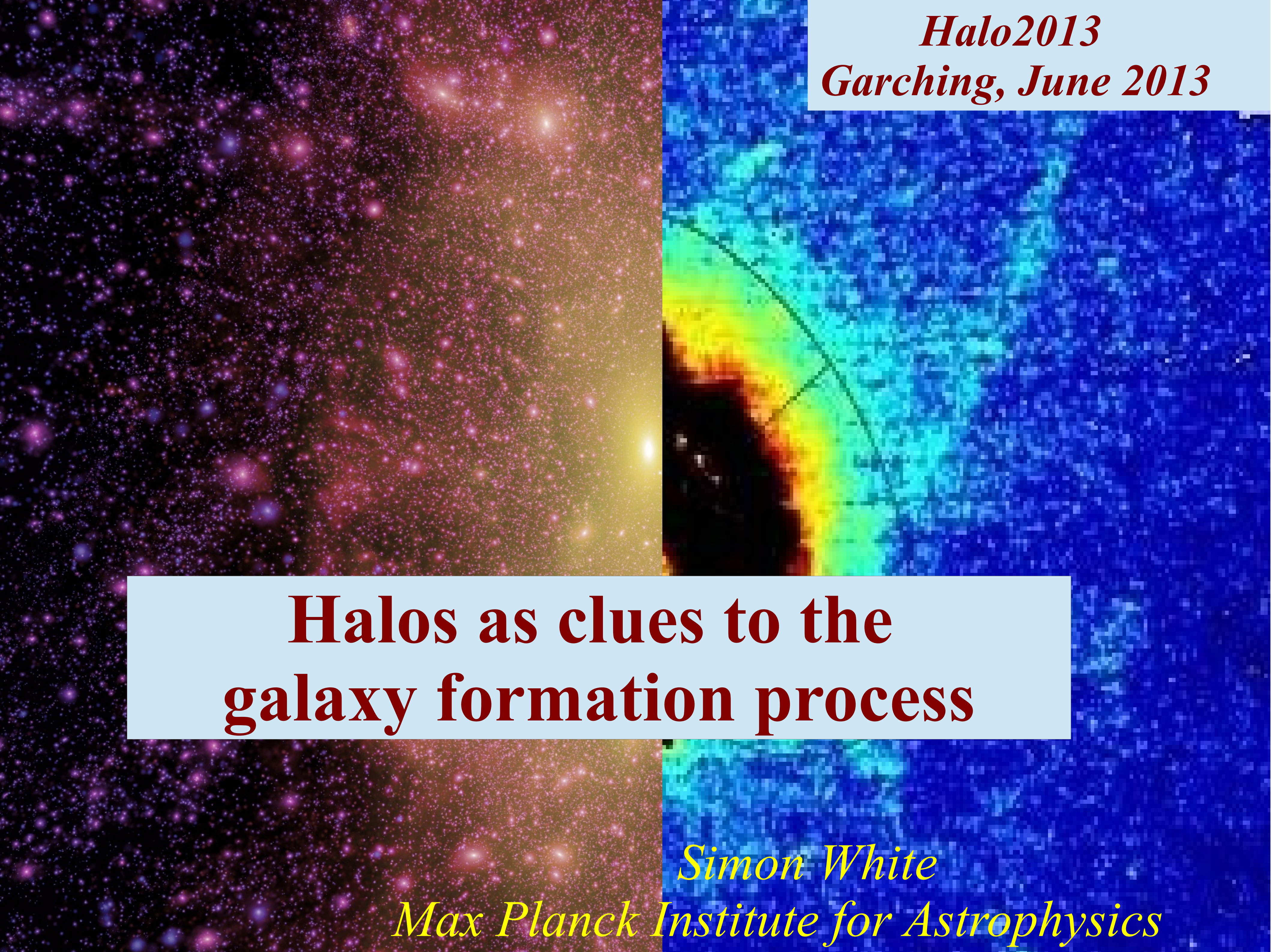


Halo2013
Garching, June 2013

Halos as clues to the galaxy formation process

Simon White
Max Planck Institute for Astrophysics

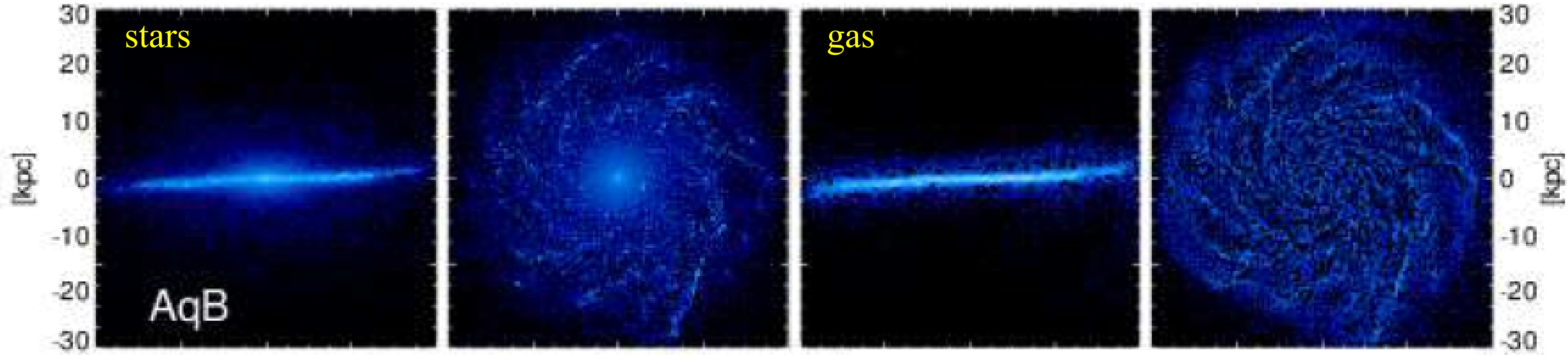
The varieties of galactic halos

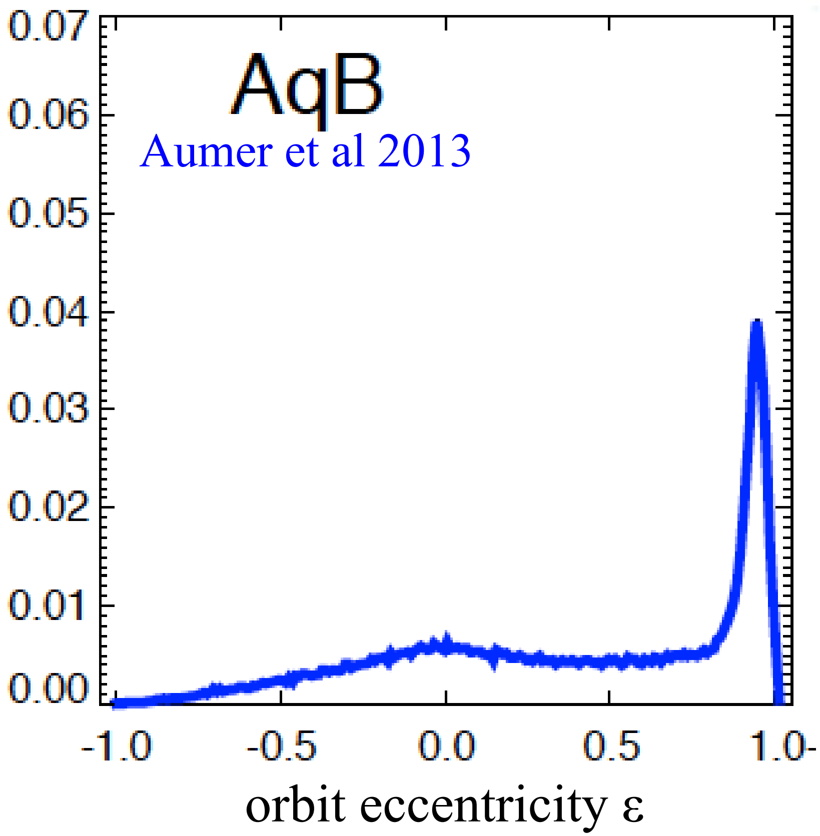
- Stellar halos
  - kinematics of nearby stars (ELS62)
  - properties of the GC system (SZ78)
  - deep resolved and unresolved imaging (stars, GCs, PNe)
  - ..and spectroscopy (stars for MW, GCs, PNe)
- Gas halos
  - quasar metal absorption lines
  - X-ray emission (FLG80 for M87)
  - SZ scattering (BGH84)
- DM halos
  - spiral rotation curves (Rubin, Roberts,.. 1970 →)
  - satellite kinematics (EKS74, OPY74)
  - strong and weak gravitational lensing (S88 for A370)

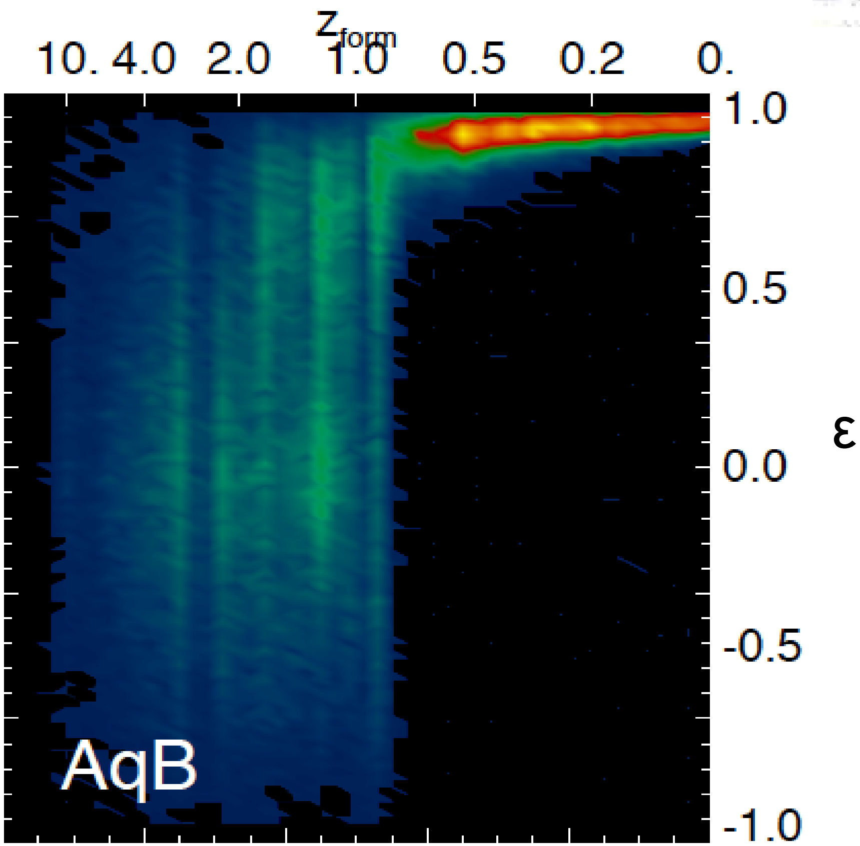
Stellar halos – issues?

- Definition
  - Where does bulge end and halo begin?
  - Is this defined by position? velocity? orbit? age? metallicity?
  - Is the separation physically meaningful?

Stellar halos – issues?





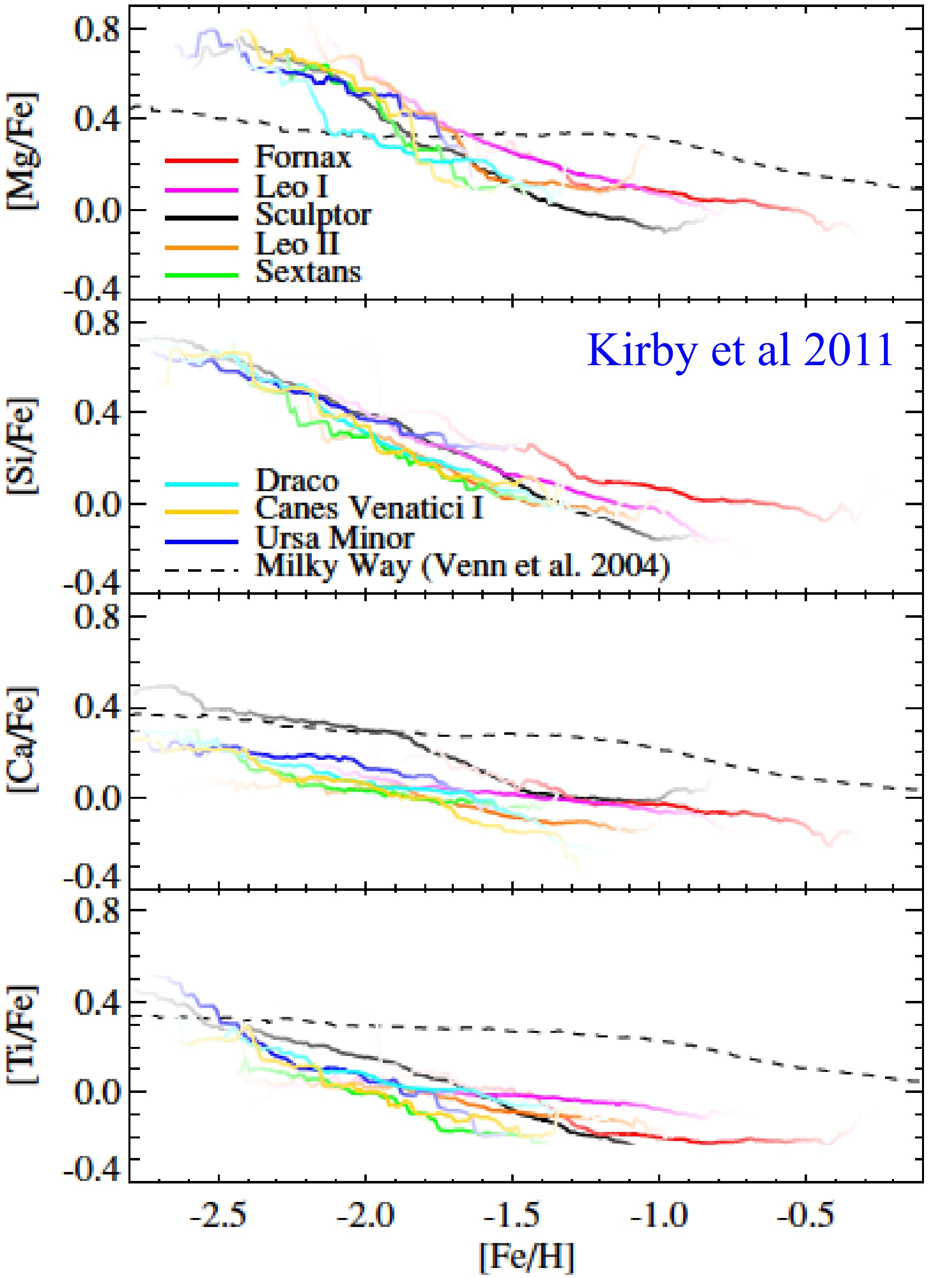


Stellar halos – issues?

- Definition
  Where does bulge end and halo begin?
  Is this defined by position? velocity? orbit? age? metallicity?
  Is the separation physically meaningful?

