The evolution of angular momentum of galaxies and halos: the view from EAGLE and Shark

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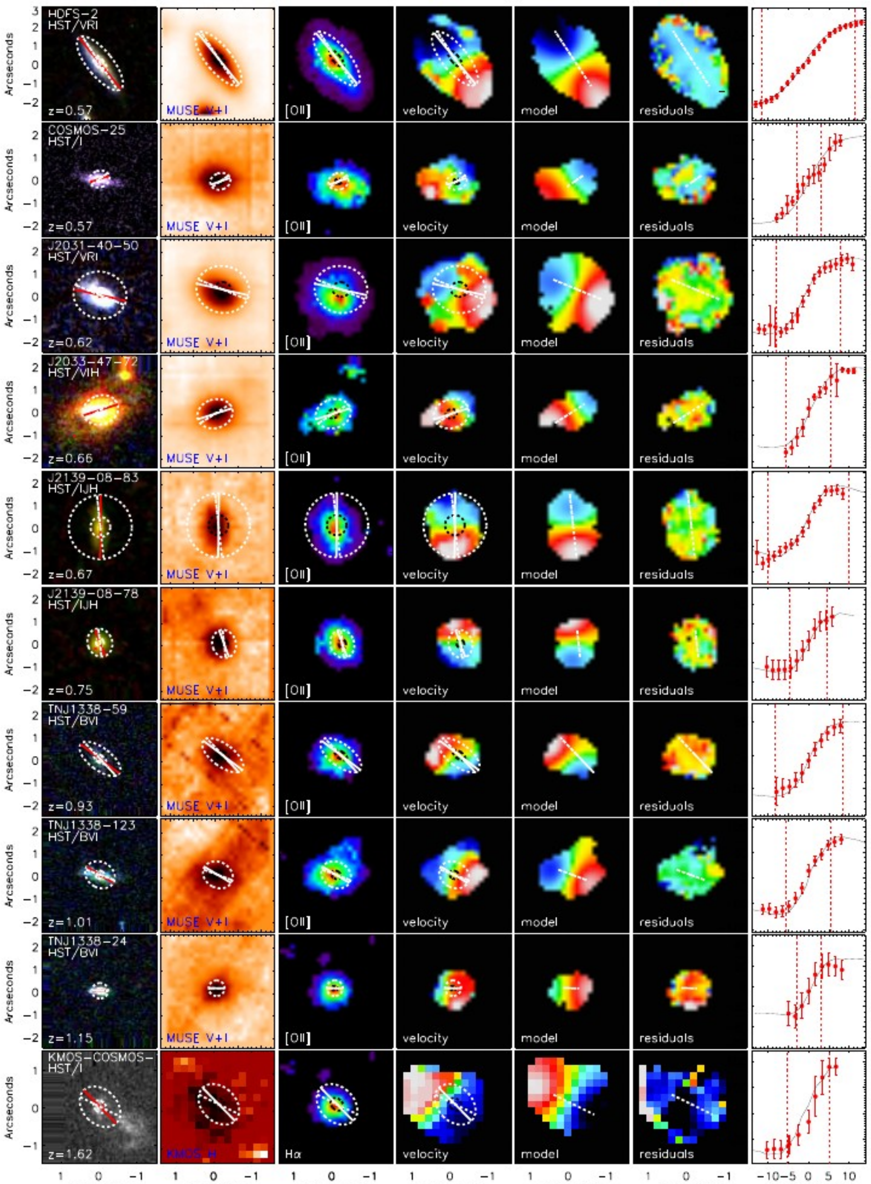
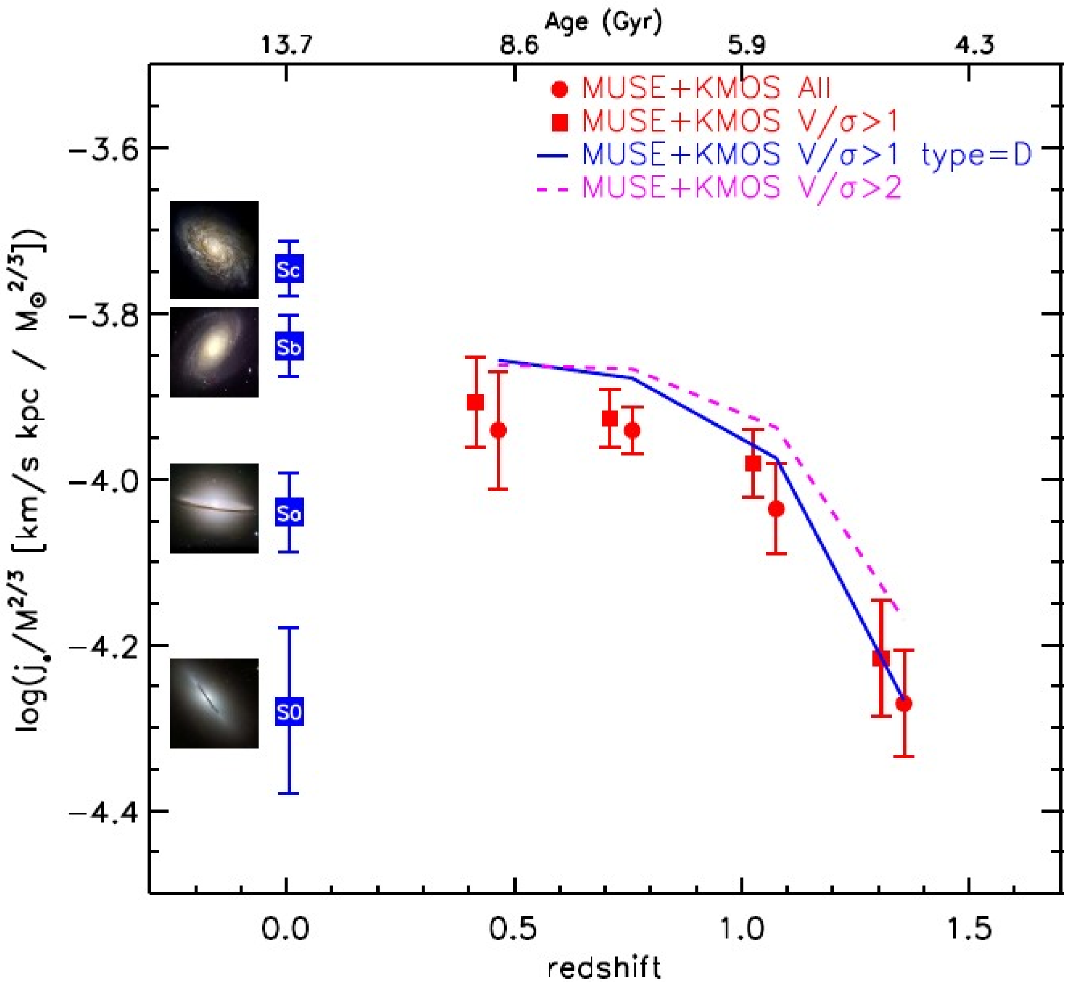
Explosion of new results measuring j

Swinbank et al. (inc Lagos) 2017: MUSE + KMOS KROSS (700 galaxies!).



Higher spin

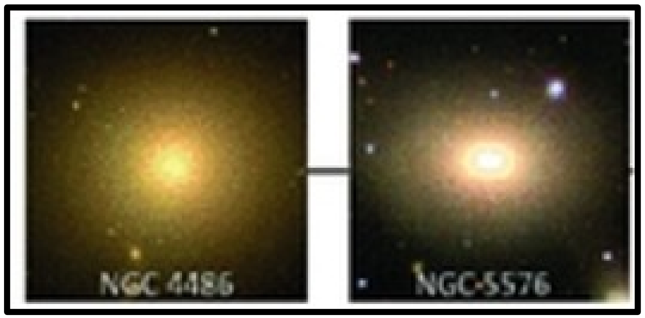


Time

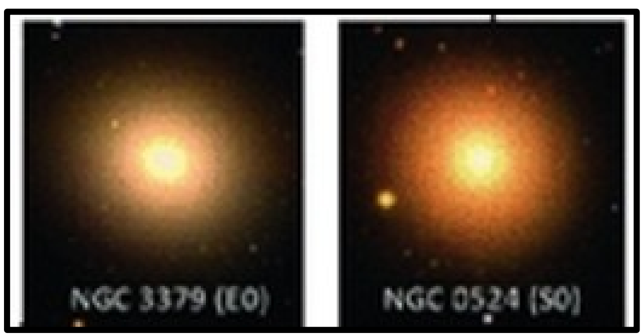
Kinematics as a morphological classification

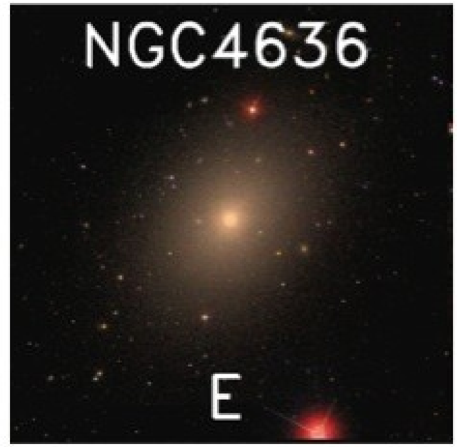
Emsellem et al. (2007, 2011)

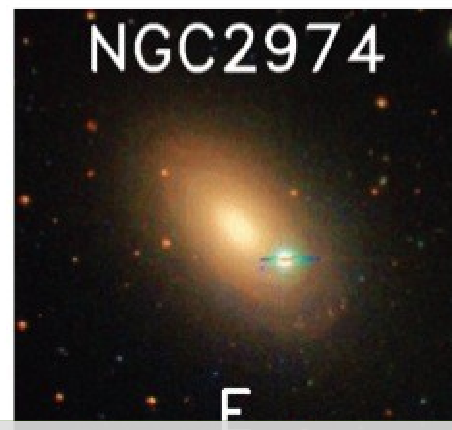
Slow rotators



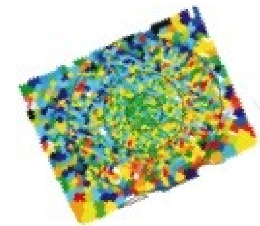
Fast rotators



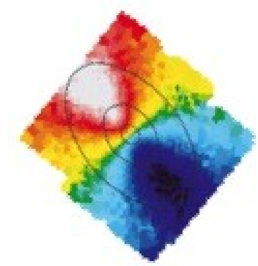




ATLAS^{3D} velocity fields



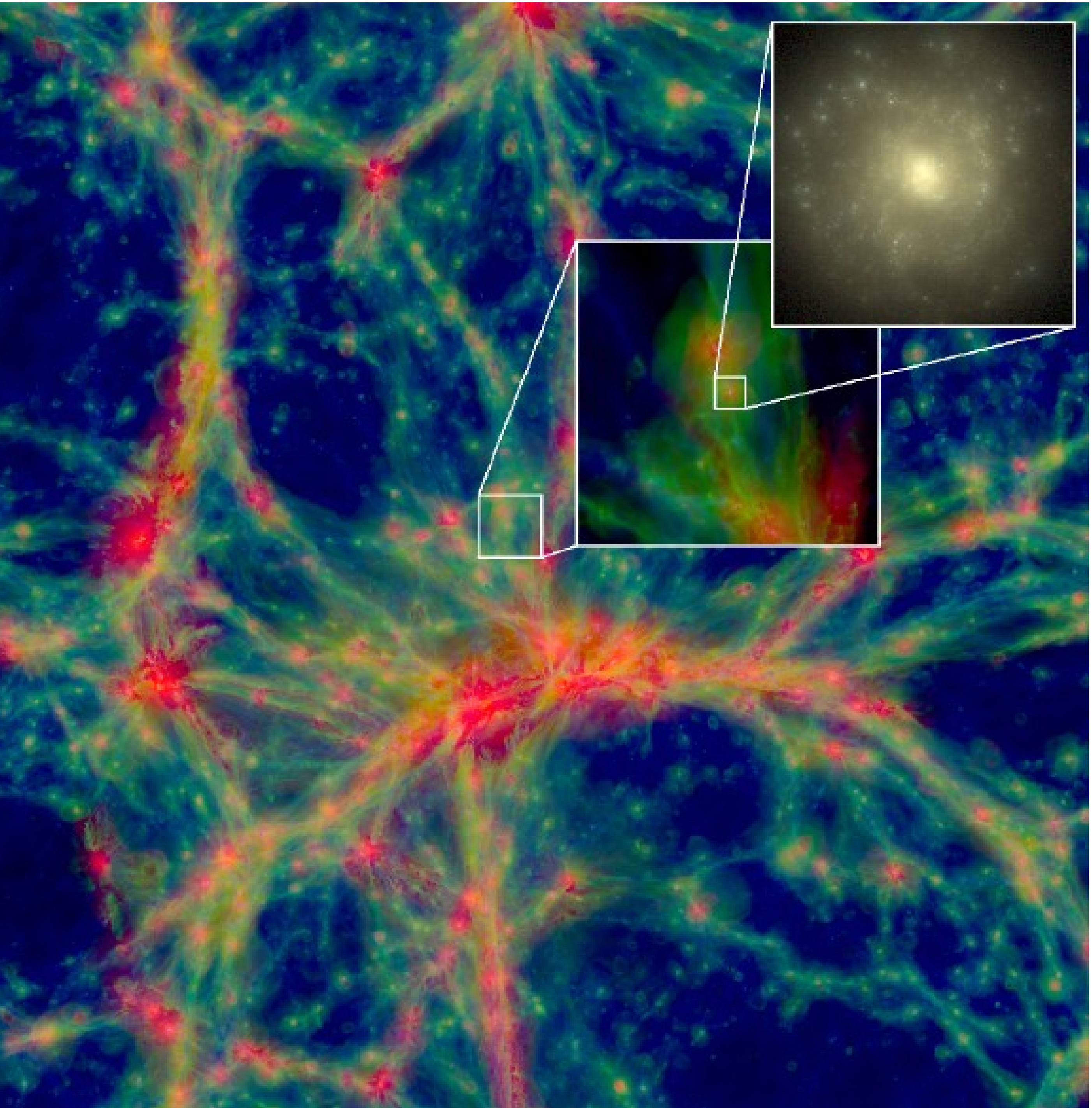
Slow rotator ($\lambda_R = 0.04$), ± 40 km/s



Fast rotator ($\lambda_R = 0.66$), ± 220 km/s

Use cosmological hydrodynamical simulations to ***identify primary AM growth*** channels and causation in scaling relations.

