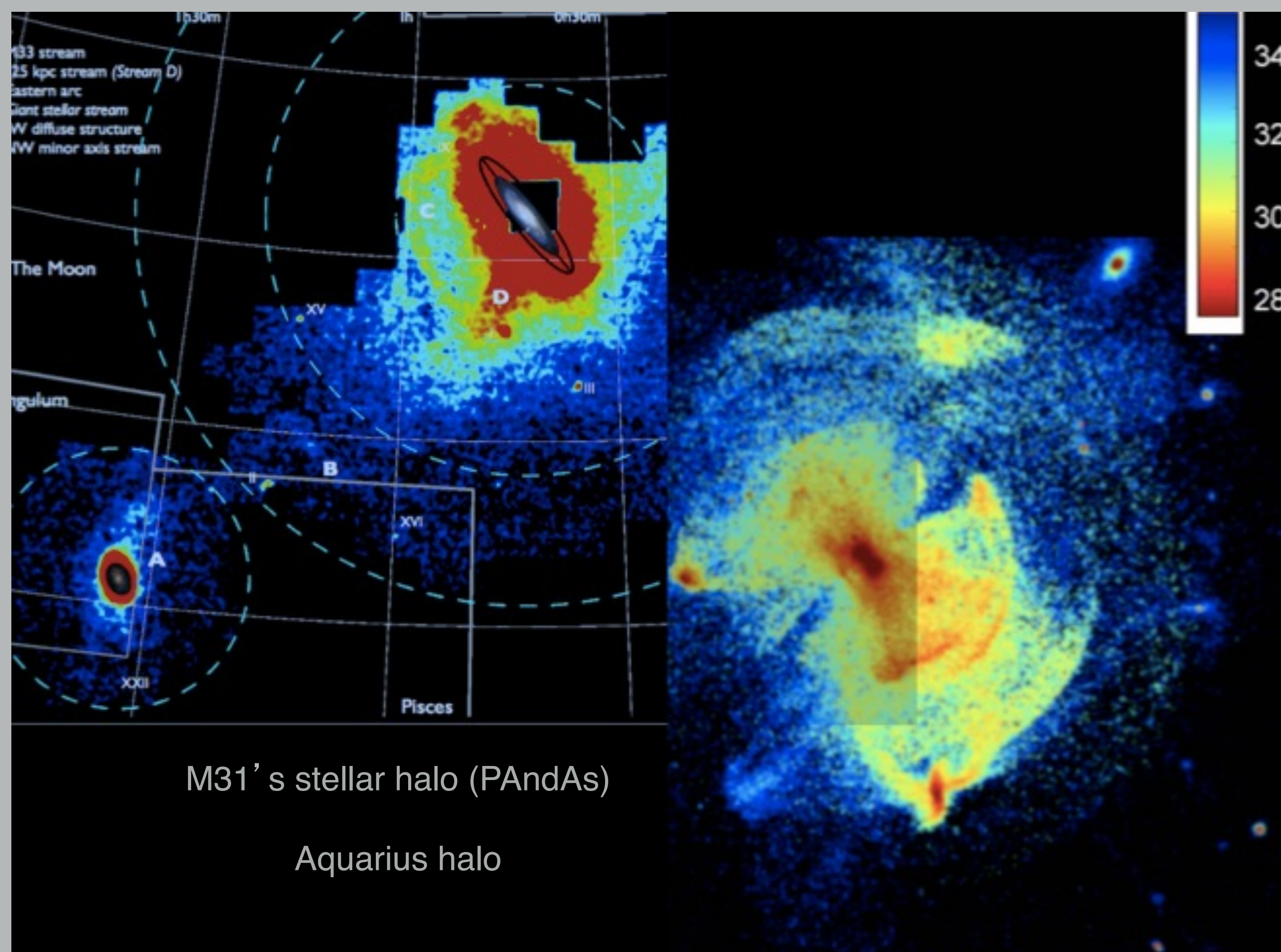
Global Properties of Simulated Stellar Halos

of Milky Way-mass galaxies



M31’s stellar halo (PAndAs)

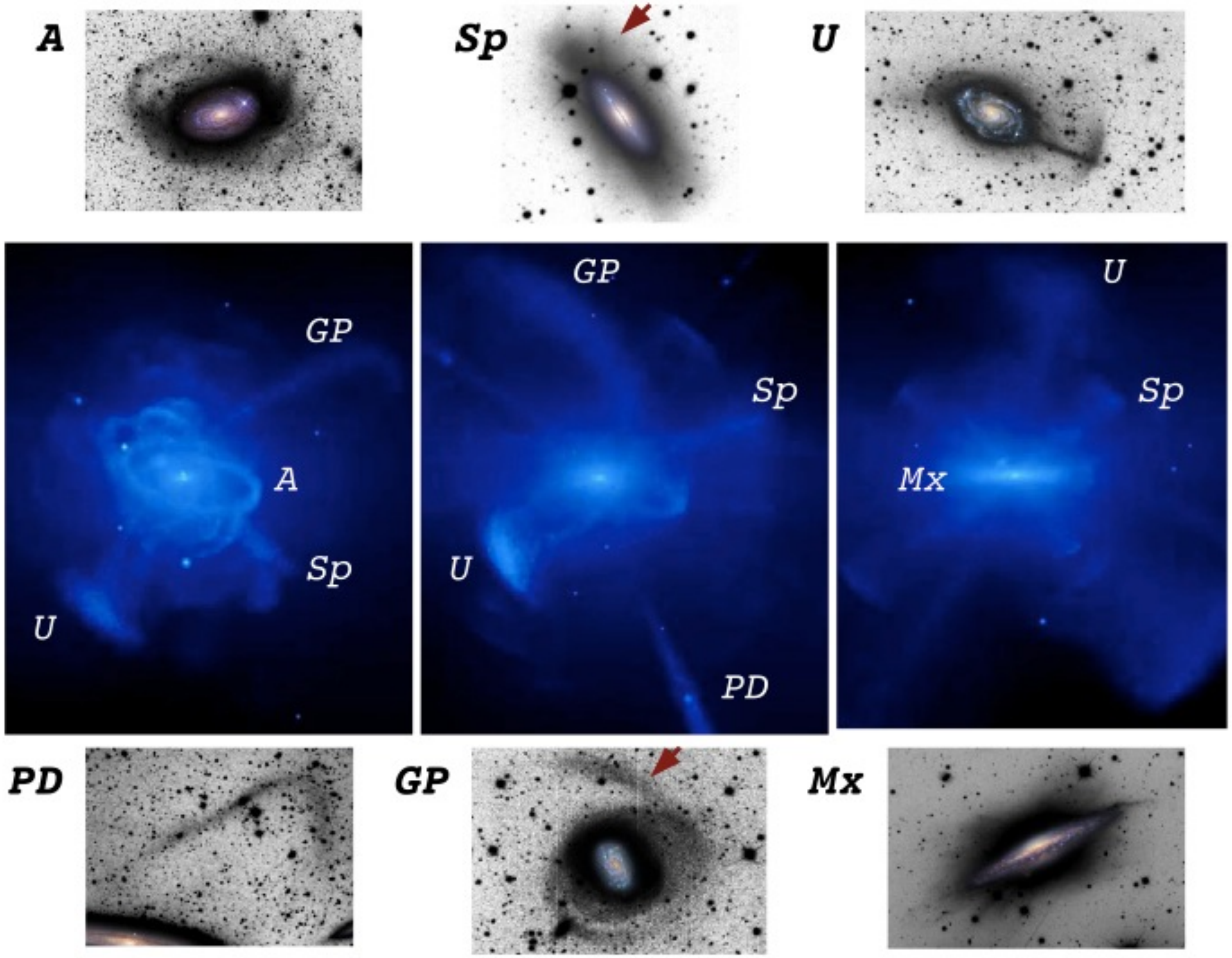
Aquarius halo

What do we want to know:

- what is the origin of stellar halos? accreted vs in situ stars
- what is the relative contribution of accreted and in situ stars versus radius (for a given stellar mass)
- what is the origin of in situ stars?
- what are the spatial, kinematic and chemical abundance properties of accreted and in situ stars?
- how lumpy is the stellar halo? how many satellites contribute, on average, and what are their properties?

Accretion only models

hybrid methods, i.e. “painting” stars on dark matter models using semi-analytical prescriptions (Bullock & Johnston 2005, Font et al 2005, 2006; Diemand et al 2010; Cooper et al 2010)



Martinez-Delgado et al 2010; simulated halos from Johnston et al 2008.

Accretion only models

Successes:

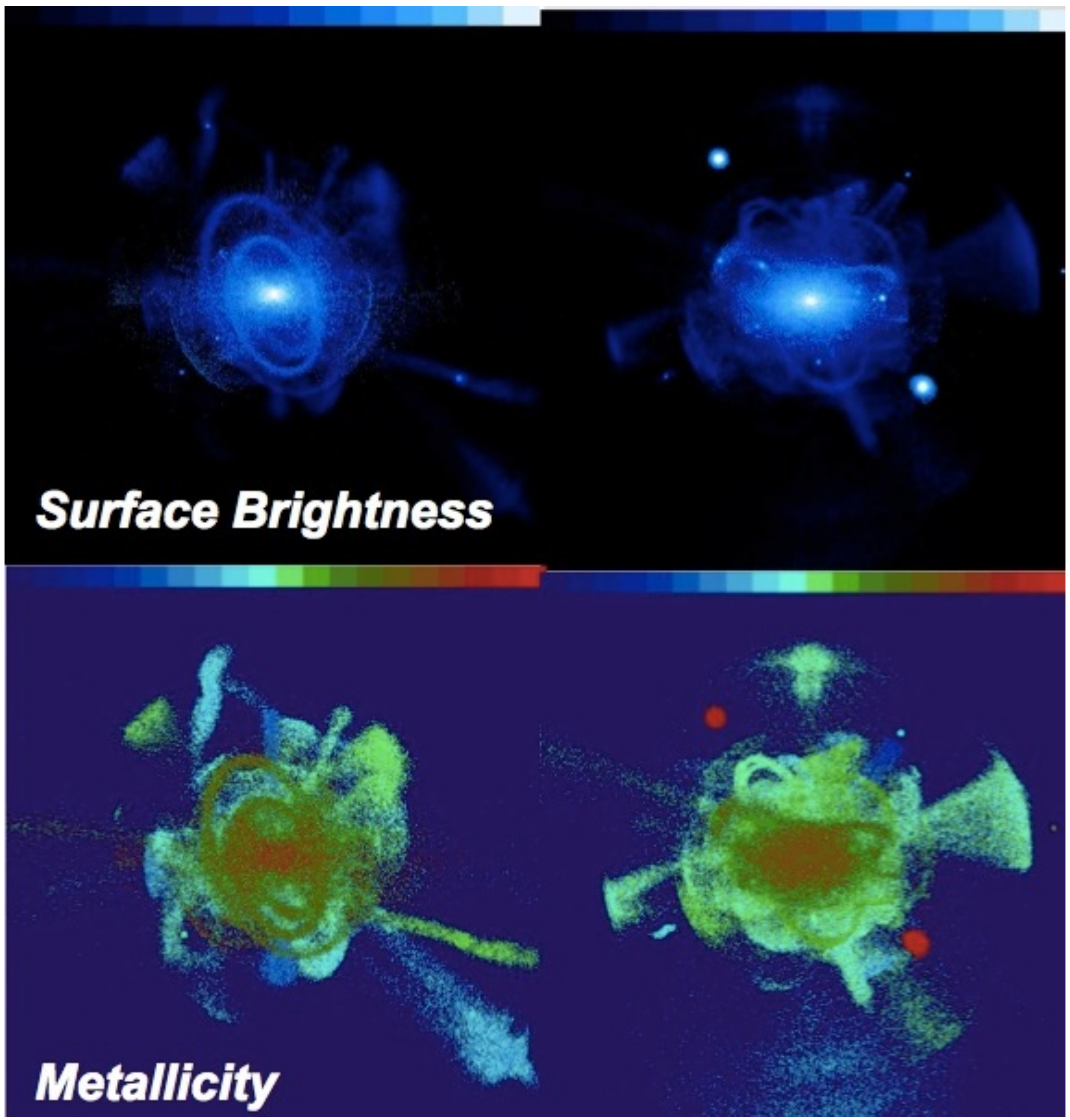
- we see in falling satellites shredded in MW, M31 and neighbouring galaxies
- stellar halo is somewhat lumpy
- demographics of streams is (at least qualitatively) reproduced

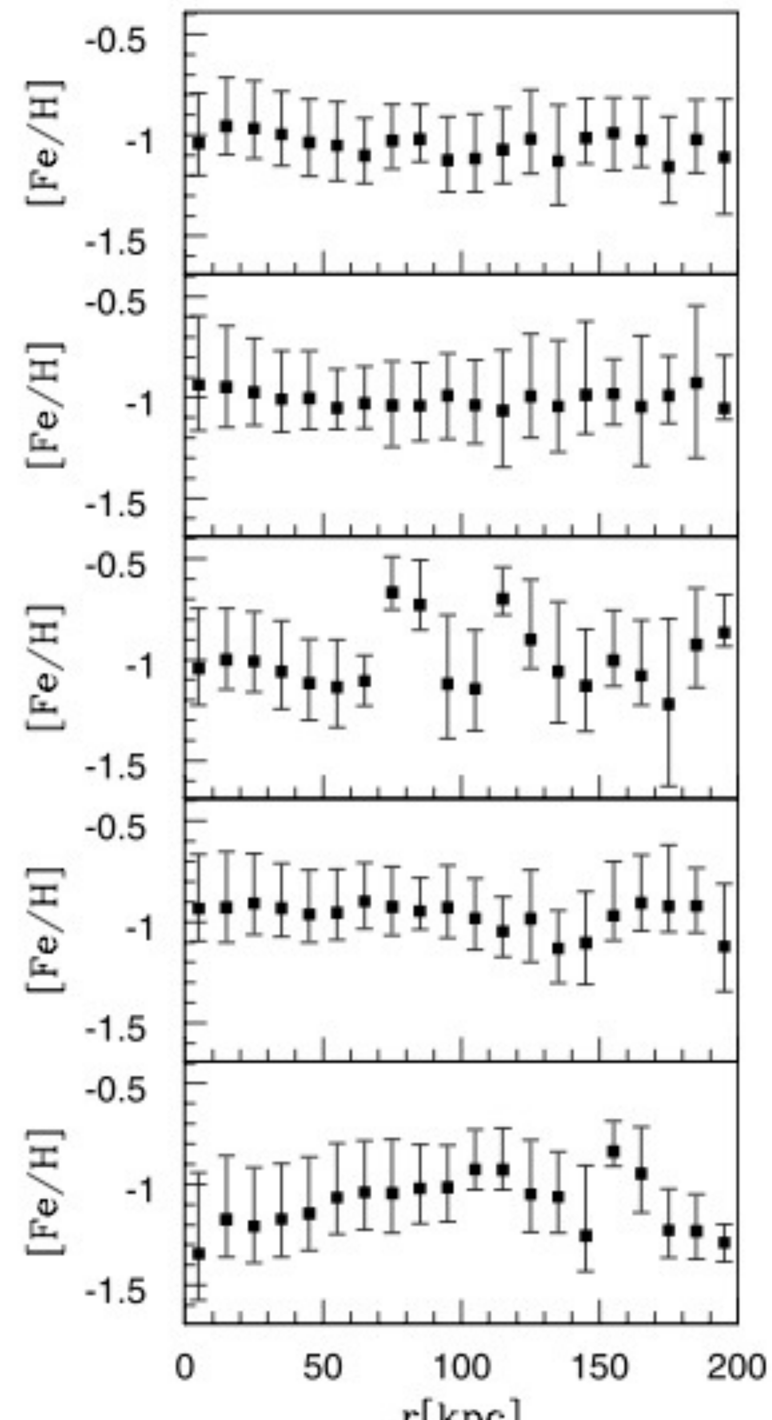
Problems:

- surface brightness profiles do not exhibit multiple components, as indicated by observations
- do not produce metallicity gradients in stellar halos, as observed (e.g. in M31)
- not obvious if produce enough rotation
- wrong shape for the halo (prolate like DM, not oblate as observed)
- cannot explain the faint diffuse component in the outskirts of halos (too lumpy)

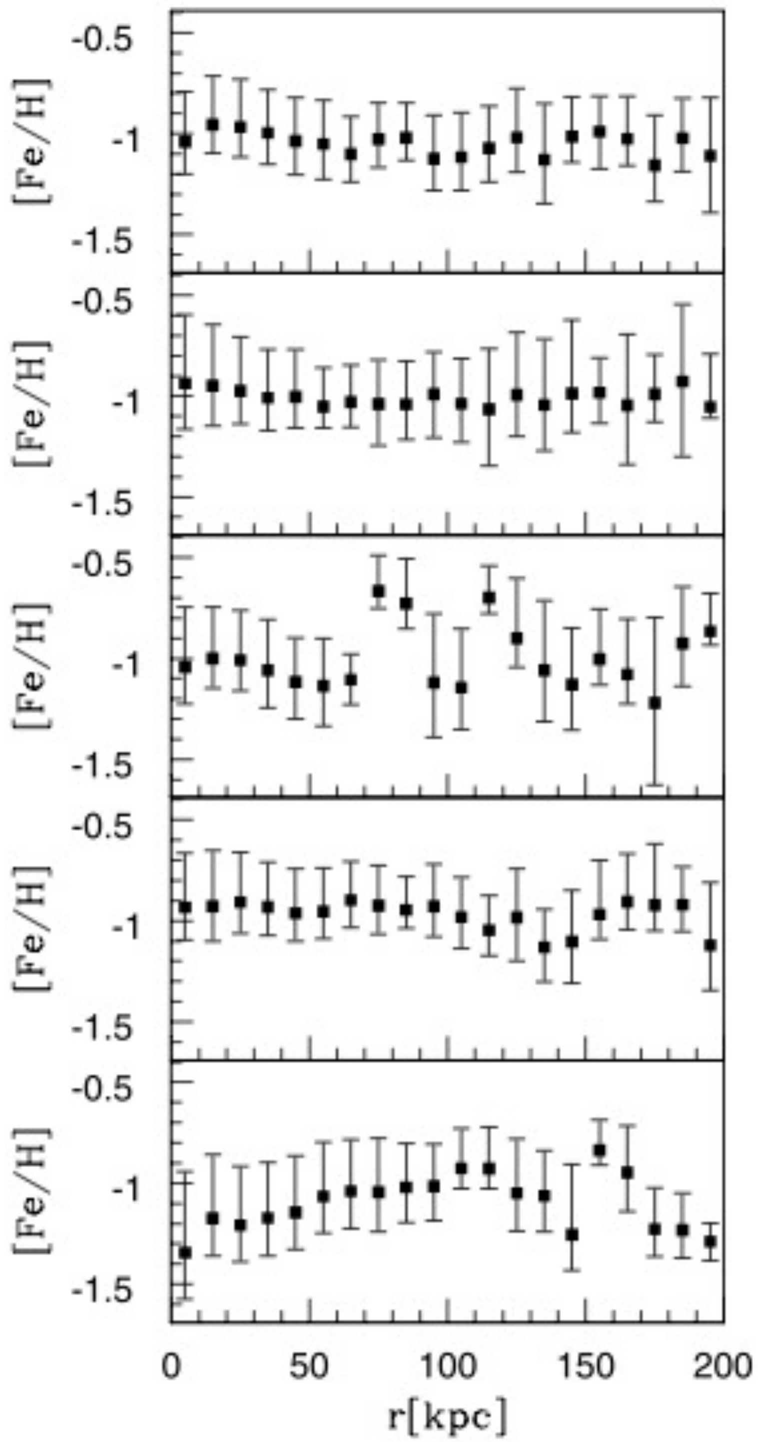
Accretion only models

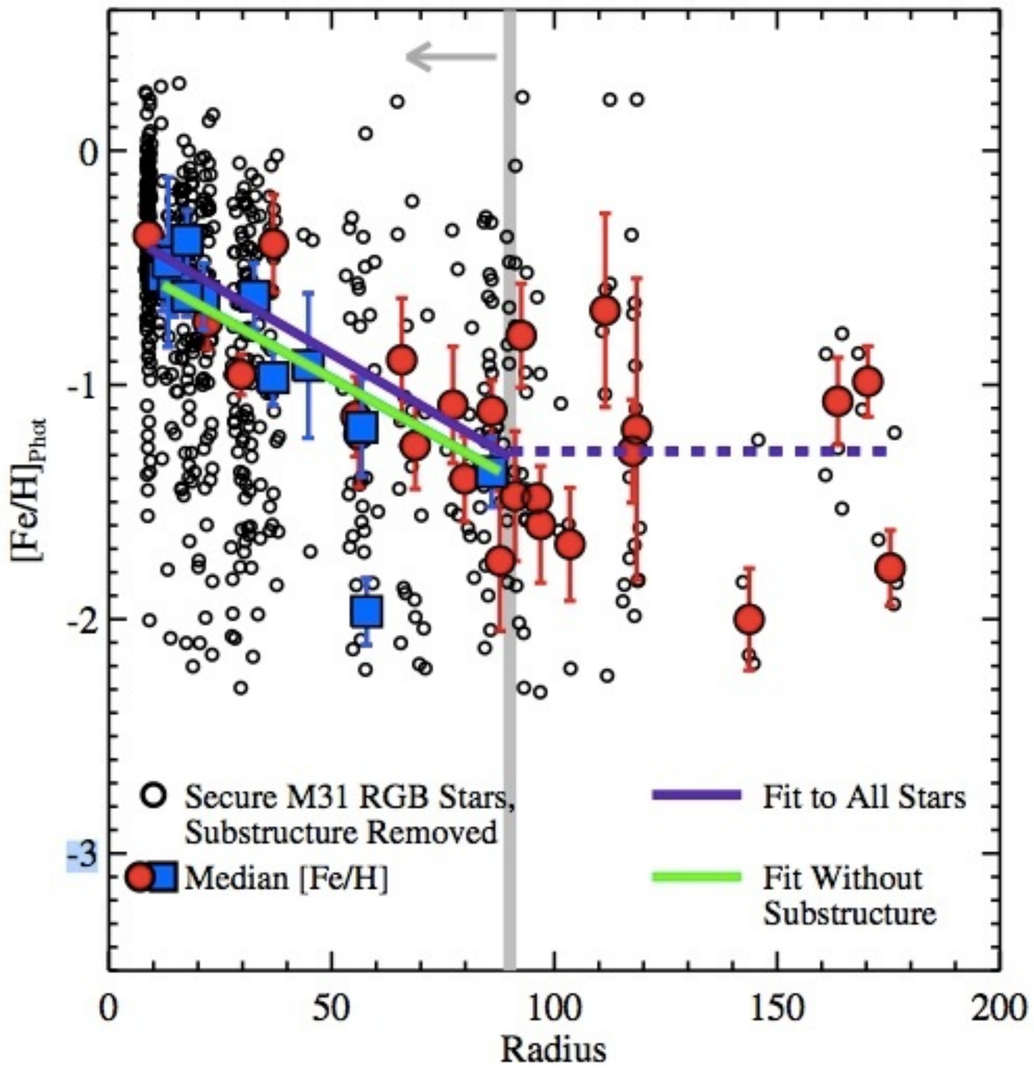
"chaotic" assembly; metallicity gradients cannot be produced or are very weak





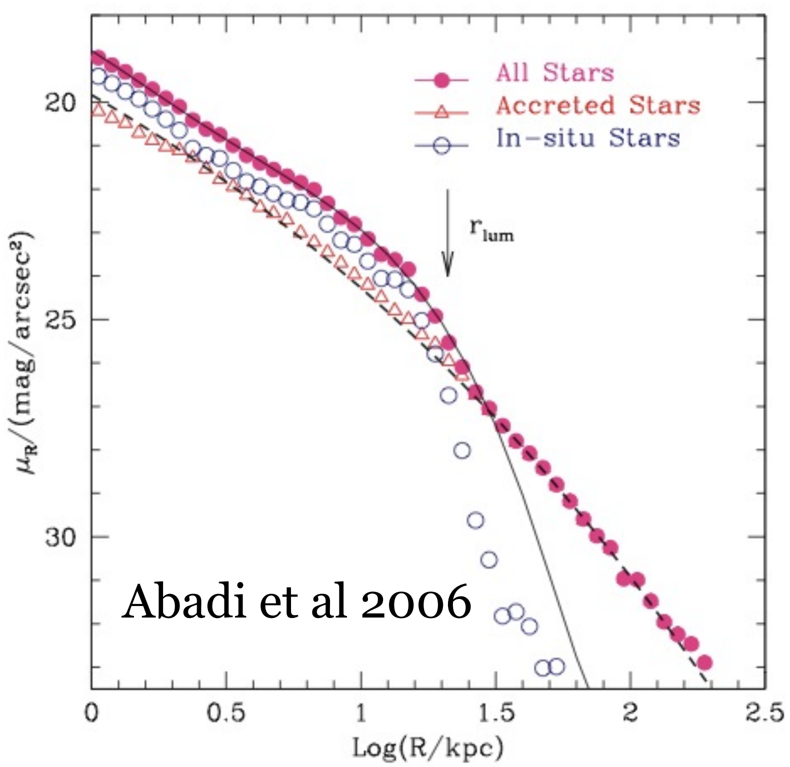
Bullock & Johnston (2005); Robertson et al 2006; Johnston et al 2008.
similar results in Cooper at al 2010.

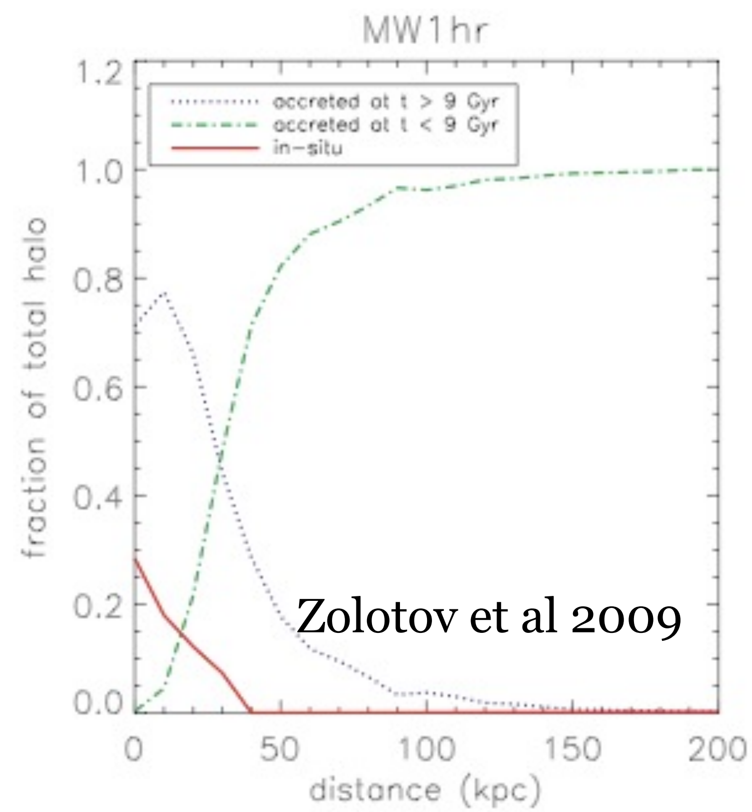


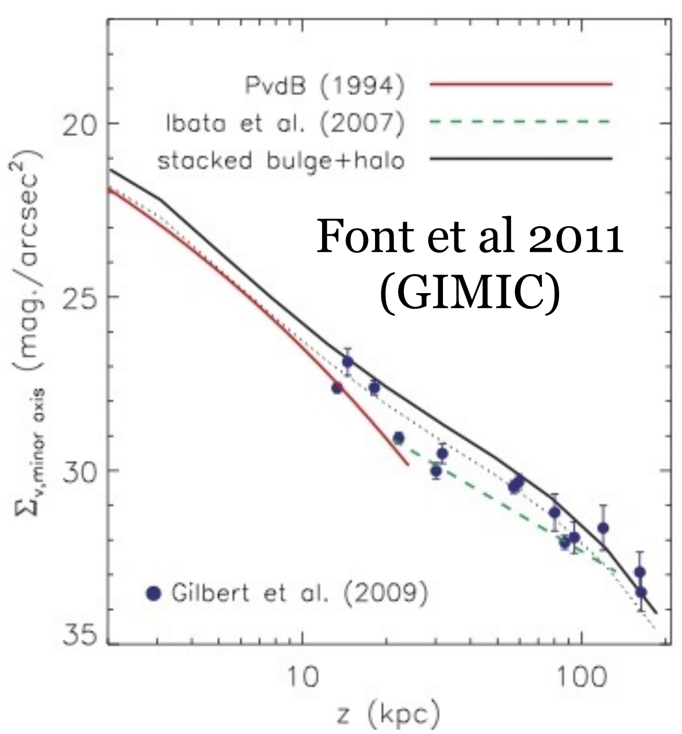


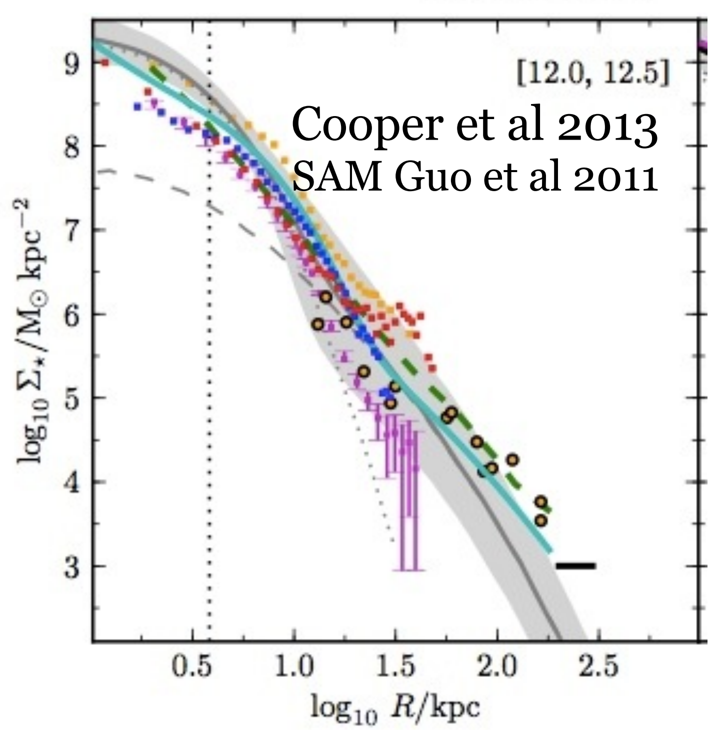
hybrid model (Font et al 2008); obs [Fe/H] gradient in M31 (Gilbert et al 2014)

