Astr 511: Galactic Astronomy

Winter Quarter 2013, University of Washington, Željko Ivezić

Lecture 10:

Merger history: observations and theory

Outline

1. **Brief recap: stellar halo substructure as seen by SDSS**

2. **A bit of theory on galaxy interactions**

Reading:

- Binney & Merrifield: section 10.7

- Battaglia et al. 2005: MNRAS 364, 433 (see also Erratum, MNRAS 370, 1055)

- Bell et al. 2008: ApJ 680, 295

- Jurić et al. 2008: section 4.3.8

- Tollerud et al. 2008: ApJ 688, 277

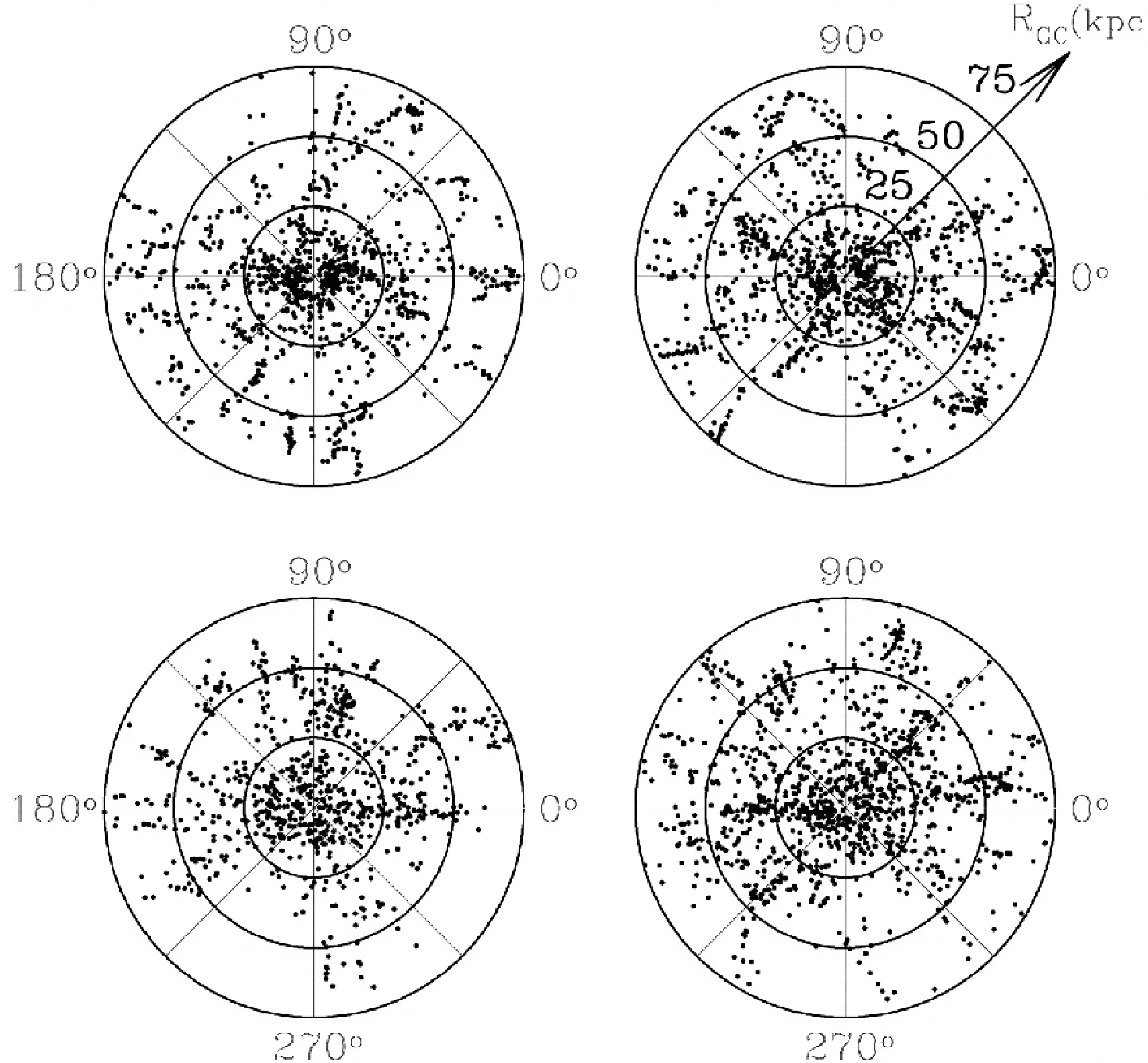
Halo (sub)structure

- Is there structure in the Milky Way halo? Monolithic collapse (Eggen, Lynden-Bell & Sandage 1962) vs. merger scenario (Searle & Zinn 1978)

  1. Is the halo spatial profile (stellar counts) smooth? E.g., is $\rho(R) \propto R^{-3}$ everywhere?

  2. Are halo kinematics described by the Schwarzschild distribution? Does the MW halo rotate?

  3. Is the halo's chemical composition (e.g. metallicity) uniform?



Bullock, Kravtsov & Weinberg (2001) predictions for counts

Outer Halo

- Is there structure in the outer halo? **Hard to reach observationally**

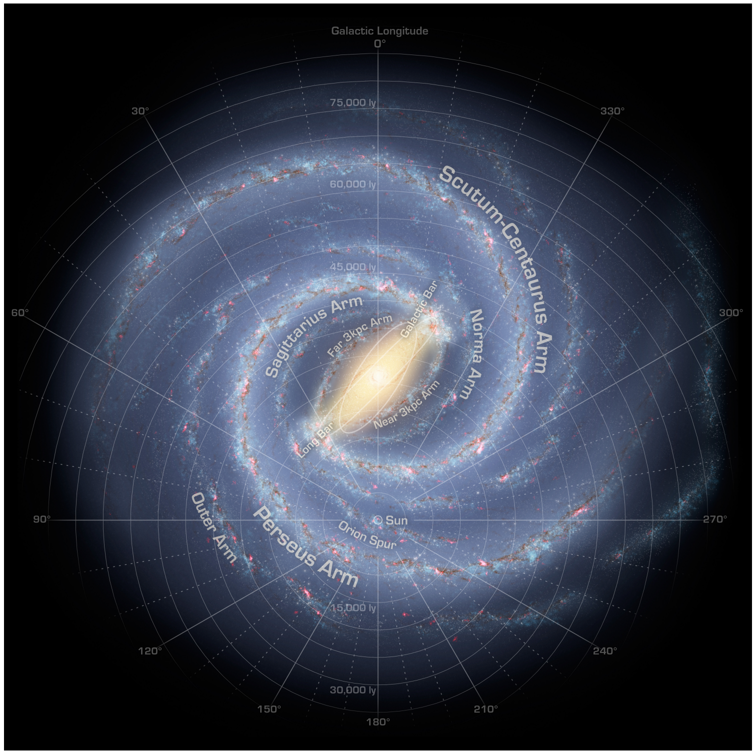
- Distance modulus for 100 kpc is 20 mag – to have an apparent magnitude $m < 21$, a star must have $M < 1$.