- Origin
  What are contributions from accreted and *in situ* stars?
  What is meant by *in situ* in the context of halo stars?
  What objects contribute to the accreted component?
  Are they systematically different from surviving dwarfs?
  Where are the oldest stars now? (GCs? dwarfs? halo? bulge?)

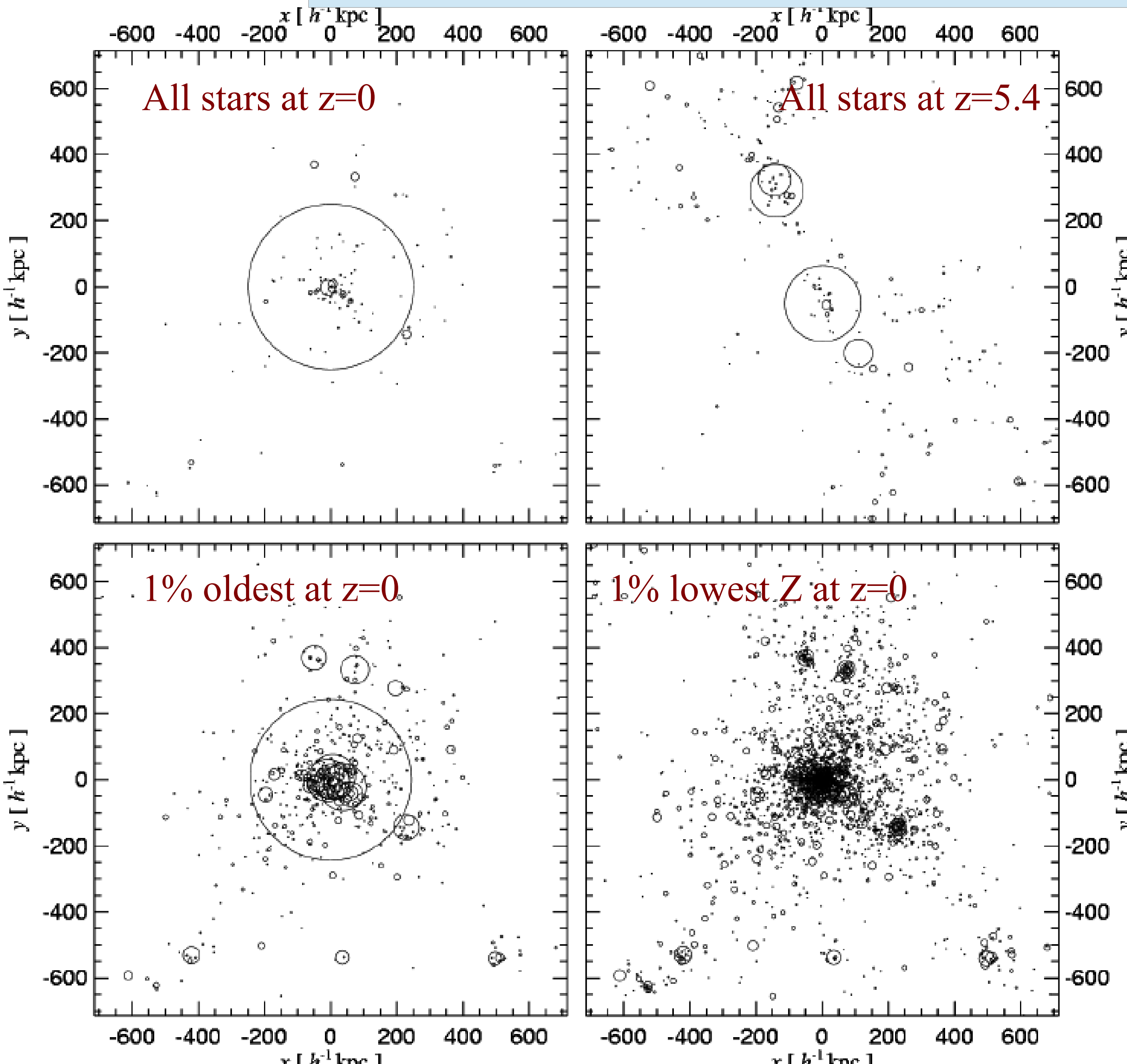
Stellar halos – issues?



The abundance patterns in MW dSph galaxies systematically differ from those in the MW's metal-poor halo

The observed dwarfs <u>cannot</u> be the "building blocks" of the halo, let alone the disk!

Stellar halos – issues?



White & Springel 1999

The oldest stars are predicted to be in the *most massive* galaxies today.

The oldest MW stars are predicted to be in the *bulge,* not the halo.

The lowest Z stars are predicted to be in the halo but are *not*, on average, the oldest.

Stellar halos – issues?

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  Where does bulge end and halo begin?
  Is this defined by position? velocity? orbit? age? metallicity?
  Is the separation physically meaningful?

- Origin
  What are contributions from accreted and *in situ* stars?
  What is meant by *in situ* in the context of halo stars?
  What objects contribute to the accreted component?
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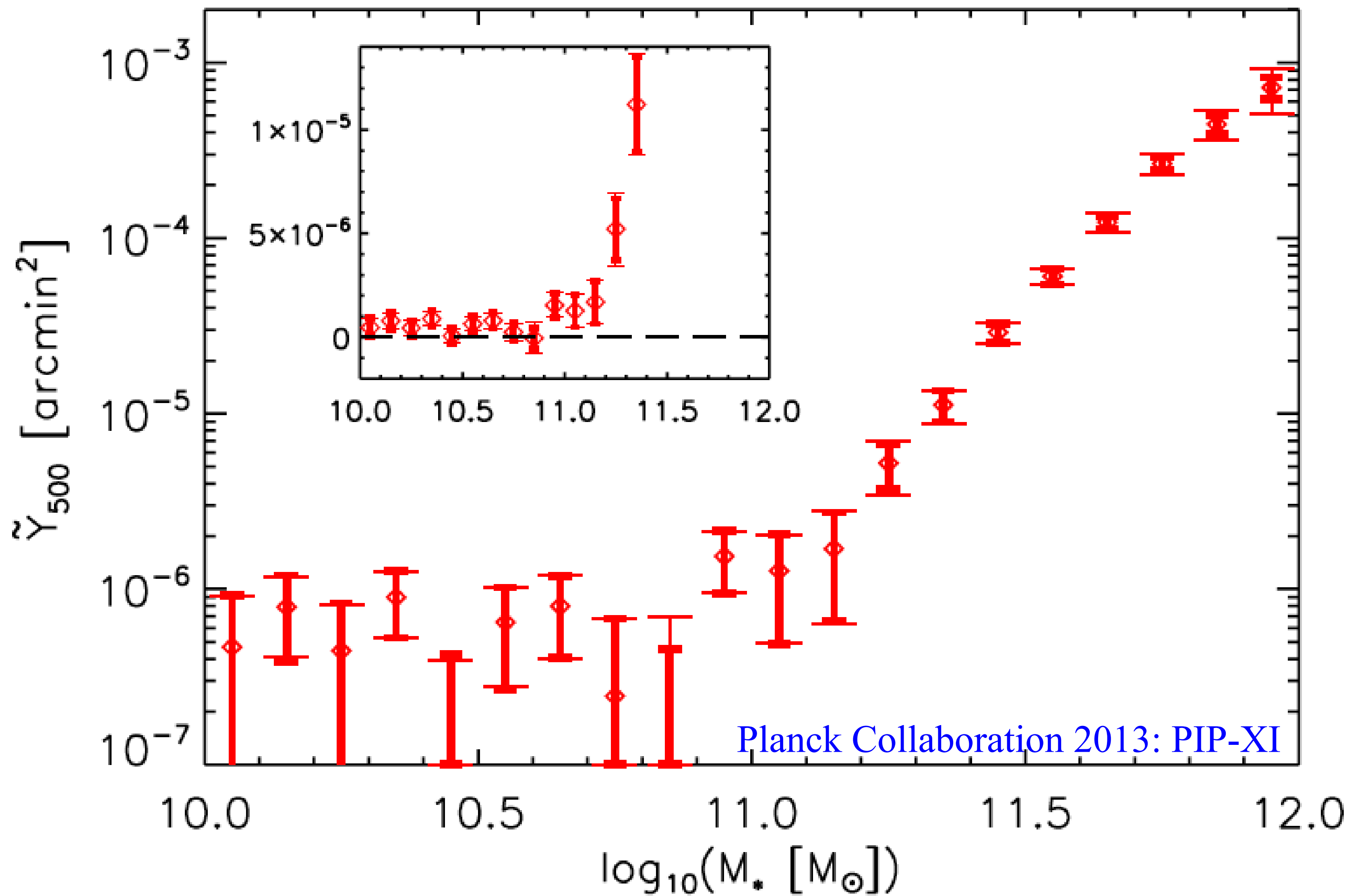
  Where are the oldest stars now? (GCs? dwarfs? halo? bulge?)

- Relation to galaxy formation
  In the MW, the halo has ~1% of stars, the bulge ~10% and the disk(s) ~90%. Is the halo relevant to the formation of the bulk of the system?

Gaseous halos – issues?

- Do they exist?
  Seen around massive ellipticals
  What about (field) spirals? (X-rays? QSO absorbers? SZ?)

Gaseous halos – issues?



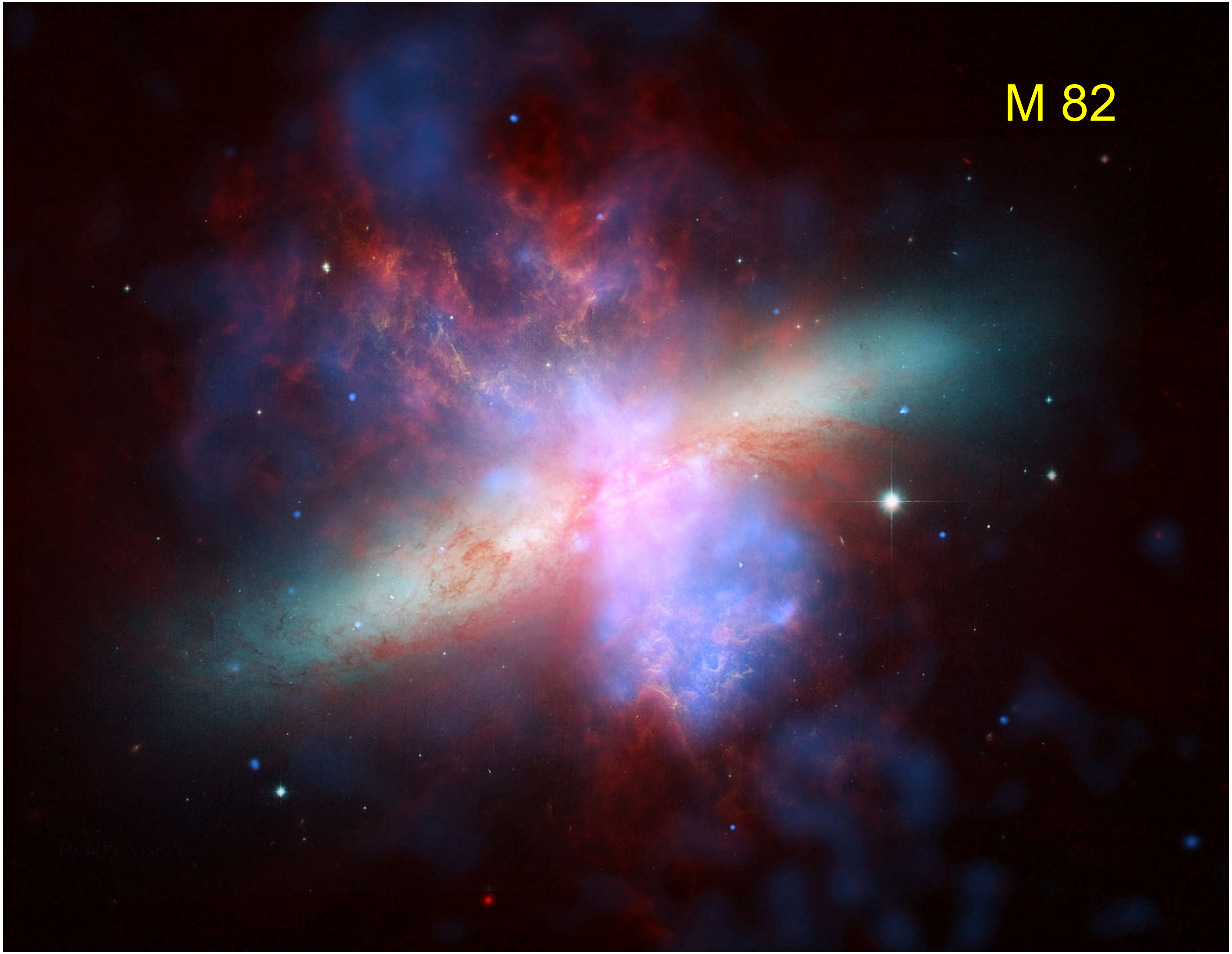
Stacked Planck SZ signal around Locally Brightest Galaxies in SDSS
Signal detected down to isolated galaxies with stellar mass of M31

Gaseous halos – issues?

- Do they exist?
  Seen around massive ellipticals
  What about (field) spirals? (X-rays? QSO absorbers? SZ?)

- Dynamical state
  Hydrostatic equilibrium? (e.g. cluster gas halos)
  Winds? (M82 and other starbusts, high z LBGs)
  Galactic fountain? (e.g. the MW)
  Phase structure? (HVCs QSO absorbers)

Gaseous halos – issues?



