Studying galaxy sizes using the Illustris simulation

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Genel et al. in prep.

Simulated versus observed sizes

- Geometry: 3D vs. projected, circular vs. ellipsoidal
- The measured quantity: mass vs. light
- "Instrumental" limitations: softening vs. PSF & sky background
- Selection bias: distribution of other galaxy properties differ
- Size definition/determination:
    - If profiles differ, how is size meaningful?
    - What is a galaxy - where does it end?

Simulated versus observed sizes

Why not just 'mock observe' the simulation, and compare apples to apples?

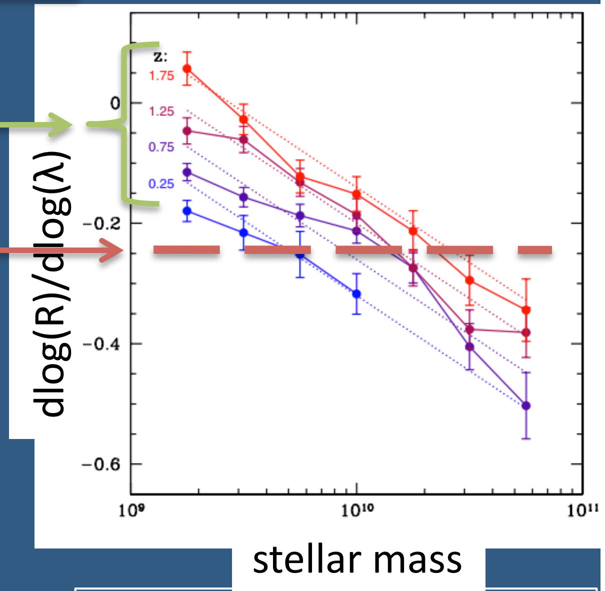
- Mass vs. light: large uncertainties in stellar populations and dust
- Mass vs. light: systematic differences in stellar populations
- Selection bias: unavoidable, as simulations not perfect match
- Varying observational conditions (wavelength, depth, aperture, fitting procedure) confuse theoretical comparisons

Hence, better to work in 'theory space', with comparisons to observations made by converting observables to physical quantities as well as possible

Mass-based sizes using colors

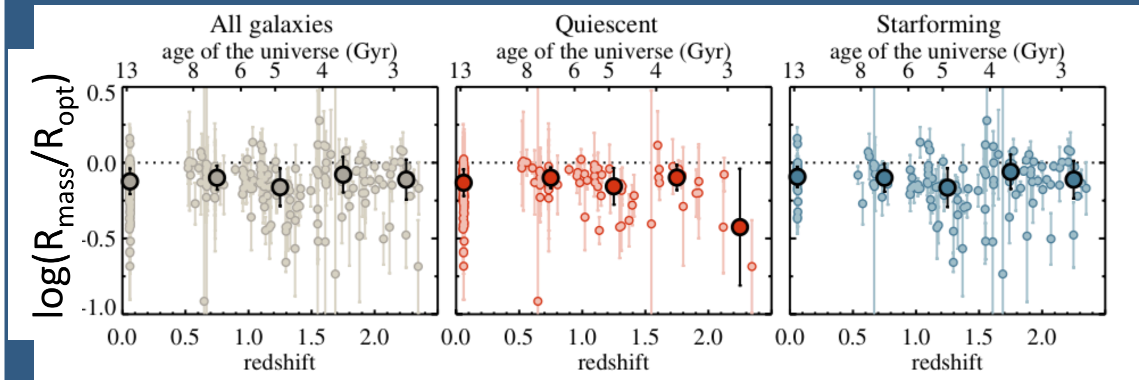
SFing galaxies: redshift & mass dependence

Quiescent galaxies: no redshift & mass dependence



van der Wel et al. 2014

$M_*>10^{10.7}M_{sun}$: $R_{mass}=0.75R_{opt}$ at all z<=2

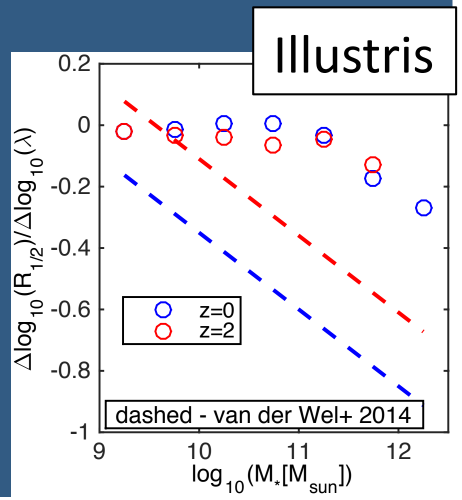


Szomoru et al. 2013

For SFing galaxies, we adopt the following correction:

$$R_{mass}/R_{opt} = 0.75 - 0.125 \log\left(\frac{M_*}{10^{11}\,M_\odot}\right)$$

Thanks to Arjen!



Definitions: which size, and what is 'the galaxy'?

• Size is a strongly reduced measure of profile, hence definition is to some degree arbitrary. Alternatives include:

• R_{pet} – agnostic to $r>R_{pet}$

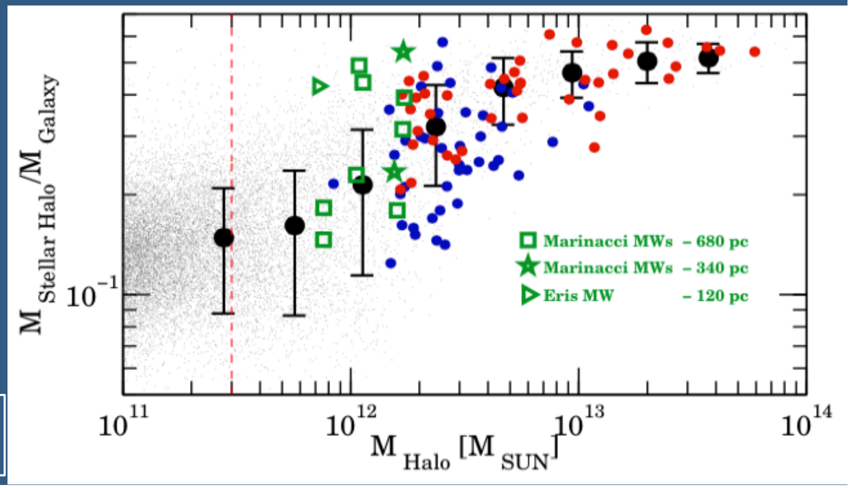
• 'direct $R_{1/2}$' – non-parametric, but requires defining an outer edge, and can be hard to measure if edge is large

• 'indirect $R_{1/2}$' – R_e based on a fit:

  • goodness of fit

  • multi-components

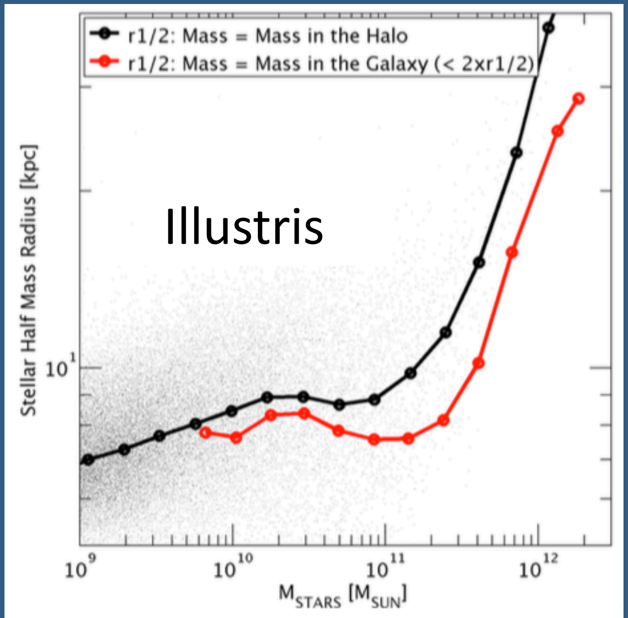
Pillepich et al. 2014

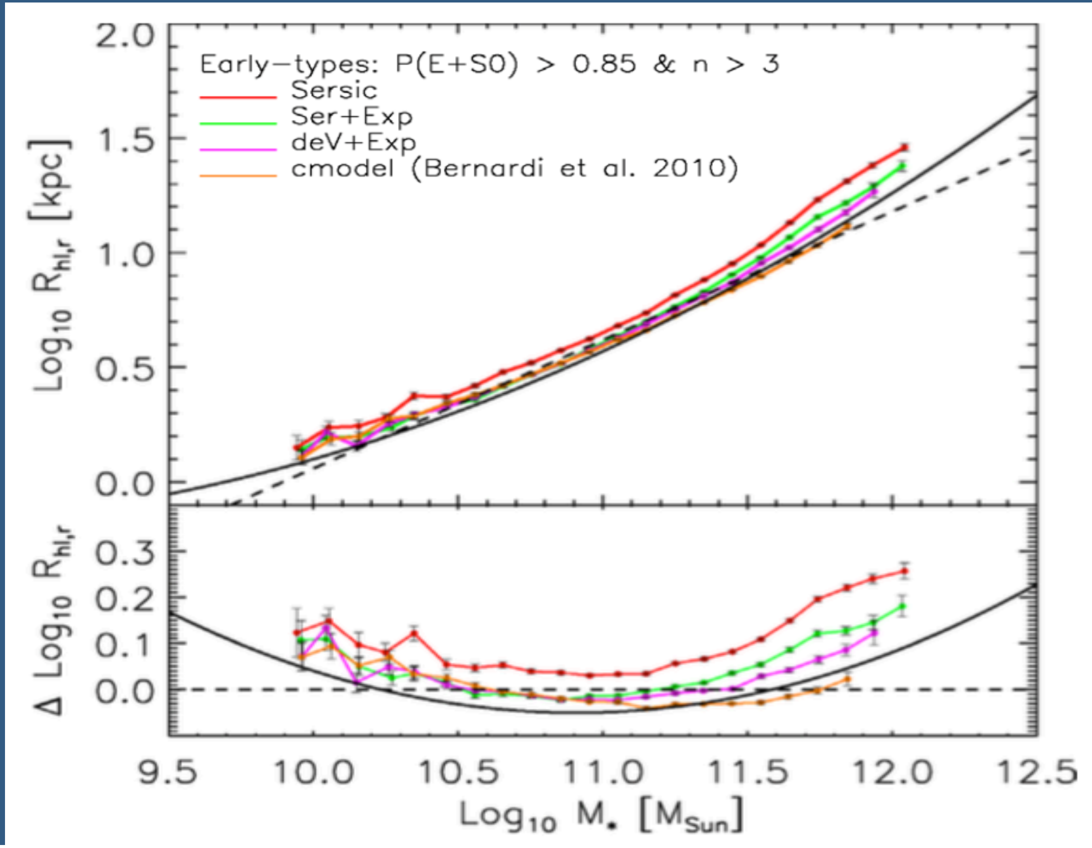


Definitions: which size, and what is ‘the galaxy’?

