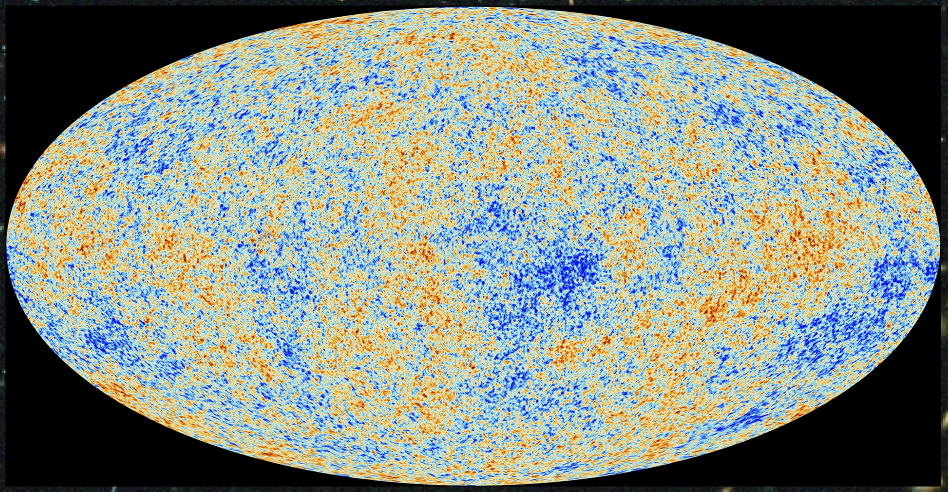
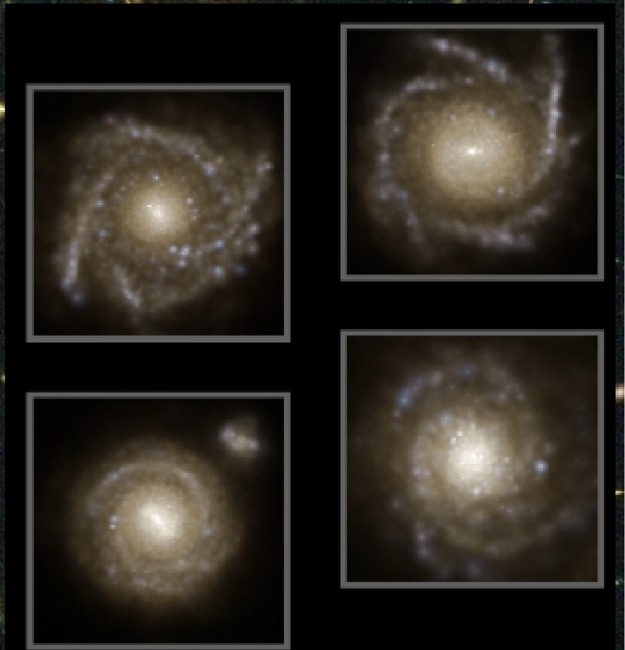


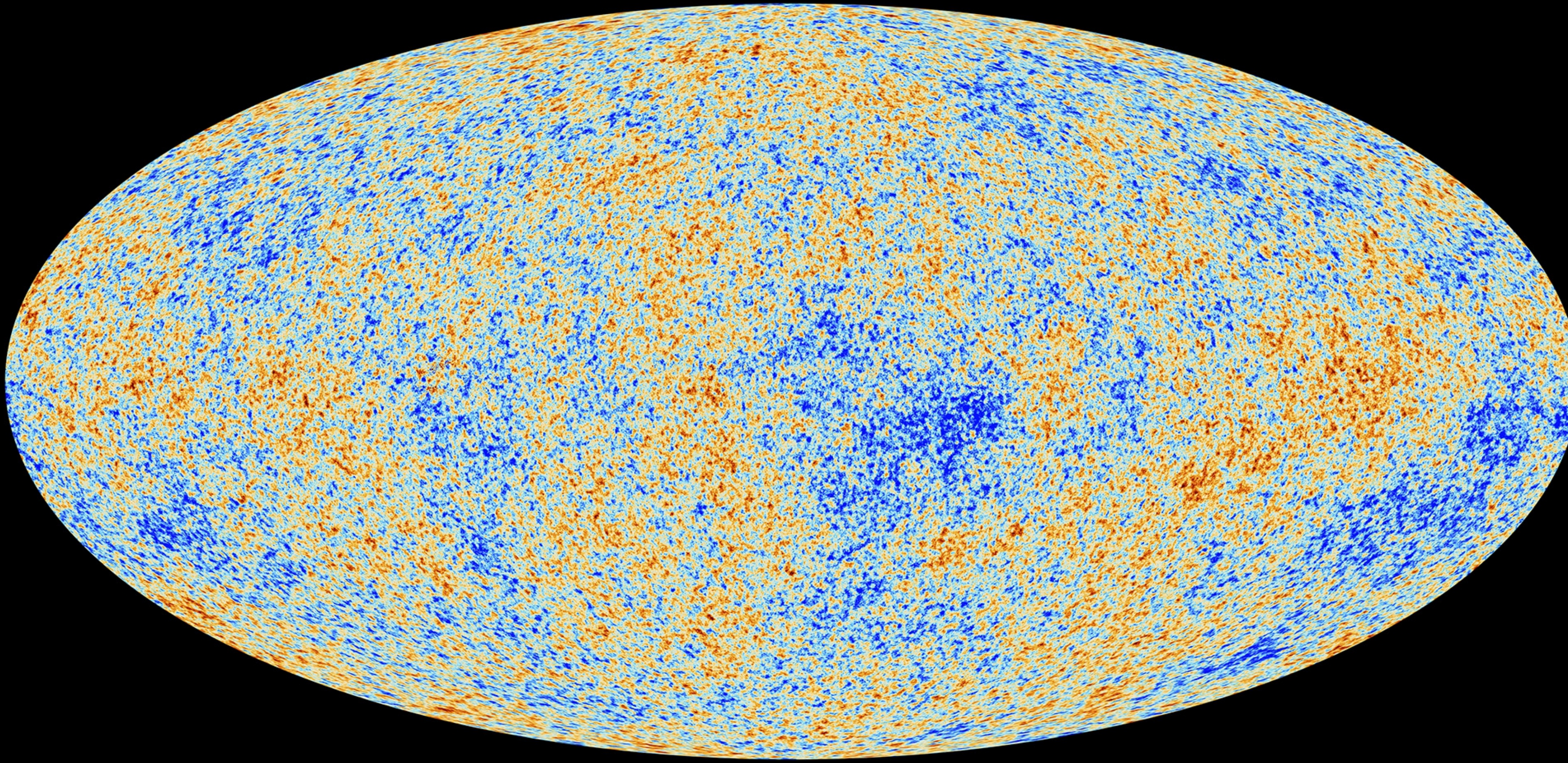
Potsdam, August 2014

Insights into galaxy formation from dwarf galaxies

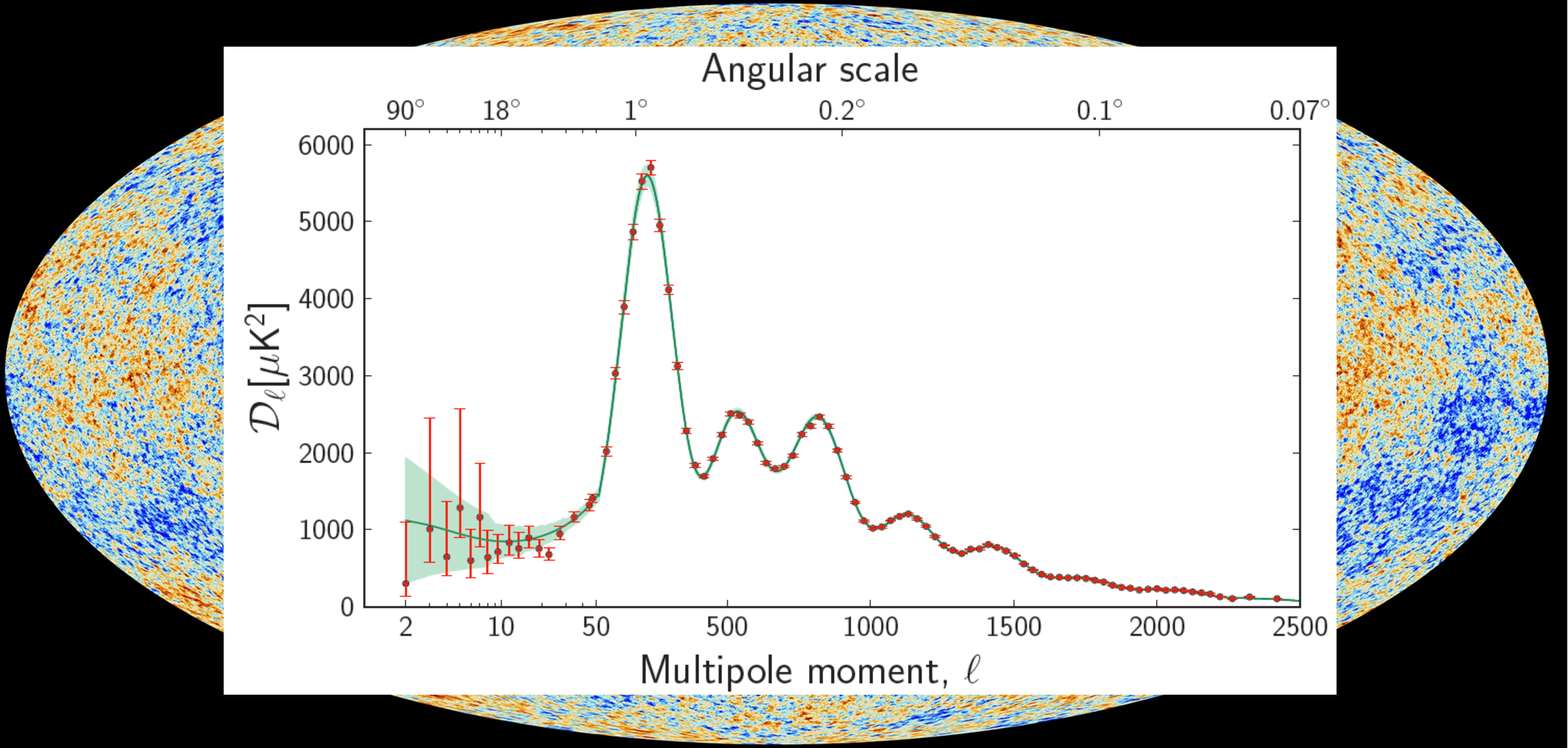


Simon White
Max Planck Institute for Astrophysics

Planck CMB map: the IC's for structure formation



Planck CMB map: the IC's for structure formation



The six parameters of the minimal ΛCDM model

	Planck+WP	
Parameter	Best fit	68% limits
$\Omega_b h^2$	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04119	1.04131 ± 0.00063
τ	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.0980	$3.089^{+0.024}_{-0.027}$

