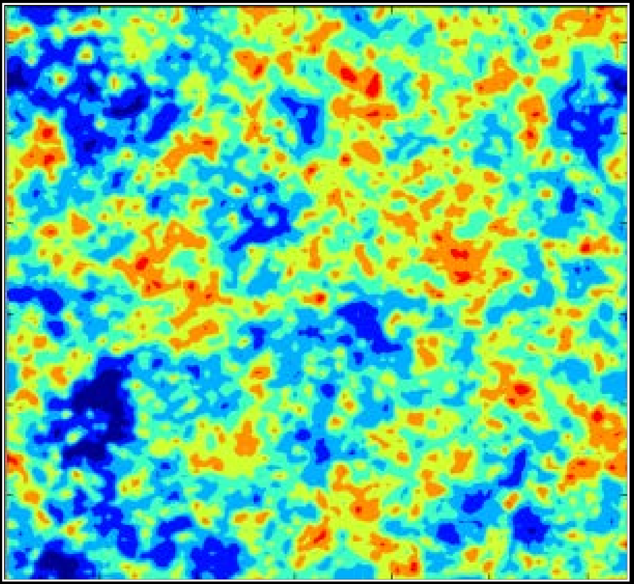
Detectable Signature of First Stars in 21-cm Signal



<u>In Collaboration with:</u>

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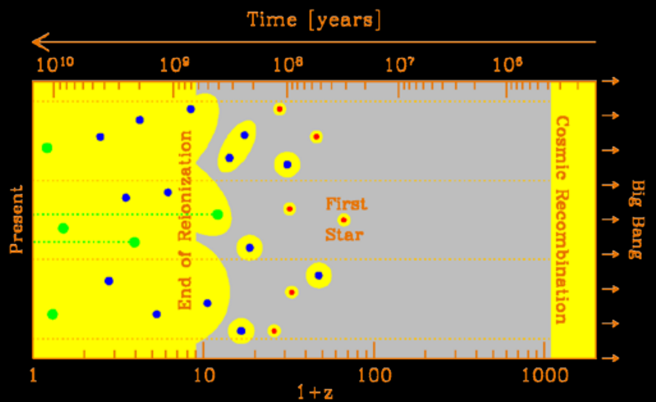
Eli Visbal, Harvard
Christopher Hirata, Caltech
Dmitri Tseliakhovich

Anastasia Fialkov
Tel Aviv University
8 November 2012, IPMU

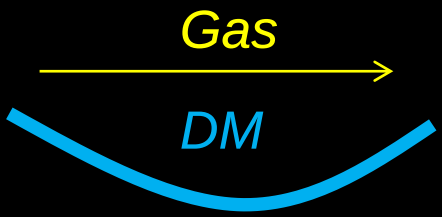
Outline:

1. **Basic Intro:**
   i. **First Stars**
   ii. **21-cm**

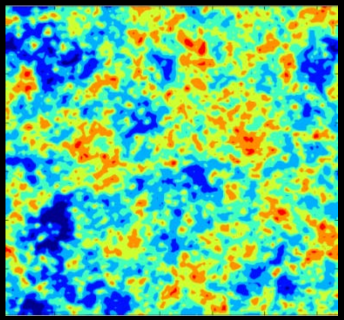


Barkana, 2006

2. **Effect of Relative Velocities on the First Stars**



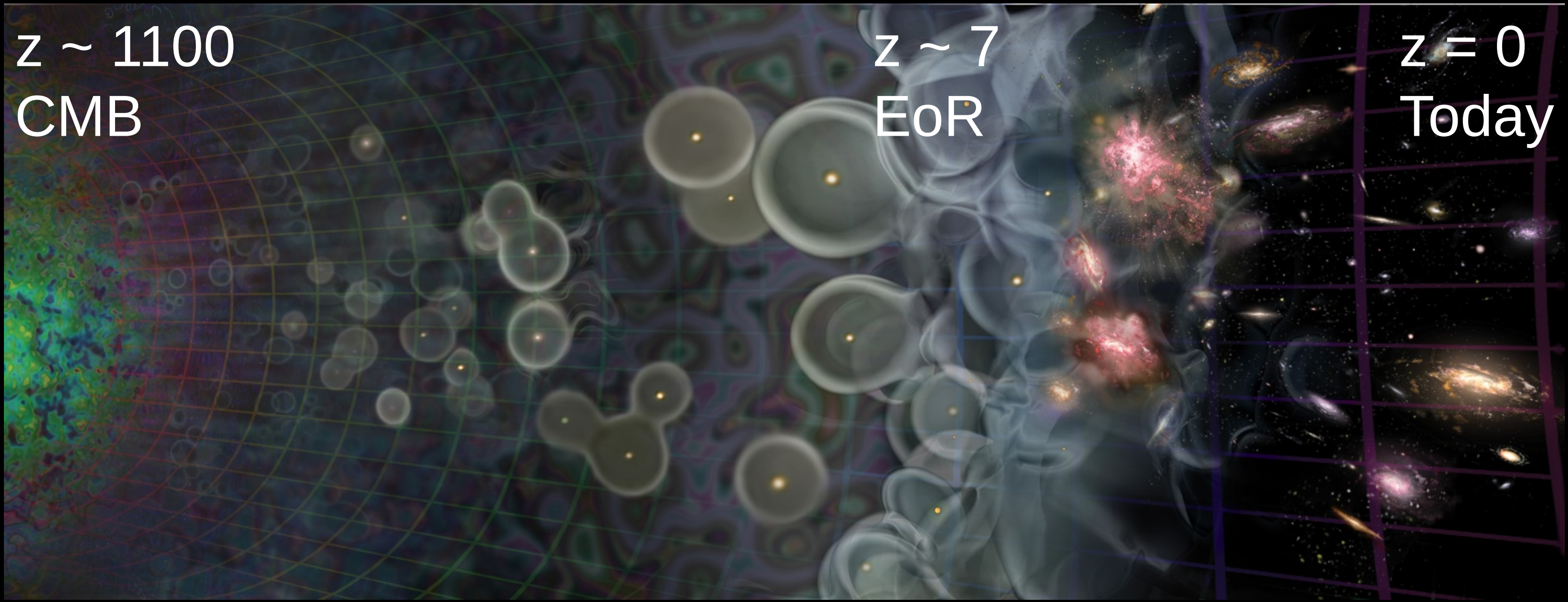
1. **Signature of First Stars in the 21-cm Signal**



- **AF**, Barkana, Tseliakhovich & Hirata (2012)
- Visbal, Barkana, **AF**, Tseliakhovich & Hirata, Nature (2012)
- **AF**, Barkana, Visbal, Tseliakhovich, Hirata, Submitted

Cosmic History:

Image: Loeb, Scientific American 2006

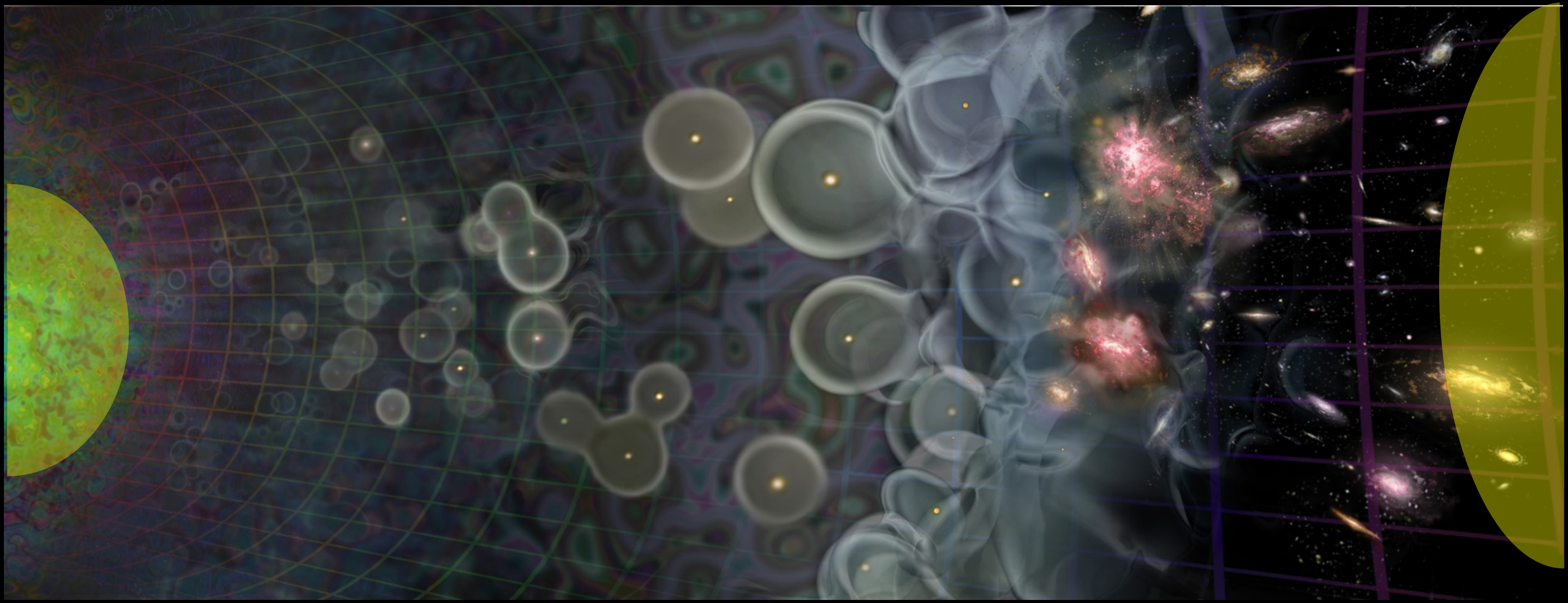


First stars heat & ionize the gas

Cold neutral gas → hot ionized gas

Observed:

Image: Loeb, Scientific American 2006



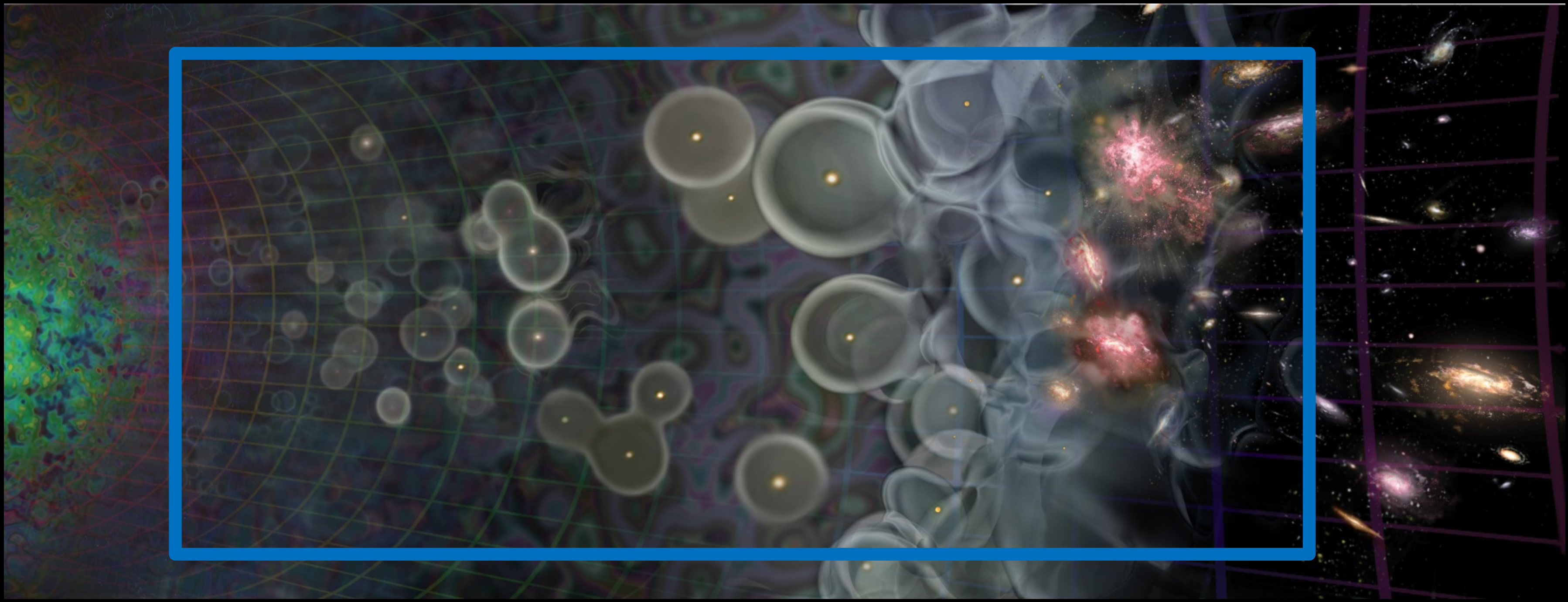
CMB (z ~ 1100)

Point sources (z < 10)

Local structure (z < 2)

Unobserved:

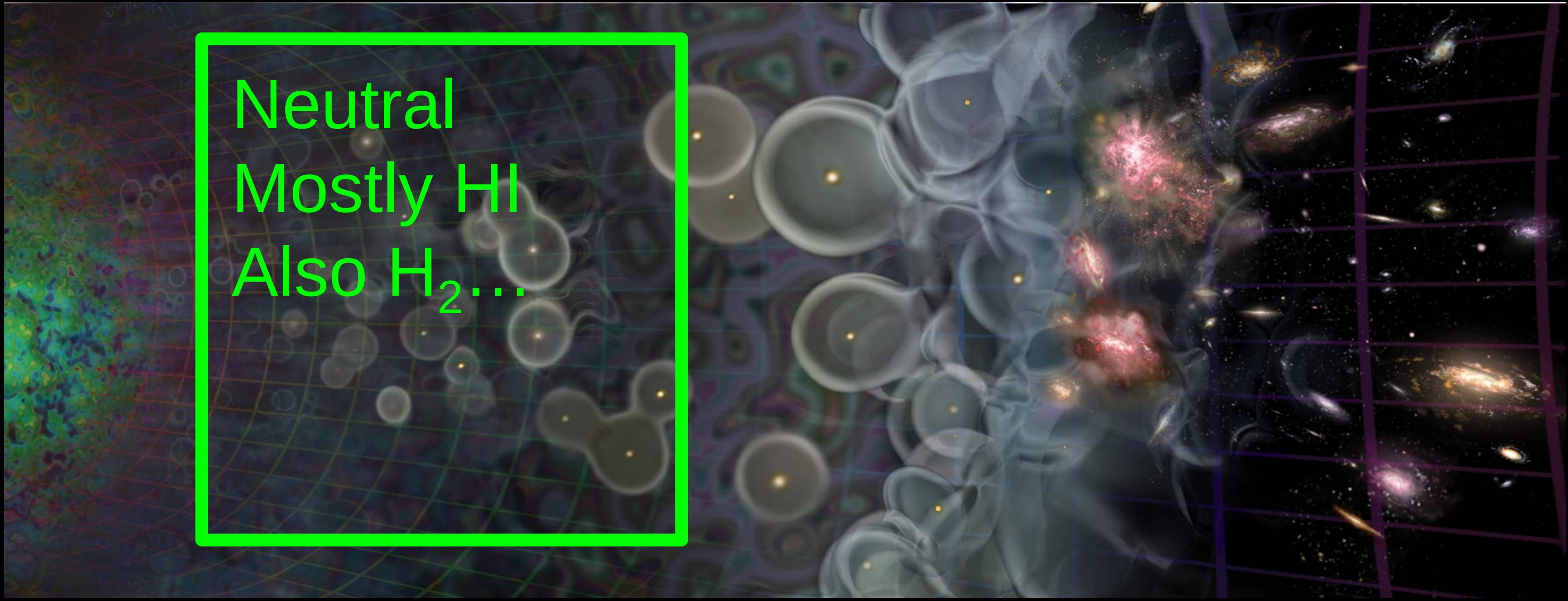
Image: Loeb, Scientific American 2006



Dark ages First stars & galaxies Reionization

This talk: The Epoch of the First Stars

Image: Loeb, Scientific American 2006



The First Stars:

From H_2 in light halos $M \sim 10^5\ M_{sun}$
Tegmark et al 1997

Formed at $z < 65$
AF, Barkana, Tseliakhovich, Hirata 2012

Hydrogen

Artist impression of the core of the SKA. Created by: Xilostudios

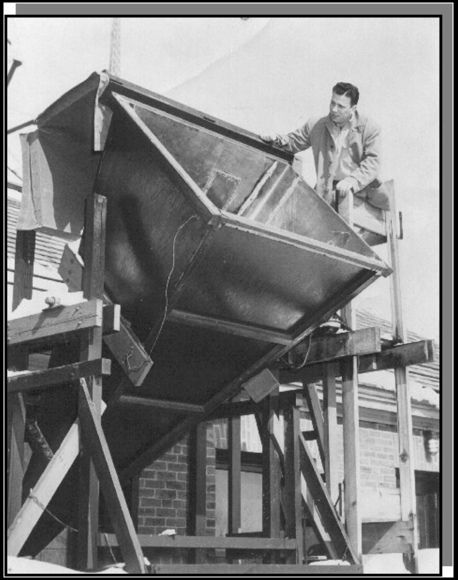
HI can be probed with redshifted 21-cm line

21-cm as a Space Probe. Since 1942

Van de Hulst

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

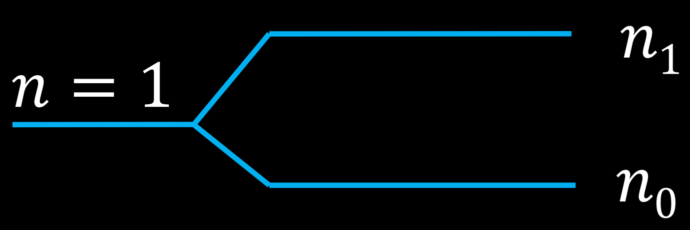
1952 – HI in the Milky Way
First detection by Ewen and Purcell

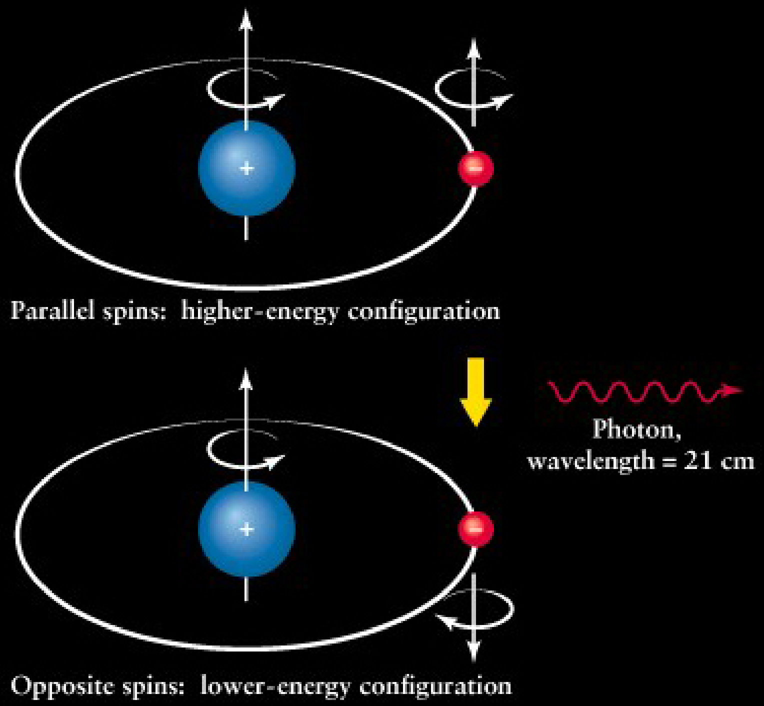


First Detector

Future – Probe the epoch of first stars

21-cm Line: Spin-Flip Transition of HI





λ = 21 cm

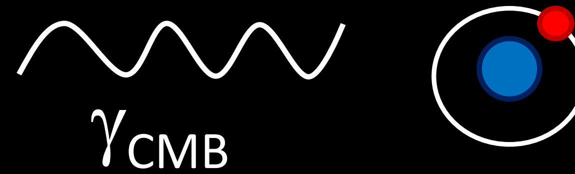
ν = 1420 MHz (Radio)

Spin Temperature

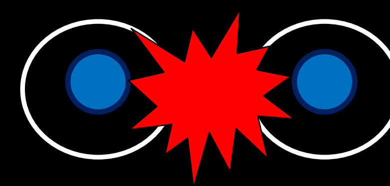
$n_1/n_0 \equiv 3\exp(-T_*/T_S)$, $T_* = 0.068$ K

What Determines T_S

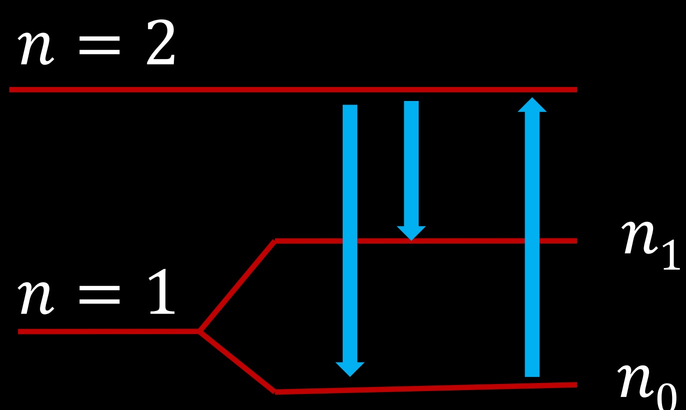
- Absorption of CMB: $T_S \rightarrow T_{CMB}$

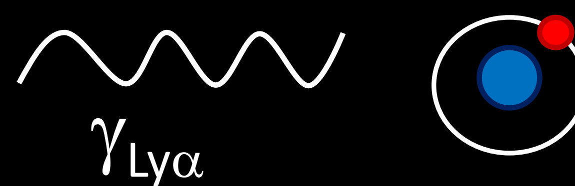


- Collisions with other HI: $T_S \rightarrow T_{gas}$



- Absorption and reemission of Lyα: $T_S \rightarrow T_{gas}$





Wouthuysen 1952, Field 1958

21-cm Signal from High Redshifts

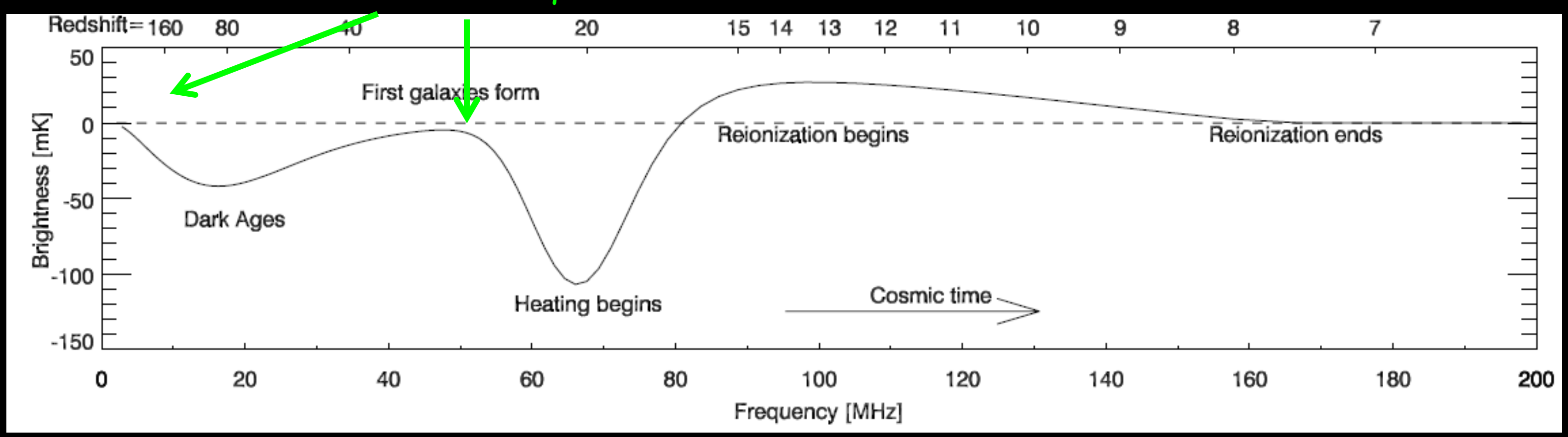
Redshifted 21-cm signal of HI from high z:

$$\approx 9 \;\; x_{HI} \, (1+\delta)(1+z)^{1/2}(1-T_{CMB}T_S^{-1})$$

Global signal (model dependent)

$T_S \rightarrow T_\gamma$

$x_{HI} \rightarrow 0$

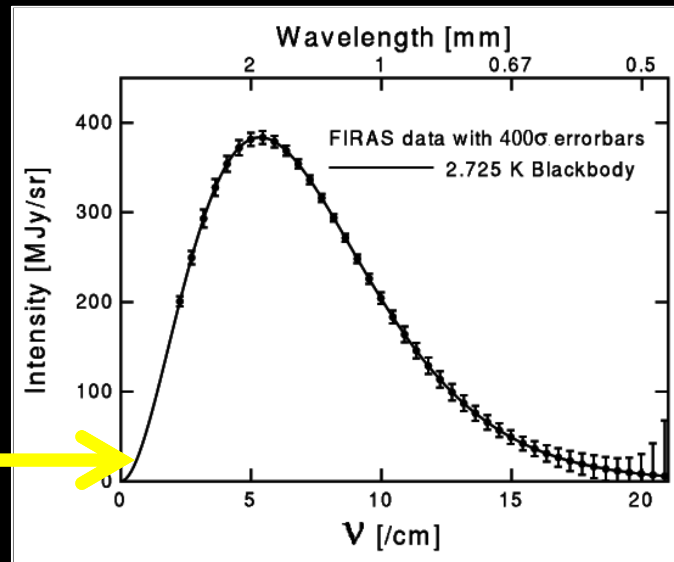


Pritchard & Loeb, 2012

$T_S \rightarrow T_{gas}$

Source: CMB Black Body

Radio



CMB → **HI at z_{HI}** →

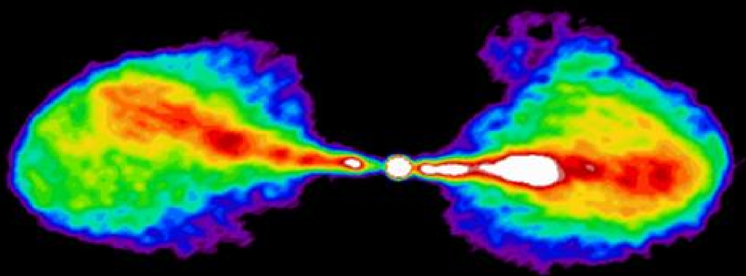
λ_{HI} = 21 cm

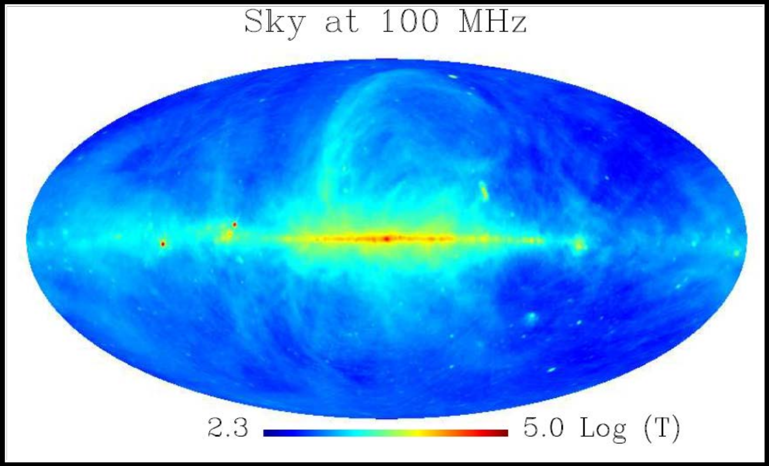
$\lambda_{obs} = 21(1+z_{HI})$ cm

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

Astrophysical Foregrounds

- Galactic Synchrotron Emission
- Extragalactic Radio Sources

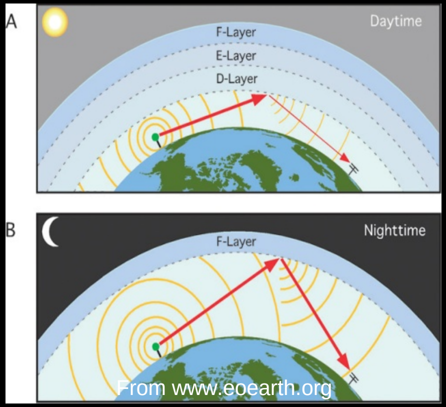




Synchrotron
De Oliveira-Costa *et al* 2008

Terrestrial

- Radio Frequency Interference
- Ionosphere Distortions



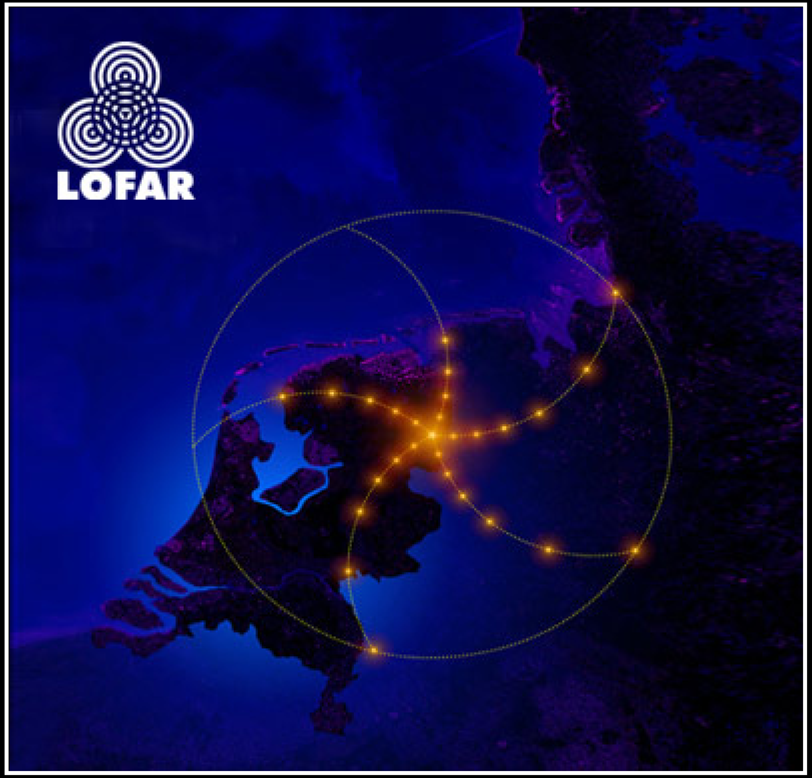
Current Effort:

Epoch of Reionization

LOFAR 11.5 > z > 6.5 (PS)

GMRT z ≈ 9 (PS)

GMRT



Future Telescopes

SKA 20 > z (PS)

LEDA 30 > z >15 (global)

DARE 35 > z >11 (global)

