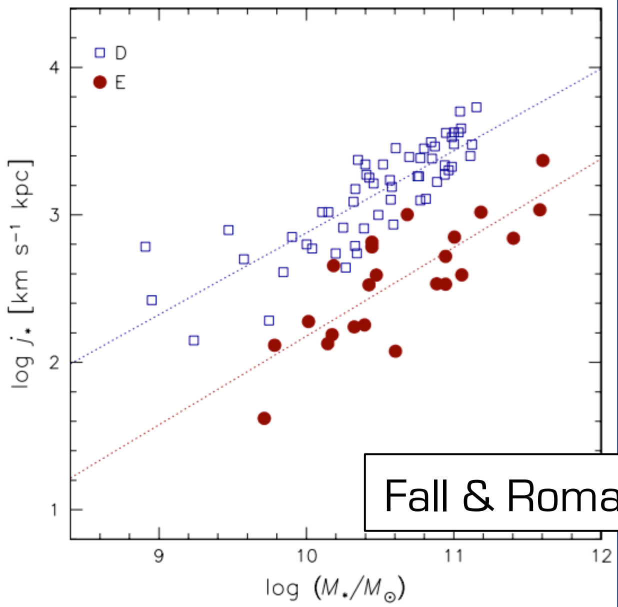
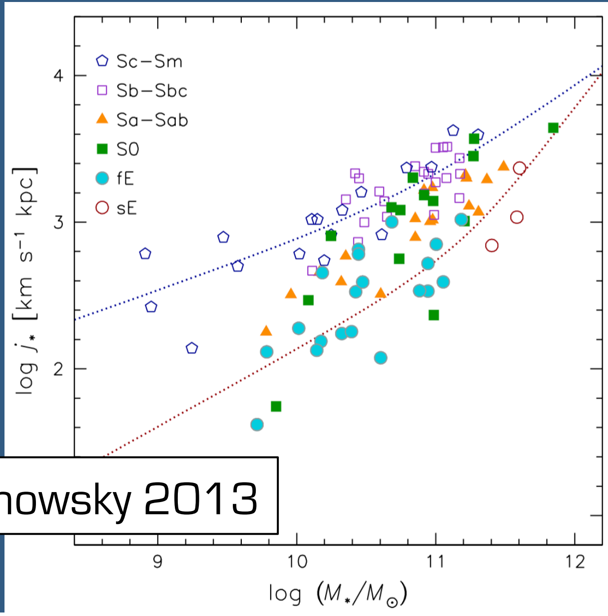
Galactic winds and the angular momentum of simulated disk galaxies

Shy Genel
Hubble Fellow
Columbia University

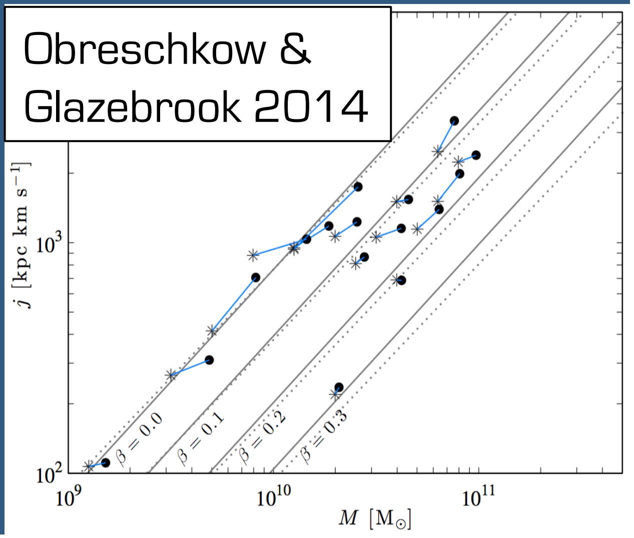
Introduction

- The stellar specific angular momentum ($j=J_*/M_*$) correlates with galaxy mass with a slope ≅0.6-1
- An observed relation between the morphological classification and this fundamental physical quantity
- Simple models relating galaxies to dark matter halos suggest "retention factors" of ~80% for disks and ~10% for ellipticals
- But there is some overlap => are disks = galaxies with high angular momentum?





Fall & Romanowsky 2013



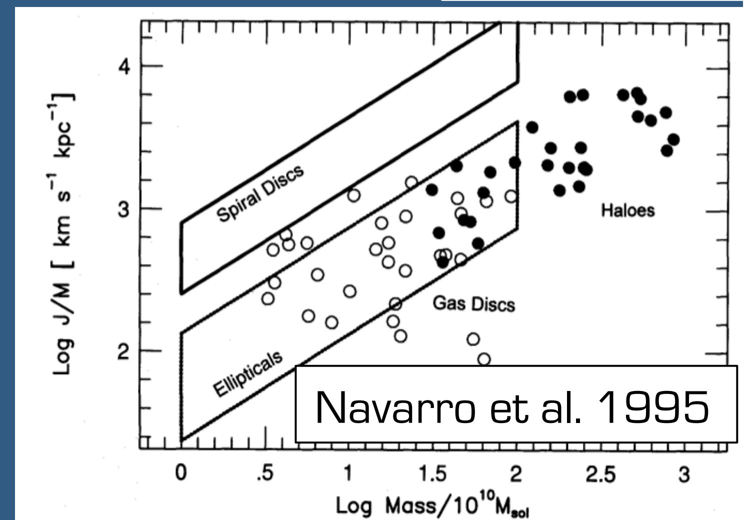
Obreschkow & Glazebrook 2014

Introduction

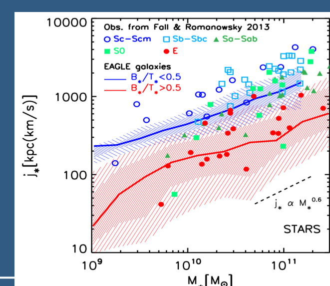
The theoretical challenge for cosmological simulations:

- Reproduce separate relations for different morphological types
- And their scatter
- Populate the “disks” region of high angular momentum
- Understand what model ingredients lead to population-level success and how unique they are
- Understand what sets the angular momentum content of any particular simulated galaxy

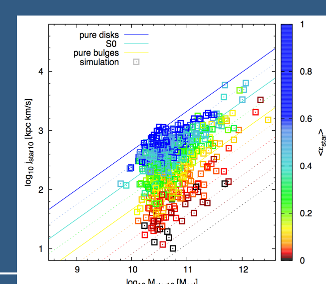
‘Catastrophe’



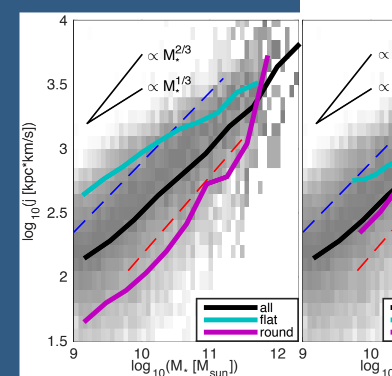
Navarro et al. 1995



Eagle



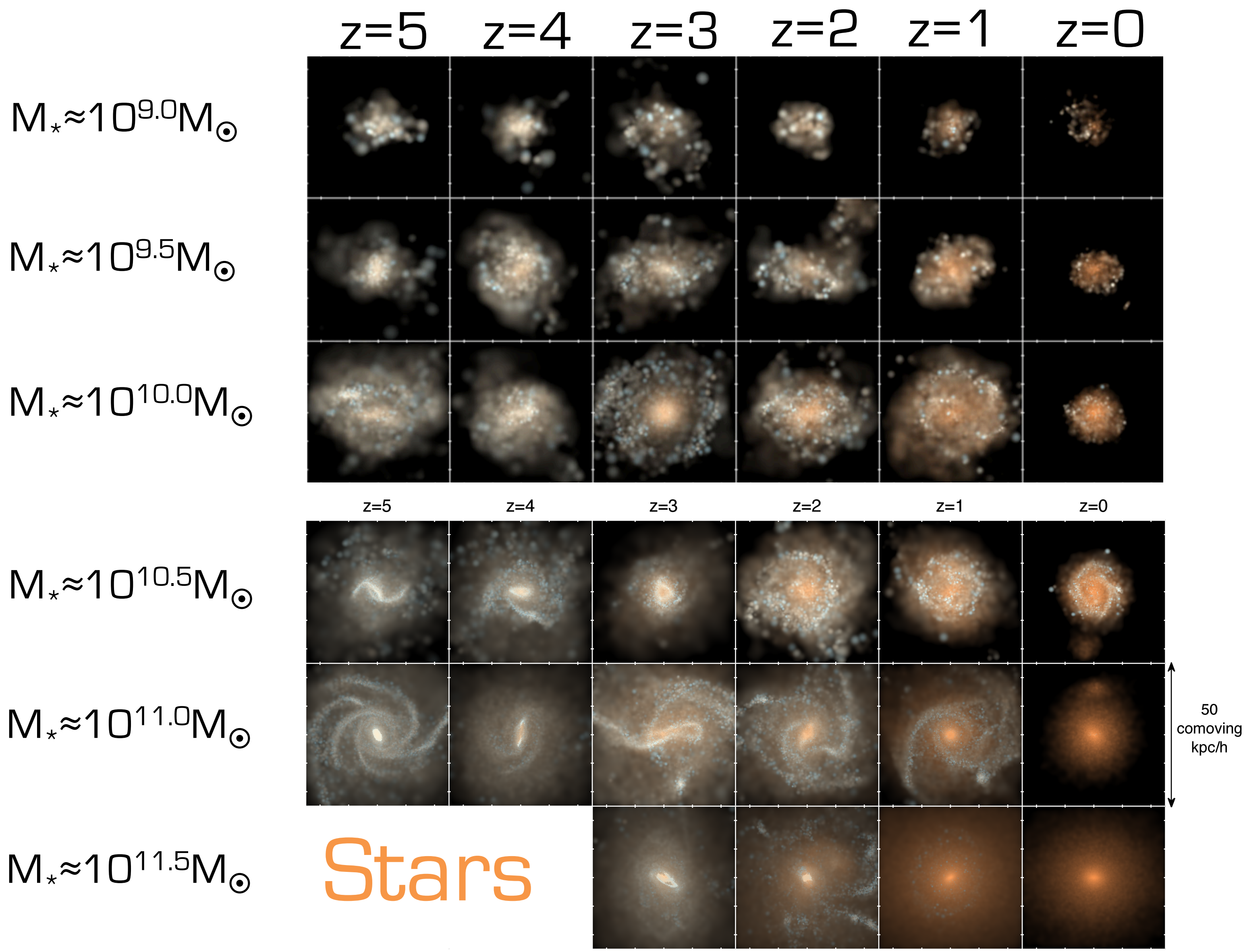
Magnetium



Illustris

Illustris @ $0 \le z \le 5$

Genel et al. 2014

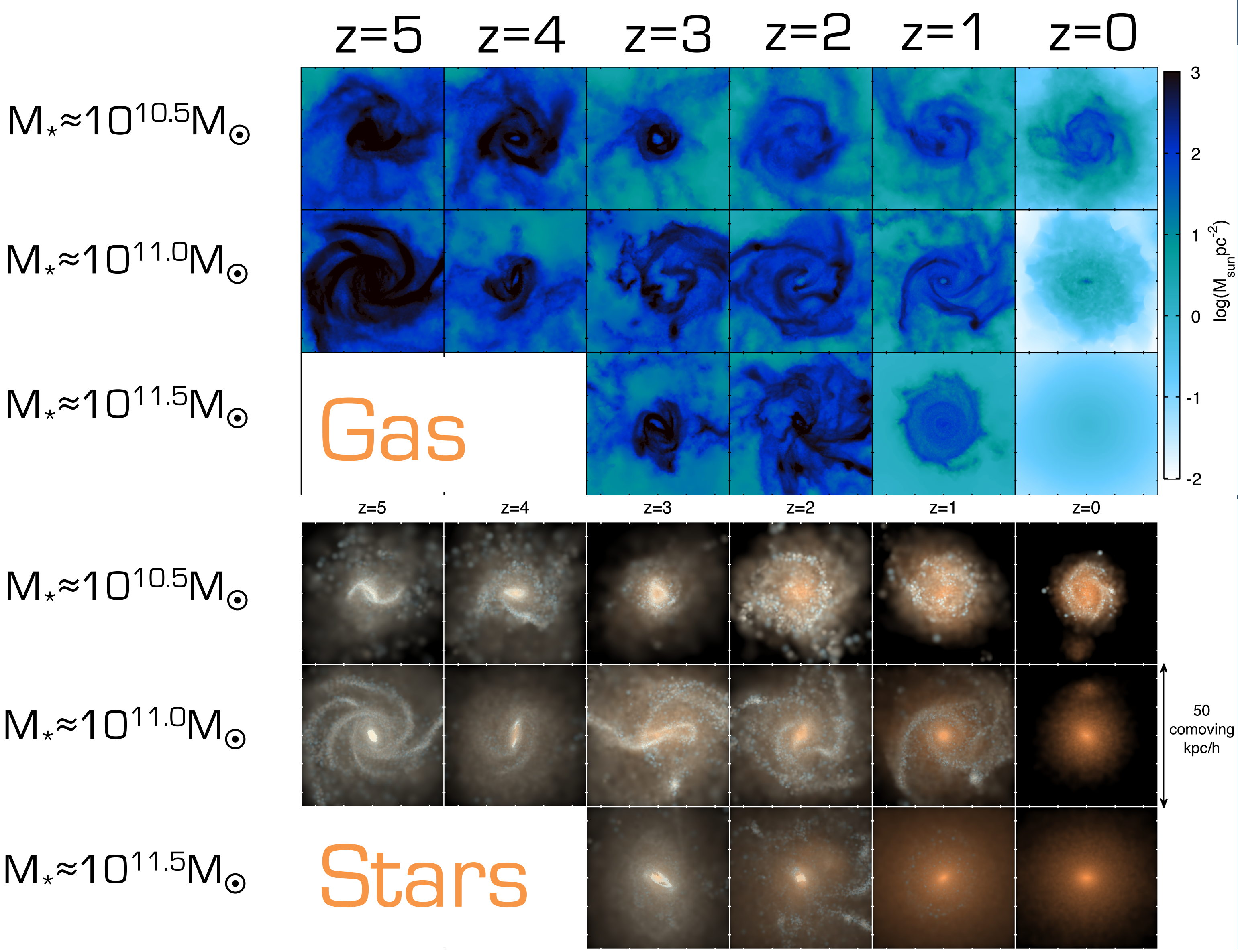


Spheroids emerging towards higher mass and/ or lower z

(all panels have same size in comoving units)

