21-cm signal from cosmic dawn

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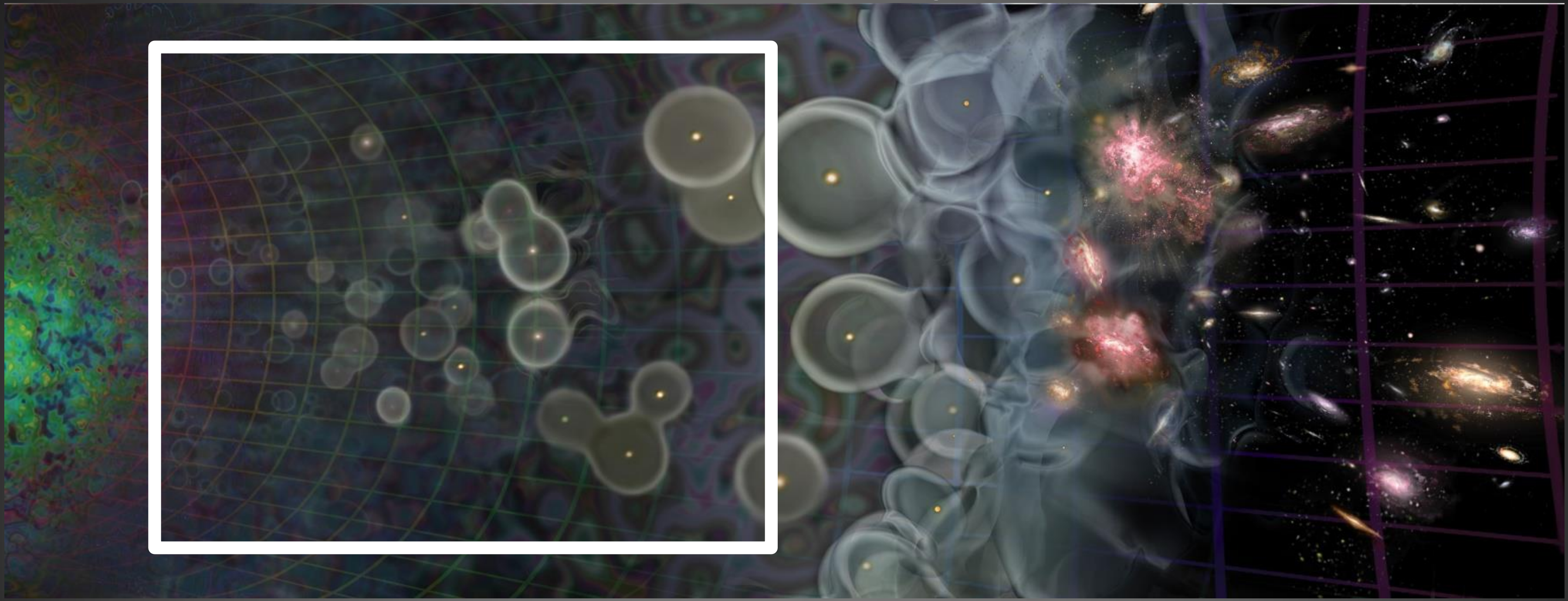
Looking back to first light:

Image: Loeb, Scientific American 2006

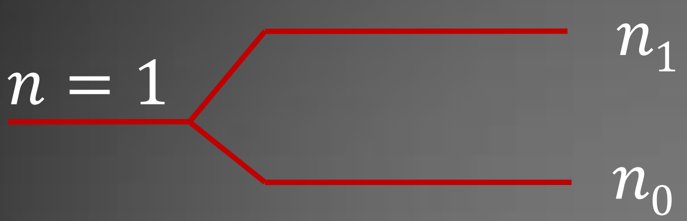


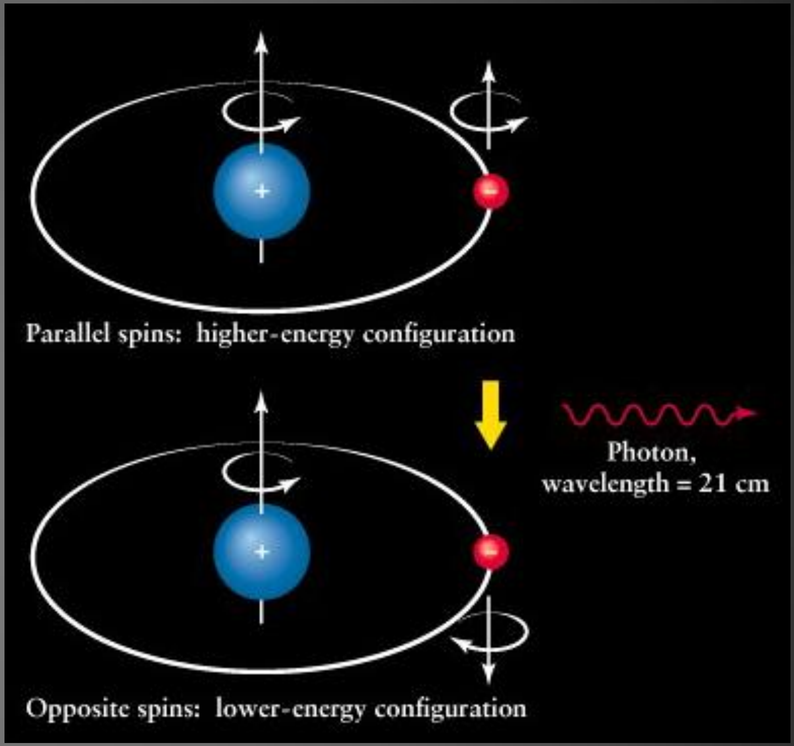
Cosmic dawn, the first stars

The dark ages

Recombination

The history can be probed with 21-cm line:





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

$T_* = 0.068$ K

Spin temperature is a complicated function of gas temperature, Lyα intensity, collision rates etc.

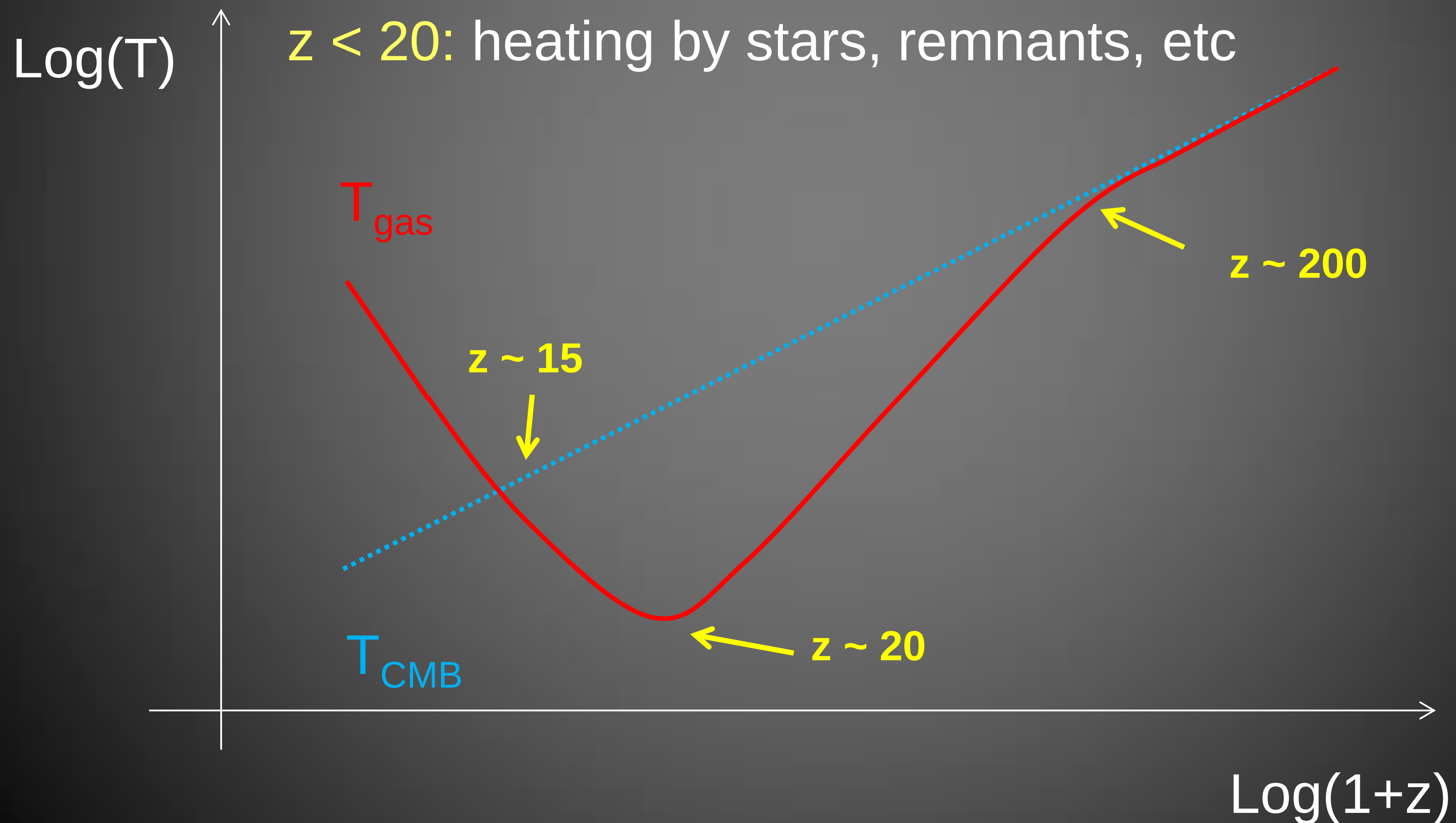
$$T_S^{-1} = \frac{T_{\rm CMB}^{-1} + x_\alpha T_c^{-1} + x_c T_K^{-1}}{1 + x_\alpha + x_c}$$

