The physics of galaxy formation: where are we now?

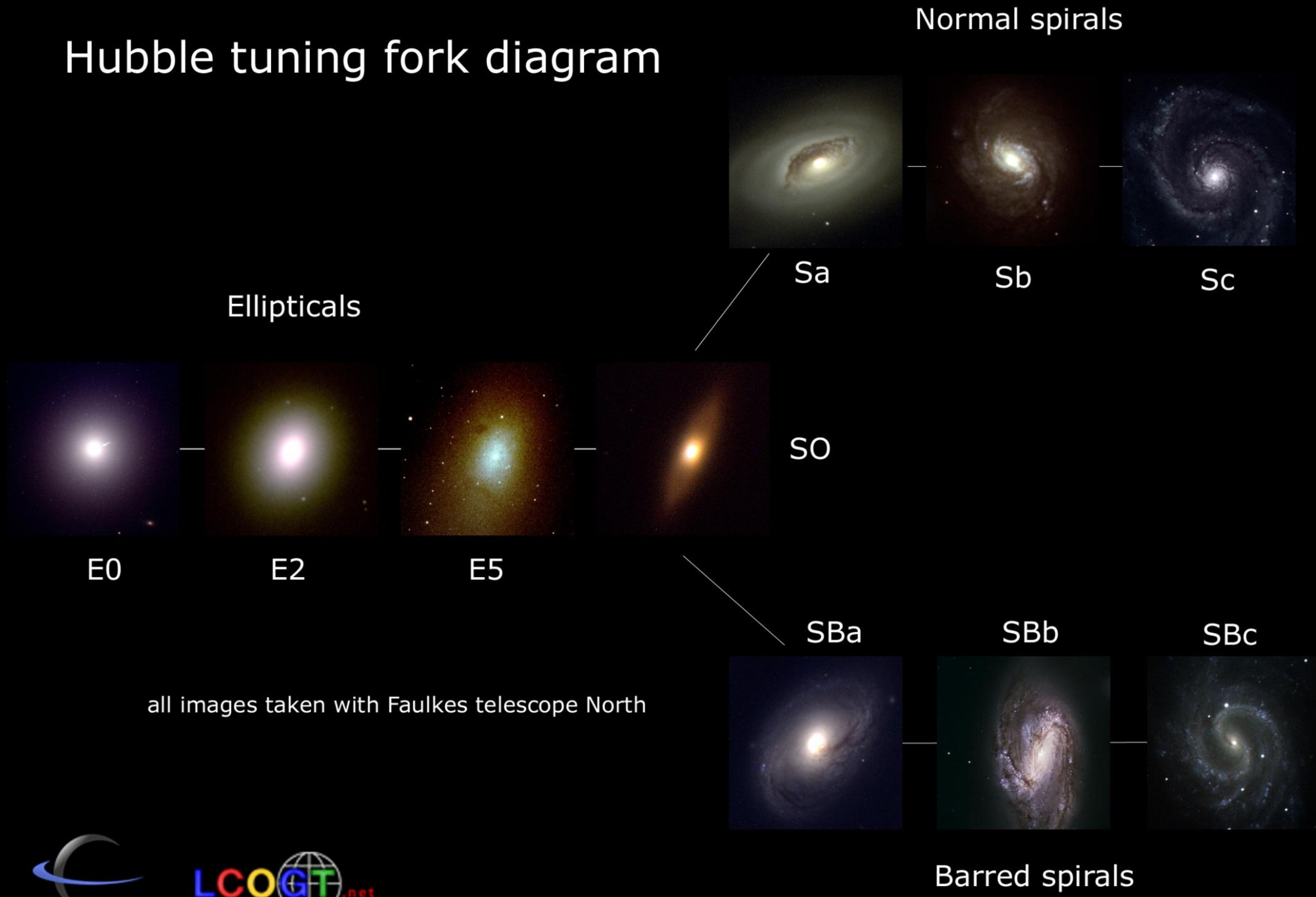
Carlton Baugh
Institute for Computational Cosmology
Durham University

Durham University

University of Sussex 2013

ICC

Hubble tuning fork diagram

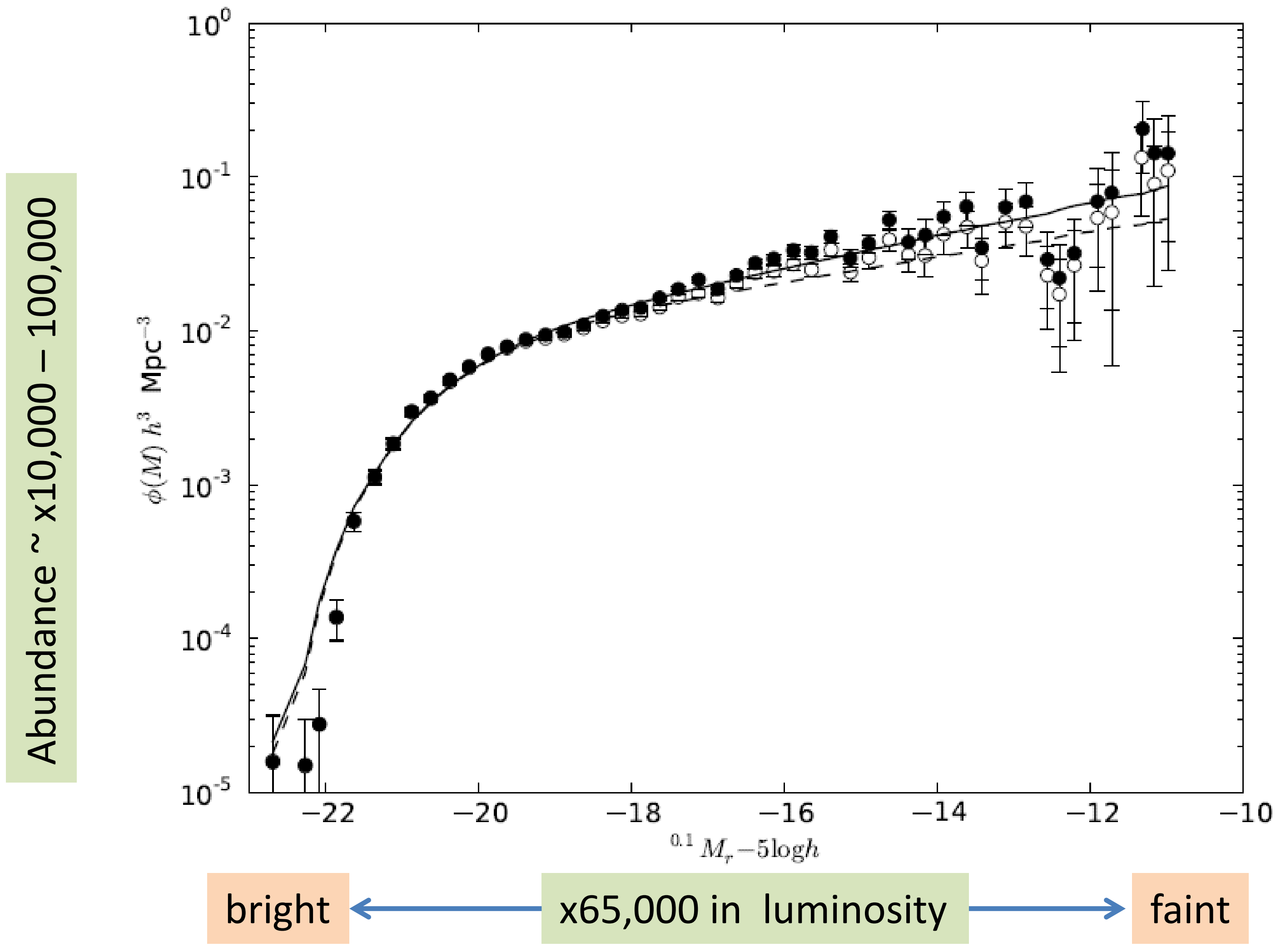


all images taken with Faulkes telescope North

FAULKES TELESCOPE

LCOGT.net

A galaxy census



GAMA survey: Loveday et al. 2012

The high redshift universe 1990

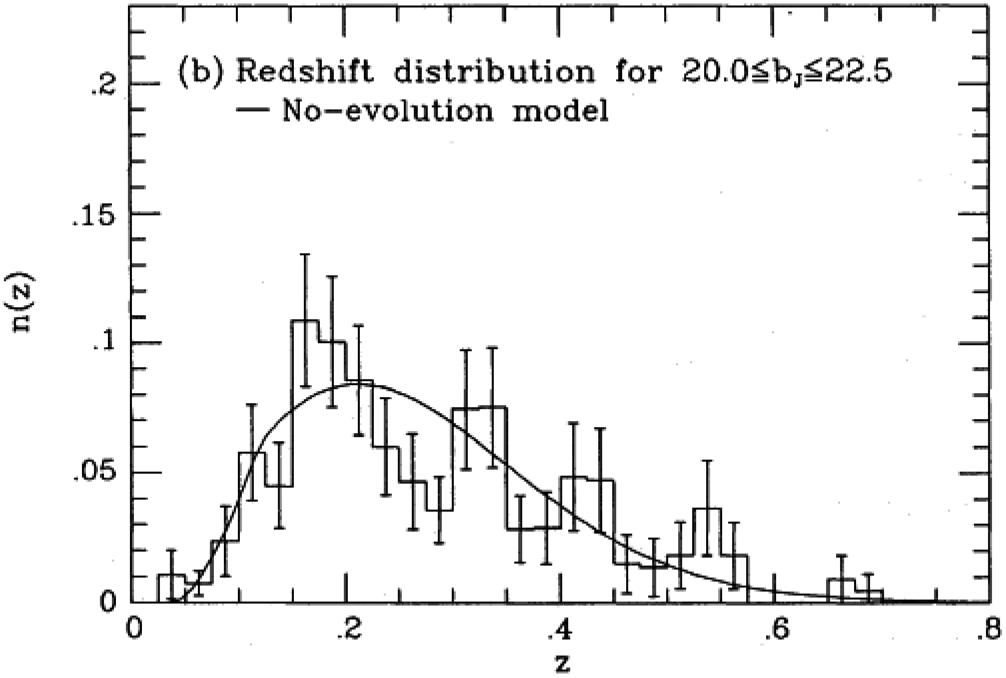
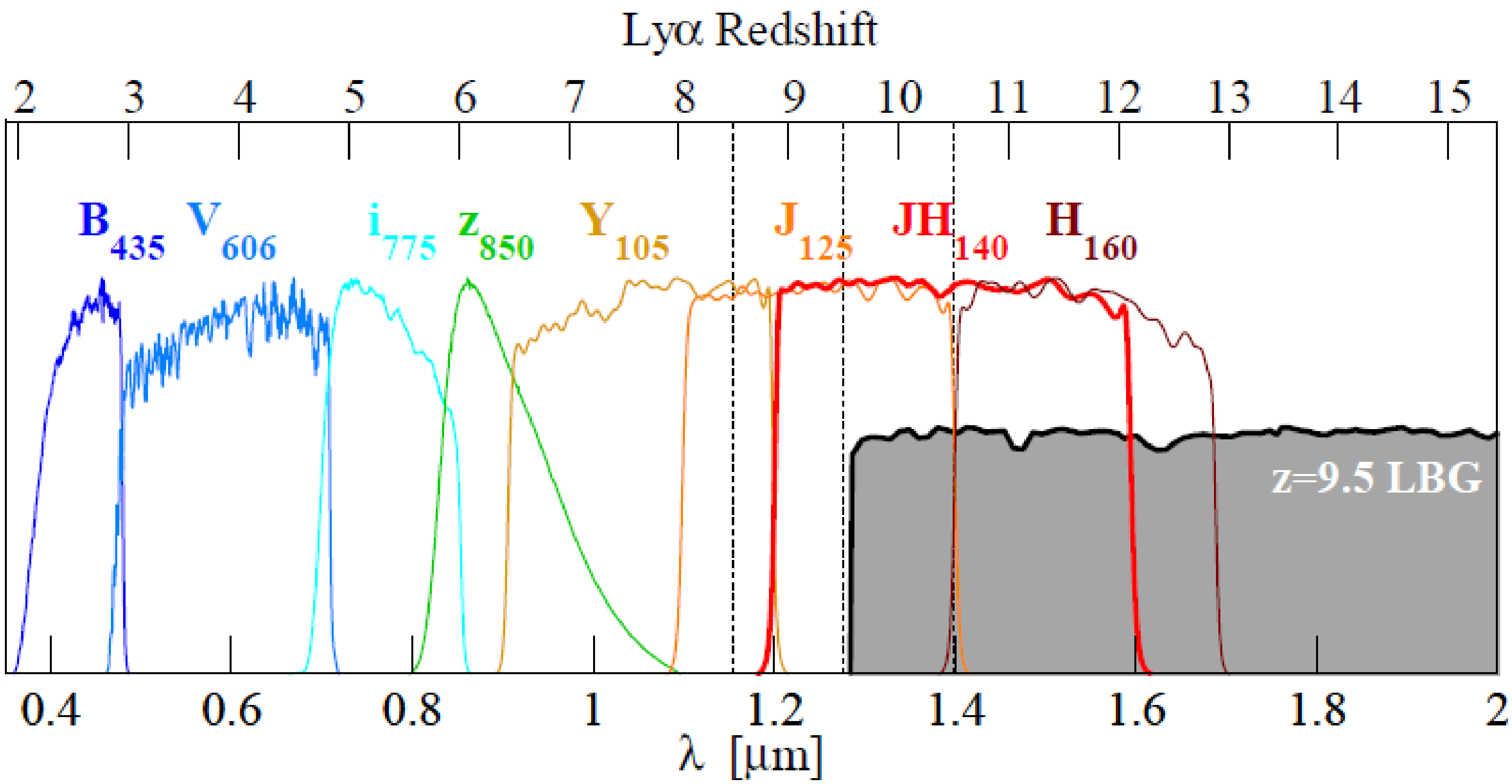


Figure 7. (a) The redshift distribution for the whole survey. The line is the no-evolution model prediction; (b) the combined redshift distribution for this survey and that of BES, normalized so that $\int n(z)\,dz = 1$. The line corresponds to the no-evolution model.

