Killing Dwarfs with Hot Pancakes

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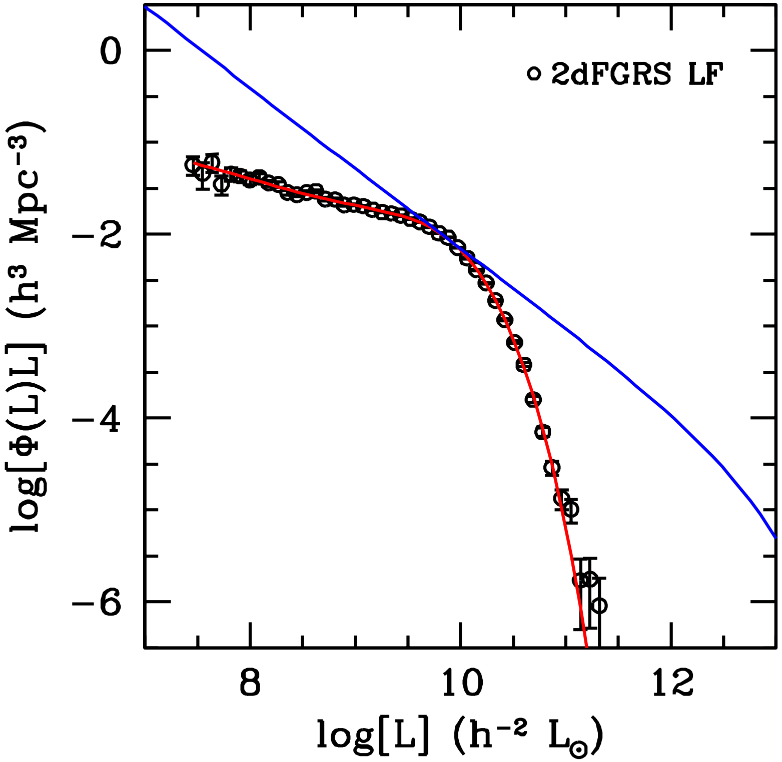
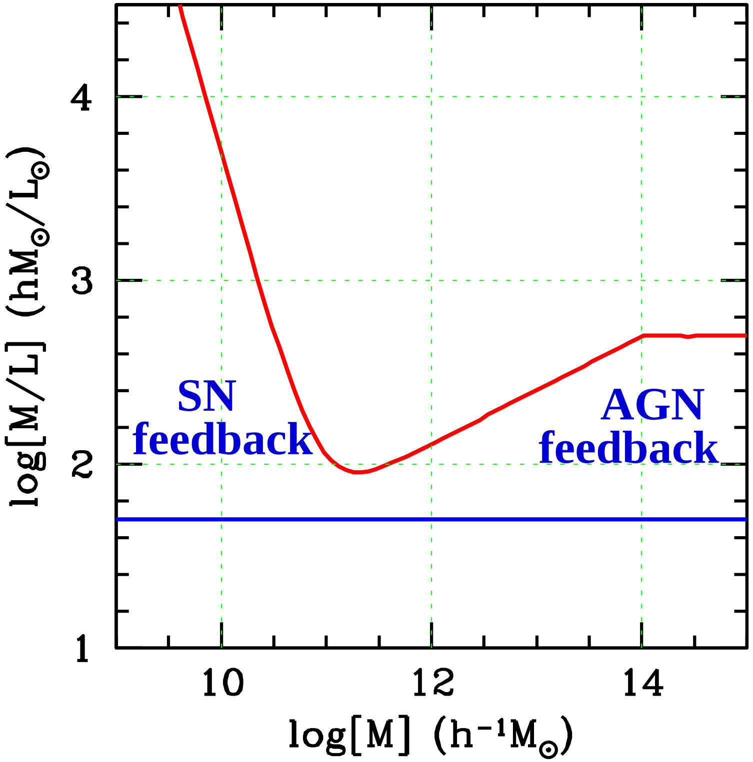
The Paradigm...





- **The halo mass function is much steeper than luminosity function**
- **Galaxy Formation has to become inefficient in low mass haloes**
- **In the standard paradigm this is interpreted as due to SN feedback**
- **Since binding energy is lower in less massive haloes, and each SN produces a constant energy of $\sim 10^{51}\mathrm{erg}$, SN feedback is indeed expected to effect less massive haloes more strongly.**

and why it is wrong

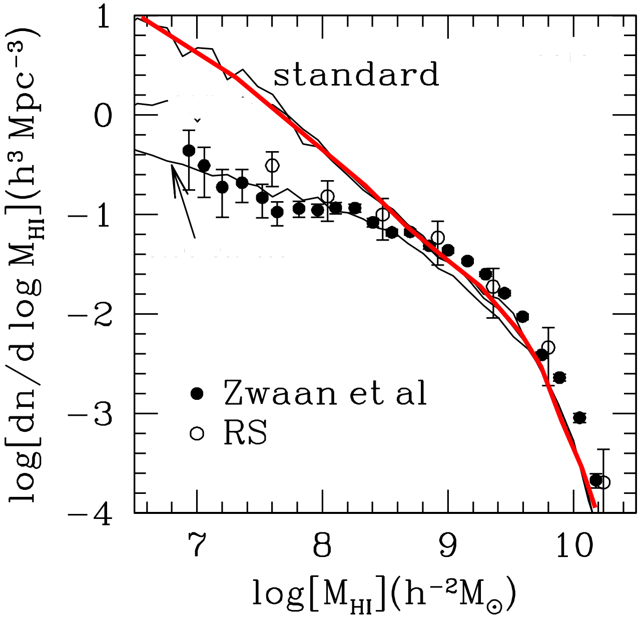
- **To keep the gas hot, you need to continuously inject it with energy As soon as energy ejection comes to halt, gas will cool.**
- **In order to have SN, you need to form stars**
- **In order to form stars, you need high column densities of HI**