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 by stars, remnants, etc



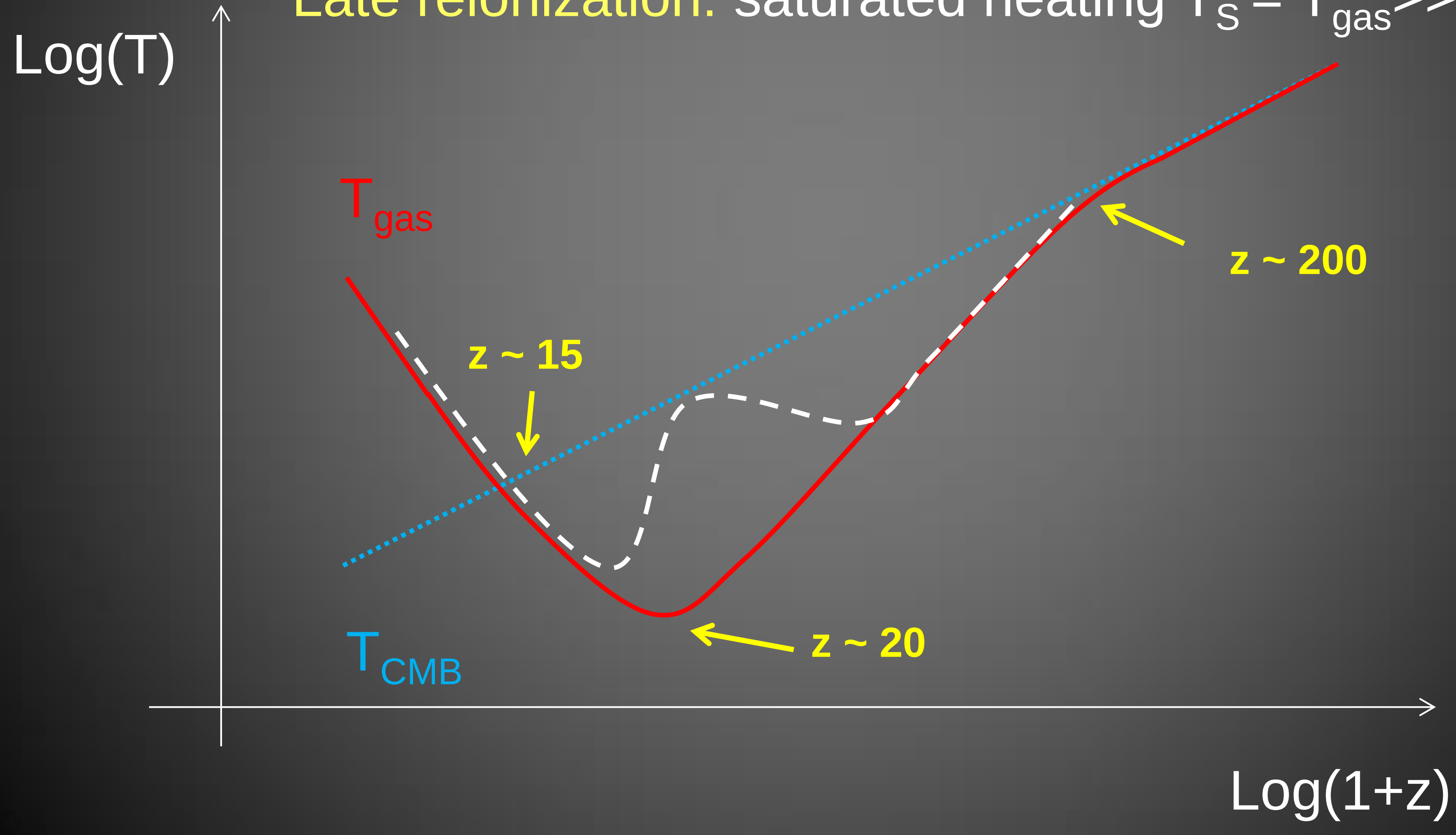
Spin temperature:

$$T_S^{-1} = \frac{T_{\rm CMB}^{-1} + x_\alpha T_c^{-1} + x_c T_K^{-1}}{1 + x_\alpha + x_c}$$

Dark ages: collisional coupling $T_S = T_{gas}$

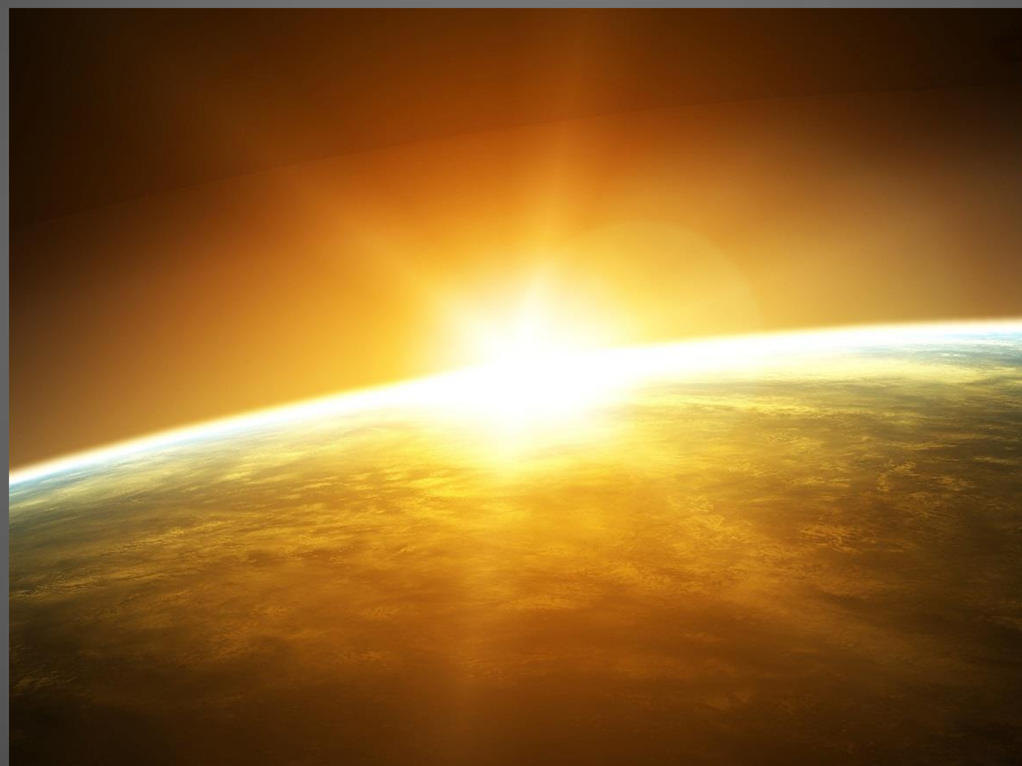
Cosmic dawn: $T_S = f(T_{gas}, J_\alpha, J_{LW}, \delta, \ldots)$

