The occurrence and origin of counterrotating galaxy components

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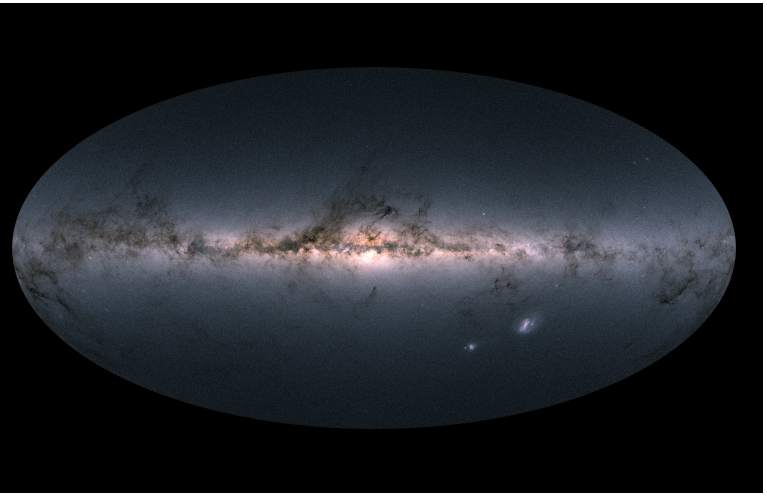
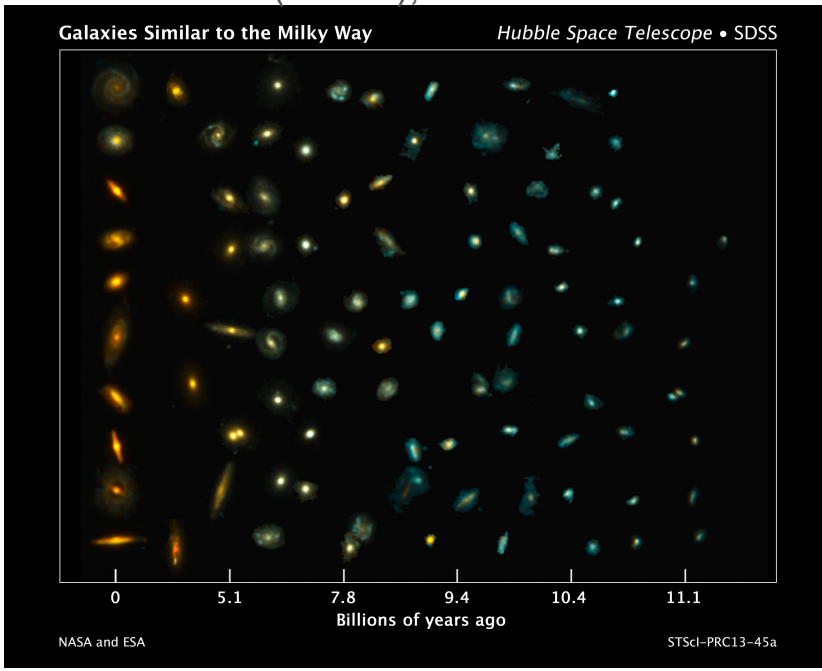
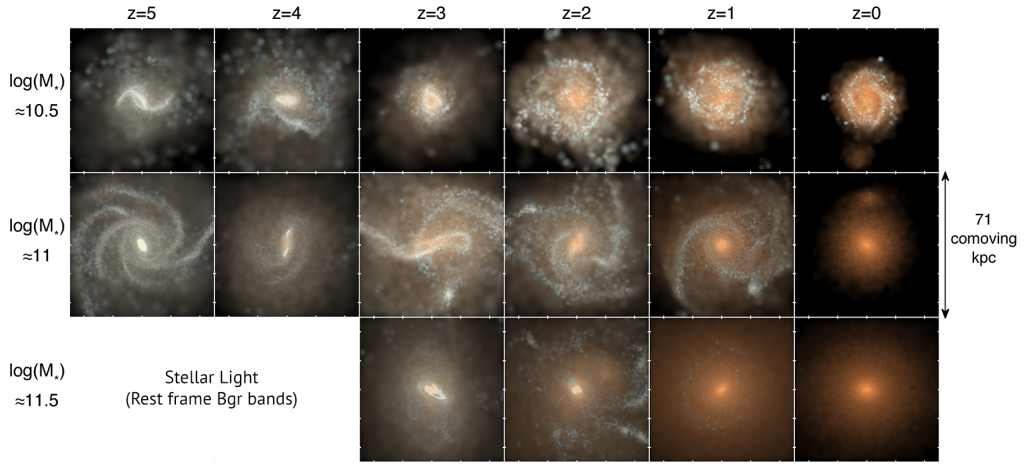
understanding the Milky Way vs. understanding galaxy evolution: good/more communication between fields will help us all

ESA/Gaia/DPAC



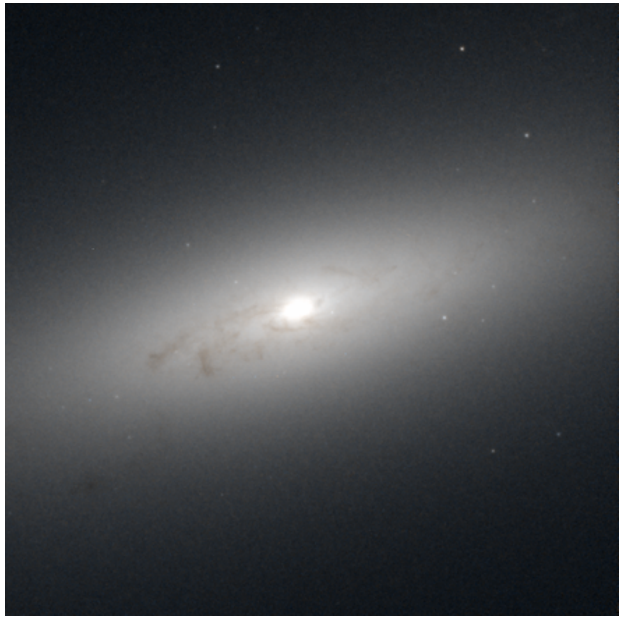
NASA, ESA, P. van Dokkum (Yale), S. Patel (Leiden), and the 3D-HST Team





Illustris Team


Polar ring galaxy NGC2685: *the Helix galaxy*
First kinematic observations that show rotation along the minor axis: Ulrich 1975
Image credit: Ken Crawford

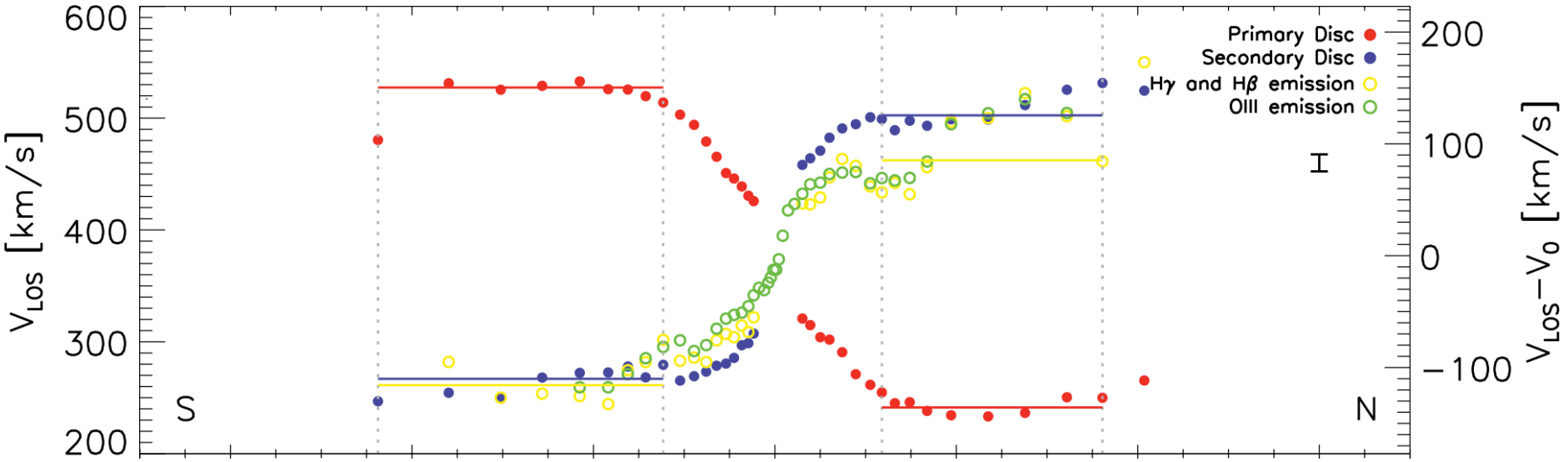


NGC 4550

Rubin et al. 1992 show gas – star counter-rotation, and an indication of a secondary stellar disk co-rotating with the gas.

Rix et al. 1992 confirmed that there are two counter-rotating stellar disks, which are almost equal in mass, and equal in size.

Johnston et al. 2013



<u>Objects with 2 counter-rotating stellar disks:</u> NGC 4550 (Rubin+1992; Rix+1992; Emsellem+2004), NGC 7217 (Merrifield & Kuijken 1994), NGC 3593 (Bertola+1996; Corsini+1998; García-Burillo+2000), NGC 4138 (Jore+1996; Haynes+2000), and NGC 5719 (Vergani+2007; Coccato+2011)

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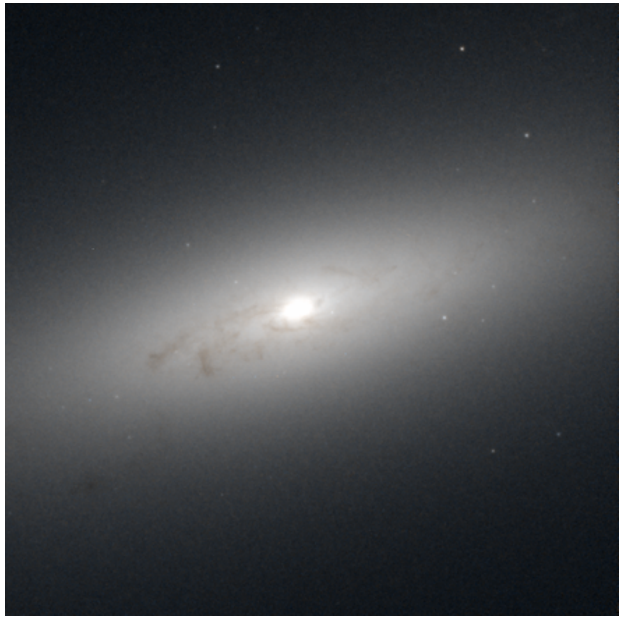

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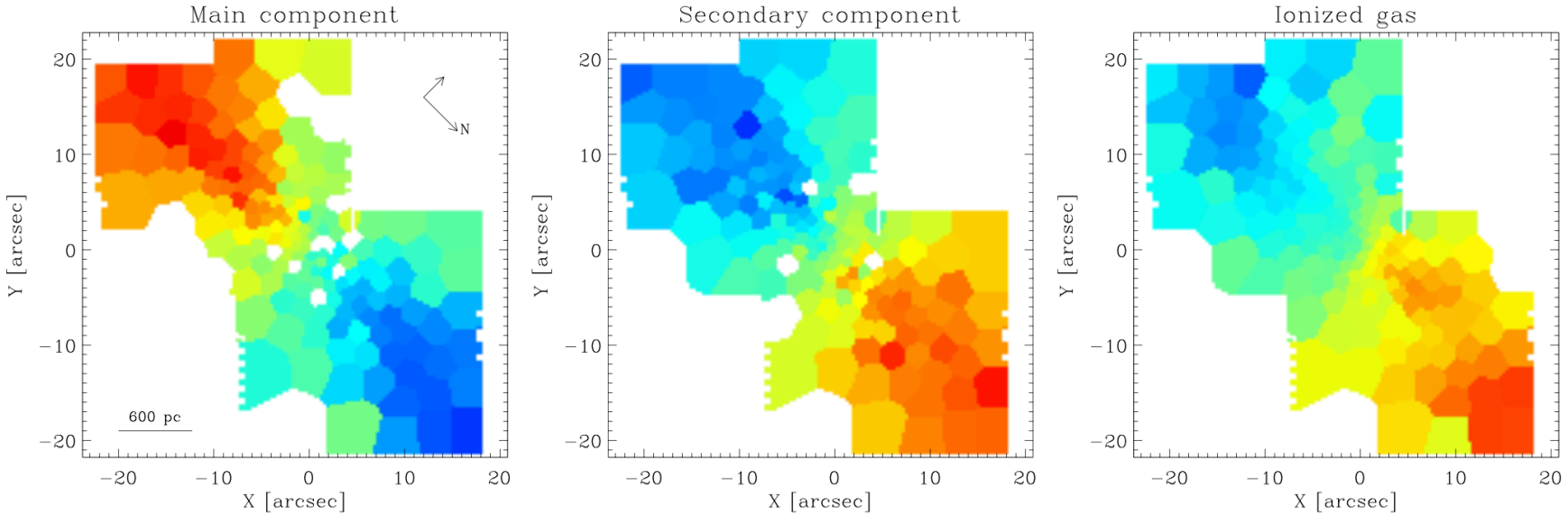
Coccato et al. 2013



