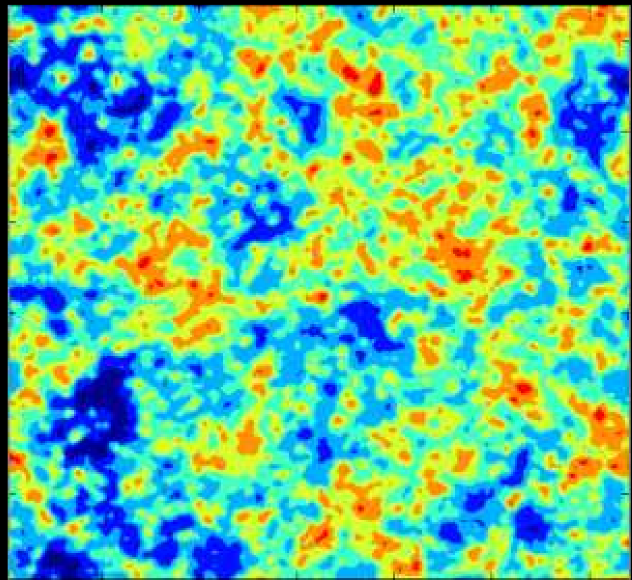
Velocity and feedback enhance 21-cm signal from first stars at z ~ 20

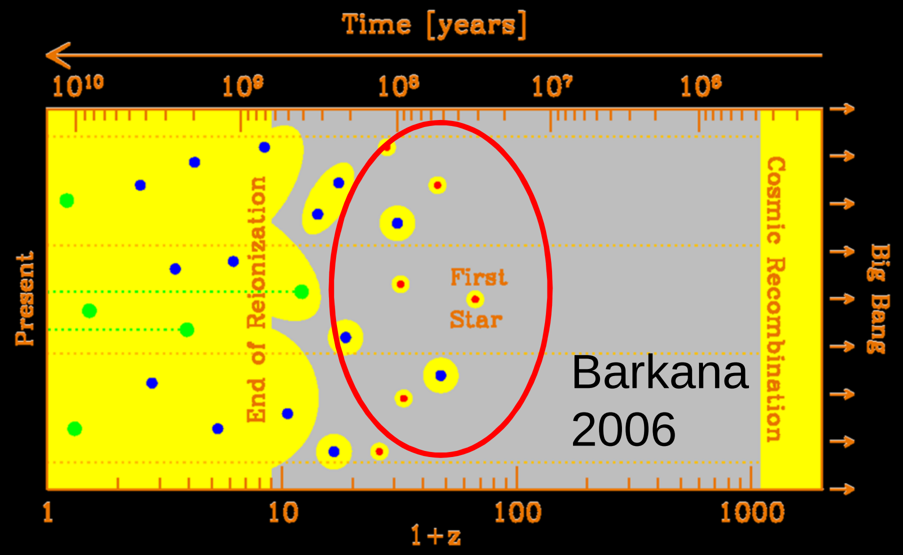


Anastasia Fialkov
Tel Aviv University
24 September 2012, Fermilab

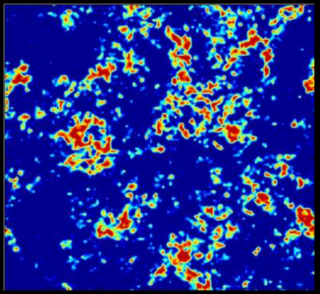
In Collaboration with:
Rennan Barkana, TAU
Eli Visbal, Harvard
Christopher Hirata, Caltech
Dmitri Tseliakhovich, Caltech

Outline:

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



2. Spatial Distribution of First Stars



3. 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

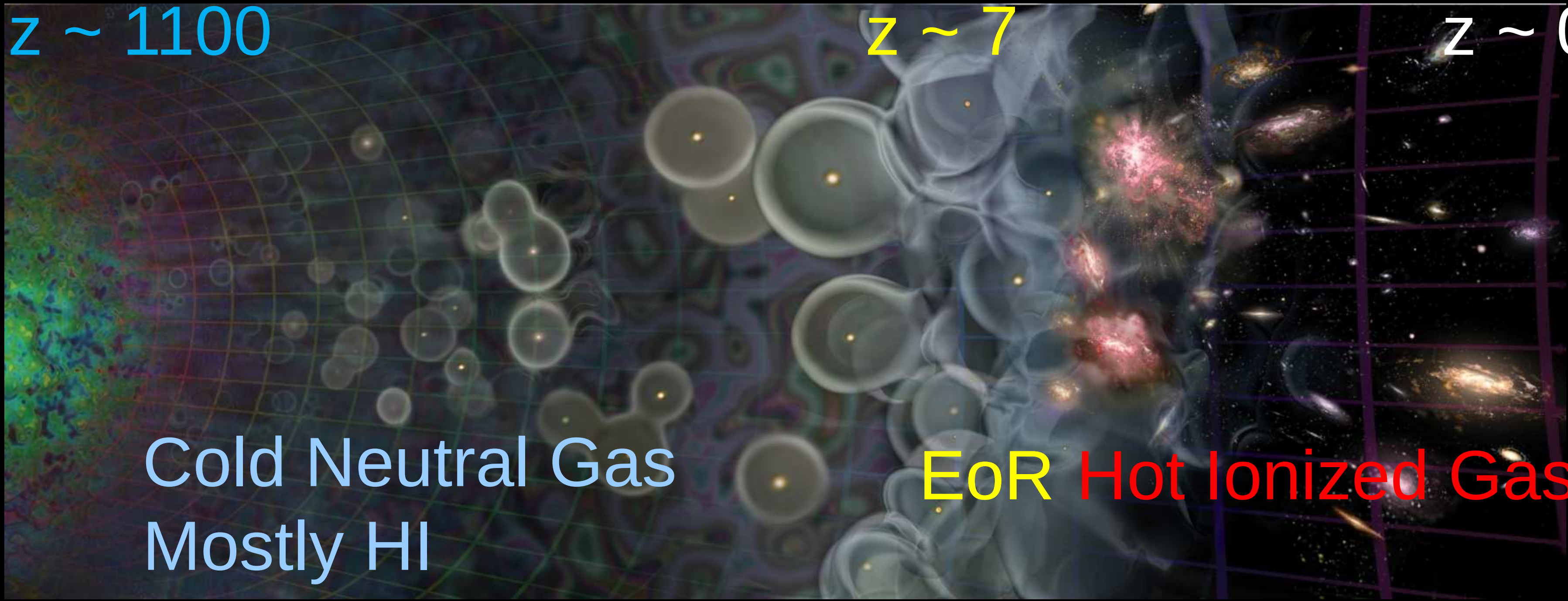


Image: Loeb, Scientific American 2006

CMB First Stars Starlight heats & ionizes the gas

Observed:

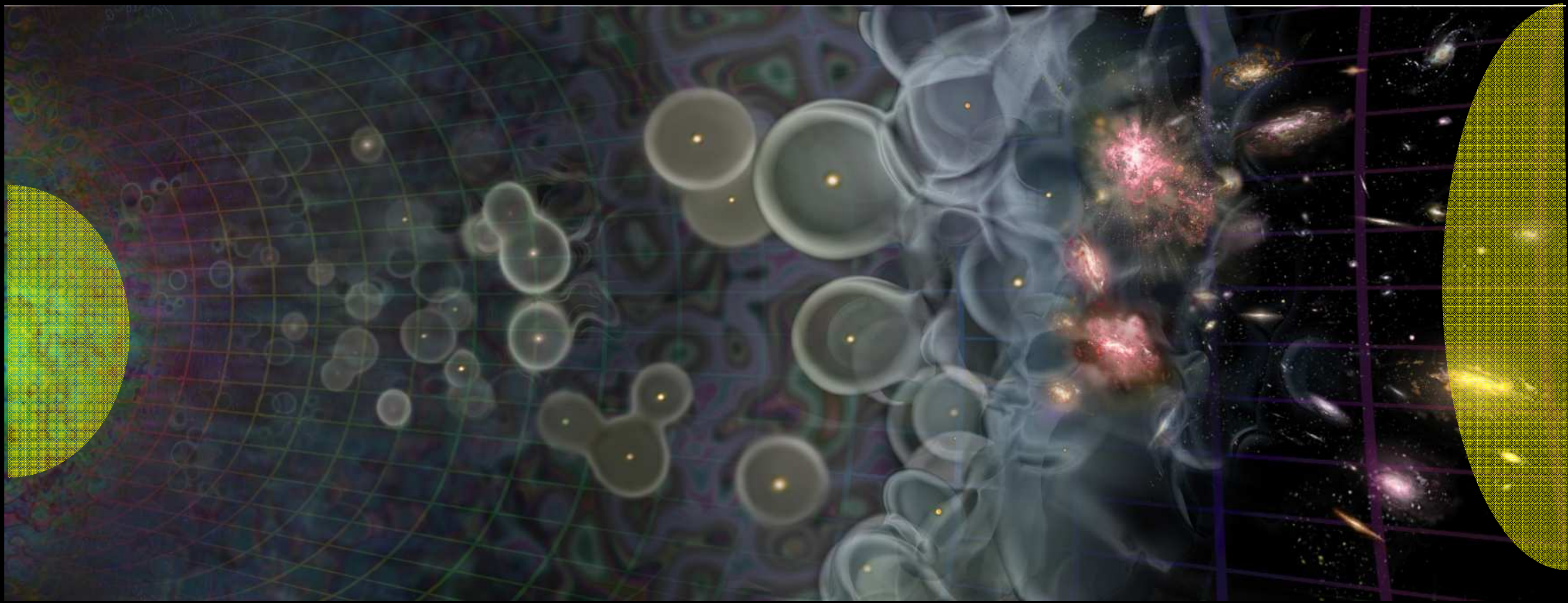


Image: Loeb, Scientific American 2006

CMB (z ~ 1100)

Point sources (z < 10)

Local structure (z < 2)

Unobserved (1000>z>7):

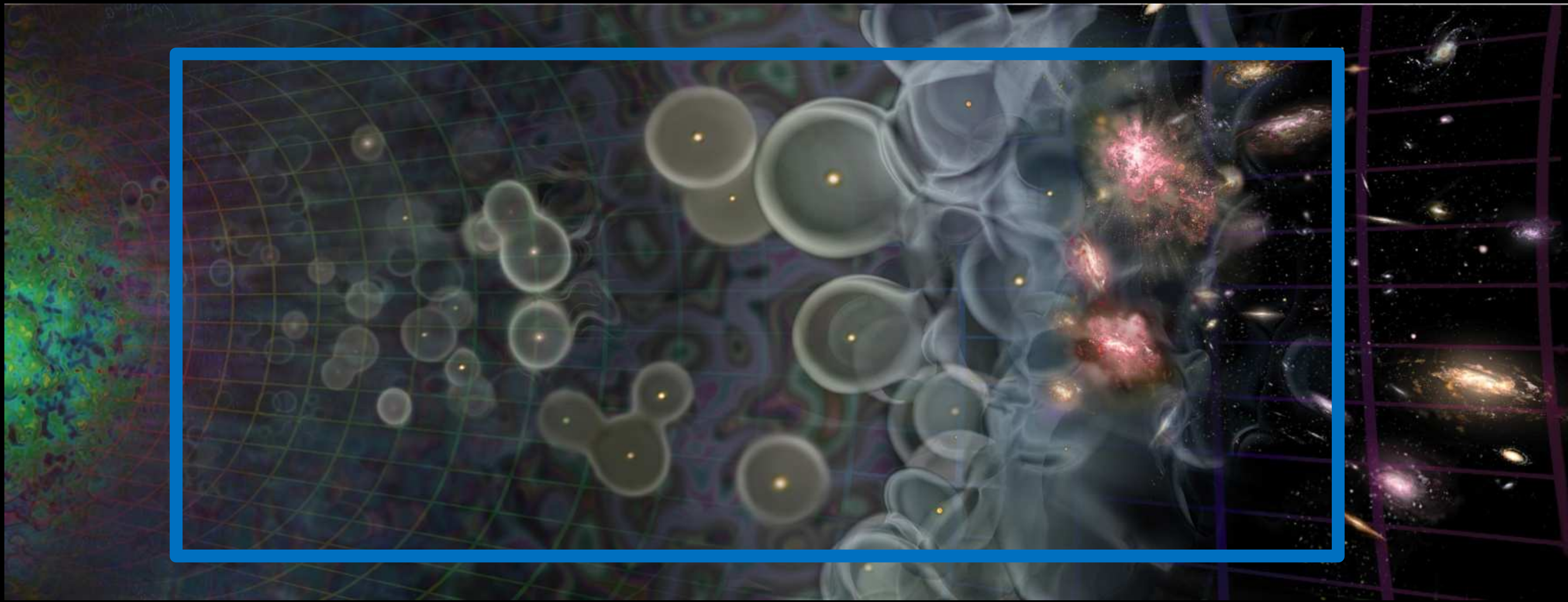
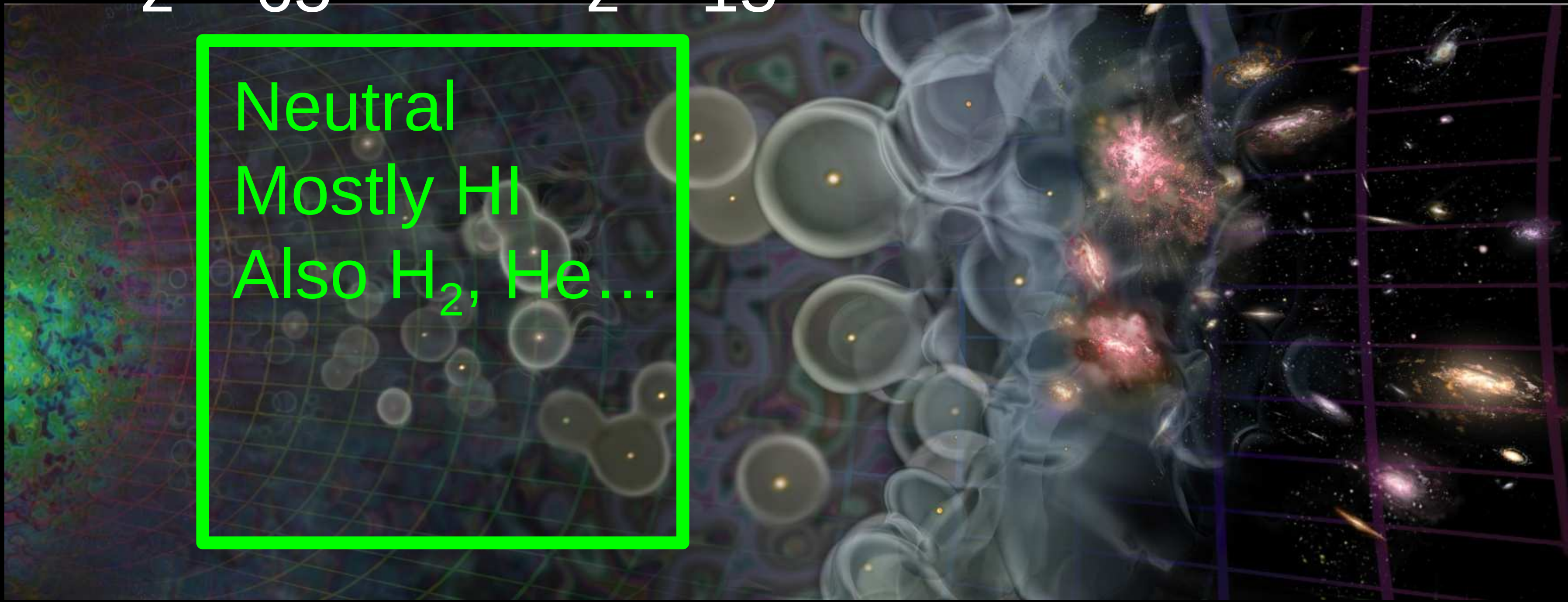


