Galaxy Formation

Carlton Baugh
Institute for Computational Cosmology
Durham University
ICTP Summer School on Cosmology
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Galaxy formation: key questions and points

- What do we know observationally?
- Galaxy formation in a cosmological context
- Why do we need “complicated’’ models?
- What physics do we need to worry about?
- How do we model galaxy formation?
- What have we learnt so far?
- Outstanding problems

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Outline of lectures

- Lecture 1: The Universe of galaxies; a simple model of hierarchical galaxy formation
- Lecture 2: The physics of galaxy formation
- Lecture 3: Simulating the formation and evolution of galaxies
- Lecture 4: Connecting galaxies to LSS

Learn more about galaxy formation

- Baugh, C. M. Reports on Progress in Physics, 2006, 69, 3101
- Benson A. J., Reviews of Modern Physics, 2010
- White & Frenk 1991, ApJ, 379, 52
- White Les Houches Lectures (arXiv.9410043)
- Cole et al 2000, MNRAS, 319, 168
- Textbook by Mo, Van Den Bosch & White 2010
- See also proceedings by Okamoto 2010, de Lucia 2009

The high redshift universe 1990

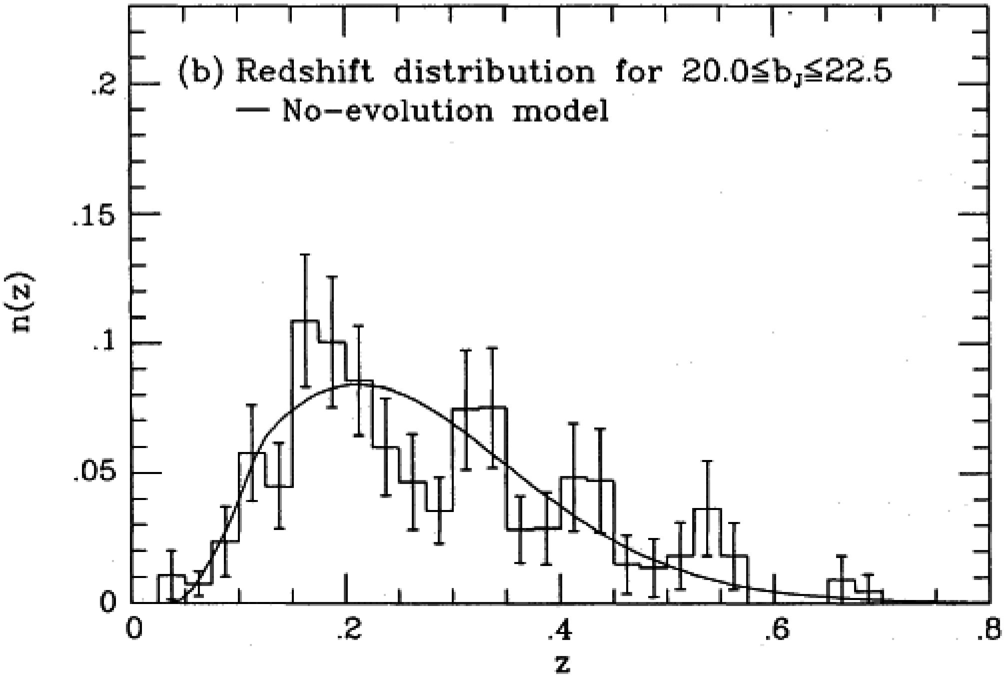
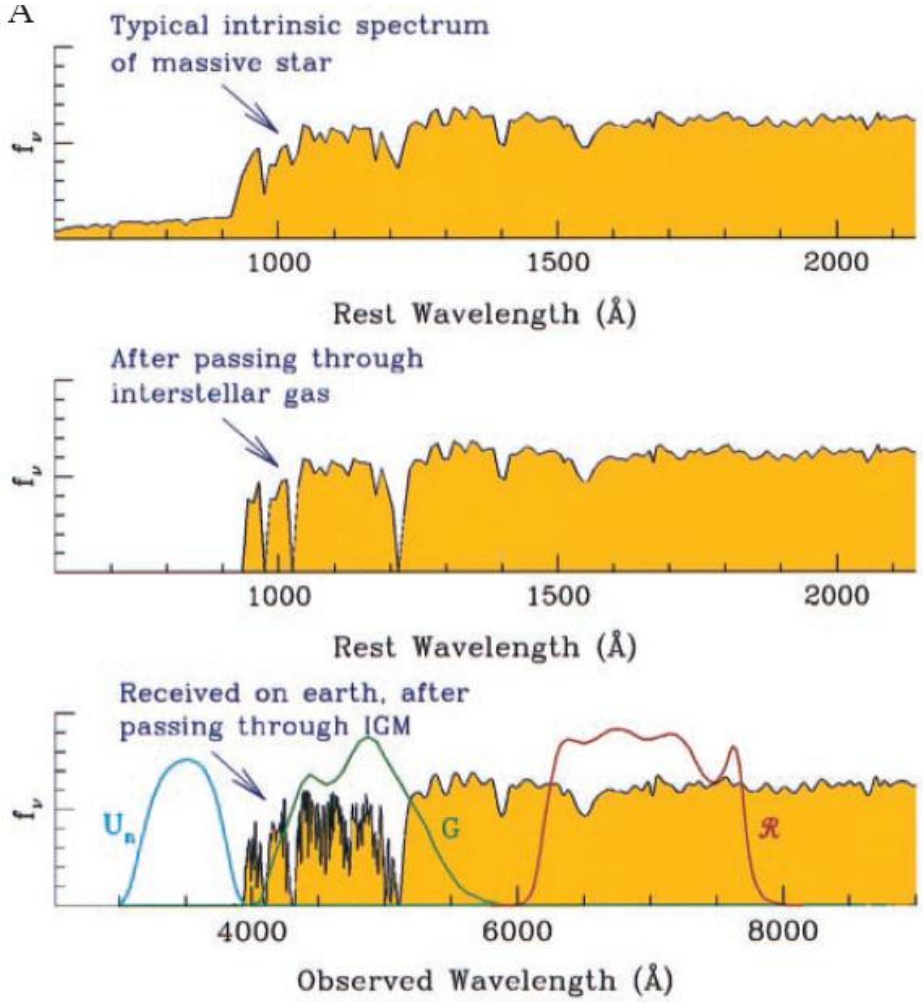
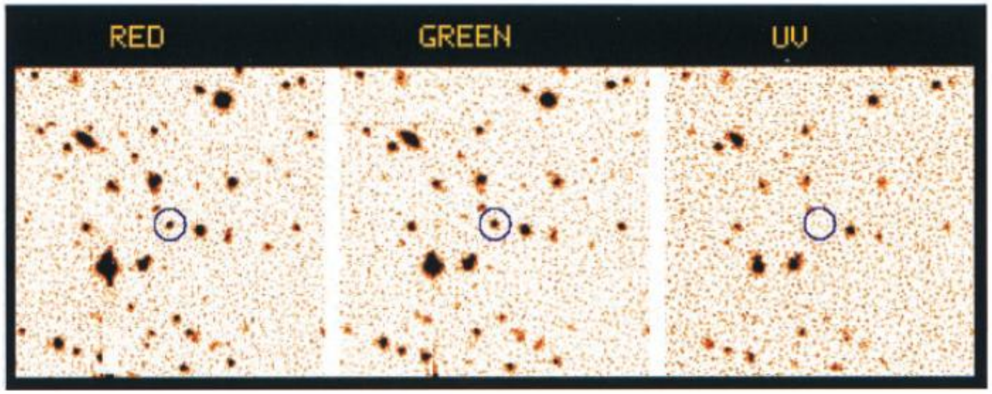


Figure 7. (a) The redshift distribution for the whole survey. The line is the no-evolution model prediction; (b) the combined redshift distribution for this survey and that of BES, normalized so that $\int n(z)\,dz = 1$. The line corresponds to the no-evolution model.

Colless et al. 1990





The Lyman break technique

Colour-colour selection of High redshift galaxies.

Efficient identification of candidate high-z galaxies for spectroscopic follow-up

Steidel et al. 1996, 1999

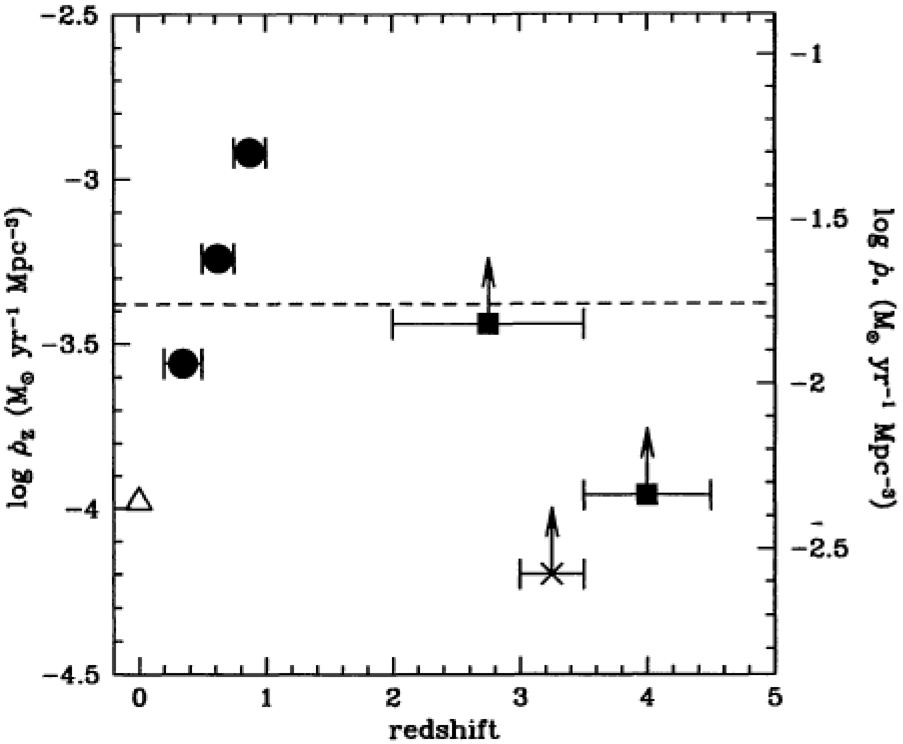
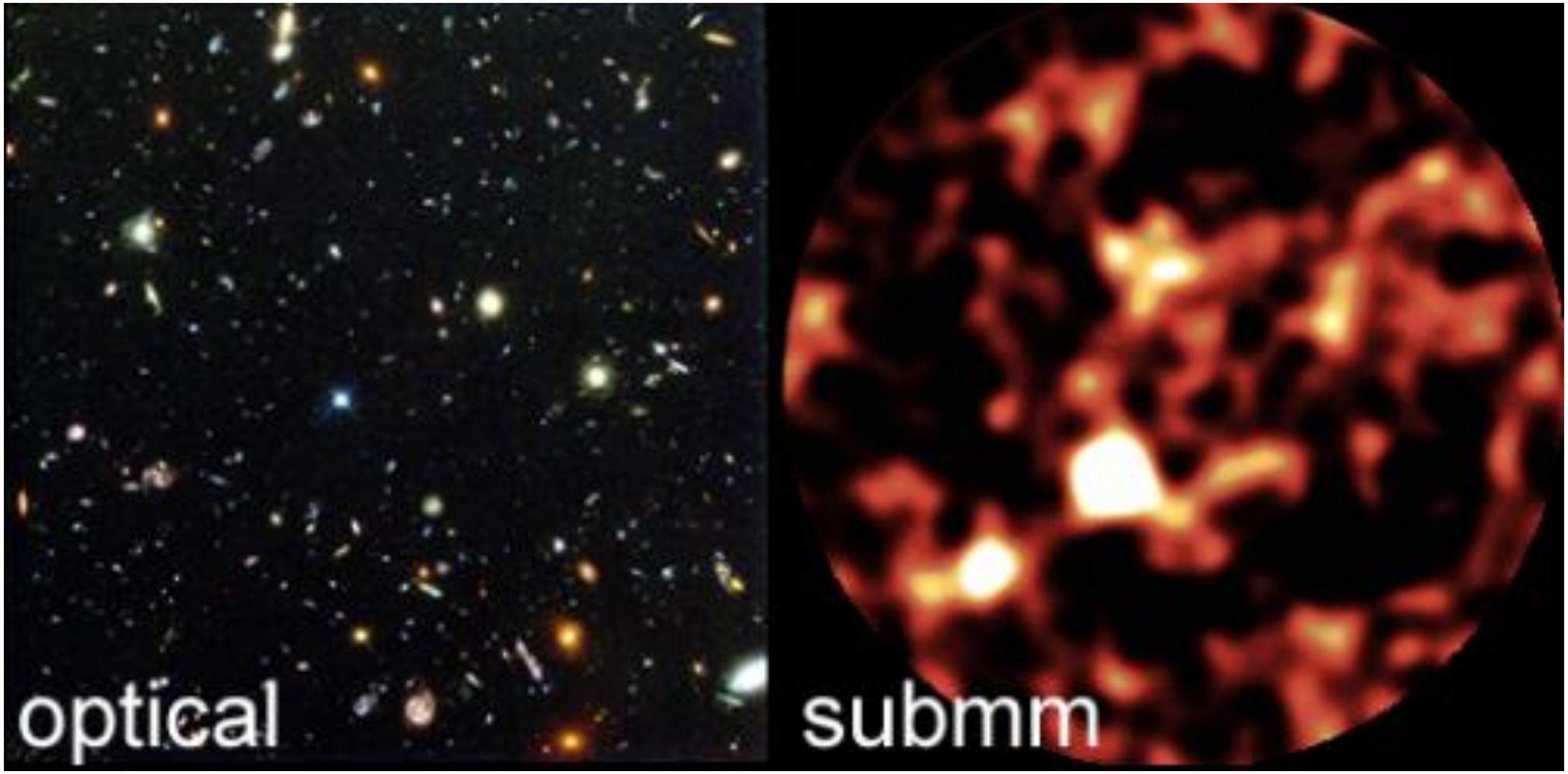


Figure 9. Element and star formation history of the Universe. The data points from various surveys provide a measurement or a lower limit to the Universal metal ejection density, $\dot{\rho}_Z$, as a function of redshift. For a Salpeter IMF, to translate $\dot{\rho}_Z$ into a total star formation density, $\dot{\rho}_*$, a factor of 42 should be applied. Triangle: Gallego et al. (1995). Filled dots: Lilly et al. (1996). Diagonal cross: lower limit from Steidel et al. (1996a). Filled squares: lower limits from the *HDF* images. The dashed line depicts the fiducial rate, $\dot{\Sigma}_Z$, given by the mass density of metals observed today divided by the present age of the Universe (see text for details). A flat cosmology with $q_0 = 0.5$ and $H_0 = 50\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ has been assumed.