The EAGLE Simulation



Planck14 – LCDM

Improved hydrodynamics
("Anarchy")

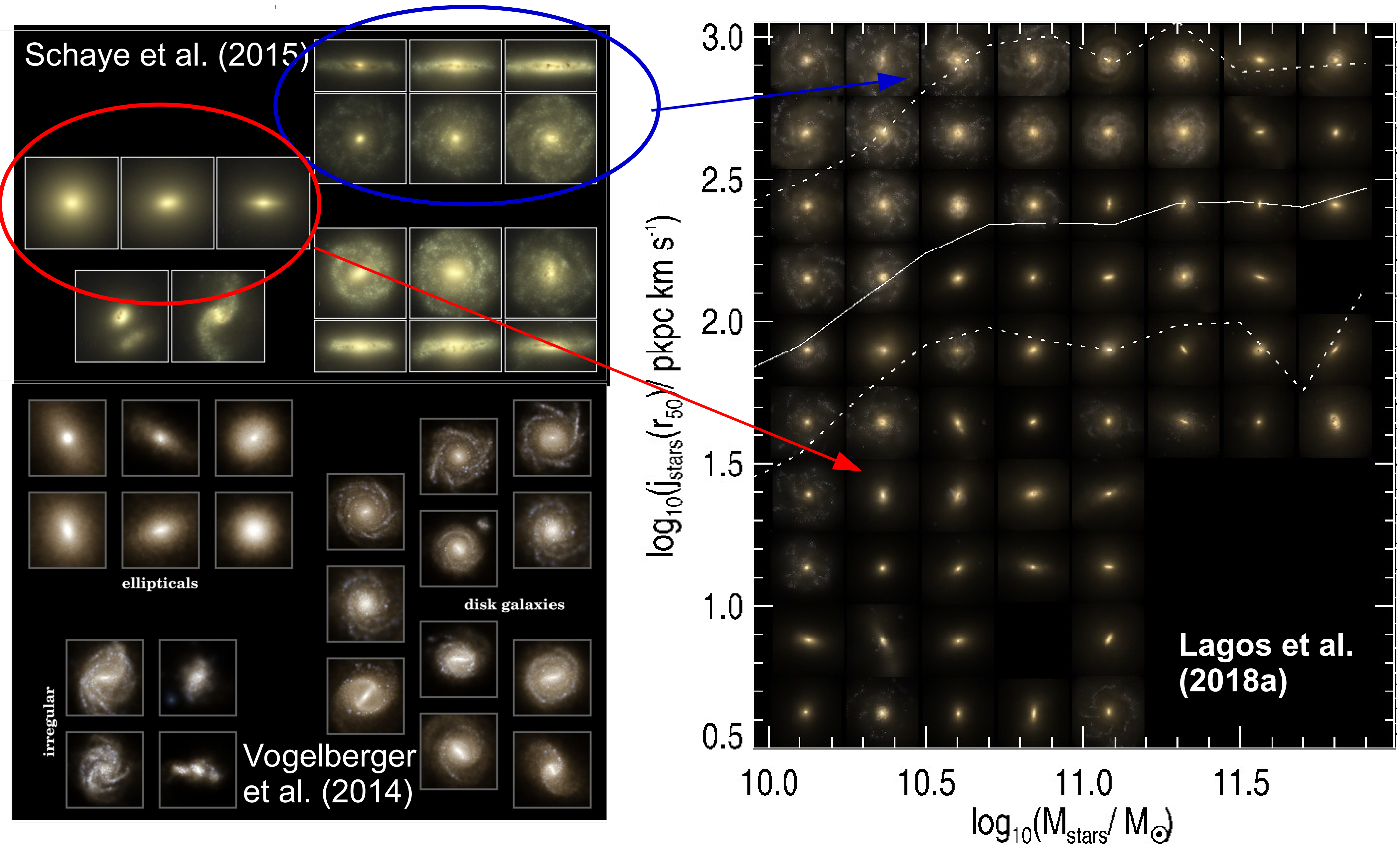
Large number of sub-grid physics module:
→ Metal-dependent cooling
→ Reionisation
→ Star formation (metallicity-dependent)
→ Stellar recycling
→ SNe feedback
→ AGN feedback

(~700pc resolution, 1e6Msun, 100Mpc box size)

+C-EAGLE: good representation of clusters

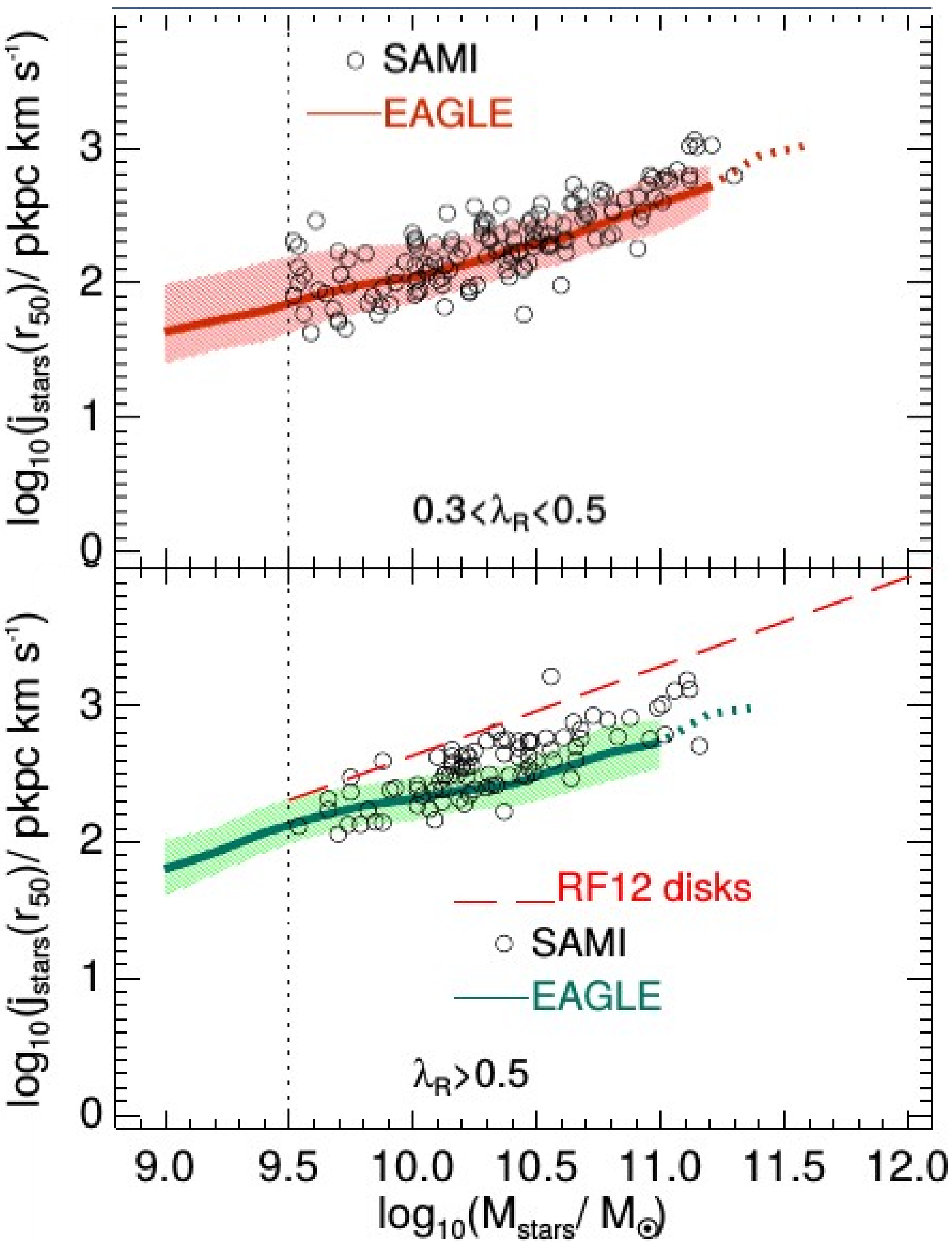
Schaye et al.(2015); Furlong et al. (2015); Crain et al. (2015); Lagos et al. (2015); Bahe et al. (2016)…

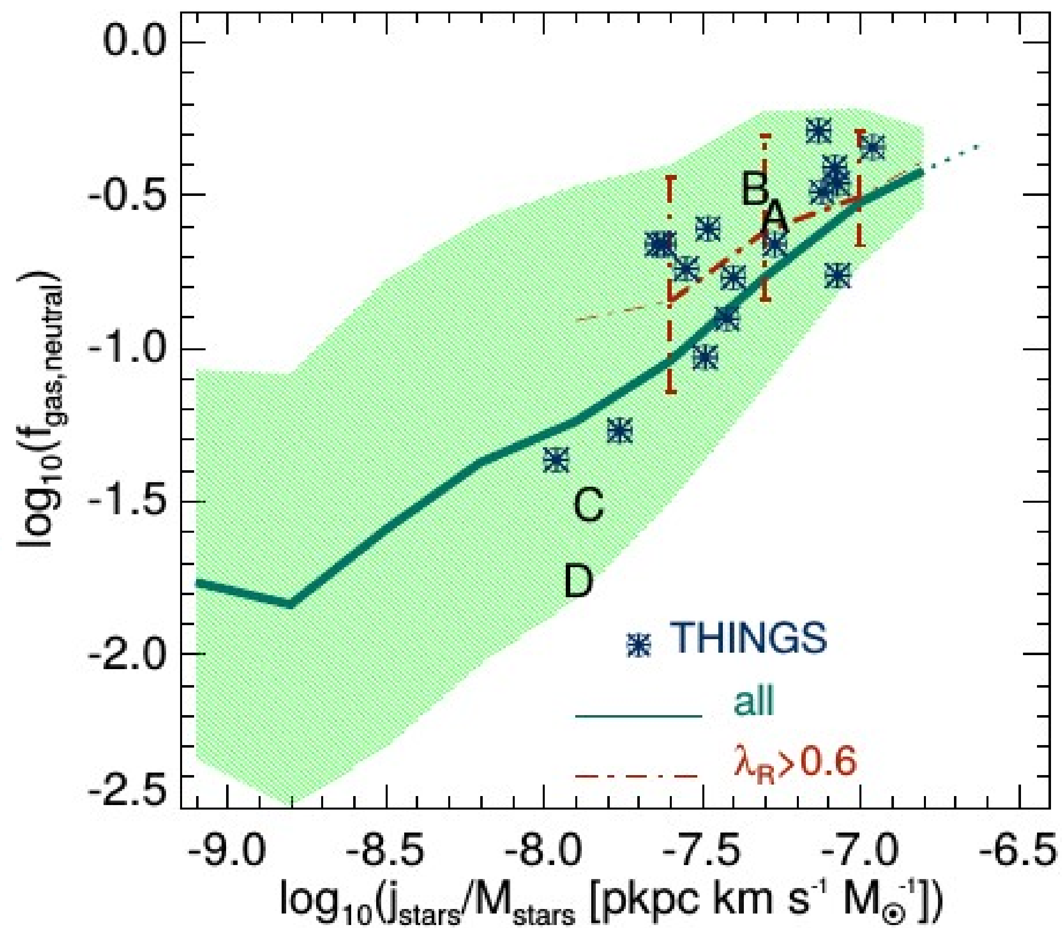
The rise of the Hubble sequence and j-M



Comparing to IFU results at z=0

Lagos et al. (2017): compared with z=0 obs (see Swinbank+17 for a high-z comparison)

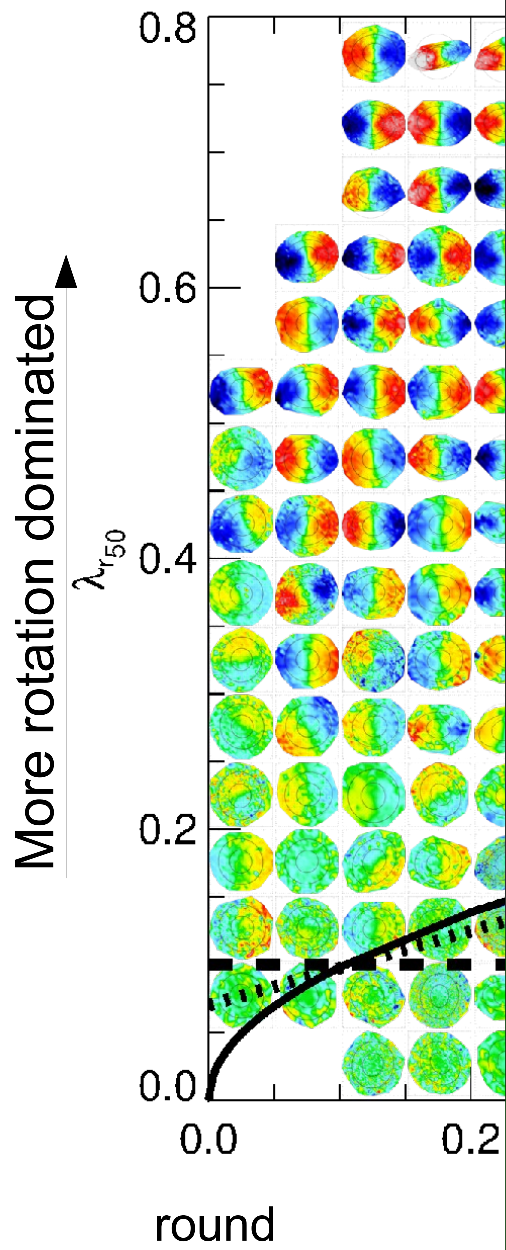


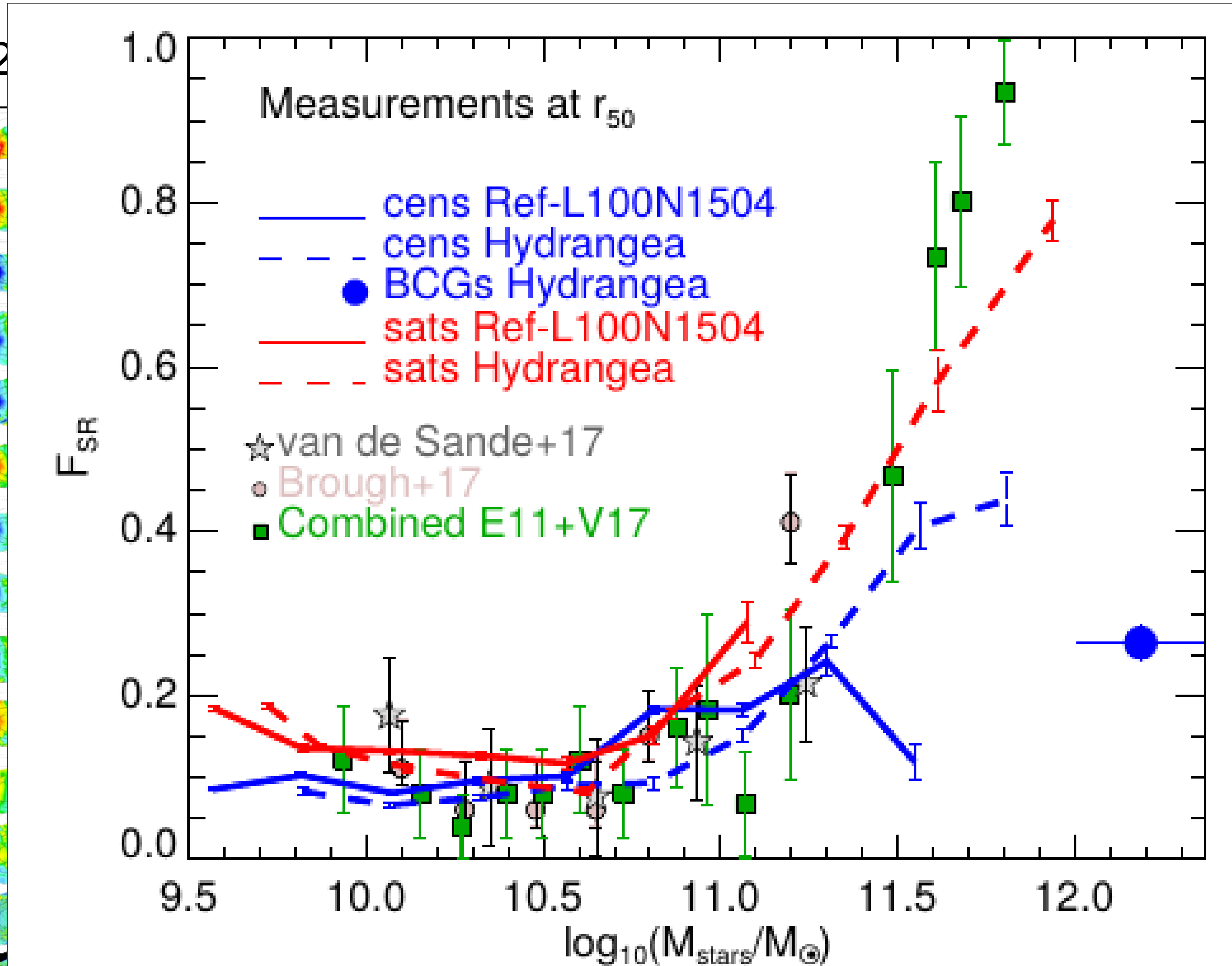


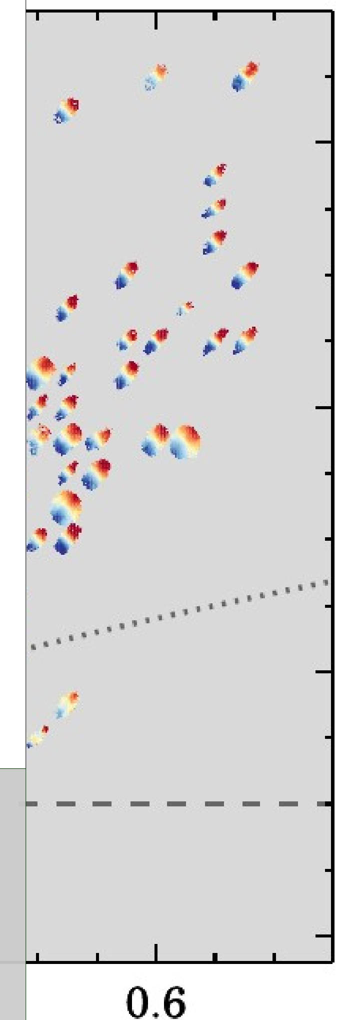
SAMs: Stevens, Lagos, et al. (2018)
Hydro: Wang, Obreschkow, Lagos, et al. (2018)
Stevens, Diemer, Lagos, et al. (2018)

Reproducing the structure of galaxies

Lagos et al. (2







Simulation agrees nicely with observations locally and at high-z. Gives us confidence to use it to study ***evolutionary paths of j***.

