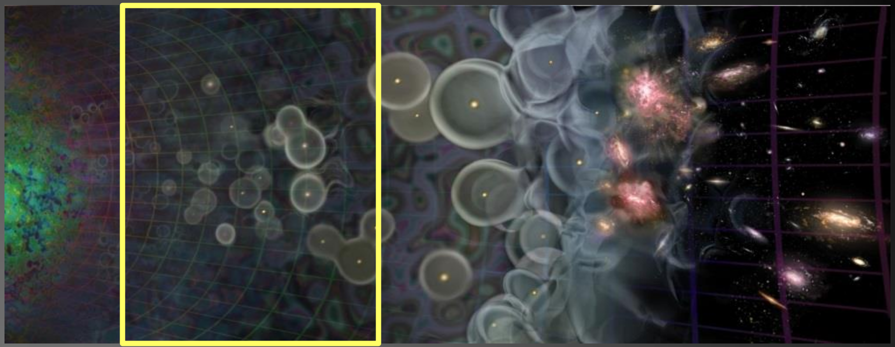
The Pre-Reionization 21-cm Signal

Anastasia Fialkov

2 October 2015

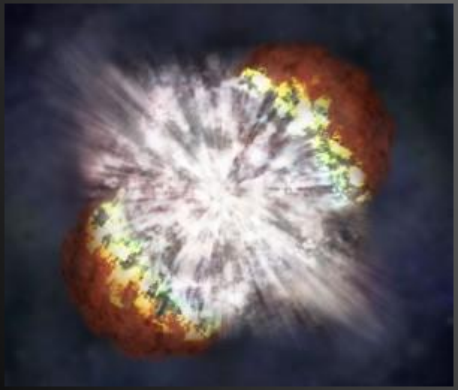
Département de Physique
École Normale Supérieure

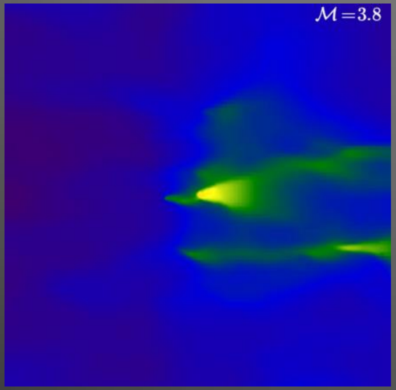
High-redshift Environment

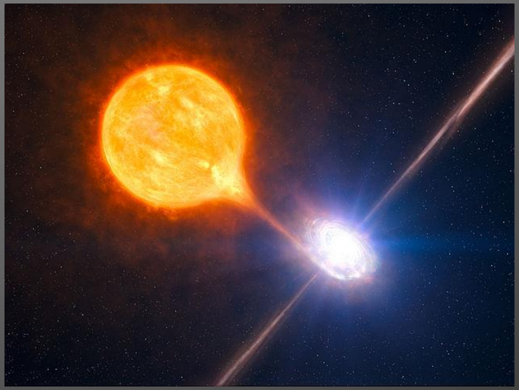


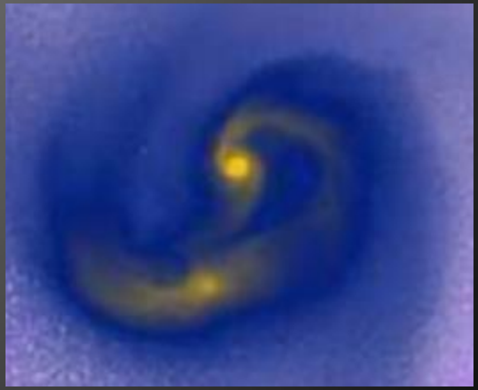
- Cold metal-poor IGM
- Small halos
- Star formation in rare regions
- Supersonic motion between baryons and gas on large scales
- Diverse populations: small black holes, heavy stars, pair instability SN, variety of X-ray sources
- Radiative feedbacks (e.g., LW)

What is the effect on 21-cm signal?







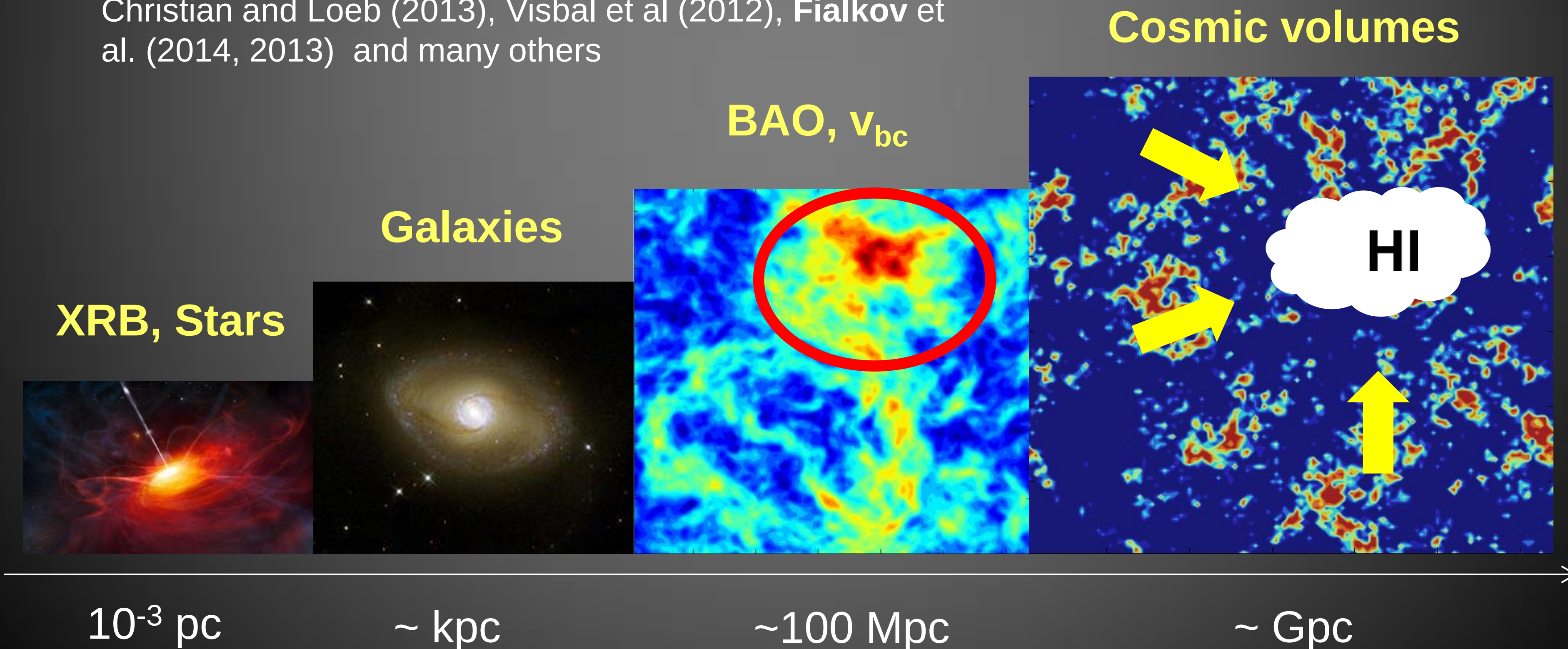


Simulating 21-cm Signal

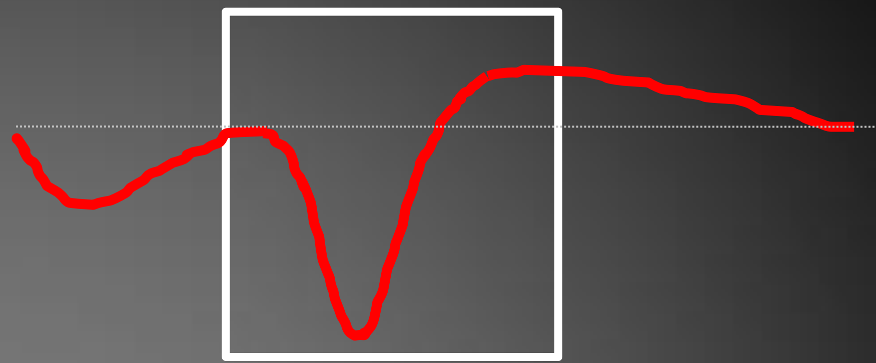
Simulate both small scales (need to know the sources) and large cosmological scales (size of the Universe)

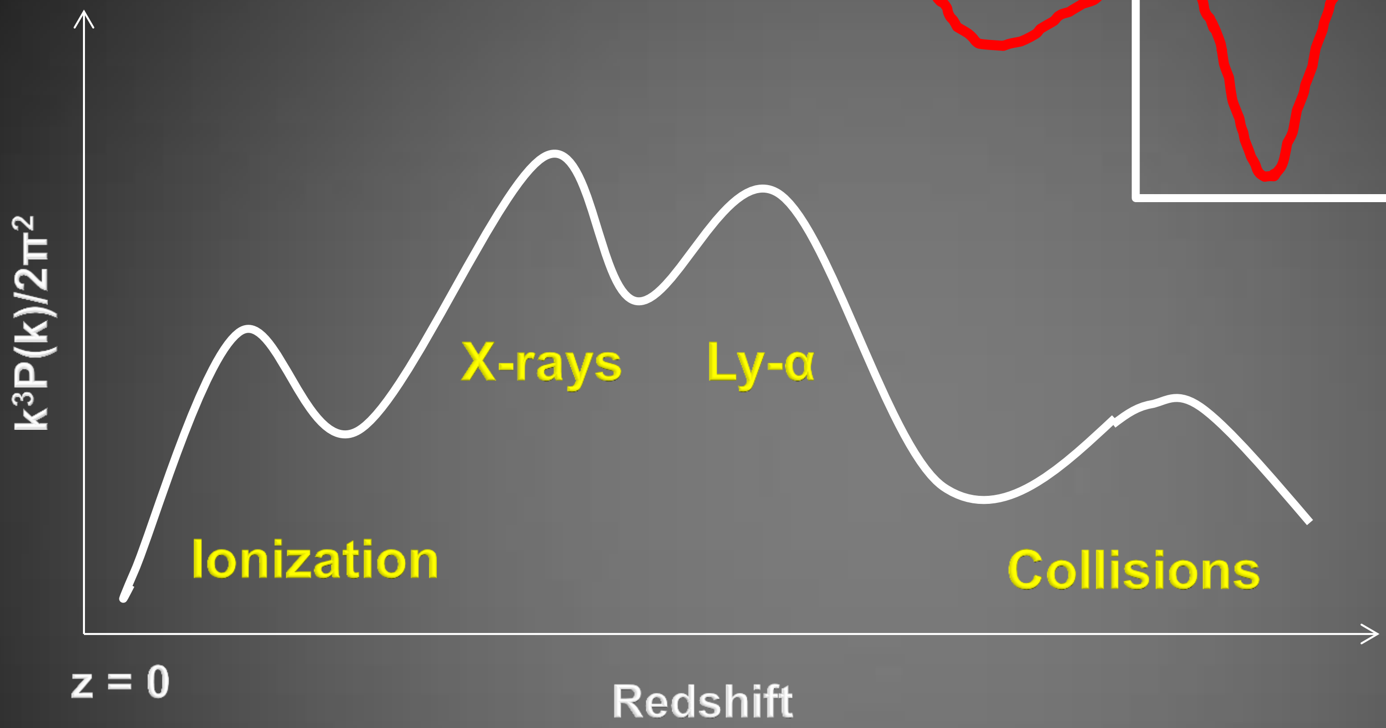
Talk by A. Mesinger.