• Fortunately, the size-mass relation is probably sensitive to the ‘galaxy definition’ issue only up to ~0.1dex

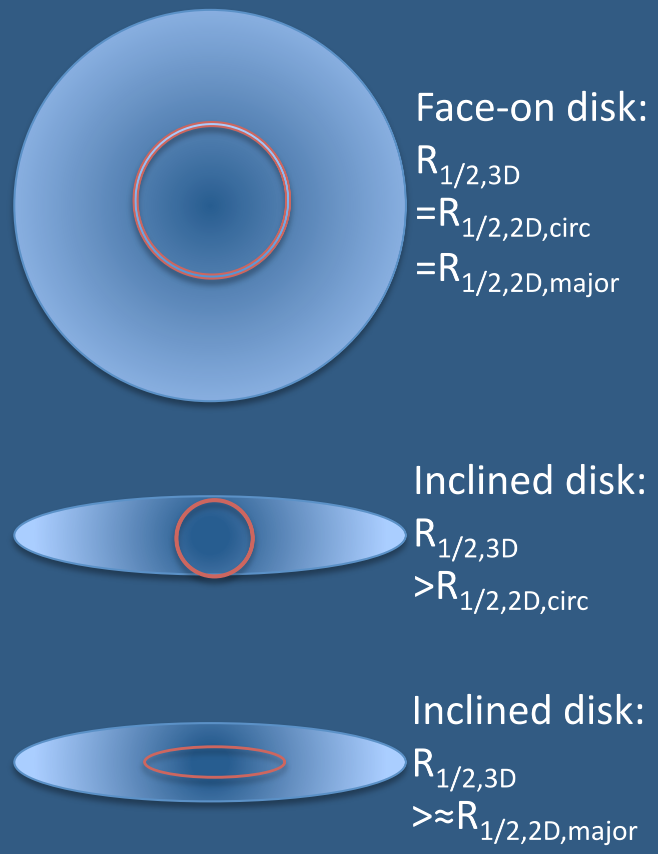
Bernardi et al. 2014





3D vs. projected, circular vs. elliptical sizes

- The simplest intrinsic measure is a 3D spherical radius, $R_{1/2,3D}$
- It is related to the observed projected radius depending on:
    - The inclination angle
    - The mass profile
    - The intrinsic shape (axial ratio)
    - The geometrical definition: circular, elliptical (major axis), circularized (mean of major and minor axes)



3D vs. projected, circular vs. elliptical sizes

Monte Carlo simulations allow to:

- average over all inclinations,
- test different profiles

(isothermal – left, exponential – right),

- and different shapes

(blueish – SFing, reddish – quiescent)

Results:

- For all galaxies,

$R_{1/2,3D}/R_{1/2,2D,circ} \approx 1.3$

- For SFing galaxies,

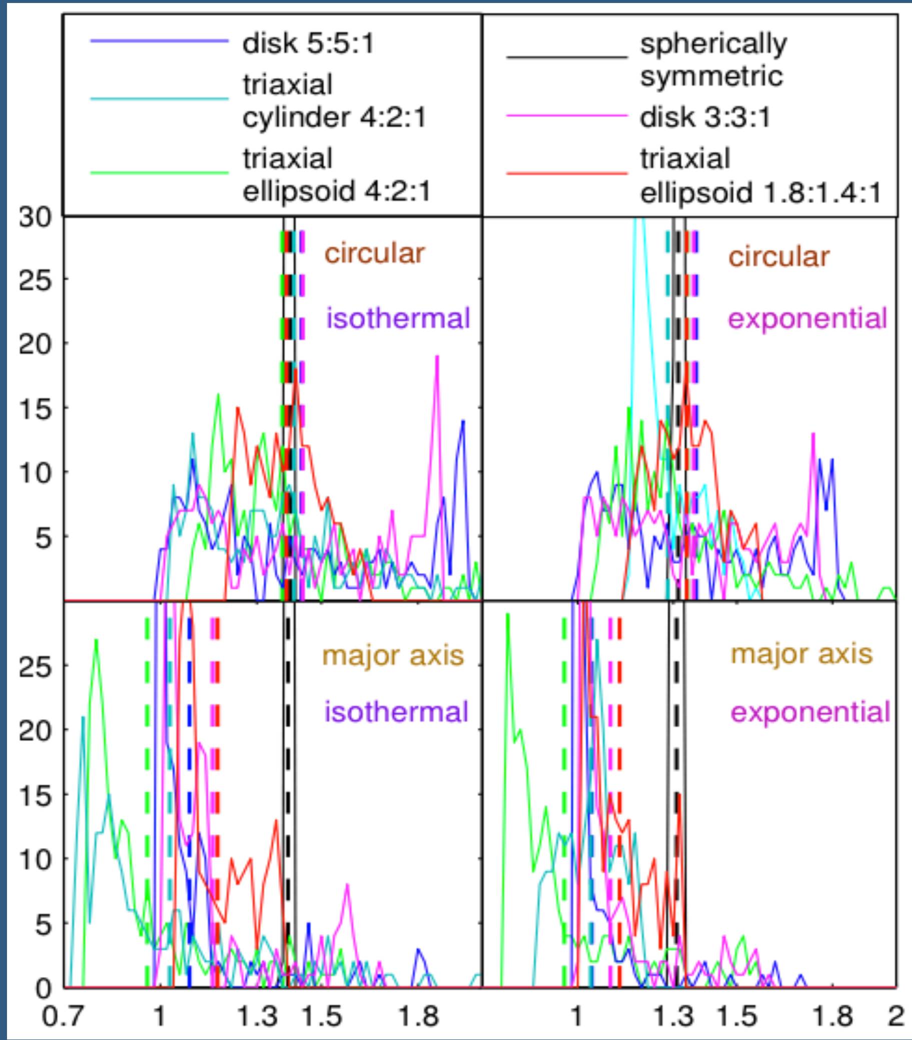
$R_{1/2,3D}/R_{1/2,2D,major} \approx 1$

- For quiescent galaxies,

$R_{1/2,3D}/R_{1/2,2D,major} \approx 1.15$

shapes motivated by:

SFing galaxies Quiescent galaxies

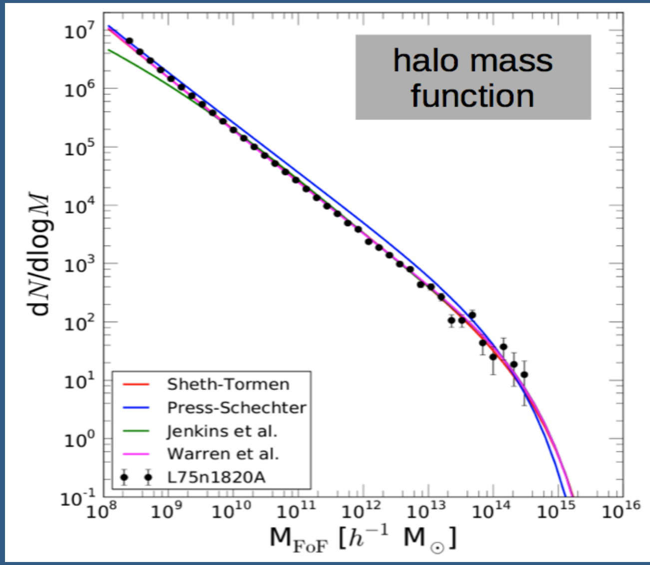


$R_{1/2,3D}/R_{1/2,2D}$

The Illustris Simulation

Vogelsberger et al. 2014
Genel et al. 2014

- A (106.5 Mpc)^3 box run to z=0
  - 10 M>$10^{14}$$M_{sun}$ halos @ z=0
  - >10^3 M≈$10^{12}$$M_{sun}$ halos @ z=0
- Baryonic resolution: 1.3×10^6 M_{sun}
- Resolution elements: 2×1820^3
- Gravitational spatial resolution: 0.7-1.4 ckpc
- N-body+hydro on an unstructured moving mesh with Arepo
- Galaxy formation physics (SF, winds, AGN…)