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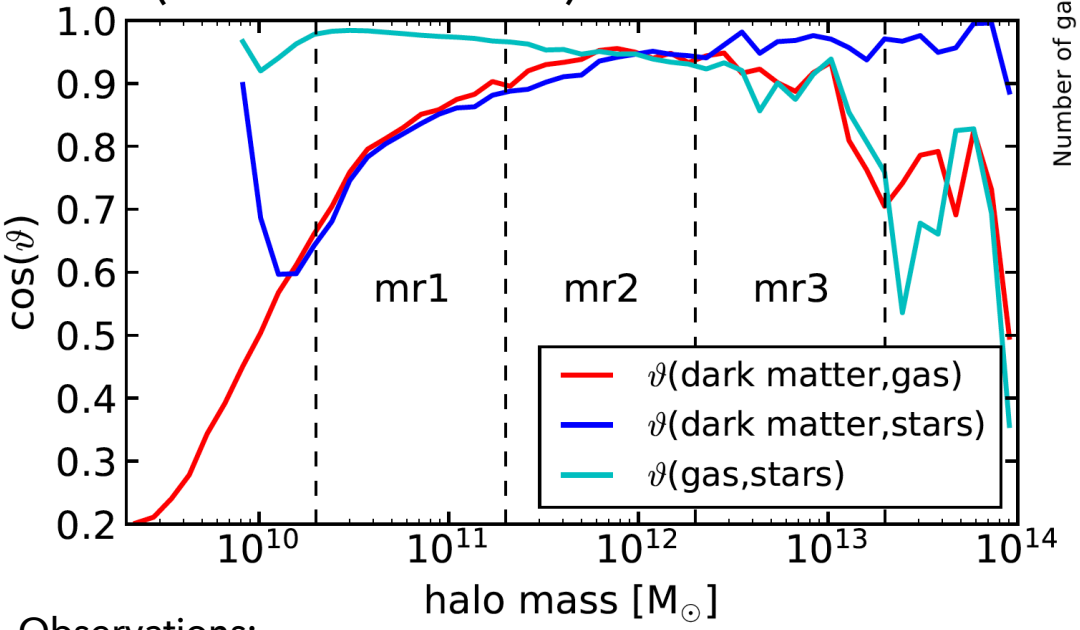
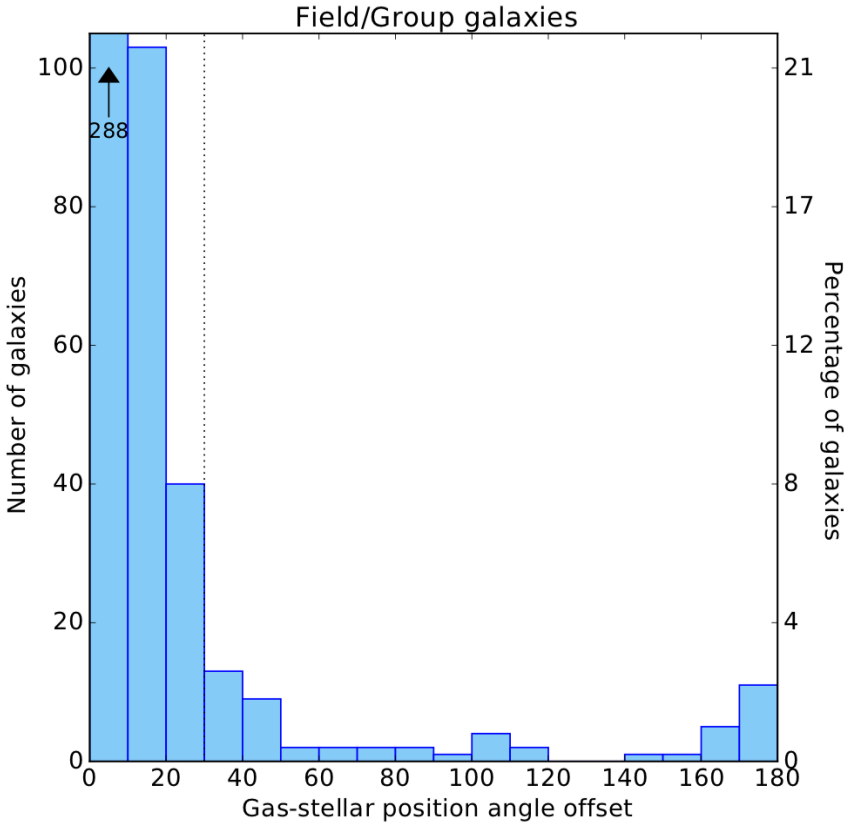
Distribution of relative angles between components in simulations and observations

Zjupa & Springel 2017

(Illustris simulation)





Bryant et al. 2019

(SAMI survey)

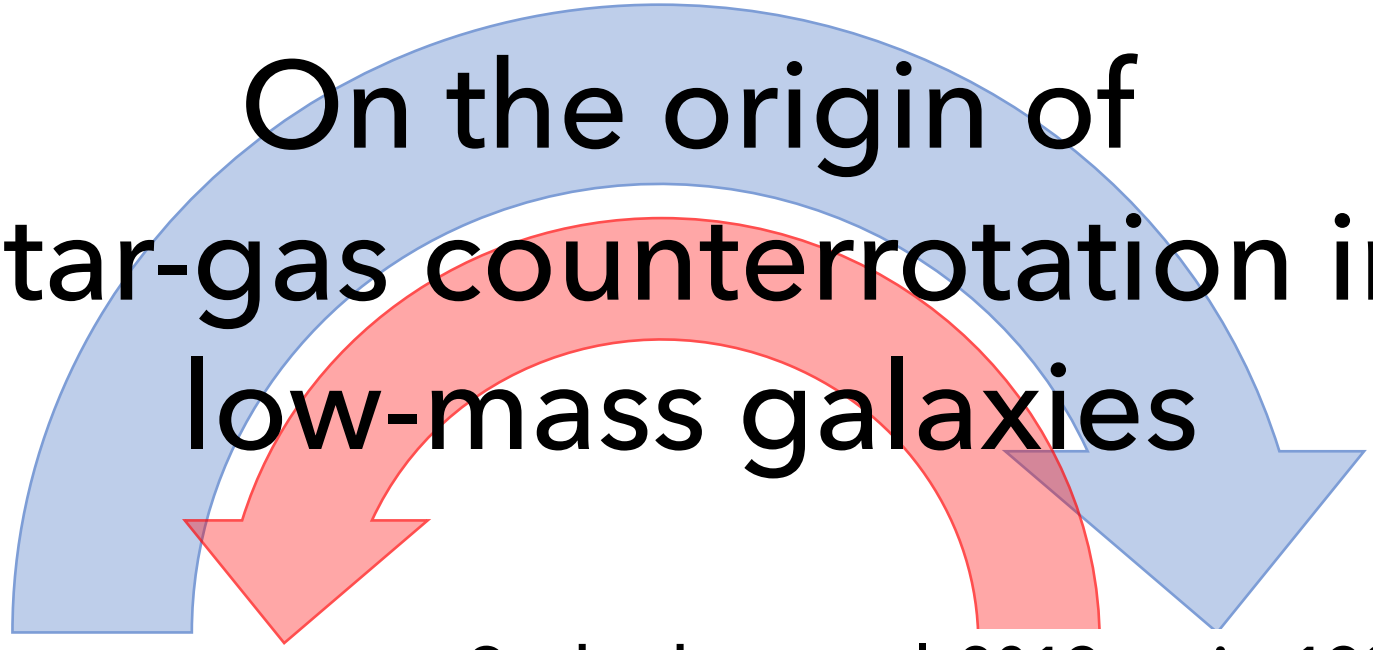
Observations:

Rix & White 1992; Prada+1996; Bertola+1996; Vergani+2007; Coccato+2011; Davis+2011; Serra+2014; Coccato+2015; Krajnovic+2015; Katkov+2016; Emsellem+2007; Barrera-Ballesteros+2014, 2015; Cappellari 2016; Jin+2016; Bryant+2019; ...

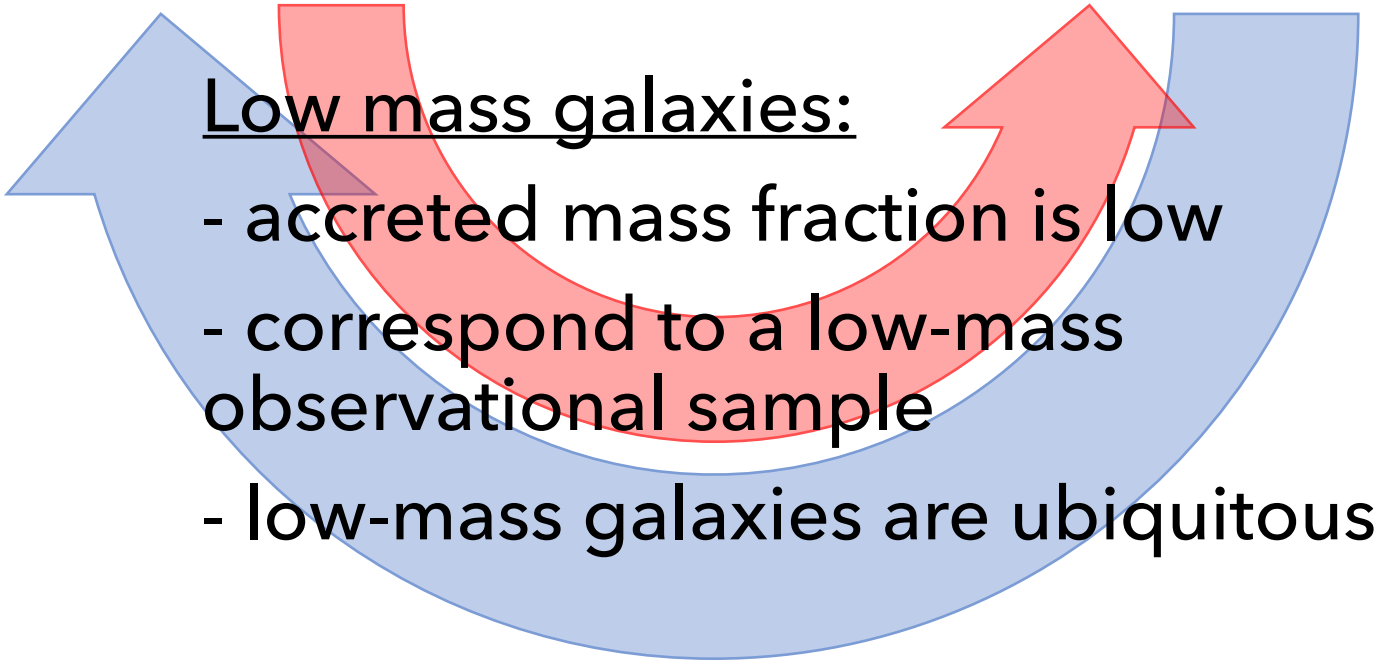
Theory:

van den Bosch+2002; Abadi+2003; Bett+2010; Brook+2011; Scannapieco+2012; Bryan+2013; Übler+2014; Dubois+2014; Teklu+2015; Zavala+2016; DeFelippis+2017; Jiang+2018; Garrison-Kimmel+2018; ...

On the origin of star-gas counterrotation in low-mass galaxies



Starkenburg et al. 2019, arxiv: 1903.03627



Low mass galaxies:

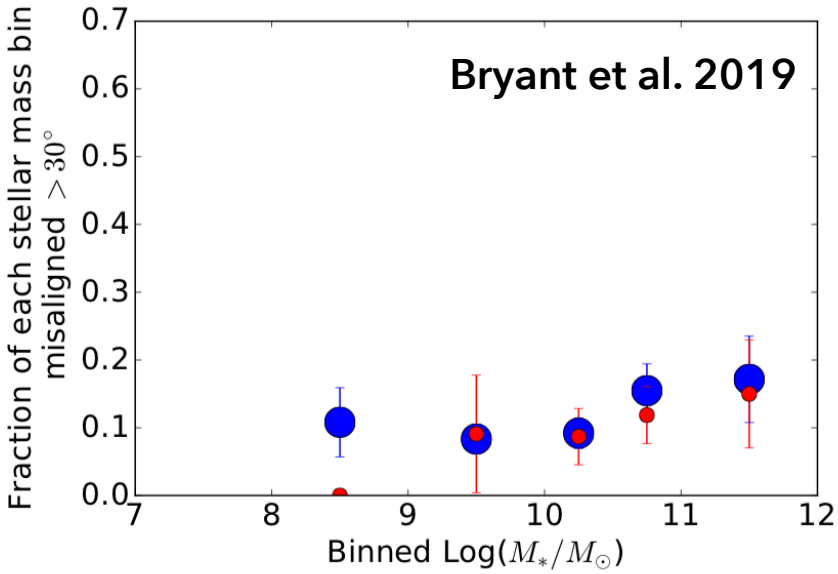
- accreted mass fraction is low
- correspond to a low-mass observational sample
- low-mass galaxies are ubiquitous

