Emerging from the Dark Ages
The Role of Baryons in Structure Formation

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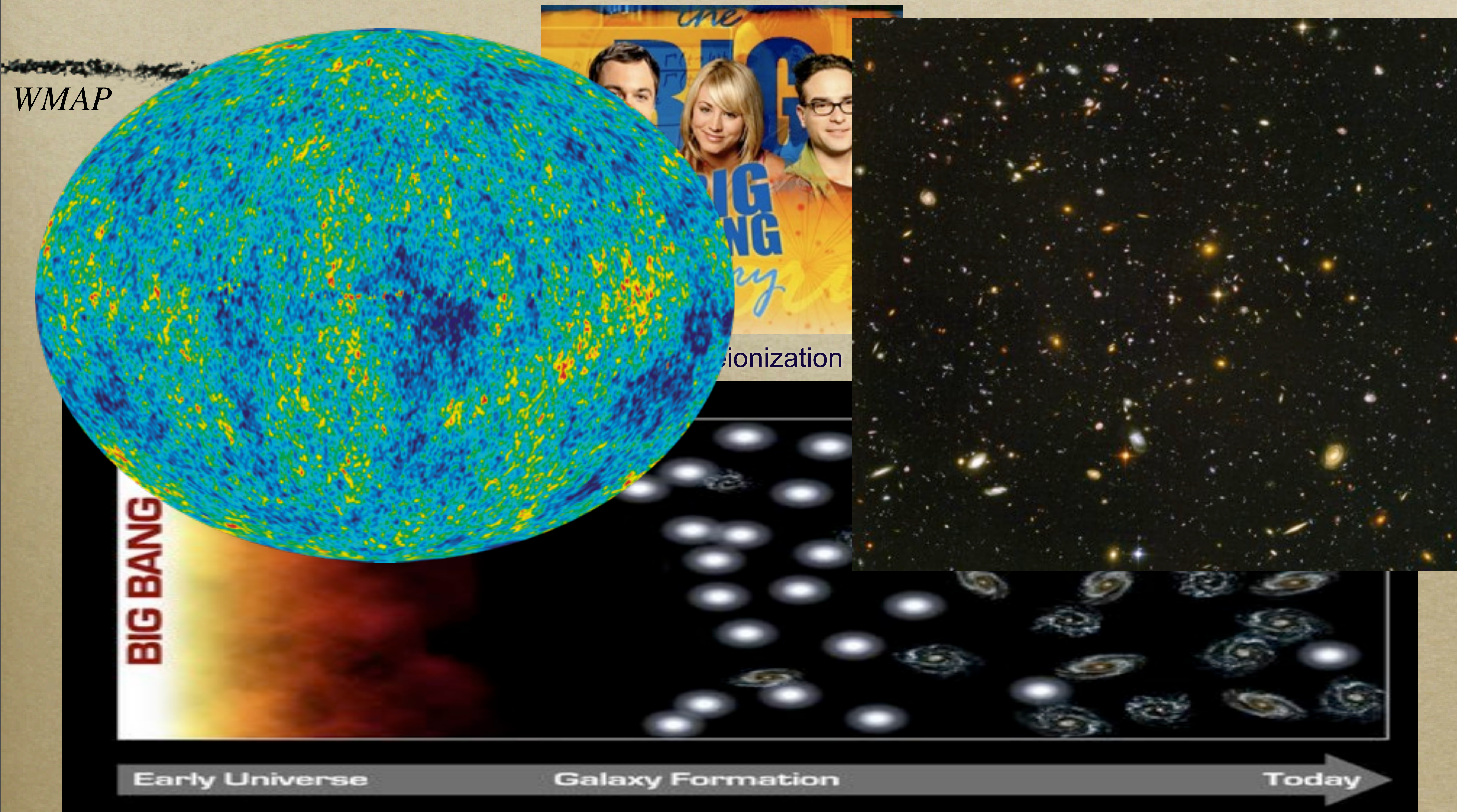
The “Theory”: The history of the Universe



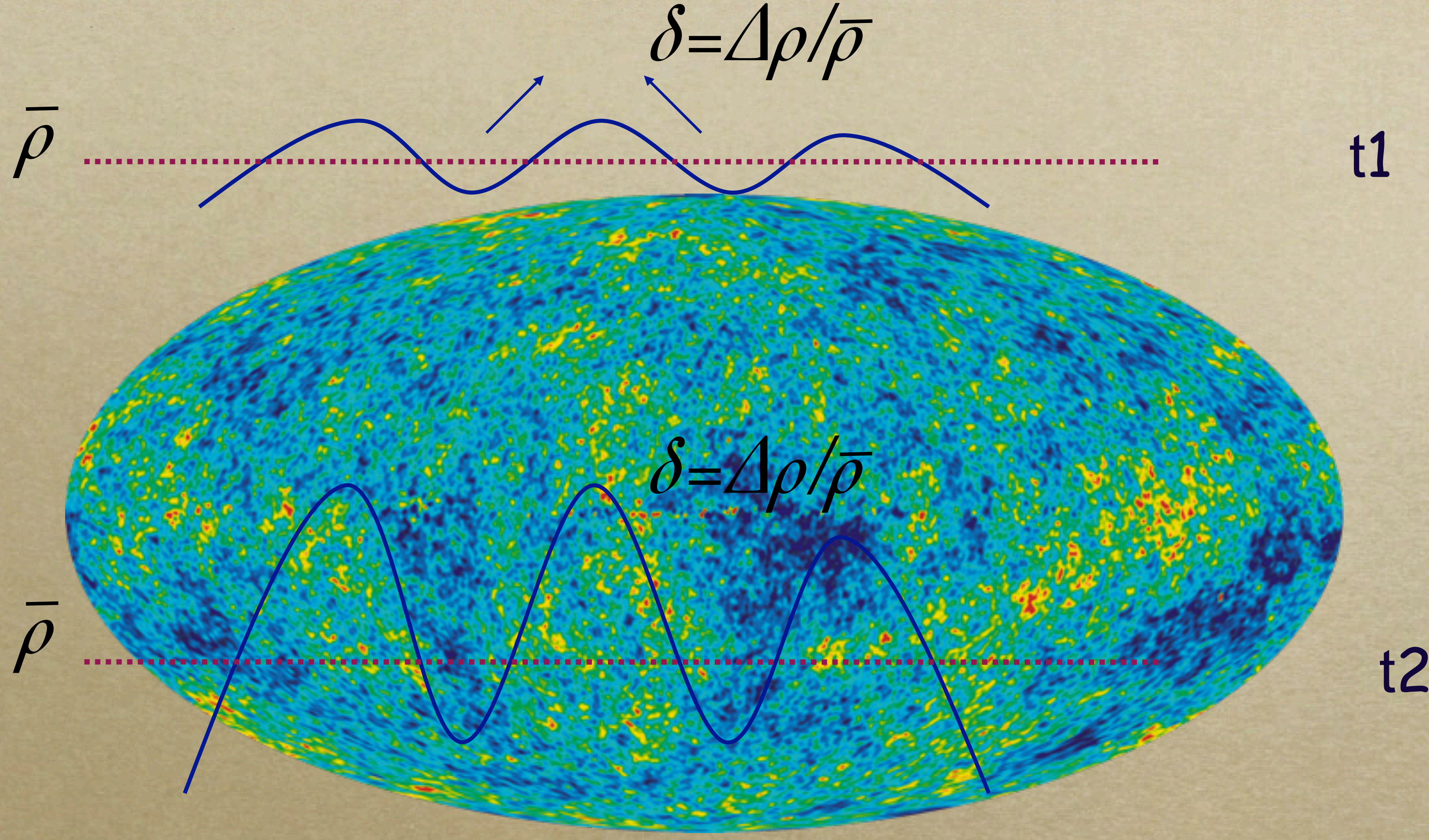
t~0.4Myr

t~0.1Myr

The Role of Baryons - Outline

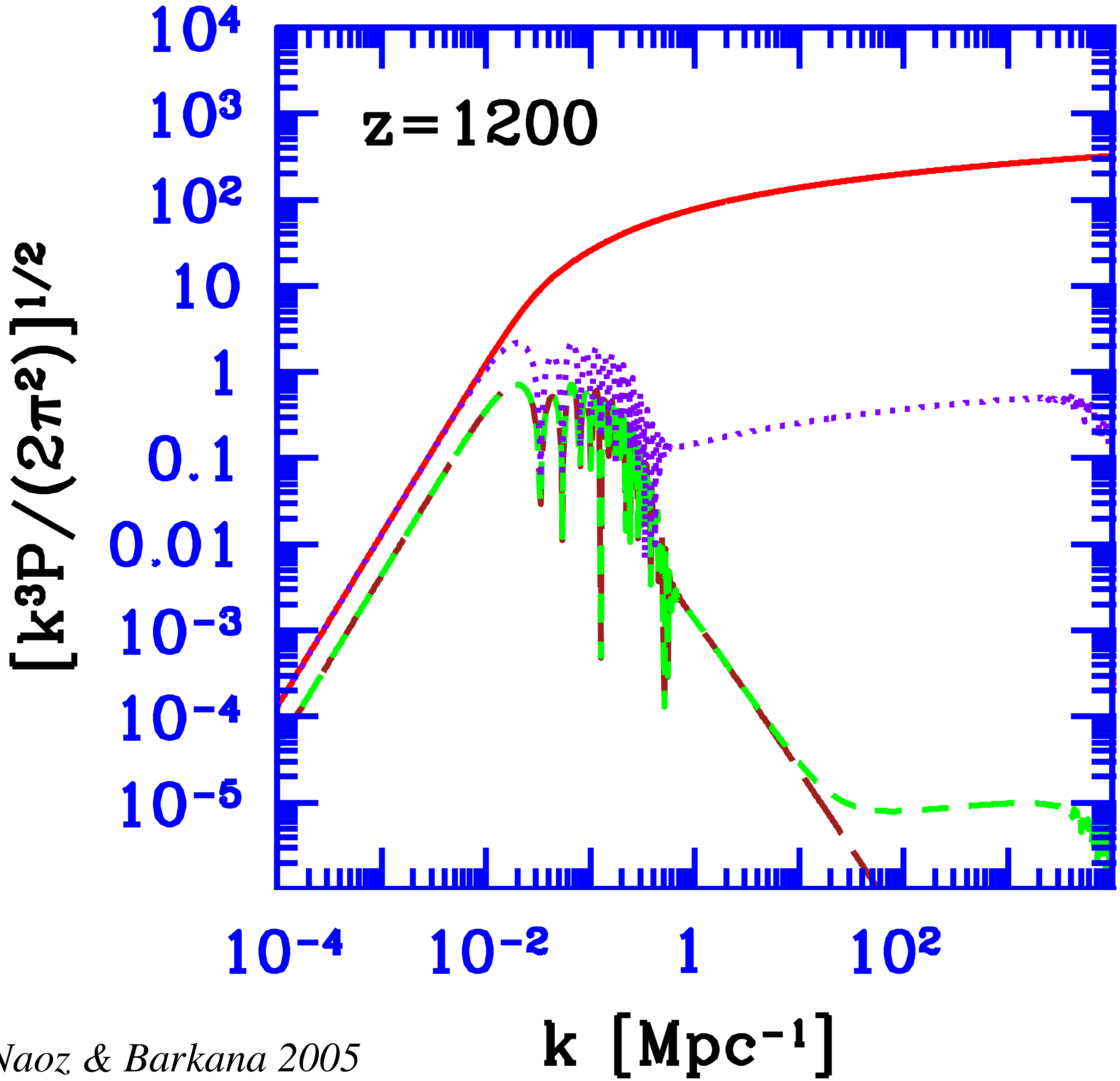
- *Linear and non linear behavior of structure*
    - *Baryon speed of sound and relative amplitude*
    - *The relative velocity of baryons compare to the dark matters' (the "stream velocity")*

