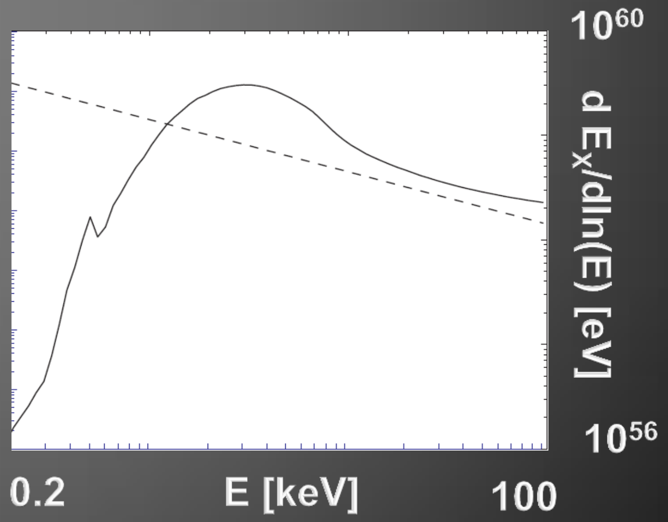
Effect on Fluctuations (vs Redshift)

Hard vs Soft X-rays

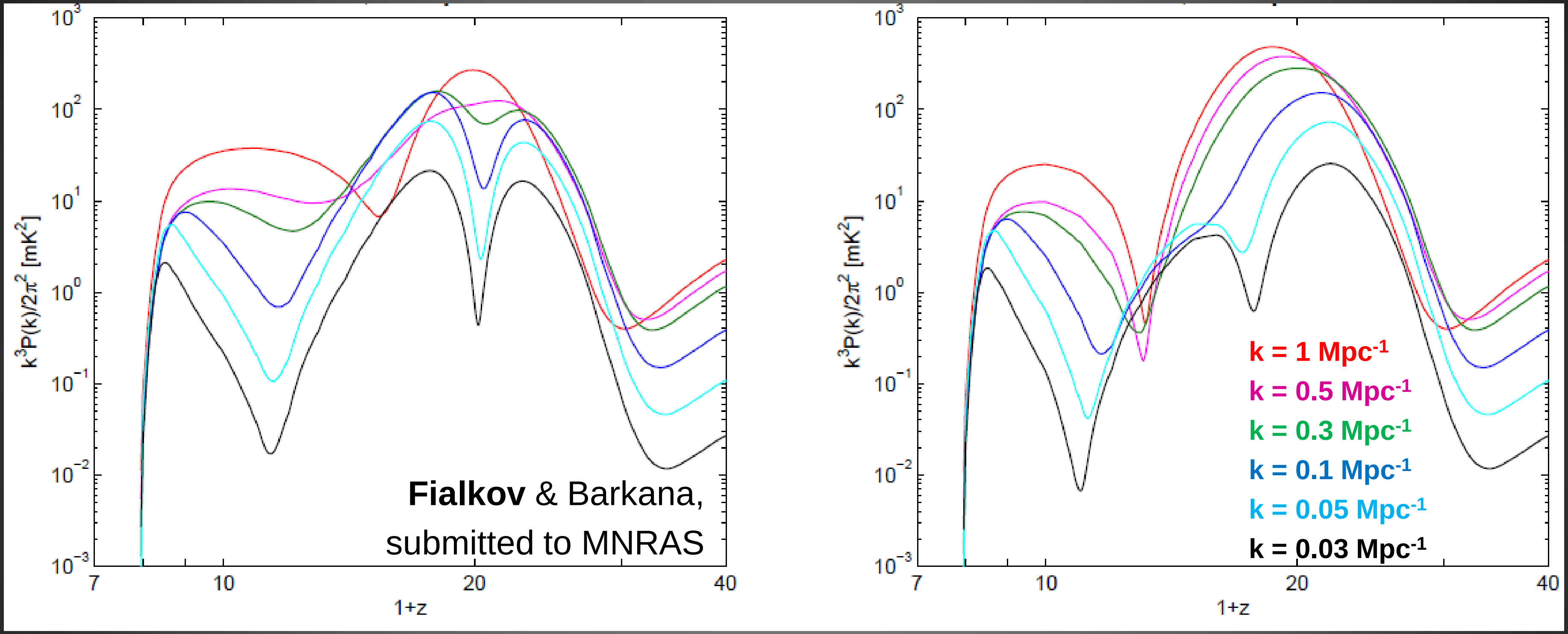
- A deeper minimum during early EoR
- No heating peak!
- Small impact on Lyα domain z > 20 and late EoR (x_i > 50%)



Fialkov & Barkana, submitted to MNRAS



Effect on Fluctuations (vs Redshift)



