The Missing Pages of Cosmic History

Anastasia Fialkov

ITC Fellow, Harvard

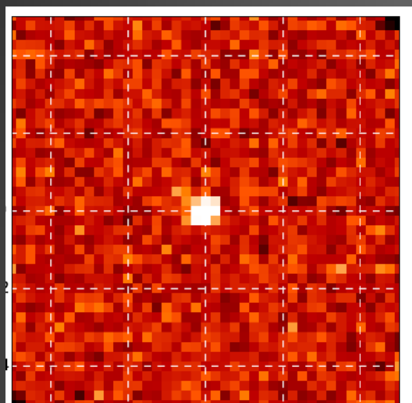
Berkeley

March 15, 2016

Département de Physique
École Normale Supérieure

Cosmic History

Cosmic Microwave Background



Quasar at z = 6.3
Wu et al. (2016)

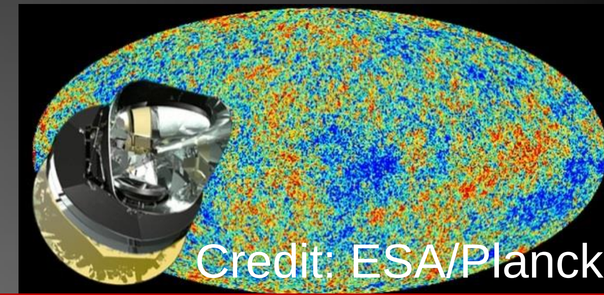
Galaxy at z = 11.1
Oesch et al. (2016)

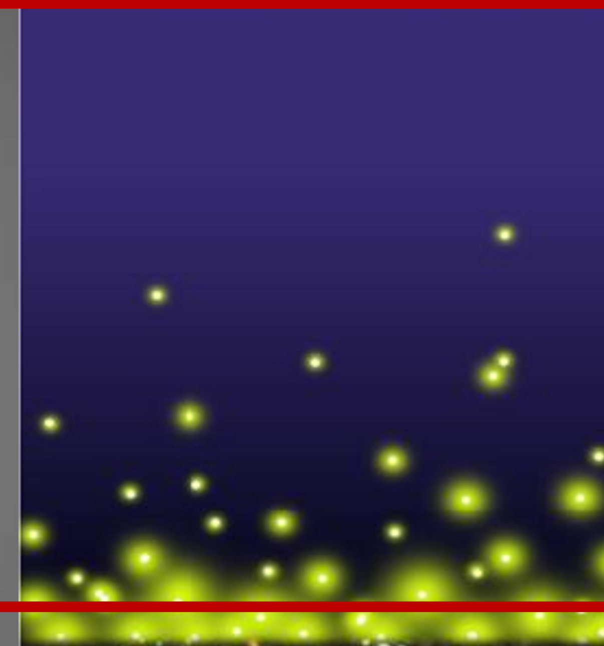
Observations of distant galaxies and quasars

The last 13 billion years, rich in data!

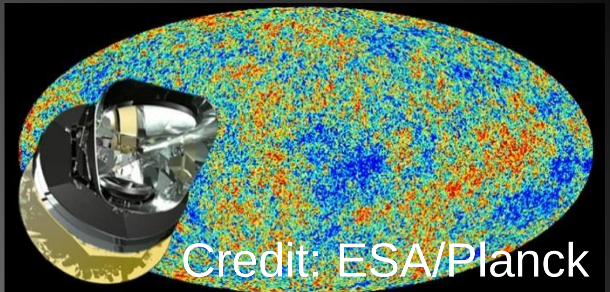
Cosmic History

Missing part of the history





Our Best Guess

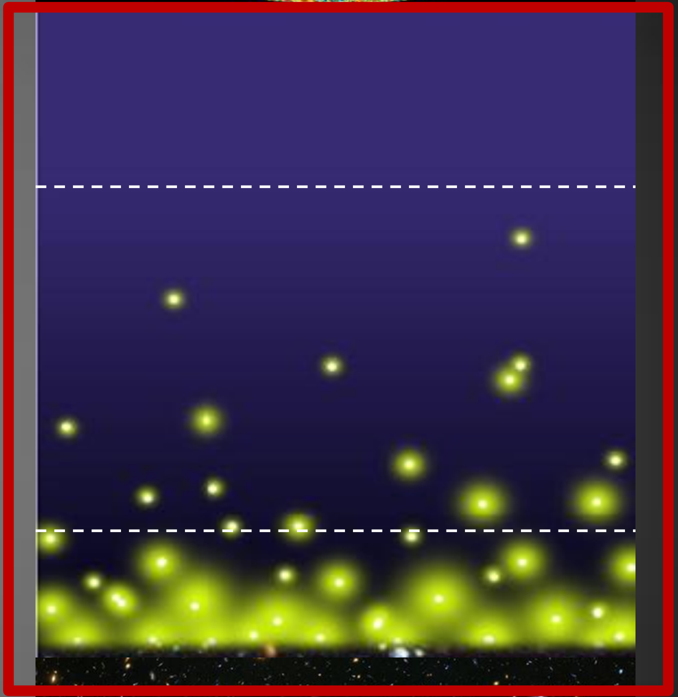


Dark Ages:

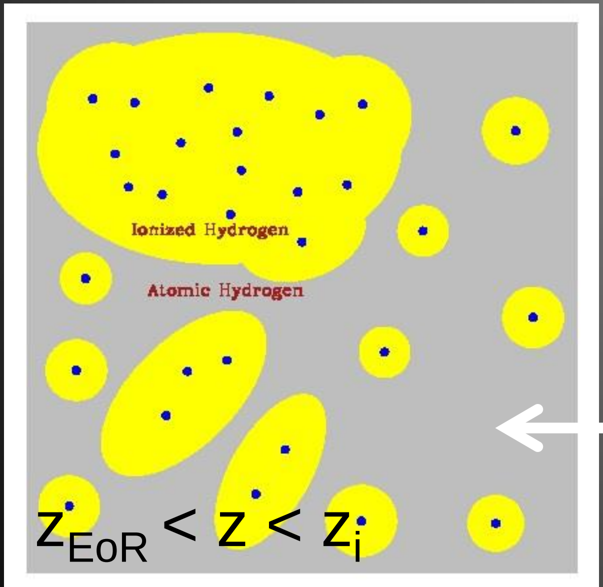
$z_{star} < z < z_{CMB}$

Cold and neutral gas

Cosmic Dawn:

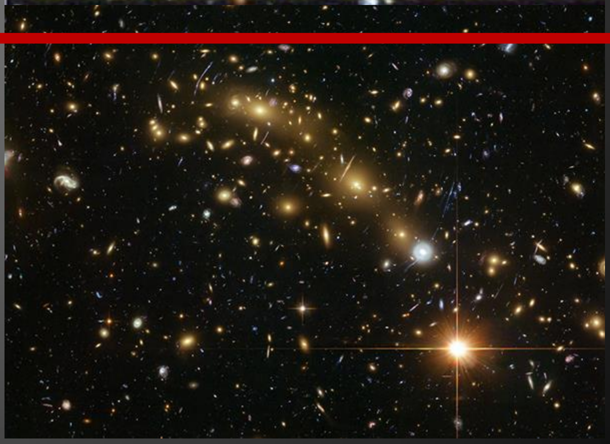


Epoch of Reionization

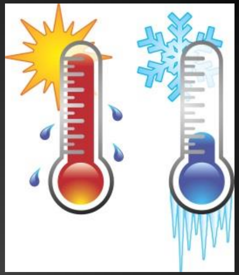


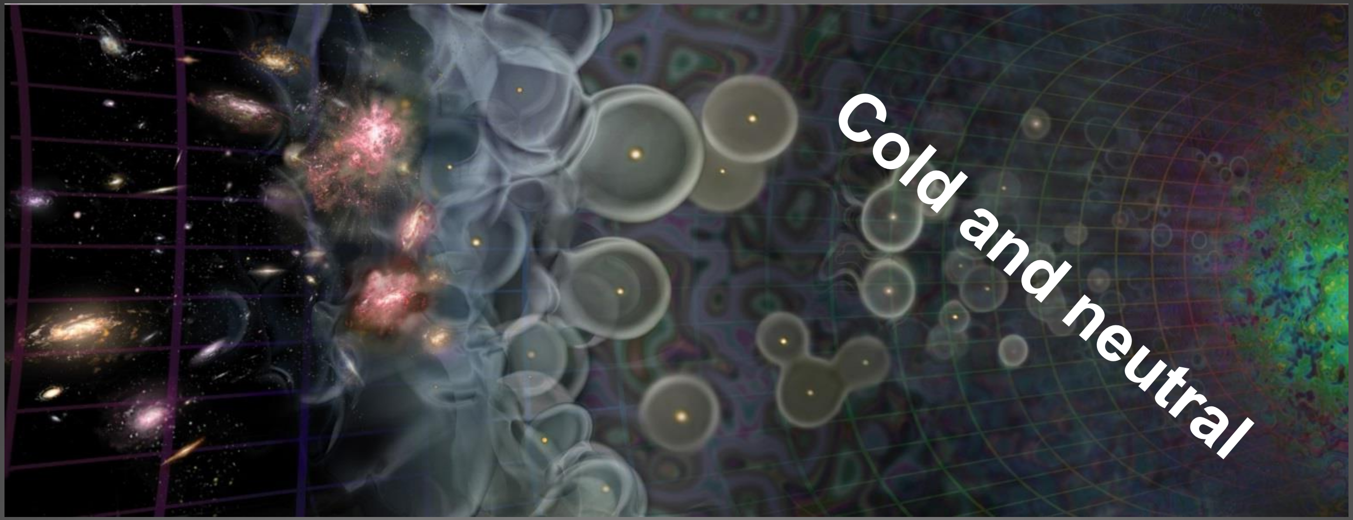
First stars at z ~ 60
Fialkov et al. (2013)

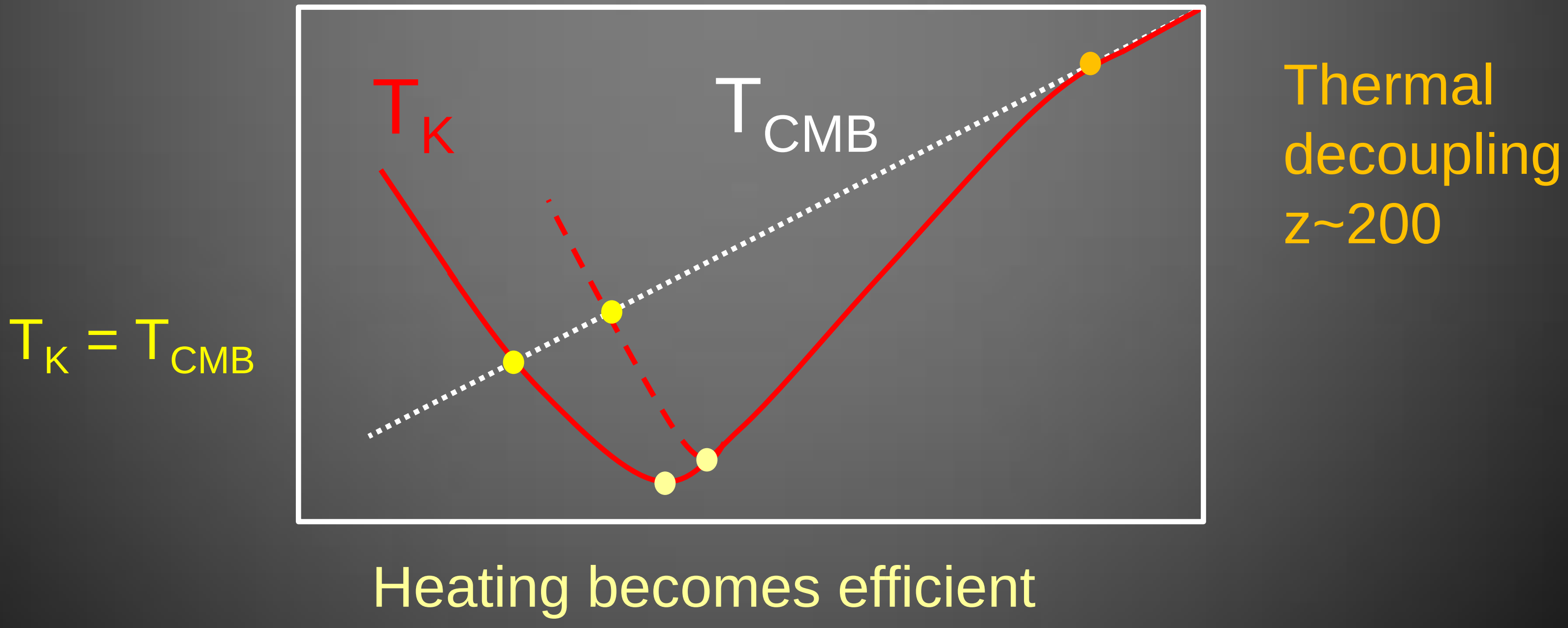
Space between stars (galaxies) is cold and neutral



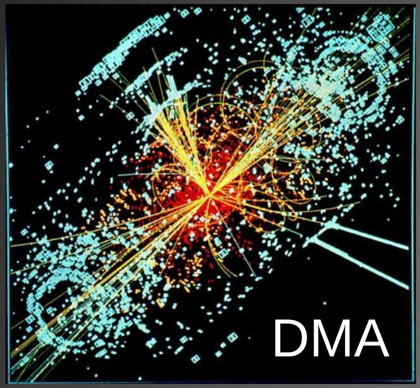
Our Best Guess: Thermal History

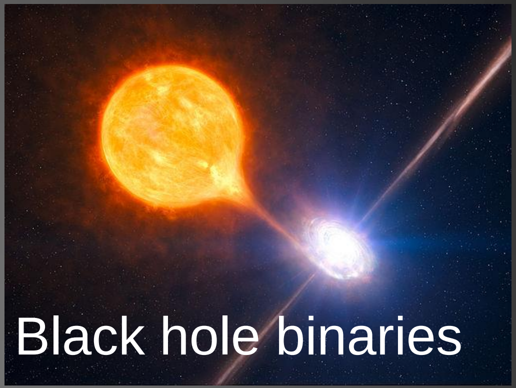






What Heated Up the Gas?





Open Questions:

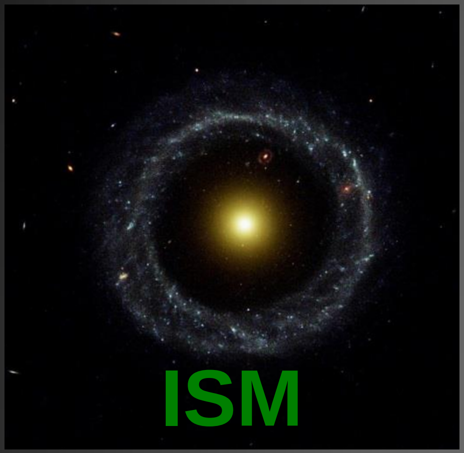
- Nature of heating sources
- Spectral energy distribution (SED)
- Efficiency
- Time dependence
- X-ray absorption
- Effects of metallicity

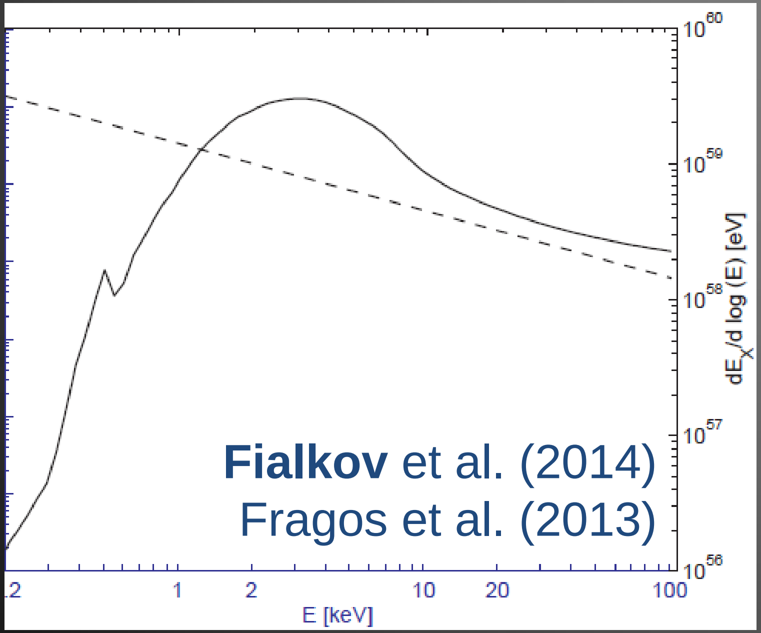
Possible Sources:

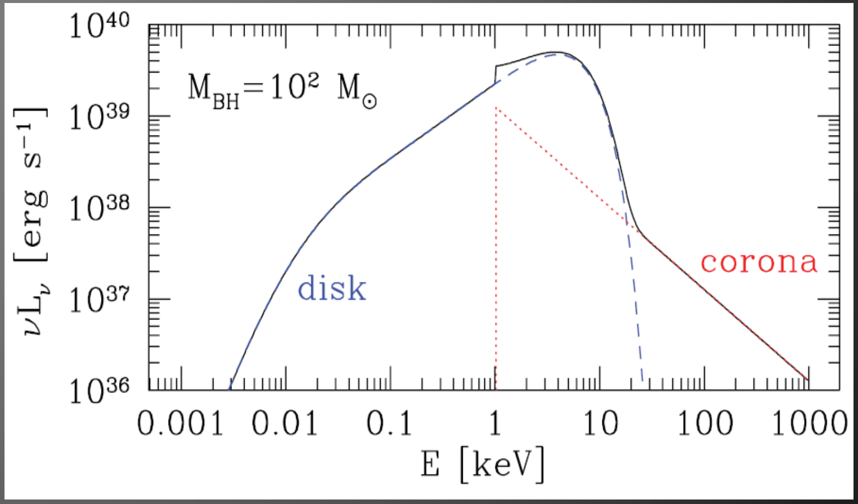
- X-ray binaries
- Mini-quasars
- Thermal emission from galaxies
- Shocks
- Dark matter annihilation
- Etc.

In this talk:

Sources with hard and soft SED



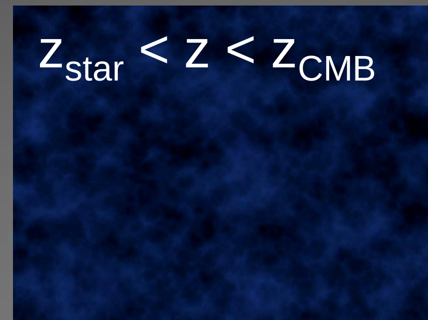




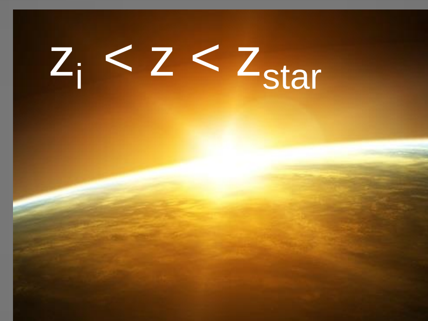
Shakura & Sunyaev (1973)
Tanaka et al. (2012)

Open Questions

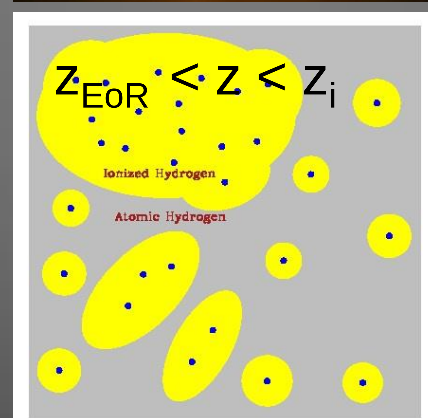
Dark Ages:
When did the first stars form?
In which halos?
Contribution of DM?