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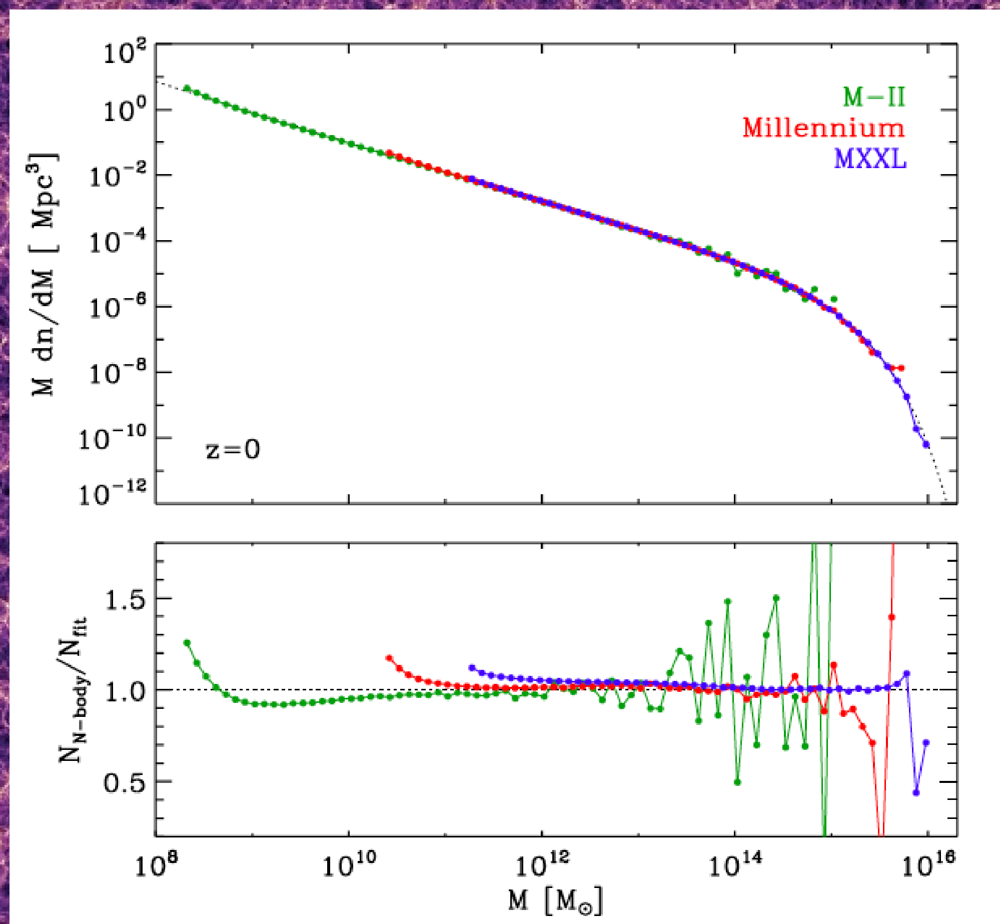
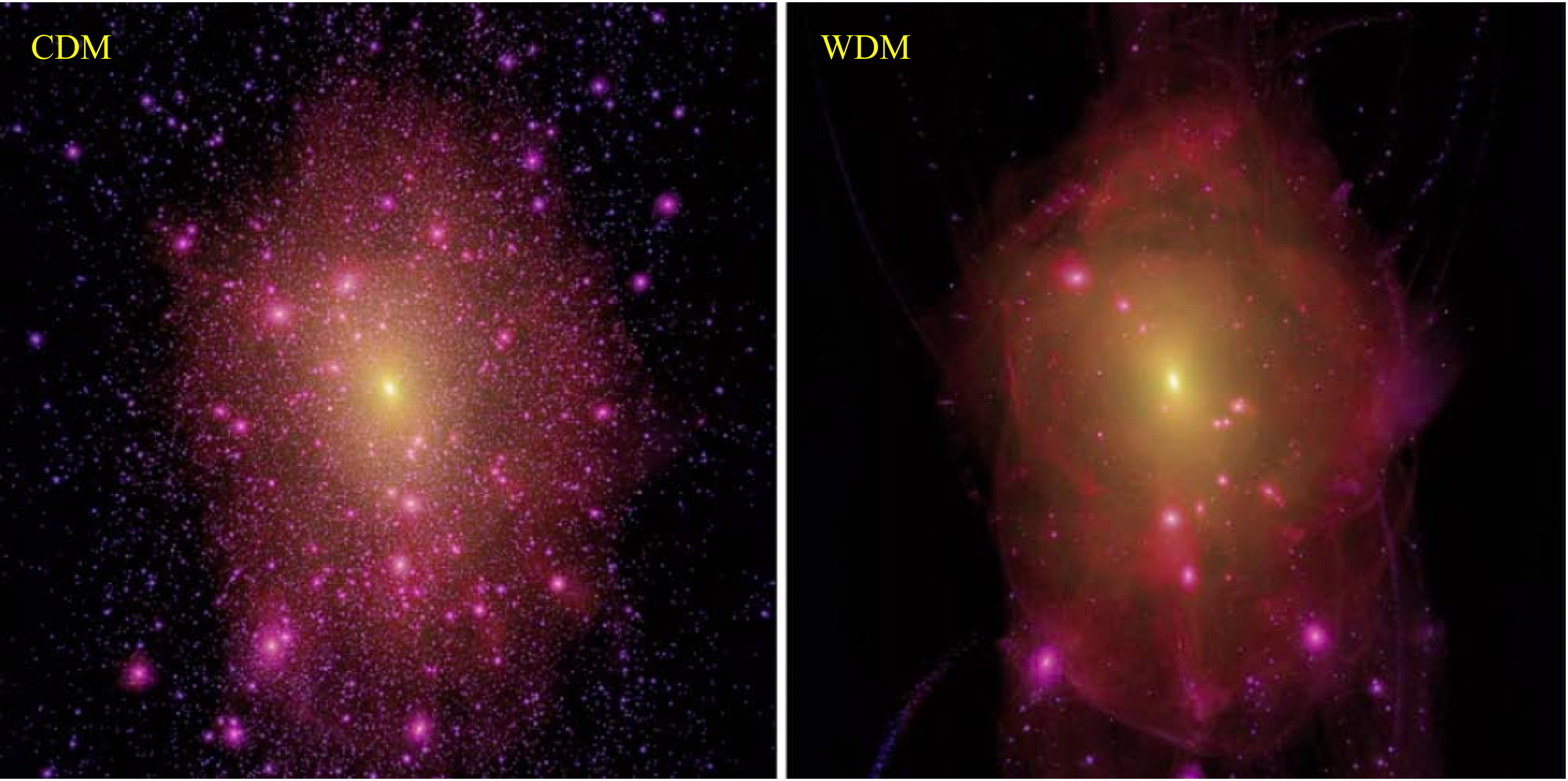
A 40σ detection of nonbaryonic DM using ***only*** z ~1000 data!

Given the known cosmology and initial conditions, N-body codes can simulate the evolution of the abundance, internal structure and clustering of dark halos at high precision



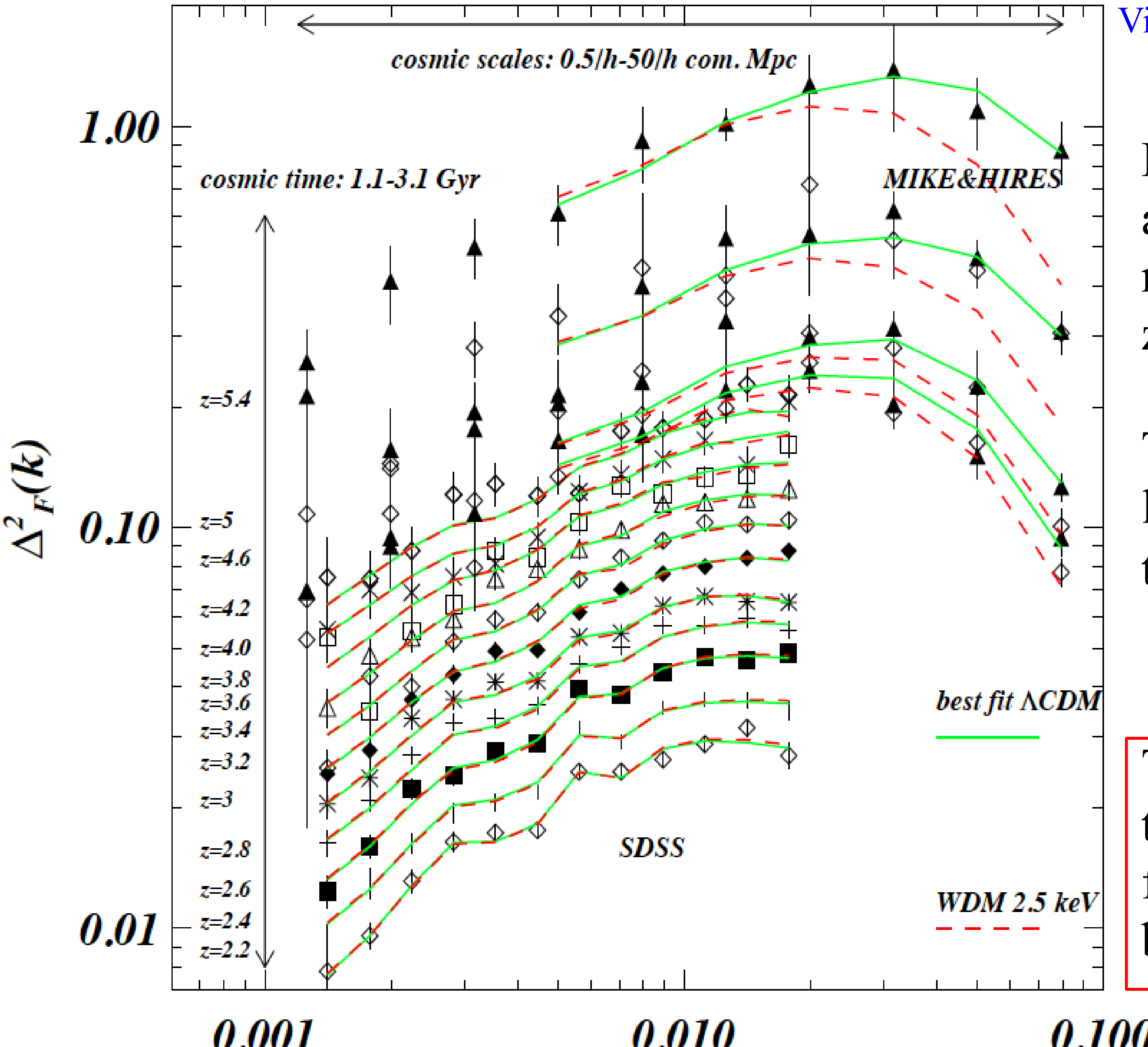
Small-scale structure and dwarf galazies

Lovell et al 2012.



A “Milky Way” halo in CDM and WDM (a 2keV sterile ν)

Lyman α forest power spectra support ΛCDM ICs



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 shows the DM to to be effectively cold for the formation of all but the faintest dwarfs

The six parameters of the minimal ΛCDM model

A 80σ measurement of the cosmic baryon density in g/cc!

A 40σ detection of nonbaryonic DM using *__only__* z ~1000 data!

	Planck+WP	
$\Omega_b h^2$	0.022032	0.02205 ± 0.00028
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The six parameters of the minimal ΛCDM model

A 80σ measurement of the cosmic baryon density in g/cc!

$$f_{bar} = \Omega_b / \Omega_m = 0.155 \pm 0.004$$

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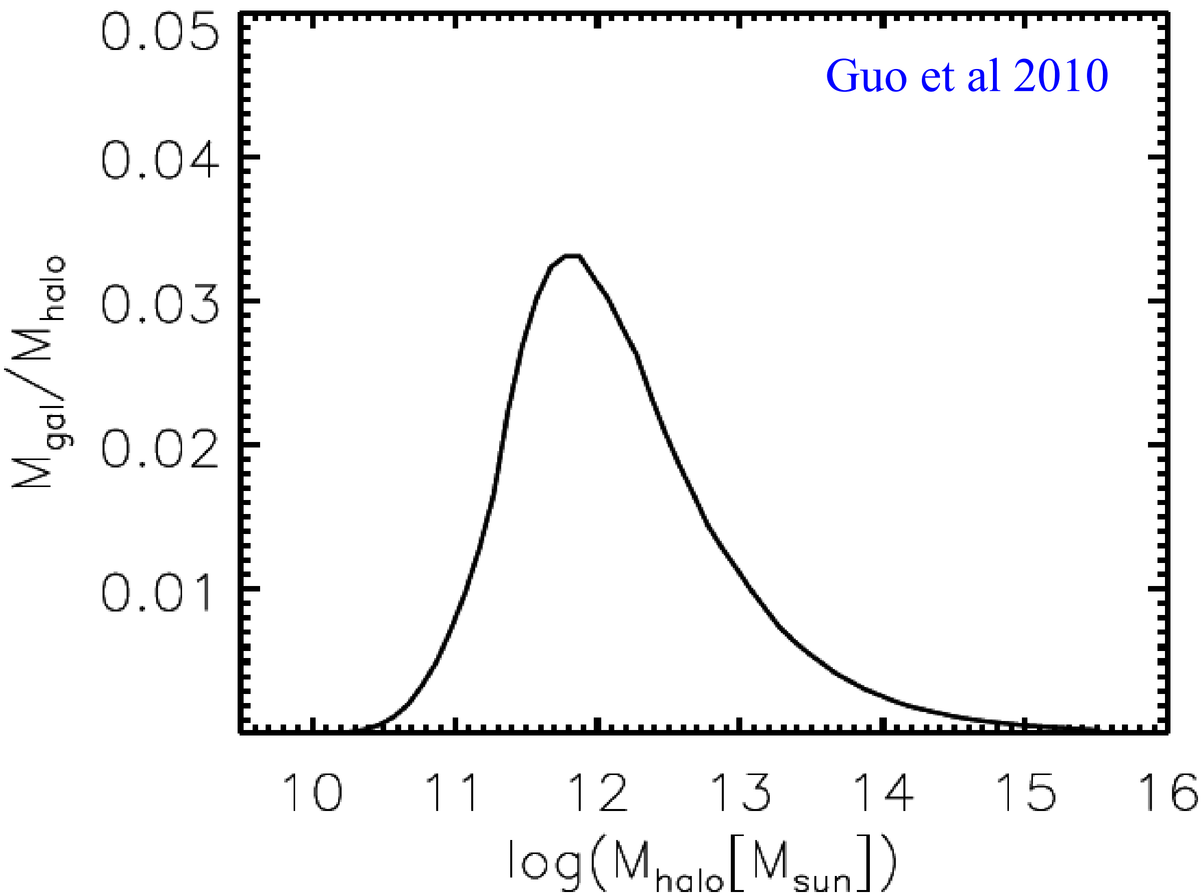
From abundance matching in ΛCDM (assuming no scatter)...



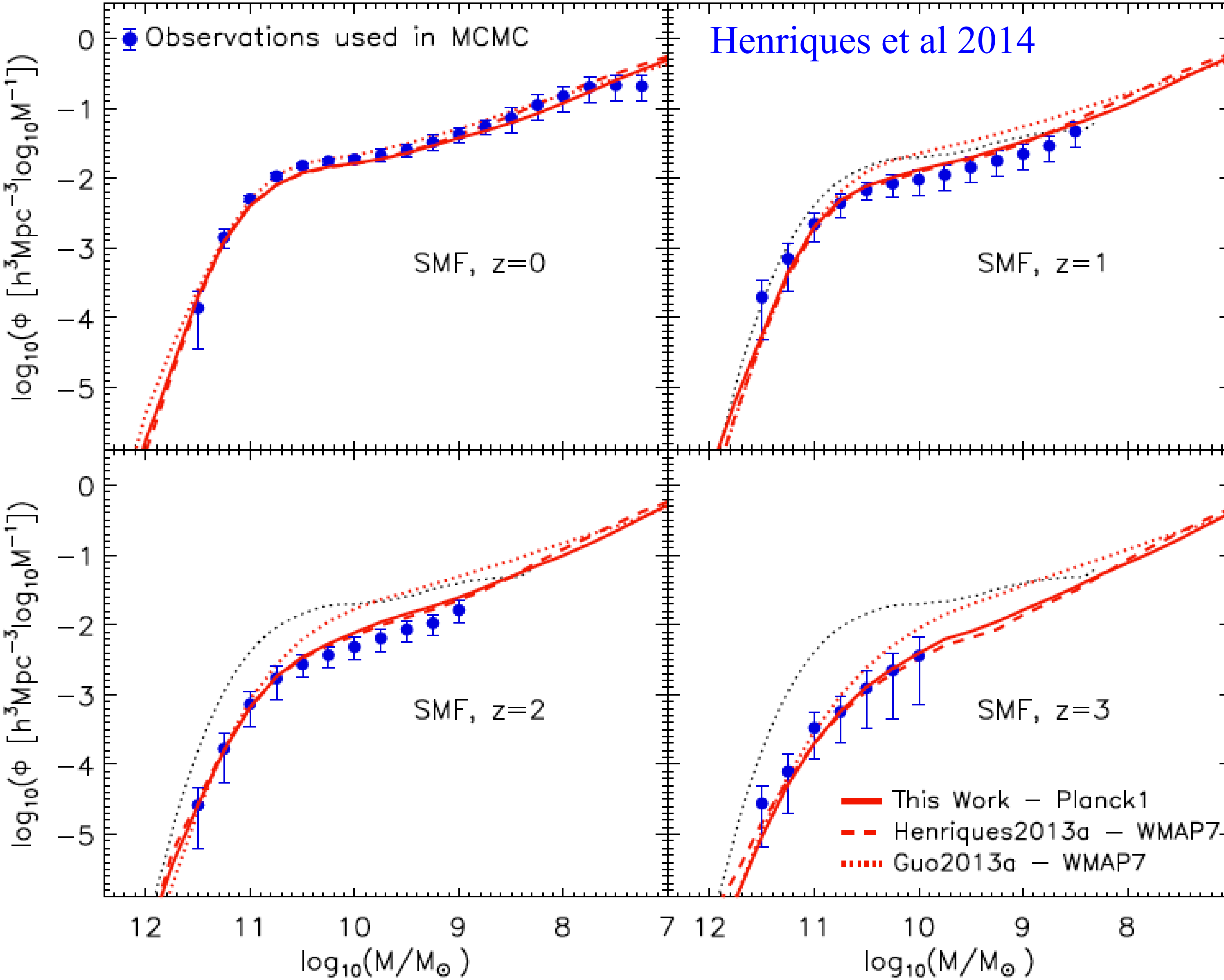
The <u>maximum</u> fraction of halo mass in central galaxy stars is 3.5%, and is attained for halos similar in mass to the Milky Way's halo

