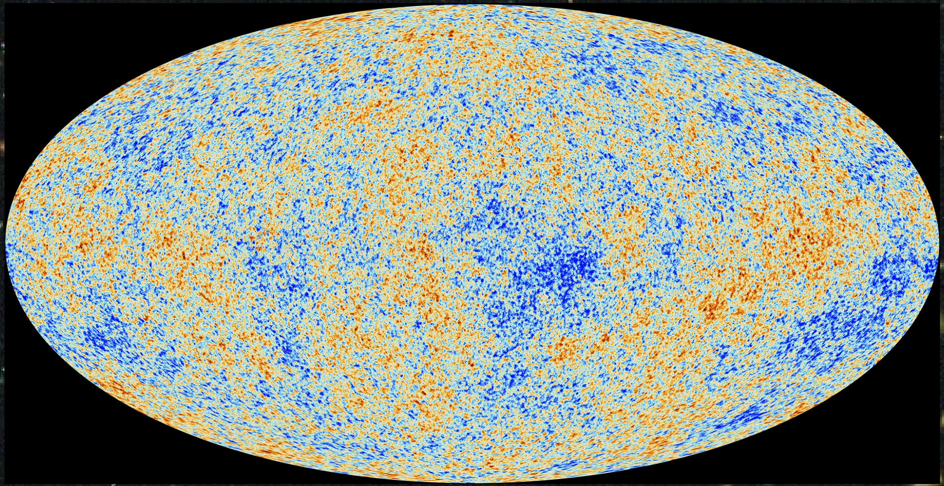
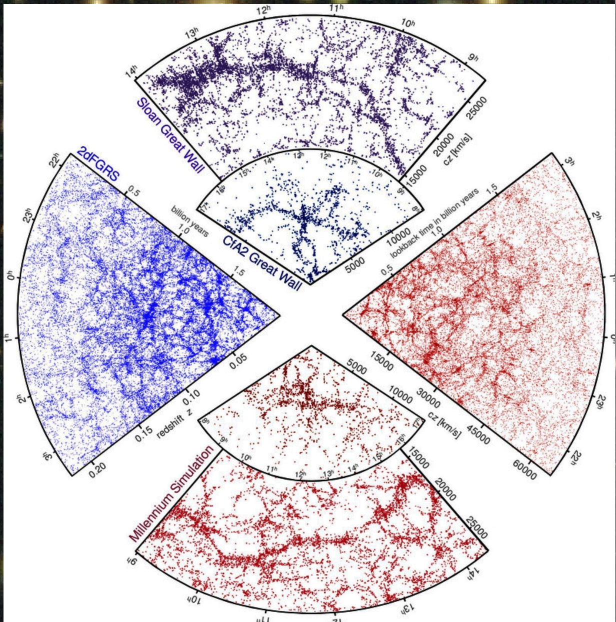


CMB@50, Princeton, June 2015

Non-linear structure formation and ΛCDM

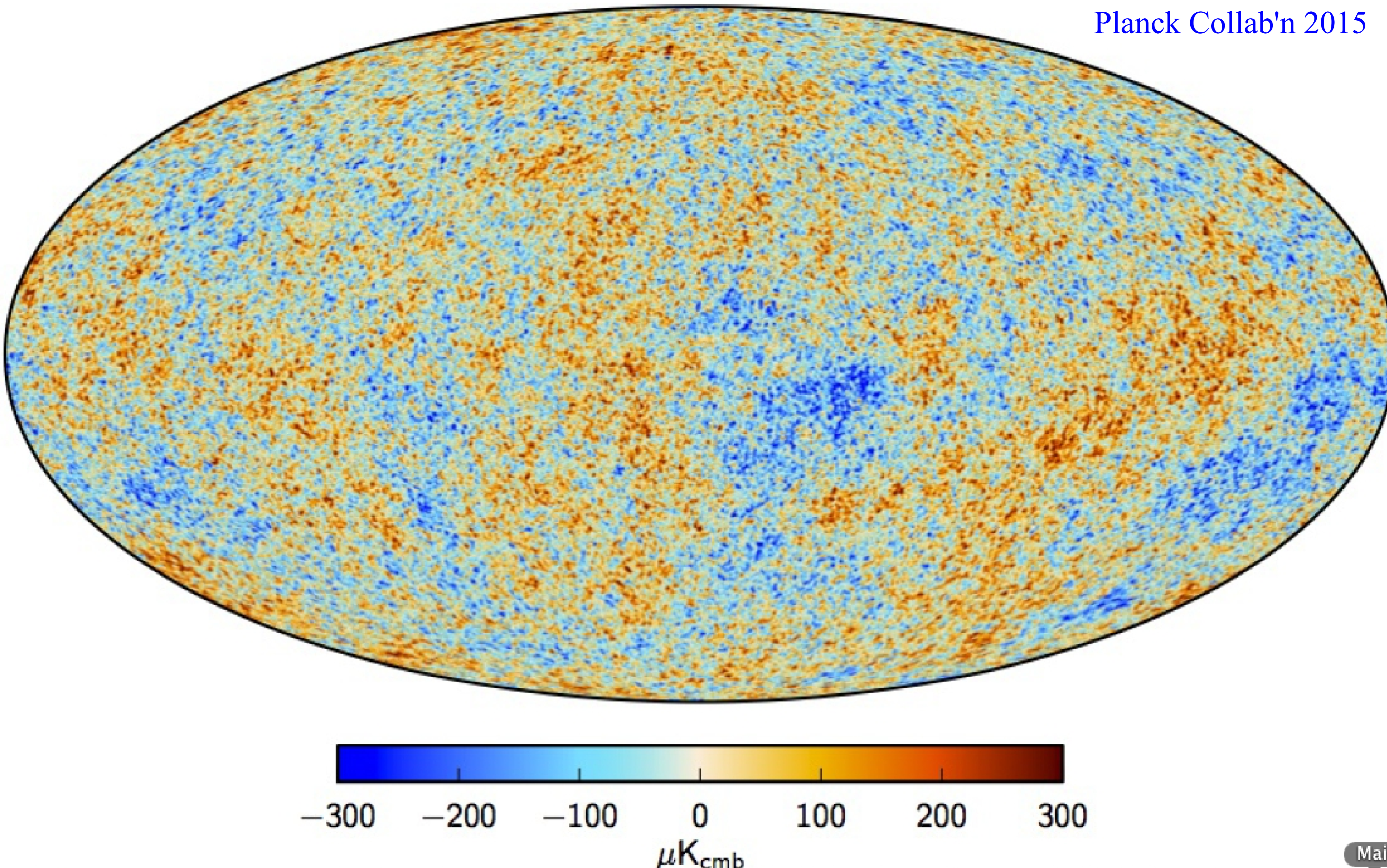


Simon White

Max Planck Institute for Astrophysics

CMB map from the full *Planck* mission

Planck Collab'n 2015



The six parameters of the base ΛCDM model

Planck Collab'n 2015

Parameter	TT+lowP 68 % limits	TT,TE,EE+lowP 68 % limits	TT,TE,EE+lowP+lensing+ext 68 % limits
$\Omega_b h^2$	0.02222 ± 0.00023	0.02225 ± 0.00016	0.02230 ± 0.00014
$\Omega_c h^2$	0.1197 ± 0.0022	0.1198 ± 0.0015	0.1188 ± 0.0010
$100\theta_{MC}$	1.04085 ± 0.00047	1.04077 ± 0.00032	1.04093 ± 0.00030
τ	0.078 ± 0.019	0.079 ± 0.017	0.066 ± 0.012
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.094 ± 0.034	3.064 ± 0.023
n_s	0.9655 ± 0.0062	0.9645 ± 0.0049	0.9667 ± 0.0040

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80σ detection of nonbaryonic DM using *only* z ~1000 data!

The six parameters of the base ΛCDM model

Planck Collab'n 2015

Total baryon density measured to 1%

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Total baryon density measured to 1%

80σ detection of nonbaryonic DM using *only* z ~1000 data!

Compton optical depth less well measured but apparently low

One parameter extensions of the base ΛCDM model

Planck Collab'n 2015

Parameter	TT, TE, EE	TT, TE, EE+lensing+ext
Ω_K	$-0.040^{+0.038}_{-0.041}$	$0.0008^{+0.0040}_{-0.0039}$
Σm_ν [eV]	< 0.492	< 0.194
N_{eff}	$2.99^{+0.41}_{-0.39}$	$3.04^{+0.33}_{-0.33}$
Y_{P}	$0.250^{+0.026}_{-0.027}$	$0.249^{+0.025}_{-0.026}$
$\mathrm{d}n_{\mathrm{s}}/\mathrm{d}\ln k$	$-0.006^{+0.014}_{-0.014}$	$-0.002^{+0.013}_{-0.013}$
$r_{0.002}$	< 0.0987	< 0.113
w	$-1.55^{+0.58}_{-0.48}$	$-1.019^{+0.075}_{-0.080}$

One parameter extensions of the base ΛCDM model

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Ω_K	$-0.040^{+0.038}_{-0.041}$	$0.0008^{+0.0040}_{-0.0039}$
Σm_ν [eV]	< 0.492	$< 0.$[illegible]94
$N_{\rm eff}$	$2.$[illegible]$_{-0.39}$	[illegible]$.04_{-0.33}$
$Y_{\rm P}$	$0.250^{+0.026}_{-0.027}$	$0.249^{+0.025}_{-0.026}$
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Curvature is <0.5% of current energy density

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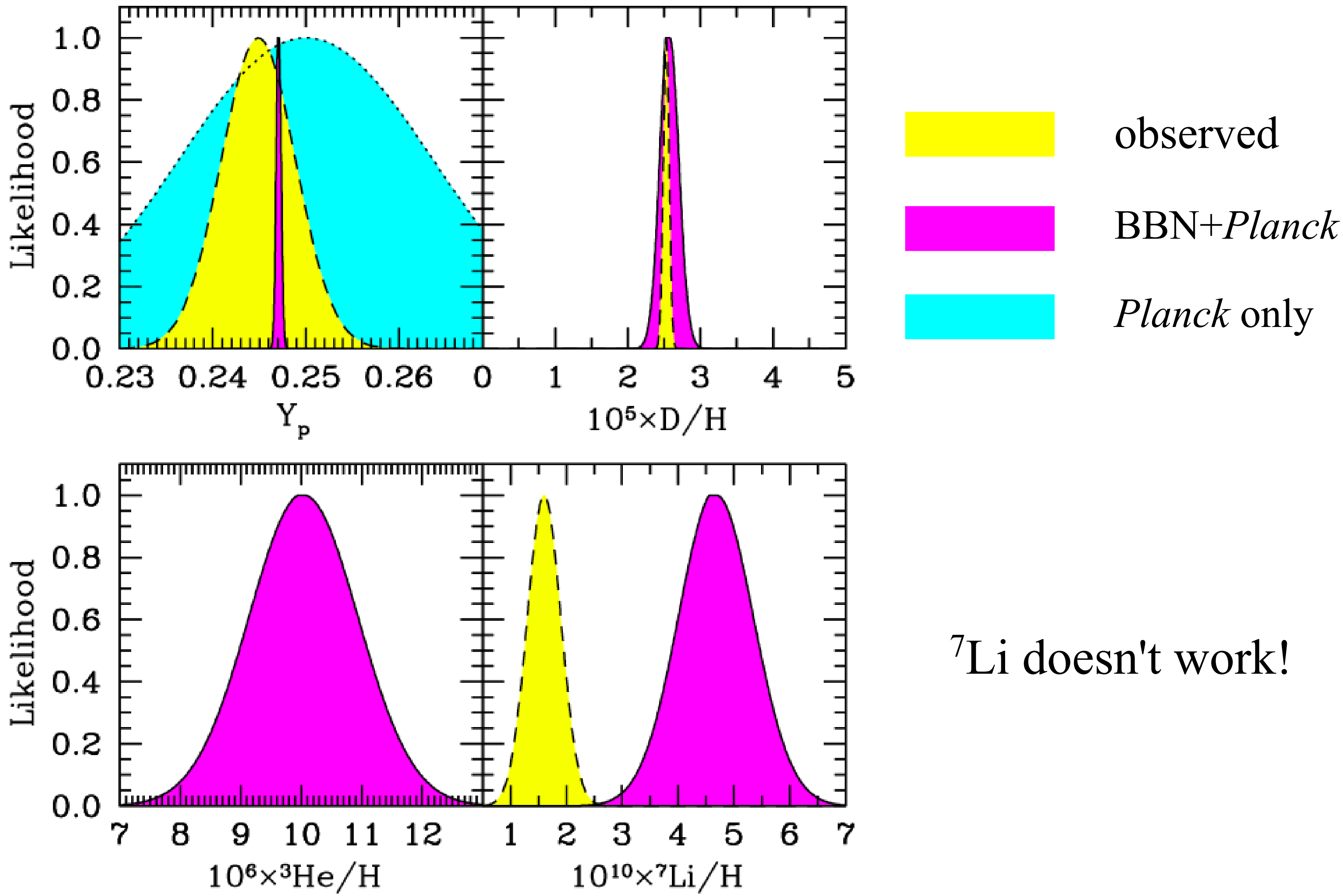
Primordial He fraction measured to 10%

Cosmic nucleosynthesis post-*Planck*



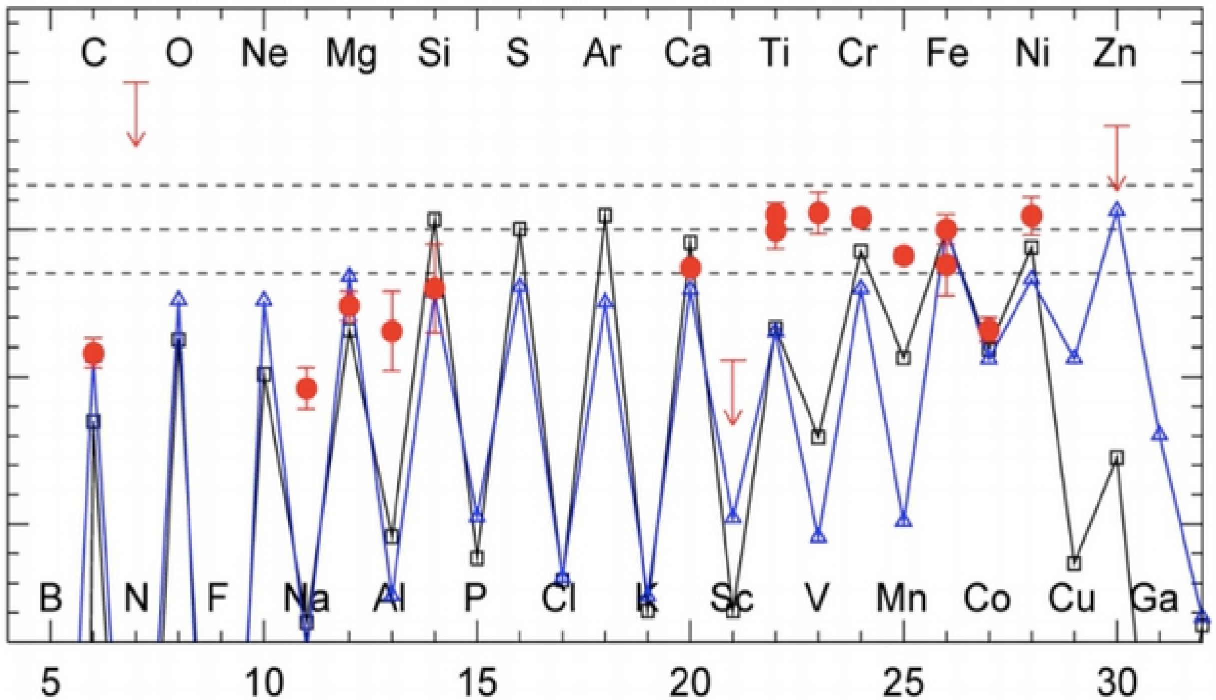
^{7}Li doesn't work!

Cyburt et al 2015

Fossils from the first stars?

SDSS J1820.5-093939.2, $M = 0.47\ M_\odot$

Aoki et al 2014

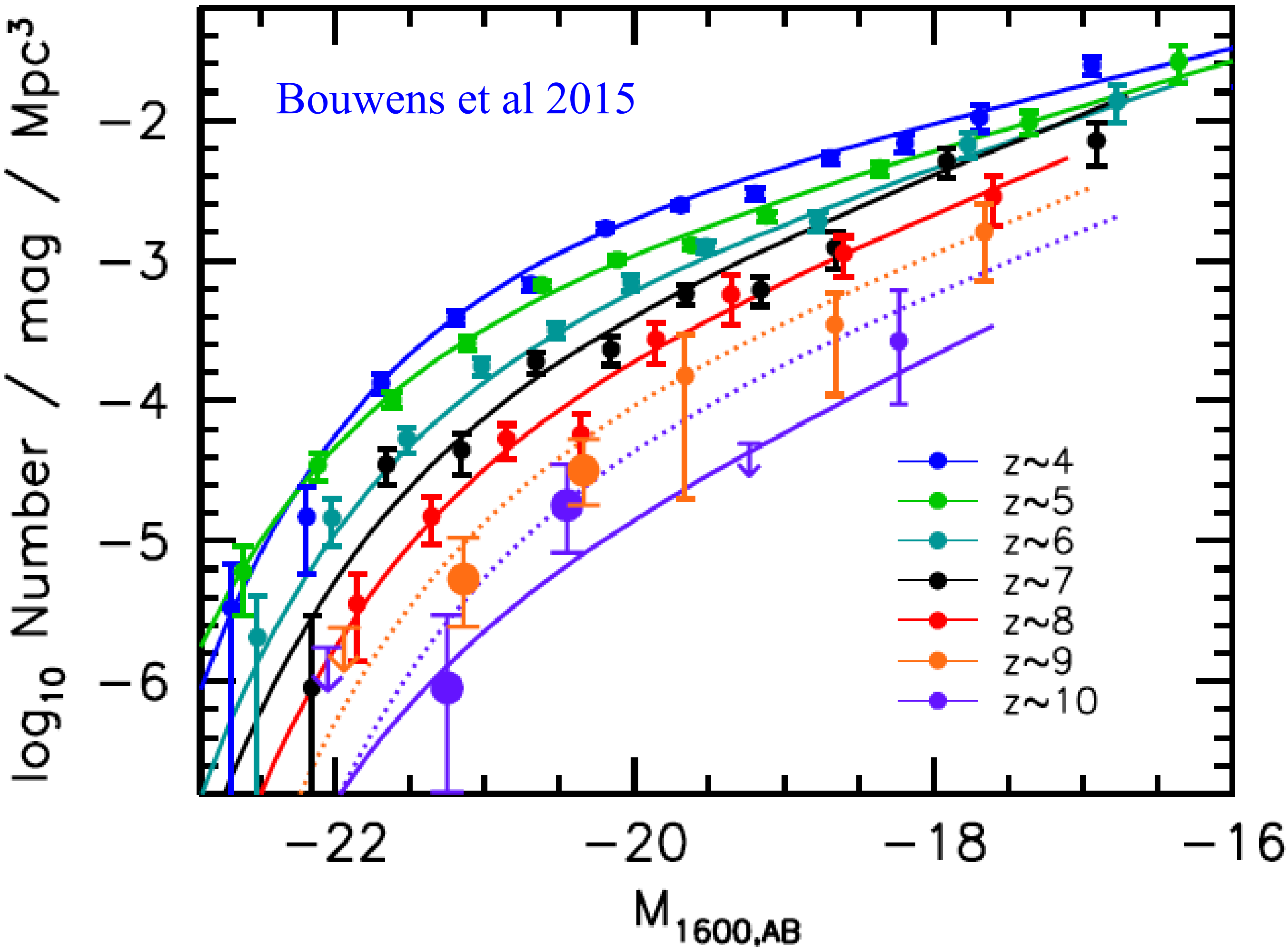


PISN: $M_{He}=130M_\odot$

ccSN: $M_p=1000M_\odot$

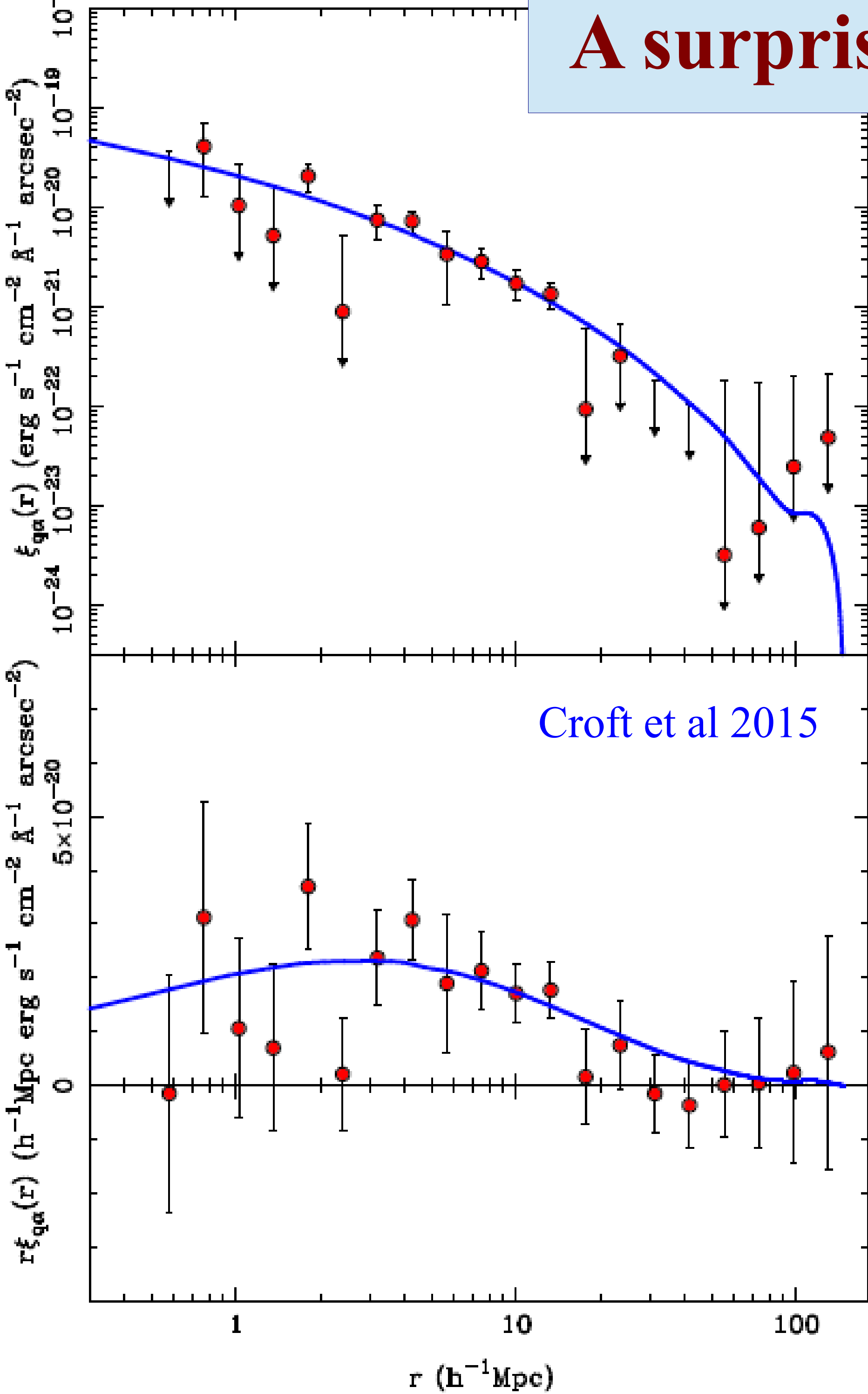
- First stars not seen yet ⟶ we have no real idea what they were like
- Their nucleosynthesis products could be seen in 2nd generation stars
- [Fe/H] = –2.5, low [α/Fe], low [Co/Ni], [Sc/Ti] ⟶ very massive SN?

