Are mergers important?
Predictions from cosmological simulations

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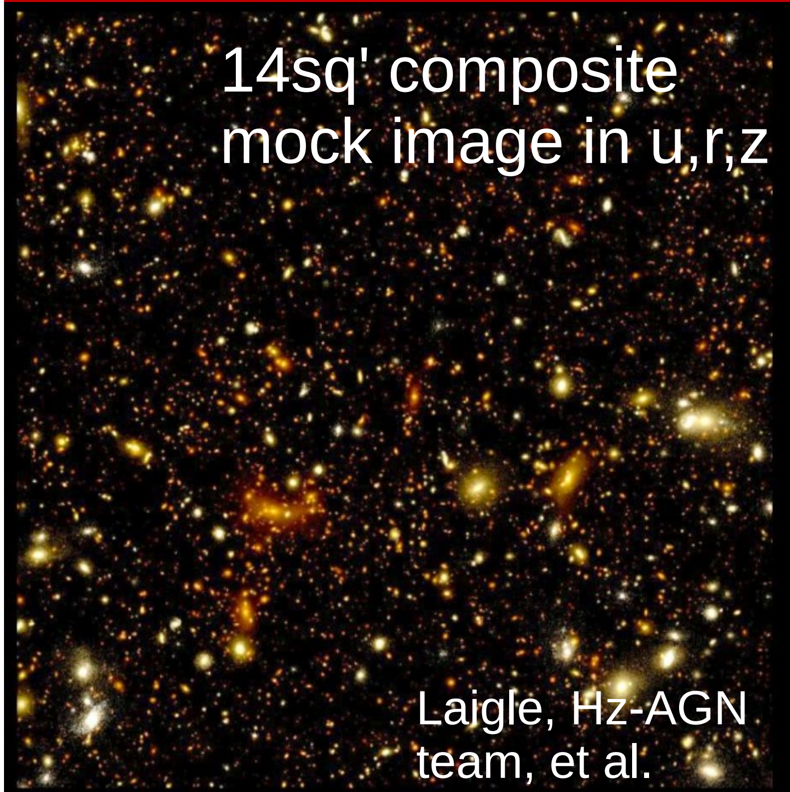
The Simulation

Mass evolution

Horizon-AGN (Dubois+16)

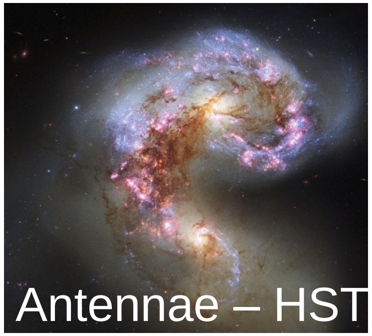
- 10 million CPU hours
- ~100h^{-1} CoMpc box length
- Minimum 1kpc resolution – 5 orders of magnitude
- Cosmology corresponding to WMAP7 results (Komatsu+ 2011)
- Hz-AGN Provides good agreement with observations (Kaviraj+2017)

People: PI – Yohan Dubois (IAP), Julien Devriendt (Ox), Christophe Pichon (IAP)



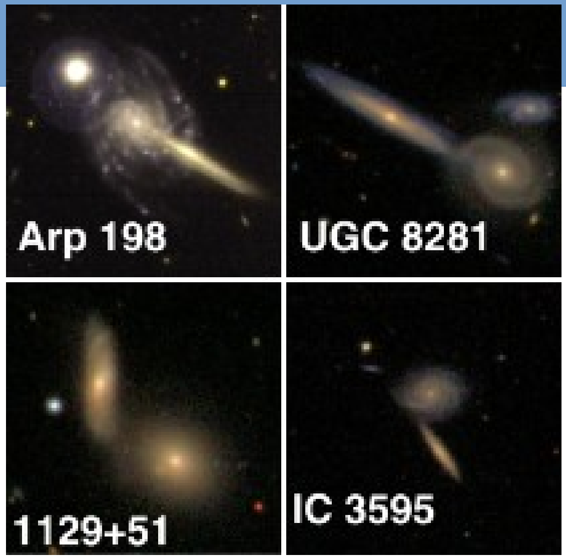
Part I: Mergers as drivers of cosmic star formation

- Star-bursts often are observed in interacting systems...
- It's not clear that *how often* mergers trigger significant star-bursts or *how much* of this star formation would have happened anyway
- Mergers were thought to be important drivers of star formation, but observations have brought this into question recently (e.g. Stott+ 2013; Lofthouse+ 2017).
- Explained by cosmological accretion only?
- Cosmological simulations like Horizon-AGN, offer an alternative to observational studies of mergers with some obvious advantages

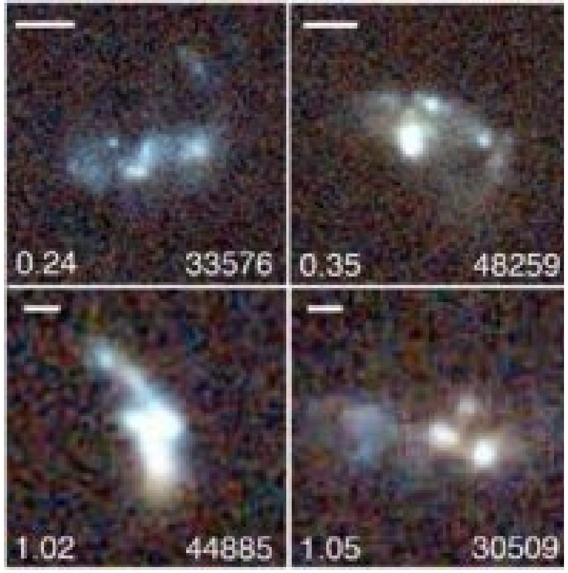


Star formation due to mergers

- Cosmological simulations like Horizon-AGN, offer an alternative to observational studies of mergers
- Observational methods probe only a particular point in time
  - Galaxy pairs are not a reliable way of identifying mergers (chance projection, fly-bys)
  - Disturbed morphologies can also emerge from secular / internal processes (e.g. Bournaud+ 2008; Hoyos+ 2016), especially at high redshift
  - Minor mergers do not produce strong tidal features (Kaviraj+ 2013) and are difficult to study (but as important as major mergers!)
- Simulations offer a more comprehensive picture



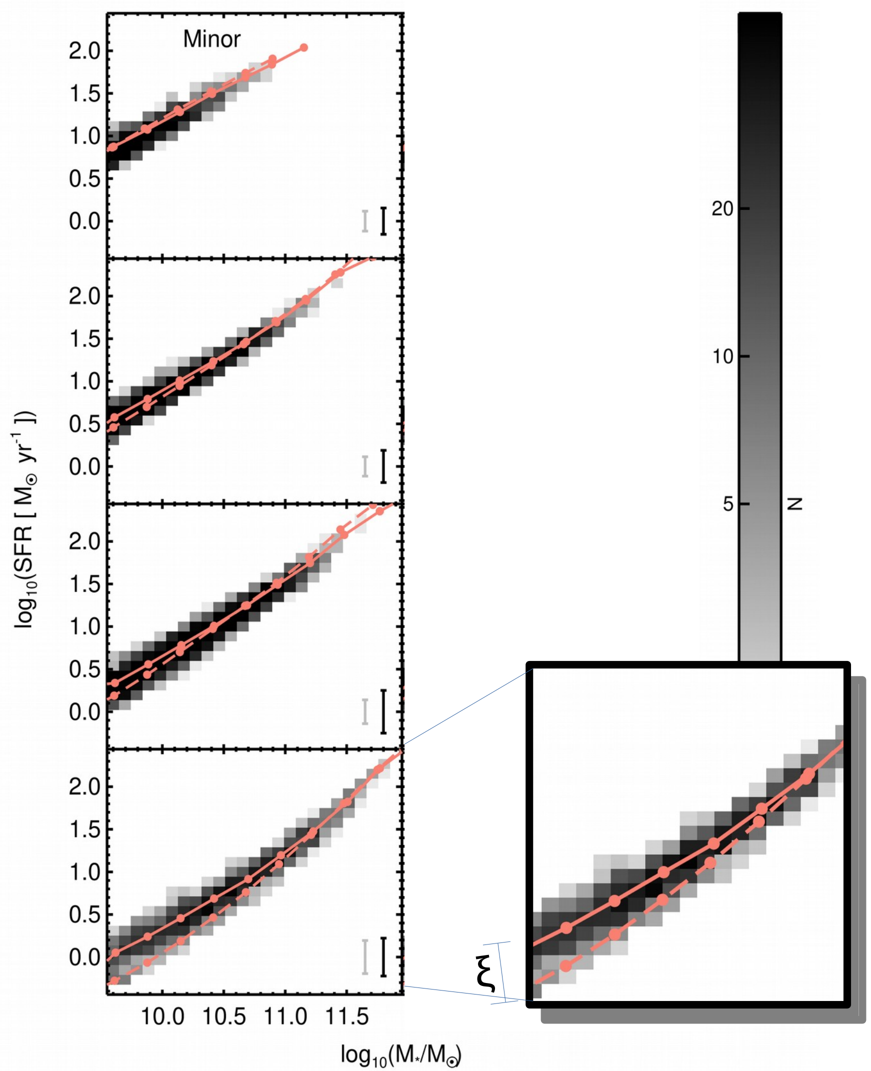
SDSS / Keel+Manning 2013



GOODS / Elmgreen+2009

Estimating the merger SF budget

Merger Enhancement



- SFR enhancement –
- merging vs non-merging populations (mean SFR over the duration of the merger)
- Define the difference in sSFR as the enhancement, ξ.
- Gas inflows during minor mergers can be of similar magnitude to major mergers
- Ambient levels of SF are lower in the local universe, allowing mergers to produce more significant enhancements

