Groups vs Clusters

Leo Triplet
Distance ≈ 10 Mpc
Mass ≈ several x 10^{12} $M_\odot$
Size ≈ few hundred kpc

Coma Cluster
Distance ≈ 100 Mpc
Mass ≈ 10^{15} $M_\odot$
Size ≈ few Mpc

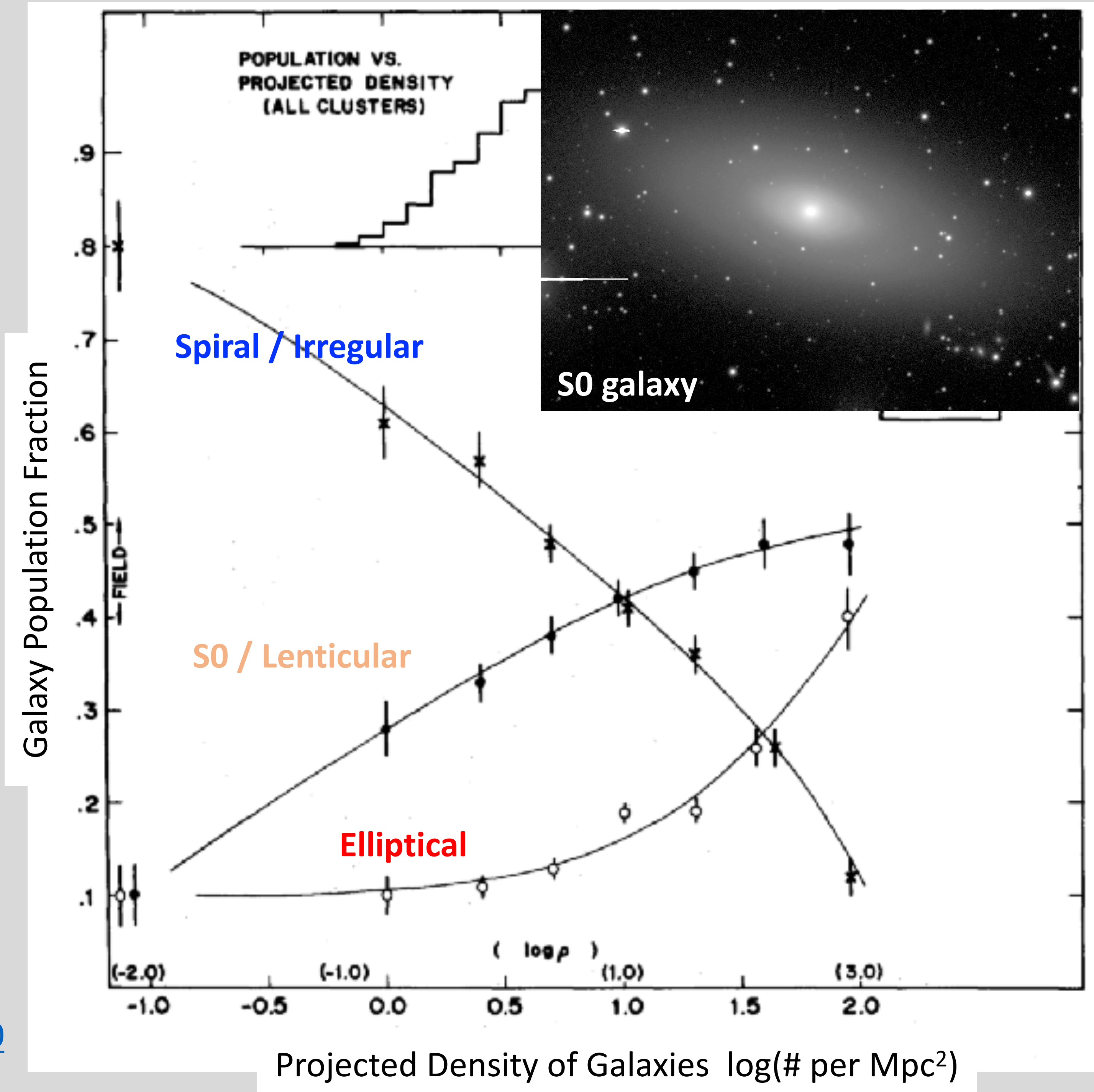
Galaxies: Morphology-Density Relationship

In the local universe, the fraction of galaxy types is a strong function of local environment.

Spirals/Irregulars dominate the in the field environment.

S0's and E's dominate in galaxy clusters.

Dressler 1980



Galaxies: Luminosity Function vs Environment

E = Elliptical
S0 = S0
Sp = Spiral
dE = dwarf elliptical
dIrr = dwarf irregular

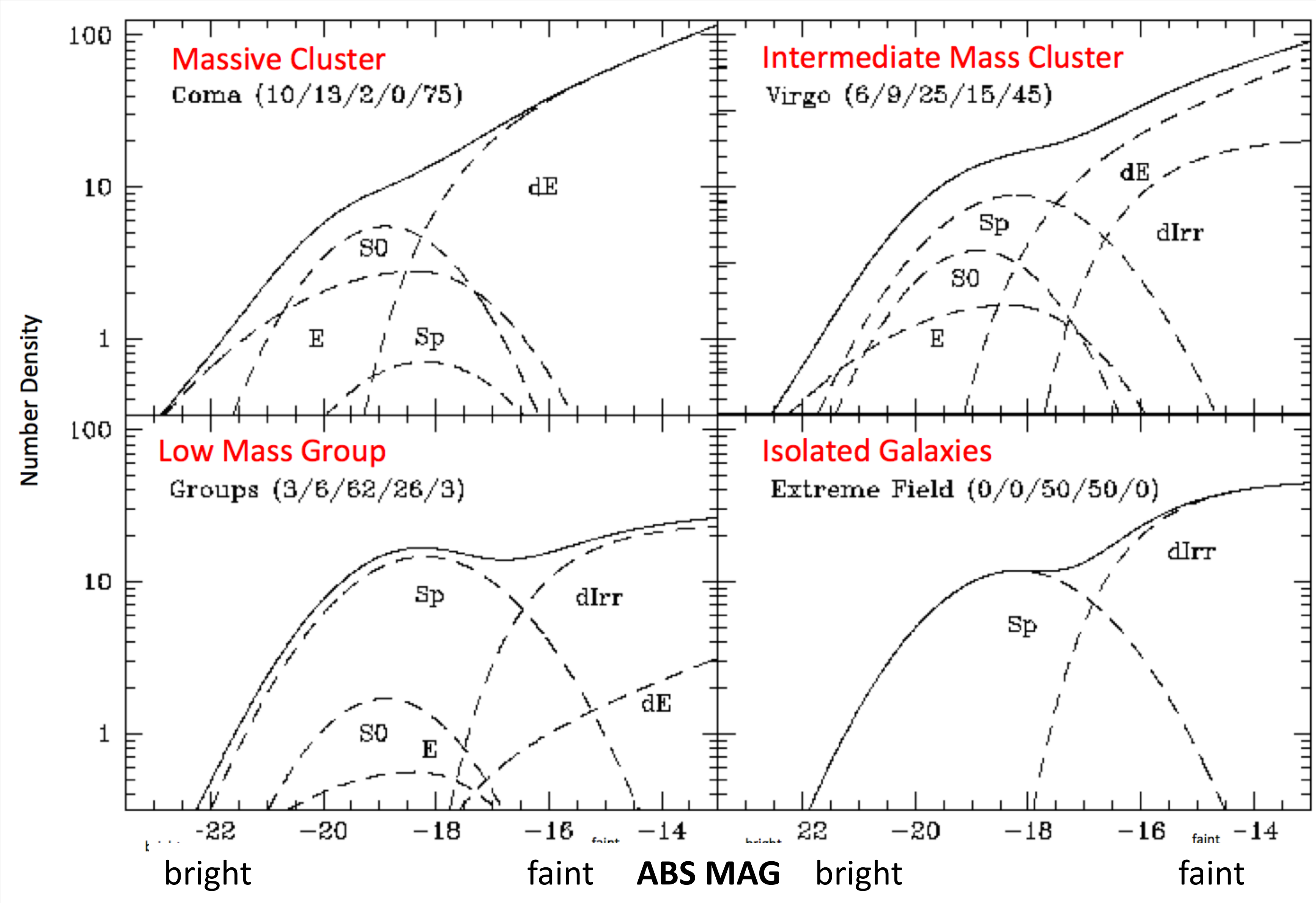
Inside big galaxy clusters:

- E/S0 dominate
- faint end mostly red things

In groups and field:

- Spirals dominate
- faint end mostly blue things

These are schematic LFs, not real ones!

