Modelling the connection between galaxies and their dark matter halos

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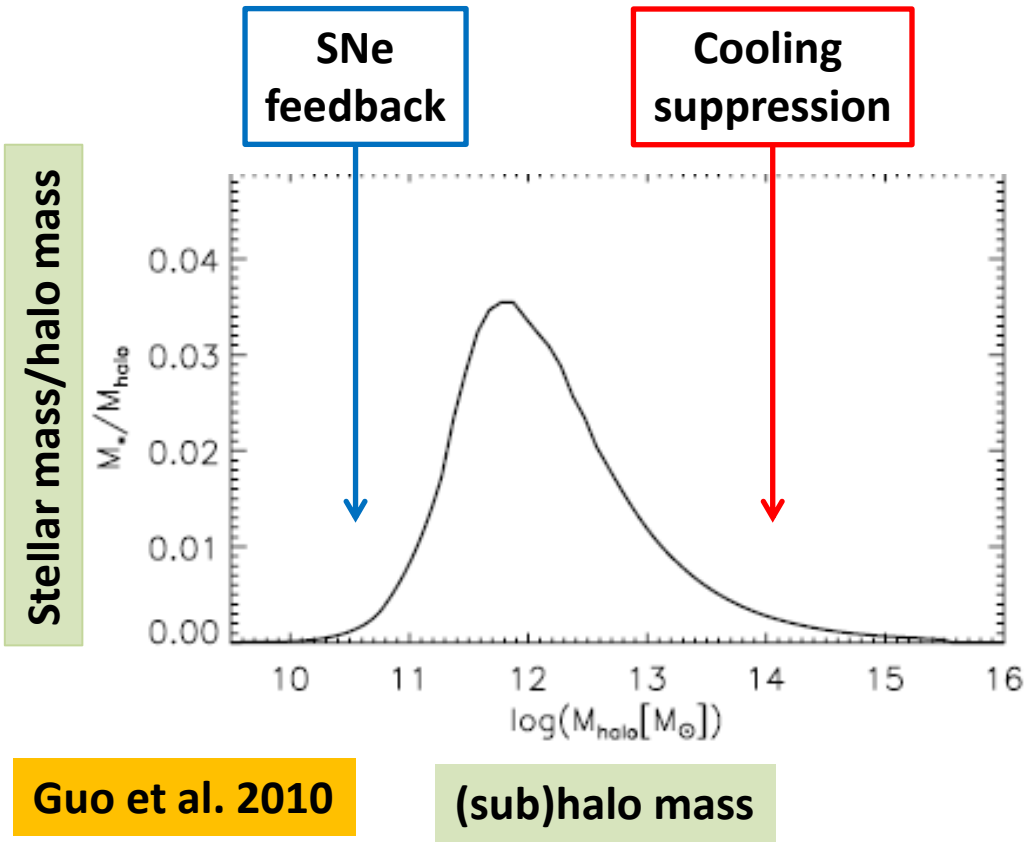
GALAXIES

DARK MATTER

The efficiency of galaxy formation

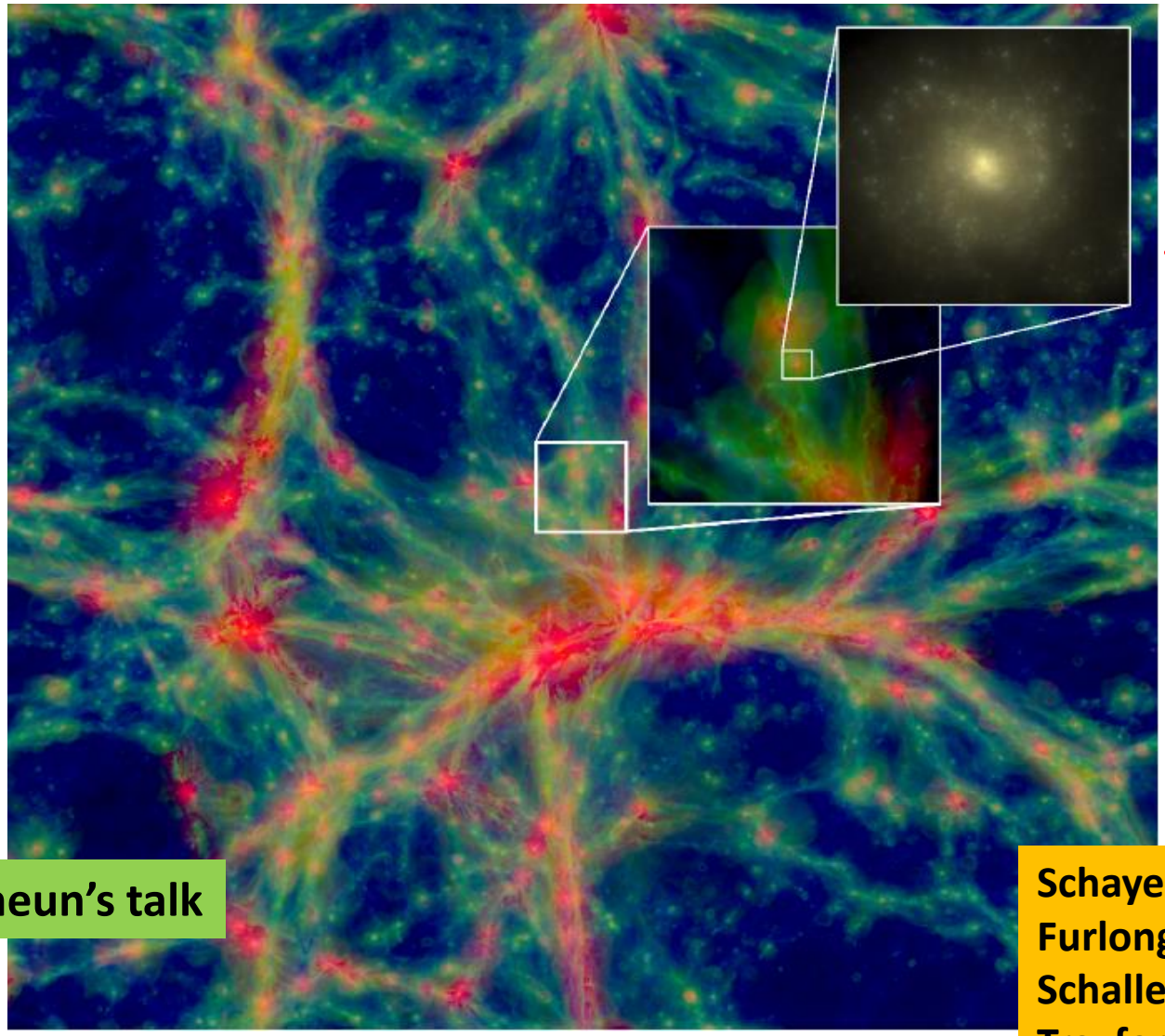


Guo et al. 2010

- Galaxy formation very inefficient
- Globally only a few percent (~5%) of baryons are stars
- Different processes set efficiency of galaxy formation in different mass DM halos

Attempt to model the physics that shape this relation using gas simulations and semi-analytical models

Gas dynamics simulations: e.g. EAGLE



See Tom Theun's talk

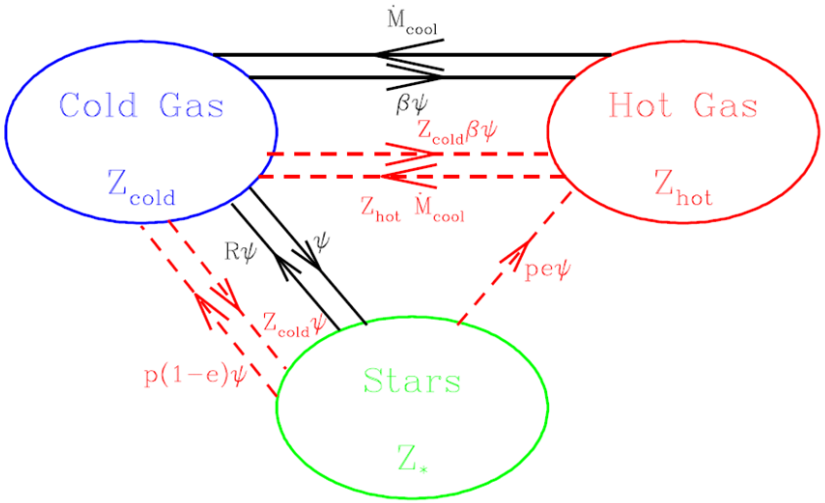
Schaye et al. 2014
Furlong et al. 2014
Schaller et al. 2014
Trayford et al 2015…..

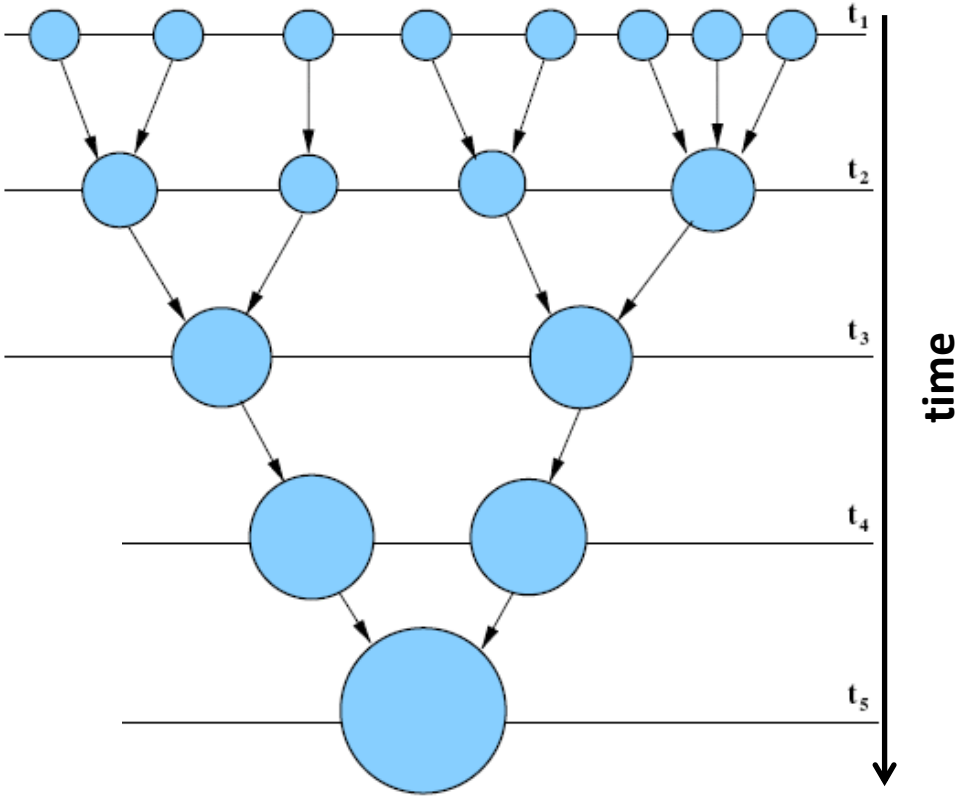
What is semi-analytical modelling?

A new model of galaxy formation

Lacey et al. 2015

Follow baryons in halo merger tree





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

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

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

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

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

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

Solve set of coupled differential equations

Baugh 2006, Benson 2010

What is semi-analytical modelling?

- Model parameters – too many?