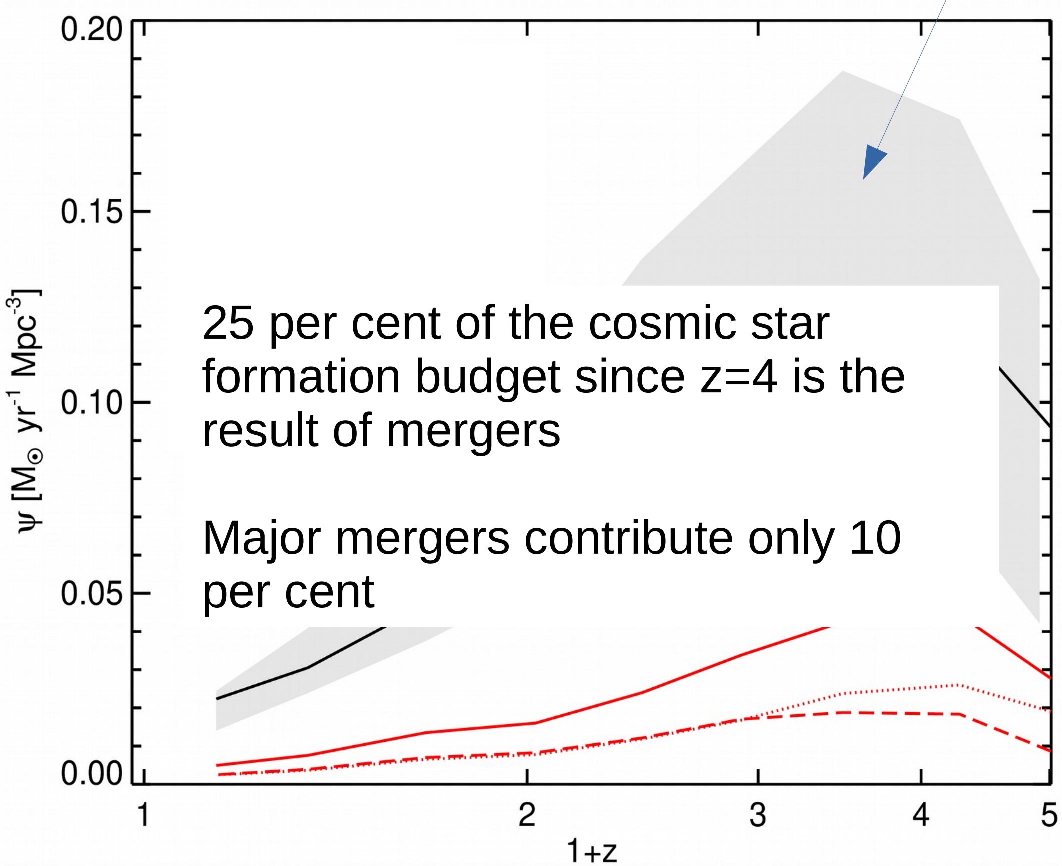
Are mergers significant?

The total SF contribution due to mergers is given by:

Merger Budget

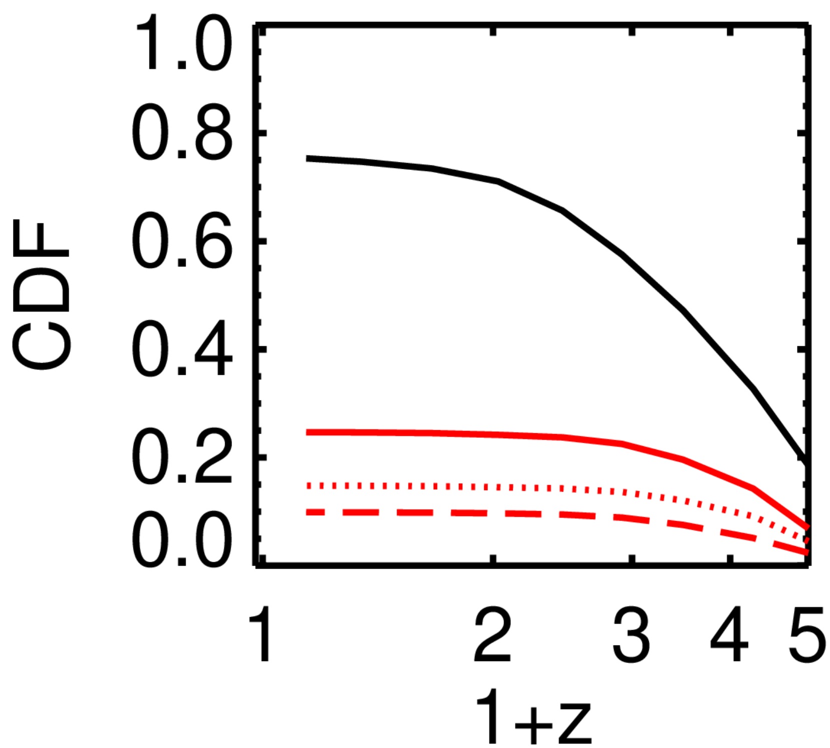
Shaded region – Hopkins and Beacom 2006

f x SFRD



25 per cent of the cosmic star formation budget since z=4 is the result of mergers

Major mergers contribute only 10 per cent



Part II: BH growth

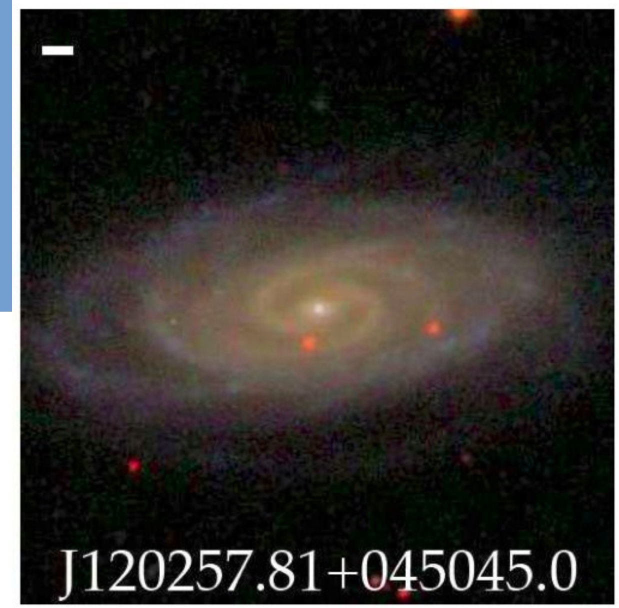
- (Observed) correlations between BH mass and various galaxy properties (e.g. dispersion, stellar mass, bulge mass) suggest co-evolution of galaxies and their BH.
  - Common explanation – major mergers

- Much of the past literature has focussed on early-type (M_*~M_{Bulge}) galaxies

- Recent studies have shown that BH – stellar mass correlation exists across the whole galaxy population (e.g. Marleau+2013;Reines+Volonteri 15)

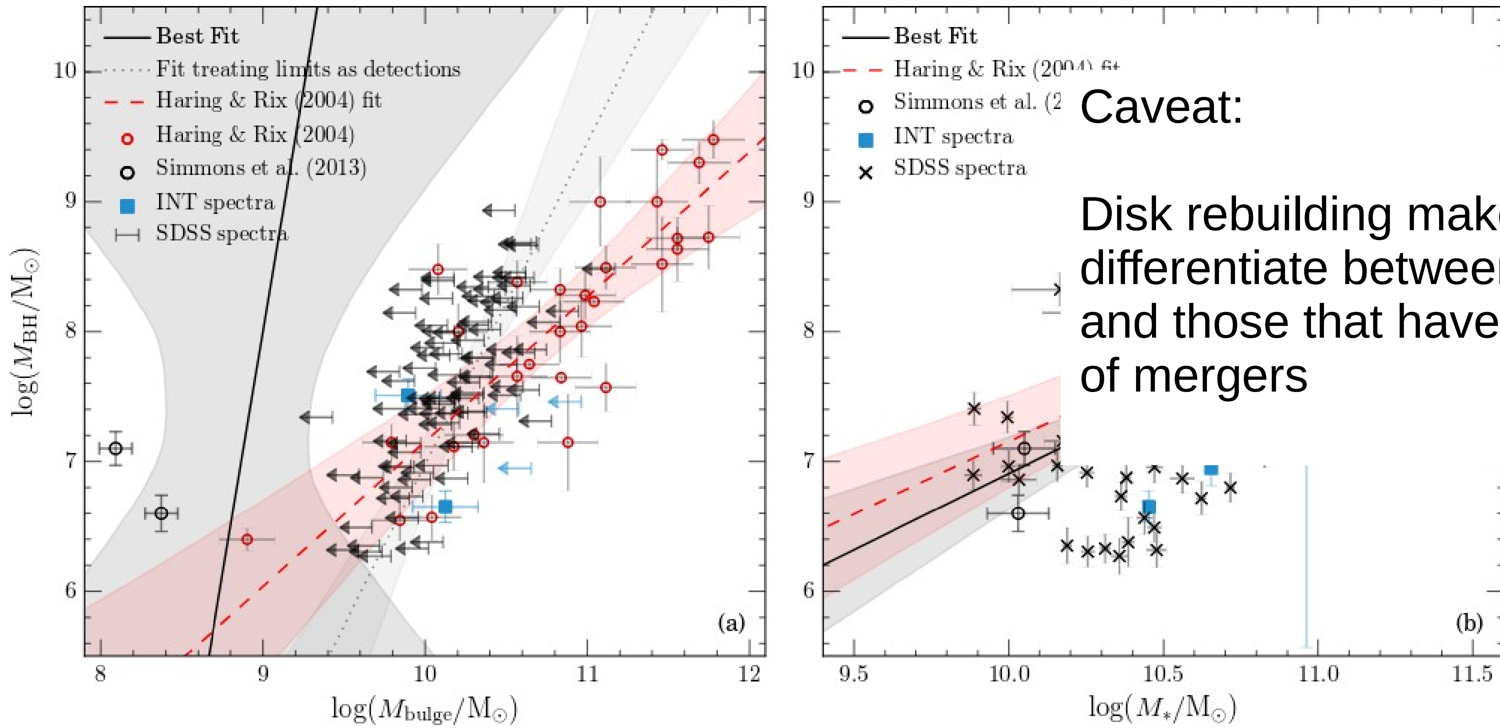
- If the same correlation exists for discs, where the bulk of stellar mass is likely to be a result of secular processes it is not as easy to see how mergers are responsible