$$\boxed{\Sigma_{\mathrm{gas}} > \Sigma_{\mathrm{crit}} = \frac{\sigma_{\mathrm{gas}}\kappa}{\pi\, G\, Q_{\mathrm{crit}}}}$$

(Kennicutt 1989)

One expects that (disk) galaxies have a cold gas mass equal to

$$M_{\mathrm{gas}} \simeq 2\pi \int \Sigma_{\mathrm{crit}}(R)\, R\, \mathrm{d}R$$



Starting from halo mass function, and assuming each halo has cold gas mass equal to M_{gas}, severely overpredicts the HI mass function!!!

SN feedback can be tuned to fit galaxy luminosity function, but it can not simultaneously match the HI mass function

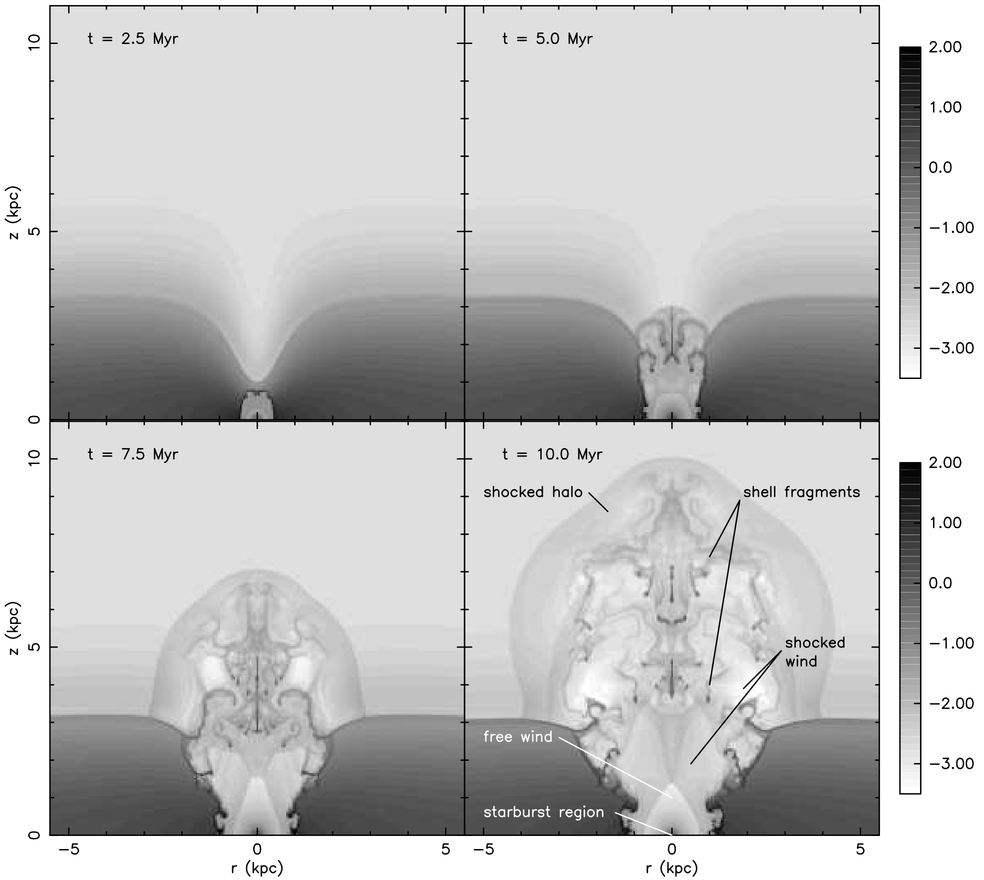
(Data: RS=Rosenberg & Schneider 2002)

and wrong

In low mass haloes, SN feedback is required to blow away (or keep hot) more than 90 percent of all baryons

Detailed, hydrodynamical simulations, however, show that mass ejection efficiency is very low, contrary to the ejection efficiency of metals and energy

(Mac-Low & Ferrara 1999; Strickland & Stevens 2000)



Mass loading efficiency of galactic winds is low because of onset of Rayleigh-Taylor and Kelvin-Helmholtz instabilities

Wind “bursts open”, hot (metal-rich) gas escapes but momentum of cold “loaded” gas stalls.