Dual nature of halos: accreted + in situ stars

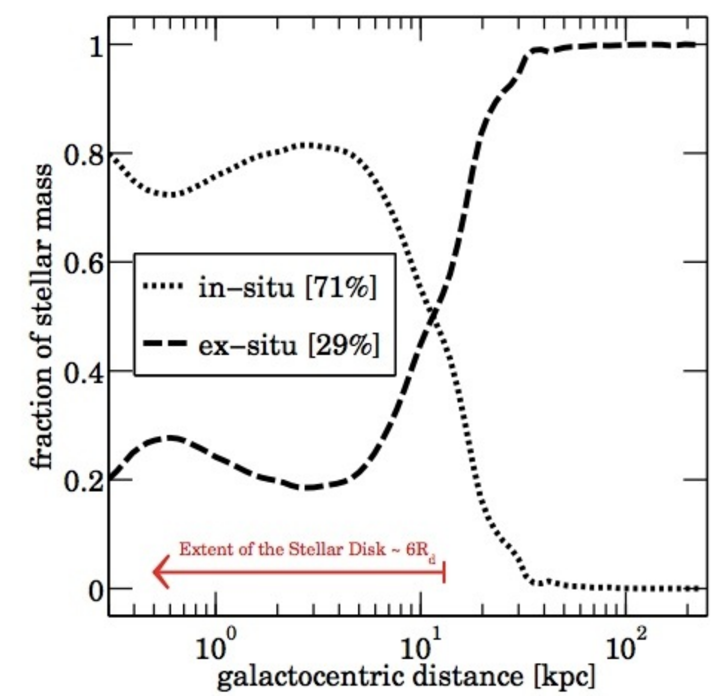




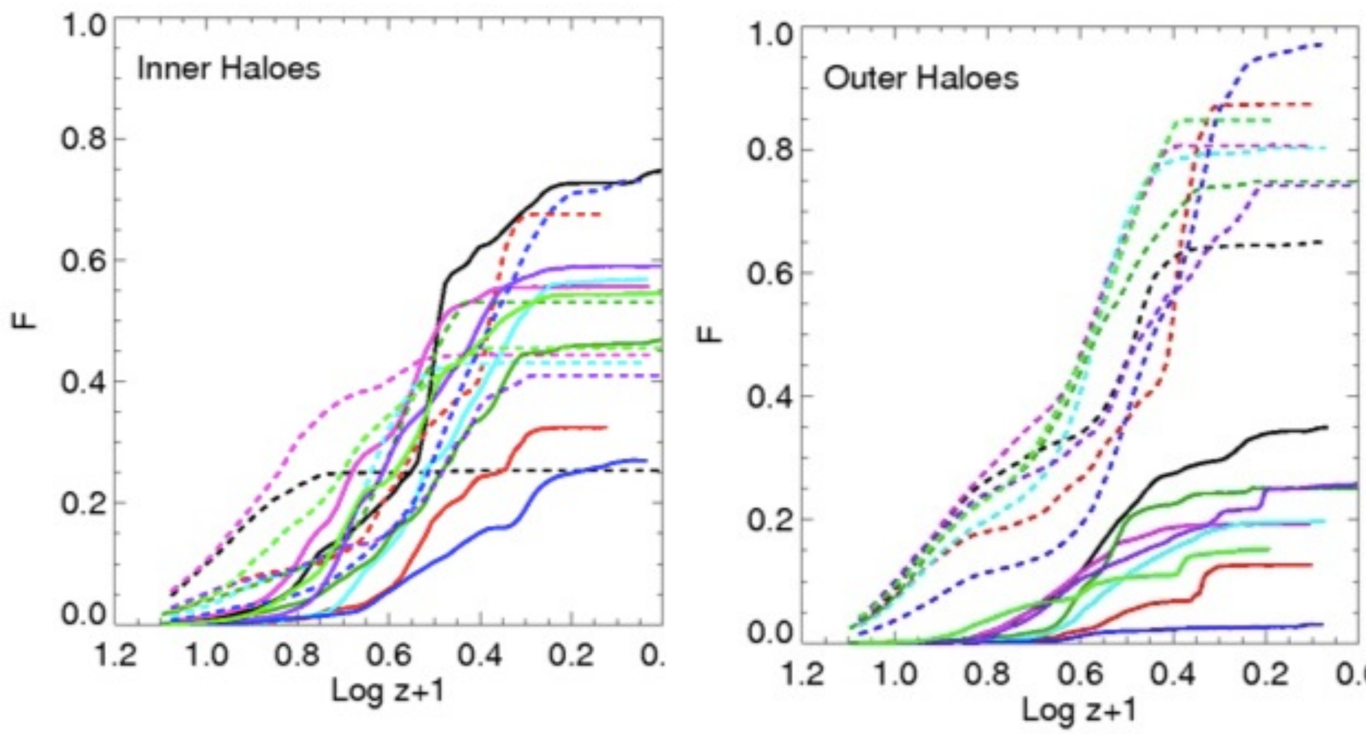




Pillepich et al 2015 (ERIS)

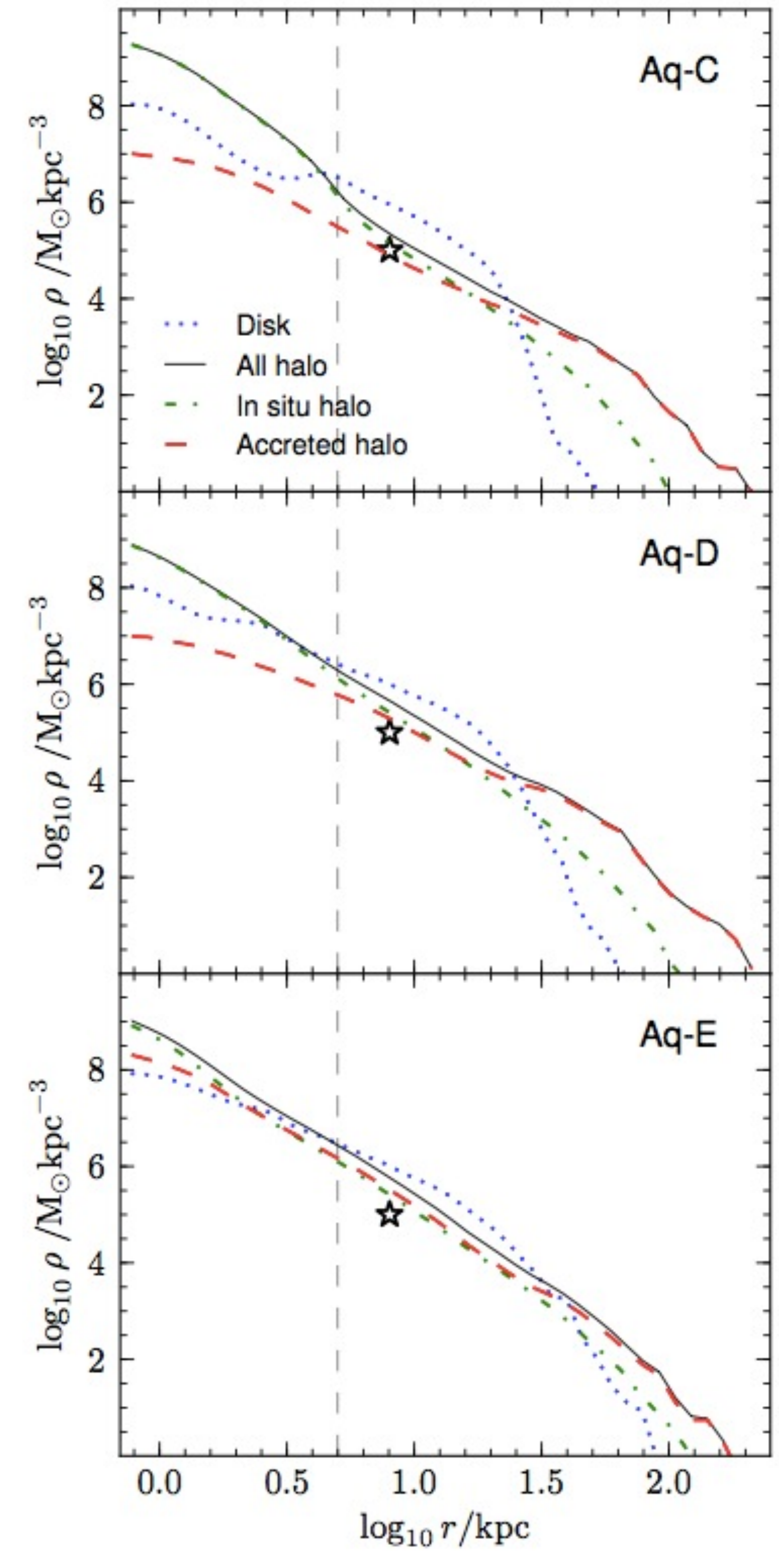


Tissera et al 2012
(Aquarius halos)



(dashed - accreted; full line - in situ)

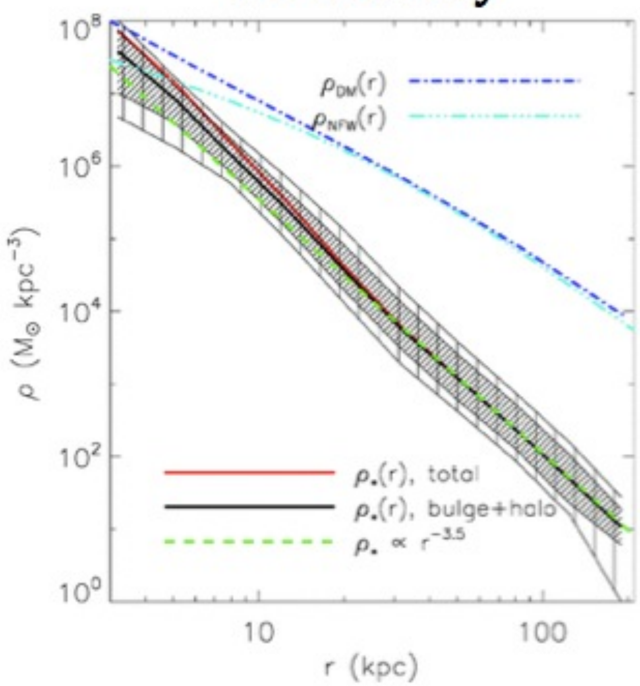
Cooper et al 2015;
high res Aquarius halos



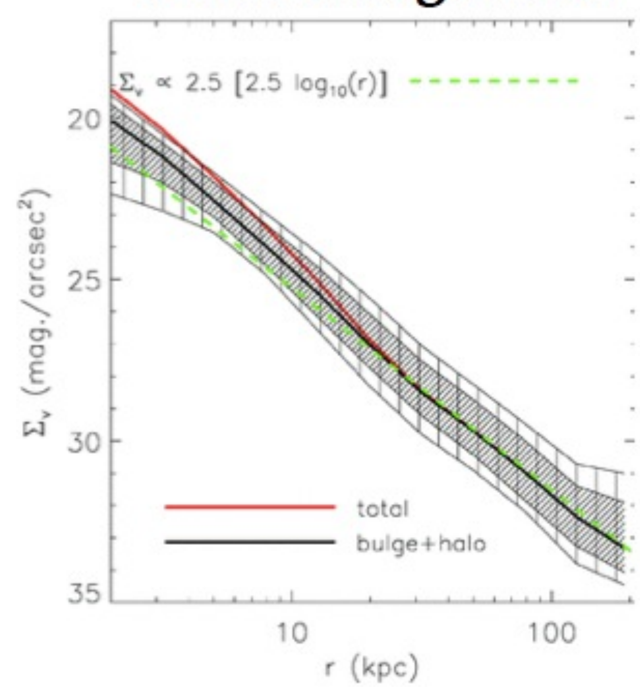
Font et al. 2011, MNRAS; McCarthy et al. 2012, MNRAS