BH growth in bulge-less galaxies



- A stringent test of this is to compare the BH masses of bulge-less (B/T < 0.1) galaxies (which should be merger free) with the general population (Simmons, Smethurst + Lintott 2017)
- Disk-dominated and bulge-less galaxies are offset from the main locus of the BH – bulge correlation, but lie on the BH – total stellar mass correlation

(Simmons, Smethurst and Lintott 2017)

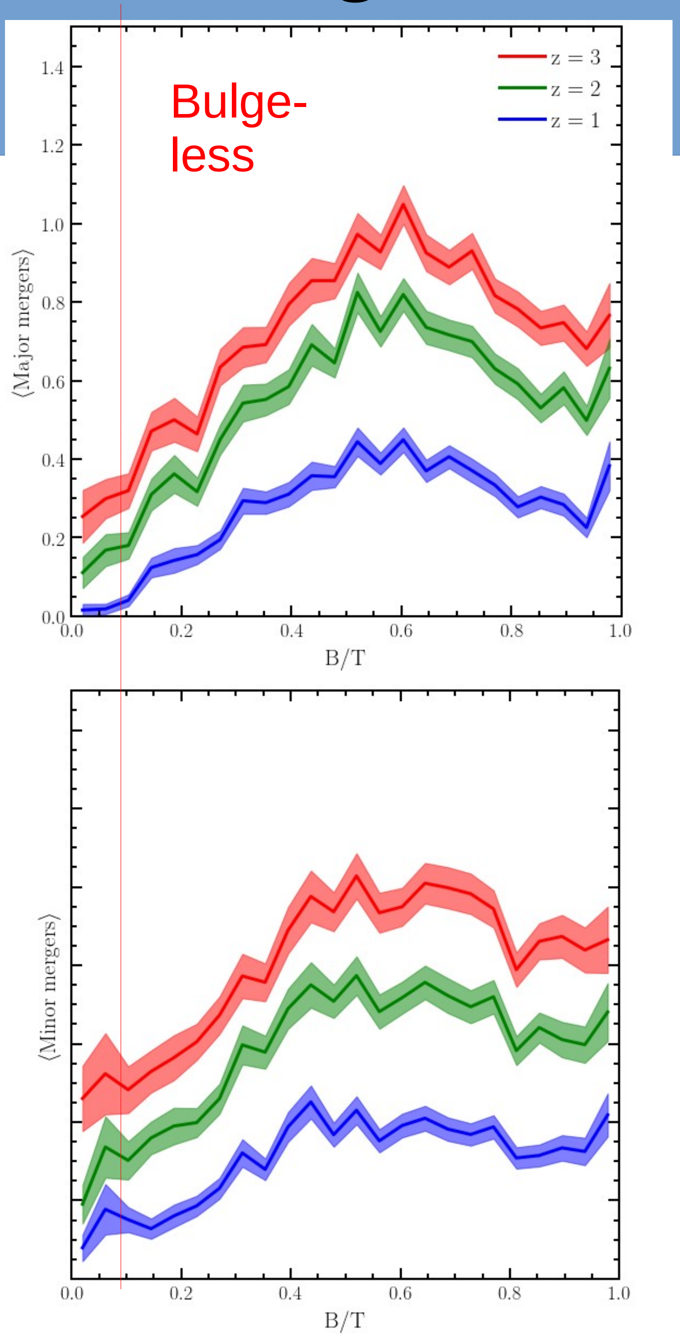


Caveat:

Disk rebuilding makes it difficult to differentiate between `normal' disc galaxies and those that have evolved in the absence of mergers

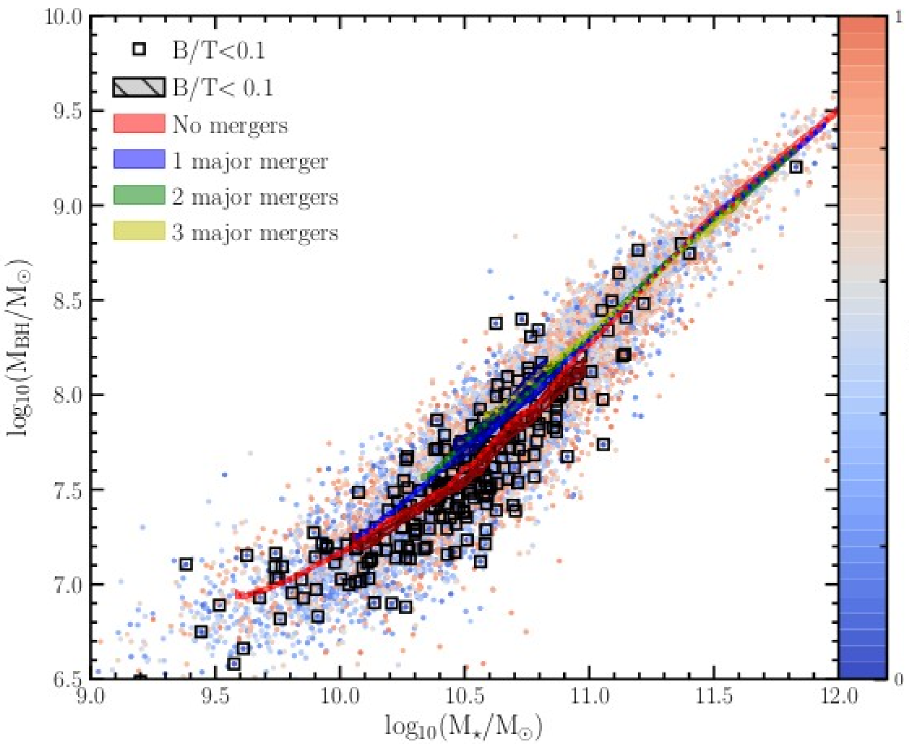
Are bulge-less galaxies also merger-less?

- Bulge-disc decomposition (Volonteri+2016)
- We plot the average number of mergers since z=1,2,3 as a function of B/T
- The assumption of no major mergers is good at z=1
- By z=3, ¼ of bulge-less galaxies are likely to have undergone a major merger
  - But accounting for < 15 per cent ex-situ mass by z=0



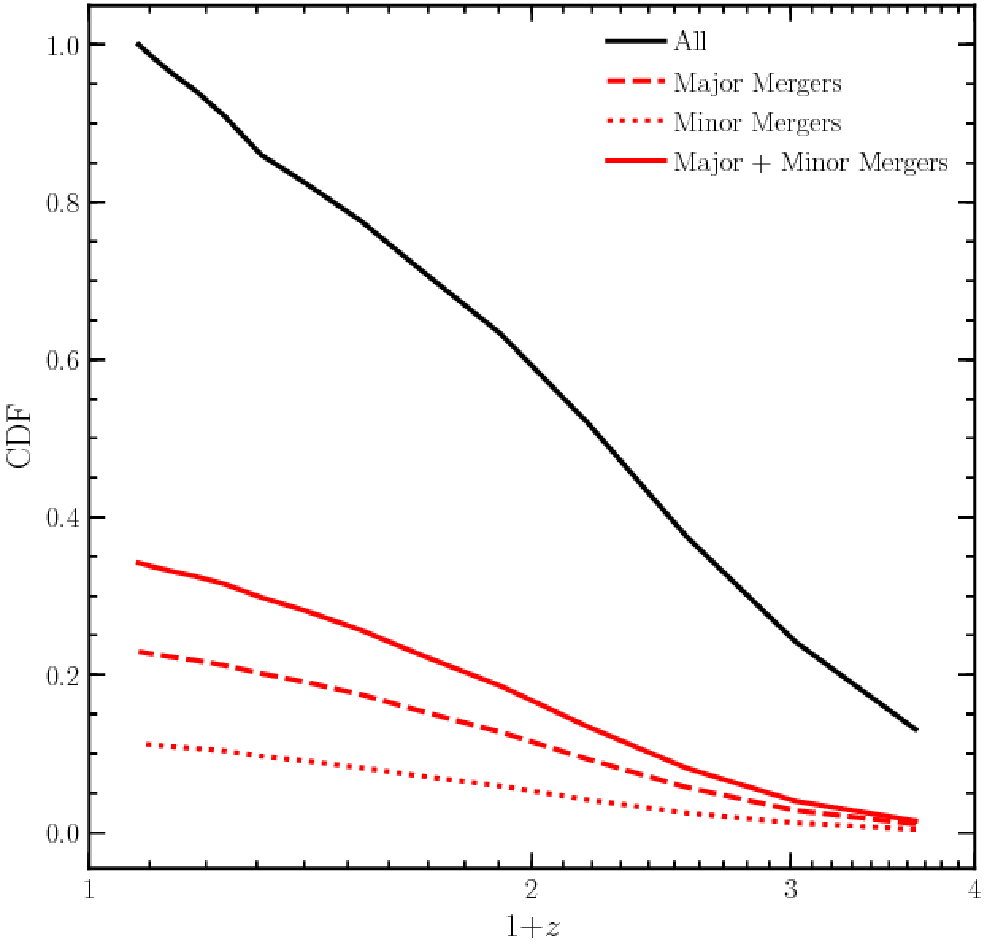
The M_{BH}–M_* plane

- Bulge-less galaxies lie on the same M_{BH} –M_* relation as the general galaxy population.
- The number of major (or minor) mergers that a galaxy has undergone does not alter a galaxy's position on the M_{BH} –M_* relation
- Mergers are not a significant mechanism for feeding the BH.
- Bulge-less galaxies lie offset from the M_{BH} –M_{Bulge} relation.
- The offset of the bulge-less galaxies is driven by their having under-massive bulges (due to a smaller number of mergers).