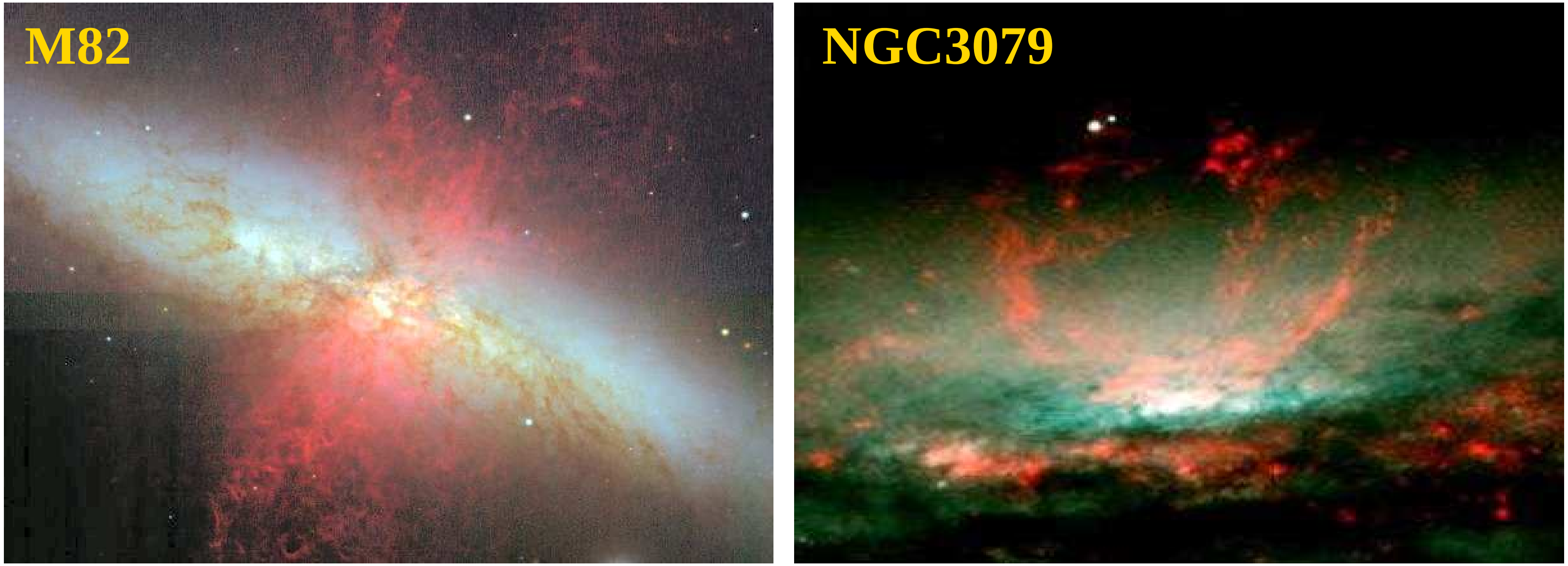
(From Strickland & Stevens 2000)

and wrong

Even in the most extreme cases (starbursting dwarfs), the observed mass outflow rate is about twice the star formation rate

(Martin 1999; Heckman et al. 2000)

One can at most blow out ~ 66 percent of all baryons!



Furthermore, Semi-Analytical Models require efficiencies with which SN energy is thermalized that are unrealistic or even unphysical

(e.g., Benson et al. 2003)

In case you didn’t get it

SN feedback is NOT the main physical mechanism that explains the faint-end slope of the LF

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QUESTION: but then what is the physical mechanism?

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QUESTION: **but then what is the physical mechanism?**

ANSWER:

The Cosmic Baryon Budget

The WMAP measurements of the CMB have constrained the baryonic and total matter densities to be

$$\boxed{\Omega_b h^2 = 0.024 \pm 0.001 \qquad \Omega_m h^2 = 0.14 \pm 0.02}$$

(Spergel et al. 2003)

This implies a Universal baryon fraction of $\boxed{f_{\rm bar} = \Omega_b/\Omega_m = 0.17}$

On large scales, we expect the baryons and dark matter to be well mixed

Within individual haloes, shocks and cooling are expected to have partially segregated the baryons from the dark matter.

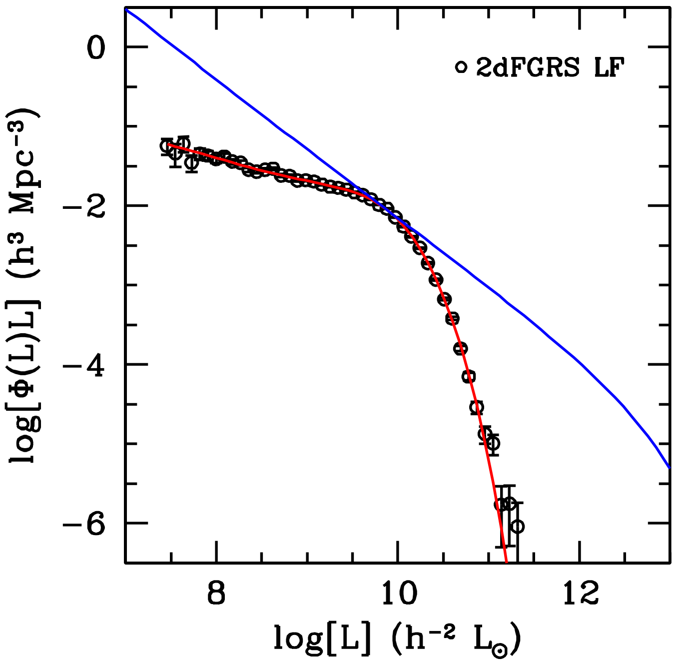
However, in the absence of feedback (galactic winds) one still expects that each halo has a baryonic mass fraction of $f_{\rm bar} \simeq 0.17$