Late reionization: saturated heating $T_S = T_{gas} >> T_{CMB}$



1. Cosmic Dawn

Rare first stars start to heat and ionize the cosmic gas

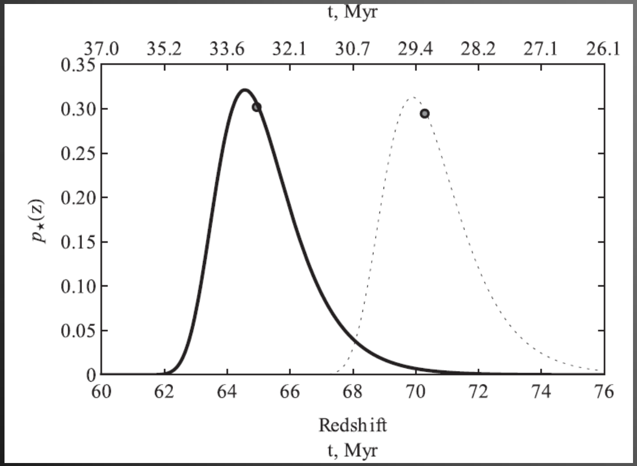


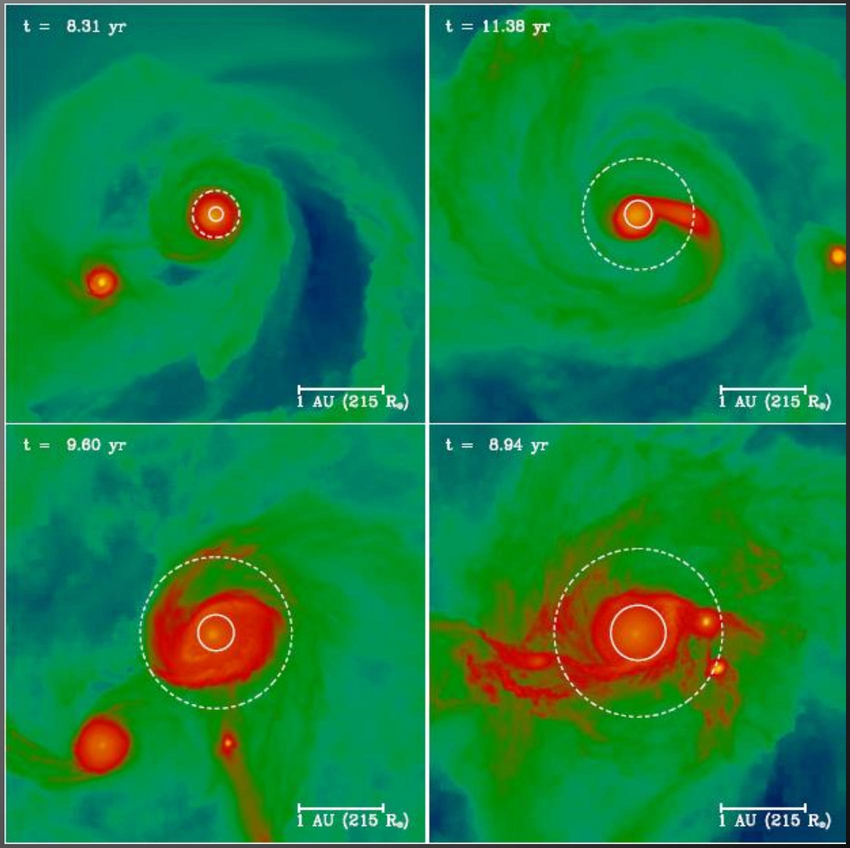
First sources of light:

Form in metal free environment
Atomic cooling in ~10^7 M_{sun} halos
Molecular cooling ~10^5 M_{sun} halos
(Tegmark et al 1997)

Formation of ~ 30 M_{sun} PopIII star under radiative feedback (Stacy et al 2013)

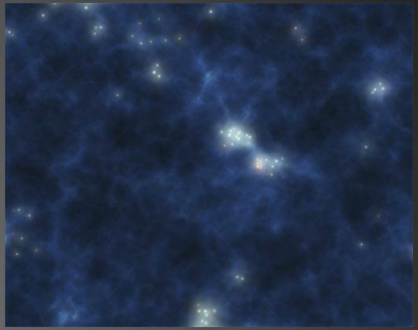
At z ~ 65
(Fialkov et al 2012)





Predicting 21-cm signal from cosmic dawn is difficult

Image: NASA



First sources are rare, effect on large scales

Interplay between:

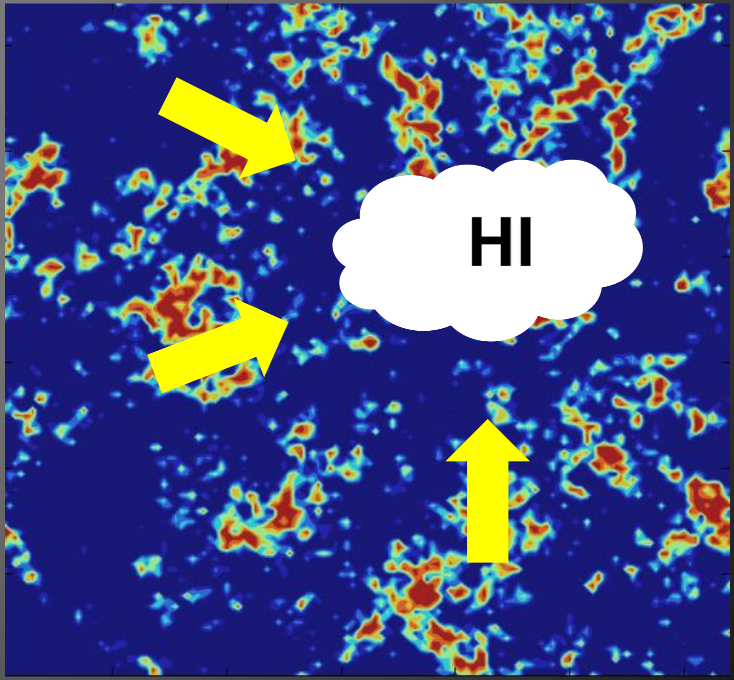
Heating

Ionization

Feedbacks

Effect of initial conditions

Exotic physics.



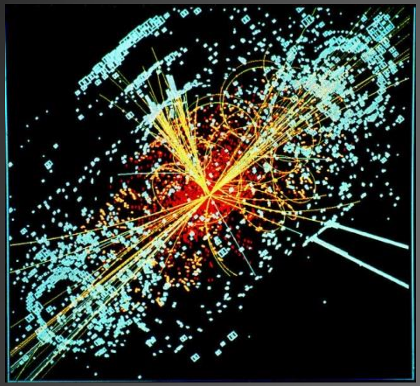
Nonlocal effects of radiation.

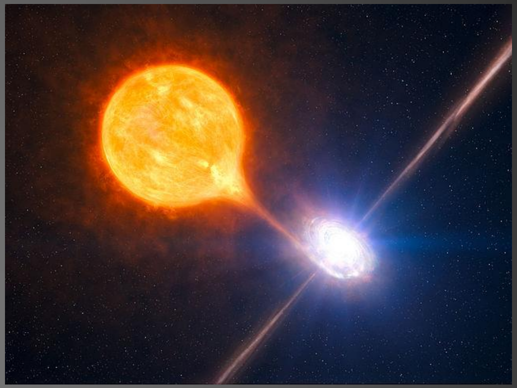
References: works by Mesinger et al (2012, 2013), Christian and Loeb (2013), Visbal et al (2012), Fialkov et al (2014, 2013) and others

Image: Visbal et al 2012

Heating of cosmic gas

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





LHC
Dark matter annihilation

A quasar

A black hole binary
(ESO image)

X-ray binaries (talk by F. Mirabel)

Thermal emission from galaxies

Quasars, mini quasars

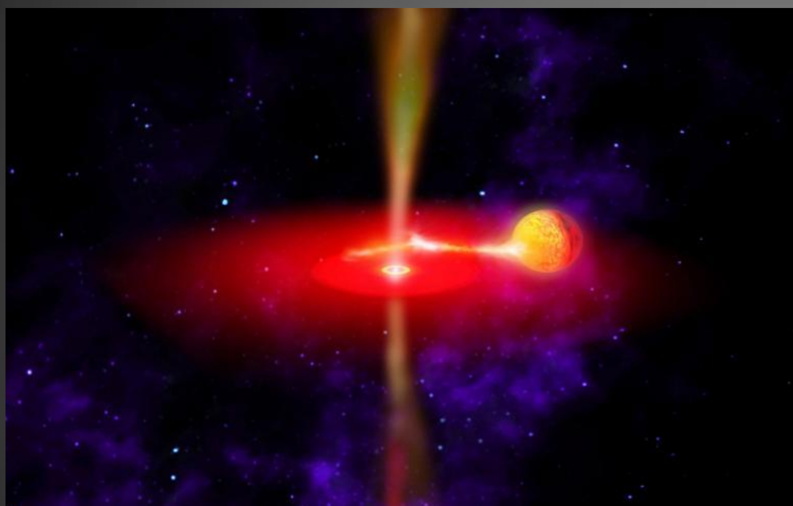
Dark matter annihilation

etc

Realistic high-z heating

Energy Feedback from X-Ray Binaries in the Early Universe

T. Fragos[1,2], B. D. Lehmer[3,4], S. Naoz[2,7], A. Zezas[1,5,6], and A. Basu-Zych[4]



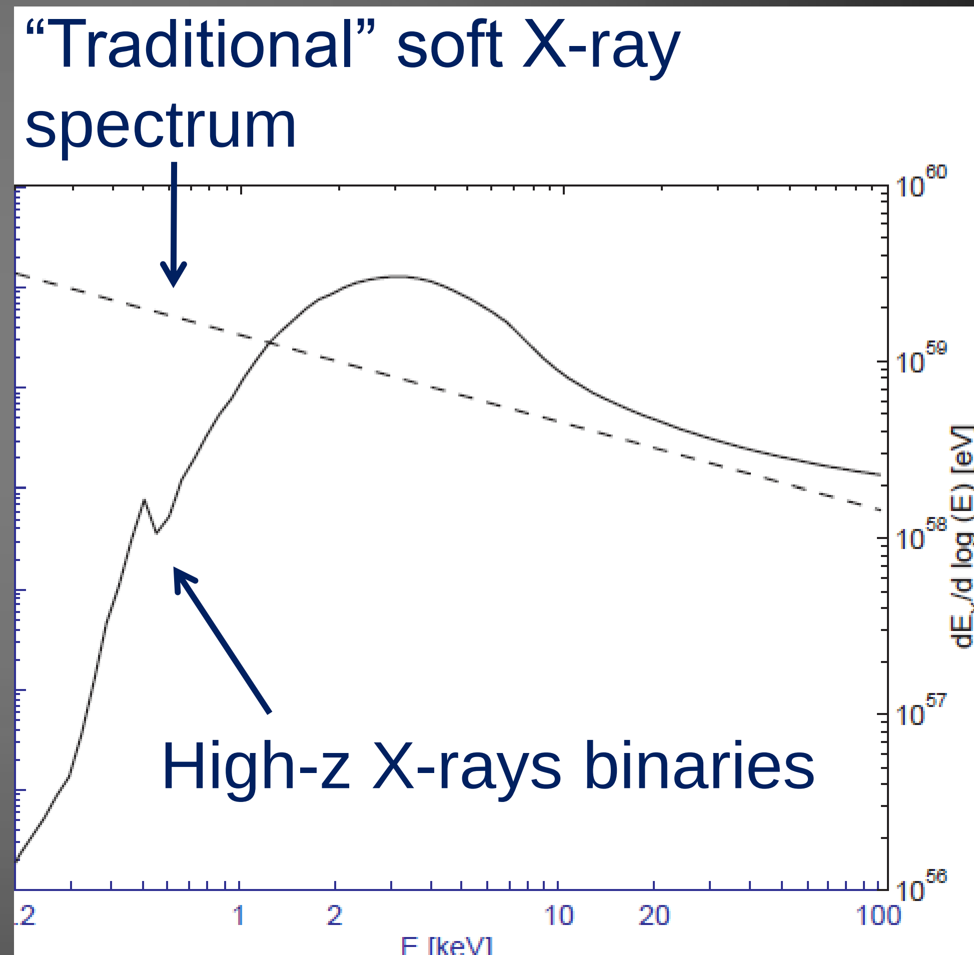
X-ray binary

LETTER

doi:10.1038/

The observable signature of late heating of the Universe during cosmic reionization