Star formation history of the Universe

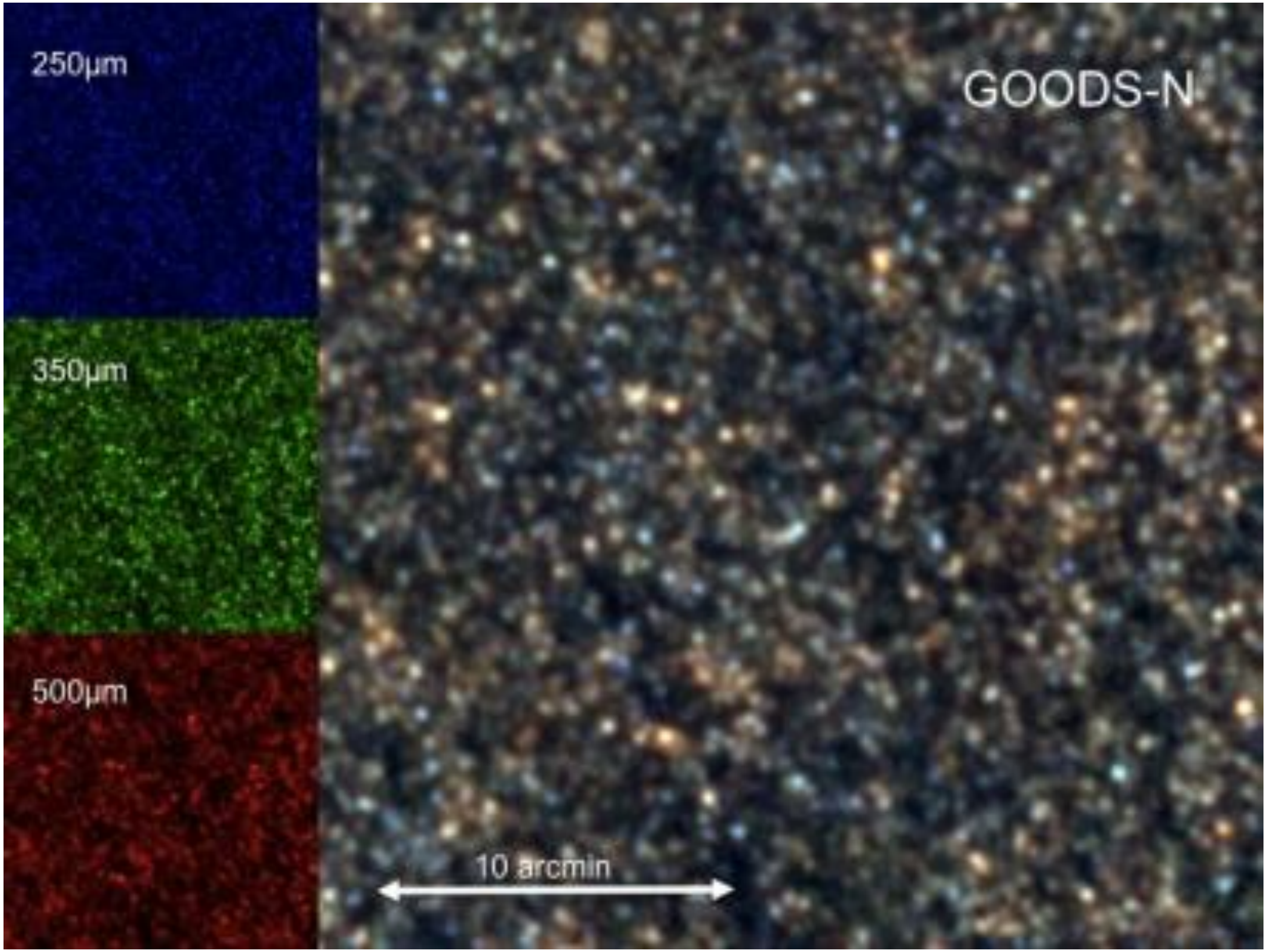
Madau et al. 1996; Lilly et al. 1995

The multi-wavelength view

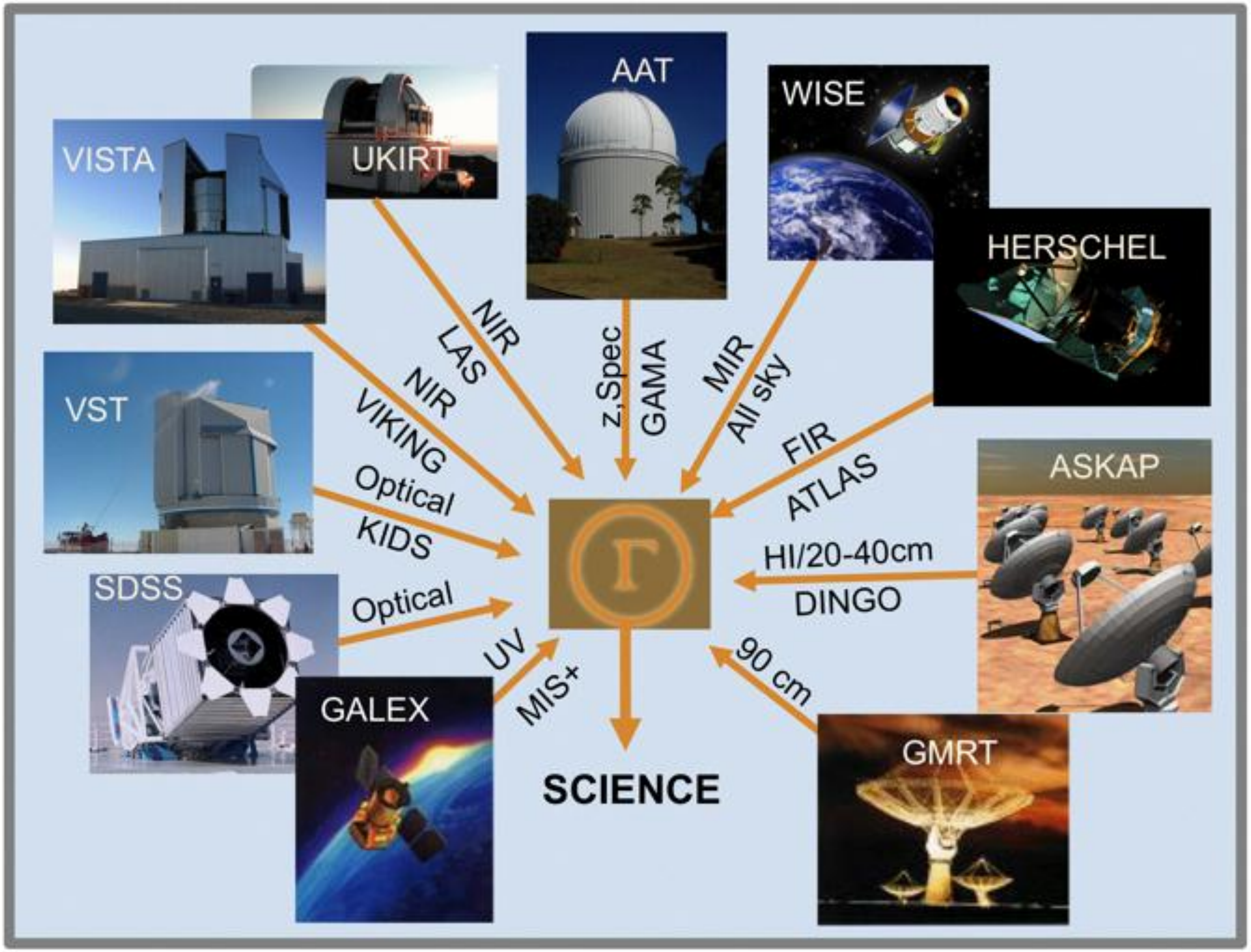


Hubble Deep Field: optical Williams et al 1996; sub-mm Hughes et al. 1998

The Herschel Space Observatory view

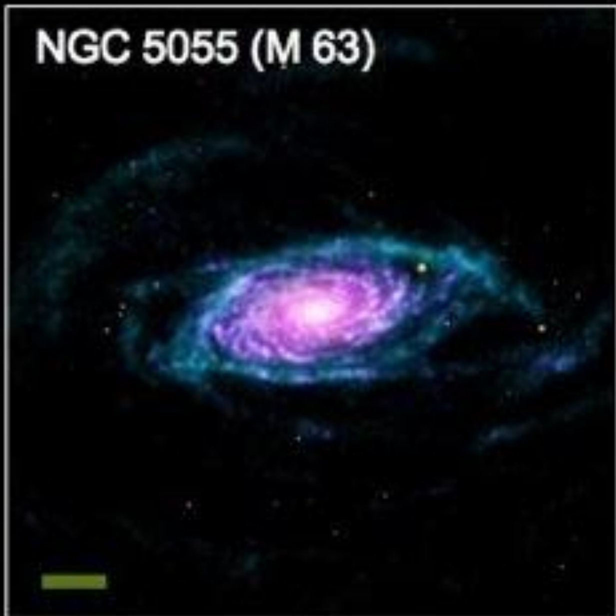


Multi-wavelength astronomy



GAMA Survey Driver et al 2009

Spiral Galaxies in THINGS — The HI Nearby Galaxy Survey



THINGS

The HI Nearby Galaxy Survey

color coding:

THINGS Atomic Hydrogen *(Very Large Array)*

Old stars *(Spitzer Space Telescope)*

Star Formation *(GALEX & Spitzer)*

scale: 15,000 light years

Image credits:
VLA THINGS: Walter et al. 08
Spitzer SINGS: Kennicutt et al. 03
GALEX NGS: Gil de Paz et al. 07

Pseudo-models

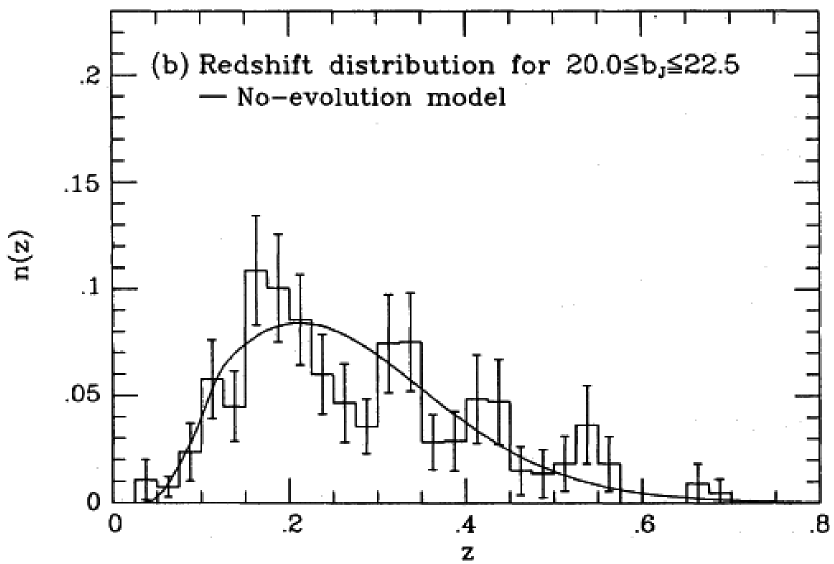


Figure 7. (a) The redshift distribution for the whole survey. The line is the no-evolution model prediction; (b) the combined redshift distribution for this survey and that of BES, normalized so that $\int n(z)\,dz = 1$. The line corresponds to the no-evolution model.

Backwards models:

- Passive evolution
- No evolution
- Luminosity evolution

Brief description of data

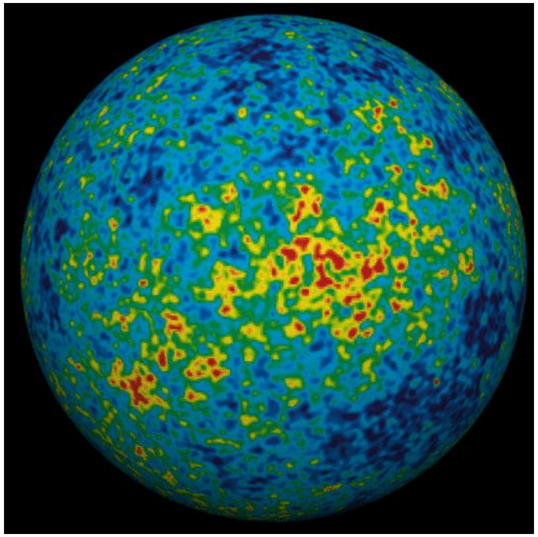
Unphysical

Ignore structure formation

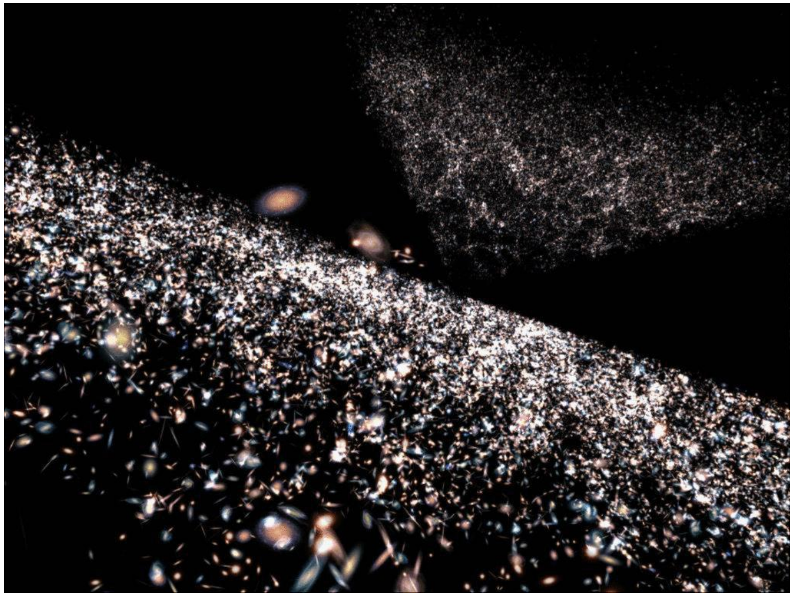
No predictions

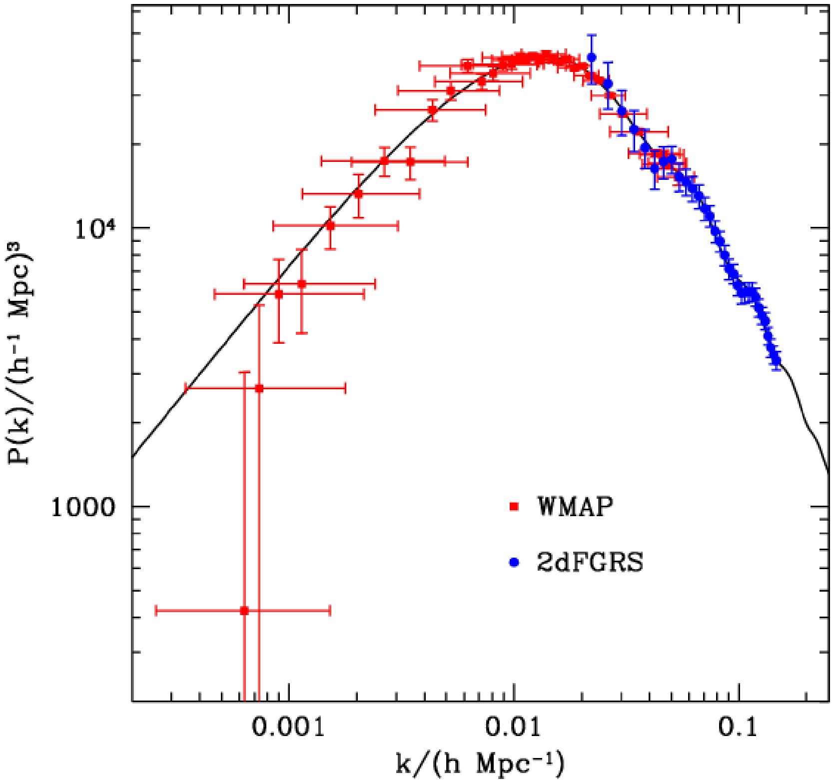
The cosmological setting: Hierarchical structure formation