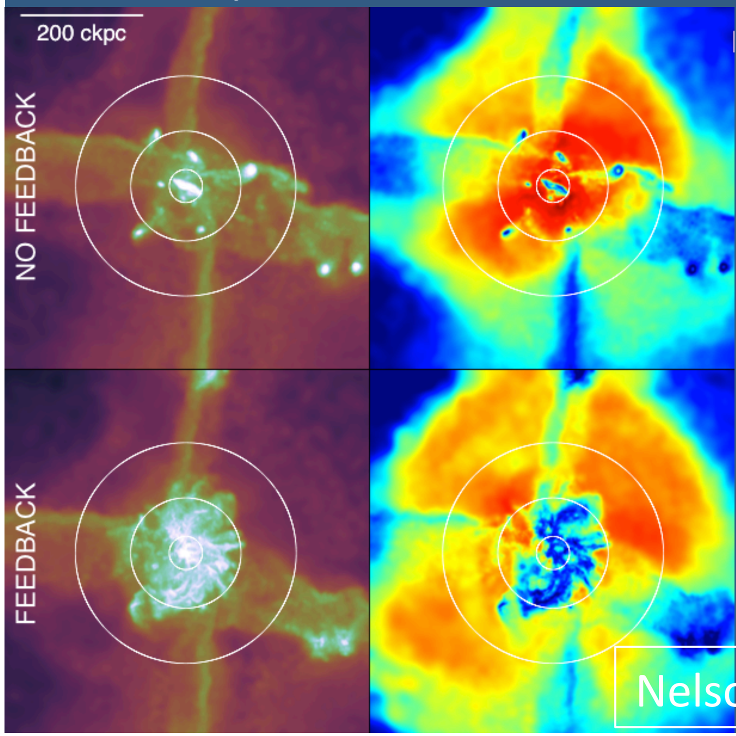
Vogelsberger et al. 2013

Galaxy formation physics

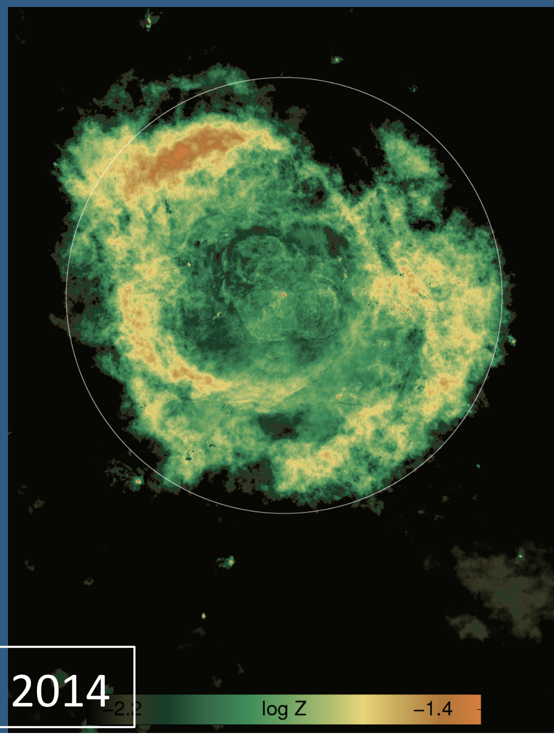
Tuned to solve the overcooling problem

- Galactic winds
- Black Holes

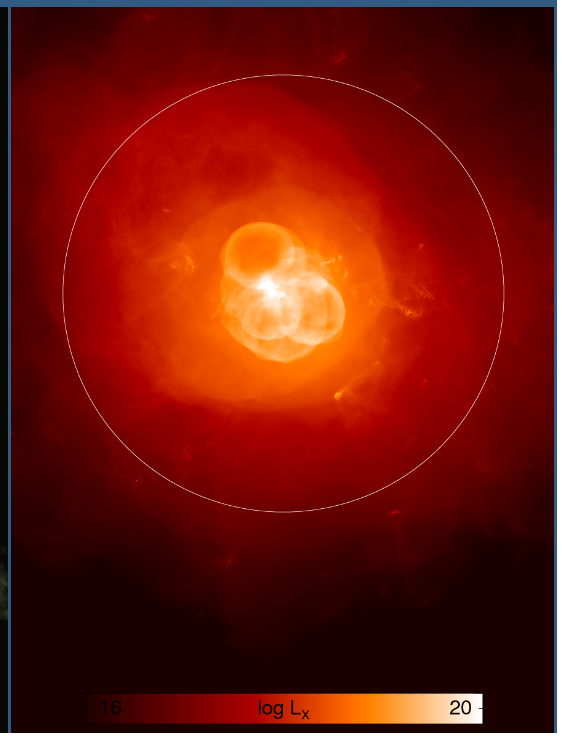
density temperature



metallicity



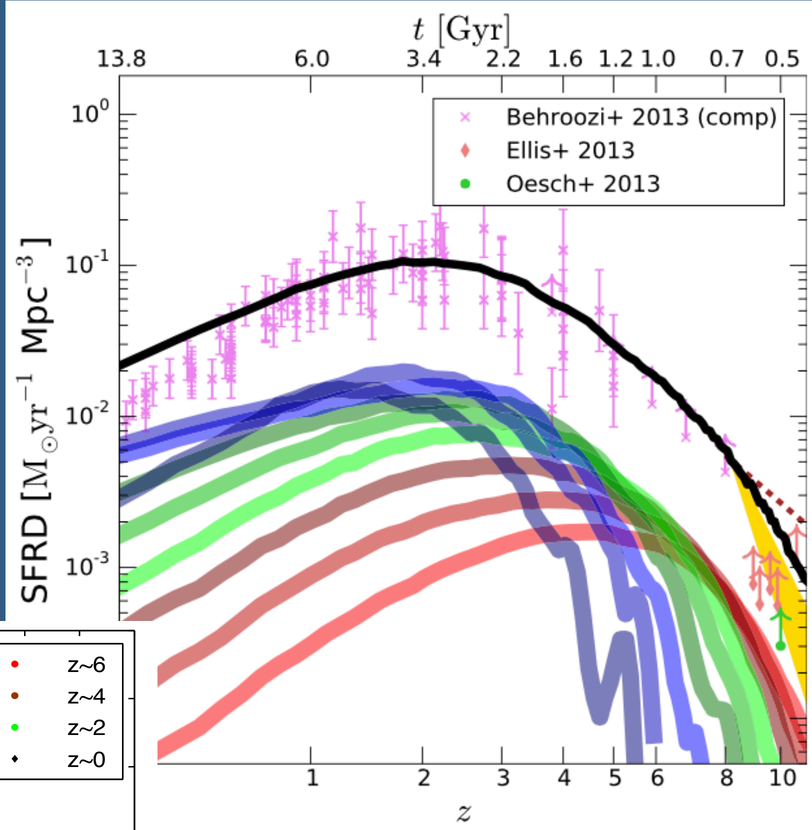
xray luminosity



Nelson et al. 2014

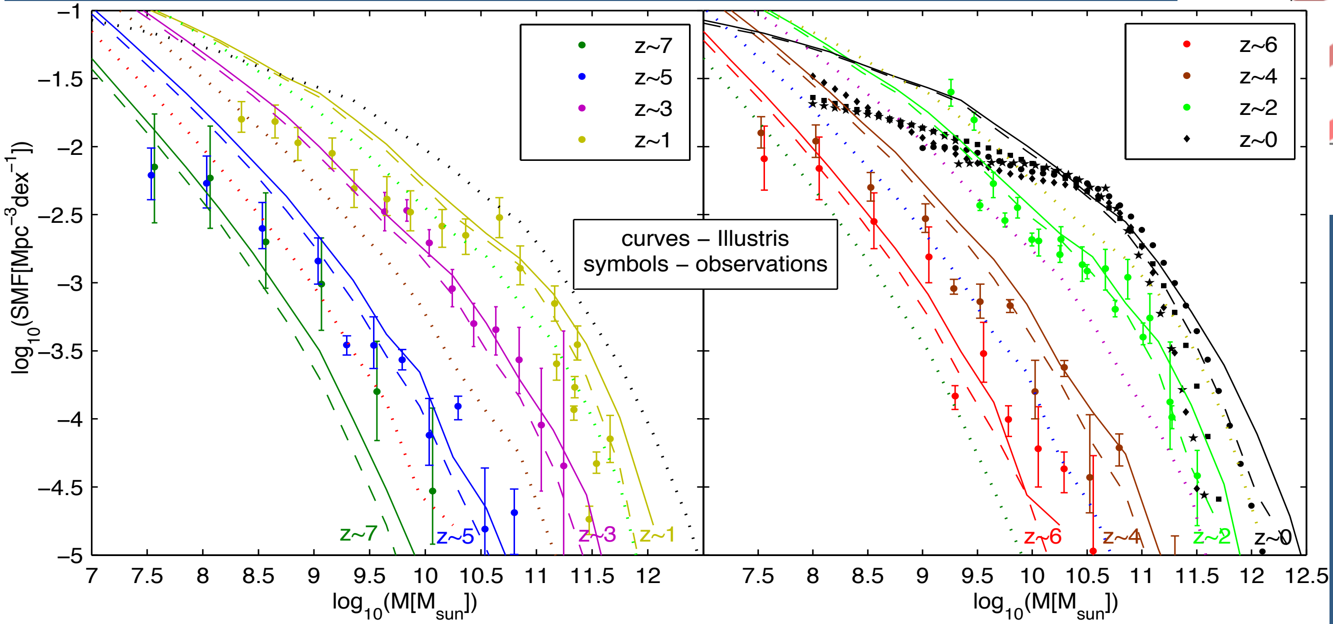
Cosmic star-formation

Cosmic SF density



Vogelsberger et al. 2014

Stellar mass functions

