Modelling Stellar Haloes with Dark Matter Simulations

Andrew Cooper, Durham

ESO, “Baryons at Low Densities”
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Outline

1. **Why** do we model **stellar** haloes using **collisionless** simulations? **How** do we do this + some results!

2. Tests of particle tagging against SPH simulations.

3. In situ (halo) stars

Why particle tagging?

- A **fast**, efficient way to make detailed predictions **for the statistical properties of stellar haloes**, in a way that directly addresses the link between CDM structure formation and **photometric and dynamical observations.**

- **Higher resolution** than SPH sims — faintest MW satellites or a 10^15 Msol cluster are in reach.

- **No need for a supercomputer to try different models** (DM simulation + semi-analytic model of star formation)

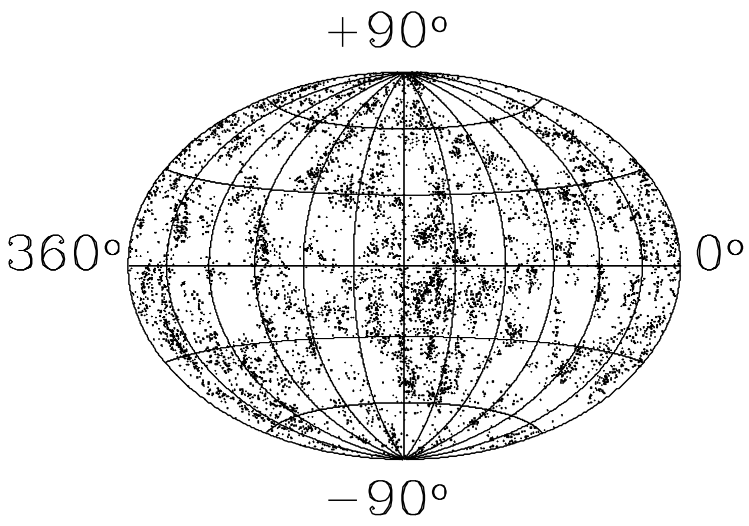
- Can make use of galaxy formation codes with physically meaningful parameters constrained by statistical observations (e.g. field luminosity functions)

- Good for generating large statistical samples and understanding effect of different physical models. However, assumes baryons don’t contribute to gravitational potentials!

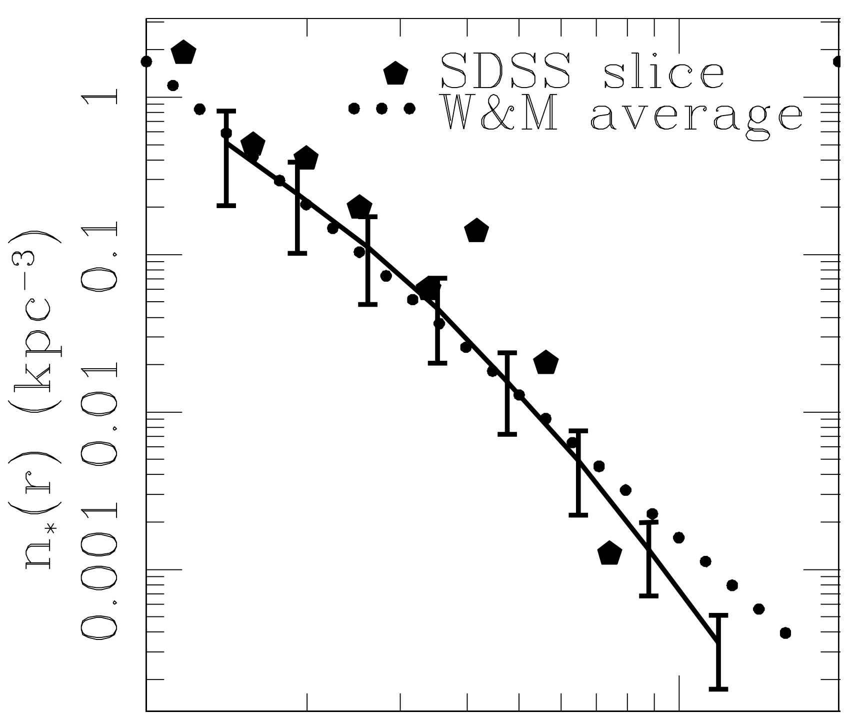
I: Particle tagging stellar halo models

Stellar haloes from collisionless simulations

see Guinevere Kauffmann's review talk

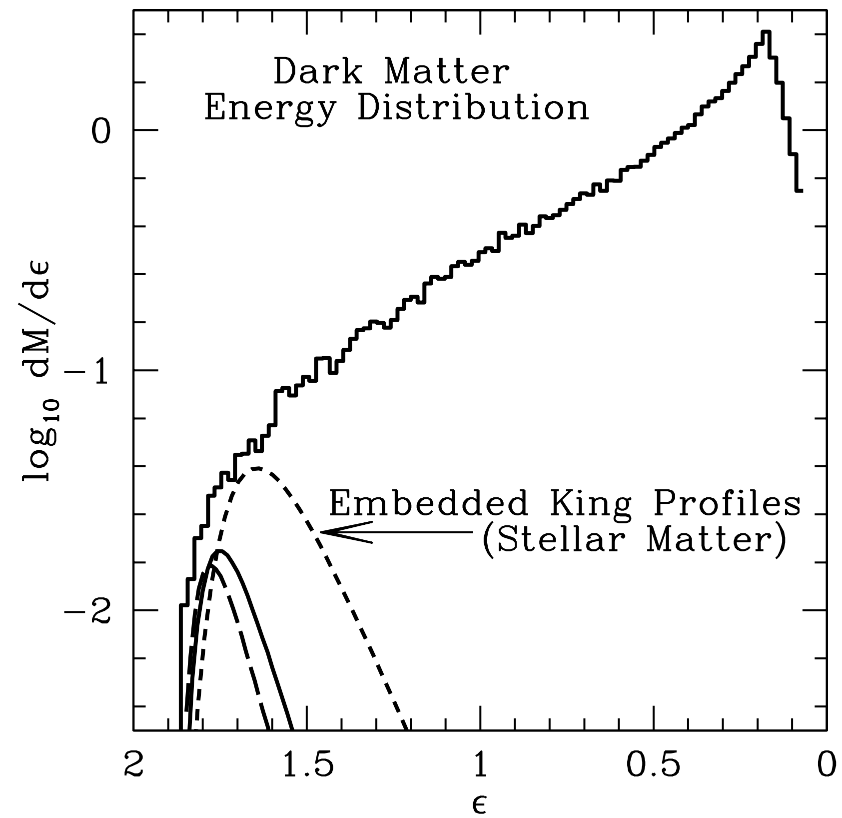


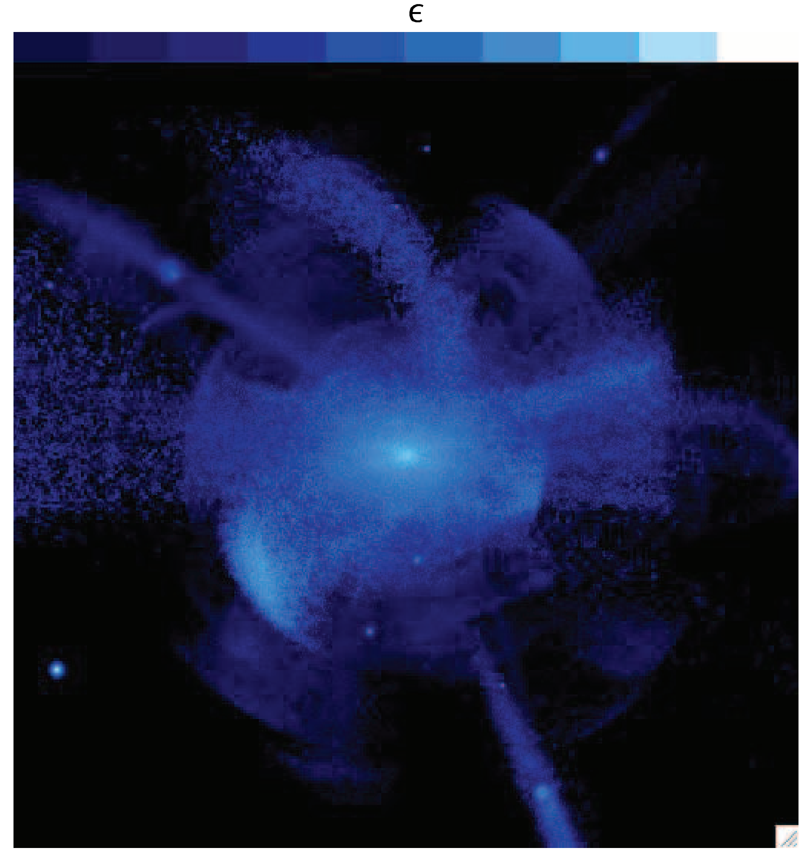
40 kpc < R < 50 kpc



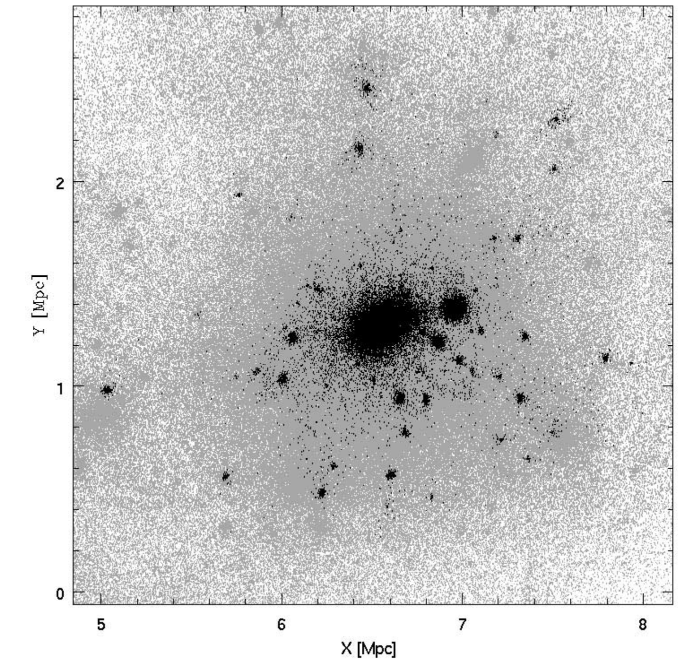
Bullock, Kratsov & Weinberg 2001

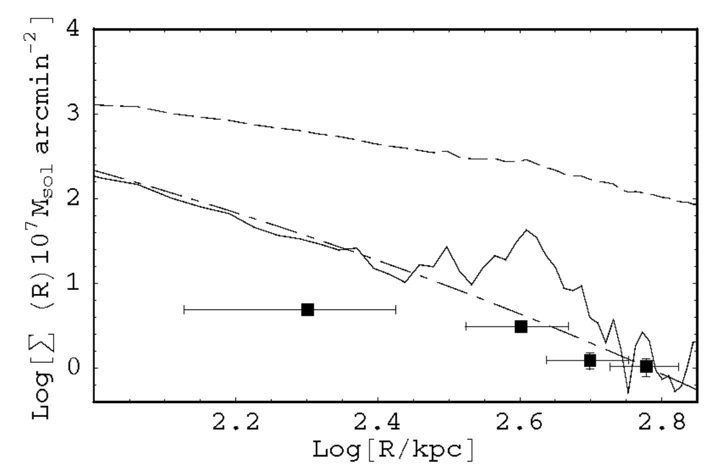
Bullock & Johnston 2005





Napolitano et al. 2003

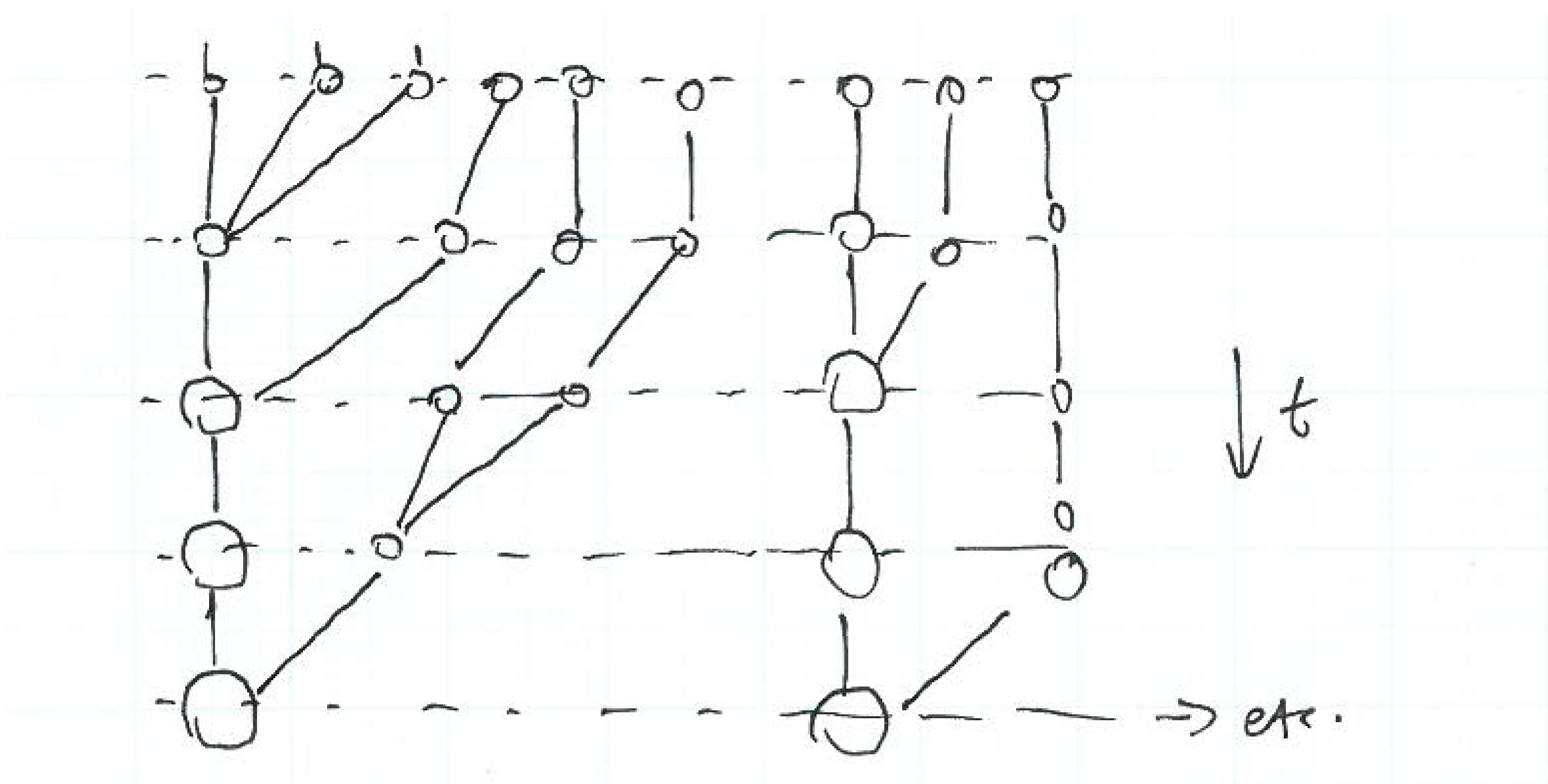




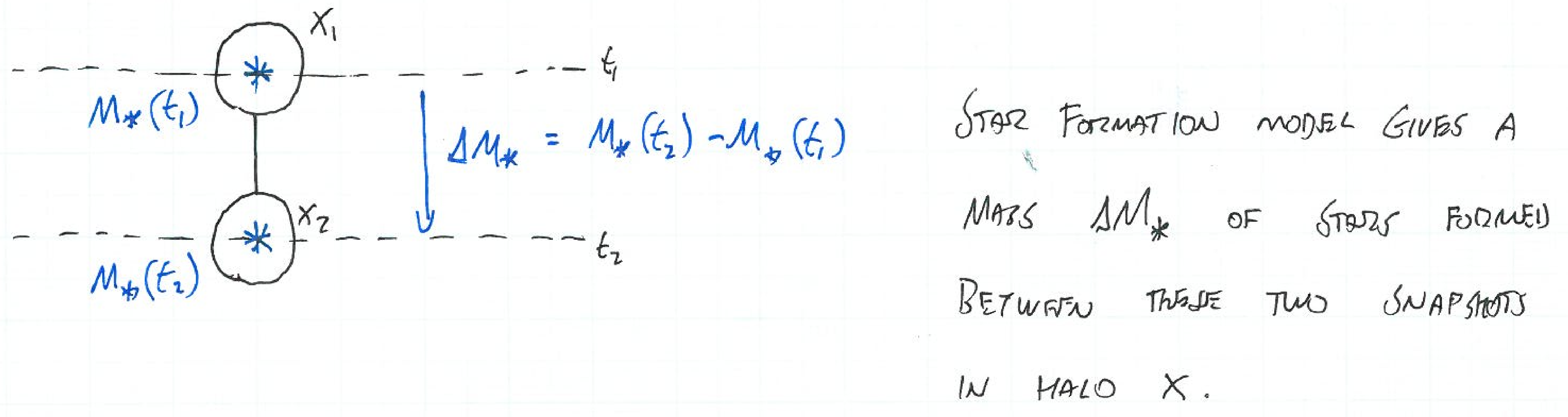
also recent work on BCG assembly by Chervin Laporte

Particle Tagging in a nutshell (following APC et al. 2010)

- Start with a collisionless cosmological simulation.
- Identify haloes, build merger trees



Particle Tagging in a nutshell



- The idea is to select a set of dark matter particles with phase-space trajectories that can be used as a proxy for newly formed stars.

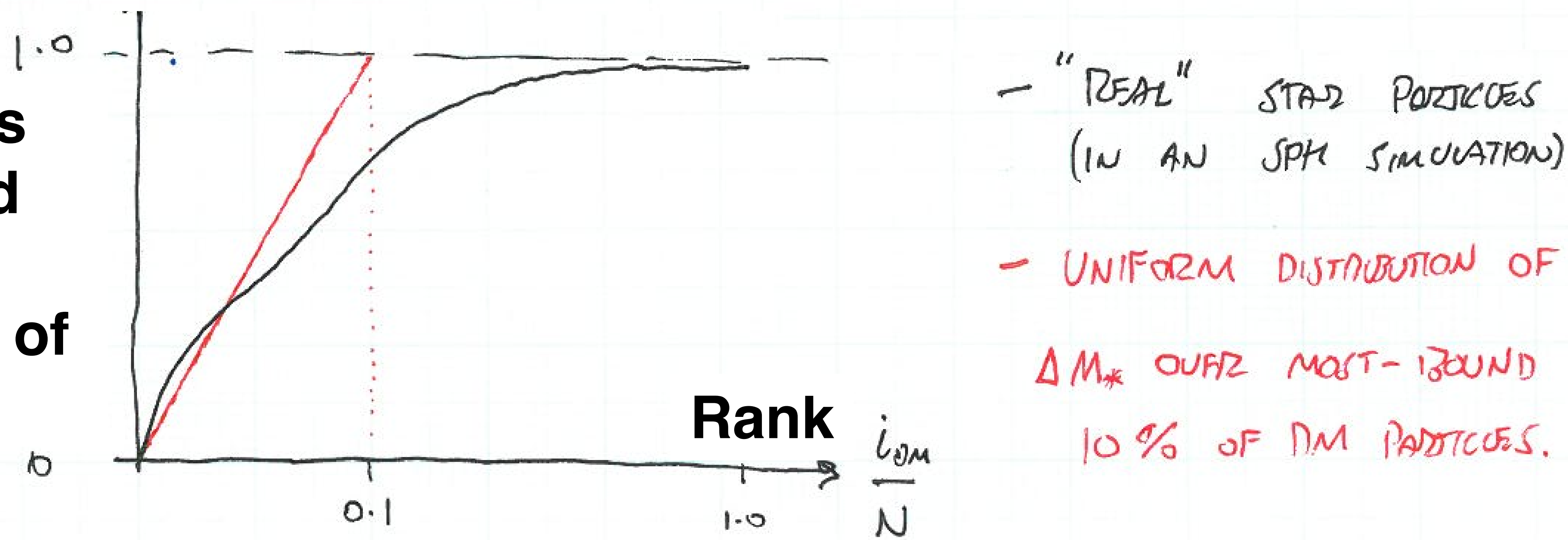
- These DM particles should at least be tightly bound!

Particle Tagging in a nutshell

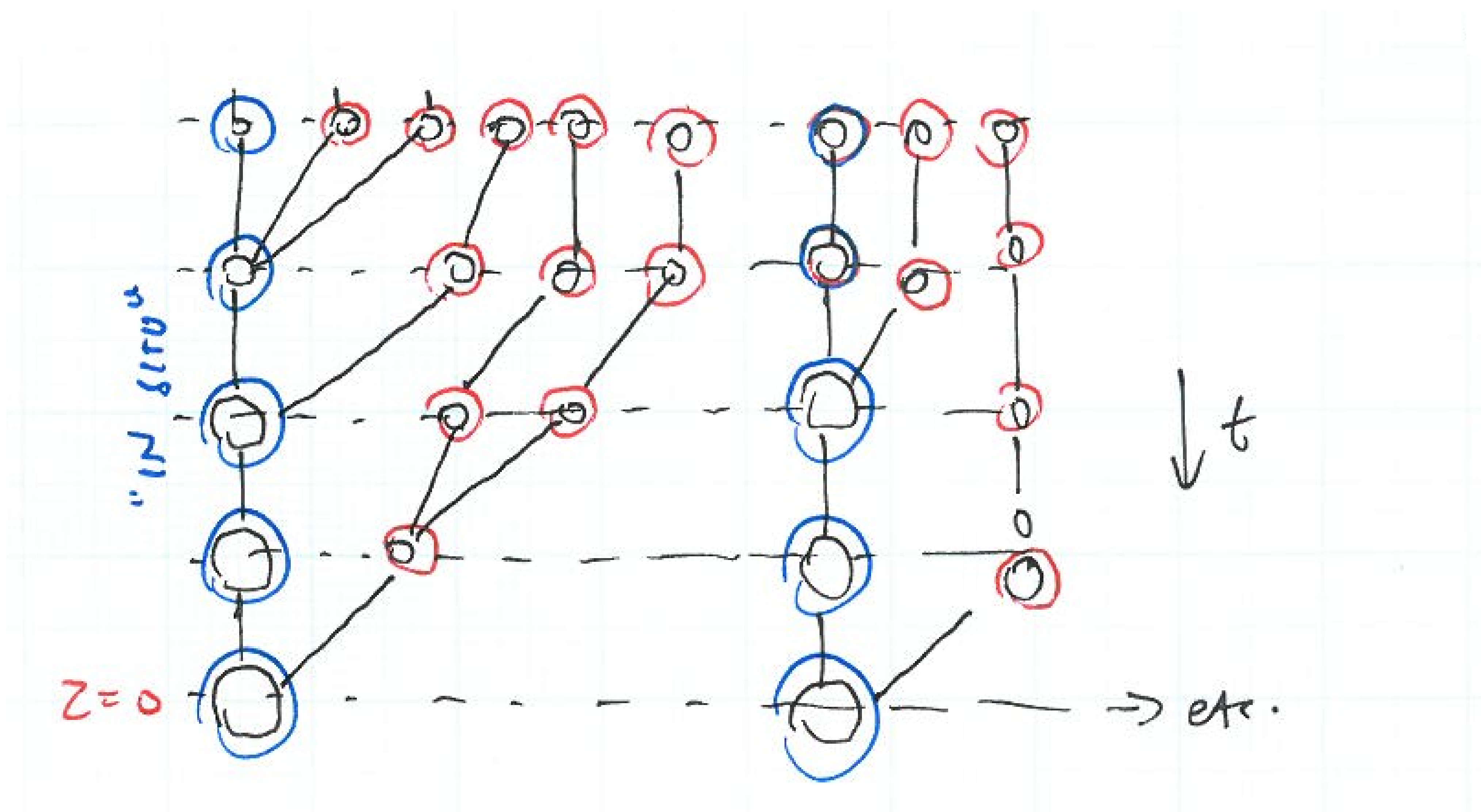
- Methods diverge from this point…
- We use energy **rank** of DM particles (from subfind), because we don't always have absolute energies.

Density profile

Stellar mass more bound than DM particle of given rank



Particle Tagging in a nutshell

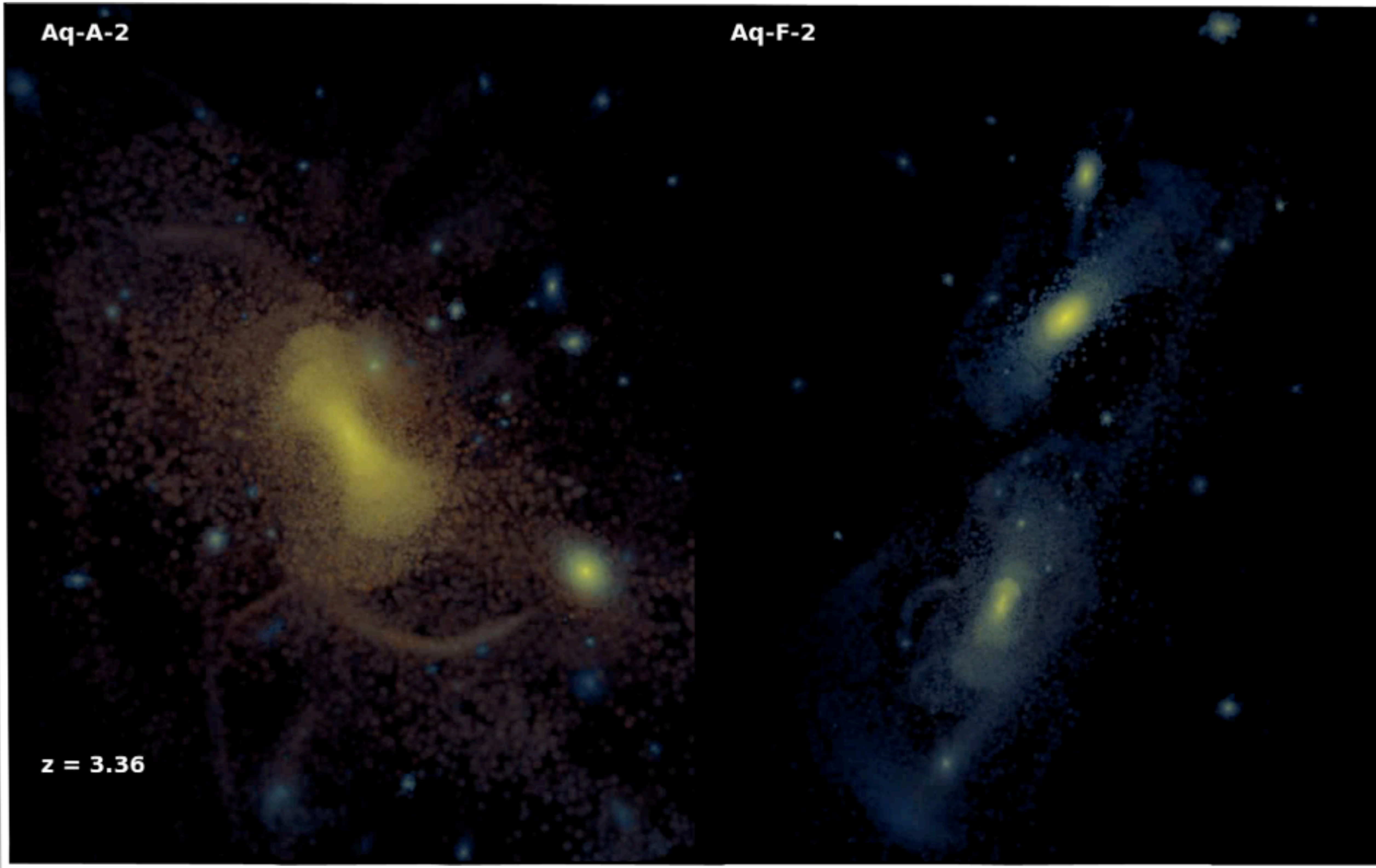


- Simulation has many snapshots, and many star-forming haloes at each snapshot. We tag every halo in which stars form, at every snapshot.

