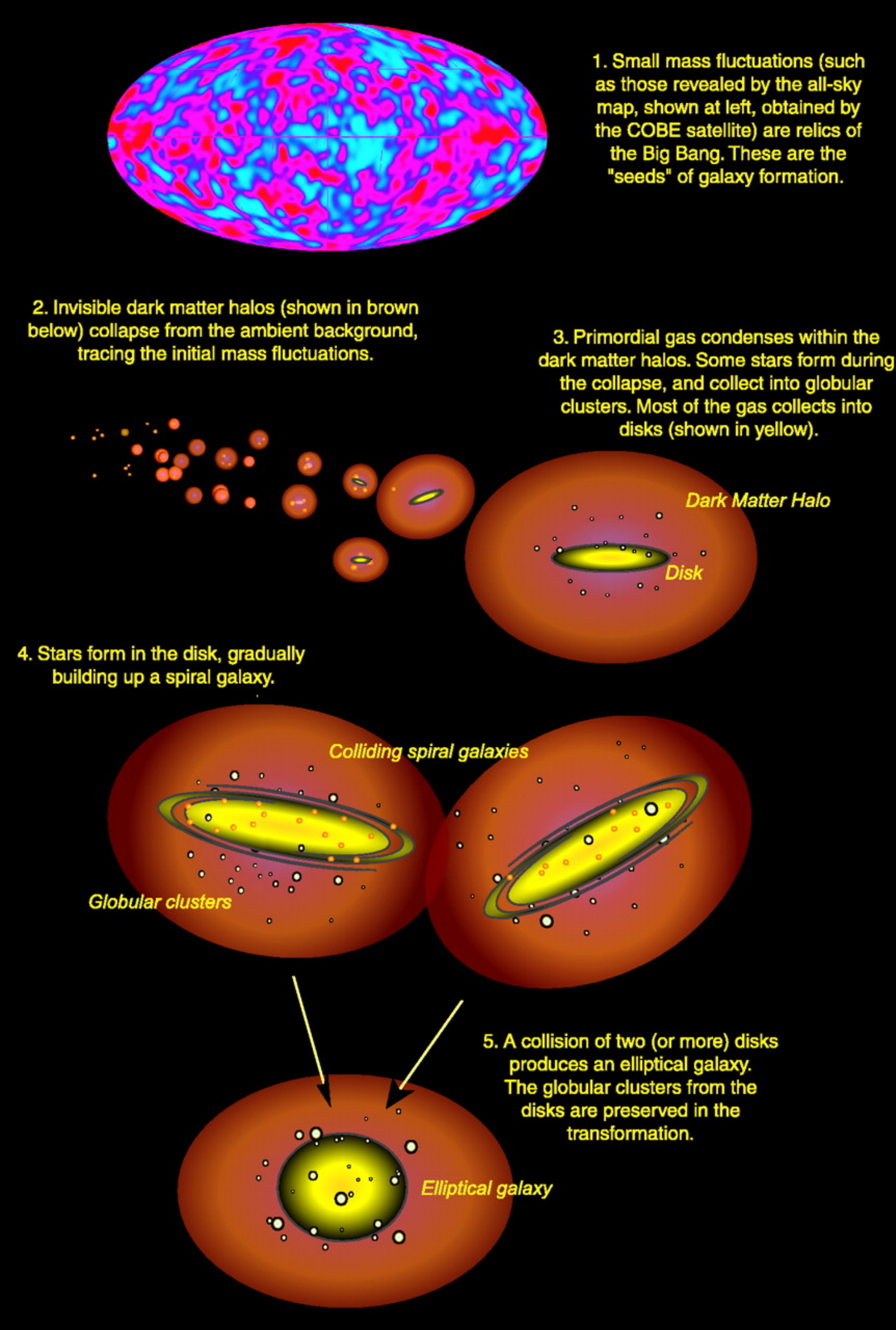
Extragalactic Astronomy

Lecture 7: Formation and evolution of galaxies: environmental mechanisms

Formation and evolution of galaxies

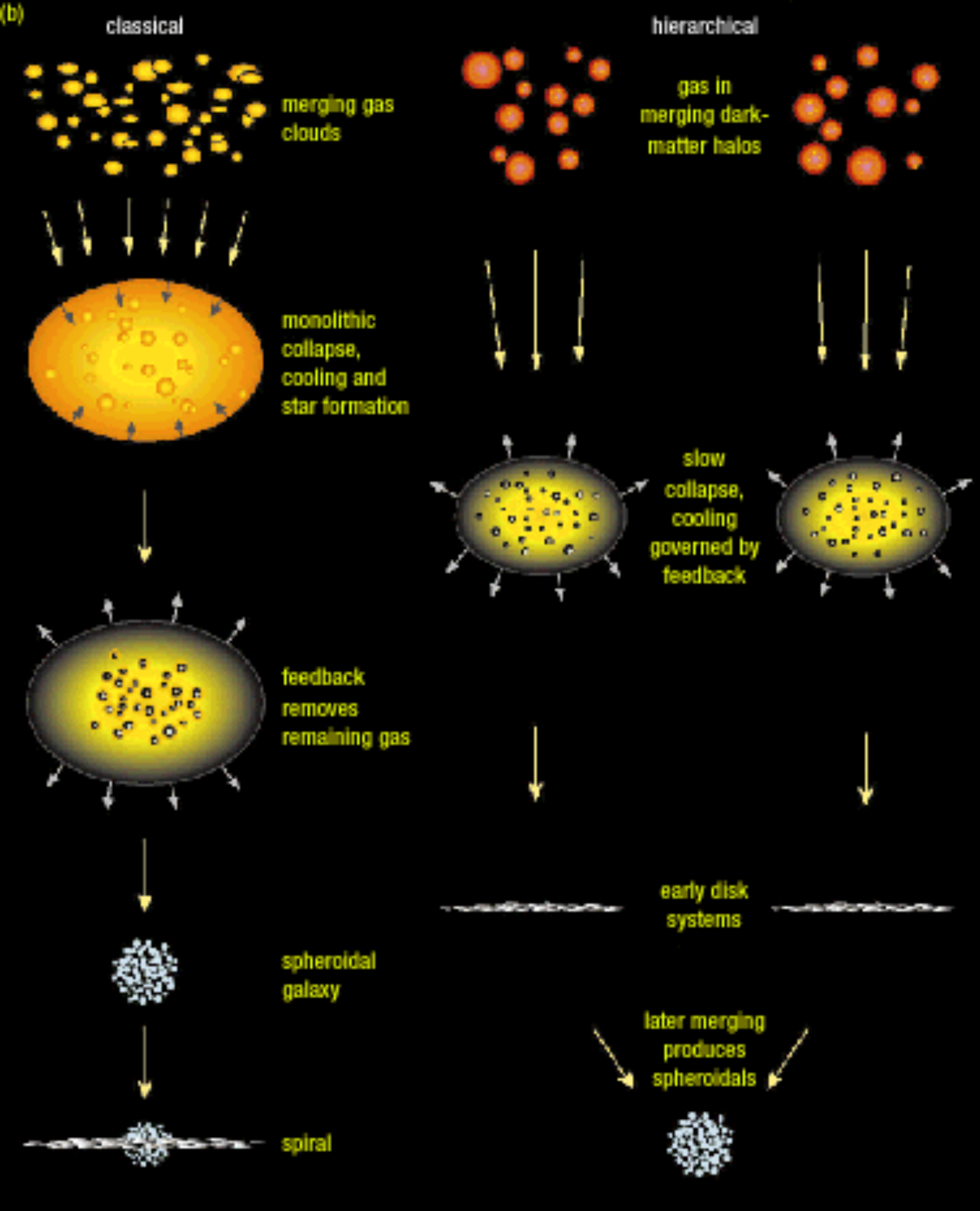
- Model: Hierarchical Clustering
- Evolution via environment (Dressler 1980)
- Environmental mechanisms:
  - Gravitational interaction (mergers)
  - Ram pressure (IGM)
- Warps (mainly of HI disk)

Hierarchical clustering



1. CMB fluctuations = seeds of galaxy formation
2. Dark Halos = IMF
3. Primordial gas collapses in the DMHs + SF + GCs
4. SF in disks = spirals
5. Merger of 2 disks = Elliptical

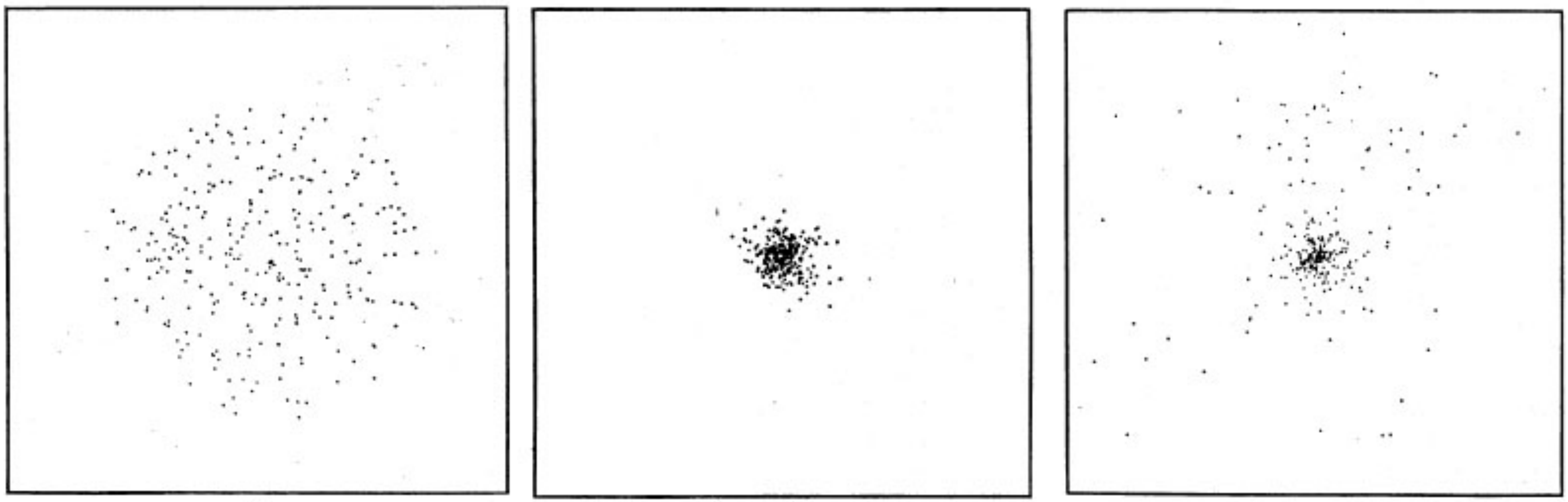
Abraham & van den Berg 2000, Science, 5533, 1273



Monolithic collapse vs Hierarchical clustering

Ellis et al. 2000

3 stages of formation



(a) (b) (c)

- (a) - contraction (collapse)
- (b) – violent relaxation
- (c) – post-virialization equilibrium

Environmental effects

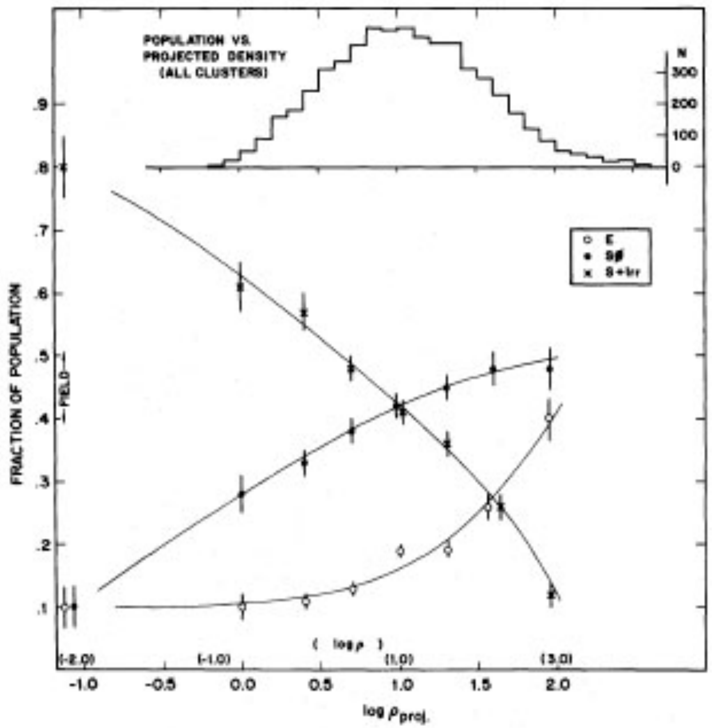


FIG. 4.—The fraction of E, S0, and S+I galaxies as a function of the log of the projected density, in galaxies Mpc^{-2}. The data shown are for all cluster galaxies in the sample and for the field. Also shown is an estimated scale of true space density in galaxies Mpc^{-3}. The upper histogram shows the number distribution of the galaxies over the bins of projected density.

(Dressler 1980, *ApJ*, 236, 351)

- Proportion E + S0 and Sp+Irr varies as a function of ρ
- 2 suggested mechanisms:
  - Merger: Sp+Sp -> E
  - Ram pressure from the IGM: Sp -> S0

Environmental effects

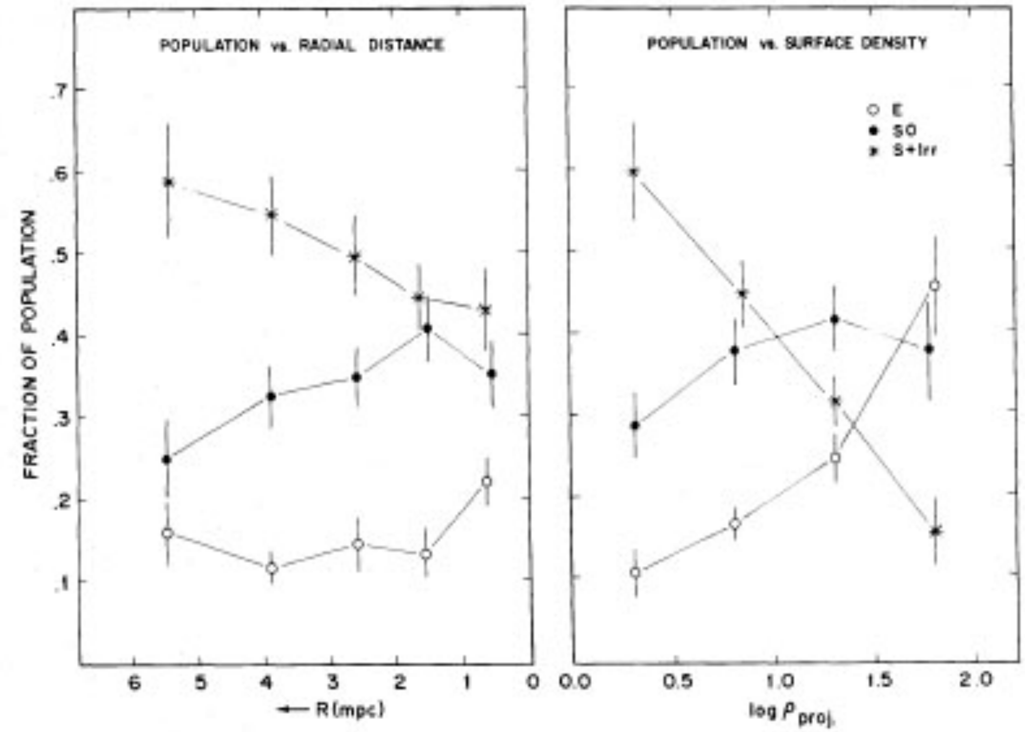
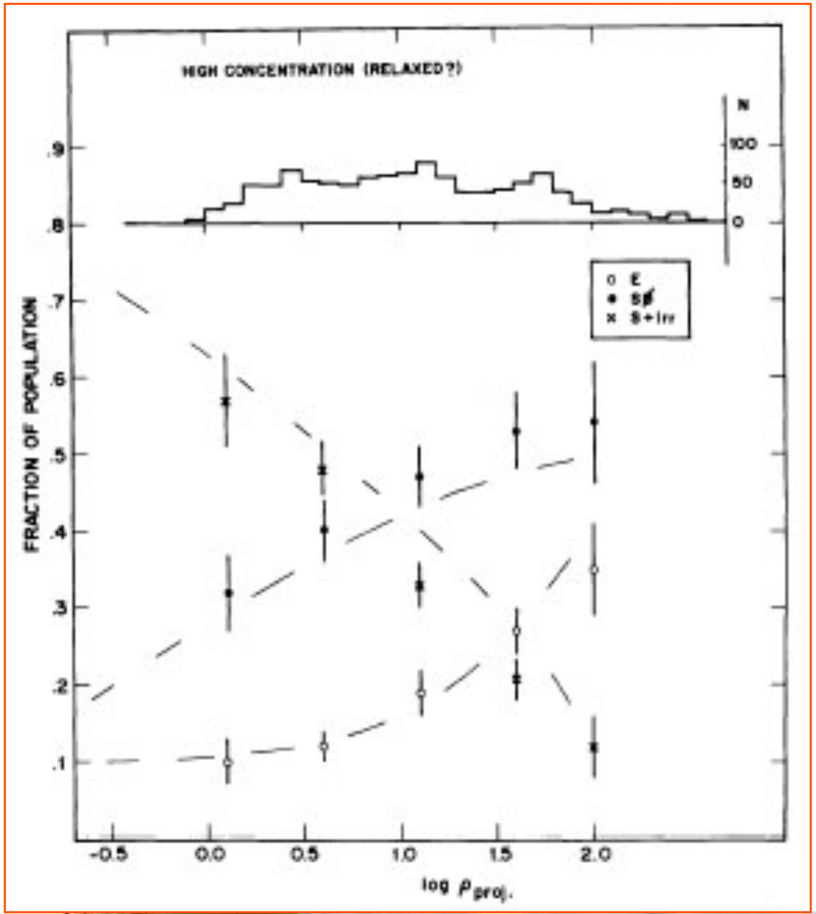
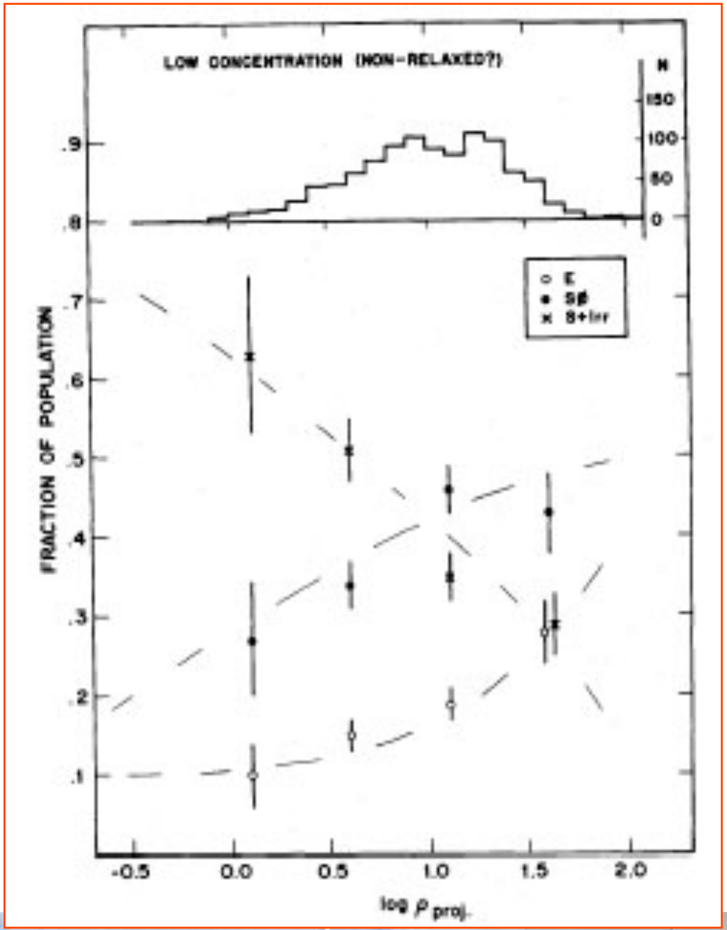


FIG. 5.—Population gradients in 6 moderately irregular clusters (A754, A993, A1736, A1983, 0326−53, 0559−40) as a function of radial distance from the cluster centroid and as a function of local surface density, showing the advantage of density as the free parameter.