Soft X-rays

Hard X-rays

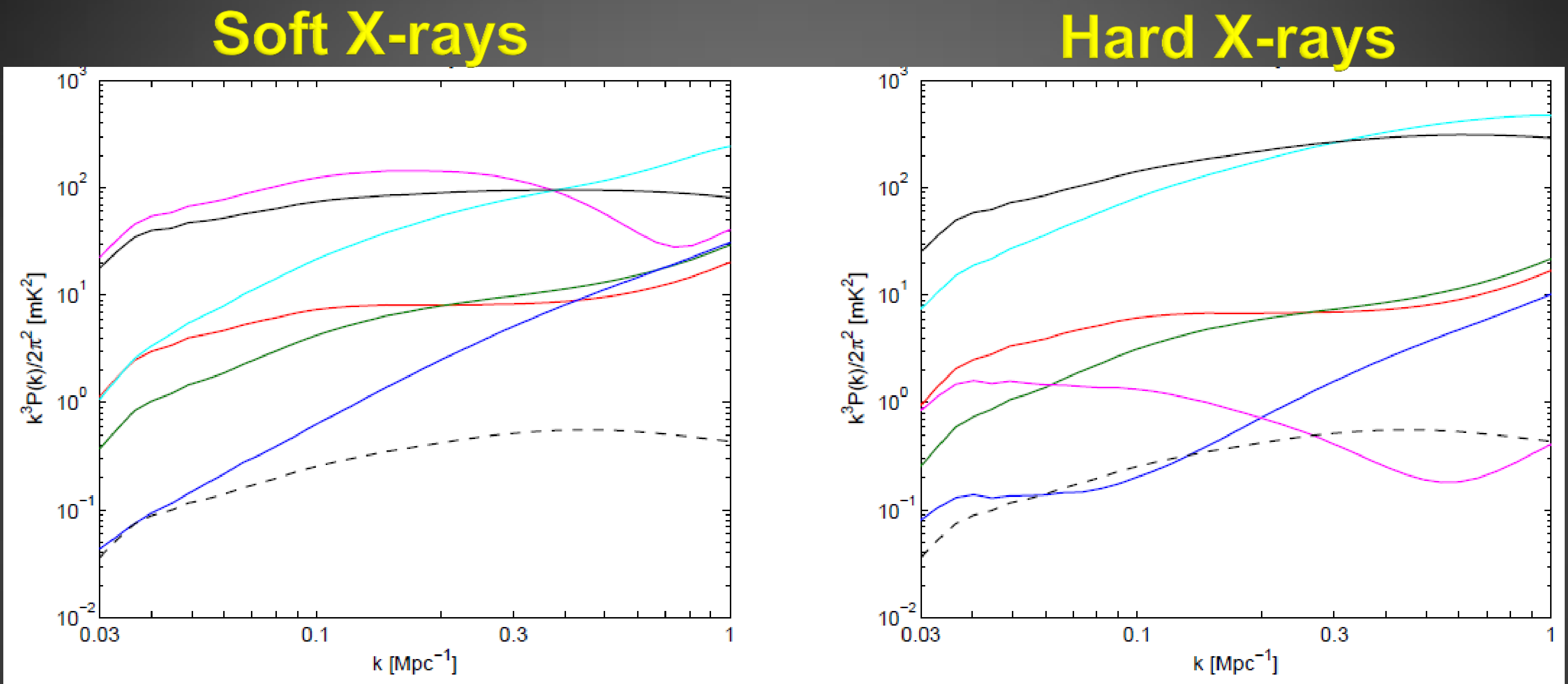
Fialkov & Barkana, submitted to MNRAS

- No heating fluctuations at k > 0.5 Mpc^{-1}

$$\lambda_X \approx 4.9\,\bar{x}_{HI}^{1/3}\left(\frac{1+z}{15}\right)^{-2}\left(\frac{E}{300\ \mathrm{eV}}\right)^{3}\ \mathrm{Mpc}$$

- No heating fluctuations at k > 0.05 Mpc^{-1}
- Almost uniform heating. No fluctuations on scales < MFP

Shape of the Power Spectrum


Soft X-rays

Hard X-rays

Fialkov & Barkana, submitted to MNRAS

- Most sensitive to SED during heating and beginning of Reionization (magenta and blue)
- Complex dependence on astrophysics
- Overall flat

Reionization peak (k = 0.1 Mpc^{-1})