The Linear Regime: The Power Spectrum



WMAP

The Linear Regime: The Power Spectrum



Naoz & Barkana 2005

$|\delta|=[k^3P/(2\pi)]^{1/2}$

$\delta=\Delta\rho/\rho$

Dark Matter

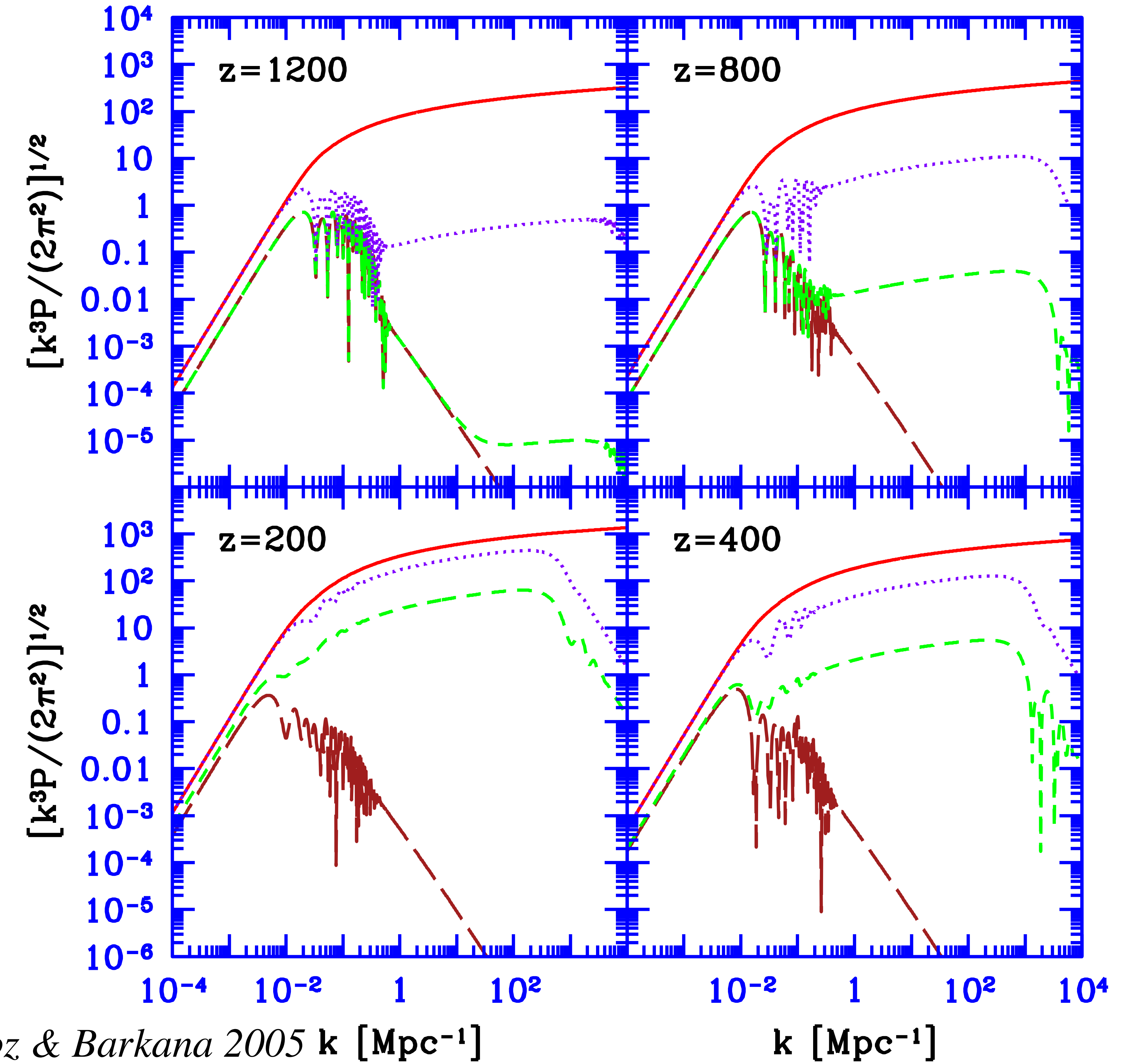
Gas

Gas temp

Radiation temp

NASA/WMAP Science Team

The Linear Regime: The Power Spectrum



Naoz & Barkana 2005

$|\delta|=[k^3P/(2\pi)]^{1/2}$

$\delta=\Delta\rho/\rho$

Dark Matter

Gas

Gas temp

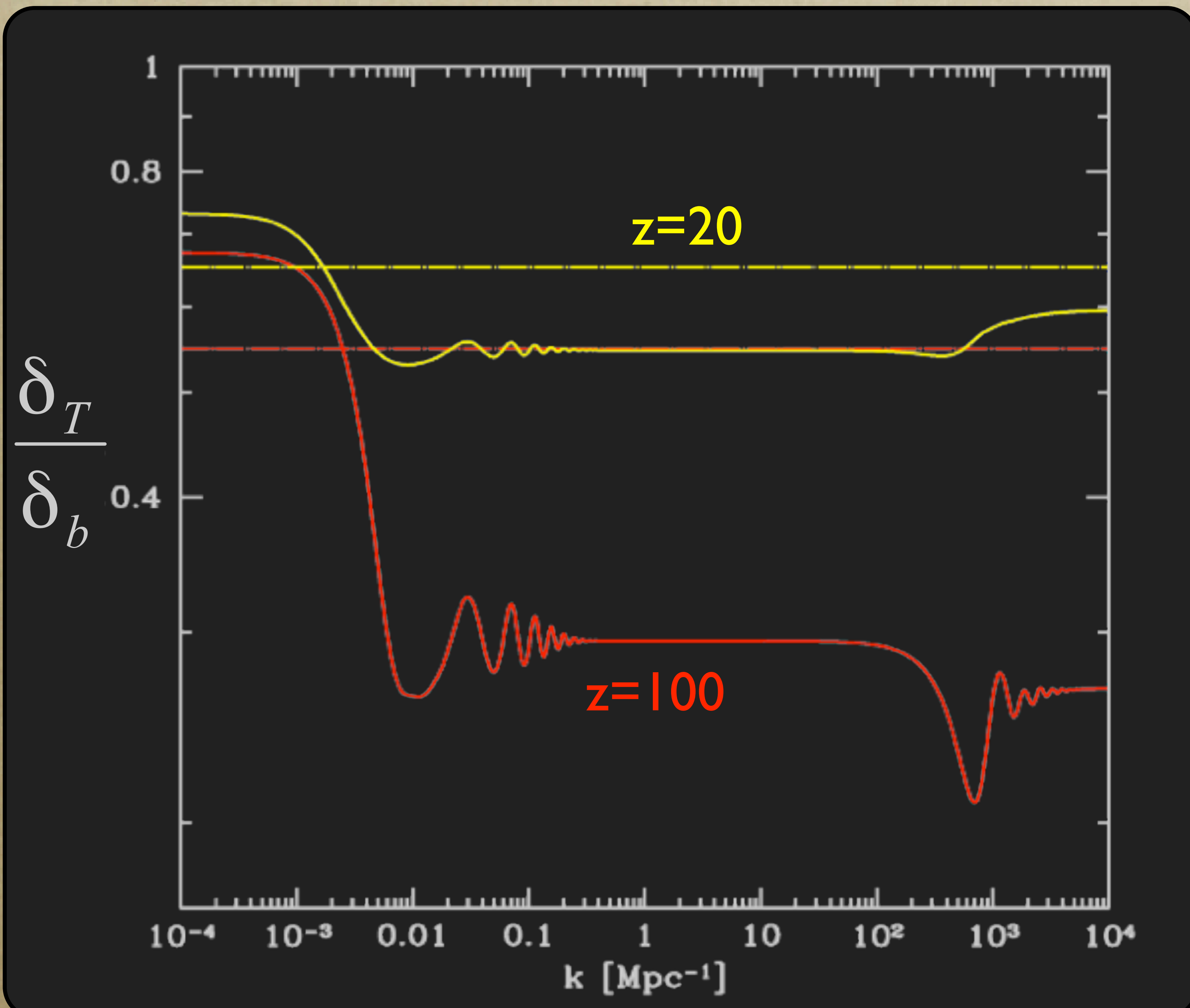
Radiation temp

Numerical calculations were done by modifying CMBFAST (Seljak & Zaldarriaga 1996)

The Linear Regime: Baryon's speed of sound

First order correction in linear perturbations theory:

Baryons's speed of sound is spatially varying



Uniform $c_s(r)$

Vs

spatially varying

Naoz & Barkana 2005

(see also Yamamoto et al. 1997, 1998)

The Linear Regime: Baryon's speed of sound

First order correction in linear perturbations theory:

Baryons's speed of sound is spatially varying

Q:why is it 1st order term?

A:

The motion equation for baryonic fluctuations:

$$\ddot{\delta}_{\rm b} + 2H\dot{\delta}_{\rm b} = \frac{3}{2}H_0^2\frac{\Omega_m}{a^3}\left(f_{\rm b}\delta_{\rm b} + f_{\rm dm}\delta_{\rm dm}\right) - \frac{k^2}{a^2}c_s^2\delta_{\rm b}$$

since: $c_s^2 \equiv \frac{dP}{d\rho} = \frac{k_B\bar{T}}{\mu}\left(1 - \frac{d\log\bar{T}}{d\log\rho}\right)$

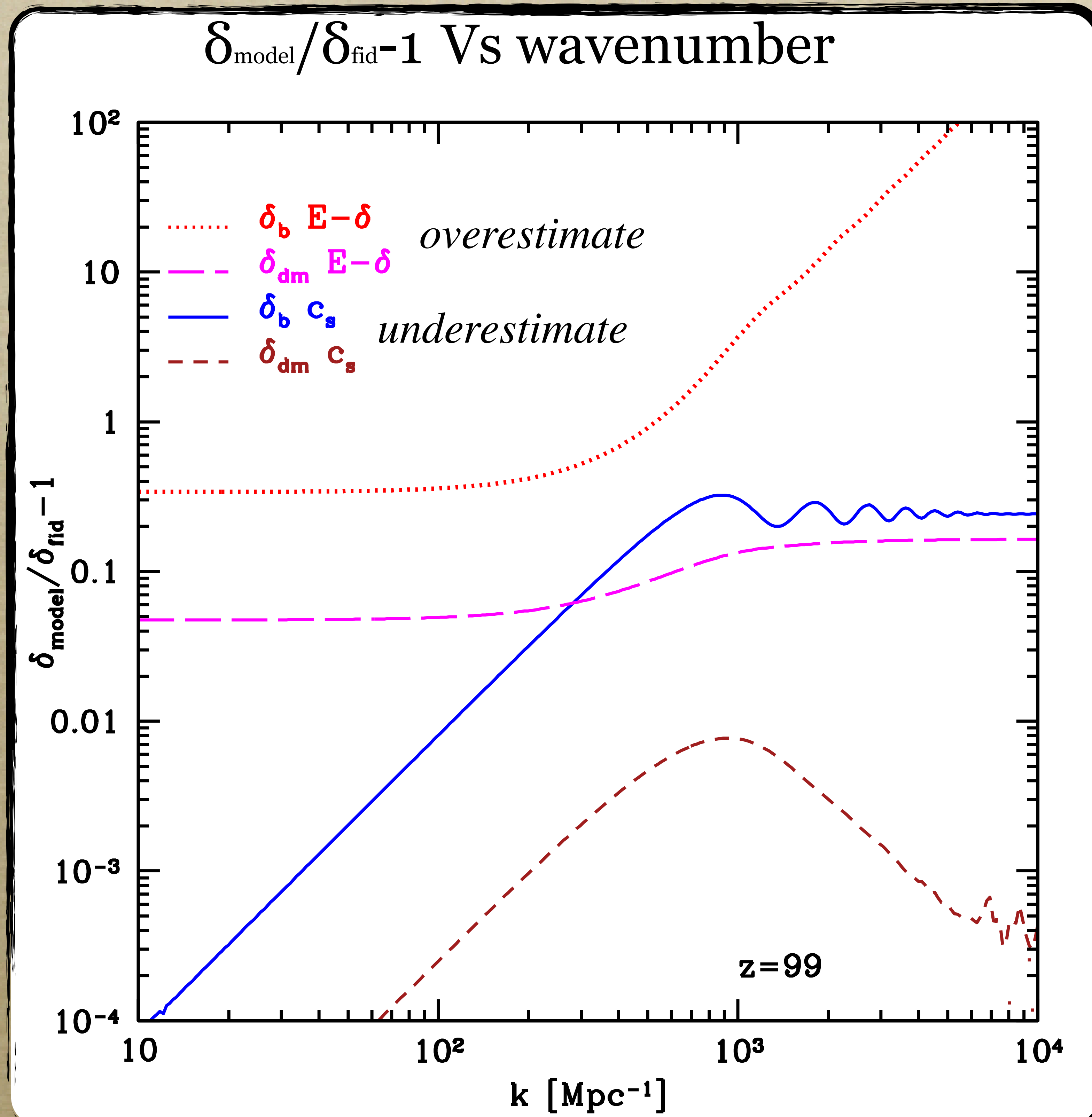
So:

$$\ddot{\delta}_{\rm b}+2H\dot{\delta}_{\rm b} = \frac{3}{2}H_0^2\frac{\Omega_m}{a^3}\left(f_{\rm b}\delta_{\rm b} + f_{\rm dm}\delta_{\rm dm}\right) - \frac{k^2}{a^2}\frac{k_B\bar{T}}{\mu}\left(\delta_{\rm b} + \delta_T\right)$$

Naoz & Barkana 2005

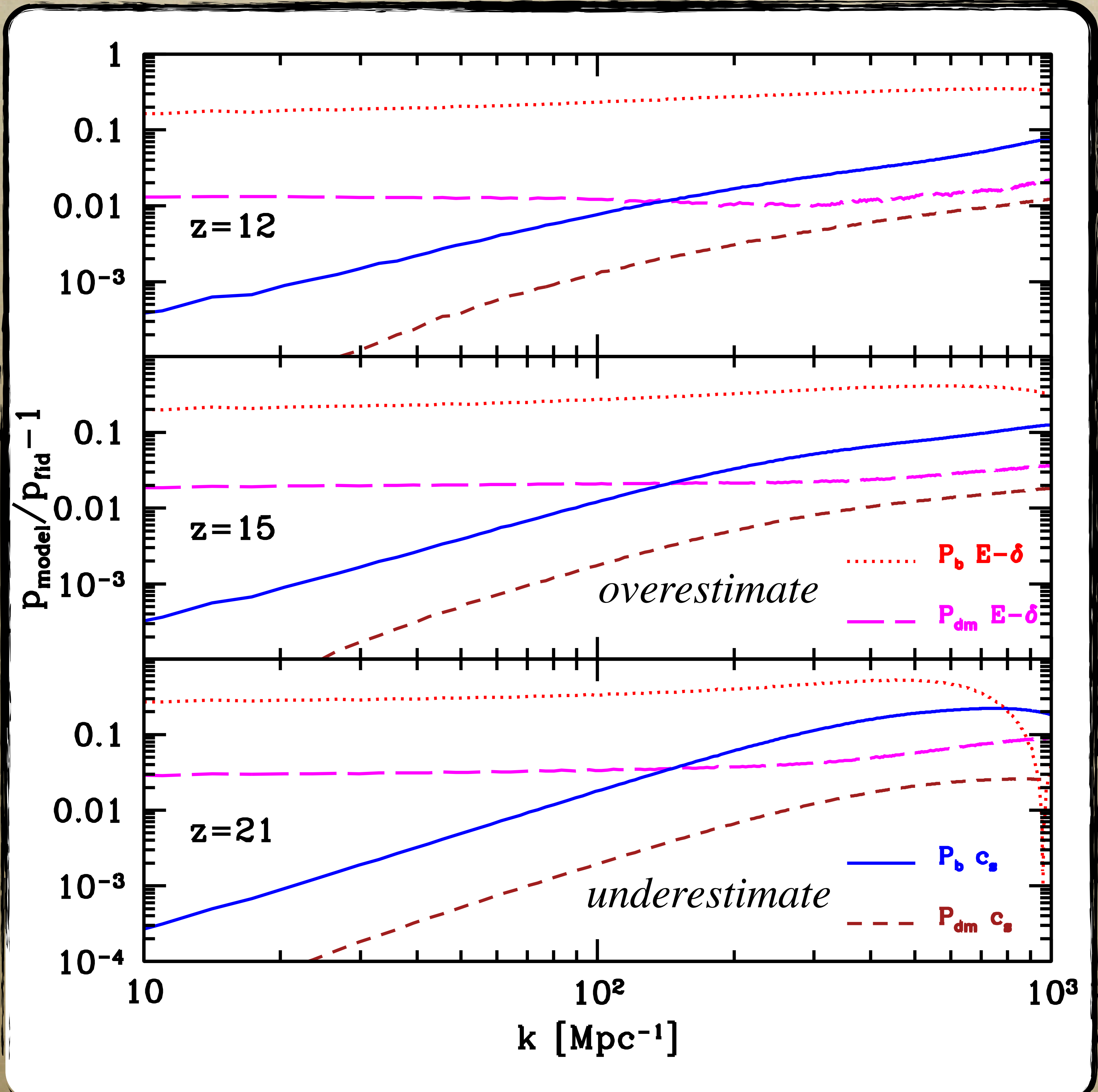
The Linear Regime: Baryon's speed of sound

- *Fid (Complete heating)*
- $c_s(r)$=const δ_b , δ_{dm}
- $\delta_b=\delta_{dm}$ δ_b , δ_{dm}



Naoz & Barkana 2005
Naoz, Yoshida, Barkana 2011

None-Linear Regime: Baryon's speed of sound



Gadget 2

768^3 (baryons + DM)

(starting at z=99, 2Mpc, soft~0.2kpc, M_{dm}~$10^3 M_\odot$ M_b~$225 M_\odot$)

- *Fid (Complete heating)*
- *$c_s(r)$=const* P_b , P_{dm}
- *$\delta_b = \delta_{dm}$* P_b , P_{dm}

Naoz, Yoshida, Barkana 2011

The Linear Regime: The role of pressure

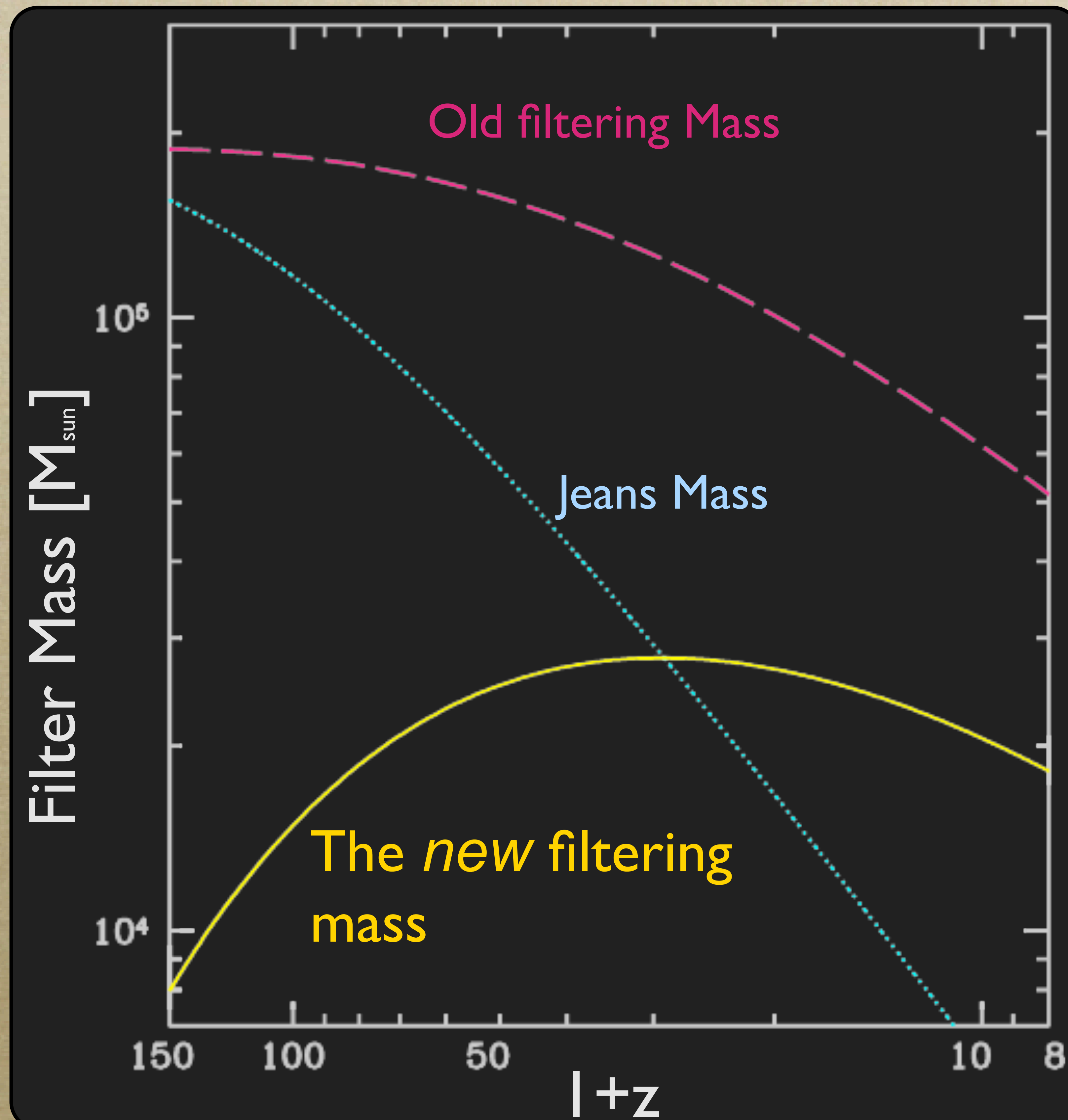
The Filtering mass:

Q: What is the minimum halo mass at which baryon overdensities can still grow?