Colless et al. 1990

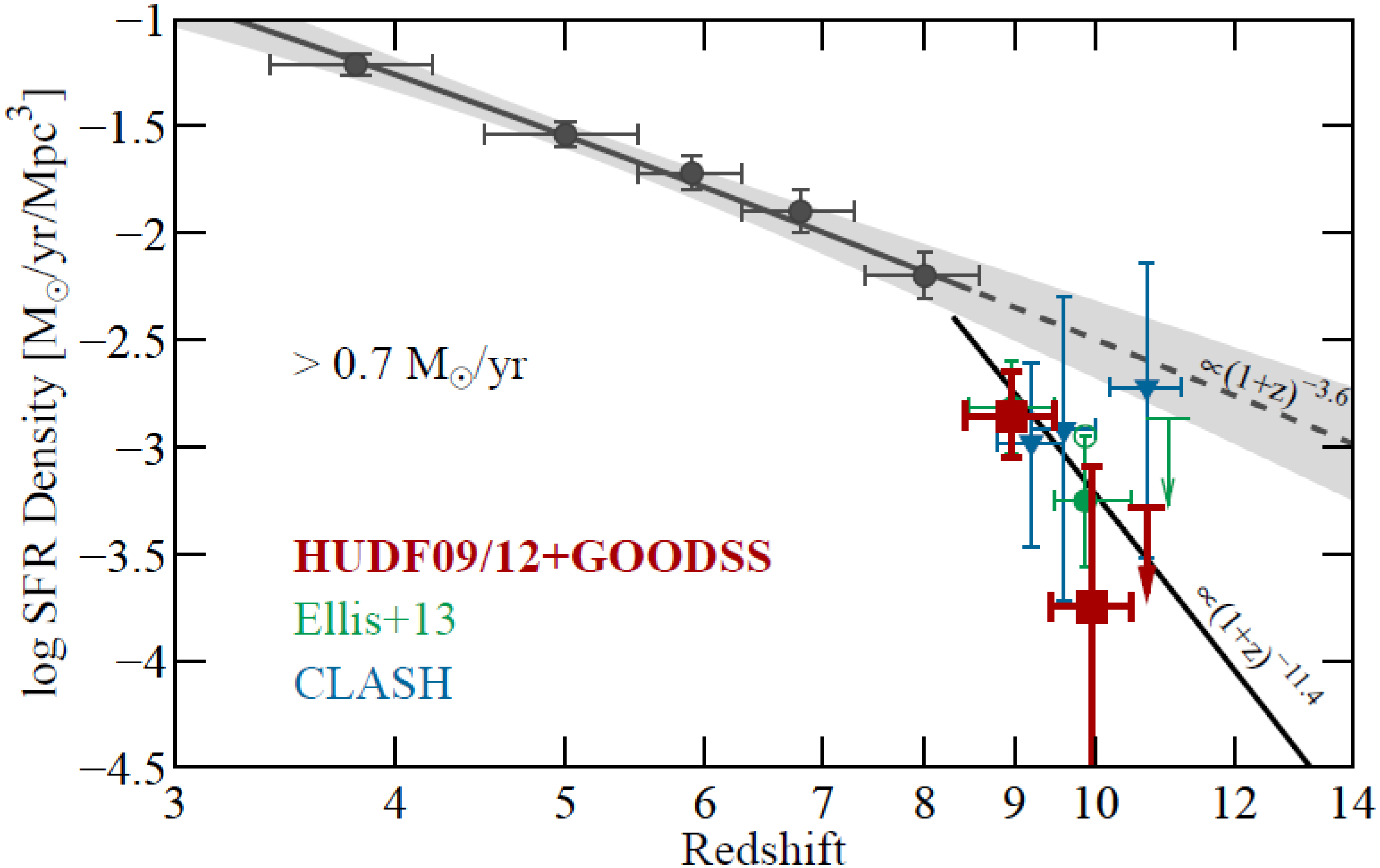
Lyman break drop-outs in near IR



Use colour selection to target candidate high redshift galaxies

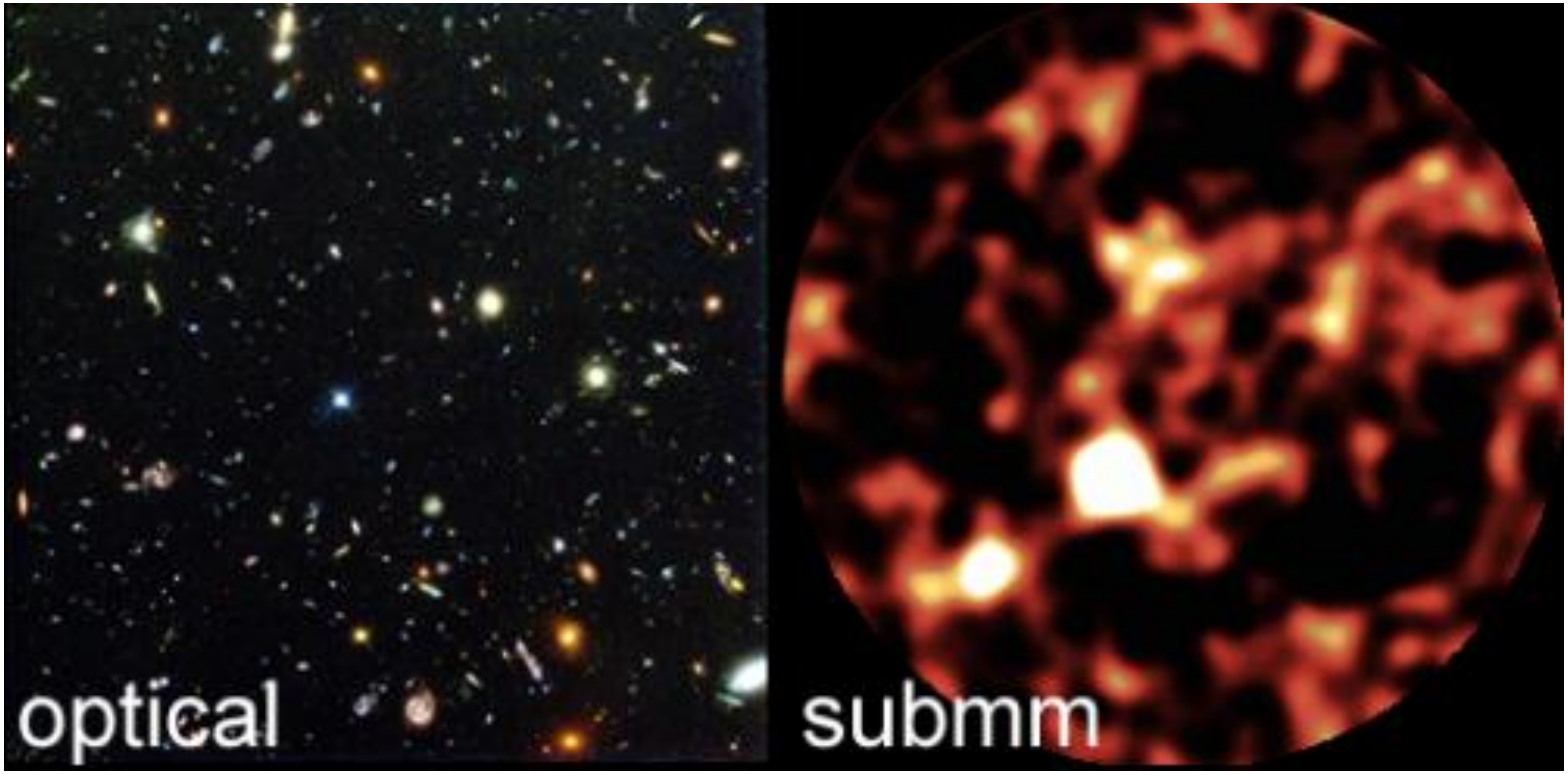
Oesch et al. 2013

Redshift frontier 2013: z=10



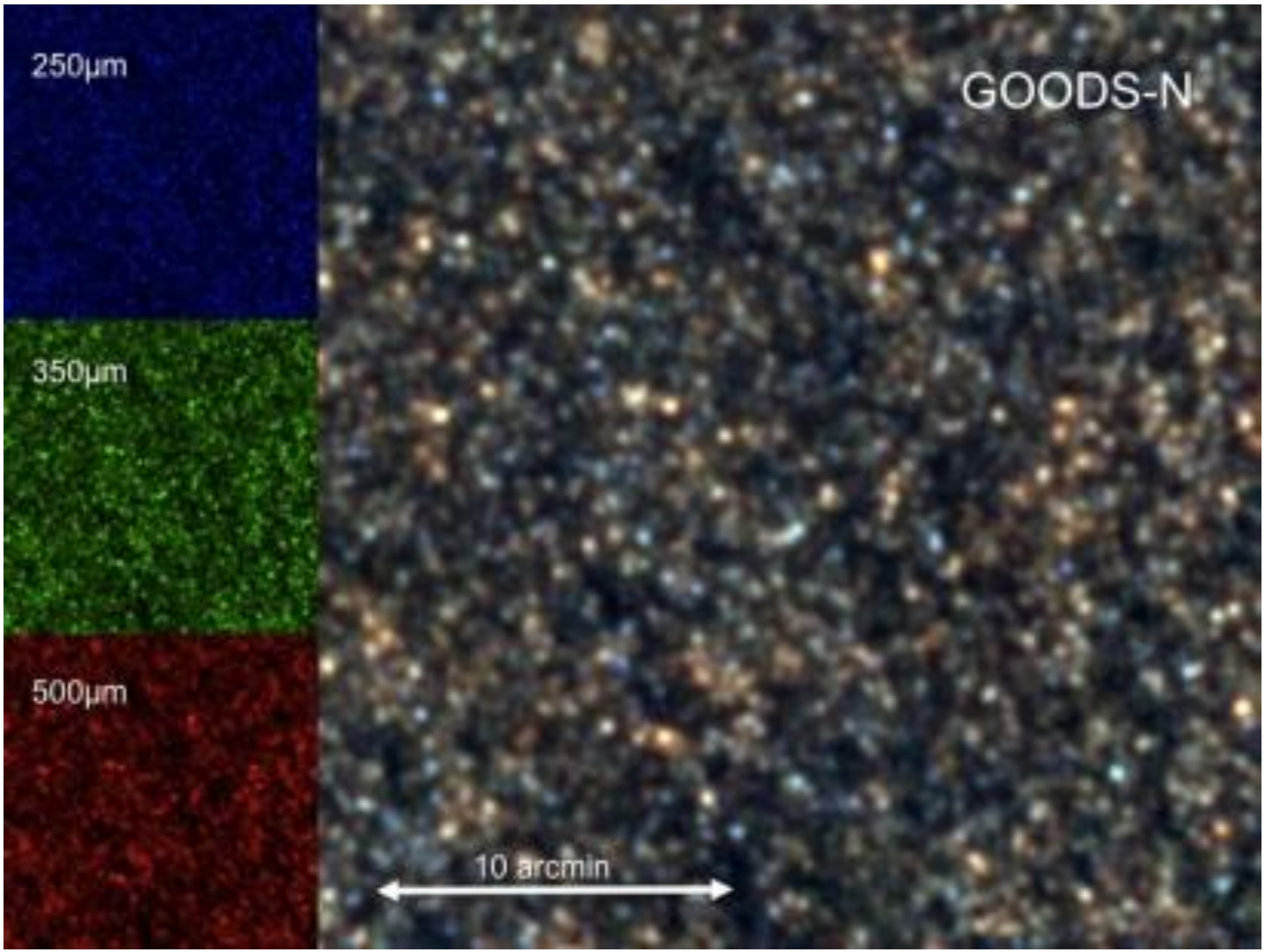
Oesch et al. 2013

The multi-wavelength view

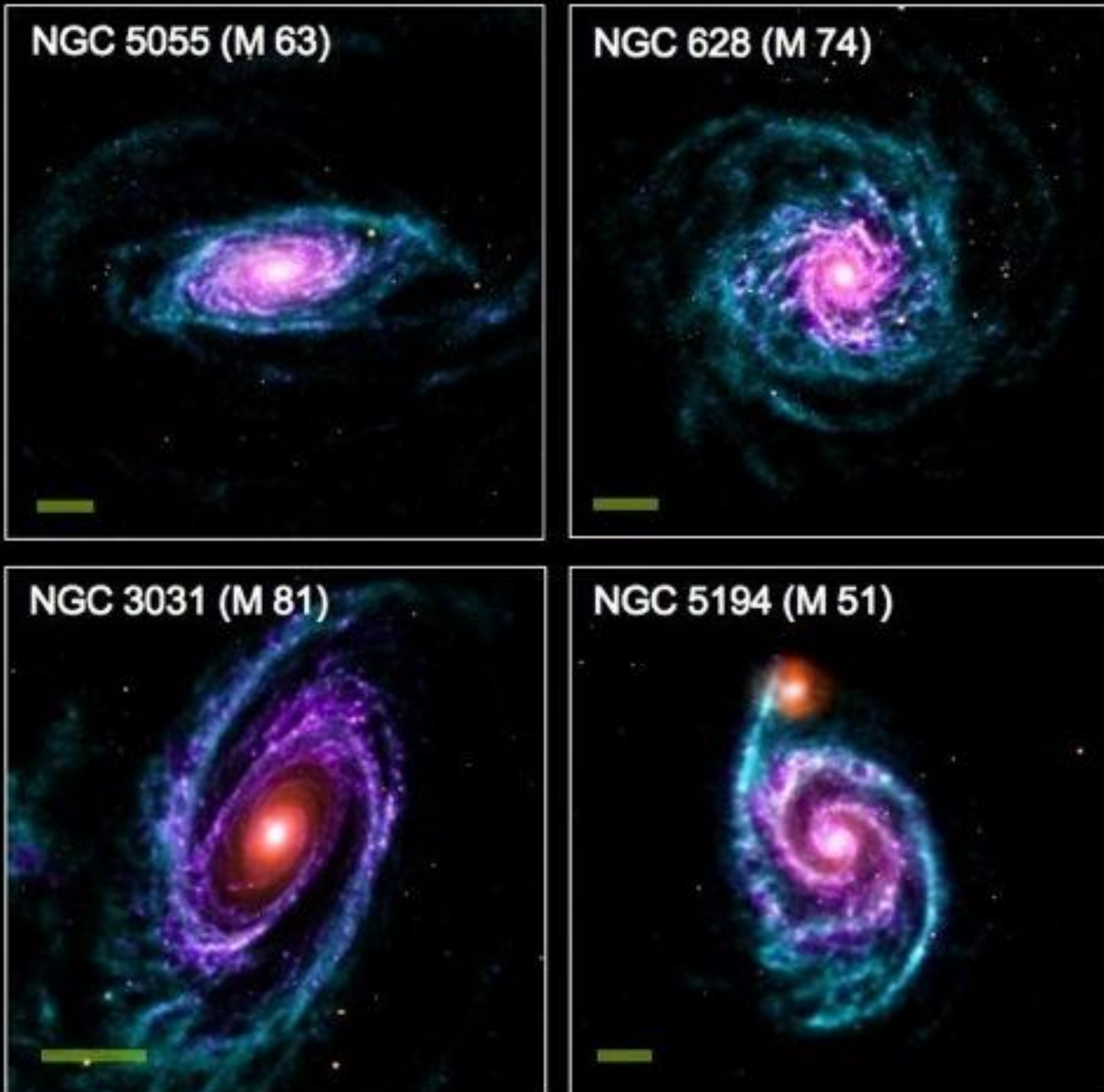


Hubble Deep Field: optical Williams et al 1996; sub-mm Hughes et al. 1998

The Herschel Space Observatory view



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)

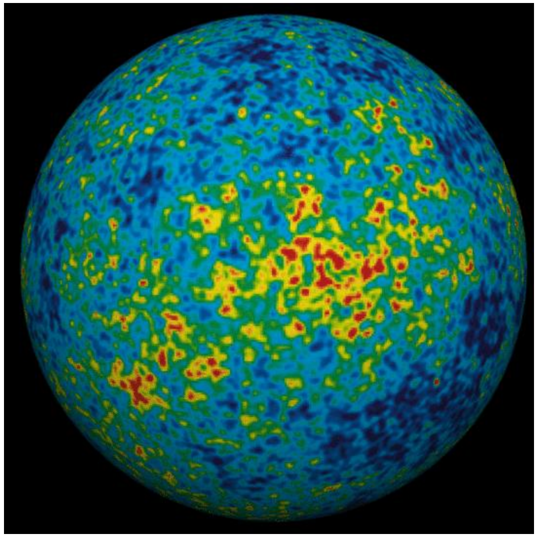
Star Formation
(GALEX & Spitzer)

scale: 15,000 light years

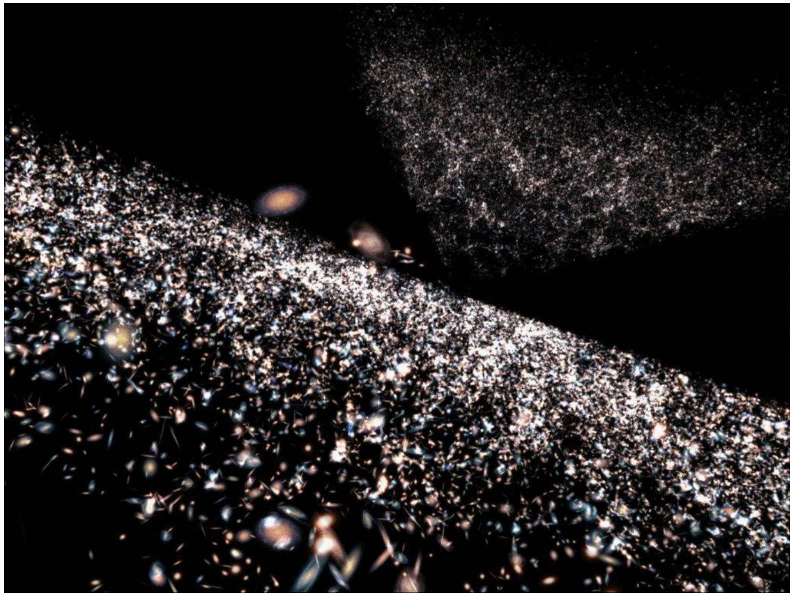
Image credits:
VLA THINGS: Walter et al. 08
Spitzer SINGS: Kennicutt et al. 03
GALEX NGS: Gil de Paz et al. 07

