Formation of dwarf galaxies (in voids)

or

Dwarf galaxies in the Universe Why aren´t there more of them?

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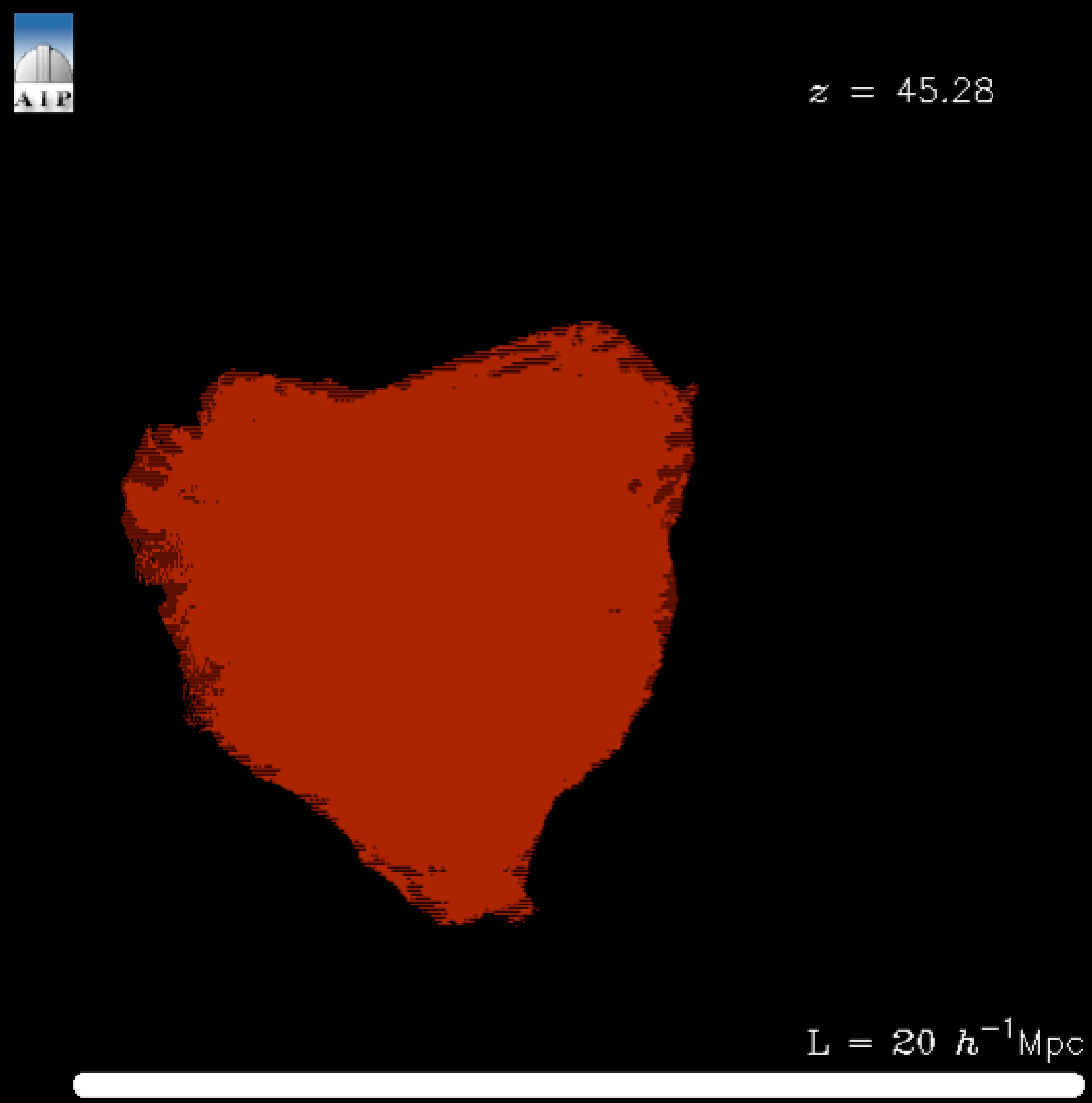
Volker Springel
Max Planck Institut für Astrophysik

Dwarf galaxies in cosmological voids?

N-Body simulations:
"Yes"

Surveys:
"No (???)"



Gottlöber et al. 2003

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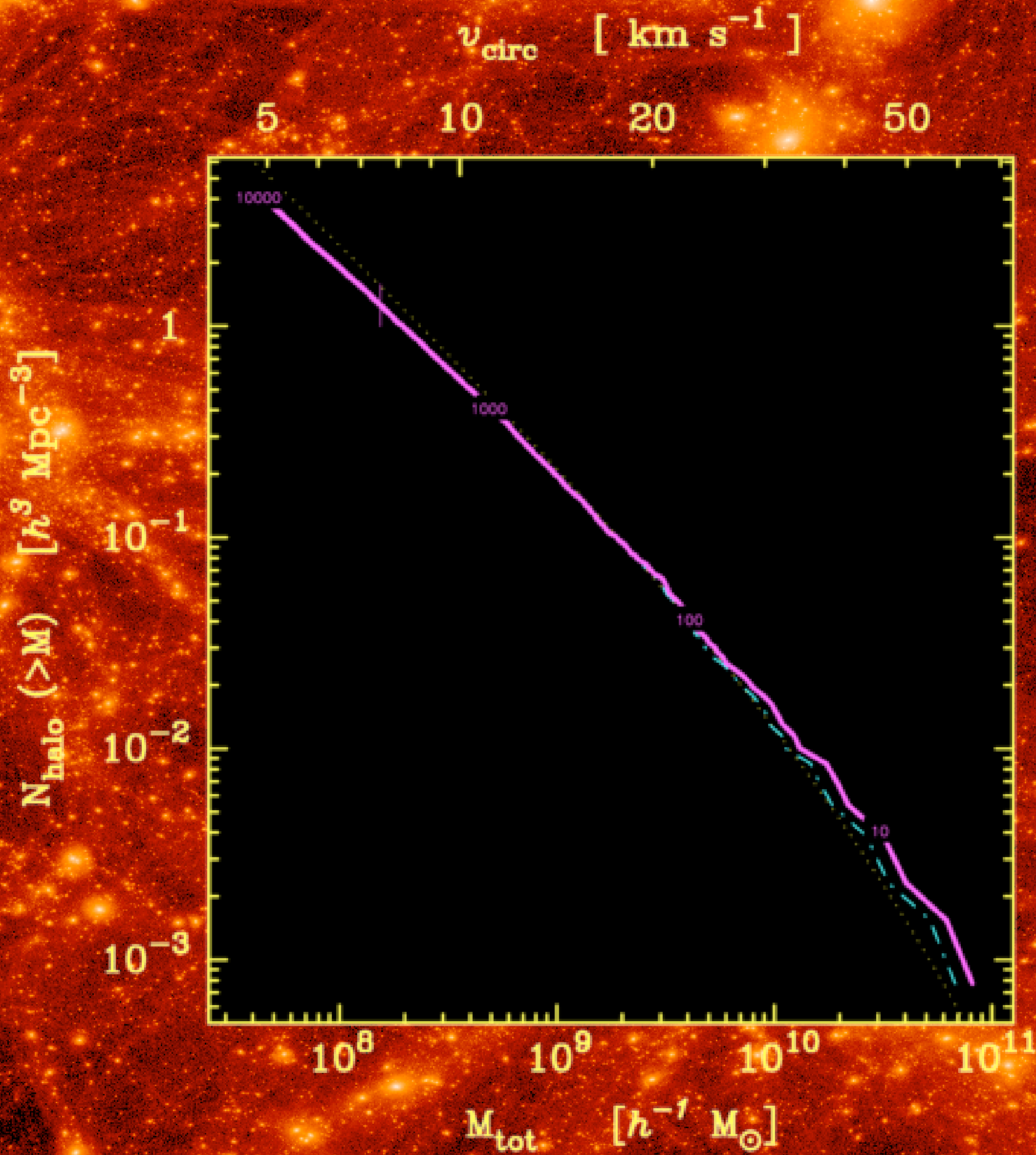
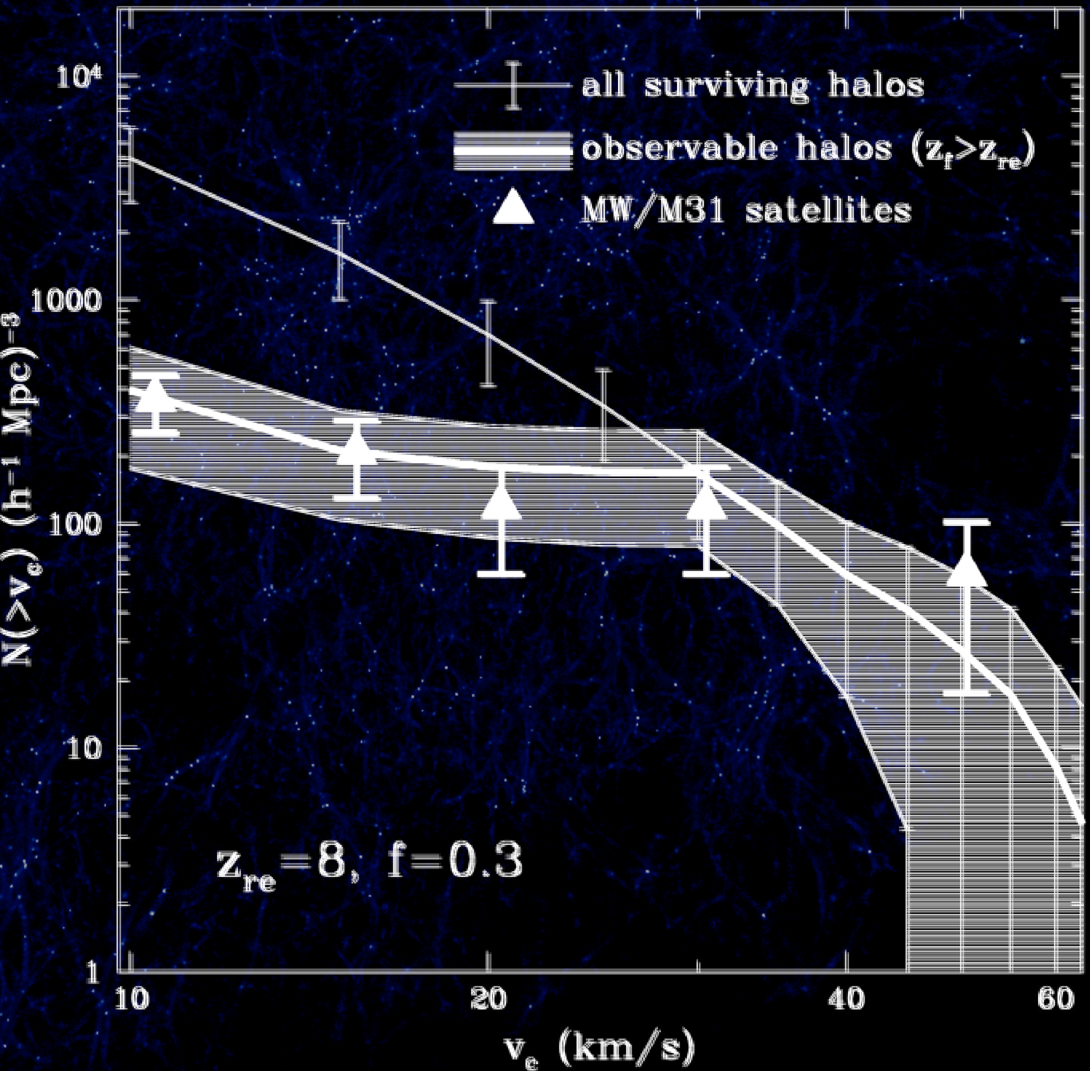
The halo mass function



infinite (?) number of small halos

Do we see all these halos?

Bullock, Kravtsov, Weinberg



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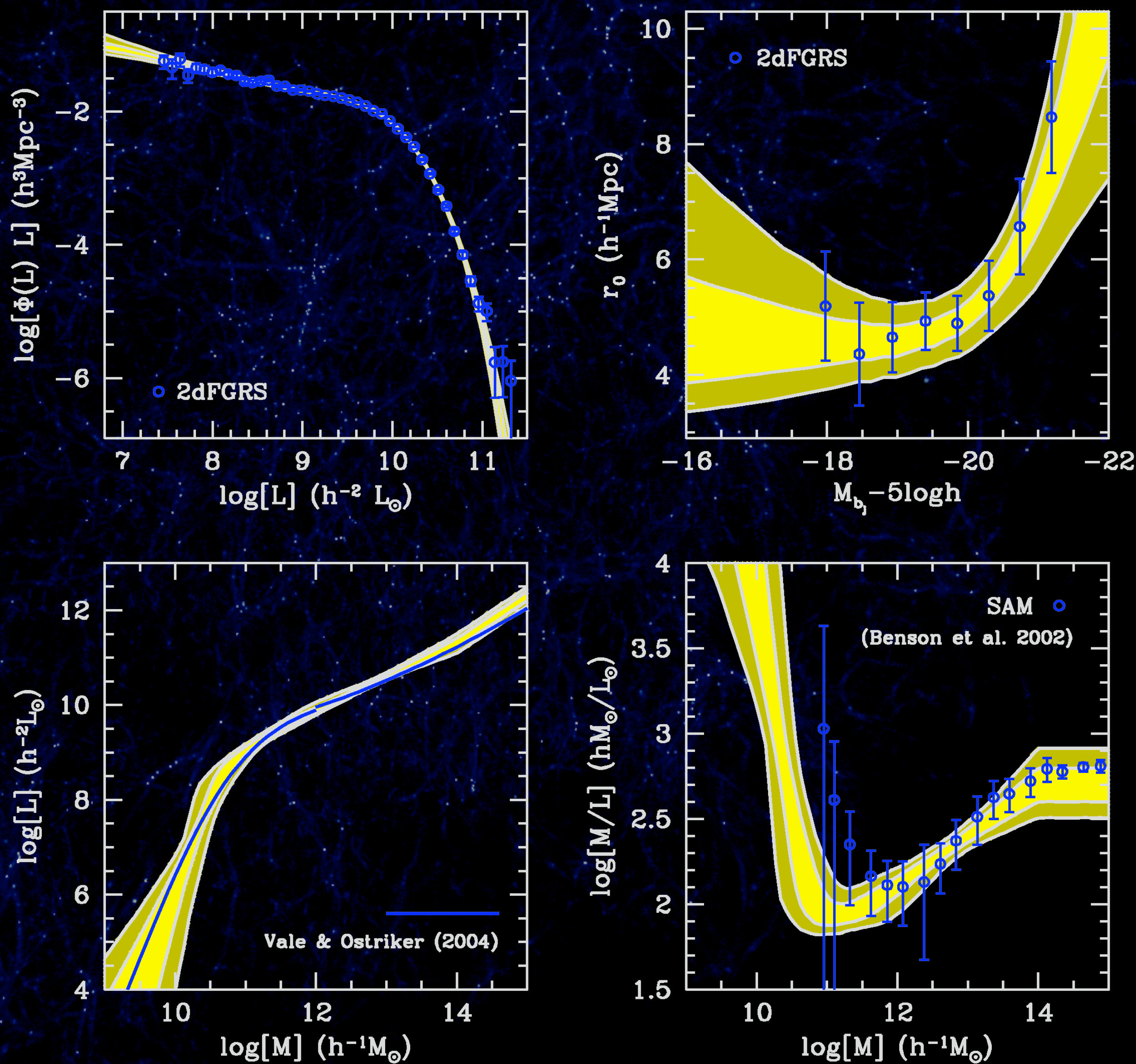
The galaxy dark matter connection

populate simulated dark matter distributions with observed galaxies



van den Bosch, Yang, Mo, 04

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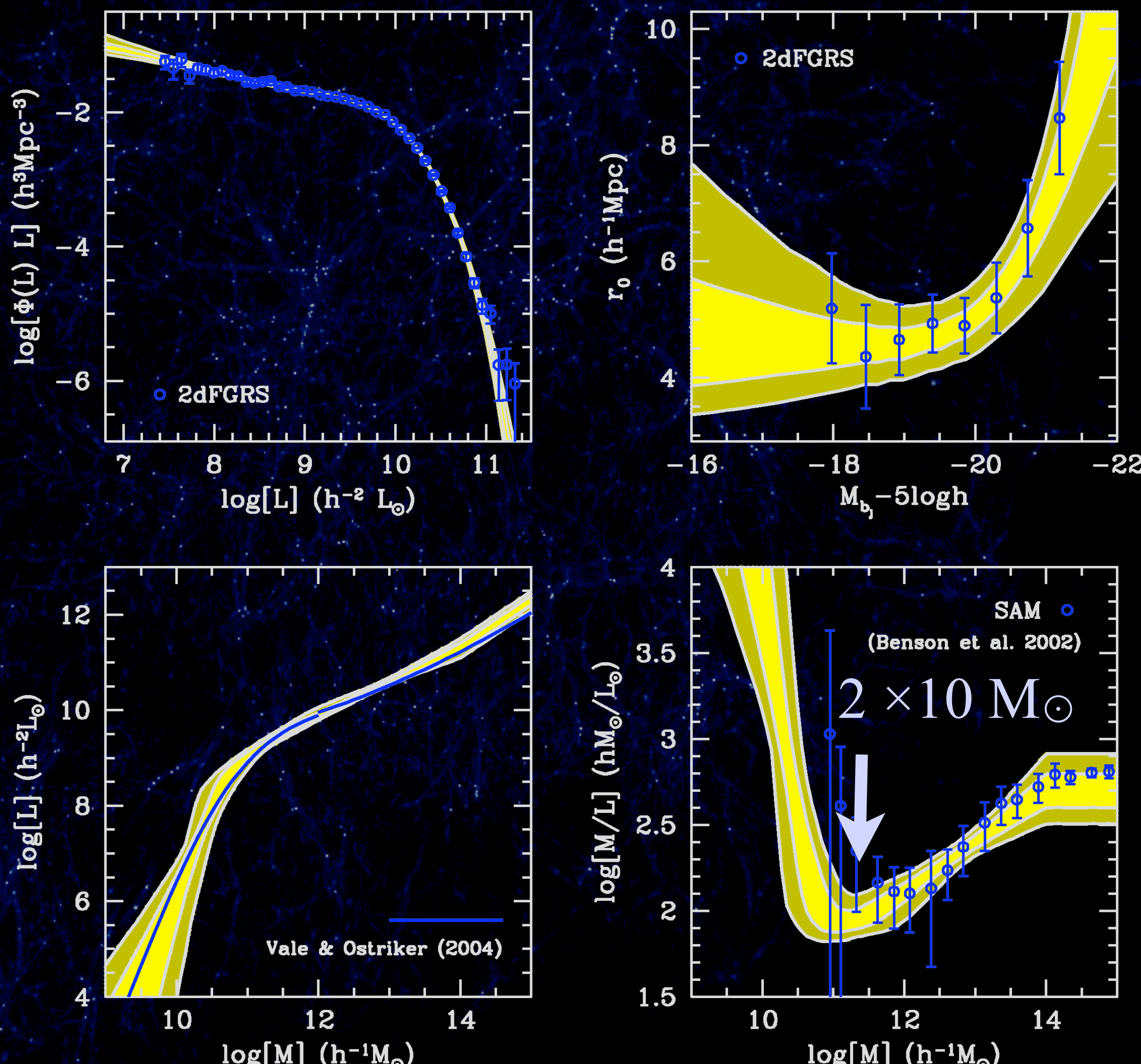

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What determines the minimum size of a galaxy?