Also van de Sande, Lagos, et al. (2018)

AM evolution of galaxies across time

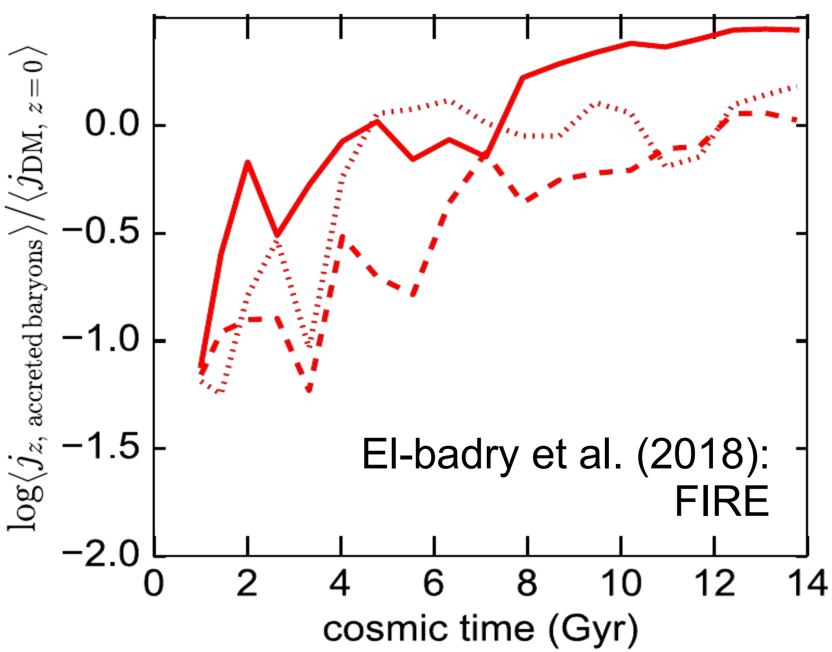
Lagos et al. (2017): EAGLE

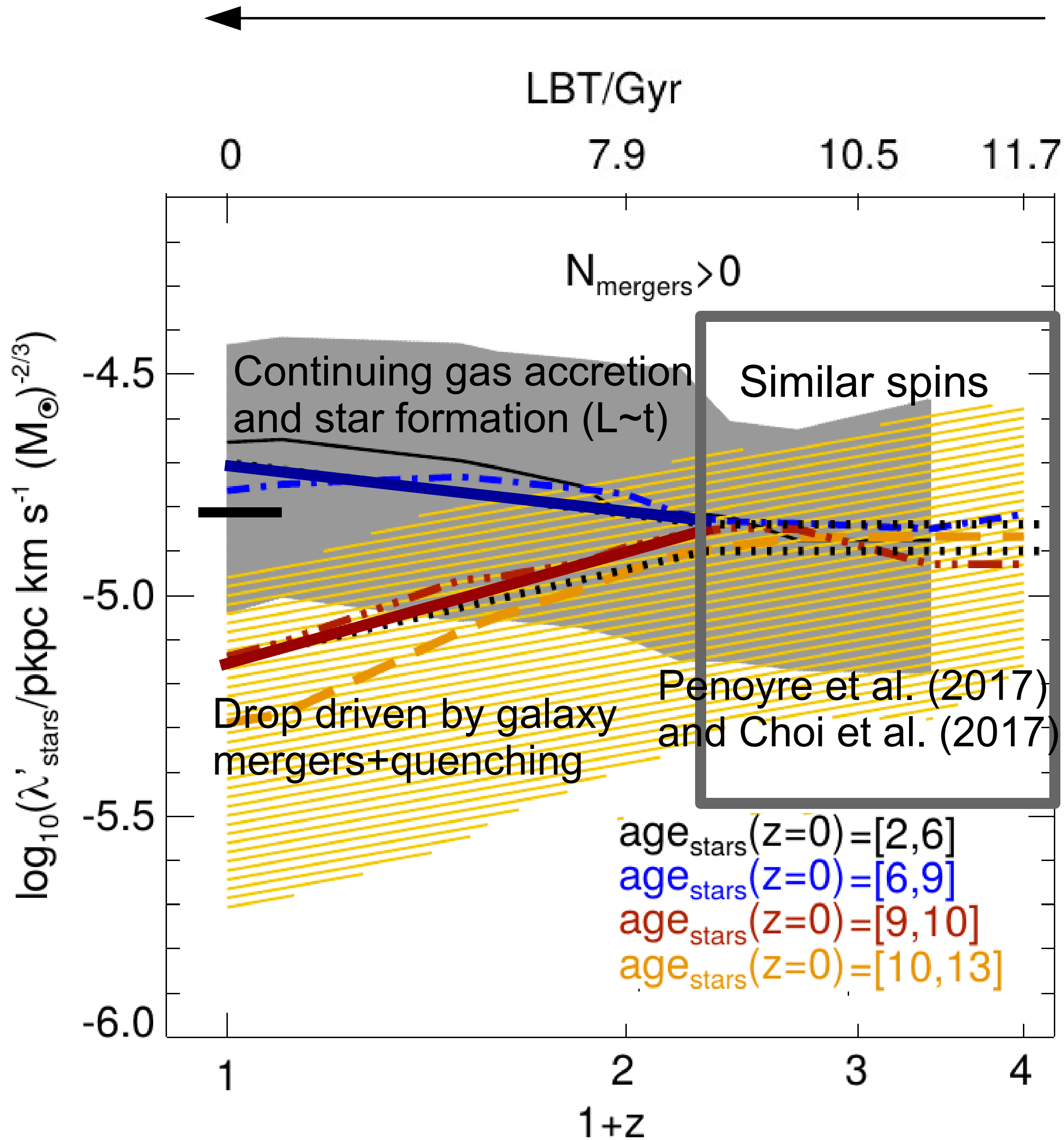
z=0 population

Young, high j

Old, low j

$$\lambda'_{\rm stars} \equiv j_{\rm stars}(r_{50})/M_{\rm stars}^{2/3}$$





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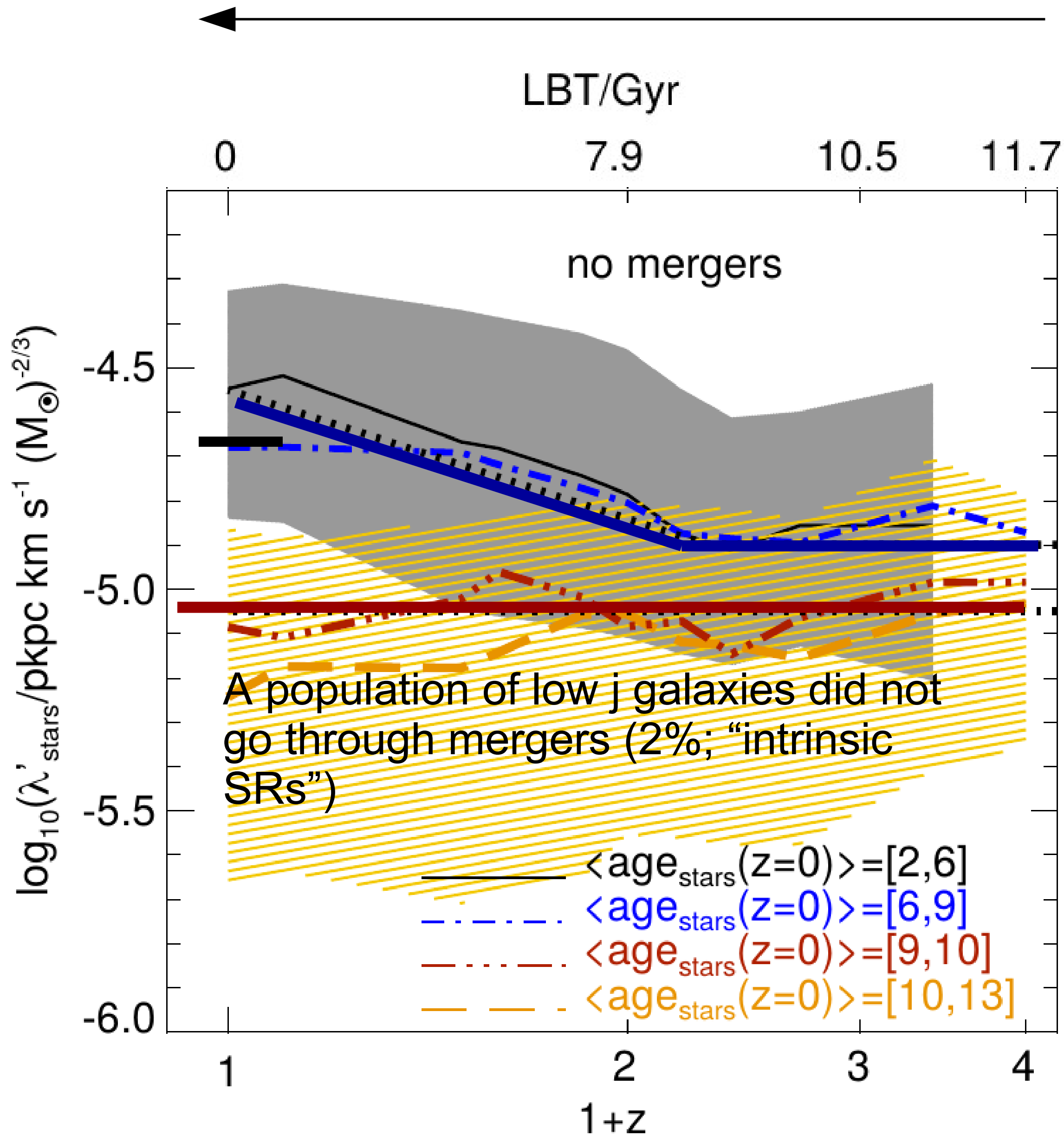
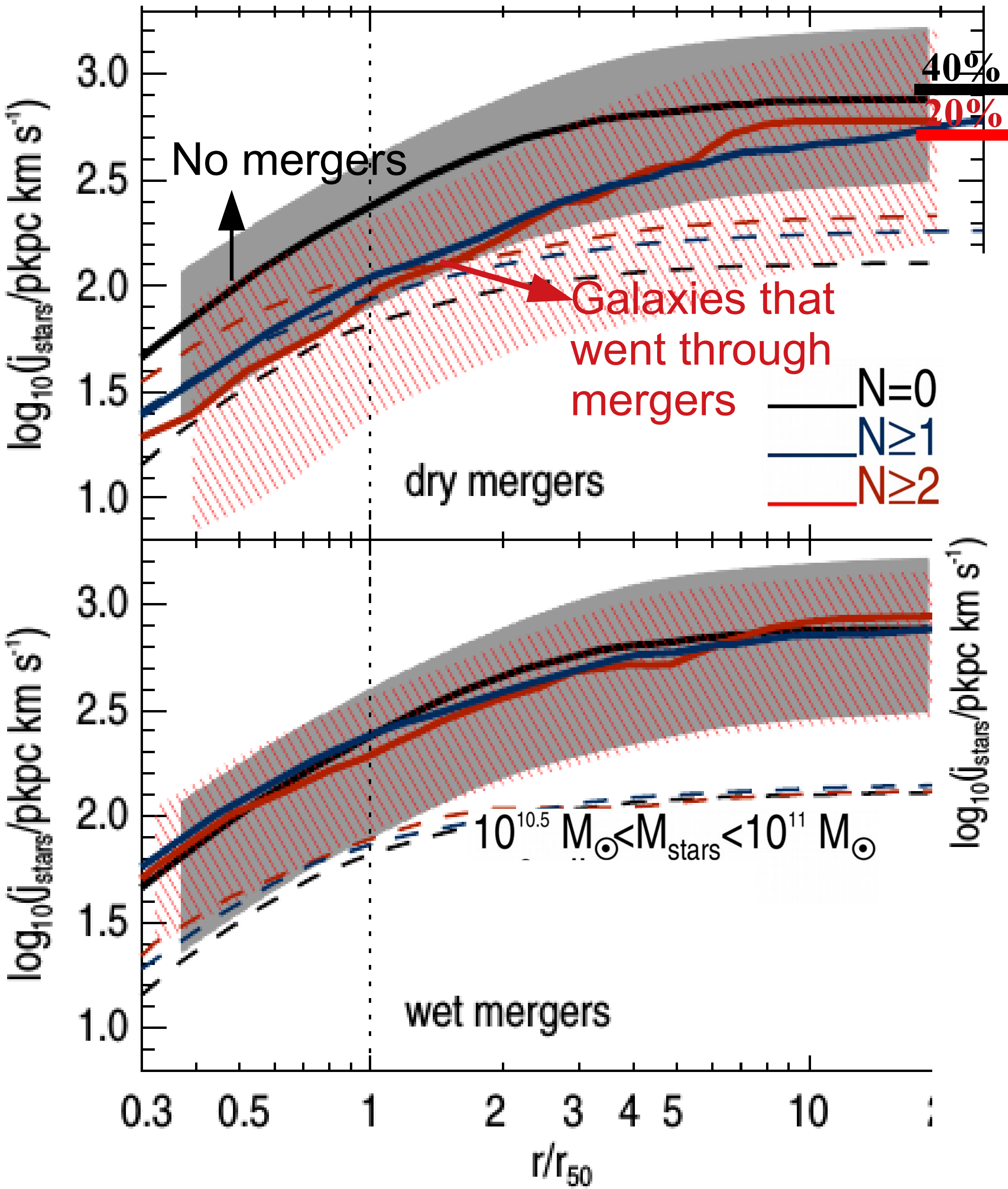


