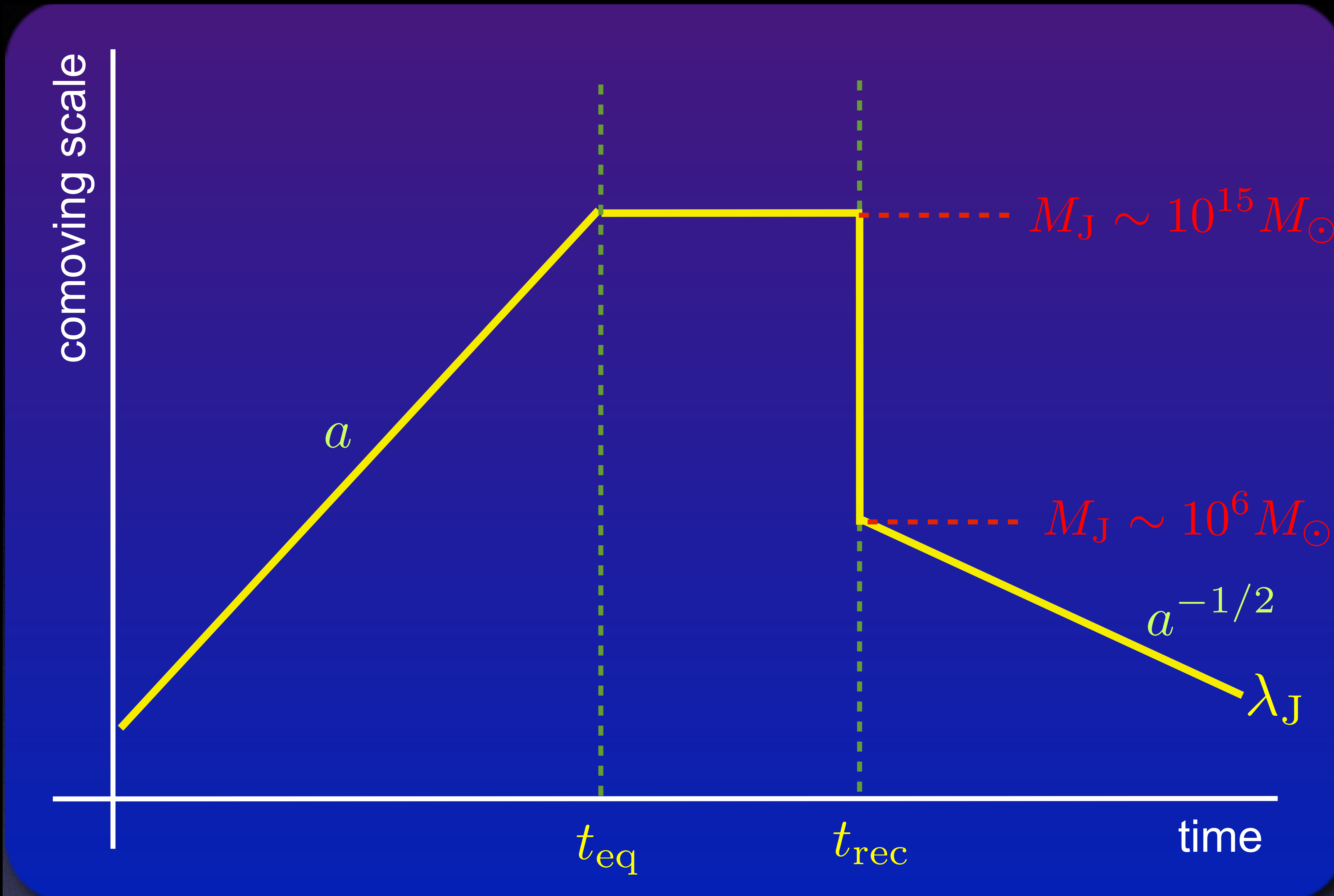
Heating and Cooling of Baryons

ASTR:6782

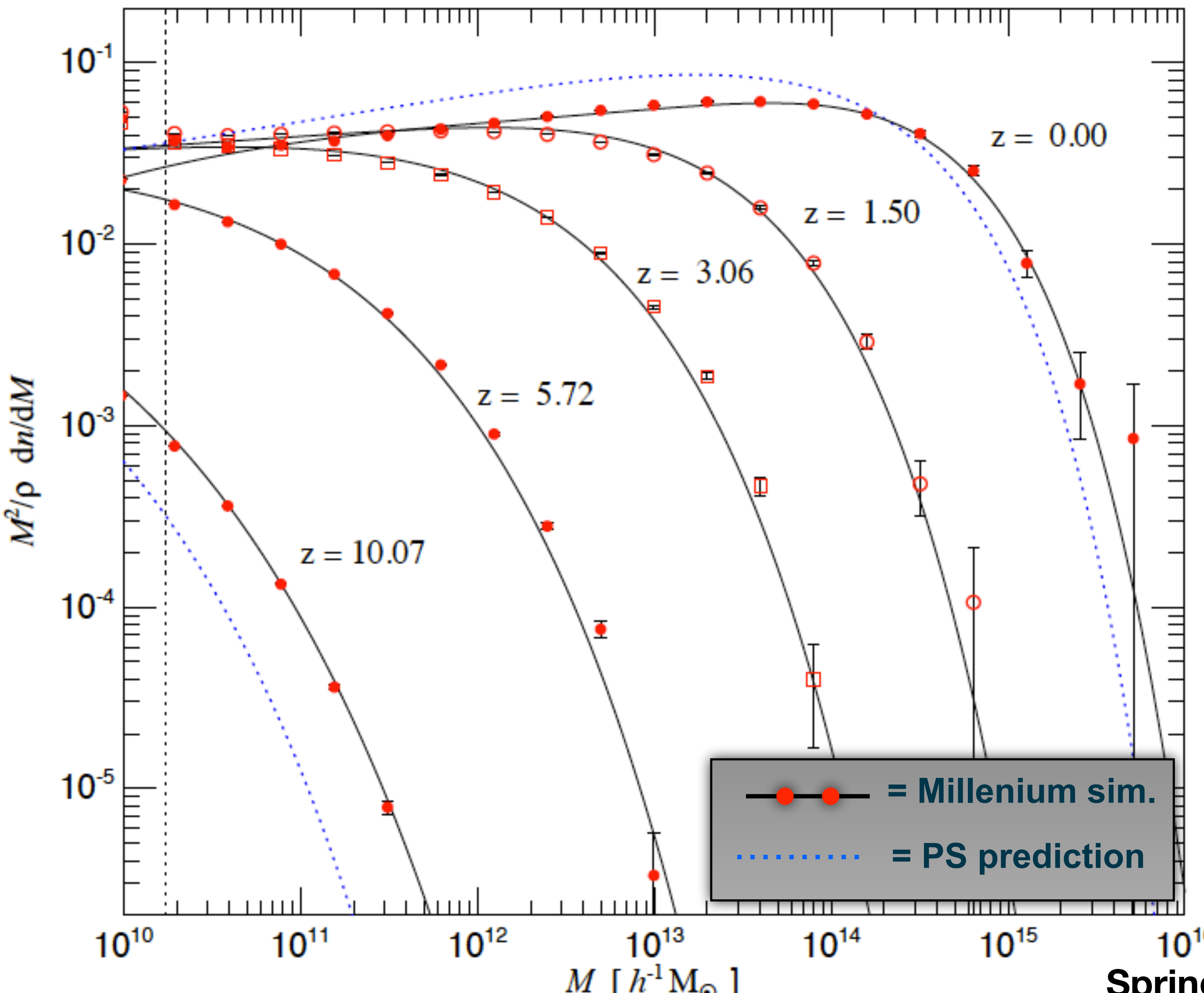
Hai Fu

The Evolution of the Jeans Length (comoving)



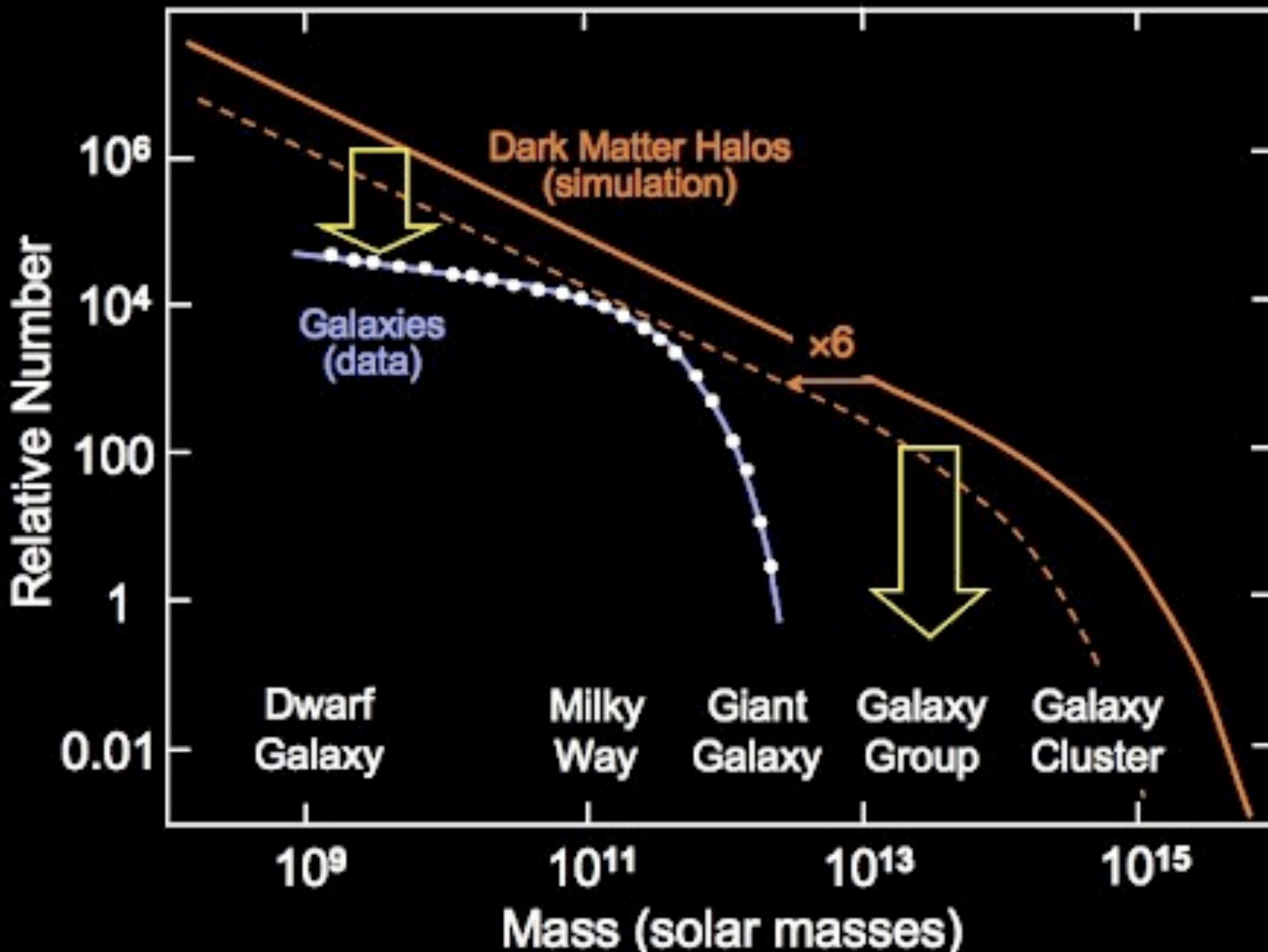
Mo, van den Bosch, White (2010), Cambridge Press