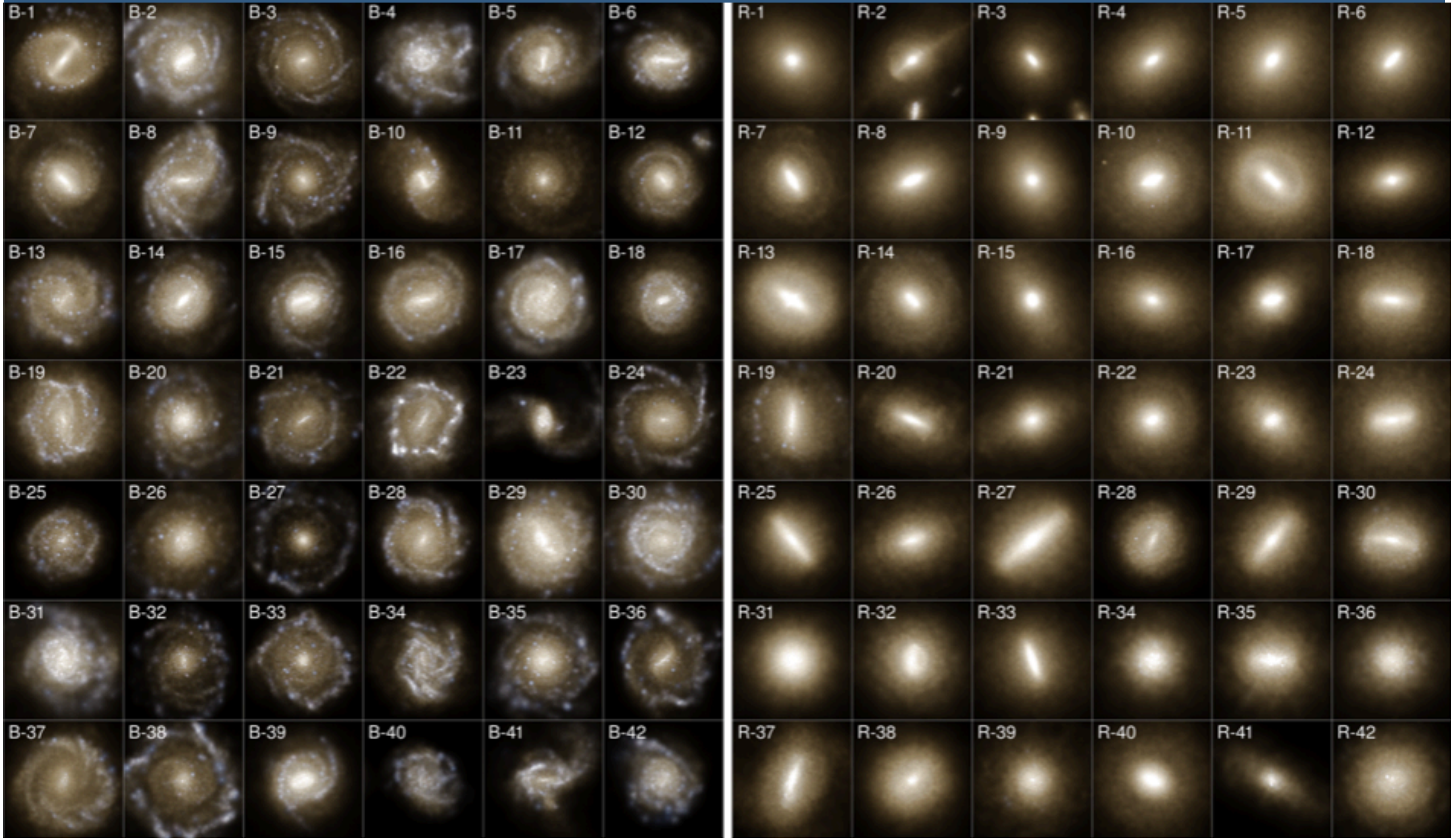


Genel et al. 2014

Vogelsberger et al. 2014

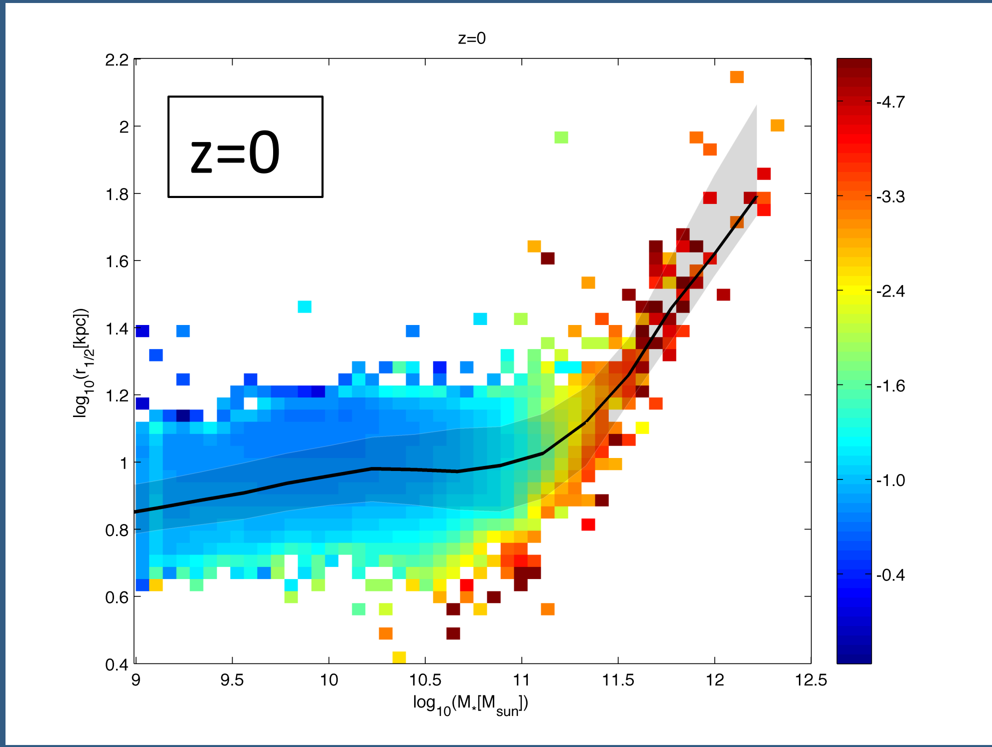
Galaxy bimodality

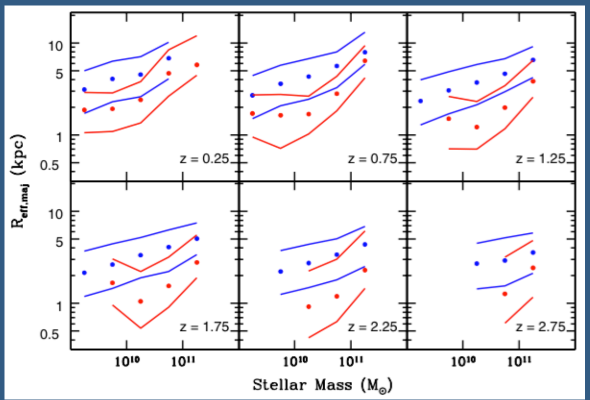
$10^{12\text{-}13} M_{sun}$ halos



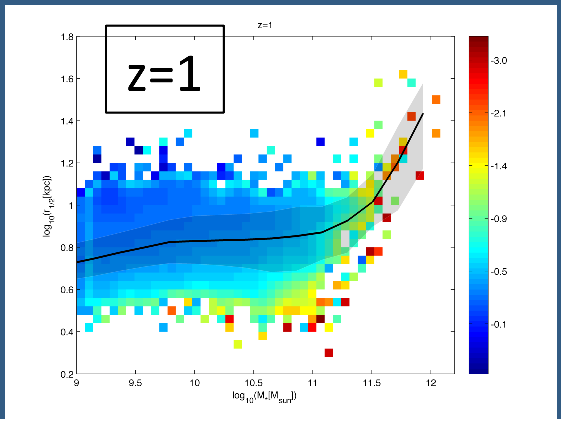
Size-mass-SFR-redshift

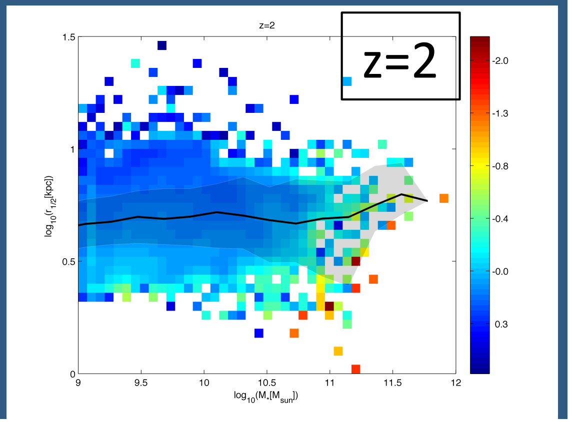
- The size-mass relation is almost flat at low masses, and steepens at $M_{*} \approx 10^{11} M_{sun}$
- Larger galaxies have higher star-formation rates, at a given mass





