Topics in Extragalactic Astronomy

2. Galaxy Evolution and Environment

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IAG – USP

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outline

- What is environment
- Physical process
- Environmental effects in groups and clusters

What is the environment of a galaxy?



- **Everything outside a galaxy that affects it: other galaxies, gas, dark matter**
- **Environment depends on the *scale***
- **Physical measures that characterizes environment: number density of galaxies, gas density, distance to the halo center,...**

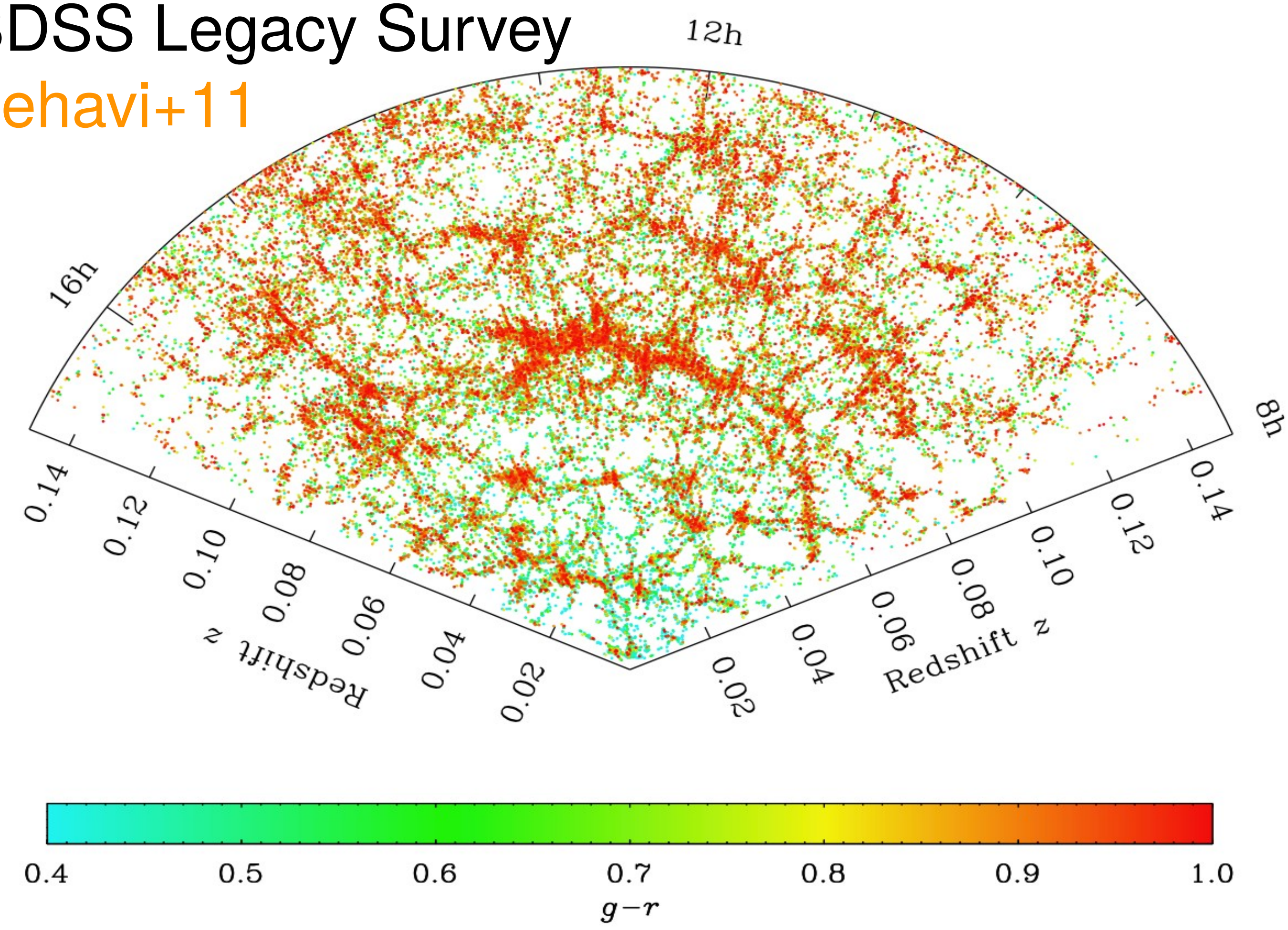


What is the environment of galaxies?

LSS: the cosmic web

"field", groups, clusters, filaments, sheets, ...

SDSS Legacy Survey
Zehavi+11



Physical process in galaxy interactions

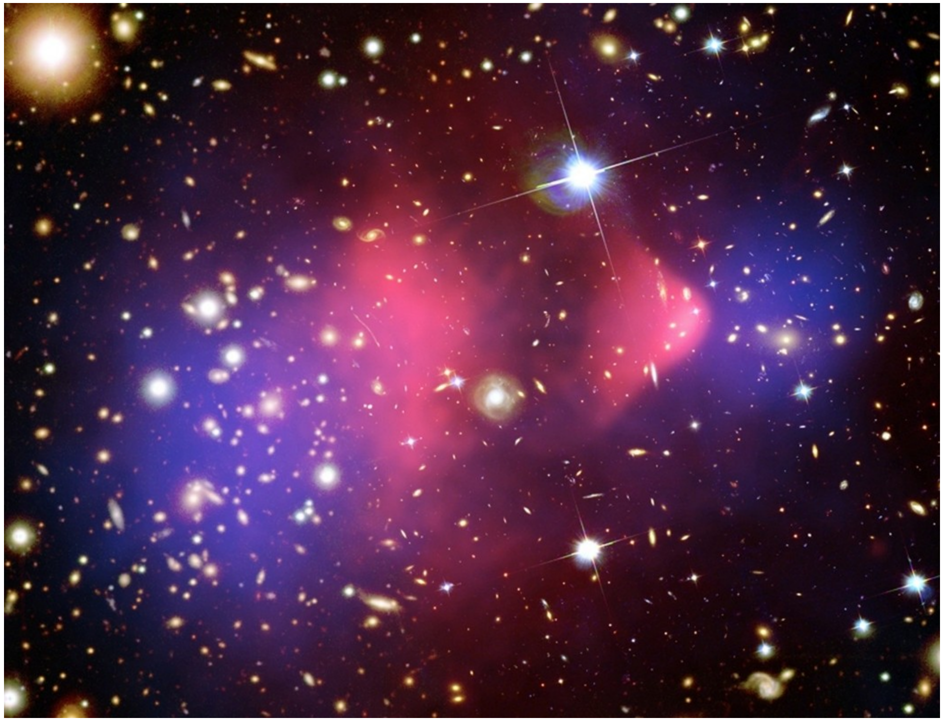
Two major classes:

- **Gravitational – conservative**

  tidal interactions, (dry) mergers, harassment, ...

- **Hydrodynamical – dissipative**

  star formation, (wet) mergers...



see Mo, van den Bosh & White, Galaxy Formation and Evolution, cap 12

Tidal interactions

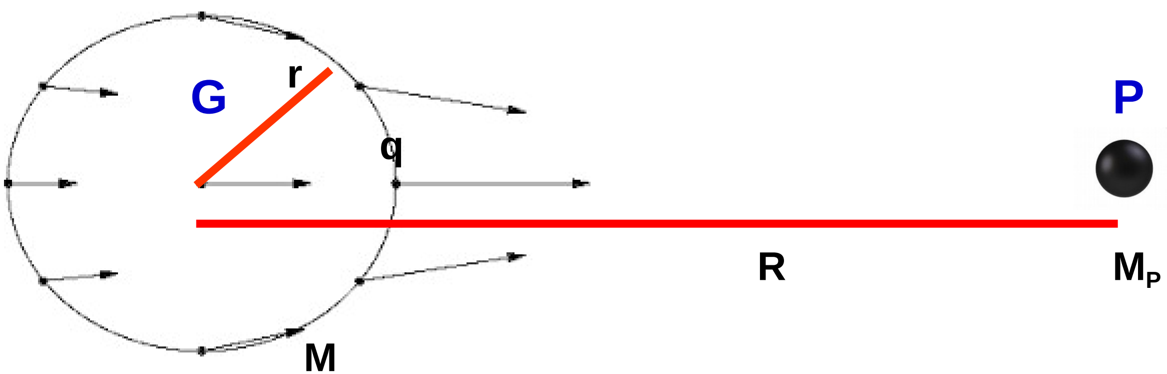
- the gravity force due to the perturber P is not uniform over the body of a galaxy G
- particle q experiences a tidal force per unit mass (acceleration):

$$\Delta F = |G\, M_P / R^2 - G\, M_P / (R - r)^2\,| \simeq 2\, G\, M_P\, r / R^3$$

- tidal radius: if the tidal force exceeds the binding force, the material is stripped away:

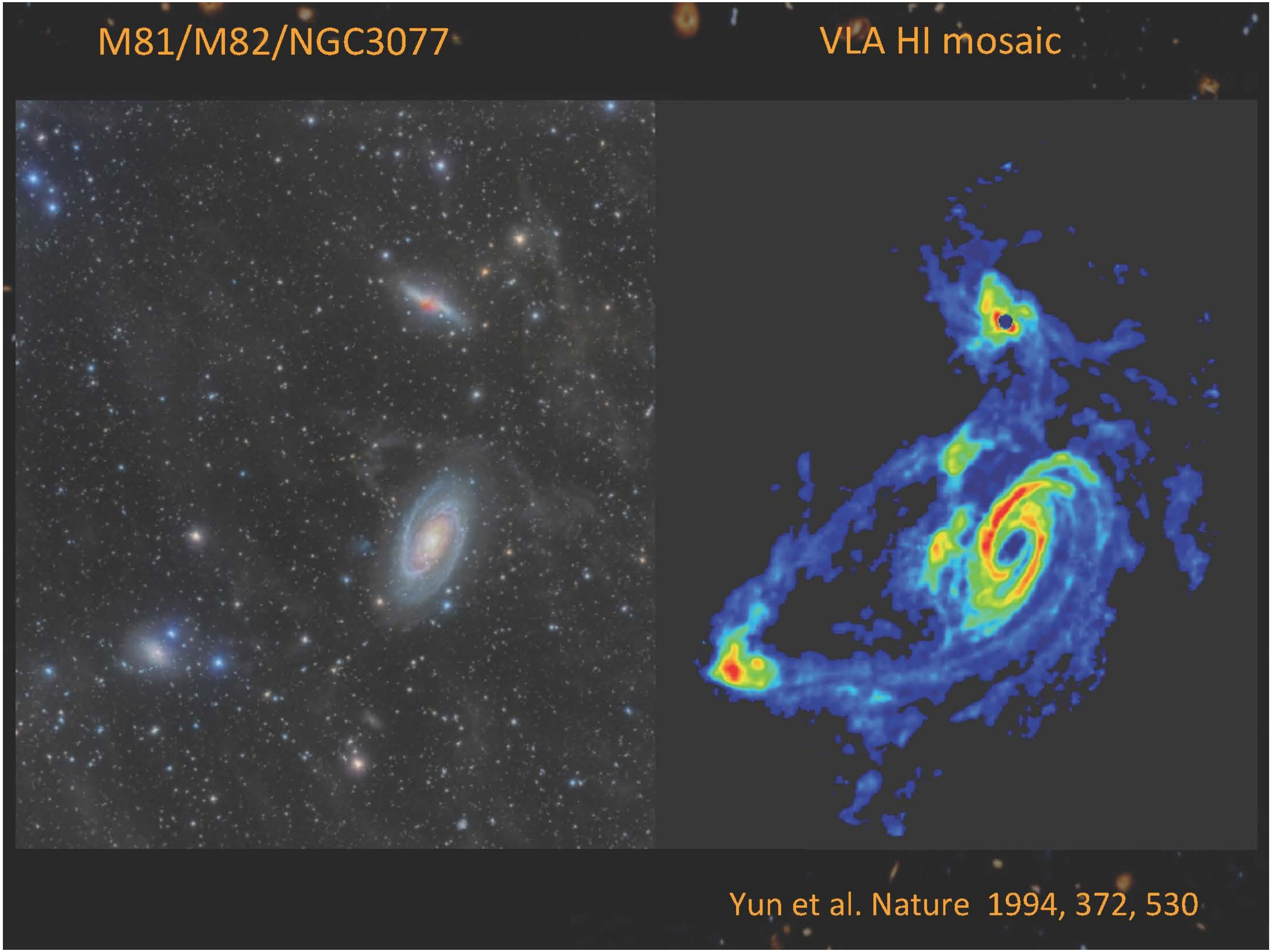
$$\Delta F \sim G\, M / r^2 \quad \rightarrow r_t \sim [M/(2M_P)]^{1/3}\, R$$

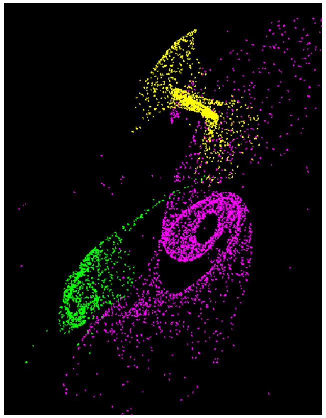
- tidal time-scale: R / v (collision time scale)
- impact of the interaction: v/σ (velocity dispersion of a galaxy)



see Binney & Tremaine

Tidal interactions in M81





Tidal interactions

a collection of useful concepts:

- **tidal forces actuate on matter: dark matter, stars, gas**
- **tidal forces produce tides, streams, stripping**
- **key parameter: v/σ**

- **slow interactions cause more damage**
- **high speed encounters may also lead to mass loss**

- **tidal forces transfer orbital energy to internal energy of the galaxies, increasing their mutual binding energy**
- **pumping energy in a galaxy causes it to become larger and colder (the heat capacity of a gravitational system is negative)**

Tidal interactions

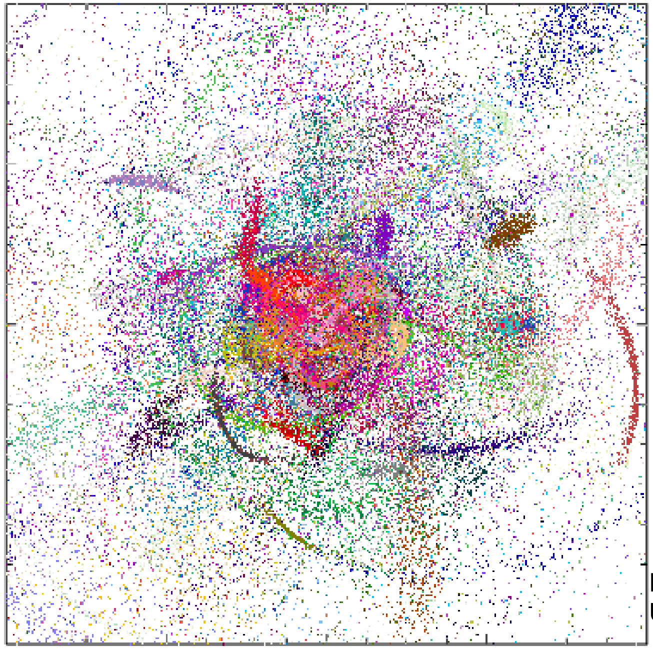
Antennae: the formation of two prominent tidal tails carries away part of the orbital energy and angular momentum, causing the galaxies to merge

Tidal interactions

- tidal stripping: remotion of a galaxy material by tidal forces
- tidal stripping of satellites:

  stripped stars move in approximately the same orbit, either leading or trailing the satelite: tidal streams
- tidal stripping may provide dynamical diagnostic on:
  - the main galaxy gravitational potential (e.g., the form of the dark matter halo)
  - the mass assembly of the main galaxy (archeology of MW)
- tidal shocks: when a massive body (e.g. a globular cluster) passes quickly by a larger body (e.g. a galaxy)- the heating of the cluster may lead to its expansion and loss of stars

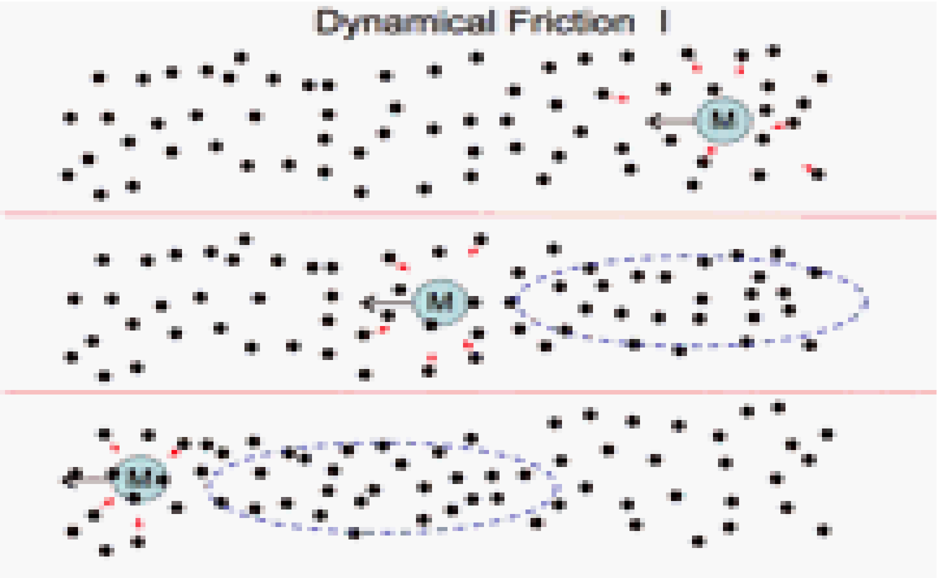
Martinez-Delgado+

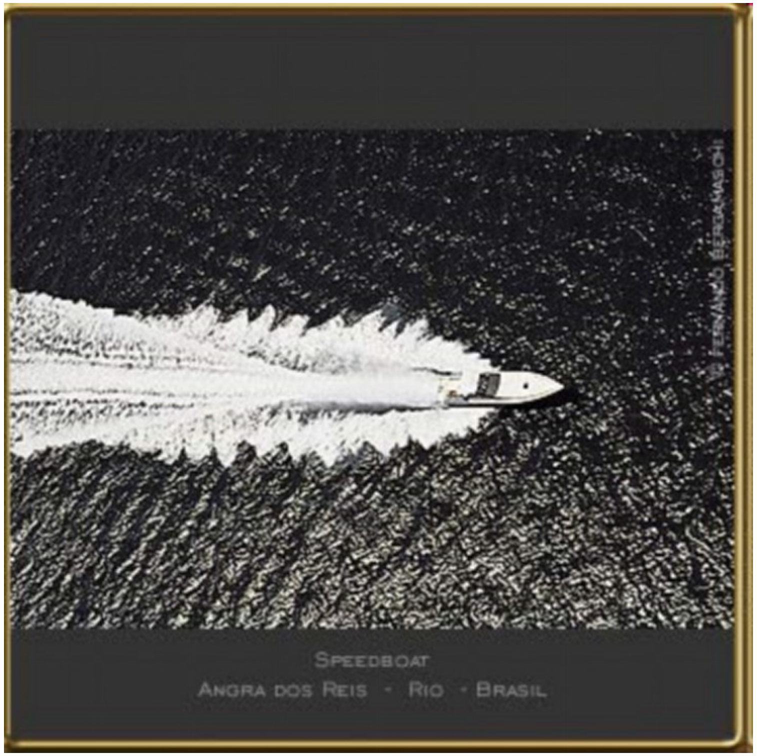


Paul Harding
U. Arizona

Dynamical friction

- **particle with mass M moving in a sea of lighter particles of mass m**
- **M will decelerate by transferring kinetic energy to the lighter particles, and will move towards the bottom of the gravitational potential well**





DF is a form of tidal interaction!

