

How do mergers affect galaxies?



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Radburn-Smith, Jeremy Bailin + GHOSTS

A galaxy is a gravitationally bound system of stars, stellar remnants, interstellar gas and dust, and dark matter.

The 'day-to-day' life of stars, gas and dust interact – a galaxy's 'secular' evolution – has been richly characterized observationally and theoretically.

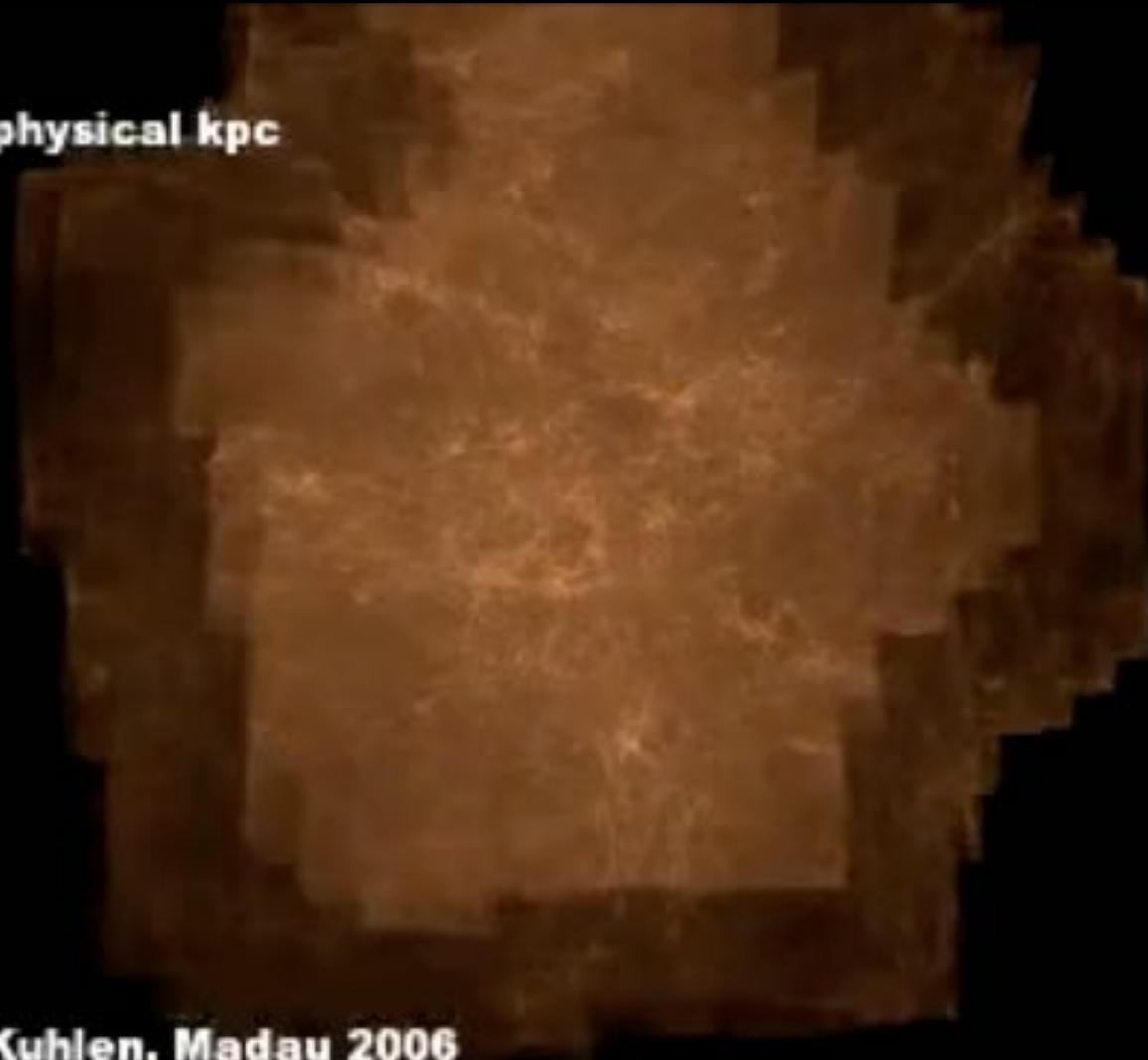


SINGS; Kennicutt et al. 2004
THINGS; Walter et al. 2007

Dark matter is thought to be the driver of galaxy formation and evolution.

$z=11.9$

800 x 600 physical kpc



Diemand, Kuhlen, Madau 2006

Dark matter halos grow by colliding and merging, and dark matter distribution encodes growth history

40 kpc



Via Lactea

Diamand, Kuhlen, Madau 2007, ApJ, 667, 859

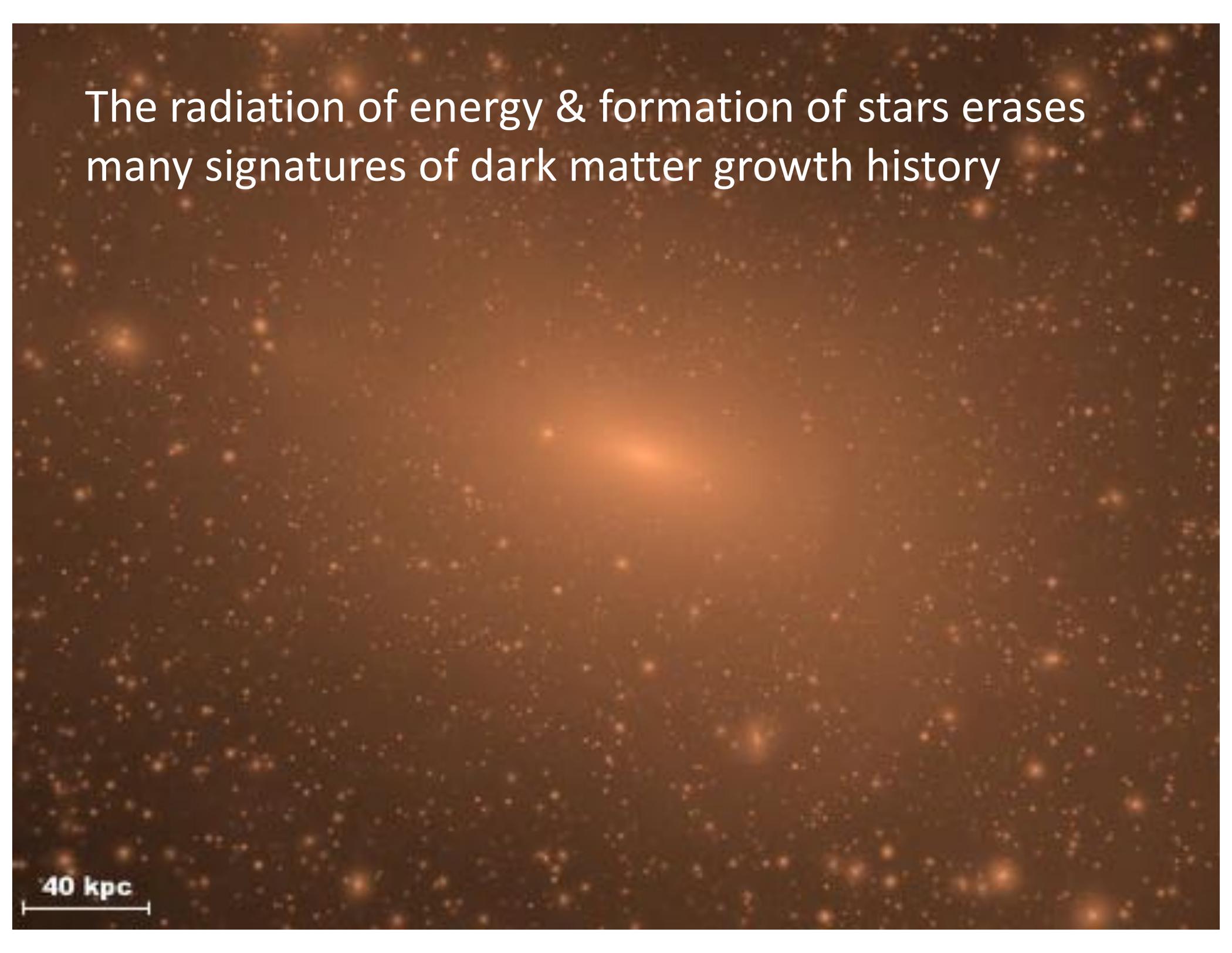
Normal matter feels 4 forces of nature and ends up following a distinctive formation pathway



NGC 2683 – HST/ACS

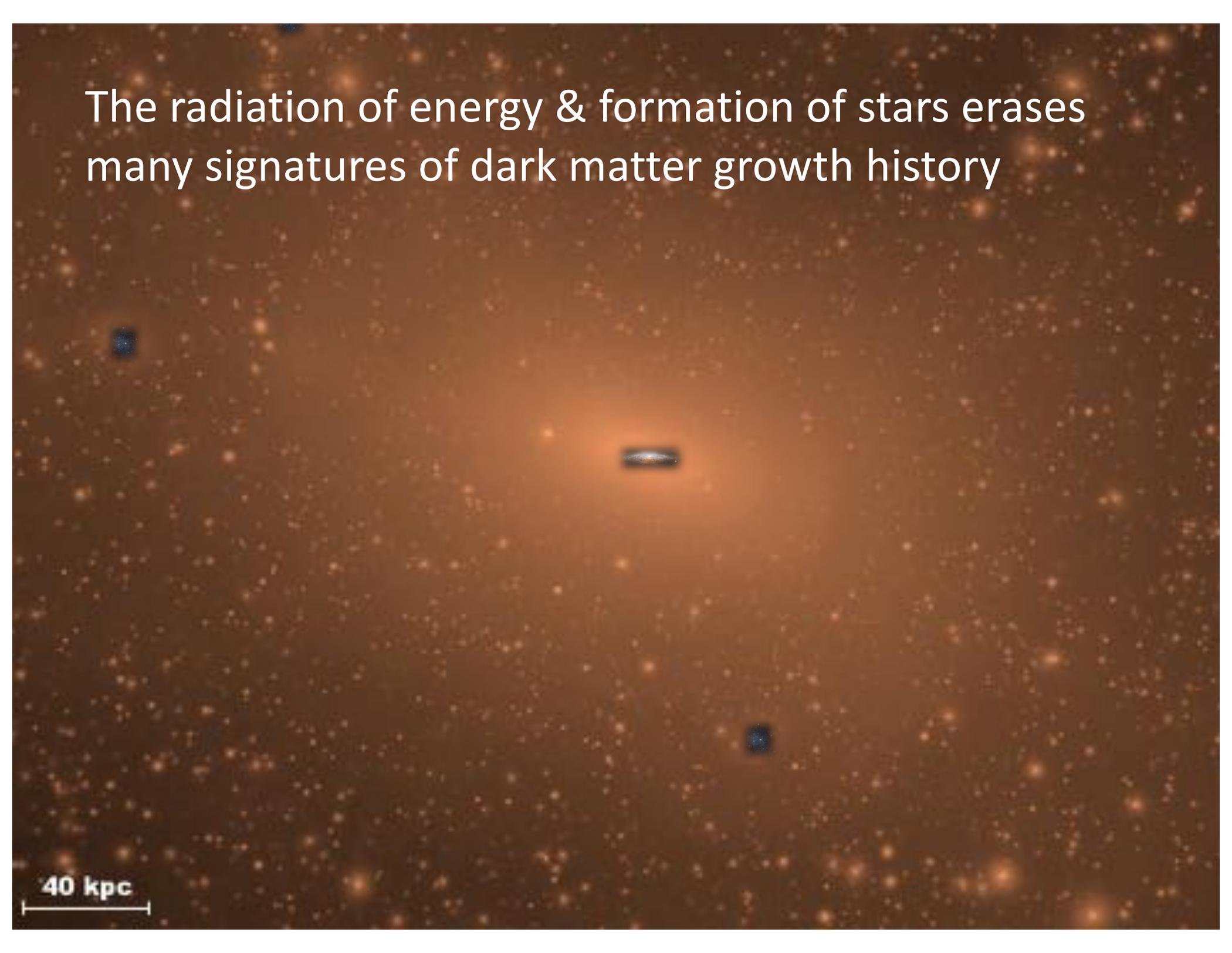
The radiation of energy & formation of stars erases many signatures of dark matter growth history