Xi = 0.5 %

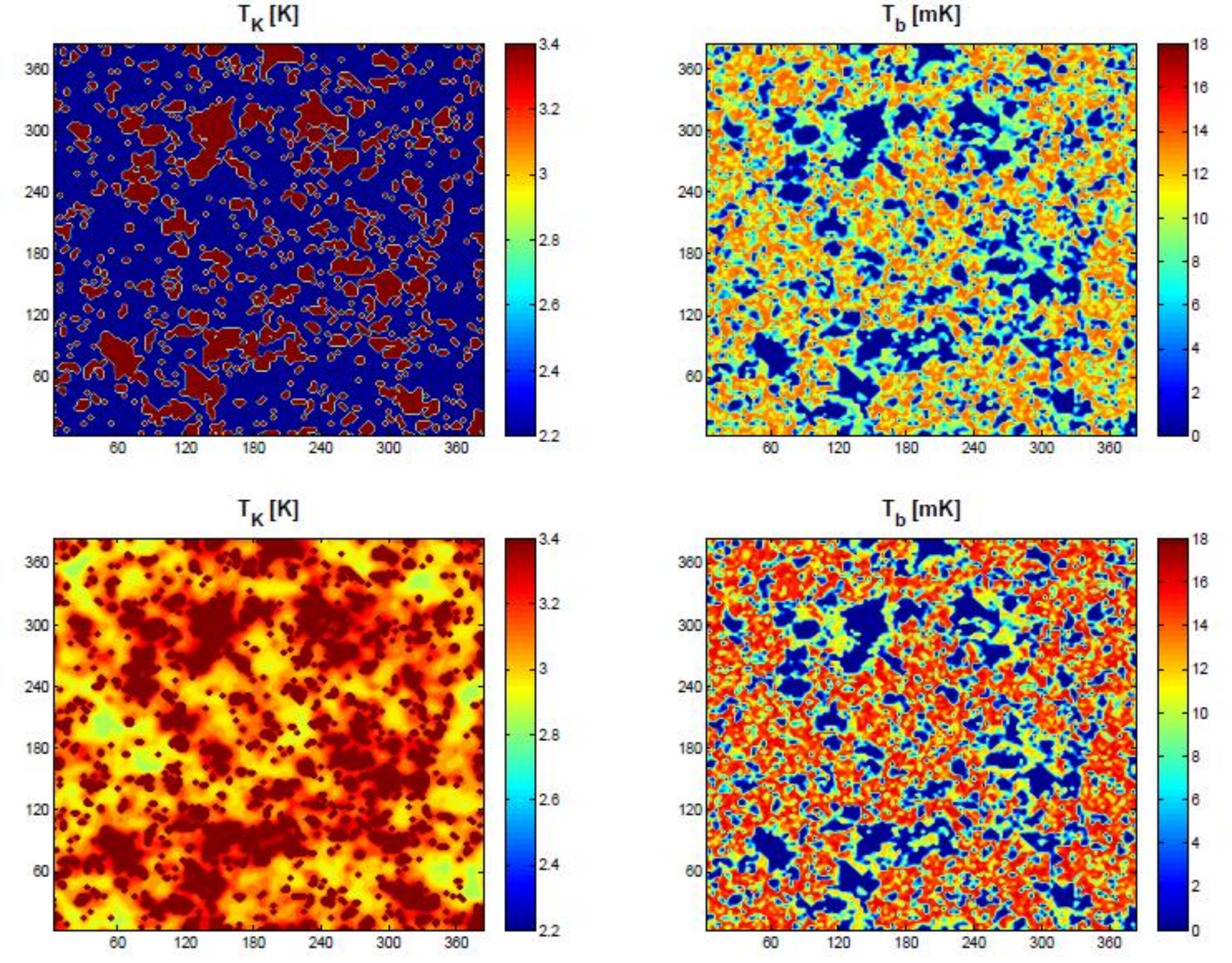
Xi = 25 %

Heating transition or peak

Minimum of global spectrum

Peak of Ly-a fluctuations

Images (z = 8.7, xi = 50%)