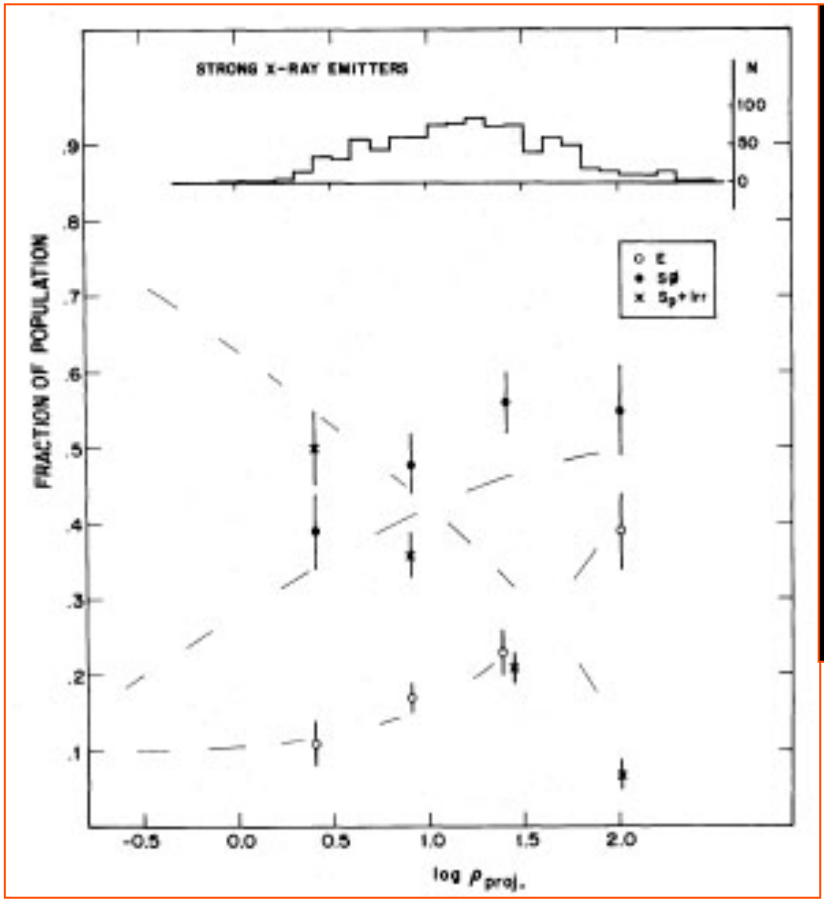
(Dressler 1980)

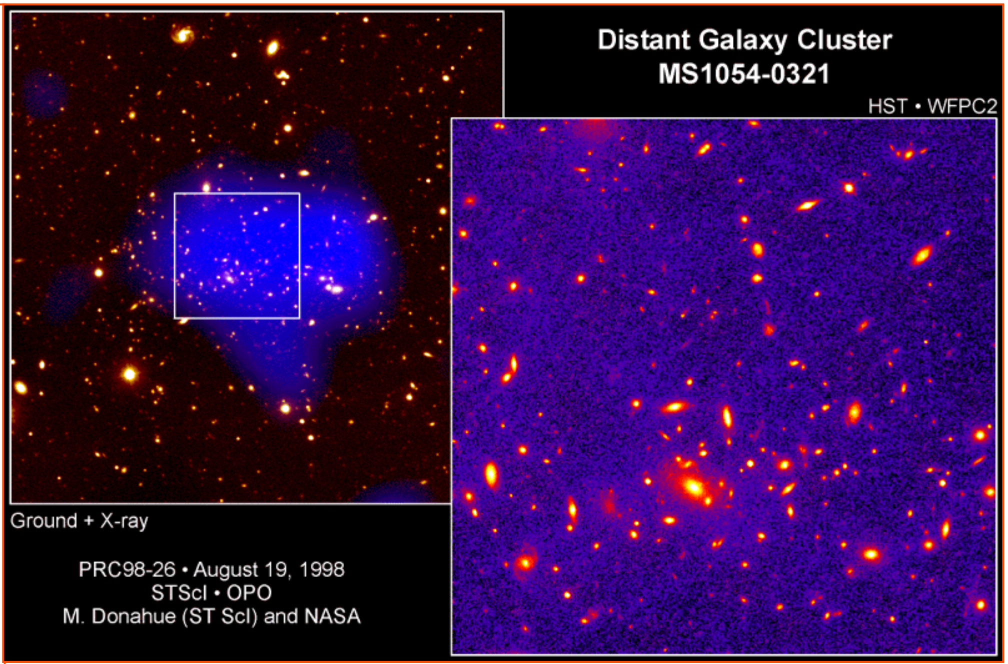
Environmental effects



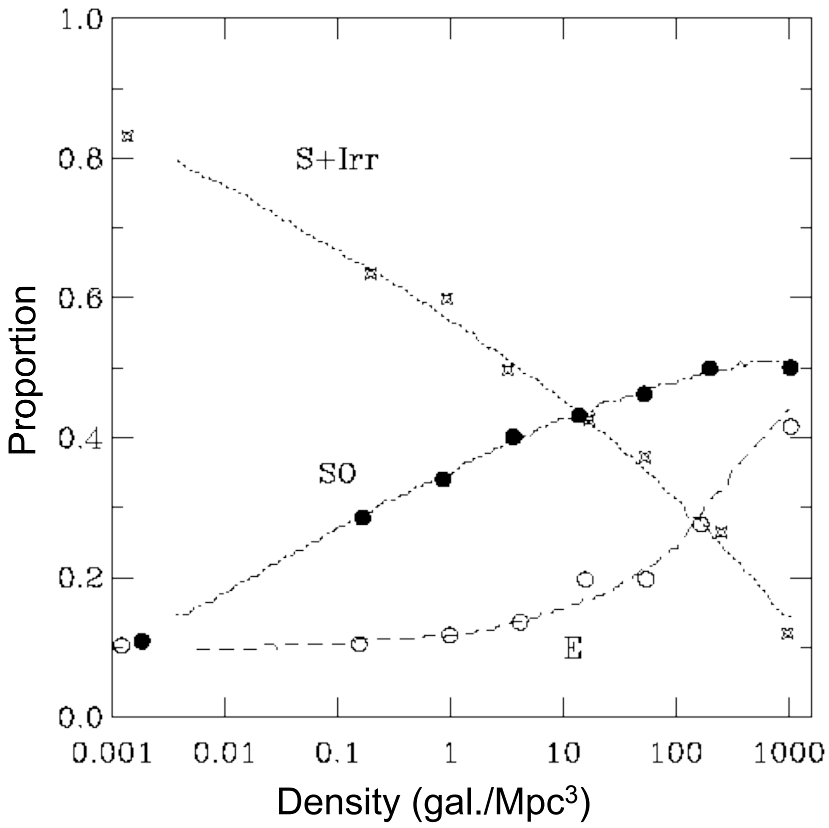


Environmental effects





Environmental effects



Proportion of the different morphological types (E, S0, S, Irr) is directly related to the mean density (galaxies/Mpc^{-3}) of the environment

Environmental effects

Concentration	E	S0	S	(E+S0)/S
High concentration	35%	45%	20%	4.0
Mean concentration	15%	55%	30%	2.3
Low concentration	15%	35%	50%	1.0
Field	15%	25%	60%	0.7

Environmental effects

- Segregation (by type and/or by mass):
  1. E & S0 in the center
  2. S in the outskirt
- Merger:

  (S + S -> E)
- Cannibalism:

  Giant E (cD) absorbs S & dwarfs

Collisions between galaxies

- Distance between stars are very big: 10^{6-7} x diameter
- Distance between galaxies are small: 15-20 x diameter
- Collision between galaxies are much more frequent than between stars

Collisions between galaxies

- Universe is in expansion: T$\downarrow$ & $\rho\downarrow$

- Collision between galaxies must have been much more frequent in the past (see HDF)

Collisions between galaxies

When 2 galaxies have a collision

It is mainly the interstellar matter

(gas) that violently reacts

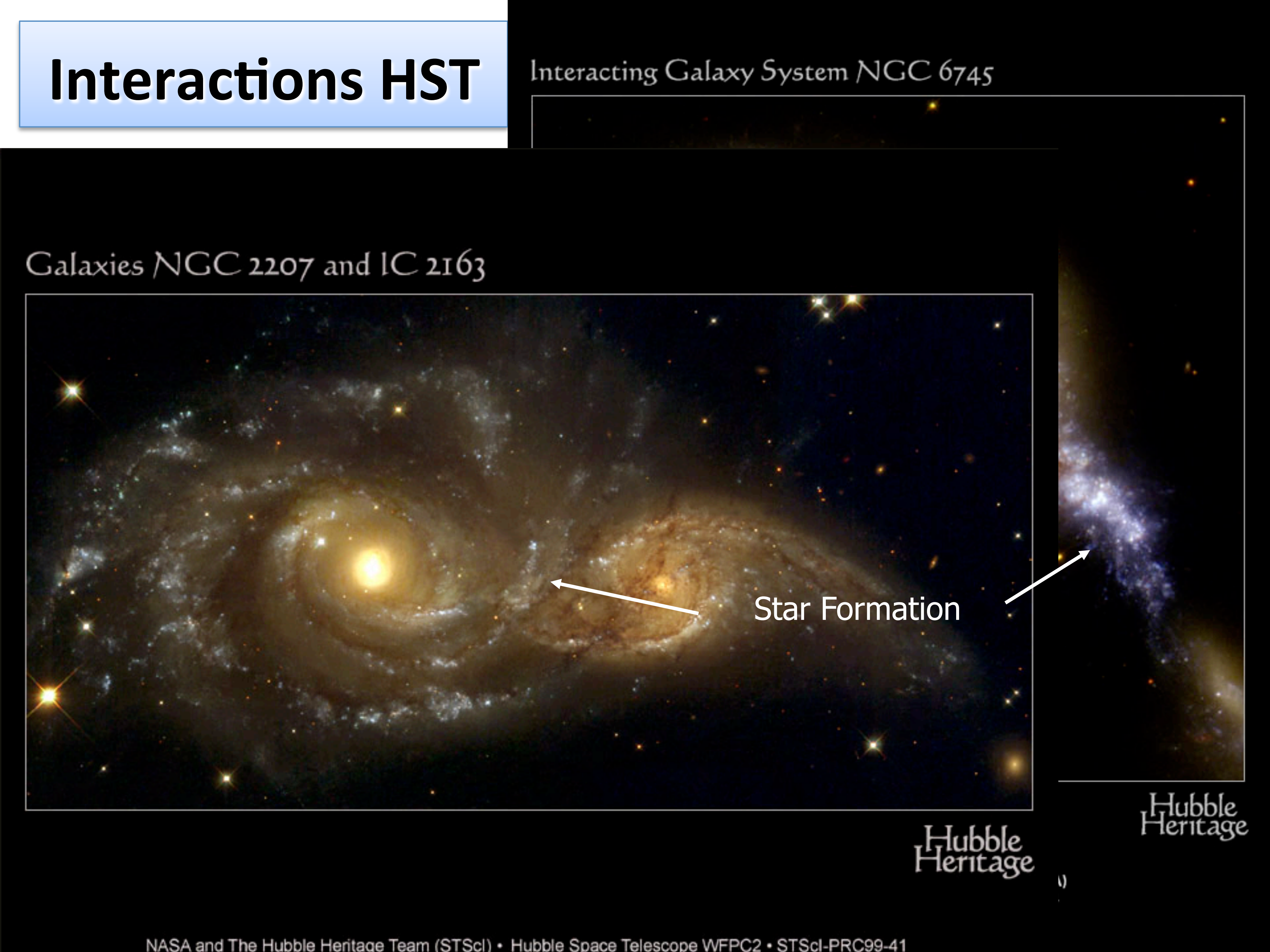
↓

Burst of star formation

↓

Blue colors

Interactions HST



Evolution of galaxies in clusters

When 2 disks have a collision

↓

ordered rotation is changed

in velocity dispersion

↓

Disks (flat) → ellipticals (spherical)

Evolution of galaxies in clusters

Ram Pressure

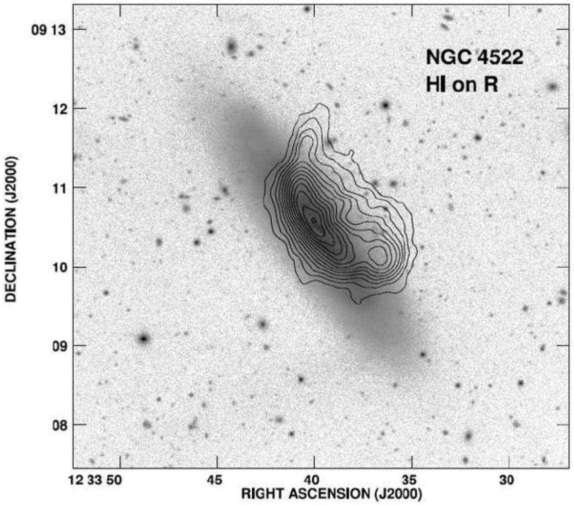
$P = \rho v^2$

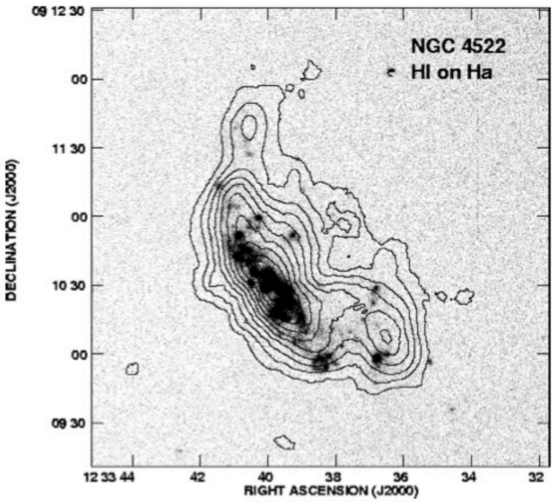
Spiral get stripped of its gaseous component by the intergalactic medium

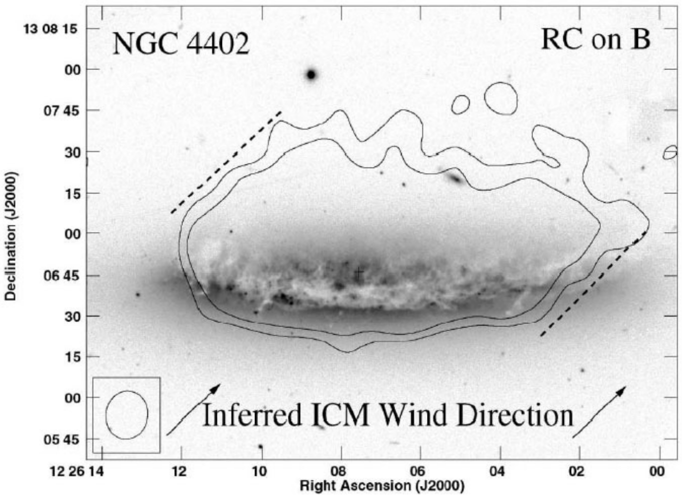
S -> S0

Evolution of galaxies in clusters

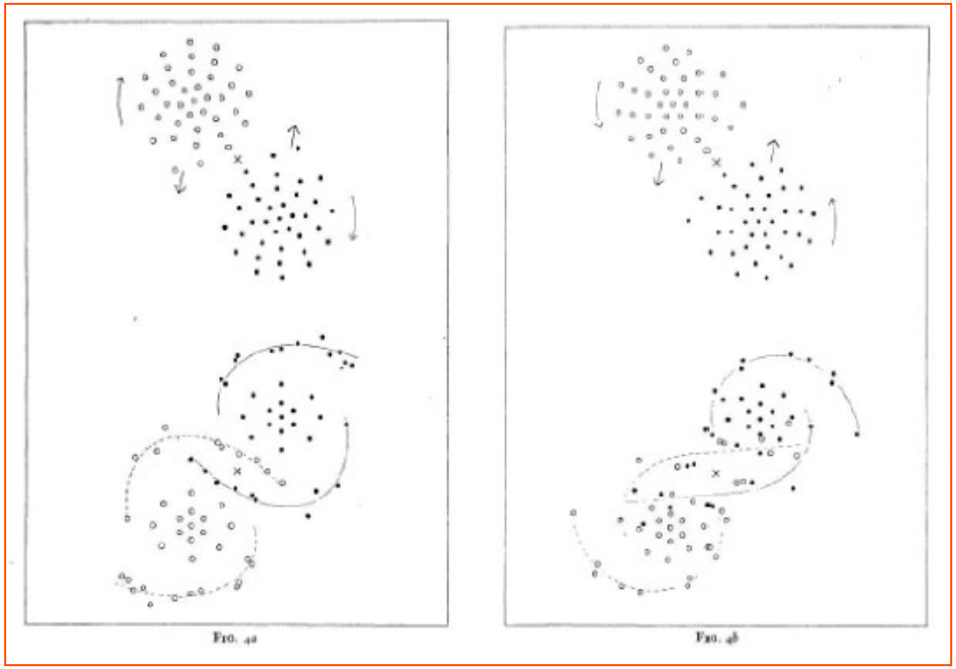
In Virgo







Gravitational Interaction

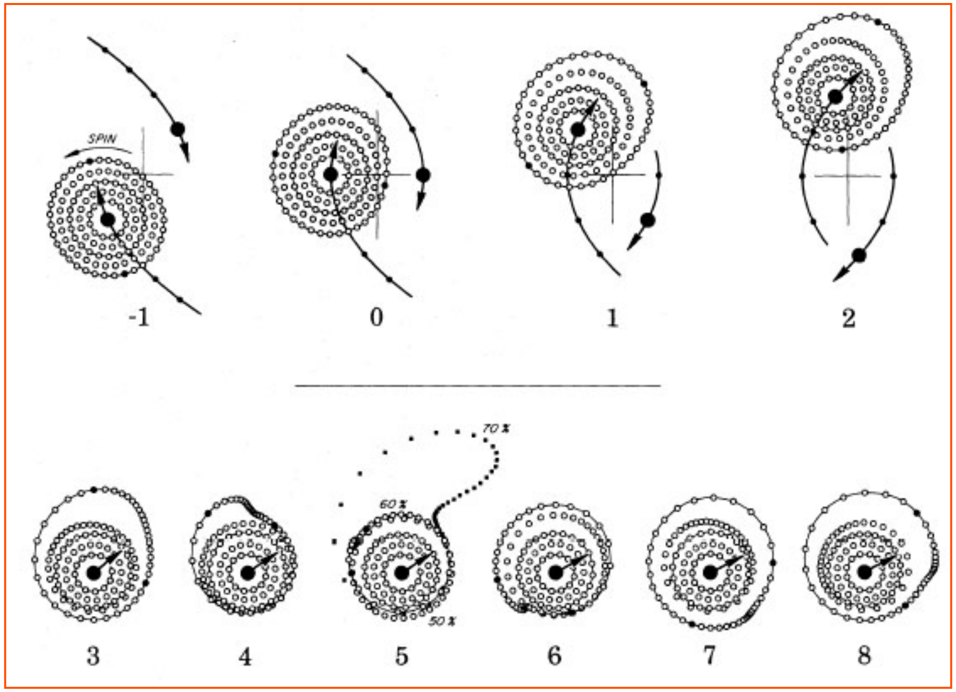


Holmberg 1941

- First simulations of gravitational interaction (1941) with light bulbs to simulate the gravitational potential