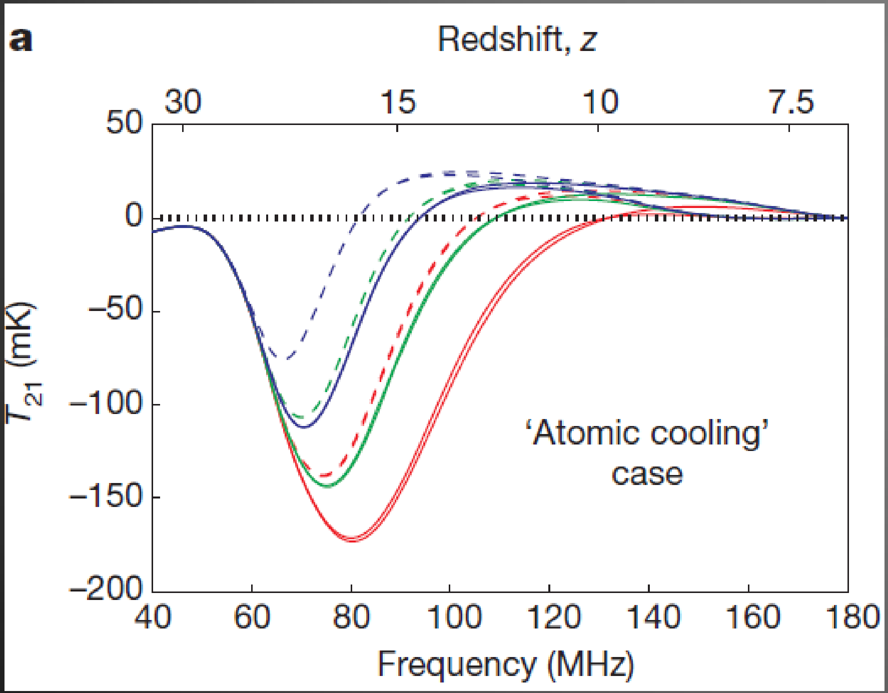
Anastasia Fialkov[1,2], Rennan Barkana[1] & Eli Visbal[3,4,5]

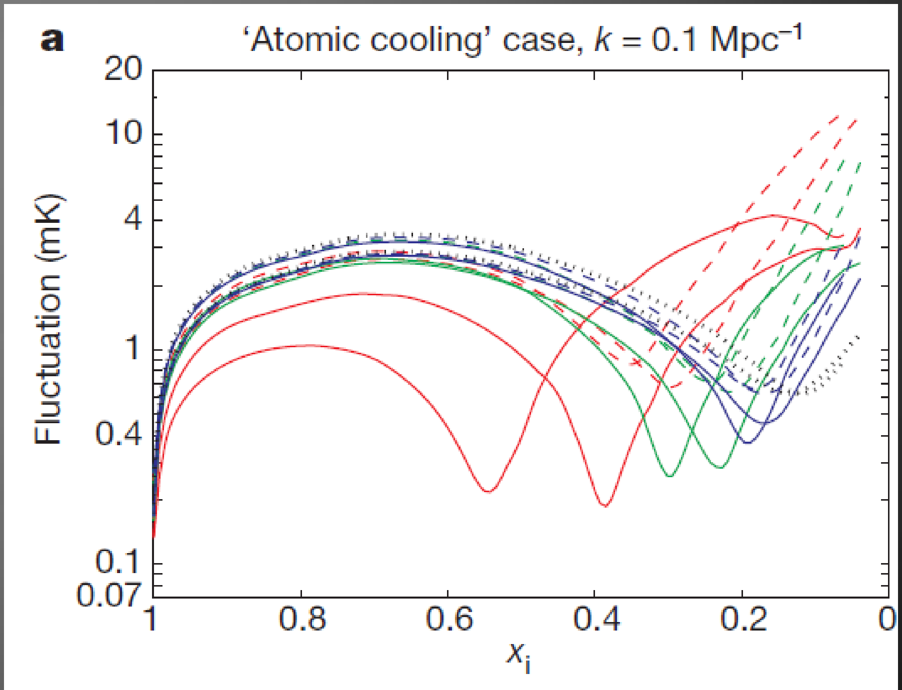


Fragos et al (2013), **Fialkov** et al (2014)

Effect of realistic heating on 21-cm: More complex signal from early EoR

Hard X-rays heat the gas slower than previously thought





Fialkov et al (2014)

Effect of realistic heating on 21-cm: More complex signal from early EoR

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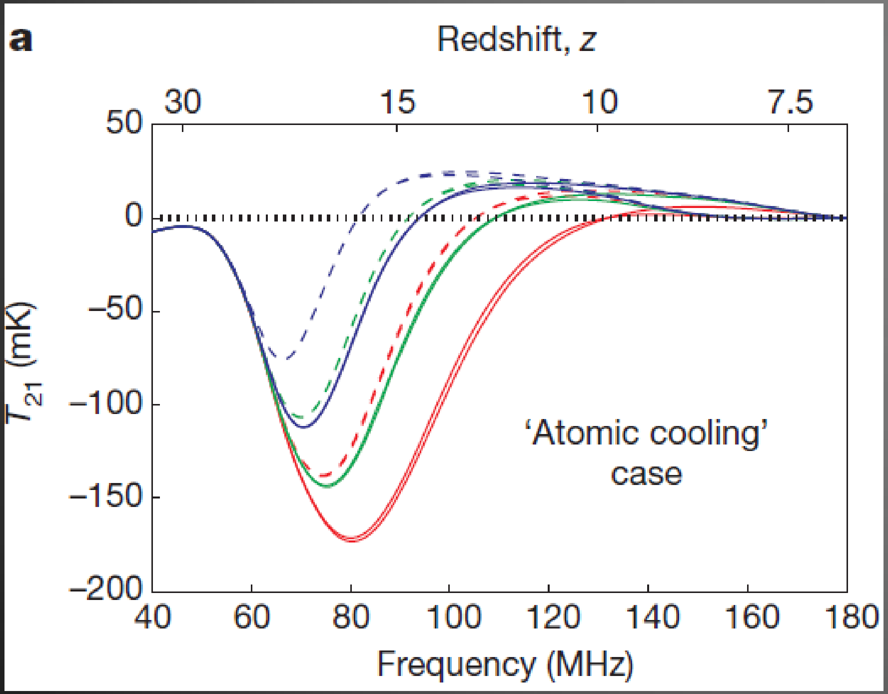
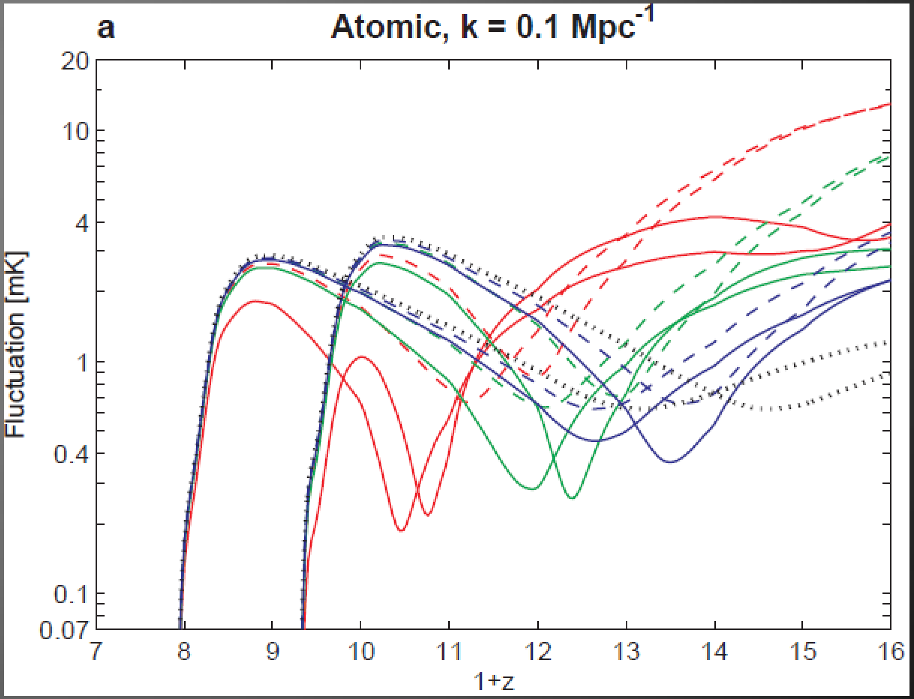