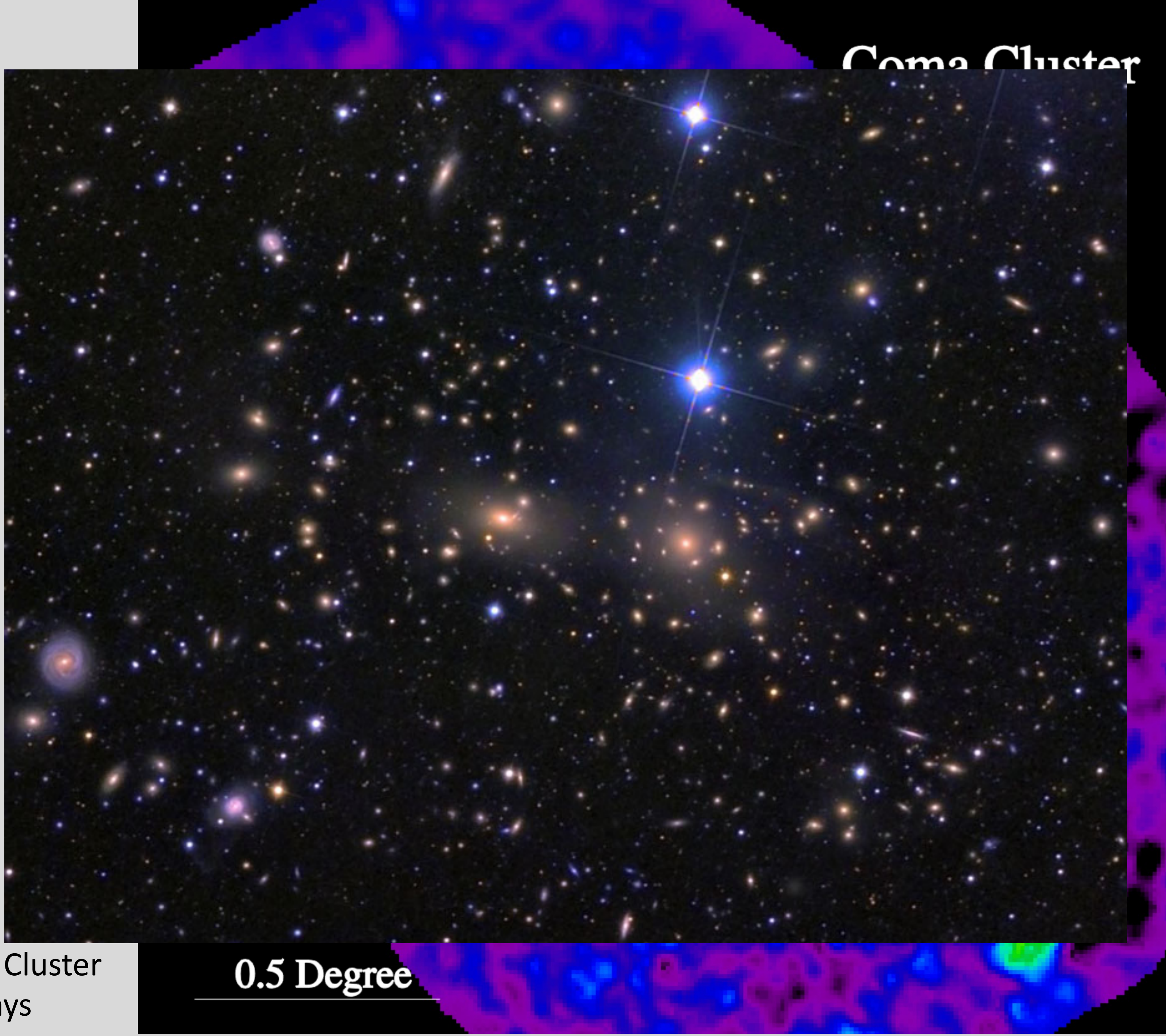


What processes drive evolution in denser environments?

- Ram pressure stripping of gas
- Interactions and mergers
- Tidal stripping and kinematic heating

Cluster X-ray gas

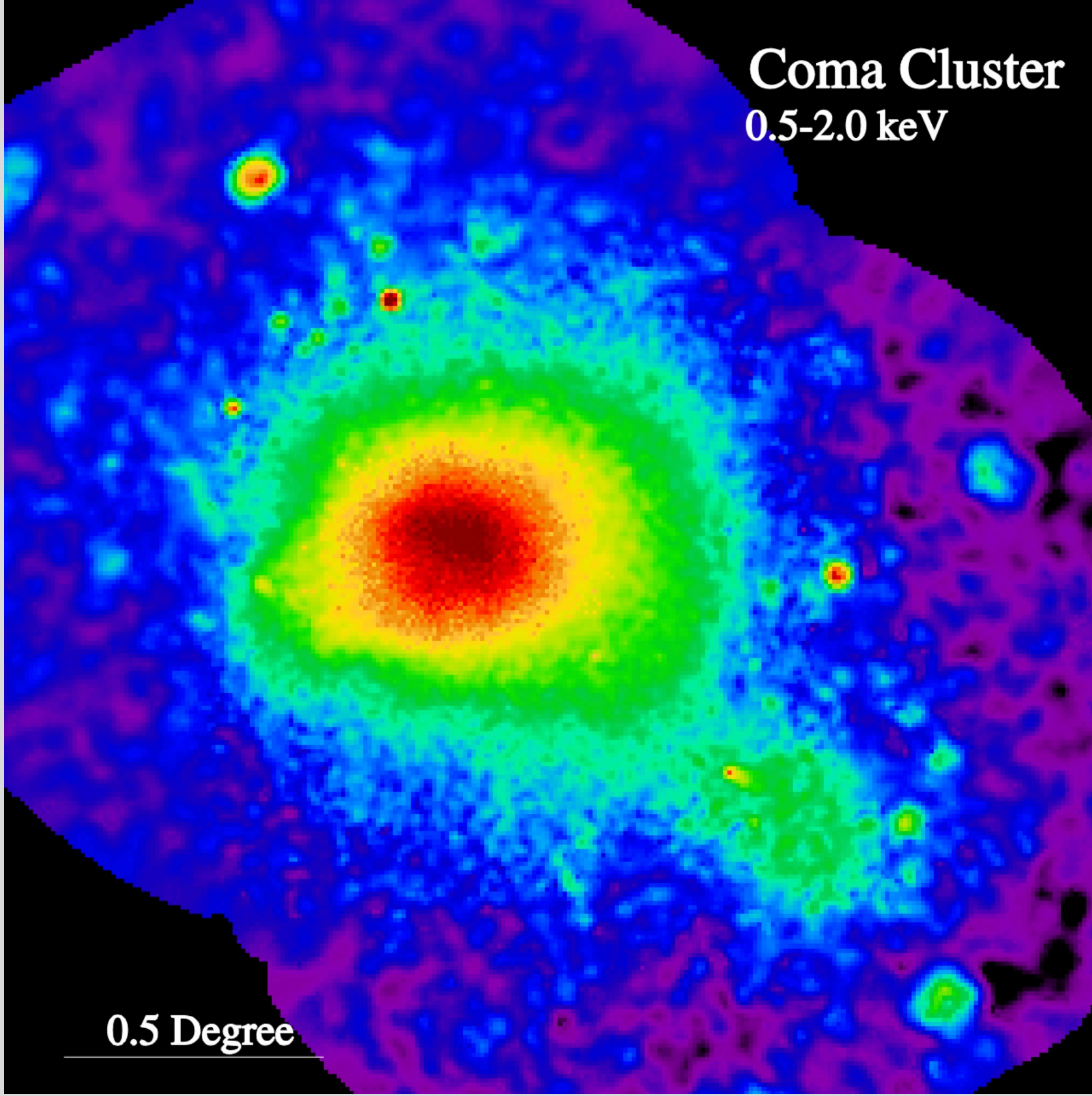
X-ray emission: free-free emission from hot ($\sim 10^7$ K) ionized gas spread throughout the cluster.



Coma Cluster in X-rays

Cluster X-ray gas

X-ray emission: free-free emission from hot ($\sim 10^7$ K) ionized gas spread throughout the cluster.



Coma Cluster
in X-rays

Hot gas in galaxy clusters

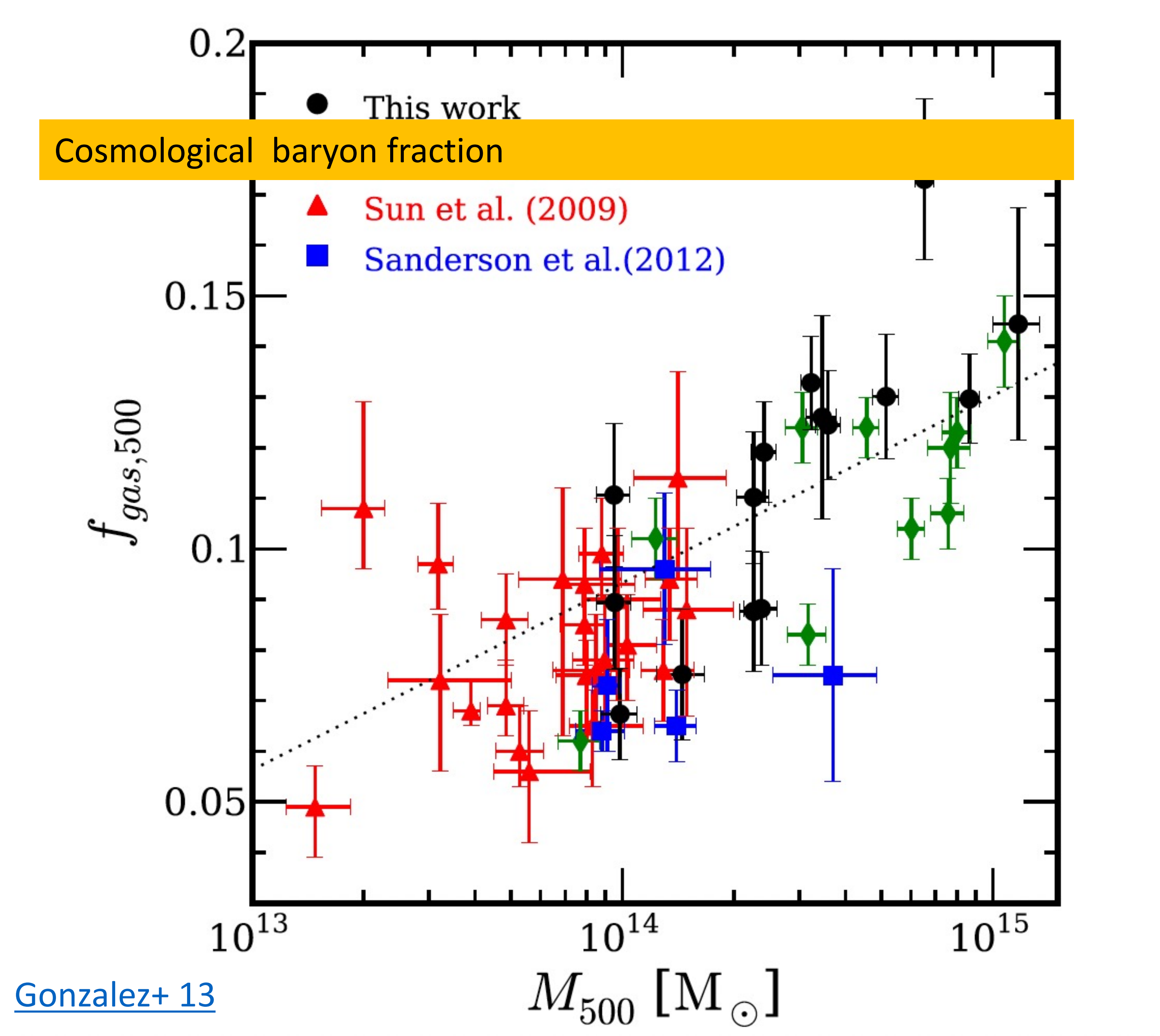
Hot gas become the dominant baryonic component in massive clusters.

If the gas is in hydrostatic equilibrium, thermal energy is comparable to gravitational potential:

$$kT \approx \frac{GM}{R}$$

So massive clusters have ***hotter*** X-ray gas, and ***more of it***.