- Tagging at infall produces different results to 'live' tagging **unless** using a distribution function-based method.

Particle tagging in action

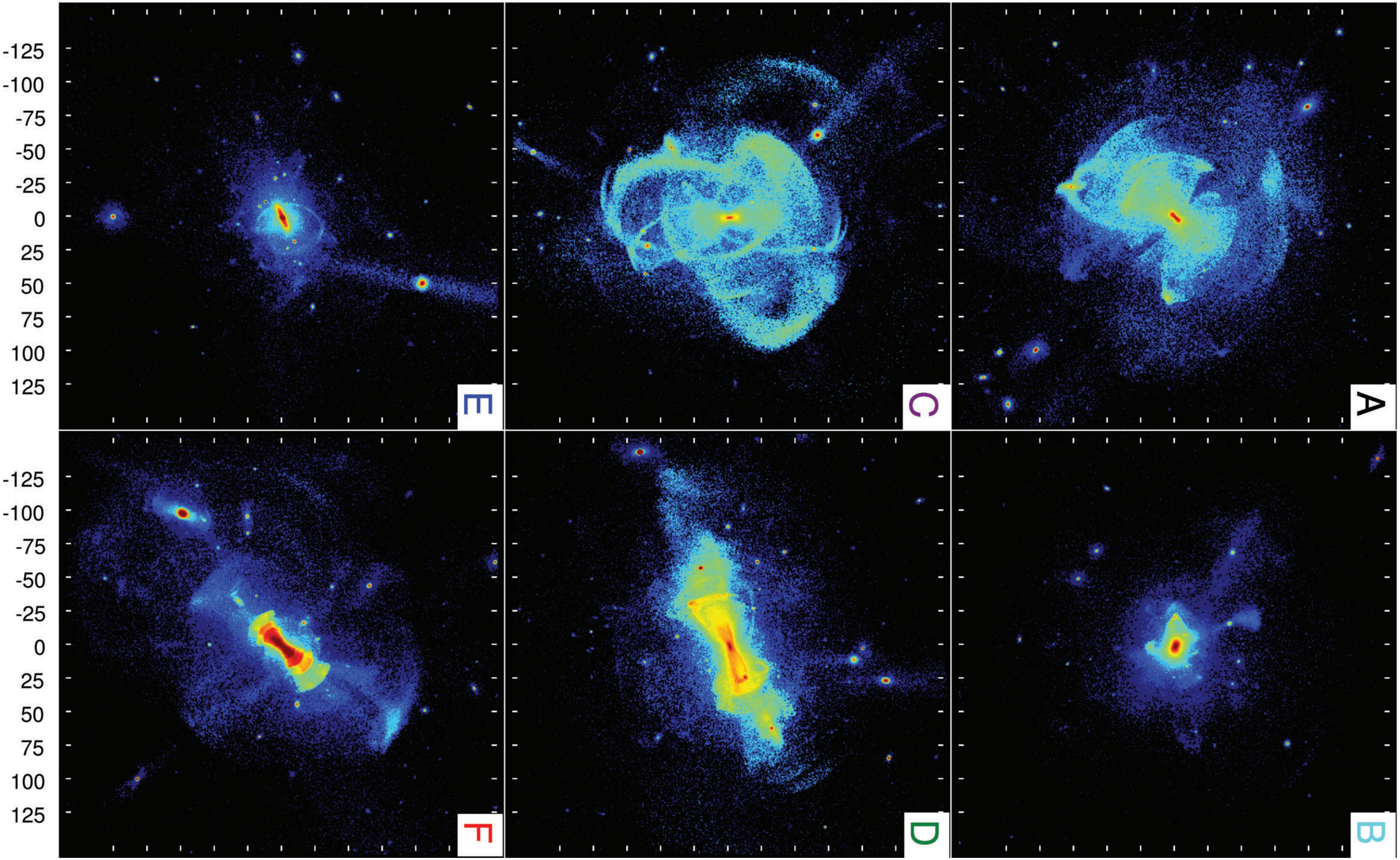
'hiding' in situ stars in the main branch!



www.virgo.ac.uk/shell-galaxies

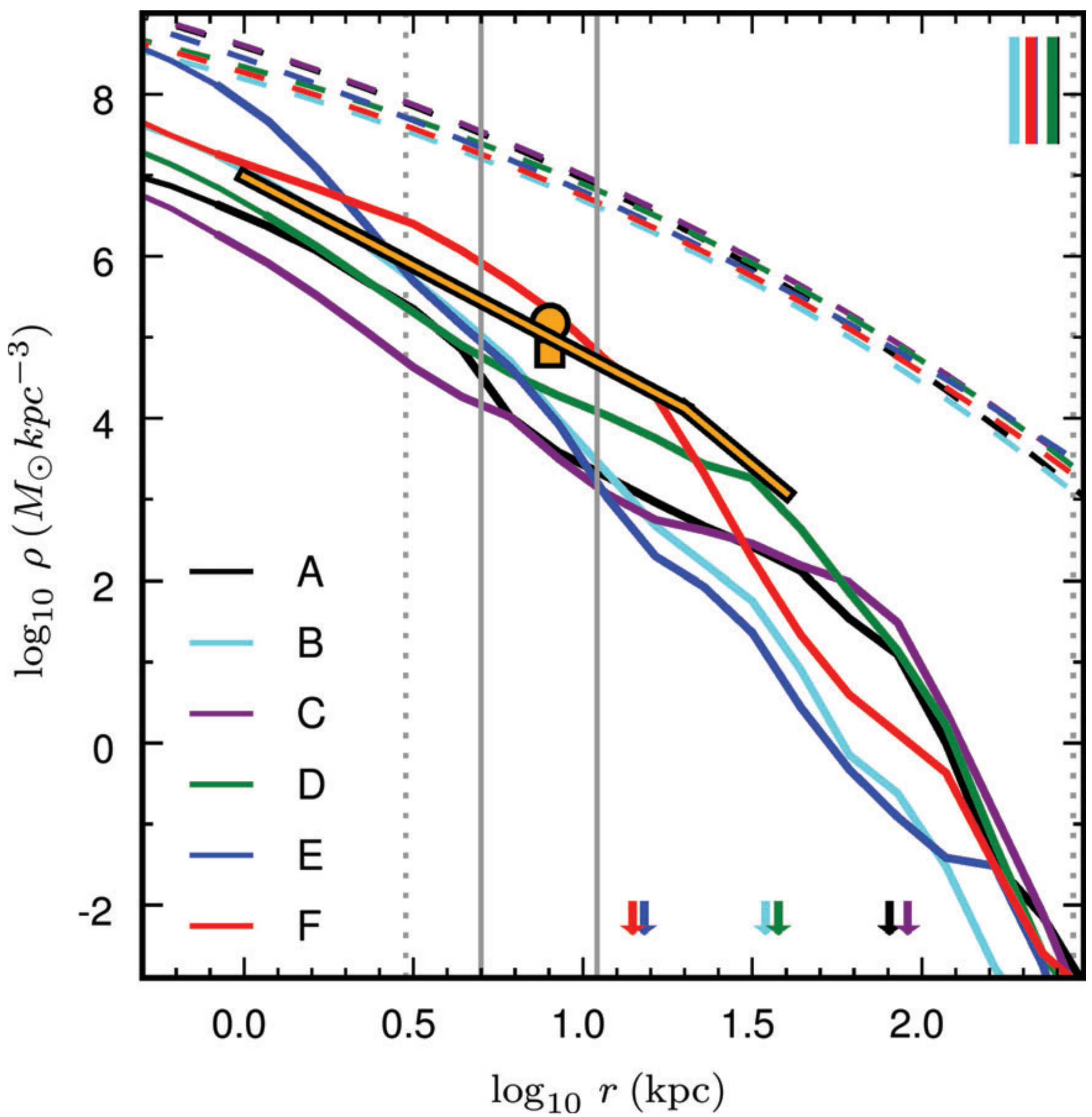
Selected Results

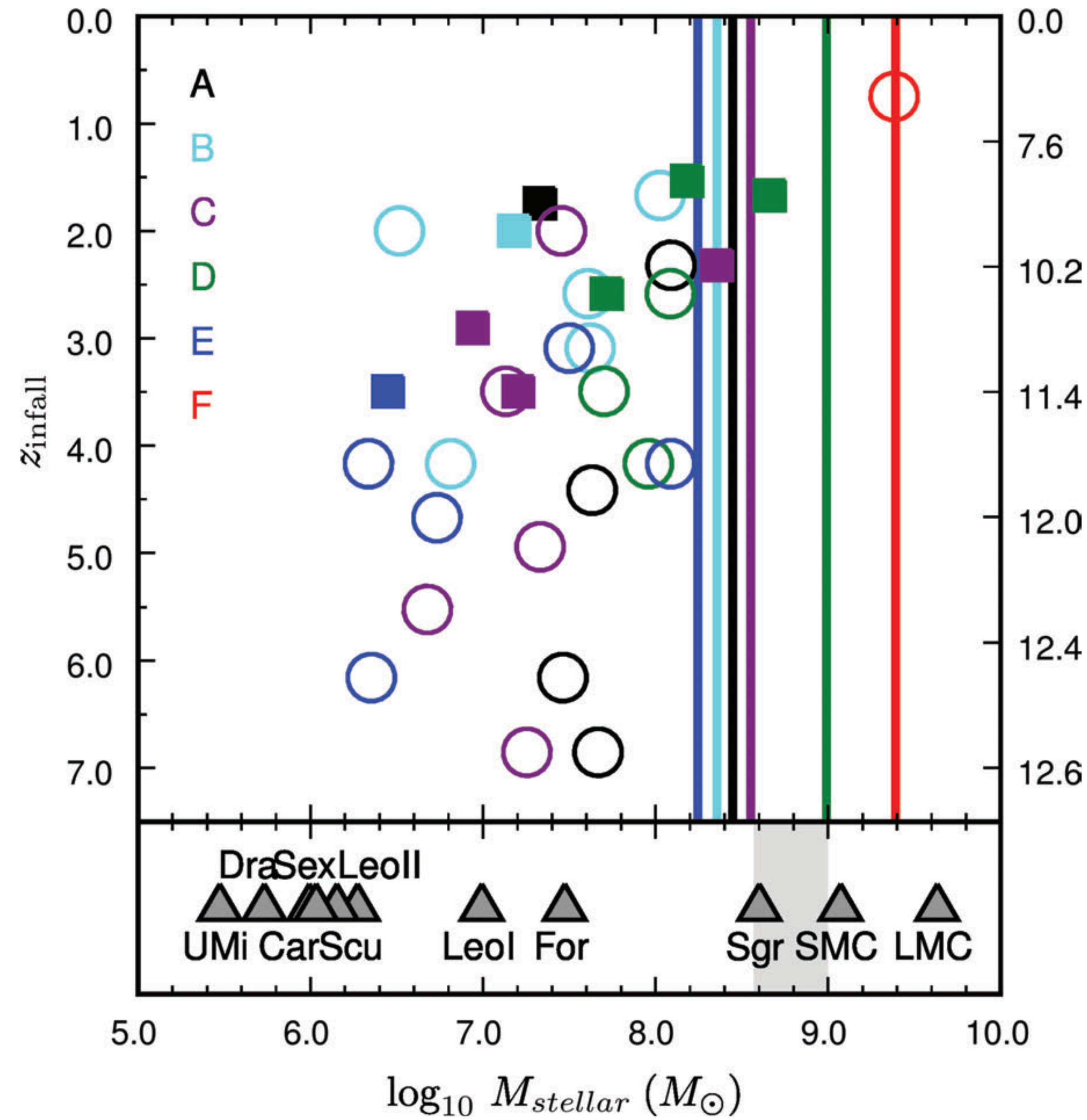
The Milky Way halo (tagging Aquarius)



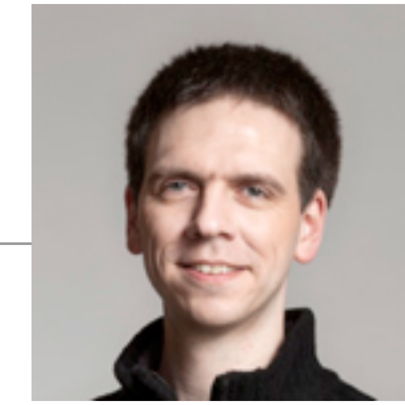
The Milky Way halo (tagging Aquarius)

- MW haloes have individually complex density profiles and some dominated by single accretion events.

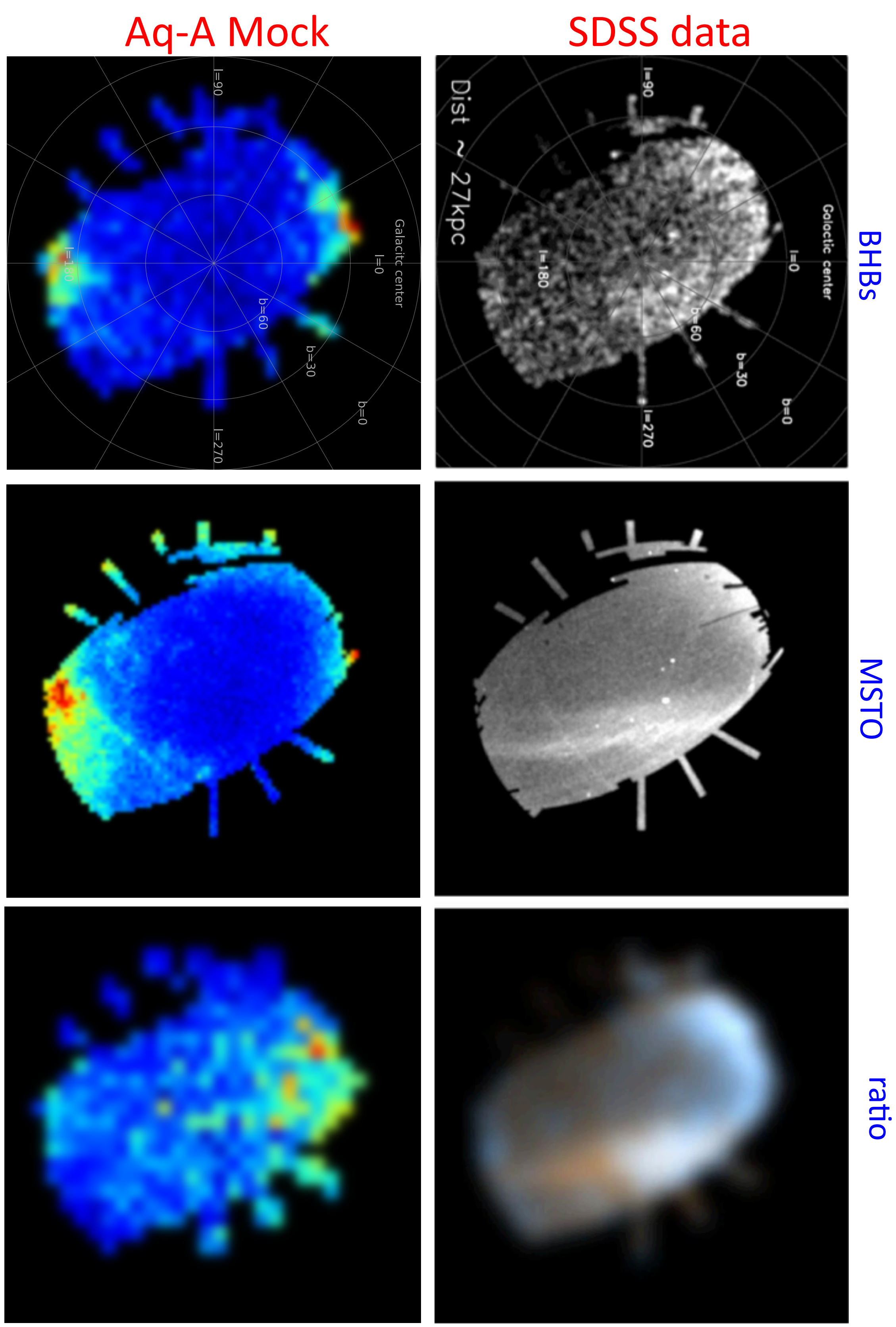


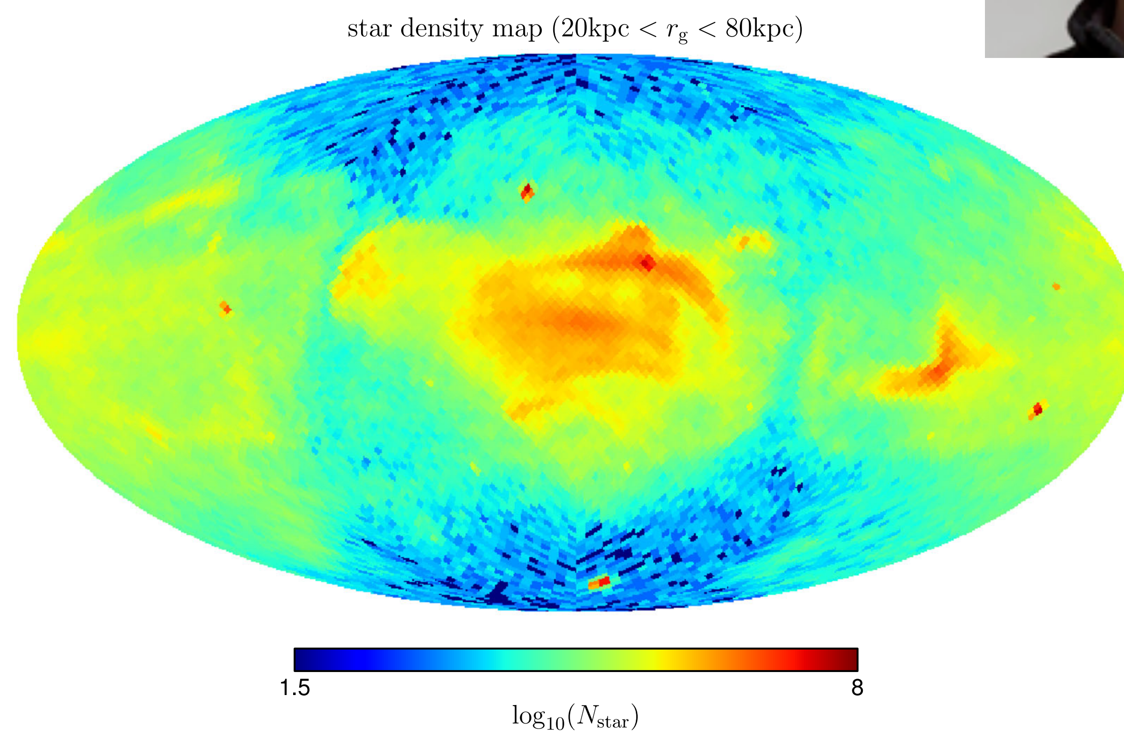


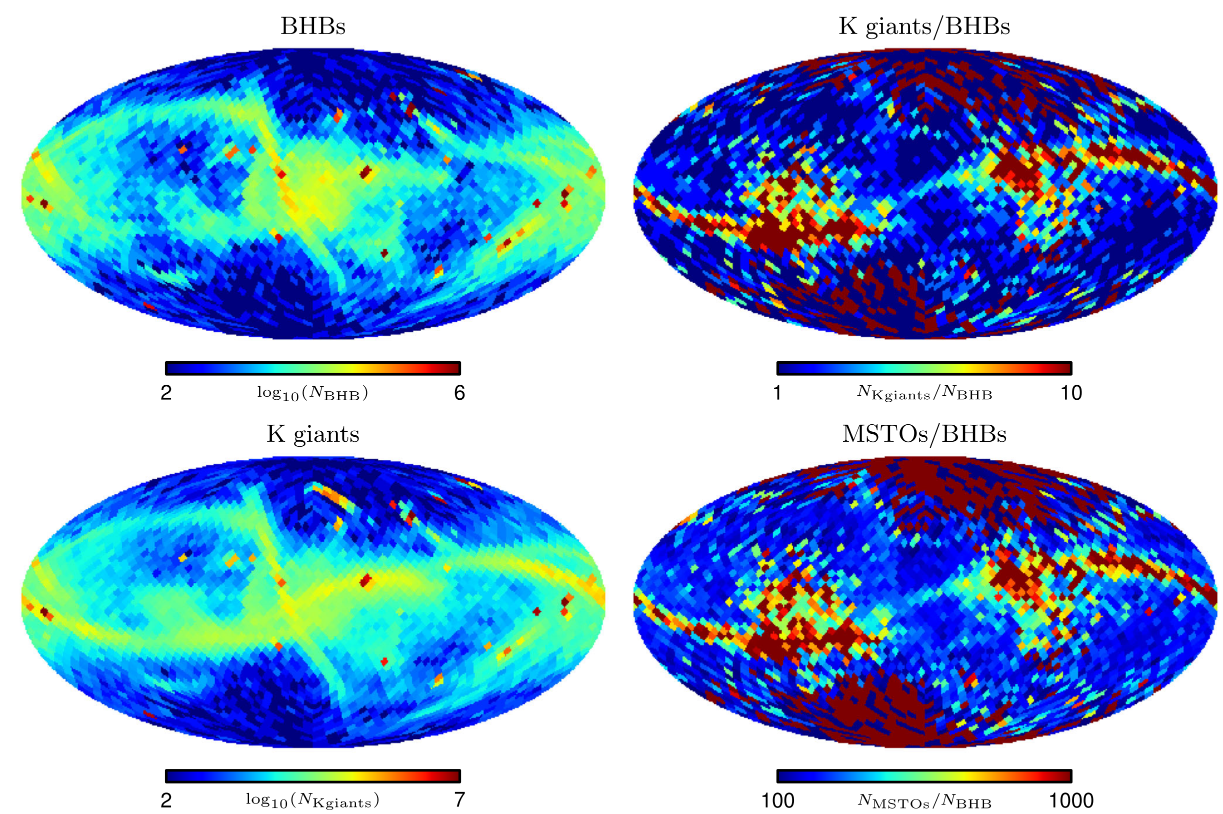
Mock catalogues: Lowing+ 2015



http://galaxy-catalogue.dur.ac.uk:8080/StellarHalo

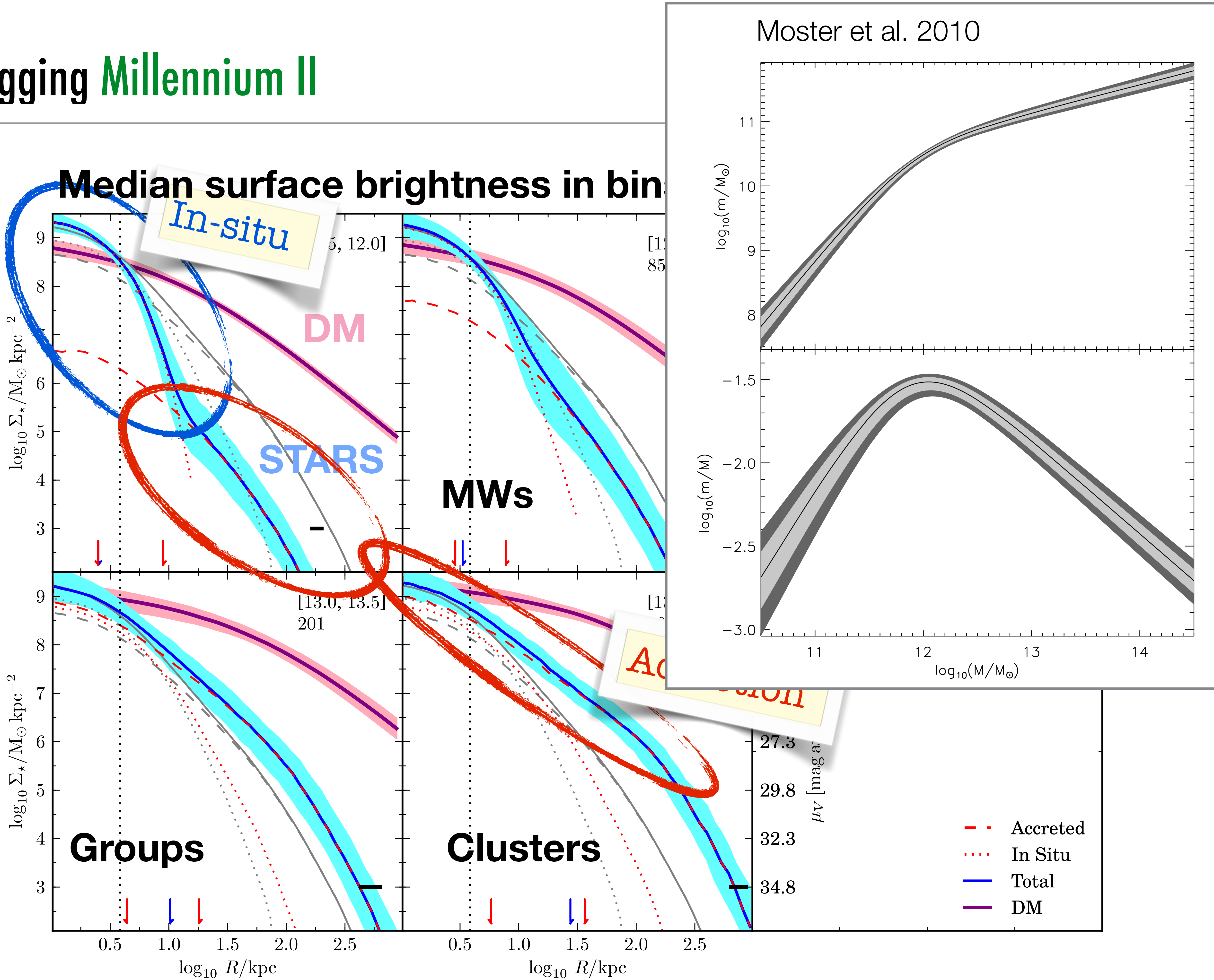






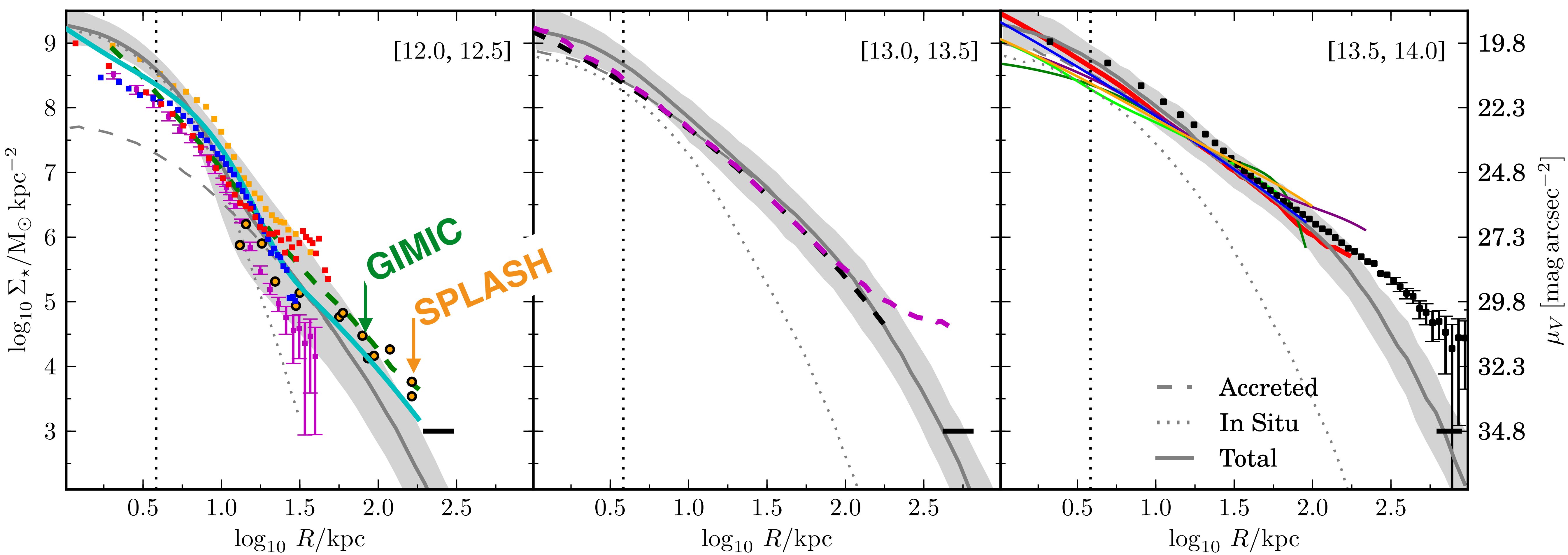
http://adsabs.harvard.edu/abs/2015MNRAS.446.2274L