LEDA

SKA

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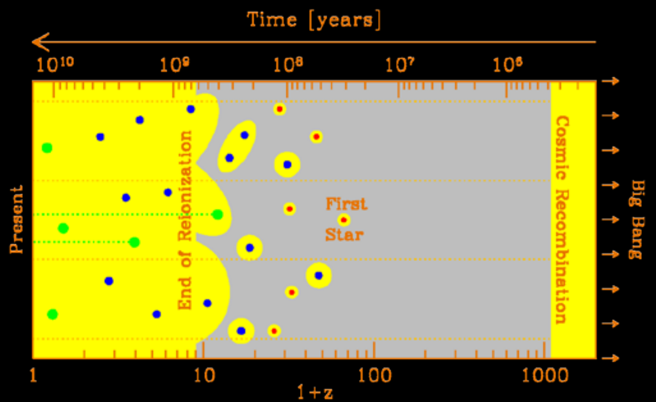

Barkana, 2006

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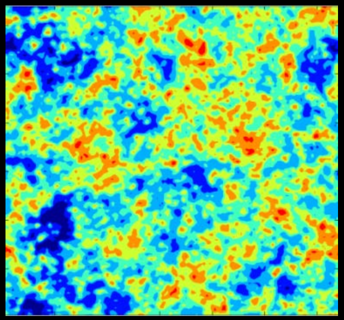
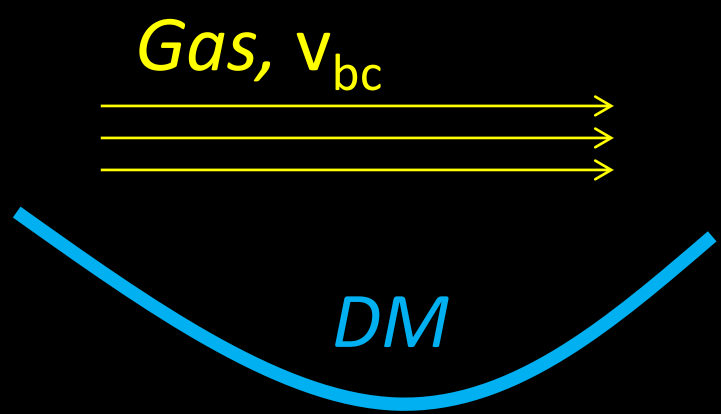


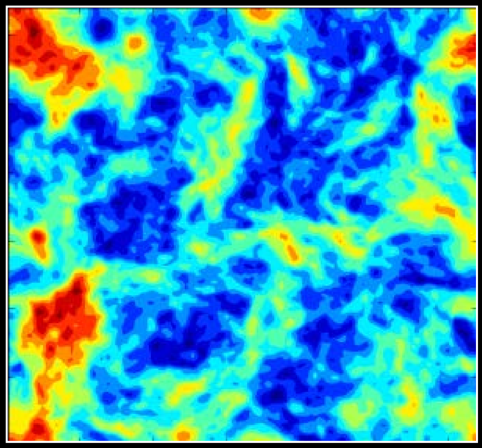
IC for Structure Formation
Baryon – DM Relative Velocity

Tseliakhovich & Hirata, 2010

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



Gas overshoots DM halos



400 Mpc

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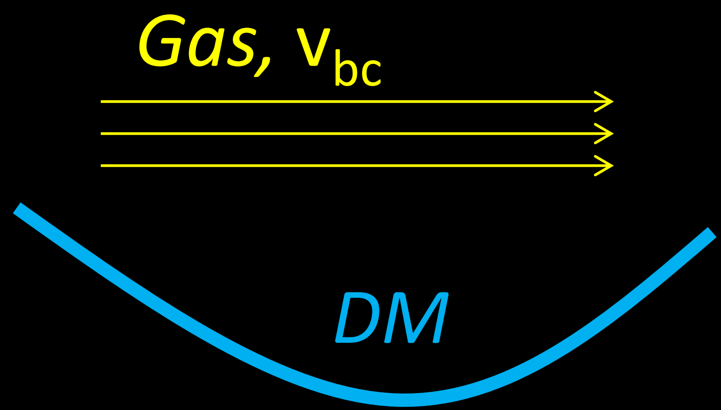

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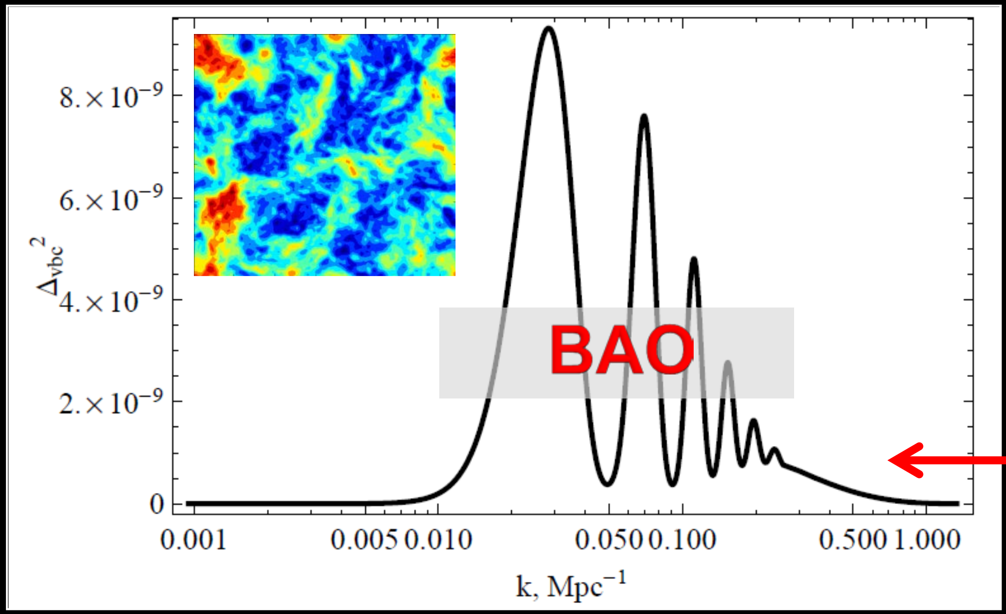
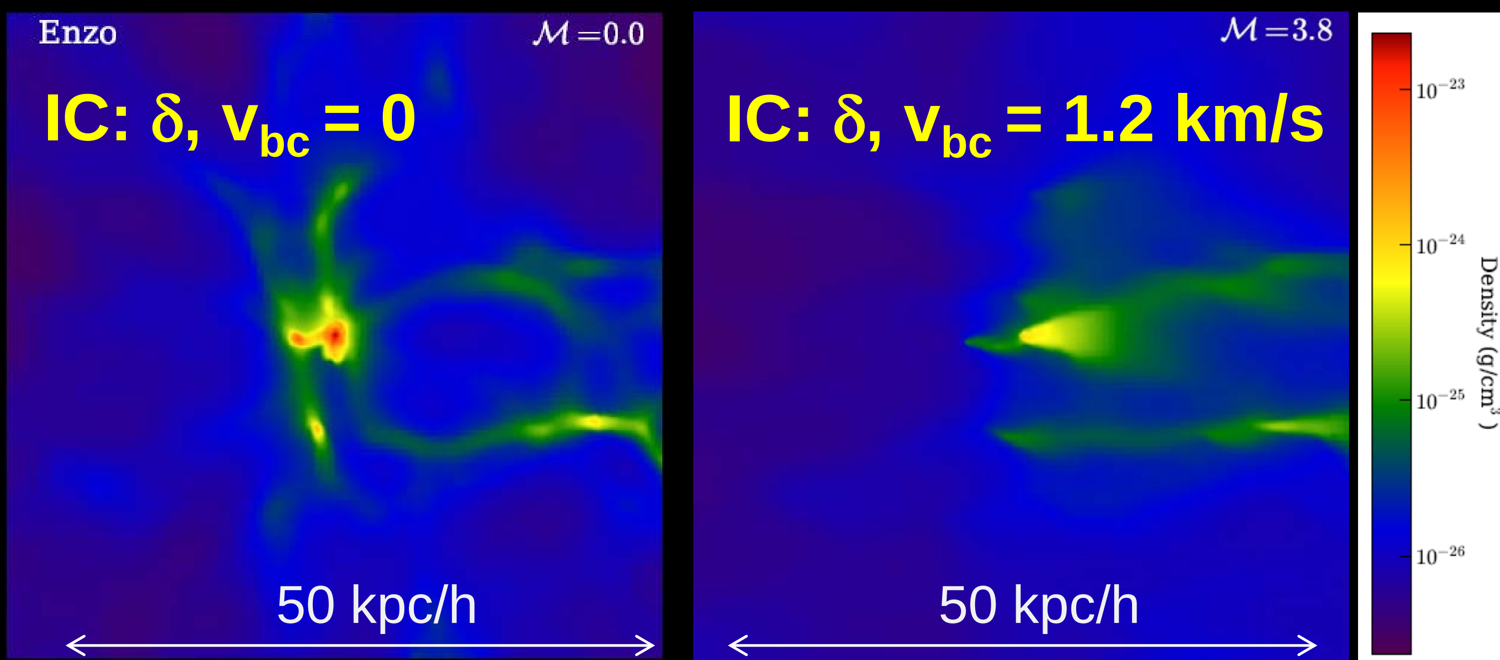


Silk damping:
Coherence scale ~ 3 Mpc

v_{bc} → Large Impact on Structure Formation at High z

ρ_{gas}

$z = 20$, $M_h \sim 1.5\times10^5$



O'Leary & McQuinn, 2012

v_{bc} Main Impact on High z and Small Scales 10^4 - 10^7 M_{sun}

- Scale-dependent bias
- Suppresses halo abundance

Tselikhovich & Hirata 2010; Naoz, Yoshida, Gnedin 2012

- Suppresses amount of gas in halos
- BAO in PS of early structure

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

- Harder to form stars (boosts minimal cooling mass)

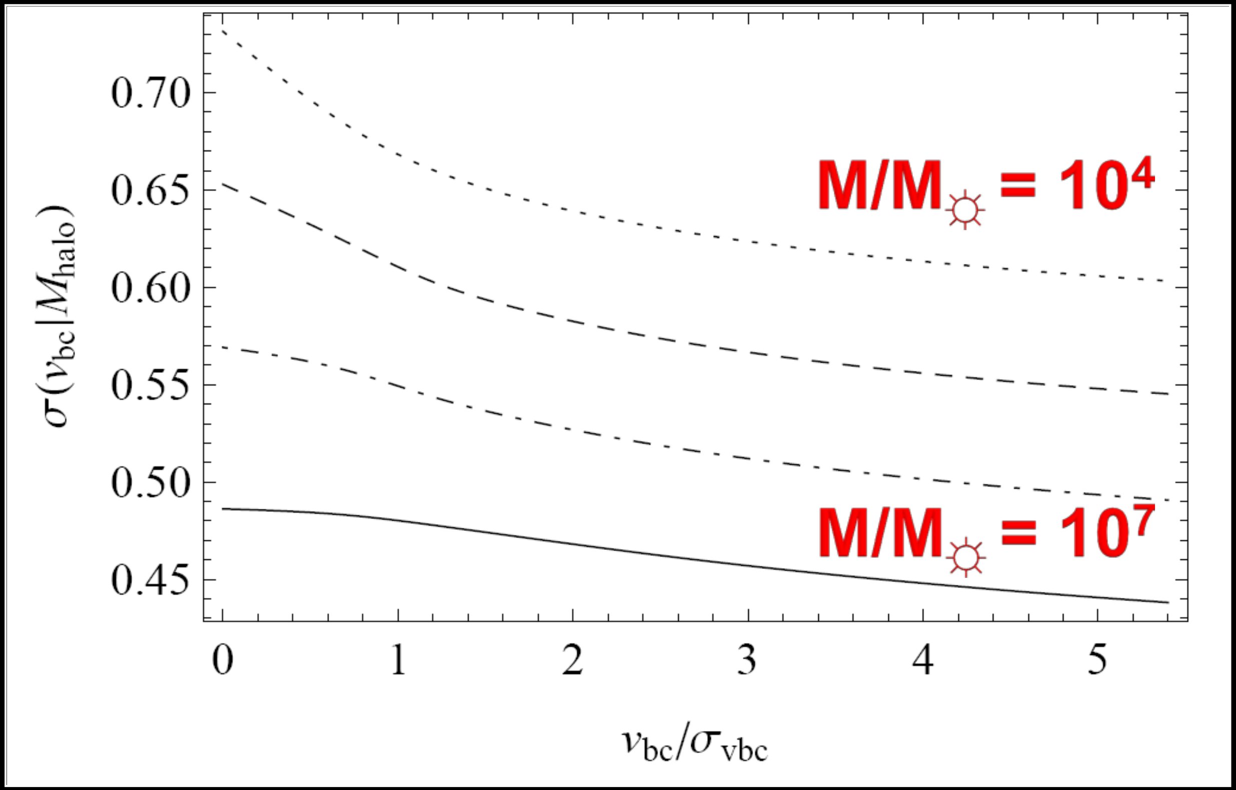
AF, Barkana, Tselikhovich & Hirata 2012

(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)

$v_{bc} \rightarrow$ Less Halos Form

Tseliakhovich & Hirata(2010)

The variance of fluctuations in spheres with mass M



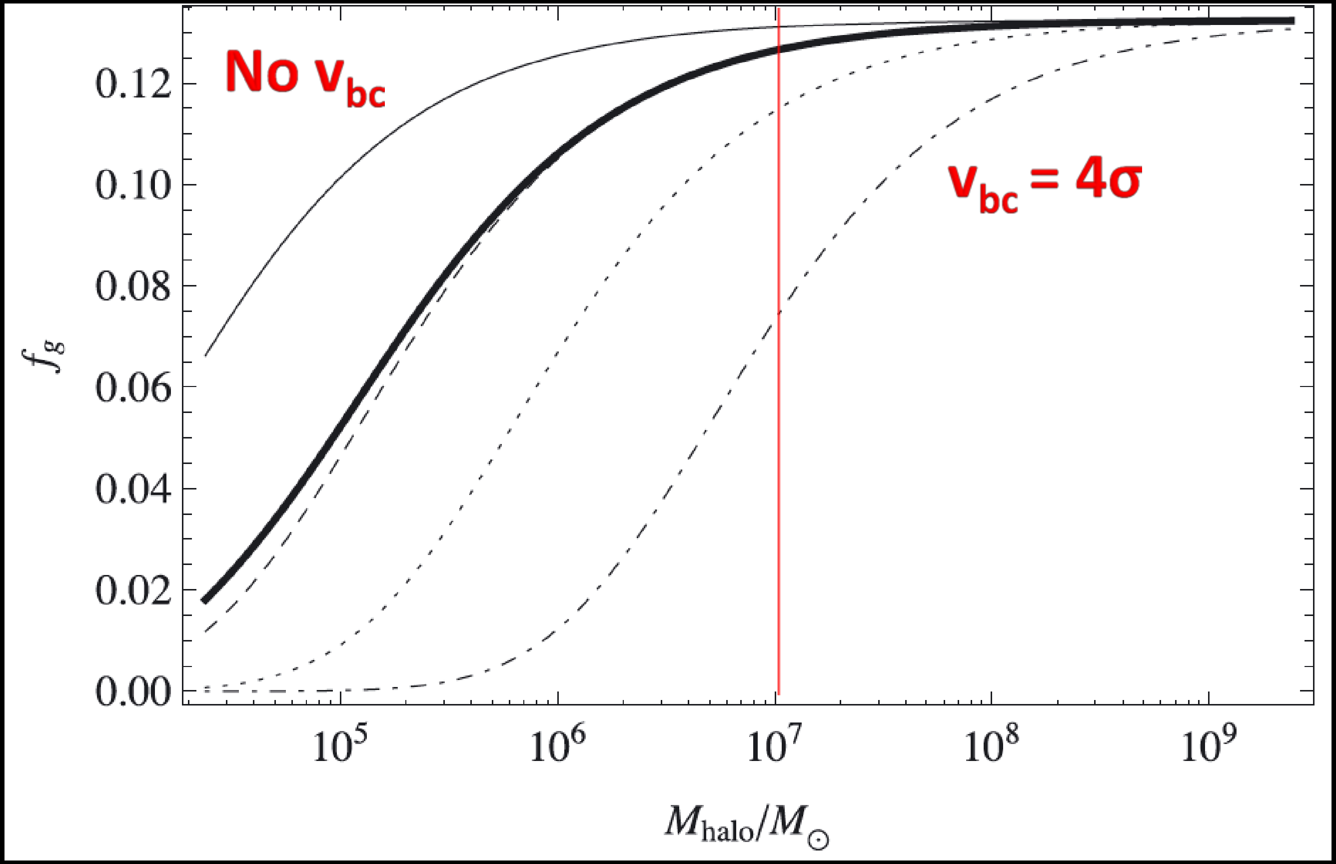
z = 20

Tseliakhovich, Barkana & Hirata (2010)