Image: Loeb, Scientific American 2006

Dark ages First stars & galaxies Reionization

In this talk: The Epoch of the First Stars



The First Stars:

Image: Loeb, Scientific American 2006

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

Tegmark et al 1997

Formed at $z < 65$

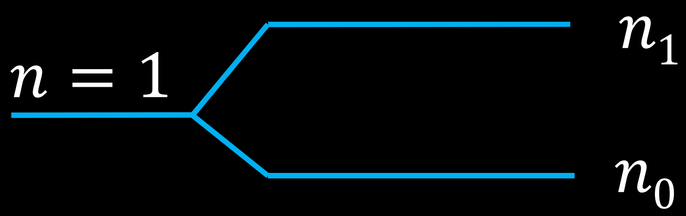
AF, Barkana, Tseliakhovich, Hirata 2012

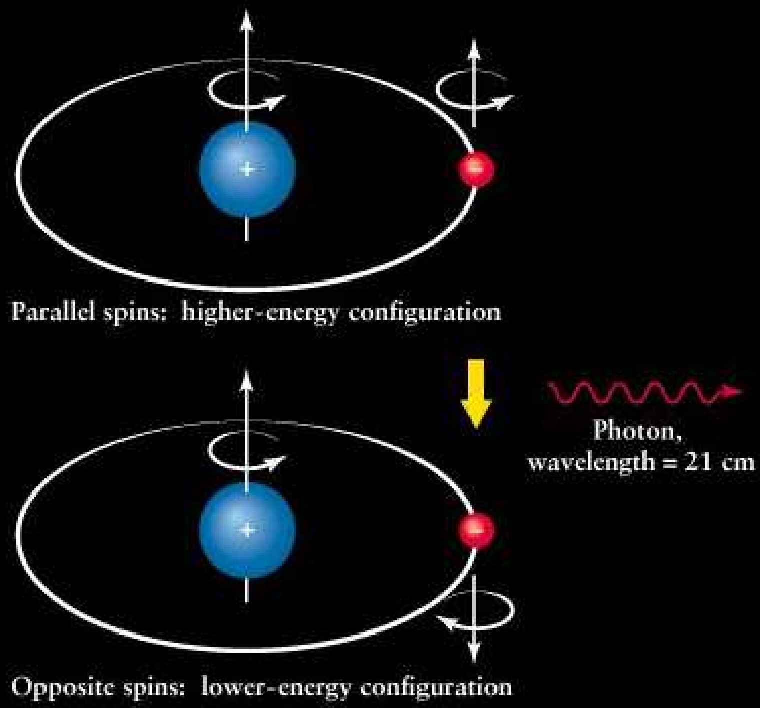
HI cloud

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

The epoch of first stars can be probed with redshifted 21-cm line of HI

21-cm Line from 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

n_1/n_0 depends on the ambient

Atomic Physics Teaches about the Early Universe

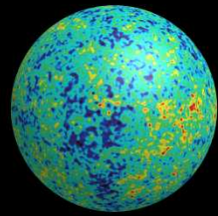
- 21-cm signal of HI from high z:

$$\approx 9\,(1+\delta)(1+z)^{1/2}(1-T_{CMB}T^{-1}_{S})$$

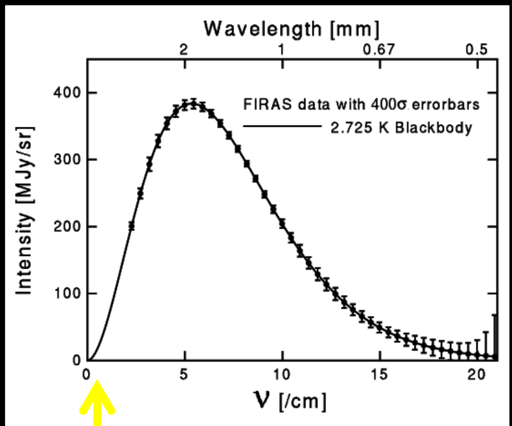
- T_S depends on the gas, radiation etc. (Epoch of first stars: $T_S \approx T_{gas}$)

- Redshifted 21-cm photons have $\tau \approx 0 \rightarrow$ are observable!

Source for 21-cm observations: CMB



CMB Black Body Spectrum



$h\nu << k_B T$

$I_\nu = 2\, k_B T\, \nu^2/c^2$

HI at z_{HI}

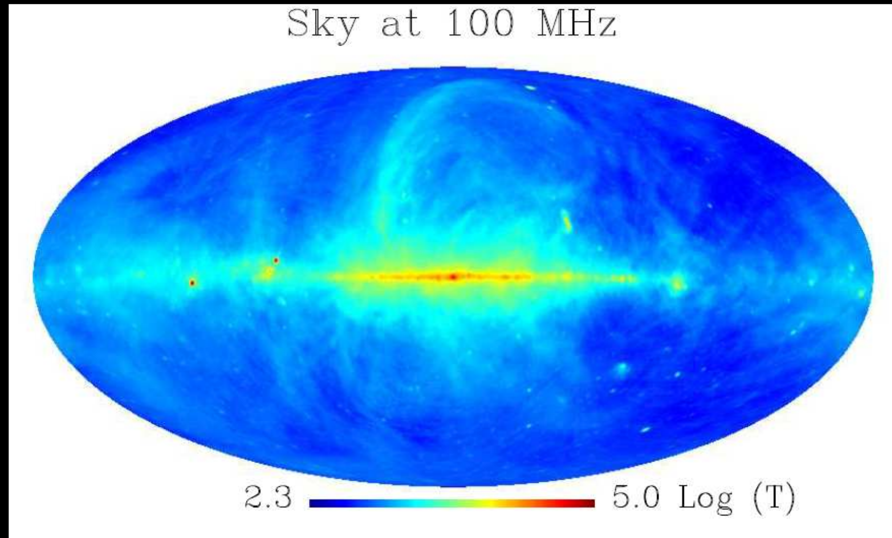
$\lambda_{obs} = 21(1+z_{HI})$ cm

Distorted Spectrum:

hot gas → emits 21 cm

cold gas → absorbs 21 cm

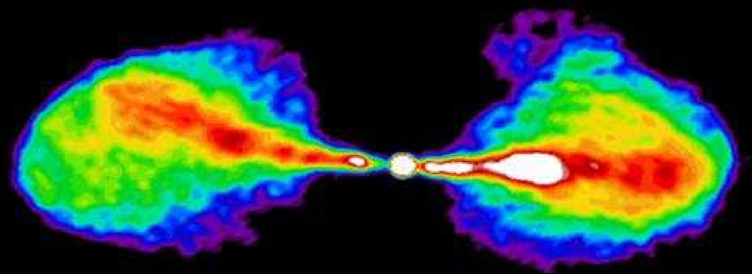
Observations are challenging!
Foregrounds ≈ $(10^5 - 10^9) \times$ Signal



Synchrotron
De Oliveira-Costa *et al* 2008

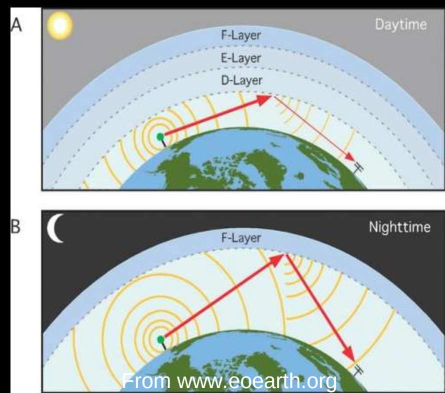
Astrophysical Foregrounds

- Galactic Synchrotron Emission
- Extragalactic Radio Sources



Terrestrial

- Ionosphere Distortions
- Radio Frequency Interference



Future Telescopes

SKA 20 > z (PS)

LEDA 30 > z >15 (global)

DARE 35 > z >11 (global)

LEDA

Outline:

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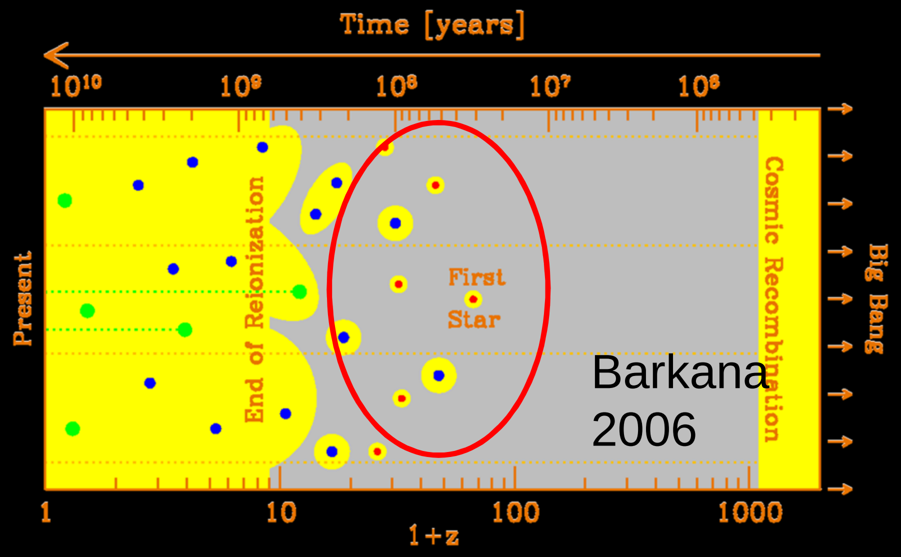

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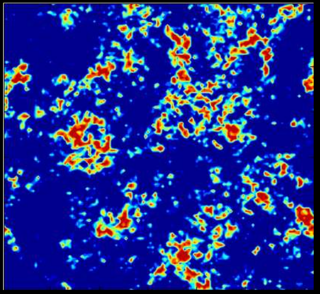


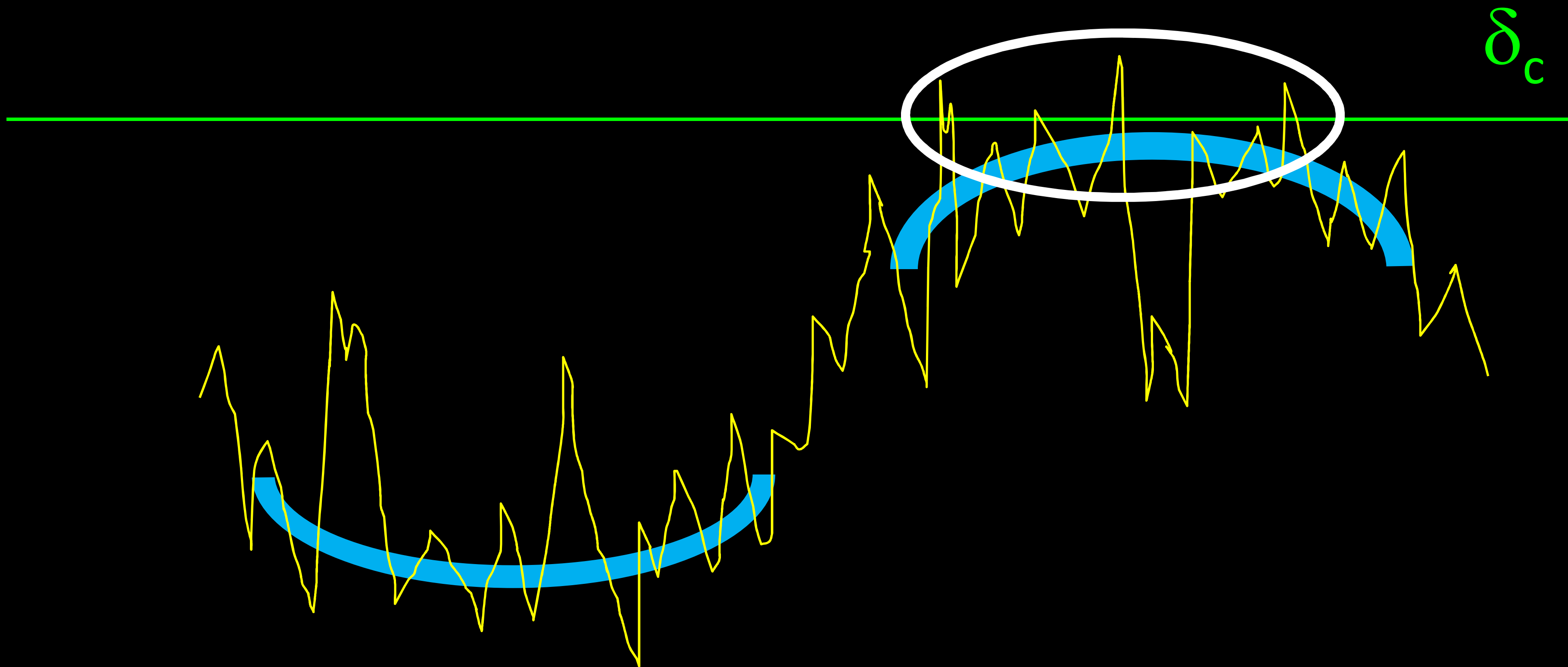
3. Signature of First Stars in the 21-cm Signal

First Stars are Highly Clustered:

1. 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

- Star formation starts at high δ_{LS}



First Stars are Highly Clustered:

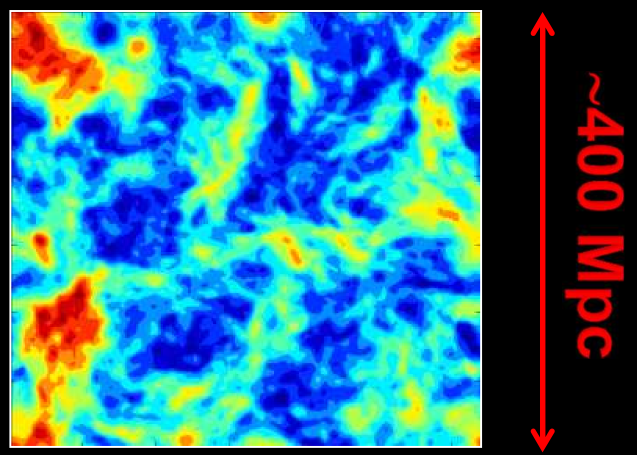
1. Local density fluctuations are biased by δ_{LS}

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

2. 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;

High velocity suppressed star formation

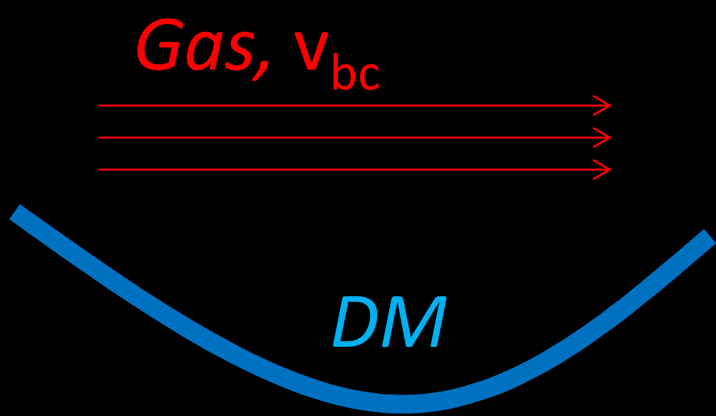


Velocity Pattern

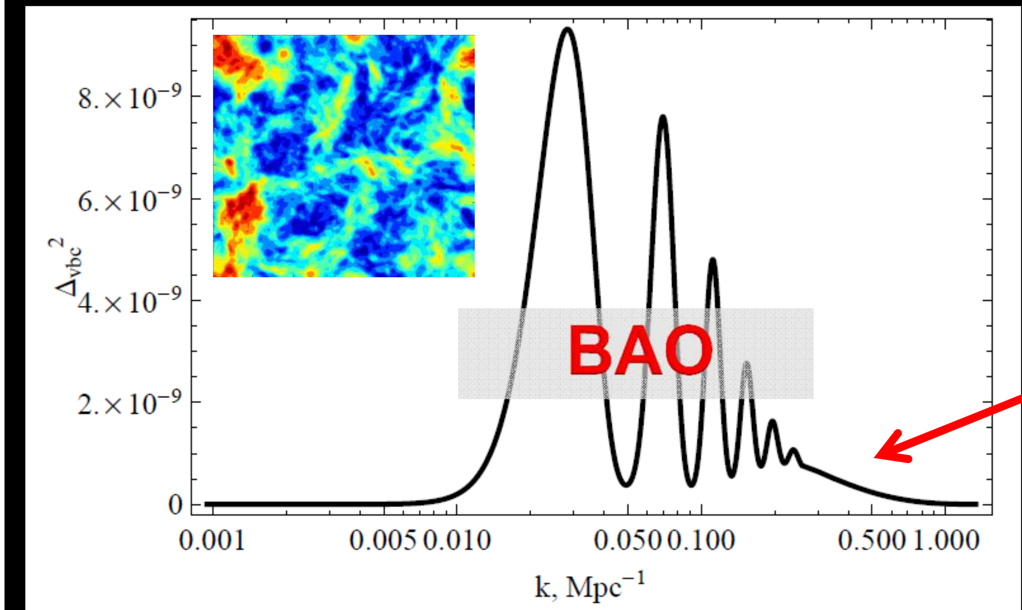
Baryon - DM Relative Velocity is Supersonic after Recombination

Tseliakhovich & Hirata, 2010

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



Gas overshoots DM halos



Coherence scale ~ 3 Mpc

LARGE effect at LARGE k and LARGE z!

$v_{bc} \rightarrow$ Non-linear Terms are Non-perturbative

EOM: Fluid equations in expanding background

$$\frac{\partial \delta_c}{\partial t} + a^{-1} v_c \nabla \delta_c = -a^{-1} (1+\delta_c) \nabla v_c$$

$$\frac{\partial v_c}{\partial t} + a^{-1} (v_c \nabla) v_c = -\frac{\nabla \Phi}{a} - H v_c$$

$$\frac{\partial \delta_b}{\partial t} + a^{-1} v_b \nabla \delta_b = -a^{-1} (1+\delta_b) \nabla v_b$$

$$\frac{\partial v_b}{\partial t} + a^{-1} (v_b \nabla) v_b = -\frac{\nabla \Phi}{a} - H v_b - a^{-1} c_s^2 \nabla \delta_b$$

$$a^{-2} \nabla^2 \Phi = 4\pi G \bar{\rho}_m \delta_m$$

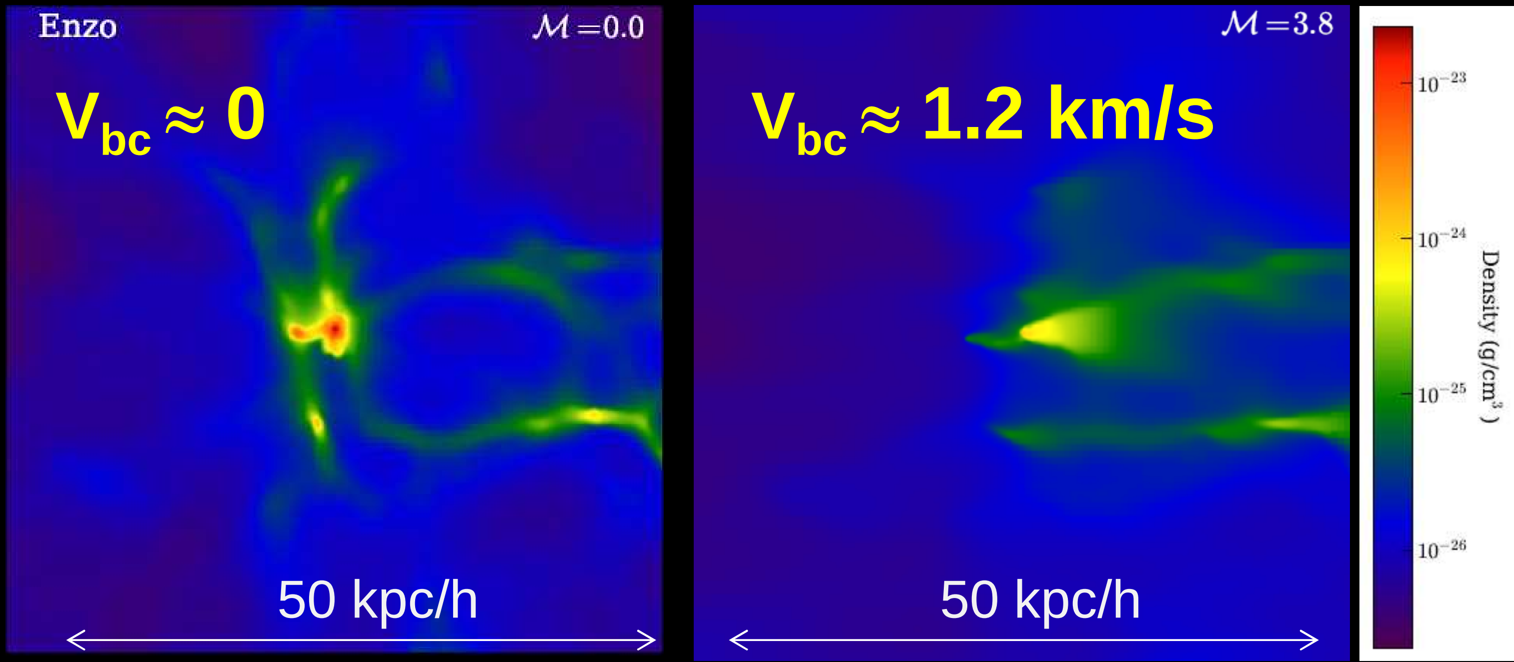
Nonlinear terms are **LARGE!**

Coherence scale $\rightarrow$ ~ linear eom at $\leq$ 3 Mpc

ρ_{gas} , z = 20, M_h ~1.5×10^5

O'Leary & McQuinn, 2012

Supersonic DM bullet

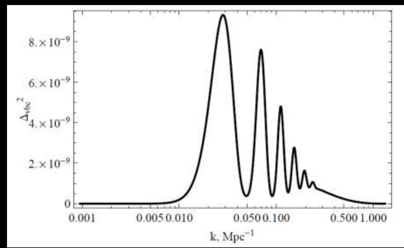


Supersonic velocities have large impact on structure formation

The Effect of v_{bc} on Structure Formation

- Scale-dependent bias
- Suppresses halo abundance on scales **10^4-10^8 M_{sun}**

Tselikhovich & Hirata 2010



- Suppresses halo baryon fraction
- BAO in PS of early structure

Dalal, Pen & Seljak 2010; Tselikhovich, Barkana &Hirata 2011

- Boosts minimal cooling mass (harder to form stars)

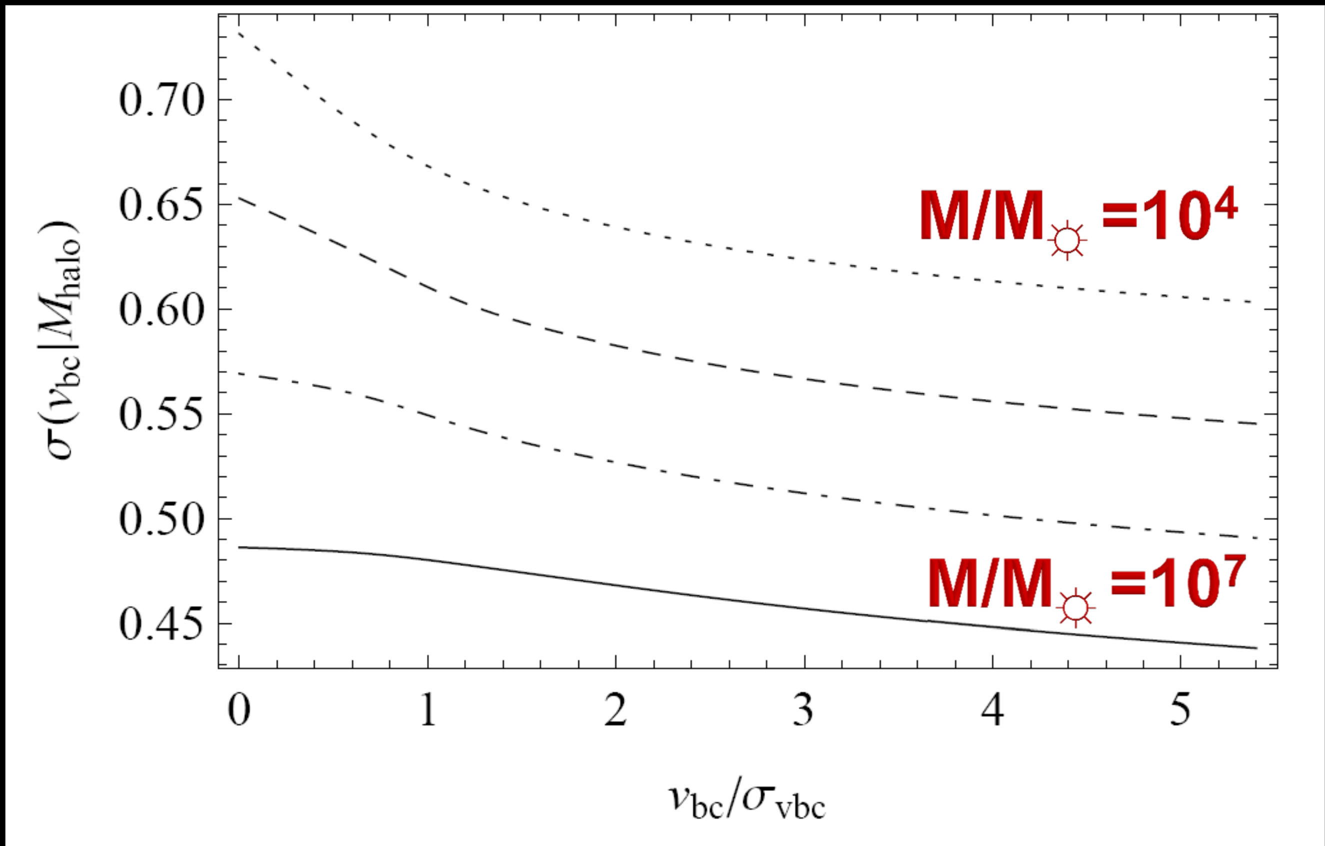
AF, Barkana, Tselikhovich & Hirata 2012

(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} Suppresses Halo Abundance