Model parameters

Table 1. Table of parameters. F=fixed, P=primary, S=secondary. P_0 has units $k_B \mathrm{cm}^{-3}\mathrm{K}$.

parameter	value	range	type=F/P/S	description	Eqn/paper
Cosmology				Komatsu et al. (2011)	
Ω_m	0.272	-	F	matter density	
Ω_b	0.0455	-	F	baryon density	
h	0.704	-	F	Hubble parameter	
σ_8	0.81	-	F	Fluctuation amplitude	
n_s	0.967	-	F	Scalar spectral index	
Stellar population					Maraston (2005)
IMF : quiescent					
x	Kennicutt	-	F	IMF	Eq. 32
p	0.021	-	F	yield	Eq. 31
R	0.44	-	F	recyled fraction	Eq. 30
IMF : starburst					
x	1	0-1	P	IMF slope	Eq. 32
p	0.048	-	P	yield	Eq. 31
R	0.54	-	P	recyled fraction	Eq. 30
Star formation: quiescent					Lagos et al. (2011b)
ν_SF	$0.74\mathrm{Gyr}^{-1}$	$0.25 - 0.74\mathrm{Gyr}^{-1}$	P	efficiency factor for molecular gas	Eq. 7
P_0	1.7×10^4	-	F	normalisation of pressure relation	Eq. 6
α_P	0.8	-	F	slope of pressure relation	Eq. 6
Star formation: bursts					Baugh et al. (2005)
f_dyn	20	0 - 100	P	Multiplier for dynamical time	Eq. 9
$\tau_{*\mathrm{burst,min}}$	0.1 Gyr	0-1.0	P	minimum burst timescale	Eq. 9
Photoionization feedback					Benson et al. (2003)
z_reion	10	-	F	reionization redshift	
V_crit	$30\mathrm{km\,s}^{-1}$	-	F	threshold circular velocity	

Lacey et al. 2015

Model parameters

SNe feedback					Cole et al. (2000)
$V_{\rm SN}$	$320{\rm km\,s^{-1}}$	anything	P	pivot velocity	Eq. 10
$\gamma_{\rm SN}$	3.2	0-5.5	P	slope on velocity scaling	Eq. 10
$\alpha_{\rm ret}$	0.64	0.3-3	P	reincorporation timescale multiplier	Eq. 11
AGN feedback & SMBH growth					Bower et al. (2006)
$f_{\rm BH}$	0.005	0.001-0.01	S	fraction of mass accreted onto BH in starburst	Malbon et al. (2007)
$\alpha_{\rm cool}$	0.8	0-2	P	ratio of cooling/free-fall time	Eq. 12
$f_{\rm Edd}$	0.01	-	S	controls maximum BH heating rate	Eq. 13
$\epsilon_{\rm heat}$	0.02	-	S	BH heating efficiency	
Disk stability					Cole et al. (2000)
F_{stab}	0.9	0.9-1.1	P	Threshold for instability	
Galaxy mergers					Jiang et al. (2008)
Size of merger remnants					Cole et al. (2000)
$f_{\rm orbit}$	0	0 - 1	S	orbital energy contribution	Eq. 19
$f_{\rm DM}$	2	-	S	dark matter fraction in galaxy mergers	
Starburst triggering in mergers					Baugh et al. (2005)
$f_{\rm ellip}$	0.3	0.2 - 0.5	P	Threshold on mass ratio for major merger	
$f_{\rm burst}$	0.05	0.05 - 0.3	P	Threshold on mass ratio for burst	
Dust model					Granato et al. (2000)
$f_{\rm cloud}$	0.5	0.2 - 0.8	P	fraction of dust in clouds	
$t_{\rm esc}$	1Myr	$1-10{\rm Myr}$	P	escape time of stars from clouds	
β_b	1.5	1.5 - 2	S	sub-mm emissivity slope in starbursts	Eq. A17

Lacey et al. 2015

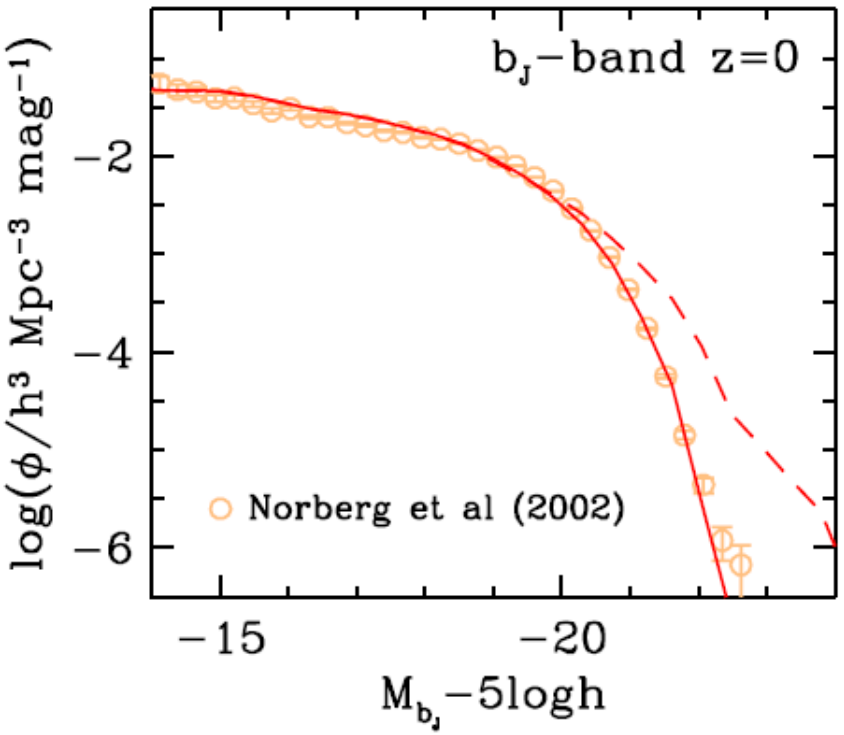
What is semi-analytical modelling?