This fraction drops very rapidly to higher and to lower masses

→ Star-formation efficiency is <u>very</u> low in dwarfs

→ A large <u>scatter</u> in M_*/M_{halo} should be expected

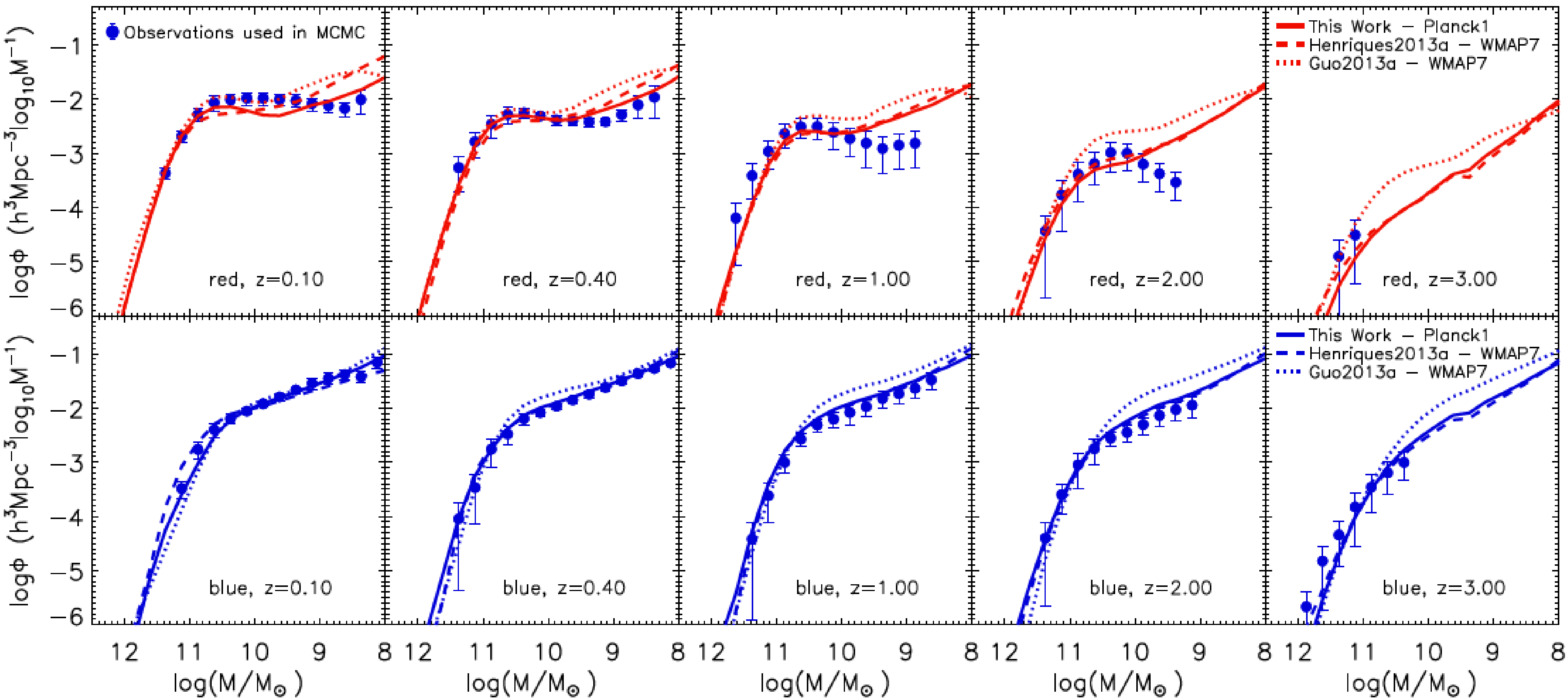
Simulating the galaxy population in the Planck cosmology



Plausible models for the efficiency of cooling/condensation, star formation, stellar and AGN feedback reproduce abundances down to $M_* < 0.001\ M_{MW}$

Simulating the galaxy population in the Planck cosmology

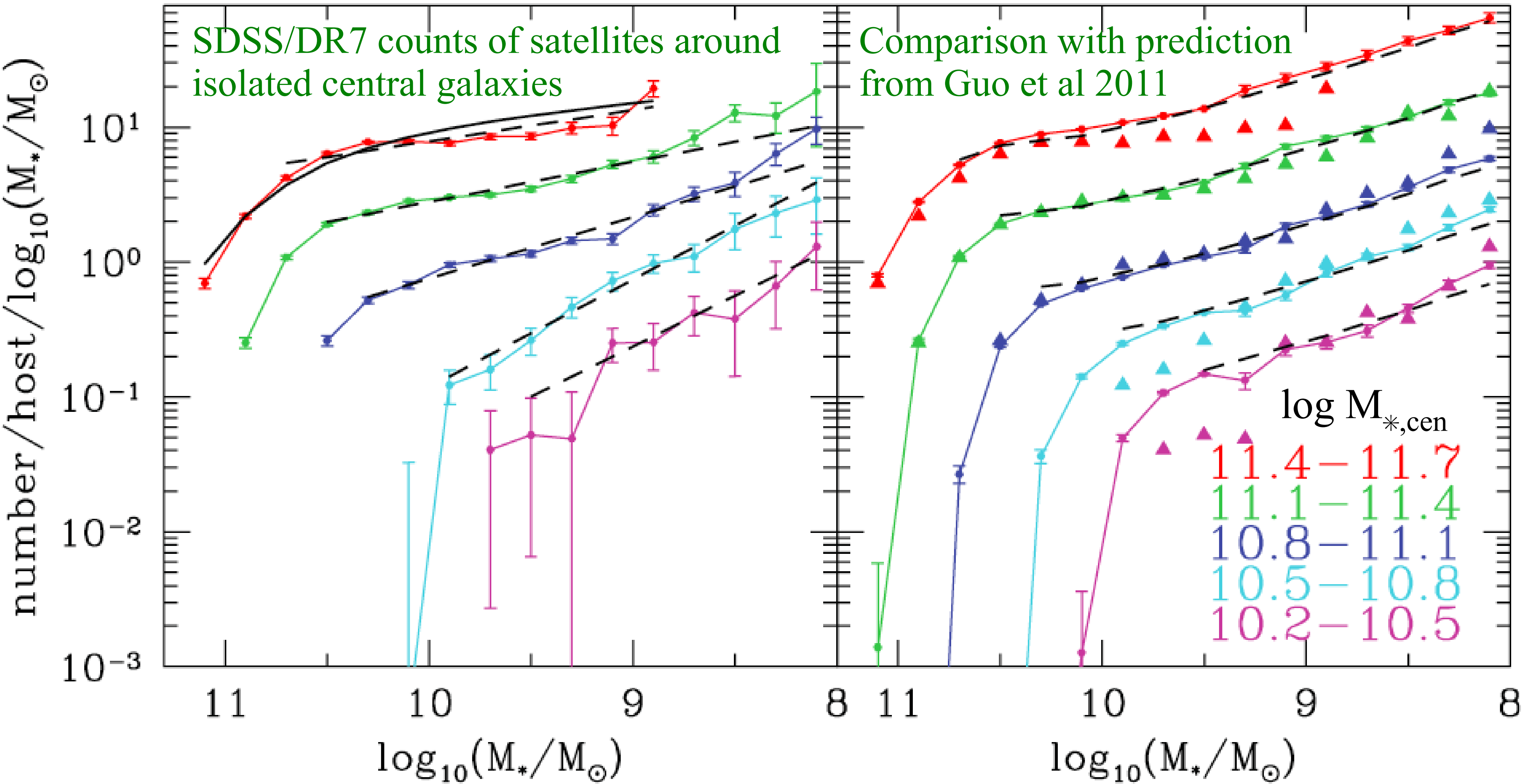
Henriques et al 2014



Plausible models for the efficiency of cooling/condensation, star formation, stellar and AGN feedback reproduce abundances down to $M_* < 0.001\ M_{MW}$ for both passive and actively star-forming galaxies

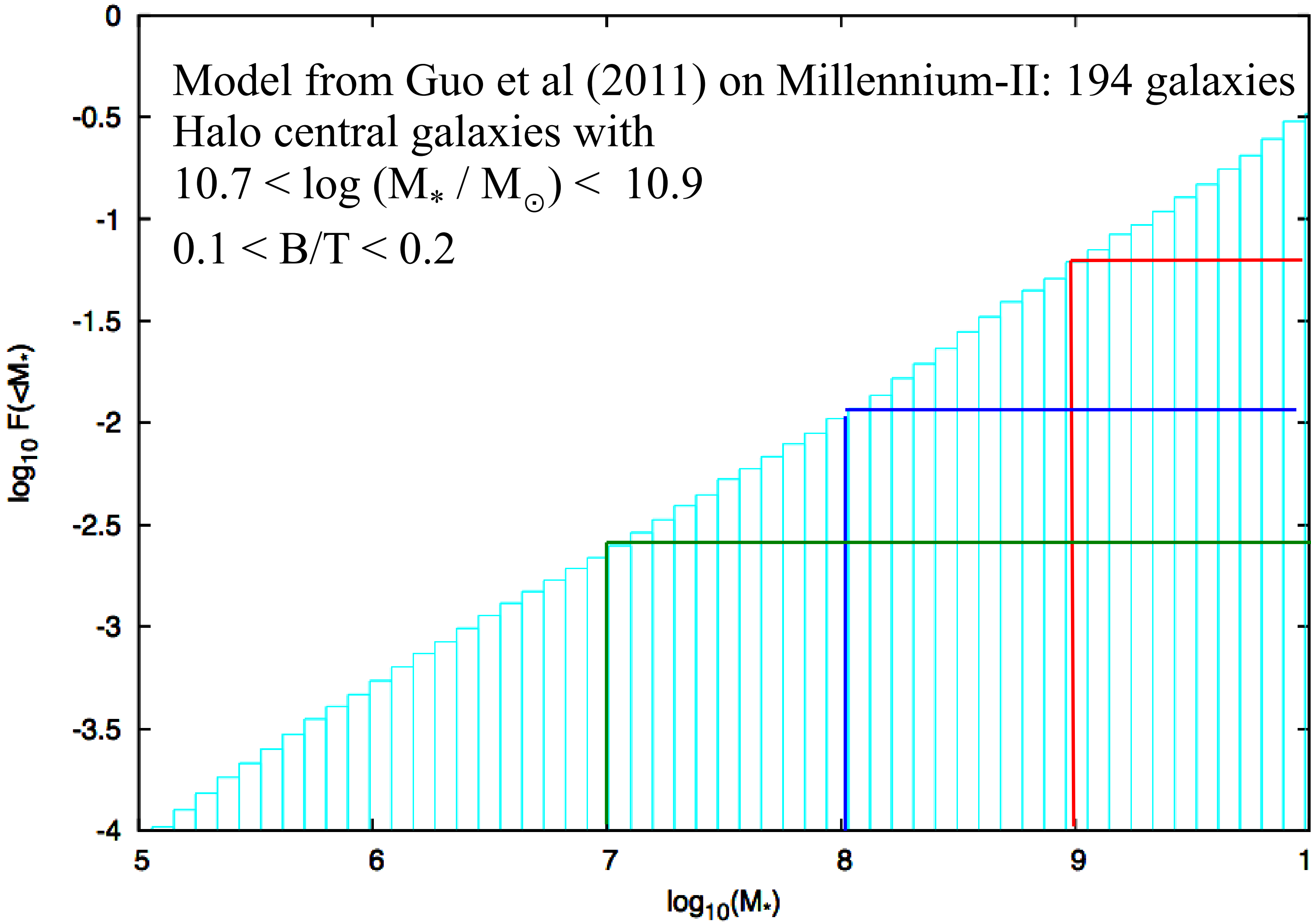
Simulating the galaxy population in the Planck cosmology

