Cold gas in dark halos and the formation of late-type galaxies

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CDM Paradigm of Galaxy Formation

Galaxies form through gas cooling and condensation (**cold gas**) in extended **CDM halos**

A crucial step in understanding galaxy formation is to establish the link between galaxies, cold gas and dark matter halos

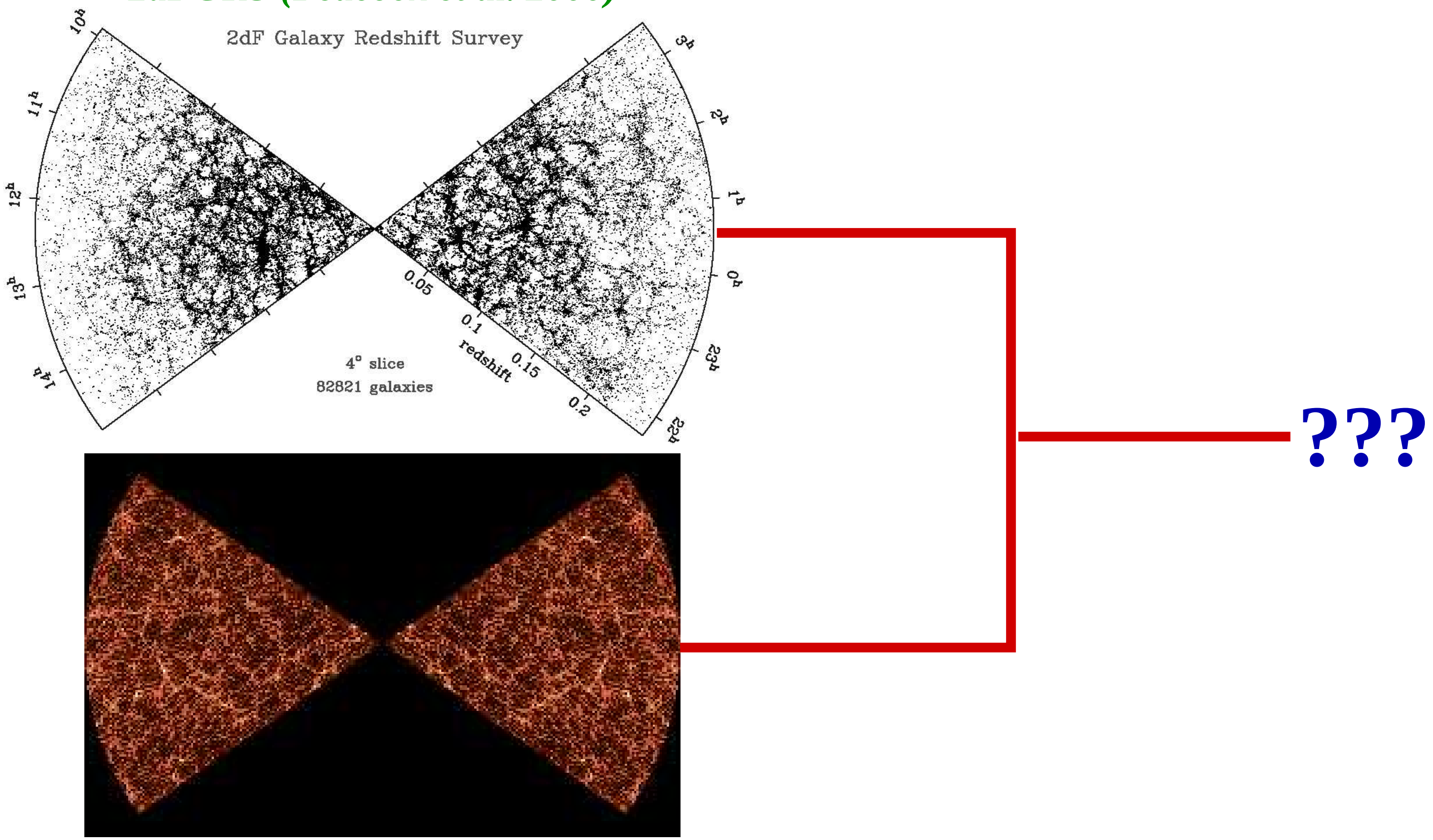
Properties of CDM structure formation

- Dark matter dominates the universe
- Hierarchical clustering due to gravitational instability

Well understood based on N-body simulations and analytical models

Galaxy-dark matter connection: a missing link

2dFGRS (Peacock et al. 2000)



CDM simulation (Virgo consortium)

Depending on how galaxies form in the dark matter density field complicated physics: gasdynamics, star formation, feedback.

Dark matter halos: an important link in the galaxy

- Dark matter halos are quasi-static clumps of dark matter
- Well-defined objects: $\overline{\rho}_{\mathbf{halo}} \sim \mathbf{350}\overline{\rho}_{\mathbf{U}}$
- Galaxies are assumed to form in dark matter halos

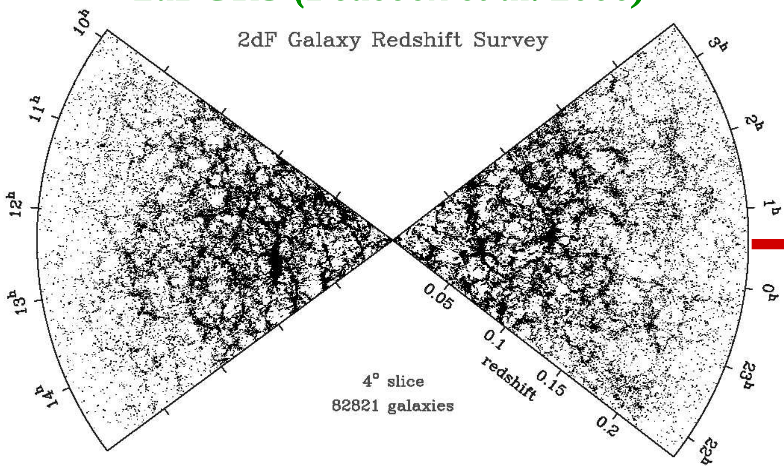
Properties of CDM halos:

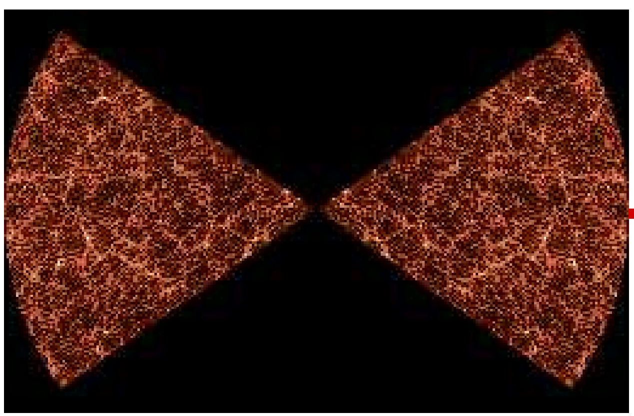
Well understood in the standard ΛCDM model