Dynamical friction

- **Chandrasekhar (1943; for a pedagogical introduction see Aceves & Colosimo 2006)**
- **particle with mass m moving in a sea of lighter particles with velocity v_m**
- **dyna** $$\vec{F}_{df} = -\frac{4\pi \ln \Lambda G^2 \rho M^2 F(X)}{v_M^3} \vec{v}_M$$ **scal** $$\tau_{df} \sim \frac{M v_M}{F_{df}} \simeq \frac{v_M^3}{4\pi \ln \Lambda G^2 F(X) \rho M}$$

ρ: density of lighter particles;

$\ln\Lambda = \ln(b_{max}/b_{bmin})$: Coulomb logarithm (typical values ~2 – 5); F(X)~1

- **force proportional to M^2 and v_M^{-2}:**

drag is larger for larger masses and smaller velocities; the time-scale is correspondingly smaller

Mergers

- **transfer of orbital energy to internal energy of the galaxies in a tidal interaction:**
  if the lost orbital energy is large enough, the galaxies merge

- **for mergers occur the velocities should be small:**
  mergers are common in groups, where the velocity dispersion of the system is similar to the velocities of the stars in the galaxies

- **in clusters: the relative galaxy velocities are too large (> 700 km/s) for conventional mergers**
  (but cDs grow by mergers due to the dynamical friction)

Mergers

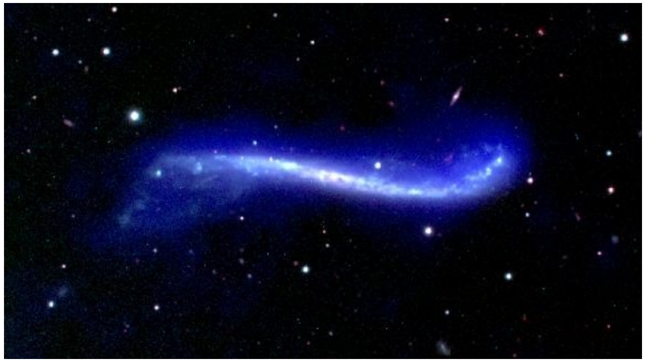
a merger of two galaxies depends primarily of four properties:

- **mass ratio of the galaxies:**
  <u>major mergers</u>: $M_2/M_1 \sim 1 - 3$
  <u>minor mergers</u>: otherwise; satellites
  major mergers are more destructive than minor mergers

- **morphologies of the progenitors (disks or spheroids):**
  disks are more fragile; even minor mergers may have a structural impact (e.g. disk thickening, bars, warps)

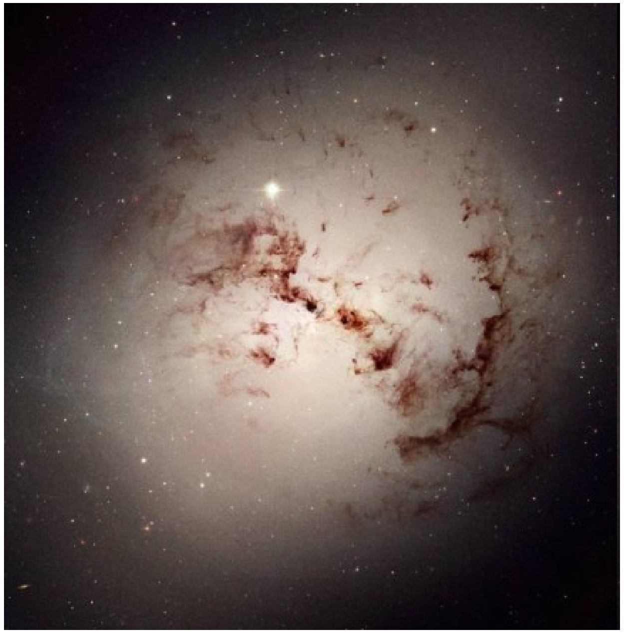
- **gas mass fraction of the progenitors:**
  ***<u>wet mergers</u>:* between gas-rich galaxies**
  ***<u>dry mergers</u>:* with gas-poor progenitors**
  gas responds to pressure as well as to gravity and may loose energy by radiation

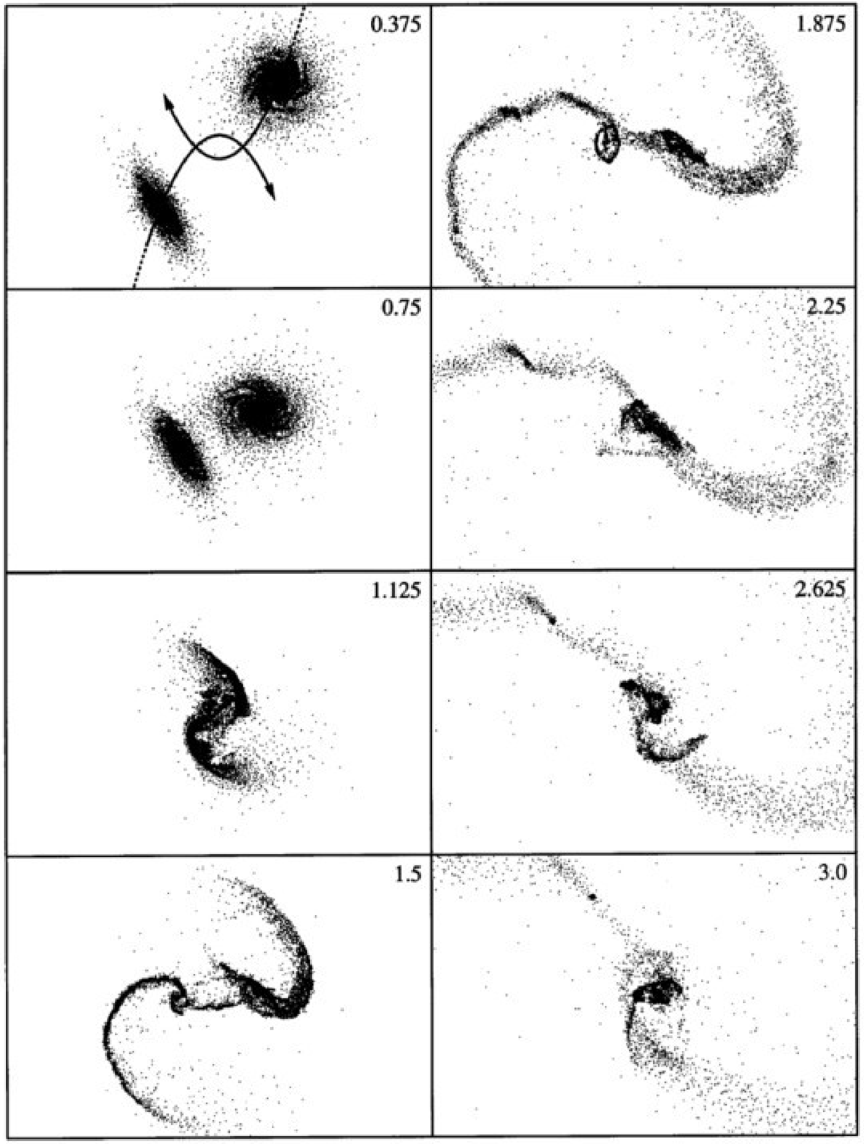
- **orbital properties:**
  the orbital energy and angular momentum determine the fate of a merger



Mergers

- **The merger of two spirals may lead to an elliptical galaxy (Toomre & Toomre 1972)**
- **Many Es show evidence of mergers: dust lanes, multiple nuclei**





Barnes & Hernquist (1996)

Mergers

Connection with starbursts and AGNs:

- **Wet mergers may trigger nuclear starbursts and AGNs**
- **Mergers can cause the disks to develop prominent bars gaseous and stellar bars generally have different phases and produce torques in each other; these torques may remove angular momentum from the gas that then flows towards the galaxy center**
- **This gas may create a nuclear starburst or feed a massive black hole**

- **M82: a recent merger of a disk galaxy?**
  - **-it contains $\sim 2 \times 10^8$ $M_\odot$ in gas**
  - **-current SFR: a few $M_\odot$ / yr**
  - **-time for gas consumption: $\sim 10^8$ yr**

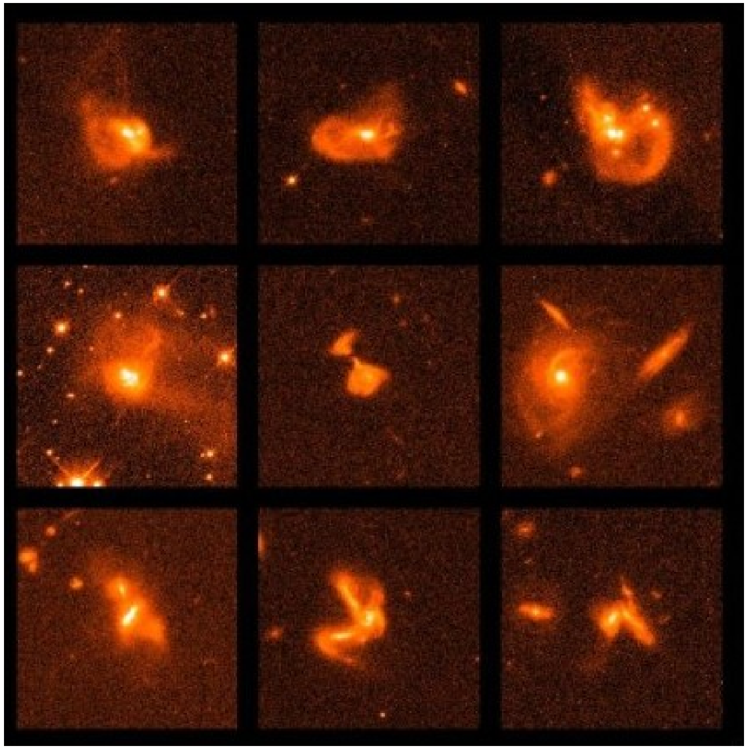
1 - 2 Gyr from now M82 may become a "typical" E

Mergers

ULIRGs (Ultra Luminous Infrared Galaxies): strong starbursts fired by mergers

- **gas mass ~ $10^9 - 10^{10}$ $M_\odot$**

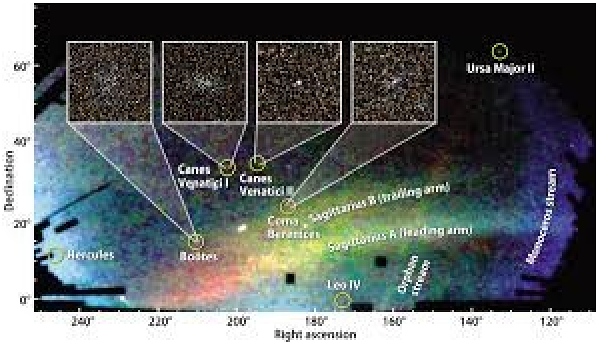
- **dense interstellar medium: the bulk of the UV radiation emitted by young stars is absorbed and re-emitted in the FIR, with luminosities above ~ 10^{12} $L_\odot$**