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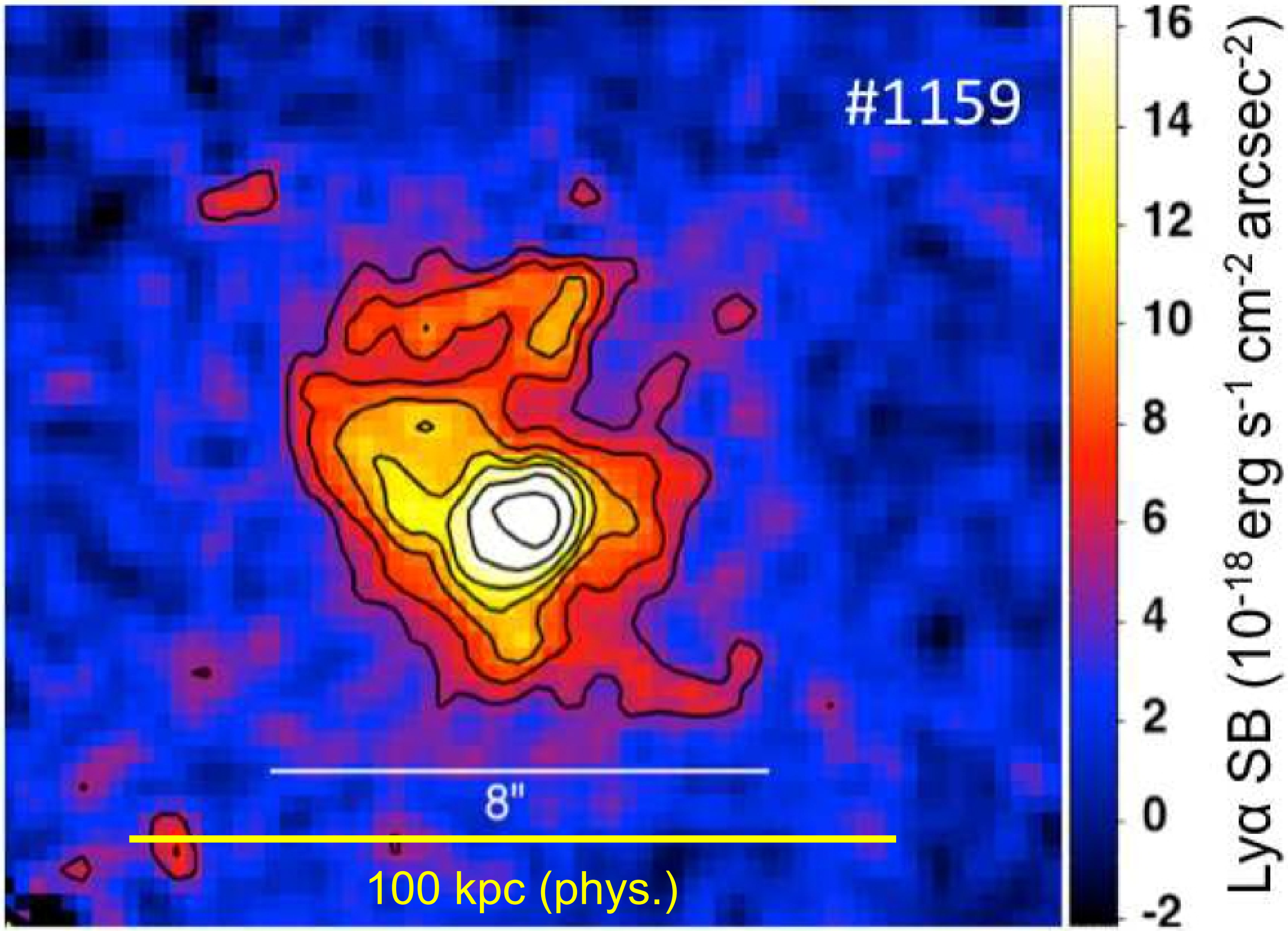
  Phase structure? (HVCs QSO absorbers)

- Origin
  Primordial infall or disk ejection? (metals)
  Cold flows? (HVCs, flourescent high-z emission)

Gaseous halos – issues?

Cantalupo, Lilly & Haehnelt 2013



Ly α flourescent emission from cold filaments around a z=2..4 quasar

Gaseous halos – issues?

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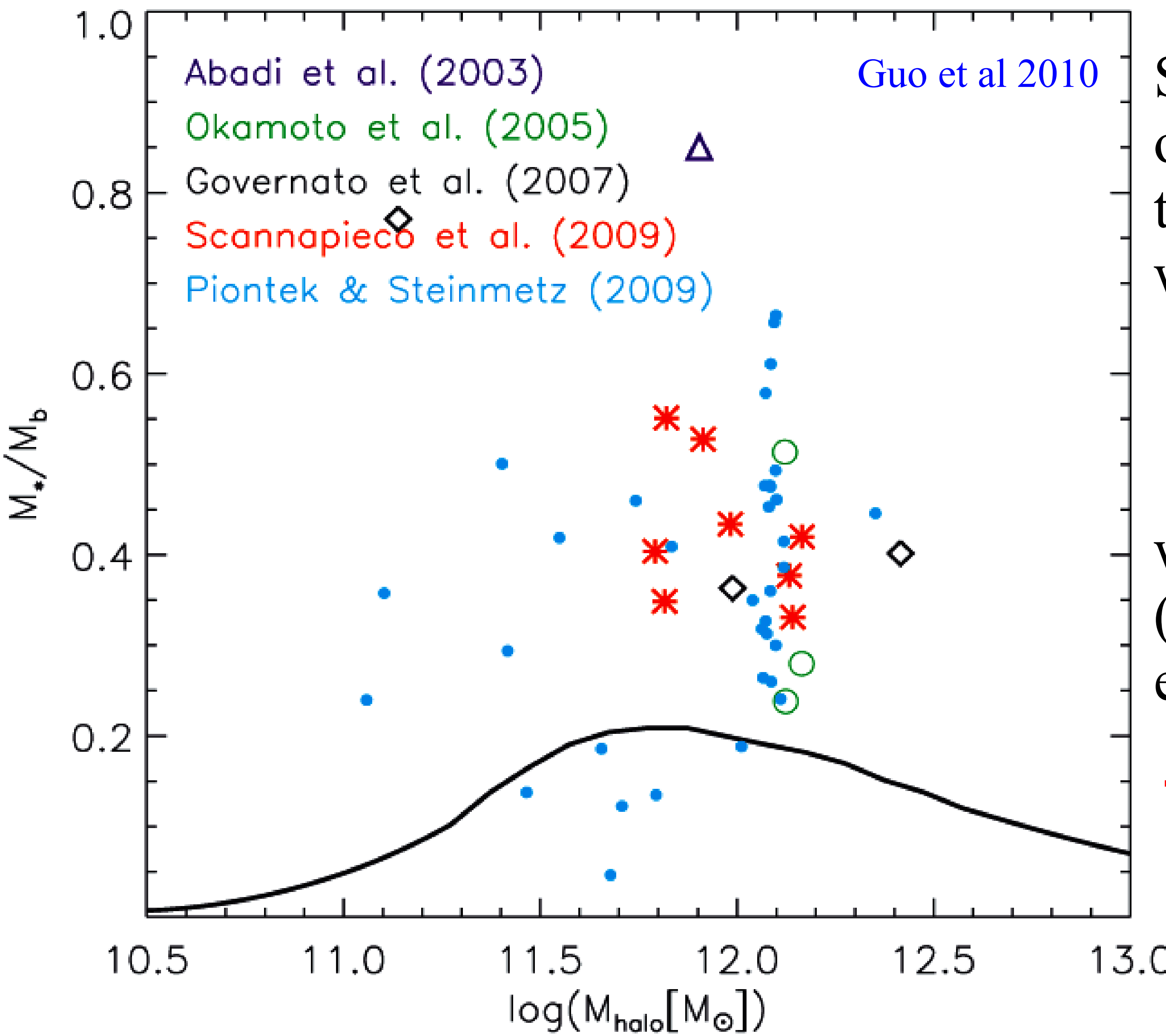
- Relation to galaxy formation
  Where are most of the baryons associated with each halo?

Gaseous halos – issues?



Stars in a galaxy are only a small fraction of the baryons associated with the DM in its halo

$$M_* / M_{halo} << \Omega_b / \Omega_m$$

where are the rest?
(Not seen in the halo except in rich clusters?)

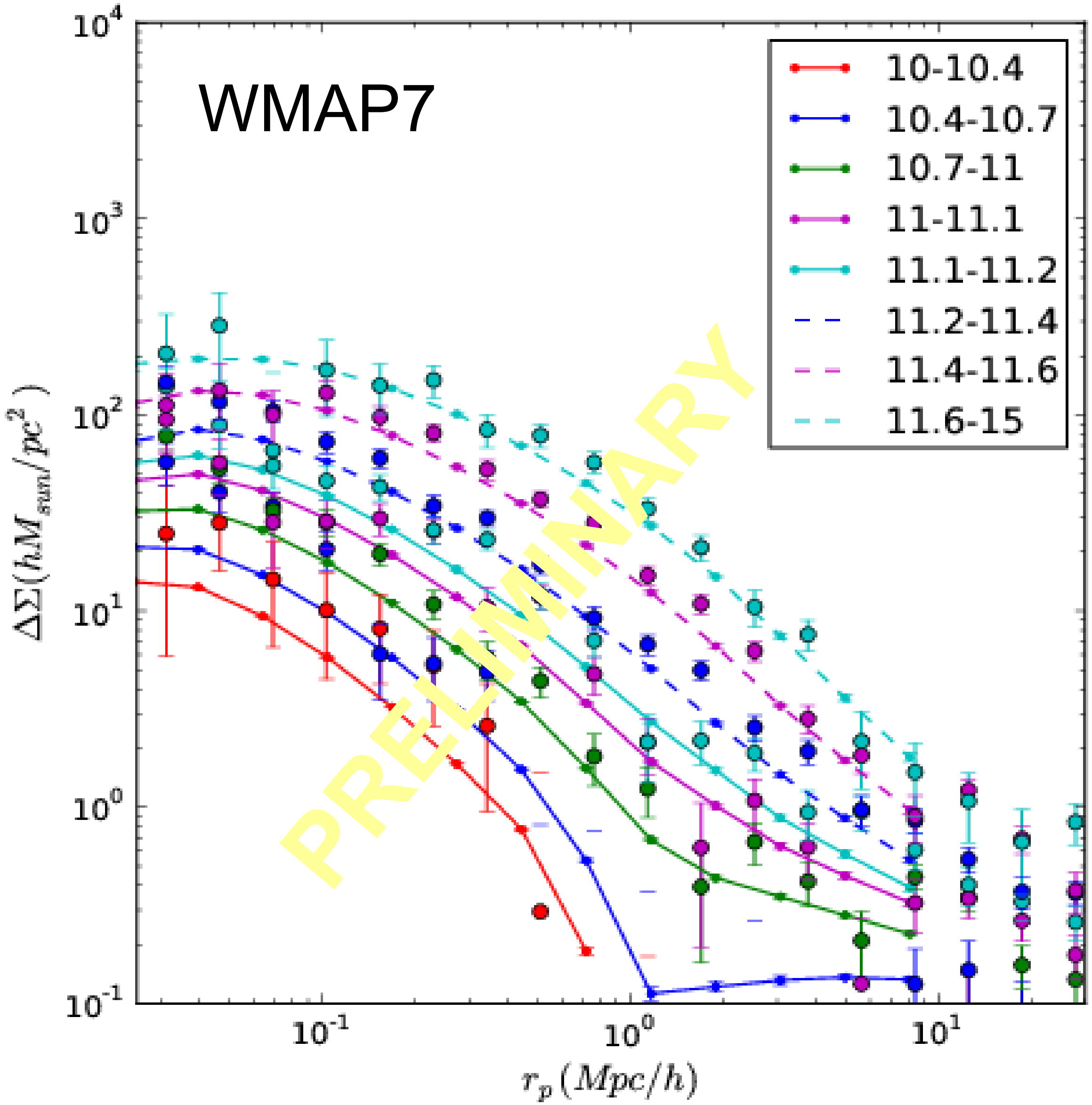
→ strong winds or failure to accrete?

Dark matter halos – issues?

- Profiles as predicted?
  NFW over the bulk of the mass?
  Central cusps? (nature of DM?)

Dark matter halos – issues?

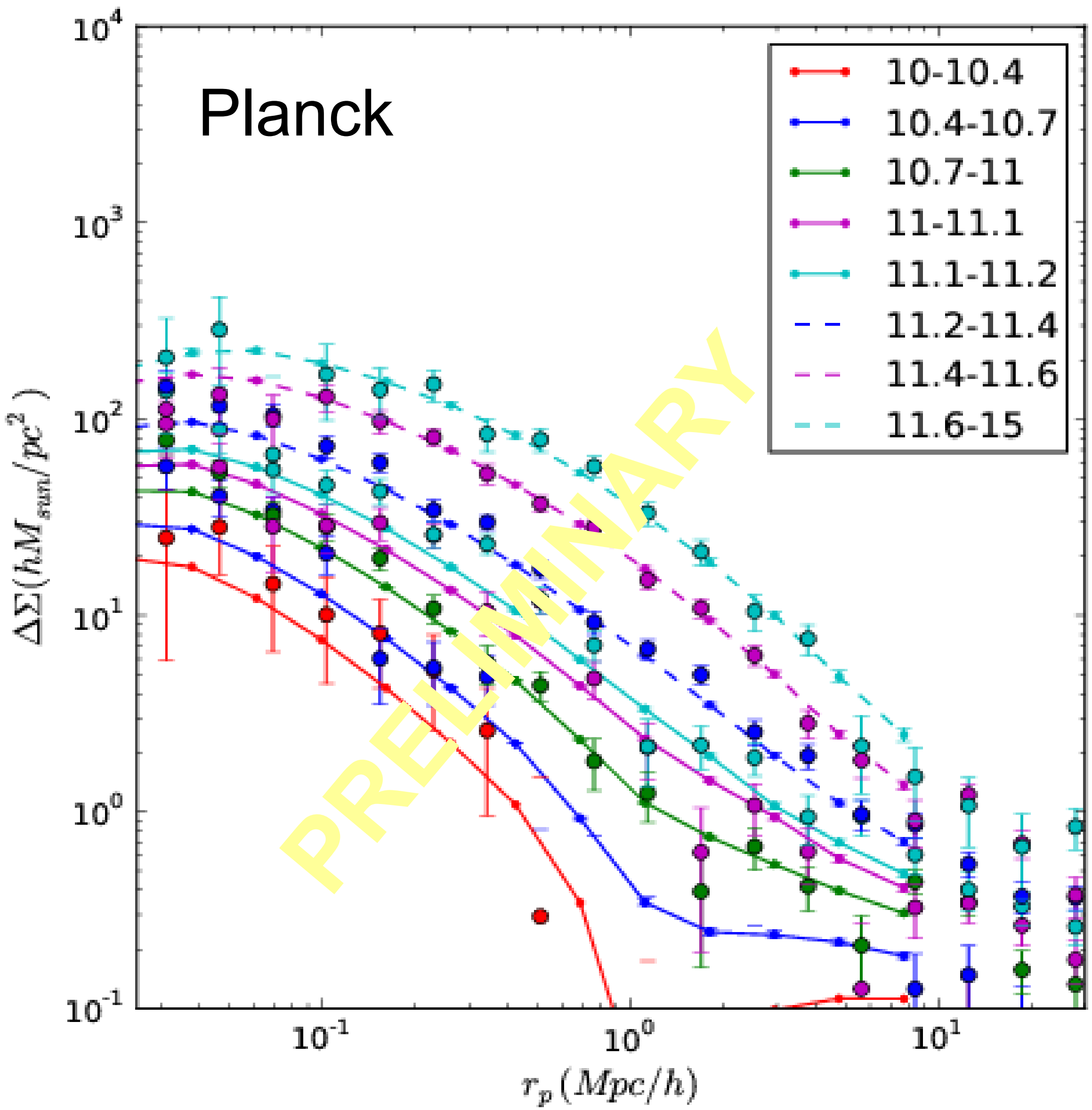
Wang, Mandelbaum et al, in prep.



Stacked weak lensing signal around Locally Brightest Galaxies in the SDSS/DR7 in bins of LBG stellar mass.

Dashed lines are similarly selected samples from the Guo et al (2013) galaxy formation model assuming WMAP7 cosmology

Dark matter halos – issues?