40 kpc

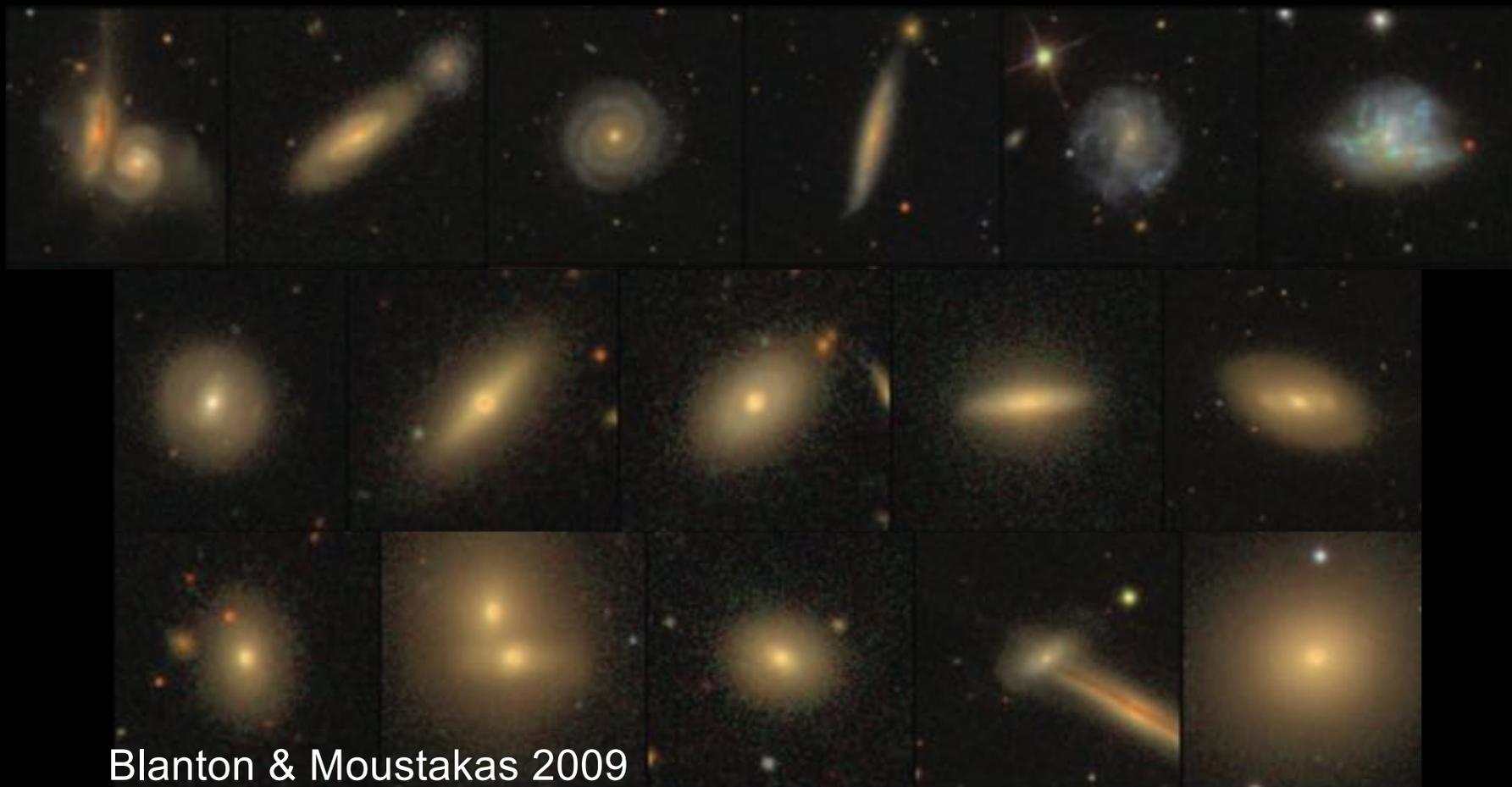
A simulated galaxy cluster with a scale bar of 40 kpc. The image shows a dense field of stars and galaxies, with a bright central region. The background is a dark, reddish-brown color, and the foreground is filled with numerous small, bright orange and yellow stars. A scale bar in the bottom left corner indicates a length of 40 kpc.

The radiation of energy & formation of stars erases many signatures of dark matter growth history

40 kpc



This is a shame – the dark matter growth history, and the galactic collisions that they cause, are thought to drive galaxy diversity.



Blanton & Moustakas 2009

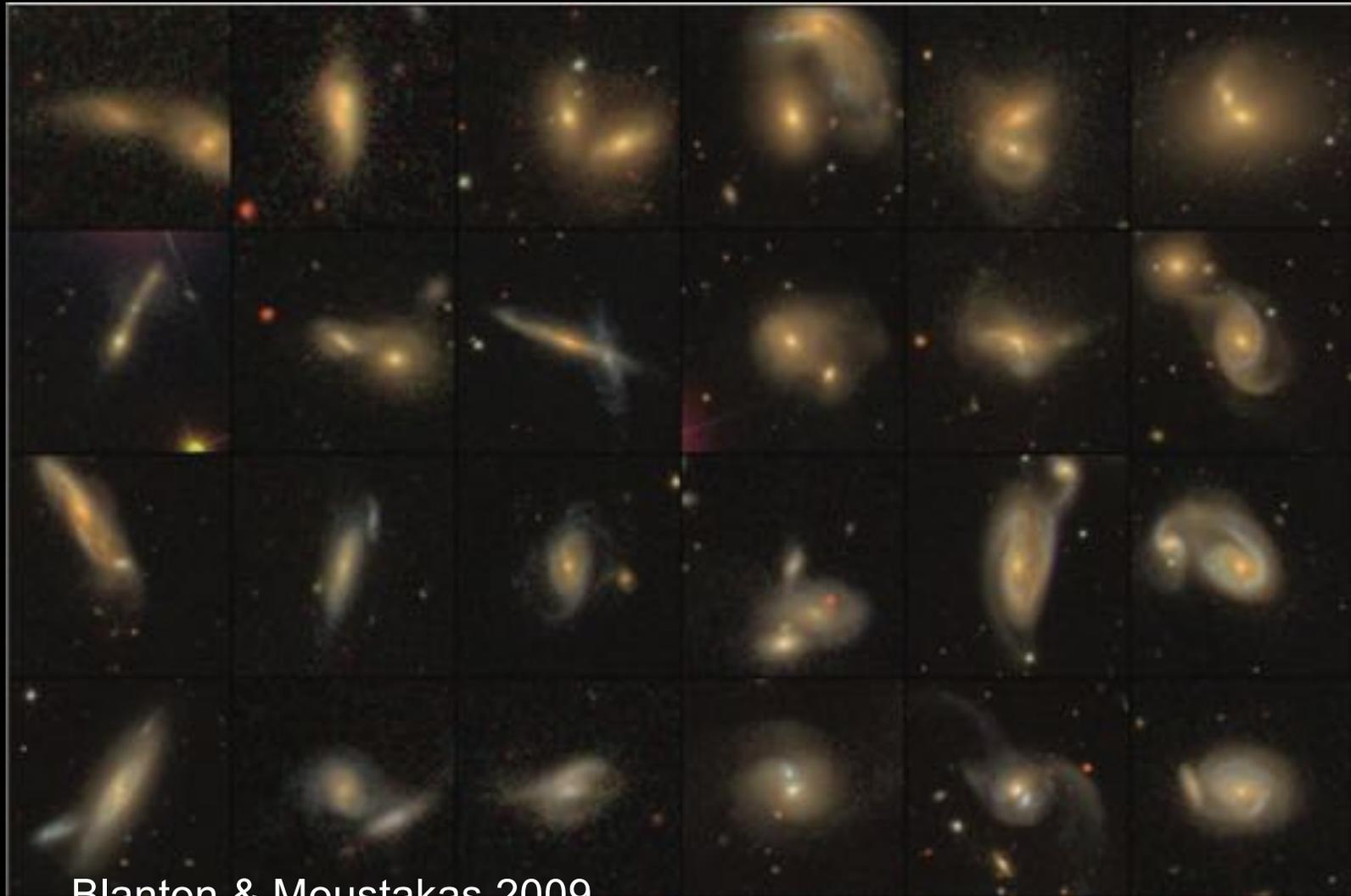
Collisions between large halos and the galaxies in them can destroy disks and make bulges

0.0 Gyr

Stars

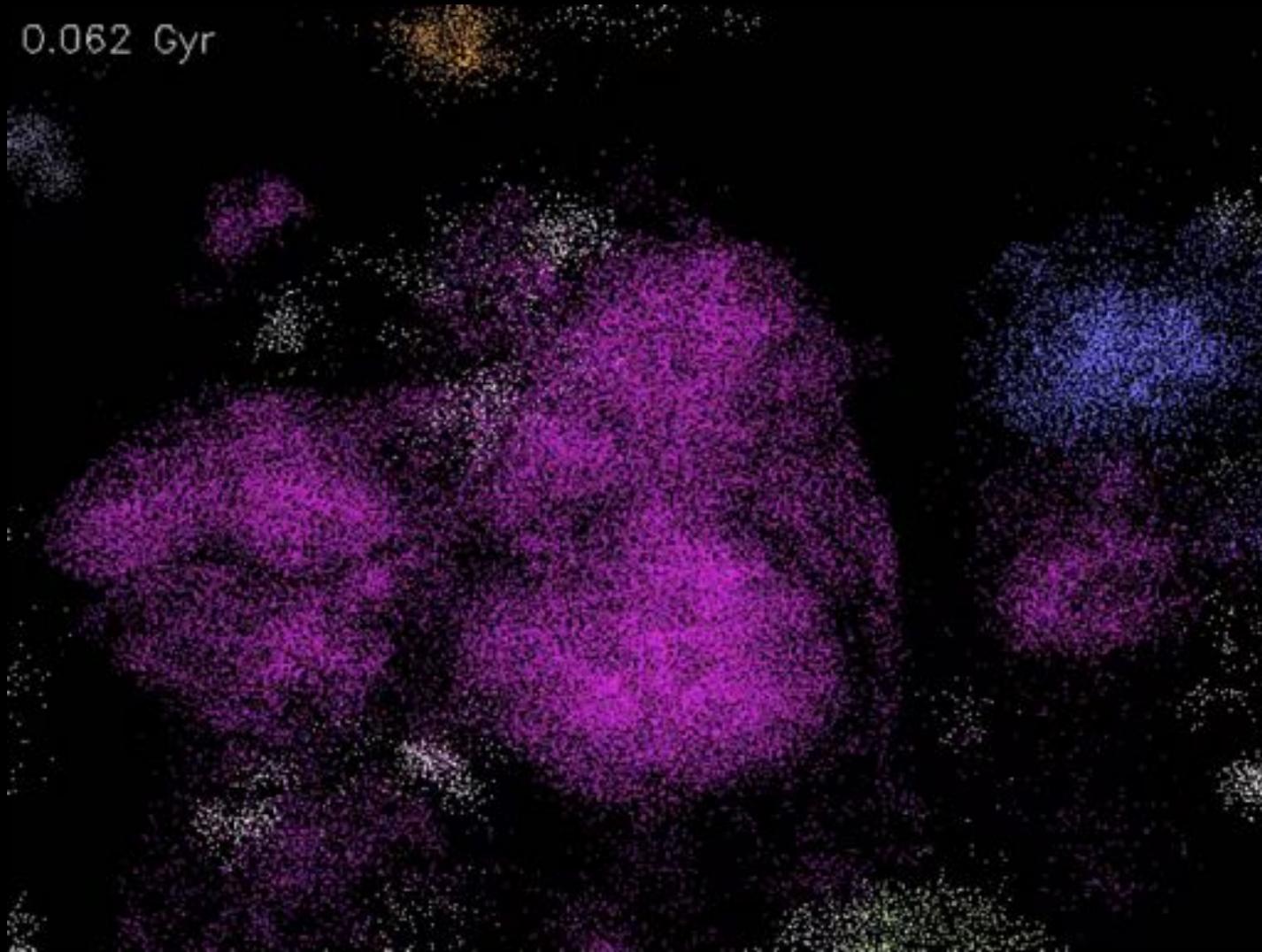
10 kpc

We can see what collisions / mergers do when they are happening, but we don't know what the final effects of a merger are.



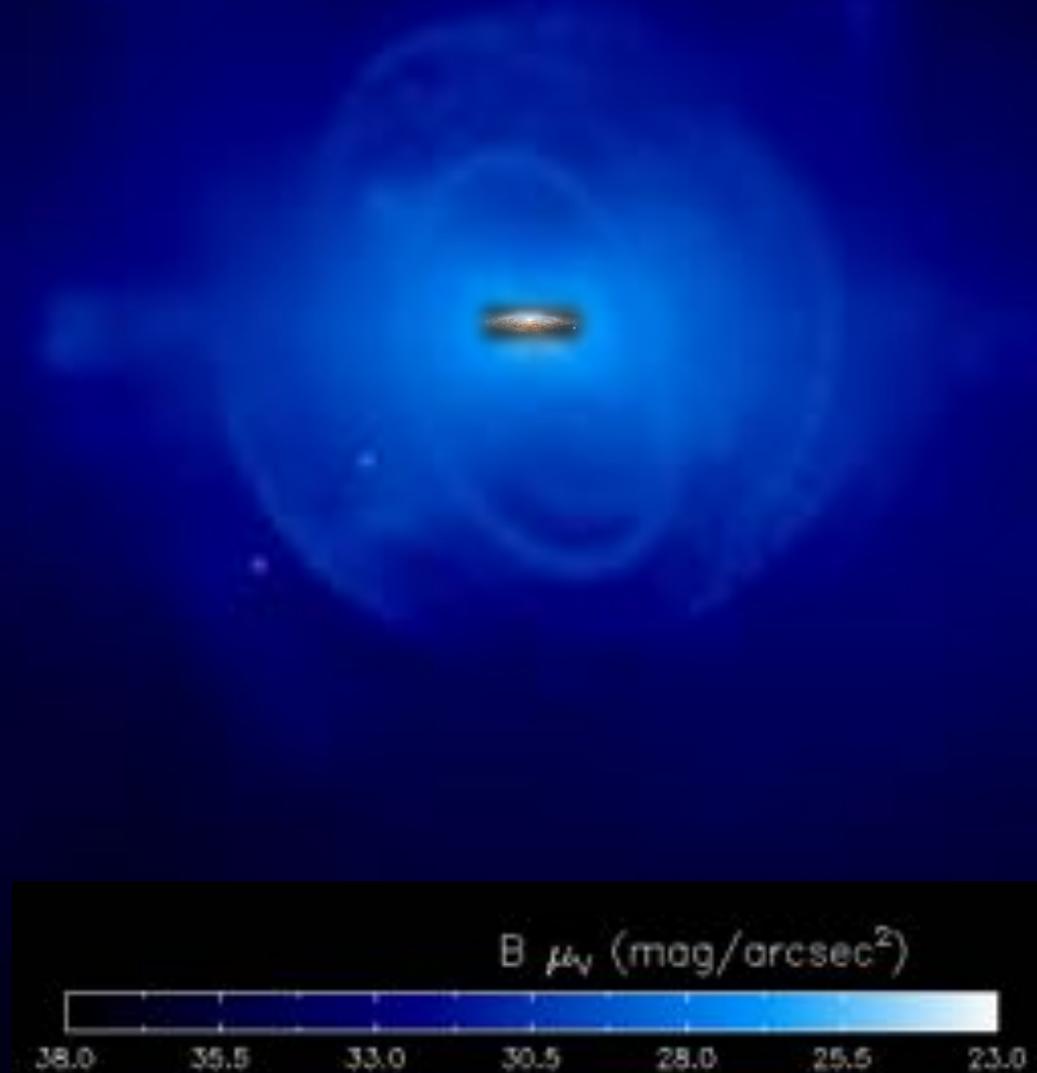
Blanton & Moustakas 2009

Can we quantify the properties of the galaxies that merged with my final galaxy?