- Model parameters
- Parameter calibration

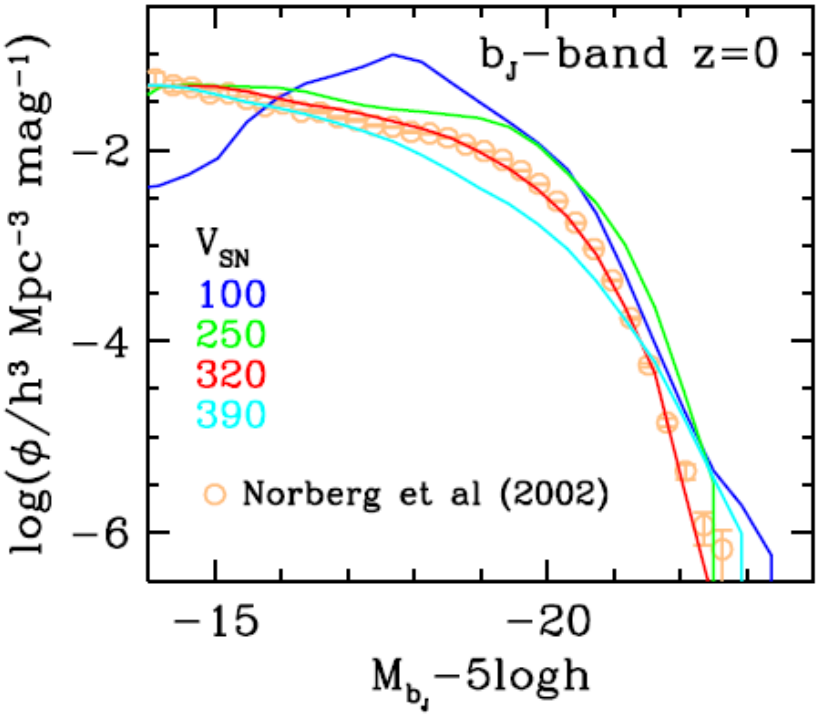
Lacey et al. 2015

Local galaxy luminosity function

Calibrated model



Vary strength of SNe feedback

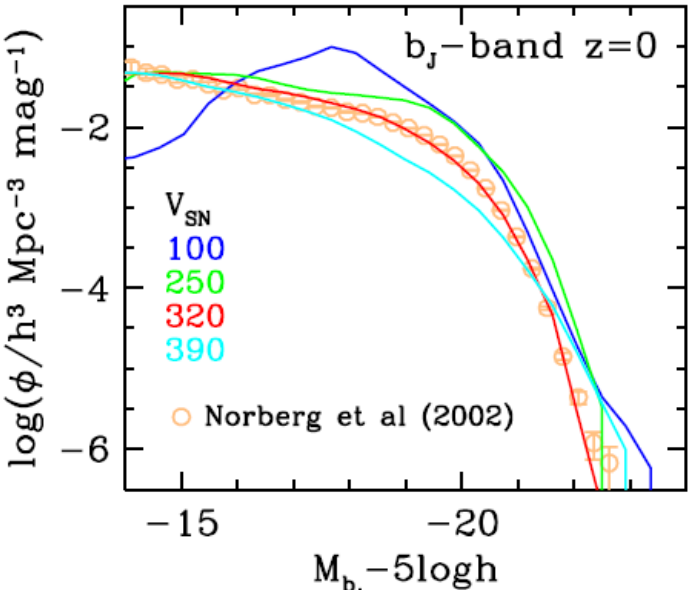


Try different parameter values until model reproduces target data

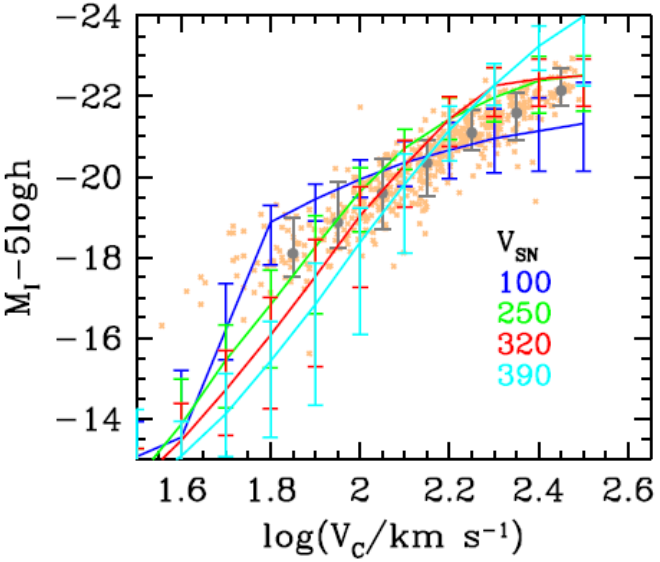
Lacey et al. 2015

Parameter calibration – multi-property space

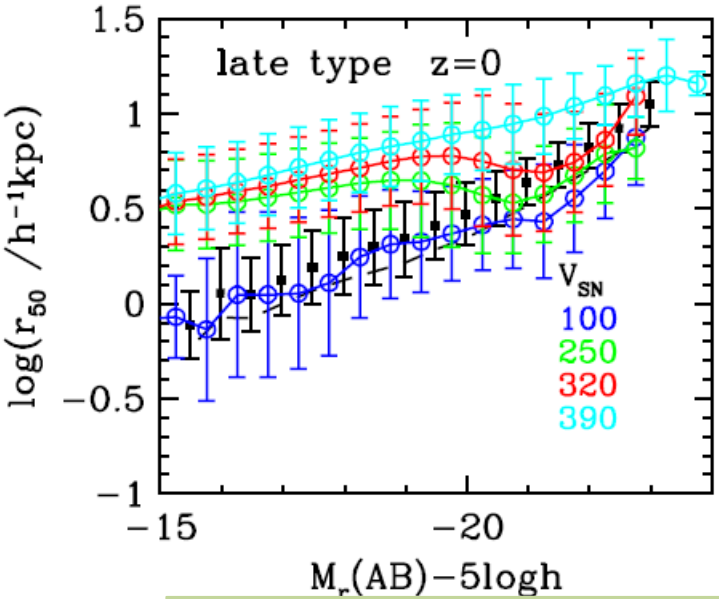
Luminosity function



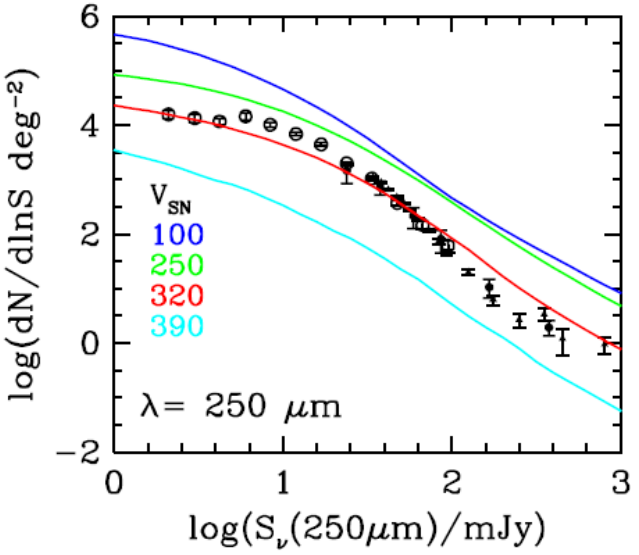
Tully- Fisher



Lacey et al 2015



Size – luminosity for disks



250 micron counts

What is semi-analytical modelling?

- Model parameters
- Parameter calibration
- Modular – upgrade implementation of physics

Lacey et al. 2015

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 $\tau_\star$?

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

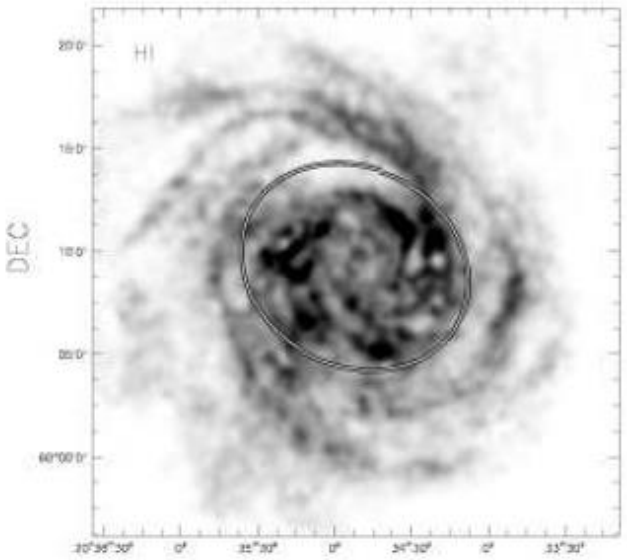
Cole et al. (2000)

Two free-parameters to model the SF activity

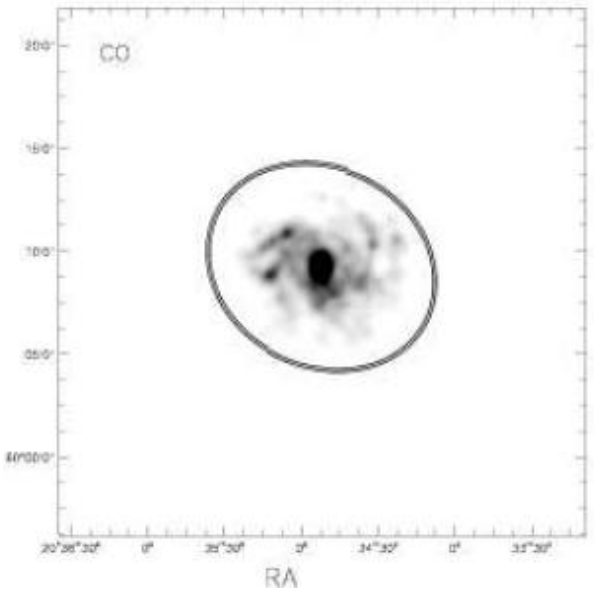
Lagos et al. 2011

What drives star formation?