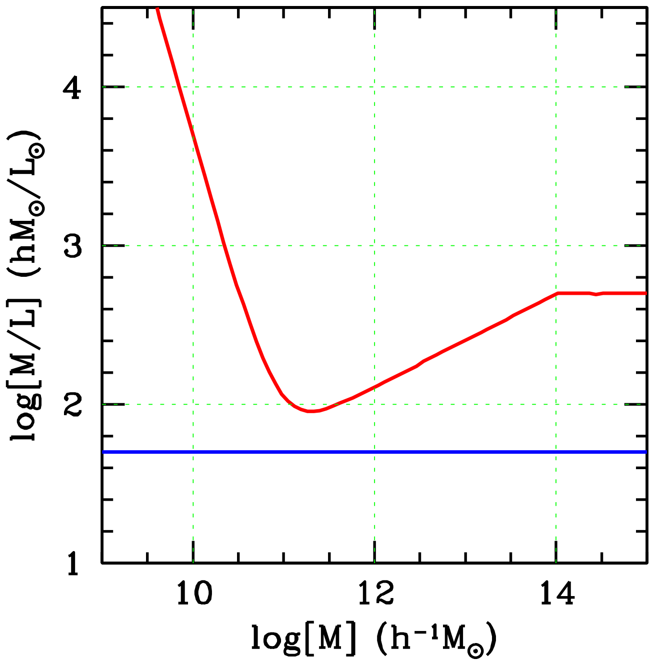
Baryons come in the form of:

- stars plus their remnants
- cold gas; both atomic & molecular
- hot gas (plasma)

How are the baryons distributed among these different components?

The stellar mass fraction





With an average total mass-to-light ratio of $M/L_B \sim 200$ and an average stellar mass-to-light ratio of $M_*/L_B \sim 5$ we obtain

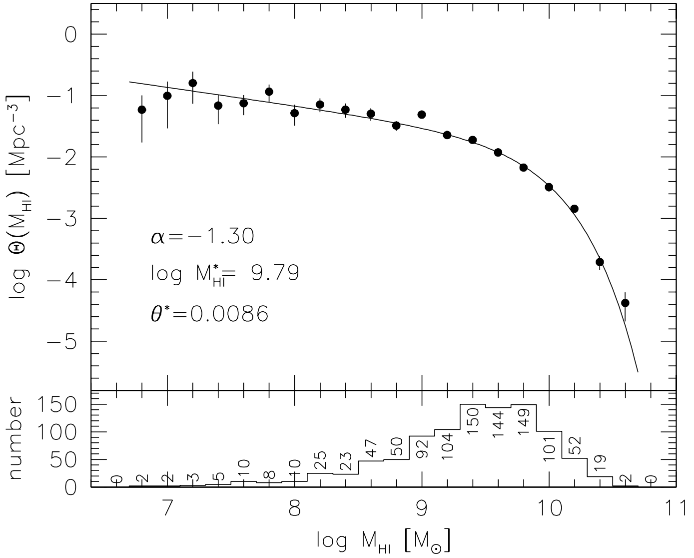
$$\langle \frac{M_*}{M} \rangle = \langle \frac{M_*}{L_B} \rangle \cdot \langle \frac{L_B}{M} \rangle \simeq \frac{5}{200} = 0.025$$

Only ~ 15 percent of all baryons are in stars

NOTE: a similar result is obtained when integrating the LFs of disks and spheroids and multiplying by their respective stellar mass-to-light ratios

(Fukugita, Hogan & Peebles 1998)

Cold & Hot Gas



The matter density in neutral Hydrogen can be obtained from integrating the HI mass function.

Multiply by 1.32 to account for Helium

Multiply by 1.8 to account for Molecules

(Data from Zwaan et al. 2003)

Only $\sim$ 3 percent of the baryons are in cold gas

The matter density in hot gas can be obtained from X-ray measurements

Using a constant, measured ratio between the mass of X-ray emitting gas and the gravitational mass of clusters, and integrating over the cluster mass function, yields matter density contributed by hot cluster gas.

Adding contribution from groups, using a similar method, finally yields

About $\sim$ 37 percent of the baryons are in hot, X-ray emitting gas

(Fukigita, Hogan & Peebles 1998)

Where are the baryons?

In summary, observational we have accounted for the following baryons:

Stars	15%
Cold gas	3%
Hot gas	37%
TOTAL	55%

About 45% of expected baryons have not been accounted for observationally

Question: Where are the missing baryons?