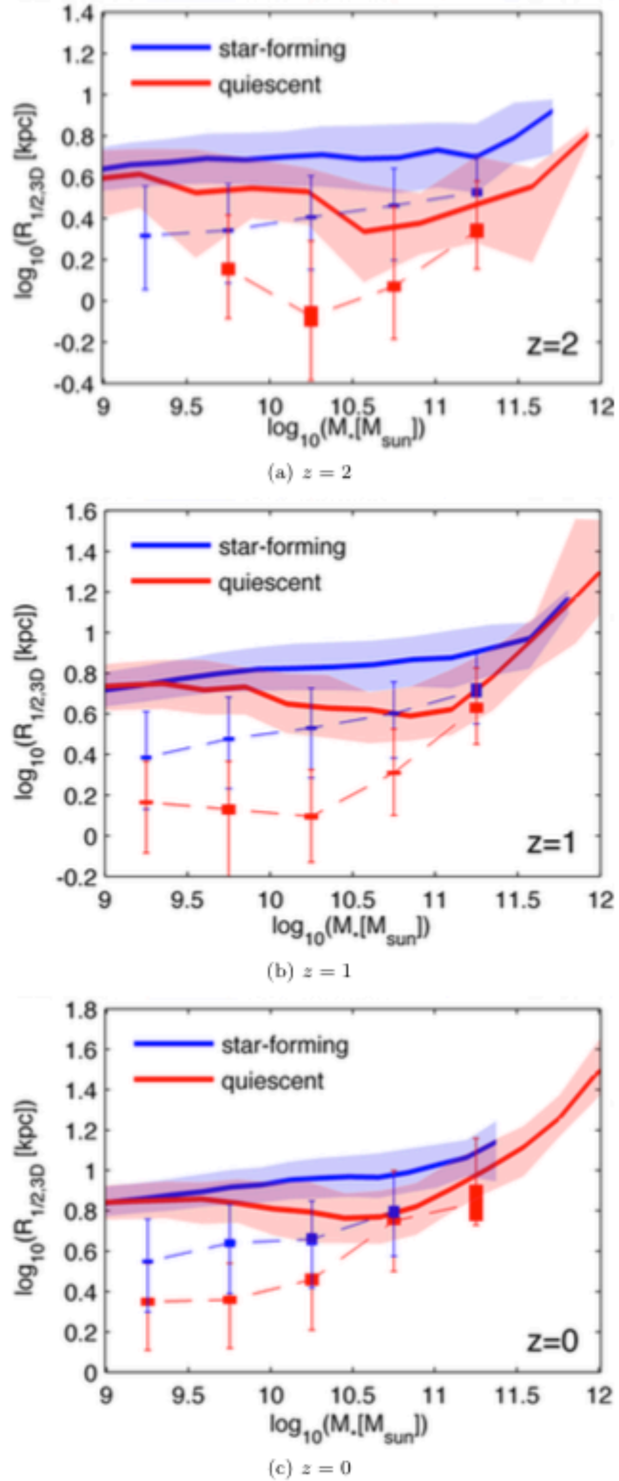
van der Wel et al. 2014





Size-mass-SFR-redshift

- Observed trends qualitatively reproduced:
  - Separation between SFing and quiescent
  - Quiescent galaxies have a steeper relation than SFing galaxies, at M_{*}>~$10^{10.5}$
  - At M_{*}<~$10^{10.5}$, the relation for quiescent galaxies obtains a negative slope
- But quantitatively:
  - All SFing galaxies are too large
  - Slope for SFing galaxies is too shallow
  - Flattening at too high mass for quiescent
  - All M_{*}<~$10^{10.5}$ galaxies are too large



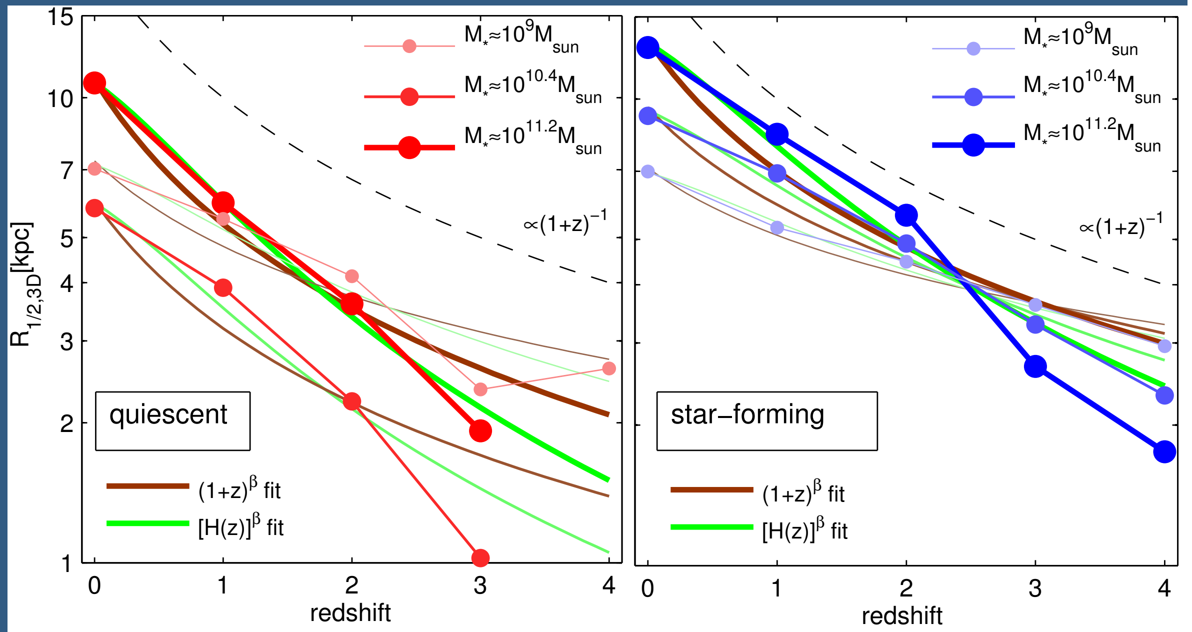
(a) $z = 2$

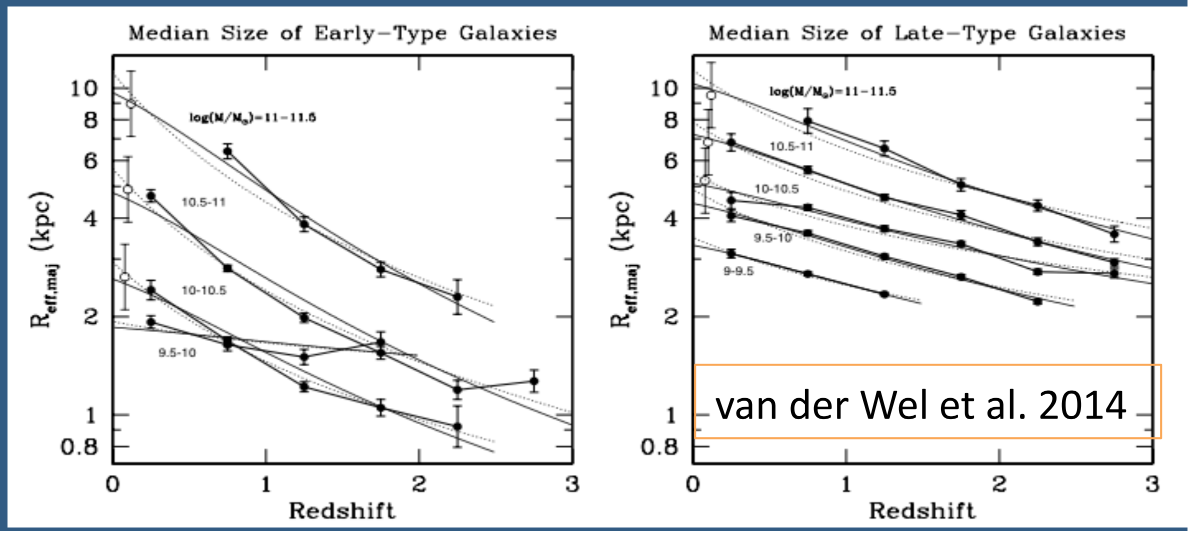
(b) $z = 1$

(c) $z = 0$

Size-mass-SFR-redshift

- Observed trends qualitatively reproduced:
  - Quiescent galaxy sizes evolve faster than star-forming ones
  - More massive galaxies evolve faster than lower-mass ones
  - Evolution is better described by $H(z)^{\beta}$ than $(1+z)^{\beta}$, like for DM halos





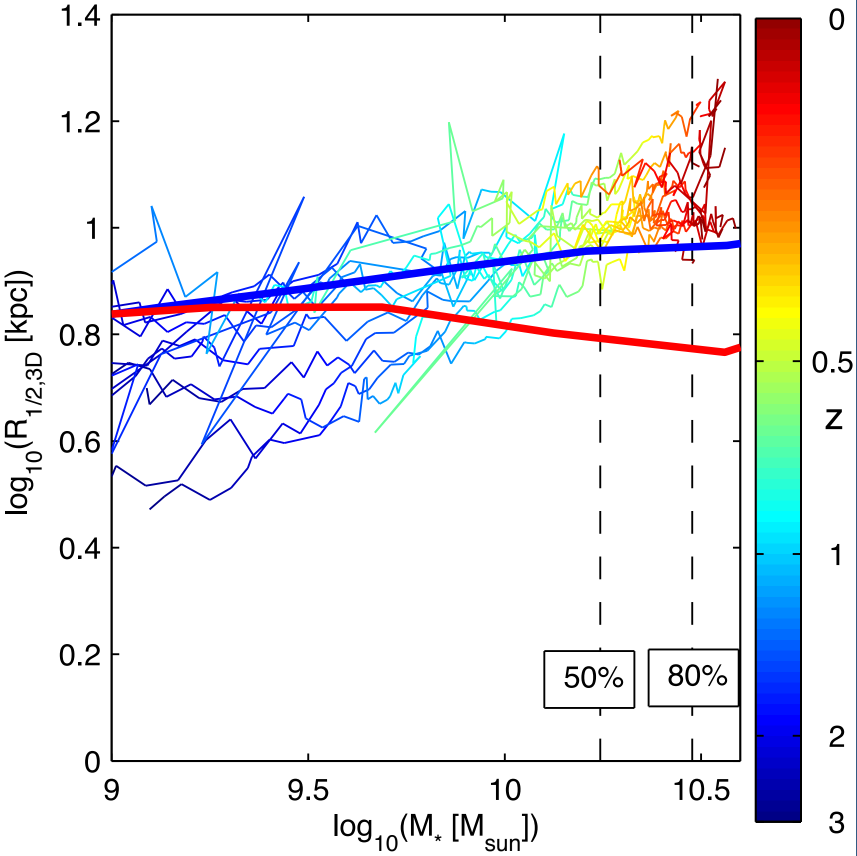
The pressing questions

- What separates the SFing and quiescent galaxies, as observed?
- Why does the quiescent relation steepen so strongly, as observed?
- Why do quiescent, as well as massive, galaxies, evolve faster, as observed?
- Why are the simulated galaxies generally larger than observed?