BH growth over cosmic time

- Major mergers not a primary driver of BH growth at any redshift.
- Only ∼35 per cent of the BH mass in galaxies more massive than 10 9.5 M in today’s Universe is directly attributable to mergers.
- ∼22 per cent is driven by major mergers and ∼13 per cent is driven by minor mergers.
- Secular processes, account for the creation of the majority (∼65 per cent) of BH mass over the lifetime of the Universe.



Conclusion I

- In general mergers contribute weakly to the star formation budget and BH growth

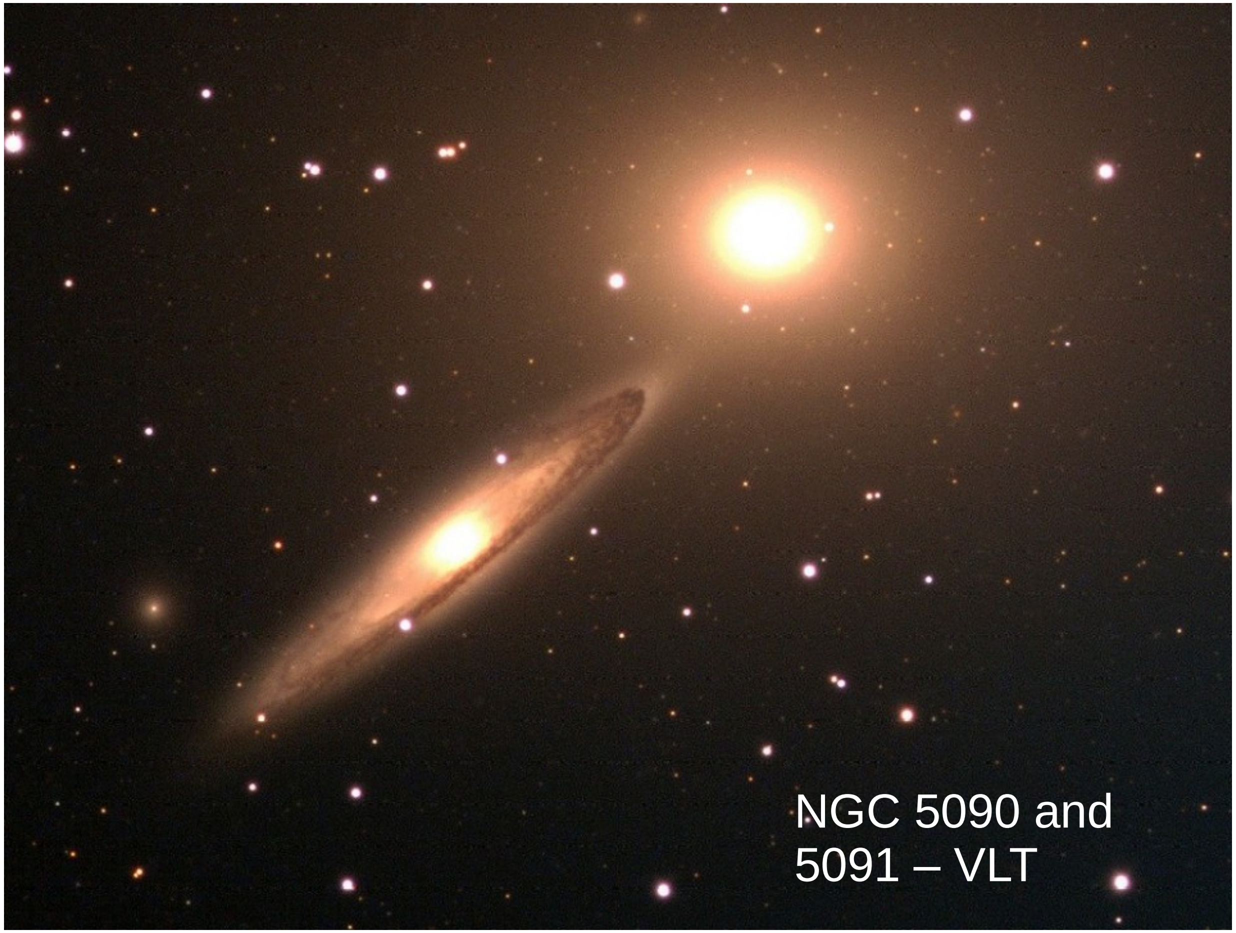
- Mergers directly trigger ~25 per cent of stellar mass growth over cosmic time, with major mergers accounting for only 10 per cent

- Mergers trigger 35 per cent of BH growth, similar to stellar mass growth

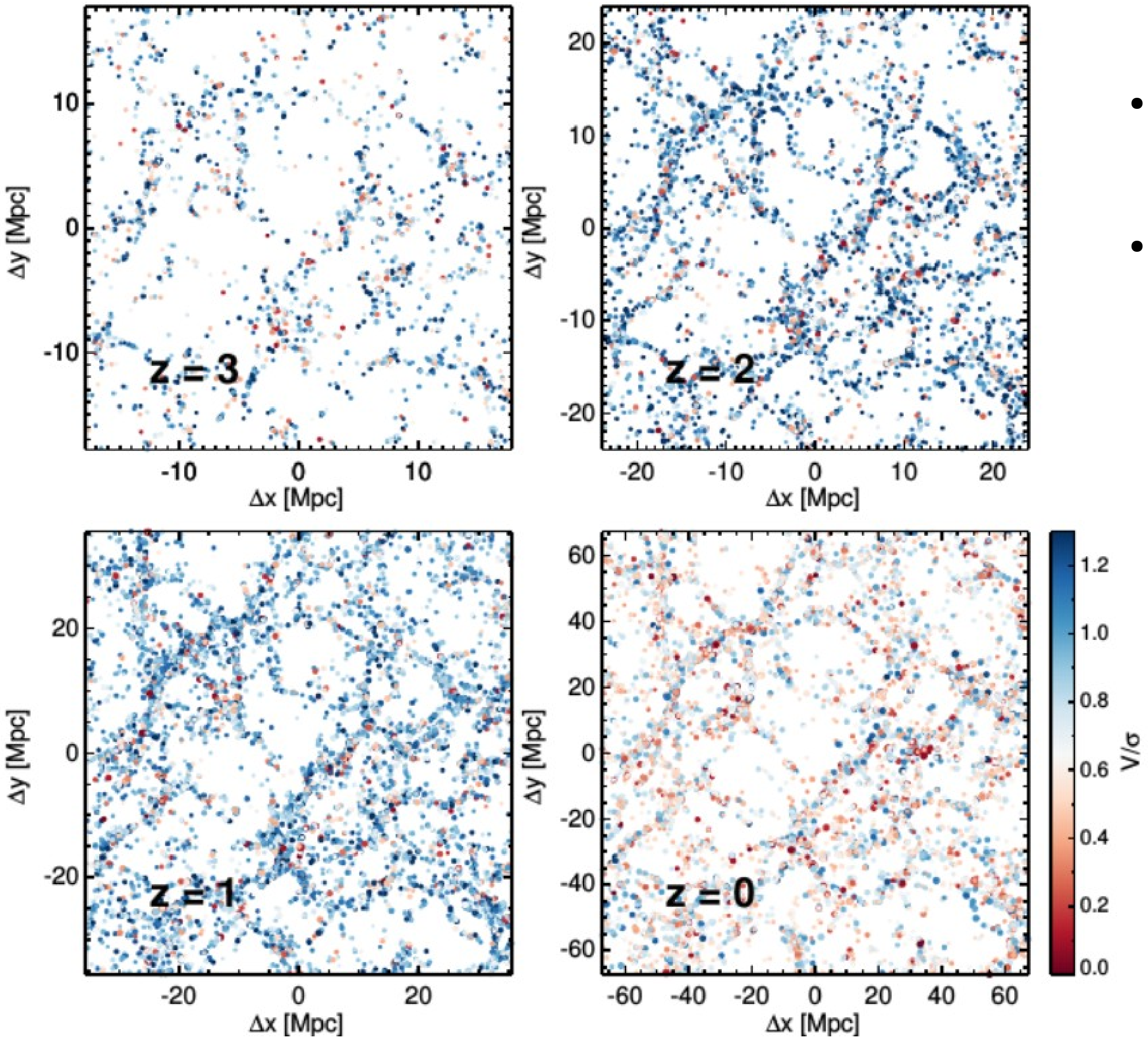
Part III: Spheroid Creation

The many paths to spheroidal morphology

- Many possible pathways to spheroidal morphology:
- Single major merger (violent relaxation) (e.g. Springel+ 2005)?
  - Are there enough?
- Multiple minor mergers (instability driven)?
- Environment (harassment etc.) (e.g. Moore+ 1998)
- Accretion (disk formation, accretion driven turbulence) (e.g. Elmegreen+ 2009)
- Internal processes (density wave, instabilities) (e.g. Zhang and Buta 2010; Bae+ 2016)