- Can compute the gravit. force at each point by measuring the intensity (light similar to gravity goes as r^{-2})

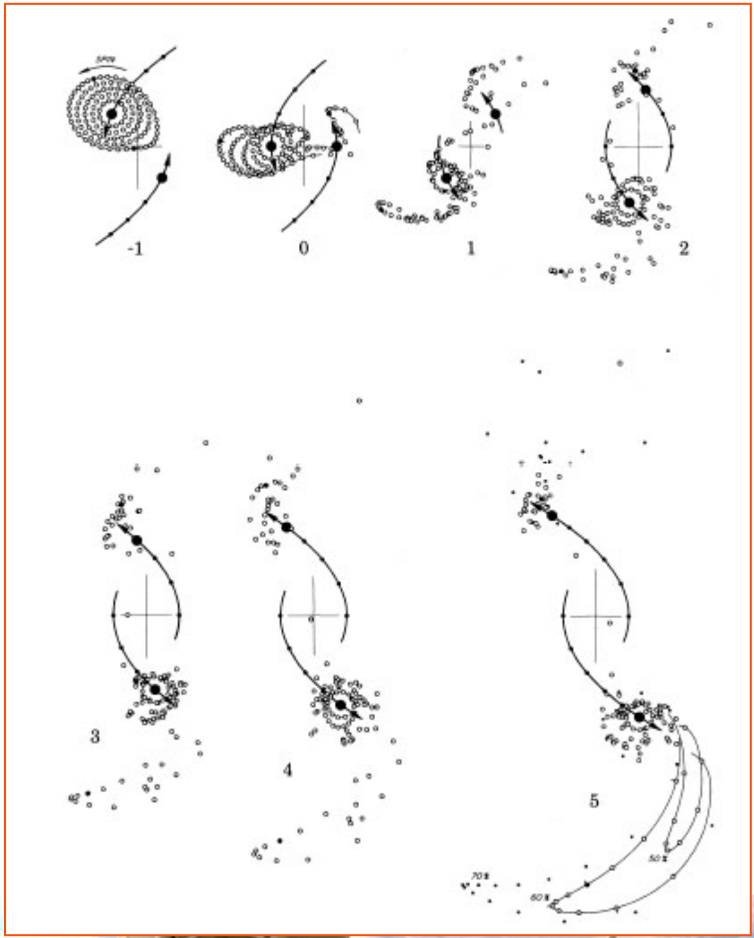
Gravitational Interaction



Toomre 1972

- First numerical simulations: 12 to 36 particules ! Interact with a point mass
- Near miss, opposite spins
- Disk becomes lopsided 1->8

Gravitational Interaction



- Start: formation of a bridge

- After minimal approach: formation of tidal tails

- Galaxy looses its original structure

Gravitational Interaction

- The *tidal stripping* (mass stripped off M by the close encounter of another galaxy m) happens when the Roche limit is reached (like in binary star systems):

$$R = (2M/m)^{1/3} r$$

- e.g.: M_{cd} ~ 500 x m -> tidal disruption R = 10r
- Tidal force: F ~ $GMmr/R^3$ -> decrease rapidly

Gravitational Interaction

Collision de 2 disks:

1. Central part stabilizes first

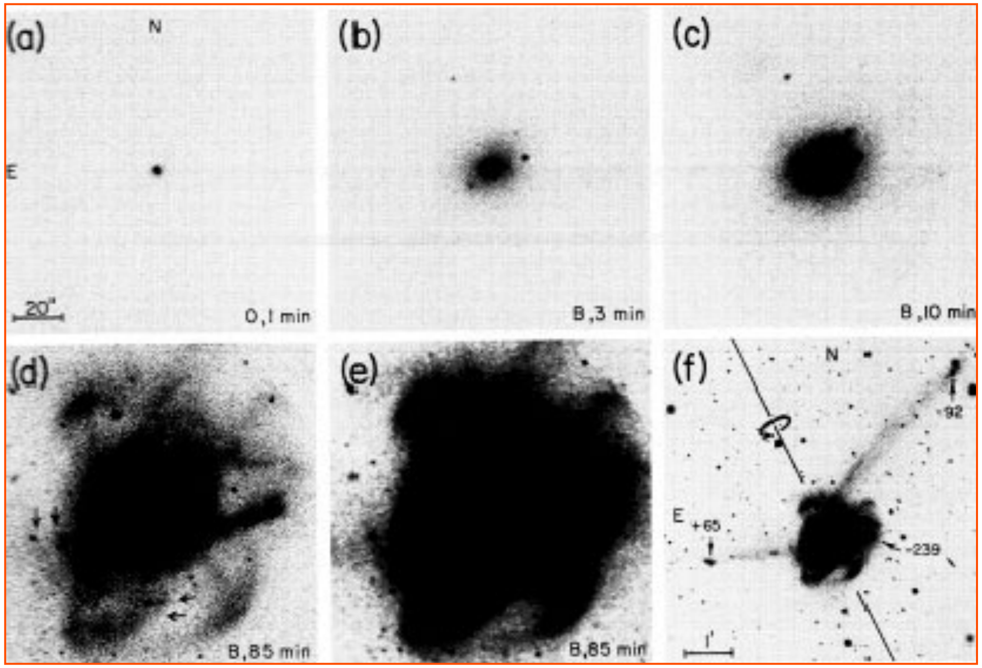
Elliptical

(because short dynamical time)

2. External parts still perturbed

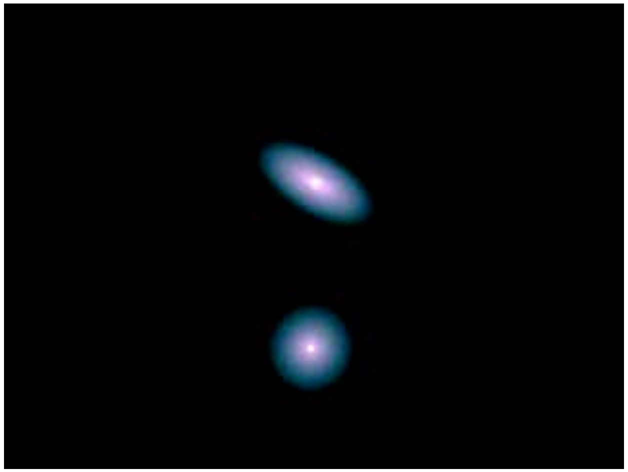
chaos + star formation

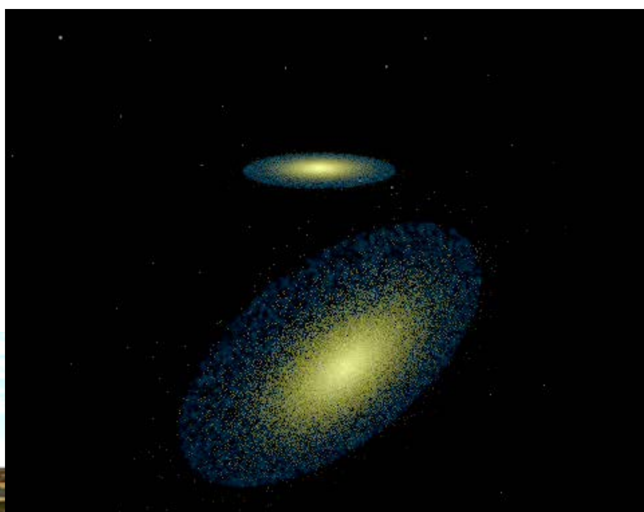
(because long dynamical time)

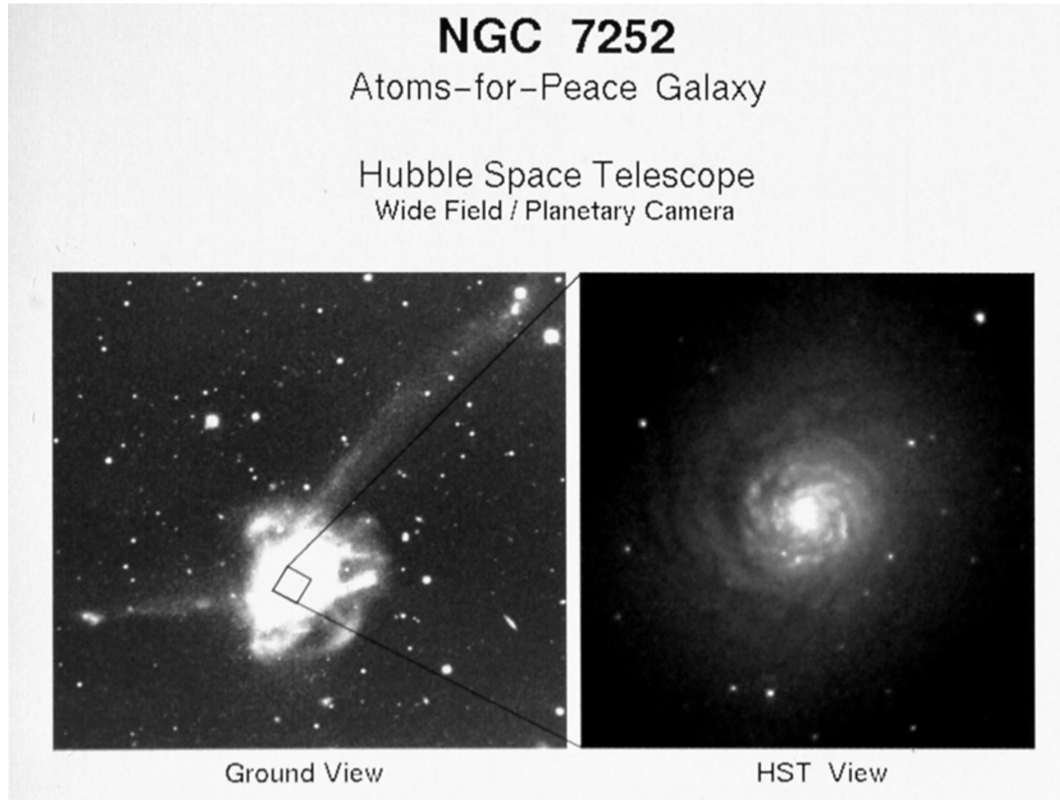


NGC 7252

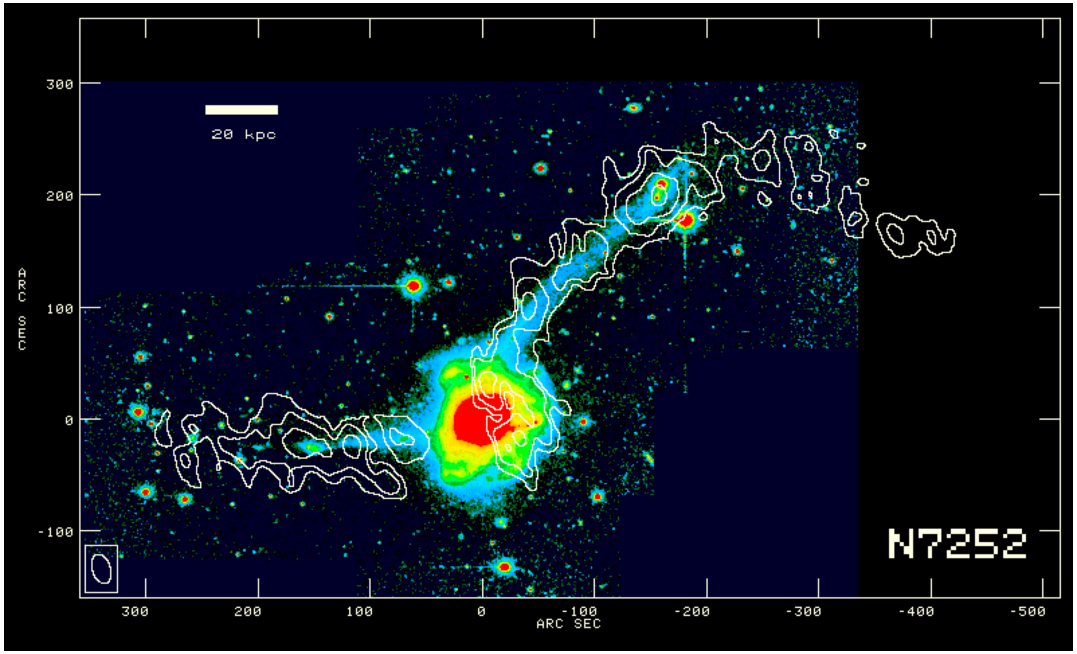
Gravitational Interaction





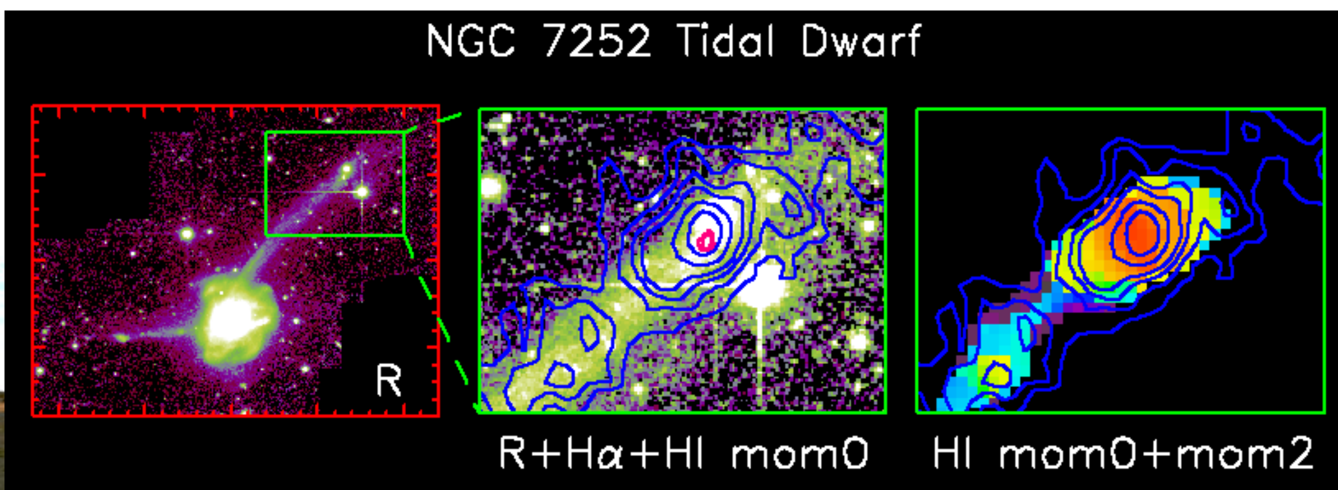


Gravitational Interaction

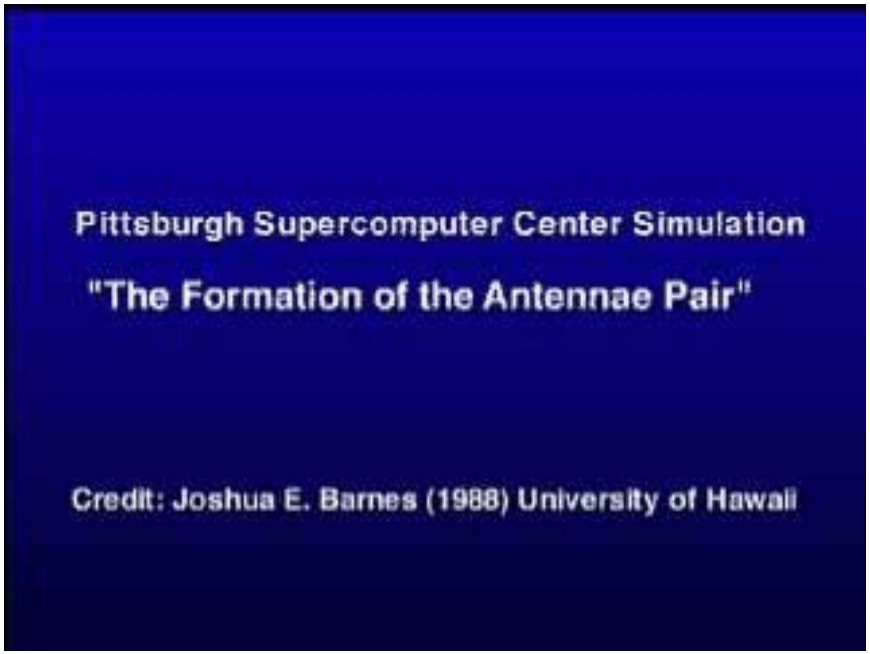


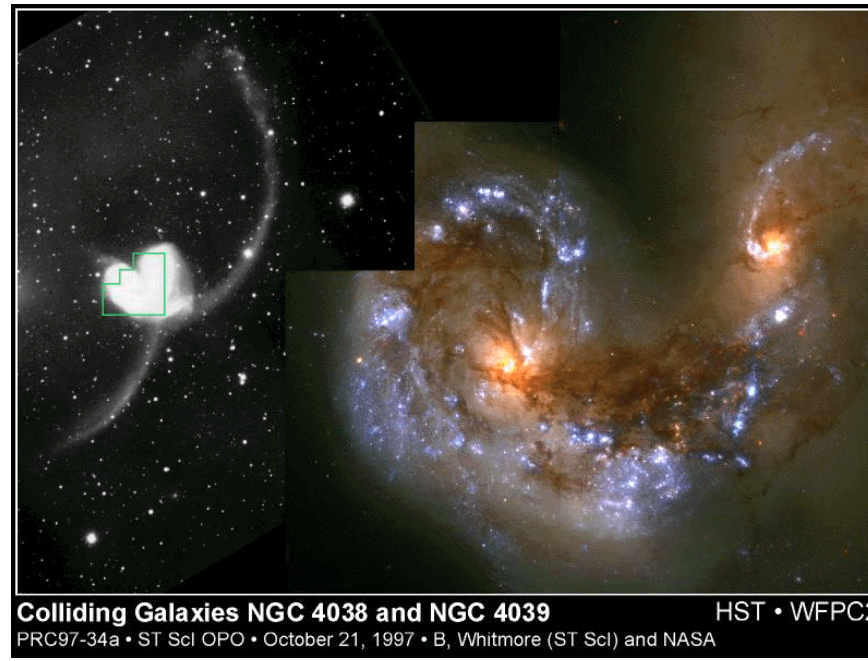
HI

Formation of tidal dwarfs



Gravitational Interaction





Joshua Barnes, Univ. of Hawaii homepage

Gravitational Interaction

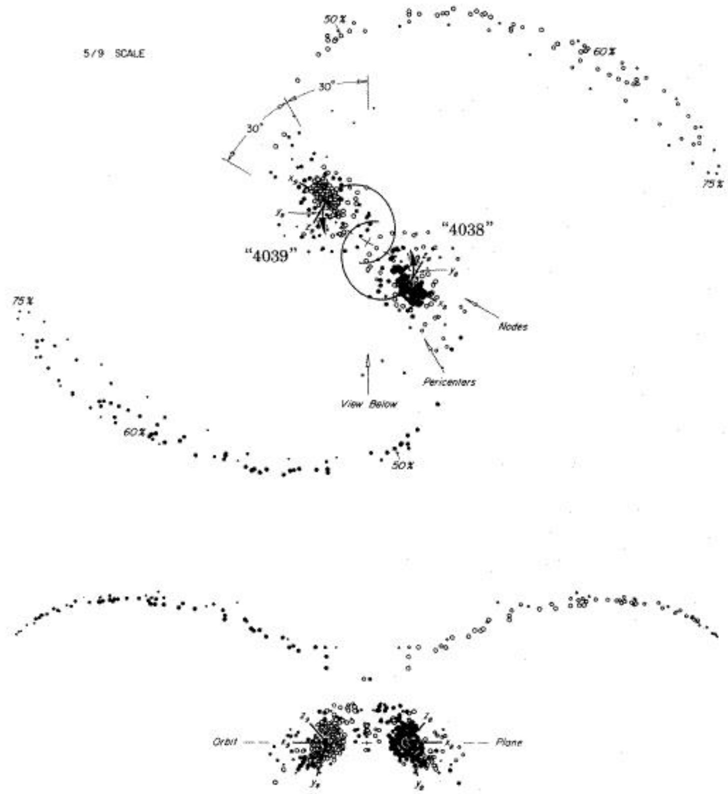
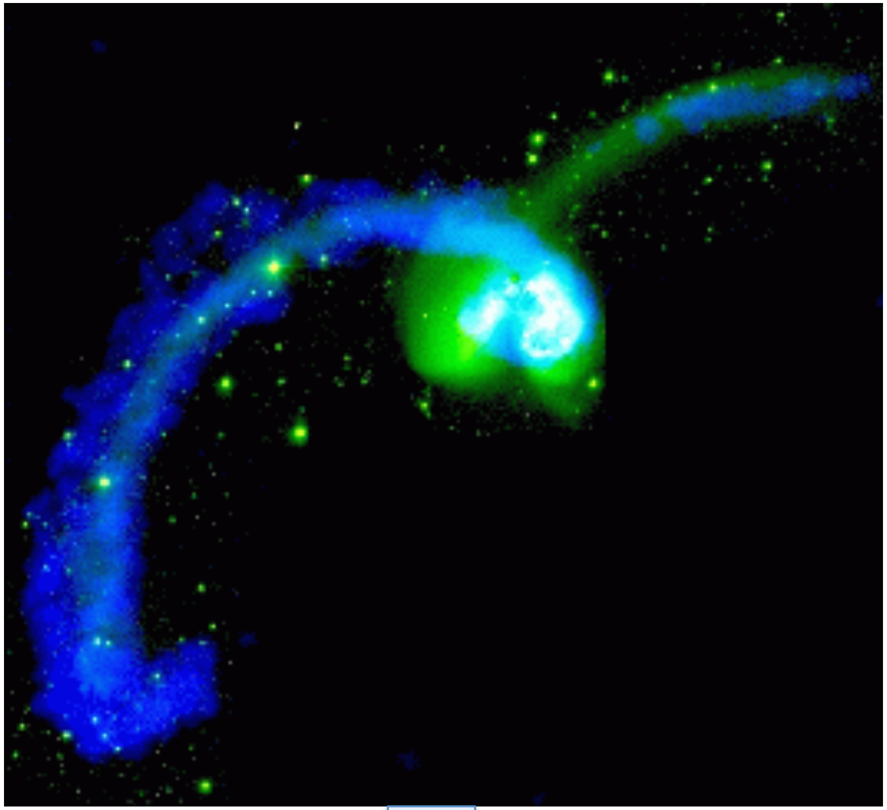