Plot of fraction of total cluster mass (including dark matter) that is in hot X-ray gas, as a function of total cluster mass. ⇒



Gonzalez+ 13

Ram pressure stripping

Imagine a galaxy sweeping through the hot intracluster medium (ICM). It sweeps up hot gas at a rate

$$\frac{dM}{dt} = \pi R^2 \rho_{ICM} V$$

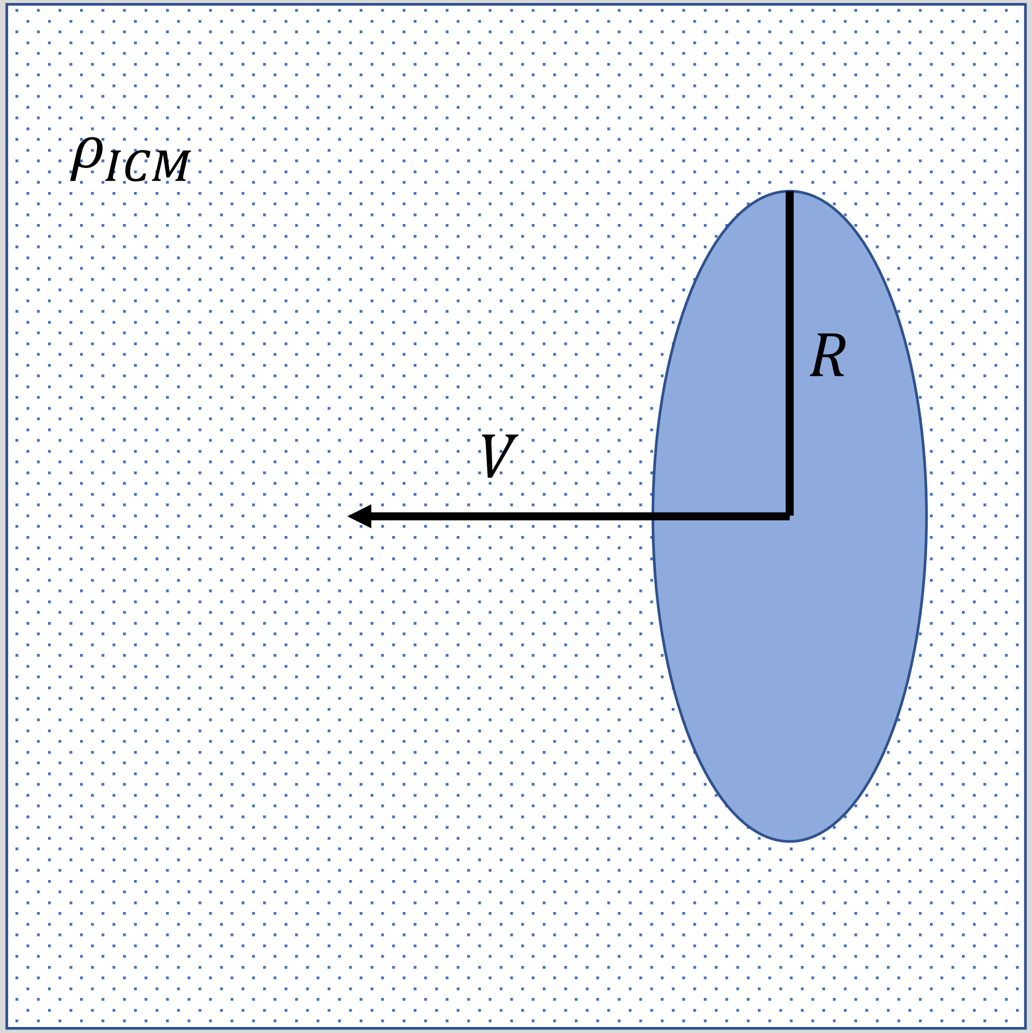
This transfers momentum ($p = mv$) to the disk gas at a rate

$$\frac{dp}{dt} = \frac{dM}{dt} V = \pi R^2 \rho_{ICM} V^2$$

Force is the rate of change of momentum, and pressure is force per unit area, so

$$P = \frac{Force}{Area} = \frac{dp/dt}{\pi R^2} = \rho_{ICM} V^2$$

The galaxy's gas will be stripped out of the disk if this "ram pressure" is greater than the gravitational force per unit area binding it to the disk.



Ram pressure stripping

Gravitational force per unit area holding the gas in the disk is given roughly by (Gunn & Gott 72)

$$F/area \approx \left(\frac{\partial\Phi}{\partial z}\right)_{grav} \Sigma_{ISM} \approx 2\pi G \Sigma_* \Sigma_{ISM}$$

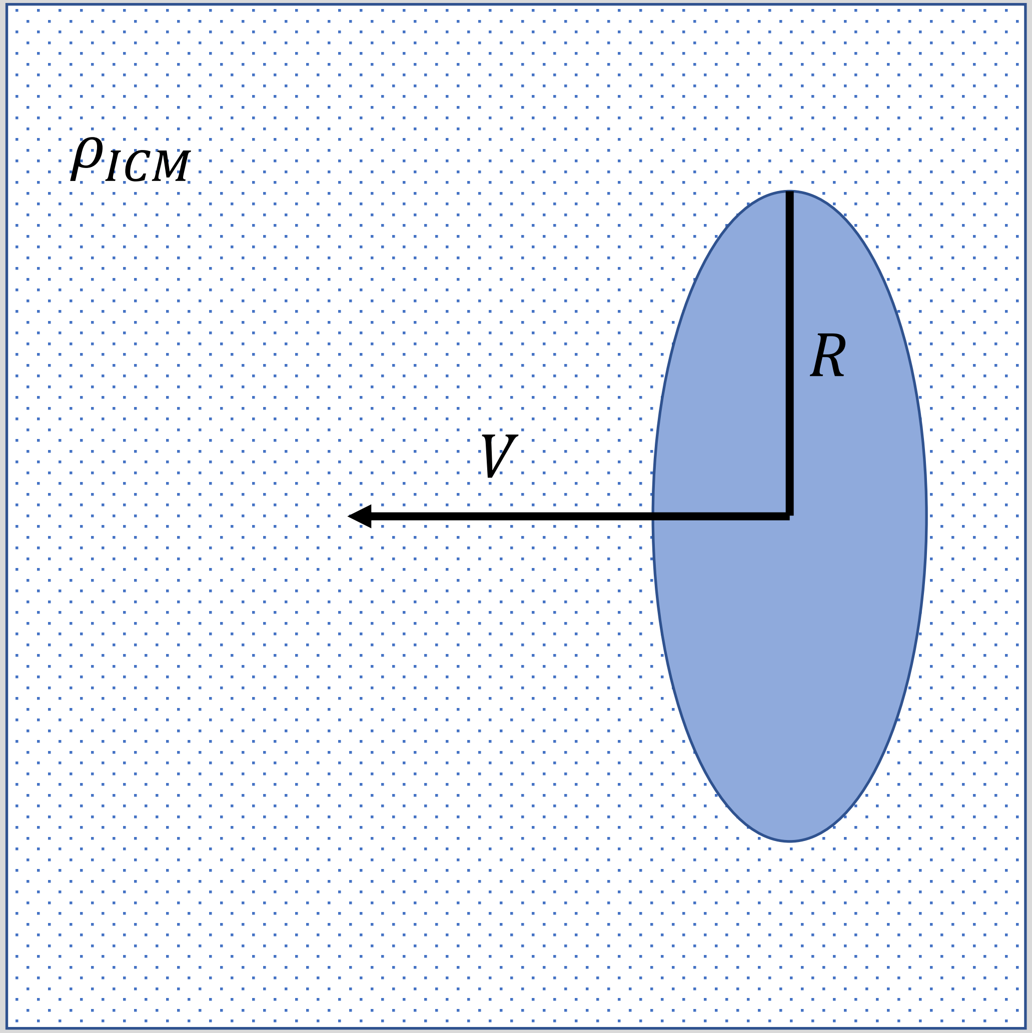
where Σ_* and Σ_{ISM} are the surface densities of stars and the interstellar medium in the galaxy's disk.

So stripping will happen when

$$\rho_{ICM} V^2 > 2\pi G \Sigma_* \Sigma_{ISM}$$

Things to note:

- Stripping happens faster at high speeds and high ICM density.
- The outskirts of galaxies will be stripped first, since they have low mass density (Σ_*) and cannot provide much restoring force.



Ram pressure stripping

Galaxy cluster ESO 137-001

Optical image + Chandra X-ray (diffuse blue)

As gas is stripped it is shock heated and shows up in X-rays. Adds material to the intracluster medium (hot gas)

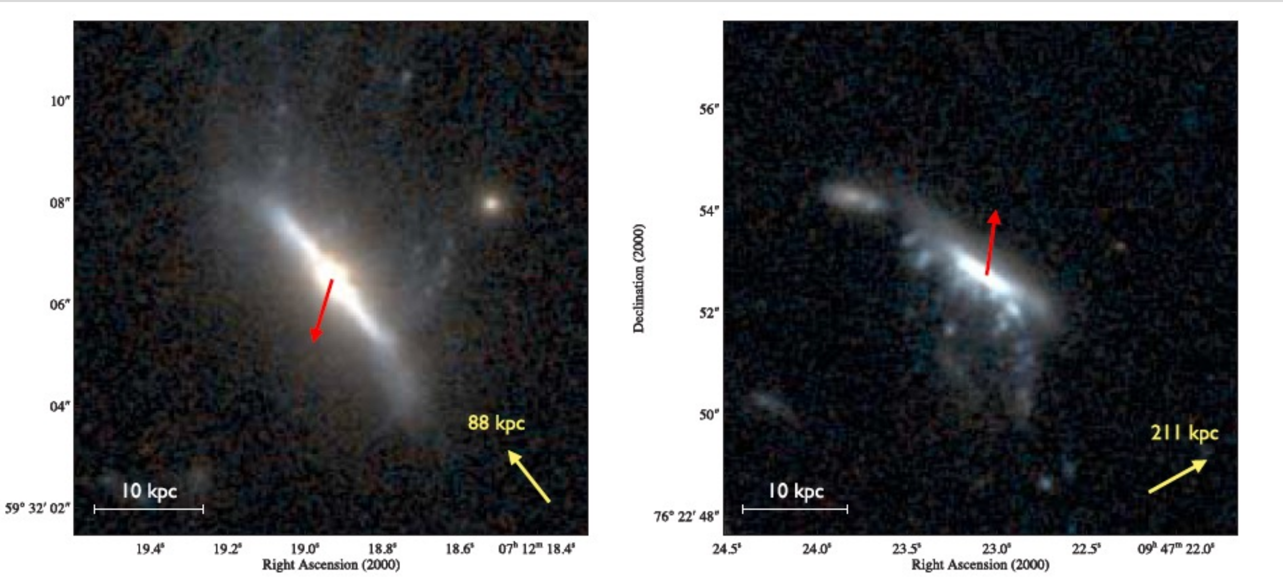
Note also blue knots close to the galaxy: star formation triggered by gas compression.