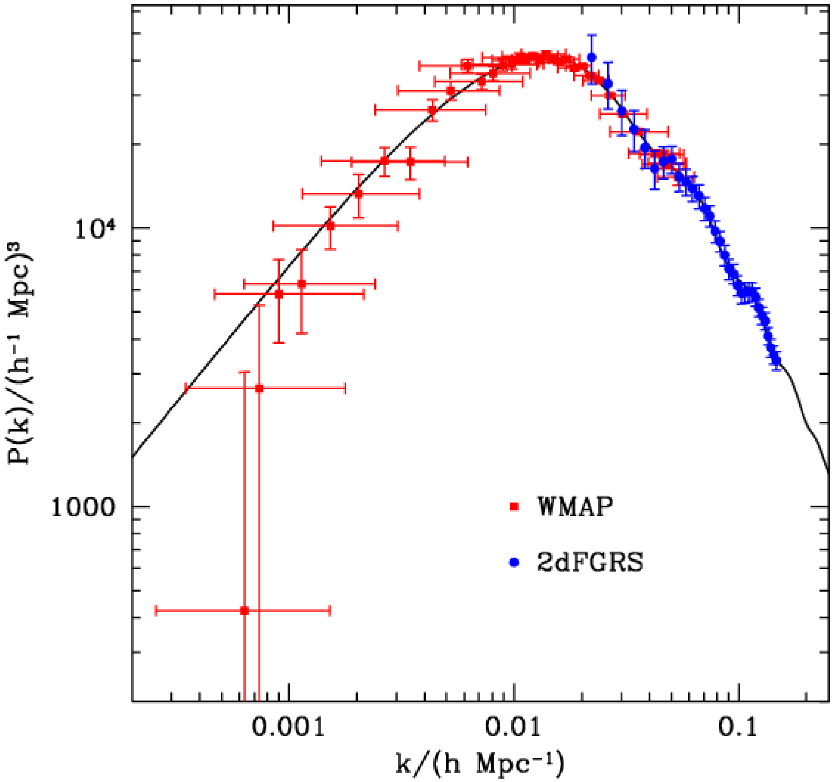
Cosmological setting: Hierarchical structure formation

z ~ 1100

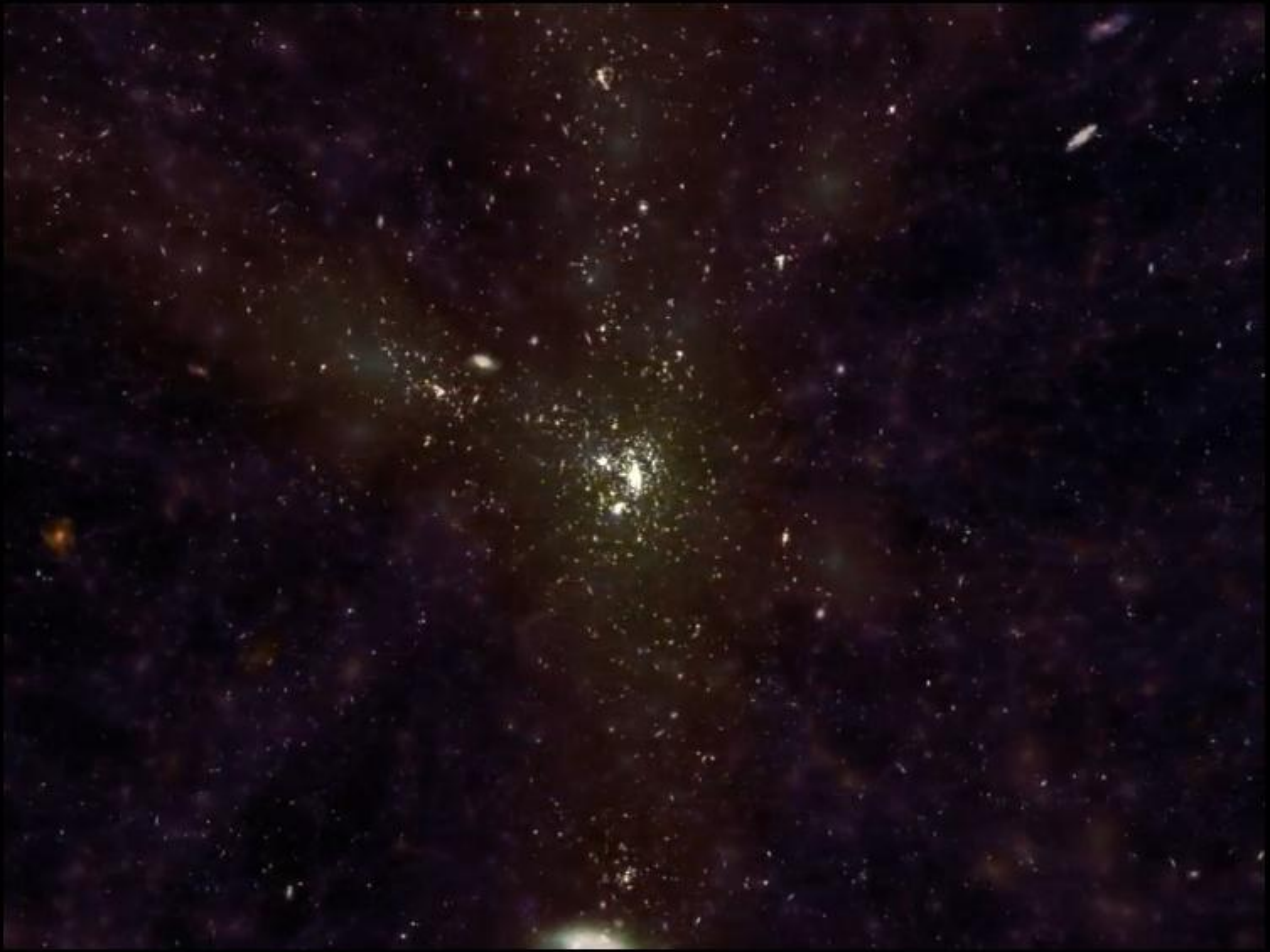


z~0





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



Galaxy formation is inefficient

Cosmic baryon density

$$\Omega_b = 0.0462 \pm 0.0015$$

Cosmic density of stars

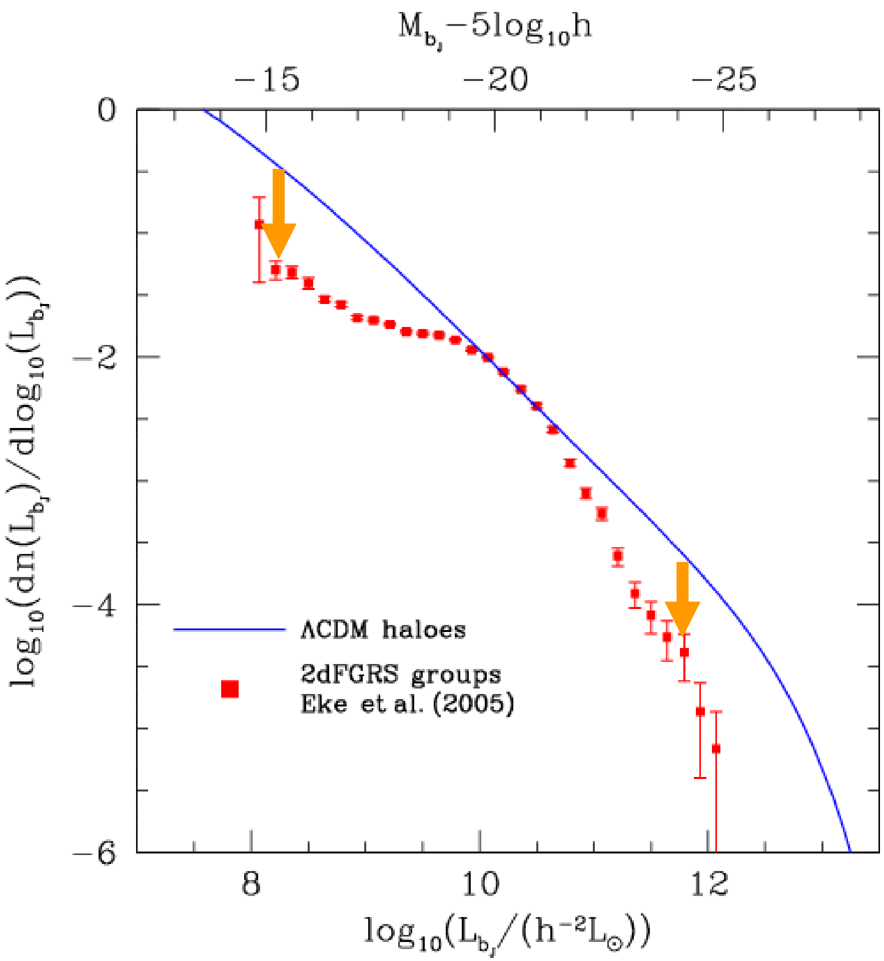
$$\Omega_\star = (2.3 \pm 0.34) \times 10^{-3}$$

Only ~5 % of available baryons are in stars today

Cole et al. 2001

The efficiency of galaxy formation

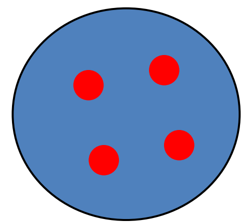
abundance



Total group luminosity

Baugh 2006

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



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

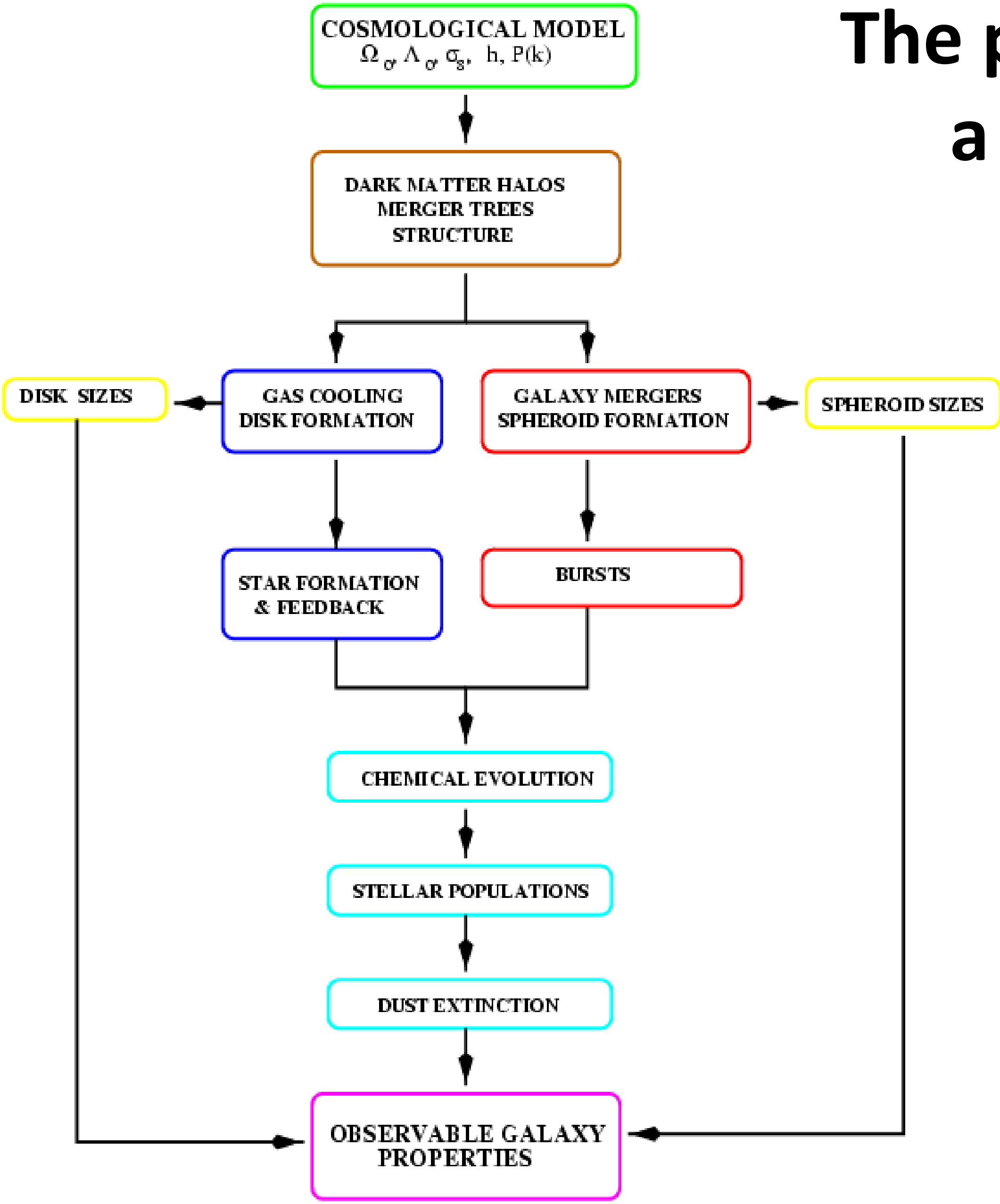
Simple prediction:
Take CDM halo mass function
plus fixed M/L ratio

Galaxy formation TOO efficient
in both low and high mass haloes

The Physics of Galaxy Formation

What is semi-analytical modelling?

Can we trust it?

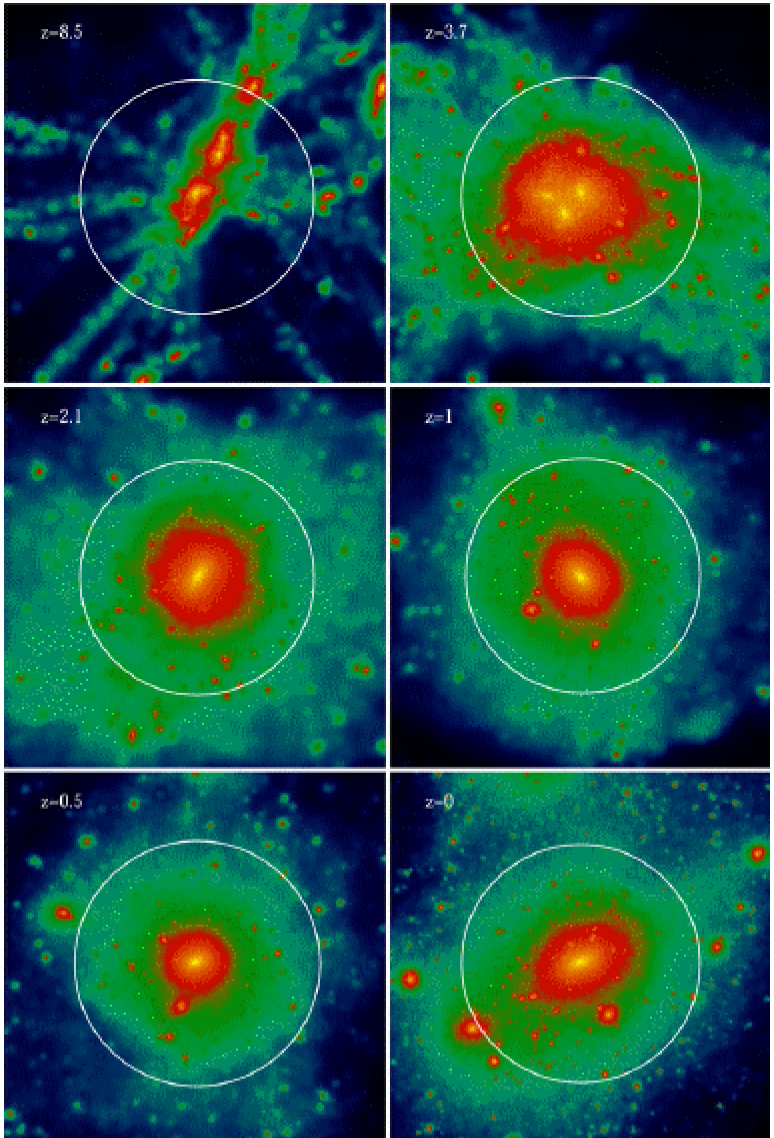


The physics processes in a model of galaxy formation

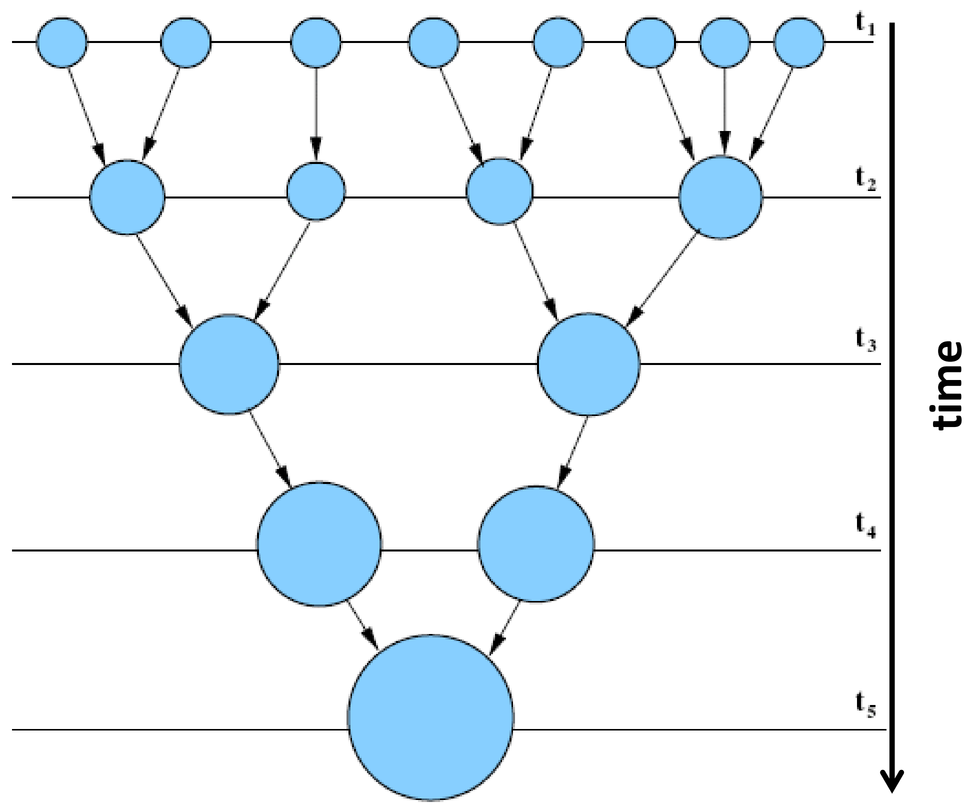
- Complex, nonlinear processes
- Complete understanding still lacking in many areas
- Physically motivated equations which may contain parameters
- Crucial to model the interplay between processes