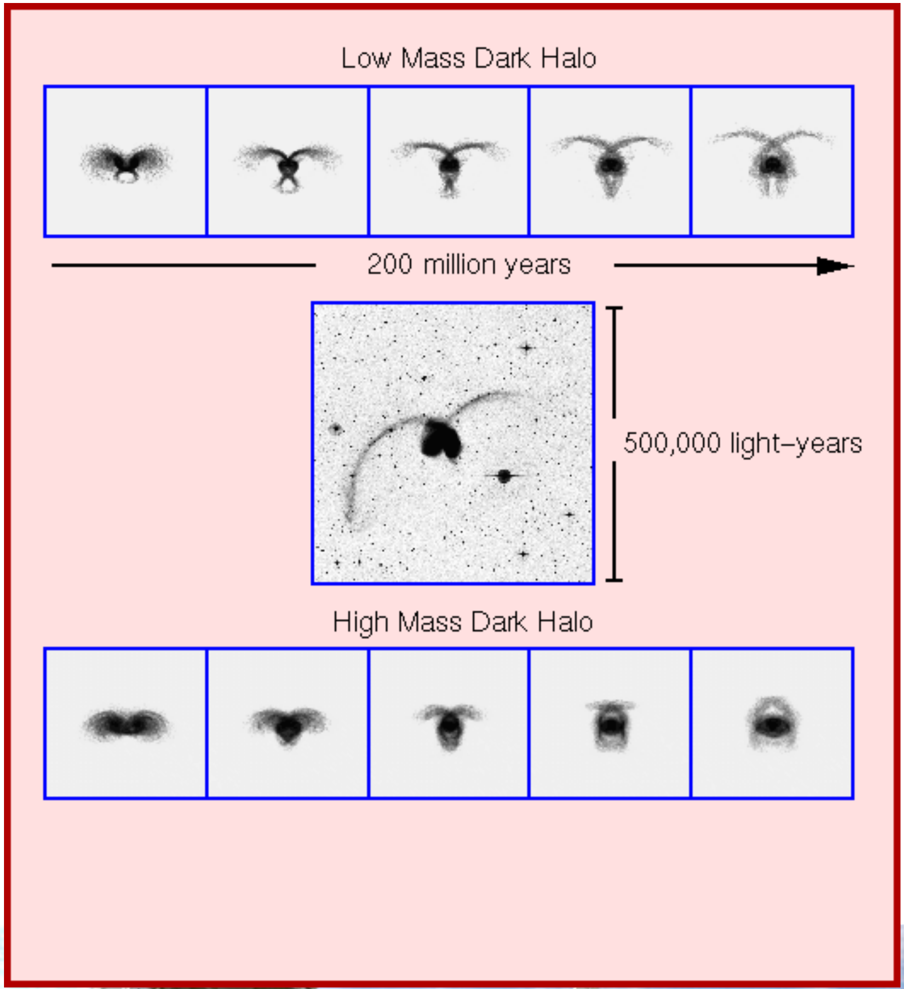
FIG. 23.—Symmetric model of NGC 4038/9. Here two identical disks of radius $0.75R_{\min}$ suffered an $e \approx 0.5$ encounter with orbit angles $i_8 = i_9 = 60°$ and $\omega_8 = \omega_9 = -30°$ that appeared the same to both. The above all-inclusive views of the debris and remnants of these disks have been drawn exactly normal and edge-on to the orbit plane; the latter viewing direction is itself 30° from the line connecting the two pericenters. The viewing time is $t = 15$, or slightly past apocenter. The filled and open symbols again disclose the original loyalties of the various test particles.

Toomre & Toomre 1972



HI

Gravitational Interaction



Numerical simulations (Dubinski et al. 1996)

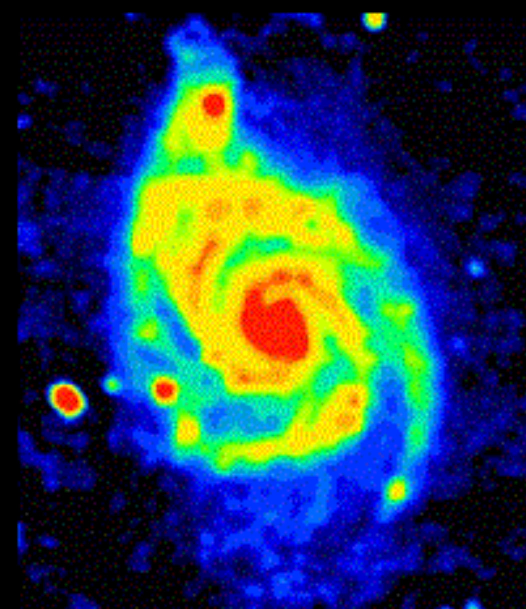
The length of the tidal tails constraint the quantity of dark matter and mainly its concentration

Messier 51
couleur

DSS

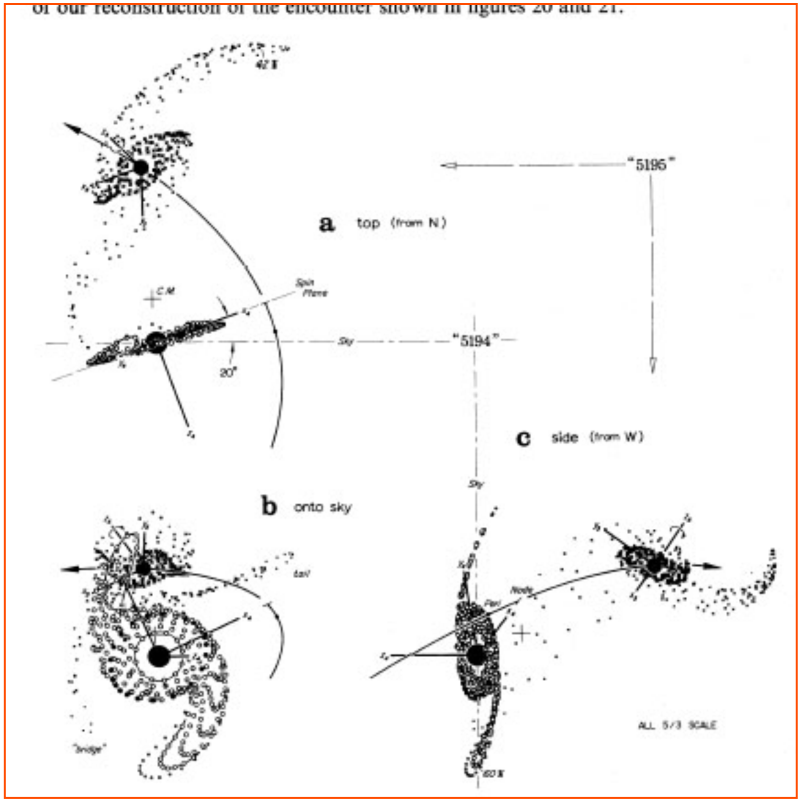
2Mass NIR

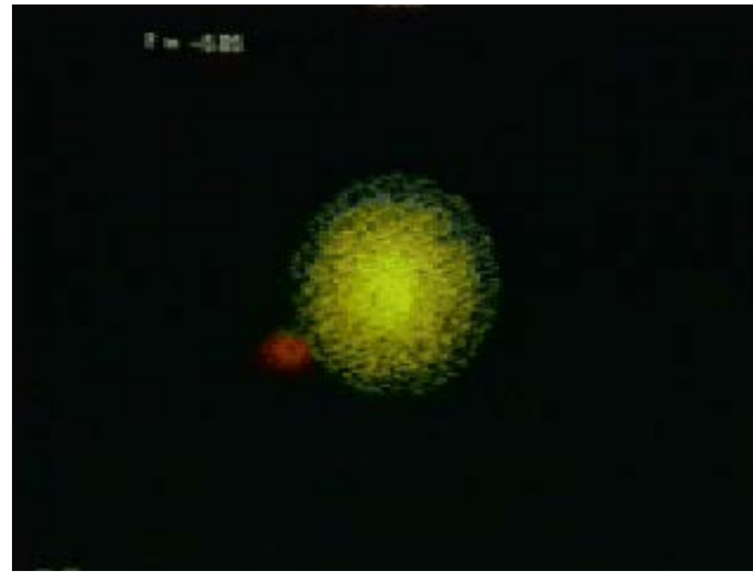
Radio, VLA



Keel website

Gravitational Interaction

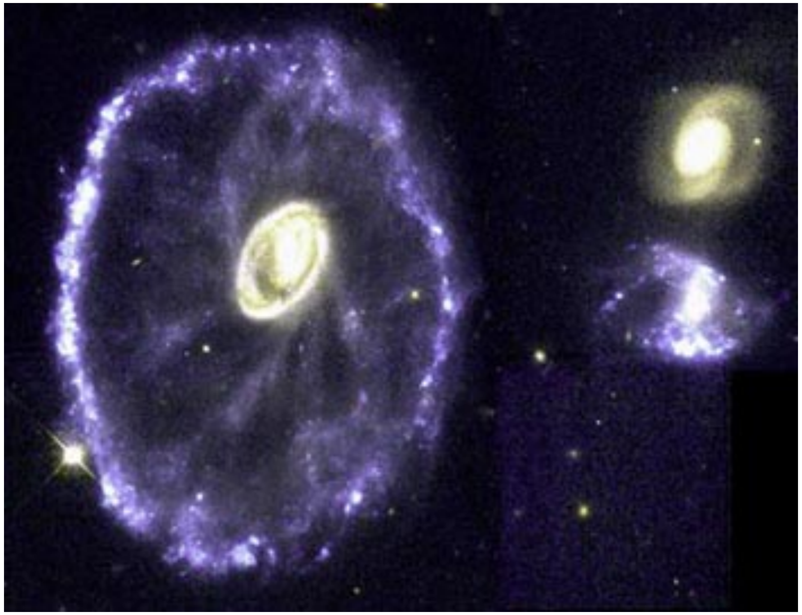




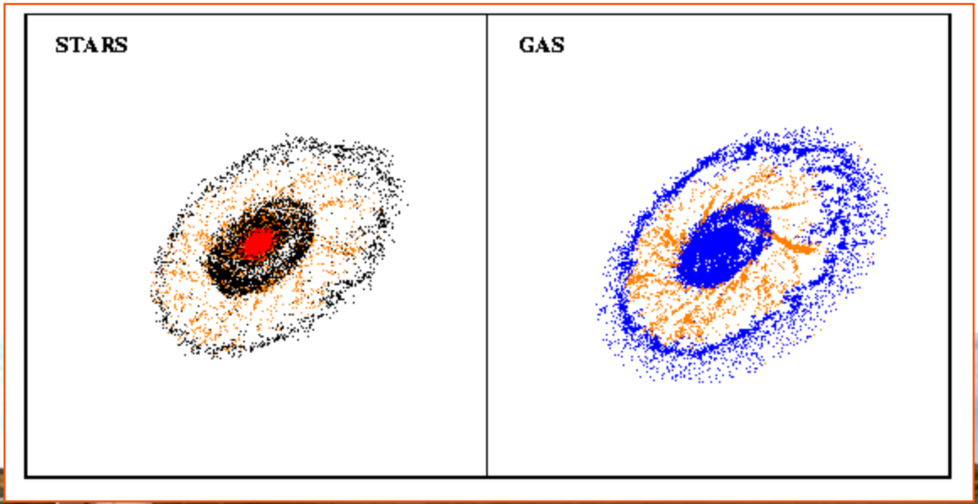
Toomre 1972

Gravitational Interaction

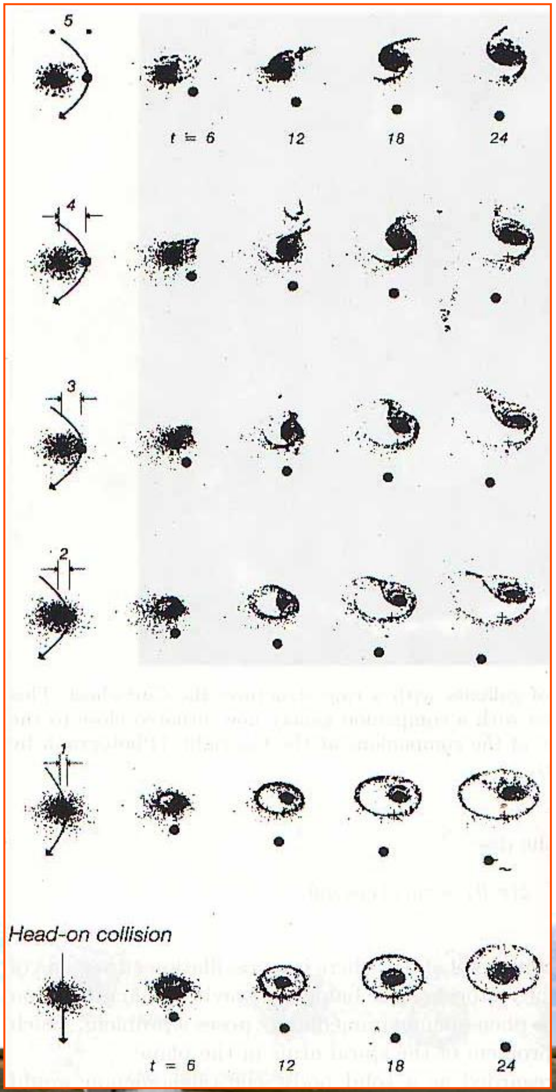
The annuli are off-centered and cannot be confused with resonant rings in barred galaxies