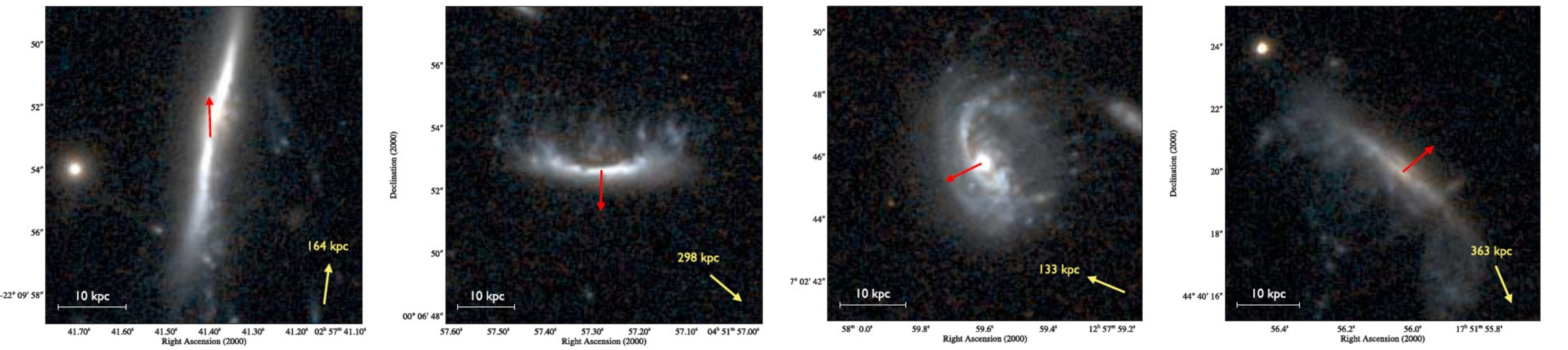
Ram pressure stripping

Hubble imaging showing signs of ram pressure at work in massive clusters at higher redshift.

Red arrows: direction of motion
Yellow arrows: point to cluster center.

Ebeling+ 14





Ram pressure stripping in the Virgo Cluster

White contours show HI-21cm emission (neutral hydrogen)

Top row: galaxies in **cluster outskirts**. Extended HI distributions.

Middle row: galaxies at **intermediate cluster radius**. HI doesn't stick out beyond the stellar radius.

Bottom row: galaxies nearer to the cluster center. HI-deficient – less gas, largely in the centers of the galaxy.

If you remove a galaxy's ISM, it can no longer form stars; the galaxy reddens and fades as existing stars evolve.

Spiral ⟹ Lenticular/S0 galaxy.

Chung+ 09

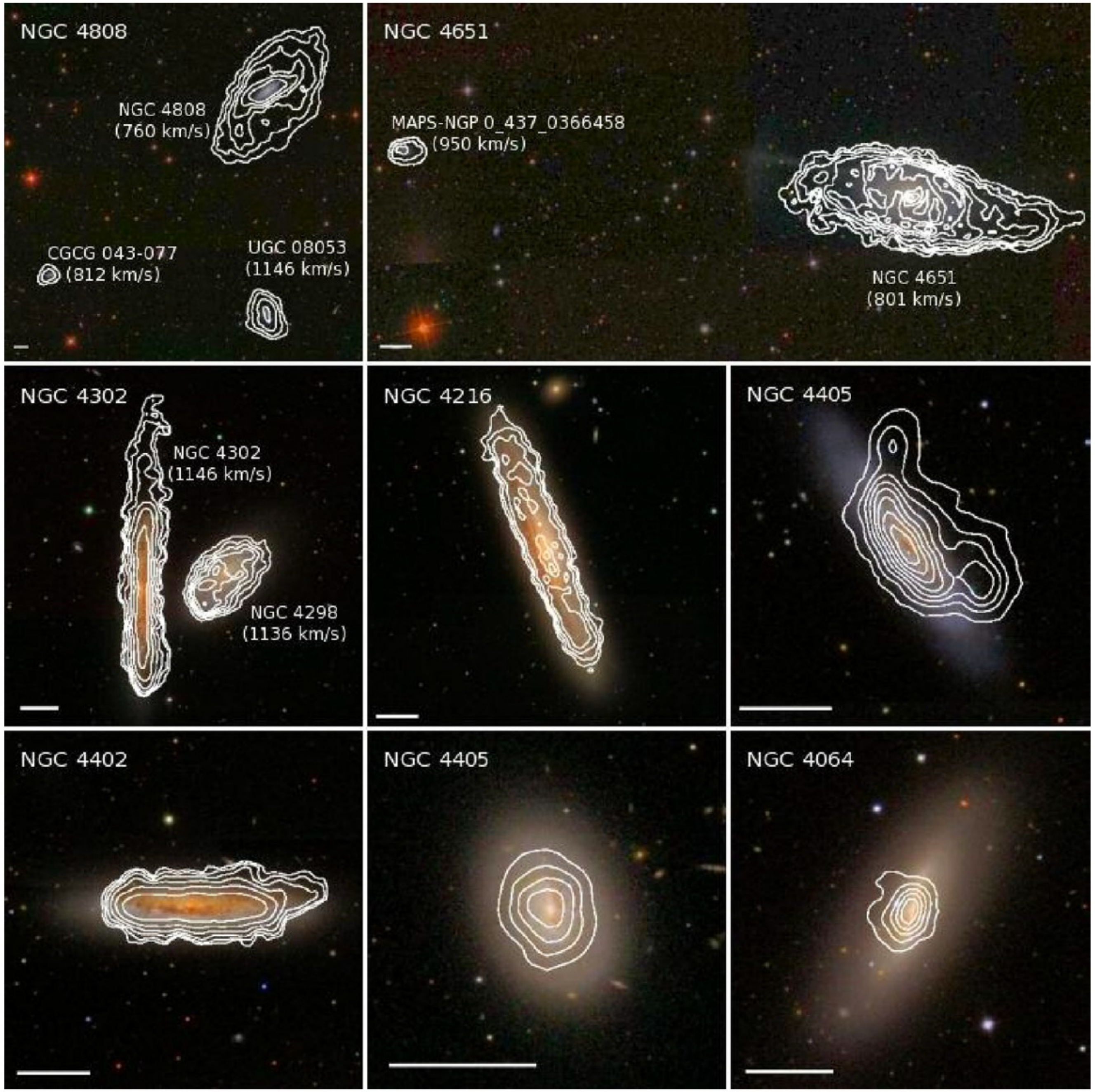


Figure 8. Examples of the different H I morphologies found in the survey. Total H I images are shown in white contours overlaid on the SDSS images. The thick white bar in the bottom-left corner indicates 1 arcmin in each panel. The top row shows examples of gas-rich galaxies in gas rich environments in the outskirts, the middle row shows galaxies at intermediate distances, while the bottom row shows examples of severely truncated H I disks at a range of projected distances from M87.

Galaxy Interactions: Flybys vs Mergers

Consideration #1: Conservation laws

During an interaction, energy (E) and angular momentum (L) are conserved, but can change between type.

Example: Angular Momentum (L) consists of both orbital angular momentum and internal angular momentum (spin) of each galaxy:

$$L_{tot} = L_{orb} + L_{spin,1} + L_{spin,2}$$

L_{tot} is conserved, but angular momentum can be transferred from L_{orb} to L_{spin}.

The interaction can add angular momentum to the galaxies, but that comes from the orbital angular momentum. Galaxies “spin up”, orbit decays.

To transfer E, L efficiently, the encounter velocity must be slow: $V_{orb} \sim V_{rot}$.

Galaxy Interactions: Flybys vs Mergers

Consideration #2: Dynamical Friction

During a close encounter, galaxies pass through each other's dark matter halos and feel dynamical friction:

$$\frac{dV}{dt} = -\frac{4\pi G^2 M\rho}{V^2}\ln\Lambda$$

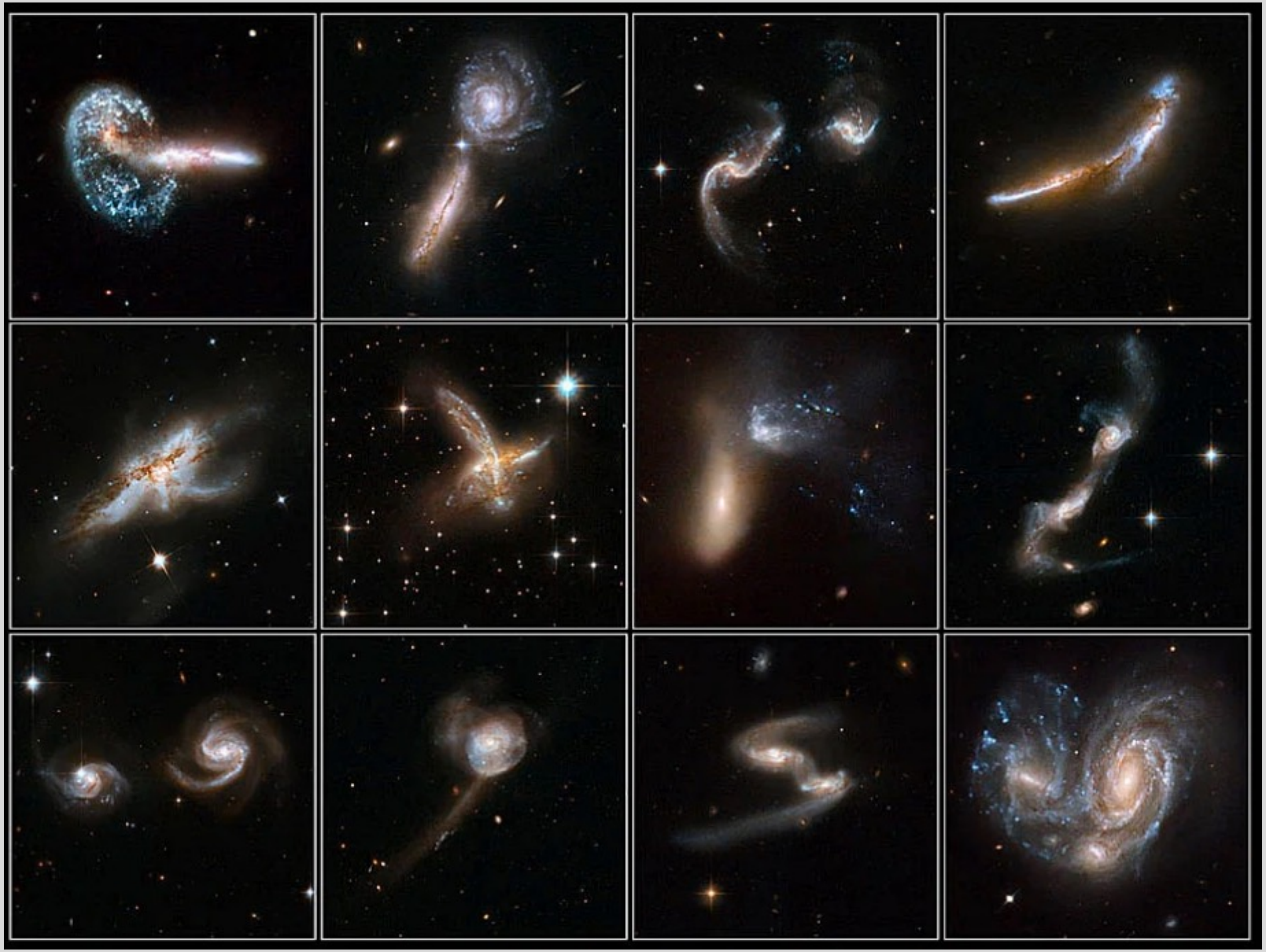
This dynamical friction slows the galaxies down, leading to orbital decay and eventually a merger.

