INAF ISTITUTO NAZIONALE DI ASTROFISICA
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UNIVERSITÀ DEGLI STUDI FIRENZE

Lecture X: Dynamical processes of galaxy evolution

Astrophysics of Galaxies 2019-2020

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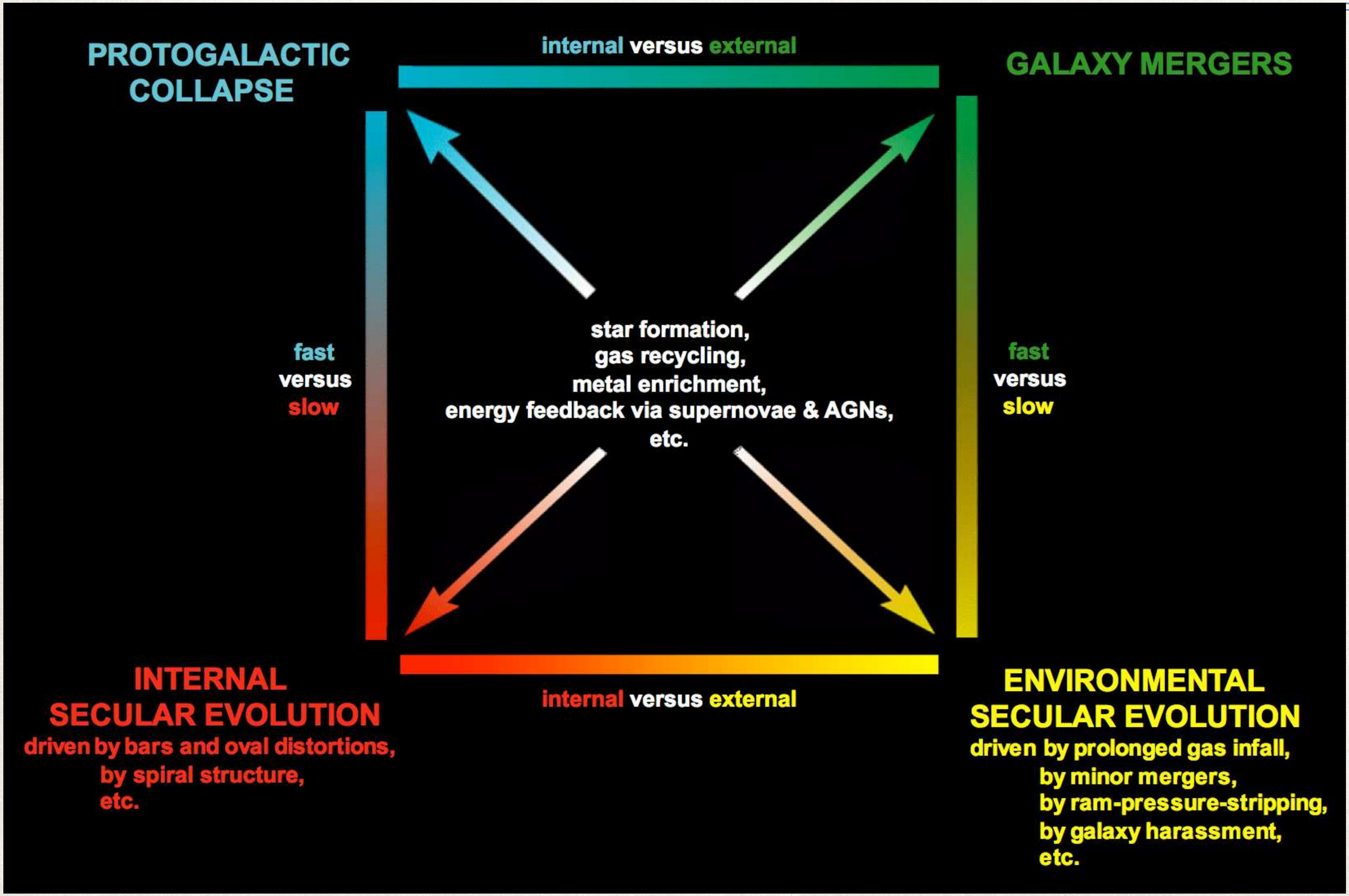
Evolution of galaxies: fast vs slow (secular) processes (credits to Kormendy 2011 IAC WS)



Most relevant at early times

Time→

Most relevant at late times

Secular evolution of self-gravitating systems

It is energetically favorable to spread — to form a denser core and a more diffuse halo.

Galaxy disks are supported by rotation; they spread in 2-D by outward angular momentum transport driven by nonaxisymmetries like bars. Growth of pseudobulge is analogous to growth of star from protostellar disk.

Protoplanetary disks are supported by rotation; they spread in 2-D when big planets fling little planets, making hot Jupiters & colder Neptunes.

Spherical stellar systems are supported by random motions; they spread in 3-D by outward energy transport driven by 2-body relaxation ("core collapse").

Stars are supported by hydrostatic pressure; they spread in 3-D by outward energy transport via radiation and convection, and by outward angular momentum transport driven by magnetic coupling to protostellar disks. Result: compact remnants such as stellar-mass BHs.

BH accretion disks are supported by rotation; gas flows inward in 2-D via outward angular momentum transport mediated by magnetic coupling to jets. BH growth is as natural in galaxies as proto-BH core growth is in stars.

Secular processes in galaxies

- In systems supported by random motion
  - evolution by “heat” transport
  - virial theorem: $E=K+U=-K=-Nmv^2/2$
  - Temperature: $3/2kT=1/2mv^2$
  - Negative specific heat $C \equiv dE/dT \propto d(-Nmv^2/2)/d(v^2)$
  - If the center gets hotter, then heat flows outwards and makes the periphery cooler, through expansion. This reinforces the temperature gradient and promotes further the heat flow.
  - Timescale is the key: in ellipticals it’s too long to be effective.

Secular processes in galaxies

- In systems supported by rotation
  - evolution by angular momentum transport

The "goal" is to minimize the total energy at fixed total angular momentum. A rotationally supported ring at radius r in a fixed potential $\Phi(r)$ has specific energy $E(r)$ and specific angular momentum $L(r)$ given by

$$E(r) = \frac{r}{2}\frac{d\Phi}{dr} + \Phi \quad \text{and} \quad L(r) = \left(r^3 \frac{d\Phi}{dr}\right)^{1/2} . \qquad (1.1)$$

Then $dE/dL = \Omega(r)$, where $\Omega = (r^{-1} d\Phi/dr)^{1/2}$ is the angular speed of rotation. Disks spread when a unit mass at radius r_2 moves outward by gaining angular momentum dL from a unit mass at radius $r_1 < r_2$. This is energetically favorable: the change in energy,

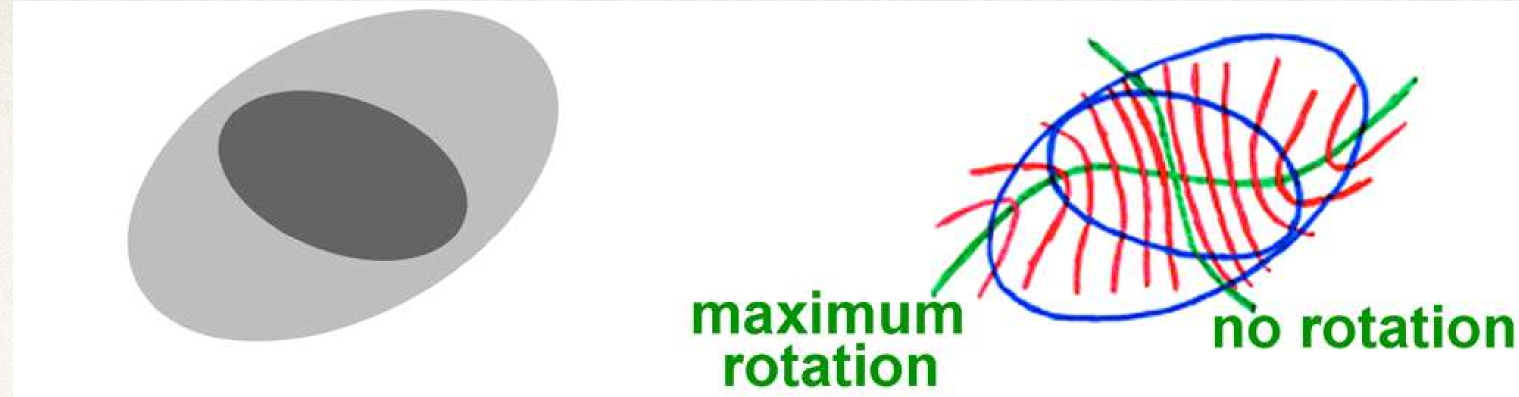
$$dE = dE_1 + dE_2 = \left[-\left(\frac{dE}{dL}\right)_1 + \left(\frac{dE}{dL}\right)_2\right] dL = [-\Omega(r_1) + \Omega(r_2)]\, dL\,, \quad (1.2)$$

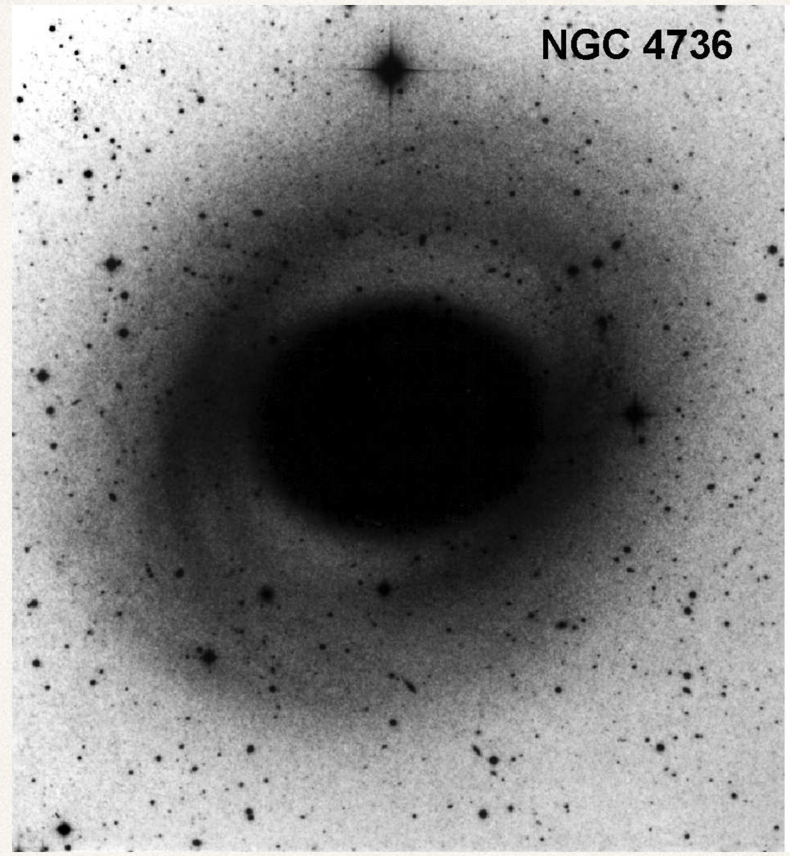
is negative because $\Omega(r)$ usually decreases outward. "Thus disk spreading leads to a lower energy state. In general, disk spreading, outward angular momentum flow, and energy dissipation accompany one another in astrophysical disks" (Tremaine 1989).

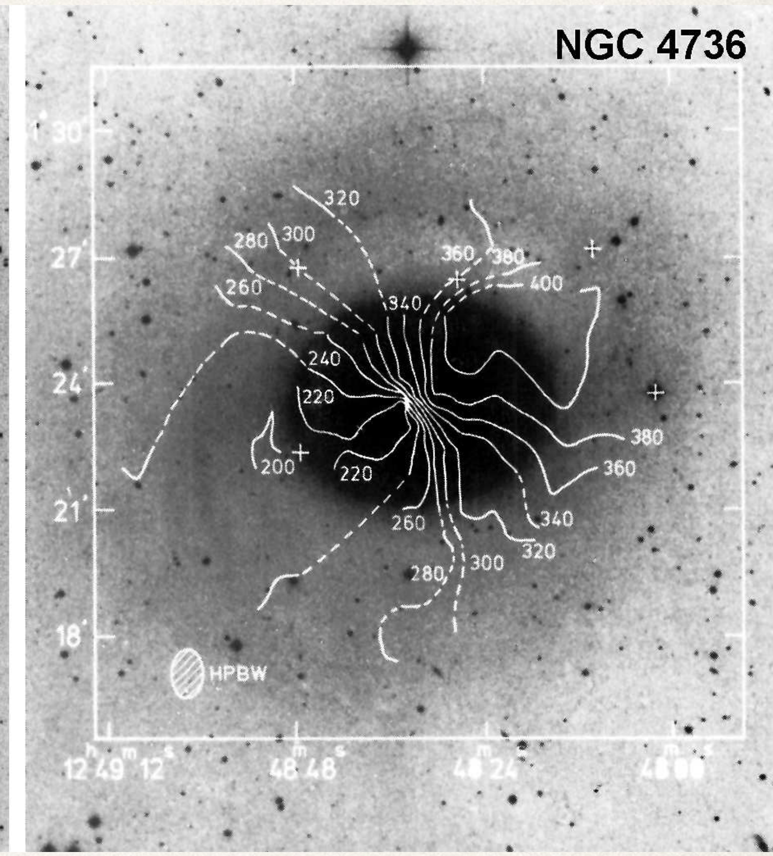
Secular processes in (disk) galaxies

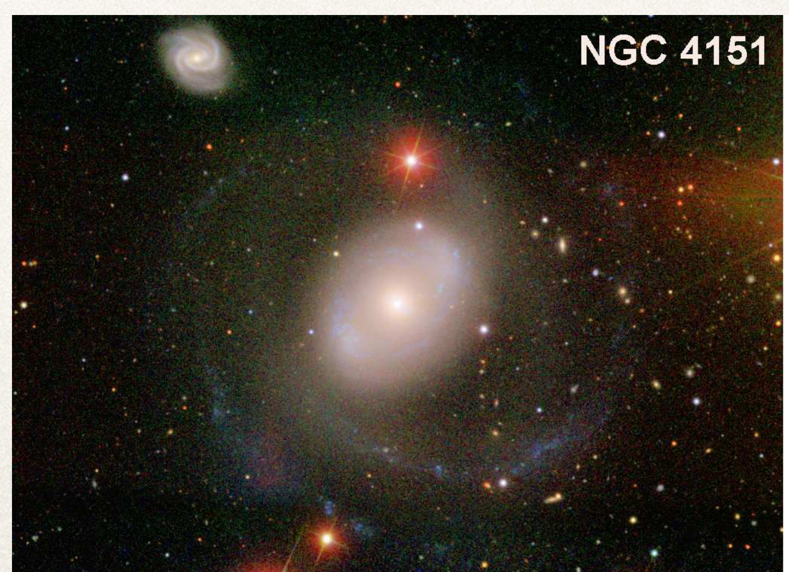
- Which galaxies?
  - angular momentum redistribution and therefore radial mass transport happens mostly to gas. The need for gas disfavors early-type galaxies and favors late-type galaxies.
- Secular evolution in galaxy disks is, in the current Universe, happening mostly in intermediate-late-type (e.g., Sbc) galaxies. These are the galaxies in which pseudobulges turn out to be most prominent.
- Secular evolution is too slow to be important in the latest-type galaxies, because the mass distribution is too “fluffy”, and so it is not energetically favorable to transport angular momentum outward.
- Secular processes no longer transport much gas in S0 and Sa galaxies, because they no longer contain much gas. Nevertheless,
  - purely stellar secular processes are expected to happen in these galaxies
  - secular evolution is believed to have been important in the past, because many S0 galaxies are observed to contain disky pseudobulges.