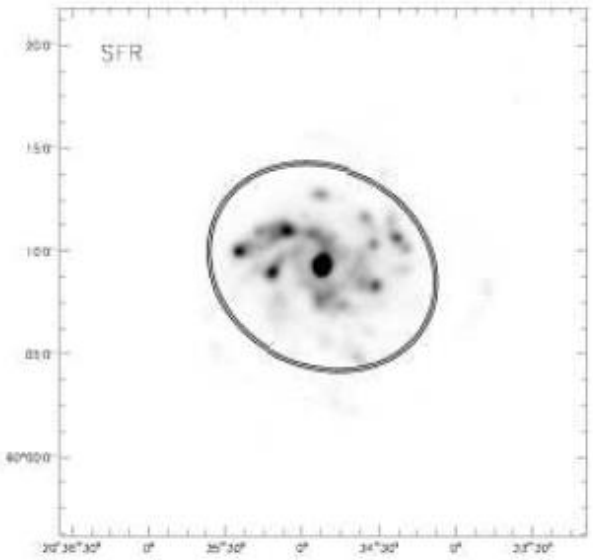
Atomic hydrogen



CO – molecular hydrogen



Star formation activity



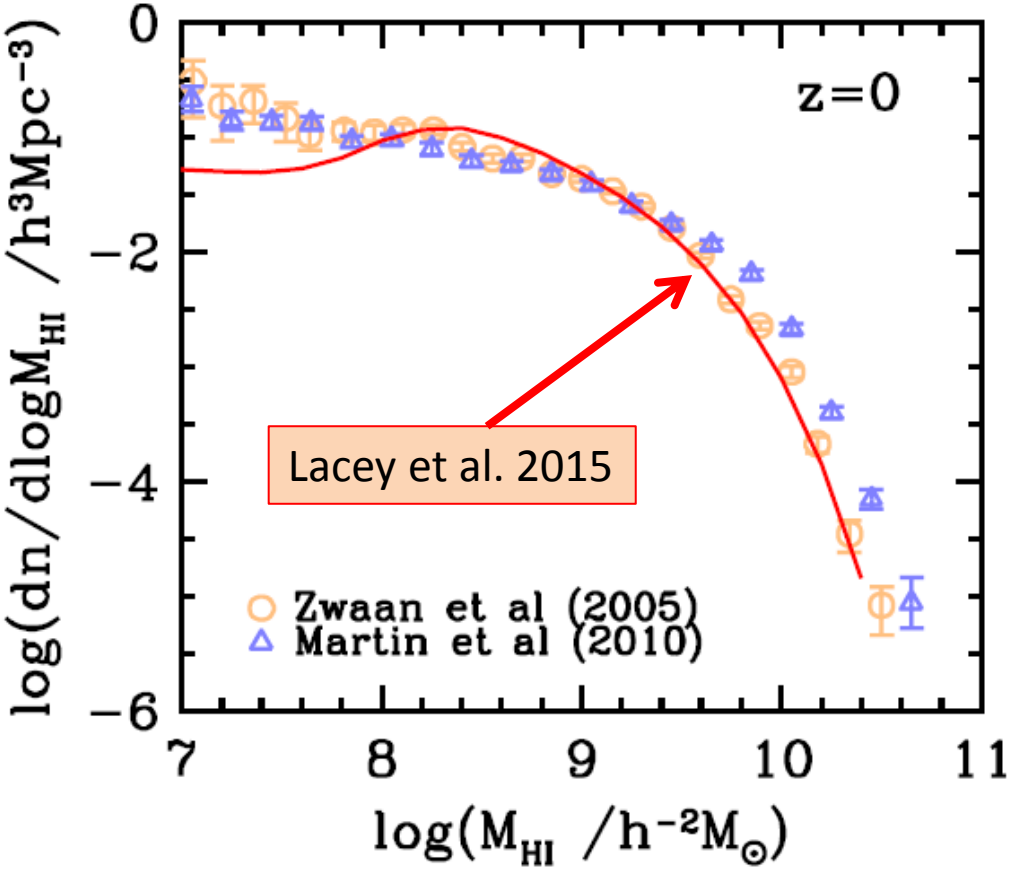
Leroy et al. 2008

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

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

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

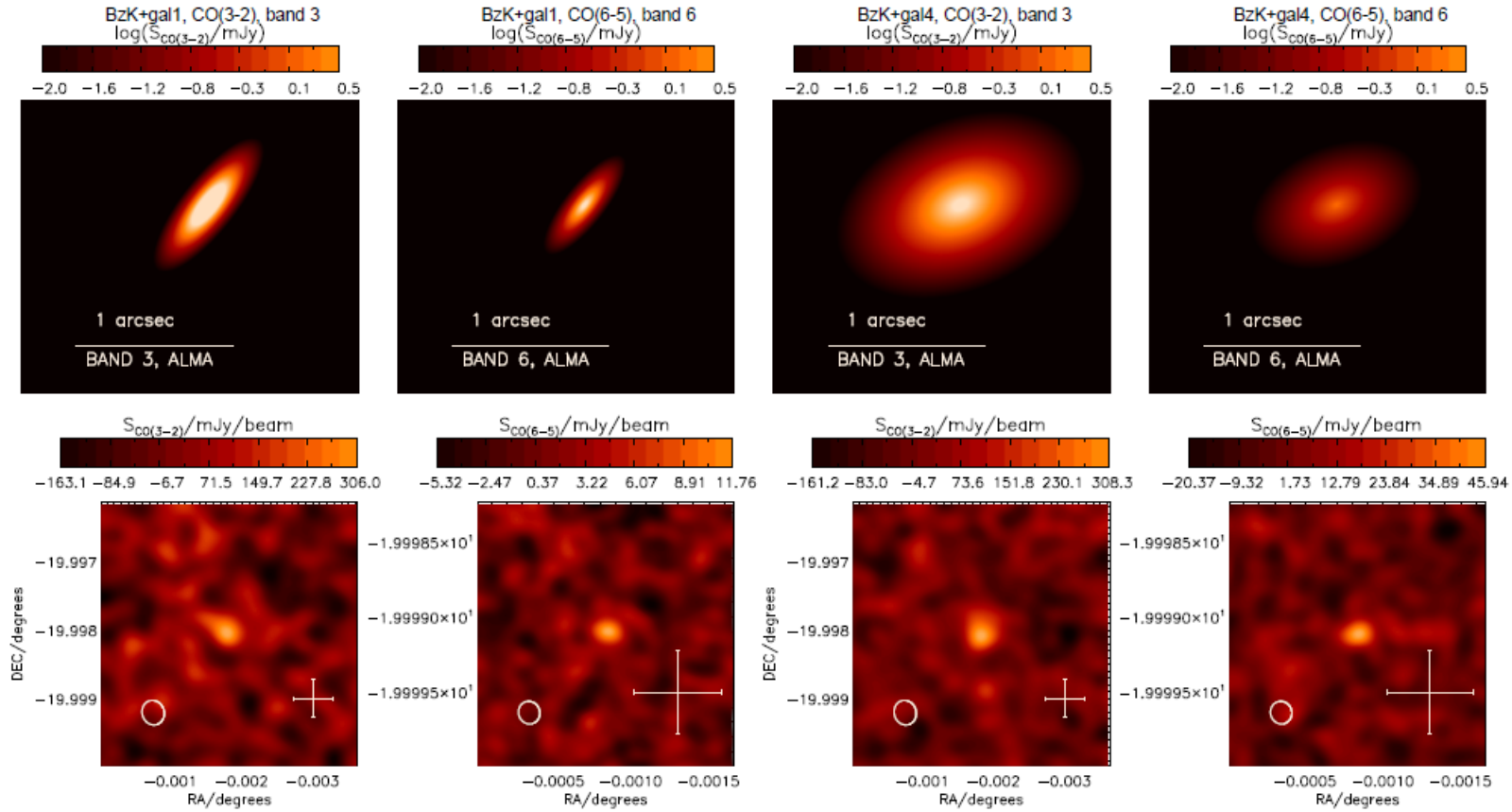
The mass function of atomic hydrogen



- 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



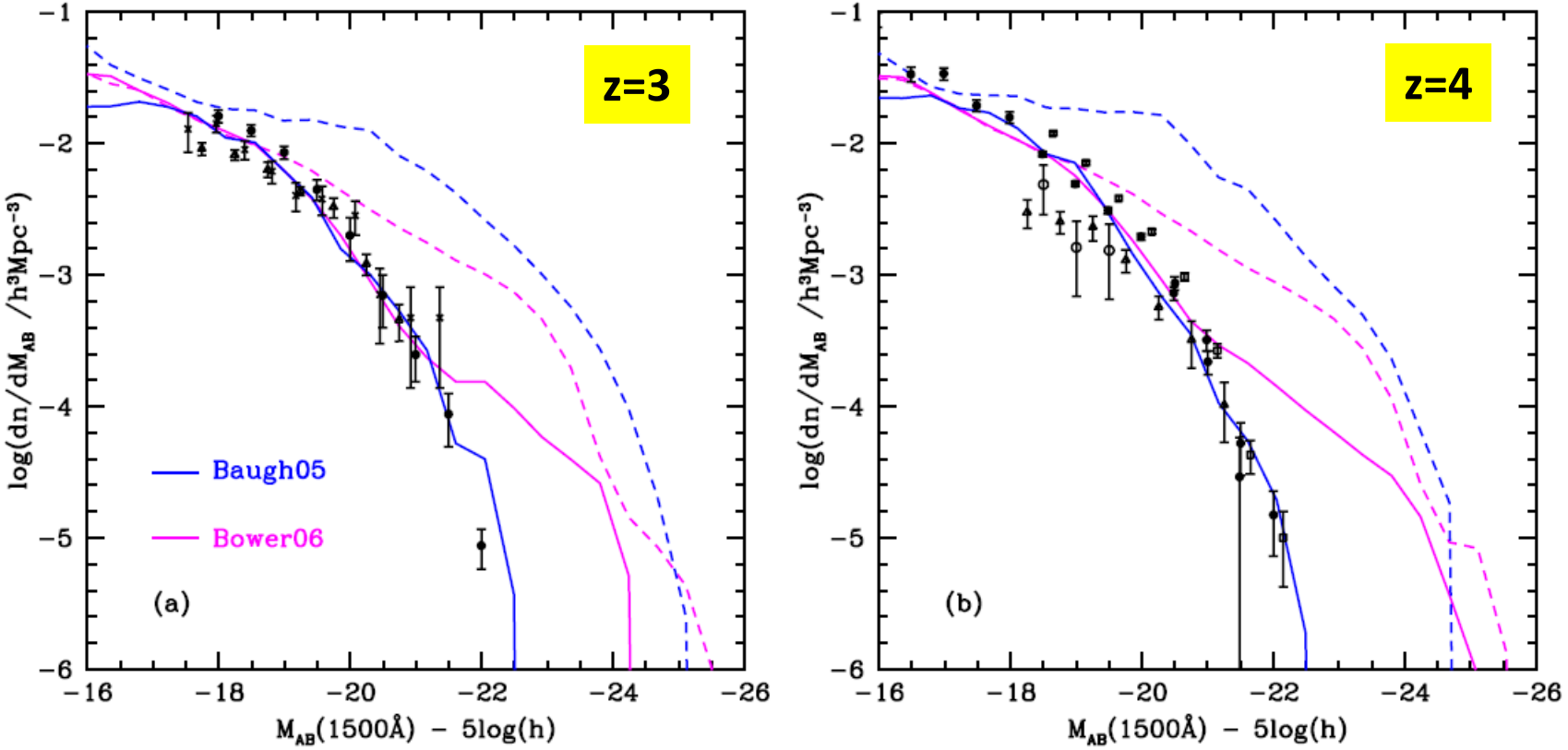
(see Lagos et al. 2012 GALFORM + UCL_PDR model)

What is semi-analytical modelling?

- Model parameters
- Parameter calibration
- Modular – upgrade implementation of physics
- Multi-wavelength/multi-property outputs