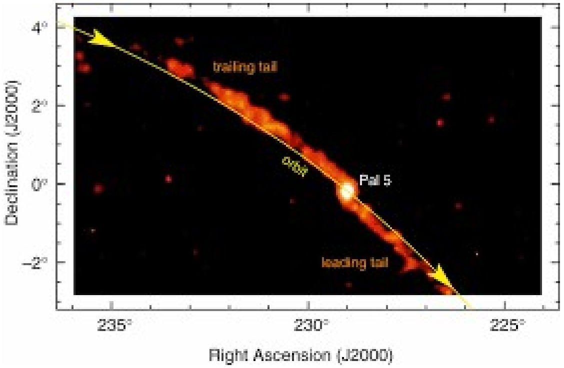


Mergers

Galaxy Archeology:

Tóth & Ostriker (1992): the fact that the disk of MW is thin (scale height ~ 0.3 kpc) at the solar radius suggests that the MW cannot have accreted more than a few percent of its mass within this radius in the last 5 Gyr





Ram-pressure

galaxy groups and clusters have a hot, low density gaseous medium: the inter-galactic medium (ICM)

$M_{gas} = 10^{12} - 10^{14}\, M_{\odot}$,

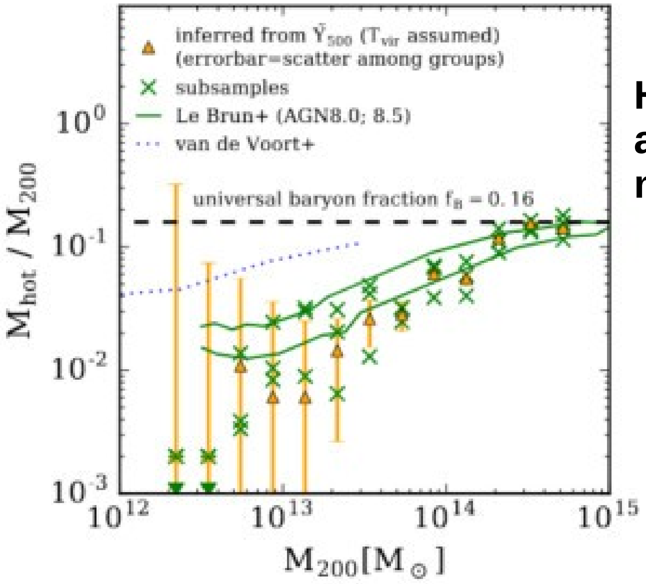
$L_x = 10^{42} - 10^{45}$ erg/s,

$T \sim 10^{7} - 10^{8}$ K,

$n < 10^{-2}\ cm^{-3}$

Gunn & Gott (1972): the gas in a disk galaxy traveling in a cluster may be removed by the pressure of the ICM gas: the ram-pressure

ESO 137-001



S. H. Lim+ (2017)

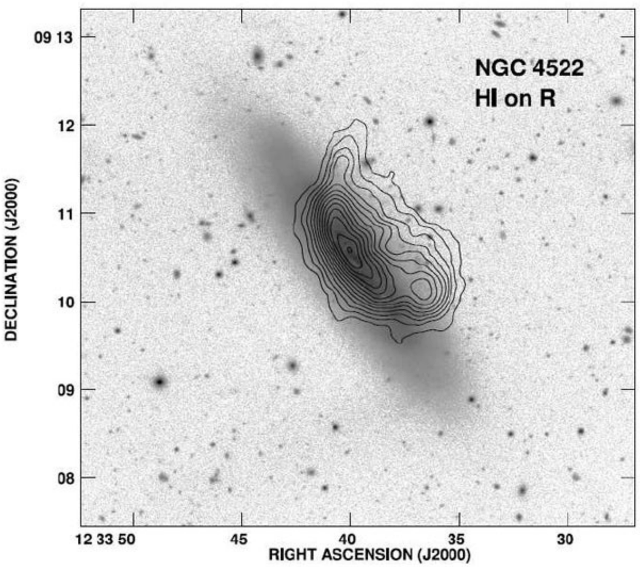
Hot gas fraction as a function of halo mass

Ram-pressure

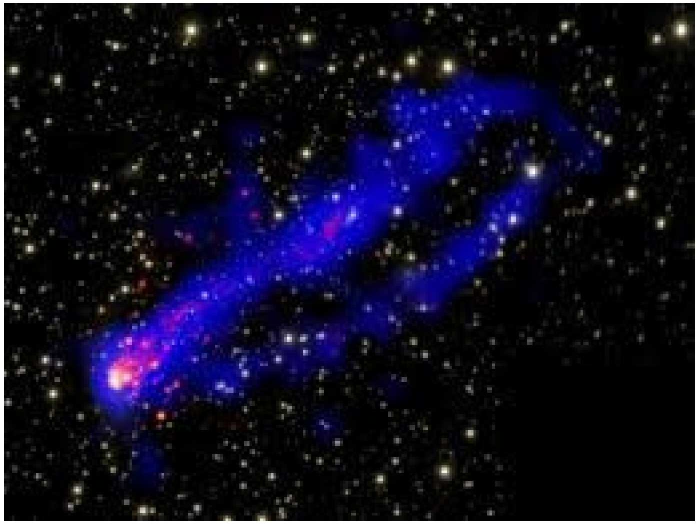
- Gunn & Gott (1972): a galaxy with velocity v moving in an ICM with density ρ_{ICM} will feel a pressure $P \approx \rho_{ICM}\, v^2$
- ram-pressure stripping: to remove at least part of the gas associated with the galaxy, P should be larger than the force per unit area that binds the interstellar medium (ISM) to the galaxy:

$$P = \rho_{ICM}\, v^2 > 2\pi G\, \Sigma_* \Sigma_{ISM}$$

Σ_* and Σ_{ISM}: surface mass density of stars + dark matter and gas, respectively



Kenney+ 2004


ESO 137-002 (Zhang+ 2013)

Ram-pressure

- **ram-pressure stripping:**

  $P = \rho_{ICM}\, v^2 > 2\pi G\, \Sigma_* \Sigma_{ISM}$

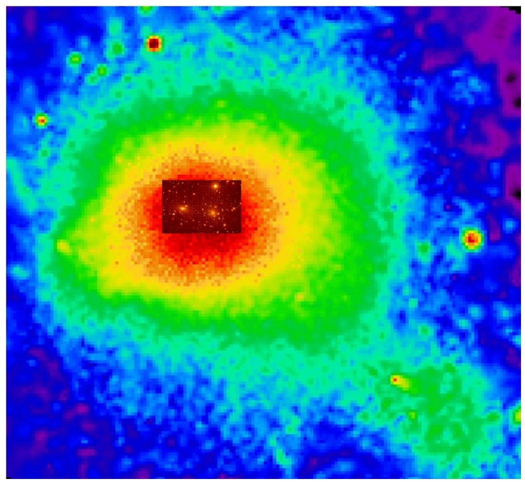
- **Example: disk similar to that of MW moving with**

  $v = 1000$ km/s

  $M_* = 5 \times 10^{10}\, M_\odot$

  $M_g = 5 \times 10^9\, M_\odot$

  $R = 10$ kpc



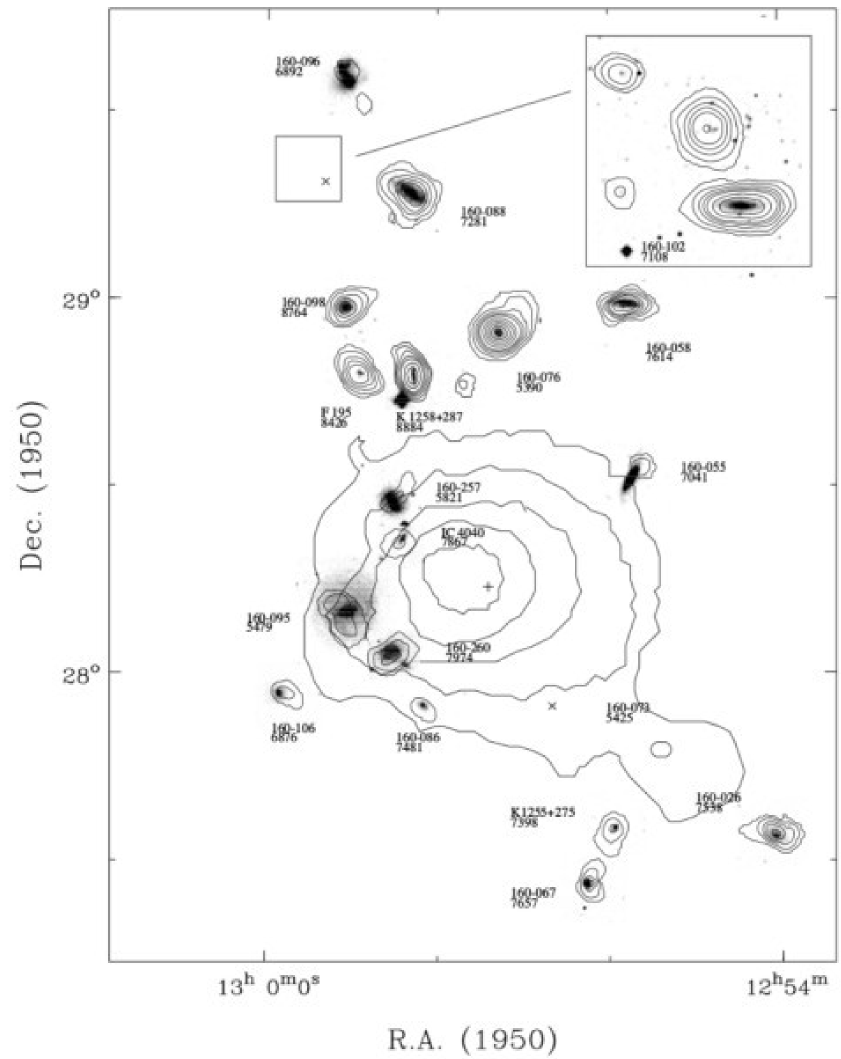
stripping: $\rho_{ICM} > 4.6 \times 10^{-27}$ g cm^{-3}

few 10^{-3} particles per cm^3 → similar to a cluster ICM

Coma cluster

21cm images with the VLA

Bravo-Alfaro+ 2000



The Local Group

Binary system:

MW + Andromeda

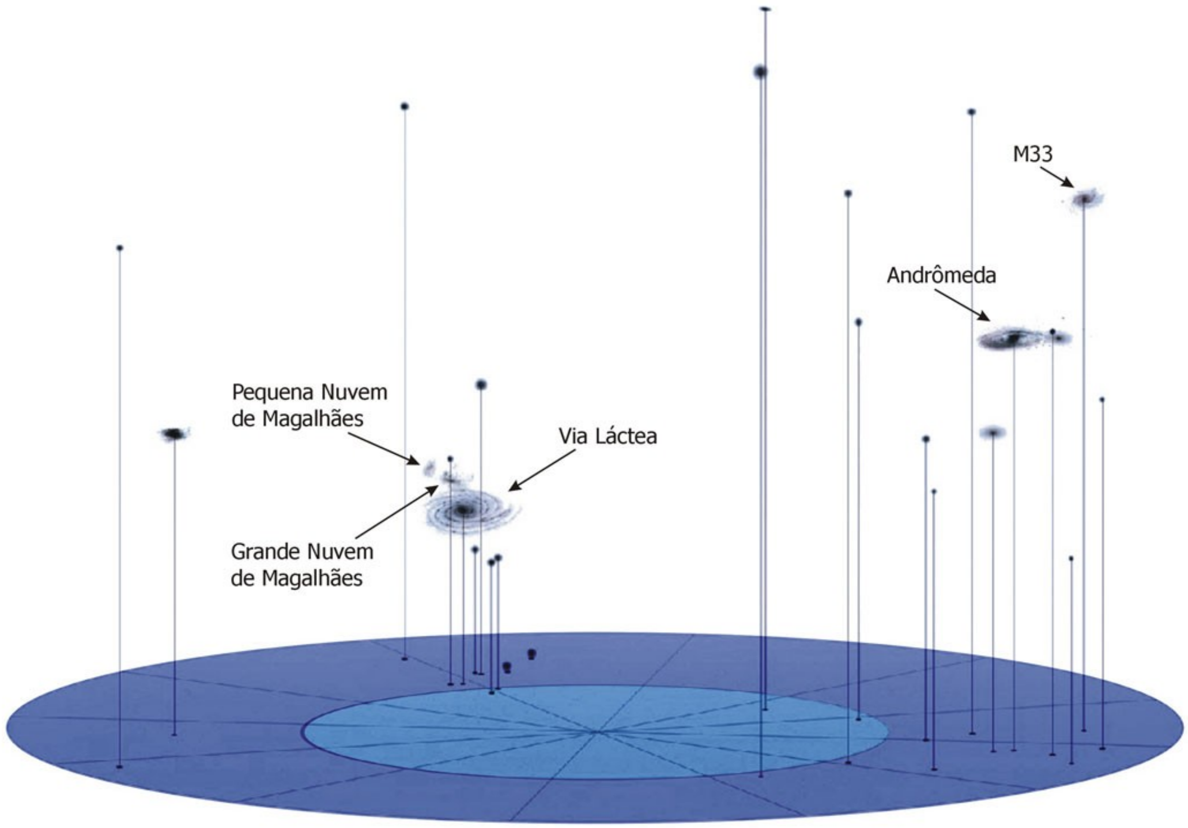
Kashibadze & Karachentsev (2017):

- **$M \sim (1.6 \pm 0.2) \times 10^{12} M_{sun}$**
- **R ~ (0.91 +/- 0.05) Mpc**

(zero-velocity surface)

(known) satellites :

- **MW: 45**
- **Andromeda: 51**



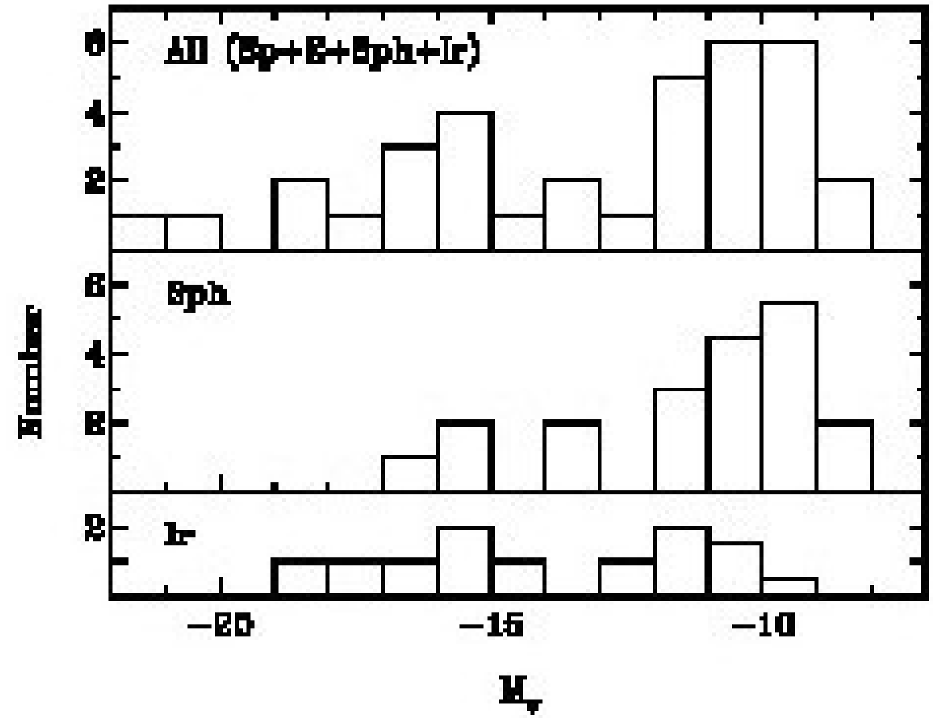
Galaxy Archeology

The LG is the closest structure for analyzing the fossil record of the hierarchical process of galaxy formation

Galaxy populations in the Local Group

- **3 spirals: MW, M31, M33 – massive, luminous, star-forming**
- **Massive irregulars: LMC, SMC**
- **Dwarfs (Grebel 2000):**
  - **Dwarf irregulars (dIrr): gas-rich, current or recent star formation; range of stellar ages**
  - **Dwarf Ellipticals (dE): bright, strong central concentration (e.g. M32); old/intermediate stars; some gas; probably in the E family**
  - **Dwarf Spheroidals (dSph): faint, very low central concentration; old/intermediate stars; low HI**

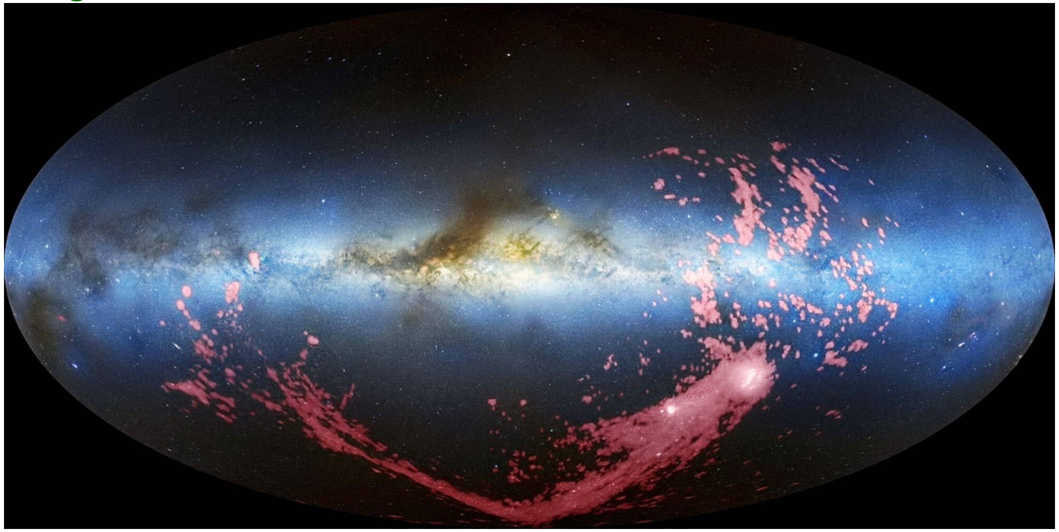
Pritchet & van den Bergh (1999)