Spheroid Creation in Horizon



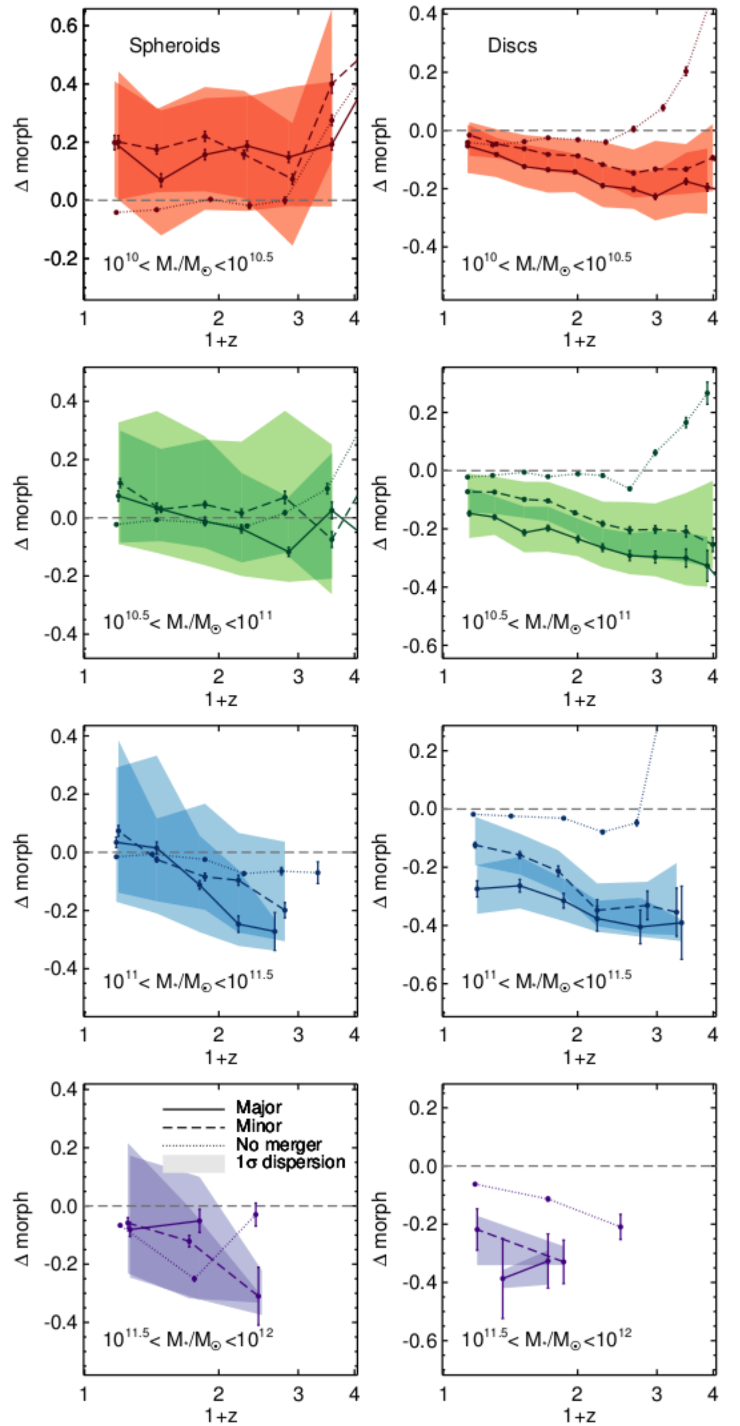
- Disks dominate at high z (blue points)
- Population becomes more spheroid dominated towards present day (red points)

How do galaxy properties effect morphological changes?

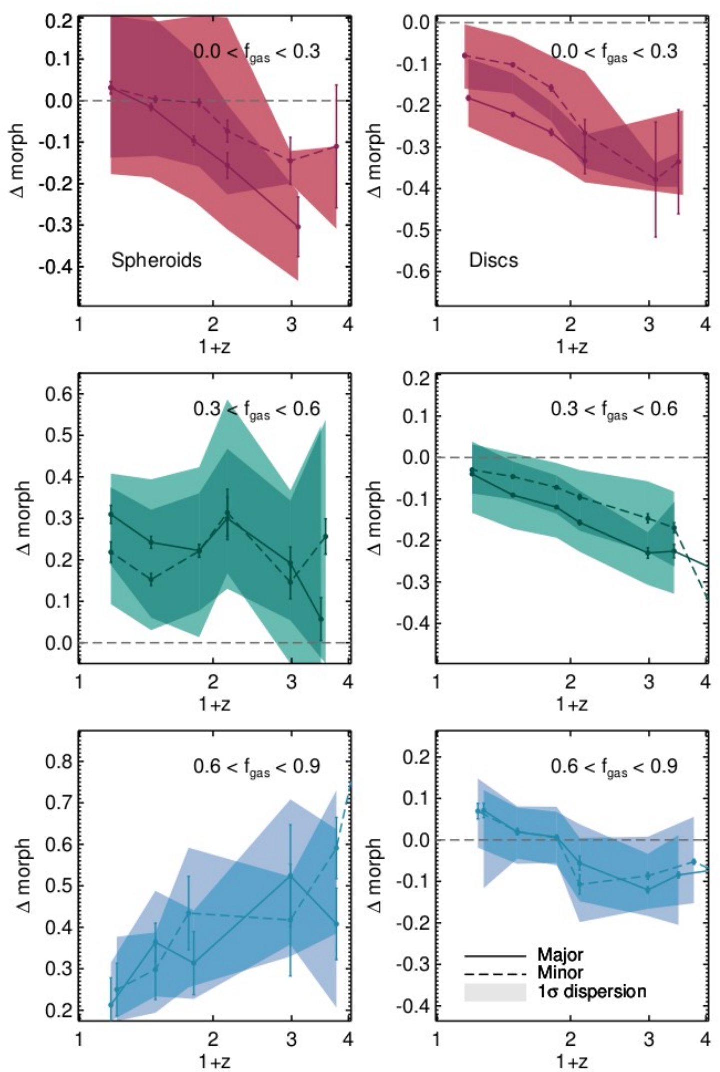
- We define morphological change as the fractional change in v/σ between the beginning and end of the merger:

$$\Delta\mathrm{morph} = \frac{{}^{V}/\sigma_{t=1\ \mathrm{Gyr}} - {}^{V}/\sigma_{t=-1\ \mathrm{Gyr}}}{{}^{V}/\sigma_{t=-1\ \mathrm{Gyr}} \cdot \Delta t}$$

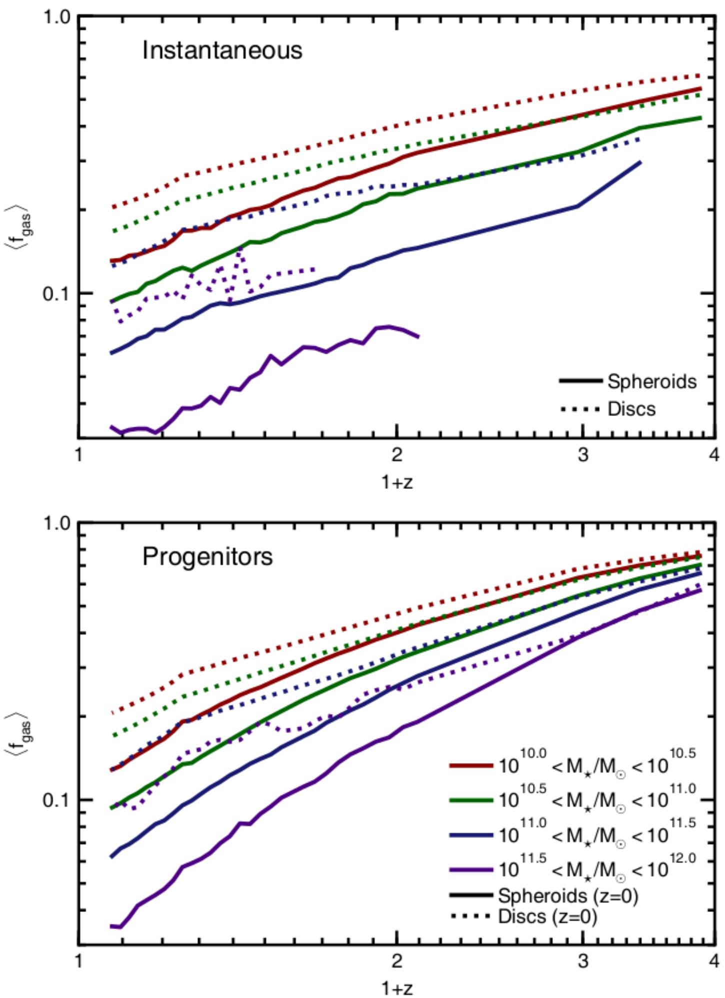
- Spin up due to cosmological accretion is an important effect, especially at early epochs.
- In the early universe (z > 2), stellar mass forms in discs more rapidly than it can be removed by mergers.
- On average, major and minor mergers increase dispersion in discs
- The picture is more complicated for spheroids, where there is already considerable dispersion