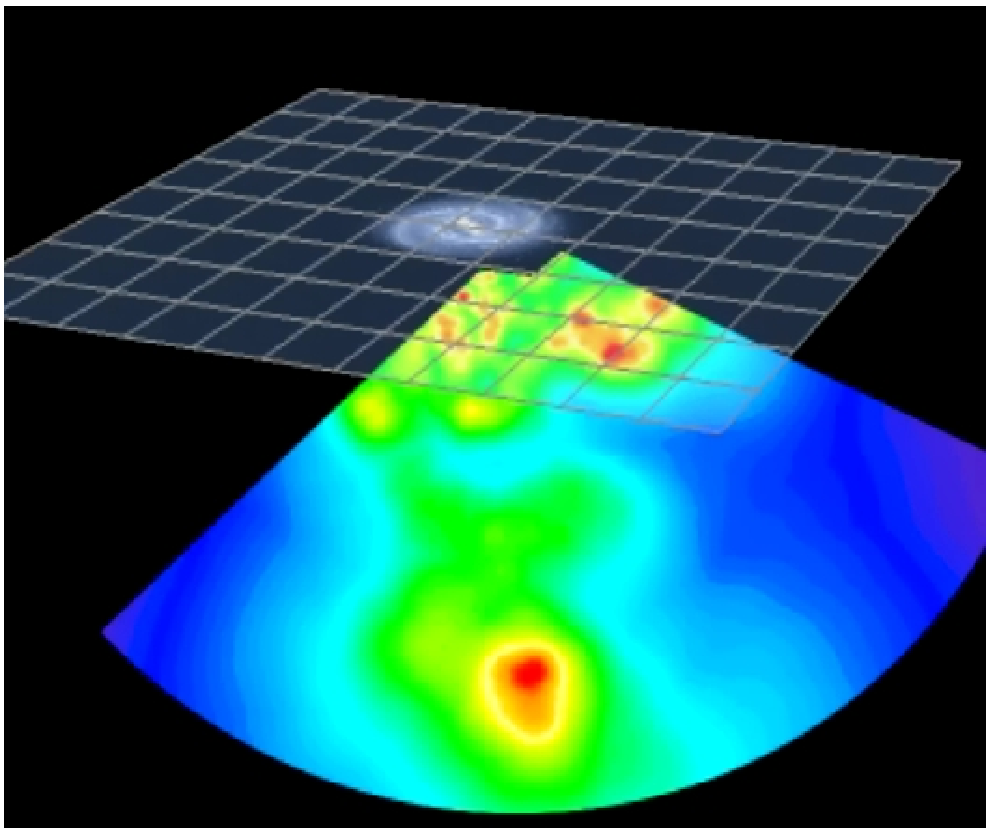
- Horizontal branch stars (including RR Lyrae) and red giants are good **luminous** tracers of the outer halo

- RR Lyrae stars: variability, color, spectroscopic selection

- BHBs, RGs: color, spectroscopic selection

Ideally, would like to study outer halo with main sequence stars because they are much more numerous (see the last lecture on LSST)





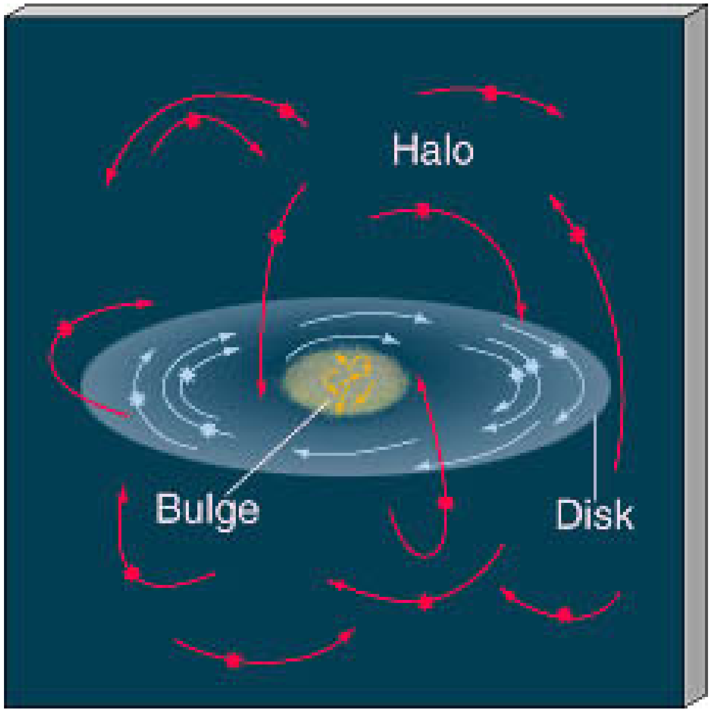
RR Lyrae from SDSS Stripe 82

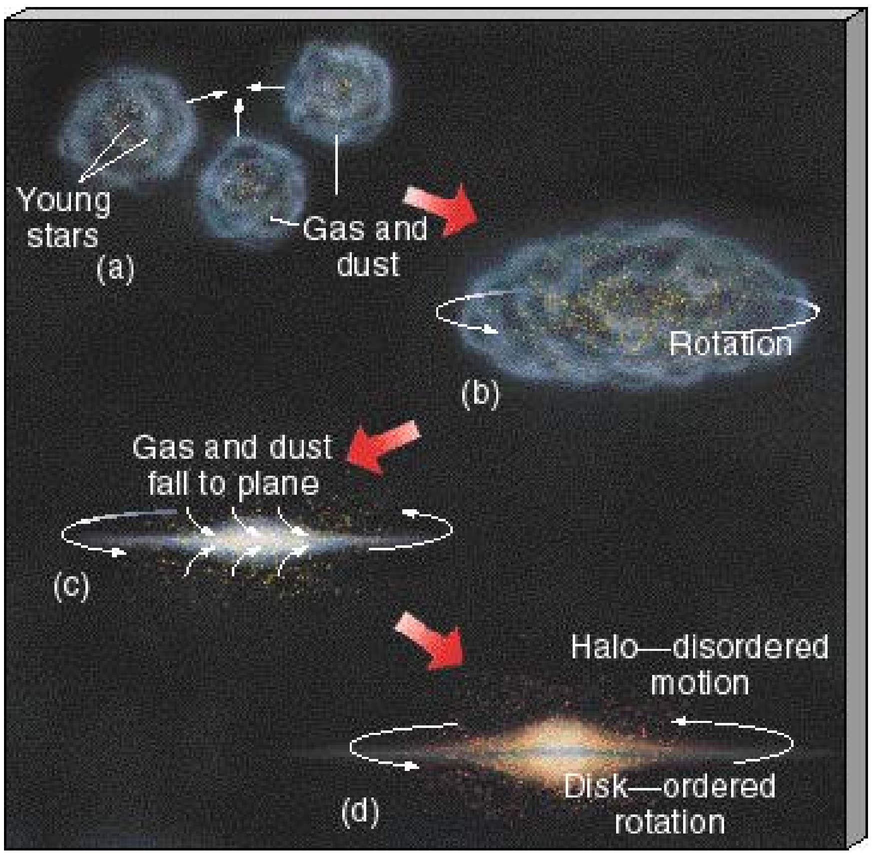
- **Top left:** the disk structure (artist's conception based on the Spitzer and other surveys of the Galactic plane)
- **Bottom left:** the halo density (multiplied by R^3; yellow and red are overdensities relative to mean $\rho(R) \propto R^{-3}$ density) as traced by RR Lyrae from SDSS Stripe 82 (Sesar et al. 2009), compared in scale to the top panel
- Conclusions: the halo is big! The spatial distribution of halo stars is highly inhomogeneous (clumpy); when averaged, the stellar volume density decreases as $\rho(R) \propto R^{-3}$.