If the relative encounter speed V is large, dynamical friction is less effective, leading to less orbital decay.

Summary: Conservation laws and dynamical friction arguments both say that slow encounters lead to strong interactions and mergers, while fast encounters are fly-bys that do less damage.

What determines response of a galaxy to a collision?

- **Galaxy masses**: more massive, more damage
- **Encounter speed**: Faster, less time during encounter, less damage.
- **Encounter geometry**: Prograde (spin/orbit aligned) do more damage than retrograde (spin/orbit opposite).
- **Viewing angle**: Doesn’t determine outcome, but can make the same object can look very different.
- **Merger vs Flyby**: combination of mass and encounter speed.



Encounter geometry

Prograde

spin/orbit motions in same sense (i.e. counterclockwise)

rough match between orbital and rotation velocity and sense of rotation ⇒ *resonance*.

Retrograde

spin/orbit motions in opposite sense.

no resonance, much weaker response.

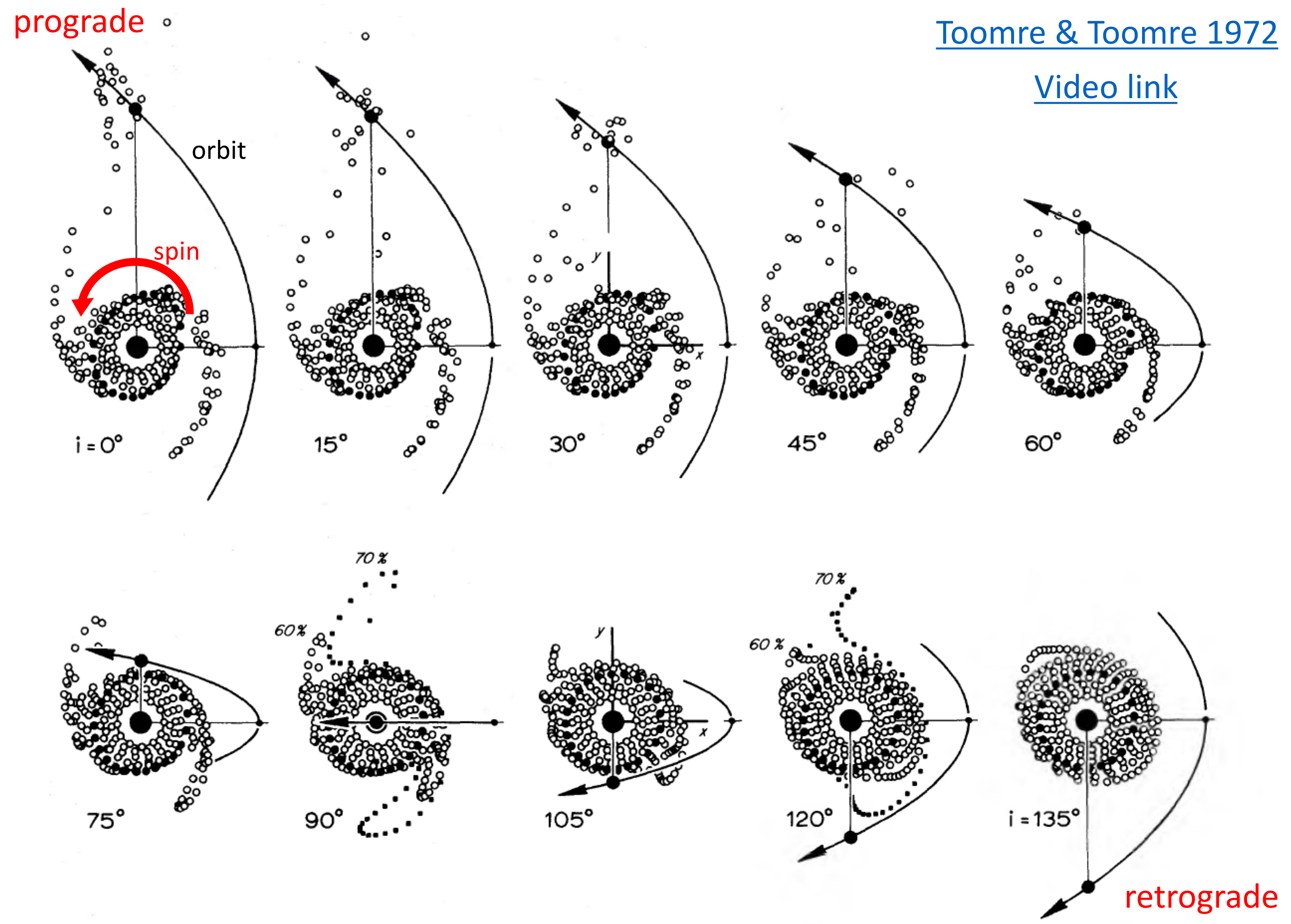


FIG. 7.—Face-on ($\beta = 0°$) views at $t = 3.143$ of disks perturbed by a quarter-mass companion during variously inclined parabolic passages of fixed argument $\omega = 0°$.

Real galaxies can be modeled

*(but models are **very** parameter-dependent!)*

[Toomre & Toomre 1972]

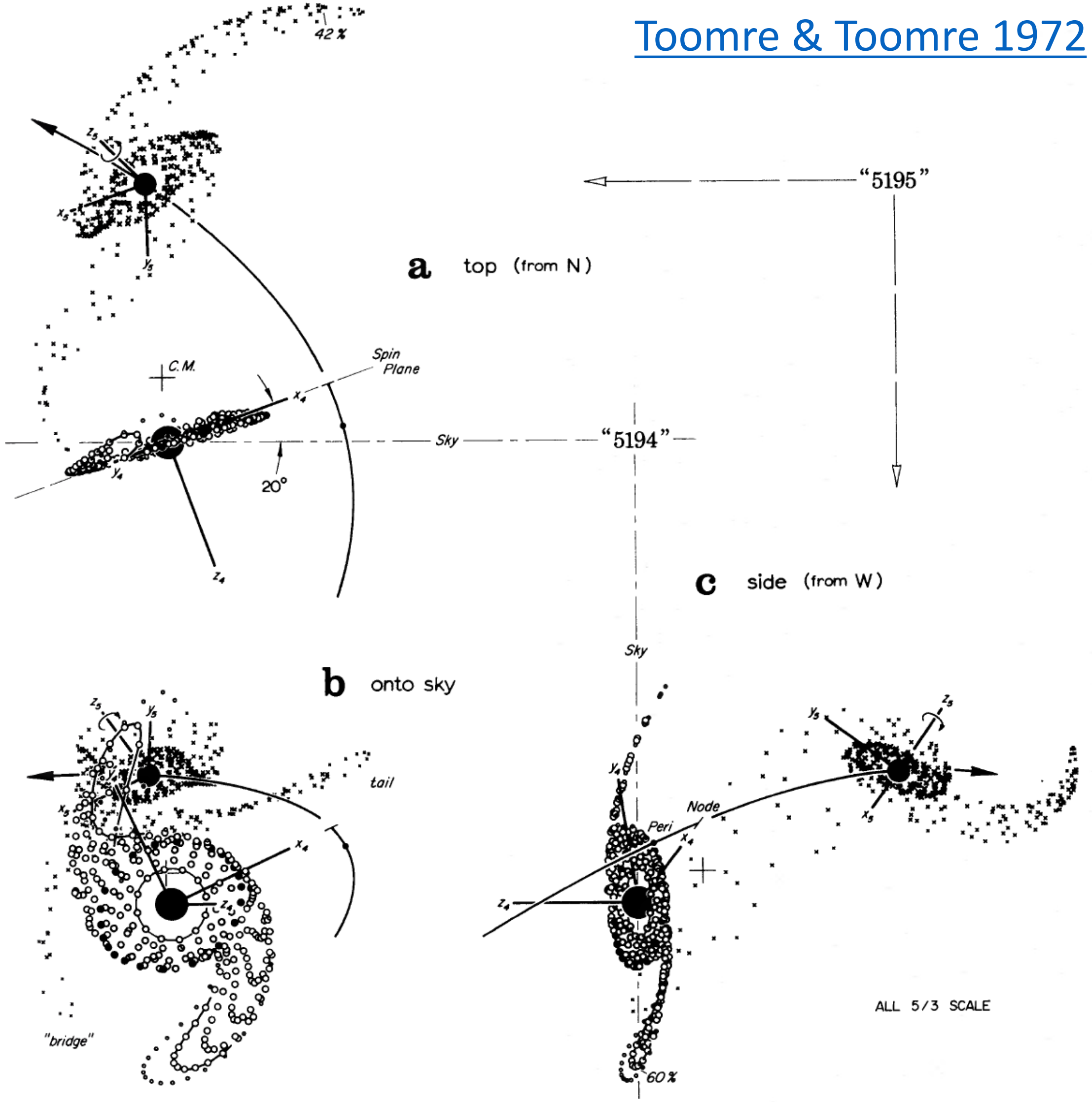


FIG. 21.—Model of the recent encounter between M51 and NGC 5195. Shown here at $t = 2.4$ are three mutually orthogonal views of the consequences of a highly elliptic $e = 0.8$ passage of a supposedly disklike "5195." This satellite was chosen to be one-third as massive, and of exactly 0.7 times the linear dimensions, of the "5194" primary—which itself contains particles from initial radii 0.2(0.05)0.4(0.033)0.633$R_{\min}$. The orbit plane differs by an angle $i_4 = -70°$ from the initial spin plane of the larger disk and by $i_5 = -60°$ from that of the smaller; however, the arguments $\omega_4 = \omega_5 = -15°$ of the pericenters were here kept identical, to make the above nodal axes x_4 and x_5 exactly antiparallel. The three views show the combined system as it would appear not only (*b*) to us ($\lambda_4 = 65°$, $\beta_4 = -20°$), but also edge-on to our sky from (*a*) the "north" ($-25°$, 90°) and (*c*) the "west" (65°, 70°) directions.