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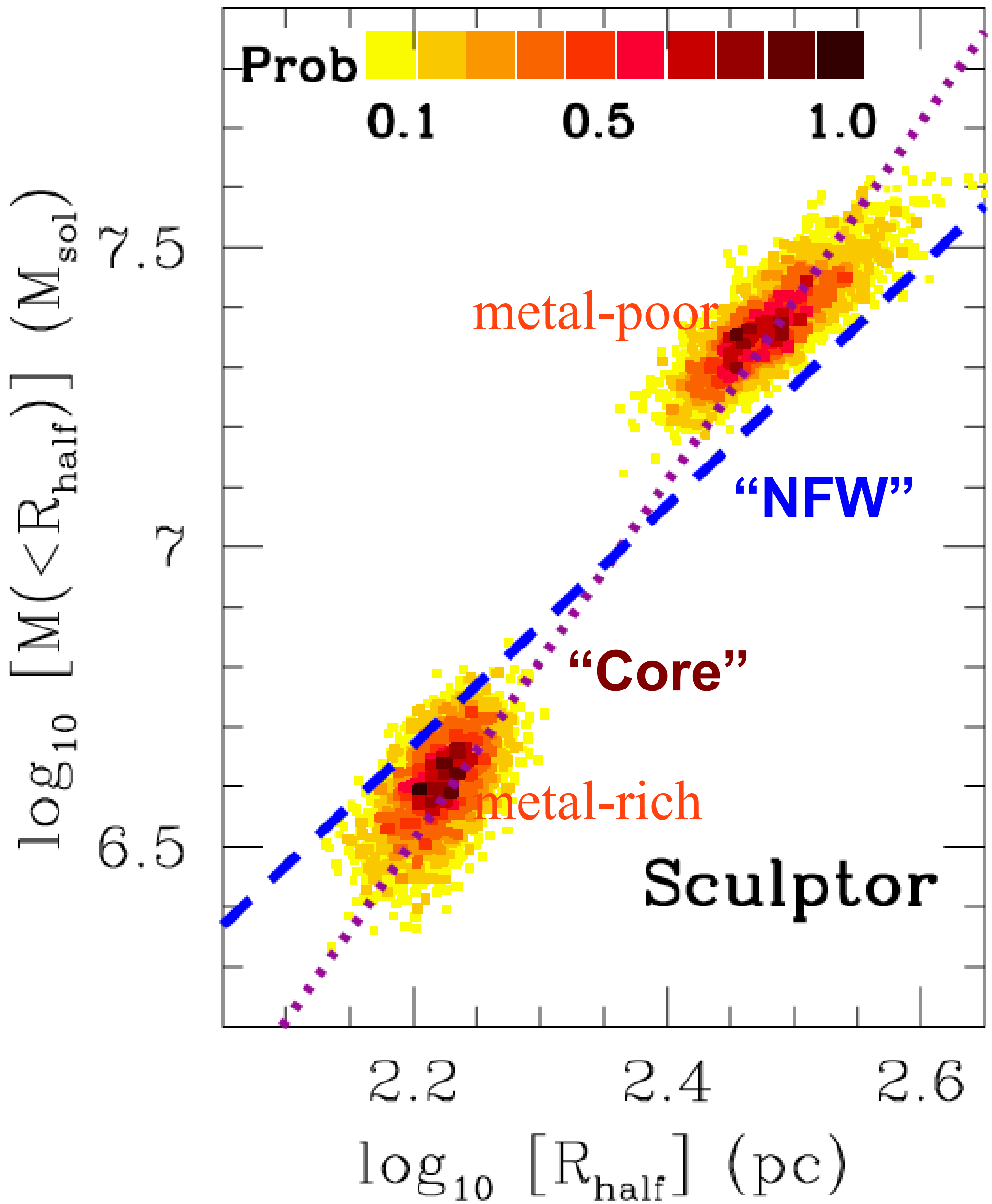
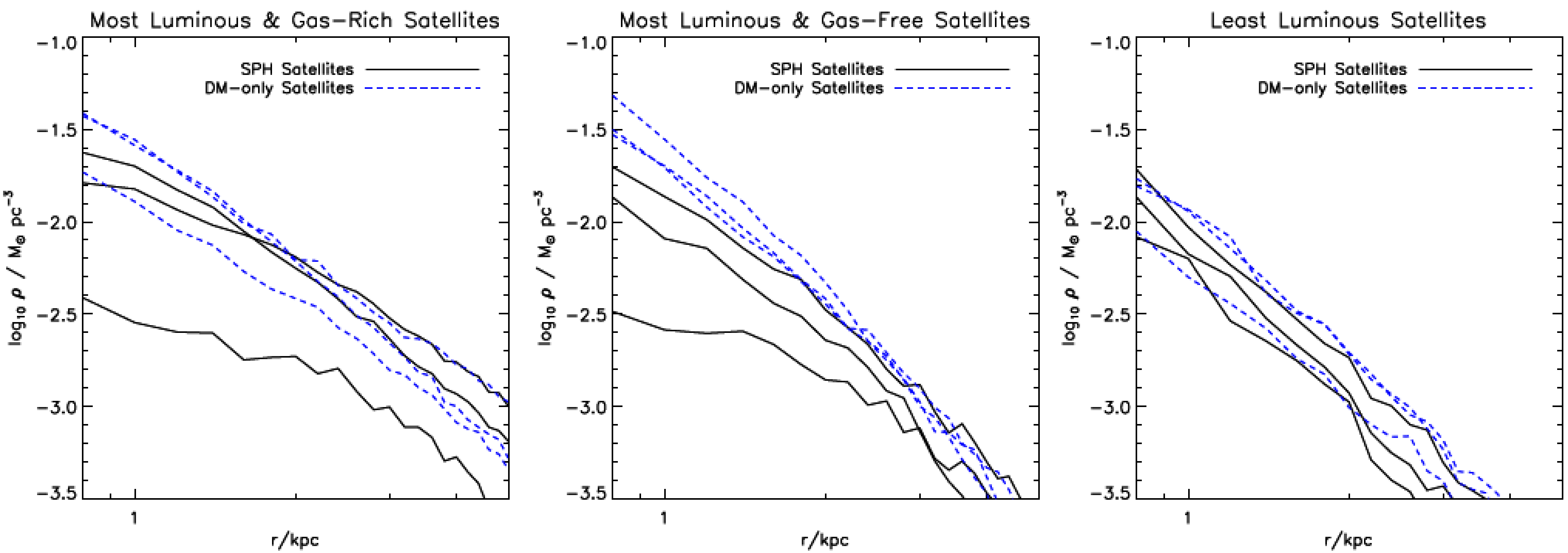


Sculptor (and also Fornax) has two well defined populations. Metal-rich stars are clearly more centrally concentrated and have lower velocity dispersion than metal-poor stars. Assuming

$$M(r_{1/2,proj}) = C_W \, r_{1/2,proj} \, \sigma^2_{l.o.s.} / G$$

with $C_W \approx 2.5$, Walker & Penarrubia (2011) exclude NFW mass distributions

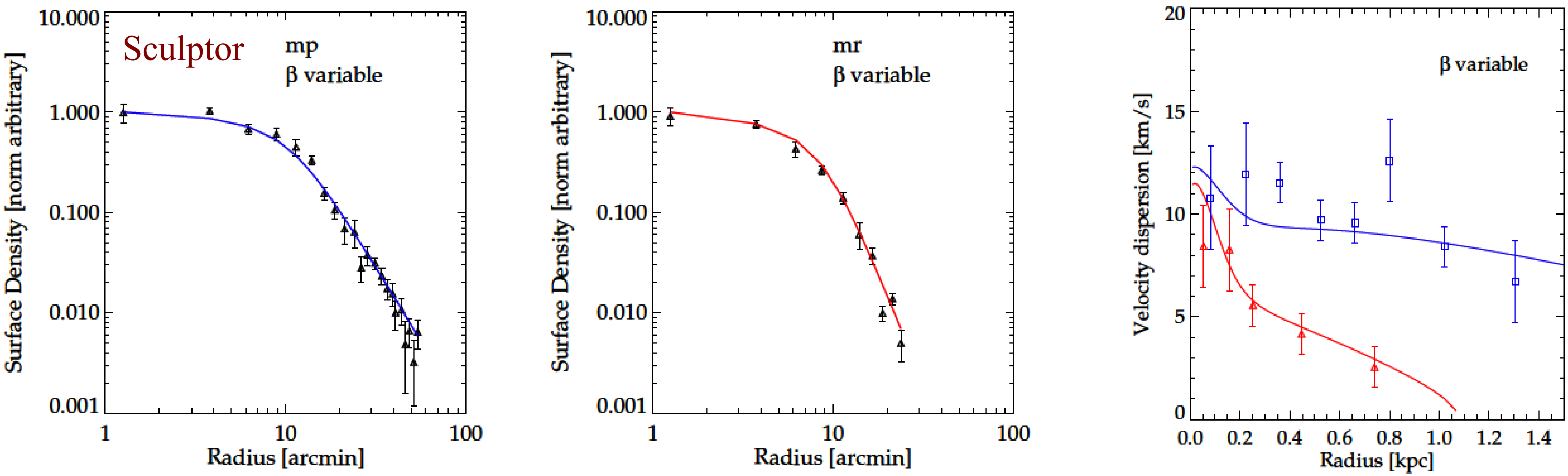
Dark matter halos – issues?



SPH simulations by Zolotov et al (2012) suggest dynamics associated with star formation may "flatten" cores in more massive dwarfs

Dark matter halos – issues?

Strigari et al 2013, in prep.



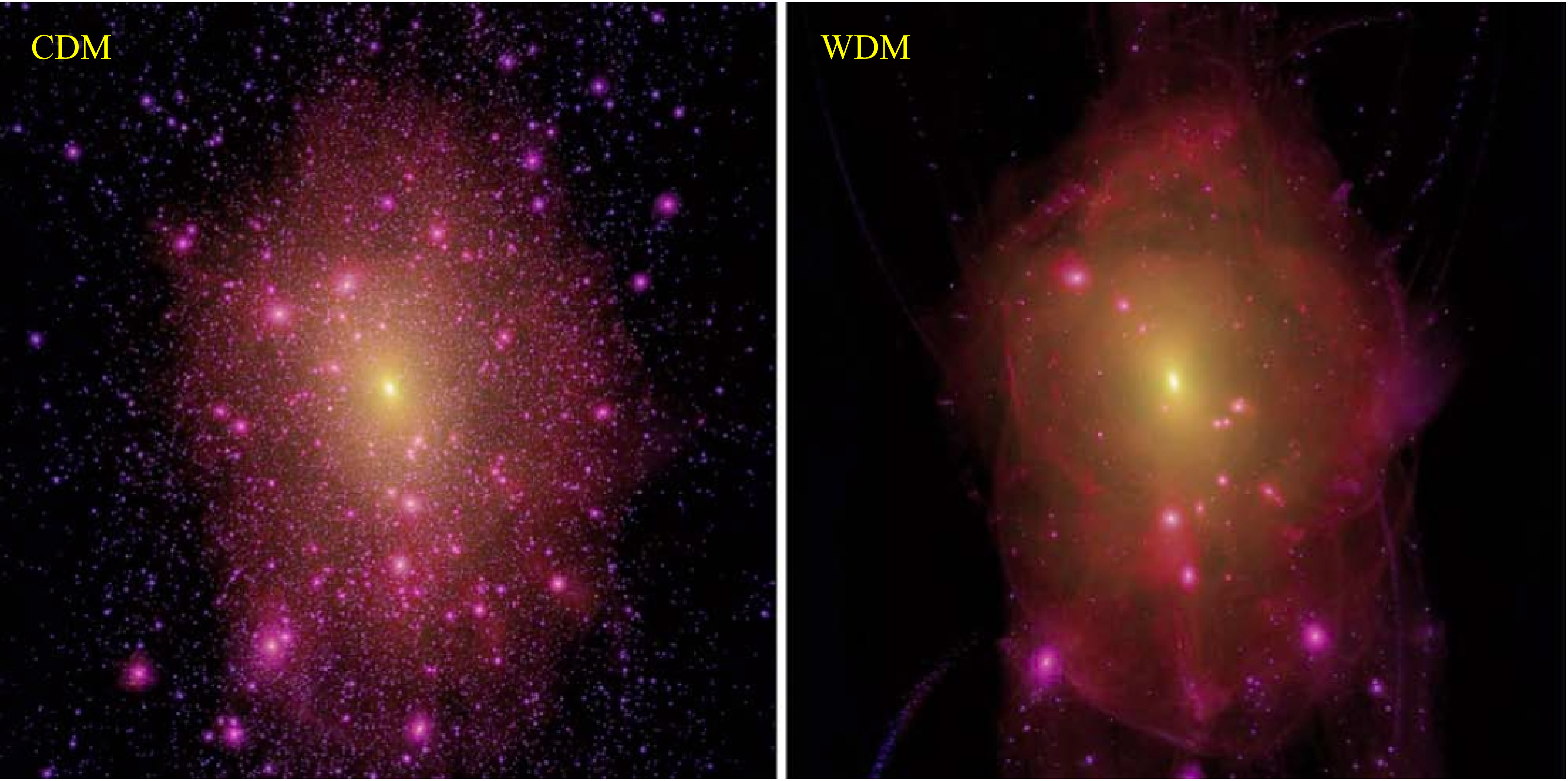
The counts and dispersion profiles of the MR and MP populations in Sculptor *can* be well fit as equilibria within a single NFW potential.

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

Dark matter halos – issues?

Lovell et al 2012.



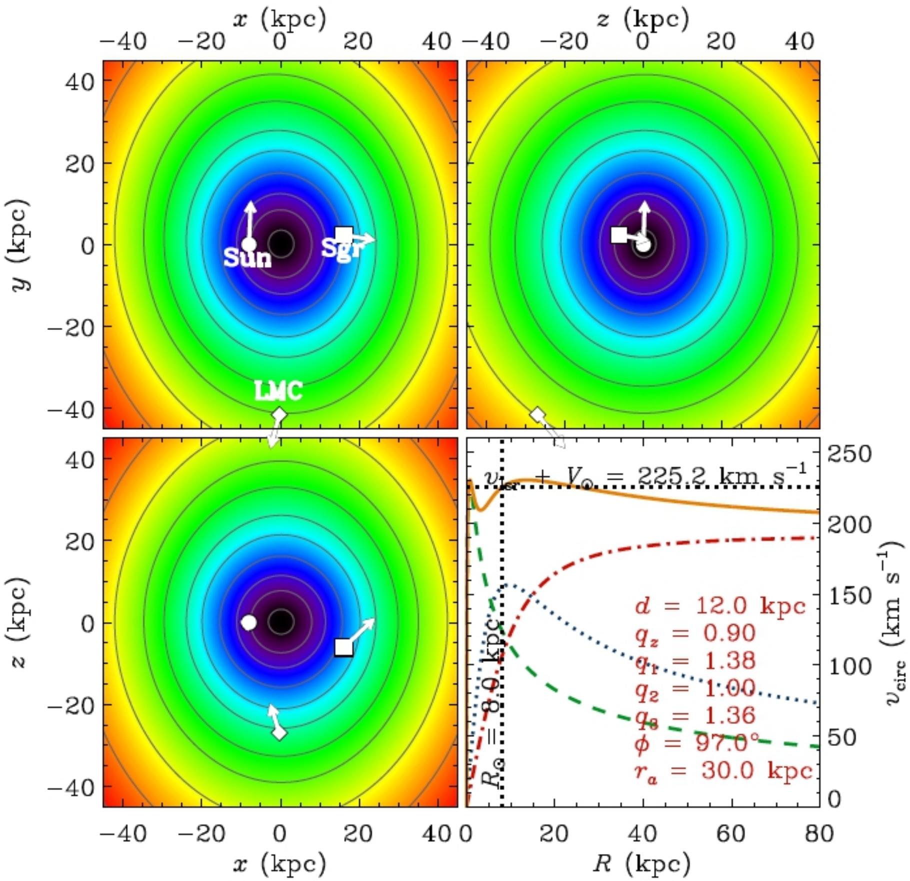
A "Milky Way" halo in CDM and WDM (a 2keV sterile ν)