UV luminosity functions of high z galaxies



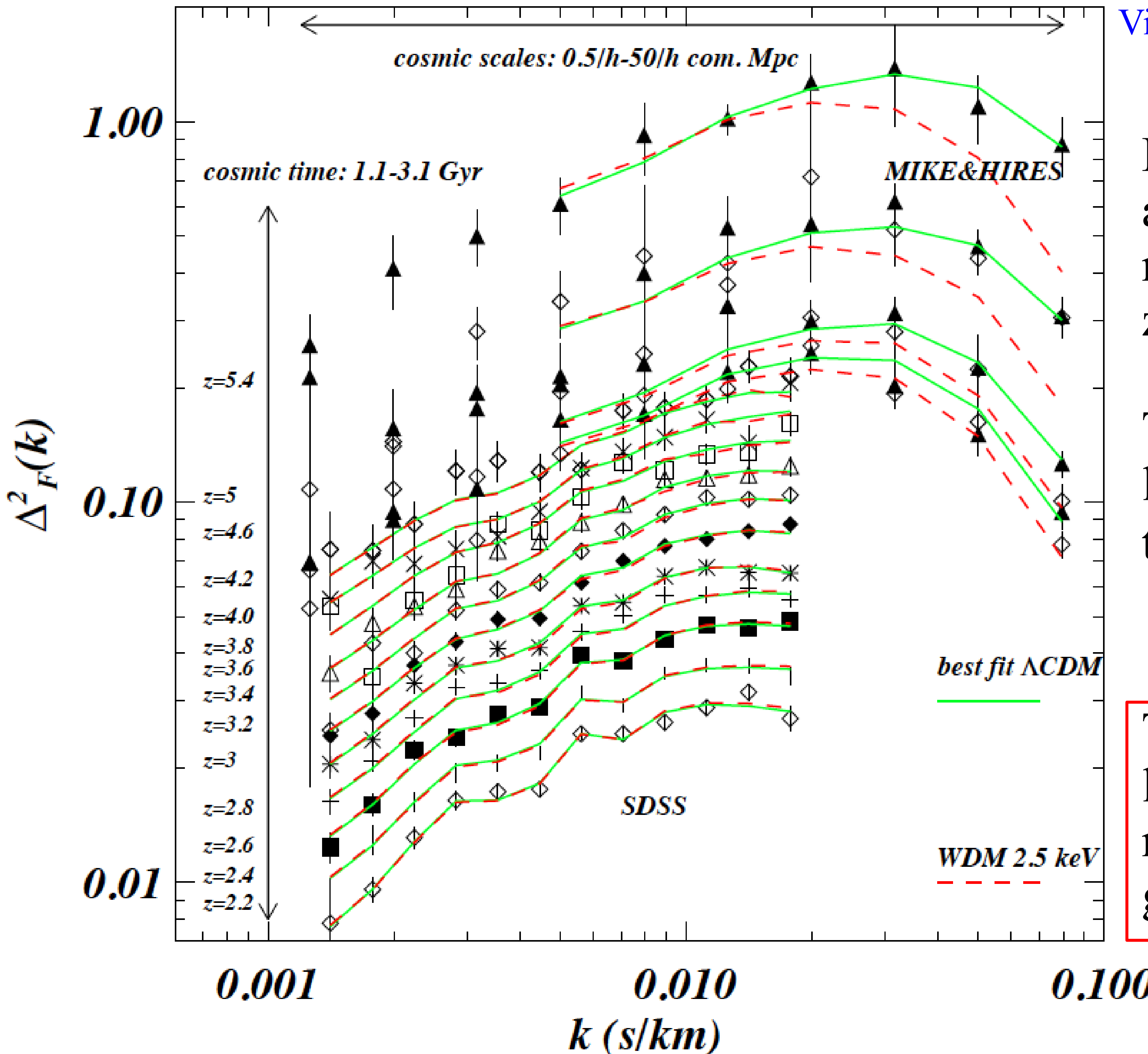
- Reasonably good LF's with photo-z's now available out to z ~ 8
- Reionisation requires extrapolation to much fainter magnitudes
  a large escape fraction for Ly continuum photons
  relatively few losses through recombinations
- This all is made easier by *Planck*'s low measured value for τ

A surprising luminosity density in Ly α



- Cross-correlating spectra towards 10^6 galaxies with 130,000 quasars at $2<z<3.5$ in the BOSS databases detects correlated Ly α emission at 8σ
- The implied Ly α emission at $z\sim2.5$ is 20 to 35 times that expected from extrapolating Ly α emitter surveys
- It is much larger than flourescent emission from the IGM
- It is consistent with **all** Ly α emission associated with SFR being seen as extended halos around galaxies

Lyman α forest spectra for WDM relative to CDM



Viel, Becker, Bolton & Haehnelt 2013

High-resolution Keck and Magellan spectra match ΛCDM up to z = 5.4

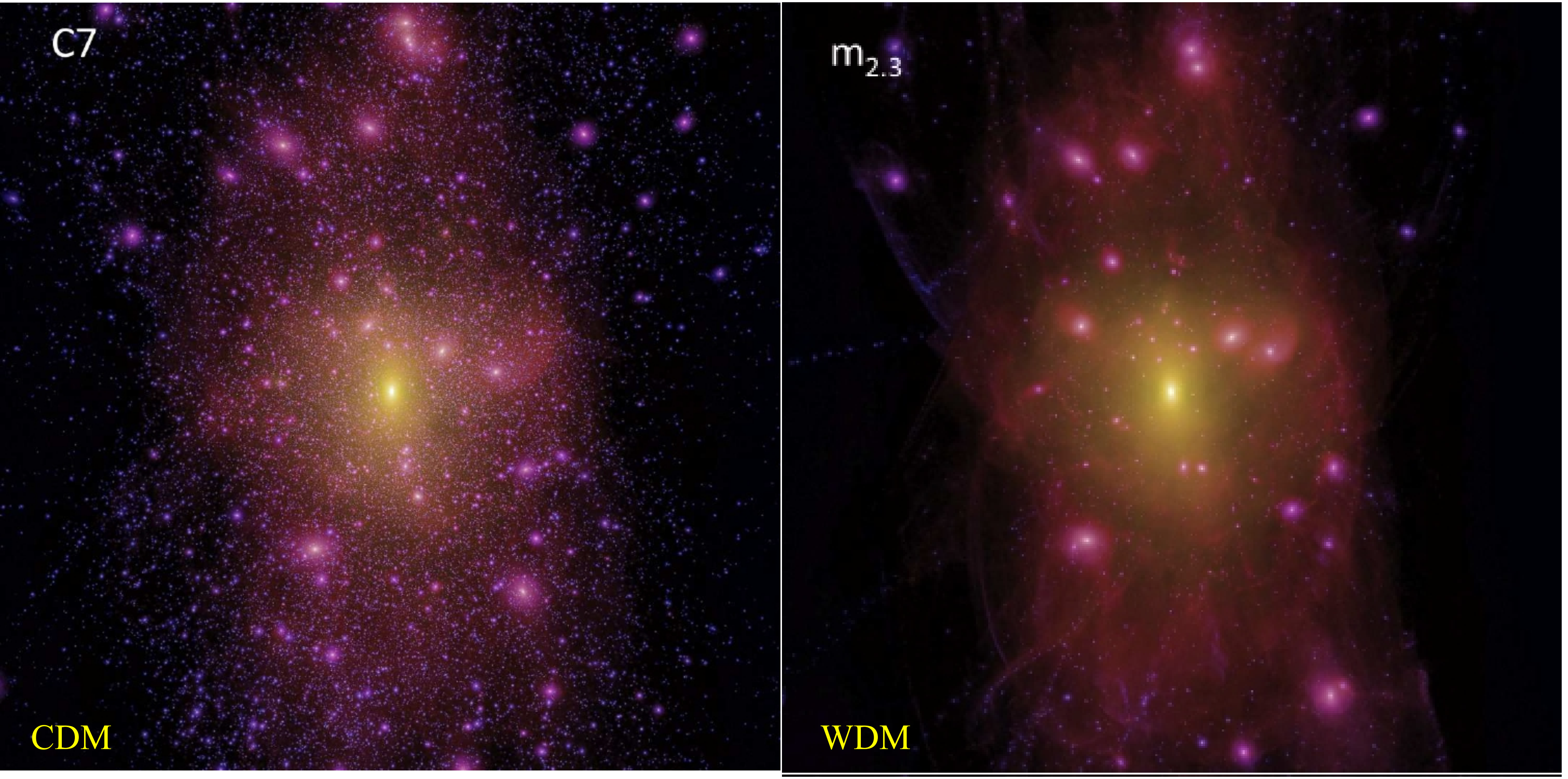
This places a 2σ lower limit on the mass of a thermal relic

$$m_{WDM} > 3.3 \text{ keV}$$

This lower limit is too large for WDM to have much effect on dwarf galaxy structure

Dark matter effects on galaxy formation?

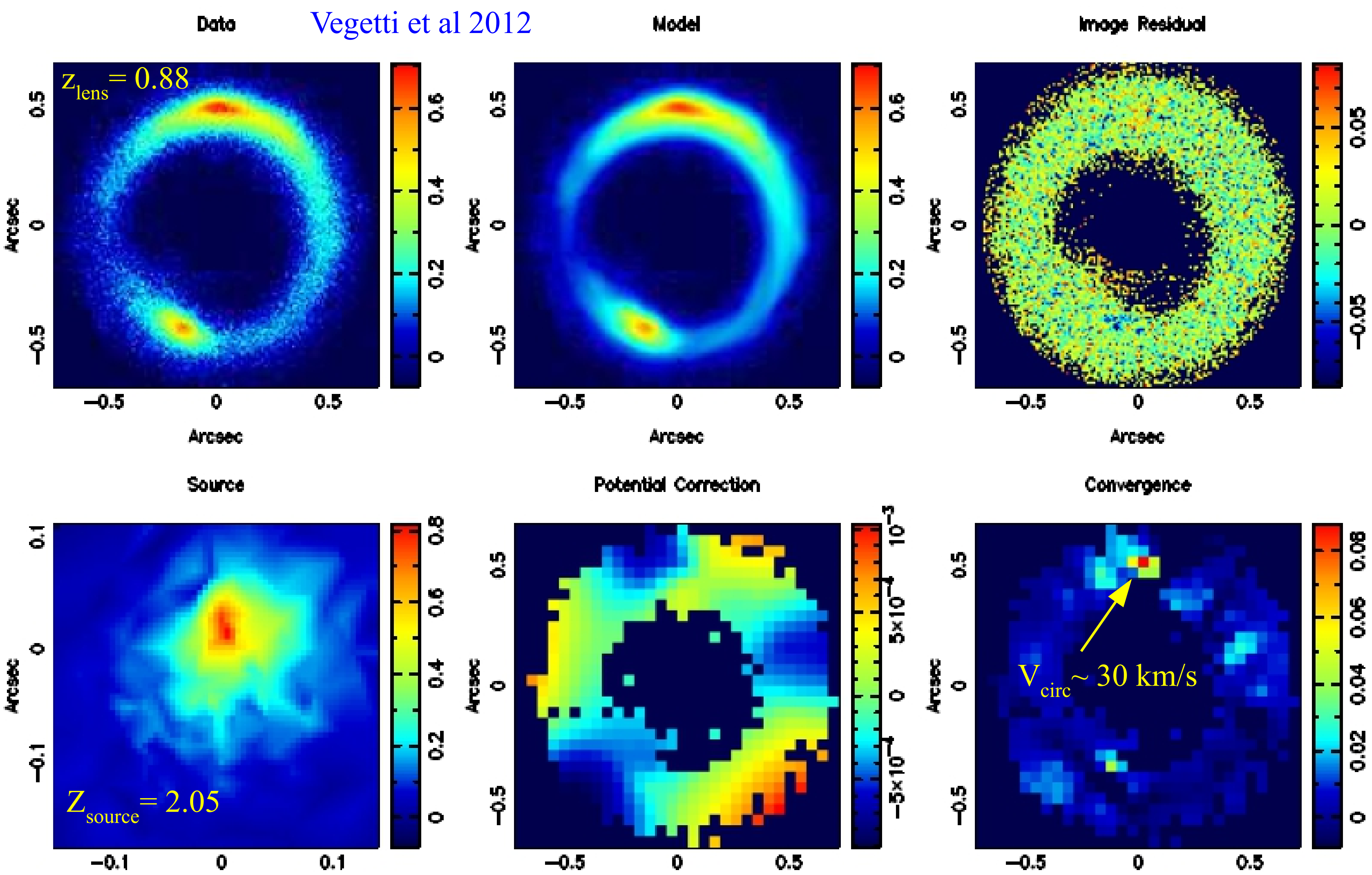
Lovell et al 2014.



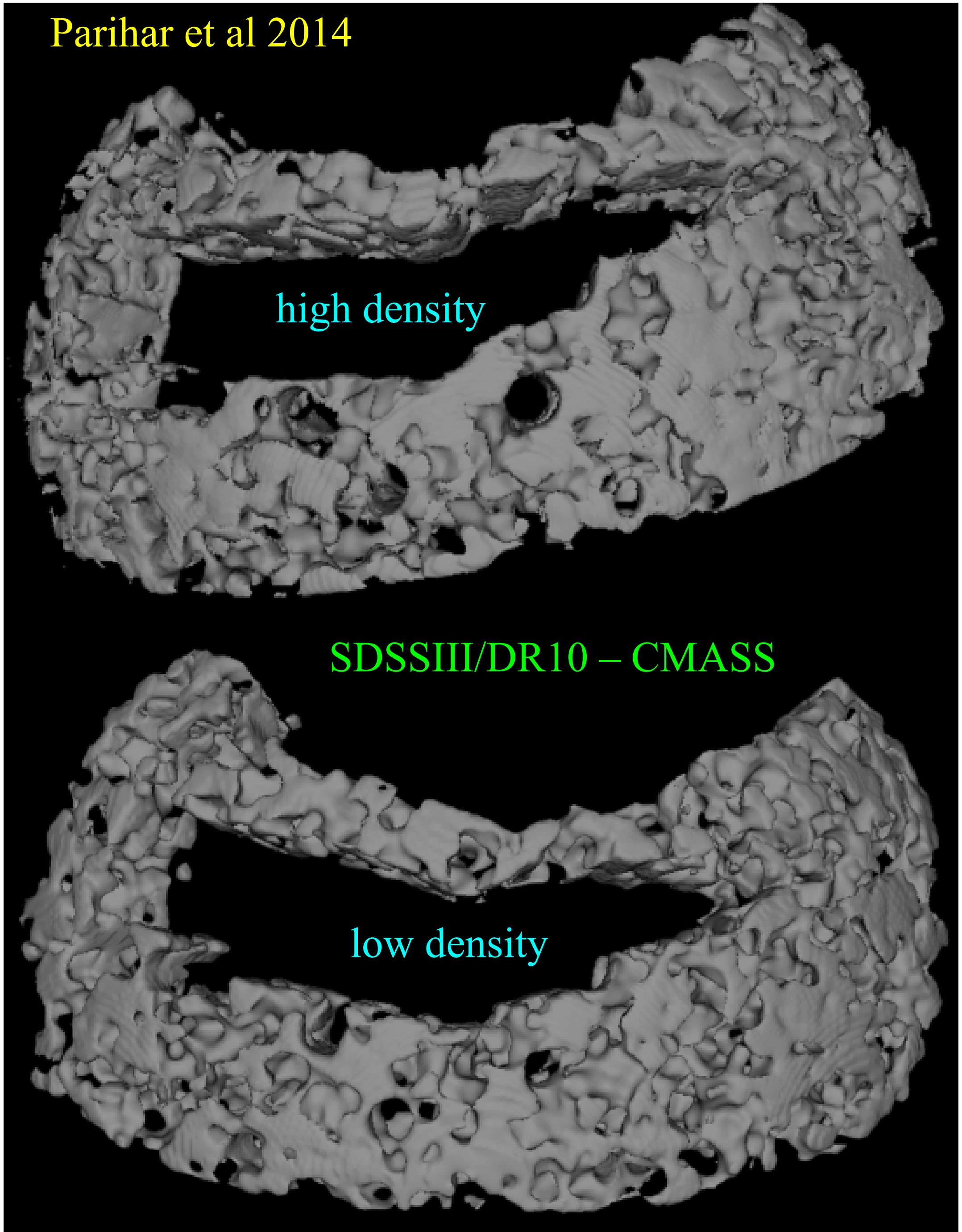
"Milky Way" halos in CDM and WDM. Note, the Ly α forest 2σ lower limit gives a limiting halo mass 6.5 times *smaller* than assumed here.

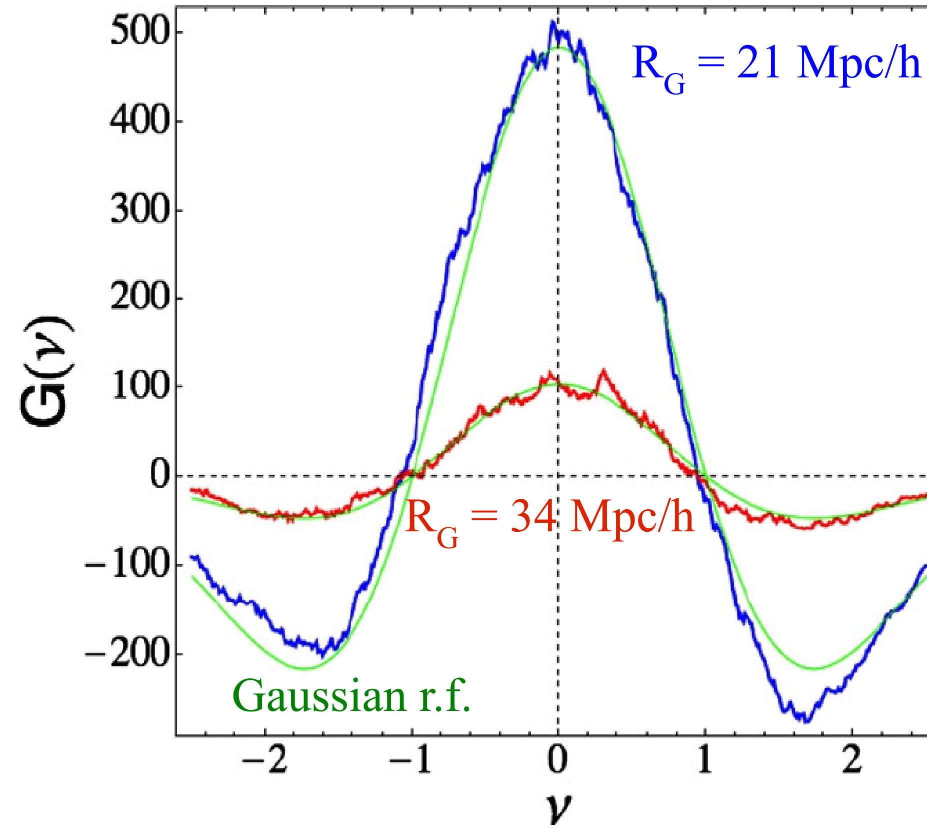
→ real IC's are ~ΛCDM on essentially all scales relevant to galaxies

Detecting substructures with no stars...



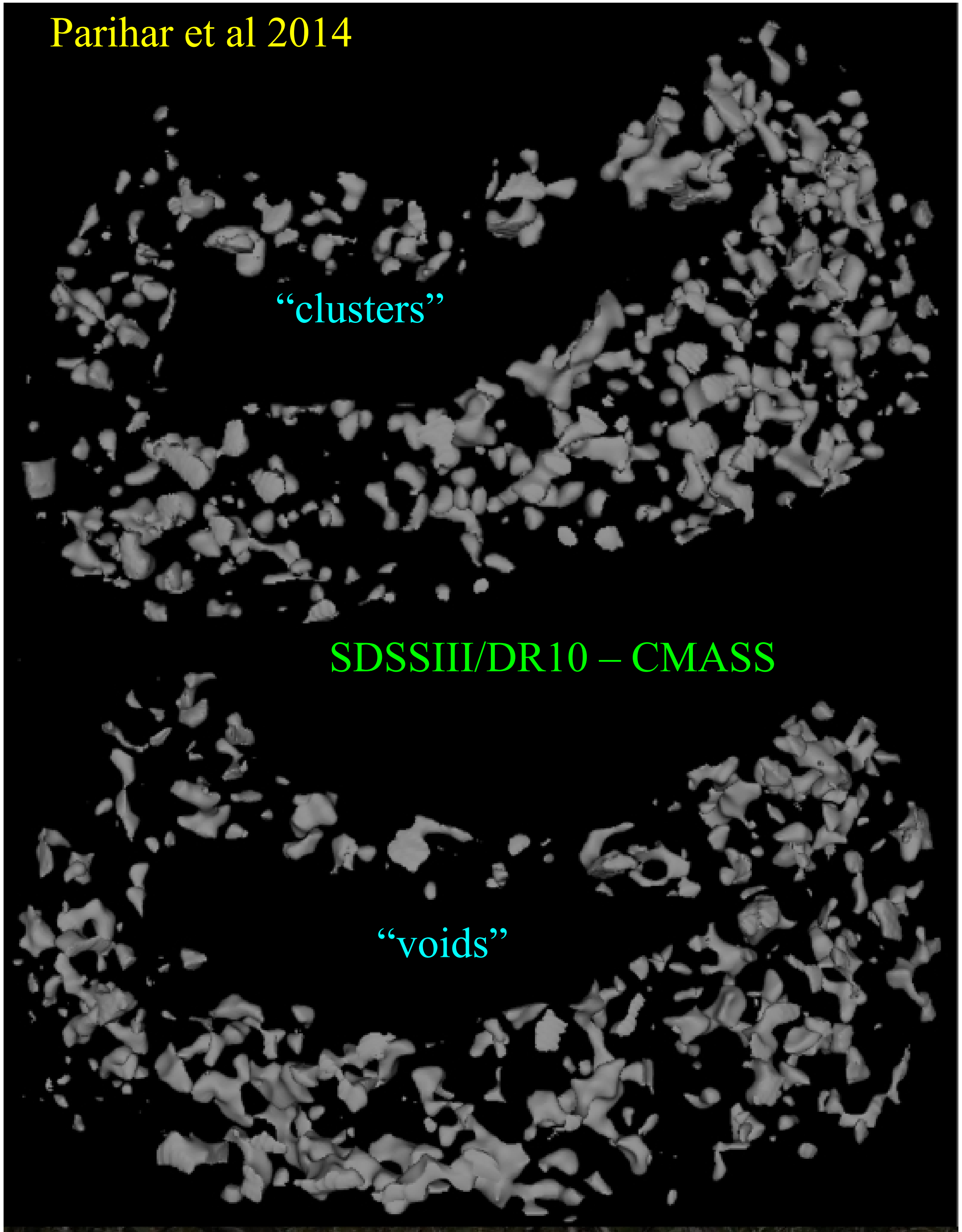
The topology of the galaxy distribution

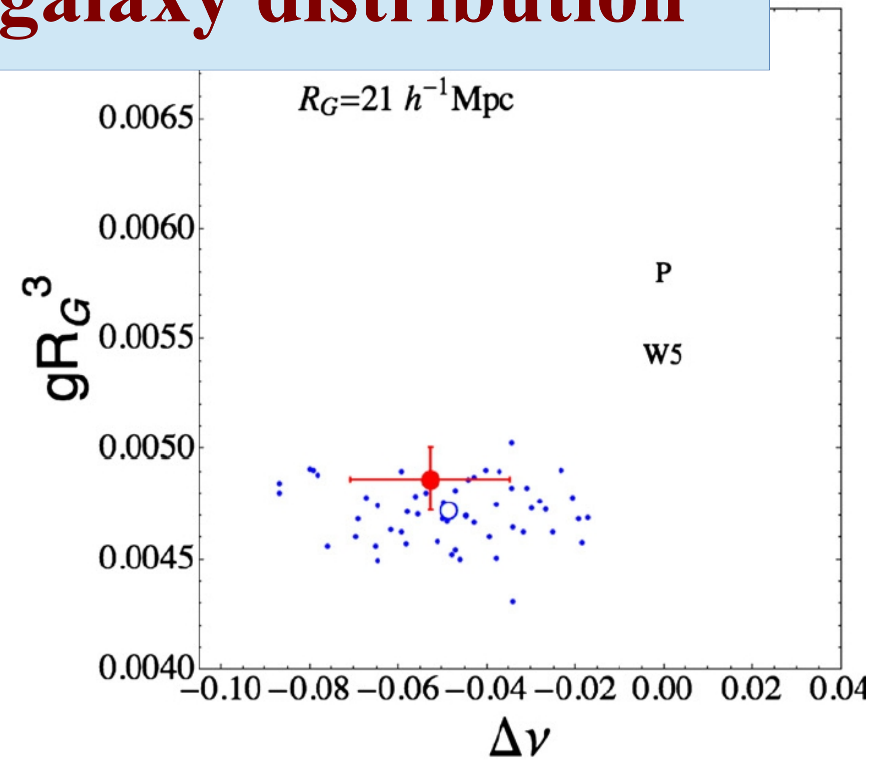


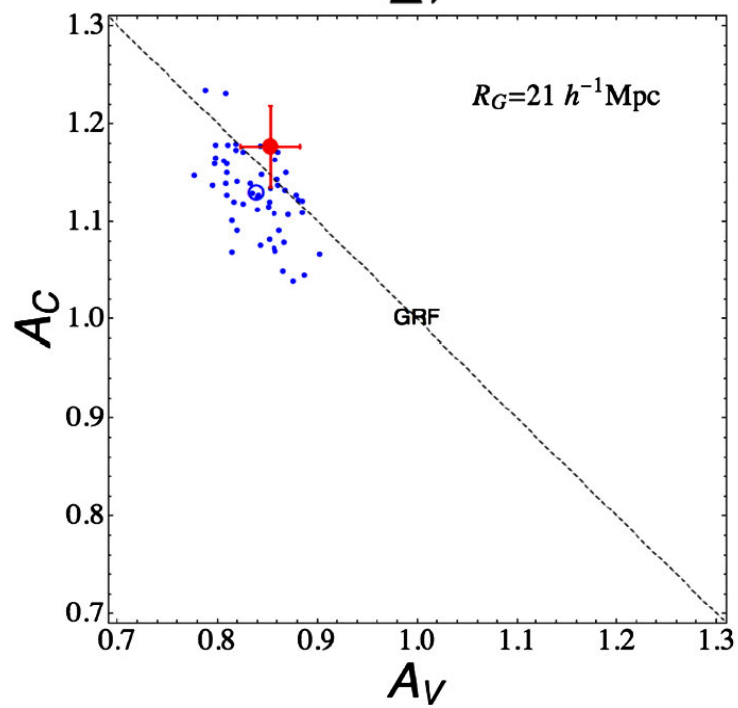


- Genus measured for equidensity surfaces of the gaussian-smoothed galaxy density field as a function of enclosed volume fraction

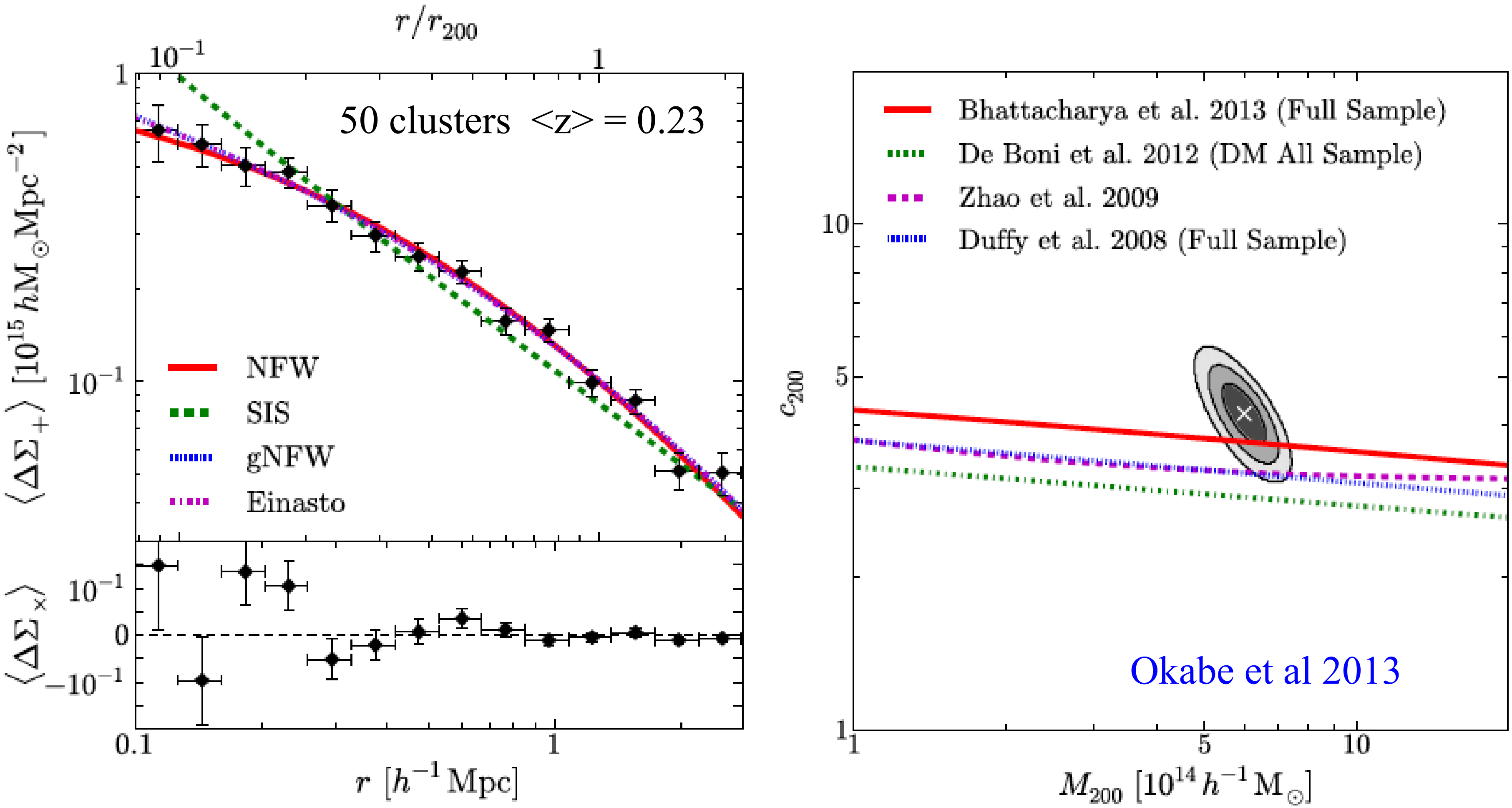
The topology of the galaxy distribution







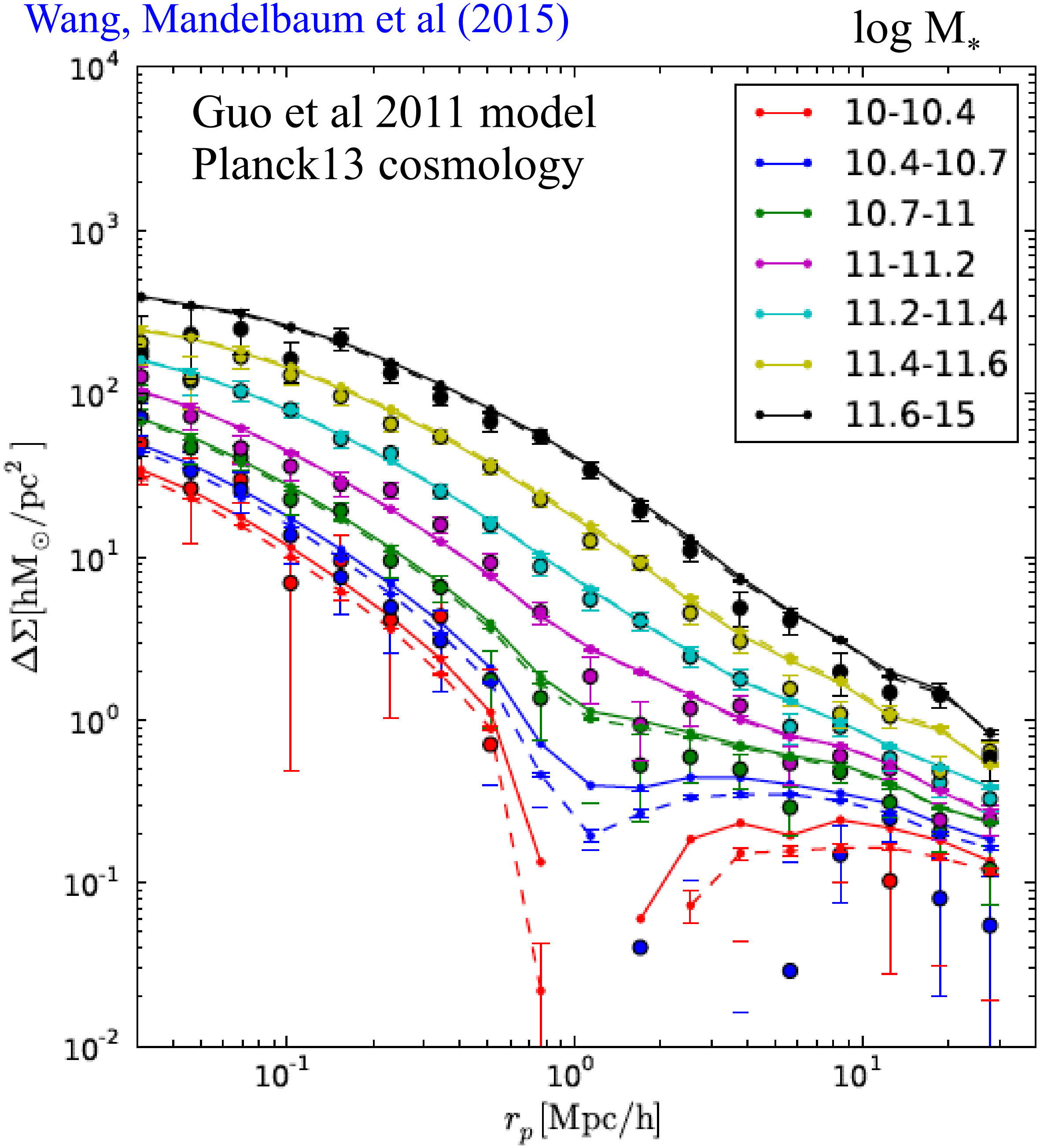
The mass profiles of massive galaxy clusters