Textbook solution: (Padmanabhan)

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$$t_{cool} < t_{grav}$$

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$nk_BT \;/\; n^2\Lambda V$ $(GM/R^3)^{-1/2}$

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Bremsstrahlung: $R = 74$ kpc

$M = 3\times10^{11}\, M_\odot$

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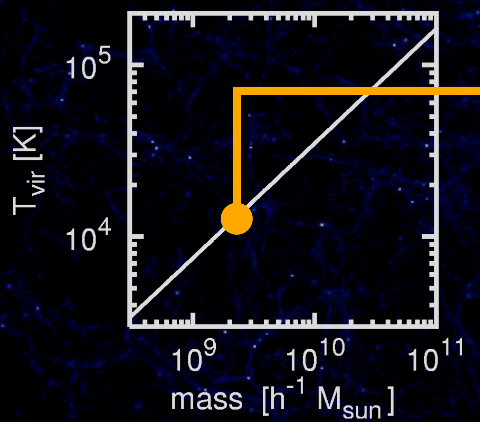
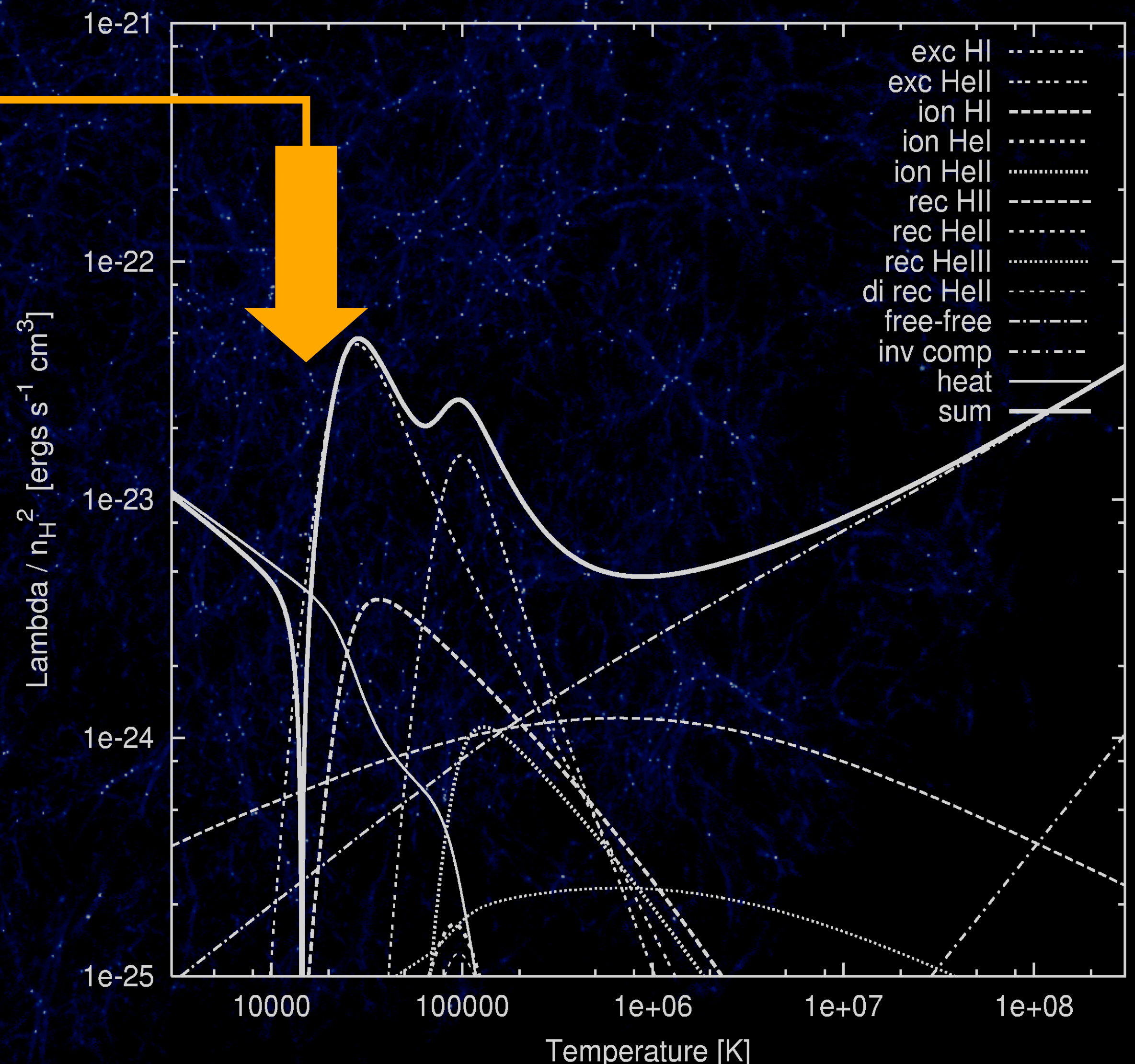
Cooling of primordial plasma





no cooling
below ~10^4 K

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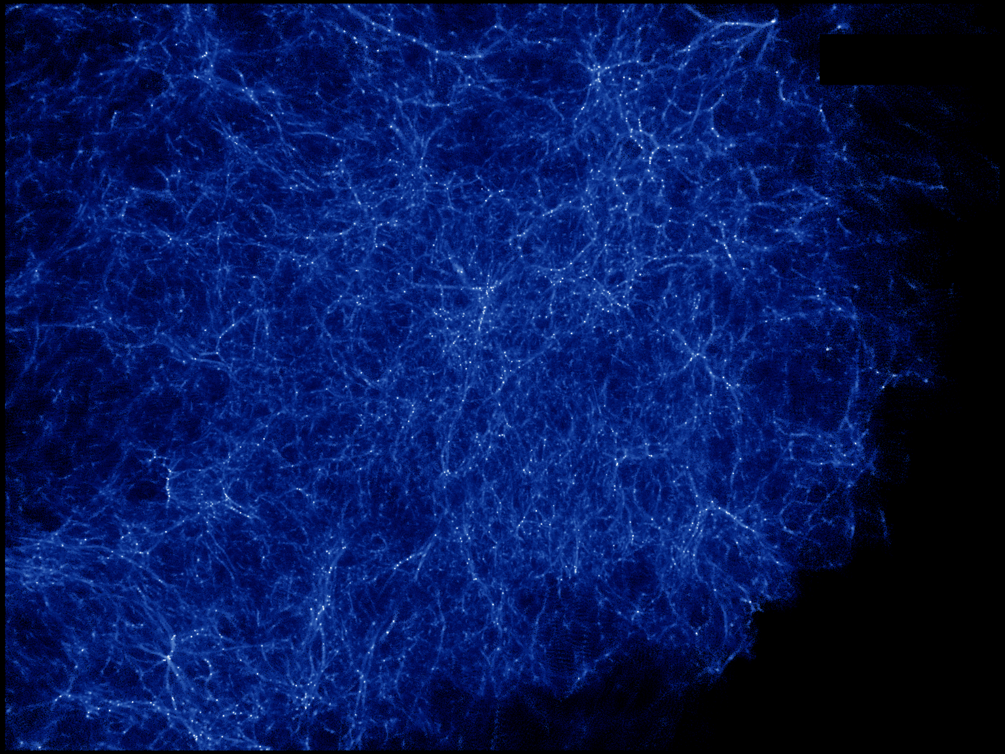
Cosmological hydrodynamical void simulation

Diameter = 16 Mpc
Ω_M = 0.03
Mass resolution (gas) ~ $2\times10^5\ h^{-1}\ M_\odot$

TreeSPH
- Gadget2

Radiative
- cooling
- UV-heating

Star formation
- subgrid model
- feedback



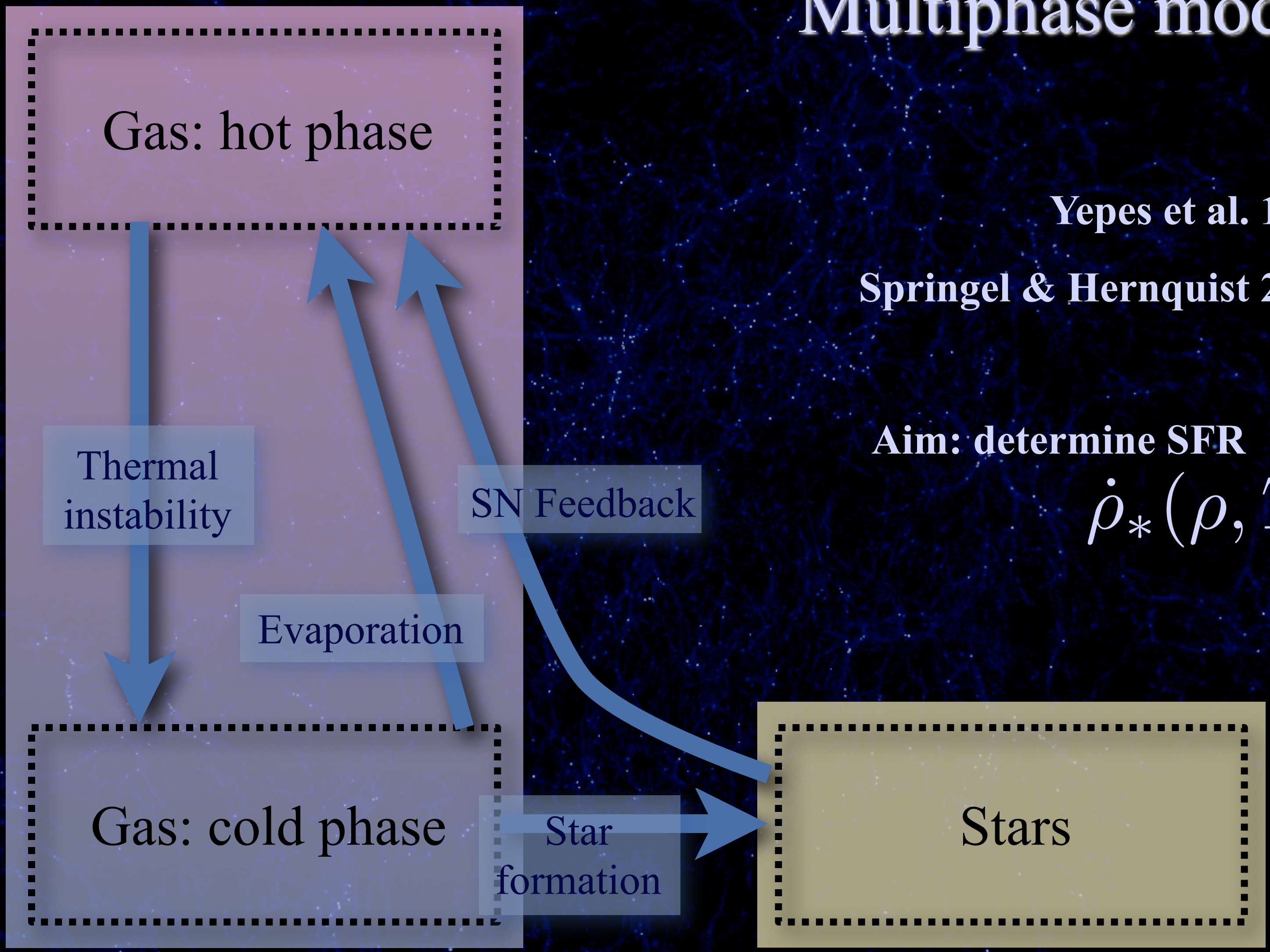
Multiphase model

Yepes et al. 1997

Springel & Hernquist 2002

Aim: determine SFR

$$\dot{\rho}_*(\rho, T)$$



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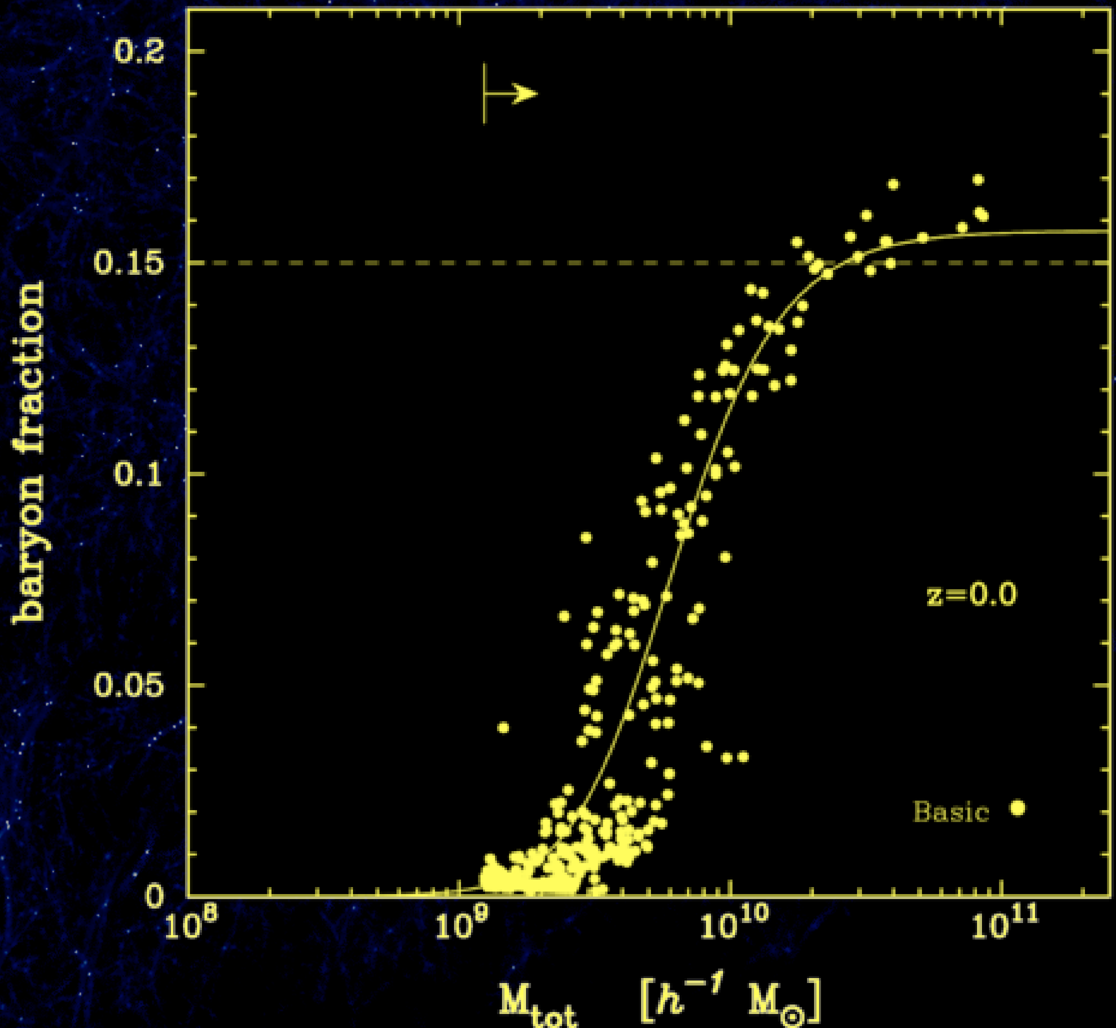
Baryon fraction

Halos below few times $10^9\ M_\odot$ are *baryon-poor*

***Characteristic mass* scale depends on redshift**



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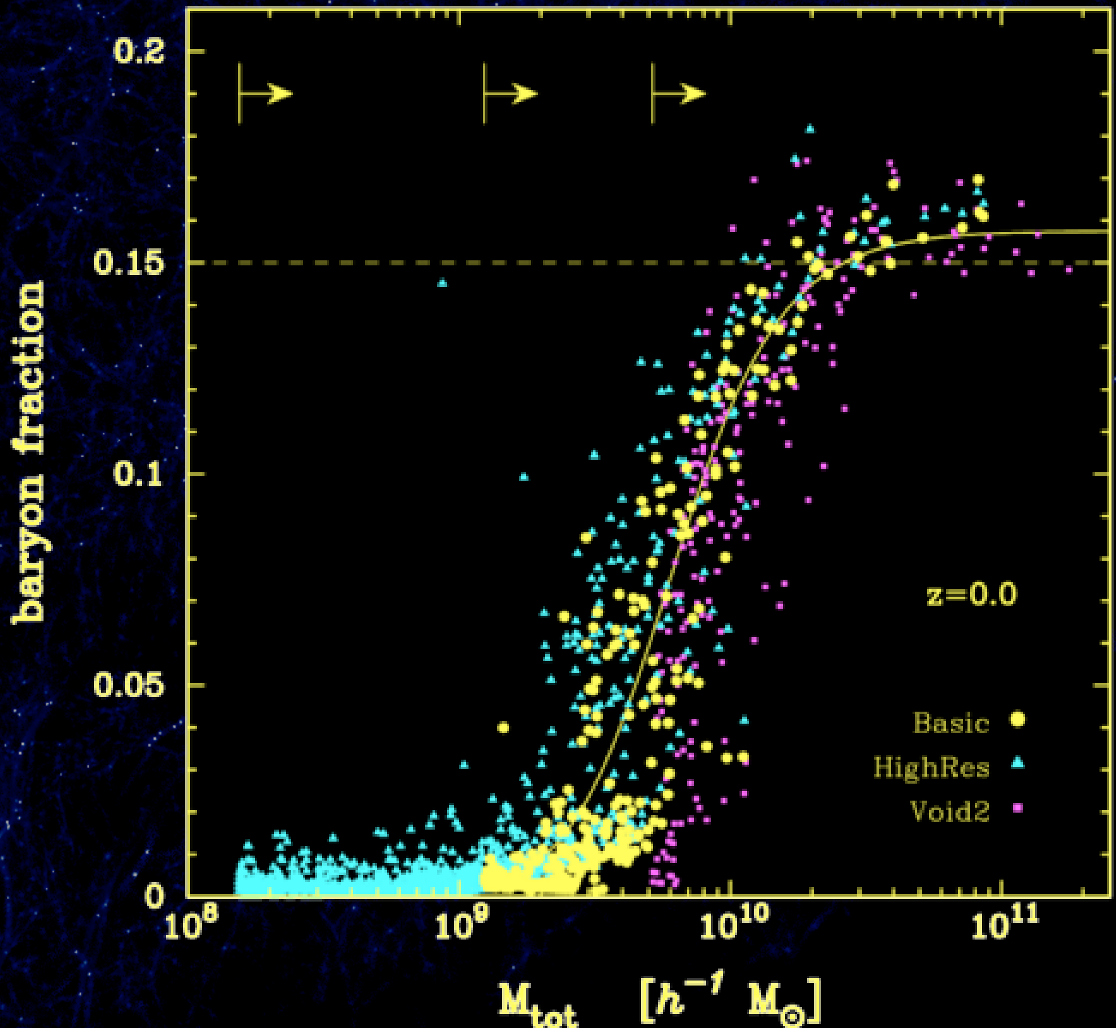

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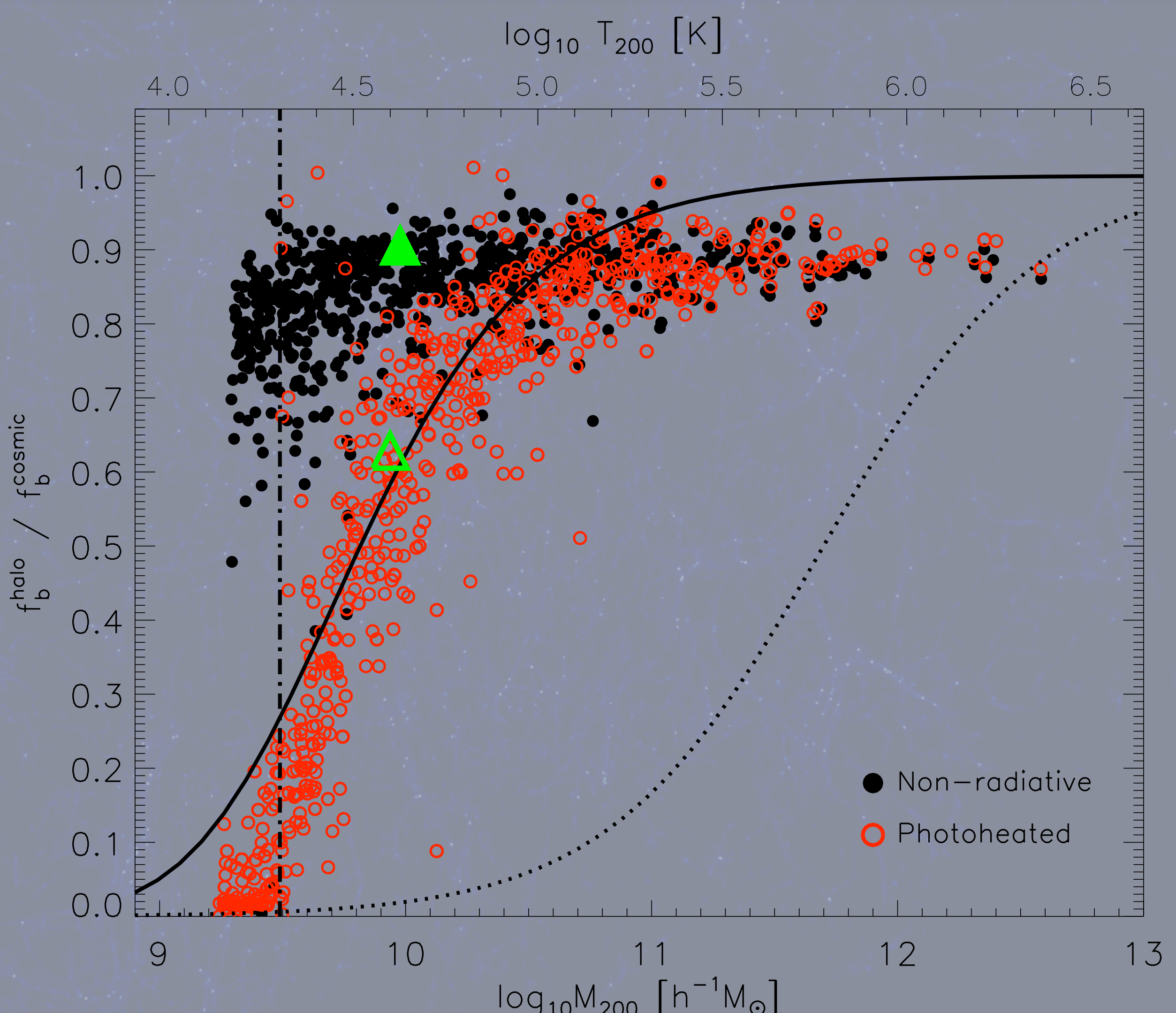
Mimic the UV-background: lower T limit