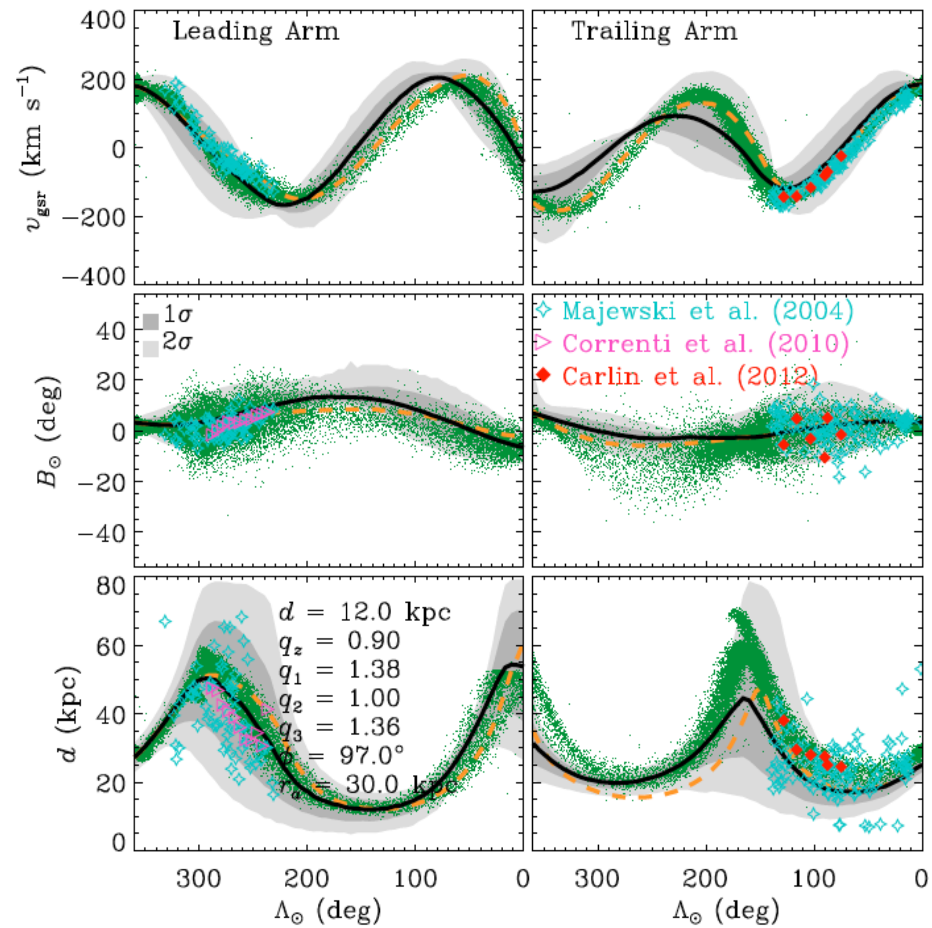
Dark matter halos – issues?

- Profiles as predicted?
  - NFW over the bulk of the mass?
  - Central cusps? (nature of DM?)

- Shapes as predicted?
  - Shapes from lensing (individual clusters? stacked galaxies?)
  - Orbits of the streams in the MW or M31 halos

Dark matter halos – issues?





Matching kinematics of both leading and trailing arms of Sagittarius can be accomplished by a potential which is oblate at r << 30 kpc and triaxial at r >> 30kpc. The LMC can have a significant effect.

(Vera-Ciro & Helmi 2013)

Dark matter halos – issues?

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- Shapes as predicted?
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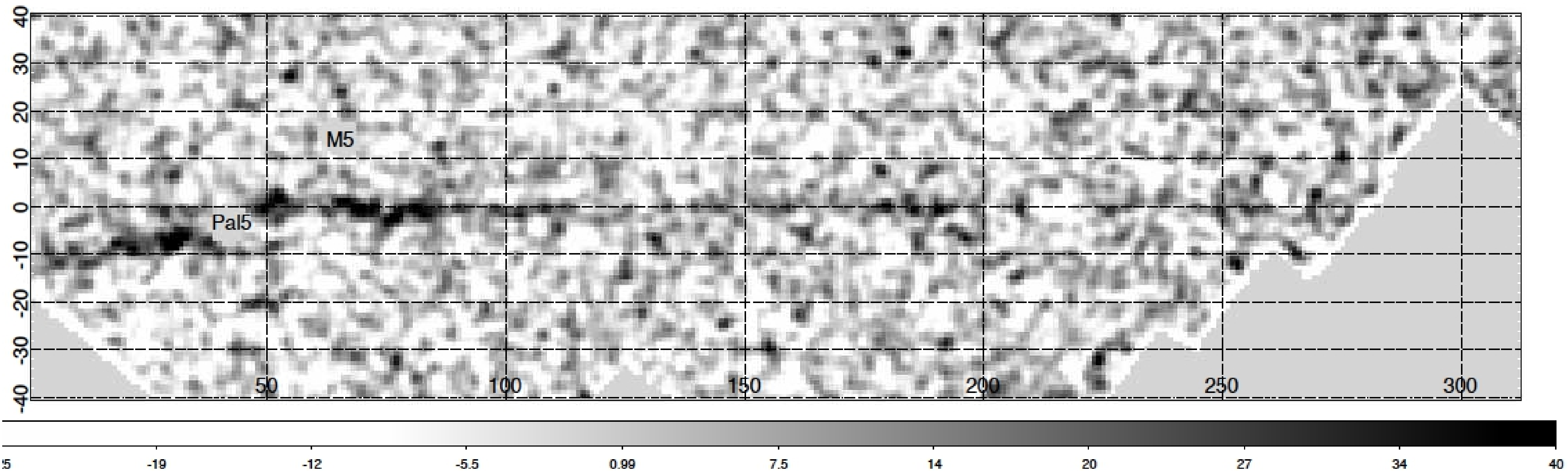
  - Orbits of the streams in the MW or M31 halos
- Substructure as predicted?
  - Effects on disk? GCs? Streams?
  - Effects on strongly lensed background objects
  - Satellite counts – abundances, M_*–V_{max} relations

Dark matter halos – issues?

Carlberg, Grillmair & Hetherington 2013



Gaps in the Pal 5 star stream may be induced by DM subhalos
Five gaps at >99% confidence requires >1000 substructures within 30 kpc with V_{max} > 1 km/s, consistent with ΛCDM predictions.

Dark matter halos – issues?

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  NFW over the bulk of the mass?
  Central cusps? (nature of DM)

- Shapes as predicted?
  Shapes from lensing (individual clusters? stacked galaxies?)
  Orbits of the streams in the MW or M31 halos

- Substructure as predicted?
  Effects on disk? GCs? Streams?
  Effects on strongly lensed background objects
  Satellite counts – abundances, M_*–V_{max} relations

- Correspondance of halos/subhalos to galaxies

The halo–galaxy correspondance

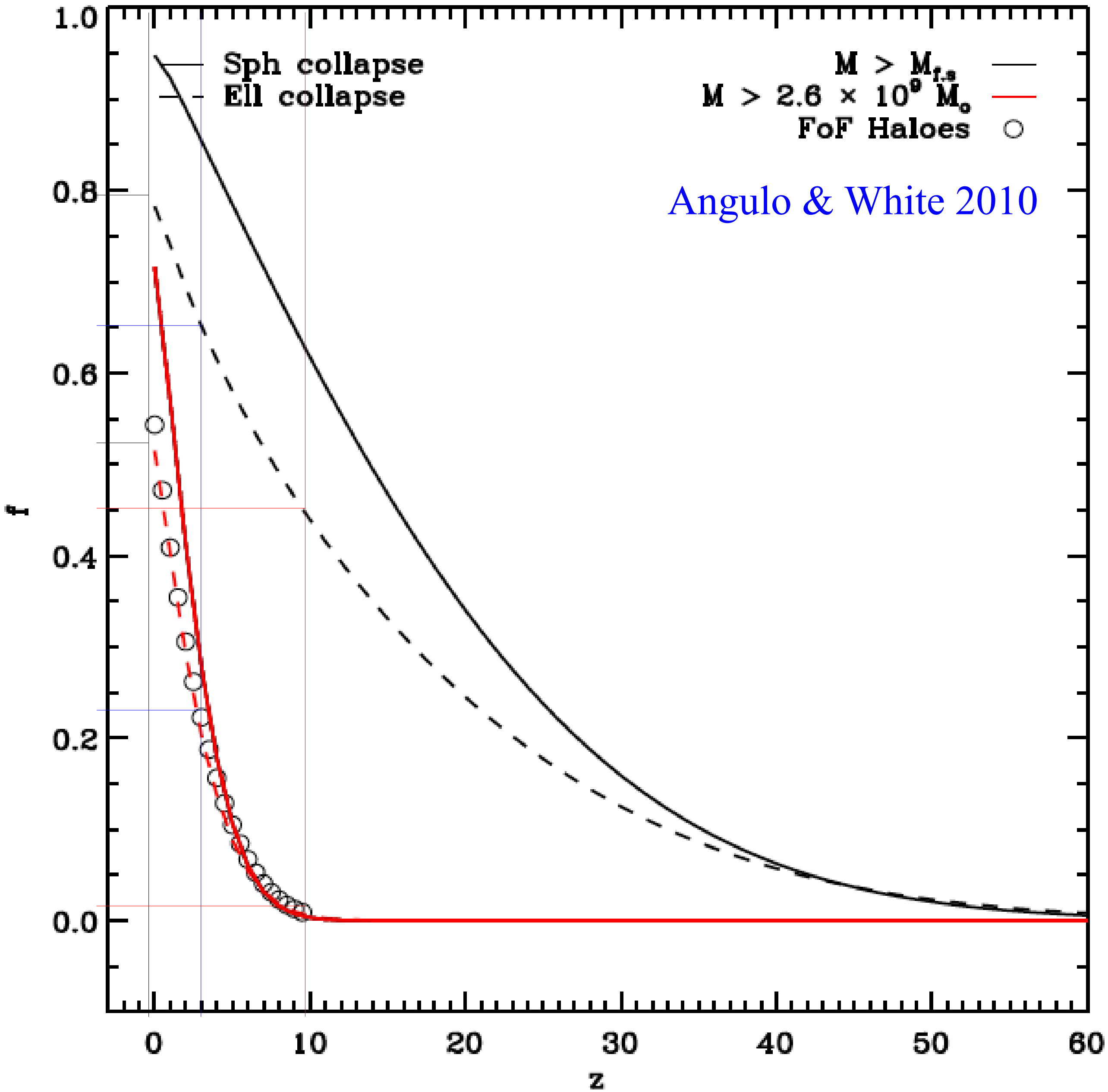
- Today ~half of all DM is in halos massive enough to host galaxies

  Galaxies are biased tracers of the mass

  → <50% of all baryons are in galaxy halos

  a small fraction of baryons is in galaxy halos at high z

The halo–galaxy correspondance



At z=0:
80% of all mass is in halos
52% is in galaxy halos

At z=3:
65% of all mass is in halos
23% is in galaxy halos

At z=10:
45% of all mass is in halos
1% is in galaxy halos

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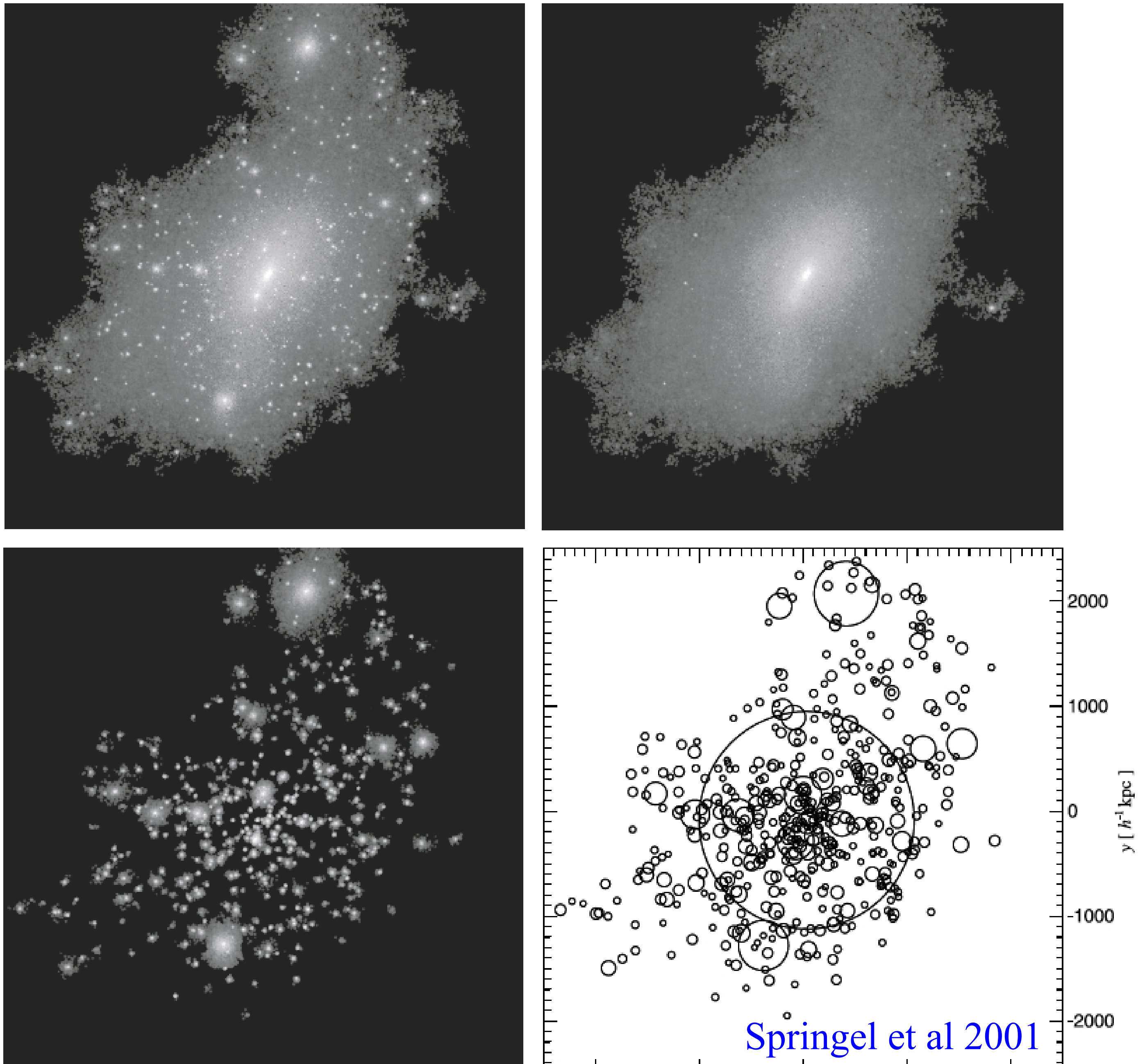
  Galaxies are associated with *sub*halos, not halos
  Not all subhalos may have a galaxy
  Not all galaxies may have a subhalo in a DM-only simul'n