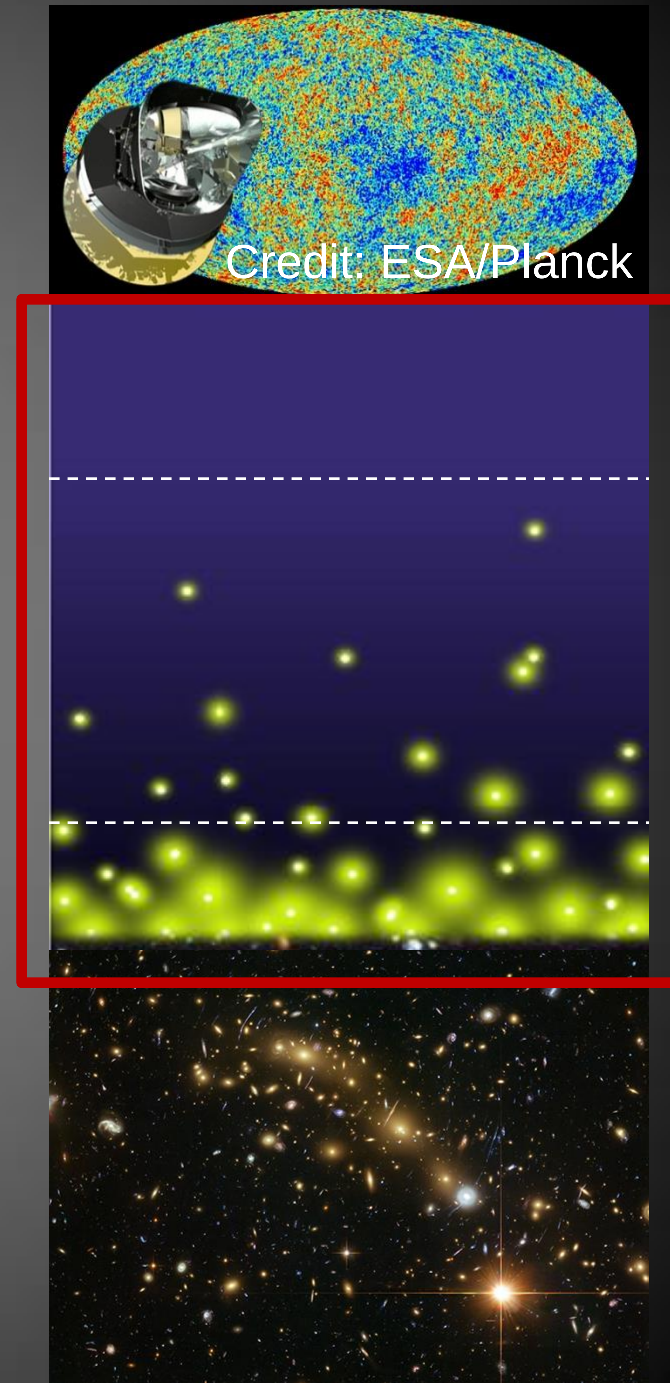


Cosmic Dawn:
What heated up the IGM?
Feedbacks?



Epoch of Reionization:
How did it happen?
Sources?
Topology?



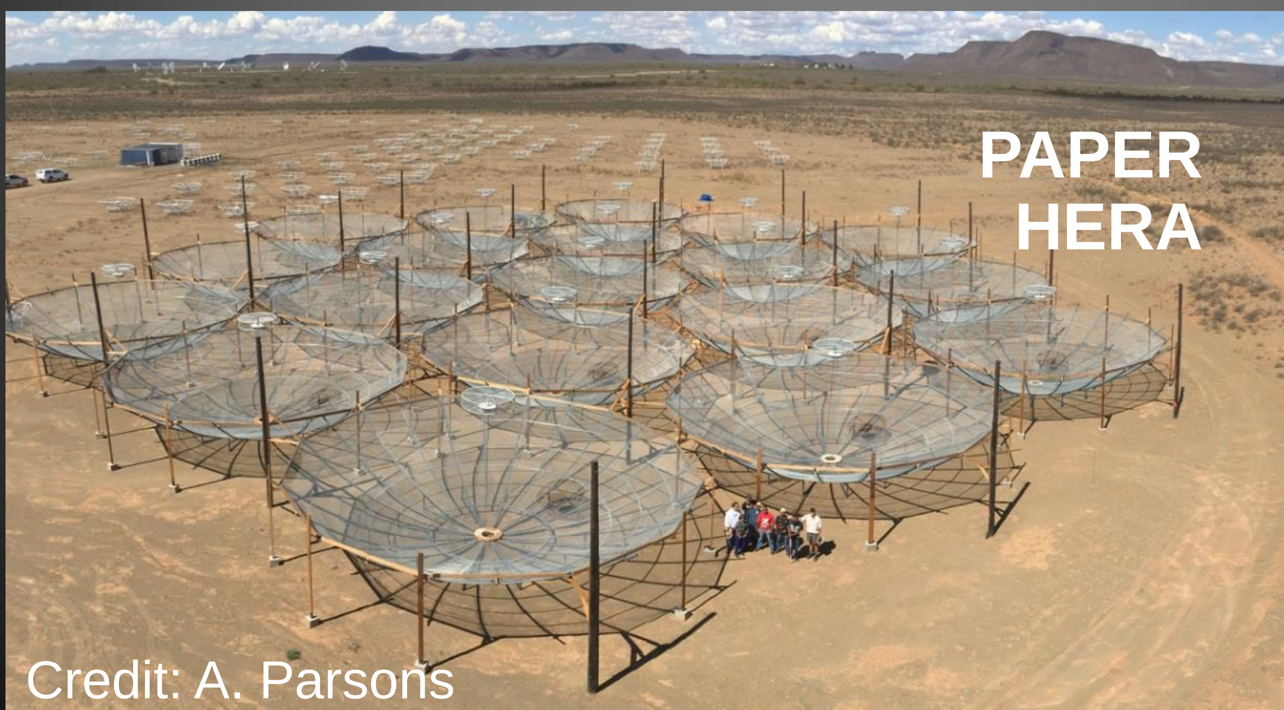


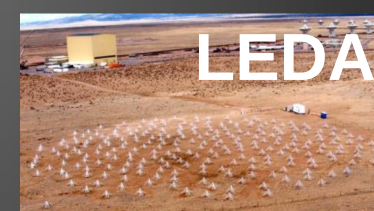
Bright Future

JWST and WFIRST will probe the earliest galaxies

X-ray Surveyor and Athena will measure the X-ray emission, count the dimmest quasars.

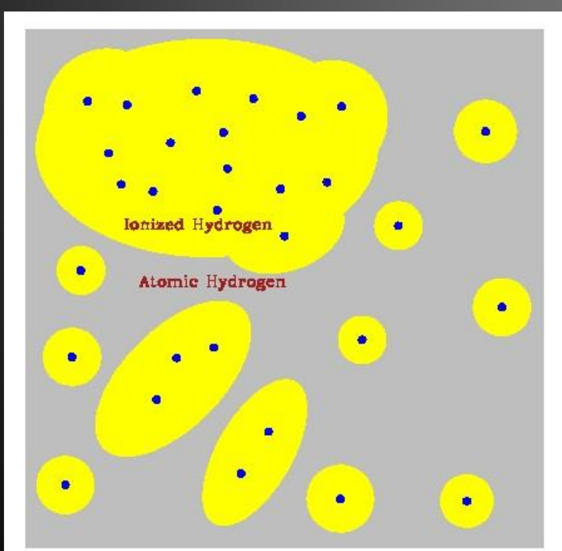
Radio telescopes are seeking to probe 21-cm signal of HI





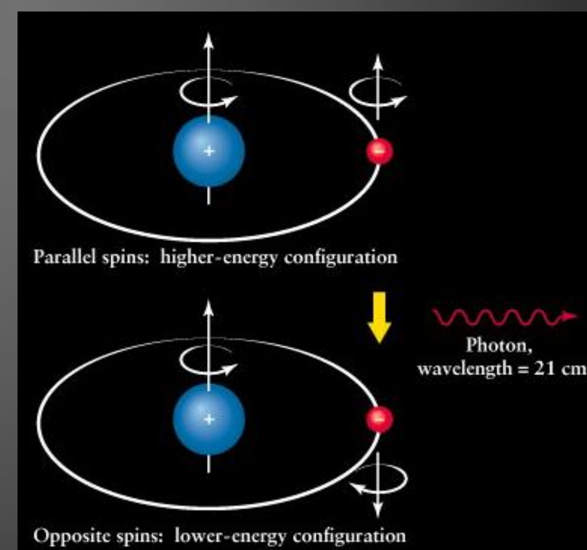
Faint Signal of Neutral Hydrogen

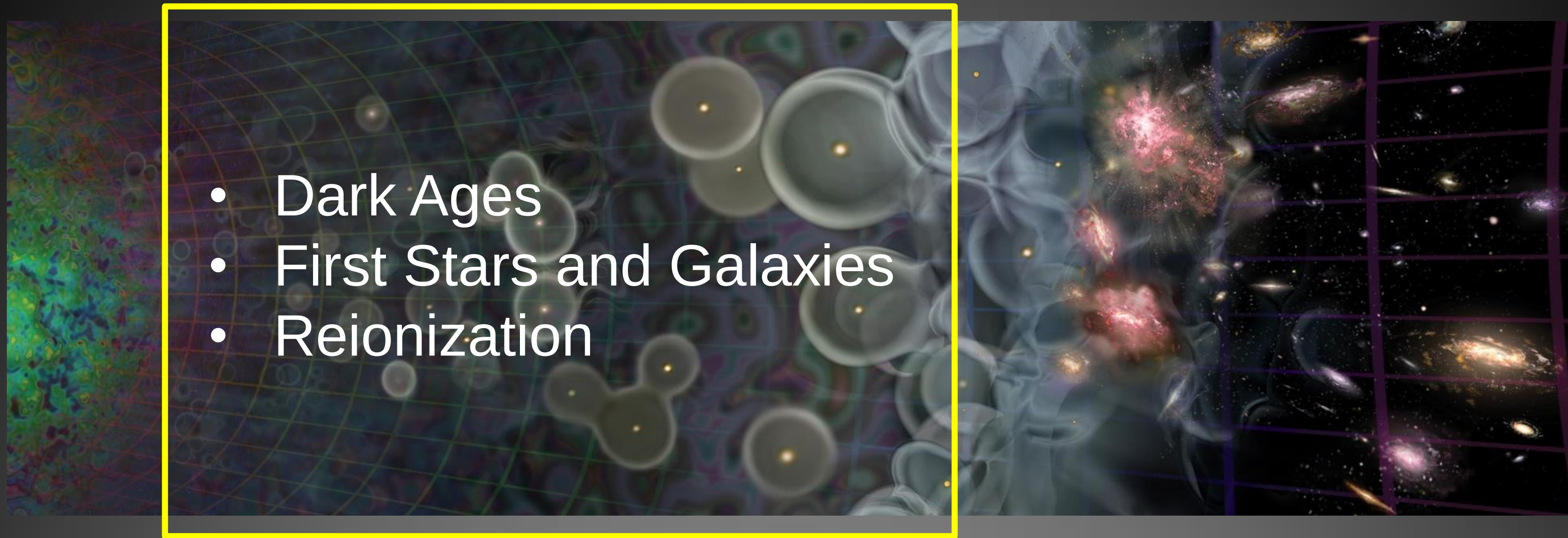
- The “highly forbidden” spin-flip transition ($2.9 \times 10^{-15}\ s^{-1}$) happens often enough in the volume of the Universe.
- Photon of 21-cm are produced, they do not get re-absorbed and can be observed today.



λ = 21 cm
ν = 1420 MHz

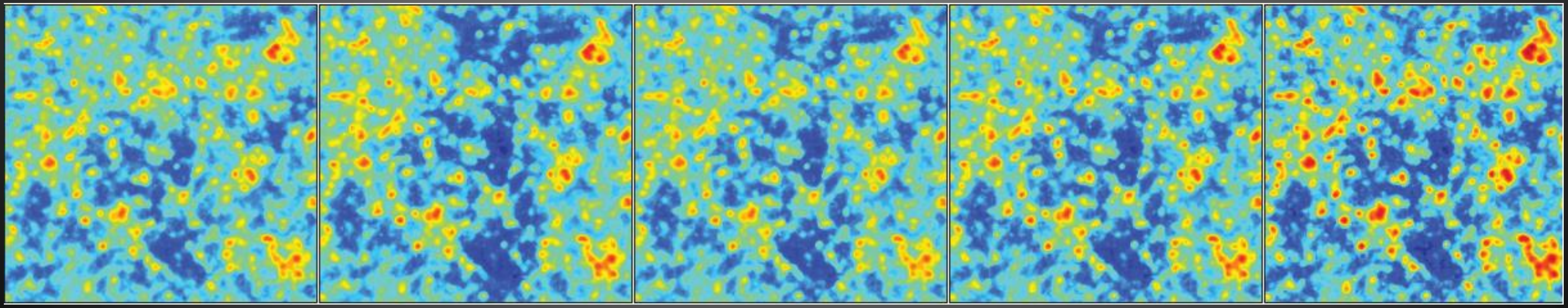
Spin Temperature
$n_1/n_0 \equiv 3\exp(-T_*/T_S)$,
$T_* = 0.068$ K





21-cm experiments will map signal from high z

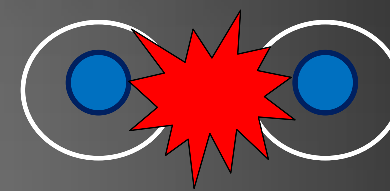
What can we learn by reading the 21-cm maps?



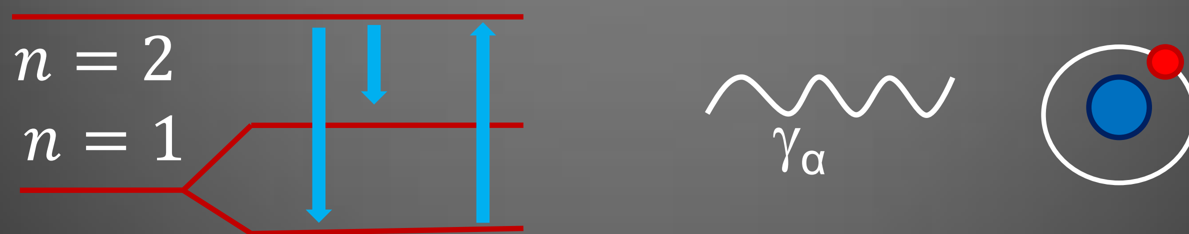
Spin Temperature is Determined by 3 Processes

Equilibrium with CMB: $T_S \rightarrow T_{CMB}$

Collisions with other HI:
x_C, $T_S \rightarrow T_{gas}$



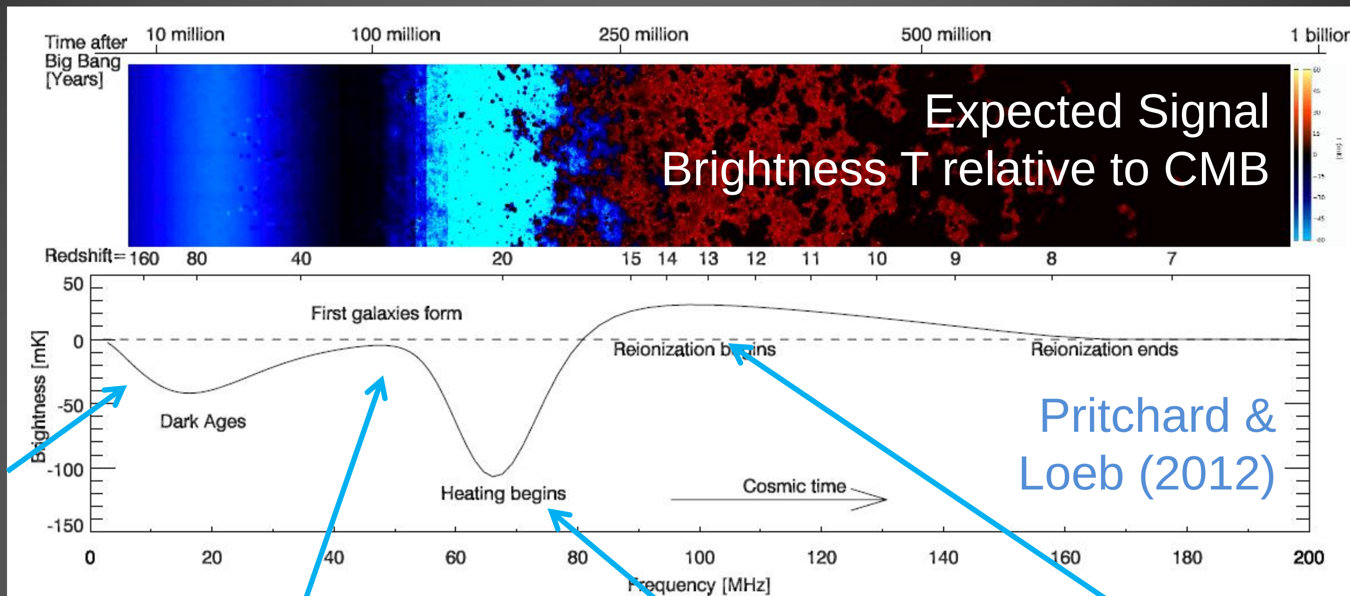
Absorption and reemission of Lyα:
x_α, $T_S \rightarrow T_c \sim T_{gas}$ (Wouthuysen 1952, Field 1958)



T_S depends on astro and cosmo parameters

$$\frac{1}{T_S} = \frac{T^{-1}{}_{CMB} + x_C T^{-1}{}_K + x_\alpha T^{-1}{}_K}{1 + x_C + x_\alpha}$$