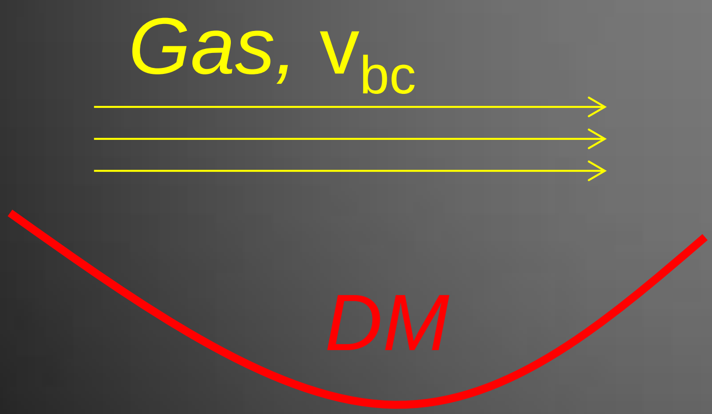


Fialkov et al (2014)

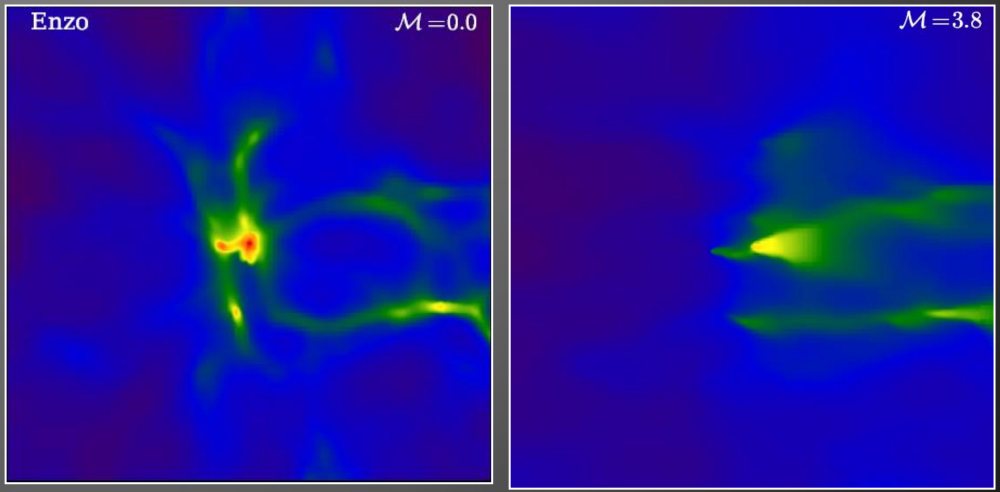
Another example:
Initial condition for structure formation

Relative motion between gas and dark mater

After recombination gas and dark matter halos move at supersonic relative speed (Tseliakhovich and Hirata 2010)



Gas overshoots DM halos



O'Leary & McQuinn (2012)

Main impact on high z and small scales $10^4 - 10^7\ M_{sun}$

- Suppresses halo abundance

Tselikhovich & Hirata 2010; Naoz, Yoshida, Gnedin 2012…

- Suppresses amount of gas in halos

Dalal, Pen & Seljak 2010; Tselikhovich, Barkana &Hirata 2011; Naoz, Yoshida, Gnedin 2012…

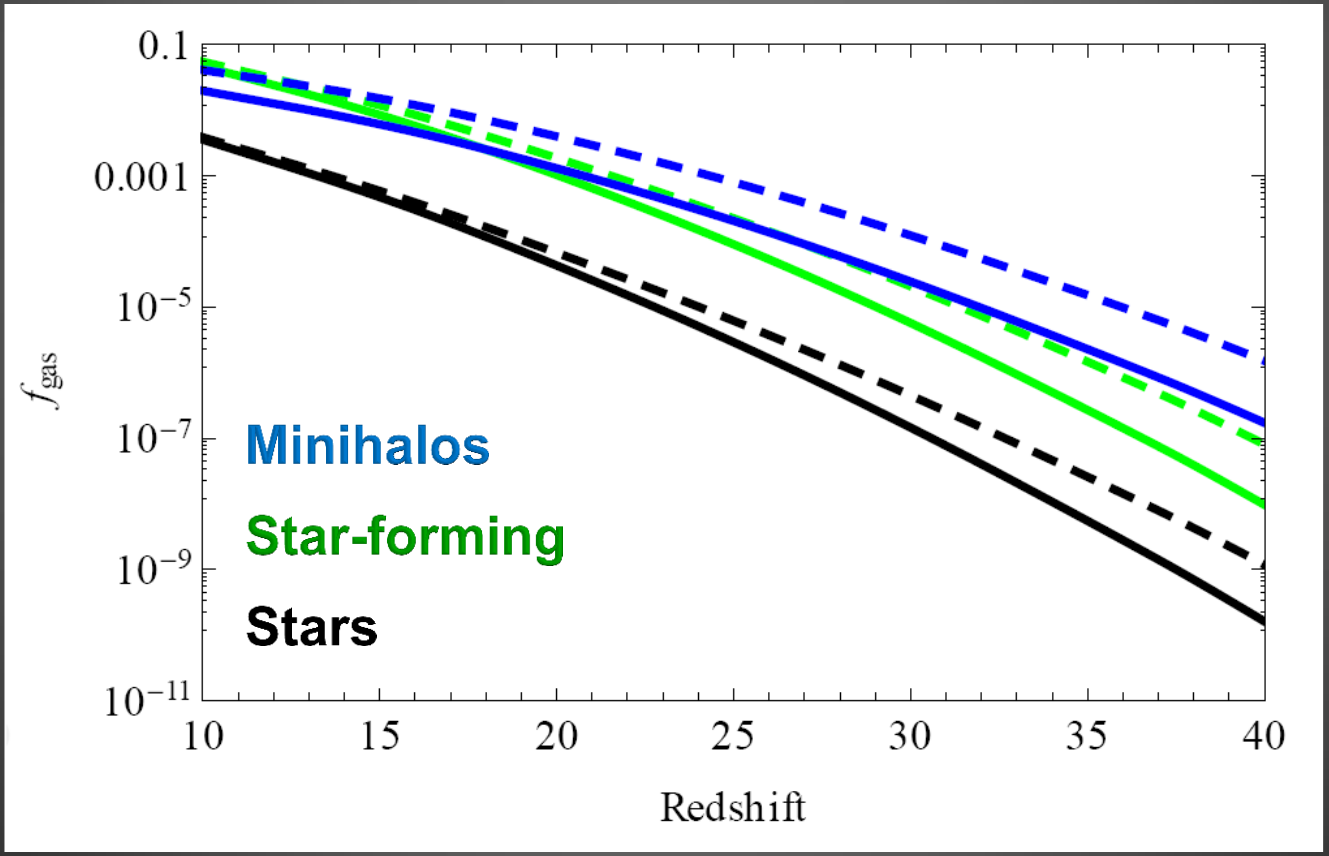
- Harder to form stars (boosts minimal cooling mass)

Fialkov et al 2012, (relying on the simulations: Maio, Koopmans & Ciardi 2011; Stacy, Bromm & Loeb 2011; Greif, White, Klessen & Springel 2011; Naoz, Yoshida & Gnedin 2011; O'Leary & McQuinn 2012; Bromm 2013) …