$v_{bc} \rightarrow$ Less Gas in Halos

Dalal, Pen & Seljak (2010)

v_{bc} acts as pressure $\rightarrow$ less gas in halos $M/M_{\odot} < 10^7$

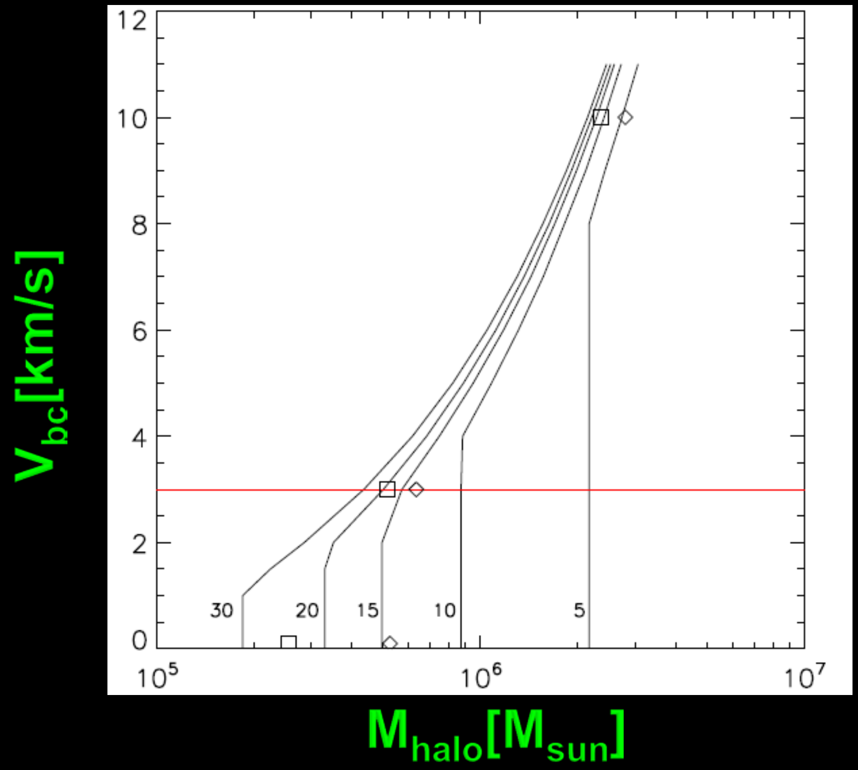


z = 20

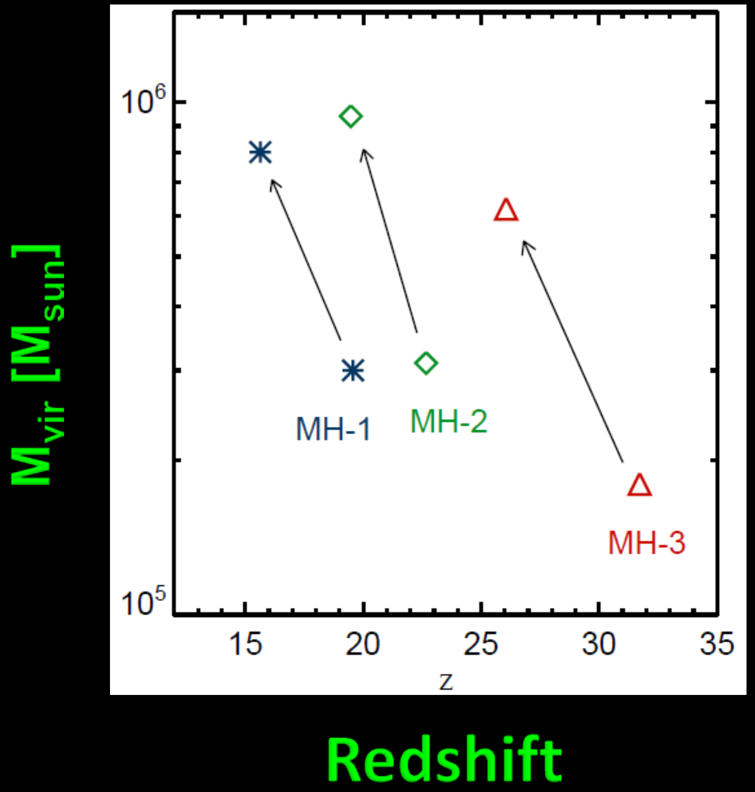
Tseliakhovich, Barkana & Hirata (2010)

Simulations:
Minimal H_2 Cooling Mass

Stacy, Bromm & Loeb (2011)



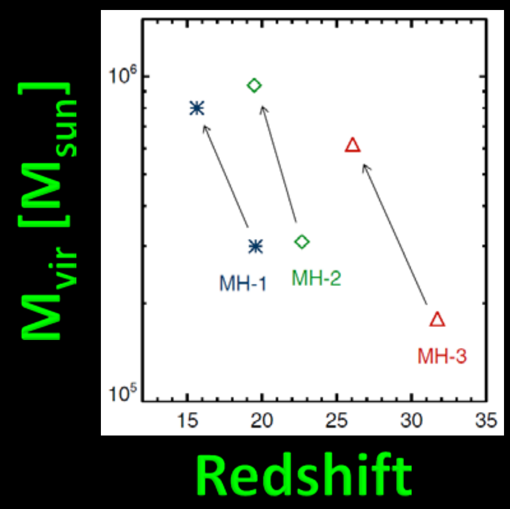
Greif, White, Klessen & Springel (2011)



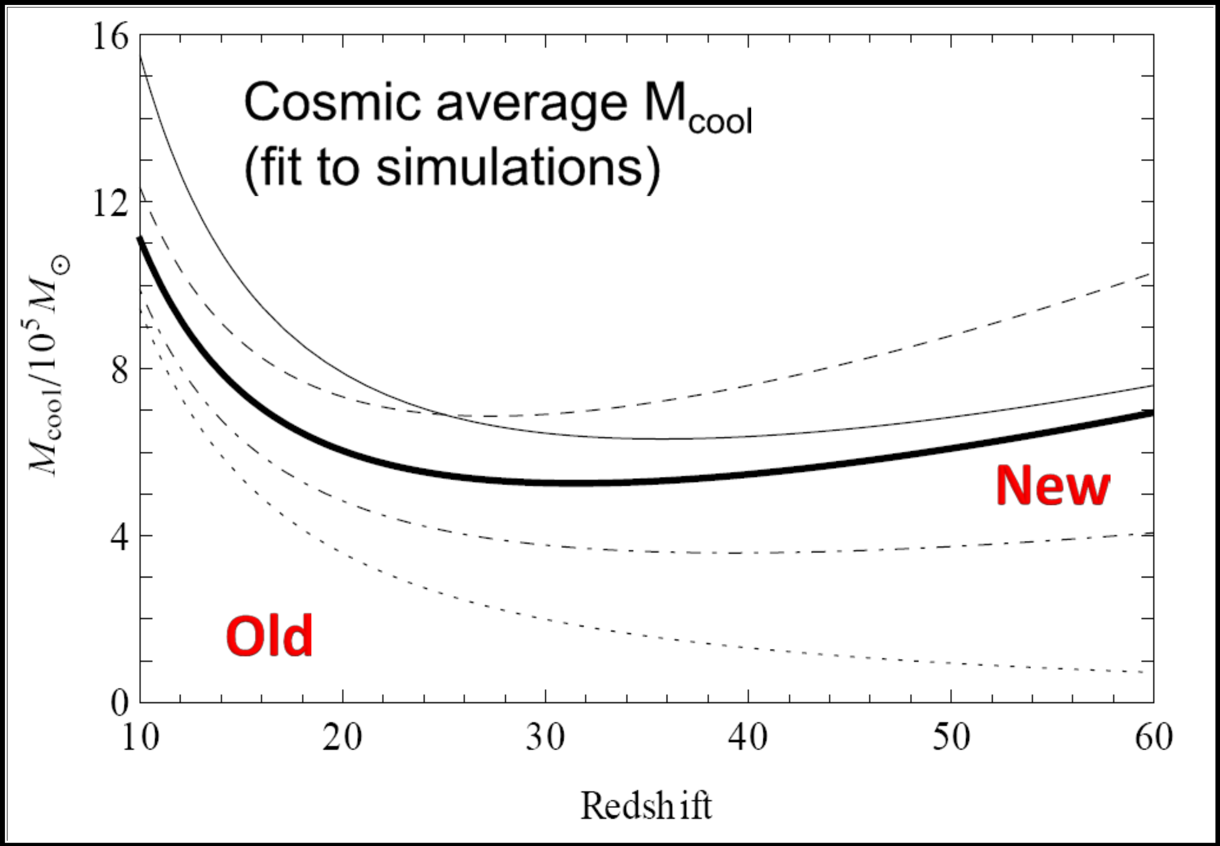
Stars form later and in more massive halos

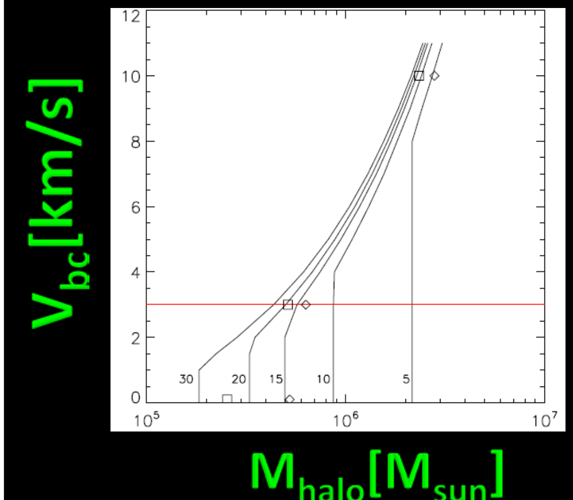
M_{cool} Depends on v_{bc}

Greif, White, Klessen & Springel (2011)



$M_{cool}(v_{bc}) \rightarrow v_{bc}$ affects star formation





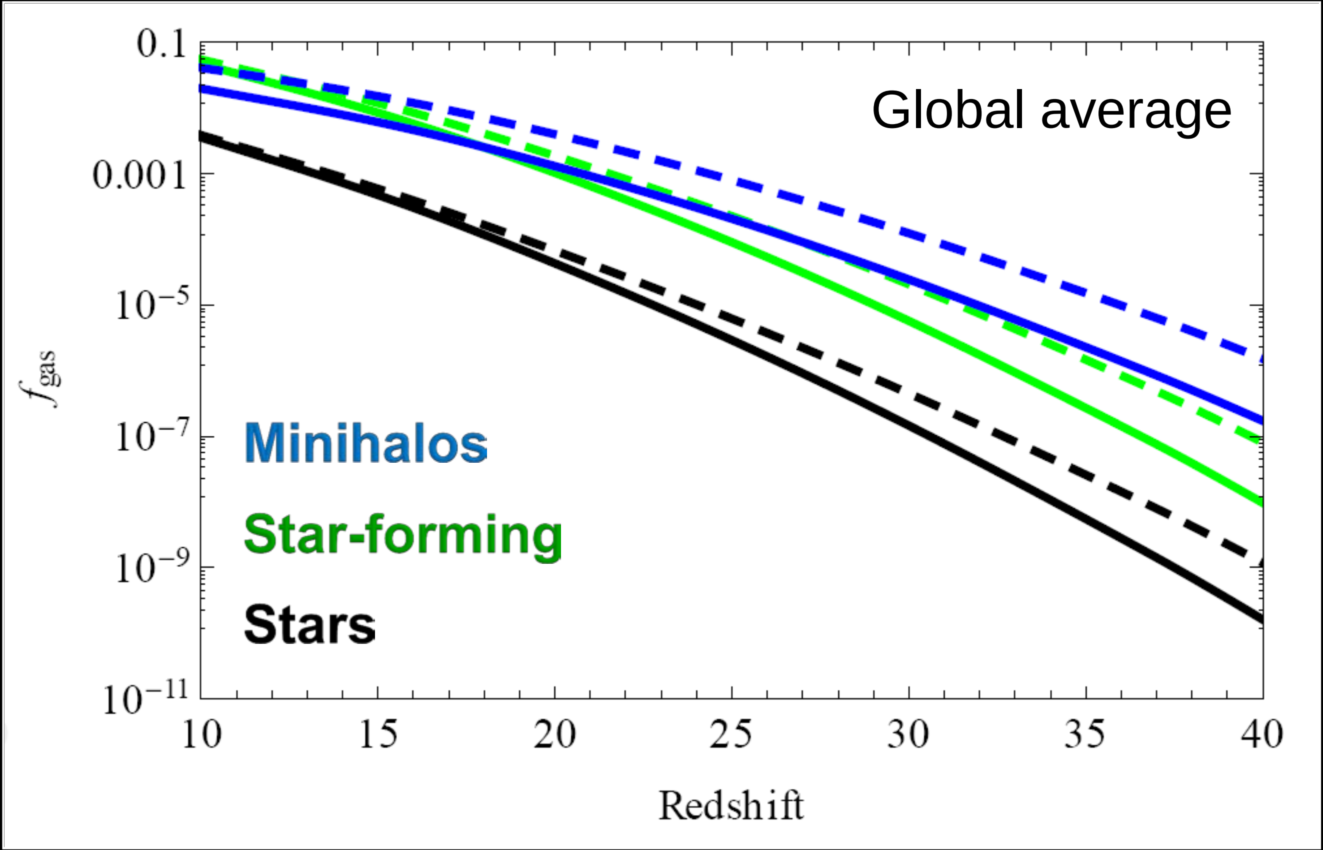
Stacy, Bromm & Loeb (2011)

AF, Barkana, Tseliakhovich & Hirata (2012)

v_{bc} Suppresses Gas Fraction in Halos

Minihalos at z = 20: by 3.1

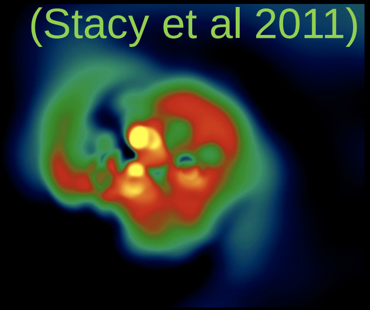
Star-forming halos & stars at z = 20: by 1.8



Tseliakhovich, Barkana & Hirata (2010)