z ~ 1100



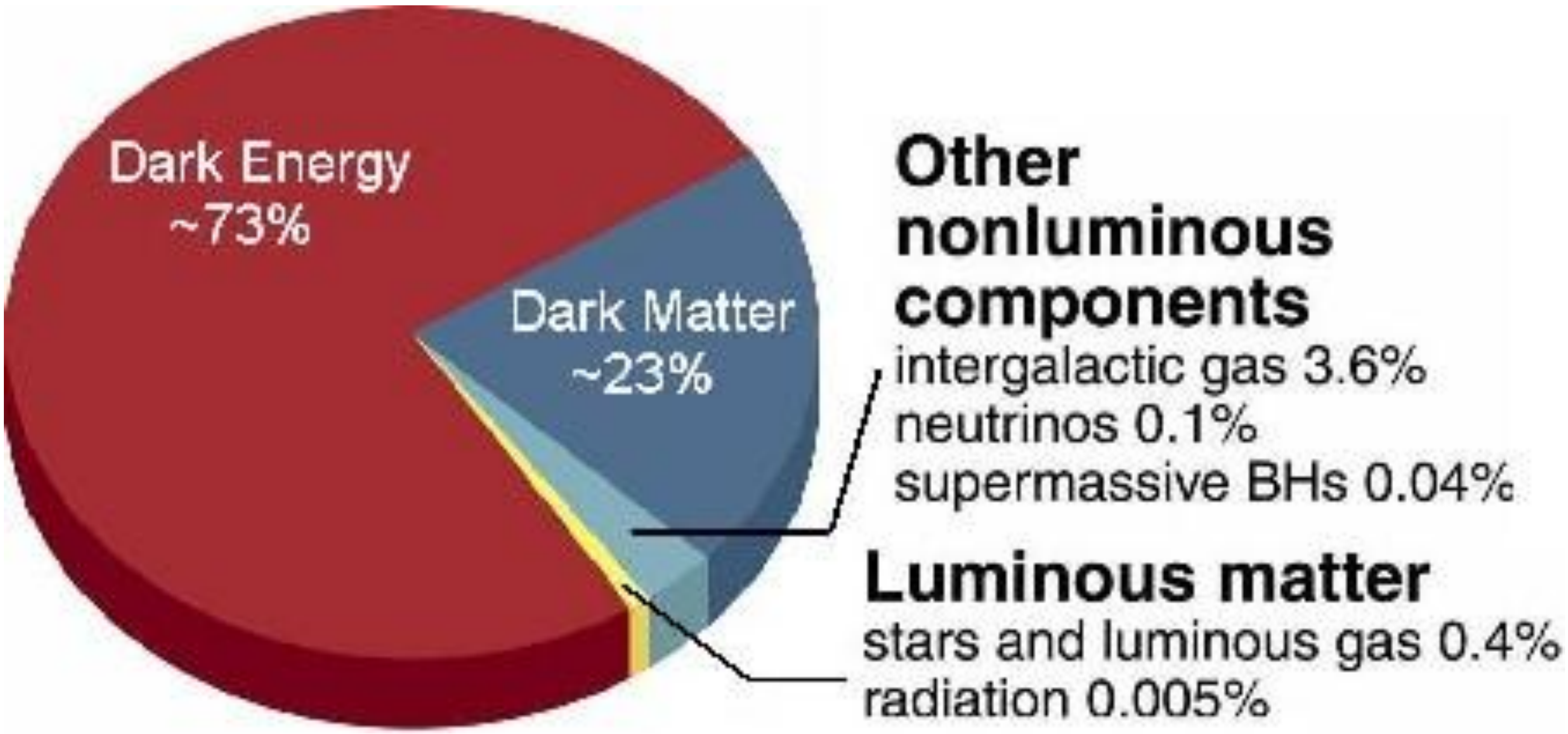
z~0



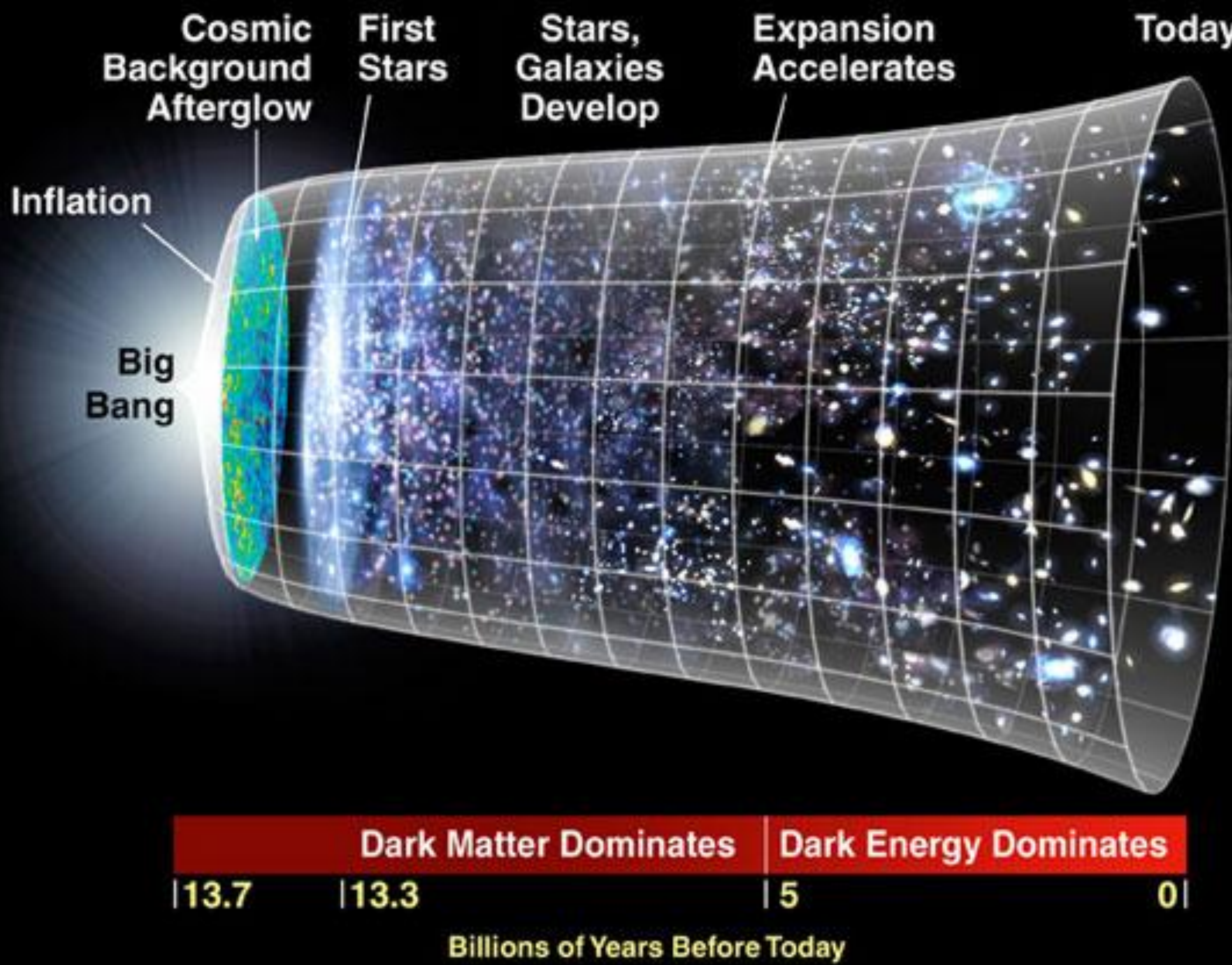


Sanchez et al. 2006, 2009
Komatsu et al. 2010

What is the universe made of?

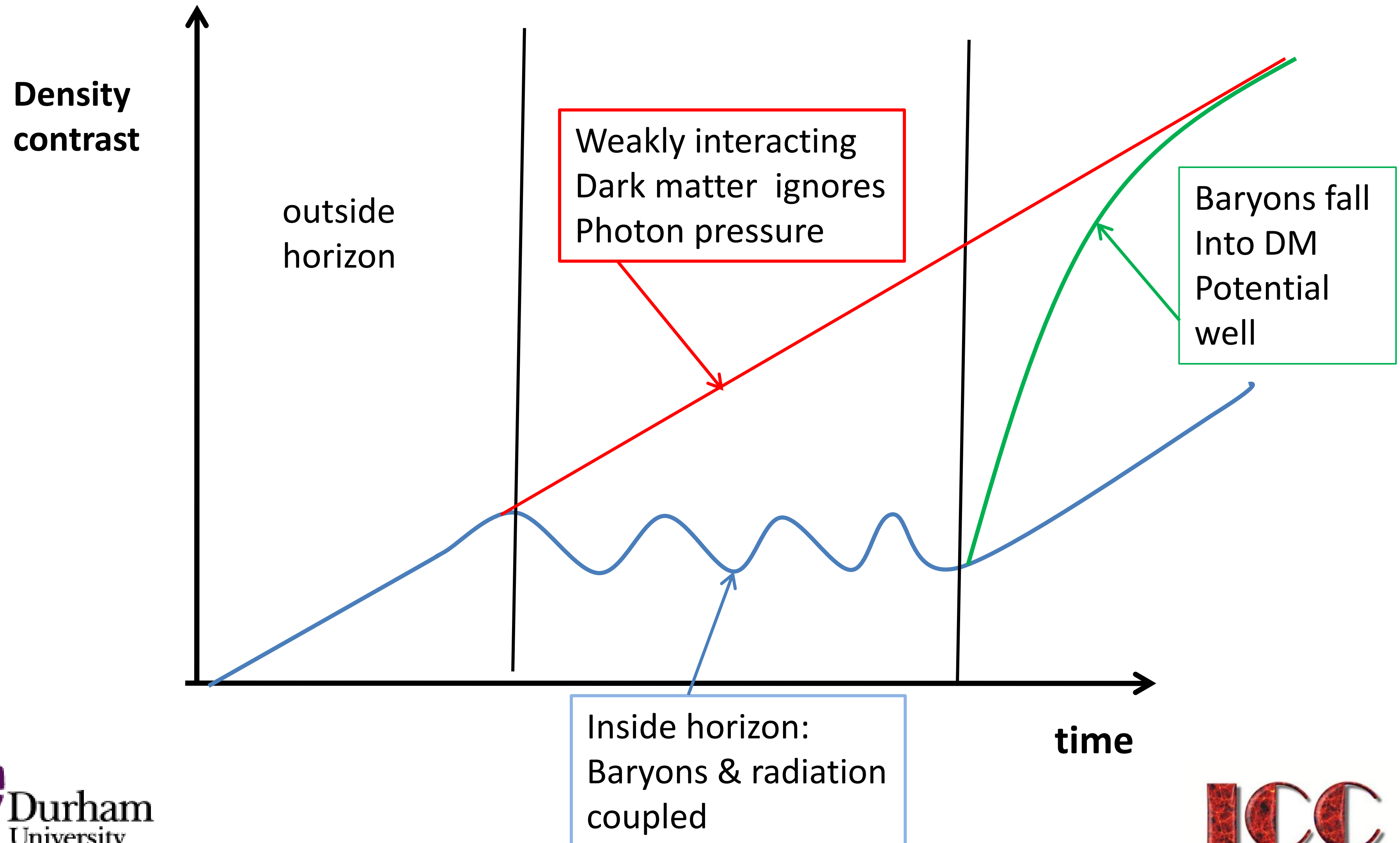


The Expanding Universe: A Capsule History

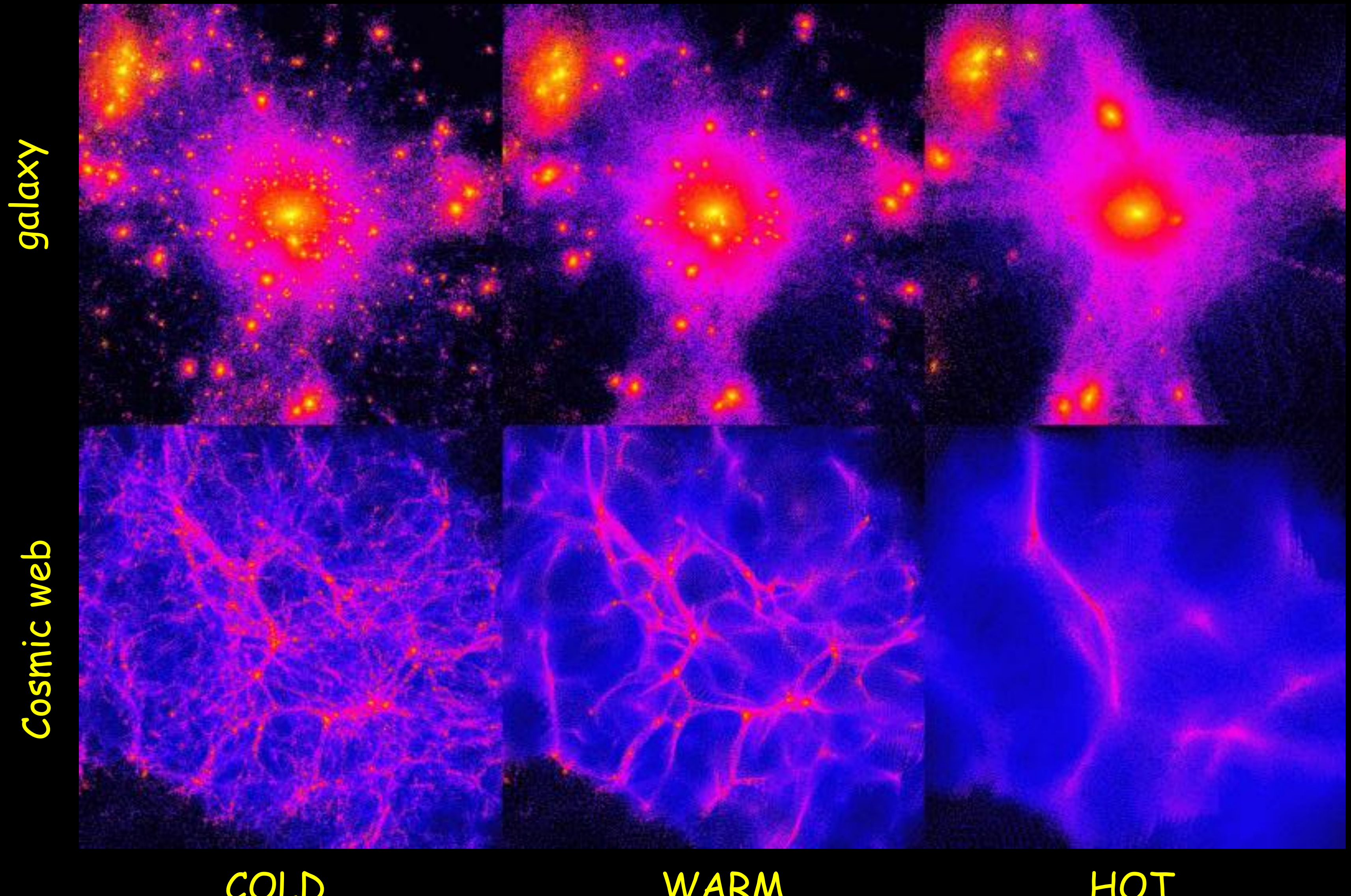


ICC

The growth of a dark matter perturbation

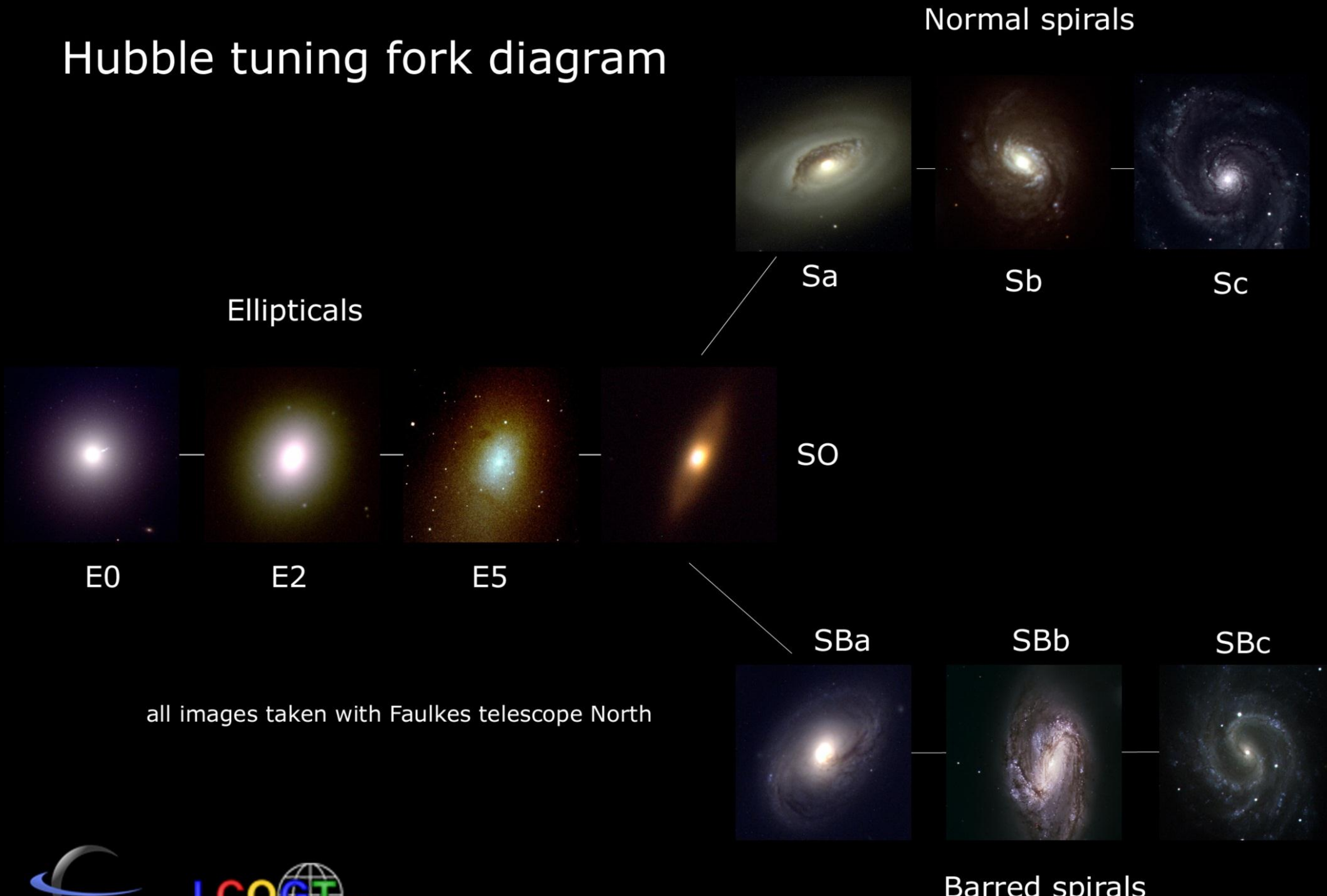


Why cold dark matter?