Predicted Global 21-cm Signal



Dark ages, Collisional coupling

Stars appear
Ly-a coupling

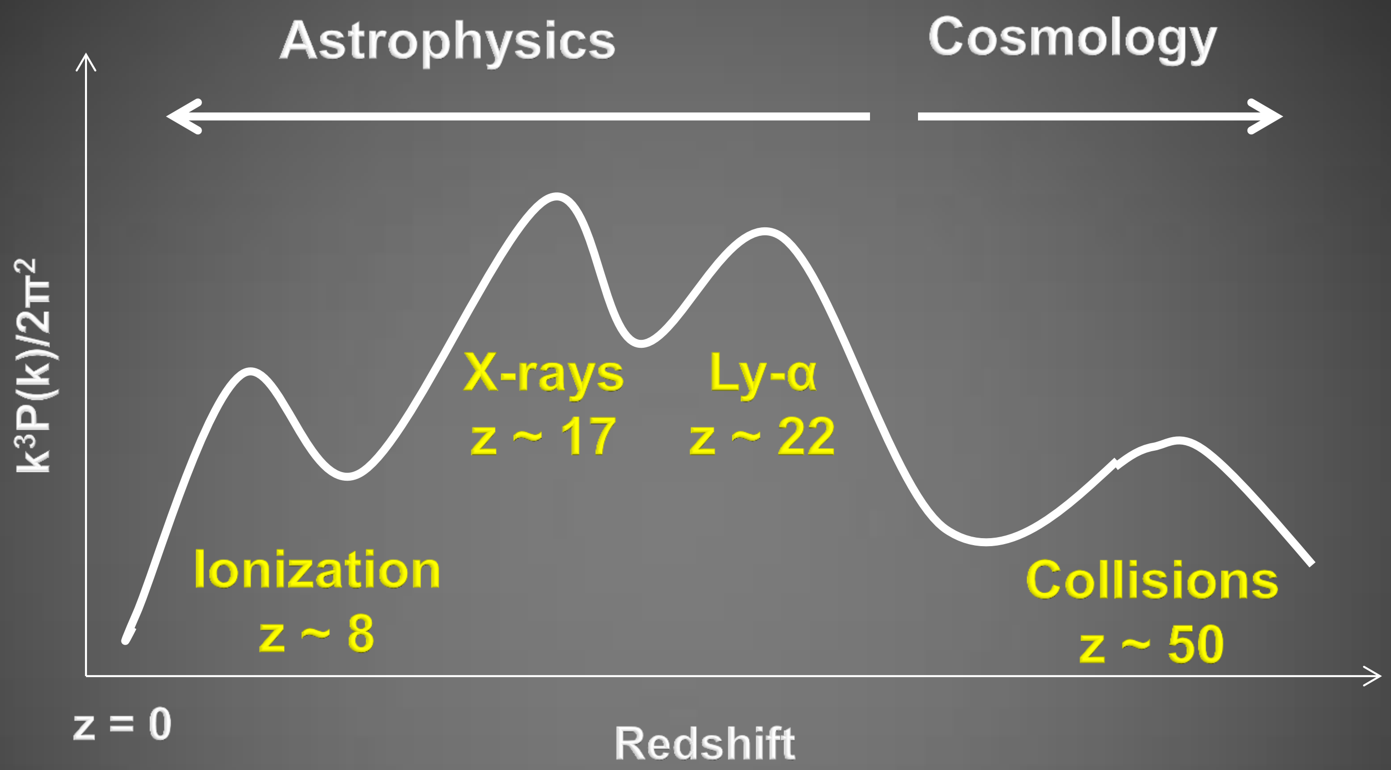
Heating

Ionization

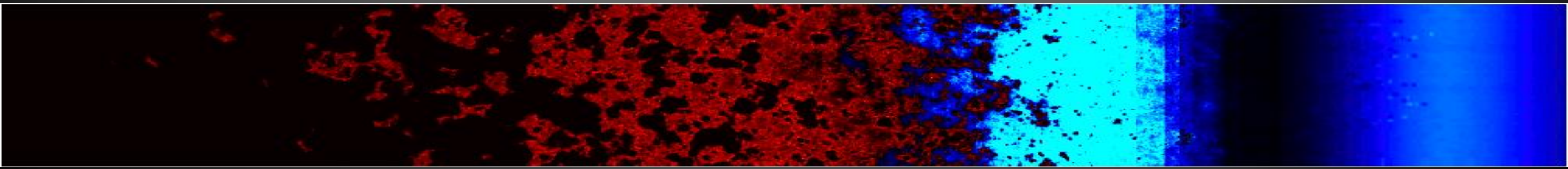
$$\delta T_b \propto x_{HI}(1+\delta)(1+z)^{1/2}\left[1-\frac{T_{CMB}}{T_S}\right]\left[\frac{H(z)/(z+z)}{dv_{||}/dr_{||}}\right]$$

$$\frac{1}{T_S}=\frac{T^{-1}{}_{CMB}+x_C T^{-1}{}_K+x_\alpha T^{-1}{}_K}{1+x_C+x_\alpha}$$

Inhomogeneous Signal. Fluctuations



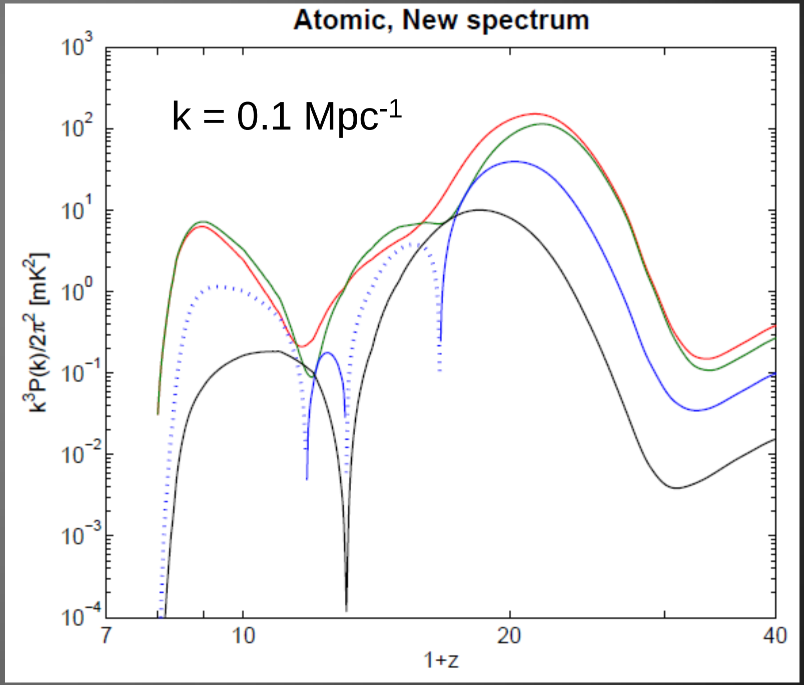
- Generic dependence of power spectrum on z for a given k
- Each source of fluctuations contributes at different epoch



Line-of-Sight Anisotropy: 3 in 1

$$\delta T_b \propto x_{HI}(1+\delta)(1+z)^{1/2}\left[1-\frac{T_{CMB}}{T_S}\right]\left[\frac{H(z)/(z+z)}{dv_{||}/dr_{||}}\right]$$

- Gradient along the LOS of the LOS velocity adds anisotropy to the otherwise isotropic signal
- Sign change
- Component separation according to their angular dependence: μ = cos ϑ



$$P(k) = P_{iso} + P_X + P_\delta$$

Total Isotropic μ^4 term (cosmology)

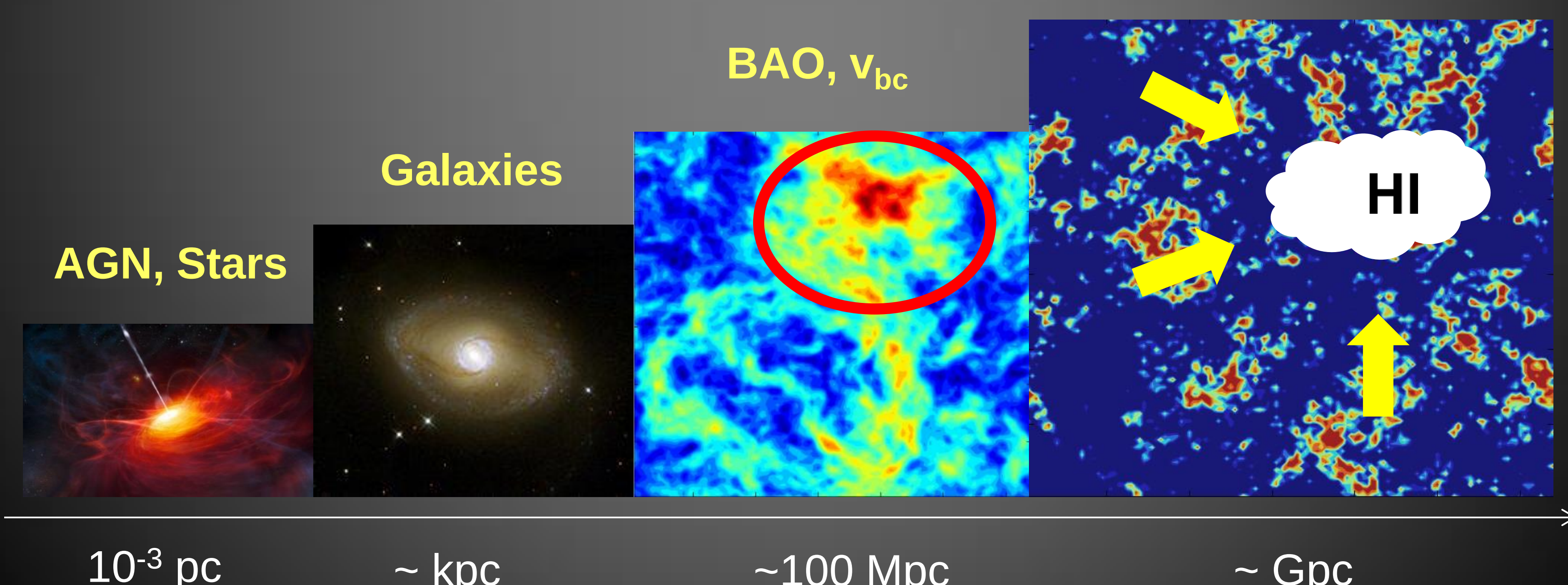
μ^2 term (cross-correlation)

Fialkov, Barkana (2014)

21-cm Signal is Science-rich but Hard to Model

Simulate both small scales (stars) and large cosmological scales (size of the Universe)

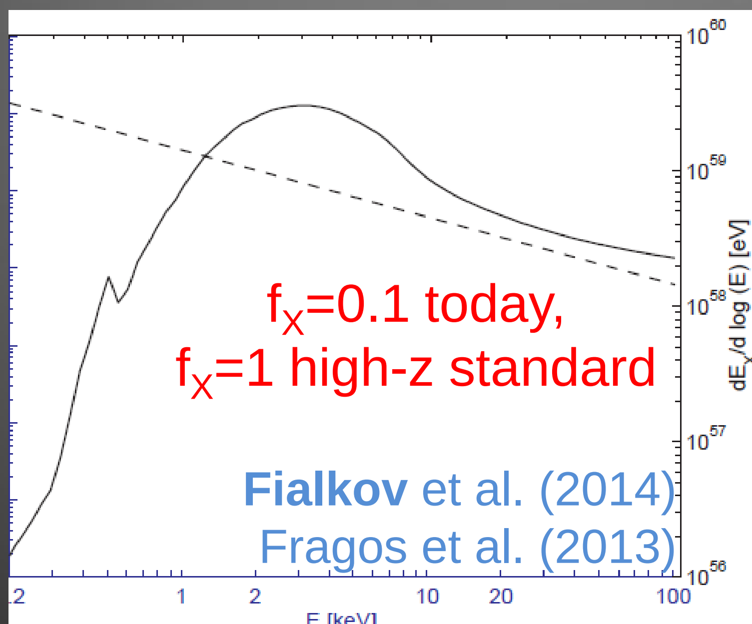
Include many parameters: IC, first stars, their radiation, environment, temperature of the gas etc.

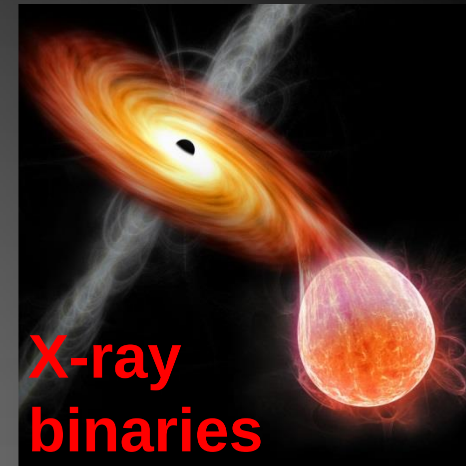


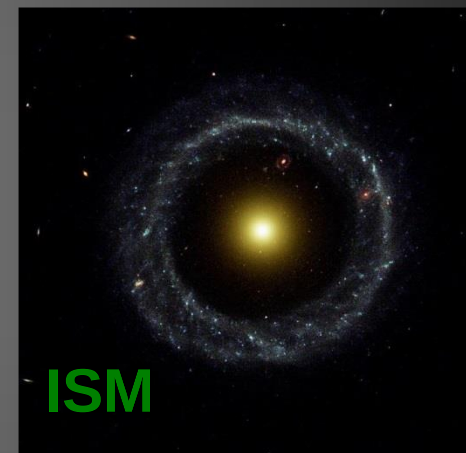
The Role of First X-ray Sources

Were first X-ray sources hard or soft?
What was their efficiency?
How did it affect the 21-cm signal and the EoR?

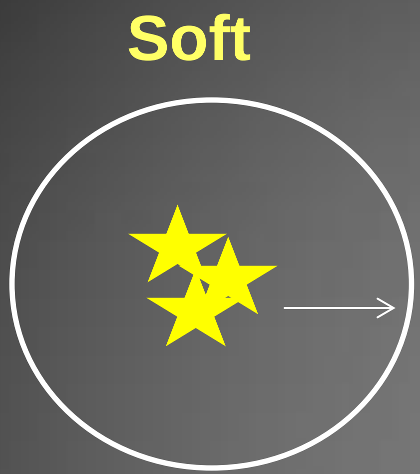
$$\frac{L_X}{\mathrm{SFR}} = 3 \times 10^{40} f_X \ \mathrm{erg\ s^{-1}} M_\odot^{-1}\ \mathrm{yr}$$

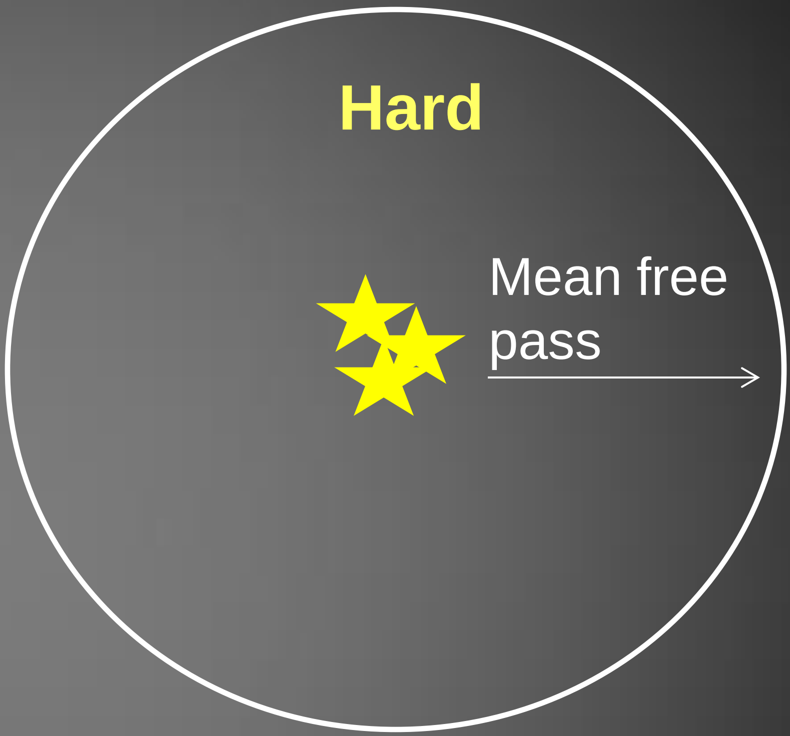






Were First X-ray Sources Soft or Hard?



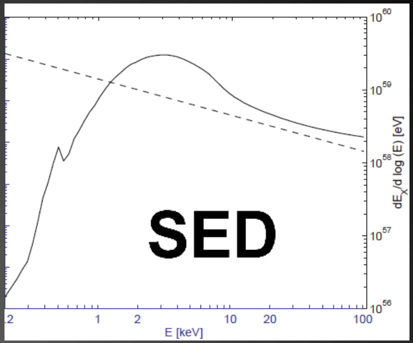


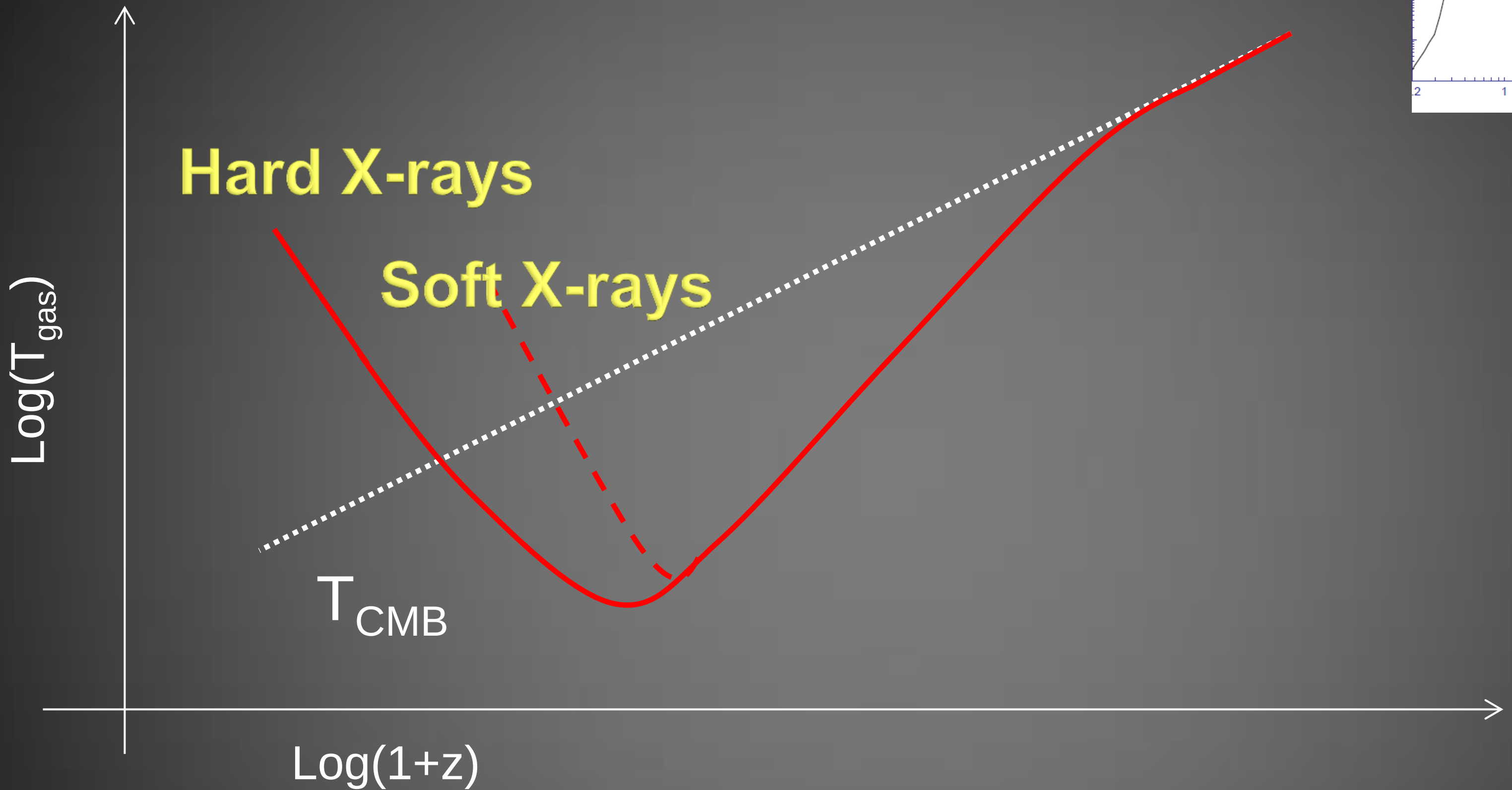
Details of SED are crucial!