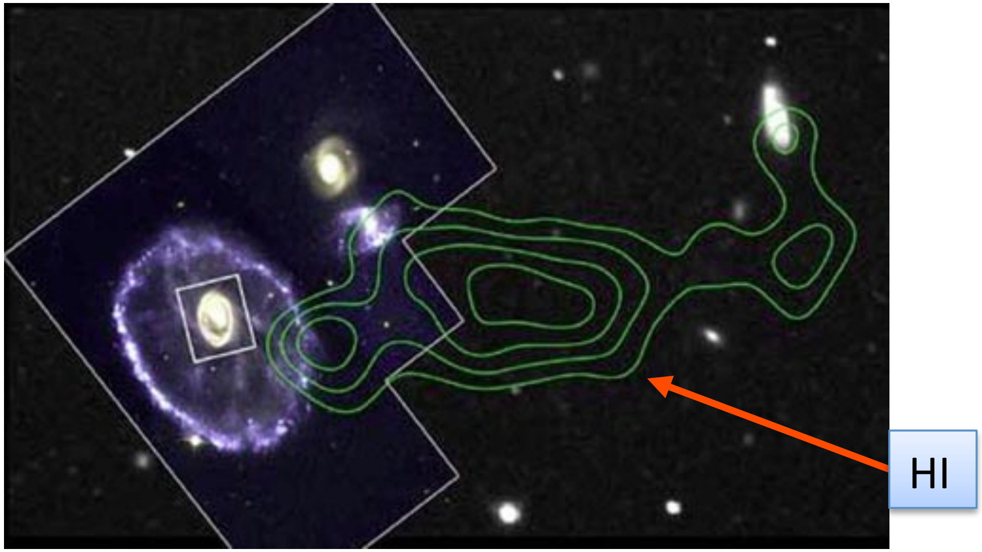


Cartwheel



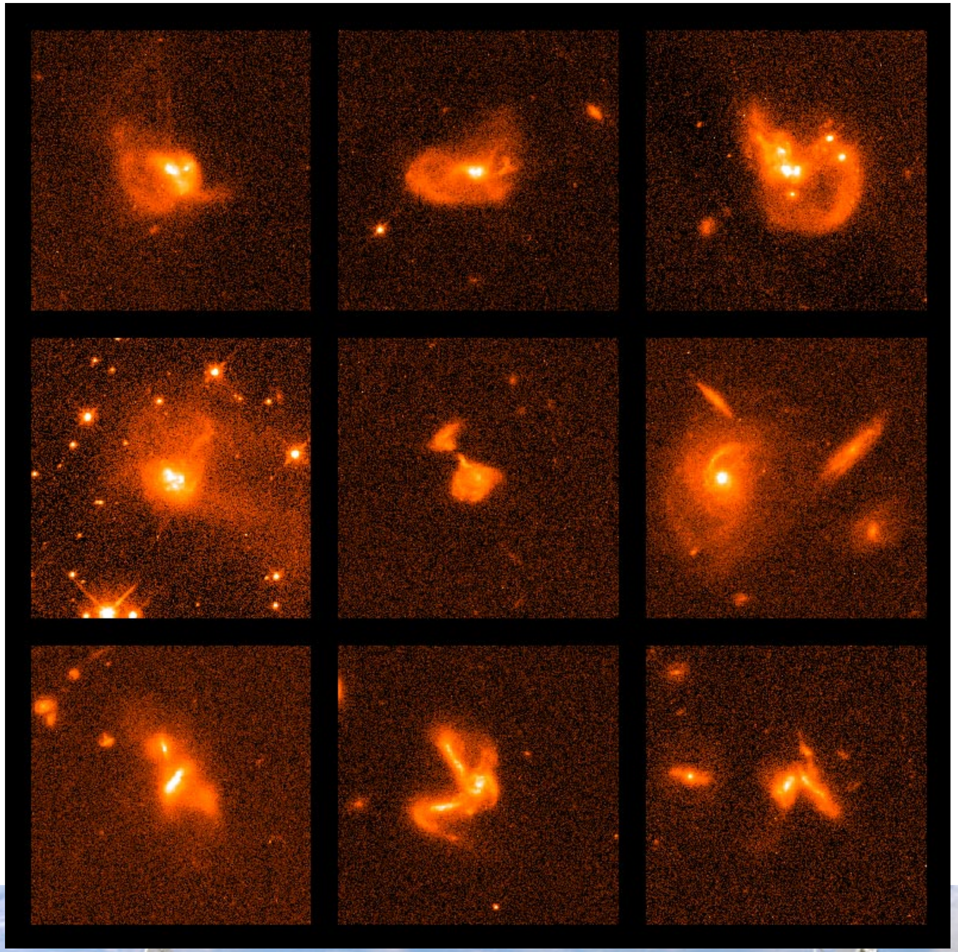
Gravitational Interaction



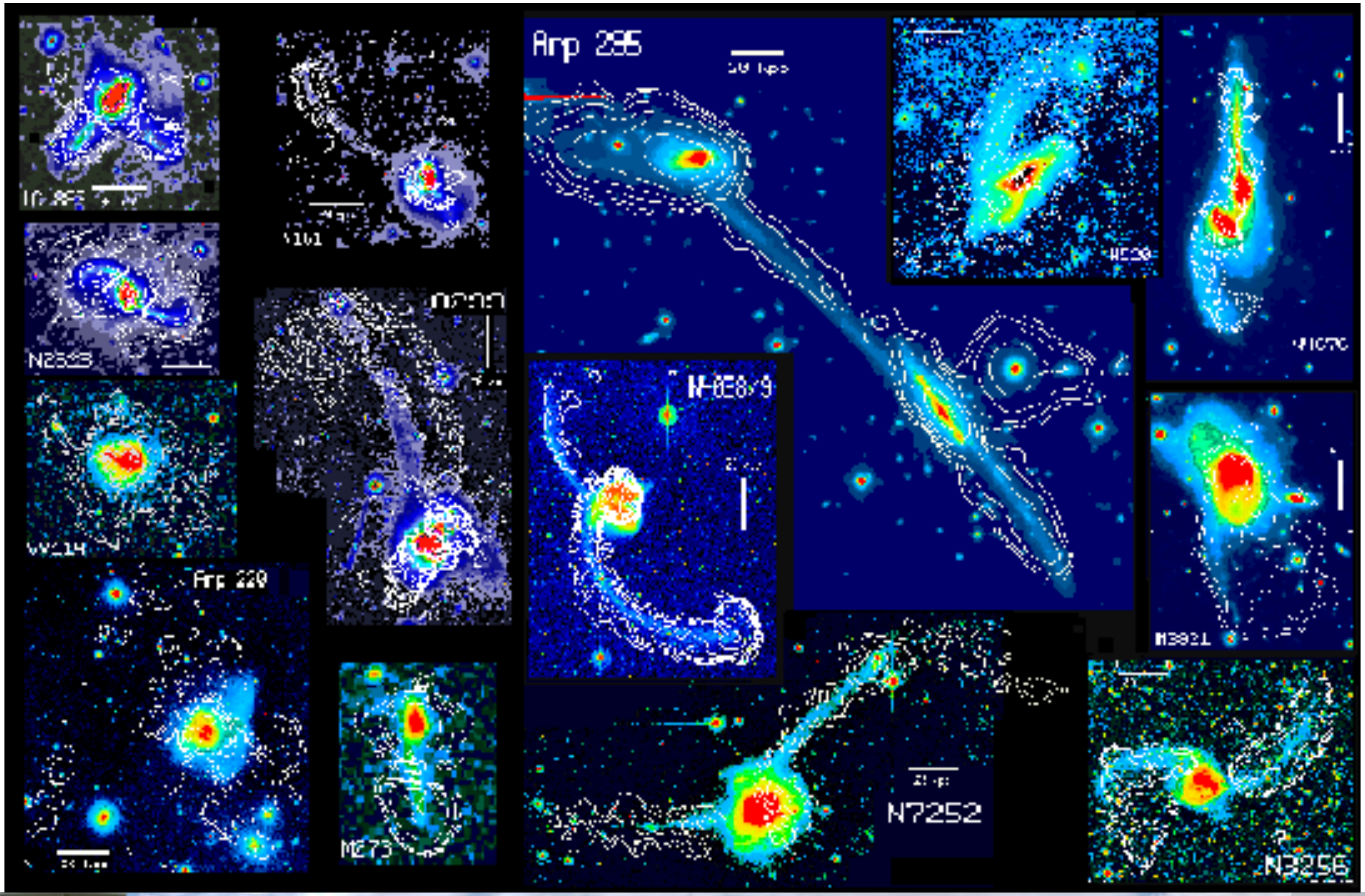


When the collision is head-on, the spiral arms form a ring

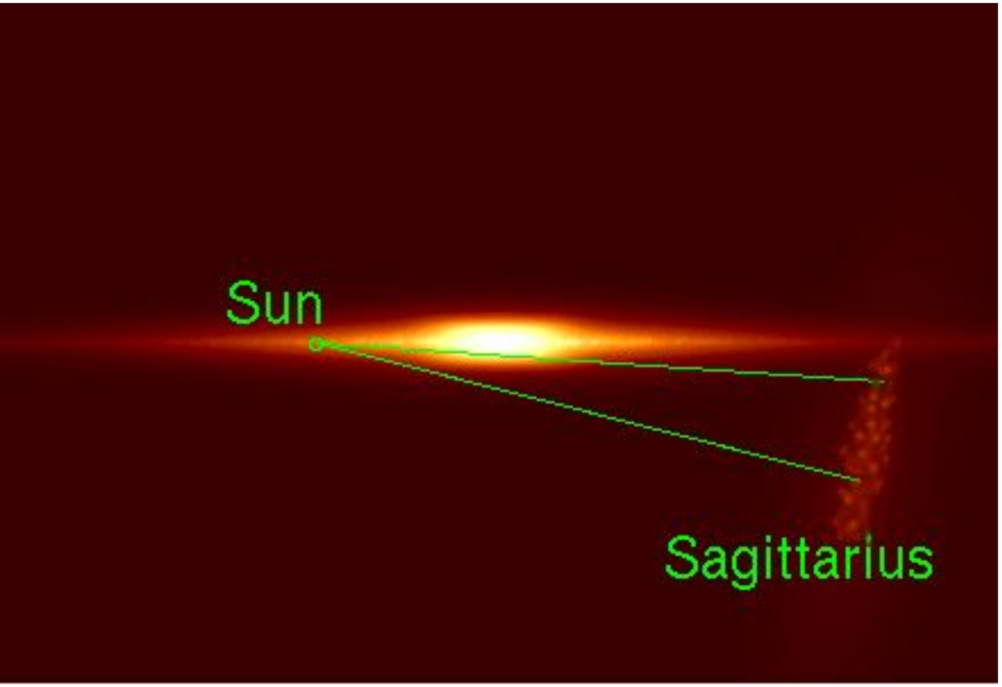
Mergers – HST – large z

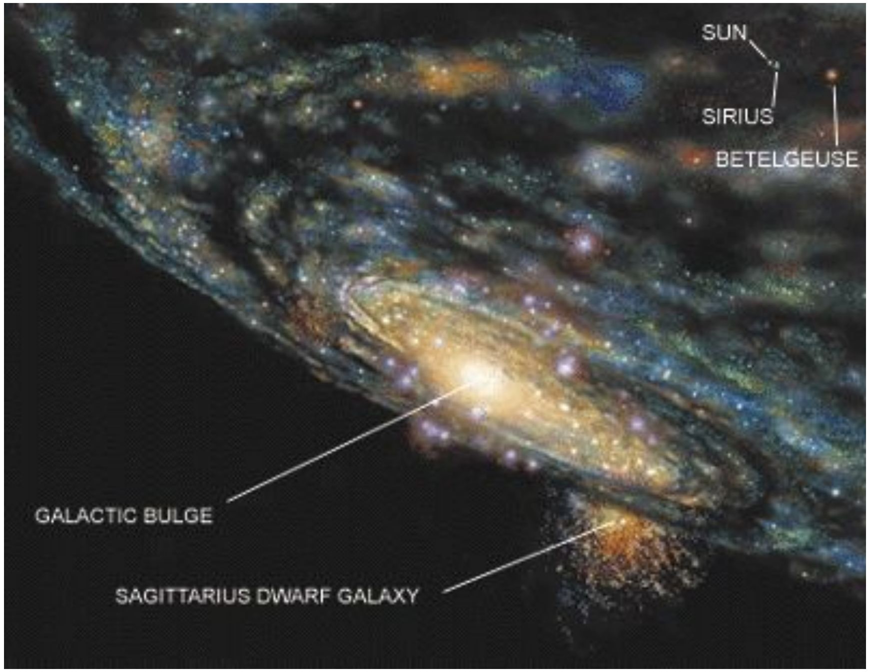


Mergers – HI

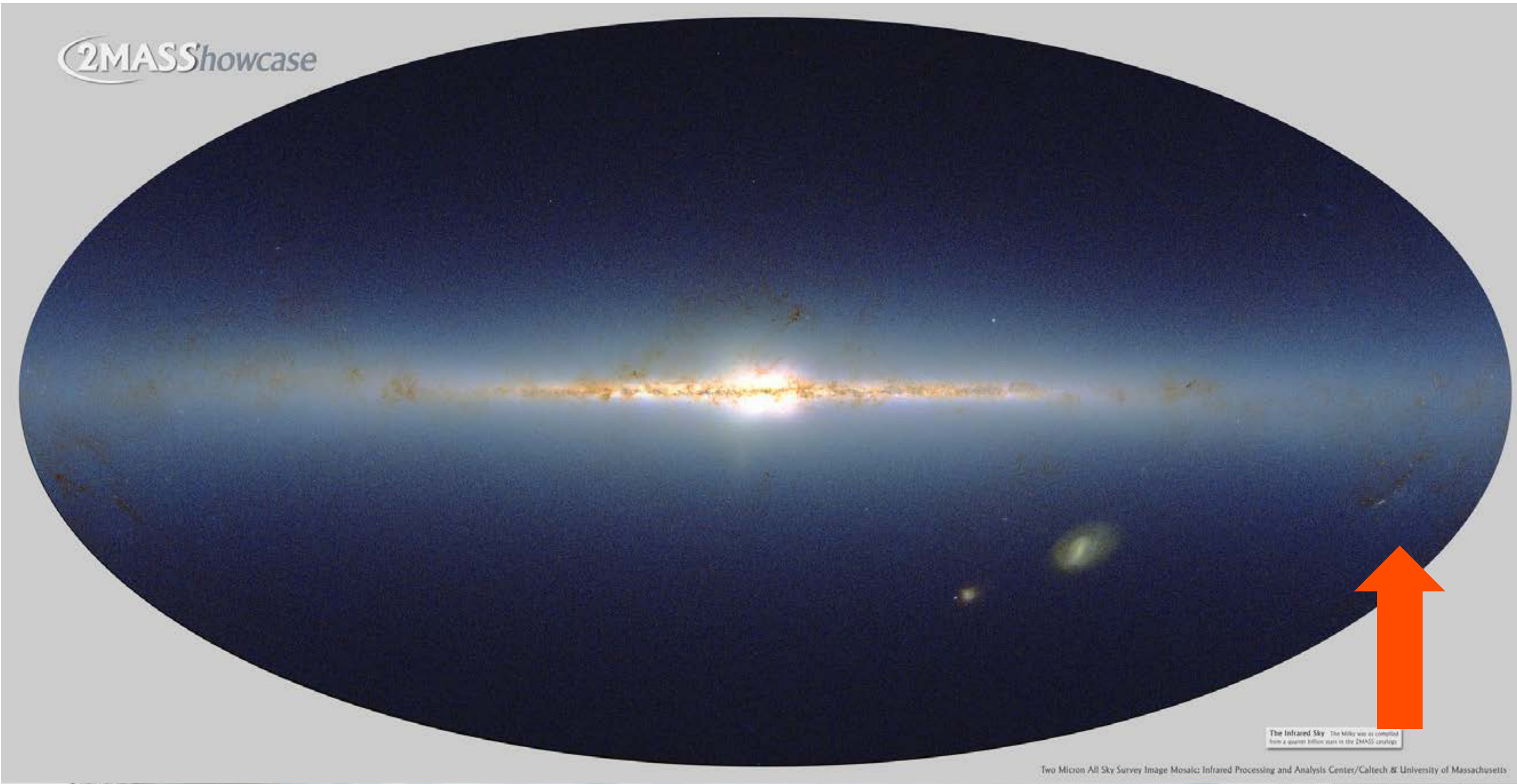


MW & Sagittarius

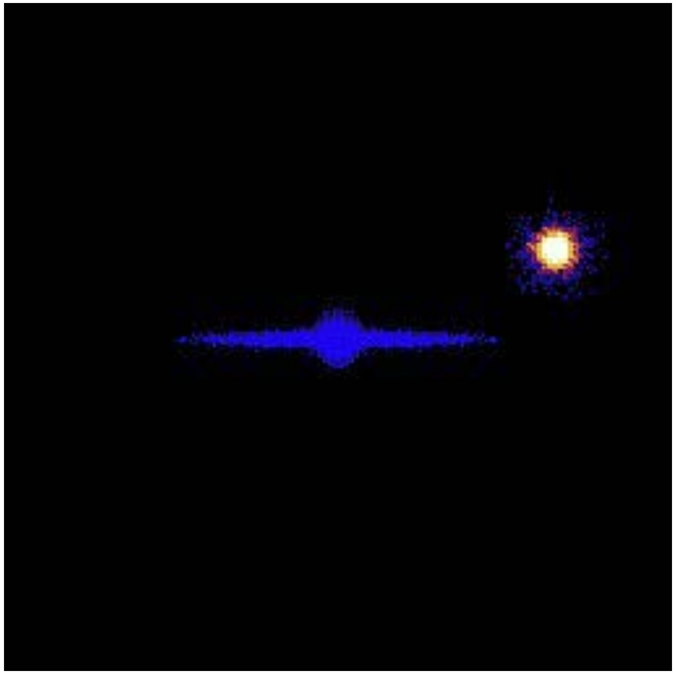


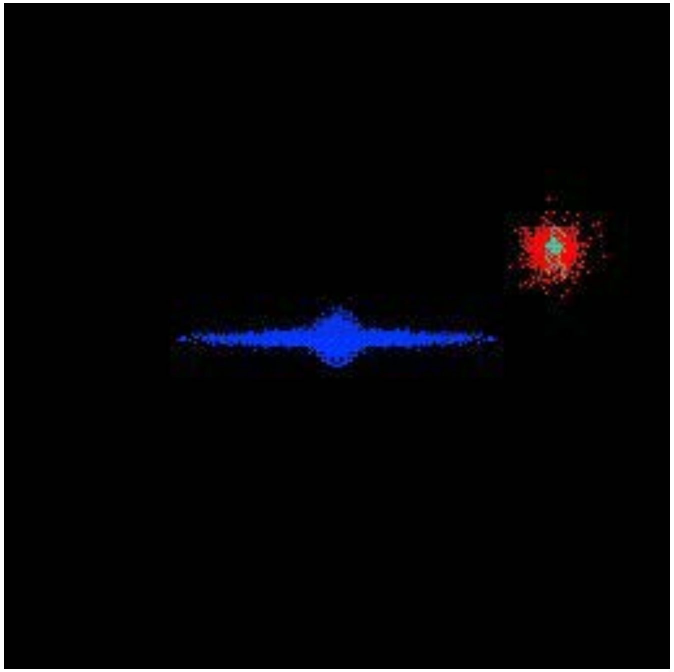


MW & Sagittarius



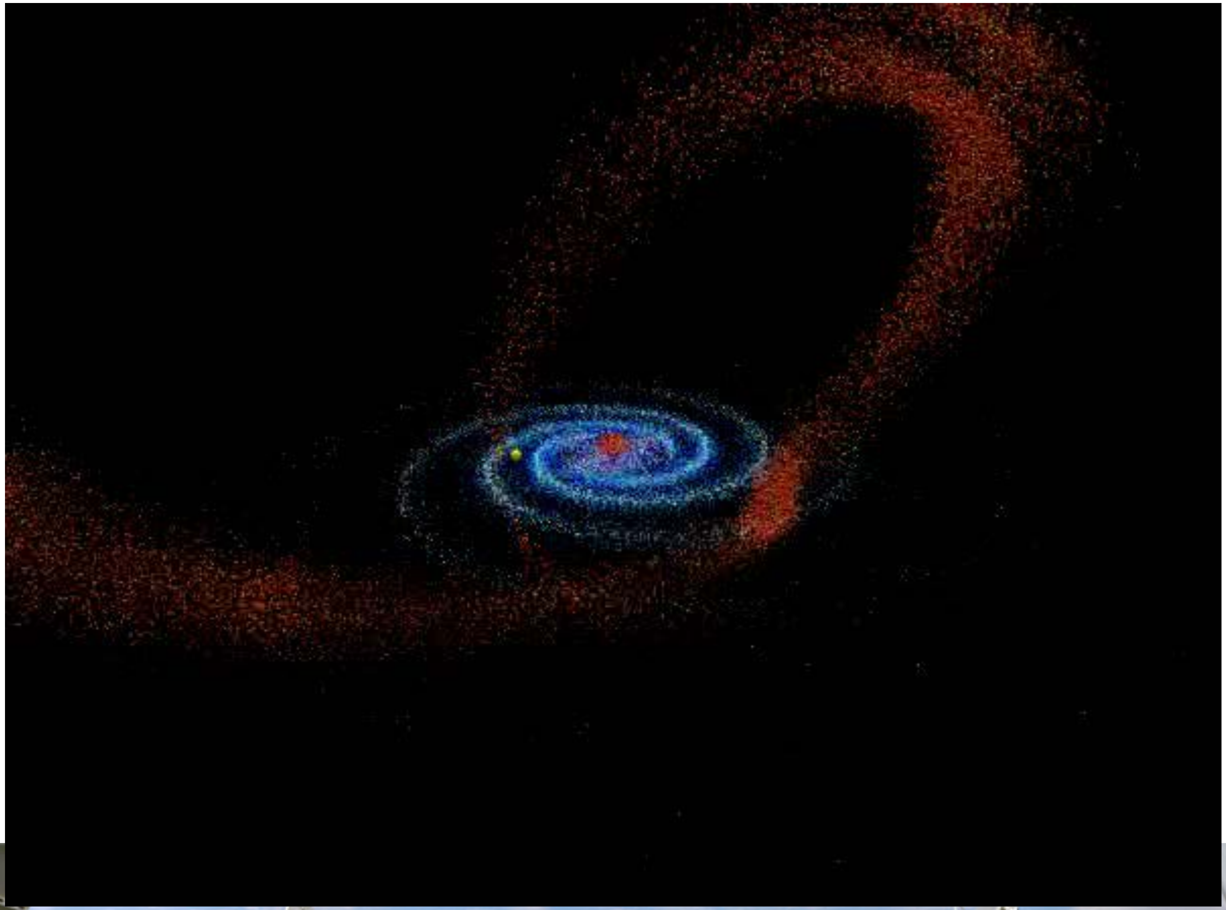
MW & Sagittarius



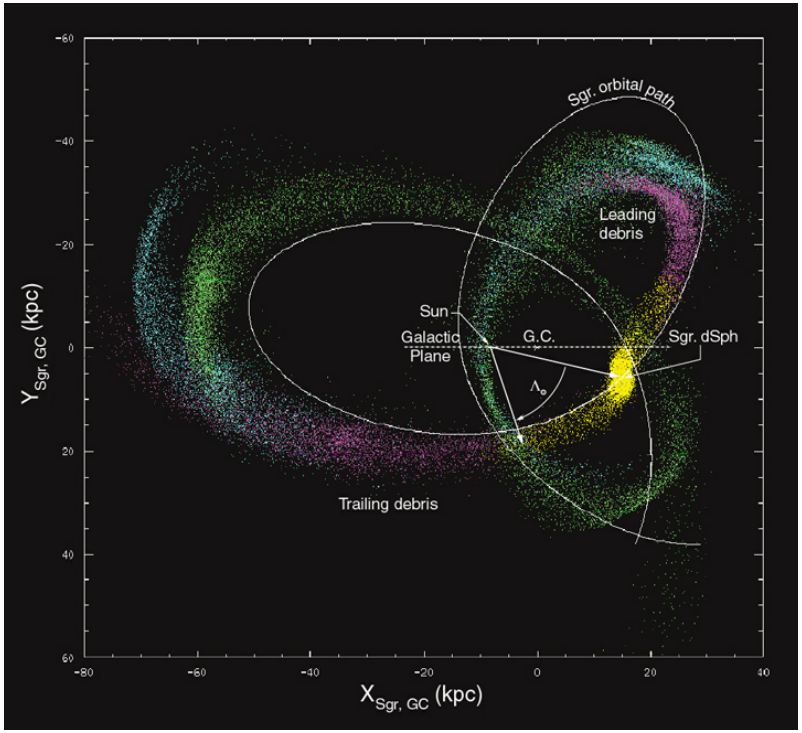


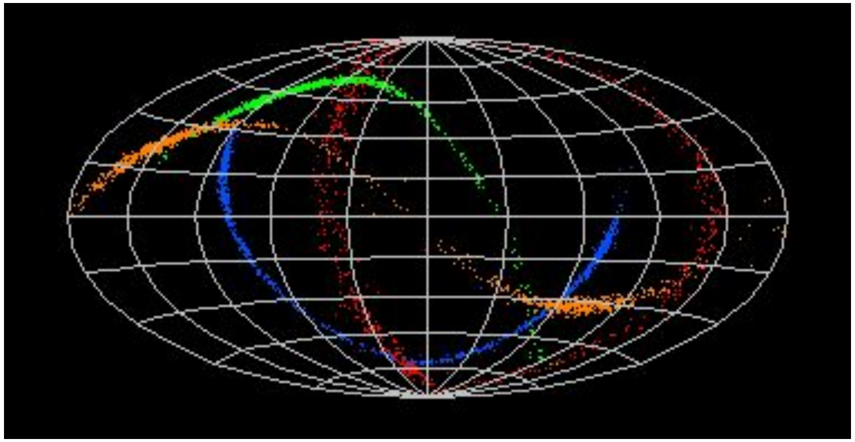
The above images are taken from two animations made from the same simulation of a satellite being torn apart by the Milky Way's tidal field. The simulations followed the satellite's evolution for several billion years. In the both images, the Milky Way is represented in blue in the center, with the satellite orbiting around it. The satellite itself appears much larger than it really is in these animations because the images were colored to emphasize the structure of the debris. The one on the left has been color coded to show the density of stars being stripped from the satellite. Click