What do we know about galaxies?

Hubble tuning fork diagram



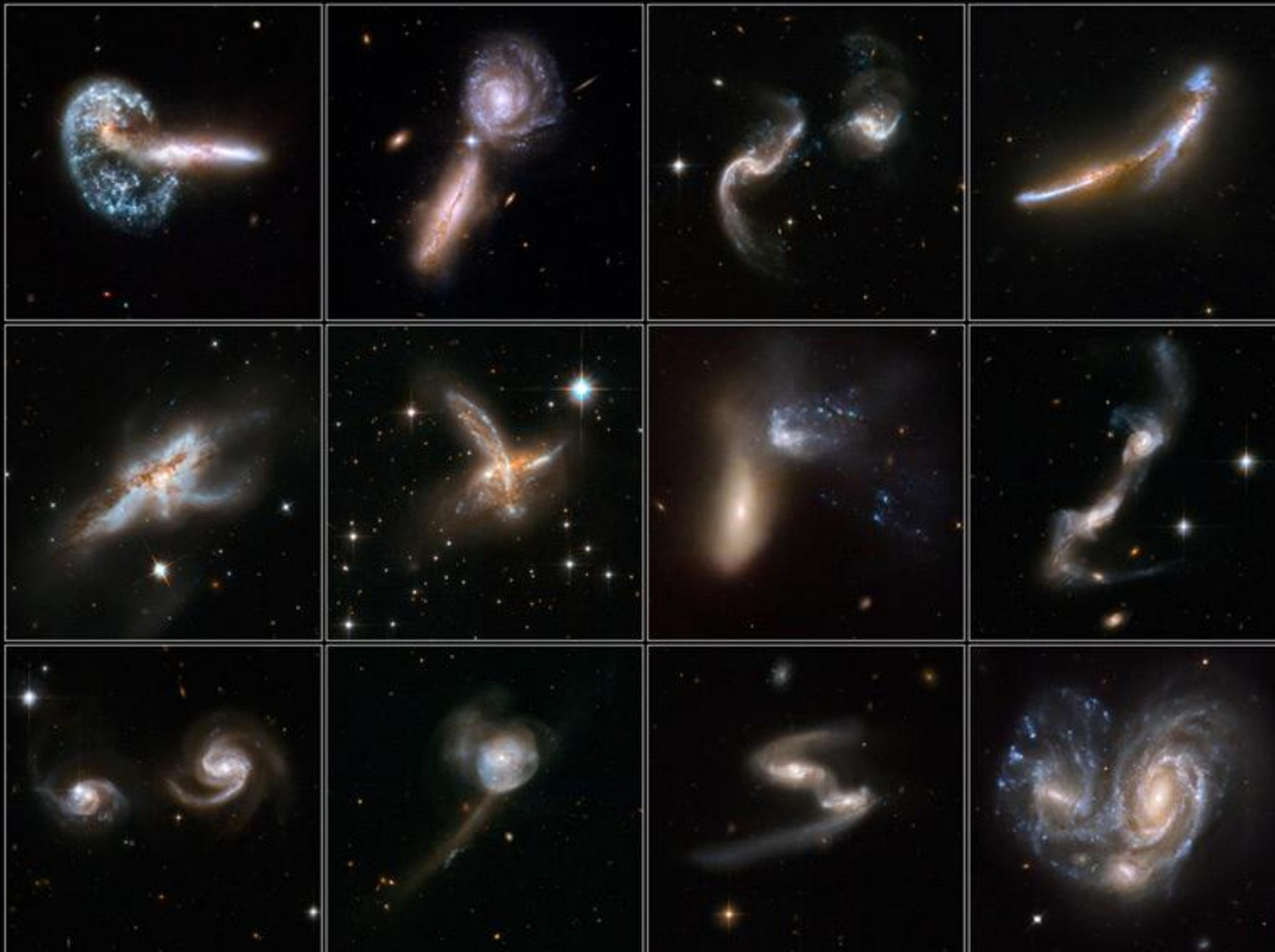
all images taken with Faulkes telescope North

FAULKES TELESCOPE

LCOGT.net

Interacting Galaxies

Hubble Space Telescope • ACS/WFC • WFPC2



NASA, ESA, the Hubble Heritage (AURA/STScI)-ESA/Hubble Collaboration, and A. Evans (University of Virginia, Charlottesville/NRAO/Stony Brook University)

STScI-PRC08-16a

Galaxy formation is inefficient

Cosmic baryon density

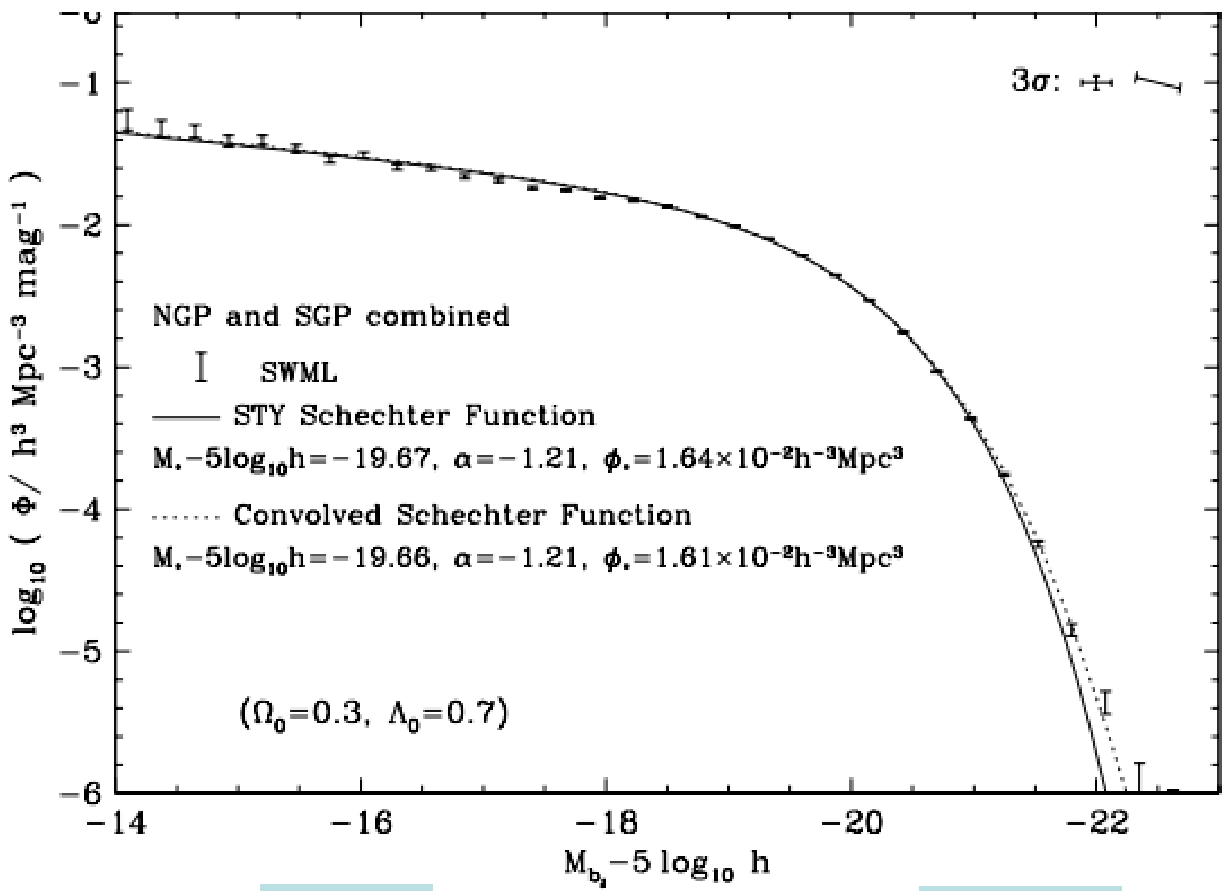
$$\Omega_b = 0.0462 \pm 0.0015$$

Cosmic density of stars

$$\Omega_\star = (2.3 \pm 0.34) \times 10^{-3}$$

Only ~5 % of available baryons are in stars today

Basic galaxy properties: the galaxy luminosity function



← fainter

brighter →

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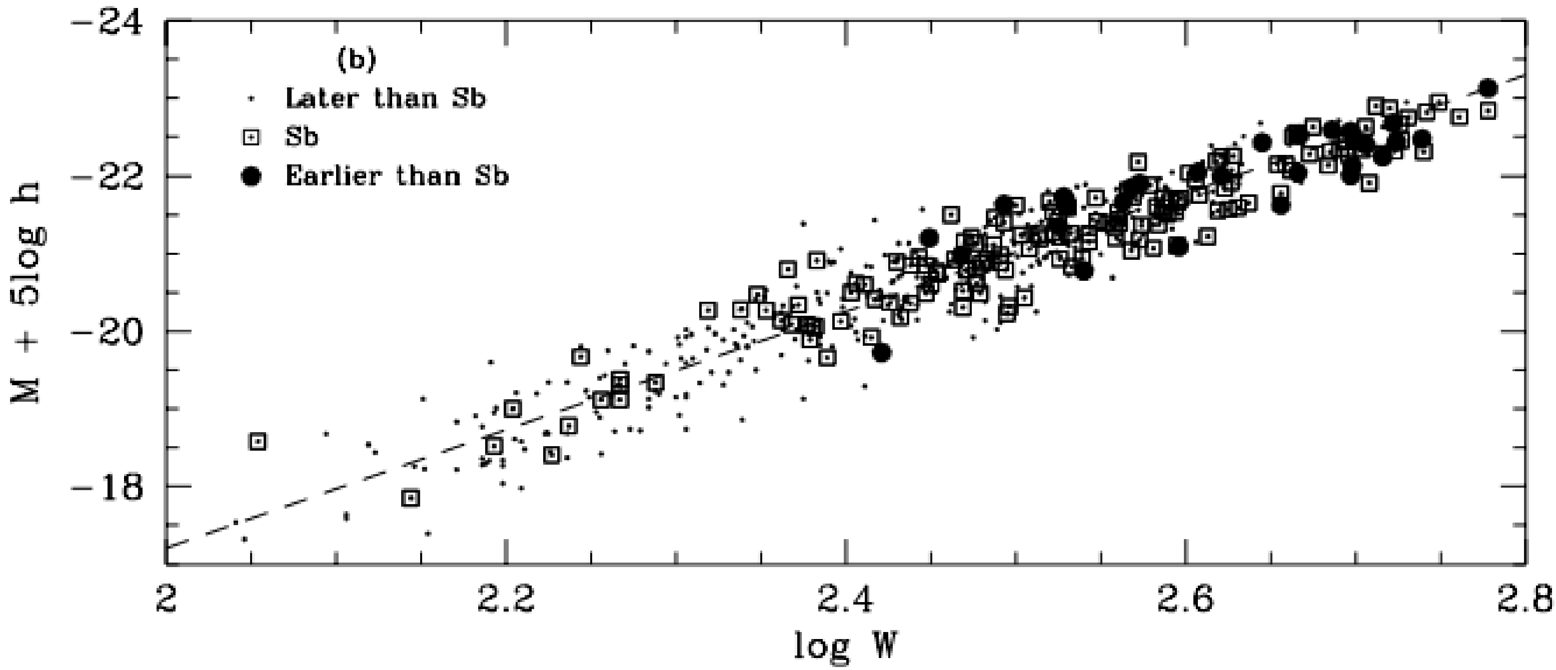
Norberg et al. 2002

Basic galaxy properties: the "Tully-Fisher" relation

Example of tight correlation between stellar content of galaxy and structural properties

luminosity



Log rotation speed

Giovanelli et al 1997

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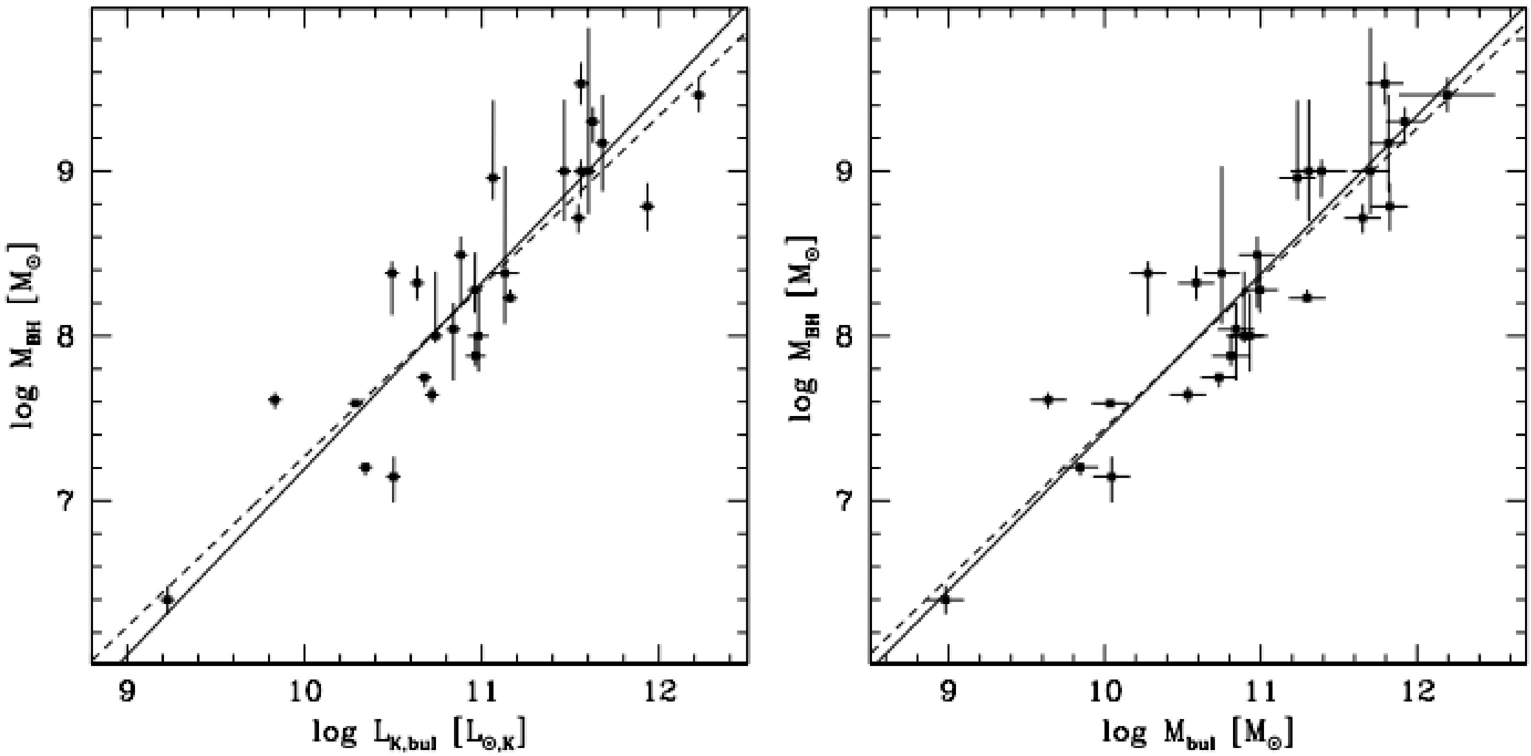
Basic galaxy properties: galactic bulge- black hole mass



BH mass ~ 0.001 x stellar mass of bulge

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Black hole mass – bulge properties: Marconi & Hunt

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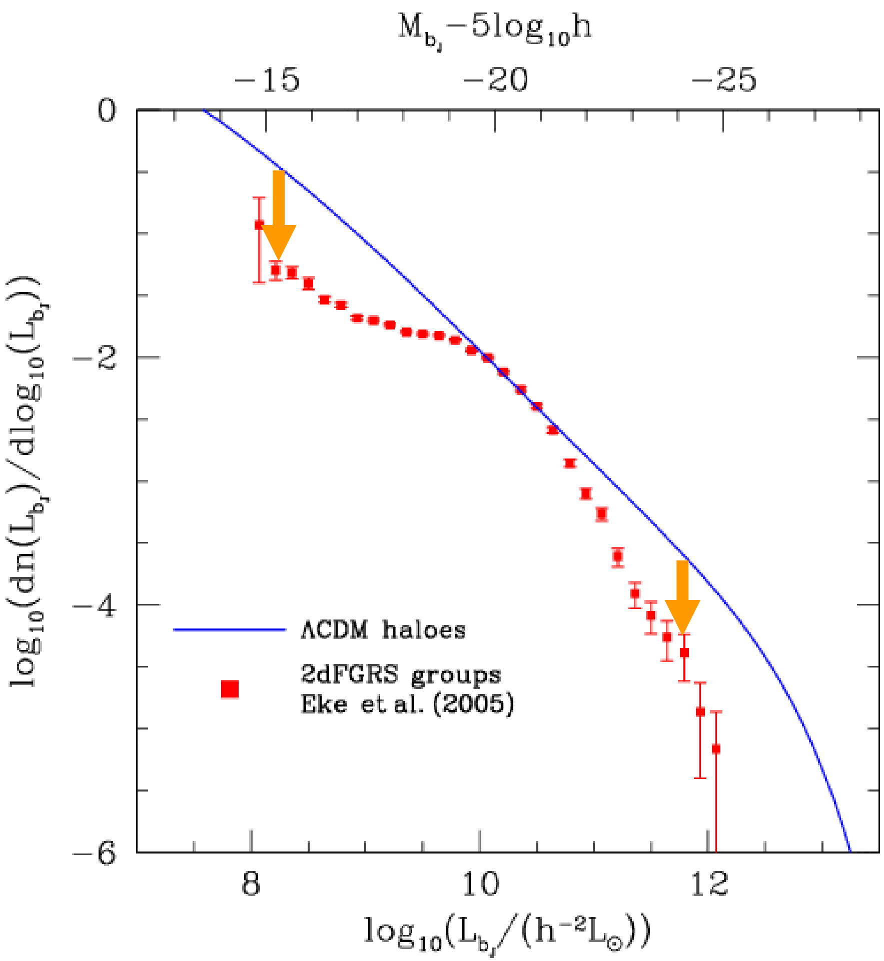
Why do we need “complicated” models?