Merger Outcomes: Disk destruction

The strong and rapidly changing gravitational forces scatter stars off circular orbits and into random orbits.

A form of violent relaxation.

Transformation from disk to spheroidal structure.

Kinematically hot remnant ($\sigma_v / V_c \gg 1$).

NGC 7252 Hibbard+ 94

Merger Outcomes: Evolution of Tidal Debris

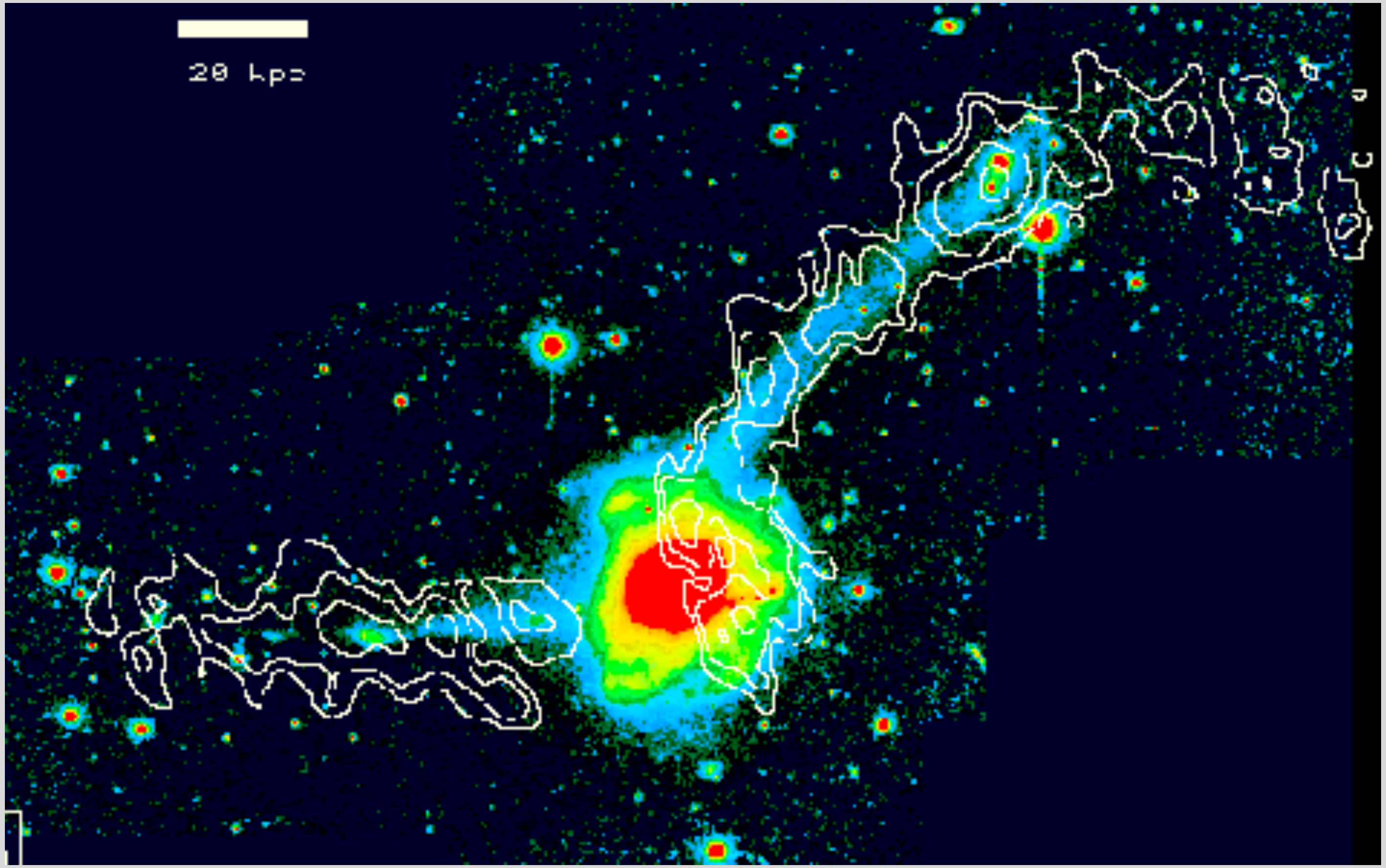
Tidal tails can contain both stars and gas.

Material near the end of the tails is least bound and moving outwards.

Material near the base of the tail is more tightly bound and infalling.

Tails are thus rapidly dispersing and fading.
Typically visible for ≈ 1 Gyr or so.

Infalling gas may resettle into a disk.



False color: surface brightness of starlight
Contours: neutral hydrogen gas (HI-21cm)

NGC 7252 (inner disk)

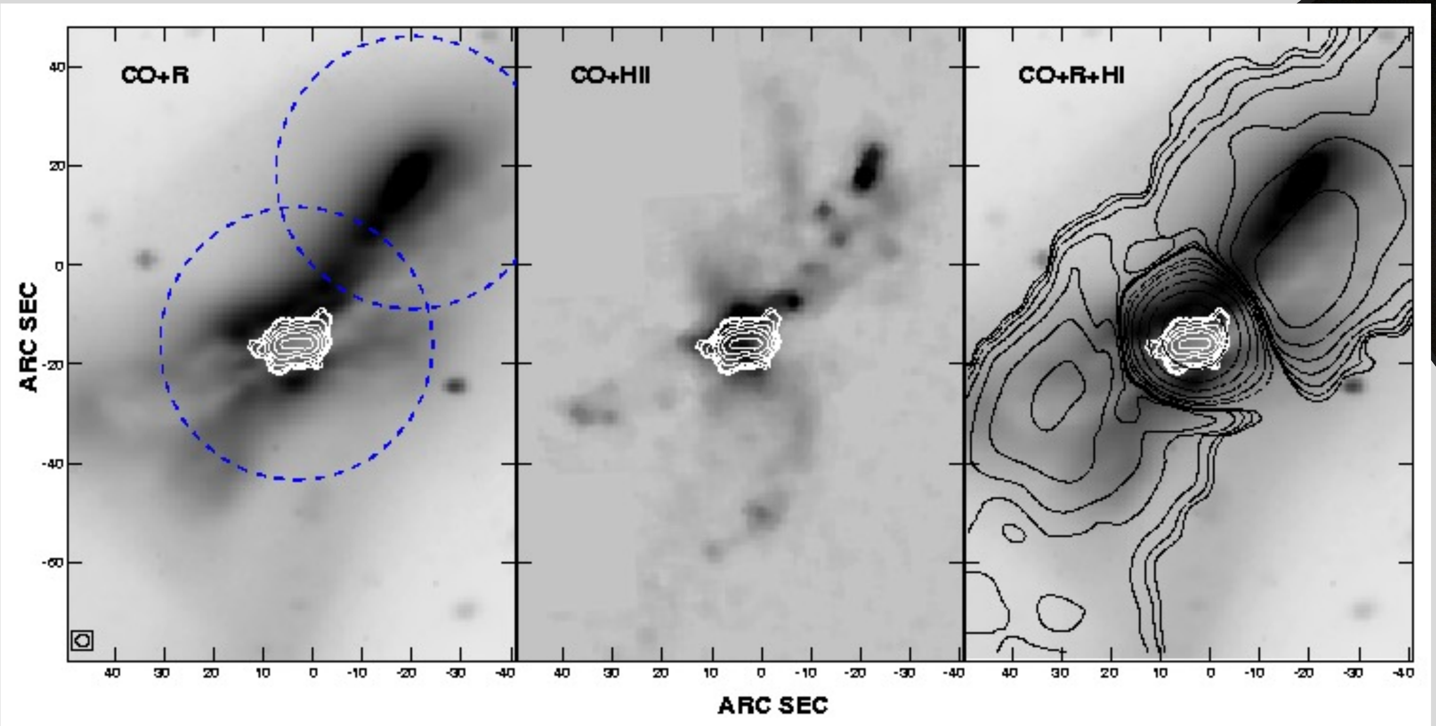
Merger Outcomes: Gas inflow to nucleus

Strong shocks and gravitational torques can drive gas into the center of the merging galaxies.