Crain
et al. 2006

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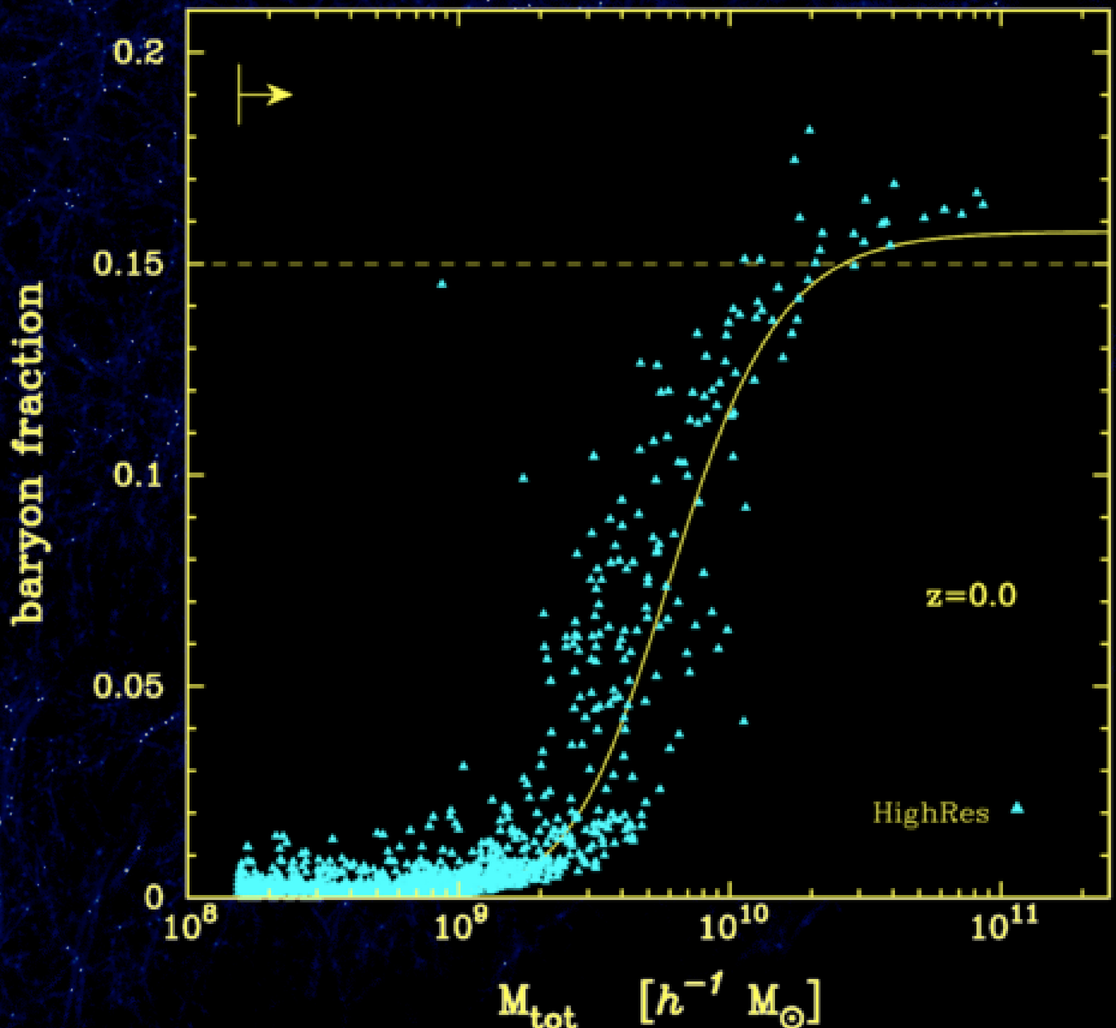
Redshift evolution of the baryon fraction

Characteristic mass **scale decreases with redshift**



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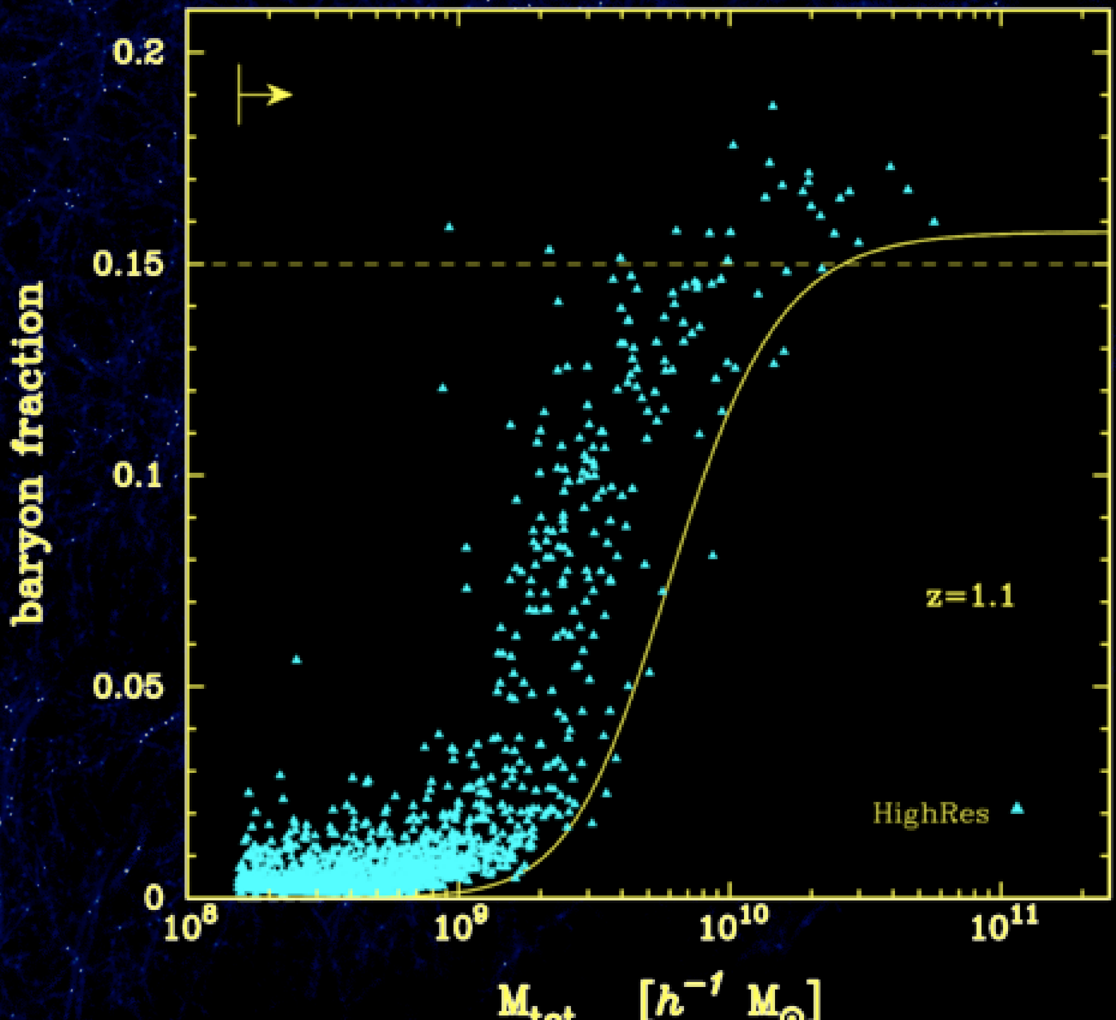

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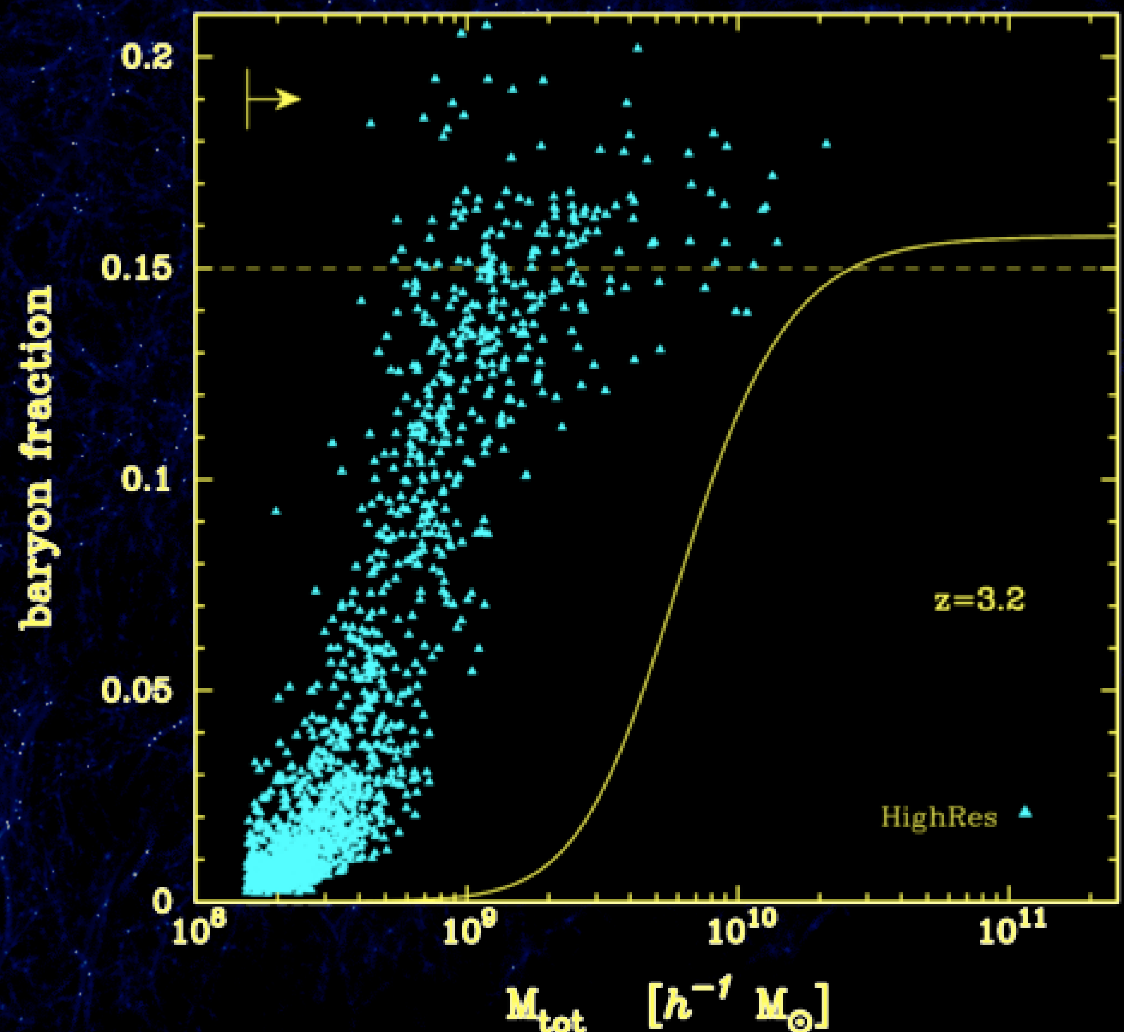

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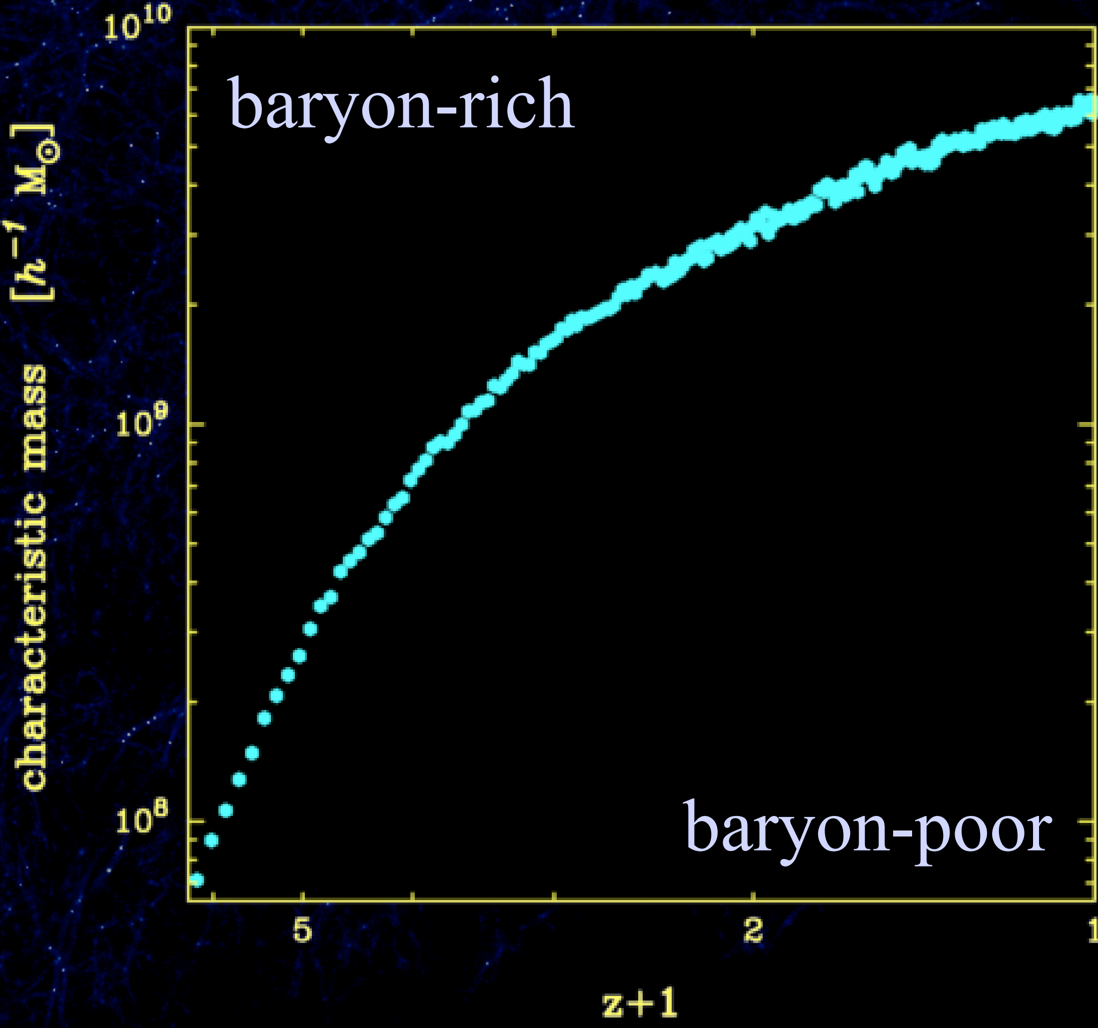
Characteristic mass M_c

M_c rises significantly with redshift

Halo may start baryon-rich and become later baryon-poor



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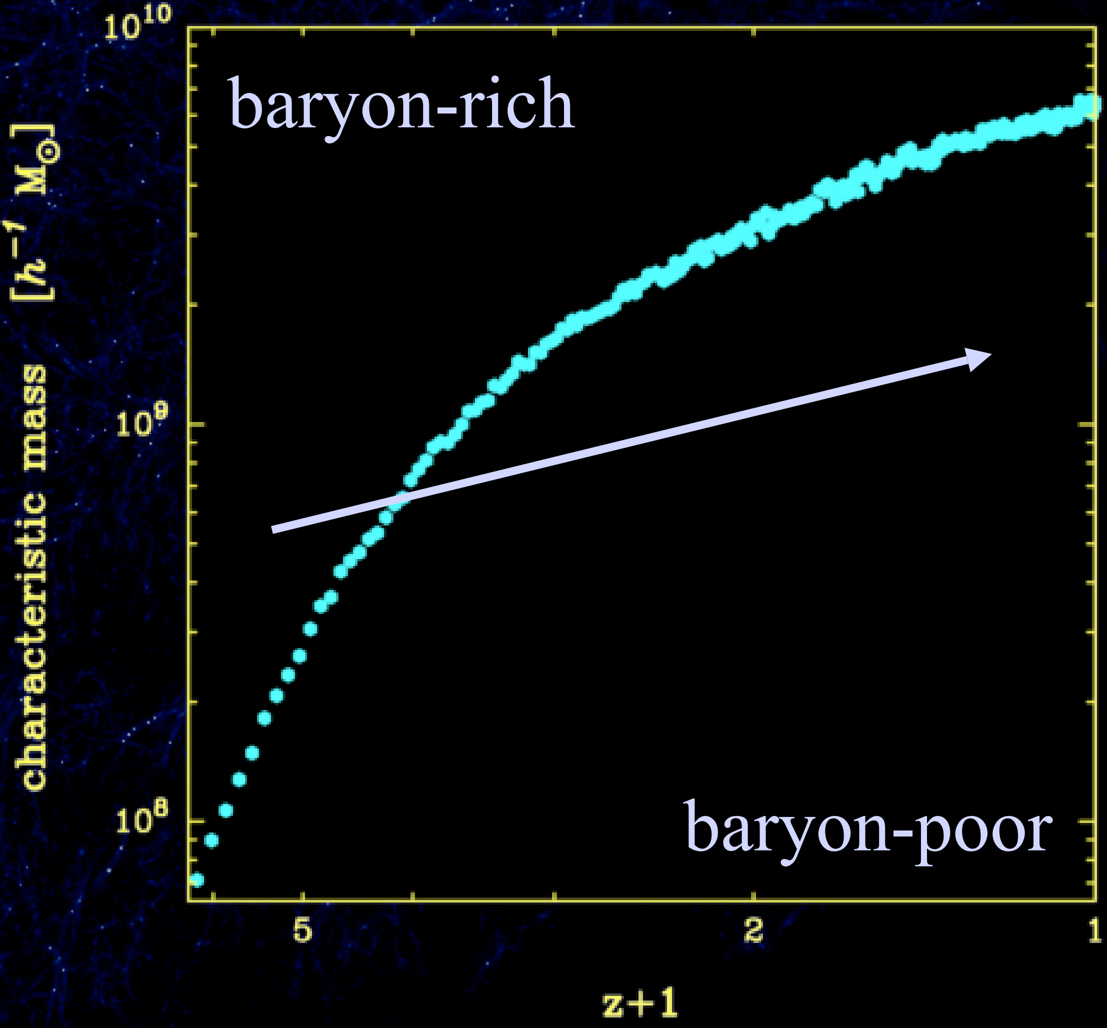

