Large Scale Structure and Galaxy Formation

Jarle Brinchmann

http://www.strw.leidenuniv.nl/~jarle/Teaching/GalaxyFormation/

Course overview

Lecturer: Jarle Brinchmann (jarle@strw.leidenuniv.nl). Room O455 - office hours Wednesday 16-17.

Teaching assistant: Marco Velliscig (Room O435) (velliscig@strw.leidenuniv.nl) - Office hours Friday TBD

Lectures: 11:15-13:00 on Tuesdays
Problem classes: Fridays & 15:45-16:30 on Tuesdays

Evaluation: Written exam + 2 problem sets.
Problem sets: Obligatory, two hand-in sets. They will contribute up to 25% of the final grade.

The plan

“Cosmology”

- 4/2 - Introduction.
- 11/2 - Horizon crossing, basic perturbation growth theory. What slows the collapse down?.
- 18/2 - The power spectrum & further perturbation damping.
- 25/2 - Statistical properties of the density field. The Correlation function. Window functions & the statistics of the filtered density field. Non-linear scaling laws..
- 4/3 - Spherical collapse. The Press-Schechter mass function.
- 21/3 - Redshift distortions, extended P-S formalism.

“Astrophysics”

- 25/3 - Hydrostatic equilibrium and Jeans mass. Virial relations and circular velocity of halo.
- 1/4 - Time-scales of collapse and cooling processes.
- 8/4 - Photo-ionization, self-shielding, cooling flows and predictions for massive galaxies.
- 15/4 - Heating/cooling, cold & hot accretion and feedback.
- 22/4 - The formation of disk galaxies. Density profiles. NFW/Spherical collapse.
- 29/4 - Absorption by the IGM. Gunn-Peterson throughs. Observations + theory. Thermal balance.
- 13/5 - The thermal state of the IGM and expanding Strömgren spheres. Re-ionization.
- 22/5 - The formation of the first objects. The cooling barrier and why the first stars might be very massive.
- 27/5 - Recap lecture?

What do we want to explain?

Interlude - the anatomy of galaxies

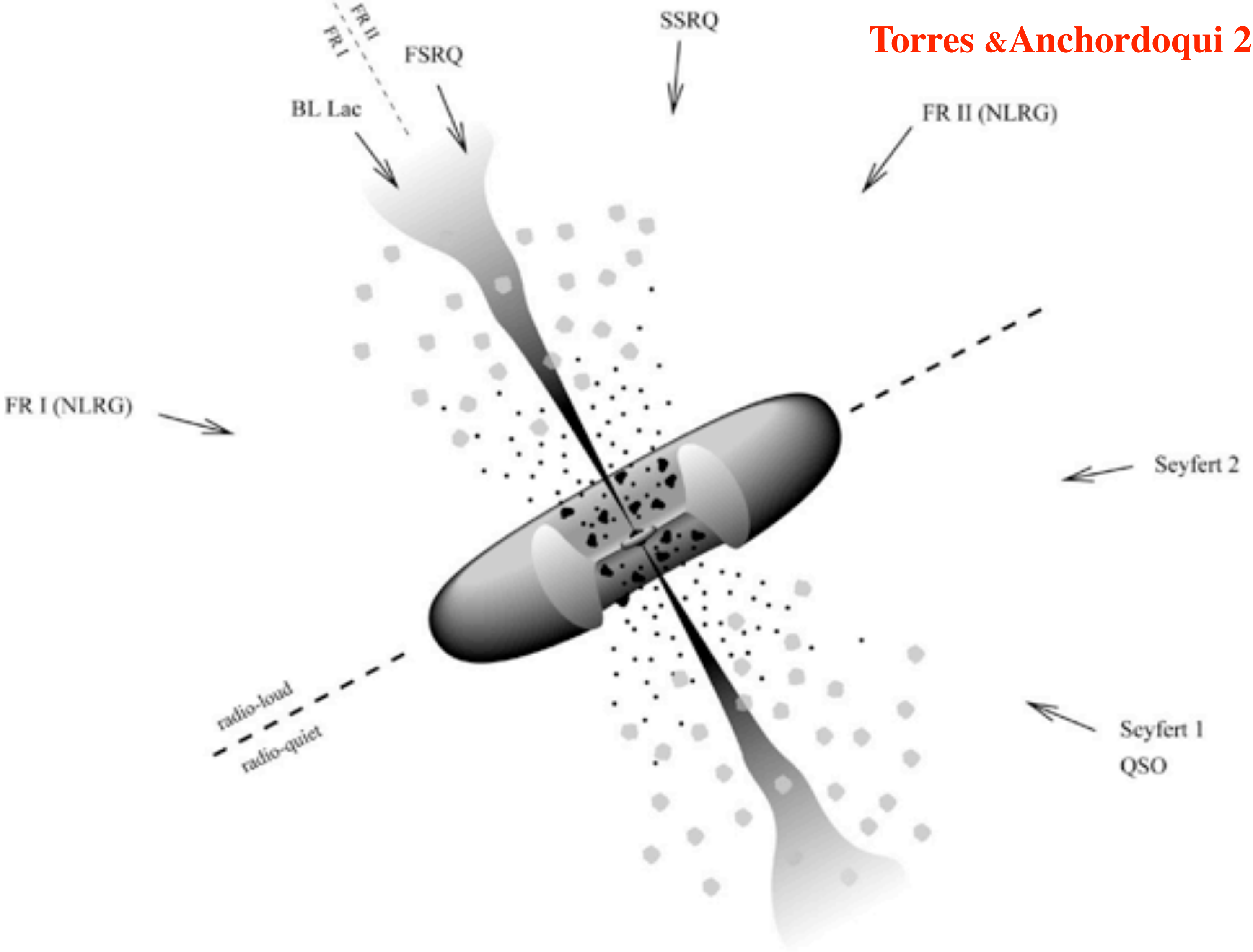
Gas rich galaxies are typically less massive, have on-going star formation and might be more isolated.

Most galaxies have close companions - typically there is a dominant galaxy.

The most massive galaxies have often little gas & frequently an active galactic nucleus (AGN).

Images from the Hubble Heritage project

Interlude - the anatomy of galaxies



Torres &Anchordoqui 2004

The most massive galaxies have often little gas & frequently an active galactic nucleus (AGN).

Images from the Hubble Heritage project

Interlude - the anatomy of galaxies

Spirals: Typically have a disk and the light/mass profile of the disk is exponential

$$I(r) = I_0 e^{-r/h}$$

Elliptical/spheroidal: Typically smooth light distribution, little star formation

$$I(r) = I_0 e^{-k[(r/r_h)^n - 1]}$$

Distribution functions

We have learned a lot about the low redshift Universe over the last few decades.

If we can characterise a galaxy by a set of numbers:

$$\mathcal{G}(Z, \mathrm{SFR}, M_*, M_{\mathrm{gas}}, \sigma, V_c, \ldots)$$

We have found a large number of scaling relations,

Tully-Fisher: $M \propto V_c^4$

Faber-Jackson: $L \propto \sigma^4$

Fundamental plane: $\log r_e = a \log \sigma - b \log \mu_e + \gamma$

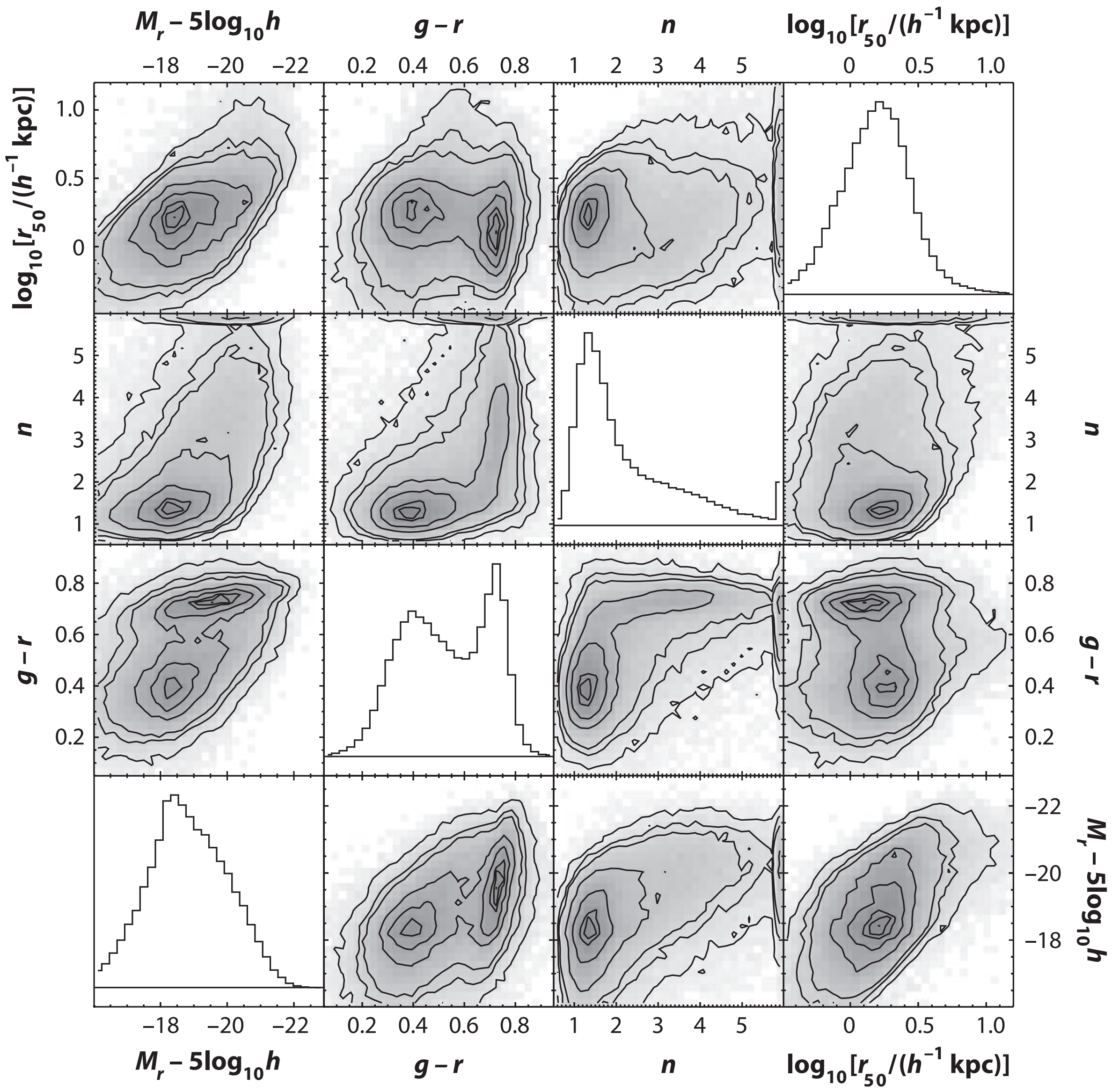
Star-forming sequence: $\mathrm{SFR} \propto M_*^{0.8}$

Mass-metallicity relation: $Z \approx f(M_*)$

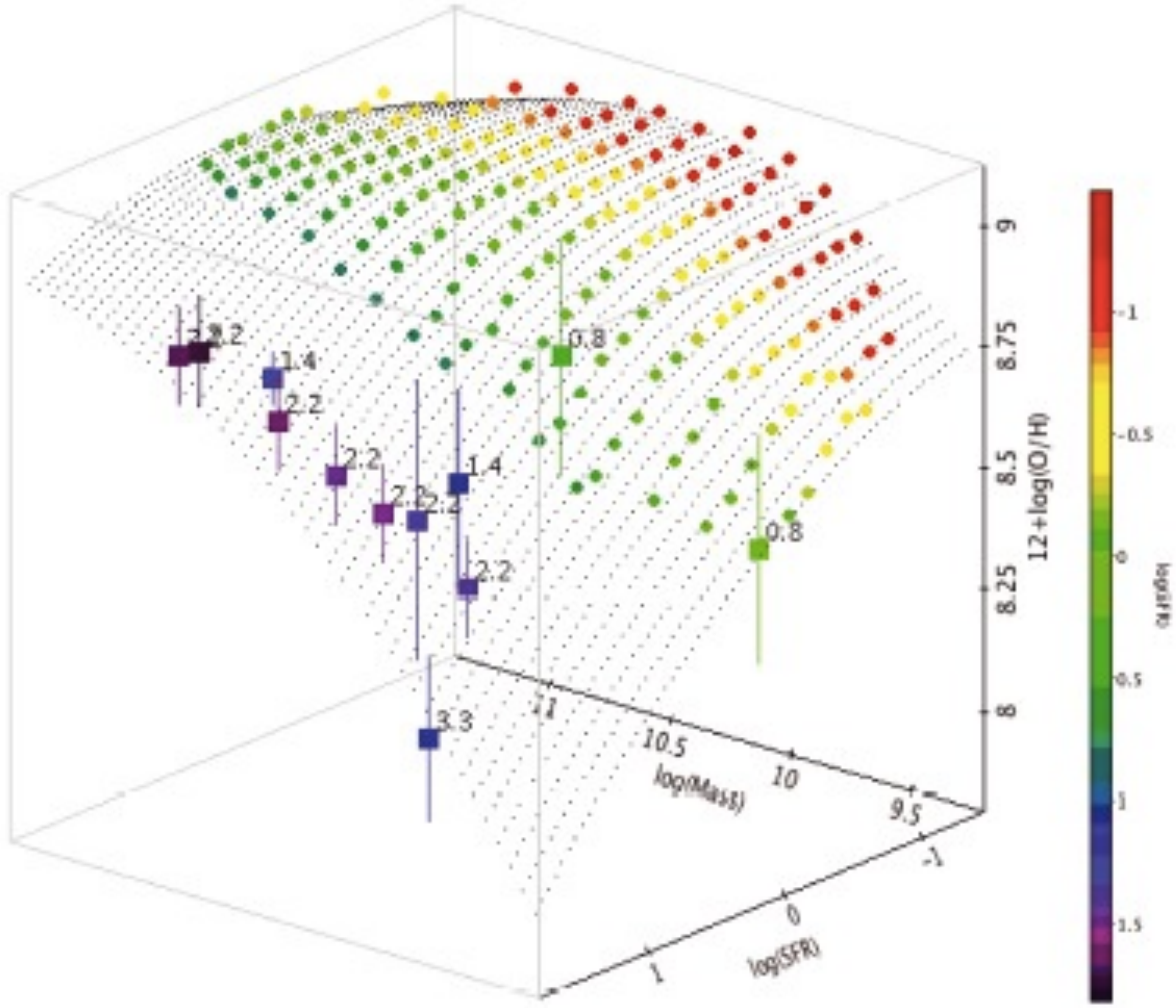
Distribution functions

$$\mathcal{G}(Z, \mathrm{SFR}, M_*, M_{\mathrm{gas}}, \sigma, V_c, \ldots)$$

We have found a large number of scaling relations, and at low redshift we can see that some of these are projections of higher dimensional distributions.

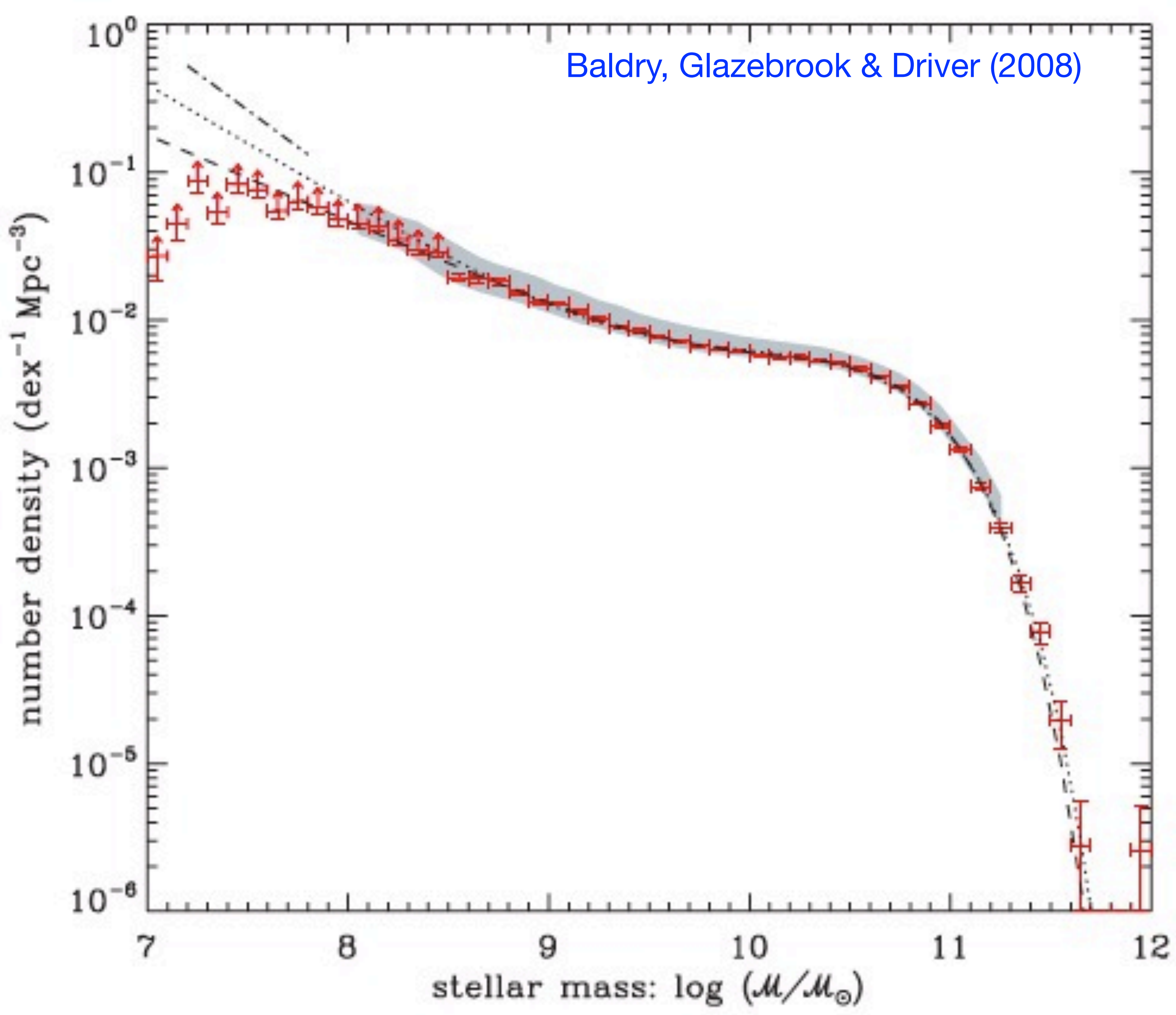


Blanton & Moustakas (2009)