A bit of theory on galaxy merging

1. Galaxy Formation
   - The Monolithic Collapse Model (top-down)
   - The Merger Model (bottom-up)

2. Galaxy Interactions
   - Fast Encounters
   - Slow Encounters





Kinematics

- Stars move in a gravitational potential
- Two types of motion: disk stars **rotate** around the center, while halo stars are on randomly distributed elliptical orbits
- The motion of stars was set during the formation period
- The details are governed by the laws of physics: conservation of energy and conservation of angular momentum!
- As the cloud collapses, its rotation speed must increase. As it spins faster, it must flatten.

The ELS Monolithic Collapse Model

- The ELS model (Eggen, Lynden-Bell and Sandage, 1962): the Milky Way formed from the rapid collapse of a large proto-galactic nebula: top-down approach
  - the oldest halo stars formed early, while still on nearly radial trajectories and with low metalicity
  - then disk formed because of angular momentum conservation, and disk stars are thus younger and more metal-rich
  - first thick disk ($\sim$ 1 kpc scale height) was formed, and then thin disk ($\sim$ 300 pc scale height)
  - the ongoing star formation is confined to a scale height of $\sim$50 pc, at a rate of a few $M_\odot$ per year

Galaxy Formation

The ELS Monolithic Collapse Model

How fast did the Galaxy form?

The free-fall time is

$$t_{ff} = \sqrt{\frac{3\pi}{32}\frac{1}{G\rho_o}}, \tag{1}$$

where ρ_o is the mean density:

$$\rho_o = \frac{3M}{4\pi r^3}. \tag{2}$$

For $M = 6 \times 10^{11}\ M_\odot$ and $r = 100$ kpc, $t_{ff} = 7 \times 10^8$ yr ~ 1 Gyr (upper limit, centrally peaked clouds collapse somewhat faster)

NB the lifetime of most massive stars is ~ 1 Myr: many stellar generations lead to chemical enrichment

Problems with the monolythic collapse scenario:

- Why are half the halo stars in retrograde orbits? We would expect that most stars would be moving in roughly the same direction (on highly elliptical orbits) because of the initial rotation of the proto-Galactic cloud.

- Why there is an age spread of ~ 3 Gyr among globular clusters (GCs)? We would expect < 1 Gyr spread (free-fall time).

Some important questions that are left without robust answers:

- Why GCs become more metal-poor with the distance from the center?

- Detailed calculations of chemical enrichment predict about 10 times too many metal-poor stars in the solar neighborhood (the G-dwarf problem), why?

An alternative model for galaxy formation

- A bottom-up scenario: galaxies are built up from merging smaller fragments (similar but not the same as hypothesis that giant ellipticals formed from merging spiral galaxies)

- by observing galaxies at large redshifts (beyond 1), we are probing the epoch of galaxy formation – indeed, galaxies at large redshifts have very different morphologies, and the fraction of spirals in clusters is greater than today (Butcher-Oemler effect). Also, the volume density of galaxies was larger in the past: consistent with the merger hypothesis

- We have some important evidence for galaxy merging in our own backyard: recent SDSS and 2MASS results.

Model fit residuals

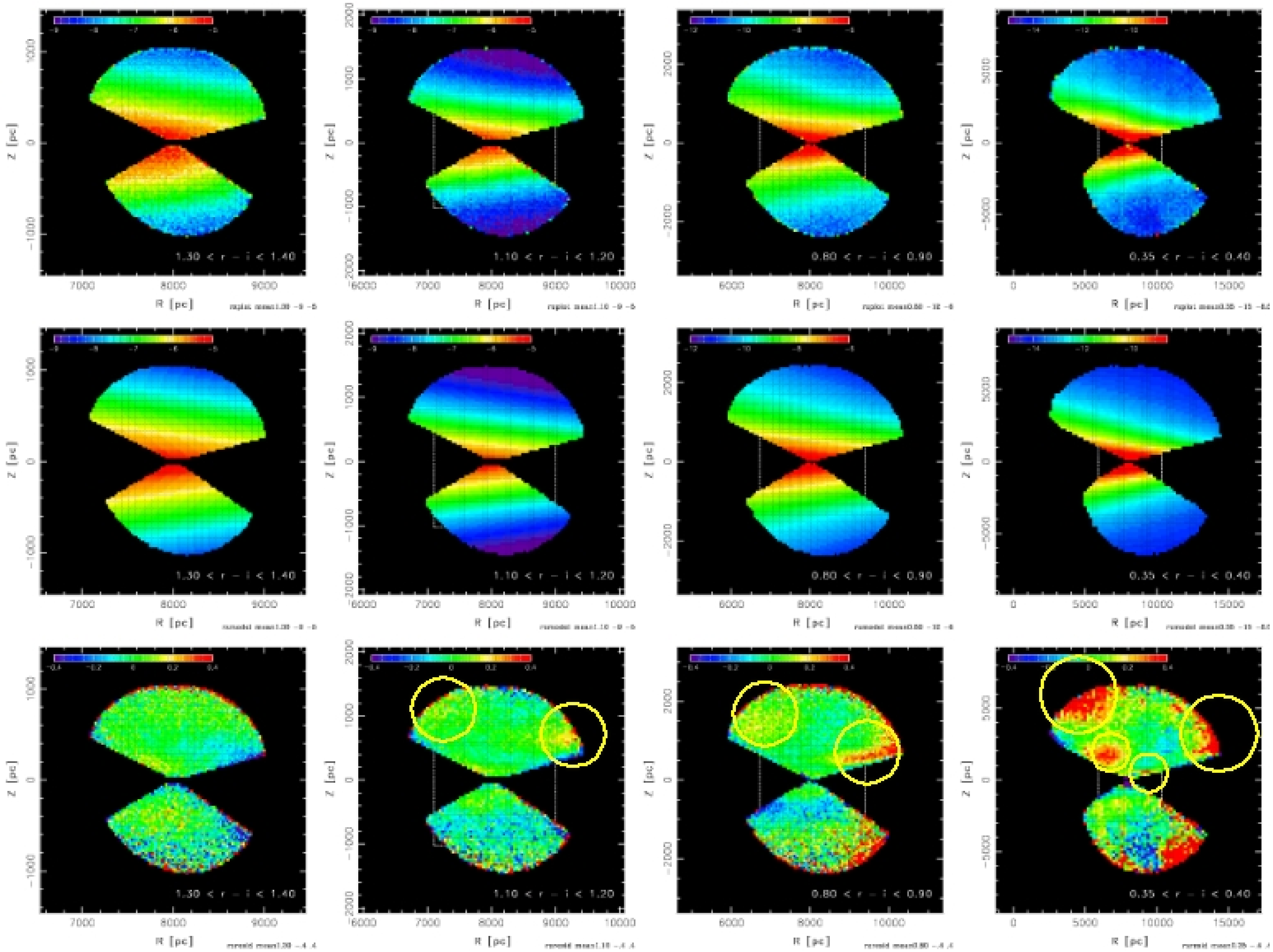
Scale increases this way

1.3 < r-i < 1.4 | **1.1 < r-i < 1.2** | **0.8 < r-i < 0.9** | **0.35 < r-i < 0.40**