- The mean density profile of rich clusters has the predicted ΛCDM shape
- This is effectively a one-parameter fit (the mean cluster mass)

Stacked weak lensing profiles for LBG's

Wang, Mandelbaum et al (2015)



LBG's are SDSS/DR7 galaxies brighter than any neighbor with $\Delta r_p <$ 1 Mpc, $\Delta v <$ 1000 km/s

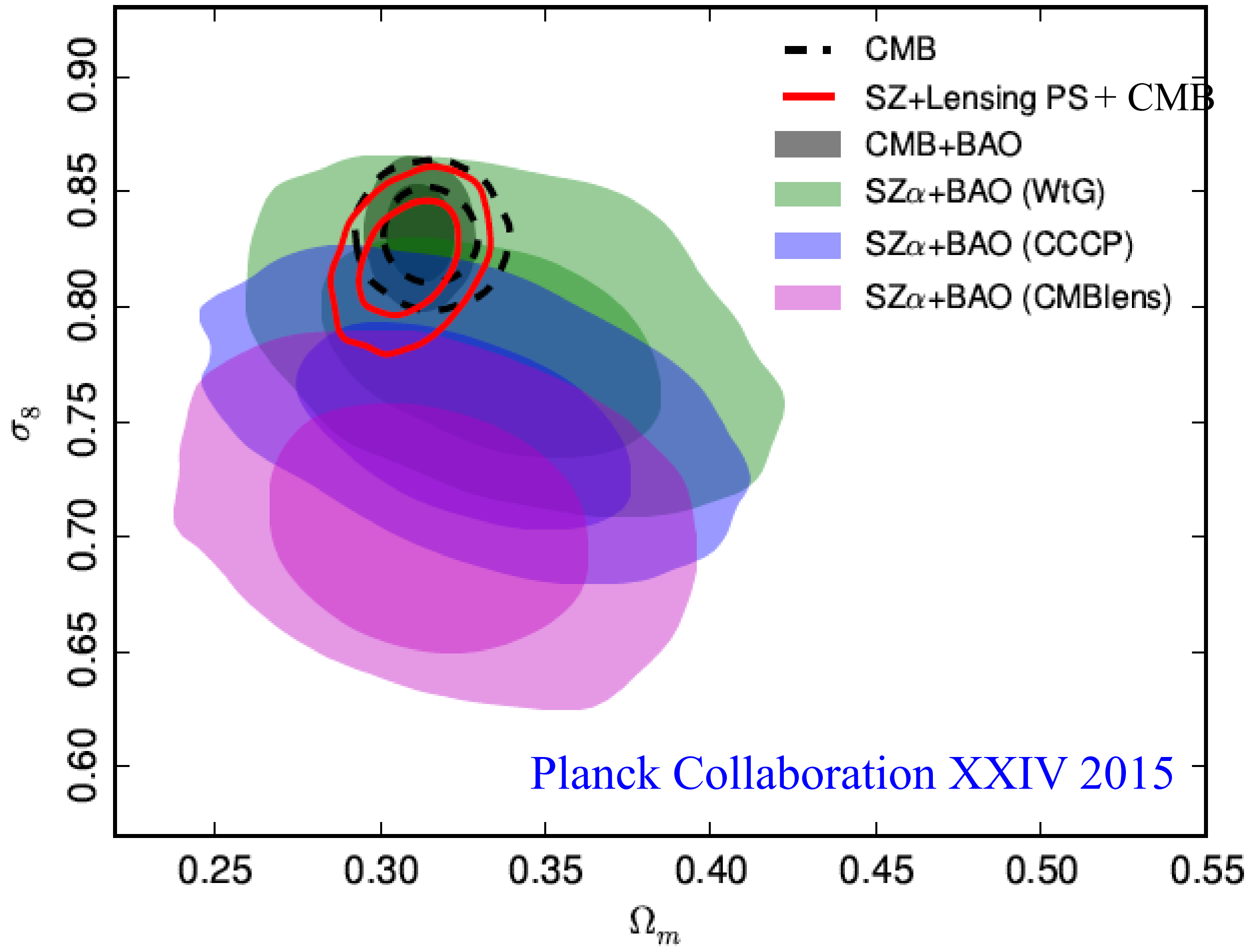
These are predominantly (>83%) centred in their halos

Symbols are observed results stacked in bins of log M_*

Predictions are from a simulation in Planck cosmology tuned to fit the observed stellar mass function

No parameters were adjusted to fit the lensing data

Problems with cluster abundances?

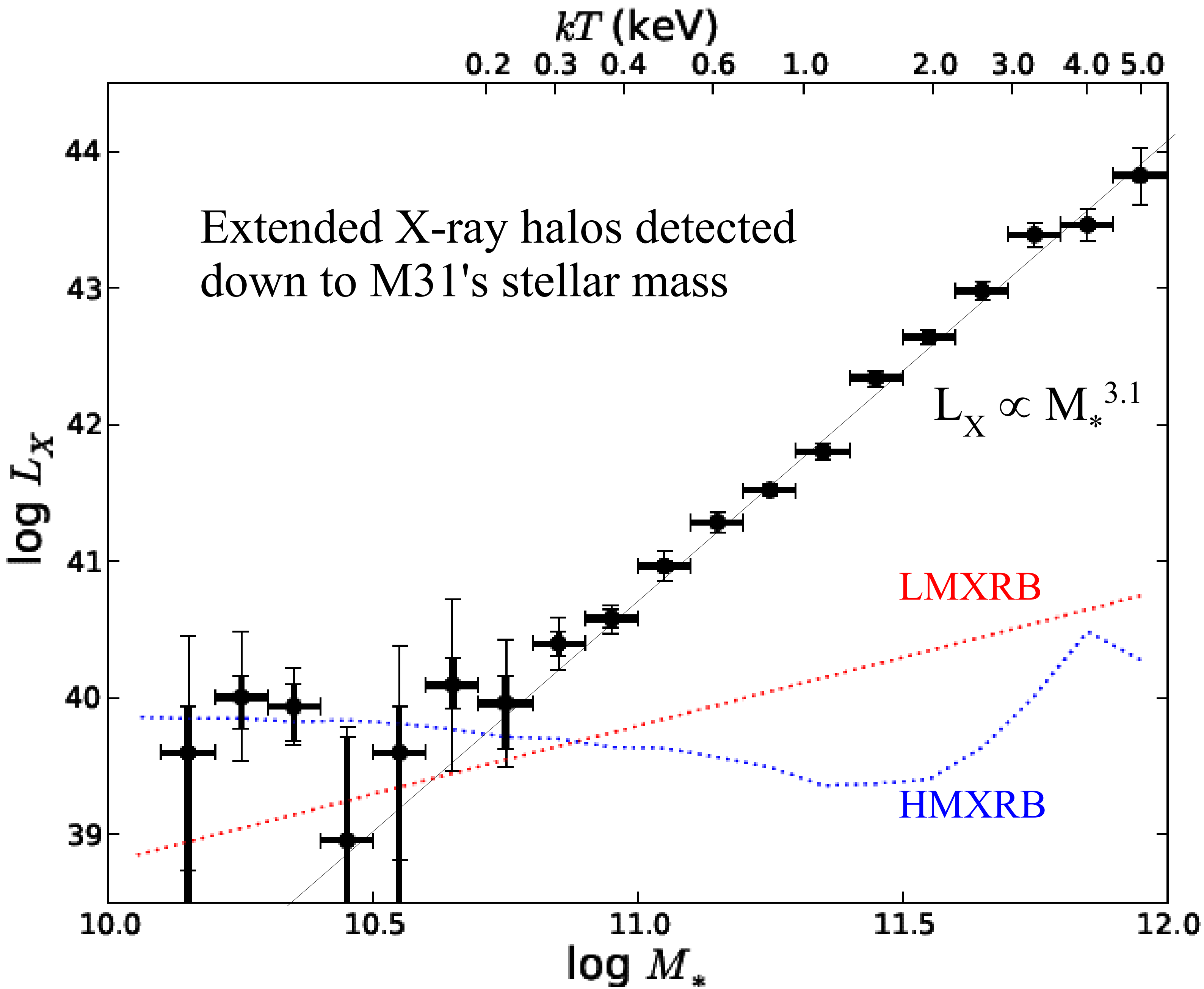


- Cluster counts as a function of SZ flux (or X-ray mass proxy) and z imply a lower σ_8 than *Planck* infers from primary CMB fluctuations

- This depends critically on the M_h – Y or M_h – Y_x calibration
  - are calibrations obtained for the "right" clusters? –

Stacked Rosat X-ray signal from LBGs

Anderson et al 2015



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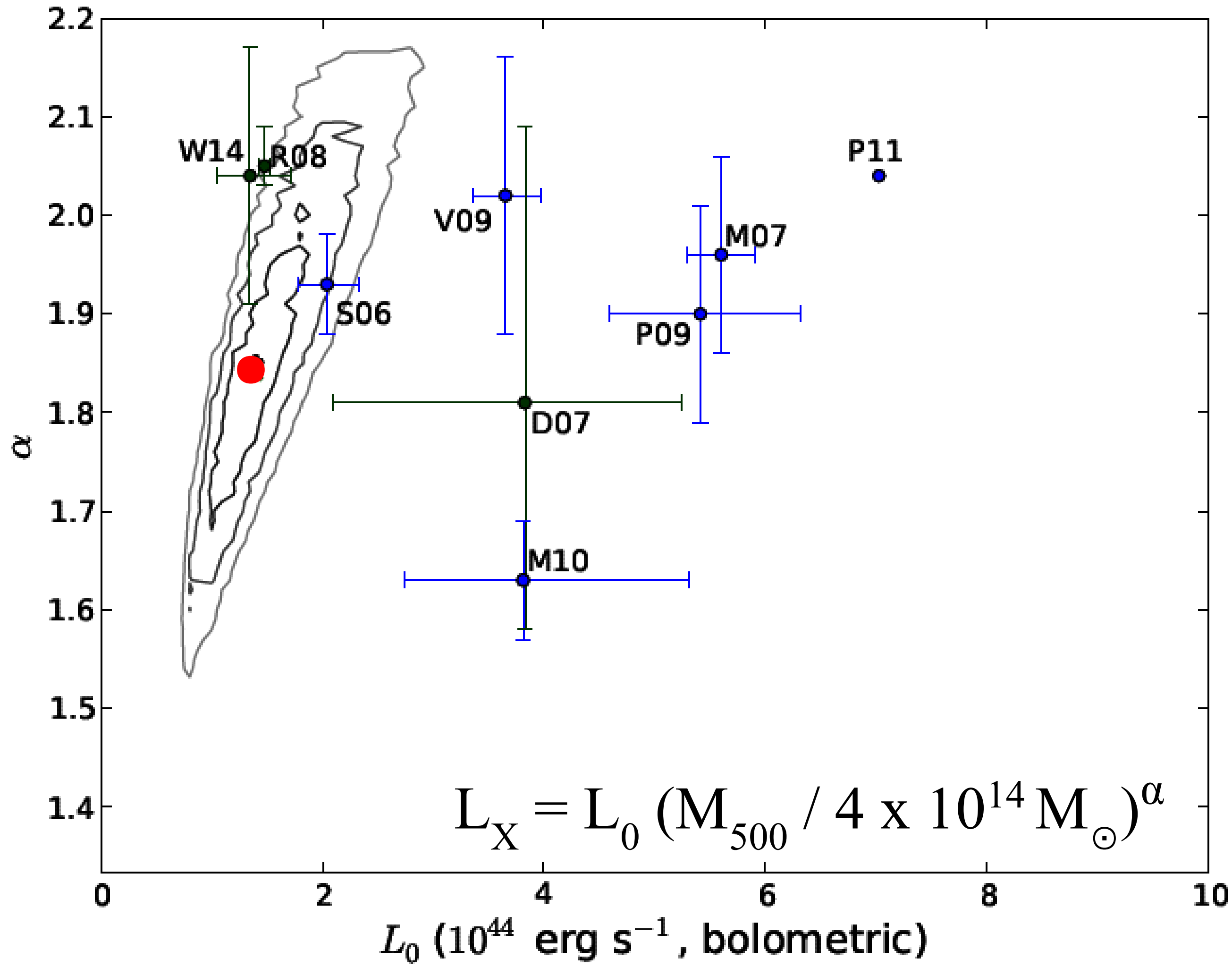


Anderson et al 2015

$\alpha = 4/3$ is expected for self-similar halos with constant baryon fraction

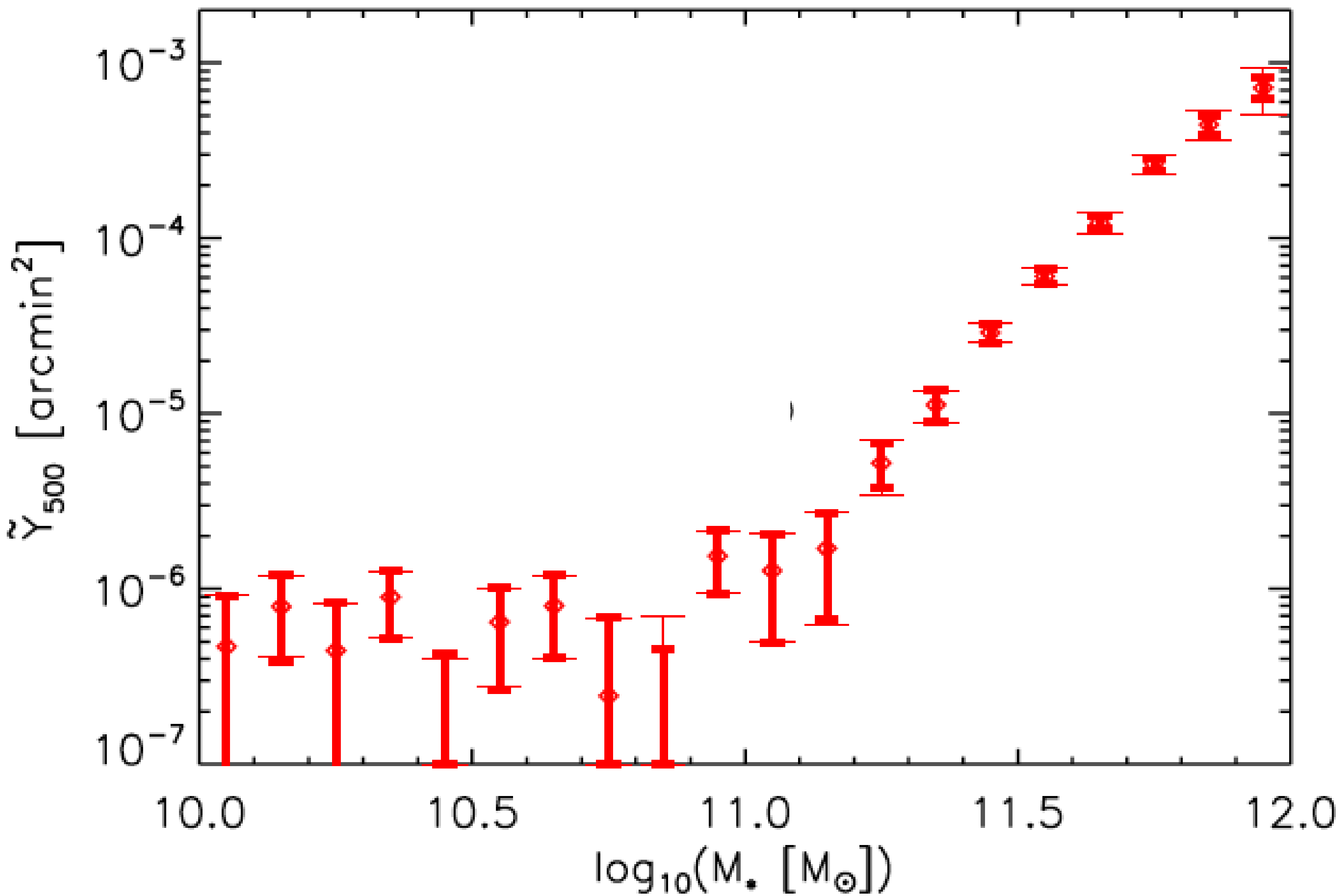
X-ray luminosity drops much faster at low mass than this

Forward modelling using the Guo13 mock LBG catalogue gives 1, 2 and 3σ ranges for the parameters of the $L_X - M_{500}$ relation

→ rough agreement with results for optically selected clusters •
disagreement in normalisation with results for X-ray selected clusters •

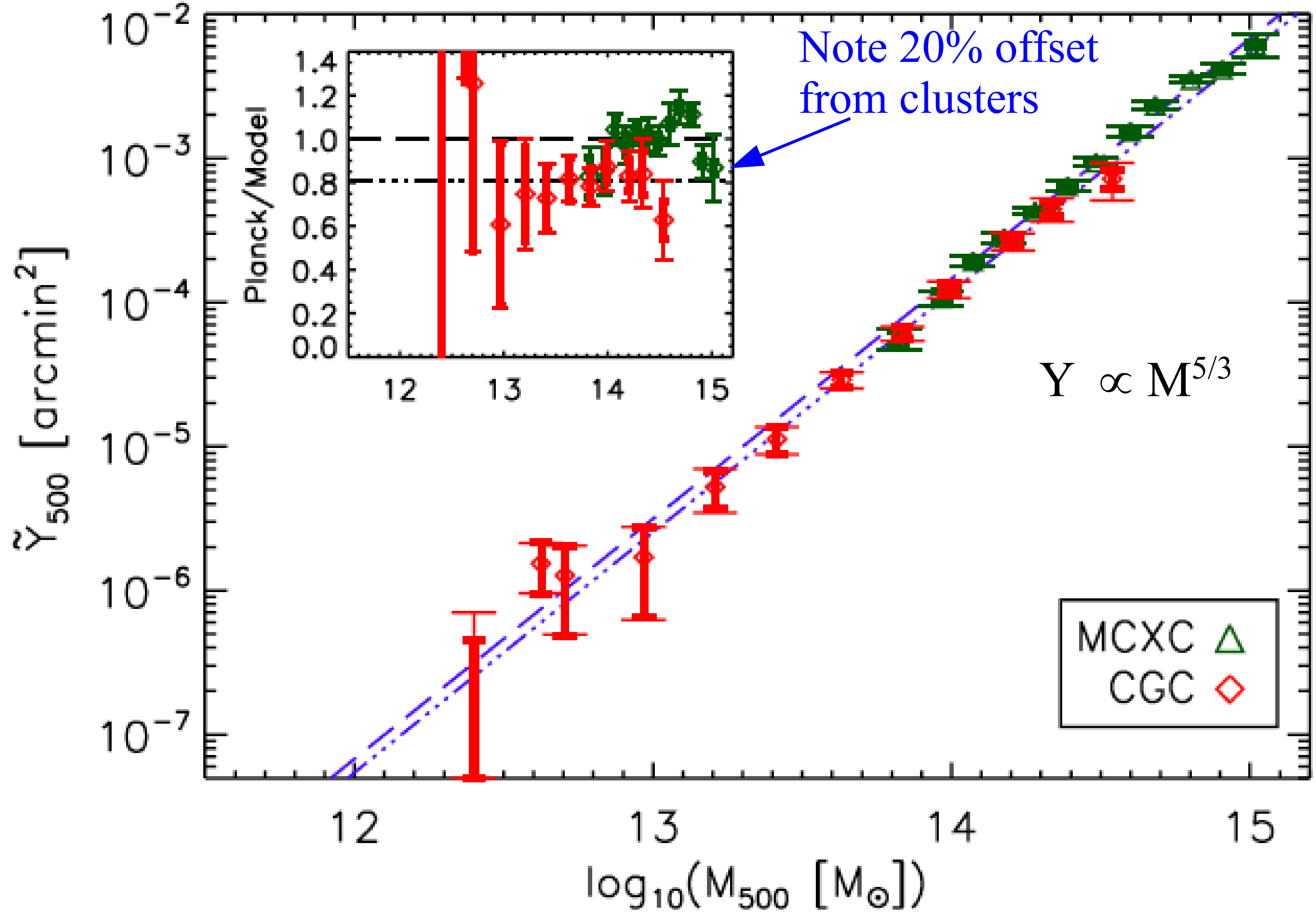
Stacked *Planck* SZ signal from LBGs

Planck Collaboration 2013



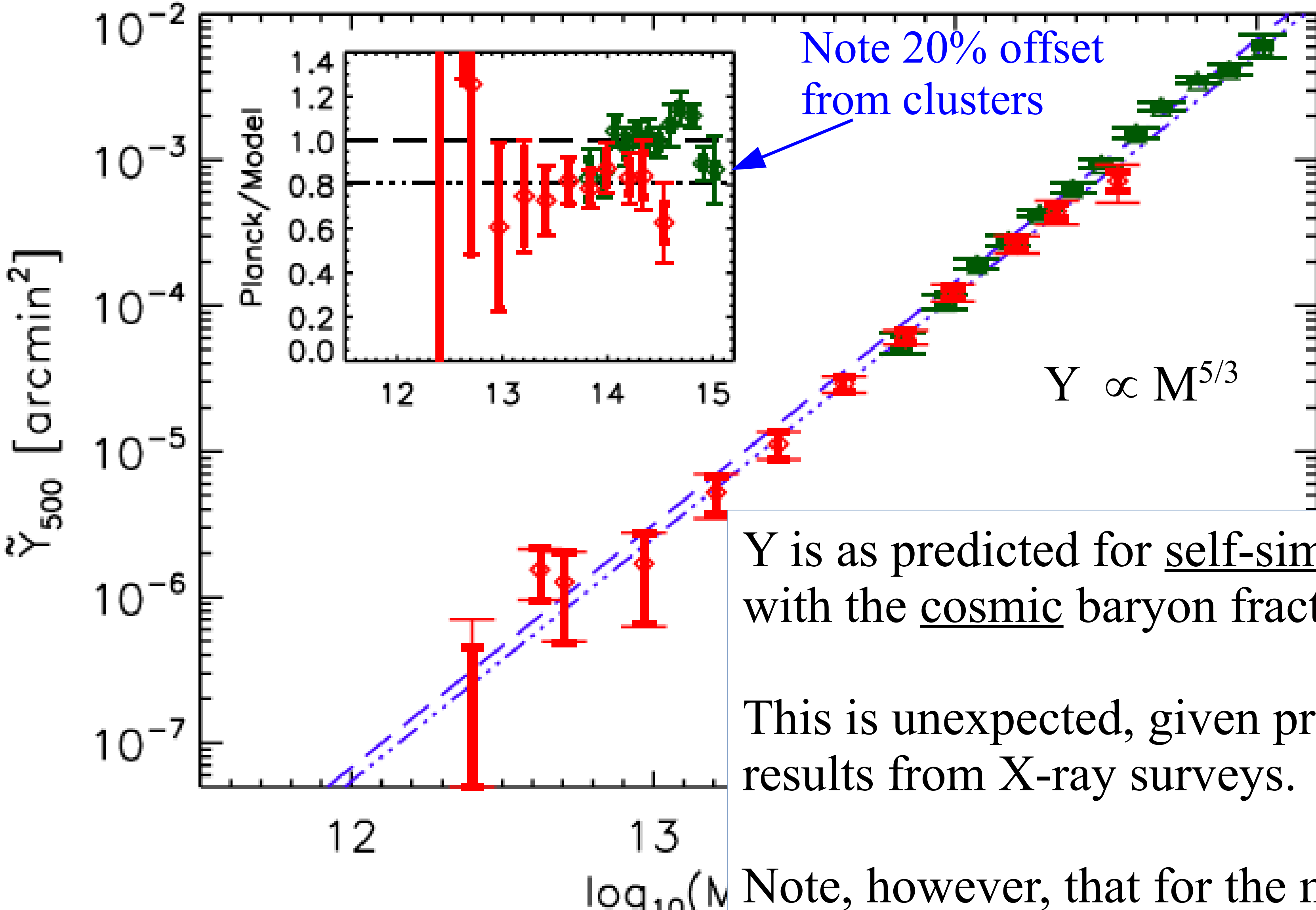
Stacked *Planck* SZ signal from LBGs

Planck Collaboration 2013



Stacked *Planck* SZ signal from LBGs

Planck Collaboration 2013



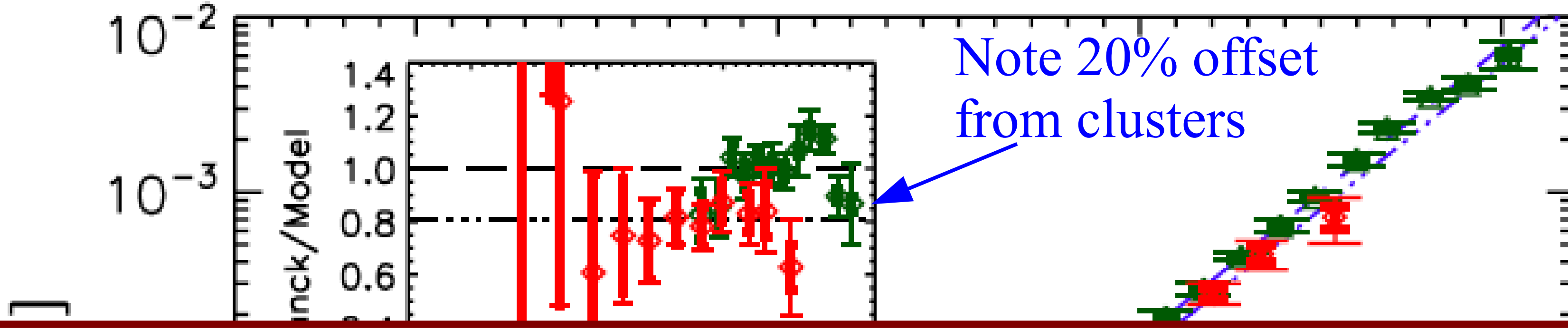
Y is as predicted for <u>self-similar</u> halos with the <u>cosmic</u> baryon fraction

This is unexpected, given previous results from X-ray surveys.