Illustris @ 0 ≤ z ≤ 5

Genel et al. 2014



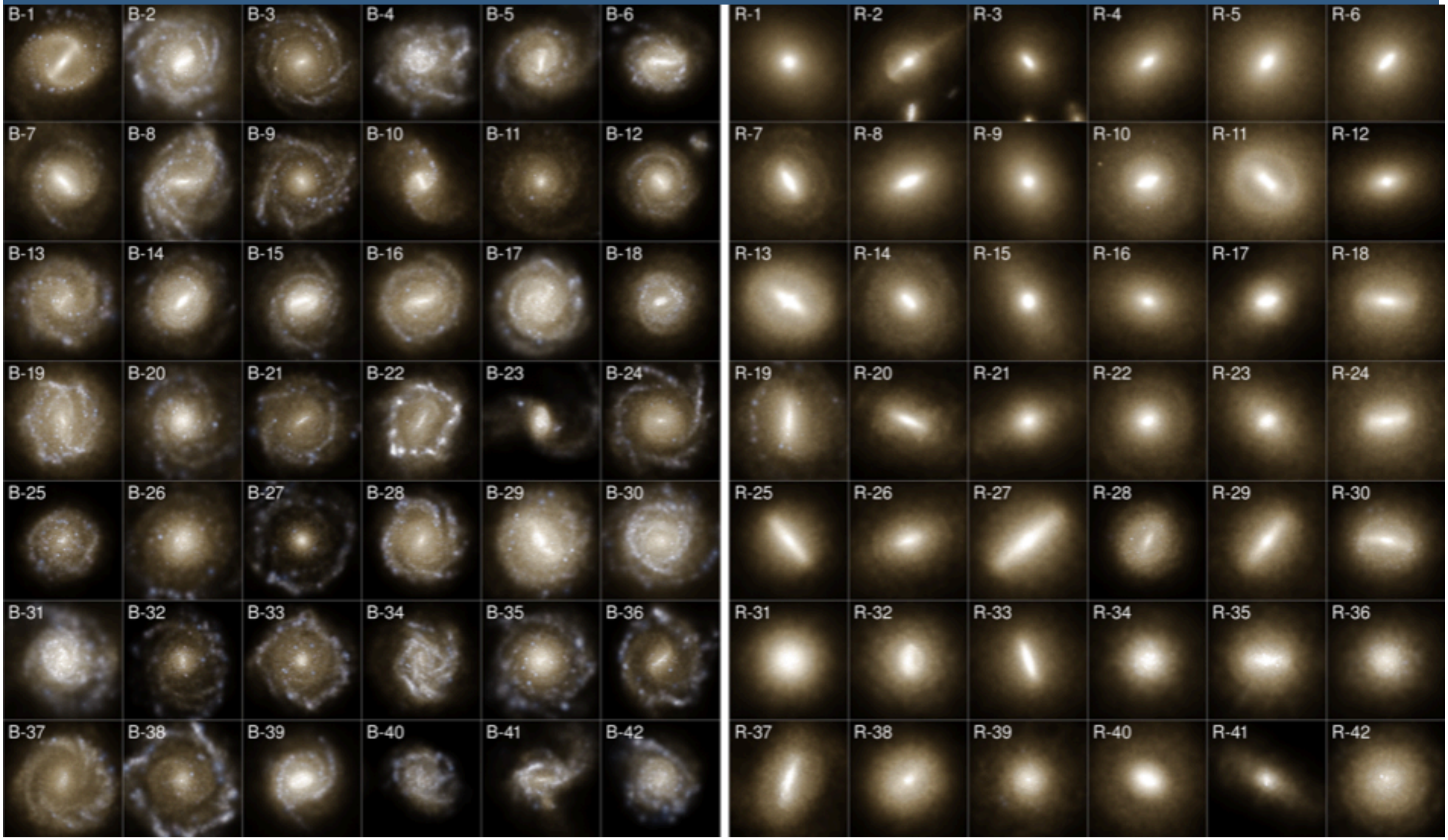
Gas depleted/ ejected towards higher mass at lower z

(all panels have same size in comoving units)

Vogelsberger et al. 2014

Illustris - Galaxy bimodality

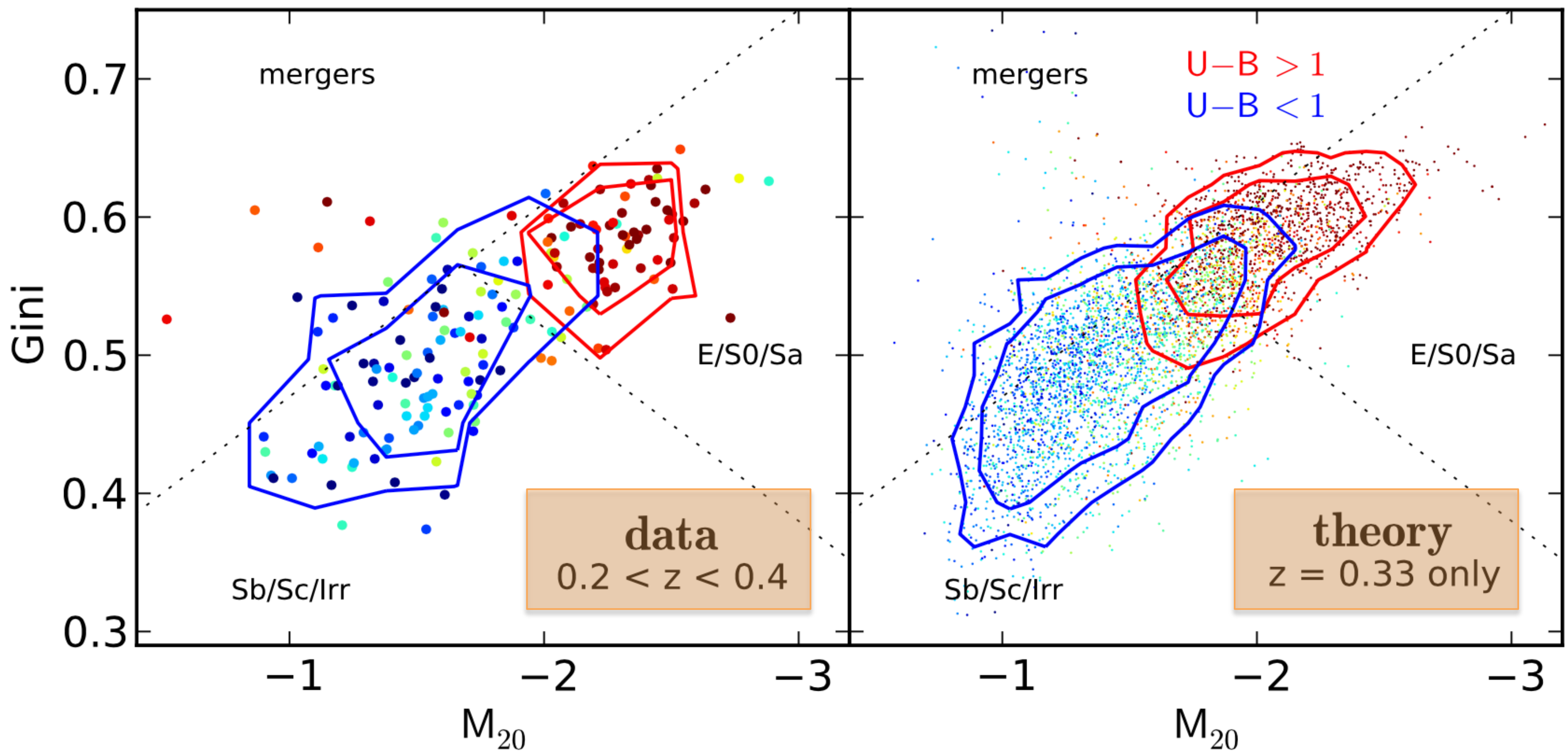
Galaxies in $10^{12\text{-}13}M_{\odot}$ halos at z=0



Snyder et al. 2015

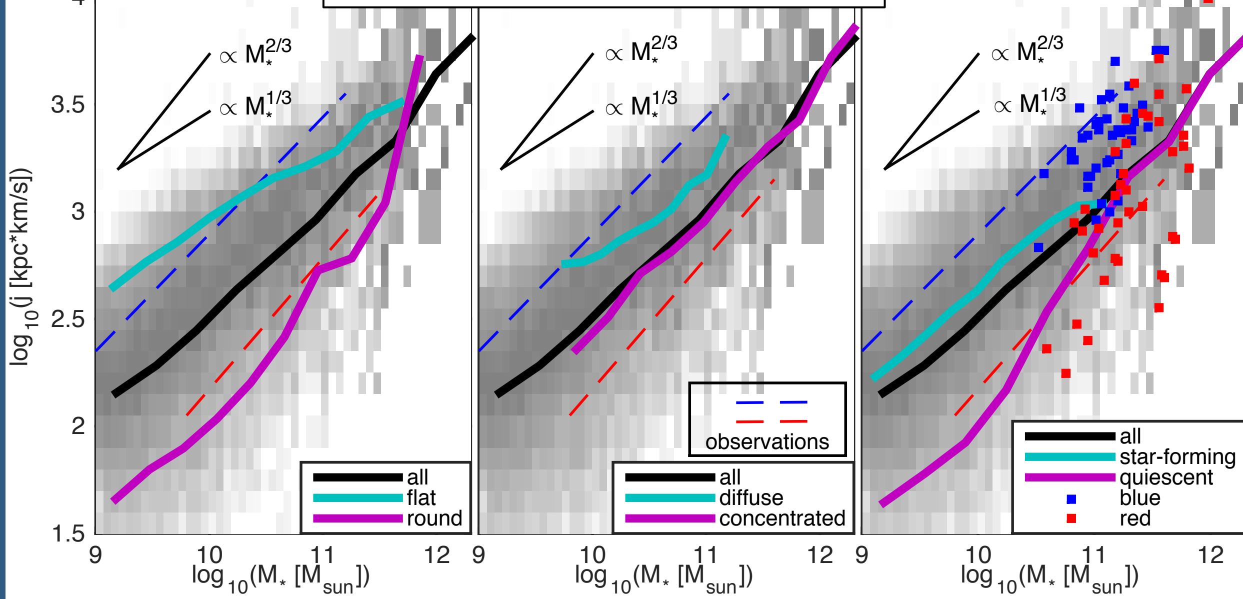
Morphological classification

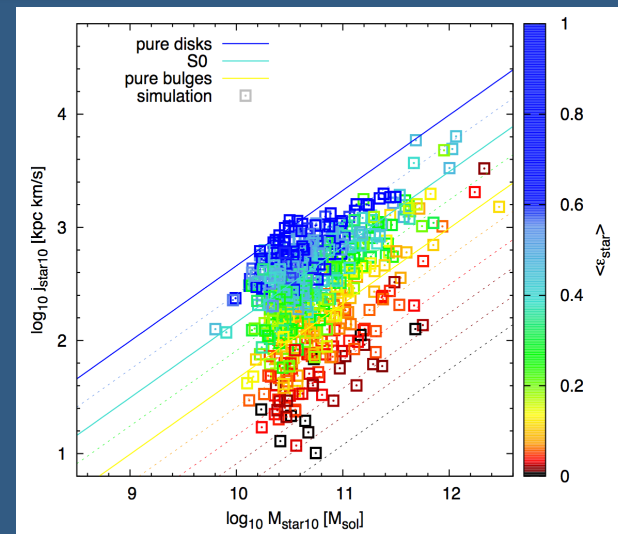
Non-parametric morphological classification for the low redshift galaxy population compares favorably with observations