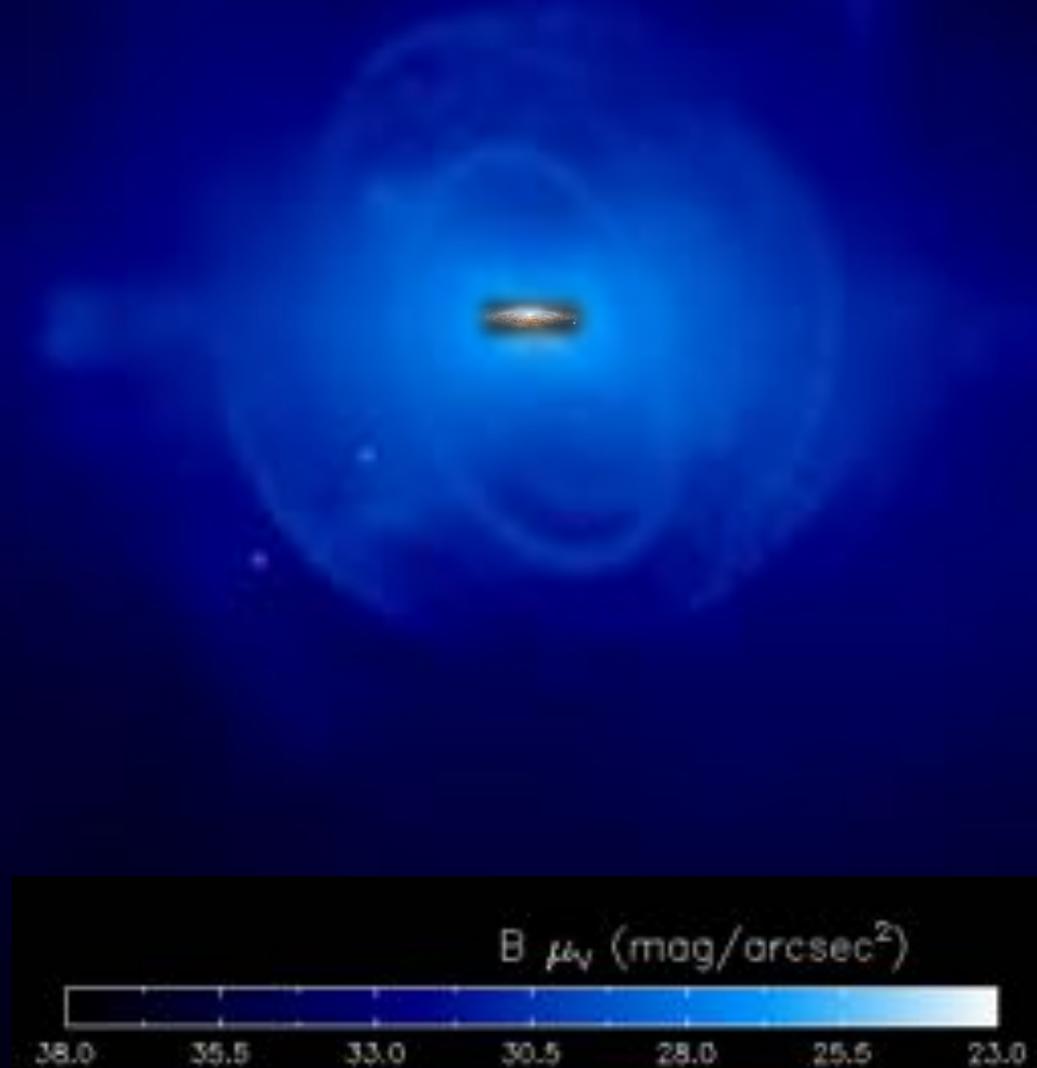
Cooper et al. 2010

Stars in the infalling satellite dark matter halos are tidally liberated and spread into a **stellar halo**



Bullock & Johnston 2005
ApJ, 635, 931

Stellar halos are predicted to have properties that **do** reflect accretion history



Bullock & Johnston 2005
ApJ, 635, 931

Stellar halos are very diffuse, and have been historically very hard to detect.



NGC 5907; Milky Way like galaxy

https://en.wikipedia.org/wiki/NGC_5907#/media/File:NGC_5907.jpg
24" Mt. Lemmon

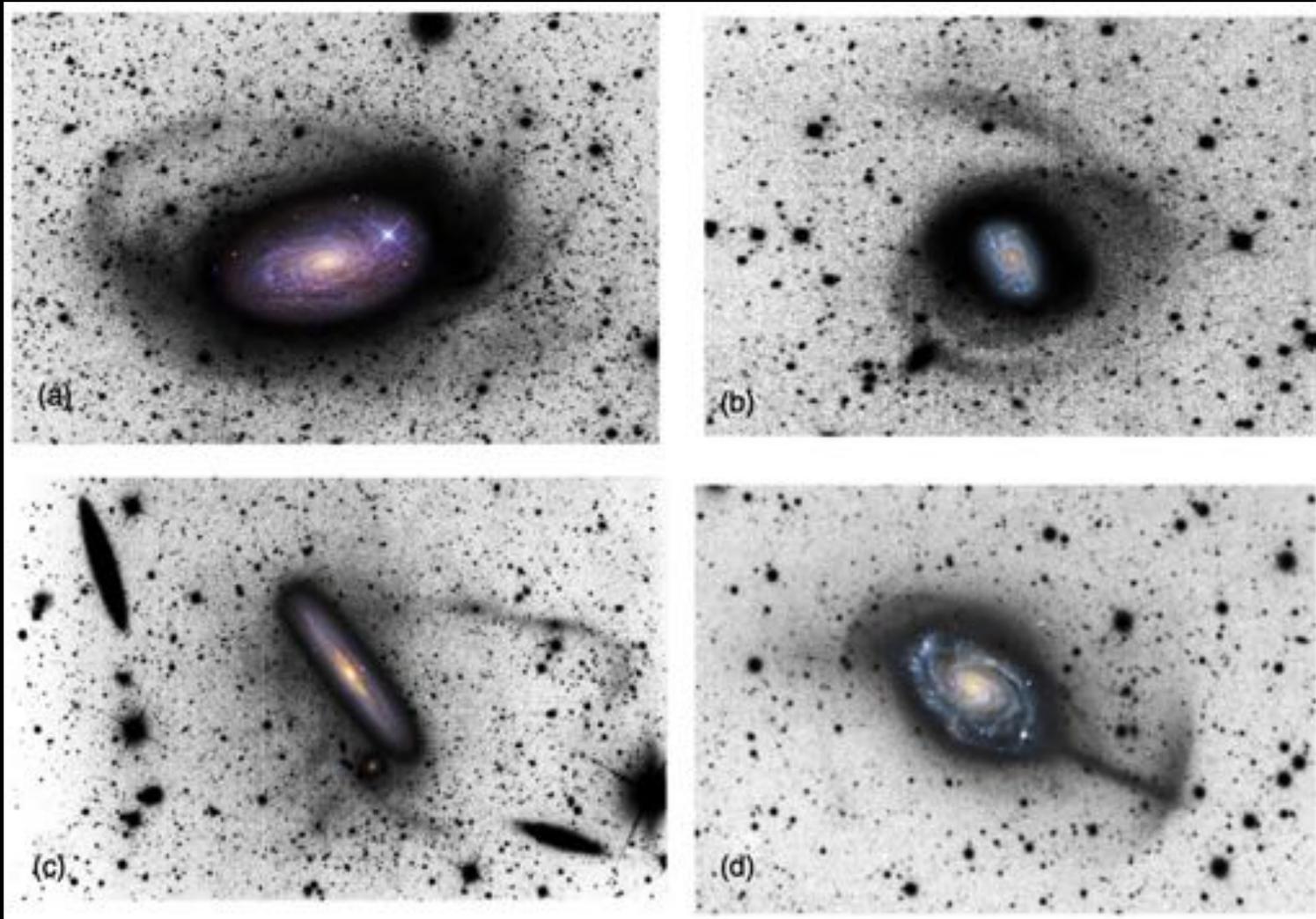


NGC 5907; Milky Way like galaxy

<http://apod.nasa.gov/apod/ap080619.html>

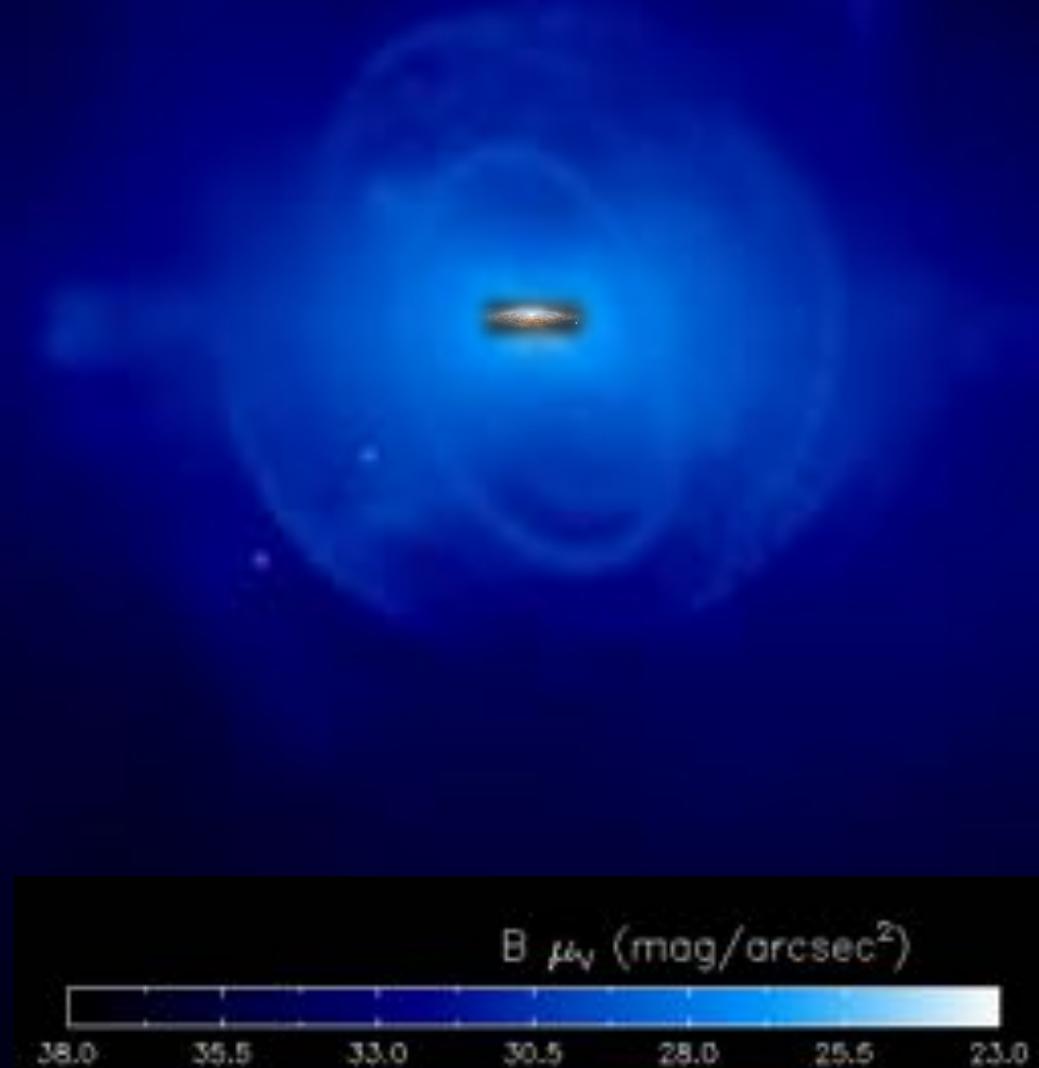
R. Jay Gabany, Blackbird Observatory; Martinez-Delgado et al. 2008; ApJ, 689, 184

Diffuse stellar streams are in reach of specially-designed telescopes...