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

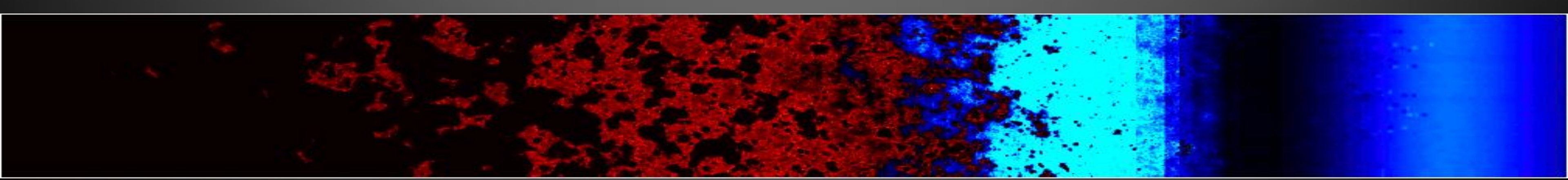


Expected Signal

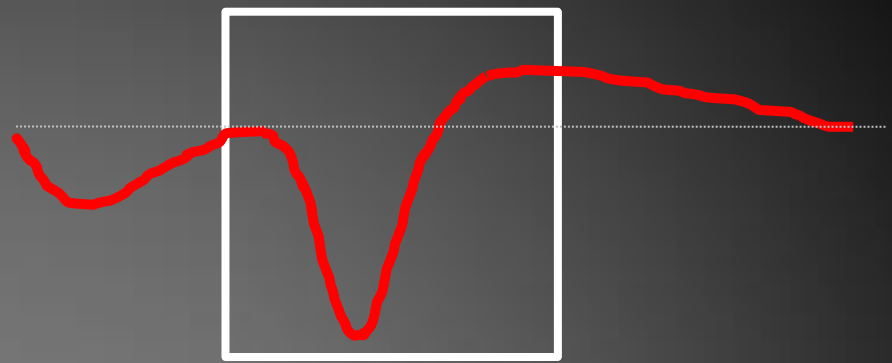




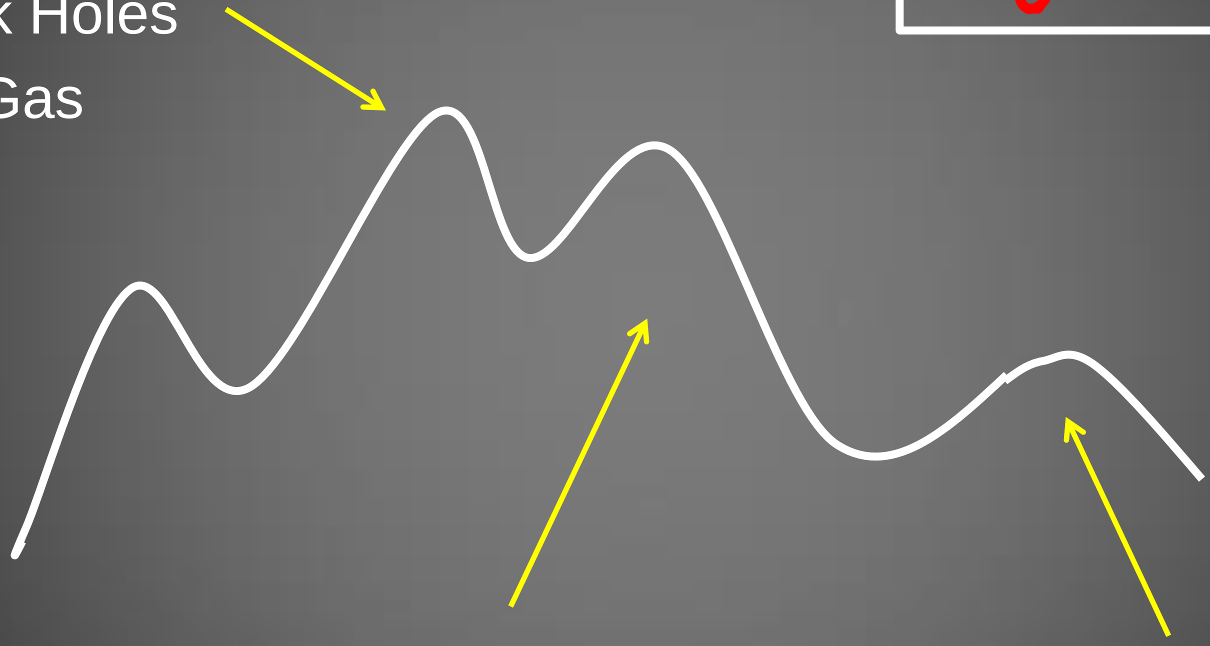
- We agree on the shape
- Details are controversial



Expected Signal



- XRB
- Black Holes
- Hot Gas
- SN

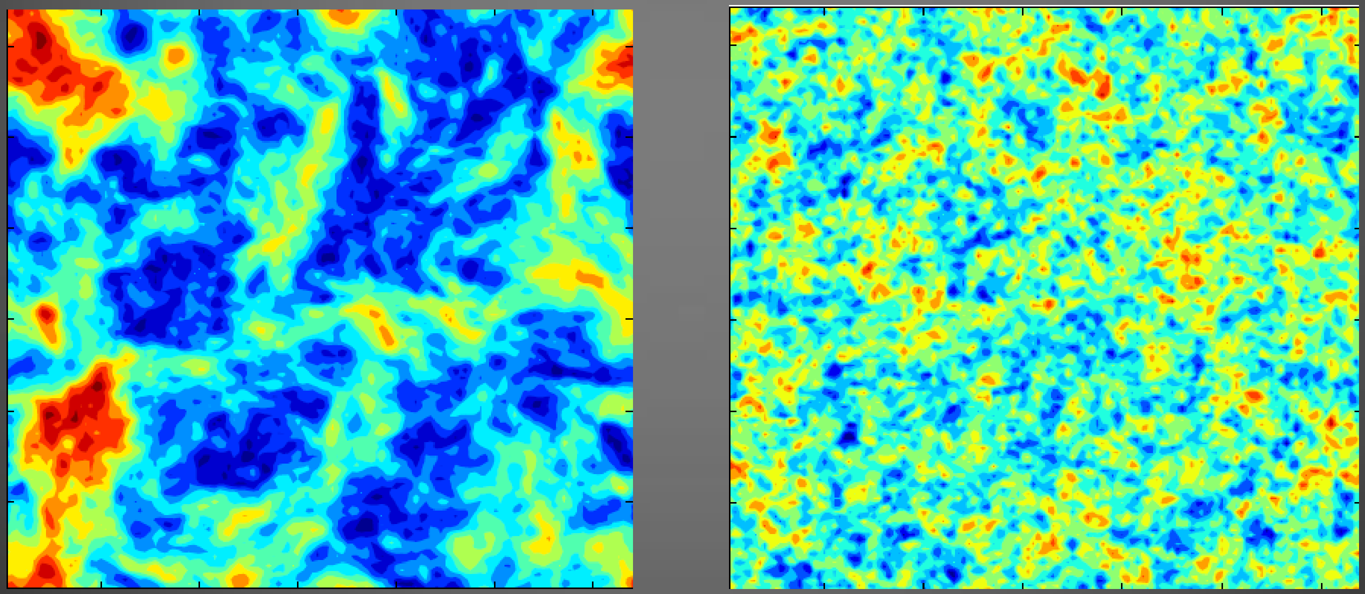


- Stars
- X-ray excitations

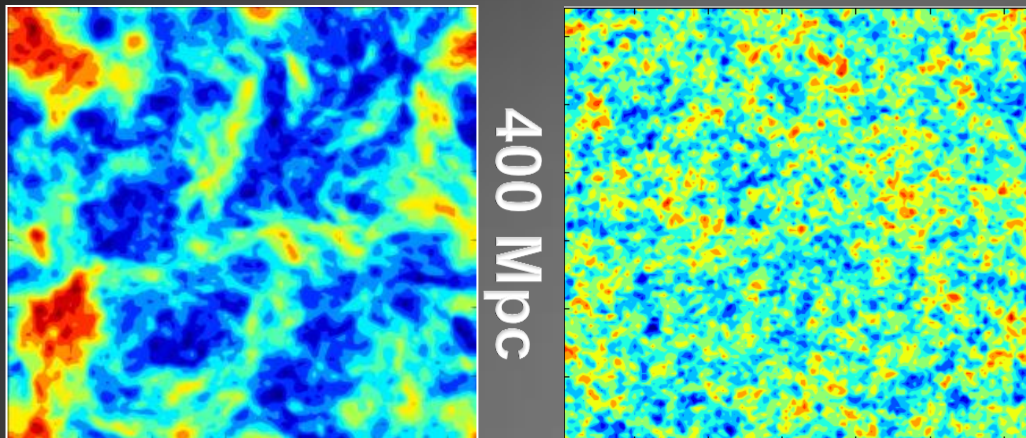
- Atomic physics
- DM?
- Magnetic fields?

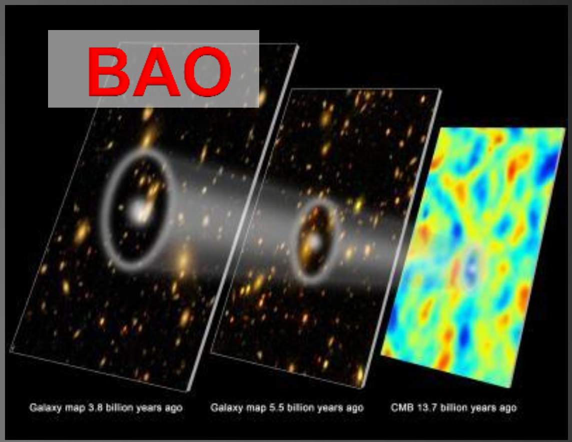
Distribution of First Star-Forming Regions