- Mass function: $n(M)\mathrm{d}M$
- Spatial clustering: halo bias
- Internal structure: density profile, shape, substructure, angular momentum, etc

The galaxy-dark halo connection

2dFGRS (Peacock et al. 2000)





CDM simulation (Virgo consortium)

HON

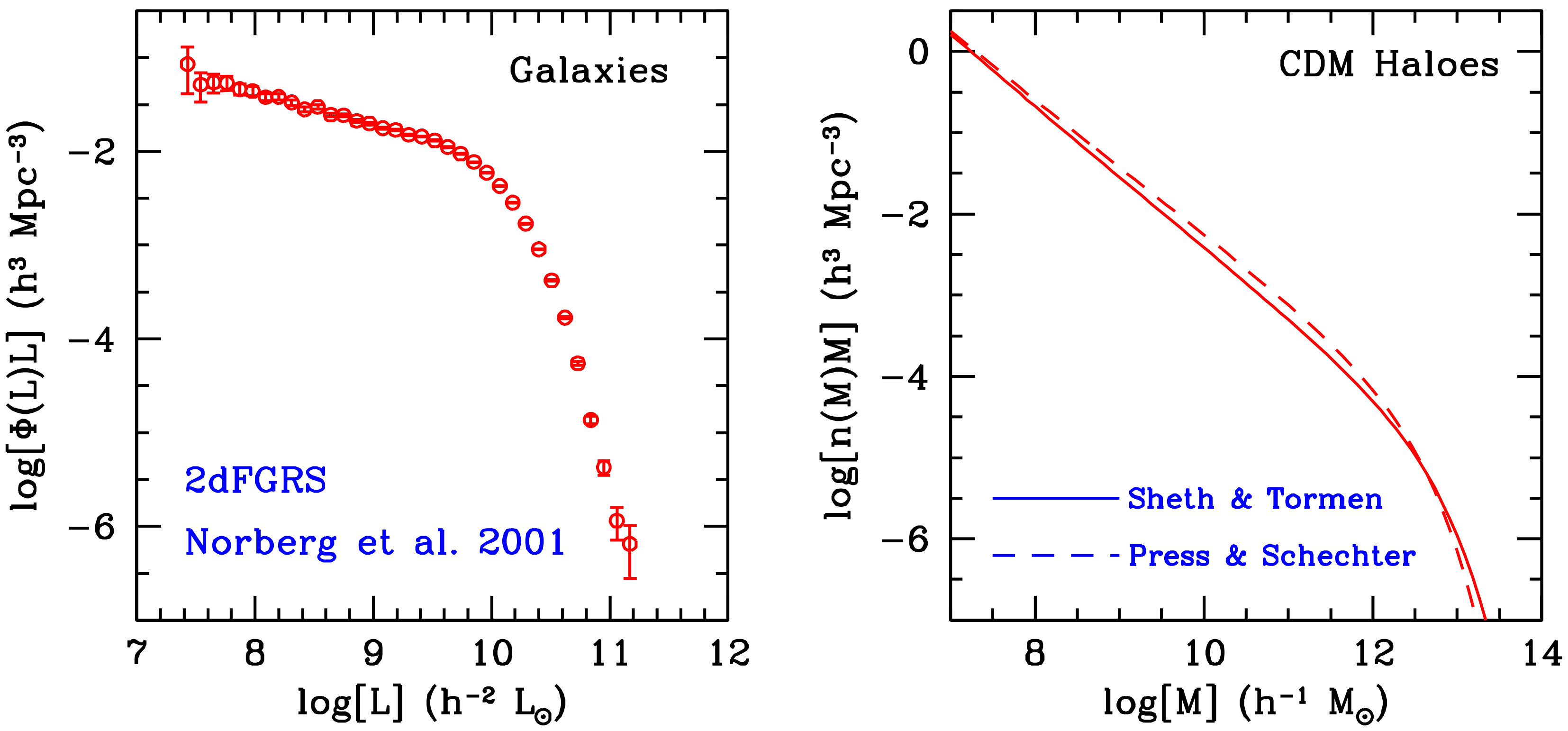
P(N|M)

The key: Halo Occupation Number, $P(N|M)$,
the probability that a halo of mass M contains N galaxies (of given properties).

The halo occupation model

We use the Conditional Luminosity Function to link the distributions of galaxies and CDM halos

$\Phi(L|M)\mathrm{d}L =$ average number of galaxies with luminosities in the range L, $L + \mathrm{d}L$ that 'live' in halos of mass M.



The Conditional Luminosity Function

Yang, Mo, van den Bosch (2003)

The luminosity function:

$$\Phi(L) = \int_0^\infty \Phi(L|M)\, n(M)\, \mathrm{d}M$$

The average luminosity in a halo of mass M:

$$\langle L \rangle(M) = \int_0^\infty \Phi(L|M)\, L\, \mathrm{d}L$$

The average number of galaxies in a halo of mass M with $L > L_1$:

$$N_M(L > L_1) = \int_{L_1}^\infty \Phi(L|M)\, \mathrm{d}L$$

Clustering properties of galaxies as function of luminosity:

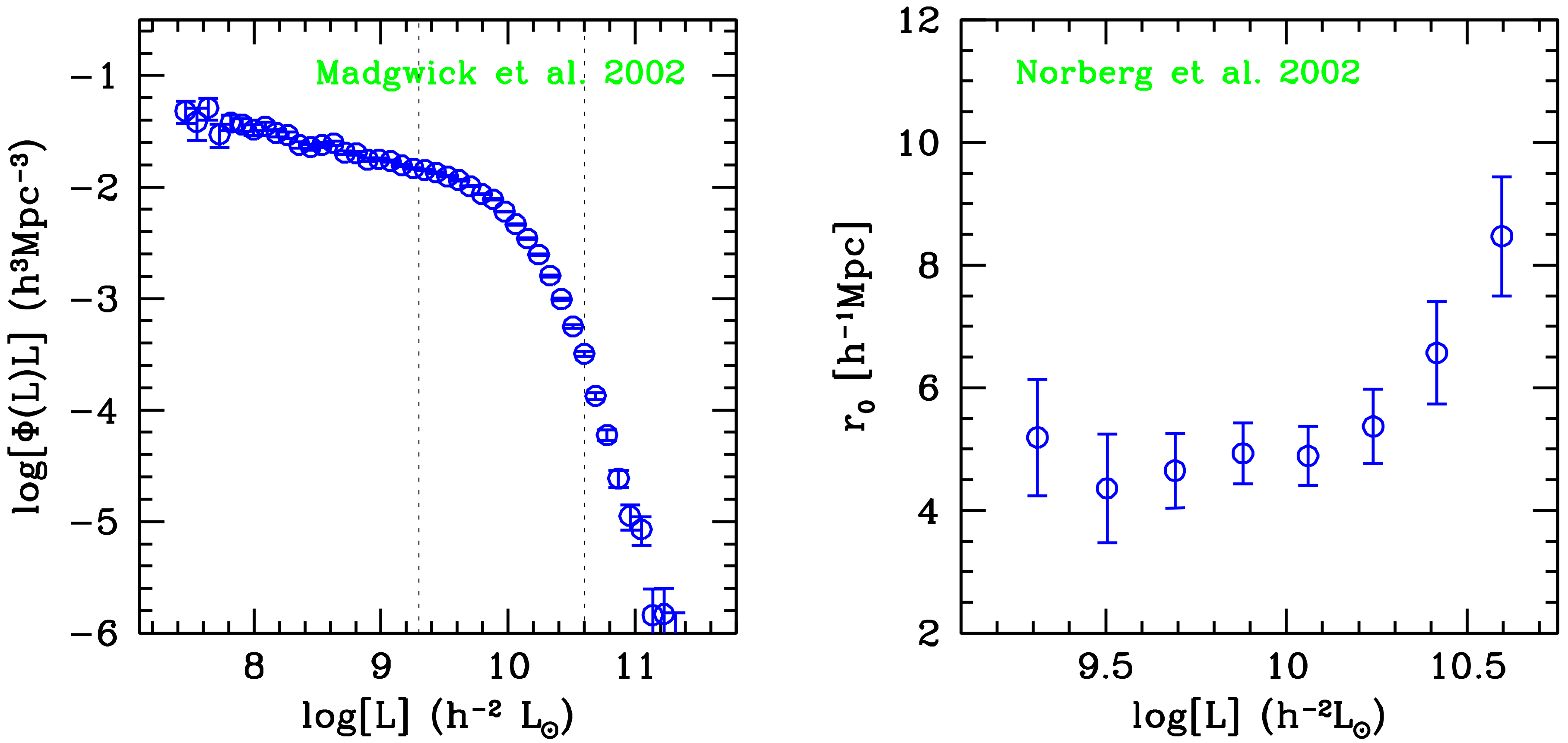
$$\xi_{\rm gg}(r|L) = b^2(L)\, \xi_{\rm dm}(r)$$