Spherically- & azimuthally-averaged profiles

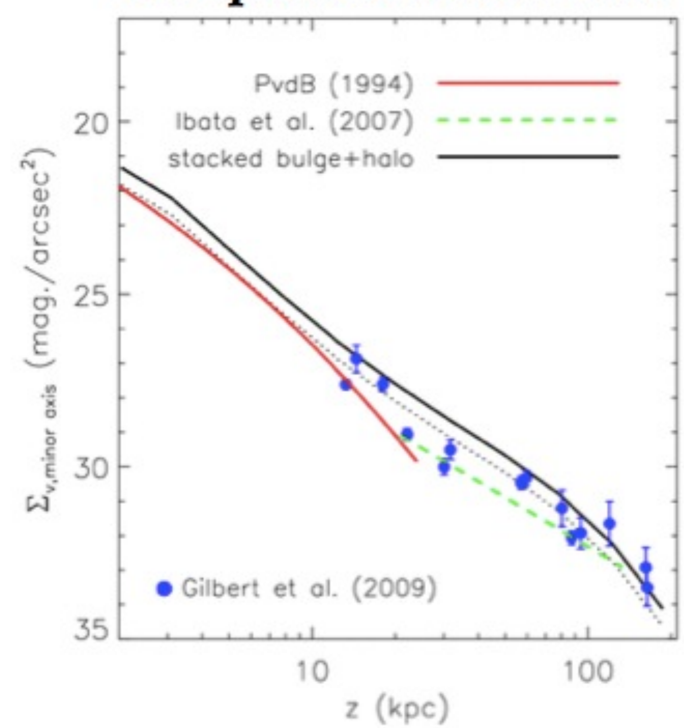
3D density



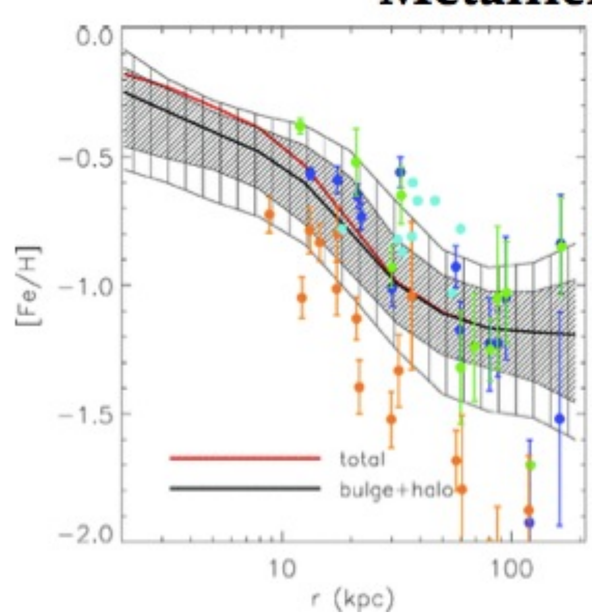
Surface brightness

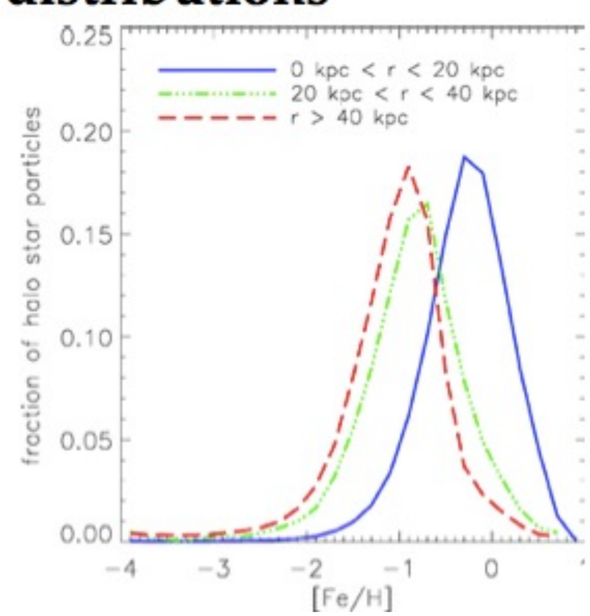


Comparison with M31



Metallicity distributions



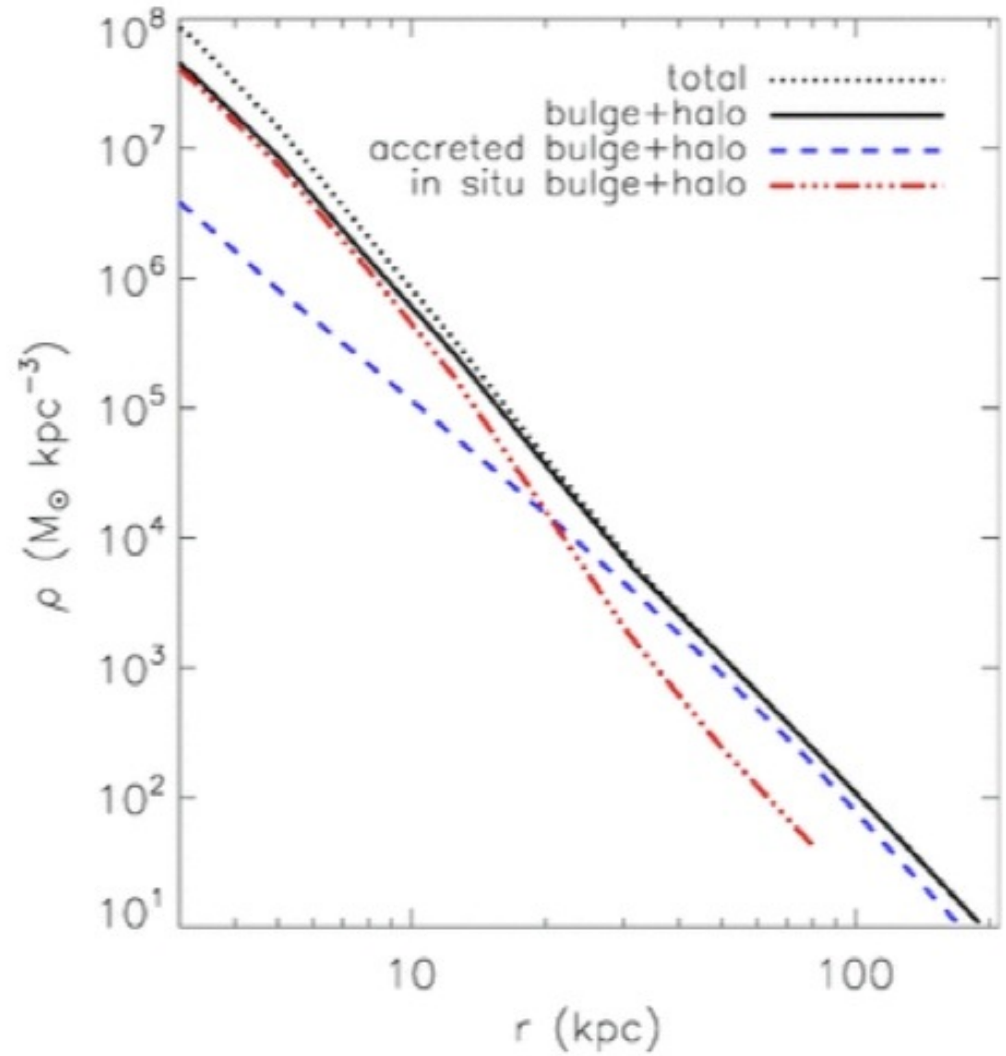


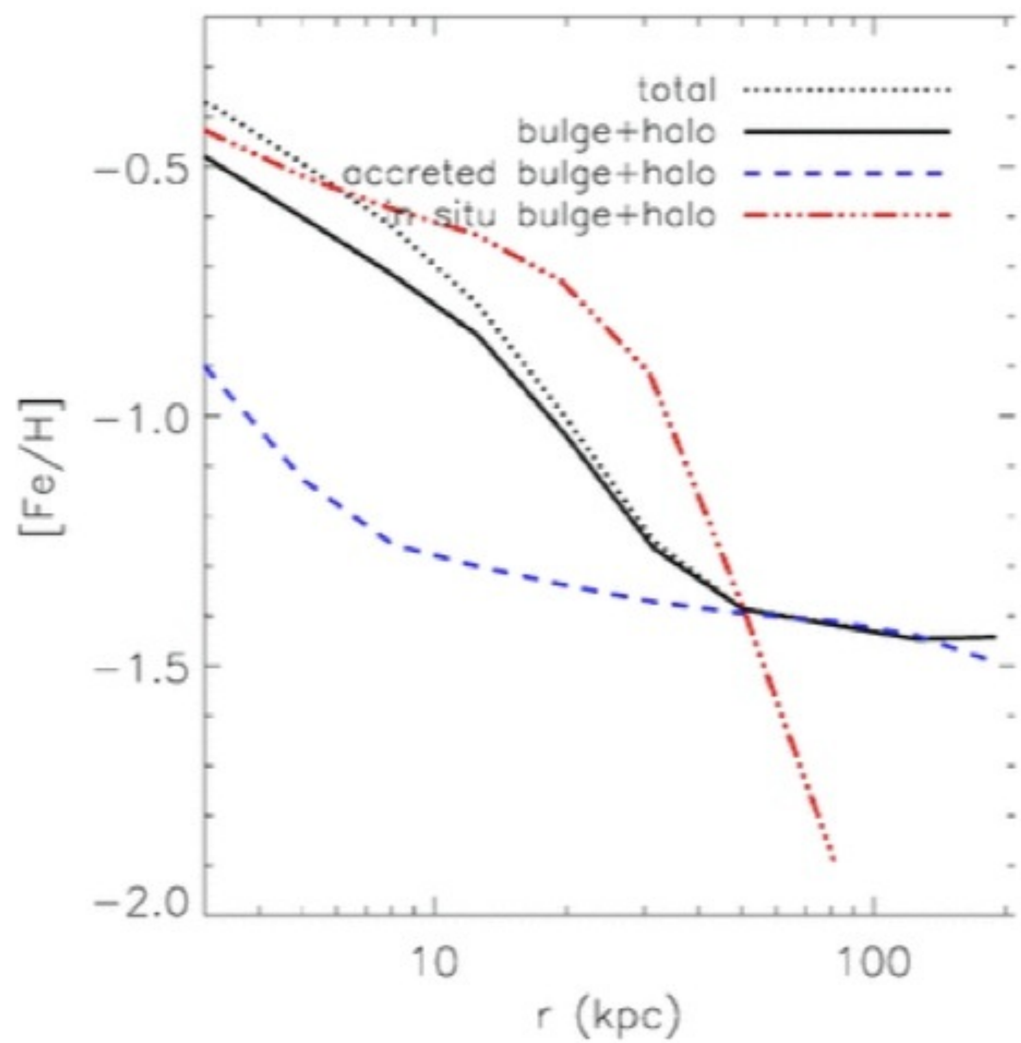
Reproduces surface brightness and metallicity distributions of M31.

Compatible with MW obs. too (comparison is tougher).

Font et al. 2011, MNRAS; McCarthy et al. 2012, MNRAS

Why does it work? In situ star formation

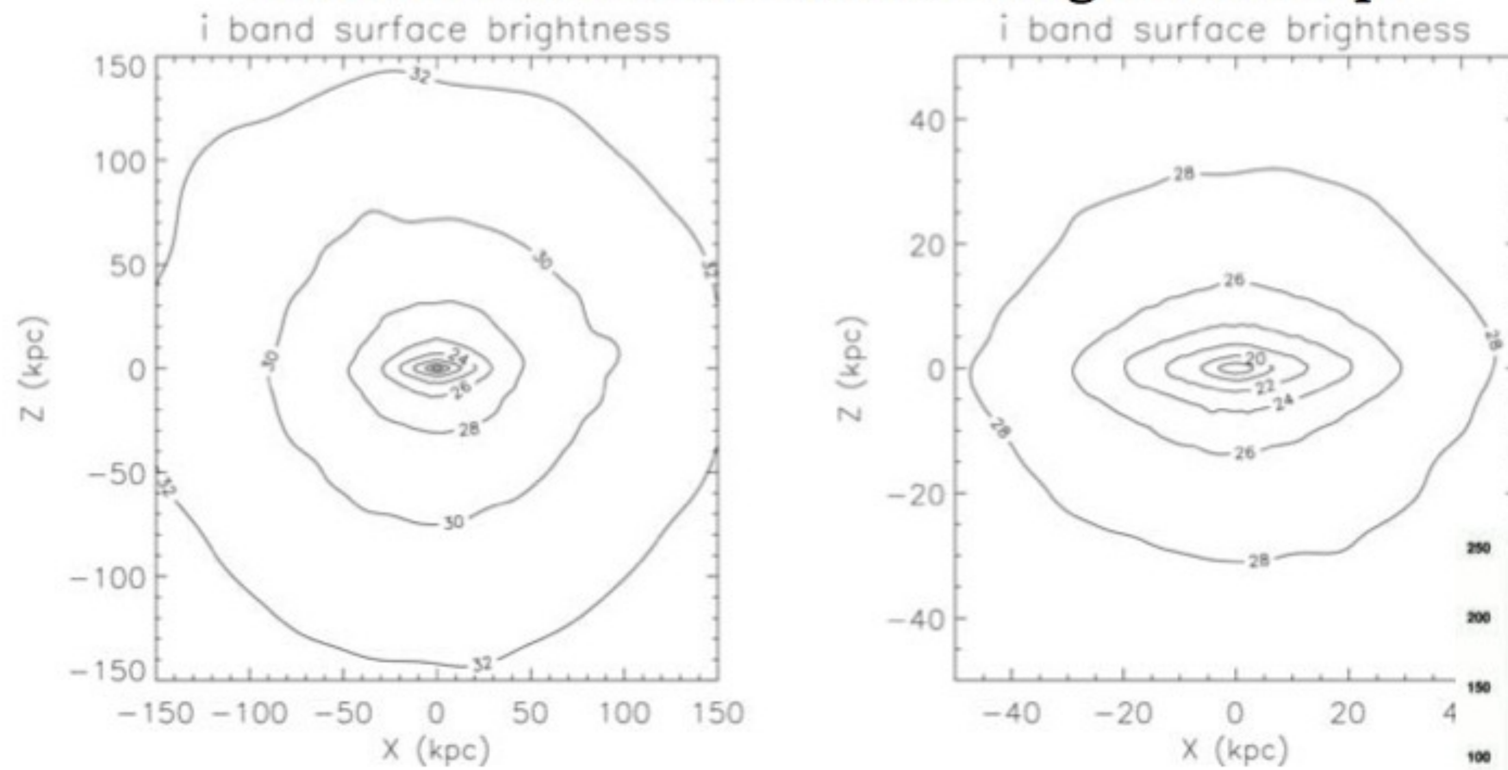




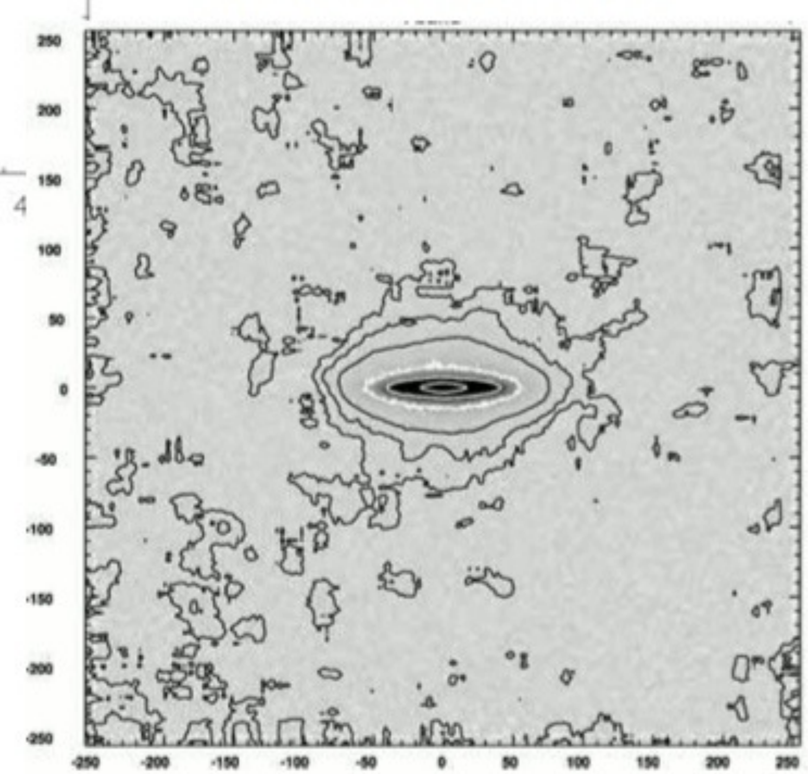
See also Zolotov et al. 2009; Tissera et al. 2011

In situ stars were born in a disc at z ~1.5-2 and later dispersed

Stacked & smoothed surface brightness maps



Zibetti et al. (2004)

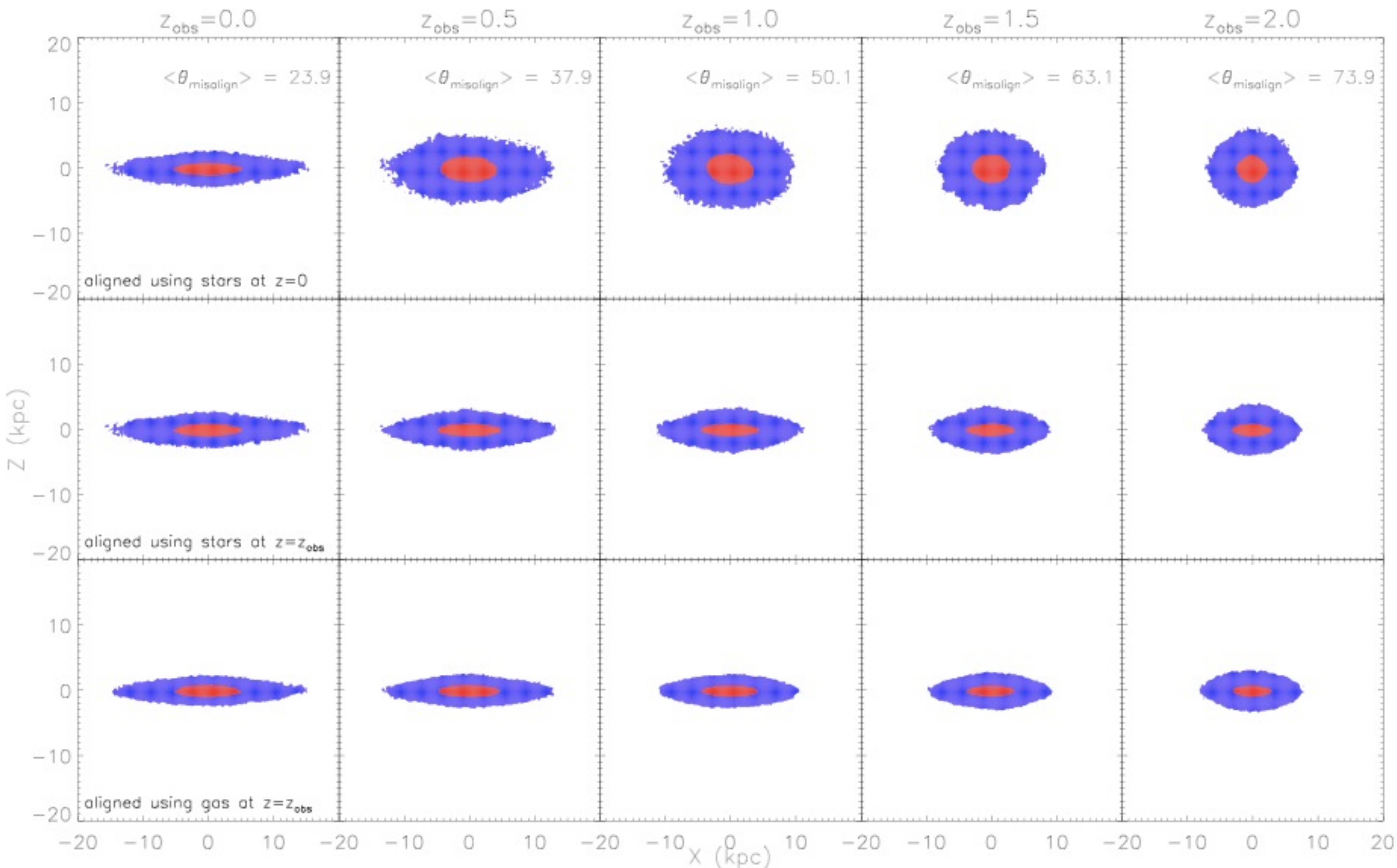


Oblate haloes with approximately correct shape.

M31, MW, and 1000 stacked edge-on galaxies from SDSS all have b/a ~ 0.6 within 10-15 kpc.