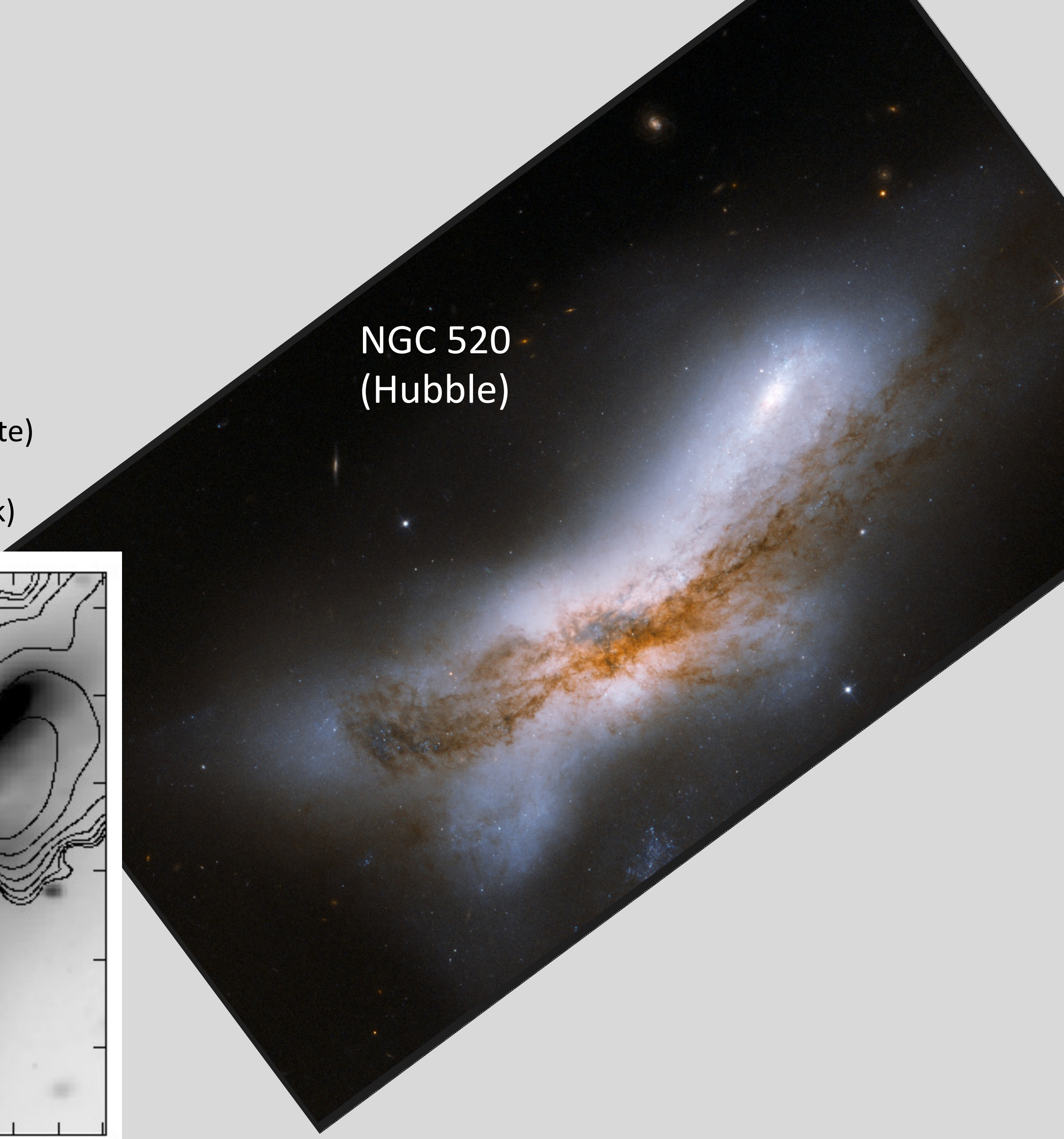
molecular gas (white) and starlight (grey)

molecular gas (white) and $H\alpha$ emission (grey)

molecular gas (white) starlight (grey) HI emission (black)



[Yun & Hibbard 2001]



Merger Outcomes: Strong starburst activity

Star formation triggered across the galaxies and deep inside dusty inner regions.

Star formation rates elevated by 100x or more.

Short gas depletion times:

$$t_{deplete} = \frac{M_{gas}}{SFR} \sim 10^7 - 10^8 \text{ years}$$

Results in supernovae, stellar winds, heating and dispersal of much of the remaining gas.

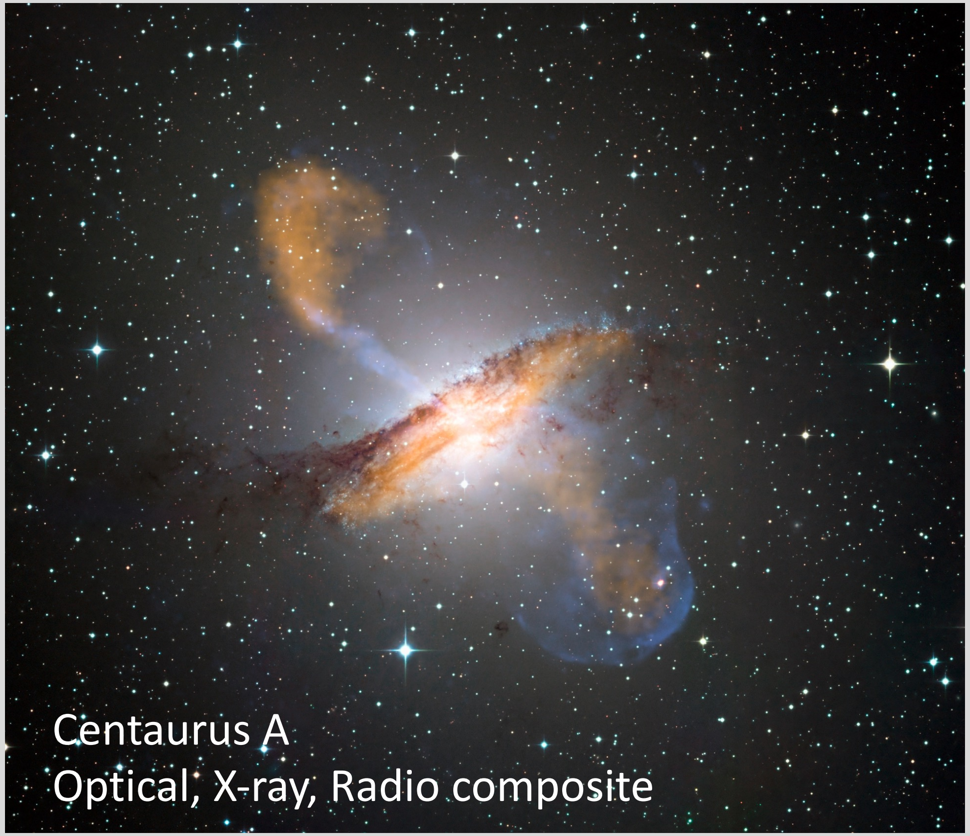
NGC 4038/9 (Hubble)

Merger Outcomes: Strong AGN activity

Infall of gas can accrete onto a black hole: AGN

Black holes grow by accretion of gas and by coalescing/merging.

Gas accretion can fuel AGN for quite a while



Centaurus A
Optical, X-ray, Radio composite

NGC 6240
(Chandra X-ray)

NGC 6240
(Hubble)

Making Ellipticals from mergers

Disk destruction: makes $r^{1/4}$-like spheroid.

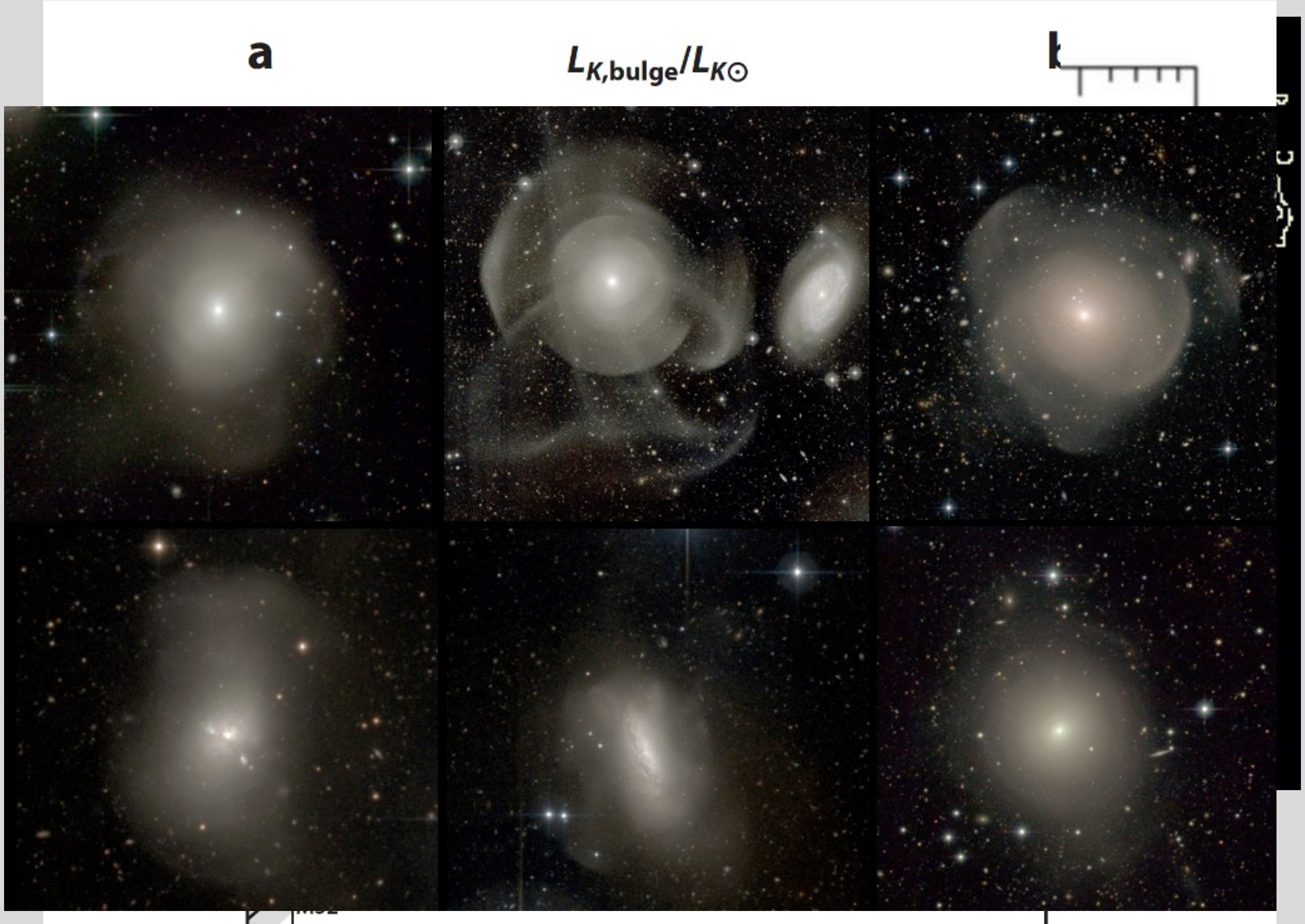
Gas evolution: lots of gas expelled in tails or driven into nucleus.

Star formation: consumes gas, creates central starburst, heats gas

AGN: grows central black holes, heats gas

Explains:

- central cusps and cores
- black hole mass connected to spheroid mass
- absence of cold gas, presence of hot gas
- presence of tidal debris around many ellipticals



Good *conceptual* picture, but many questions remain. What were mergers like at early times? What about dry vs wet mergers? Is it mostly a few big mergers or many small mergers? How does it depend on environment? Galaxy type? etc…

Fly-by Encounters, Cluster Tides, and Galaxy Evolution

In clusters, the velocity dispersion is high ($\sigma_V \approx 1000$ km/s) so interaction velocities are much higher than galaxy internal velocities (≈ 200 km/s). Galaxies generally do not merge, but pass by each other at high speeds: ”fly-by” encounters.