If hard X-rays

- Mean free pass is longer
- Heat and ionize the gas far from the source
- Fluctuations in gas temperature are washed out at scales below the mfp
- Delayed heating (energy redshifts away)

Effect on Global Thermal History





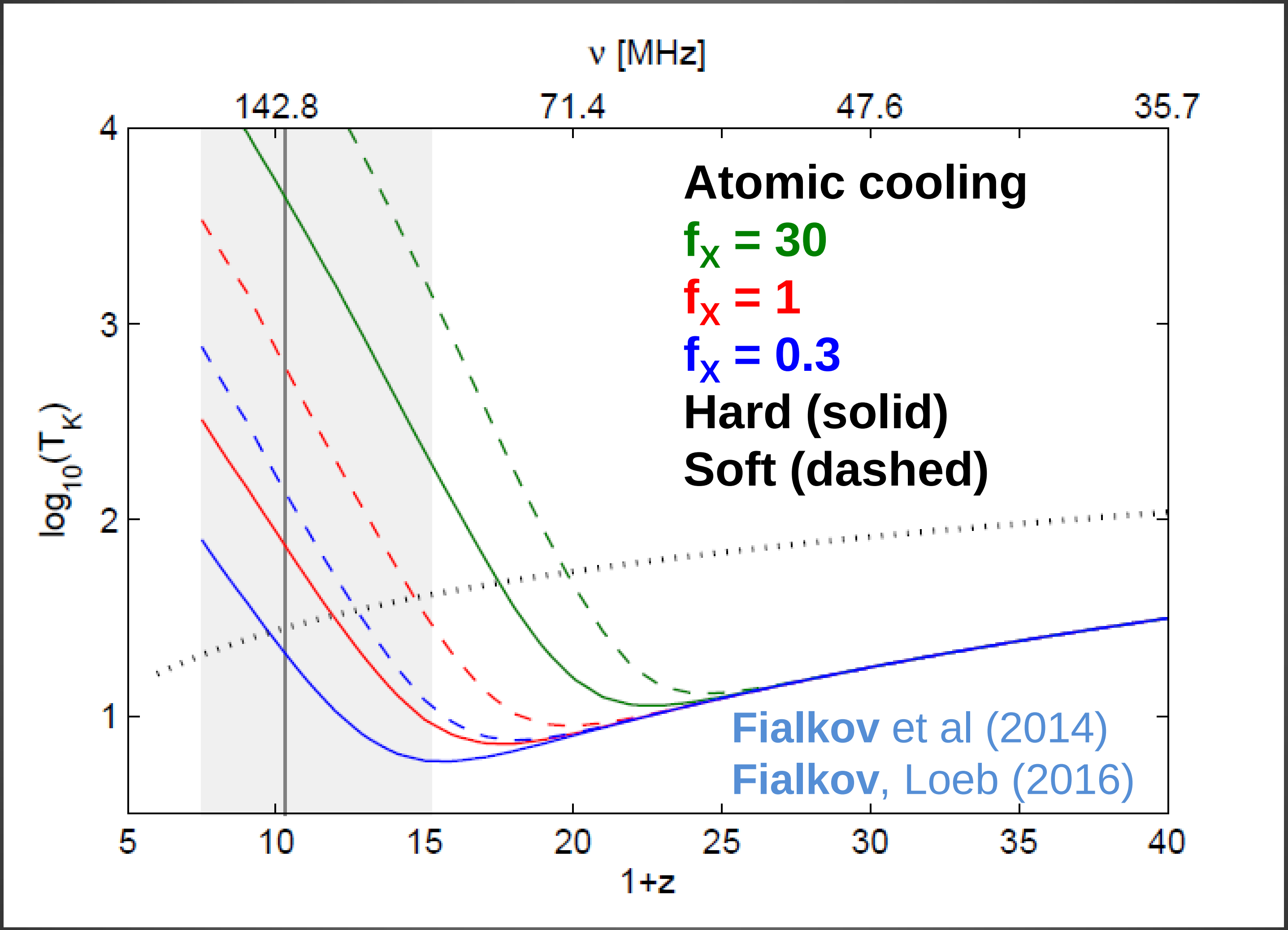
Historical note:

Gas is thought to be pre-heated before EoR, $T_K > T_{CMB}$

Madau et al. (1997)

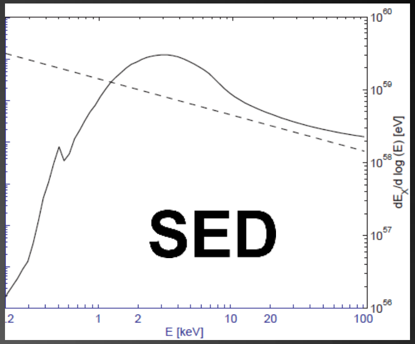
But is it really the case?

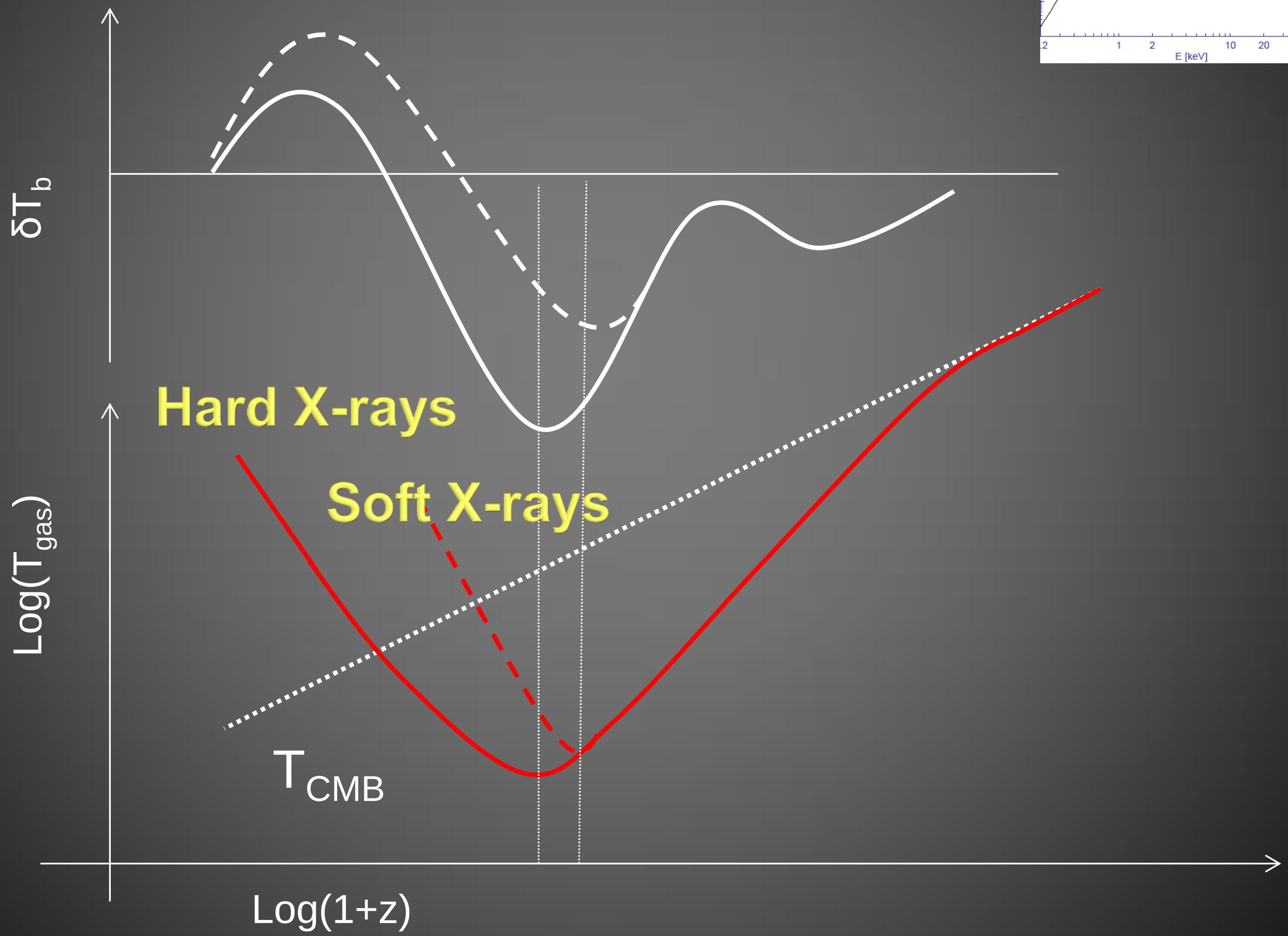
Gas Temperature

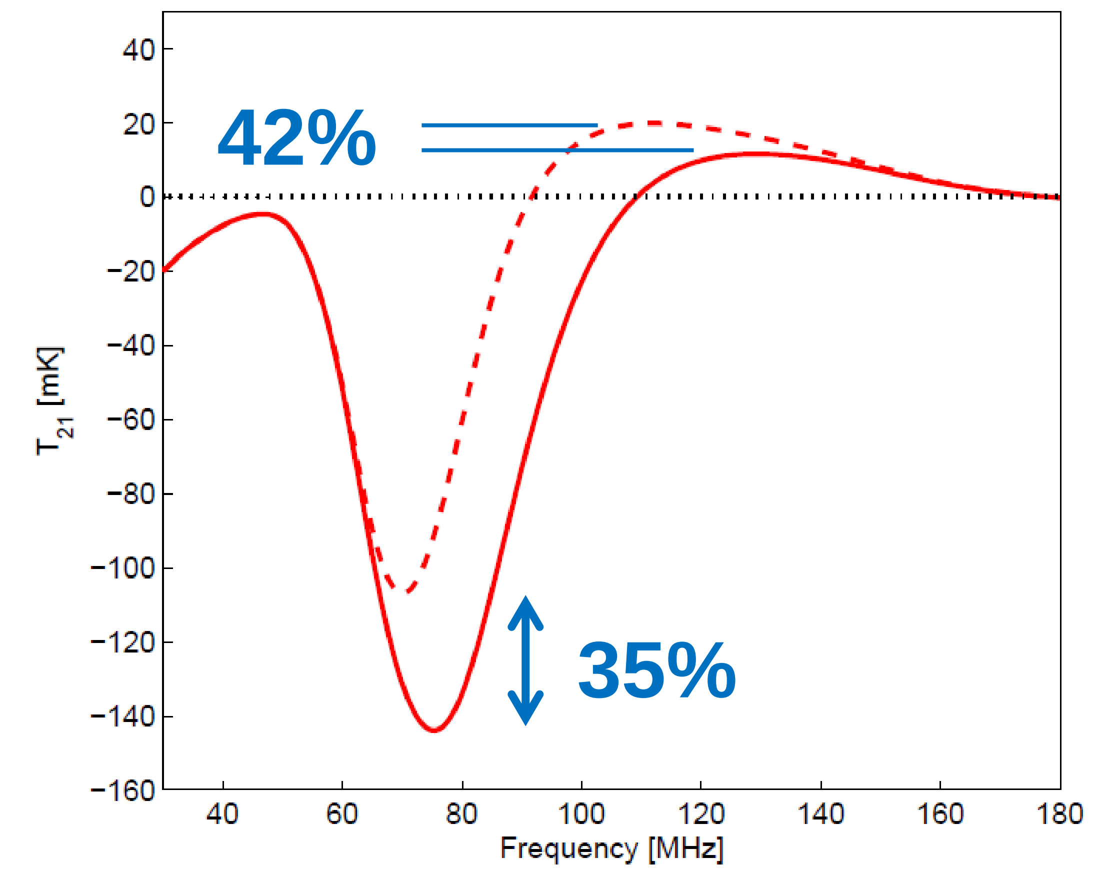


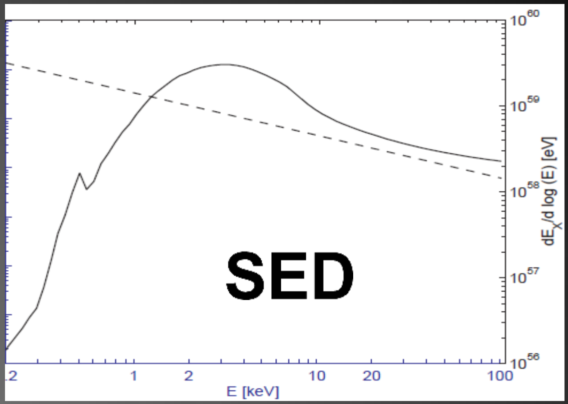
Gas can be rather cold during EoR!

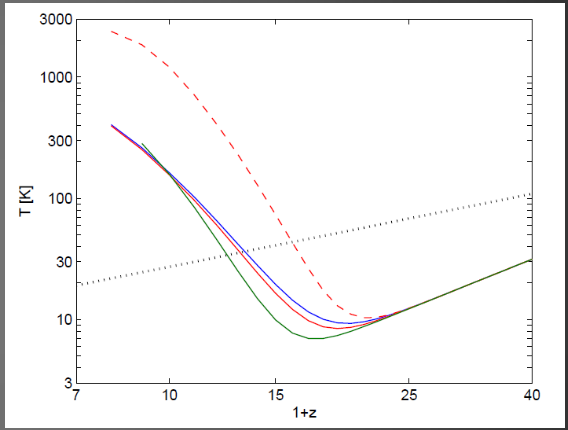
Effect on Global Thermal History and 21-cm Signal









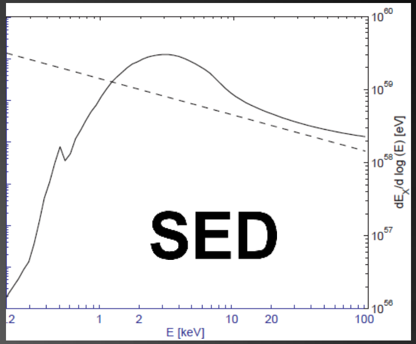


Fialkov, Barkana, Visbal (2014)

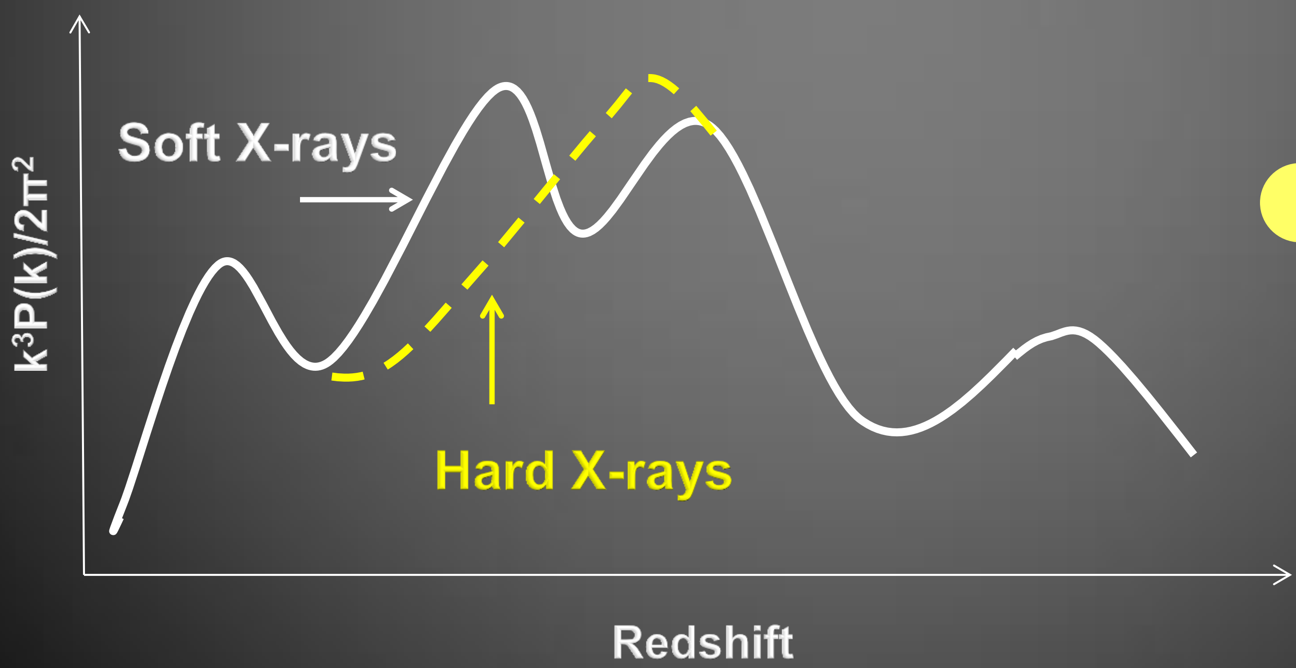
Soft SED: Heating and reionization are separated in time (heating transition at z = 15, x_i ~ 3.8 %).

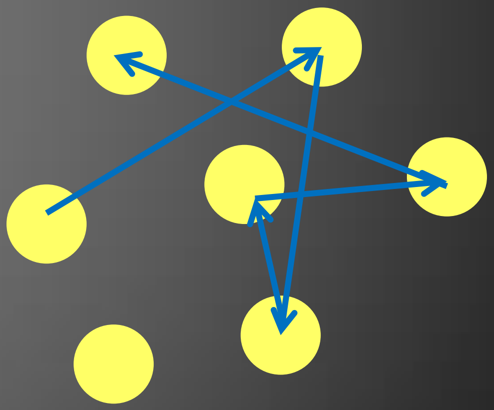
Hard SED: Reionization and heating happen simultaneously (heating transition at z = 12, x_i ~ 14 %).