Galaxy sizes – progenitor bias

Star-forming galaxies:

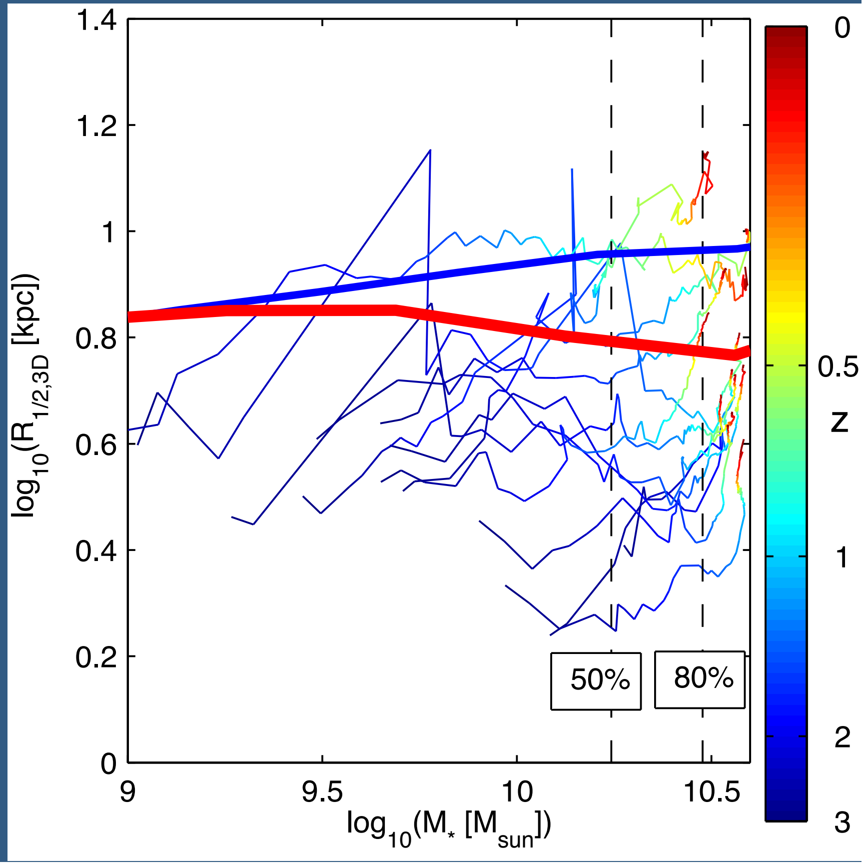
steady mass and size growth



$10^{10.5}$ M_{sun}

Quiescent galaxies:

early, small, formation



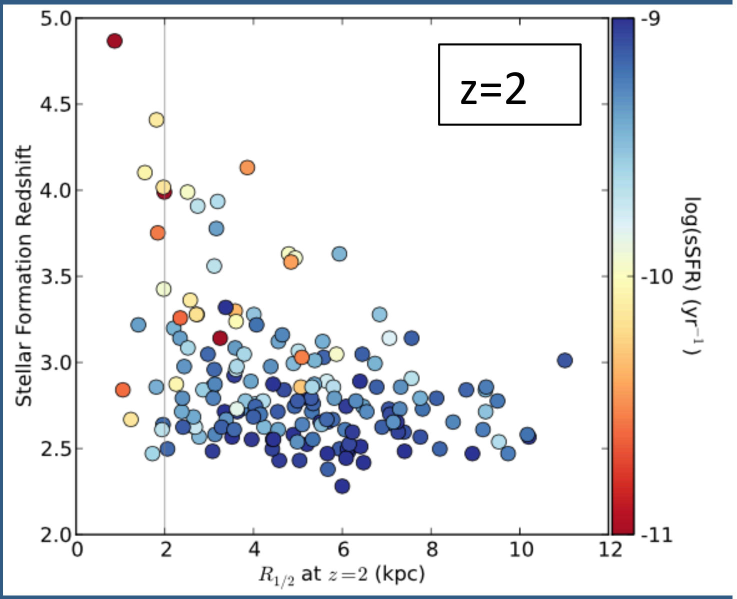
Galaxy sizes – progenitor bias

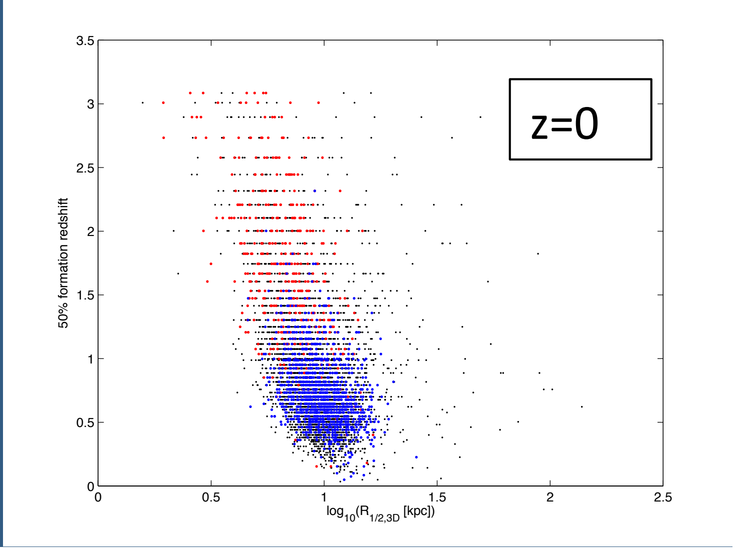
Wellons et al. 2014

• Quiescent galaxies are formed earlier than SFGs, i.e. their size is set when the universe was denser and the overall population was smaller

• This, however, only gives a roughly constant factor of ≈1.5 at different redshifts, thereby not accounting for:

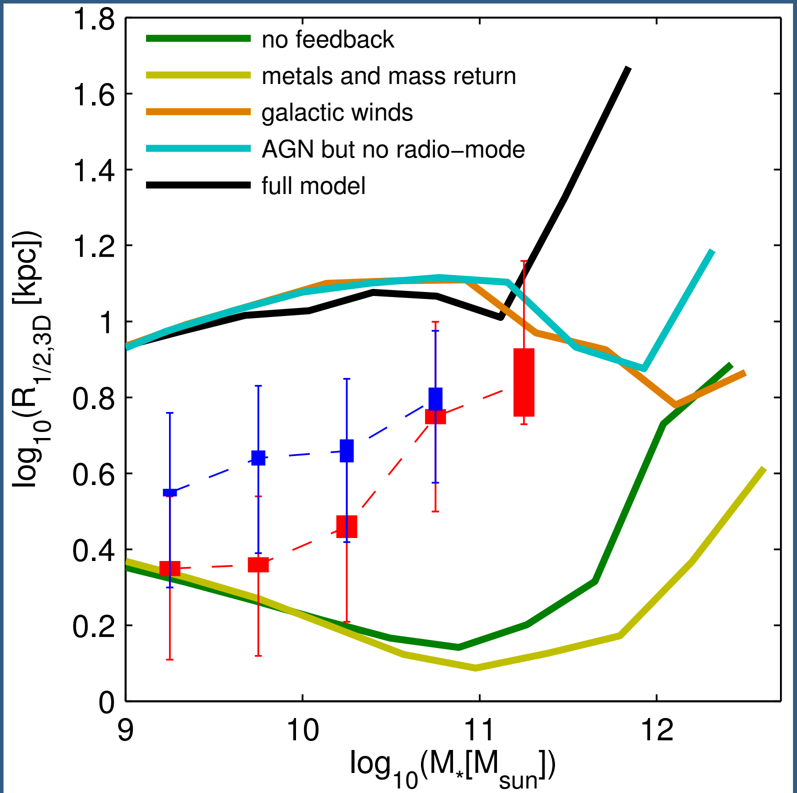
- The significant size difference at high z
- The stronger evolution with redshift of quiescent galaxies