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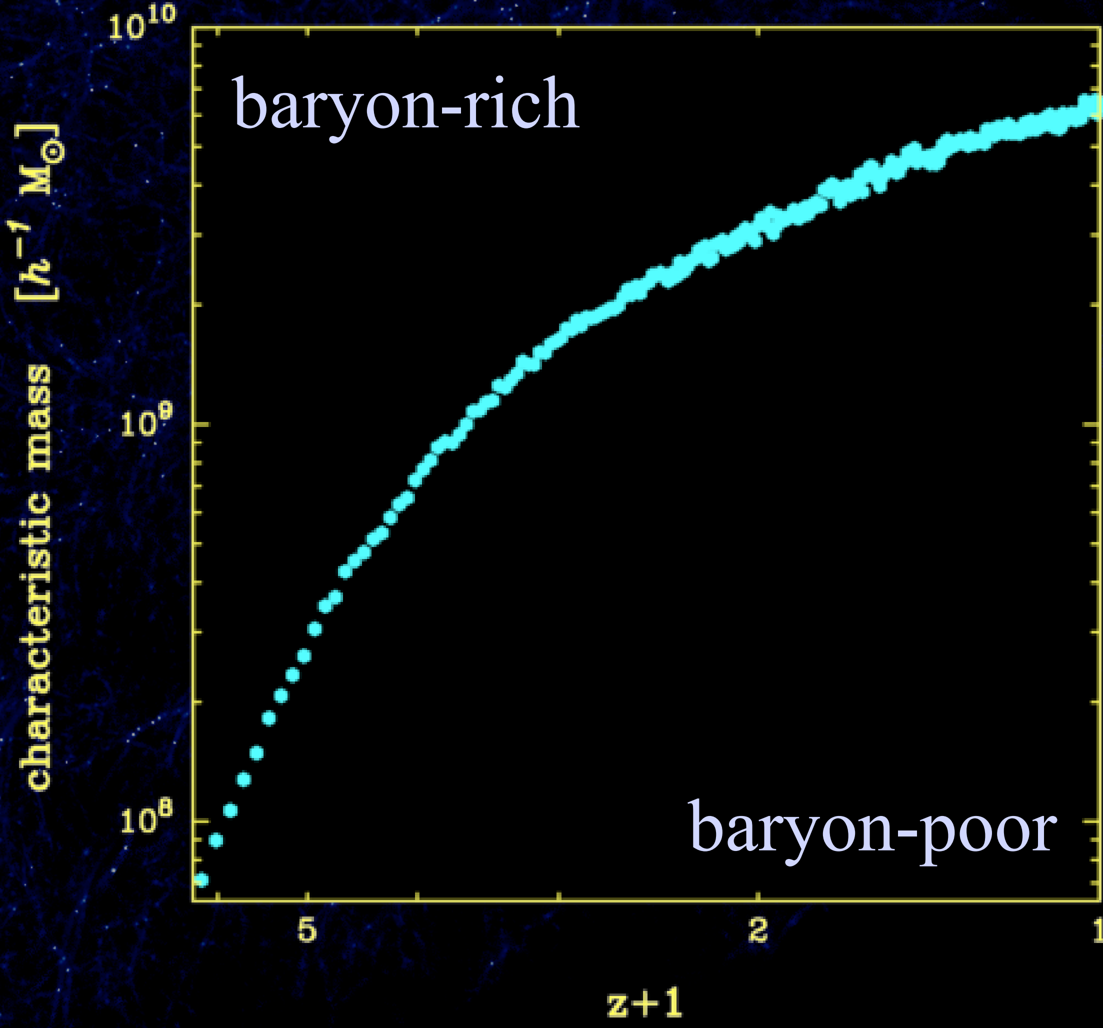

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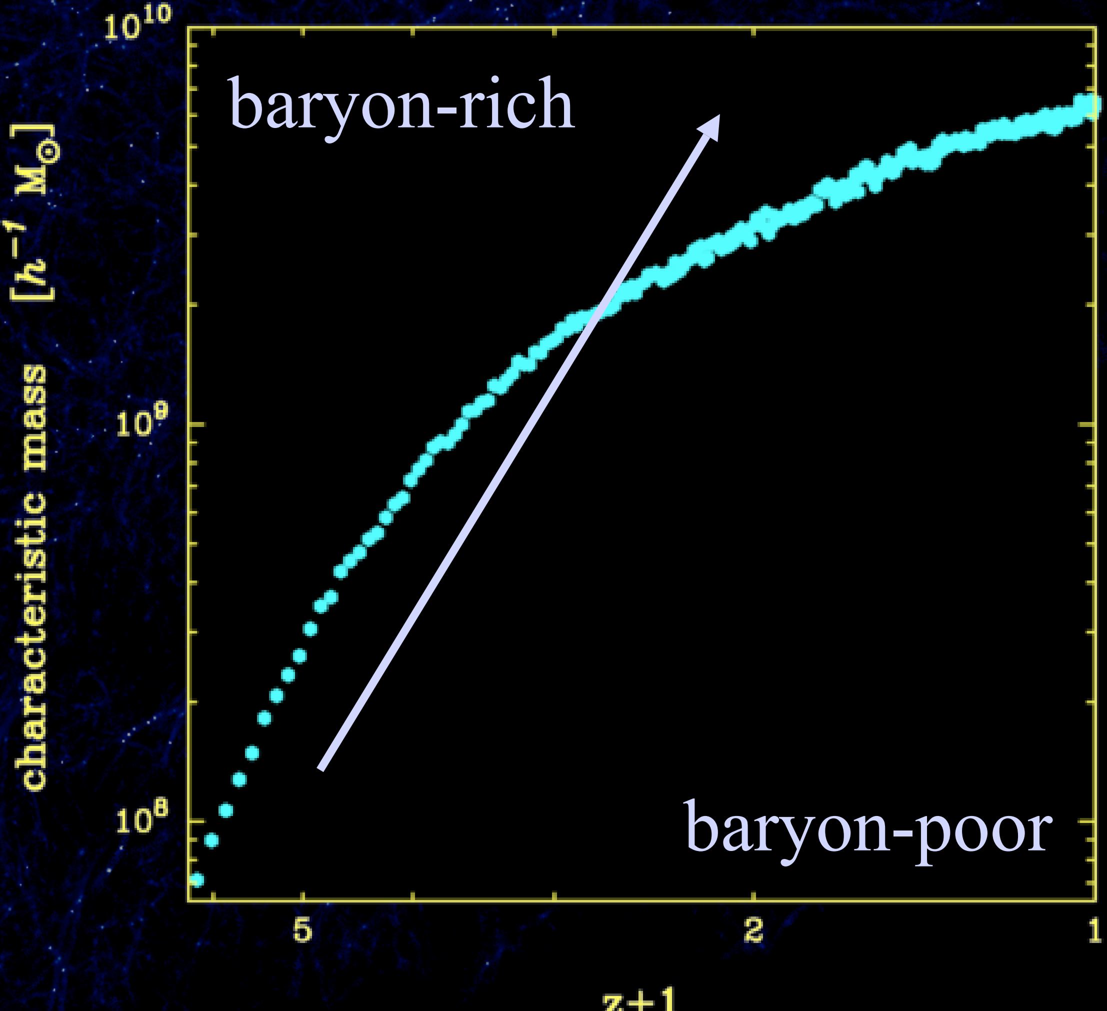

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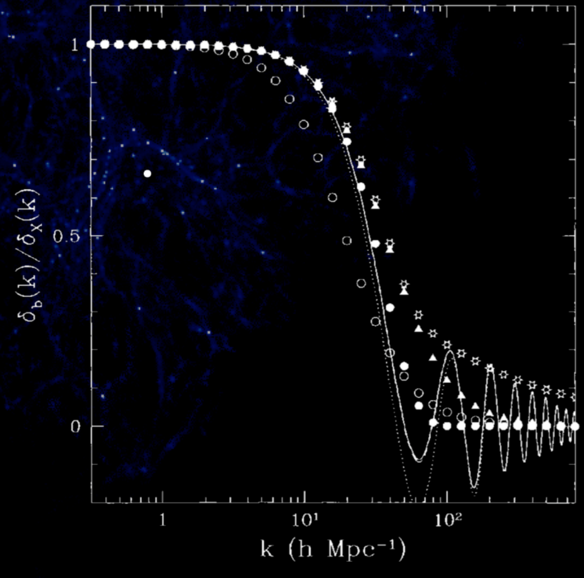
Filtering Mass

$$\frac{\mathrm{d}^2\delta_X}{\mathrm{d}t^2} + 2H\frac{\mathrm{d}\delta_\mathrm{X}}{\mathrm{d}t} = 4\pi G\bar{\rho}(f_\mathrm{X}\delta_\mathrm{X} + f_\mathrm{b}\delta_\mathrm{b})$$

$$\frac{\mathrm{d}^2\delta_\mathrm{b}}{\mathrm{d}t^2} + 2H\frac{\mathrm{d}\delta_\mathrm{b}}{dt} = 4\pi G\bar{\rho}(f_\mathrm{X}\delta_\mathrm{X} + f_\mathrm{b}\delta_\mathrm{b}) - \frac{c_\mathrm{S}^2}{a^2}k^2\delta_\mathrm{b}$$

$$\frac{\delta_b}{\delta_X} = 1 - \frac{k^2}{k_F^2}$$



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Gnedin & Hui 1997

Filtering mass (cont.)

$$\frac{1}{k_{\rm F}} = \frac{3}{2}\Omega_0 \frac{1}{D(a)} \int_0^a da' \frac{D}{S\, a' k_{\rm J}^2} \int_{a'}^a da'' \frac{1}{a''^2 S}$$

$$S^2 = 1 + \Omega_0(1/a - 1) + \Omega_\Lambda(a^2 - 1)$$

$$c_{\rm s}^2 = \frac{3}{5} \frac{k_{\rm B} \langle T \rangle_{\rm something}}{\mu m_{\rm p}}$$

$$M_{\rm F} = \frac{4\pi}{3}\, \rho \, \left(\frac{2\pi a}{k_{\rm F}}\right)^3$$

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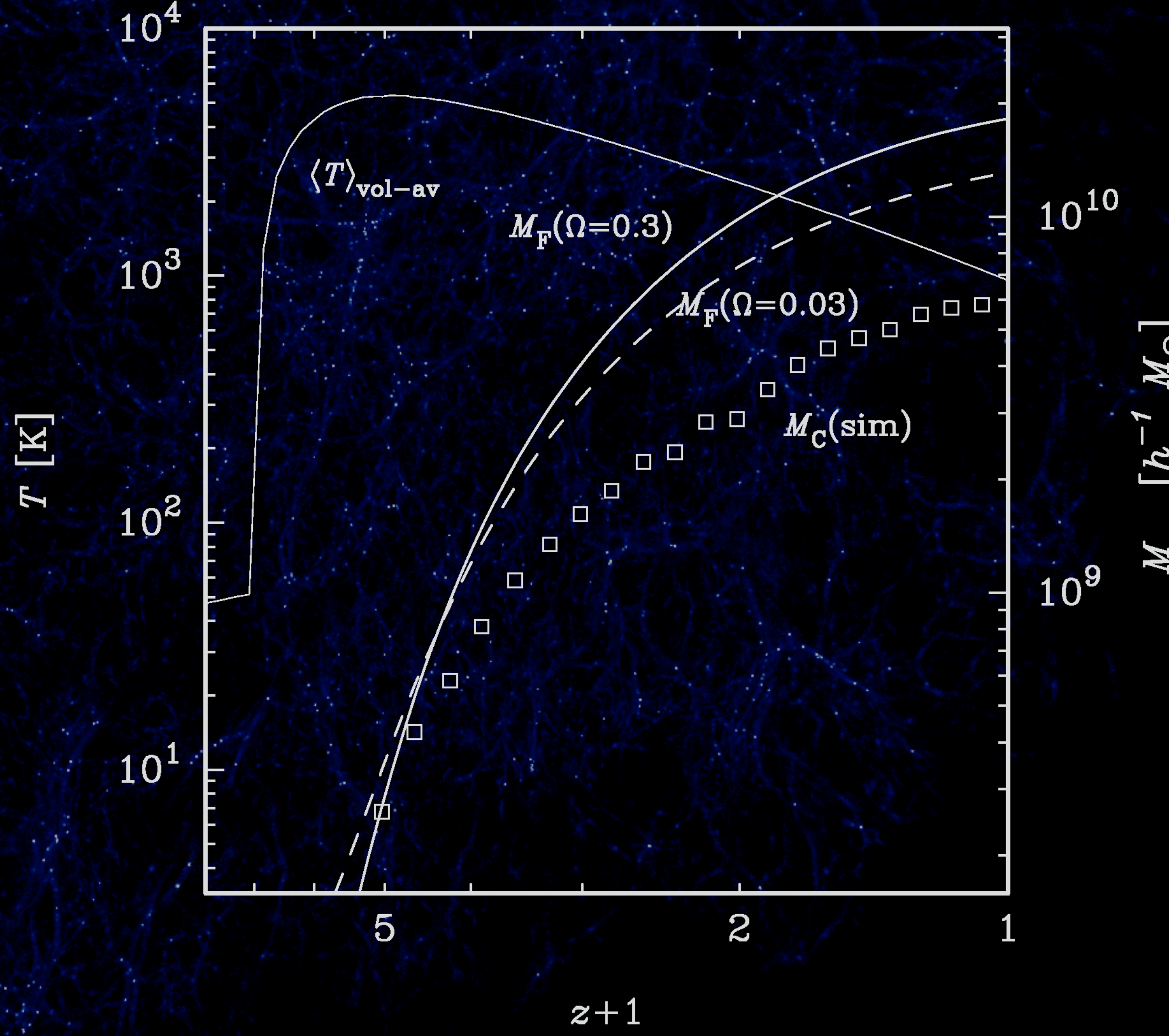
Filtering mass (final)



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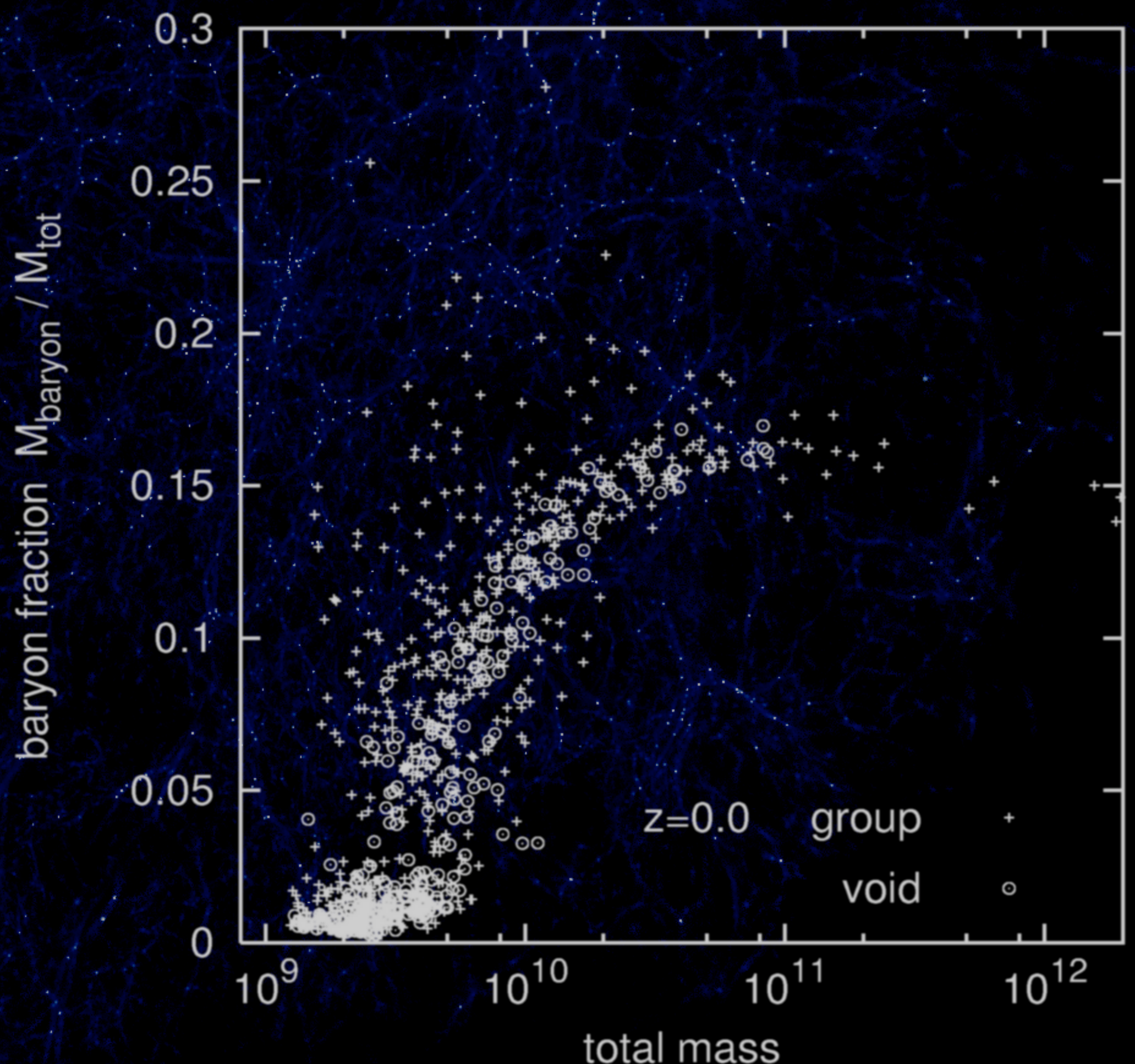
Baryon fraction: Void + Group

In dense environments the characteristic mass corresponds to that in void regions



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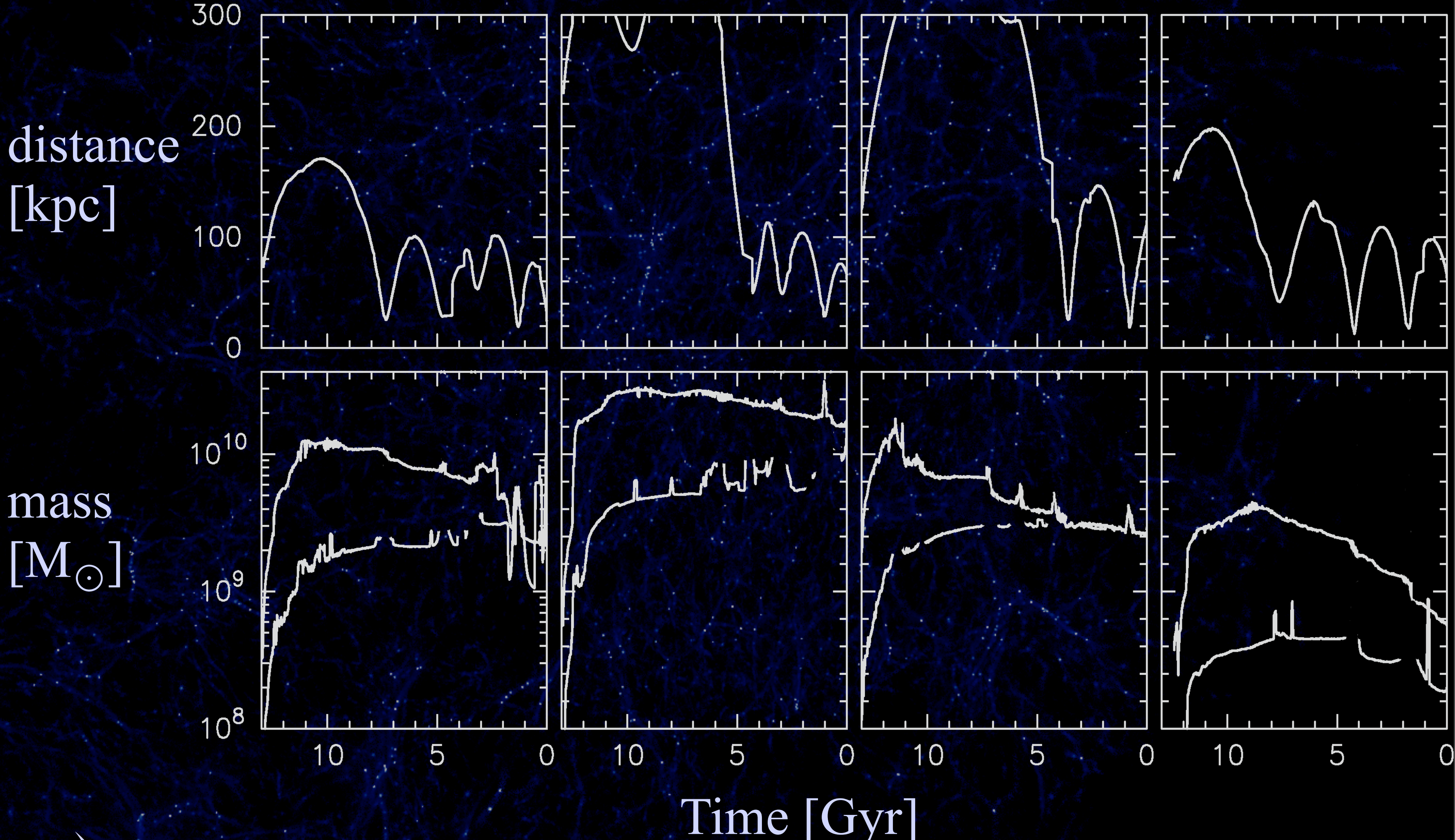
Tidal stripping with cool gas + stars