Observational dwarf galaxy sample

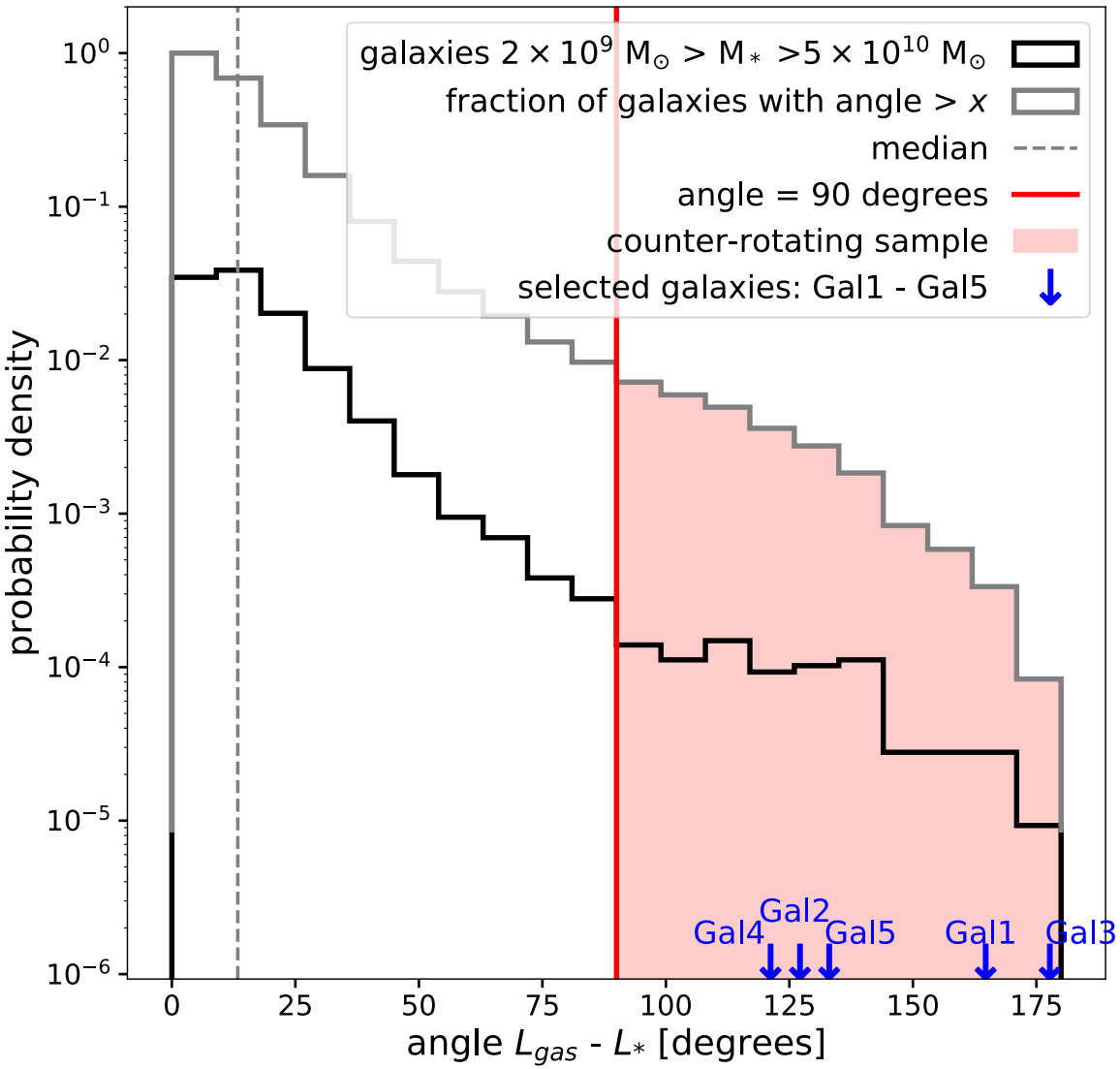
Manzano-King et al., TKS, in prep.:

from a sample of 50 dwarf galaxies 5 are strongly counter-rotating: 10%
all 5 of these show evidence of the presence of an AGN

A similar fraction is seen for low-mass field galaxies in SAMI:



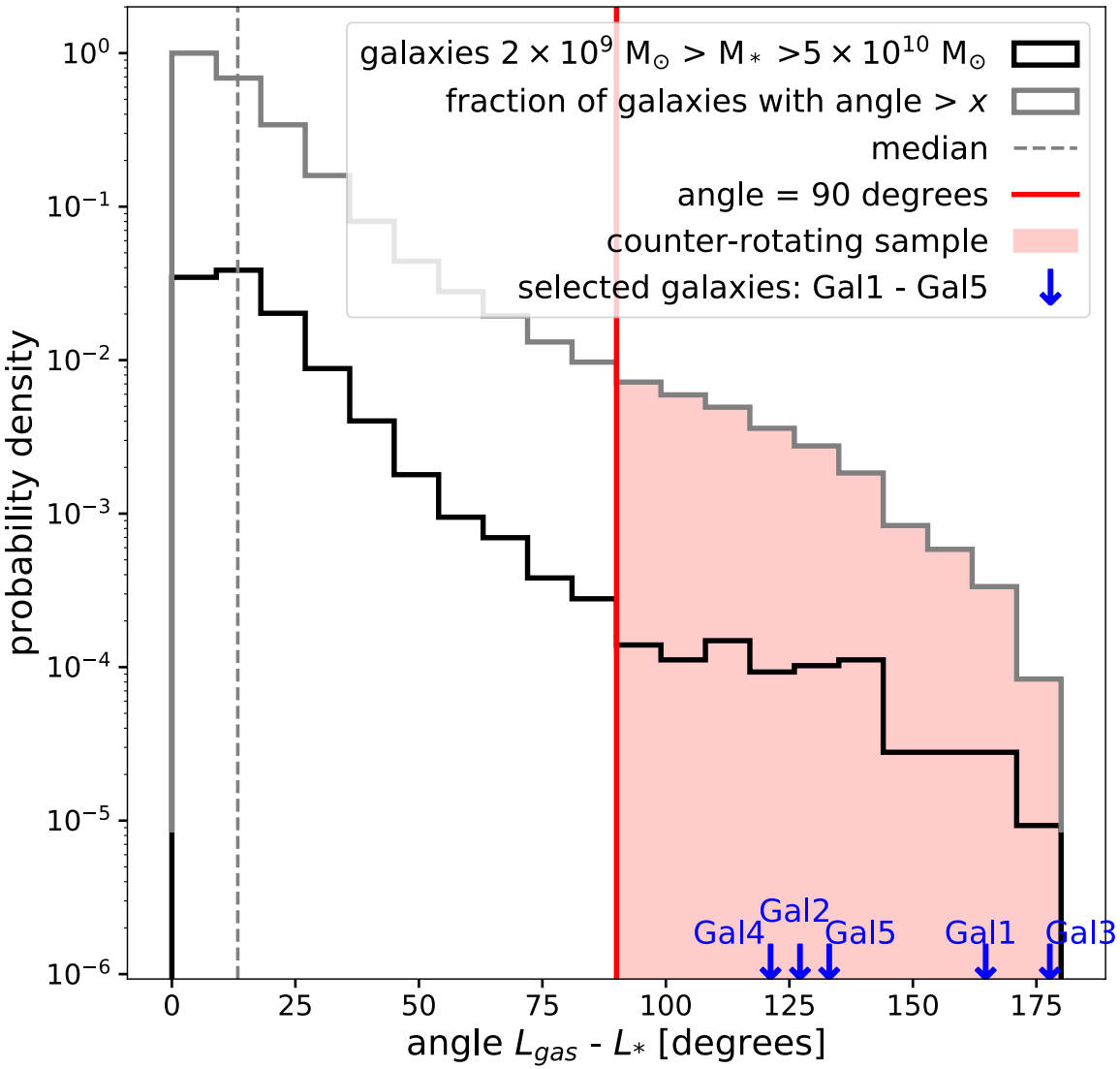
Occurence of counterrotating dwarf galaxies in Illustris



Low-mass galaxies

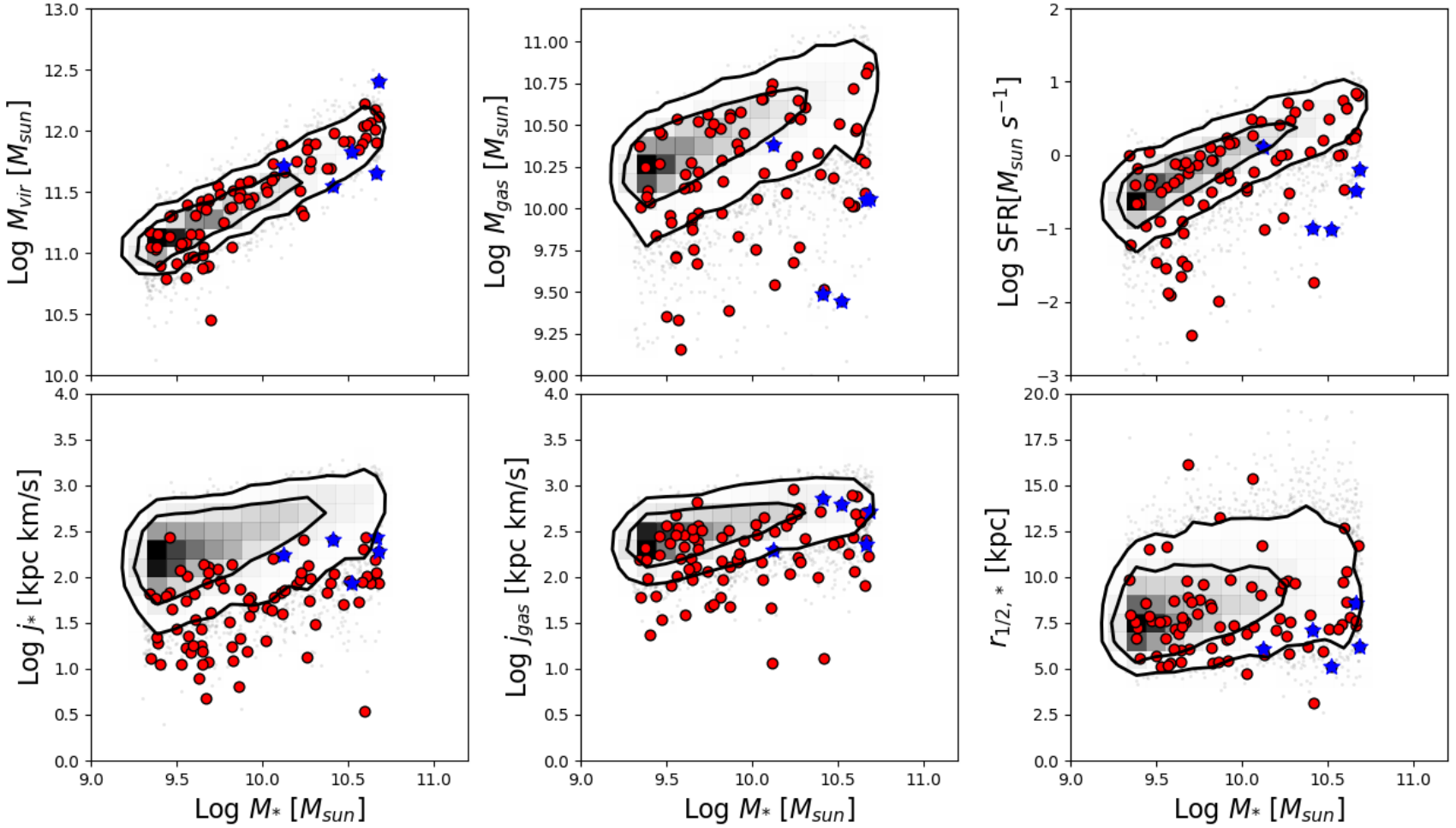
- Inspired by observational data of a companion paper
- No significant mergers
- most prevalent galaxies in the universe and in simulations

Occurence of counterrotating dwarf galaxies in Illustris

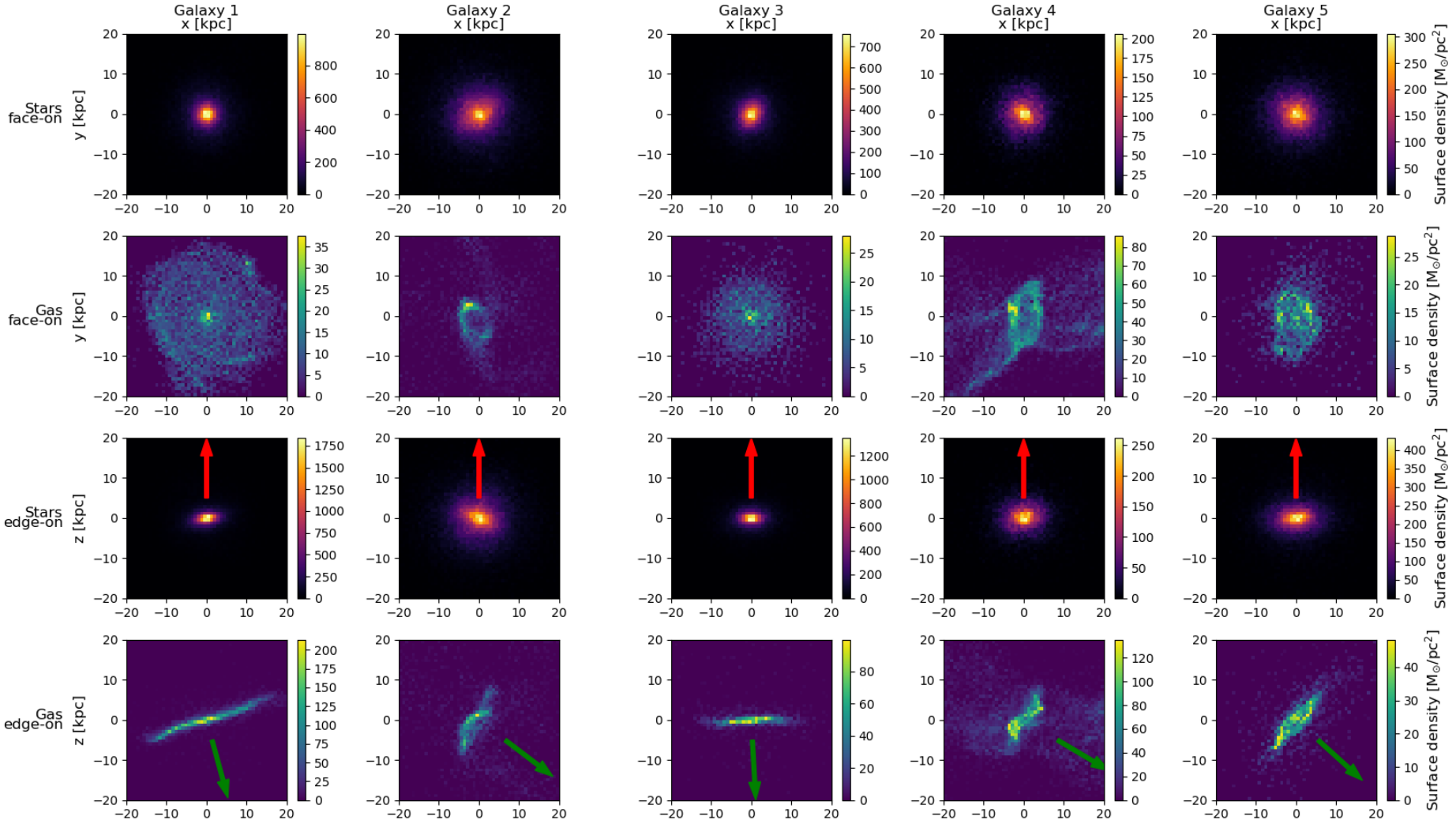


- Fraction counterrotating: Angle > 90 degrees = ~1%
- median angle for the full population is 13 degrees
- No evidence of a secondary peak at perfect anti-alignment

