Galaxies *Out* of Equilibrium: Interactions & Mergers

There is ample evidence that interactions & mergers significantly influence galaxy structure & evolution

Main classes of evidence:

- Theoretical expectations
- Observations of individual systems
- Statistical behavior of galaxy populations

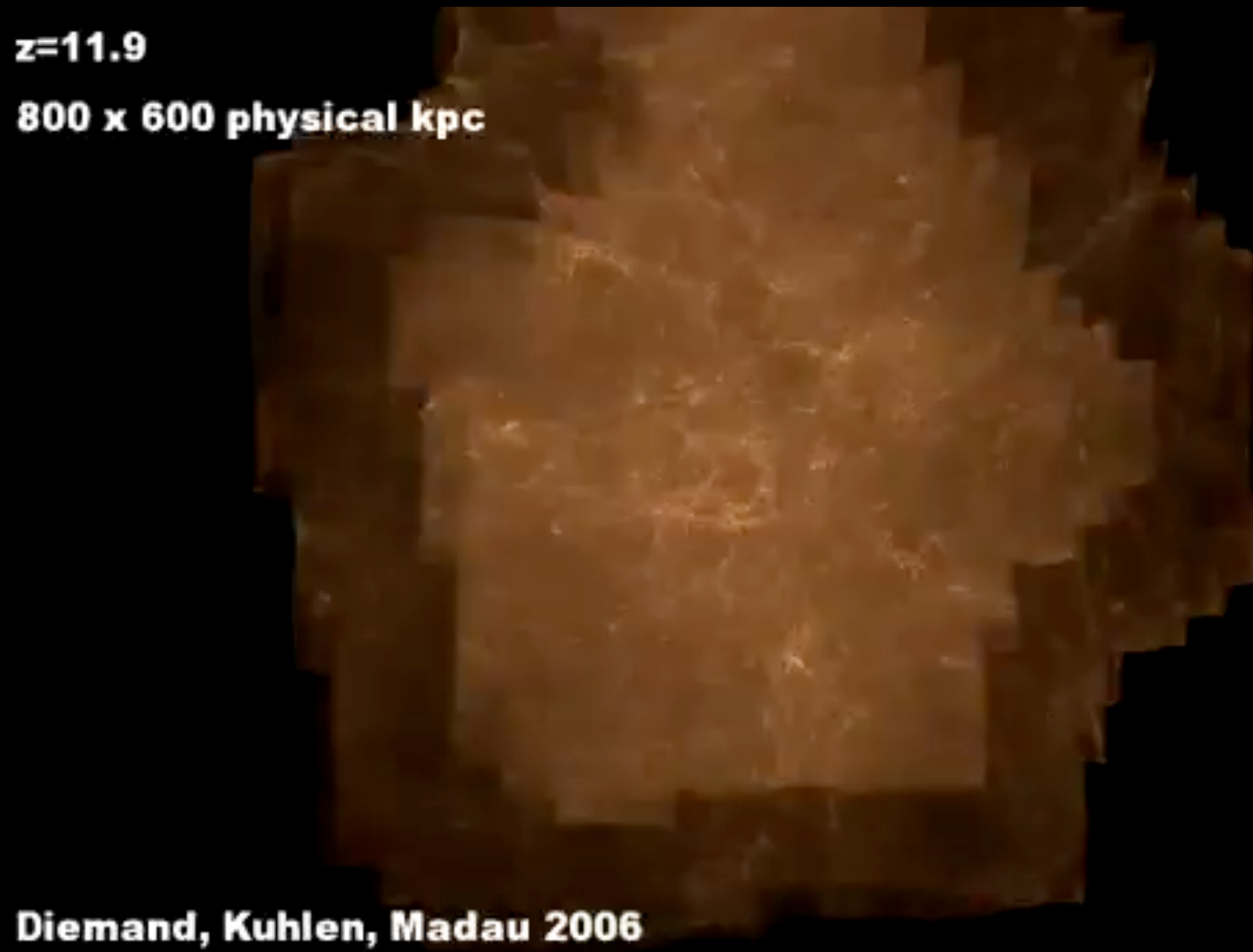
Theoretical Expectations

In dominant* cold dark matter (CDM) paradigm, structure builds "hierarchically" — small structures collapse first, then merge together into larger structures

"bottom-up"

* In alternate models like hot (i.e. relativistic) dark matter, large structures tend to collapse before smaller structures within them ("top down" fragmentation)

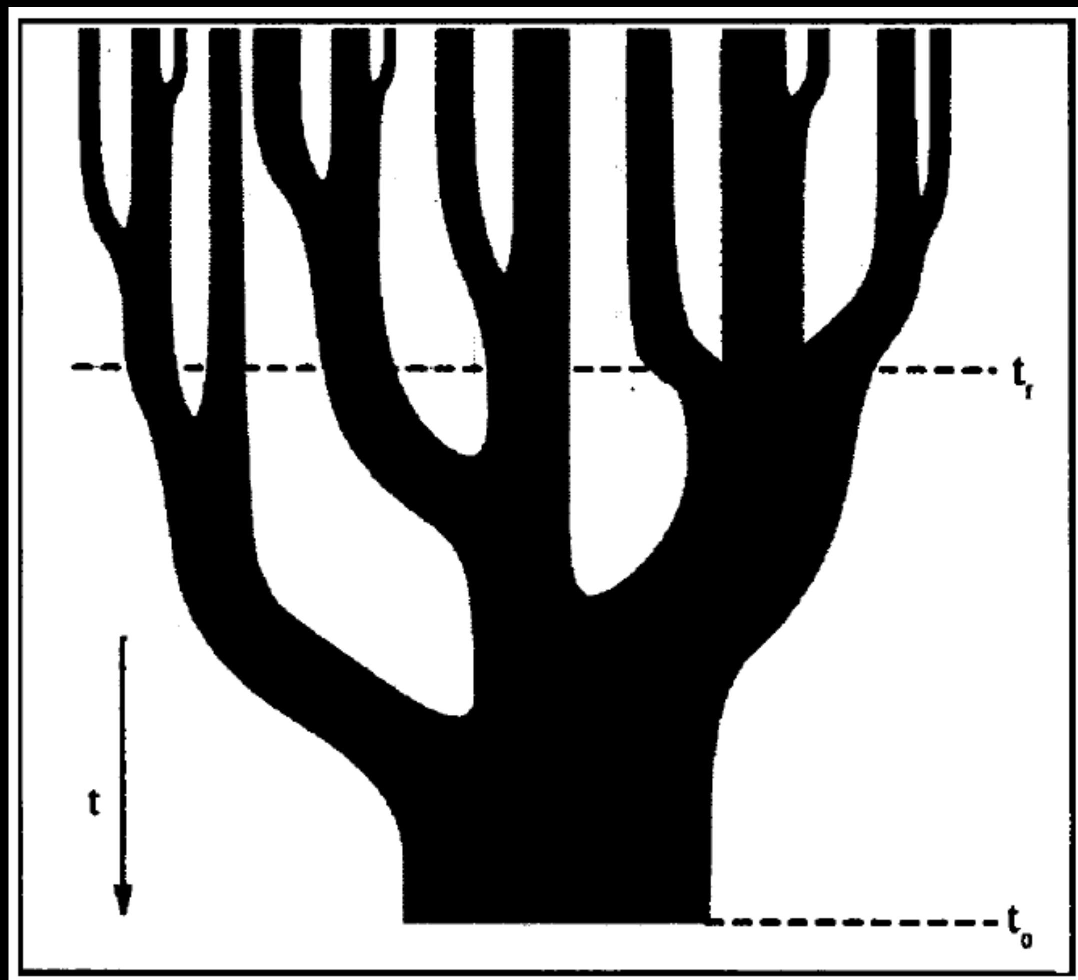
Example of merging in dark-matter only simulation



http://www.ucolick.org/~diemand/vl/movies.html

Driven almost entirely by the initial power spectrum of dark matter fluctuations and the law of gravity.
No other baryonic physics needed.

Merging histories of individual dark matter halos characterized by "merger trees"



Lacey & Cole, 1993, MNRAS, 262, 627

Past

Width of "branches" at each time indicates mass of the various progenitors

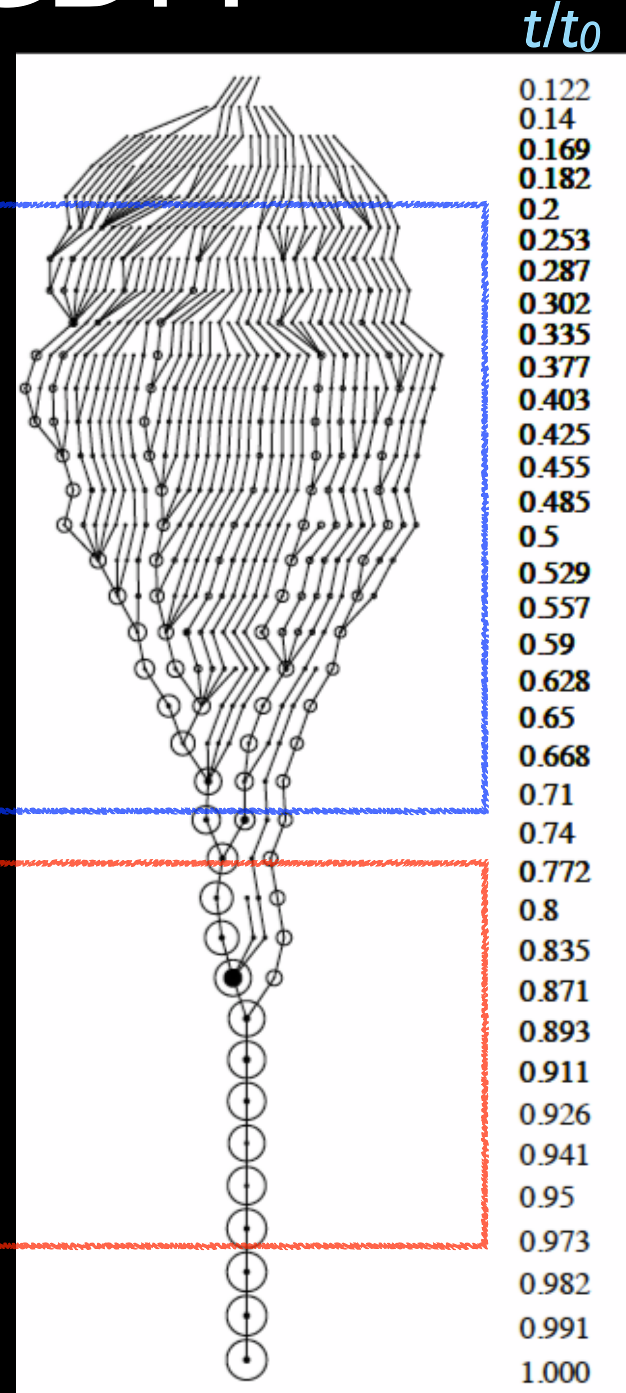
Present

Tracks mass history of individual dark matter halos vs time

(Note: Lots of technical decisions to make in constructing these. Conservation of mass, uniqueness of progenitors, steady field vs bound subhalo accretion. Many constructions based on the extended Press-Schechter formalism (EPS) and numerical simulations. See Jiang & van den Bosch 2014 for summaries of the vast literature, and J. Lee et al 2014 for discussion of interaction with semi-analytic models.)

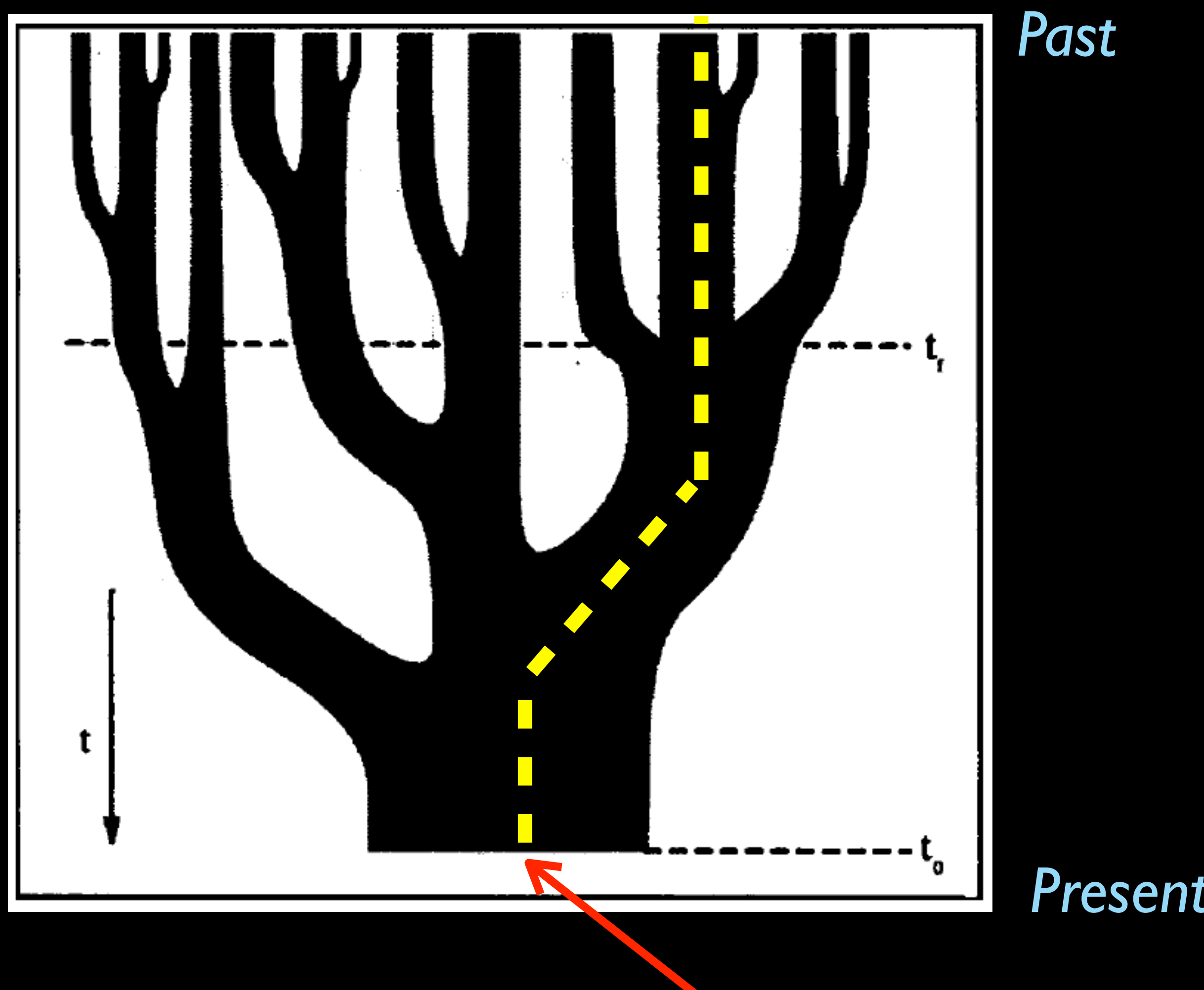
Merger trees in CDM

- Early assembly through many "major" mergers of comparable-sized progenitors
- Late assembly through accretion of much smaller progenitors ("minor" mergers)



Wechsler et al. 2002, ApJ, 568, 52

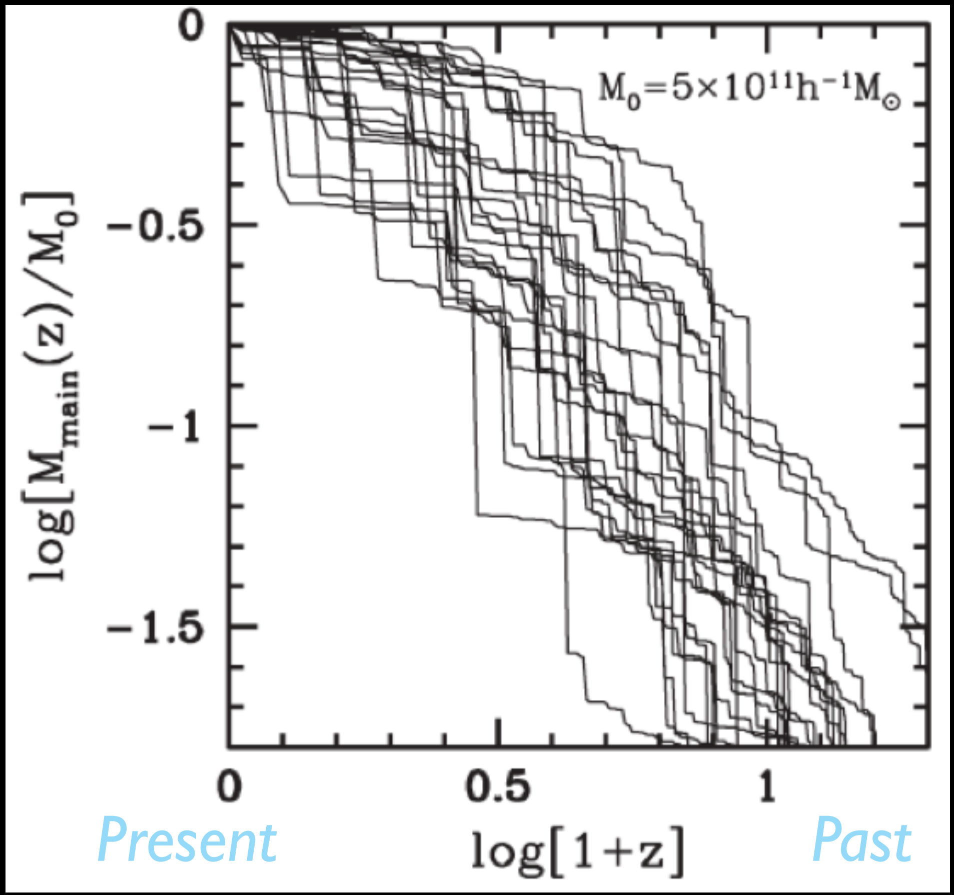
Variant: "Mass Assembly History" (MAH)



Tracks mass history of only the *largest* individual dark matter halo progenitor at each time

Mass Assembly History good way to track the past of the massive galaxies seen today

van den Bosch, 2002, MNRAS, 331, 98

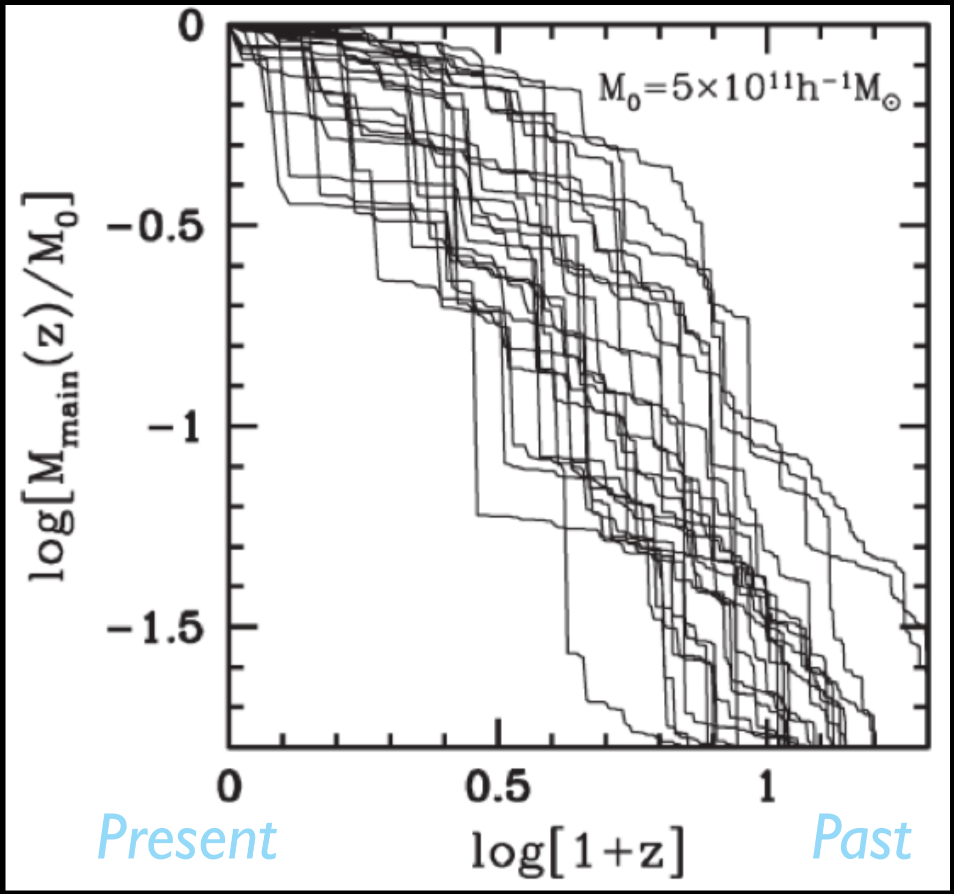


Lots of variance:

Not all massive galaxies have the same history

Mass Assembly History good way to track the past of the massive galaxies seen today