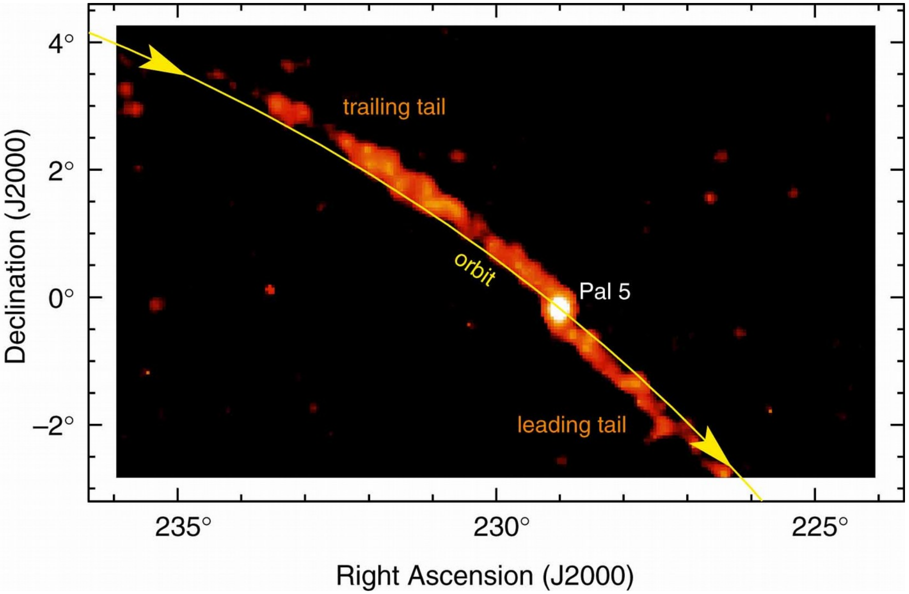
M33, LMC, NGC 205, WLM, Fornax, Segue 1

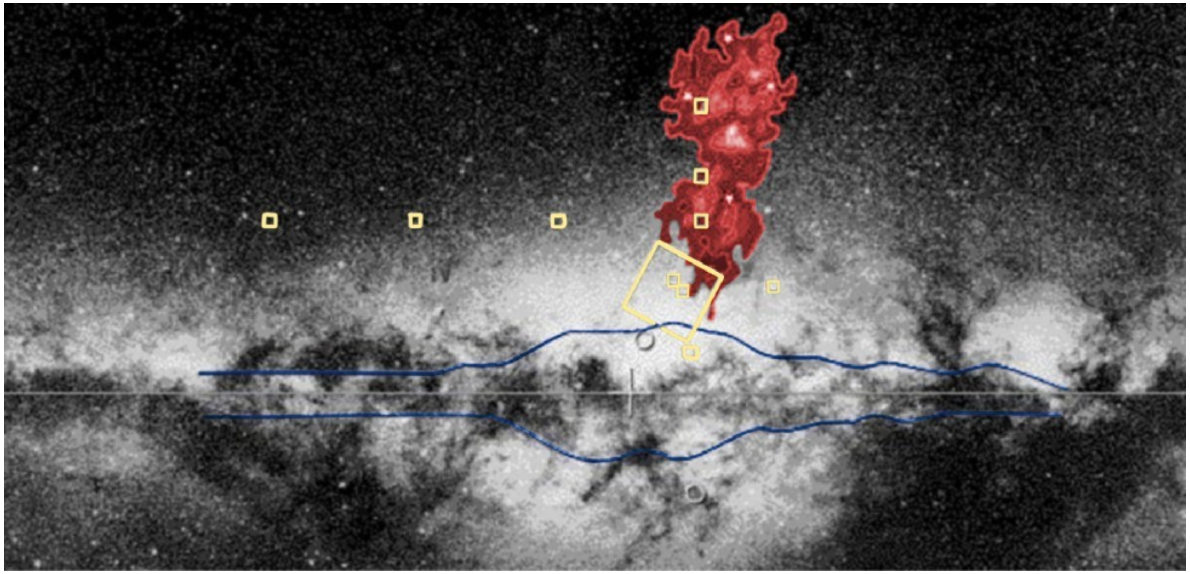
Environmental effects in the Local Group

Magellanic stream

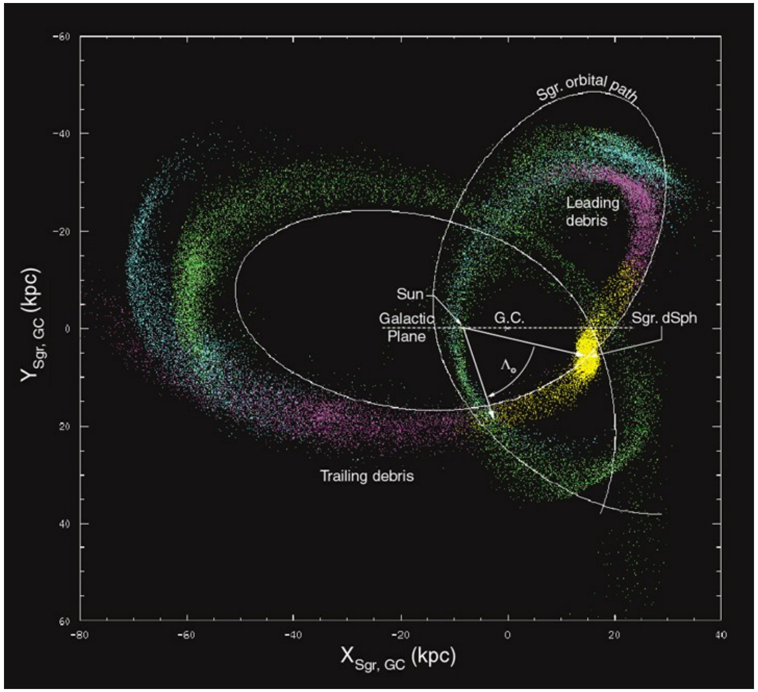


Pal 5





Sagittarius (Ibata+)



Tidal streams: Sagittarius (Majevsky+ 2003)

Morphological segregation in the LG

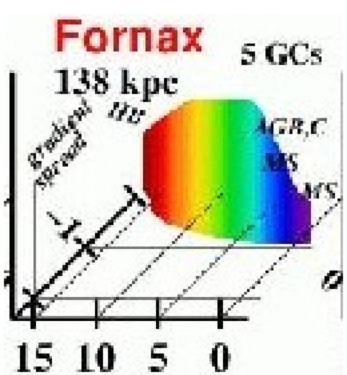
Evidence of environmental effects on galaxy evolution:

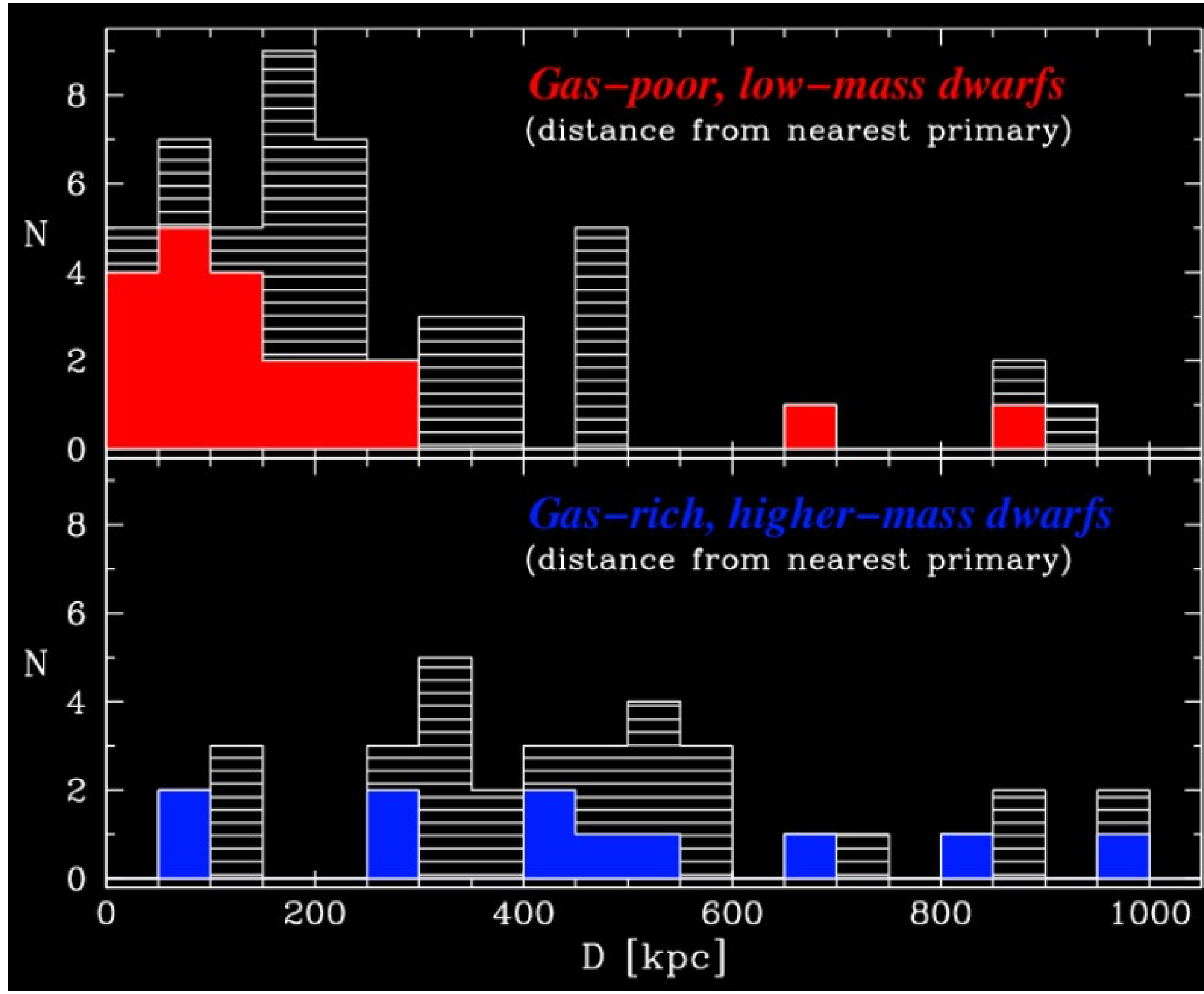
dE and dSph are within ~300 kpc of the MW and M31; dIrr shows little concentration

- **dIrr seems to evolve to dSph**
- **removal of the gas to stop SF: <u>quenching</u>**

Fig 4.8 (D. Malin) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Fornax- lost its gas after 13 Gyr of continuous SF





Ram-pressure models for the Magellanic Stream

D'Onghia & Fox (2016)