$$\bar{b}(L) = \frac{1}{\Phi(L)} \int_0^\infty \Phi(L|M)\, b(M)\, n(M)\, \mathrm{d}M$$

REMINDER: $n(M)$, $b(M)$, $\xi_{\rm dm}(r)$ are well-understood halo properties

The conditional LF is the ideal statistical 'tool' to link the distributions of dark matter halos and galaxies.

Luminosity & Correlation Functions

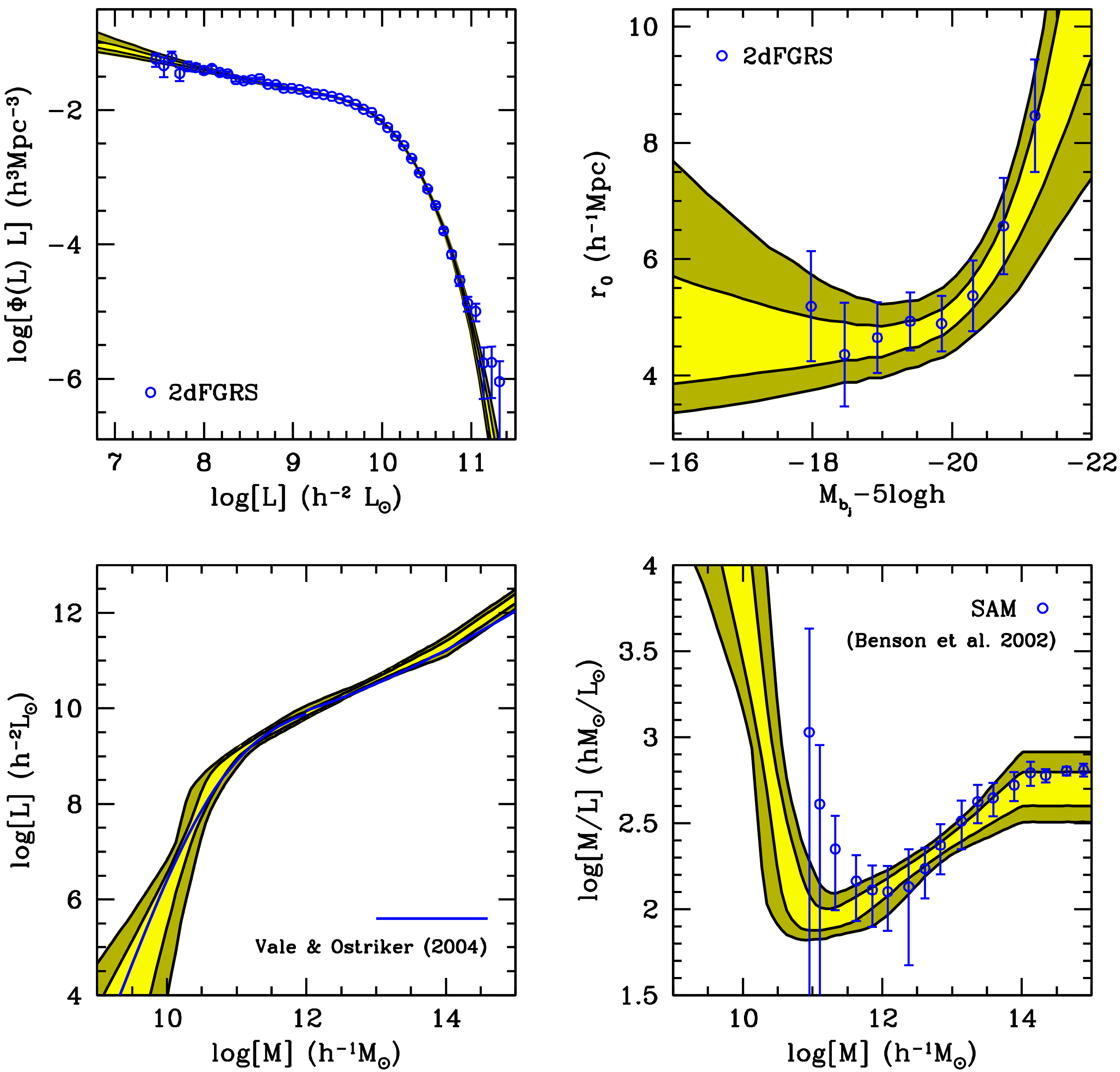


- **2dFGRS:** More luminous galaxies are more strongly clustered.
- **ΛCDM:** More massive halos are more strongly clustered.