Hard vs Soft X-rays: Heating Peak in the PS



- Mean free path of X-ray photons → characteristic scale
- Fluctuations at scales smaller than mfp are washed out



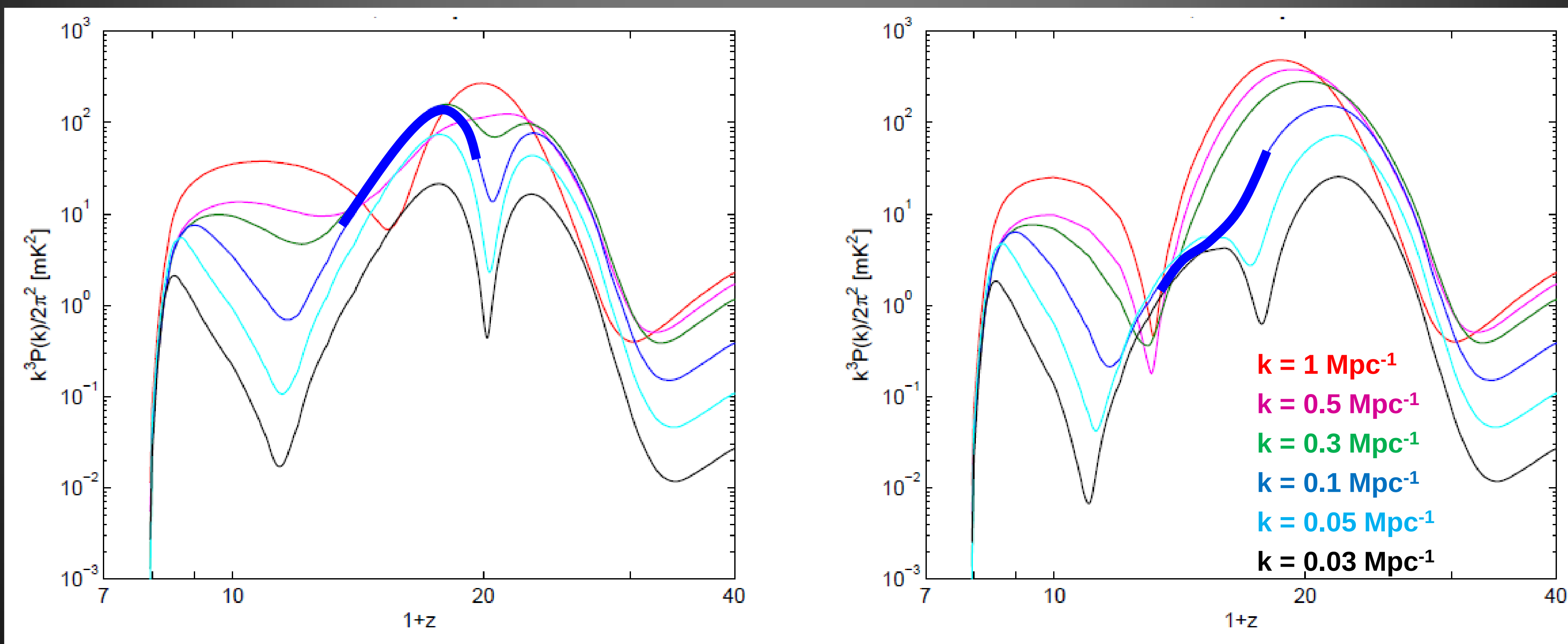


Hard vs Soft X-rays: Heating Peak

Soft X-rays

Hard X-rays

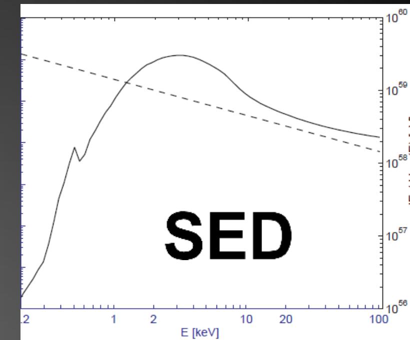
Almost uniform heating

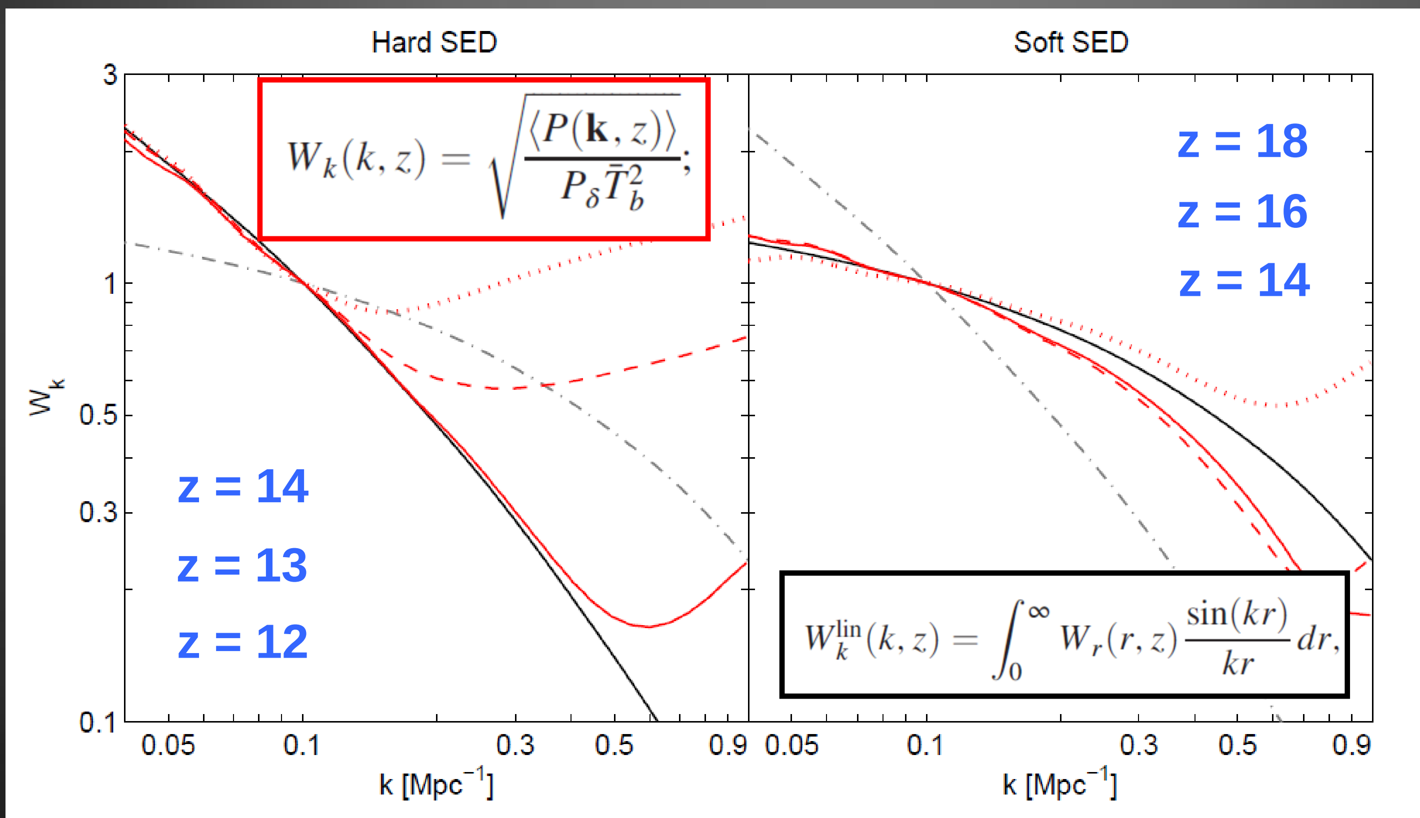


Fialkov & Barkana (2014)

Model-independent Direct Probe of X-ray SED

Low anisotropy,
Linear regime

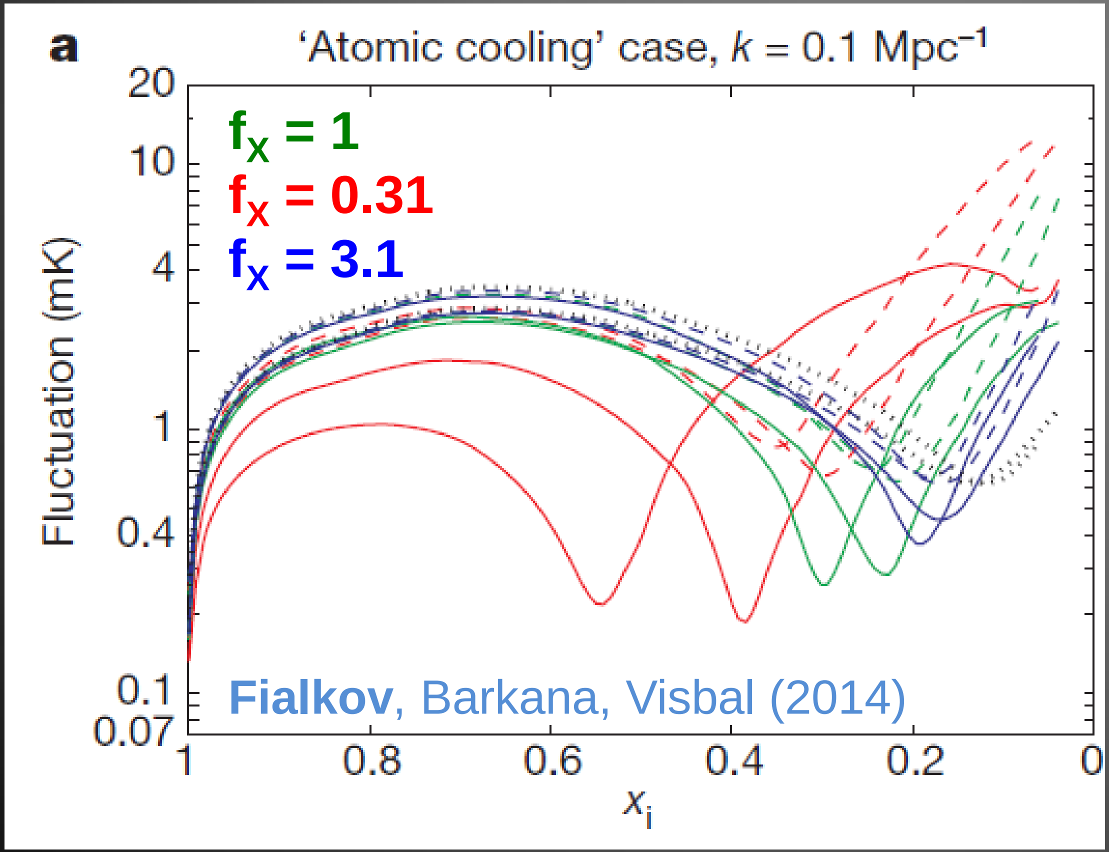




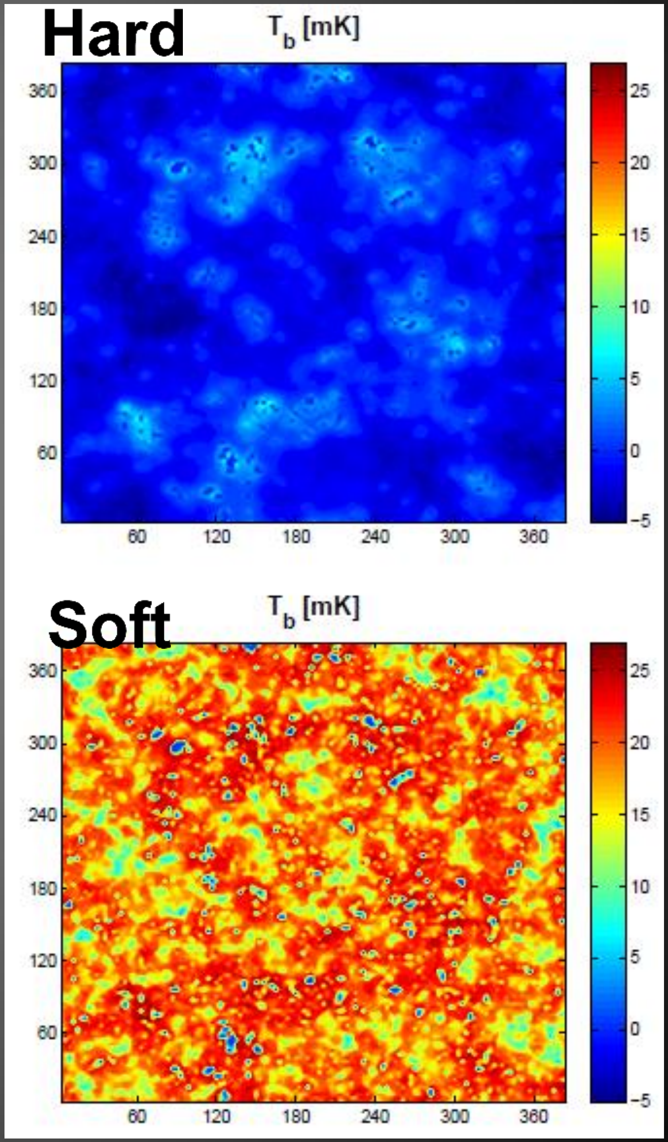
Fialkov, Barkana, Cohen, (2015)

Effect of X-rays on EoR:

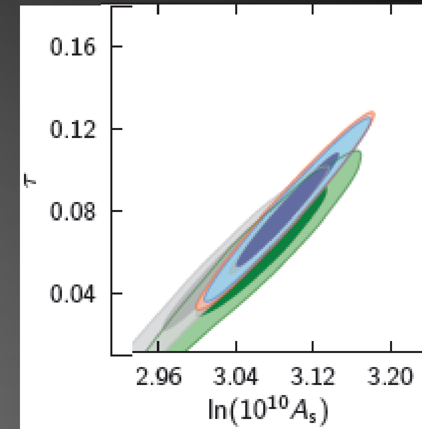
- Partial ionization by X-rays:
  $\Delta\tau = 14\%$ (soft), $\Delta\tau = 2\%$ (XRBs)
- Reionization is smoother
- Fluctuations in the 21-cm are suppressed



Fialkov & Barkana (2014)

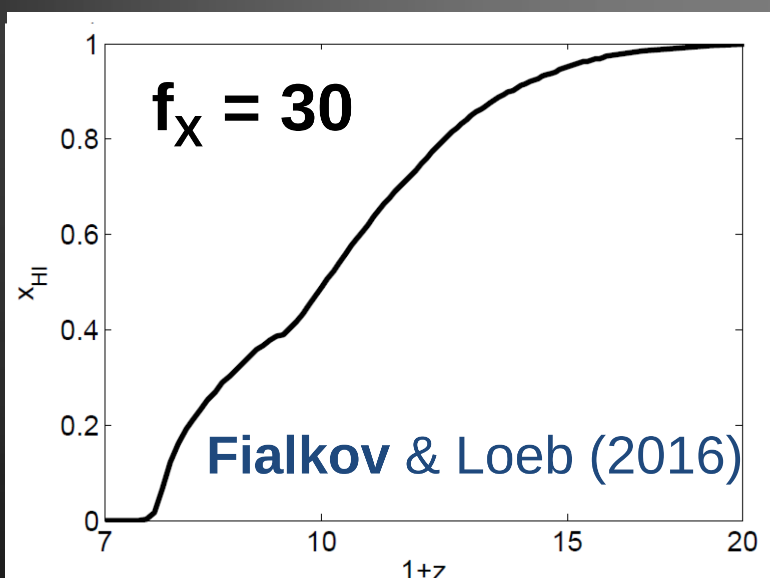


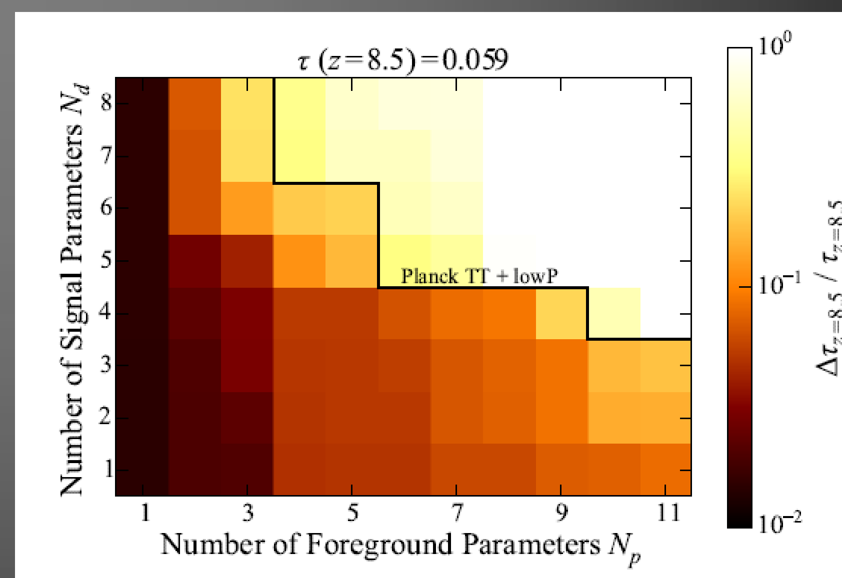
Cosmology from 21-cm!



- Saturated heating
- Fully recover x_{HI} from the global 21-cm signal
- Measure the CMB optical depth much better than the CMB experiments

$$\delta T_b \propto x_{HI}(1+\delta)(1+z)^{1/2}\cancel{\left[1-\frac{T_{CMB}}{T_S}\right]} \Rightarrow x^{rec}{}_{HI} \propto \frac{\delta T_b}{(1+\delta)(1+z)^{1/2}}$$





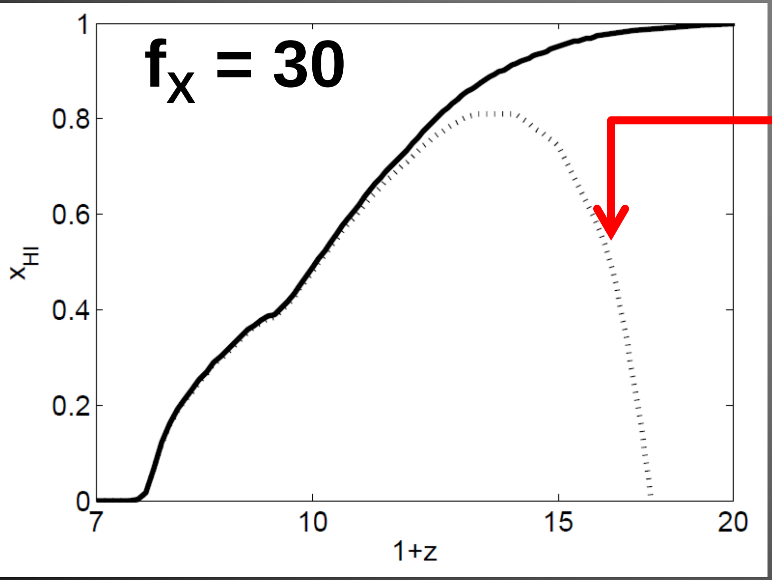
Liu et al. 2015

With Complication from X-rays

$$\delta T_b \propto x_{HI}(1+\delta)(1+z)^{1/2}\left[1-\frac{T_{CMB}}{T_S}\right]$$