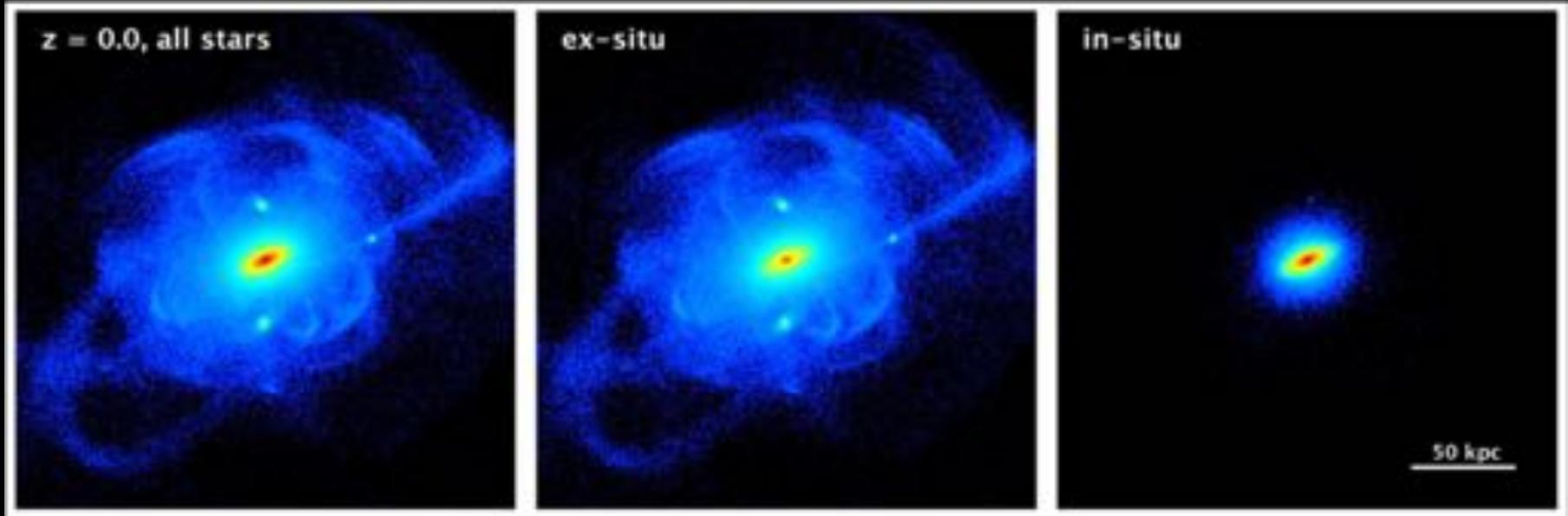
Martinez-Delgado et al. 2010; AJ,140, 962
van Dokkum et al. 2014; Dragonfly Array

The more diffuse extended stellar halo –
reflecting accretion history – were inaccessible



Bullock & Johnston 2005
ApJ, 635, 931

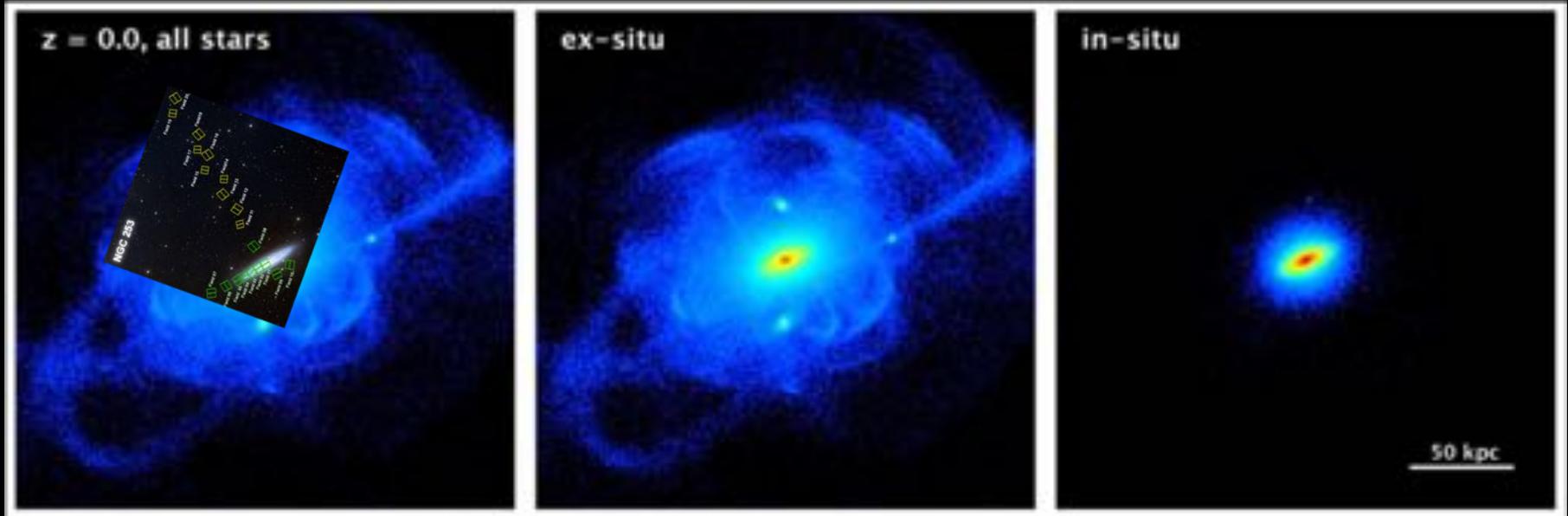
We use Hubble Space Telescope to measure stars far from the main galaxy.



Eris; hydrodynamical model
Pillepich et al. 2015

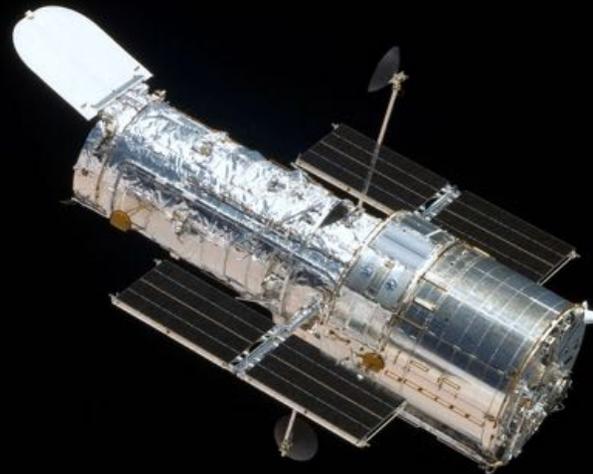
For similar results from the
Auriga hydrodynamical model;
See also Monachesi et al.
2016, 2018

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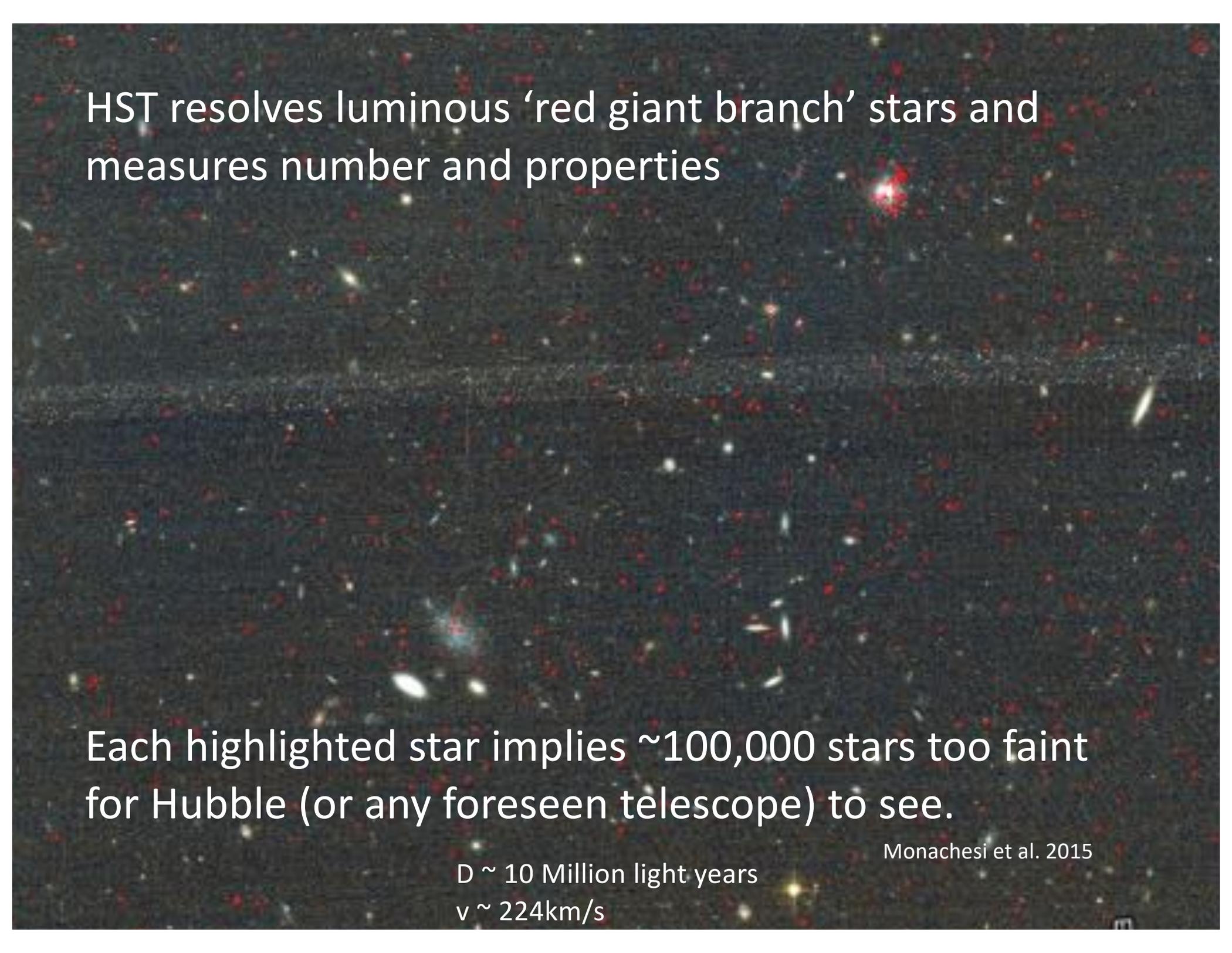
Credit: A. Fuji

HST resolves luminous 'red giant branch' stars and
measures number and properties



$D \sim 10$ Million light years
 $v \sim 224$ km/s

Monachesi et al. 2015



HST resolves luminous 'red giant branch' stars and
measures number and properties

Each highlighted star implies $\sim 100,000$ stars too faint
for Hubble (or any foreseen telescope) to see.

$D \sim 10$ Million light years

$v \sim 224$ km/s

Monachesi et al. 2015



[https://en.wikipedia.org/wiki/Andromeda_Galaxy#/media/File:Andromeda_Galaxy_\(with_h-alpha\).jpg](https://en.wikipedia.org/wiki/Andromeda_Galaxy#/media/File:Andromeda_Galaxy_(with_h-alpha).jpg)



The whole stellar halo is accessible by counting individual stars in the outskirts of nearby galaxies

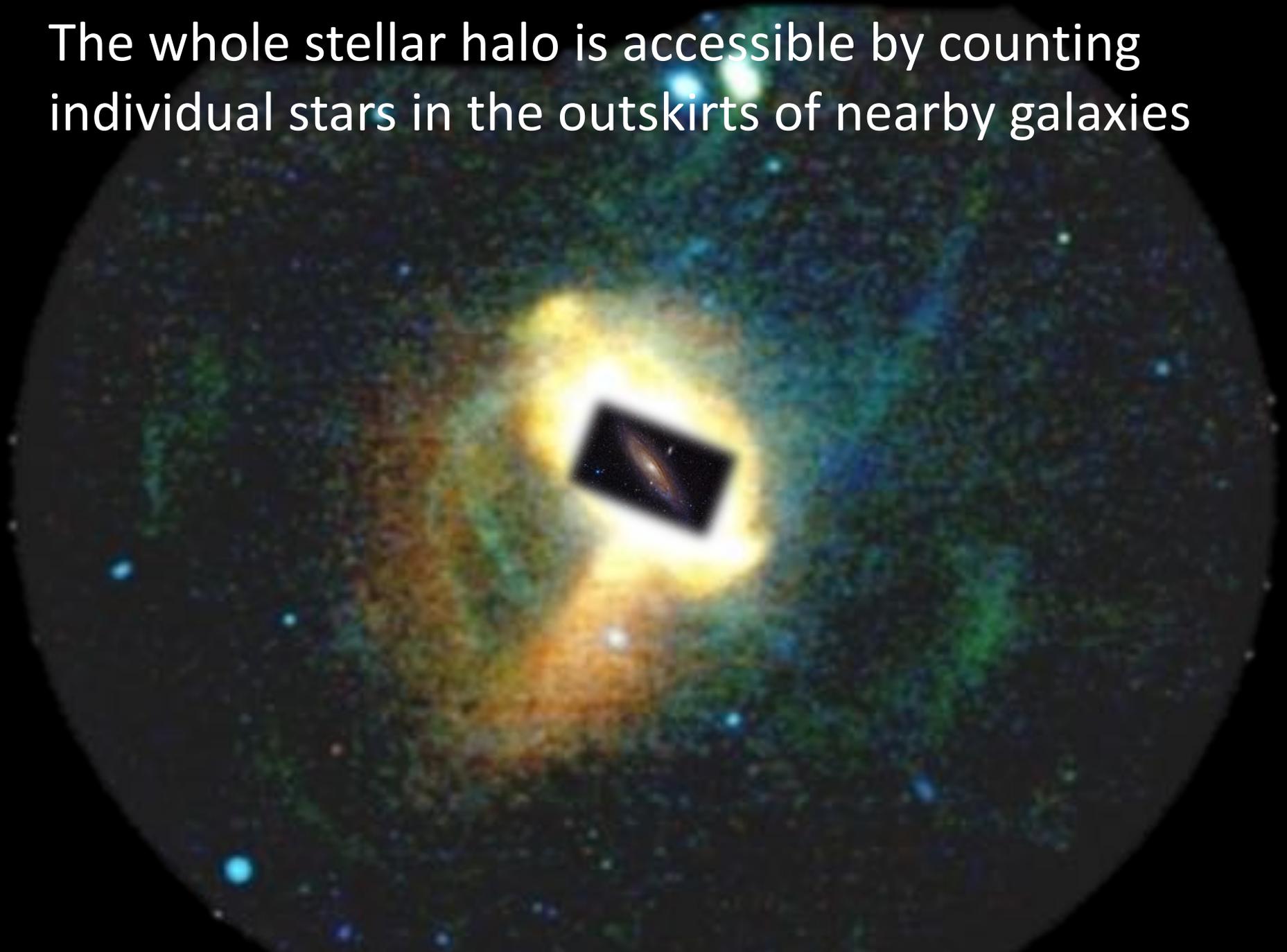


Figure 2 from The PAndAS View of the Andromeda Satellite System. I. A Bayesian Search for Dwarf Galaxies Using Spatial and Color-Magnitude Information
Nicolas F. Martin et al. 2013 ApJ 776 80 doi:10.1088/0004-637X/776/2/80