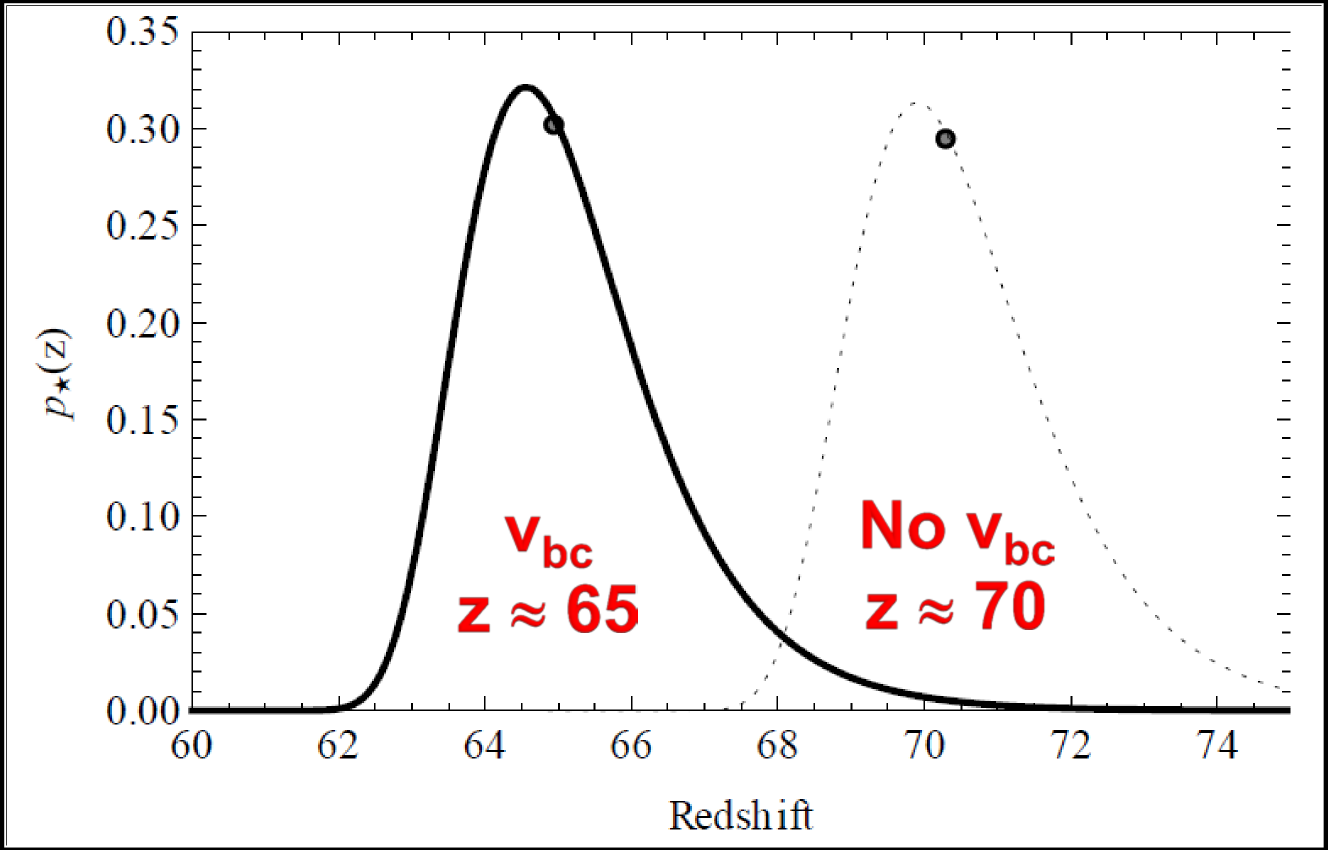
AF, Barkana, Tseliakhovich & Hirata (2012)

v_{bc} Delays Star Formation



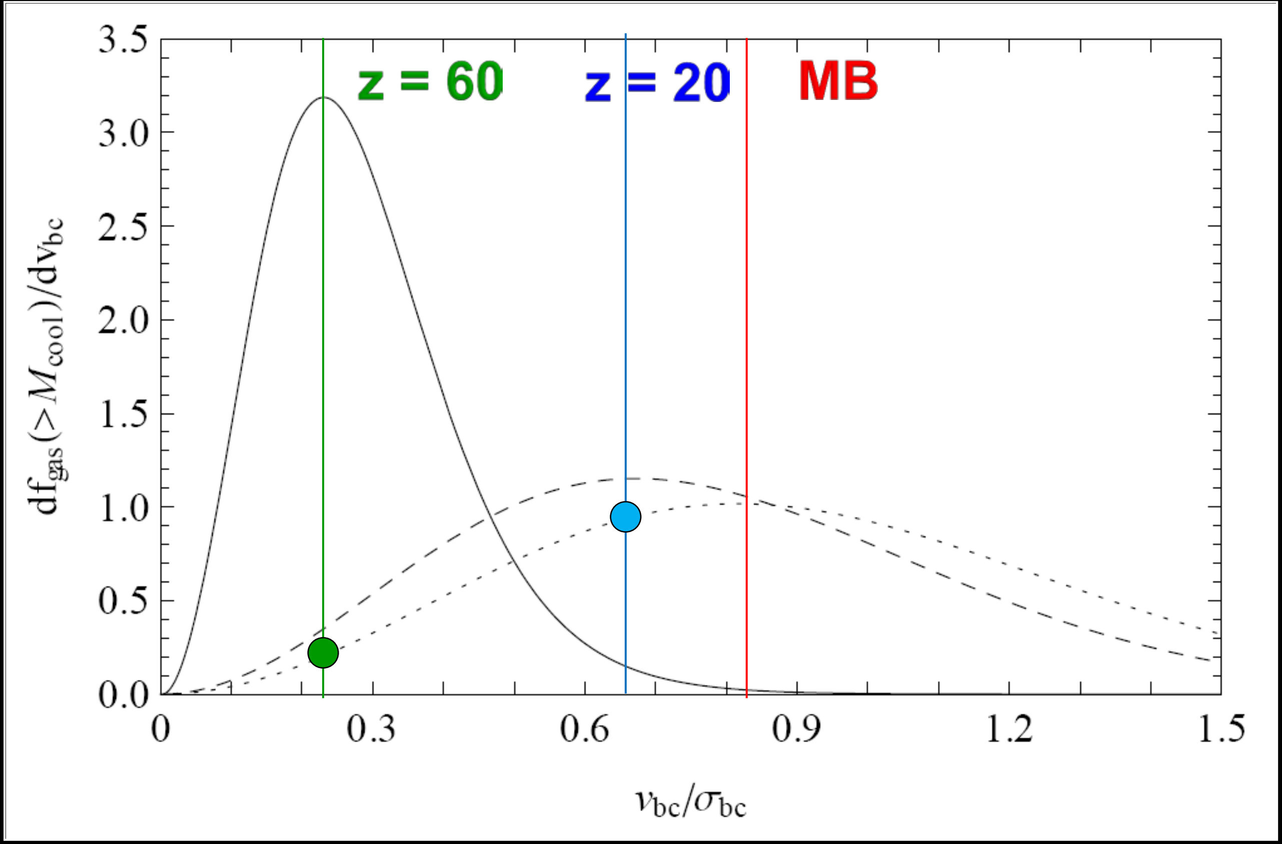
The redshift of the first star

$\Delta z \sim 5$, $\Delta t \sim 3.6$ Myr, ~ 10% effect

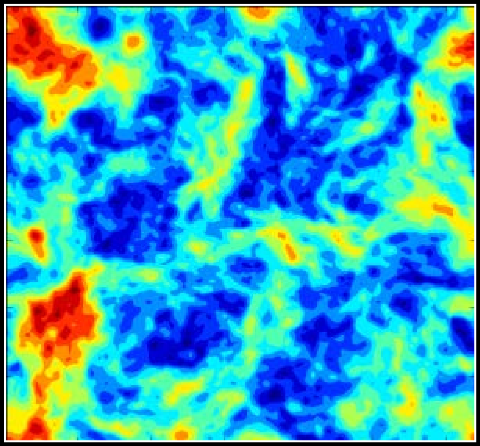


Random $v_{bc} \rightarrow$ Patchy Early Universe

Contribution of v_{bc} bins to star formation



400 Mpc



AF, Barkana, Tseliakhovich & Hirata (2012)

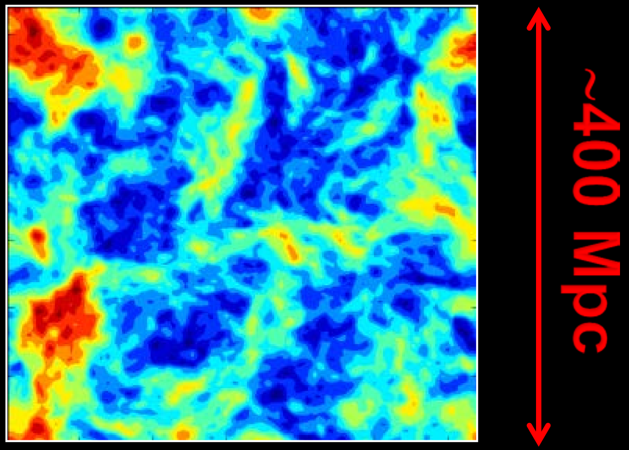
First Stars are Highly Biased

1. Supersonic relative velocities $\rightarrow$ scale dependent bias

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

v_{bc} suppresses star formation

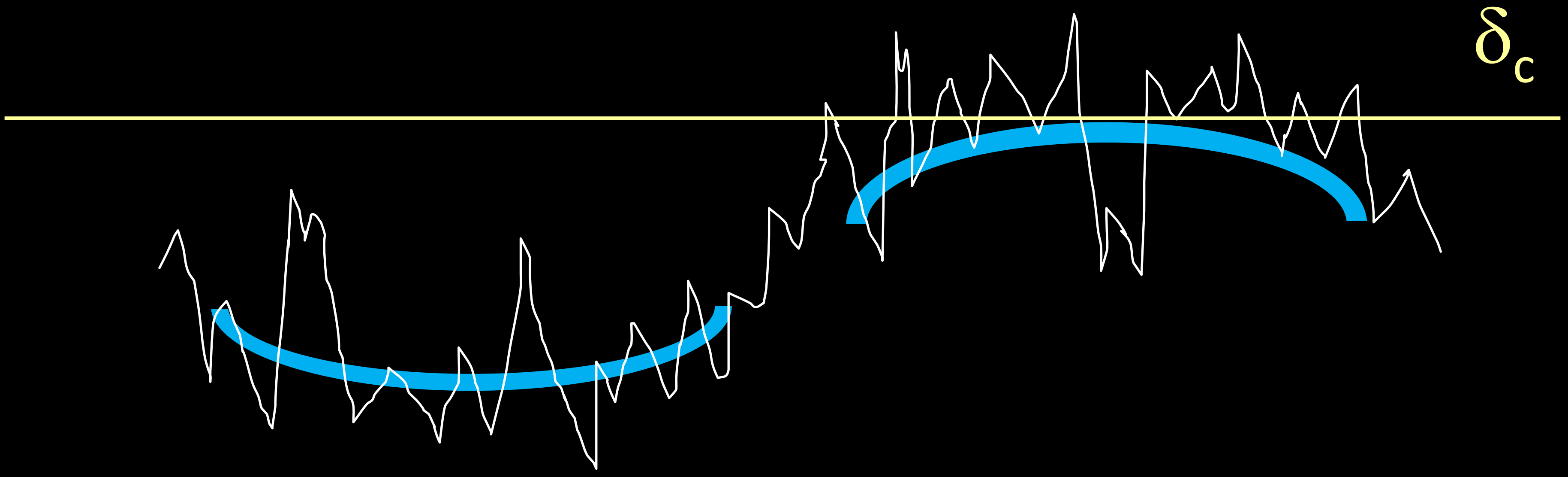
Velocity Pattern



First Stars are Highly Biased

1. Supersonic relative velocities → scale dependent bias
2. Local density fluctuations are biased by δ_{LS}

Press & Schechter 1974; Bardeen, Bond, Kaiser & Szalay 1986; Kaiser 1984; Bond, Cole, Efstathiou & Kaiser 1991; Cole & Kaiser 1989; Mo & White 1996



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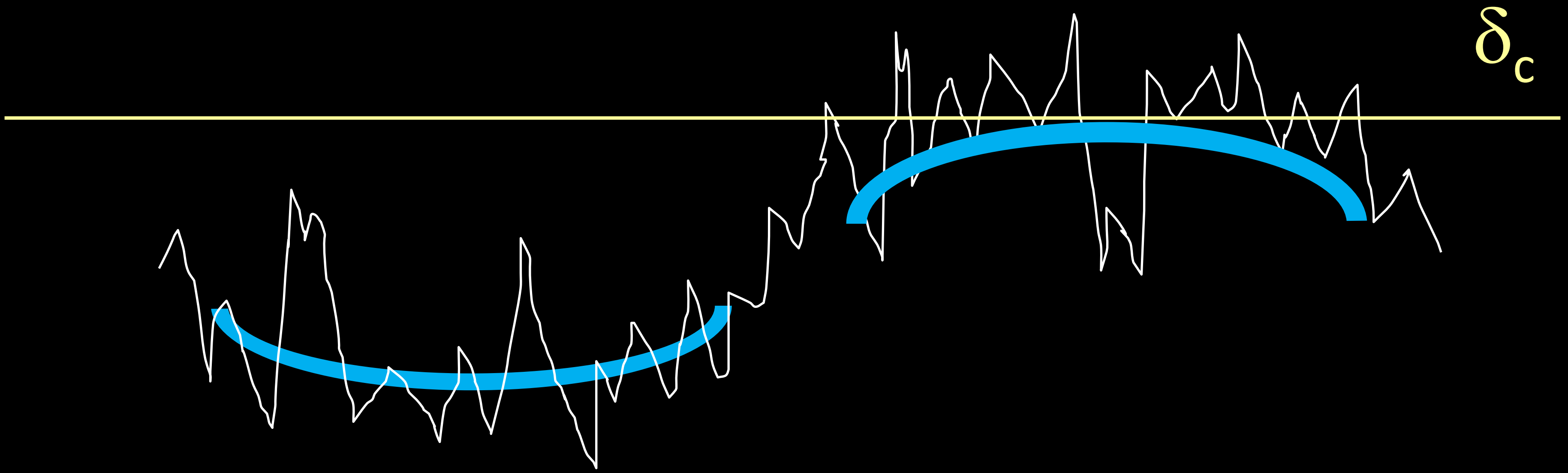
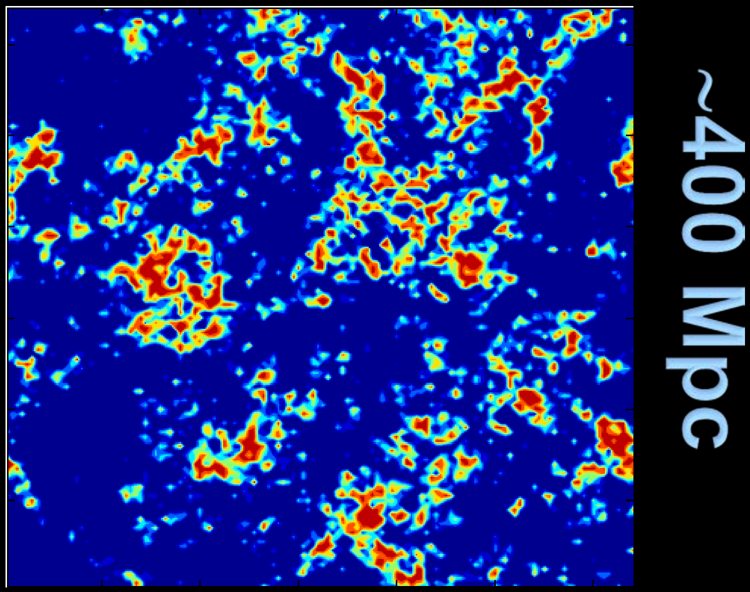