Note, however, that for the majority of LBGs Planck does <u>not</u> resolve R_{500}

Stacked *Planck* SZ signal from LBGs

Planck Collaboration 2013



- *Planck* appears to see all the expected baryons associated with halos with mass down to about that of the Milky Way

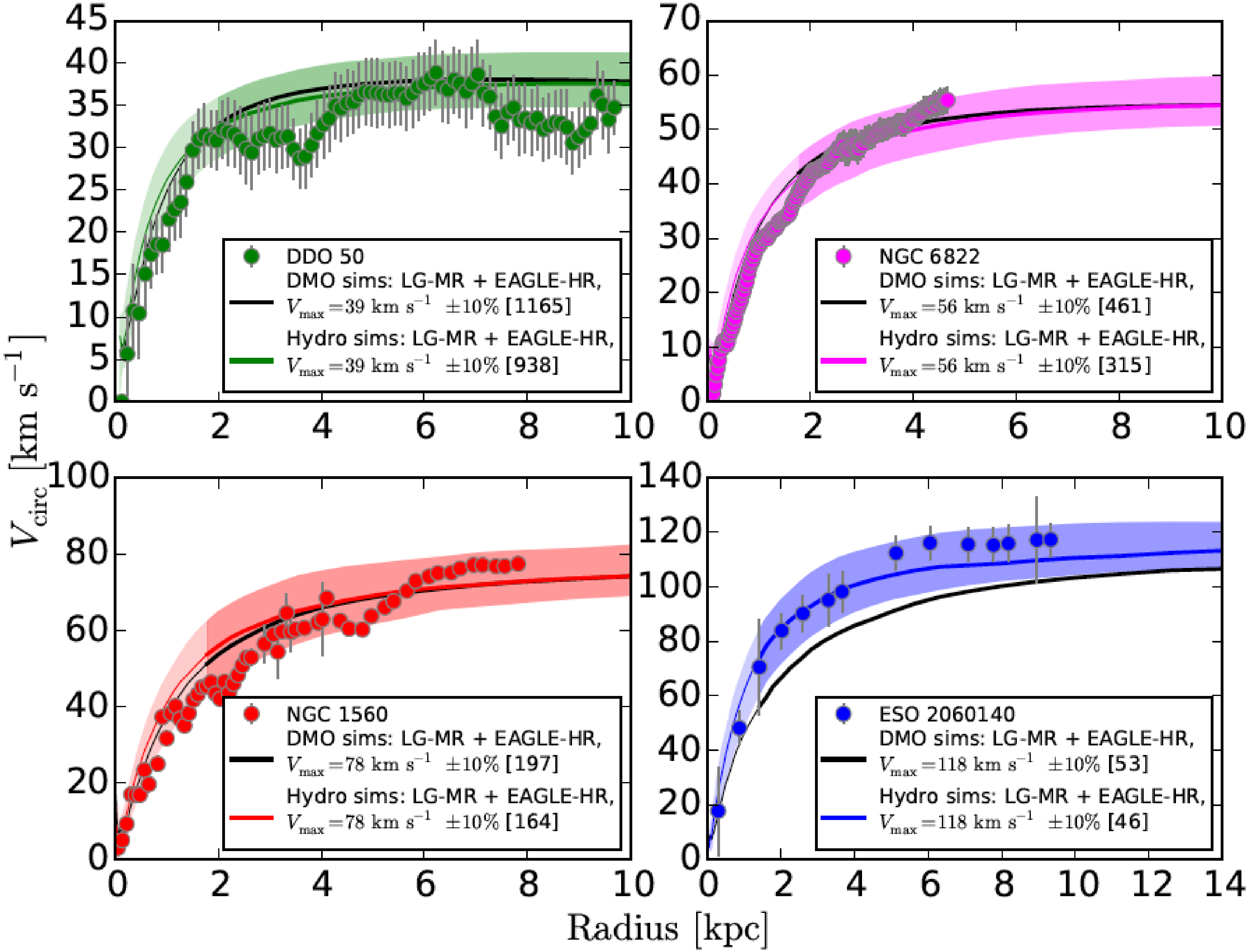
- These baryons must be hot but they must be less centrally concentrated in lower mass halos

- The offset in Mh – Y relation between LBG halos and X-ray cluster halos is in the direction needed to reconcile the σ_8 discrepancy

log₁₀(M

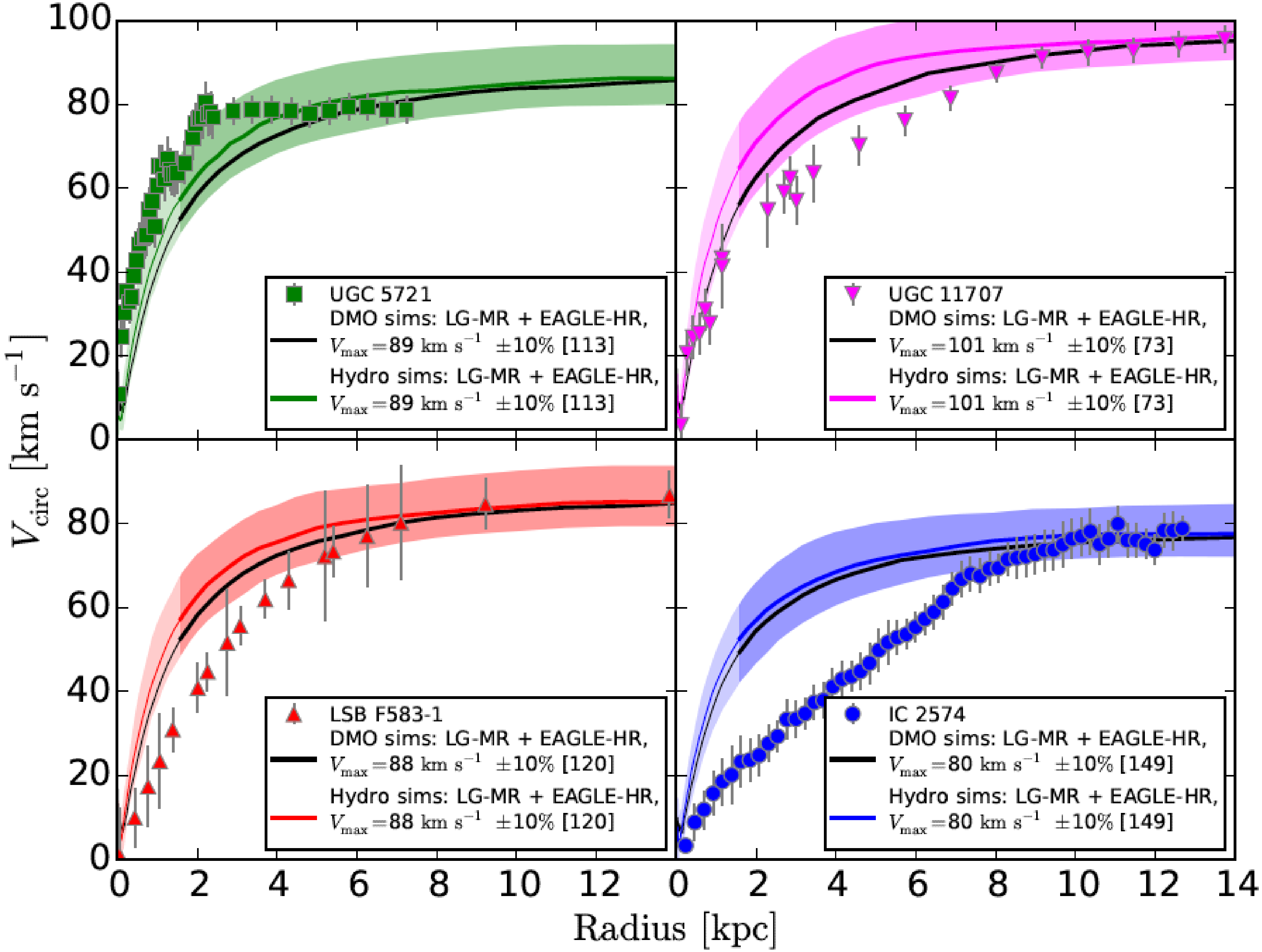
Note, however, that for the majority of LBGs Planck does <u>not</u> resolve R_{500}

Dwarf galaxy rotation curves: cusps vs cores



Many dwarf galaxies have rotation curves that fit ΛCDM predictions well

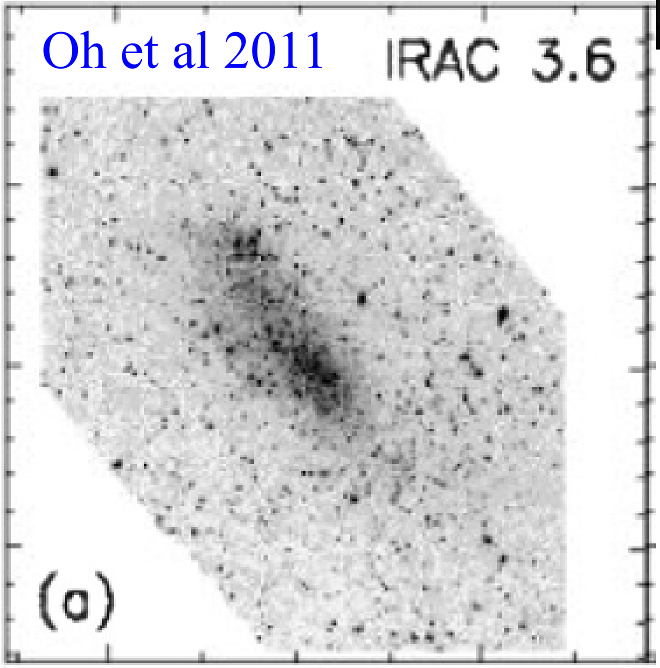
Dwarf galaxy rotation curves: cusps vs cores

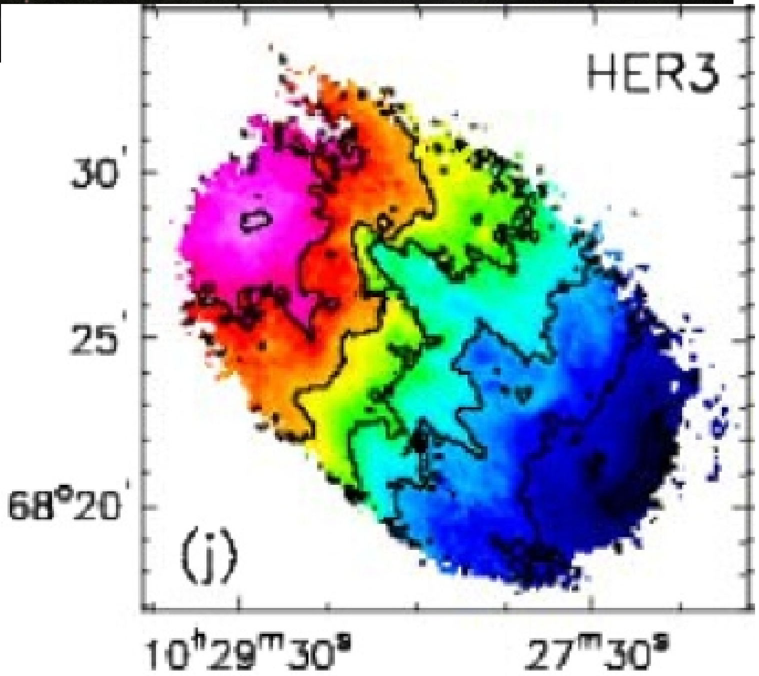


Many others fail dramatically to fit ΛCDM predictions.

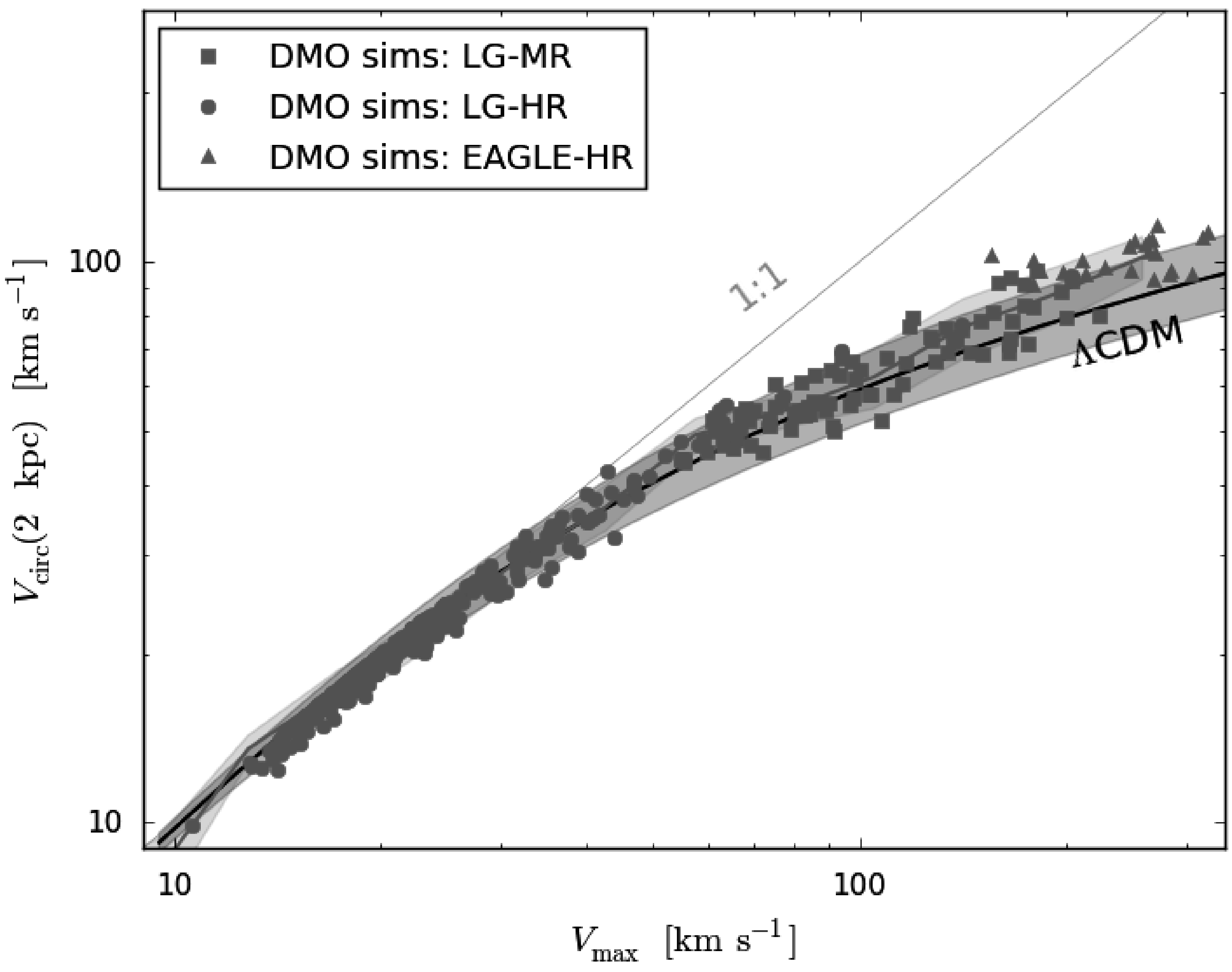
"Cores" from: (i) DM properties? (ii) Baryon effects? (iii) Incorrect modelling?


IC 2574


Oh et al 2011
IRAC 3.6
(a)