Mannucci et al (2010)

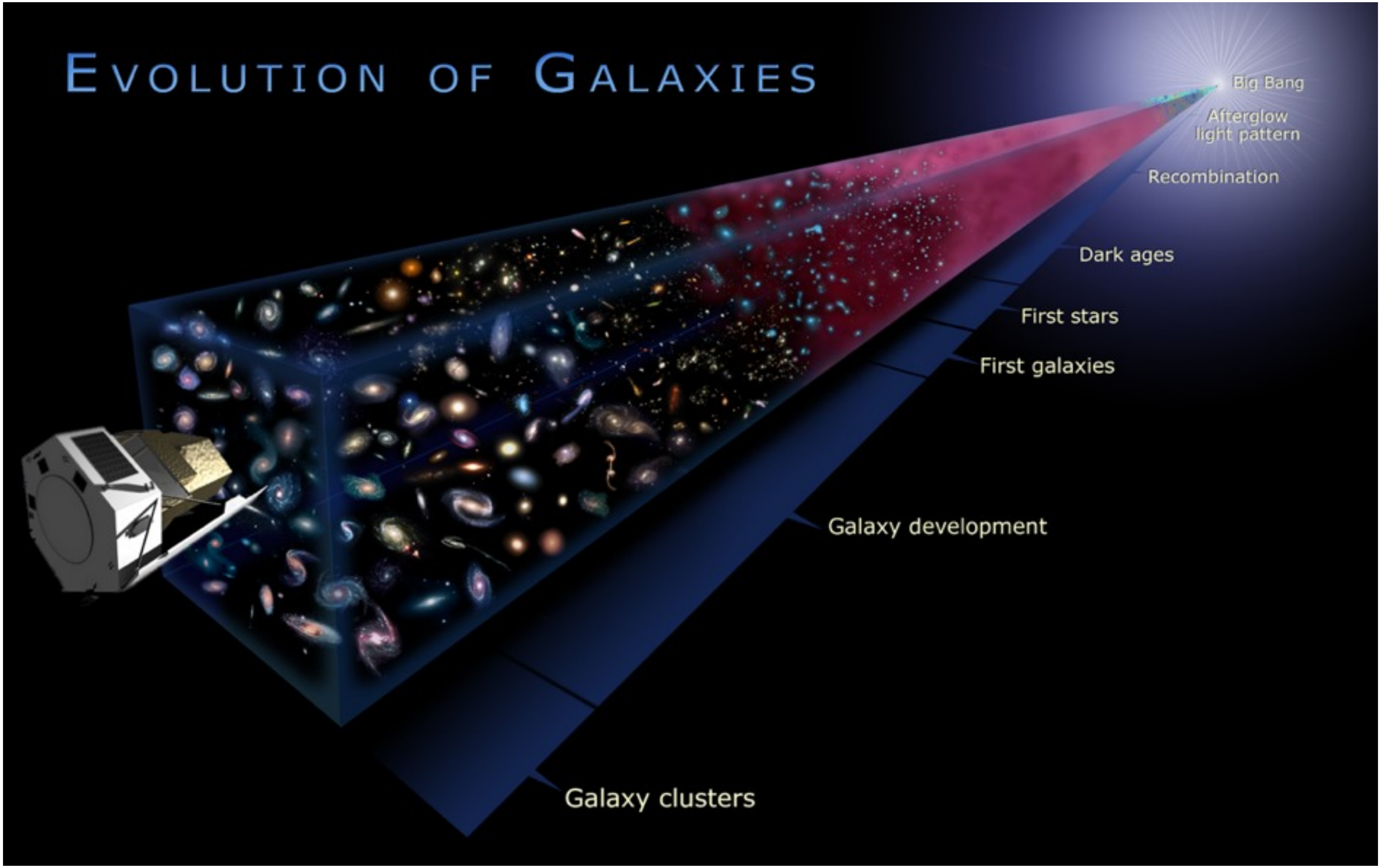
Distribution functions



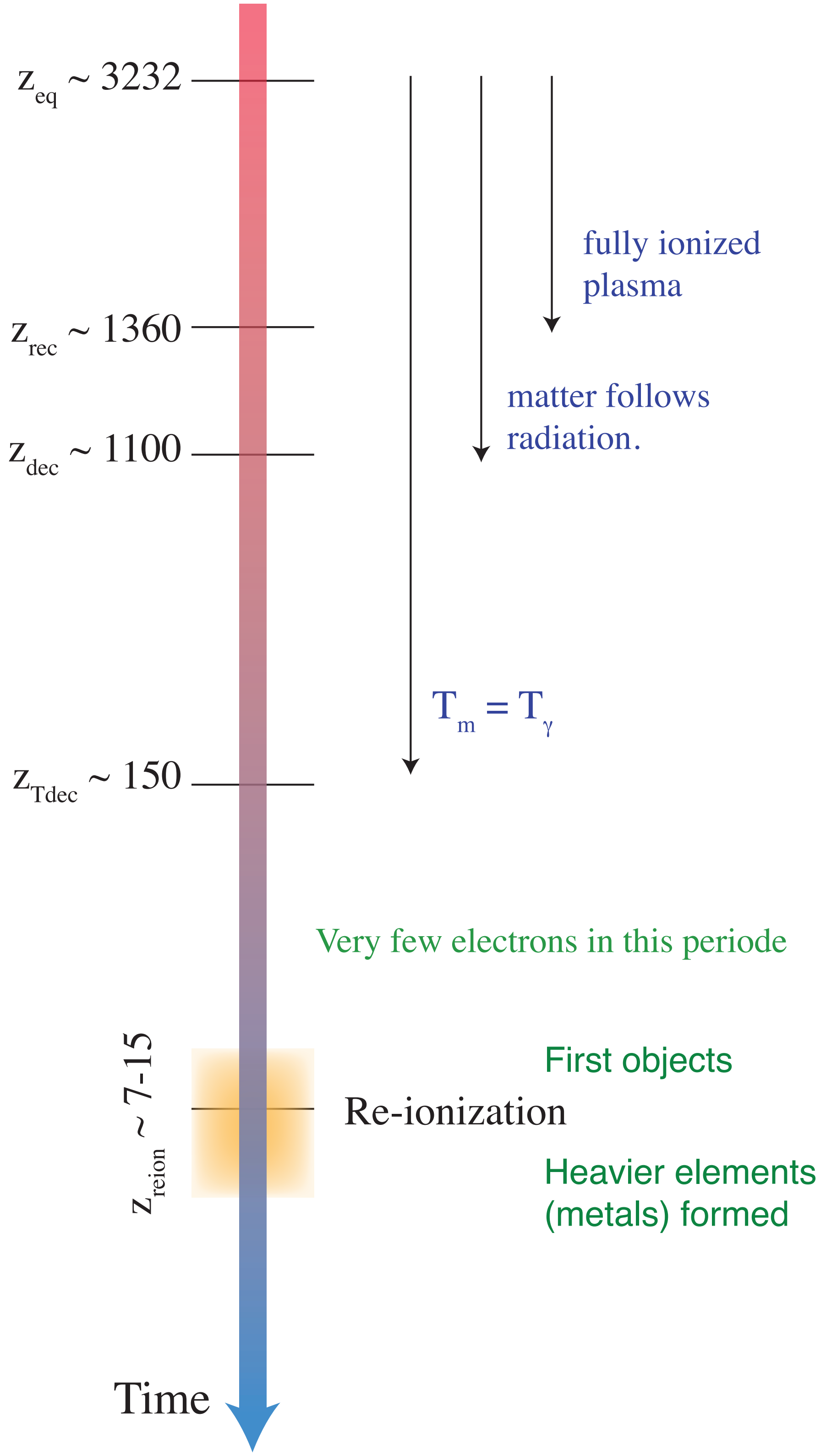
Mass functions - the distribution of galaxies with mass or luminosity.

If I pick a galaxy at random, the chance that it has mass around M is $n_d(M)$.

Galaxy formation & evolution - the cartoon



Galaxy formation in dark matter halos



$z_{eq} \sim 3232$

$z_{rec} \sim 1360$

$z_{dec} \sim 1100$

$z_{Tdec} \sim 150$

$z_{reion} \sim 7\text{-}15$

fully ionized plasma

matter follows radiation.