here to see this movie (1.7 Mbyte MPEG animation.) or here to see a selection of frames (0.02 Mbyte). The one on the right has been color coded with the time when particles are lost from the satellite (ie the particles that are lost the first time the satellite goes around the Galaxy are shown in red, and each subsequent time in green, blue, yellow....) Click here to see the movie (1.7 Mbyte MPEG animation.) or here to see a selection of frames (0.02 Mbyte) from the movie.

MW & Sagittarius



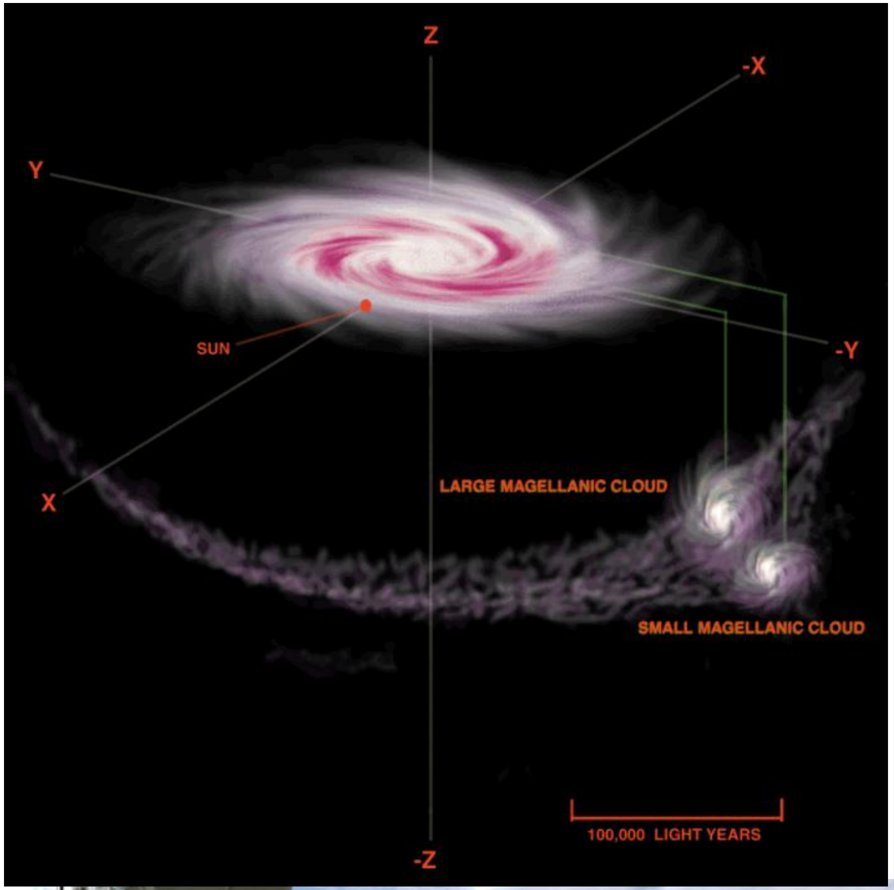
MW & Sagittarius

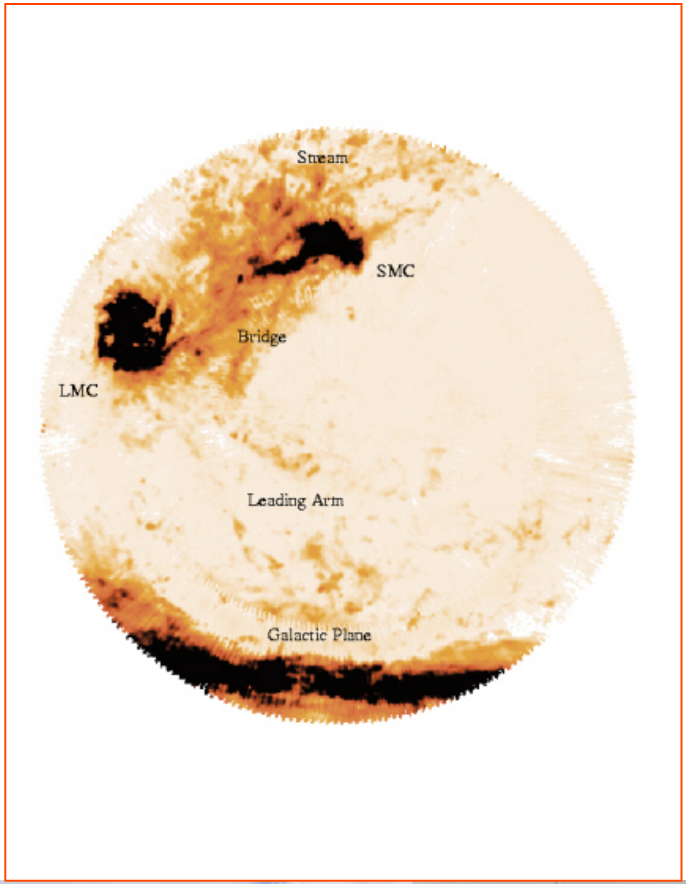




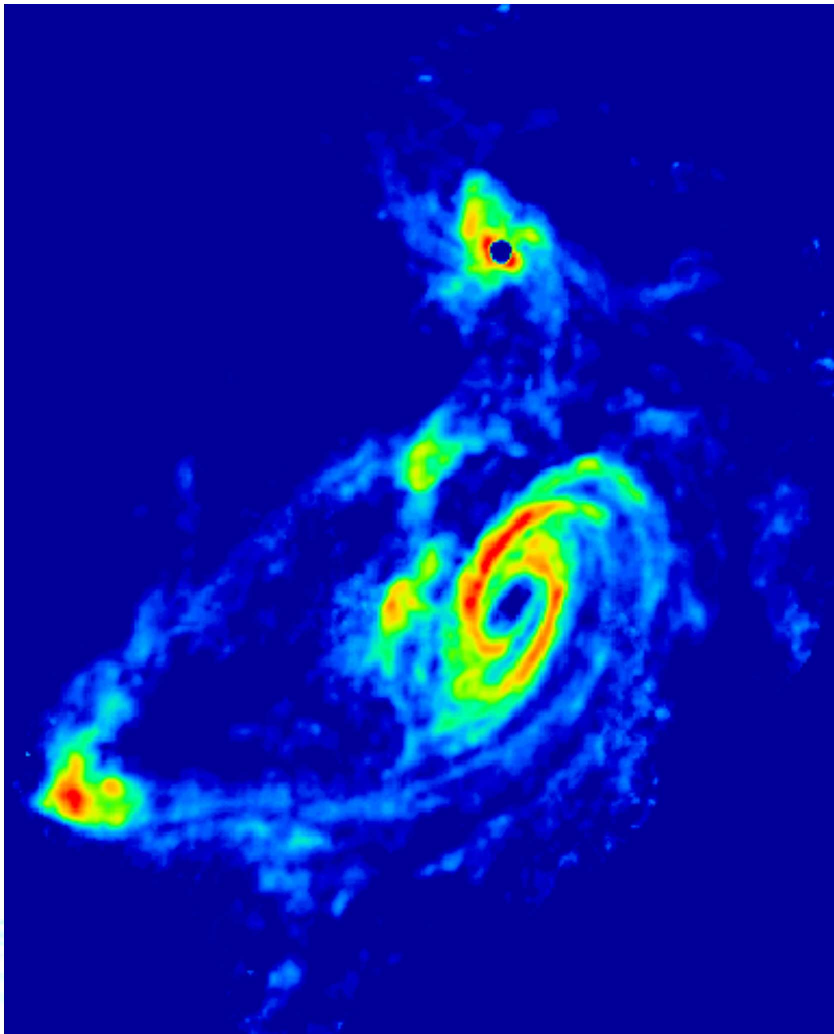
Stars streams

MW & MCs

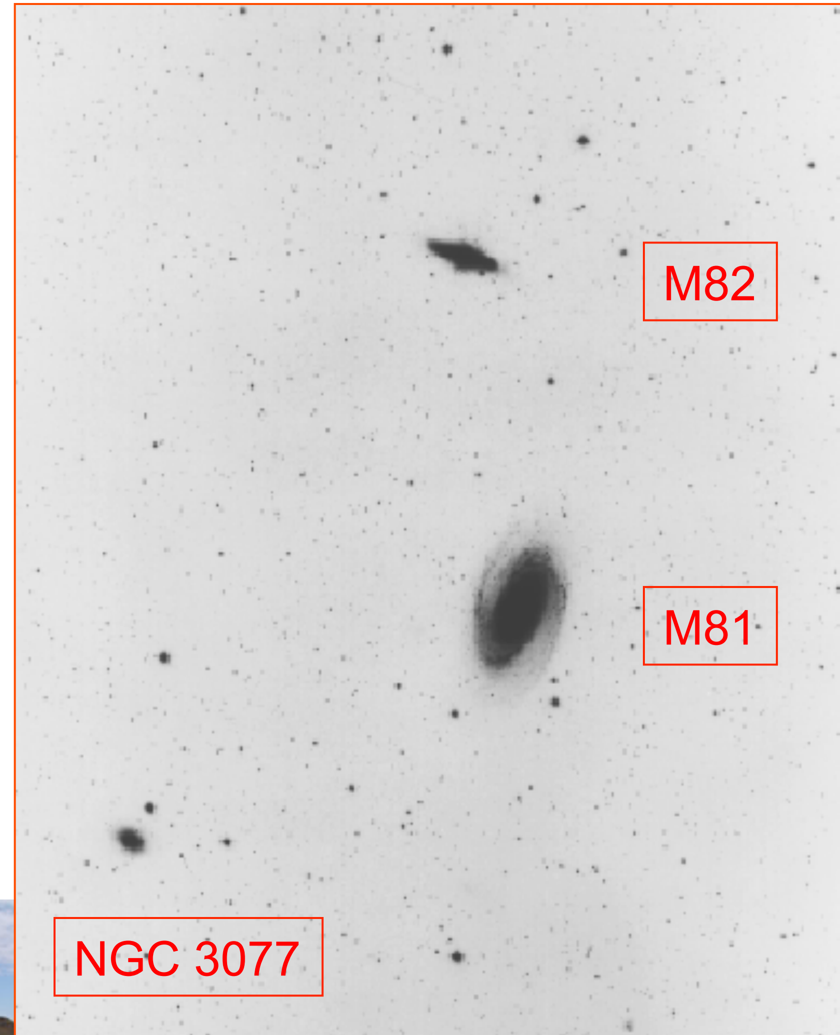

Z
-X
Y
SUN
-Y
X
LARGE MAGELLANIC CLOUD
SMALL MAGELLANIC CLOUD
100,000 LIGHT YEARS
-Z


Stream
SMC
Bridge
LMC
Leading Arm
Galactic Plane

Inter Galactic Gas (IGM)



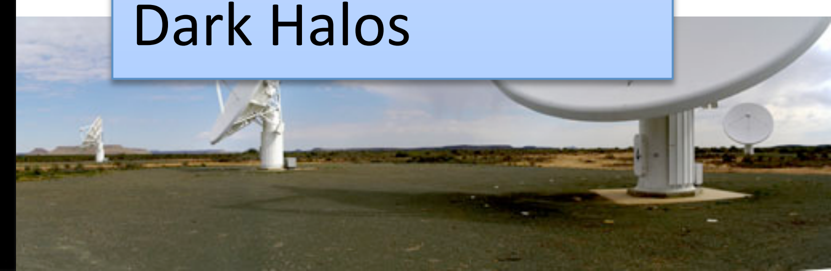
HI



Formation of polar rings

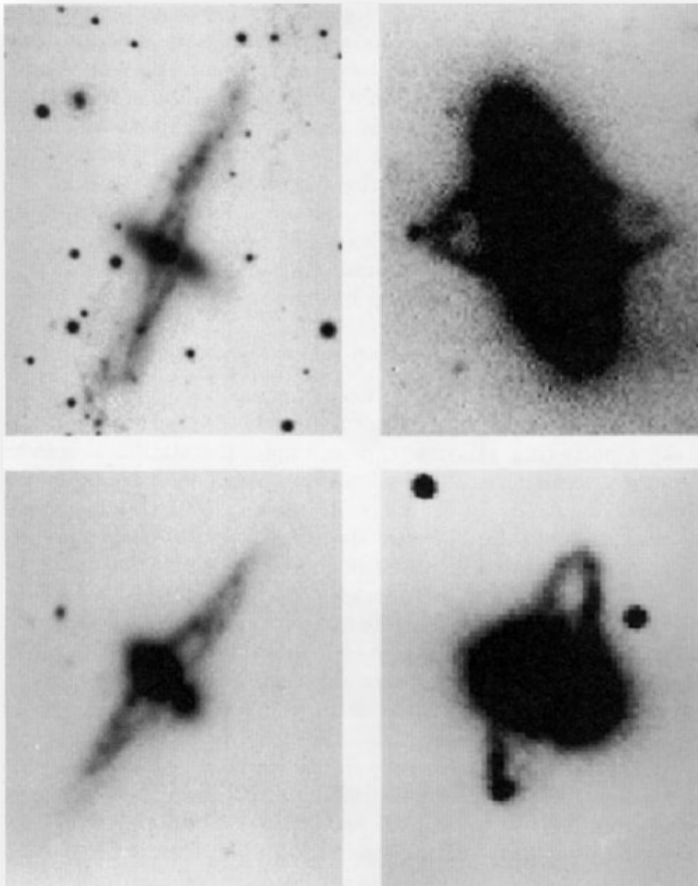
•Either by merger of galaxies with perpendicular J
• Either by accretion of gas e.g. MW/LMC

Allow to study the 3D structure of Dark Halos



Polar rings

Polar rings



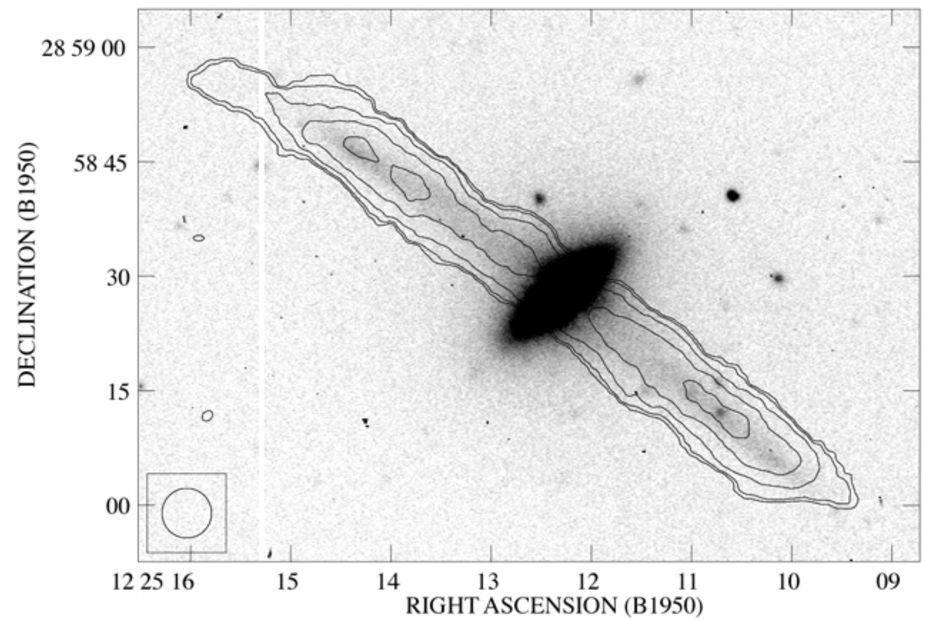
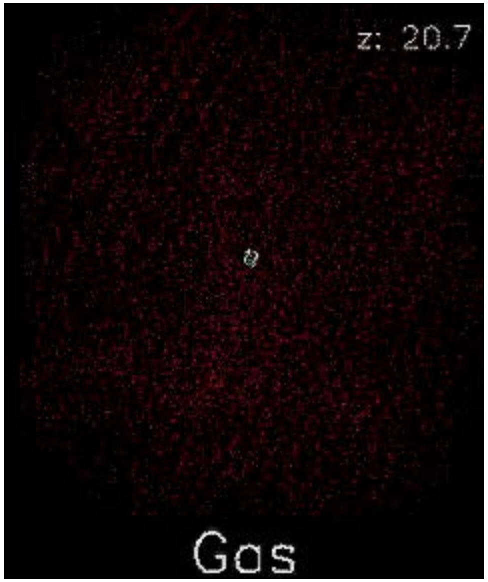