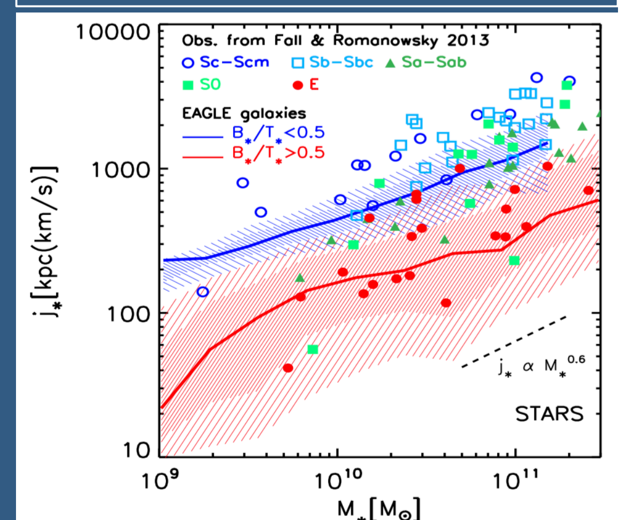
The current status of simulations

Genel et al. 2015 - Illustris



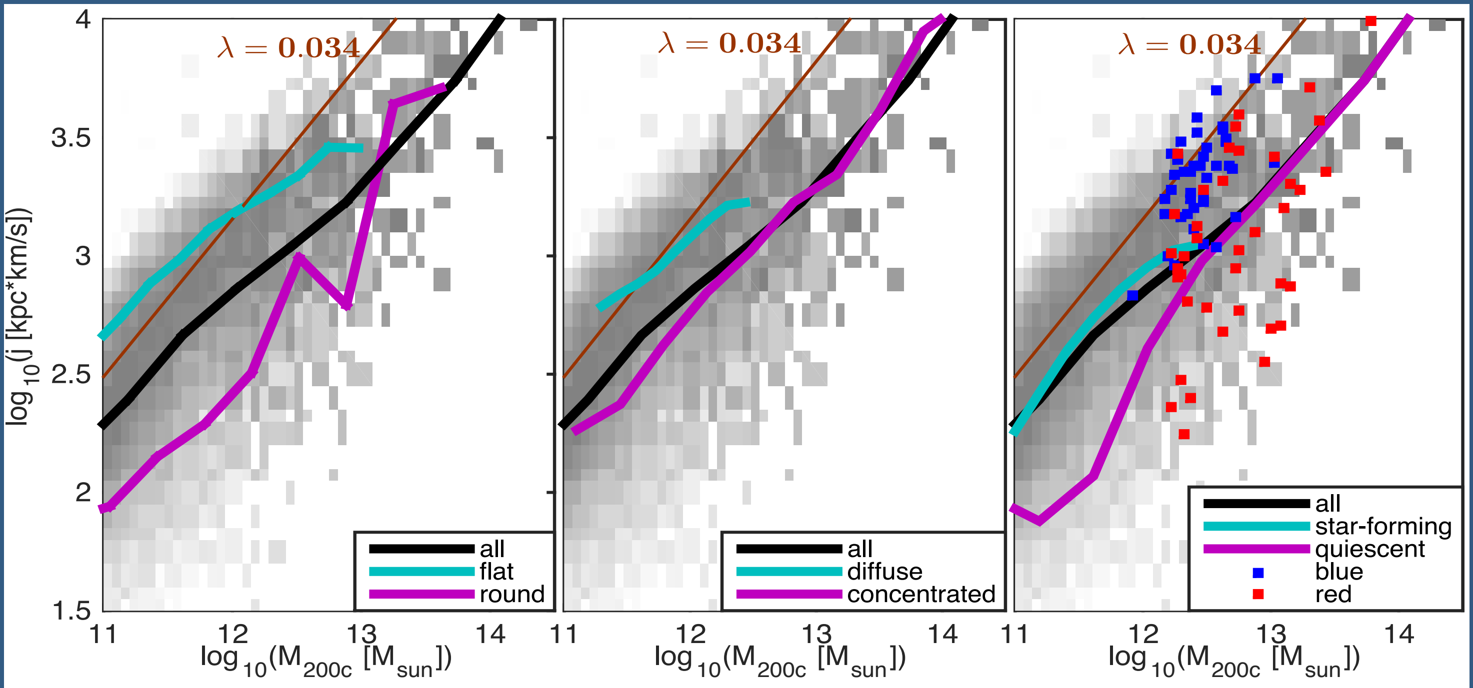


Teklu et al. 2015 - Magneticum
Zavala et al. 2016 - Eagle



- The stellar specific angular momentum correlates with galaxy mass with a slope close to (2/3)
- Shape, concentration & SFR separate relations
- Simulations are probably still 0.2-0.3dex below the observed late-type relation

The current status of simulations

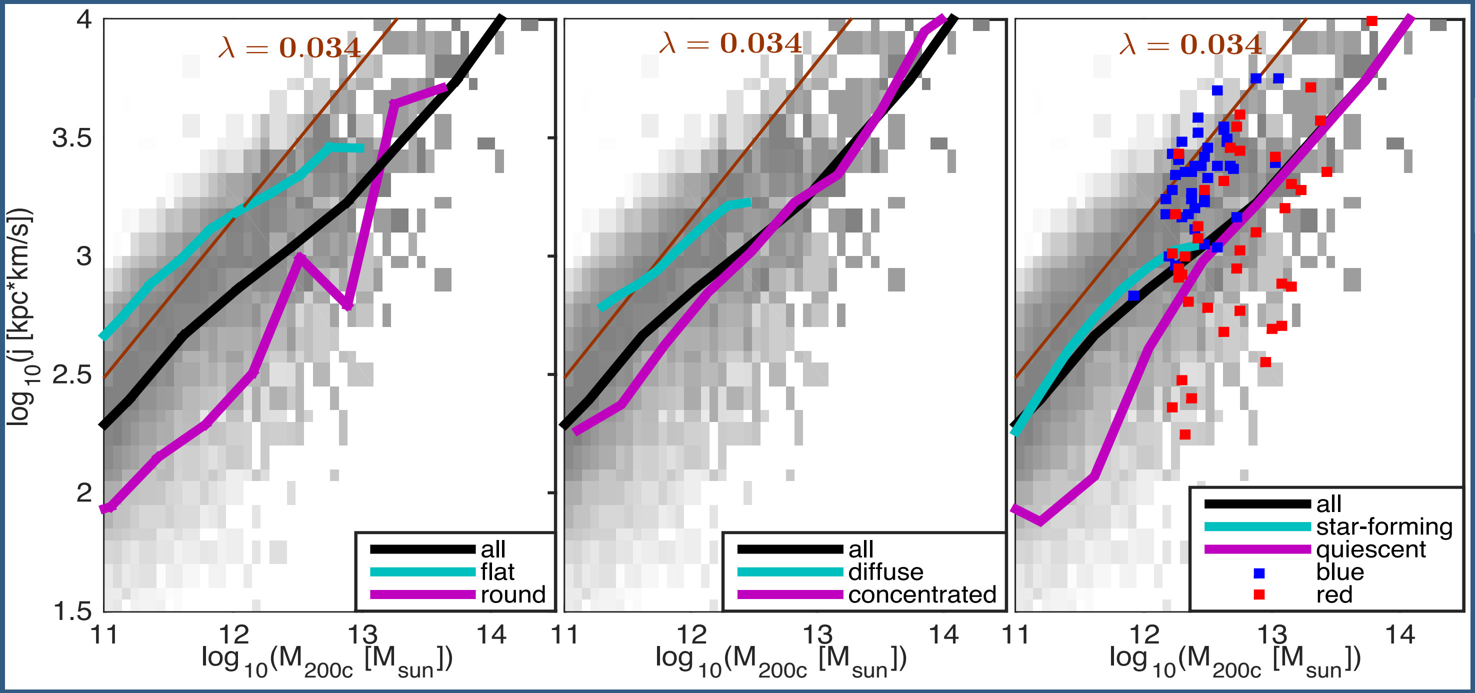


Genel et al. 2015

Placing M_{halo} instead of M_* on the x-axis allows comparison with simple theory:

- Late-types are consistent with having 80-100% of the mean specific angular momentum of dark matter halos
- Early-types retain ≈15-50%

The current status of simulations



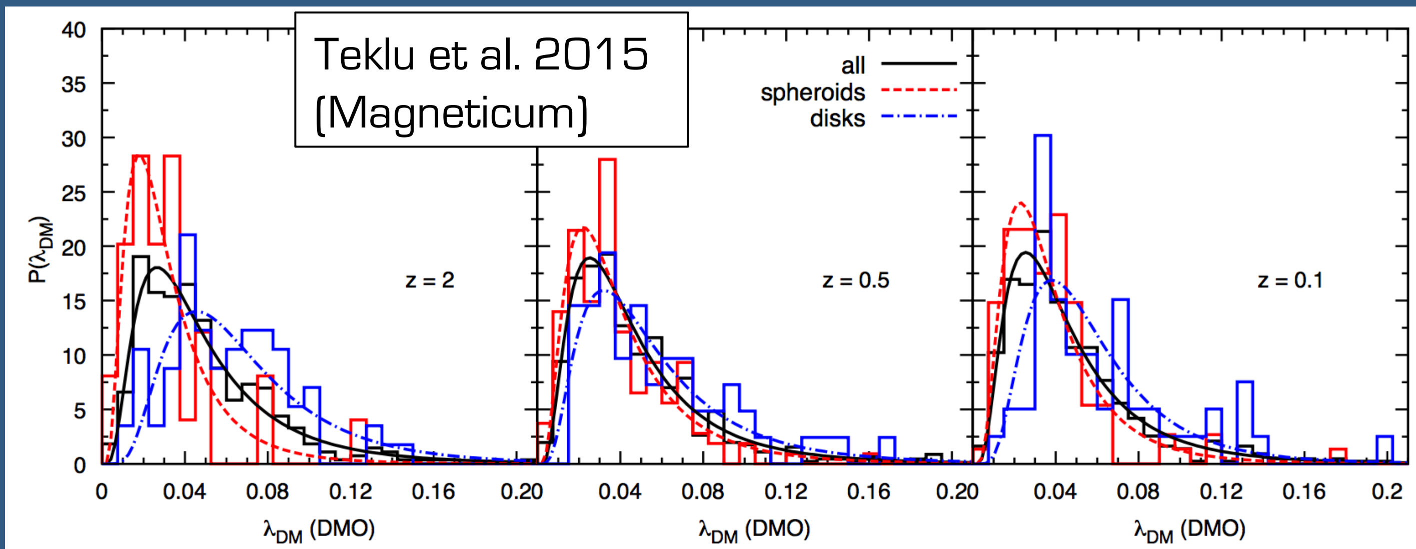
Genel et al. 2015

- Why do late-types appear as if they have a ~100% retention factor?

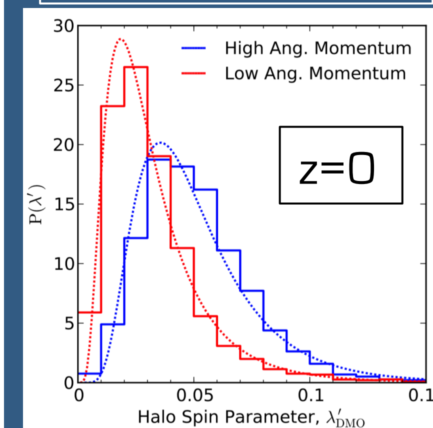
(A. Dekel, R. Bower talks – coincidence?)

- What is the actual role of cosmological tidal torques?
- What role does the merger history play?
- How is feedback related?