A: Time averaging Jeans mass

✓ Baryons overdensties are smooth compared to the dark matter $\delta_b \neq \delta_{dm}$

✓ Spatially varying speed of sound $c_s(r) \neq const$



Naoz & Barkana 2005,2007
Gnedin & Hui 1998
Gnedin 2000

None- Linear Regime: The role of pressure

The Filtering mass: *Vs* *The Characteristic mass:*

Q:What is the minimum halo mass that keeps most of its baryons (> 1/2 f_b) during formation?

$$f_{g,\mathrm{calc}} = f_{\mathrm{b},0}\left[1 + \left(2^{\alpha/3} - 1\right)\left(\frac{M_c}{M}\right)^{\alpha}\right]^{-3/\alpha}$$

Gnedin & Hui 1998

Gnedin 2000

None- Linear Regime: The role of pressure

The Filtering mass: *Vs* *The Characteristic mass:*

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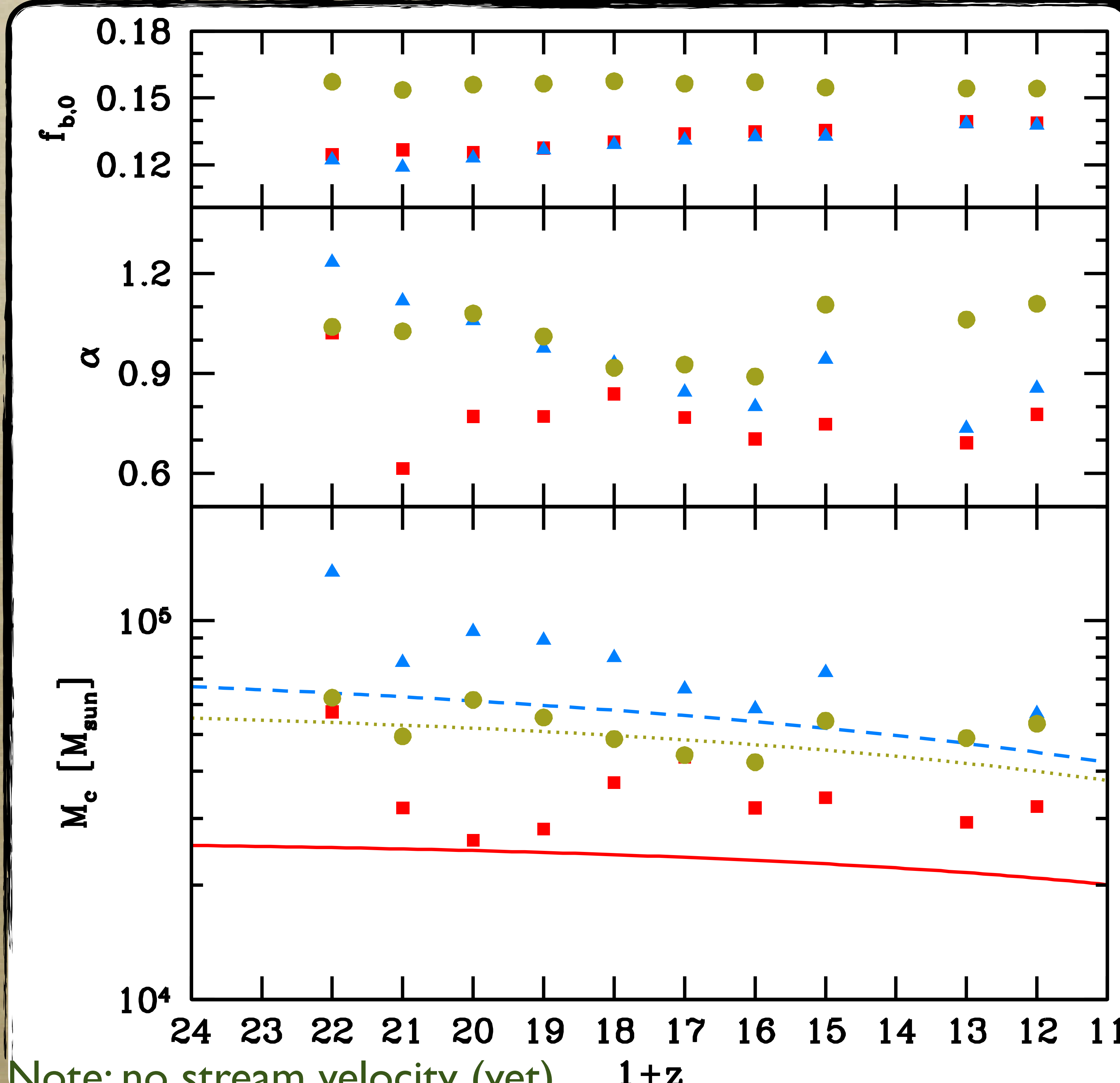


Note: no stream velocity (yet)

Characteristic mass:

- ■ *Fid (Complete heating)*
- ▲ $c_s(r)=const$
- ● $\delta_b=\delta_{dm}$

Filtering mass:

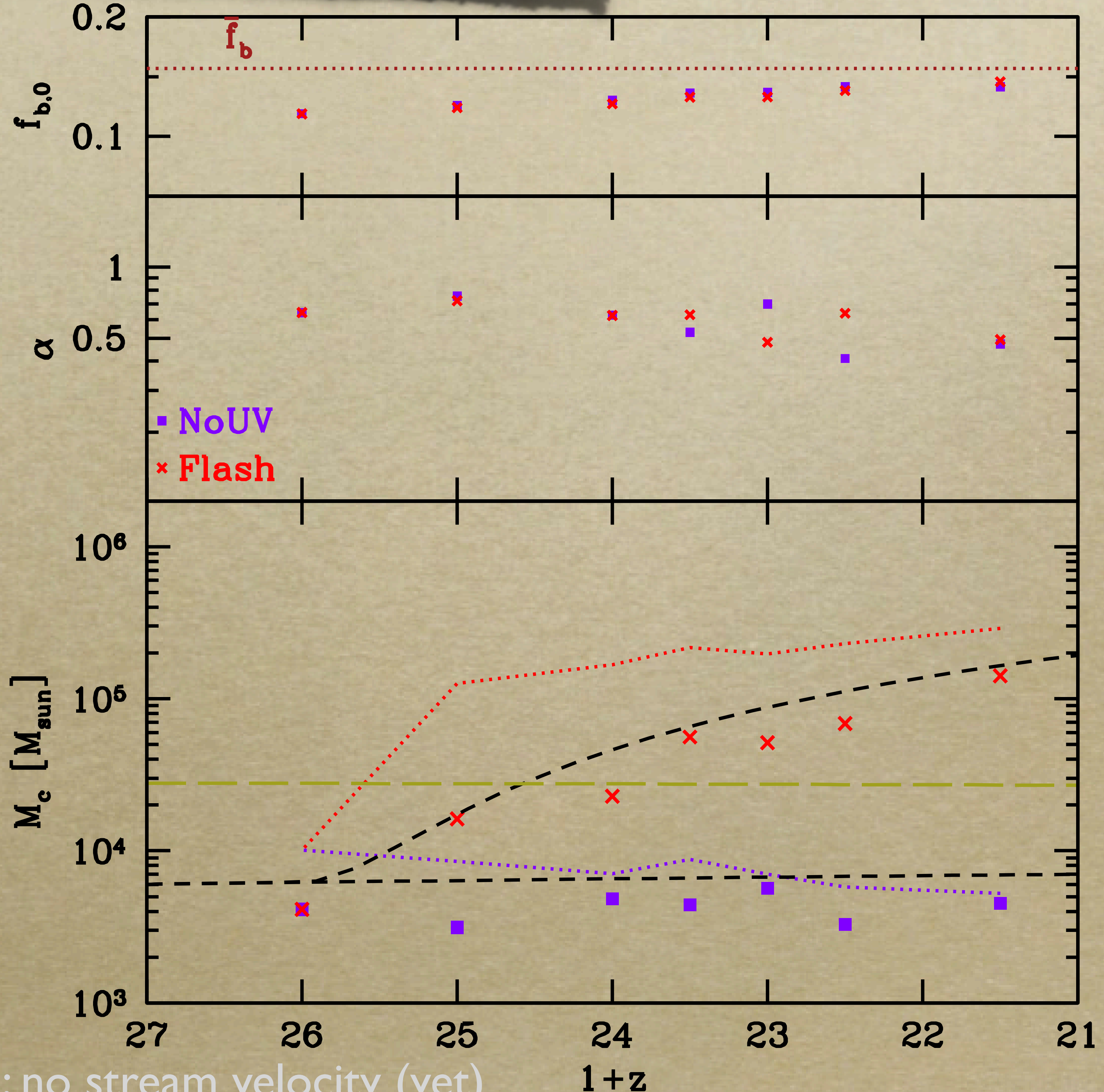
- —— *Fid (Complete heating)*
- - - - $c_s(r)=const$
- • • • • $\delta_b=\delta_{dm}$

Naoz, Yoshida, Barkana 2011

None- Linear Regime: The role of pressure + *heating*

The Filtering mass: *Vs* *The Characteristic mass:*

AMR - Enzo sim.
Box 0.25 Mpc/h
Inner: 0.0625 Mpc/h
(starting at z=99)



Naoz, Barkana & Mesinger 2009

Note: no stream velocity (yet)

From Linear to Non-Linear

$c_s(r)$ + $\delta_{dm} \neq \delta_b$

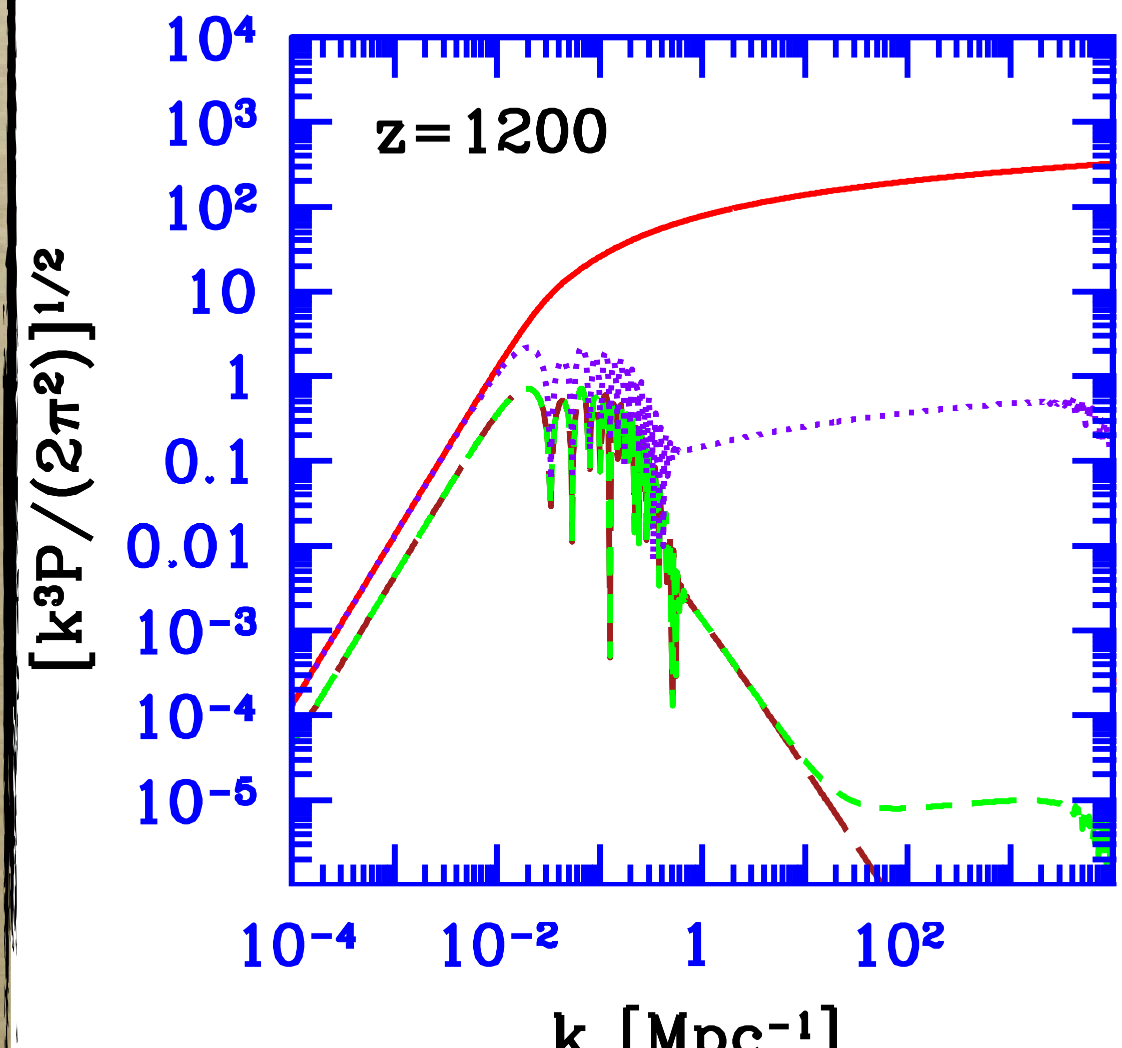
- *Initial conditions are important ☺*
- *The minimum gas-rich halo is highly sensitive to the baryon ICs*
- *Use linear theory to understand non-linear behavior*