$T_m = T_\gamma$

Very few electrons in this periode

Re-ionization

First objects

Heavier elements (metals) formed

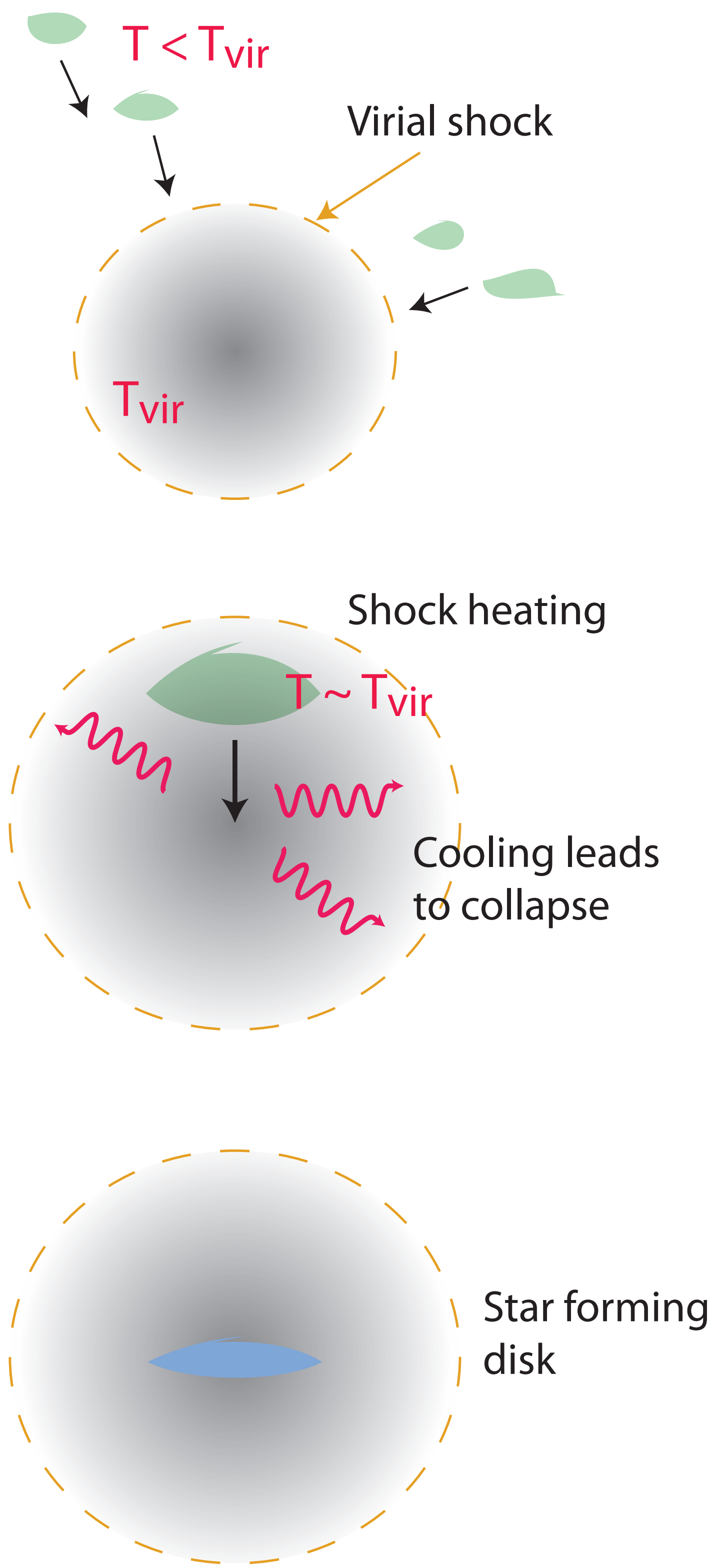
Time

Baryons fall into the dark matter structures which eventually virialise and become “halos”. Low mass first, more massive later

The first galaxies form.

Virial radii & dark matter halos

What happens when baryonic matter falls into a dark matter halo?



Simple view:

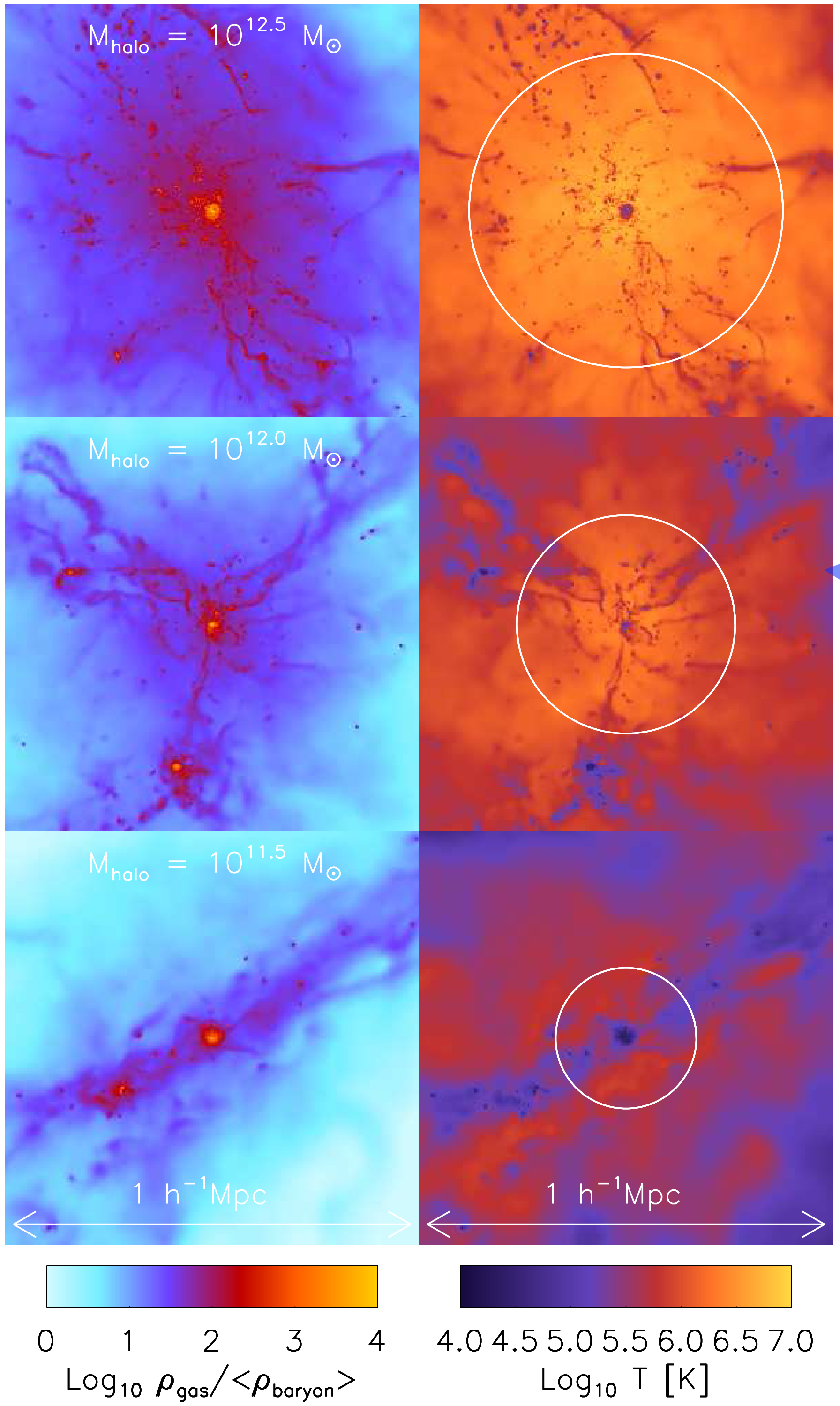
Cold gas flows in, gets shock heated at the virial radius.

The gas then cools, and falls further to the centre.

When the temperature is low enough and the density high enough, stars form and we get a galaxy in the centre.

Virial radii & dark matter halos

What happens when baryonic matter falls into a dark matter halo?