Correlation with halo spin

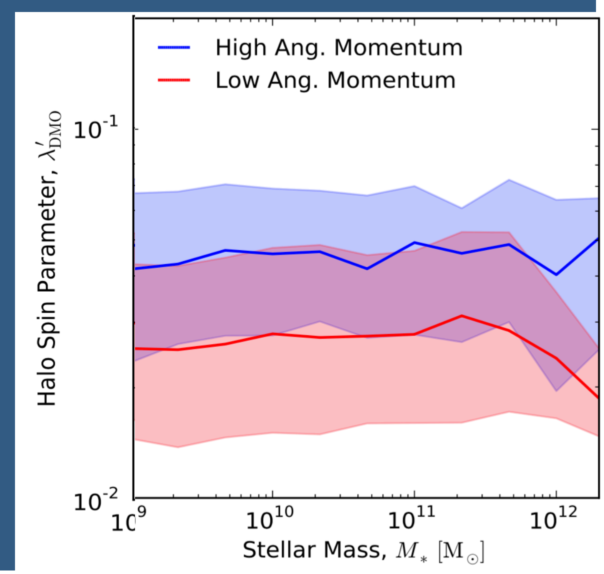


Rodriguez-Gomez et al. in prep (Illustris)



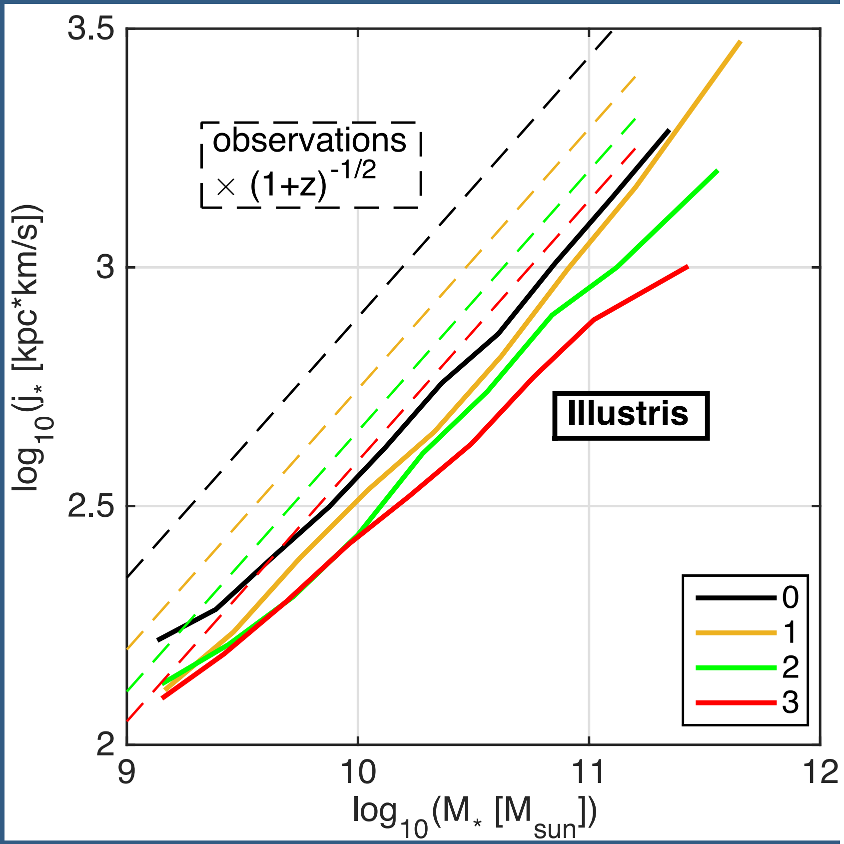
- In both Magneticum and Illustris (also Eagle, Zavala et al. 2016), the DM halo spin (λ) distribution (in the DM-only run!) separates by the galaxy ‘stellar λ’

(compare to A. Dekel talk, where no per-galaxy correlation)



Evolution & correlation with halo spin

- The scaling with redshift approximately matches the scaling for DM halos: $(1+z)^{-1/2}$ – i.e. angular momentum retention is approximately redshift-independent
- Though in detail, the evolution for galaxies is weaker than for halos
- Possible interpretations:
    - Accumulated loss inside galaxies over time
    - Weaker galaxy-halo coupling at later times



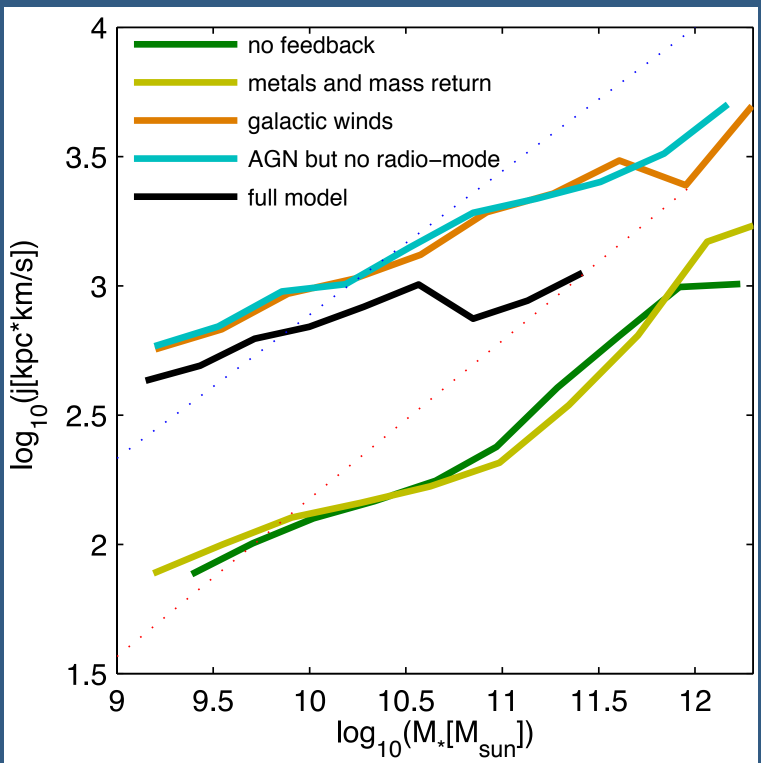
Observations at high-z (Burkert+, Contini+) so far probing star-forming gas, not yet stars

Genel et al. 2015

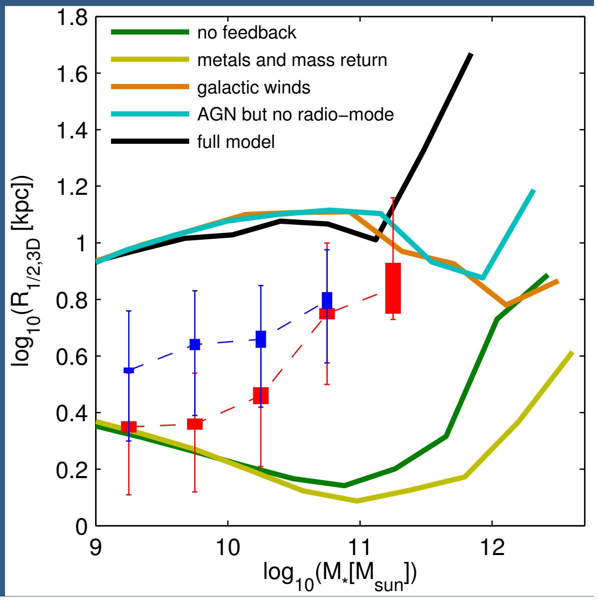
The role of feedback

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

angular momentum



size

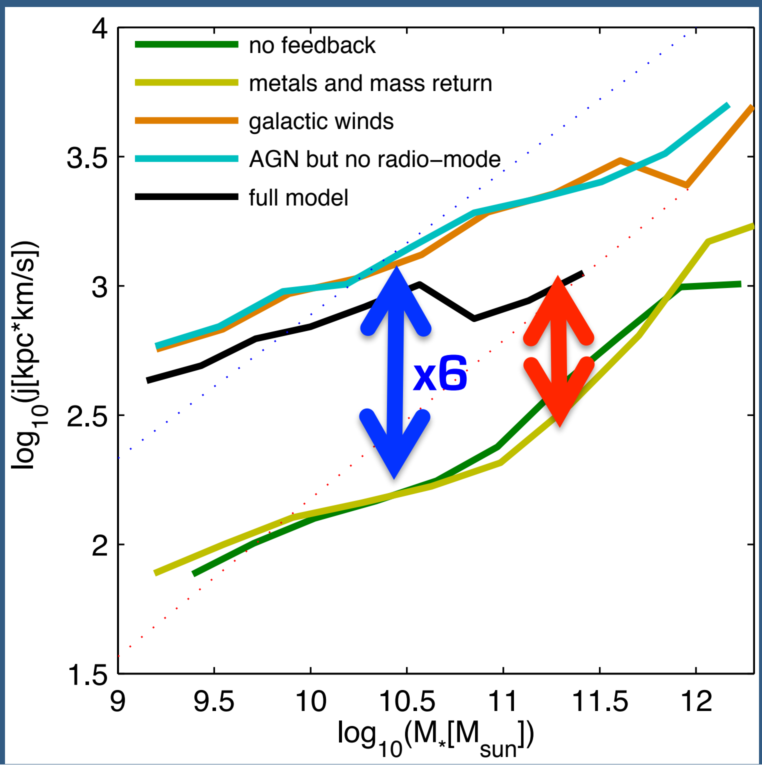


Genel et al. 2015

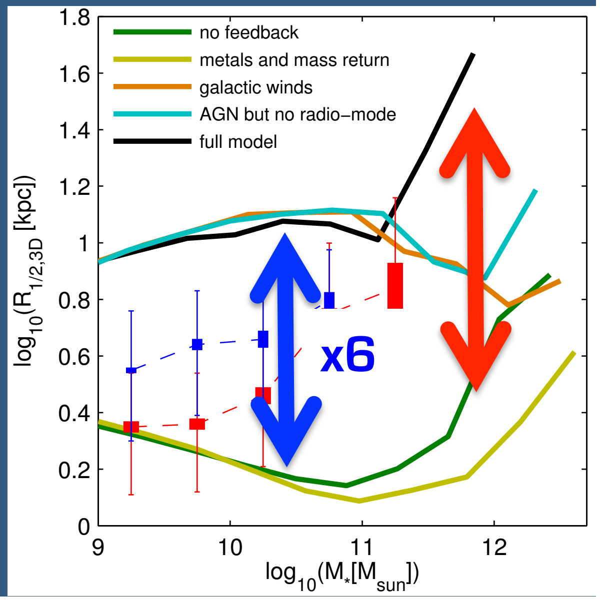
The role of feedback

- At $M_*<10^{11}M_\odot$, the angular momentum and size change similarly with feedback, i.e. in all simulations, $M_*<10^{11}M_\odot$ galaxies are rotation-dominated
- Only at $M_*>10^{11}M_\odot$, AGN FB decouples size and angular momentum, leading to dispersion-dominated galaxies. How? Dry mergers.

angular momentum

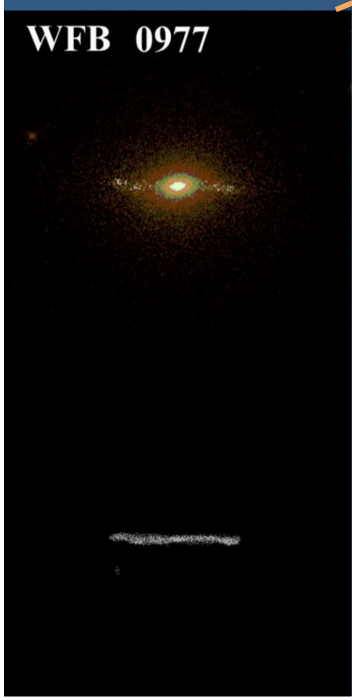


size



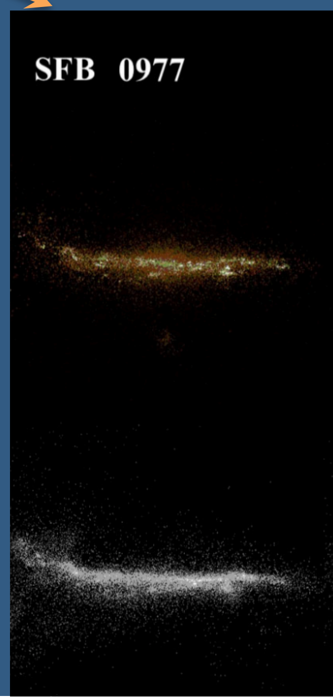
The role of feedback

- Galactic winds make nice, big disks
- AGN feedback (indirectly) destroys them



Galactic wind feedback

(Übler et al. 2014)



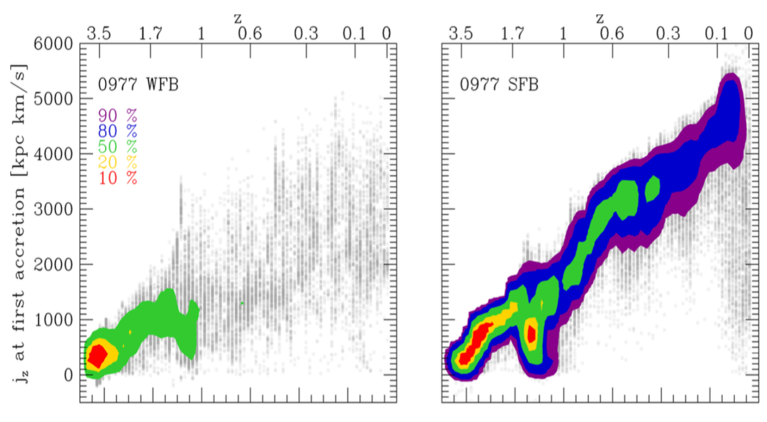
AGN feedback

(Dubois et al. 2013)