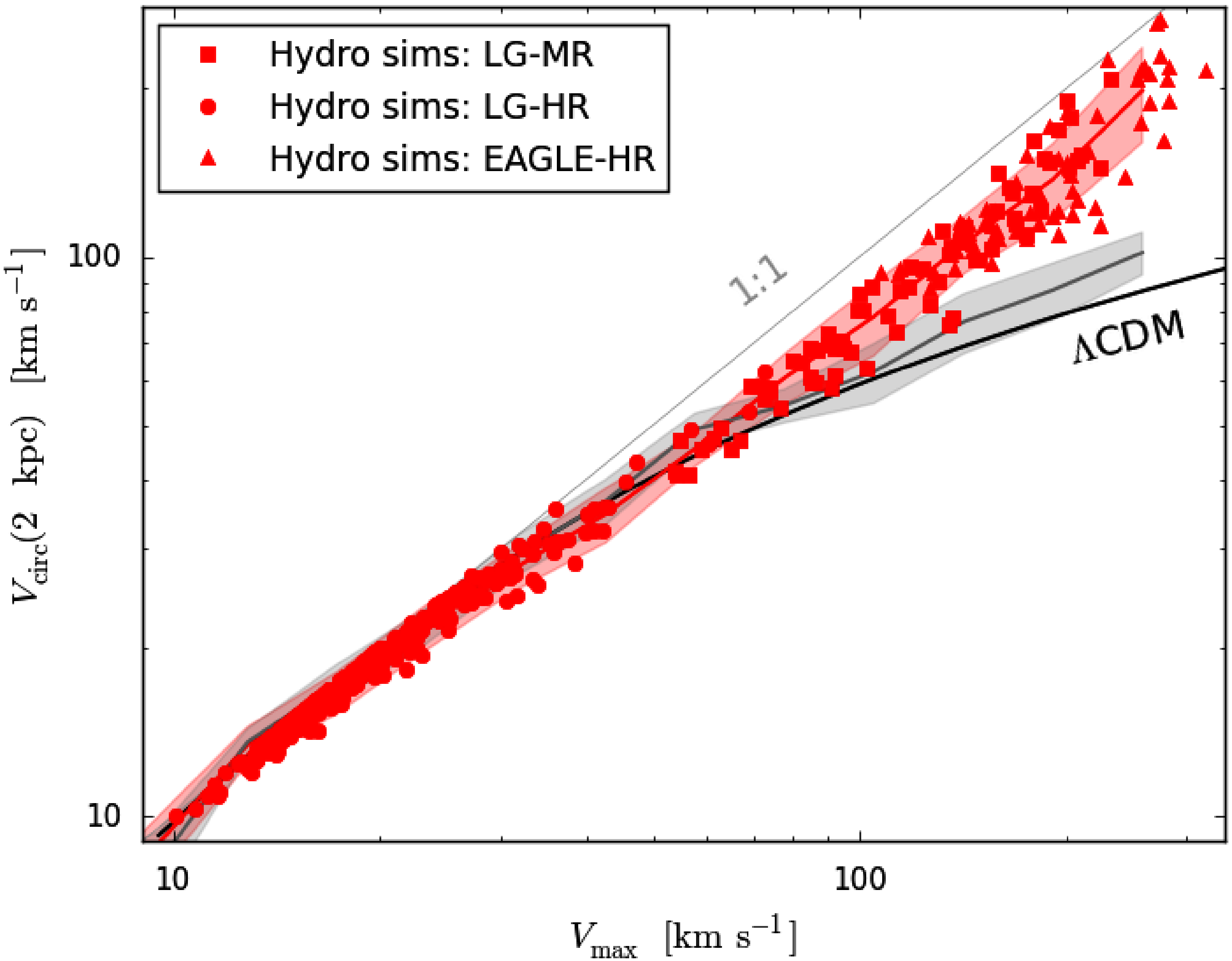

HER3
30'
25'
68°20'
(j)
10h29m30s
27m30s

V_{circ}(2 kpc) versus V_{max} for ΛCDM halos



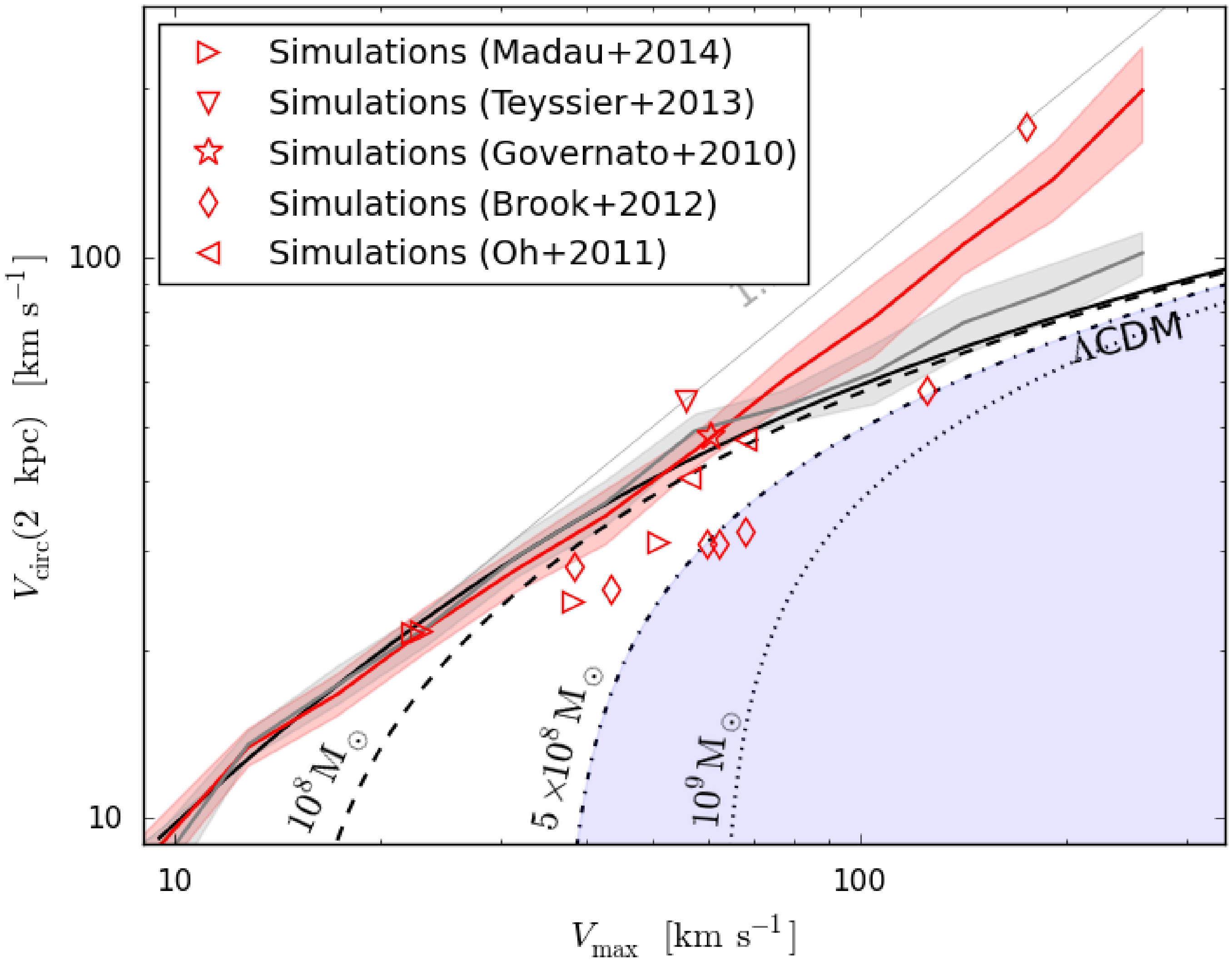
Oman et al 2015

V_{circ}(2 kpc) versus V_{max} for ΛCDM galaxies



Oman et al 2015

V_{circ}(2 kpc) versus V_{max} for ΛCDM galaxies

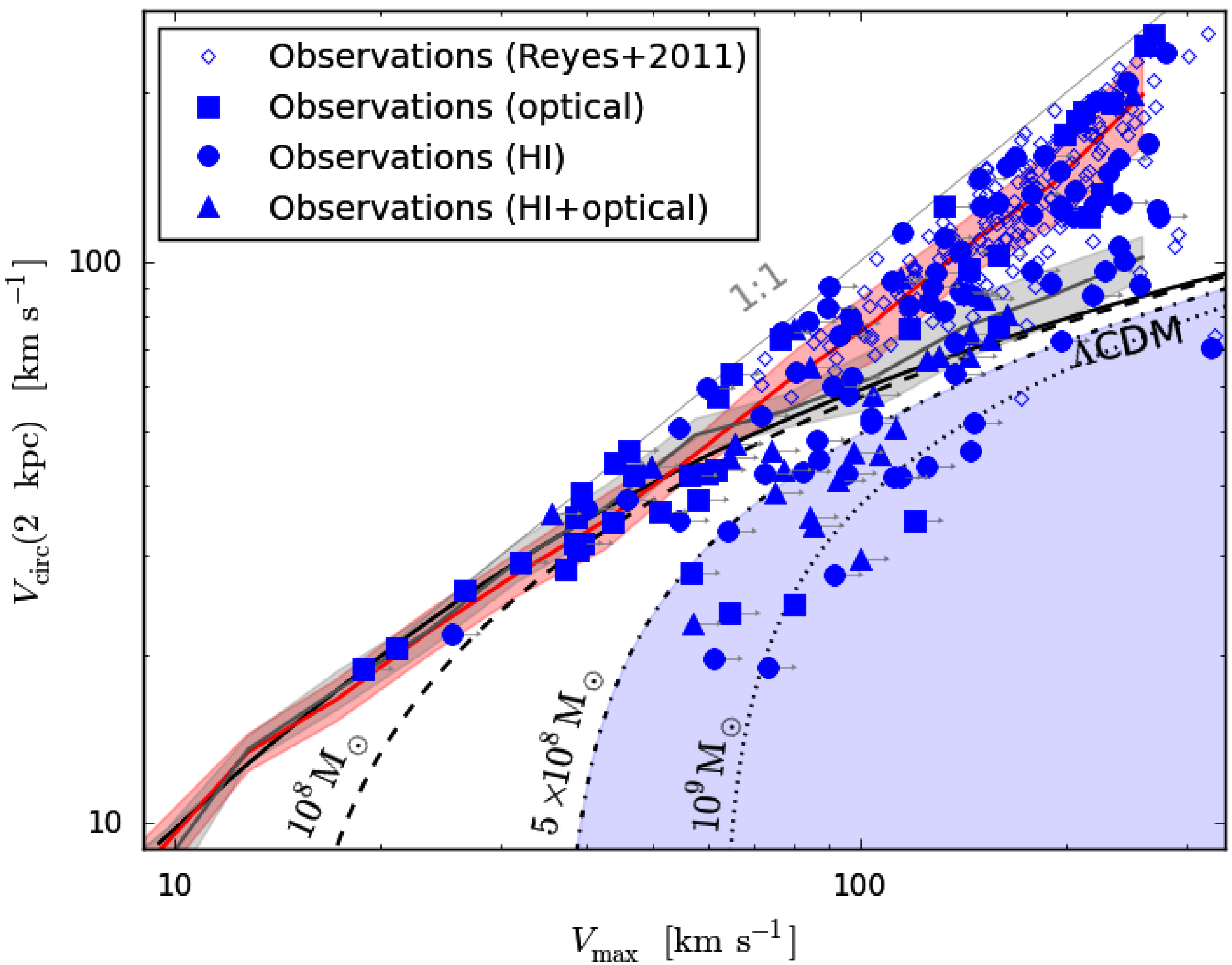


Simulations with high SF thresholds and strong feedback

→ cusps expand into cores

Oman et al 2015

V_{circ}(2 kpc) versus V_{max} for observed dwarfs



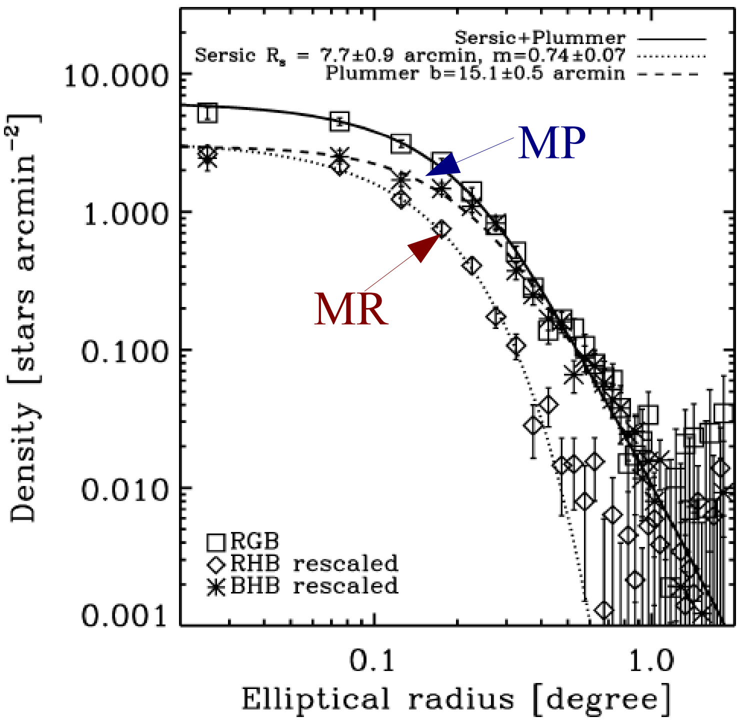
Enormous apparent <u>diversity:</u>

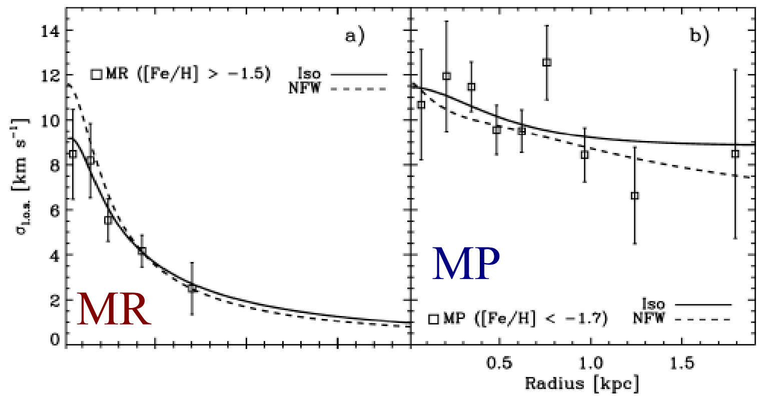
Too large for baryon effects proposed so far?

Too large to reflect DM properties alone?

Oman et al 2015

A core in the Sculptor dwarf spheroidal?

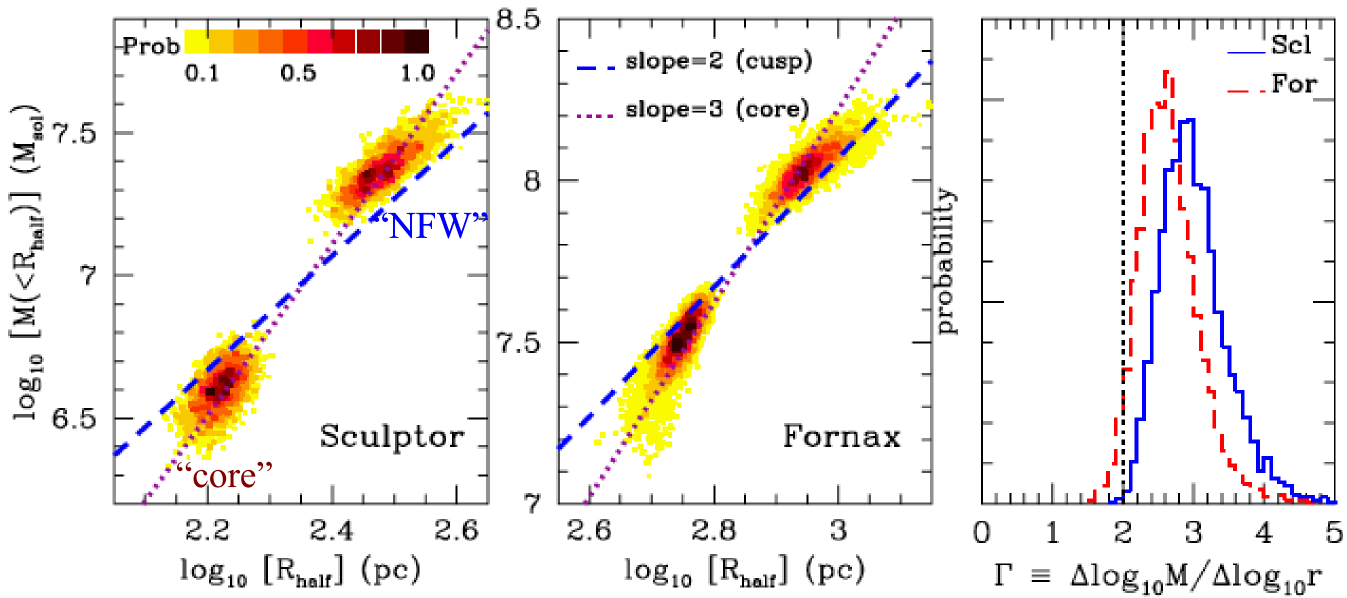




Battaglia et al 2008
~500 stars

NFW
"core"

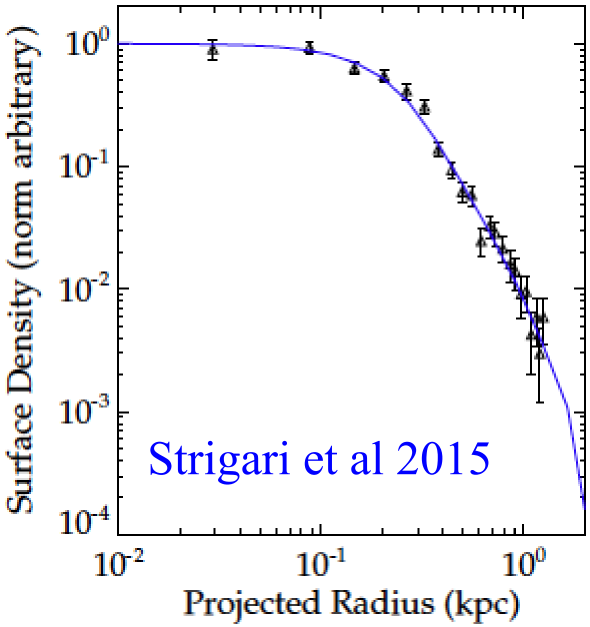
- Sculptor has 2 populations
- Counts for both show cores
- MR stars less extended and cooler than MP
- Both cusped and cored potentials can fit

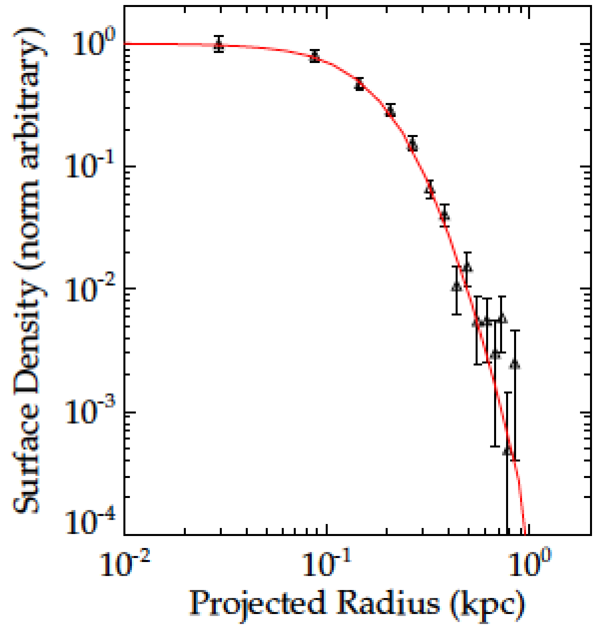


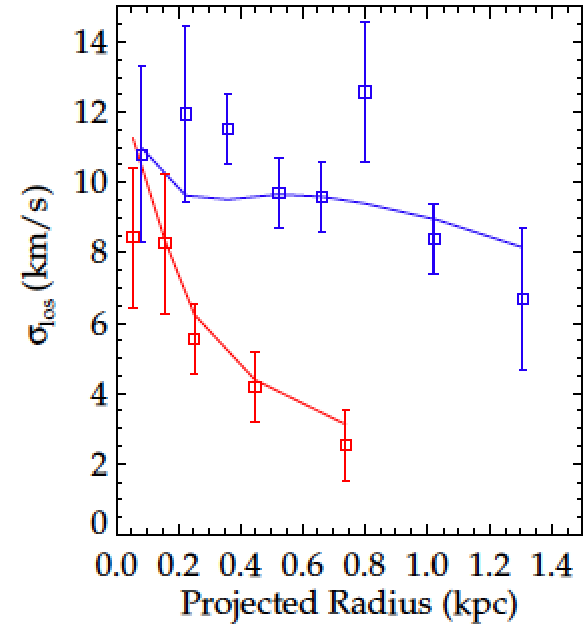
Walker & Penarrubia 2011
~1500 stars

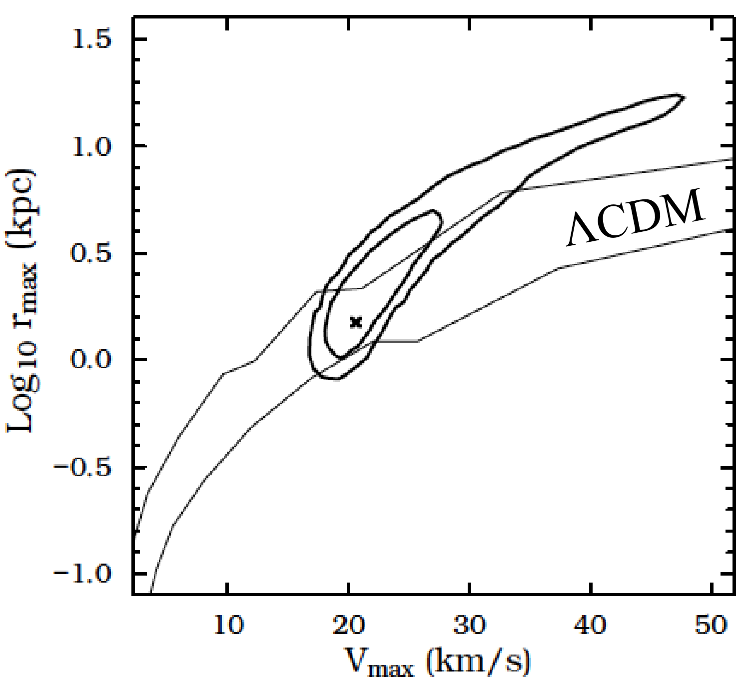
Two populations separated <u>statistically</u>. $r_{1/2}$, $M(r_{1/2})$ estimated for each. An NFW potential is excluded

A core in the Sculptor dwarf spheroidal?



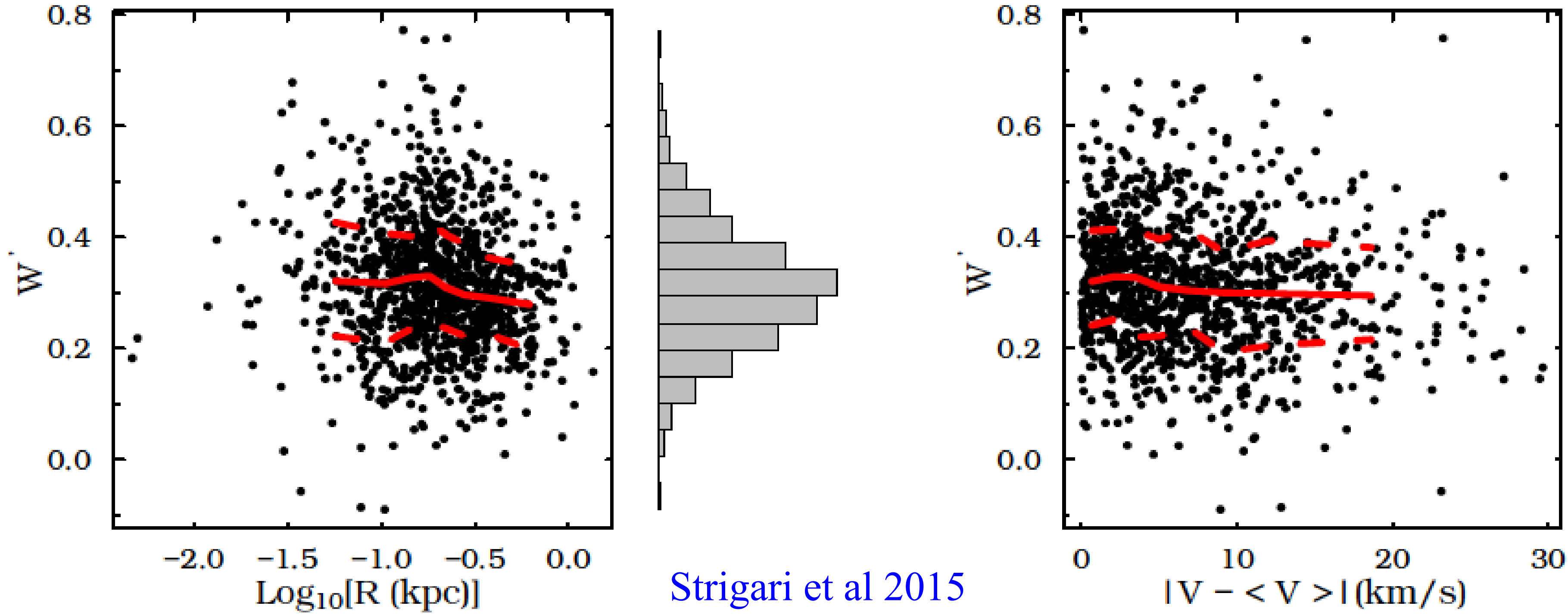






- The Battaglia count and velocity dispersion data can be well fit by a distribution function f(E,J) in an NFW potential $\Phi(r)$
- The characteristic parameters of $\Phi(r)$ are consistent with the expected ΛCDM relation
- A “cored” potential fits equally well but not significantly better

A core in the Sculptor dwarf spheroidal?

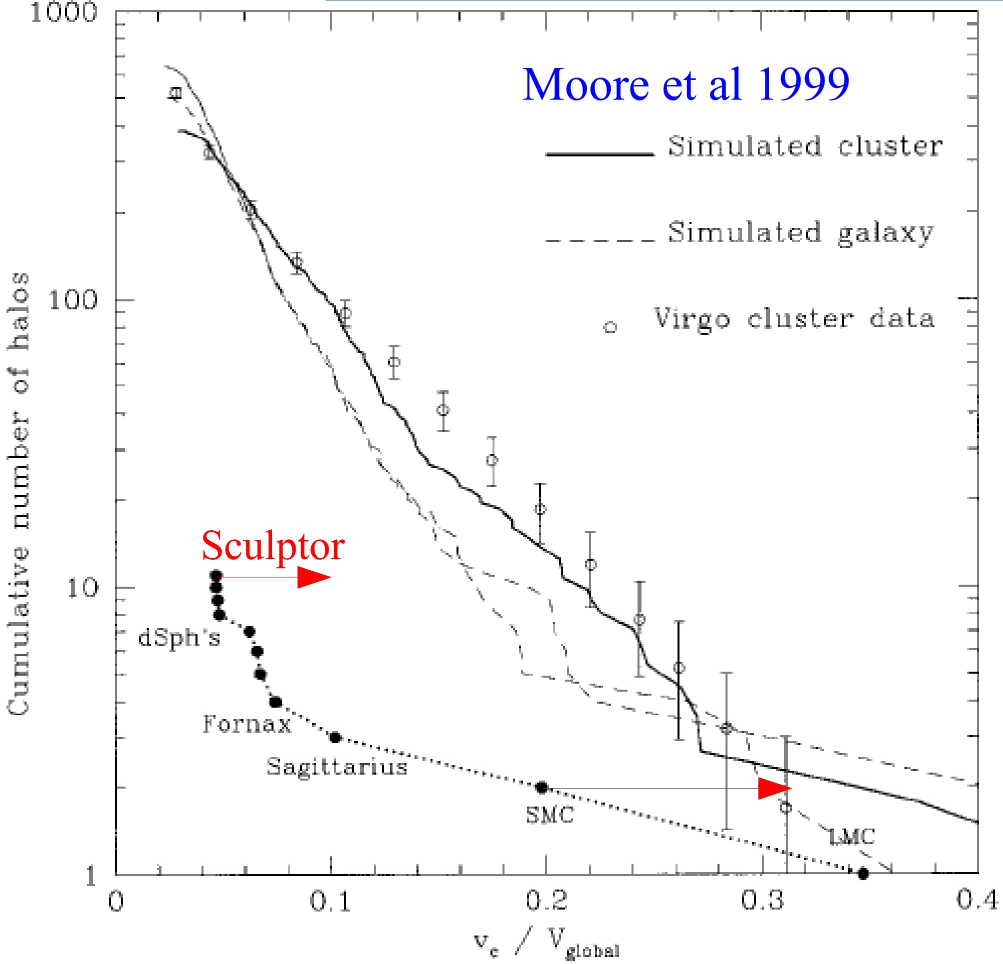


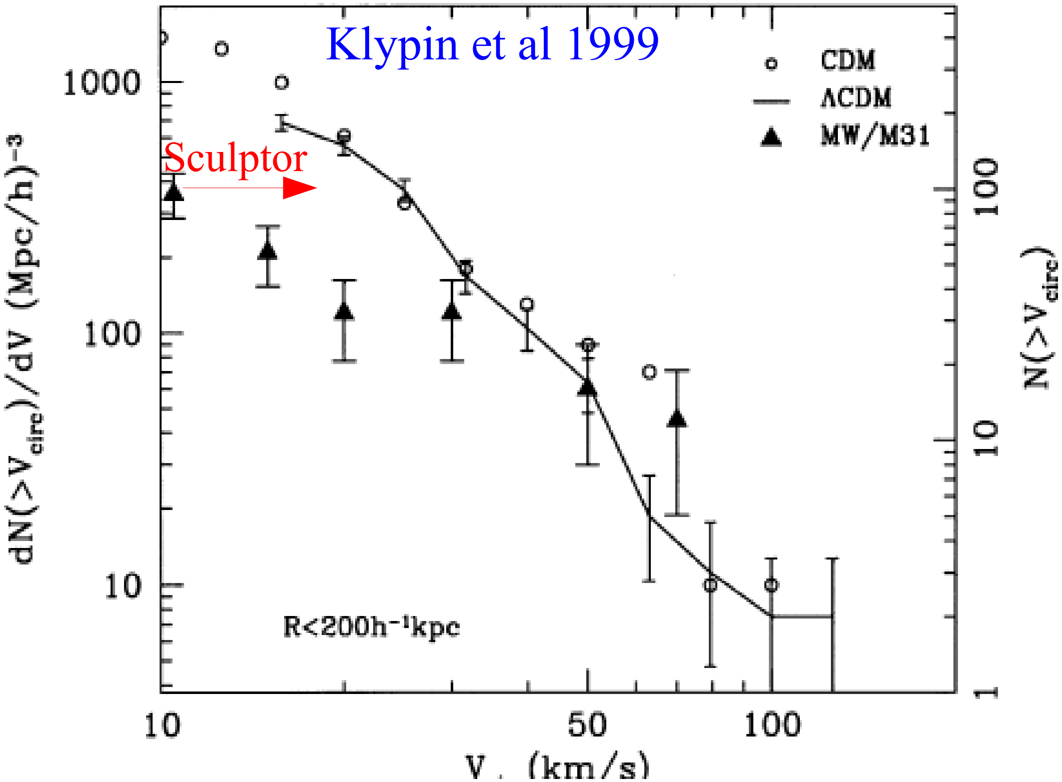
Strigari et al 2015

The Walker & Penarrubia (2011) data show no clear indication of two populations and only very weak correlations of metallicity (W') with radius or radial velocity

→ No robust way to separate into distinct populations to carry out an analysis like that of Battaglia et al (2008) or Strigari et al (2015)

Problems with numbers of dwarfs?





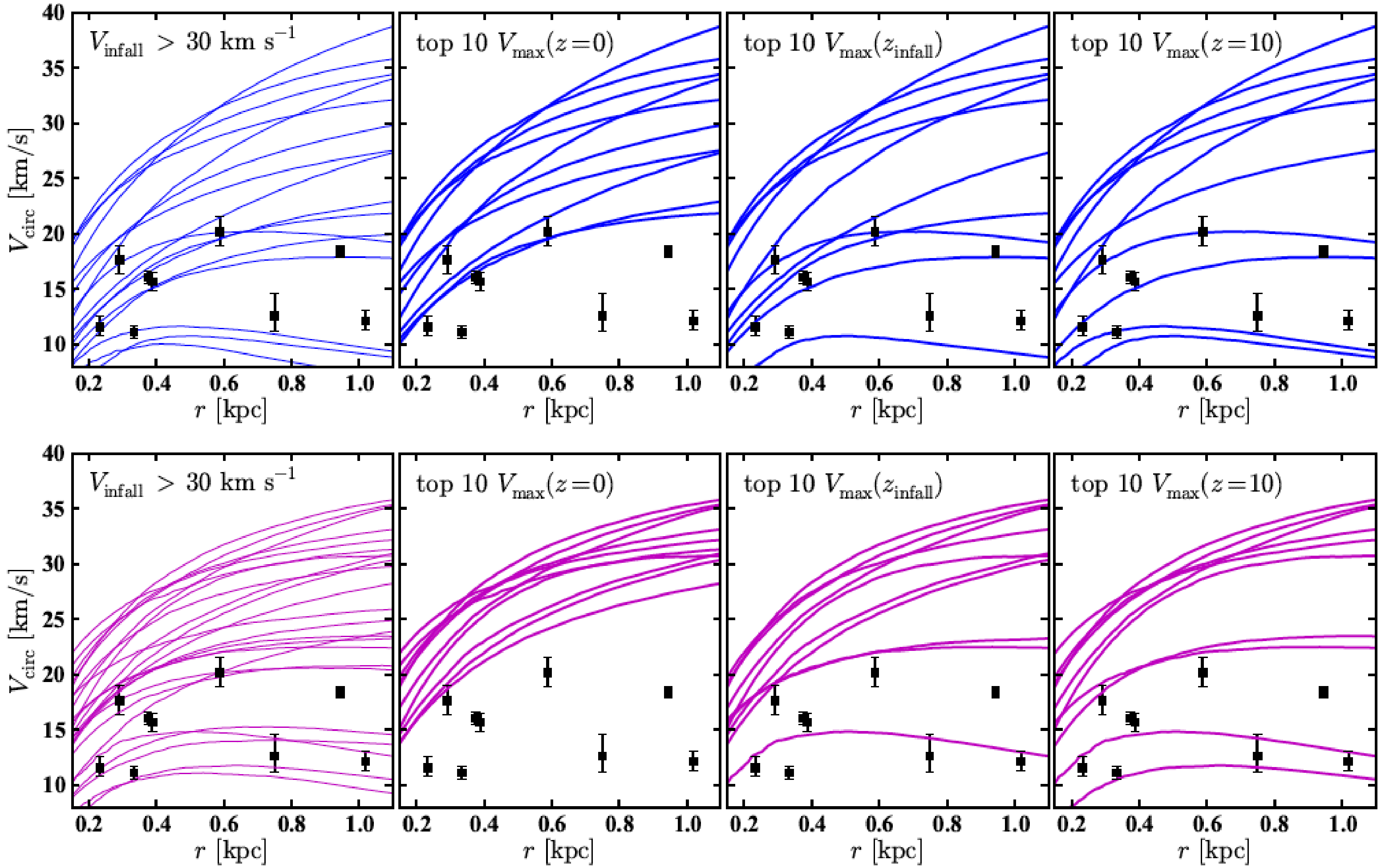
- N(Vmax / Vmax,MW) for LG dwarfs lies far below ΛCDM subhalo predictions
- ...but observed galaxies were plotted wrongly, greatly enhancing the problem
- After correction a problem nevertheless remains at the low mass end

There are fewer low Vmax subhalos than ΛCDM predicts

or many low Vmax subhalos contain no stars

or Vmax is incorrectly estimated for observed galaxies

Problems with numbers of dwarfs?