- **Stellar Remnants & Machos**
- **Primordial Black Holes**
- **Warm/Hot Intergalactic Medium (WHIM)**

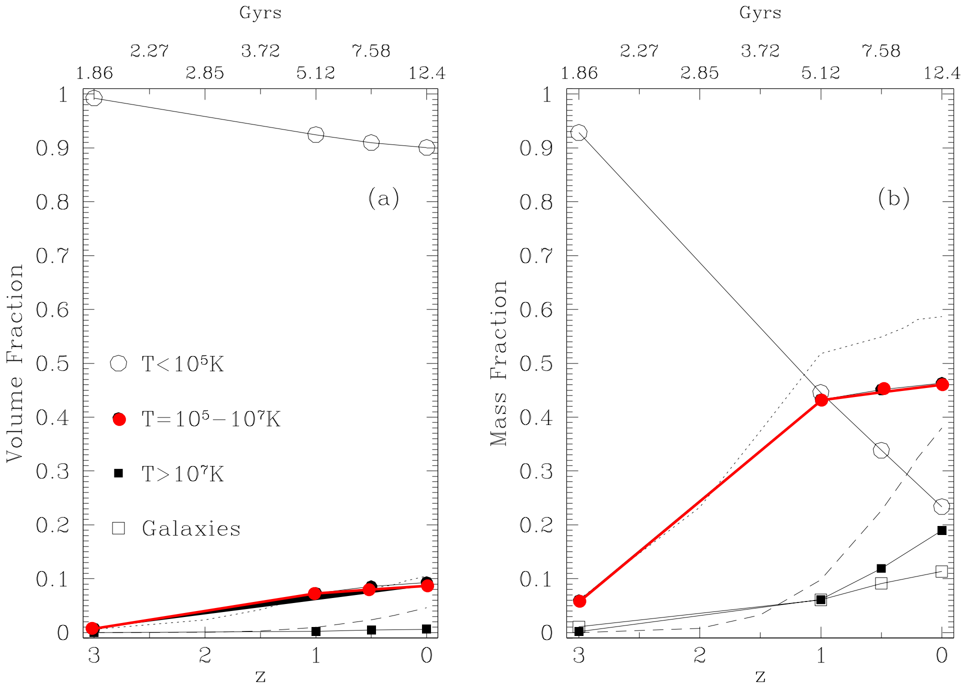
Although the former two options are serious possibilities, we focus on the case of a significant WHIM

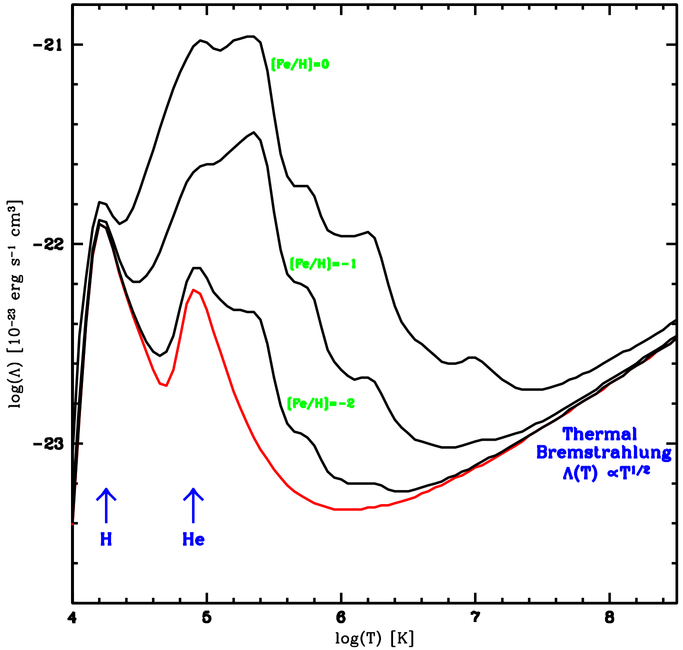
The Warm/Hot Intergalactic Medium

Cosmological hydrodynamical simulations predict that about 45% of the baryons are in WHIM at $z = 0$

This gas is located in pancakes & filaments and heated due to shocks

(From Cen & Ostriker 1999)