Properties of counterrotating dwarf galaxies in Illustris



counterrotating dwarfs in Illustris



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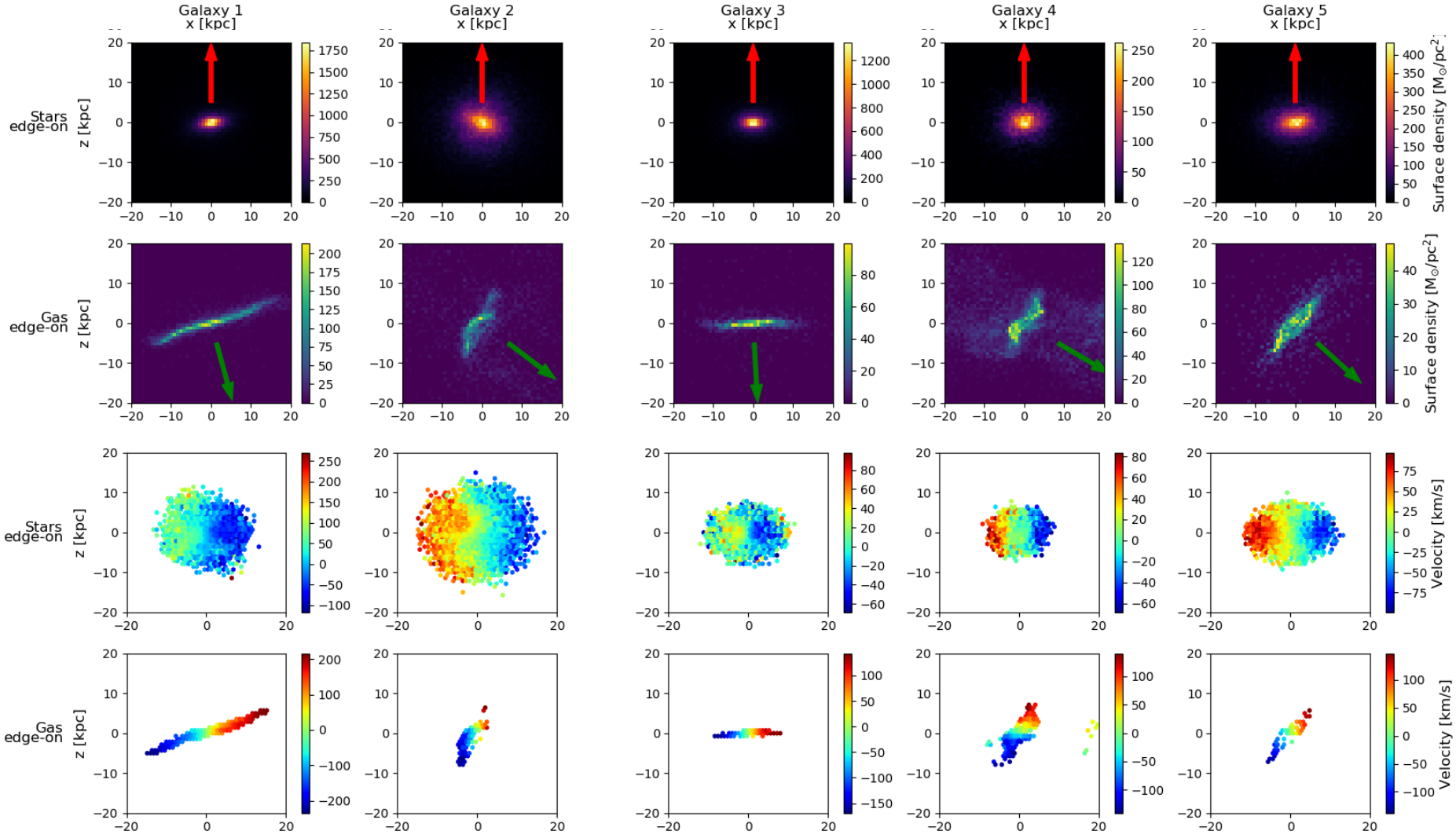
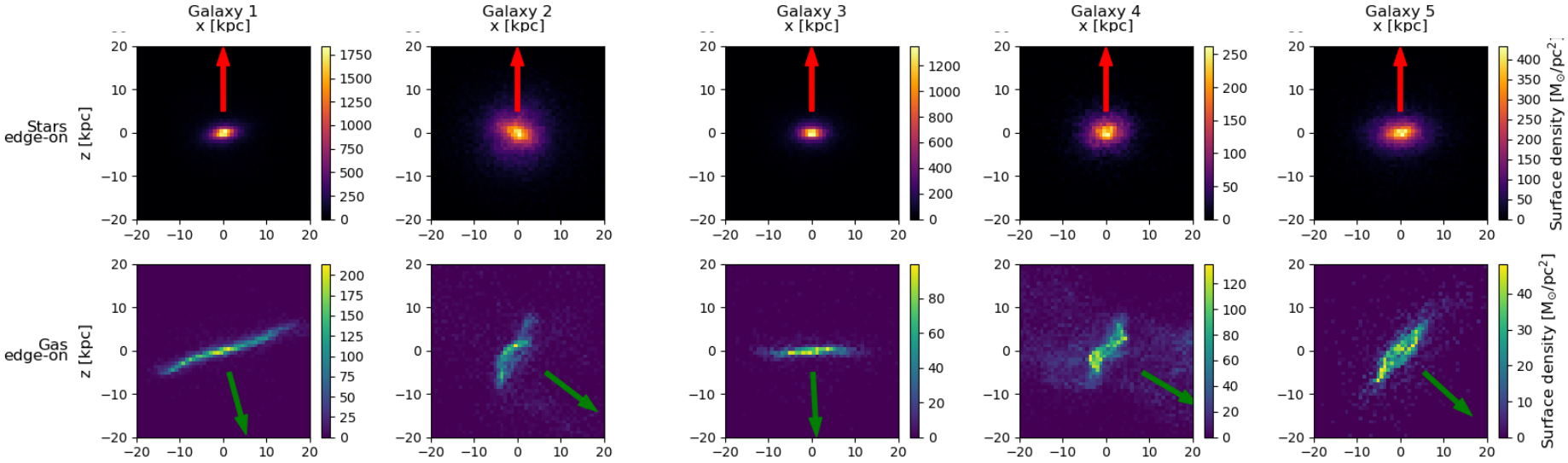
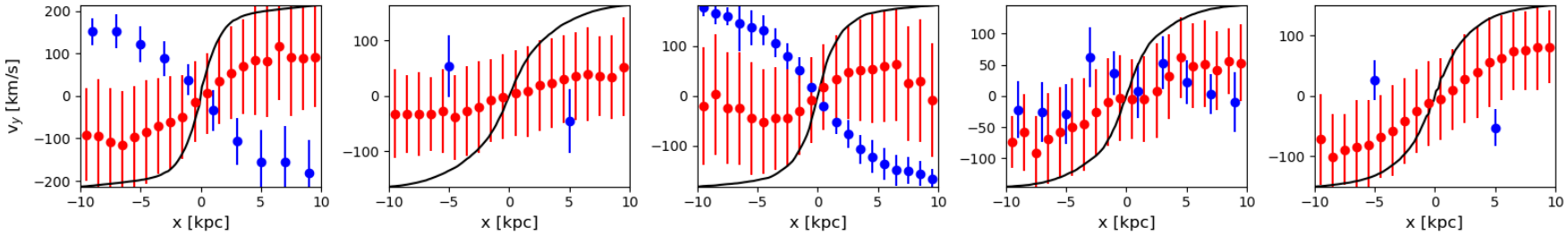


counterrotating dwarfs in Illustris



Mock rotation curves



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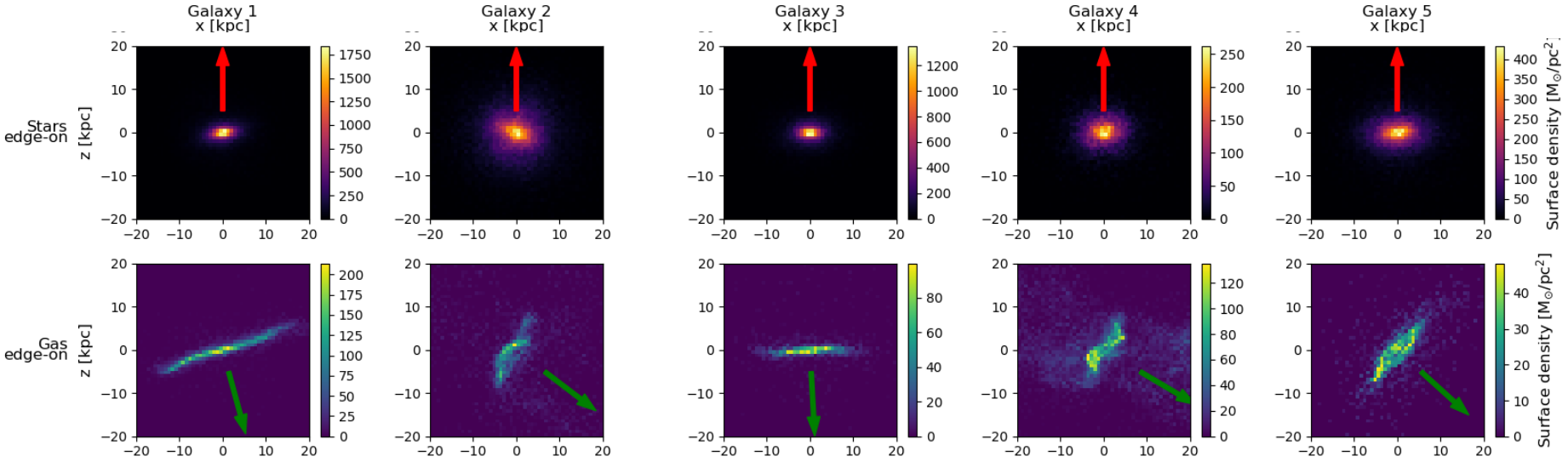
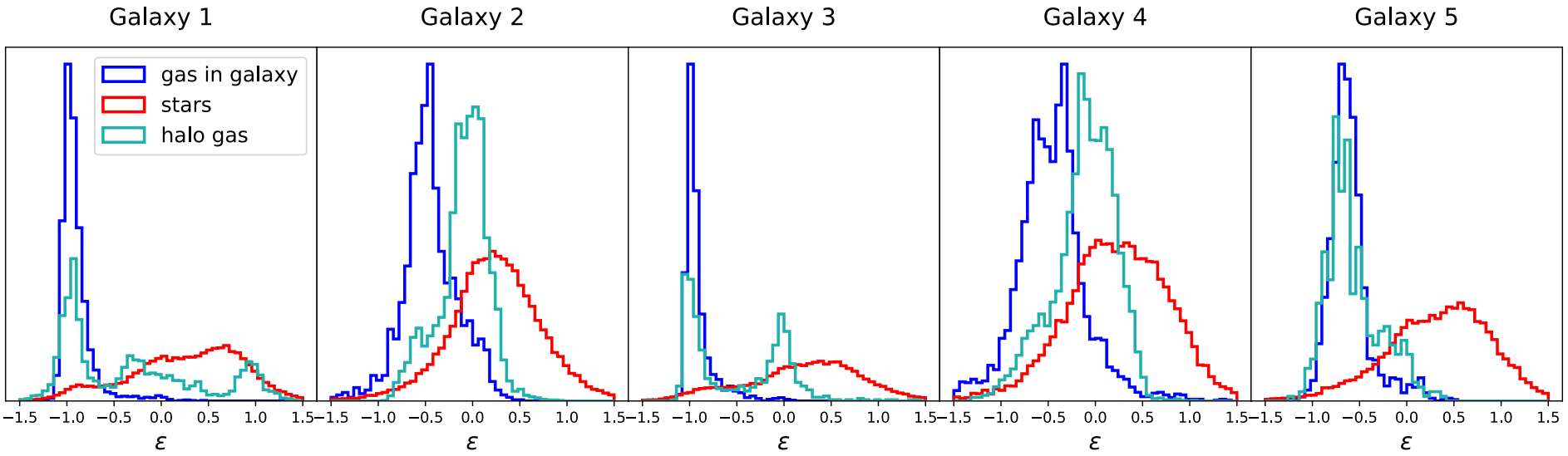
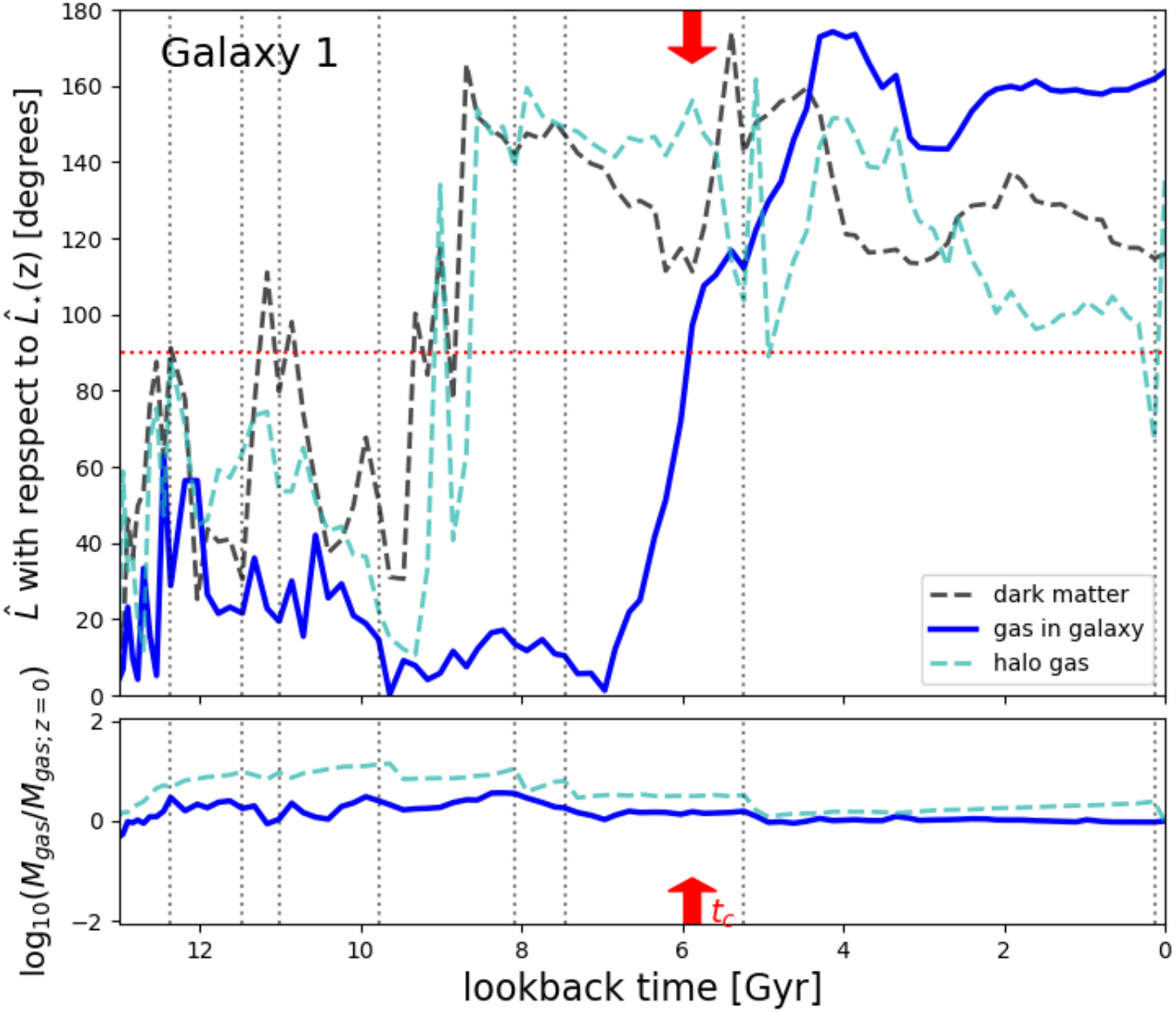