GIMIC: in situ stars were born in a disc at z~1.5-2 and later dispersed

(disc destruction, flipping, heating)



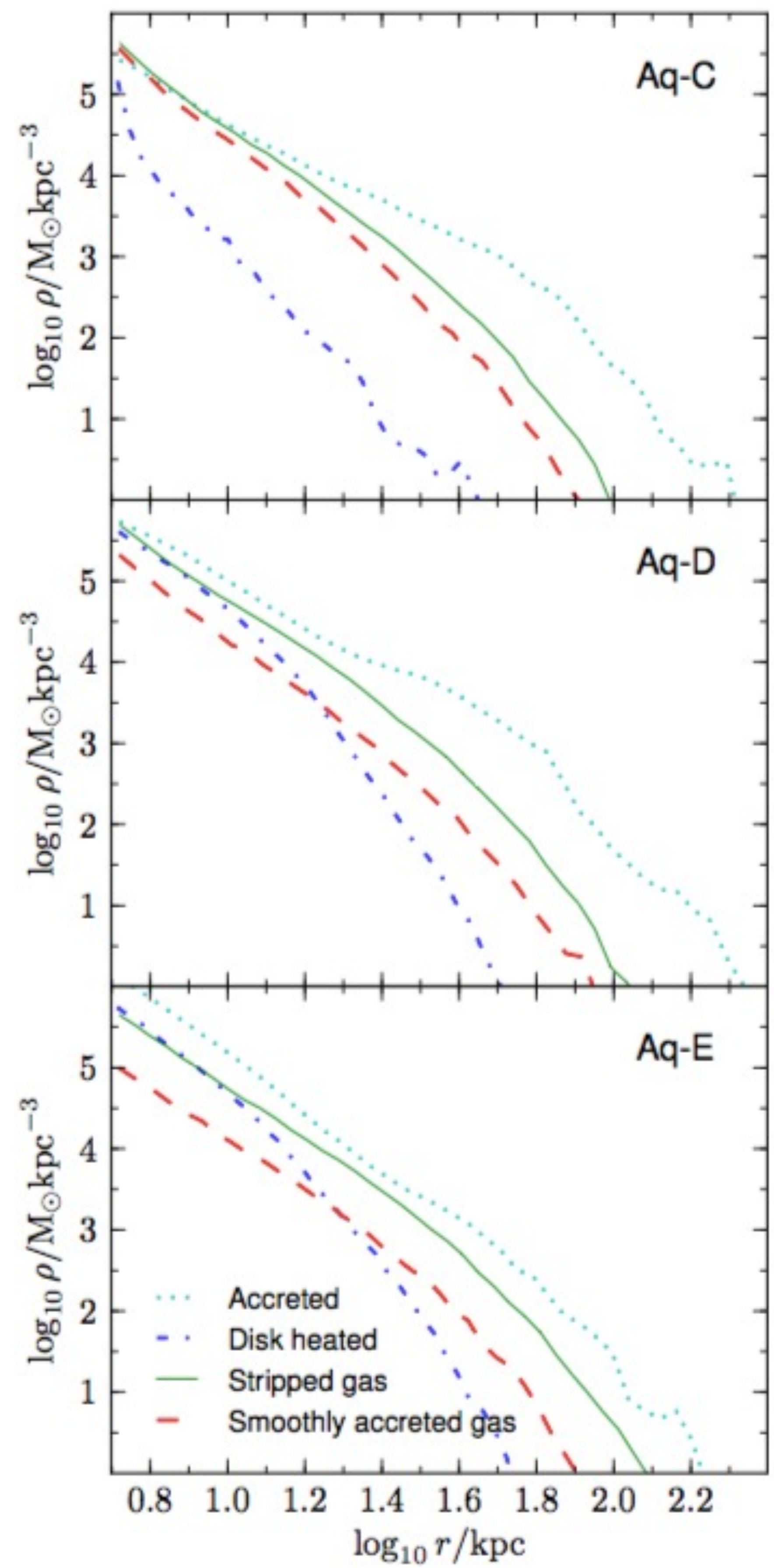
In situ stars : from which gas?

•Zolotov et al 2009, 2010: cold flows

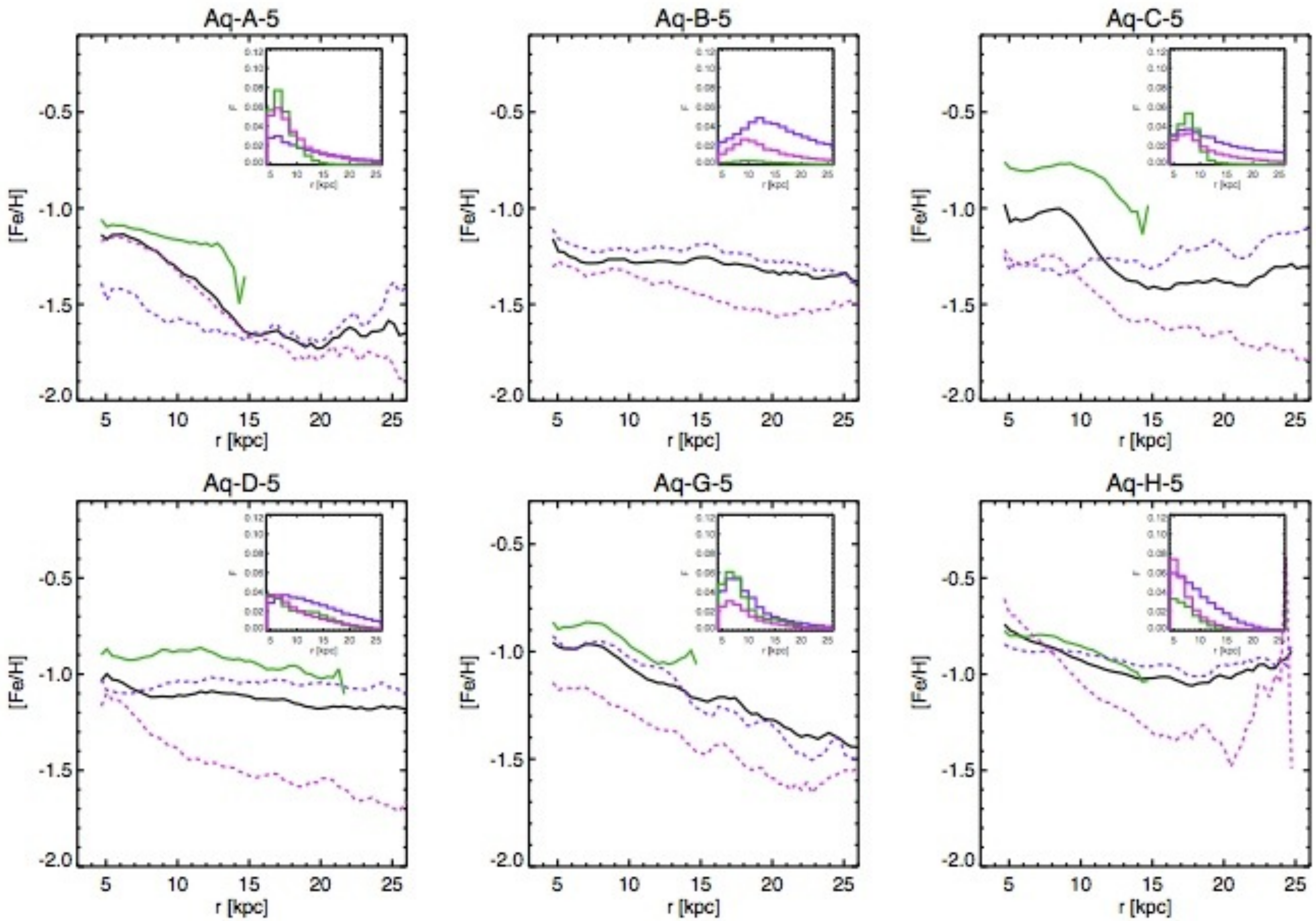
•Font et al 2011, McCarthy et al 2012:
~50% from shock-heated gas

•Tissera et al 2012, Cooper et al 2015 investigate further the origin of the gas forming in situ stars :

- some of it is brought in by satellites (stripped gas);
- gas accreted in cold mode.

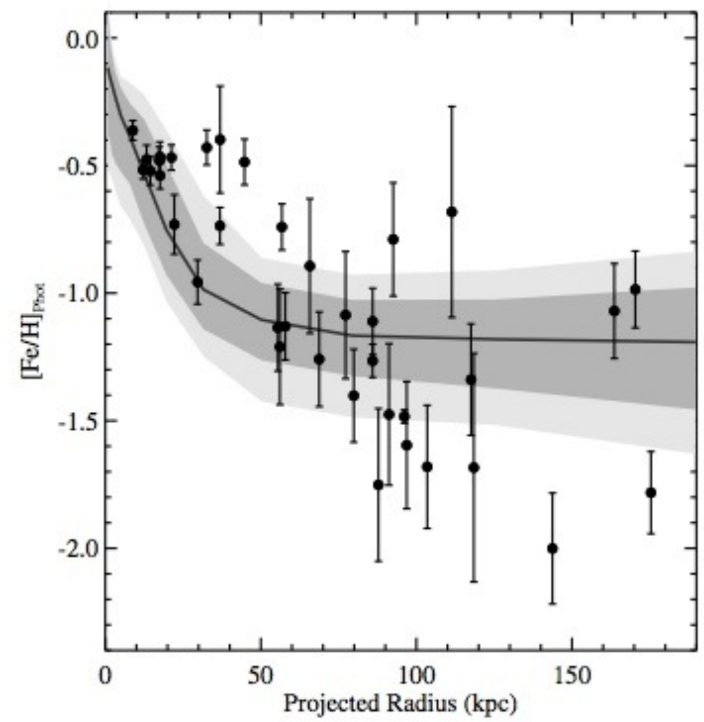


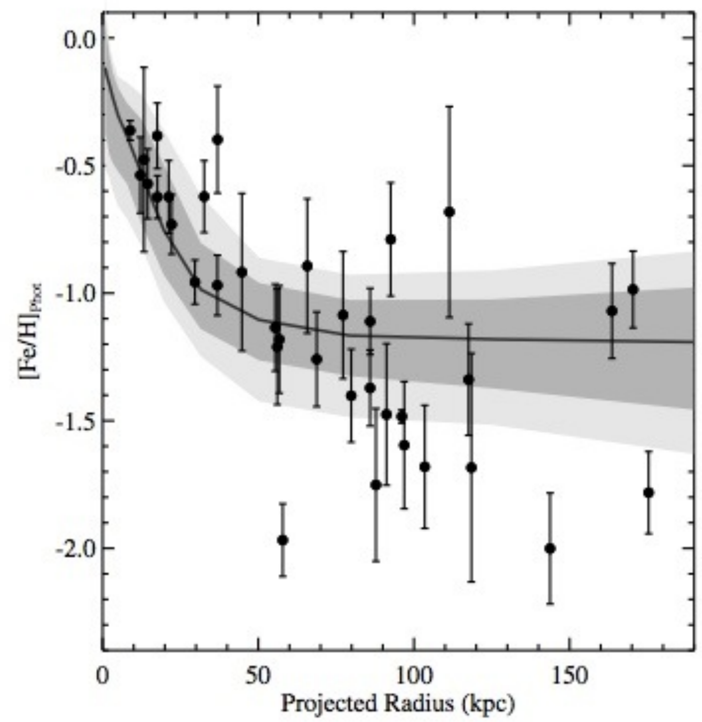
Cooper et al 2015



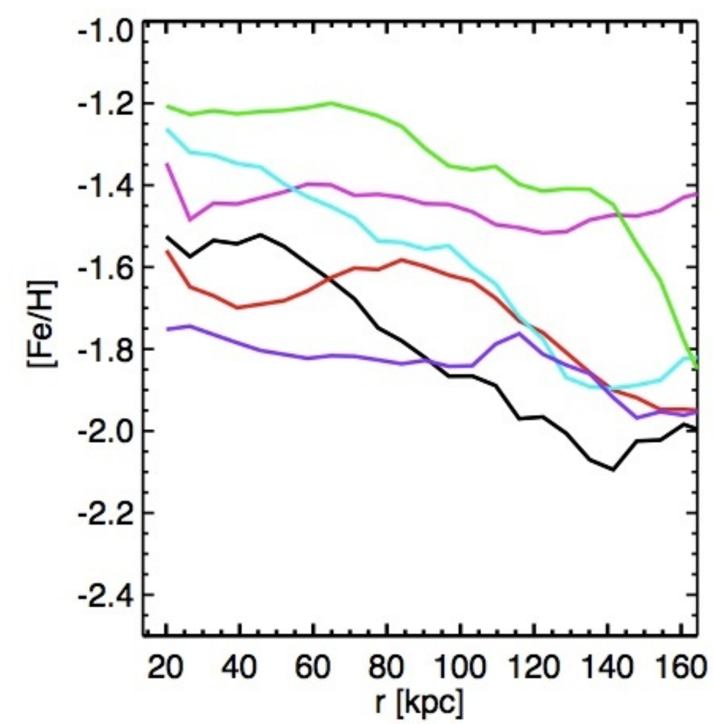
Tissera et al 2013

disc-heated stars (green), endo-debris stars (magenta); debris stars (violet)





recent M31 data from the SPLASH survey (Gilbert et al 2014); comparison with GIMIC sims.



Tissera et al 2013

EAGLE Simulations
(Schaye et al 2015)