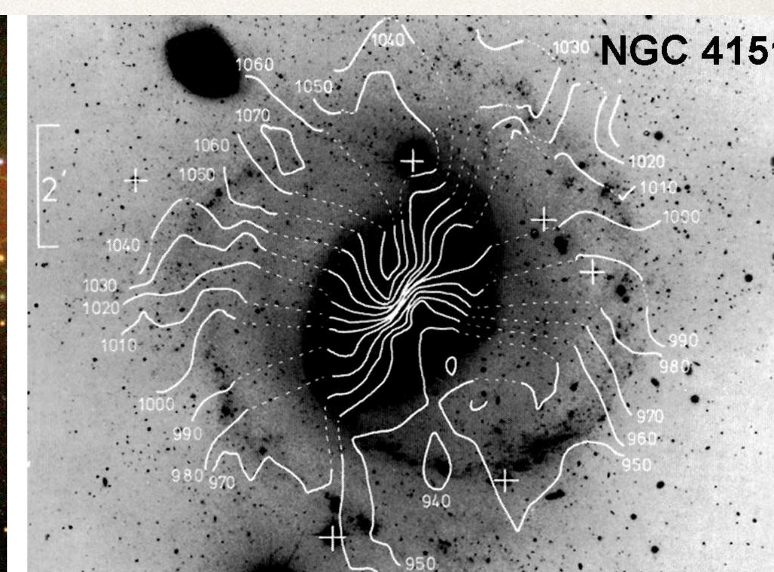
The engines of secular evolution: I. oval disks







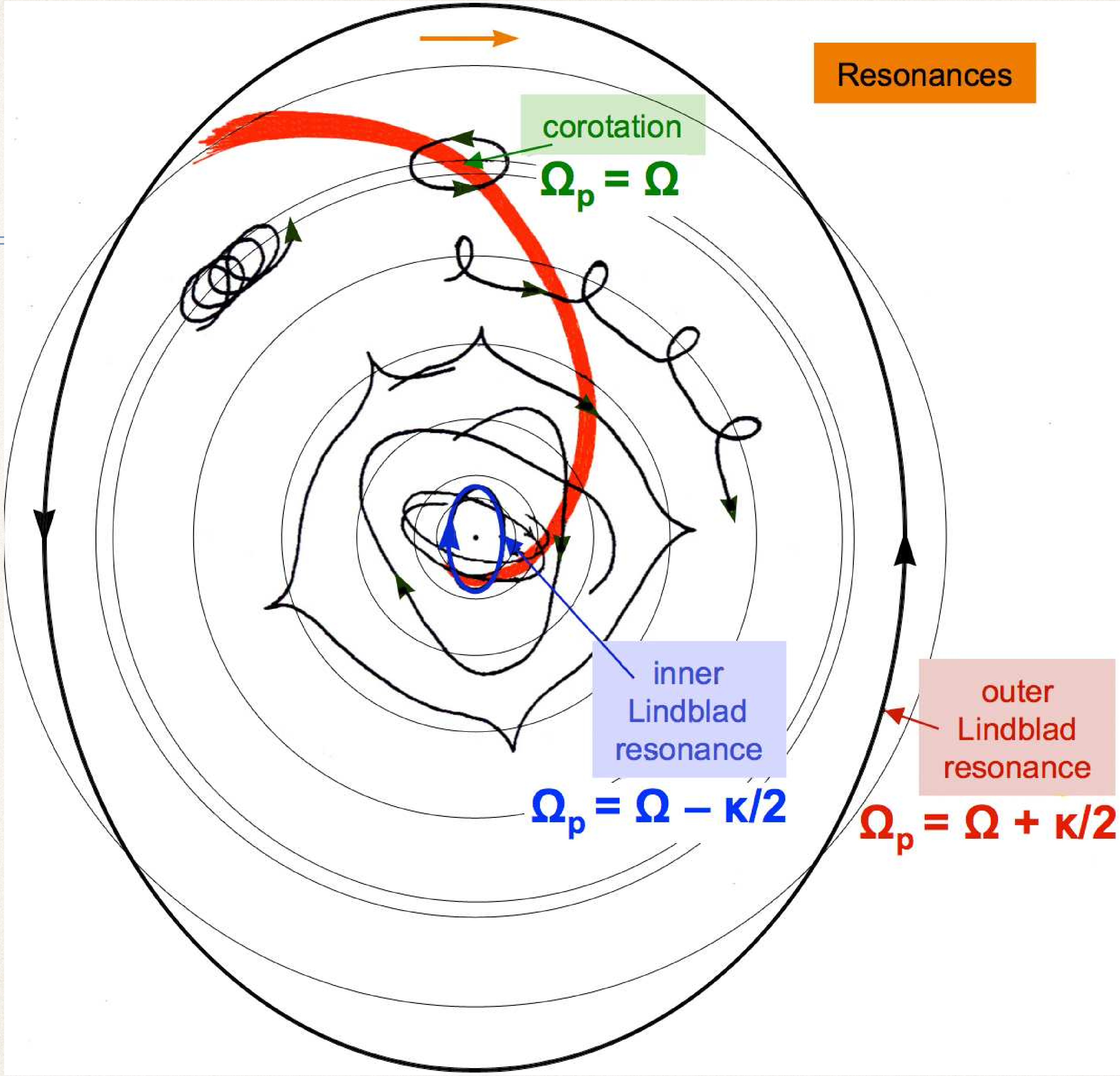




- Introduce global non-axisymmetry
- axial ratio ~0.85
- as effective as bars

The engines of secular evolution:

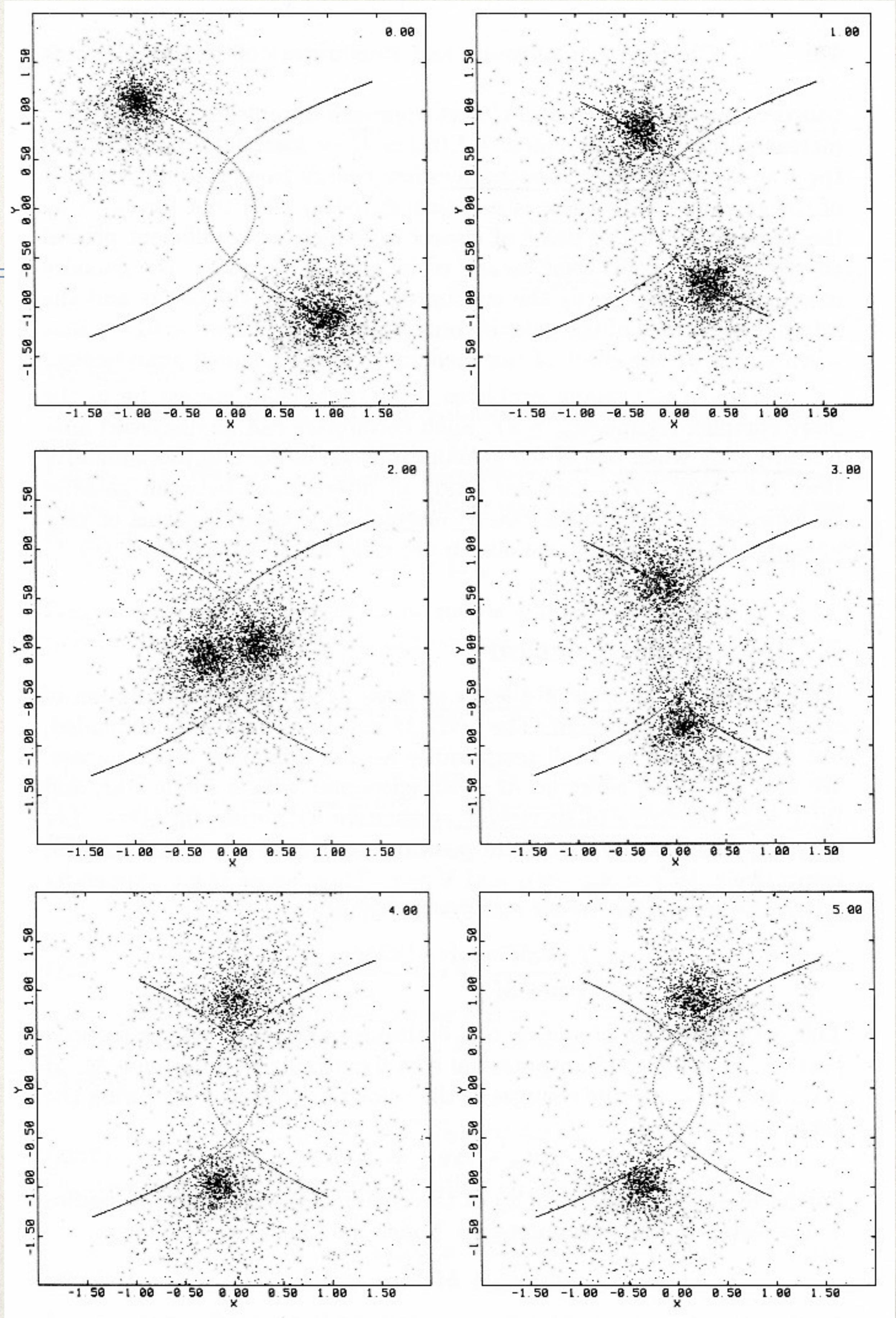
II. spirals
III. bars



- recall all discussion about the m=2 breaking of axisymmetry from previous lecture...
- why m=2 is the most common mode

Galaxy encounters and mergers from the dynamical point of view

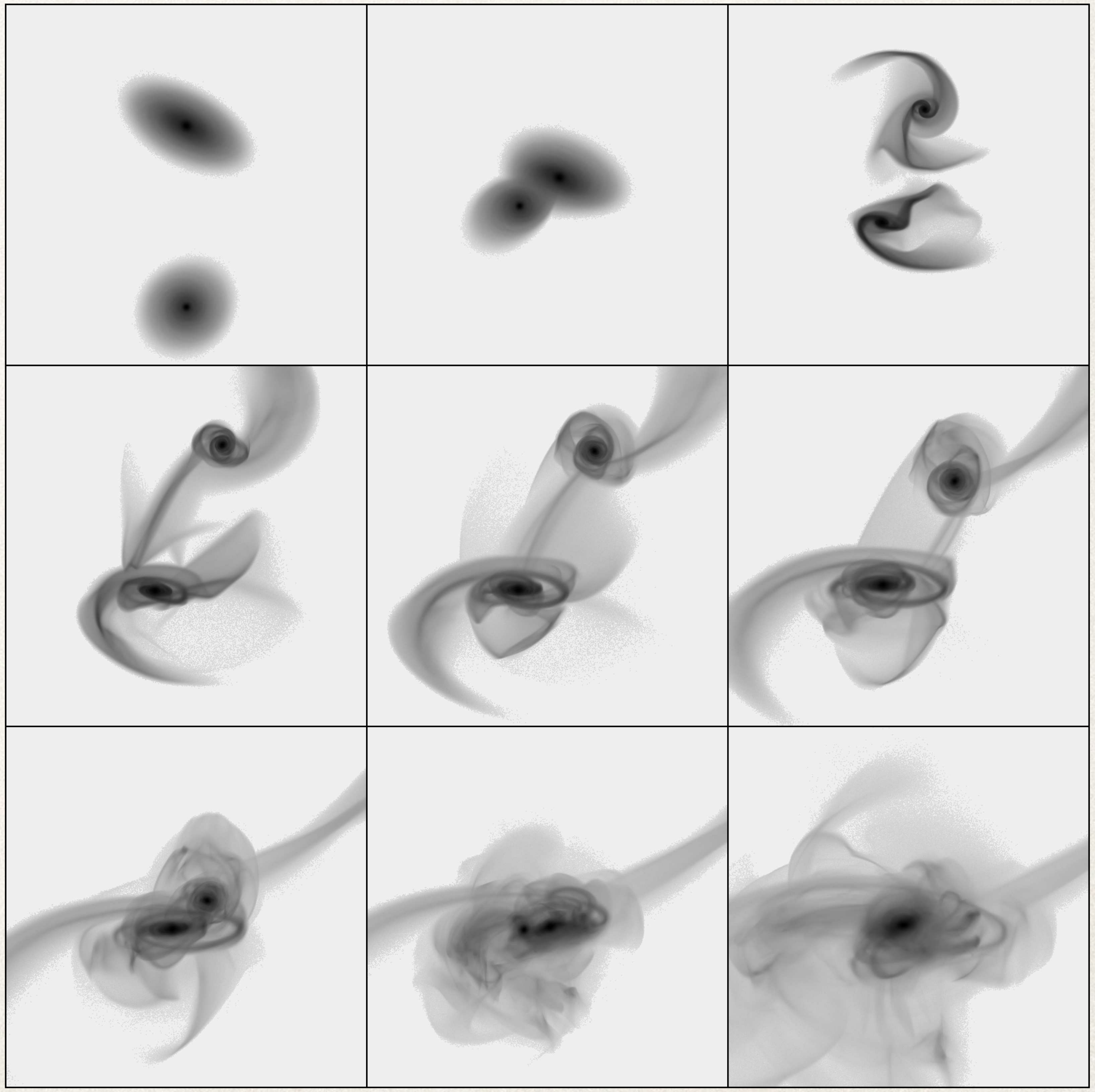
Galaxy encounters



- Galaxies don't follow the trajectories they would follow if they were point masses!
- In case of pure N-body total energy is conserved, BUT kinetic energy of the two galaxies is redistributed as internal energy (as if galaxies were viscous fluids!)
- Merger happens only if encounter is "slow" enough

A “major” merger (MW-M31)

Figure 8.1 An N-body simulation of the collision between the Galaxy (bottom) and M31 (top) which is expected to occur roughly 3 Gyr from now. The simulation follows only the evolution of the stars in the two galaxies, not the gas. Each galaxy is represented by roughly 10^8 stars and dark-matter particles. The viewpoint is from the north Galactic pole. Each panel is 180 kpc across and the interval between frames is 180 Myr. After the initial collision, a open spiral pattern is excited in both disks and long tidal tails are formed. The galaxies move apart by more than 100 kpc and then fall back together for a second collision, quickly forming a remnant surrounded by a complex pattern of shells. The shells then gradually phase mix, eventually leaving a smooth elliptical galaxy. Image provided by J. Dubinski (Dubinski, Mihos, & Hernquist 1996; Dubinski & Farah 2006).