First in Tseliakhovich & Hirata(2010)

v_{bc} washes out density perturbations on small scales



σ drops with $\mathbf{v_{bc}}$

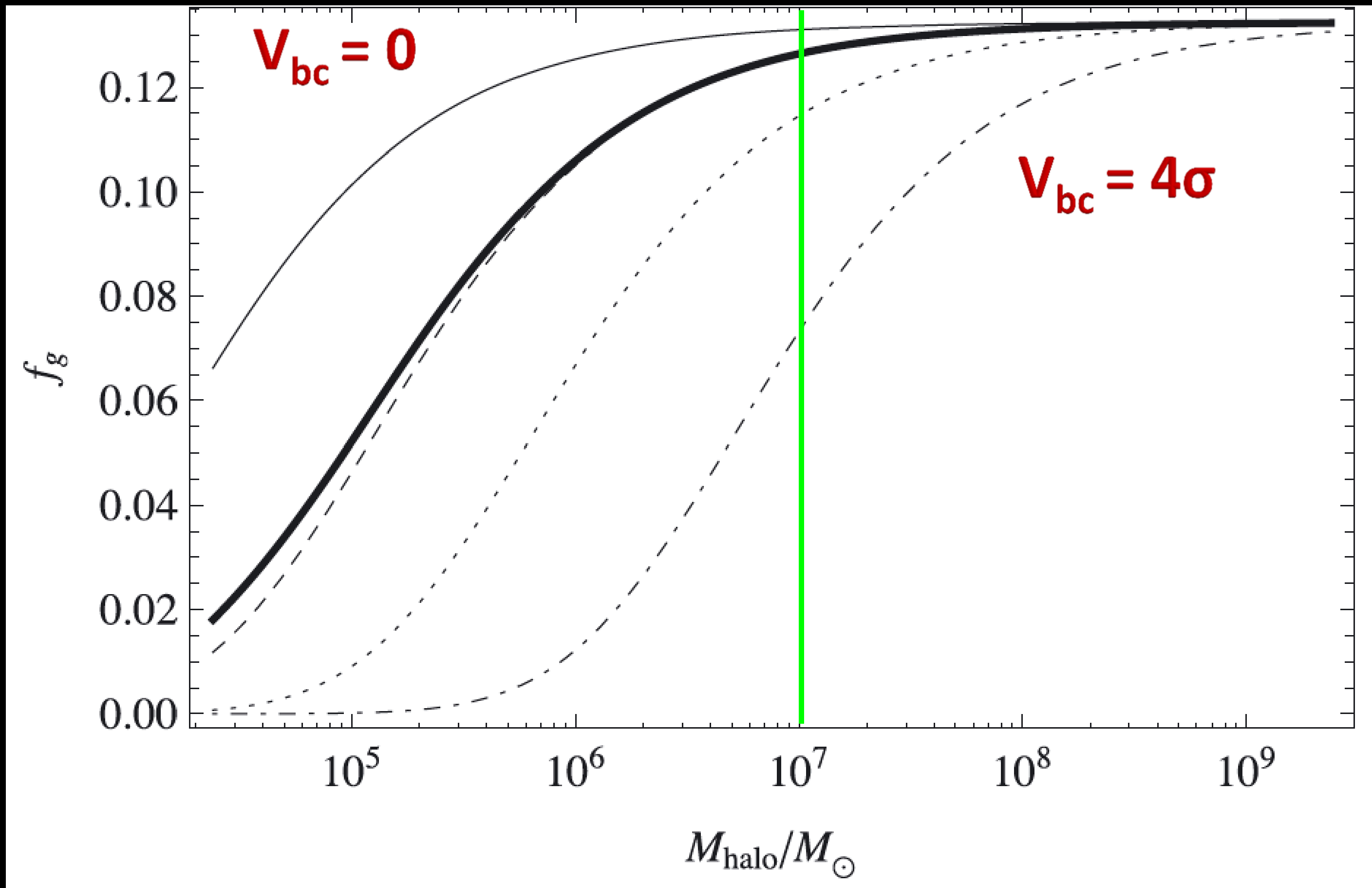
Large effect
on small M

Tseliakhovich, Barkana & Hirata (2010)

v_{bc} Suppresses Gas Content

First in Dalal, Pen, & Seljak (2010)

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

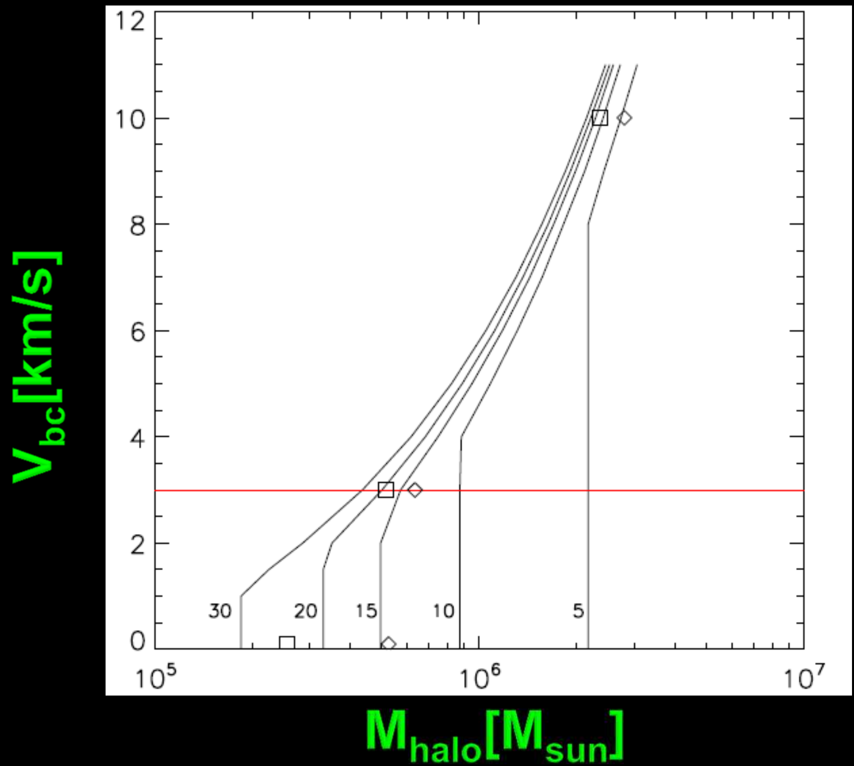


Tseliakhovich, Barkana & Hirata (2010)

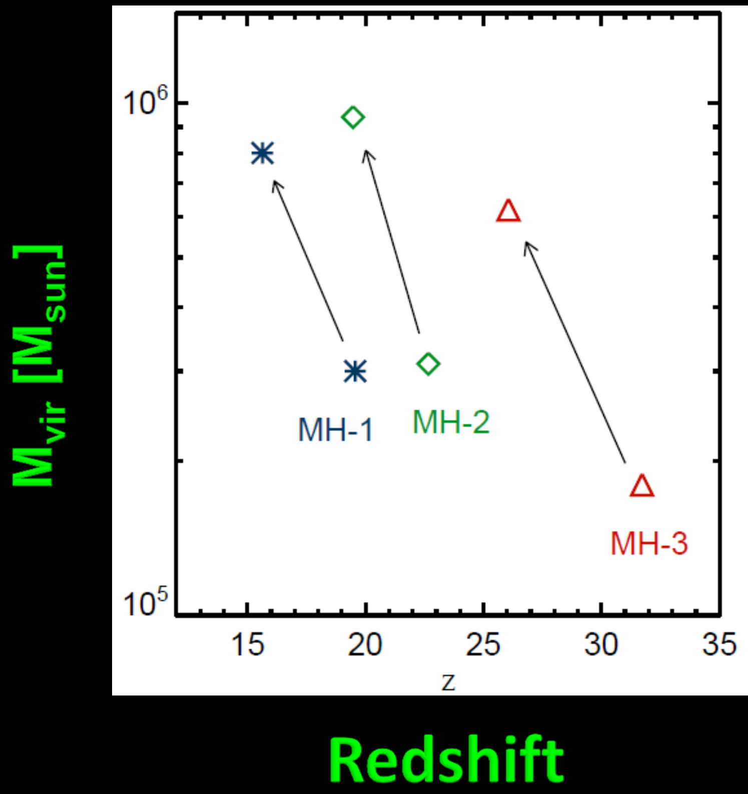
Minimal H_2 Cooling Mass from Simulations:

With v_{bc} = 3 km/s at z =99

Stacy, Bromm & Loeb (2011)



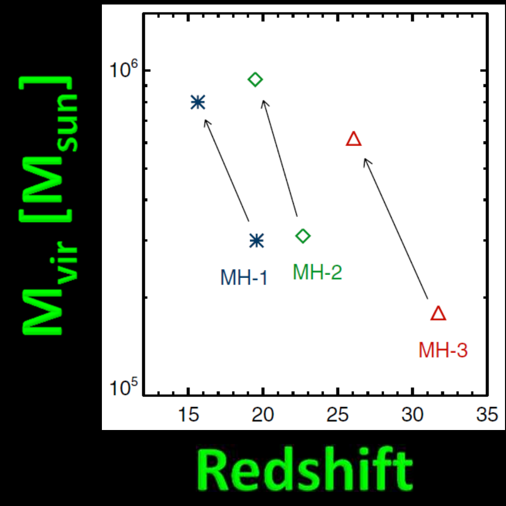
Greif, White, Klessen & Springel (2011)



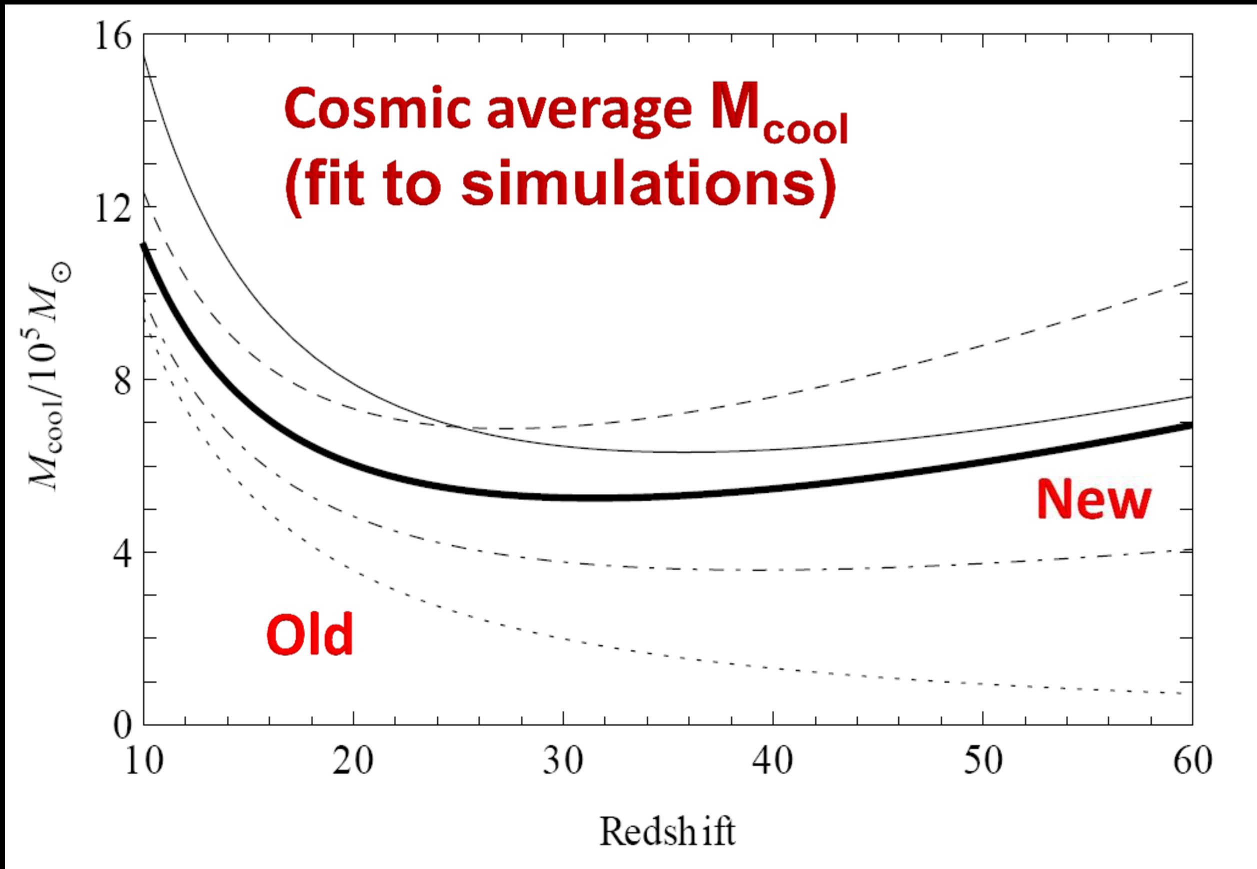
Stars form later and in more massive halos

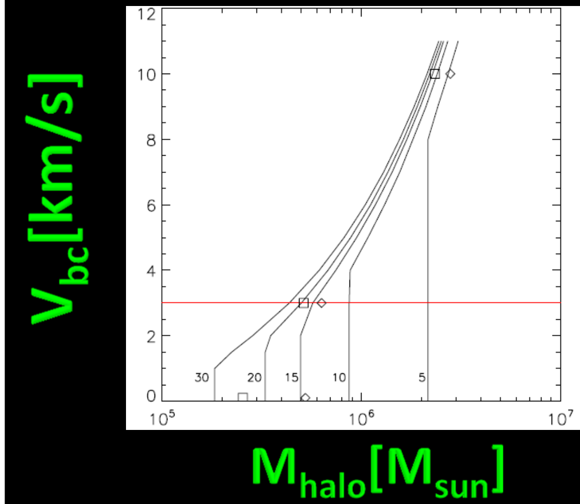
Minimal H_2 Cooling Mass $M_{cool}(v_{bc})$:

Greif, White, Klessen & Springel (2011)



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



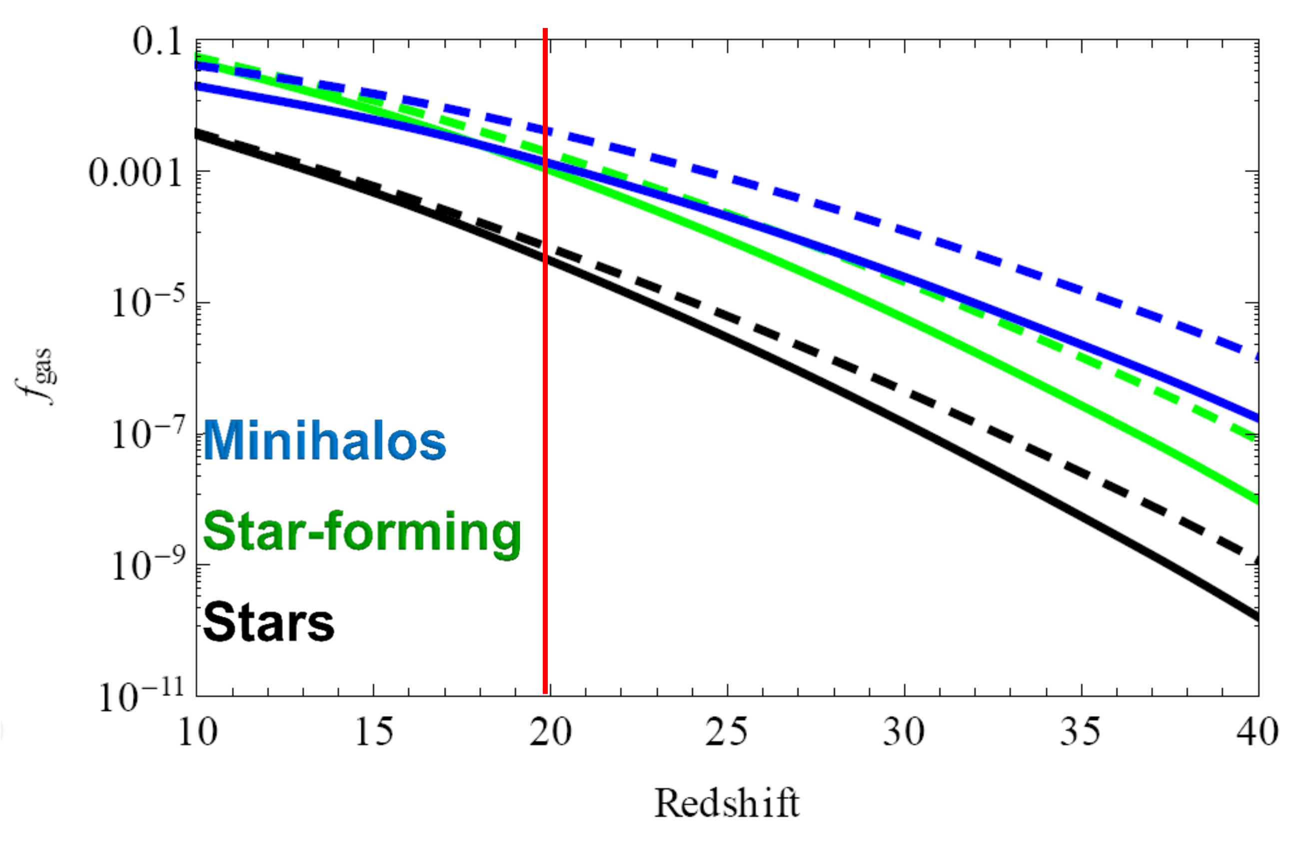


Stacy, Bromm & Loeb (2011)