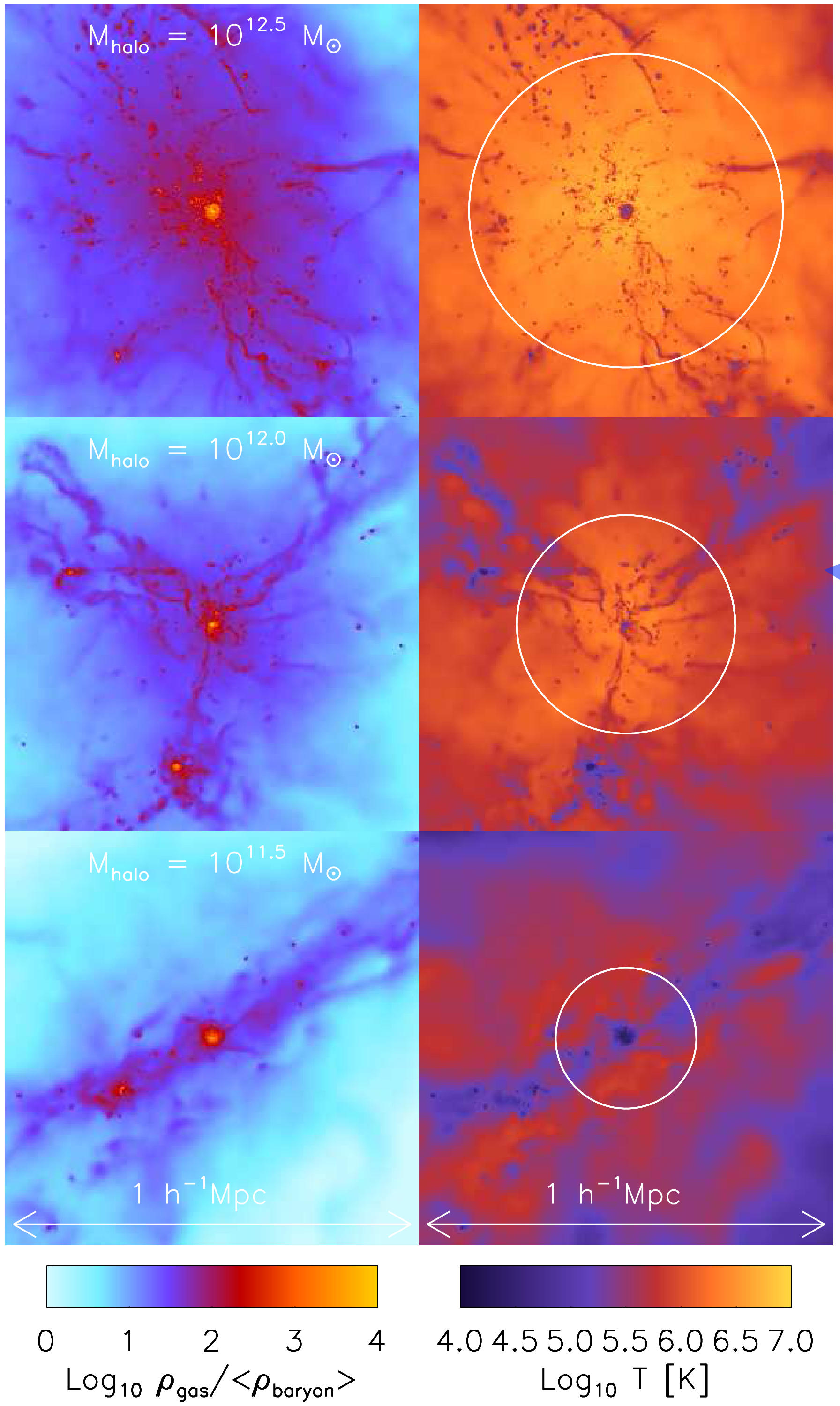


But

This depends on mass

Virial radii & dark matter halos

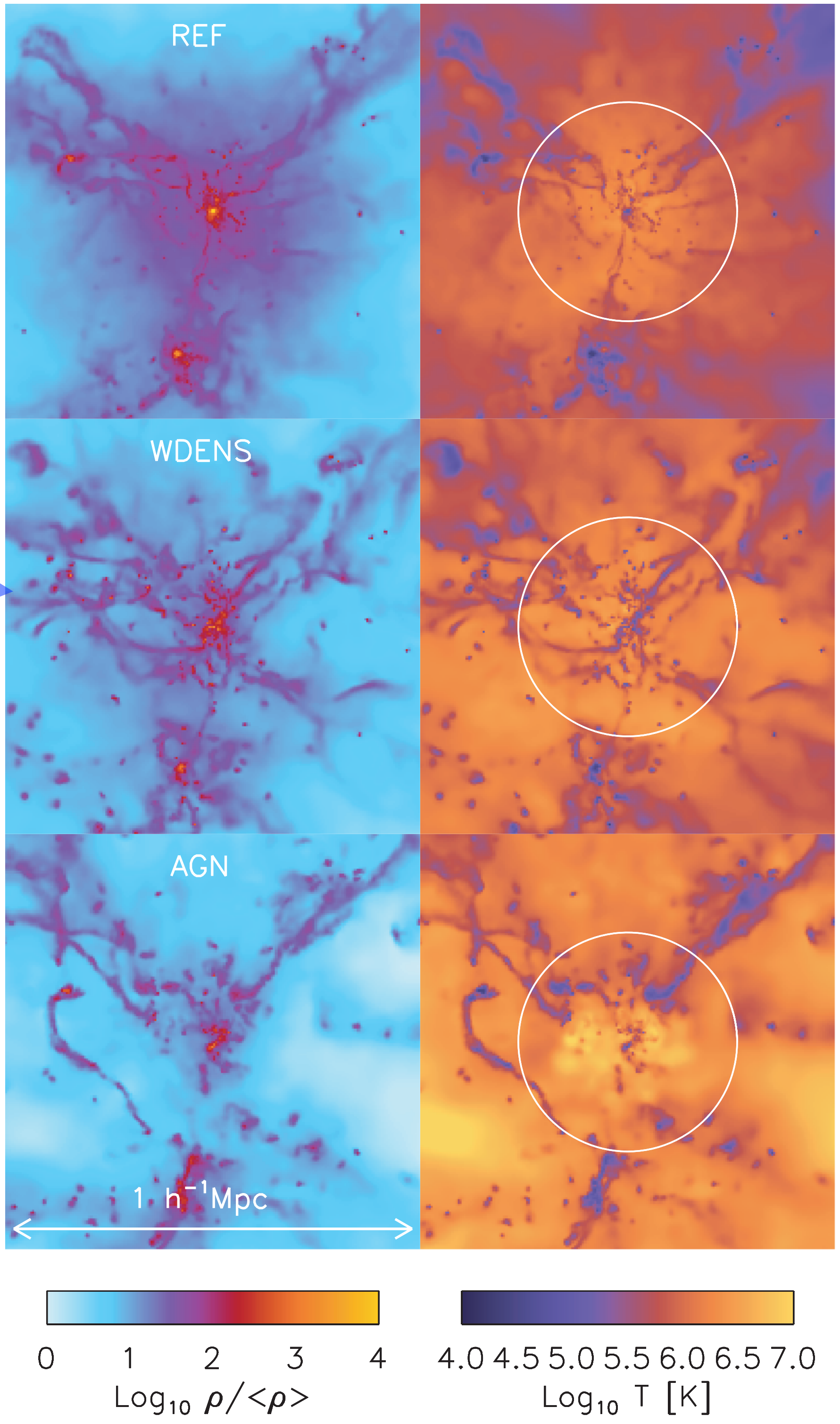
What happens when baryonic matter falls into a dark matter halo?