Wang & White 2012



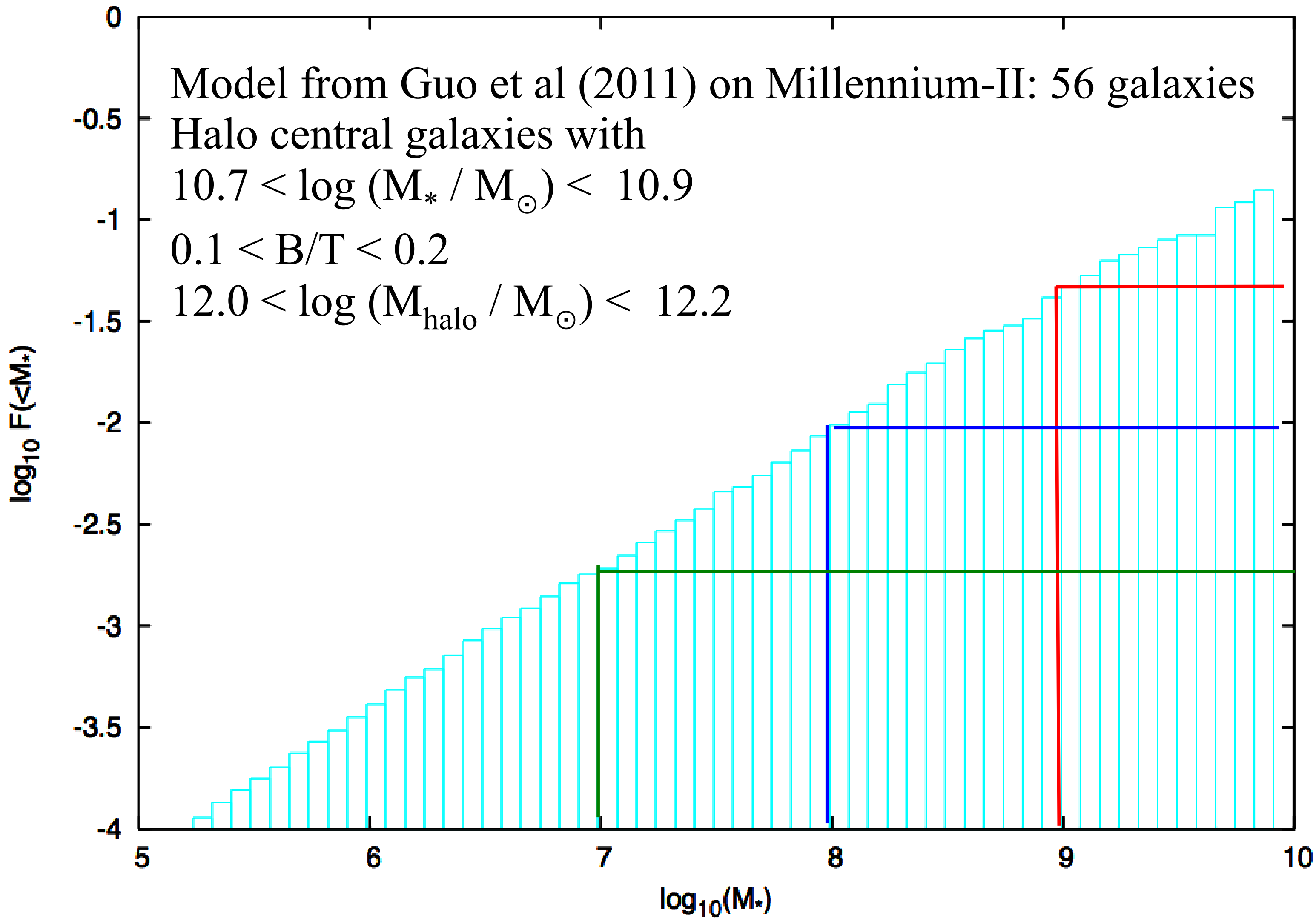
Current simulations reproduce quite well the counts of satellites around isolated bright galaxies with log $M_{*,cen}$ > 10.2 down to log $M_{*,sat}$ ~ 8.0

Are dwarfs the "building blocks" of the Milky Way?



~7%, 1.3% and 0.3% of Milky Way stars are added by accretion of satellites with $\log (M_* / M_\odot) <$ 9.0, 8.0 and 7.0, respectively

Are dwarfs the "building blocks" of the Milky Way?



~5%, 1% and 0.2% of Milky Way stars are added by accretion of satellites with $\log(M_* / M_\odot) < 9.0$, 8.0 and 7.0, respectively

- The abundances, spatial distributions and star-forming/passive fractions of dwarfs are plausibly reproduced by ΛCDM simulations
- The “missing satellite” problem may be solved by any of a number of astrophysical effects, given our current ability to calculate them
- Details of formation history are likely to introduce a large scatter into the stellar mass – halo mass relation of dwarfs
- Dwarfs have contributed a very small fraction of the Milky Way's current complement of stars -- they are **not** its building blocks!

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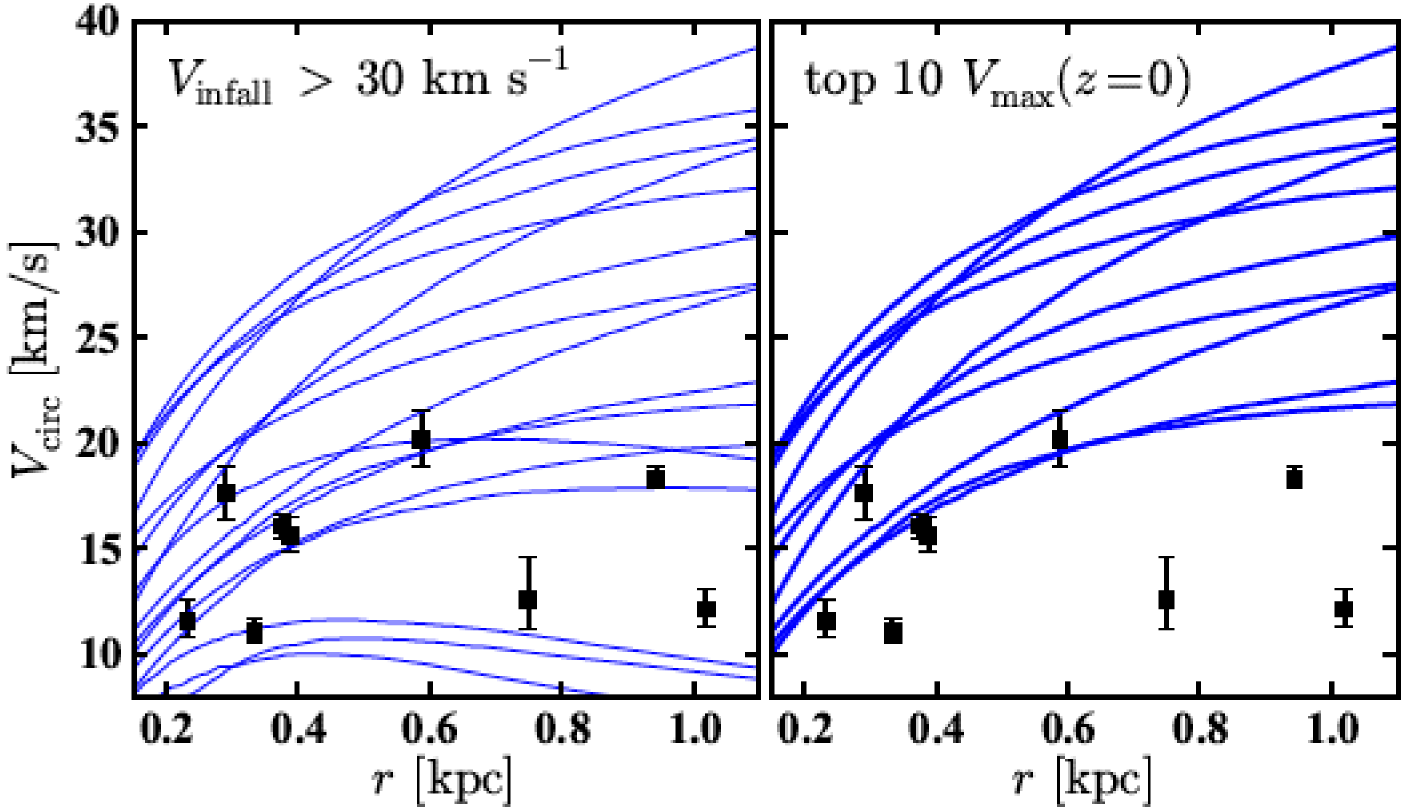
- Dwarfs have contributed a very small fraction of the Milky Way's current complement of stars -- they are **<u>not</u>** its building blocks!
- Satellite colours are **not** well reproduced in most current models

Is dwarf <u>structure</u> consistent with ΛCDM?

Too big to fail? -- a central density problem

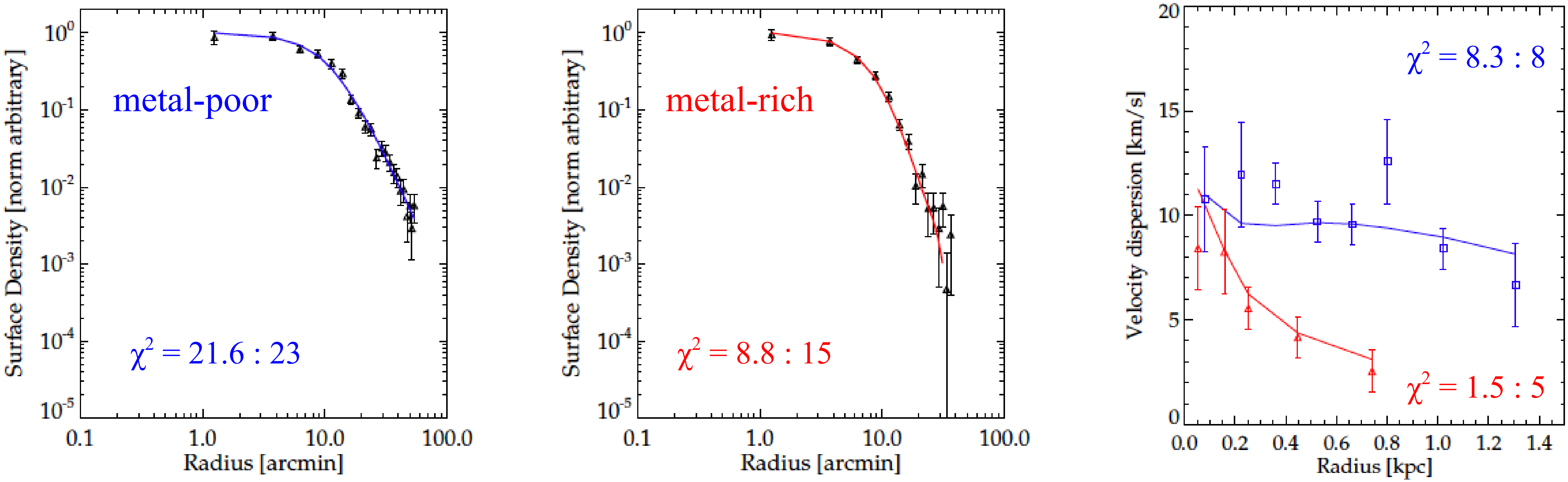
Boylan-Kolchin et al 2012



The estimated mass densities within $r_{1/2}$ for the 9 brightest MW dSph's (excluding Sag.) are lower than those predicted for the most massive subhalos in a DM-only simulation of a ΛCDM halo with $M_{vir} = 10^{12} M_{\odot}$

A core or a cusp in Sculptor?

Strigari et al 2014



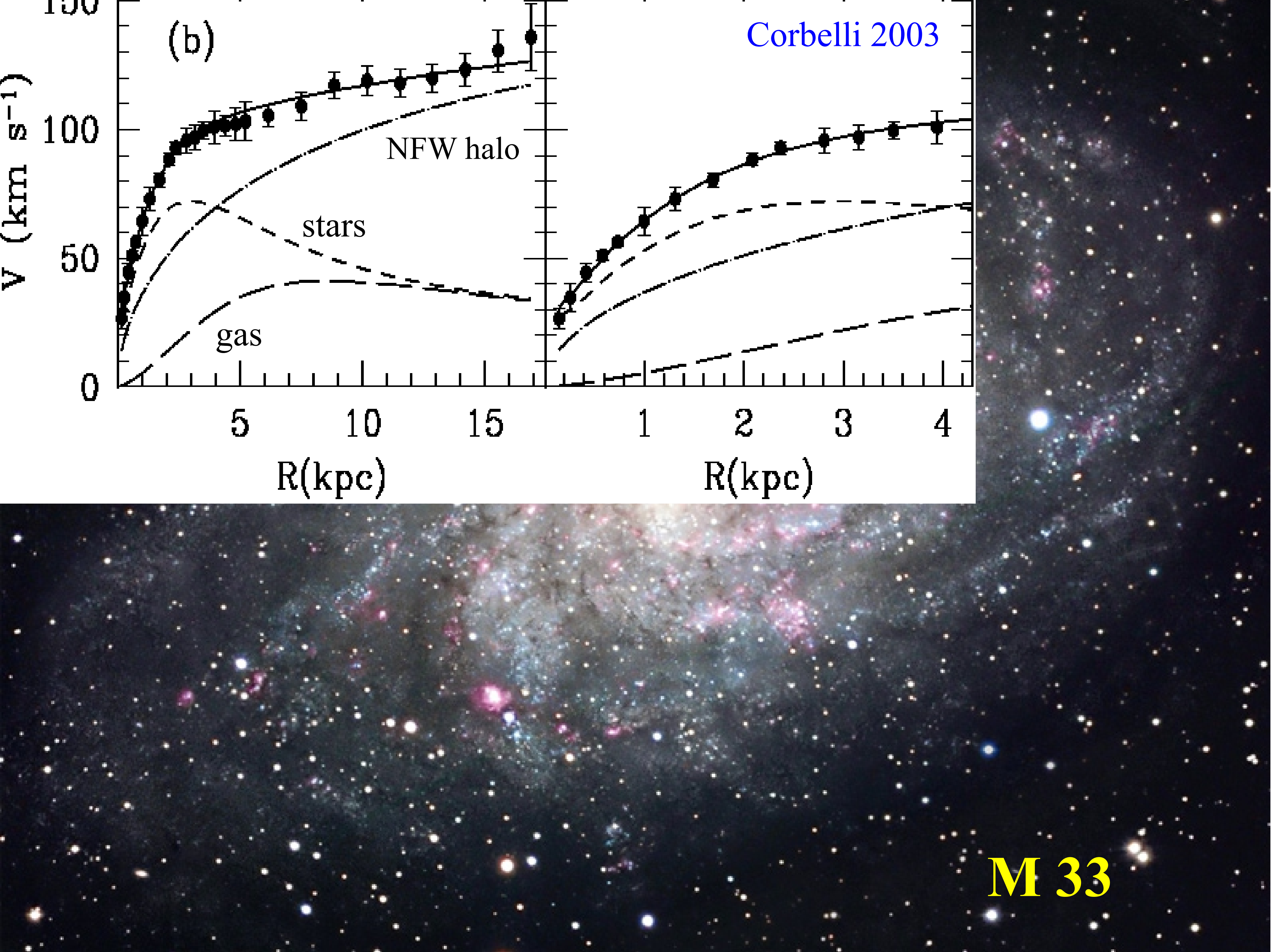
The counts and dispersion profiles of the MR and MP populations in Sculptor *can* be well fit as equilibria within a single NFW potential.