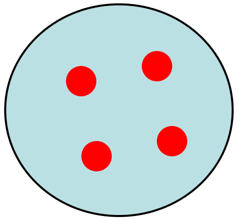
Baugh 2006 Reports on Progress in Physics, astro-ph/0610031



abundance

Total group luminosity

Galaxy group luminosity function
Measured from 2dFGRS by
Eke et al. 2004, 2005



$L_{group} = \Sigma L_{galaxy}$

Simple prediction:
Take CDM halo mass function
plus fixed M/L ratio

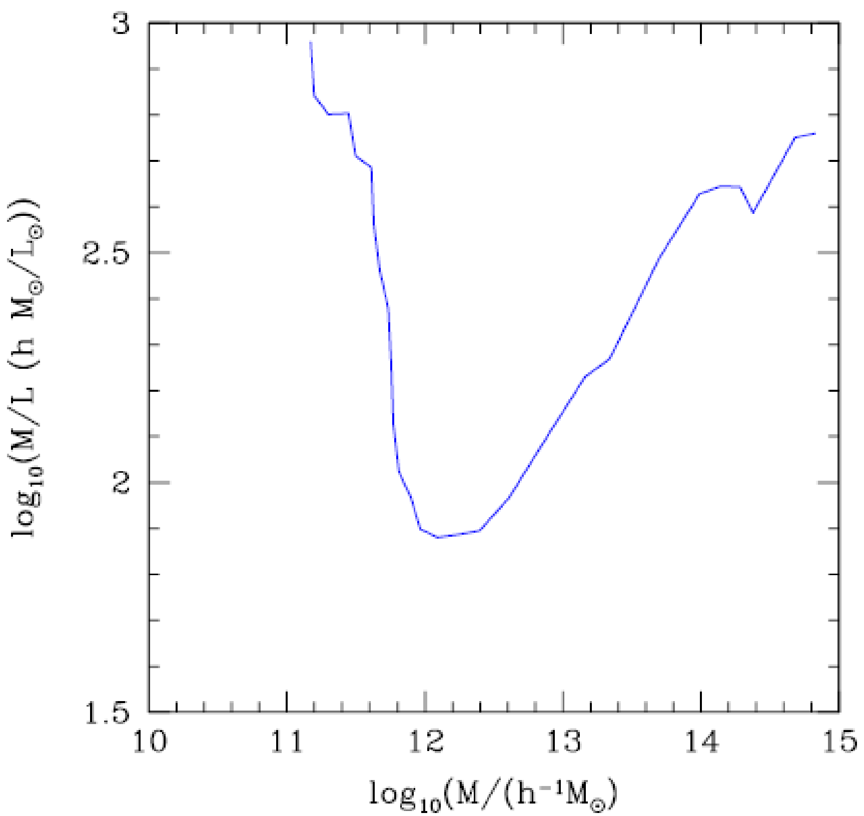
↓

Galaxy formation TOO efficient
in both low and high mass haloes

Why do we need “complicated” models?

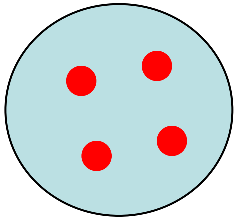
Baugh 2006 Reports on Progress in Physics, astro-ph/0610031

Mass to light ratio



DM halo mass

Galaxy group luminosity function
Measured from 2dFGRS by
Eke et al. 2004, 2005



$L_{group} = \Sigma L_{galaxy}$

Simple prediction:
Take CDM halo mass function
plus fixed M/L ratio

↓

Galaxy formation TOO efficient
in both low and high mass haloes

Key ideas in galaxy formation

- Structure formation driven by gravitational instability (Landau?)
- Haloes spin due to tidal torques (Hoyle 1949)
- Galaxies form inside DM haloes: Two stage collapse: dissipationless (DM haloes) and dissipative (galaxies) (White & Rees 1978)
- Typical galaxy mass set by cooling arguments (Hoyle 1953, Silk 1977, Binney 1977 Rees & Ostriker 1977)
- Disk galaxy formation can be understood by cooling gas conserving AM in DM halo (Fall & Efstathiou 1980)
- The need to regulate galaxy formation in low mass haloes (White & Rees 1978)
- Heating by Sne (Larson 1972, Dekel & Silk 1986)

A simple model of galaxy formation

- Hierarchical growth of DM haloes
- Galaxies form inside DM haloes
- Look at infall, outflow, star formation

Growth of DM haloes

$$\dot{M}_{\rm h} \simeq 510\, M_{{\rm h},12}^{\,s} (1+z)_{3.2}^{t}\, M_\odot\ {\rm yr}^{-1}\,, \qquad (5)$$

where $M_{\rm h,12} \equiv M_{\rm h}/10^{12}\ M_\odot$, $(1+z)_{3.2} \equiv (1+z)/3.2$, $t \simeq 2.2$, and $s \simeq 1.1$, with the estimates for s ranging from 1.08 to 1.14 (Neistein & Dekel 2008; Genel et al. 2008; McBride et al. 2009)

A simple model for baryons

$$\dot{M}_{\rm gas} = \dot{M}_{\rm gas,in} - (1-R)\dot{M}_\star - \dot{M}_{\rm gas,out}$$

$$\dot{M}_{\rm gas,in} = \epsilon_{\rm in}\, f_{\rm b}\, \dot{M}_{\rm h}$$
$$\simeq 90\, \epsilon_{\rm in}\, f_{\rm b,0.18}\, M_{\rm h,12}^{1.1}\, (1+z)_{3.2}^{2.2}\, M_\odot\ {\rm yr}^{-1}$$

$$\dot{M}_{\rm gas,out} = a \times {\rm SFR},$$

A simple model for baryons

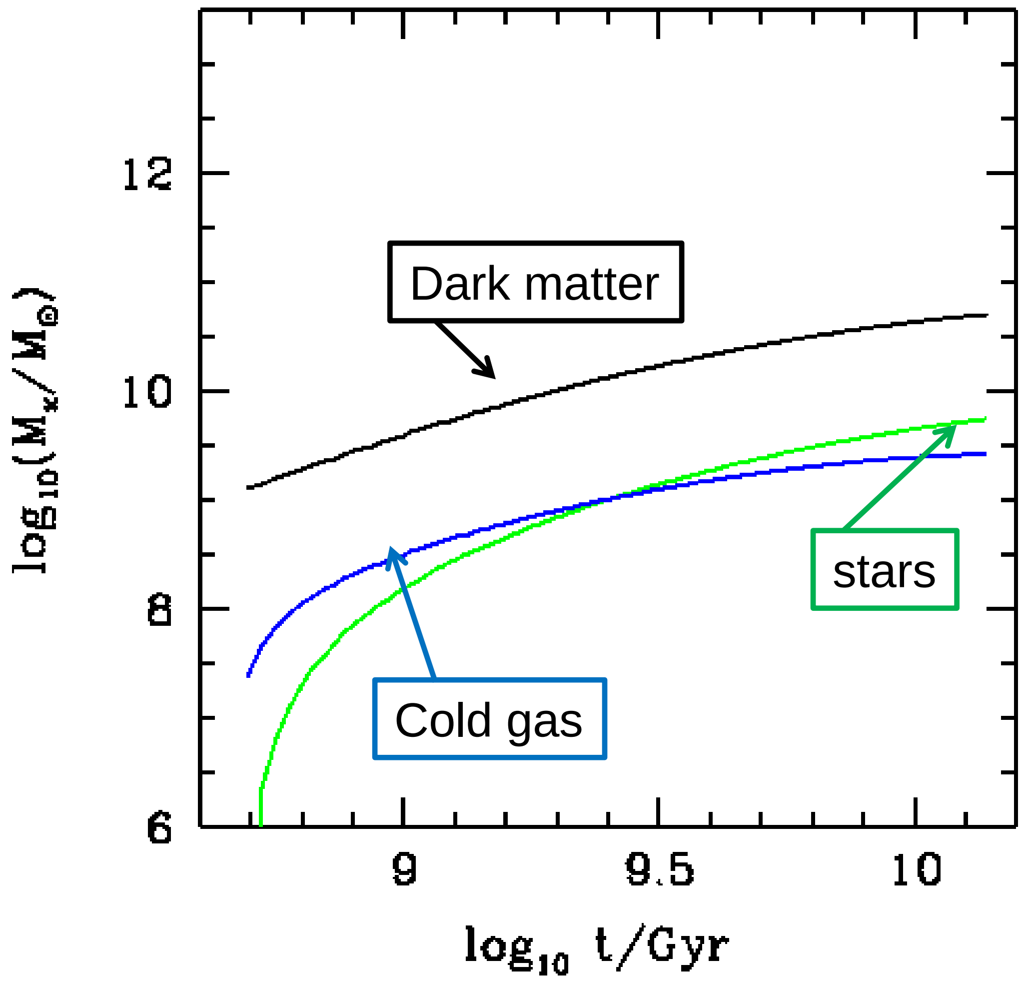
$$\dot{M}_{\rm gas} = \dot{M}_{\rm gas,in} - (1-R)\dot{M}_{\star} - \dot{M}_{\rm gas,out}$$

After connecting outflow to SFR: $\dot{M}_{\rm gas,out} = a \times {\rm SFR},$

Where the SFR is defined as ${\rm SFR} = \epsilon_{\rm sfr} M_{\rm gas} / (t_{\rm dyn})$

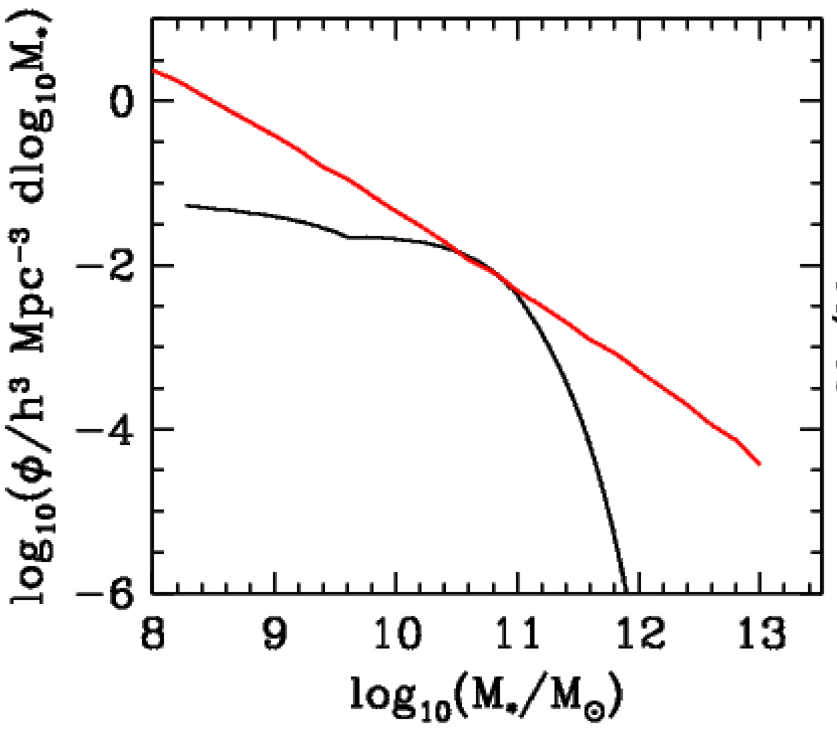
$$\dot{M}_{\rm gas} = \dot{M}_{\rm gas,in} - \alpha \dot{M}_{\star}$$

Evolution within a halo

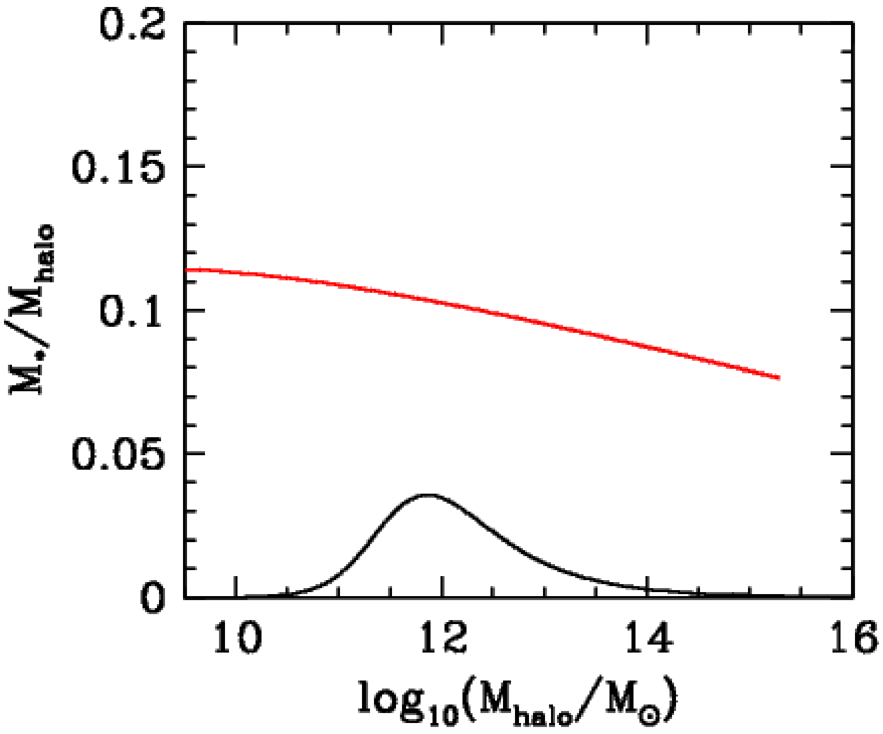


No suppression of “cooling”

STELLAR MASS FUNCTION



MSTARS/MHALO: GALAXY FORMATION “EFFICENCY”