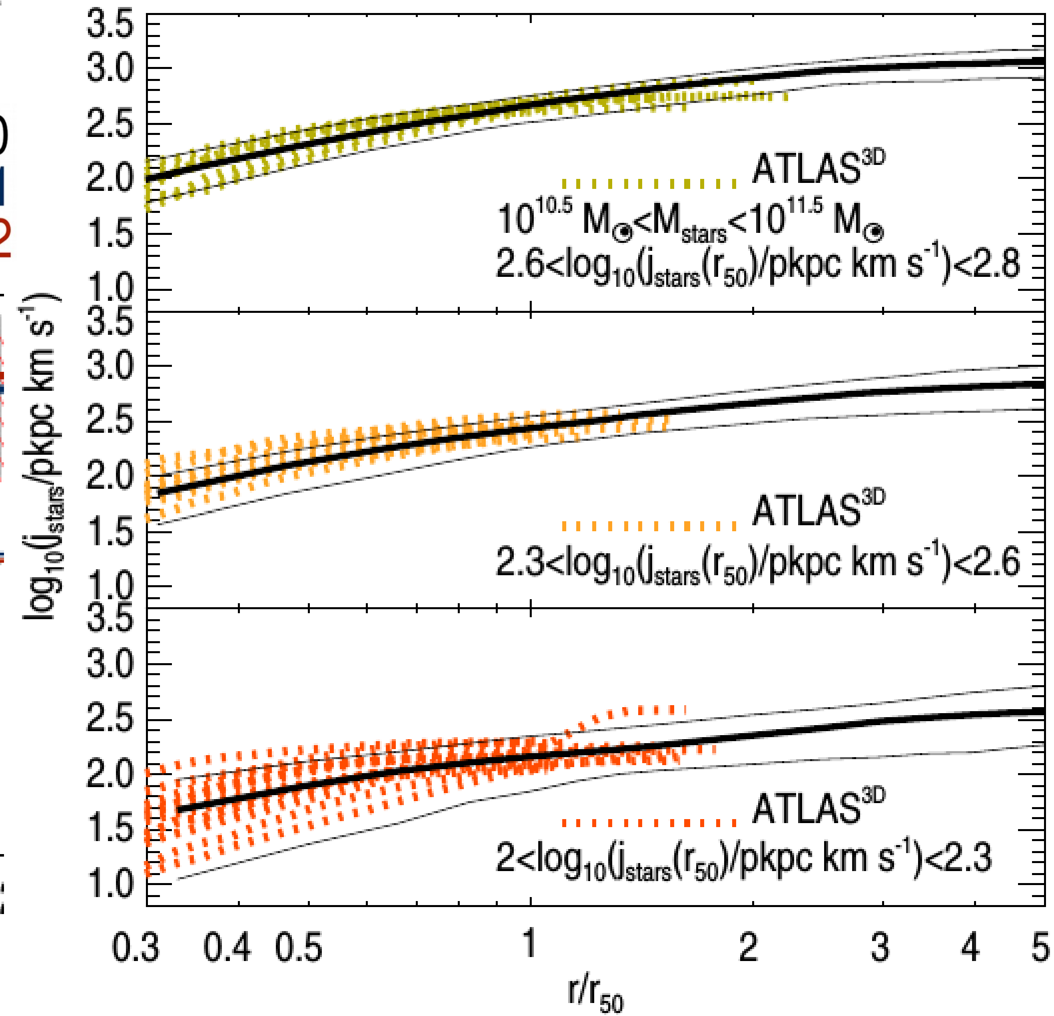
Dry mergers and the spin down of galaxies

Lagos et al. (2018a)



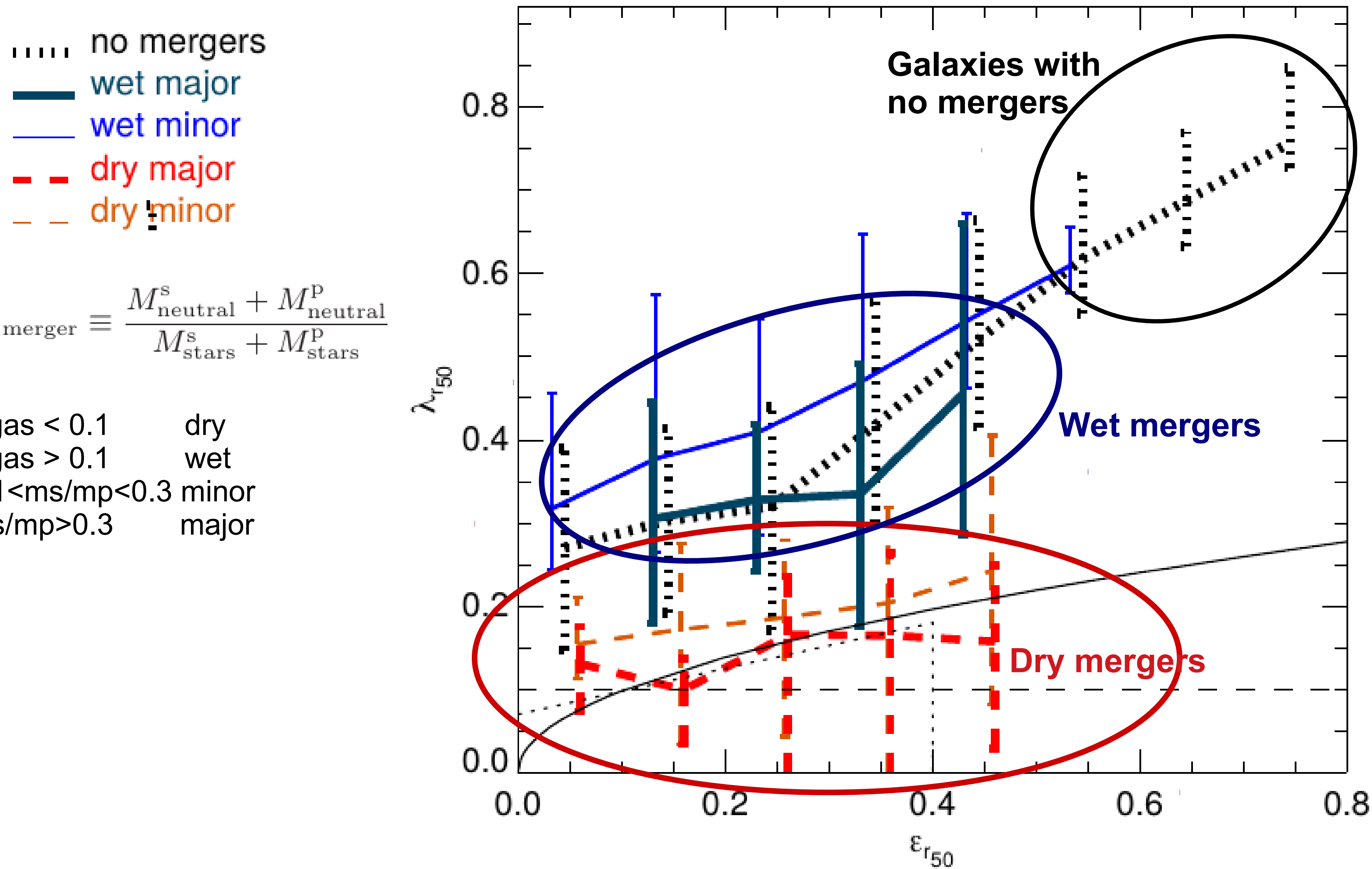
Dry mergers:
(1) Diverse (but deficient) inner j profiles
(2) Keep raising beyond 10r50

Is this seen in observations?



Formation mechanisms of slow rotators

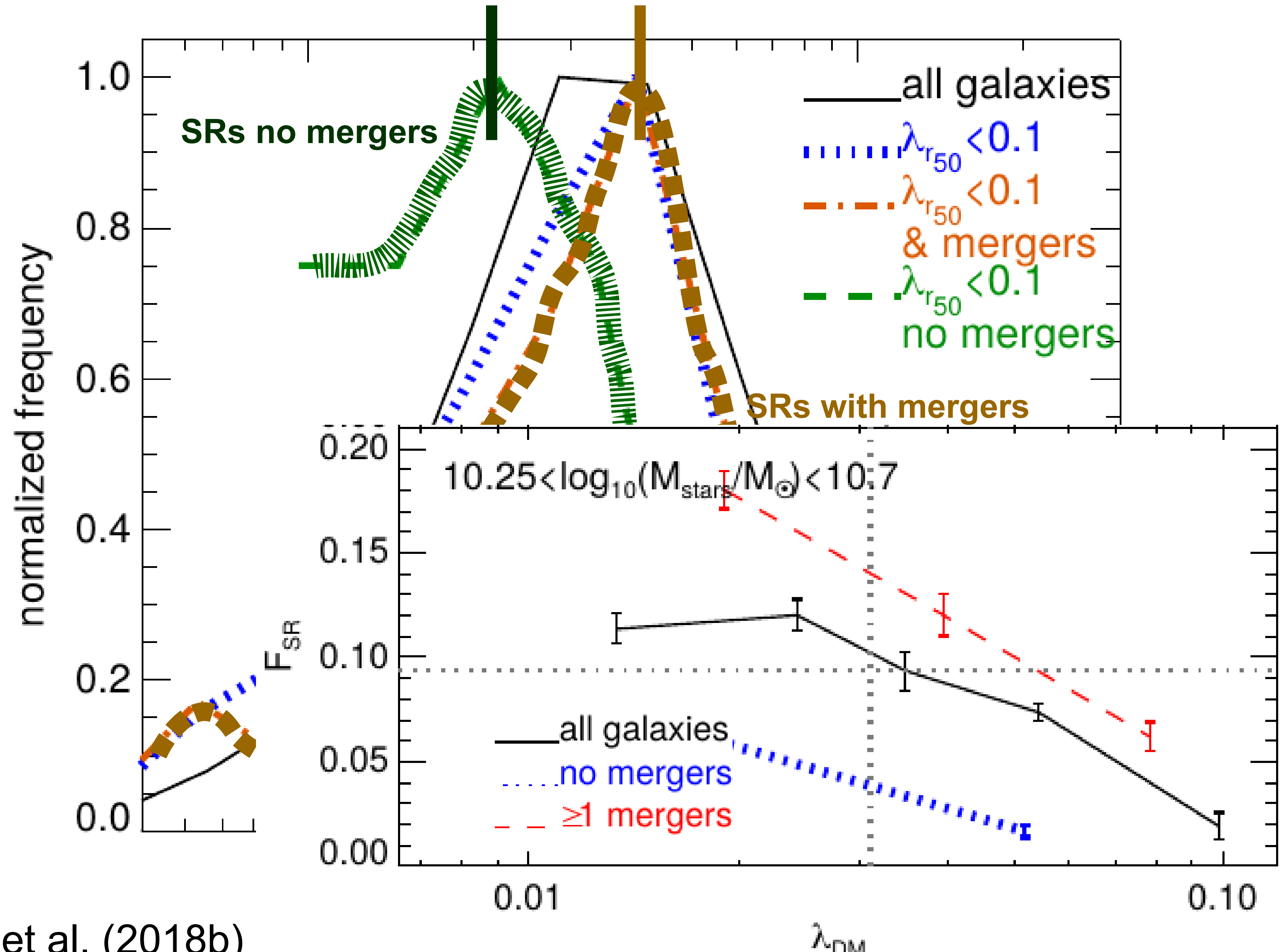
Lagos et al. (2018b)



$$R_{\rm gas,merger} \equiv \frac{M^{\rm s}_{\rm neutral} + M^{\rm p}_{\rm neutral}}{M^{\rm s}_{\rm stars} + M^{\rm p}_{\rm stars}}$$

- Rgas < 0.1 dry
- Rgas > 0.1 wet
- 0.1<ms/mp<0.3 minor
- ms/mp>0.3 major

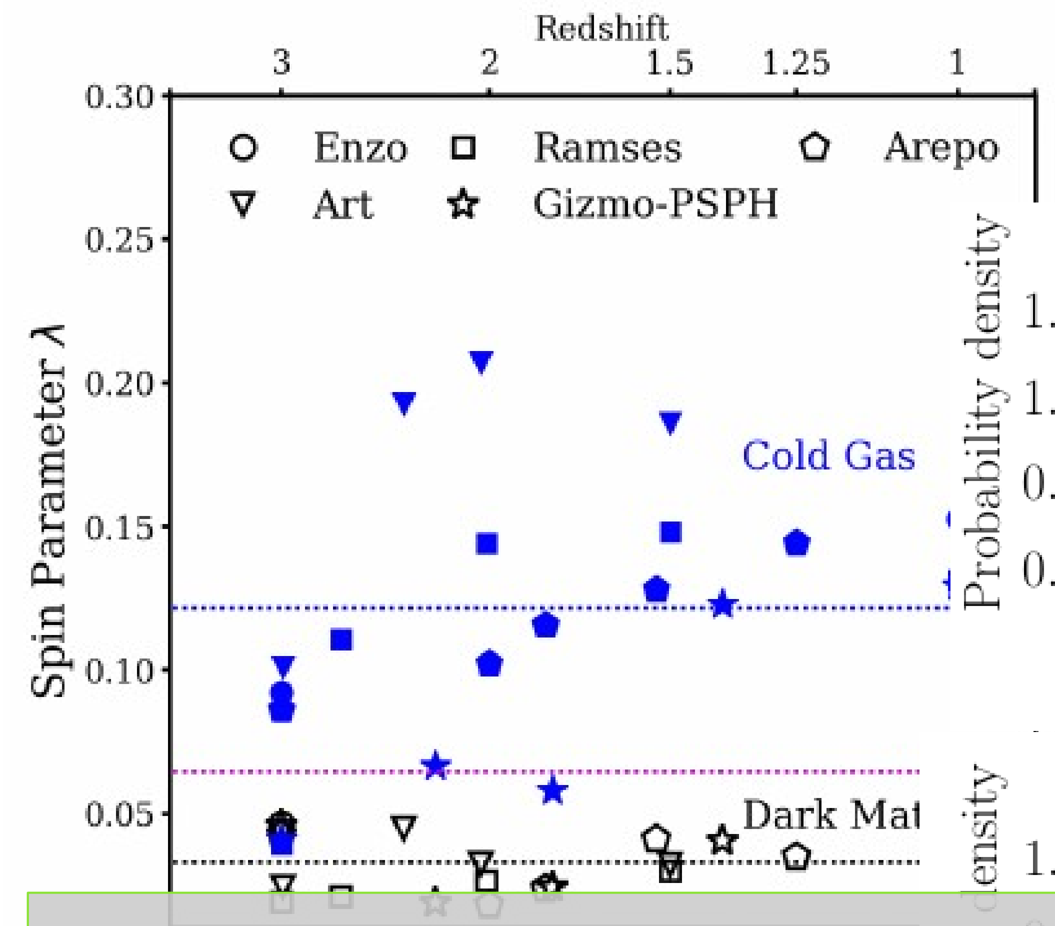
The connection between halo and galaxy spin



