Result from:
Tseliakhovich, Barkana & Hirata (2011),
AF, Barkana, Tseliakhovich & Hirata (2011),
Visbal, Barkana, AF, Tseliakhovich & Hirata (2012).

Impact of the Relative Motion on the Large Scale Distribution of the First Stars

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Tel Aviv University
24 May 2012, CosmoBias

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Rennan Barkana, TAU
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Dmitri Tseliakhovich, Caltech

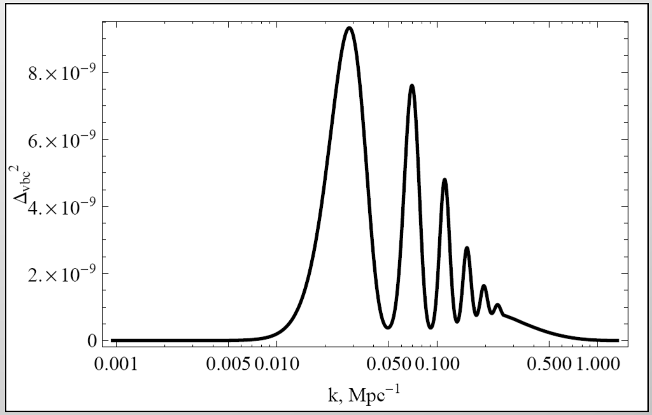
Which Relative Motion?

First reported in Tseliakhovich & Hirata *(2010)*

Properties:

- Between dark and baryonic matter
- $<v_{bc}>$=30 km/sec at recombination
- Vector perturbation $\rightarrow$ decays with z
- Coherence scale of several Mpc
- Correlation scale of ~100 Mpc

Power spectrum of the relative velocity



Effect on structure formation because:

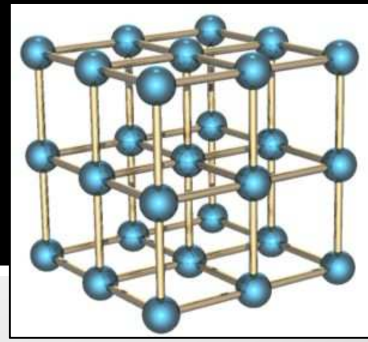
- Nonlinear terms **v∇δ** & **(v∇)v** become large at small scales

Strong effect on small halos at large redshifts (where the first stars are formed)

$\Downarrow$

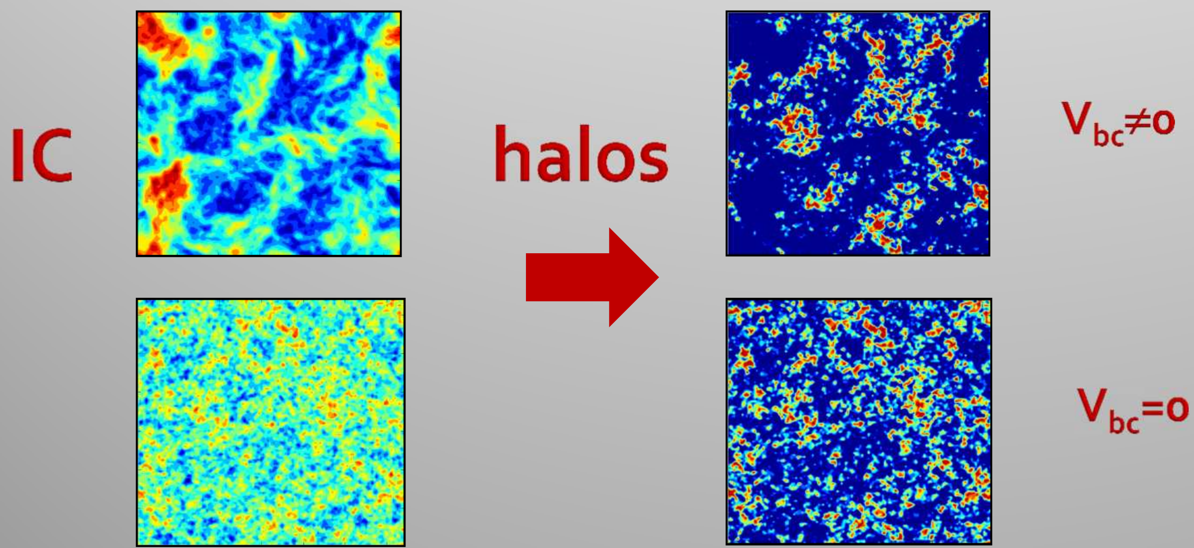
Aim: to quantify the effect on the first stars

Fluctuation at Large Scales (LS) Hybrid Numerical Method.



1. Known statistics → simulate the universe at LS.
2. Resolution of 3 Mpc → coherent velocity in each pixel
3. Small scales: analytical models + results of numerical simulations