AF, Barkana, Tseliakhovich & Hirata (2012)

v_{bc} Suppresses Gas Fractions

Gas fractions in halos. Global average over the sky



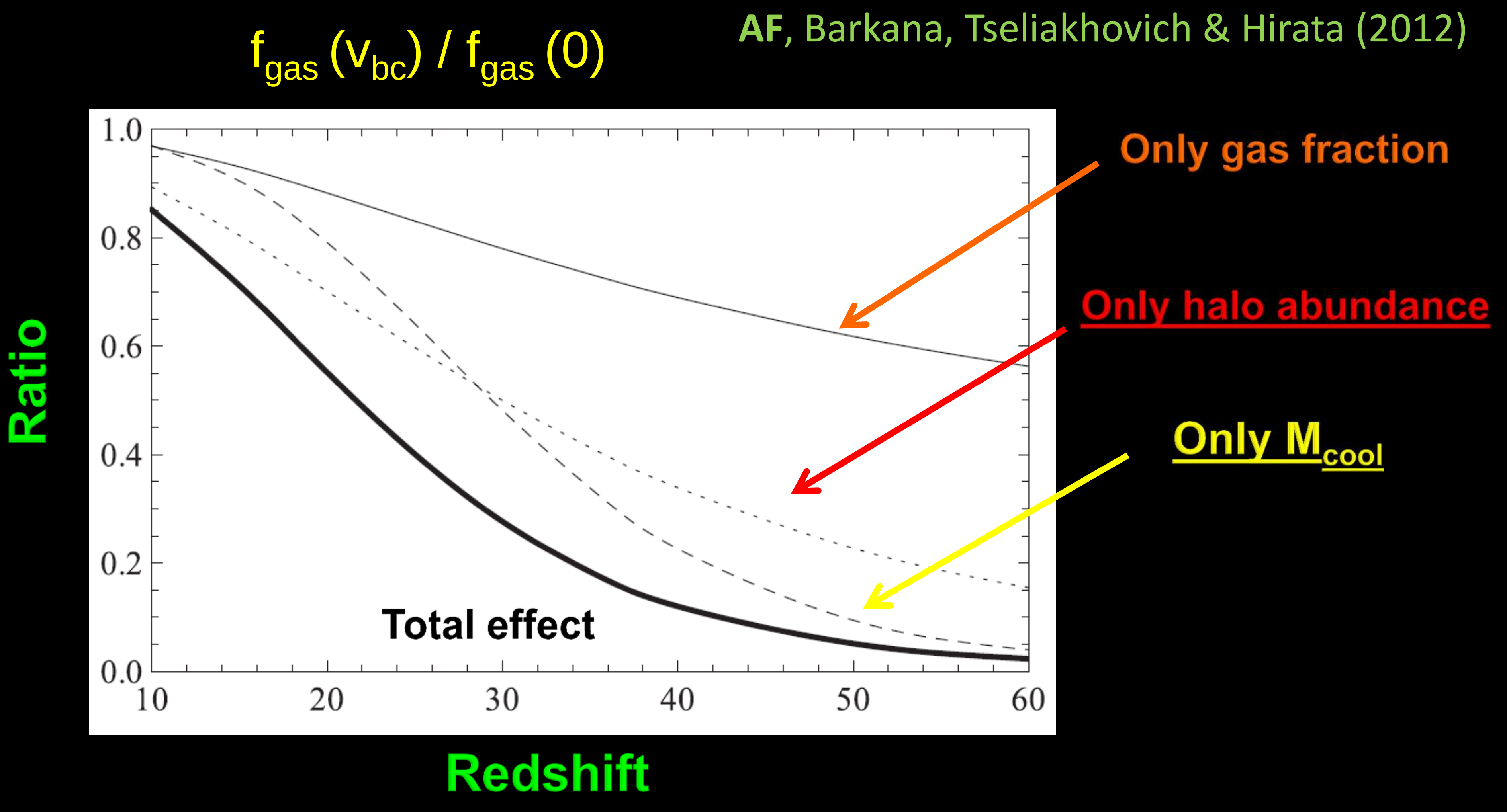
Suppression in Gas fractions:

Minihalos :
by ~ 3.1 at z = 20
(by ~ 21 at z = 40)

Star-forming halos & stars
by ~ 1.8 at z = 20
(by ~ 3.4 at z = 40)

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

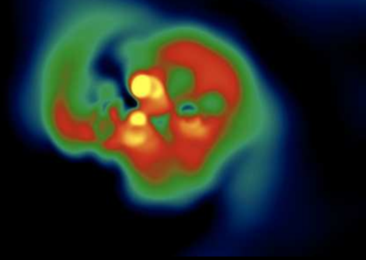
Relative Importance of the v_{bc} Effects for Stars



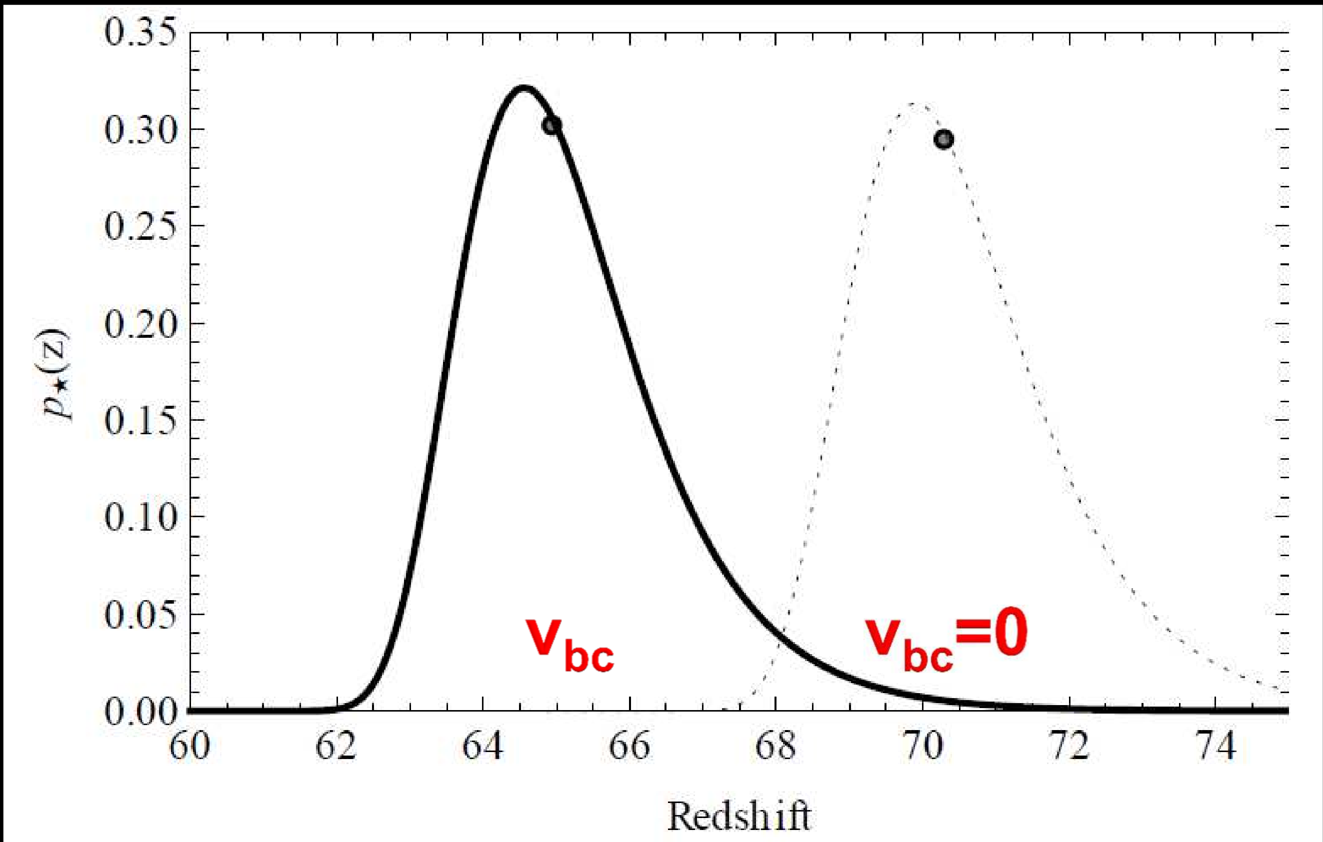
v_{bc} Delays Star Formation

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

(Stacy et al 2011)



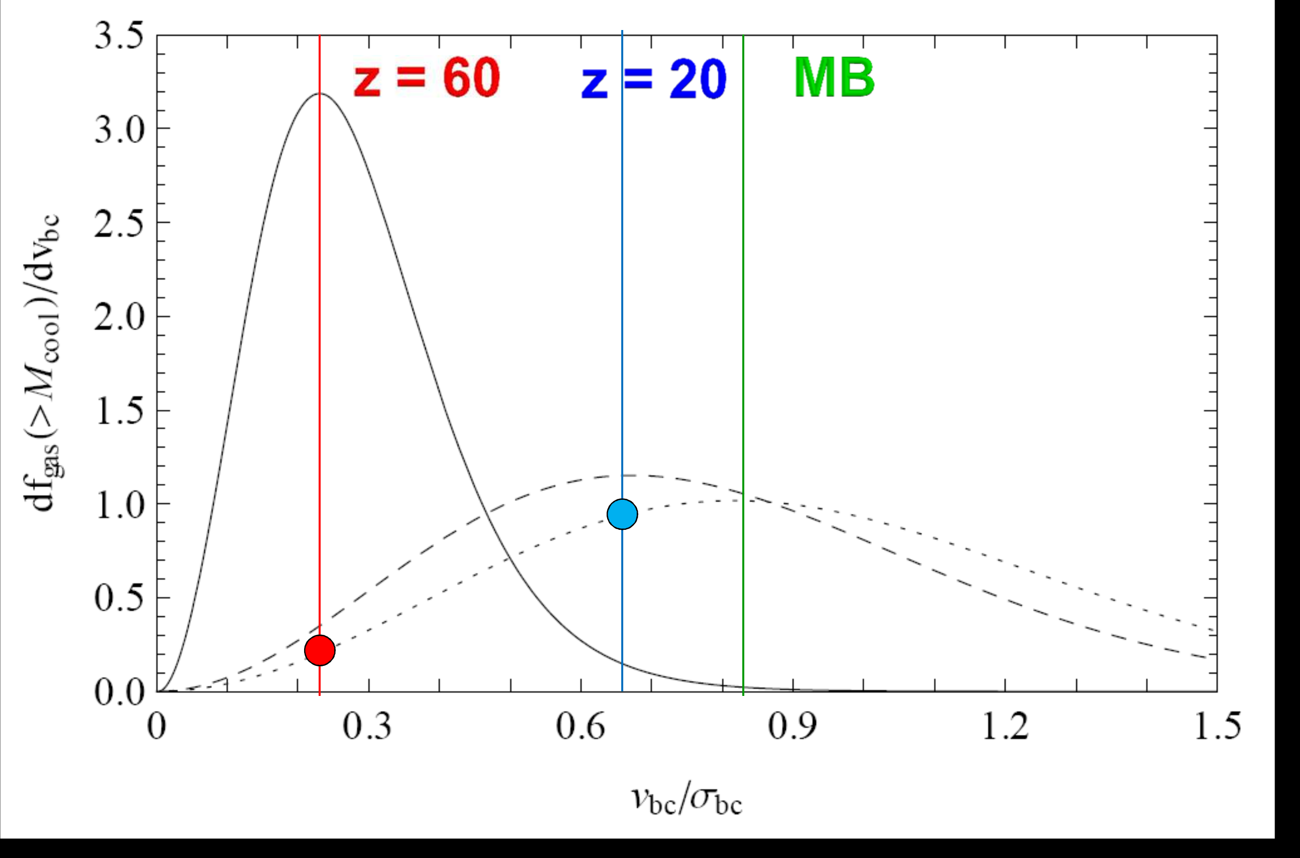
z ~ 65 z ~ 70



Random v_{bc} → Patchy Early Universe

At z = 60: 68% of stars in 10% of volume

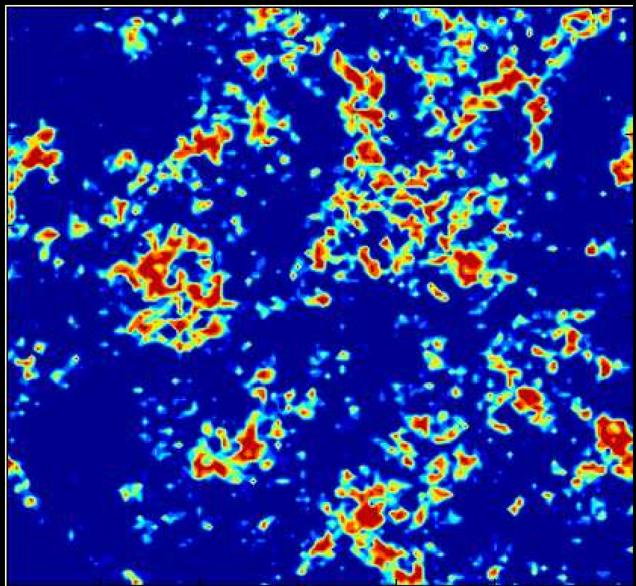
At z = 20: 68% of stars in 35% of volume



AF, Barkana, Tseliakhovich & Hirata (2012)