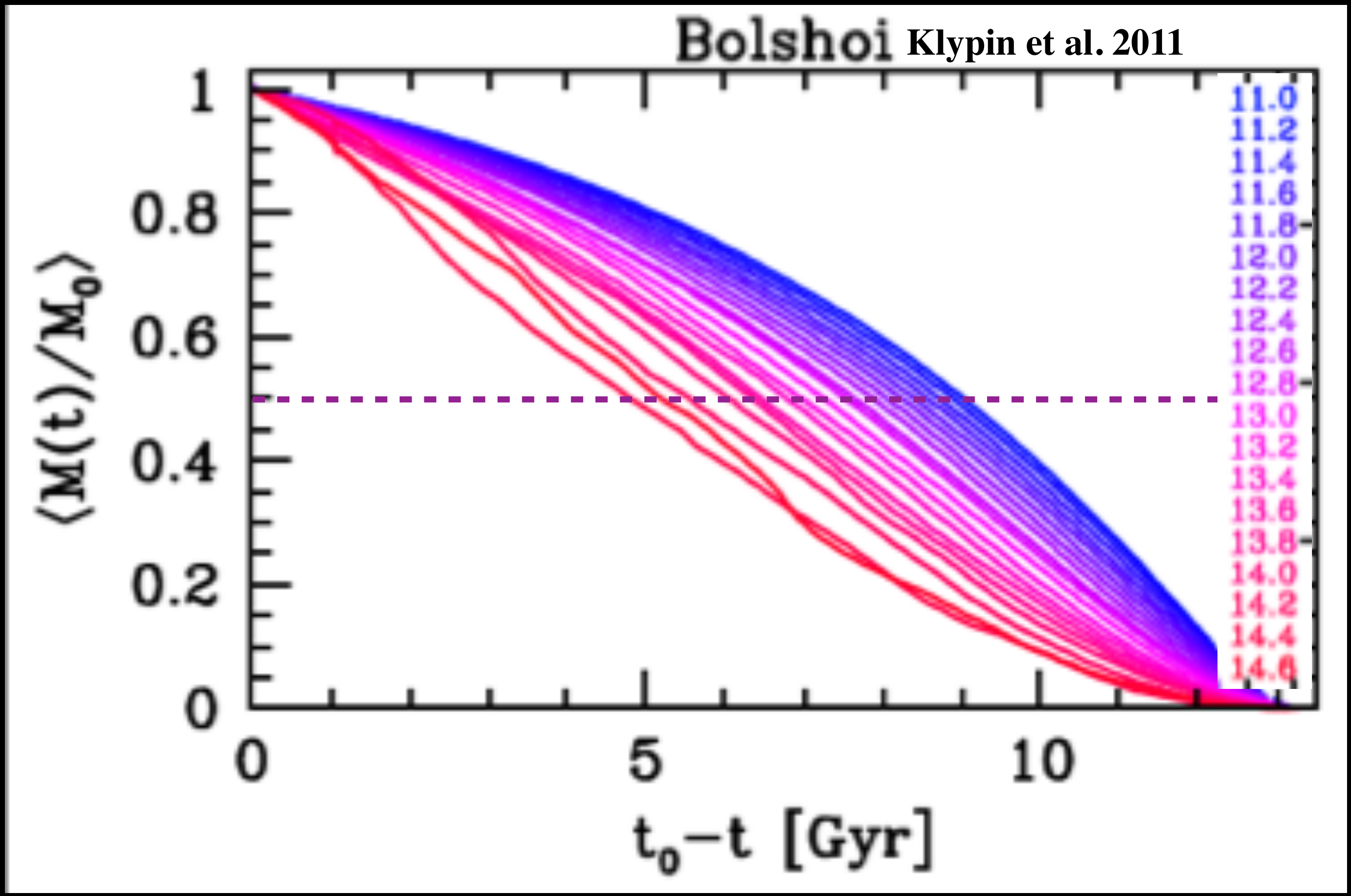
van den Bosch, 2002, MNRAS, 331, 98



Lots of growth:

The progenitors of the massive halos we see today were much less massive when we observe them at higher redshift

Mass Assembly History good way to track the past of the massive galaxies seen today



van den Bosch et al., 2014, MNRAS, 445, 1713

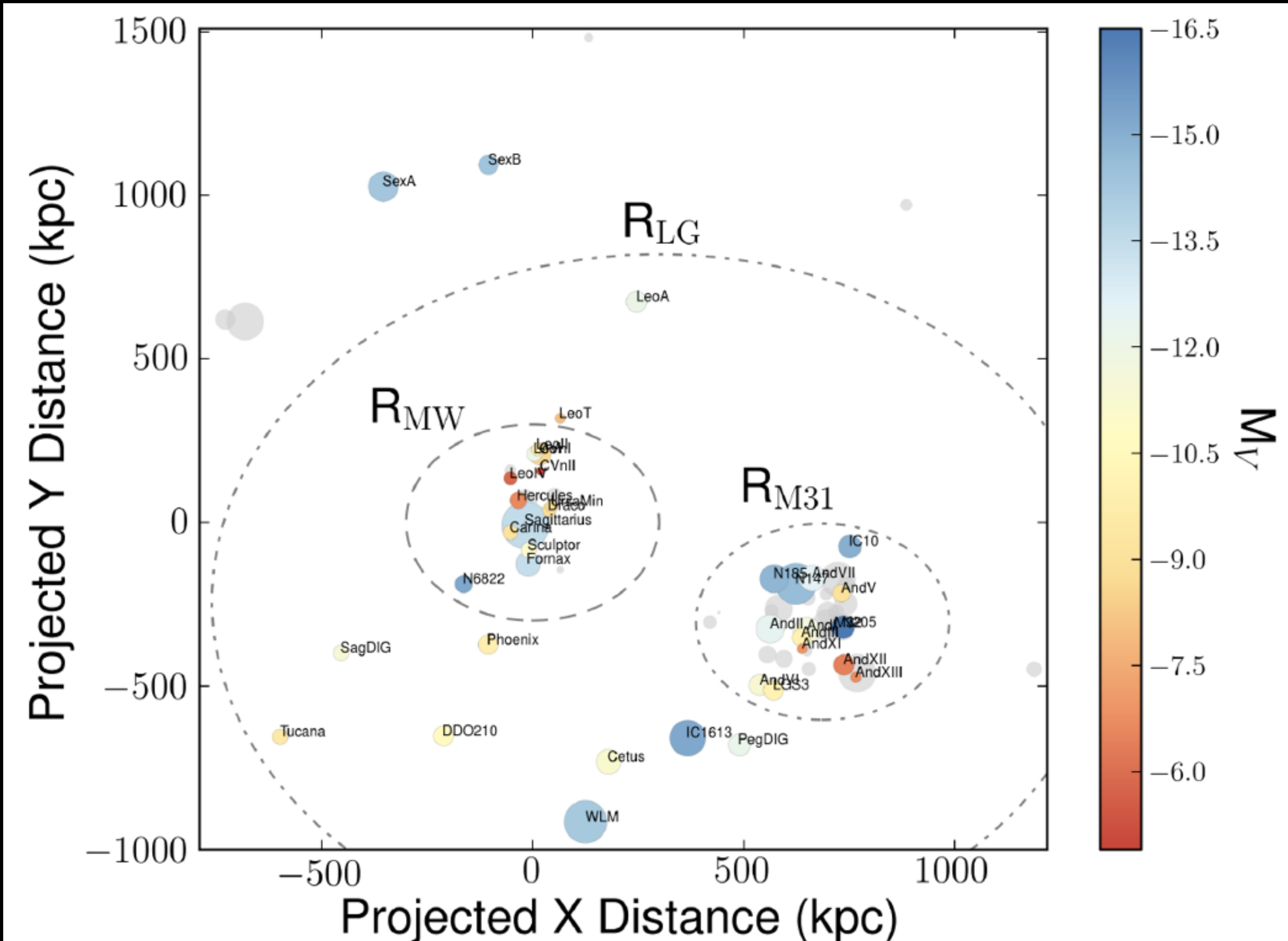
Massive halos assemble later:

More massive halos take longer to assemble half their mass, on average

Note: Merging of dark matter halos is ***not*** the same as merging of visible galaxies

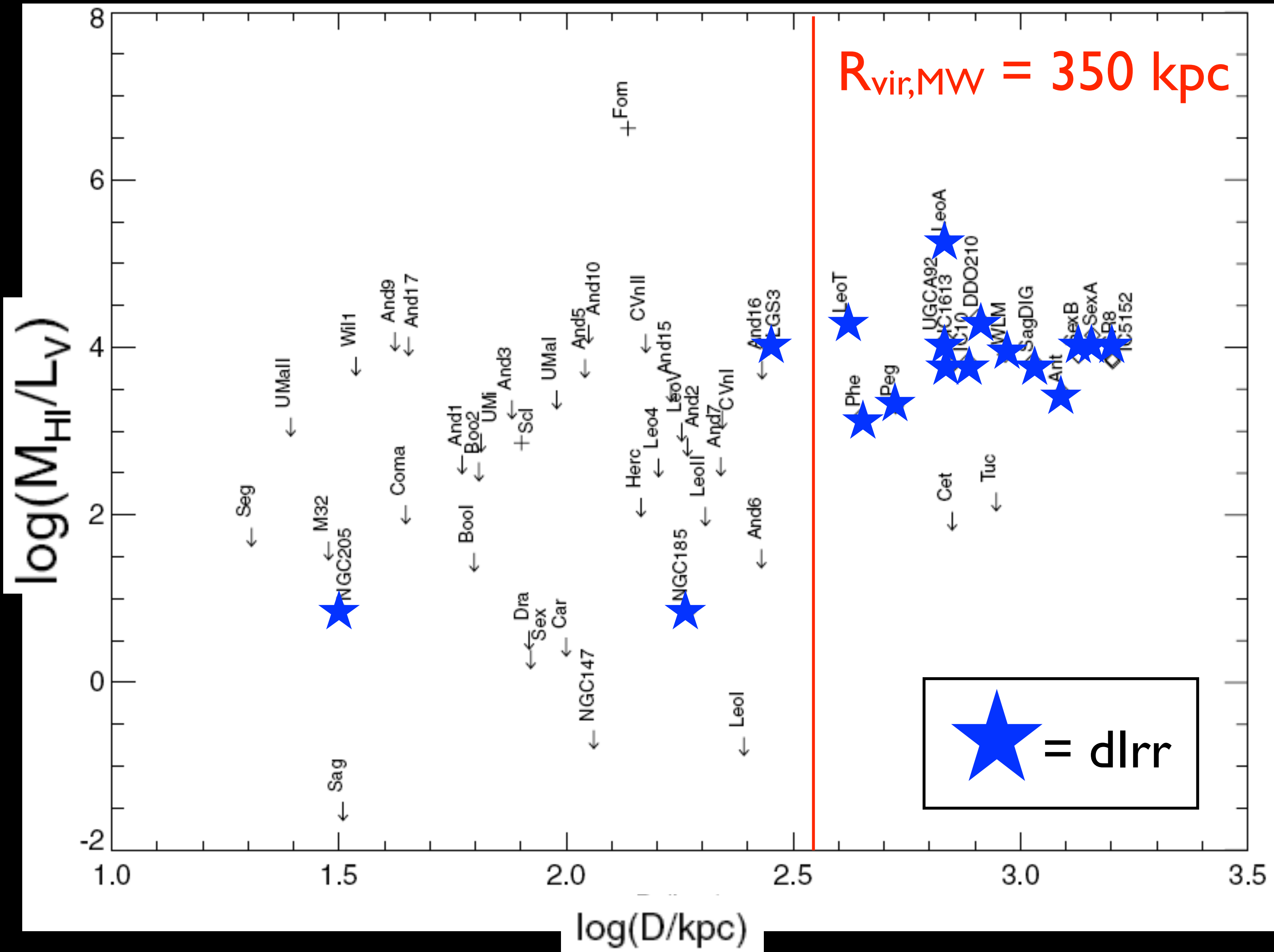
1. Definition of “merging”
2. Timing

1. Lots of halos have "merged" into MW, M31, or Local Group's virialized DM halos, but some are still recognized as distinct



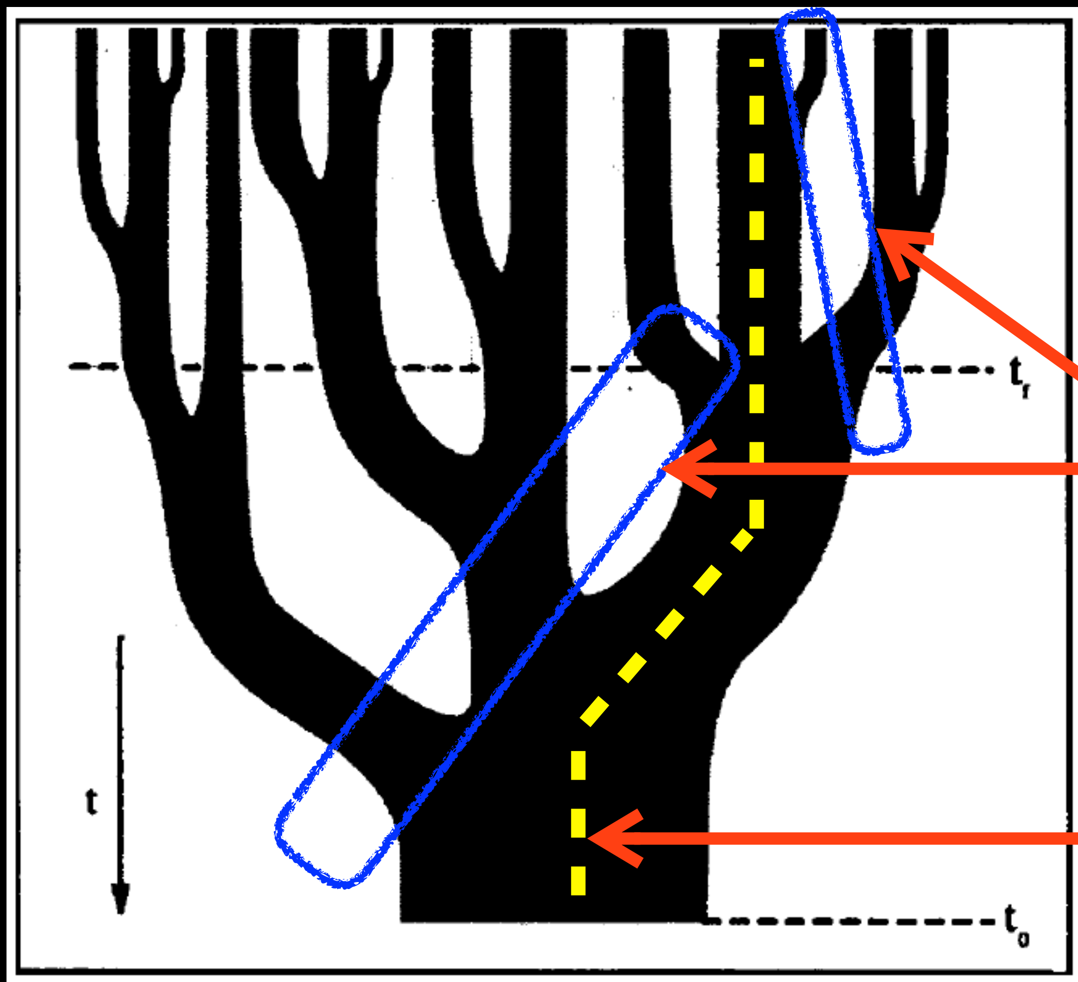
Weisz et al 2014

Merging into the halos has *affected* galaxies, but not necessarily destroyed them (survivor bias, though)



Grcevich & Putman 2009

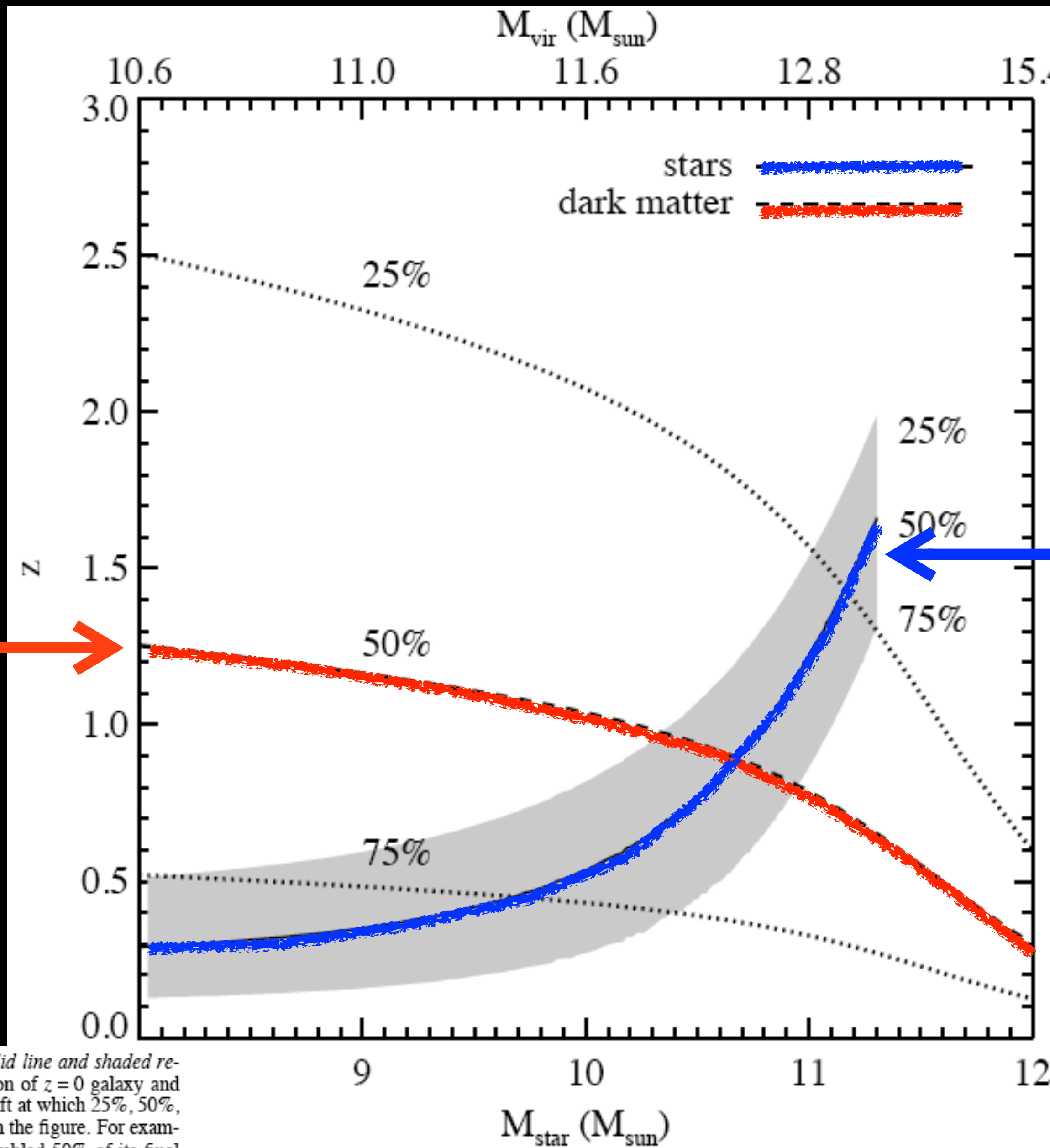
Because of these effects, we often consider evolution of main progenitor differently than the galaxies it absorbs



Terminology: "*central*" & "*satellites*", or "*halos*" & "*subhalos*". The former usually survives interactions/mergers largely intact.

2. Timing of dark matter growth ≠ stellar growth

Dark matter assembly history



Stellar assembly history

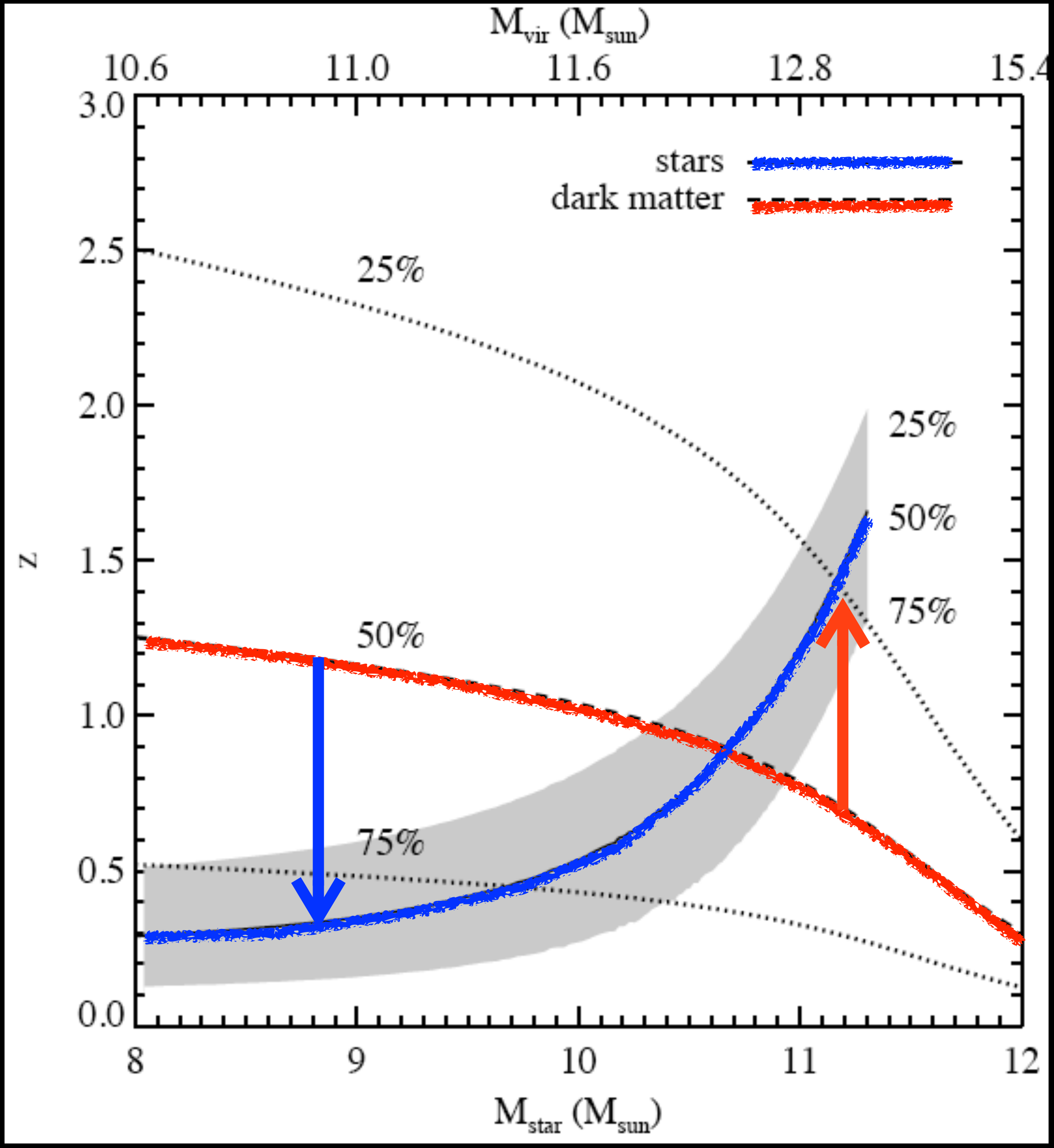
FIG. 5.— Average formation times for galaxies (*solid line and shaded region*) and halos (*dashed and dotted lines*) as a function of $z = 0$ galaxy and halo mass. Lines and shaded region indicate the redshift at which 25%, 50%, and 75% of the final mass was assembled, as labeled in the figure. For example, a galaxy with stellar mass $10^{10} M_{\odot}$ at $z = 0$ assembled 50% of its final mass by $z \approx 0.5$. Such a galaxy resides in a halo of mass $10^{11.6} M_{\odot}$, which was half assembled by $z \approx 1.0$. At $M_{star} \lesssim 10^{10.7} M_{\odot}$ halos are assembled before galaxies while at higher masses the opposite is true, in agreement with the trends seen in Figure 4.