   → Gas in halos in each pixel



The Effect of v_{bc} on Structure Formation

v_{bc} →

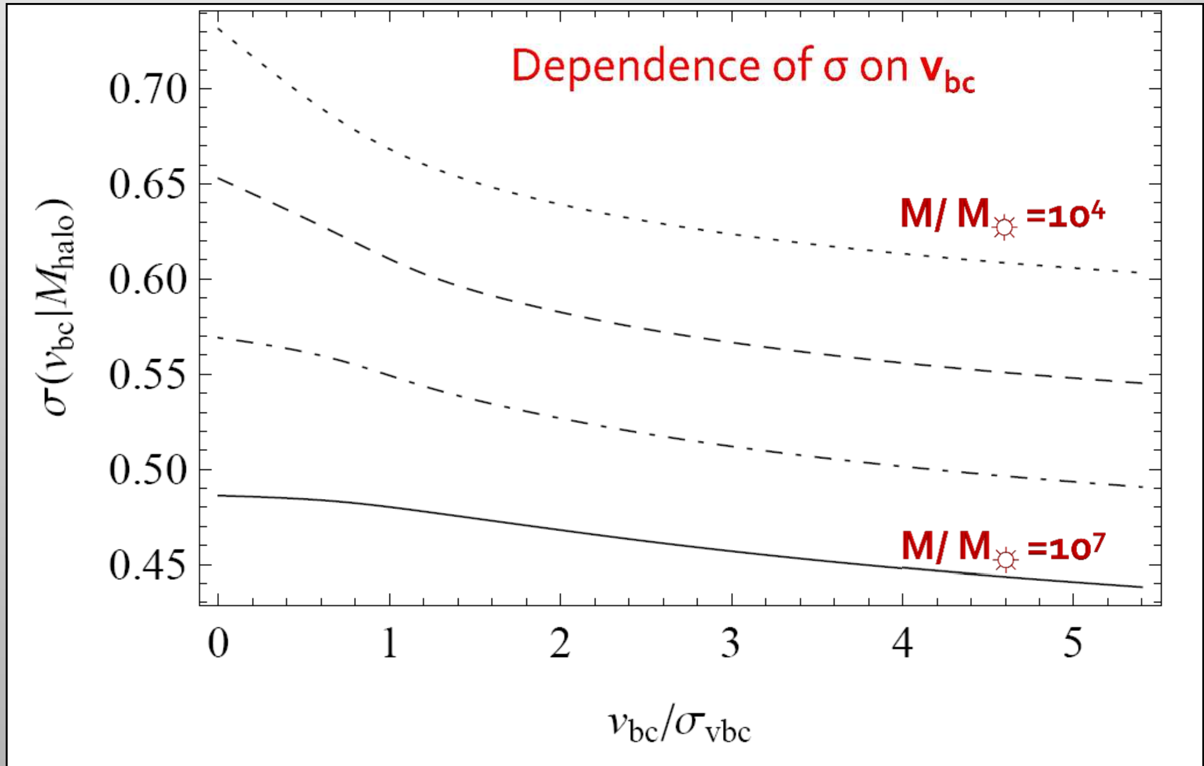
- Suppresses halo abundance
- Suppresses gas content of halos
- Boosts minimal cooling mass

The Effect of v_{bc} on Halo Abundance

First in Tseliakhovich & Hirata(2010)

$v_{bc} \rightarrow$ washed out perturbations on small scales
$\rightarrow$ suppressed halo abundance at small scales

Strong effect on star-forming halos at z < 30



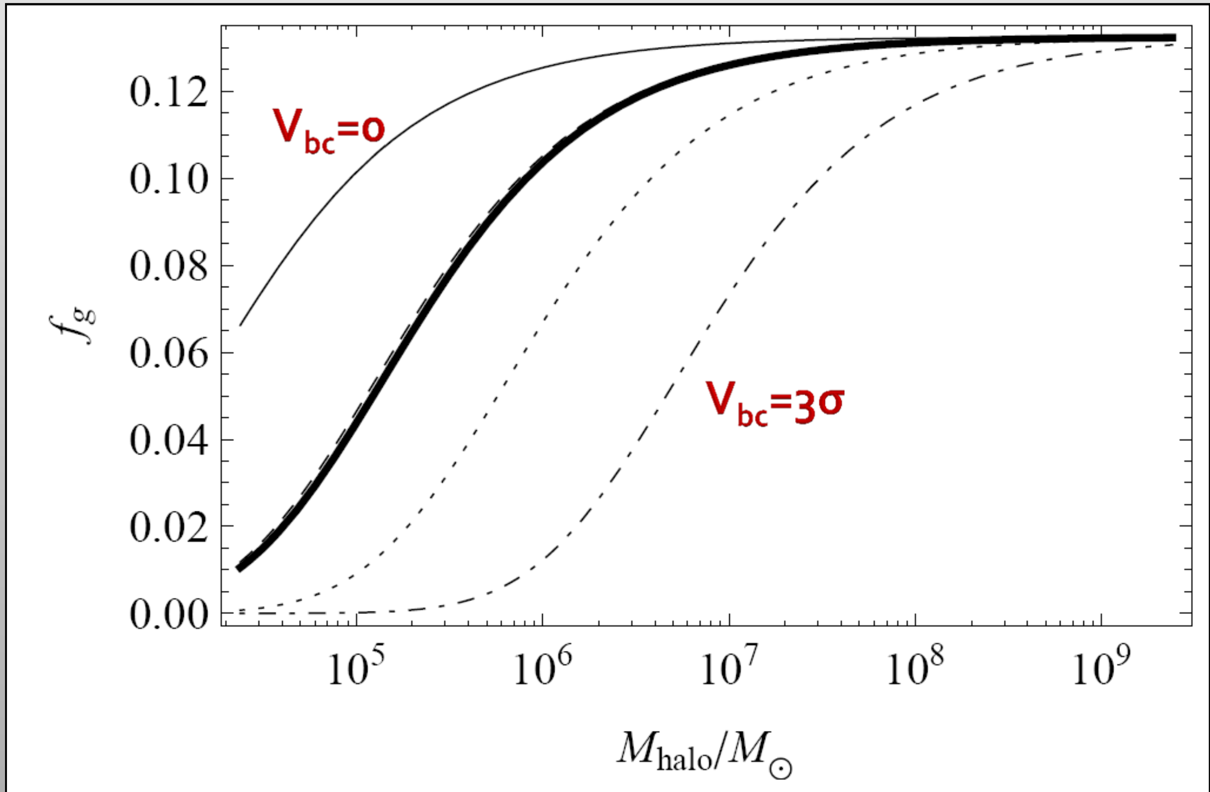
Tseliakhovich, Barkana & Hirata (2010)