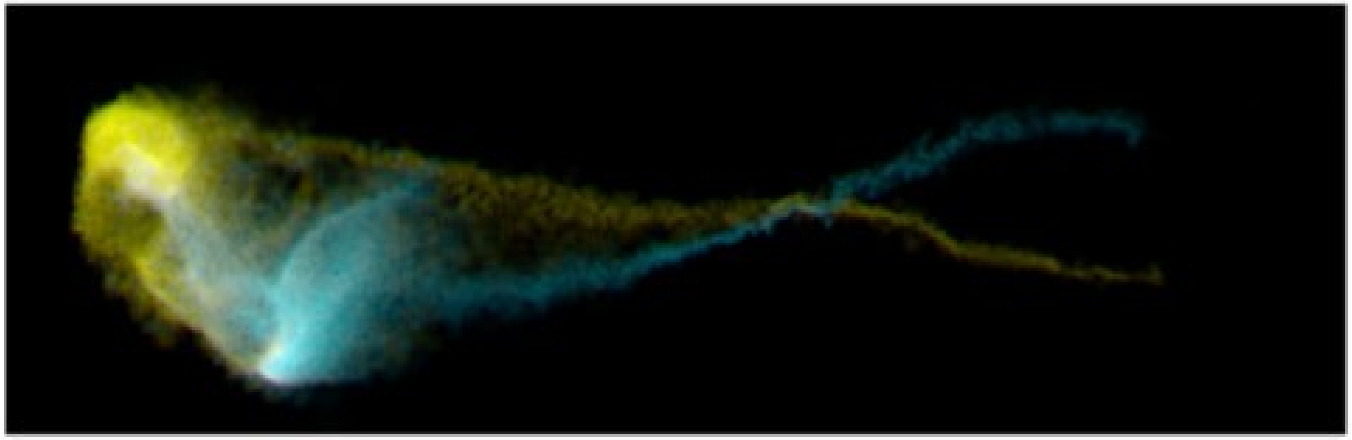
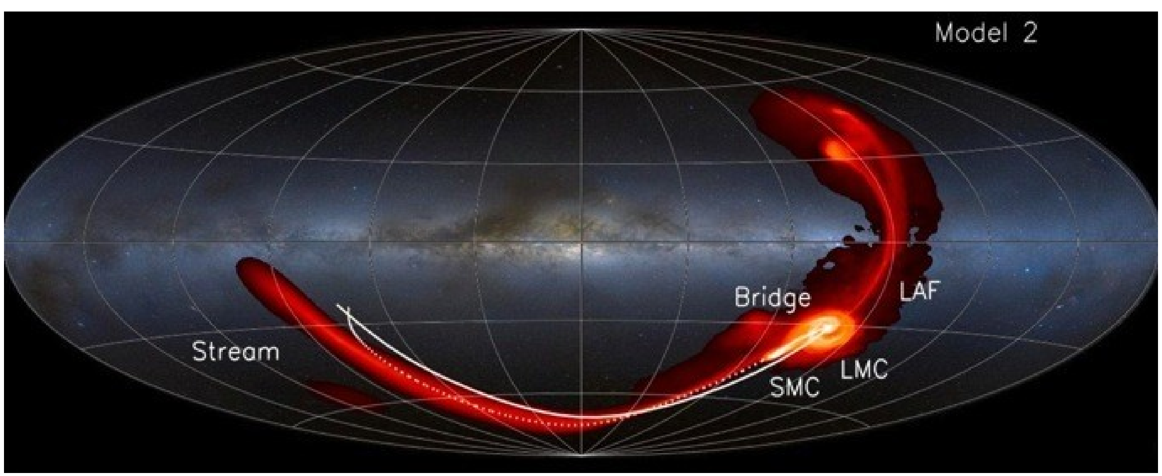


Figure 5

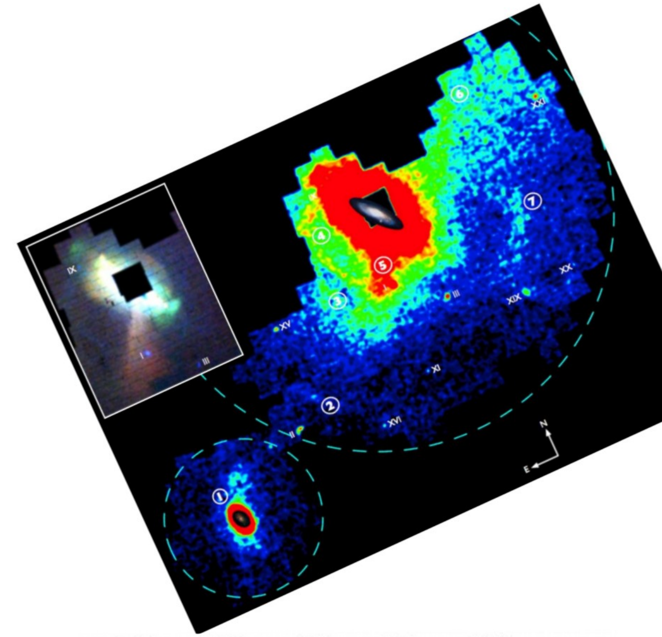
Simulation of the Stream that reproduces its spatial extent and filamentary nature. In this model the Magellanic Clouds collided ≈200–300 Myr ago and the two filaments of the Stream are formed by the ram pressure exerted by a hot MW corona with a gas density ≈10^{-4} cm^{-3}. Gas from the LMC is shown in yellow; gas from the SMC is shown in blue. Credit: Hammer et al. (2015).

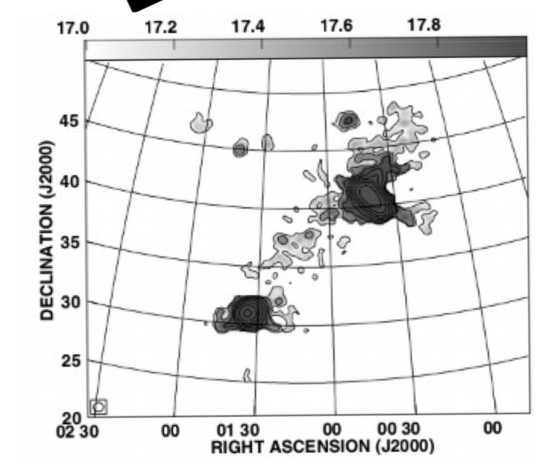


Salem+ (2015)

M31-M33 interaction

Stars: McConnachie+ (2009)



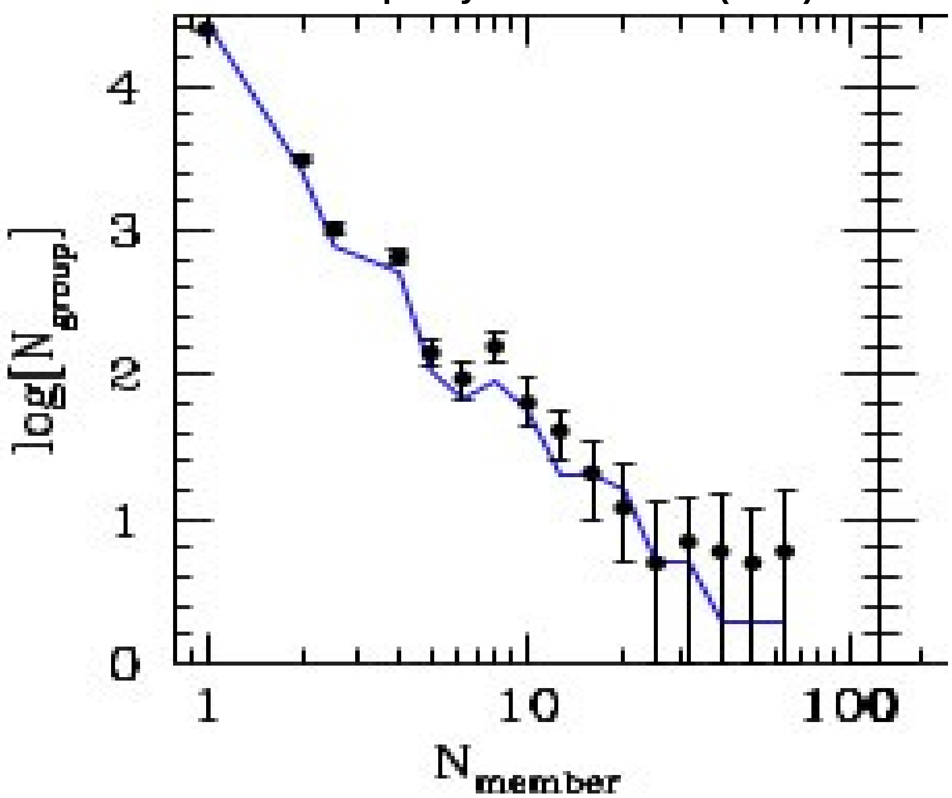


H I - Braun & Thilker (2004)

Groups

- **Most galaxies are in groups with small number of members**
- **~10% of the galaxies are in clusters**

Multiplicity function   Lu+ (2016)



- **~few L* galaxies**
- **$M_{halo} \sim 10^{12}$ - 5×10^{13} (σ < 500 km/s)**
- **physically associated – but not necessarily virialized**

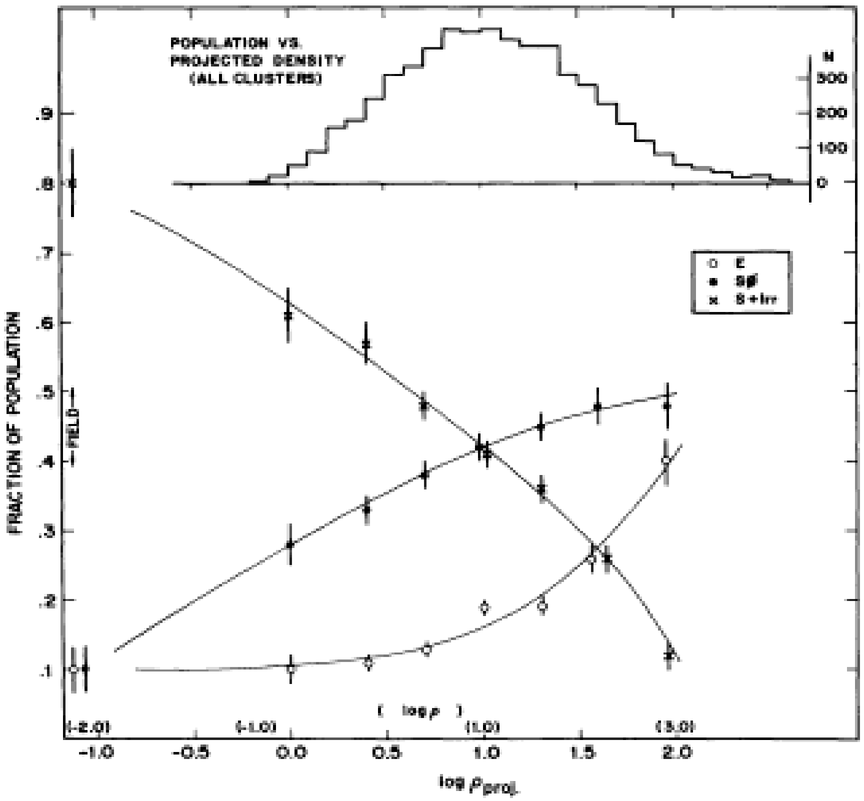
Pre-processing:

- **Most galaxies spend most of their life in groups**
- **Environmental effects are acting on galaxies**

Environmental effects on galaxies in clusters

- **clusters are a hostile environment for galaxies: large number of galaxies; hot gas in the intra-cluster medium (ICM)**

morphology-density relation (Dressler, 1980)



In dense environments most galaxies are early-type (E and S0), whereas spirals are found in low density environments

Sa, Sb → S0 → E

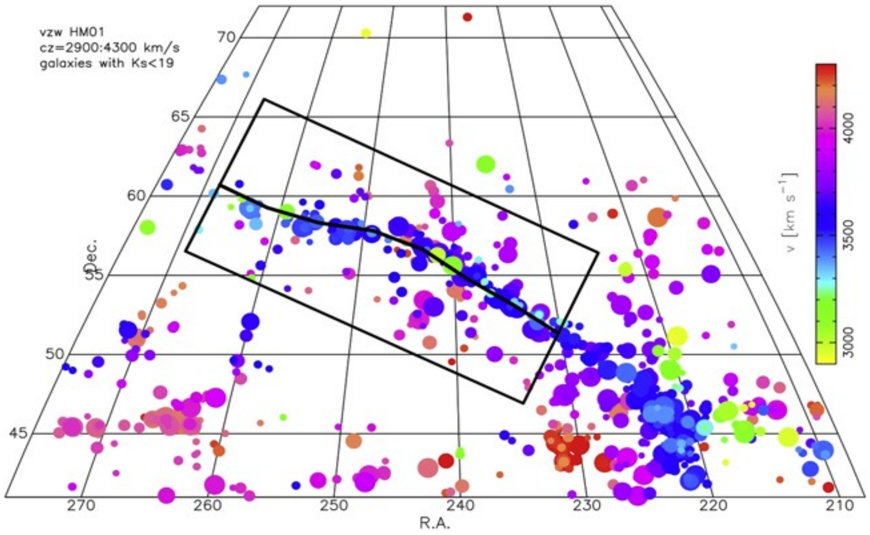
- **3 main types of interactions:**
- **tidal interactions**
- **dynamical friction**
- **interactions with the ICM**

Environmental effects on galaxies in clusters

Clusters: top of the food chain

- **they grow by mergers between them and accretion of groups and isolated galaxies**

- **Berrier+ (2008), McGee+ (2009):**
- **M=$10^{14.2}$ clusters accrete 35% of galaxies via groups**
- **For Coma-like clusters, fraction is 50%.**



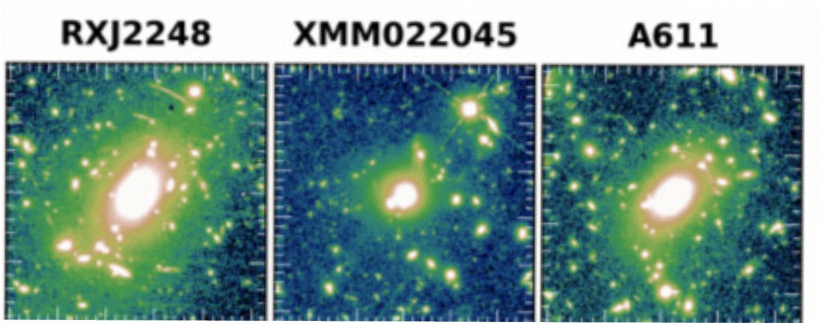
A2151 (Hercules)

Environmental effects on galaxies in clusters

tidal interactions and the origin of diffuse light in clusters:

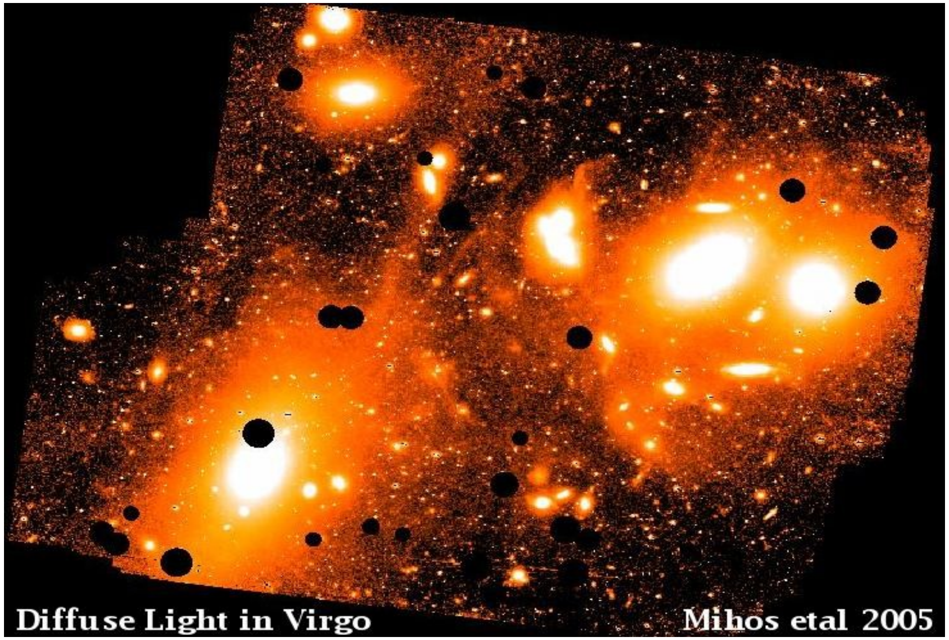
- **galaxy encounters are at high speed: ~1000 km/s**
- **The cumulative effect of these encounters is called *galaxy harassment***
- **Farouki & Shapiro (1981): disks are destroyed by 1-2 passages through the cluster**
- **E and S0 are “heated” by the collisions: they may loose stars by harassment or tidal shocks:**

Cypriano+ (2006): at the same luminosity, E galaxies in the inner and denser regions of clusters are ~5% smaller than those in the outer regions



DeMaio+ (2017)

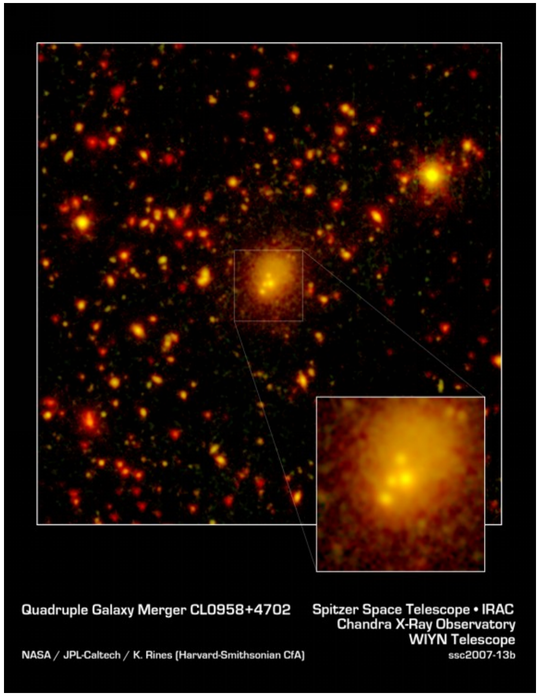
Diffuse light in clusters



Environmental effects on galaxies in clusters

dynamical friction: galactic cannibalism

- **galaxies loose orbital energy and momentum and sink towards the center of the potential well**
- **two important effects:**
  - **the mass of the central galaxy grows**
  - **It produces a depletion of massive satellite galaxies, for which the DF time-scale is the shortest**



A3827

- **A galaxy with mass M in a cluster can move to the center due to the dynamical friction in a time-scale:**

$$\tau_{df} \sim 2\,(\sigma_v / 1000\ \mathrm{km/s})^3\,(n_g / 10^3\ \mathrm{gal.\ pc^{-3}})^{-1}\,(M / 10^{12}\,M_{sun})^{-2}\,(\ln \Lambda)^{-1}\ \mathrm{Gyr}$$

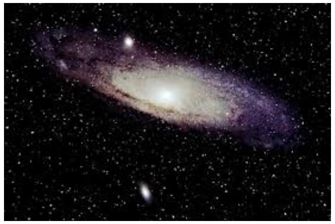
for a cluster with velocity dispersion σ_v and galaxy density n_g (mass loss increases this time-scale)

- **evidences: galaxies with multiple nuclei**

Environmental effects on galaxies in clusters

interactions with the ICM: ram-pressure

- **When a galaxy loses most of its interstellar gas, its potential for future star-formation is greatly reduced (*quenching*)**
- **Simulations indicate that if a galaxy like the MW falls on to a cluster like Coma, ~80% of the gas is removed (Abadi+ 1999); the remaining gas can form stars or be removed later**
- **Ram-pressure stripping is one of the mechanisms that may explain why clusters have a larger fraction of S0 than the field**
- **ram-pressure and galaxy winds enriches the ICM with metals**



interactions with the ICM: <u>strangulation or starvation</u>

- **remotion of the gas of a galaxy by ram-pressure or tidal stripping, leading to the interruption of star-formation (Larson+ 1980)**

summary

- Galaxies, like humans, are social ‘animals’; their evolution is strongly dependent of the environment
- The main mechanisms have been identified, but in many cases it is not clear which prevails!

- How dIrr evolve to dSph in the LG?
- The Magellanic stream is due mainly to tidal stripping or ram-pressure?
- What fraction of the stars is formed in mergers?
- What is the impact of minor mergers on the disks?
- What is the relevant time-scale for pre-processing in groups?
- What is the mass-assembly history of cD galaxies?
- What is the main origin of the diffuse light in clusters? Harassment? Tidal shocks?
- ...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