The Linear Regime: The Stream Velocity

Second order correction in linear perturbations theory:

Baryons's peculiar velocity differ from the dark matter at the time of recombination

- $|v_b - v_{dm}| \approx 30$ km/sec at Recombination time
- scales as 1/a



Naoz & Barkana 2005

$v_b \neq v_{dm}$ *(Tseliakhovich & Hirata 2010)*

The Linear Regime: The Stream Velocity

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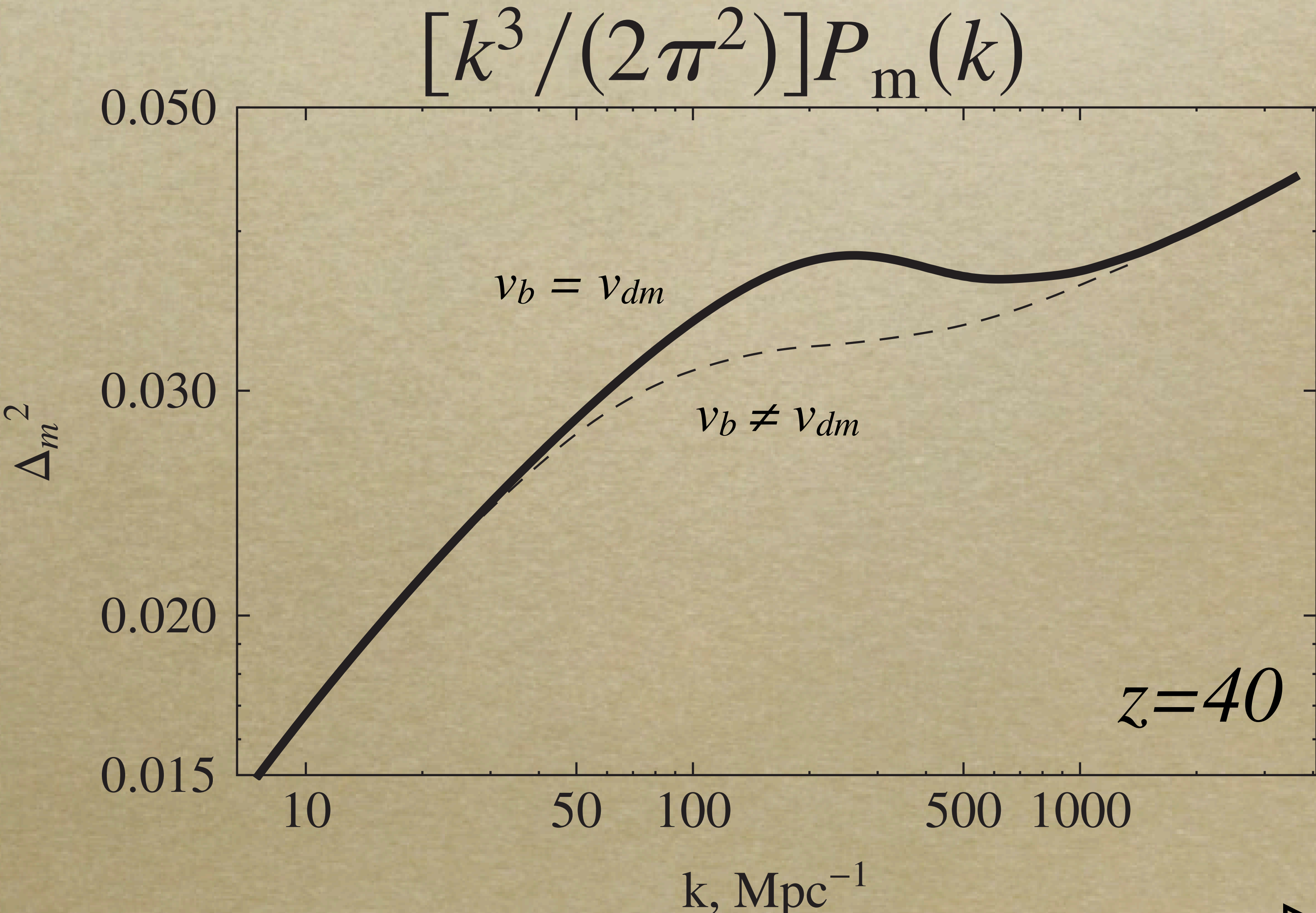


$v_b \neq v_{dm}$ *(Tseliakhovich & Hirata 2010)*

The Linear Regime: The Stream Velocity

Second order correction in linear perturbations theory:

Q:Why only this term?

A: (Tseliakhovich & Hirata 2010) Compare:

$$\frac{i}{a}\mathbf{v}_{\rm bc}^{\rm (bg)} \cdot \mathbf{k}\delta_{\rm c} \quad Vs \quad \frac{\partial \delta_{\rm c}}{\partial t} \sim \delta_c / H$$

The ratio is: $\dfrac{v_{\rm bc}^{\rm (bg)} k}{aH}$

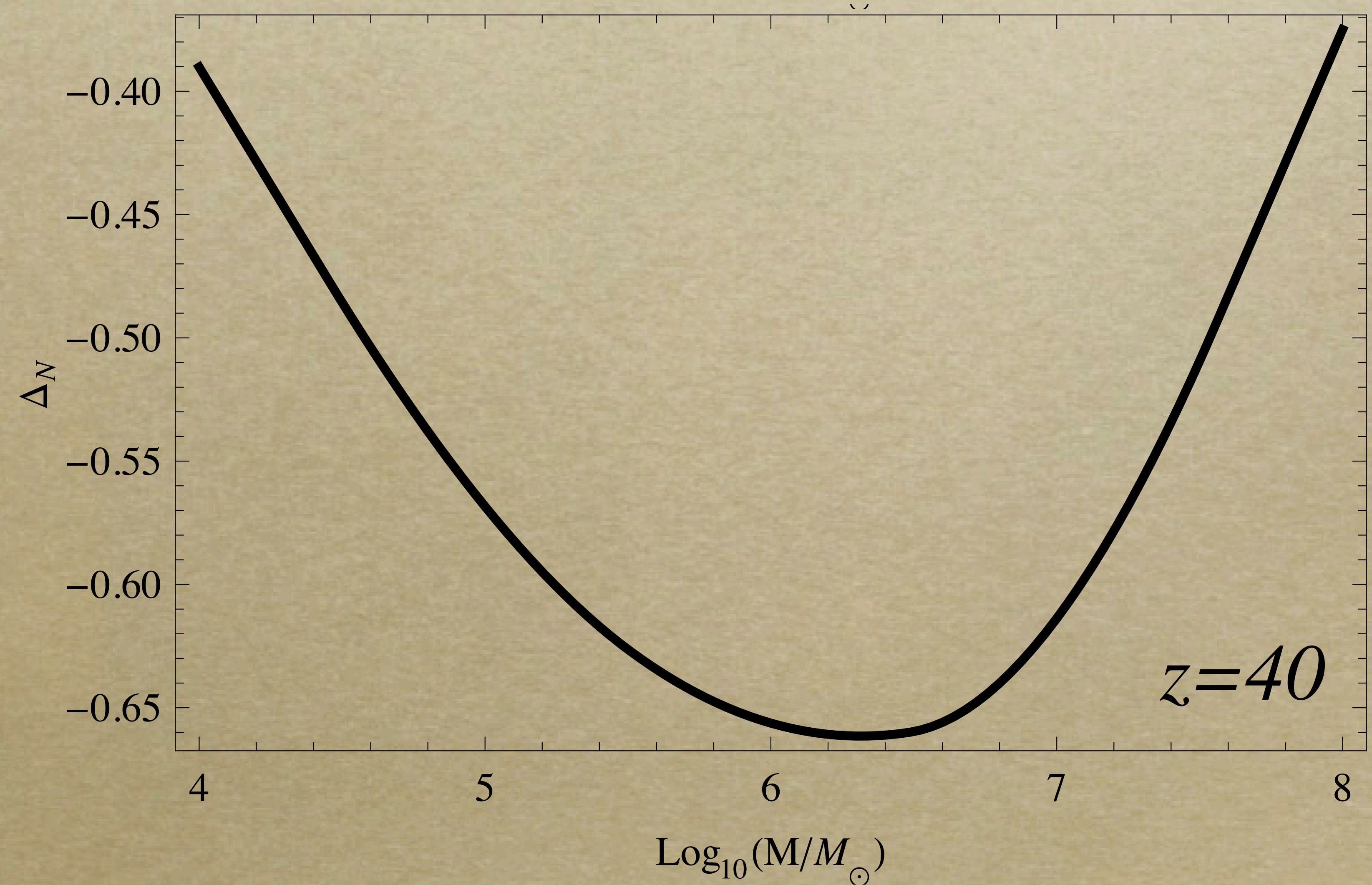
The Linear Regime: The Stream Velocity

Second order correction in linear perturbations theory:

Baryons's peculiar velocity differ from the dark matter at the time of recombination

$$\Delta_{\rm v} = \frac{N_{\rm vbc}(> M) - N_0(> M)}{N_0(> M)}.$$

For more implications:
Dalal et al 2010, Stacy et al 2011, Maio et al 2011, Greif et al 2011, Yoo et al 2011, Fialkov et al 2011, Bittner & Loeb 2011, Visbal et al 2012.....



Tseliakhovich & Hirata 2010

None-Linear Regime: The Stream Velocity

The effect of the stream velocity in cosmological simulations:

See also: Stacy et al 2011, Maio et al 2011, Greif et al 2011, Naoz et al 2012...