The Effect of v_{bc} on Gas Content (z=20)

First in Dalal, Pen, & Seljak (2010)

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

Least significant for stars



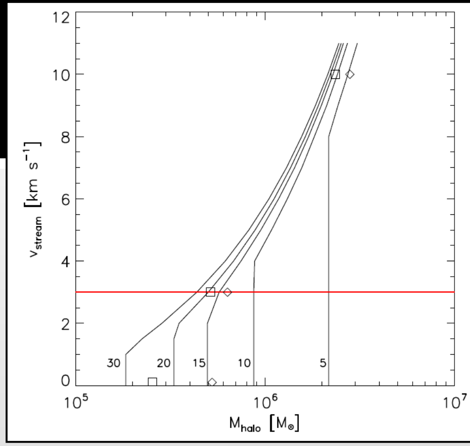
Tseliakhovich, Barkana & Hirata (2010)

Minimal H_2 Cooling Mass from Simulations:

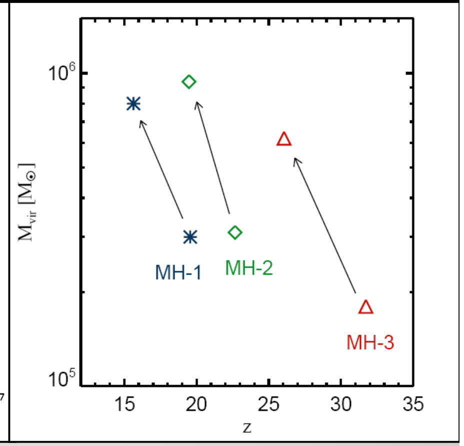
AF, Barkana, Tseliakhovich & Hirata (2011)

- Stars form in $M > 10^5 M_\odot$ (Tegmark et al 1997)
- V_{bc} affects gas distribution $\rightarrow M_{cool}(V_{bc})$

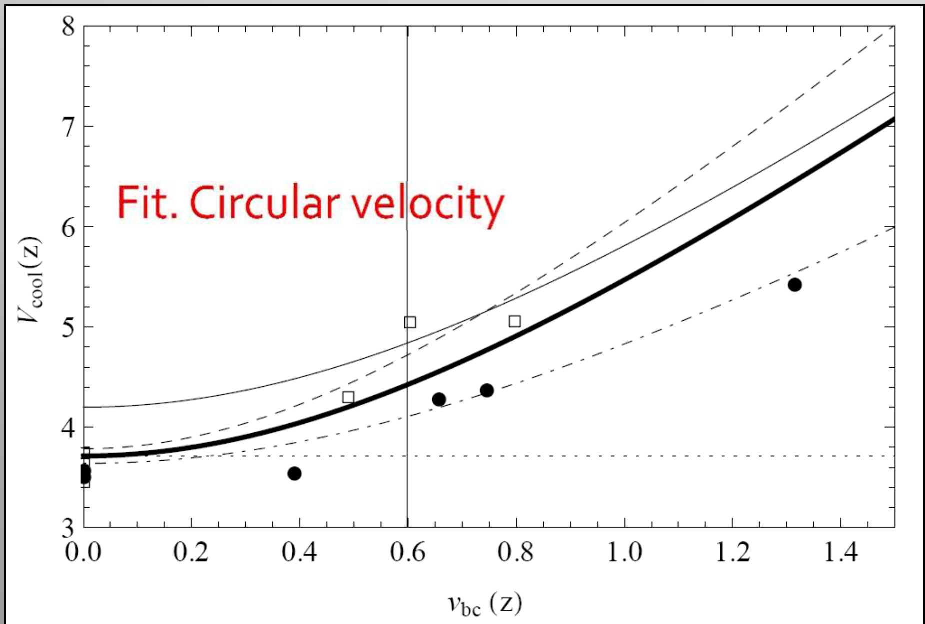
$$V_{cool}(z) = \sqrt{V_{cool,0}{}^2 + (\alpha\, v_{bc}(z))^2}$$

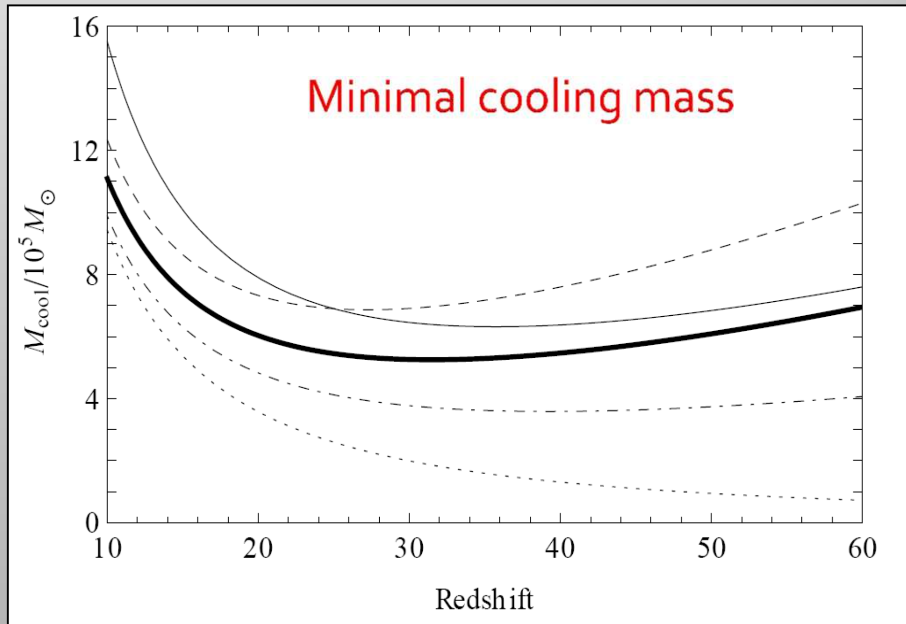


Stacy, Bromm & Loeb (2011)