Success: N-body Simulation agrees with PS Prediction

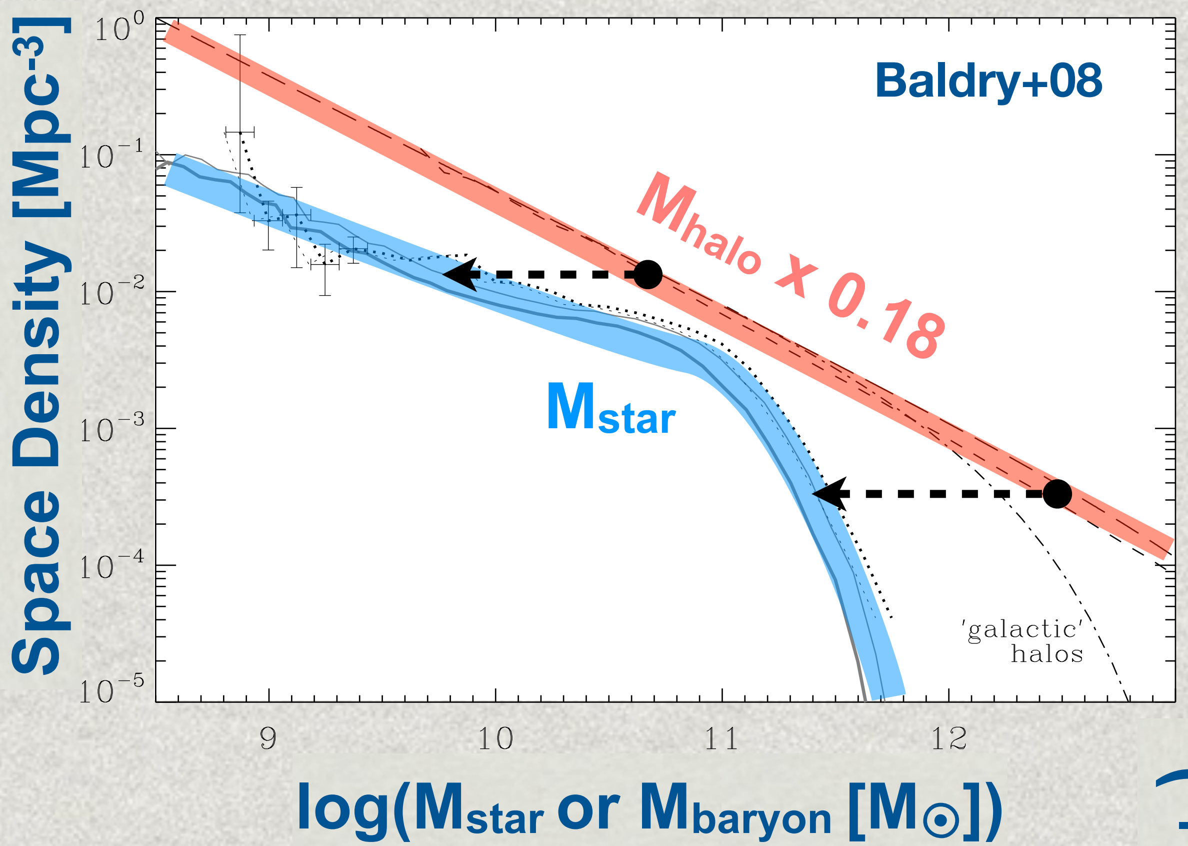


Springel+2005

Problem: both the PS and N-body halo mass function strongly disagrees w/ *Observed* galaxy mass function



Stellar Mass Fraction vs. Halo Mass

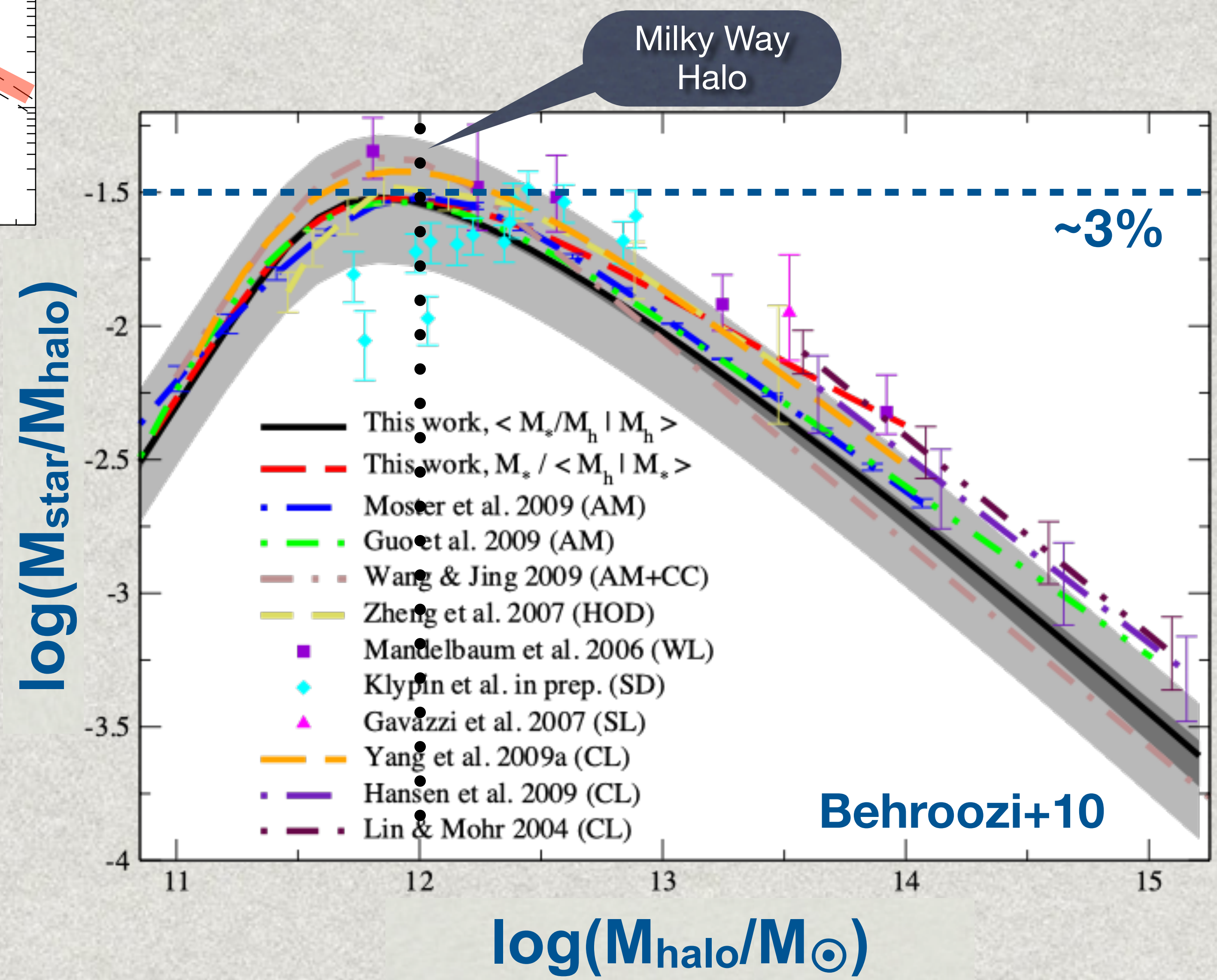


Mismatch between halo and stellar mass distributions

- Halo mass function has been scaled with the cosmic baryon fraction (0.16)
- Large fractions of baryons fail to form stars, i.e., they remain in gaseous phase in the halos

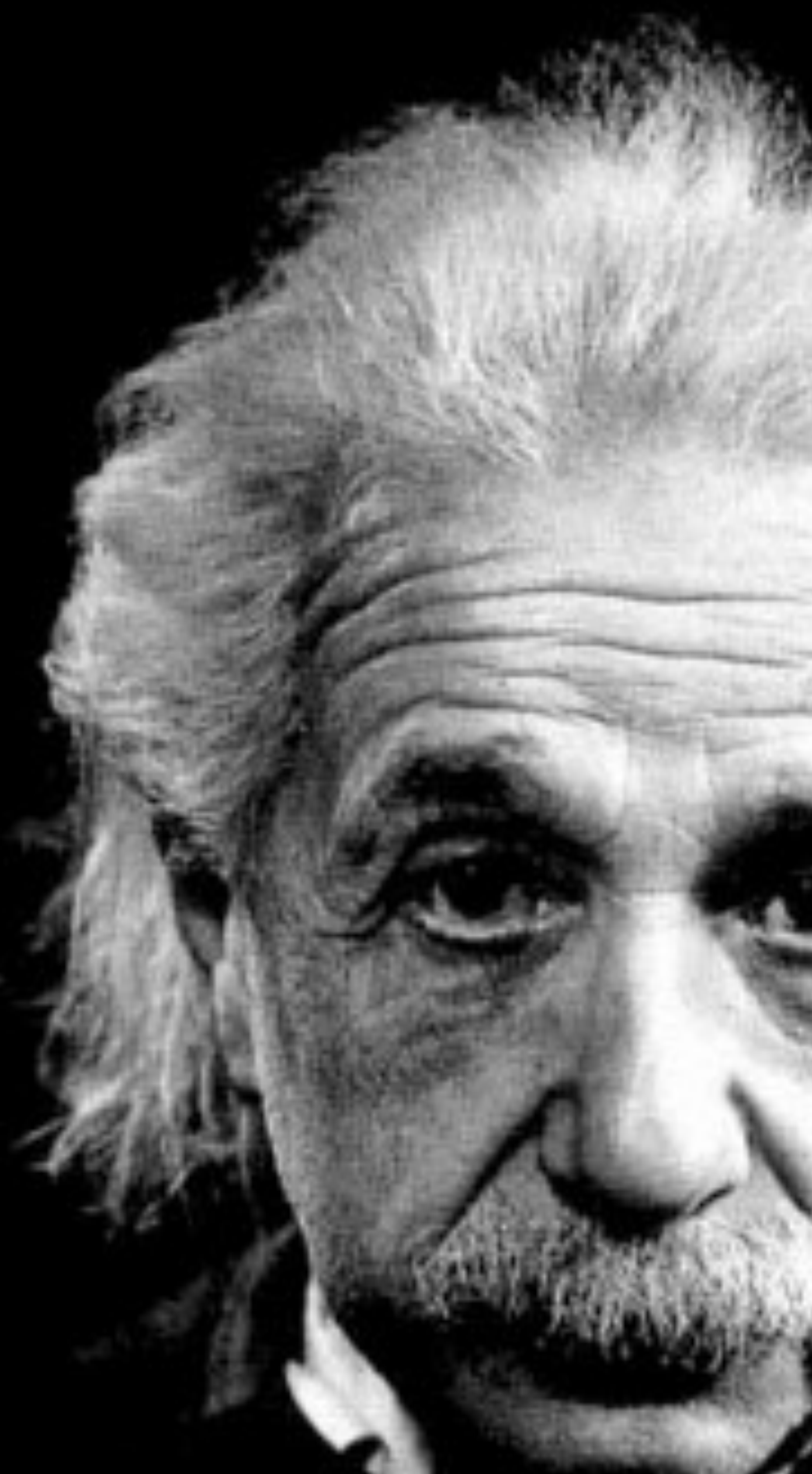
Stellar mass fraction vs. halo mass

- The fraction peaks at only ~3% (cf. f_{gas} = 16%) in 5 x 10^{11} M⊙ halos
- The gas-to-star conversion efficiency is low in both lower mass and higher mass halos