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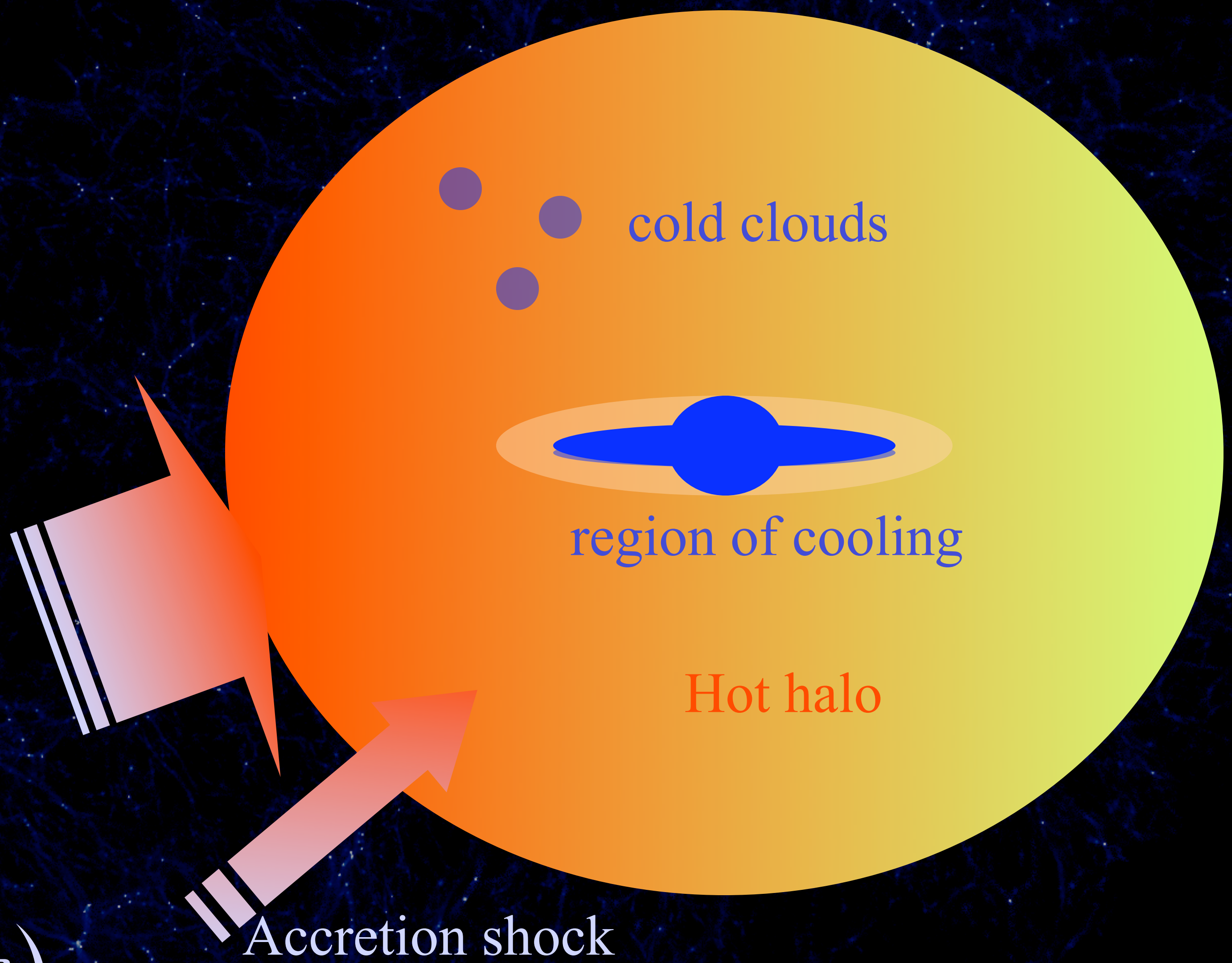
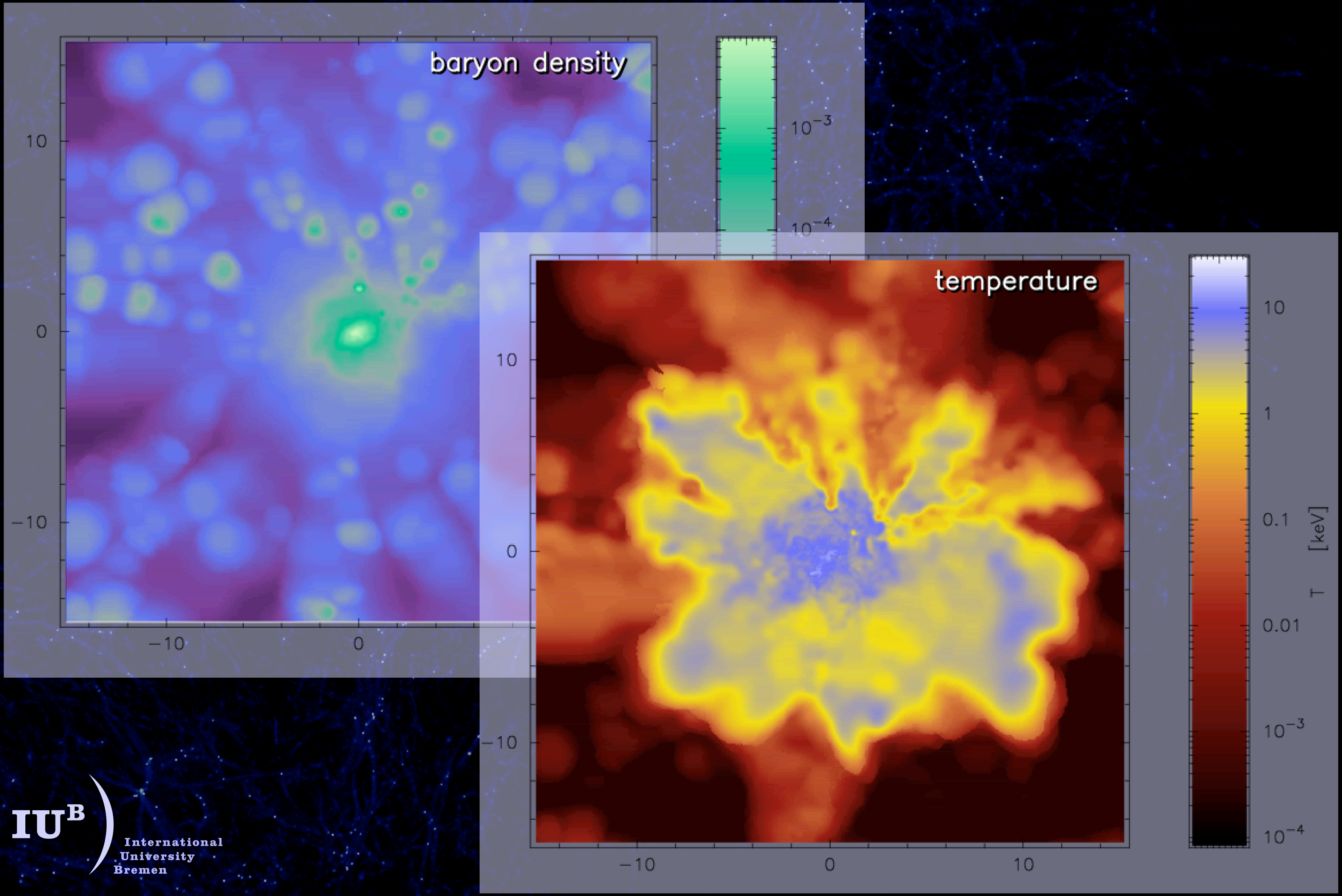
Gas accretion, schematically



... more realistically shaped



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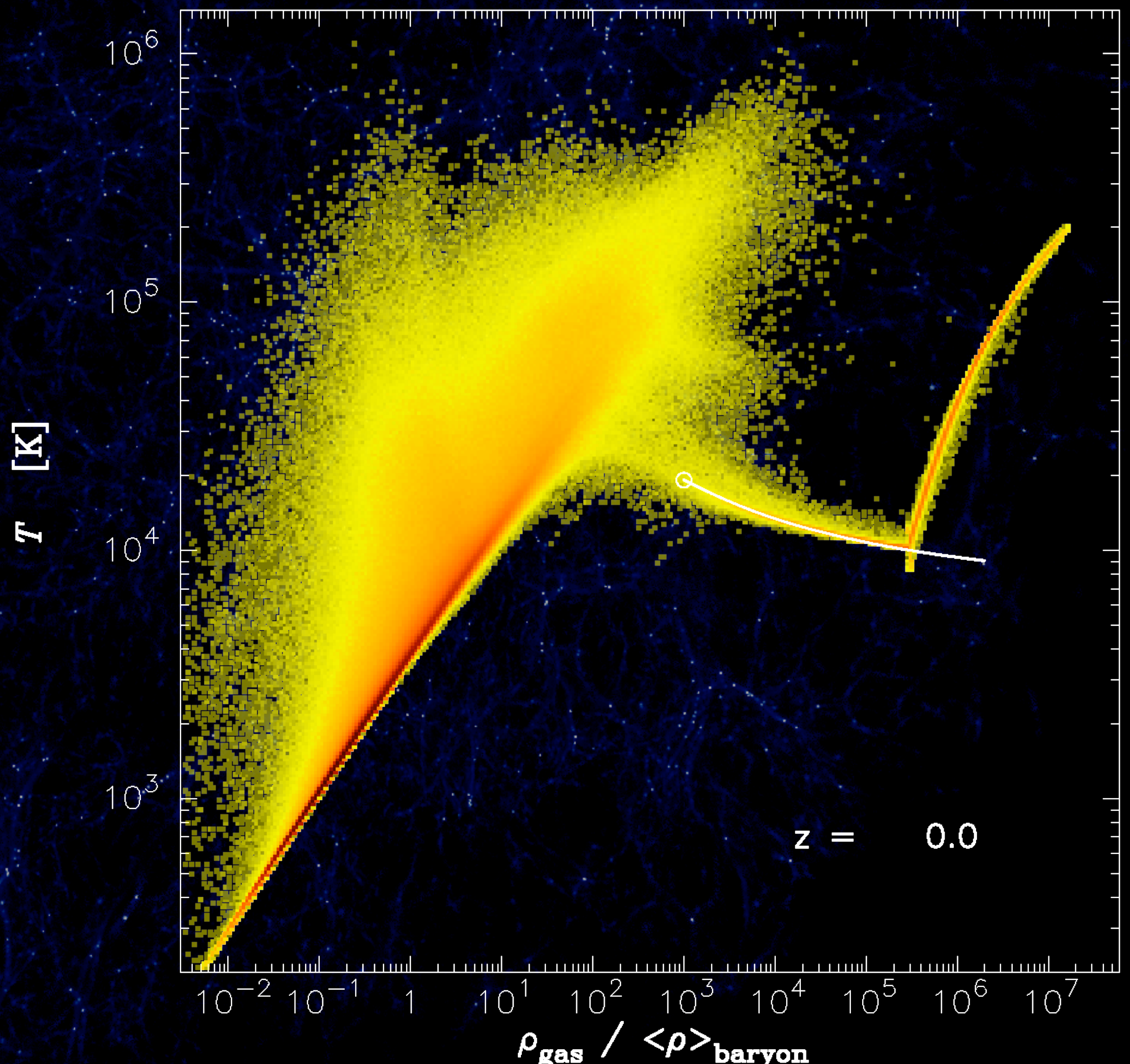
Gas accretion, in density temperature space

"Cold mode" (Keres et al. 04) of galactic gas accretion: gas creeps along the equilibrium line between heating and cooling



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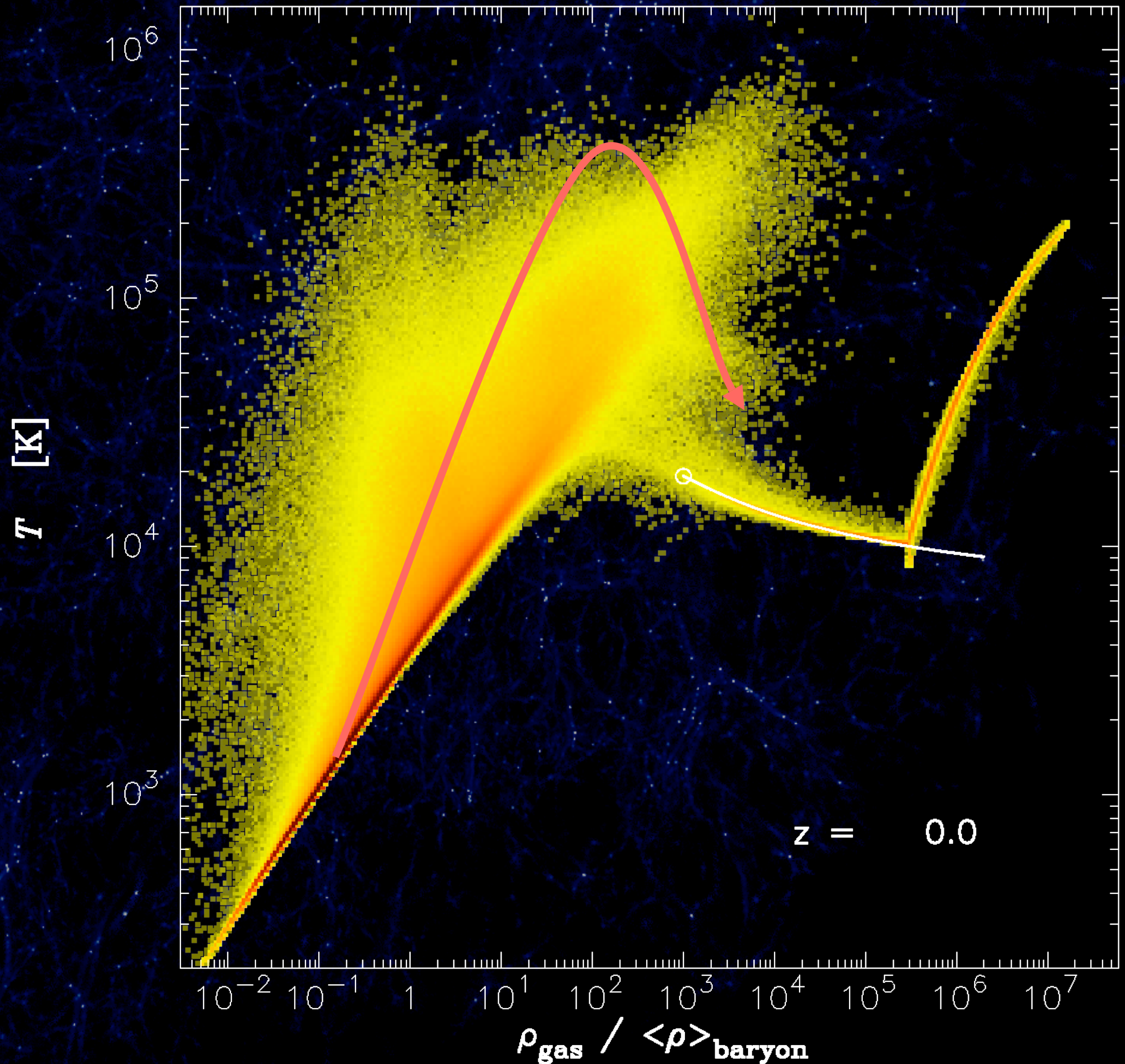

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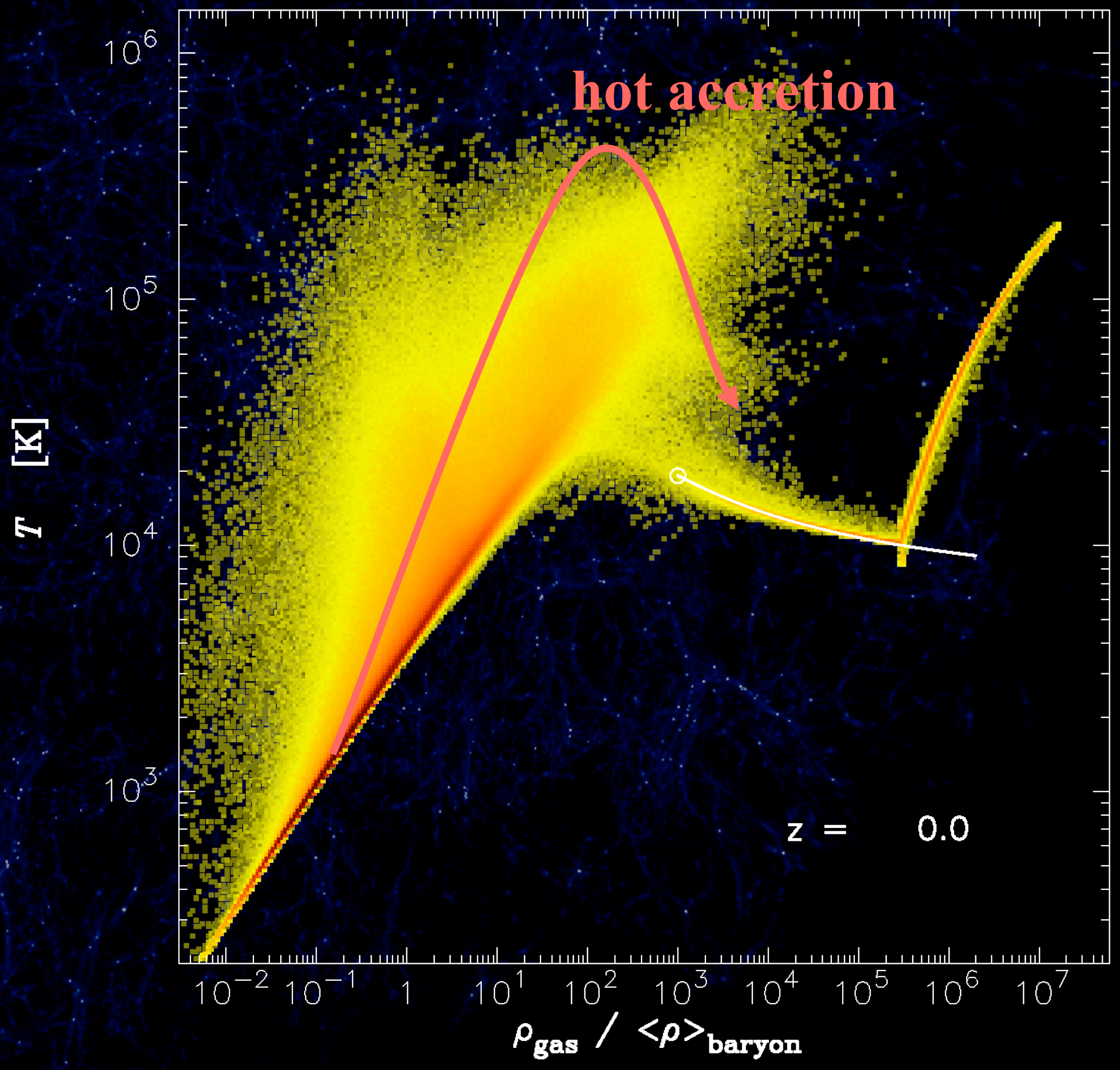