Gas content

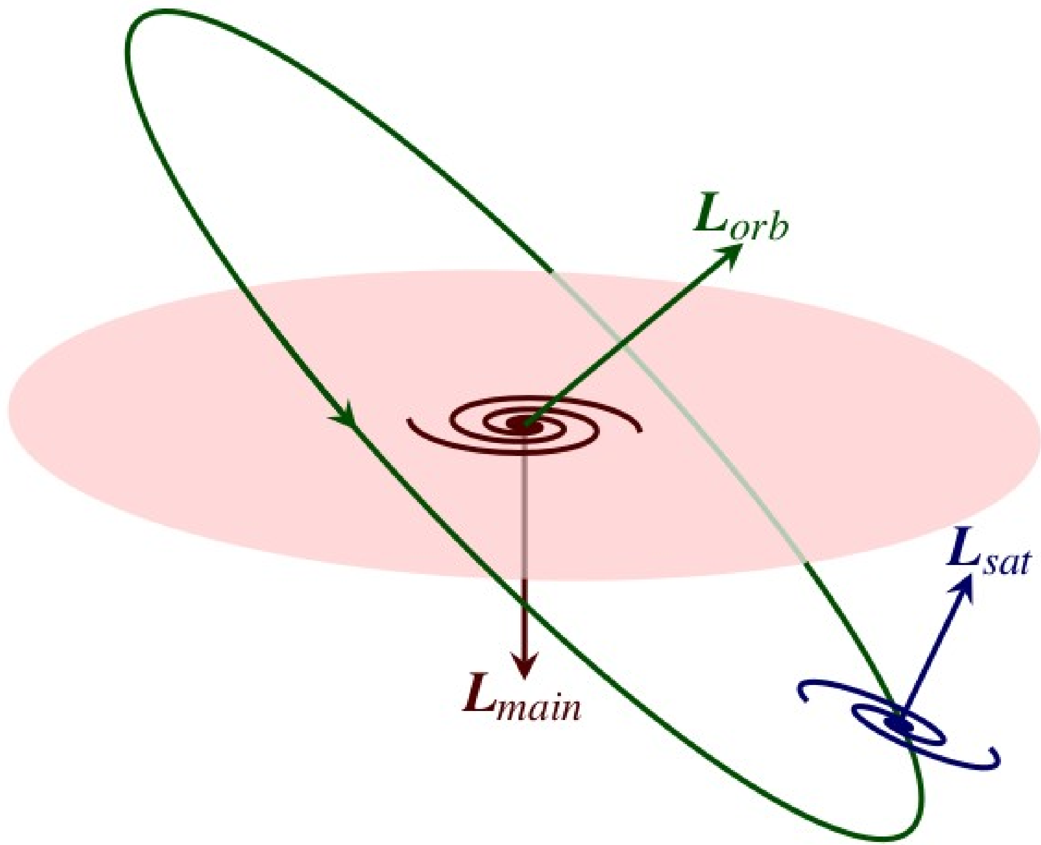


- The outcome of a merger is a strong function of the gas fraction of the merging pair.
- Mergers with higher gas fractions are more likely to produce remnants with increased V / σ .
- Low mass galaxies remain fairly gas rich: At later times and gas-rich minor mergers may become increasingly important for spinning up galaxies as cosmological accretion declines
- see also e.g. Springel +05, Font +17

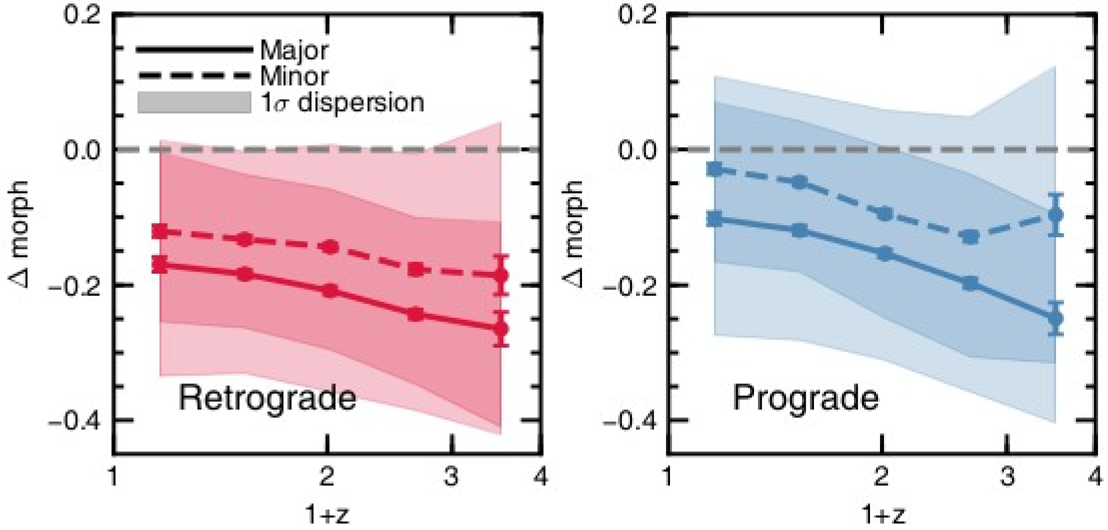


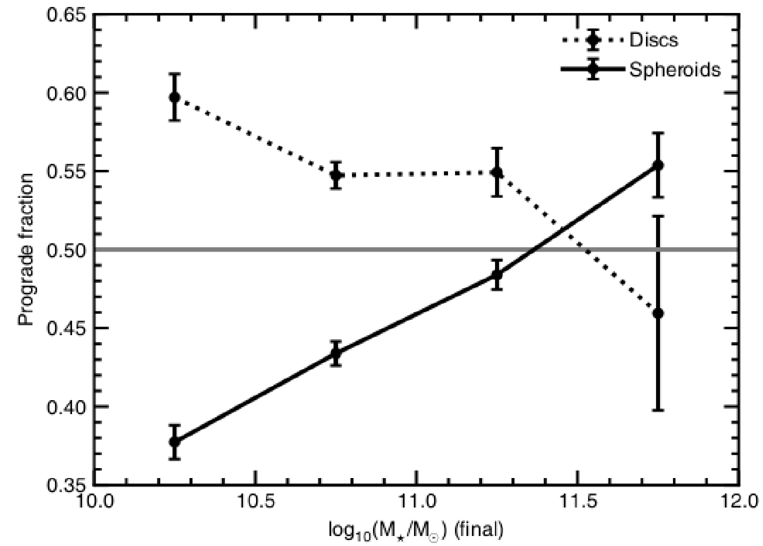
$$|\boldsymbol{L}_{sat}|\cos(\theta_{L_{main},L_{sat}}) + |\boldsymbol{L}_{orb}|\cos(\theta_{L_{main},L_{orb}}) > 0 \sim \text{prograde}$$

$$|\boldsymbol{L}_{sat}|\cos(\theta_{L_{main},L_{sat}}) + |\boldsymbol{L}_{orb}|\cos(\theta_{L_{main},L_{orb}}) < 0 \sim \text{retrograde}$$



Orbital configuration

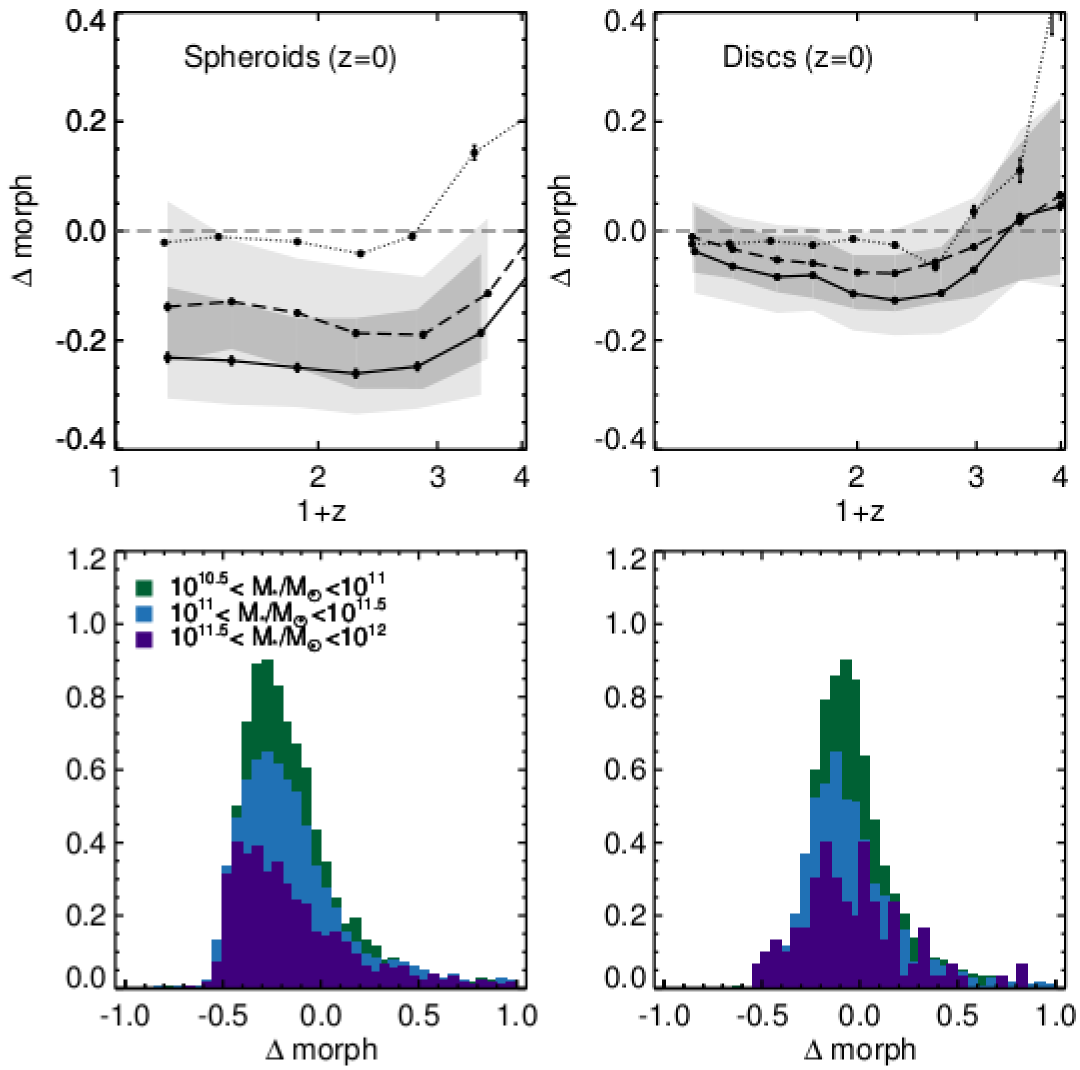




- The orbital configuration of a merger has a measurable impact on the properties of the remnants.
- Mergers that are prograde produce smaller decreases in the spin of discs (i.e. milder morphological transformation) than retrograde mergers.