With X-rays, reconstructed x_{HI} deviates from the real one

$$\boxed{{x^{rec}}_{HI} \propto \frac{\delta T_b}{(1+\delta)(1+z)^{1/2}}}$$

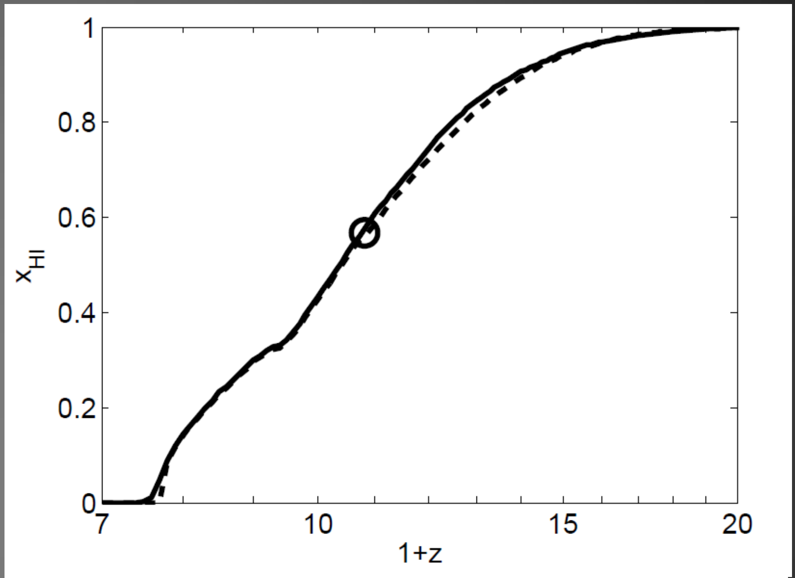


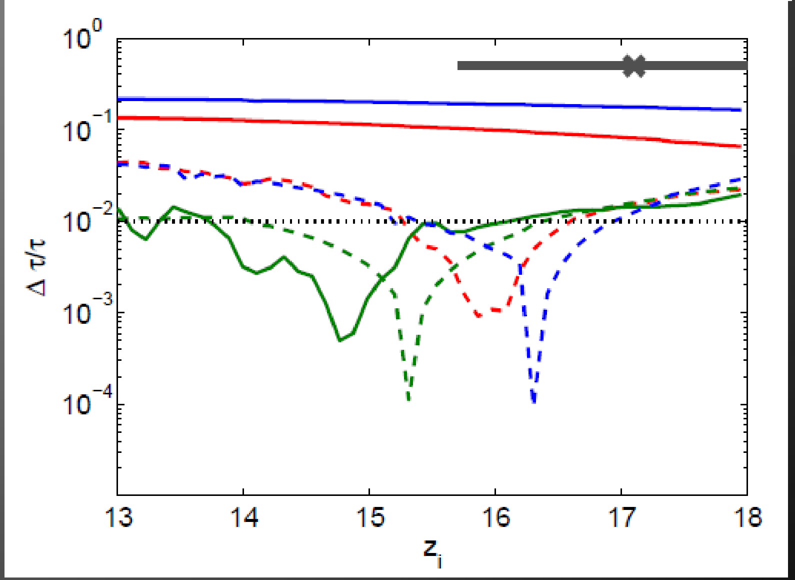
Fialkov & Loeb (2016)

With Complication from X-rays

$$\delta T_b \propto x_{HI}(1+\delta)(1+z)^{1/2}\left[1-\frac{T_{CMB}}{T_S}\right]$$

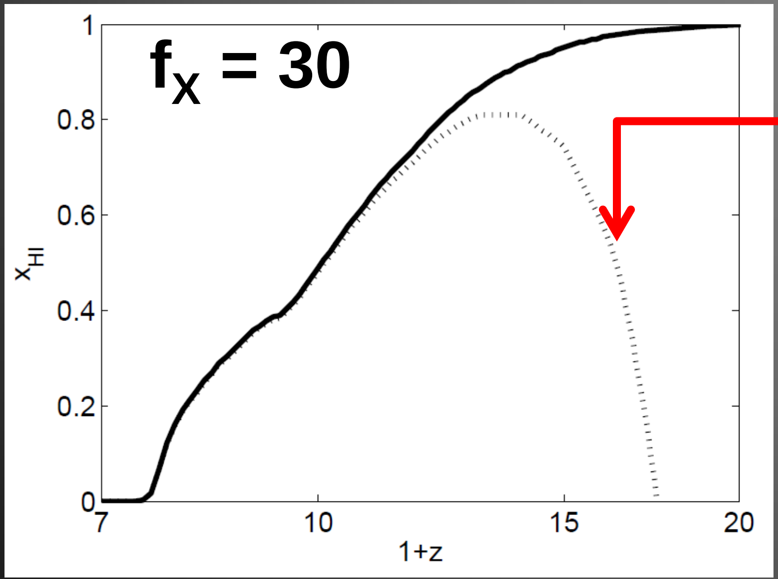
Thermal info & fitting = x_{HI}





With X-rays, reconstructed x_{HI} deviates from the real one

$$\boxed{x^{rec}{}_{HI} \propto \frac{\delta T_b}{(1+\delta)(1+z)^{1/2}}}$$



Fialkov & Loeb (2016)

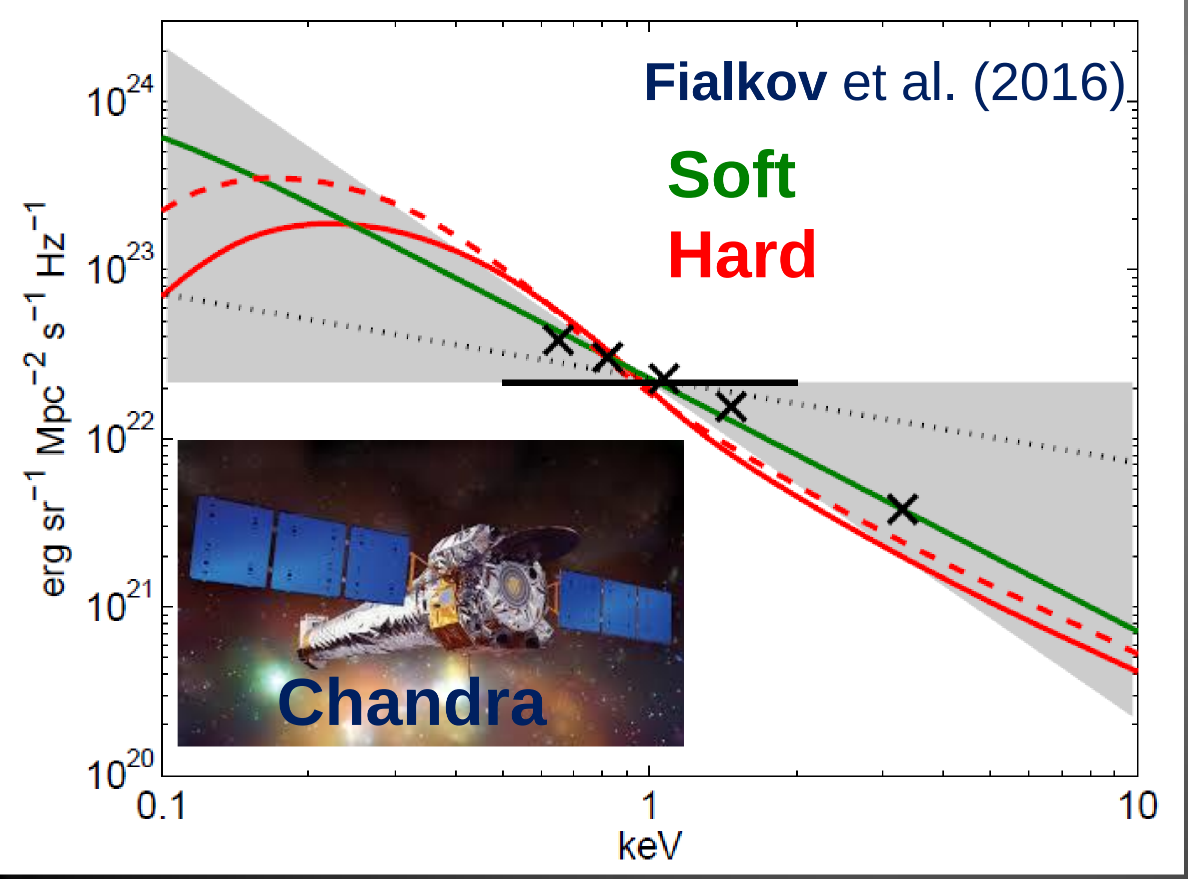
Limits on X-ray Efficiency, f_X

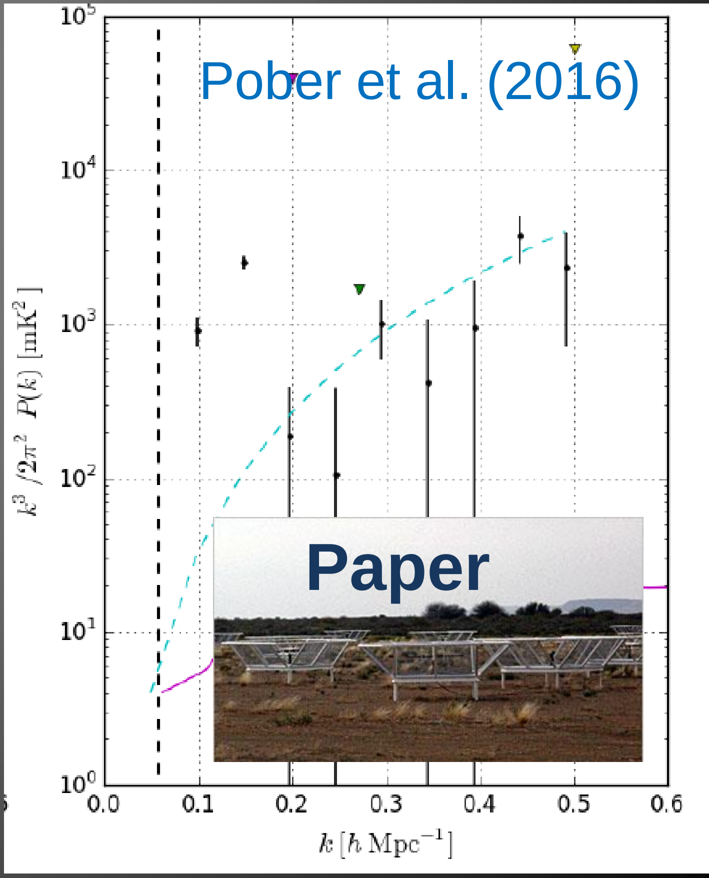
Upper Limit (f_X ~ 15 – 450)

Unresolved X-ray background (~ 12%), Lehmer et al. (2012).

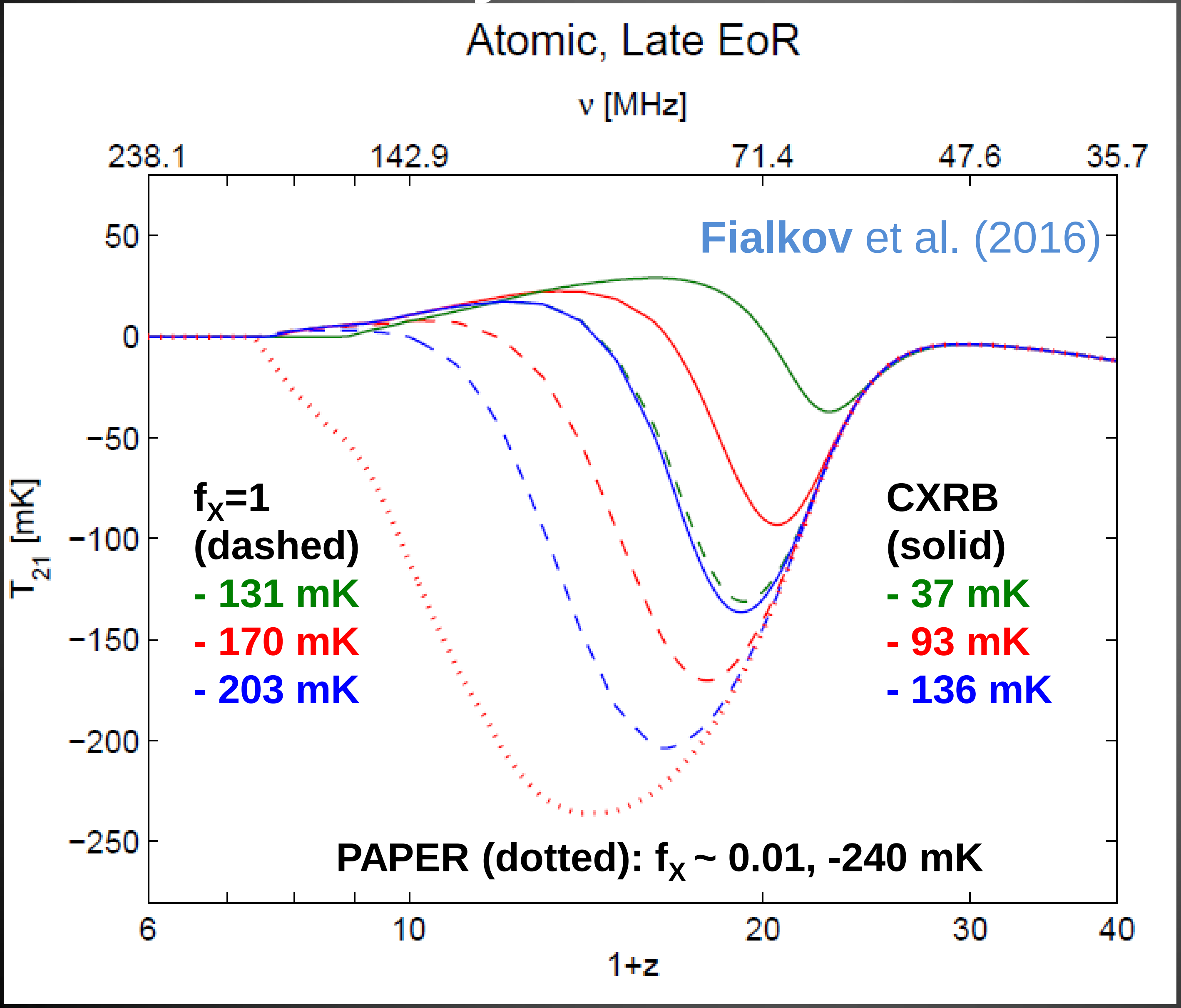
Lower Limit (f_X ~ 0.001-0.01)

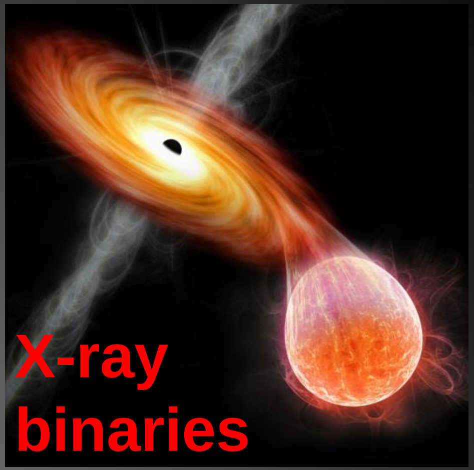
21-cm power, Ali et al. (2015), Pober et al. (2015).