Greif, White, Klessen & Springel (2011)





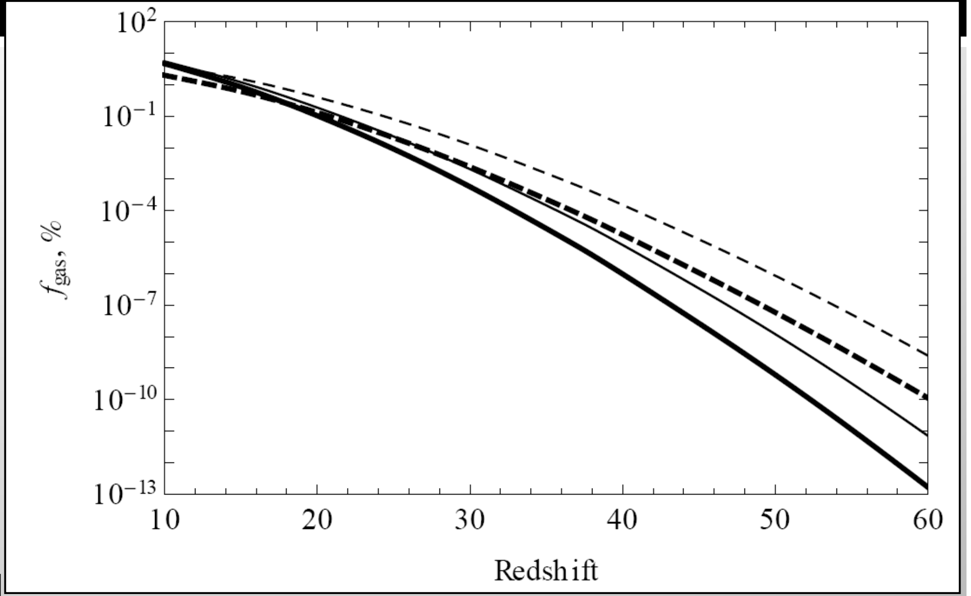
(•) Stacy et al (2011) , (□) Greif et al (2011)

$v_{bc} \rightarrow$ Suppressed Gas Fractions

Tseliakhovich, Barkana & Hirata (2010) and AF, Barkana, Tseliakhovich & Hirata (2011)

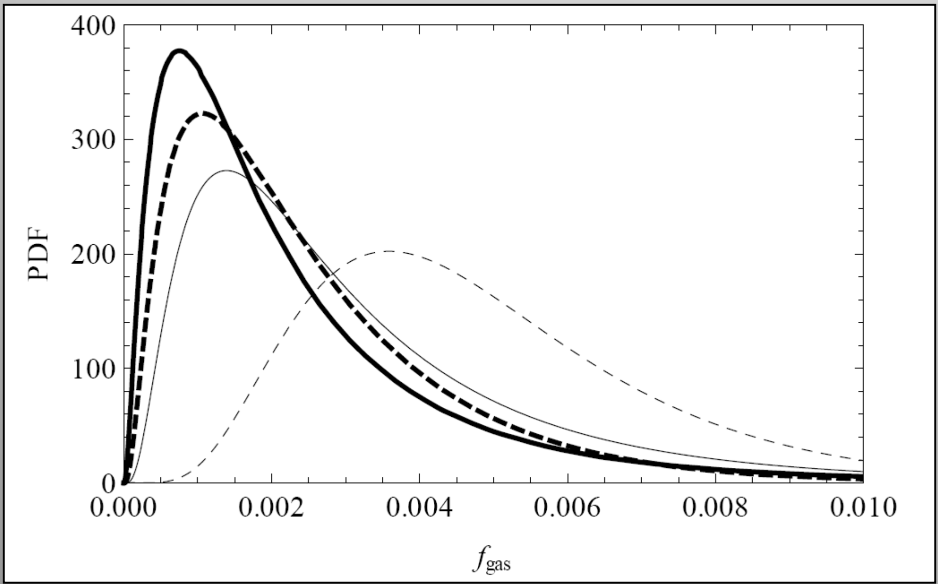
- Total effect on the gas fraction Global average over velocity patches (with MB distribution)

$$f_{gas}(\mathrm{v}_{bc},..) = \int_{M_{cool}(\mathrm{v}_{bc},..)}^{\infty} \frac{M}{\rho_0} \frac{dn(\mathrm{v}_{bc},..)}{dM} f_{gas}(\mathrm{v}_{bc}, M)\, dM$$



Global mean gas fraction in star-forming halos (solid) and star-less halos (dashed)

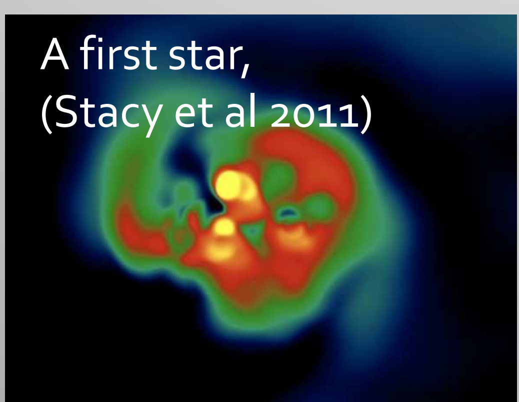
- V_{bc} shifts the f_{gas} to lower values