The halo–galaxy correspondance



FoF halos have arbitrary and irregular boundaries

They can have many subhalos

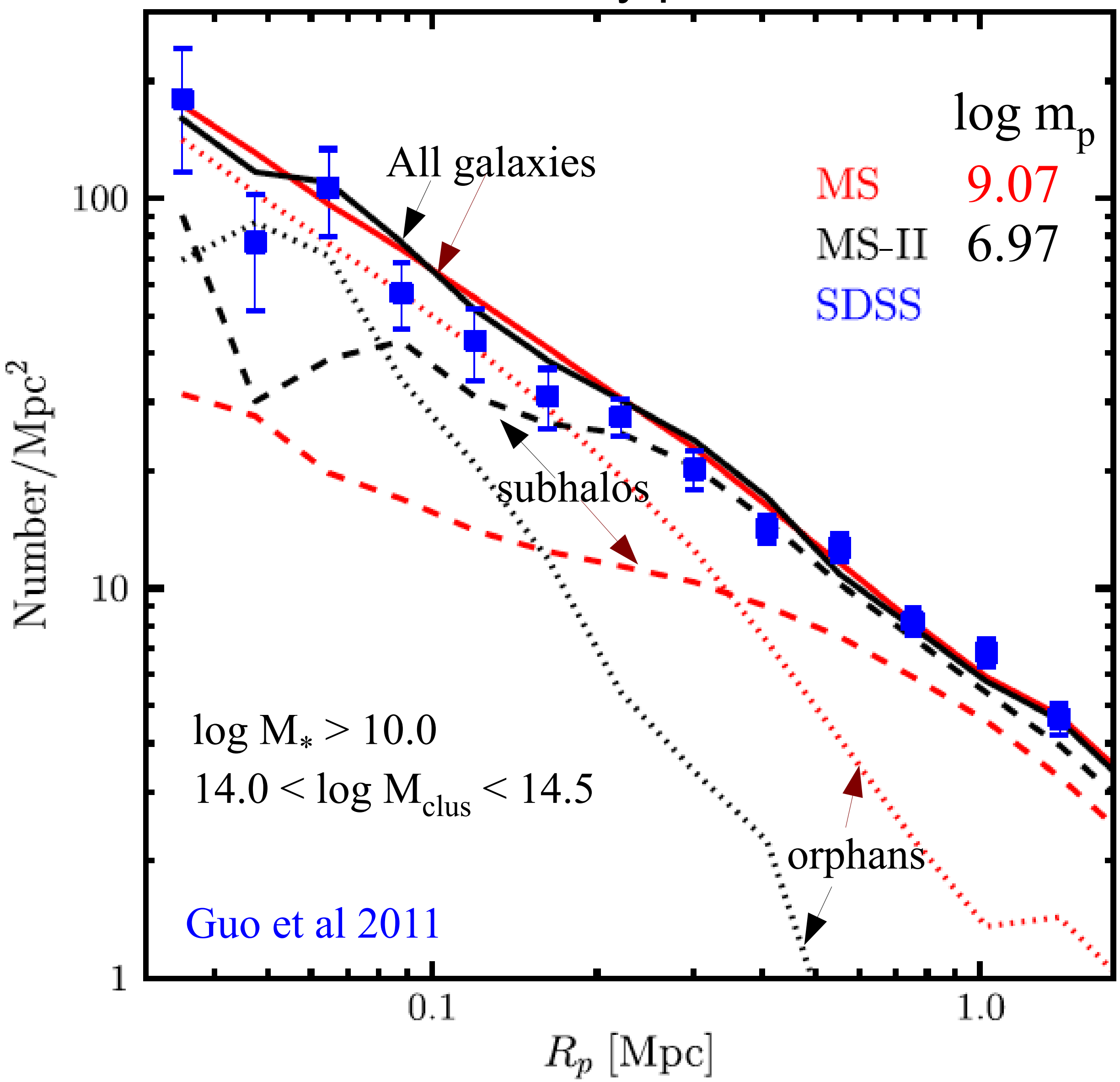
Some subhalos are effectively independent

The main subhalo inherits extra mass

<u>Subhalos</u> correspond to galaxies

The halo–galaxy correspondance

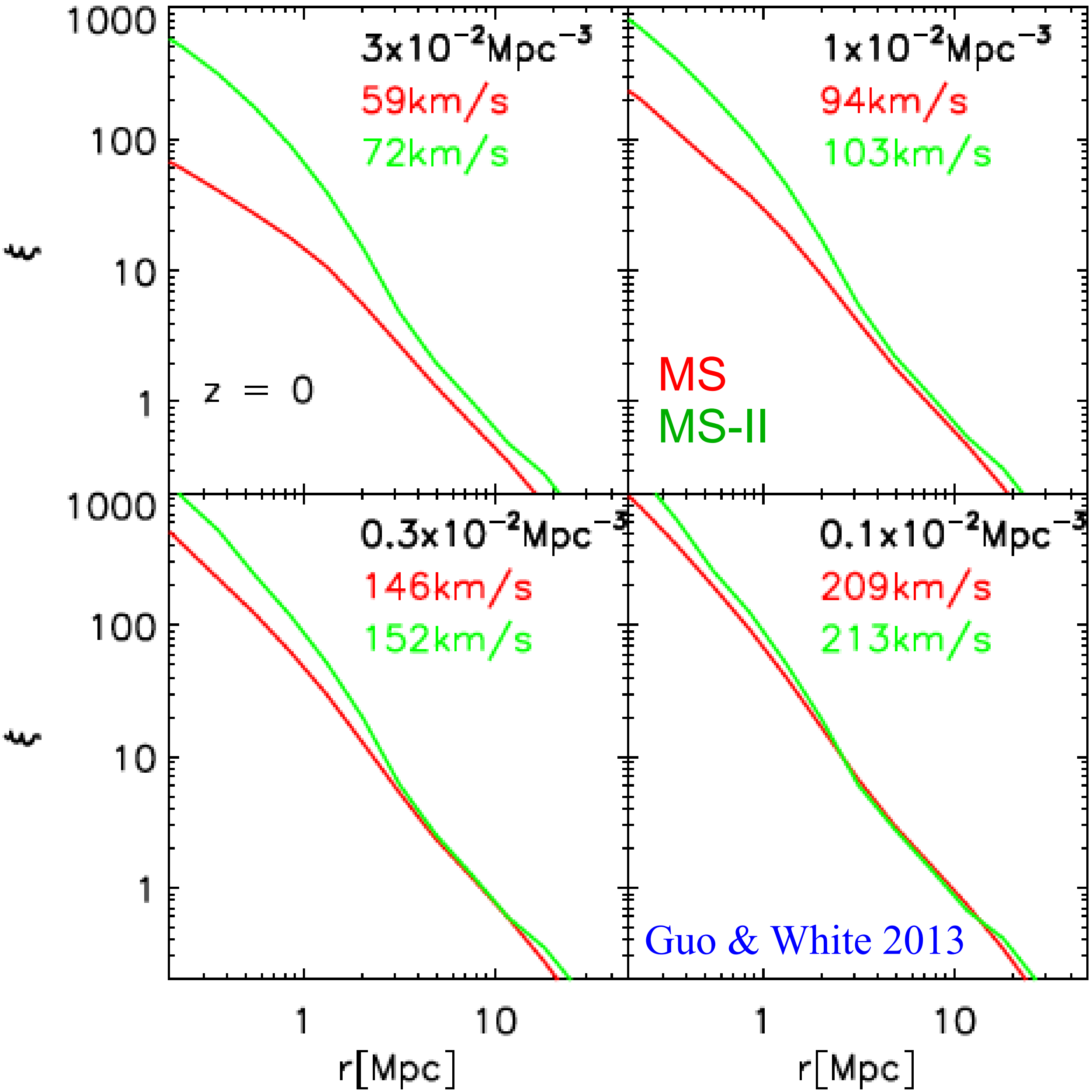
Stacked number density profile of rich clusters



Following subhalos in an N-body simulation results in galaxy loss near cluster centre even at MS-II resolution.

Appropriate semi-analytic treatment of "orphans" can restore convergence.

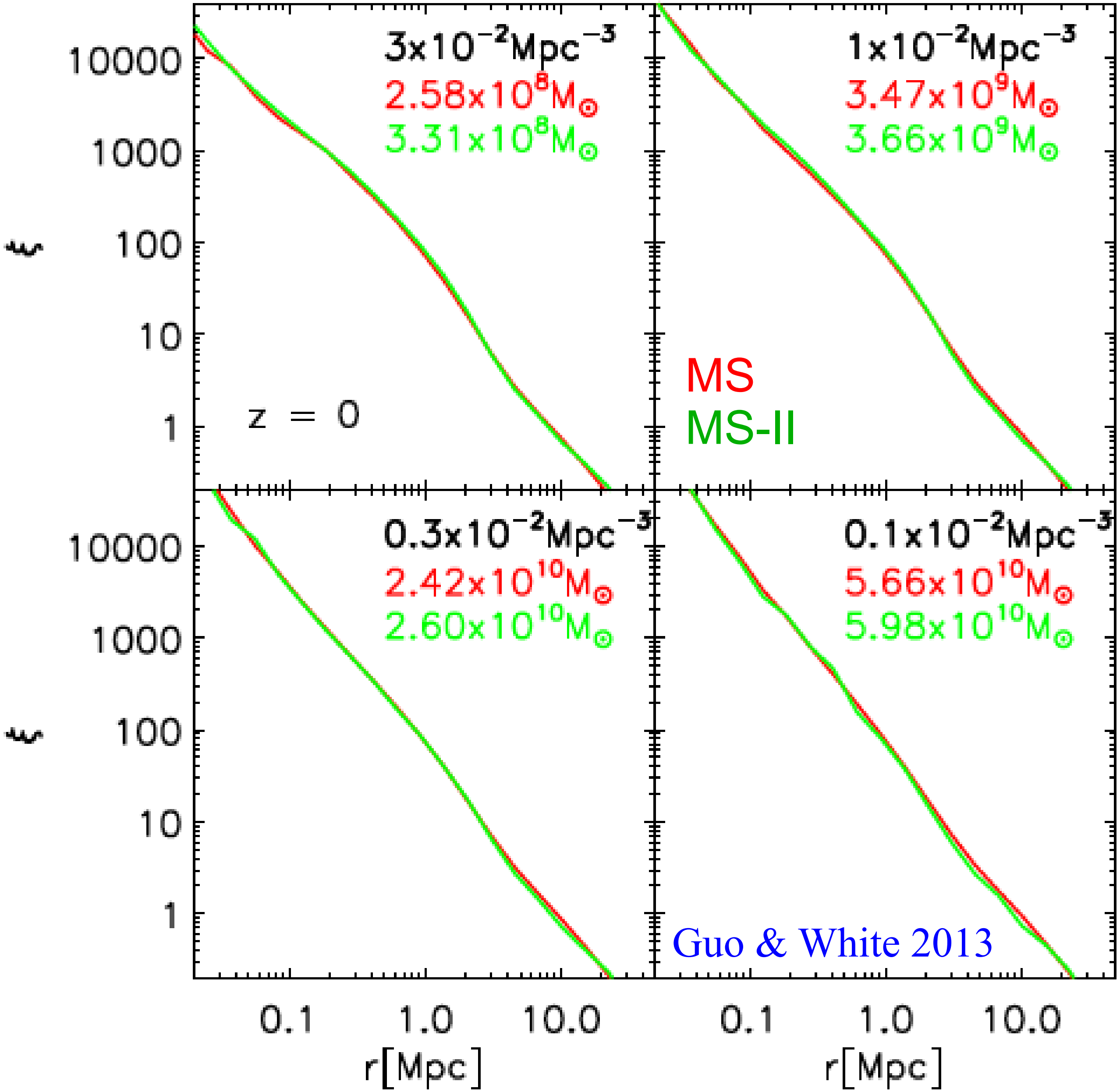
The halo–galaxy correspondance



Following subhalos in an N-body simulation results in galaxy loss near cluster centre even at MS-II resolution.

Subhalo abundance matching is thus sensitive to numerical resolution

The halo–galaxy correspondance



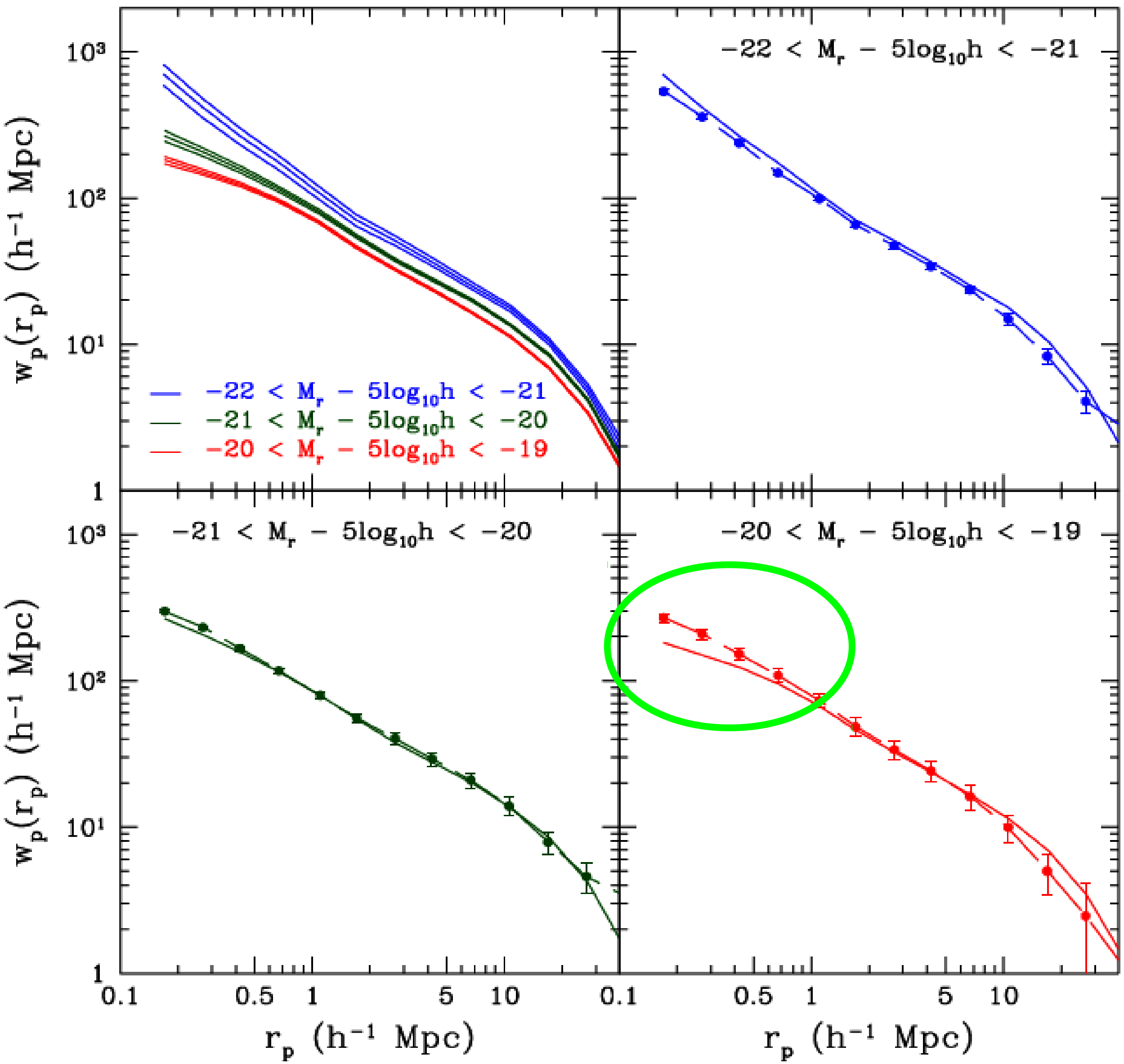
Following subhalos in an N-body simulation results in galaxy loss near cluster centre even at MS-II resolution.