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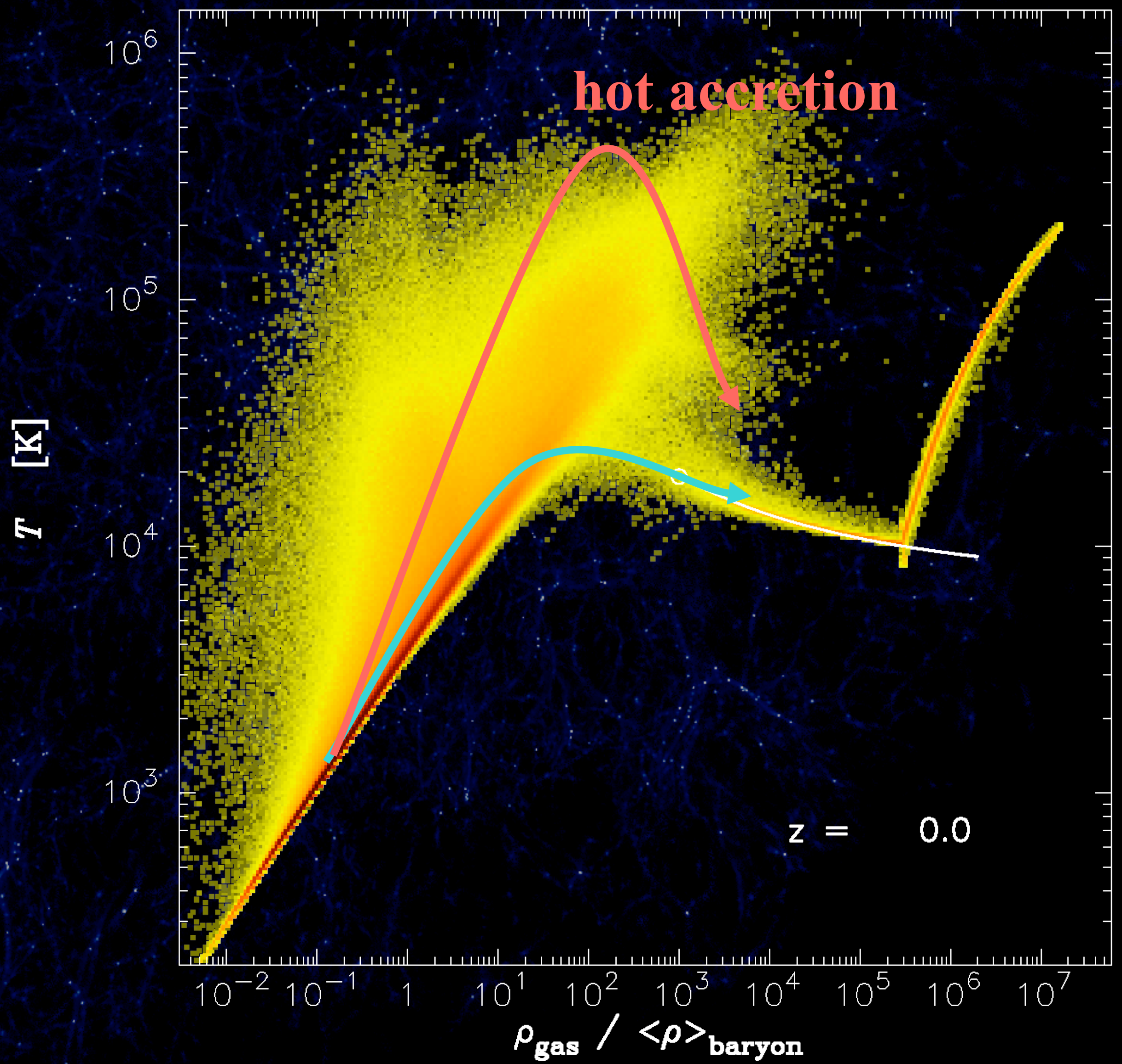

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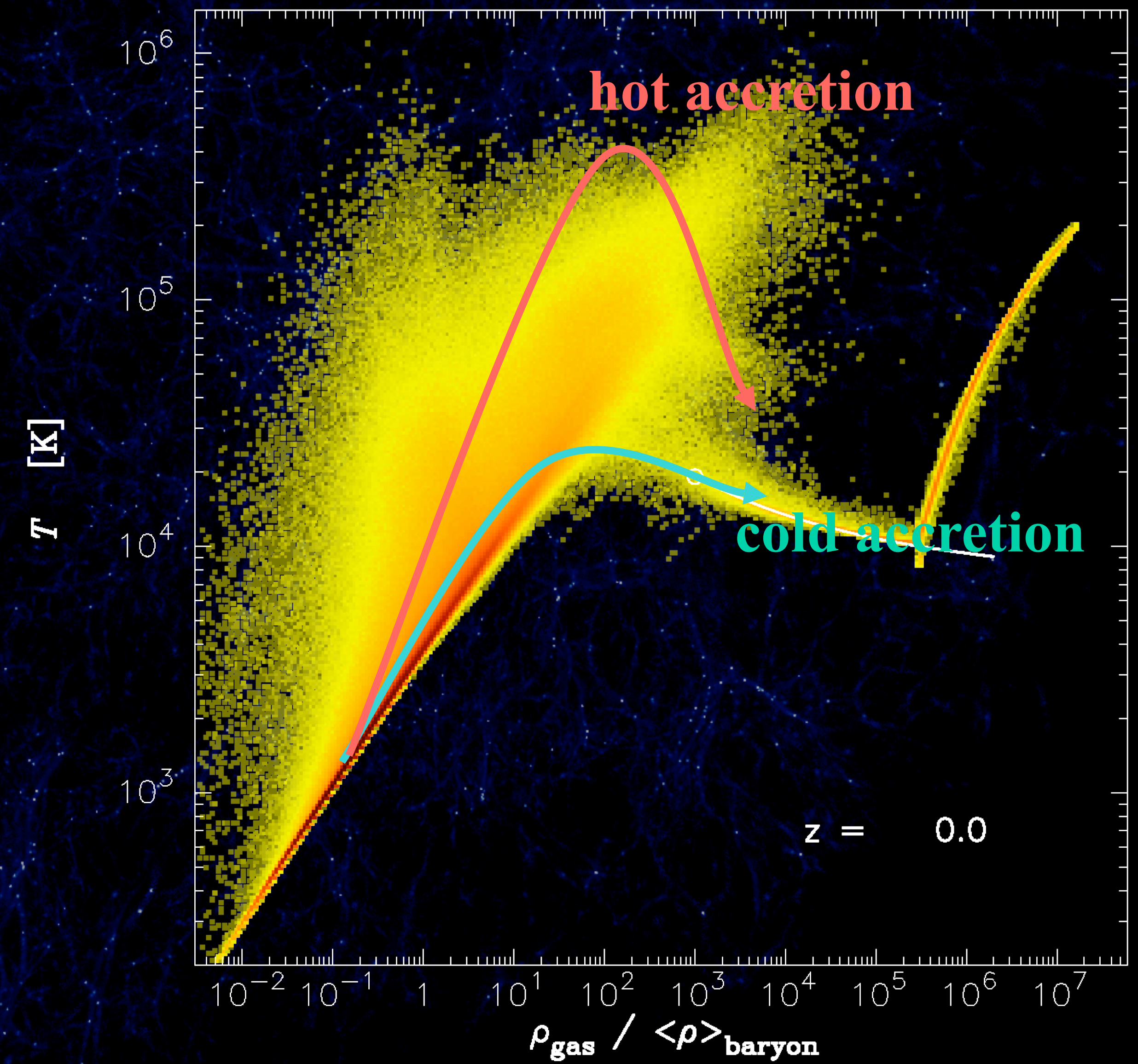

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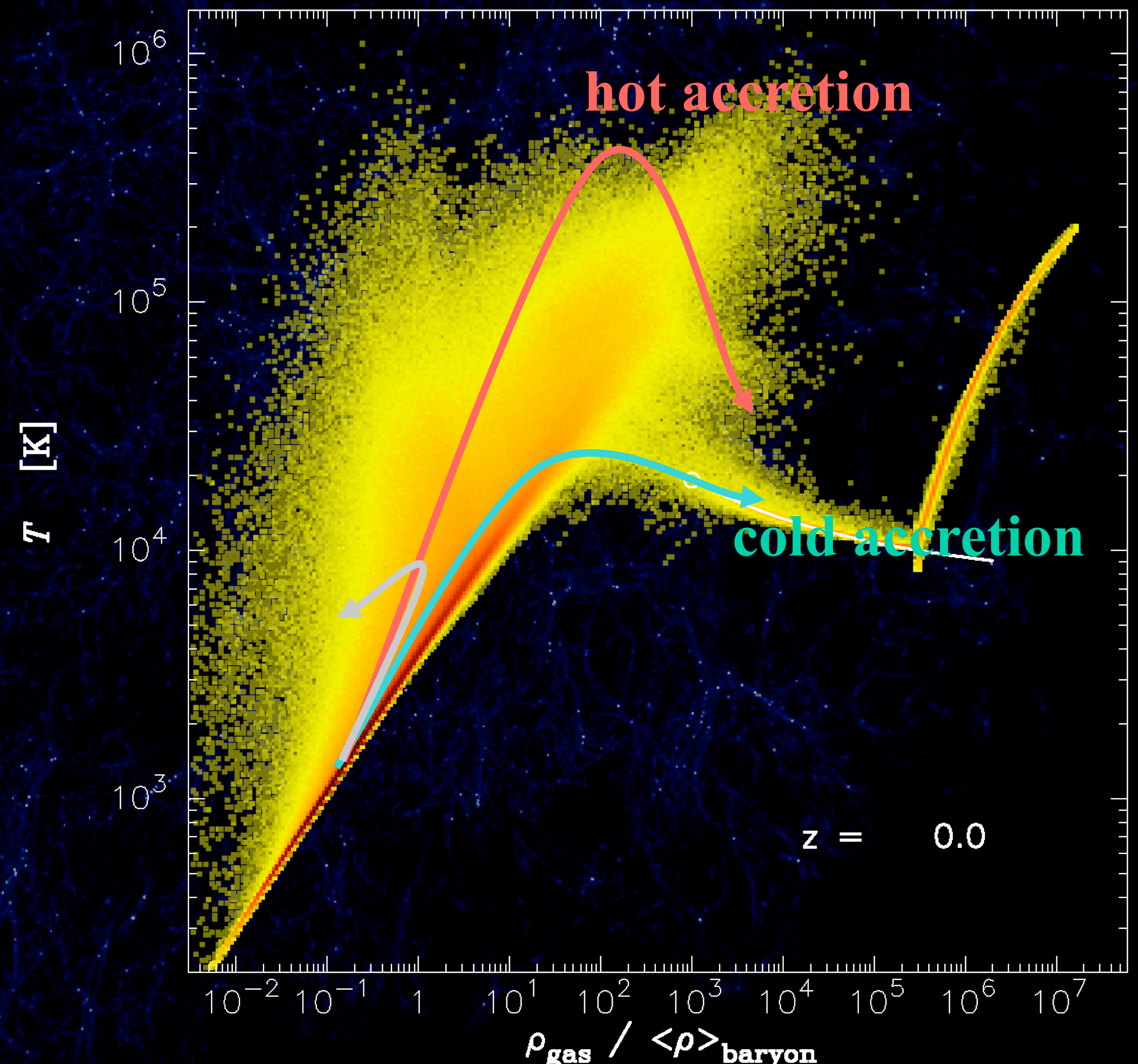

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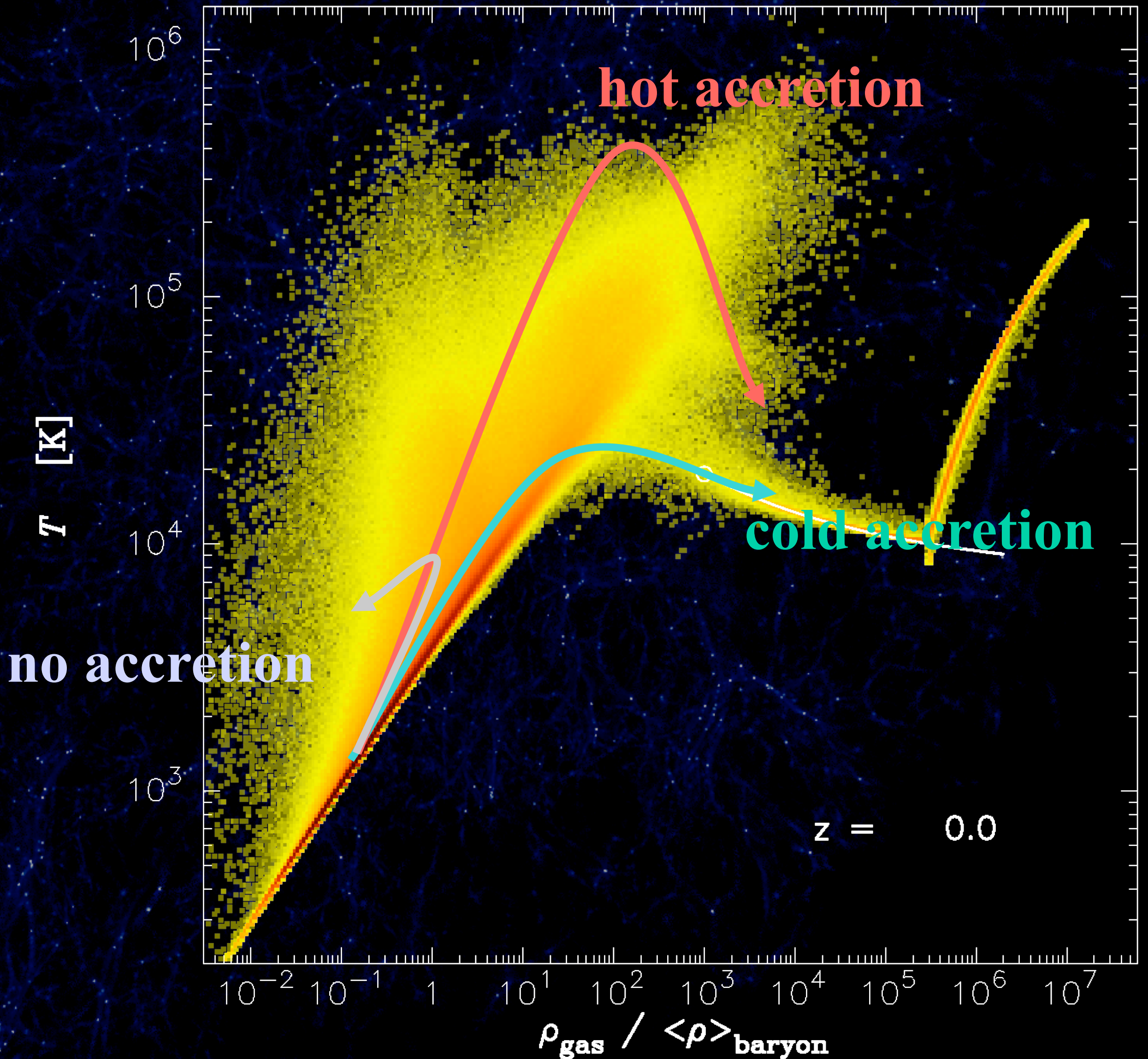

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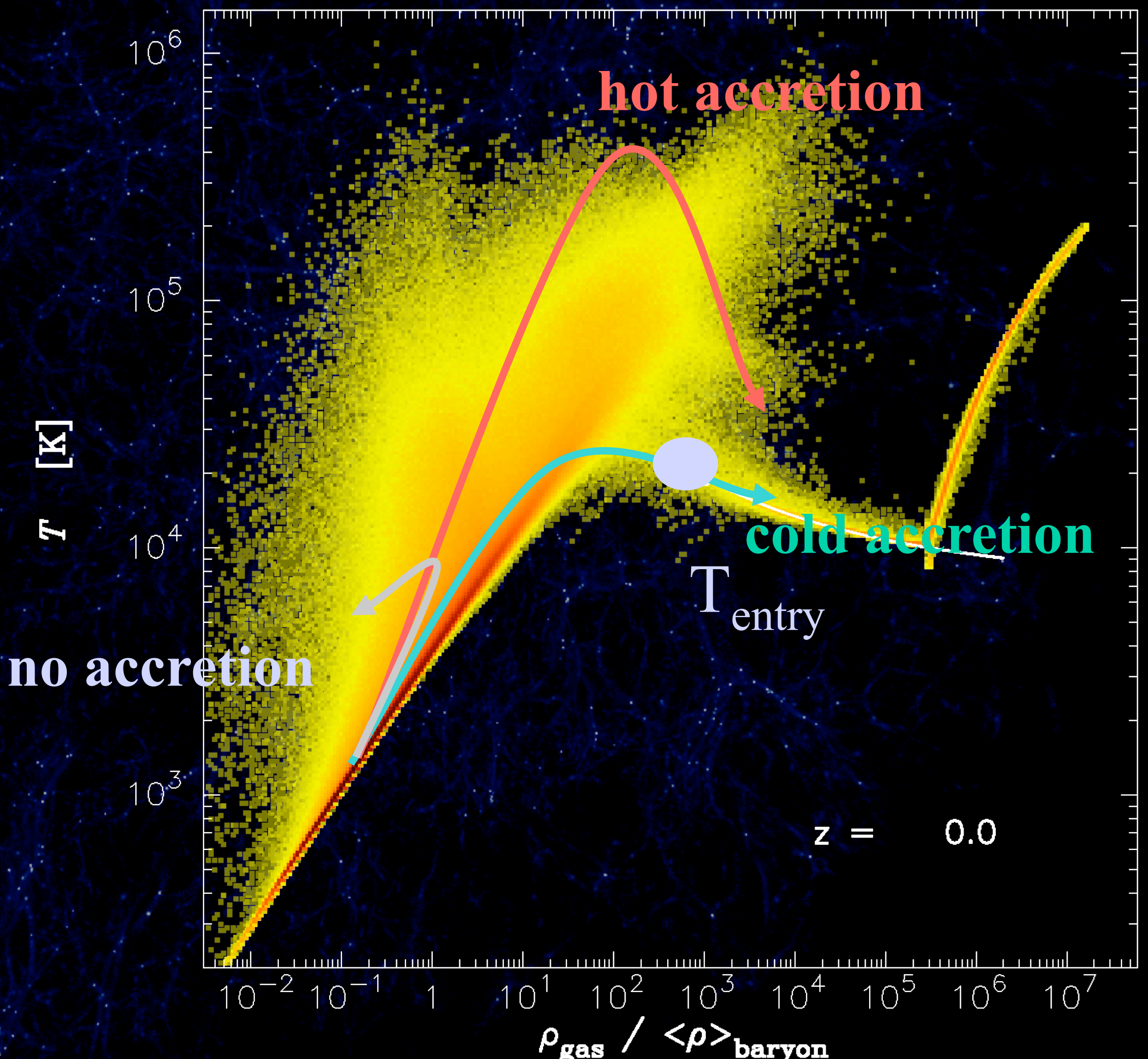

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How to suppress gas condensation?

$$k_B T_{\rm vir} = \frac{1}{2}\mu m_p \frac{G M_{\rm vir}}{r_{\rm vir}}$$

$$\frac{M_{\rm vir}}{4/3\,\pi\, r_{\rm vir}^3} = \Delta_c(z)\,\langle\rho\rangle$$

$$T_{\rm entry} \geq T_{\rm vir}$$

$$\frac{M_{\rm c}(z)}{10^{10}\, h^{-1} M_\odot} \simeq \left\{\frac{T_{\rm entry}(z)}{3.5\times 10^4\ {\rm K}}\frac{1}{1+z}\right\}^{\frac{3}{2}} \left\{\frac{\Delta_c(0)}{\Delta_c(z)}\right\}^{\frac{1}{2}}$$