Cole et al. 2000
Baugh 2006
Benson 2010

Starting point: halo merger tree

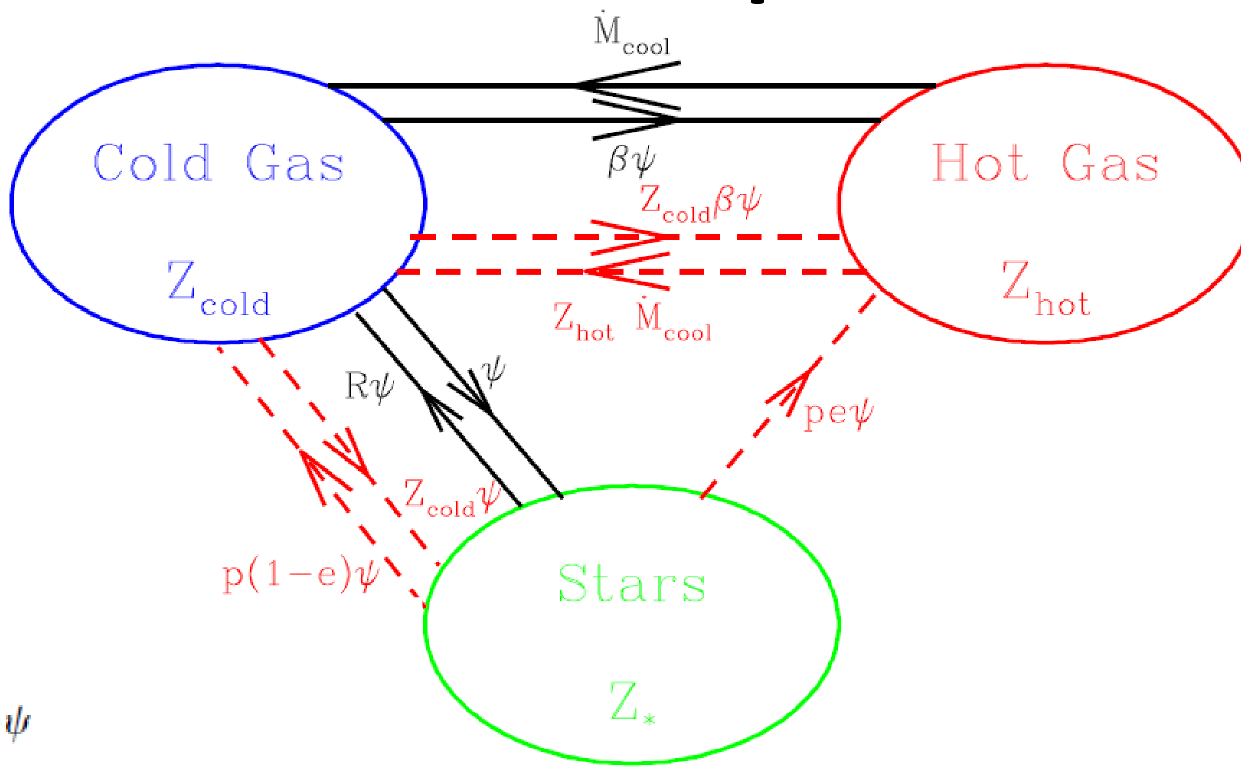


Images by Chris Power



Baugh 2006

Solve set of differential equations



$$\dot{M}_* = (1 - R)\psi$$

$$\dot{M}_{hot} = -\dot{M}_{cool} + \beta\psi$$

$$\dot{M}_{cold} = \dot{M}_{cool} - (1 - R + \beta)\psi$$

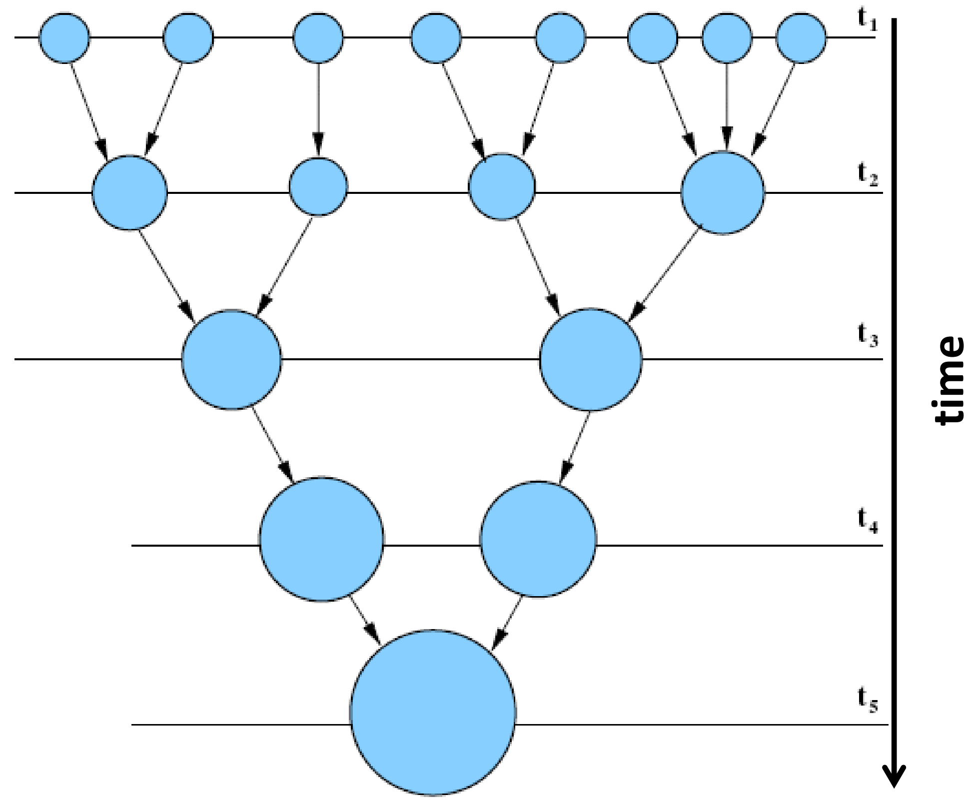
$$\dot{M}^Z_* = (1 - R)Z_{cold}\psi$$

$$\dot{M}^Z_{hot} = -\dot{M}_{cool}Z_{hot} + (pe + \beta Z_{cold})\psi$$

$$\dot{M}^Z_{cold} = \dot{M}_{cool}Z_{hot} + [p(1 - e) - (1 + \beta - R)Z_{cold}]\psi,$$

Cole et al. 2000

Follow baryons in halo merger tree



$$\dot{M}_* = (1 - R)\psi$$

$$\dot{M}_{\rm hot} = -\dot{M}_{\rm cool} + \beta\psi$$

$$\dot{M}_{\rm cold} = \dot{M}_{\rm cool} - (1 - R + \beta)\psi$$

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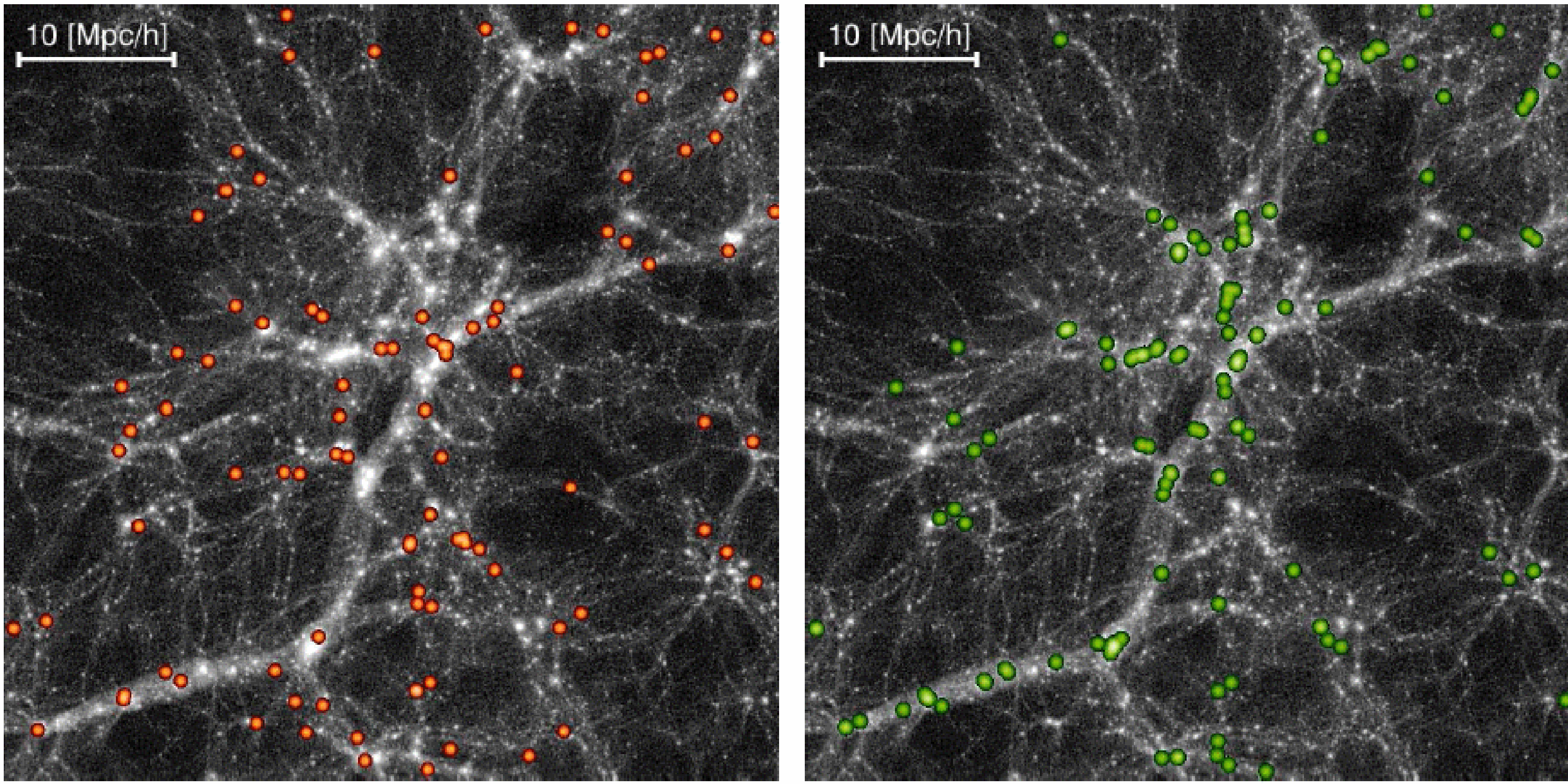
$$\dot{M}^Z_{\rm cold} = \dot{M}_{\rm cool}Z_{\rm hot} + [p(1 - e) - (1 + \beta - R)Z_{\rm cold}]\psi,$$

Baugh 2006, Benson 2010

Connecting galaxies to haloes



H-α **z=1** **H-band**

Orsi et al. 2010

Semi-analytic models - are we kidding ourselves?

The 11th Birmingham-Nottingham Extragalactic Workshop

June 24-25th 2008

www.sr.bham.ac.uk/workshop/2008/

Why should I believe any of this?

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- Too complicated!

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- Too many free parameters!

Why should I believe any of this?

- Too complicated!
- Too many free parameters!
- Can’t you get anything you want?

Reductionist galaxy formation: the bathtub model

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

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

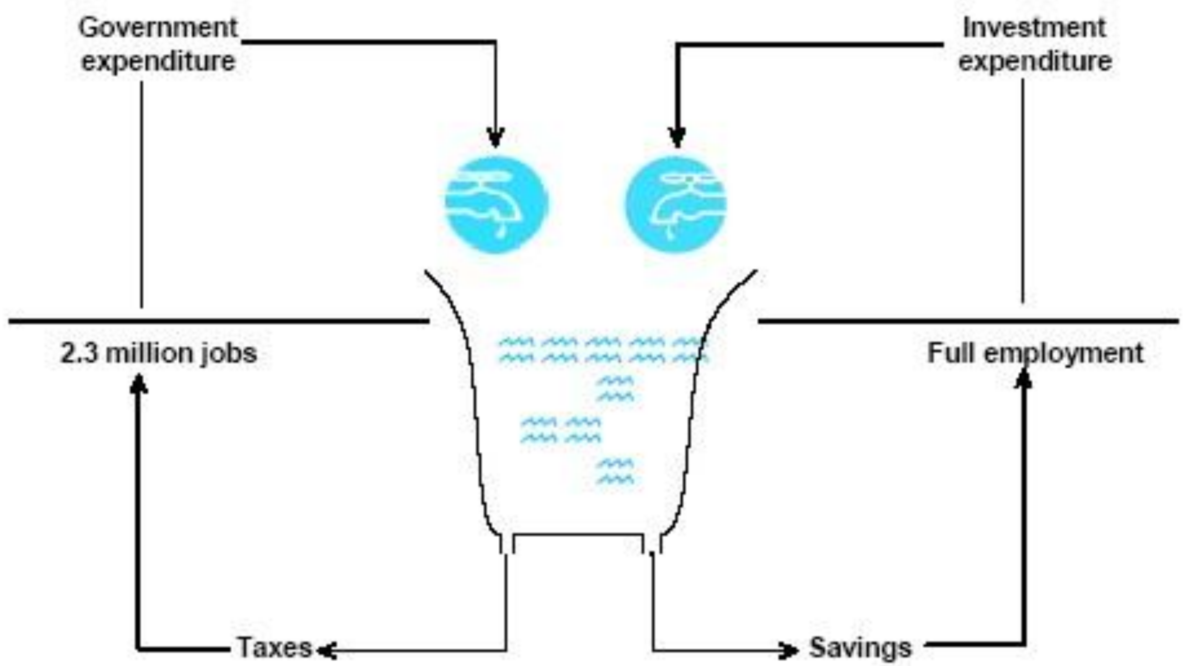
$$\dot{M}_{\rm gas,out} = a \times {\rm SFR},$$

Bouche et al 2010

The bathtub model

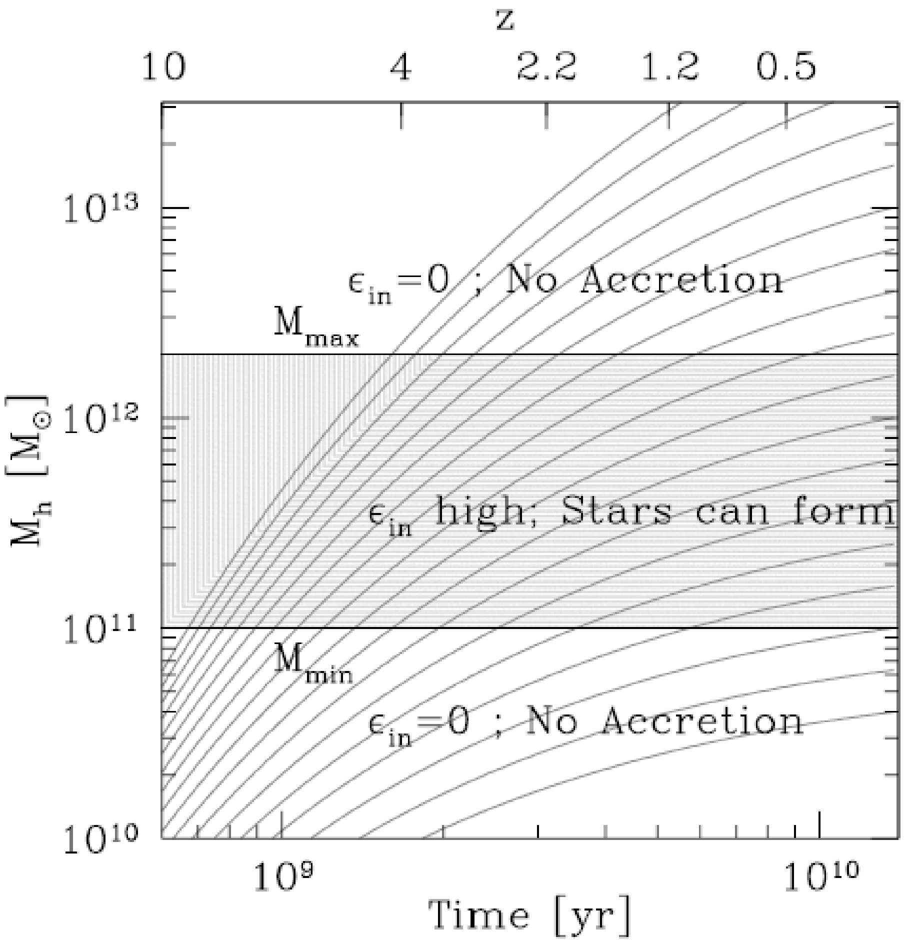
“Economics…. The dismal science”   - Thomas Carlyle

Figure 1 A bathtub approach to macroeconomics



Source: Pool & Roy, “The Instant Economist”