Data

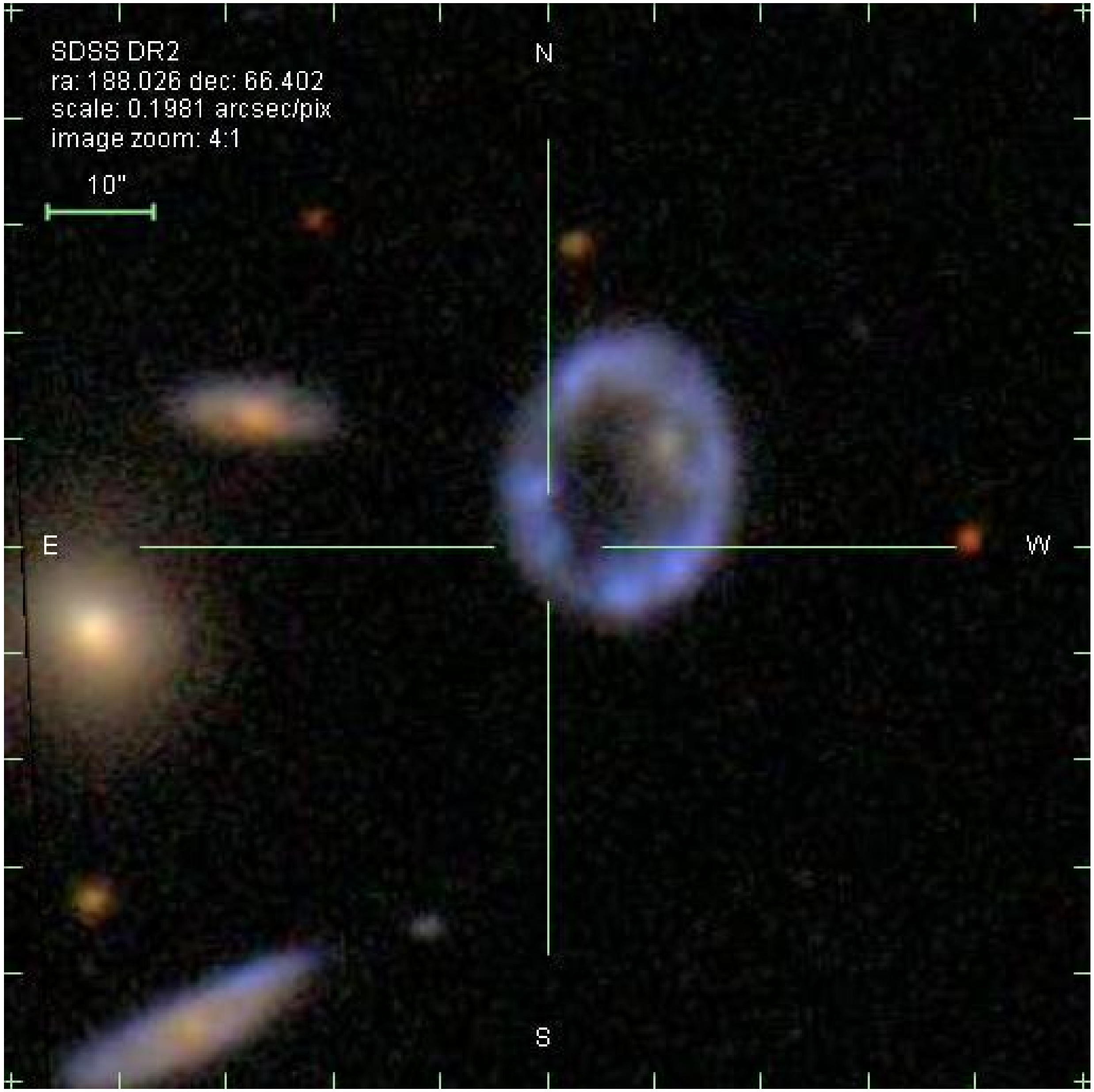
Model

D/M-1



Evidence for Galaxy's cannibalistic nature

- The spatial distribution of halo stars is clumpy
- Tidal streams in the halo (e.g. the Sgr dwarf tidal stream, the Monoceros stream, the Orphan stream)
- Large scale stellar counts overdensities that are inconsistent with standard thin/thick disk & power-law halo model
- Deviations from the expected velocity distribution (expect 3D Gaussian distribution, aka the Schwarzschild ellipsoid)



Interactions can results in various shapes and forms!

Galaxy Interactions: basic considerations

It is much more likely for two galaxies to interact/collide than for two stars because typical distance between two galaxies (say $\sim$ 1 Mpc) is only about 10-100 times larger than the size of a typical galaxy. For stars, typical distance (say 1 pc) is about 10^8 times larger than typical stellar size!

E.g. Andromeda is coming overhere at 100 km/s – expect collision 6 Gyr from now!

Fraction of the Milky Way's disk that is covered by stars: 10^{-14}! Even if another galaxy, such as Andromeda with 10^{11}–10^{12} stars, would score a direct hit, the probability of a direct stellar collision is still negligible.

The main effect of a galaxy collision is on interstellar gas, which is shocked and heated. The compressed gas cools off rapidly and fragments into new stars. A collision usually triggers a burst of star formation!

Star formation and starbursts

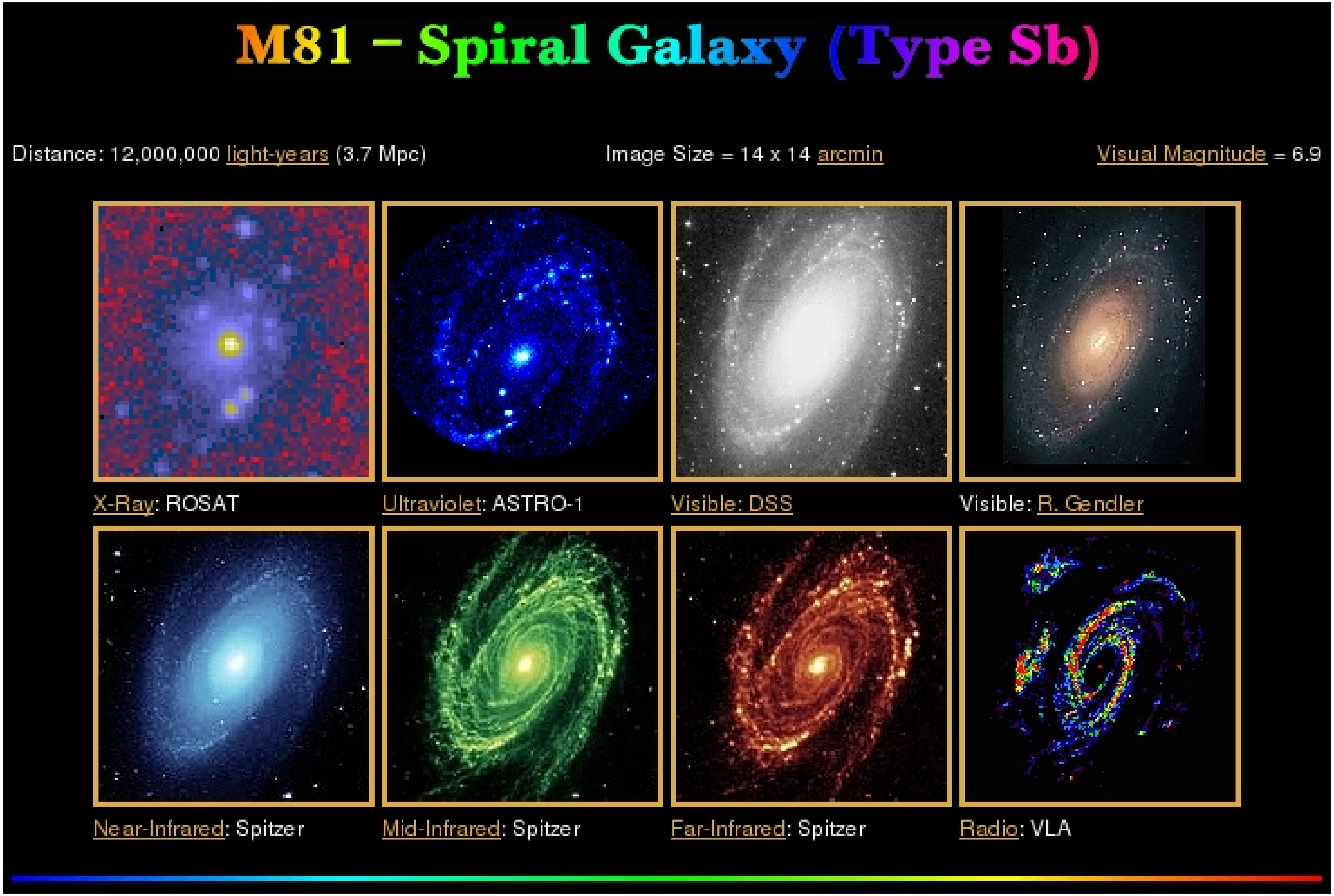
- The hottest stars, which have the shortest lifetimes, can be present only if there is an ongoing star formation; hence, the strong UV radiation is a sign of ongoing star formation (however, note that AGN spectrum is similar so one needs to be careful: spatially resolved observations, X-ray and radio observations, etc)