Tagging Millennium II

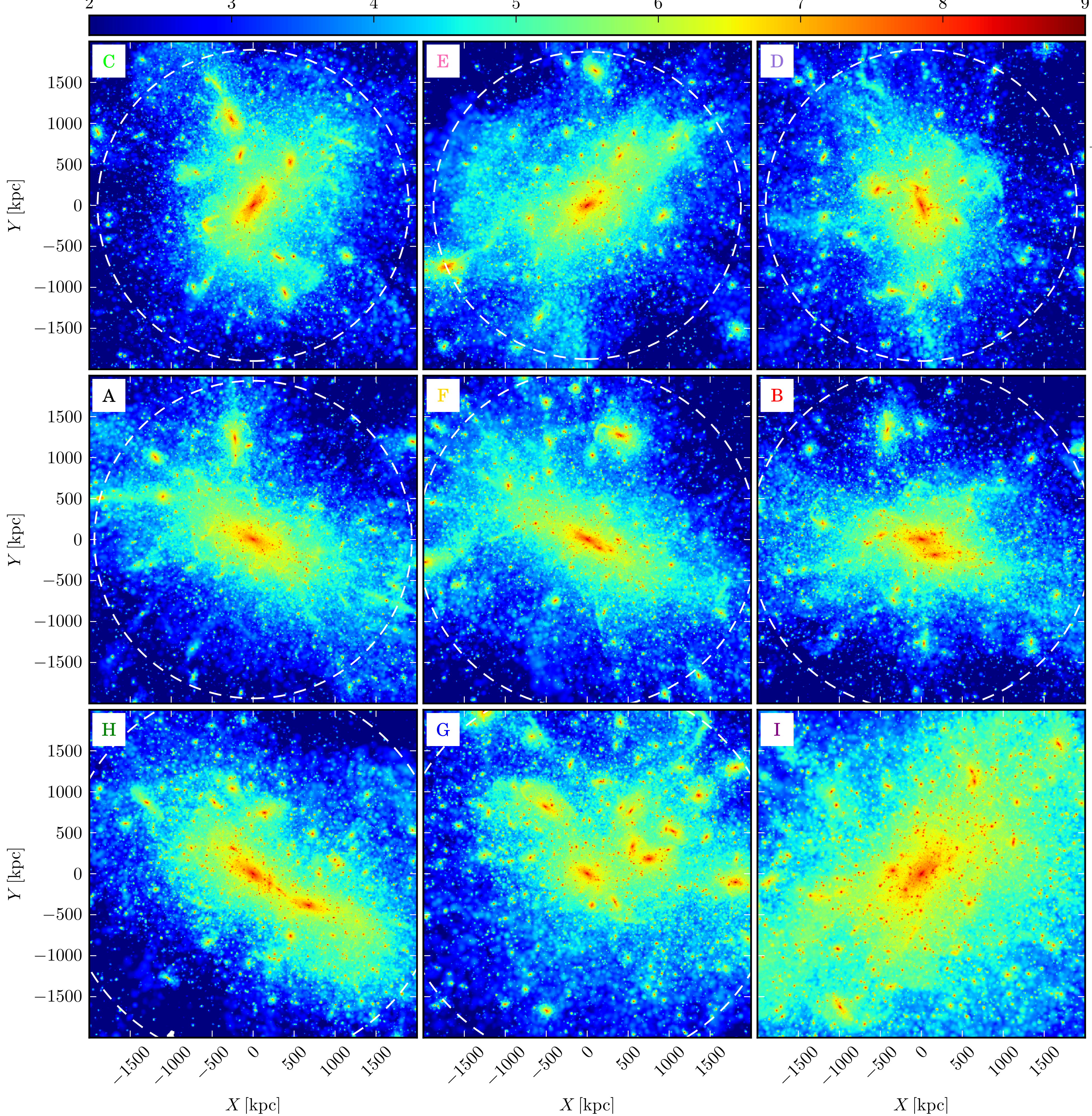


Compared to individual observations

See APC. et al. (2013) for citations to the data



see Richard d'Souza's talk
for comparison with SDSS stacking



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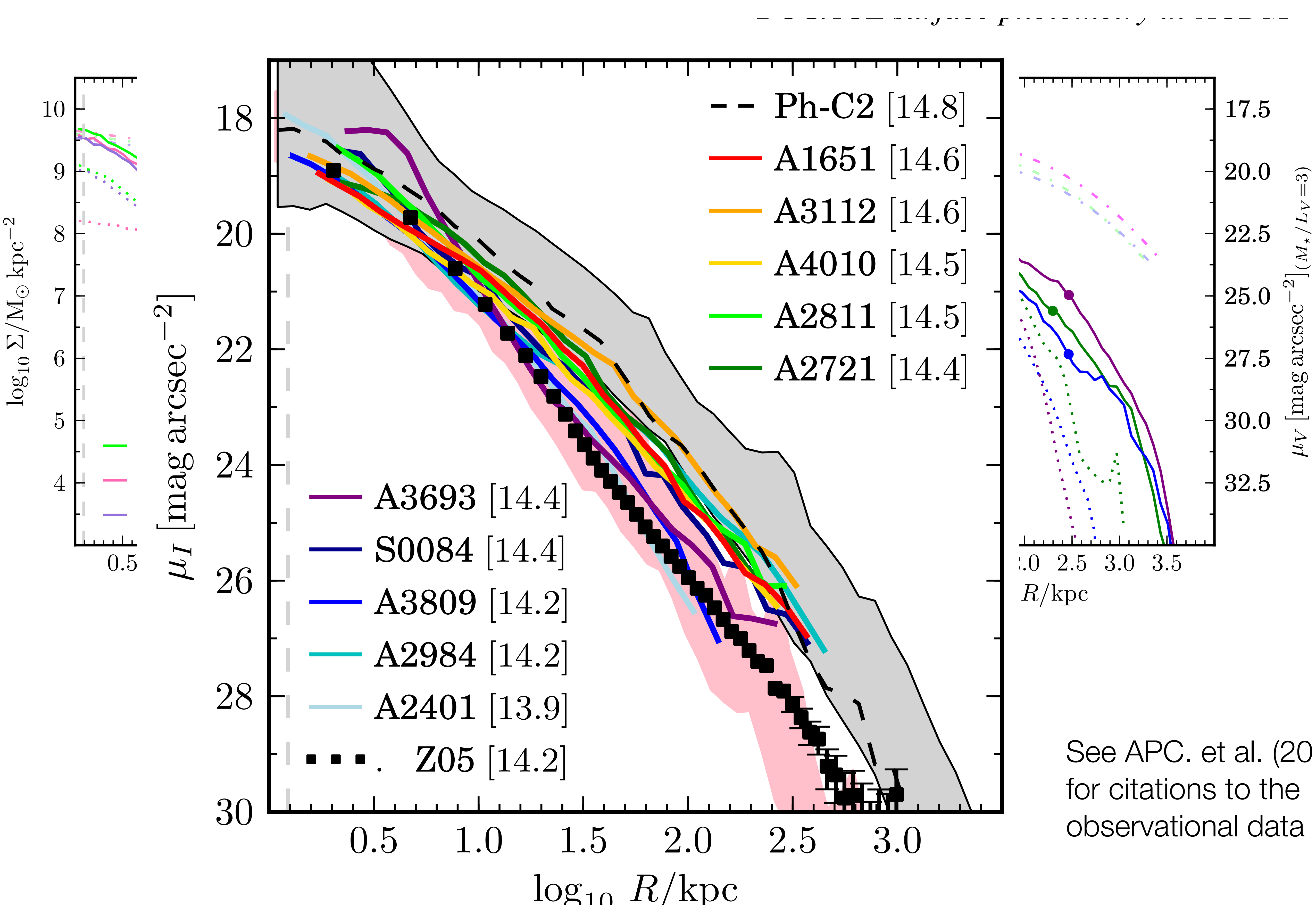
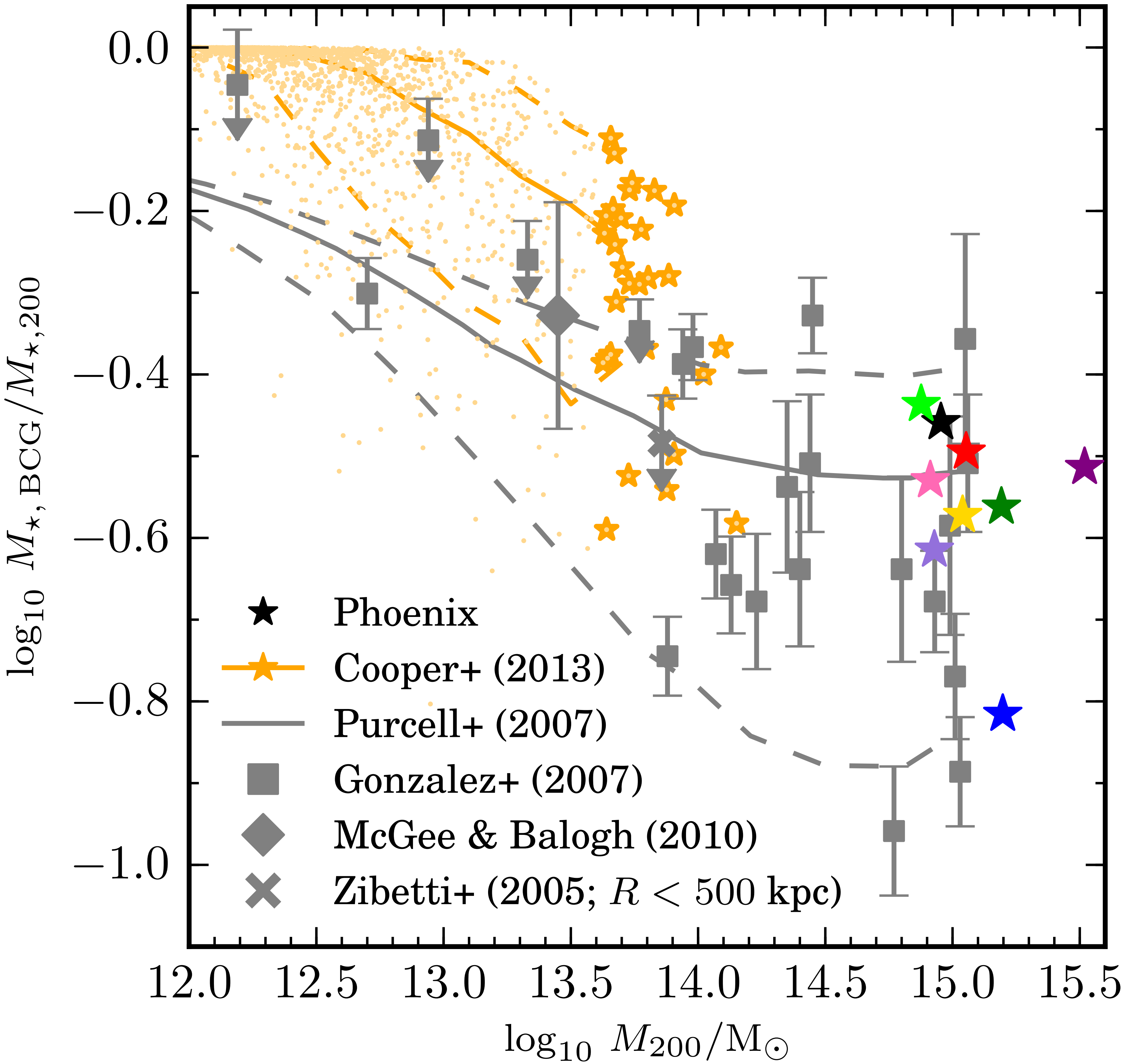
Massive galaxy clusters (tagging Phoenix)

http://arxiv.org/abs/1407.5627



See APC. et al. (2014) for citations to the observational data

Massive galaxy clusters (tagging Phoenix)



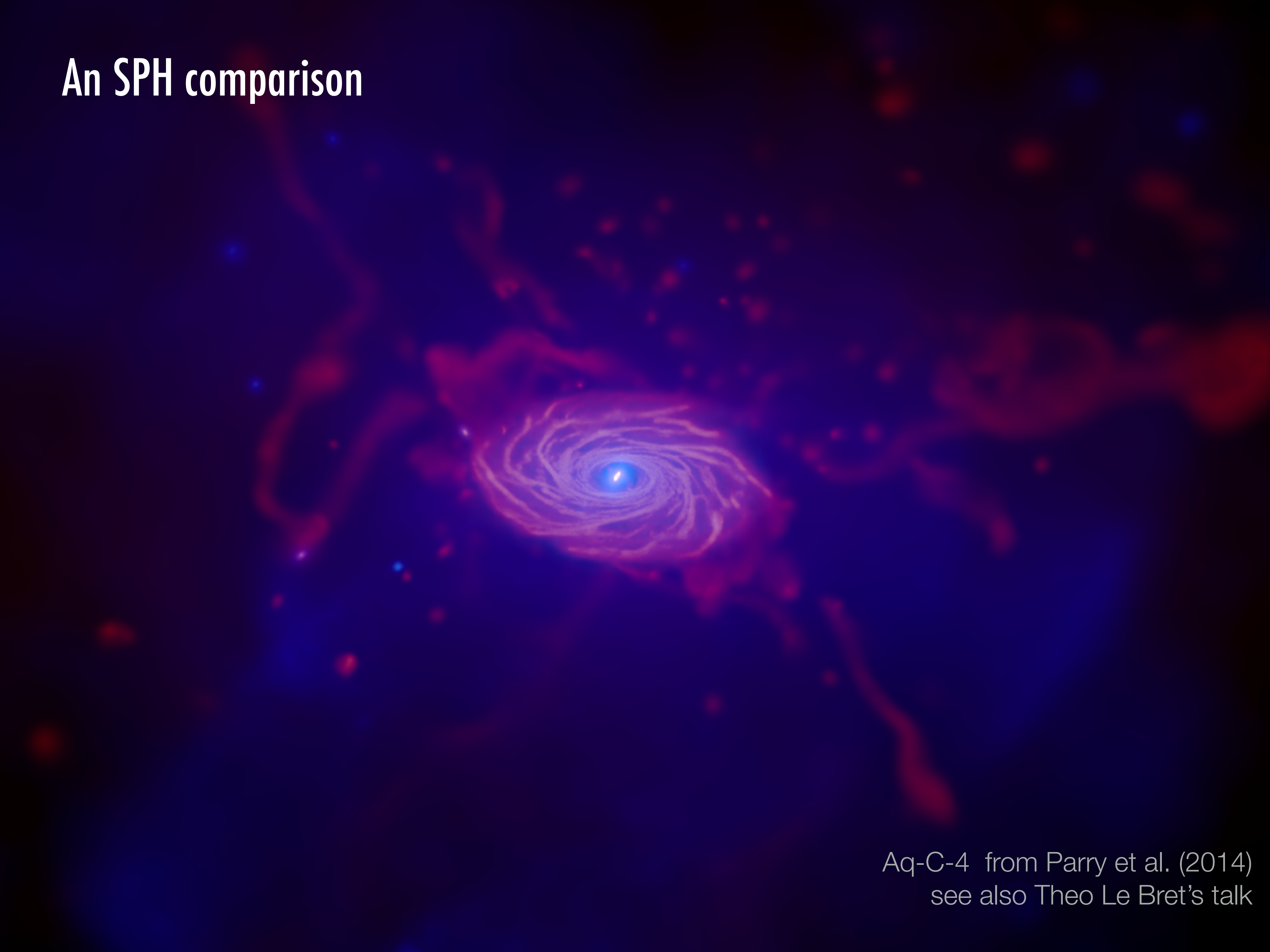
II: Testing assumptions of particle tagging against SPH simulations

Particle tagging FAQs

- Since baryons obviously dominate the potential at the centres of haloes, can tagging ever give the same answer as a self-consistent hydrodynamical simulation?

- Hydro simulations predict some fraction of halo stars form in situ: can particle tagging say anything about those?

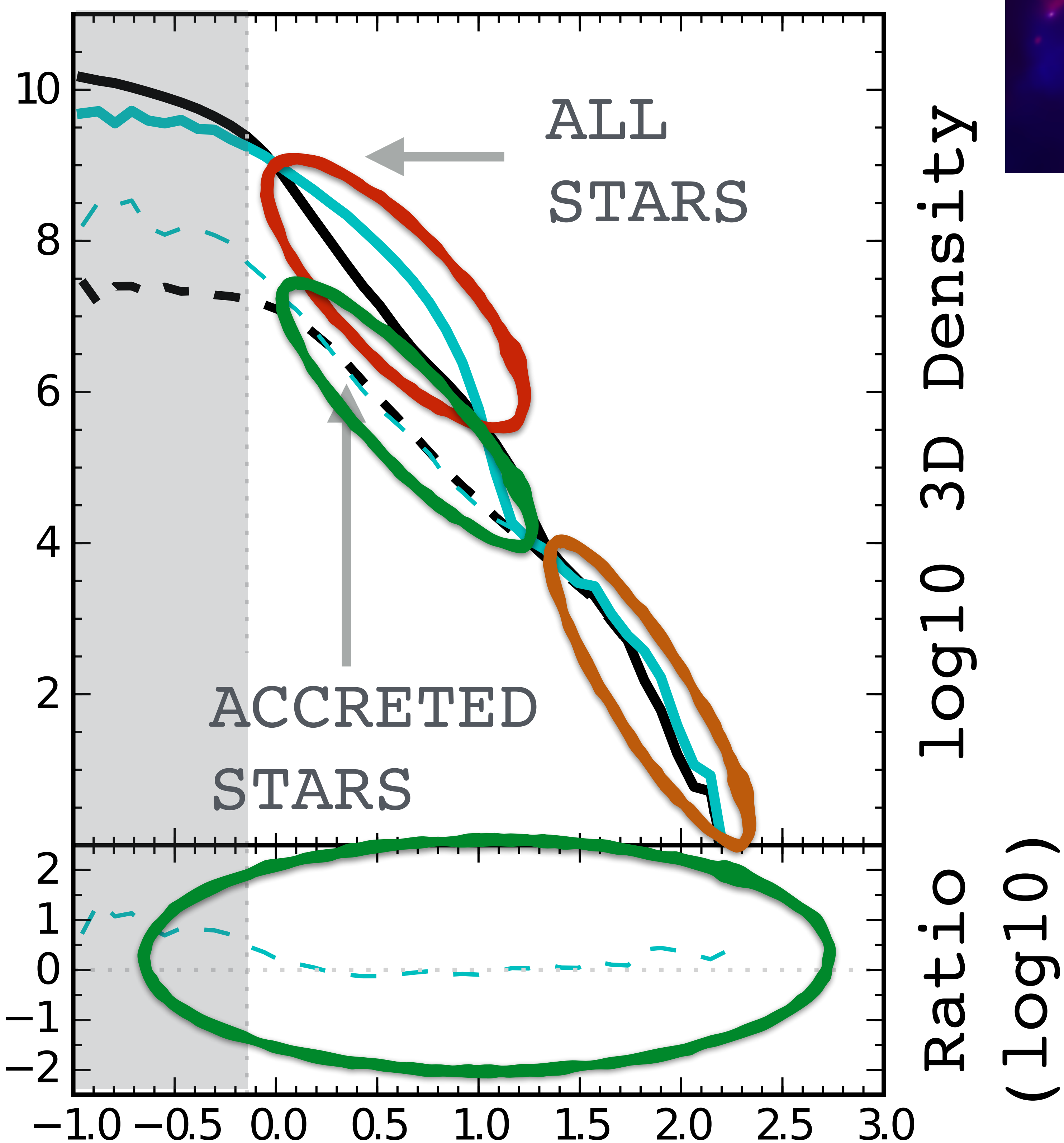
An SPH comparison

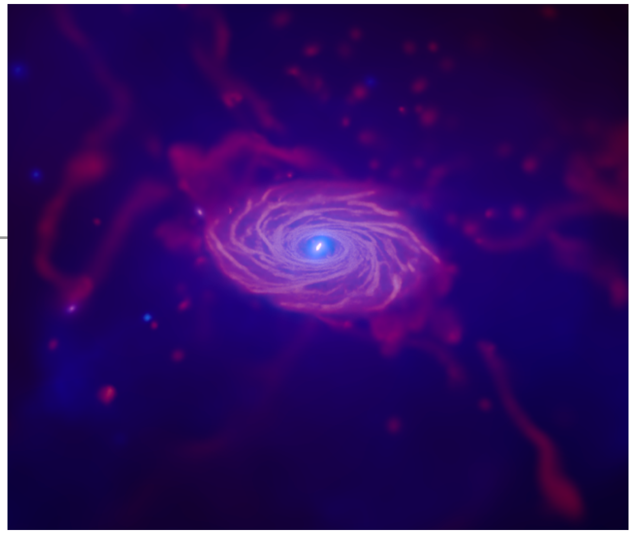


Aq-C-4 from Parry et al. (2014)
see also Theo Le Bret's talk

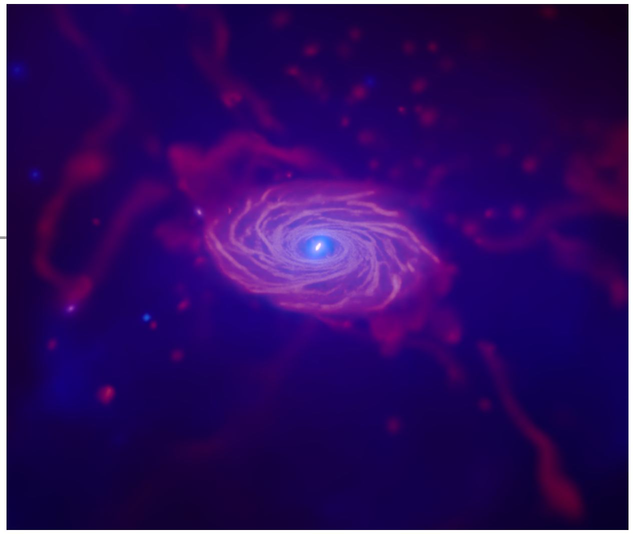
An SPH comparison

SPH Particles vs. DM only Tags (star formation from Galform, tagging 5%)





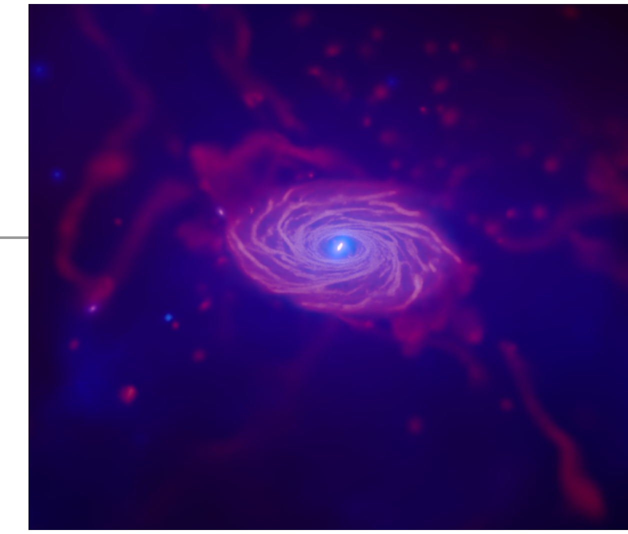
An SPH comparison



Discrepancies due to:

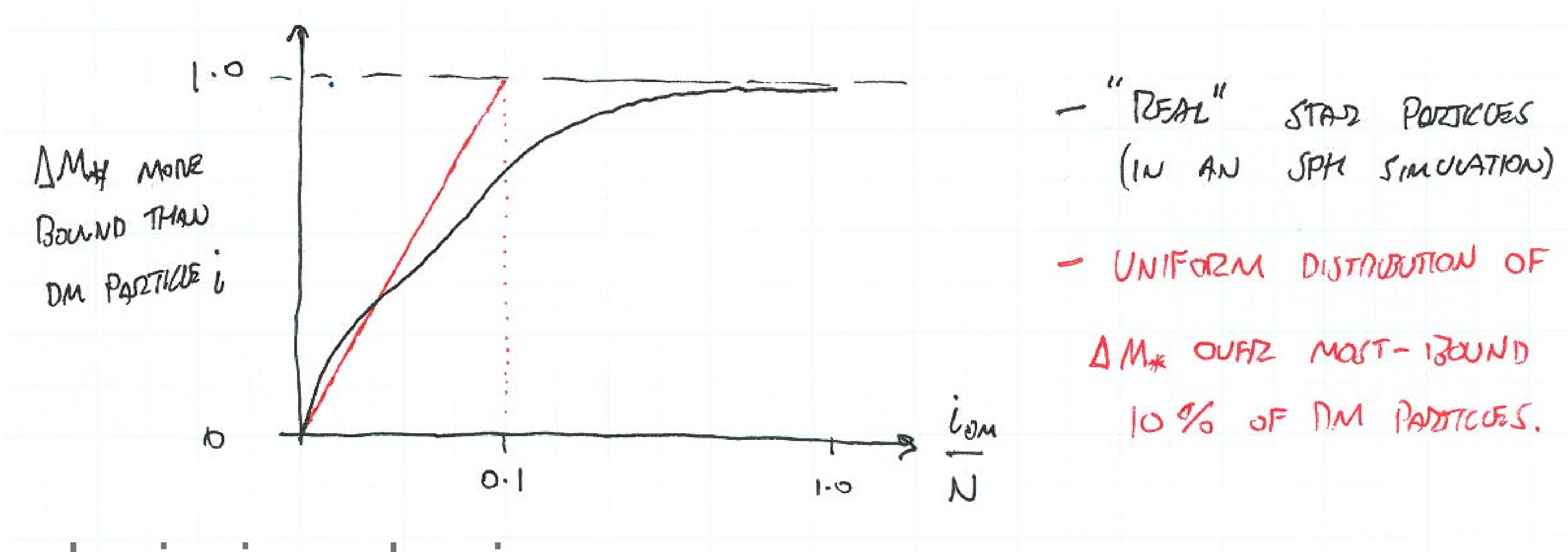
- **Different star formation histories**
    - Strength of feedback in Galform only adjusted to roughly match SPH
- Simply tagging a fixed fraction of DM by energy
- Real missing physics

An SPH comparison



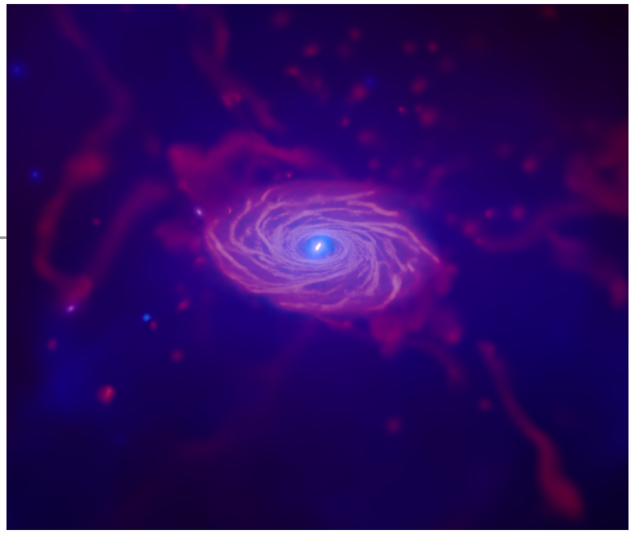
Discrepancies due to:

- Different star formation histories
- **Simply tagging a fixed fraction of DM by energy**

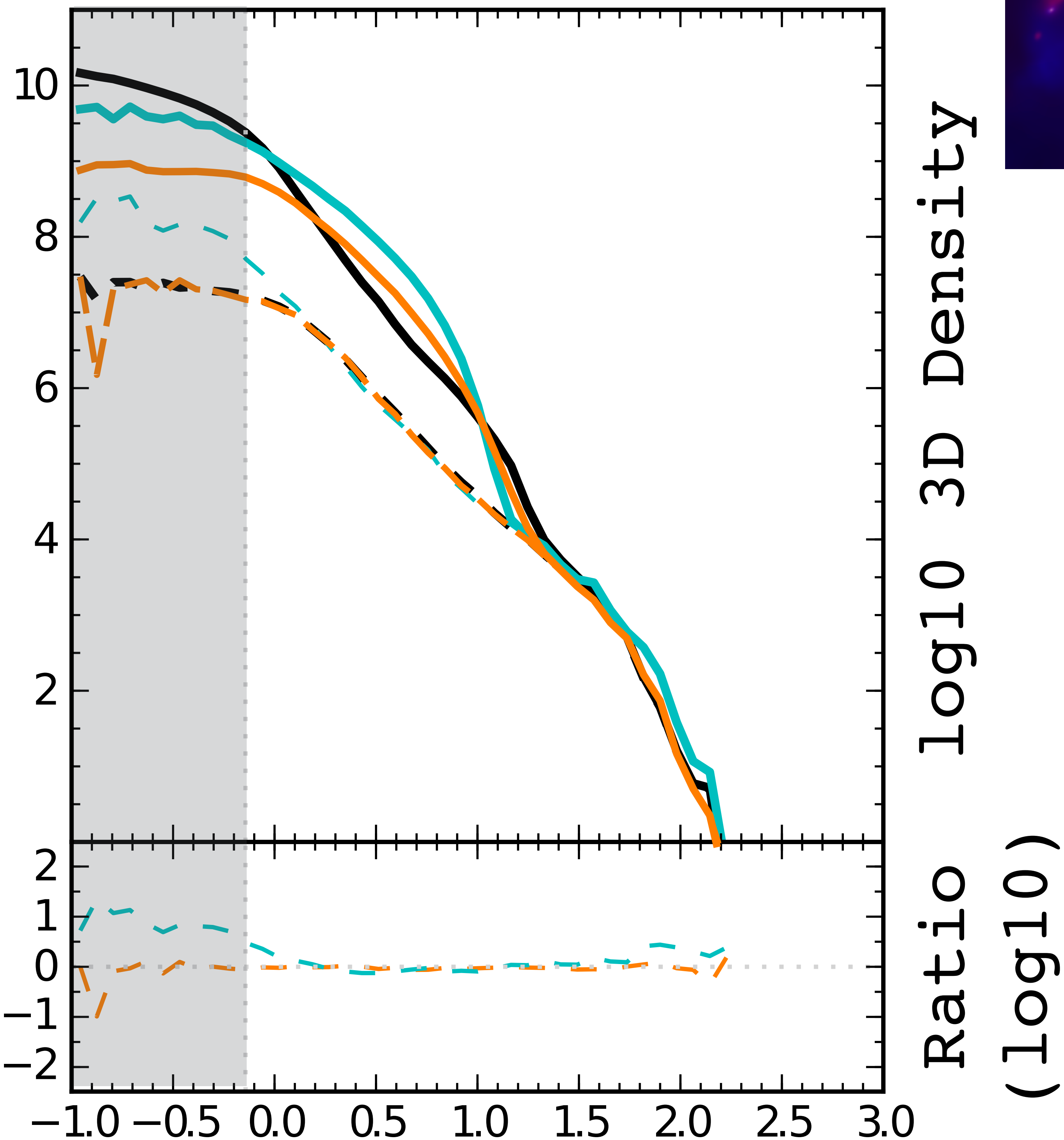


- Real missing physics

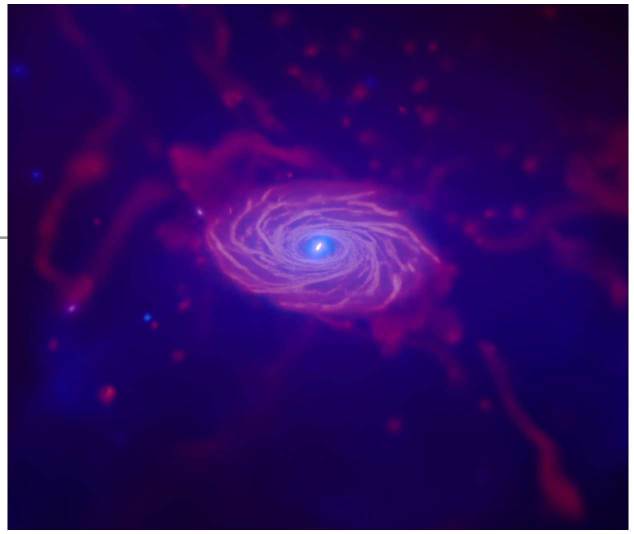
Differences due to tagging a fixed DM fraction



DM only
Tags
vs.
DM particles tagged in SPH sim



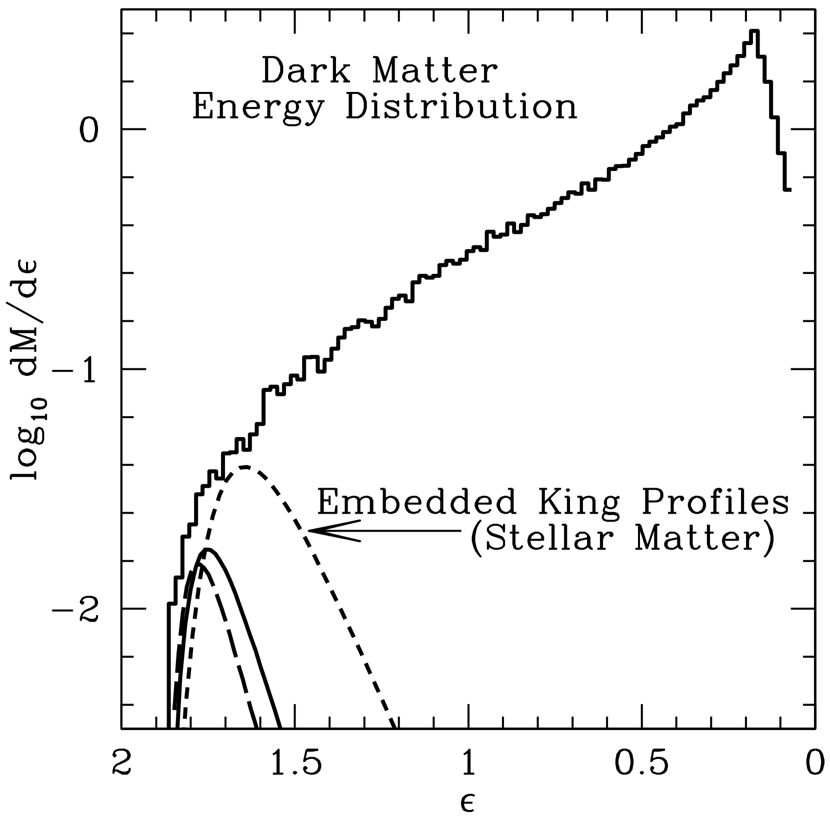
An SPH comparison



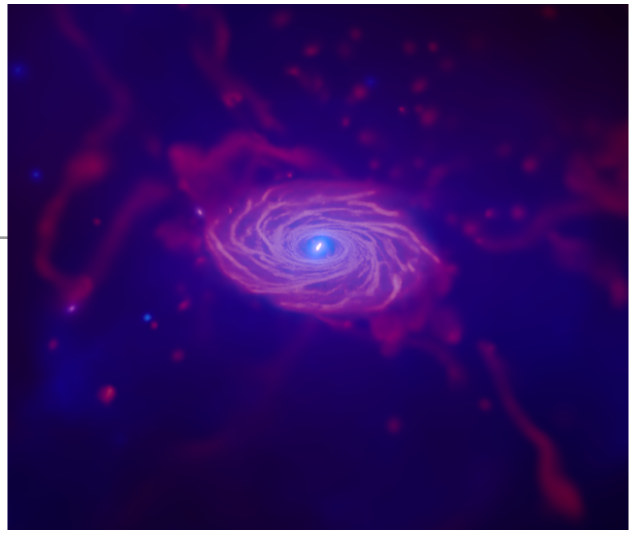
In an SPH simulation, how well can we trace star particles with tagged DM if we use a **more complicated tagging function?**

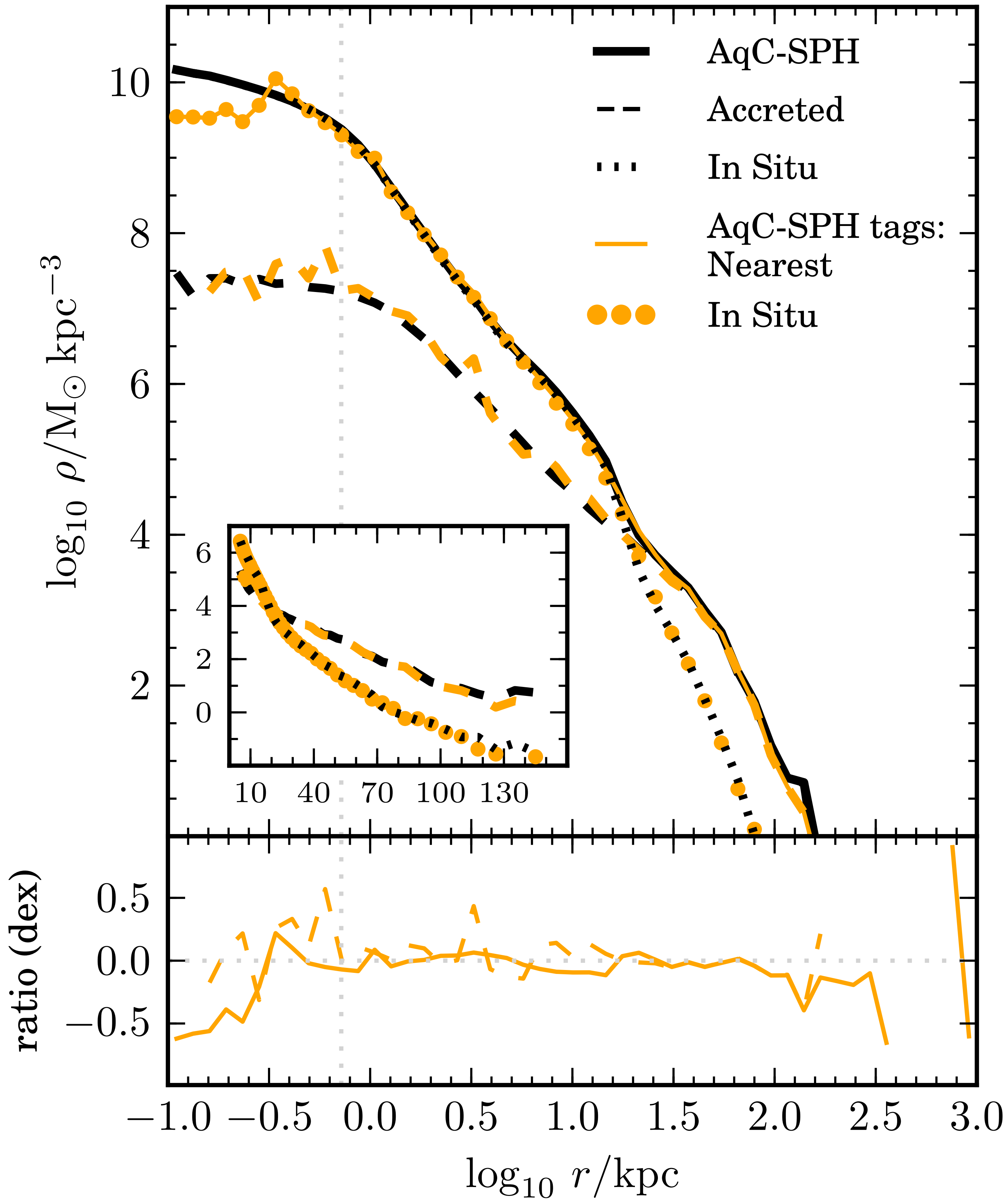
For example, what if we could reproduce the **exact** energy distribution of every stellar population in the SPH simulation?

Can the phase space trajectories of DM particles be entirely faithful proxies for those of stars?



An SPH comparison





An SPH comparison

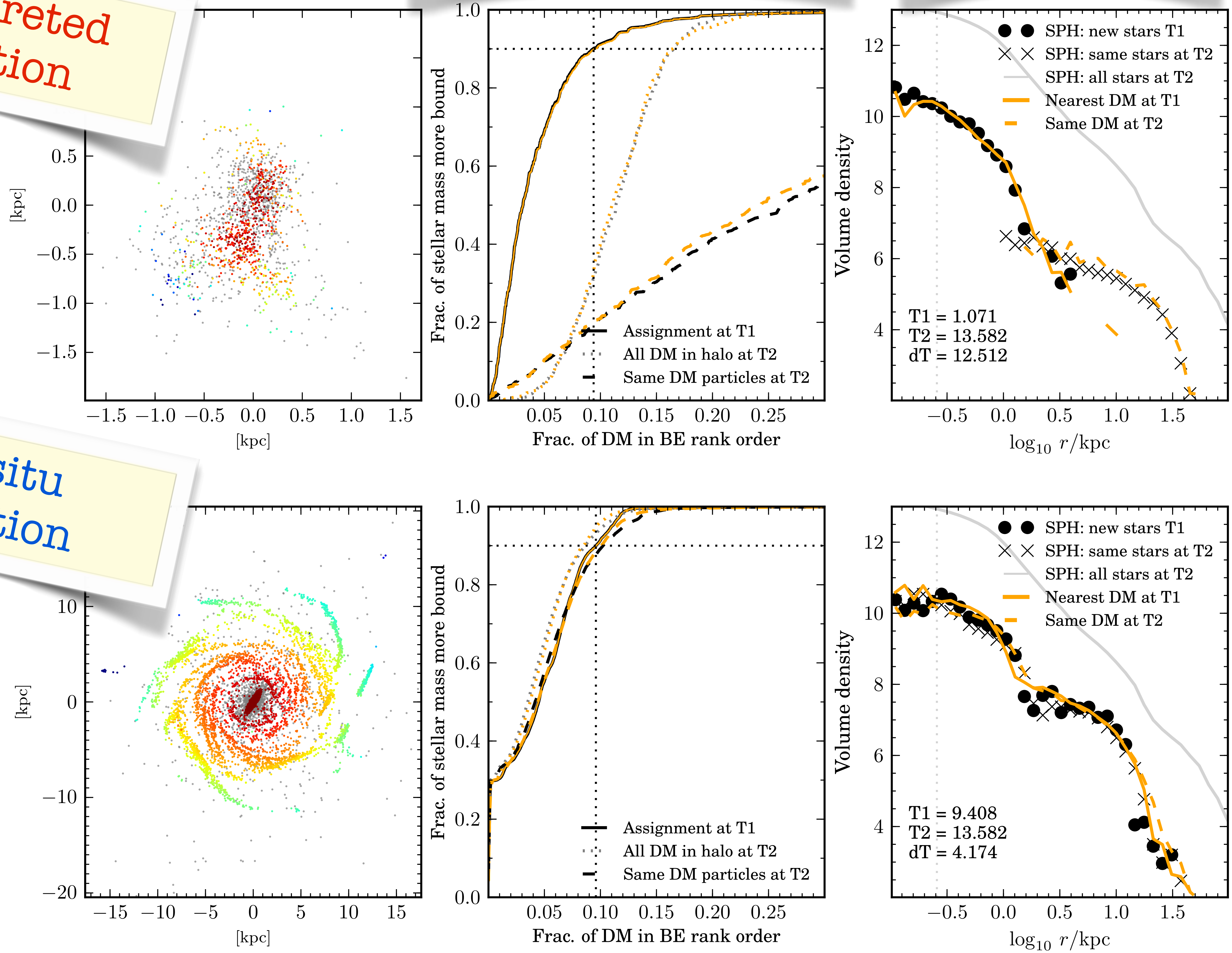
z_form and **z=0**

Energy rank distribution

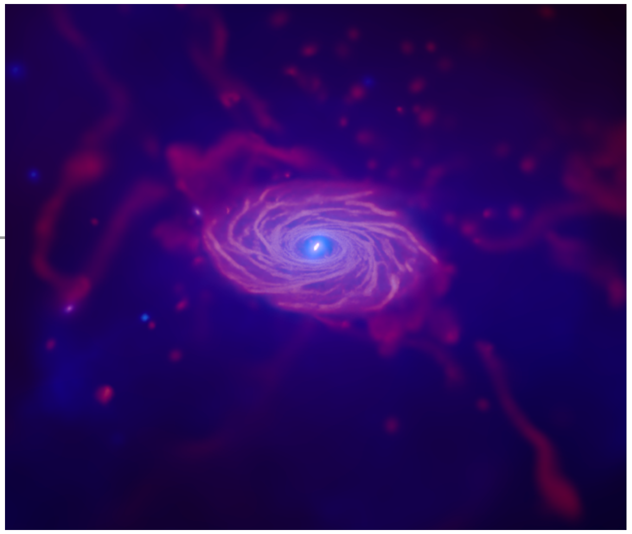
Density profile

An accreted population

An in-situ population



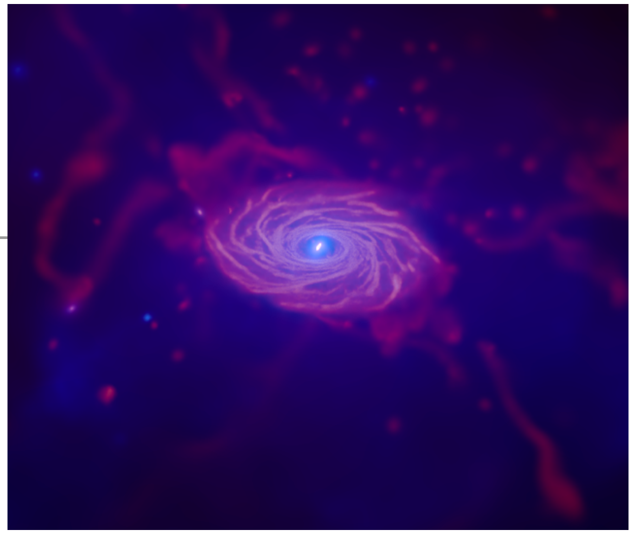
An SPH comparison

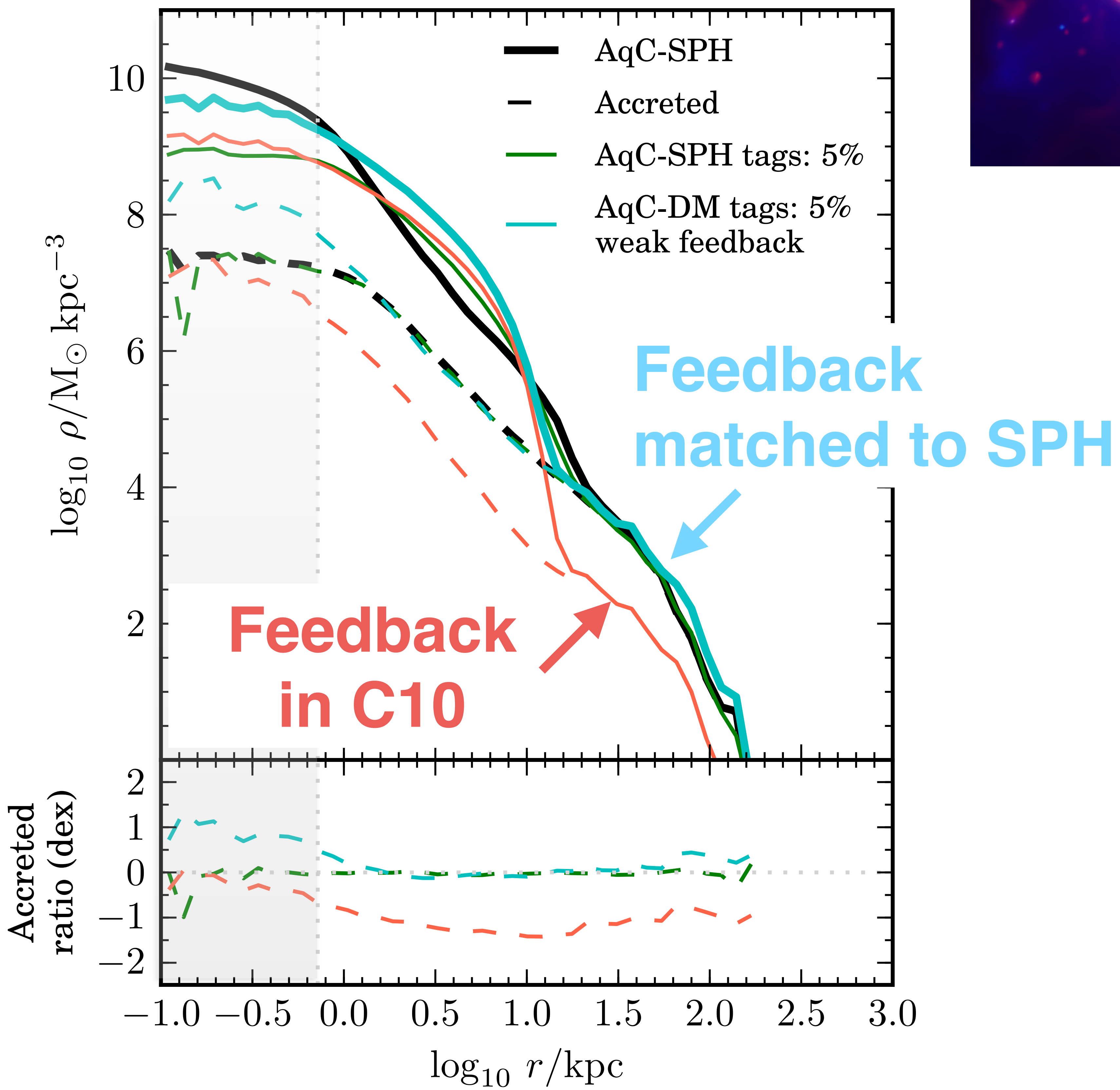


Discrepancies arise from:

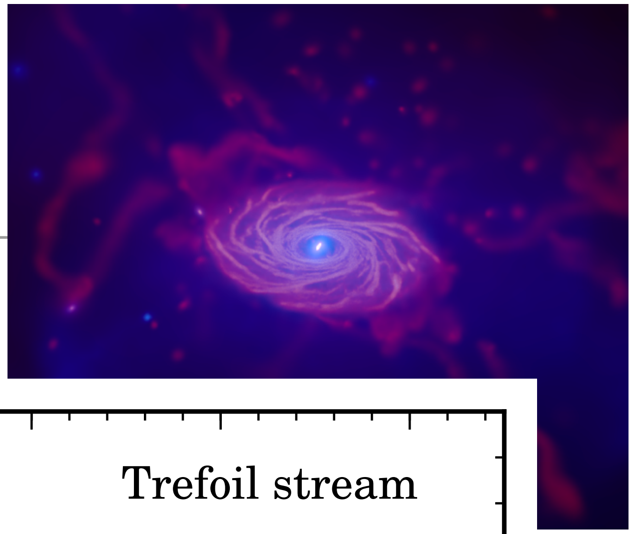
- Different star formation histories
- Simply tagging a fixed fraction of DM by energy
- **Real missing physics**
  - Rearranging baryons rearranges DM (especially by flattening potentials)
  - Gas collapses to a disk — geometry can be wrong even if scale is ok and profile is exponential.