More luminous galaxies reside in more massive halos

REMINDER: Correlation length r_0 defined by $\xi(r_0) = 1$

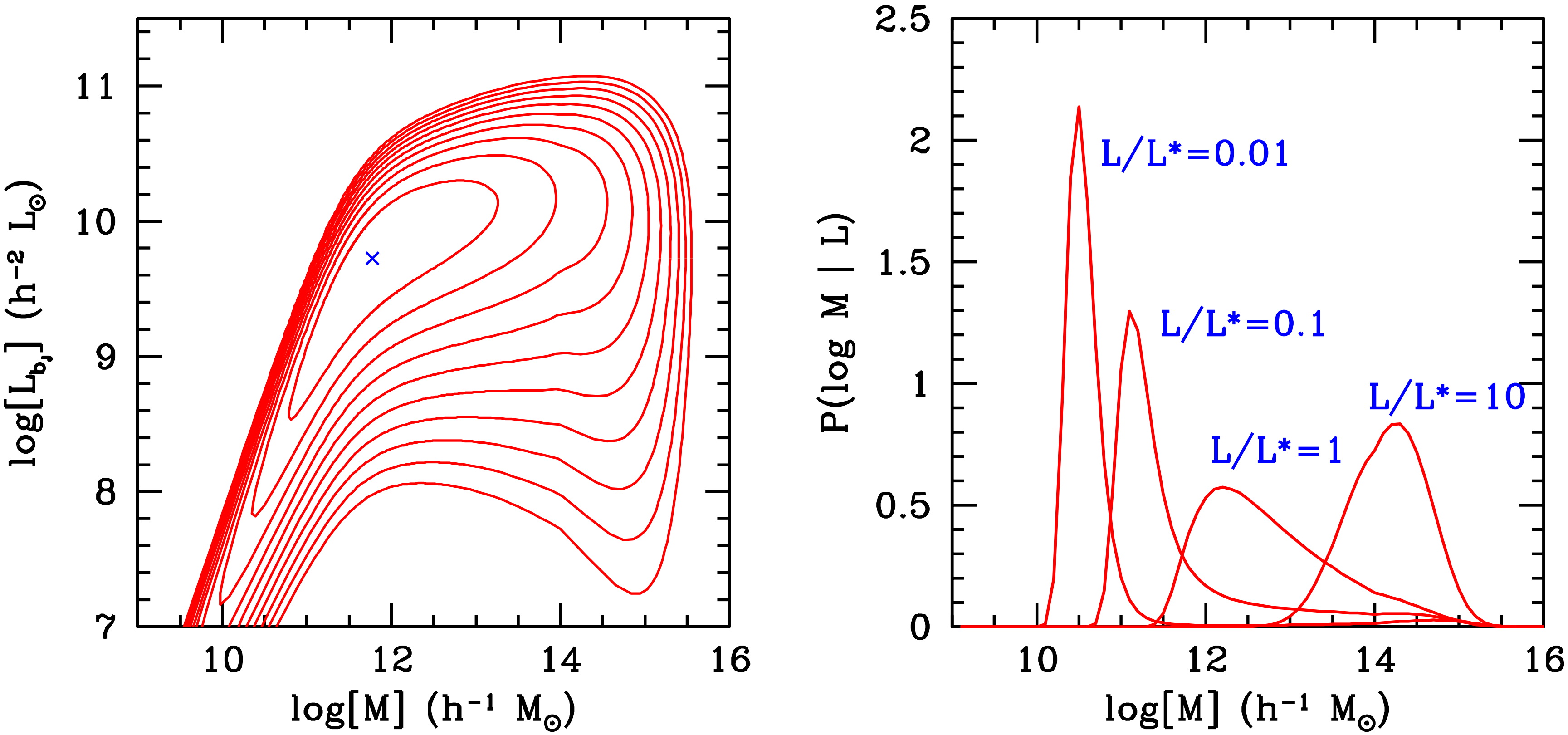
The Relation between Light and Mass



Light distribution in the Universe

$$P(L,M)\,\mathrm{d}L\,\mathrm{d}M = \frac{1}{\bar{\rho}_L}\,n(M)\,\Phi(L|M)\,L\,\mathrm{d}L\,\mathrm{d}M$$

$$P(M|L)\mathrm{d}M = \frac{\Phi(L|M)\,n(M)\,\mathrm{d}M}{\Phi(L)}$$



50% of light is produced in halos $M \lesssim 2\times 10^{12} h^{-1}\,\mathrm{M}_{\odot}$.

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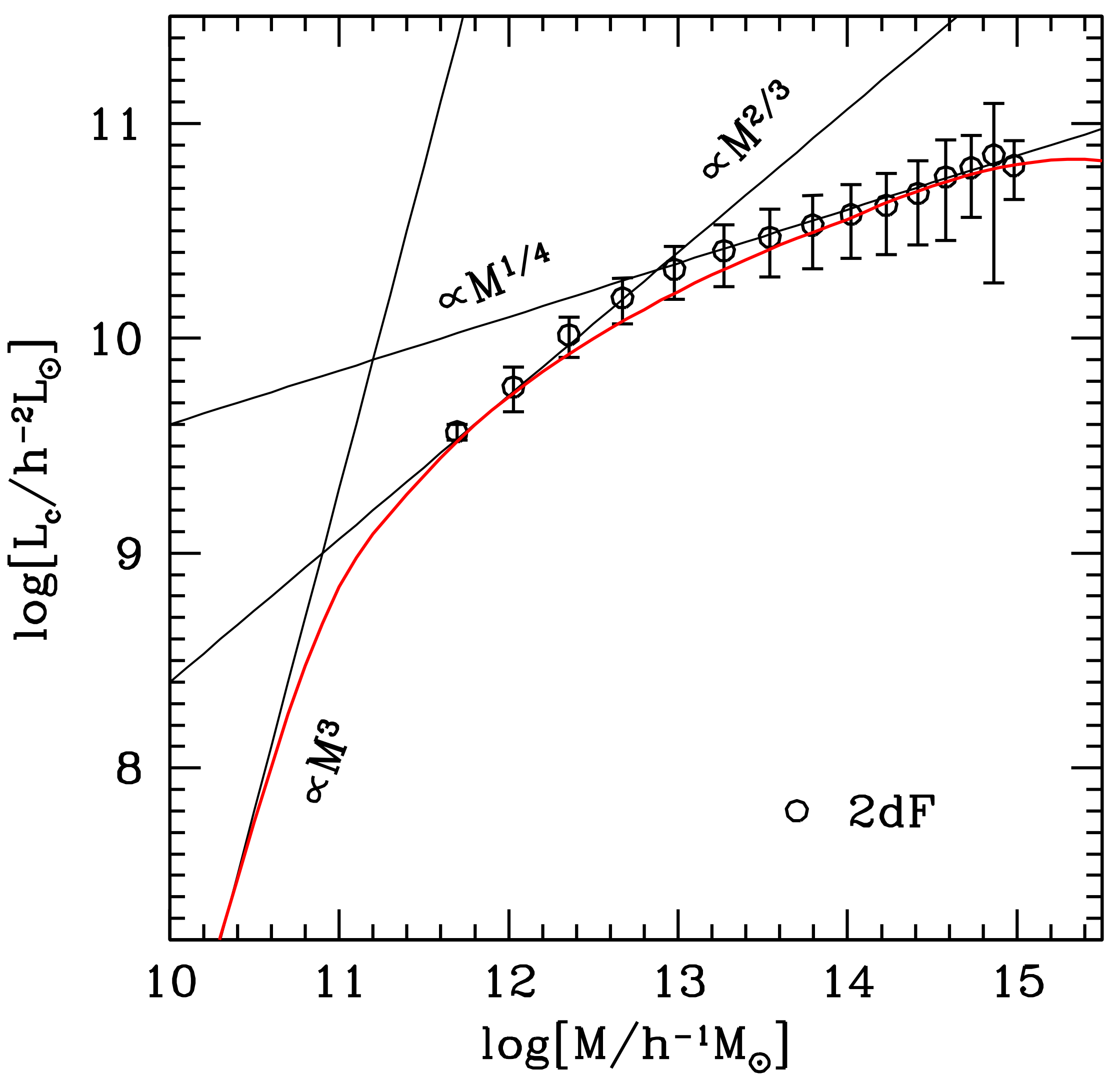
Characteristic mass scales