In total:
Nonhomogeneous delay in star formation

The effect of motion on gas in halos

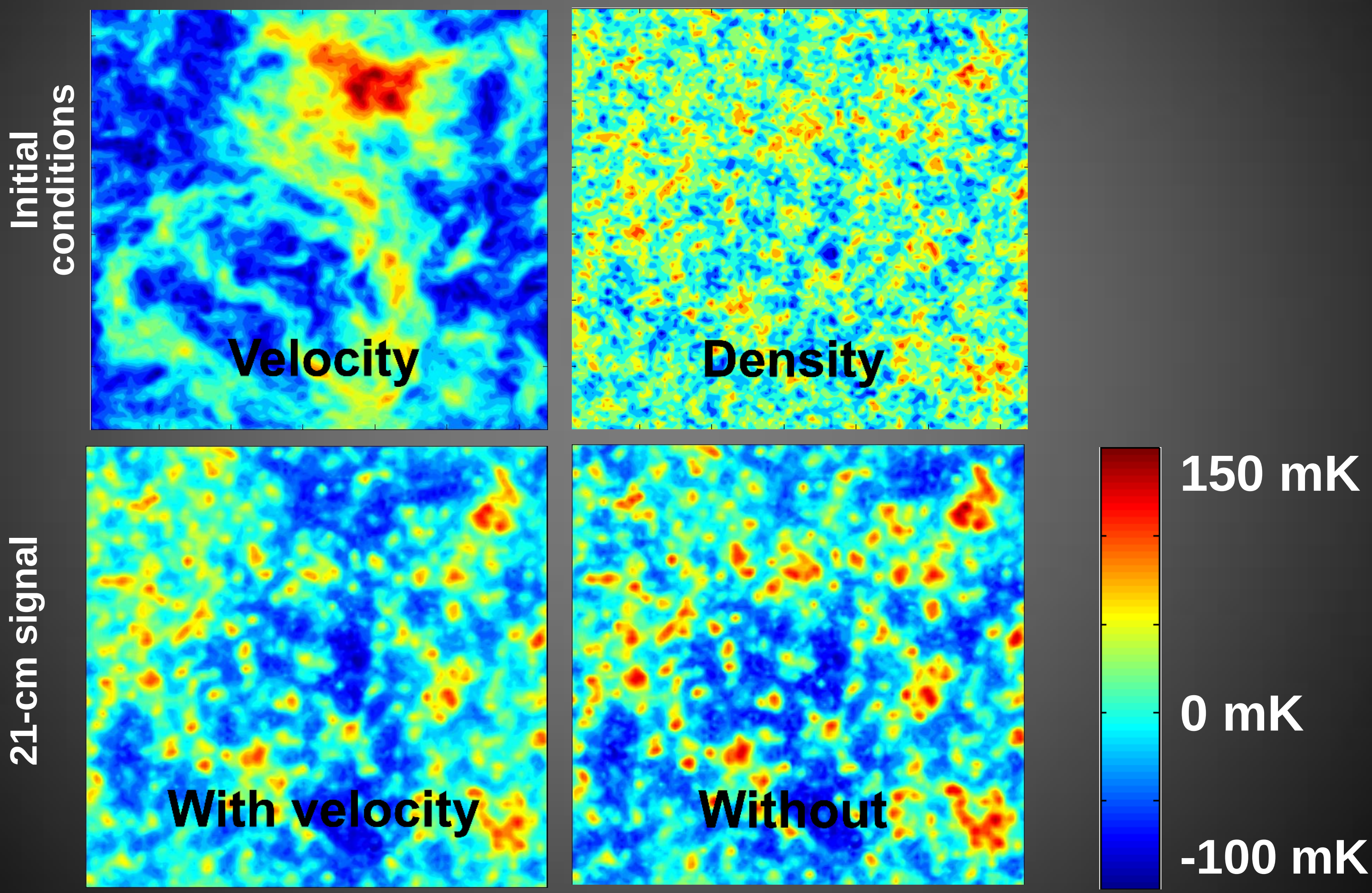
Average f_{gas} in star-forming halos is lower by ~ 2 at z = 20



Tseliakhovich, Barkana & Hirata (2010)
AF, Barkana, Tseliakhovich & Hirata (2012)

Effect of the motion on 21-cm signal

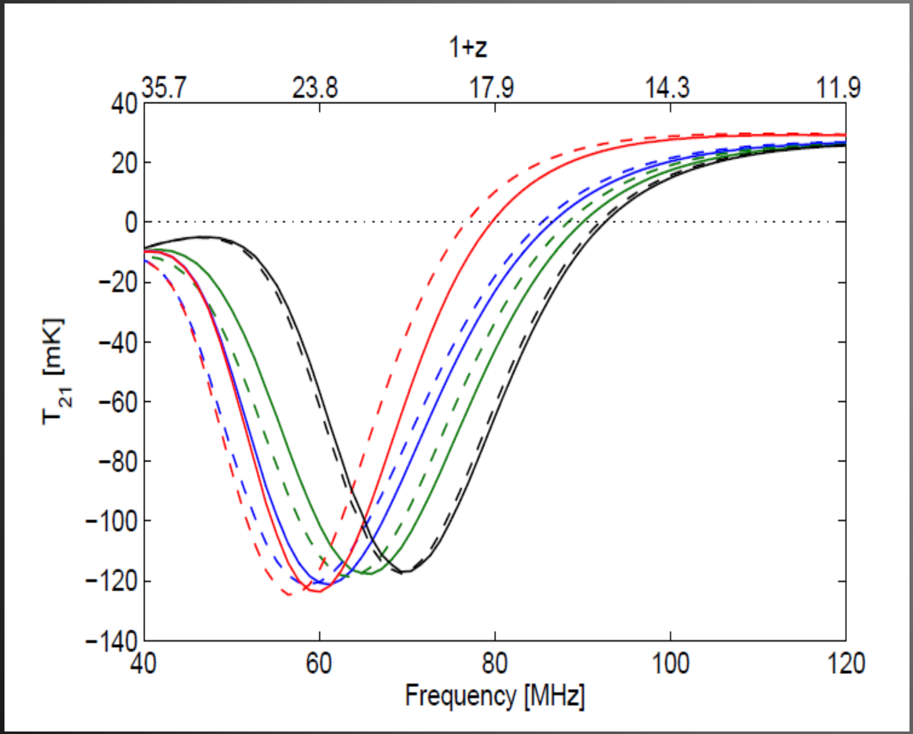
Visbal et al (2012), **Fialkov** et al (2013)

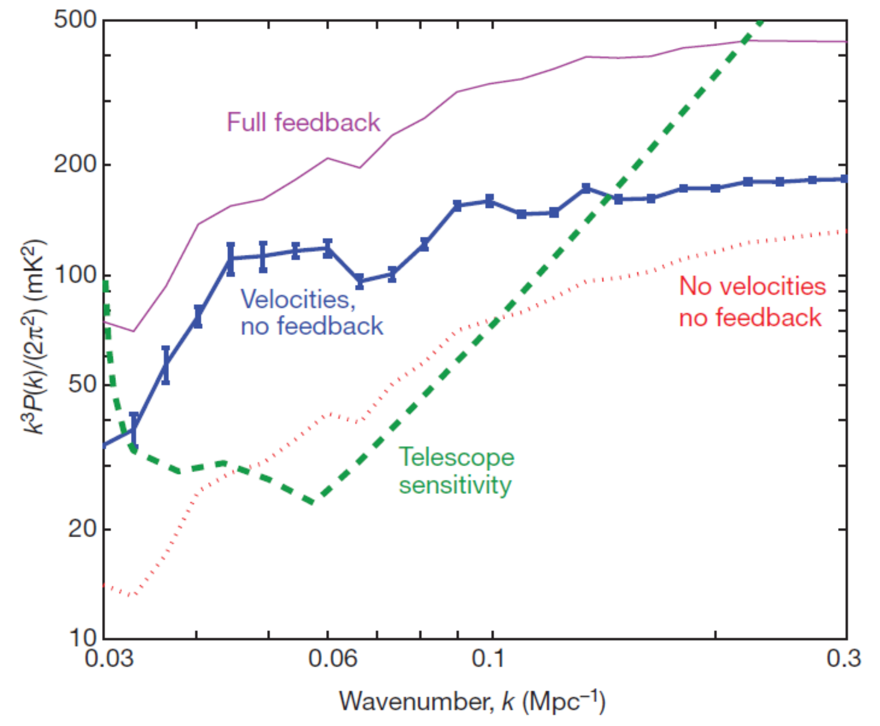


Effect of the motion on 21-cm signal

Probe of LW feedback

How heavy were the first star forming halos?





Fialkov et al (2013)

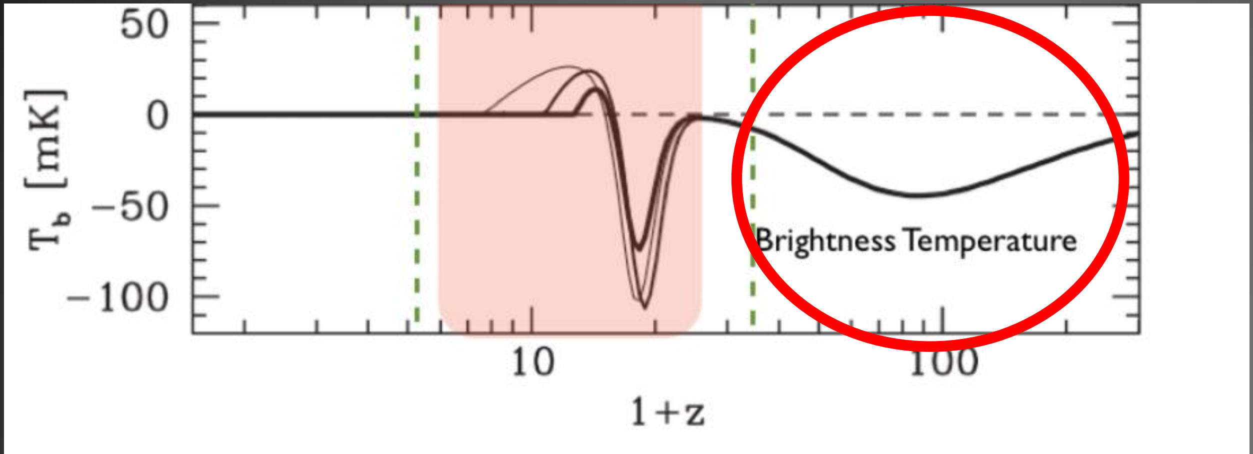
Visbal et al (2013)