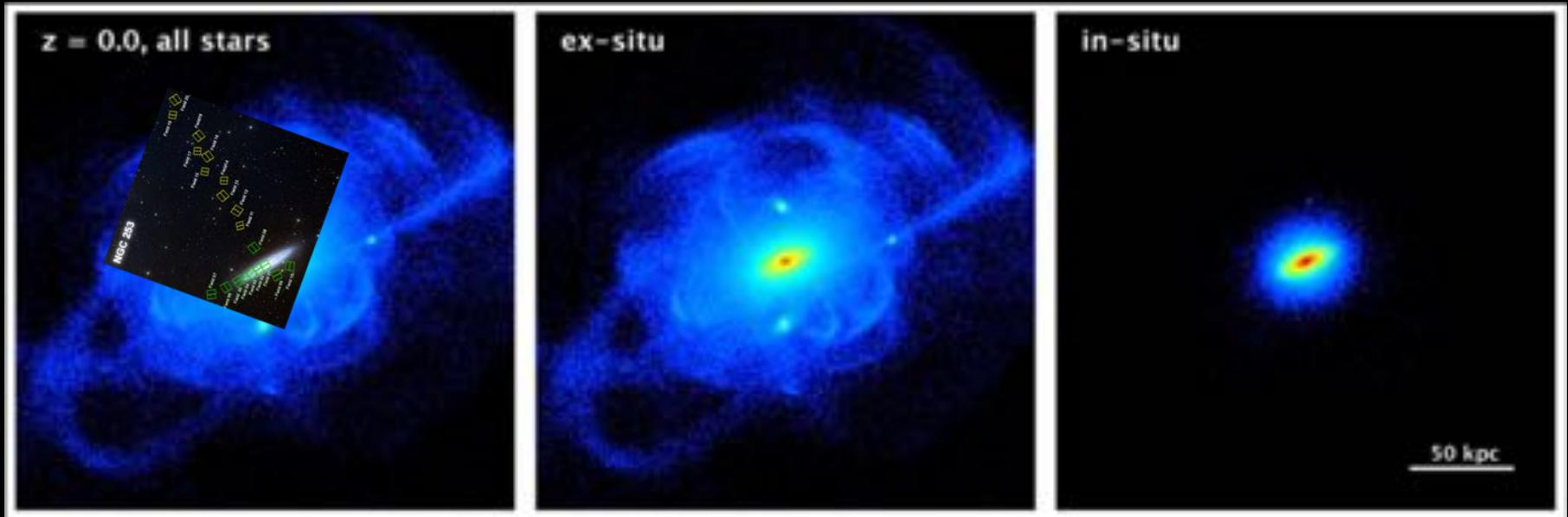
What have we learned about the stellar halos (and dark matter growth histories) of galaxies?



GHOSTS

Roelof de Jong
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David Radburn-Smith
Eric Bell
Jeremy Bailin
Ben Harmsen
+others

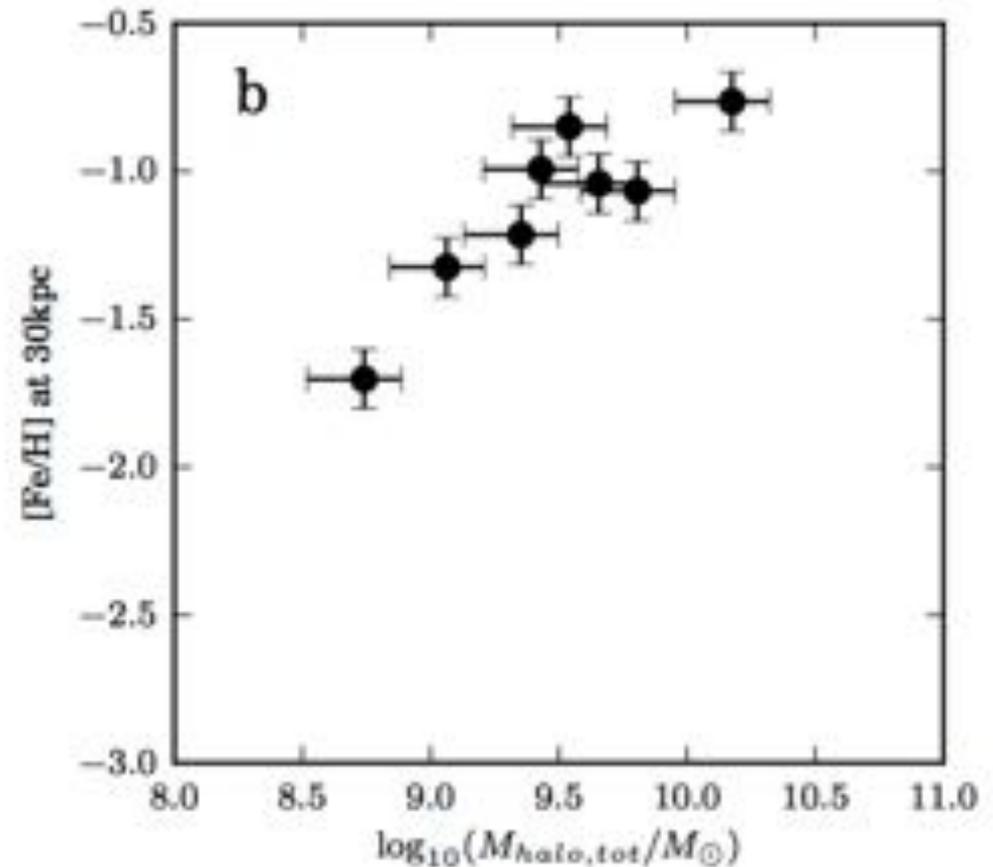
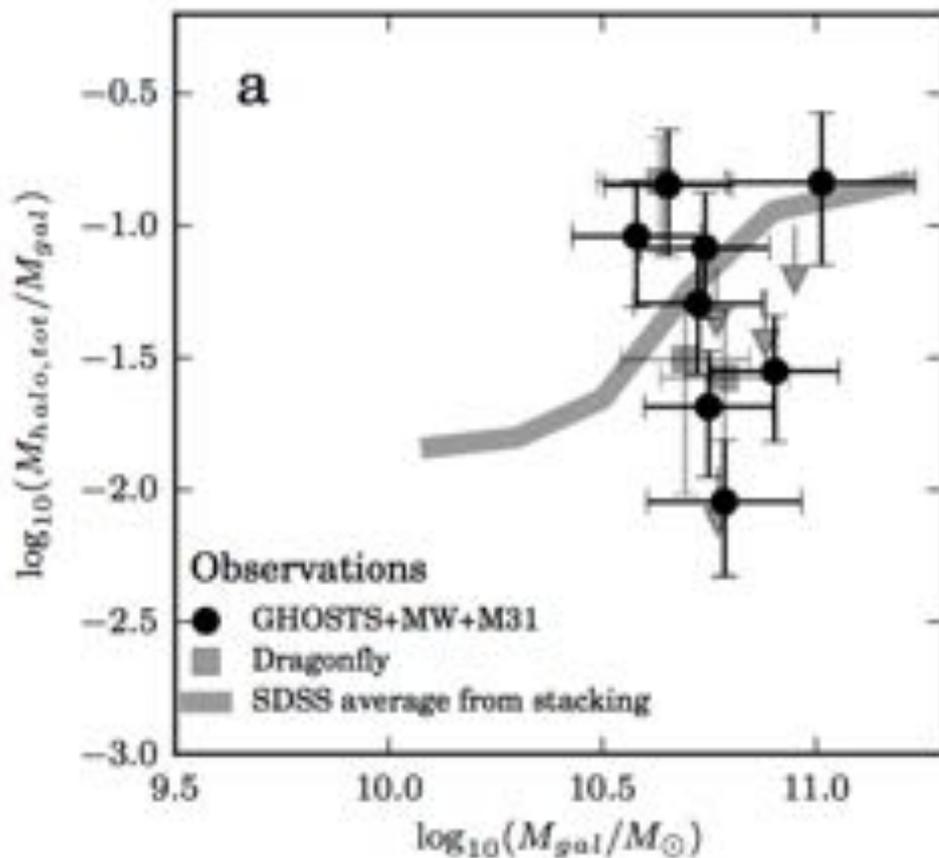
We determine stellar halo masses from minor axis data and compare with models



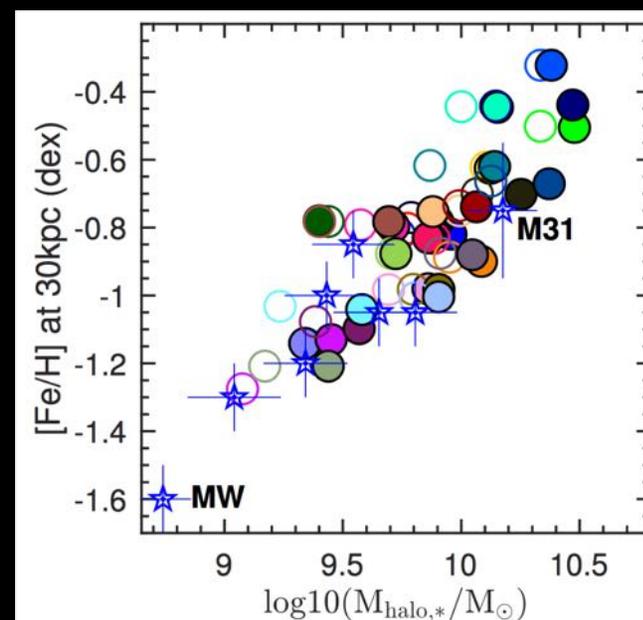
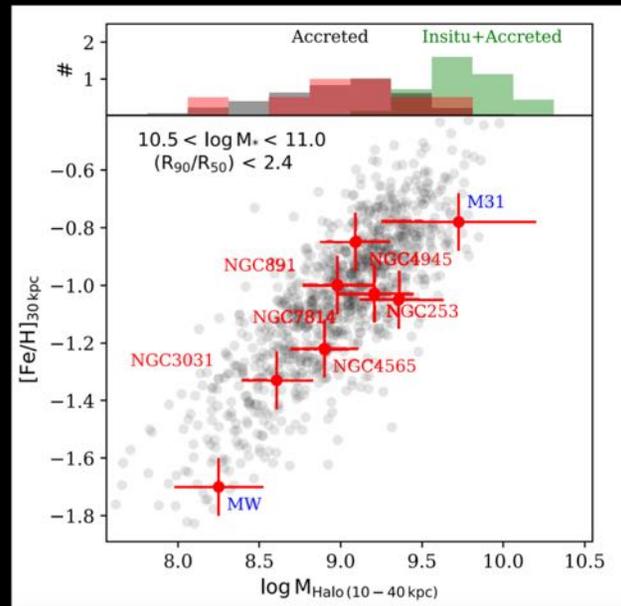
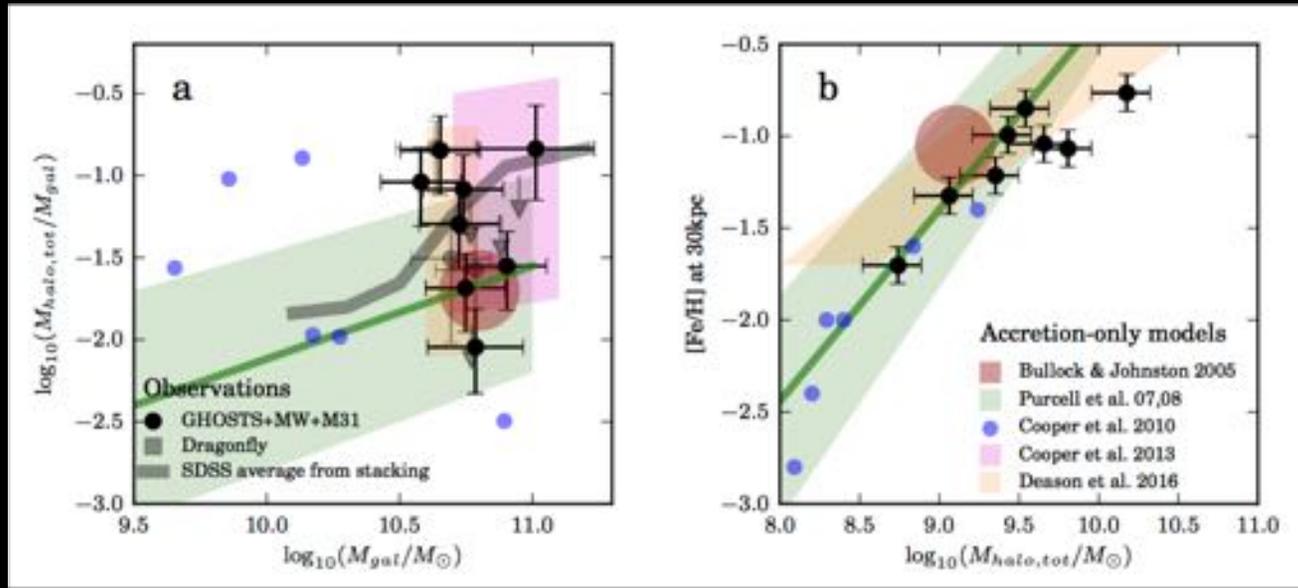
Eris; hydrodynamical model
Pillepich et al. 2015

For similar results from the
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2016, 2018

Milky Way mass galaxies have diverse stellar halo masses, and a halo mass-metallicity correlation

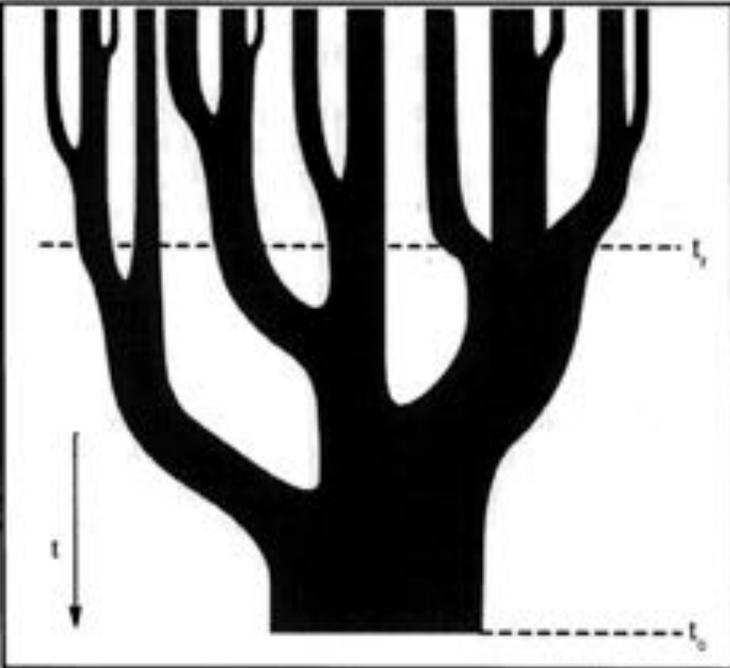


Observations agree with both accretion only models and accreted part of hydro models