From one particular model, but probably not a bad estimate.

Conroy & Weschler 2009

2. Timing of dark matter growth ≠ stellar growth

Low mass galaxies: halos merge first, then stars form within halos.



Massive galaxies: stars form *before* the dark matter is assembled.

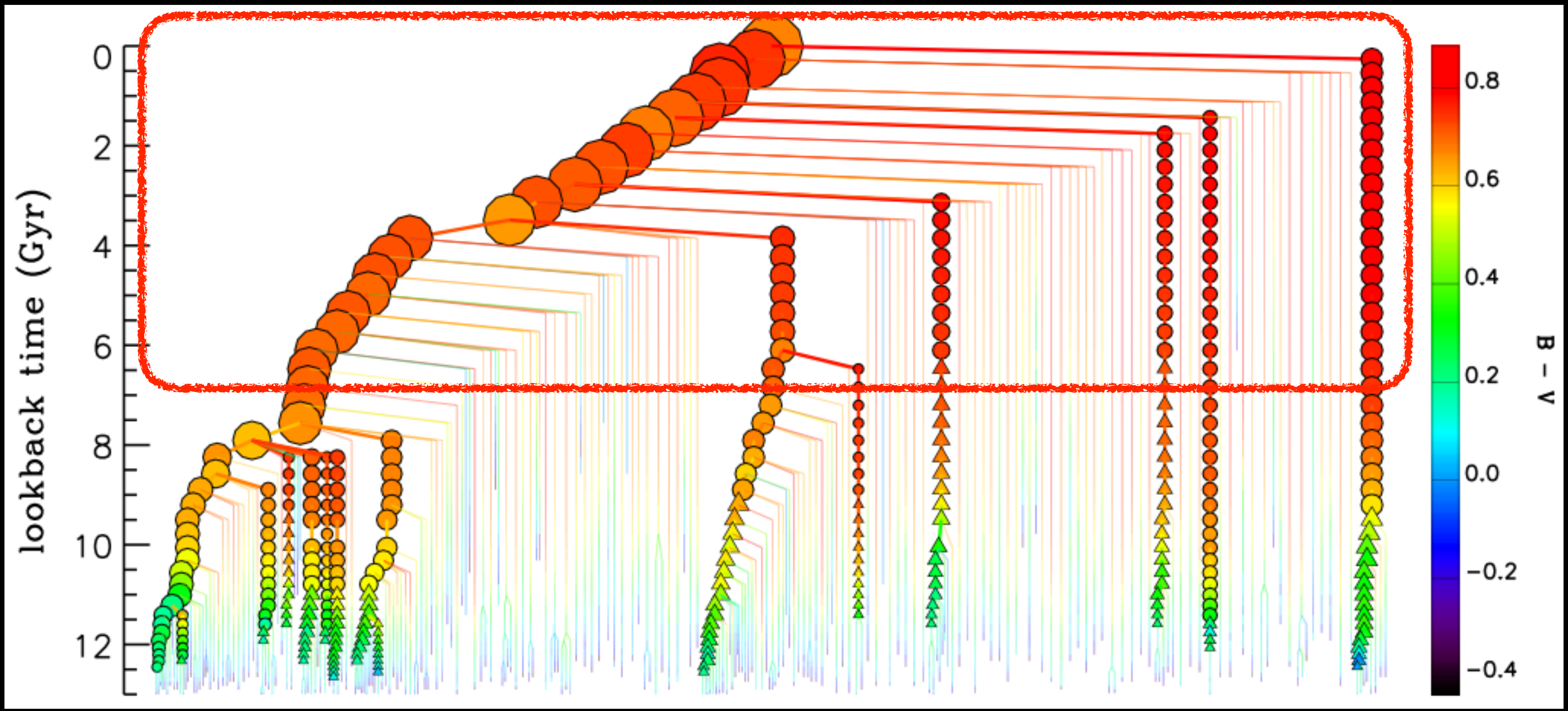
Gas-rich mergers dominate

Star-rich mergers dominate

From one particular model, but probably not a bad estimate.

Merger tree for a massive elliptical galaxy

(color-coded by stellar color: red=old)



Growth of Brightest Cluster Galaxies: de Lucia & Blaizot 2007

Most stellar growth through acquiring new stars, not forming them.

Summary of theoretical expectations

- Merging is important and will happen
- Merging is proportionally more important at higher redshift
- The timing, amount, and nature of merging will depend on galaxy mass, but with substantial variance.
- Merging of dark matter halos is not the same as merging of the galaxies within them.

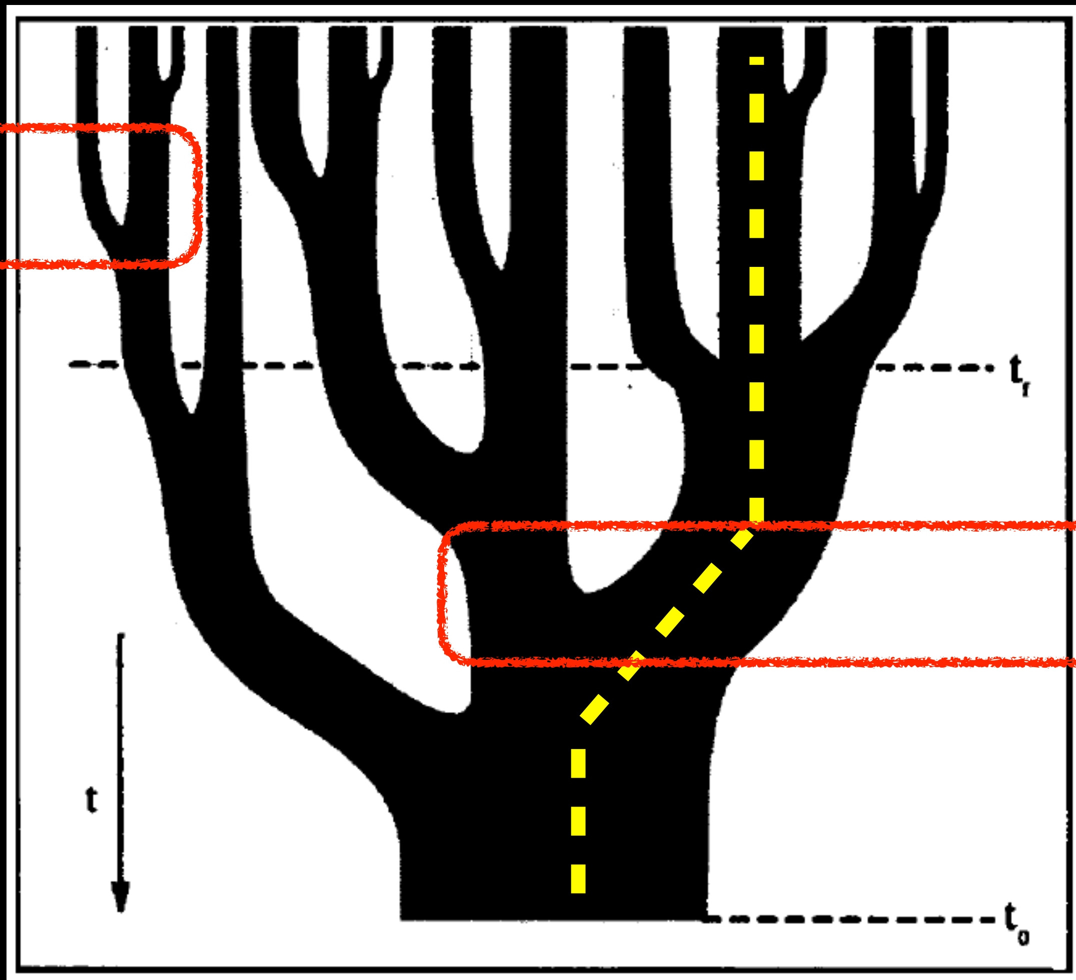
It's not up to date, but a nice on-line bibliography of merger-related papers up to ~2009 is here: http://w.astro.berkeley.edu/~jcohn/mergers.html

Main classes of evidence:

- ~~Theoretical expectations~~
- Observations of individual systems
- Statistical behavior of galaxy populations

Before proceeding further, some terminology

Major vs minor mergers



Minor

- >4:1 mass ratio
- Massive partner mostly unchanged
- Smaller partner highly affected

Major

- <4:1 mass ratio
- Both partners substantially changed

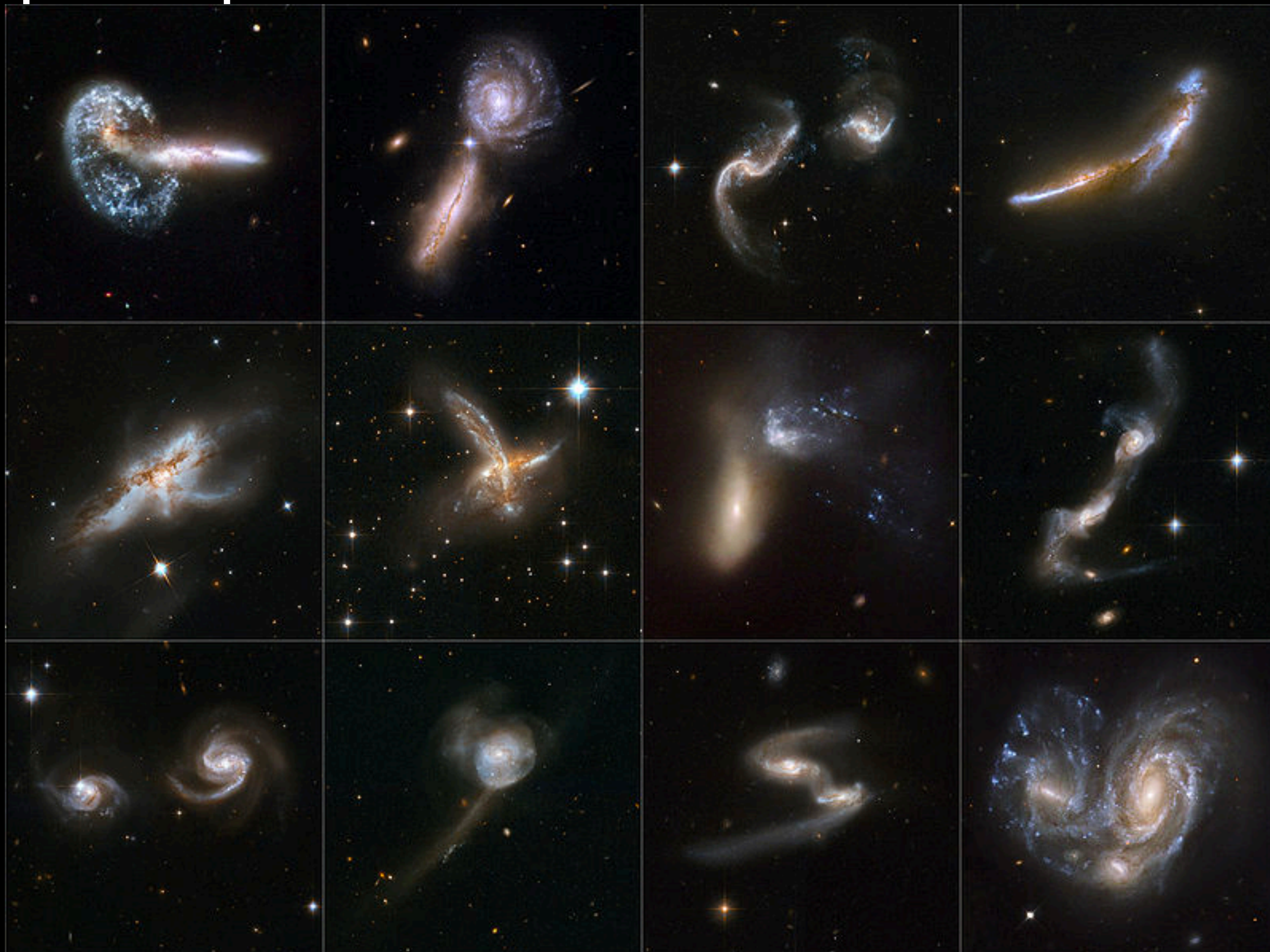
For observations, we will focus on using these terms for visible galaxies, not the halos.

Main classes of evidence:

- ~~Theoretical expectations~~
- Observations of individual systems
- Statistical behavior of galaxy populations

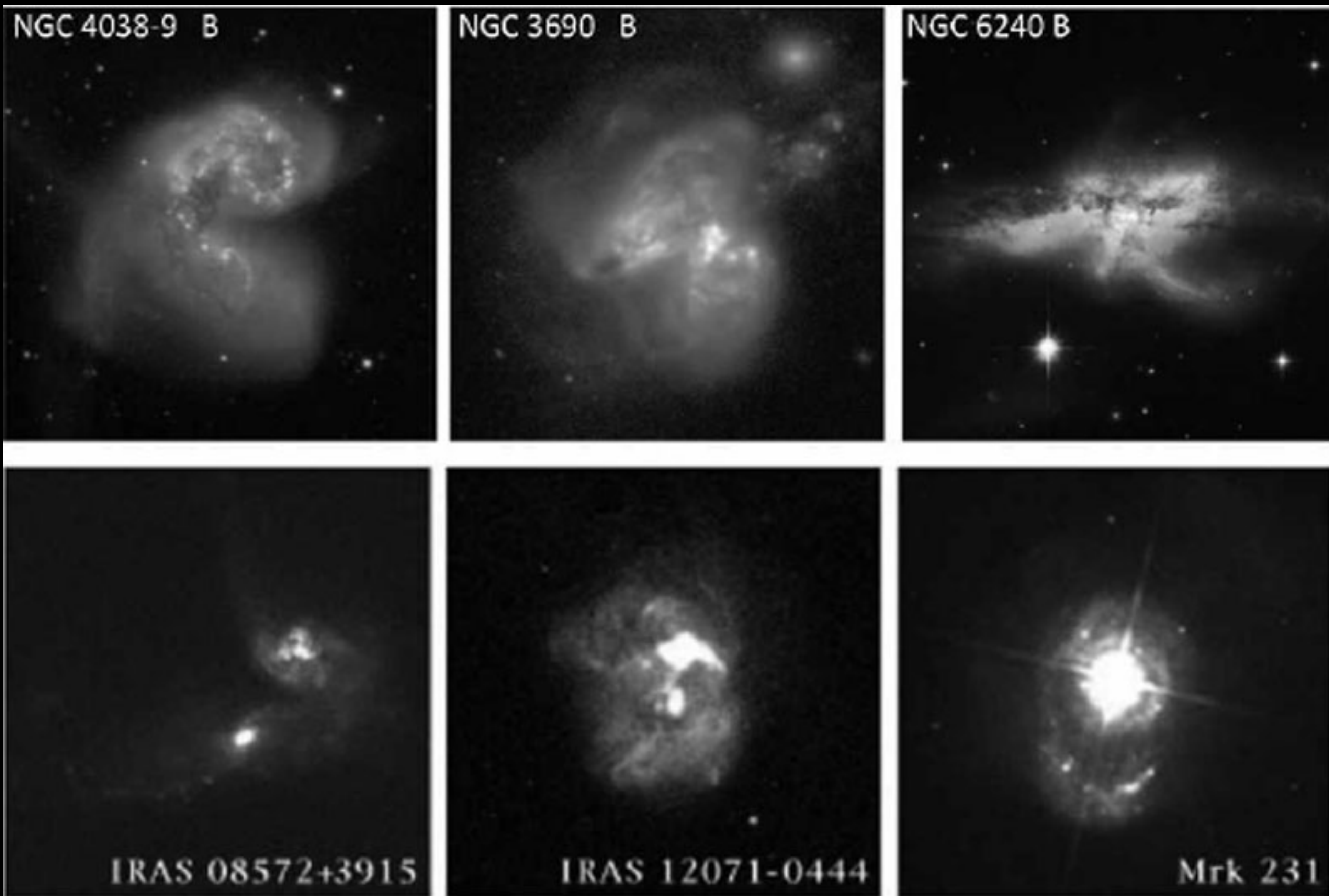
Major Mergers

We see many massive galaxies that are clearly out of the quasi-equilibrium* states we've considered so far



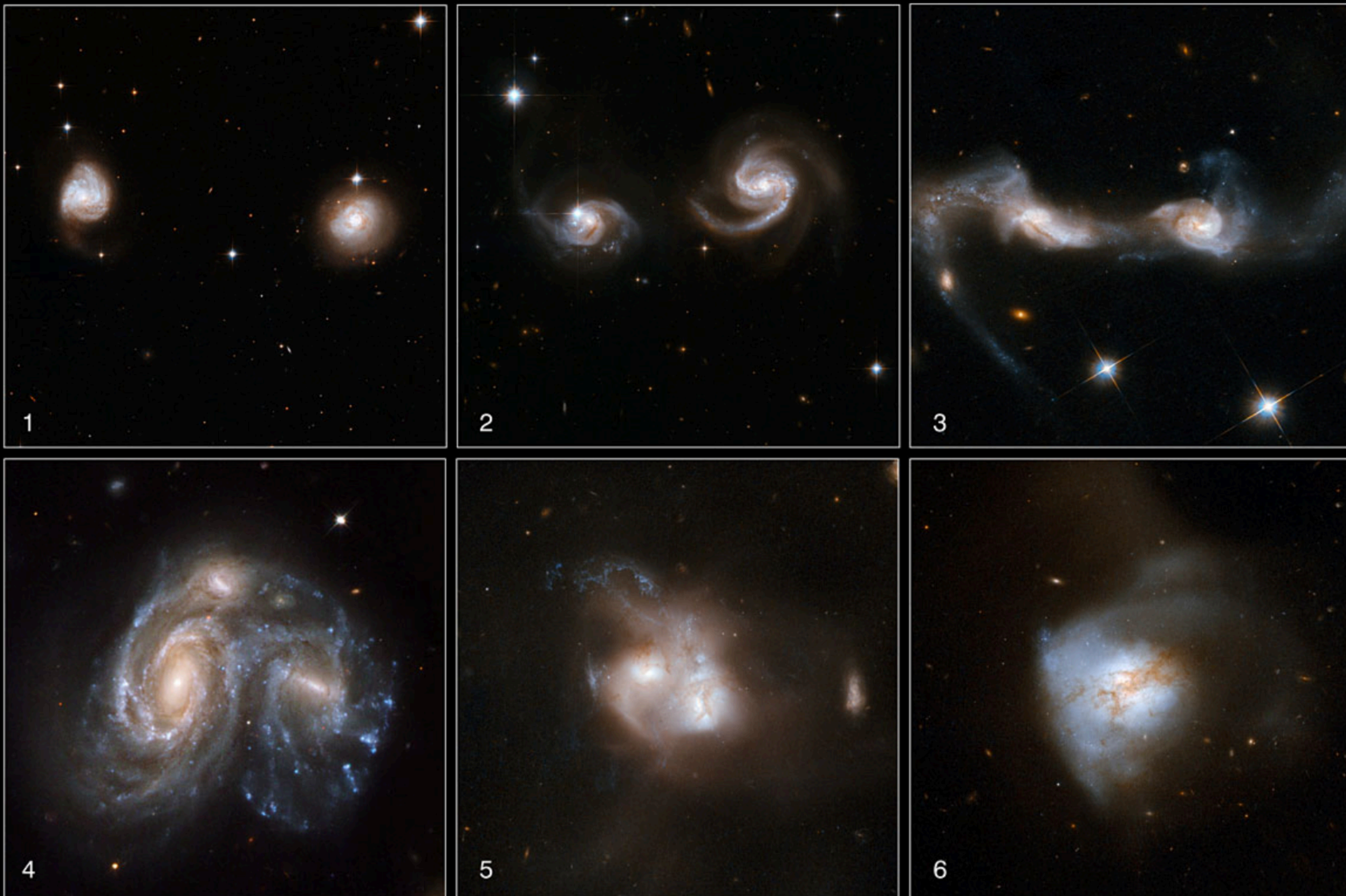
* i.e., not virialized, no stable balance of gravity and dynamical pressure.