Biased by large scale density and velocity modes

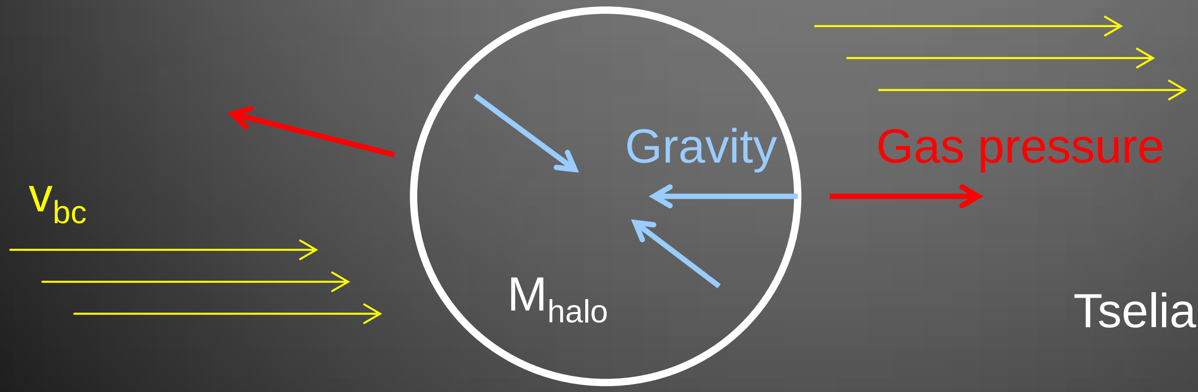


Supersonic Relative Velocities





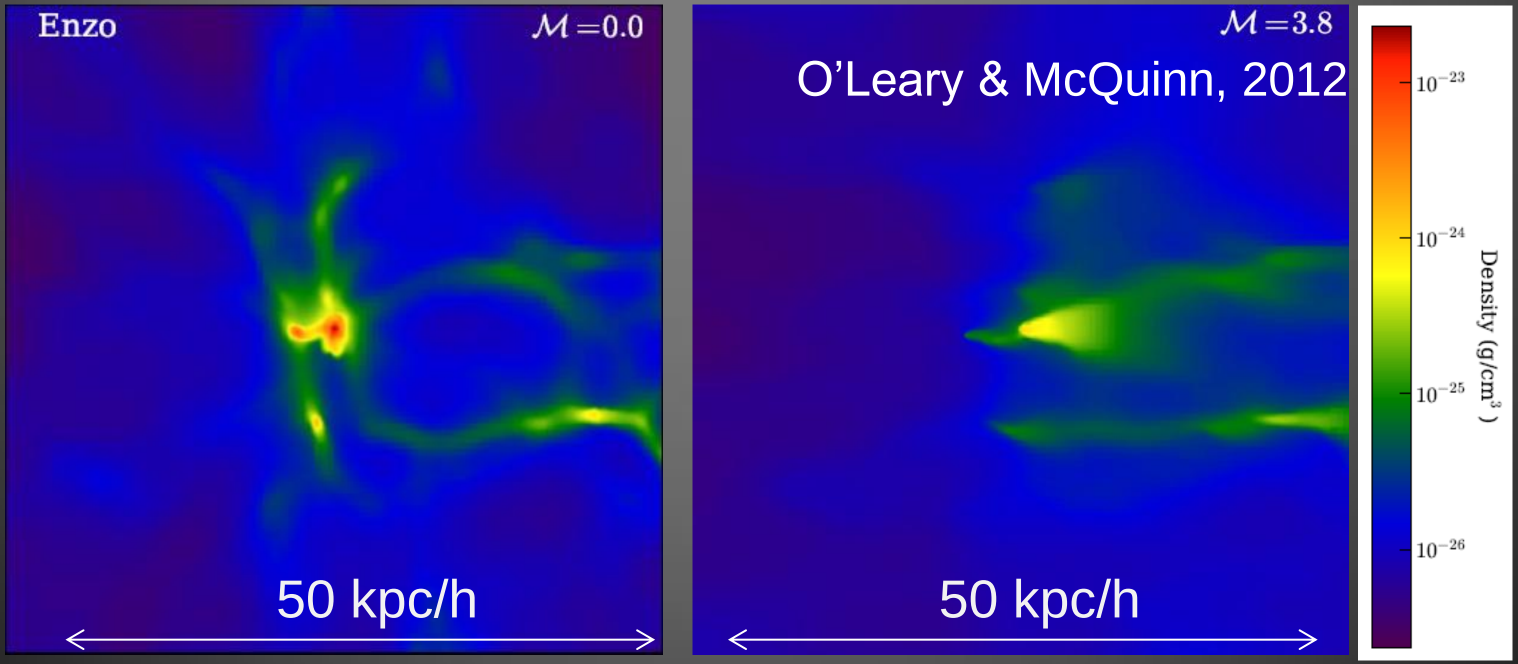
- Supersonic: $\sigma_{vbc} \approx 30$ km/s $\approx 5c_s$
- Random distribution with ~100 Mpc scale
- Gas overshoots DM halos, Largest impact on 10^5 M halos (H_2 cooling)



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

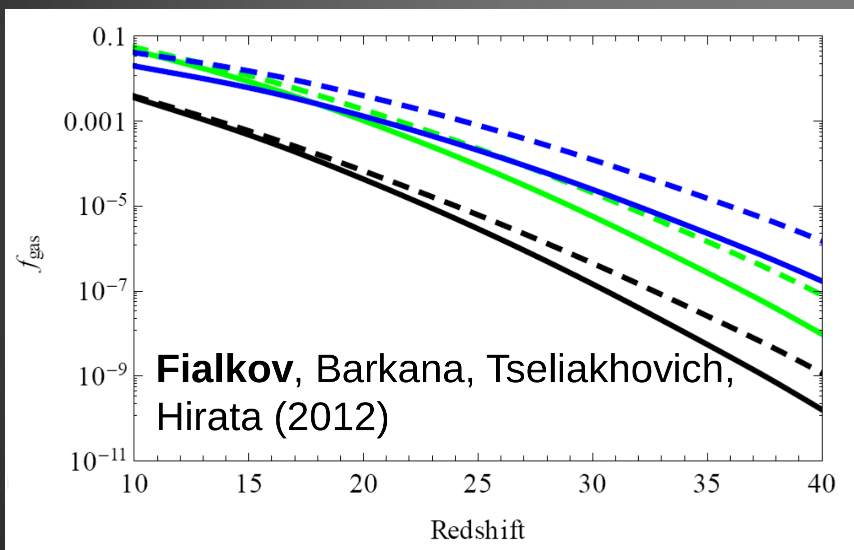
Large Impact on Structure Formation at High z

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



Large Impact on Structure Formation at High z

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

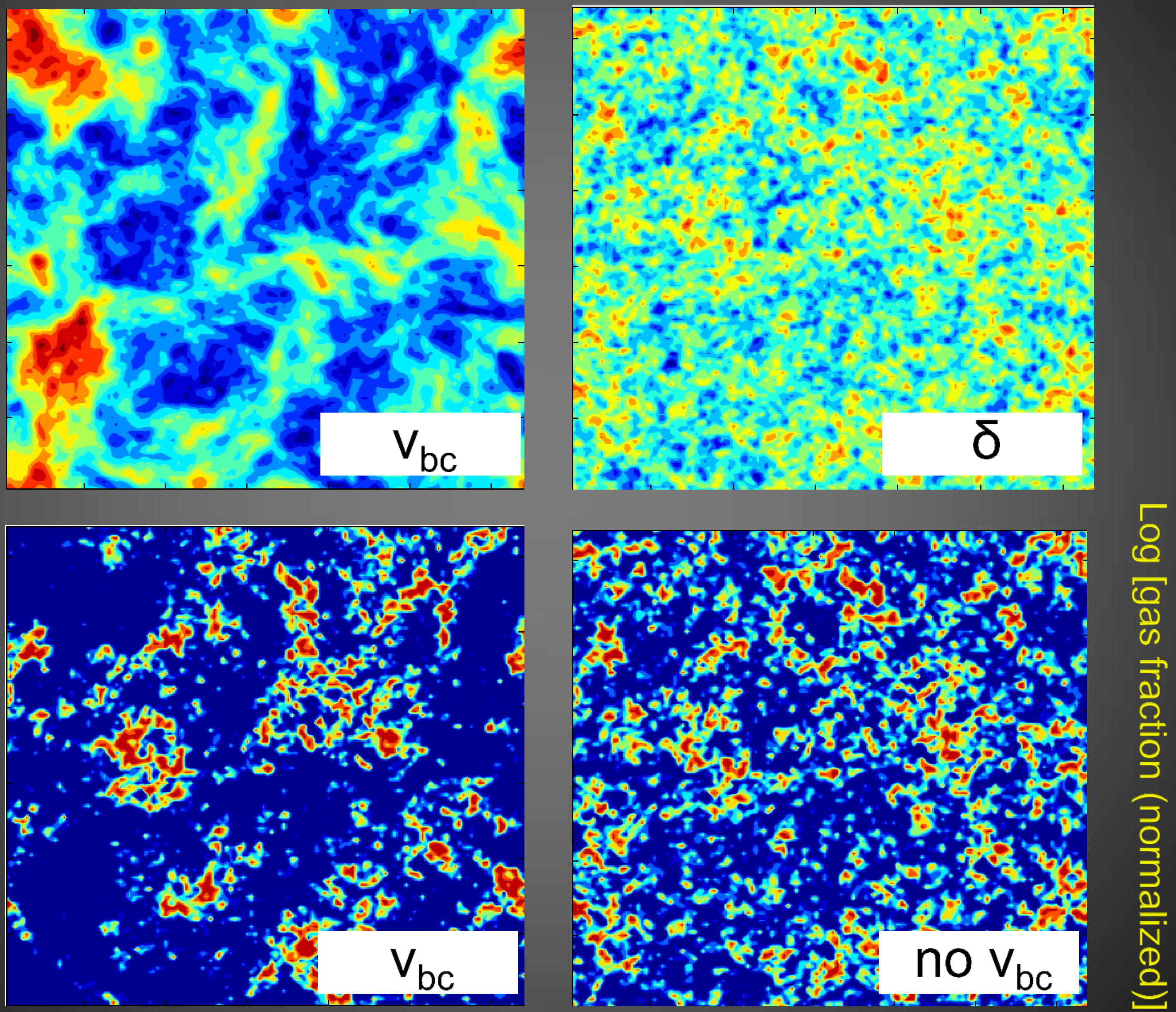


- Suppresses halo abundance
- Suppresses amount of gas in halos
- Delays star formation

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 …

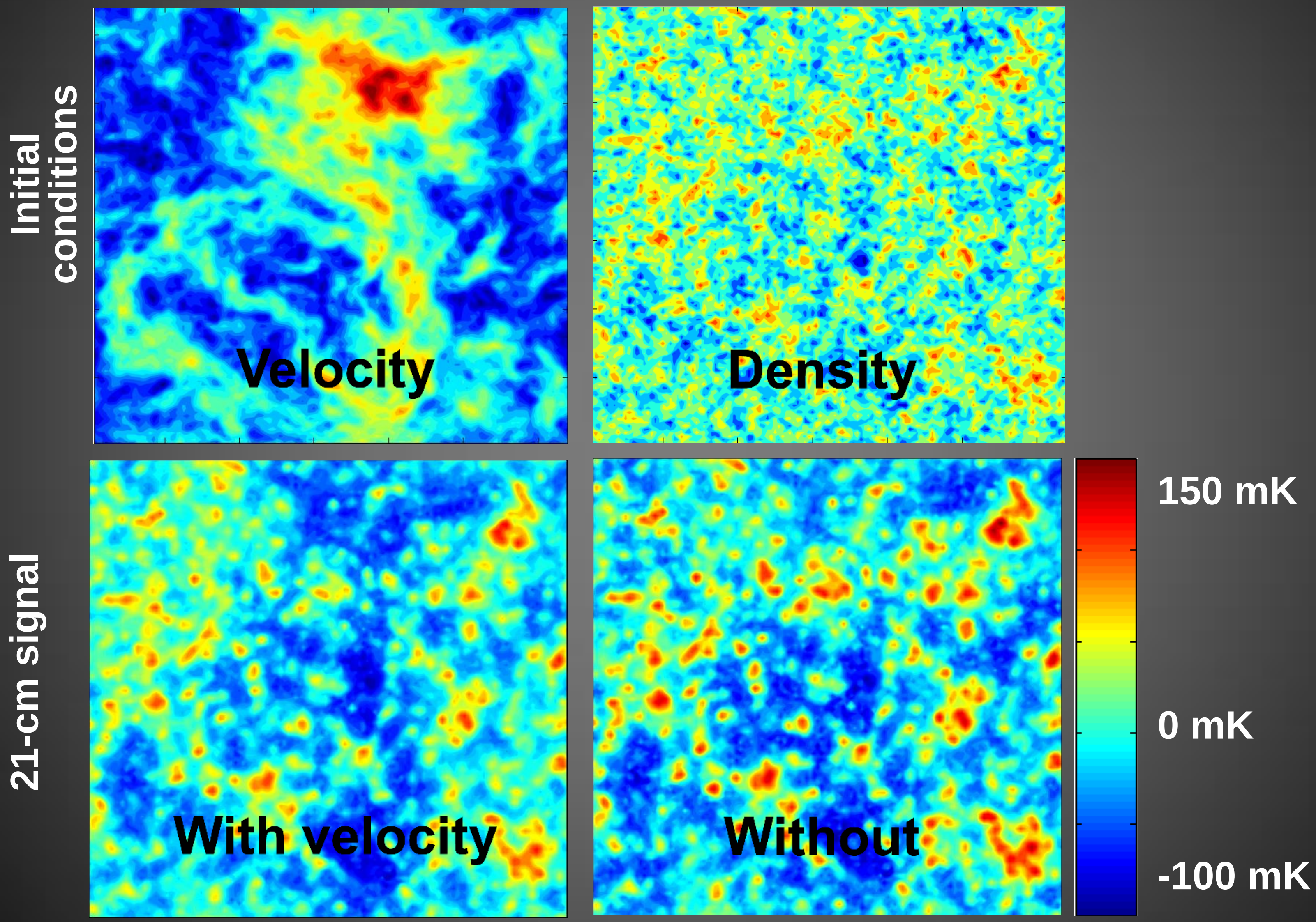
SF Regions

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



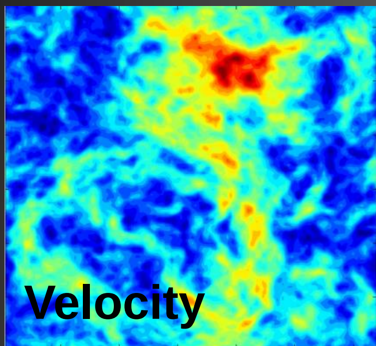
21-cm

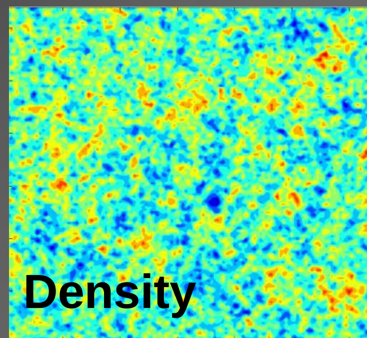
Visbal et al (2012), **Fialkov** et al (2013)