- A larger proportion of discs (at z=0) have undergone prograde mergers compared to spheroids of a similar stellar mass.
- May link with large scale structure e.g. Welker+2017…
  - Still a small excess (few percent) of prograde mergers in galaxies that are discs *when they merge*.

Aggregate morphological evolution



- Spheroids have undergone more mergers on average since z = 3 compared with discs of equivalent stellar mass.
- The fraction of stellar mass formed ex-situ (i.e. accreted directly via mergers) is around 1.5–2 times higher in spheroids (at intermediate masses only).
- The average morphological transformation induced per merger is around a factor of 2 larger in disc progenitors compared to in spheroid progenitors.

$\log_{10}(M_\star/M_\odot)$	z of largest (i)	ratio of largest (ii)	# major (iii)	# minor (iv)	ex situ mass (v)
10.5–11.0	$1.224(1.092)^{+0.509}_{-0.341}$	$2.864(2.485)^{+0.996}_{-0.238}$	1.178 ± 0.921	1.118 ± 1.063	$0.412(0.401)^{+0.089}_{-0.070}$
	$1.169(1.027)^{+0.614}_{-0.396}$	$3.249(2.719)^{+1.413}_{-0.444}$	0.726 ± 0.803	0.816 ± 0.872	$0.201(0.176)^{+0.091}_{-0.050}$
11.0–11.5	$1.203(1.027)^{+0.488}_{-0.322}$	$2.815(2.367)^{+0.978}_{-0.284}$	1.355 ± 1.032	1.504 ± 1.185	$0.542(0.533)^{+0.078}_{-0.061}$
	$1.121(0.968)^{+0.601}_{-0.364}$	$3.244(2.679)^{+1.291}_{-0.419}$	0.946 ± 0.981	1.150 ± 1.052	$0.336(0.321)^{+0.093}_{-0.059}$
11.5–12.0	$1.235(1.092)^{+0.520}_{-0.369}$	$3.076(2.523)^{+1.141}_{-0.282}$	1.217 ± 1.114	1.548 ± 1.246	$0.609(0.597)^{+0.081}_{-0.067}$
	$0.901(0.632)^{+0.573}_{-0.538}$	$2.210(2.099)^{+0.538}_{-0.128}$	1.238 ± 0.921	1.714 ± 1.201	$0.536(0.555)^{+0.070}_{-0.119}$

Massive discs and spheroids share similar average merger histories – isolated histories are not the dominant channel for the formation of discs above a certain mass.

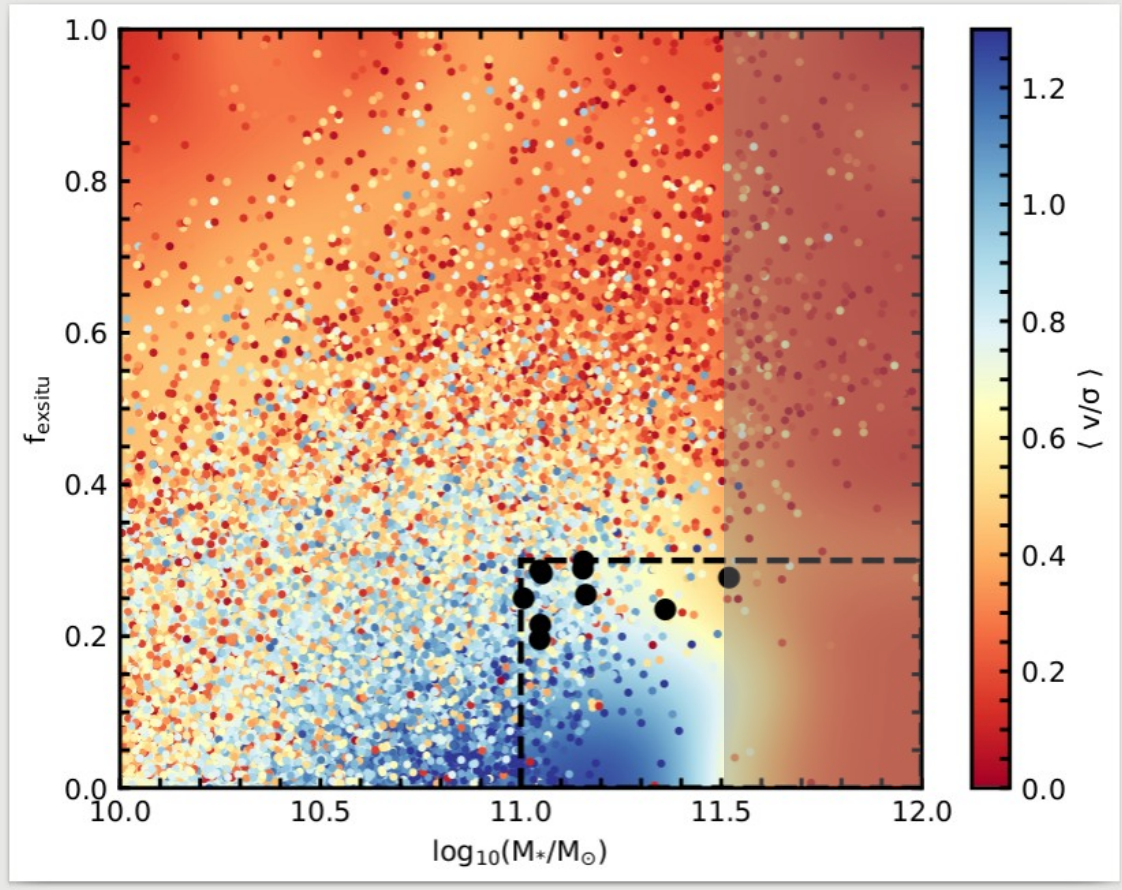
Two interesting populations

Low f_exsitu spheroids

- Most spheroids have high ex-situ mass fractions, but a minority do not
- How are these galaxies, which have extremely poor merger histories transformed into spheroids

Massive Discs

- How exactly do massive discs (beyond the knee of the mass function – logM* > 11.5) survive to the present day?
  - Very difficult to form this much stellar mass in-situ
  - The majority of discs possess significant fractions of stars formed from ex-situ sources (e.g. Faber+07)
- Yet at logM* > 11.5, around 10% of galaxies have significant disc components (e.g. previous slides, Concellice+06) while having roughly similar merger histories.