For such models, $C_{MP} < C_{MR}$ [in $M(r_{1/2,}) = C\ r_{1/2}\,\sigma^2_{l.o.s.} / G$].

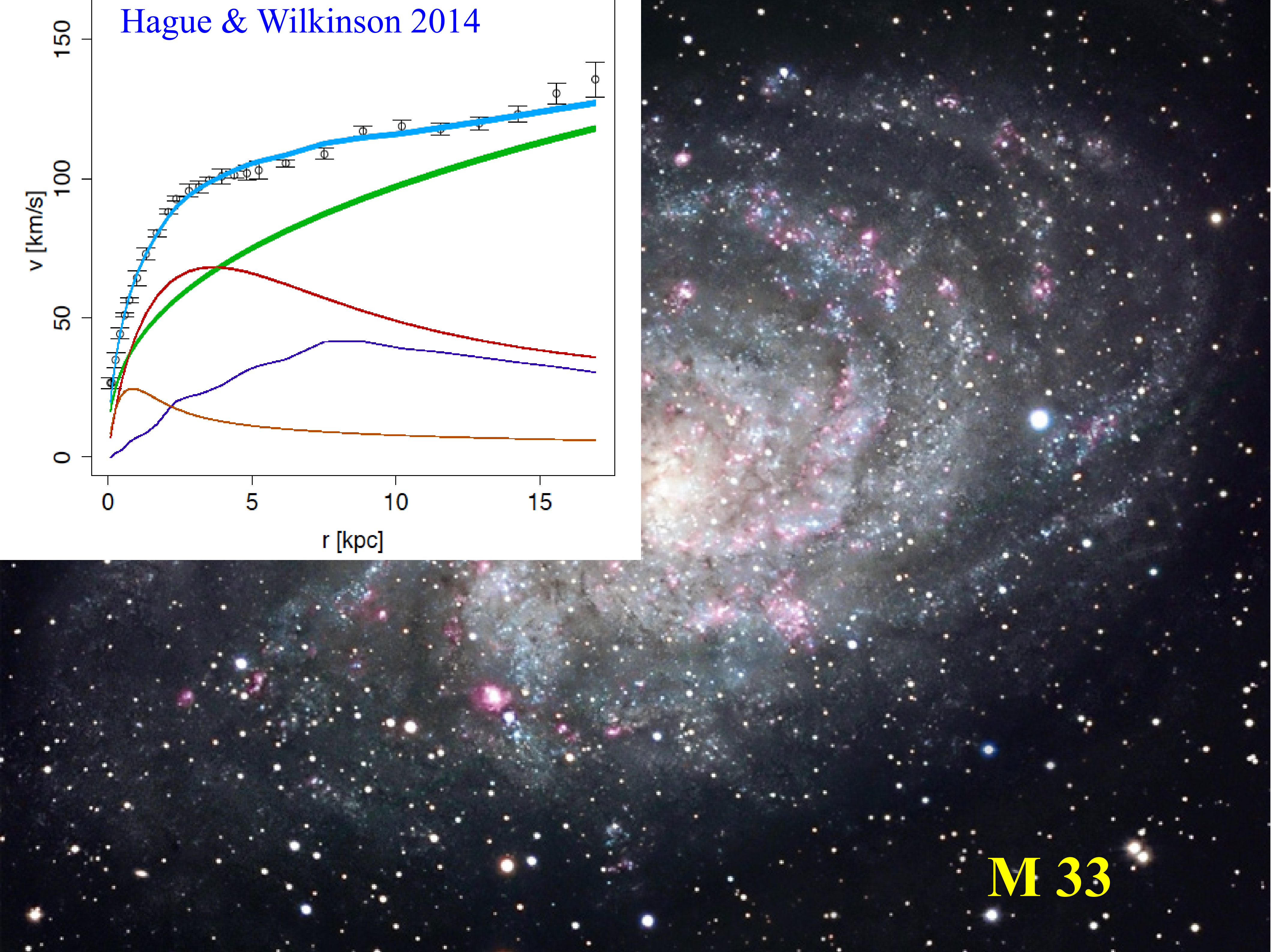
The required NFW parameters are as expected for ΛCDM subhalos

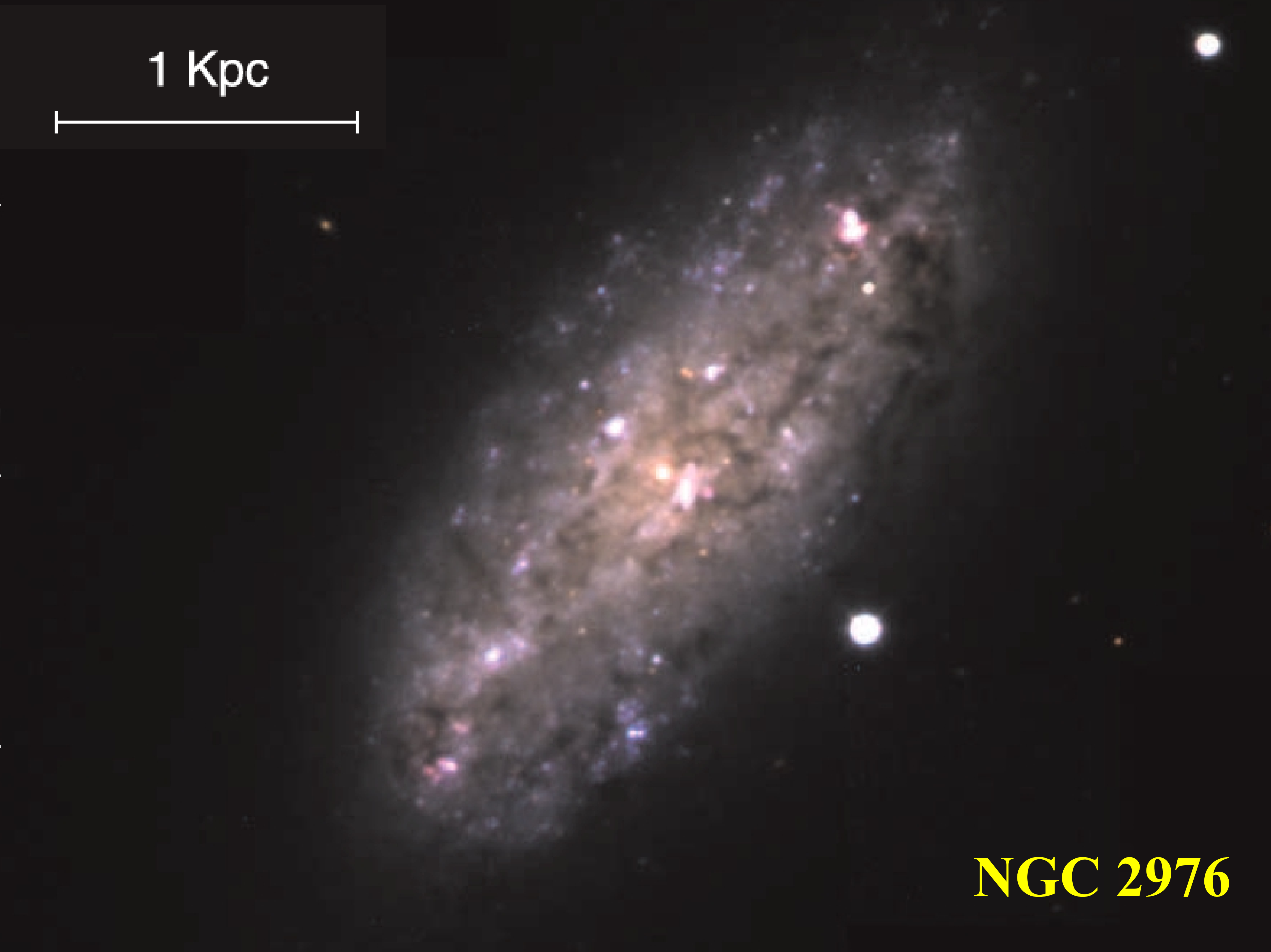
Models *still* not general (spherical, static, no rotation, f(E,J) = g(E)h(J)..)

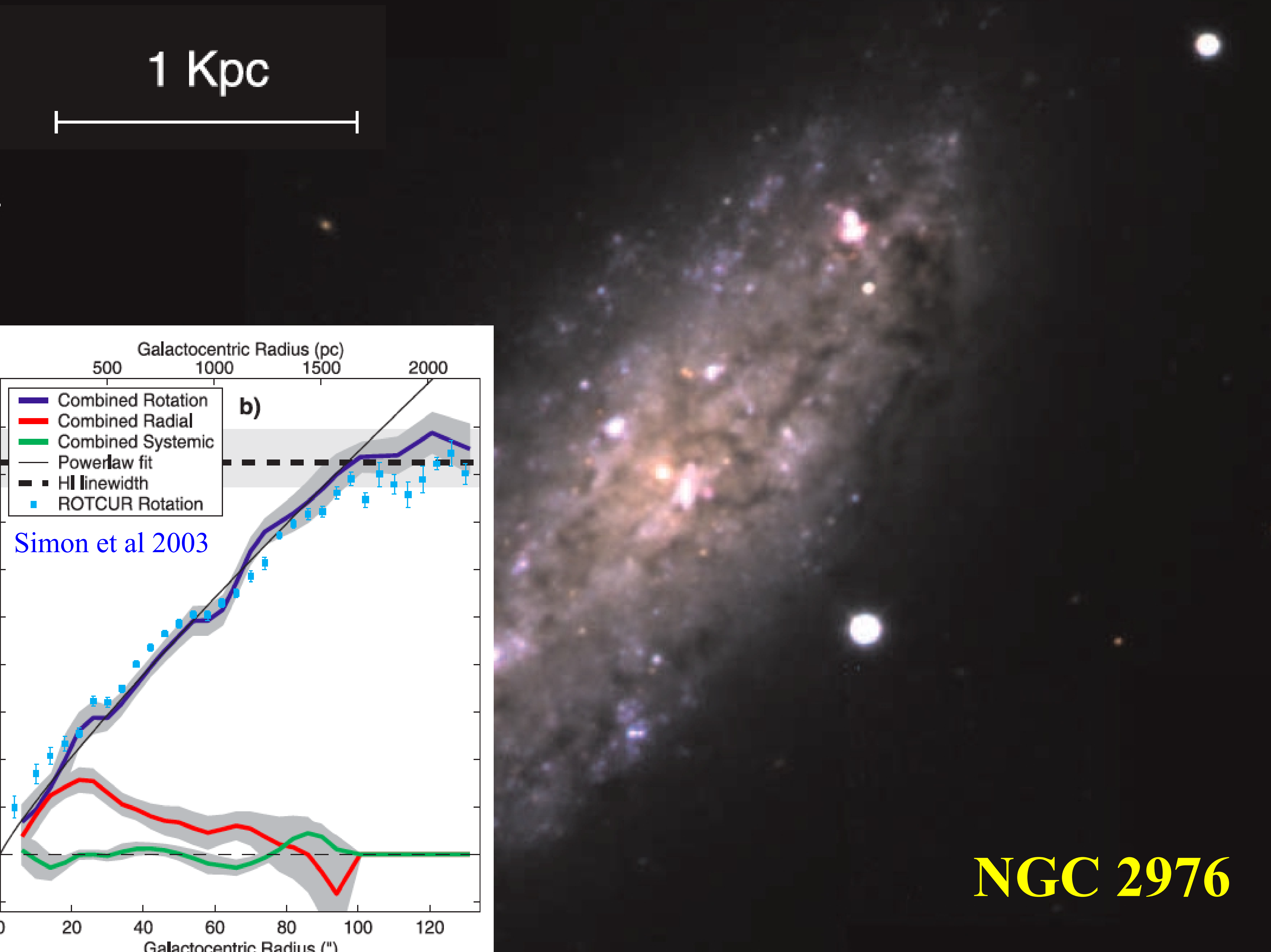

NFW
halo
star
s
gas
M 33

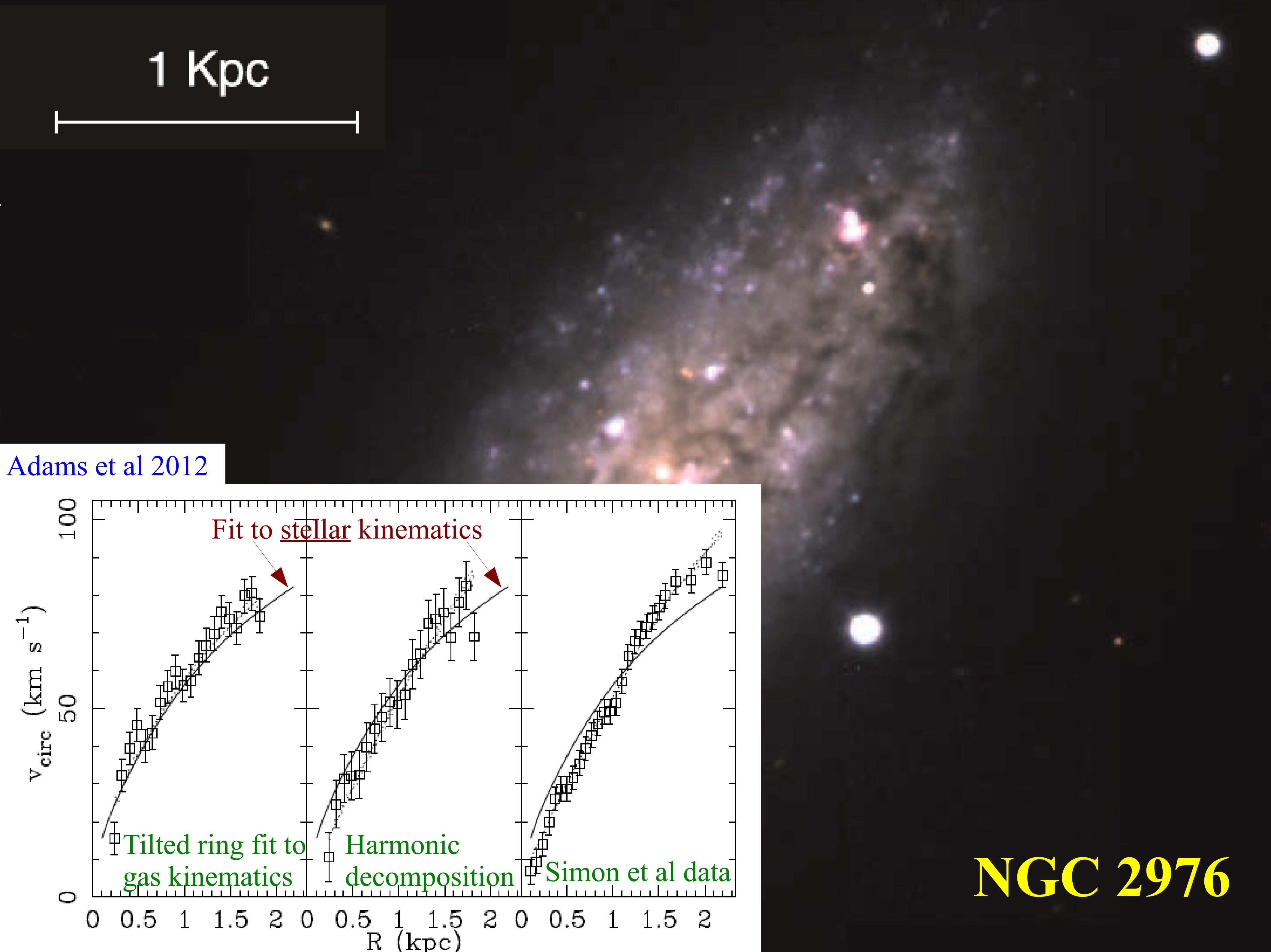


(b)
Corbelli 2003
NFW halo
stars
gas
V (km s^-1)
100
50
0
5
10
15
R(kpc)
1
2
3
4
R(kpc)
M 33