BAO are Easily Erased

Initial conditions



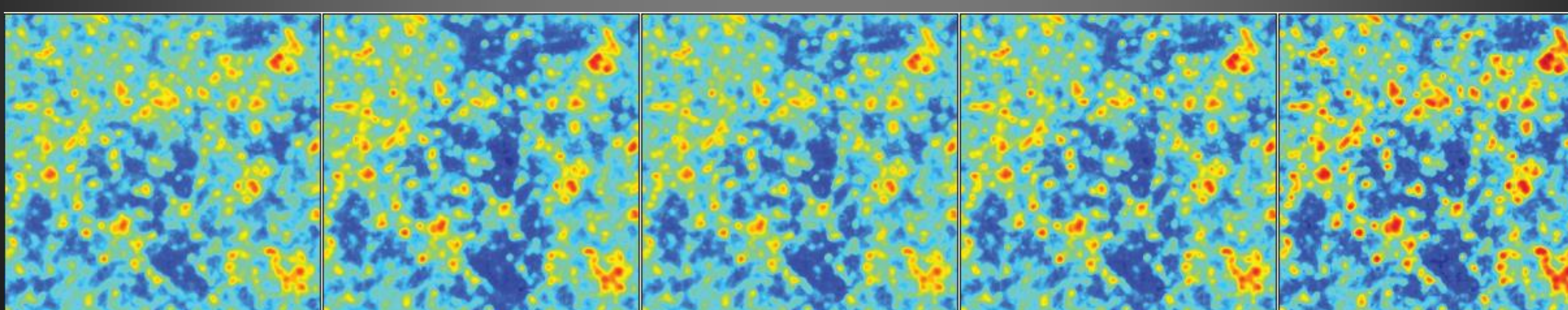


- H_2 cooling can be inefficient (LW feedback)
- HI cooling – mildly sensitive to v_{bc}
- Metal line cooling can revive v_{bc}

21-cm brightness temperature

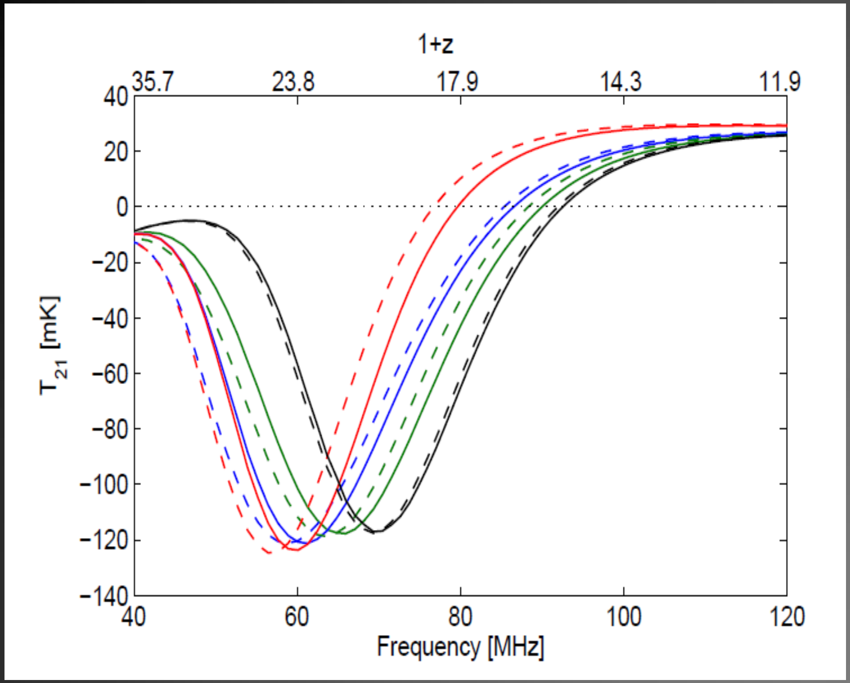
Molecular cooling

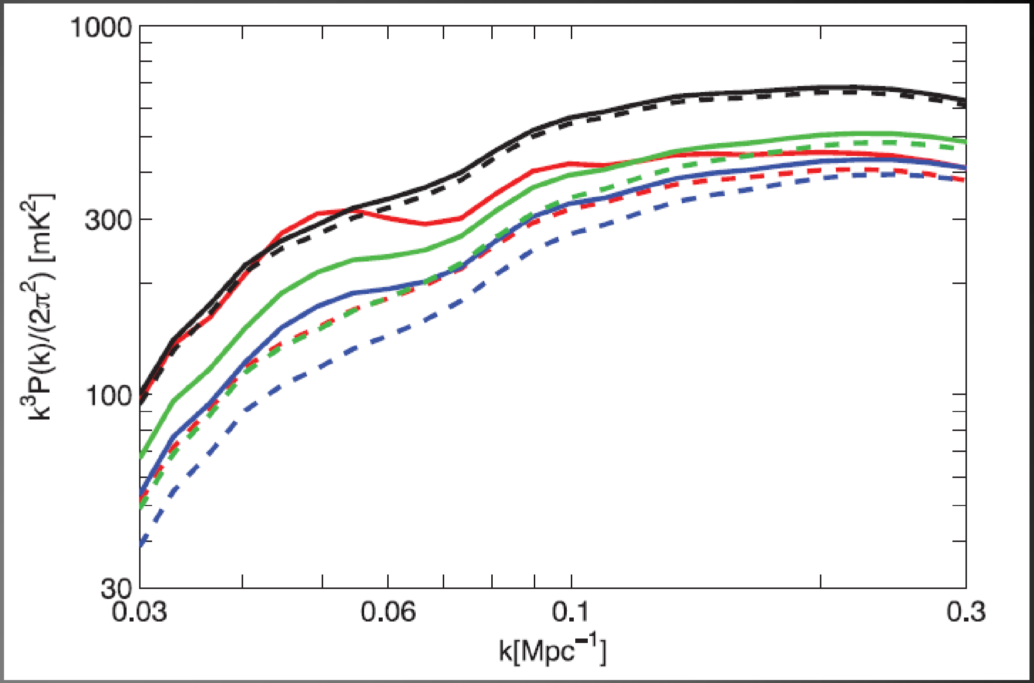
Atomic cooling



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

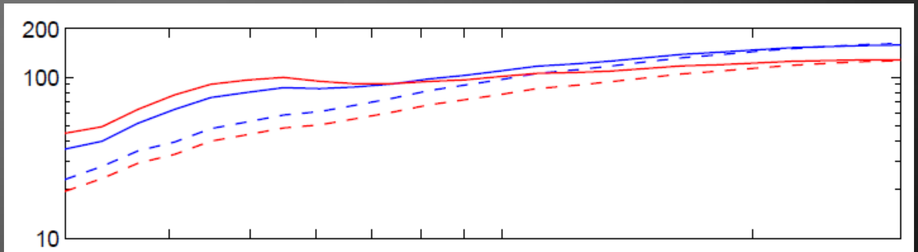
Fialkov, Barkana, Visbal, Tseliakhovich, Hirata (2013)





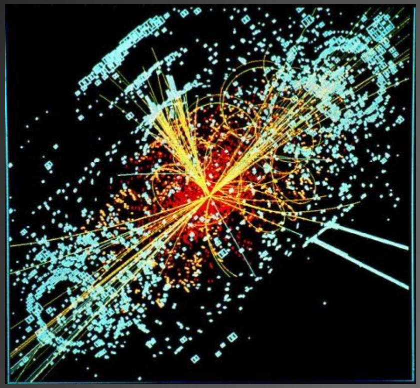
Fialkov, Barkana, Visbal, Tseliakhovich, Hirata (2013)

- H_2 and HI cooling : Delay star formation and cosmic milestones by $\Delta z \sim 3.5$
- Metal line cooling



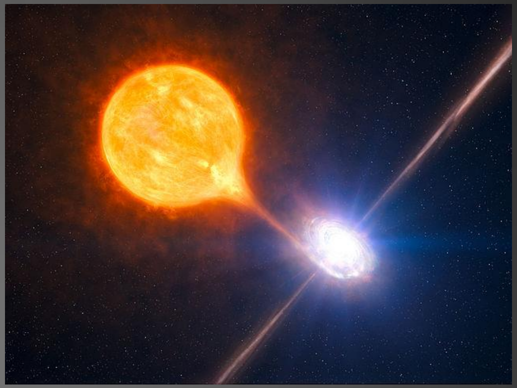
Cohen, **Fialkov**, Barkana (2015)

Signature of Heating



Dark matter annihilation

A quasar



A black hole binary (ESO image)

Possible heating sources:

X-ray binaries?

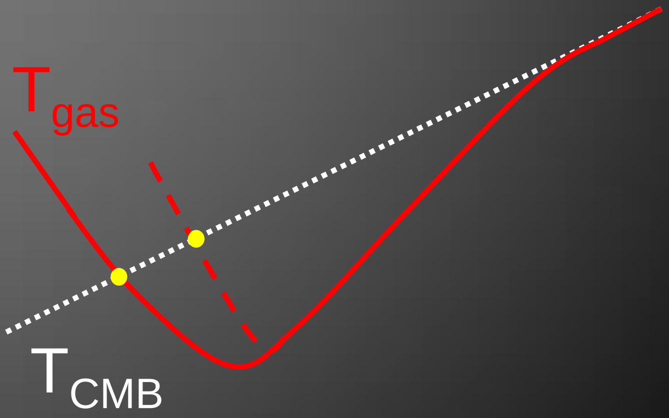
Thermal emission from galaxies?

Black holes, mini quasars?

Dark matter annihilation?

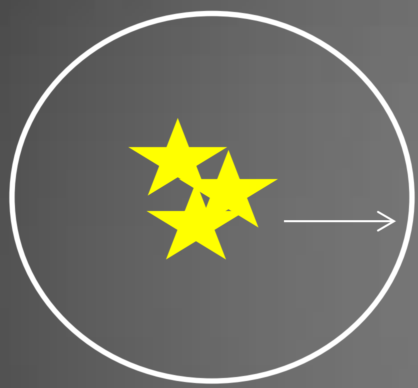
Cosmic rays?