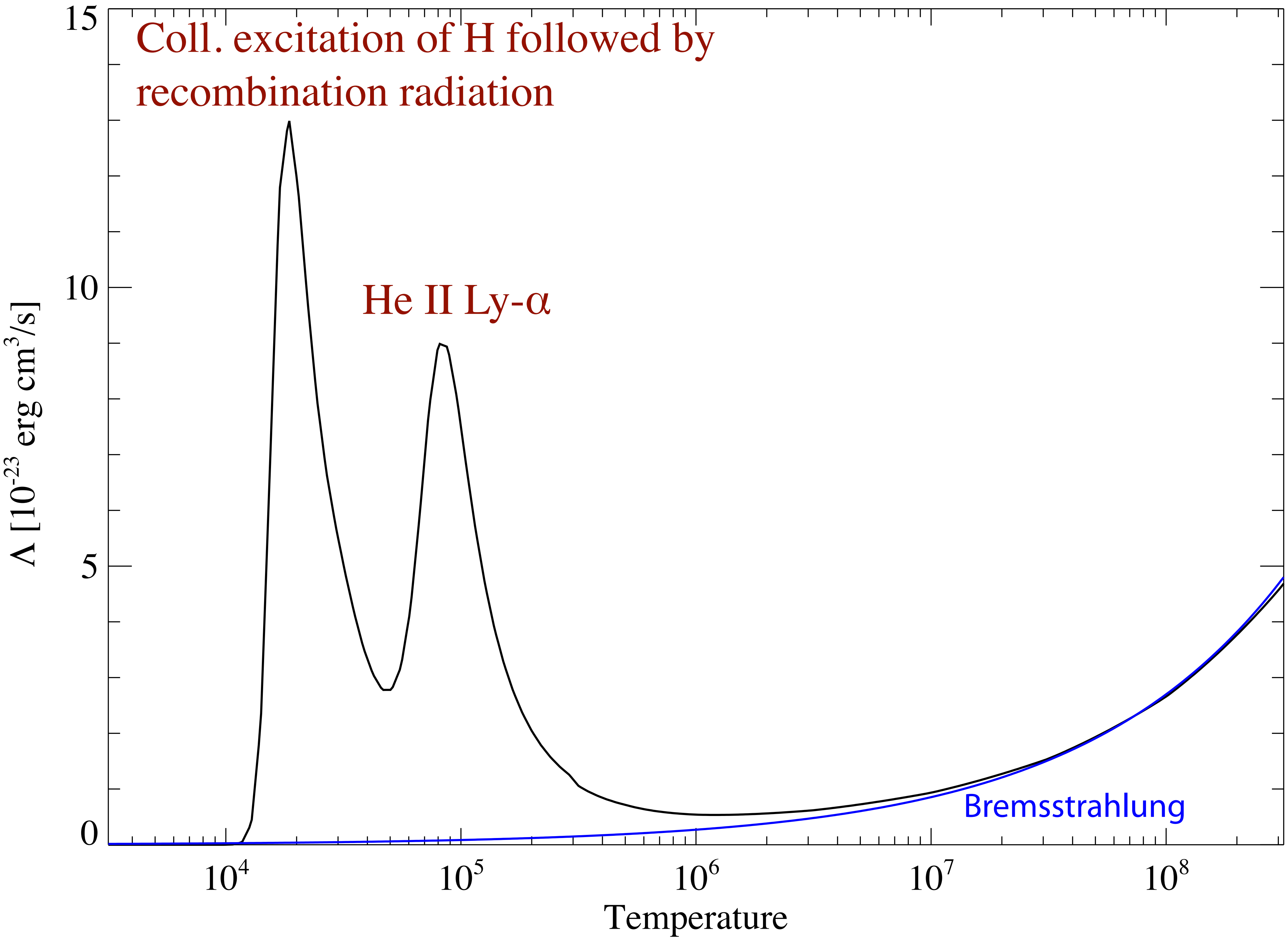
But

This depends on mass

And on feedback from stars & AGN



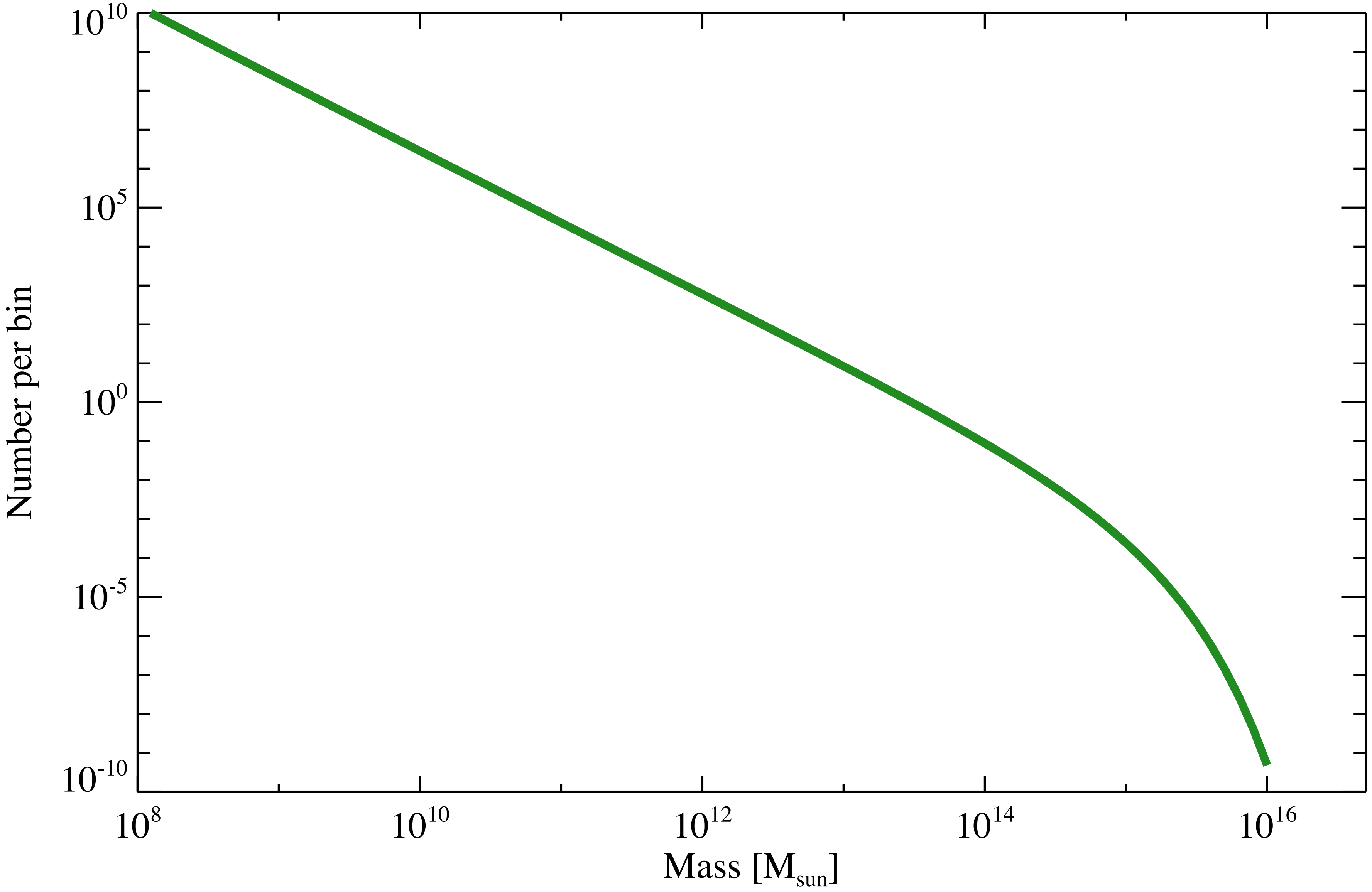
Cooling function for zero metallicity



The mass distribution of galaxies.

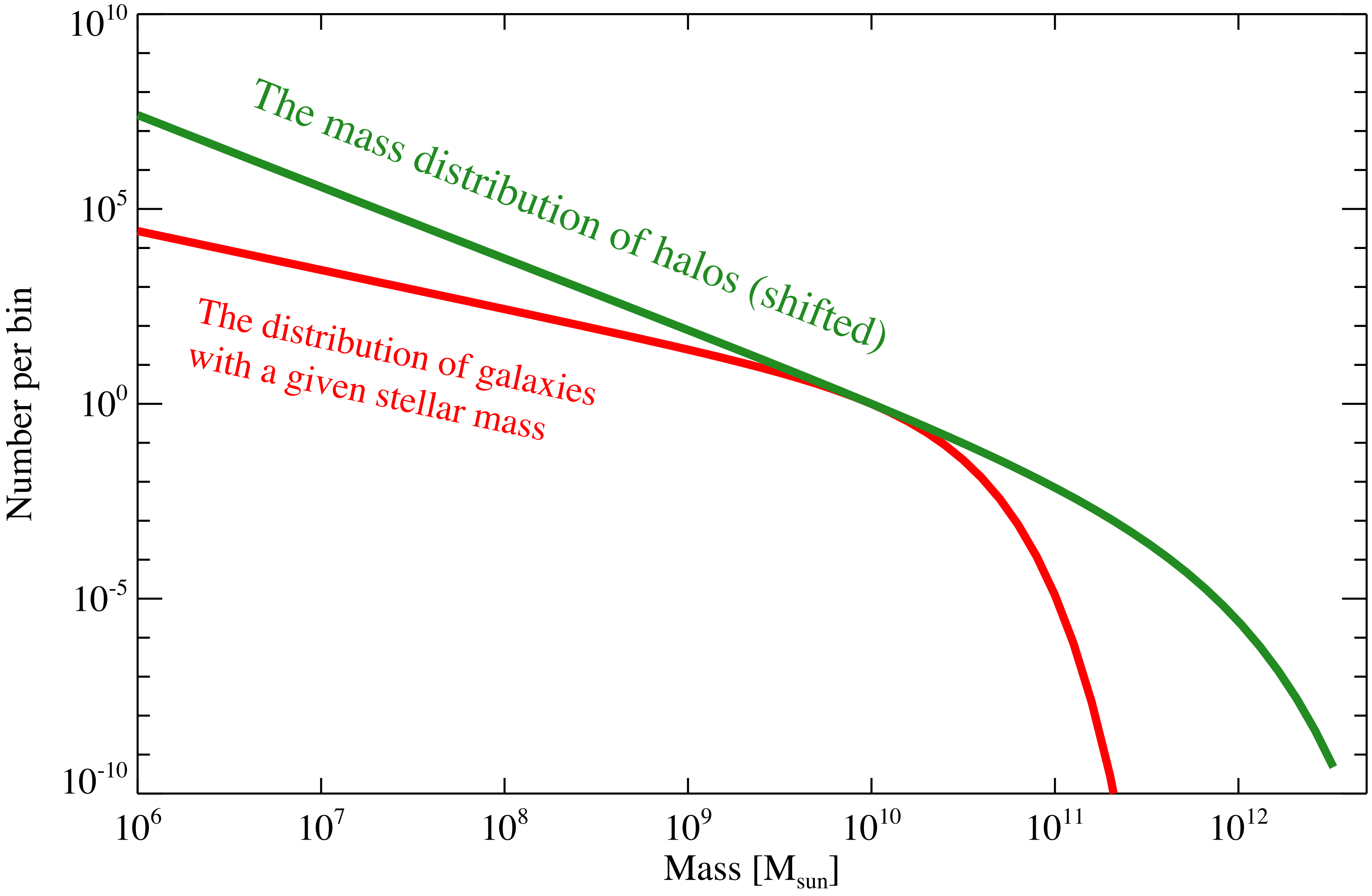
The power-spectrum + the statistics of small density perturbations in the Universe allows us to predict the mass distribution of **halos**.