NASA/ WMAP

2. The dark ages

Linear regime
No stars

In LCDM the dark ages are well-understood

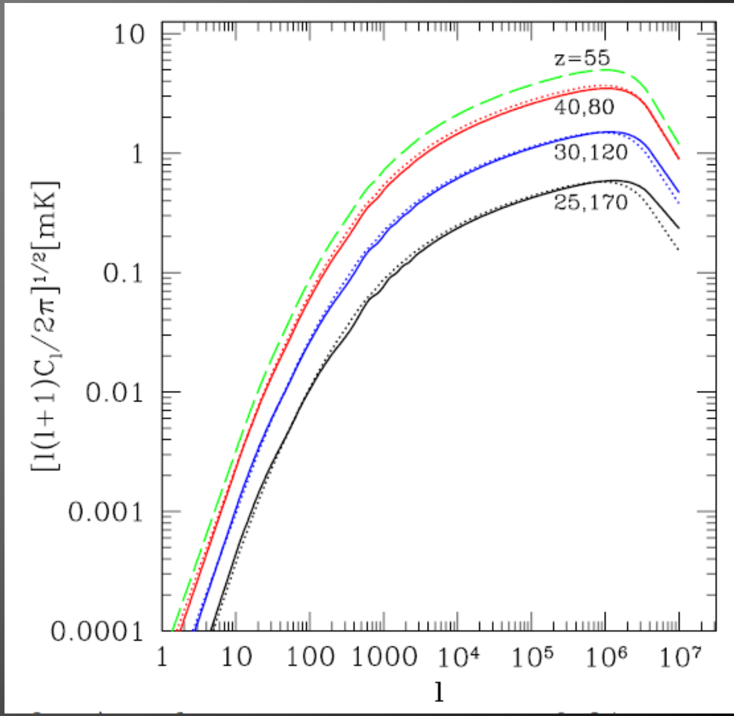


Mellema et al (2013)

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

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

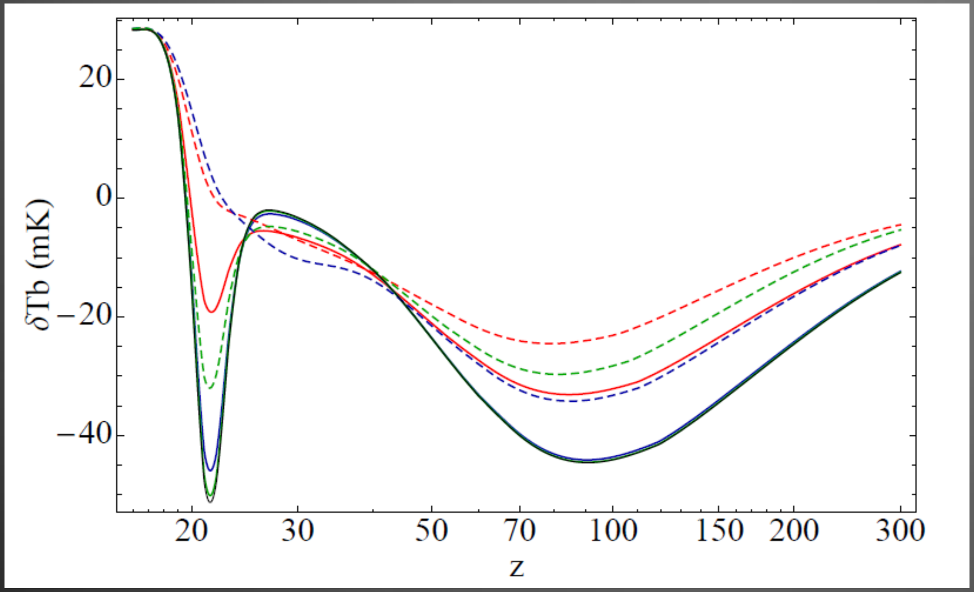
The main source of fluctuations: density of neutral hydrogen



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



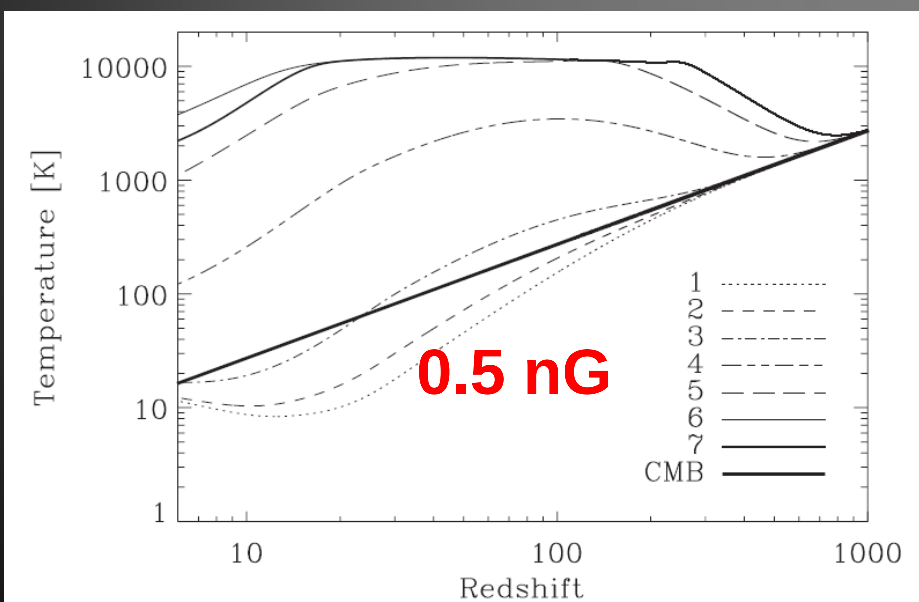
Valdes et al (2013)

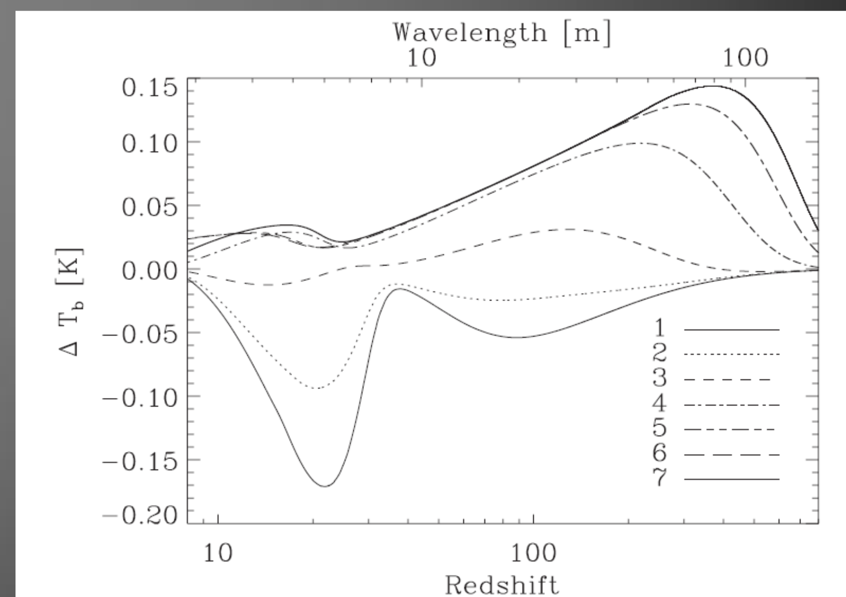
Imprint of dark matter annihilation in the global 21-cm signal

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)

Future Prospects: Radio Astronomy on the Moon

Also talk by B. Cecconi

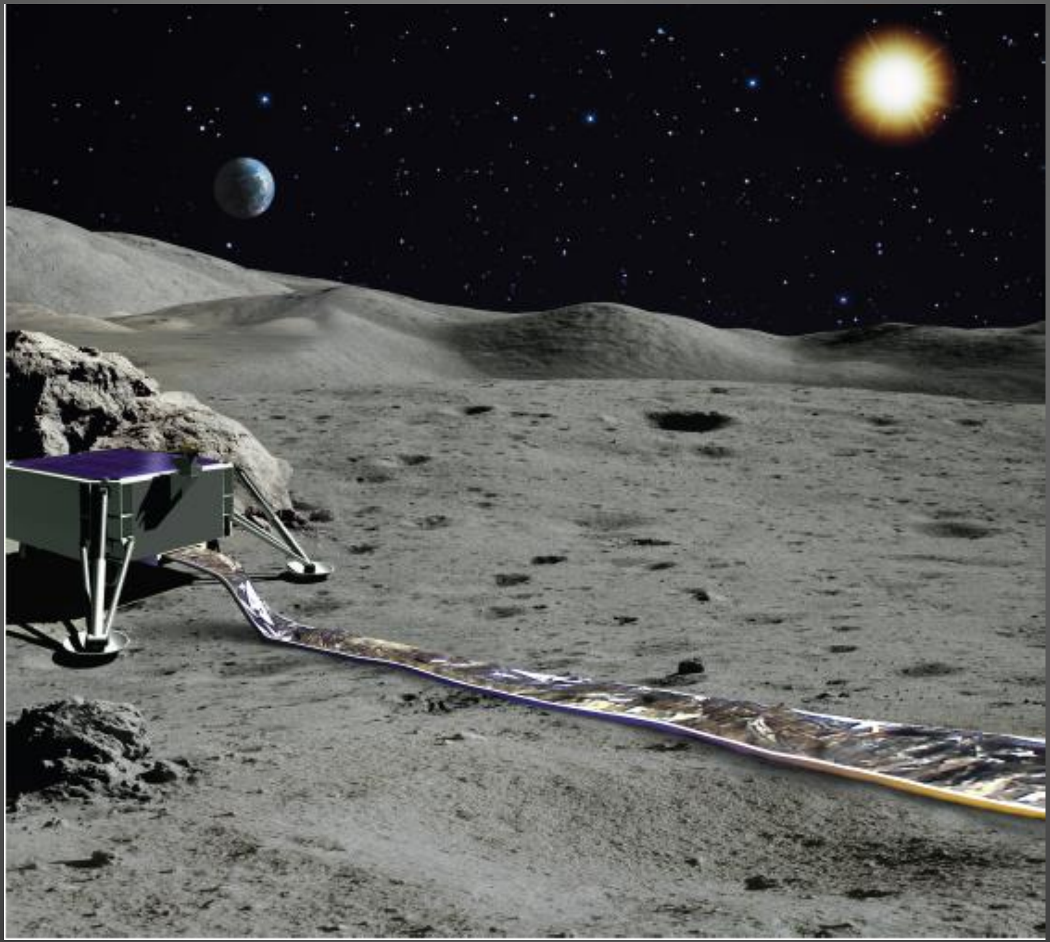
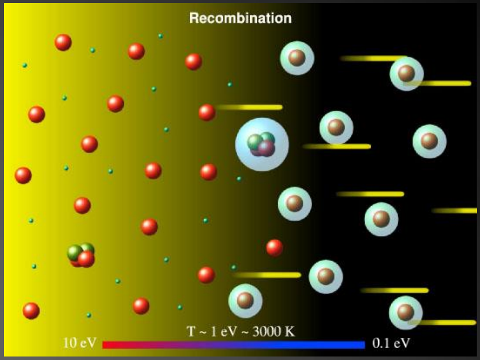
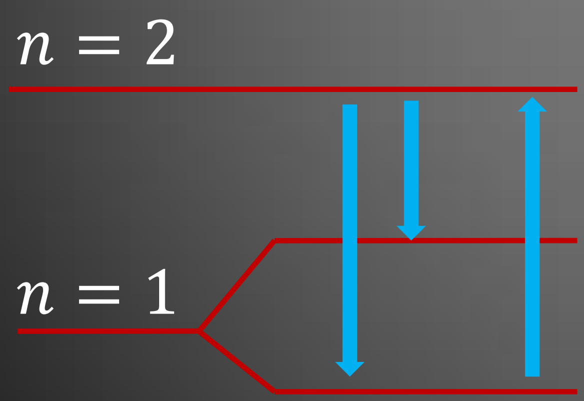