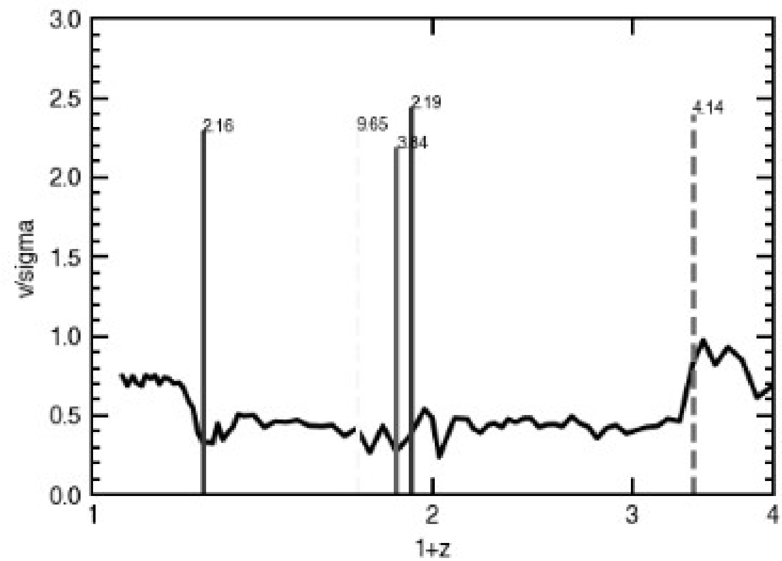


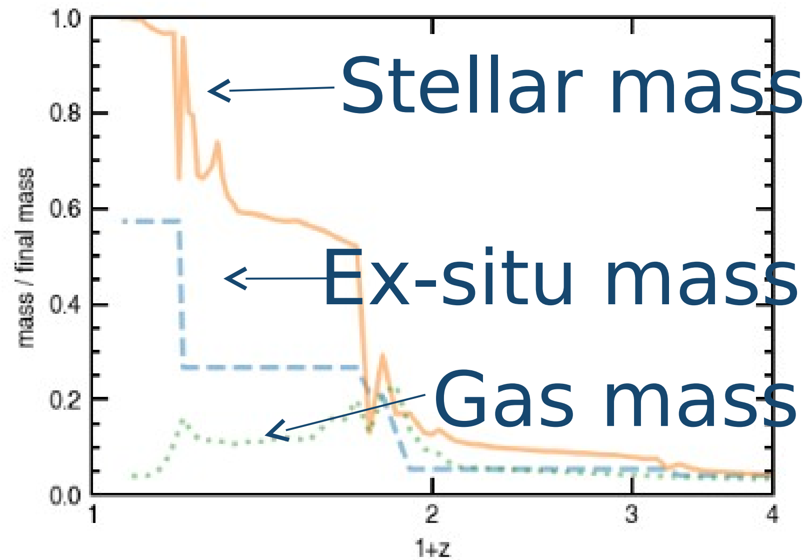
Jackson+2019 in prep

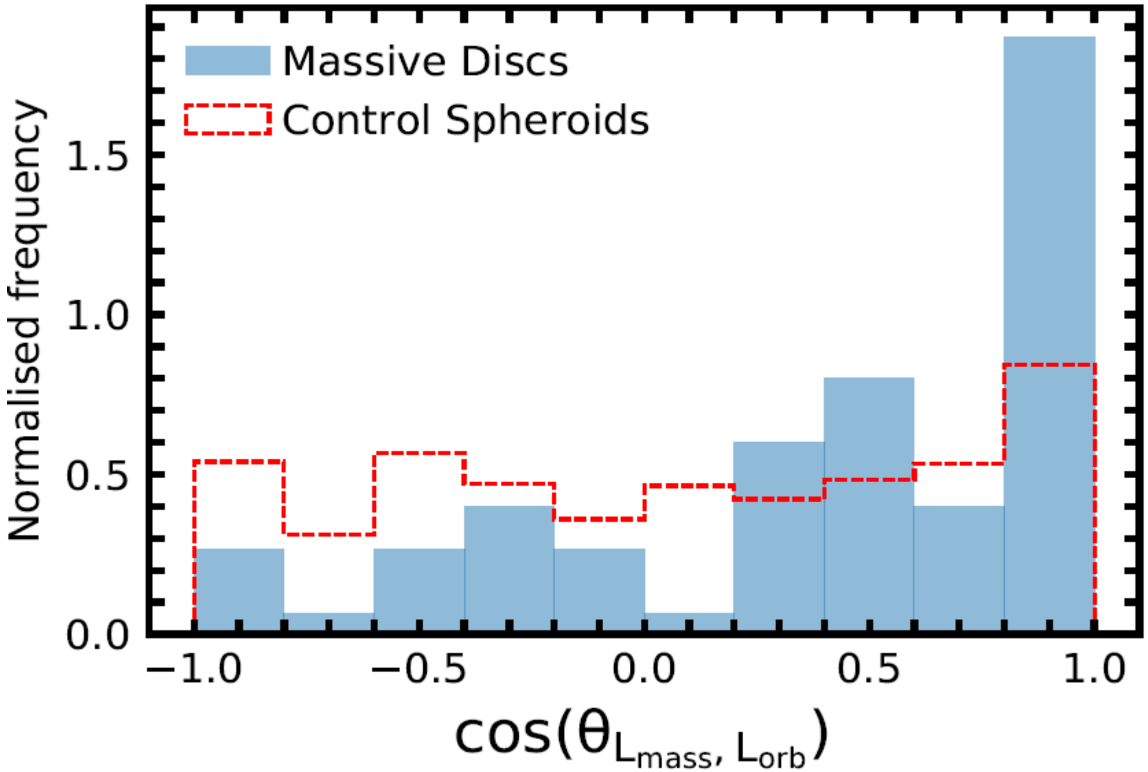
WHY DO MASSIVE DISCS EXIST TODAY?

Every massive disc shows a recent uptick in v/sigma coincident with a gas-rich merger

Compare the properties of the last mergers in massive discs to a control sample of last mergers in massive spheroids…







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Last mergers in massive disks:

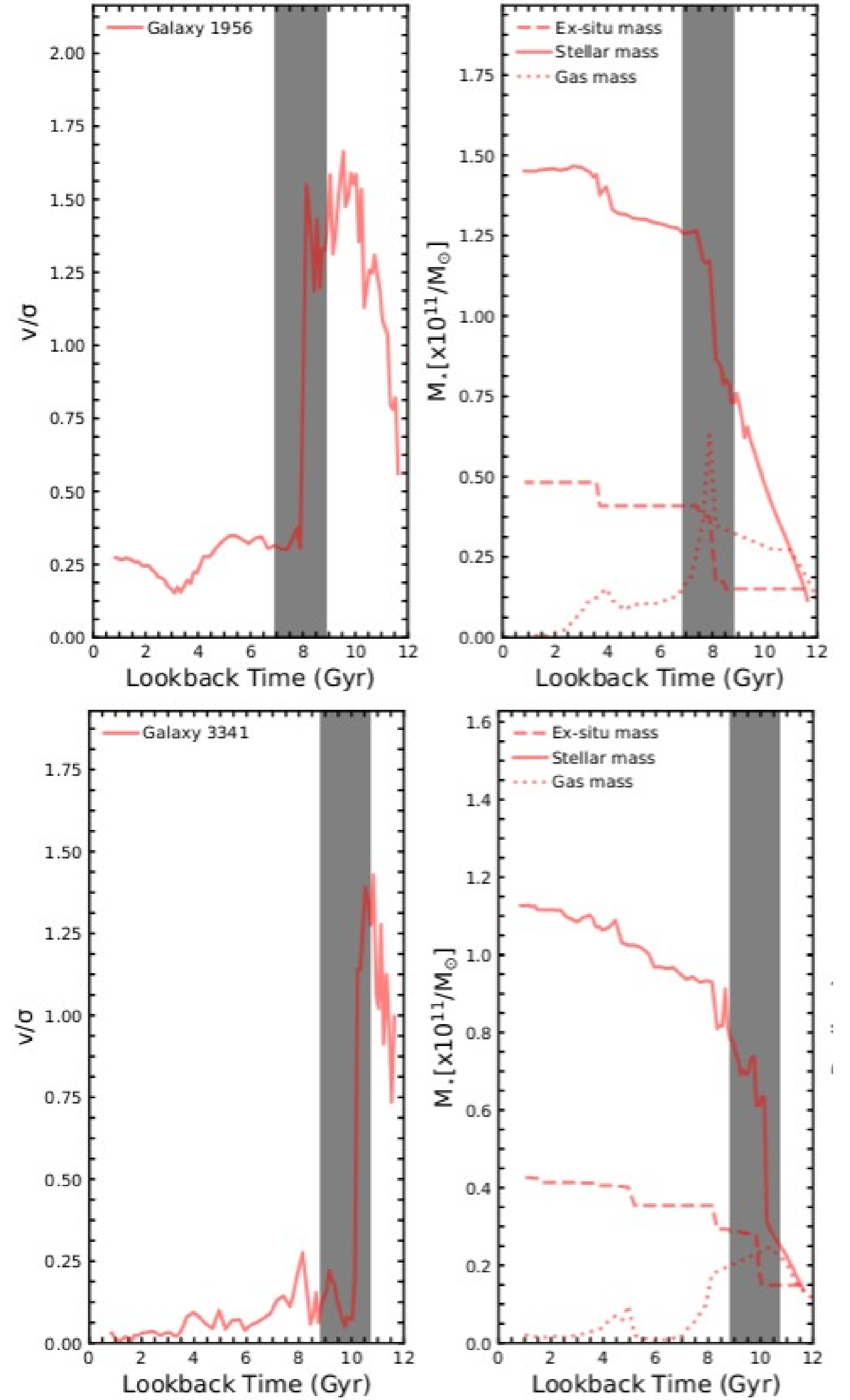
- Are more recent
- Have higher gas fractions
- Bring in a higher absolute mass of gas
- Have slightly higher mass ratios
- Show a slight preference for prograde and coplanar orbits

Other questions to consider:

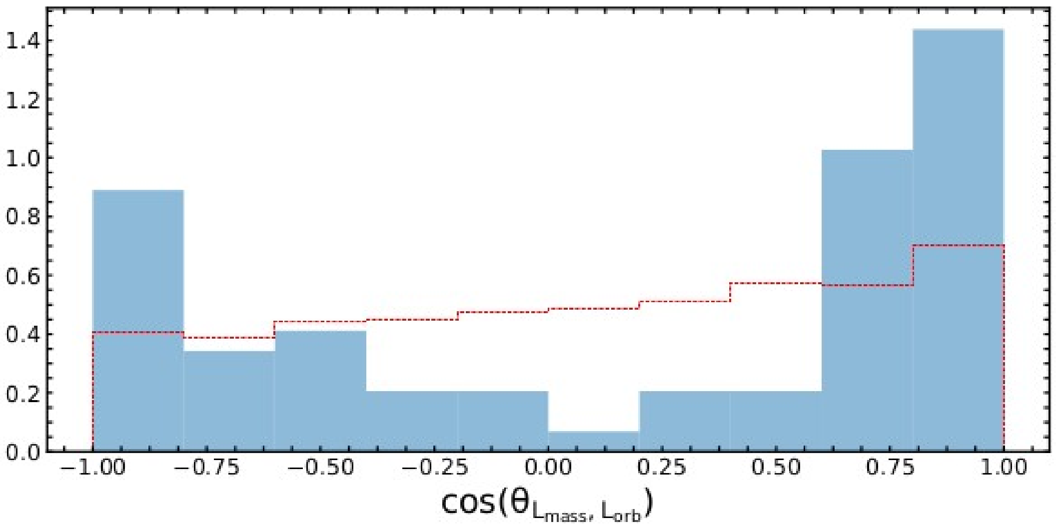
Do the mergers spin up the whole system or create a new fast-rotating component?

If massive discs are relatively ephemeral, does the frequency of extremely massive discs correlate with gas fraction of the Universe?

- Two typical low f_exsitu spheroids
- Low mass ratio merger is followed by a catastrophic and permanent fall in v/sigma that lasts to the present day
  - Typical remnants are relatively diffuse and highly star forming
- Typically triggers a prolonged period of in-situ star formation in the remnant
- These spheroids are above the star-formation main sequence, which offers a route to identifying such systems in observations
- Spheroids with SFRs well above the star formation main sequence are known (e.g. Fukugita et al. 2004; Schawinski et al. 2010)
- Similar number fractions to our findings (a few percent)



- Sample of massive spheroids with low exsitu mass fractions (f_exsitu < 0.3, log M* > 11, no major mergers vs control sample of massive galaxes
- No preference for different alignment in galaxy spins
- Strong preference for mergers in the plane of the disc
  - which maximize the tidal forces and therefore the transfer of orbital energy (e.g. Cox et al. 2008)



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