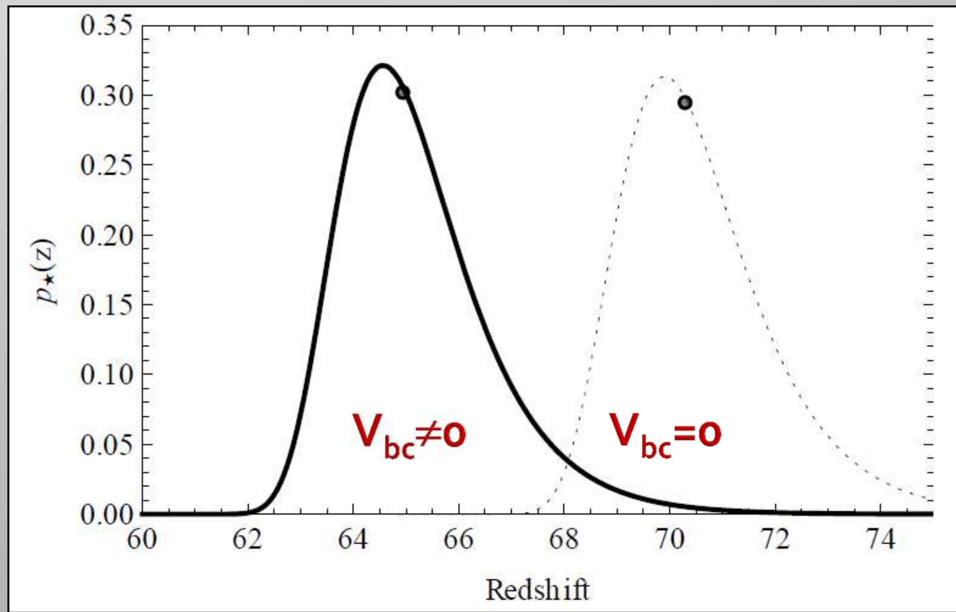


Full PDF of the gas fraction @ z = 20 in star-forming (solid) and empty (dashed) halos

The Redshift of the First Star

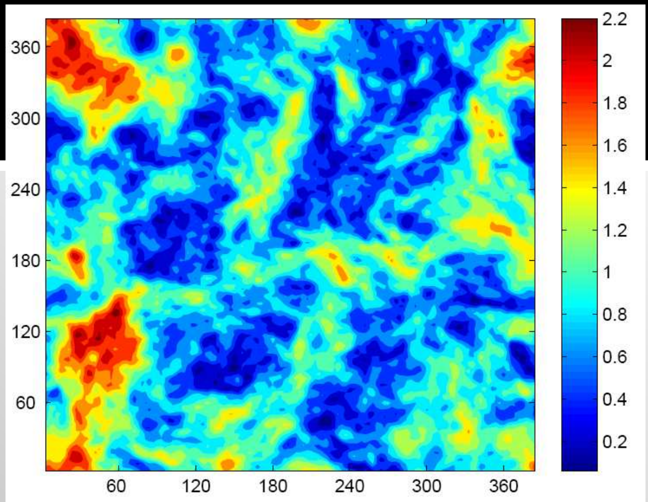
- First stars are rare events
- Numerical stars are too young ($z_* \sim 30$ in numerical simulations)
- Averaging over $V_{observed}$
  - $V_{bc} = 0 \rightarrow$ the first star is formed at $z_* \sim 70$ (Naoz, Noter & Barkana (2006))
  - $V_{bc} \rightarrow$ the first star is formed at $z_* \sim 65$



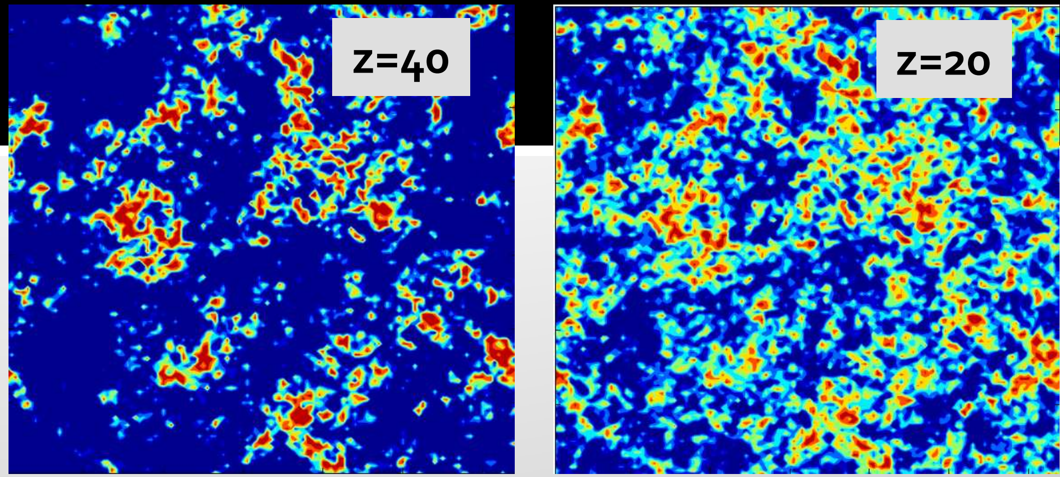


AF, Barkana, Tseliakhovich & Hirata (2011)