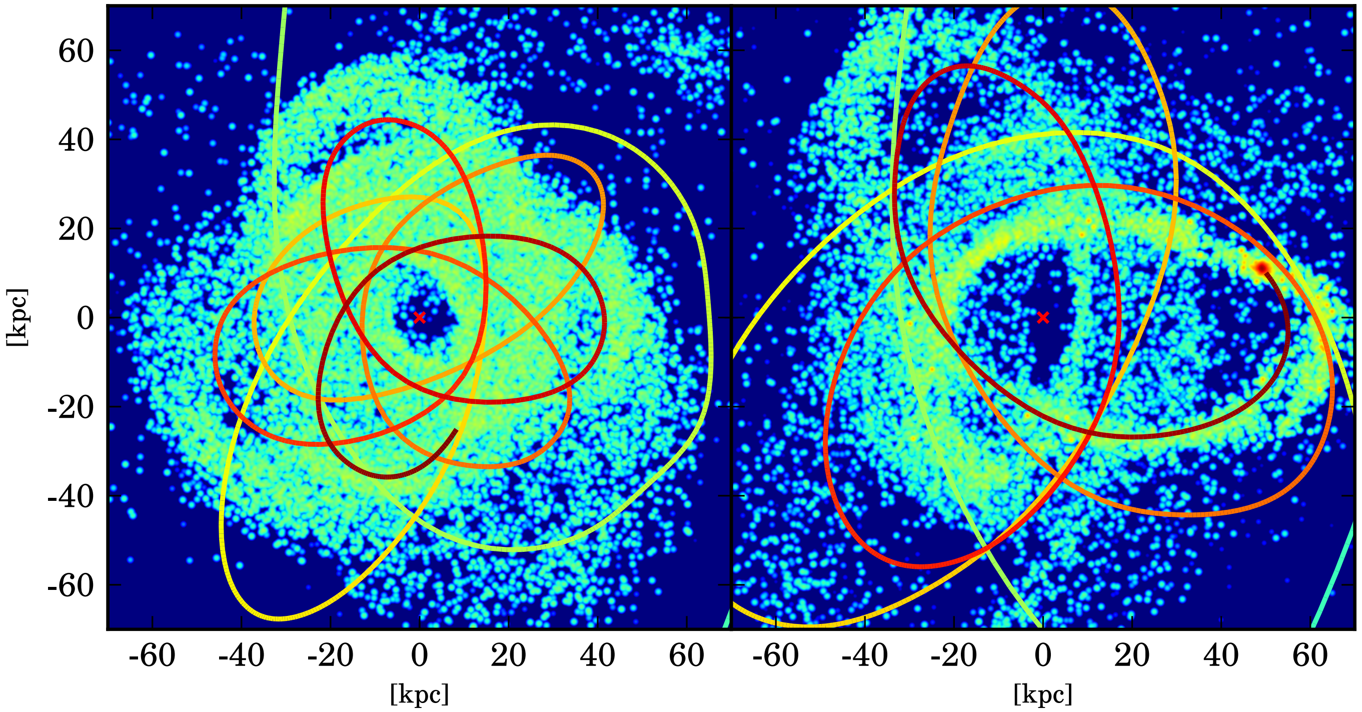
Star formation models can make a big difference

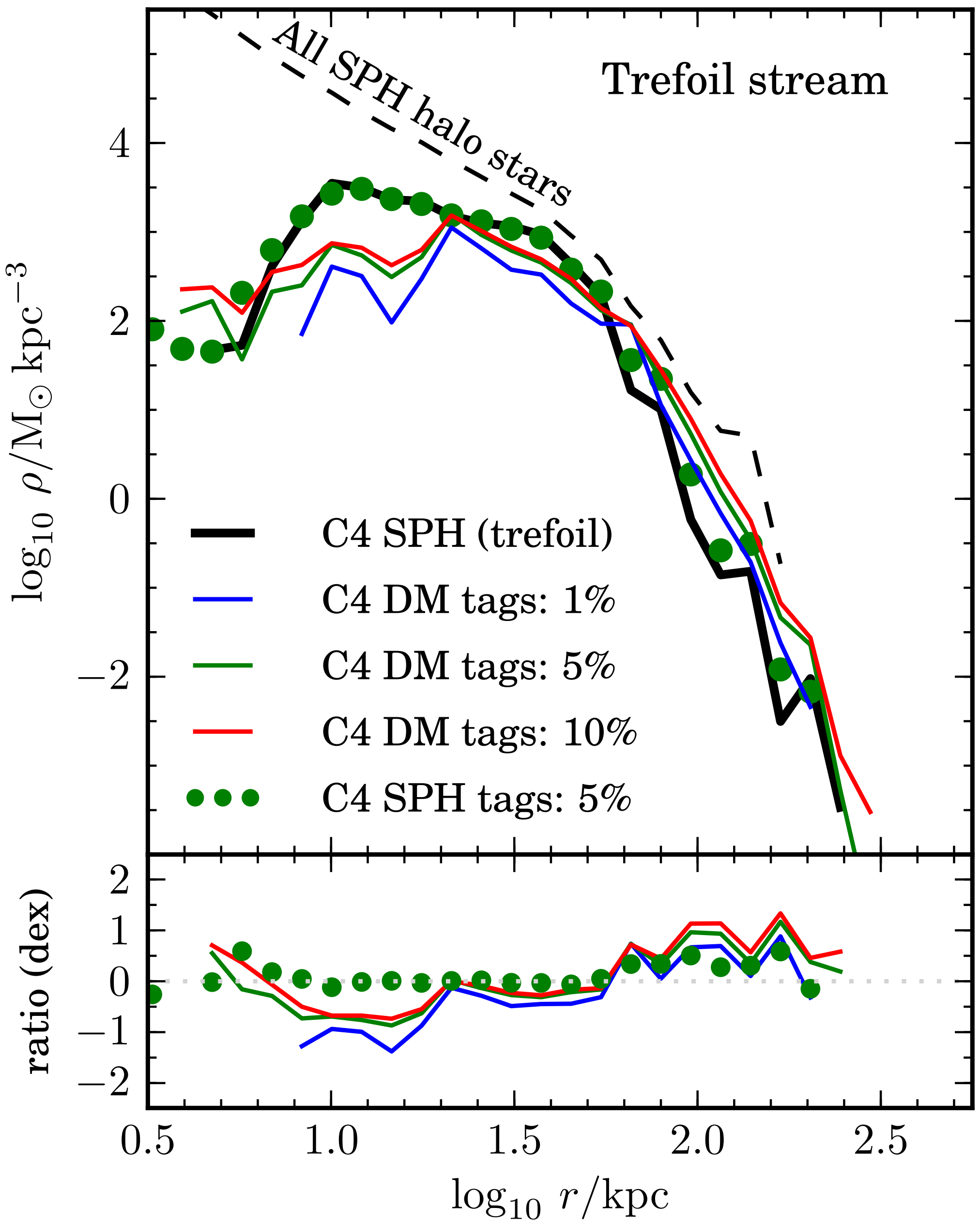




Where does it go wrong?







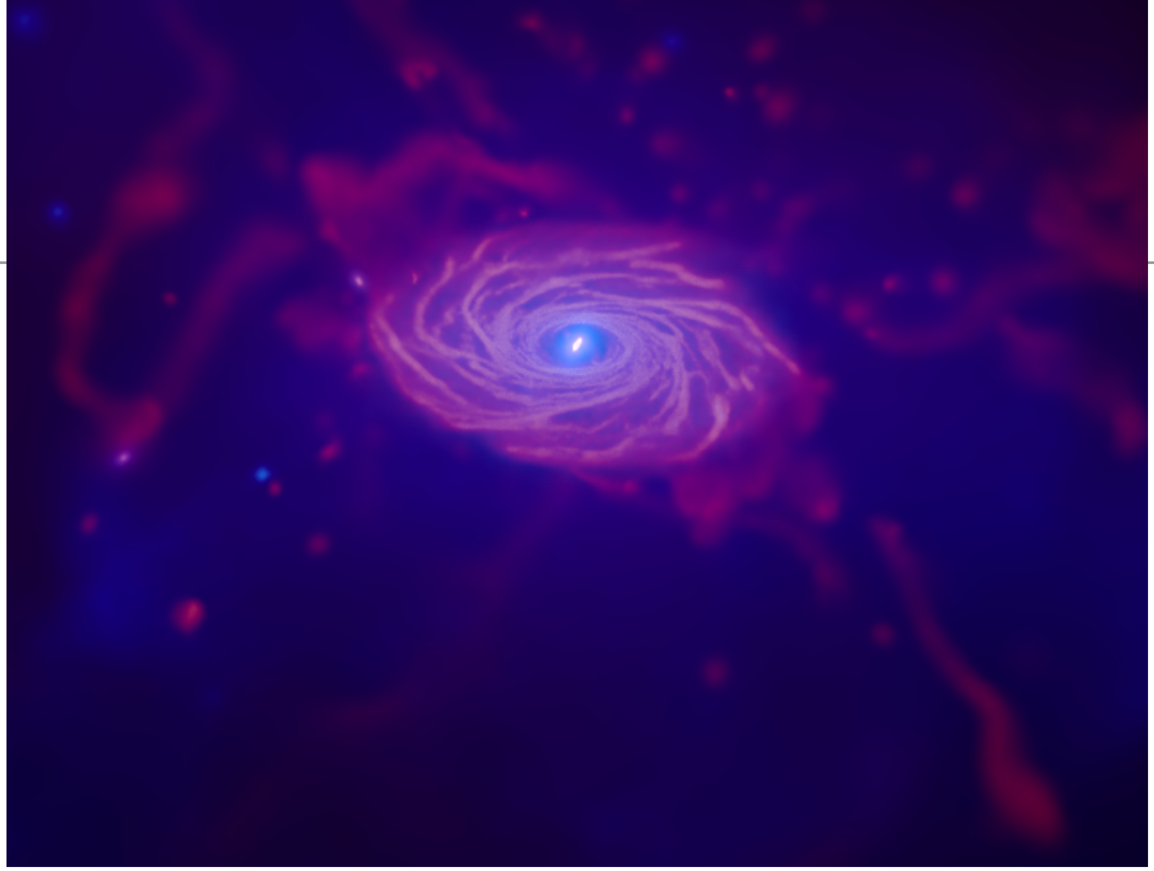
- **'Core-forming' feedback**
- **Interactions with disc**

How to improve particle tagging models?

- **Understand distributions of stellar halo progenitors in `baryon effect' space (varying with halo mass!)**
  - Interactions with disks / central potentials
  - Degree of departure from NFW (through feedback etc.)
- Room for some elaboration over fixed fraction tagging (but risk diminishing returns)
  - Varying the fraction from population to population or imposing physically motived distribution functions
  - Resolving multiple components in individual star-forming events

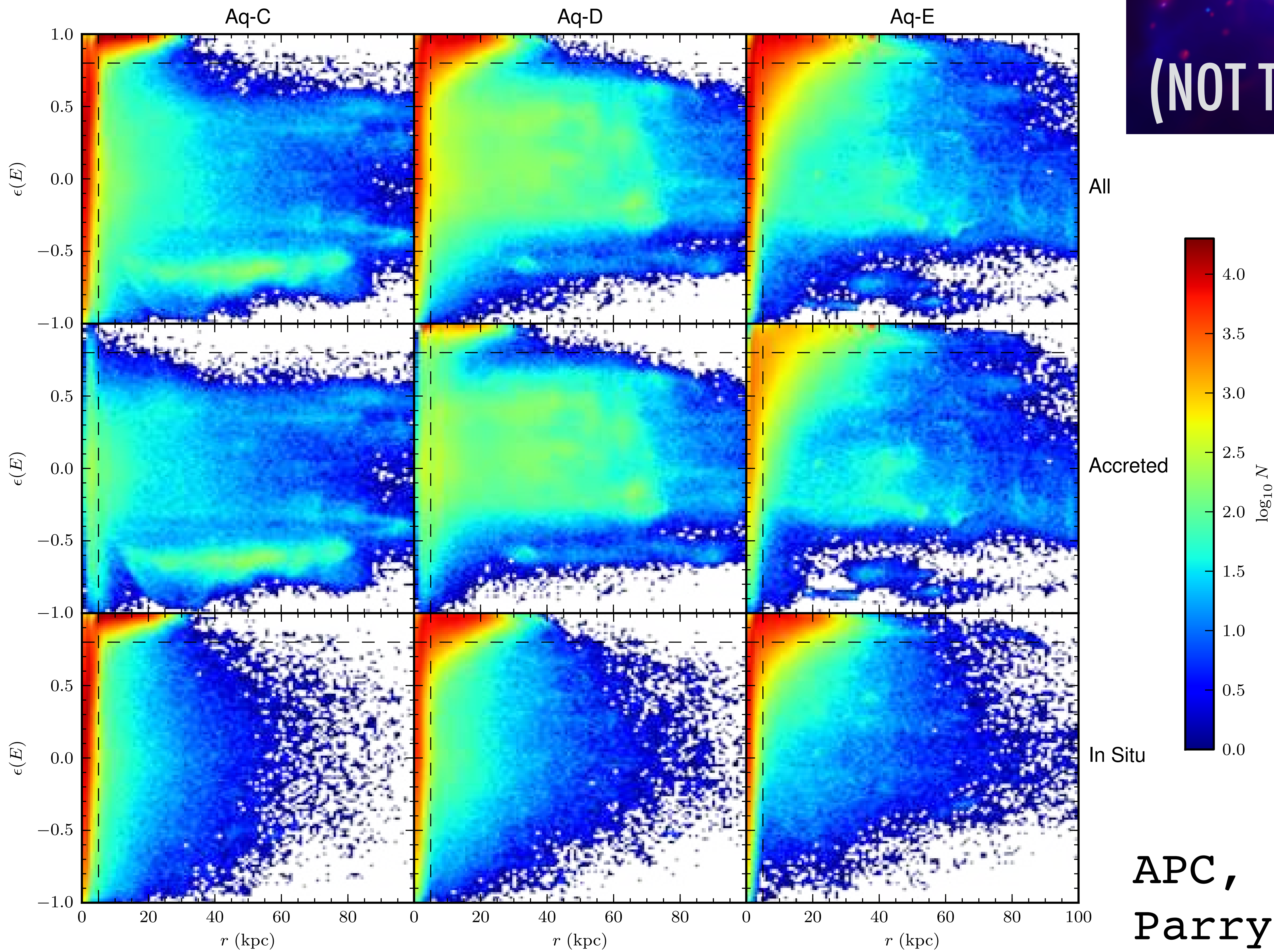
III: What about the in situ stars?

This part is not about dark matter particle tagging!



In Situ Stars ≫ In Situ Halo

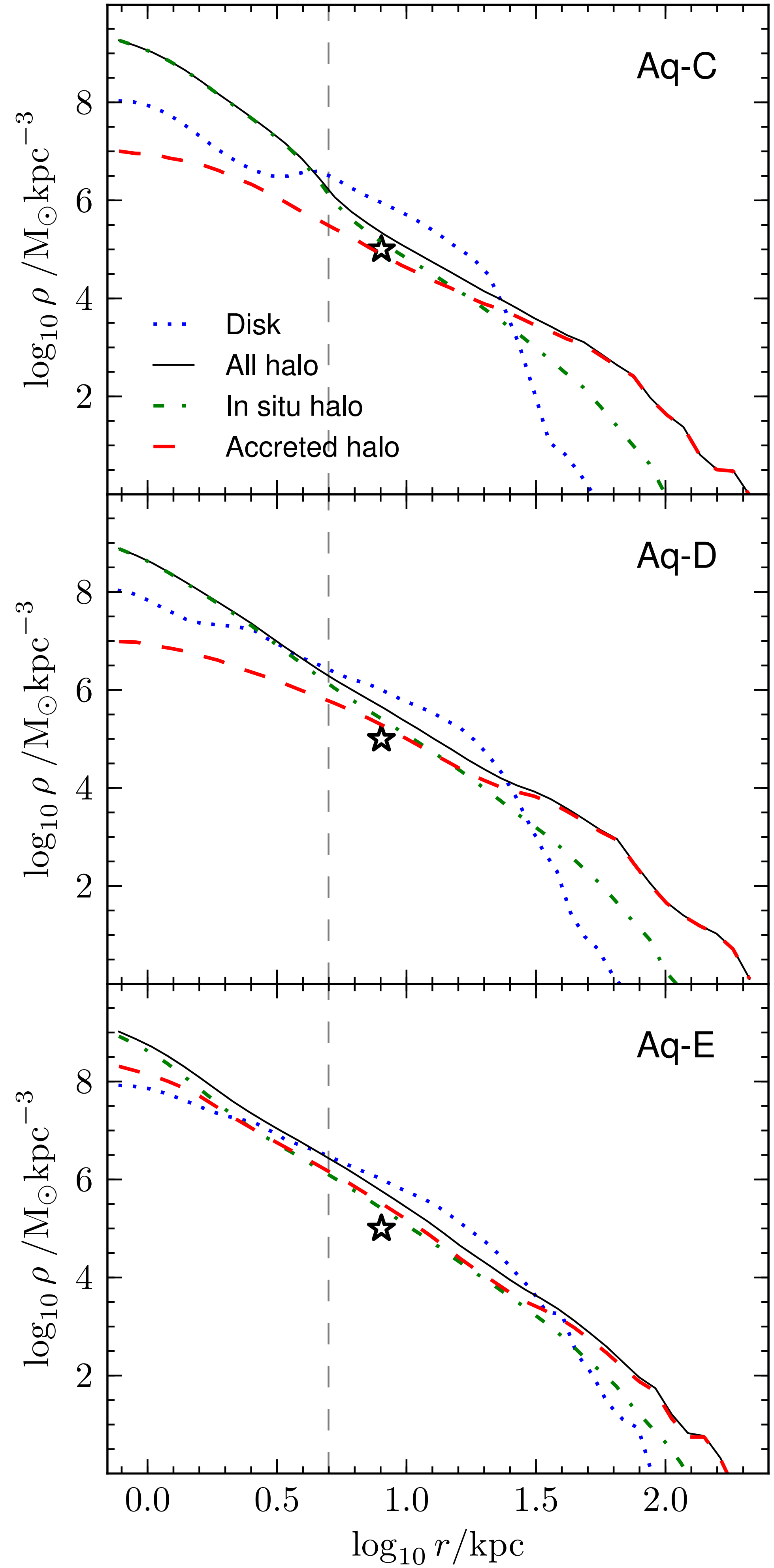
The In Situ Halo



APC, Owen Parry et al. 2015

The In Situ Halo

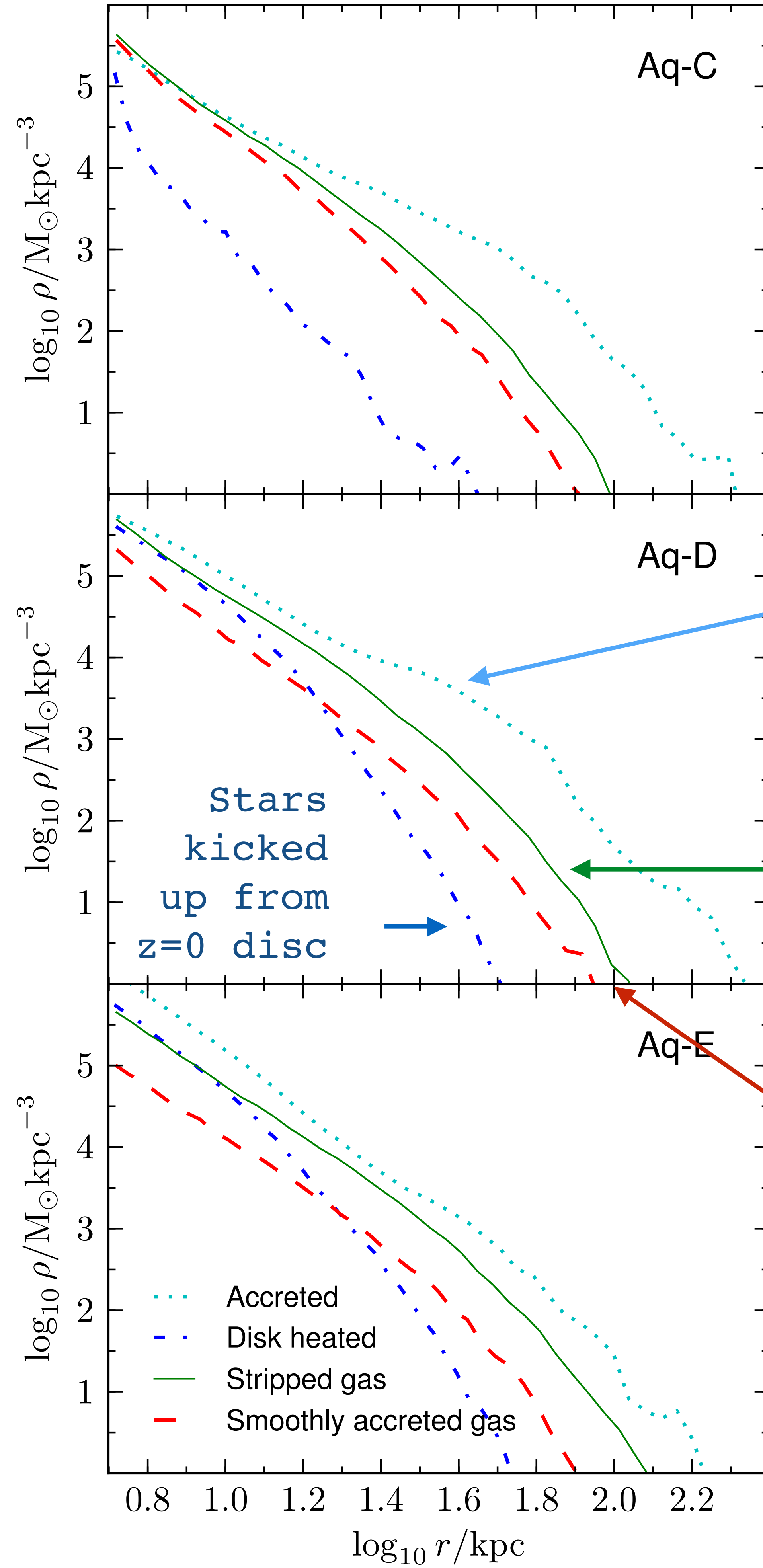
- Three MW examples with the same physics show **different** accreted/in situ fractions (at different radii)!



APC, Owen Parry et al. 2015

The In Situ Halo

- In these particular simulations, most of **the in situ halo is accreted** — i.e. it forms from gas stripped from satellites!
- In situ halo predictions from **any** hydro simulation should be treated with caution!