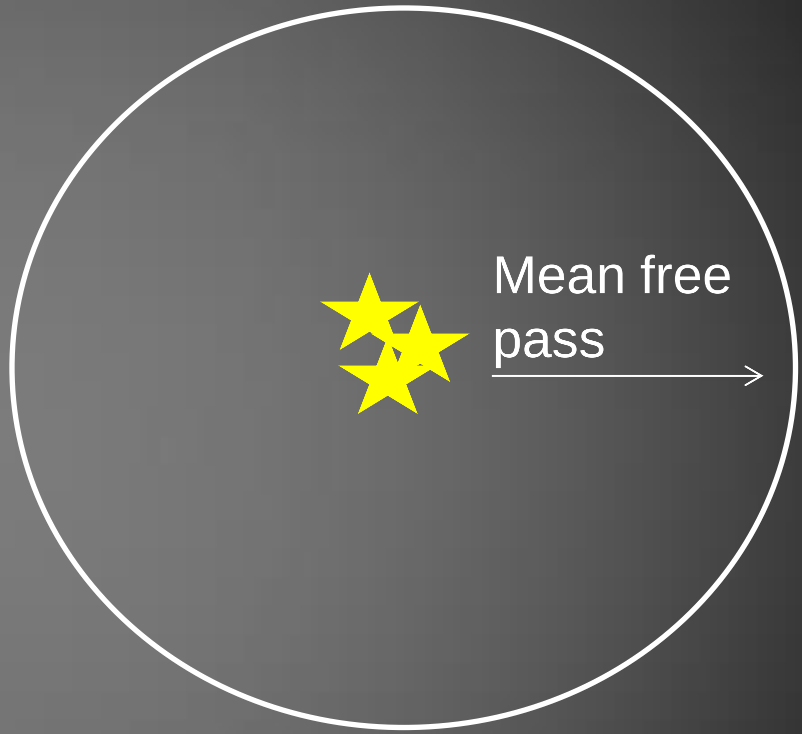
Magnetic fields?



Soft or Hard X-ray Sources? How does it affect 21cm signal?

Details of SED are crucial!

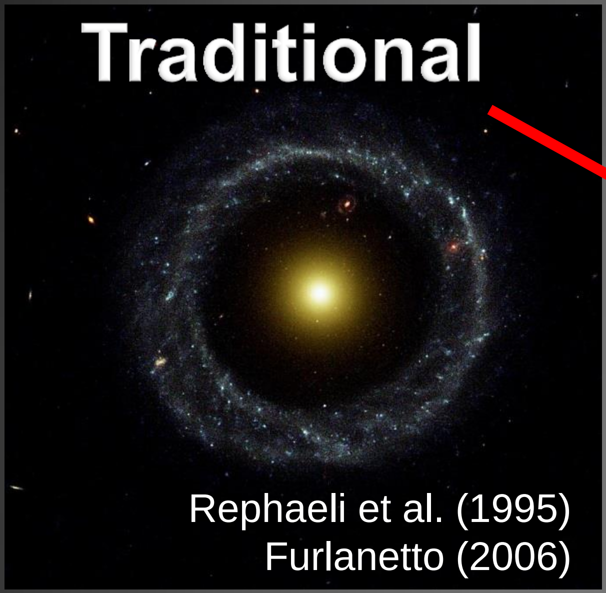




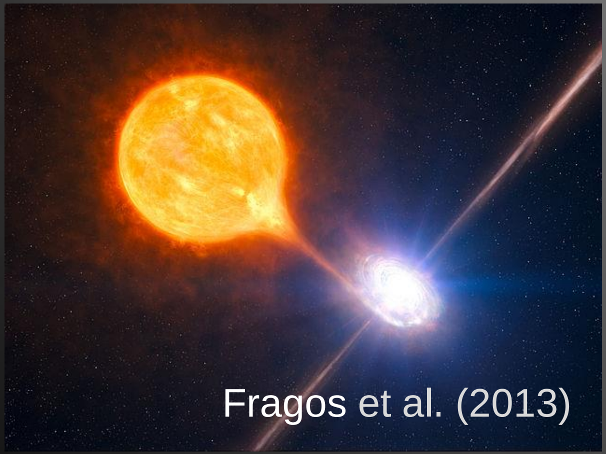
If hard X-rays

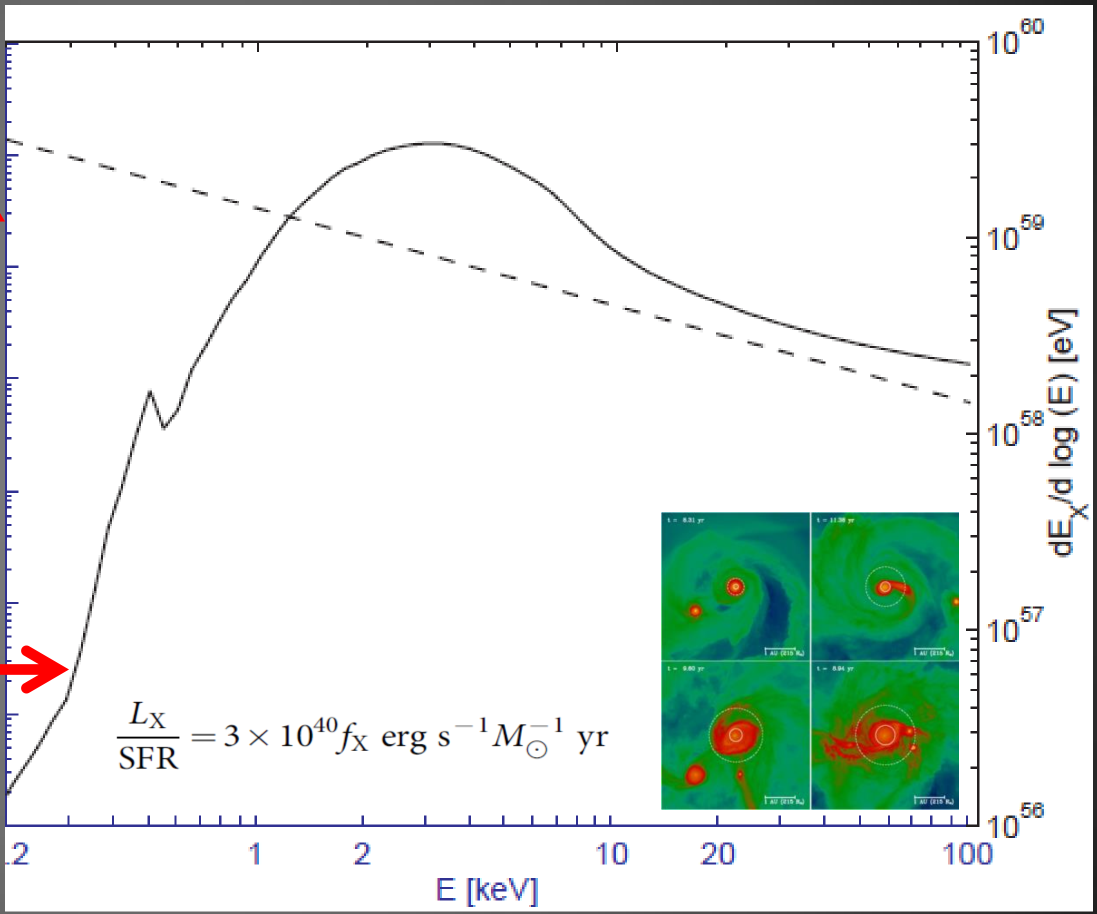
- Mean free pass is longer
- Delayed heating (energy redshifts away)
- Heating fluctuations are washed out at scales below mfp

Spectral Energy Distribution of X-rays



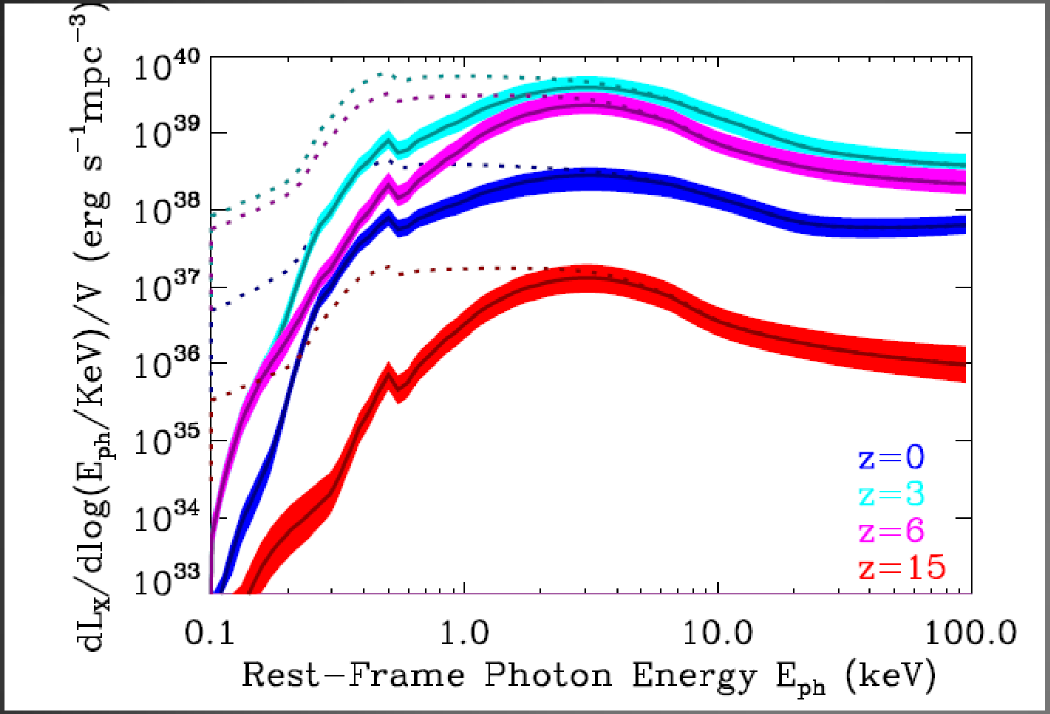
X-ray binary

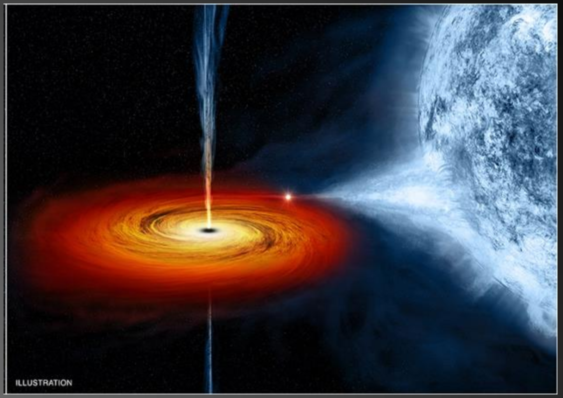


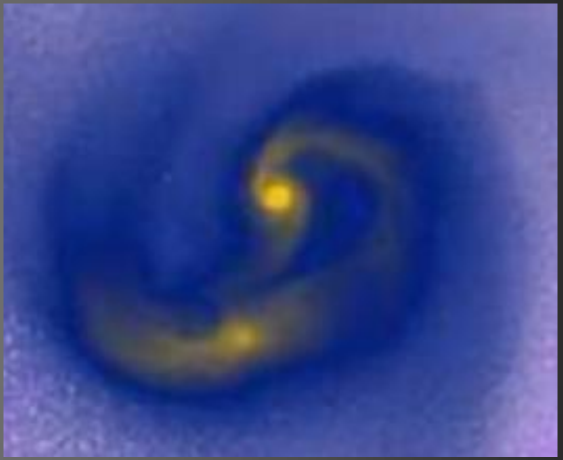


First stars likely form in multiple systems (e.g., Stacy et al 2013, Hirano et al. 2015)
Good chances to form X-ray binaries