Criteria for merging

$$\hat{E} \equiv \frac{E_{orb}}{\frac{1}{2}\langle v^2 \rangle}, \quad \hat{L} \equiv \frac{L}{r_h \langle v^2 \rangle^{1/2}}$$

- E_{orb} and L normalized by total mass
- r_h median radius; $\langle v^2 \rangle$ internal velocity dispersion
- For head-on encounters there is a maximum energy (i.e. maximum velocity) that allows the merger

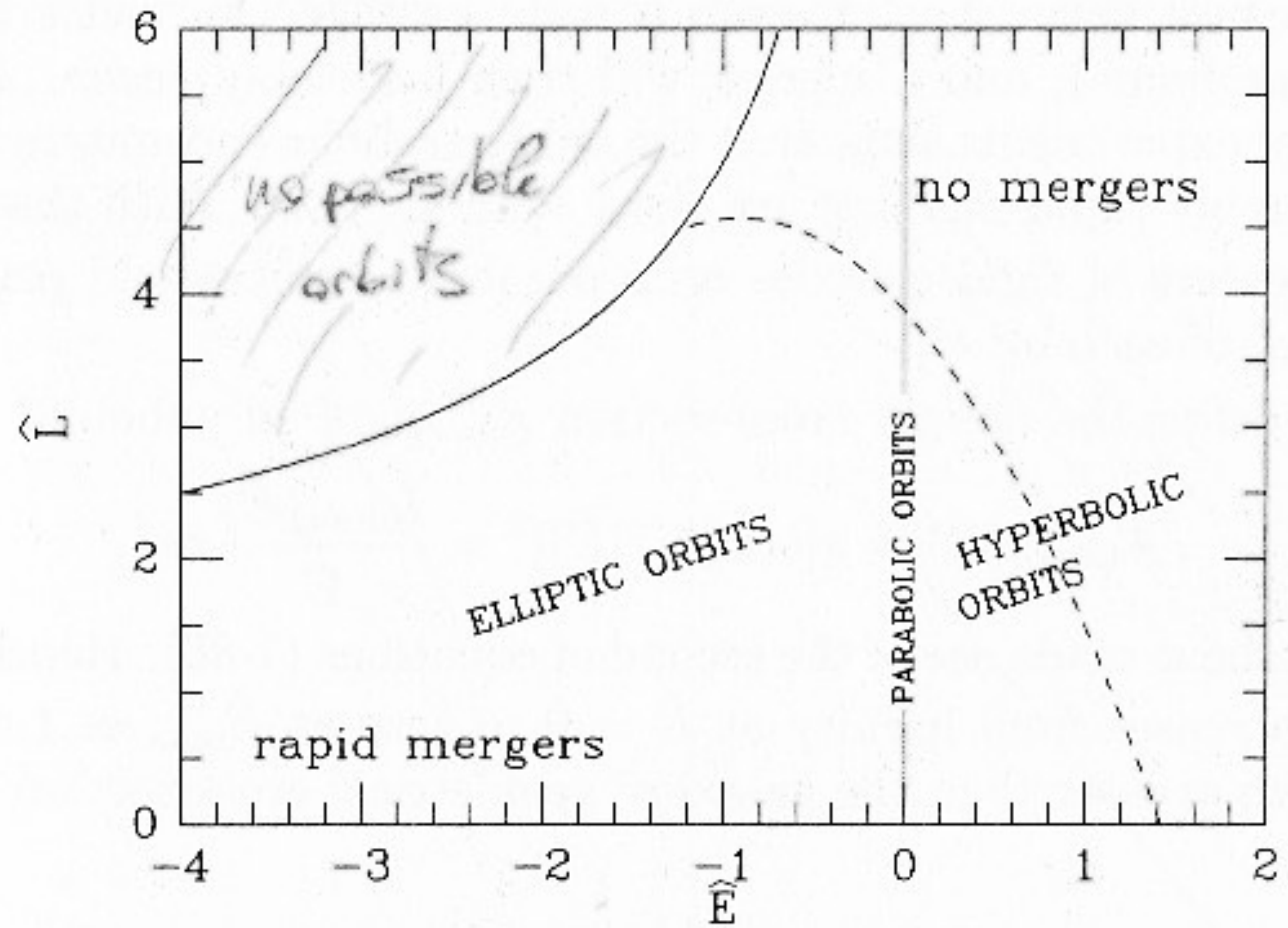


Figure 7-9. The time required for two galaxies to merge is a function of the initial position of the binary orbit in the $(\hat{E}, \hat{L})$ plane defined by equations (7-85). Orbits are only possible below and to the right of the full curve formed by the circular orbits. In principle all elliptic orbits ($\hat{E} < 0$) will eventually lead to a merger, but the time to merging increases rapidly toward the upper right portion of the diagram. For typical galactic parameters, orbits below and to the left of the dashed line evolve to mergers in about a Hubble time.

The outcome of a merger depends on:

- The mass ratio M1/M2 of progenitors (e.g., major vs minor mergers)
- The gas content of progenitors
- The structure (e.g. bulge to disk ratio)
- The orbital geometry of the encounter
  - prograde (orbital and spin angular momentum are parallel)
  - retrograde (orbital and spin angular momentum are anti-parallel)
- Orbital parameters
(e.g., eccentricity of orbits, radial vs non-radial orbits)

Mergers of spinning galaxies: the retrograde case

- Long time for merger
- Interaction with stars is impulsive and does not produce dramatic effects as in the prograde case...

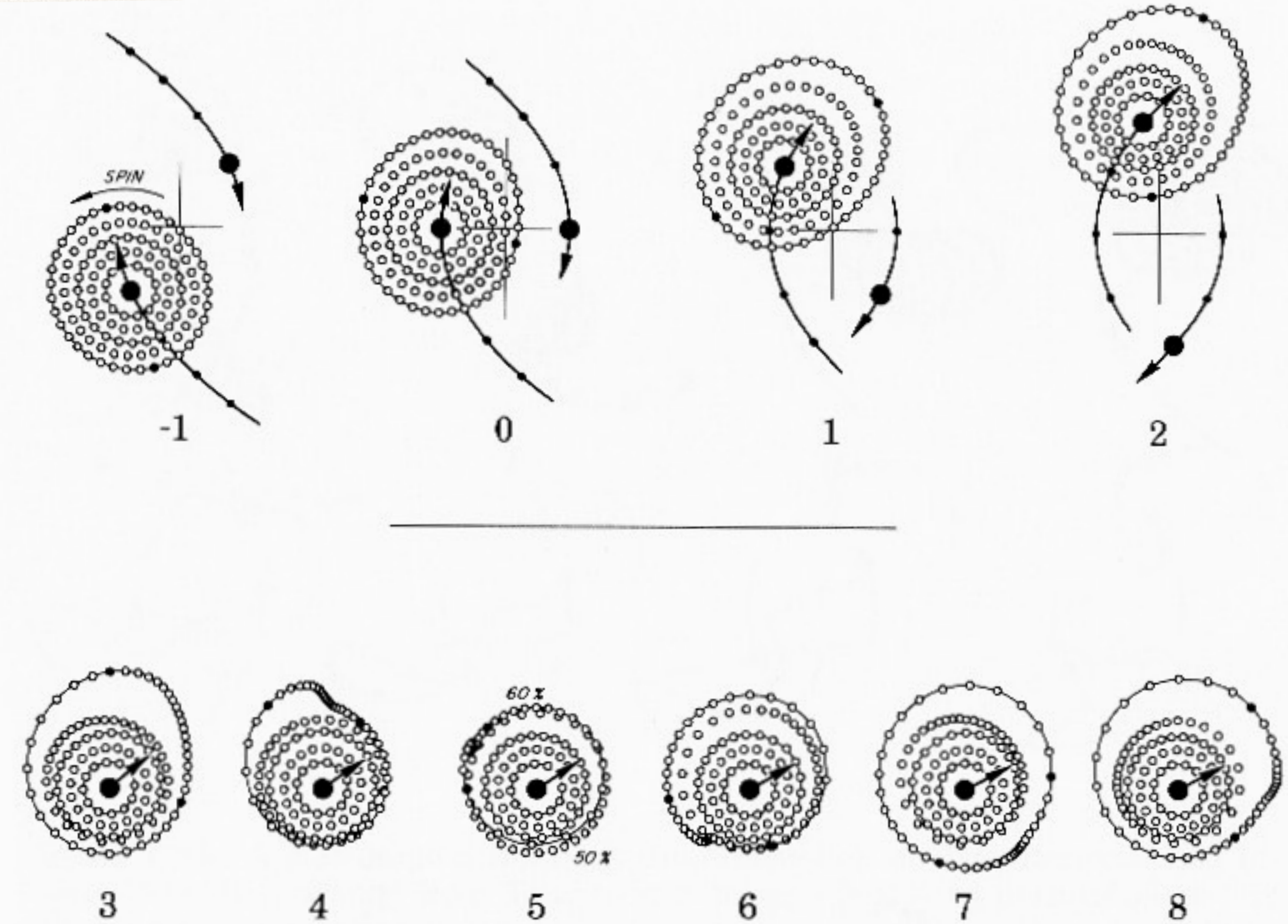


Figure 7-13. Two equal point masses move on a parabolic trajectory. Five rings of test particles form a counter-rotating disk about one of the masses. Reproduced from Toomre and Toomre (1972) by permission of *The Astrophysical Journal*.

Mergers of spinning galaxies: the prograde case

- Lead to faster merger
- Effect on individual stars is much less impulsive, interaction lasts longer

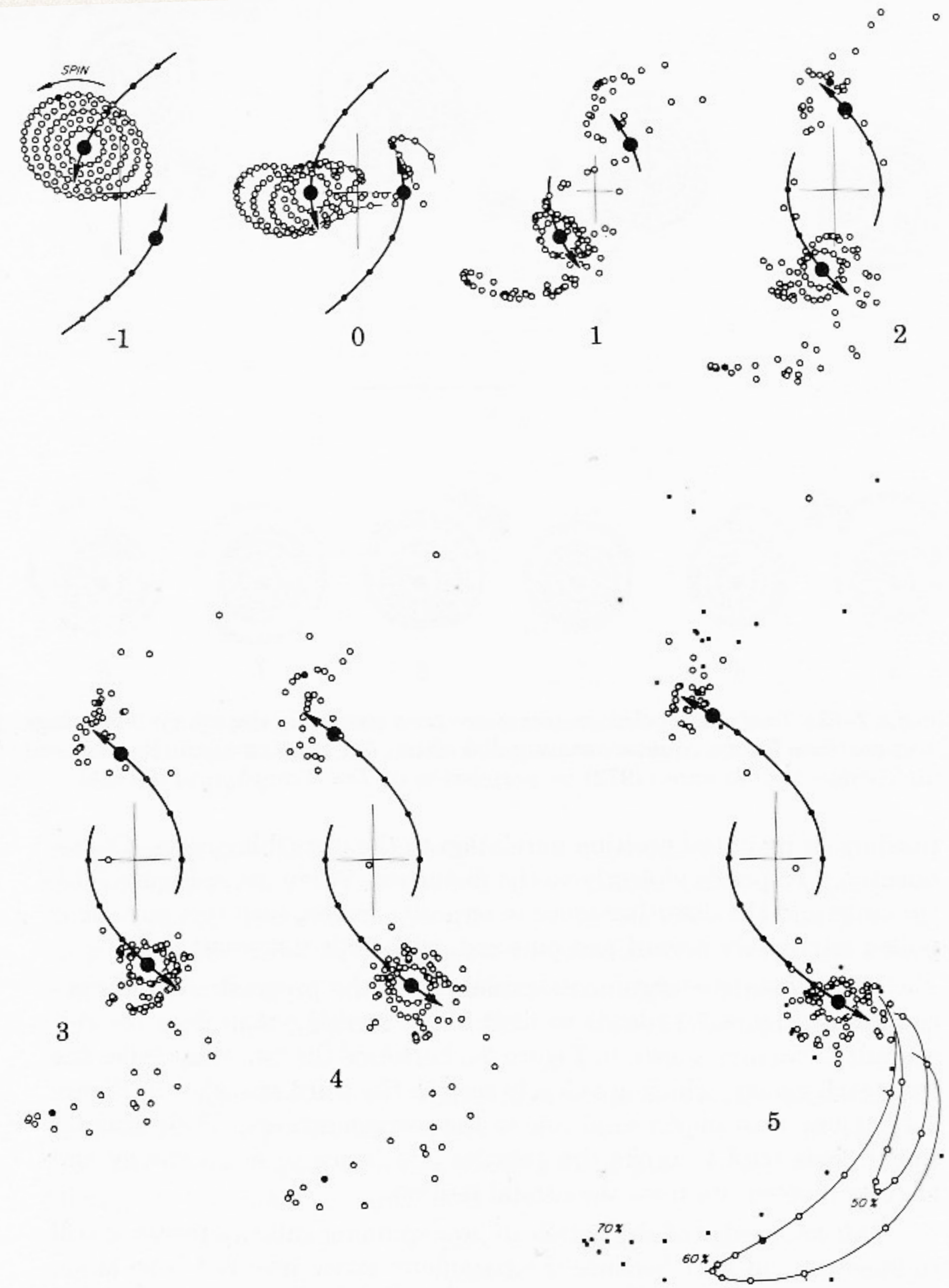


Figure 7-14. The same setup as that shown in Figure 7-13 except that the disk of test particles now corotates with the binary orbit. Reproduced from Toomre and Toomre (1972) by permission of *The Astrophysical Journal.*

Key mechanisms at work in galaxy encounters

- Dynamical friction
- Tides
- Violent relaxation (in the final phases of a merger): motion in a time variable potential
- Phase mixing (in the final phases of a merger)

Dynamical friction

Chandrasekar (1943)

- Ideal case: mass M moving in a sea of particles m with a velocity dispersion σ

$$\frac{d\mathbf{v}_M}{dt} \simeq -\frac{16\pi^2}{3} G^2 M m_a \ln\Lambda f(0)\, \mathbf{v}_M \quad (v_M \text{ small})$$

Coulomb integral

$$\frac{d\mathbf{v}_M}{dt} = -4\pi G^2 M m_a n \ln\Lambda \frac{\mathbf{v}_M}{v_M^3} \quad (v_M \text{ large})$$