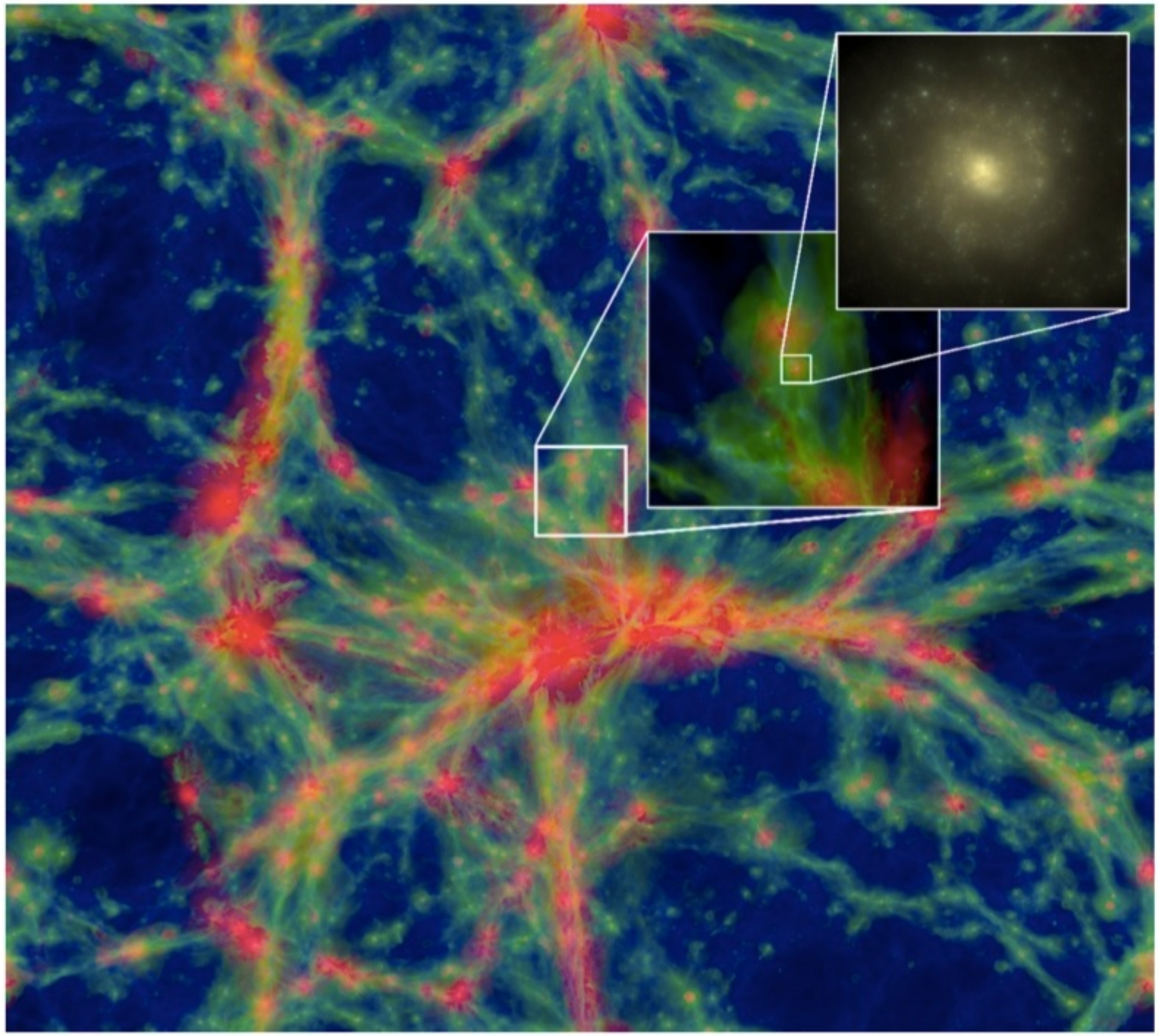
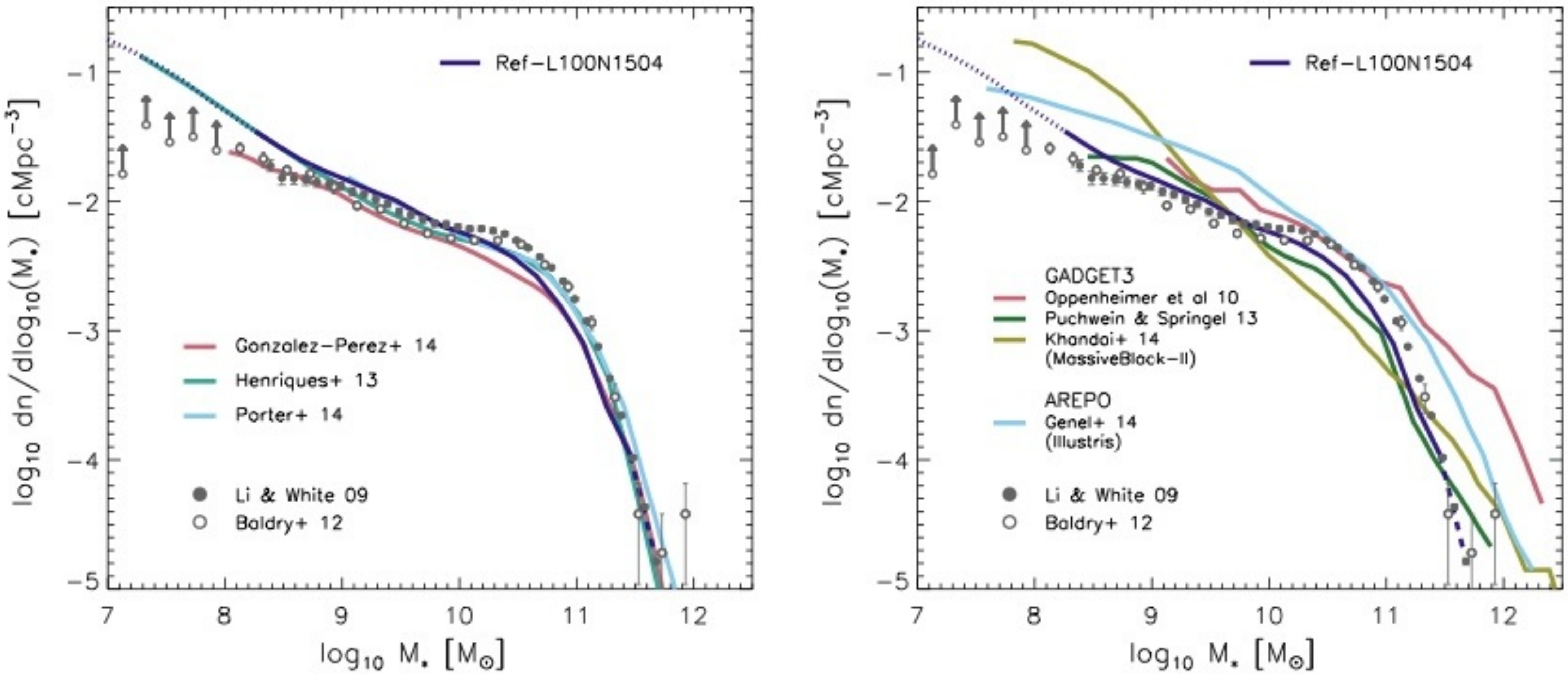


Figure 1. A $100 \times 100 \times 20$ cMpc slice through the Ref-L100N1504 simulation at $z = 0$. The intensity shows the gas density while the colour encodes the gas temperature using different colour channels for gas with $T < 10^{4.5}$ K (blue), $10^{4.5}$ K $< T < 10^{5.5}$ K (green), and $T > 10^{5.5}$ K (red). The insets show regions of 10 cMpc and 60 ckpc on a side and zoom into an individual galaxy with a stellar mass of 3×10^{10} $M_{\odot}$. The 60 ckpc image shows the stellar light based on monochromatic u, g and r band SDSS filter means and accounting for dust extinction. It was created using the radiative transfer code SKIRT (Baes et al. 2011).