Boylan-Kolchin et al 2012

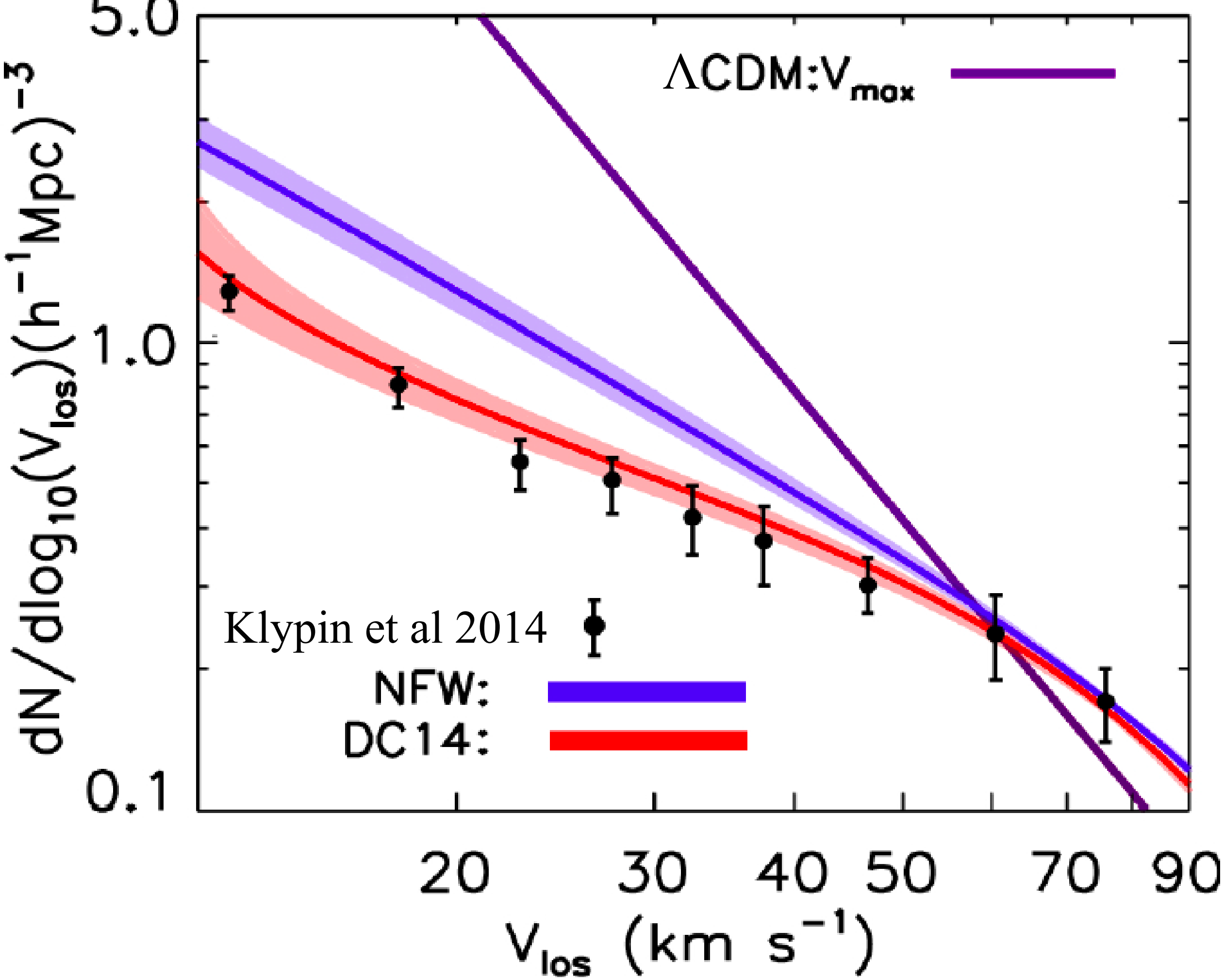
Aquarius B
$M_{vir} \sim 9.5\text{x}10^{11} M_\odot$

Aquarius E
$M_{vir} \sim 1.4\ \text{x}10^{12} M_\odot$

- For the 9 bright dSph's in the MW halo, $r_{1/2}$ and $V_{circ}(r_{1/2})$ are well measured
- The implied densities are lower than expected in massive ΛCDM subhalos
- Such subhalos are "too big to fail" to make galaxies, so **either**:
  (i) galaxy formation has changed the inner structure of halos, **or**
  (ii) the IC's and/or DM properties differ from ΛCDM

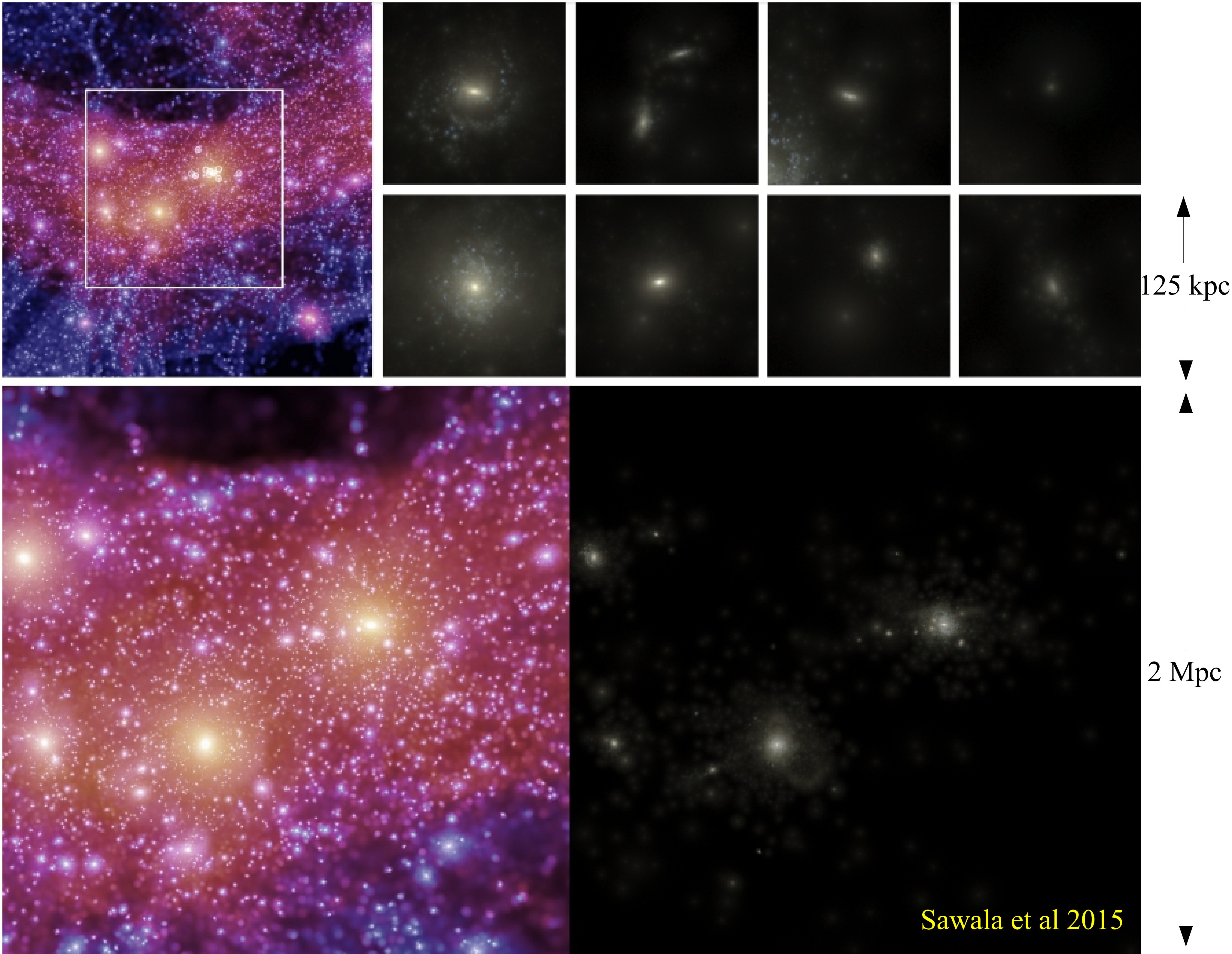
Problems with numbers of dwarfs?

Abundance of dwarf galaxies in the field



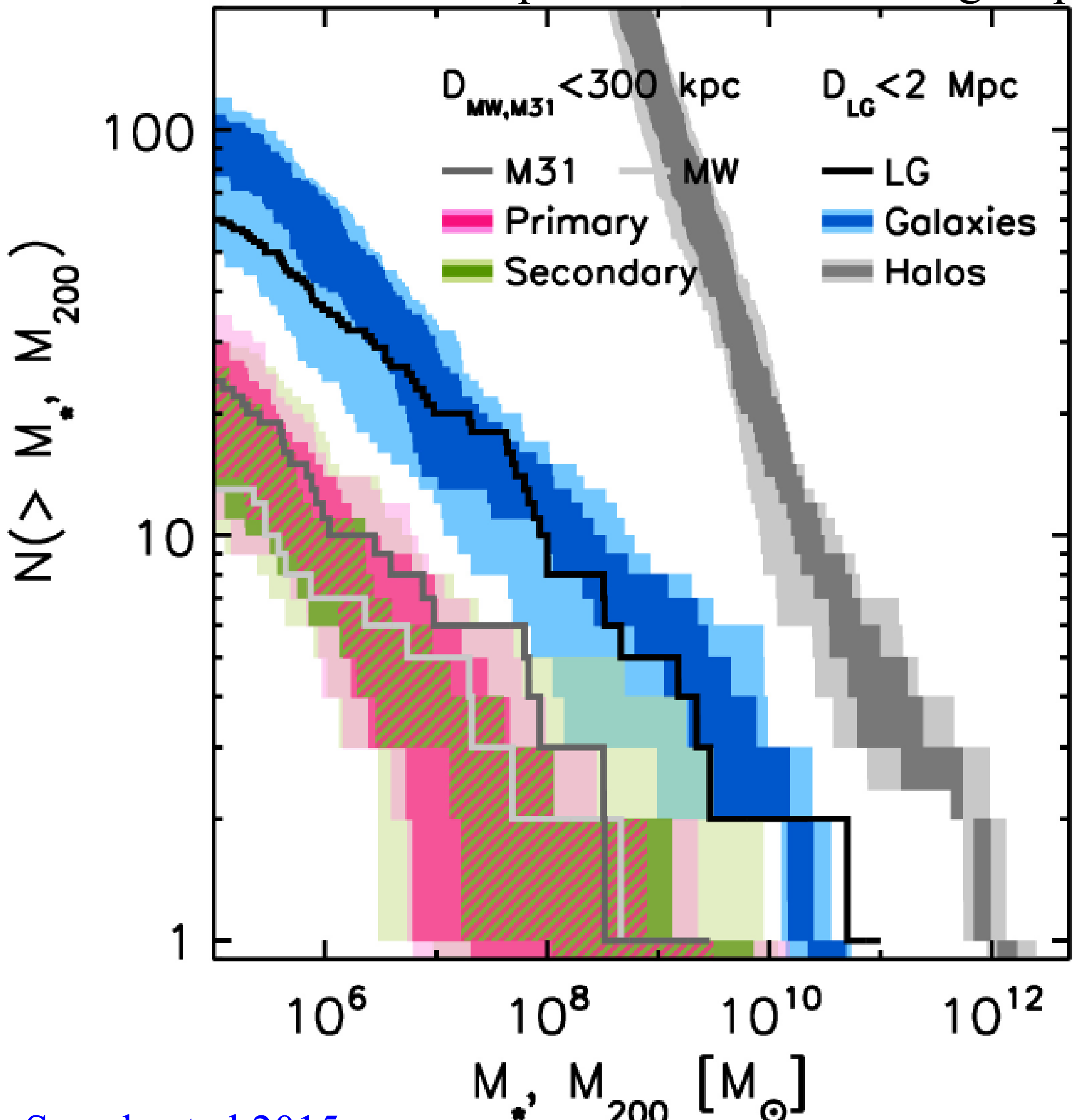
- n(V) for field galaxies lies well below n(V_{max}) for halos
- Much of the effect may be due to small size of dwarfs
- The rest may be due to the effects of galaxy formation
- Alternatively it may reflect WDM or SIDM

Brook & Di Cintio 2015


125 kpc
2 Mpc
Sawala et al 2015

Problems with numbers of dwarfs?

Results for 12 Local Group simulations with 'Eagle" physics

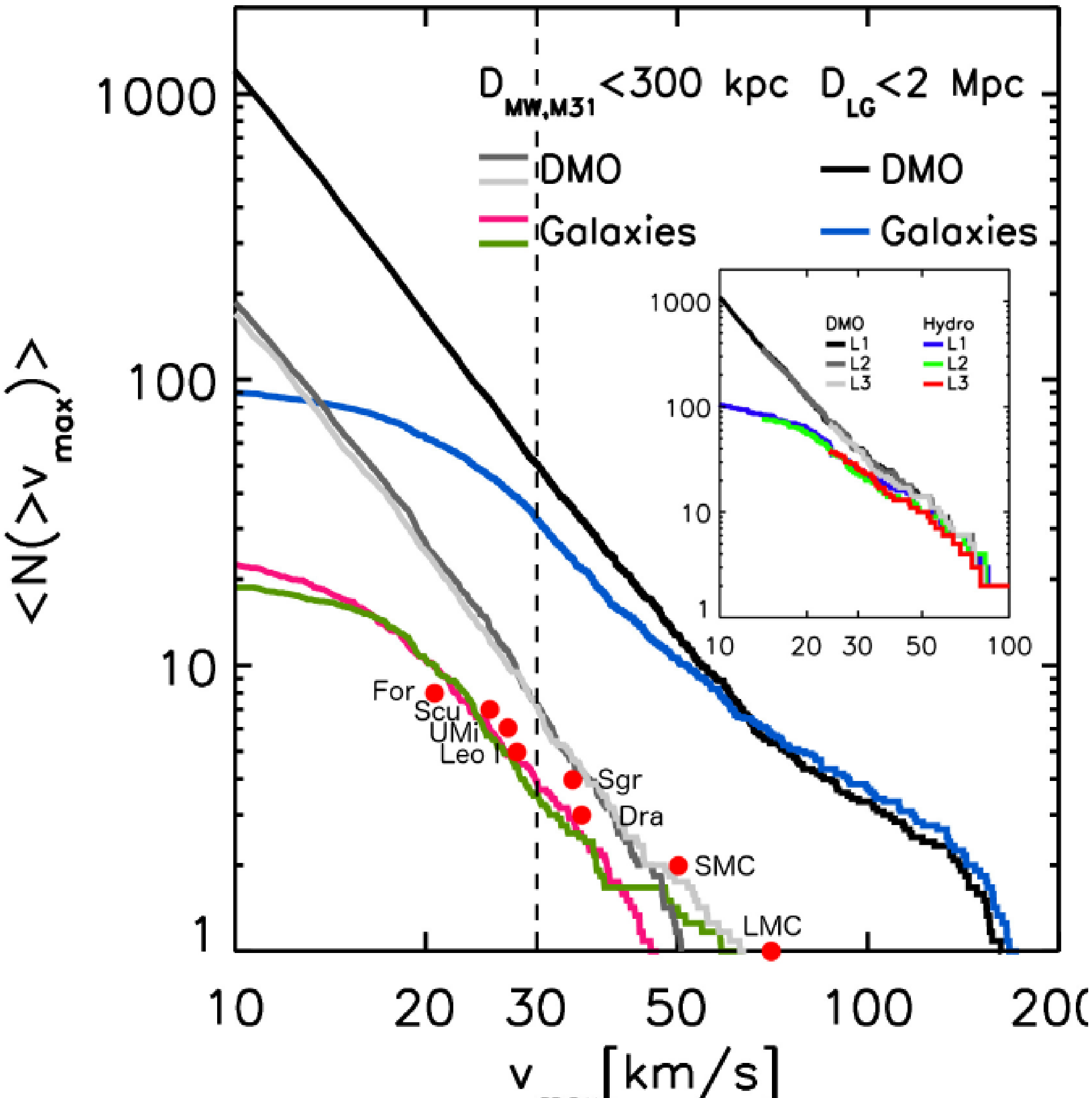


Sawala et al 2015

- The number of halos in the Local Volume increases rapidly with decreasing DM mass
- The number of galaxies increases much less rapidly with M* and agrees with that observed
- The number of satellites around the primary/secondary galaxies agrees with M31/MW data

Problems with numbers of dwarfs?

Results for 12 Local Group simulations with 'Eagle" physics



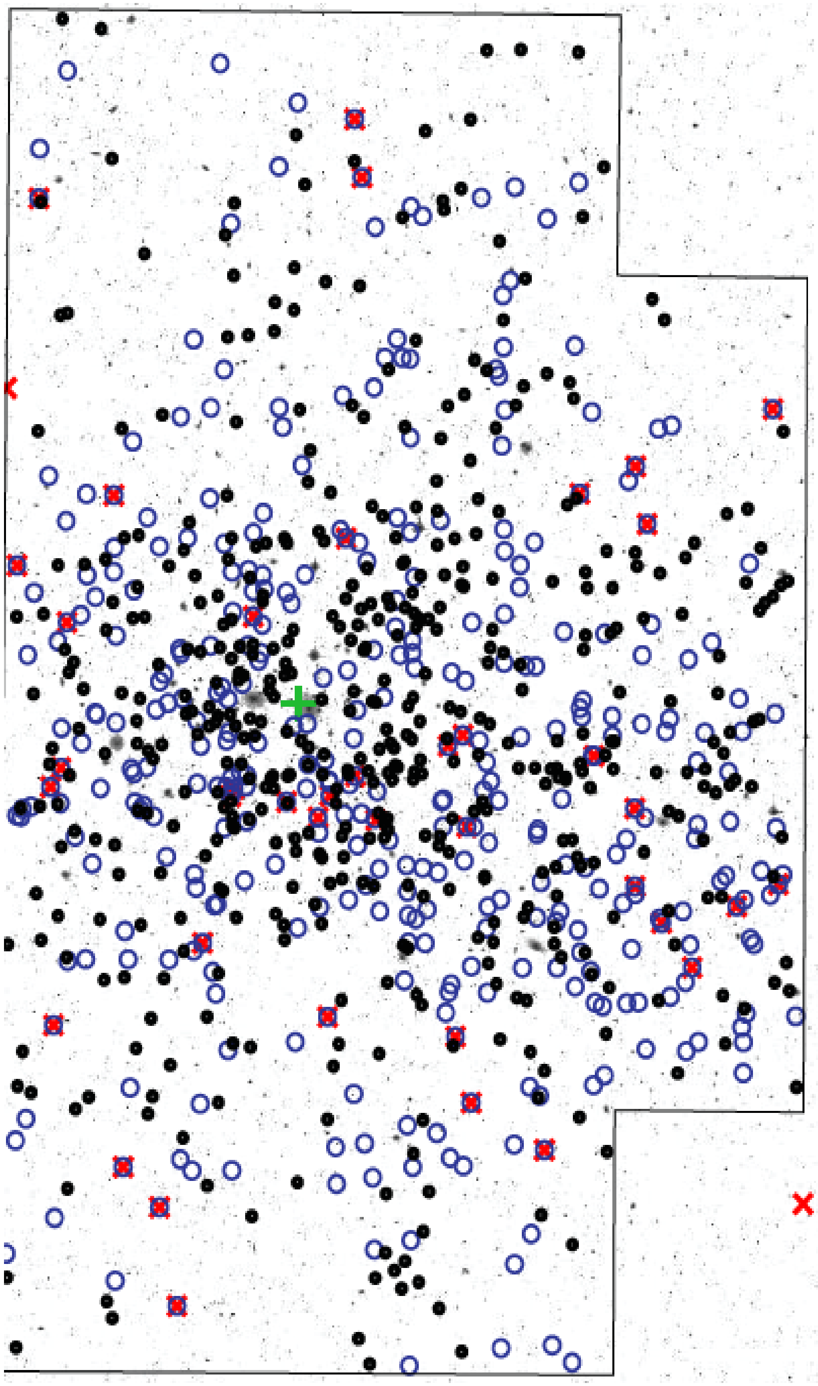
Sawala et al 2015

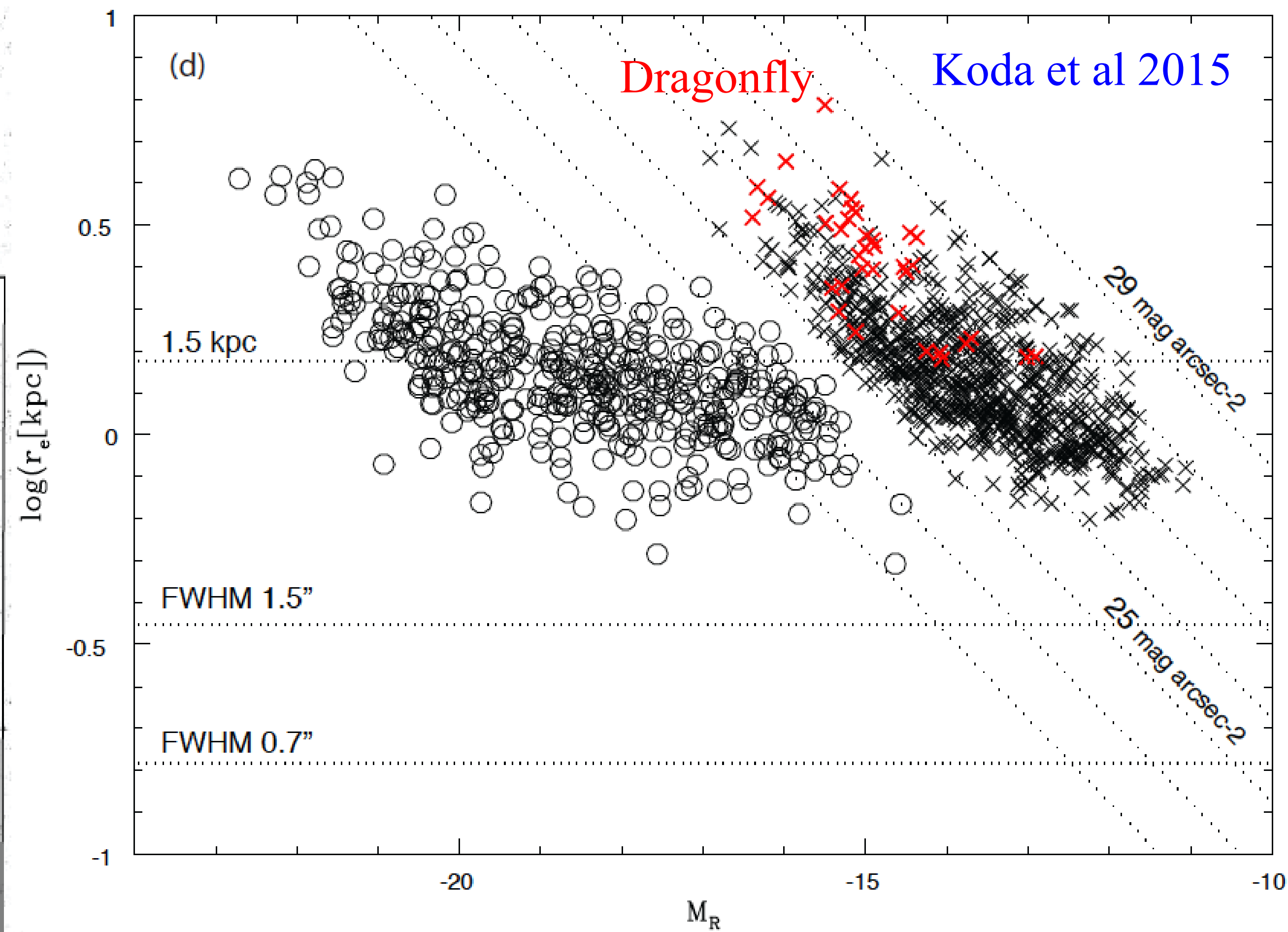
- Few Local Volume halos with Vmax < 20 km/s contain galaxies
- The number of galaxies with Vmax > 20 km/s is a third the number of such DM subhalos
- The number of satellites around the primary/secondary galaxies agrees MW data for Vmax values from Penarrubia et al (2008)

→ No satellite problems?

NB Strong effects here from reionisation, SN feedback, stochastic assembly histories but **no** cusp/core conversion

Another surprise from "dwarfs"?



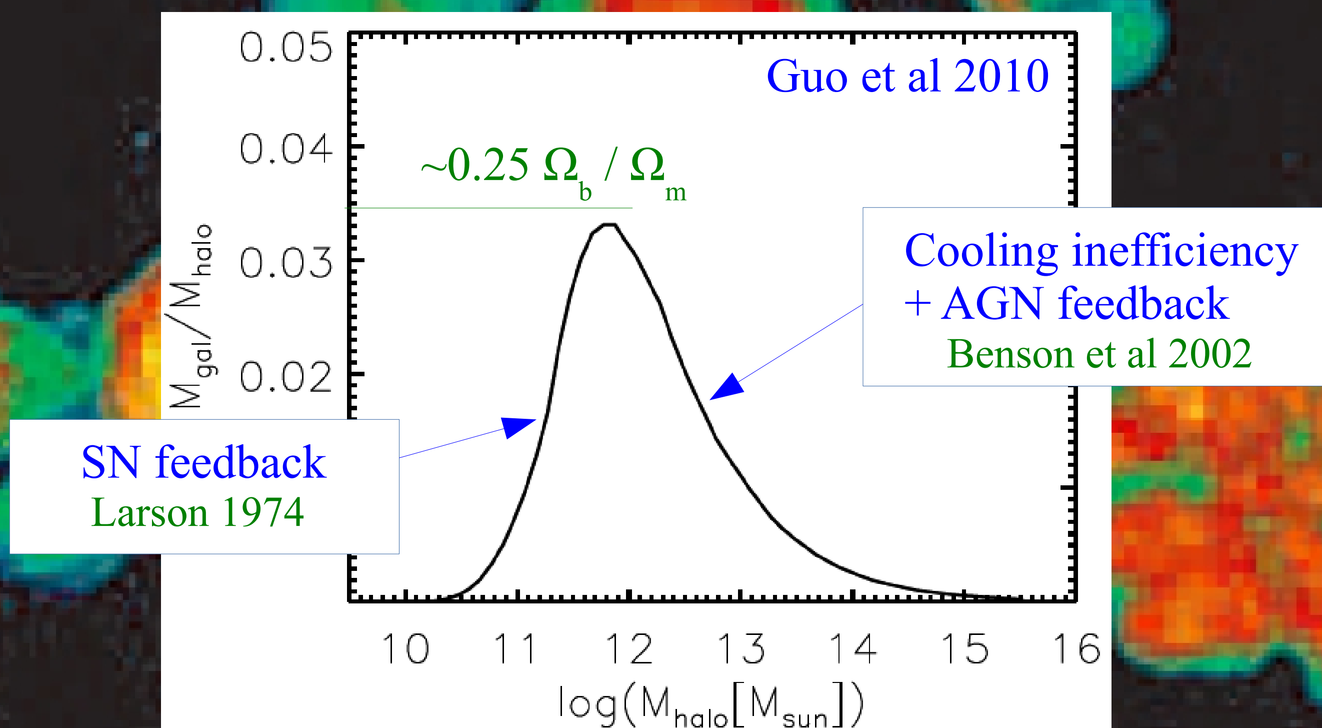


- Subaru has found ~10^3 "new" Coma galaxies
- Smooth, passive and similar size to known galaxies but >100 times fainter
- How do they form and survive?