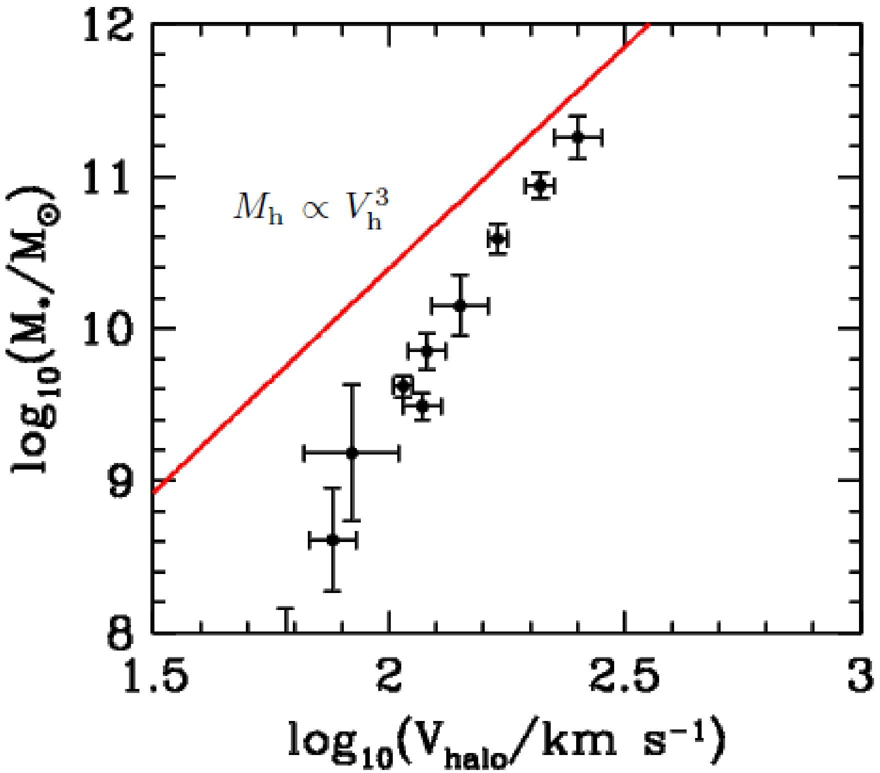


Infall of cold baryons tracks infall of dark matter

Black: observational constraints z=0 Guo et al. 2012 RED: model

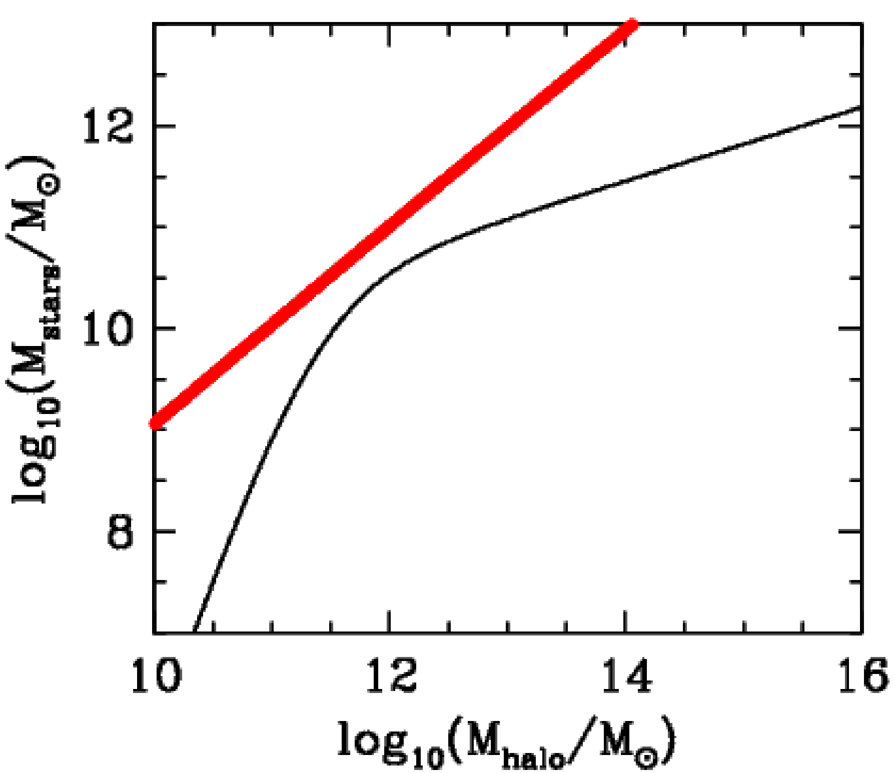
No suppression of cooling

Stellar mass vs halo circular velocity



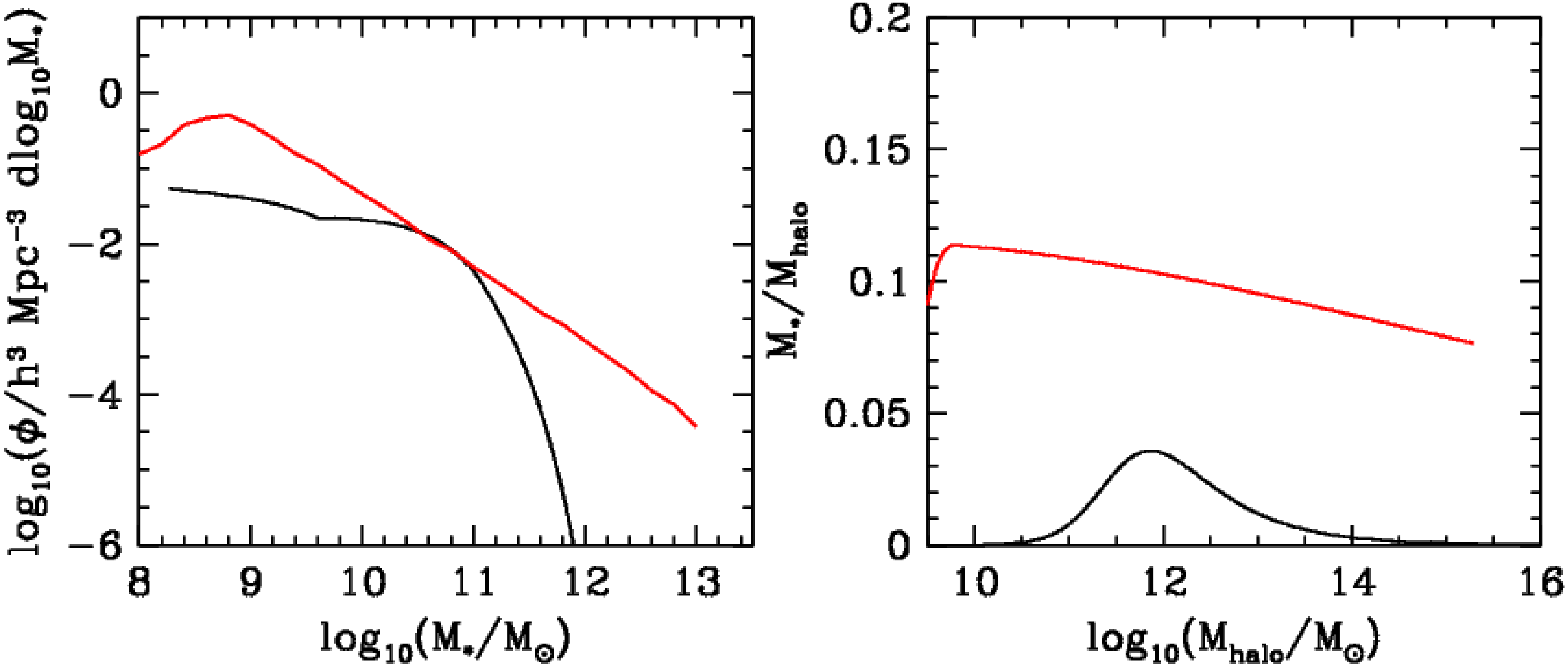
Obs data: McGaugh et al.

Stellar mass vs host halo mass



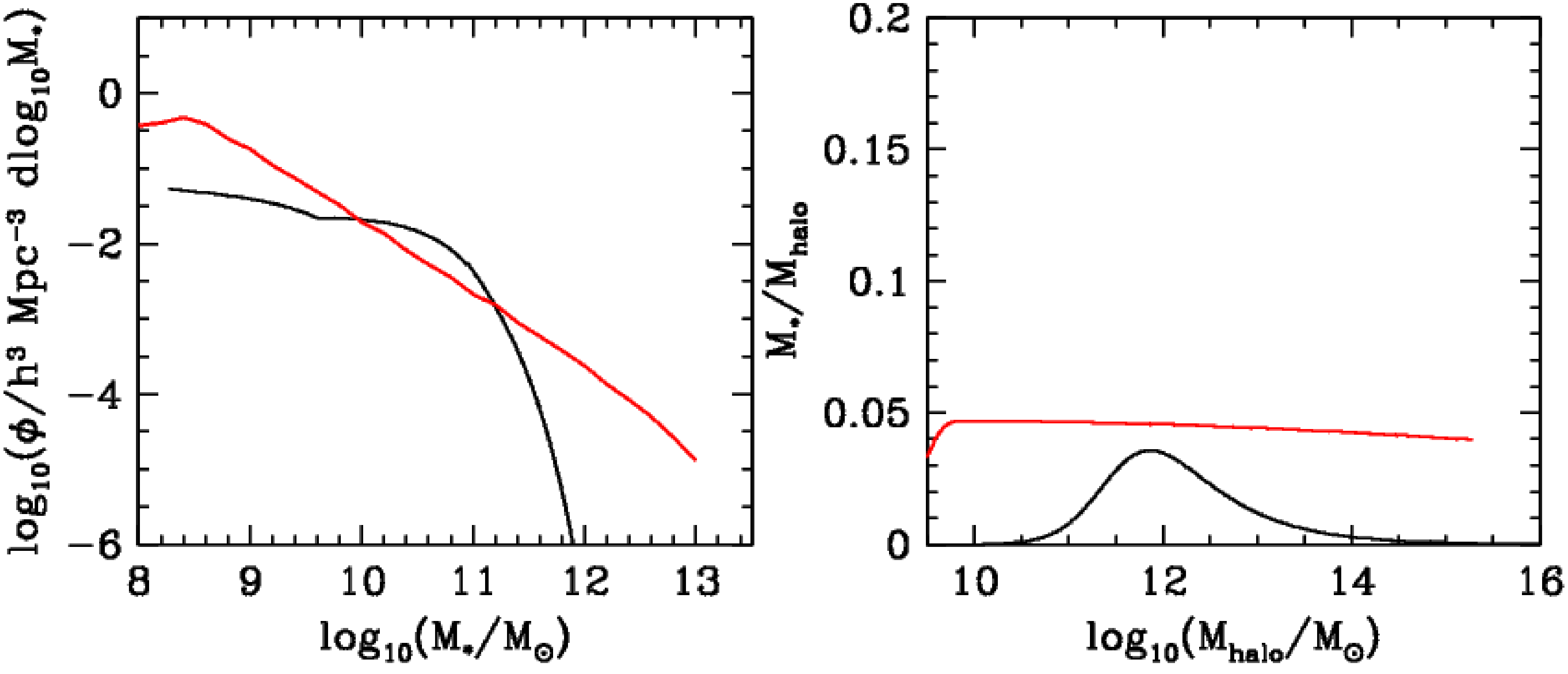
Obs data: Guo et al.

IGM heating?



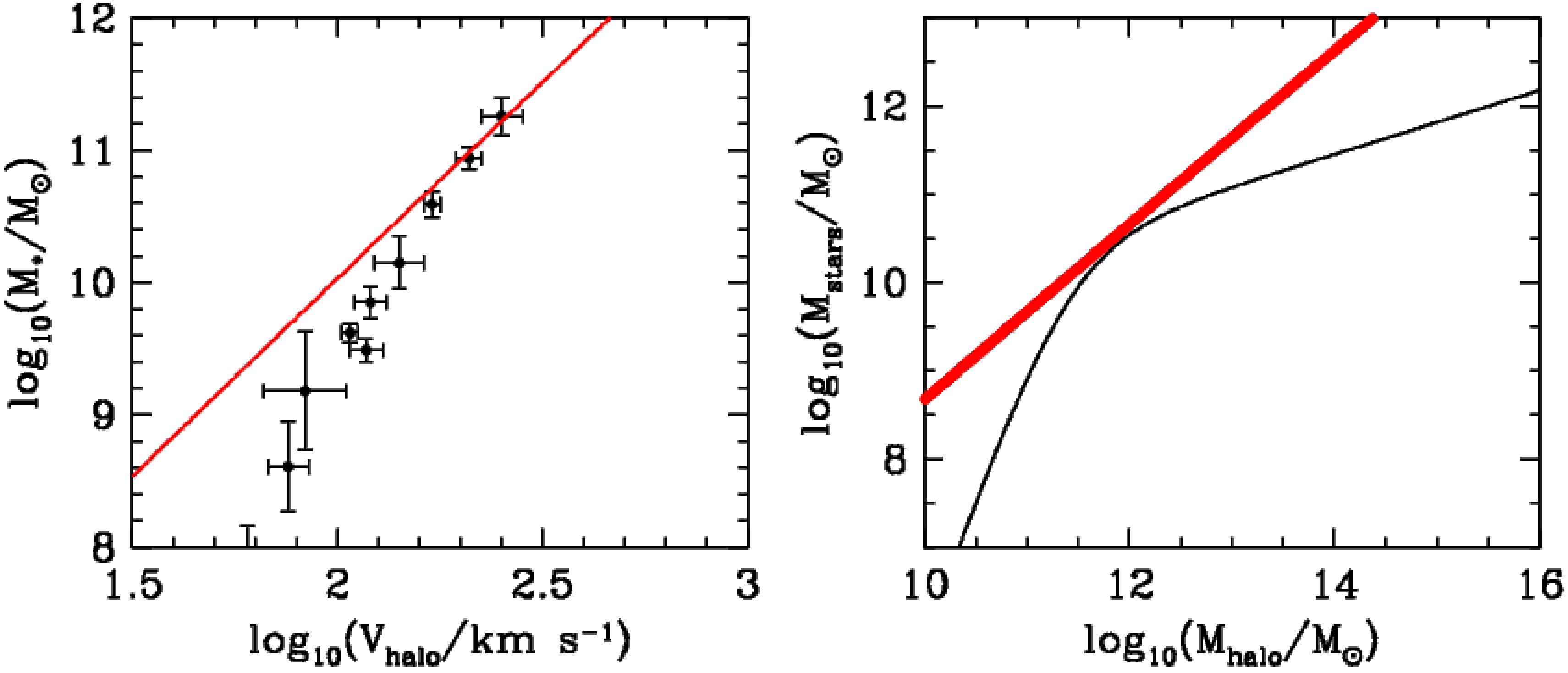
Photoionising background heats IGM, effectively stopping cooling into DM haloes with circular velocity below 30 km/s

SNe feedback: mass loading=1



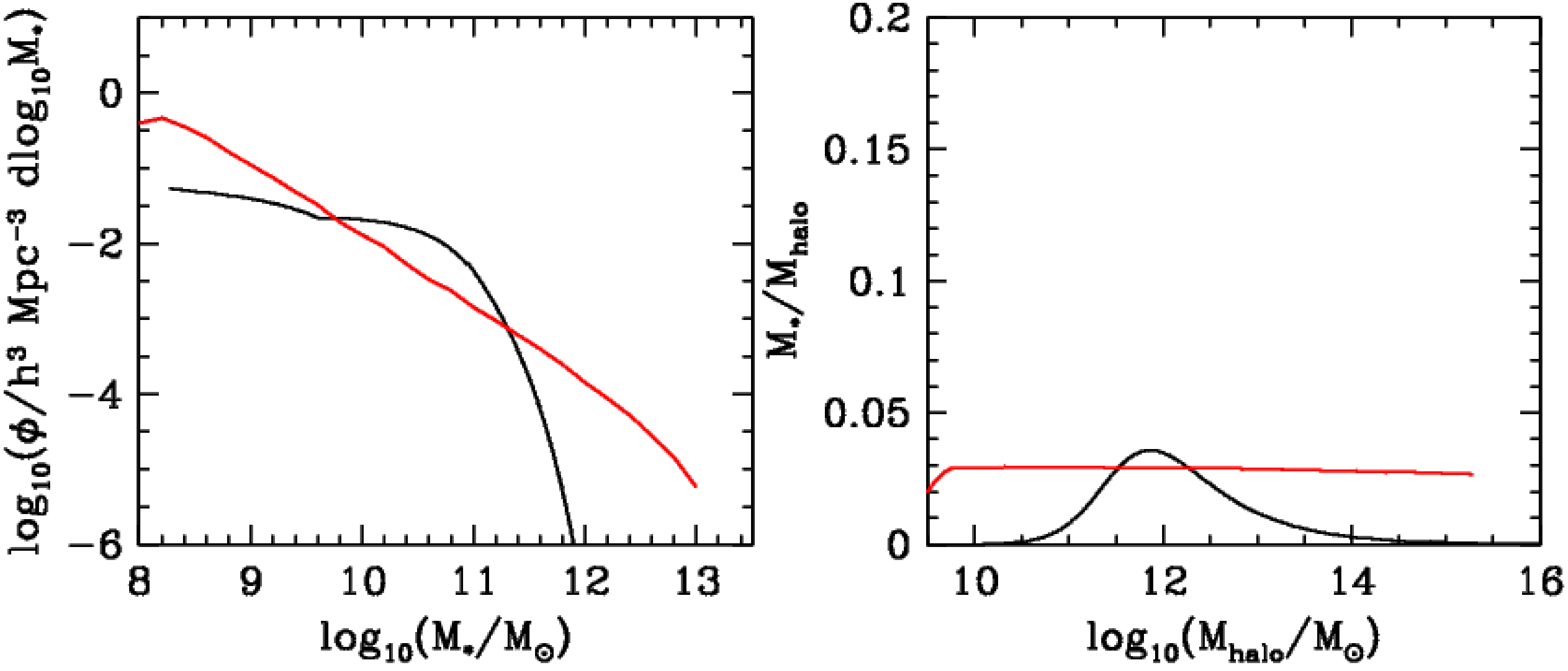
Invoke an outflow of gas with mass loading equal to SFR