High Mass X-ray Binaries

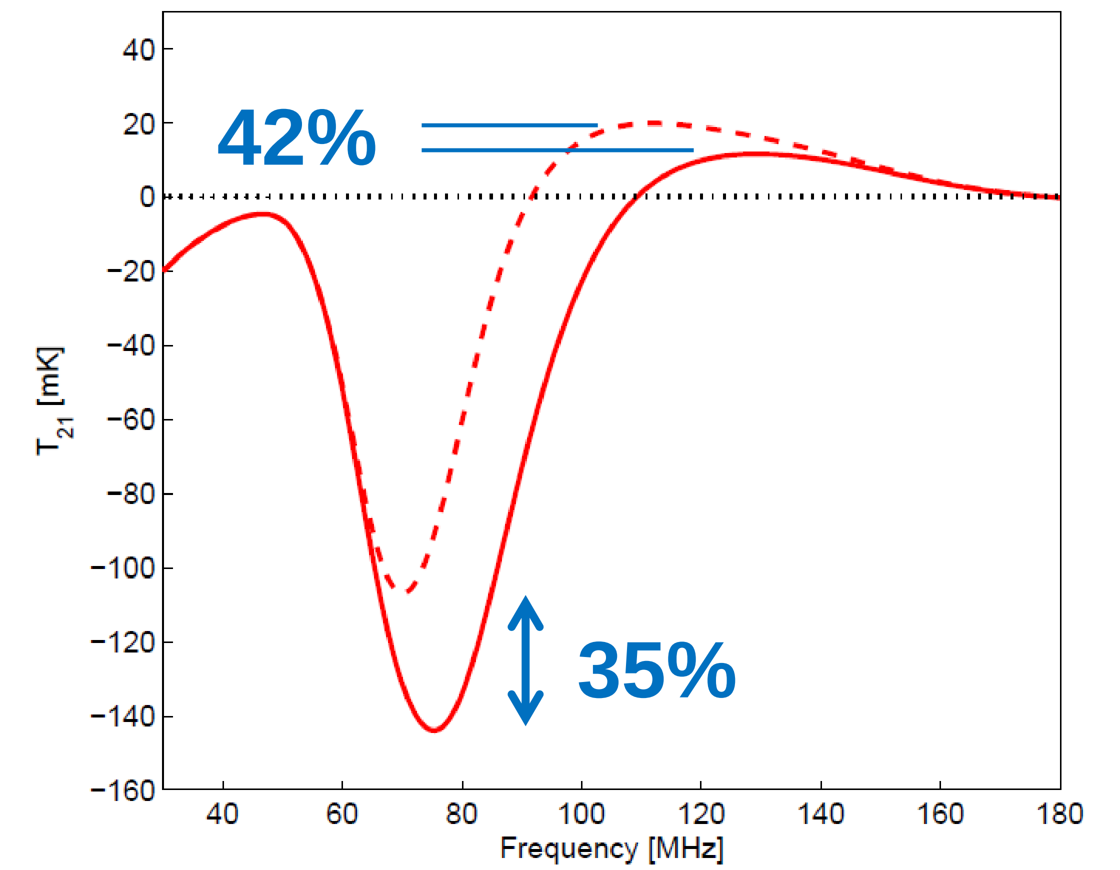


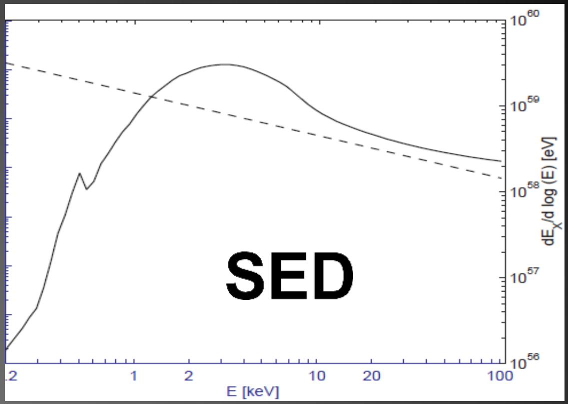


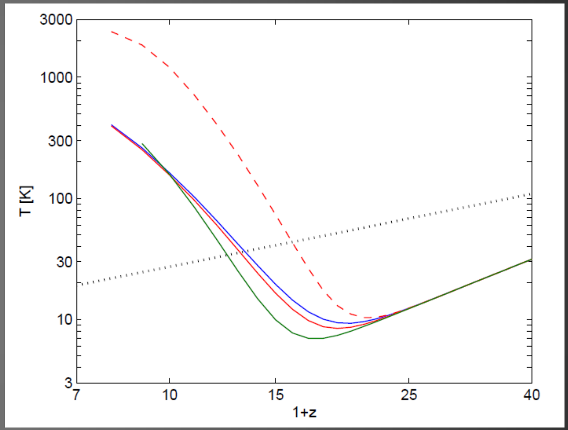


- Hard SED
- Win over AGN in heating at z > 6

Results of a population synthesis simulations calibrated to all available observations of XRBs (Fragos et al. 2013). Scaling of emission from XRB populations with SFR and stellar mass, and the evolution of these relations with redshift.







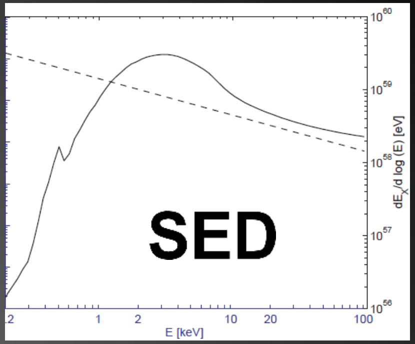
Fialkov, Barkana, Visbal (2014)

Redshift of $T_K = T_{CMB}$

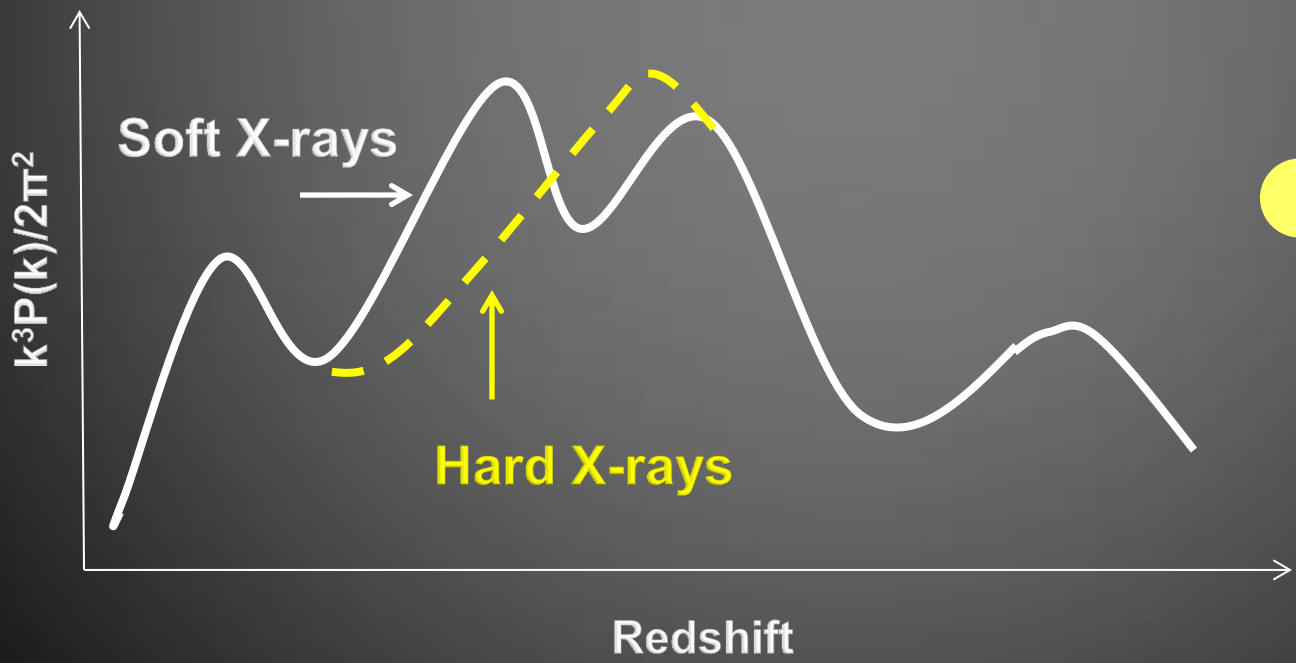
Soft SED: Heating and reionization are separated in time (heating transition at z = 15, x_i ~ 3.8 %).

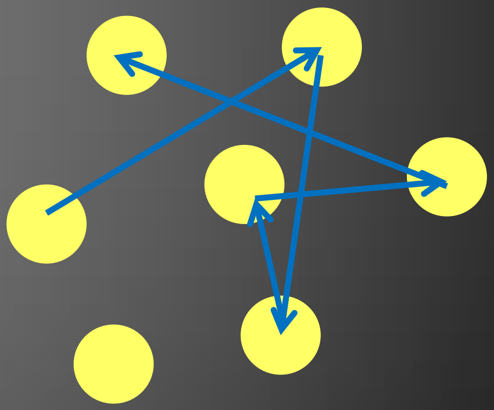
Hard SED: Reionization and heating happen simultaneously (heating transition at z = 12, x_i ~ 14 %).

Effect on Fluctuations

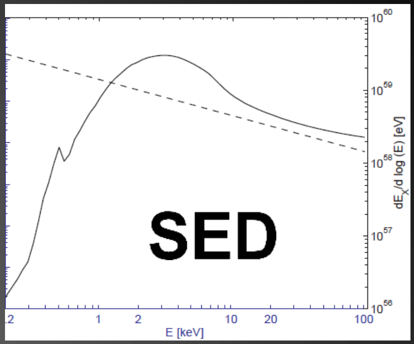


- Mean free path of X-ray photons → characteristic scale
- Fluctuations at scales smaller than mfp are washed out





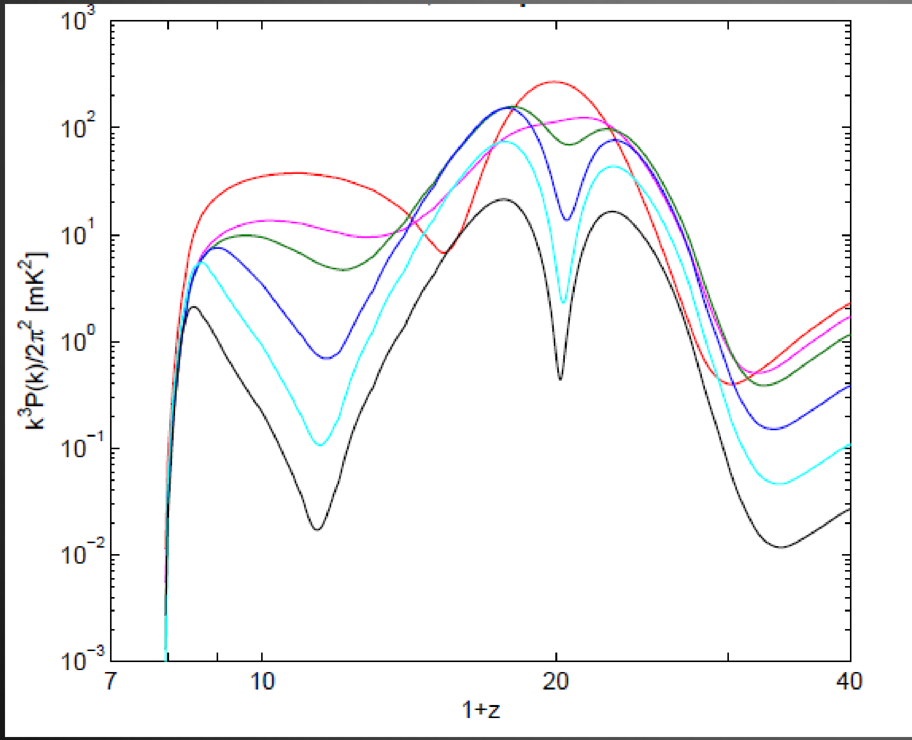
Hard vs Soft X-rays: Heating Peak in the PS