Central galaxies contain <25% of the expected halo baryons, even for the *most* efficient halo mass, roughly that of the Milky Way

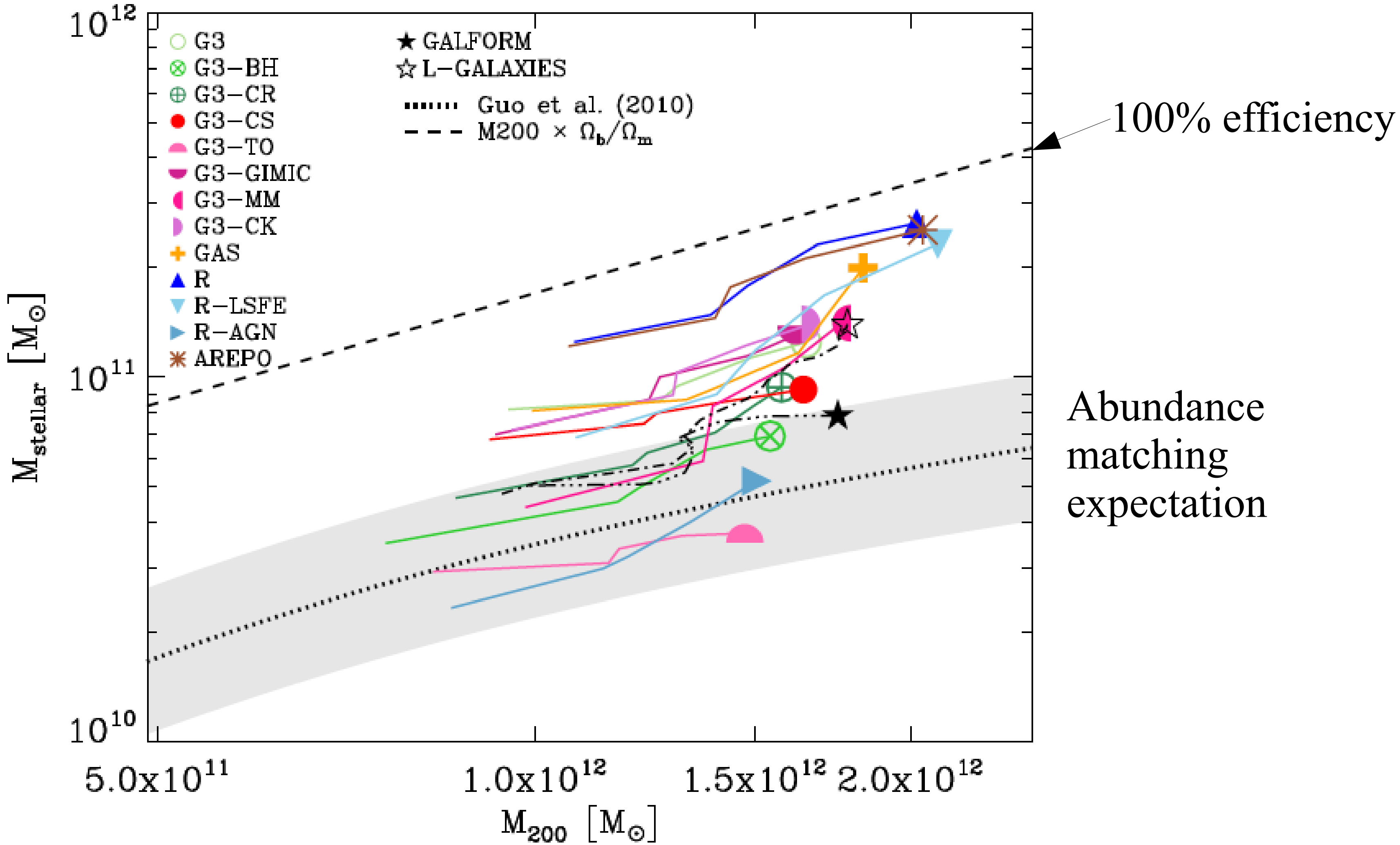
In rich clusters most of the expected baryons are in the IGM, but in lower mass halos most are seen only through their SZ signal (?)

Blown out? How far? What are the consequences for galaxy formation?



Can we simulate galaxy formation?

Scannapieco et al 2012



13 "state-of-the-art" hydrodynamic and 2 semi-analytic simulation codes run on the <u>same</u> initial condition set (for a "Milky Way" halo).

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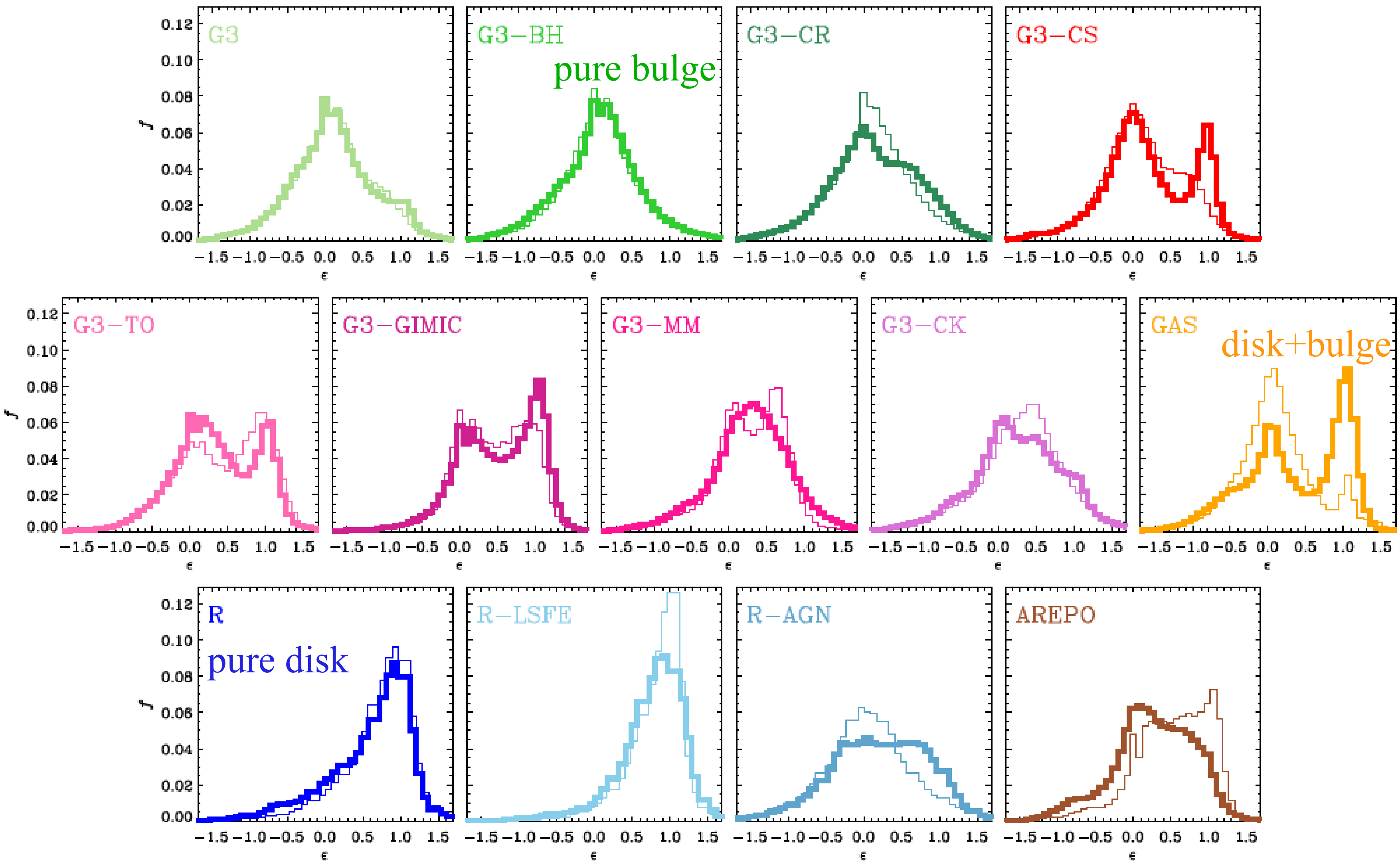
Scannapieco et al 2012



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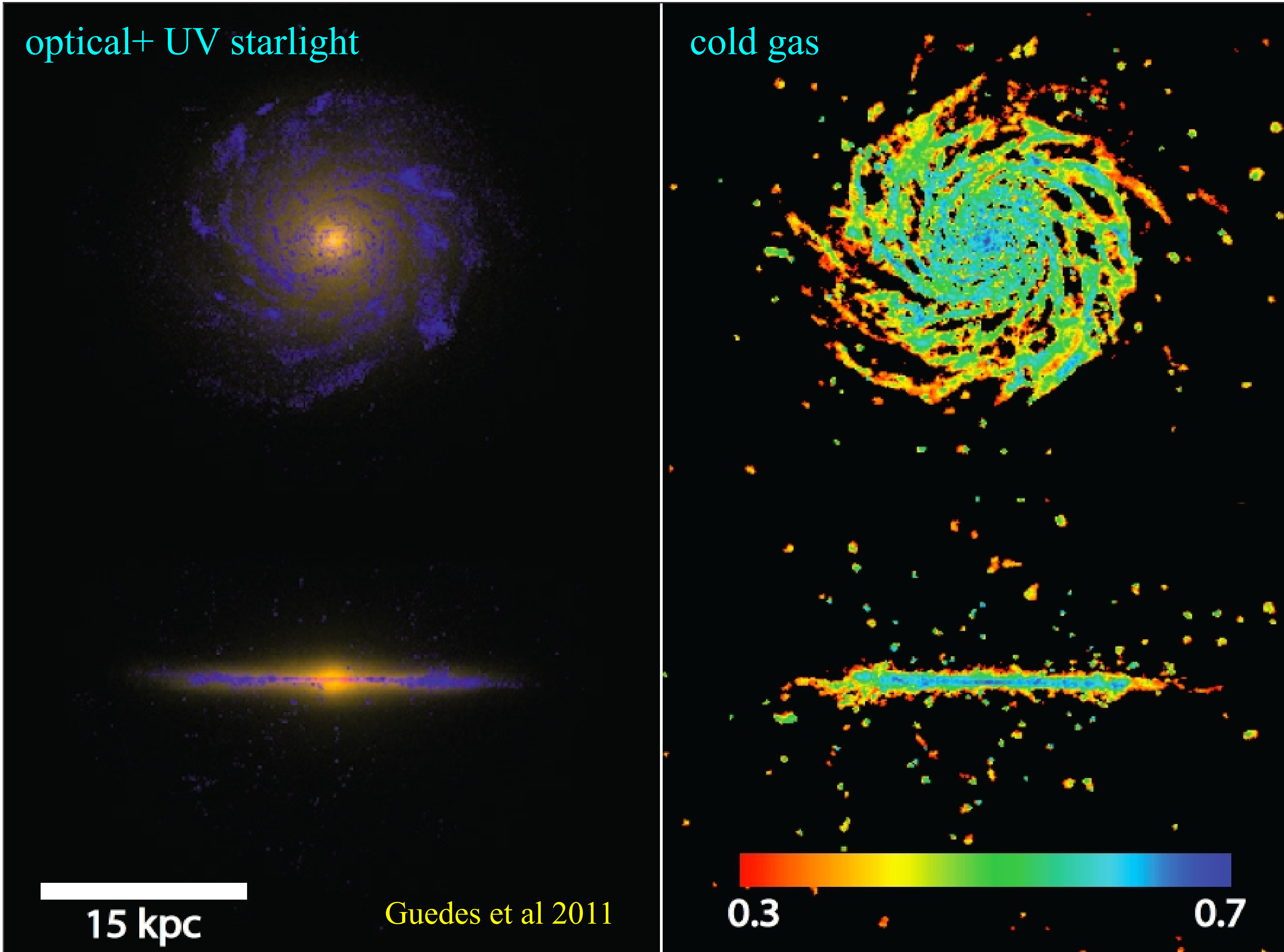
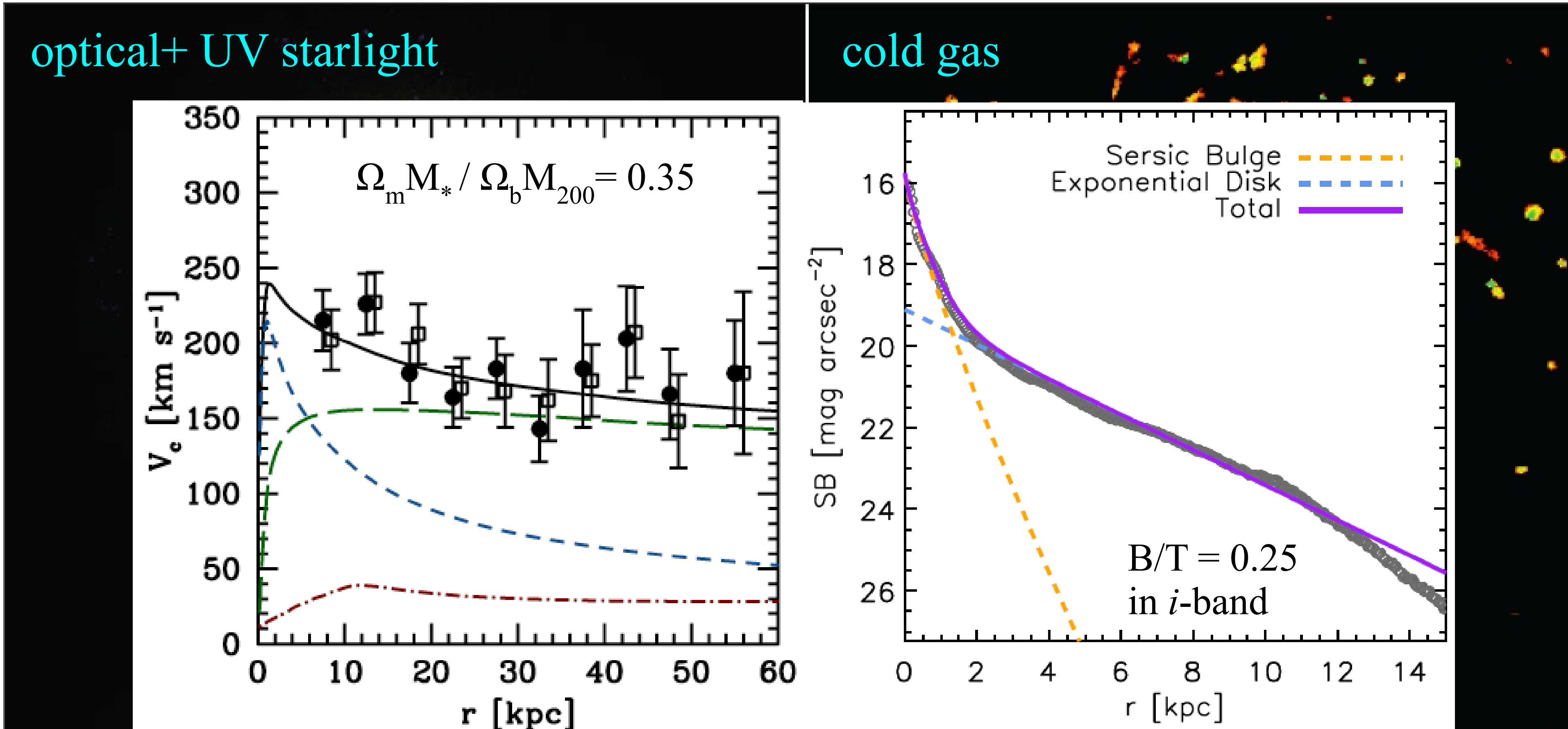
Eris – a particularly successful example ?

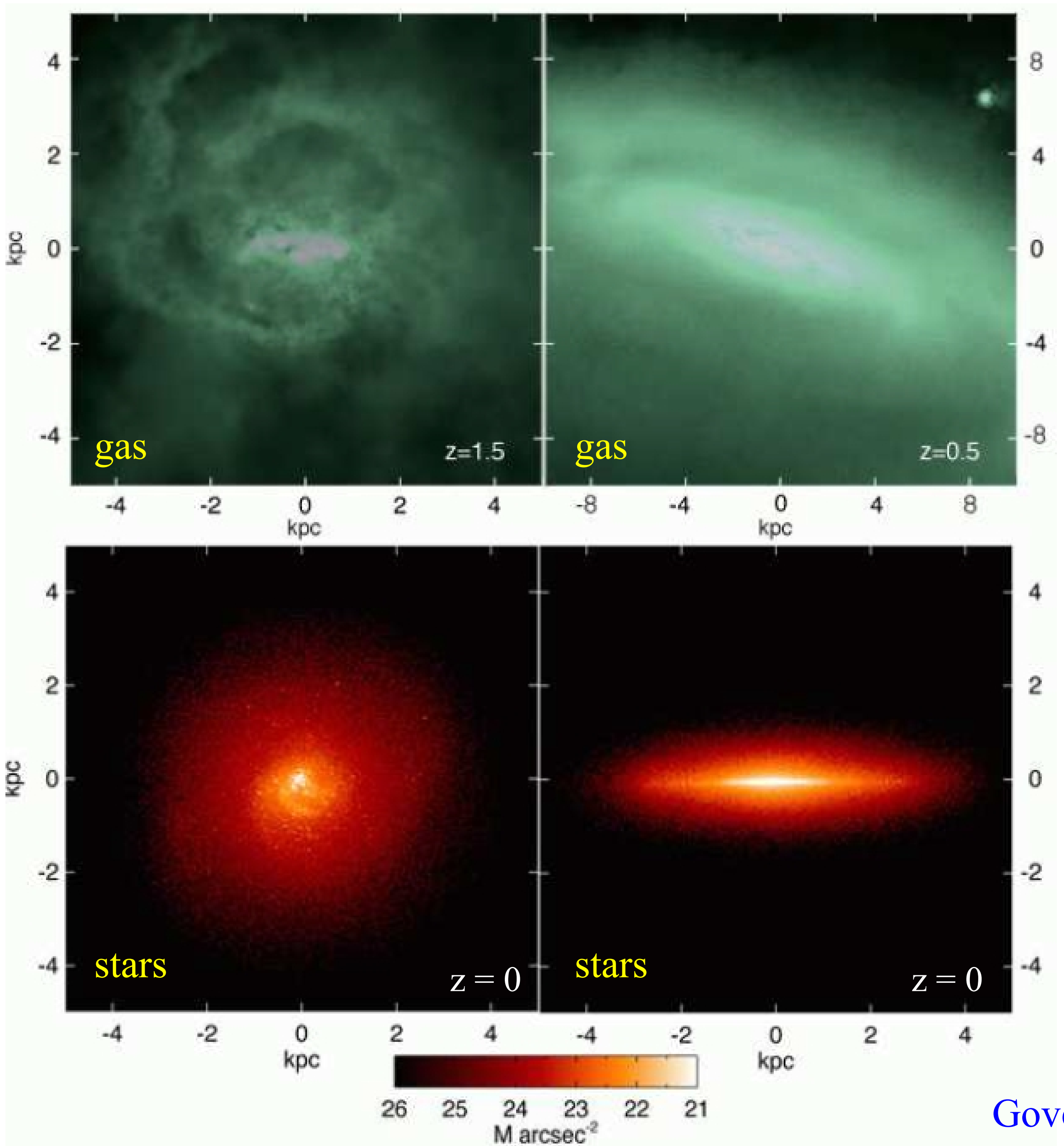


Eris – a particularly successful example ?



Success due to: high spatial and mass resolution
high density threshold for star formation
→ efficient wind generation

DG1 – a bulgeless dwarf



Governato et al 2010

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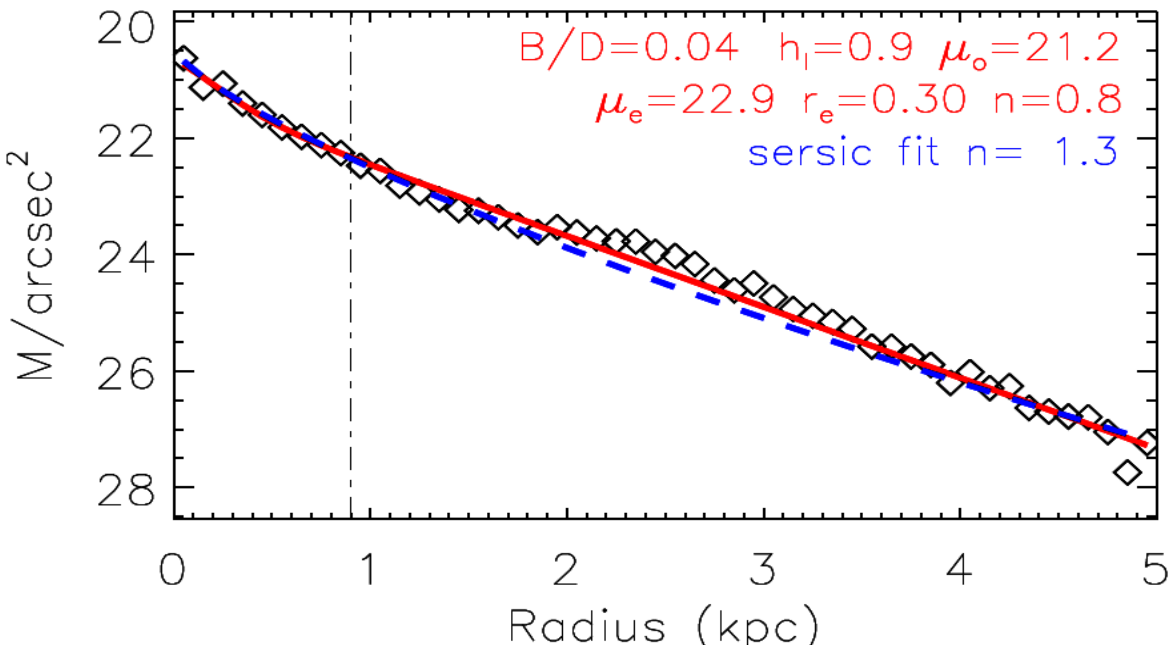
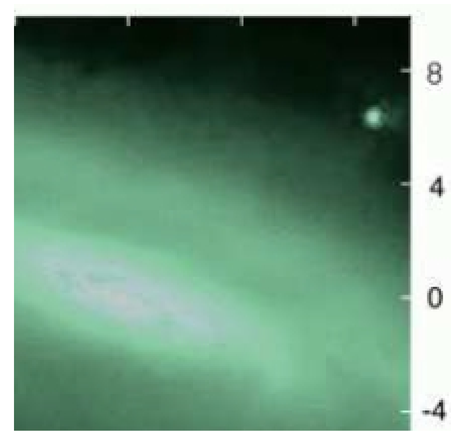
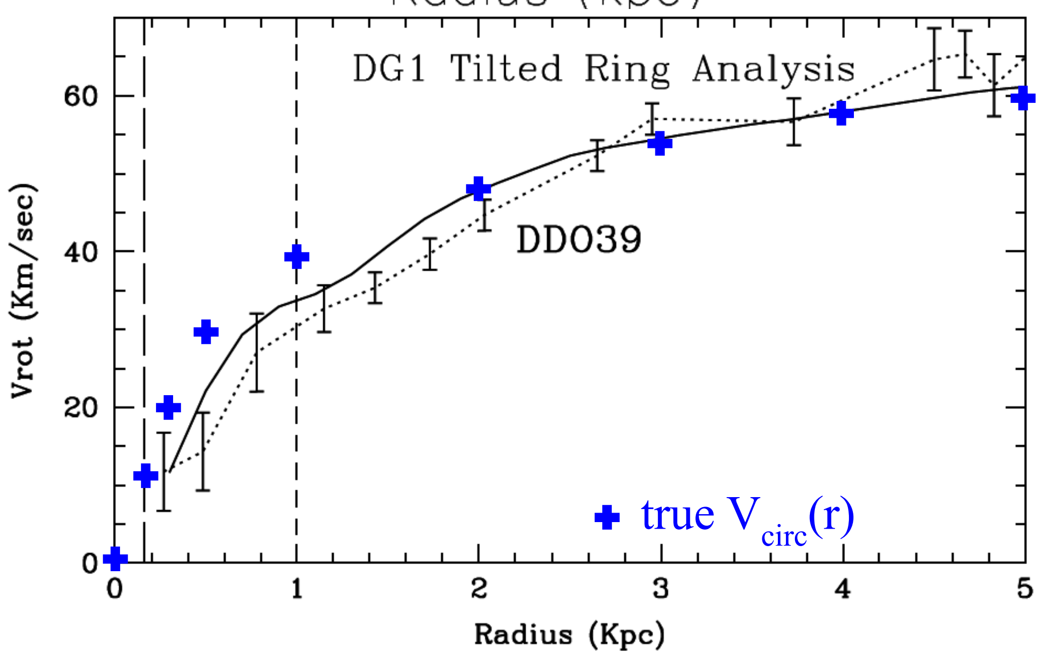
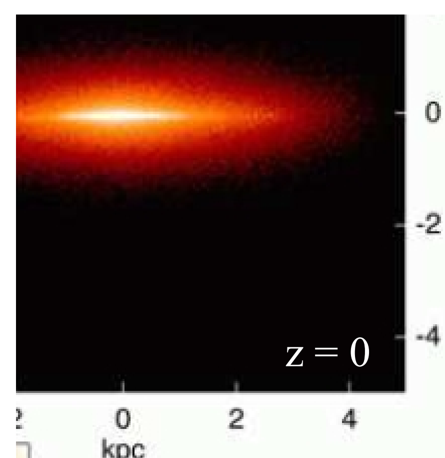


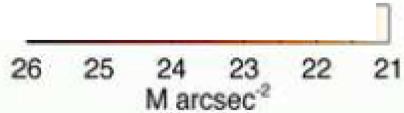


- Success again due to bursty, high threshold star formation?