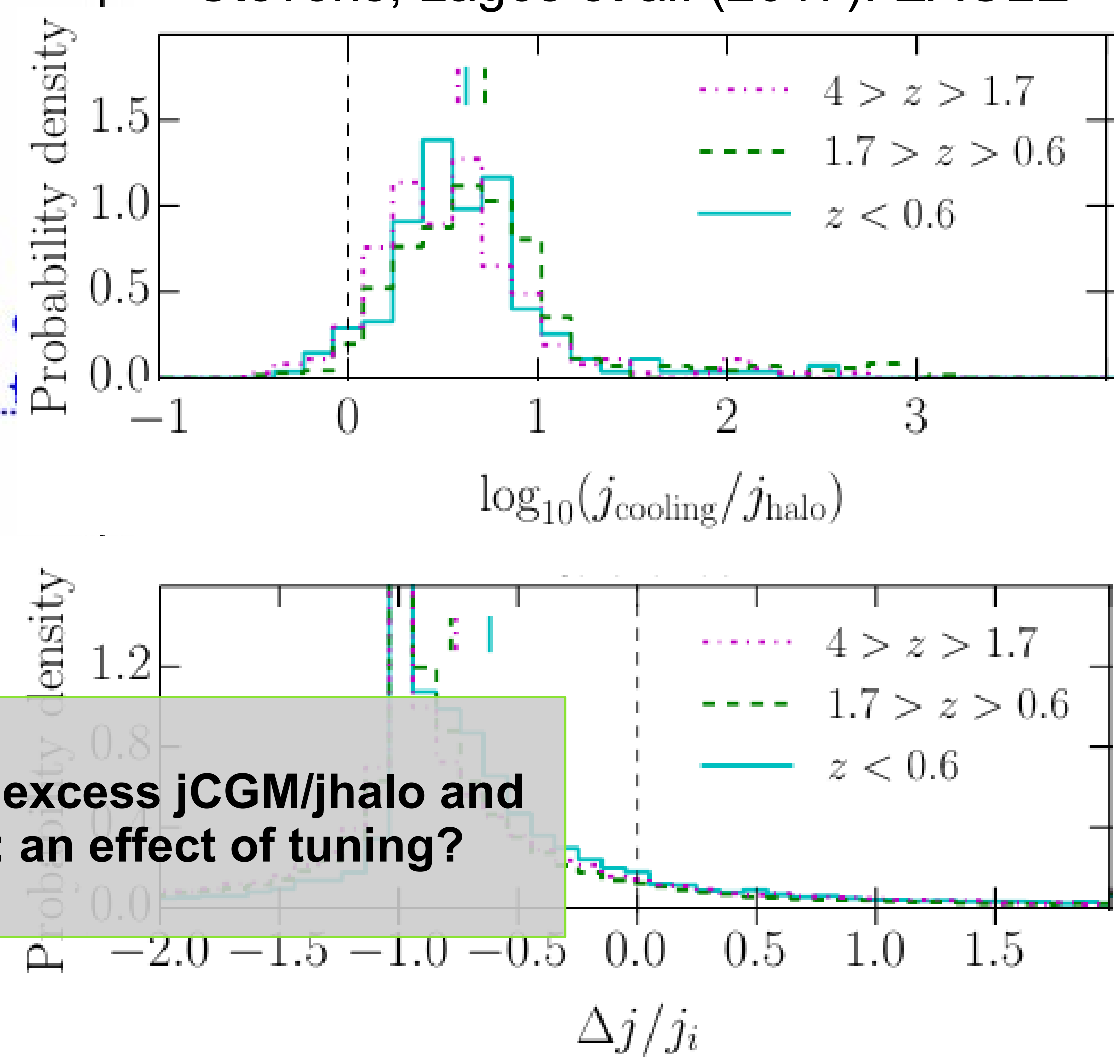
Lagos et al. (2018b)

DM, gas and galaxy spin

Stewart et al. (2017): gas > DM spin



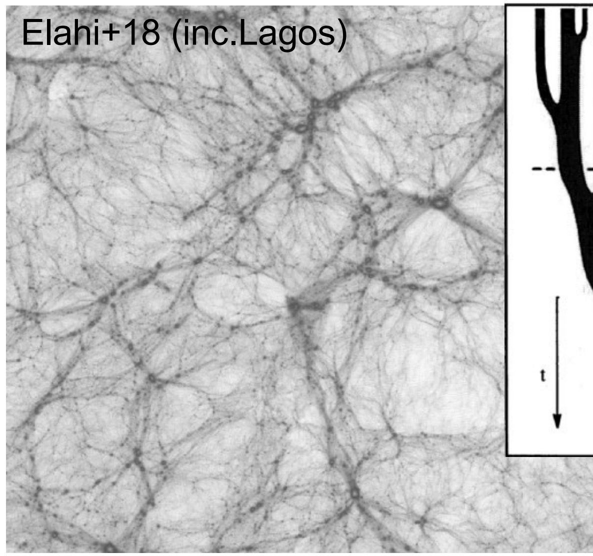
Stevens, Lagos et al. (2017): EAGLE

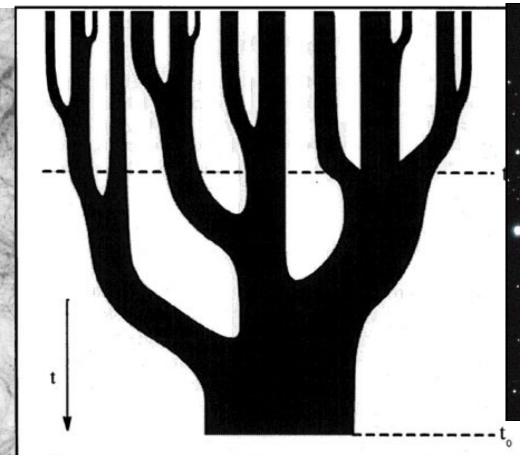


Interesting "coincidence" between the excess jCGM/jhalo and loss of jCGM in the process of cooling: an effect of tuning?

Using semi-analytic models to learn about AM

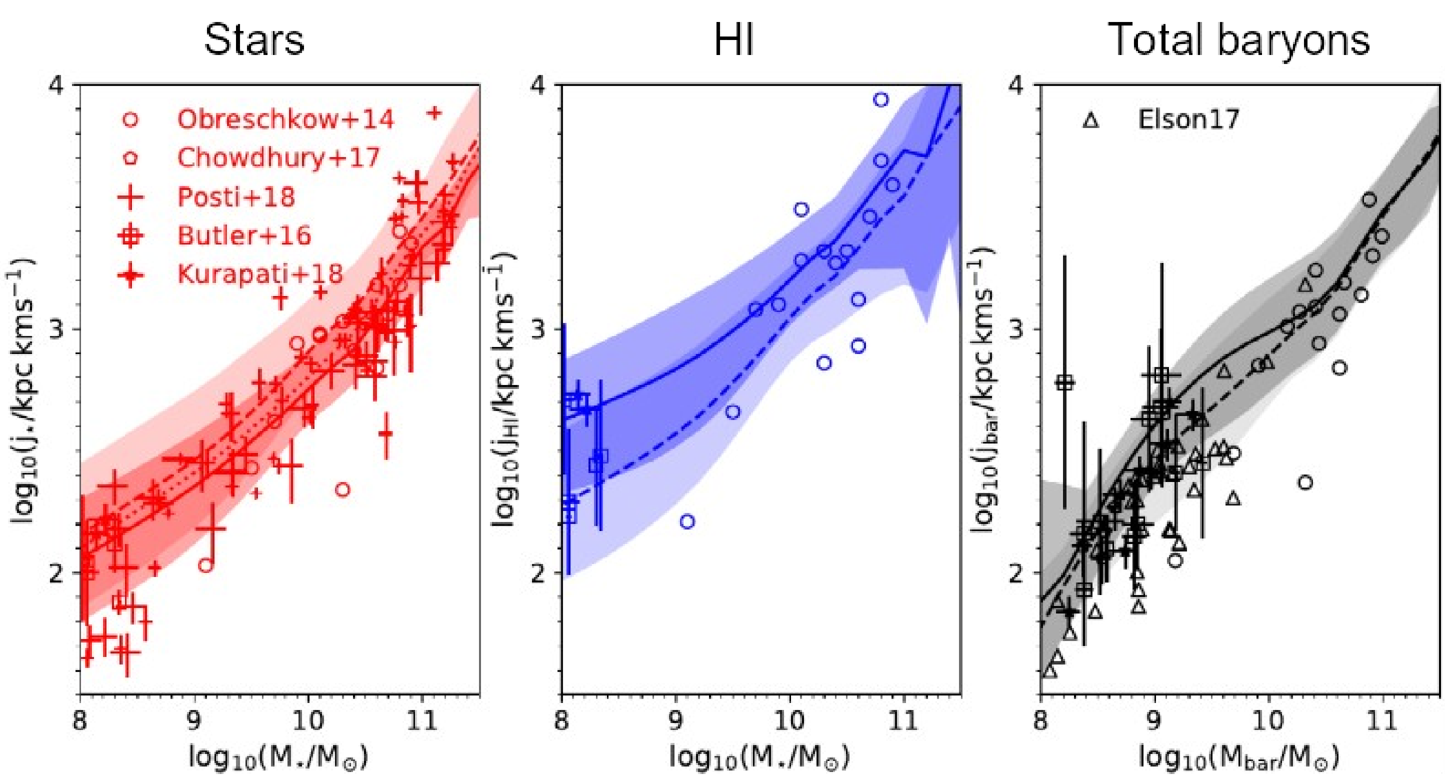
Lagos et al. (2018c)
c++, cmake, GSL, python,
very flexible, free, open source SAM





Lagos et al. (in preparation)

$$\dot{j}_\star = (1-R)\,\dot{j}_{g,s}$$
$$\dot{j}_{cold} = \dot{M}_{cool}\, j_{cool} - (1$$
$$\dot{j}_{cold,halo} = -\dot{M}_{cool}\, j_{cool}$$
$$\dot{j}_{hot,halo} = \dot{m}_{outflow}\, j_{out} -$$
$$\dot{j}_{ejec} = \dot{m}_{ejected}\, j_{out}.$$



Simple star/ISM j exchange

Realistic star/ISM j exchange

Feedback decouples jgal-jhalo

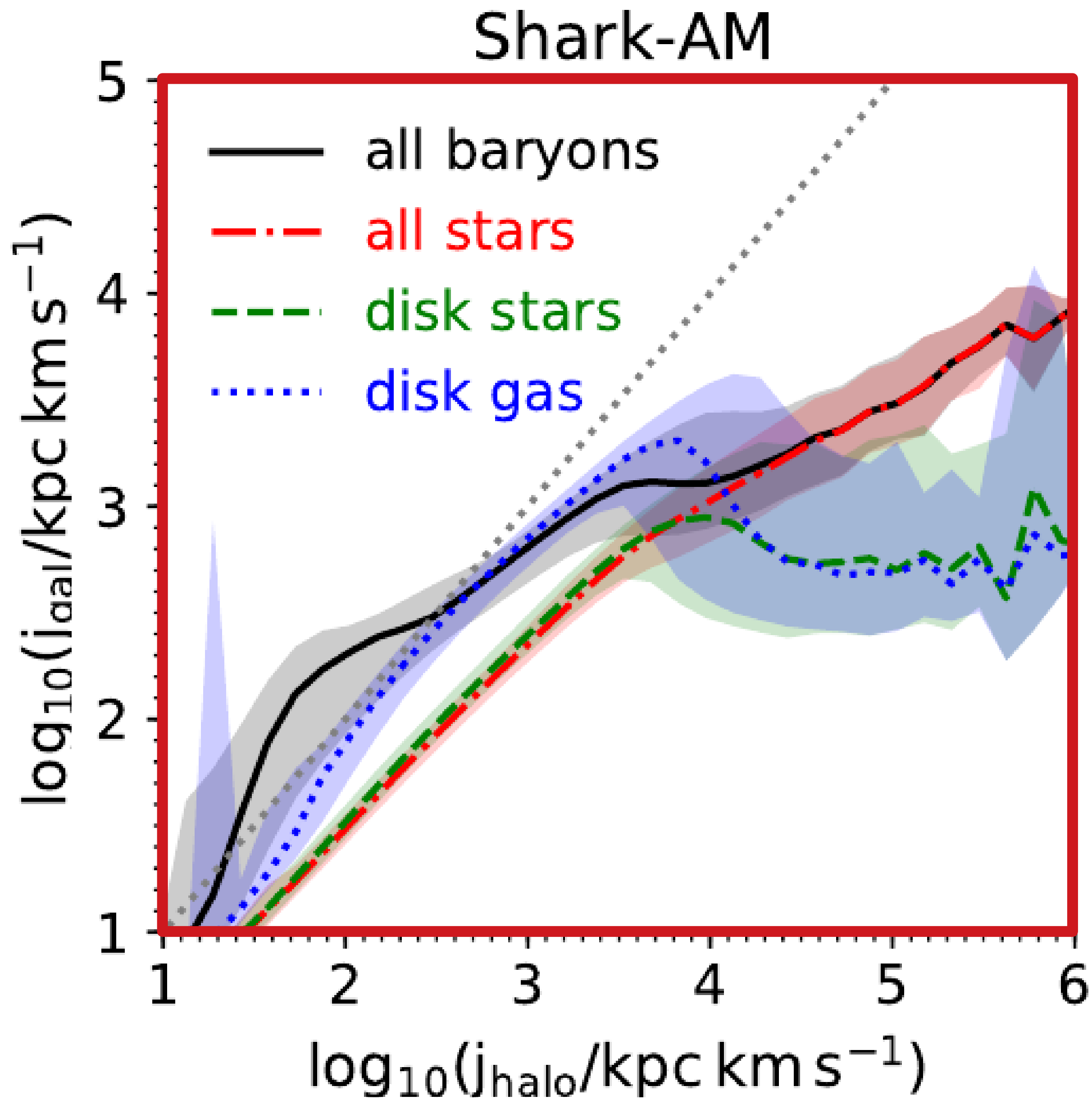
Lagos et al. (in prep.)

- No feedback

+ AGN feedback

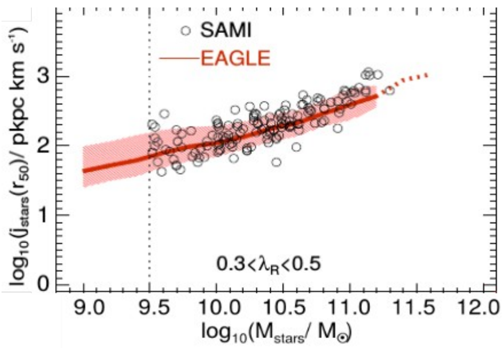
+ Stellar feedback

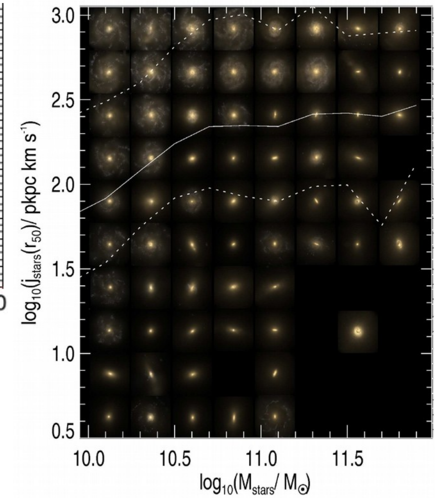
+ Realistic ISM/stars AM transfer

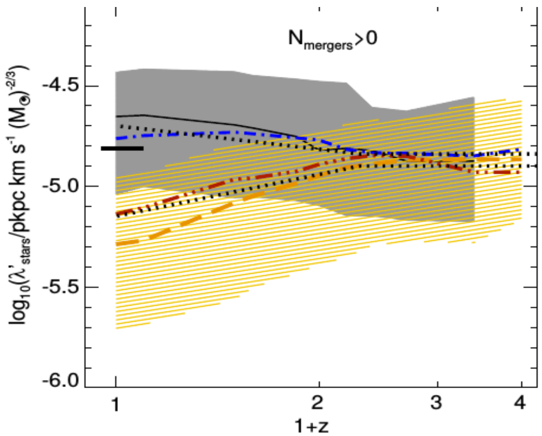


Conclusions

(1) Current simulations are able to *reproduce reasonably well the morphological diversity* of galaxies and j-M relation (**caveat of flat disks, ε>0.7-0.8**)

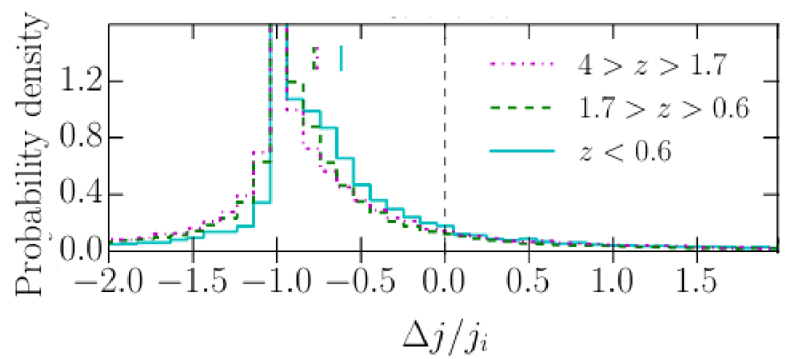


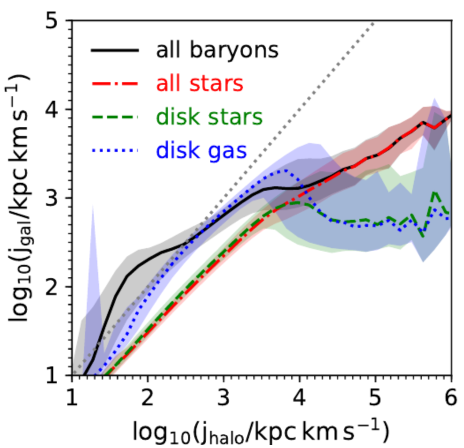




(2) For galaxies to have *high j at z=0, later gas accretion and star formation is preferred*. For low j, *two clear channels are found: (i) galaxy mergers (some more than others), (ii) early quenching.*

(3) CGM has j consistently in excess of the DM halo j (perhaps exception is dwarfs), but *looses right amount* so that jgalaxy~0.4 jhalo.