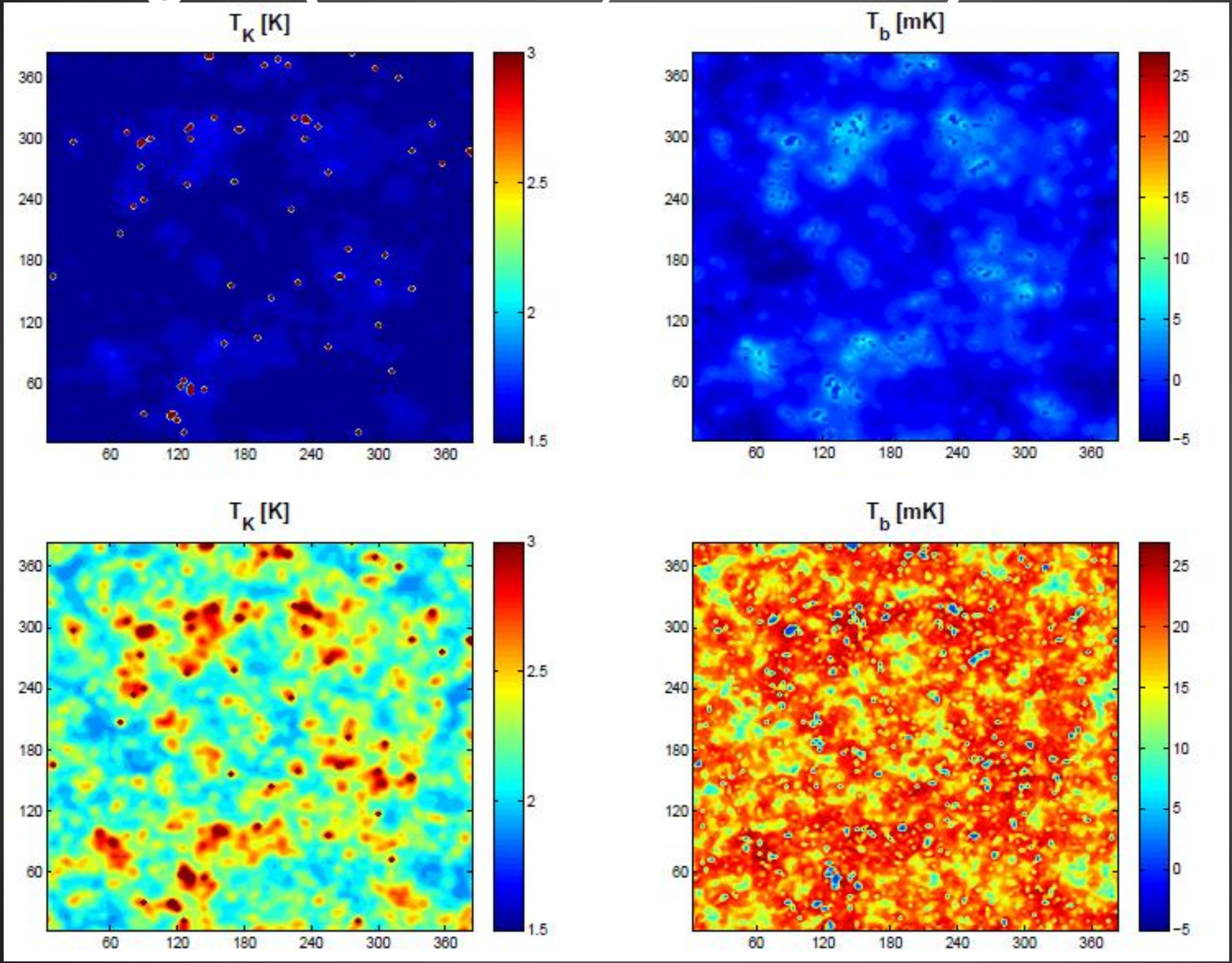


Hard X-rays

Soft X-rays

A. Fialkov & R.Barkana, submitted to MNRAS

Images (z = 12.1, xi = 14%)



Hard X-rays

Soft X-rays

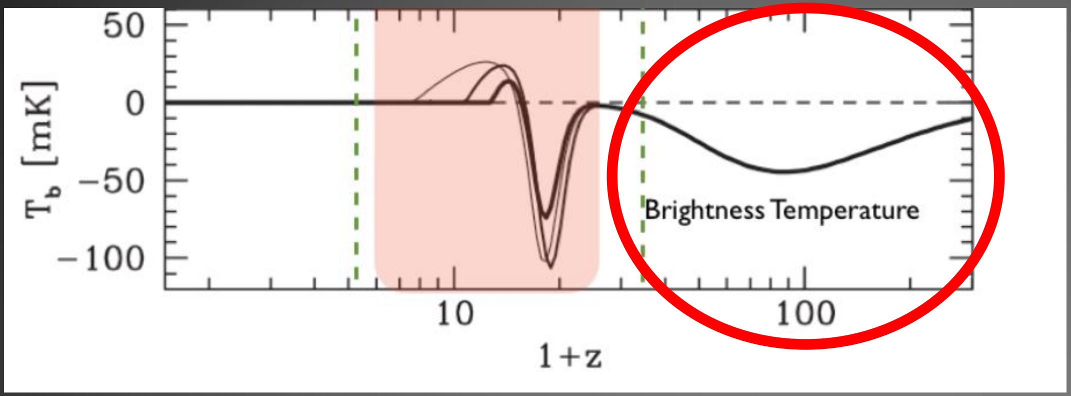
A. Fialkov & R.Barkana, submitted to MNRAS

NASA/ WMAP

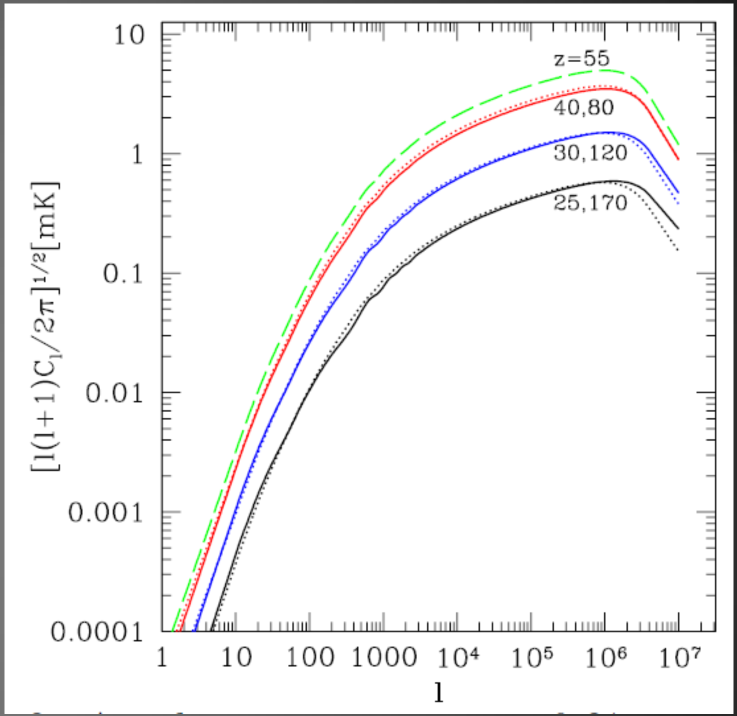
2. The dark ages

Linear regime
No stars

In LCDM the Dark Ages are Well-understood



Mellema et al (2013)



Loeb & Zaldarriaga (2004)
Lewis & Challinor (2007)