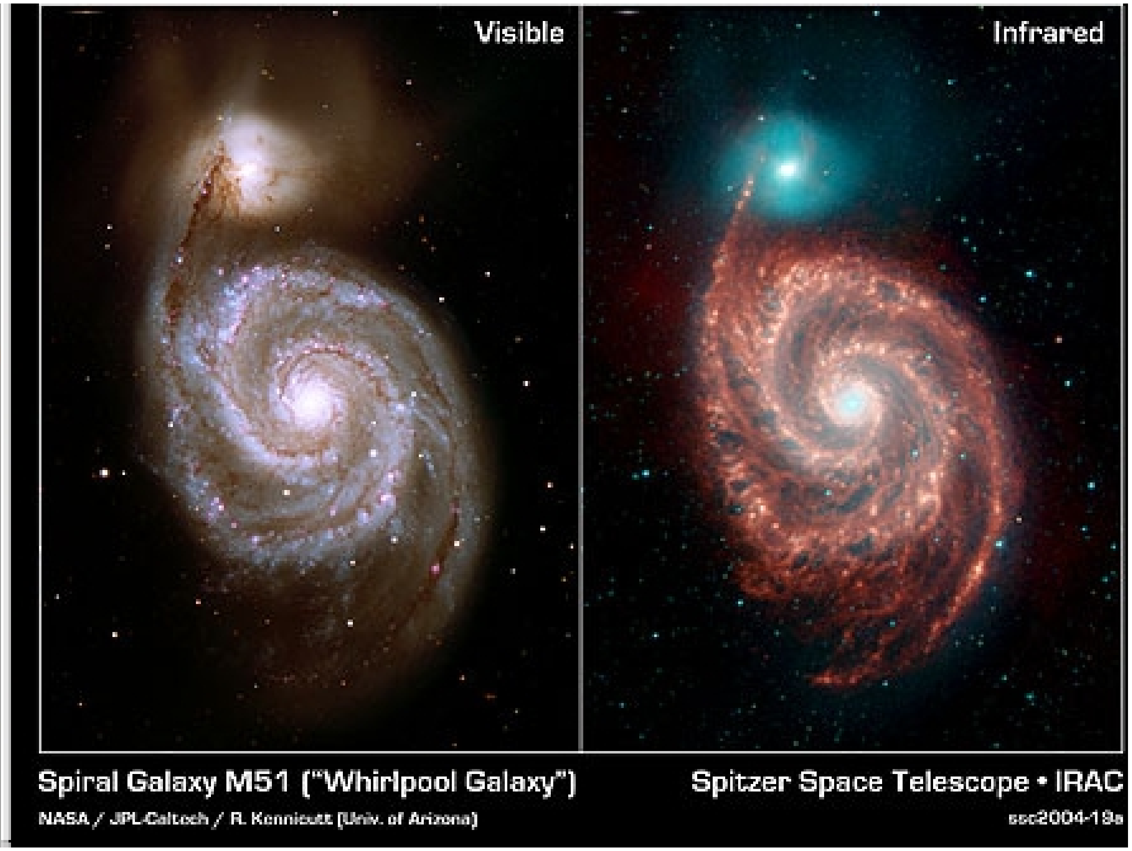
- Strong IR emission from circumstellar and diffuse dust is also a good sign of ongoing star formation (although here too confusion with AGN is possible)