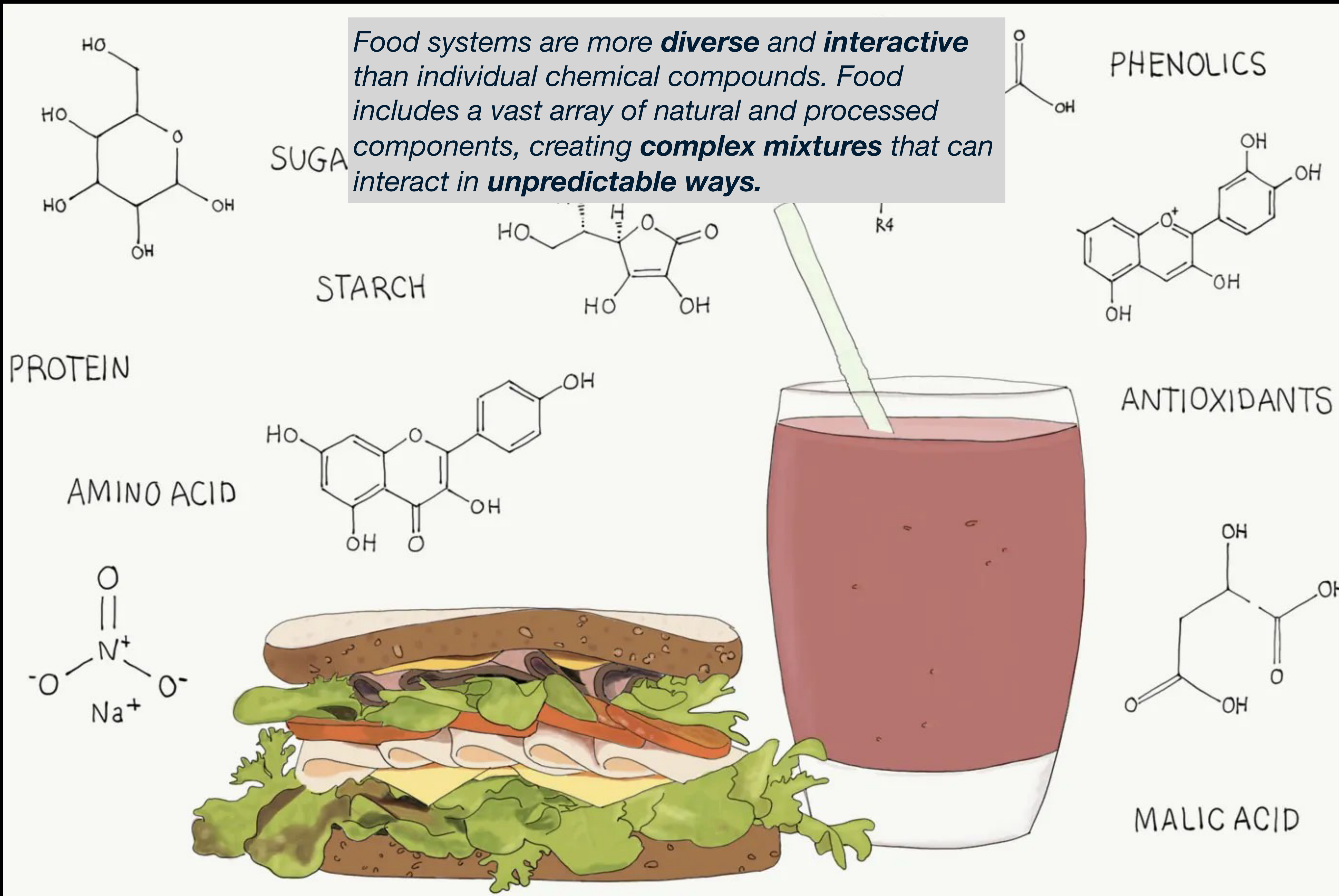
Everything should be made as simple as possible, but not simpler.

Albert Einstein

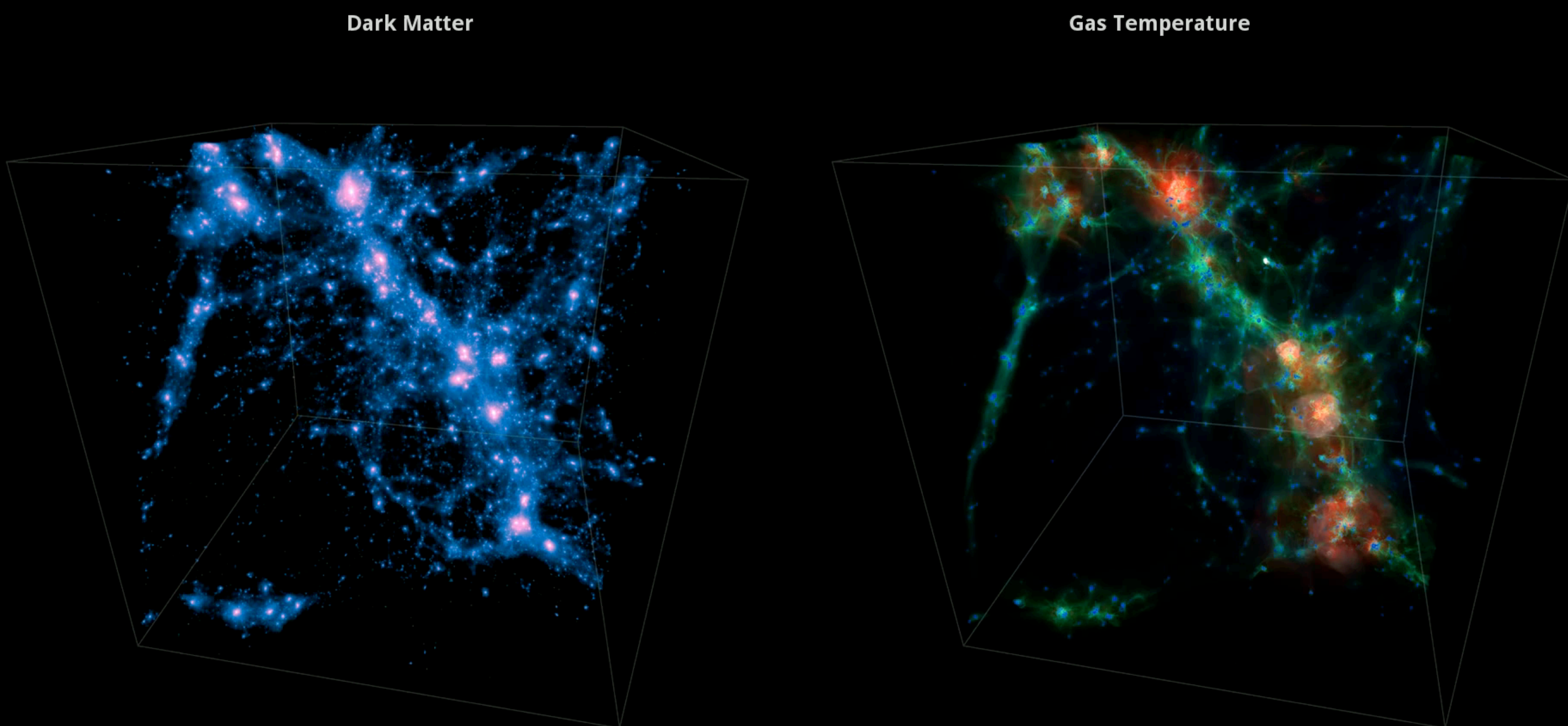


I wonder what he thinks about this …

*Food systems are more **diverse** and **interactive** than individual chemical compounds. Food includes a vast array of natural and processed components, creating **complex mixtures** that can interact in **unpredictable ways.***