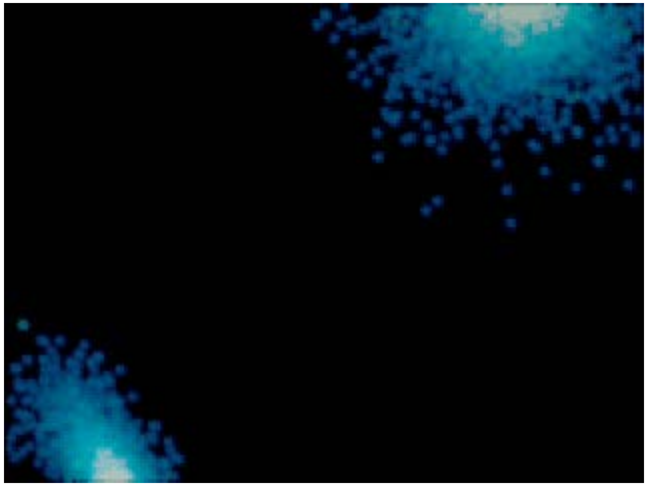
Fig 5.17 (A. Cox) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Multiple mergers (HC)

- Simulation of the formation of a galaxy through multiple collisions
- $z=20 \rightarrow z=0$
- Most of the mergers $0.2 < z < 0.8$
- Before: not enough galaxies
- After: ρ goes down because of the expansion

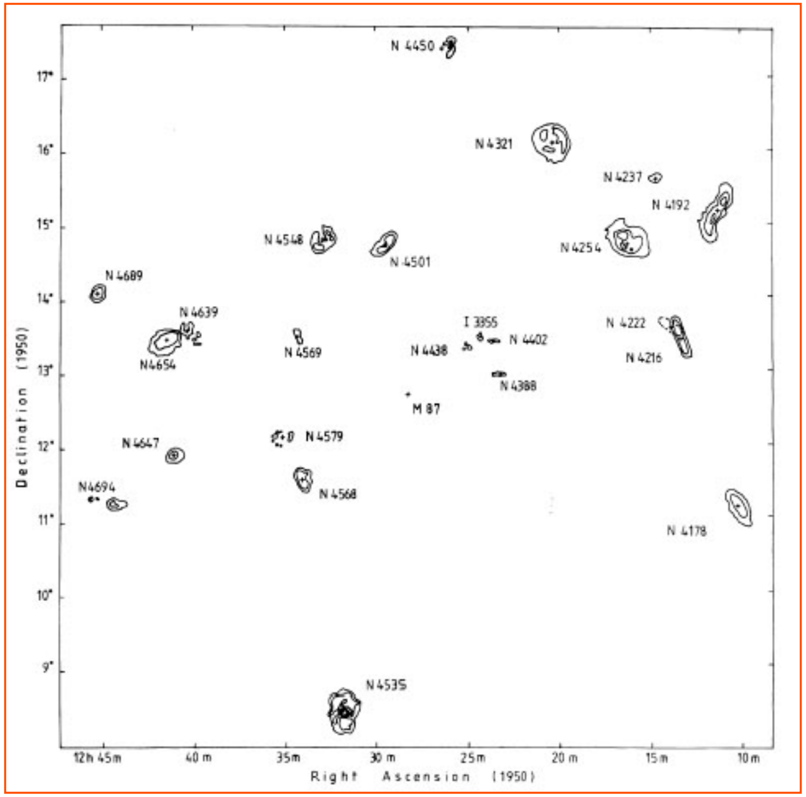


Collision of gas-rich galaxies

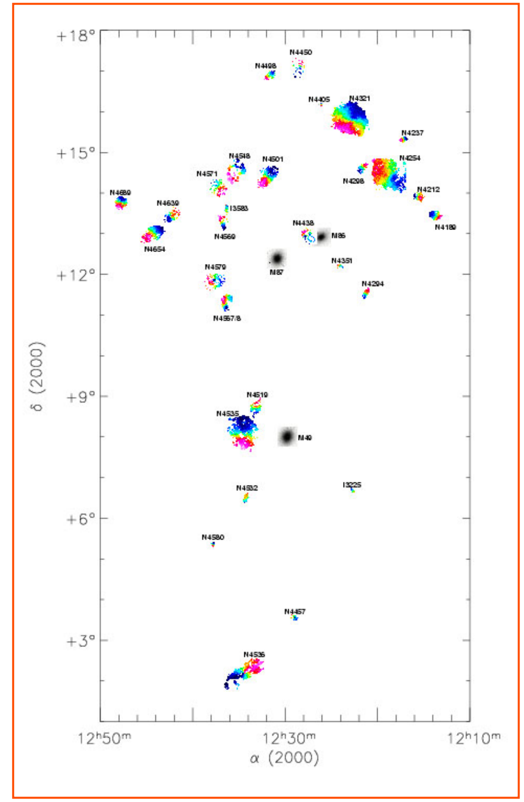


Ram Pressure

Virgo - HI



Virgo - Hα



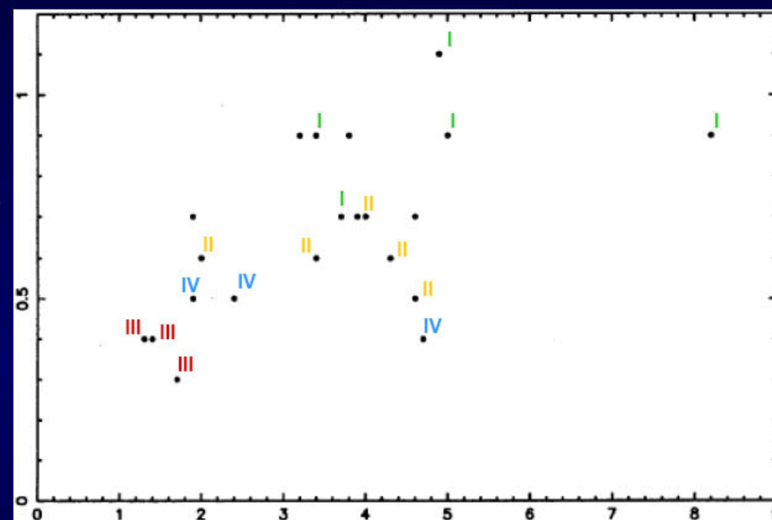
Ram Pressure

Virgo Spirals: Surface Densities

(Cayatte et al. 1994)

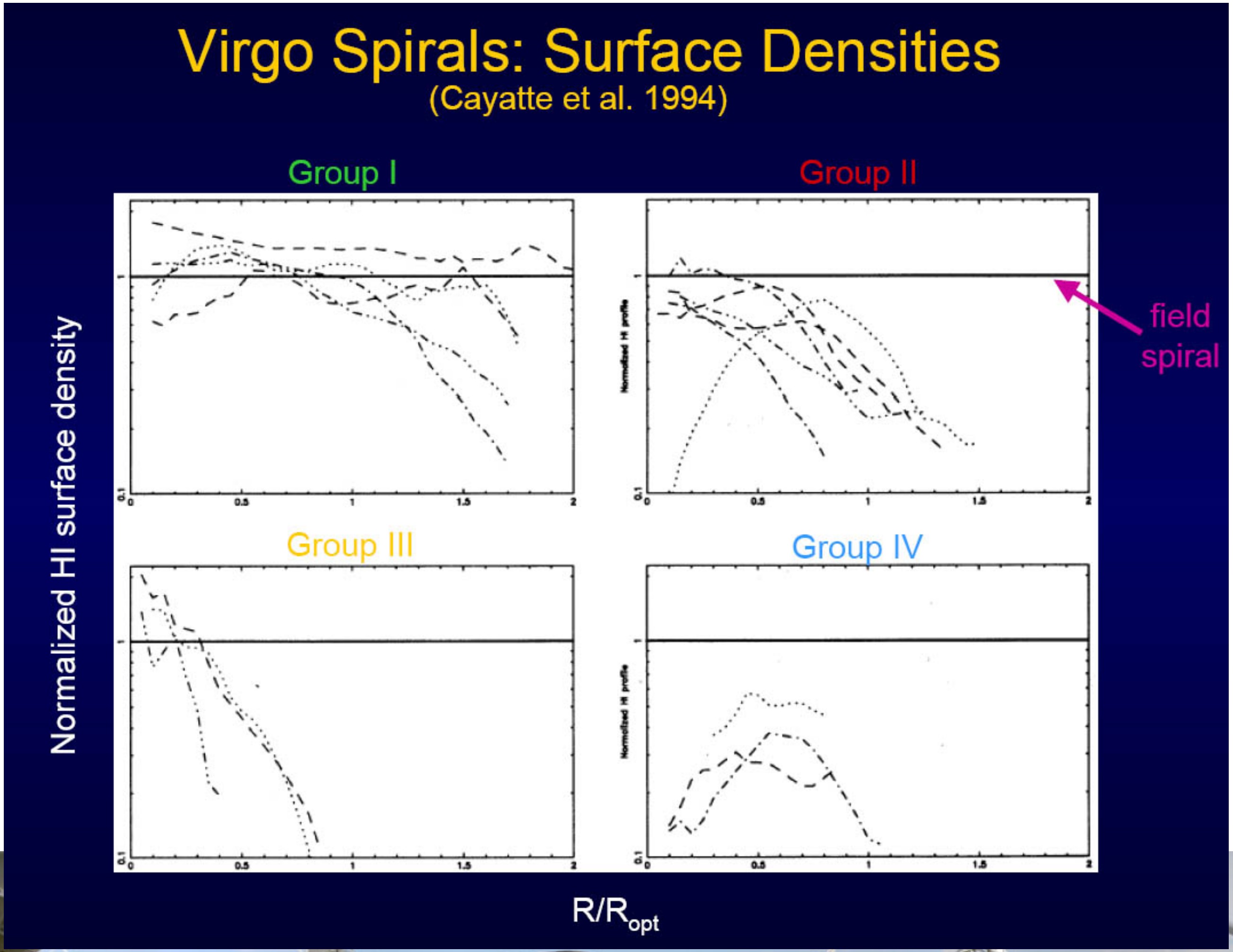
Divide galaxies into 4 groups:

I	$D_{HI}/D_{opt} > 1.3$
II	$0.75<D_{HI}/D_{opt}<1.3$
III	$D_{HI}/D_{opt}<0.75$
IV	Anemic spirals



CENTER

Ram Pressure



Ram Pressure

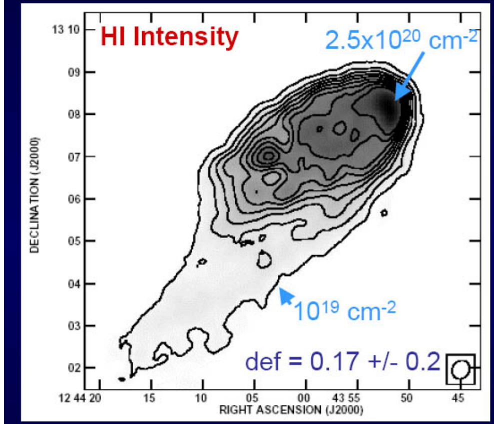
NGC 4654 – Optical and HI Morphology

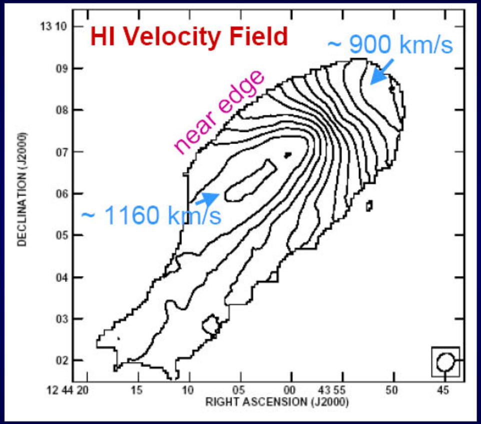
Optical Image:

http://www.noao.edu/outreach/aop/observers/n4654.html

NGC 4654 – Optical and HI Morphology

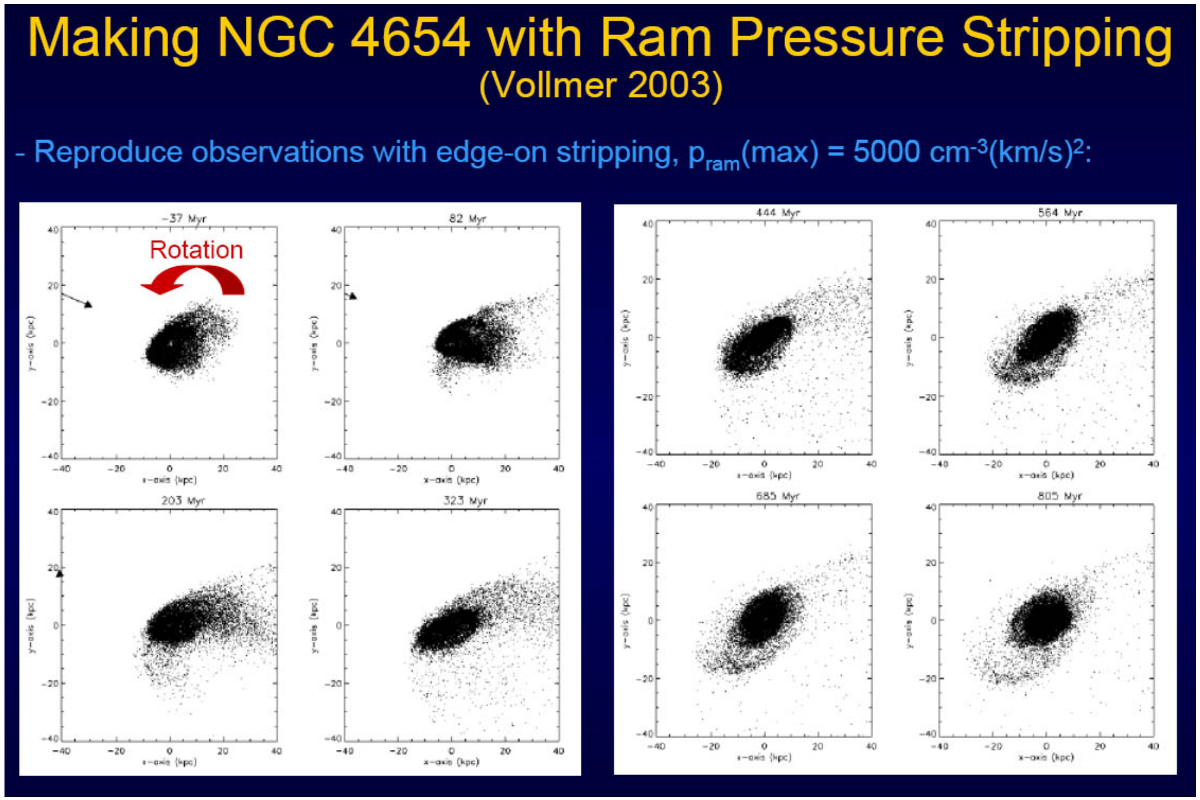
HI Morphology:





Phookun & Mundy 1995

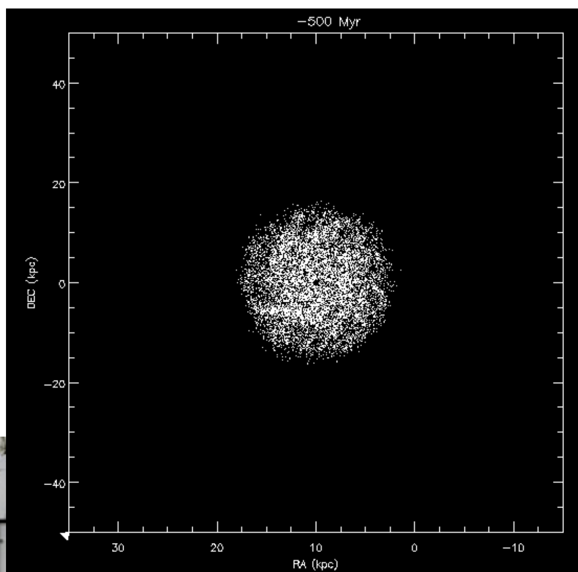
Ram Pressure



$$p_{ram} = \rho_{ICM} V_{gal}^{2}$$

Ram Pressure stripping

- Simulation of a galaxy passing at the center of Virgo
- IGM hot 10^7K
- IGM low density: $\sim 10^{-4}$ cm^{-3}
- IGM mass: 10^{13} M_{sun}



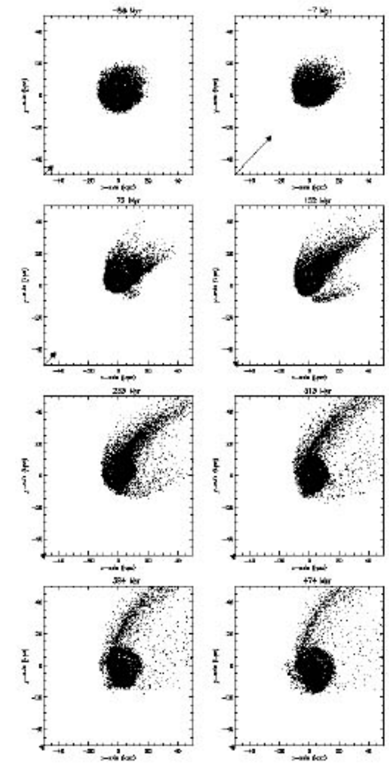
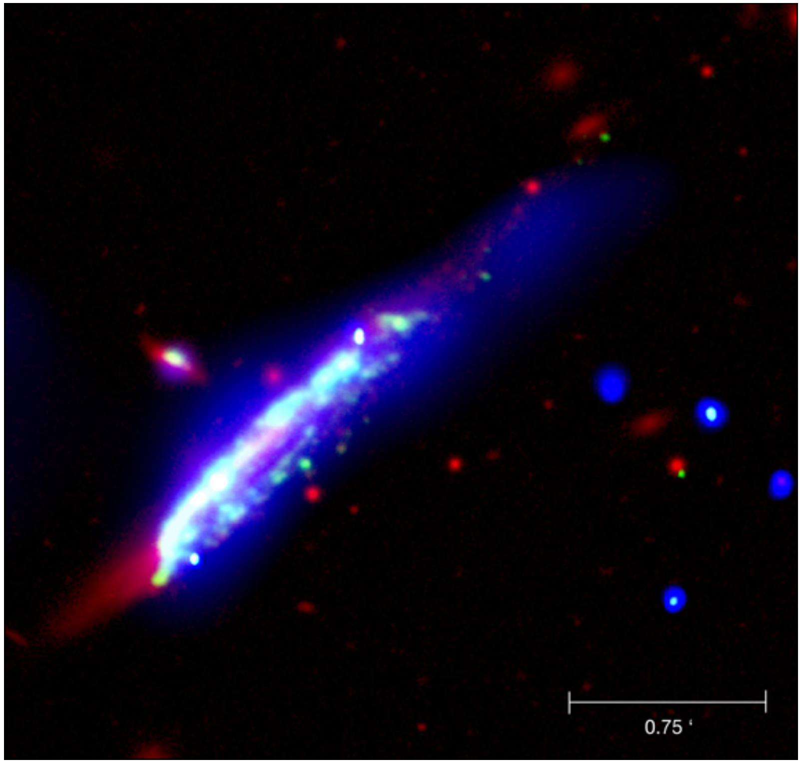


Fig. 11.— Snapshots of RUN C(50, 0). The elapsed time is indicated at the top of each panel. The galaxy is seen face-on and is moving in the south-east direction, i.e. the wind is coming from the south-east. This wind direction is indicated by the arrows whose length is proportional to ρv^2.