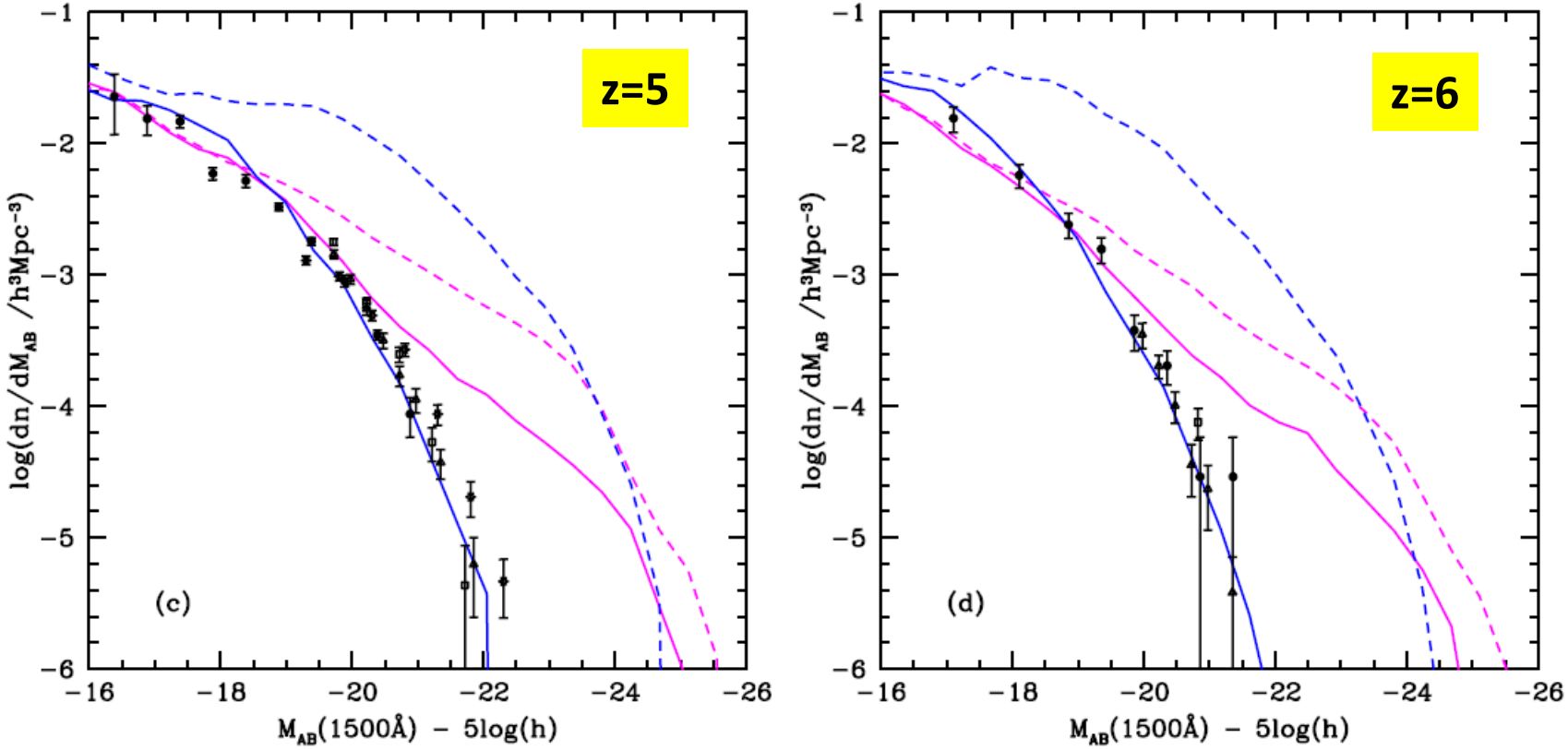
Lacey et al. 2014

UV luminosity function at high-z

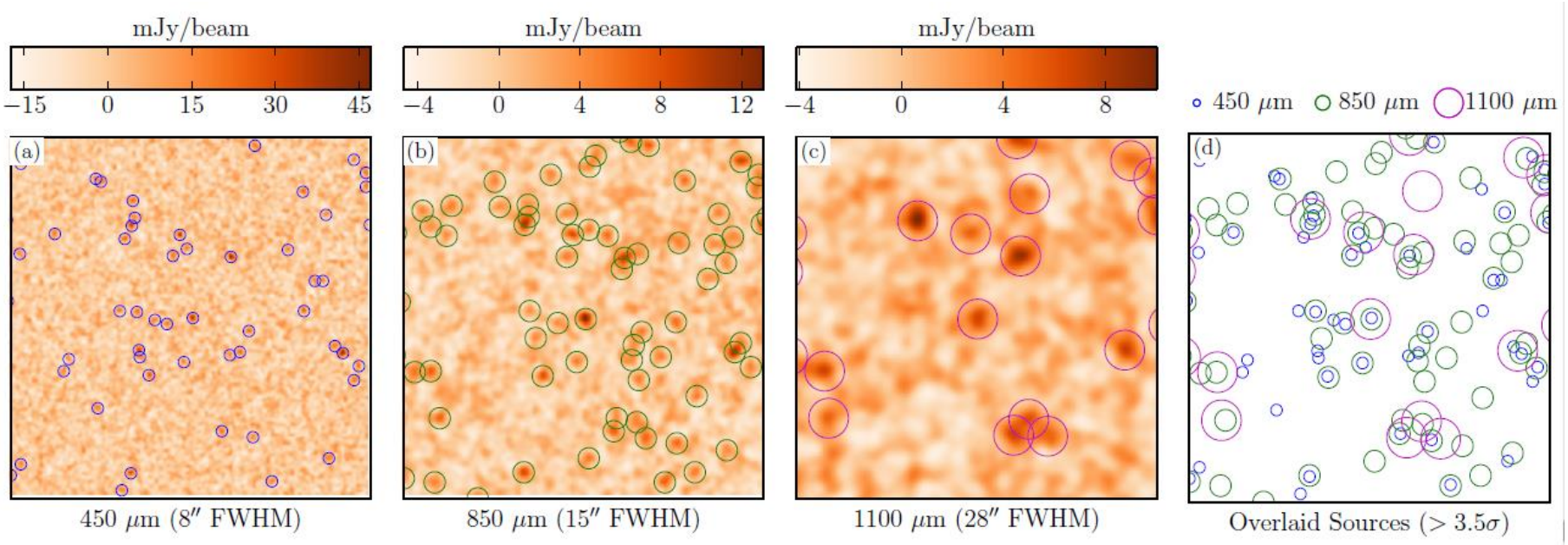


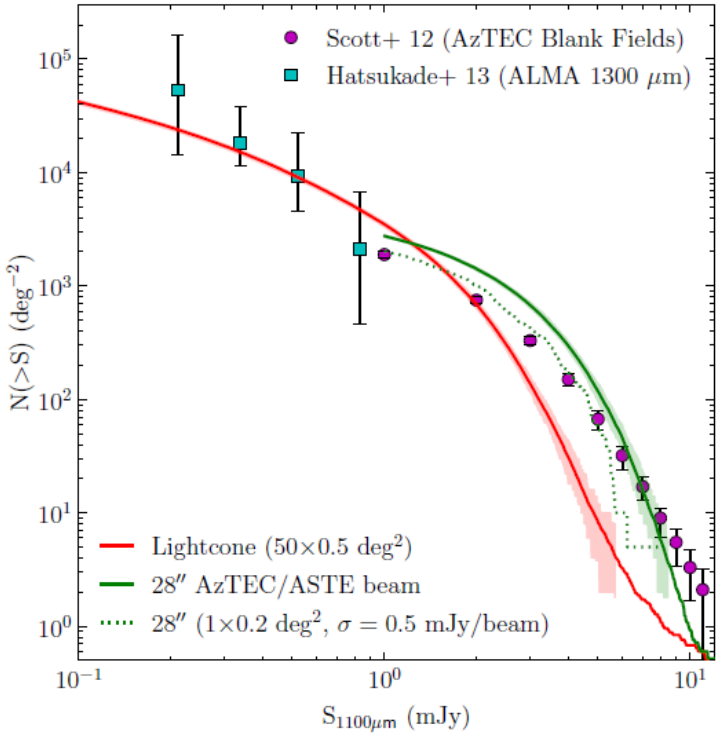
Lacey et al. 2011

UV luminosity function at high-z



Lacey et al. 2011





Multi-wavelength maps of dusty star-forming galaxies

Cowley et al. 2014

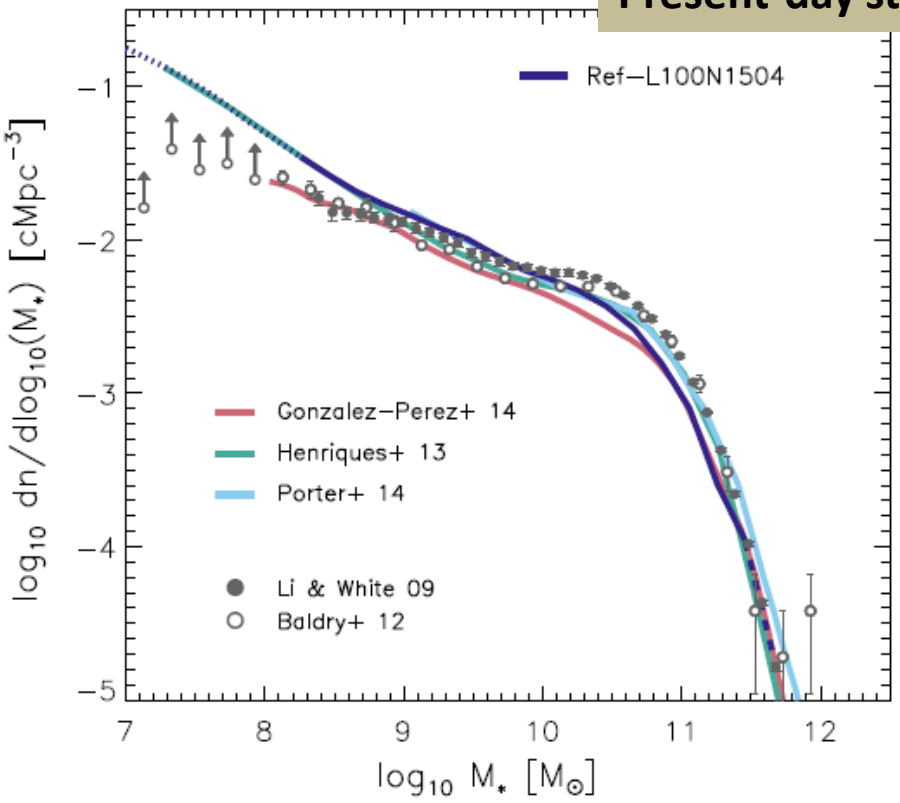
What is semi-analytical modelling?

- Model parameters
- Parameter calibration
- Modular – upgrade implementation of physics
- Multi-wavelength outputs
- Complementary to gas simulations

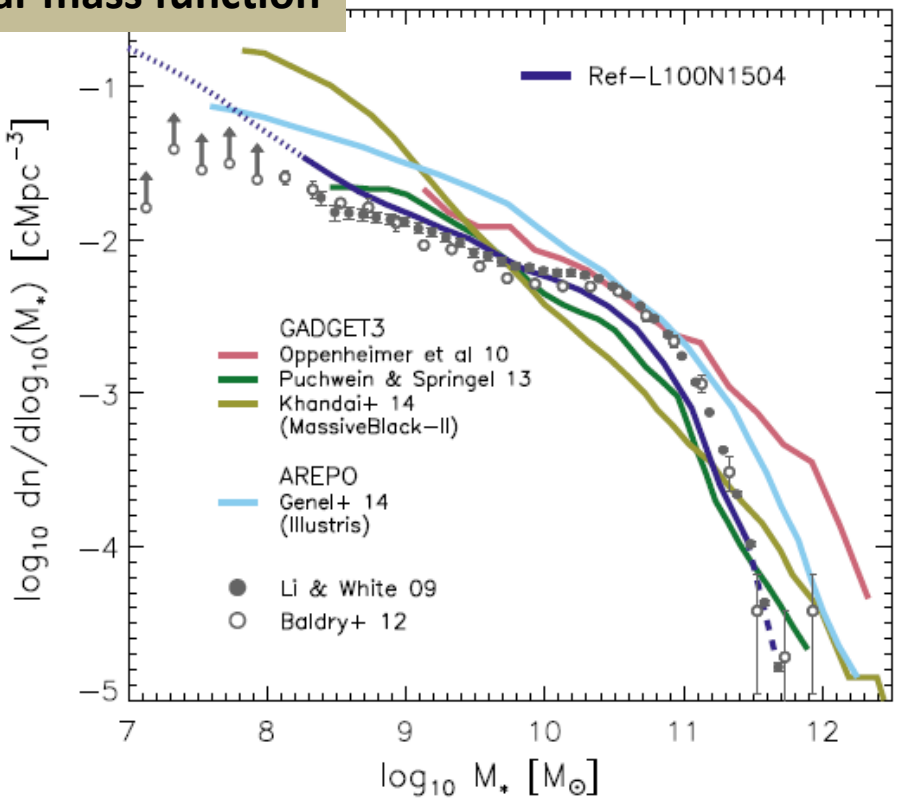
Lacey et al. 2014

SAMs vs gas simulations

Present-day stellar mass function



SAMs vs EAGLE



GAS SIMs vs EAGLE

Schaye et al. 2014

The galaxy – halo connection

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

How well do empirical clustering models (HOD, SHAM) describe SAMS?

Contreras et al. 2013, arXiv:1301.3497
Contreras et al. 2014

Web galaxy-catalogue.dur.ac.uk:8080/Millennium/

Virgo - Millennium Database

Documentation

CREDITS/Acknowledgments

Registration

News

Databases

millimil (context)

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

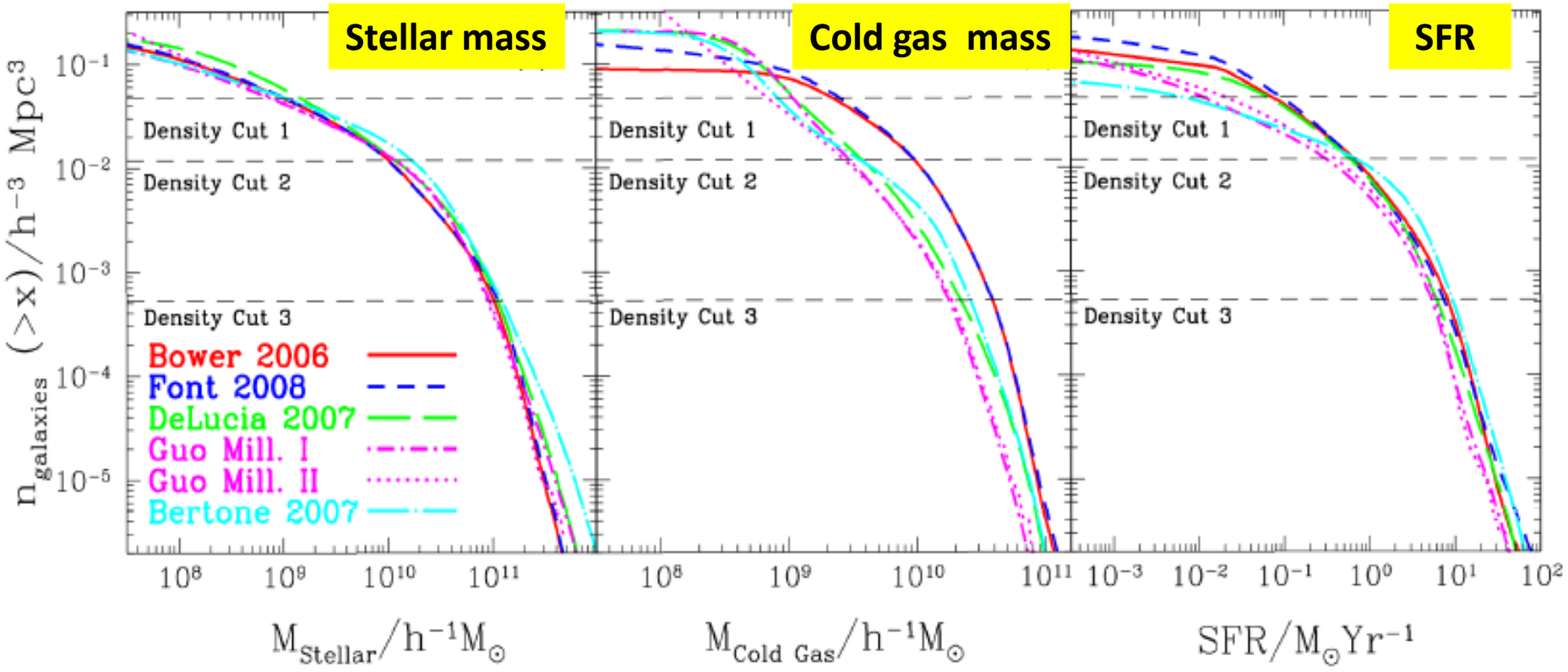
Different physics implementations:
AGN feedback, SNe feedback,
gas cooling in satellites

Different observations used to set
Model parameters

Contreras et al. 2013

How many galaxies?