The Patchy Early Universe

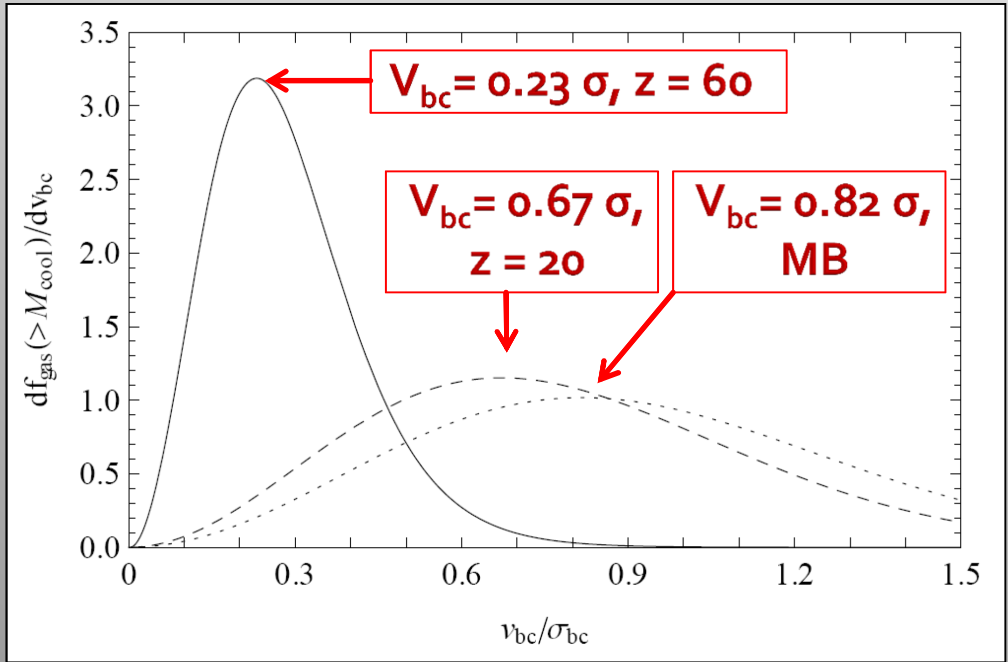


Relative velocity, v_{bc}/σ_{bc}



Density of star-forming halos

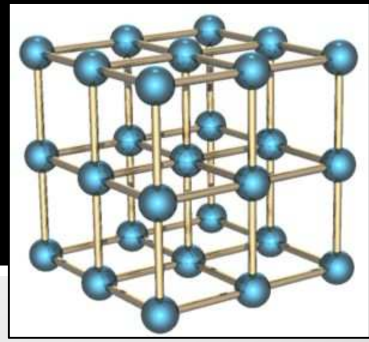
Visbal, Barkana, AF,
Tseliakhovich & Hirata (2012)



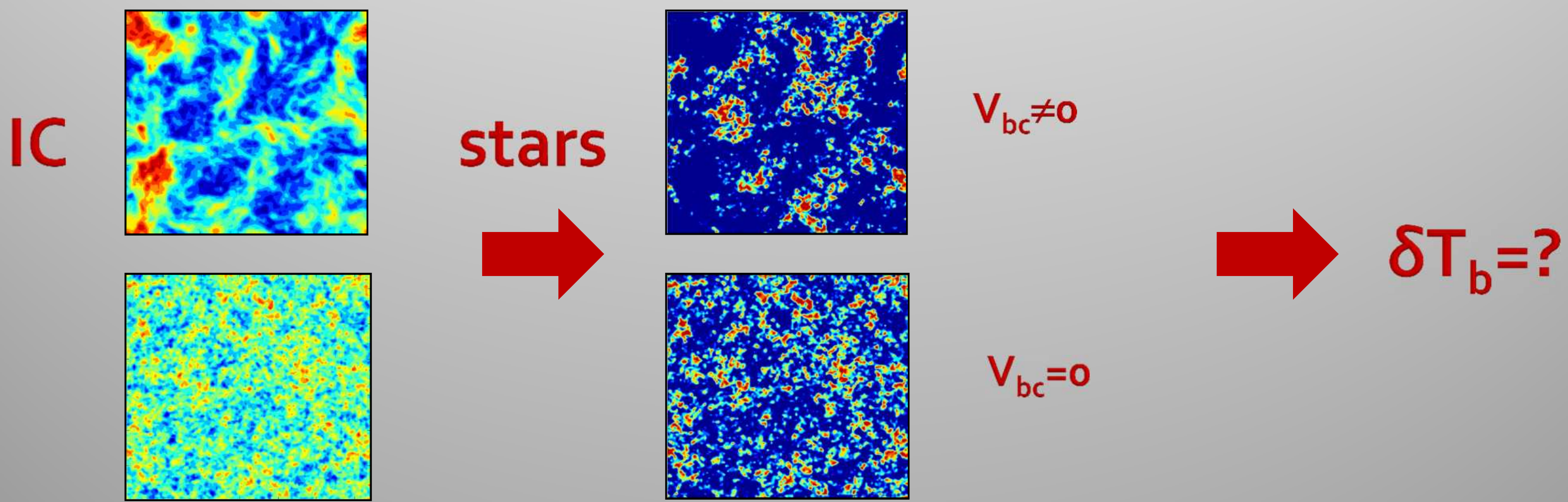
AF, Barkana, Tseliakhovich & Hirata (2011)

Contribution of regions with v_{bc} to the total gas fraction

Fluctuation at Large Scales (LS) Hybrid Numerical Method.