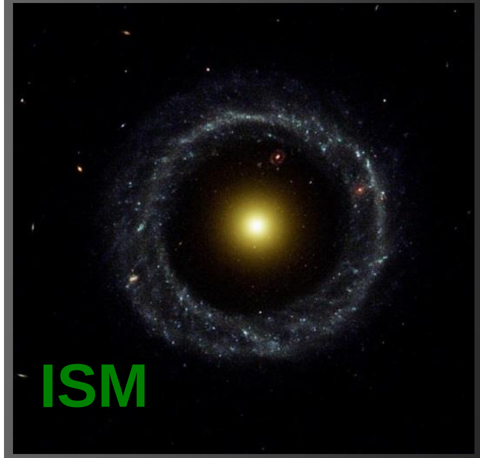




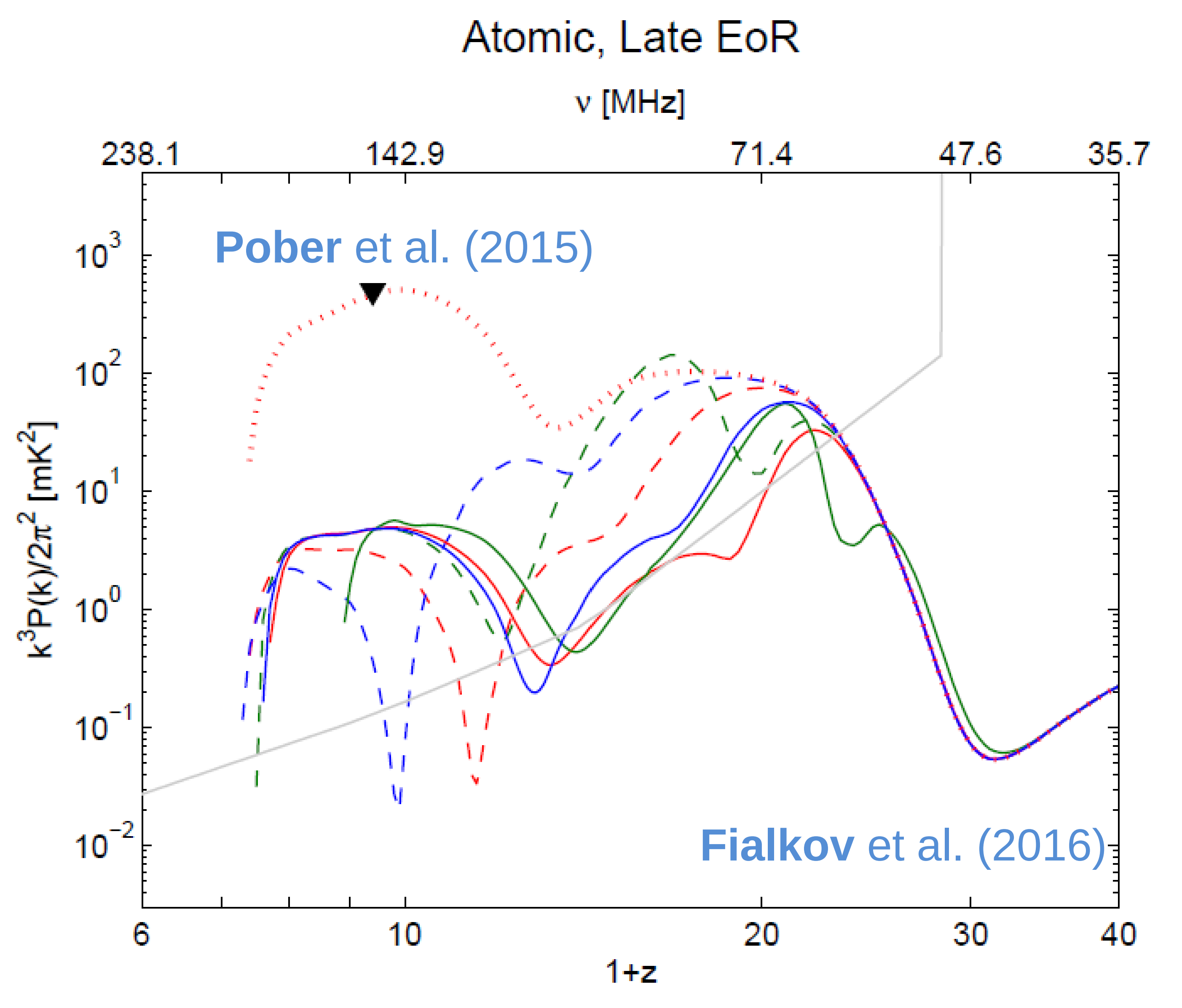
Limits on f_X
Uncertainty in the Global

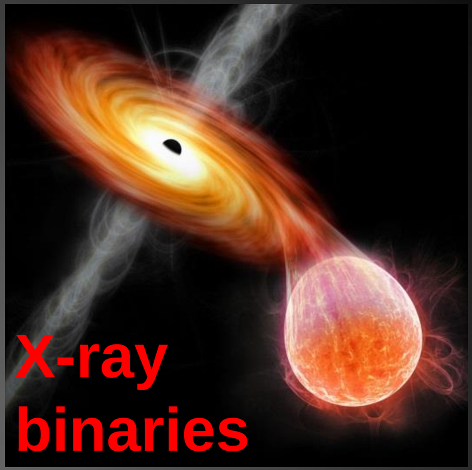


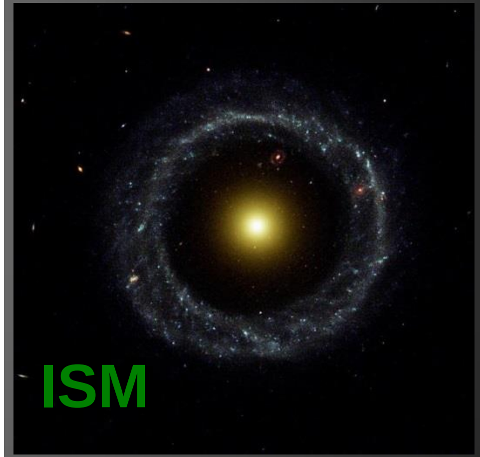




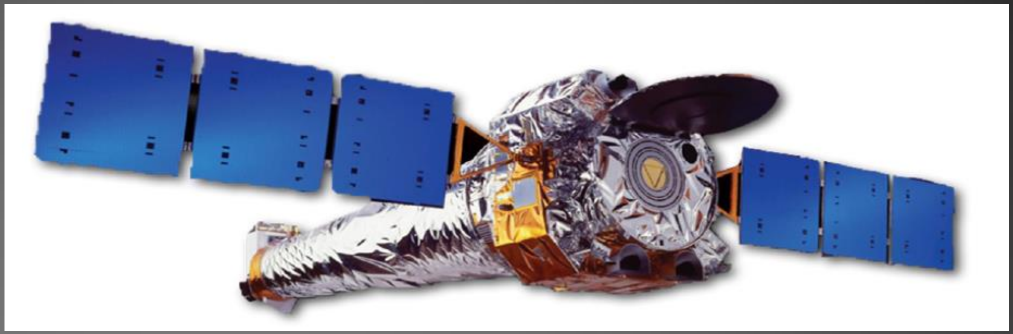
Limits on f_X
Uncertainty in the PS







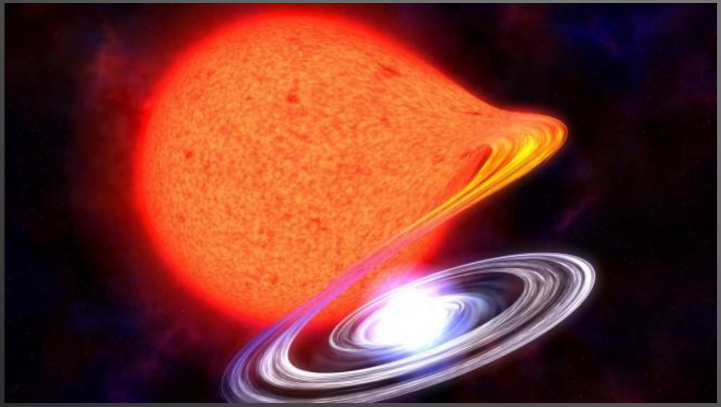
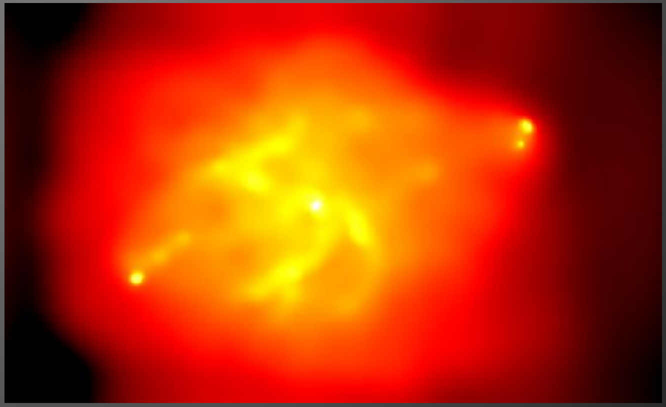
New Frontier:

Cross-correlating the 21-cm signal and the X-ray background, observed in future by X-ray Surveyor and Athena,

can help to constrain the nature of the first X-ray sources!

Work in progress.

The Role of Mini-halos

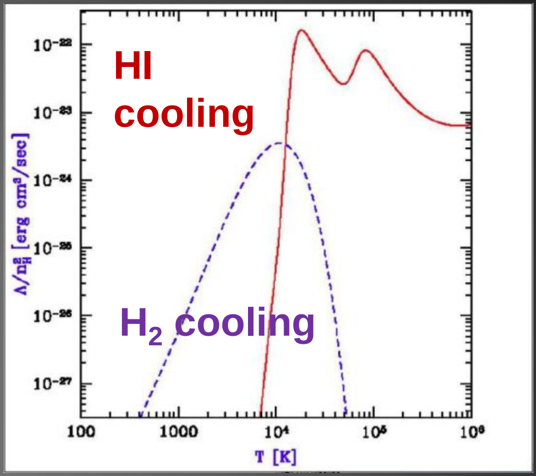
Did first stars form in small or large DM halos?
How did it affect the 21-cm signal?

1. Effect of feedbacks
2. Effect of initial conditions

1. The Effect of Radiative Feedback

Formation of first stars is via H_2 or HI cooling

- H_2 cooling in ($M_h \sim 10^5\ M_{sun}$)
- HI cooling in ($M_h \sim 10^7\ M_{sun}$)

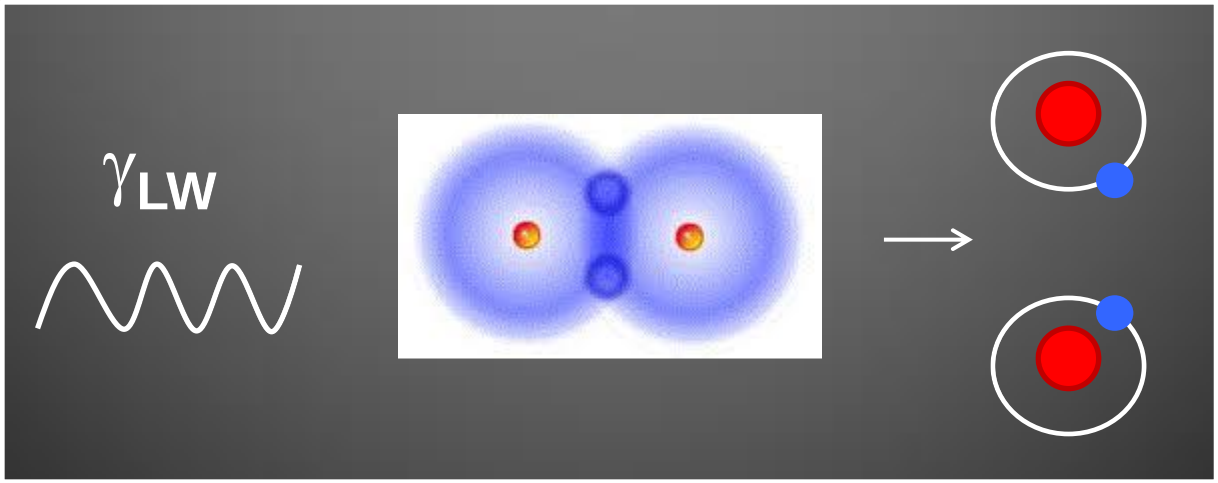


Barkana & Loeb (2001)
Bromm (2012)

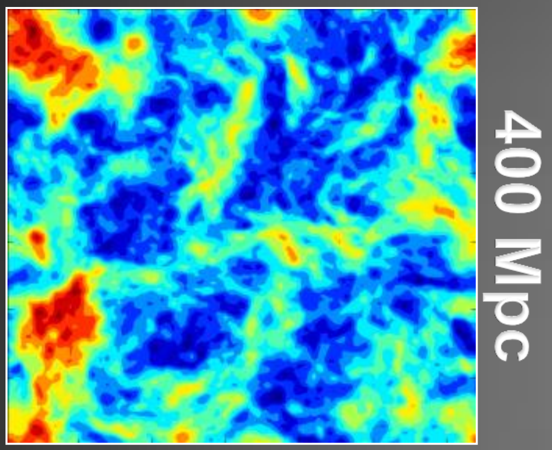
Lyman Werner photons from stars

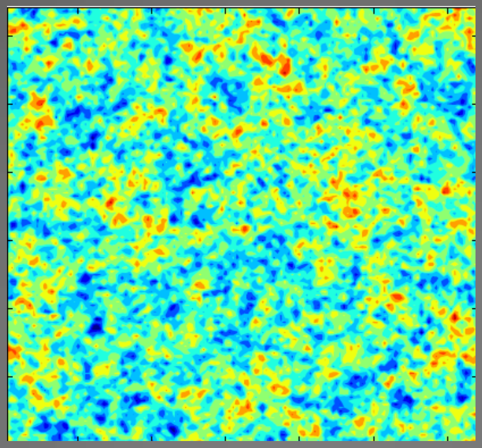
- Dissociation of H_2
- Negative feedback to star formation

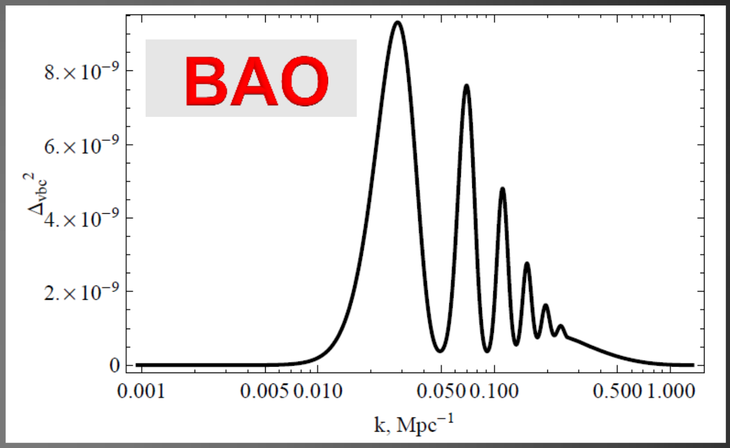
e.g., Machacek et al. (2001)



2. The Effect of Initial Conditions Relative Velocities between DM & Gas

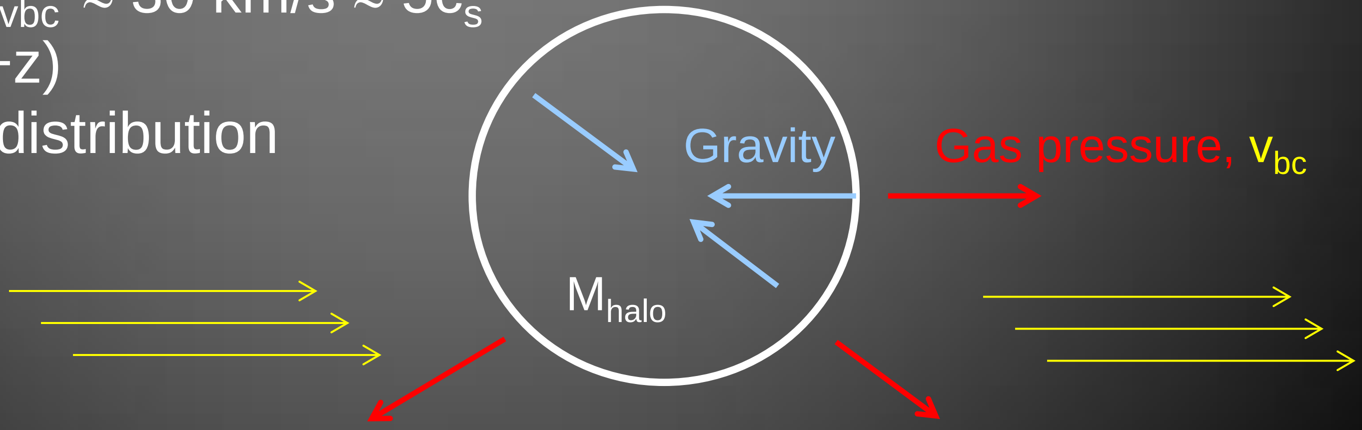






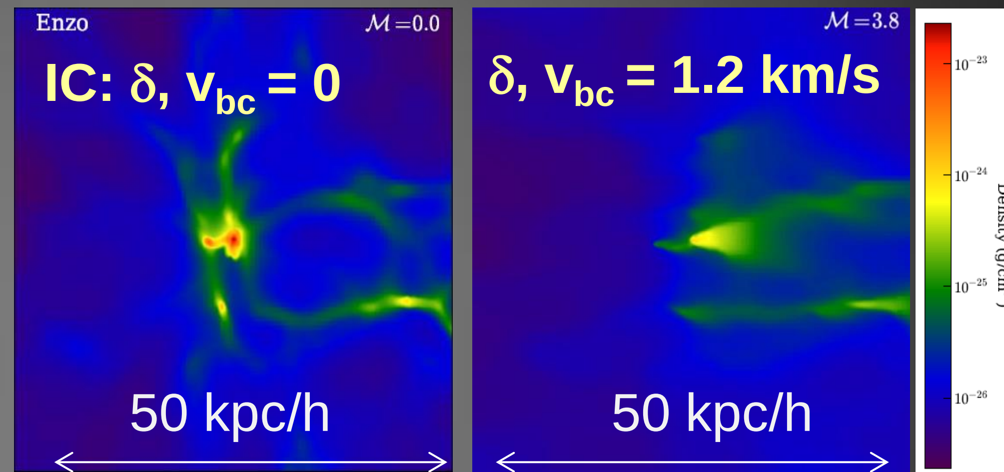
Tseliakhovich & Hirata, (2010), **Fialkov, review** (2014)

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

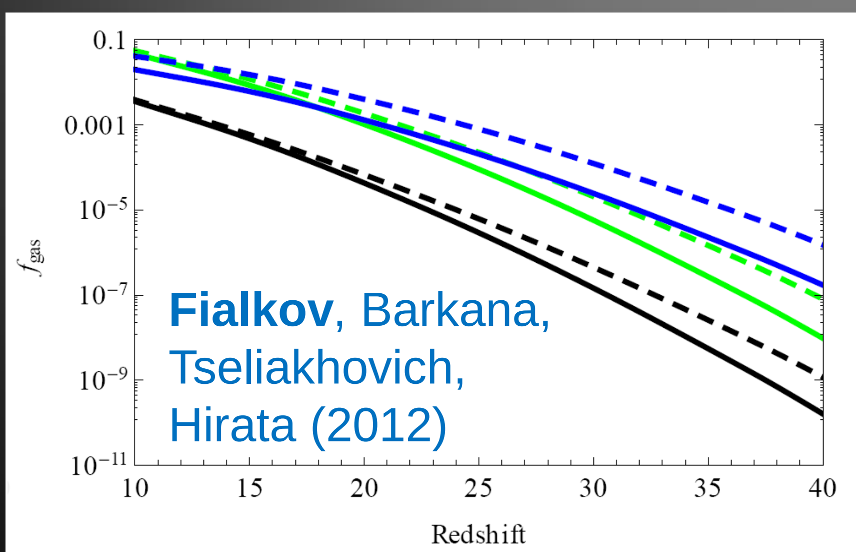


Velocities: Large Impact on Structure Formation at High z

Relative velocities affect 10^4-10^8 M_{sun} halos



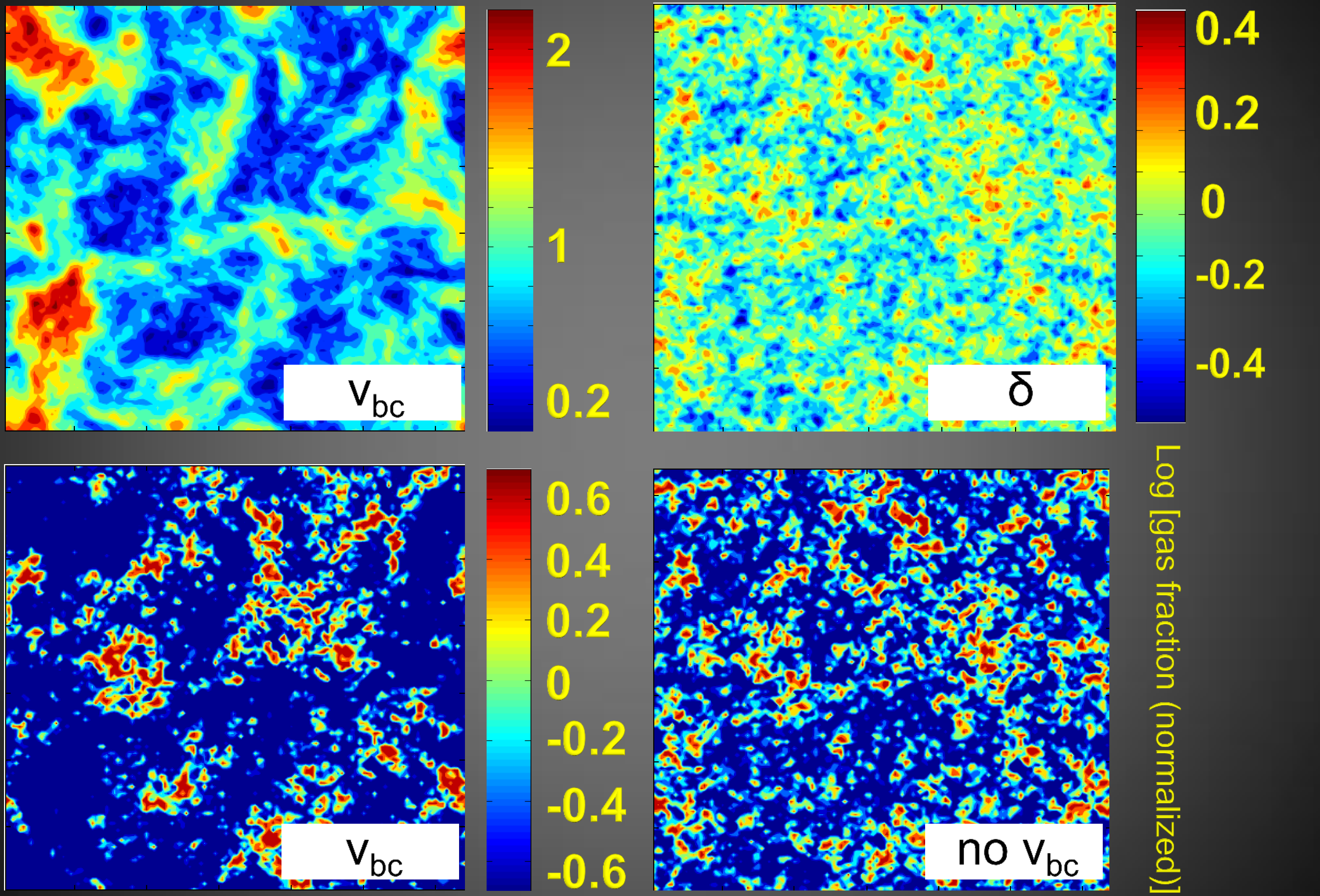
O'Leary & McQuinn (2012)



- Suppresses halo abundance
- Suppresses amount of gas in halos
- Delays star formation

Fialkov, review (2014)