Star formation starts in regions with high δ_{LS} and low v_{bc}

Spatial Distribution of First Rare Stars



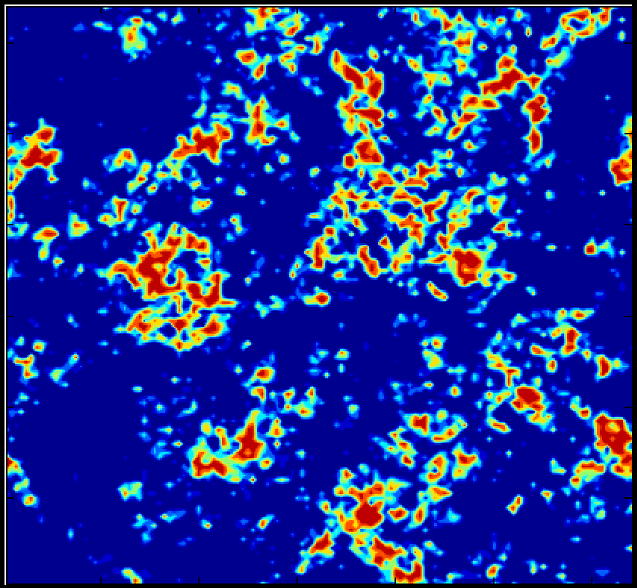
Visbal, Barkana, **AF,** Tseliakhovich & Hirata, ***2012, Nature***

We need to include

1. Stars (small scales)
2. Fluctuations (large scales)

Hard to do in numerical simulations

Spatial Distribution of First Rare Stars



~400 Mpc

Visbal, Barkana, **AF,** Tseliakhovich & Hirata, ***2012, Nature***

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2. Fluctuations (large scales)

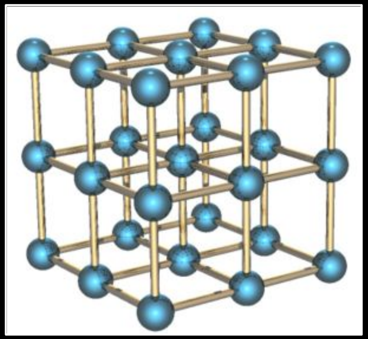
Use hybrid methods

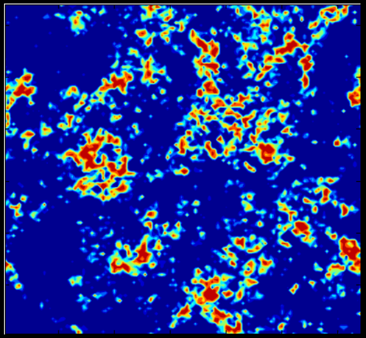
- Zagh et al 2005; Mesinger & Furlanetto 2007; Geil & Wyithe 2008; Alvarez et al 2009; Choudhury, Heahnelt & Regan 2009; Thomas et al 2009; Mesinger, Furlanetto, Cen 2011 **(21CMFAST);**
- Visbal, Barkana, **AF**, Tseliakhovich & Hirata, ***2012, Nature; AF***, Barkana, Visbal, Tseliakhovich & Hirata, ***2012, submitted***

Hybrid Method

- Large scales (> 3 Mpc): linear evolution

- Small scales (< 3 Mpc): evolve nonlinearly
  Analytical models, small scale simulations

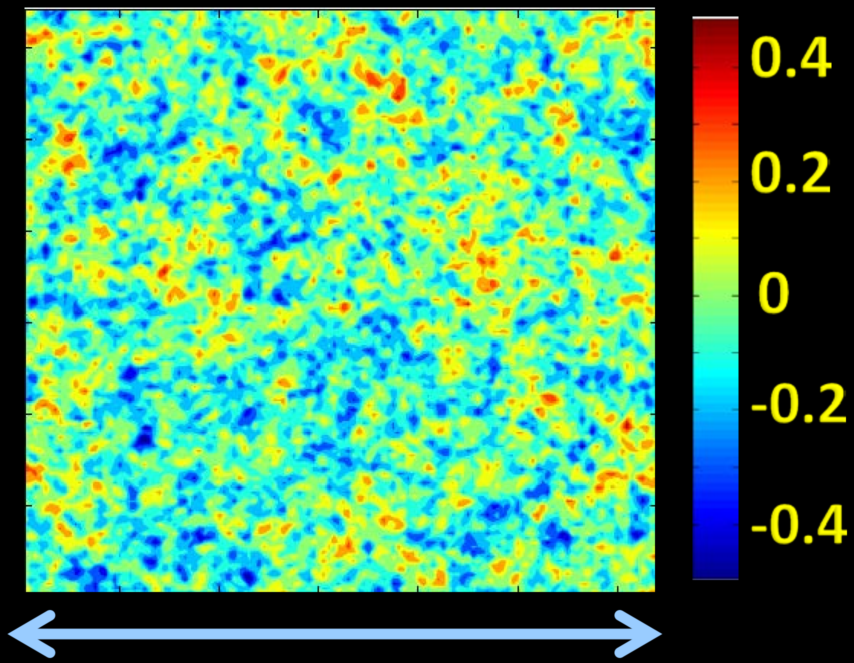


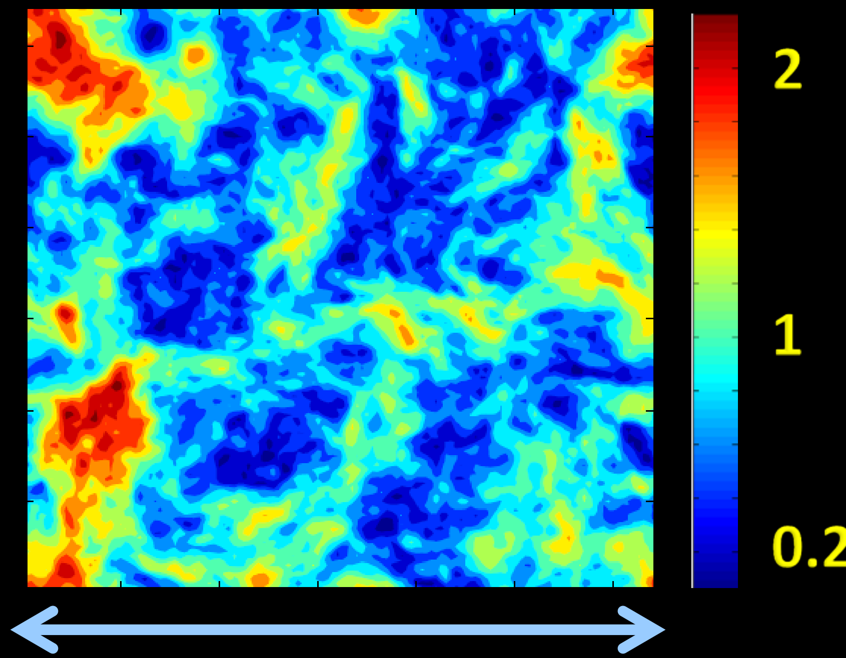


- Volume ~ (400 Mpc)^3
- Initial conditions for δ_{LS} and v_{bc}
- Pixels of 3 Mpc each of fixed δ_{LS} & v_{bc}

Initial Conditions:
Realistic Sample of the Universe

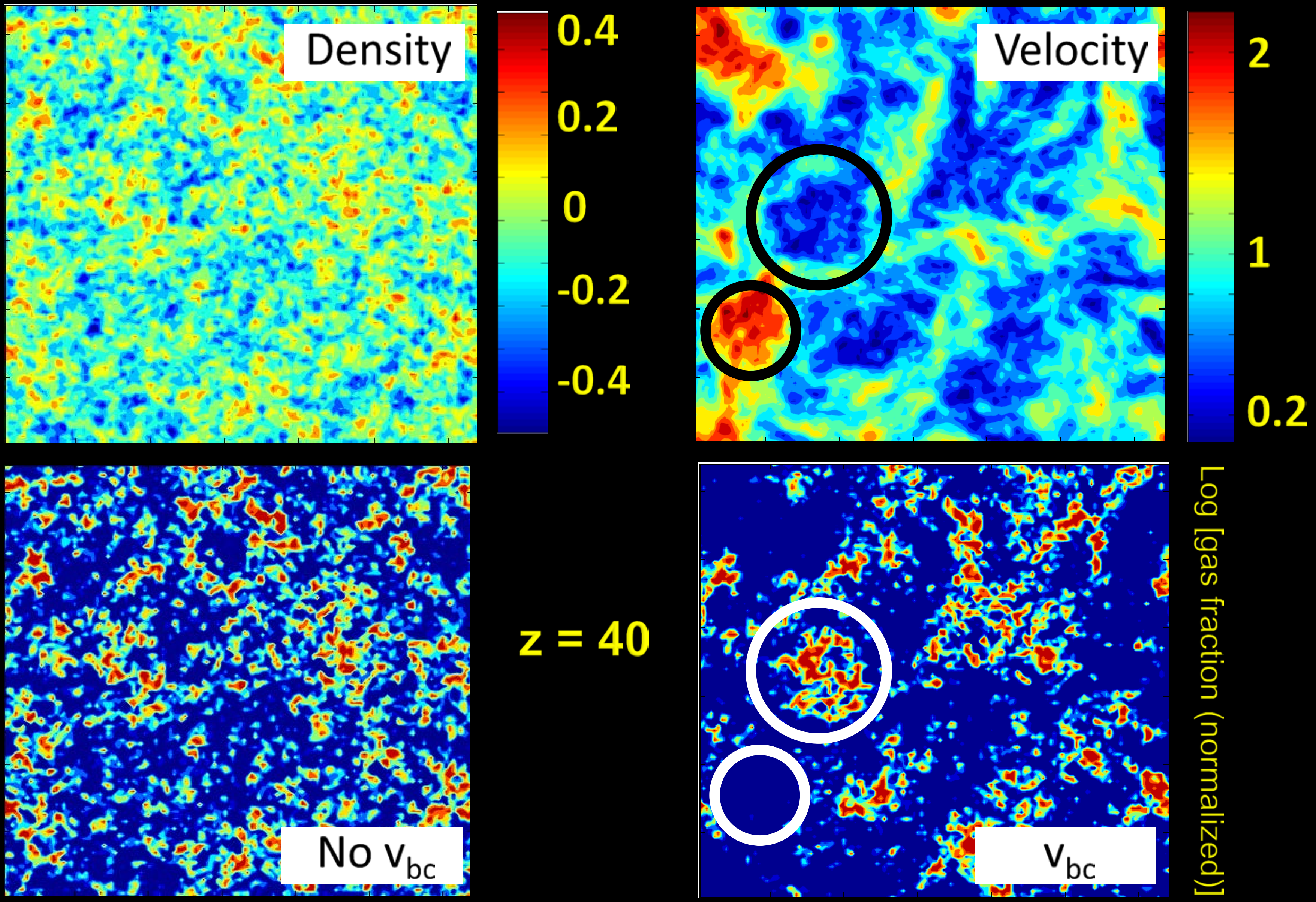
Realistic samples of the Universe on large scales





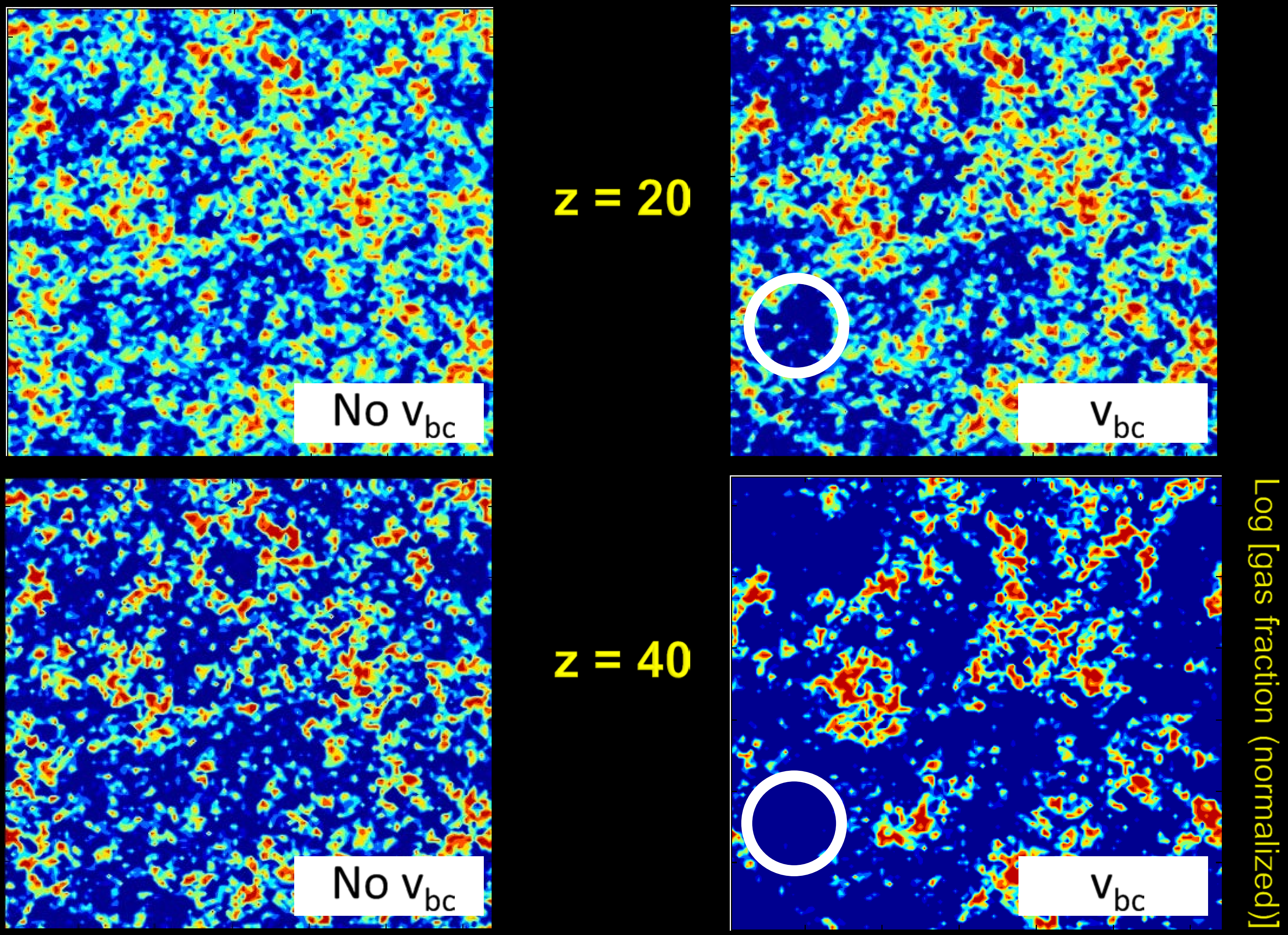
Gas Fraction in Star Forming Halos

Visbal, Barkana, **AF**, Tseliakhovich, Hirata, **Nature** ***(2012)***



The Effect of v_{bc} Decays with Redshift

Visbal, Barkana, **AF**, Tseliakhovich, Hirata, **Nature** ***(2012)***



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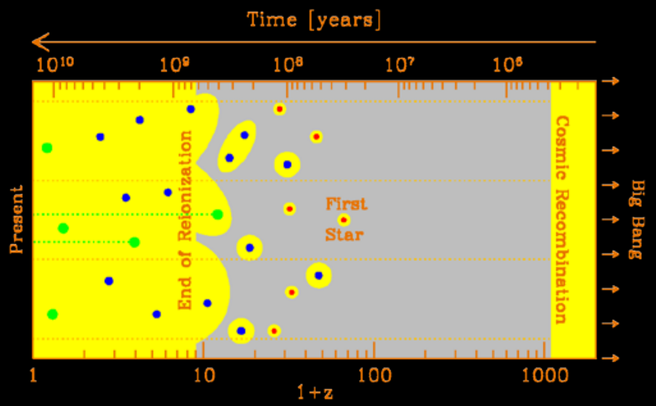
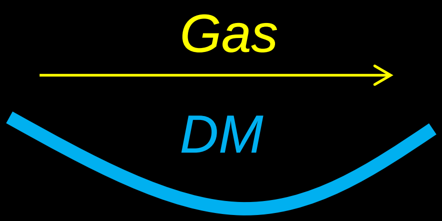
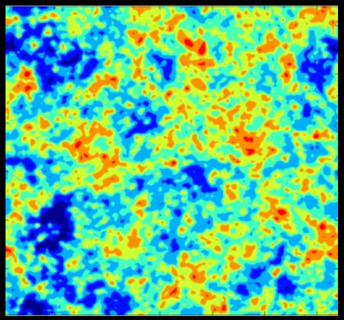