Subhalo abundance matching is thus sensitive to numerical resolution..

..but can be fixed by following orphans

The halo–galaxy correspondance

Trujillo-Gomez et al 2011



Resolution effects will depend on N-body integrator and suhalo finder, but are expected in all SHAM schemes, as here in *Bolshoi*

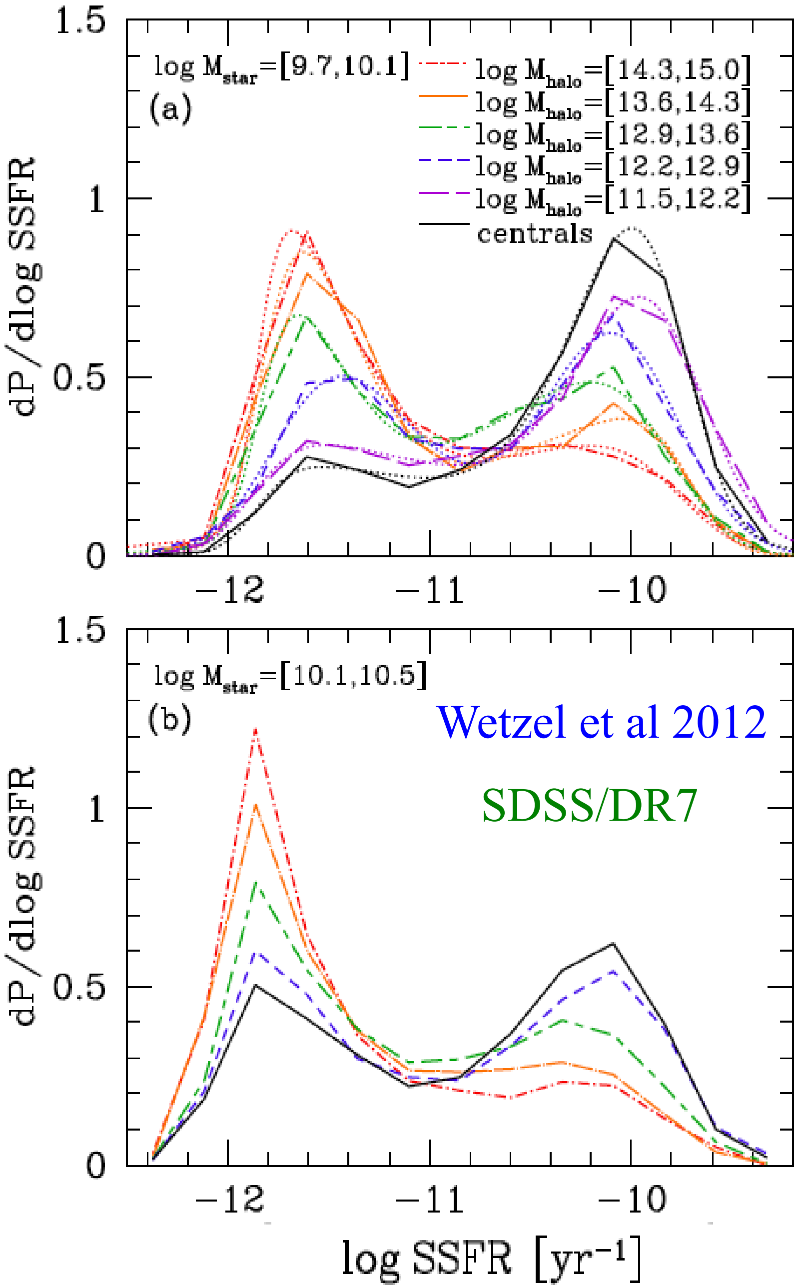
The halo–galaxy correspondance

- Today ~half of all DM is in halos massive enough to host galaxies
  Galaxies are biased tracers of the mass
  $\longrightarrow$ <50% of all baryons are in galaxy halos
  a small fraction of baryons is in galaxy halos at high z

- Galaxies *form* by cooling and condensation of gas in halo *cores*
  Galaxies are associated with *sub*halos, not halos
  Not all subhalos may have a galaxy
  Not all galaxies may have a subhalo in a DM-only simul'n

- The set of galaxy properties $\underline{\mathbf{G}}$ depends on subhalo mass and assembly history and possibly on larger scale environment
  Minimally, $\underline{\mathbf{G}} = \underline{\mathbf{G}}\,(M_{infall}, z_{infall}, M_{host})$

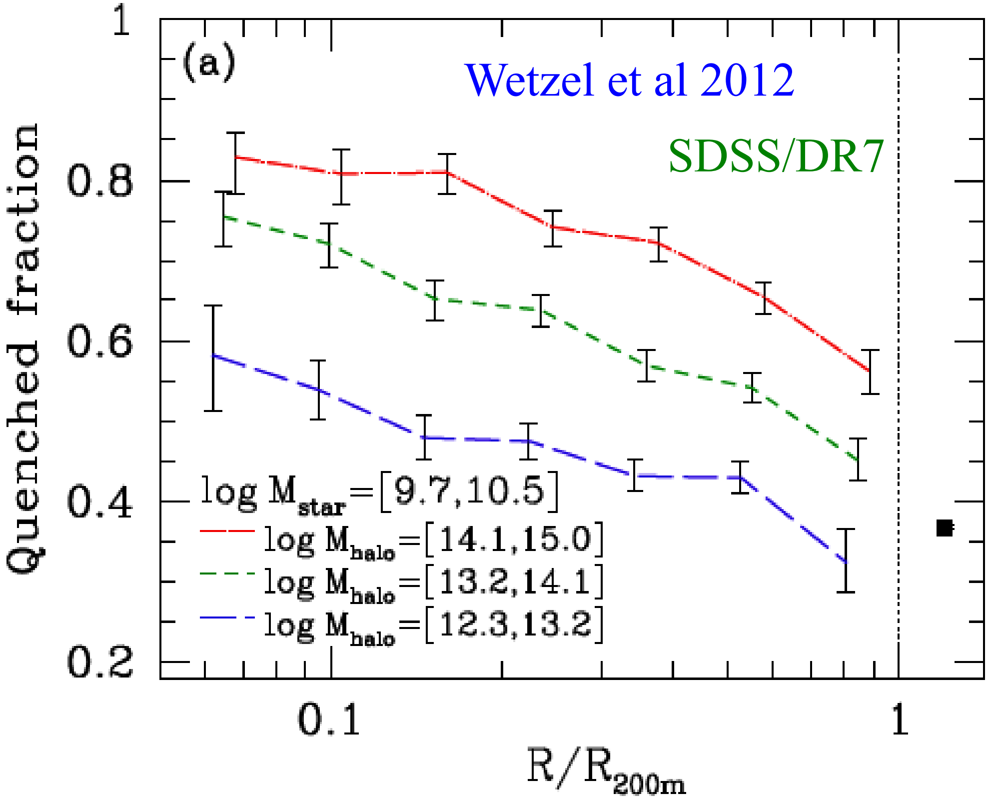
The halo–galaxy correspondance



At *given* stellar mass, the SSFR of satellite galaxies depends on the mass of their host halo and differs from the SSFR of centrals.

G (M_{infall}, z_{infall}, M_{host}) depends in a significant way on M_{host}

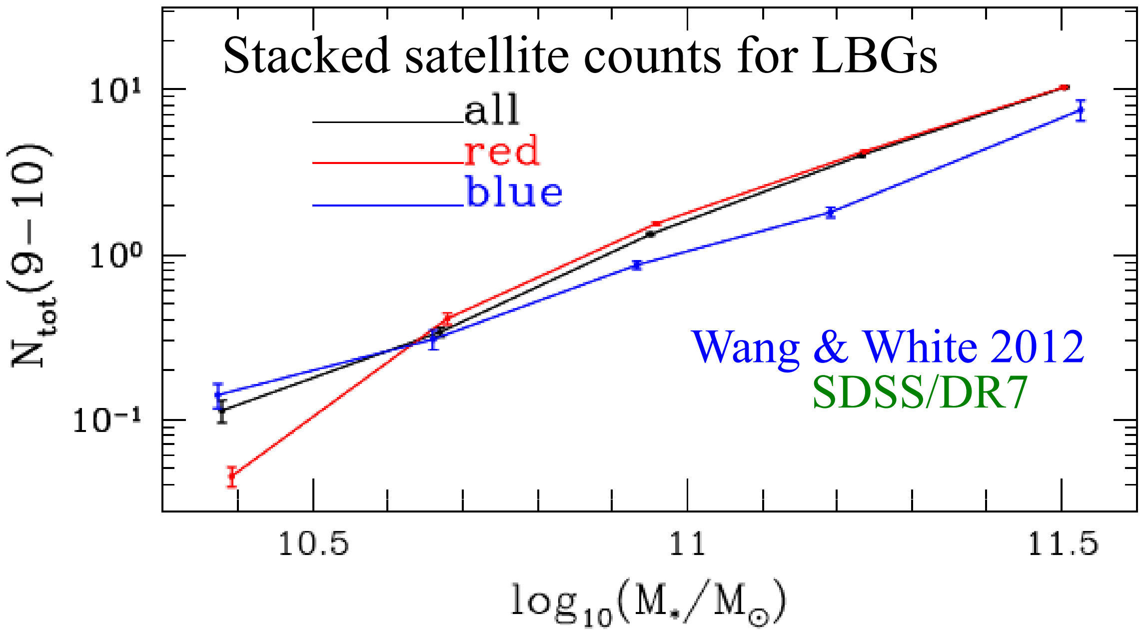
The halo–galaxy correspondance

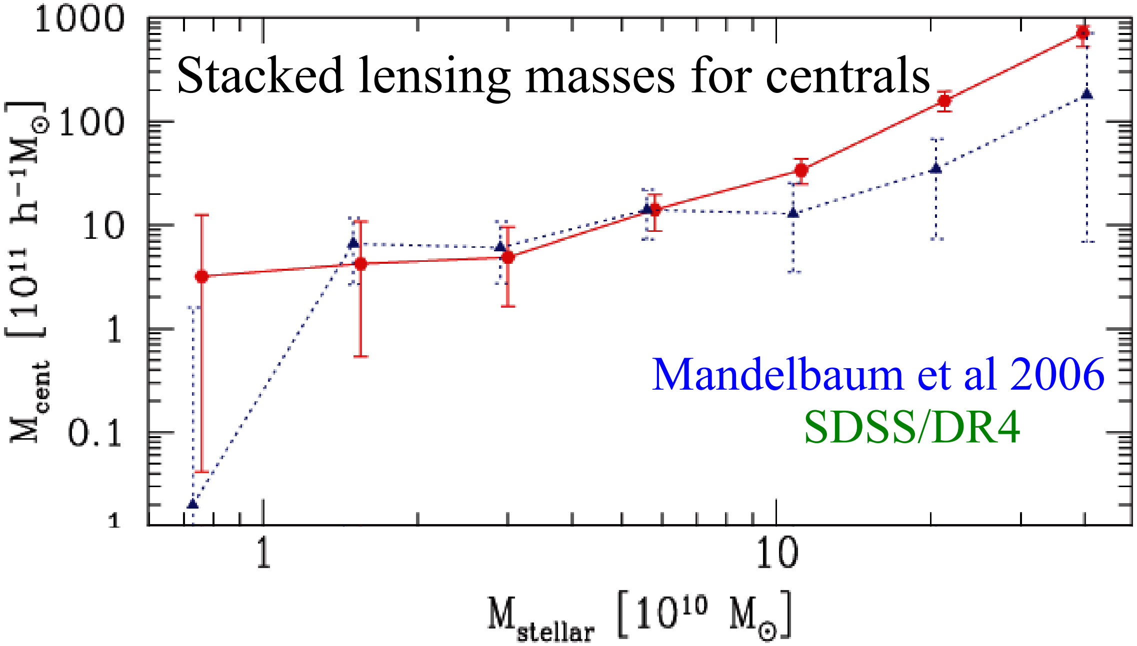


At *given* stellar mass, the SSFR of satellite galaxies depends on the radius in their host halo and differs from the SSFR of centrals.

<u>**G**</u> (M_{infall}, z_{infall}, M_{host}) depends in a significant way on z_{infall} (or J_{infall})

The halo–galaxy correspondance





At given stellar mass, the halo mass of central galaxies depends on their SSFR.

→ At given halo mass, the colour and stellar mass of central galaxies are correlated.