1. Known statistics → simulate the universe at LS
2. Small scales: analytical models + results of numerical simulations
   → Halos in each pixel
   → Stars, starlight
   → 21-cm



The Effect of the Starlight

RADIATIVE BACKGROUNDS

- Lyman-α $\rightarrow$ couples 21-cm to T_k
- X-rays $\rightarrow$ heat the gas
- Lyman-Werner (11.2-13.6 eV) $\rightarrow$ dissociate H_2

Fluctuations in the backgrounds

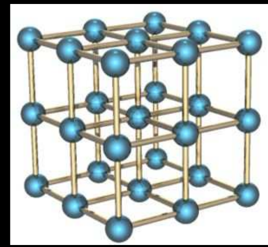
⇓

What are the fluctuations in the 21-cm (at z = 20)?

TIMING OF TRANSITIONS

- Early $\rightarrow$ saturated at z = 20
- Late $\rightarrow$ we fix it at z = 20
- Uncertain $\rightarrow$ we consider:
  - Late: H_2 cooling at z = 20 $M_{cool} \sim 10^5\ M_{sun}$
  - Saturated: H cooling at z = 20 $M_{cool} \sim 10^7\ M_{sun}$

Fluctuation at Large Scales (LS). Hybrid Numerical Method.



X-ray heating rate (as in: Mesinger, Furlanetto, Cen (2010) 21CMFAST)