- At small v_M the motion is like in a viscous fluid

- If v_M is very large, M just goes through ballistically

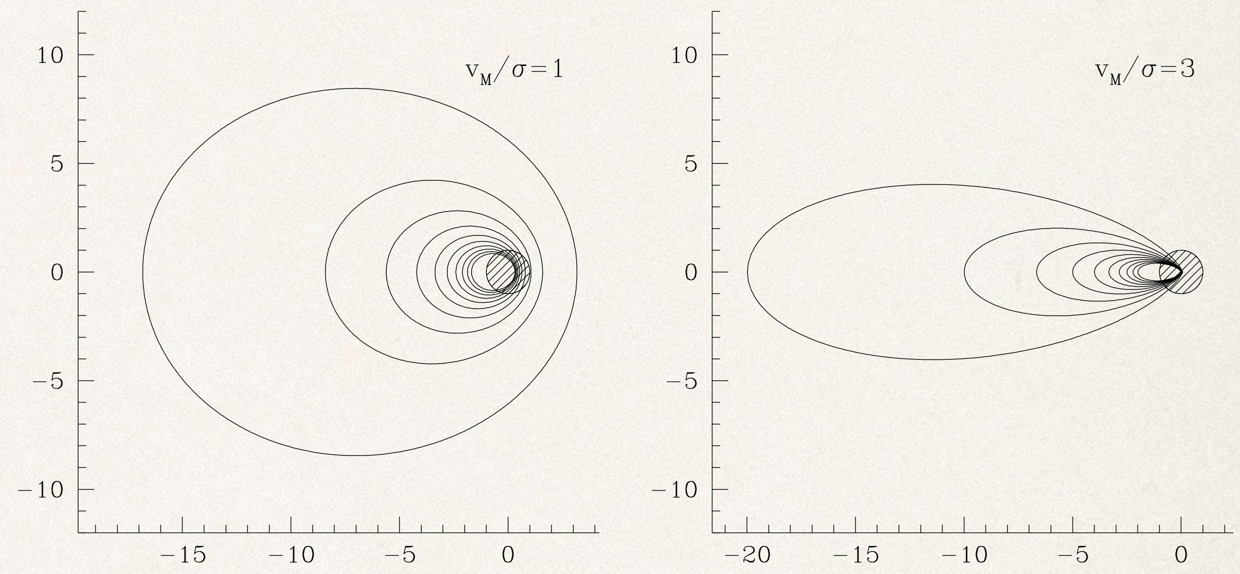
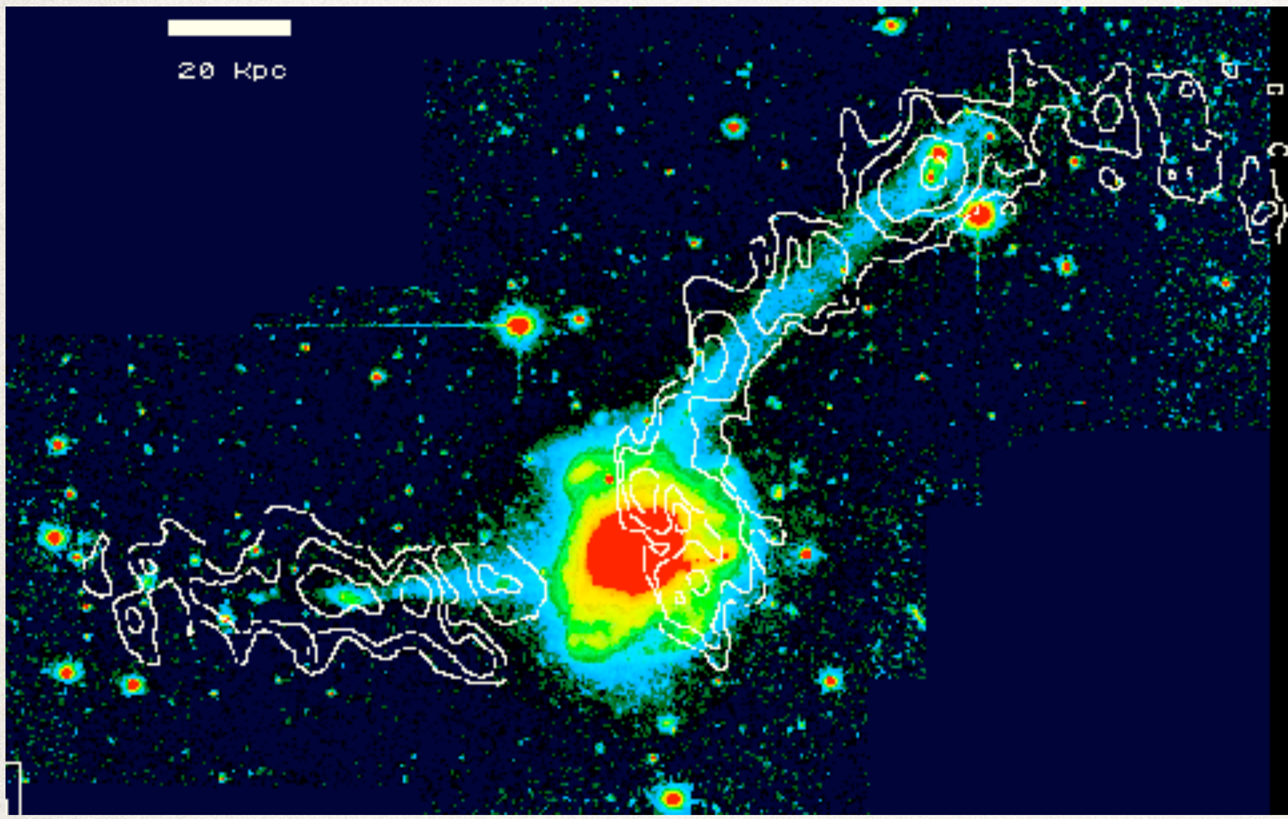
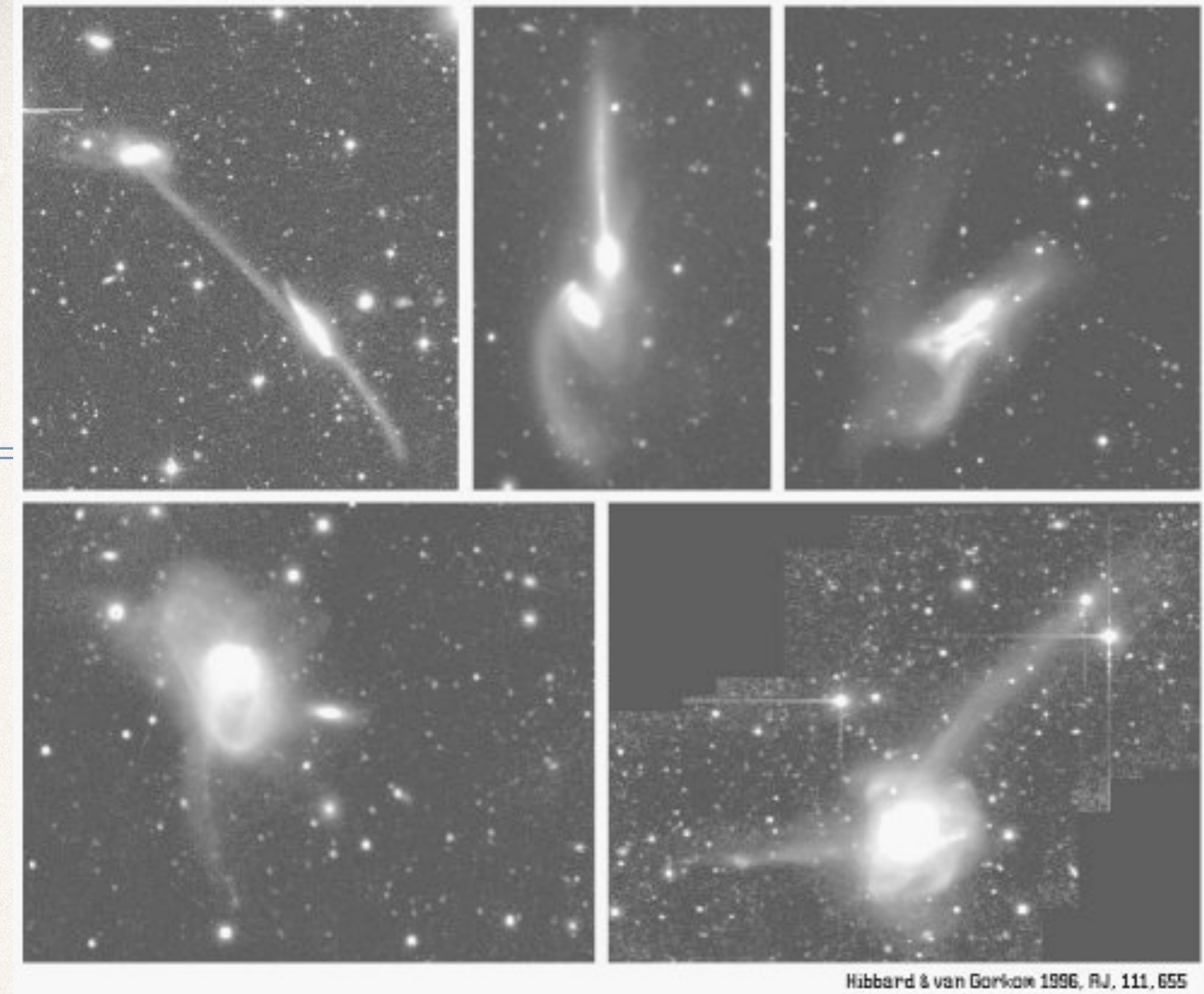


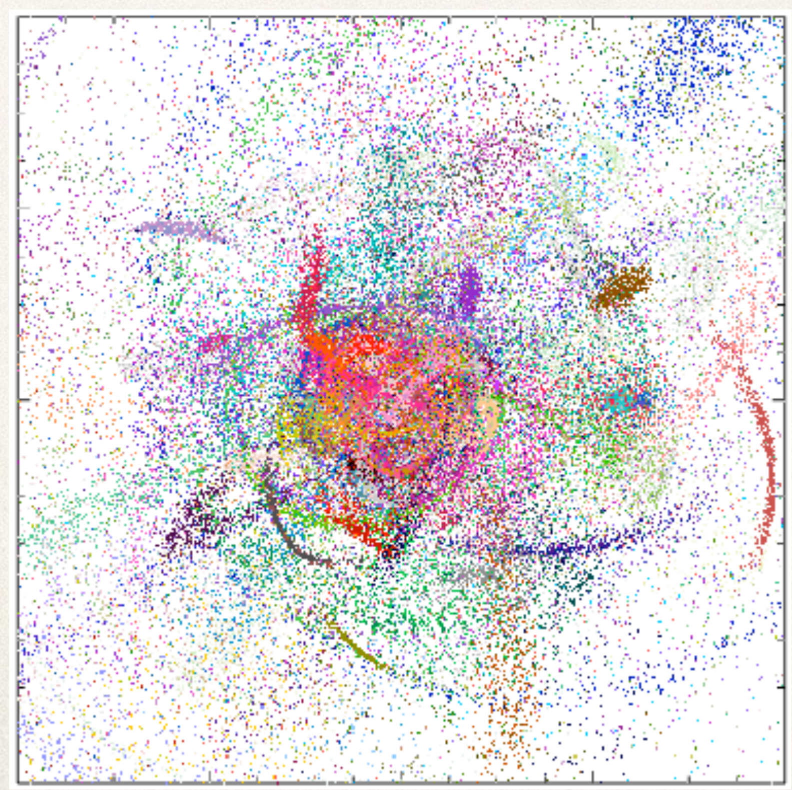
Figure 8.2 A mass M travels from left to right at speed v_M, through a homogeneous Maxwellian distribution of stars with one-dimensional dispersion σ. Deflection of the stars by the mass enhances the stellar density downstream, and the gravitational attraction of this wake on M leads to dynamical friction. The contours show lines of equal stellar density in a plane containing the mass M and the velocity vector $\mathbf{v}_M$; the velocities are $v_M = \sigma$ (left panel) and $v_M = 3\sigma$ (right panel). The fractional overdensities shown are $0.1, 0.2, \ldots, 0.9, 1$. The unit of length is chosen so that $GM/\sigma^2 = 1$. The shaded circle has unit radius and is centered at M. The overdensities are computed using equation (8.148), which is based on linear response theory; for a nonlinear treatment see Mulder (1983).

Merger (remnants)



The merger remnant NGC 7252. The false color image shows the starlight from the remnant (red=bright, blue=faint), while the white contours show where the hydrogen gas is distributed. (John Hibbard, NRAO)



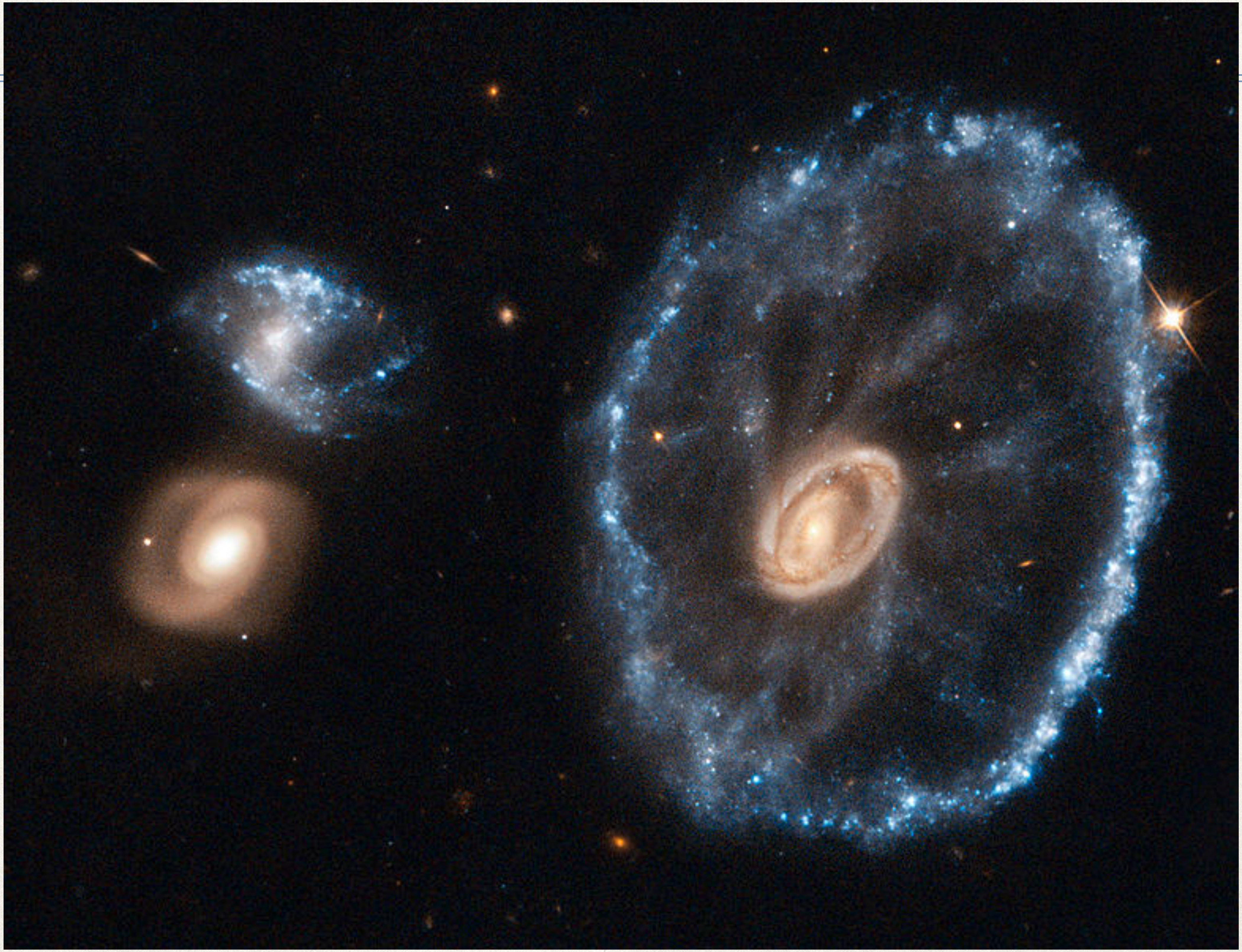


A computer simulation of a galaxy halo made up of an ensemble of disrupted satellites. Each color shows stars from a single disrupted satellite galaxy. Note how some individual streams stay intact, while others form a more diffuse halo. (Paul Harding, University of Arizona)

High speed encounters

- Impulse approximation
- Kinetic energy δT transferred to stars
- Going back to virial equilibrium requires transforming 2 δT to potential energy ($2T' = 2T + 2\,\delta T = -U' = -(U + \delta U)$ —> $\delta U = -2\,\delta T$): large impact on the structure!
  - possible mass loss (~evaporation of the hottest particles)
- Can become very important in high density environments such as clusters where the encounters are repeated (so-called harassment)

Head-on high-speed encounters: ring galaxies



Tidal truncation

- ~easy in the case of point mass
- For a star not being on a closed energy surface does not imply being tidally removed: other integrals of motions can prevent it
- Can be generalized to a potential from distributed mass (e.g. a cluster): genesis of tidally stripped galaxies

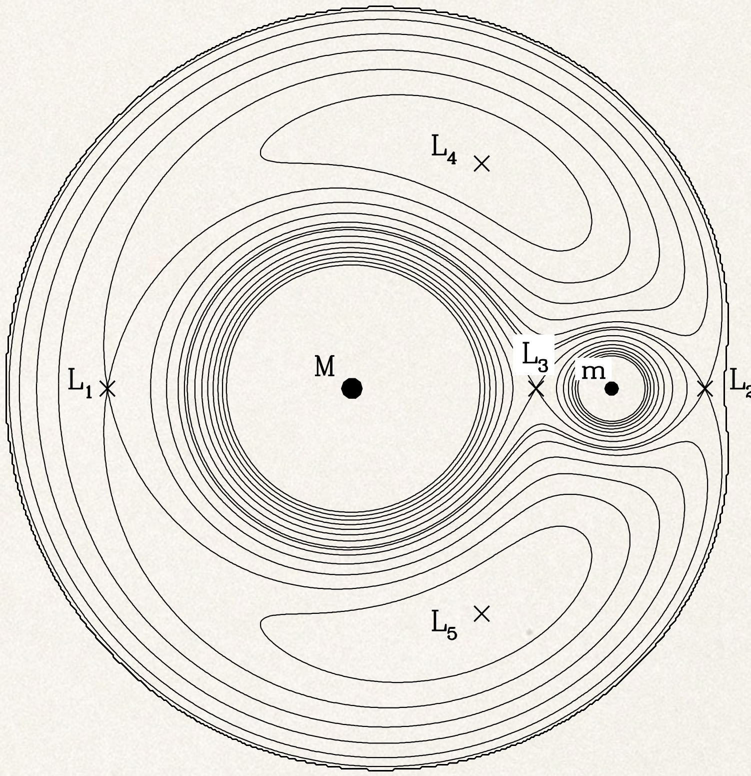


Figure 8.6 Contours of equal effective potential $\Phi_{\rm eff}$ defined by equation (8.88) for two point masses in a circular orbit. The mass ratio $m/M = \frac{1}{9}$. The points $L_1, \ldots, L_5$ are the Lagrange points. The L_4 and L_5 points form an equilateral triangle with the two masses (Problem 3.25).