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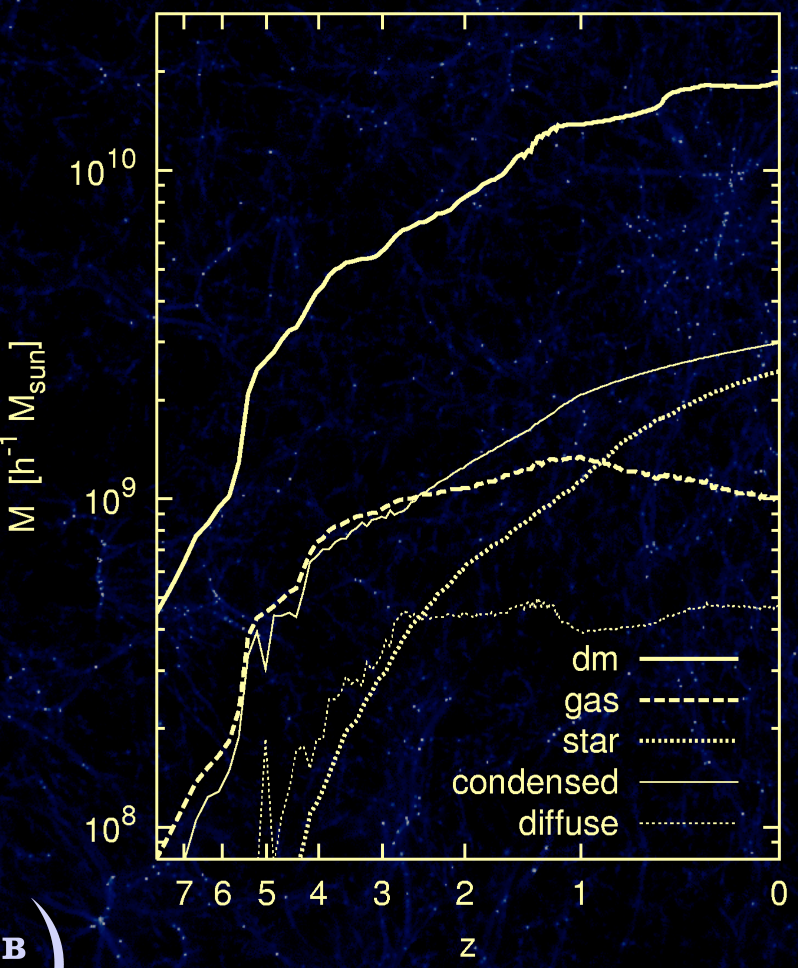
Mass accretion history



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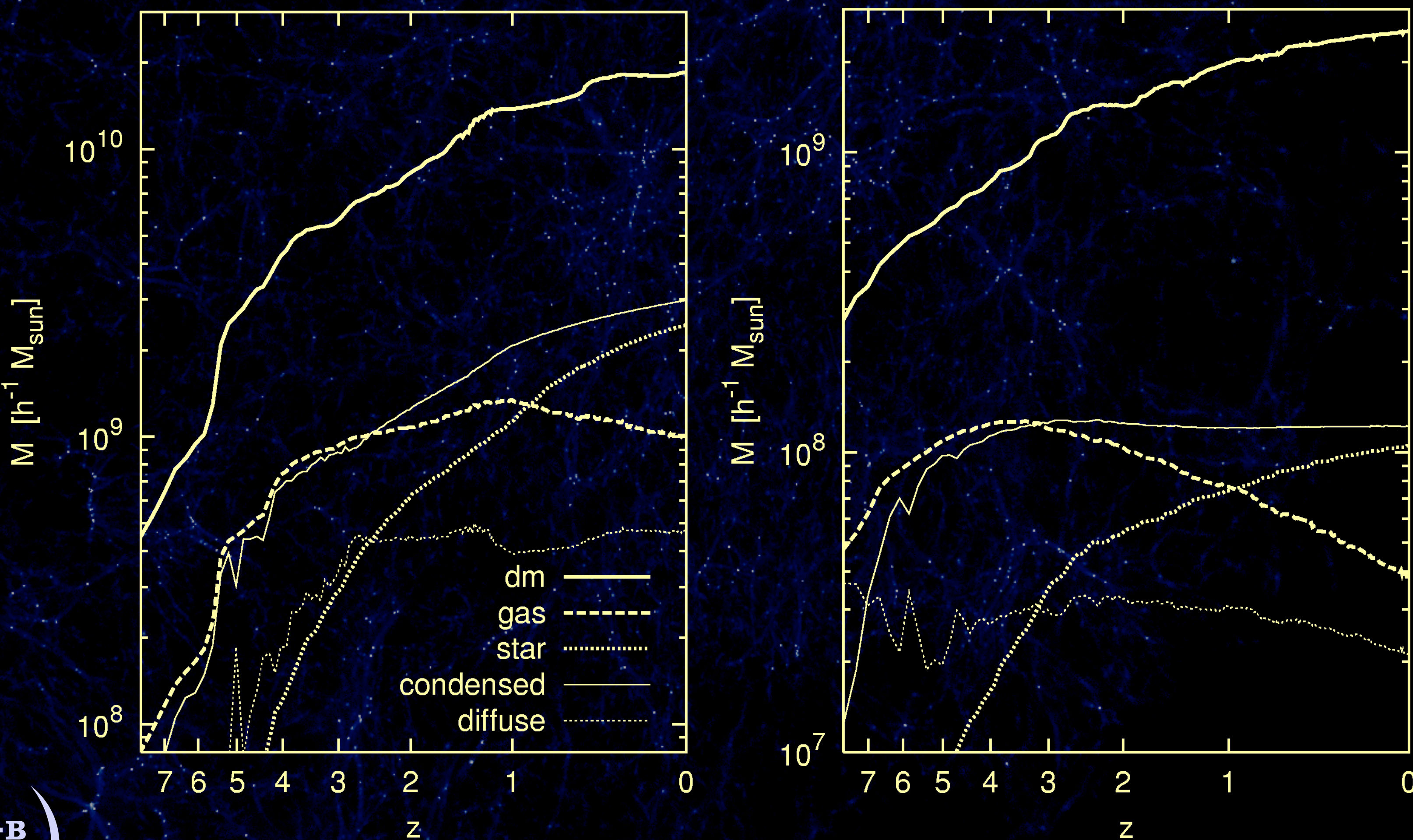

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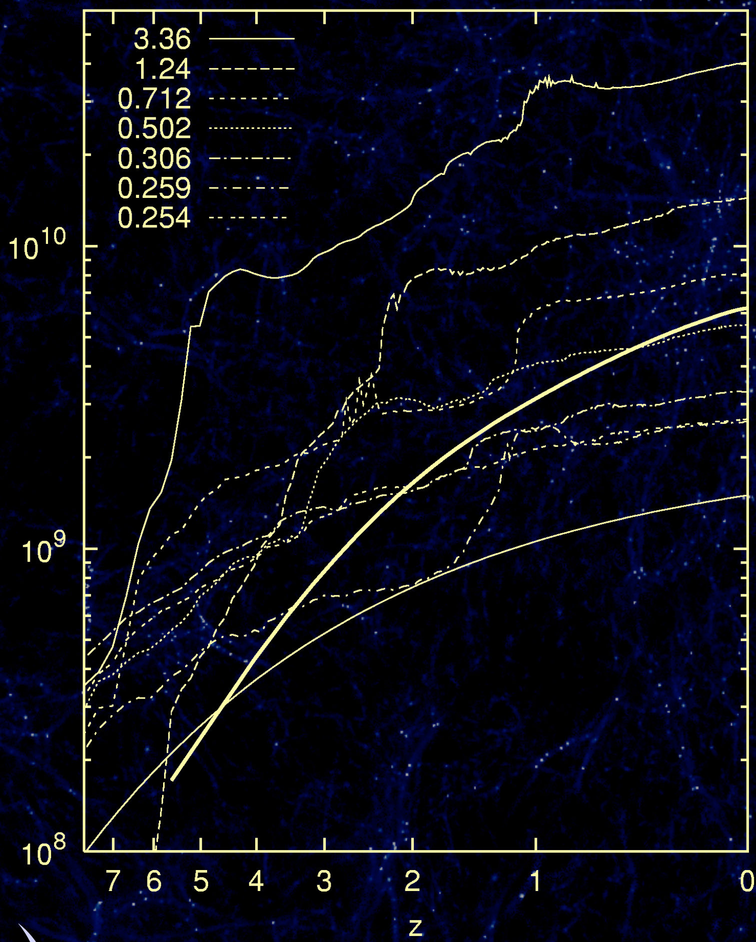
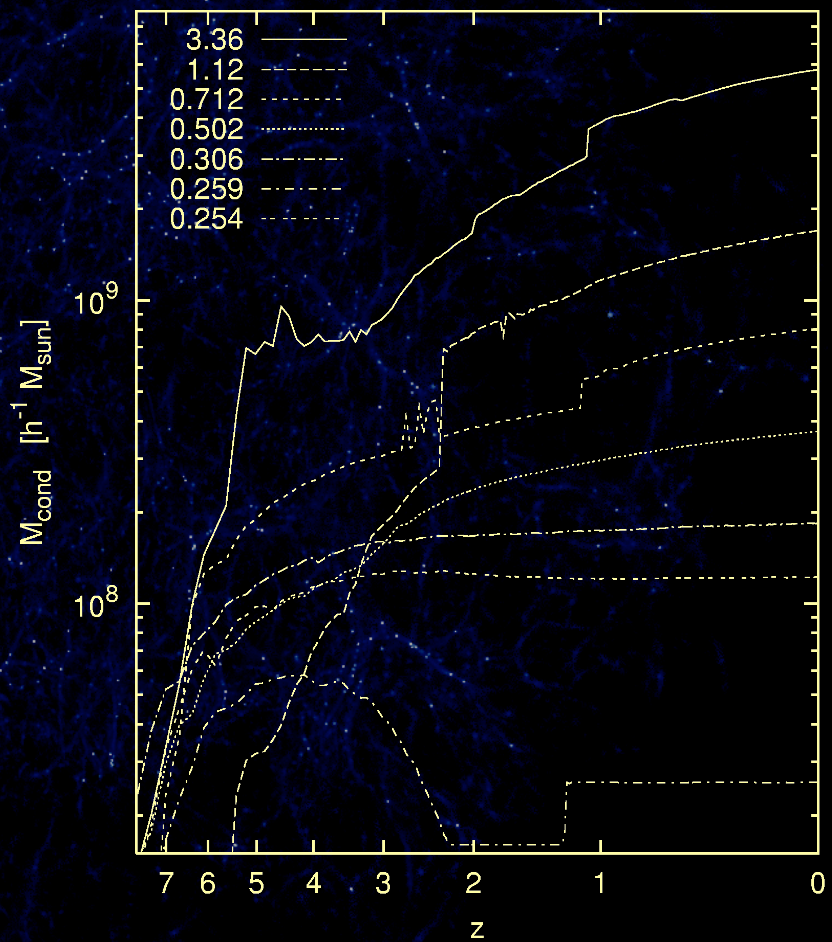
Baryon poor small halos



total mass



baryonic (condensed) mass

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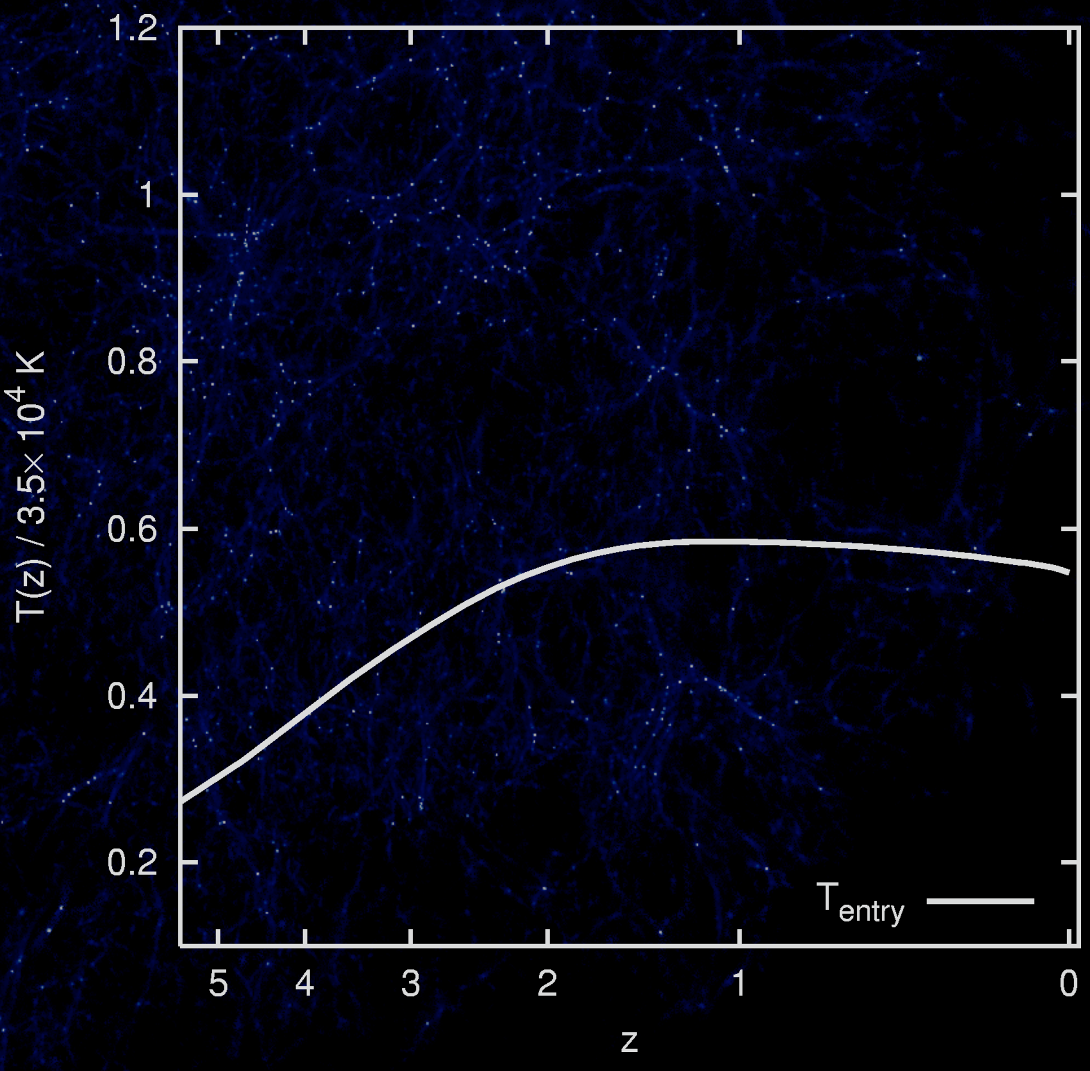
Comparison: T_{entry} versus M_C and $M_{c,acc}$

τ :
derived from the characteristic mass scales

T_{entry} :
taken from the density-temperature phase space

Good agreement in particular for the newly accreted (cooled) mass



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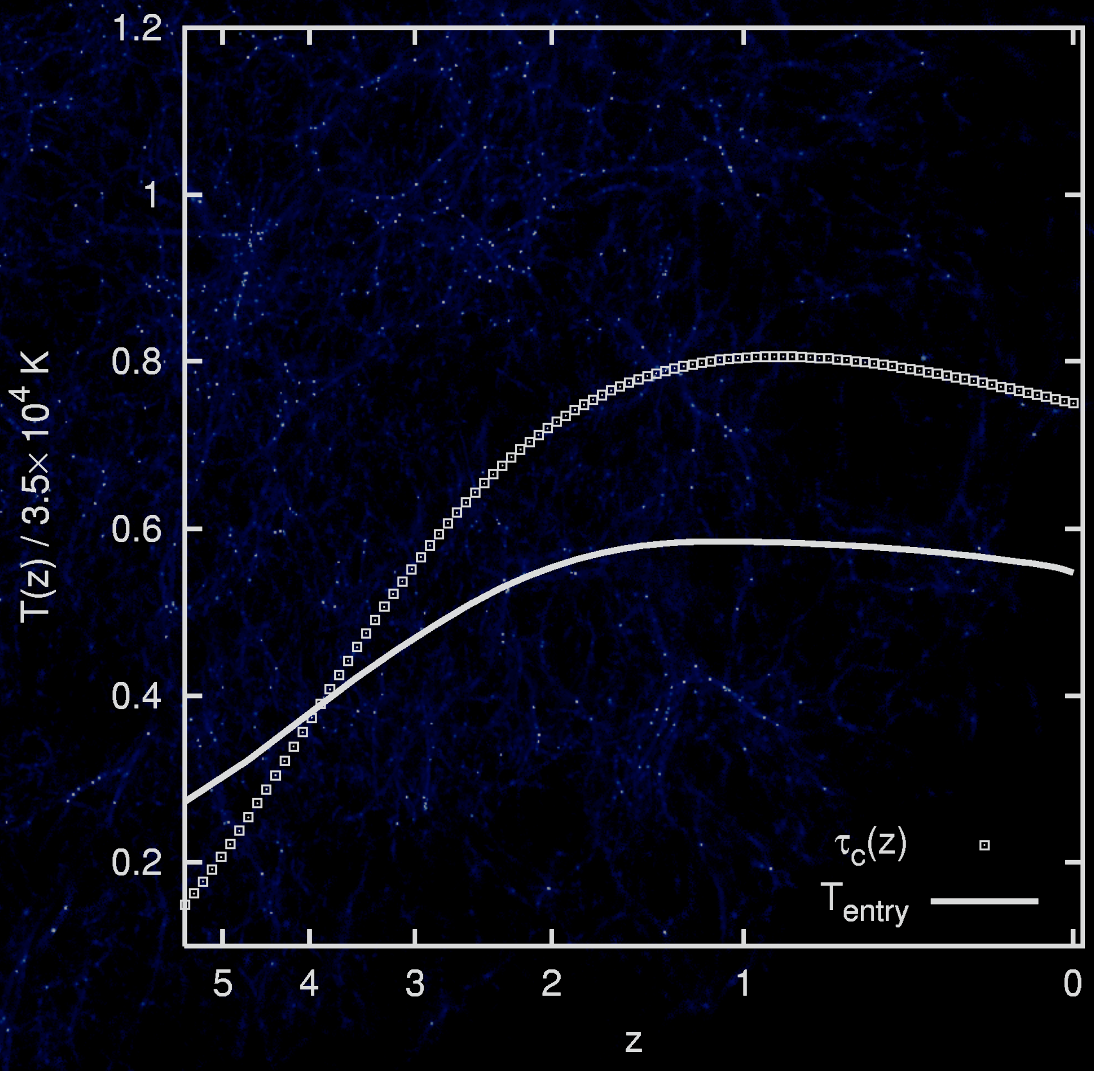

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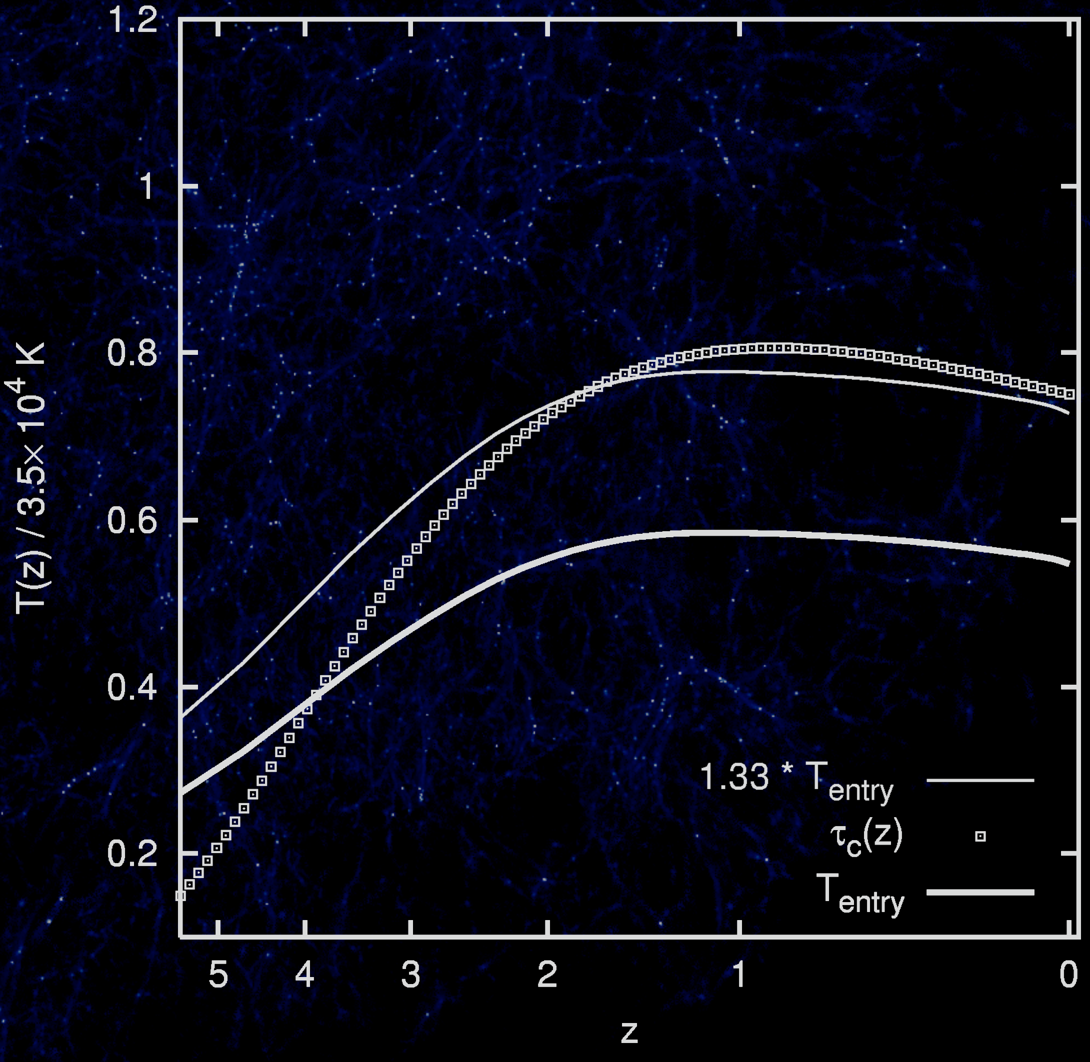