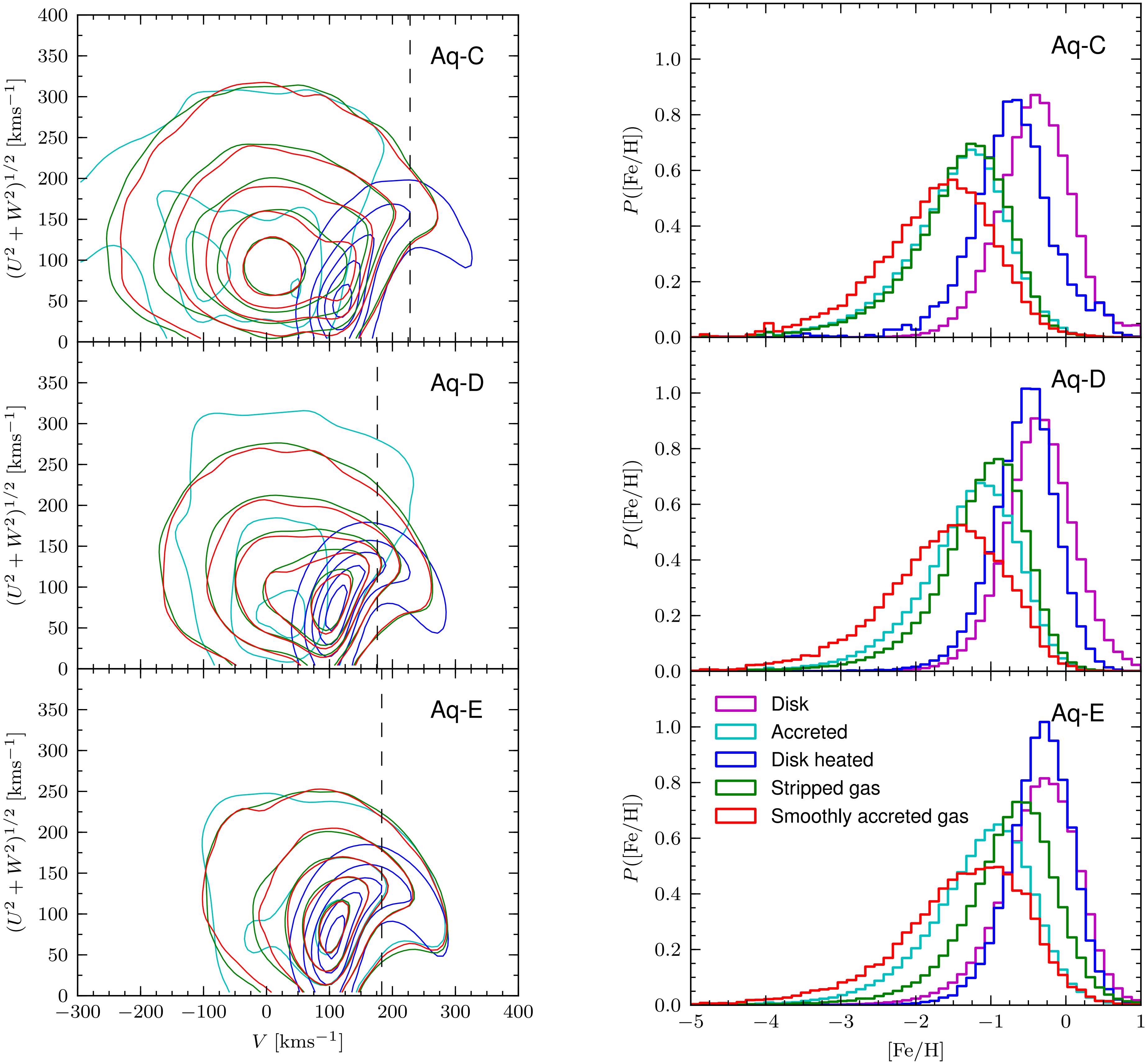
Accreted Stars

Stars from stripped gas

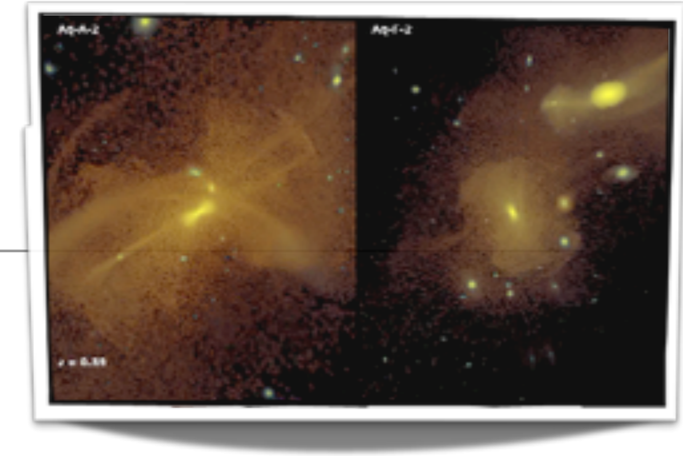
(Stars from highly uncertain hydrodynamical effects…)

APC, Owen Parry et al. 2015

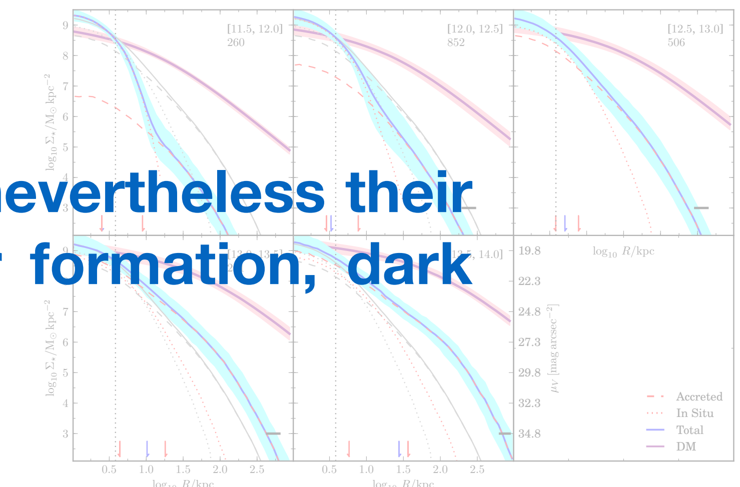
The In Situ Halo



Collisionless tagging models of stellar haloes



- A **fast**, efficient way to make detailed predictions **for the statistical properties of stellar haloes**, in a way that directly addresses the link between CDM structure formation and **photometric and dynamical observations.**



- Stellar haloes are collections of clouds, lumps and streams — **nevertheless their average properties reflect tight relationships between star formation, dark matter halo growth and structure formation.**
    - Relating these predictions to observable tests of CDM requires understanding of model dependencies and statistics: many simulations, making good use of known observational **constraints** (e.g. luminosity functions)

- Nicely **complementary** to SPH simulations, not an alternative.

- With many caveats and extreme caution, even in situ stars in massive galaxies are within reach of particle tagging.

Extra slides

Extra slides

Some questions

- What is a stellar halo?
- Halo to halo variance — what can we learn from averages? What causes scatter?
- What can we infer about cosmology/ galaxy formation physics from stellar haloes?
- Can dynamics and chemistry of halo stars / ICL constrain the DM profile and assembly history of the Milky Way / galaxy clusters?

"Forward" modelling

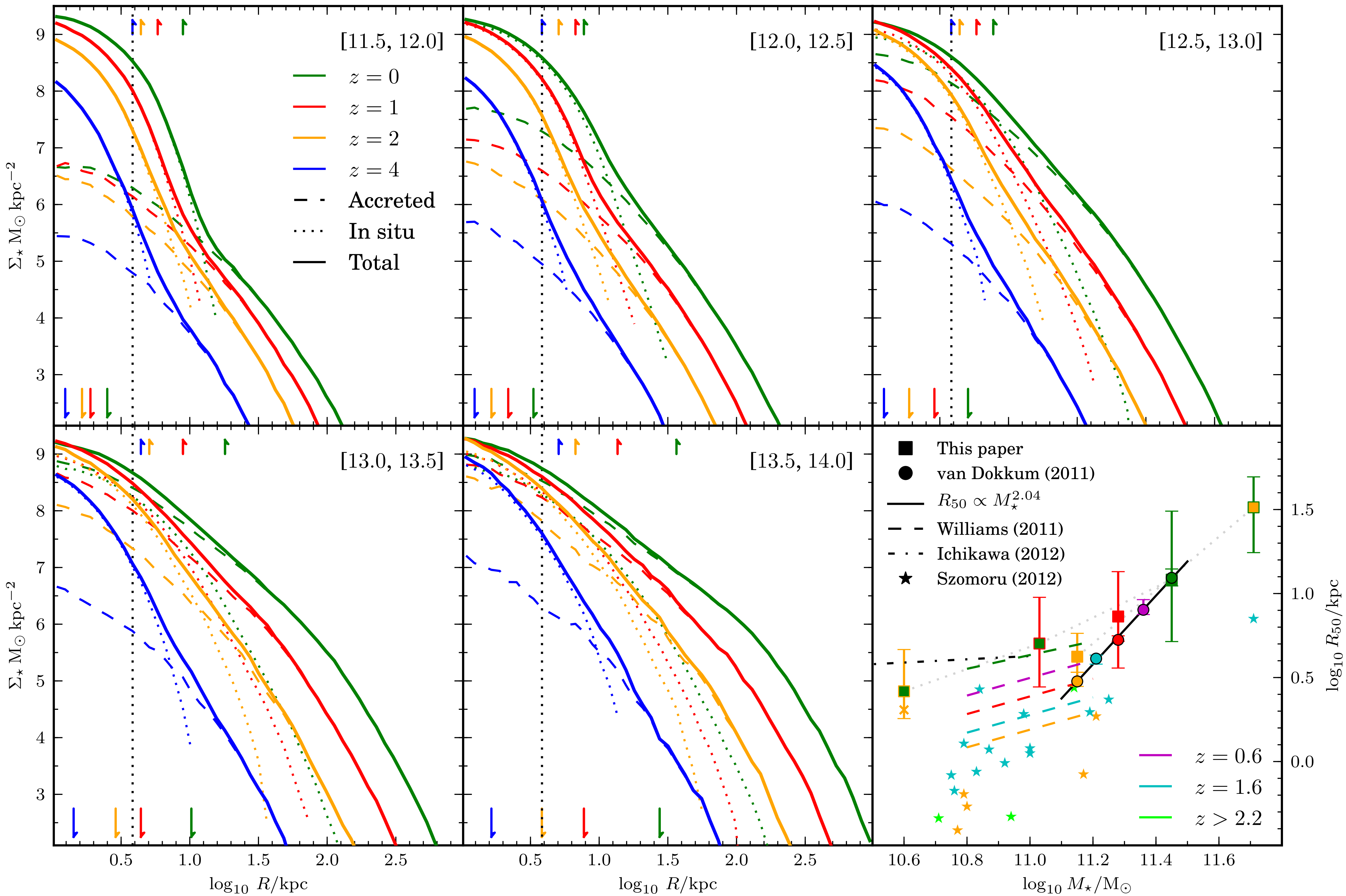
Cosmological context

Large samples

Observational constraints

High enough resolution

Evolution



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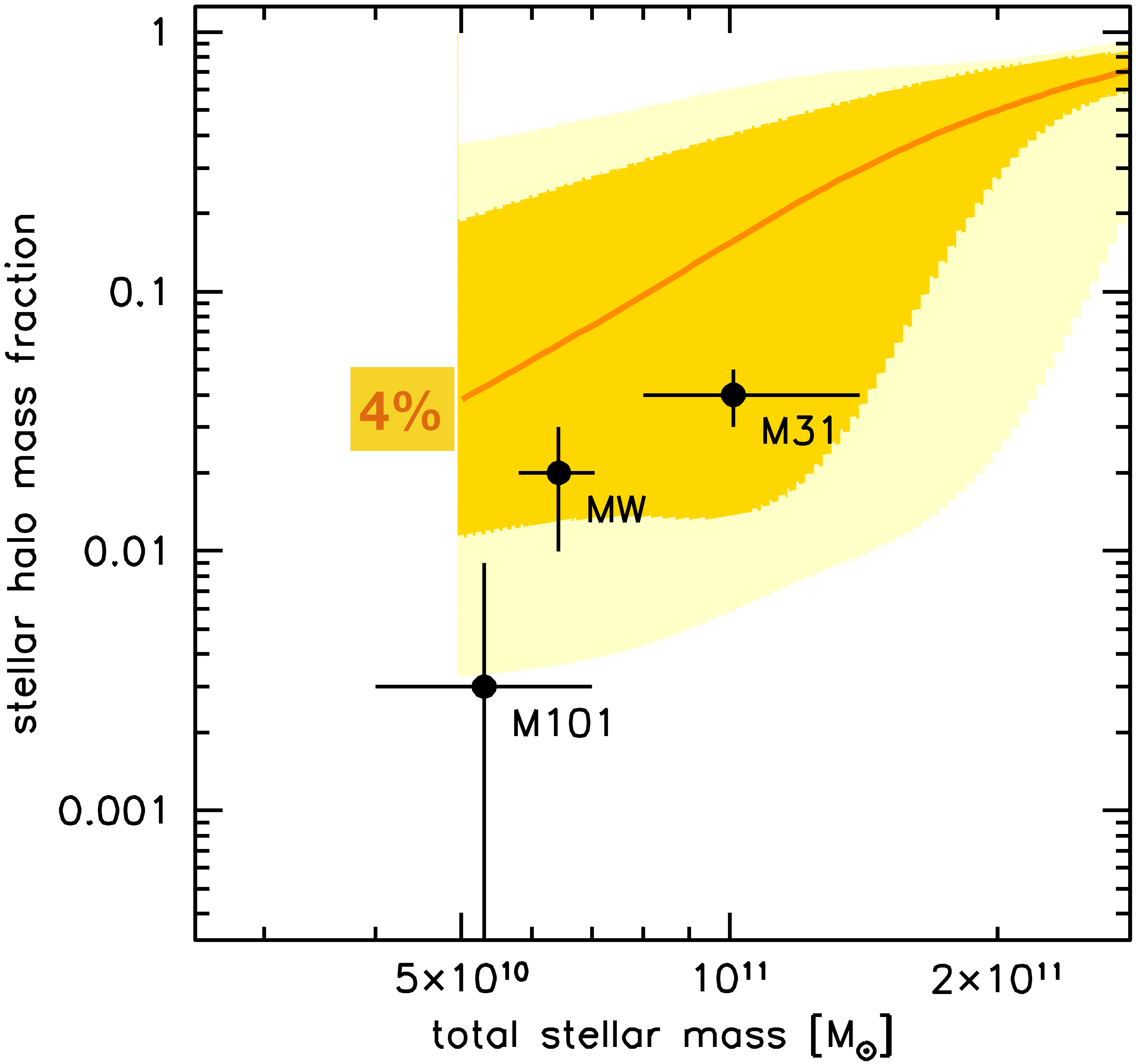
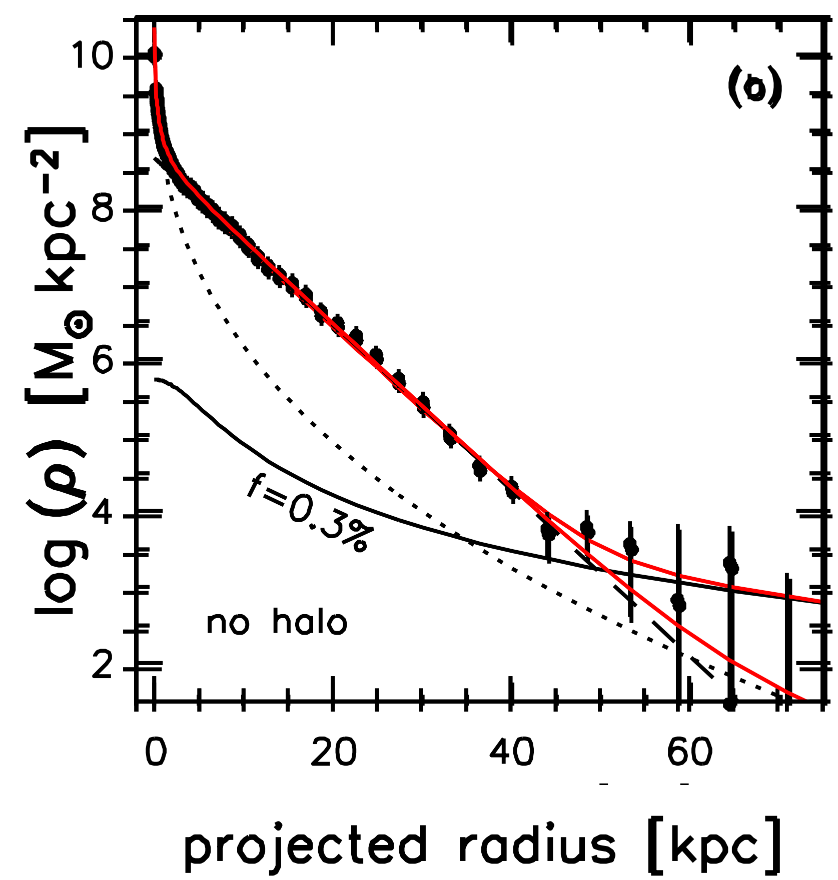
[13.5, 14.0]
$z = 0$
$z = 1$
$z = 2$
$z = 4$
Accreted
In situ
Total
$\Sigma_\star$ M$_\odot$ kpc^{-2}
$\log_{10} R$/kpc
This paper
van Dokkum (2011)
$R_{50} \propto M_\star^{2.04}$
Williams (2011)
Ichikawa (2012)
Szomoru (2012)
$z = 0.6$
$z = 1.6$
$z > 2.2$
$\log_{10} M_\star/$M$_\odot$
$\log_{10} R_{50}$/kpc

Van Dokkum, Abraham & Merritt 2014



ALL ACCRETED STARS ?

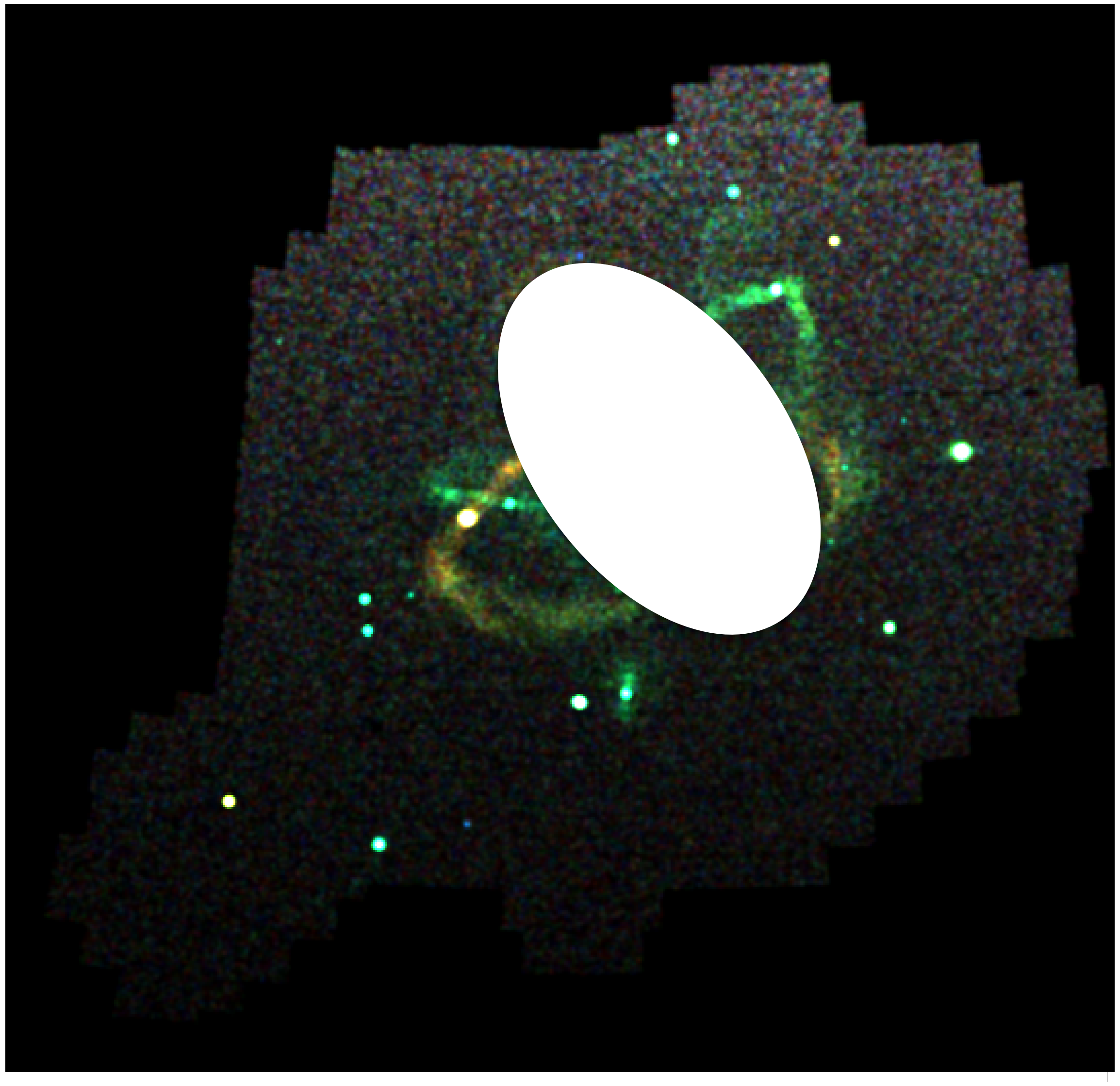


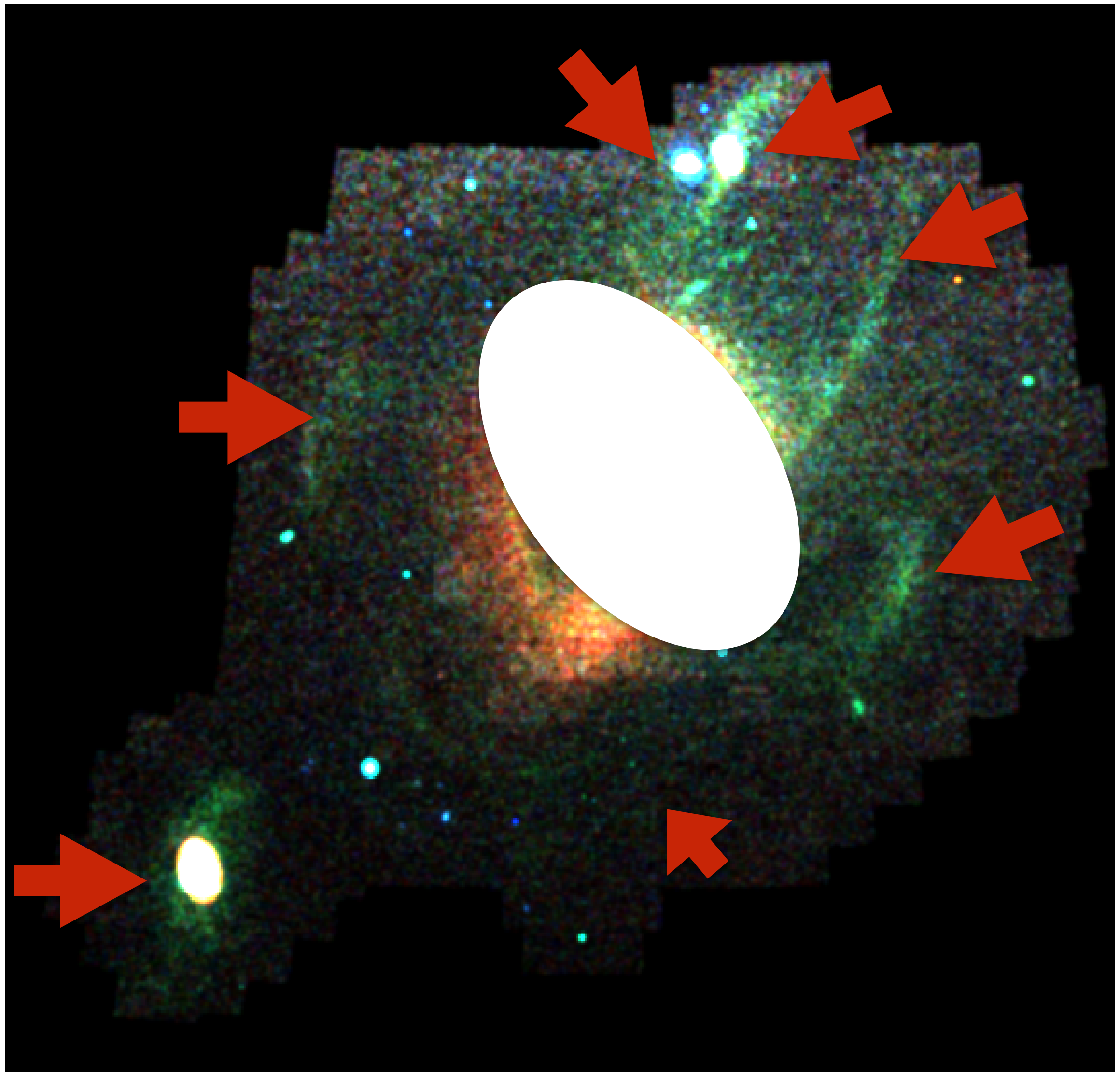
$$\rho(R) = \rho_{0,h}\left[\frac{1+(30/a_h)^2}{1+(R/a_h)^2}\right]^{\alpha}.$$

IIb: What about M31?