Transformation mechanisms of (late-type) galaxies in clusters

Galaxy encounters in a cluster

Taking rough numbers for Virgo

- ~30 galaxies brighter than L* with cross-section $\sigma \sim \pi$ (10 kpc)^2~3 10^{-4} Mpc^2
- ~1000 galaxies down to 10^{-3}L*
- Volume ~ 4/3 π (1 Mpc)^3~4 Mpc^3
- Velocity ~1000 km/s~1e-9 Mpc/yr
- Collision rate for a single (large) galaxy to be hit by another galaxy (neglecting gravitational focusing and dynamical friction) $\varepsilon \sim n\, \sigma\, v \sim 0.1$/Gyr
- For significant interaction (not necessarily head-on collision) the cross section increases by a factor ~10, thus a galaxy has a strong interaction ~every Gyr
- On the other hand, high-speed encounters are unlikely to result in a merger, unless the impact parameter is small
- In summary: in a cluster like Virgo one should see direct collisions on big galaxies roughly once every 0.3 Gyr. Interactions should be much more common, roughly every few 10 Myr.
- Mergers on the central galaxies are another story, where dynamical friction plays a big role

Galaxy-galaxy tidal interactions

$$F_{tide} \approx \frac{dF_{grav}}{dR}\delta R \propto \frac{d\left(\frac{M}{R^2}\right)}{dR}\delta R \propto \frac{M}{R^3}\delta R$$

- M is the mass of the "perturbing" body, R its distance from the center of mass of the "tidally perturbed" galaxy and δR is the size of the perturbed galaxy
- Tidal interactions are only relevant on scales of ~few 10 kpc, hence quite rare
- In clusters they are quite short and impulsive due to high speed
- Tidal stripping can affect HI and the outermost stars → ICL

Tidal interactions with the potential well

- m=2 perturbation can create ovals, (kinematic) spirals, bars. Instabilities can be generated followed by SF and/or eventual heating of disk.
- Tidal stripping: removal of material (esp. loosely bound HI) from outside the tidal radius
  - becomes effective near the cluster core (~100-200 kpc)
  - $r_{\mathrm{tidal}}/R_c \sim 0.5\Delta V_{\mathrm{gal}}/\delta V_{\mathrm{cluster}}$ Boselli&Gavazzi (2006), based on Merritt (1984)

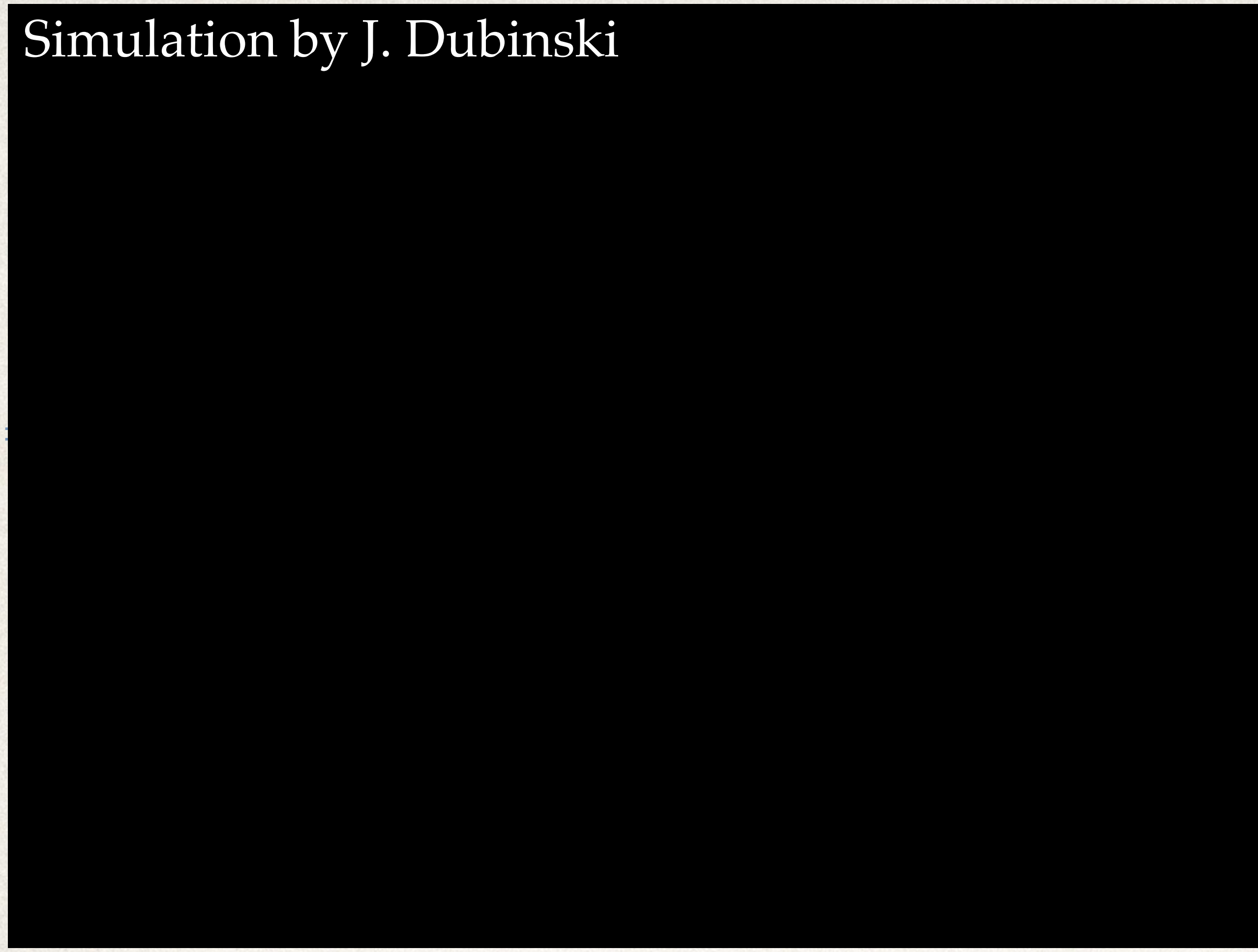
Galaxy rotation

Cluster velocity dispersion

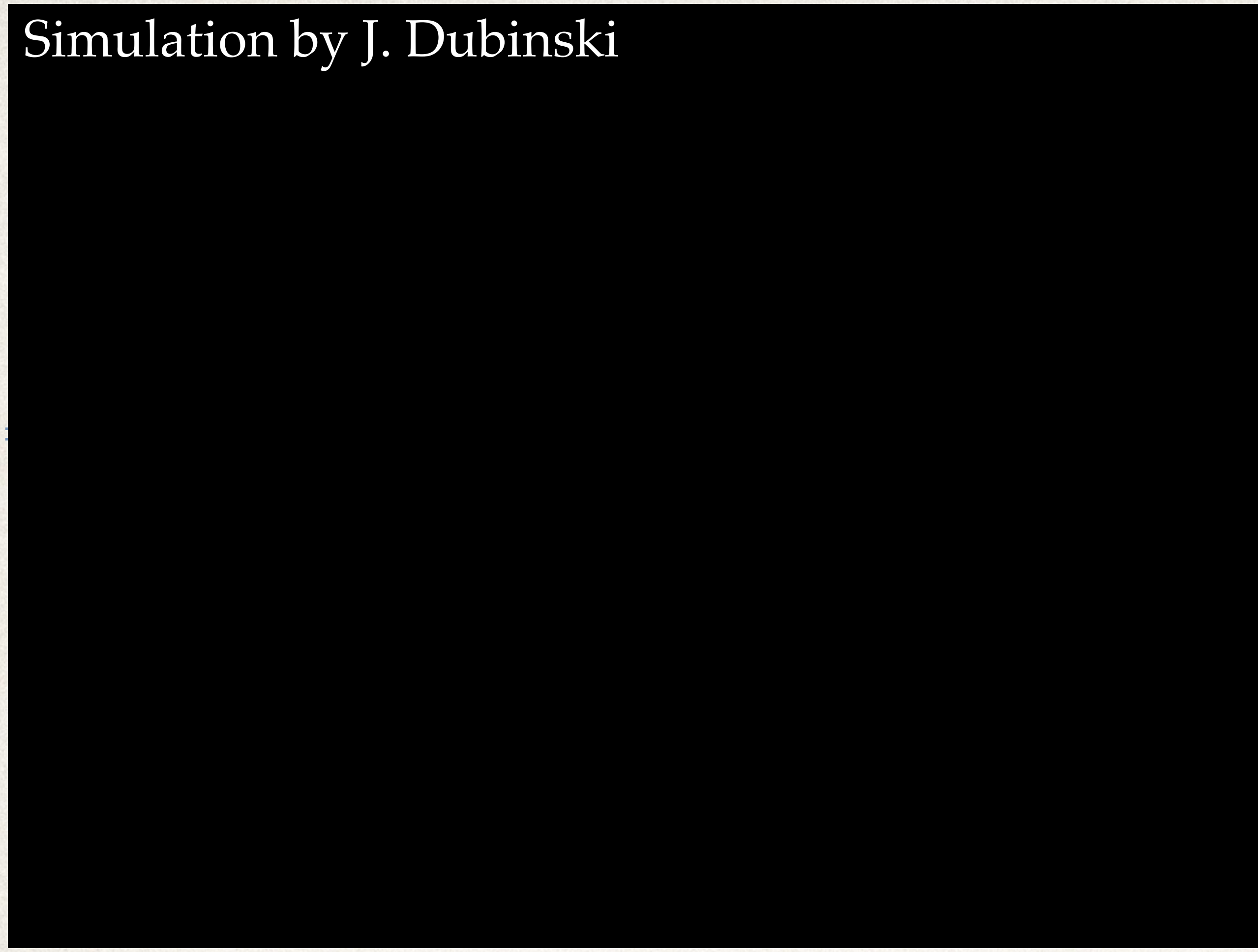
$$r_{\mathrm{tidal}}(\mathrm{Virgo}) = 1.58 r_{\mathrm{gal}} + 3.67 \ \mathrm{kpc}.$$