Illustris Simulation of a Comoving Volume 10 Mpc Across

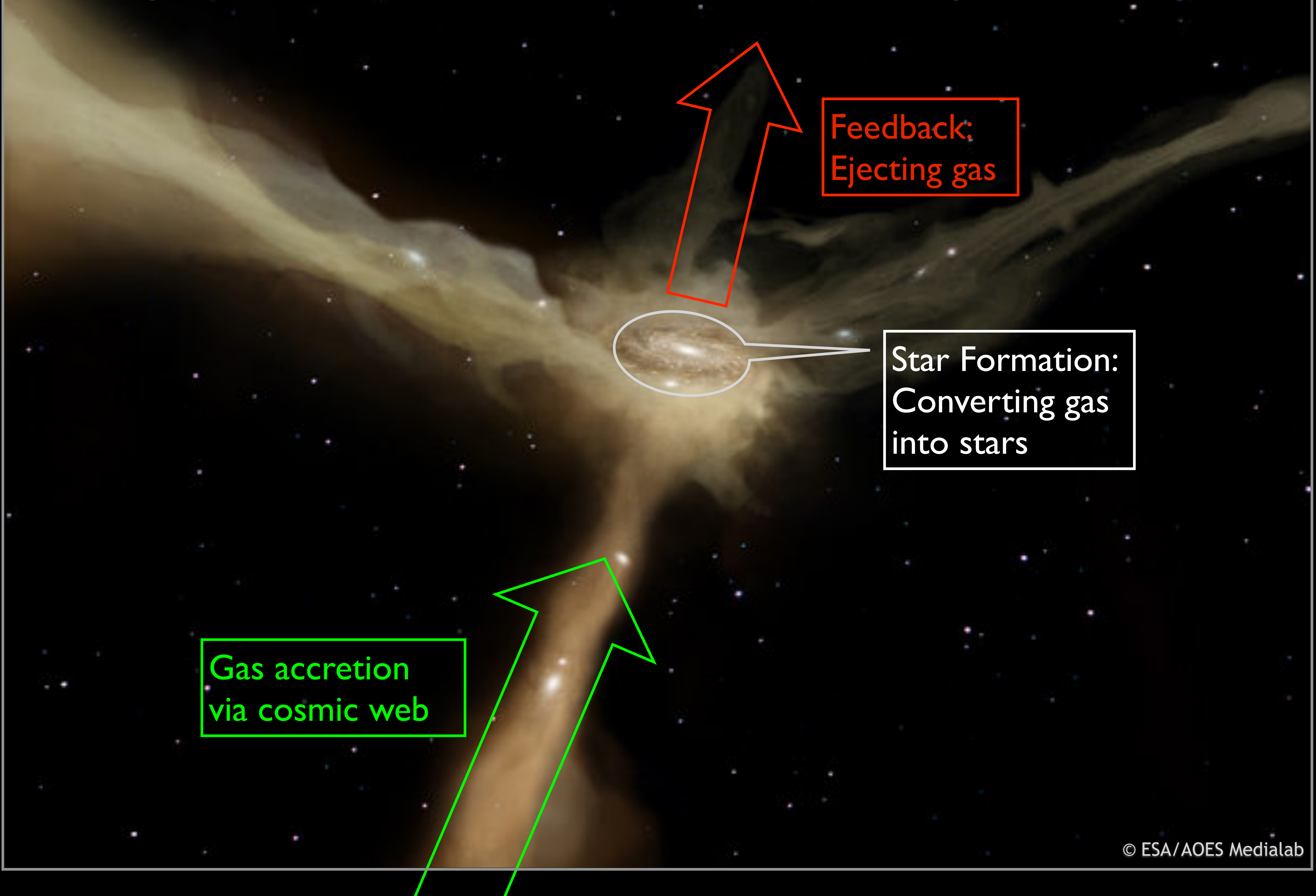


redshift : 1.54
Time since the Big Bang : 4.3 billion years

stellar mass : 27.7 billion solar masses

ILLUSTRIS

Baryonic Processes in Galaxy Evolution

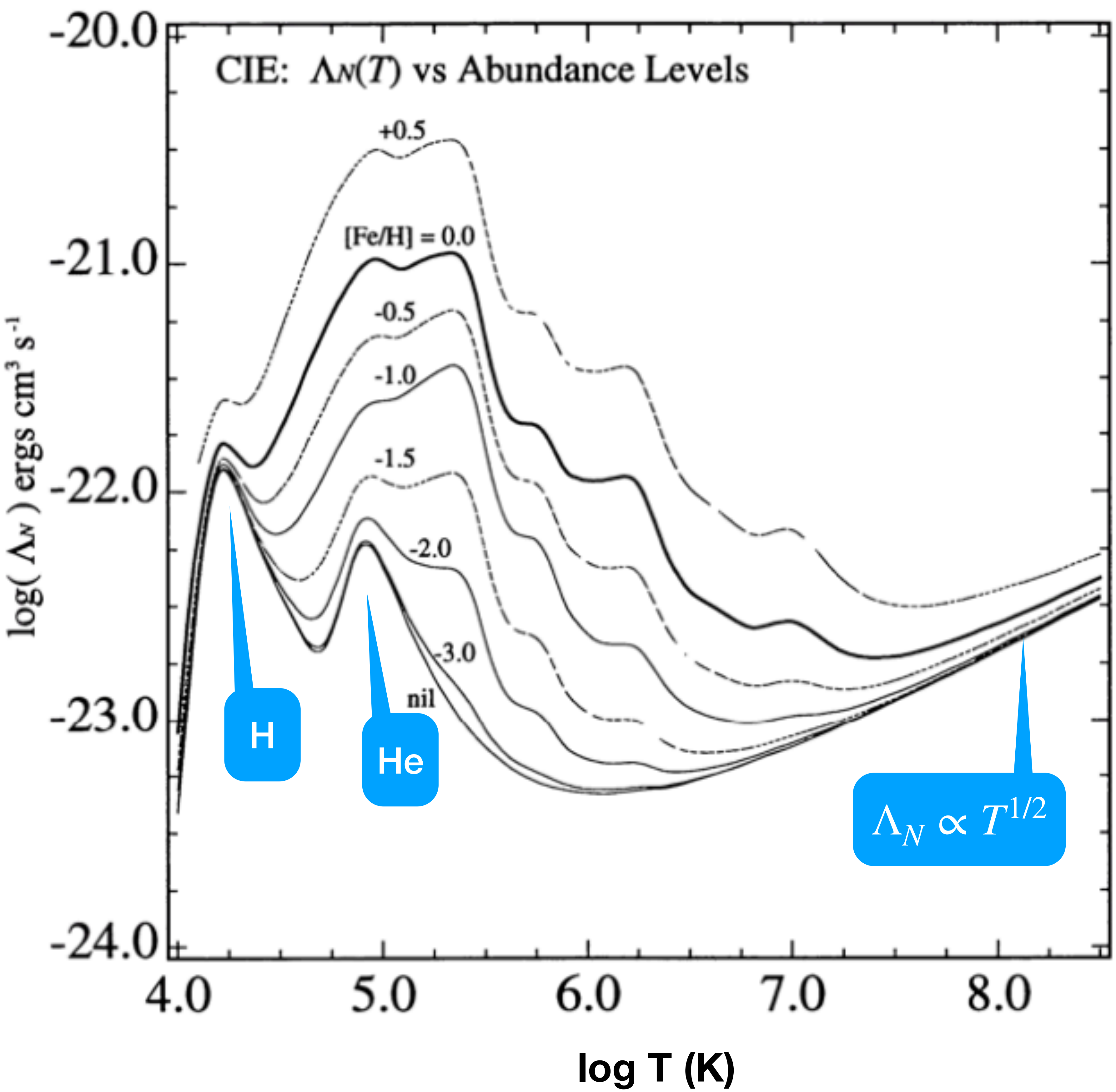


The Cooling Function: $\Lambda_N(T, Z)$

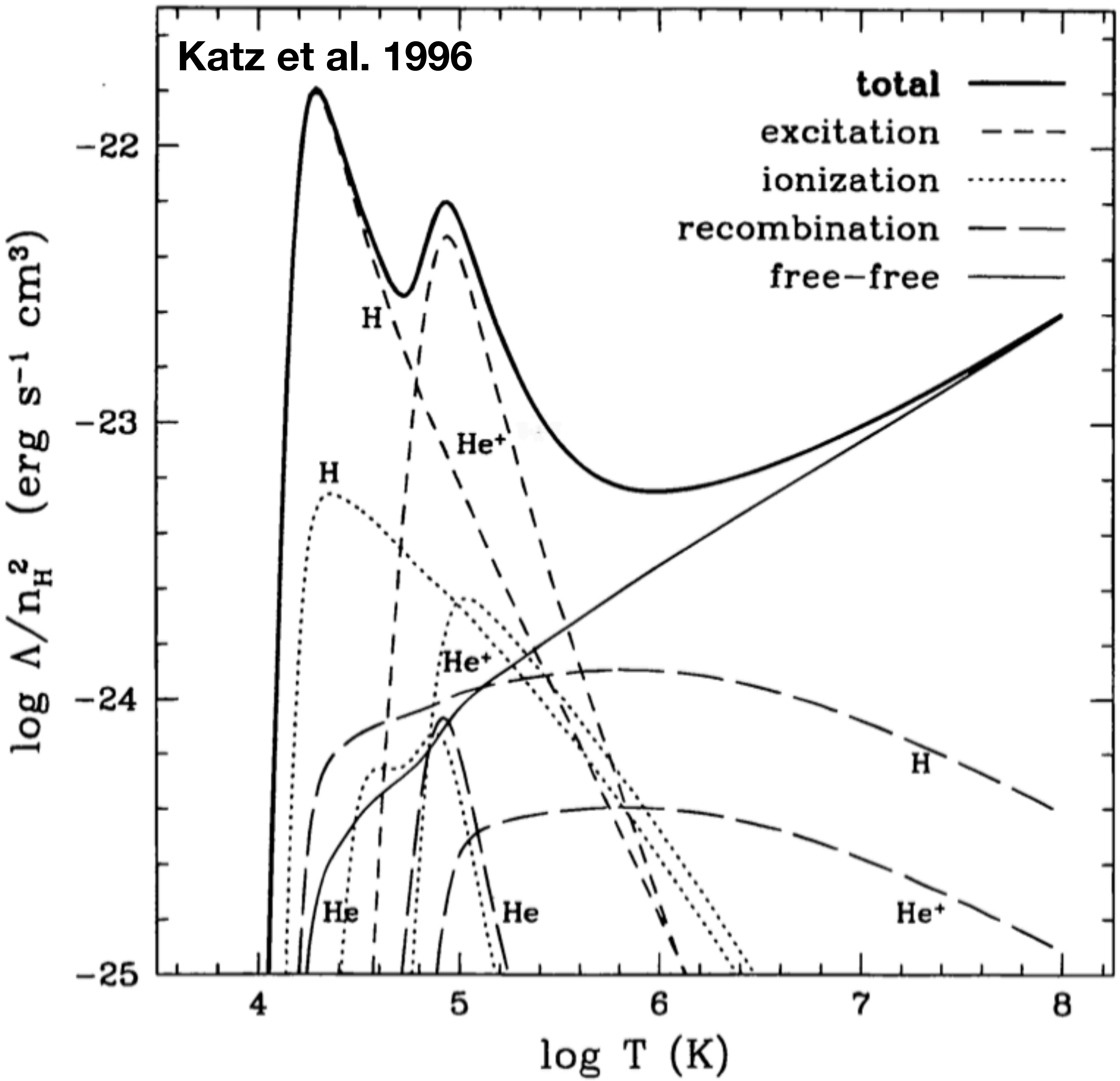
assume collisional ionization equilibrium (CIE)

Cooling Function = Cooling Rate / Hydrogen Density Squared

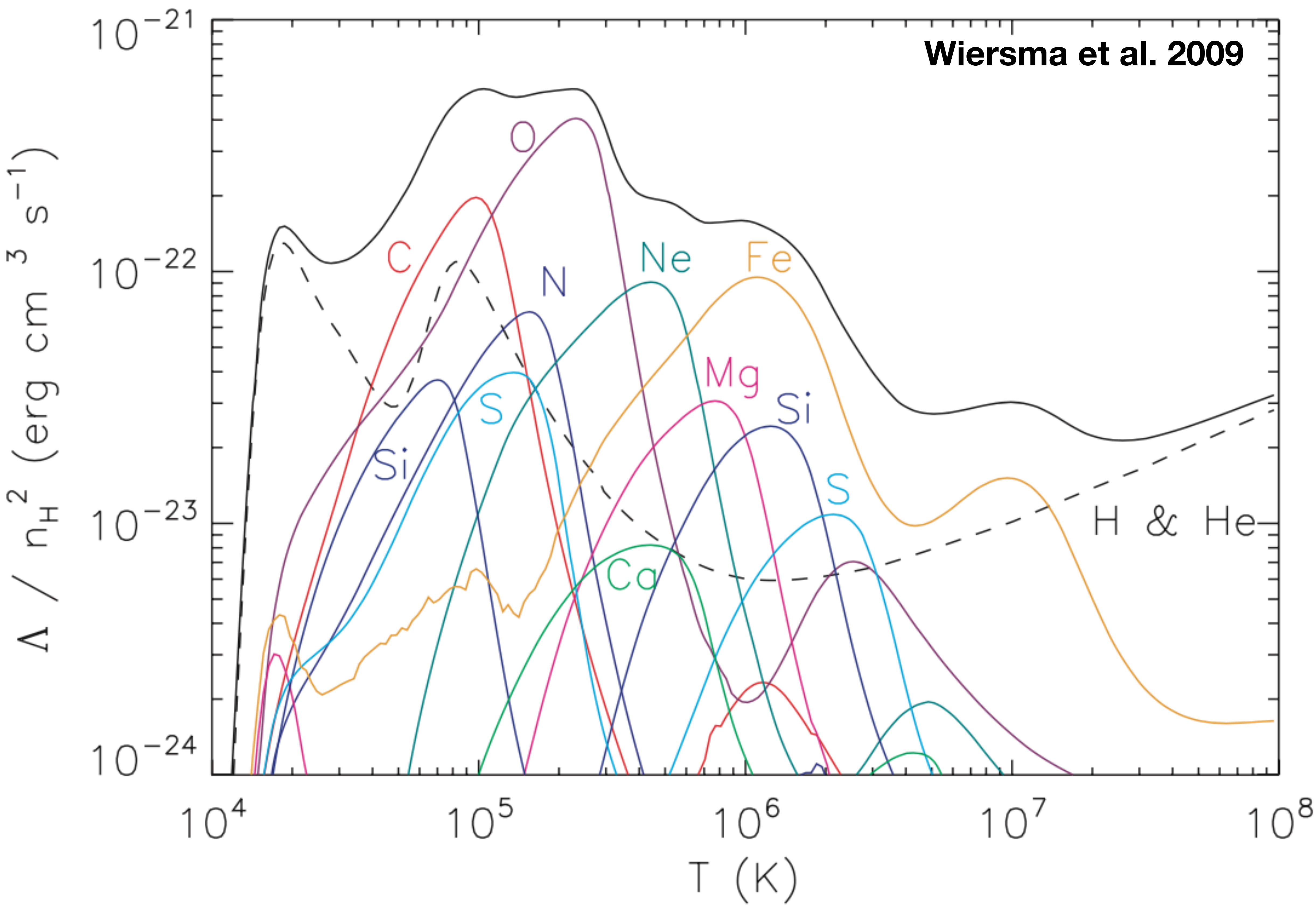
- **Cooling Rate** Λ
  unit: erg/s/cm^3
- Hydrogen Density n_H
  unit cm^{-3}
- **Cooling Function:**
  $\Lambda_N \equiv \Lambda / n_H^2$
  unit: erg/s cm^3
- **Normalization** makes cooling function depend only on T and Z



Contributions from H & He through various mechanisms



Contributions from Metals



Updated Cooling Curve for Solar Metallicity (2009 SPEX)