Winds and angular momentum

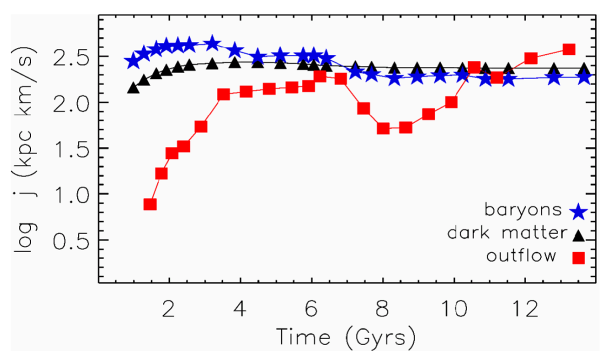
• Promotion of later accretion that has higher angular momentum

(Übler et al. 2014)



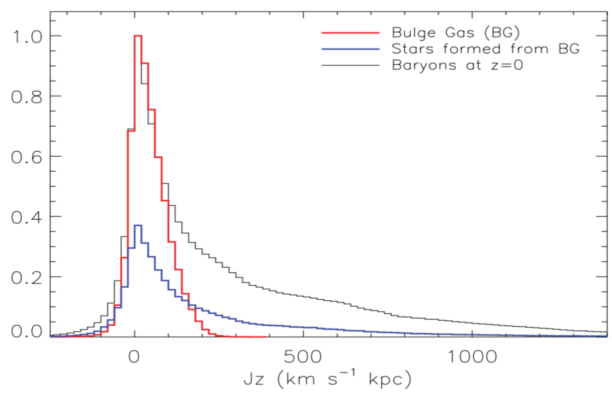
• Preferential ejection of low-j galaxy gas

(Governato et al. 2009)



• Re-accretion of previously-ejected gas after it gained angular momentum

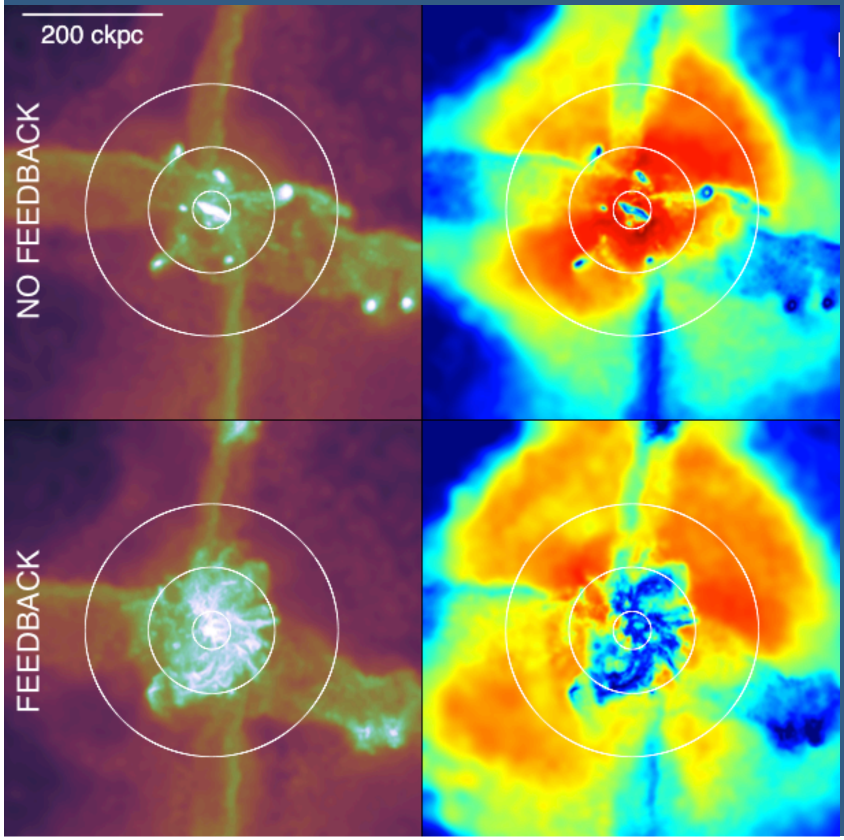
(Brook et al. 2012)

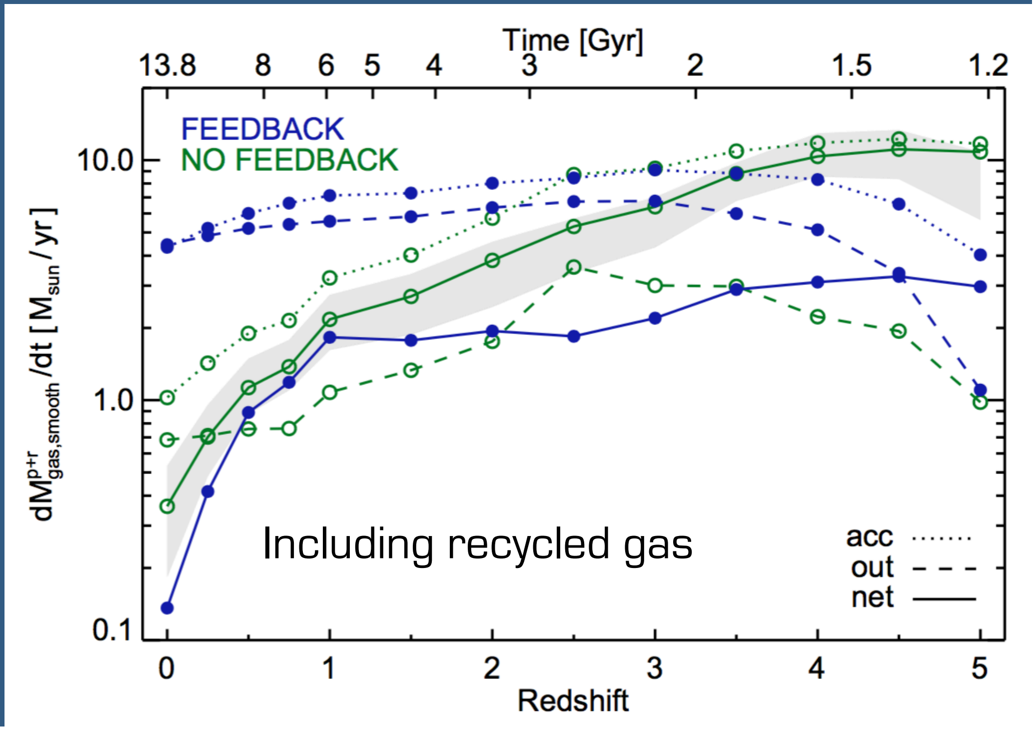


The baryon cycle

Nelson, Genel, et al. 2015

- Inside the halo ($r \lesssim 0.5R_{vir}$), galactic winds generate a ‘fountain’
- The outflow rate dramatically increases but so do inflows –
- While the net accretion decreases

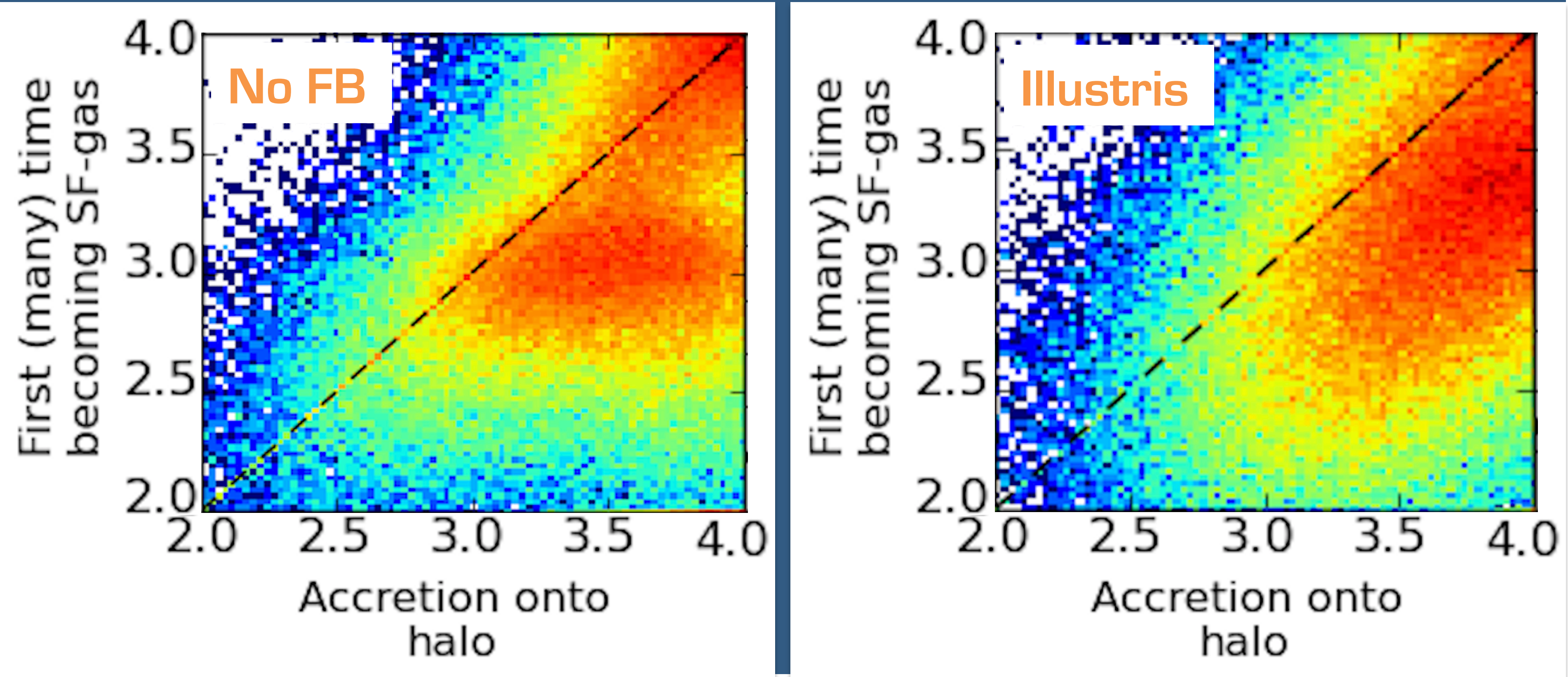




The baryon cycle and angular momentum

DeFellipis, Genel & Bryan in prep.

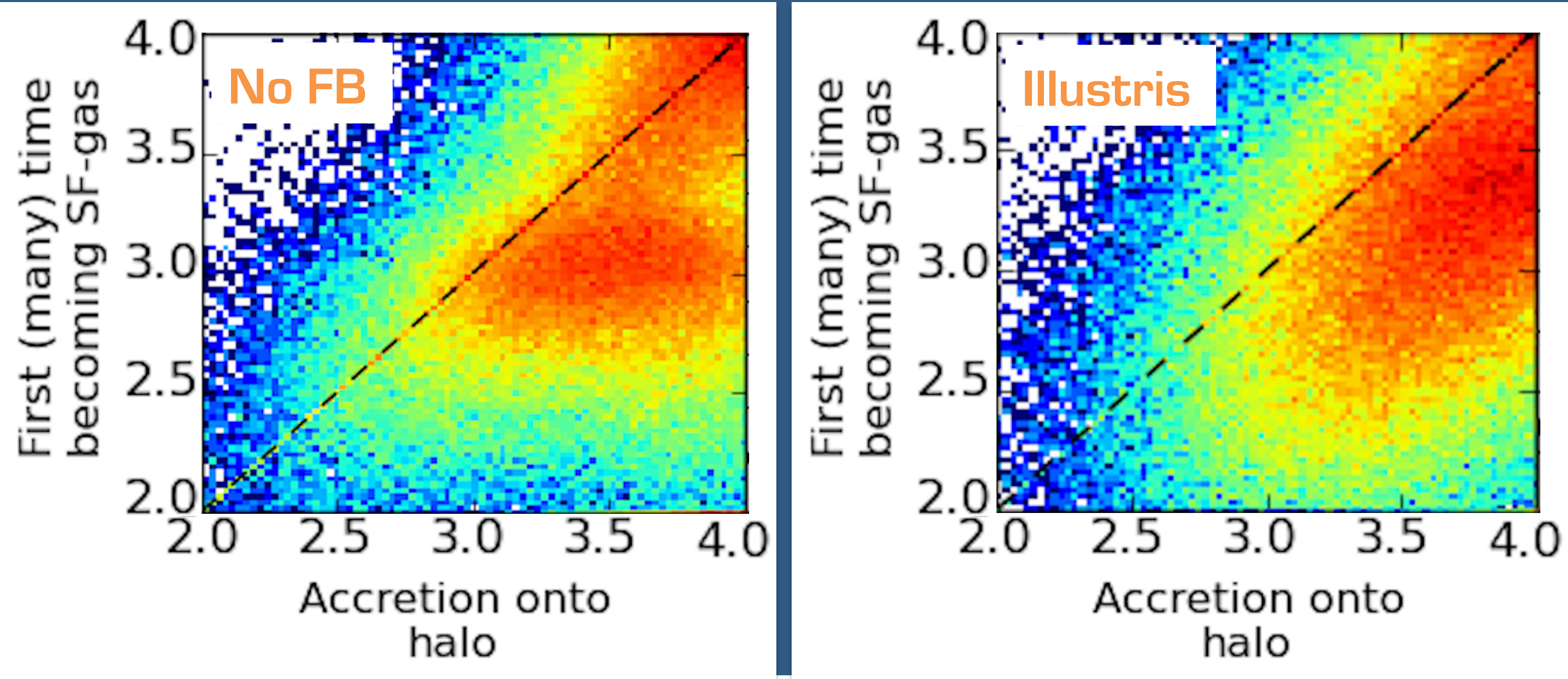
- A Lagrangian analysis of baryonic flows using Monte Carlo tracer particles (Genel et al. 2013)
- Comparison of the angular momentum of unique mass elements at different times, or ‘events’, in their evolution