  - formation of ICL

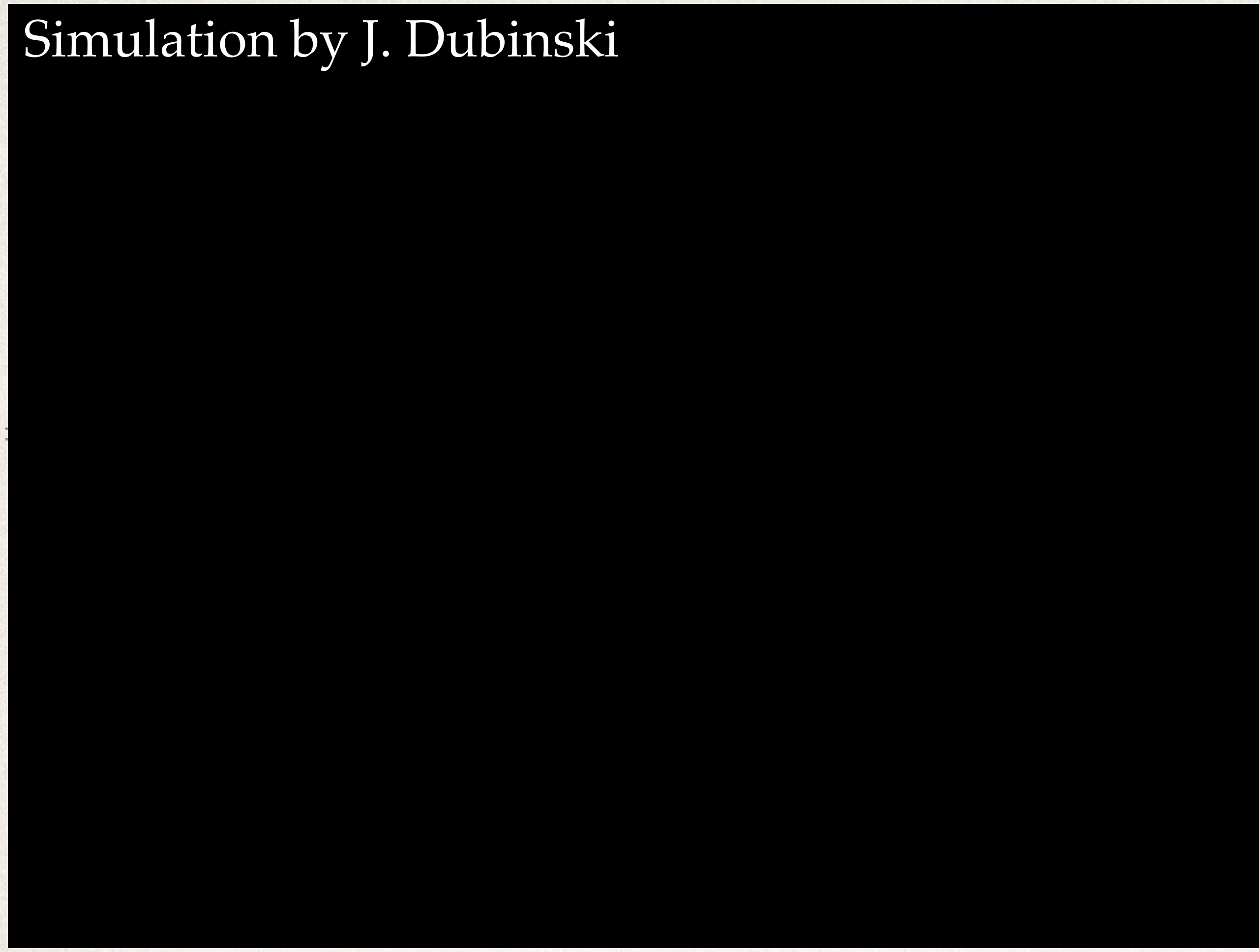
Tidal stripping and ICL

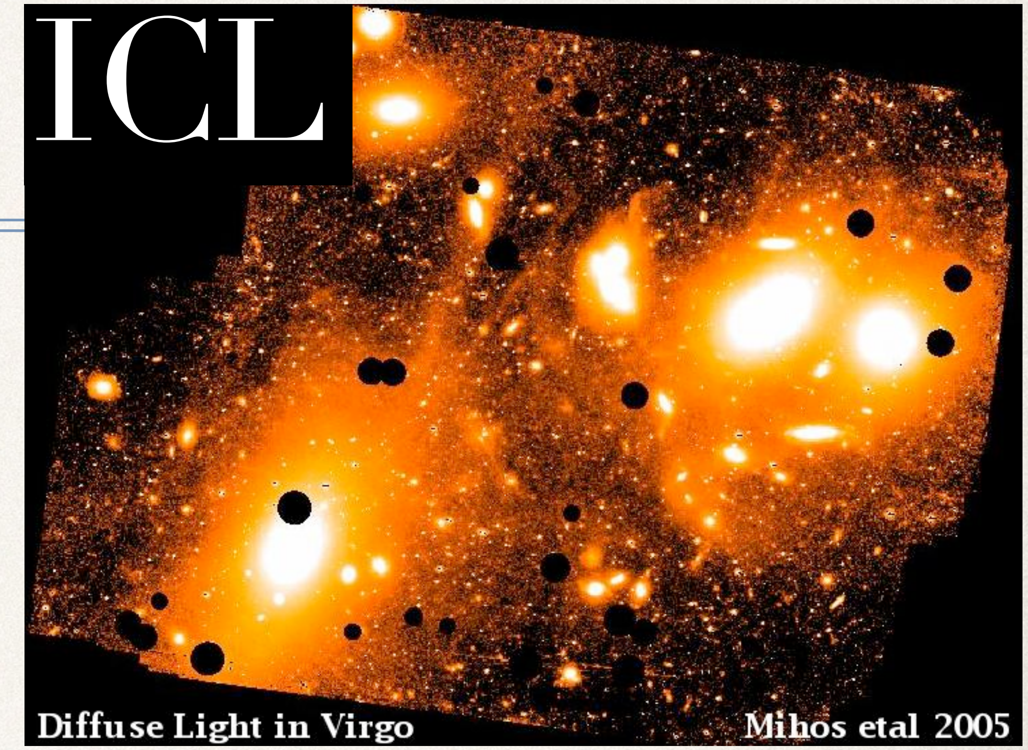


Tidal stripping and ICL



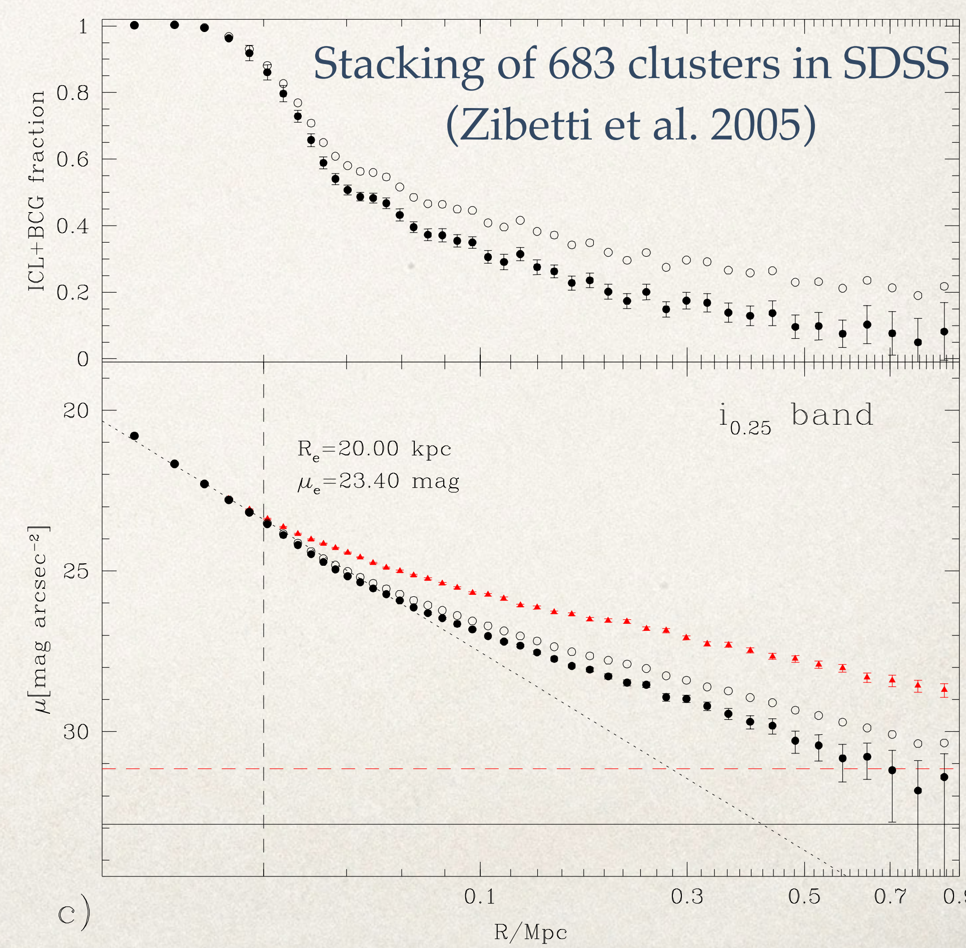
Tidal stripping and ICL





Dynamical friction

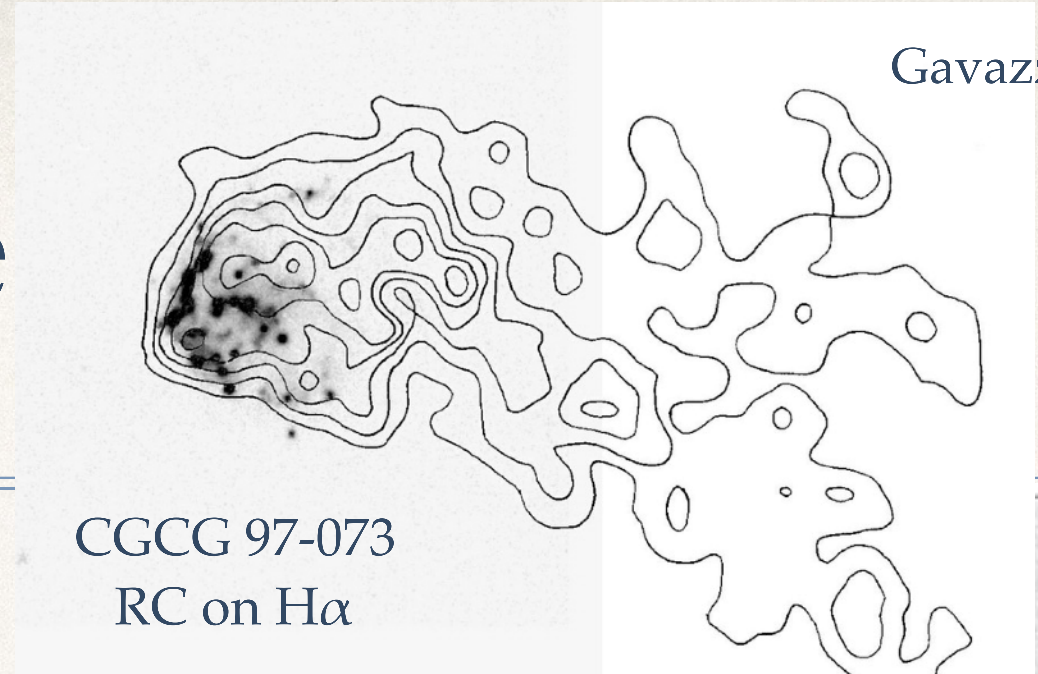
- slows down the more massive galaxies near the center of a spherical cluster; they spiral in toward the cluster center.
- The kinetic energy removed from the massive galaxies is transferred to the lighter particles (galaxies or missing mass components), which then expand.
- mass segregation: more massive galaxies are found preferentially at smaller radii.
- at fixed radius the velocity dispersion of the more massive galaxies will be lower, as they have been slowed down (is velocity segregation a mass effect?)



Galaxy "harassment" (©Ben Moore)

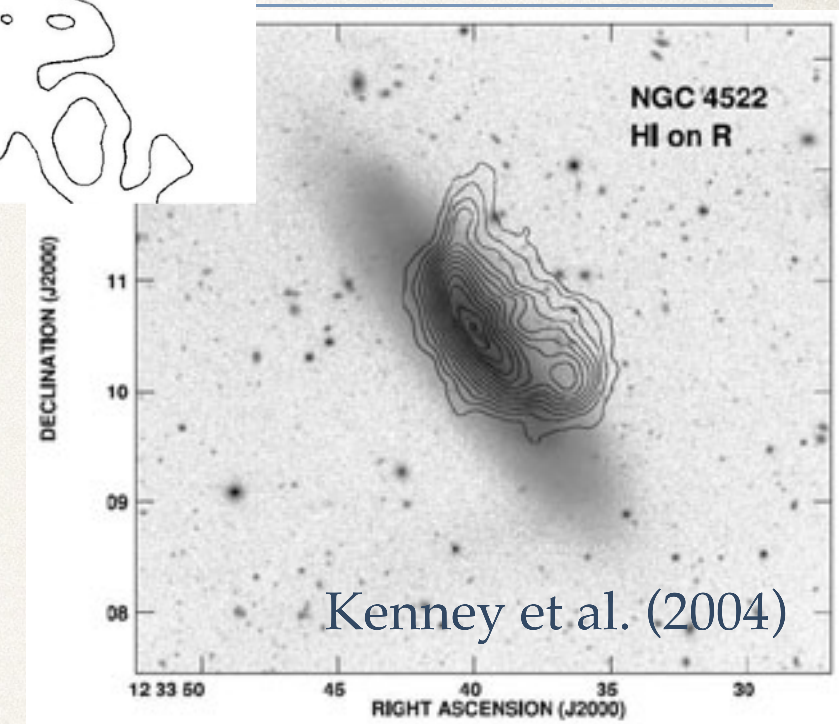
- combined effect of multiple high-speed galaxy-galaxy close (~50 kpc) encounters and the interaction with the potential of the cluster as a whole
- heating of the stellar component and excitation of bar instabilities (esp. in the first encounters)
- sinking of gas and production of nuclear starbursts
- loss of angular momentum and thickening of the system
  - possible mechanism to create dEs?

Ram pressure



Gavazzi et al. (1995)

CGCG 97-073
RC on Hα

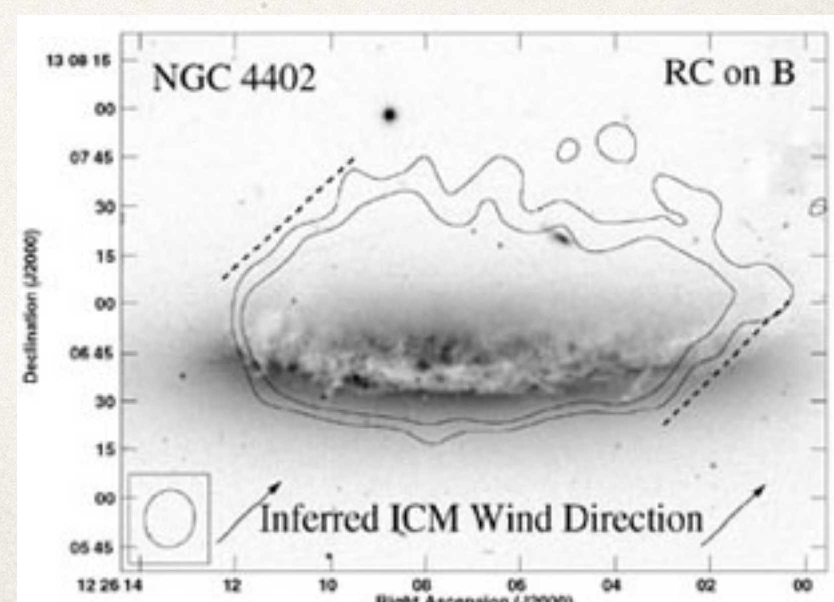


Kenney et al. (2004)

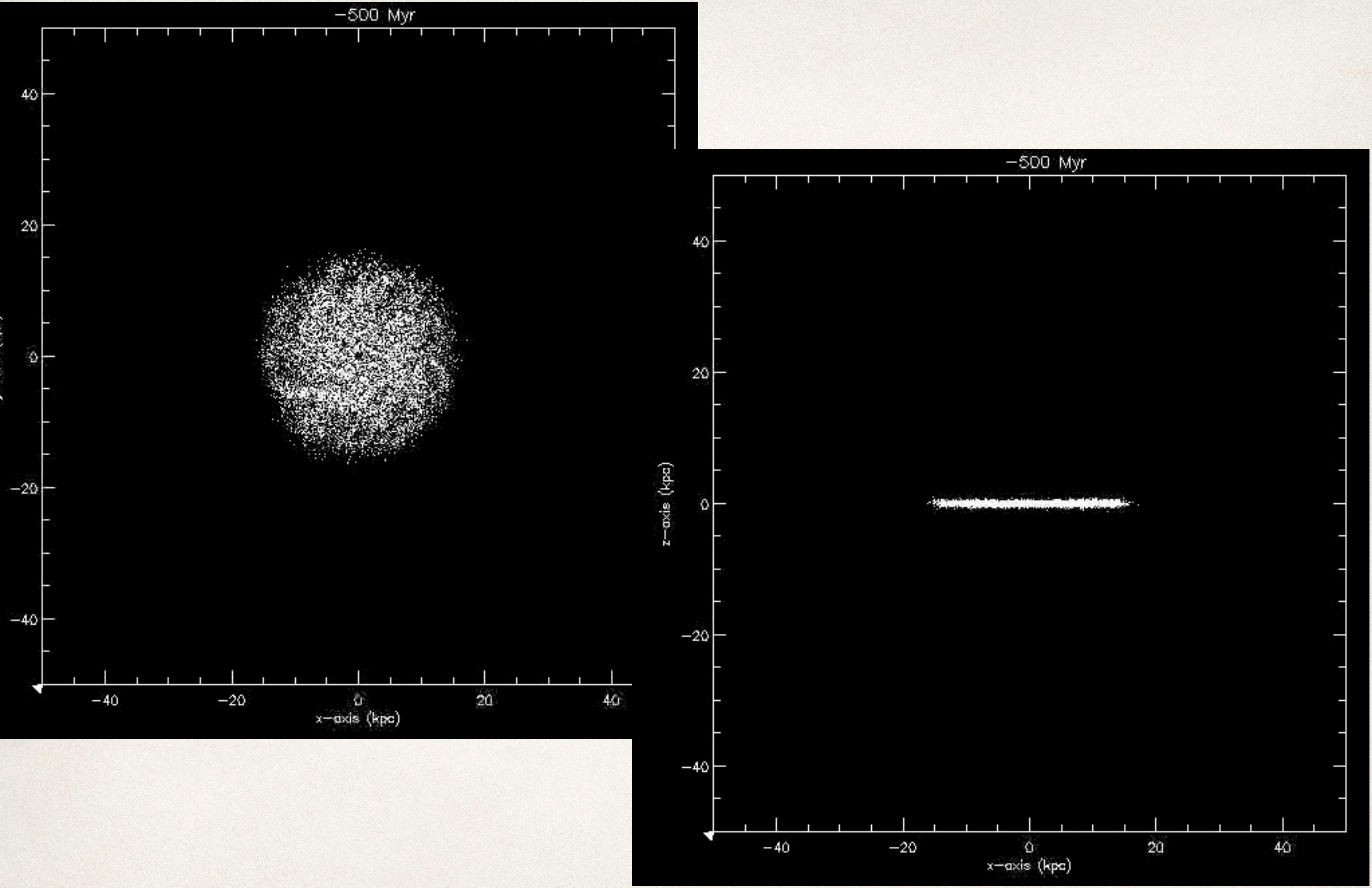
- A galaxy passing through the ICM feels an external pressure. This pressure depends on the ICM density and the relative velocity v_{rel} of the galaxy and the ICM (Gunn & Gott 1972)