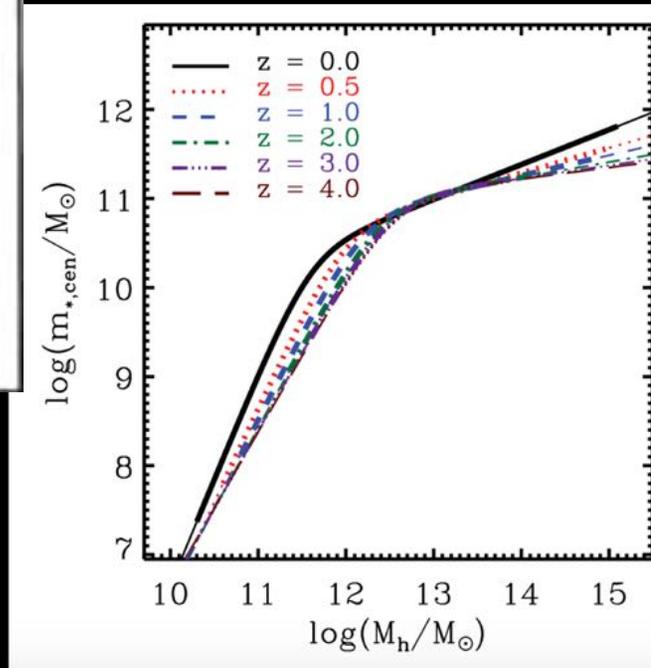


Harmsen, et al. 2017;
D'Souza & Bell 2018;
Monachesi et al. 2018

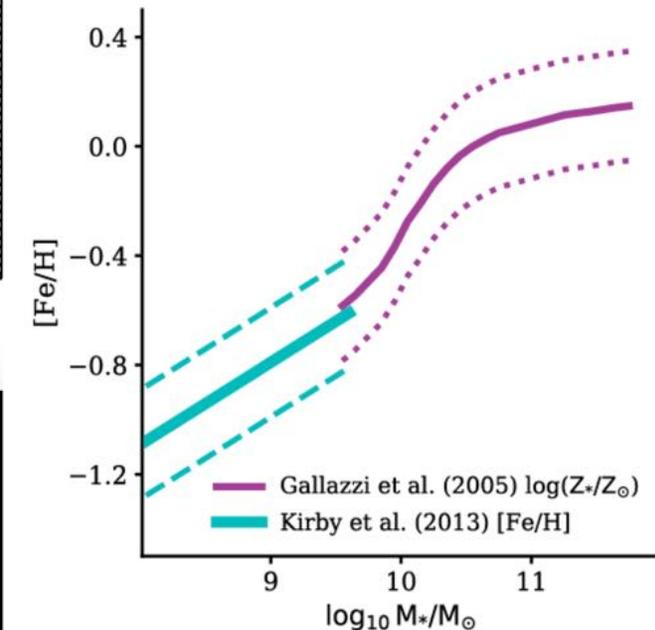
Accreted halos rely only on merger trees, halo occupation and realistic satellites, so are robust



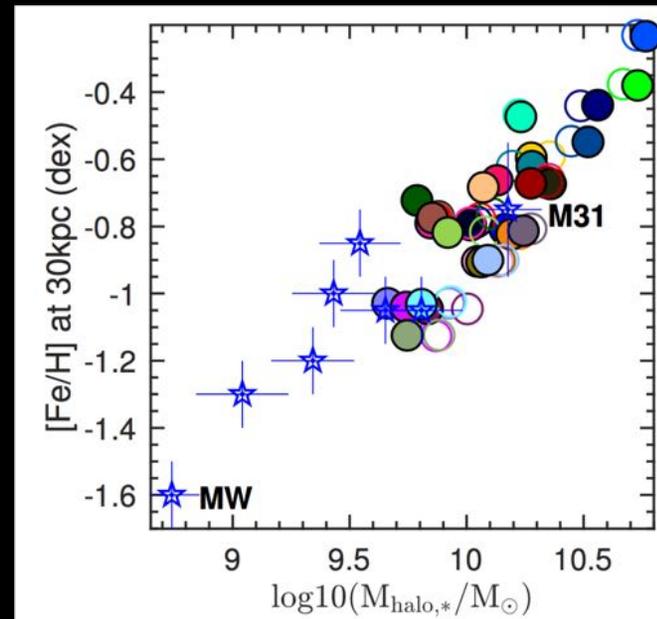
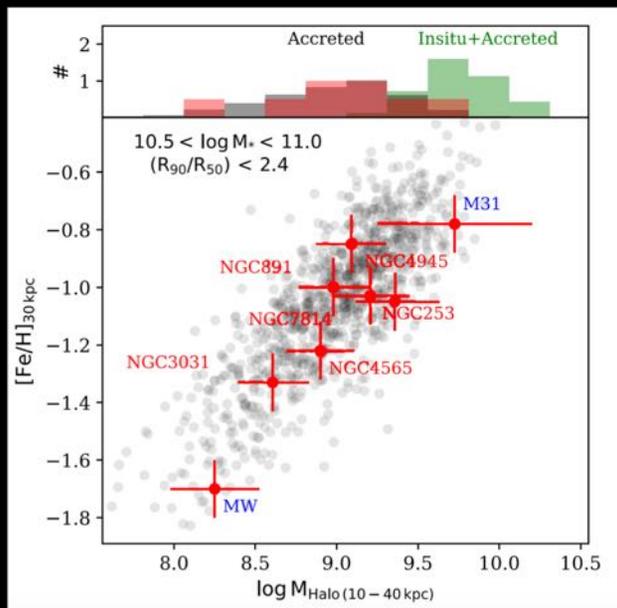
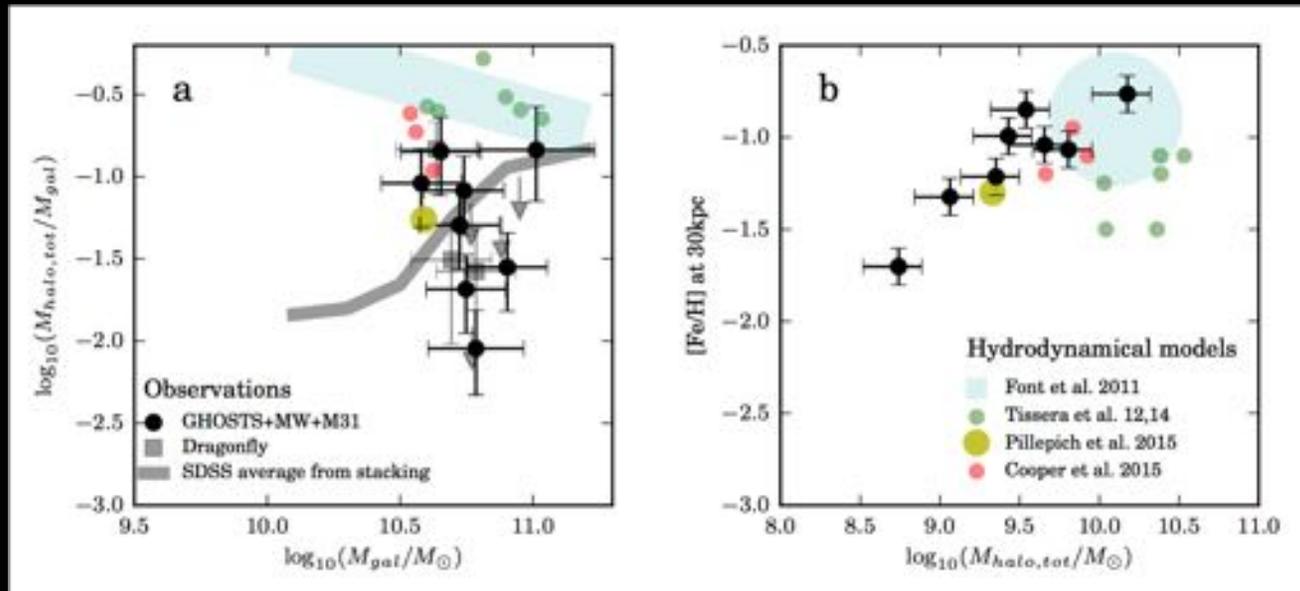
Lacey & Cole 1993



Moster et al. 2013;
Behroozi et al. 2013

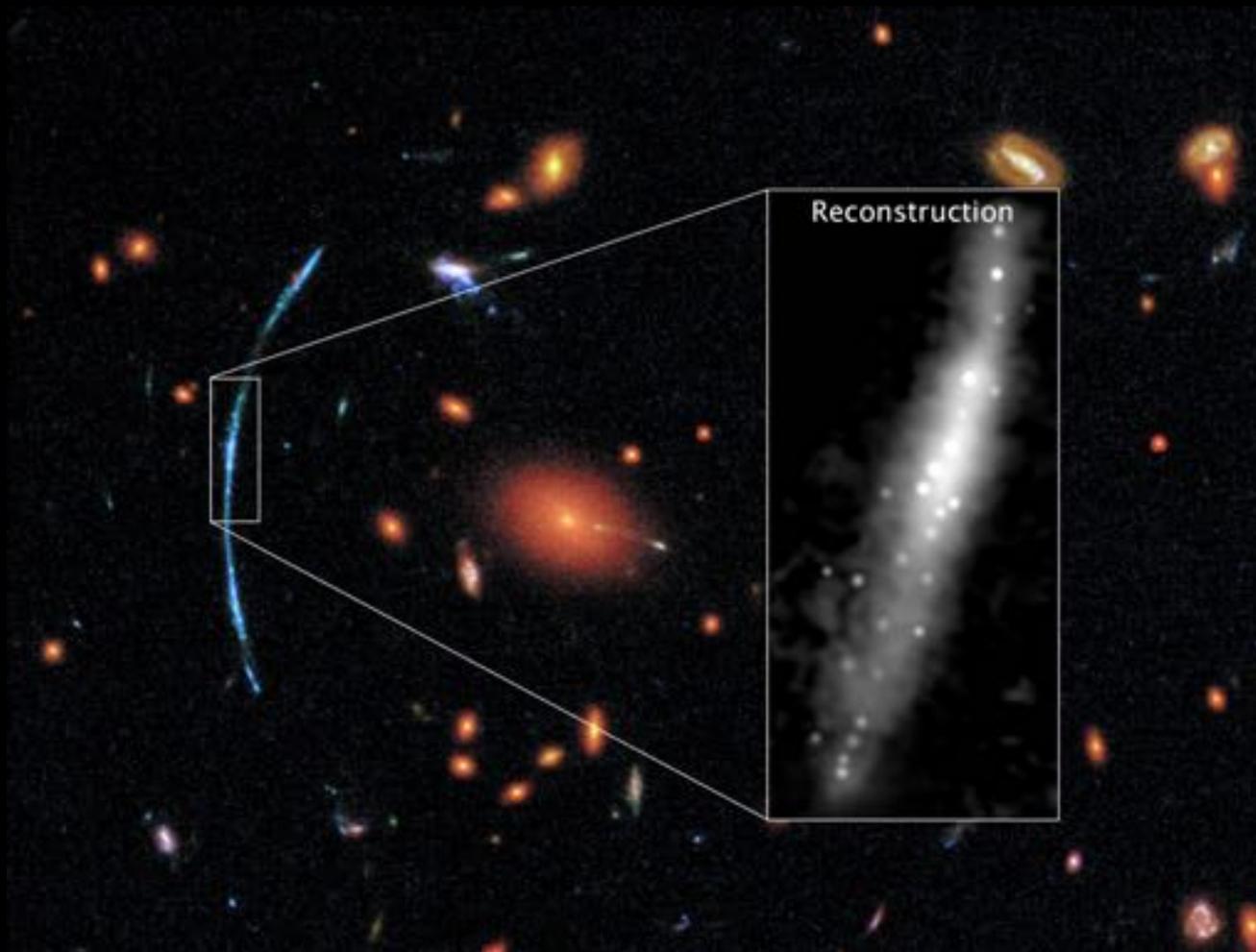


Halos including in situ stars appear to have excessive stellar masses and high metallicities