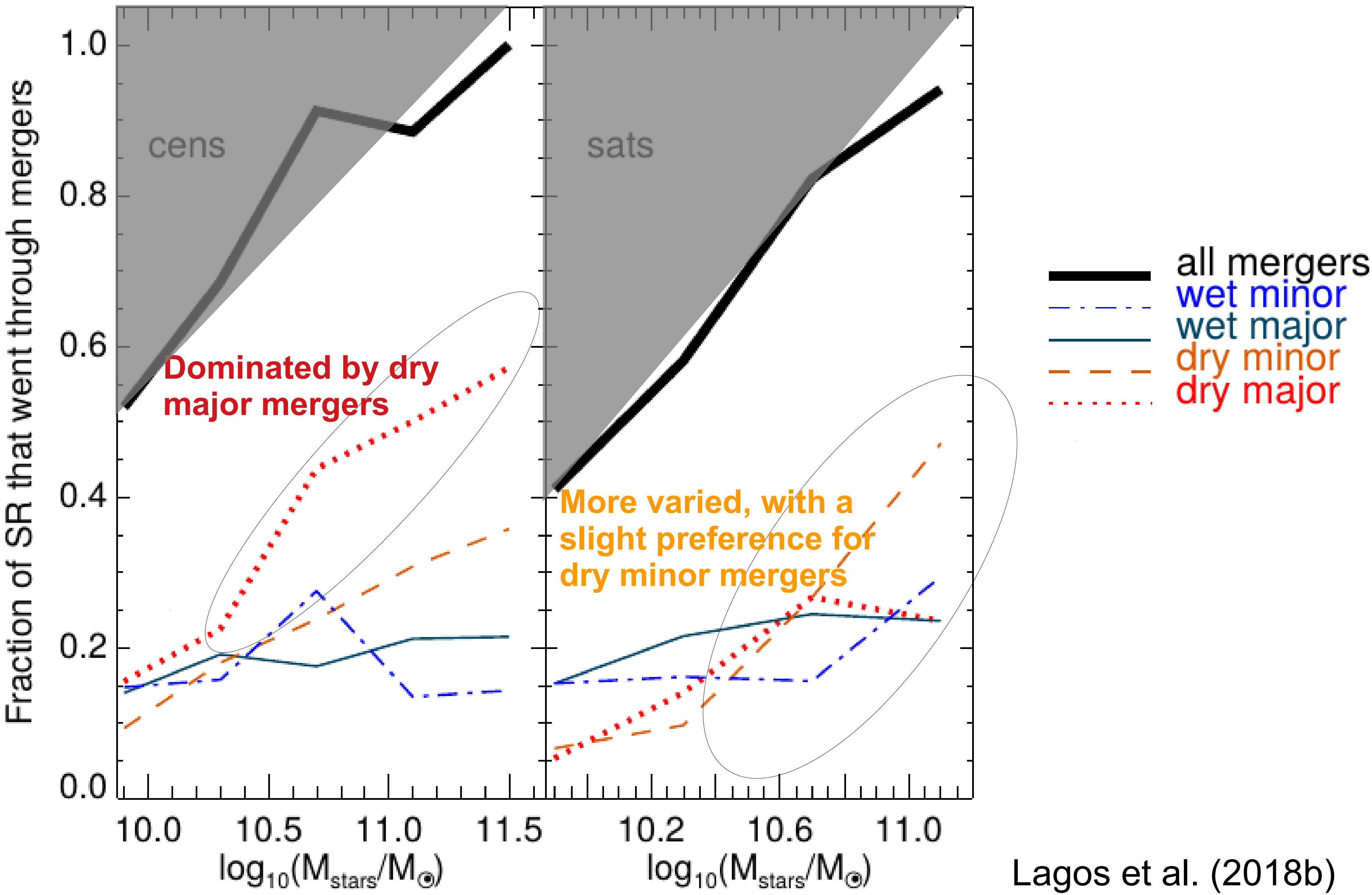




(4) Taking advantage of the unique flexibility of **Shark** to explore how *feedback acts as a chaotic mapping* of the AM of the halo onto the AM of galaxies.

The incidence of mergers on SRs

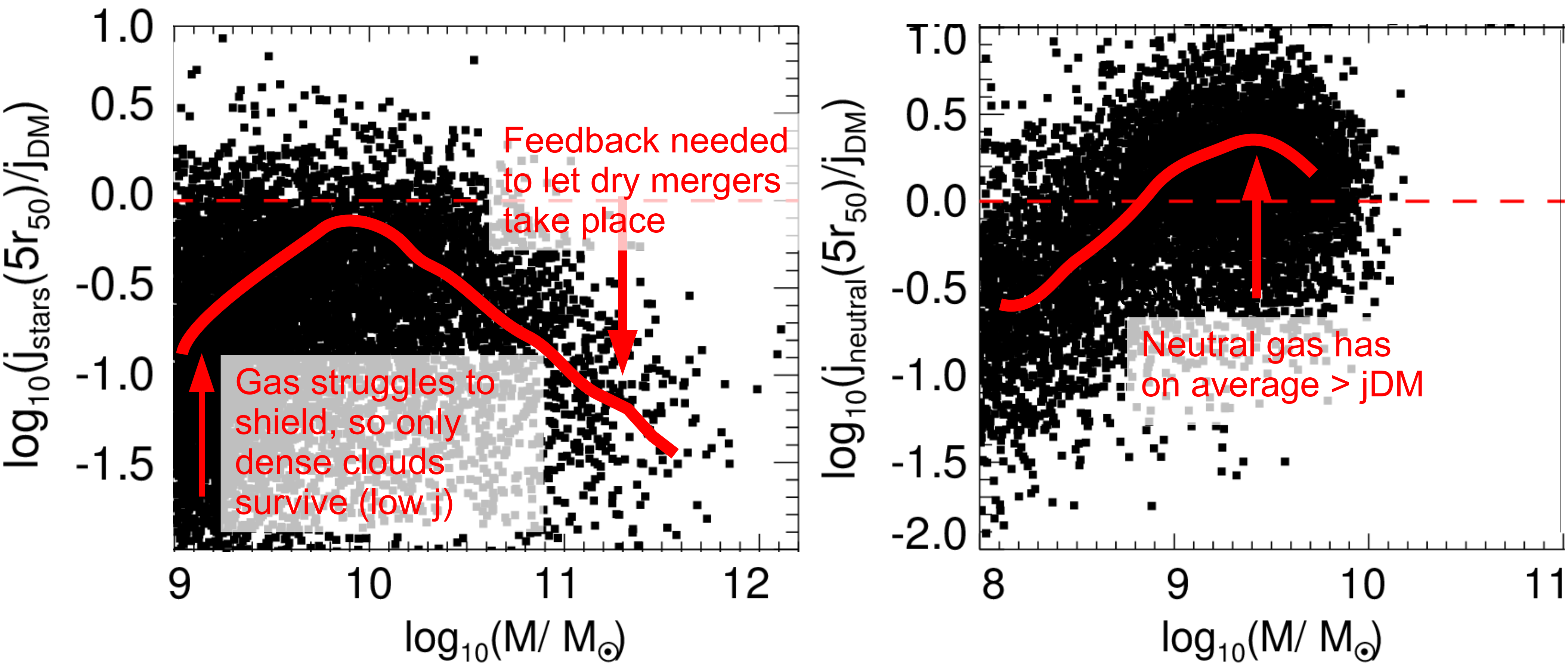
No mergers (ms/mp>0.1) but slow rotators!



Lagos et al. (2018b)

Angular momentum deficit?

F83: Angular momentum conservations sets j and sizes: physics or coincidence?



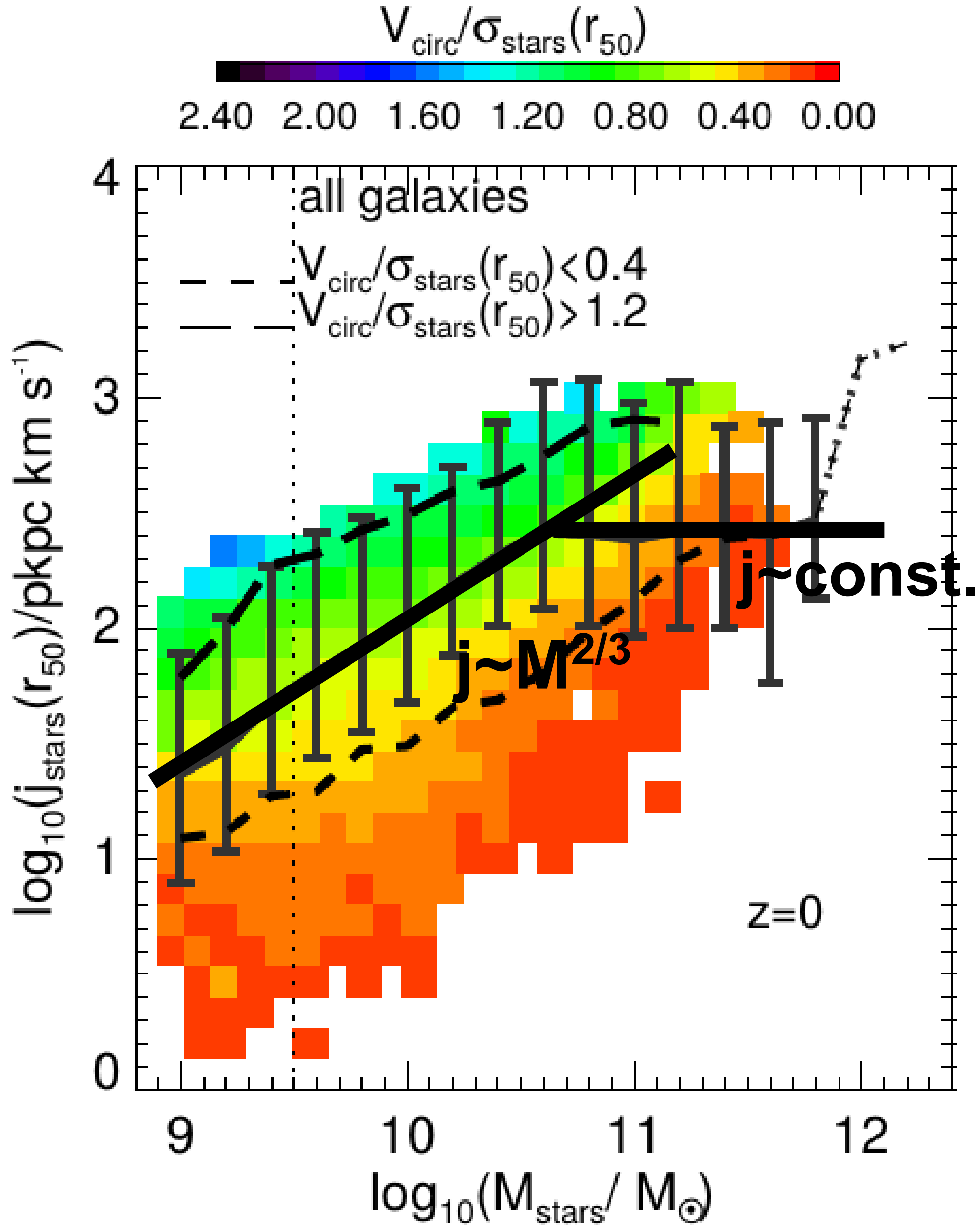
Sizes are not set by j conservation but are the result of the interplay accretion/shielding/feedback.

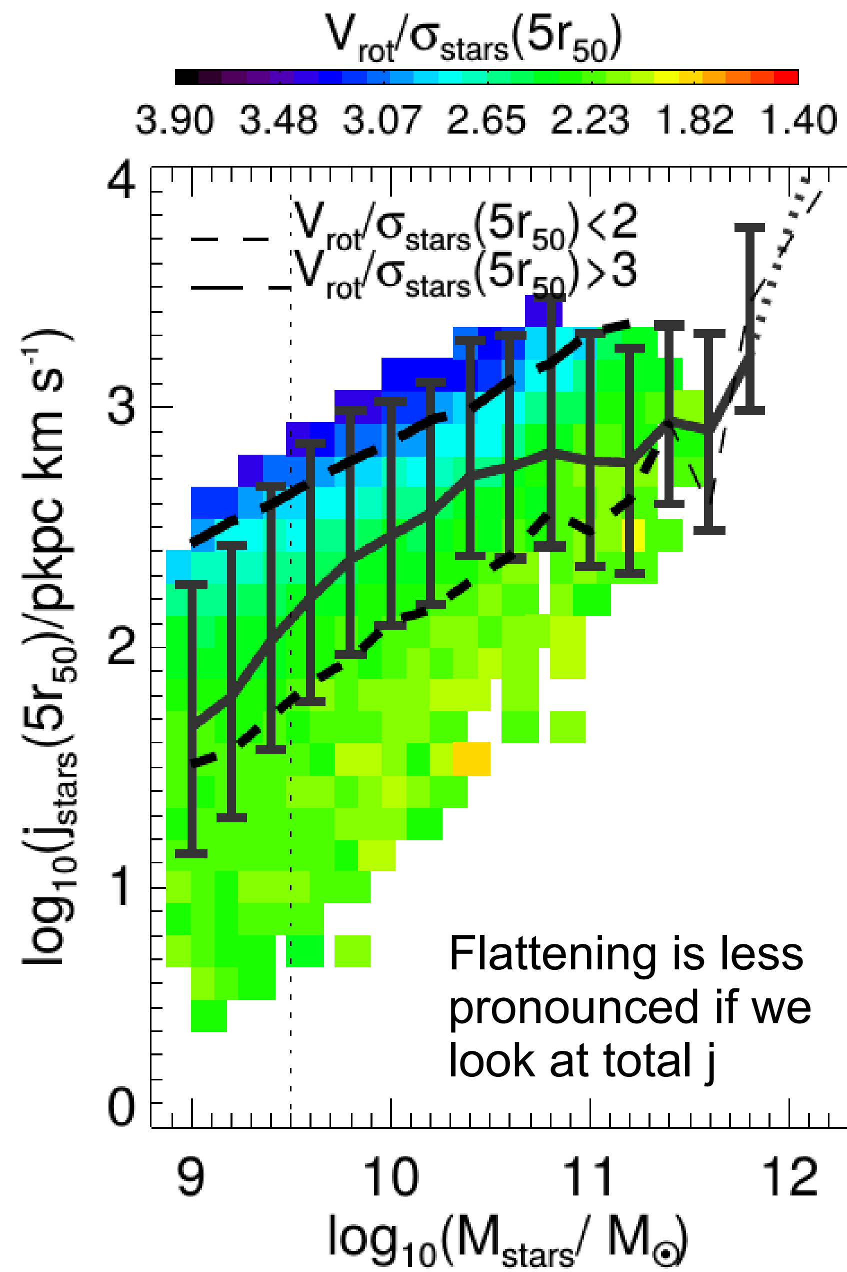
Consequence of fine tunning?