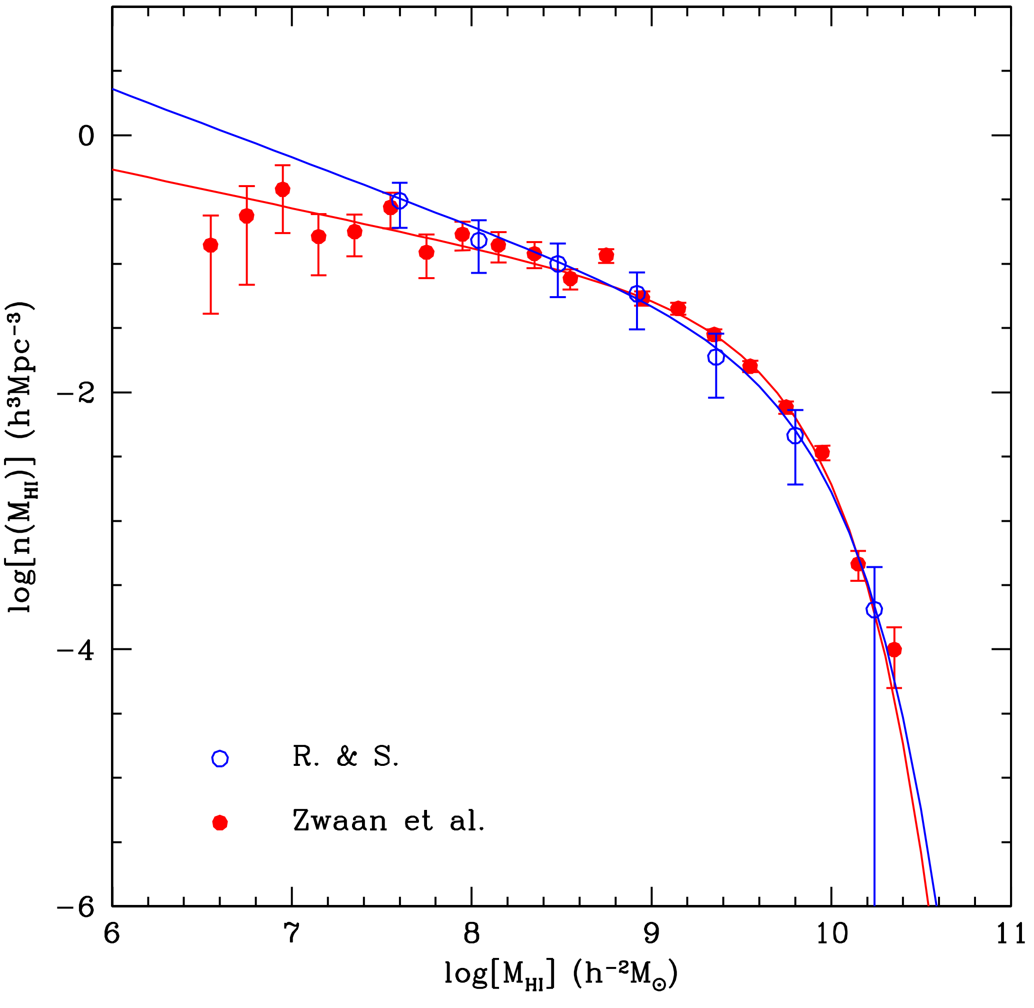
Two characteristic mass scales:

$M_h \sim 10^{11} h^{-1}\ \mathrm{M}_{\odot}$ (feedback mass scale?)

$M_h \sim 10^{13} h^{-1}\ \mathrm{M}_{\odot}$ (cooling mass scale?)

Cold gas in dark halos

Observational input: HI mass function from blind HI surveys (Rosenberg & Schneider 2003; Zwaan et al. 2004); consistent with $z \sim 0$ damped Lyman alpha systems



The Cold gas - dark halo connection

Use Conditional HI mass Function to link HI mass and CDM halos

The conditional HI mass function:

$$P(M_{\rm HI}|M)\,{\rm d}M_{\rm HI}$$

The HI-mass function:

$\Phi(M_{\rm HI}) = \int_0^\infty P(M_{\rm HI}|M) n(M)\,{\rm d}M$

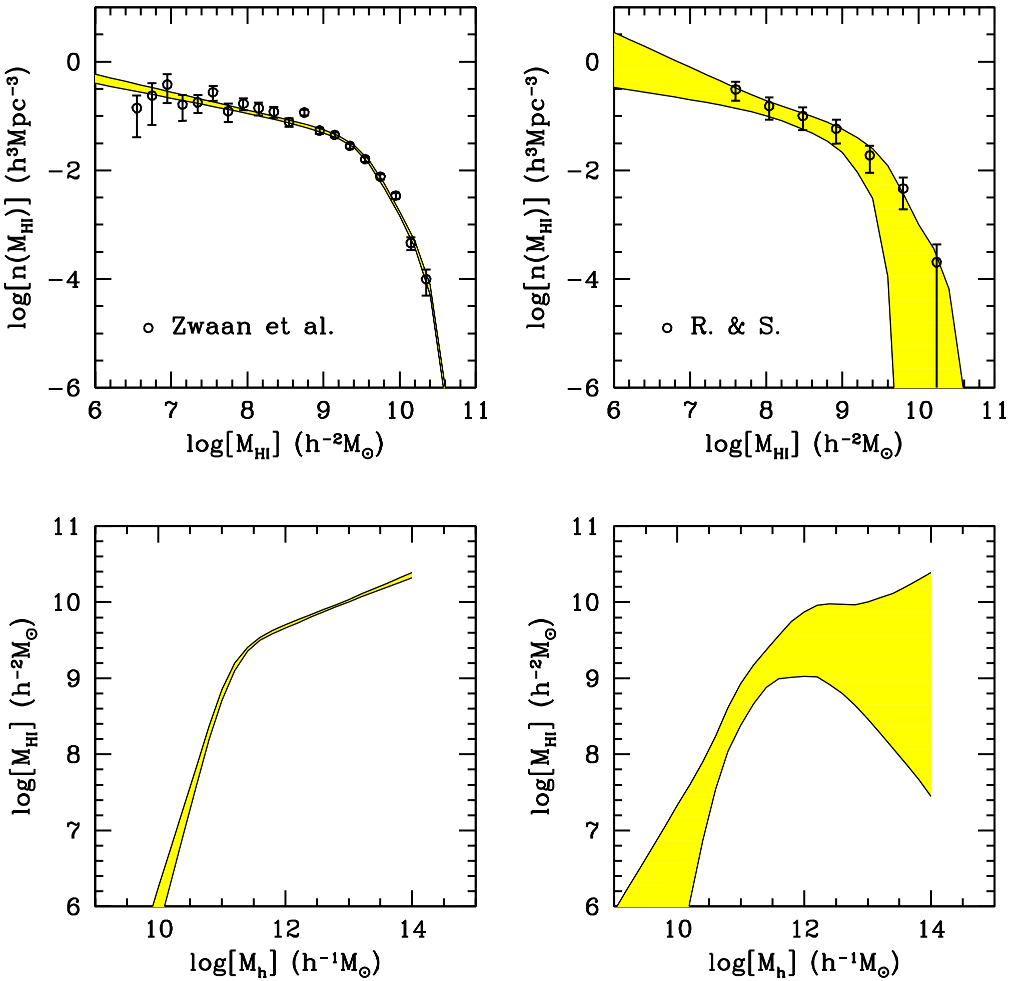
A simple model: $P(M_{\rm HI}|M)\,{\rm d}M_{\rm HI}$ has a lognormal form, with median $\overline{M}_{\rm HI}(M)$ and dispersion $\sigma(M)$. We assume σ is a constant and