Many of these advanced mergers are associated with enormous central starbursts



ULIRGS from https://ned.ipac.caltech.edu/level5/March14/Buta/Buta7.html

Individual interactions, arranged in a mock "sequence"



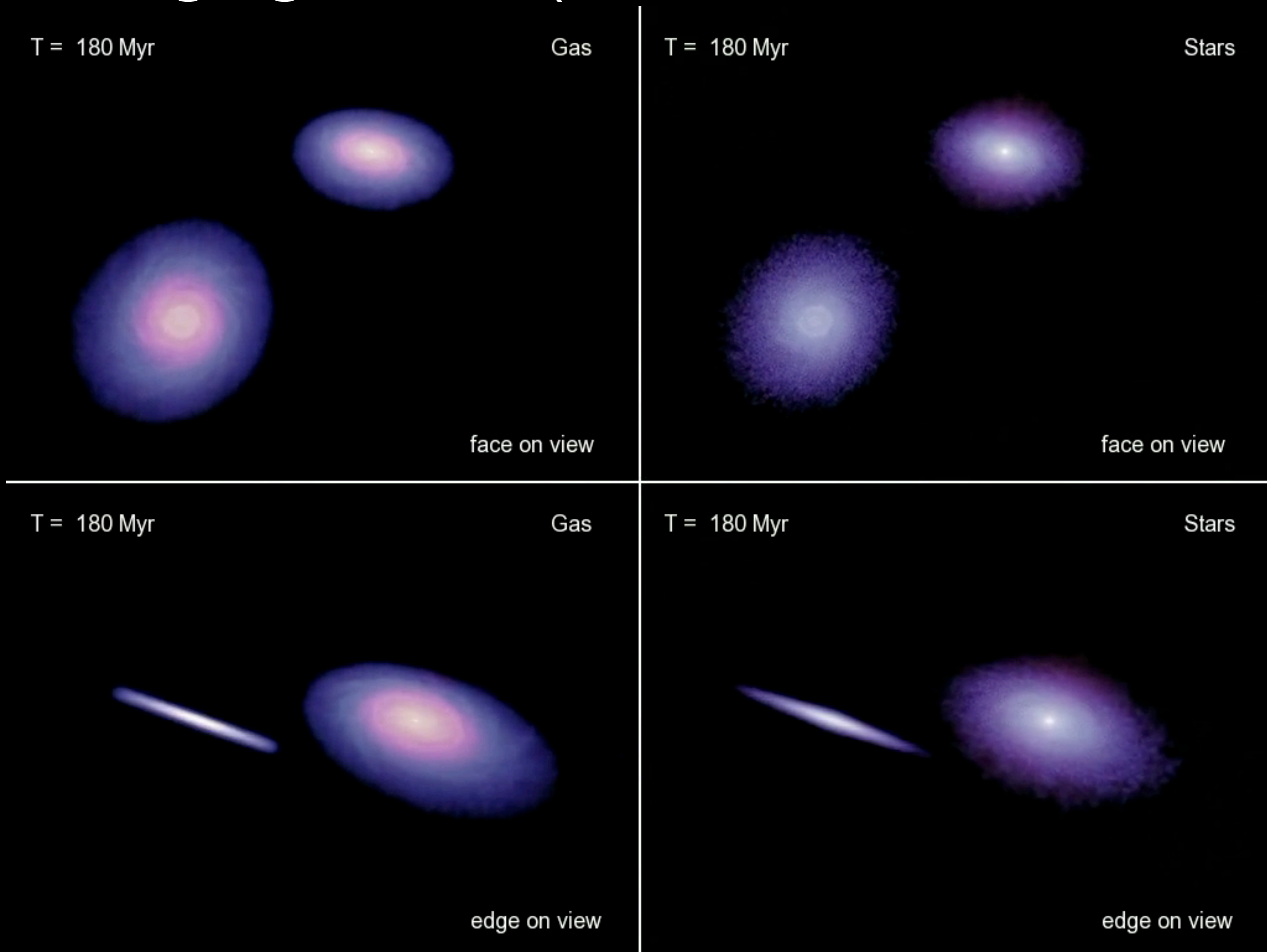
These are real galaxies all at z=0, not a simulation of a single event seen over time.

Classic assumption: Major mergers form ellipticals

Eventual merger of Milky Way and Andromeda

Sim: Summers, Besla, van der Marel: https://svs.gsfc.nasa.gov/30955

2 Merging Disks (w/ SNe + BH feedback)



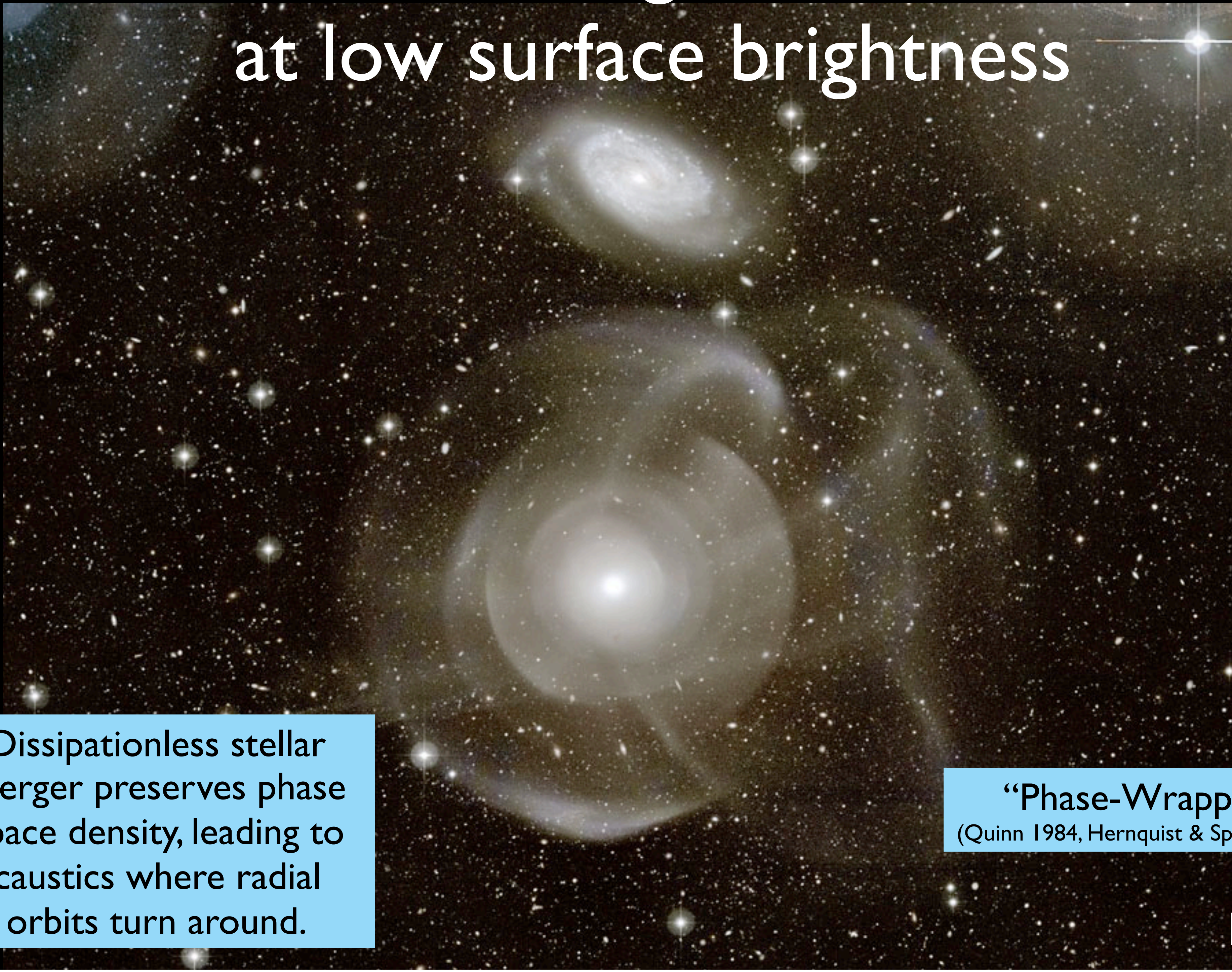
Volker Springel + Phil Hopkins

http://www.tapir.caltech.edu/~phopkins/Site/animations/Mergers/collision-gas-and-stars.html

2 Merging Disks vs Observations

From STSCI

Structure from merger often left behind at low surface brightness



Dissipationless stellar merger preserves phase space density, leading to caustics where radial orbits turn around.

"Phase-Wrapping"
(Quinn 1984, Hernquist & Spergel 1992)

P. Duc

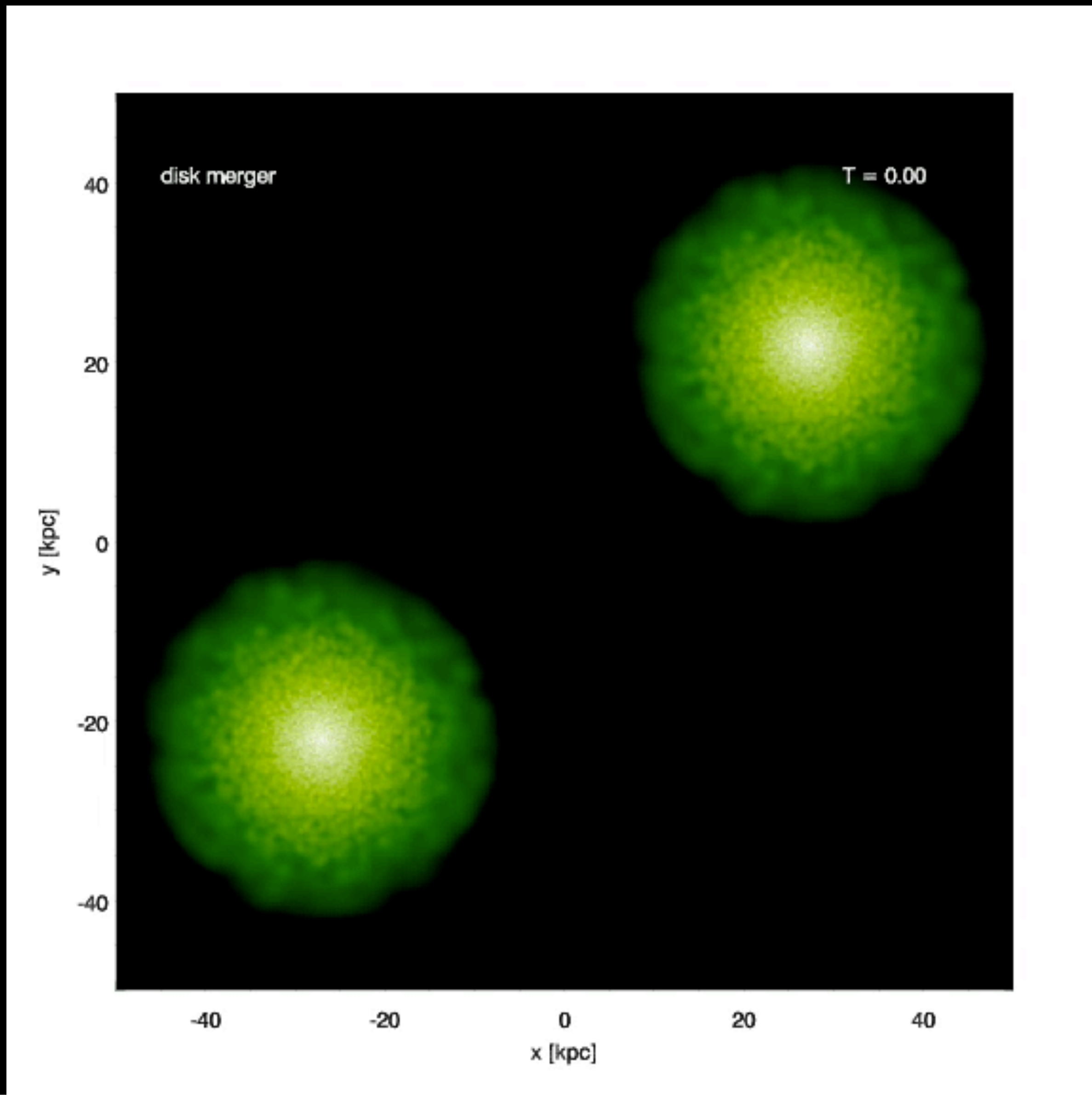
1:4 Merger between two triaxial galaxies

Top View

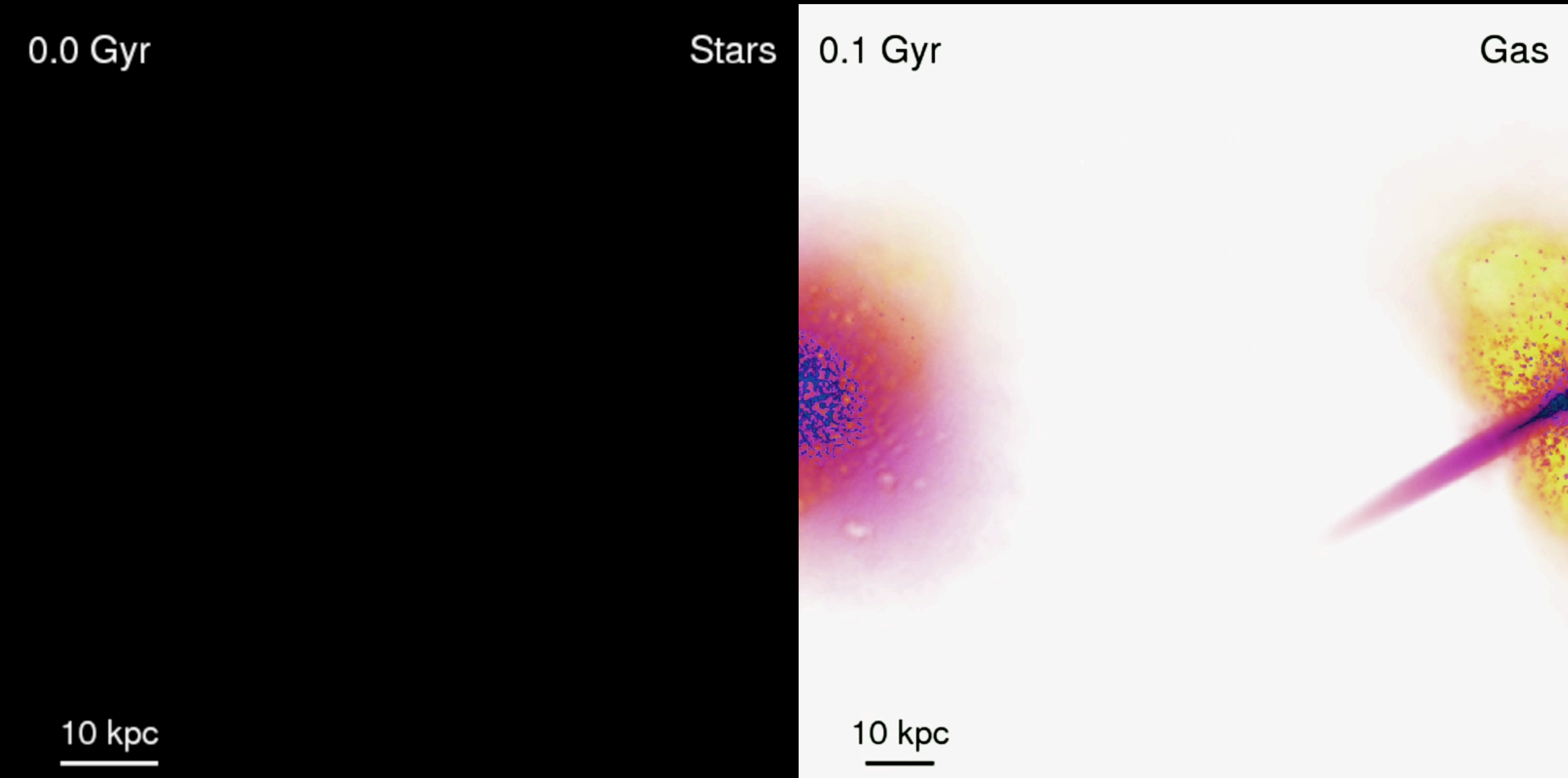
Created by Robert Feldmann
November 2006

Institute of Astronomy,
Department of Physics
ETH Zurich

Disks sometimes reform after a major merger, depending on orientation, f_{gas} and angular momentum of interaction



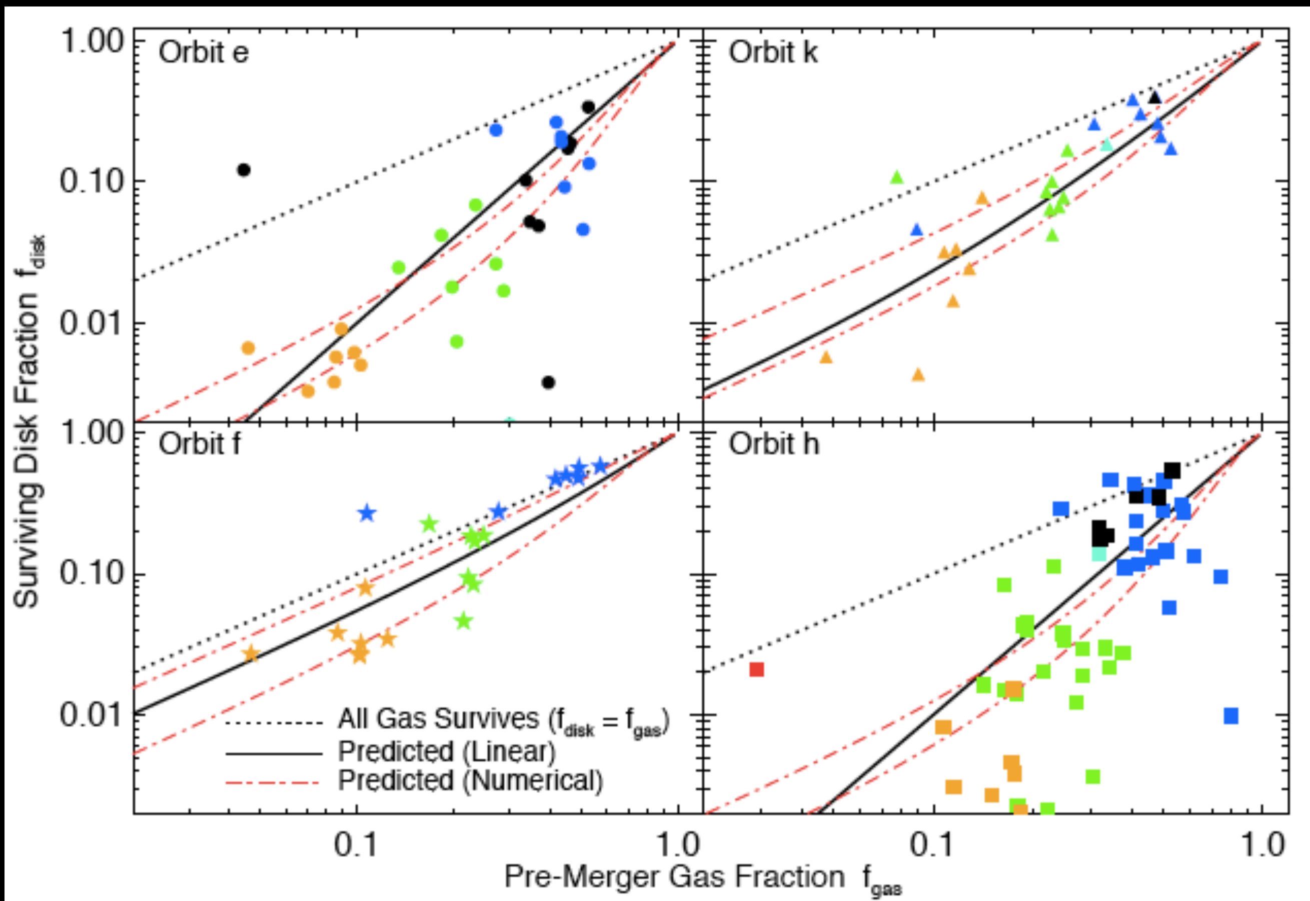
Courtesy Brant Roberston



“FIRE Simulations” from P. Hopkins group. Very strong SNe feedback.

http://www.tapir.caltech.edu/~phopkins/Site/animations/Movies_sbw_mgr.html

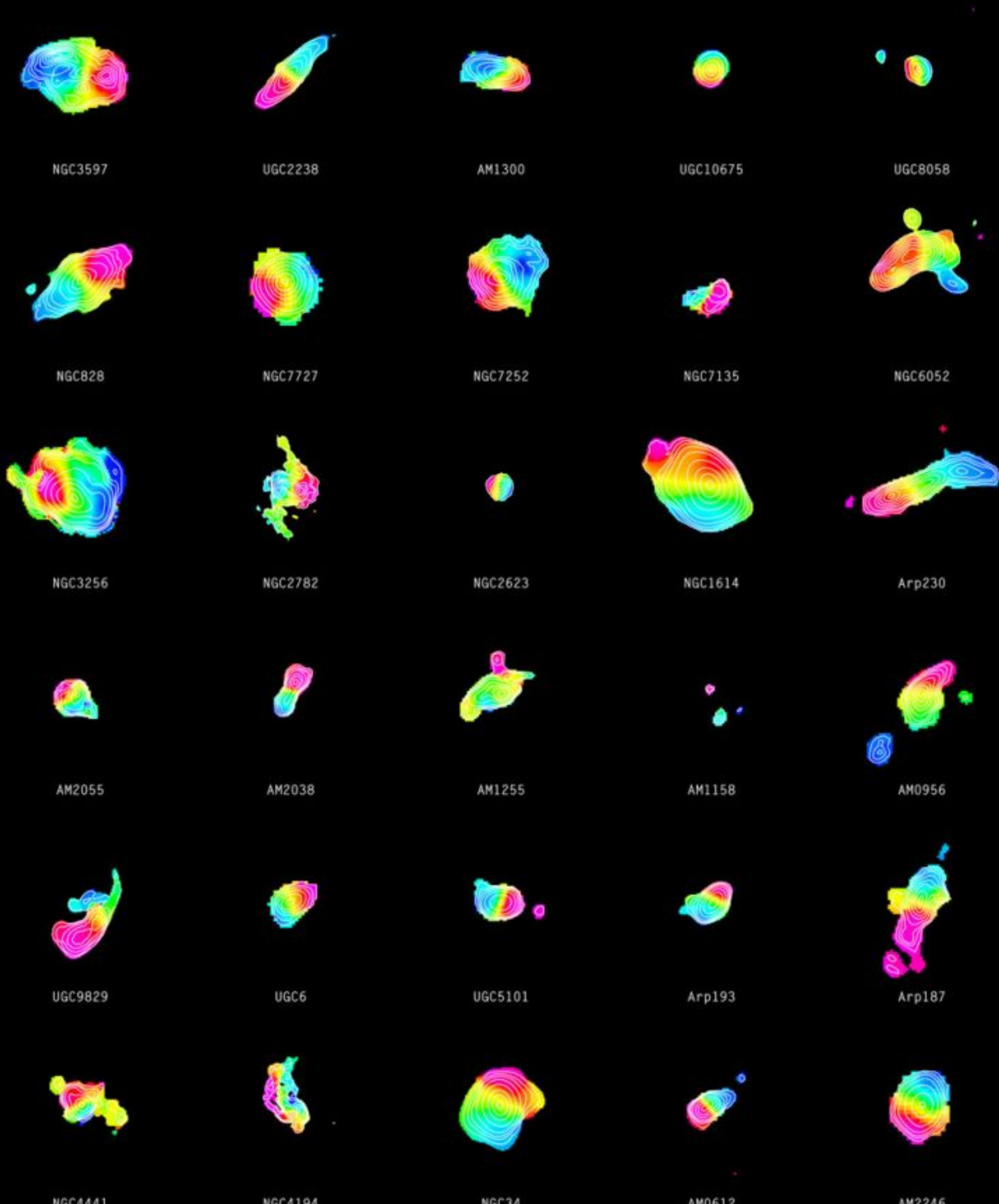
Outcome of merging depends on gas-richness of progenitors



Gas Rich = More disk after merging

FIG. 8.— Relaxed post-merger remnant disk mass fraction versus gas fraction just before the merger, for 1 : 1 major mass-ratio mergers. In this case essentially all the pre-merger stellar mass is transformed (violently relaxed) into bulge – the disk is formed from the gas that survives the merger. Panels consider different orbits, with points as Figure 7. Solid lines are our theoretical predictions ($f_{\rm disk} = f_{\rm gas}[1-(1-f_{\rm gas})\,\Psi]$, see Equation 19), dotted lines correspond to all the gas surviving and forming a disk ($f_{\rm disk} = f_{\rm gas}$). Again, the simulations agree well with our analytic predictions; gas-rich mergers are inefficient at stripping angular momentum from the gas, leaving significant gas content that rapidly re-forms a post-merger disk.