The baryon cycle and angular momentum

- Without winds, larger losses from virial radius to the disk

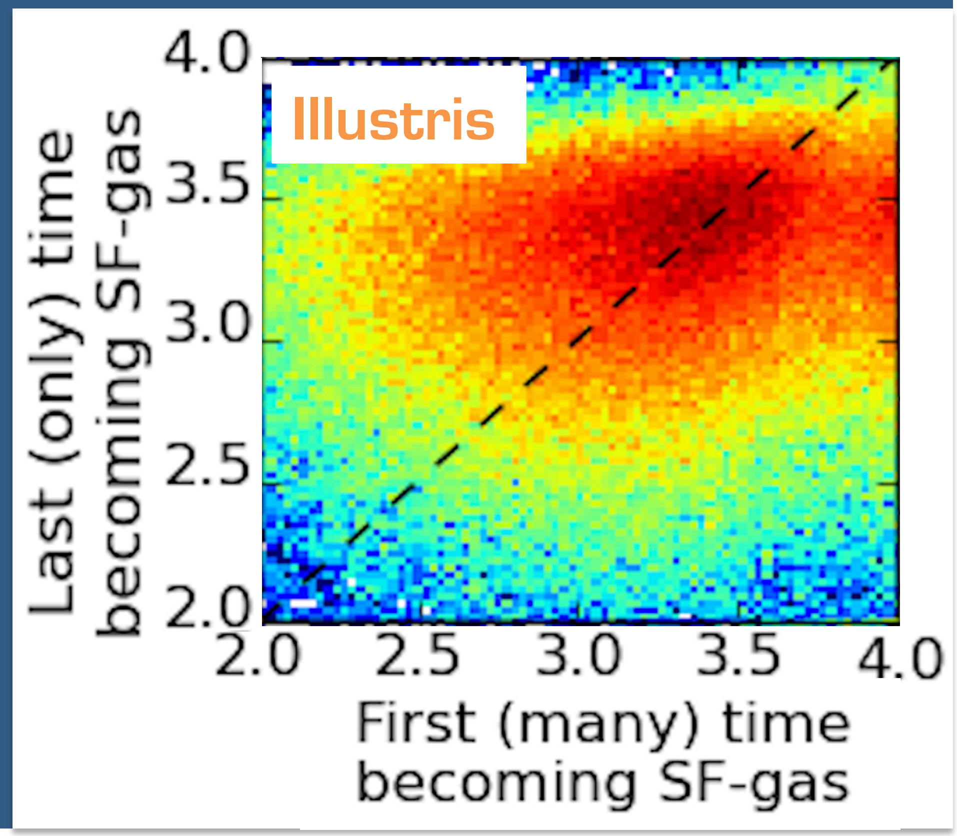
DeFellipis, Genel & Bryan in prep.



The baryon cycle and angular momentum

- Without winds, larger losses from virial radius to the disk
- With winds, ejected low-j gas gains before coming back

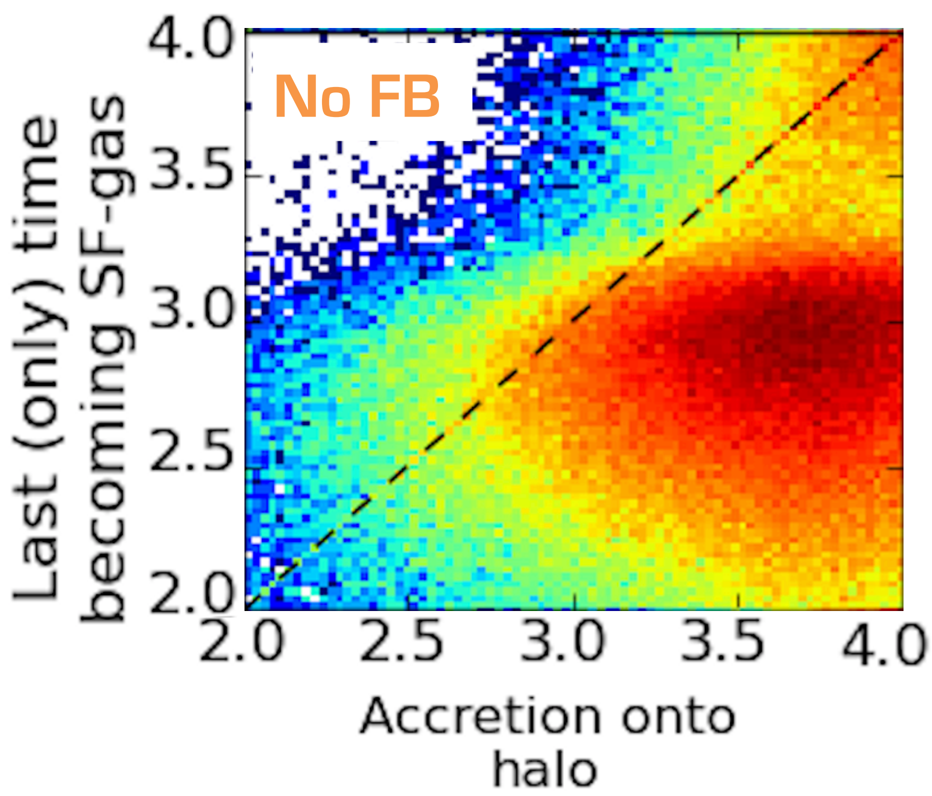
DeFellipis, Genel & Bryan in prep.

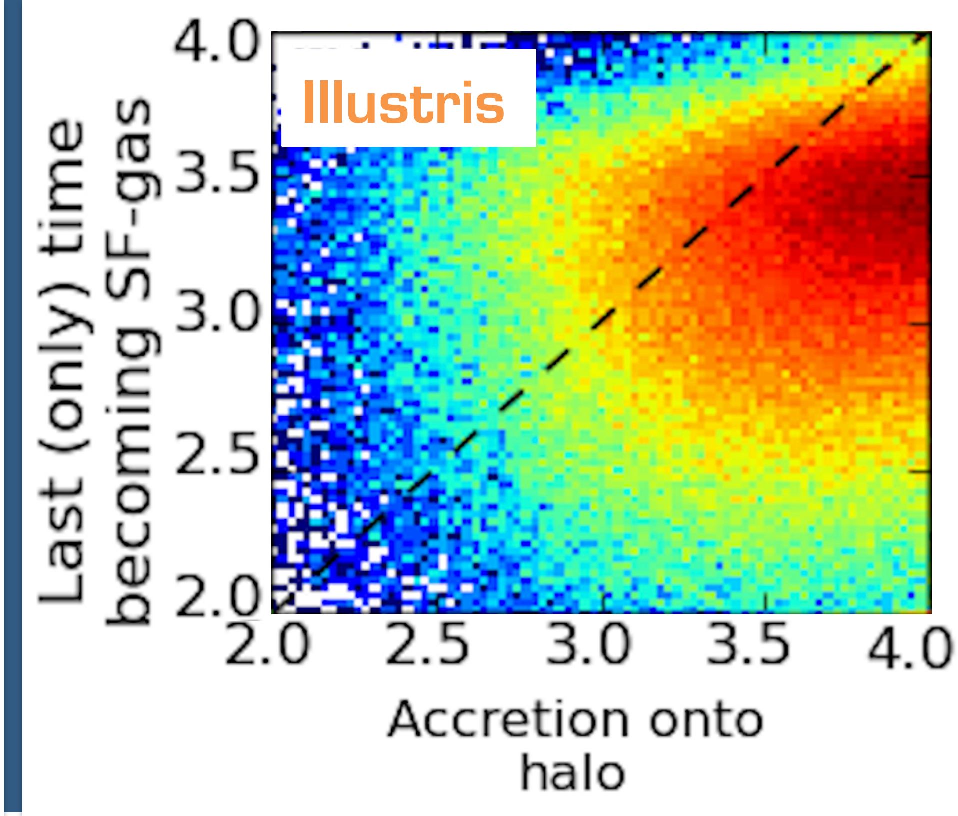


The baryon cycle and angular momentum

- Without winds, larger losses from virial radius to the disk
- With winds, ejected low-j gas gains before coming back
- Factor 3x difference at the last time of joining the disk

DeFellipis, Genel & Bryan in prep.