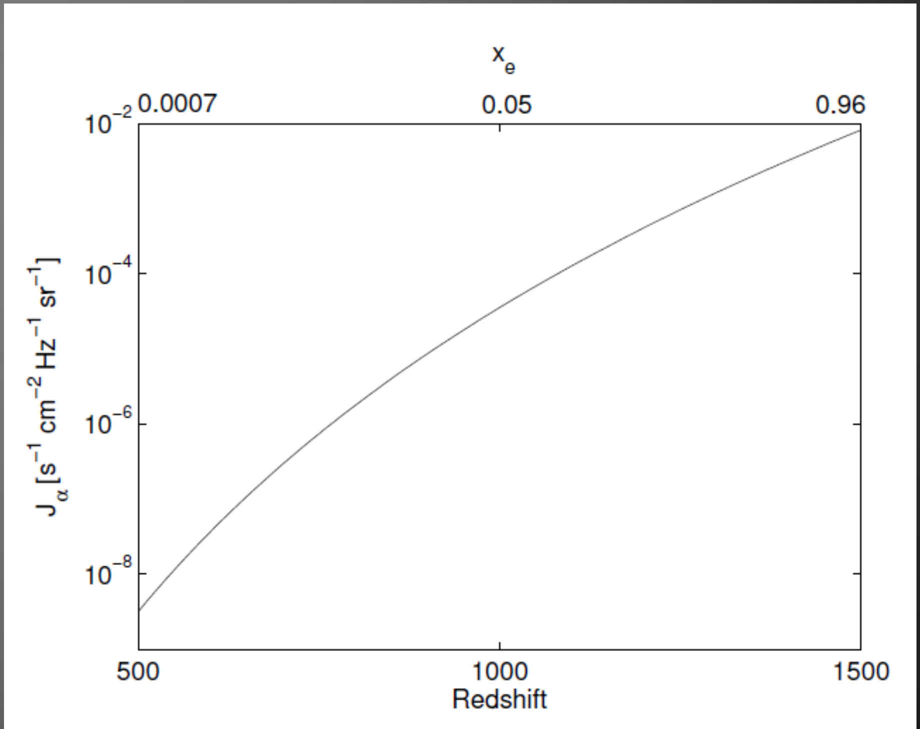
Image from poster by J. Lazio

Non-vanishing 21-cm signal from recombination



Ly-α photons from recombination enhancethe expected signal through the WF effect



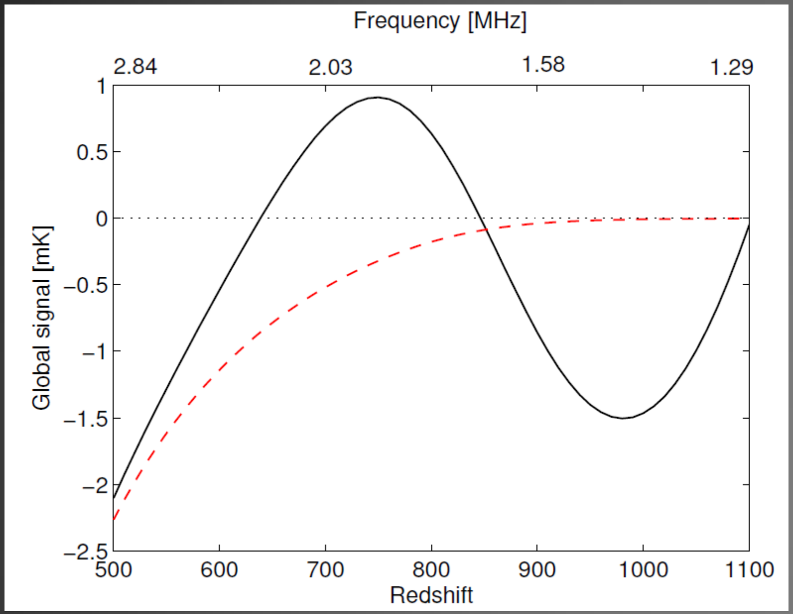


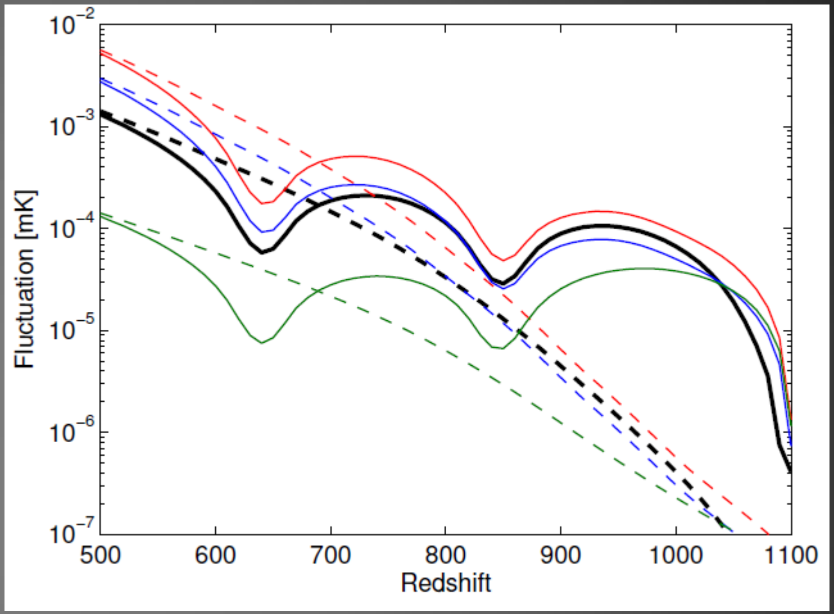
Wouthuysen 1952, Field 1958

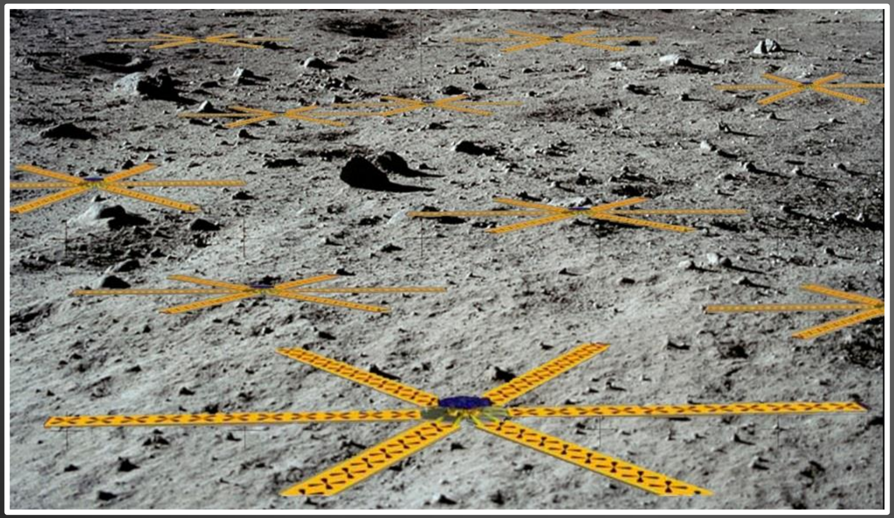
Fialkov & Loeb (2013)
Based on CosmoREC by J. Chluba et al.

New expectations for cosmological ~200 m signal

Fialkov & Loeb (2013)







Lunar Radio Array

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