- “Cored” rotation curve is due to “observational” analysis

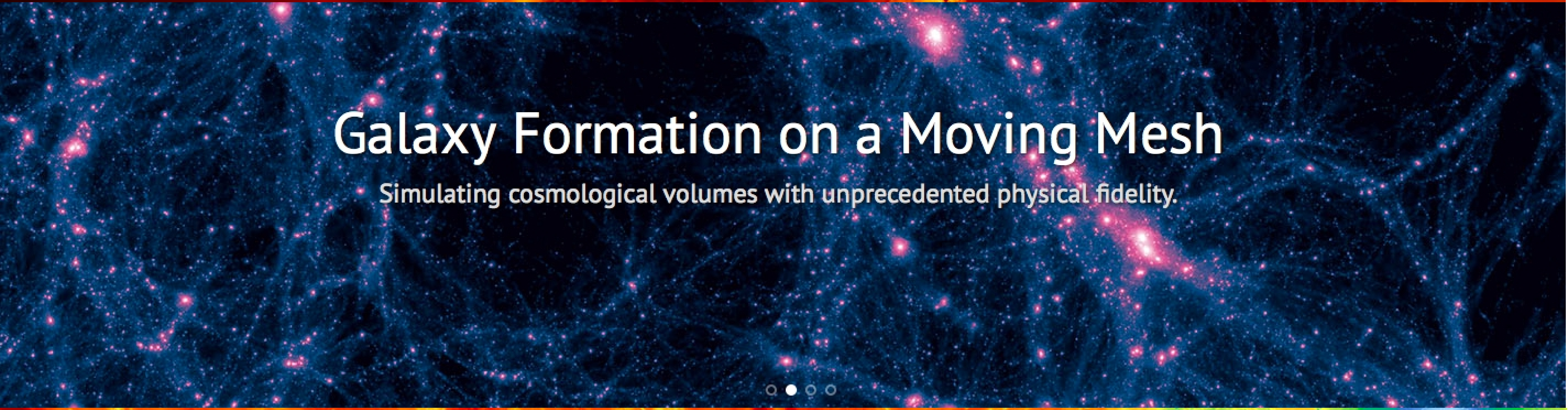






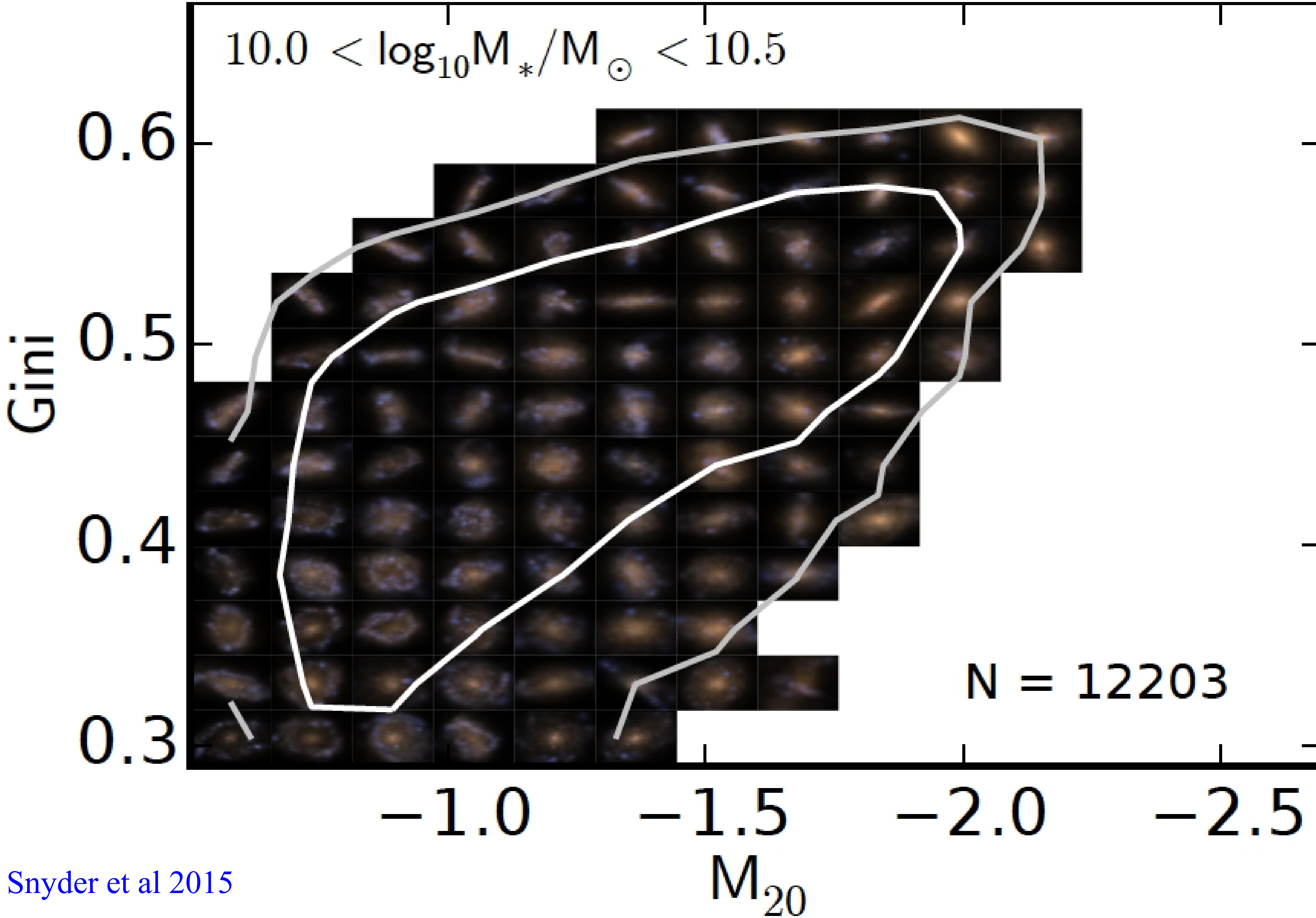
Governato et al 2010


The Illustris Simulation
Towards a predictive theory of galaxy formation.
www.illustris-project.org


Galaxy Formation on a Moving Mesh
Simulating cosmological volumes with unprecedented physical fidelity.

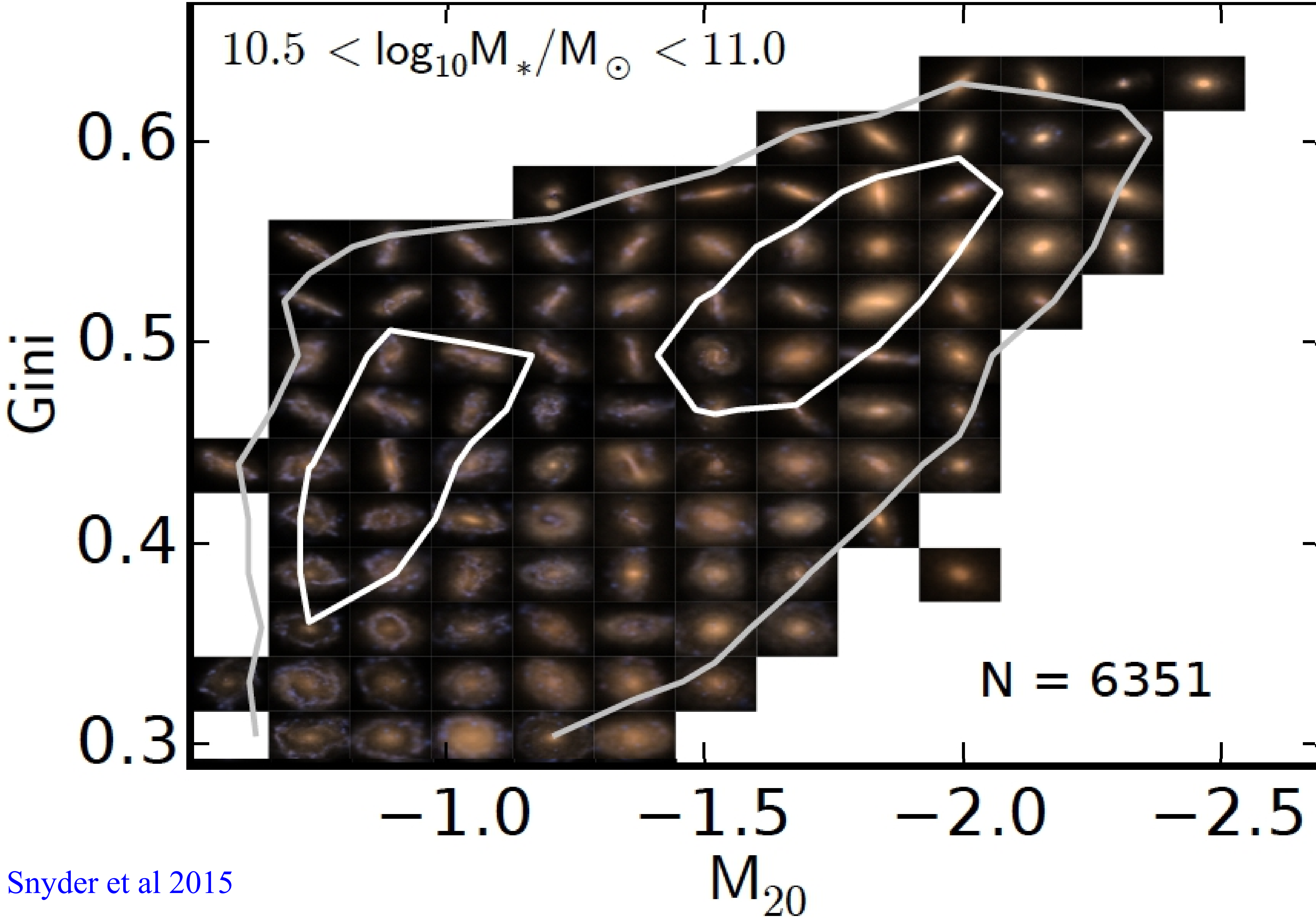

Populating the Hubble Sequence
Recovering the diversity of galaxy morphologies.

Morphologies in Illustris



Snyder et al 2015

Morphologies in Illustris



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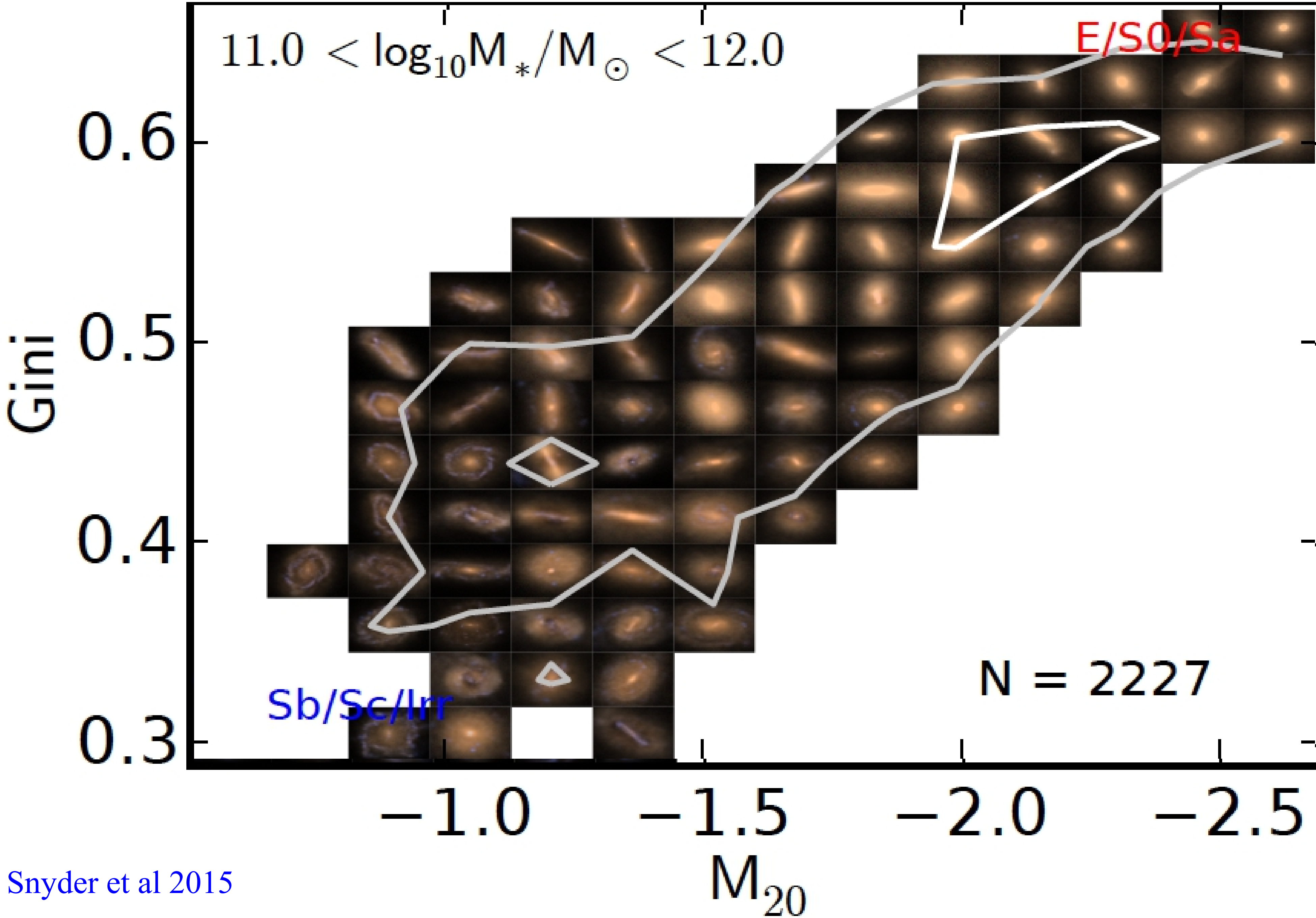

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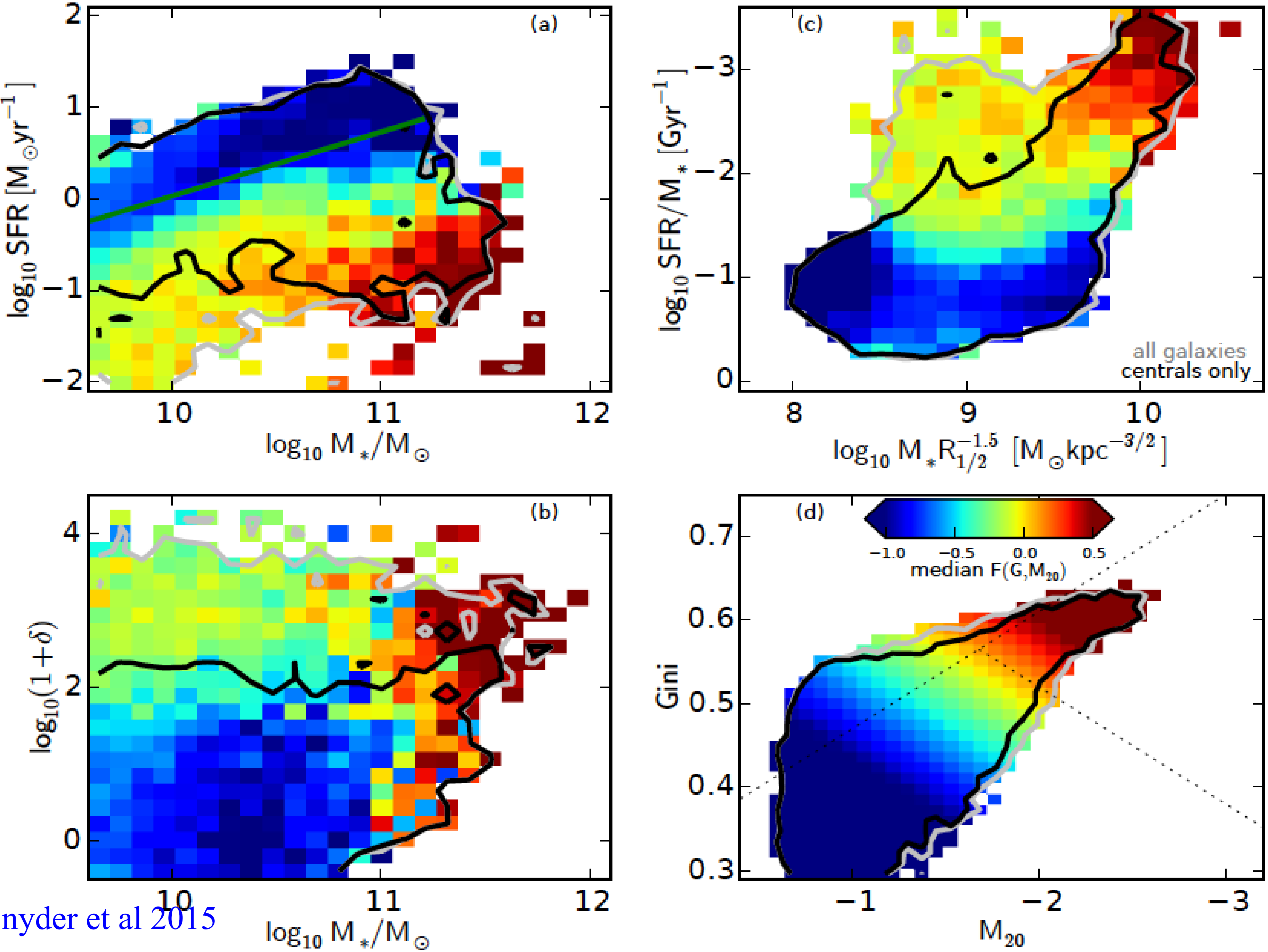
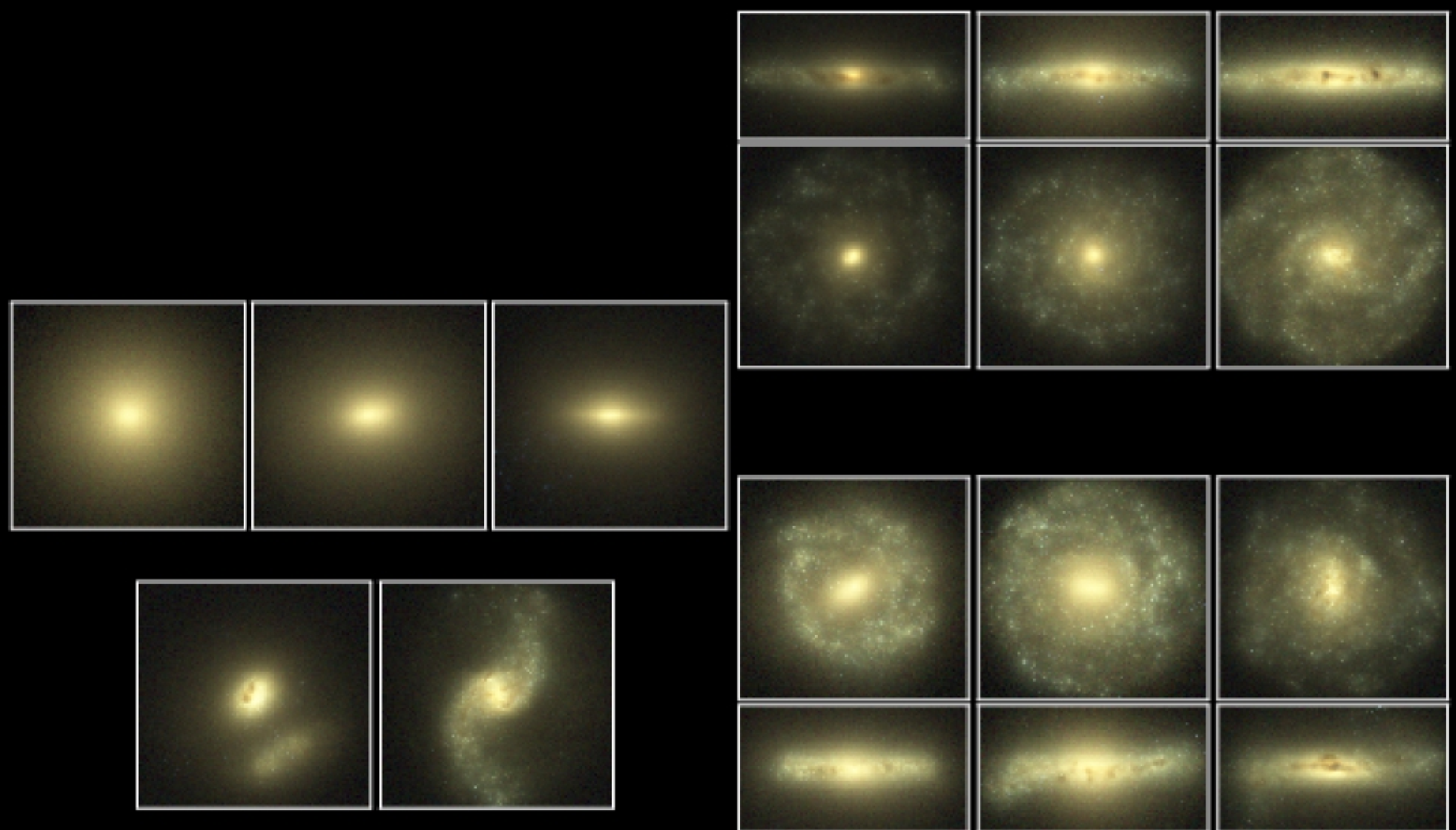


Snyder et al 2015

The EAGLE Simulations

Search

Evolution and Assembly of GaLaxies and their Environments



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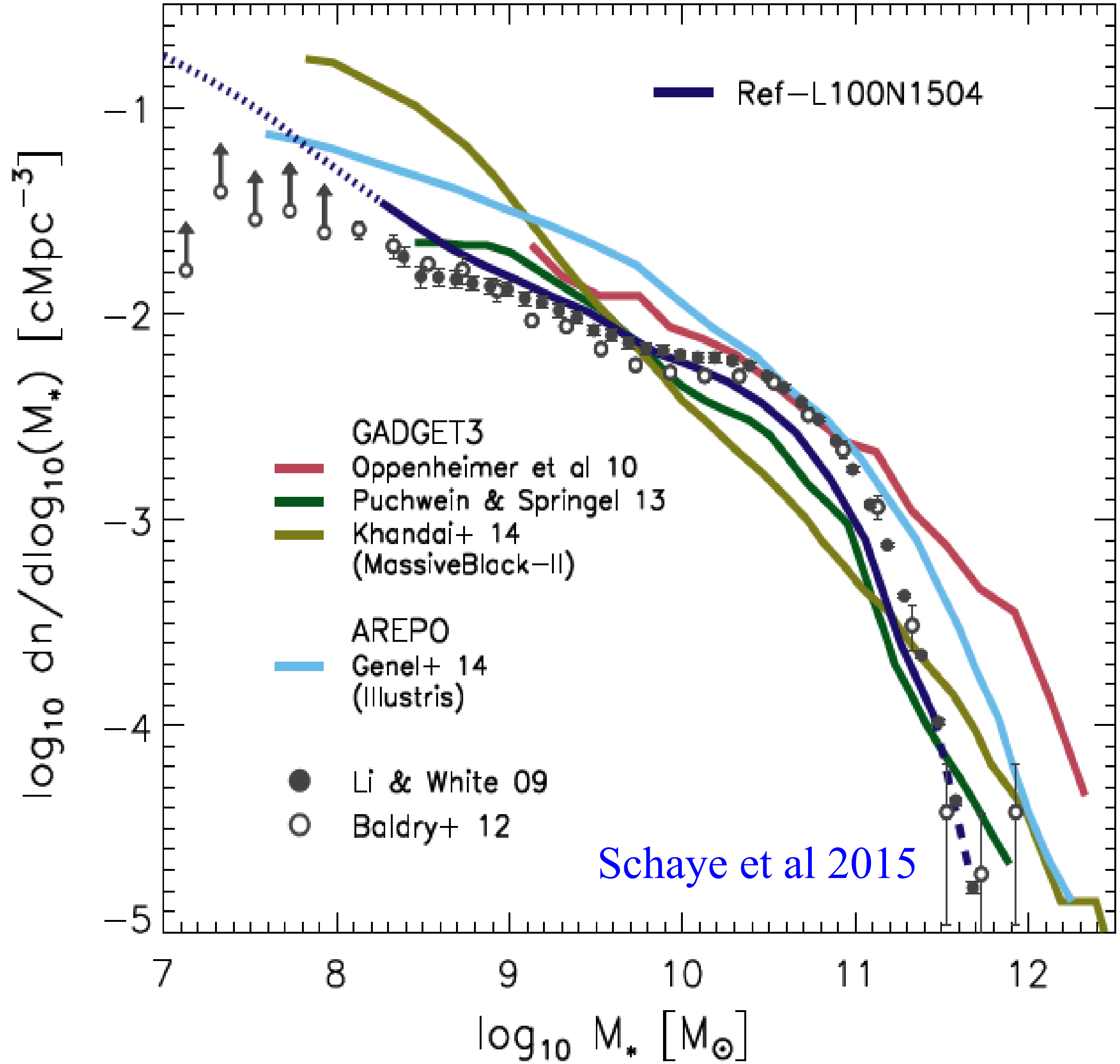
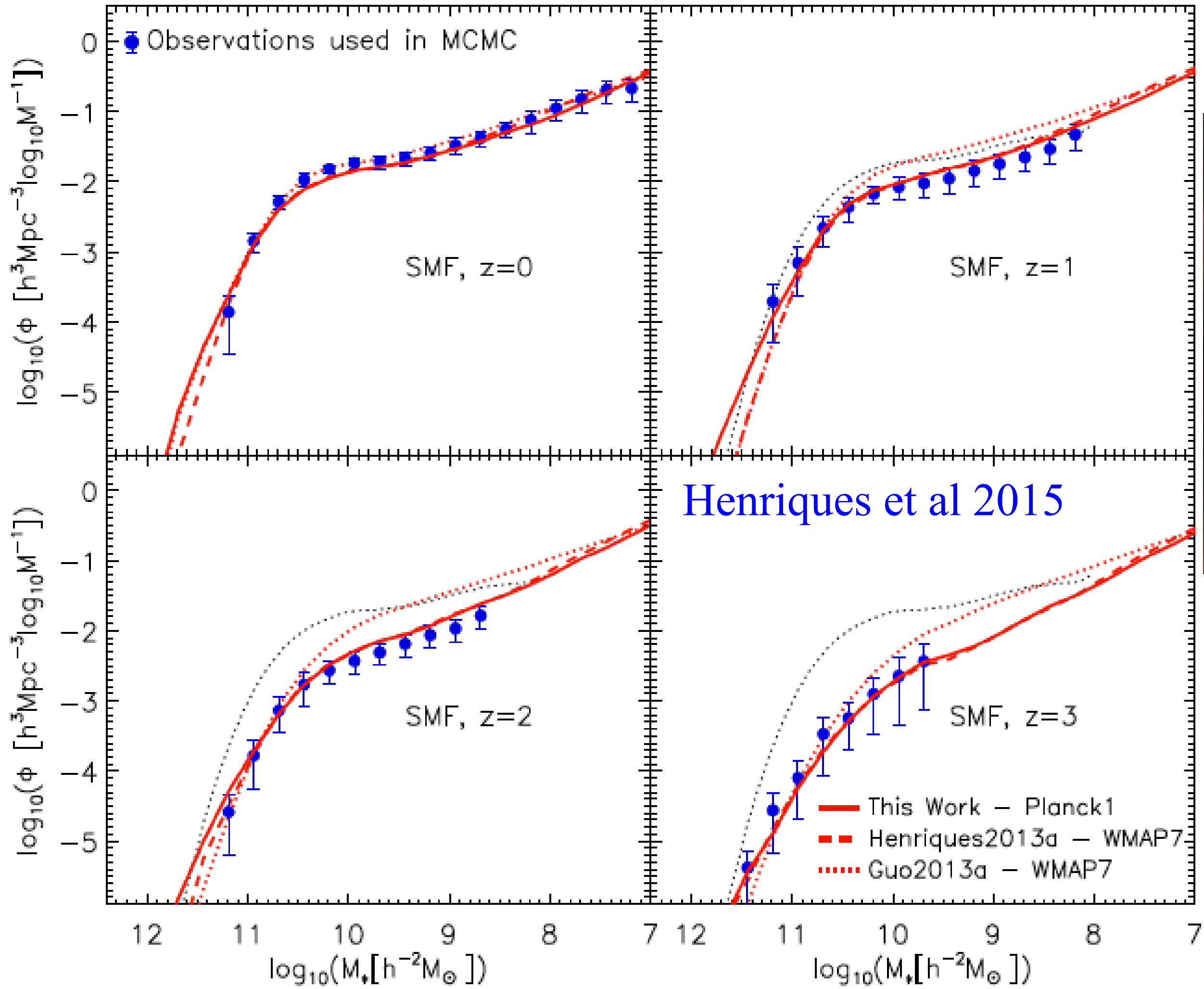


SN and BH feedback in both EAGLE and Illustris were *tuned* to reproduce the SMF at $z = 0$

Some other properties agree well with observation, but others do not (e.g. sizes, halo hot gas...)



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Systematic calibration to a range of data is much easier in semi-analytic simulations

...but some critical physics is still likely to be missing in all approaches (cosmic rays...)

Conclusions for six-parameter ΛCDM?

- On scales larger than visible galaxies the fits are excellent
- In galaxy centres DM densities appear lower than expected
- Galaxy formation is surprisingly inefficient and many aspects remain to be understood in detail, but most population systematics can be reproduced qualitatively.
- Simulation methods must all be observationally calibrated. We are still far from a full *a priori* theoretical description

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...but still no show-stoppers for the basic paradigm