Press & Schechter (1974) with many refinements.



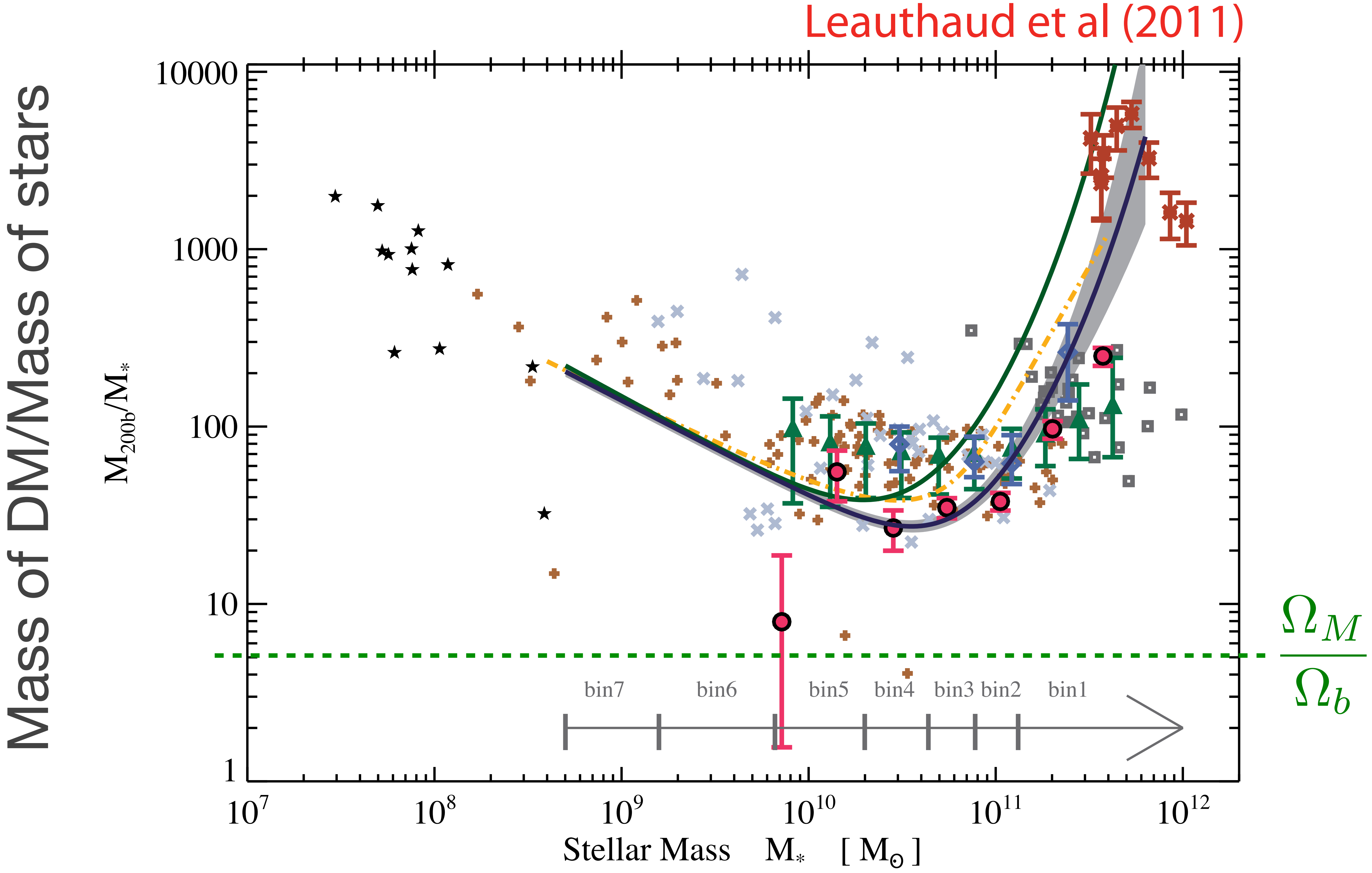
The mass distribution of galaxies.

Our simple model indicated one (main) galaxy per halo so this should be a good starting point for a galaxy mass function:

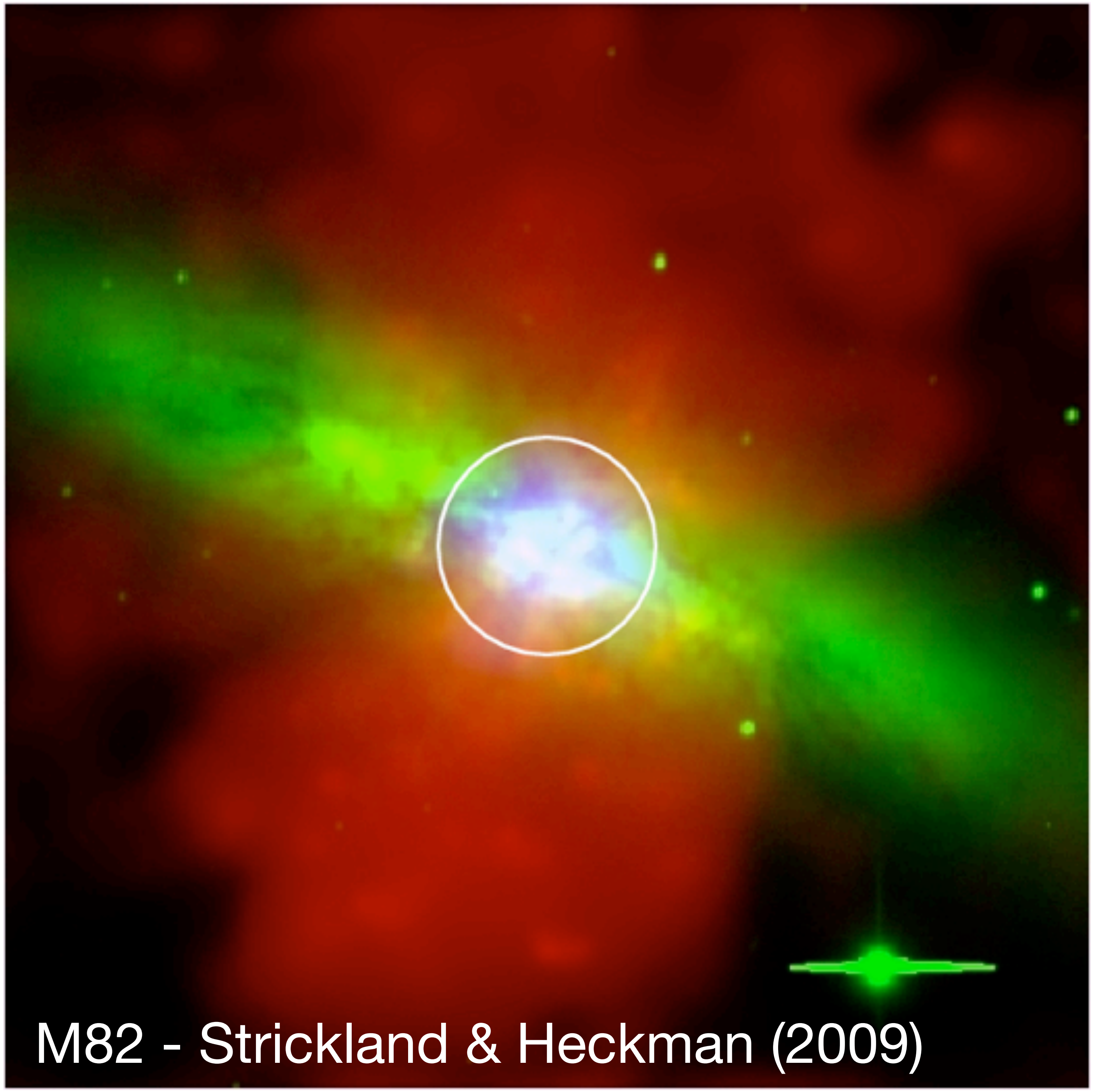


But it has some major problems!