Circularity

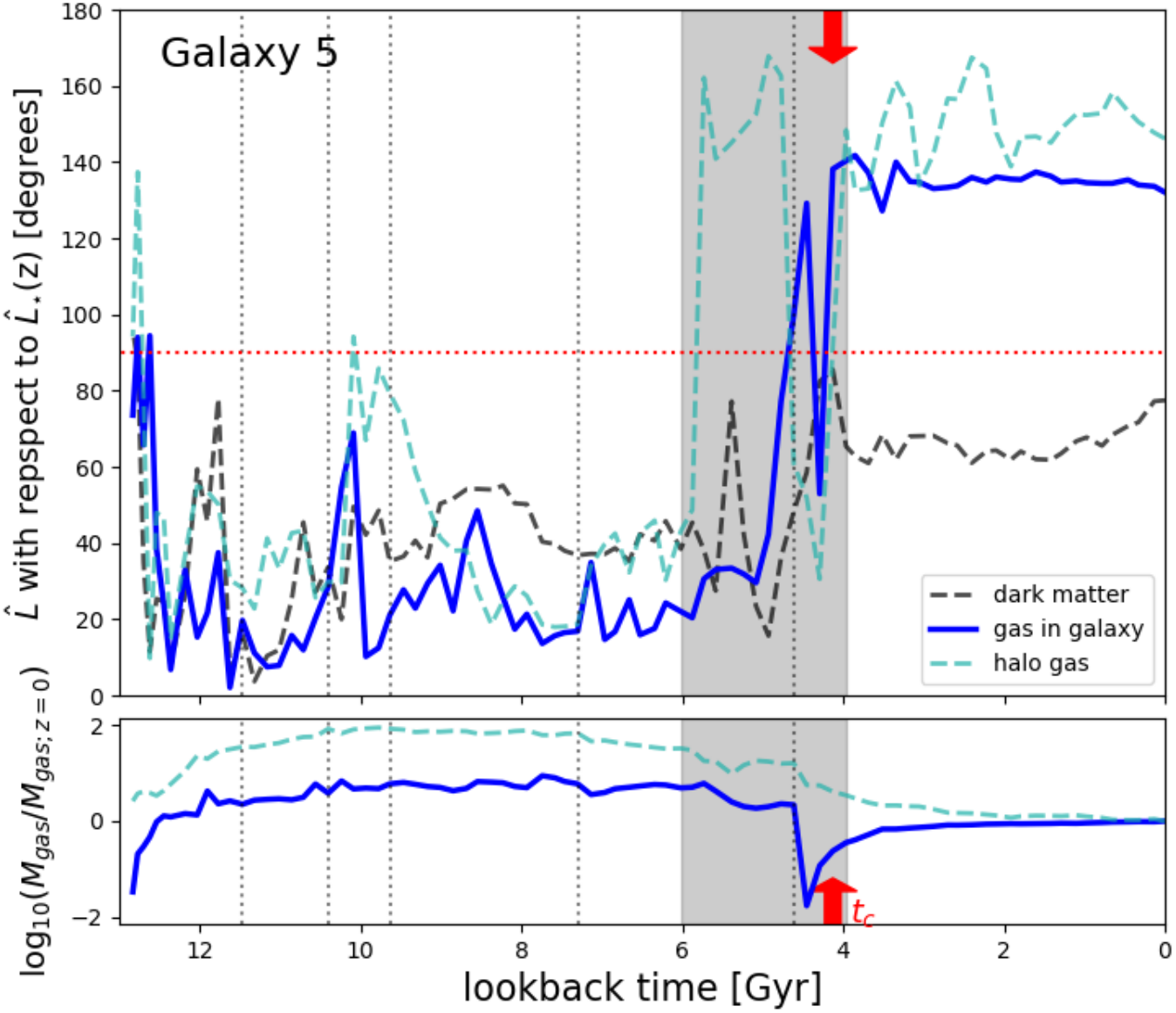


counterrotating ← $\epsilon = j / r\, v_{circ}(r)$ → corotating

The evolution of counterrotating gas example 1

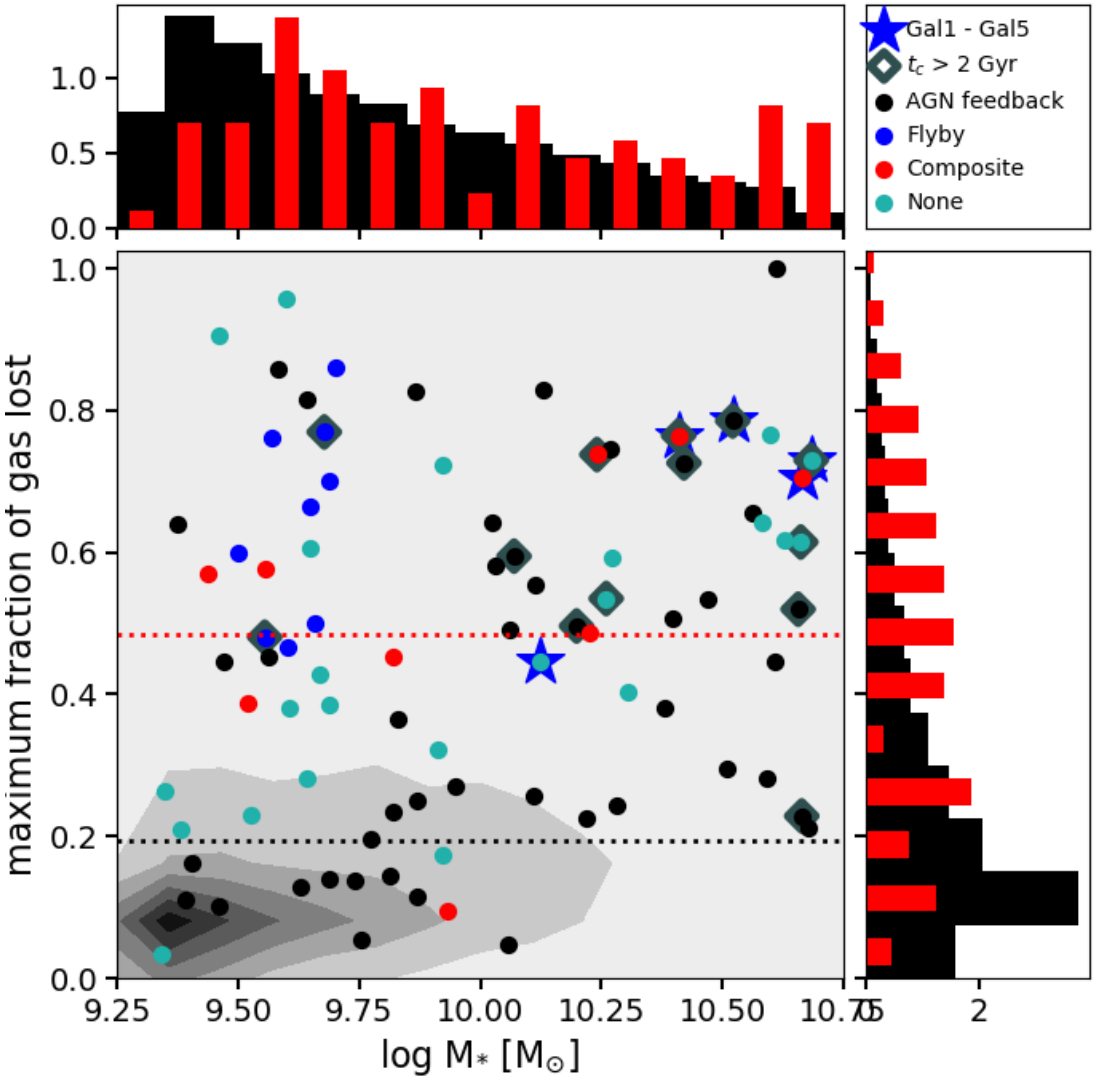


The evolution of counterrotating gas example 2



Past gas loss correlates with present counterrotation

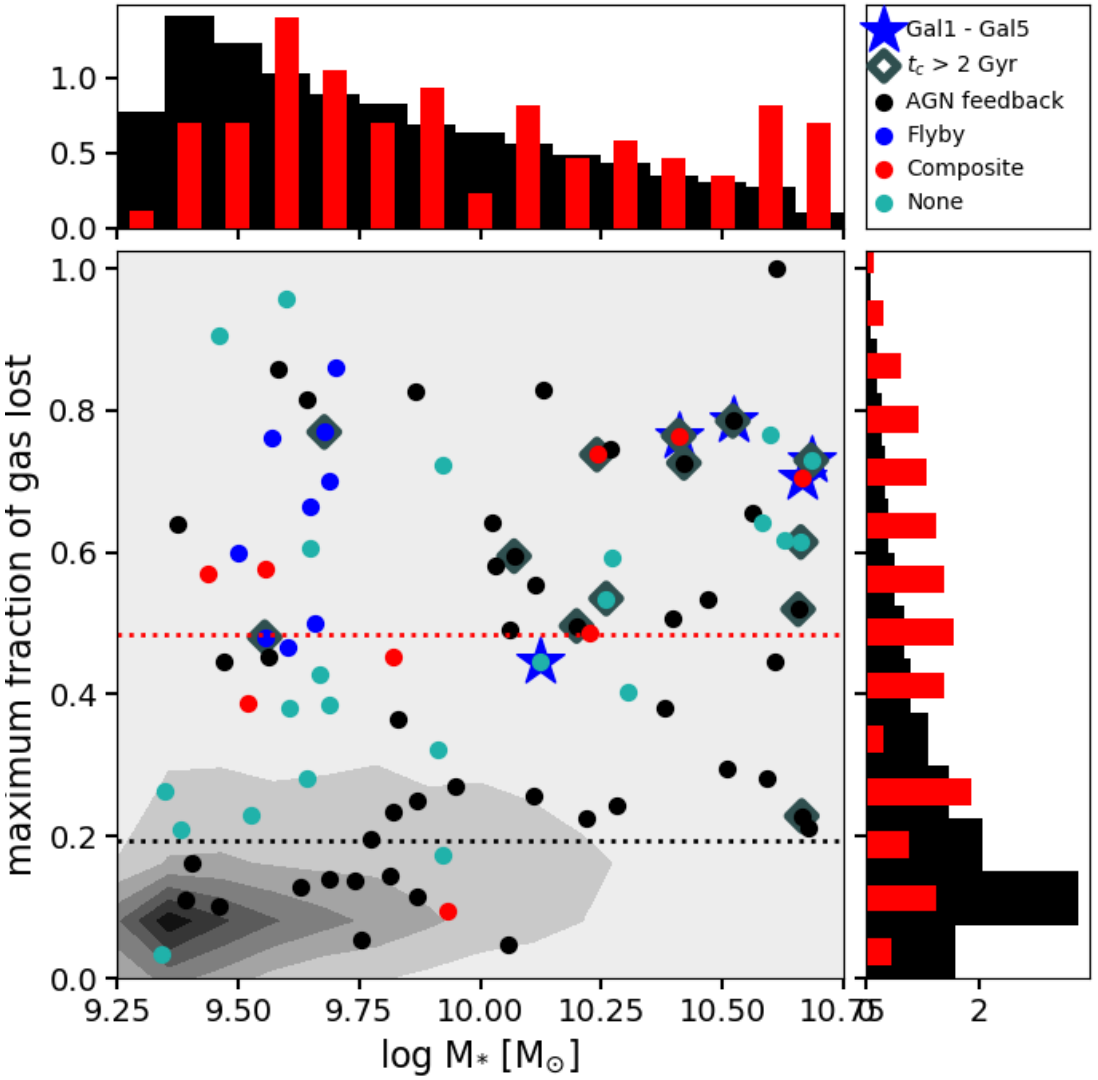
- Galaxies lose corotating gas before accreting counterrotating gas