AREPO Zoom-in simulation starting at z=99, sof=68pc

No v_{bc}

z=19.58

$n_{\mathrm{H}} = 10^9\ \mathrm{cm}^{-3}$

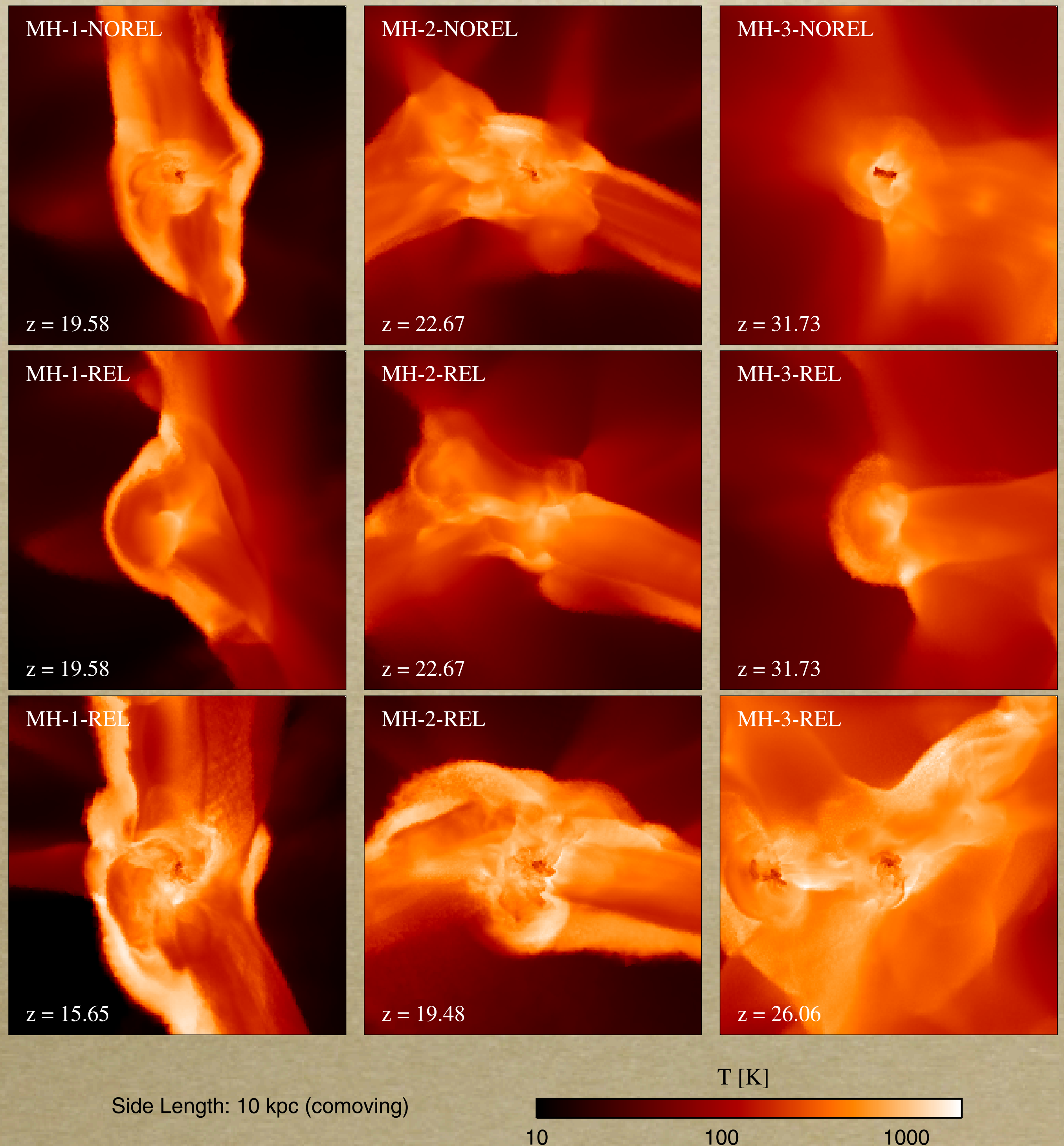
$1\sigma\ v_{bc}$

z=19.58

$1\sigma\ v_{bc}$

z=15.65

$n_{\mathrm{H}} = 10^9\ \mathrm{cm}^{-3}$



Greif et al 2011

None-Linear Regime: The Stream Velocity

Half empty of half full?

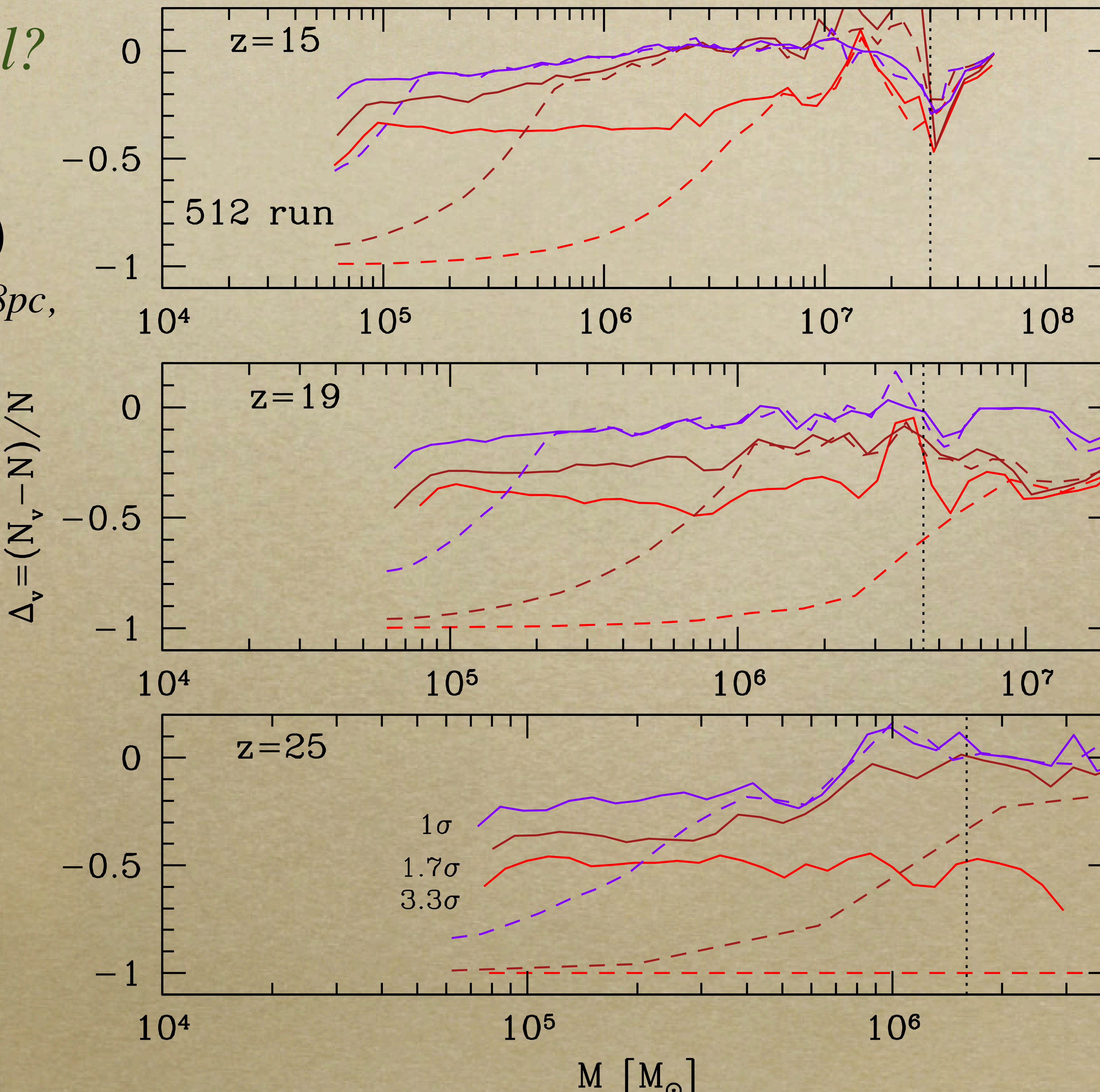
Gadget 2

512^3 (baryons + DM)

(starting at z=199, 0.7Mpc, soft~68pc, M_{dm}~198M⊙ M_b~32.6M⊙)

$$\Delta_{\rm v} = \frac{N_{\rm vbc}(>M) - N_0(>M)}{N_0(>M)}.$$

Dashed are for $N(>M, f_g > f_b/2)$



Naoz, Yoshida & Gnedin 2012a

None-Linear Regime: The Stream Velocity

Half empty of half full?

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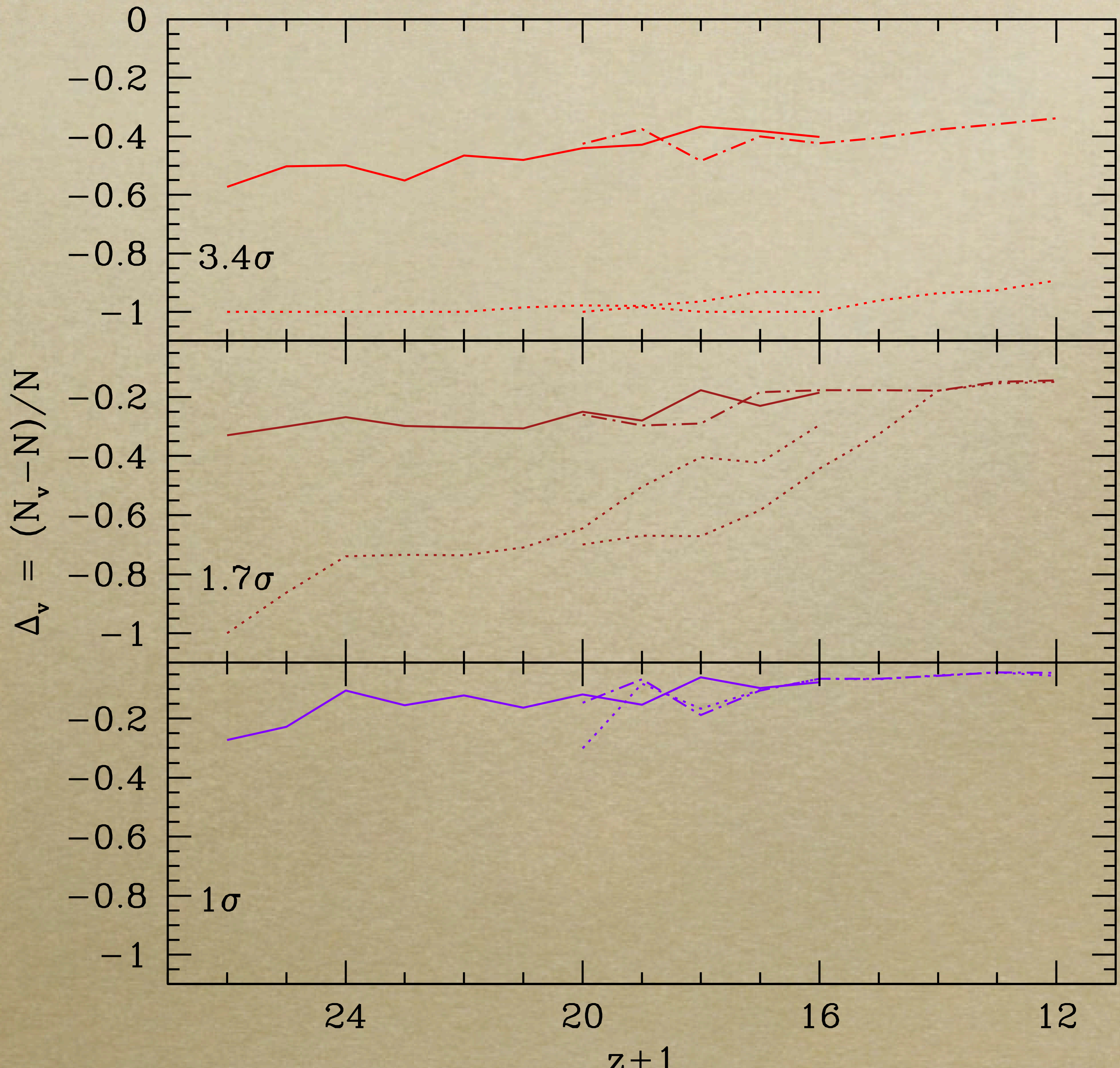
512^3 (baryons + DM)

(starting at z=199, 0.7Mpc, soft~68pc, M_{dm}~$198 M_\odot$ M_b~$32.6 M_\odot$)

For M~ $5 \times 10^5 \, \mathrm{M}_\odot$

$$\Delta_\mathrm{v} = \frac{N_\mathrm{vbc}(> M) - N_0(> M)}{N_0(> M)}.$$



Naoz, Yoshida & Gnedin 2012a

None-Linear Regime: The Stream Velocity

Half empty of half full?