Galaxy formation in halos is inefficient



Starburst feedback - M82 as an example


M82 - Strickland & Heckman (2009)

Soft X-rays ~5×10^6 K gas in a superwind

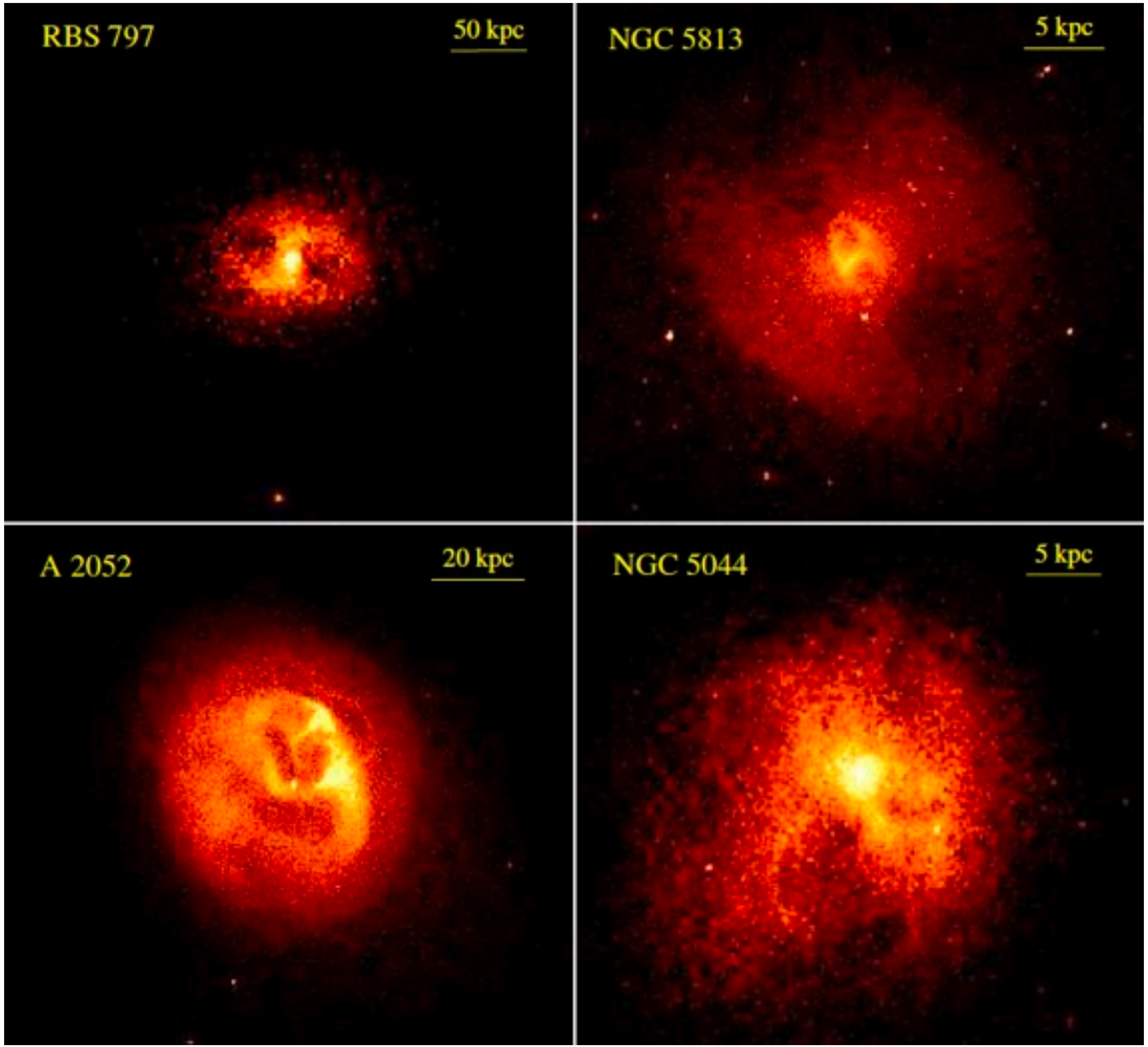
Hard X-rays (~10^{7-8} K)

Stars

AGN feedback

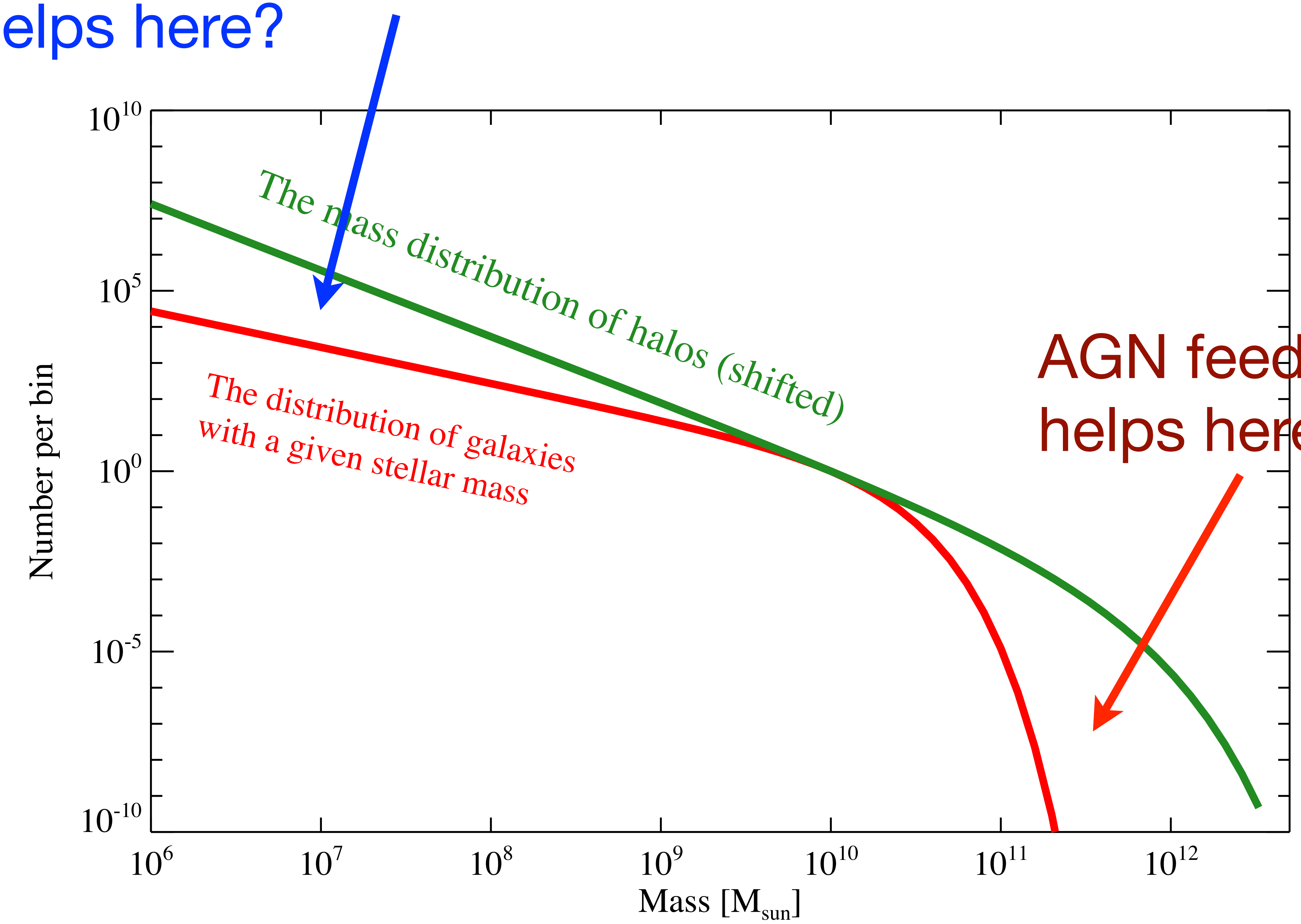
The supermassive black holes at the centre of massive galaxies also appear to influence their host galaxies

This could provide enough energy to blow out gas from very massive galaxies. We also see this on larger scales in clusters



From Fabian (2012)

Feedback from star-formation & AGNs



Star-formation feedback helps here?

AGN feedback helps here?

Time-scales of collapse

Expansion time of the Universe: $t_H \sim H(z)^{-1}$

Free-fall time-scale: $t_{\rm dyn} \sim (G\rho)^{-1/2}$

$$t_{\rm dyn} = \left(\frac{3\pi}{32G\rho}\right)^{1/2}$$

Cooling time:

$$t_{\rm cool} = \frac{E}{\dot{E}} = \frac{E}{n_H^2\Lambda} = \frac{\frac{3}{2}nkT}{\left(\frac{4}{9}\right)^2 n^2\Lambda}$$

Fully ionized monatomic gas

Time-scales of collapse

$t_{\rm cool} > t_H$

Cannot cool efficiently. No collapse

$t_{\rm dyn} < t_{\rm cool} < t_H$

Slow collapse set by cooling time, system moving along tracks of constant Jeans mass

$t_{\rm cool} < t_{\rm dyn}$

Efficient collapse on free-fall time-scale

$t_H \sim H(z)^{-1}$ $t_{\rm dyn} \sim (G\rho)^{-1/2}$ $t_{\rm cool} = \dfrac{E}{n_H^2 \Lambda}$

Collisional ionization equilibrium $Z_{met}=Z_{sun}$