Barkana, 2006

2. Effect of Relative Velocities on the First Stars



3. **Signature of First Stars in the 21-cm Signal**



Starlight Couple to T_S
$\rightarrow$ Signature of Stars it 21-cm

Lyα:

$T_S \rightarrow T_{gas}$ (Wouthuysen-Field effect)

Lyman-Werner :

Dissociate $H_2 \rightarrow$ Lessen star formation ($T_{gas} \downarrow$)

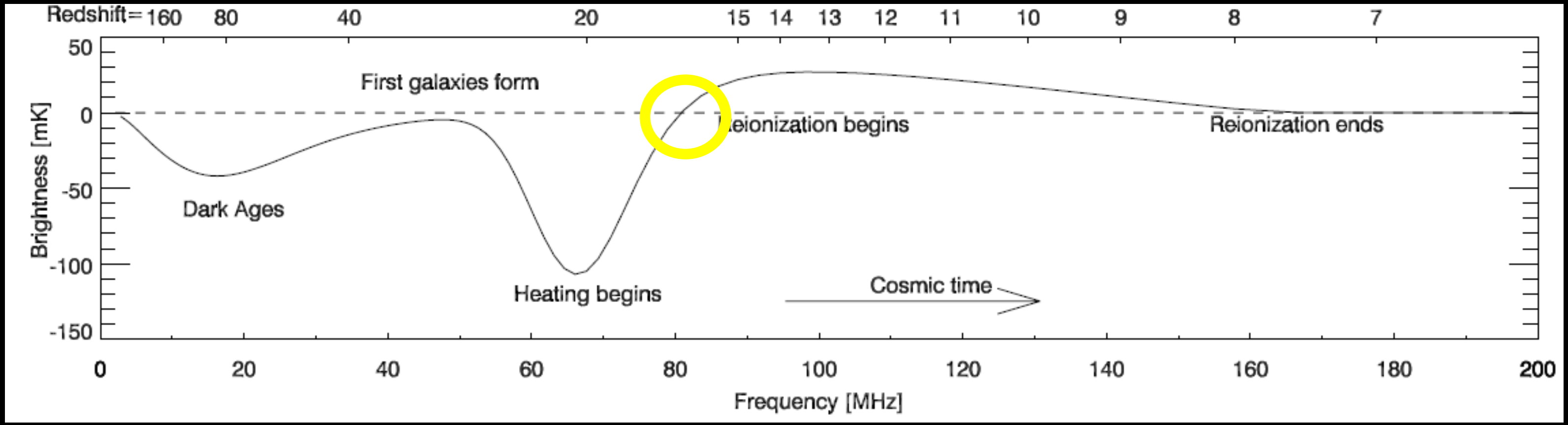
"Negative feedback to star formation"

X-rays (starbursts):

Heat the gas ($T_{gas} \uparrow$)

21-cm from Heating Fluctuations at Heating Transition

Visbal, Barkana, **AF**, Tseliakhovich, Hirata, **Nature** ***(2012)***



Pritchard & Loeb, 2012

Heating Transition $T_{gas} = T_{CMB}$ (we set z = 20)

21-cm from Heating Fluctuations at Heating Transition

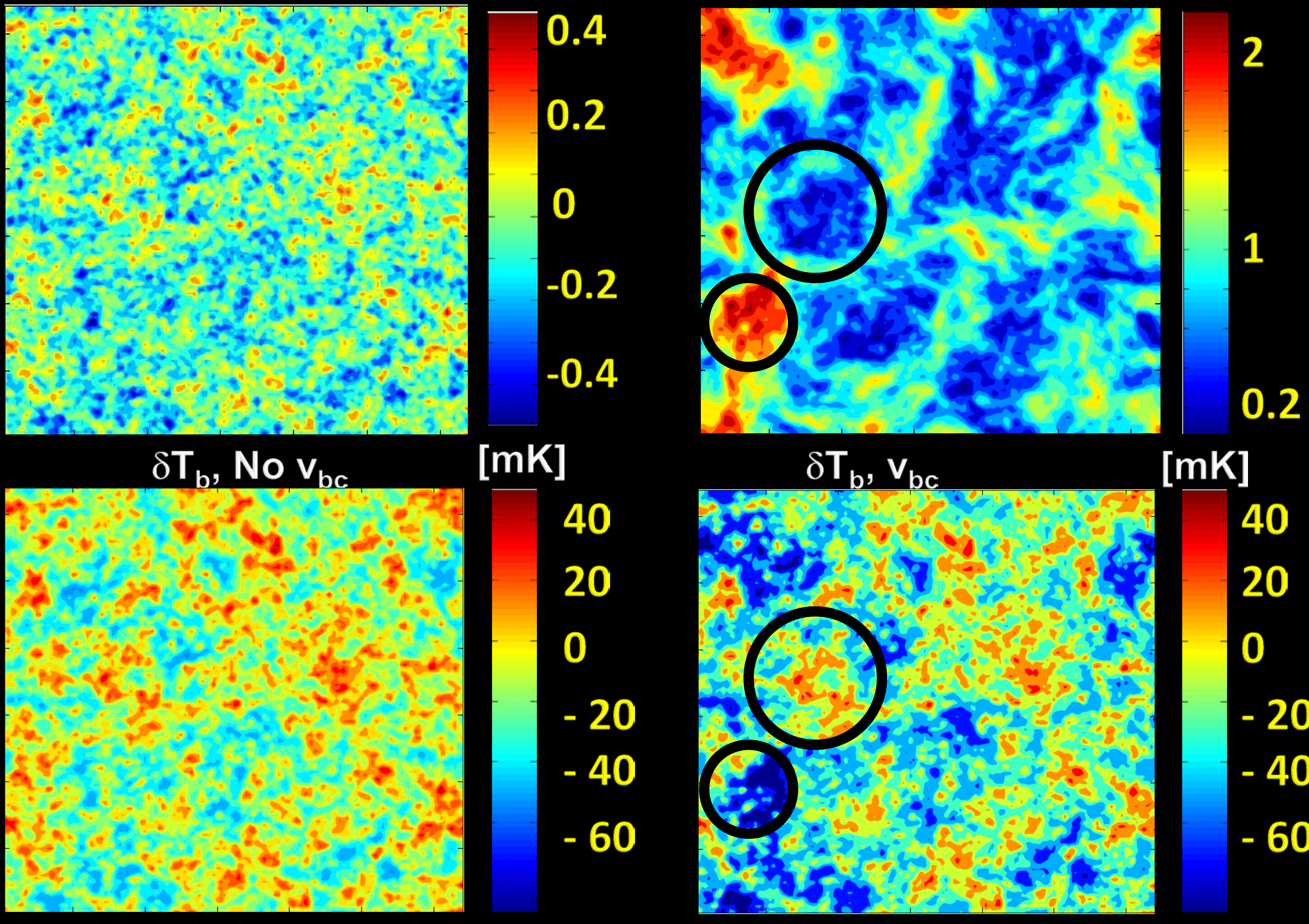
Visbal, Barkana, **AF**, Tseliakhovich, Hirata, **Nature** ***(2012)***

- ✓ Hybrid methods

- ✓ Fluctuations in X-rays (maximal around z ~ 20)
- ✓ LW “toy models”:
  - Molecular cooling (no LW feedback)
  - Atomic cooling (saturated LW feedback)

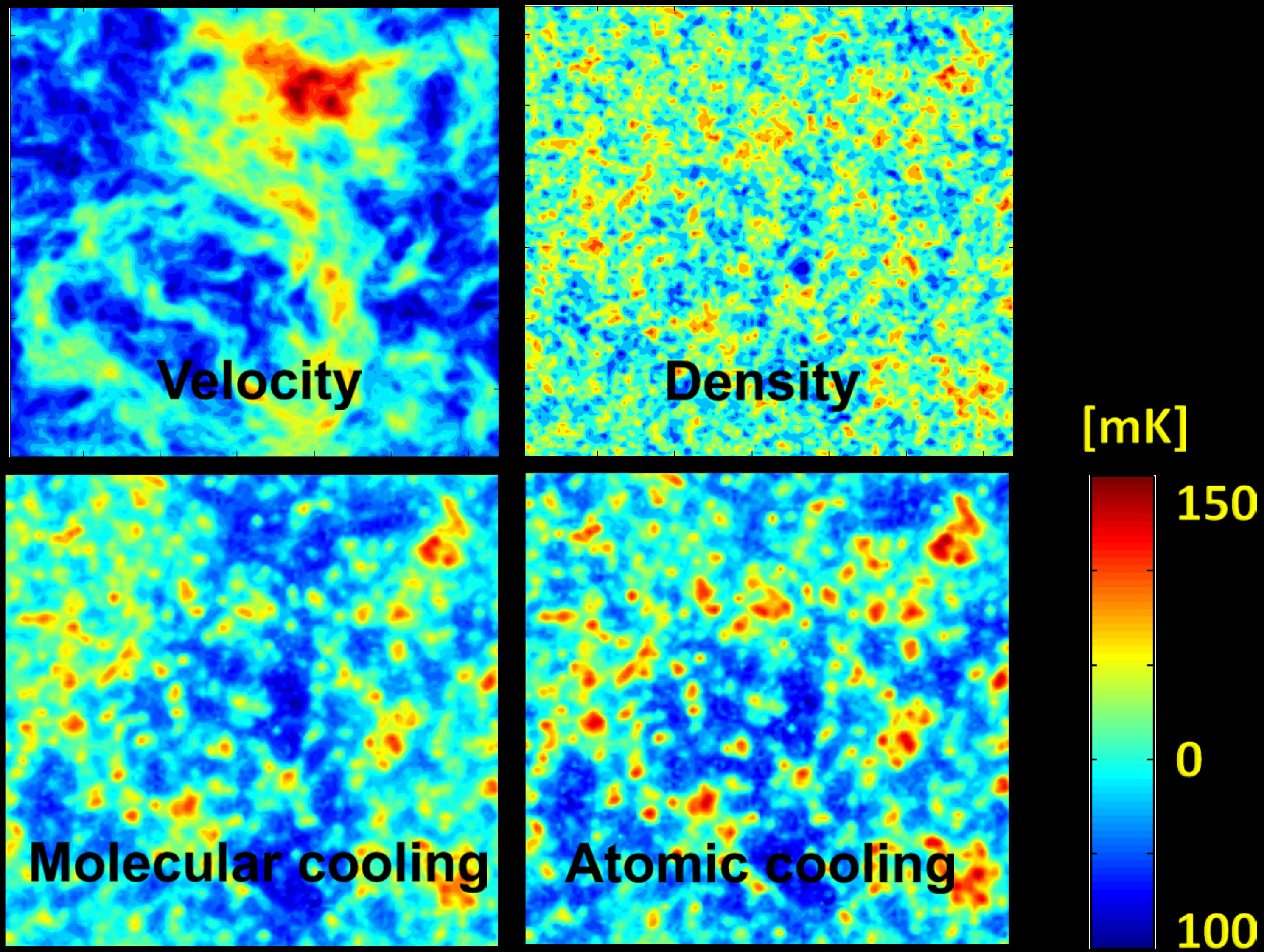
Ignore: Fluctuations in Lyα (max around z ~ 30)

21-cm from Heating Fluctuations

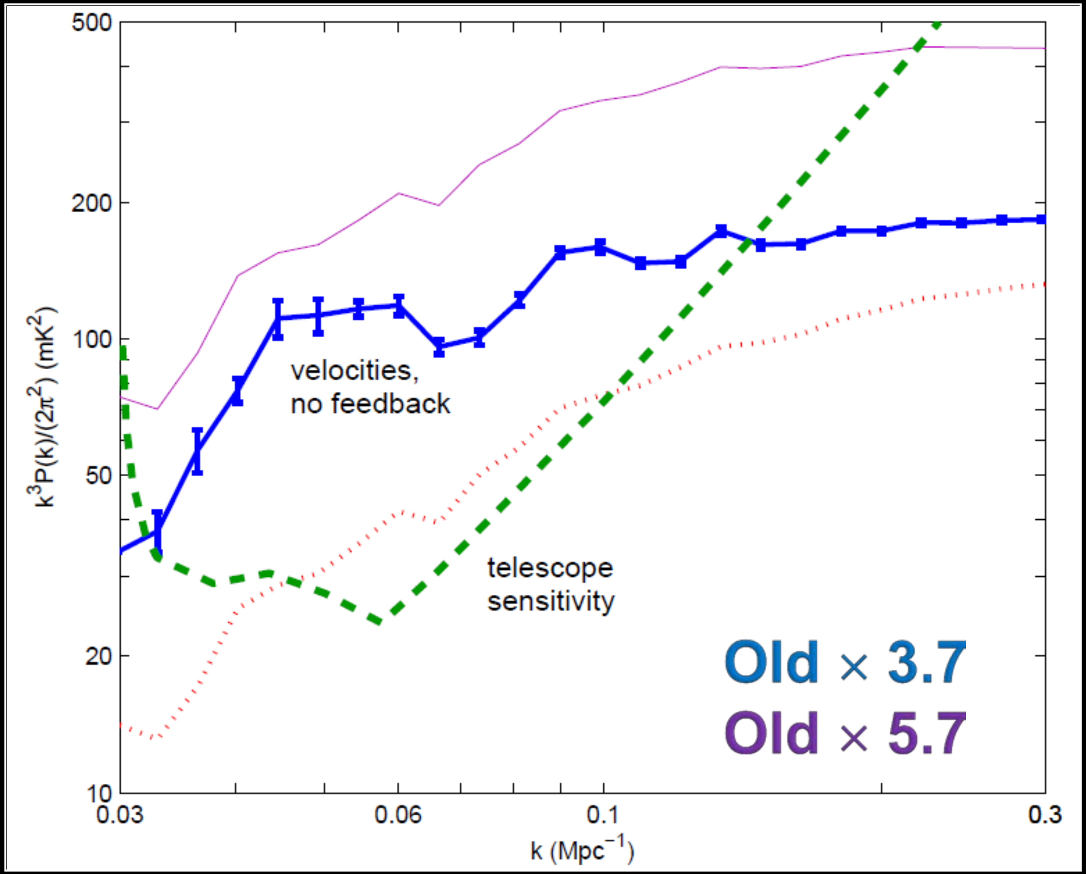


Feedback Erases BAO

(**AF**, Barkana, Visbal, Tseliakhovich, Hirata, Submitted)