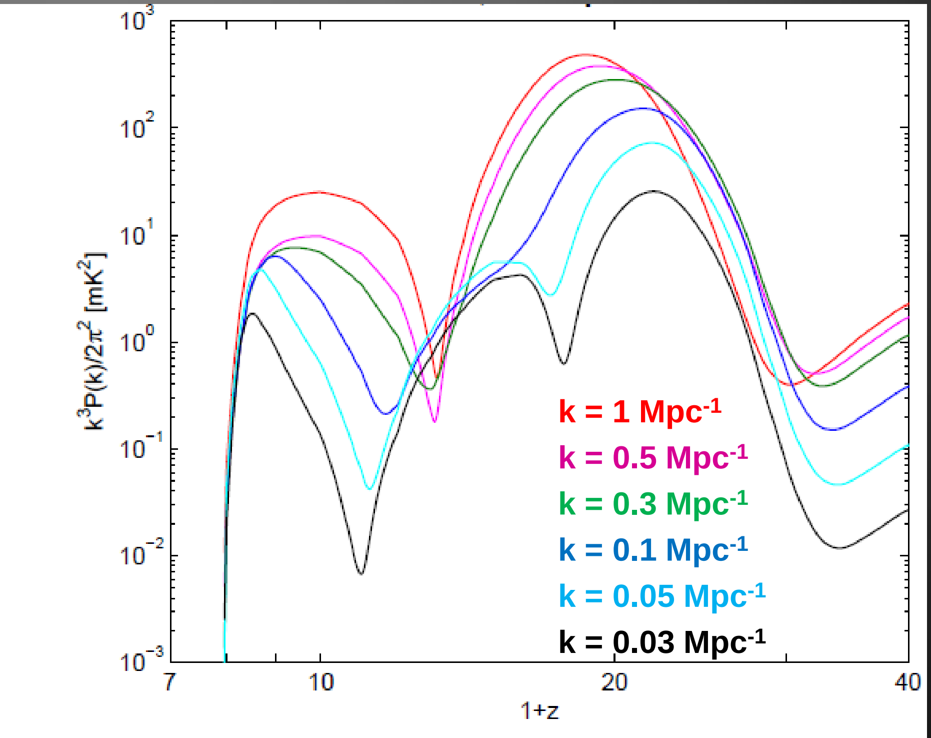


Soft X-rays

Hard X-rays

Almost uniform heating

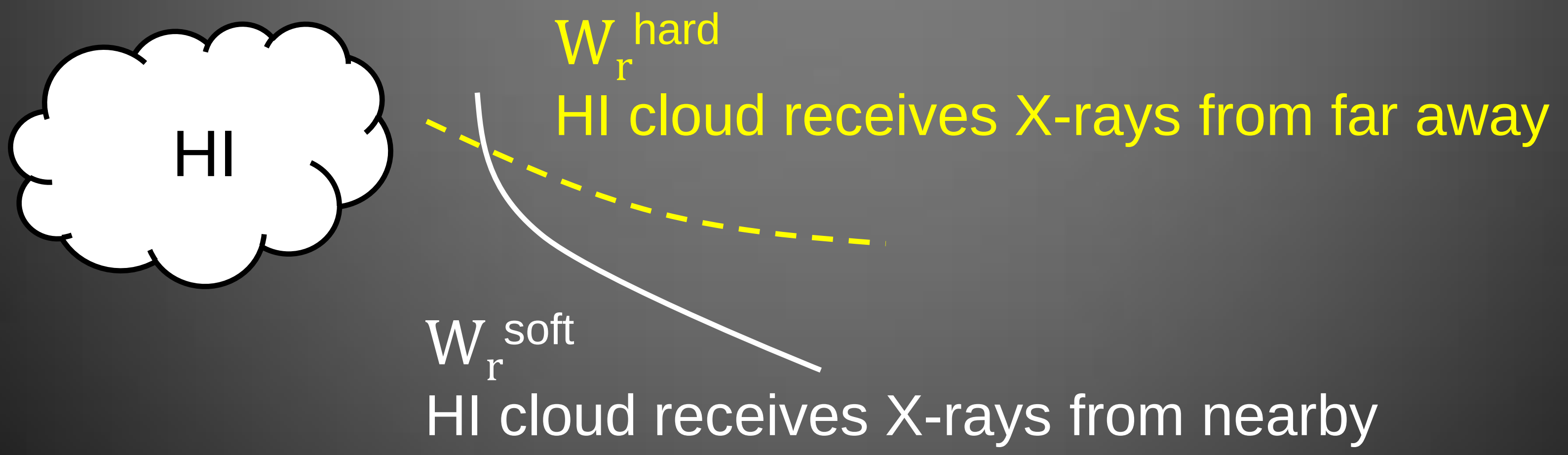




Fialkov & Barkana (2014)

Model-independent Method to Measure SED of Early X-ray Sources

The 21-cm power spectrum can be used to directly measure the radial distribution of X-ray flux W_r
Fialkov, Barkana, Cohen (2015)



Single source of fluctuations
Linear theory is valid
Anisotropy is small

$$\left.\begin{matrix} \\ \\ \\ \end{matrix}\right\} \quad \mathrm{F(Wr)} \propto \sqrt{P(k,z)/P_\delta}$$

Fialkov, Barkana, Cohen (2015)

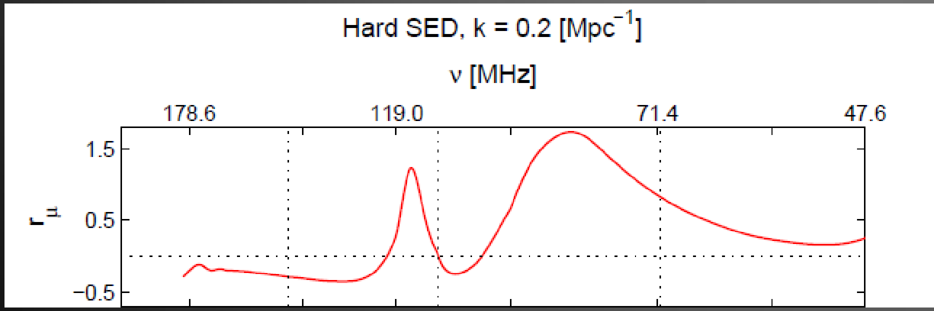
Single source of fluctuations
Linear theory is valid
Anisotropy is small

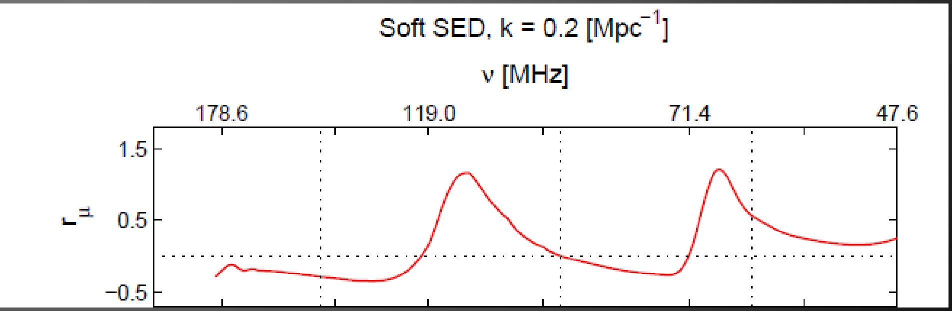
$$F(Wr) \propto \sqrt{P(k,z)/P_\delta}$$

Fialkov, Barkana, Cohen (2015)

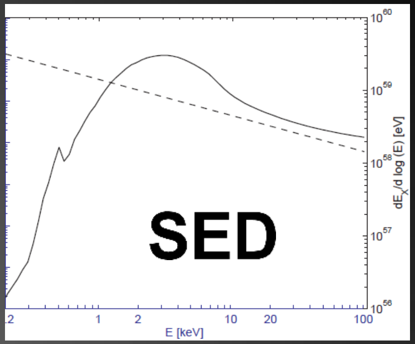
Works at $T_{gas} \sim T_{CMB}$!!!

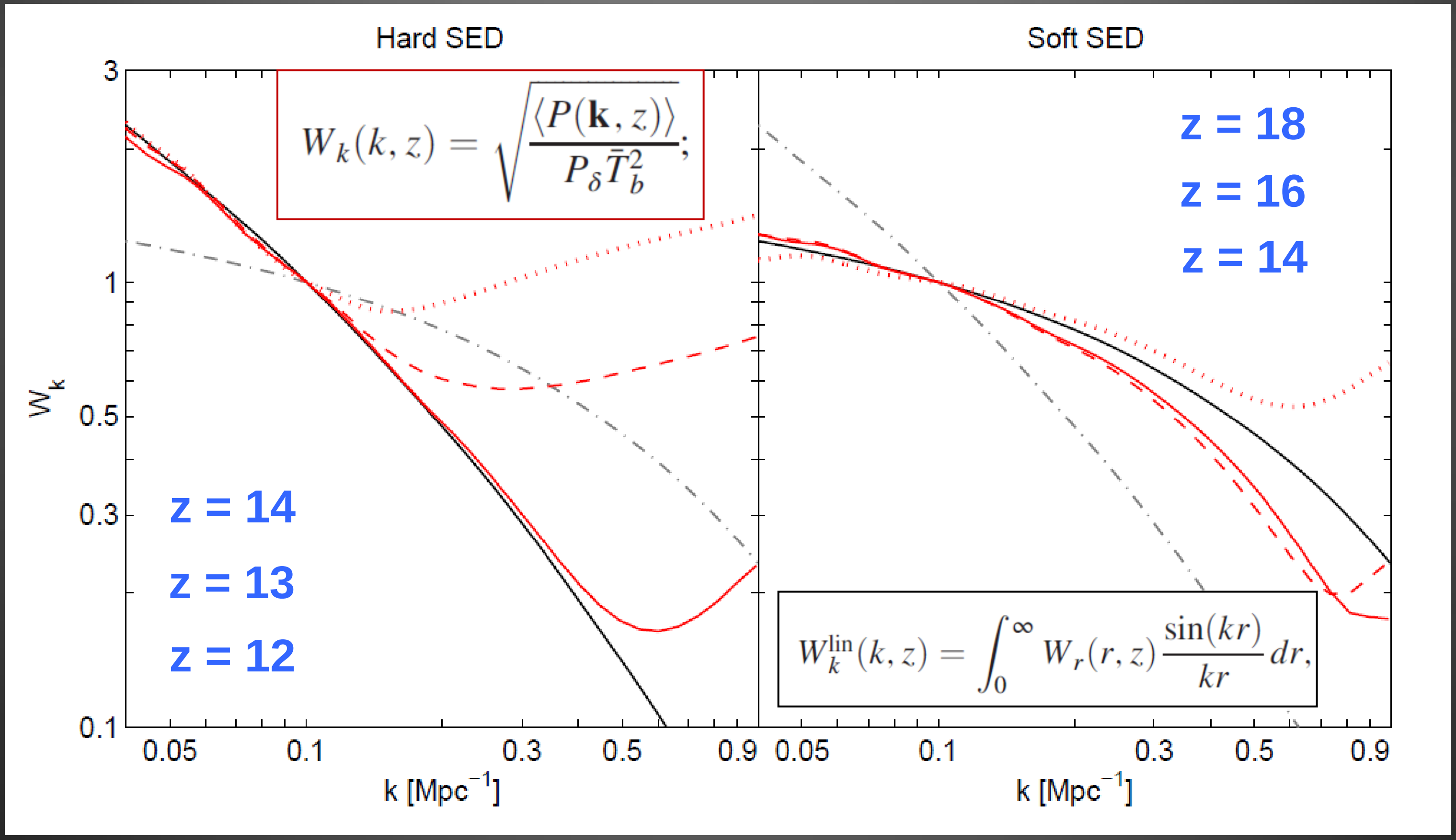
$$\text{Anisotropy ratio} = \frac{\text{Power at small angles}}{\text{Power at large angles}} - 1$$