The bathtub model



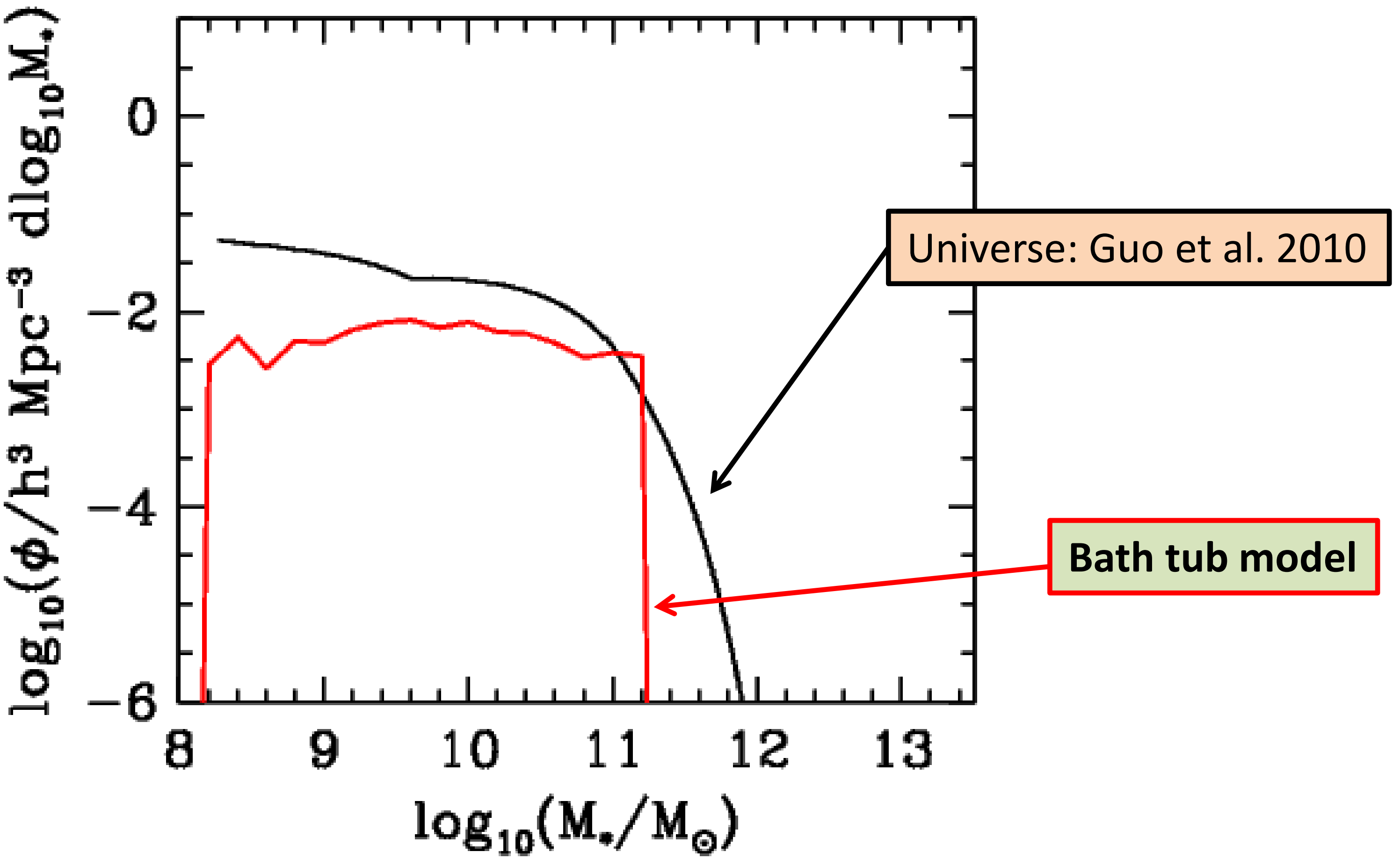
Bouche et al. 2010

$$\dot{M}_{\mathrm{gas,in}} = \epsilon_{\mathrm{in}}\, f_{\mathrm{b}}\, \dot{M}_{\mathrm{h}}$$

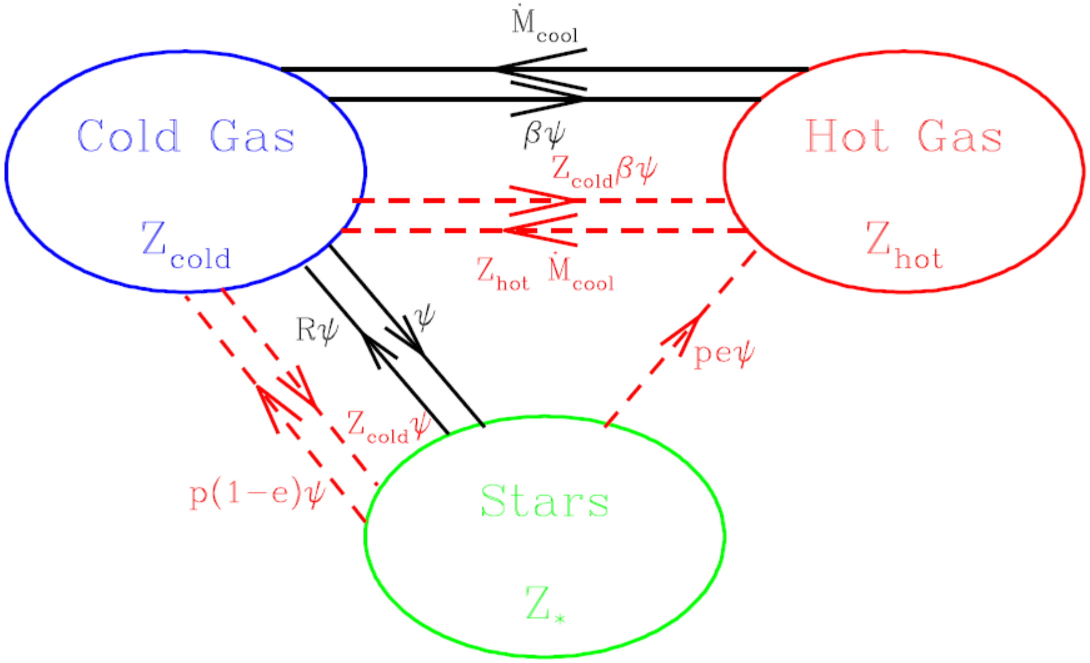
Extreme, by-hand, fine tuning of cold gas accretion efficiency as a function of mass

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

Output of the bathtub model



More than one equation needed!



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$$\dot{M}^Z_* = (1-R)Z_{cold}\psi$$

$$\dot{M}^Z_{hot} = -\dot{M}_{cool}Z_{hot} + (pe + \beta Z_{cold})\psi$$

$$\dot{M}^Z_{cold} = \dot{M}_{cool}Z_{hot} + [p(1-e) - (1 + \beta - R)Z_{cold}]\psi,$$

Cole et al. 2000

Uses for a bathtub?

Why should I believe any of this?

- Too complicated!

  Tough – galaxy formation is complicated!

- Too many free parameters!

- Can't you get anything you want?

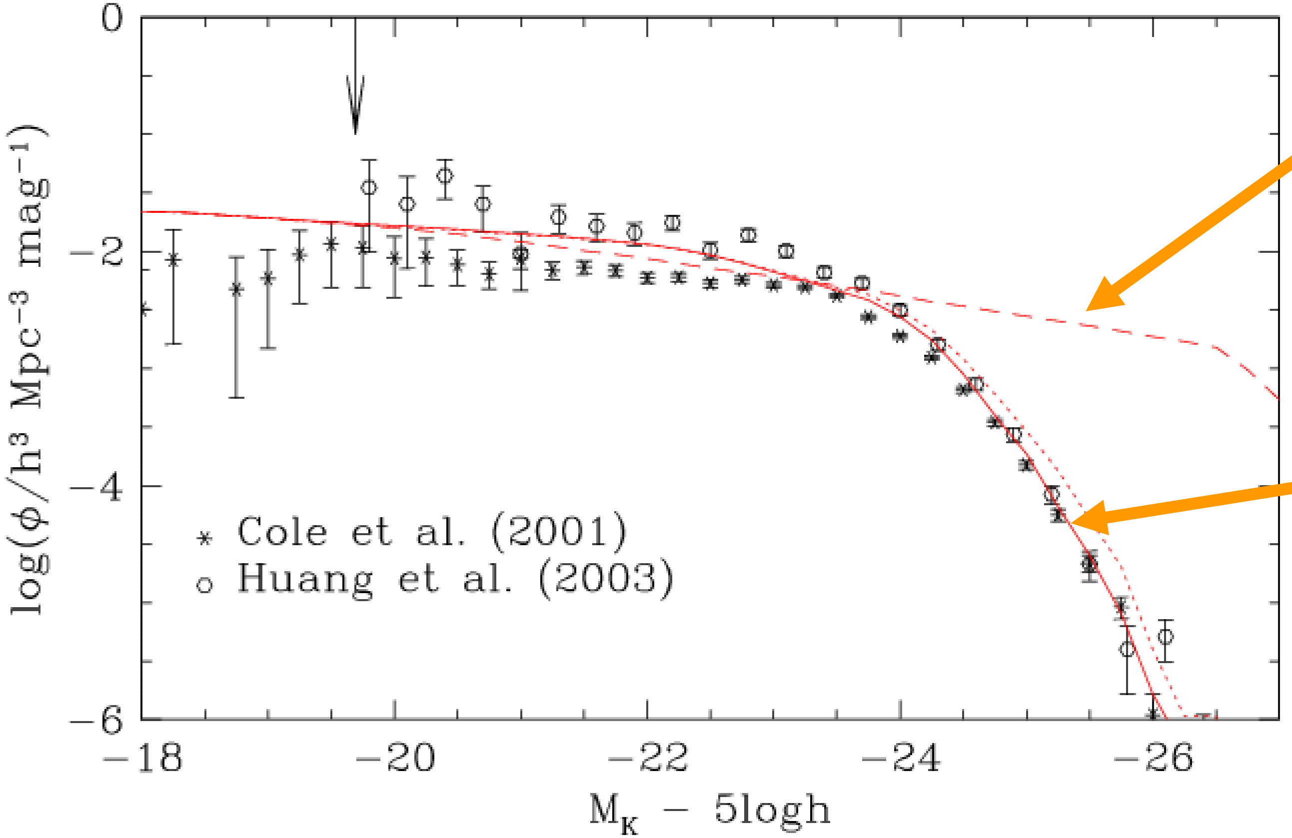
Why should I believe any of this?

- Too complicated!

  Tough – galaxy formation is complicated!
- Too many free parameters!

  More processes – more predictions – more constraints : see Henriques et al., Bower et al.
- Can't you get anything you want?

Is it a black box? Can we get anything we want?



Same parameters but turn off AGN feedback

With AGN feedback

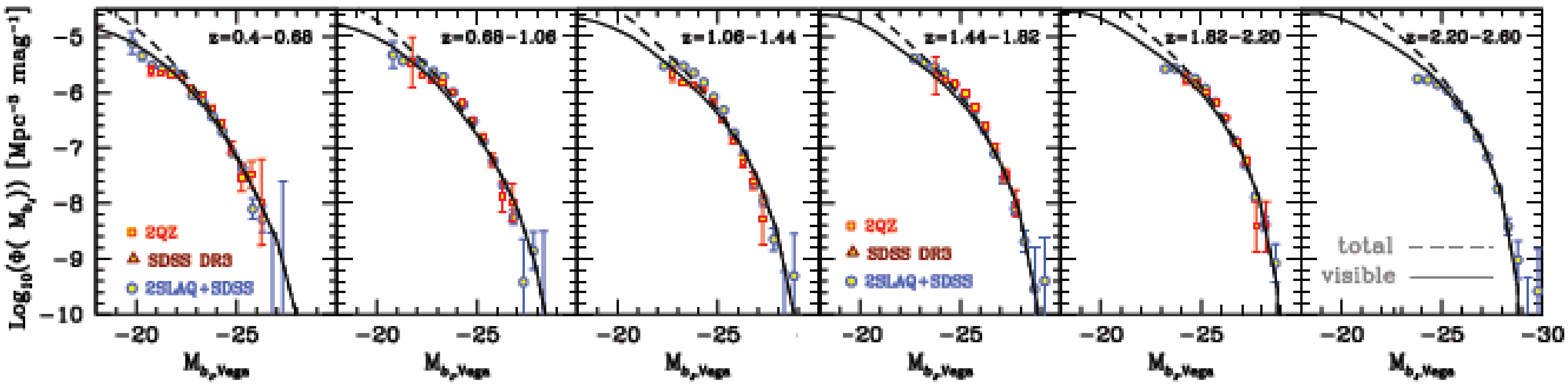
Present day K-band field luminosity function

Bower et al. 2006

Quasar luminosity functions

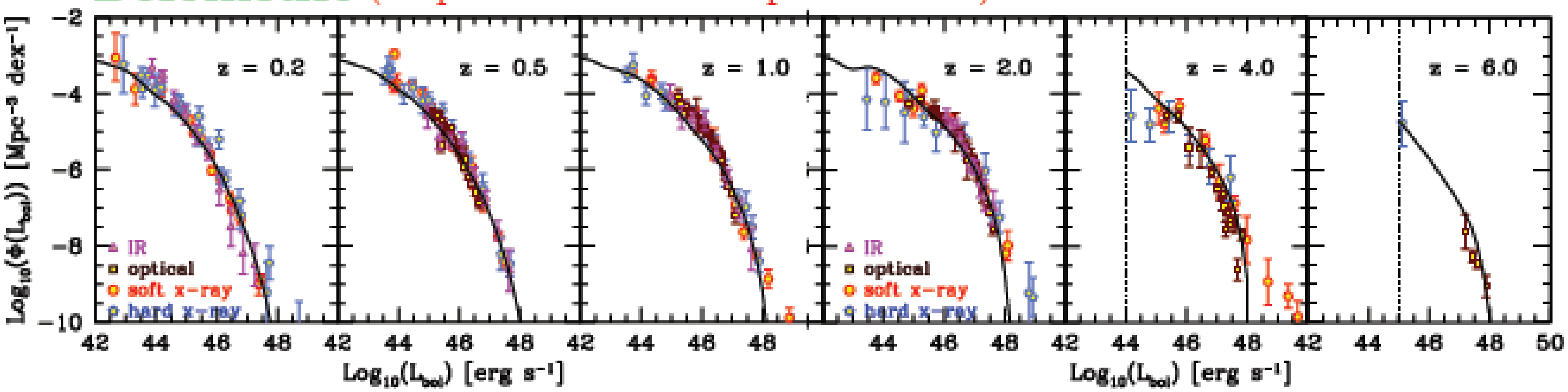
Optical

AGN are strongly obscured in the optical (and soft X-rays): $f_{obsc}=f_{obsc}(z,L)$



Bolometric

(compilation of LF's from Hopkins et al. 2007)



NF et al. 2011 (arXiv:1011.5222)

Fanidakis et al. 2011, 2012

An example of semi-analytics in action: Modelling star formation: old method

Parametric forms for the SF law

(total cold gas mass/SF timescale)

$$\psi = \frac{M_{\rm cold}}{\tau_\star}$$

What is $\tau_\star$? →

$$\tau_\star = \frac{\tau_{\rm disk}}{\epsilon_\star} (V_{\rm disk}/V_0)^{\alpha_\star}$$

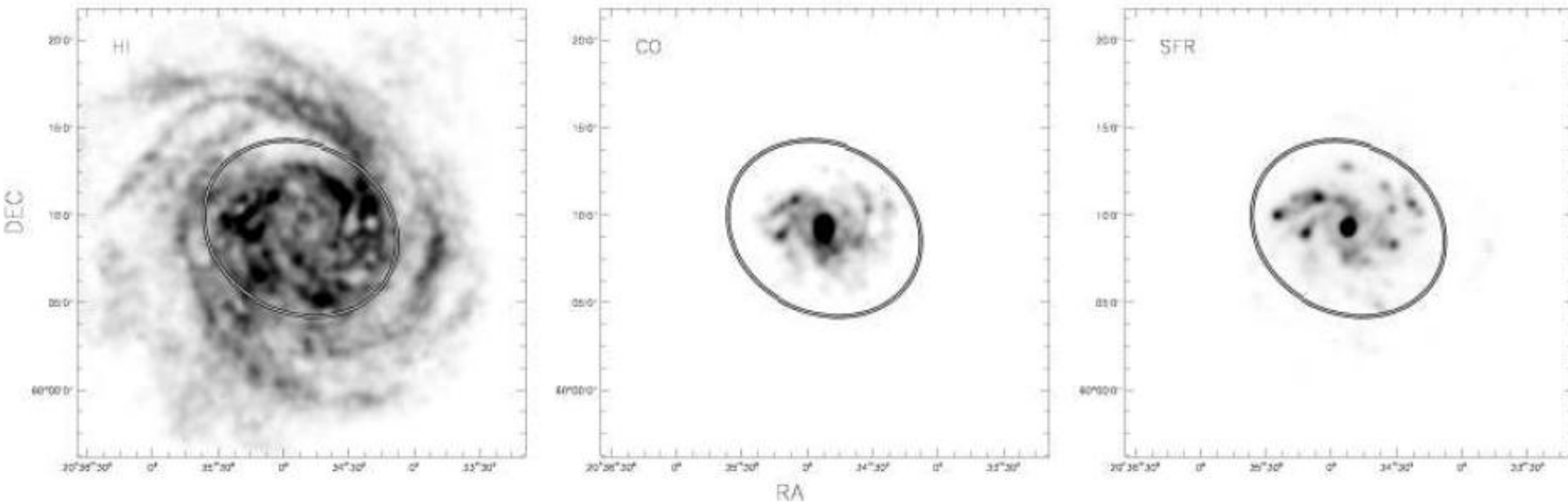
Cole et al. (2000)

Two free-parameters to model the SF activity

Lagos et al. 2011

What drives star formation?