(see also Stevens et al. 2017)

Angular momentum of galaxies in EAGLE

How do galaxy properties correlate with position in the j-M plane at z=0? (**Lagos et al. 2017a**)

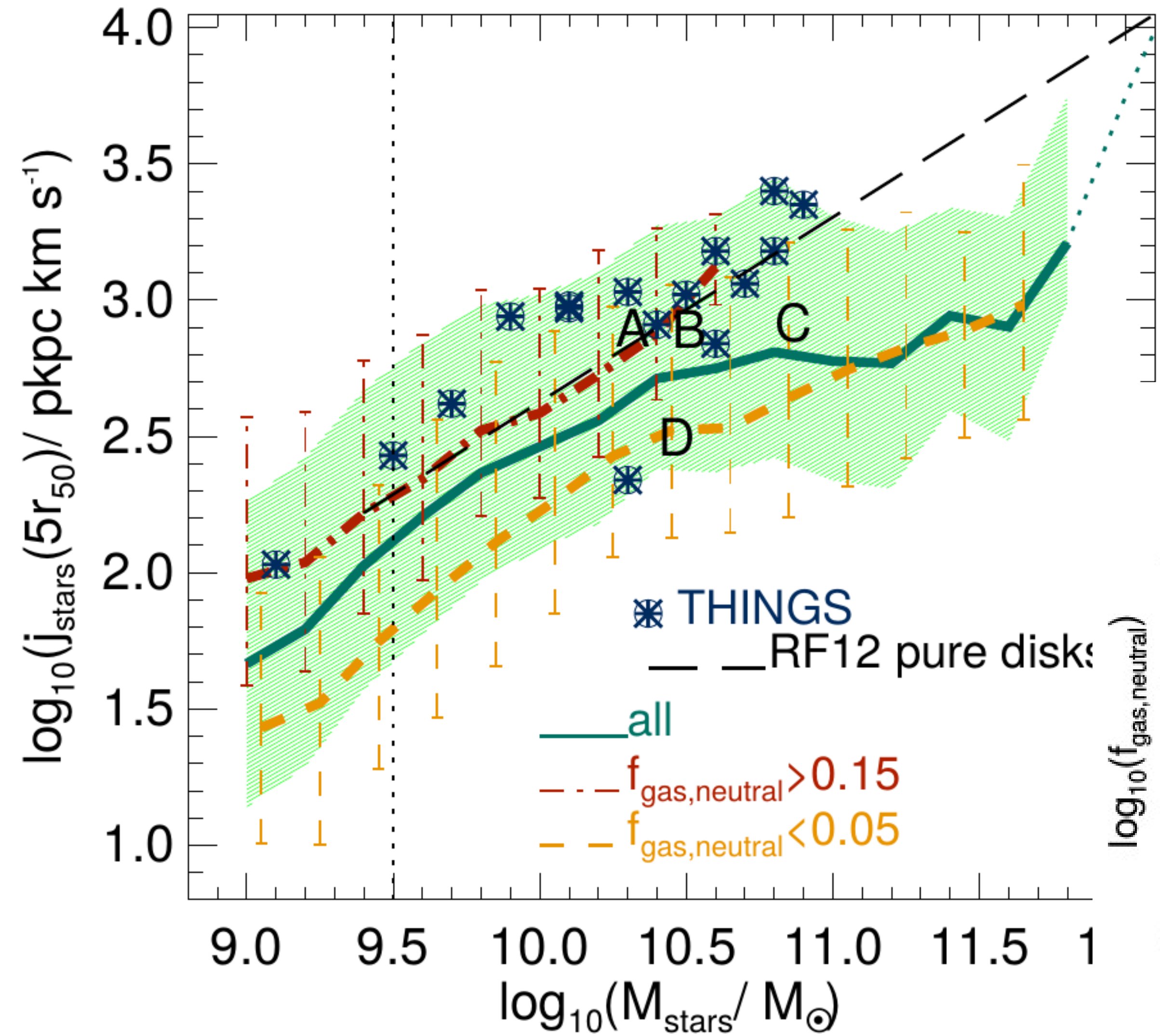


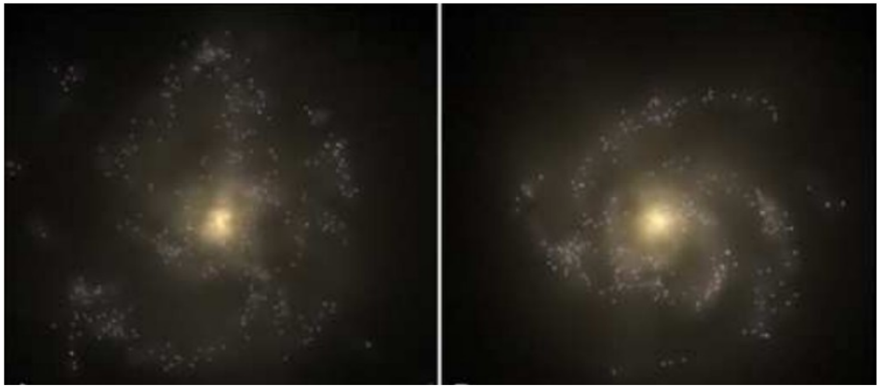


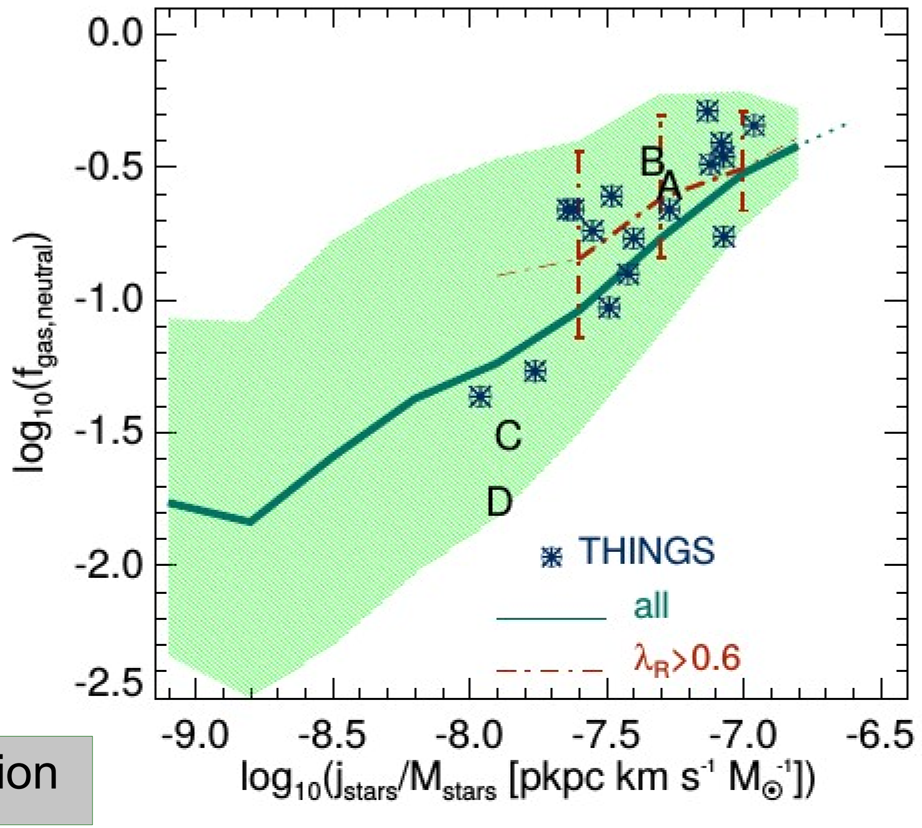
See also Teklu+15, Pedrosa+15, Genel+15

Comparison with Spiral galaxies

Obreschkow & Glazebrook (2014): measurements done within ~5r50 (close to total j) for THINGS galaxies

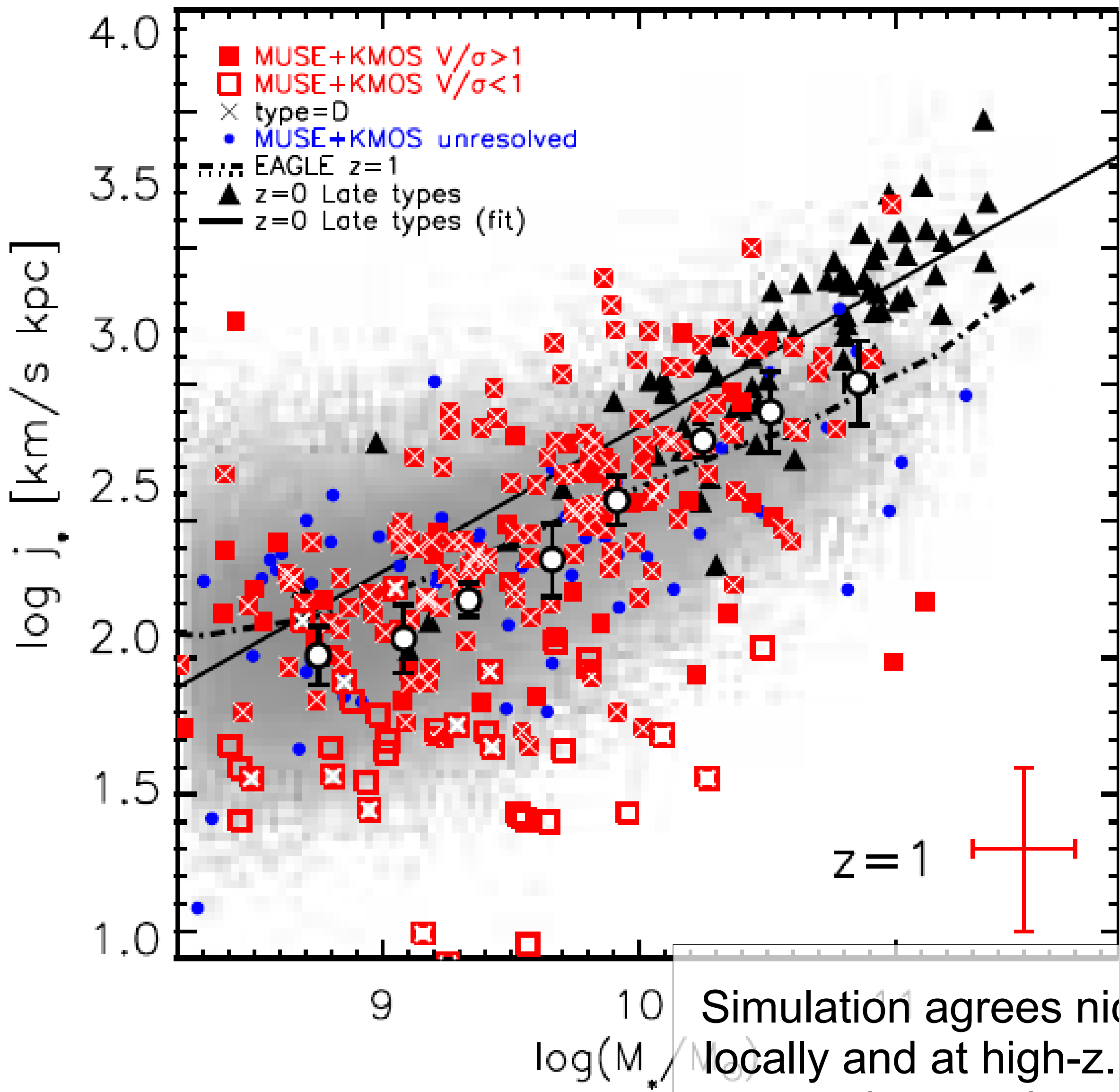






We can use EAGLE to study the pathways of j evolution

Comparing to IFU results at high-z

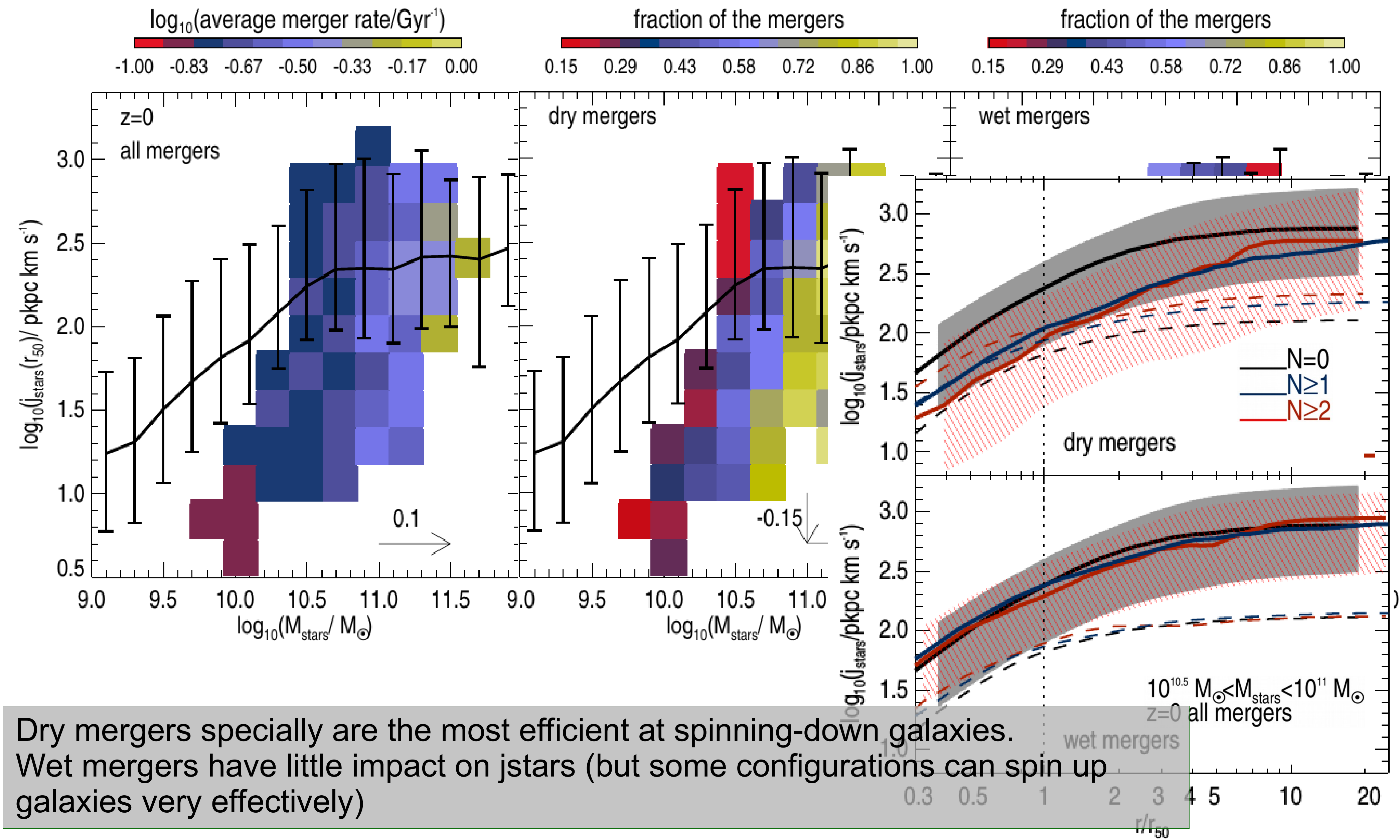


Simulation agrees nicely with observations locally and at high-z. Gives us confidence to use it to study evolutionary paths of j.

Swinbank et al. (2017)

Analysing mergers in detail

Lagos et al. (2017b): not all mergers spin-down galaxies. Special conditions are necessary.