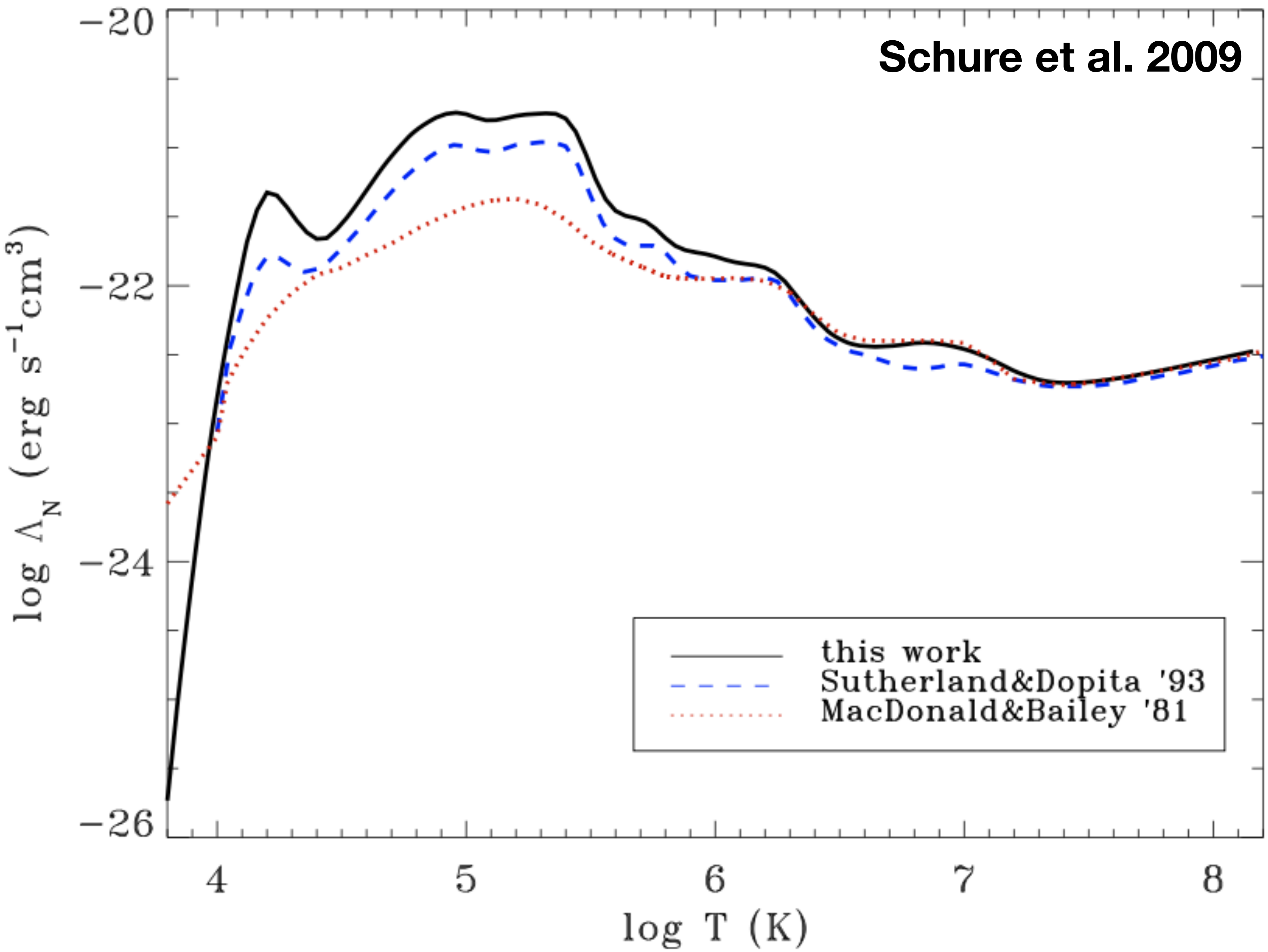


Fig. 1. Cooling curves compared: the higher cooling rates calculated with SPEX are mainly due to a more complete coverage of the line transitions, including Fe L and EUV lines.

Jeans Criteria: acoustic oscillation vs. gravitational collapse

- Based on continuity equation (mass conservation), Euler's equation (momentum conservation), and Poisson Equation (density-potential pair), the evolution of a density perturbation ($\delta \equiv \rho - \rho_0$) is described by this DE:

$$\frac{\partial^2 \delta}{\partial t^2} = c_s^2 \nabla^2 \delta + 4\pi G \rho_0 \delta$$

- Plug in the general solution $\delta = \bar{\delta} e^{i(\vec{k}\cdot\vec{x} - \omega t)}$, so that $\partial\delta/\partial t = -i\omega\delta$, $\vec{\nabla}\delta = i\delta\vec{k}$ one can obtain the **dispersion relation**:

$$\omega^2(k) = c_s^2 k^2 - 4\pi G \rho_0$$

The solution has the following scenarios:

  - when $\omega^2 > 0$, the perturbation oscillates in time (**acoustic oscillations**)
  - when $\omega^2 < 0$, the perturbation grows exponentially (**Jeans criteria**)

- **Jeans (minimum) length:**

$$\lambda_J = \frac{2\pi}{k_J} = \sqrt{\frac{\pi c_s^2}{G\rho_0}} = \sqrt{\frac{32}{3}} c_s t_{ff} = \sqrt{\frac{32}{3}} \sqrt{\frac{3\pi}{32 G\rho_0}} \sqrt{\frac{\gamma k T}{\mu m_H}} \propto \left(\frac{15kT}{4\pi G \mu m_H \rho_0} \right)^{\frac{1}{2}}$$

- **Jeans (minimum) mass:**

$$M_J = \frac{4\pi}{3} \rho_0 \lambda_J^3$$

But free-fall time is only relevant when it is longer than cooling time

- **Cooling timescale** is the ratio between thermal energy density $(3nkT/2)$ and cooling rate $[n_H^2 \Lambda_N(T,Z)]$:

$$t_{\rm cool} = \frac{2kT_\Delta}{\mu n_H \Lambda_N(T,Z)} \text{ where } \mu(T,Z) \equiv \frac{\rho/n}{m_p} \text{ (mean molecular weight)}$$

- **Free-fall timescale** is:

$$t_{\rm ff} = \left(\frac{3\pi}{32G\rho_m}\right)^{1/2} \text{ where } \rho_m \text{ is the total density (DM + baryon)}$$

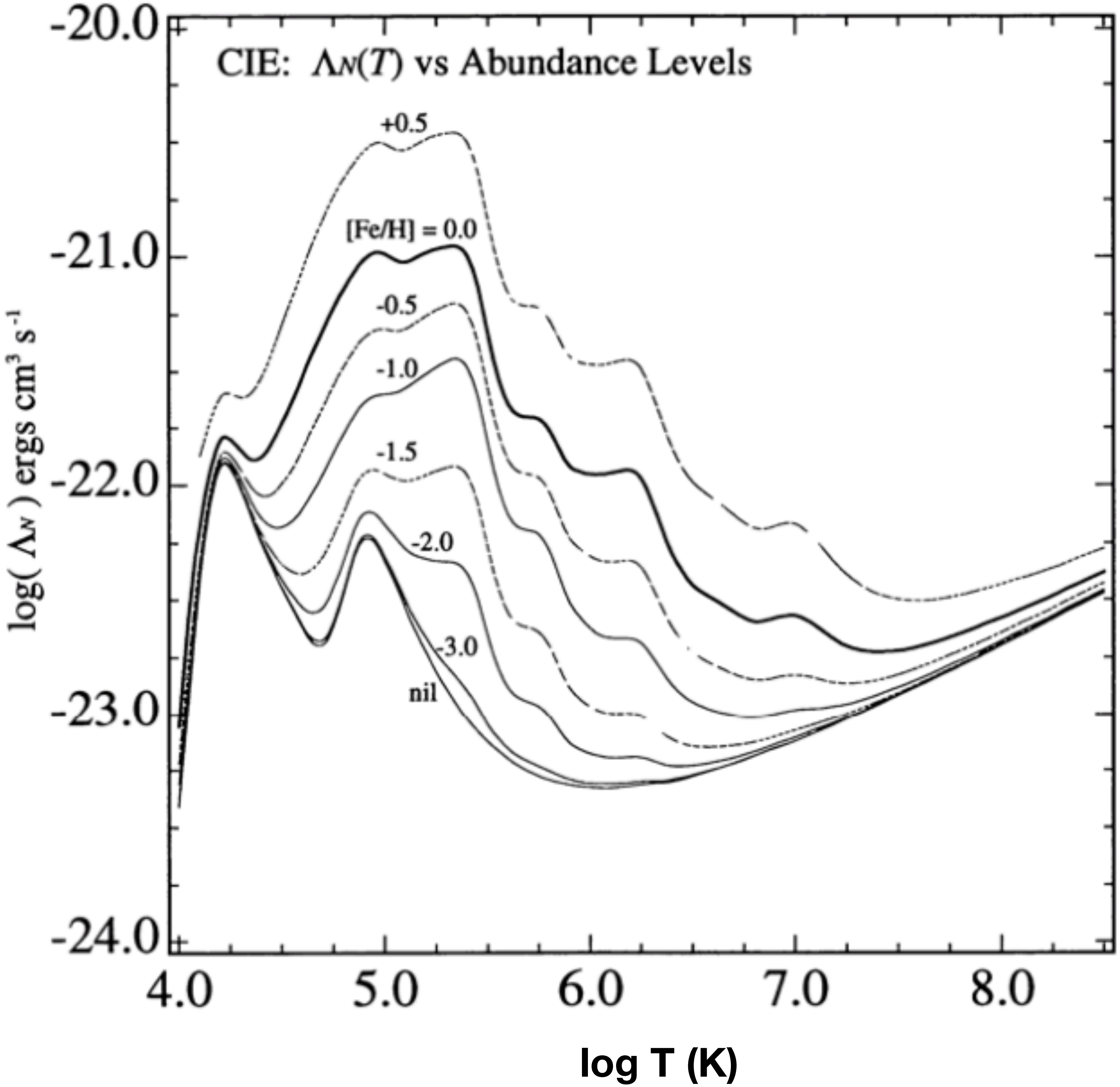
- The total mass density for **H:He** mass ratio of 3:1 is:

$$\rho_m = \frac{4}{3} n_H m_p / f_{\rm gas} \text{ where } f_{\rm gas} = \Omega_{b,0}/\Omega_{m,0} \approx 0.157$$

- **Catastrophic cooling** occurs when $t_{\rm cool} < t_{ff}$, which leads to a **H density threshold** above which baryons contracts rapidly in a halo:

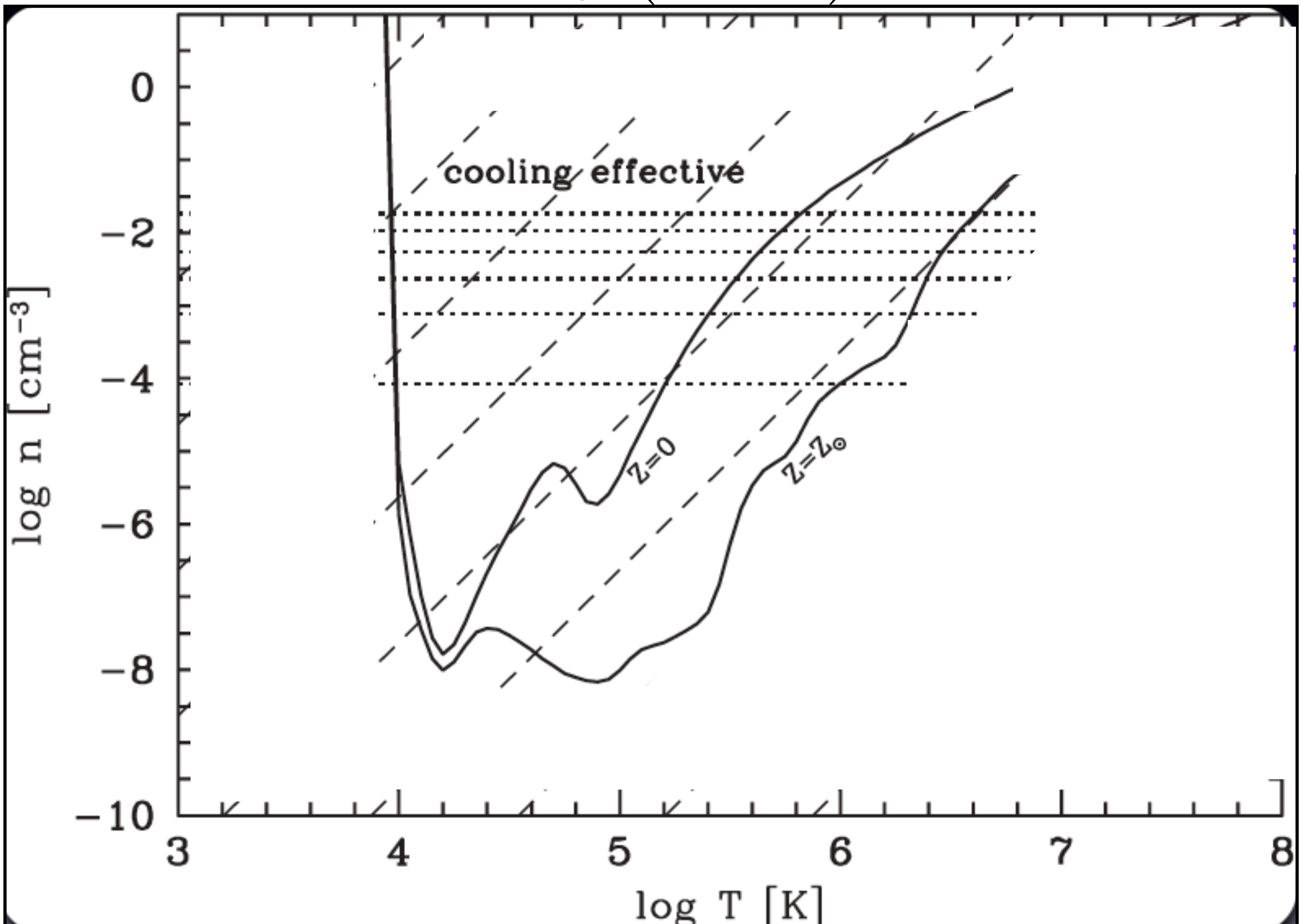
$$n_H^{cc} = \frac{2^9 G m_p}{9\pi f_{\rm gas}} \left(\frac{kT_\Delta}{\mu \Lambda_N(T_\Delta, Z)}\right)^2$$

Given cooling function $\Lambda_N(T, Z)$, imagine $T/\Lambda_N(T, Z)$



Density Threshold vs. Temperature for zero and Solar metallicities

$$n_H^{cc} = \frac{2^9 G m_p}{9\pi f_{\rm gas}} \left(\frac{k T_\Delta}{\mu \Lambda_N(T_\Delta, Z)} \right)^2$$



Mo, van den Bosch, White (2010), Cambridge Press

Virial Radius Expressed Directly with Virial Mass

- Previously, we derived the expressions of the virial radius and virial mass for a given halo **density profile** and mean density contrast $\Delta_c \approx 200$. e.g., for **SIE profile**:
  $\rho(r) = \delta_c \rho_c(z_v)(r/r_s)^{-2}$
  we derived for the homework:
  $$r_\Delta = r_s \sqrt{\frac{3\delta_c}{\Delta_c}\frac{\rho_c(z_v)}{\rho_c(z)}} = r_s \sqrt{\frac{3\delta_c}{\Delta_c}} \left(\frac{1+z_v}{1+z}\right)^{3/2}$$
  $$M_\Delta = 4\pi r_s^3 \delta_c \rho_c(z_v) x_\Delta = 4\pi r_s^3 \delta_c \rho_{c,0}(1+z_v)^3 \sqrt{\frac{3\delta_c}{\Delta_c}} \left(\frac{1+z_v}{1+z}\right)^{3/2}$$
- Here express virial radius for a given virial mass **without assuming any density profile** given $\bar{\rho}(r_\Delta) = \Delta_c \rho_m$:
  $$r_\Delta = \left(\frac{3M_\Delta}{4\pi\Delta_c\rho_m}\right)^{1/3} = \left(\frac{2GM_\Delta}{\Delta_c\Omega_m H^2}\right)^{1/3} = \left(\frac{2GM_\Delta}{\Delta_c\Omega_{m,0}H_0^2}\right)^{1/3} (1+z)^{-1}$$

Virial Velocity & Virial Temperature Expressed Directly with Virial Mass

- **Virial radius:**

$$r_\Delta = \left(\frac{2GM_\Delta}{\Delta_c \Omega_{m,0} H_0^2}\right)^{1/3} (1+z)^{-1} \propto M_\Delta^{1/3}(1+z)^{-1}$$

- **Virial (circular) velocity:**

$$V_\Delta = \sqrt{\frac{GM_\Delta}{r_\Delta}} = (\Delta_c \Omega_{m,0} H_0^2/2)^{1/6} (GM_\Delta)^{1/3} (1+z)^{1/2}$$

- **Virial Temperature:**

$$T_\Delta = \frac{\mu m_p}{2k} V_\Delta^2 \propto M_\Delta^{2/3}(1+z)$$

note: $\frac{1}{2}\mu m_p V_\Delta^2 = kT_\Delta \neq \frac{3}{2} kT_\Delta$ because it's **circular** not **rms** vel.

- **Virial temperature** is defined as the temperature of self-gravitating isothermal gas in hydrostatic equilibrium**.** It is **preserved** for a **non-evolving halo** because $M_\Delta \propto r_\Delta \propto (1+z)^{-3/2}$. It is also the **expected temperature of baryons** in the halo once shock-heated.

CC Density Threshold vs. Halo Gas Density and Temperature

- Catastrophic cooling occurs when $t_{\rm cool} < t_{ff}$, which leads to a **hydrogen density threshold** above which baryons cool rapidly in a halo:

$$n_H^{cc} = \frac{2^9 G m_p}{9\pi f_{\rm gas}} \left(\frac{kT_\Delta}{\mu \Lambda(T_\Delta, Z)} \right)^2$$

- This threshold is then compared to the **mean hydrogen density** of the halo to decide the mass range of the halos over which galaxies form:

$$\frac{4}{3} n_H^\Delta m_p = \rho_b^\Delta = \Delta_c f_{\rm gas} \rho_{c,0} \Omega_{m,0} (1+z)^3$$

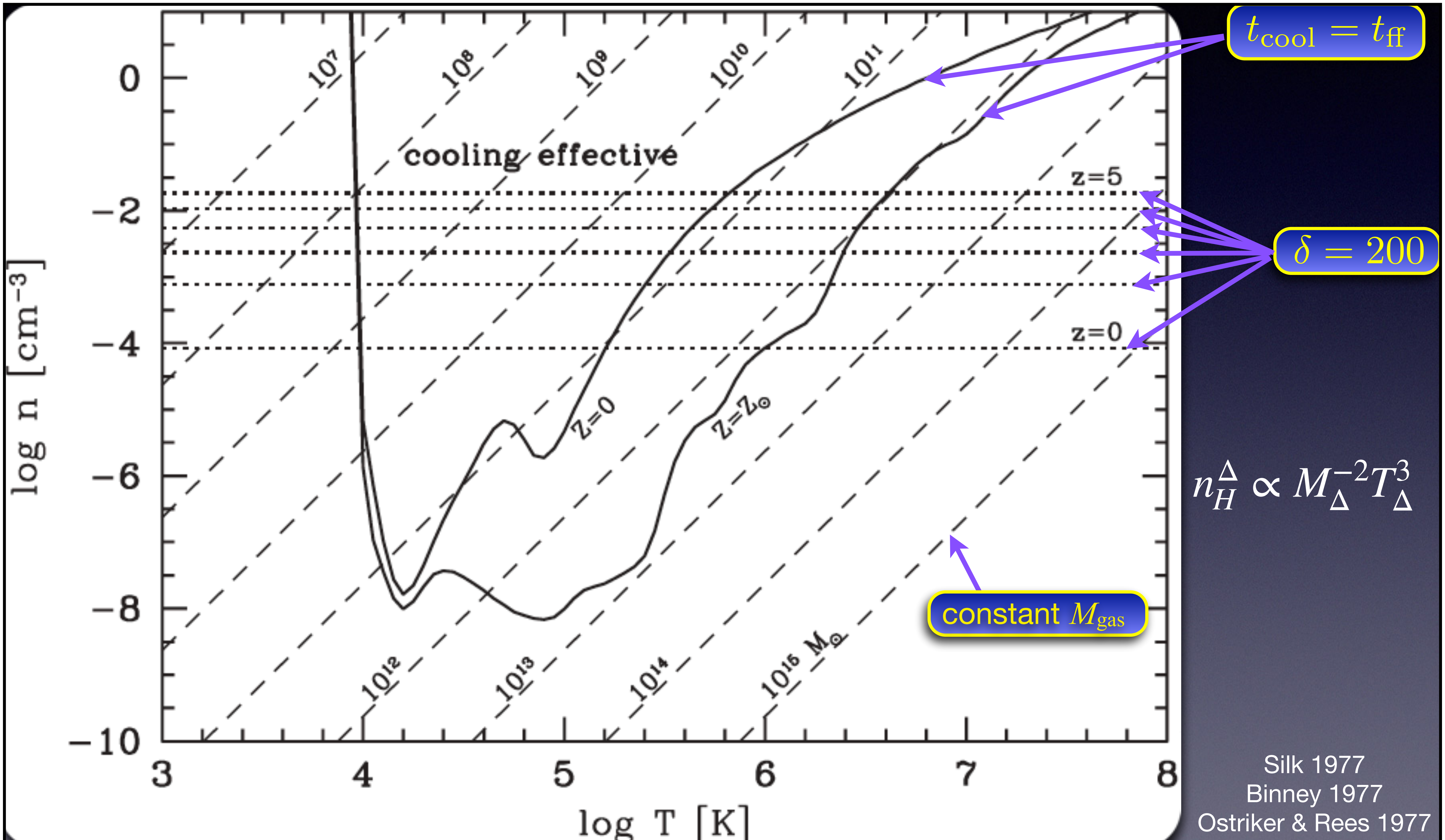
given the definition of virial radius, halos of all masses at a given redshift should have the same mean density!