- Another indicator of star formation is $H\alpha$ line

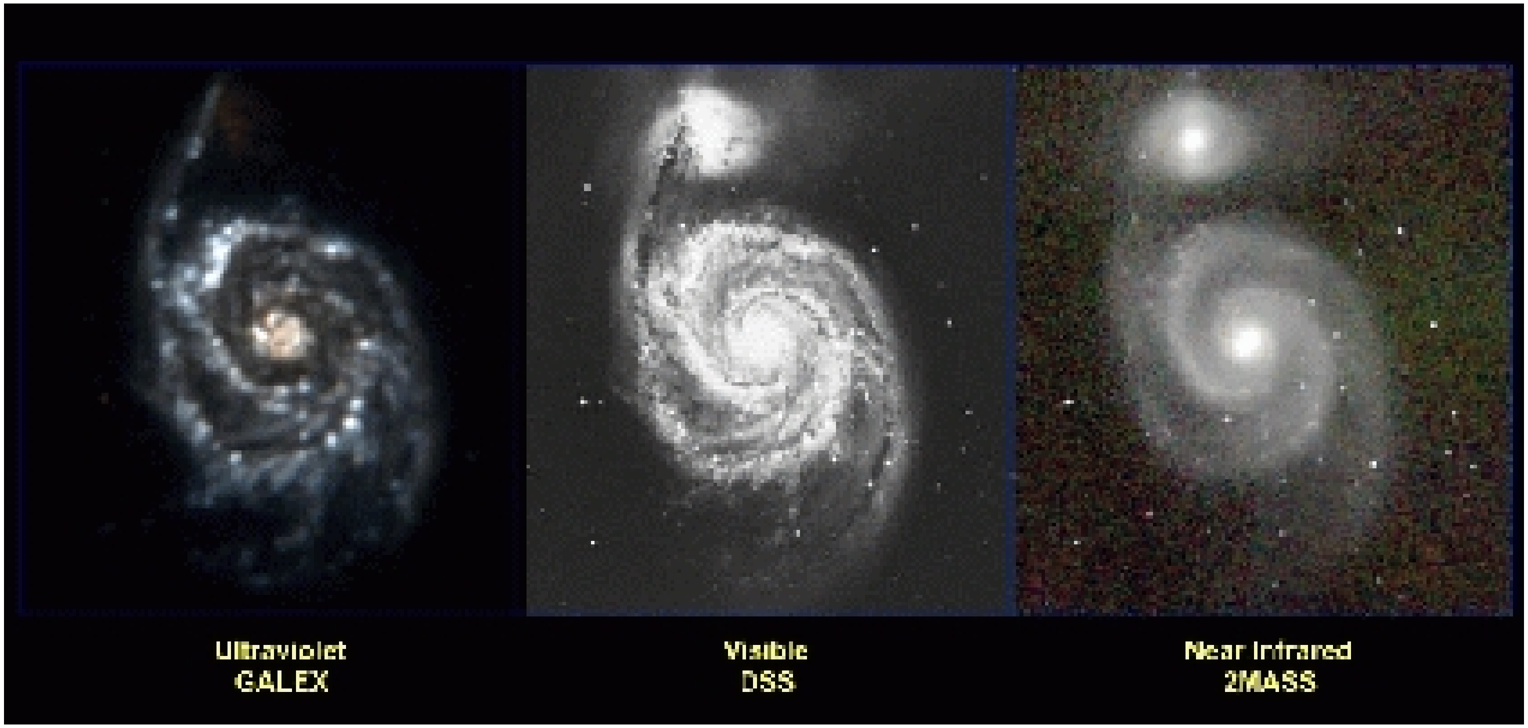
Andromeda Galaxy
GALEX

Andromeda Galaxy
Visible light image (John Gleason)


M81 – Spiral Galaxy (Type Sb)
Distance: 12,000,000 light-years (3.7 Mpc)
Image Size = 14 x 14 arcmin
Visual Magnitude = 6.9
X-Ray: ROSAT
Ultraviolet: ASTRO-1
Visible: DSS
Visible: R. Gendler
Near-Infrared: Spitzer
Mid-Infrared: Spitzer
Far-Infrared: Spitzer
Radio: VLA



Visible
Infrared
Spiral Galaxy M51 ("Whirlpool Galaxy")
Spitzer Space Telescope • IRAC
NASA / JPL-Caltech / R. Kennicutt (Univ. of Arizona)
ssc2004-19a



Note that the smaller galaxy (NGC 5195) is not visible in GALEX image (left): the burst of star formation is only in M51!

Star formation and starbursts

- After the end of star formation phase, galaxies become redder with time (in optical), $H\alpha$ becomes weaker, and IR emission disappears

- Galaxies caught right after the end of star formation will still have spiral structure, but no strong UV flux, nor $H\alpha$ line: passive (or anemic) spirals

Passive spirals in SDSS

Goto et al. (2003)

Collisions, Encounters, Tidal tails: basic physics

- **Two regimes for galaxy encounters:** fast, $v_\infty > v_f$ (elastic behavior, galaxies affect each other but do not merge, e.g. tidal tails) and slow $v_\infty < v_f$ (inelastic behavior – galaxies merge), where v_∞ is the relative velocity, and v_f is some critical velocity that depends on detailed structure of interacting galaxies ($\approx$ a few hundred km/s)

- In the fastest encounters ($v_\infty >> v_f$), stars do not significantly change their positions – **impulse approximation**

- During the not-so-fast encounters, the orbital (kinetic) energy can be transferred to the internal energy (galaxies are not point masses – better described as viscous fluid that absorbs energy when deformed)

Let's first see some N-body model results and then chat a bit more about underlying physics:

NGC 4676: When Mice Collide

Model from Toomre, A. & Toomre, J. 1972, Galactic Bridges and Tails, ApJ, 178, 623