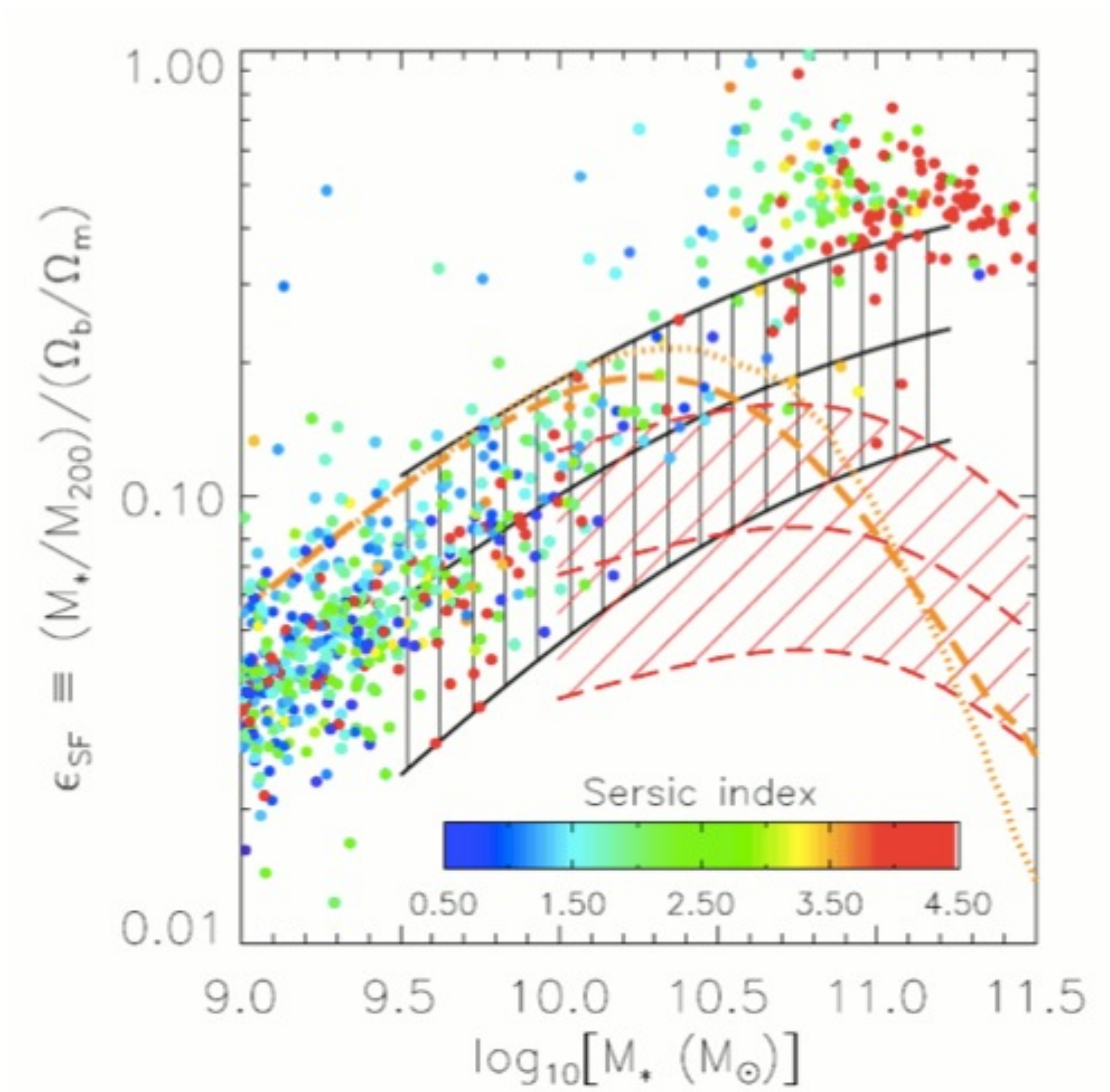
EAGLE - Stellar mass function



Schaye et al 2015

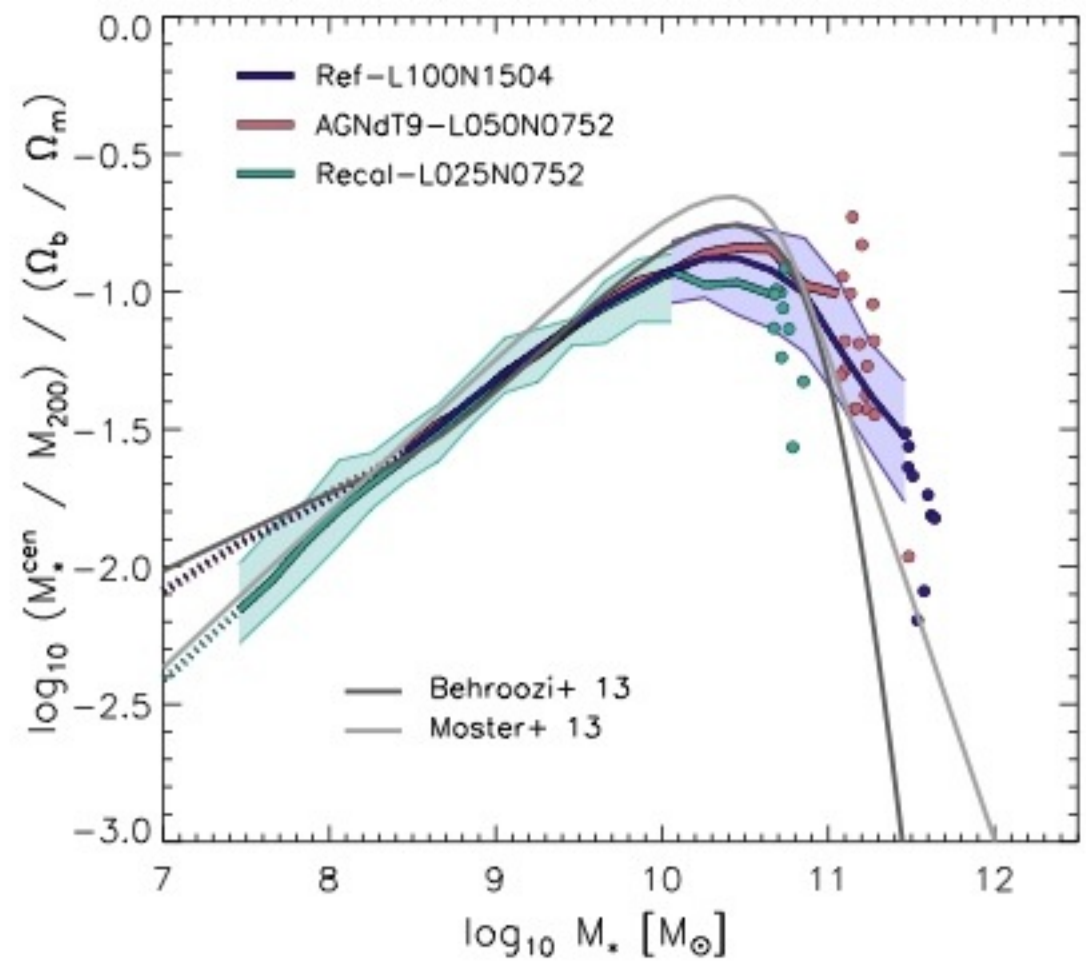
Star formation efficiency

GIMIC



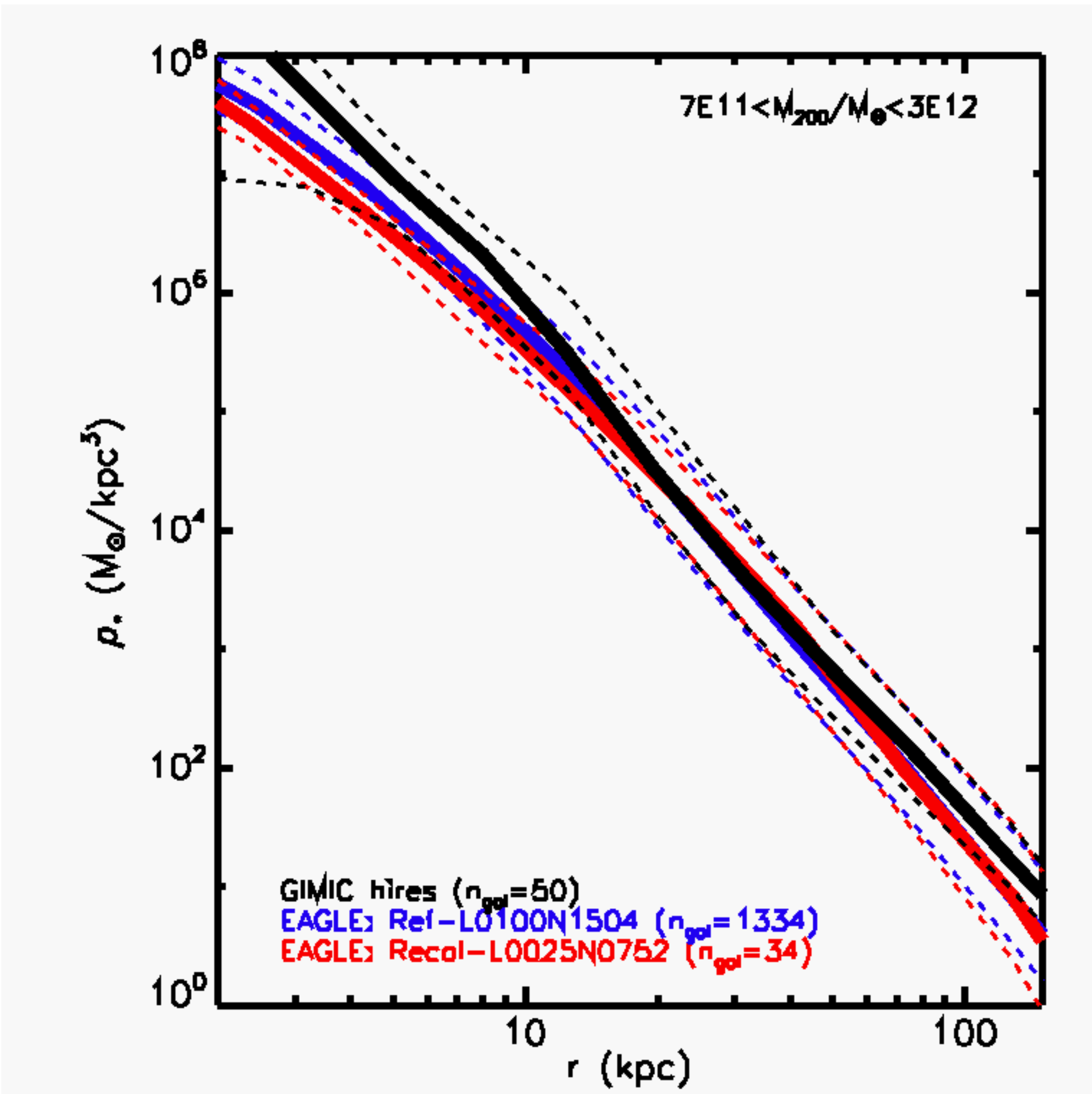
McCarthy et al 2012

EAGLE



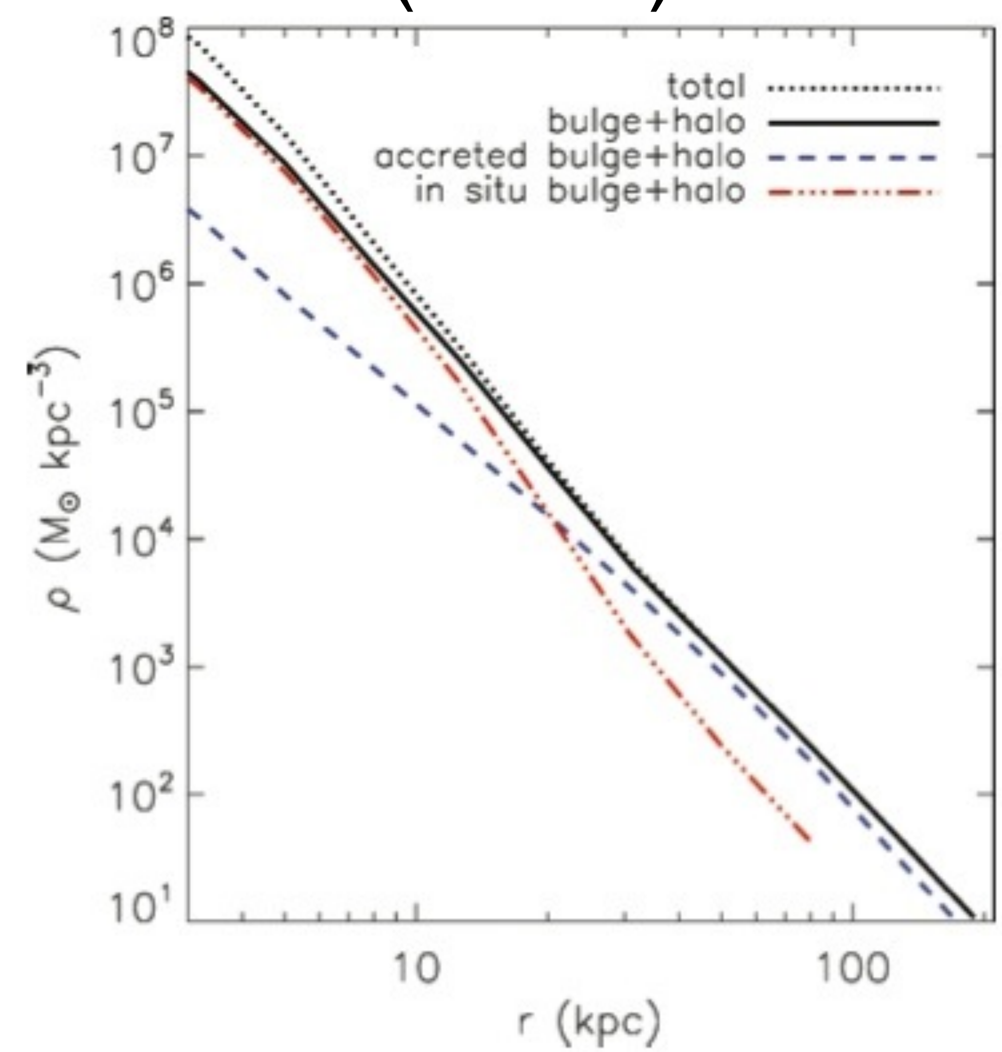
Schaye et al 2015

EAGLE: stellar mass density profiles of Milky Way-type galaxy halos



Font et al , in prep

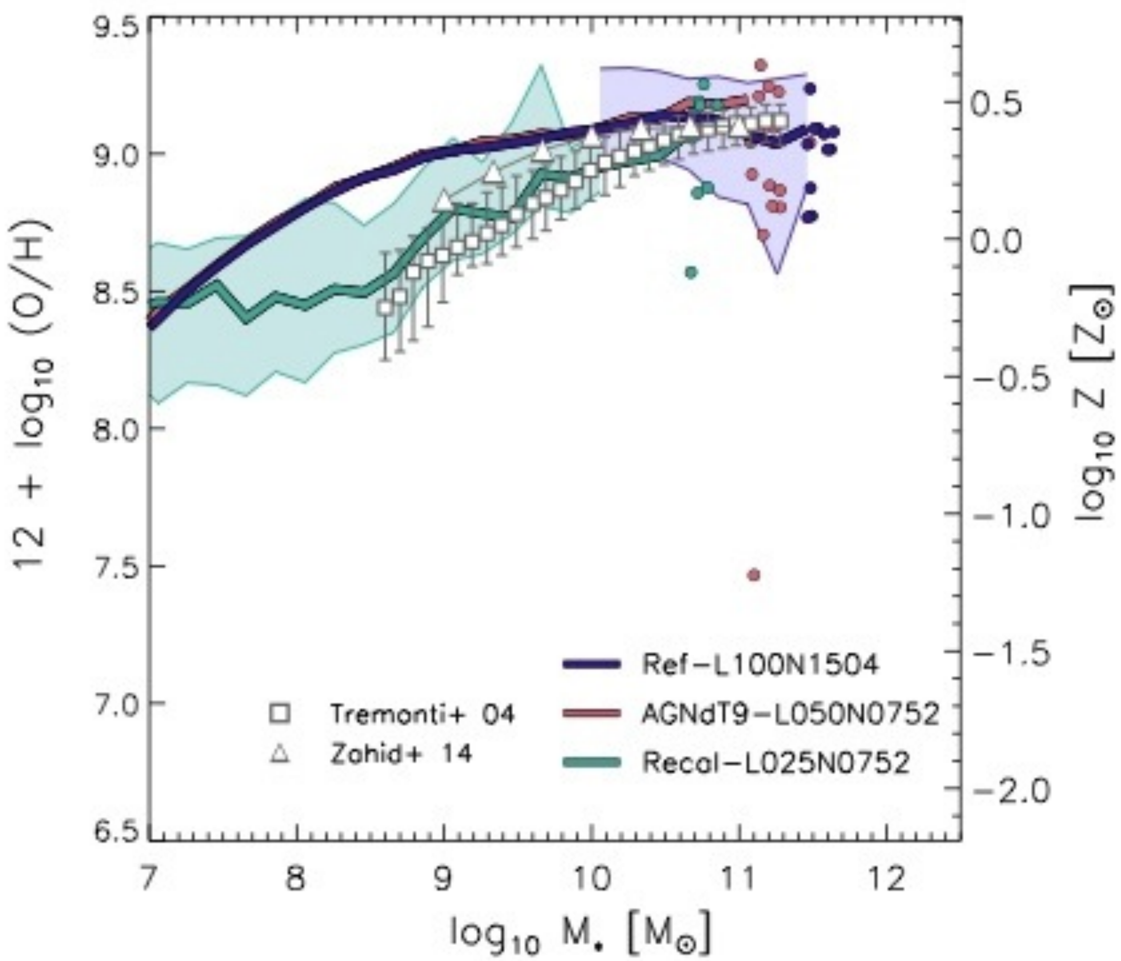
(GIMIC)



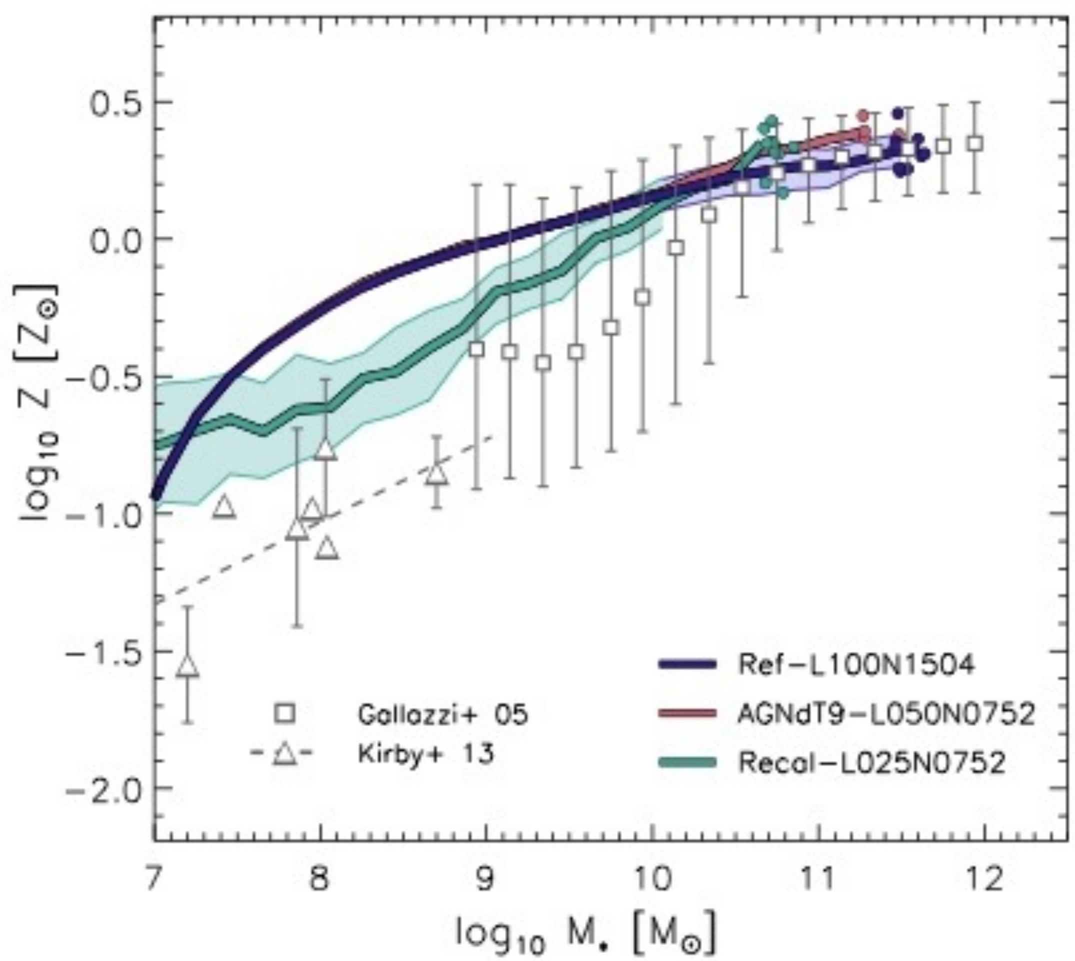
Font et al 2011

EAGLE - metallicities

ISM

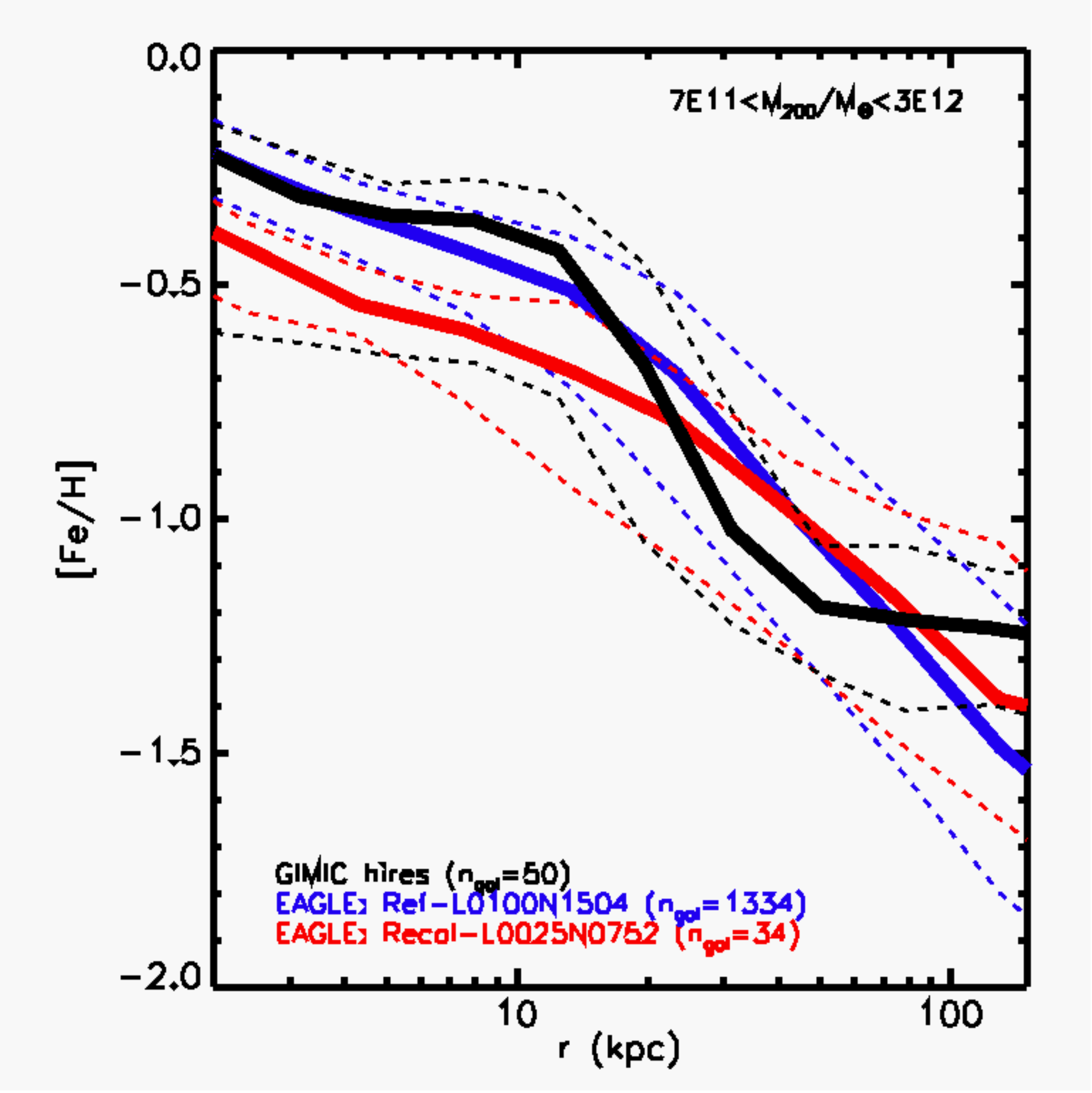


Stars



Schaye et al 2015

EAGLE: Metallicity gradients of stellar halos



EAGLE vs GIMIC:

-larger [Fe/H] scatter at large distances in EAGLE halos, as observed (in M31)