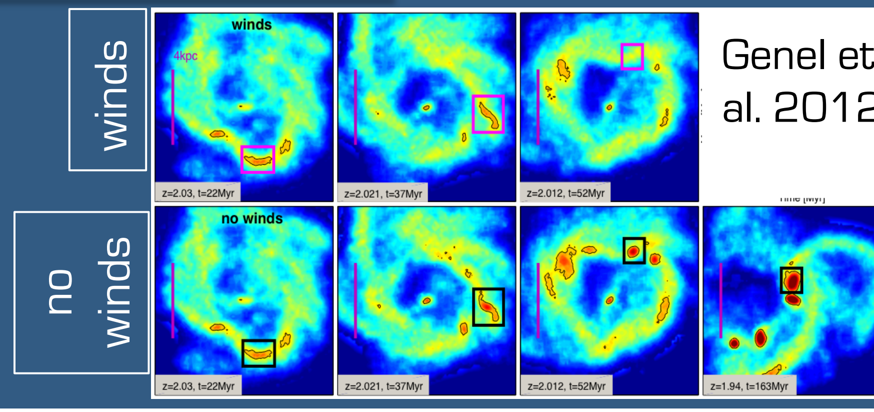




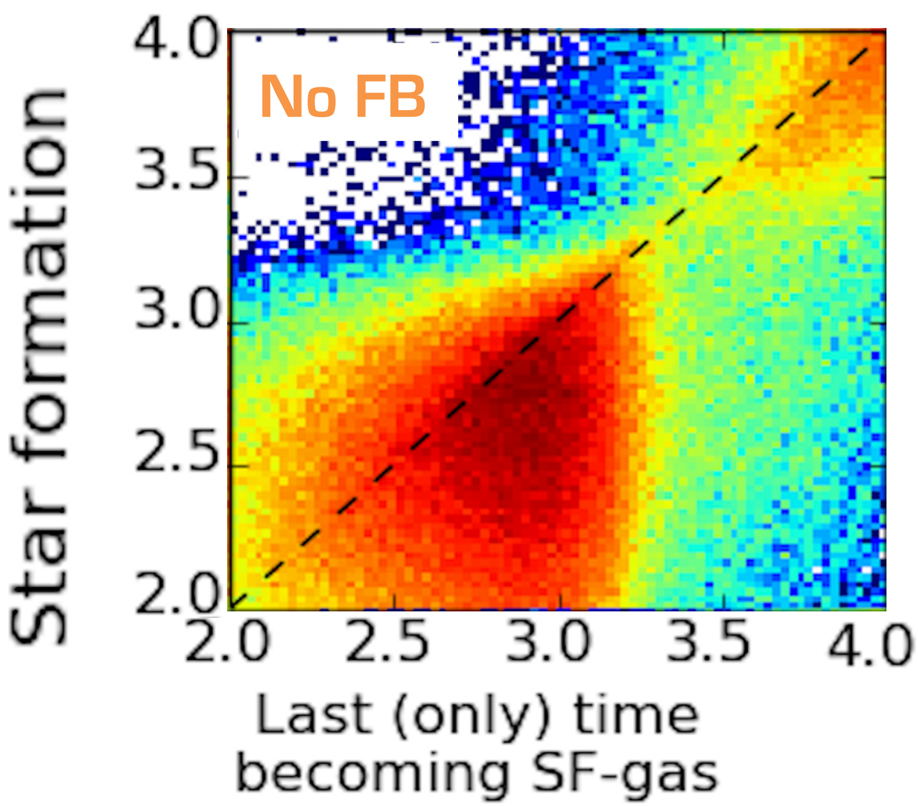
Internal losses

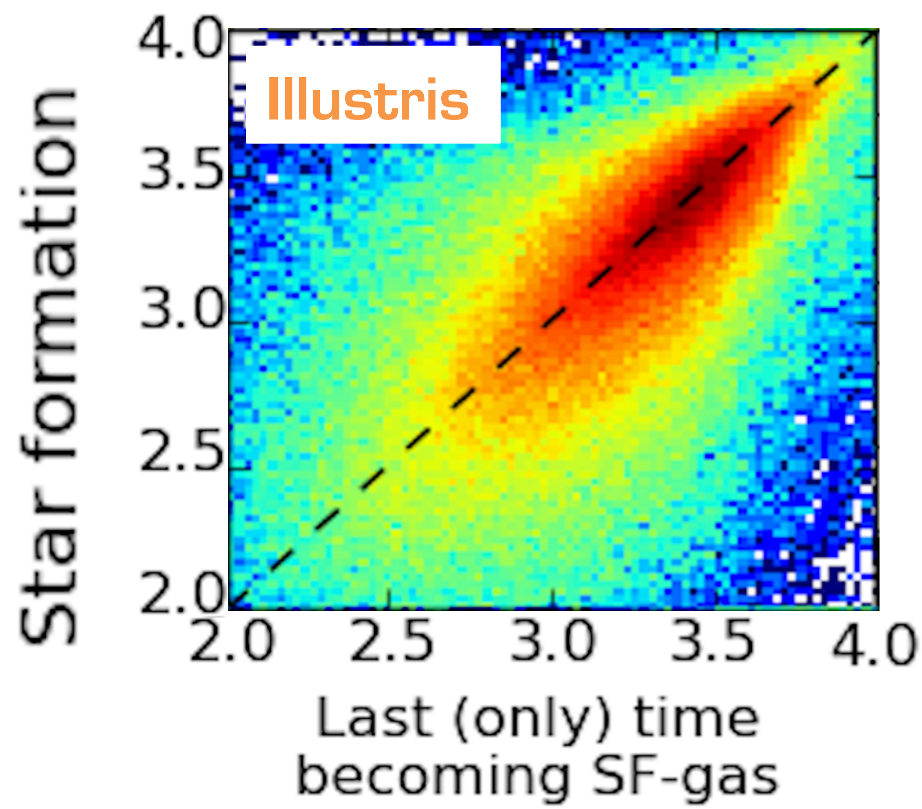
DeFellipis, Genel & Bryan in prep.

- Winds prevent losses within the disk due to dynamical friction and torques



Genel et al. 2012

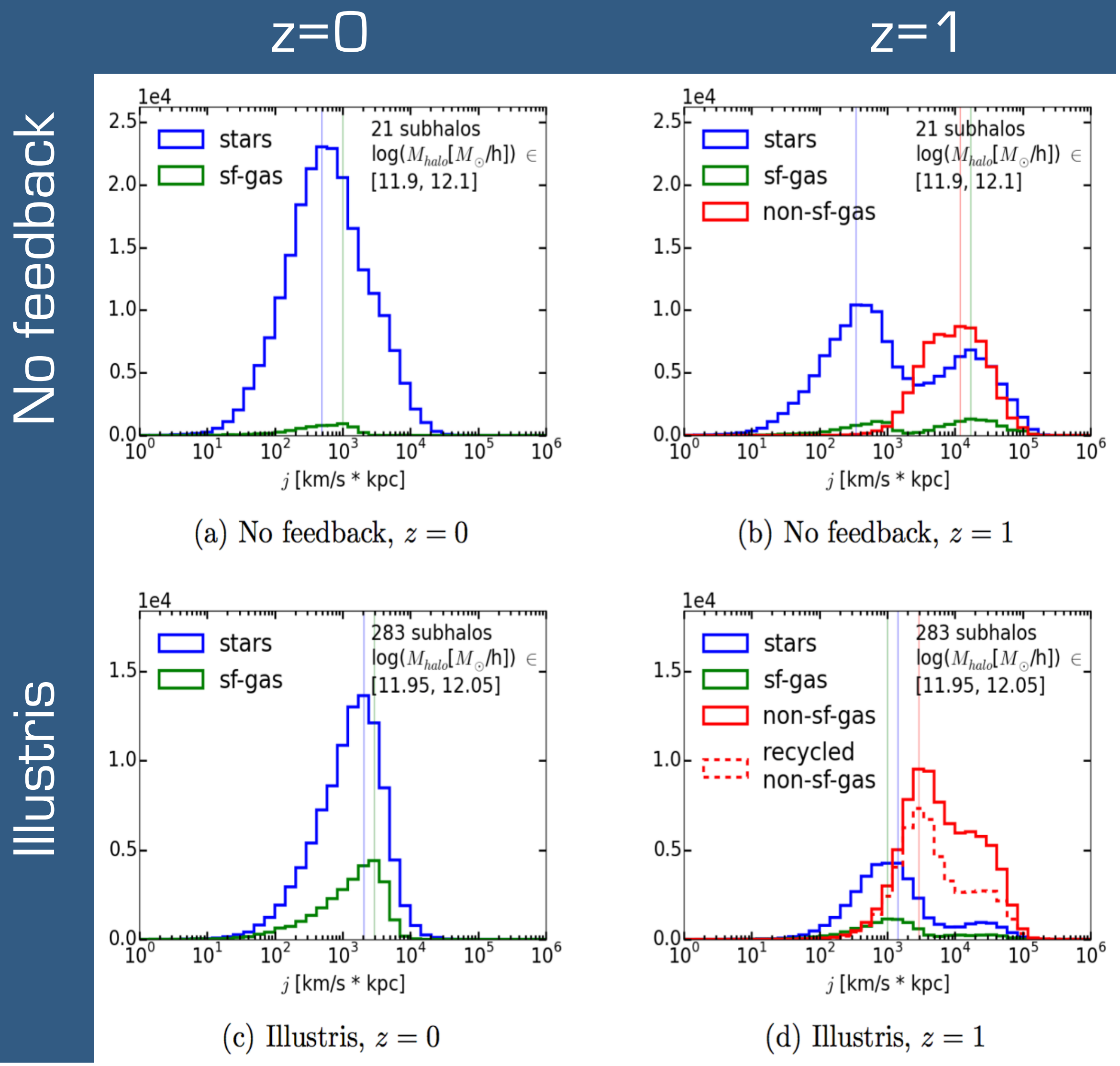




Galactic winds and CGM

DeFellipis, Genel & Bryan in prep.

- With feedback, the distribution of stellar angular momenta is shifted and skewed to higher values, already at z>1
- At z=1, there exists a large reservoir of (recycled) gas with angular momentum intermediate between central galaxy and satellites



(a) No feedback, $z = 0$

(b) No feedback, $z = 1$

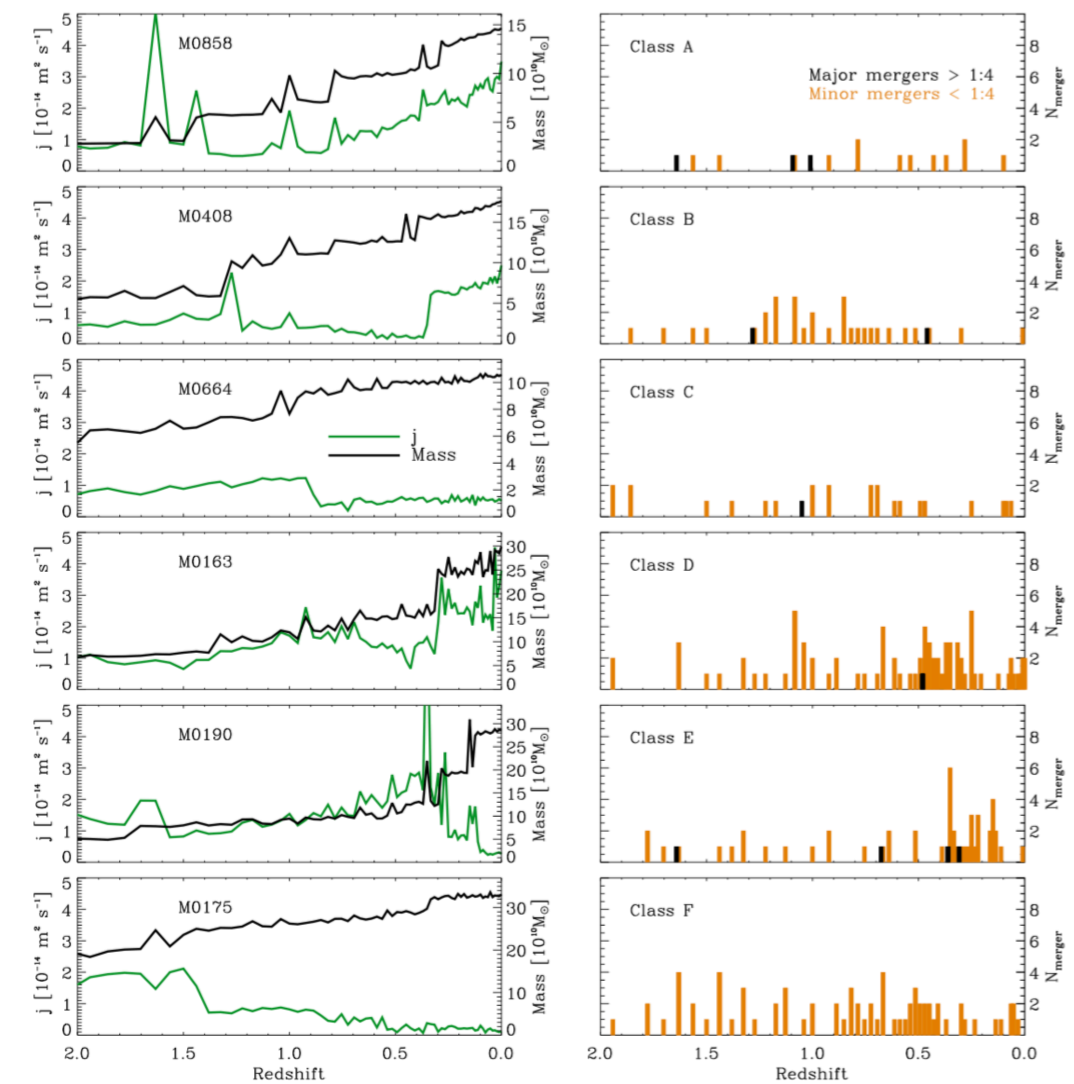
(c) Illustris, $z = 0$

(d) Illustris, $z = 1$

The role of formation history

Naab et al. 2014

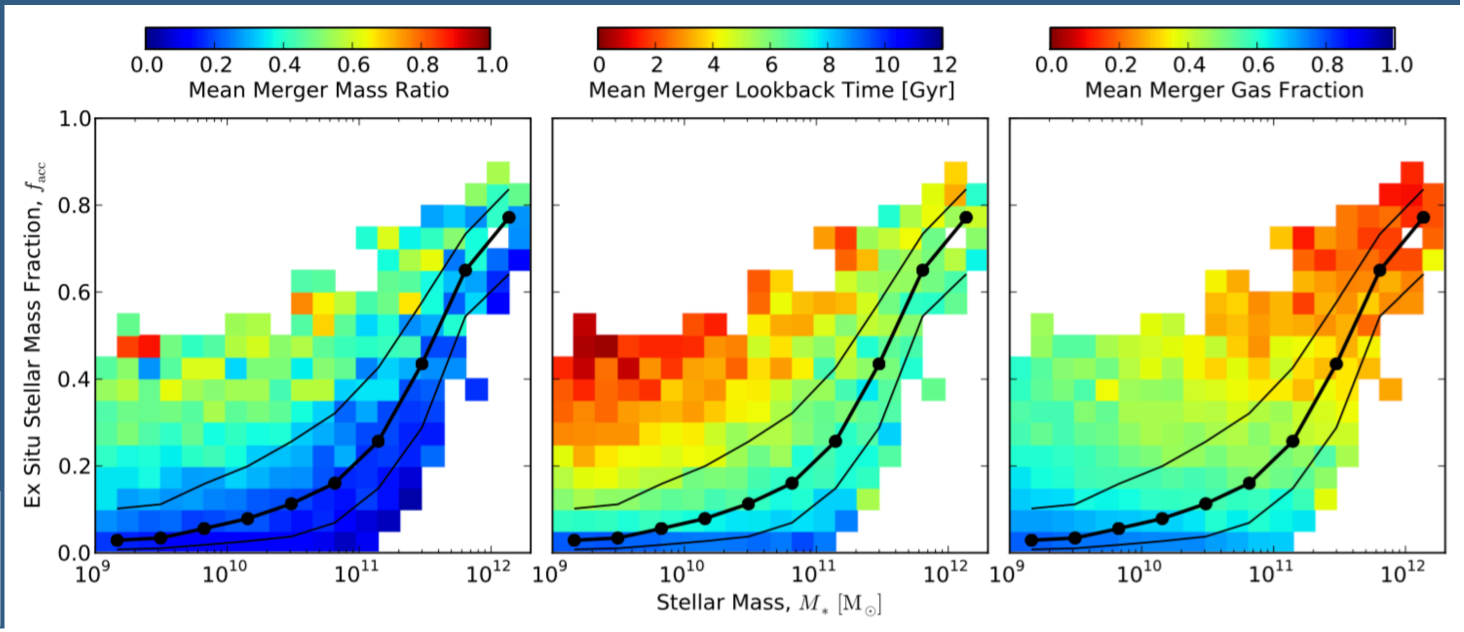
- Large variety of mass and j evolution histories
- Several classes defined based on zoom-in simulations, but not enough population statistics
- Mergers may increase or reduce the specific angular momentum