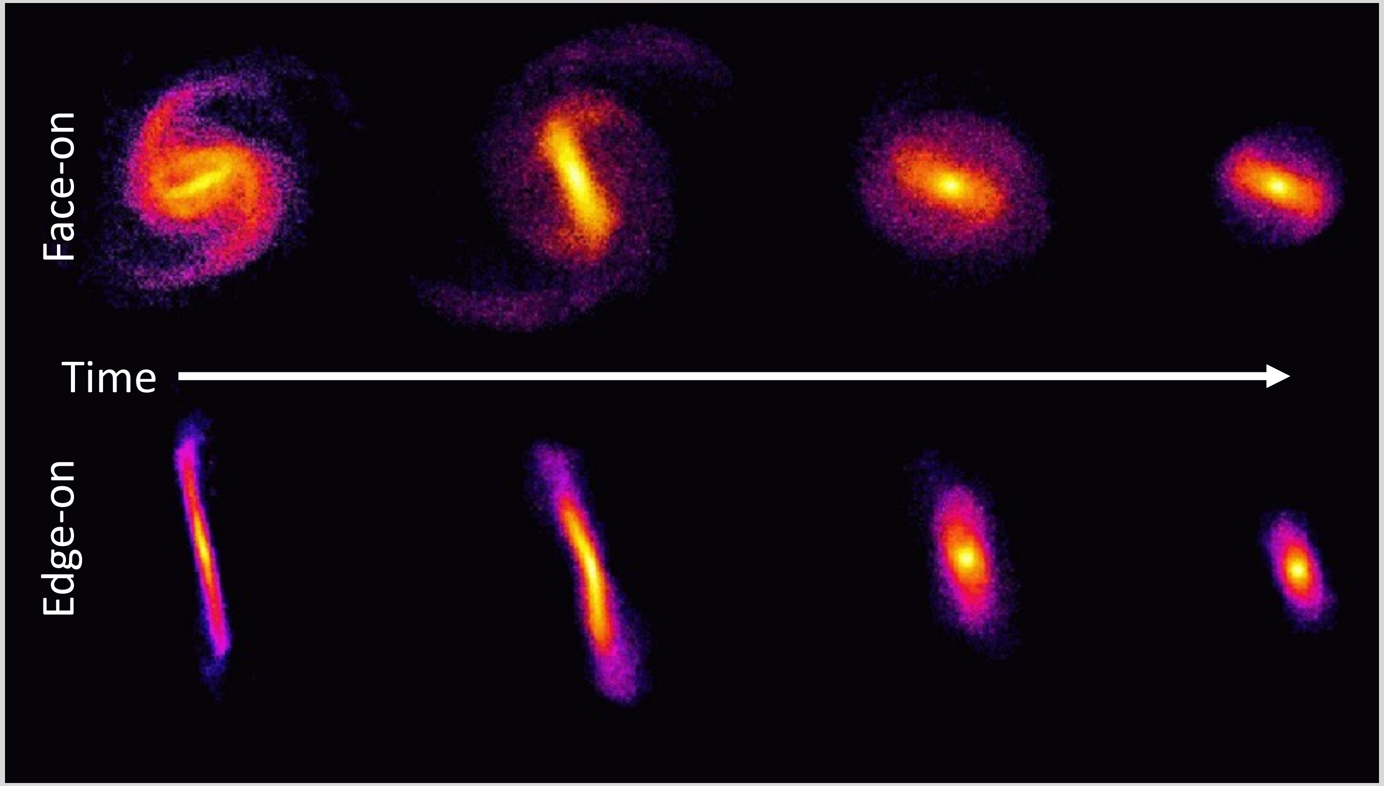
Galaxies’ stars pick up a little bit of extra kinetic energy during these fly-by encounters – resulting in a small amount of dynamical heating. Multiple fast fly-by passages in clusters can slowly and continuously ”heat” the galaxy over time.

Cluster Tides

The tidal field of the galaxy cluster can also strip stars and dynamically heat galaxies that orbit within it, similar to how the Milky Way strips stars off its satellite galaxies.

The combination of ongoing fly-by encounters and the effects of the cluster potential can drive strong evolution (particularly for low mass galaxies).

Simulation courtesy Victor Debattista



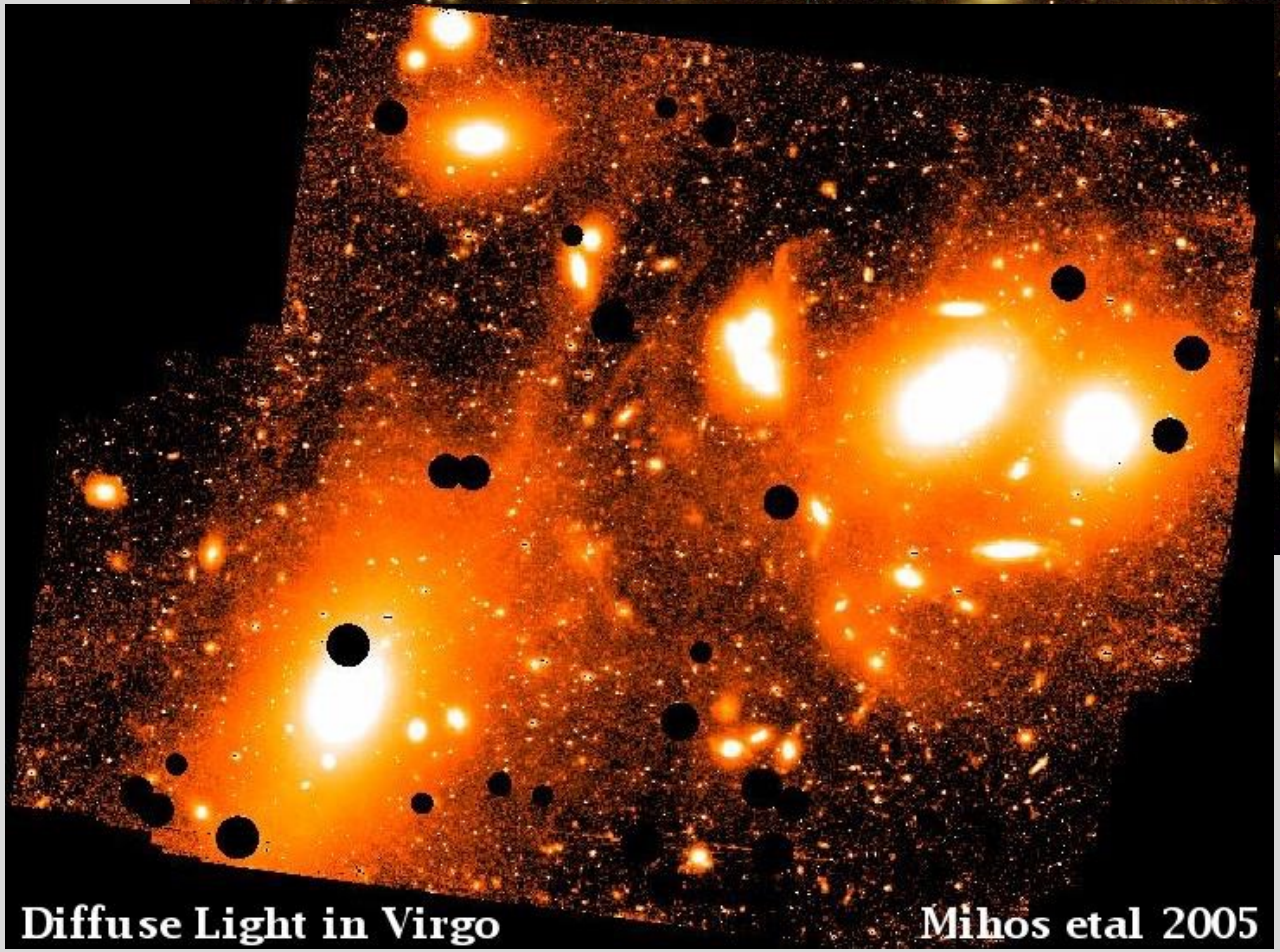
The central dominant galaxy (cD galaxy)

There is a special place in the cluster: the center, often occupied by the biggest elliptical galaxy surrounded by a very extended diffuse envelope of starlight.

Matter density is highest here, meaning dynamical friction is important. It affects massive galaxies the most, so big galaxies merge at the center: galactic cannibalism.

Meanwhile low mass galaxies are easily stripped apart due to the high mass density in the inner parts of the cluster.

cD galaxy grows more massive with time, and is surrounded by the starlight it has stripped from smaller galaxies.



Evolution in Groups vs Clusters

Note: no hard dividing line between groups and clusters!

	Groups	Clusters
Masses	few x 10^{12} – 10^{13} $M_\odot$	10^{14} – 10^{15} $M_\odot$
Velocity Dispersions	few hundred km/s	thousand km/s
Galaxy numbers	few big ones	100s – 1000s
Galaxy types	spirals more than ellipticals	ellipticals more than spirals
Intracluster gas	Cold HI/molecular gas in galaxies, not much hot intragroup gas	Not much cold gas in galaxies, clusters dominated by hot X-ray gas

Galaxies in Groups:

- Slow encounters, effective at driving strong tidal response and mergers. Formation of "normal" ellipticals?
- Ram pressure stripping not important (except maybe for dwarf galaxies orbiting near massive hosts)

Galaxies in Clusters:

- Fast encounters do less damage, but more of them
- Also encounters with the overall cluster potential: tidal stripping
- Ram pressure stripping becomes dominant
- cD galaxies grow the center through (mostly) dry mergers

Putting it all together: Hierarchical Growth and Cluster Galaxies

Cluster assemble hierarchically. Clusters today were many separate small groups in the past.

In those small groups, slow encounters lead to mergers and make ellipticals.

Over time the groups coalesce into clusters.

Hot cluster gas forms from a combination of stripping and ejection from galaxies, as well as primordial gas falling into cluster.

Spirals are continually heated and ram pressure stripped: gas-poor red disk galaxies (S0-types).

Central cD galaxy grows by cannibalism and stripping of galaxies passing near the center.

Infall of galaxies from outskirts provides new victims for the cluster....