Ram Pressure stripping



- Abell 1367 – Chandra
- Blue: X-ray
- Red: old stars
- Green: young stars
- Collision with IGM causes SF

Ram Pressure stripping

THE ASTRONOMICAL JOURNAL, 123:1316–1333, 2002 March

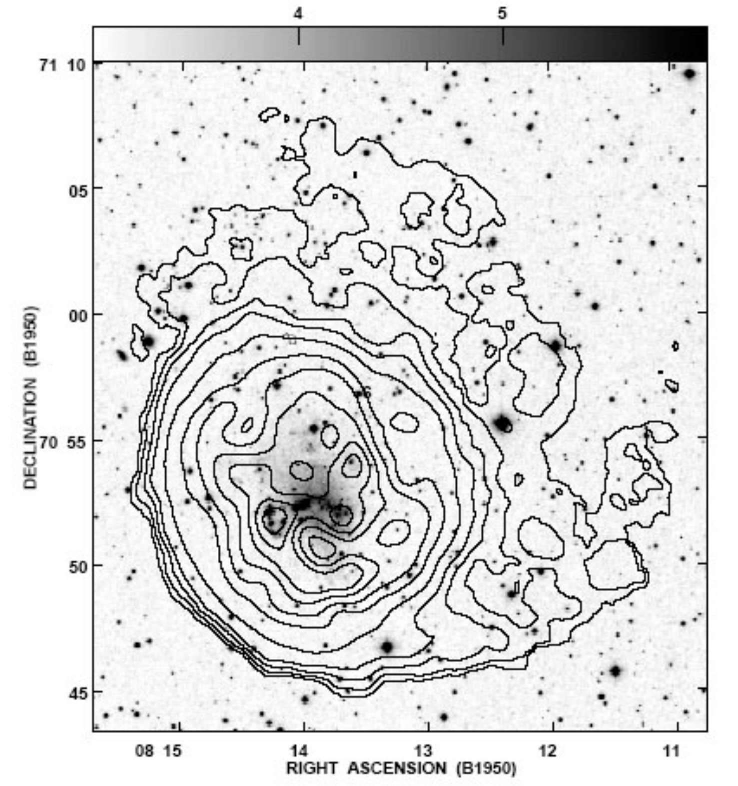
ENVIRONMENT, RAM PRESSURE, AND SHELL FORMATION IN HOLMBERG II

M. BUREAU[1,2]
Leiden Observatory, University of Leiden, Postbus 9513, 2300 RA Leiden, Netherlands; bureau@strw.leidenuniv.nl
AND
C. CARIGNAN
Department of Physics and Mount Megantic Astronomical Observatory, University of Montreal, P.O. Box 6128, Station Centre-Ville, Montreal, PQ H3C 3J7, Canada; carignan@astro.umontreal.ca
Received 2001 August 23; accepted 2001 November 28

The threshold condition for ram pressure stripping can be written simply as

$$\boxed{\rho_{\rm IGM} v^2 \geq 2\pi G \Sigma_{\rm tot} \Sigma_g} \qquad (3)$$

(Gunn & Gott 1972), where the left-hand side of the equation represents the pressure exerted by an IGM of density $\rho_{\rm IGM}$ on a galaxy moving at a relative velocity v, and the right-hand side of the equation represents the restoring force of a disk with total surface density $\Sigma_{\rm tot}$ and gaseous (ISM) surface density Σ_g.



Ram Pressure stripping

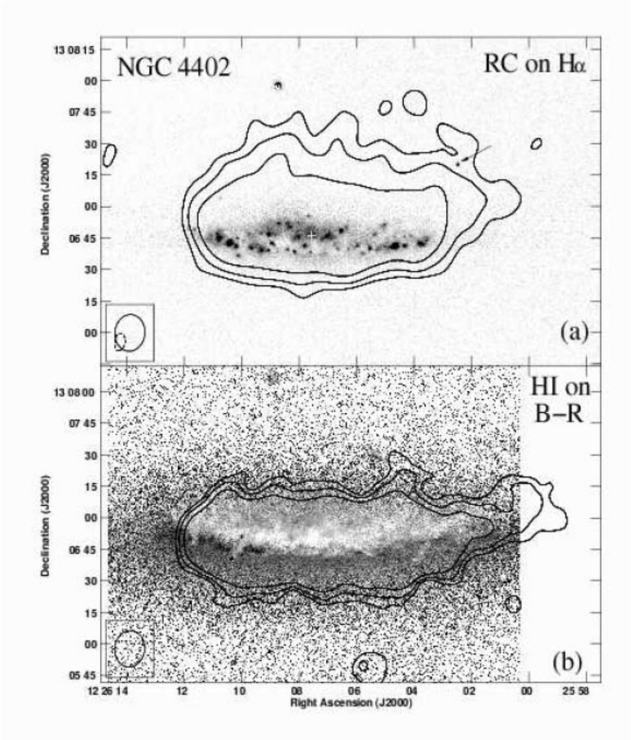
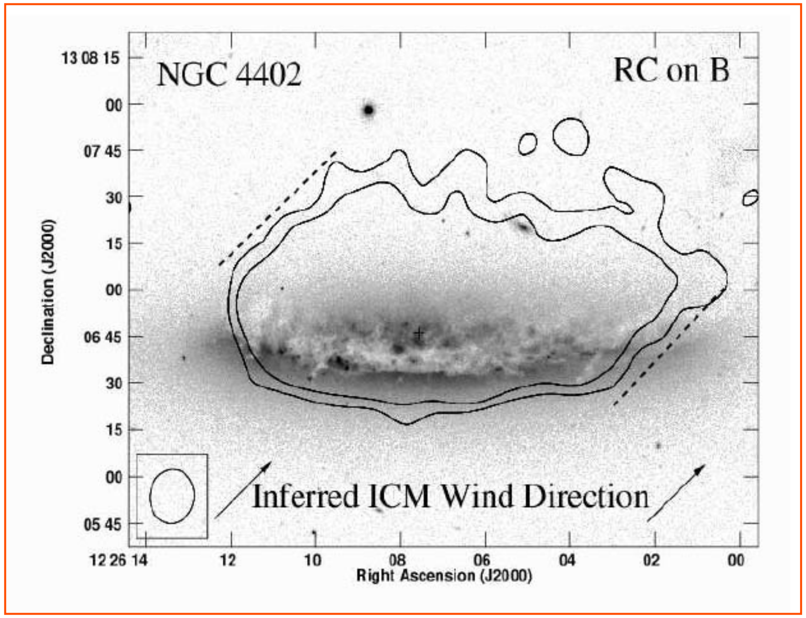
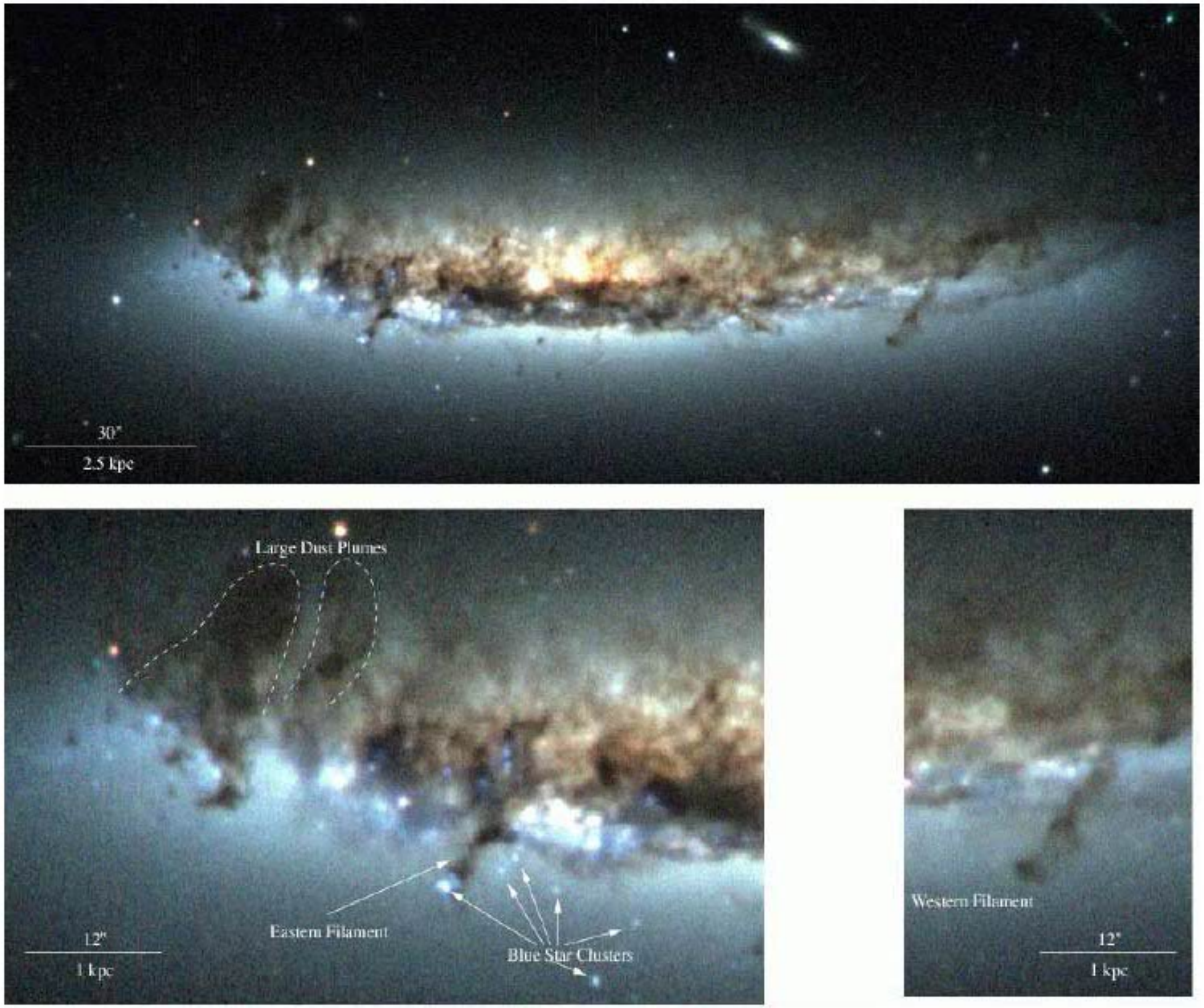


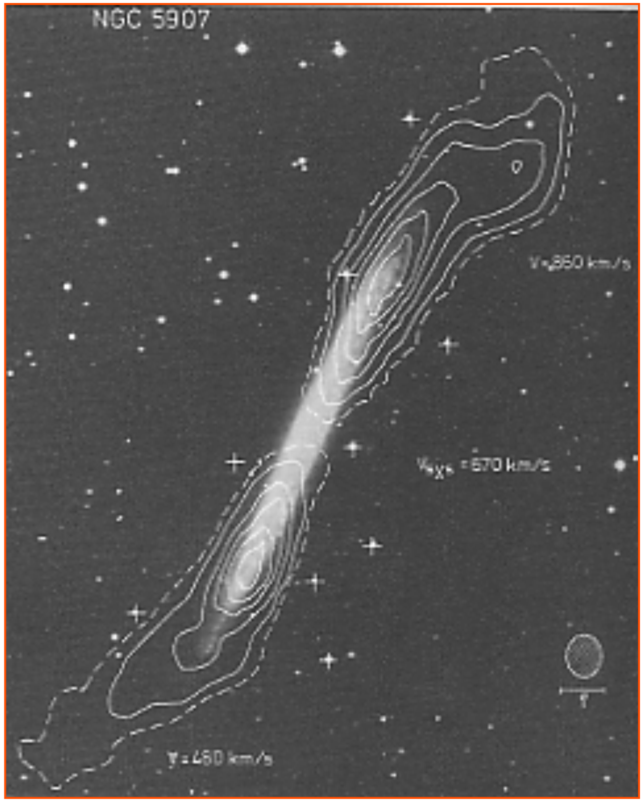
Fig. 2.— (a) $H\alpha$ image showing the outer three radio continuum contours. The extraplanar HII region from Cortese et al (2004) is marked with an arrow. (b) B-R image from WTTM images showing dust lane detail in the galaxy, along with the outer 3 HI contours. Note the very blue star clusters in the SE, probably due to minimal reddening by dust.

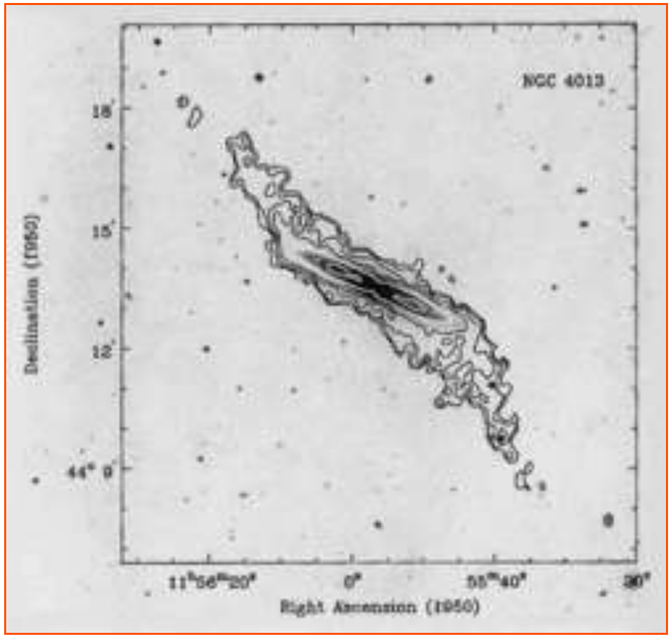


Ram Pressure stripping



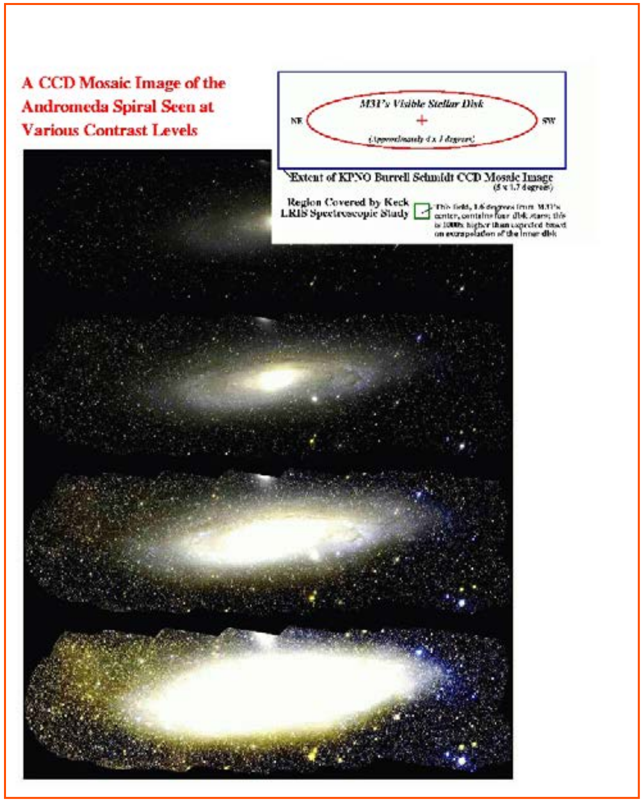
Warps

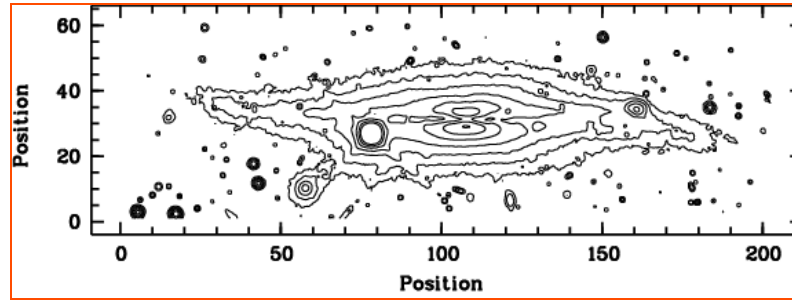




In HI, warps are the rule and not the exception

Warps





At optical wavelength, warps are the exception and not the rule

Warps

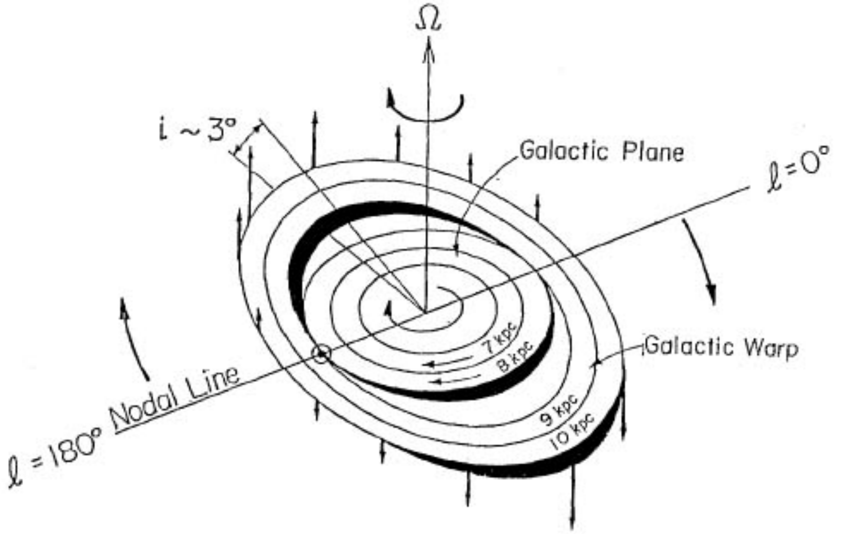


Fig. 2 A picture of the geometric and kinematic warp of the Galaxy, which is suggested by the analyses of O-B stars. According to the proper motion analyses, the O-B star belts exterior to the solar circle seem to be performing a seesaw oscillation around the nodal line of the warp.

MW

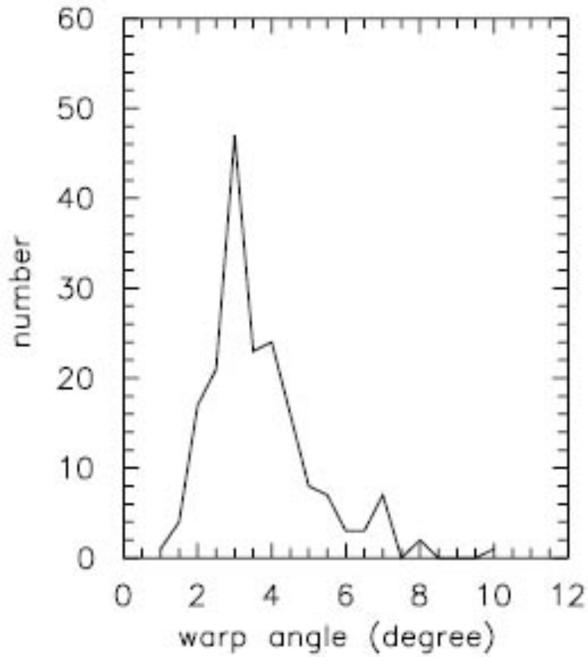


Fig. 5. Distribution of the observed warp angles for the galaxies with S-shaped warps.

Warps

- 3 possible origins for the warp:
  1. Gravitational interaction
  2. Accretion
  3. Tri-axial halo: could explain the difference between HI and optical warps – DM dominate at large r

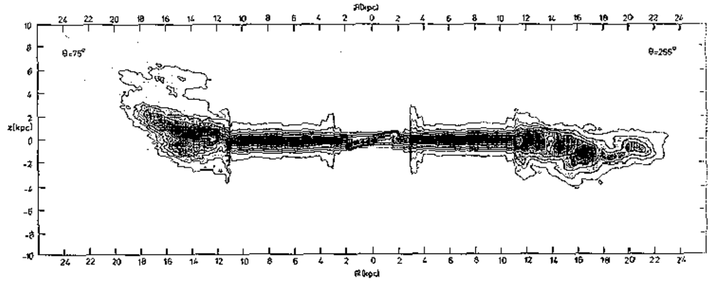


Fig. 7.23. Schematic, but not arbitrary, representation of the HI layer of our Galaxy. The cross section represents a cut through the Galactic center perpendicular t… in a sheet sampling strong deviations from a flat layer. The representation at $R > 11$ kpc is from R, z maps, like the ones in Figure 7.21, at $\Theta = 90°$ and 270 … range $2 < R < 10$ kpc, the parameters of the layer are those given by Lockman (1984) for the subcentral-point region; at $R < 2$ kpc, they are those given by … Burton (1980).