Past gas loss correlates with present counterrotation

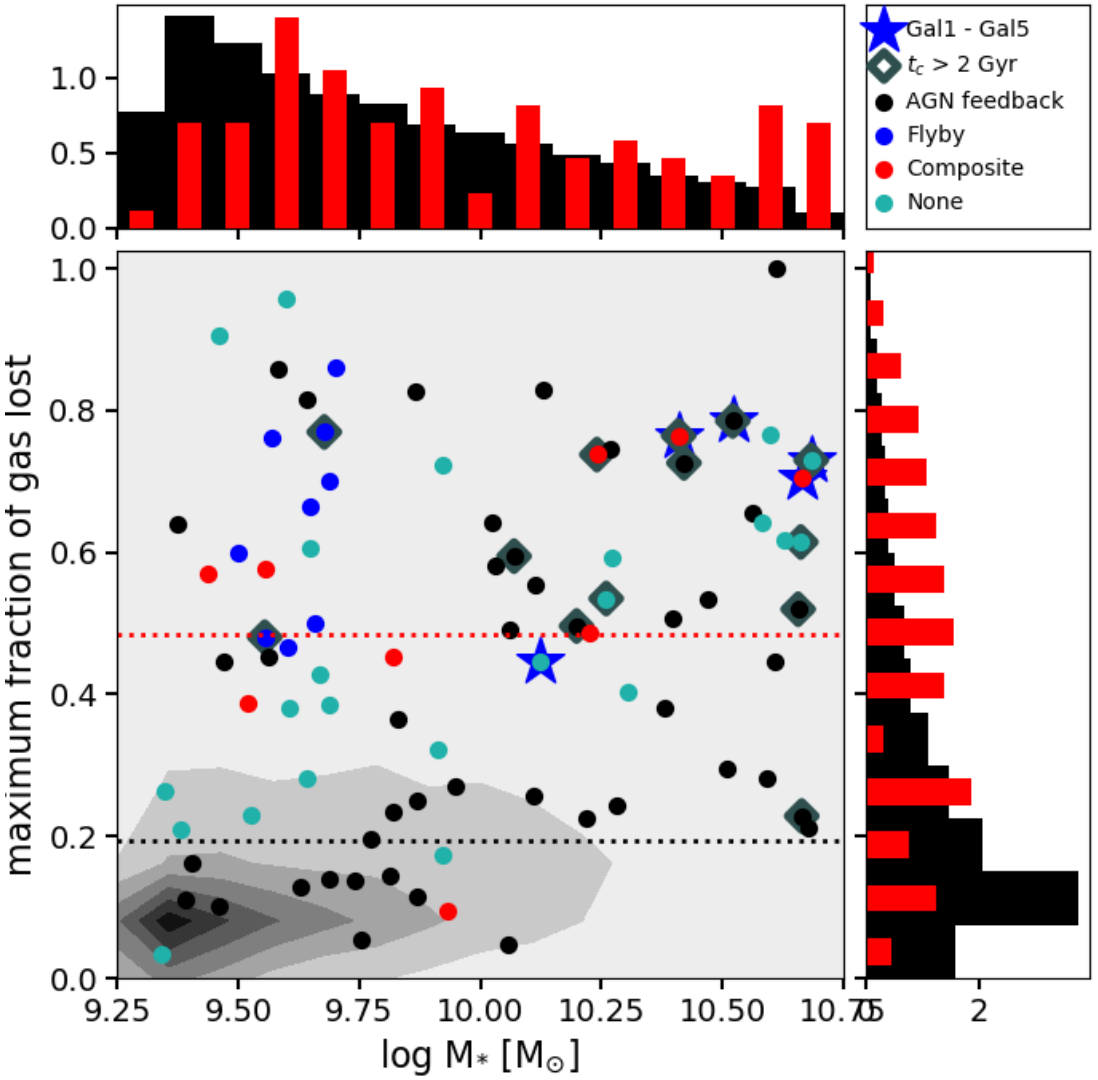
We trace the correlation between the onset of counterrotation and two events that can strongly affect the galaxy (and its gas): feedback from an AGN and fly-bys

- AGN feedback within 1 Gyr before counterrotation (52.3%)
- Fly-by event within 1 Gyr before counterrotation (10.5%)
- Both AGN feedback and fly-by within 1 Gyr before counterrotation (10.5%)
- Neither of these two events (26.7%)



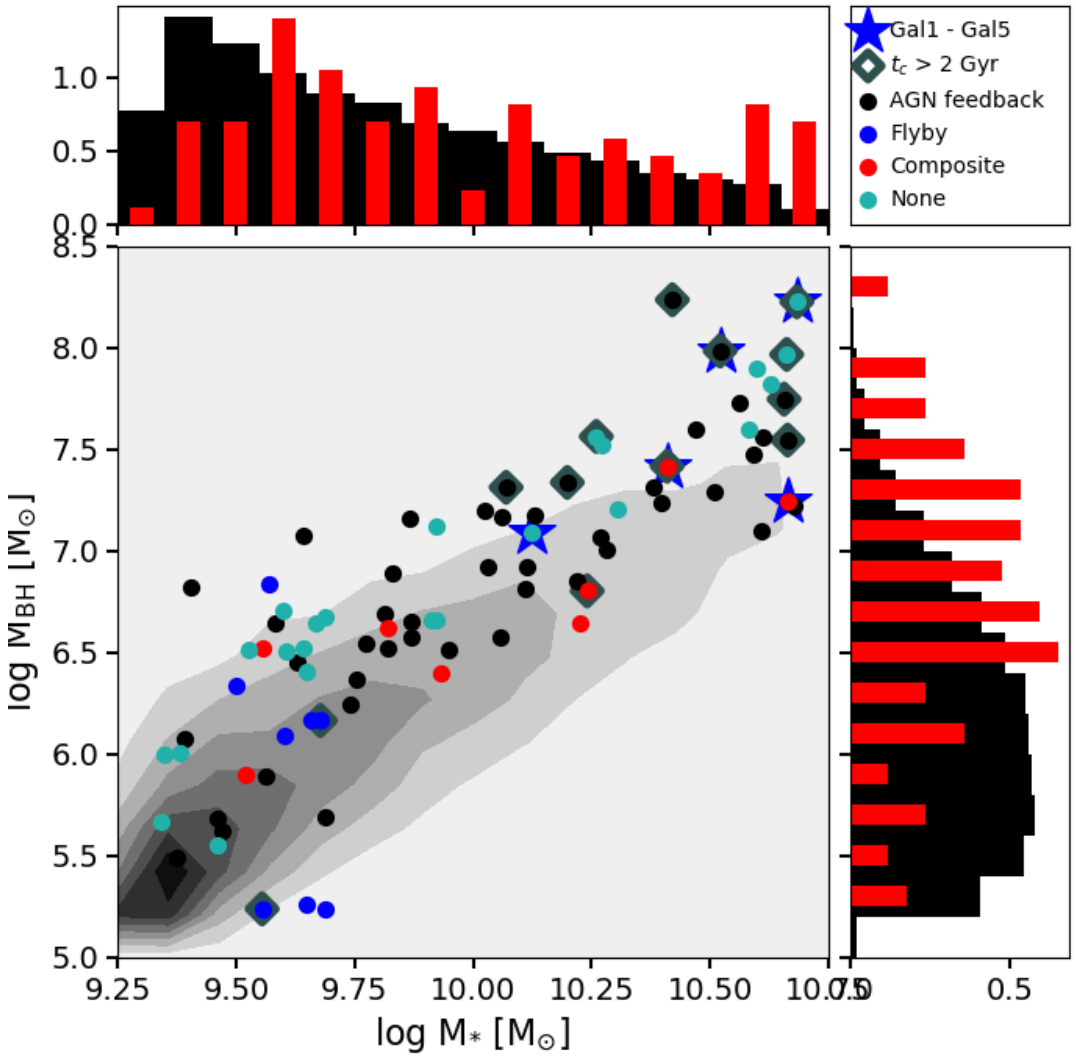
Past gas loss correlates with present counterrotation

- Galaxies lose corotating gas before accreting counterrotating gas
- There is no particular correlation between specific gas loss mechanisms and the amount of gas lost



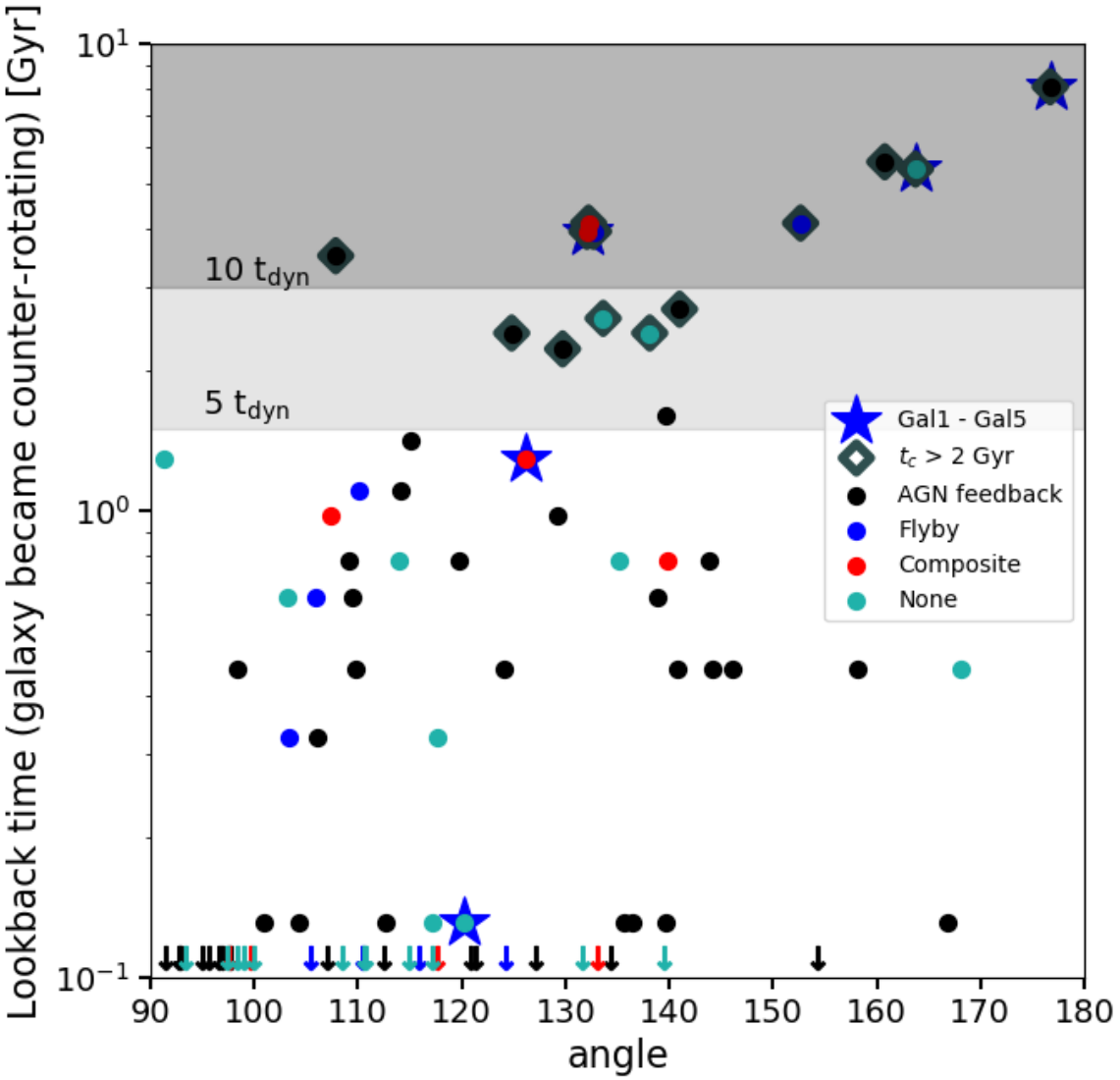
Past gas loss correlates with present counterrotation

Black hole masses seem to be on the high side for the counterrotating sample



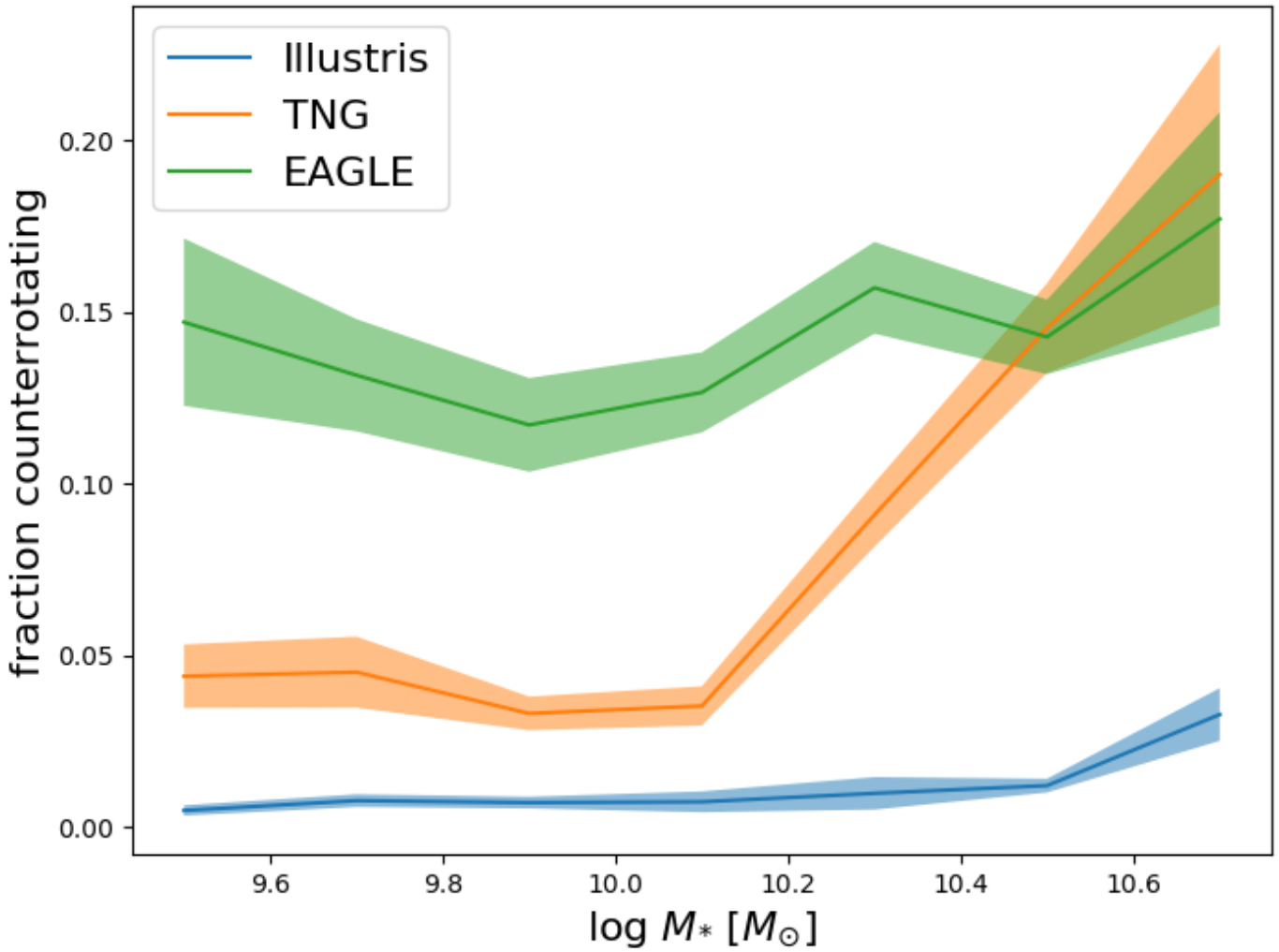
Counterrotation can be a long-term and stable configuration, even for misaligned disks