Sne feedback: mass loading =1

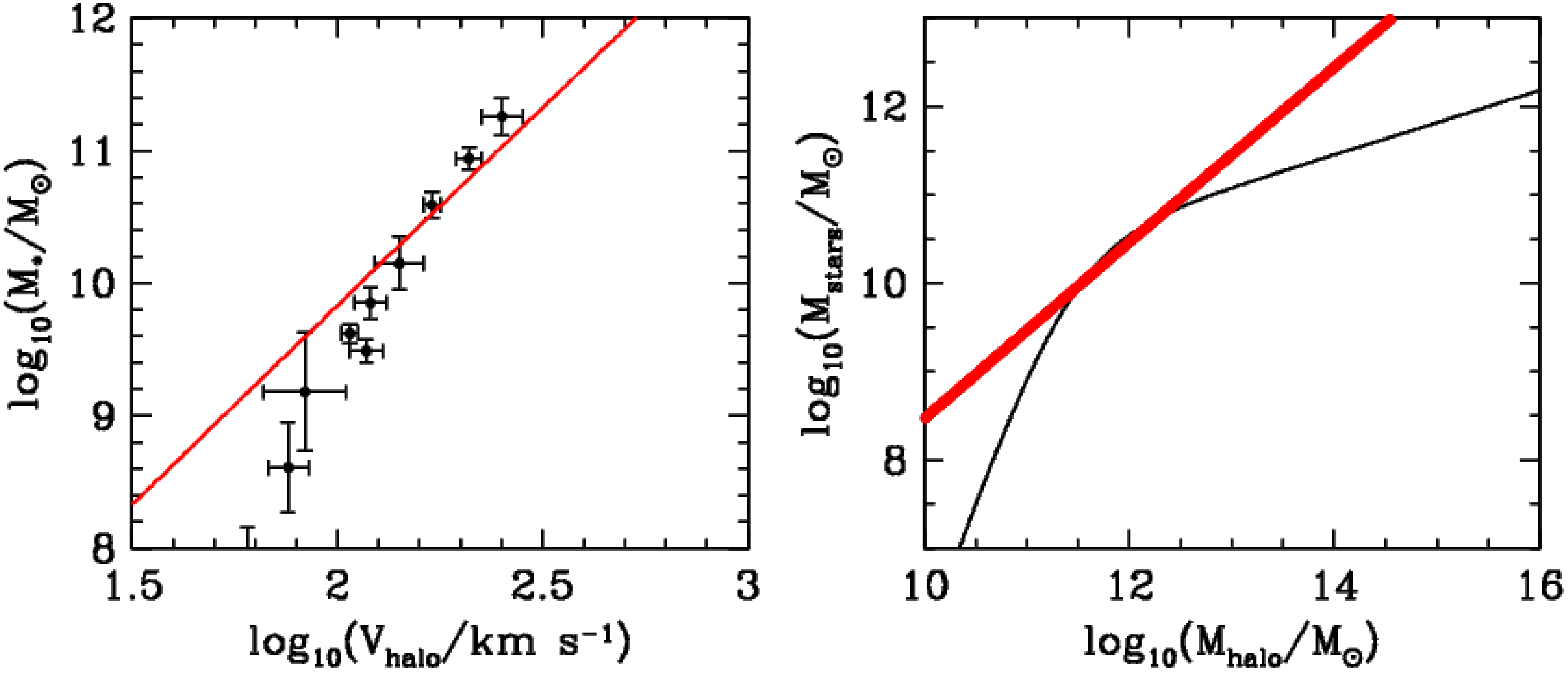


Change in normalization but no change in slope

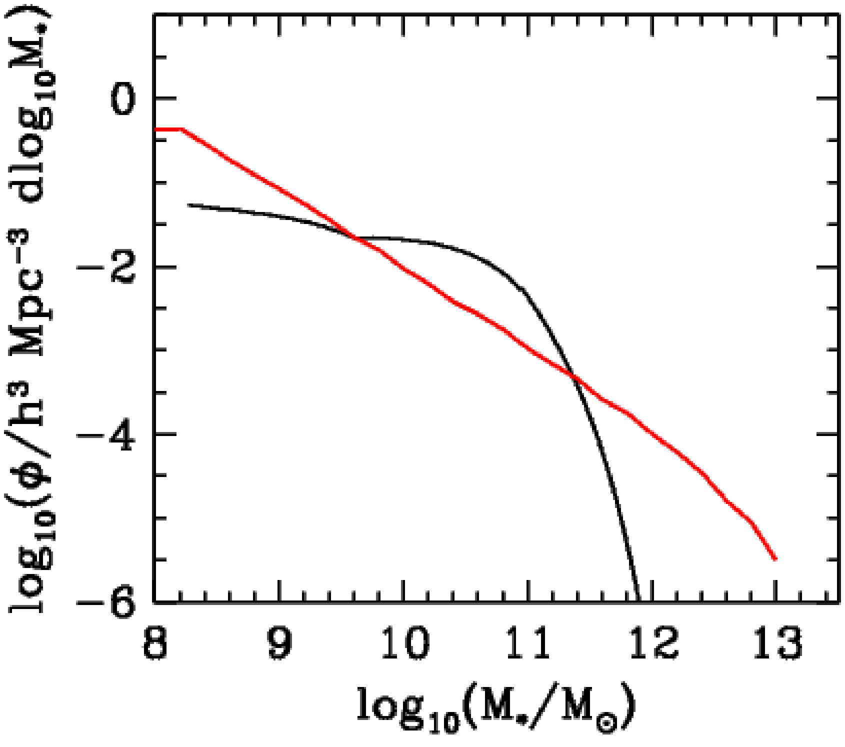
SNe outlfow : mass loading= 2

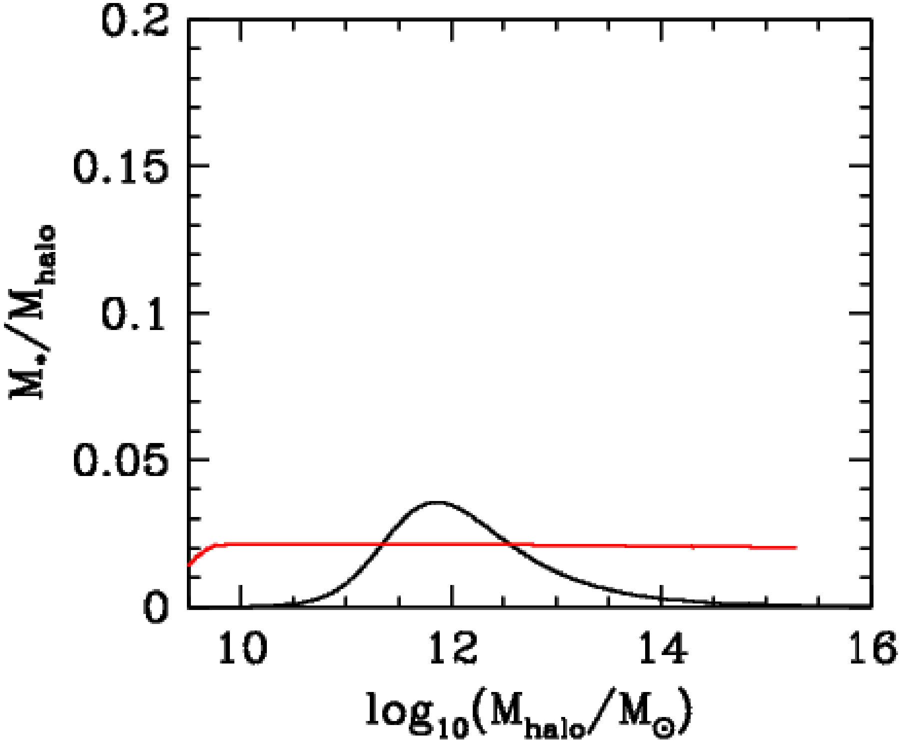


SNe outflow: mass loading=2

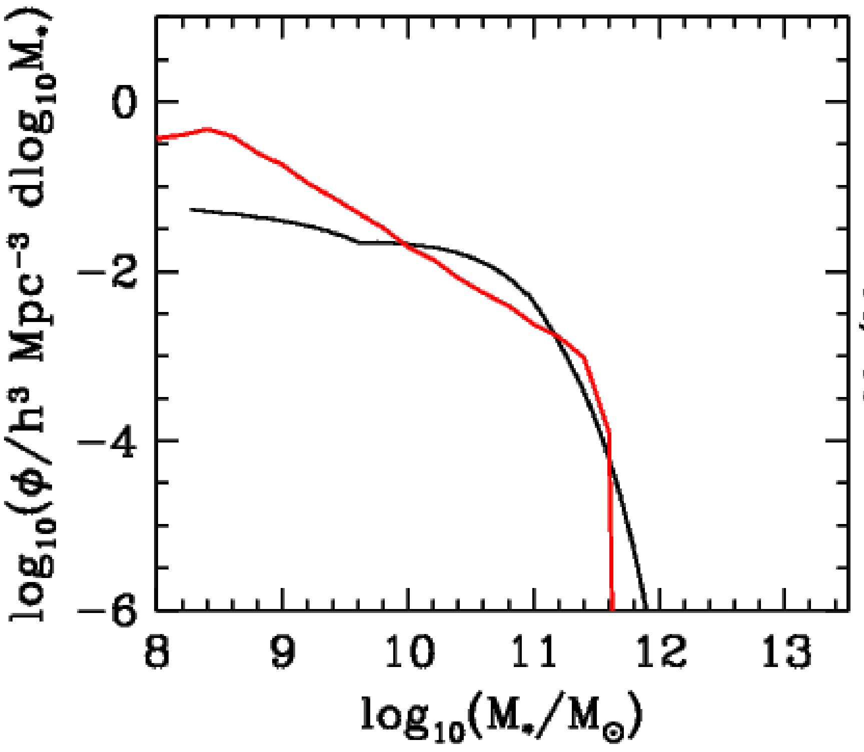


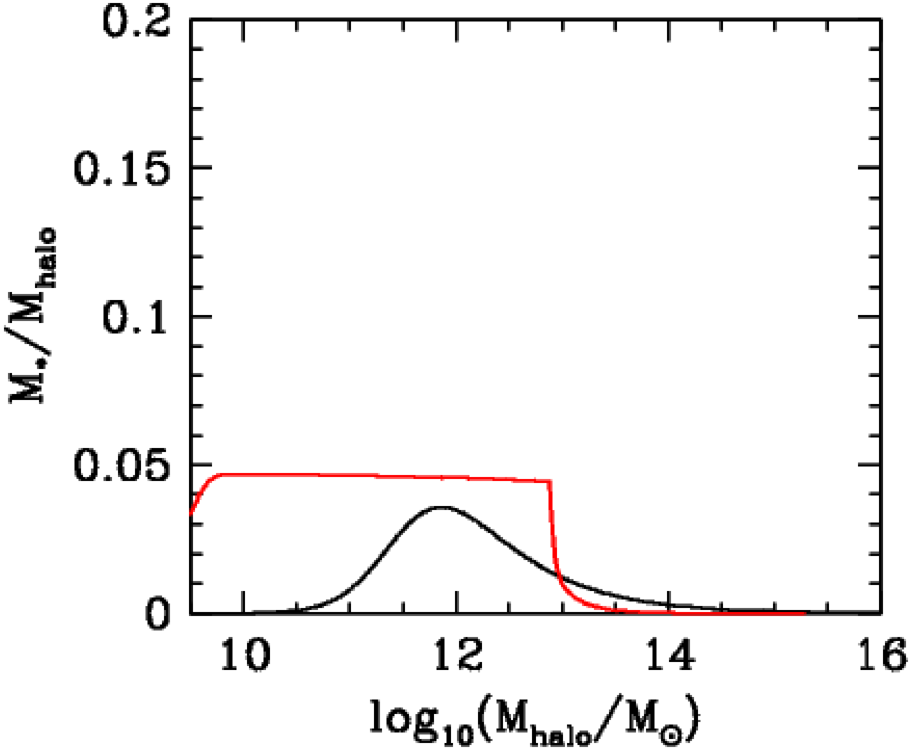
SNe outlfow: mass loading=3





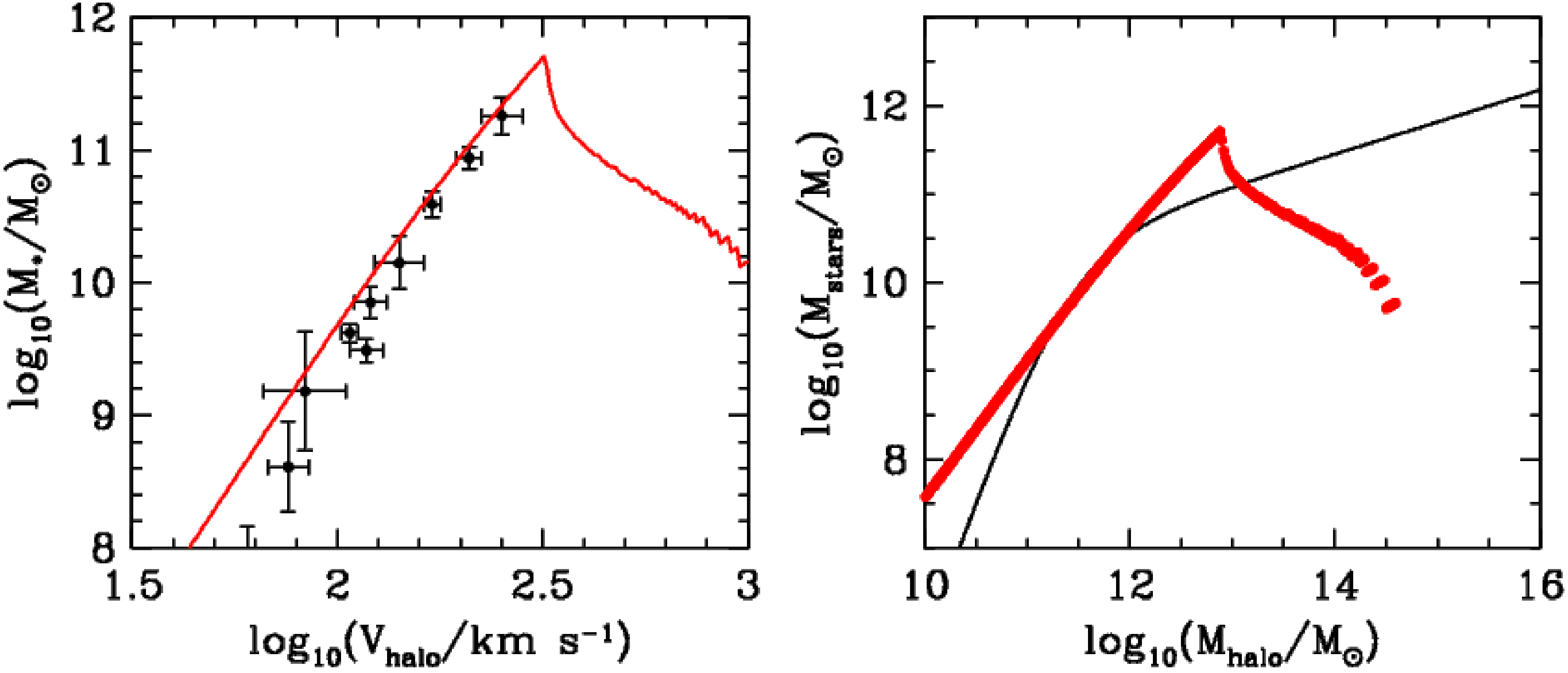
Cooling cut vc>350km/s



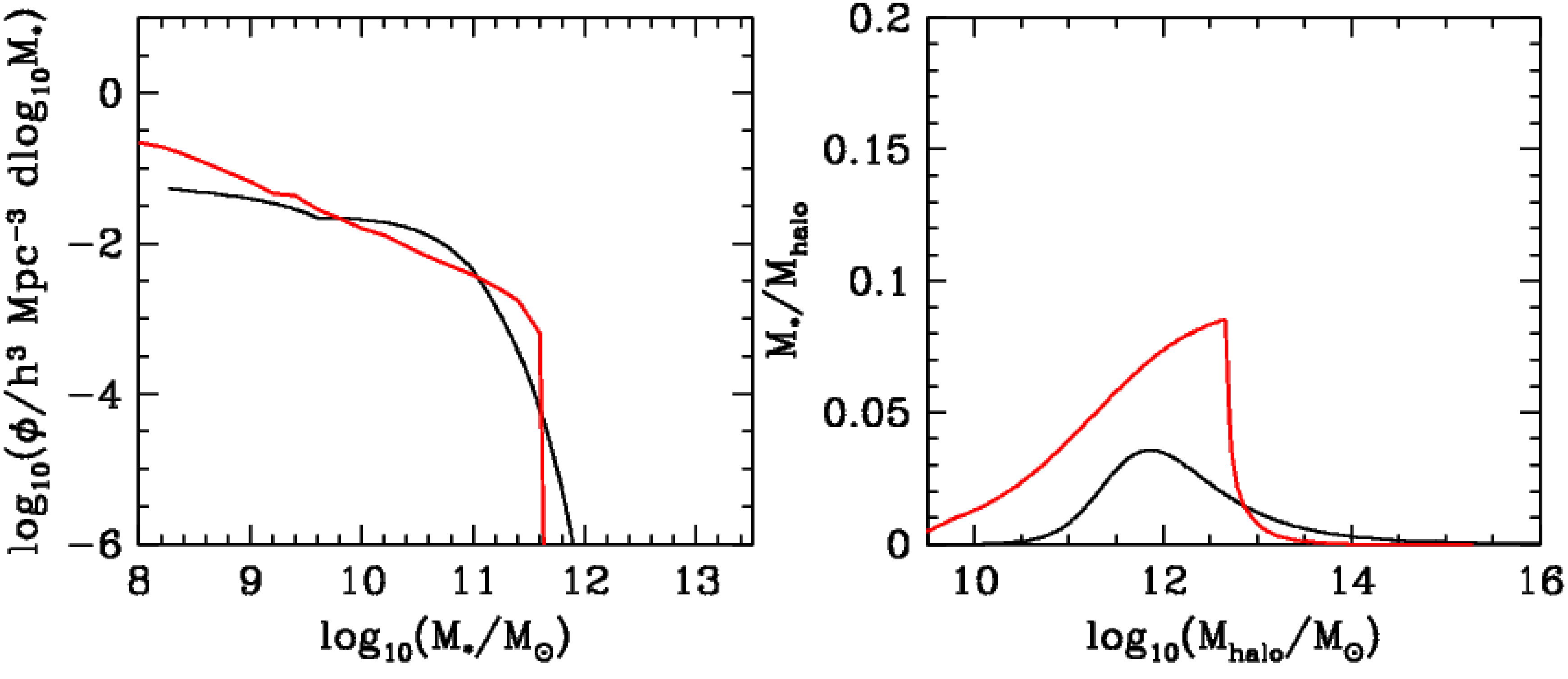


Introduce cut (by hand) on cooling of gas in DM haloes above given Vc

Cooling cut vc>350 km/s

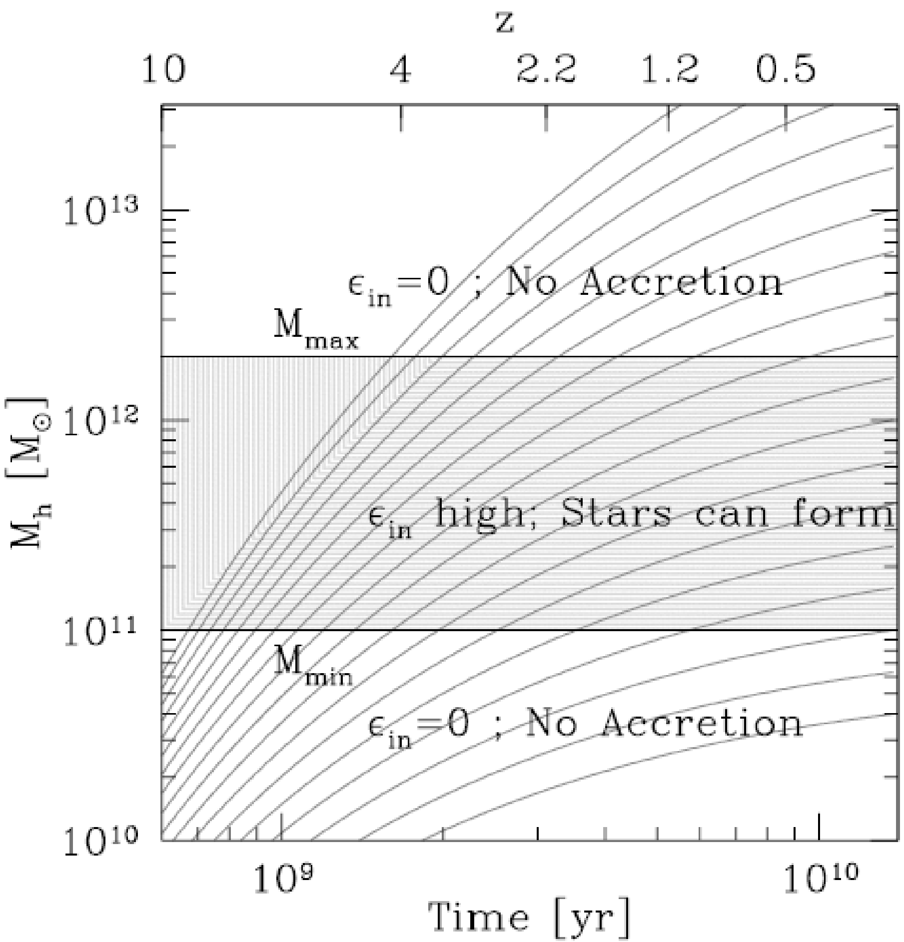


SNe vc scaling, cooling cutvc>300 km/s



Introduce scaling of mass loading in Sne wind scaling with Vc squared
Energy conserving case

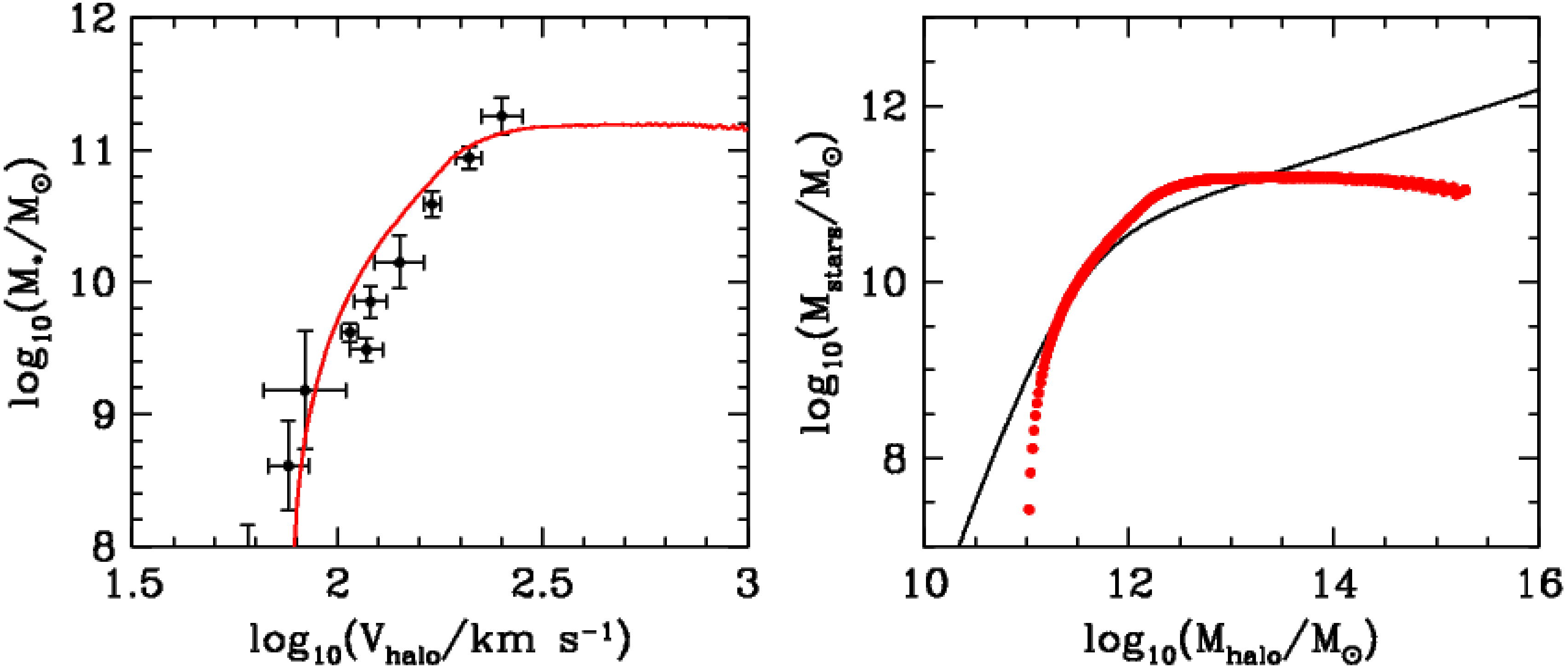
The original reservoir model



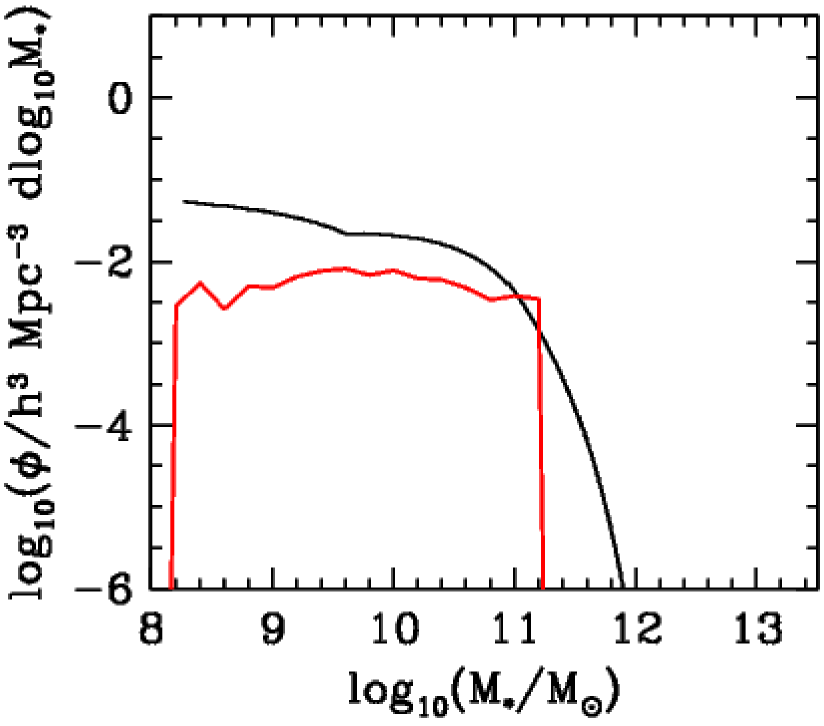
Extreme, by-hand fine tuning of cold gas accretion efficiency as a function of mass

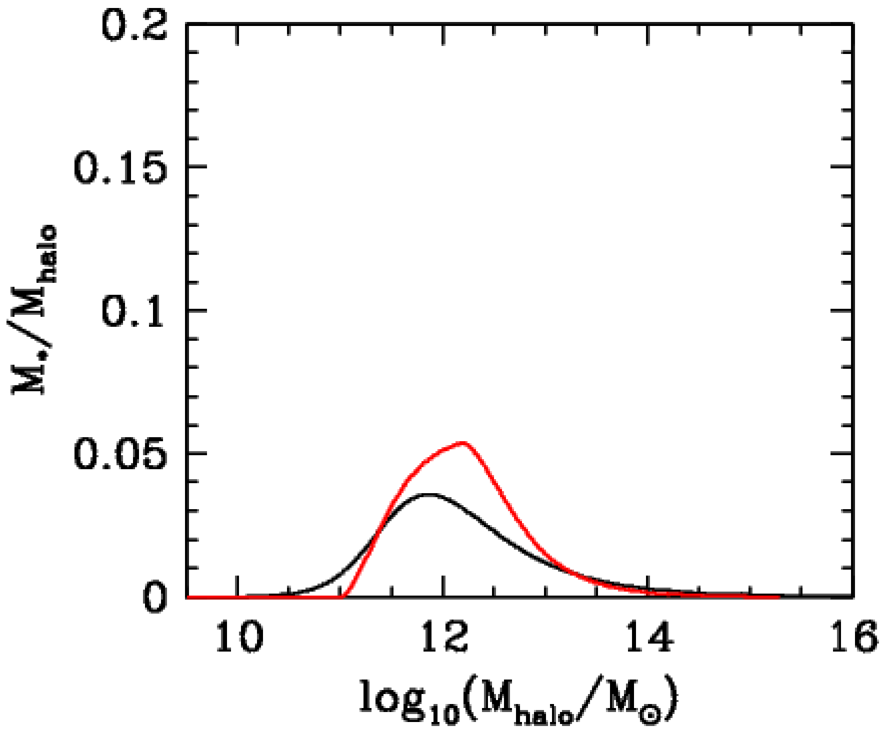
Aim is to match z=2 stellar mass vs halo mass relation and behaviour of specific star formation rates