21-cm Power Spectrum at z_{heat}



Noise (LOFAR-like but tuned to 4.5 m)
McQuinn et al 2006

Old:
No v_{bc} no feedback

New!!!
v_{bc} , molecular cooling
v_{bc} , atomic cooling

Visbal, Barkana, **AF**, Tseliakhovich & Hirata, **Nature (2012)**

Feedback, $v_{bc} \rightarrow$ BAO, stronger clustering

Following Time Evolution of 21-cm Signal

(**AF**, Barkana, Visbal, Tseliakhovich, Hirata, Submitted**)**

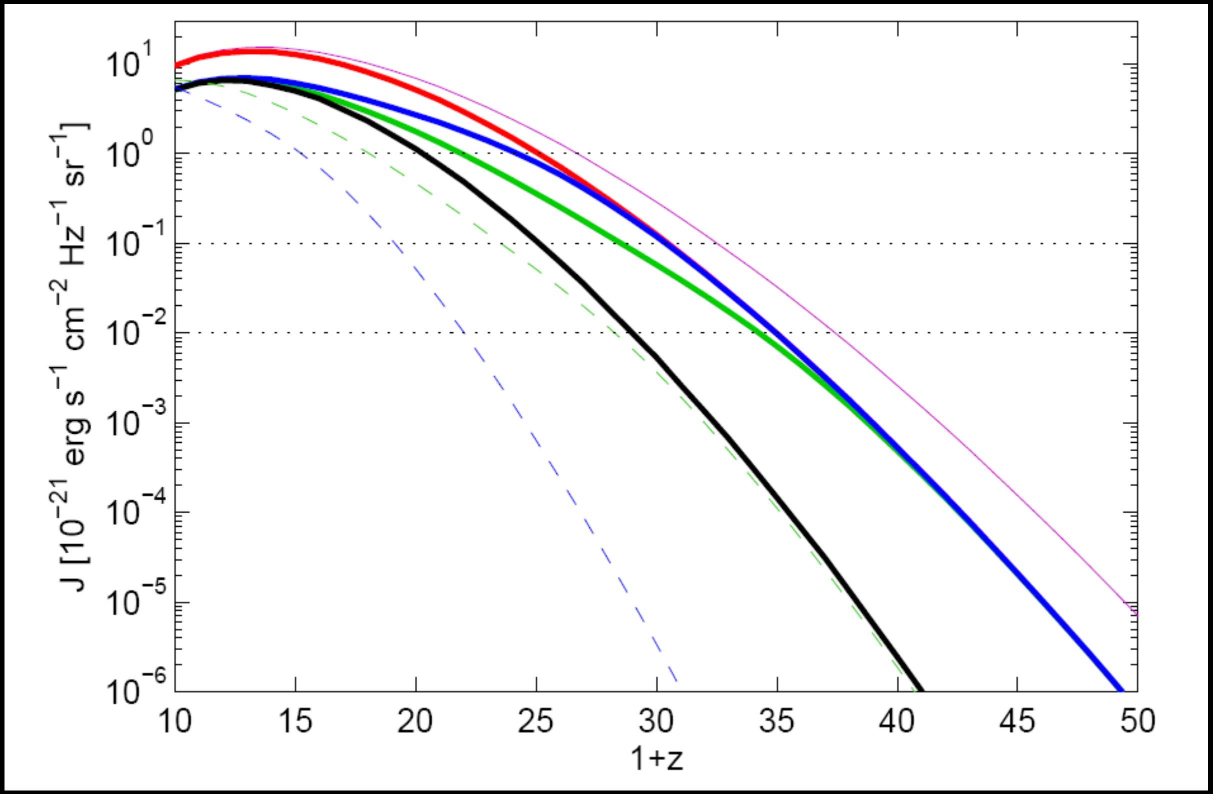
- ✓ Hybrid methods + Simulation
- ✓ Fluctuations in X-rays
- ✓ Fluctuations in LW, realistic LW
- ✓ Interplay between LW and v_{bc}

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

Machacek et al 2001; Wise & Abel 2007; O'Shea & Norman 2008

Relative Timing: LW & Heating

(**AF**, Barkana, Visbal, Tseliakhovich, Hirata, Submitted)



No v_{bc}, no fbk

v_{bc}, no fbk

v_{bc} weak fbk

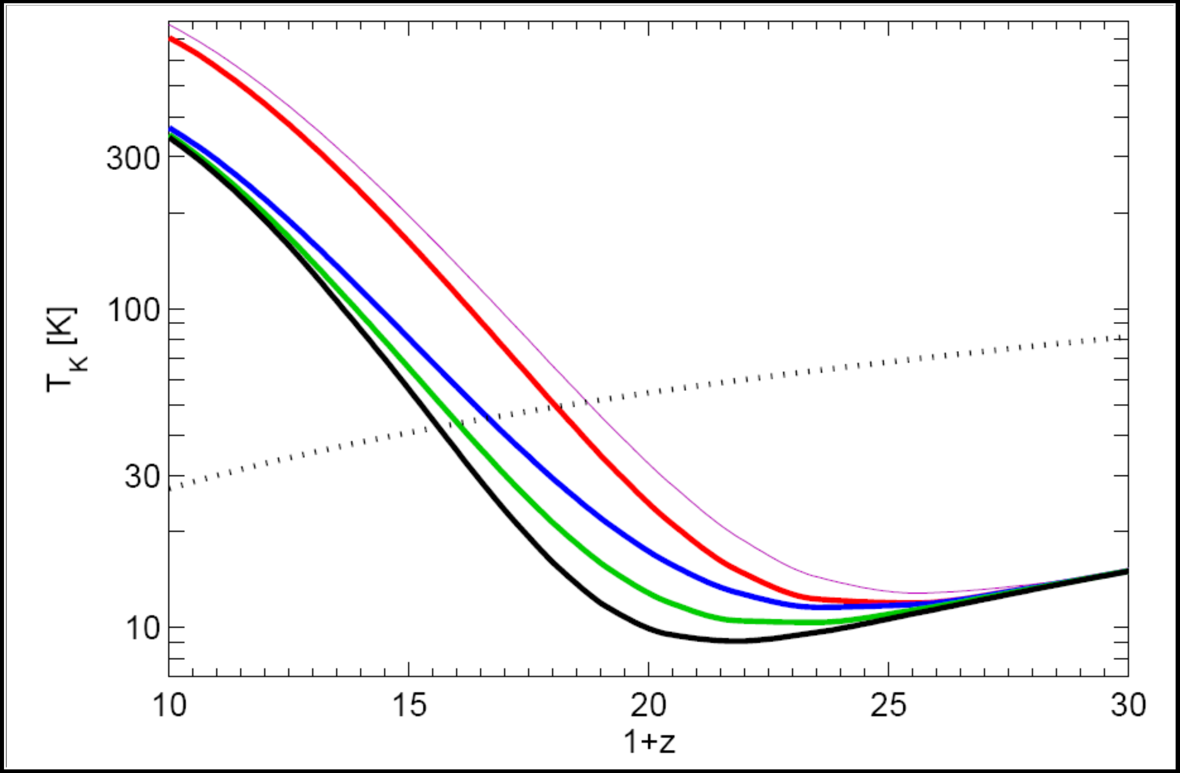
v_{bc} strong fbk

v_{bc} saturated fbk

LW transition: $z_{LW} \approx 19 - 23$

Relative Timing: LW & Heating

(**AF**, Barkana, Visbal, Tseliakhovich, Hirata, Submitted)



No v_{bc}, no fbk

v_{bc}, no fbk

v_{bc} weak fbk

v_{bc} strong fbk

v_{bc} saturated fbk

Heating: $z_{heat} \approx 15 - 18$

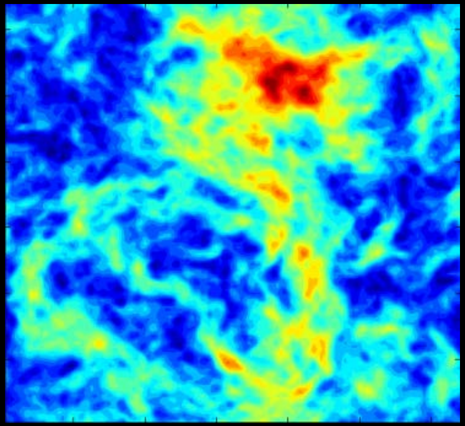
Heating is delayed by v_{bc} & LW

~ 3% (no feedback)

~ 17% (saturated feedback)

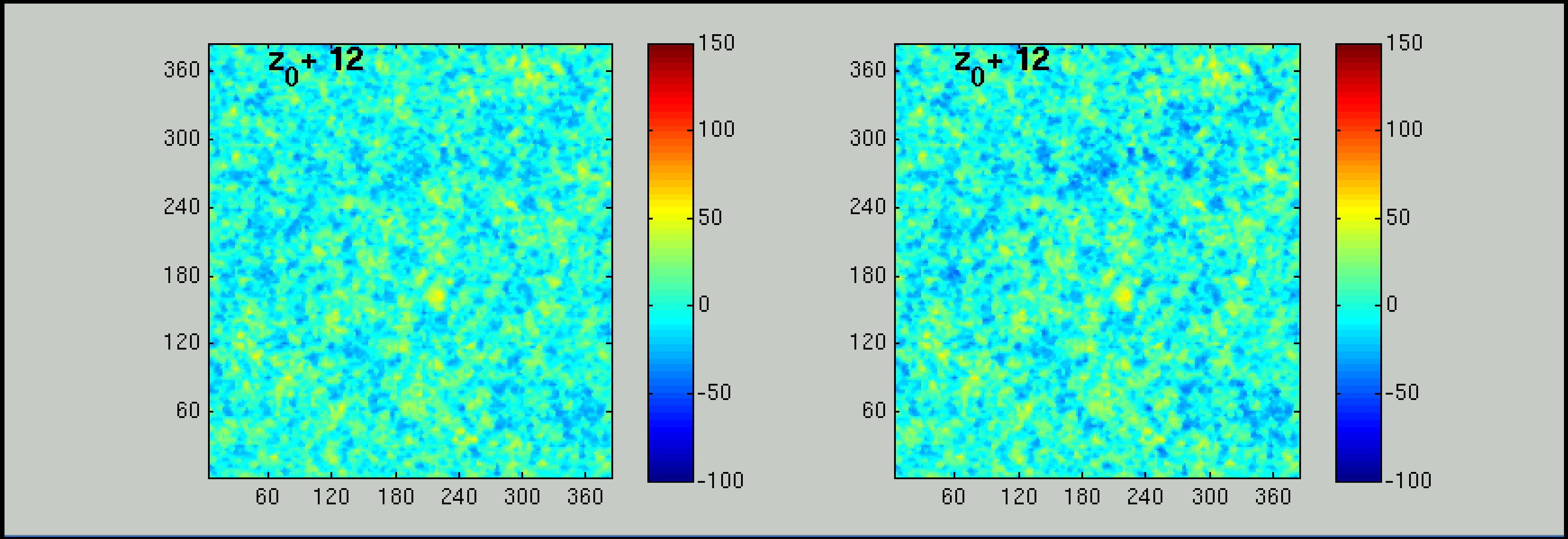
Best Prospects at $z_{heat} + 3 \approx 20$

(**AF**, Barkana, Visbal, Tseliakhovich, Hirata, Submitted)



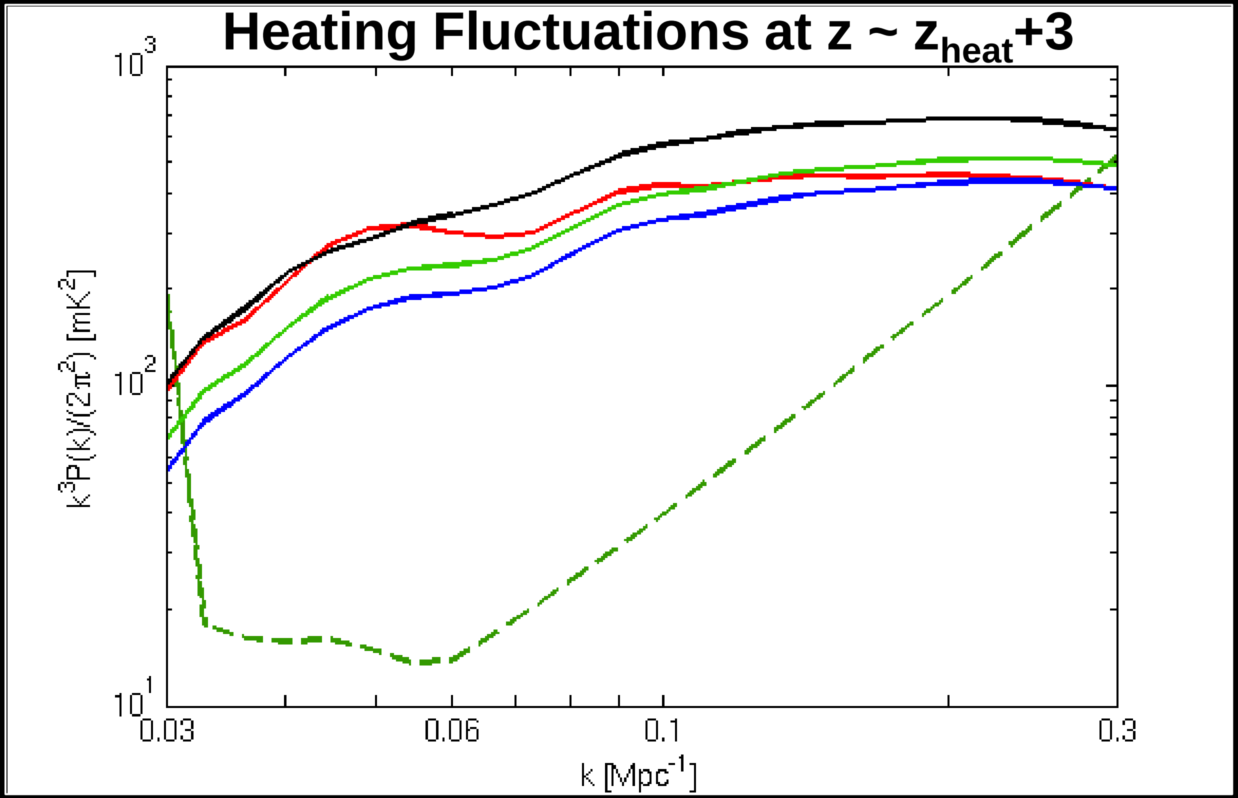
Evolution with time $\delta T_b - \langle \delta T_b \rangle$

No v_{bc} **v_{bc}**



Best Prospects at $z_{heat} + 3 \approx 20$

(**AF**, Barkana, Visbal, Tseliakhovich, Hirata, Submitted)



v_{bc} no fbk

v_{bc} weak fbk

v_{bc} strong fbk

v_{bc} saturated fbk

Dashed: noise

$S/N^2_{new} \sim 2.6 \times S/N^2_{old}$

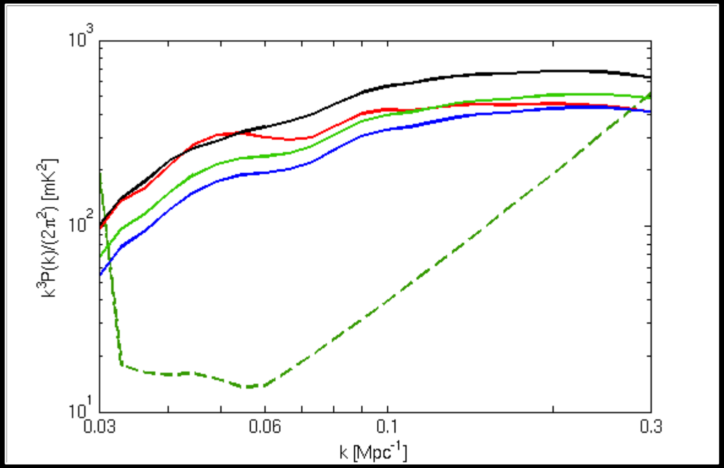
$S/N^2_{new} \sim 4.4 \times S/N^2_{old}$

Summary and Future Plans

- Velocity is important
- v_{bc} & LW have strong effect on 21-cm signal
- Good observational prospects for $z \approx 20$!

Future Plans

- Fluctuations from Lyα
- Explore parameter space
- Shock heating
- More simulations needed



Thank you!