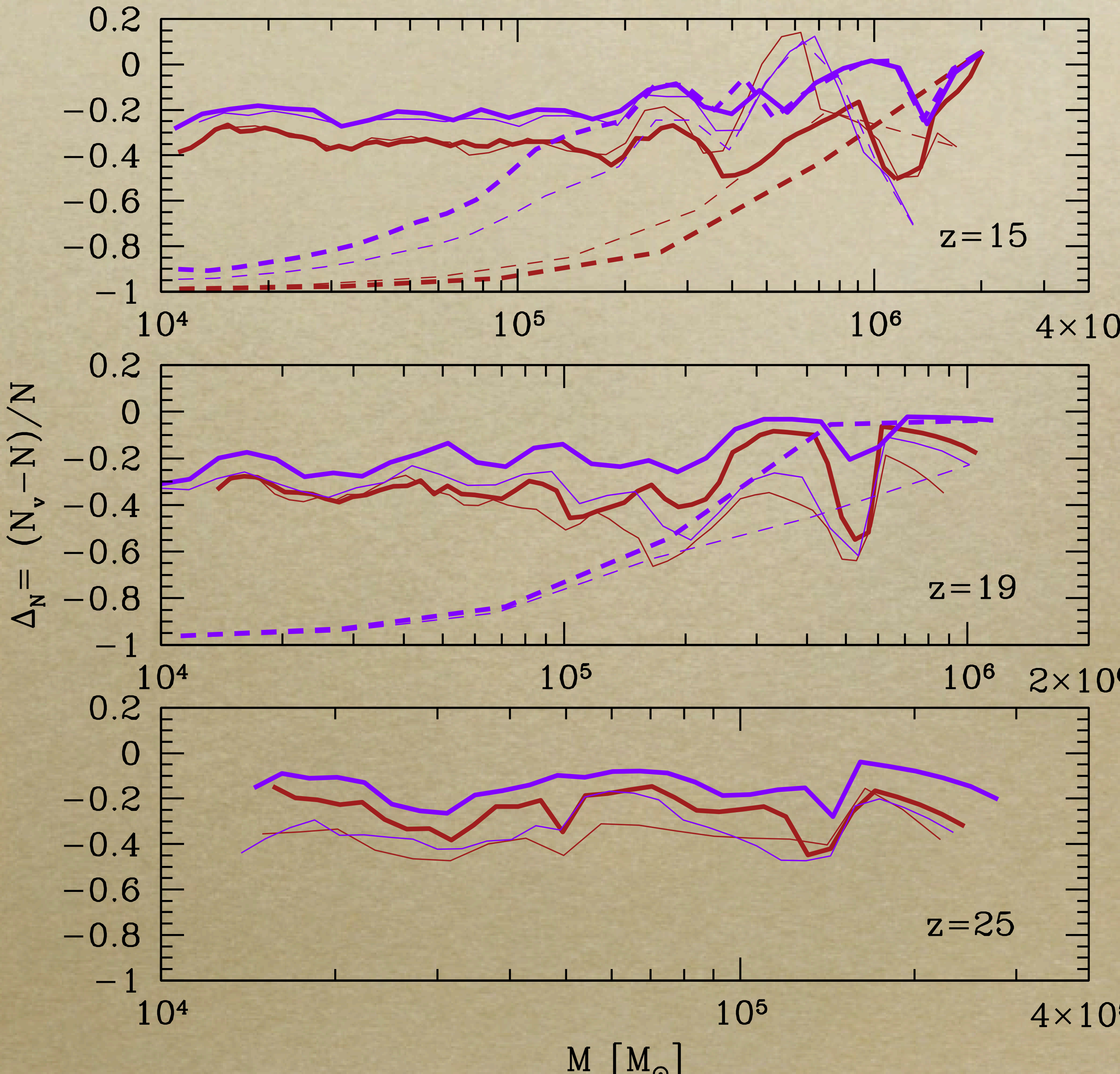
Position shift

Gadget 2

256^3 (baryons + DM)

(starting at z=199, 0.2Mpc, soft~40pc, M_{dm}~30.7M⊙ M_b~6M⊙)

$$\Delta_v = \frac{N_{vbc}(>M) - N_0(>M)}{N_0(>M)}.$$



Naoz, Yoshida & Gnedin 2012a

Linear Regime, Stream Velocity and the Role of Pressure

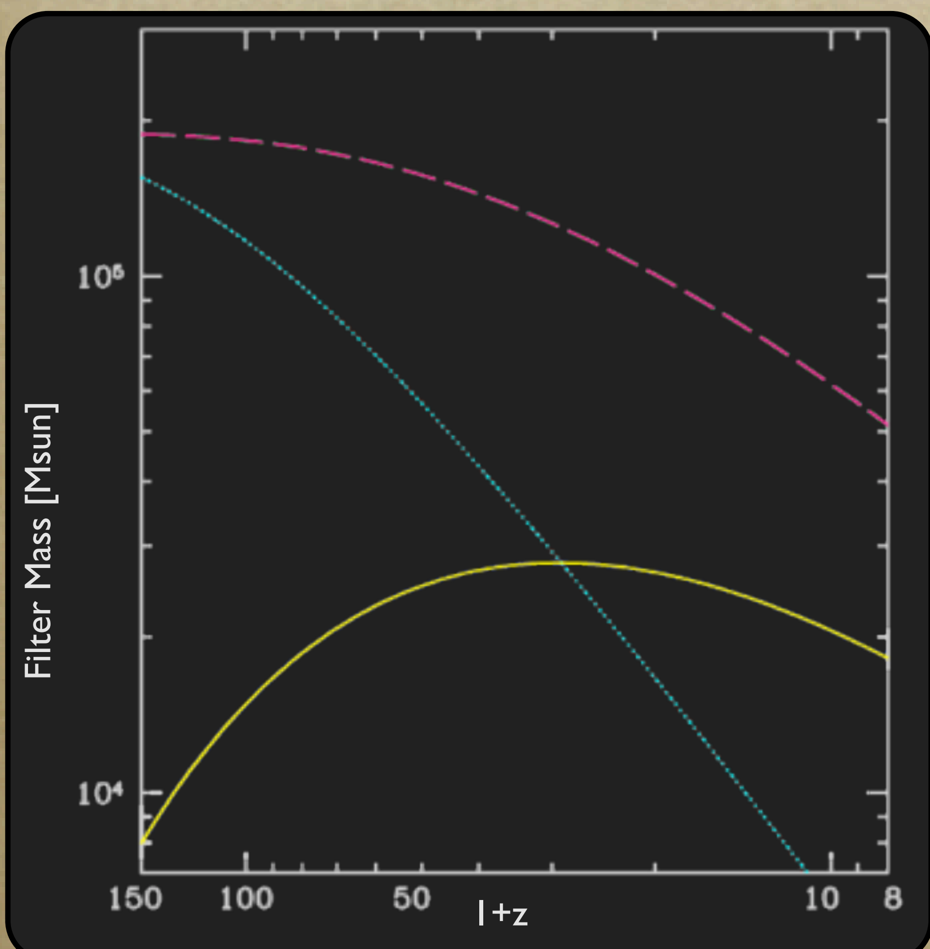
The Filtering mass:

Q: What is the minimum halo mass at which baryon overdensities can still grow?

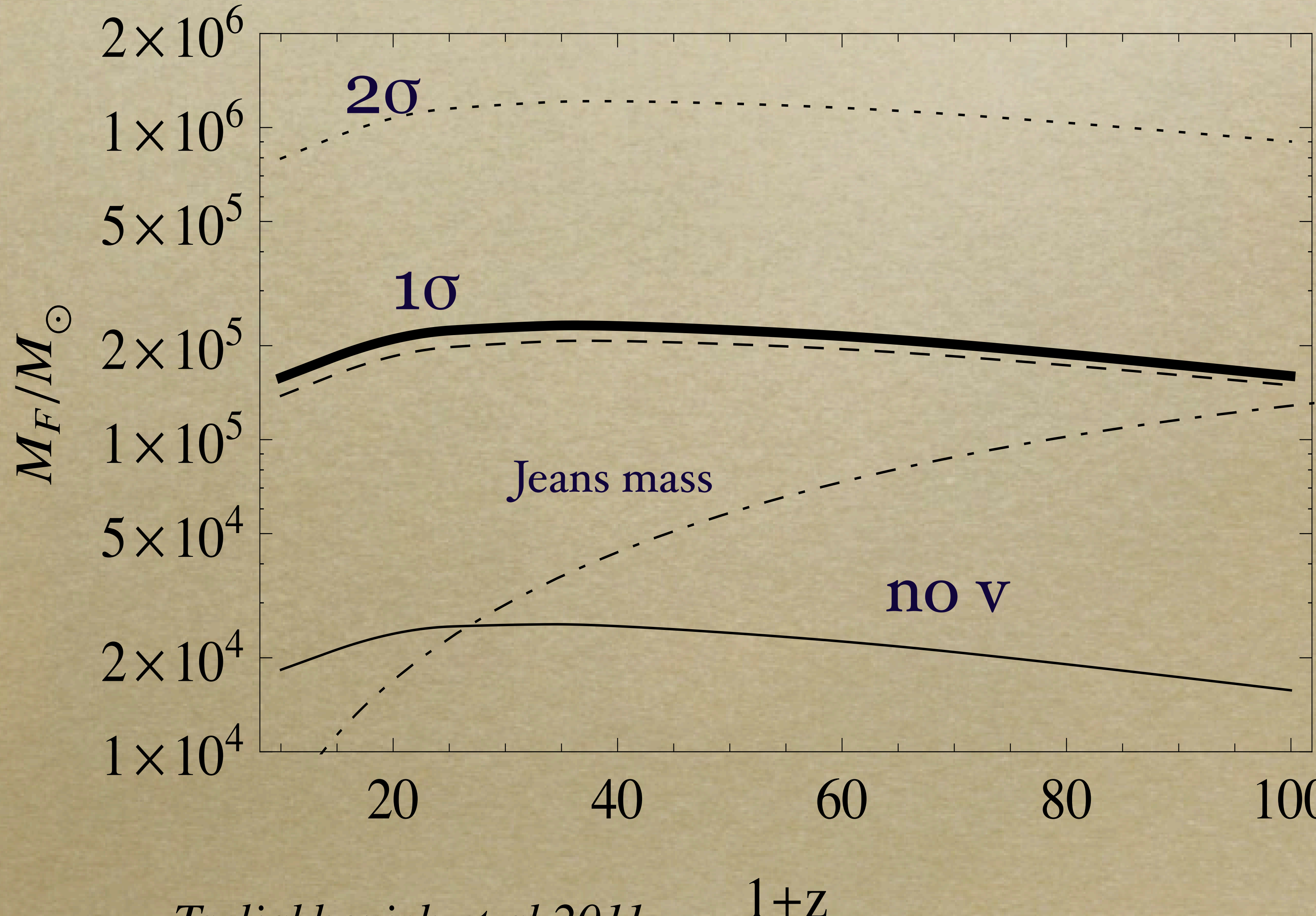
✓ Baryons overdensties are smooth compared to the dark matter $\delta_b \neq \delta_{dm}$