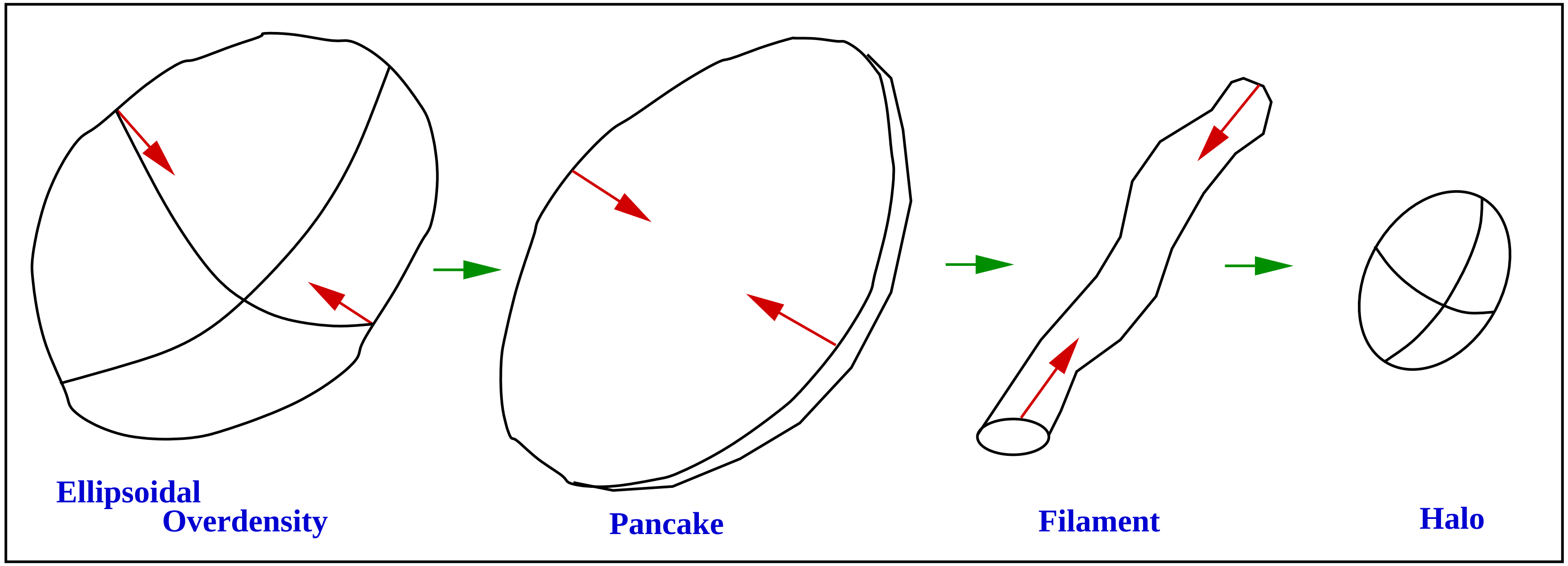




As long as the hot gas has a temperature $10^5\mathrm{K} \lesssim T \lesssim 10^7\mathrm{K}$ and is of sufficiently low density and metallicity, it will not be visible in X-rays

(Cooling Functions from Sutherland & Dopita 1993)

A Recipe for Hot Pancakes



- Structures form by ellipsoidal collapse
- Dark Matter is collisionless ⟶ orbit crossing & virialization
- Baryonic Matter is collisional ⟶ schocking & thermalization

Pancakes & Filaments are expected to be hot

Unless the cooling time in the pancakes is too short, dark matter haloes that form within pancakes, form in a preheated medium.

Pancake Physics

The internal energy density of a baryonic gas is:

$$U_{\rm int} = \frac{3}{2}\frac{\rho_{\rm gas} k_B}{\mu} T$$

The kinetic energy density of system that collapses with velocity $V_{\rm coll}$ is:

$$U_{\rm kin} = \frac{1}{2}\rho_{\rm gas} V_{\rm coll}^2$$

If we consider the strong shock jump condition ($V_{\rm after} = V_{\rm coll}/4$), and assume that kinetic energy is converted into internal energy, then

$$\boxed{T = \frac{3\mu V_{\rm coll}^2}{16 k_B} \propto M_{\rm p}^{2/3}}$$

with $M_{\rm p}$ the pancake mass. The cooling time of this shock-heated gas is:

$$\tau_{\rm cool} = \frac{U}{|{\rm d}U/{\rm d}t|} \simeq \frac{3}{2}\mu \frac{k_B T}{\rho_{\rm gas}\Lambda(T,Z)}$$

The hot pancake will stay hot as long as the cooling time, $\tau_{\rm cool}$, is longer than the Hubble time, $\tau_{\rm Hubble} \propto H^{-1}(z)$