21-cm signal from dark ages is well defined by atomic physics

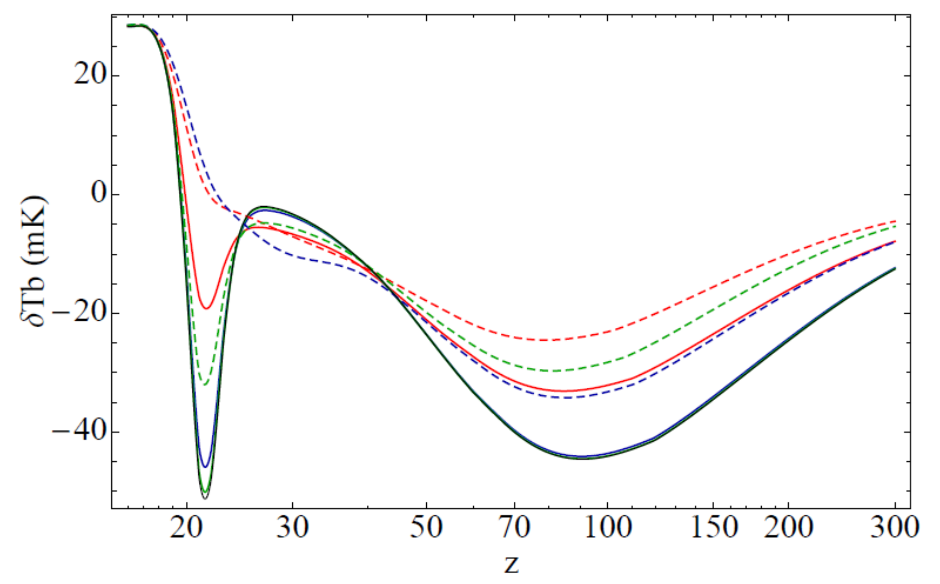
21-cm line: collision coupling of T_S to T_{gas}

The main source of fluctuations: linear fluctuations in density of HI

Good Time to Probe Cosmology and Exotic Physics!

What makes up over 95 % of the Universe?

21-cm signal offers a new window for indirect search for dark matter



Valdes et al (2013)

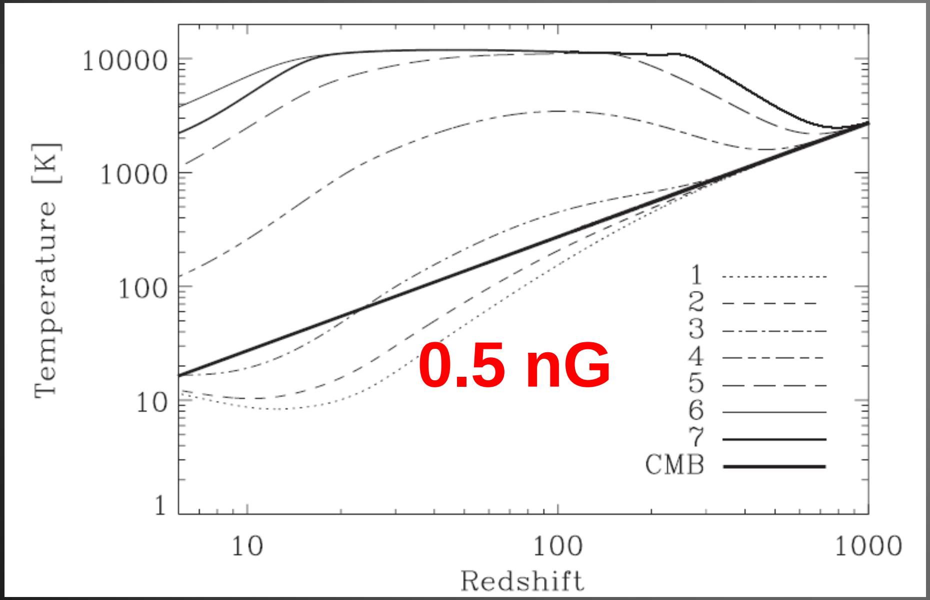
Imprint of dark matter annihilation in the global 21-cm signal

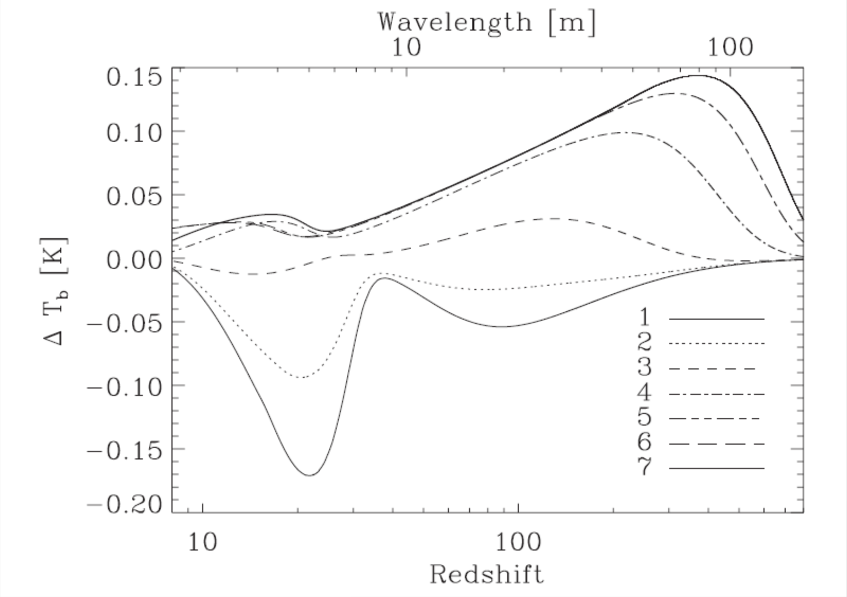
10 GeV, 200 GeV and 1 TeV particles

Good Time to Probe Cosmology and Exotic Physics!