Robertson et al 2006
Cox et al 2006
Hopkins et al 2009



Empirical evidence from ALMA, showing 24 of 37 merger remnants have rotating CO disks

Ueda et al 2014; https://public.nrao.edu/news/mergers-disks-alma/

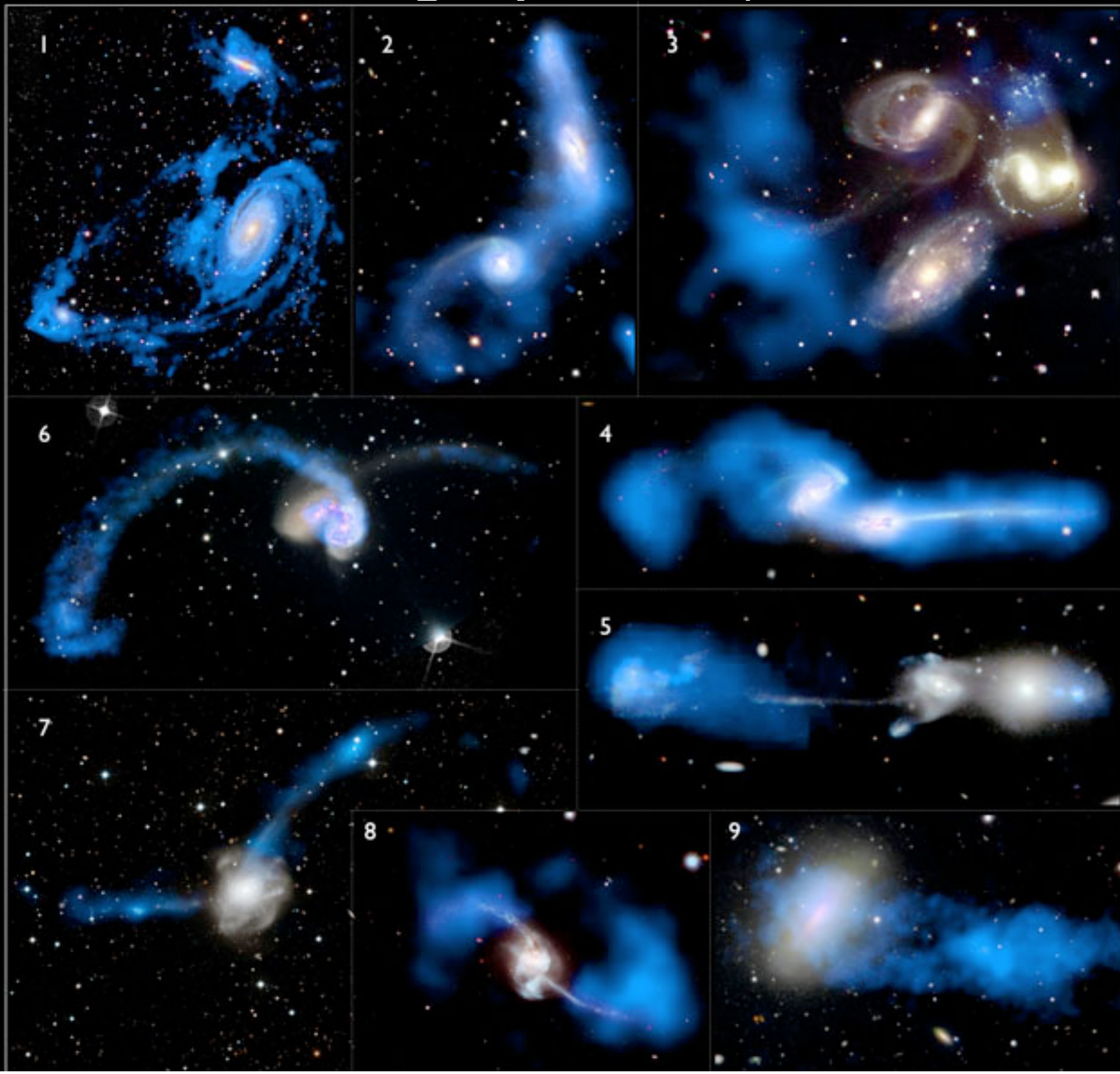
Major Merger Questions:

- Matching initial conditions to end states (disk? bulge? elliptical?)
- Timescales between infall into DM halo and coalescence? (see Solanes et al 2018, for example)
- Timescales of observability? (see Lotz et al 2008)
- Role of major mergers in triggering AGN and starbursts
- Linking observations to precursors to constrain dark matter at large radii?

Visual signatures of major mergers

“Tidal tails”: notable feature before merger, potentially probing outer halo

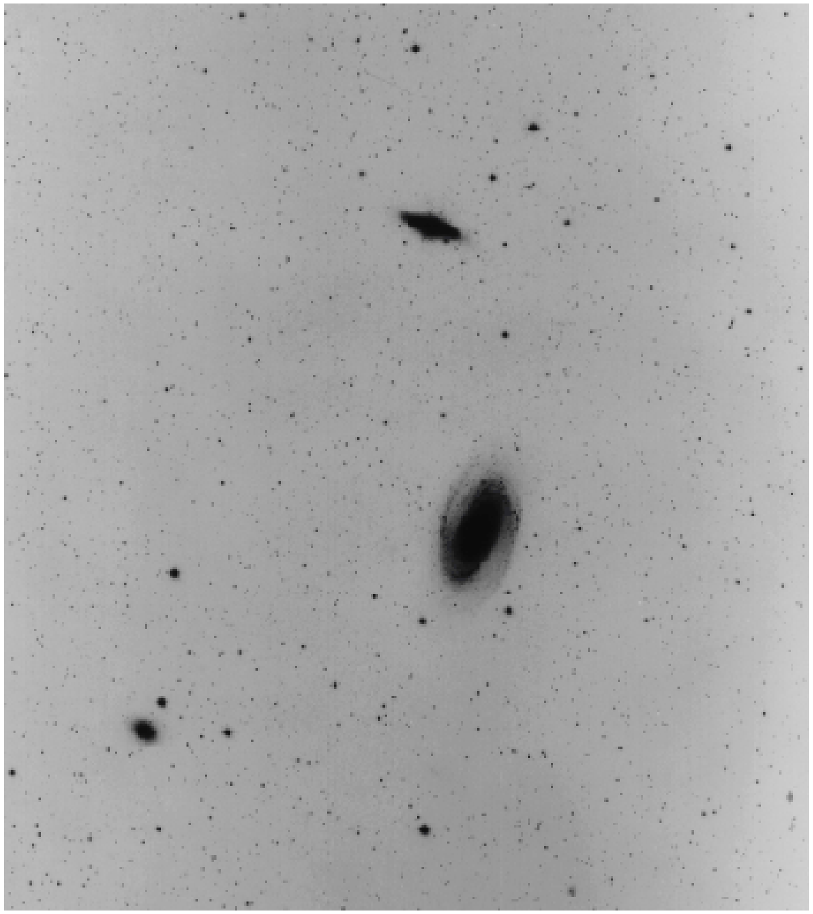
Often most dramatic in HI (more extended, so less tightly bound)



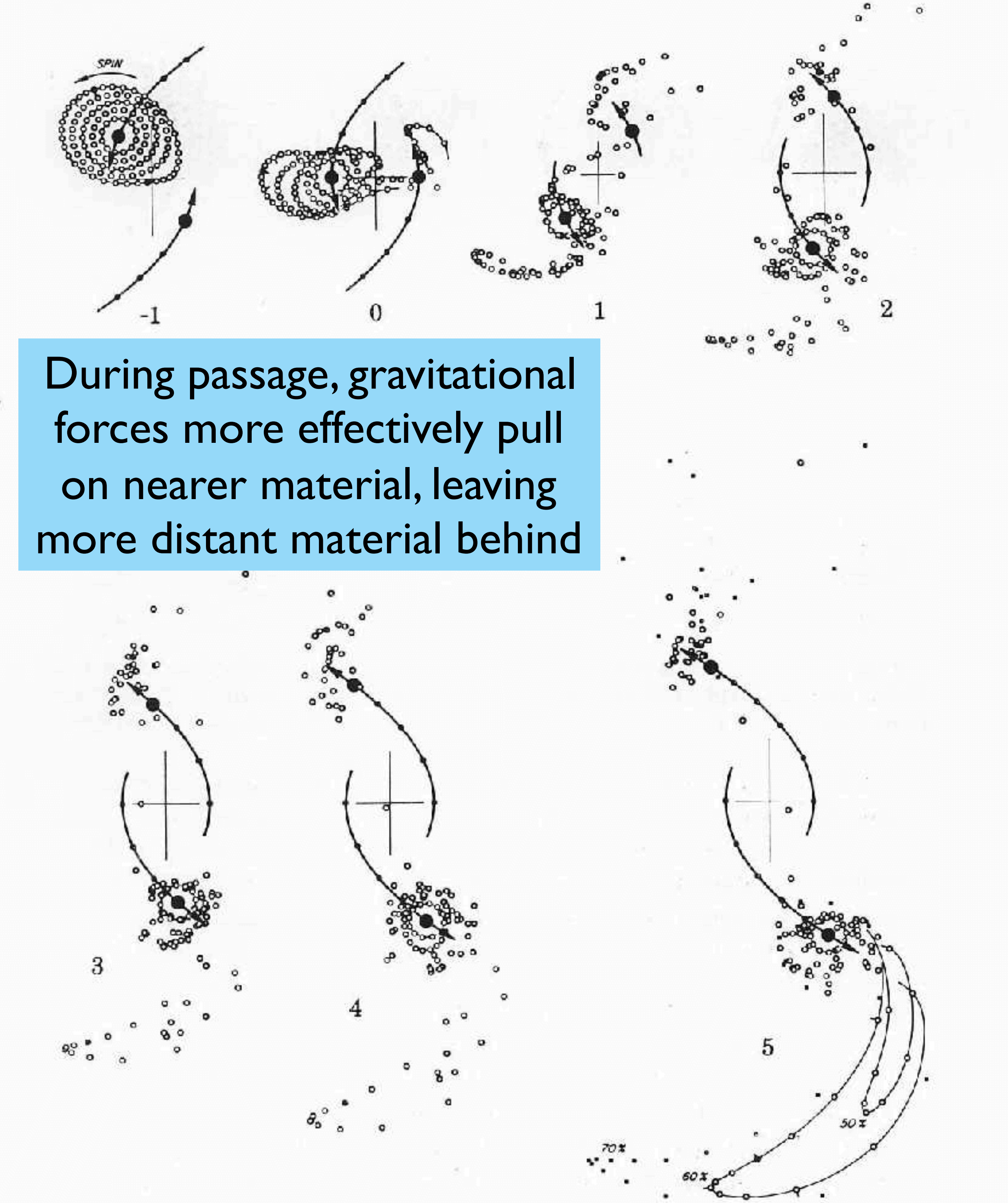
http://ned.ipac.caltech.edu/level5/Sept11/Duc/Duc4.html

HI Tidal Signature in the M81 Group

Optical Image (DSS)



VLA 12-beam mosaic
from M. S. Yun
(see Yun et al. 1994)



During passage, gravitational forces more effectively pull on nearer material, leaving more distant material behind

The basic mechanism* for explaining tidal arms first laid out in an elegant paper by Toomre & Toomre 1972

*No dark matter though

"Prograde" encounter: Disk rotates in *same* sense as interacting mass, with some disk material in resonance with orbit.

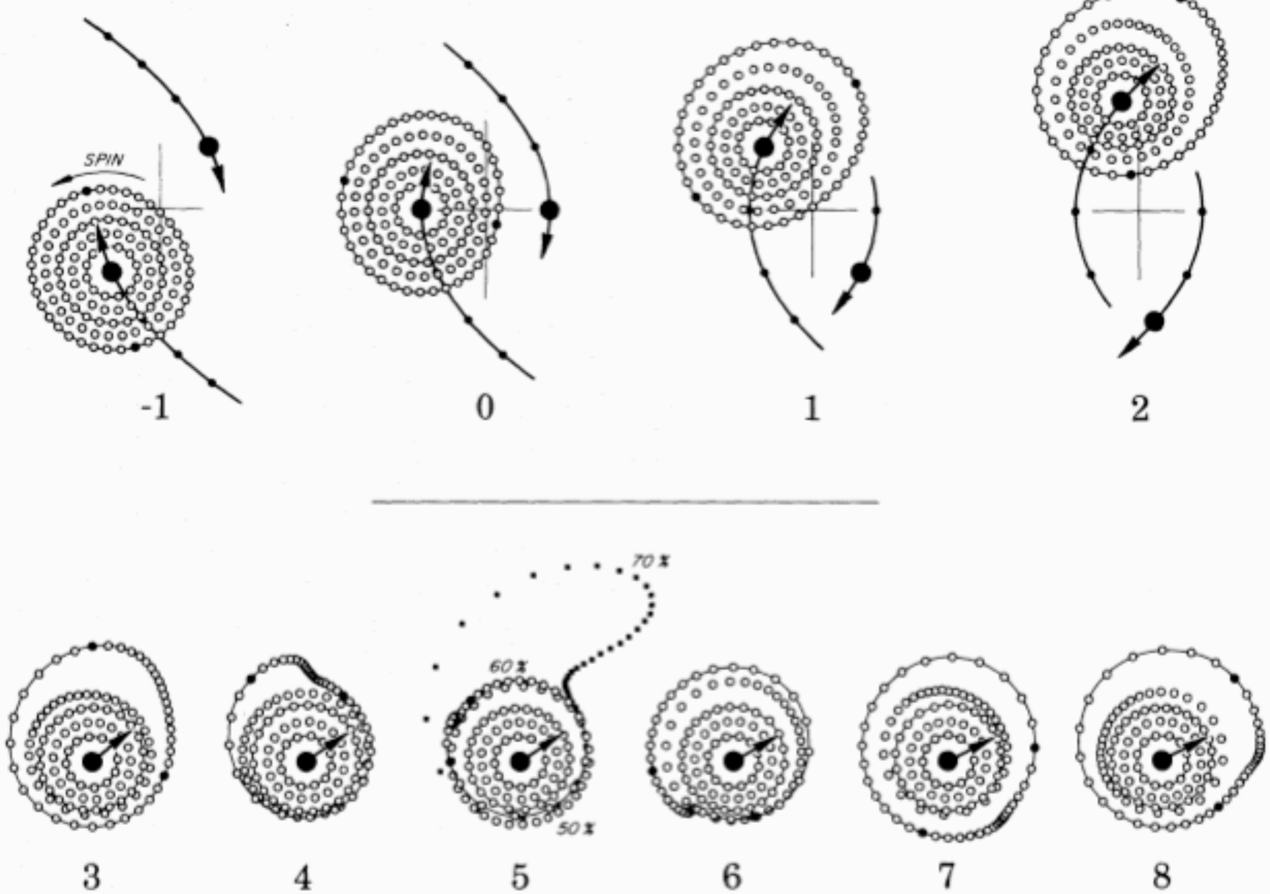


FIG. 1.—A flat retrograde (i = 180°) parabolic passage of a companion of equal mass. The two small filled circles denote test particles from the $0.6R_{min}$ ring which, in the absence of the encounter, would have reached positions exactly to the right and left of the victim mass at t = 0. The filled squares at t = 5 depict additional test particles from $0.7R_{min}$. (Note the partial interpenetrations of the outermost rings at t = 4, 5, and 6, and their continuing oscillations thereafter.)

"Retrograde" encounter: Disk rotates in *opposite* sense as interacting mass

Duration of tidal force is shorter for disk particles rotating in opposite direction

(Strength of prograde: Holmberg 1941, Toomre & Toomre 1972, Keenan & Innanen 1975, D'Onghia et al 2009, 2010)

Outer material becomes unbound. Some forms bridge to companion. Some forms bound tail.

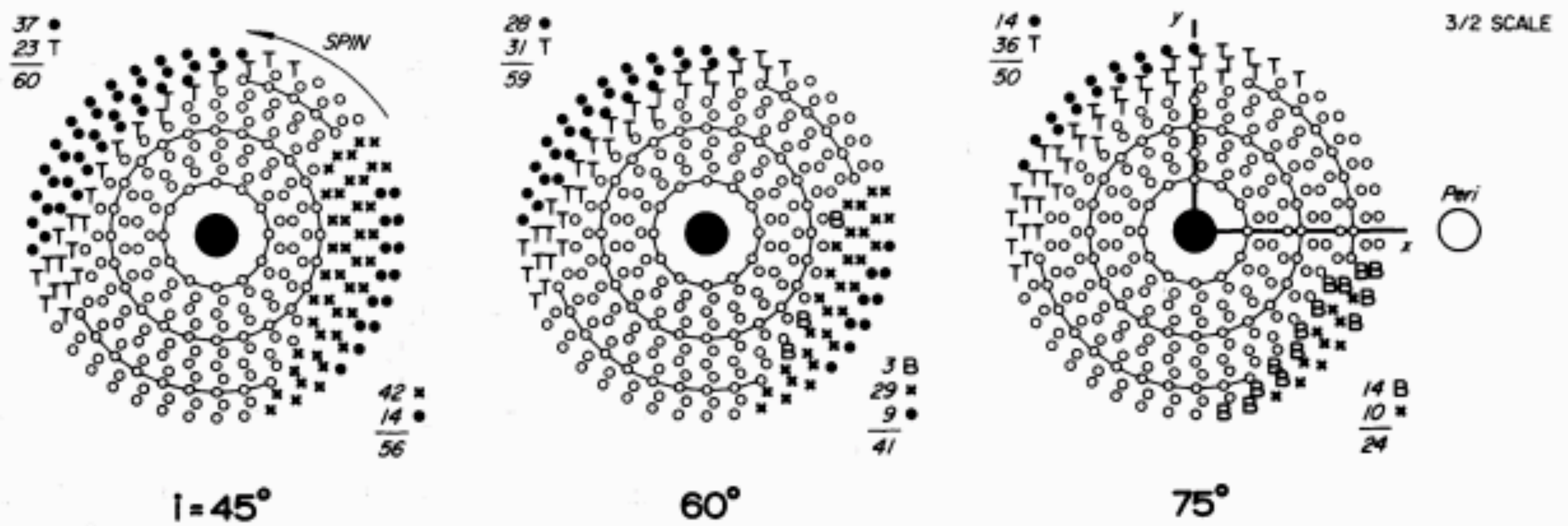
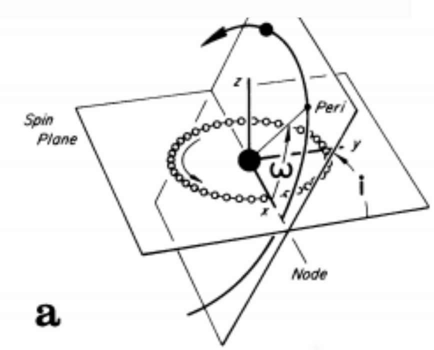


FIG. 15.—Scorecards of tail-making and accretion for three (i = 45°, 60°, and 75°) inclined ω = 0° parabolic passages of a companion of equal mass. The open symbols represent test particles retained by the primary mass point, crosses are those captured by the intruder, T's are nonescaping tail particles which at t = 5 lie farther than $1.0R_{\min}$ from their parent mass, B's are similar bridge-like particles, and the filled symbols denote particles that escape from both systems. The initial radii of the three connected rings were 0.2, 0.4, and $0.6R_{\min}$.

Simulations have advanced dramatically, but basic outlines of behavior are similar



The production of tails and their fate depends on details of the orbit and the galaxy.