Hague & Wilkinson 2014
v [km/s]
0
50
100
150
r [kpc]
0
5
10
15
M 33


1 Kpc
NGC 2976


1 Kpc
Galactocentric Radius (pc)
500
1000
1500
2000
b)
Combined Rotation
Combined Radial
Combined Systemic
Powerlaw fit
HI linewidth
ROTCUR Rotation
Simon et al 2003
20
40
60
80
100
120
Galactocentric Radius (")
NGC 2976


1 Kpc
Adams et al 2012
Fit to stellar kinematics
v_{circ} (km s^{-1})
0
50
100
0 0.5 1 1.5 2 0 0.5 1 1.5 2 0 0.5 1 1.5 2
R (kpc)
Tilted ring fit to gas kinematics
Harmonic decomposition
Simon et al data
NGC 2976

A discrepancy with the ΛCDM paradigm is apparent in the density structure of the inner halos of some (but **not** all) dwarf galaxies.

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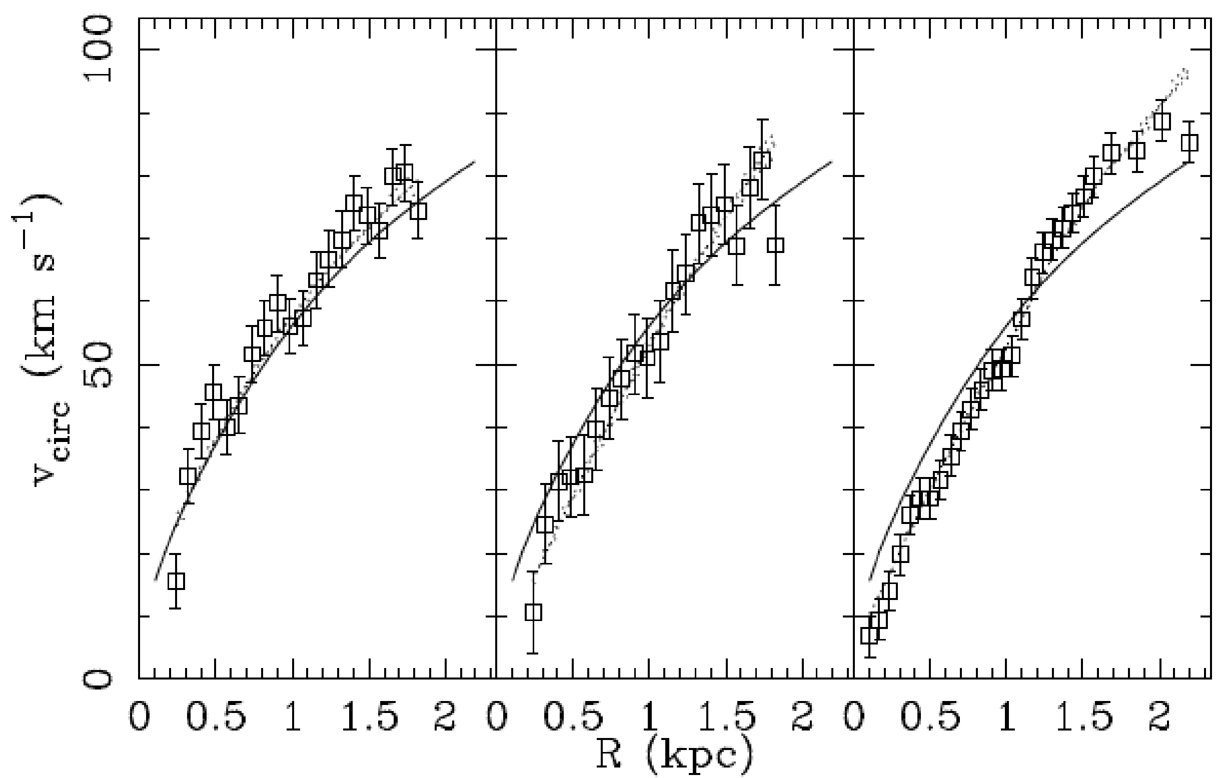
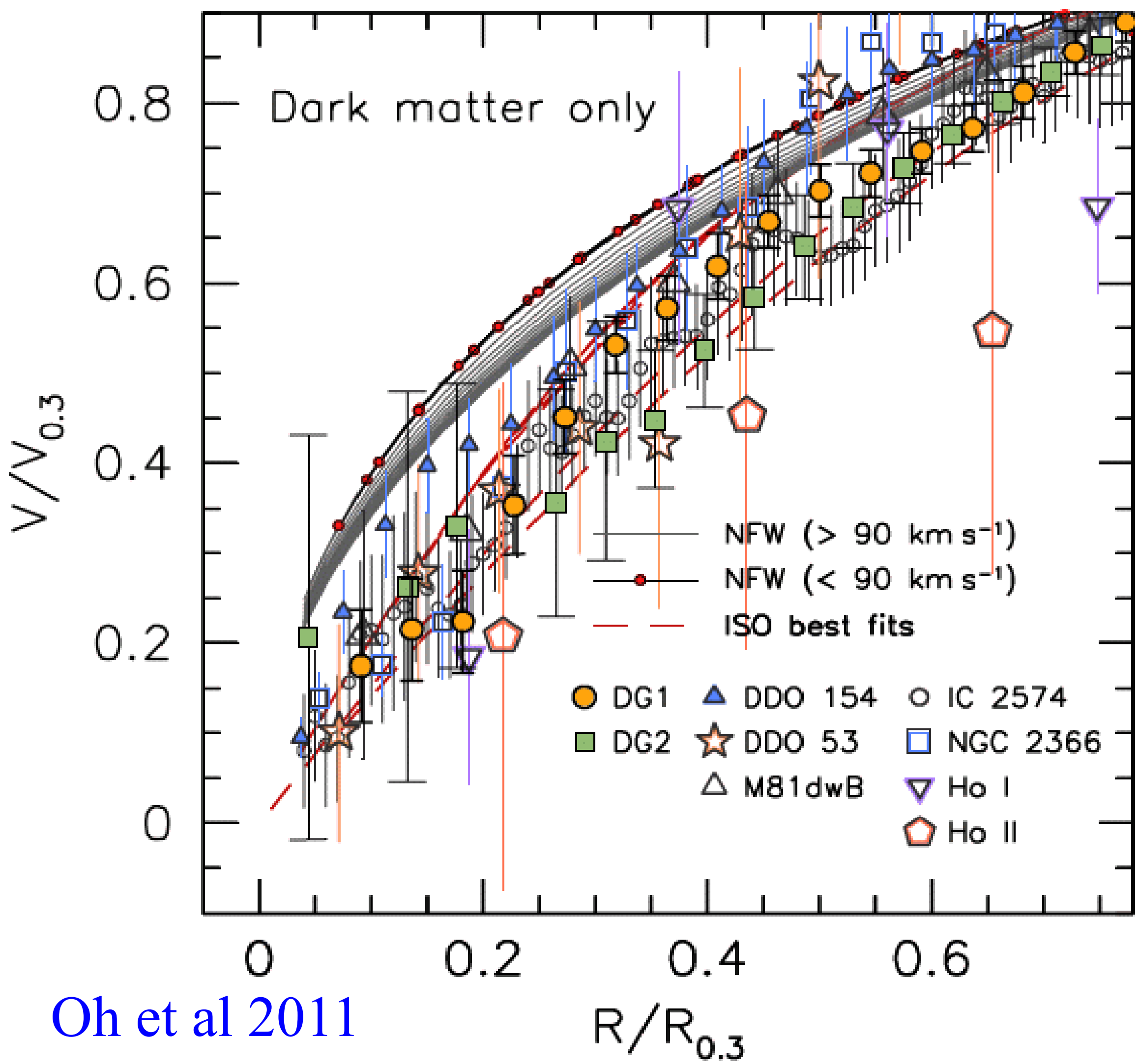


Could this be due to overly simple modelling of the dynamics? (i.e. lack of symmetry, non-circular motion, dispersion structure.)

A discrepancy with the ΛCDM paradigm is apparent in the density structure of the inner halos of some (but **not** all) dwarf galaxies.

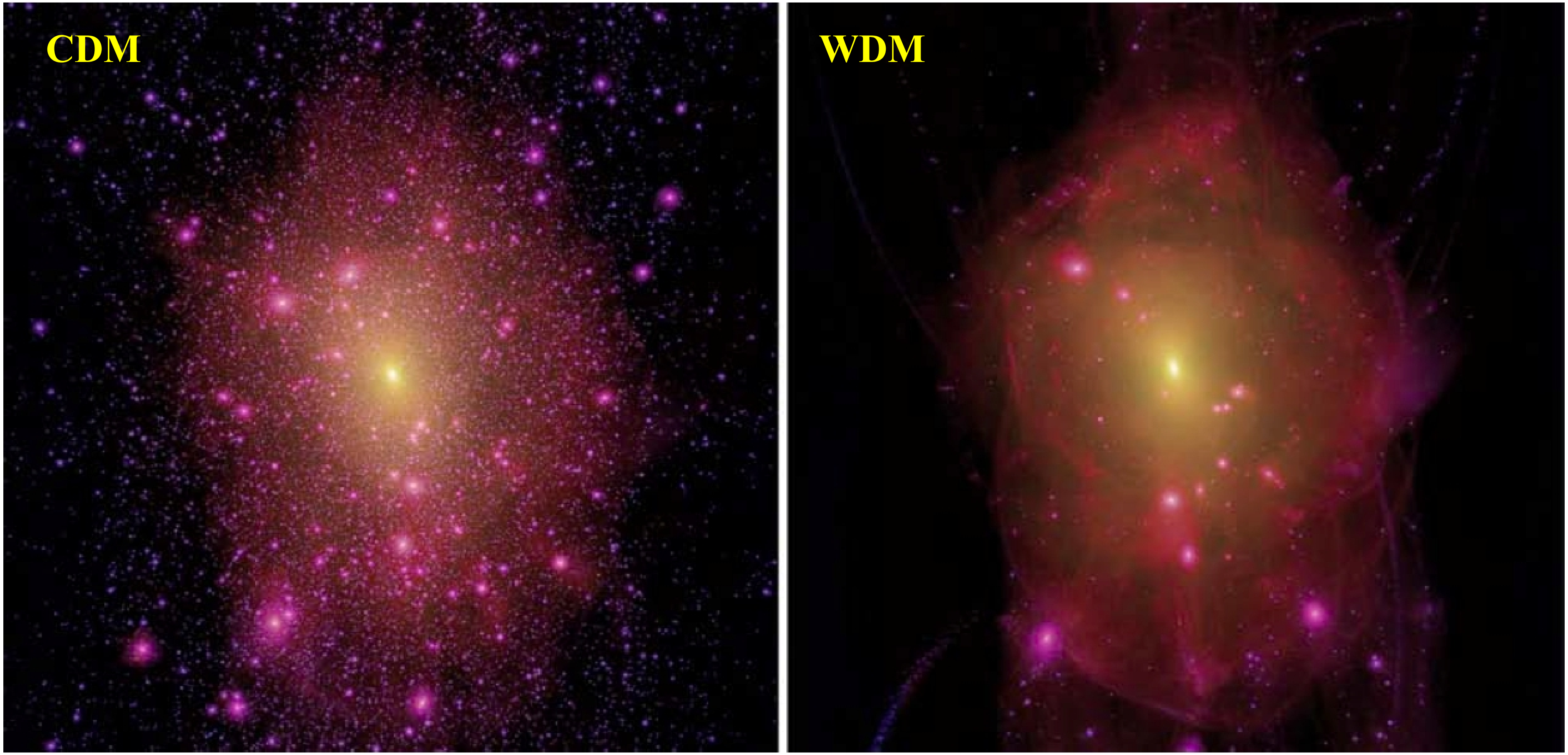


Oh et al 2011

..or could it be due to the dynamical effects of the star formation process?