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

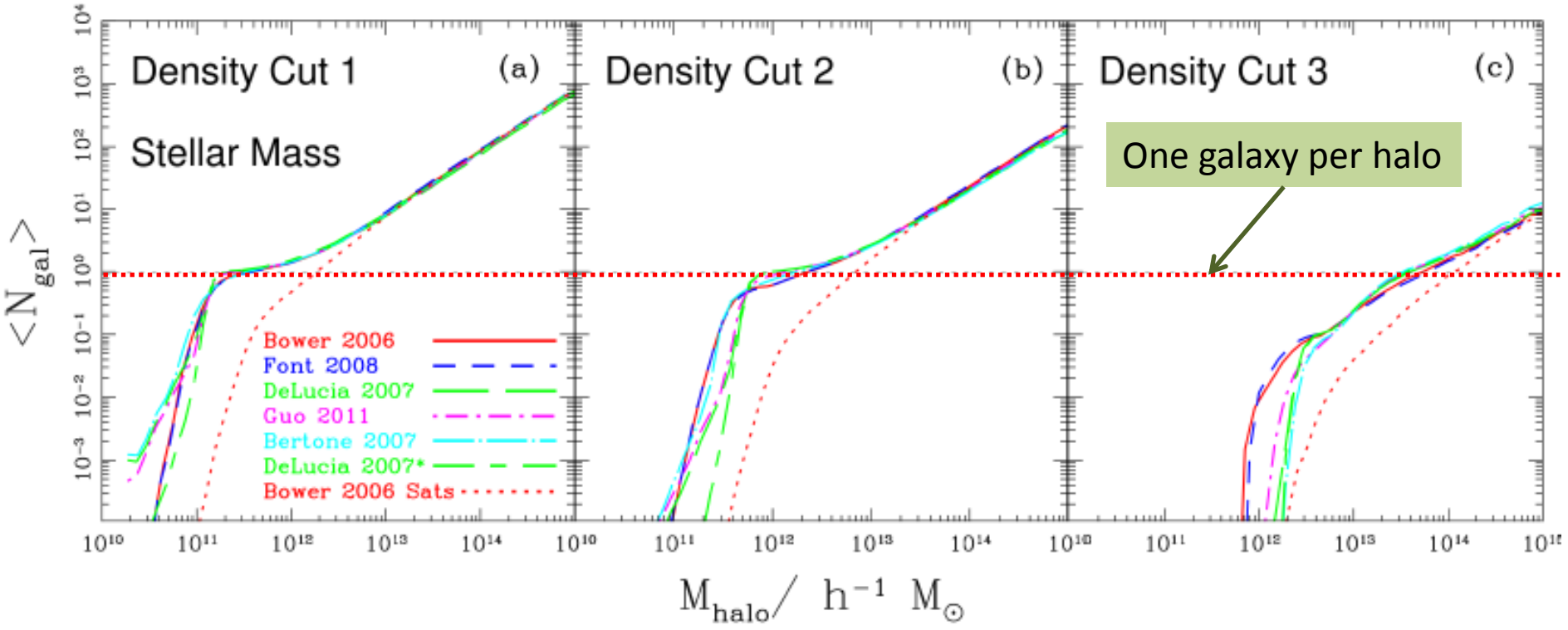


Agreement between models reflects choice of calibration data

Contreras et al. 2013

How many galaxies in each halo?

Galaxies ranked by STELLAR MASS: Decreasing galaxy abundance

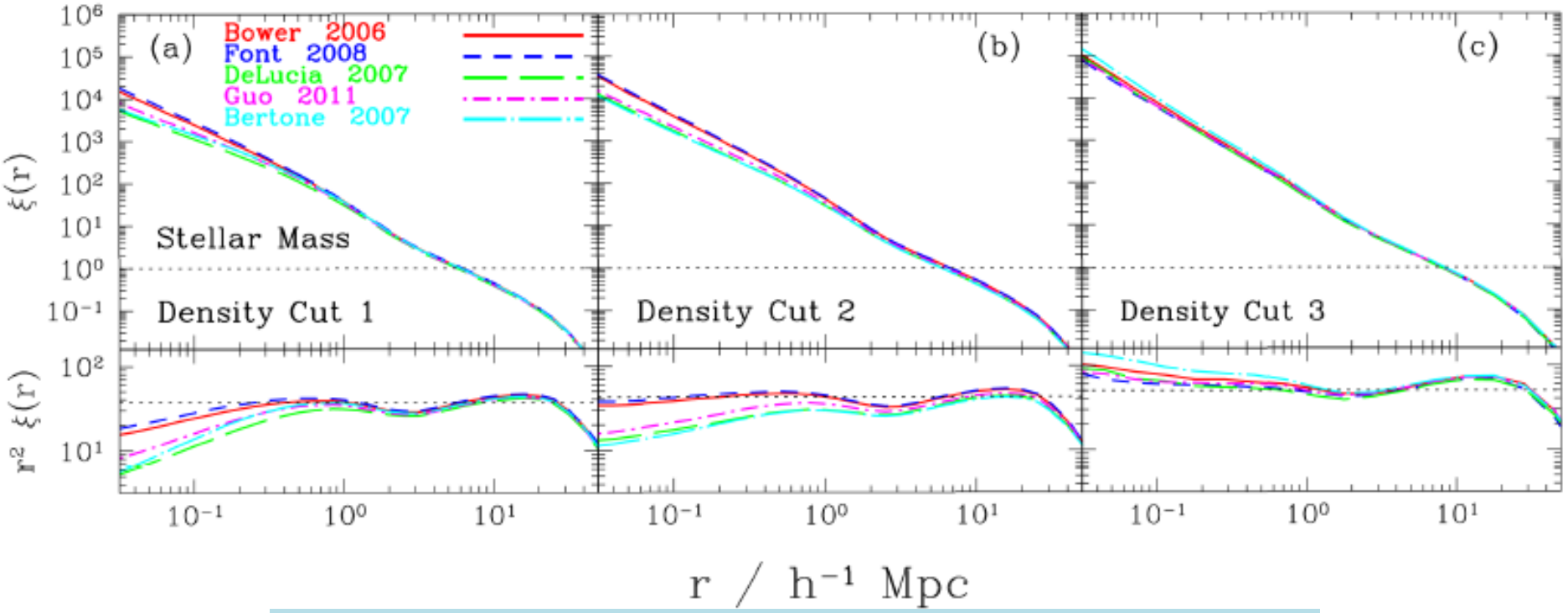


Halo Occupation Distribution: model OUTPUT

Contreras et al. 2013

Clustering: stellar mass samples

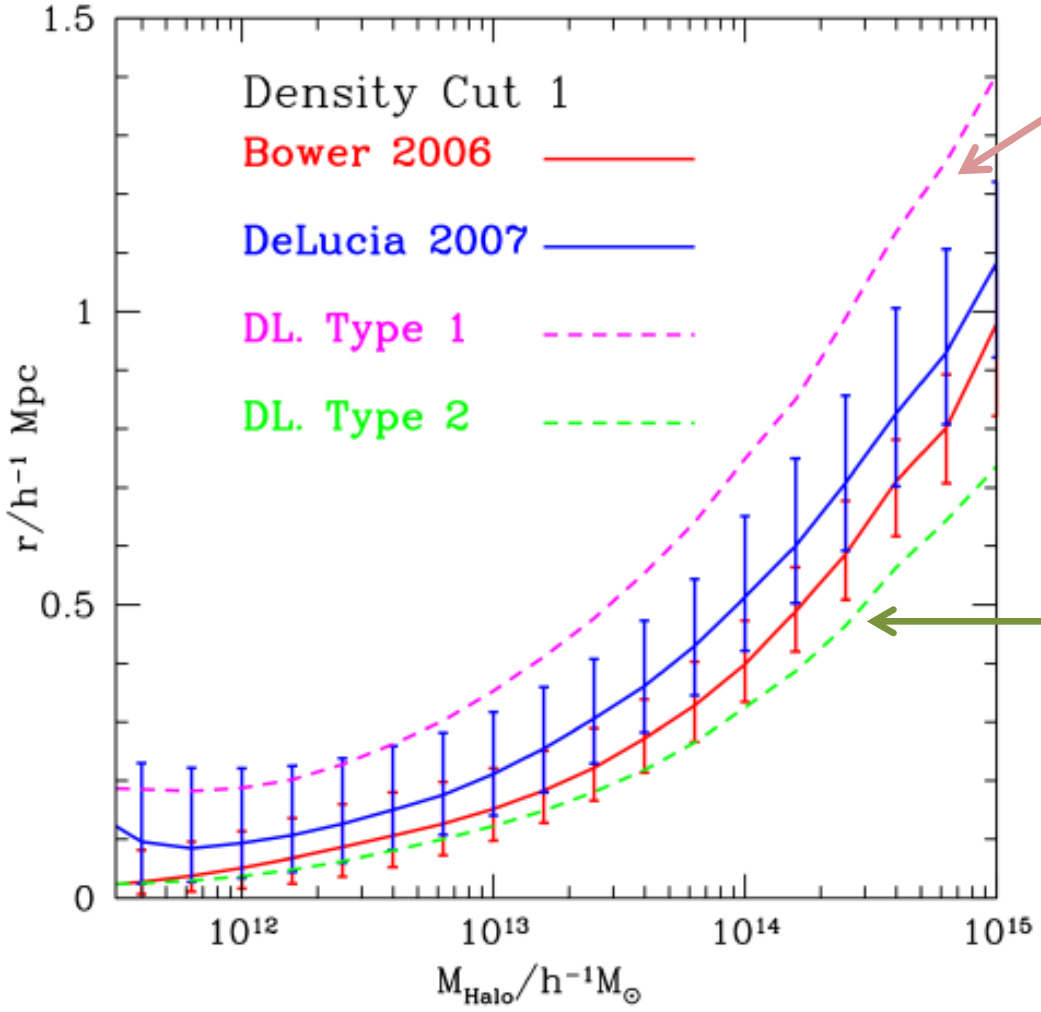
Decreasing galaxy abundance



2-halo terms remarkably similar - robust prediction of bias
1-halo terms different, but same number of satellites: why?