The role of formation history

- Low gas fraction:
- Late mergers:
- Major mergers:

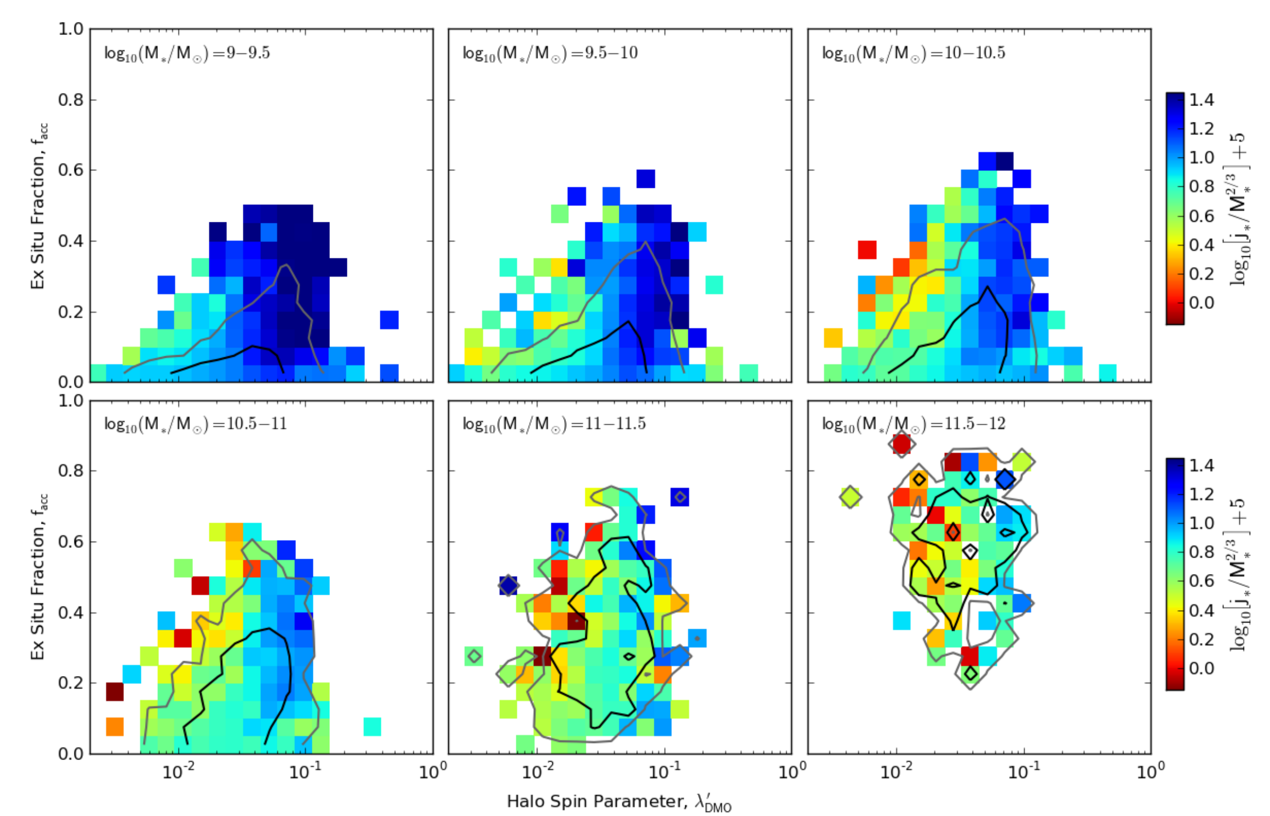
All correlate with and can be 'summarized' together using the 'ex-situ' fraction, which also strongly correlates with M_*



Rodriguez-Gomez et al. in prep

The role of formation history

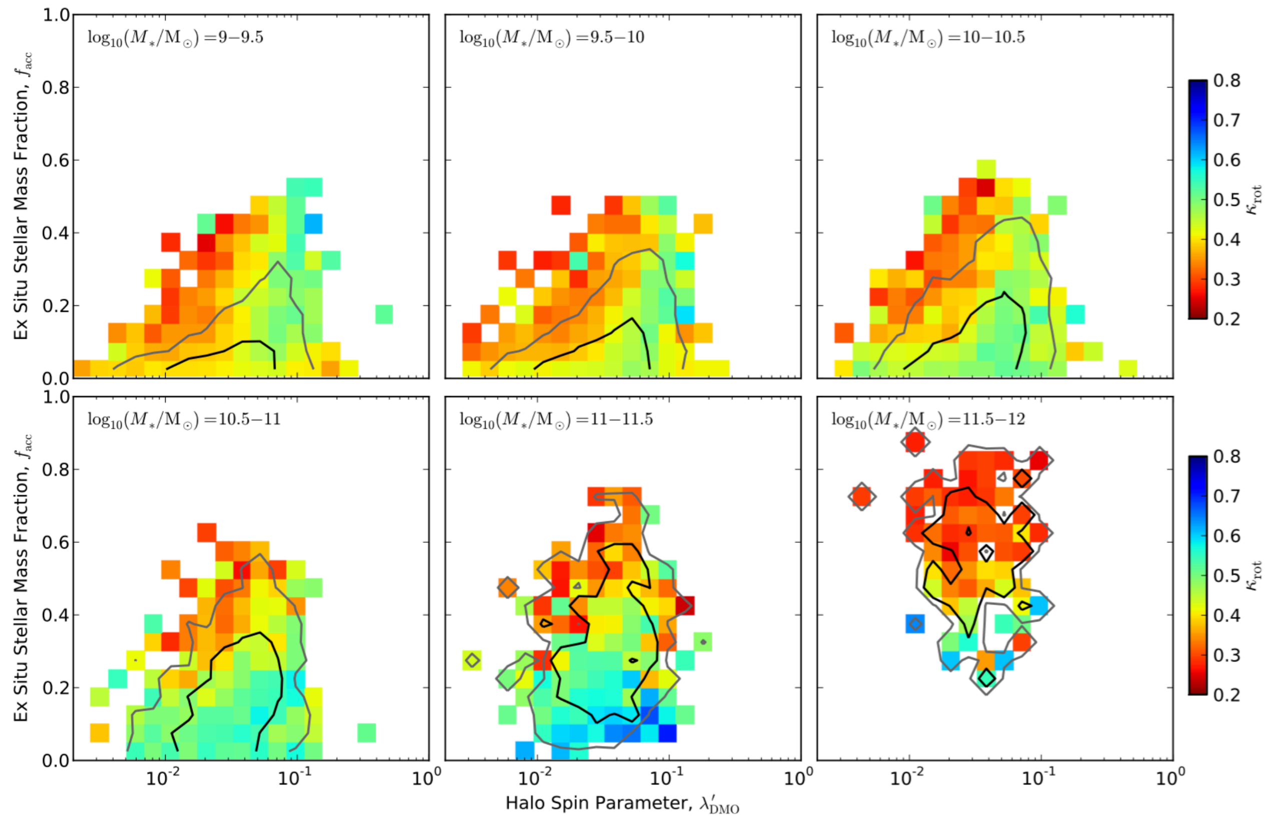
- At all masses, there is a correlation between 'stellar spin' and halo spin
- At $M_* \cong 10^{10\text{-}11} M_\odot$, there is some negative correlation with ex-situ fraction (~0.2-0.3dex), at a given halo spin



Rodriguez-Gomez et al. in prep

The role of formation history

- The inner degree of rotational support correlates more strongly with ex-situ fraction, in addition to halo spin
- But at low M_* the ex-situ fraction is small and not no significant
- At high M_* the rotational support and halo spin are no longer correlated, and the formation history dominates

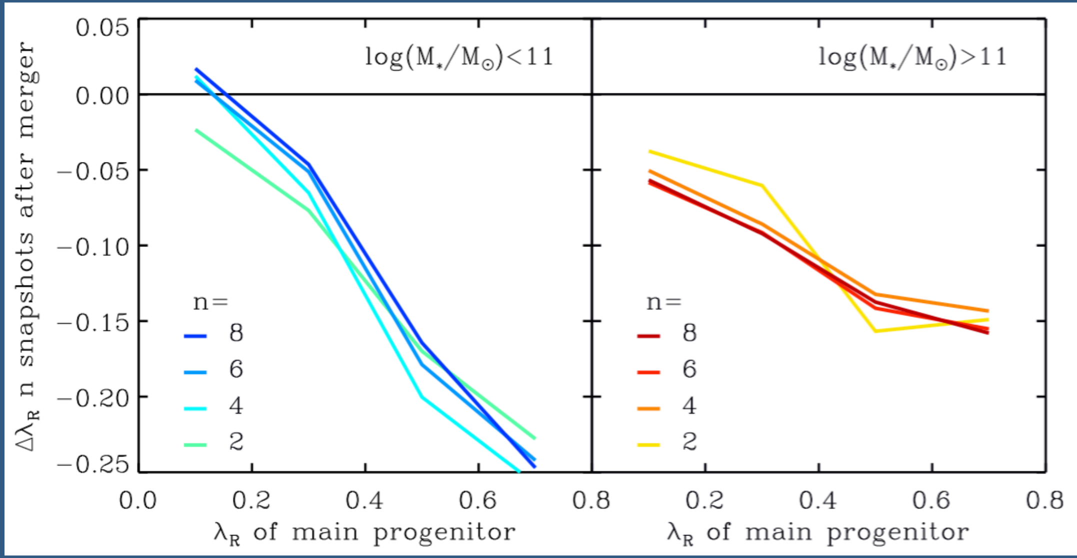


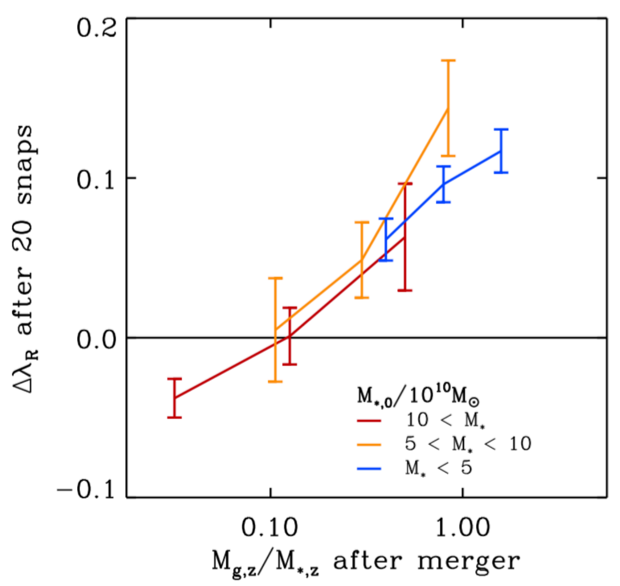
Rodriguez-Gomez et al. in prep

The role of formation history

- Fast rotators lose significant rotation support during a major merger, within ≈100Myr

- Recovery, over ≈1-2Gyr, is dependent upon gas fraction after the merger





Penoyre, Moster & Sijacki in prep.

Conclusions

Feedback:

• Galactic winds generate a reservoir of high-j circumgalactic gas, and prevent angular momentum losses inside the disk

• AGN feedback prevents accretion from this reservoir, effectively reducing j

Mergers:

• Dry mergers send j to large radii, making galaxies dispersion-dominated

• Wet mergers reduce rotation support only temporarily

Halo spin:

• Stellar j strongly correlated with halo spin (at all masses)

• Rotation support becomes more sensitive to merger history at high mass