Primordial magnetic fields can heat the gas early

- Ambipolar diffusion
- Decay of turbulences

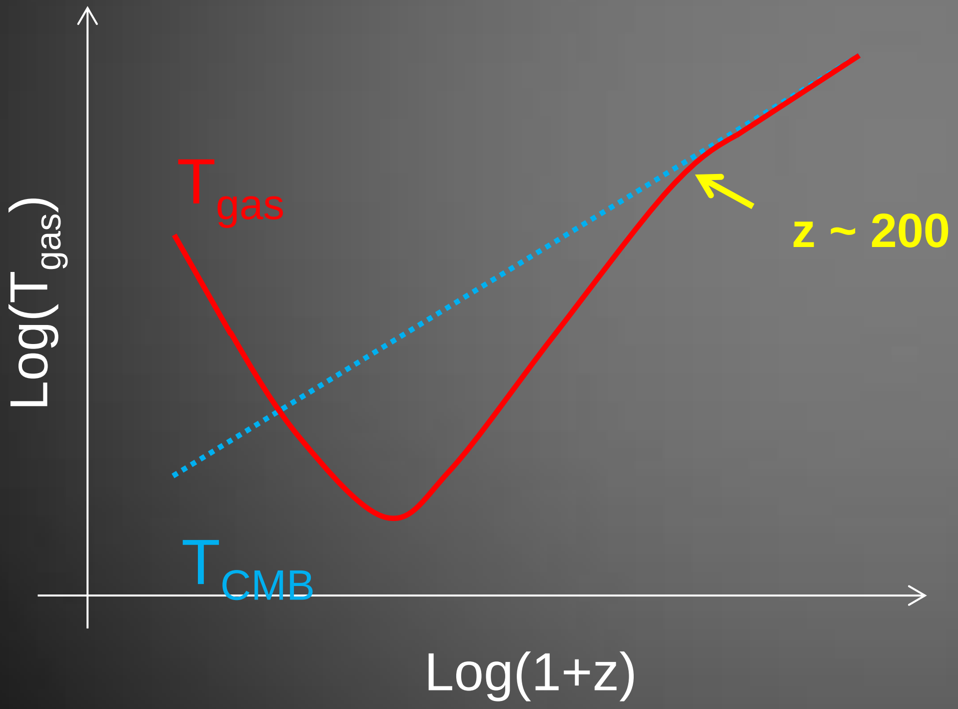


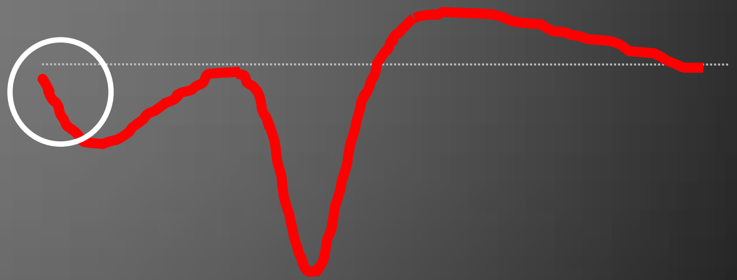


Schleicher, Banerjee, Klessen (2009)

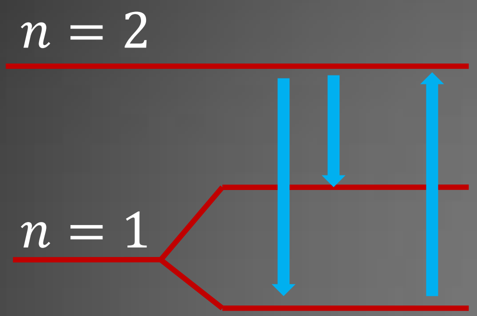
21-cm Signal from Redshifts > ~ 200

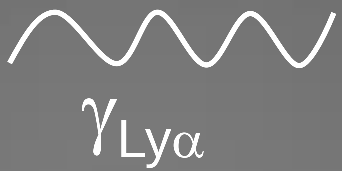
21-cm vanishes at redshifts > ~200.
Collisional coupling of 21-cm line to T_{gas}, $T_{gas} = T_{CMB}$.