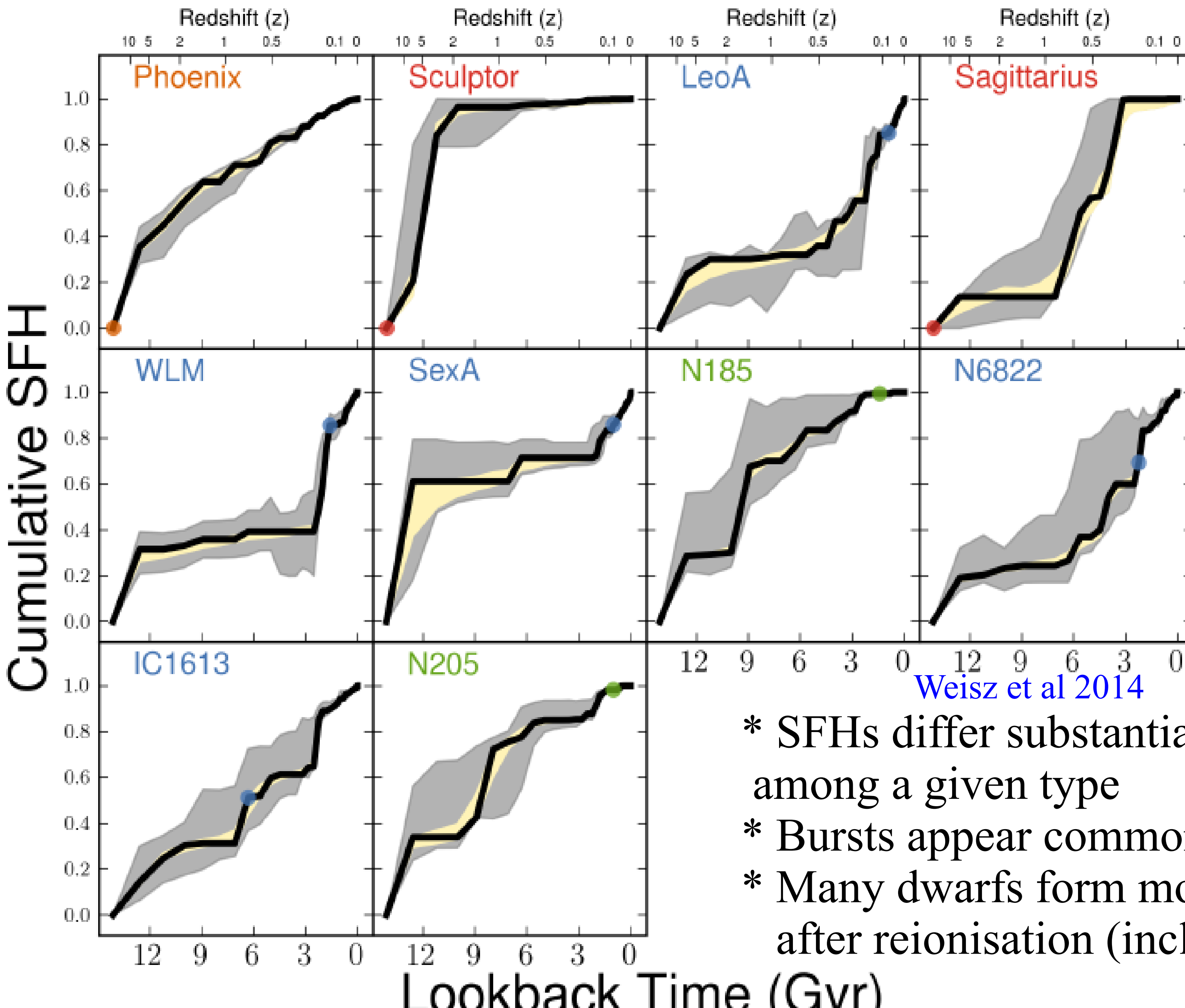
Repeated, strong and dense starbursts can turn cusps into cores

A discrepancy with the ΛCDM paradigm is apparent in the density structure of the inner halos of some (but **not** all) dwarf galaxies.



..or could it reflect more complex DM physics changimg the abundance and/or inner structure of low-mass halos?

Evidence from star-formation histories

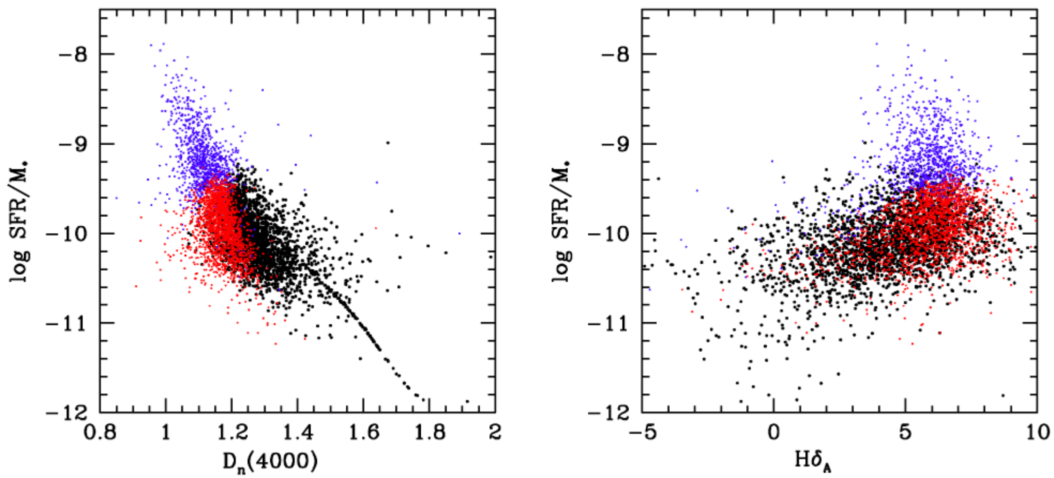


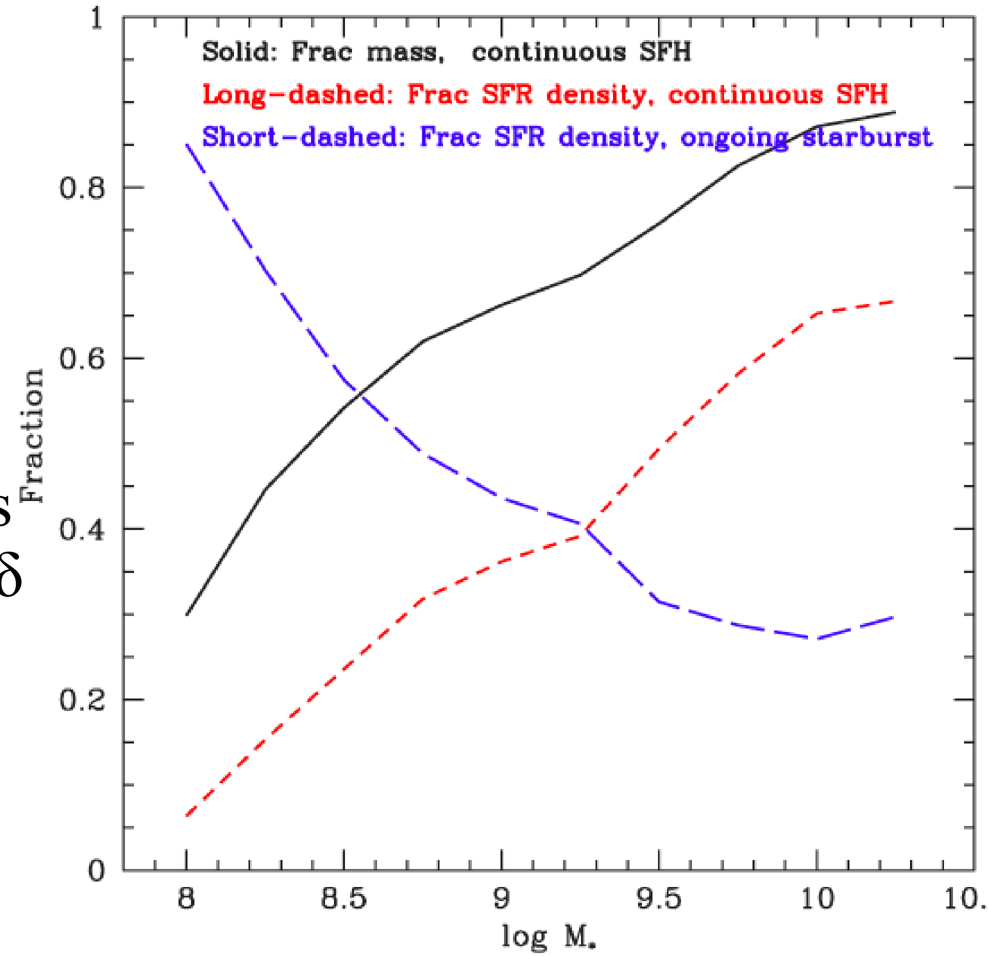
Weisz et al 2014

* SFHs differ substantially even among a given type
* Bursts appear common
* Many dwarfs form most stars after reionisation (incl. dSph's)

Quantifying "burstiness" statistically in z ~ 0 dwarfs

Kauffmann 2014





SDSS offers volume-limited statistics as a function of M_*, size, sSFR, D4000, Hδ

Galaxy SFH's can be classified as

a) consistent with continuous

b) currently starbursting

or c) a past starburst in the last 2 Gyr

At log M_* ~ 8.0:

Only 30% of objects are consistent with continuous SFH's

~85% of current star formation is in bursts and ~7% in continuous SFH's

The peak-to-trough variation in SFR is typically about a factor of 20

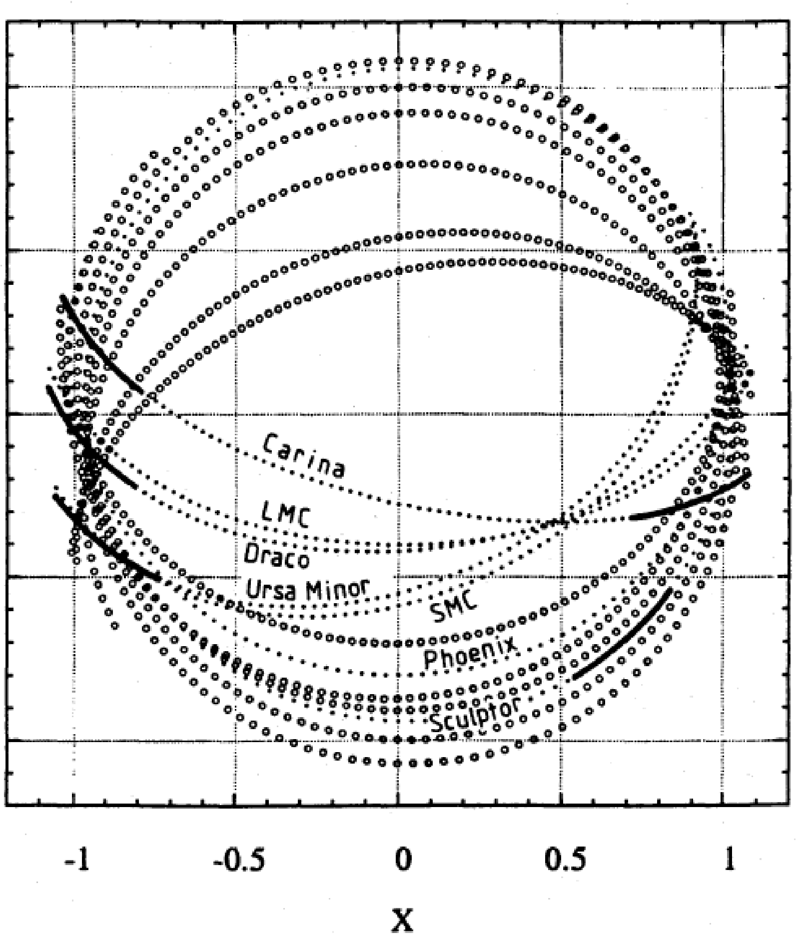
- Many Local Group dwarfs, dSph's, dIrr's and dE's, show evidence for multiple stellar populations.
- Their formation appears bursty, has large scatter among a given type, and appears qualitatively similar between types
- Many **but not all** dwarfs have a substantial population formed at high redshift (e.g. age $>$ 10 Gyr)
- There is no obvious imprint of the reionisation epoch on the population as a whole
- Current star formation in the low-redshift population of “field” dwarfs is strongly bursting, with amplitudes similar to those thought to be needed to drive cusp → core conversion