⇓

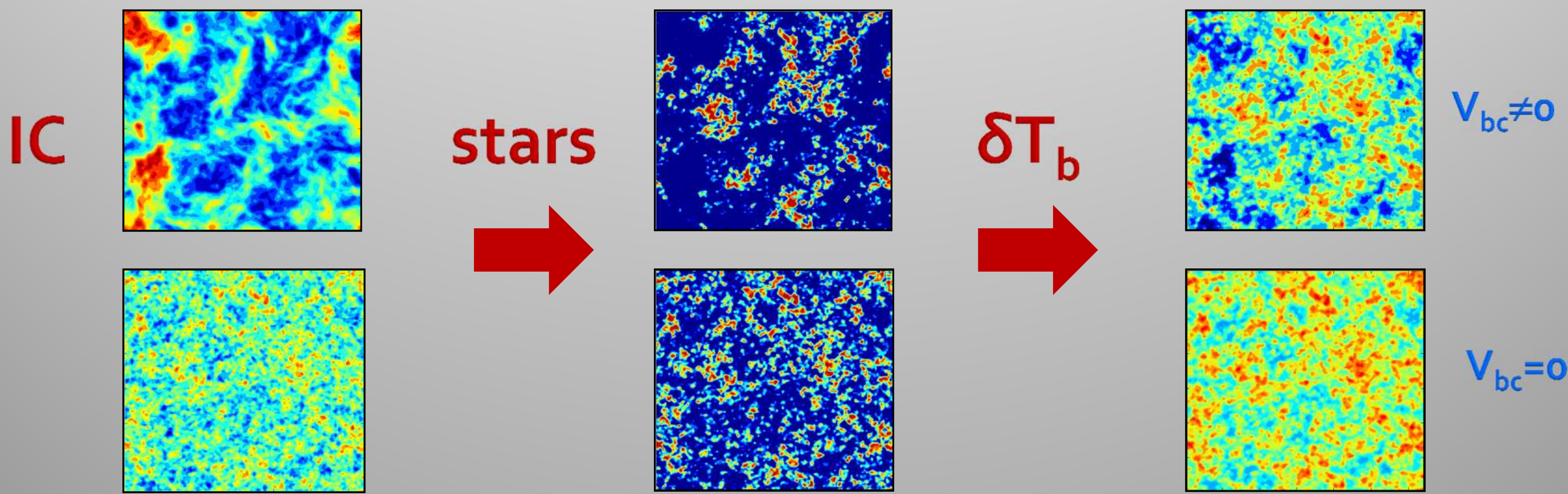
T_{gas} in each pixel at z=20

⇓

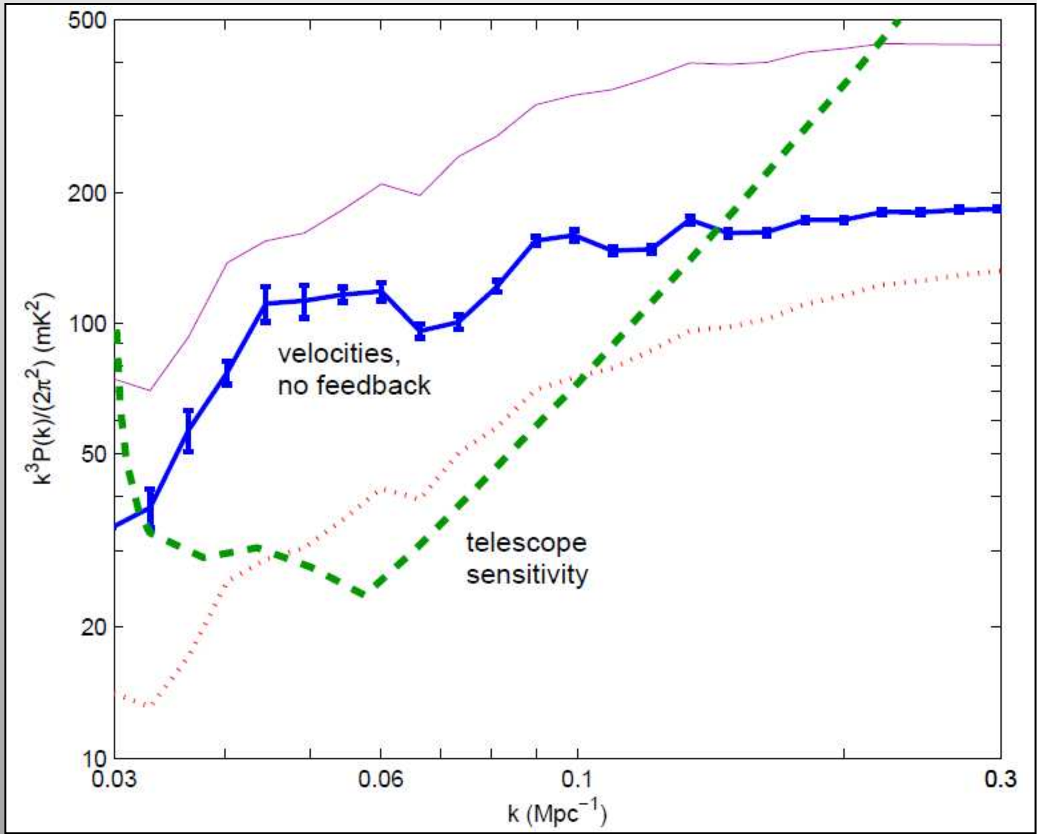
21-cm in each pixel

Assume Ly-α saturated

$$\delta T_b = 40\left(1+\delta\right)\left(1-\frac{T_{CMB}}{T_{gas}}\right)\sqrt{\frac{1+z}{21}}\ \text{mK}$$



Heating Fluctuations at z=20 Predicted 21-cm Power Spectrum



Previous expectation: No BAO

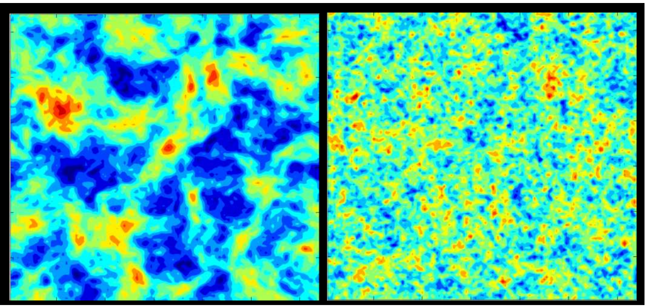
Noise
(1000 hour observations with MWA or LOFAR, but at 50–100 MHz)

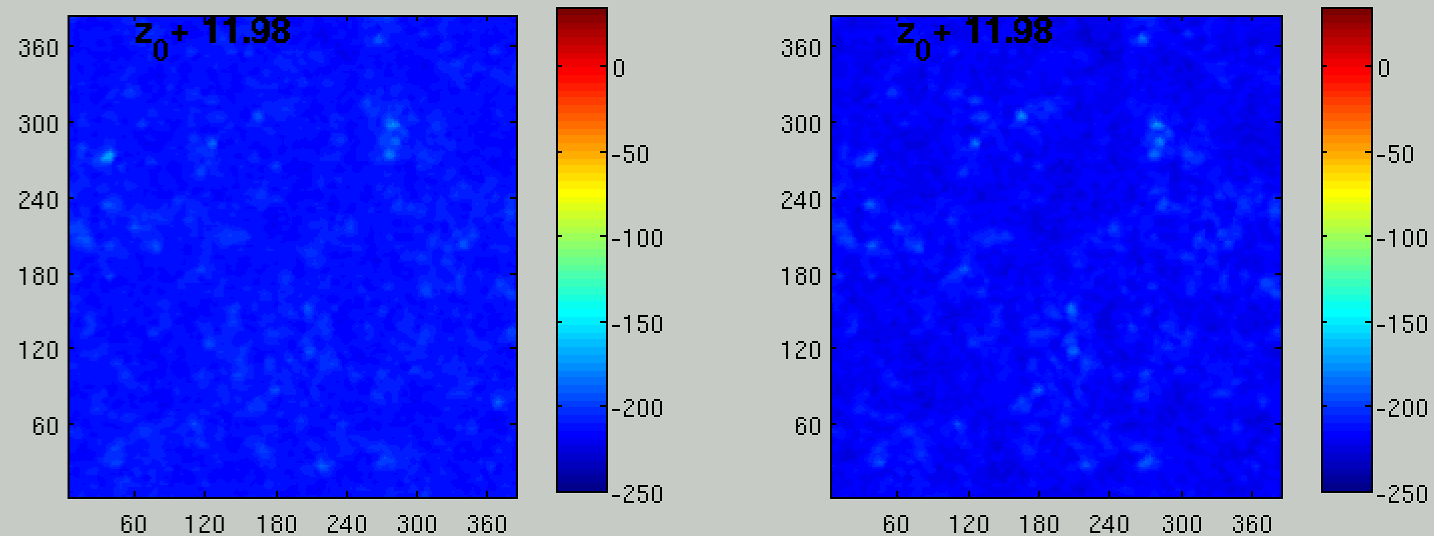
Our predictions:
late and early LW transition.

Late → BAO at 130 Mpc
(light halos)

Early → No BAO
(heavy halos)

Evolution of the 21-cm Signal. z_o is the Heating Transition





21-cm without velocity, $z_o = 19.0$ 21-cm with velocity, $z_o = 17.8$

- **Previous expectations:**
  Fluctuations in 21-cm trace matter distribution at all scales
- **Our prediction:**
  Fluctuations in 21-cm are biased (trace velocity field at large scales)

Conclusions

1. **The effect of v_{bc} is significant for the first stars and may be observed in near future**

2. **New!!!** predictions for the 21-cm power spectrum:

    i. Relative velocity & timing have strong effect on 21-cm
    ii. BAO in 21-cm
    iii. Power spectrum → info on heavy to light halos abundance.

Thank you!