Atomic hydrogen | **CO – molecular hydrogen** | **Star formation activity**



Leroy et al. 2008

Empirical and theoretical SF laws to test

Empirical laws

(ii) The Kennicutt-Schmidt law (KS) →

$$\Sigma_{\rm SFR} = A\,\Sigma_{\rm gas}^{1.4}$$

$$\Sigma_{\rm crit}$$

(i) The Blitz & Rosolowski law (BR)
Leroy et al. (2008), Bigiel et al. (2008) →

$$\frac{\Sigma({\rm H_2})}{\Sigma({\rm HI})} = \left(\frac{P_{\rm ext}}{P_0}\right)^{\alpha}$$

$$\Sigma_{\rm SFR} = \nu_{\rm SF}\,\Sigma_{\rm mol}$$

Theoretical laws

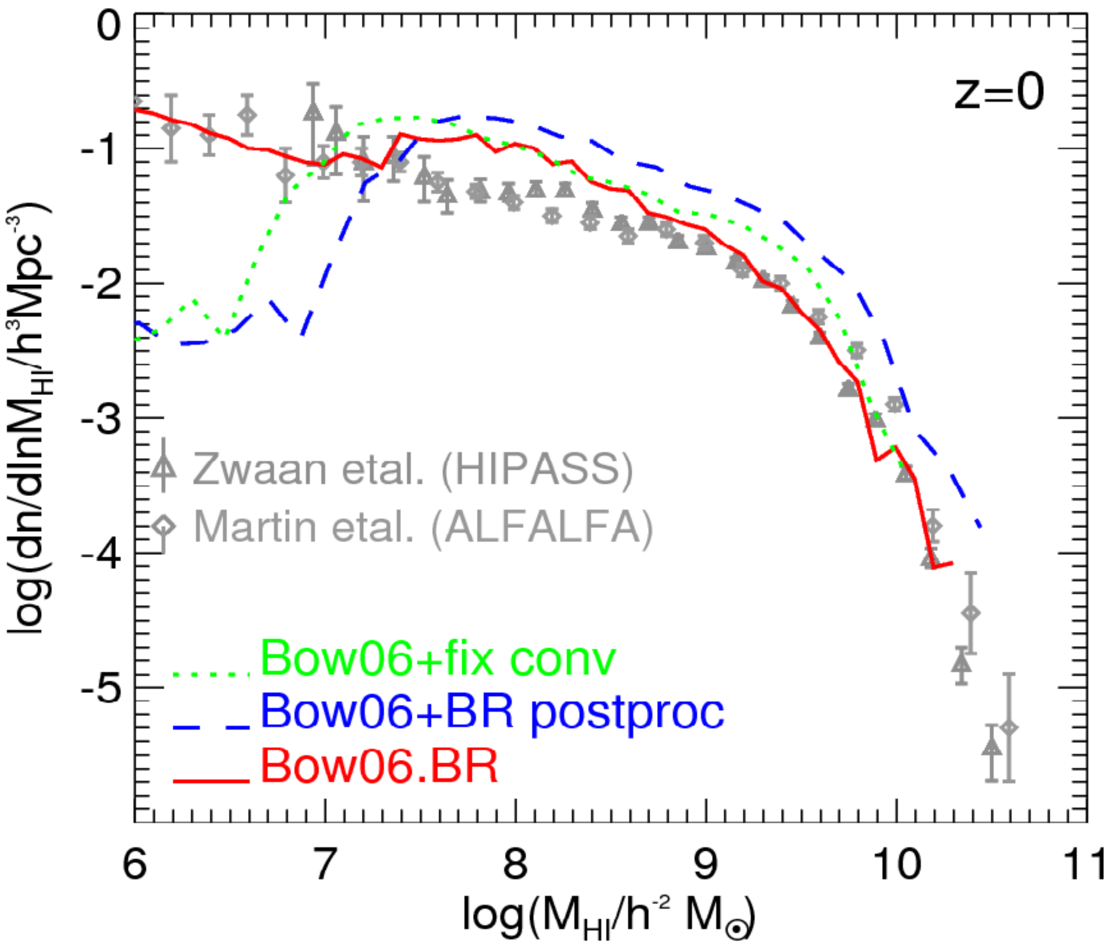
(iii) The Krumholz, McKee & Tumlinson theoretical law (KMT)

$$\Sigma_{\rm SFR} = \nu_{\rm SF}(\Sigma_{\rm gas})\,f_{\rm mol}\,\Sigma_{\rm gas}$$

$$\nu_{\rm SF}(\Sigma_{\rm gas}) = \nu_{\rm SF}^{0} \times \begin{cases} \left(\frac{\Sigma_{\rm gas}}{\Sigma_0}\right)^{-0.33}, & \frac{\Sigma_{\rm gas}}{\Sigma_0} < 1 \\ \left(\frac{\Sigma_{\rm gas}}{\Sigma_0}\right)^{0.33}, & \frac{\Sigma_{\rm gas}}{\Sigma_0} > 1 \end{cases}$$

Lagos et al. 2011

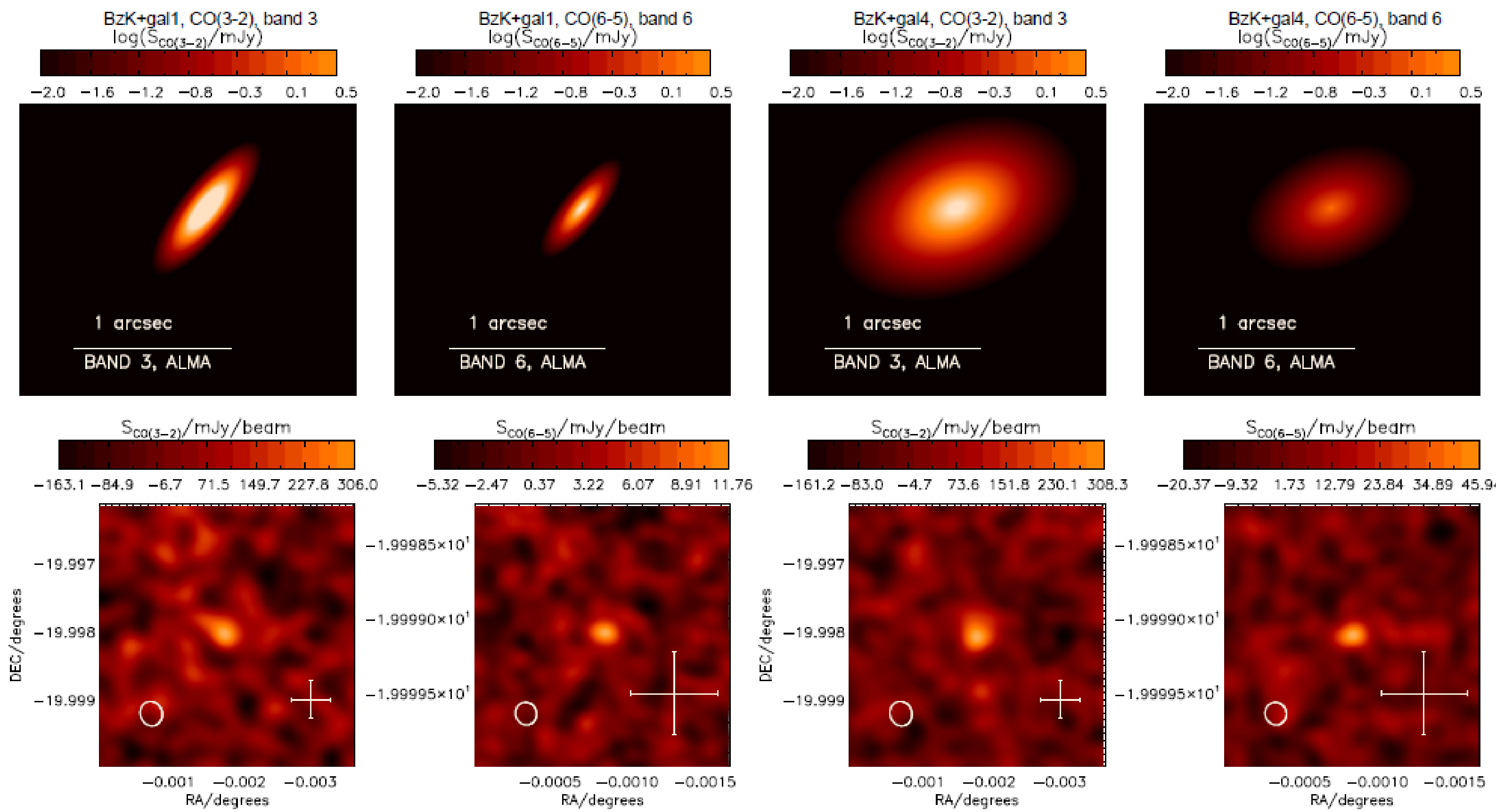
The mass function of atomic hydrogen



- Improved modelling of star formation
- Reduced volume of parameter space
- New predictions: HI mass function and CO LF
- Illustrates modular approach of semi-analytics

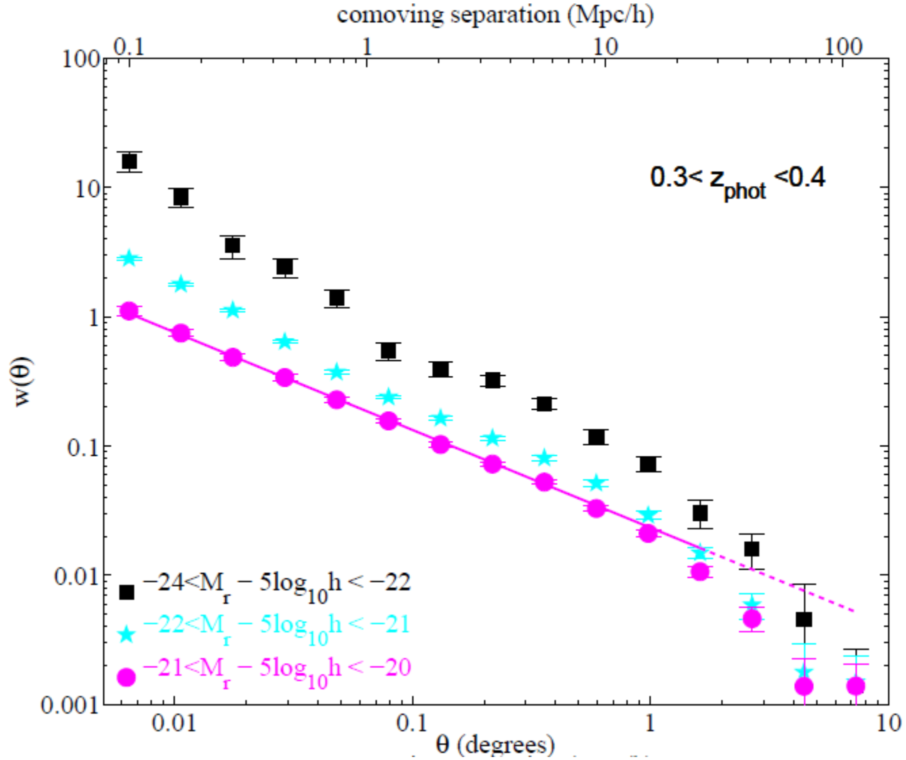
Lagos et al. 2011, 2012

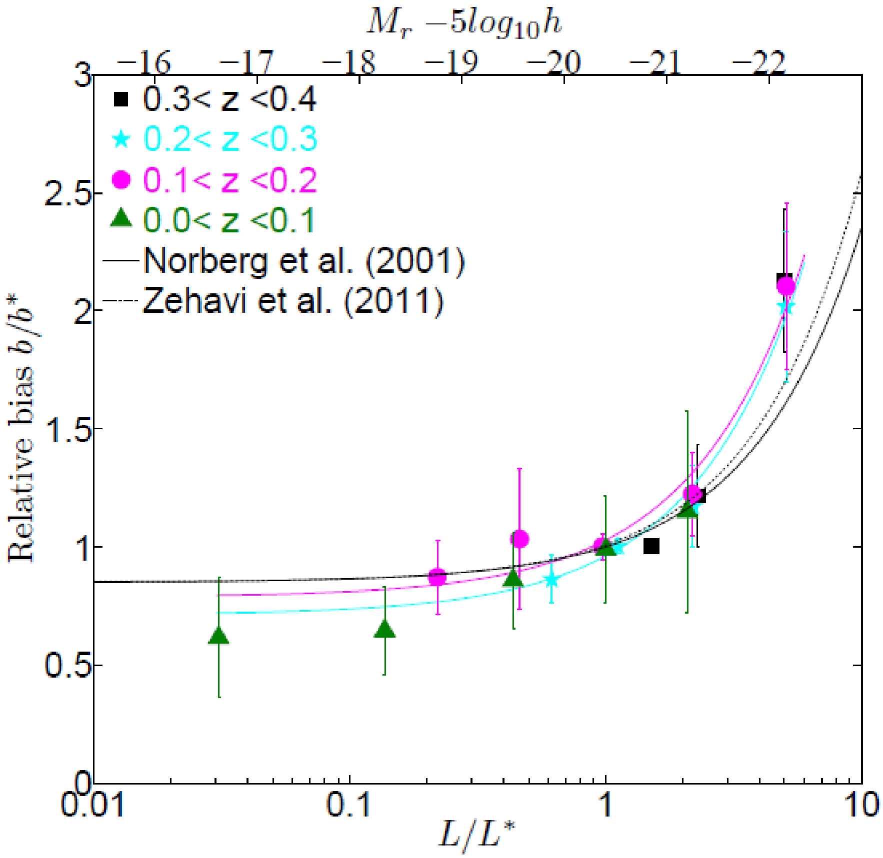
Simulated ALMA images of GALFORM galaxies



(see Lagos et al. 2012 GALFORM + UCL_PDR model)

Galaxy bias: case study





GAMA survey measurements: Christodoulou et al. 2012

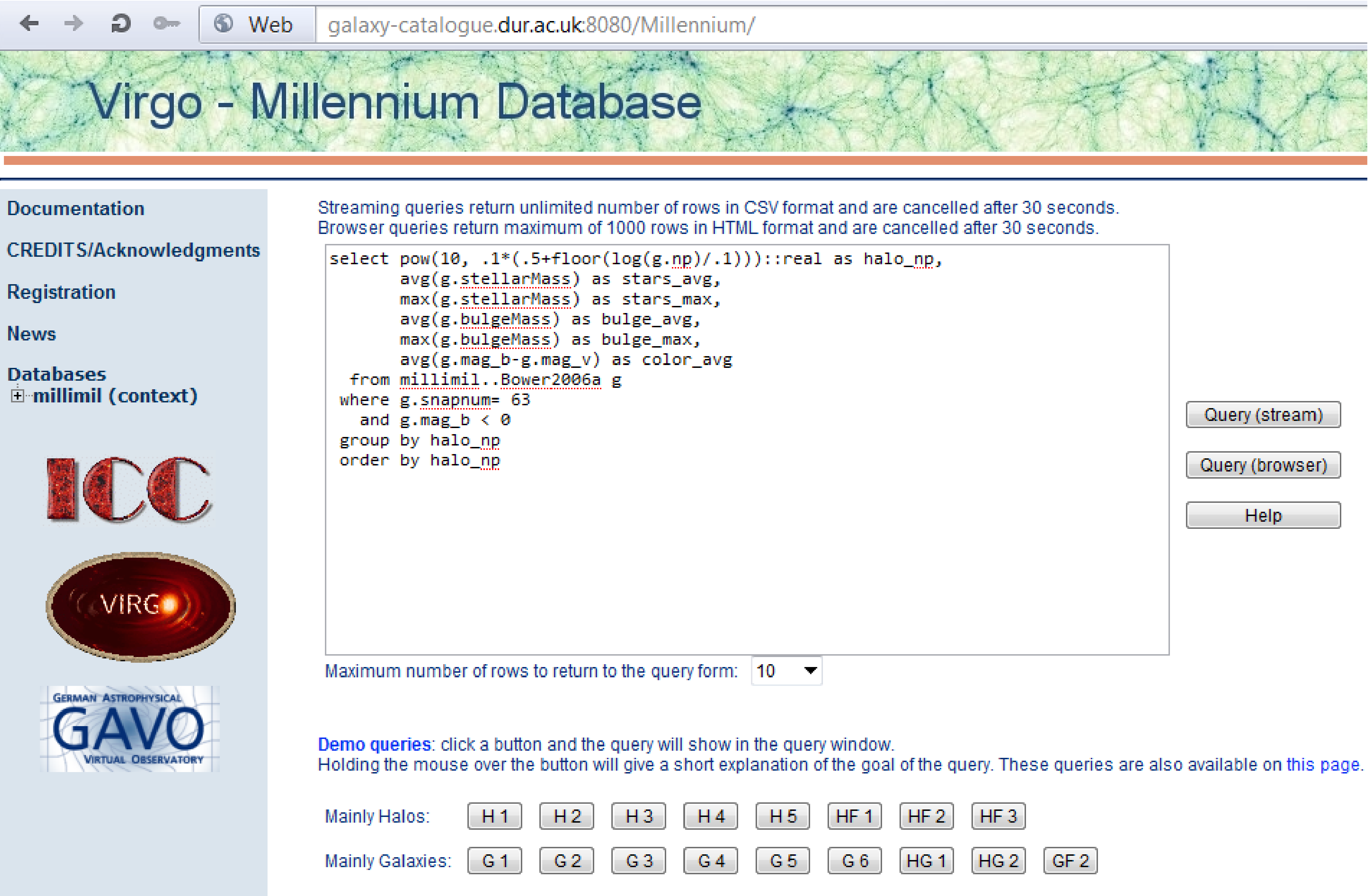
Galaxy bias: case study

- Galaxy bias can constrain physics of galaxy formation if we can model it robustly
- Galaxy bias is a nuisance parameter in cosmological studies – if we can model it robbustly

Which galaxies go in which haloes?