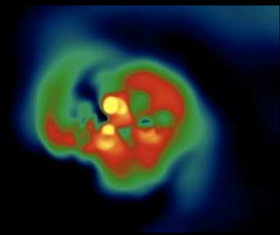
Spatial Distribution of First Stars

~400 Mpc



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

We need to include



1. Stars (small scales)
2. Fluctuations in stars (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***

The Method

- Volume ~ (400 Mpc)^3
- Pixels of 3 Mpc each of fixed v_{bc}

- Linear scales (> 3 Mpc): Simulation

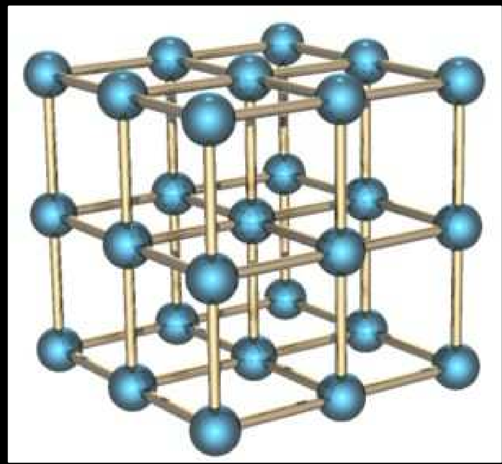
- Non-linear (< 3 Mpc)

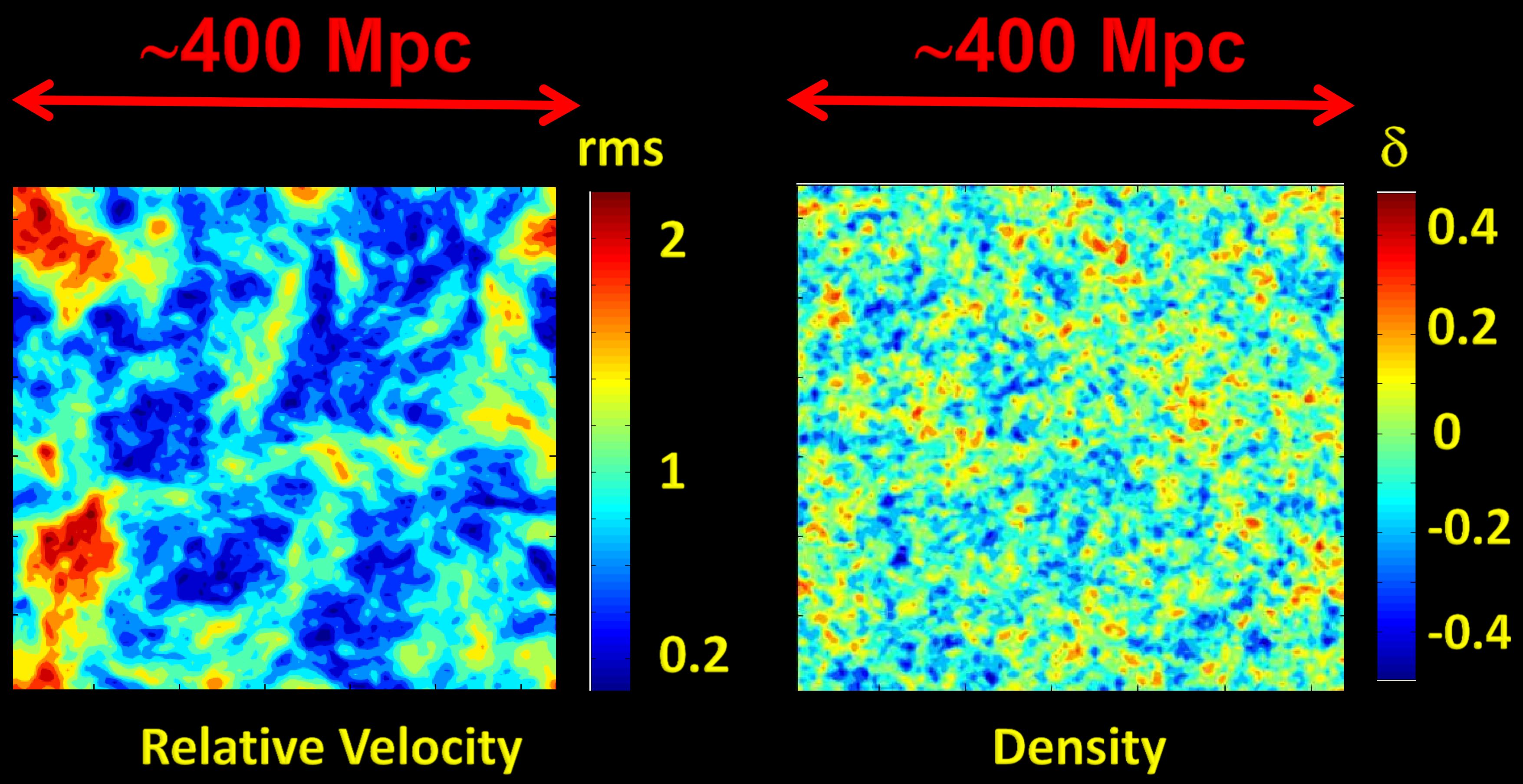
  Given v_{bc}

  Analytical models

  Fit to numerical simulations

  Find stellar content of each pixel

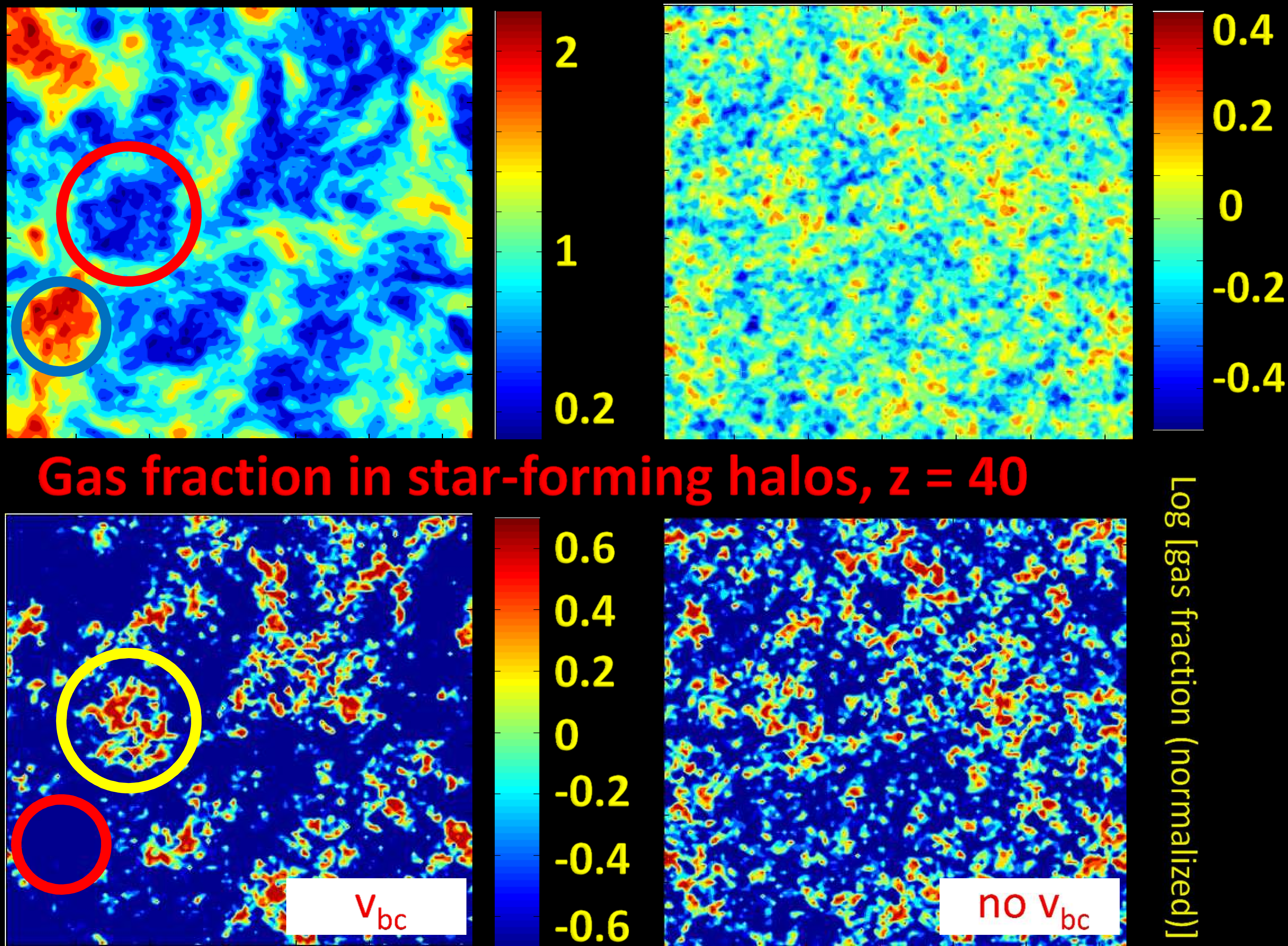




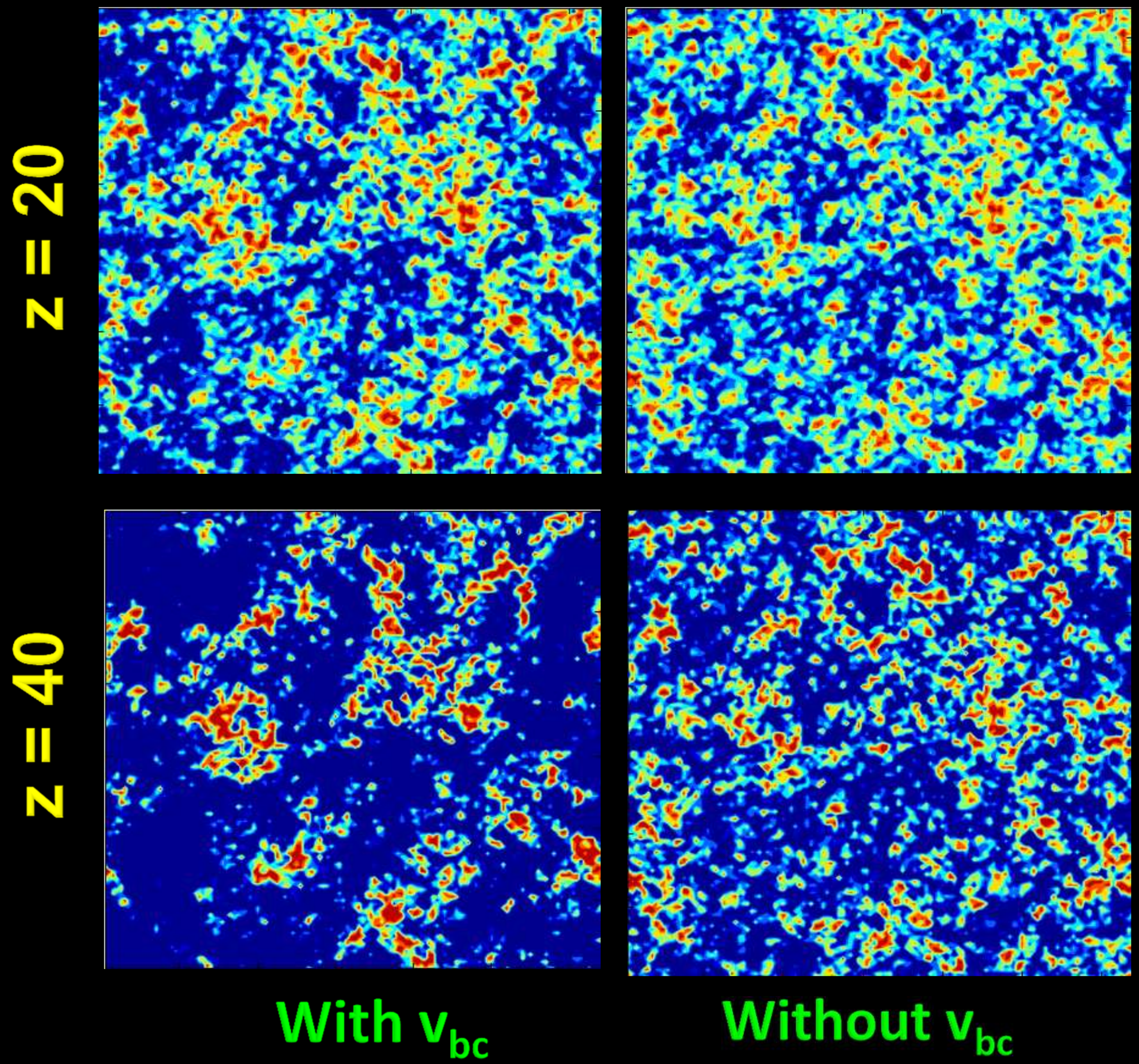
Initial Conditions:

Realistic samples of the Universe at large scales

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

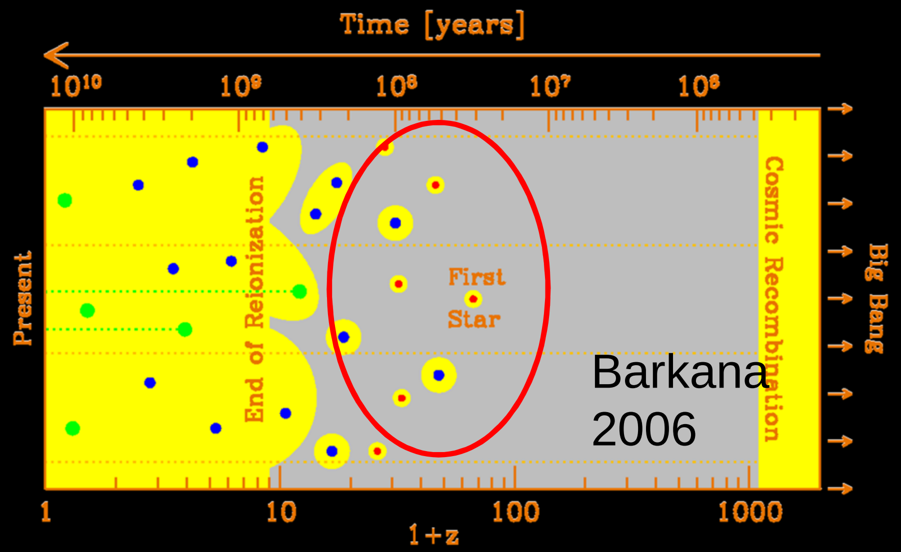


The effect of v_{bc} decays with redshift



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

Outline:



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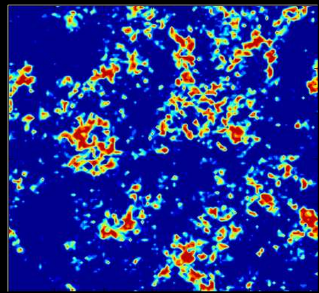


3. Signature of First Stars in the 21-cm Signal

Stars Radiate

X-rays: Heat the gas (T_{gas} ↑)

Lyman-Werner : Lessen star formation (T_{gas} ↓)
"Negative feedback to star formation"

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

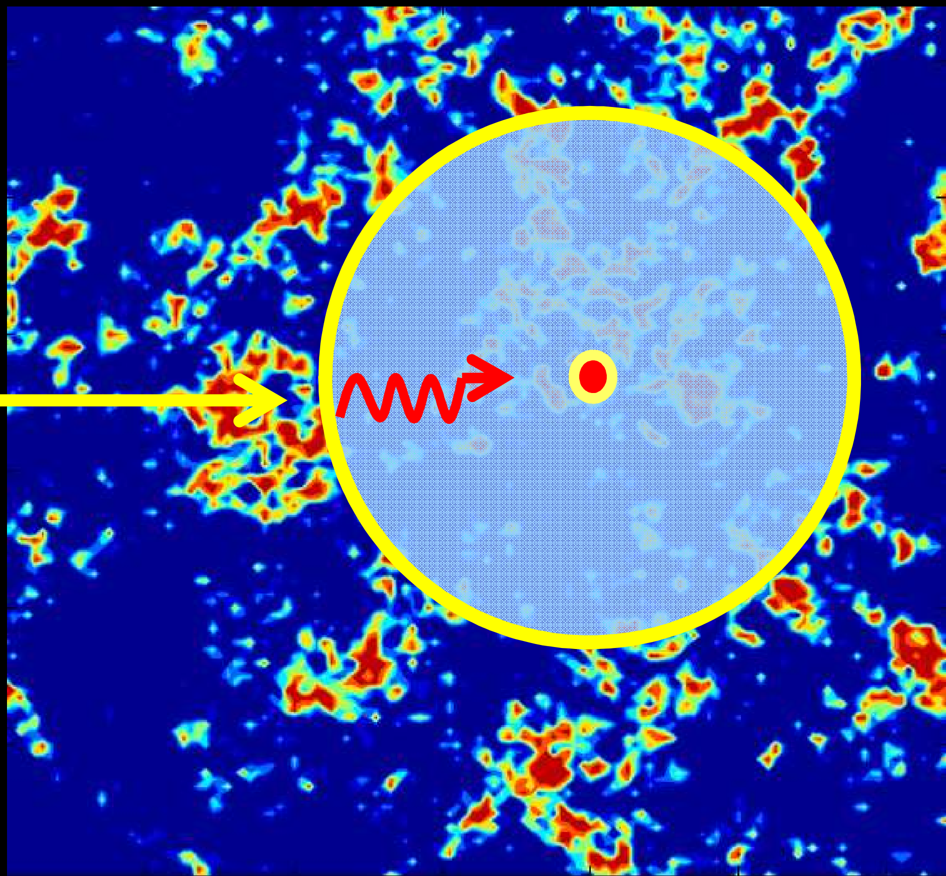
Radiation affects T_S and imprints signature of stars in 21-cm signal

$$\text{Signal} \approx 9\,(1+\delta)(1+z)^{1/2}(1-T_{CMB}T^{-1}_{S})$$

Fluctuations in Radiation ≈ Fluctuations in Stars

Local Intensity:

- Emitted by rare stars
- All sources contribute (LW, Lyα: effective horizon ~100 Mpc)
  - Time delay
  - Redshift
  - Optical depth



Inhomogeneous radiation → Inhomogeneous 21 cm signal

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

21-cm Signal from Heating Fluctuations at z ≈ 20 (Heating Transition)

Use hybrid method

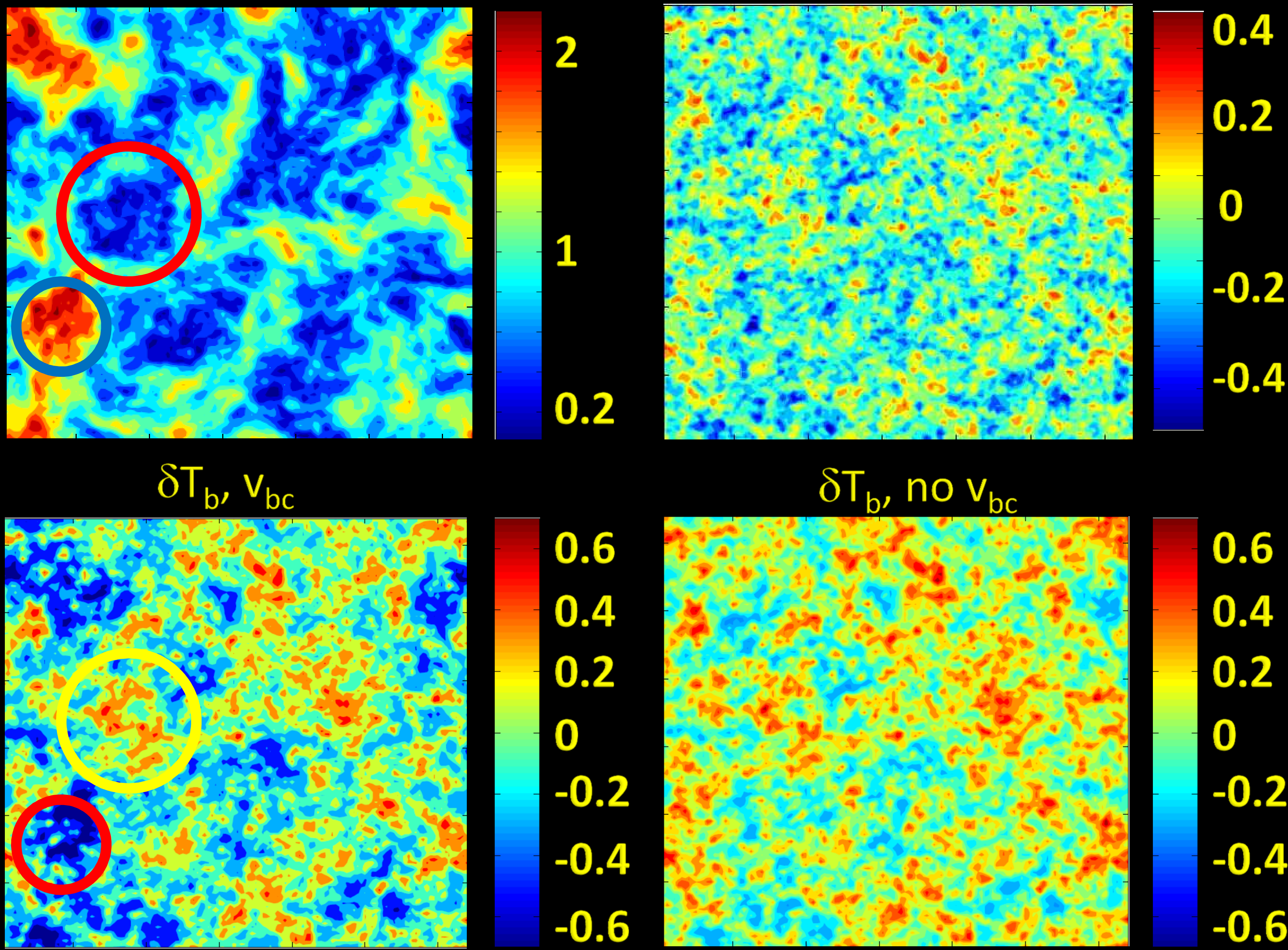
Include:

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

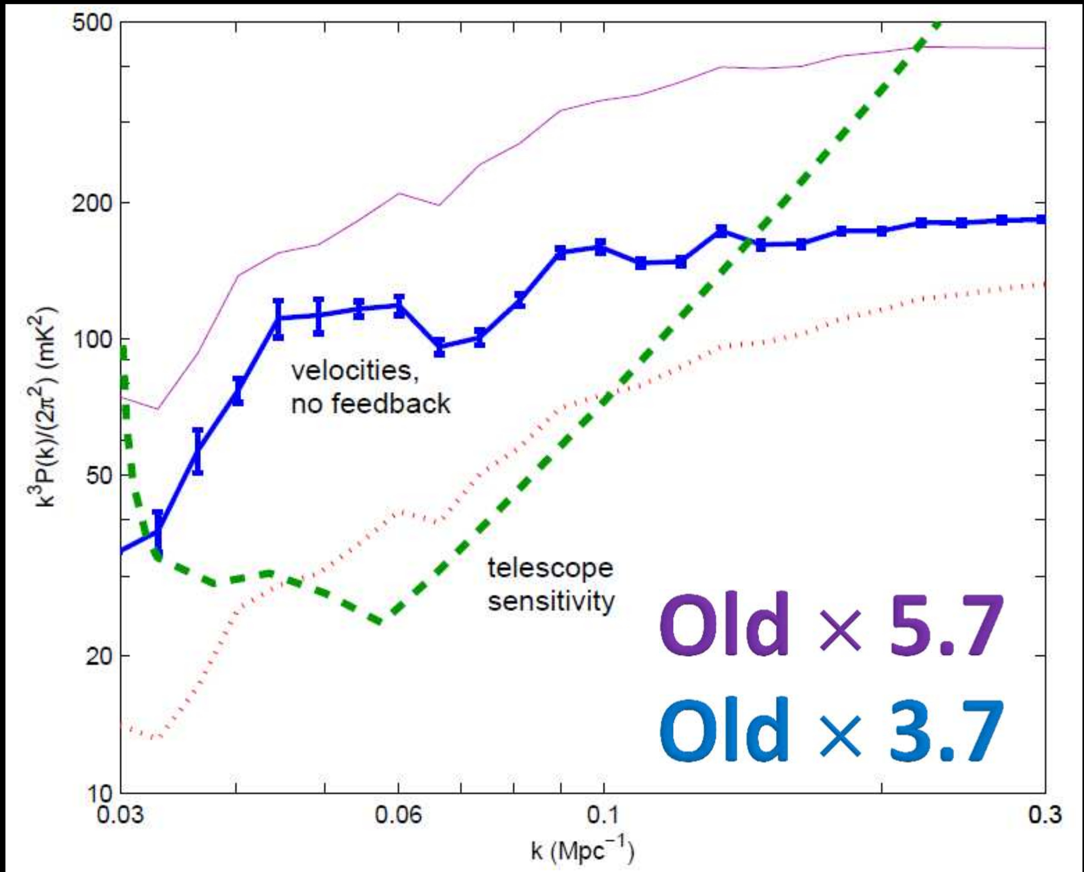
Ignore: Fluctuations in Lyα (max around z ~ 30)

Heating Fluctuation ($T_S = T_K$)

$z = 20$



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

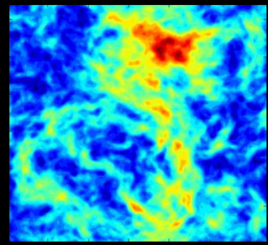
New!!!
v_{bc} , molecular cooling
v_{bc} , atomic cooling

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

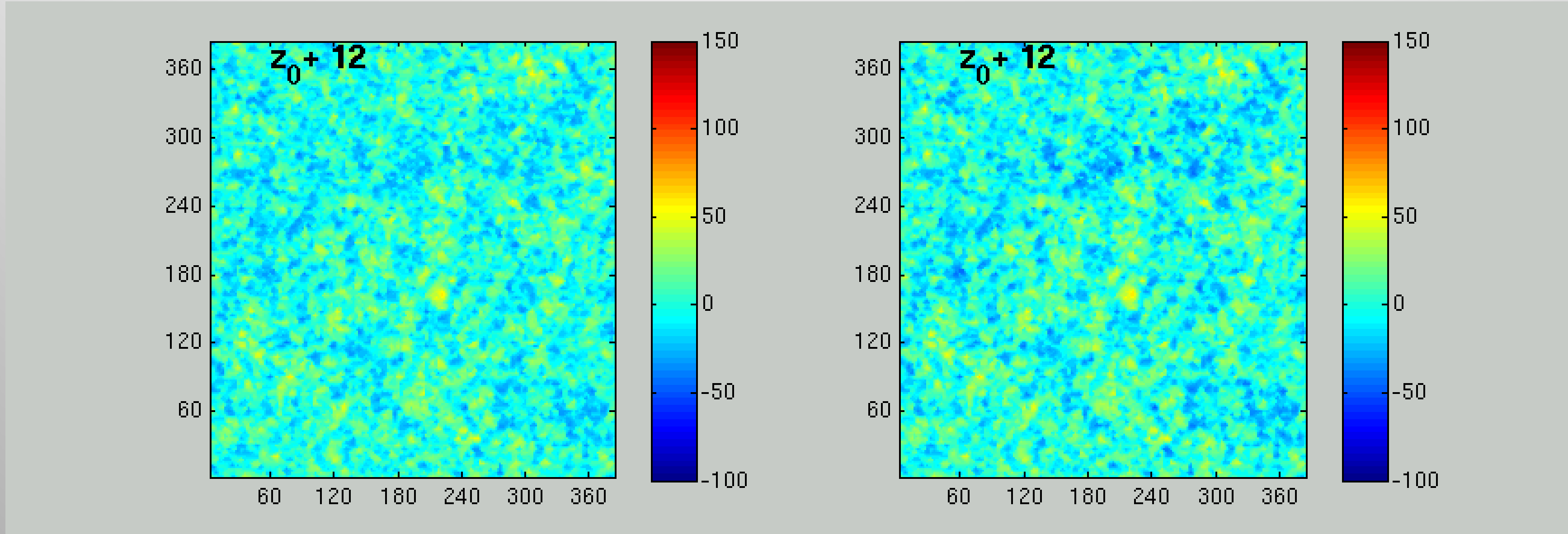
Feedback, v_{bc}: BAO, stronger clustering

Maximal Heating Fluctuations at ~z_{heat}+3

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



Simulation: Evolution with time



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

Flight Through Time δT_b - $<\delta T_b>$

“Realistic” LW Feedback

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

Machacek et al 2001; Wise & Abel 2007; O’Shea & Norman 2008
Ahn et al 2009; Holzbauer & Furlanetto 2012