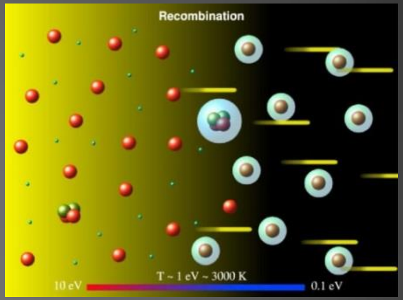




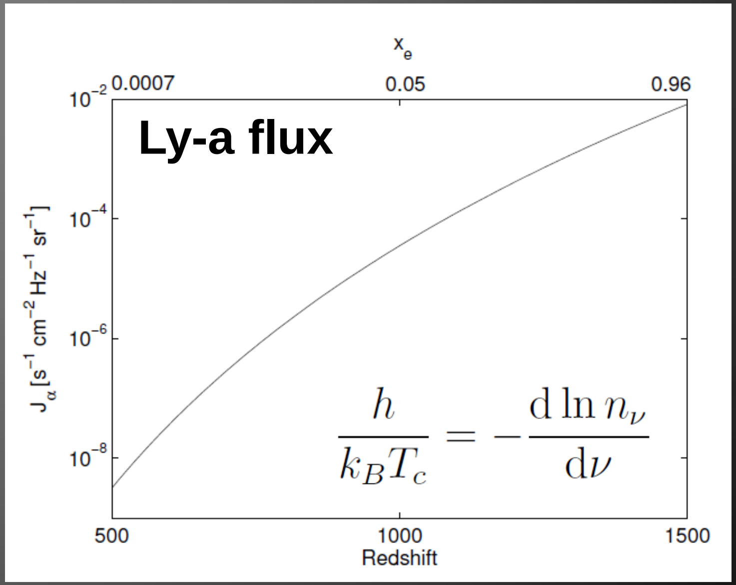
Relict Ly-a Background from Recombination







Hydrogen recombination create Ly-a background at z ~ 500-1000

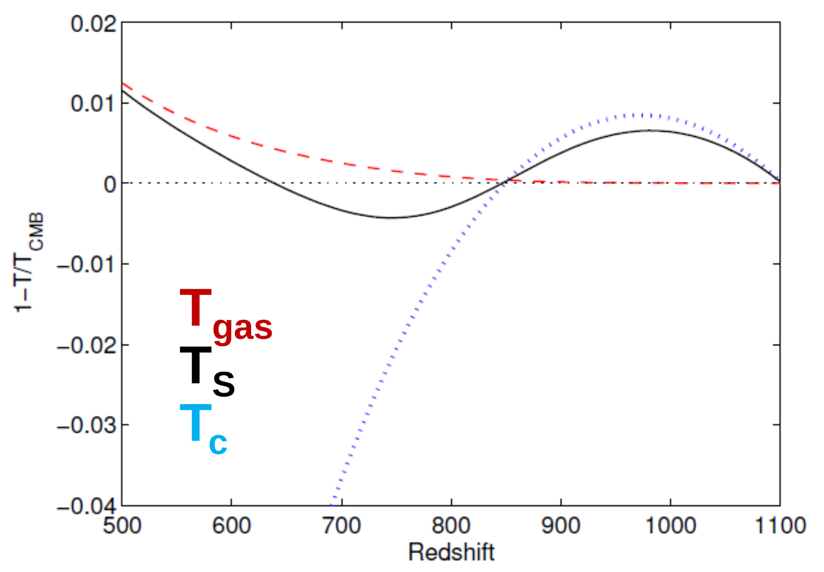


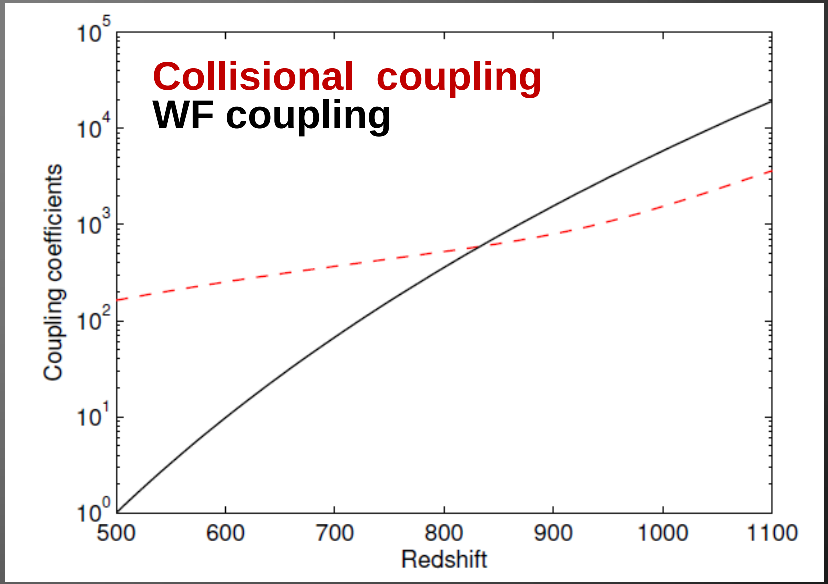
Fialkov & Loeb (2013),
Based on CosmoREC by J. Chluba et al.

New Expectations for Cosmological ~200 m Signal

$$\frac{1}{T_s} = \frac{T_{\mathrm{CMB}}^{-1} + x_C T_K^{-1} + x_\alpha T_C^{-1}}{1 + x_C + x_\alpha}$$