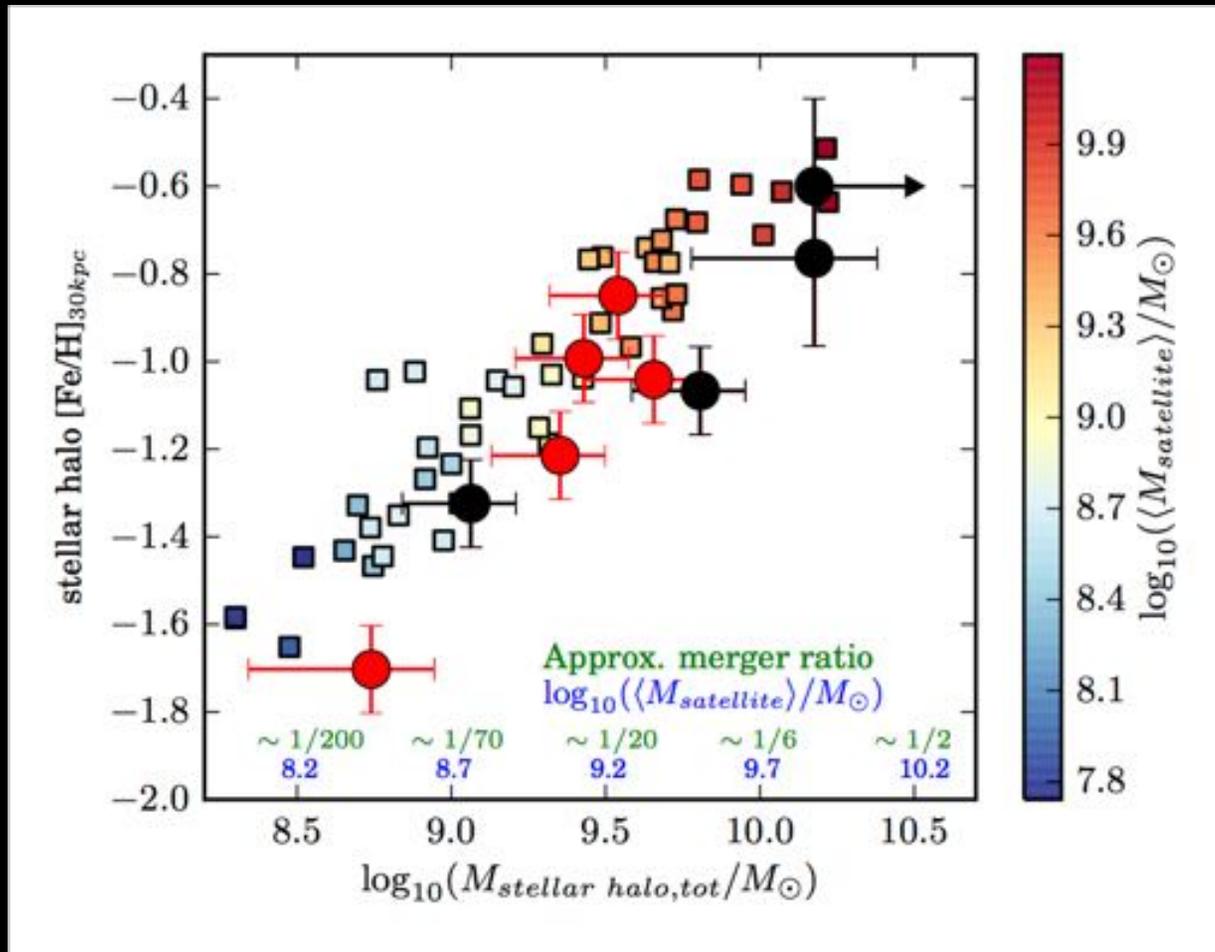


Harmsen, et al. 2017;
D'Souza & Bell 2018;
Monachesi et al. 2018

It is good that in situ predictions disagree. They are sensitive to **different** physics that we want to understand – e.g., early star formation and assembly, SF at low densities.

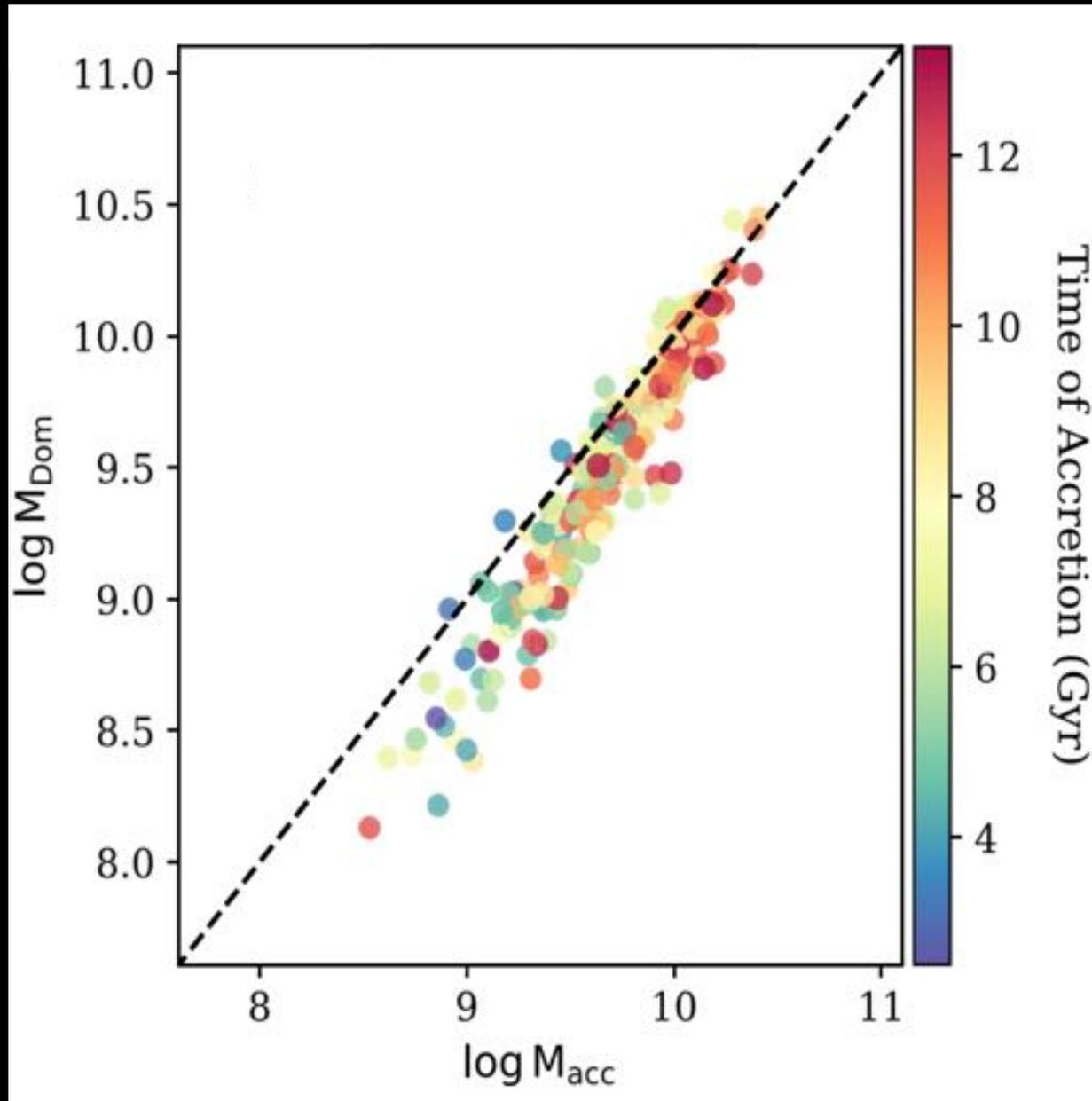


Even though lots of galaxies contribute to a halo, typically one dominates, and drives up the mass and metallicity of the halo...



Bell et al. 2017, using Deason et al. 2016 models

...meaning that we can use stellar halo mass or metallicity to quantify dominant merger



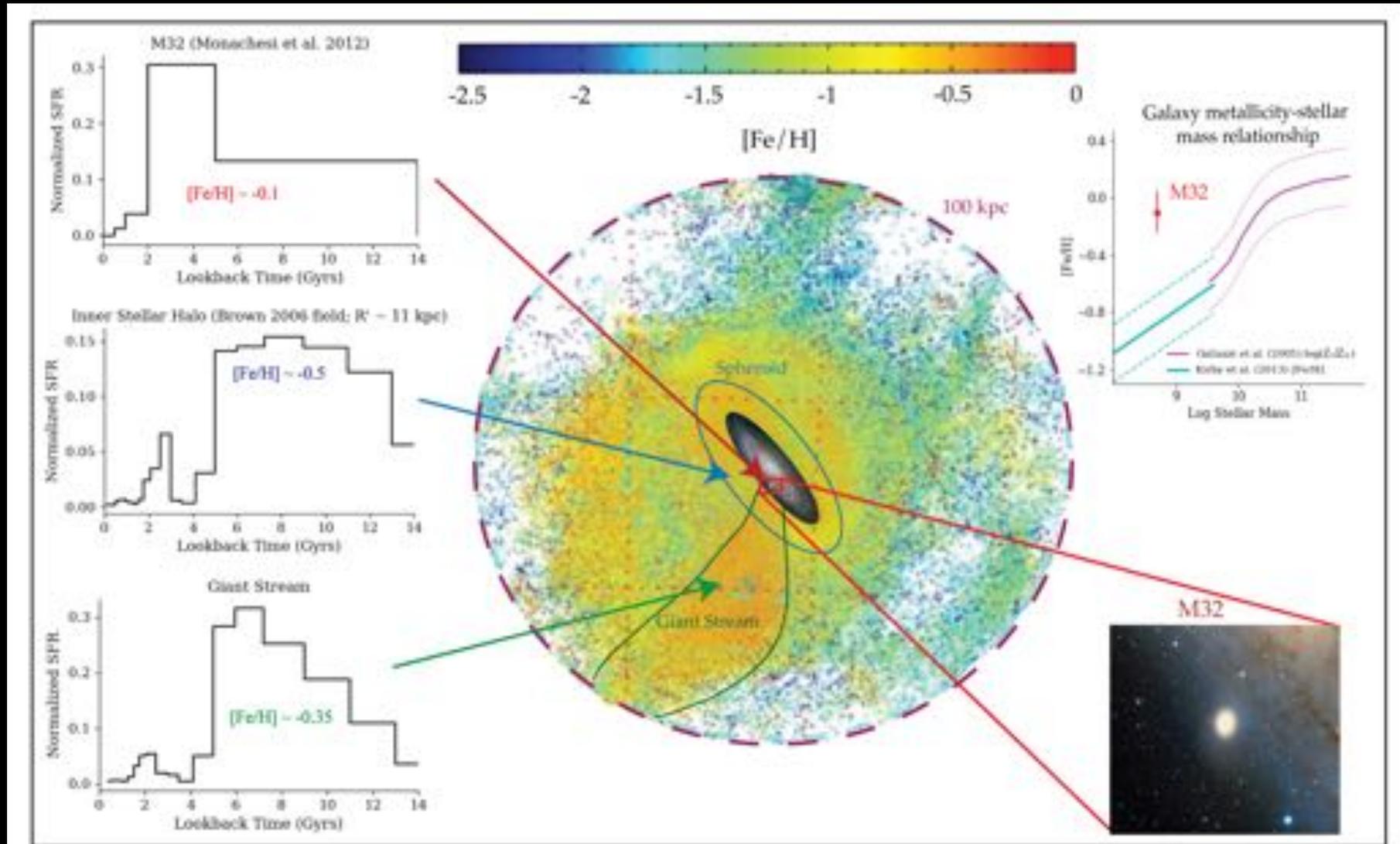
Harmsen, et al. 2017;
D'Souza & Bell 2018;
Monachesi et al. 2018

**Let's use this to learn about our good friend,
the Andromeda Galaxy.**

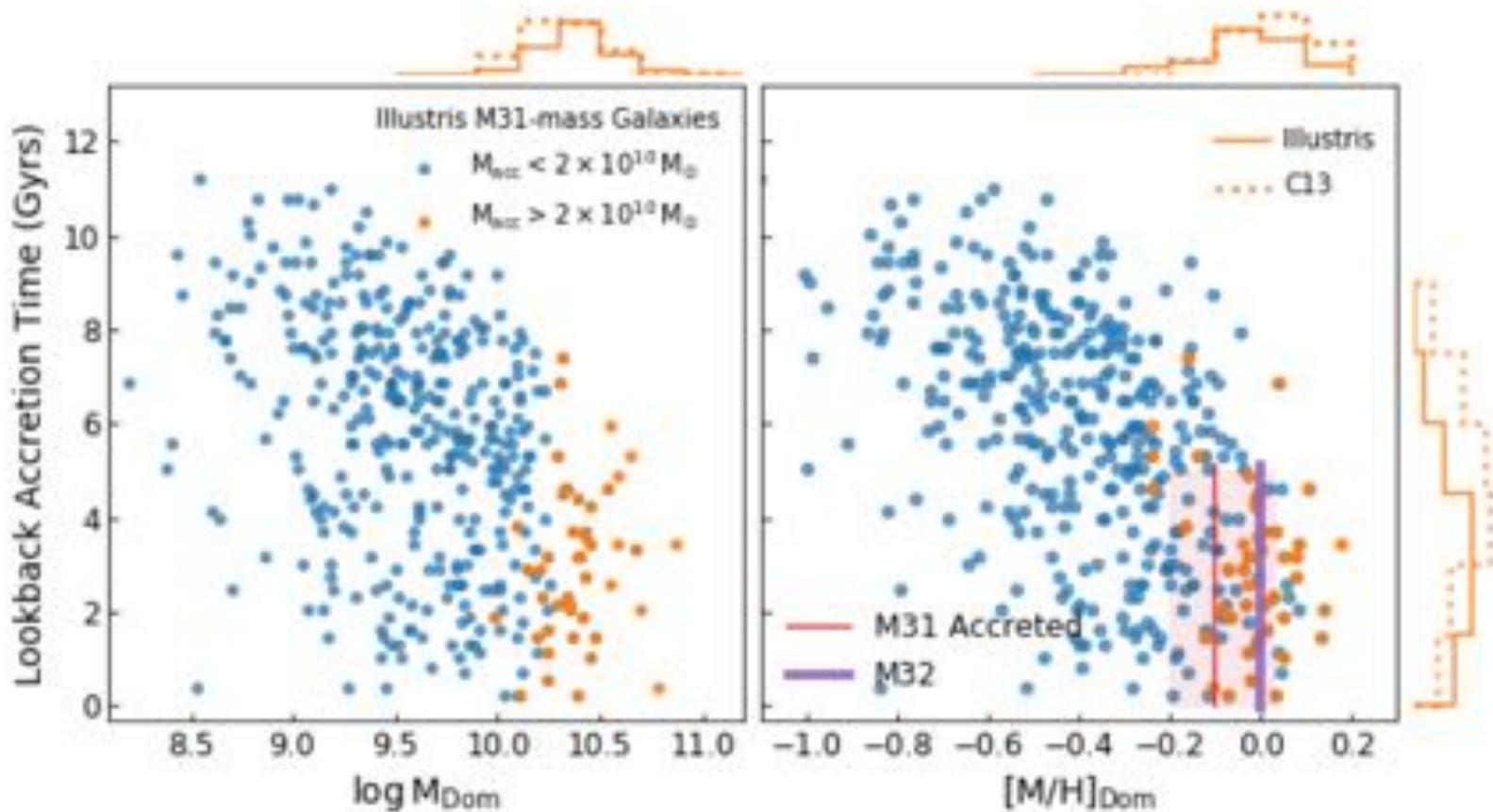


Figure 2 from The PAndAS View of the Andromeda Satellite System. I. A Bayesian Search for Dwarf Galaxies Using Spatial and Color-Magnitude Information
Nicolas F. Martin et al. 2013 ApJ 776 80 doi:10.1088/0004-637X/776/2/80