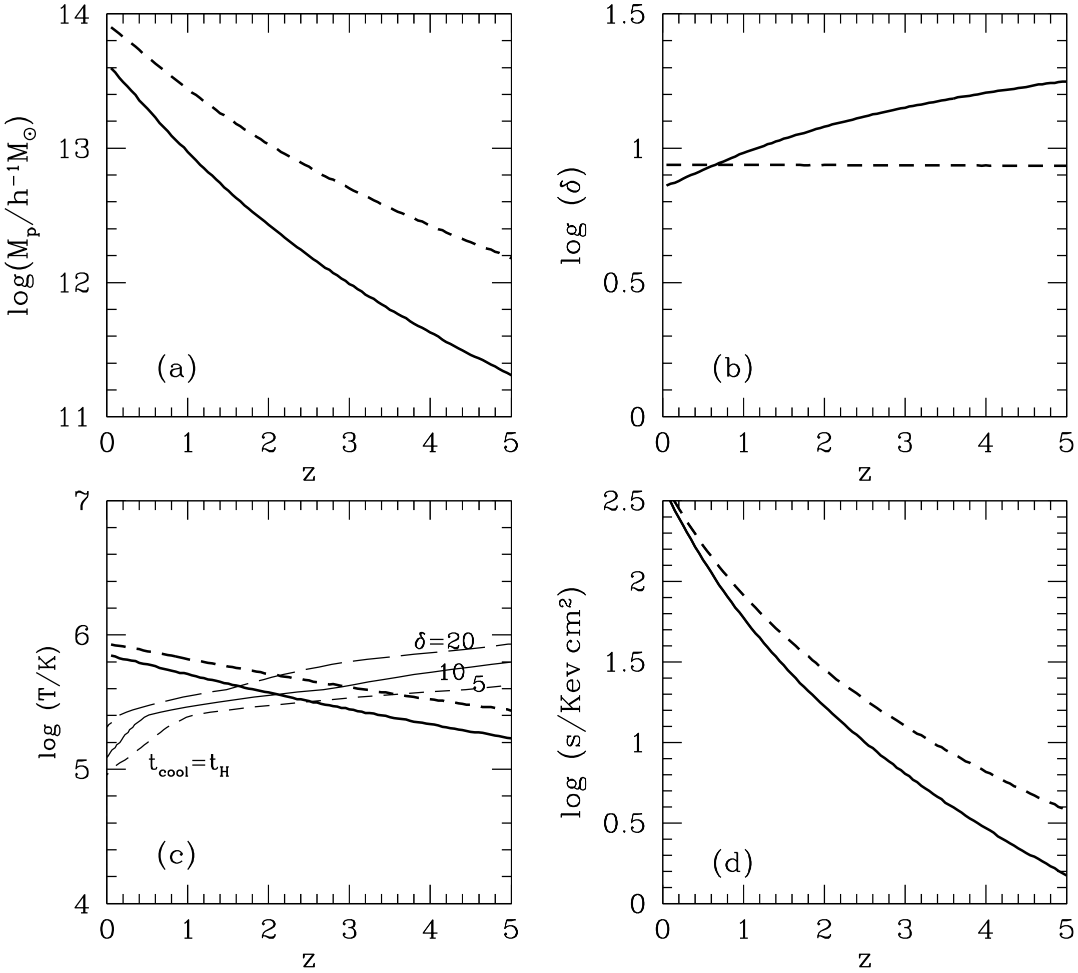
For the density of the gas in the pancakes we can write

$$\rho_{\rm gas} = \delta_{\rm p}\Omega_b \frac{3H_0^2}{8\pi G}(1+z)^3$$

with $\delta_{\rm p} \simeq 10$ the overdensity in the pancake.

More Pancake Physics

What remains is to compute the pancake mass M_p. From ellipsoidal collapse model one can compute mass of pancakes that form around present-day low mass haloes, as function of redshift z



Hot Pancakes, with $M_\mathrm{p} \gtrsim 5 \times 10^{12} h^{-1}\ \mathrm{M}_\odot$, exist for $z \lesssim 2$

The Impact on Galaxy Formation

The specific entropy of the shock heated gas in the pancakes is

$$s = \frac{T}{n_{\rm e}^{2/3}} = 17\,\mathrm{KeV\,cm}^2 \left(\frac{\Omega_b h^2}{0.024}\right)^{-2/3} \left(\frac{T}{10^{5.5}\,\mathrm{K}}\right) \left(\frac{1+\delta}{10}\right)^{-2/3} \left(\frac{1+z}{3}\right)^{-2}$$

Because of its high entropy, the gas is not bound to low mass haloes. Approximately, one finds that

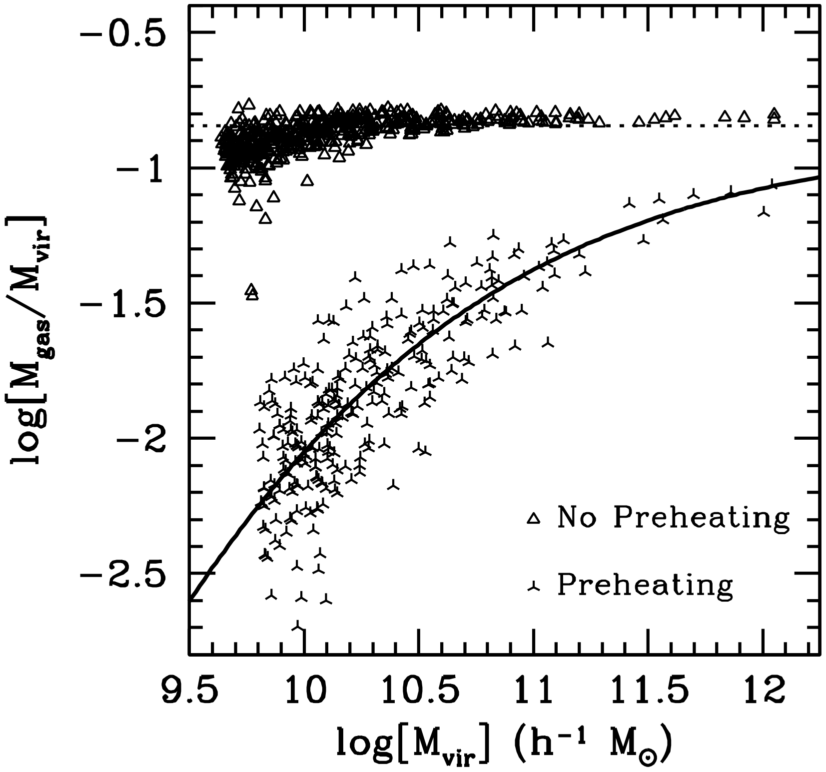
$$\boxed{\frac{M_{\rm bar}}{M_{\rm vir}} \simeq 0.17 \left[1 + \left(\frac{M}{5\times10^{11} h^{-1}\,\mathrm{M}_\odot}\right)^{-1}\right]}$$

Halo formation in preheated medium results in a strong reduction of baryonic mass fraction that can cool.