$$p_{ram} = \rho_{ICM} v_{rel}^2 > 2\pi G \sigma_{star}(r) \sigma_{gas}(r)$$

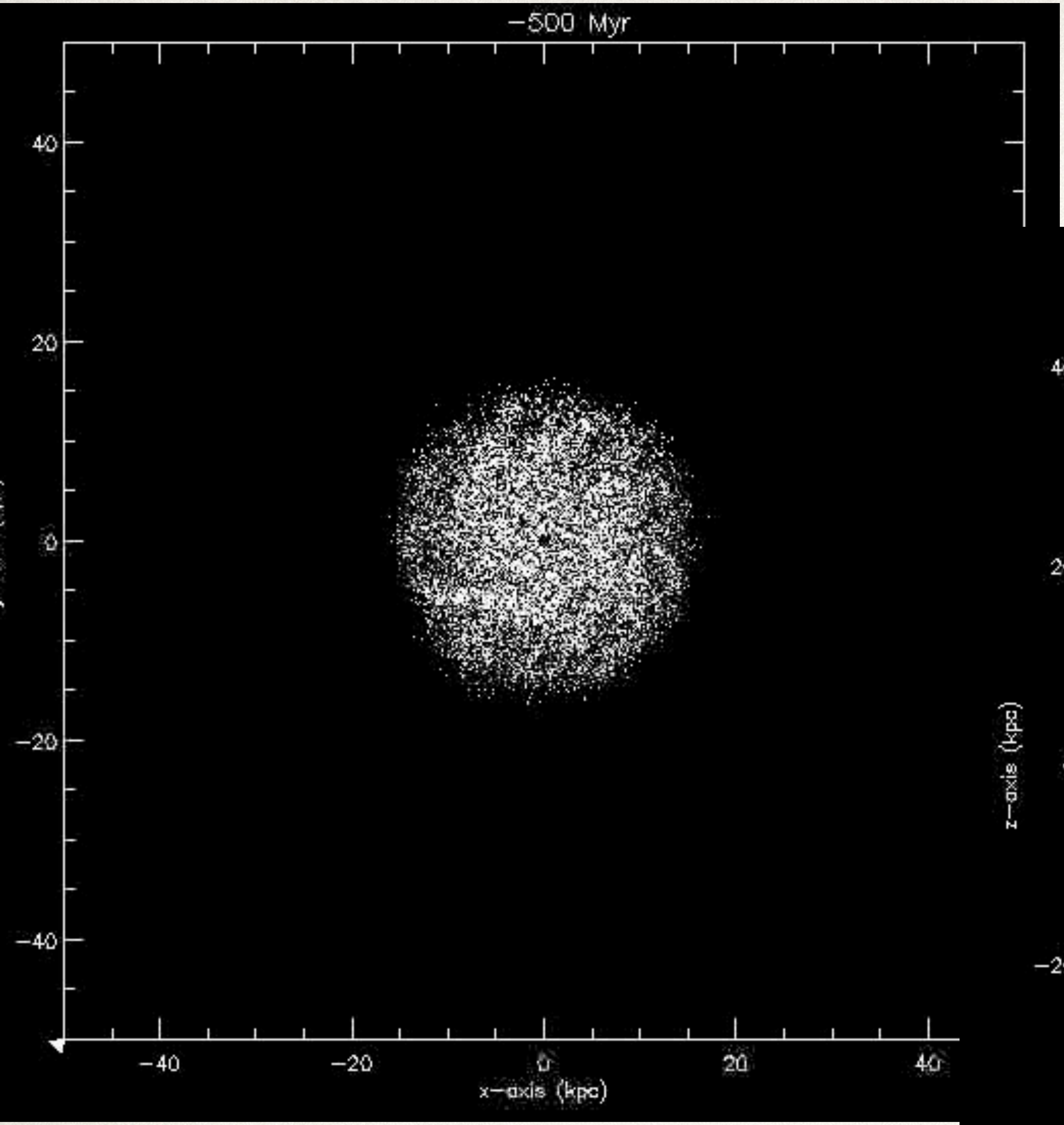
- with p_{ram} being the ram pressure, G the gravitational constant, σ_{star} the stellar surface density, σ_{gas} the surface mass density of the galactic gas.

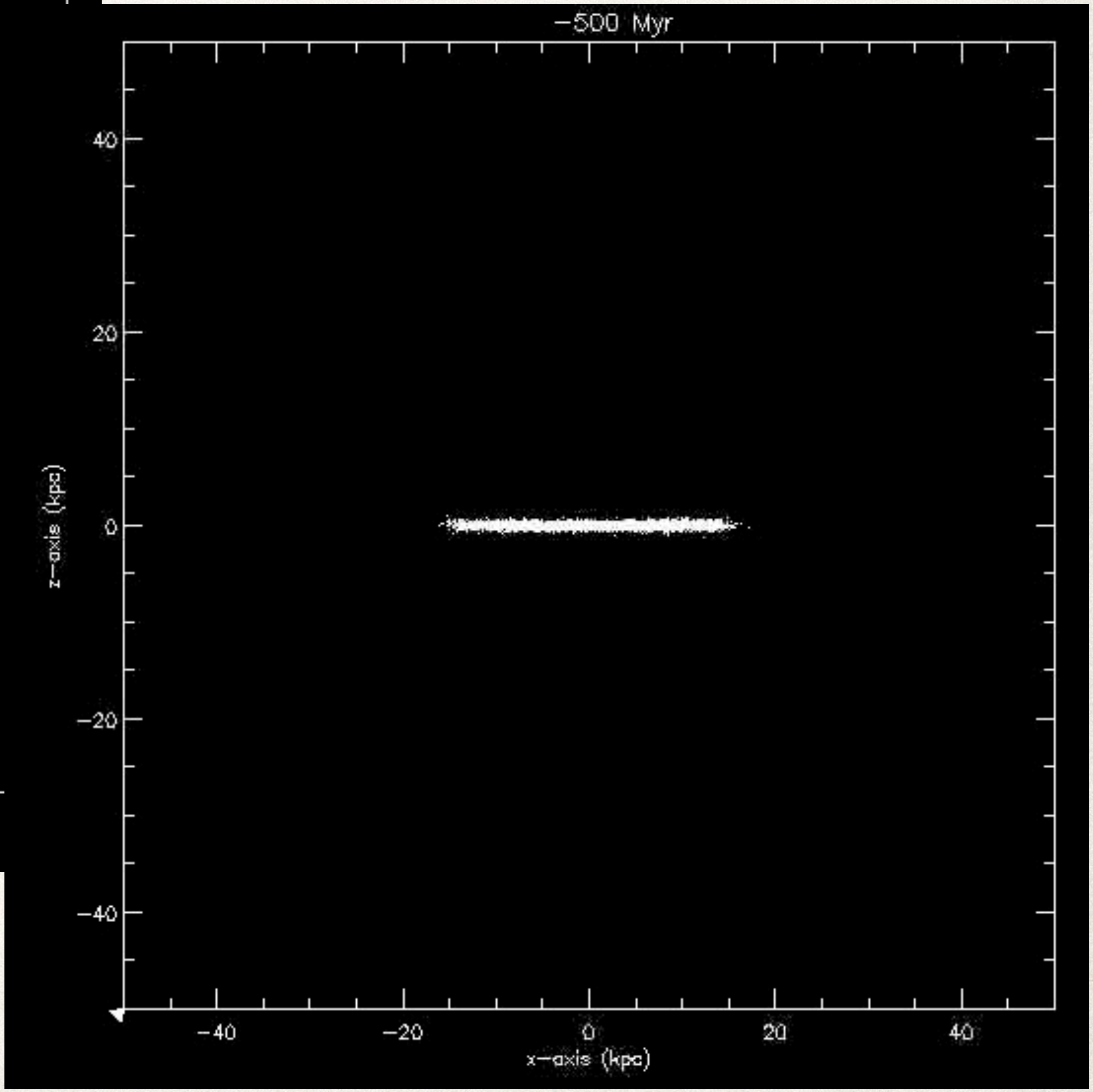


Crowl et al. (2005)

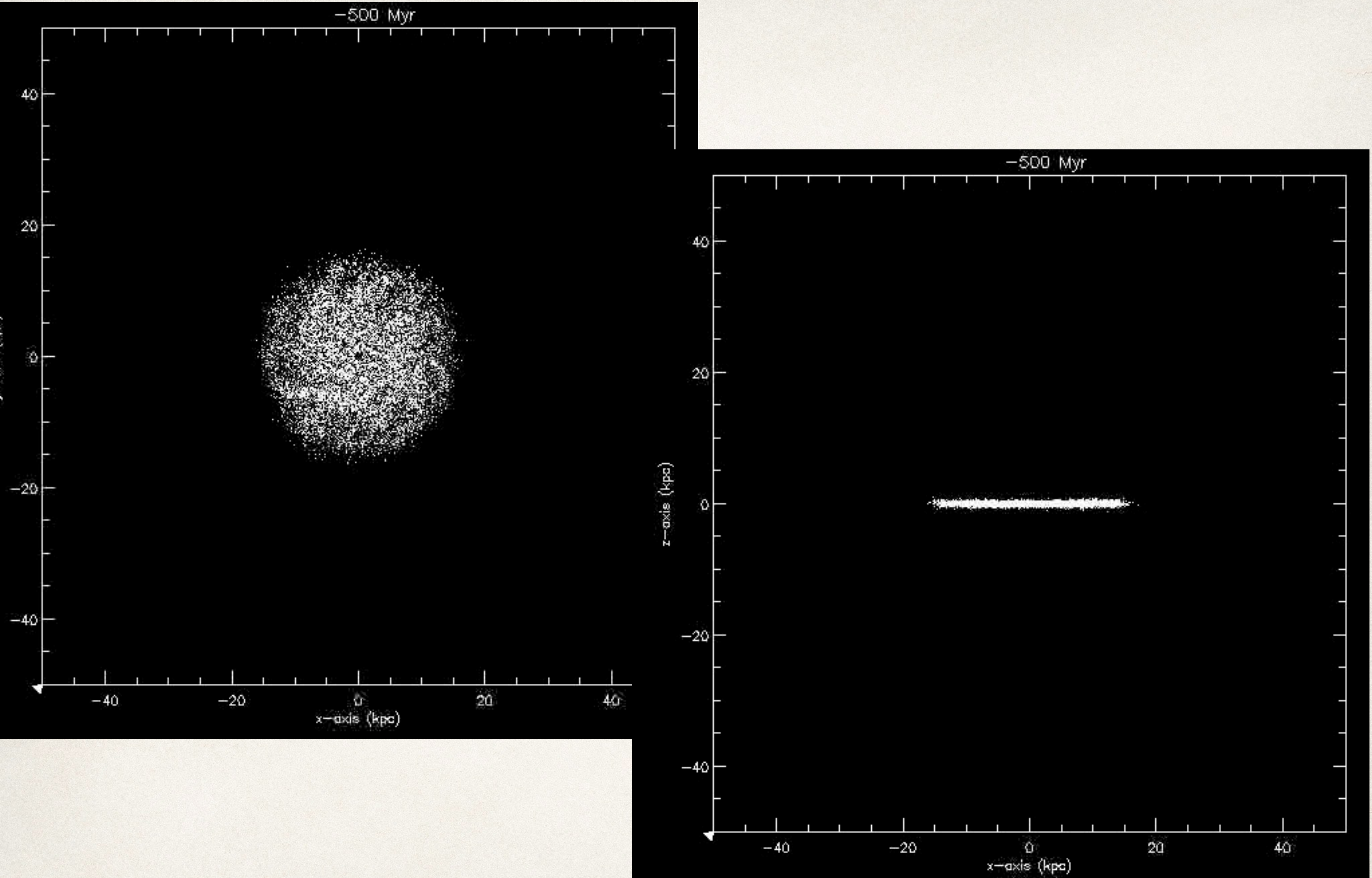


Vollmer et al. (2001)





Vollmer et al. (2001)



Vollmer et al. (2001)