Feedback: Dissociates $H_2 \rightarrow$ Boosts M_{cool}

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

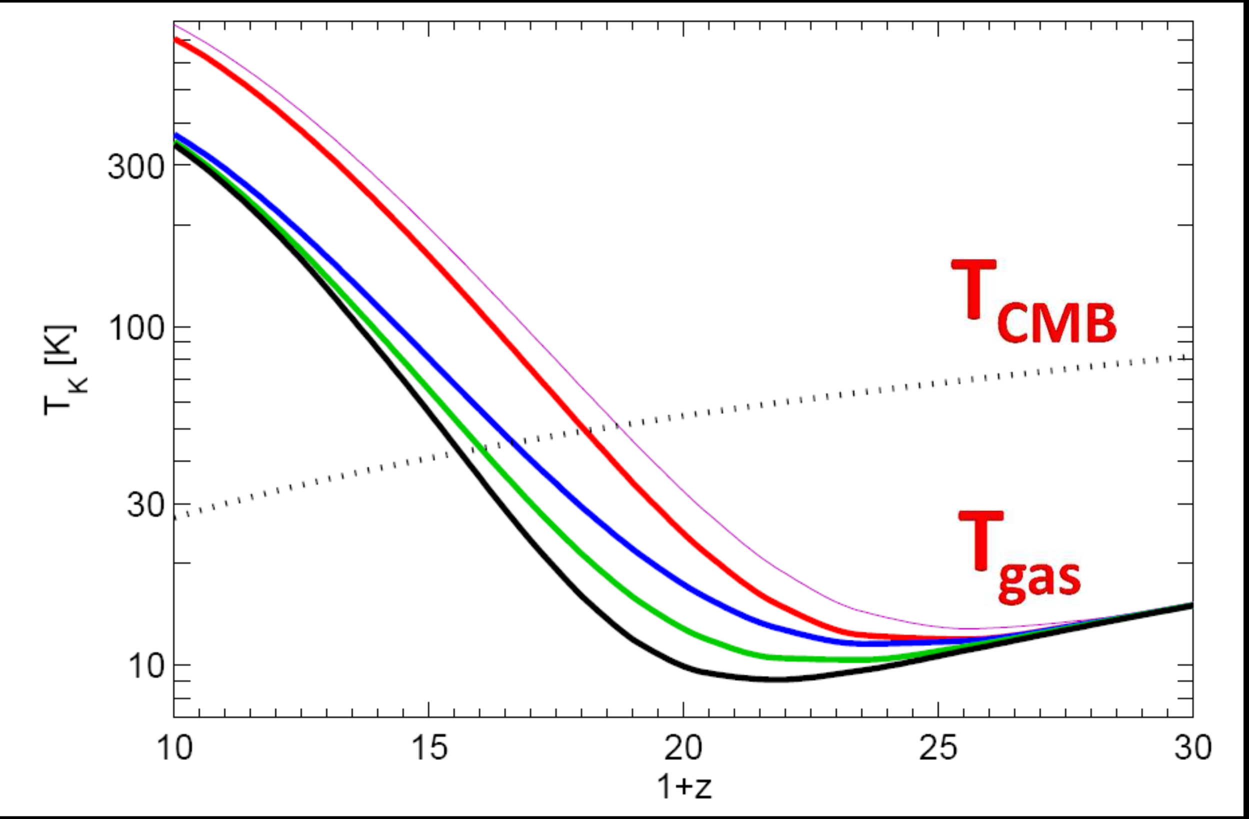
Feedback: Fixed, Independent on v_{bc}

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

We use “Realistic” Feedback:
Depends on v_{bc}, changes fast with time, is delayed

New simulations needed

Feedback and velocity delay heating



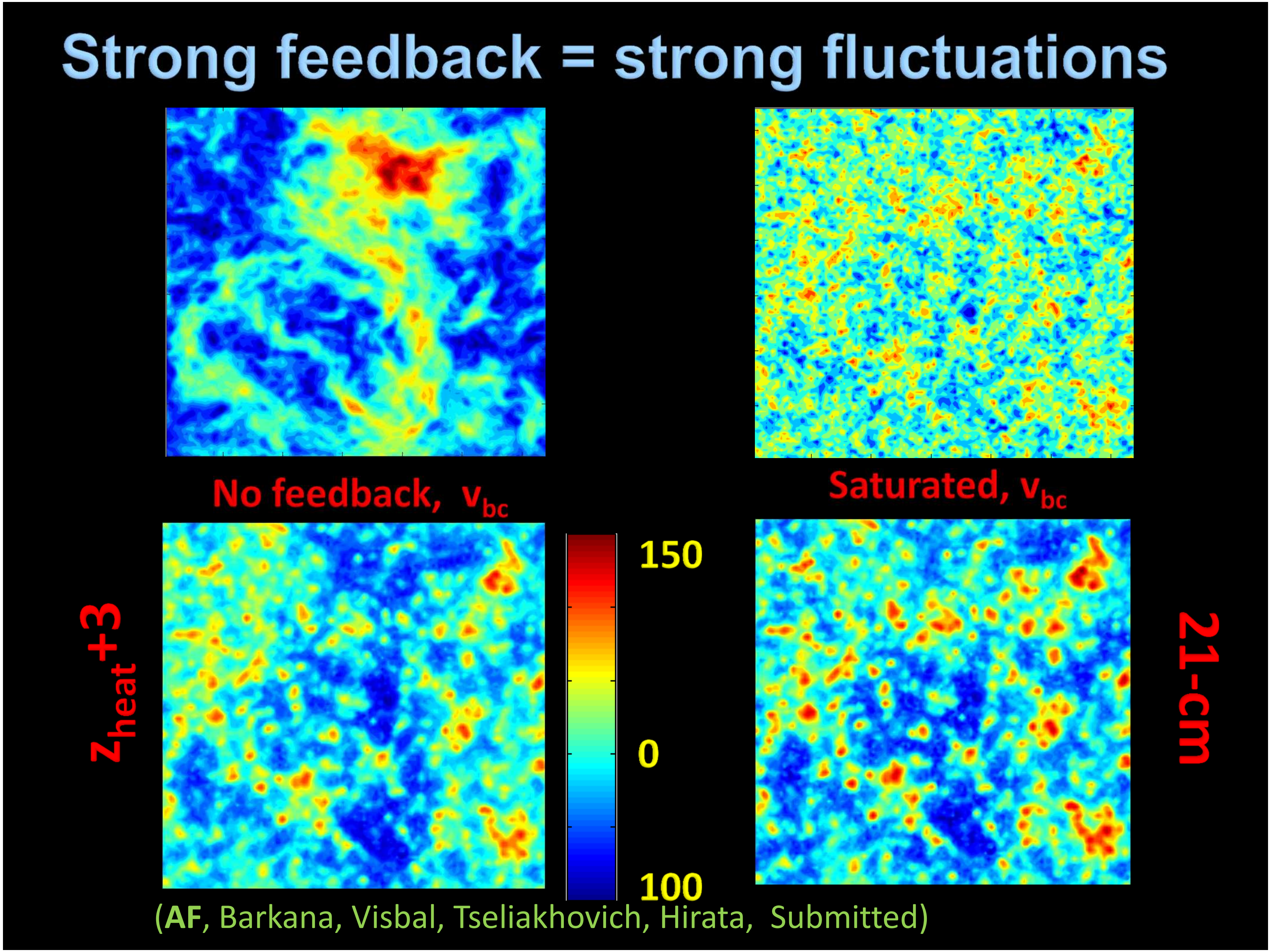
No v_{bc}, no feedback
v_{bc}, no feedback
v_{bc} weak feedback
v_{bc} strong feedback
v_{bc} saturated feedback

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

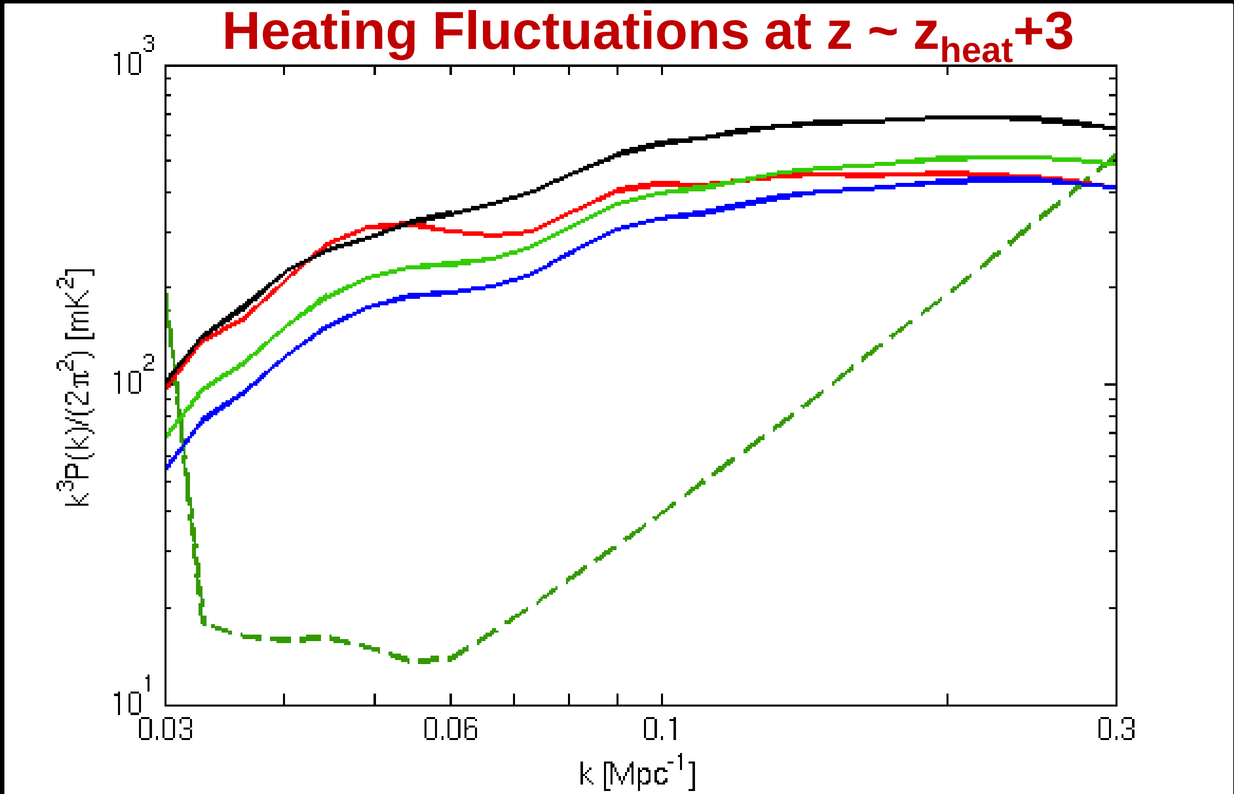
Heating transition is delayed by :

~ 3% (no feedback)

~ 17% (saturated feedback)


Strong feedback = strong fluctuations
No feedback, v_{bc}
Saturated, v_{bc}
$z_{heat}+3$
150
0
100
21-cm
(AF, Barkana, Visbal, Tseliakhovich, Hirata, Submitted)

Feedback: Enhances PS & Suppresses BAO



v_{bc} no feedback

v_{bc} weak feedback

v_{bc} strong feedback

v_{bc} saturated

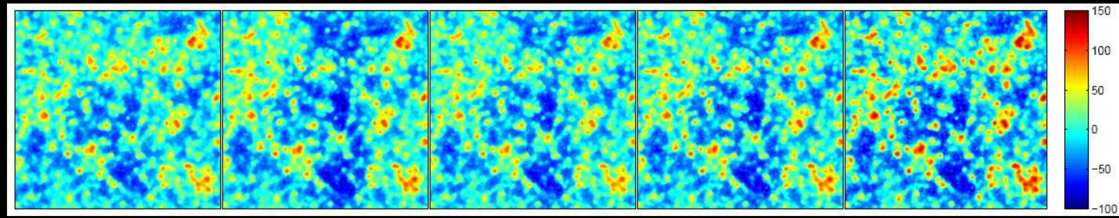
Dashed: noise

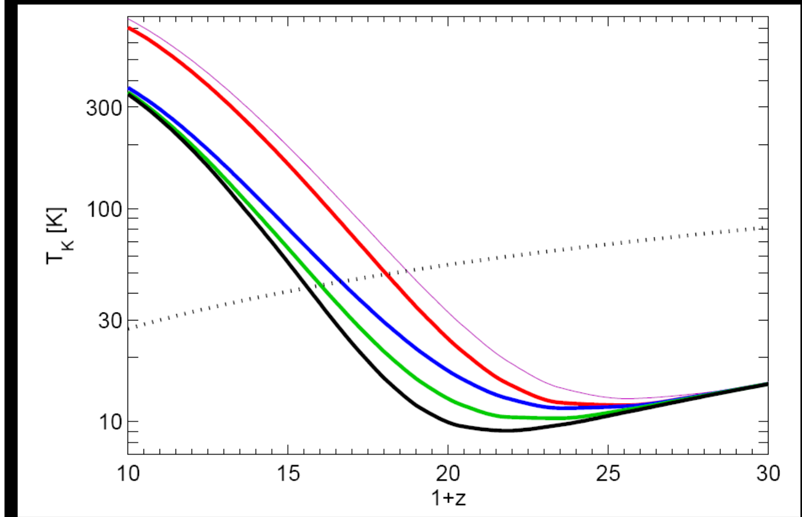
(**AF**, Barkana, Visbal, Tseliakhovich, Hirata, Submitted)

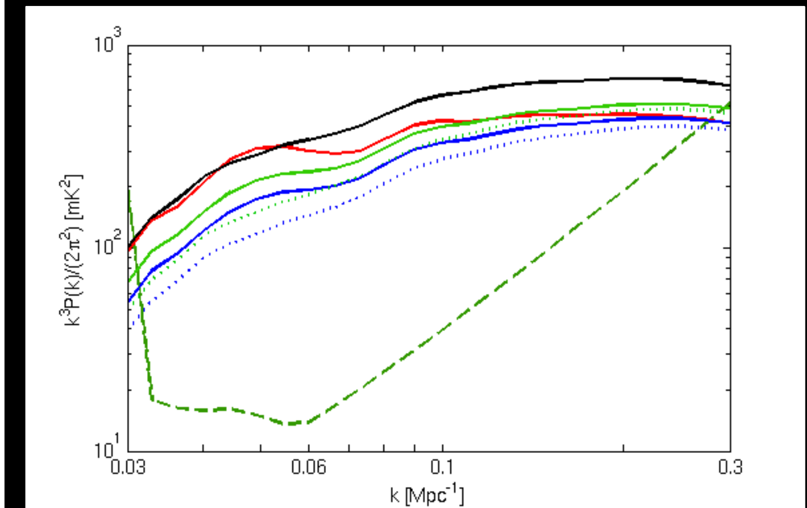
$S/N^2_{new} \sim 2.6 \times S/N^2_{old}$

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

Summary







Velocity is important

More simulations needed!

v_{bc} & LW have strong effect on 21-cm signal

Good observational prospects!

Thank you!