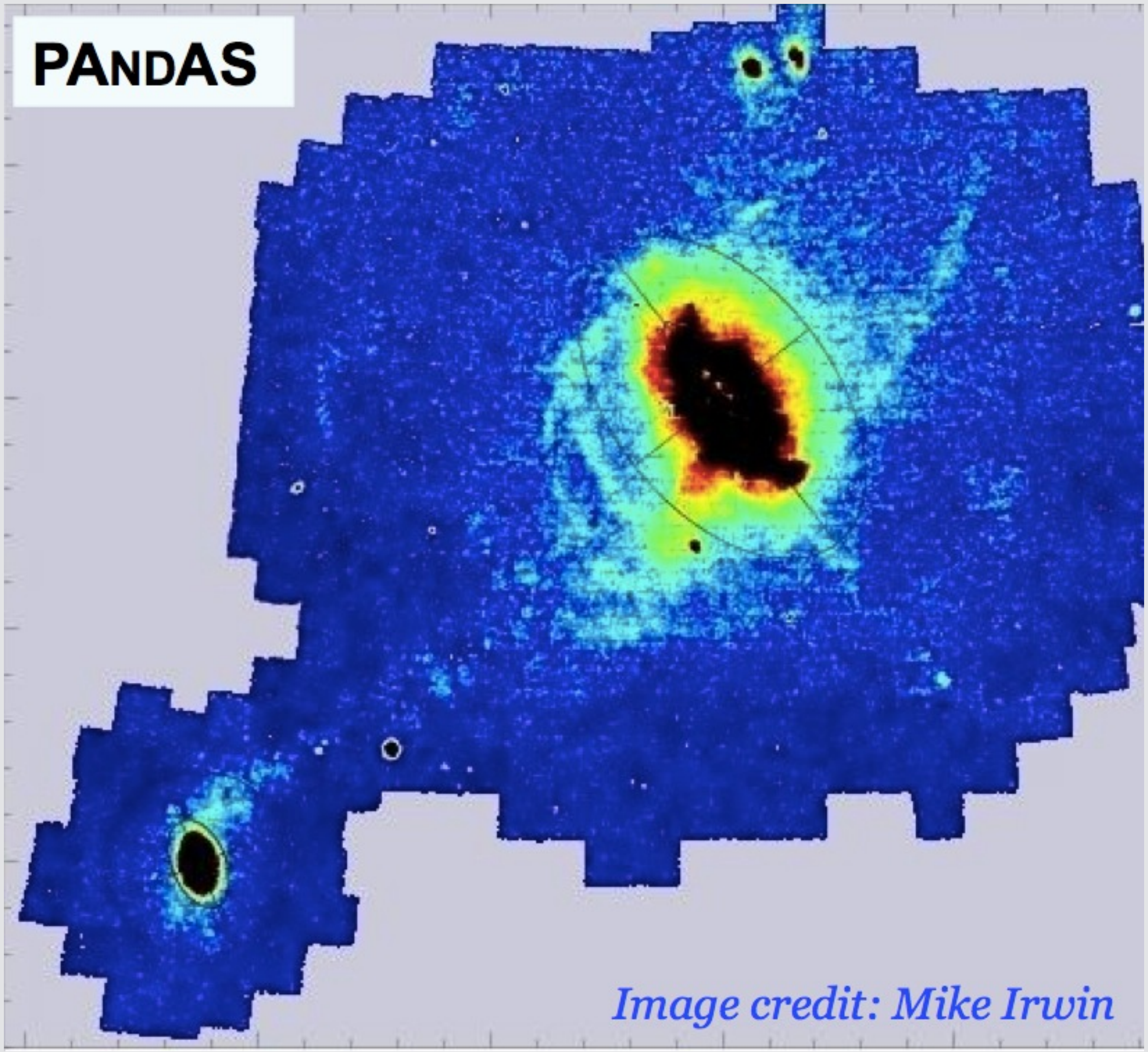
-a trend to lower [Fe/H] beyond r ~100kpc in the EAGLE halos

Font et al, in prep

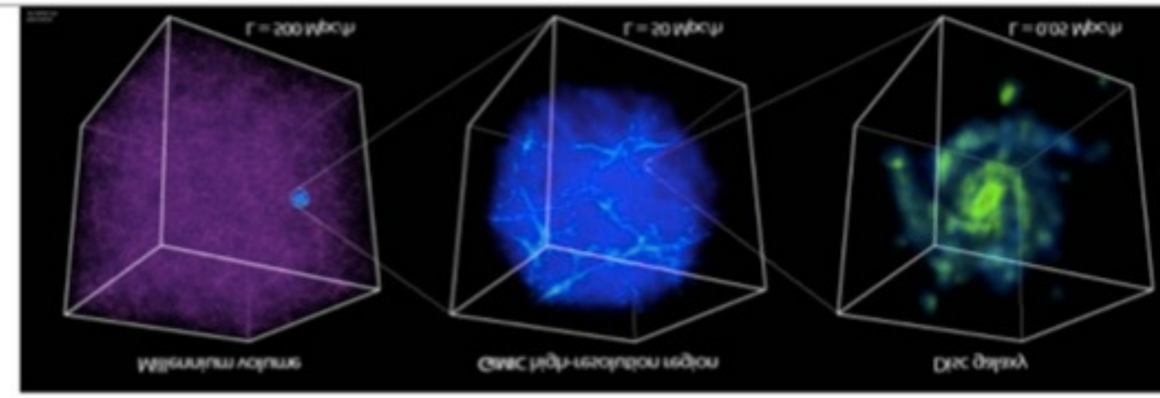
Conclusions

- dual nature of stellar halos : accreted + in situ
- in situ stars originate in proto-discs destroyed/ heated/ tilted + endo-debris (from gas stripped from satellites) + from gas accreted smoothly
- specific signatures of in situ stars: kinematics (rotation), chemical abundances (high [Fe/H] and low [alpha/Fe] -> gradients), shapes (flattened).
- gas-dynamical simulations agree qualitatively: in situ fractions ~30-40%, depending on merger/ formation history (also on physical prescriptions)
- gas-dynamical simulations disagree on the contribution of hot/cold mode gas accretion and the ages of in situ stars.
- high resolution and accurate prescriptions of star formation and feedback are crucial for modelling stellar halo components (e.g. EAGLE high res)
- large galaxy surveys (Gaia, PAndAS, etc) will reveal more information about the properties of stellar halos and streams in Milky Way and M31.

Streams in Andromeda (M31)



What is GIMIC?



• Five large, approximately spherical regions in the Millennium Simulation re-simulated at higher resolution and with gas dynamics.

• Run using Gadget-3 SPH code (Springel et al. 2005) with new sub-grid modules developed as part of the **OverWhelmingly Large Simulations** project (Schaye et al. 2010).

Key sub-grid components are:

- Star formation prescription of Schaye & Dalla Vecchia (2008) – Kennicutt-Schmidt law implemented as a pressure law for gas with $n_H > 0.1$ cm^{-3}.

- Chemodynamics & stellar evolution - enrichment by Type Ia/II and AGB stars. Following 11 chemical species separately (Wiersma et al. 2009a).

- Cooling done element by element (Wiersma et al. 2009b).

- Kinetic supernova feedback model of Dalla Vecchia & Schaye (2008). Uses 80% of available SN energy for a Chabrier IMF. Mass-loading/wind velocity tuned to match the peak of the cosmic SFR history at z~2.

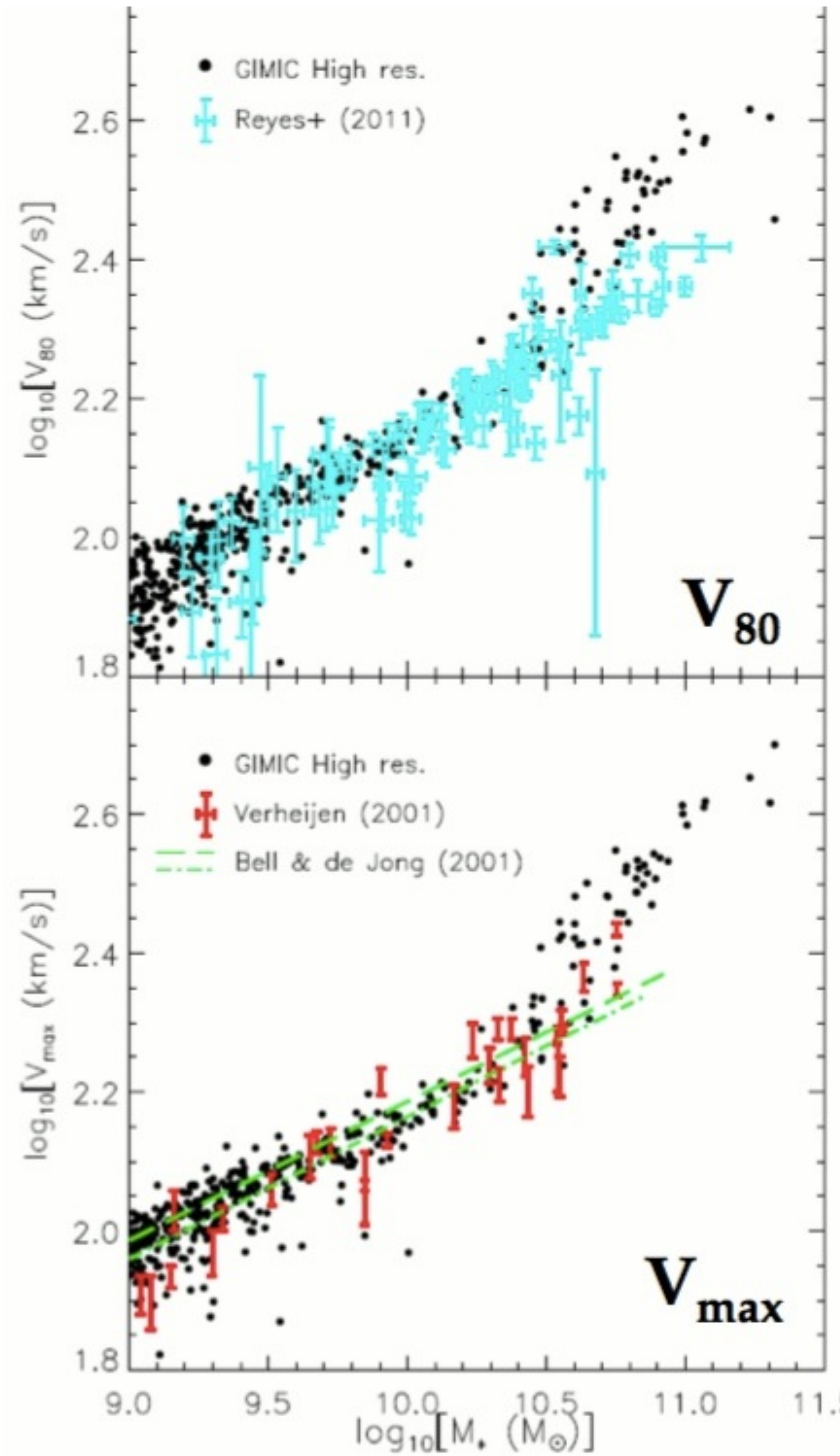
Tully-Fisher relation

- Select simulated galaxies with Sersic index $n < 2.5$ (discs). Make up 432/714 gals.

- Observed and simulated stellar mass assumed Chabrier IMF. Observed masses computed according to Bell et al. (2003) prescription and slightly adjusted to better agree with SDSS 5-band SED fitting (e.g., Blanton & Roweis 2007).

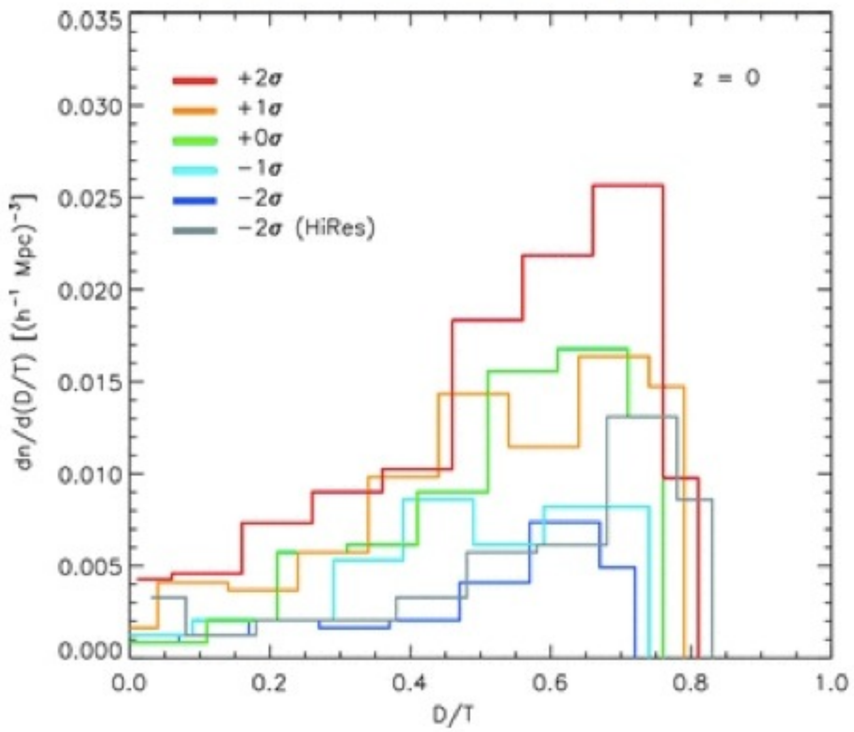
- The simulated galaxies lie approximately on top of the observed M_*-V_{80} and M_*-V_{max} relations over the range $9.0 < \log M_* < 10.5$ (slope is slightly too shallow).

- For $\log M_* > 10.5$ ($\log M_{200} > 12.3$), simulated galaxies clearly rotate too fast.

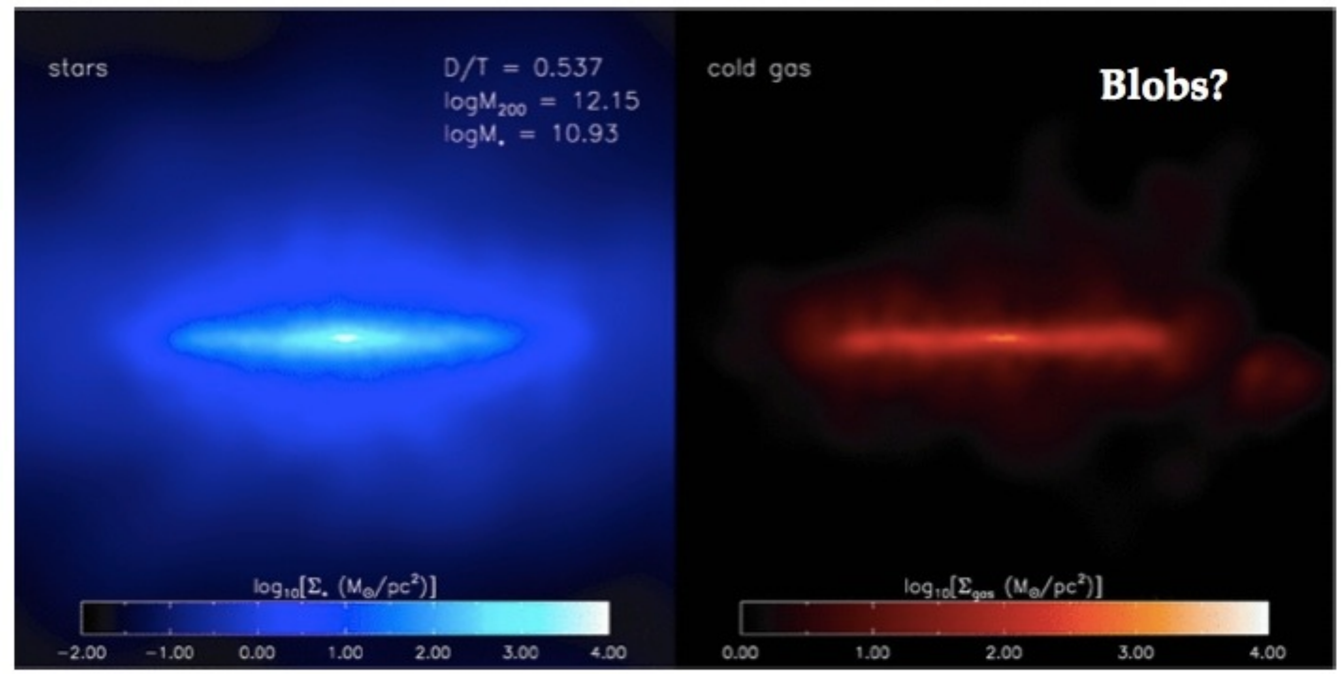


Does GIMIC make discs? Yes, lots…

From Crain et al. (2010)



From Font et al. (2011)



At z=0. Approximately 50% of normal galaxies have a *kinematic* D/T > 0.5.

In the range 9.0 < log M_* < 11.5, about 2/3 have a Sersic (*n*) index < 2.5.
For log M_* < 10.5, about 3/4 have *n* < 2.5.

The flattened shape is caused by rotation and anisotropy