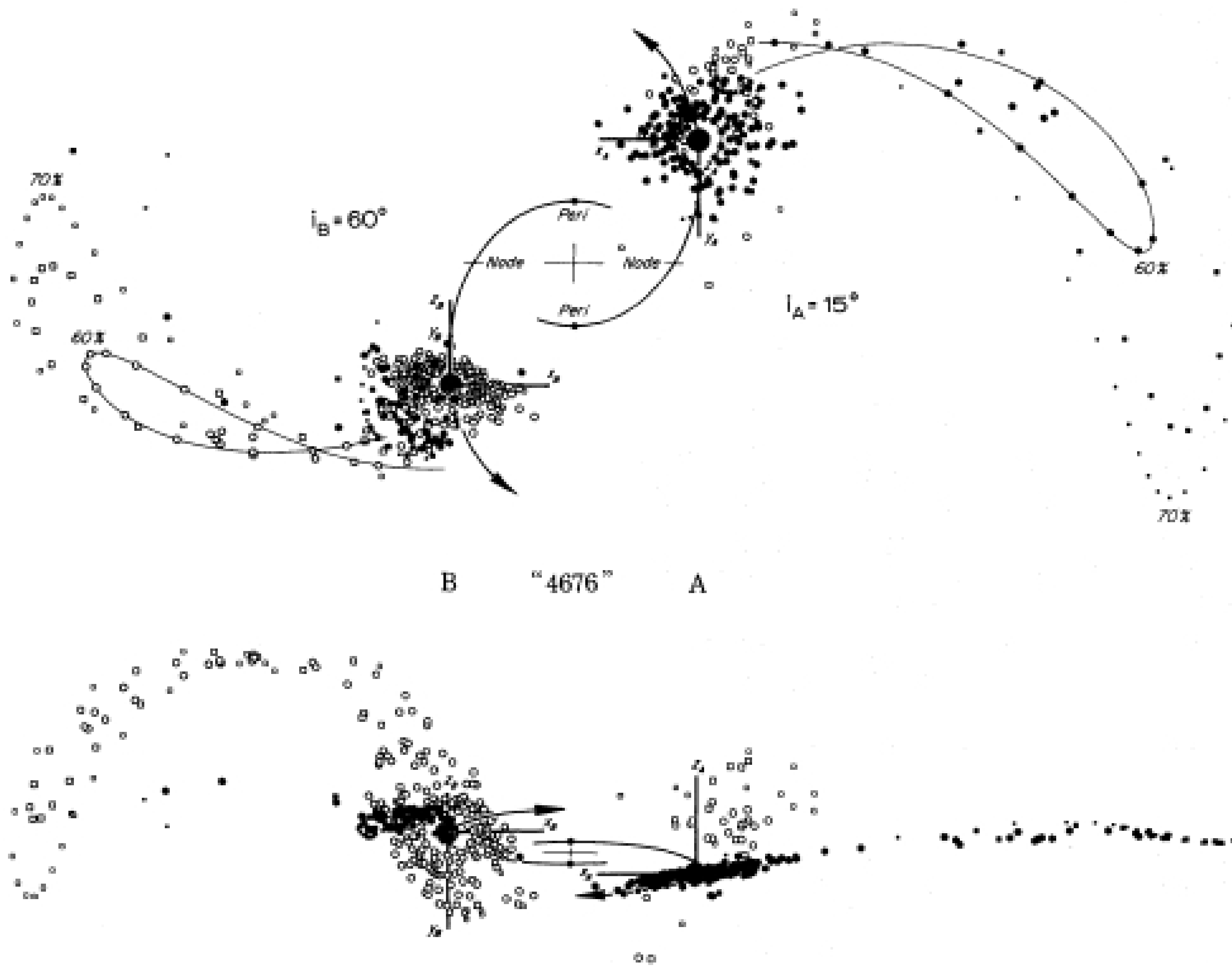
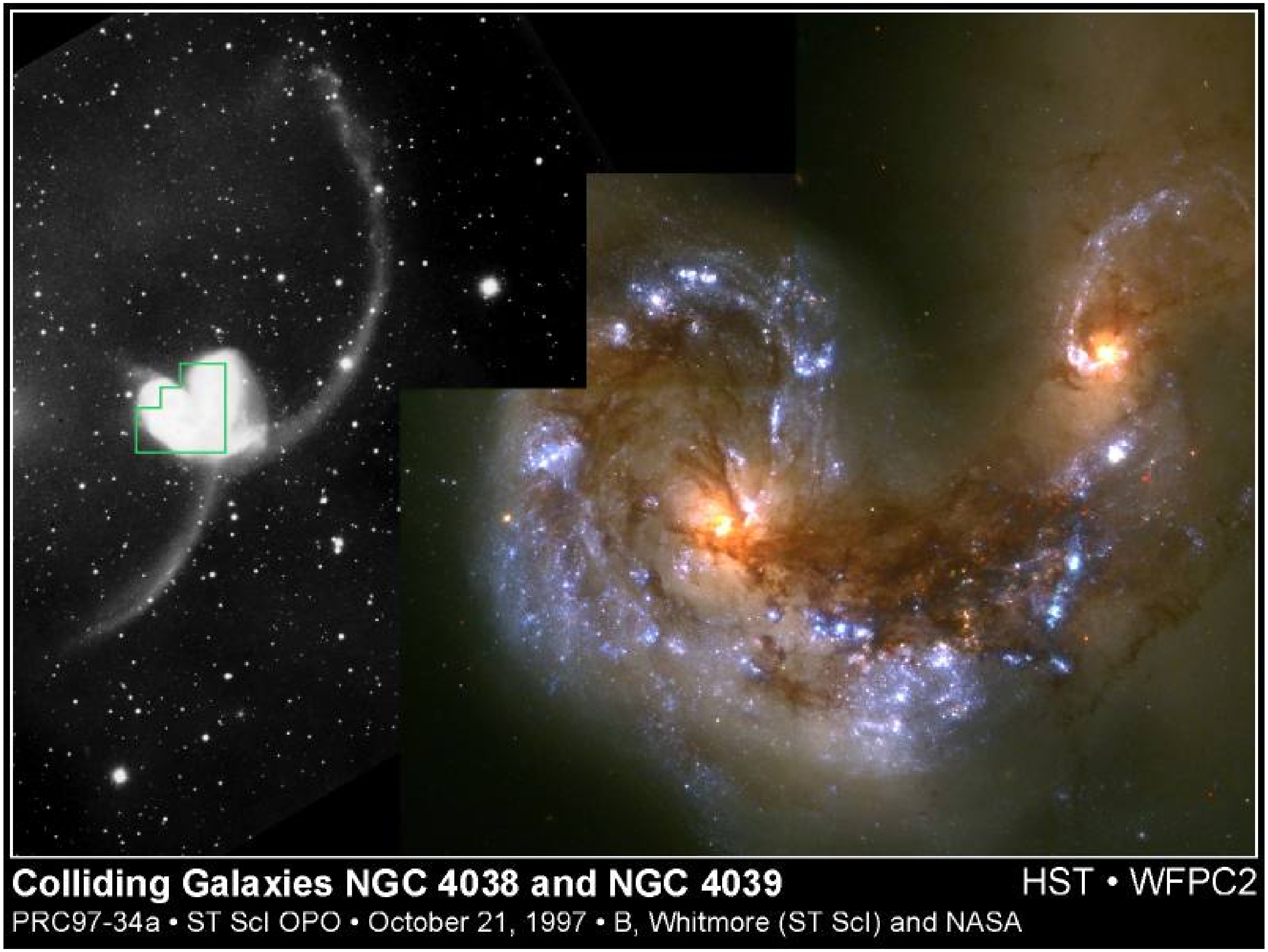
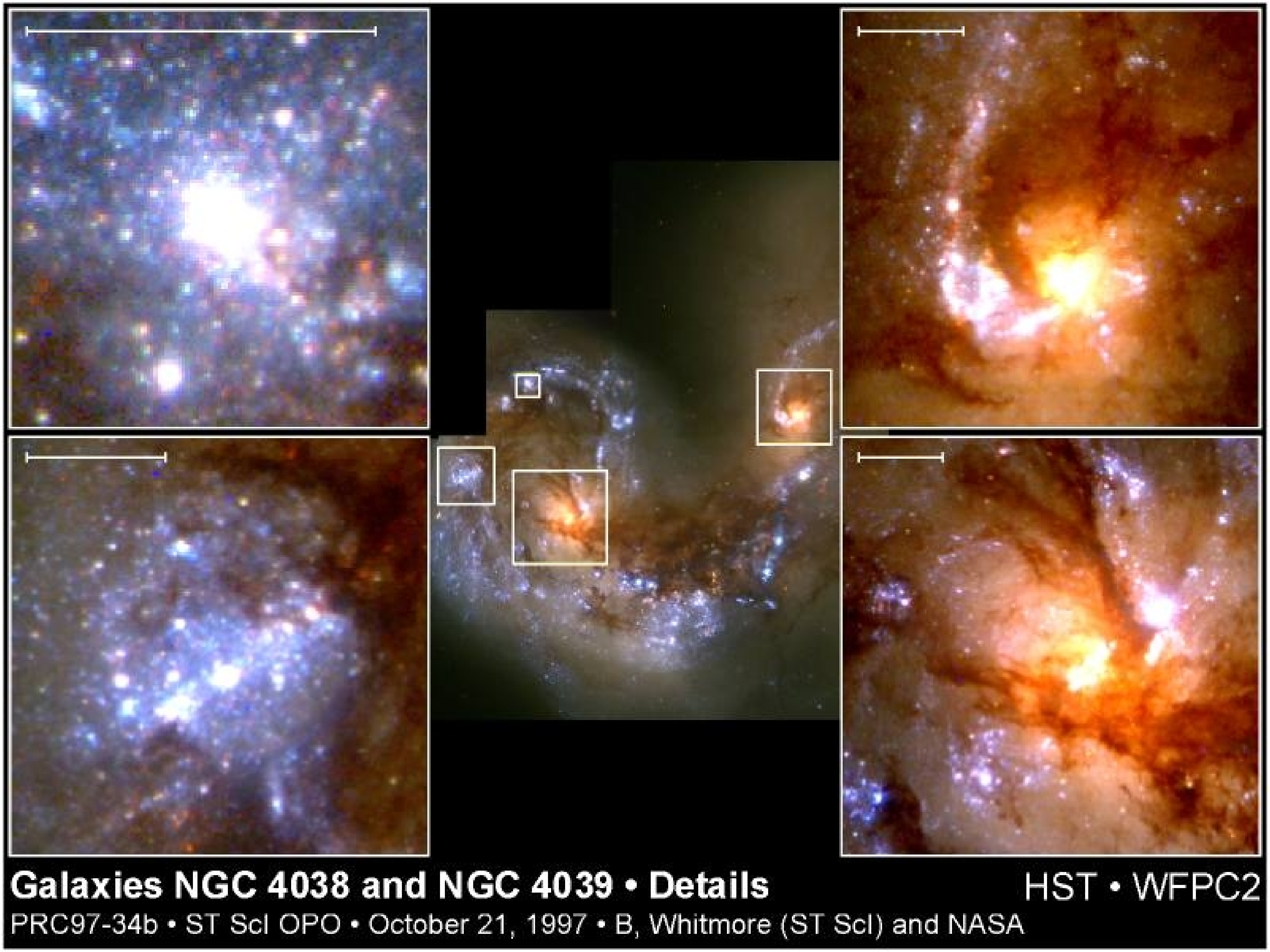