$$\overline{M}_{\rm HI}(M) = \frac{M_{\rm HI,0}(M/M_0)^{\gamma_1}}{1+(M/M_0)^{\gamma_1-\gamma_2}}\,.$$

where M_0, $M_{\rm HI,0}$, γ_1, γ_2 are free parameters.

The $\overline{M}_{HI}$-M relation

The relation is well constrained for low mass halos.



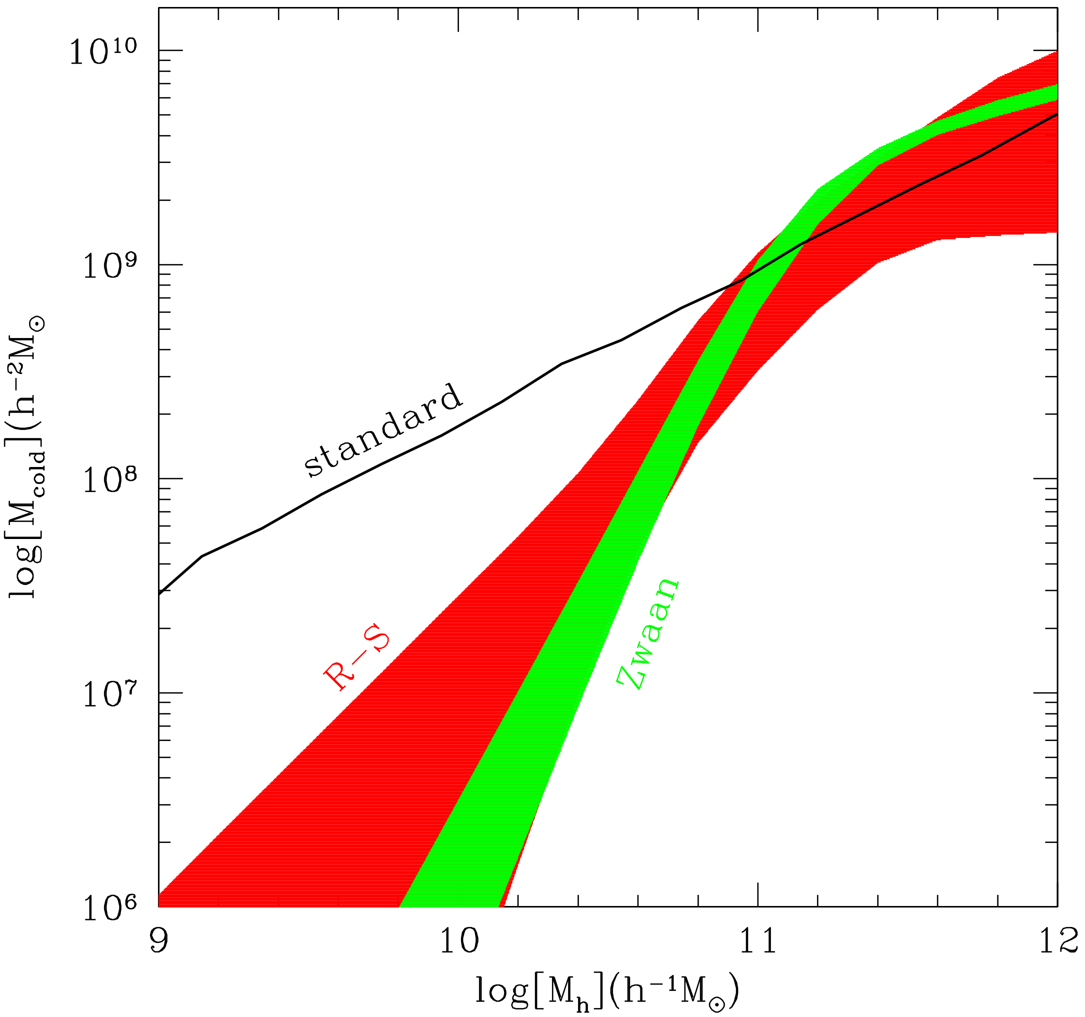
Constraining the formation of late-type galaxies

The ‘standard’ model:

- Cold gas settles into a disk
- Star formation and feedback:
  $\dot{M}_\star = M_{\rm cold}/\tau$; $\dot{M}_{\rm wind} = \beta \dot{M}_\star$; $\beta = (200{\rm kms}^{-1}/V_h)^2$
- Cold gas is being depleted by star formation until disk becomes stable:

$$\Sigma_{\rm crit} = \frac{\sigma\kappa}{\pi G Q_{\rm crit}}$$

$\sigma \sim 6{\rm kms}^{-1}$, $Q_{\rm crit} \sim 1.5$

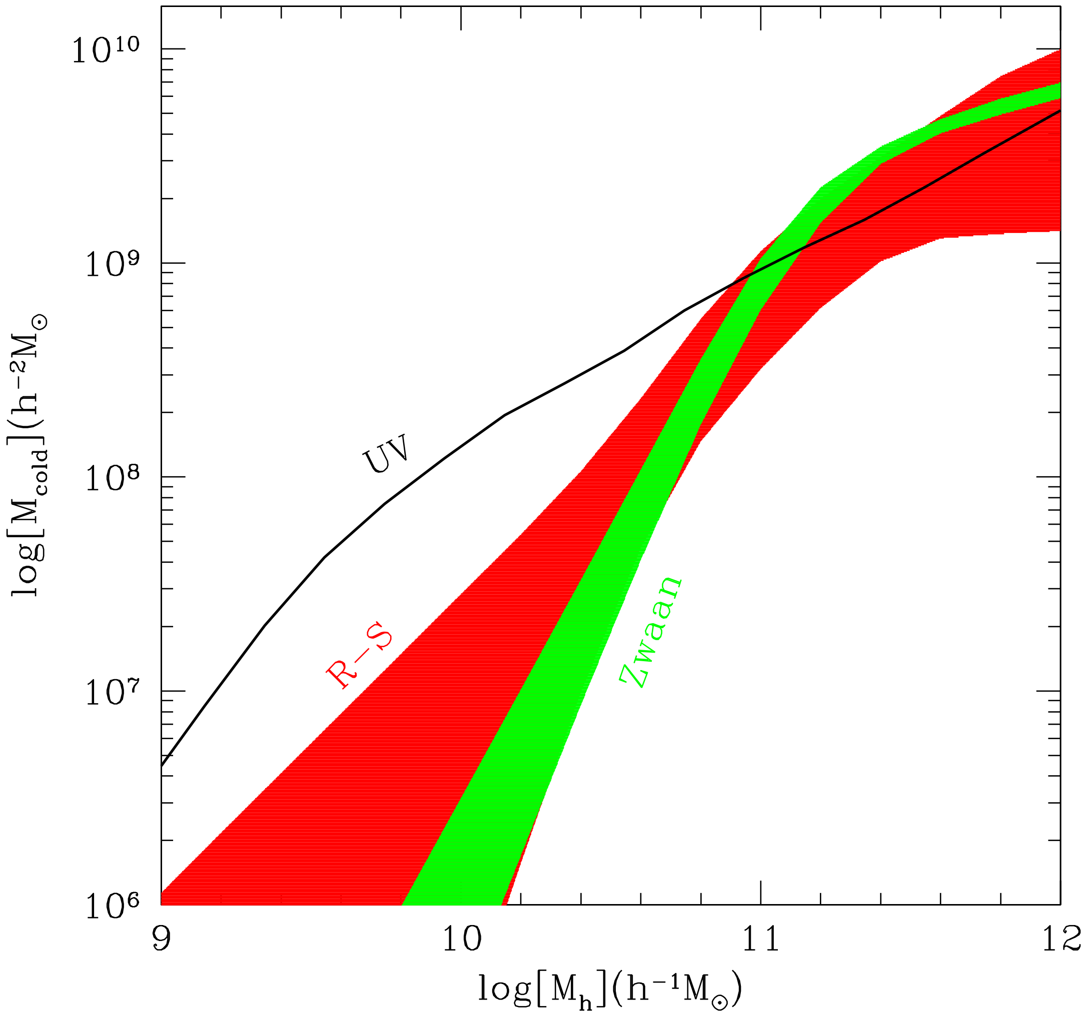


Such model predict too much HI mass in halos with masses below

$\sim 10^{11} h^{-1} M_\odot$!

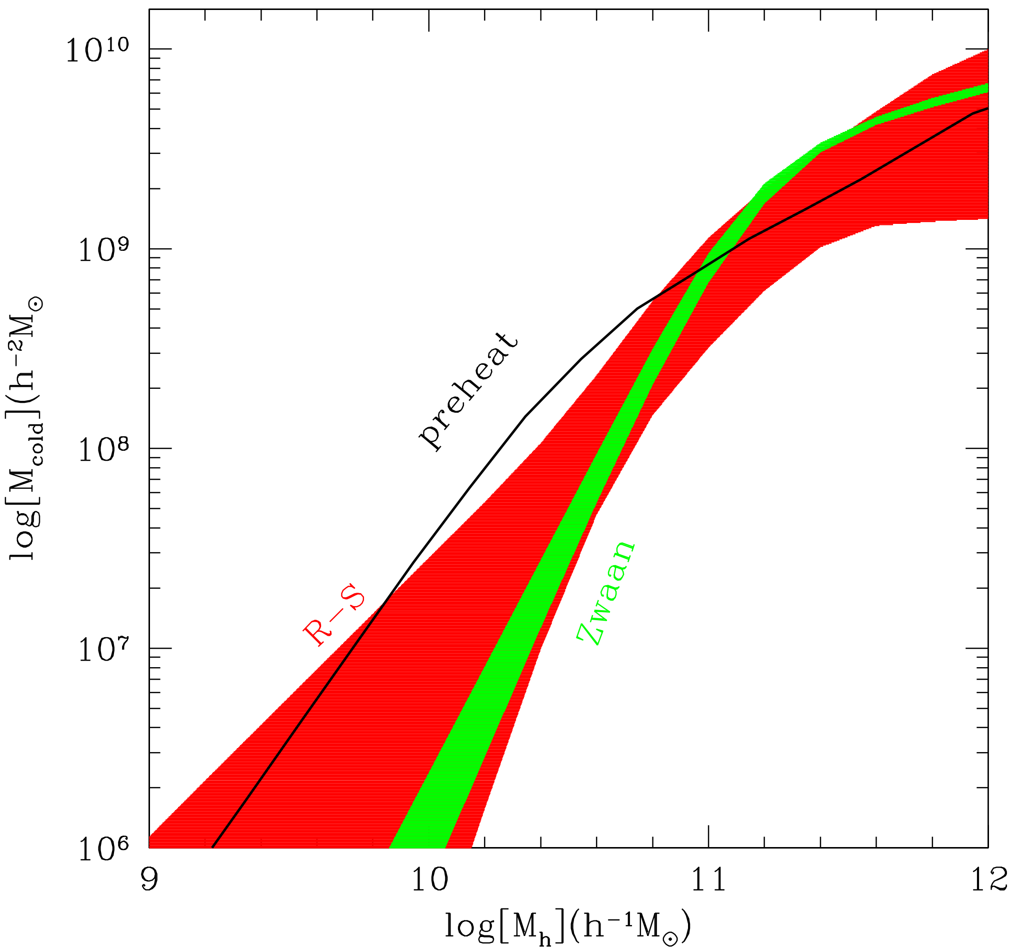
Photoionization heating by UV background

$f_{gas} = f_B/[1 + (M_0/M)^\alpha]$,
$M_0 \sim 10^{10} h^{-1} M_\odot$, $\alpha \sim 1$ (Hoeft et al 2005).