Output of the reservoir model



Output of the reservoir model

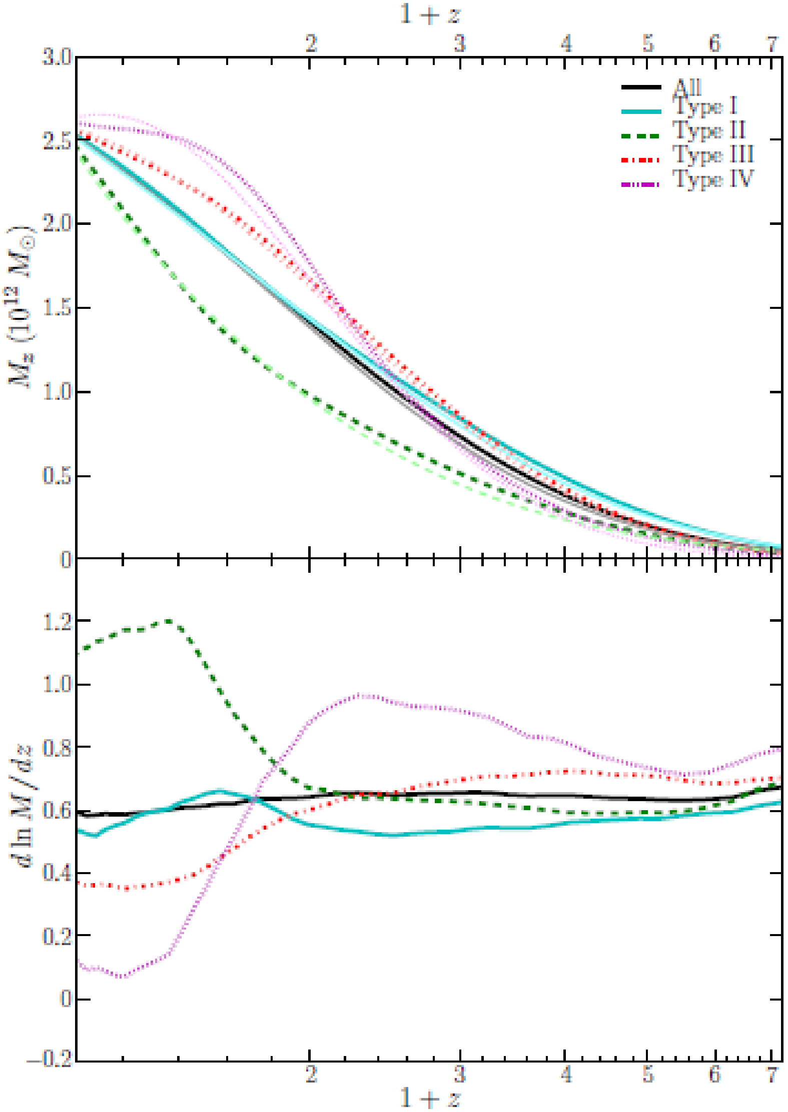




A simple model of galaxy formation

- Bathtub or reservoir model: Bouche et al 2010, Dave & Oppenheimer 2012
- Ignores scatter in DM halo growth
- All baryon effects put in by hand
- Ignores galaxy mergers/satelllite galaxies
- Infalling gas assumed pristine i.e. no prior cooling/star formation

Is this a realistic model?



- DM halo mass accretion histories more complicated than single parameter fit in Millennium Simulation
- Range of behaviours
- McBride, Fakhouri & Ma 2009

A simple model of galaxy formation

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What have we learnt so far?

- If cold gas accreted in proportion to DM, too many stars form
- Too many low mass systems, too many high mass systems (if we ignore cooling time)
- Wrong slope for stellar mass versus halo mass circular velocity relation
- Need to modulate supply of gas
- Lecture 2: the physics of galaxy formation