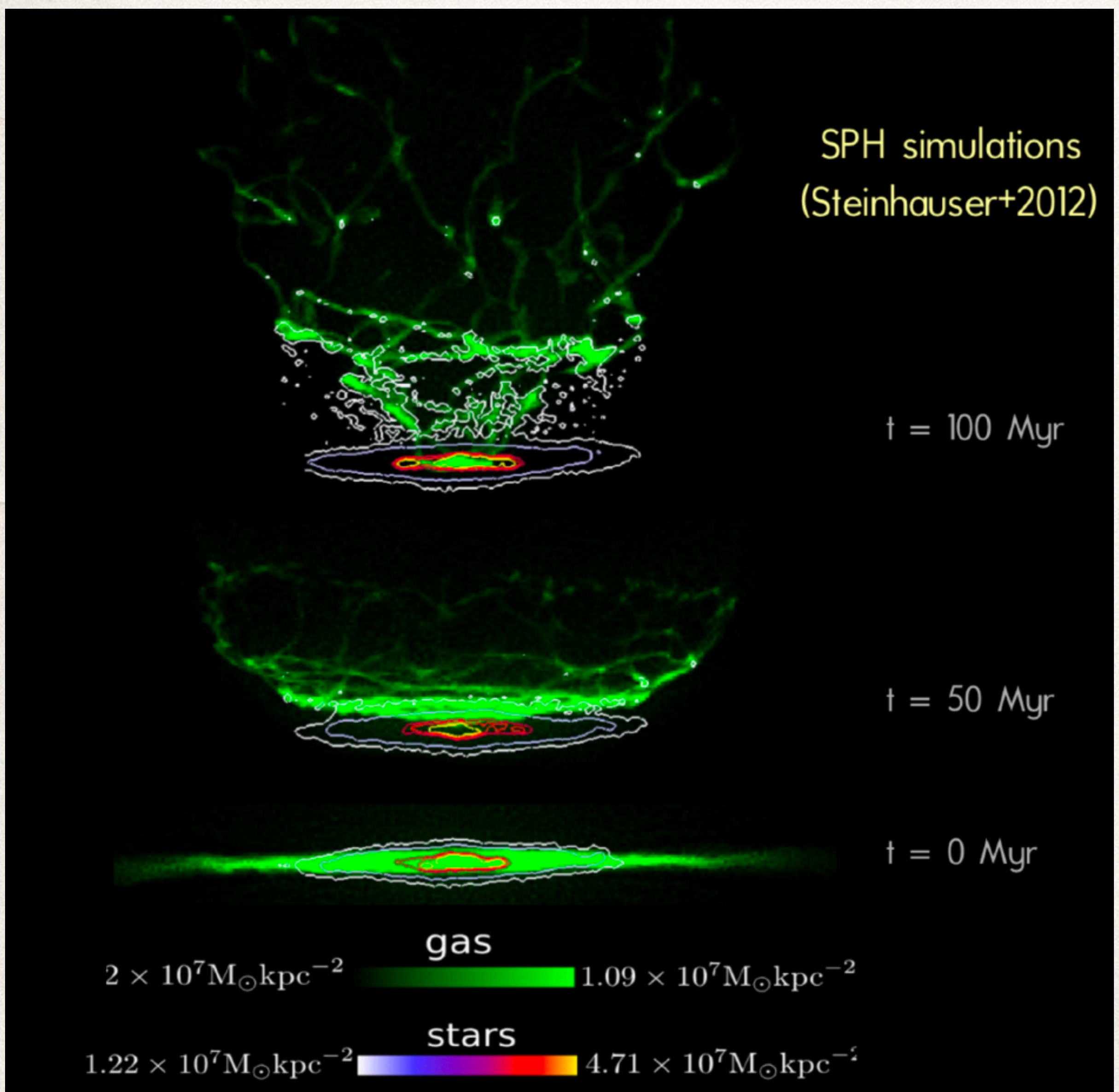
Effects of ram pressure

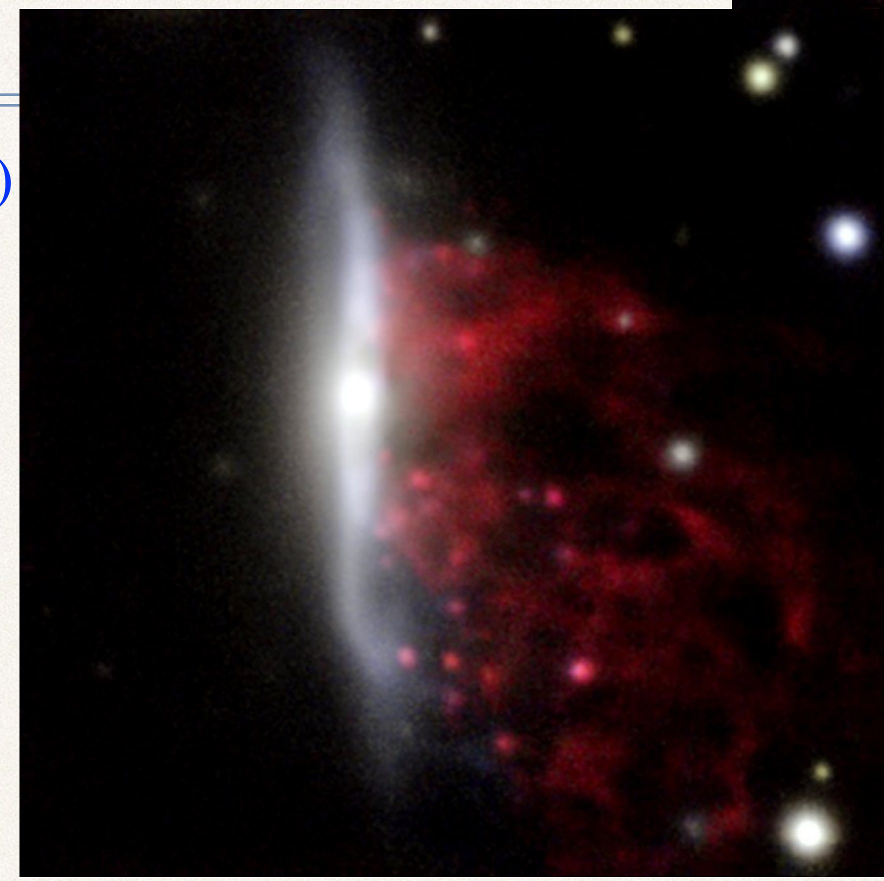
- Removal of substantial ISM on cluster crossing time scale
  - Especially applies to extended HI, more difficult for denser and more bound molecular gas
  - On the long run this leads to HI exhaustion with eventual depletion of molecular gas and cessation of SF
- Bow shock and compression of the ISM ahead of the galaxy
- Gas tail
- Displacement can trigger instabilities and generate flocculent spirals
- External pressure can cause a temporary enhancement of SF

Ram pressure at work

GAs Stripping Phenomena with MUSE (GASP)

120 hrs MUSE@VLT (PI B.M. Poggianti)





Thermal evaporation

- If the IGM temperature is high compared to the galaxy velocity dispersion, at the interface between the hot IGM and the cold ISM, the temperature of the ISM rises rapidly and the gas evaporates and is not retained by the gravitational field
- sensitive to IGM temperature and the magnetic field, and to a lesser extent to the density
- A typical galaxy with a 15 kpc radius and 5 10^9 $M_\odot$, of atomic gas can be completely evaporated (assuming no magnetic fields) in ~40 Myr in Coma, 300 Myr in A1367, and ~1Gyr in Virgo
- Becomes dominant over ram pressure for slow and small galaxies; also for large galaxies in case of hot IGM (Coma)

Starvation / strangulation

Bekki et al. (2002)

- Removal of the halo of (hot) gas that normally surrounds isolated galaxies and provides the reservoir for the cold gas and SF (Larson et al. 1980)
- Can explain the abundance of anaemic spirals in the outskirts of clusters (Goto et al. 2003)

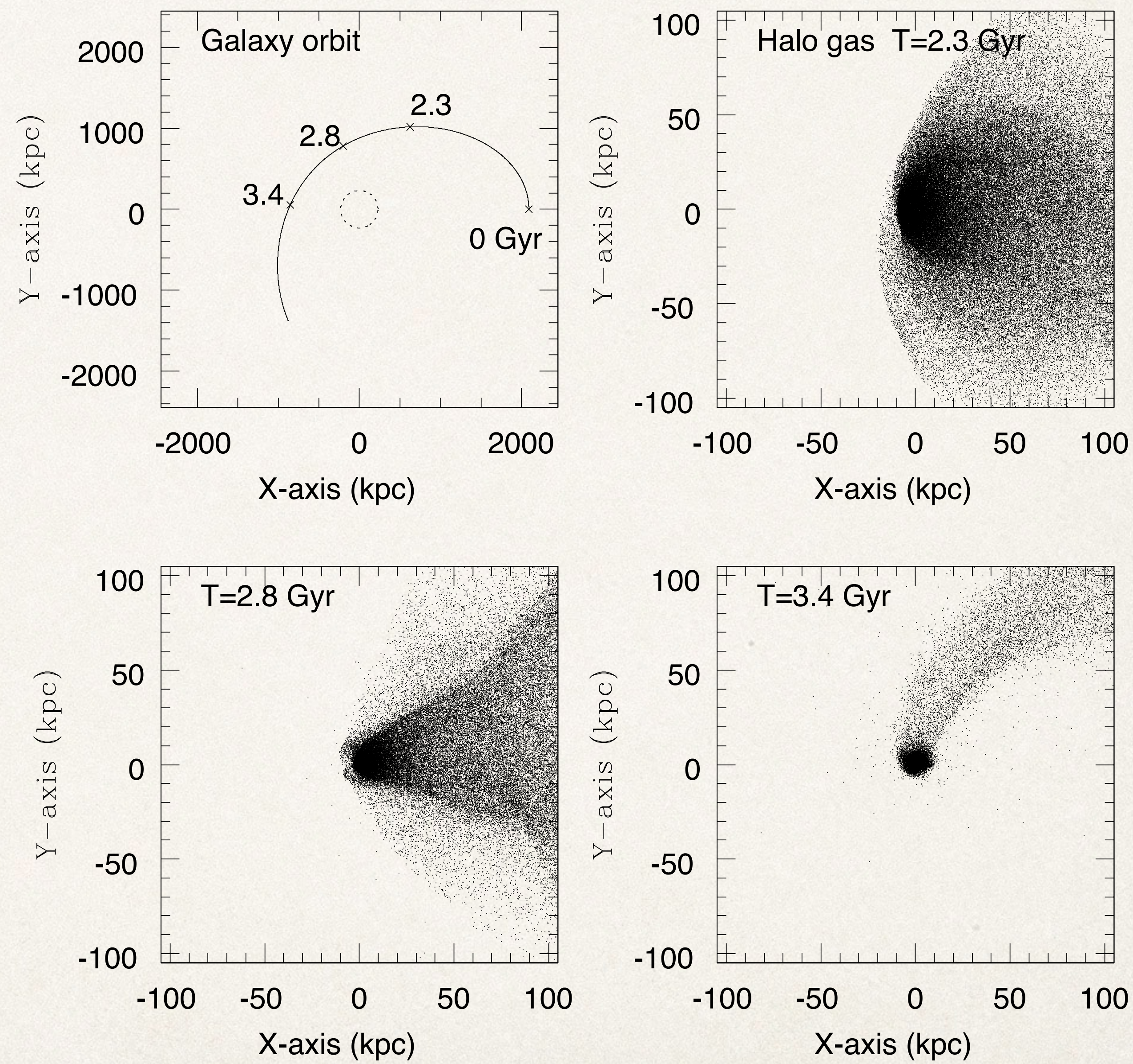
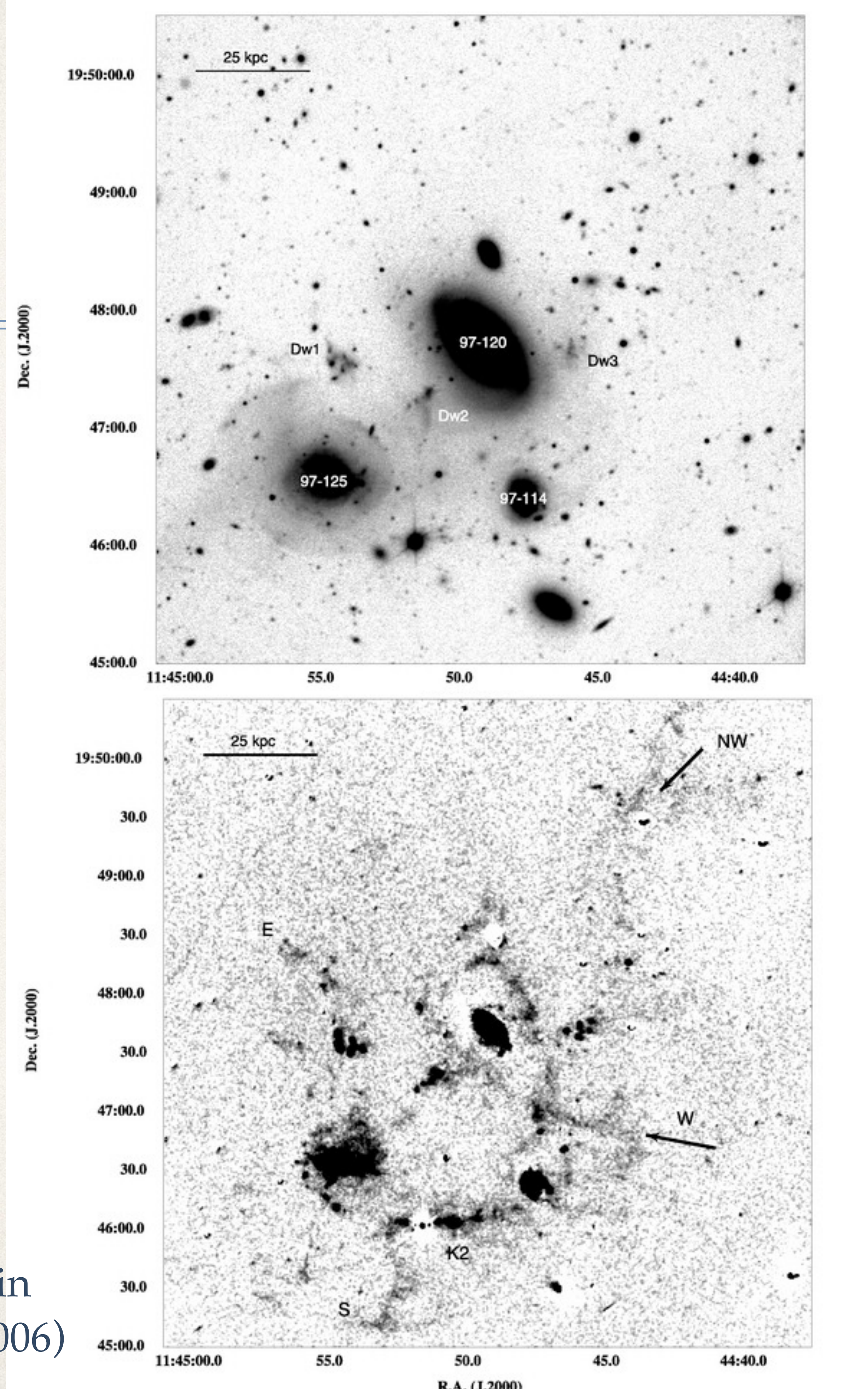


FIG. 1.—*Upper left panel*: Orbital evolution of a spiral in a cluster with $M_{cl} = 5 \times 10^{14}\ M_{\odot}$, $R_s = 230$ kpc, and $R_{vir} = 2.09$ Mpc. The orbit during 4.5 Gyr dynamical evolution of the spiral is given by a solid line. The cluster core (or scale) radius is represented by a dotted circle. The time 0, 2.3, 2.8, and 3.4 Gyr are represented by crosses along the orbit. *Three remaining panels*: Time evolution of the halo gas distribution during the dynamical evolution of the spiral.

Preprocessing

- Hierarchical mass assembly: galaxies don't (only?) fall in clusters in isolation but possibly already as part of groups
- Mergers and tidal interactions are much more effective in smaller and lower-σ groups
- This is not so commonly observed in local clusters though, but may be more common at higher z



Blue infalling group in A1367 (Cortese et al. 2006)

Comparison of different mechanisms: effects of perturbation

- Gravitational interactions (galaxy-galaxy, galaxy-cluster, harassment)
  - Induce dynamical instabilities and angular momentum transfer/loss
  - Gas sinks and nuclear starburst are produced
  - Increase of B/T, truncation of stellar and gas disks
  - Mergers (rarely)
  - Facilitate the "work" of the ICM
- Interactions with the hot ICM
  - efficiently remove the outer disk gas and quench star formation (directly by gas removal or via starvation)
  - hardly increase B/T, as required to explain the morphological segregation

Comparison of different mechanisms: timescales and probability

- Timescale for tidal interactions (relaxation time): ~10^{10} yr
- Timescales for ram pressure gas stripping: about one crossing time, 10^9 yr
- Timescale for harassment: several crossing times (multiple encounters are necessary)
- Timescales for gas removal for thermal evaporation or viscous stripping
  - in relaxed, gas-rich clusters (eg Coma) very short: $<10^8$ yr
  - in unrelaxed, gas-poor clusters (eg A1367 or Virgo): some 10^8 yr
- Timescale for galaxy starvation: some Gyr

Comparison of different mechanisms: efficiency vs clustercentric distance

- Galaxy–cluster IGM interactions are most efficient close to the cluster center, where the density and the temperature of the IGM (as well as the velocity of galaxies) reach their maxima
- The perturbations induced by the cluster potential are also most efficient in the cluster center, since the cluster tidal field is maximal at the core radius
- Galaxy-galaxy interactions: competition between frequency (higher in the core) and duration (shorter due to higher velocity in the core)
- Harassment can be effective also at the periphery
- Starvation is already effective outside the virial radius
- Preprocessing (by definition...) occurs outside the cluster

Conclusions

- Galaxy transformations in clusters are VERY COMPLEX
- Result from a number of mechanisms involving dynamics and hydrodynamics of multiple phases
- Interactions with the IGM appear to dominate the transformation of late type galaxies in present day clusters, but the efficiency of such mechanisms is very inter-dependent on all the other mechanisms