How robust are the predictions of different semi-analytical models?

Contreras et al. 2013, arXiv:1301.3497


Web
galaxy-catalogue.dur.ac.uk:8080/Millennium/
Virgo - Millennium Database
Documentation
CREDITS/Acknowledgments
Registration
News
Databases
millimil (context)
ICC
VIRGO
GERMAN ASTROPHYSICAL
GAVO
VIRTUAL OBSERVATORY
Streaming queries return unlimited number of rows in CSV format and are cancelled after 30 seconds.
Browser queries return maximum of 1000 rows in HTML format and are cancelled after 30 seconds.
select pow(10, .1*(.5+floor(log(g.np)/.1)))::real as halo_np,
avg(g.stellarMass) as stars_avg,
max(g.stellarMass) as stars_max,
avg(g.bulgeMass) as bulge_avg,
max(g.bulgeMass) as bulge_max,
avg(g.mag_b-g.mag_v) as color_avg
from millimil..Bower2006a g
where g.snapnum= 63
and g.mag_b < 0
group by halo_np
order by halo_np
Query (stream)
Query (browser)
Help
Maximum number of rows to return to the query form: 10
Demo queries: click a button and the query will show in the query window.
Holding the mouse over the button will give a short explanation of the goal of the query. These queries are also available on this page.
Mainly Halos: H 1 H 2 H 3 H 4 H 5 HF 1 HF 2 HF 3
Mainly Galaxies: G 1 G 2 G 3 G 4 G 5 G 6 HG 1 HG 2 GF 2

Comparison of public results

N-BODY

Millennium – I
N-body simulation

Independent construction of
DM halo merger trees

+

SEMI-ANALYTICS

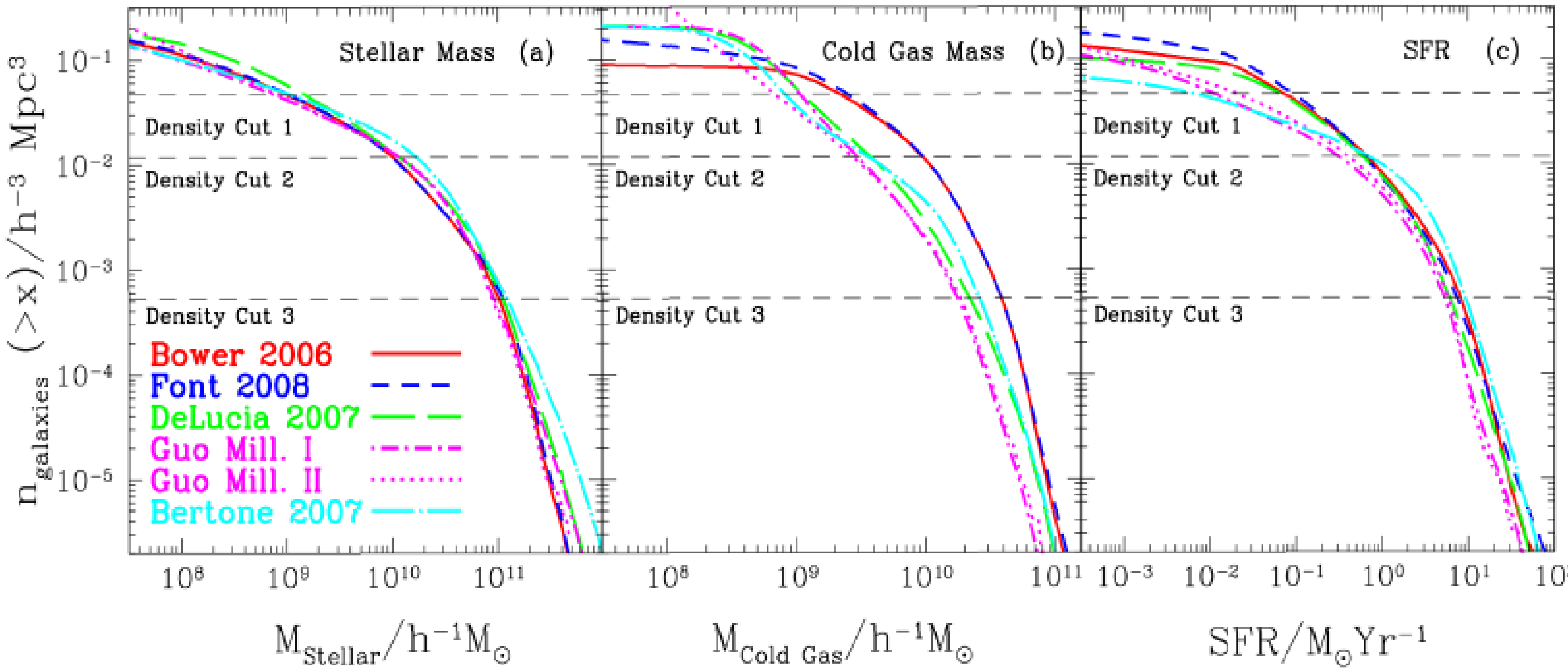
Bower et al. 20006
De Lucia & Blaizot 2007
Bertone et al. 2007
Font et al. 2008
Guo et al. 2011

Different physics: AGN feedback, SNe feedback, gas cooling in satellites

Different observations used to set Model parameters

Contreras et al. 2013

How many galaxies?

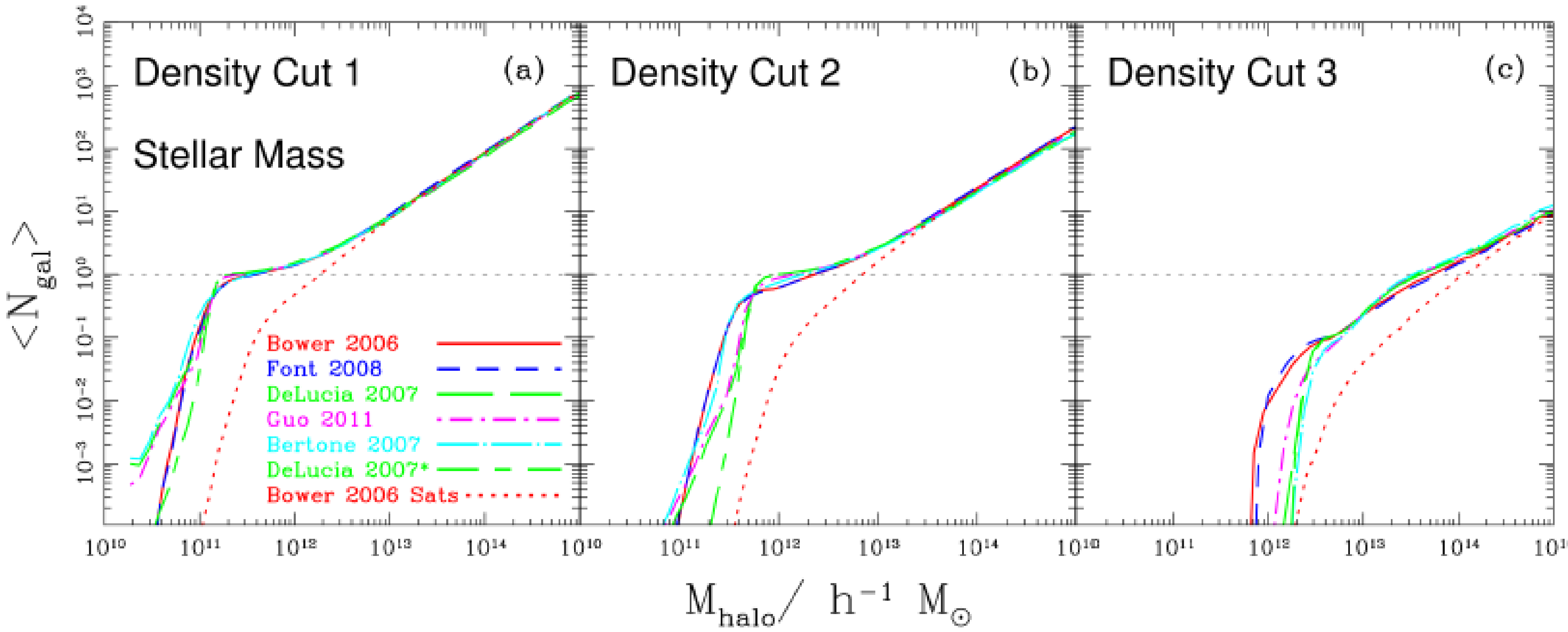


Cumulative number densities for stellar mass, cold gas mass, SFR

Contreras et al. 2013

How many galaxies in each halo?