Contreras et al. 2013

Small scale clustering differences: Median radius of galaxy pairs in halo



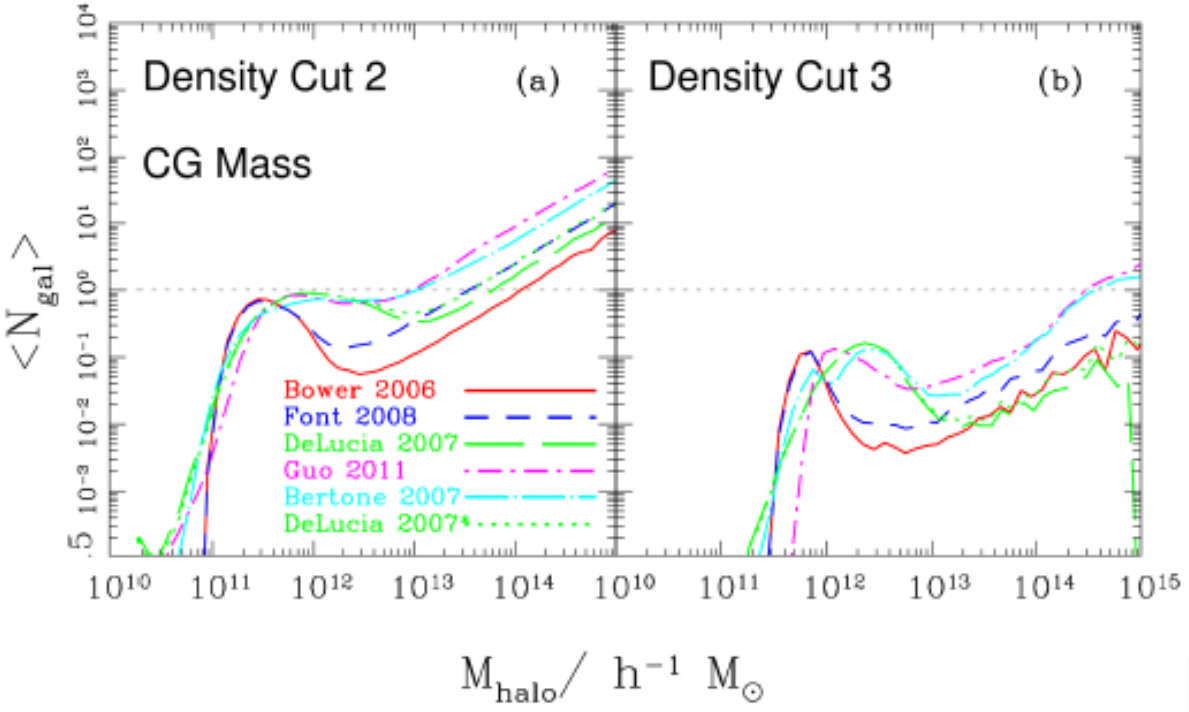
Satellites with sub-halo

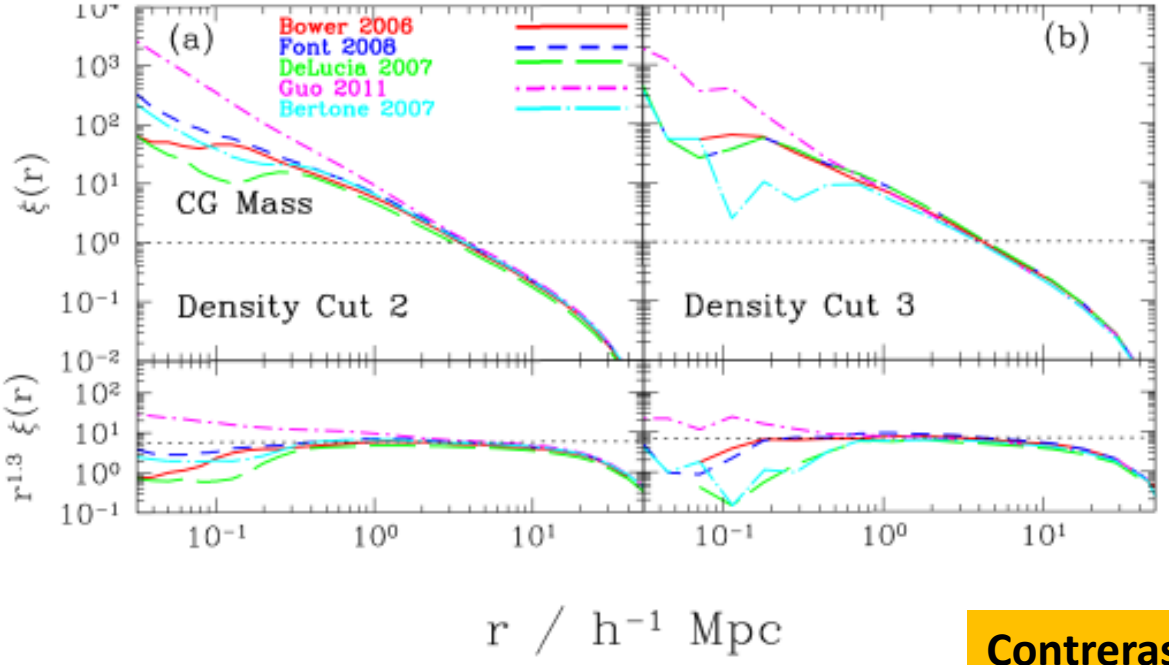
Satellites with no sub-halo

Explained by modelling of galaxy mergers

Contreras et al. 2013

Cold Gas Mass Sample

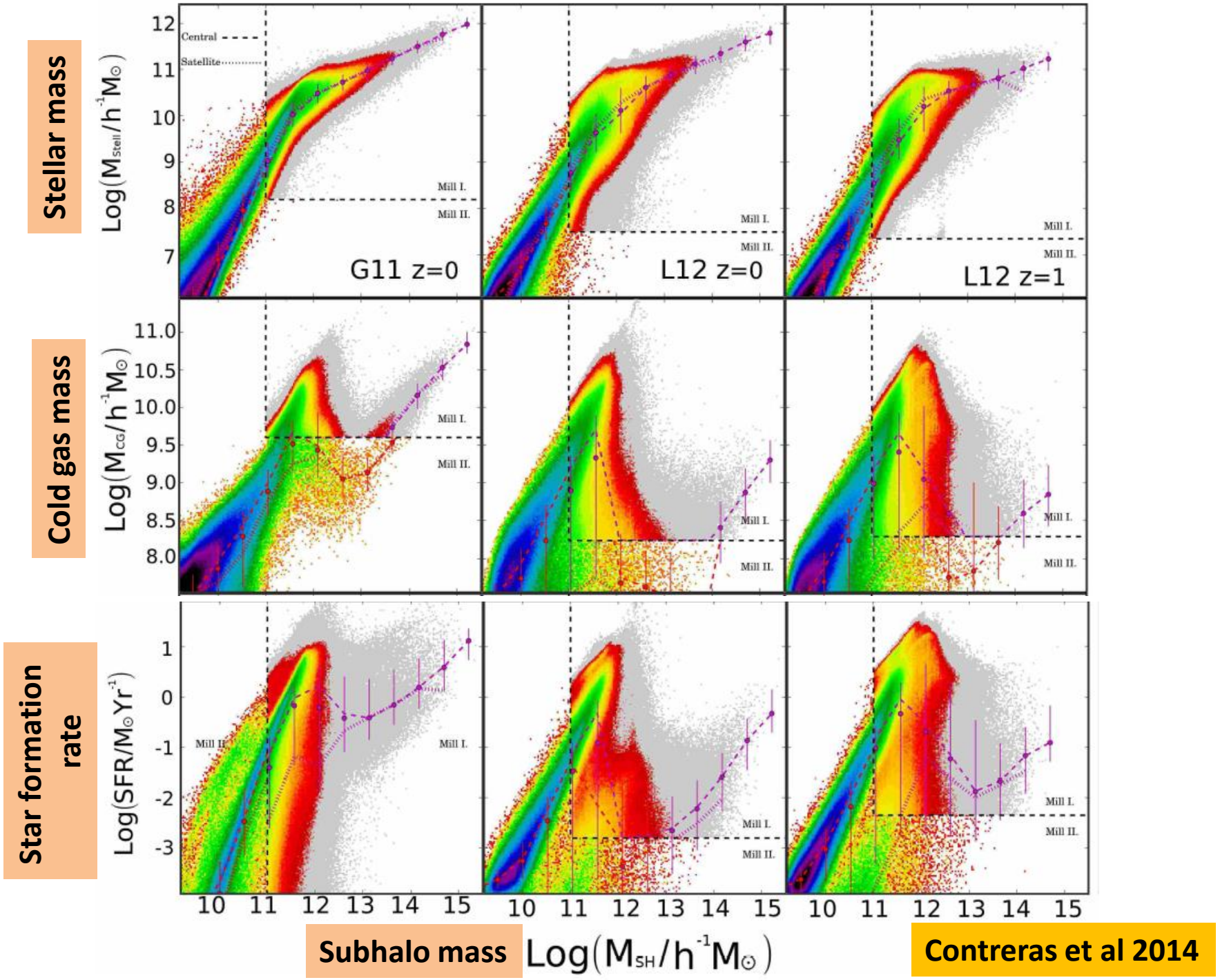




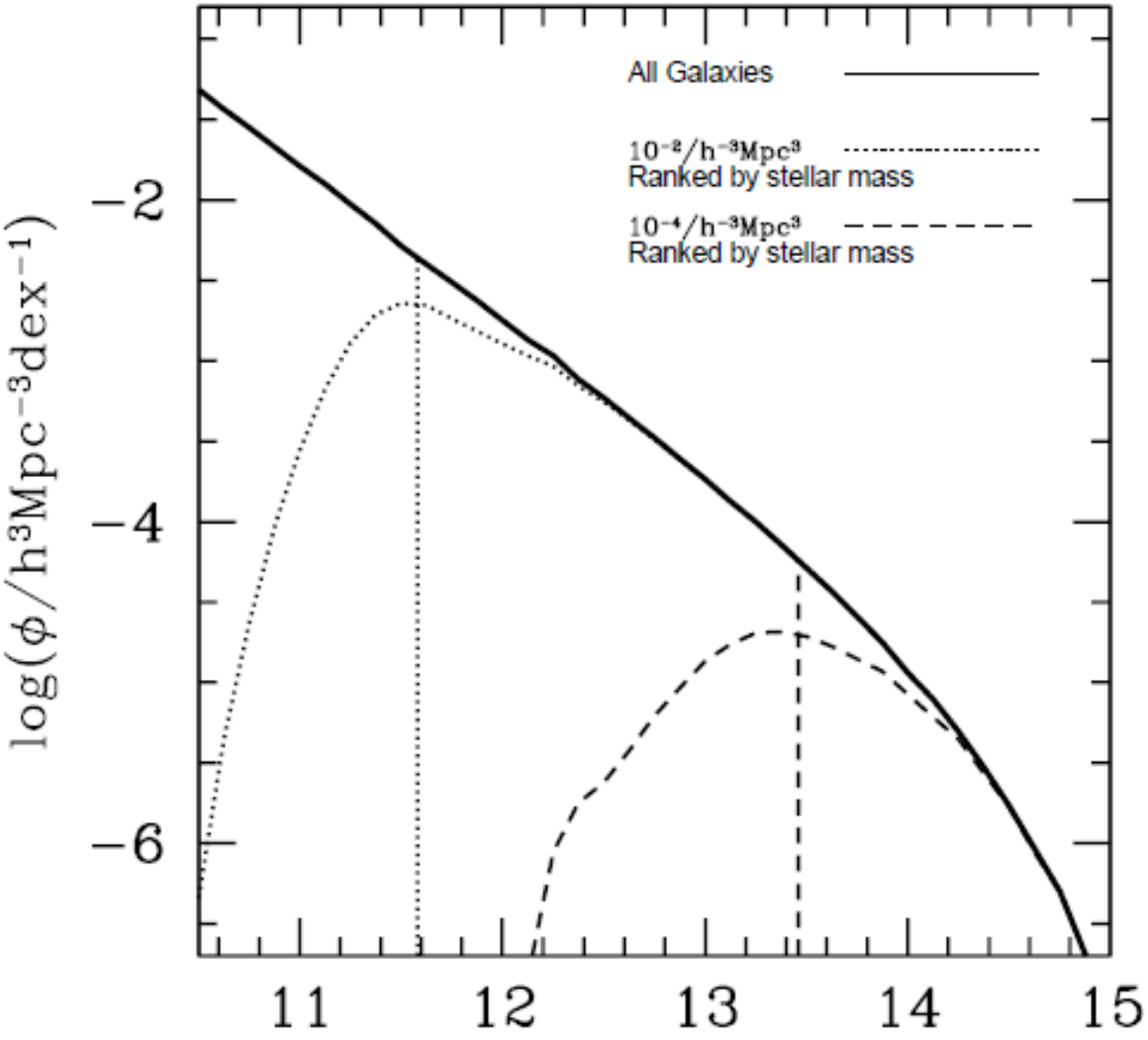
Contreras et al. 2013

How do galaxy properties change with sub-halo mass?