- 15% of our sample exhibits counterrotation for > 2 Gyr
- This is surprising in view of dynamical theory which predicts perfect co- or anti-alignment within a few dynamical times
- Continued accretion and tidal torques from large scale structure may explain this difference



Future: comparing Illustris and TNG and EAGLE

Large differences in similar simulations with different modeling of sub grid physics: counterrotating galaxies may provide us with information to help constrain sub grid models, for example for strong feedback



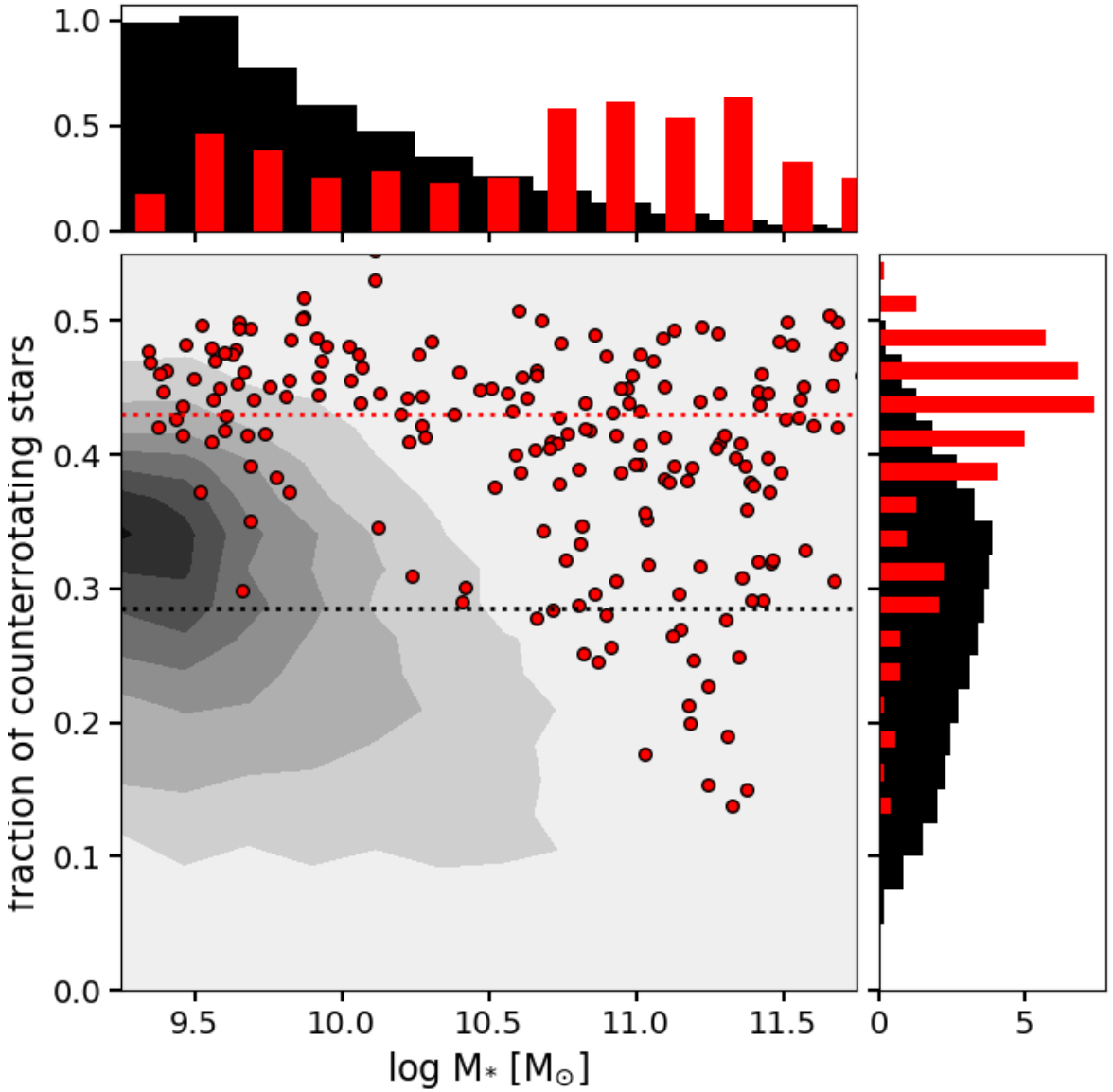
Conclusions

- Illustris has a low fraction of star-gas counterrotating low-mass galaxies: ~1% (mass range $M_* = 2e9 - 5e10\ M_{sun}$)
- Counterrotating galaxies have lower gas masses, and lower gas and stellar spin, but are otherwise normal
- AGN feedback and fly-by encounters may be related to (corotating) gas loss, and counterrotation
- **Therefore, counterrotating galaxies today may hold clues to past environment and past evolution**
- Once established counterrotation can persist for very long time, also at imperfect alignments

Starkenburg et al. ArXiv: 1903.03627

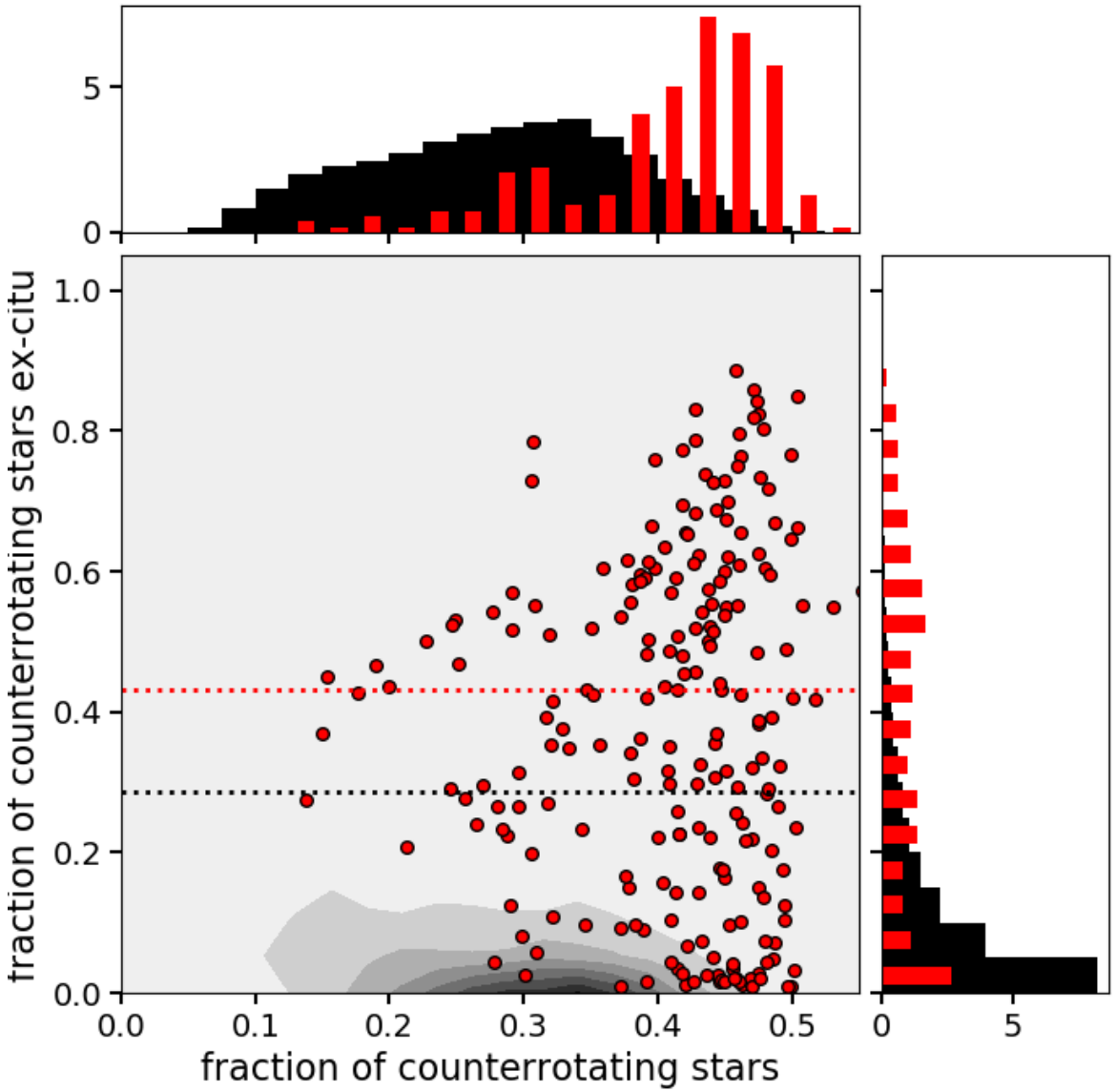
Counterrotating stars in all Illustris galaxies

- Almost all galaxies have *some* fraction of counterrotating stars
- Galaxies with counterrotating gas disks have a high fraction of counterrotating stars

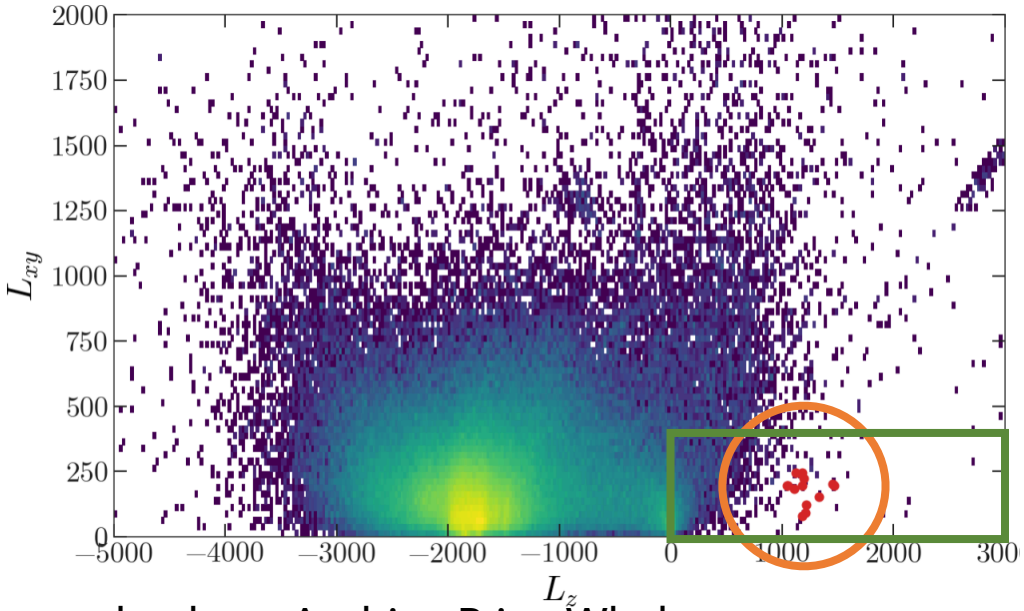


Counterrotating stars in all Illustris galaxies

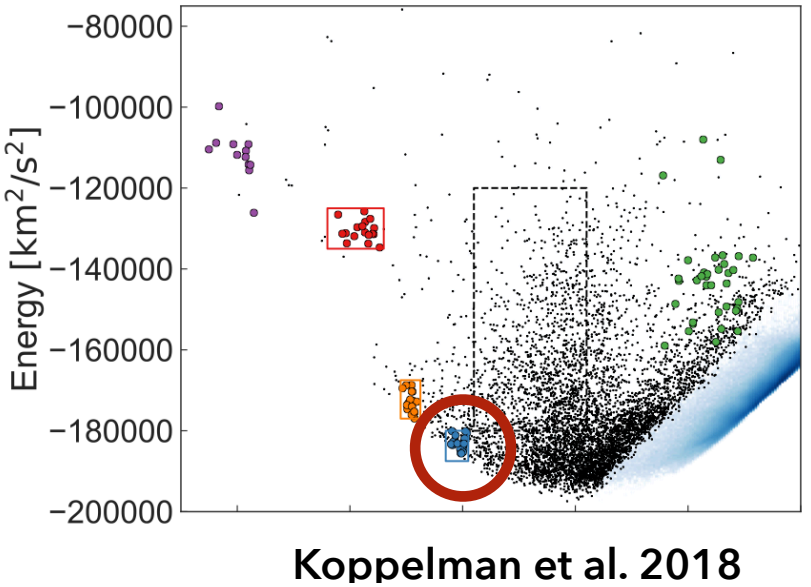
- The fraction of counterrotating stars that are ex-citu (accreted) has a large scatter, but has median values < 0.5
- This fraction is higher for galaxies with counterrotating gas disk