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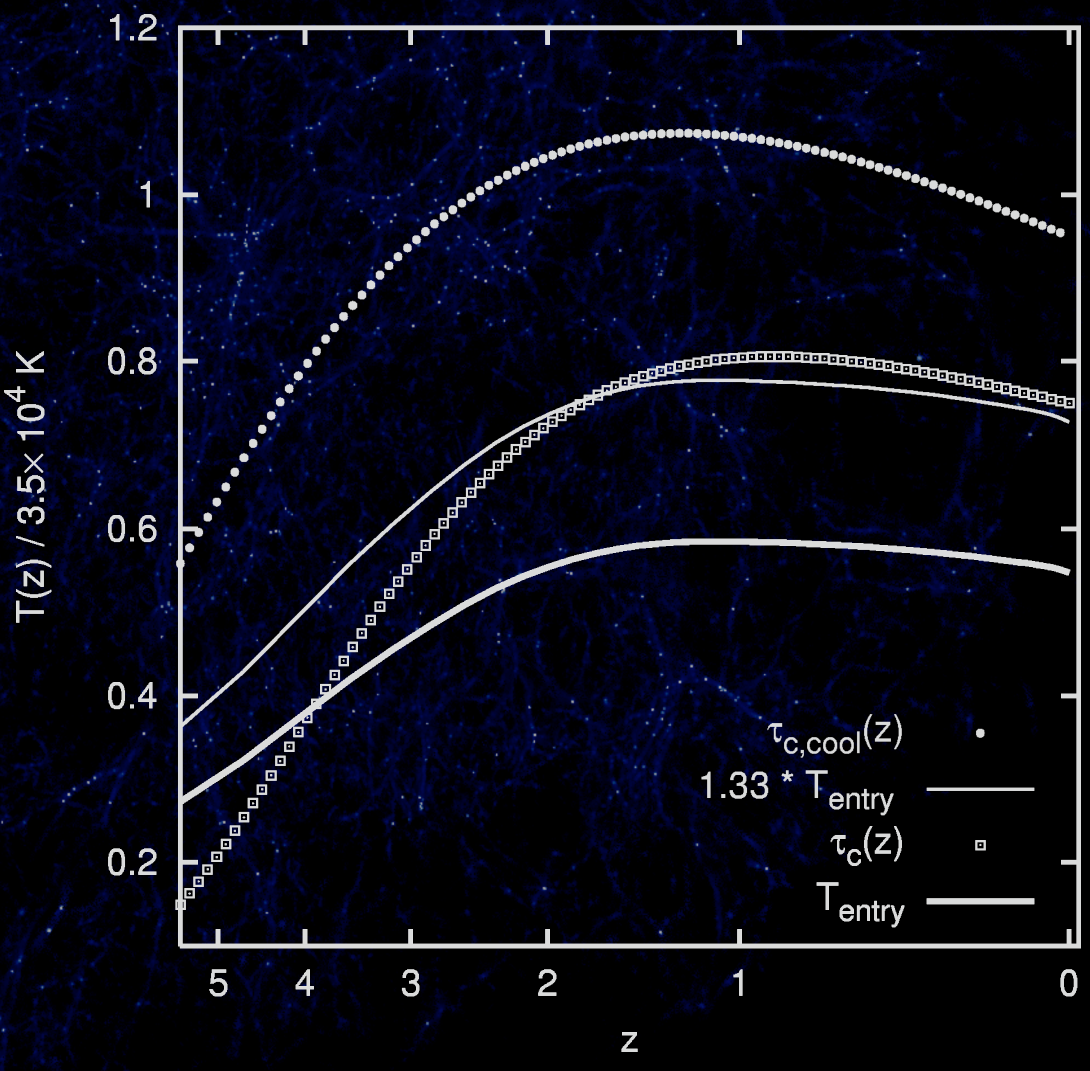
Comparison: T_{entry} versus M_C and $M_{c,acc}$

τ :
derived from the characteristic mass scales

T_{entry} :
taken from the density-temperature phase space

Good agreement in particular for the newly accreted (cooled) mass



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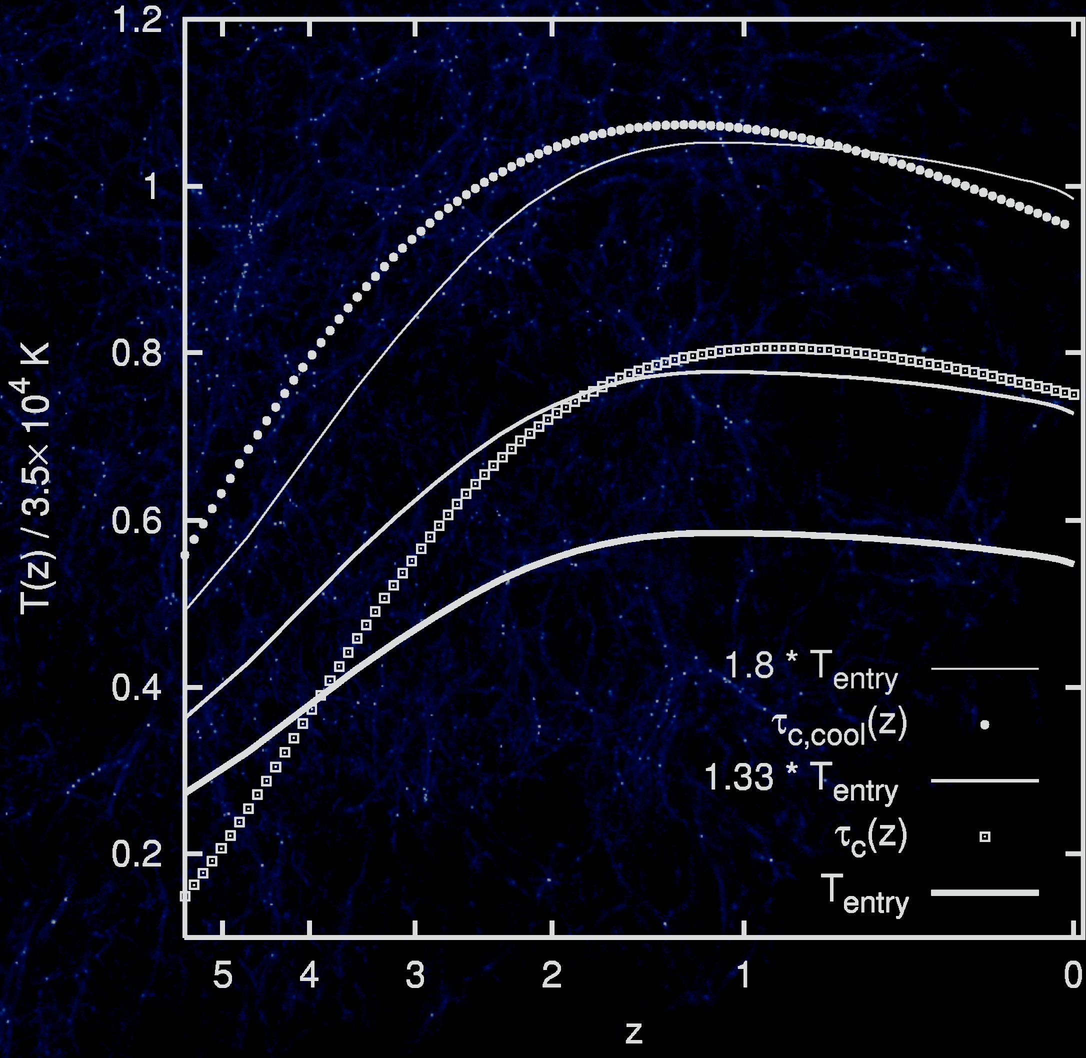

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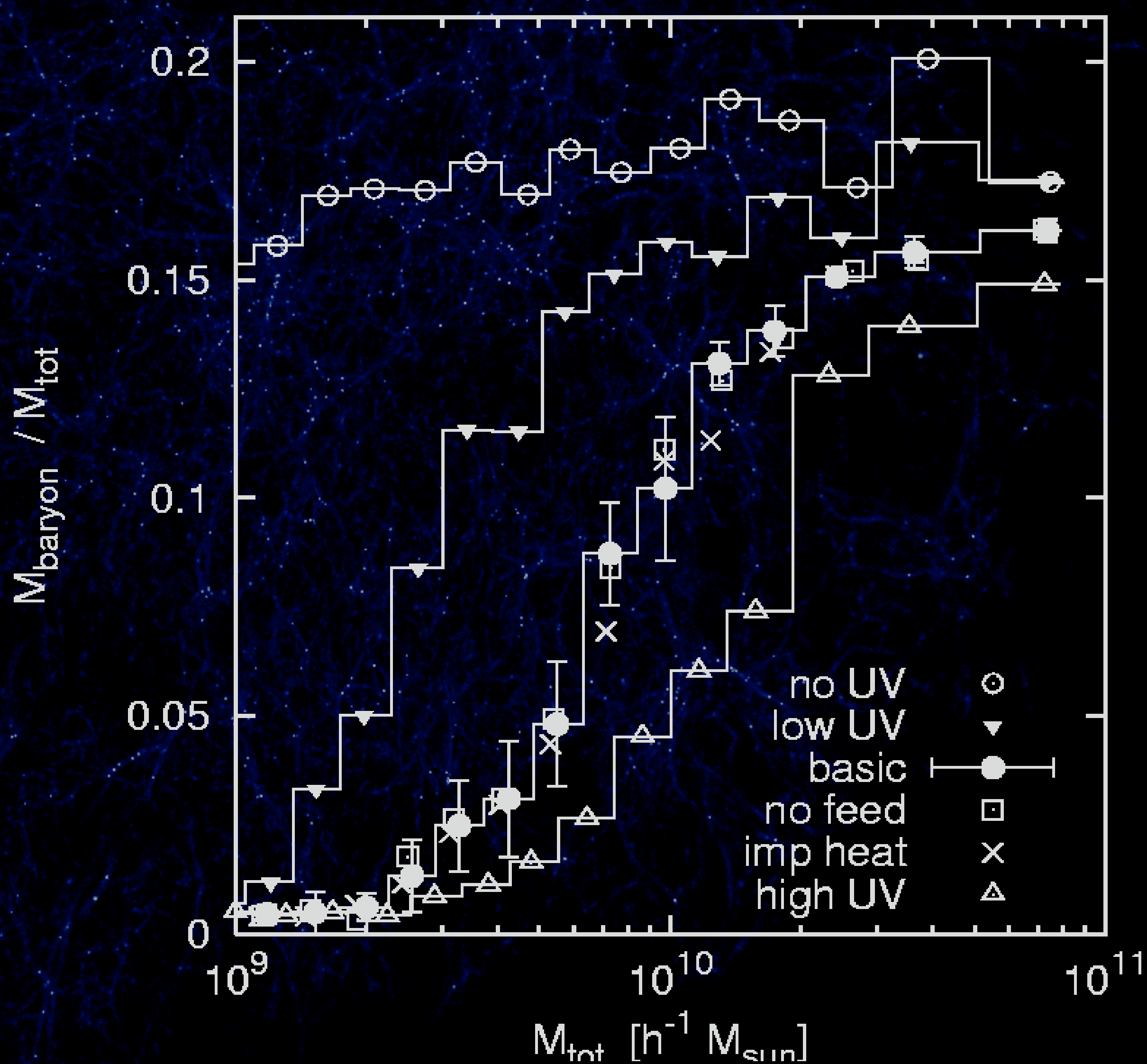
The characteristic mass is "robust"

even a significantly different heat input has only little effect



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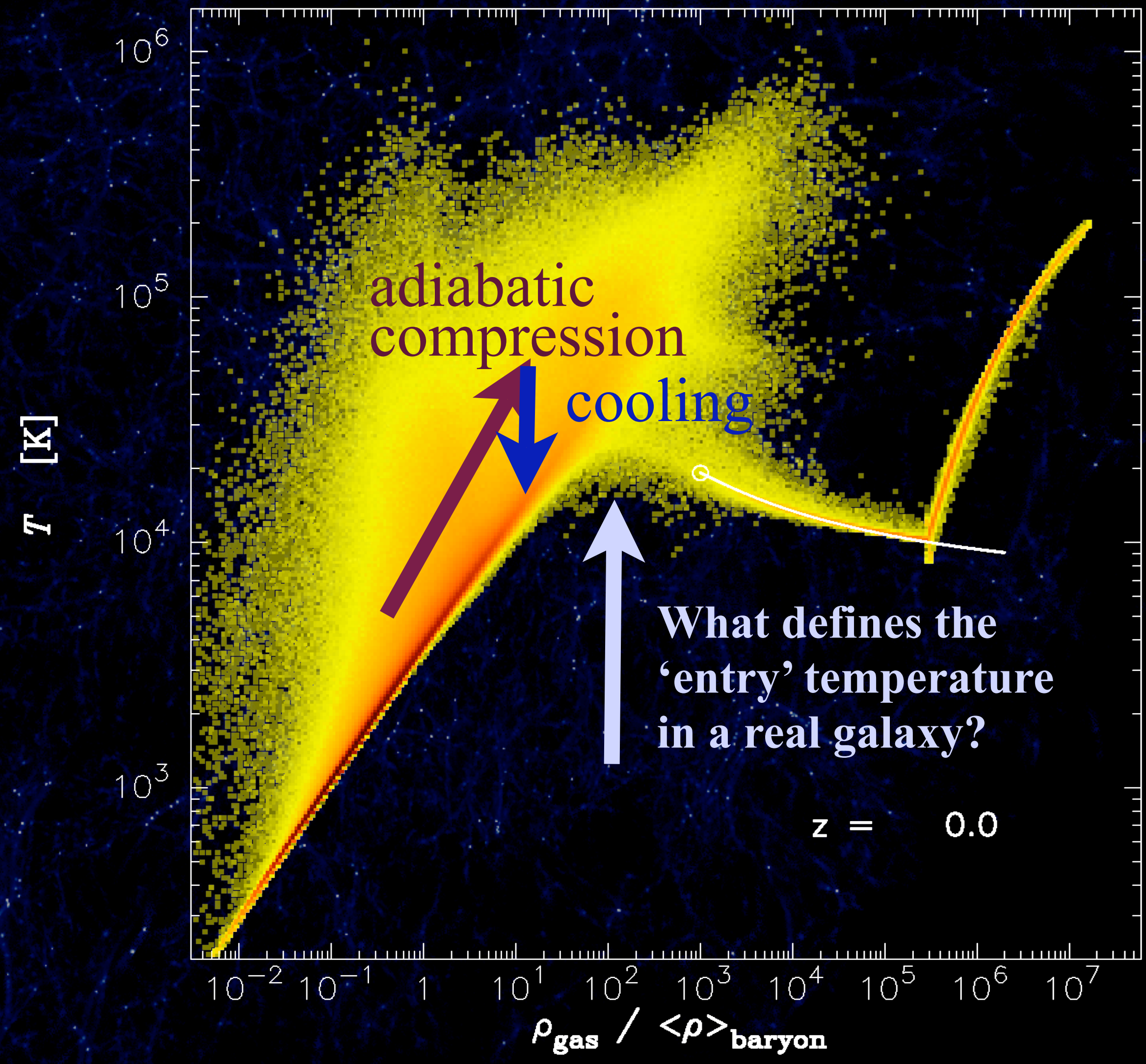
Gas accretion revisited

Total heat input by UV heating

10^{43} -10^{47} erg yr^{-1}

(Very crude estimate!)



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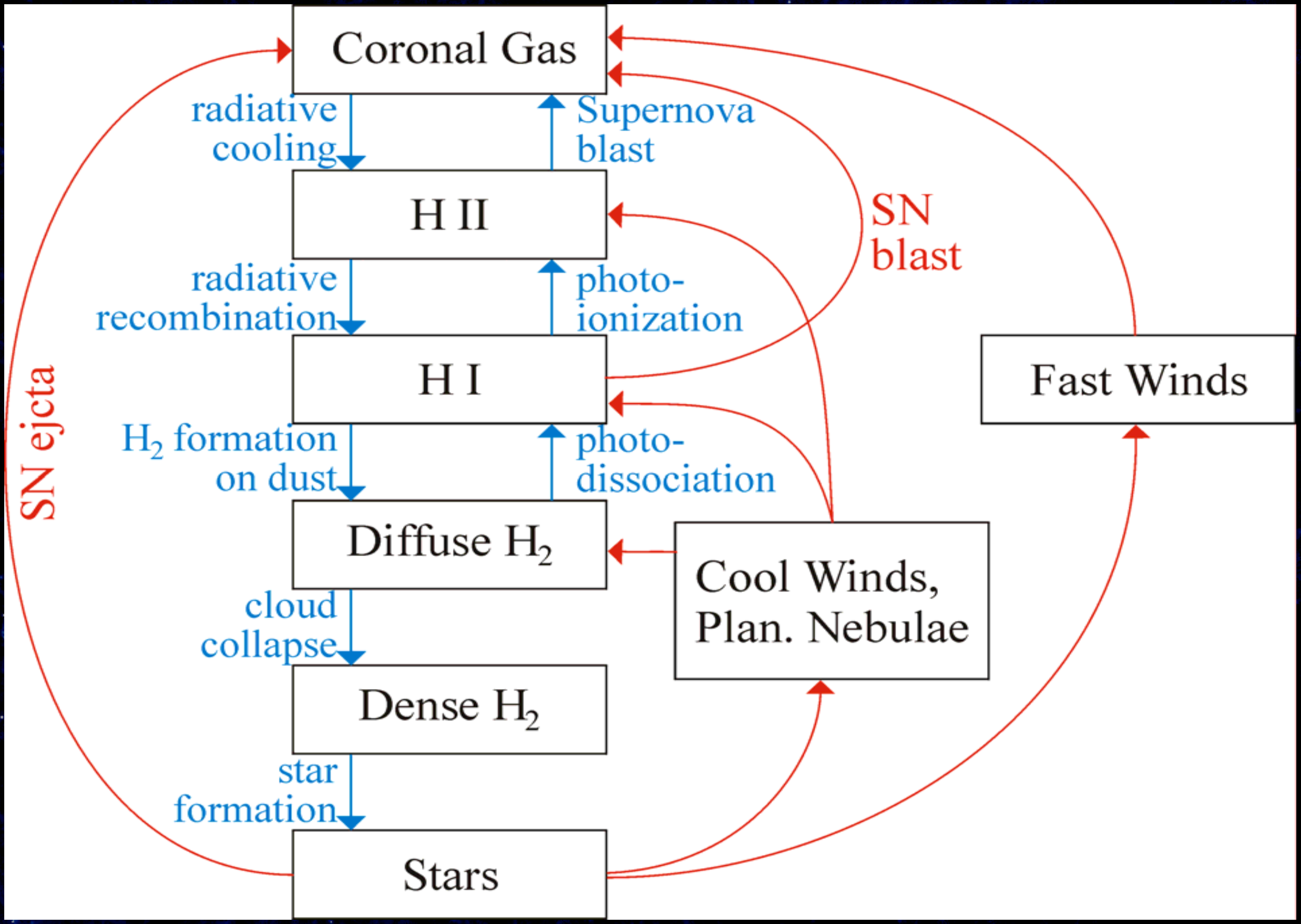
In which reservoir does the halo cool?



Lecture notes by J. Graham

Summary

- Photoheating suppresses the condensation of gas in halos < M_c

- $T_{vir} < T_{entry}$ is a very good criteria for ongoing accretion

- Photoheating by UV-background is not sufficient to explain the paucity of dwarf galaxies

- Galactic feedback (even without winds) provides much more heat, and suppresses therefore accretion much stronger