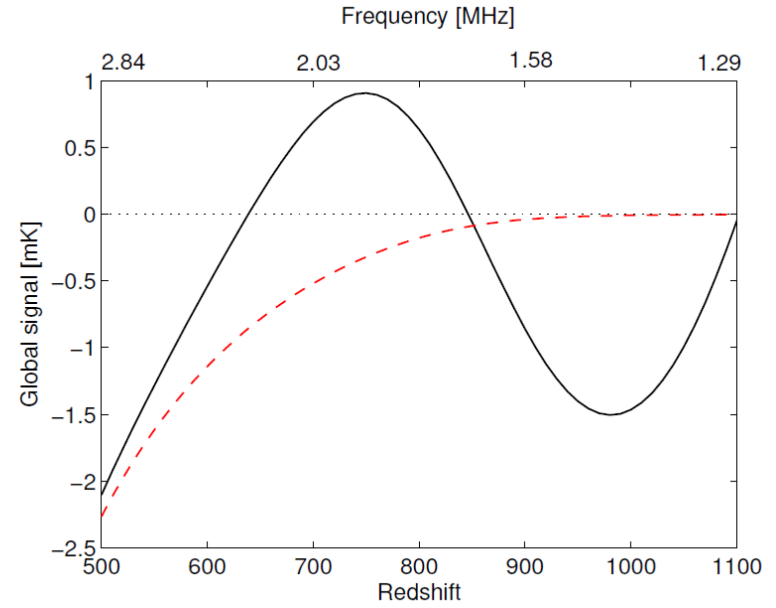
At z > 800 WF coupling wins and $T_S \neq T_{gas}$

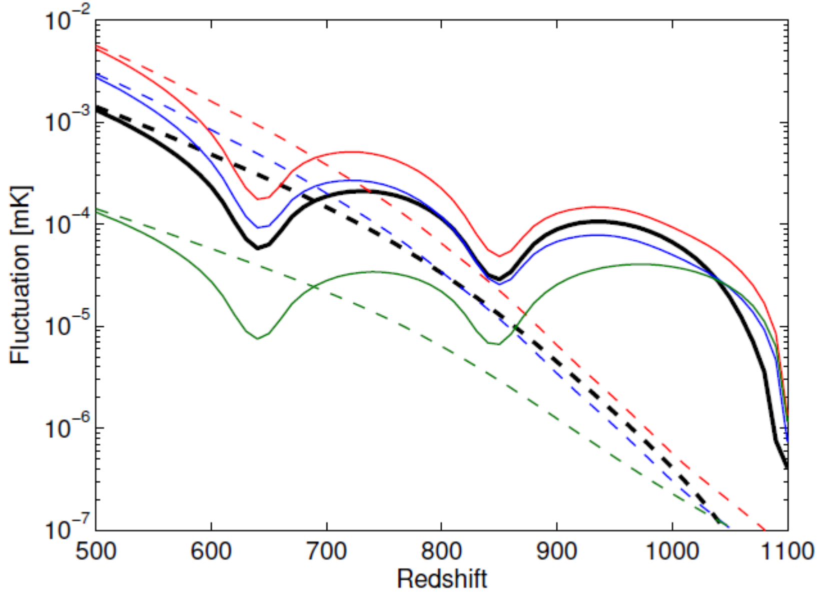




New Expectations for Cosmological ~200 m Signal

Fialkov & Loeb (2013)





- With Ly-a the cosmological signal from z > 800 is several orders of magnitudes larger than expected.
- If detected, unique way to probe the early Universe
- Extremely hard to detect!

New Window for Observations
Radio Astronomy on the Moon!

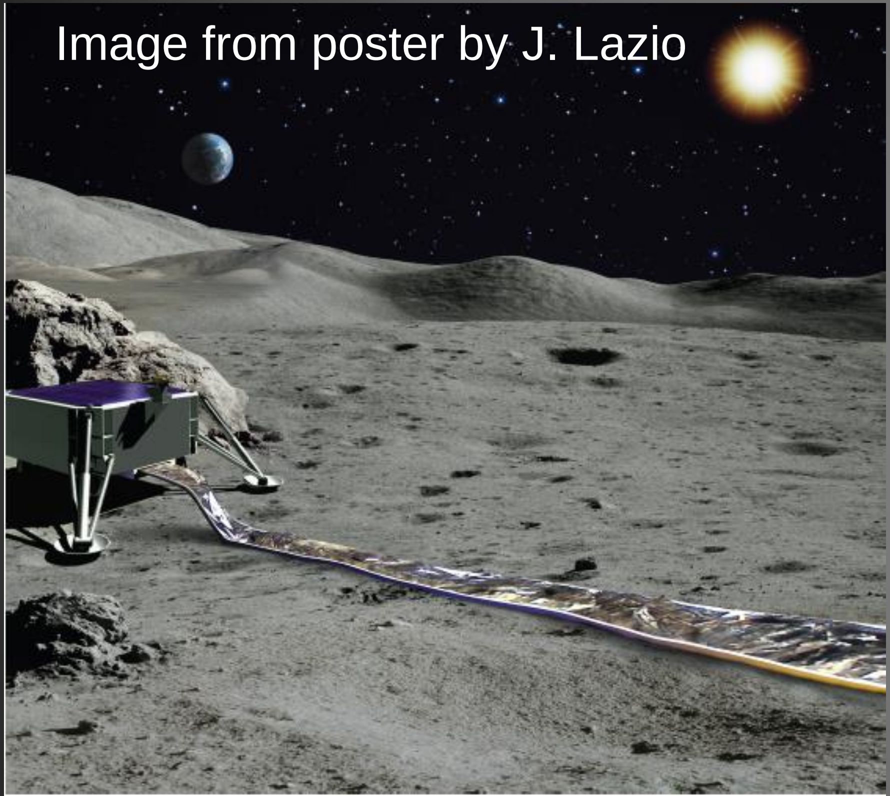


Image from poster by J. Lazio

http://lunar.colorado.edu/lowfreq/

Lunar Radio Array