✓ Spatially varying speed of sound $c_s(r) \neq const$

✓ Stream velocity



Naoz & Barkana 2005,2007



Tseliakhovich et al 2011

None- Linear Regime, Stream Velocity

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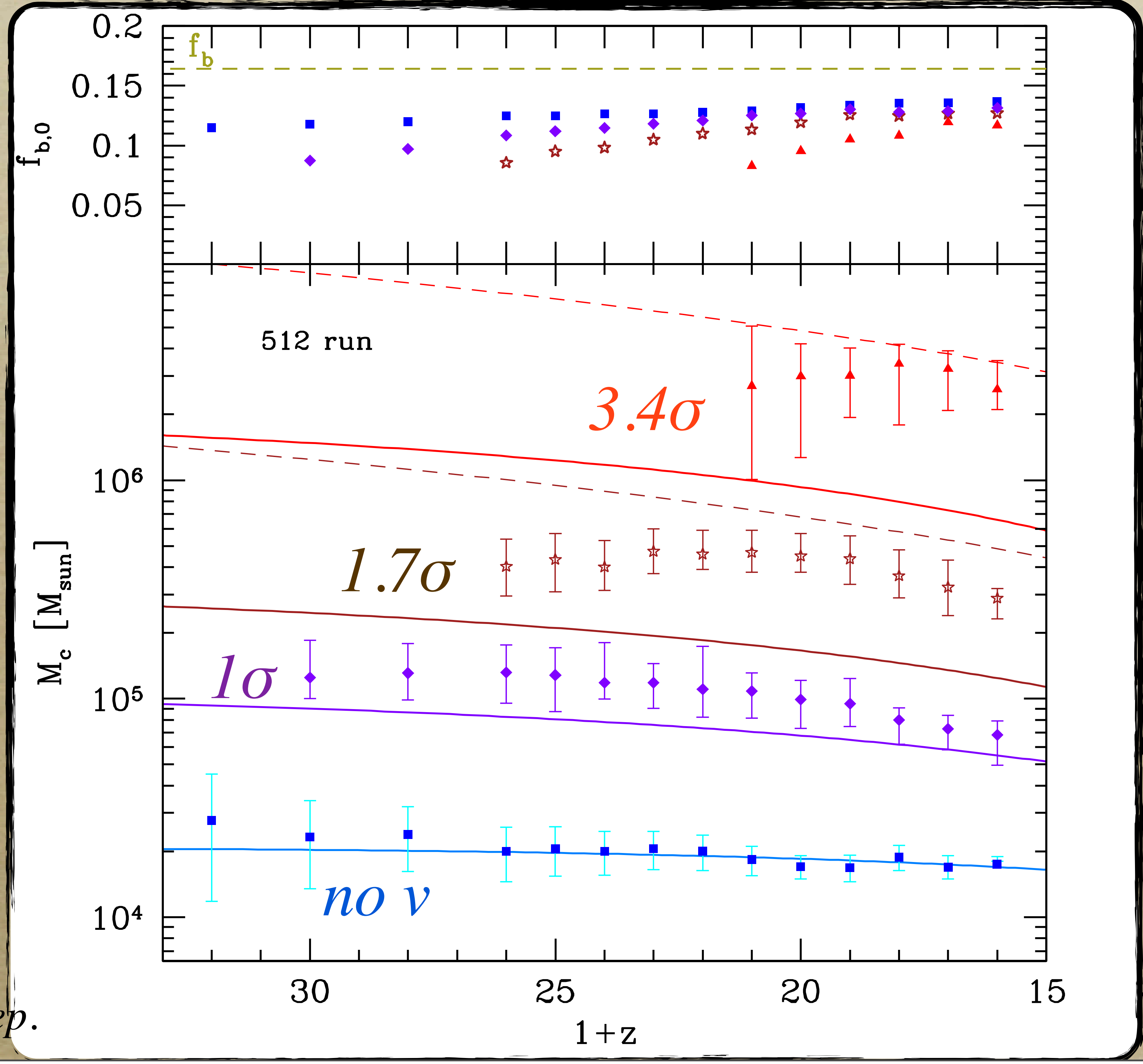

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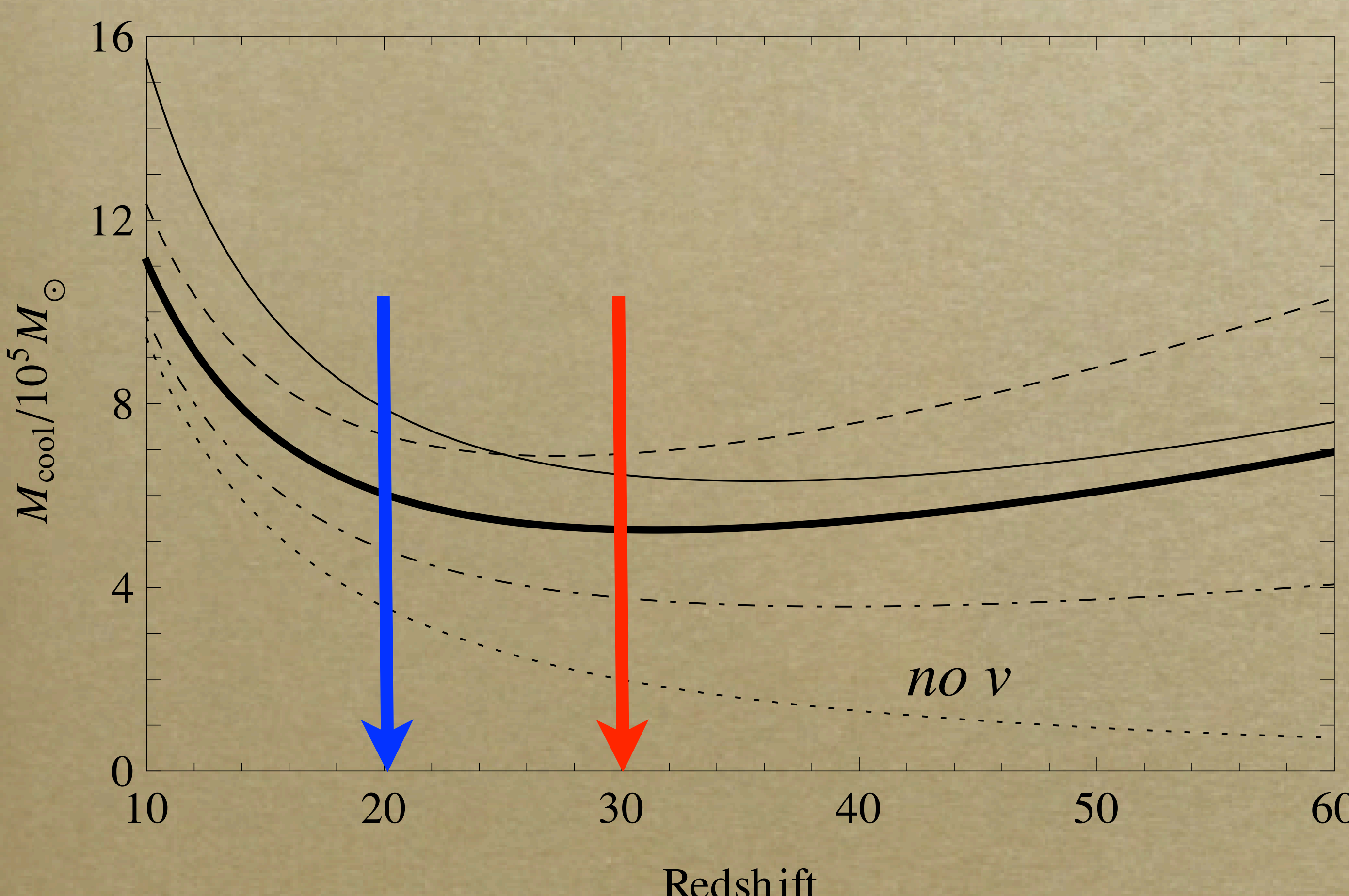
512^3 (baryons + DM)

(starting at z=199, 0.7Mpc, soft~68pc, M_{dm}~198M⊙ M_b~32.6M⊙)

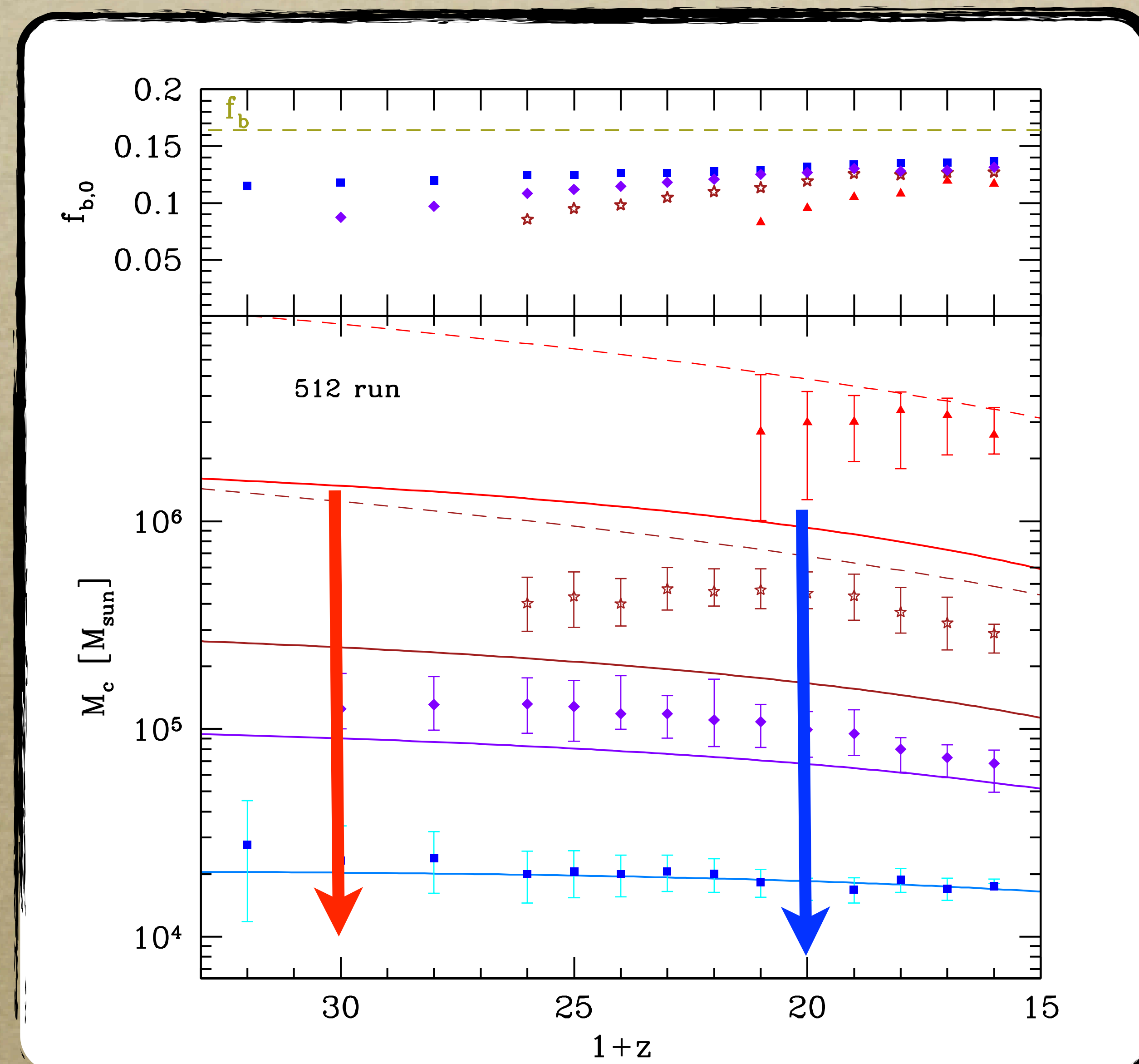
Naoz, Yoshida & Gnedin 2012b in prep.

None- Linear Regime, Stream Velocity

The Filtering mass: Vs The Characteristic mass: Vs The Cooling mass:



Fialkov, et al 2011



Naoz, Yoshida & Gnedin 2012b in prep.

The Role of Baryons

- *First order correction of the linear theory:* $c_s(r)$ + $\delta_{dm} \neq \delta_b$ *at time of recombination*

    - *Effect the power spectrum:* $c_s(r) = Const. \Rightarrow$ *underestimate the baryons, and the baryon temperature fluctuations.*

    - *Role of pressure is only moderate, and gas can accumulate on smaller halos*

- *Second order correction:* $v_b \neq v_{dm}$

    - *Suppression of small mass halos + sterile halos*