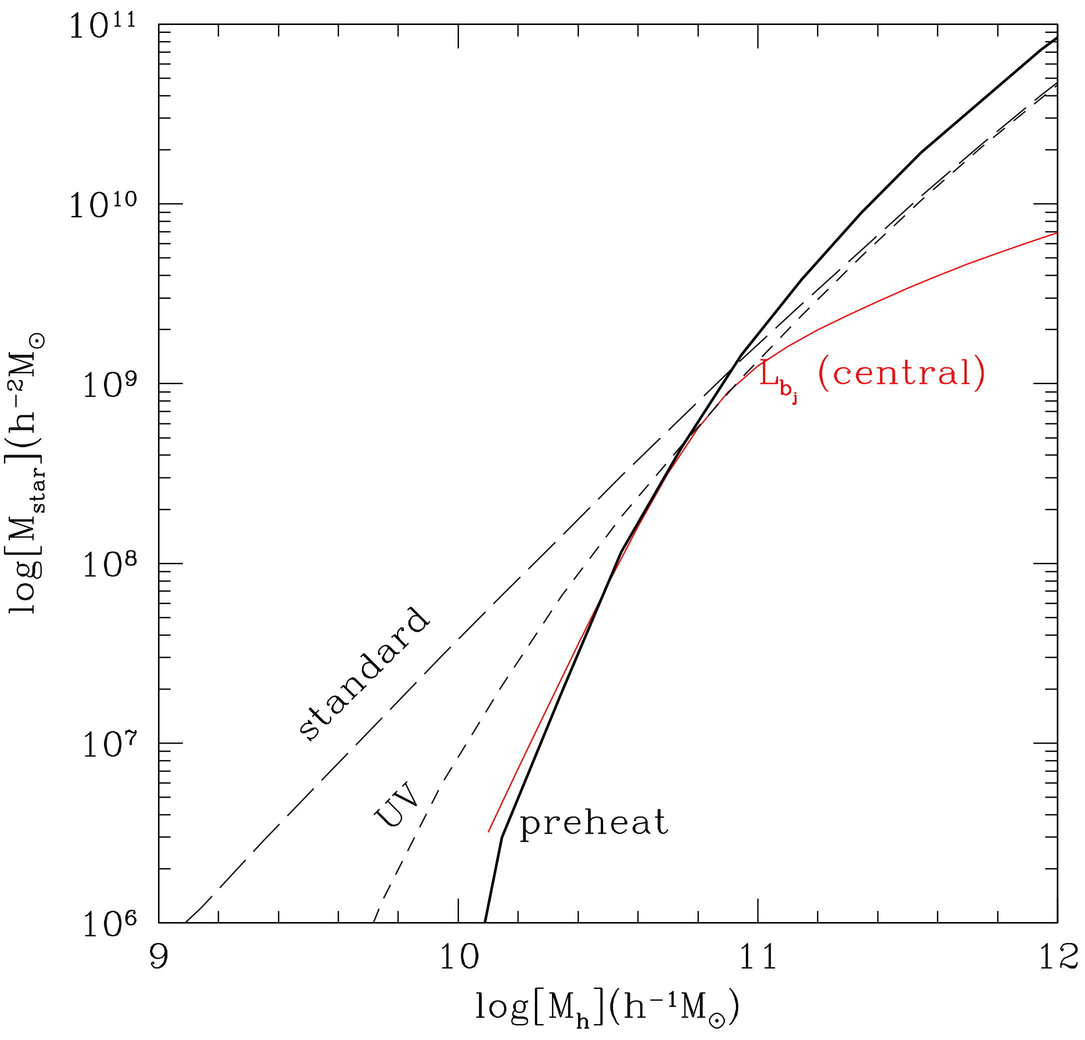
Formaion in preheated media

If the ISM is preheated to some high entropy, then
$f_{\rm gas} = f_B/[1 + (M_0/M)^\alpha]$
where $\alpha \sim 1$, and $M_0 \sim 10^{11.5} h^{-1} \mathrm{M}_\odot$ describes the level of preheating (Lu & Mo 2005): $s \sim 10 \mathrm{kev\, cm^2}$.

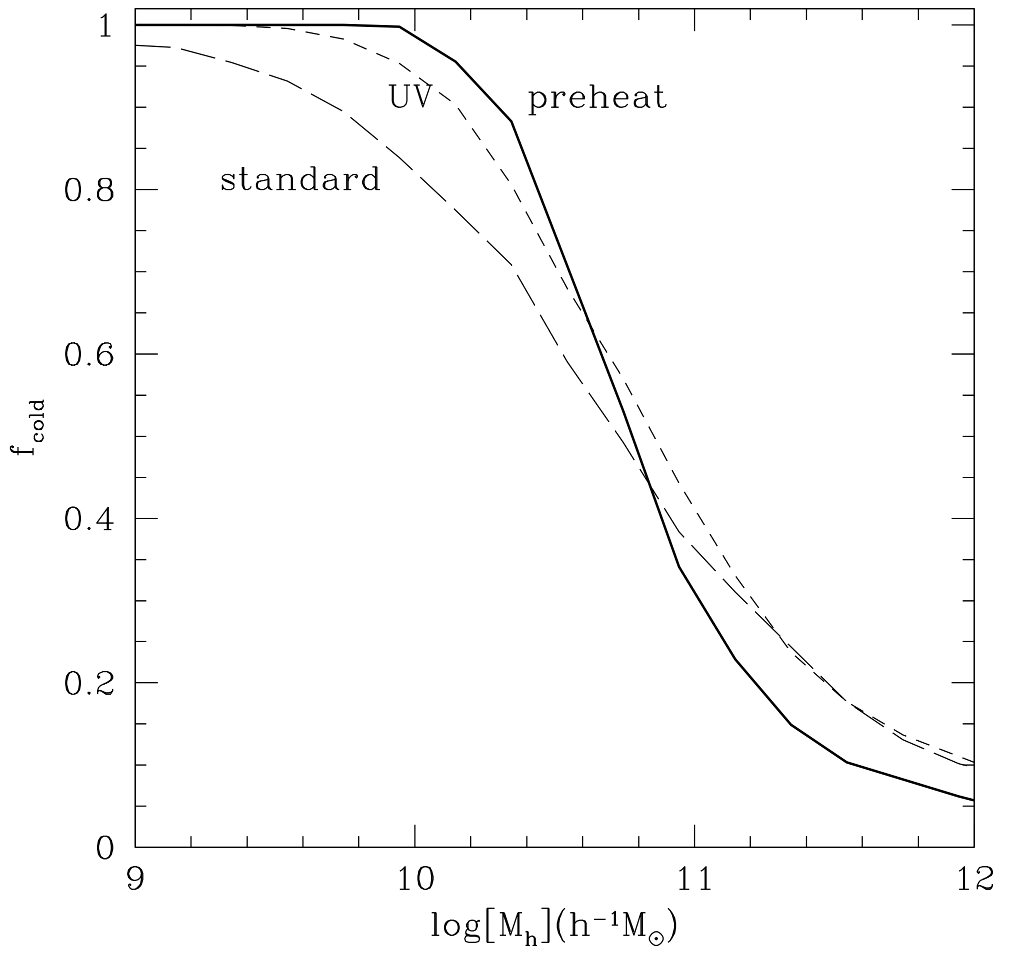


Stellar mass

Assuming mass loss is insignificant:



Gas fraction and metallicity



Metallicity is expected lower in lower mass systems.
Lower-mass systems must have lost larger fraction of metal in order to explain their lower metal yield, but not much gas mass.

Conclusions

- The observed HI mass in the universe is not consistent with the standard model in which gas first settles into disks and star formaion ejects gas from dark halos.
- A large fraction of the IGM associated with low-mass halos may have never collapsed into dark halos.
- A consistent model can be found if galactic-sized halos accrete gas from a medium that is mildly preheated.