Ghostly streams, disks and other arcana

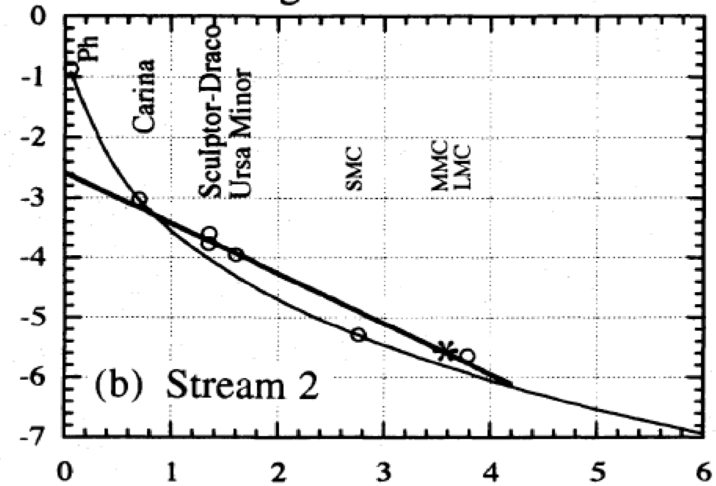
Ghostly streams from the Galaxy's halo

D. Lynden-Bell and R. M. Lynden-Bell 1995

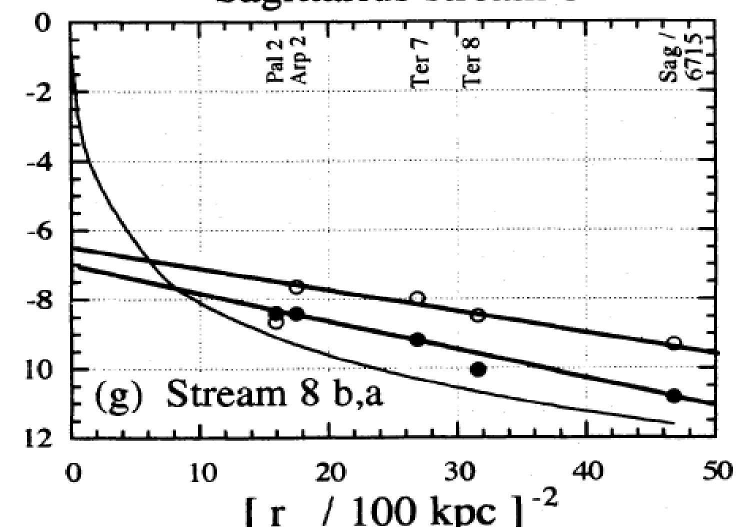
(b) Magellanic Stream



Magellanic Stream



Sagittarius stream 8



Ghostly streams, disks and other arcana

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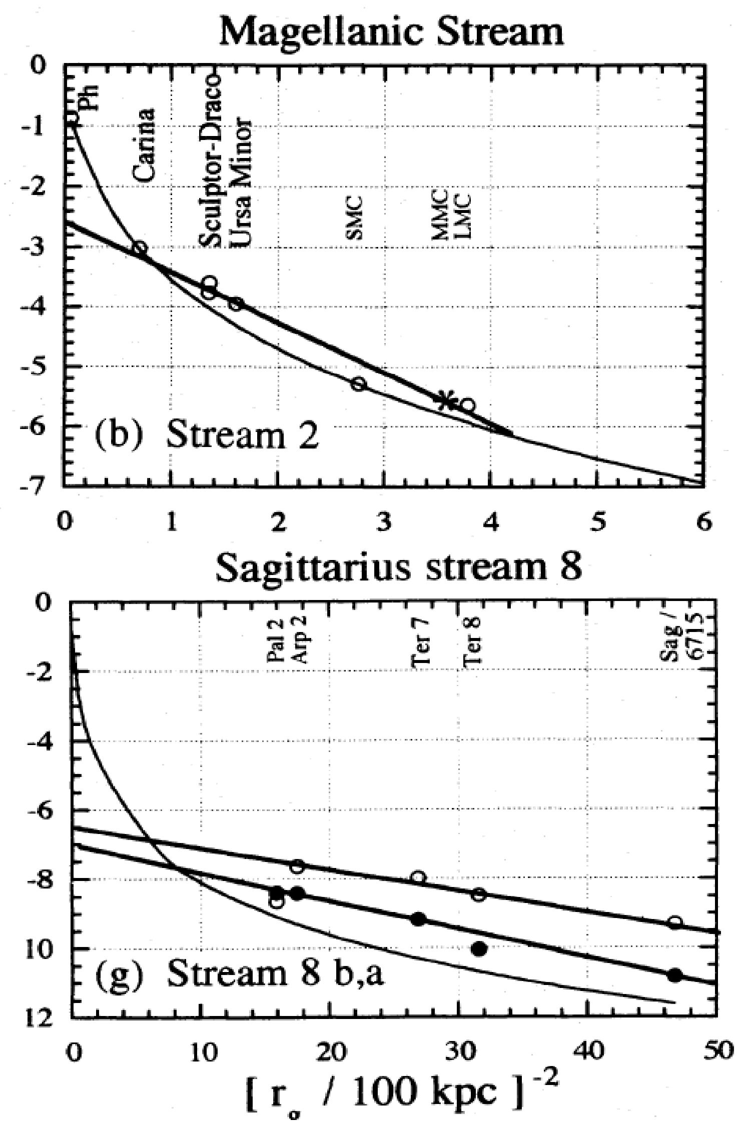
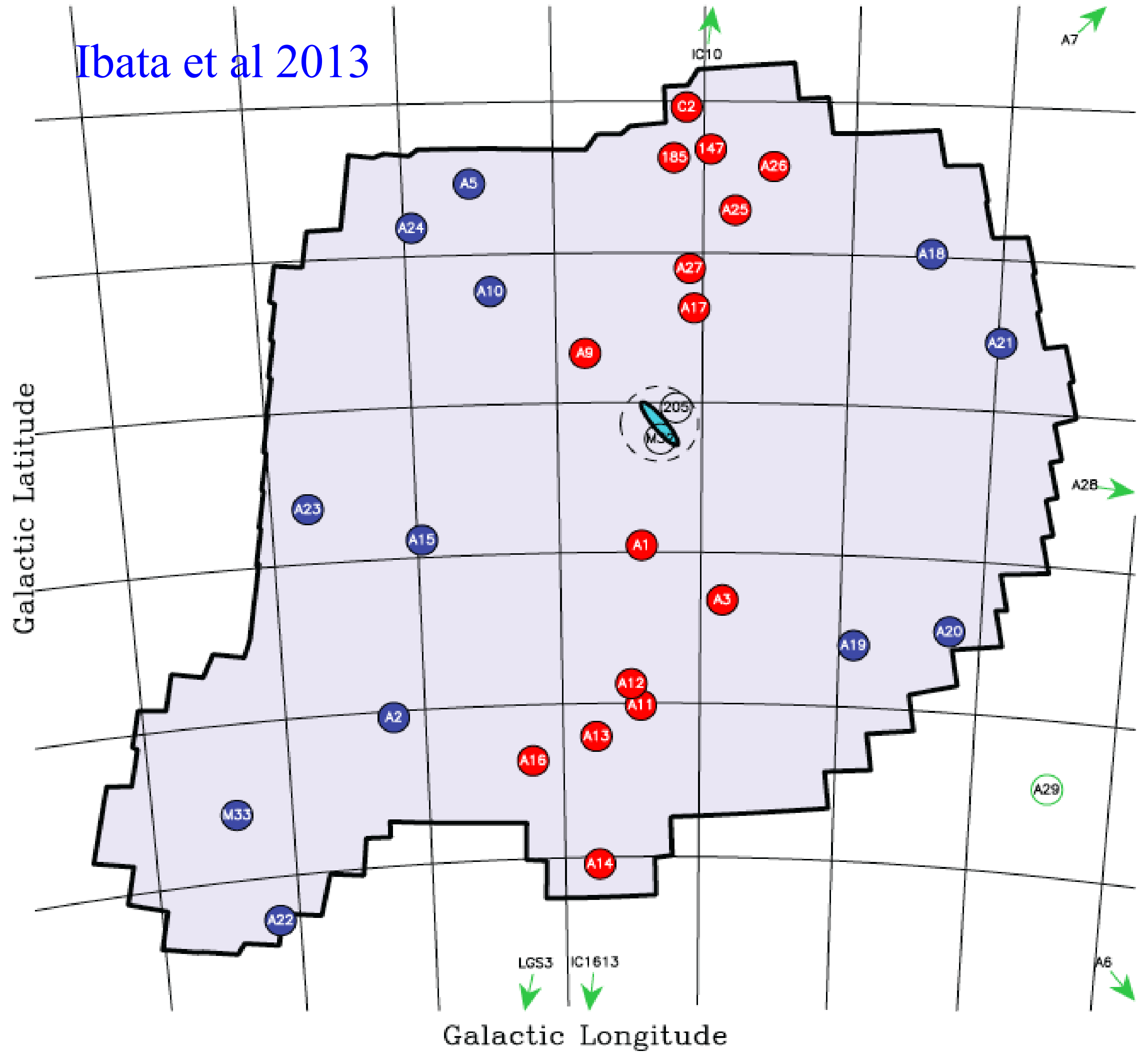
and R. M. Lynden-Bell 1995

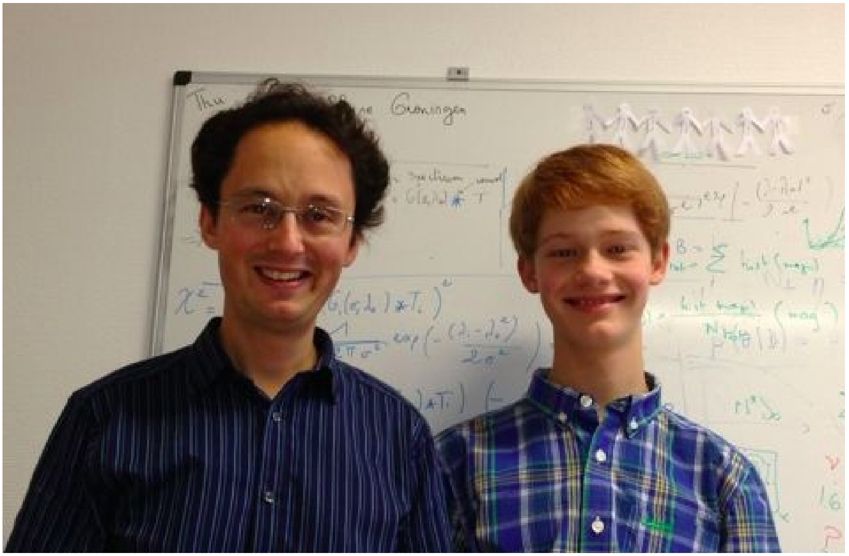


Ghostly streams, disks and other arcana



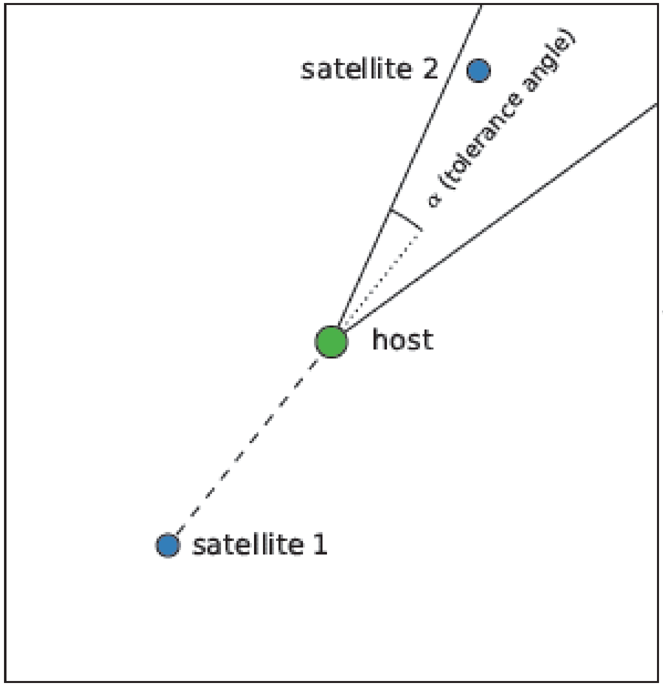
- 15/27 M31 satellites in the PanDAS area lie in a thin disk like structure.
- 13/15 of these “rotate” around M31 in the same sense

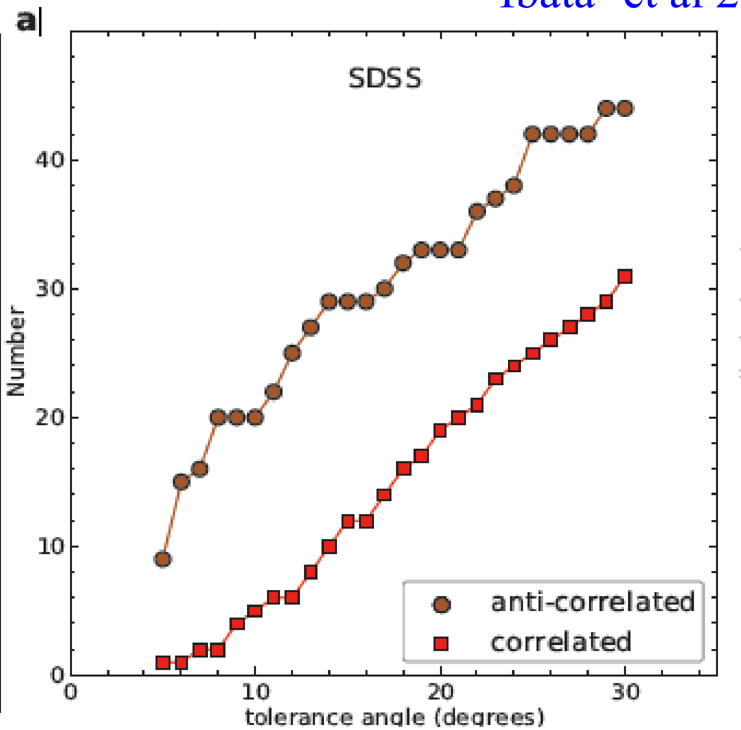
Ghostly streams, disks and other arcana

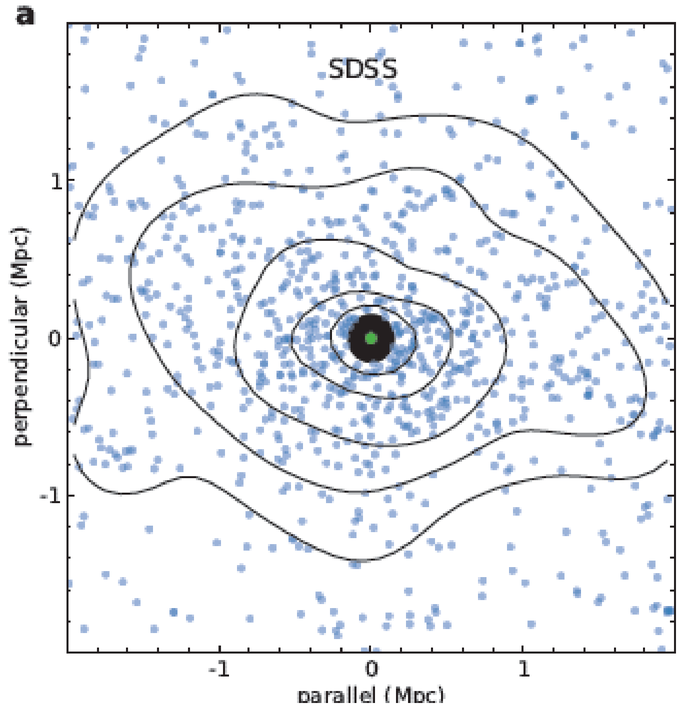


- Find isolated bright SDSS galaxies that have diametrically opposed satellite pairs
- Compare numbers in which the two values $\Delta v = v_{host} - v_{sat}$ have the same/opposite sign
- Opposite signs appear to be preferred
- Pair axis aligns with larger scale structure

Ibata[2] et al 2014







- Some correlated structure in satellite systems is expected in the ΛCDM paradigm because of correlated infall from the environment

- The degree of correlation seen around the MW, M31 and now apparently around nearby SDSS galaxies seems surprisingly large

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Dwarf galaxy studies in the Local Group and beyond provide interesting insights into galaxy formation physics in the ΛCDM paradigm, and may eventually test/extend the paradigm itself.