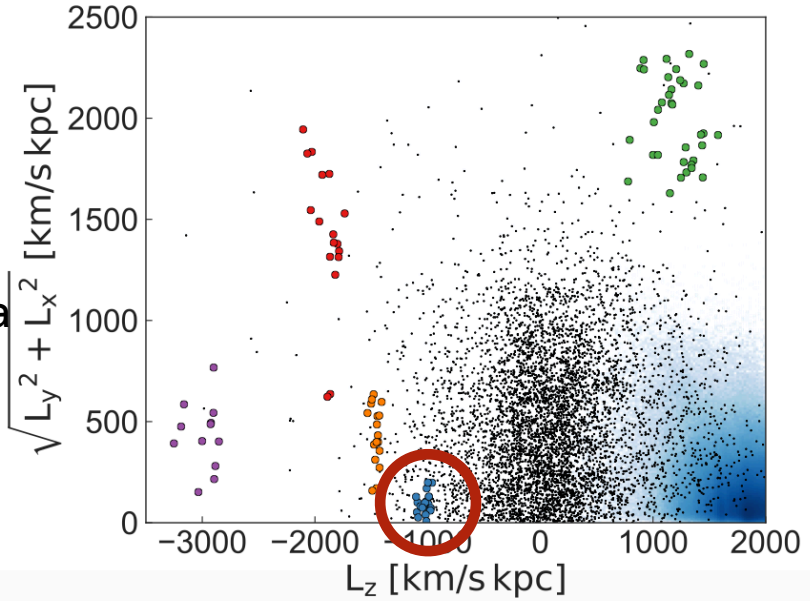
Counterrotating stars in the Milky Way



thanks to Andrian Price-Whelan



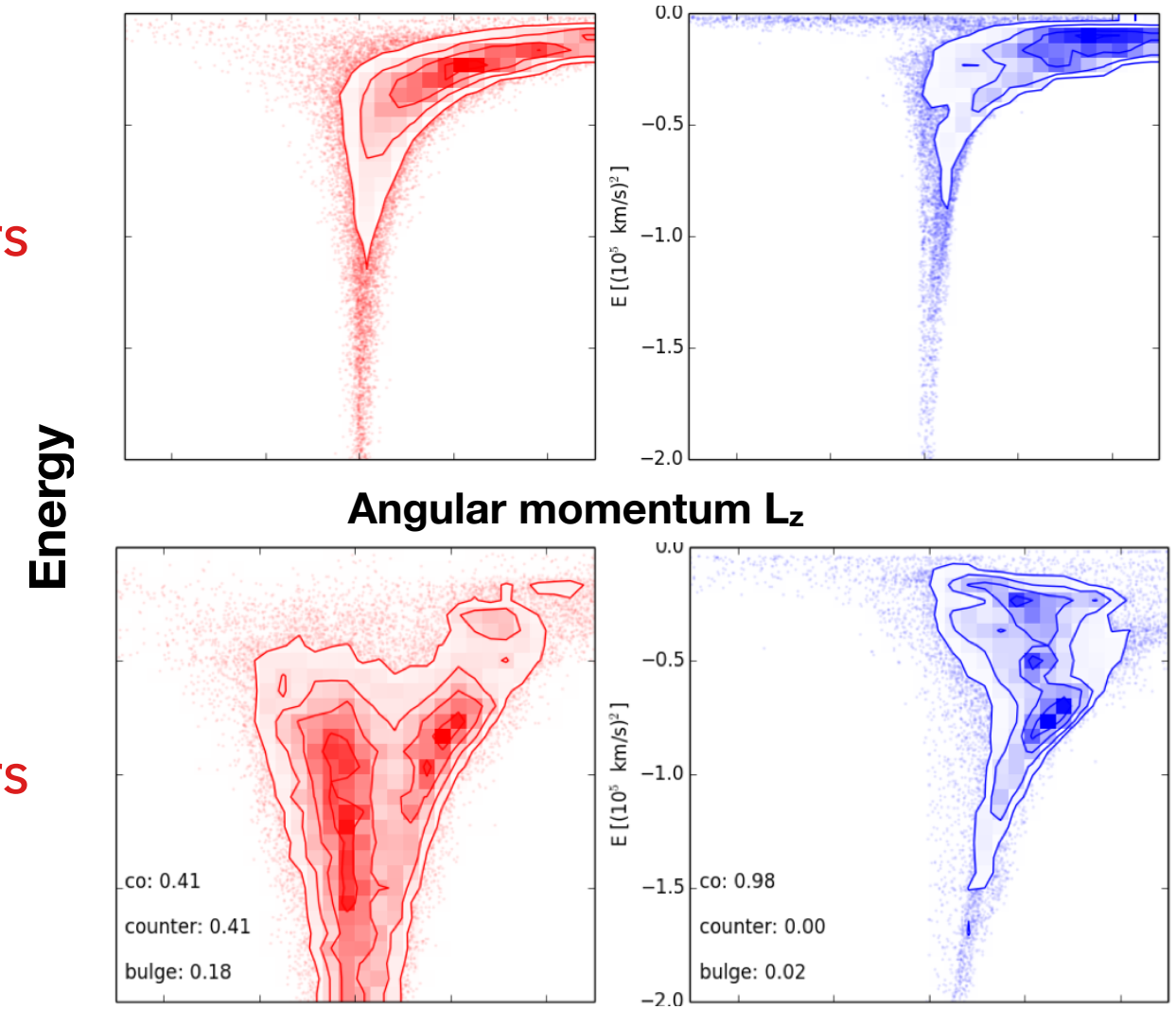
Koppelman et al. 2018



<u>Group of counterrotating stars in disk-like orbits:</u>

- Seen earlier in Koppeman+2018, Helmi+2017 (VelHel-4), and maybe more
- Very quick look at properties seem to indicate a coherent (space & metallicity) group with metallicity unlike the disk
- Probably no in-situ counterrotating stars. Otherwise very little in that class

Milky Way-mass galaxies in the Illustris simulation can have small or large counter-rotating components

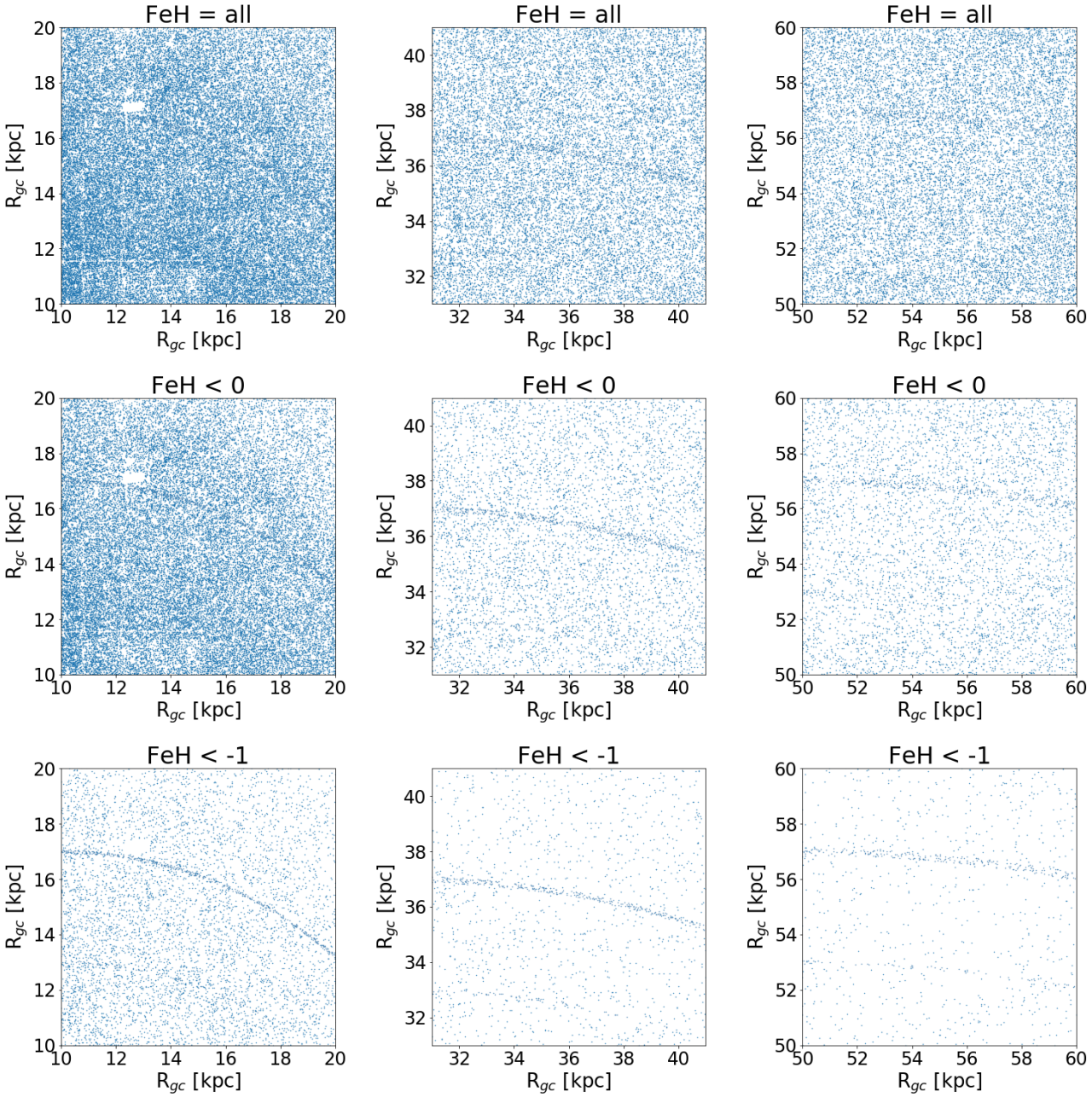


Future questions/plans

- Where do counterrotating stars come from (formed in counterrotating gas or accreted) and can we use the properties of counterrotating stellar components to constrain their origins?
- What does the scatter in the fraction of counterrotating stars tell us in general about galaxy formation, and external vs. internal processes?
- In particular for the Milky Way, can we use the extreme detail that we have to constrain more about its formation and past environment?
- Is there a cluster/dwarf galaxy accreted on a planar retrograde orbit?

The observability of cold streams in external galaxies

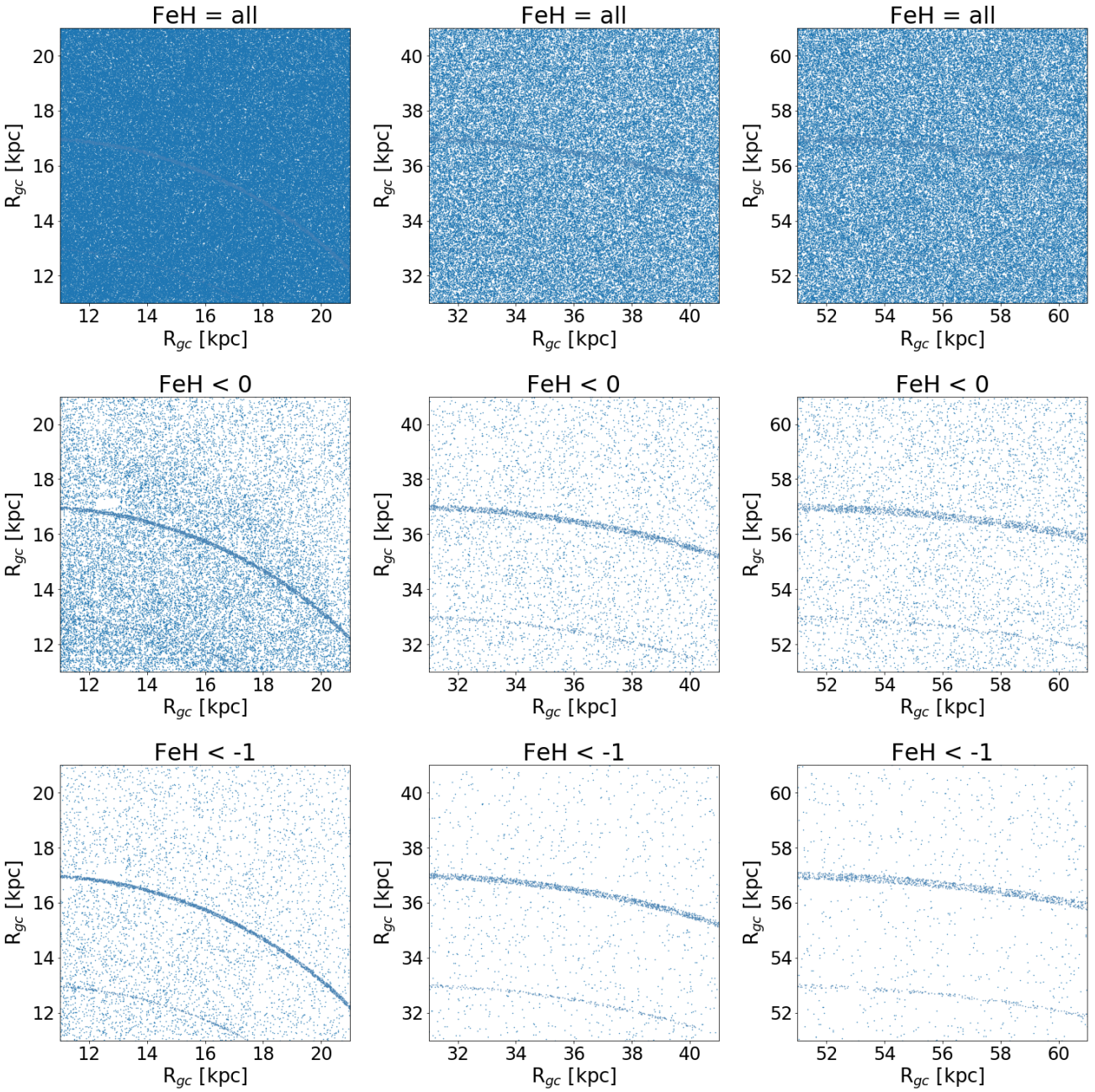
the possibility of seeing cold streams in Andromeda with PANDAS: These fields contain one Pal-5 like stream and one 10 times as massive



Pearson, TKS et al. in prep

The observability of cold streams in external galaxies

the possibility of seeing cold streams in Andromeda with WFIRST: These fields contain one Pal-5 like stream and one 10 times as massive



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