- Production of tails depend on ratio of escape to circular velocity:

$$\mathcal{E} = \frac{v_e^2}{v_c^2}$$

Tails require $\mathcal{E} \lesssim 6.5$ for equal mass encounters

- In equal-mass encounters, very little of the tails actually escape; material falls back in or expands to invisible surface brightness

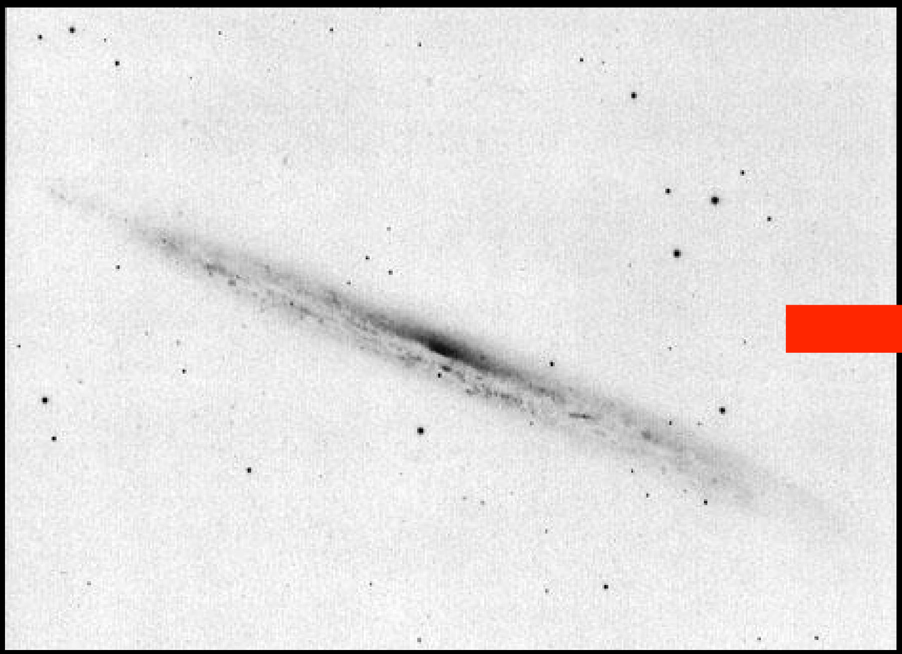
See Barnes 2016

Minor Mergers

Less dramatic, but more common

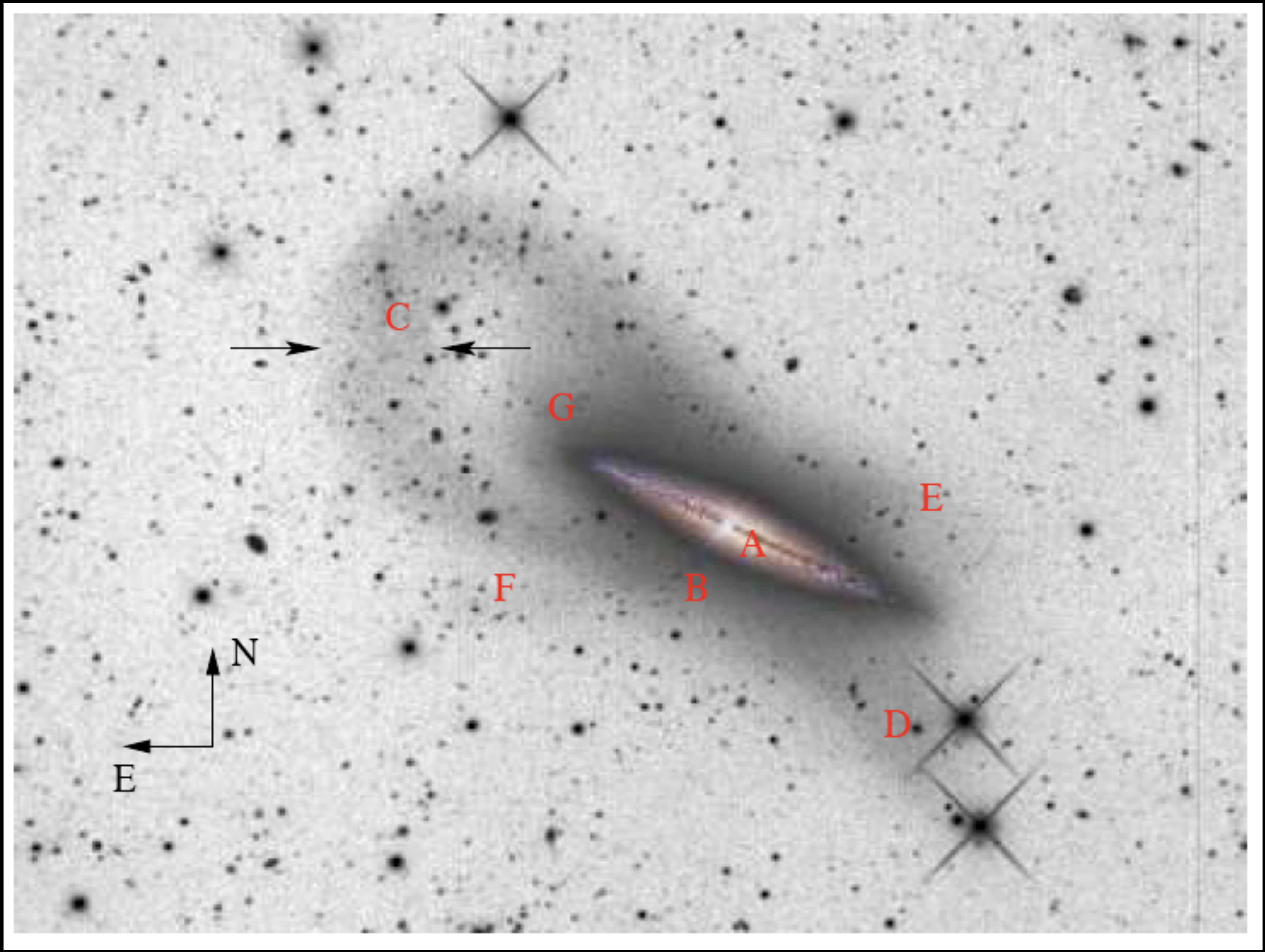
Minor mergers do not drastically transform *central* galaxies

NGC 5907

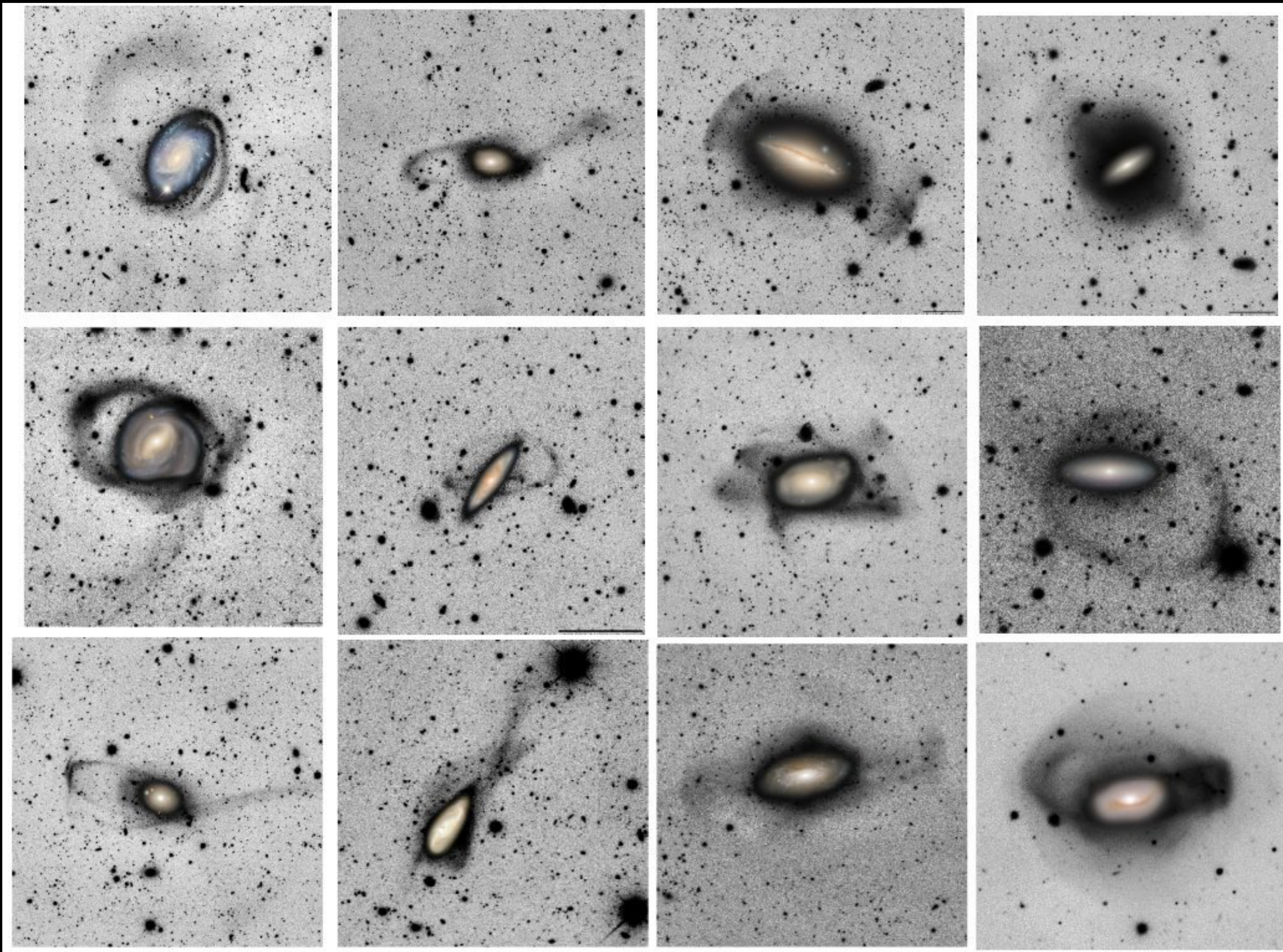


They can, however, obliterate the infalling *satellite* galaxy through tidal disruption

Main disk looks “normal”

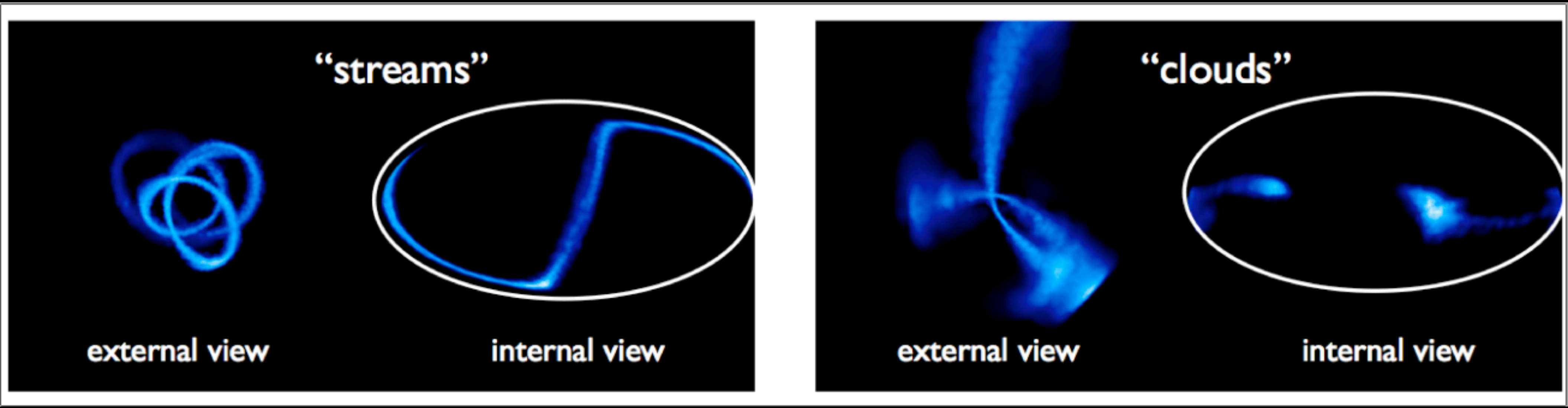


Martinez-Delgado et al 2008



https://twitter.com/astro_delgado/status/1117123434876755970

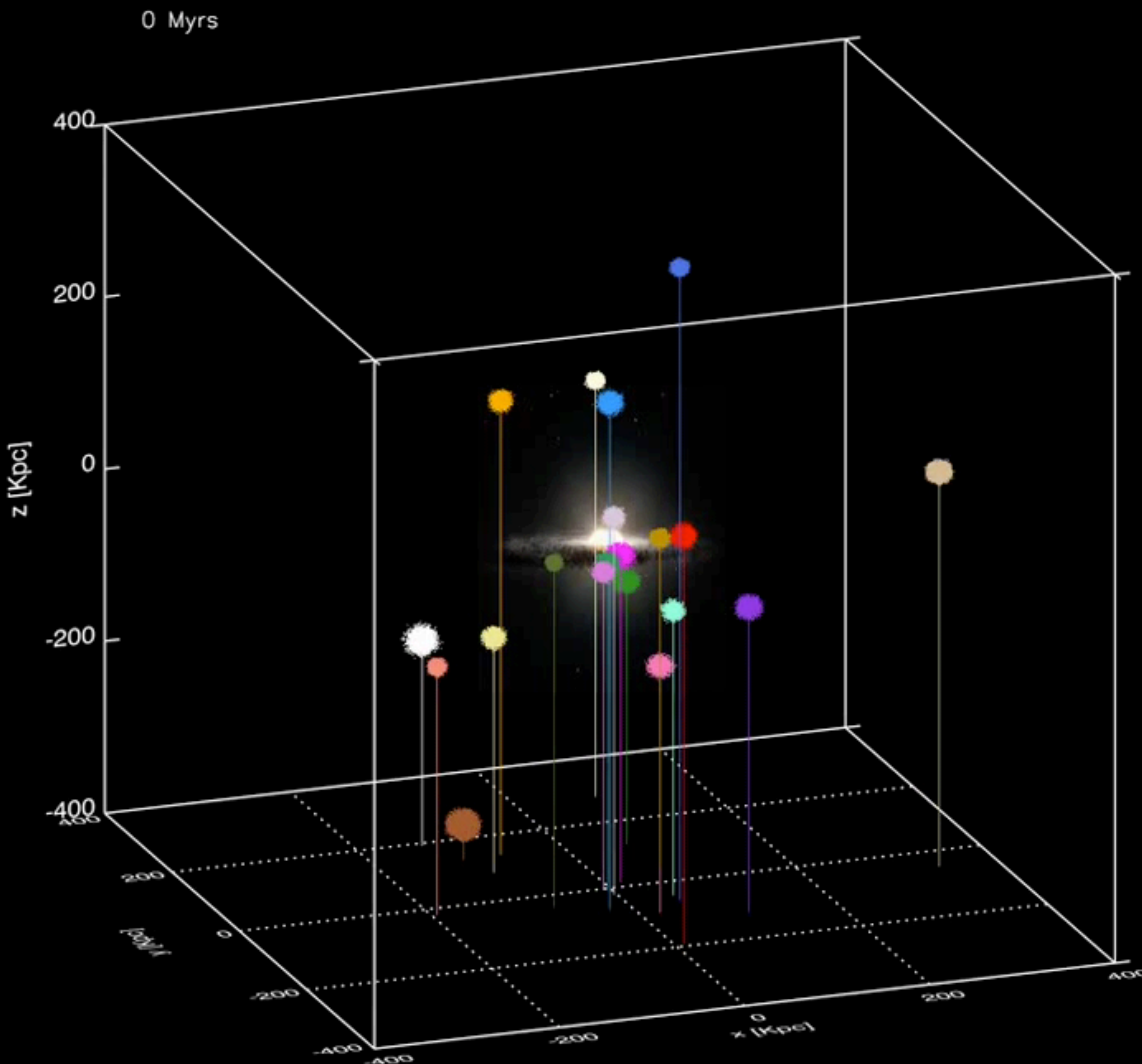
Remnant tidal features depend on angular momentum of satellite (i.e., circular vs radial orbits)



http://user.astro.columbia.edu/~kvj/research/stellar.html

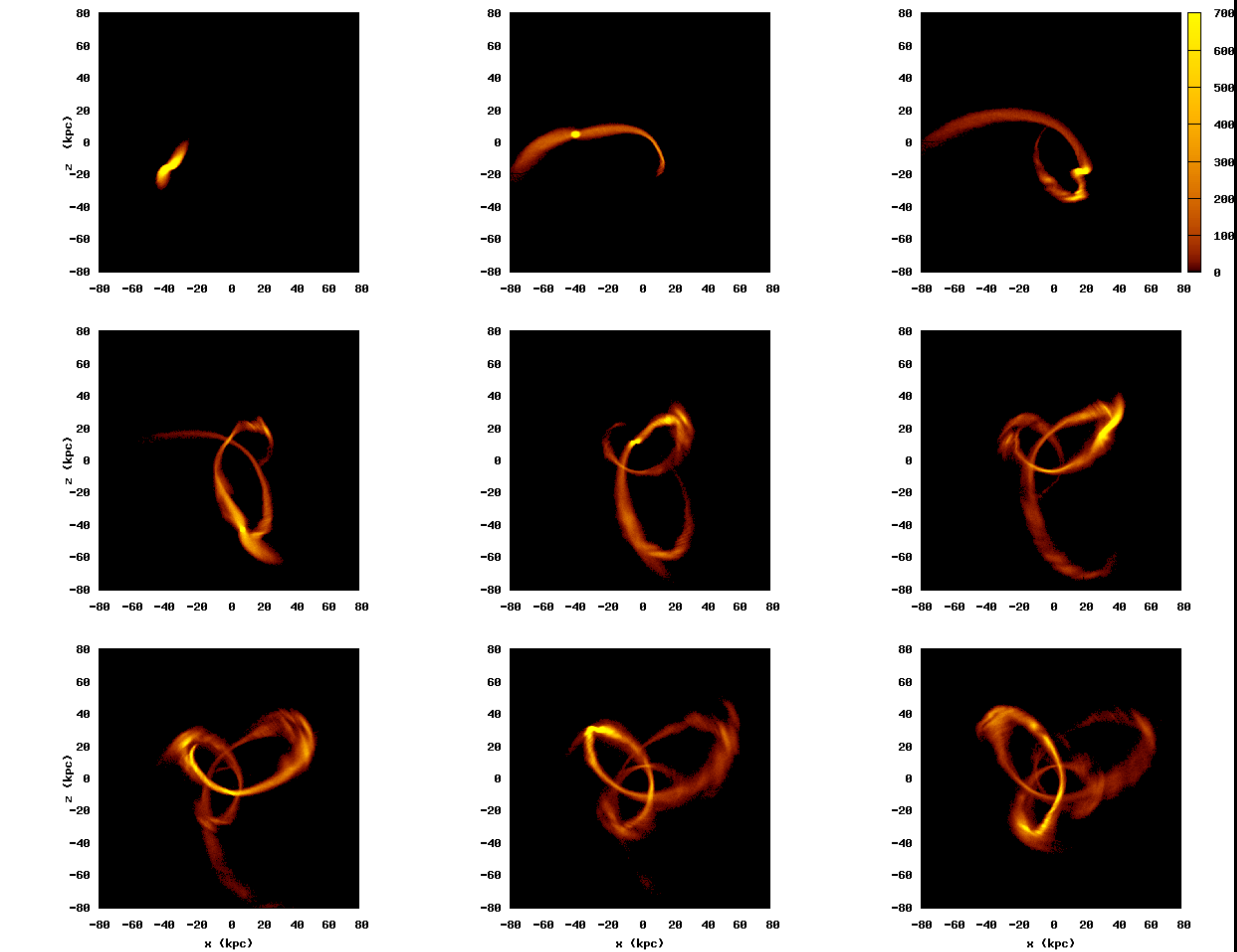
Streams can persist for many Gyr, but can become undetectable due to becoming increasingly diffuse

Probe of DM halo and "invisible" DM subhalos



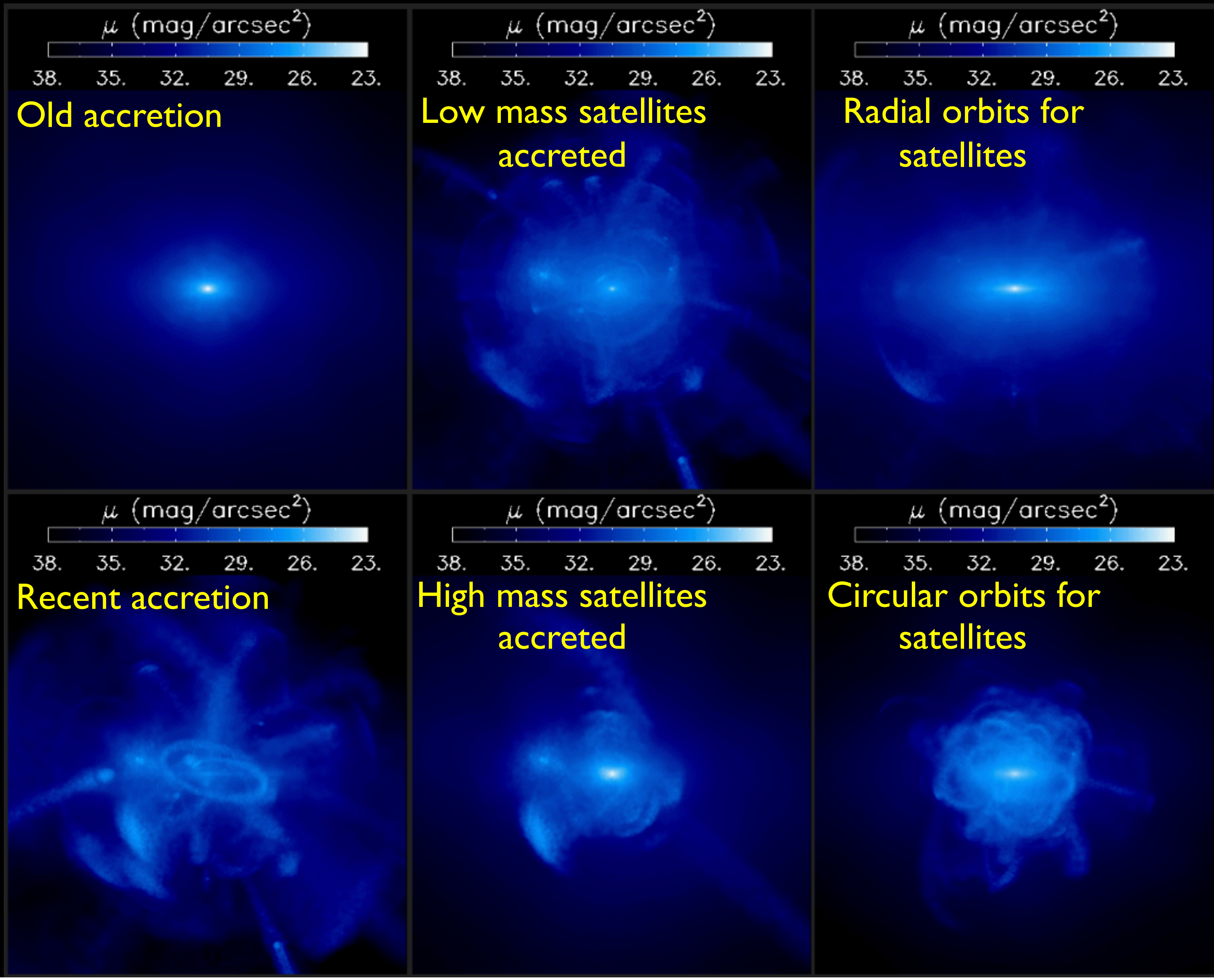
From Aquarius simulation: https://www.youtube.com/watch?v=TIQE0_U4gXk