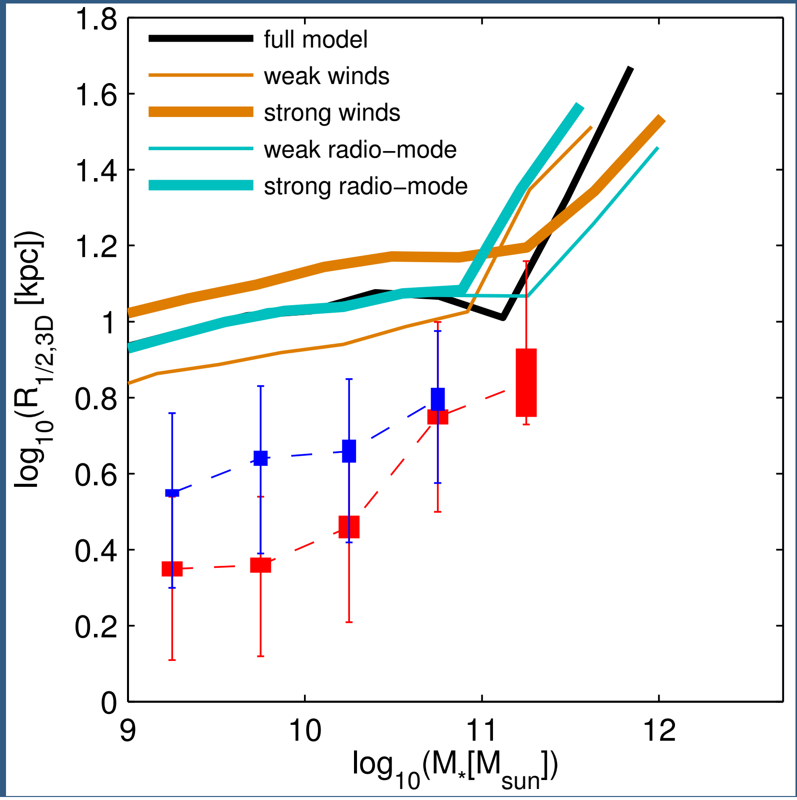




The role of feedback

- Enhancement/addition of feedback always makes galaxies larger

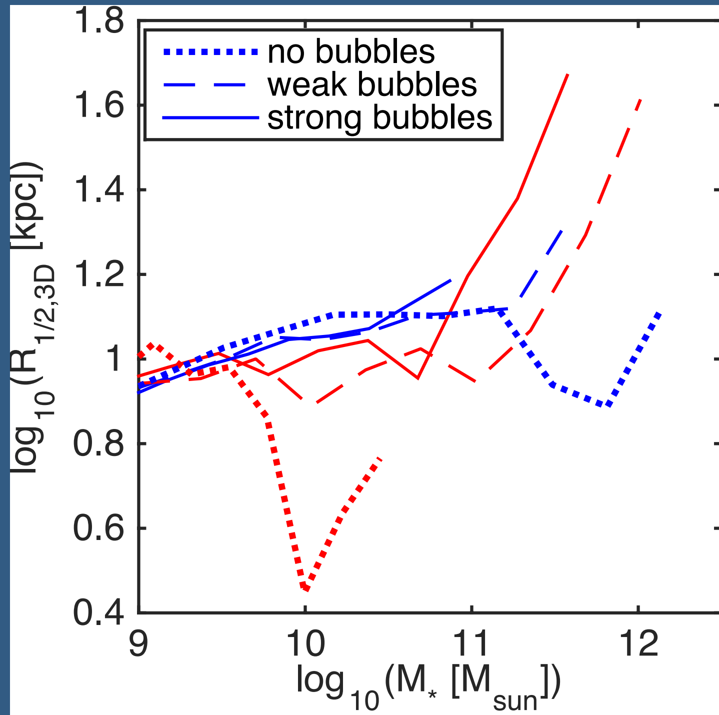




The role of feedback

• But if AGN feedback makes galaxies both larger and more quenched – how come quenched galaxies are preferentially small?

• Without AGN feedback, quenched galaxies are even smaller

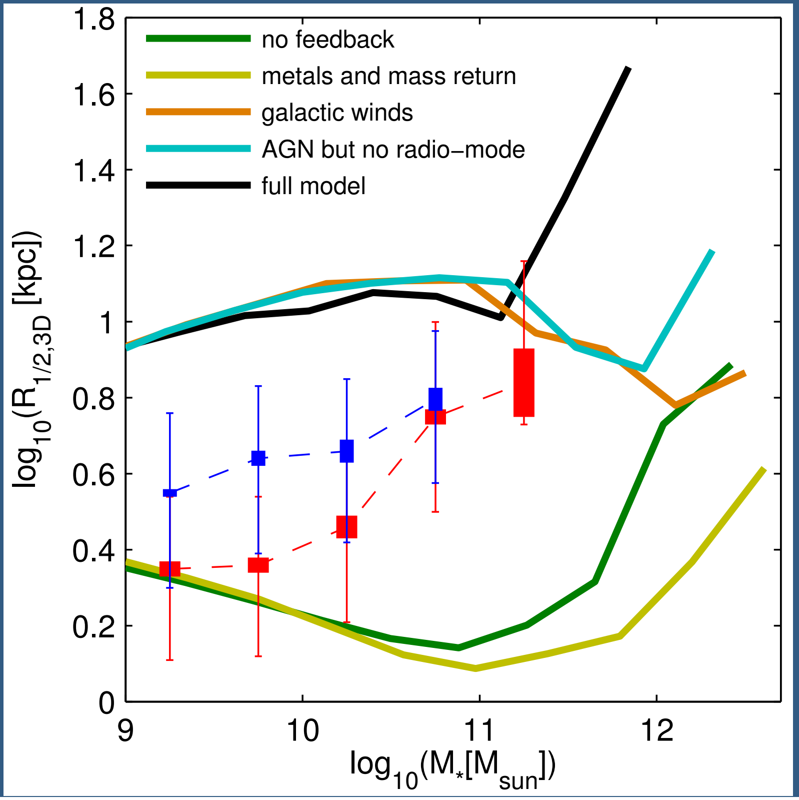


• AGN feedback is working against the quenched-SFG size separation – it is not the reason for it

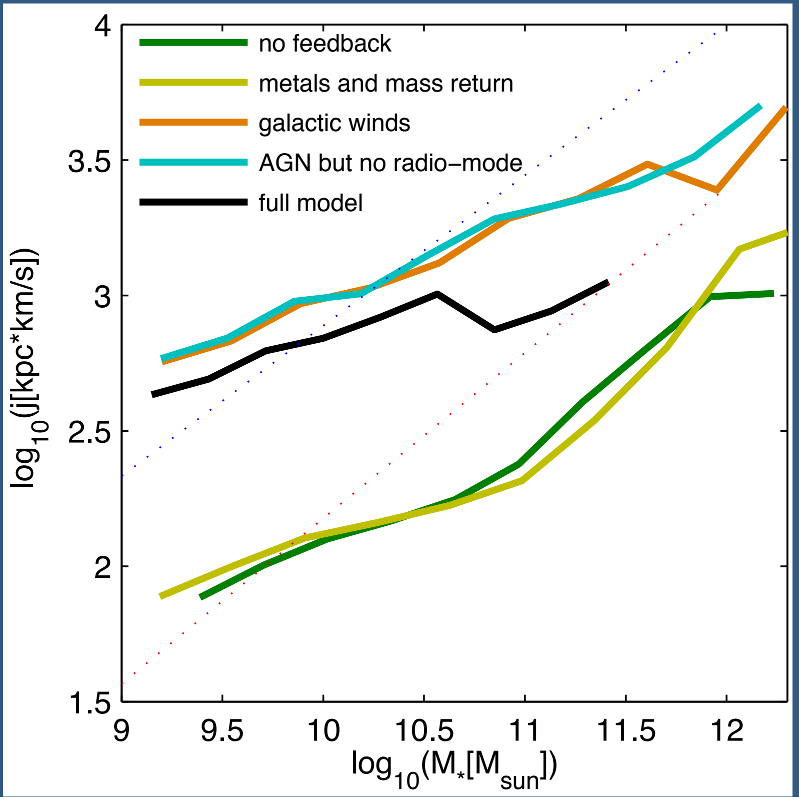
The role of feedback

- Enhancement/addition of feedback always makes galaxies larger
- But while galactic winds boost the angular momentum, radio-mode AGN feedback reduces it