- The **mean density** can be expressed with virial mass and virial temperature given that $T_\Delta \propto M_\Delta^{2/3}(1+z)$ and $n_H^\Delta \propto (1+z)^3$:

$$\left(\frac{n_H^\Delta}{0.04 cm^{-3}} \right) = \left(\frac{M_\Delta}{10^8 M_\odot} \right)^{-2} \left(\frac{T_\Delta}{10^4 K} \right)^3$$

CC Density Threshold vs. Halo Gas Density and Temperature

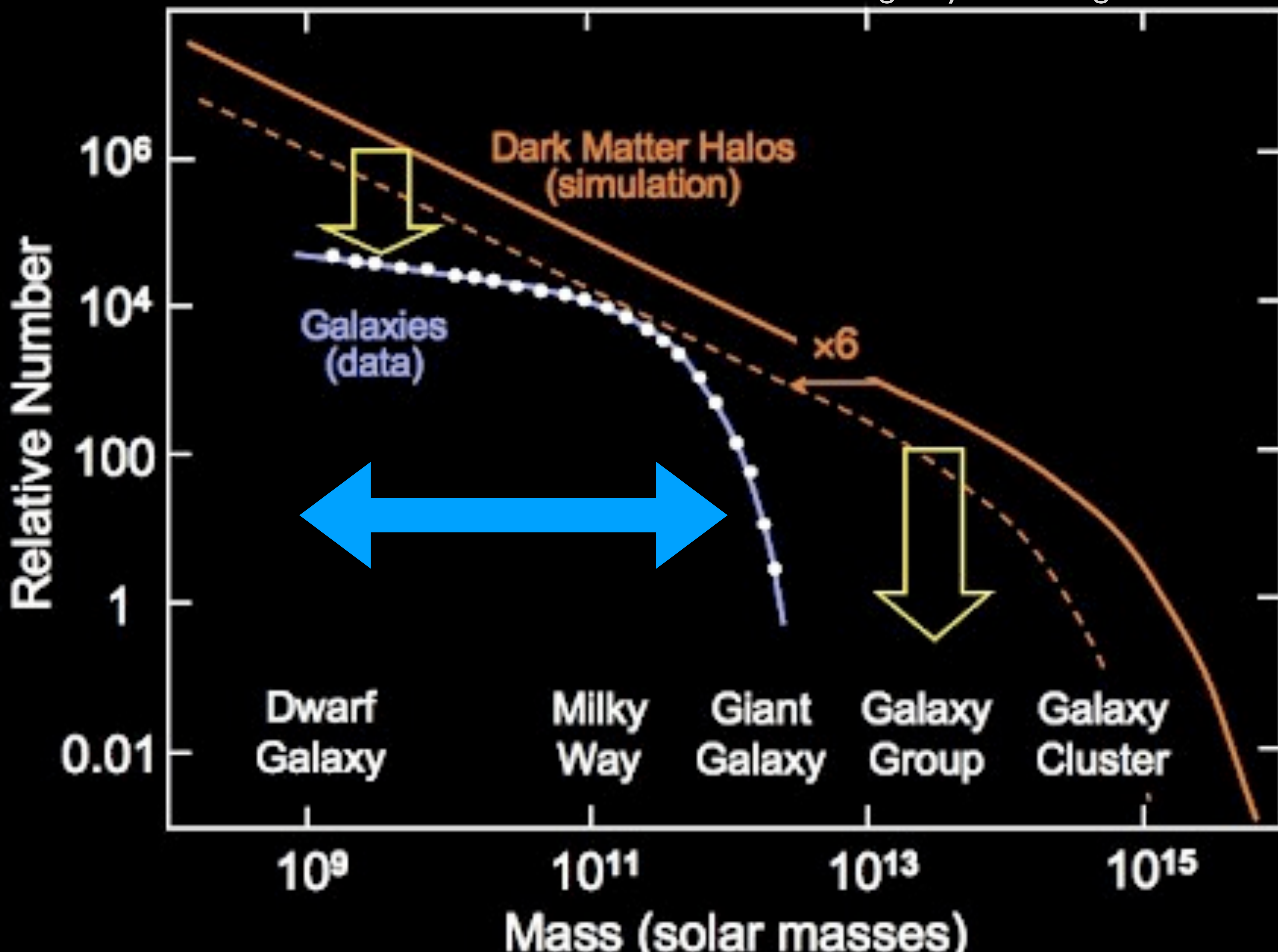
For solar-metallicty gas, efficient cooling at 0 < z < 5 occurs in halos between $10^9 M_\odot < M_{gas} < 10^{12} M_\odot$



Mo, van den Bosch, White (2010), Cambridge Press

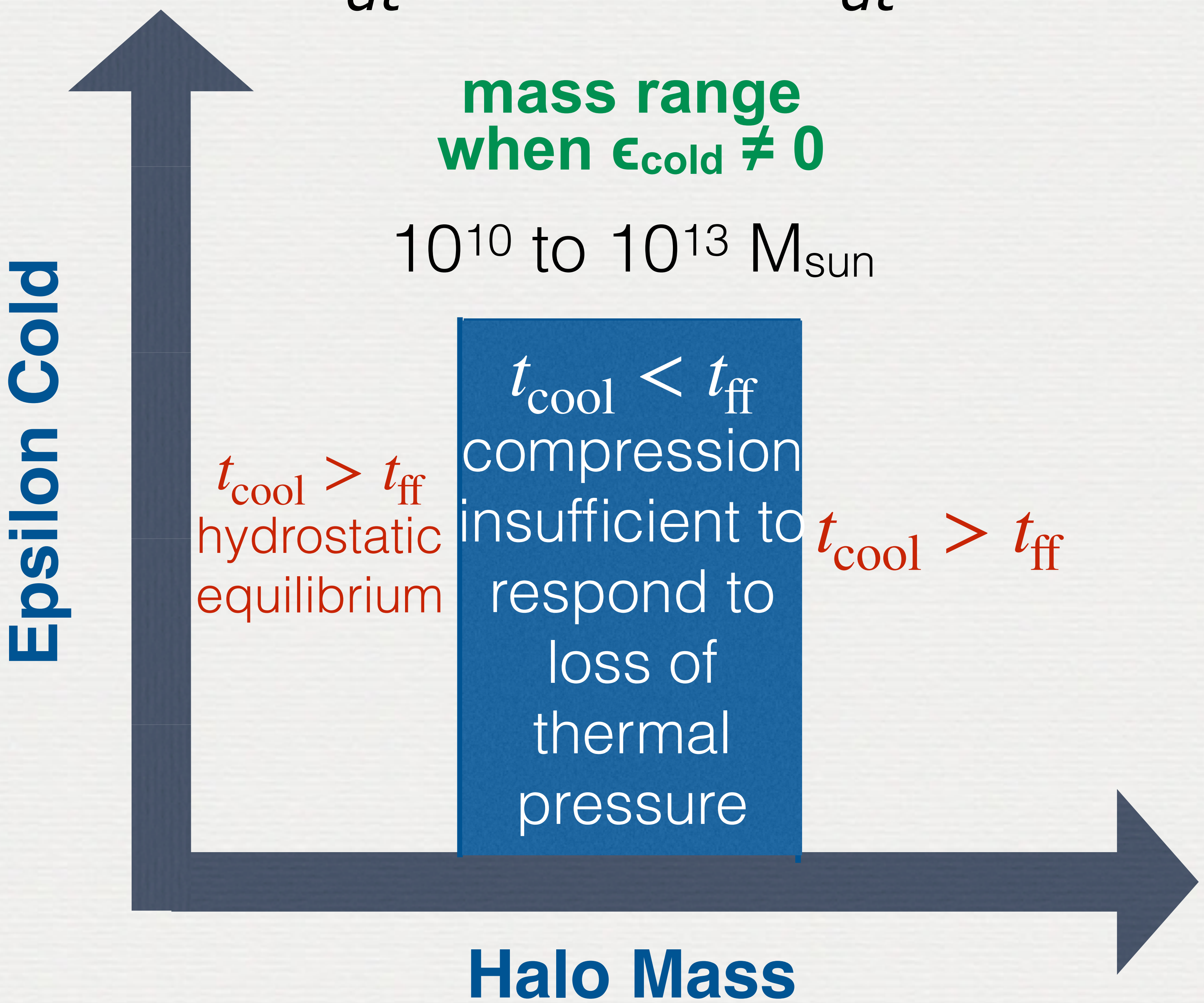
For solar-metallicty gas, efficient cooling at 0 < z < 5 occurs in halos between $10^9 M_\odot < M_{gas} < 10^{12} M_\odot$

which seems to match that of the observed galaxy mass range



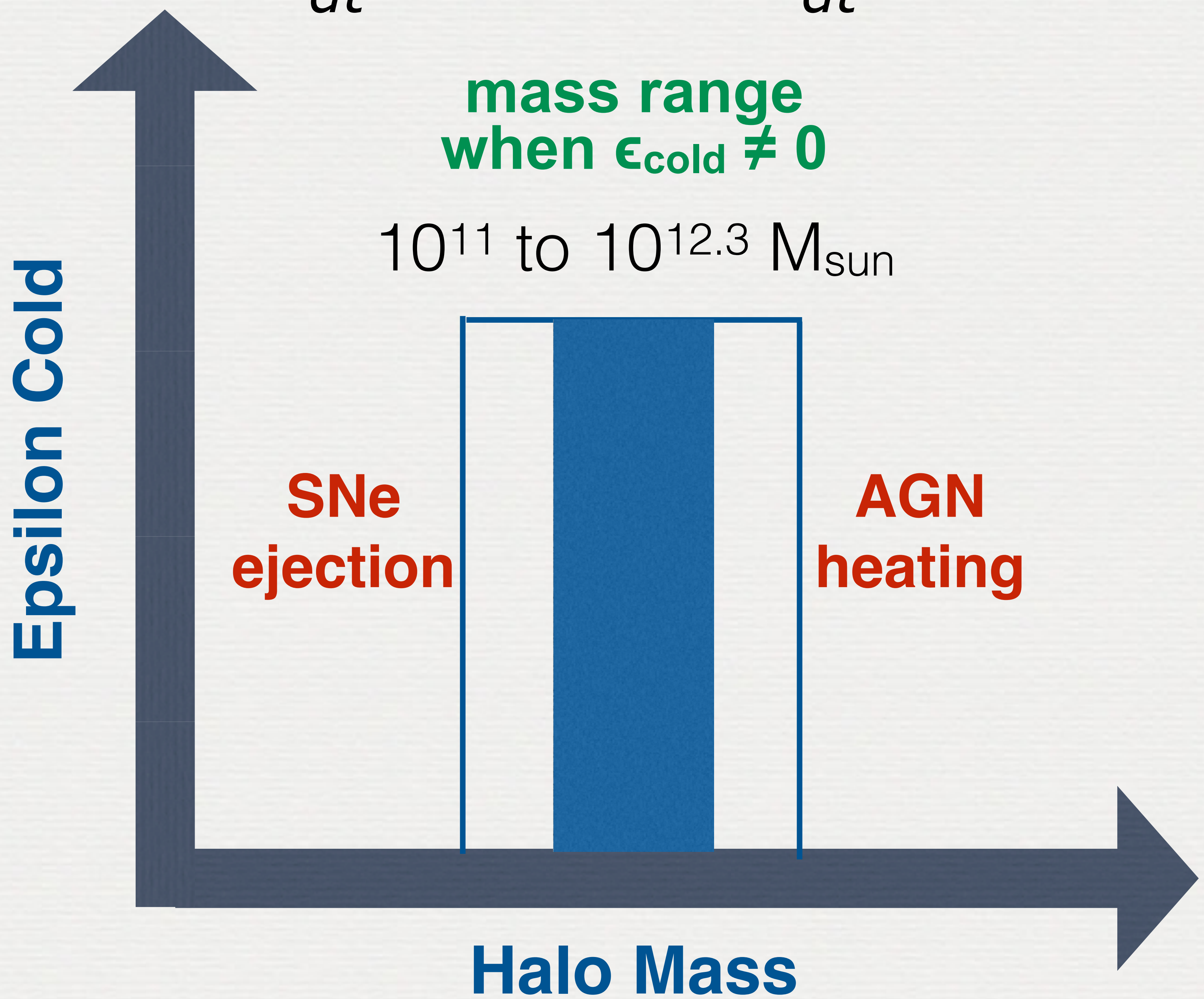
The Cold Gas Accretion Rate

$$\frac{dM_{\mathrm{gas}}}{dt} = \epsilon_{\mathrm{cold}} f_{\mathrm{baryon}} \frac{dM_{\mathrm{halo}}}{dt}$$