Tail sub-structure in even a *smooth* halo can be complex



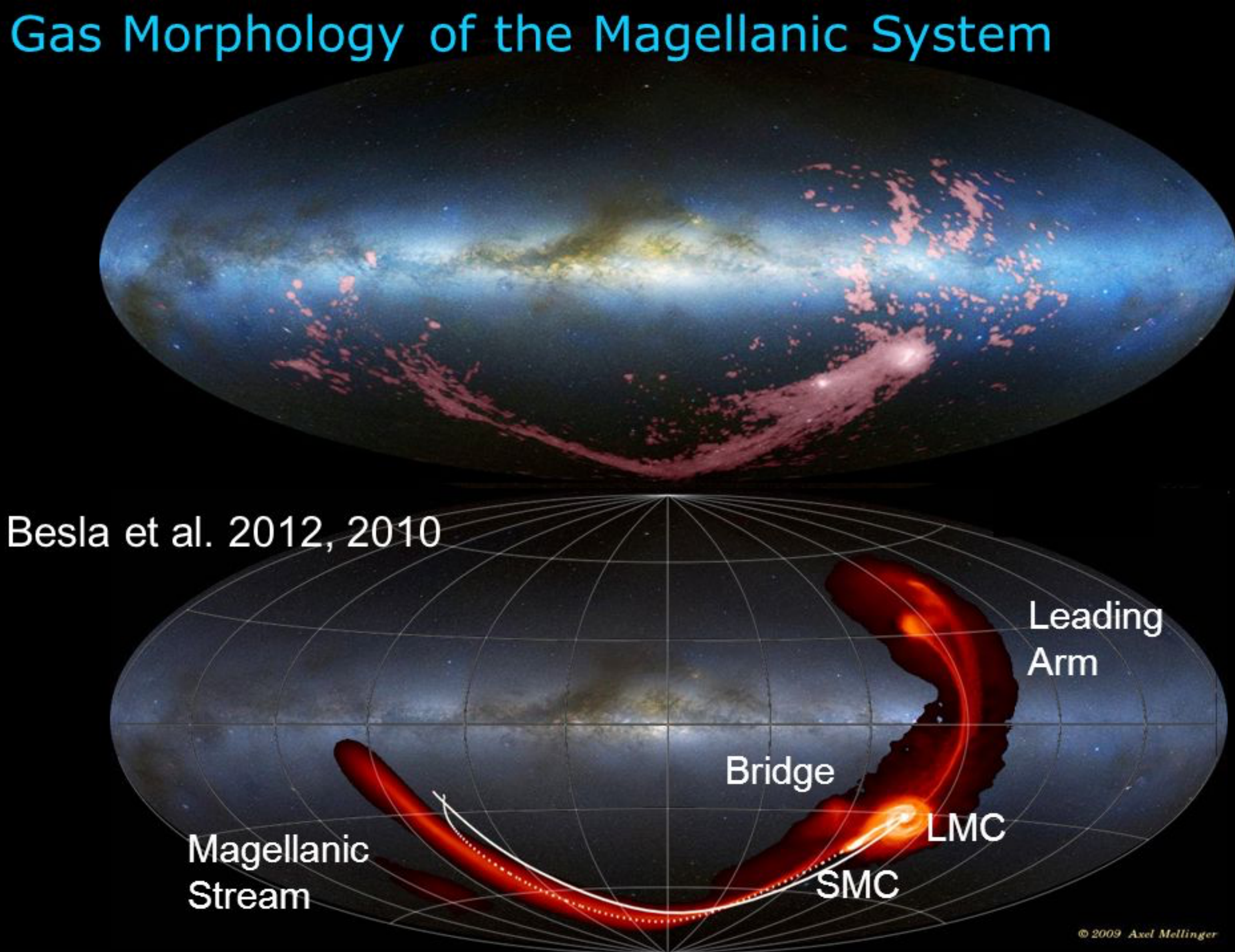
Disk & DM halo not shown; Comparetta & Quillen 2011

“Archeology” of stellar halo structure constrains history of accretion



http://user.astro.columbia.edu/~kvj/research/archaeology.html

Streams from accretion also seen in HI, but will persist for much less time than stars

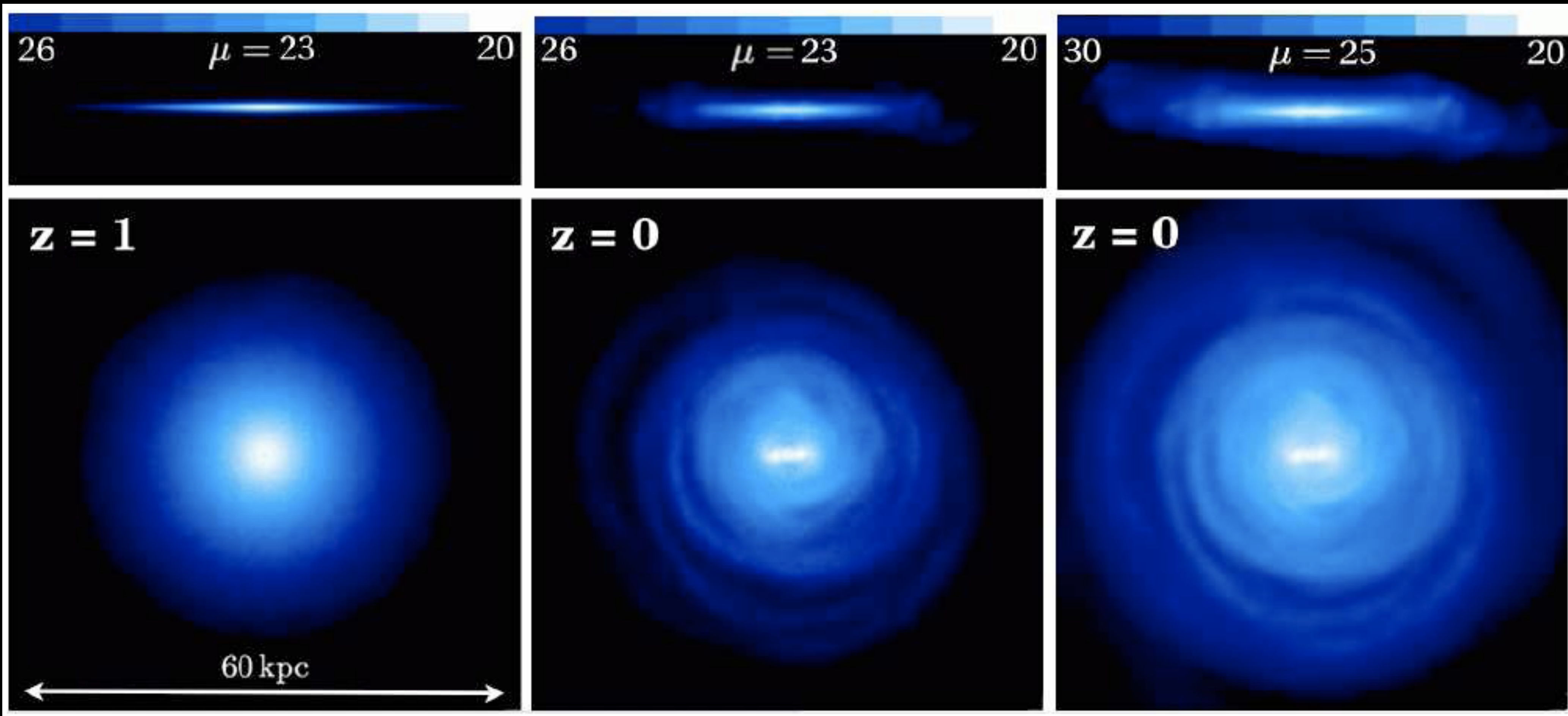


Minor Merger Questions

- What can we learn about accretion history from stellar streams?
- How long between when a galaxy enters the virial radius of a halo and when it is disrupted?
- What physics controls the transformation and/or disruption?
- How long are substructures/streams detectable?
- Can we use streams to constrain "invisible" dark matter halos?
- How do tidal effects and disruption affect the properties and mass function of satellite galaxies & subhalos?

Minor mergers can affect the central galaxy in subtle ways

Satellite interactions can "heat" stellar disk

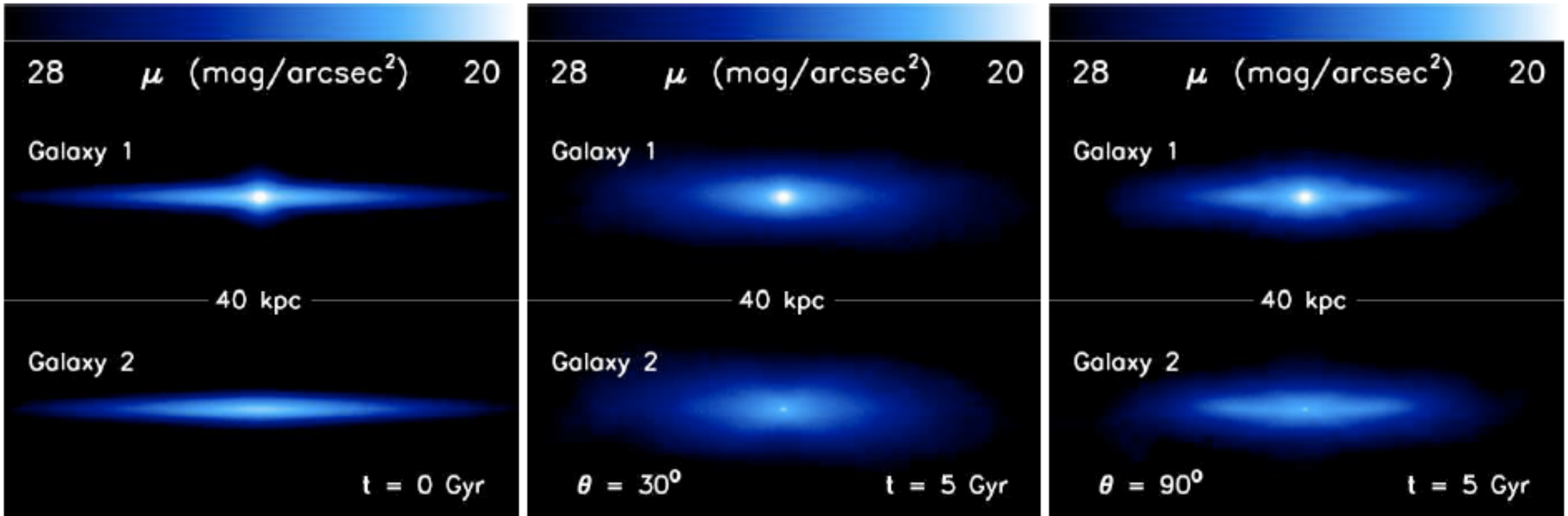


Kazantzidis et al 2008

$0.2M_{disk,bary} < M_{satellite,tot} < M_{disk,baryon}$

FIG. 3.— Surface brightness maps of disk stars in the simulated accretion history of host halo G_1. The edge-on (*upper panels*) and face-on (*bottom panels*) views of the disk are displayed in each frame and the color bar in each upper panel indicates the surface brightness limits used to generate the maps. In constructing these images, a stellar mass-to-light ratio equal to $M_*/L = 3$ is assumed. Bottom images are 60 kpc on a side, while top images measure 18 kpc by 60 kpc. The *left* panel shows the initial disk assuming that the sequence of satellite-disk interactions initiates at $z = 1$. The *middle* and *right* panels depict the disk after the last satellite passage, evolved in isolation for additional ~ 4 Gyr, so that the evolution of disk stars is followed from $z = 1$ to $z = 0$. In the left and middle panels, images are shown to a limit of $\mu = 26$ mag arcsec^{-2}, while the right panel corresponds to a "deeper" surface brightness threshold of $\mu = 30$ mag arcsec^{-2}. Results are presented after centering the disk to its center of mass and rotating it to a new coordinate frame defined by the three principal axes of the total disk inertia tensor. Considerable flaring and a wealth of features that they might falsely be identified as tidal streams can be seen in the perturbed disk down to 26–30 mag arcsec^{-2}. The existence of non-axisymmetric structures such as extended outer rings and bars after a significant amount of time subsequent to the last accretion event confirm their robustness and indicate that axisymmetry in the disk has been destroyed and is not restored at late times.

Somewhat bigger mergers have a more significant effect



Purcell et al 2009

FIG. 1.— Edge-on surface brightness maps, assuming $M_\star/L = 3$, for primary galaxies 1 (upper panels) and 2 (lower panels). Initia
nodels ($t = 0$ Gyr) are shown in the left panel, while the results ($t = 5$ Gyr) for satellite-infall orbital inclinations of $\theta = 30°$ and 90
ppear in the center and right panels, respectively.

$M_{satellite,tot} \sim 3 M_{disk,baryon}$

Keeping the MW thin over a Hubble time is difficult!

Gas helps though.

Moster et al 2010

Interactions can excite strong spiral structure

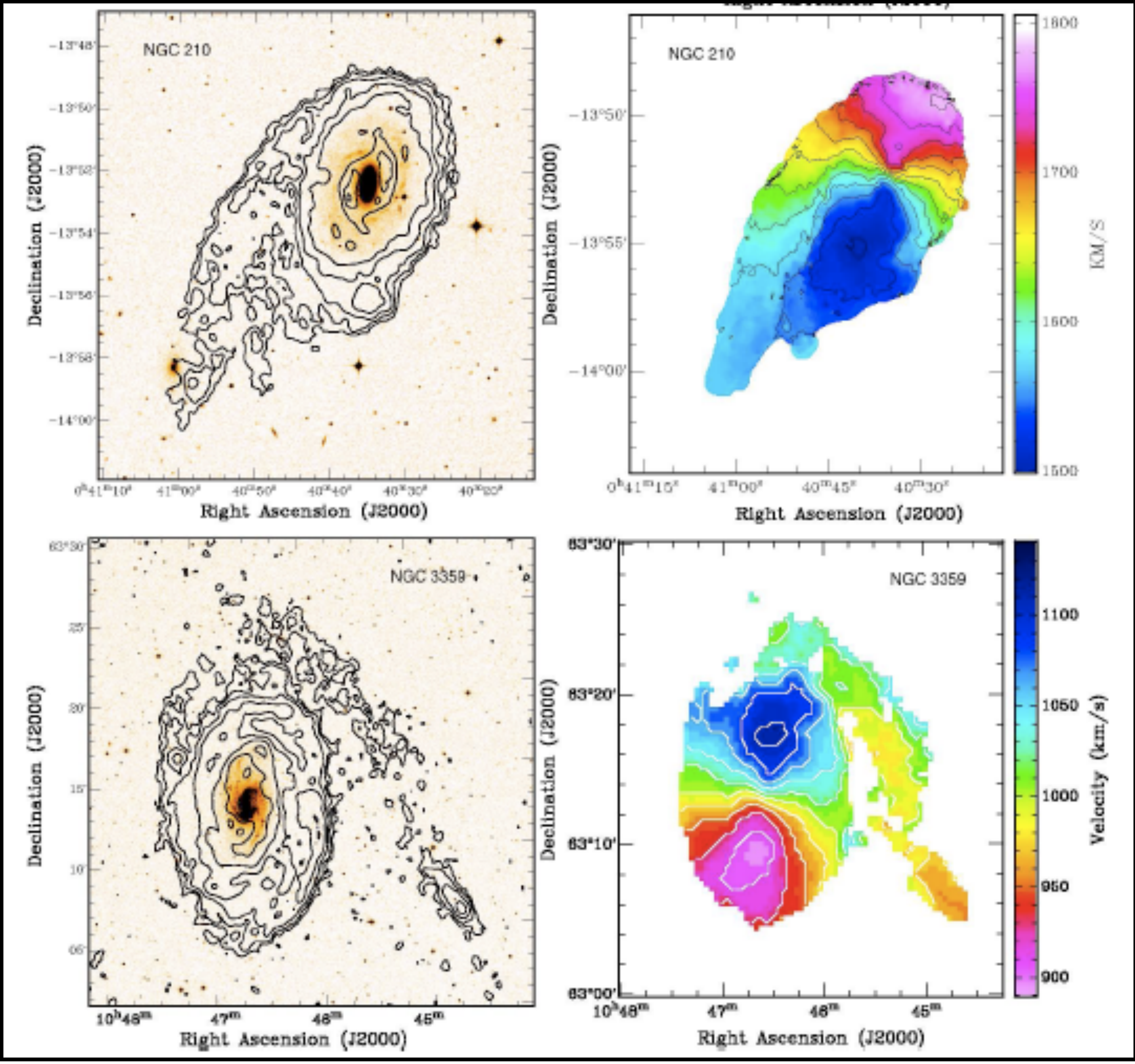
Supercomputer simulation
of a *dark matter dwarf galaxy*
colliding with the ***Milky Way galaxy***
over the course of 1 billion years.

https://www.youtube.com/watch?v=Njhvu2i_ZSc

Drives disturbances in the disk:
Strong spirals, resonant heating of stars

"Fly-bys*" can pull off tails or create warps

HI Contours on optical image



HI velocity field

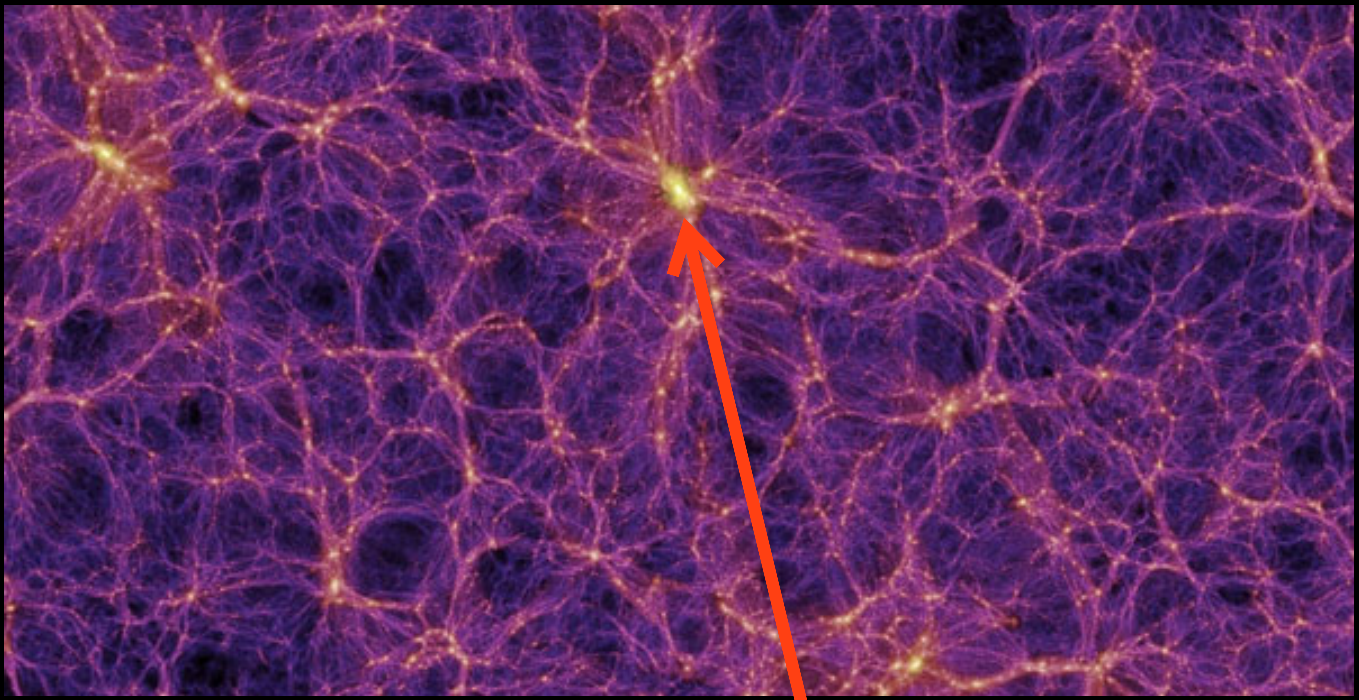
*passage without merging

Impact of minor merger questions

- What is the impact of minor mergers on the disk thickness?
- Can we use the structures imprinted on the disk to trace dark matter substructure?
- Kinematic impact (especially MW+Gaia)?
- Can we find evidence for smooth infall, not just lumpy accretion?