FIG. 22.—Model of NGC 4676. In this reconstruction, two equal disks of radius $0.7R_{\min}$ experienced an $e = 0.6$ elliptic encounter, having begun flat and circular at the time $t = -16.4$ of the last apocenter. As viewed from either disk, the adopted node-to-peri angles $\omega_A = \omega_B = -90°$ were identical, but the inclinations differed considerably: $i_A = 15°$, $i_B = 60°$. The resulting composite object at $t = 6.086$ (cf. fig. 18) is shown projected onto the orbit plane in the upper diagram. It is viewed nearly edge-on to the same—from $\lambda_A = 180°$, $\beta_A = 85°$ or $\lambda_B = 0°$, $\beta_B = 160°$—in the lower diagram meant to simulate our actual view of that pair of galaxies. The filled and open symbols distinguish particles originally from disks A and B, respectively.



Another example: Antennae Galaxy


Galaxies NGC 4038 and NGC 4039 • Details
HST • WFPC2
PRC97-34b • ST ScI OPO • October 21, 1997 • B, Whitmore (ST ScI) and NASA

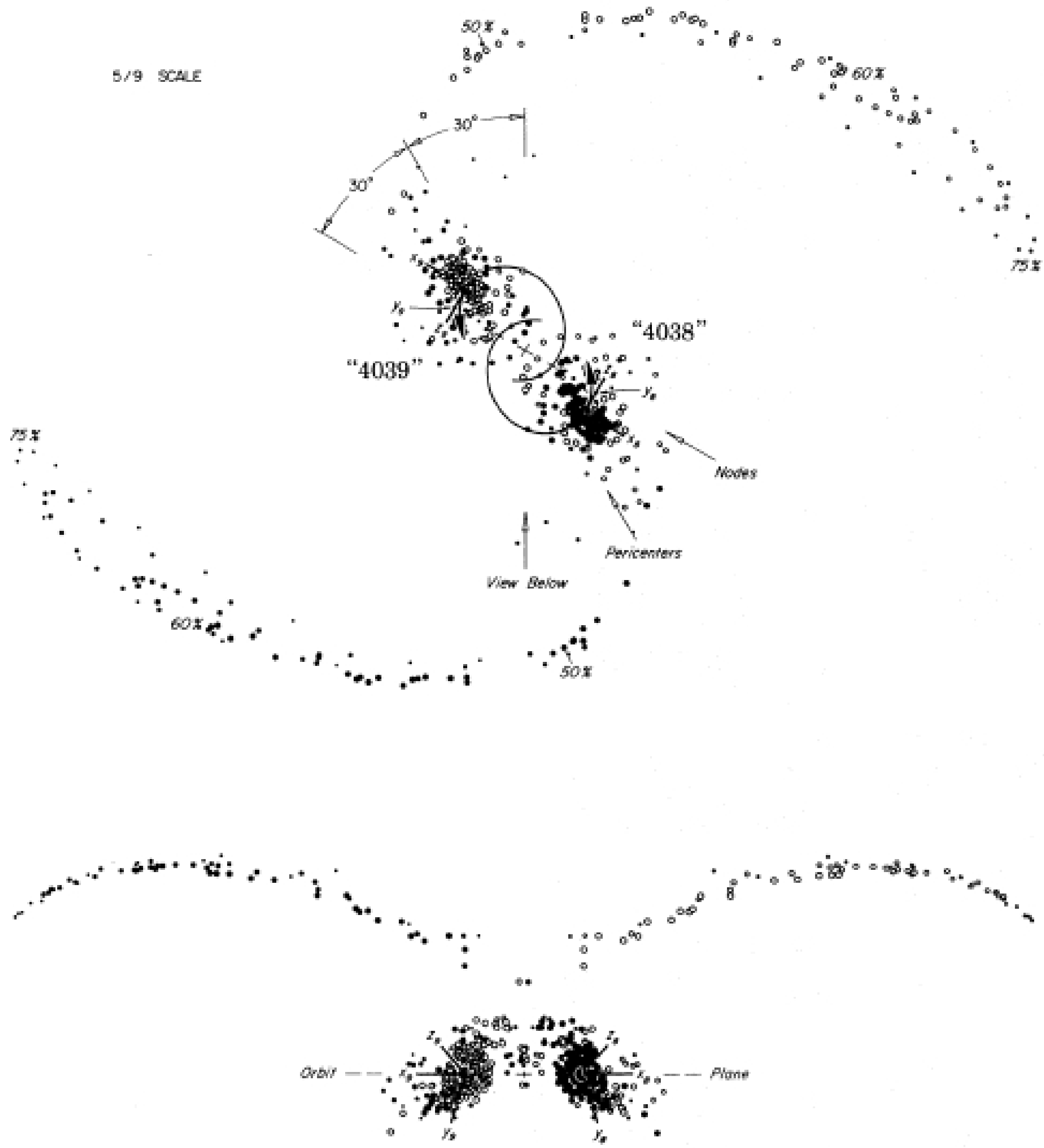


FIG. 23.—Symmetric model of NGC 4038/9. Here two identical disks of radius $0.75R_{\min}$ suffered an $e \approx 0.5$ encounter with orbit angles $i_8 = i_9 = 60°$ and $\omega_8 = \omega_9 = -30°$ that appeared the same to both. The above all-inclusive views of the debris and remnants of these disks 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.

Fast Galaxy Encounters

- Impulse approximation: the potential energy doesn't change during the encounter, but the internal kinetic energy changes by, say, ΔK. This change of the kinetic (and total) energy takes the system out of virial equilibrium! What is the final equilibrium state? (before the encounter: $E = E_o$ and $K = K_o$, with $E_o = -K_o$)

- After the encounter, and before returning to the equilibrium: $K_1 = K_o + \Delta K$ $(= -E_o + \Delta K)$ and $E_1 = E_o + \Delta K$ (note that it is NOT true that $E_1 = -K_1$).

- After returning to the equilibrium: $E_2 = E_1$, and it must be true that $K_2 = -E_2$ because of virial theorem. Hence, $K_2 = -E_1 = -E_o - \Delta K = K_1 - 2\Delta K$! During the return to virial equilibrium, the system loses $2\Delta K$ of kinetic energy (which becomes potential energy because energy is conserved). Therefore, the (self-gravitating) system **expands**!

Slow Galaxy Encounters

- Need N-body numerical simulations for the full treatment
- In a special case when galaxies are very different in size, analytic treatment is possible to some extent
- Dynamical friction: a compact body of mass M (small galaxy) passes through a population of stars with mass m (large galaxy). The net effect is a steady deceleration parallel to the velocity vector (just like ordinary friction). For small speed of the impactor (compared to the internal velocity dispersion), the deceleration is proportional to speed, for large speeds to the inverse squared speed (c.f. Chandrasekhar dynamical friction formula).