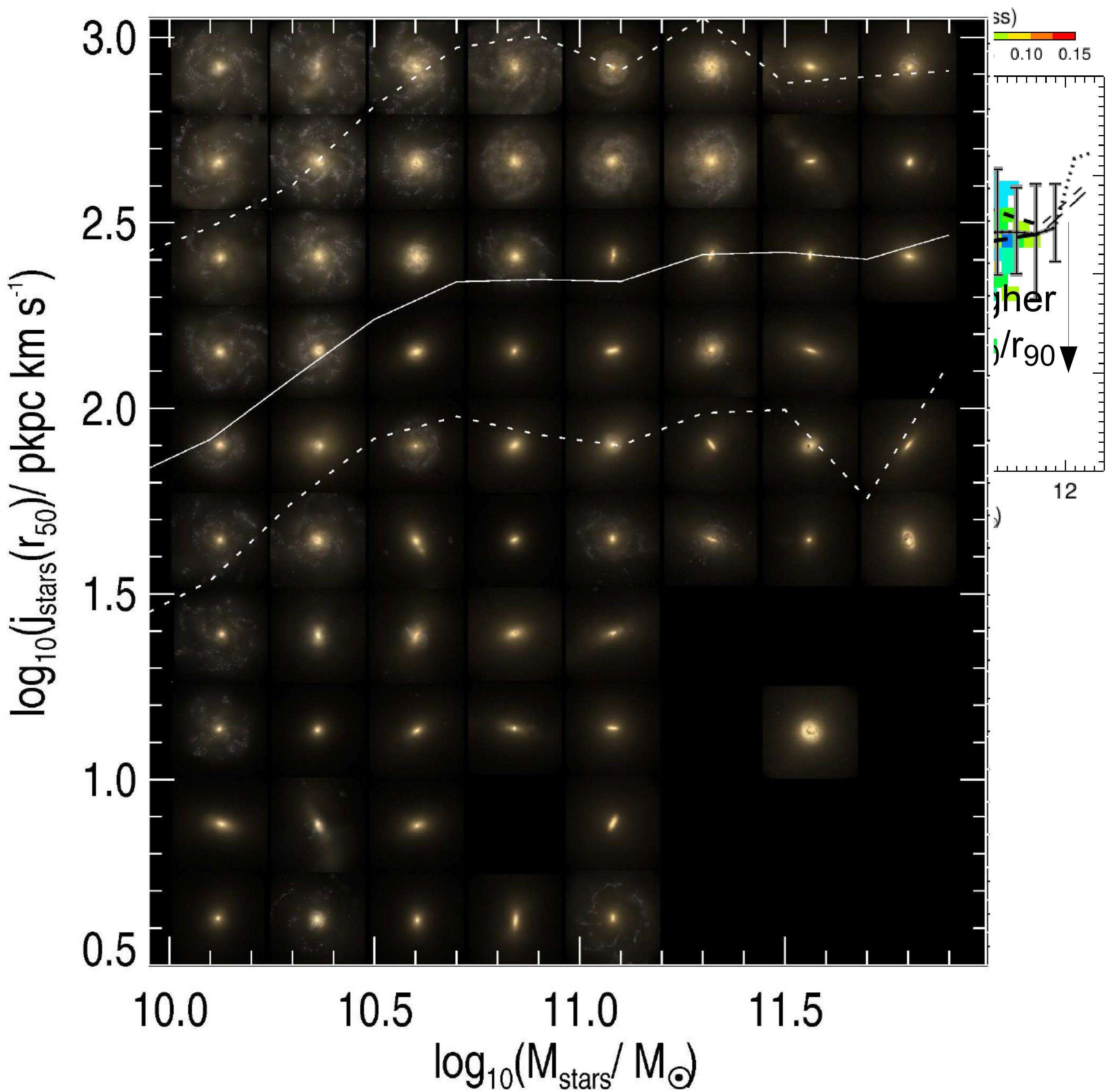


Dry mergers specially are the most efficient at spinning-down galaxies.
Wet mergers have little impact on jstars (but some configurations can spin up galaxies very effectively)

Galaxy properties in the j-mass plane

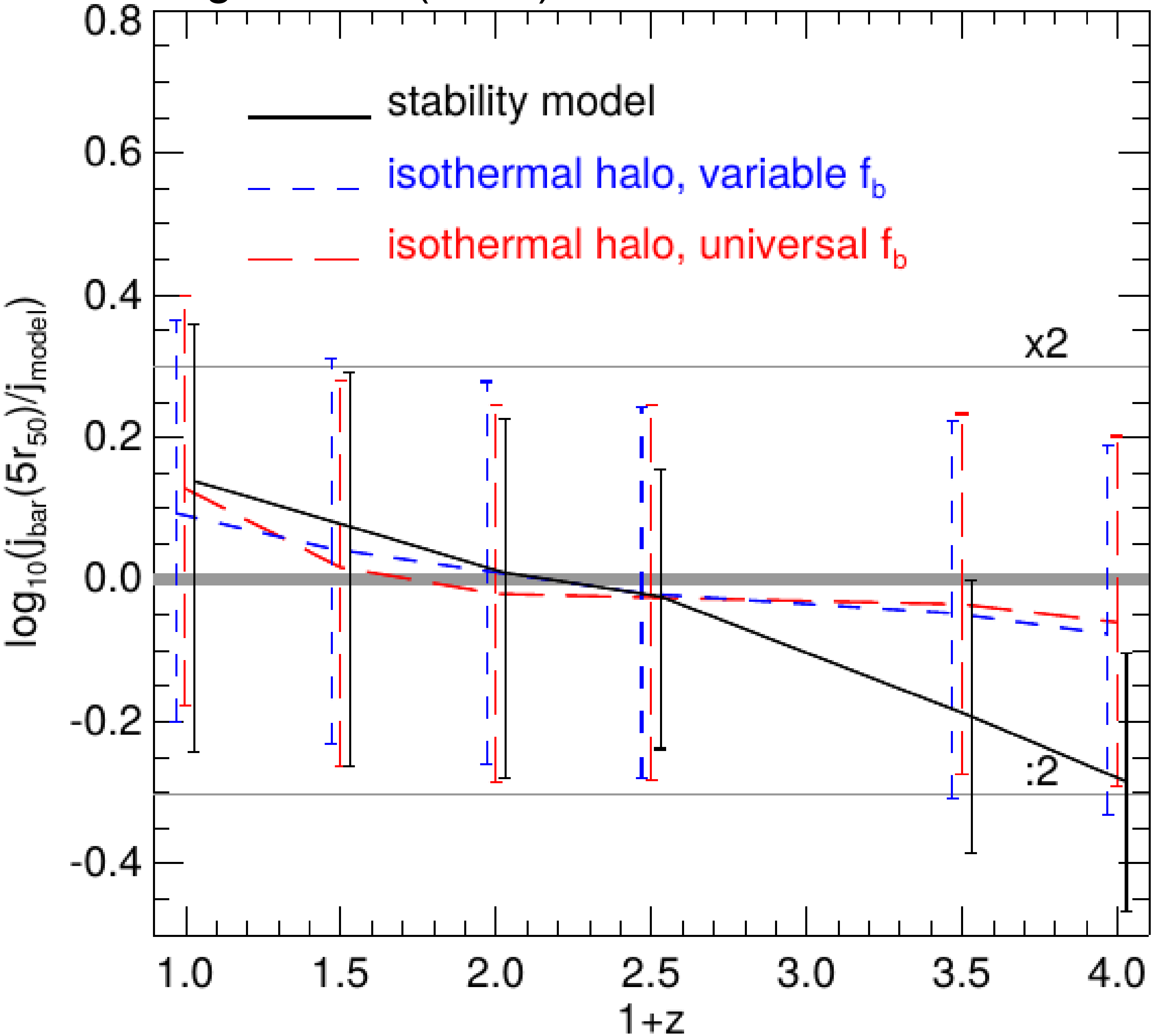
How do galaxy properties correlate with position in the j-M plane at z=0?
(**Lagos et al. 2017**)

Continuous sequence of j, with position being strongly correlated with morphological proxies at fixed stellar mass



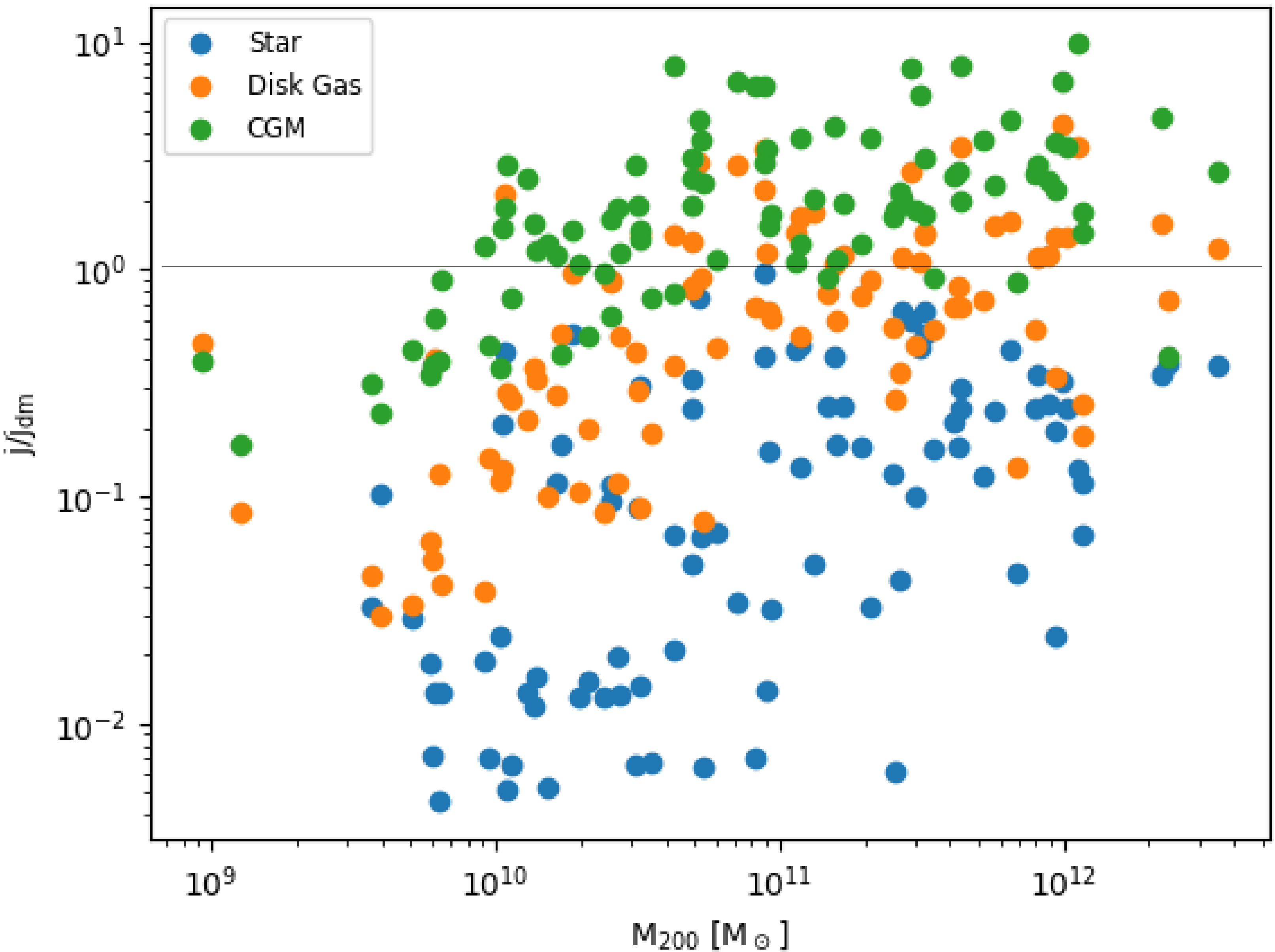
Galaxy vs. Halo

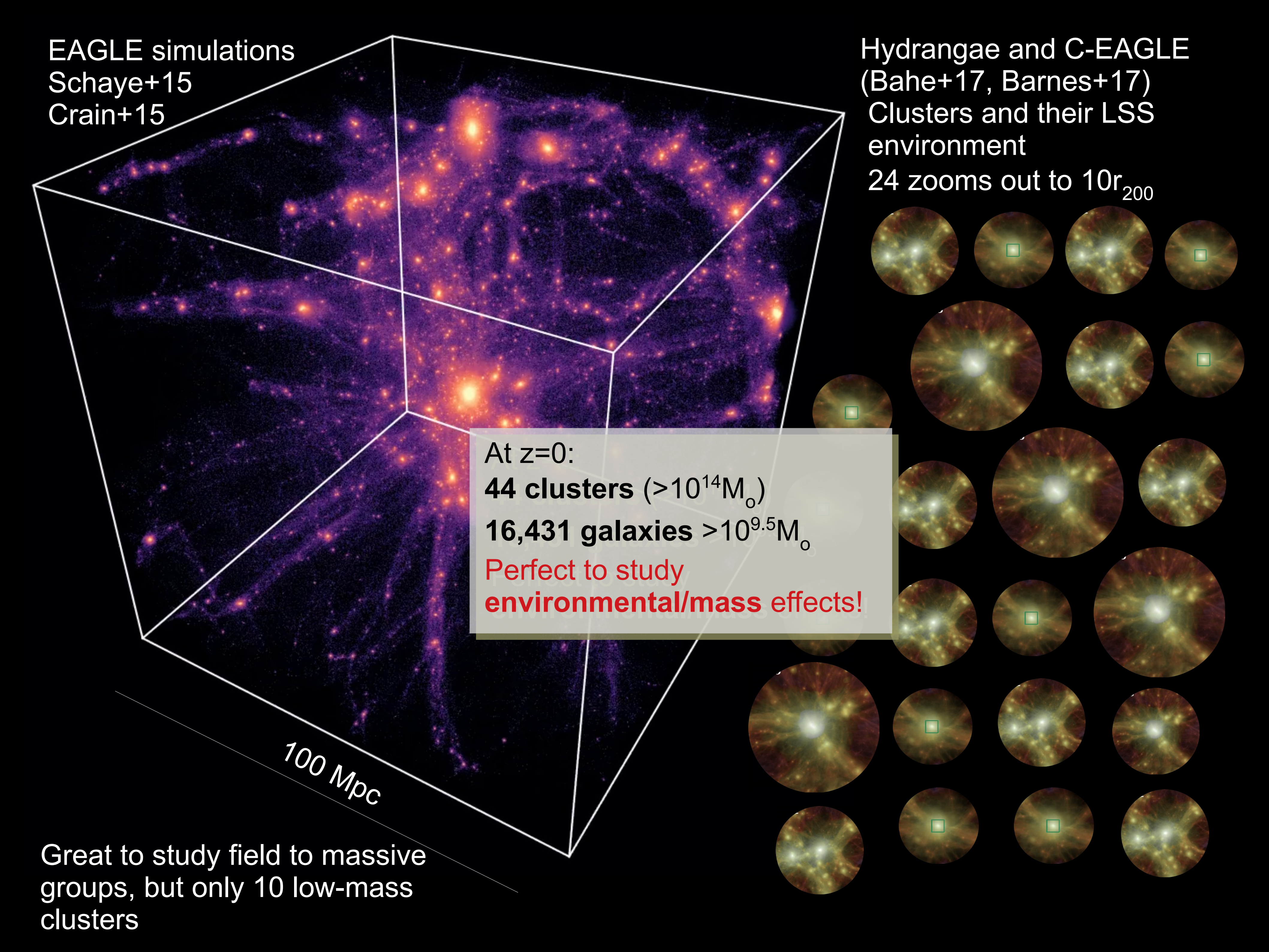
Lagos et al. (2017)



NIHAO

Wang, Obreschkow, Lagos et al. (in prep.)




EAGLE simulations
Schaye+15
Crain+15
Hydrangae and C-EAGLE
(Bahe+17, Barnes+17)
Clusters and their LSS environment
24 zooms out to $10r_{200}$
At z=0:
44 clusters ($>10^{14}M_o$)
16,431 galaxies $>10^{9.5}M_o$
Perfect to study
environmental/mass effects!
100 Mpc
Great to study field to massive groups, but only 10 low-mass clusters