Massive galaxies merging into larger structures

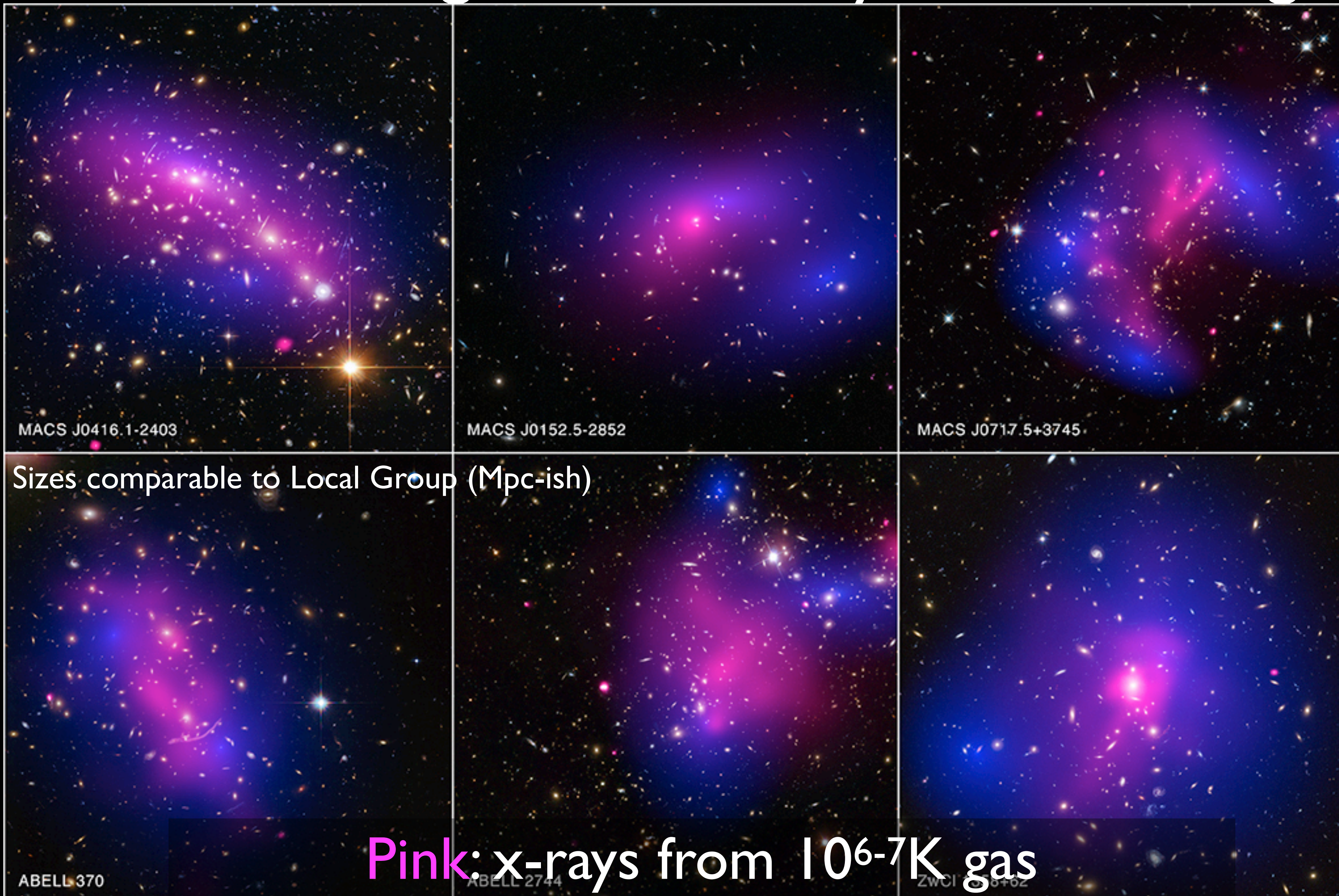
Galaxy clusters



Massive ~$10^{14} M_{sun}$ dark matter concentrations at intersections of filaments.

http://chandra.harvard.edu/photo/2015/dark/

Thousands of galaxies + very hot ionized gas



Sizes comparable to Local Group (Mpc-ish)

Pink: x-rays from $10^{6\text{-}7}$K gas

Blue: dark matter from gravitational lensing

Massive galaxies entering a galaxy cluster: *same tidal disruption* as satellite galaxies falling into central massive galaxies

http://www.tng-project.org/media/

Infalling galaxies also go through regions of high pressure from hot, dense intercluster gas (ICM)

Examples from simulations by Steinhauser et al 2019

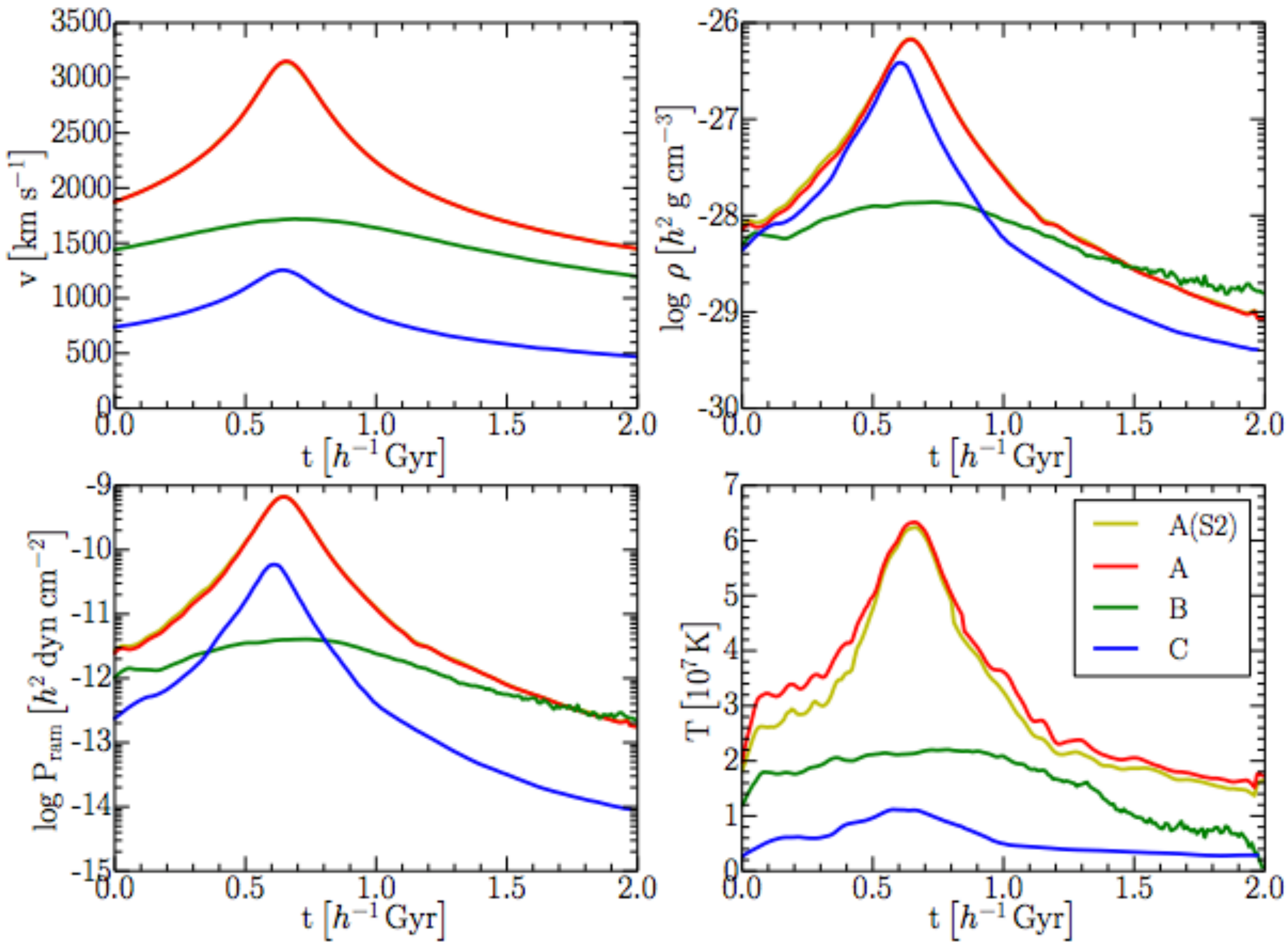


Fig. 3. Physical conditions encountered by galaxy G1 as it falls into different galaxy clusters. The top left panel shows the relative velocity of the galaxy, the top right panel shows the ICM density, the bottom left panel gives the resulting ram pressure P_{ram}, and the bottom right panel indicates the ICM temperature encountered by galaxy G1a for runs S1, S3, and S4, respectively. Galaxy inclination does not affect these values significantly, hence run S2 looks essentially the same as S1 and is hence not shown. Also, as in Fig. 2, the values for galaxy G2 in runs S5-S7 are very similar as the trajectories are nearly the same.

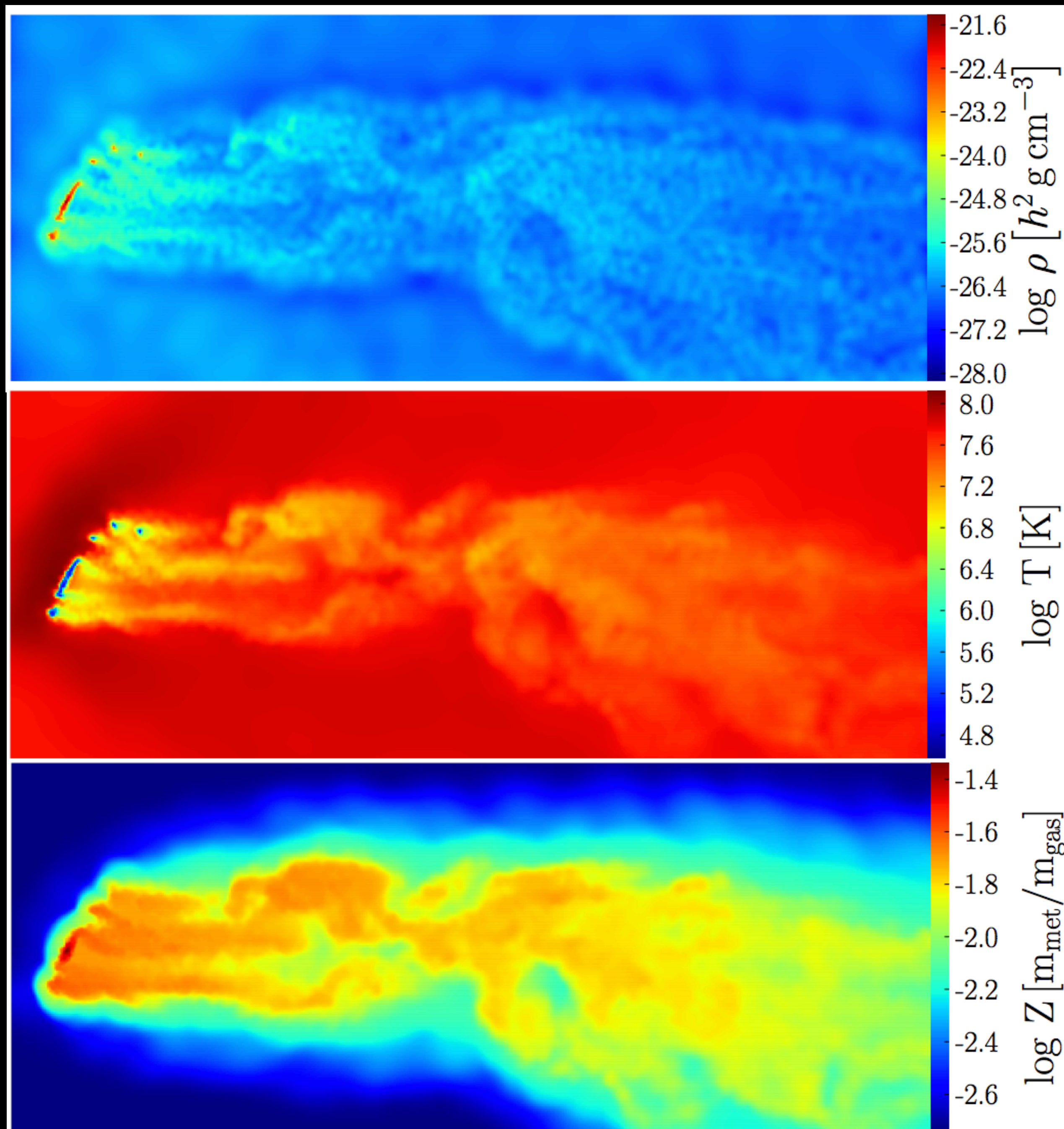
High T, n implies high gas pressure (P=nkT), which pushes on gas in infalling galaxies

Galaxy's gas experiences additional pressure force which "strips" the gas from the galaxy

High pressure leads to “ram pressure stripping”

Examples from simulations by Steinhauser et al 2019

Fig. 7. Slices of thickness $0.2\,h^{-1}$kpc and extension $100\,h^{-1}$kpc$\times 40\,h^{-1}$kpc through the galaxy and its wake in run S1, after $600\,h^{-1}$Myr of evolution. Quantities are mapped using an SPH kernel. The different panels show: (a) gas density, (b) velocity magnitude, (c) metallicity, (d) temperature, and (e) vorticity magnitude.



Gas density

Gas Temperature

Gas Metallicity

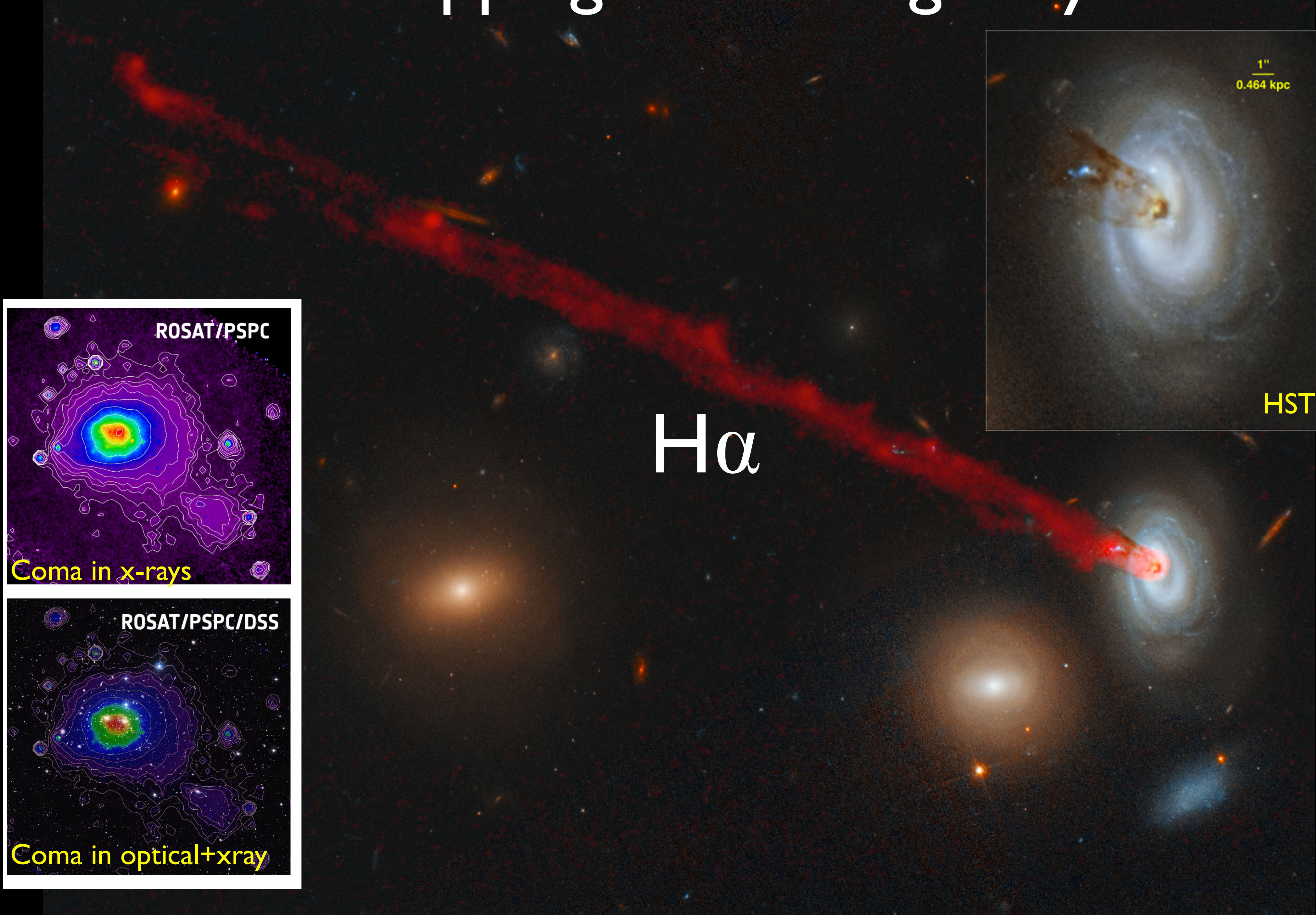
Tidal Stripping in action

Red: Hα Emission from ionized gas, heated by shocks & thermal conduction from $10^{6\text{-}7}$K cluster gas

Gas can be stripped by “ram pressure” as it falls into the hot gaseous halo of a more massive galaxy or group

GASP: Poggianti et al 2017; https://www.ifa.uv.cl/sites/yara/jelly.html

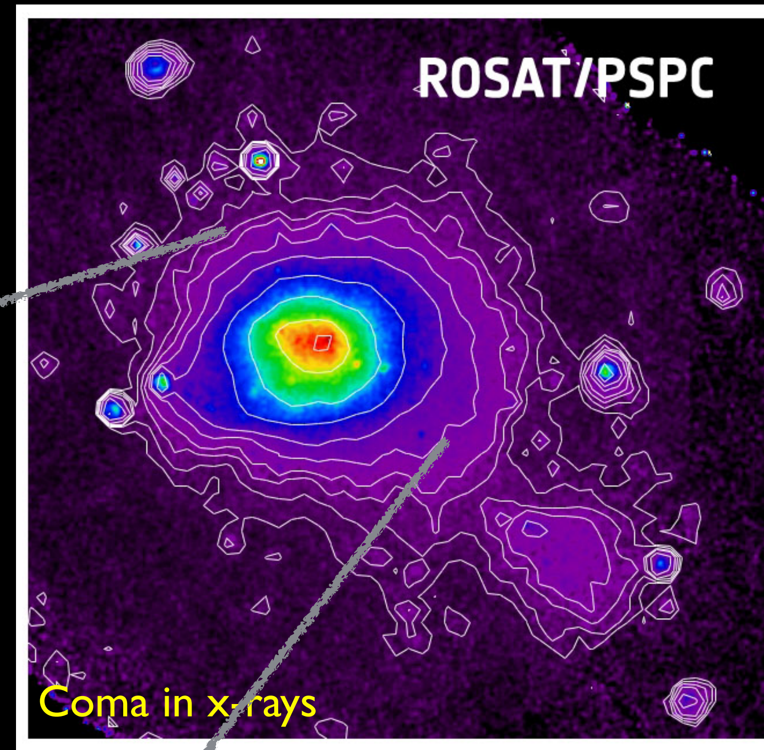
Extreme stripping in Coma galaxy cluster

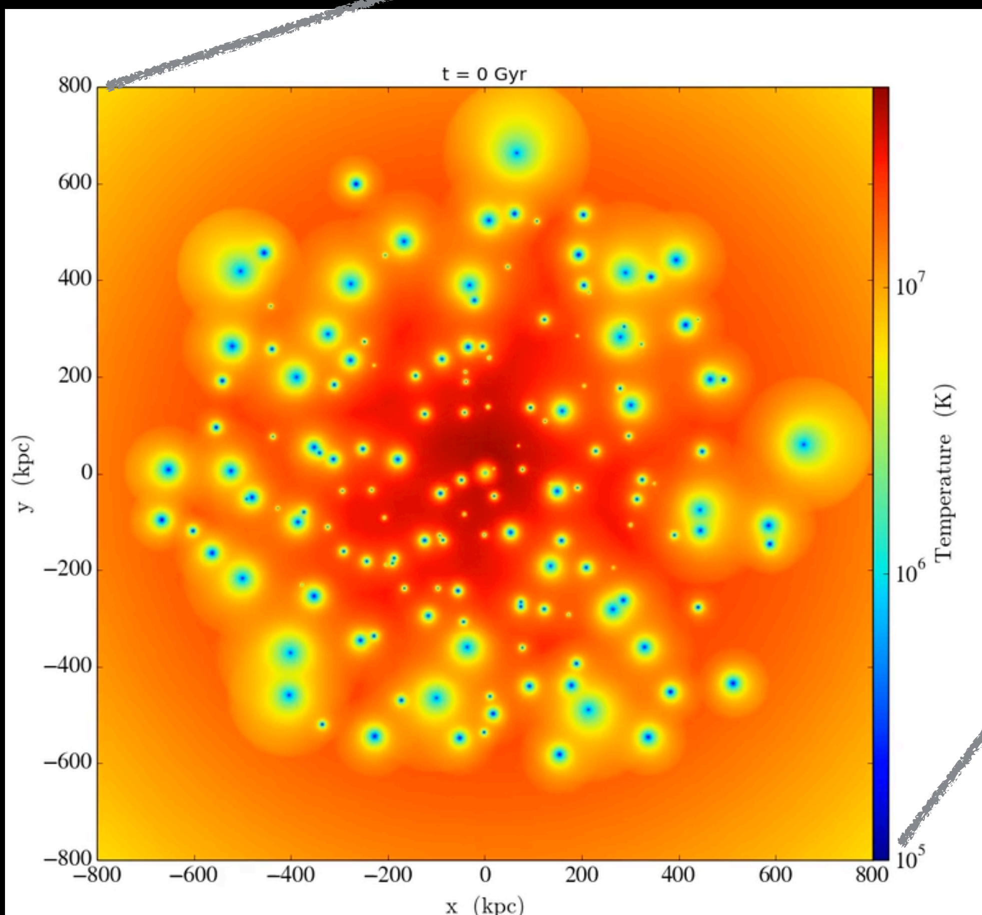


 http://sci.esa.int/planck/47695-the-coma-cluster/

Cramer et al 2019; http://hubblesite.org/news_release/news/2019-05

Ensemble effect is to progressively remove gas from galaxies that have passed through the cluster center





Collectively shuts down SF in cluster galaxies, while building up metallicity of ICM

 R.Vijayaraghavan (w/ Sarazin) https://vimeo.com/202585261

Main classes of evidence:

- ~~Theoretical expectations~~
- ~~Observations of individual systems~~
- Statistical behavior of galaxy populations

We'll do this later when we assess correlations with "environment"

Key physics to cover later in quarter

- Relaxation time
- Dynamical friction
- Tidal “stirring”
- Tidal stripping
- Ram pressure stripping (gas)

Important for morphological transformation/ disruption, and quenching of SF

 Good detailed derivations of many of these in Frank van den Bosch’s lecture notes http://www.astro.yale.edu/vdbosch/astro610_lecture14.pdf