<u>**G**</u> (M_{infall}, z_{infall}, M_{host},....) for centrals depends on halo assembly history at given halo mass ($M_{infall} = M_{host}$, $z_{infall} = 0$)

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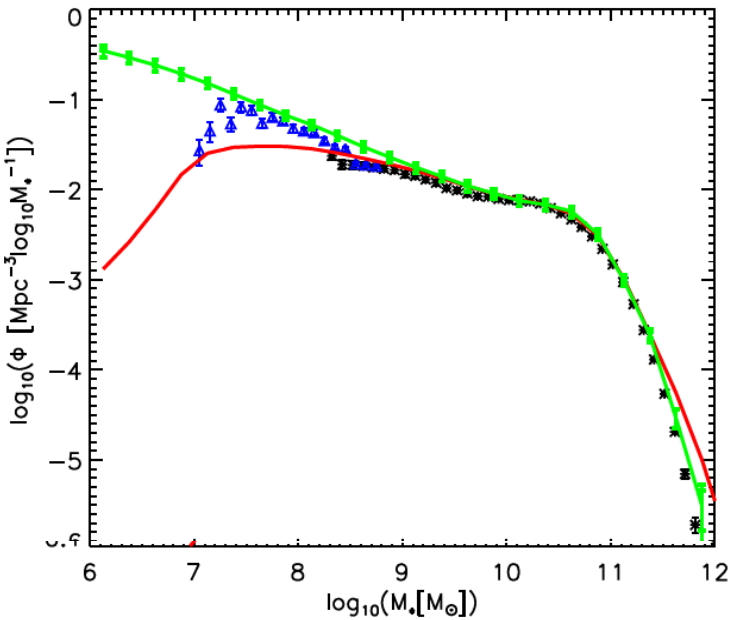
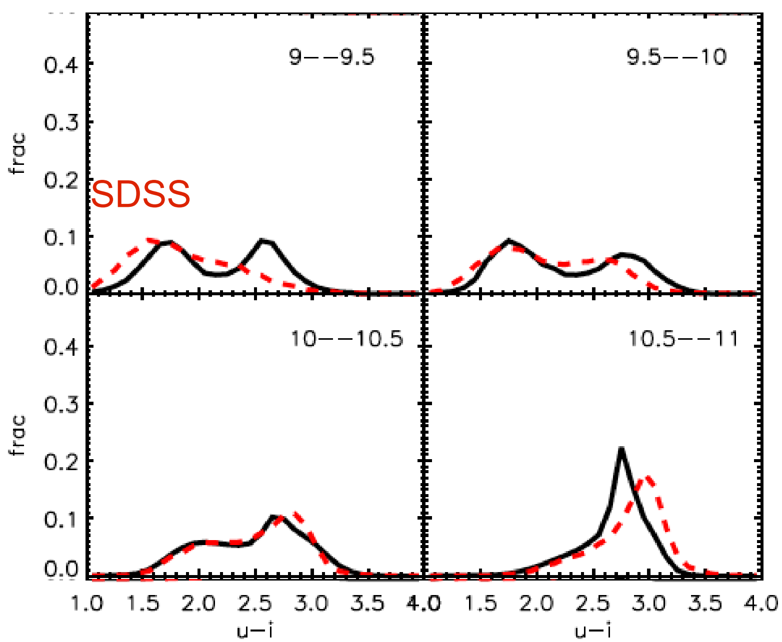
  Minimally, $\underline{\mathbf{G}} = \underline{\mathbf{G}}\,(M_{infall}, z_{infall}, M_{host})$
  Dependences on $\underline{\mathbf{J}}_{infall}$ and pre-infall MAH and spin also
  → limited precision for abundance matching

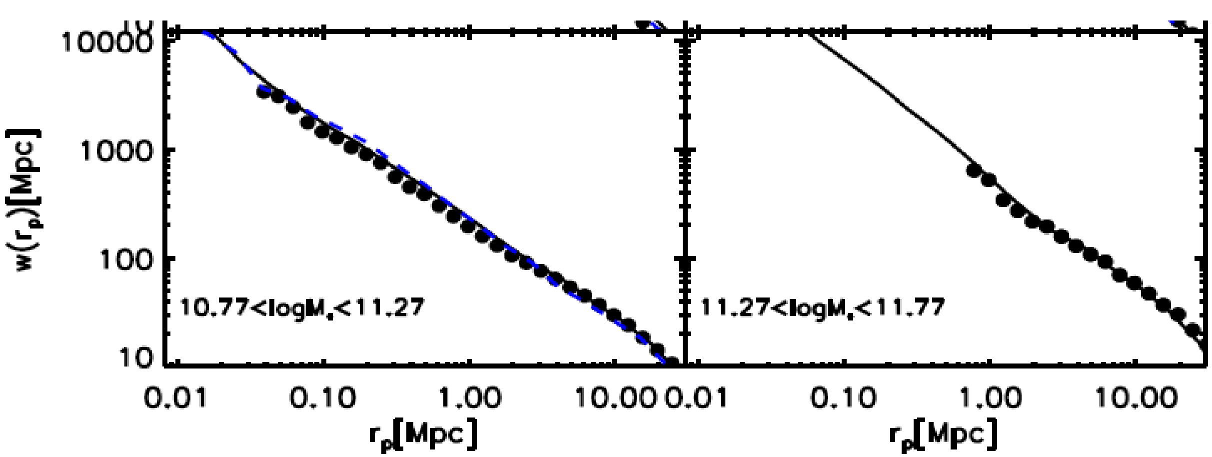
The halo–galaxy correspondance



When simulating the astrophysics of galaxy formation, agreement with data is a measure of success...



Guo et al 2011



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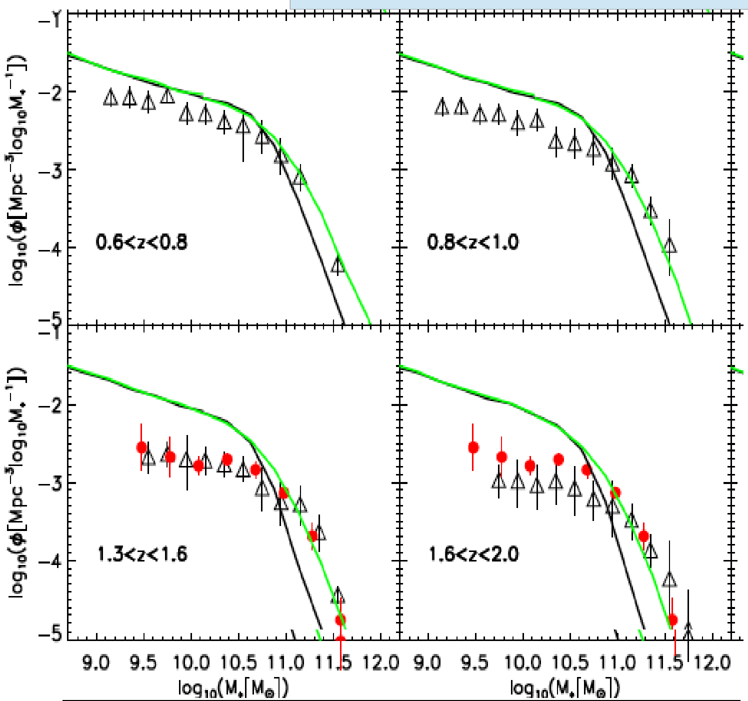
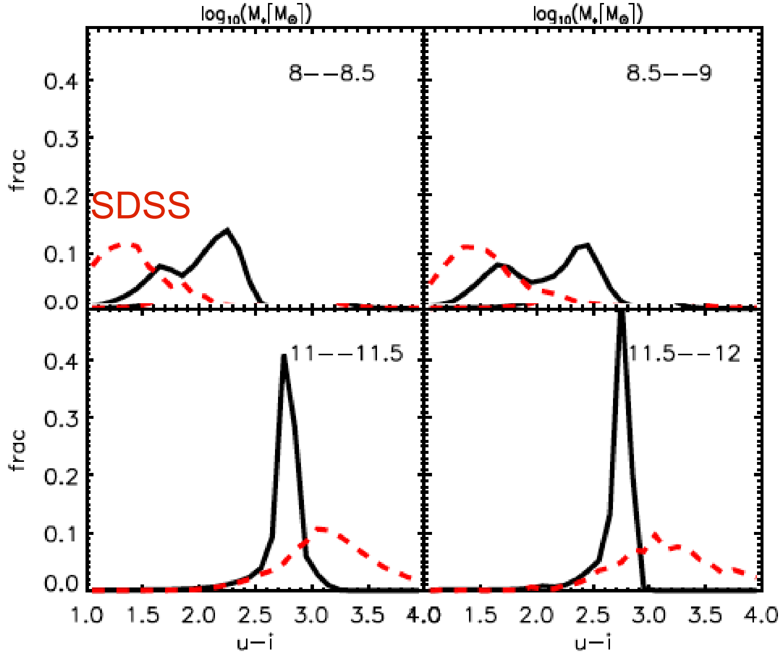


When simulating the astrophysics of galaxy formation, agreement with data is a measure of success...

...but it is the failures which show where there is missing or inadequate physics

cosmology? star formation? enrichment and feedback? environmental effects?



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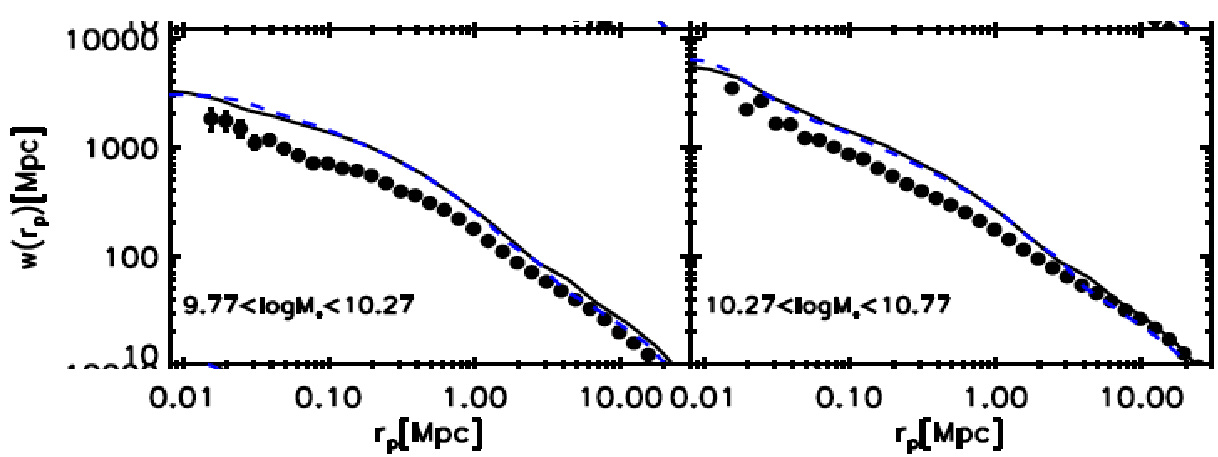

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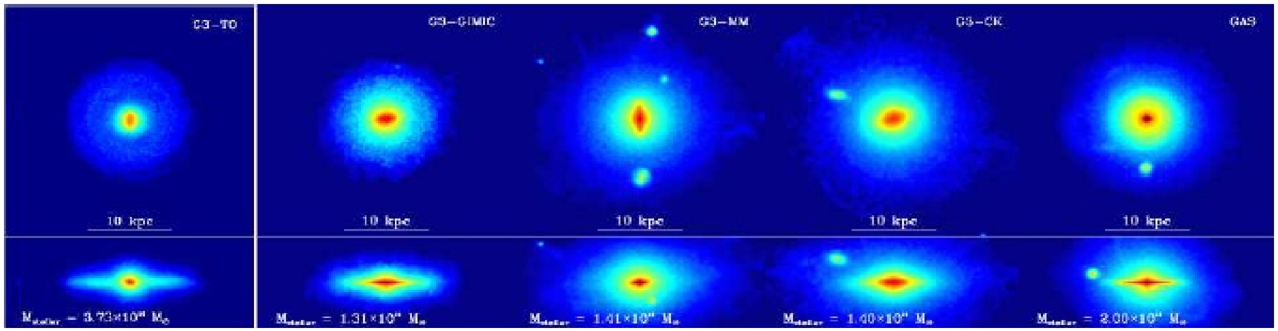
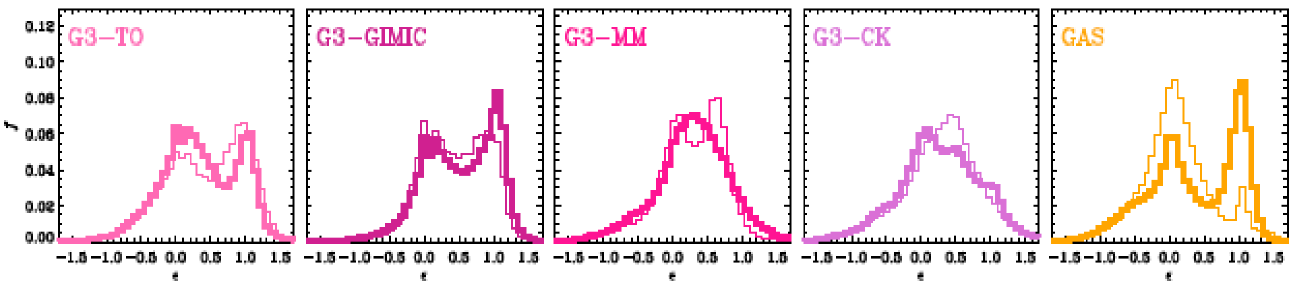
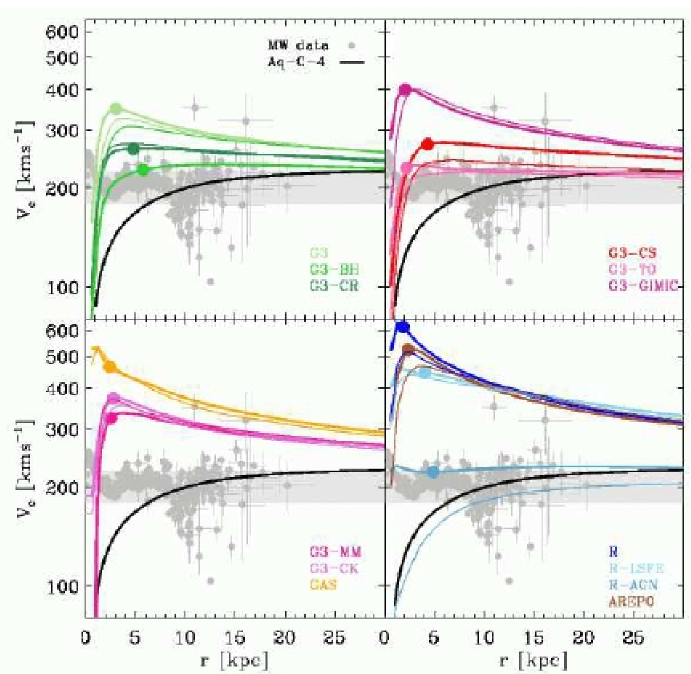
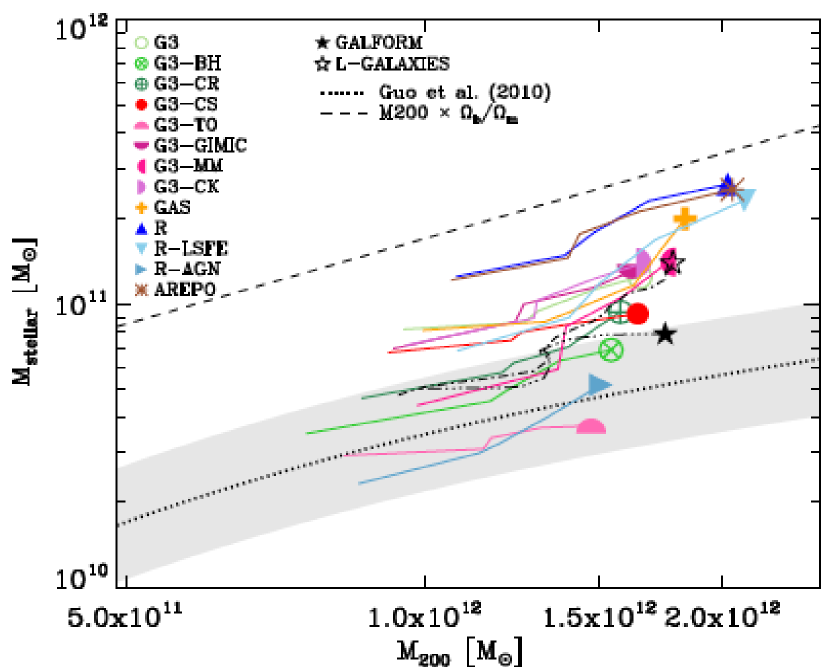




Different baryonic physics codes give very different galaxies when applied to the <u>same</u> initial conditions

→ clues to how to make a realistic galaxy





The Aquila Project
Scannapieco et al 2012

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- The set of galaxy properties $\underline{\mathbf{G}}$ depends on subhalo mass and assembly history and possibly on larger scale environment

  Minimally, $\underline{\mathbf{G}} = \underline{\mathbf{G}}\,(M_{infall}, z_{infall}, M_{host})$

  Dependences on $\underline{\mathbf{J}}_{infall}$ and pre-infall MAH and spin also

  Physical modelling requires physical models!