2010 Aquarius simulations don't look like PANDAS

See Nicolas Martin's talk

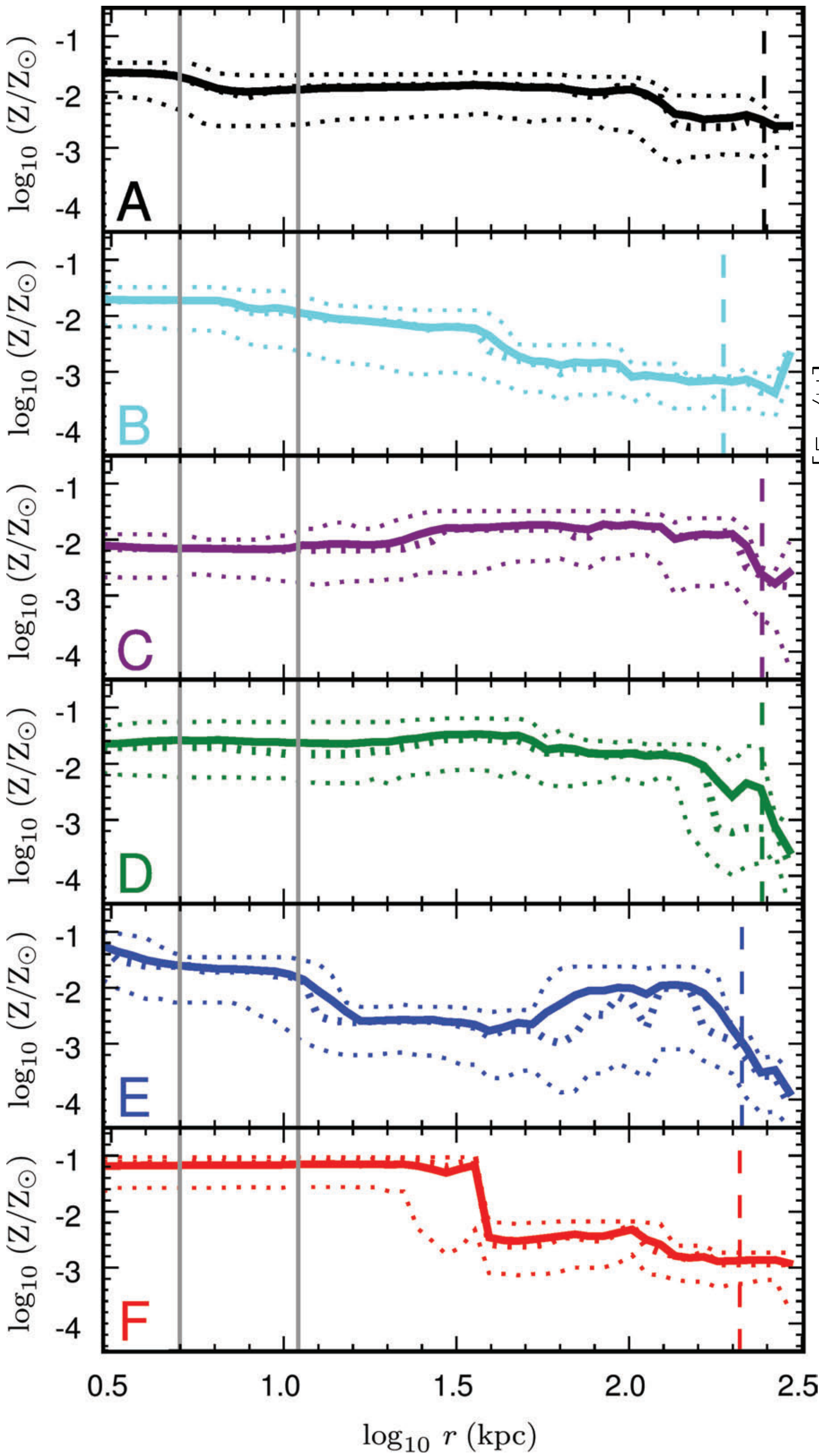


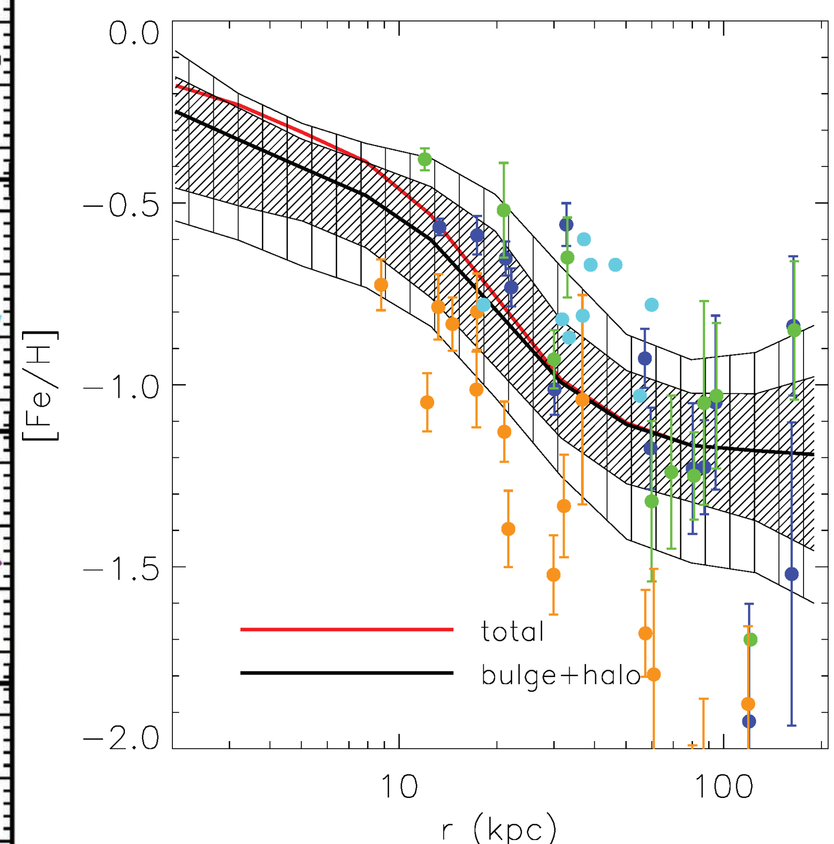


2010 Aquarius simulations don't have strong metallicity gradients

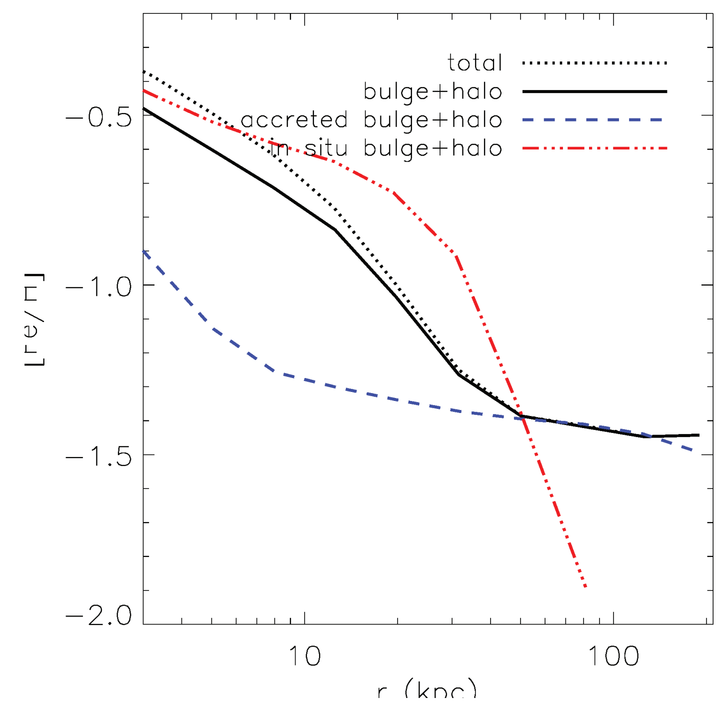
Talks by Alis Deason, Andreea Font, Antonela Monachesi

APC+ 2010

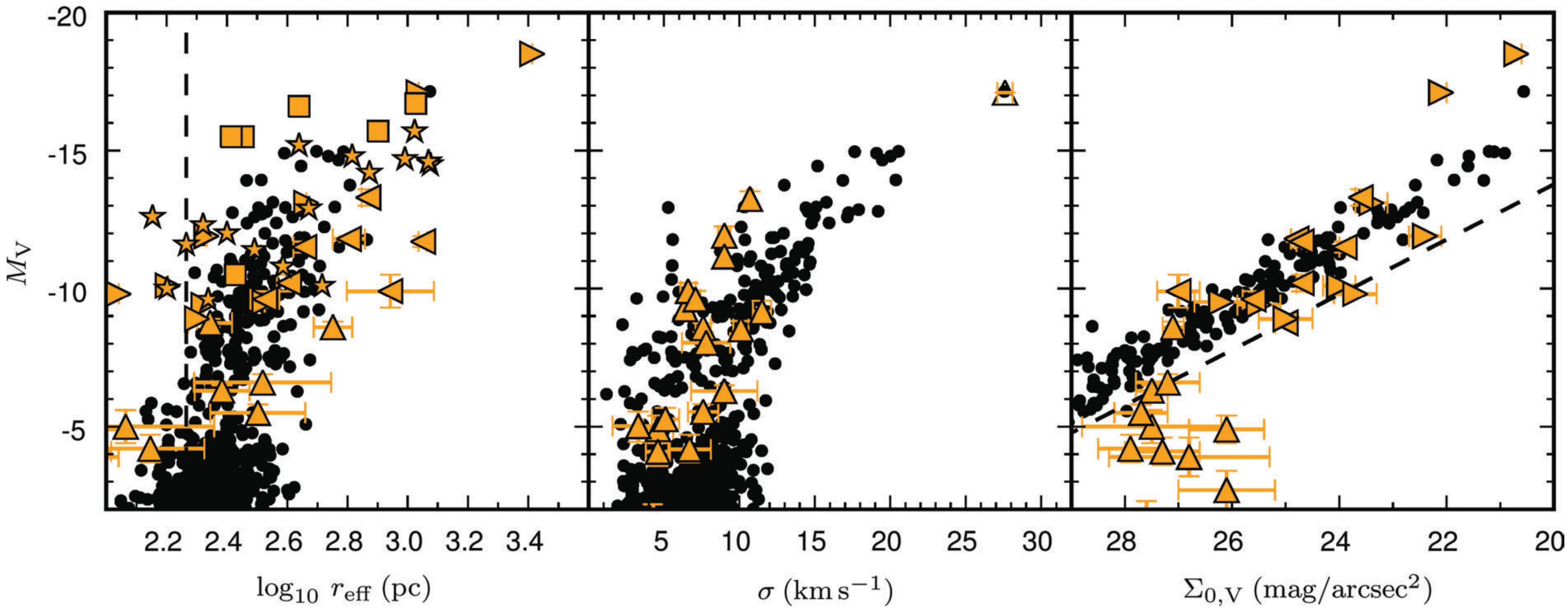


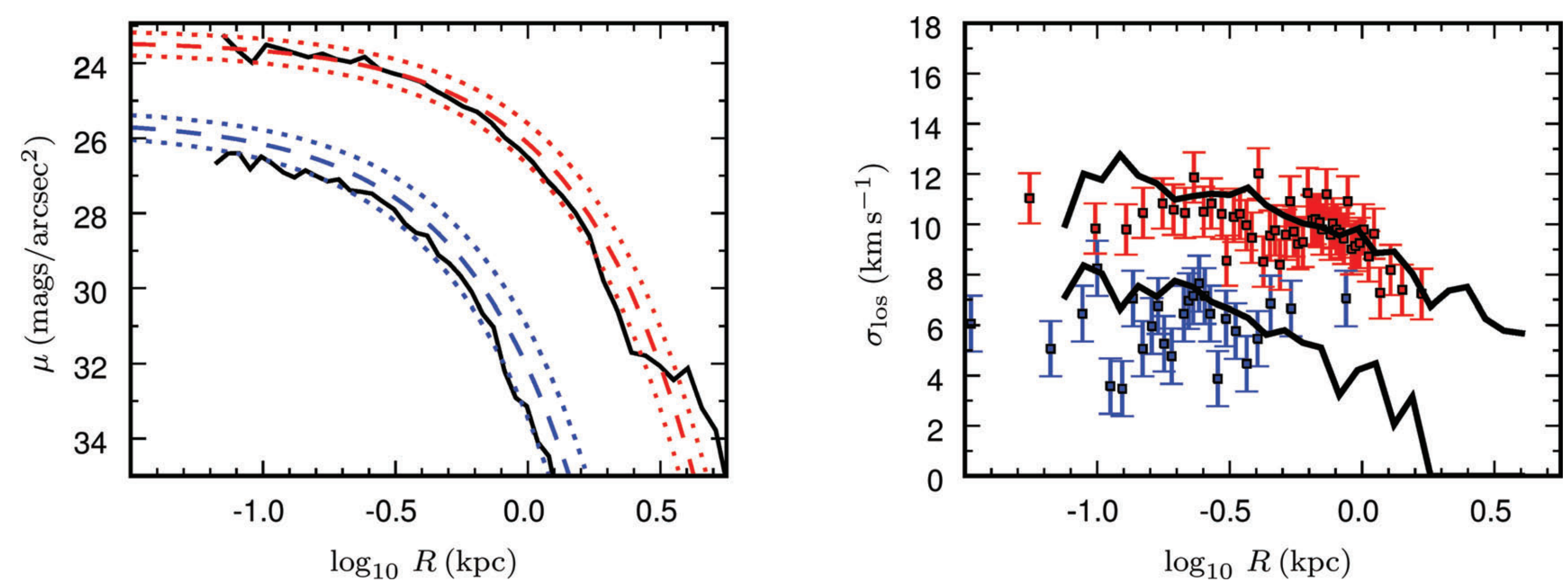


MW haloes in GIMIC (Font et al. 2011)

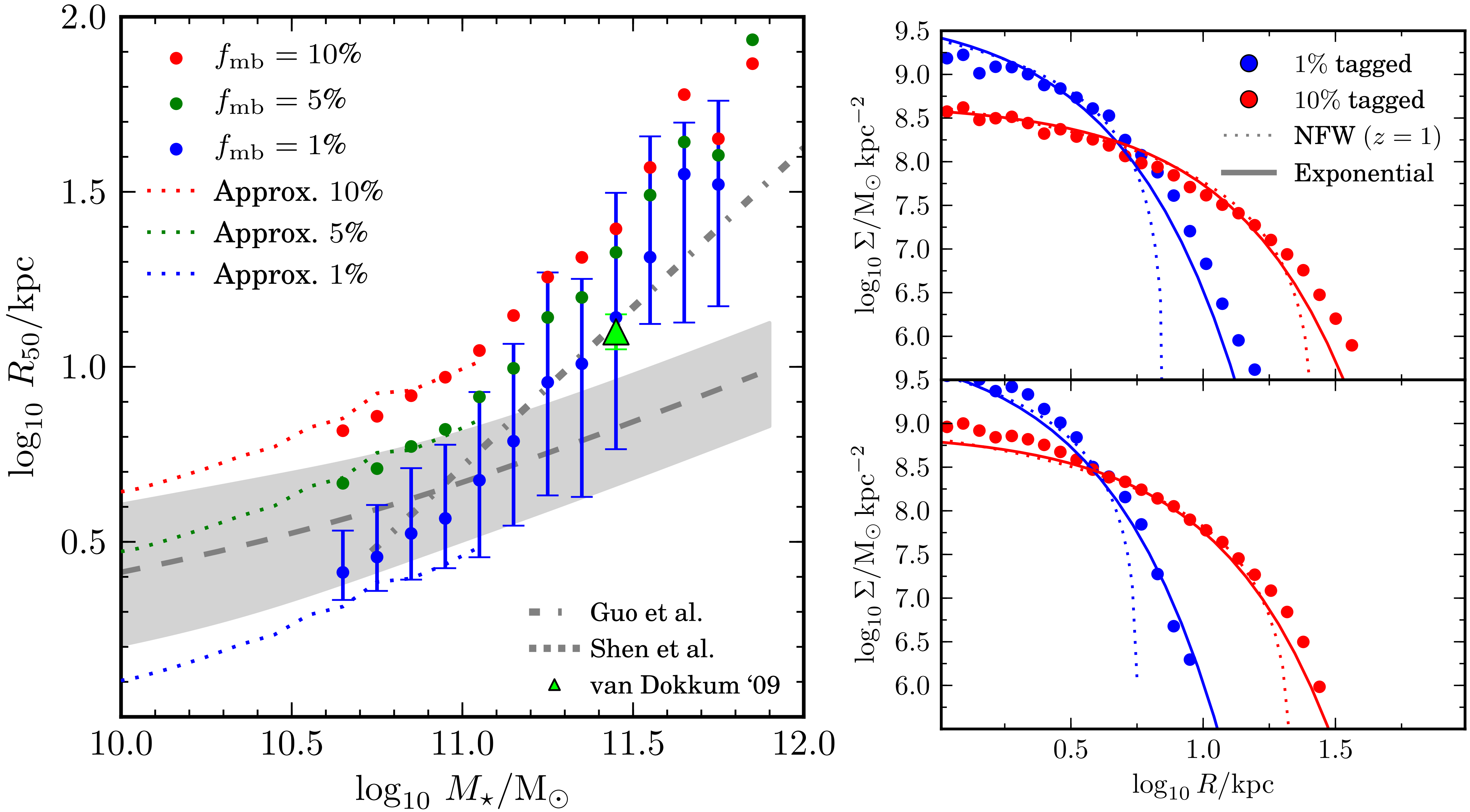


MW satellite size-mass relations (APC+ 2010)

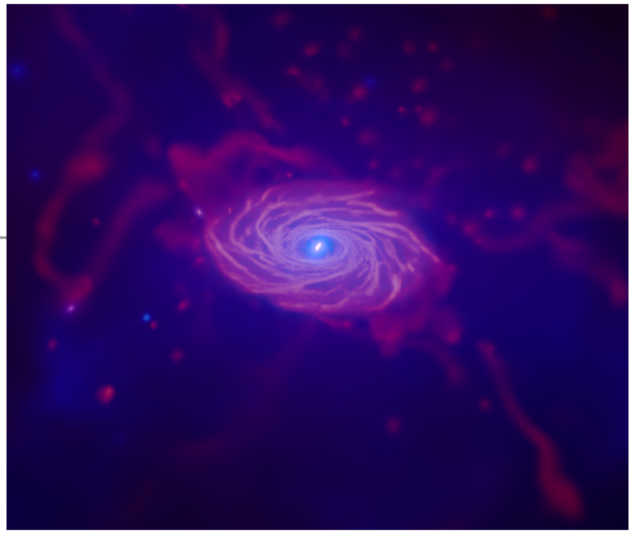


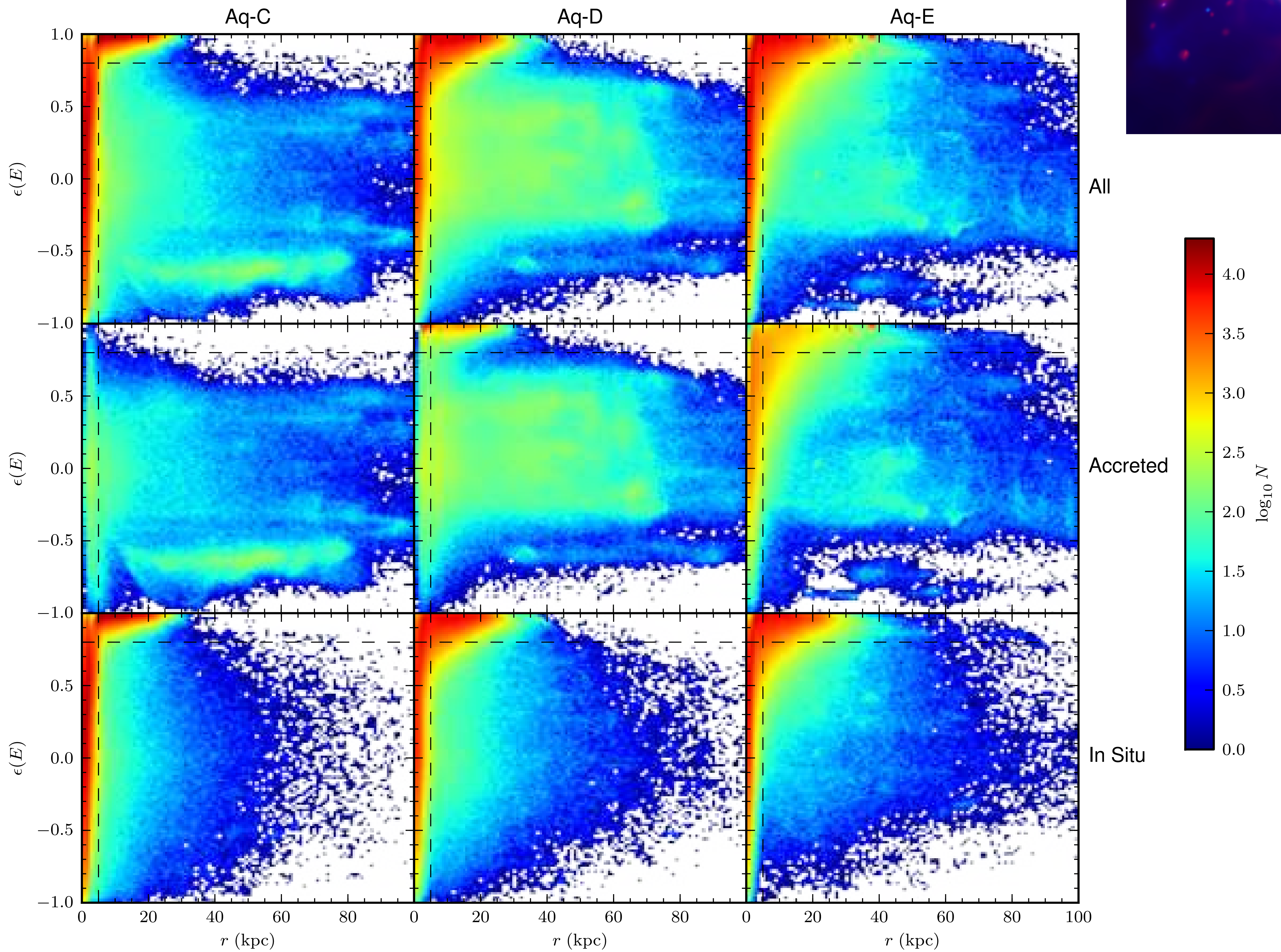


Massive galaxy size-mass relations (APC+ 2013)