In particular, galaxy formation in low mass haloes is severly inhibited:

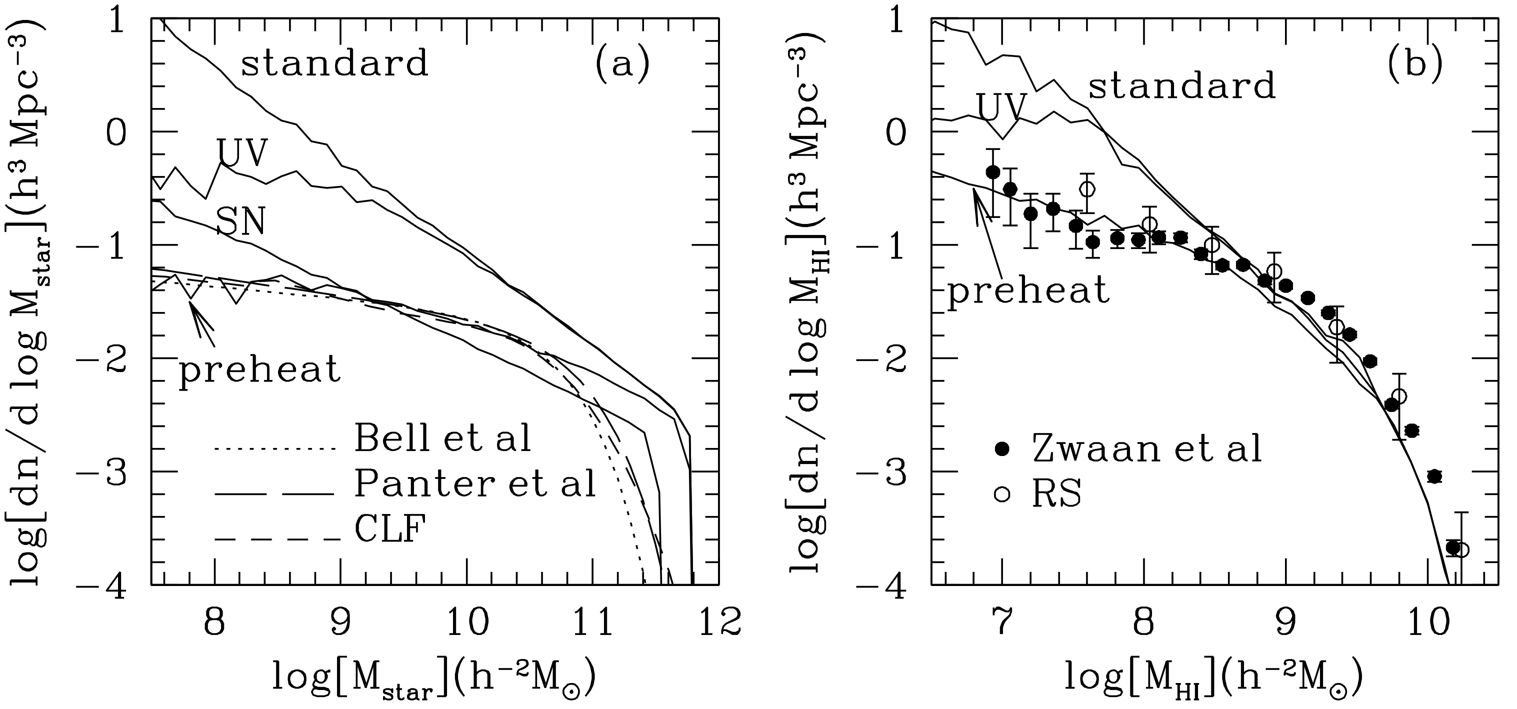
Hot Pancakes kill Dwarfs

(From van den Bosch, Abel & Hernquist 2003)



The Punchline

The baryonic mass fractions predicted for haloes embedded in shock heated pancakes are exactly what is required to fit both the stellar mass function and the HI mass function:



Here $M_{\rm star} = 2\pi \int [\Sigma_{\rm disk}(R) - \Sigma_{\rm crit}] R \,{\rm d}R$

and $M_{\rm gas} = M_{\rm bar} - M_{\rm star}$.

The disk surface density $\Sigma_{\rm disk}(R)$ **is computed using the standard MMW model for disk formation**

Mo, Mao & White 1998

NOTE: No feedback is included here!!!

Conclusions

- Galaxy Formation in extremely inefficient in low mass haloes
- Supernova feedback can not simultaneously explain the stellar mass function and the HI mass function
- Below a redshift $z \simeq 2$, about half the baryons are in a WHIM. This is consistent with simulations, observations, and analytical predictions
- Most low mass haloes form inside preheated pancakes
- The predicted amount of preheating is exactly what is needed to explain the stellar mass function and the HI mass function

Supernova feedback is only efficient at $z \gtrsim 2$

At lower redshifts hot pancakes rule.

For details, see Mo, Yang, van den Bosch & Katz, 2005, MNRAS, 363, 1155