Decreasing galaxy abundance

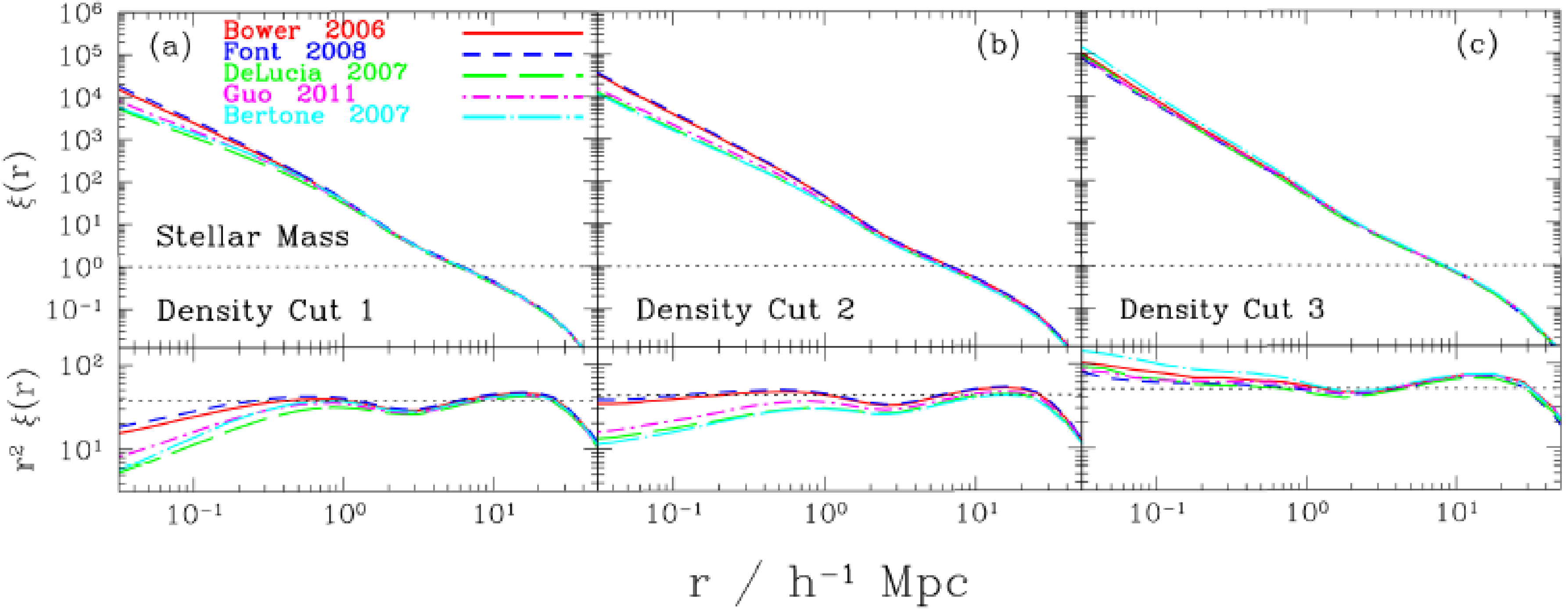


Halo Occupation Distribution: model OUTPUT

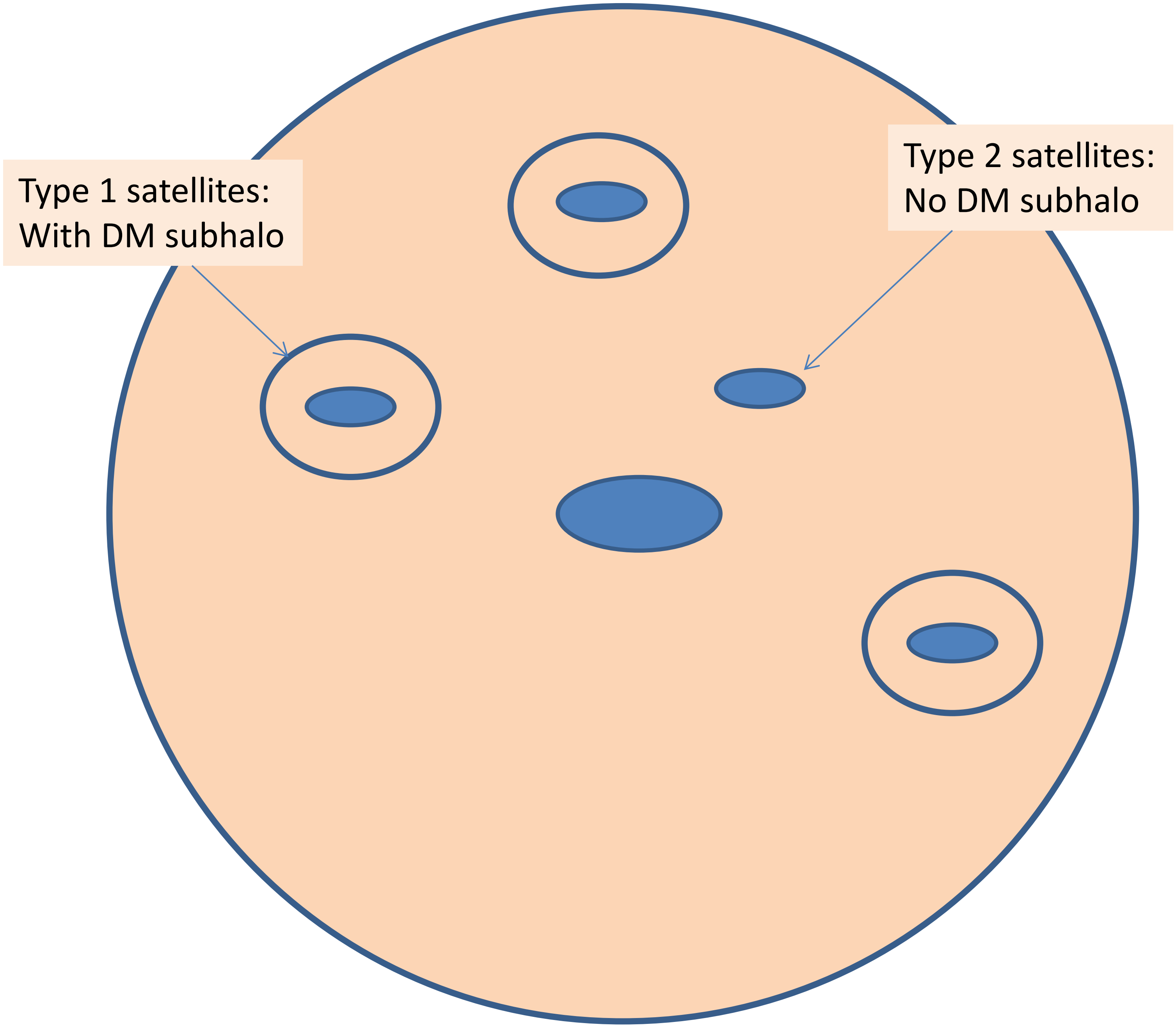
Contreras et al. 2013

Clustering: stellar mass samples

Decreasing galaxy abundance →

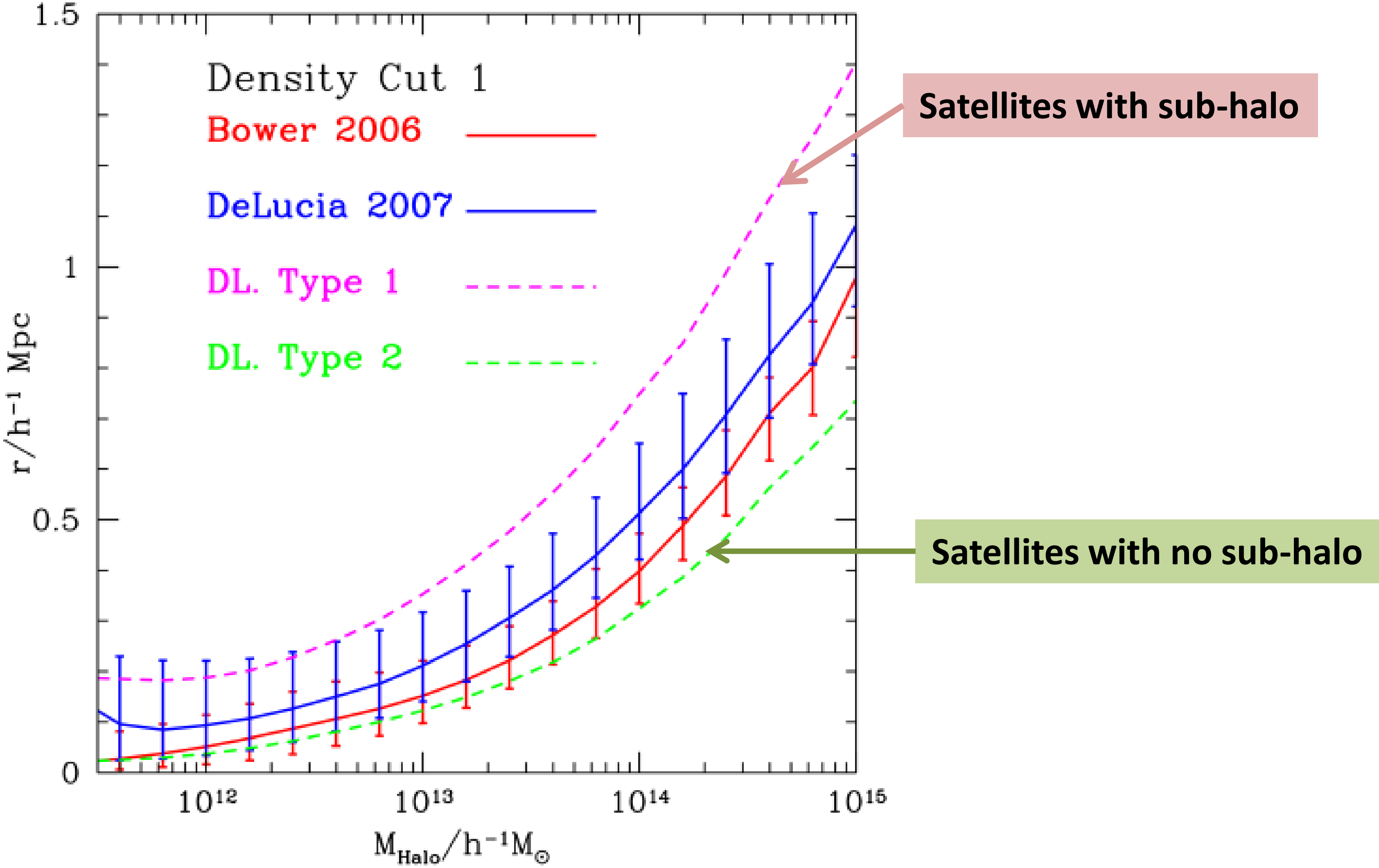


Contreras et al. 2013



Type 1 satellites:
With DM subhalo
Type 2 satellites:
No DM subhalo

Median radius of galaxy pairs in halo

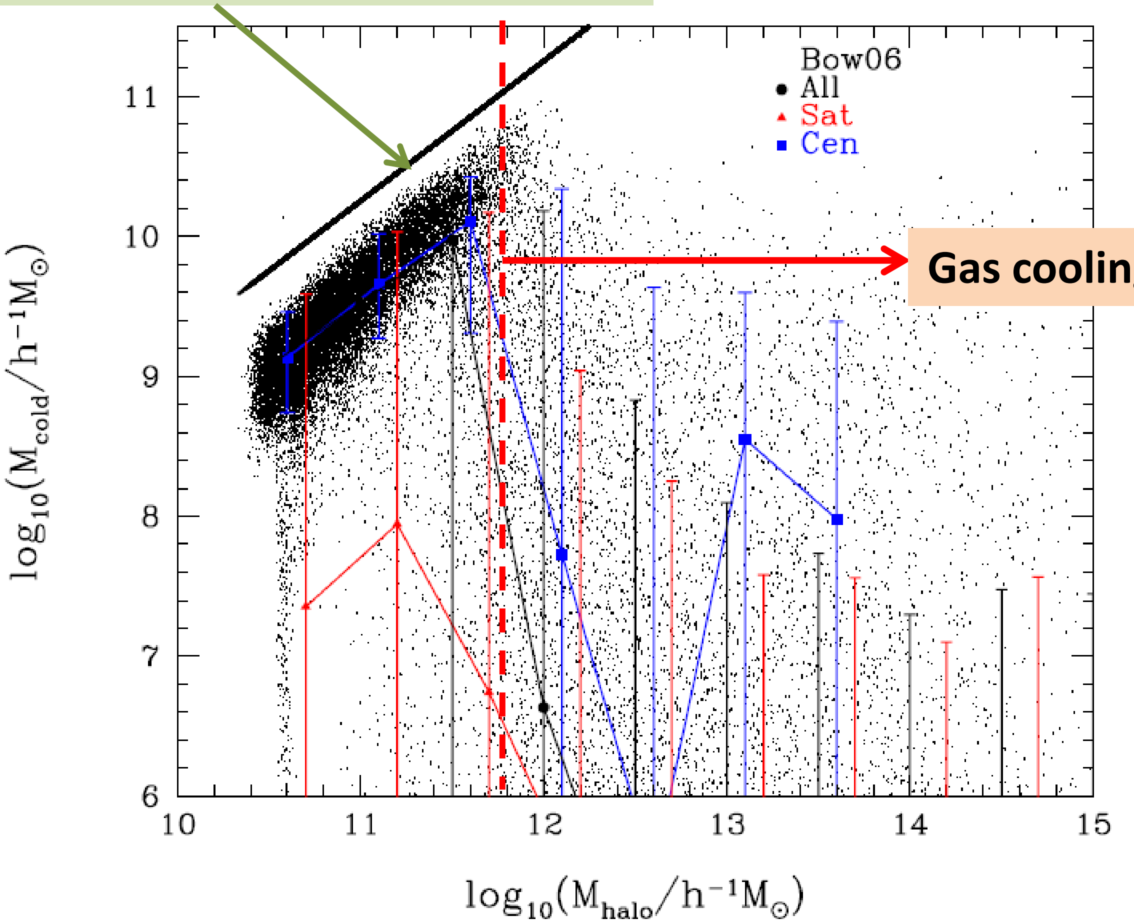


Contreras et al. 2013

Cold gas in galaxies

All baryons in halo turned into cold gas

Cold gas mass

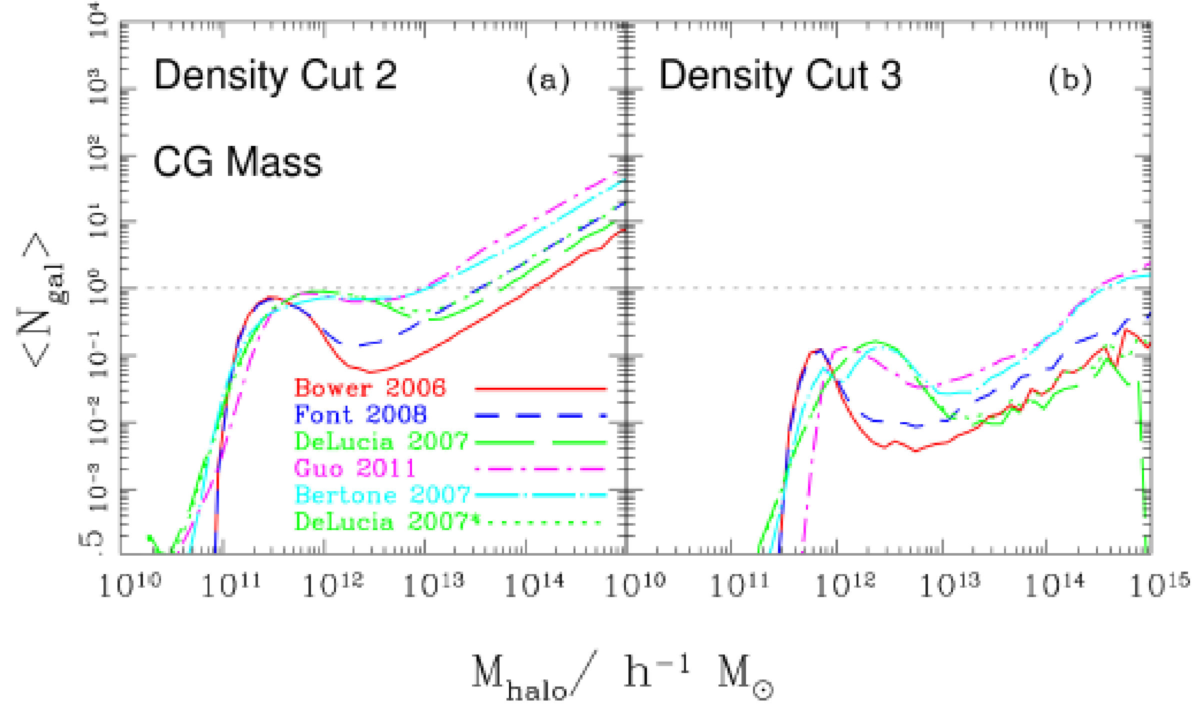


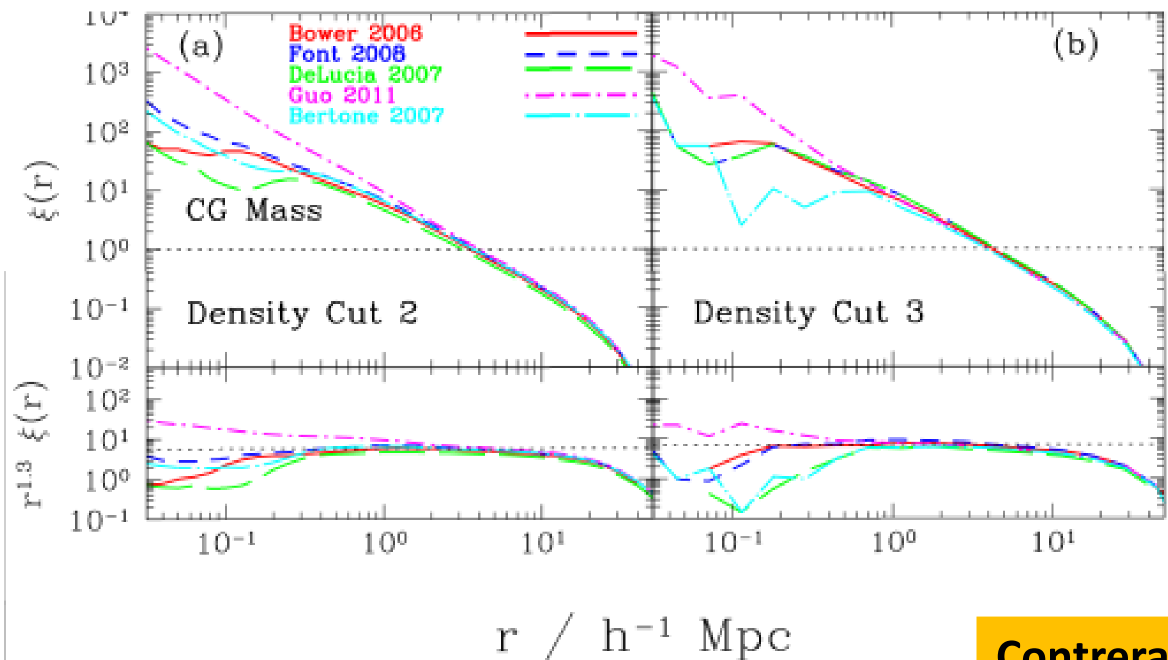
Gas cooling suppressed by AGN

Halo mass

Kim et al. 2011

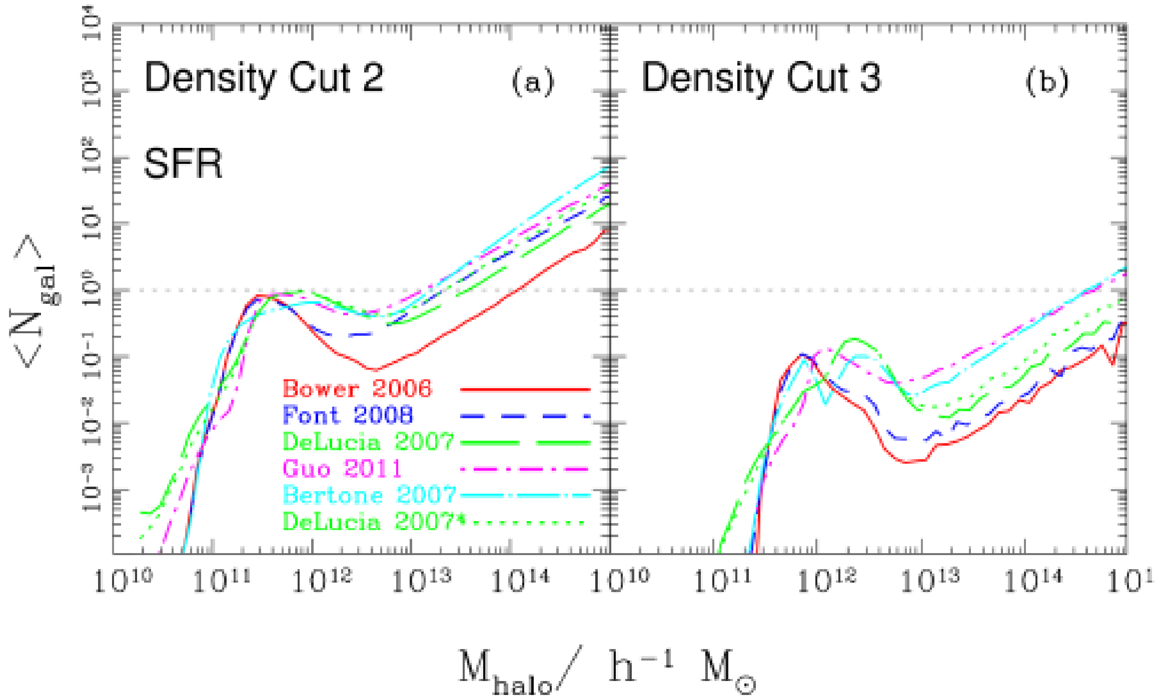
Cold Gas Mass Sample

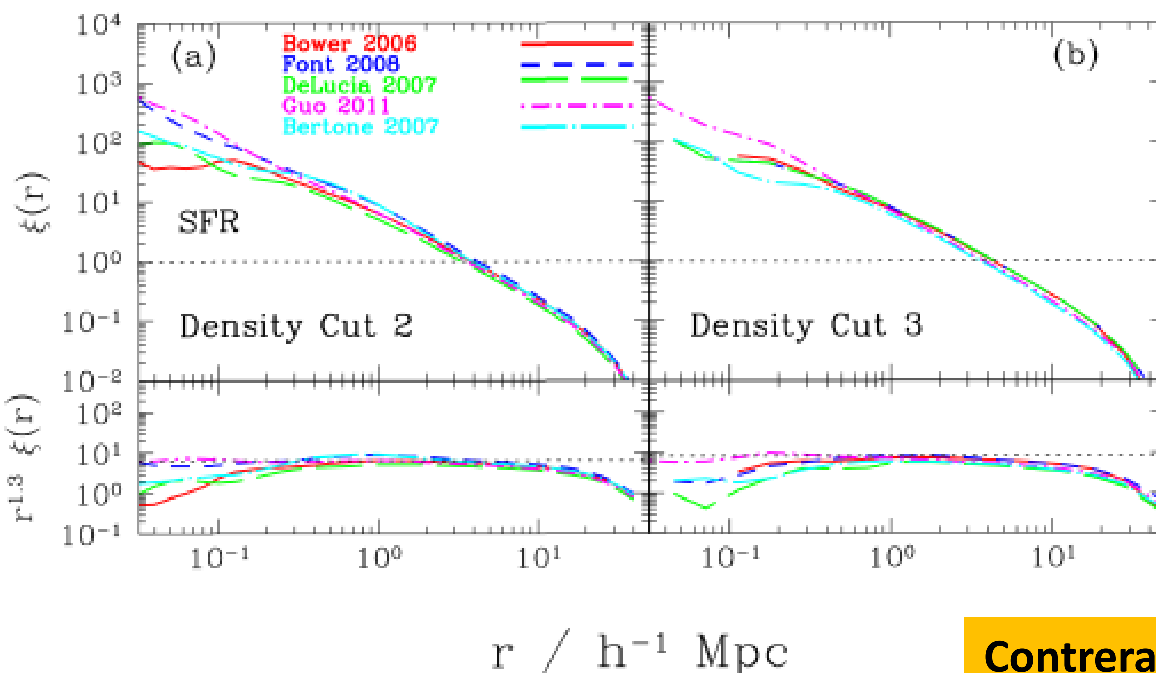




Contreras et al. 2013

Star Formation Rate Samples





Contreras et al. 2013

Conclusions

- Semi-analytical models allow us to test our ideas about galaxy formation
- Improved treatment of star formation: HI, CO
- Robust predictions for clustering of galaxies selected by stellar mass
- Less robust predictions for clustering of SFR & cold gas mass selected samples
- Generic features predicted in HOD
- HOD(M*) looks like standard form
- HOD(SFR or cold gas) peaked – different

Lagos et al. 2011, 2012

Contreras et al. 2013, arXiv:1301.3497