Does the output of SAM look like SHAM?


Stellar mass
Cold gas mass
Star formation rate
Central
Satellite
Mill I.
Mill II.
G11 z=0
L12 z=0
L12 z=1
Log(M_stell/h^-1 M_⊙)
Log(M_CG/h^-1 M_⊙)
Log(SFR/M_⊙ Yr^-1)
Subhalo mass
Log(M_SH/h^-1 M_⊙)
Contreras et al 2014

Which subhalos host galaxies?



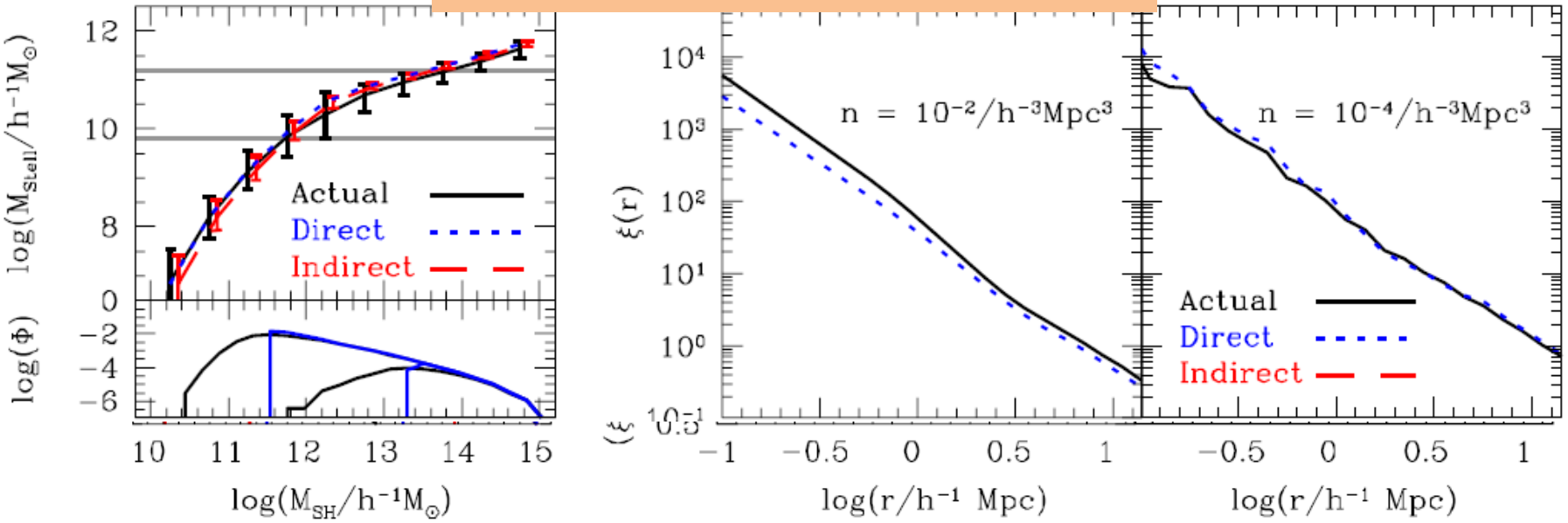
Samples defined by STELLAR MASS

Contrast SAM predictions with simple SHAM

Contreras et al 2014

Does SHAM reproduce SAM? Impact on correlation function

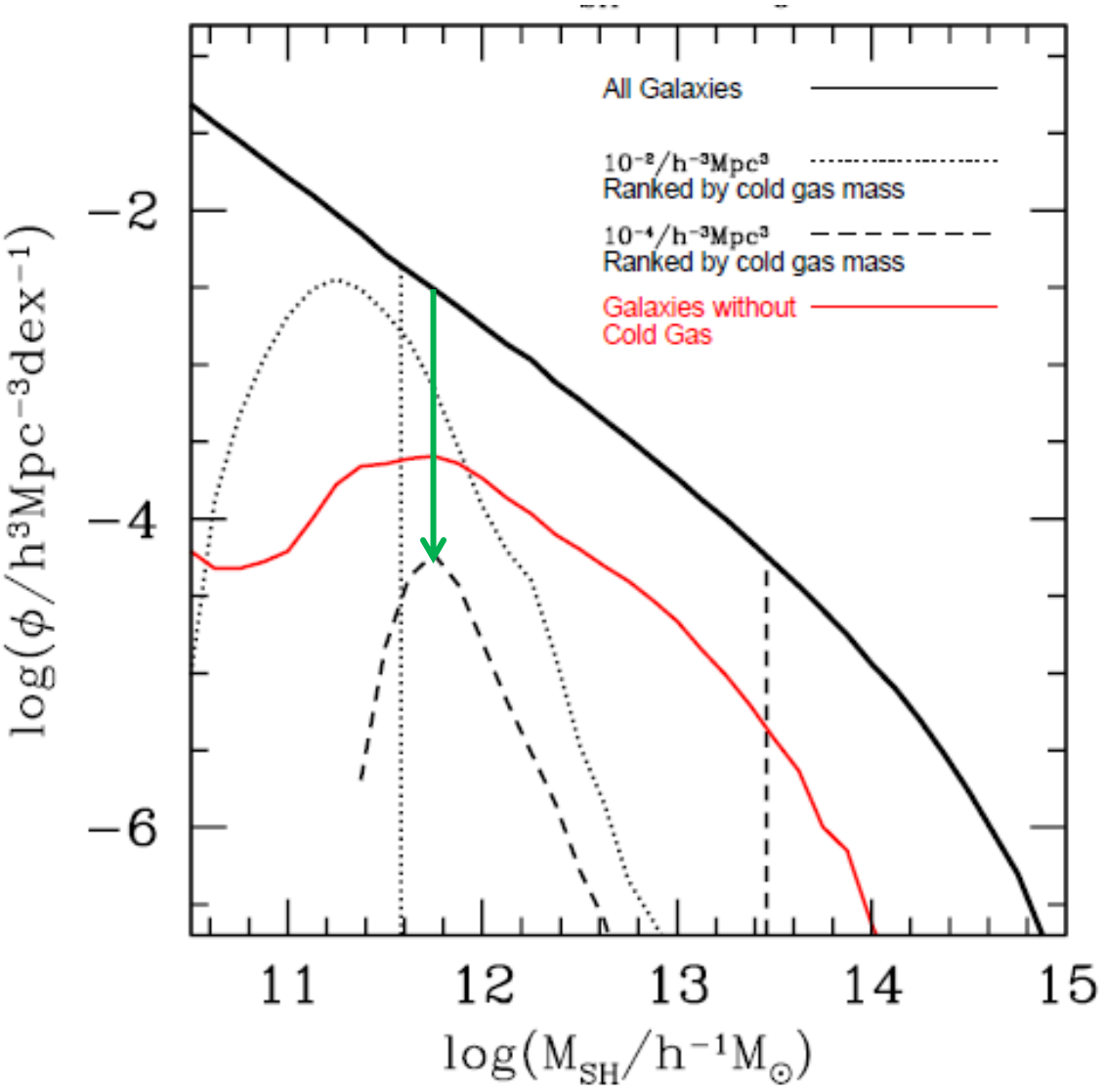
Galaxies ranked by their STELLAR MASS



Compare clustering predicted directly by semi-analytic model with that predicted using a simple SHAM reconstruction

Contreras et al. (2014)

Which subhalos host galaxies?



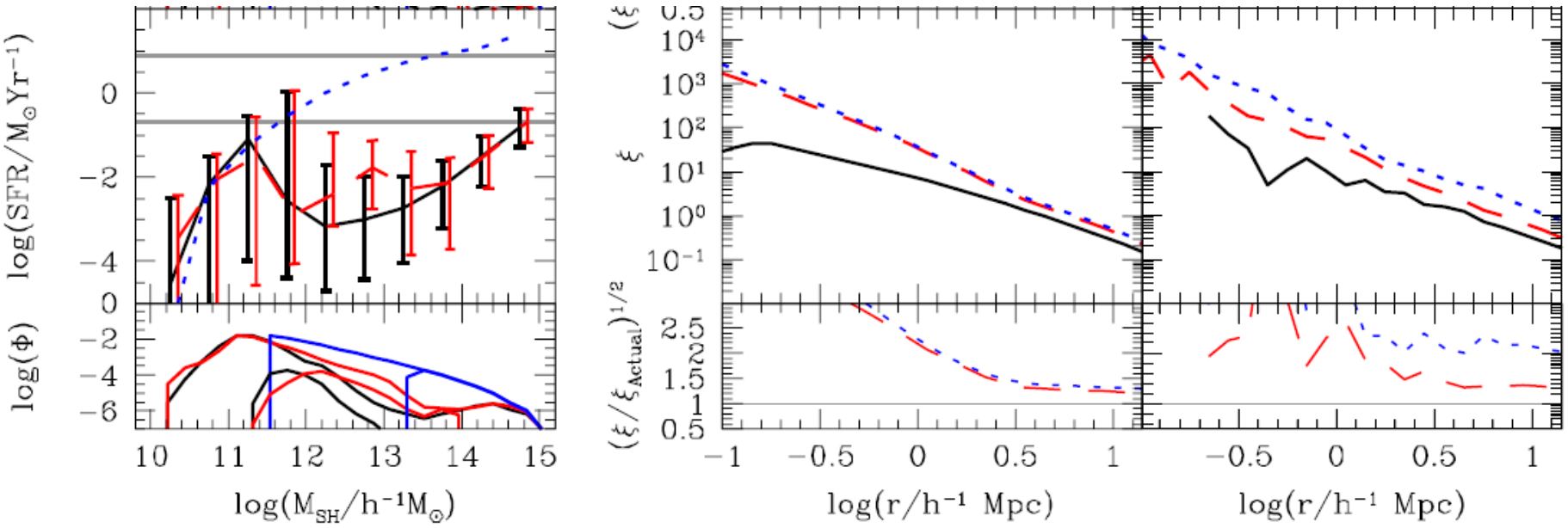
Samples defined by COLD GAS MASS

Contrast SAM predictions with SHAM

Contreras et al 2014

Does SHAM reproduce SAM? Impact on correlation function

Galaxies ranked by their STAR FORMATION RATE



RED: Indirect: SHAM on stellar mass, use model SFR/stellar mass ratio

Empirical reconstructions over predict the semi-analytic clustering

Contreras et al. (2014)

Conclusions

- Semi-analytical models allow us to test our ideas about galaxy formation: complementary to gas sims
- Robust predictions for clustering of galaxies selected by stellar mass
- Less robust predictions for abundance and clustering of SFR & cold gas mass selected samples: variation in one-halo term – different numbers of satellites
- Generic features predicted in HOD
- HOD(M*) looks like standard form
- HOD(SFR or cold gas) peaked – different
- Some properties close to SHAM assumption e.g. M*
- Others very different from SHAM e.g. cold gas mass

GALAXIES

DARK MATTER

GALFORM – The Movie