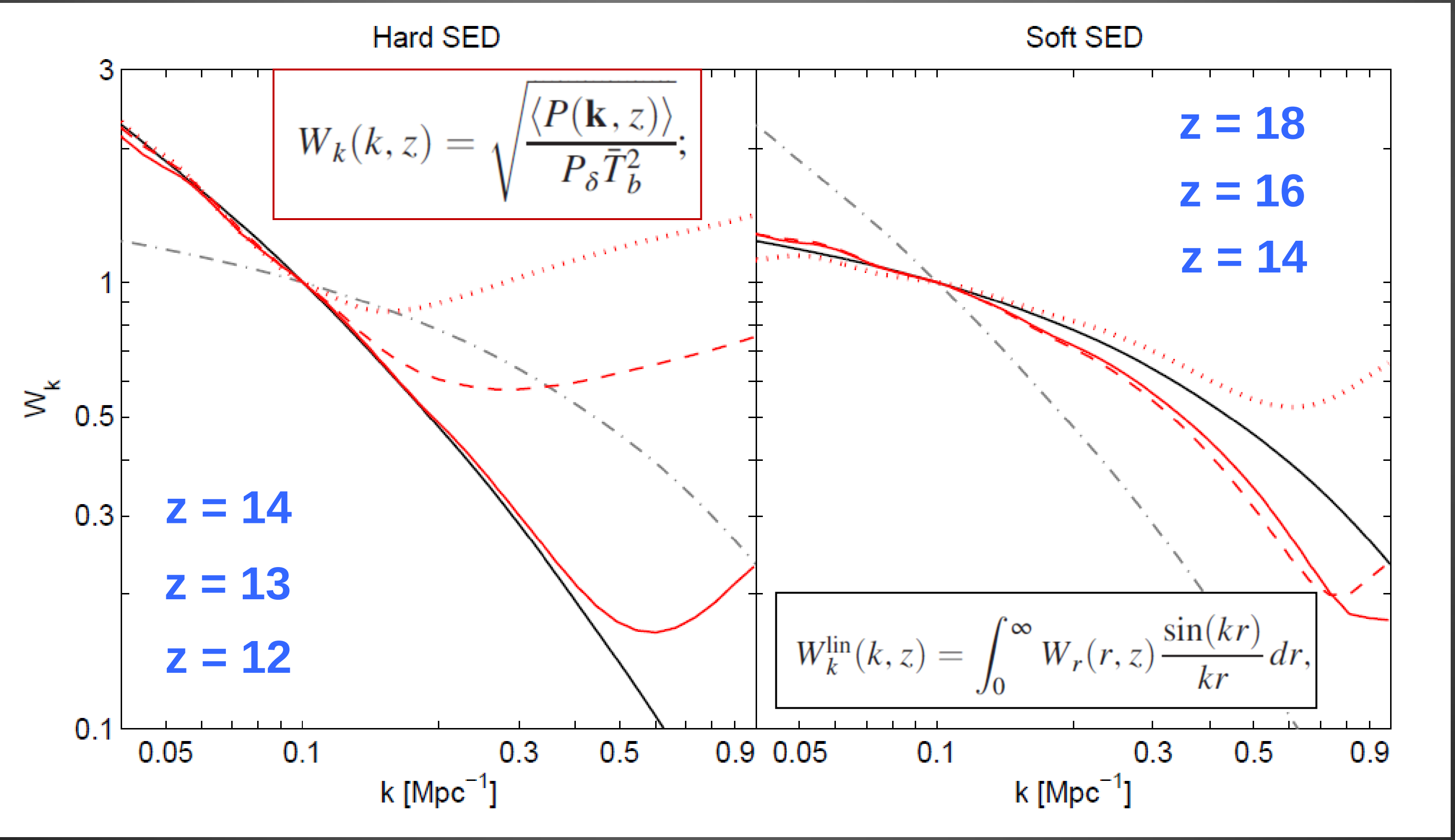
Measure $\sqrt{P(k,z)/P_\delta}$ from mock data and compare the shape to $\mathrm{F(Wr)}$ of sources





Fialkov, Barkana, Cohen (2015)

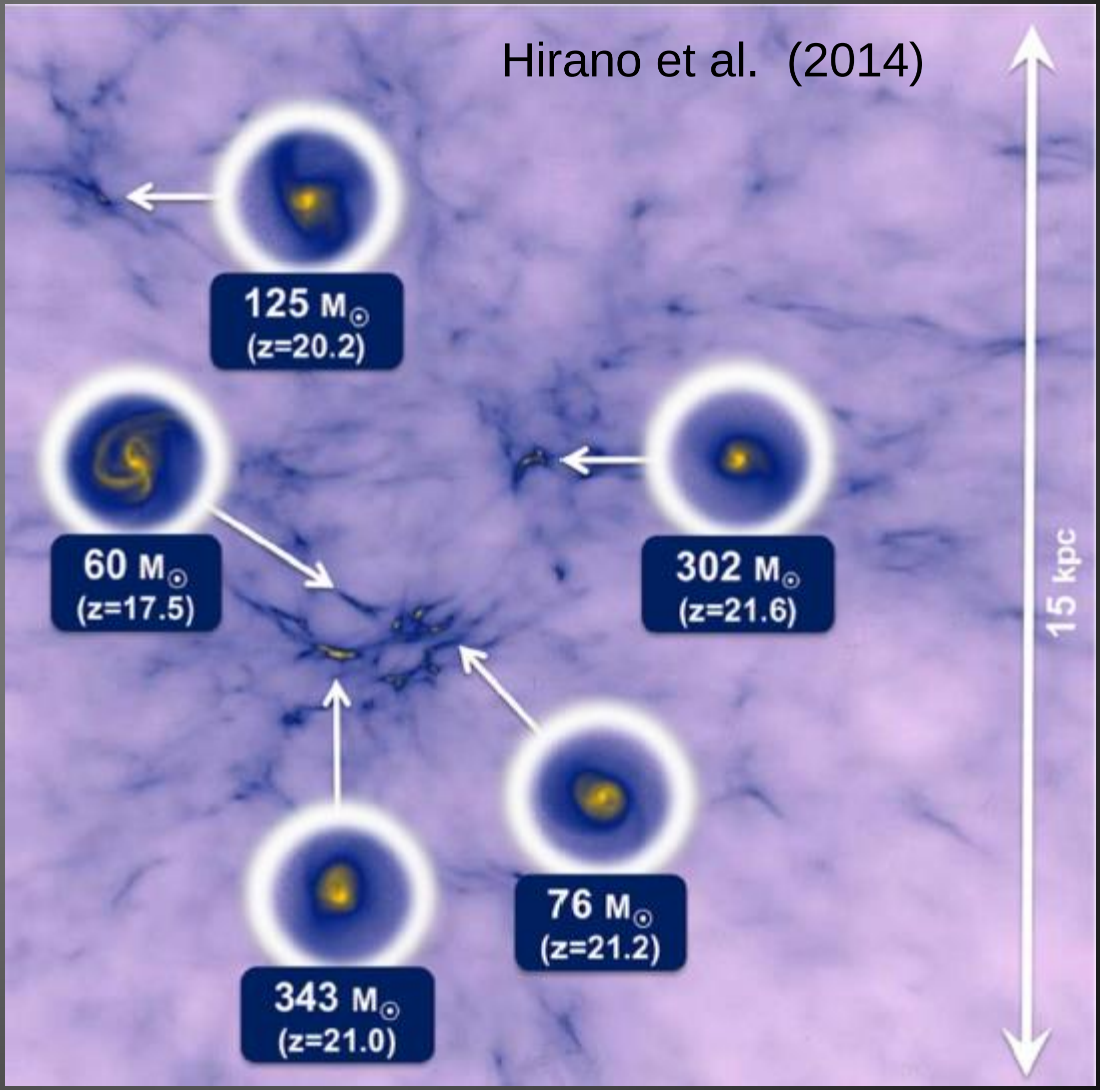
- Works on the scales at which the heating fluctuations dominate
- The slopes of $\sqrt{P(k,z)/P_\delta}$ and $\mathrm{F(Wr)}$ are similar
- Slopes are different for hard and soft SEDs



Fialkov, Barkana, Cohen (2015)

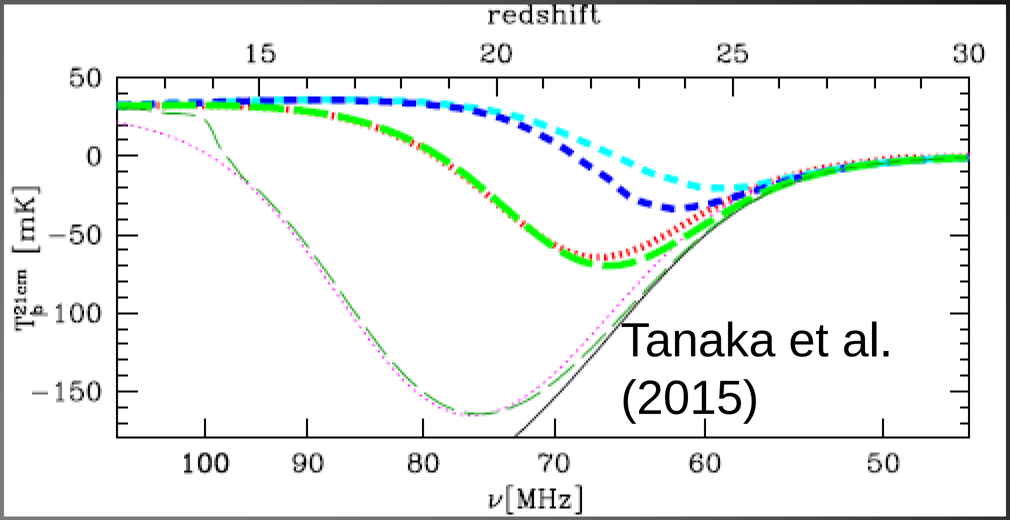
Controversial High-z: Star Formation

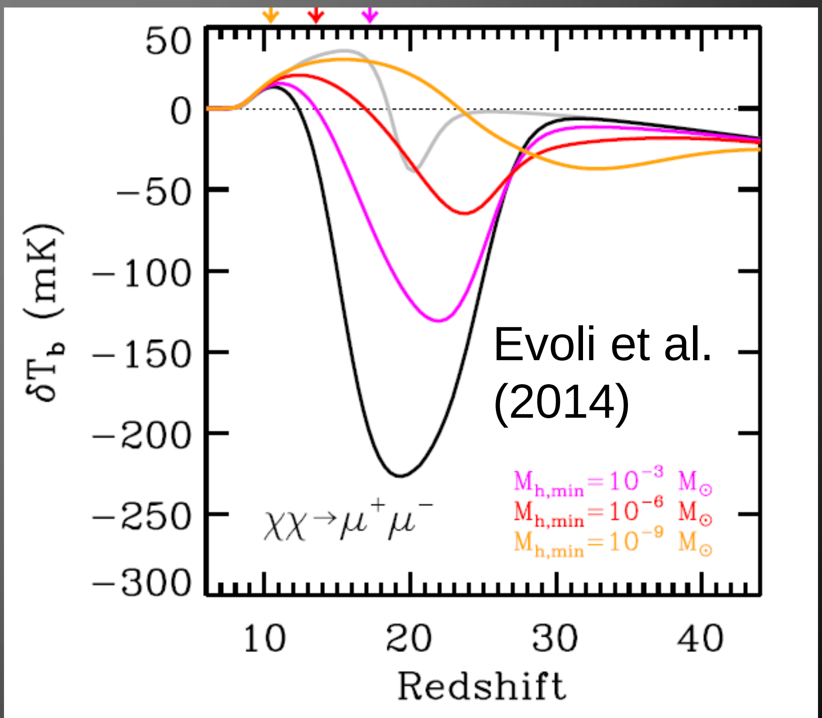
- IMF of first stars
- Fate of the stars
- Origin of SMBHs
- Nature of X-rays
- Feedbacks
- …



Controversial High-z: Heating

- X-ray Binaries
- Seeds of SMBH
- Hot gas
- SN
- DM annihilation
- Magnetic Field





Conclusions

- We agree on the shape of predicted 21-cm signal, but details are still controversial (Interpretation)
- Early Universe might be more stochastic than we think
- Before EoR: IC, feedbacks, heating mechanisms