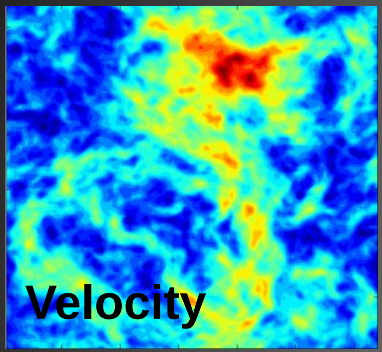
Example: Gas fraction in star-forming halos, z = 40

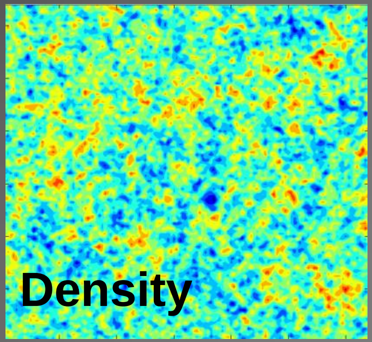


Visbal, Barkana, **Fialkov**, Tseliakhovich, Hirata (2012)

Effect of LW Feedback and Velocities

Initial conditions



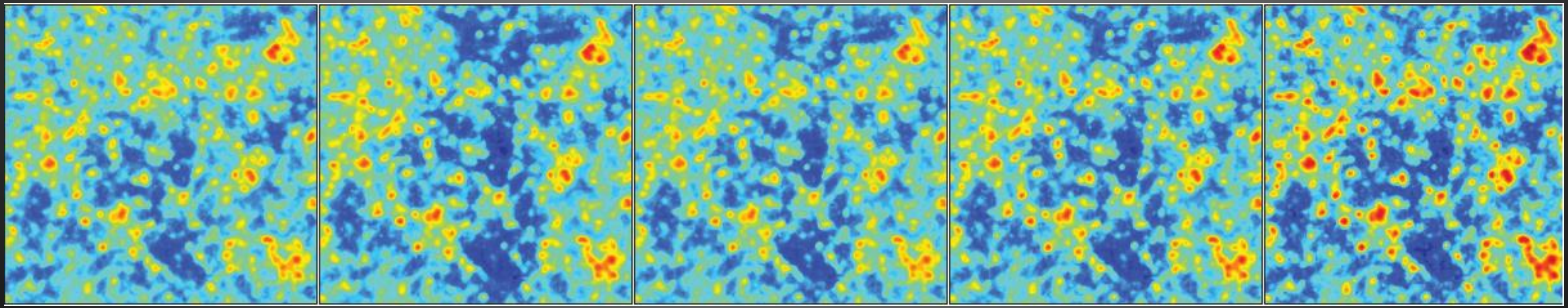


- H_2 cooling – sensitive to v_{bc} and LW feedback
- HI cooling – mildly sensitive to v_{bc}

21-cm brightness temperature

Molecular cooling

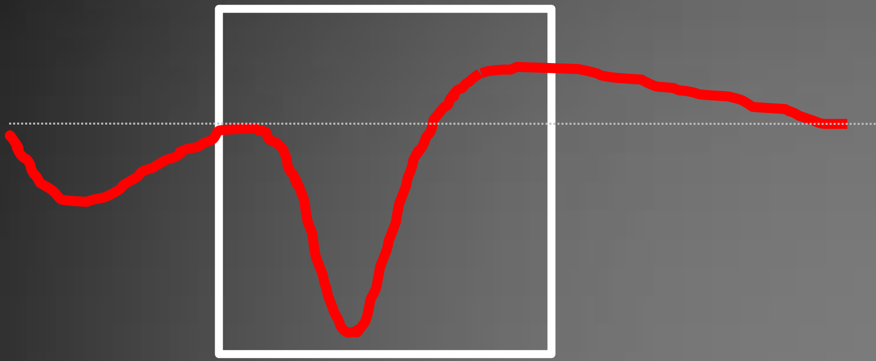
Atomic cooling



No feedback, No vbc | **No feedback** | **Weak feedback** | **Strong feedback** | **Saturated feedbback**

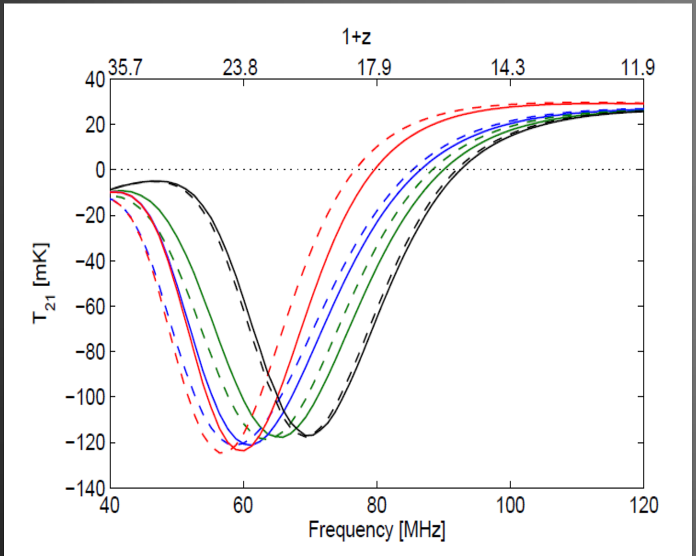
Fialkov, Barkana, Visbal, Tseliakhovich, Hirata (2013)

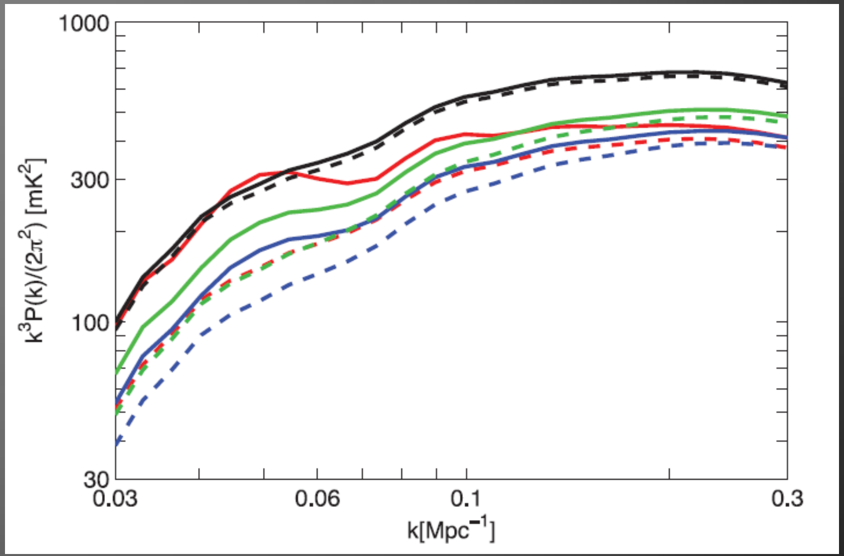
Uncertainty due to Feedback and Velocities



Delay star formation and cosmic milestones by $\Delta z \sim 3.5$

BAO in power spectrum





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

New Frontier:

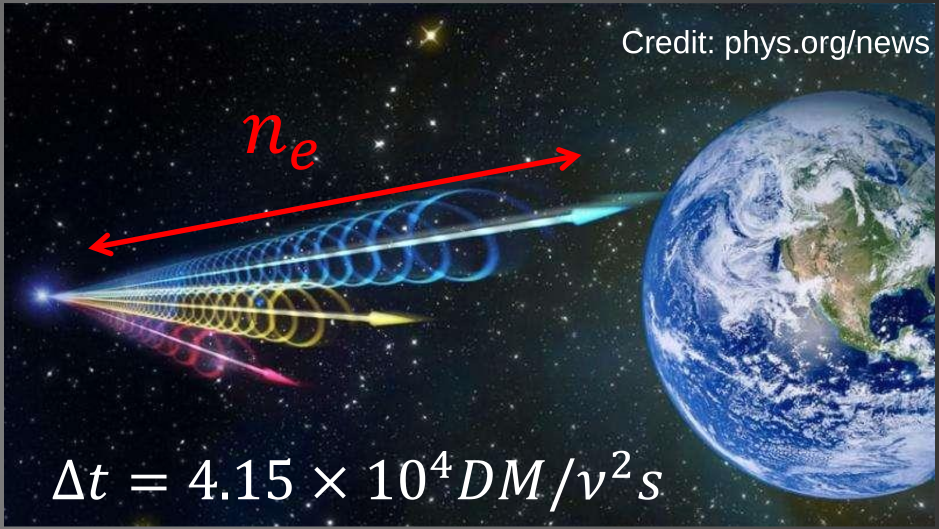
Including the velocities in initial condition of cosmological radiative hydrodynamics simulations

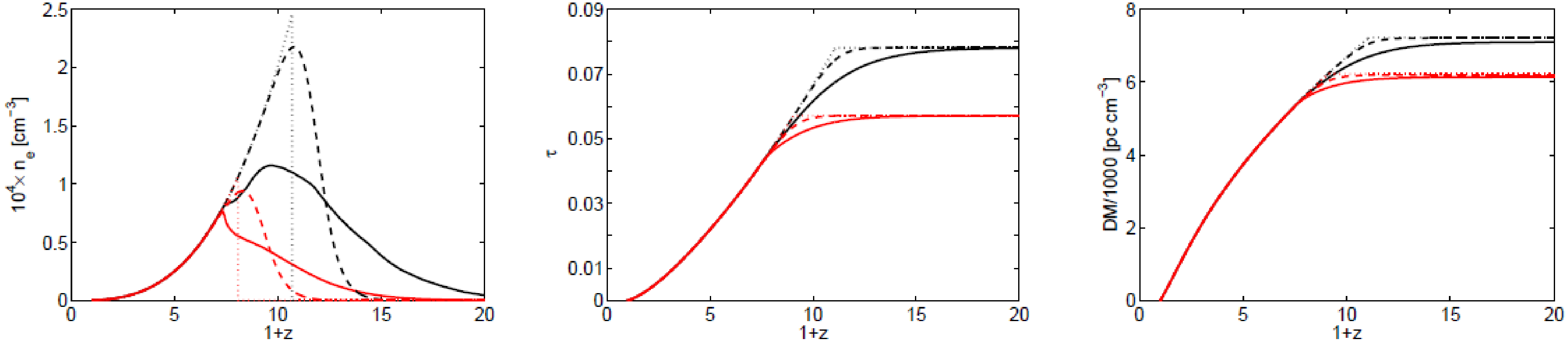
Work in progress, in collaboration with I. Iliev, D. Sulivan et al.

Alternative Probe of EoR: Dispersion Measure of Fast Radio Transients

$$DM = \int_0^z \frac{n_e}{1+z} dl$$

$$\tau = \int_0^z n_e \sigma dl$$



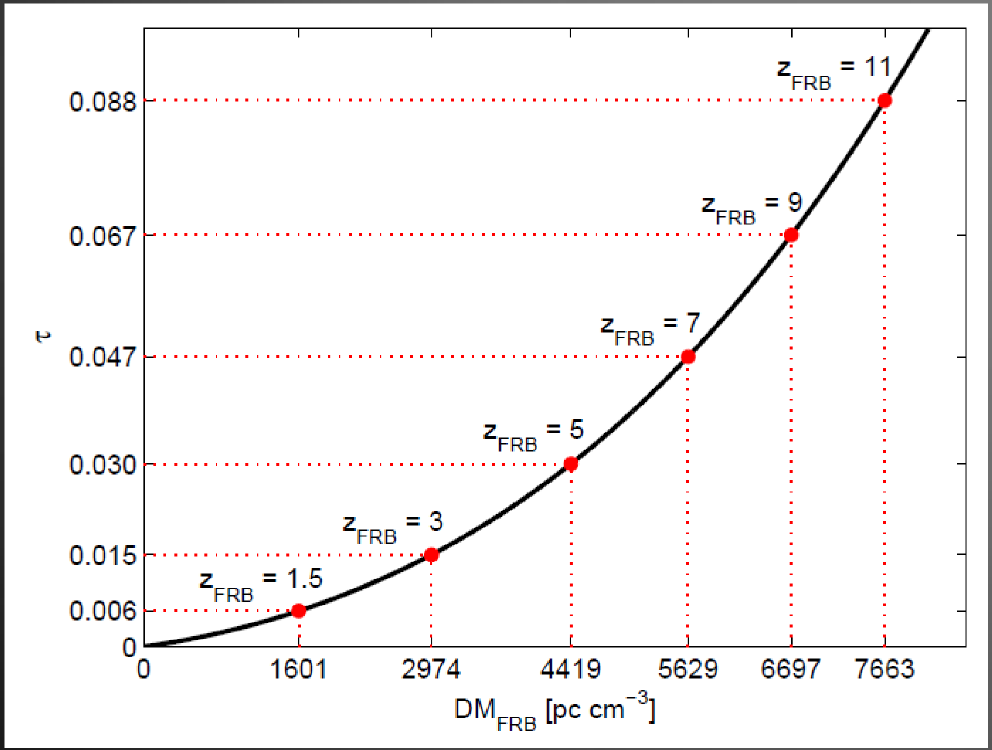


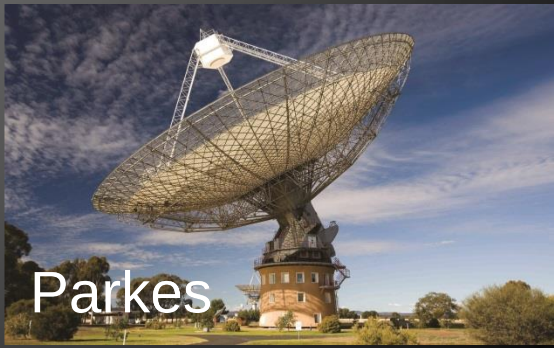
Fialkov & Loeb (2016b)

Alternative Probe of EoR

Total optical depth can be probed through the DM of high-z fast radio transients such as FRBs
(now at 0.3 < z < 1.5)

$$\tau(z) = \left[DM(z)(1+z) - \int DM(z')dz' \right] \sigma$$

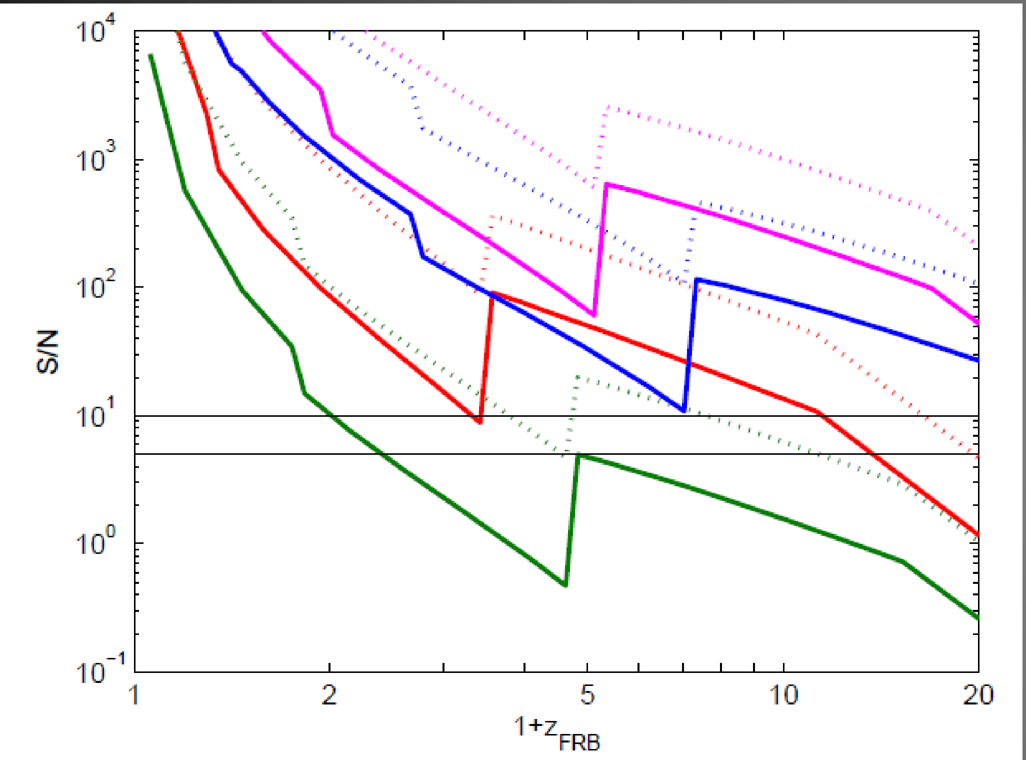




Fialkov & Loeb (2016b)

Alternative Probe of EoR

Signal to Noise with SKA



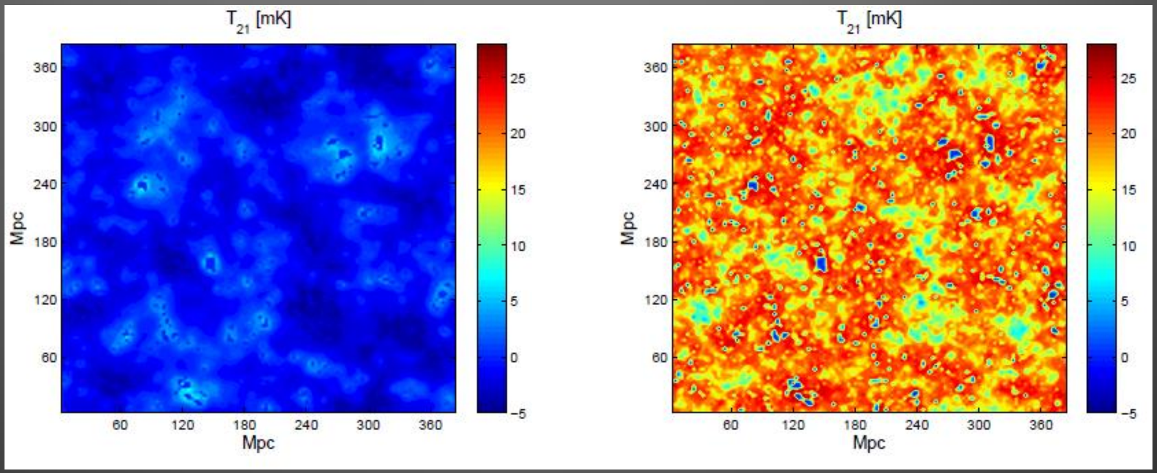
To probe $\tau = 0.055$ we need DM of 6100 pc/cm^3

Type	Event	Telescope	$\mathrm{DM_{EG}}$ [pc cm^{-3}]	z_0	ν_0 [GHz]	$L_{\nu_0}^{\mathrm{peak}}$ [erg s^{-1} Hz^{-1} sr^{-1}]
Min	FRB010621	Parkes	748	0.22	1.7	5.2×10^{32}
Median	FRB110523	GBT	623	0.55	1.2	5.0×10^{33}
Max	FRB110220	Parkes	944	0.85	2.55	2.6×10^{34}
Lorimer	FRB010724	Parkes	375	0.32	1.86	$> 8.2 \times 10^{34}$

Summary

- Bright future in radio
- X-rays are important for EoR and Cosmic Dawn
- With 21-cm we can constrain the nature of heating sources and the role of mini-halos in star formation
- Transients as a probe of EoR

Hard X-rays Soft X-rays



Fialkov, Barkana, Visbal (2014)