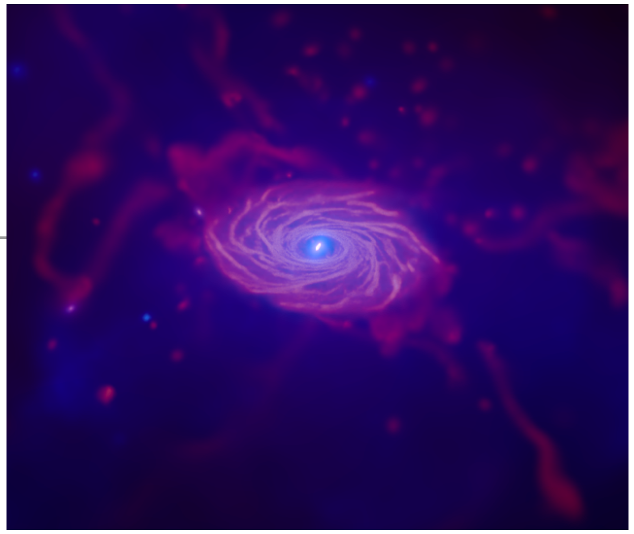


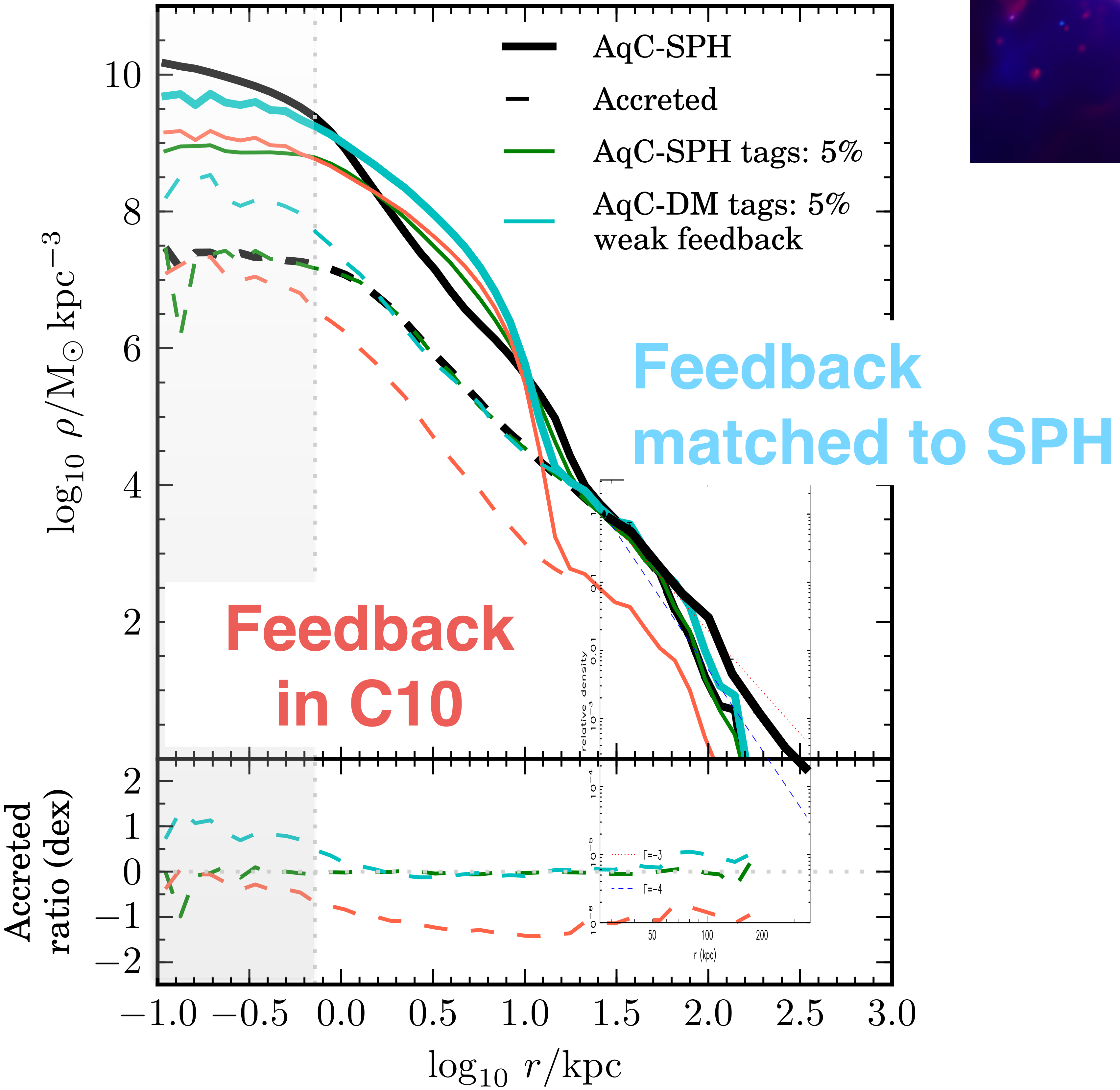
The In Situ Halo



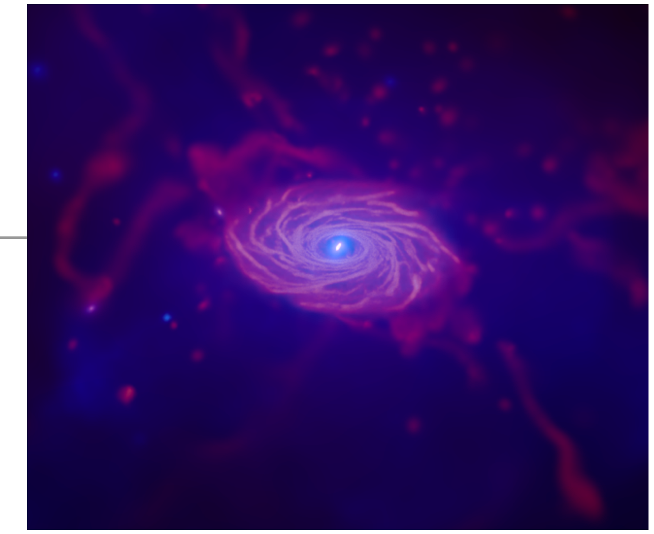


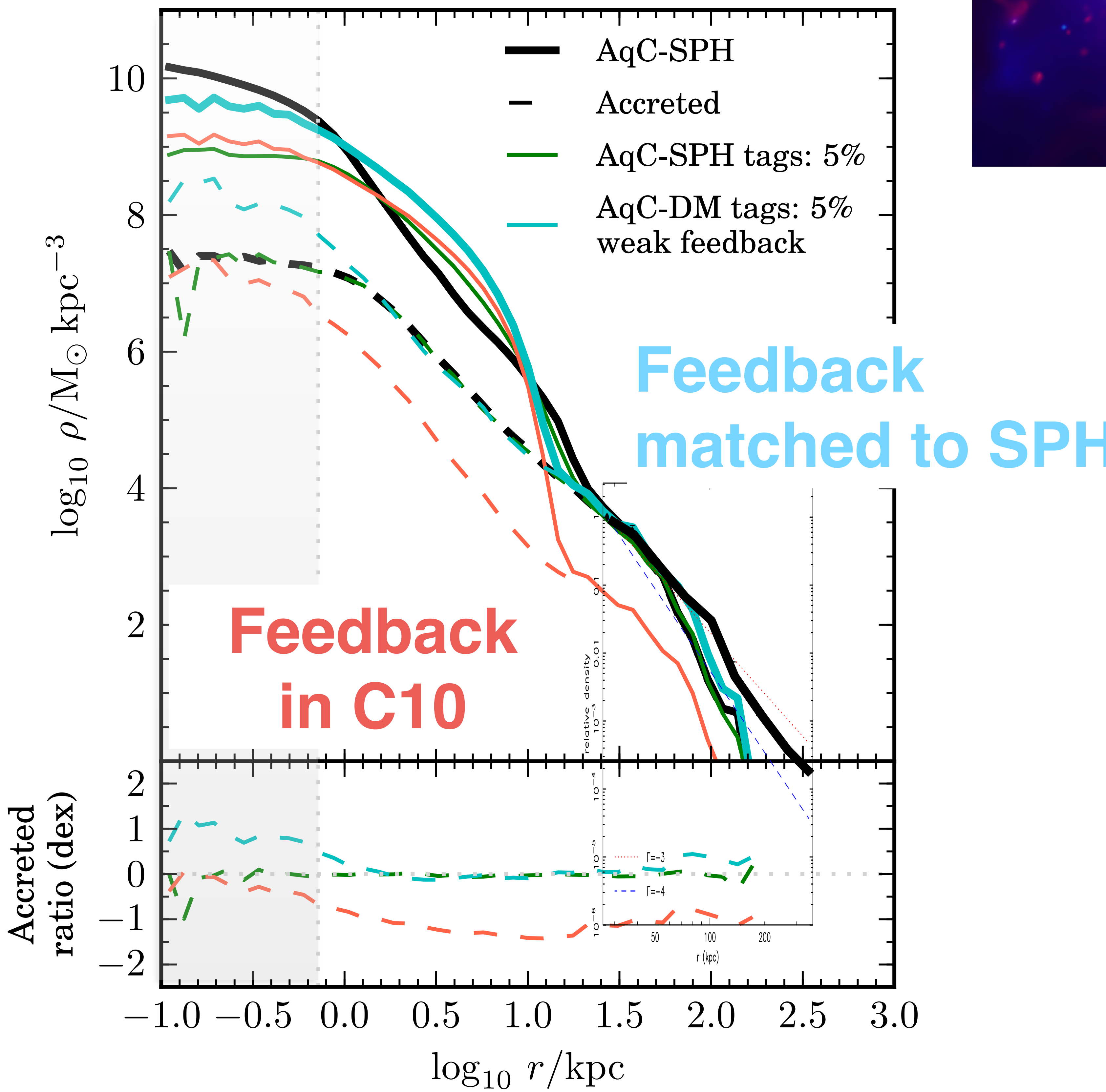
An SPH comparison





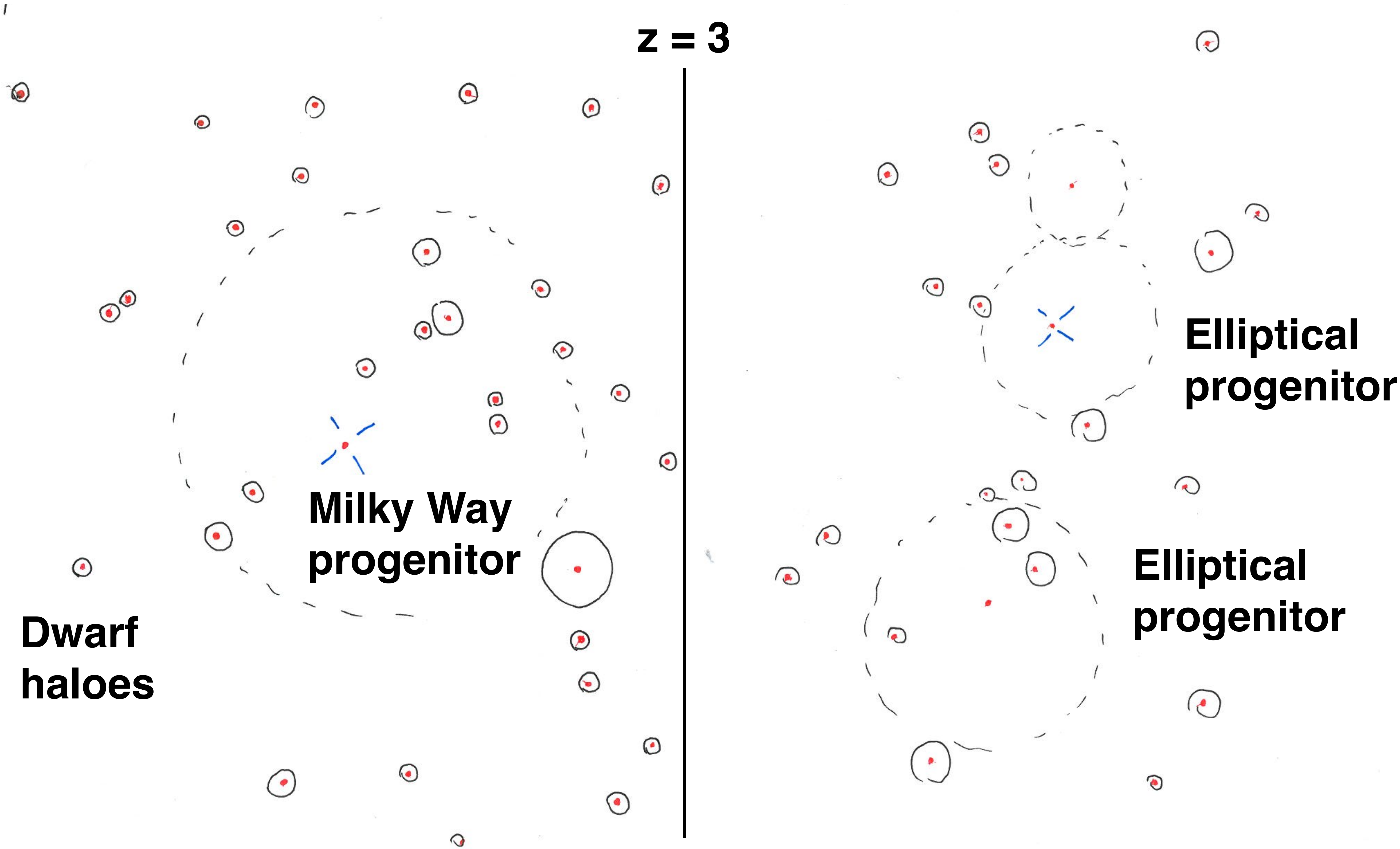
An SPH comparison





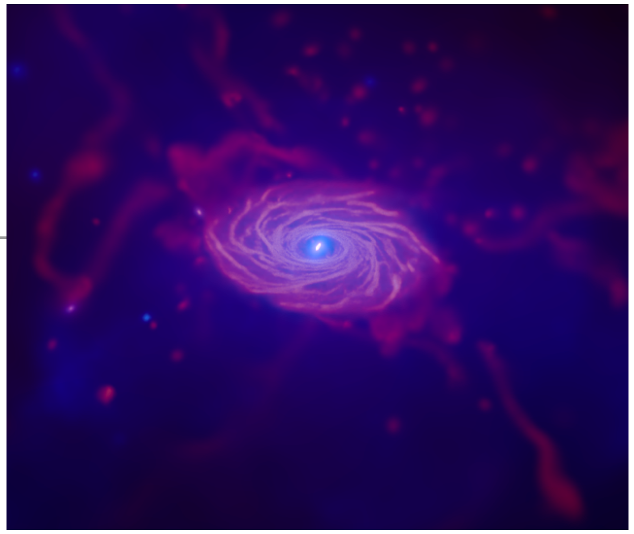
Particle tagging in action

'hiding' in situ stars in the main branch!



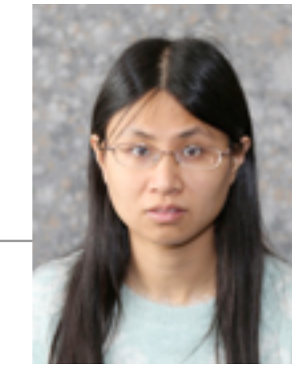
www.virgo.ac.uk/shell-galaxies

Diffusion of stars in energy rank (see Théo Le Bret's talk)



- Feedback causes rapid **diffusion** in energy of stars and DM
- Baryonic processes alter the DM central density: **core formation** (also contraction/cusps)

Particle tagging in the Milky Way halo (Wang+ 2015) ...

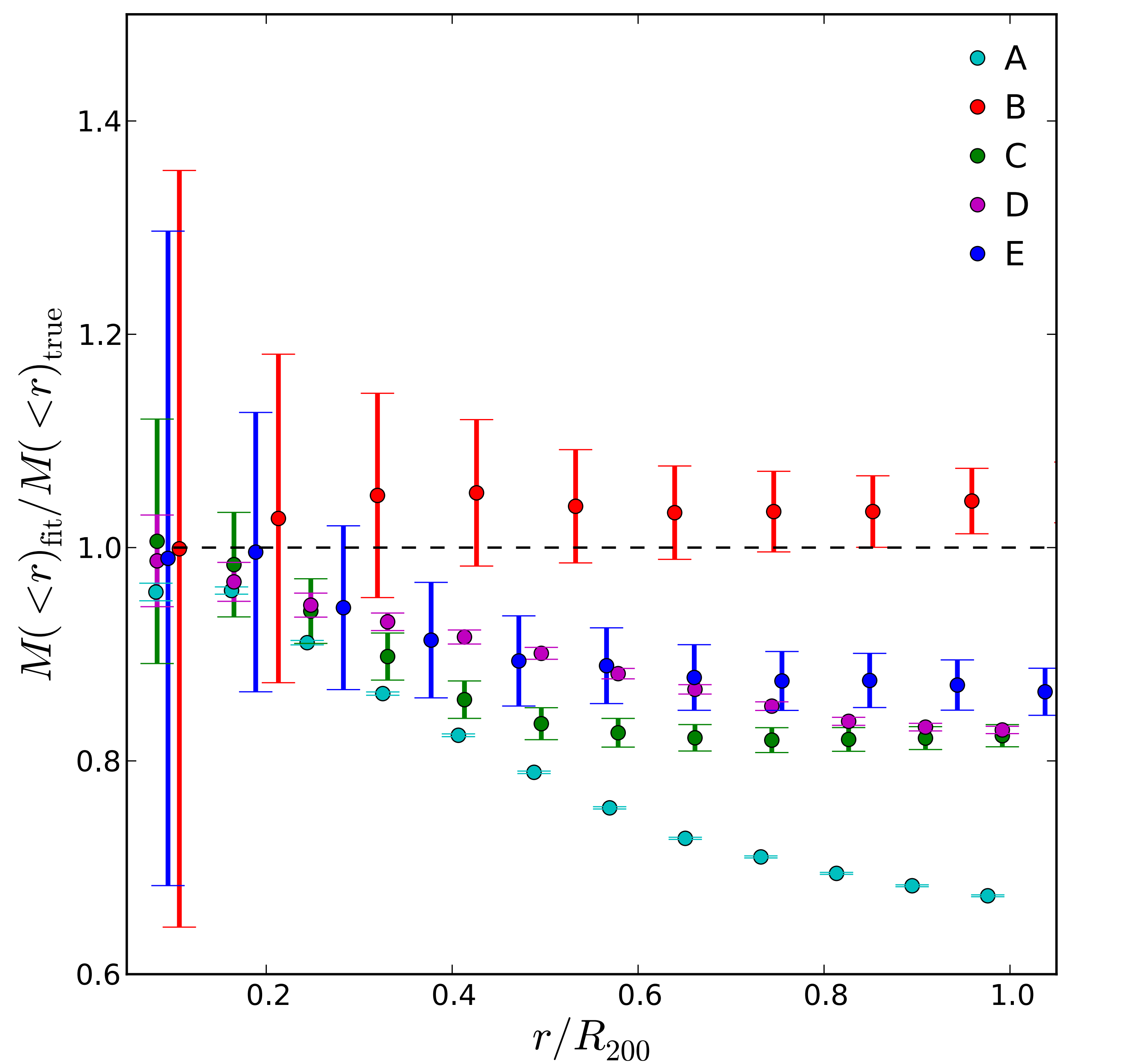


http://arxiv.org/abs/1502.03477

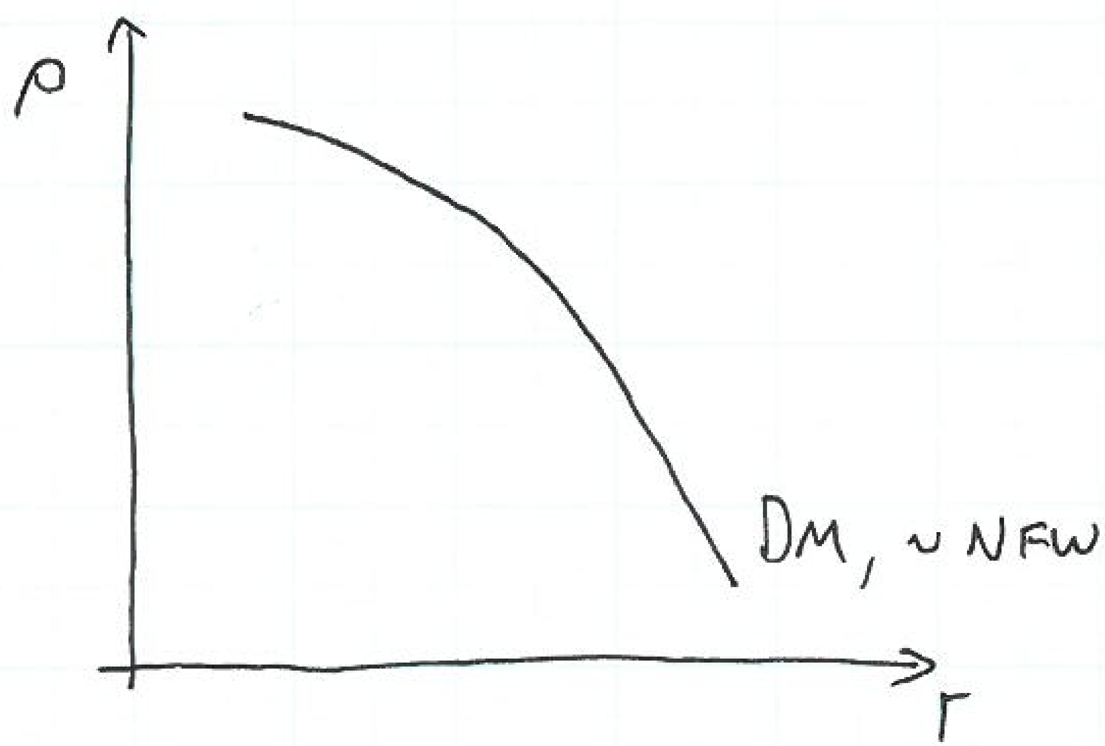
Distribution function fitting using kinematic tracers, in the spirit of Wilkinson & Evans (1999)

$$
\begin{aligned}
&P(r, v_r, v_t|\rho_s, r_s, \beta, \alpha, \gamma, r_0) = \\
&-\frac{r_s^{-\alpha-\gamma} l^{-2\beta}}{2^{3/2-\beta}\pi^{3/2} v_s^3 \Gamma(\beta+1/2)\Gamma(1-\beta)} \times \\
&\int_{R_{\rm inner}}^{R_{\rm max,t}} \mathrm{d}R' (\epsilon(r) - \phi(R'))^{\beta-1/2} \times \\
&\left\{ \frac{(2\beta+1)R'^{2\beta}\left(\frac{R'}{1+R'} - \ln(1+R')\right) - \left[\frac{1}{(1+R')^2} - \frac{1}{1+R'}\right] R'^{2\beta+1}}{\left[\frac{R'}{1+R'} - \ln(1+R')\right]^2} \times \right. \\
&\frac{(2\beta-\alpha)\left(\frac{R'}{r_0}\right)^{\alpha} r_s^{-\gamma} + (2\beta-\gamma)\left(\frac{R'}{r_0}\right)^{\gamma} r_s^{-\alpha}}{\left[\left(\frac{R'}{r_0}\right)^{\alpha} r_s^{-\gamma} + \left(\frac{R'}{r_0}\right)^{\gamma} r_s^{-\alpha}\right]^2} + \\
&\frac{R'^{2\beta+1}}{\left[\frac{R'}{1+R'} - \ln(1+R')\right]\left[\left(\frac{R'}{r_0}\right)^{\alpha} r_s^{-\gamma} + \left(\frac{R'}{r_0}\right)^{\gamma} r_s^{-\alpha}\right]^2} \times \\
&\left[(2\beta-\alpha) r_s^{-\alpha-\gamma}\left(\frac{\alpha}{r_0} - \frac{2\gamma}{r_0}\right)\left(\frac{R'}{r_0}\right)^{\alpha+\gamma-1} + \right. \\
&(2\beta-\gamma) r_s^{-\alpha-\gamma}\left(\frac{\gamma}{r_0} - \frac{2\alpha}{r_0}\right)\left(\frac{R'}{r_0}\right)^{\alpha+\gamma-1} - \\
&\left.\left.(2\beta-\alpha) r_s^{-2\gamma}\frac{\alpha}{r_0}\left(\frac{R'}{r_0}\right)^{2\alpha-1} - (2\beta-\gamma) r_s^{-2\alpha}\frac{\gamma}{r_0}\left(\frac{R'}{r_0}\right)^{2\gamma-1}\right]\right\}.
\end{aligned} \quad (12)
$$

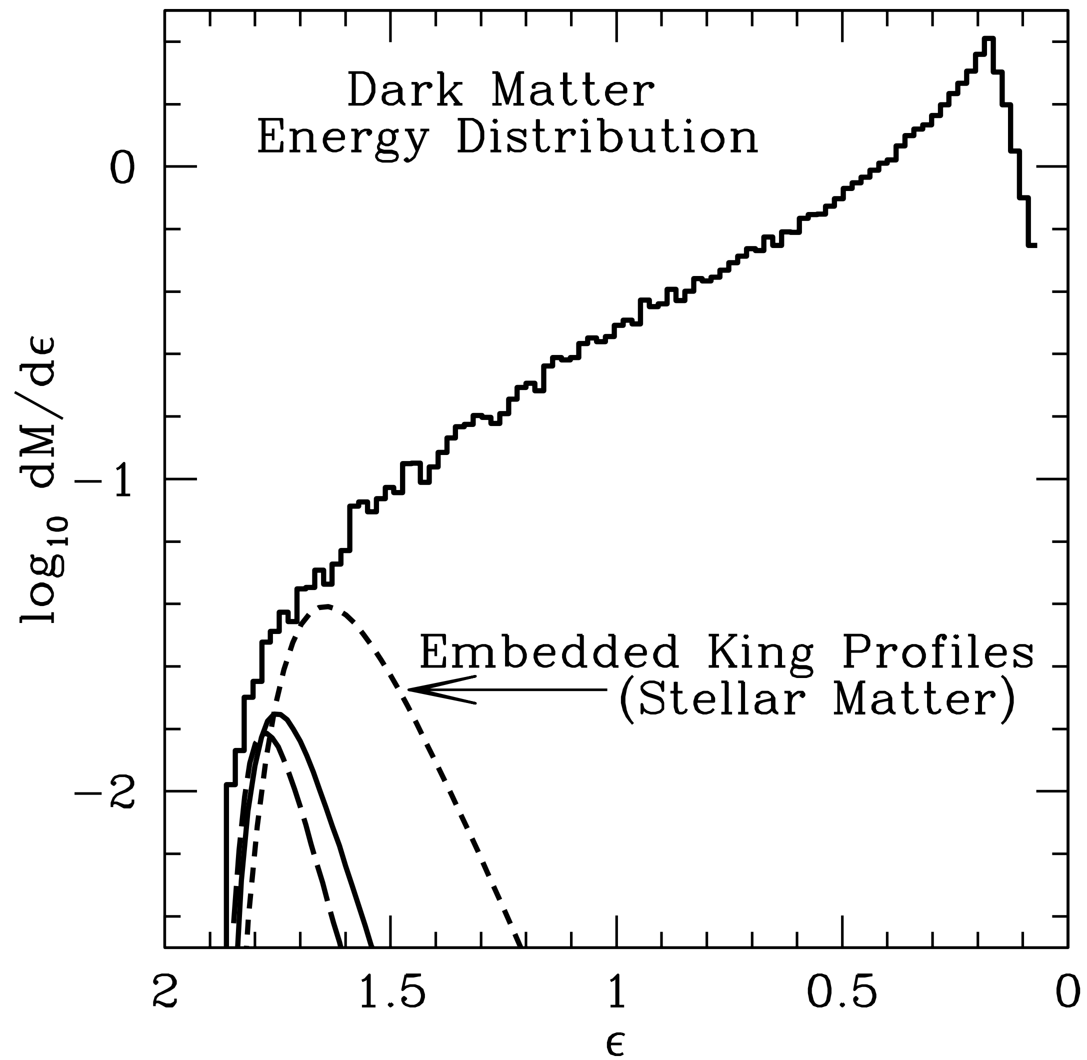
Constraints on M(<r)



Particle Tagging in a nutshell



Density profile

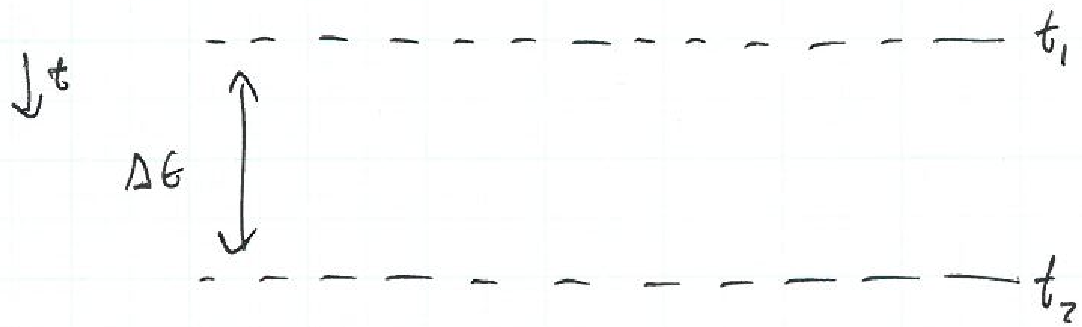


Bullock & Johnston 2005

Differential energy distribution

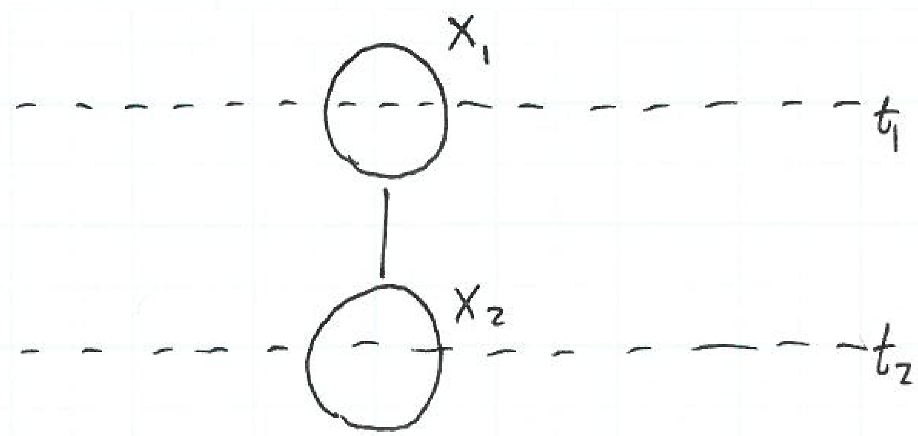
Particle Tagging in a nutshell (following APC et al. 2010)

- Add a model for star formation



TWO ADJACENT SIMULATION SNAPSHOTS

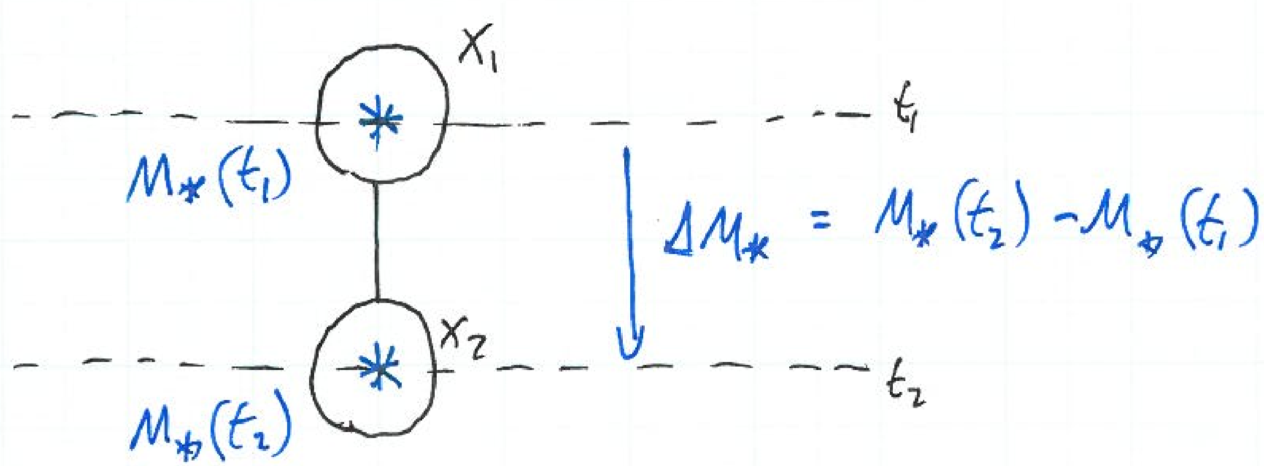
($\Delta t \sim 100$ Myr)



IDENTIFY A PARTICULAR HALO (ANY HALO)

IN THESE TWO SNAPSHOTS

(CALL THIS HALO "X")



STAR FORMATION MODEL GIVES A

MASS ΔM_* OF STARS FORMED

BETWEEN THESE TWO SNAPSHOTS

IN HALO X.