The Andromeda Galaxy has a massive, unusually 'metal'-rich stellar halo, with recent star formation

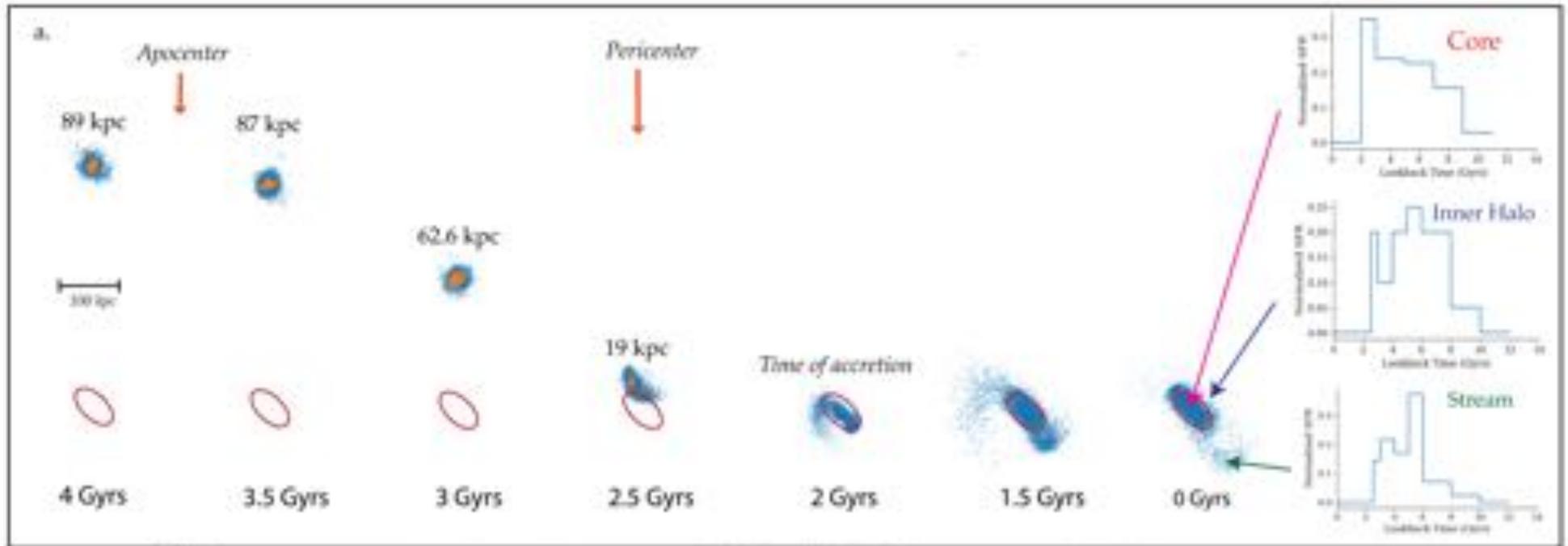


M31's large stellar halo mass dramatically limits the range of possible mergers to massive and recent.

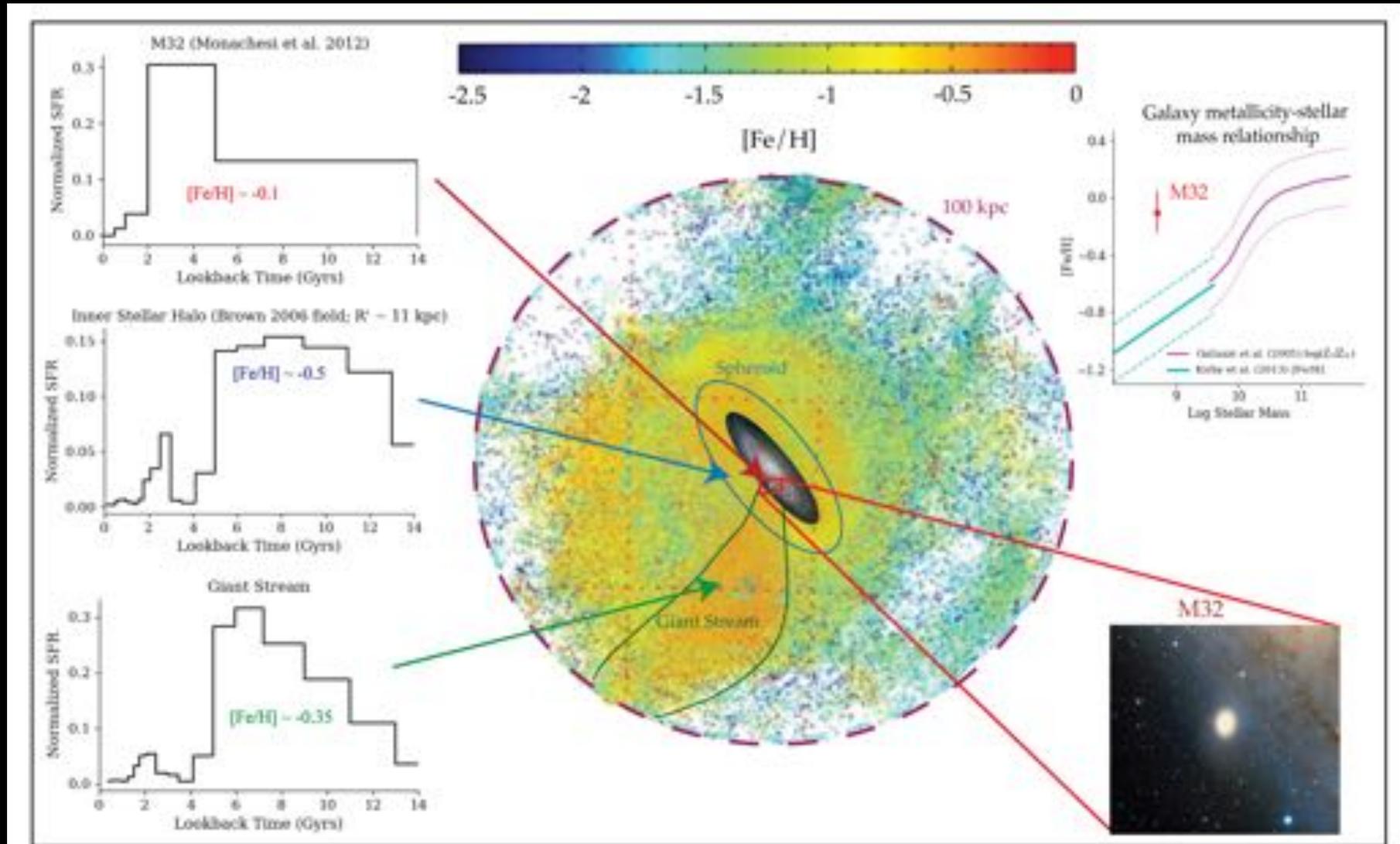


M31 should have merged with a galaxy about 1/3 the MW mass in the last 5 Gyrs – can we check this idea?

A massive collision should leave a large stellar halo, where the youngest stars show the merger time



M32, the inner stellar halo and the stream have the high metallicity and SF shut-off signaling a merger.



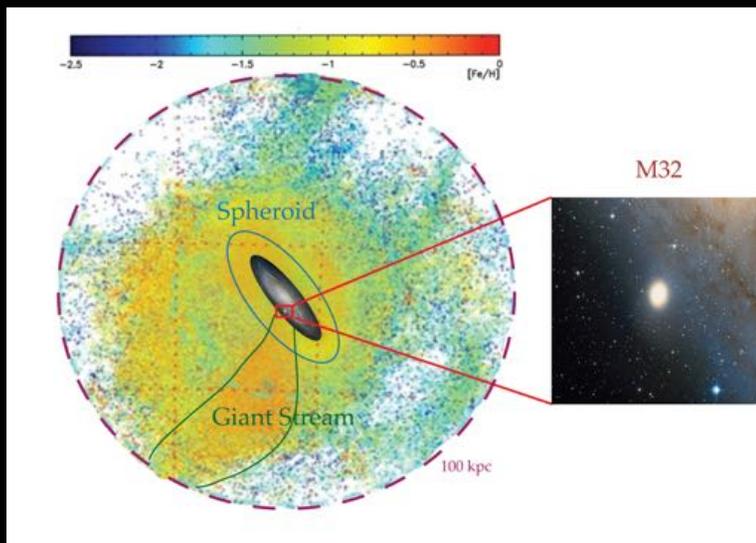
D'Souza & Bell, 2018b, Nature Astronomy

**M31 merged with a galaxy
about 1/3 the size of the Milky
Way ~2 Gyrs ago, called M32p.**

M32 is likely the core of M32p.

**The inner stellar halo contains
most the debris.**

**The giant stellar stream was likely
caused by the accretion of M32p.**

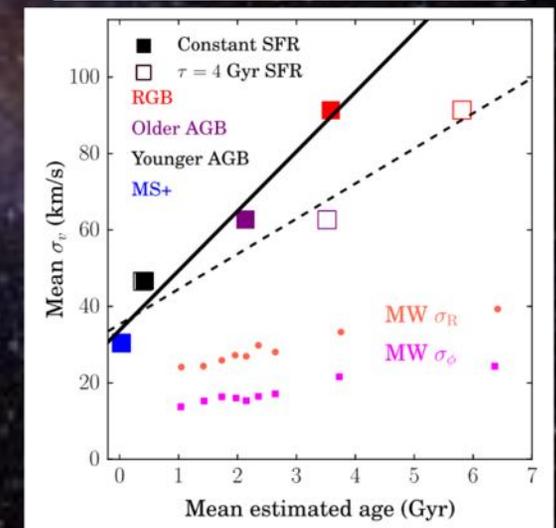
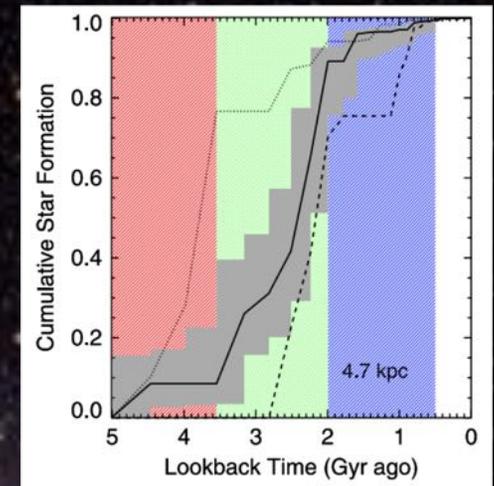


M32p was the third largest member of the local group



What did the merger of M32p do to M31?

- Disk wide SF ~ 2 Gyrs ago (Williams et al. 2015) in which 1/5th of its stars were formed (Williams et al. 2017).
- M31's disk survived a large merger.
- Disk thickening (disk scale height ~ 0.8 kpc, Dalcanton et al. 2015, 2018) and high velocity dispersion in the RGB stars (Dorman et al. 2015; $\sigma \sim 90$ km/s; see also Hammer et al. 2018)
- M31's bulge is substantially older (Olsen et al. 2006) than the merger



Other nearby galaxies appear to be at different stages of similar interactions, and offer clues as to how these mergers progress (!?!)

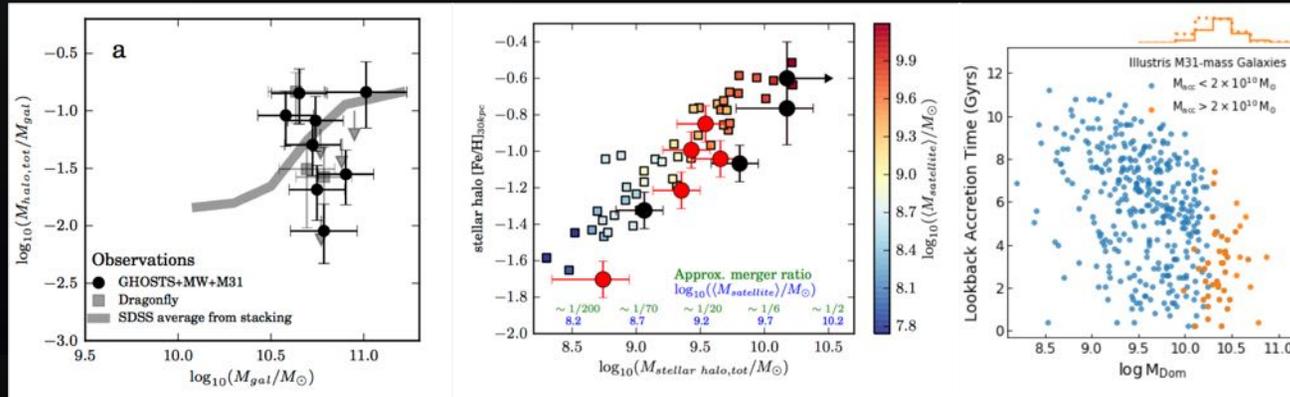
Choose M32p analogues to have right mass and dense core



M81 + M82

M51a + M51b

M31+M32



Minor axis studies of resolved stars in nearby MW-mass galaxies reveals diverse stellar halos.

Comparison with robust accretion models strongly suggests MW minor axis at $>10\text{kpc}$ is accretion-dominated.

The most massive accretion dominates a halo's properties, allowing us to quantify merger history.

M31 merged with a $\sim 1/3$ MW-mass galaxy 2Gyr ago. This appears to have triggered SF and thickened the disk.

May be able to learn about whole life-cycle of a minor (or small major) merger