size



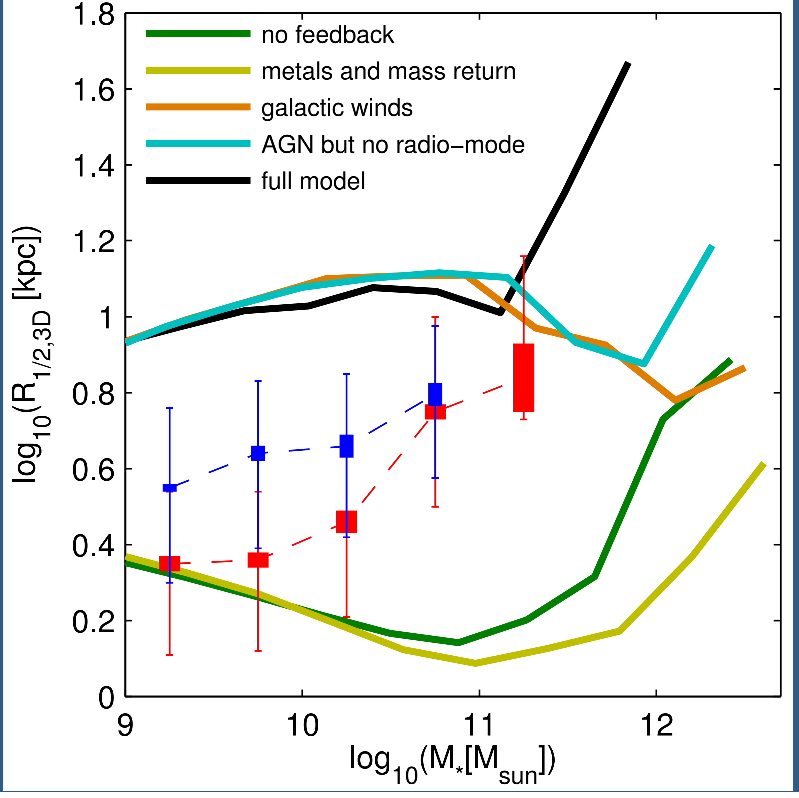
angular momentum



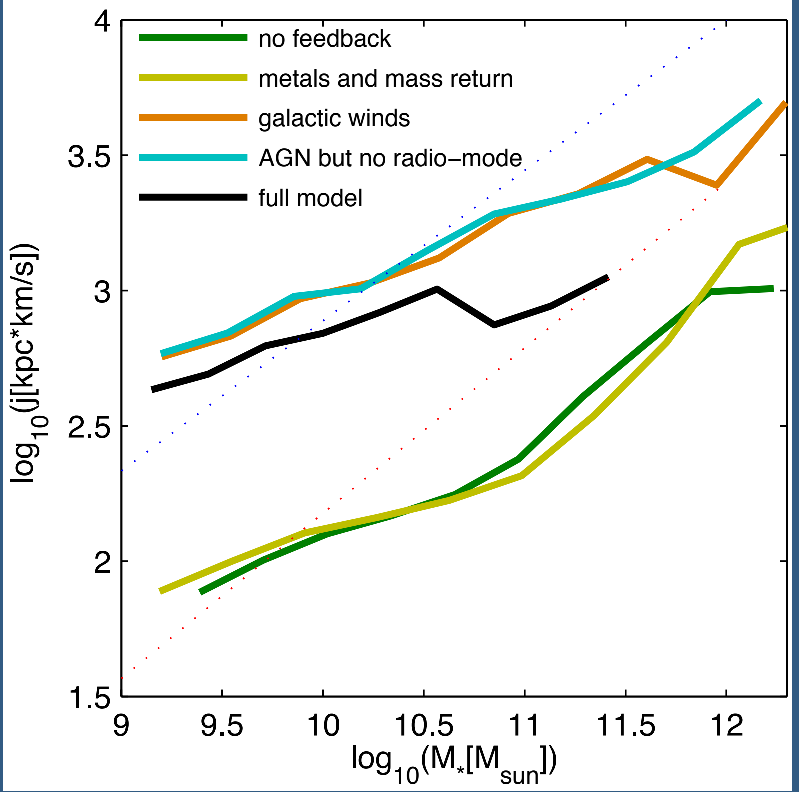
The role of feedback

- Galactic winds remove early-accreting low-J gas, generating fountain
- Galactic winds do not disrupt the rotation support of the disk
- Therefore, galactic winds increase sizes via increase of angular momentum

size



angular momentum



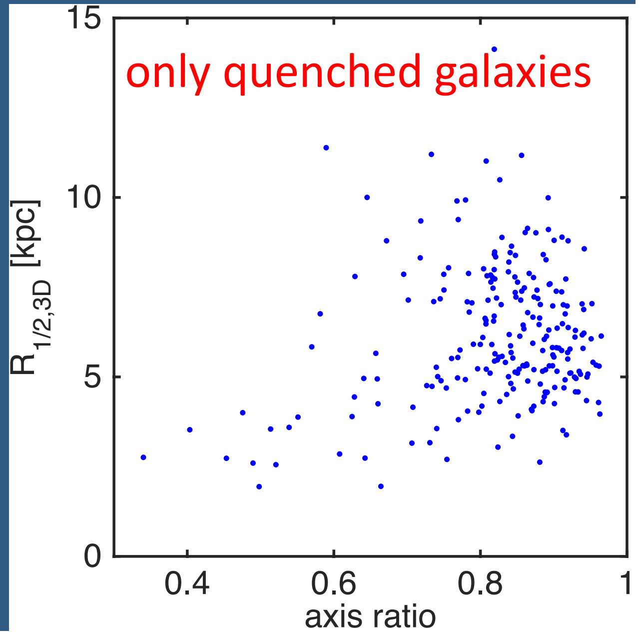
The role of feedback

- AGN feedback:
  - Makes galaxies dry, reducing dissipation during mergers, thus forcing sizes up
  - Causes adiabatic expansion via gas ejection

  (but which??)
- AGN feedback prevents late-accreting high-J gas, thus reducing angular momentum
- The result: dispersion-dominated galaxies

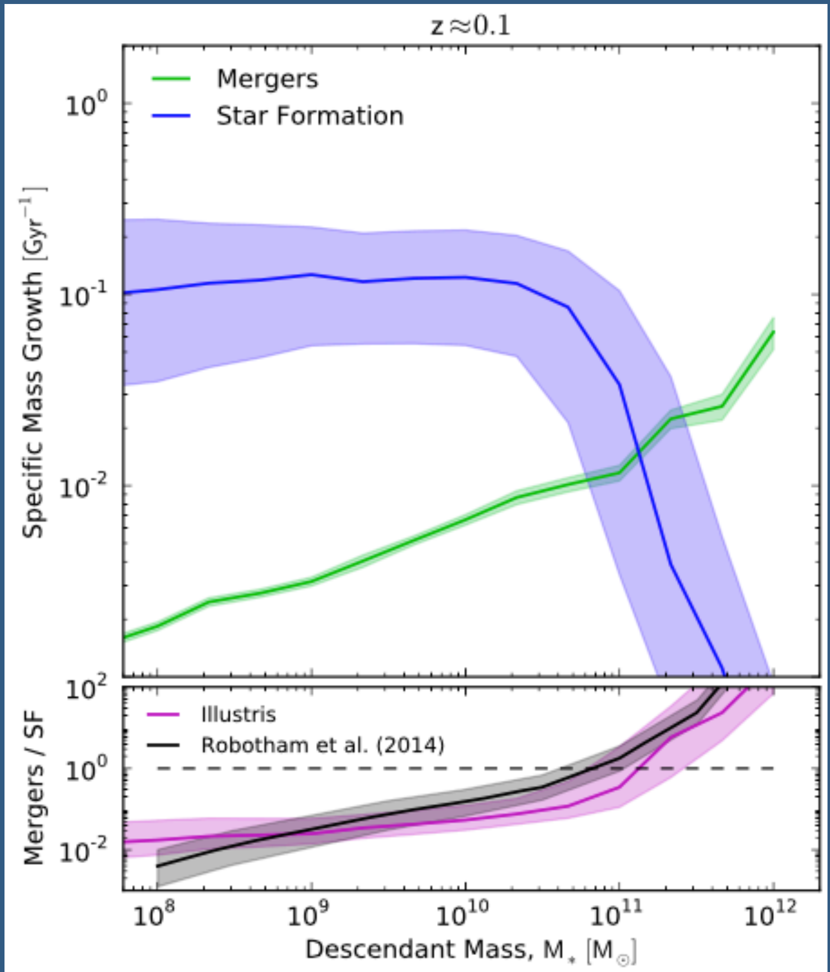
=> Does the type of dominant feedback determine the galaxy morphology?

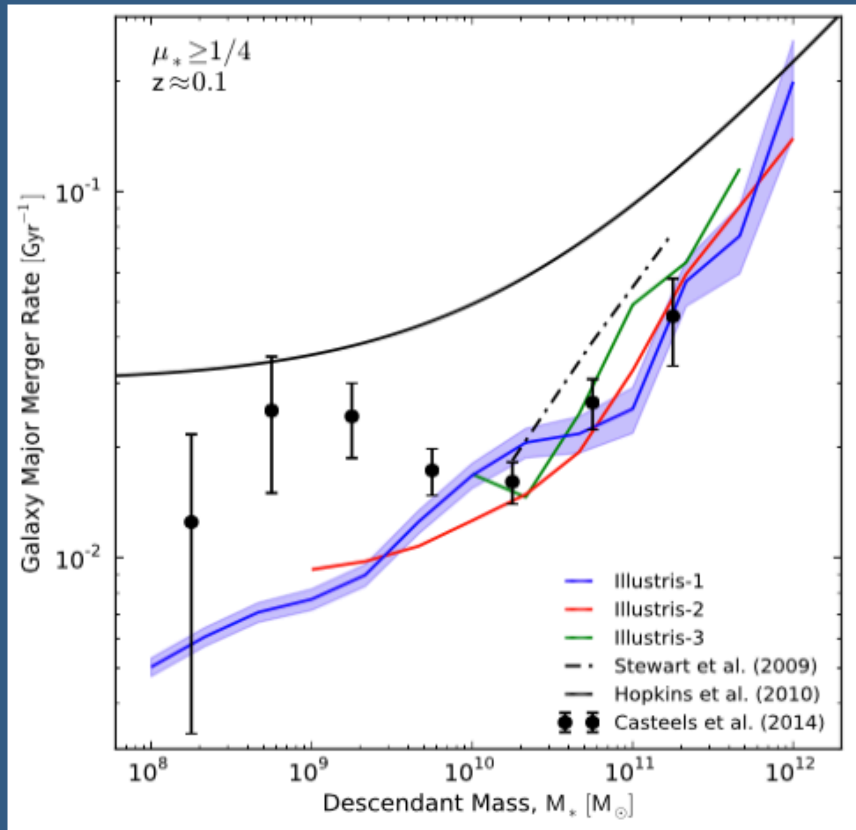
More AGN feedback: more quenched, larger, more elliptical (is this observed?)



The role of mergers

Rodriguez-Gomez et al. 2015





The pressing questions

- What separates the SFing and quiescent galaxies, as observed?

  dissipation before quenching?

- Why does the quiescent relation steepen so strongly, as observed?

  many more mergers at higher masses? More AGN feedback?

- Why do quiescent, as well as massive, galaxies, evolve faster, as observed?

  AGN feedback?

- Why are the simulated galaxies generally larger than observed?

  too efficient fountain?

Additional discussion points

- Better to work in 'theory space', with comparisons to observations made by converting observables to physical quantities as well as possible
- How much are we missing when we ignore the "ICL"?
- The type of dominant feedback determines the galaxy morphology?
- How important is AGN feedback in giving rise to dry mergers?
- How robust are simulated galaxy sizes, and their dependence on feedback subgrid recipes?