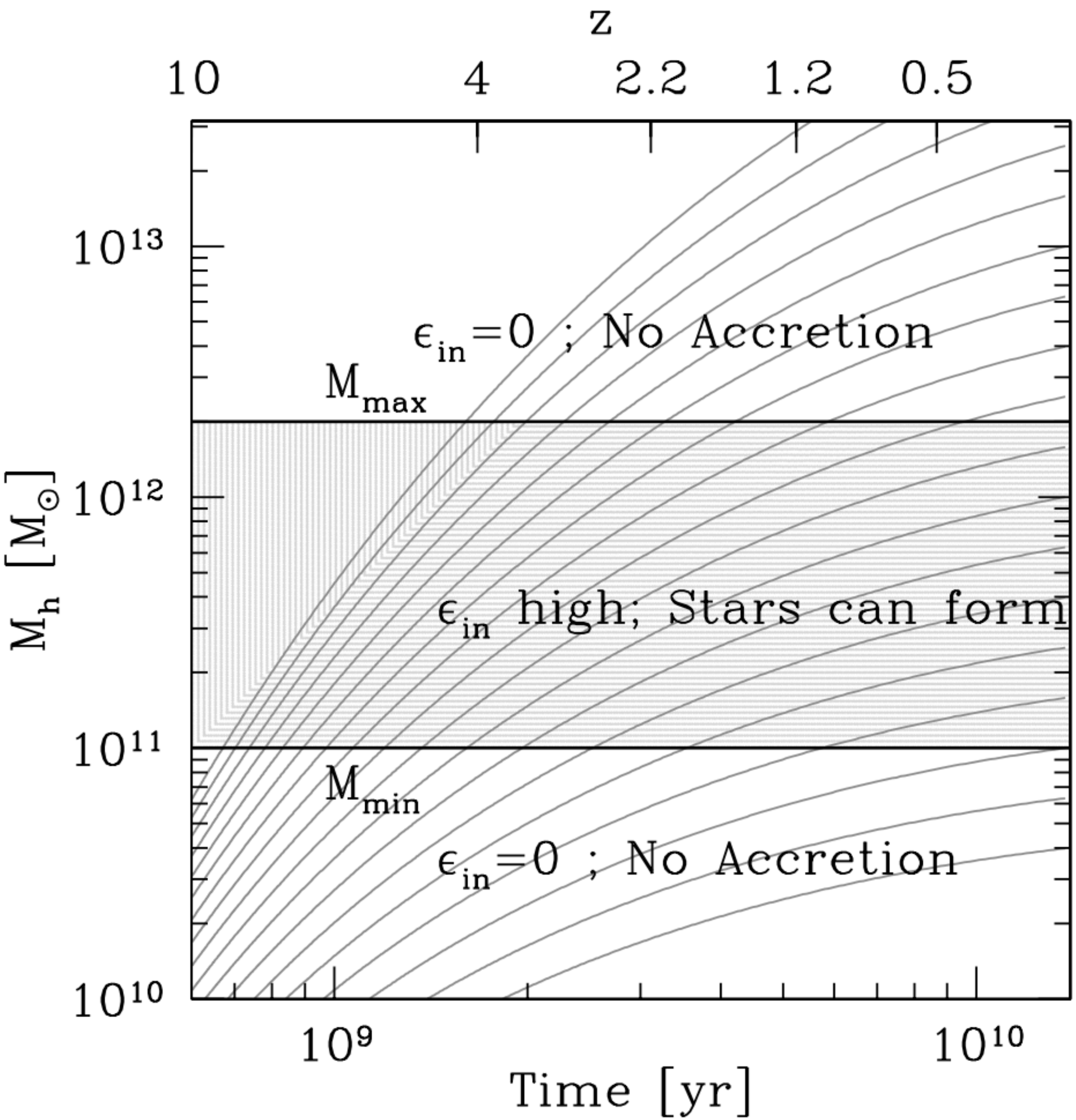


The Cold Gas Accretion Rate

$$\frac{dM_{\rm gas}}{dt} = \epsilon_{\rm cold} f_{\rm baryon} \frac{dM_{\rm halo}}{dt}$$

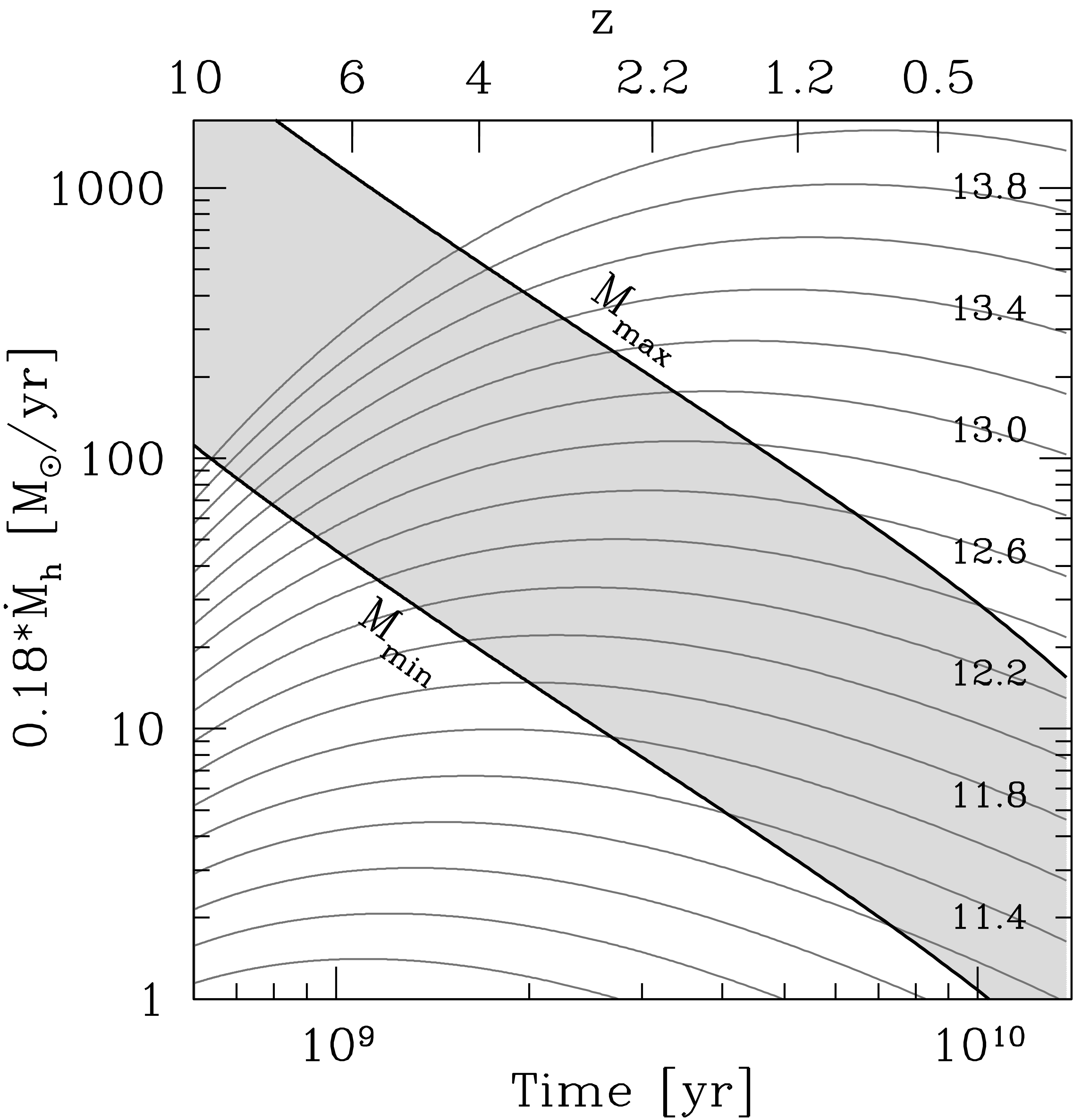


Halo mass vs. redshift & time



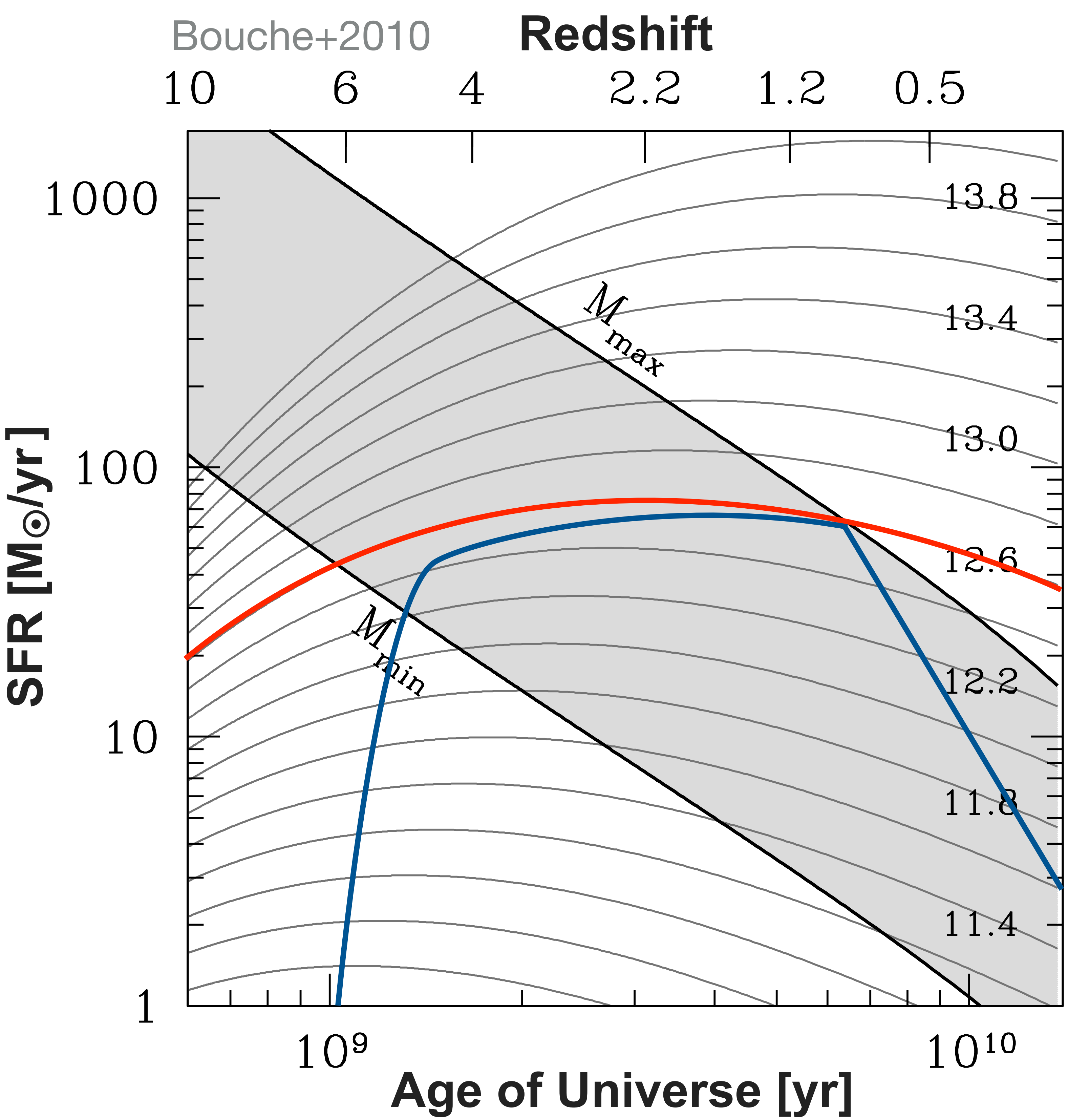
Bouche+2010

Halo growth rate vs. redshift & time



Bouche+2010

Accretion-Driven Star Formation History



- **Grey region**: efficient cold gas accretion **$10^{11} < M_{Halo} < 1.5 \times 10^{12}\ M_\odot$**
- **Gas accretion history** of a $10^{12.6}\ M_\odot$ halo (mass at $z = 0$)
- **Star formation history** from the continuity equation:

1. Once the halo crosses the minimum mass (**$10^{11}\ M_\odot$**), the SFR rapidly rises to reach a steady state;
2. As the halo mass reaches **$10^{12.3}\ M_\odot$**, cold gas accretion is choked and the SFR starts to decline with an e-folding time of **2-3 Gyr (=2 τ_{dyn}/ϵ_{SF})**.