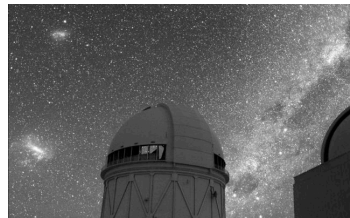


Astronomy 303

Our Neighbourhood: The Local Group and Surroundings

1. The Local Group members
2. Spirals and satellites
3. The importance of tides
4. Hierarchical Formation
5. The Fate of the Local Group



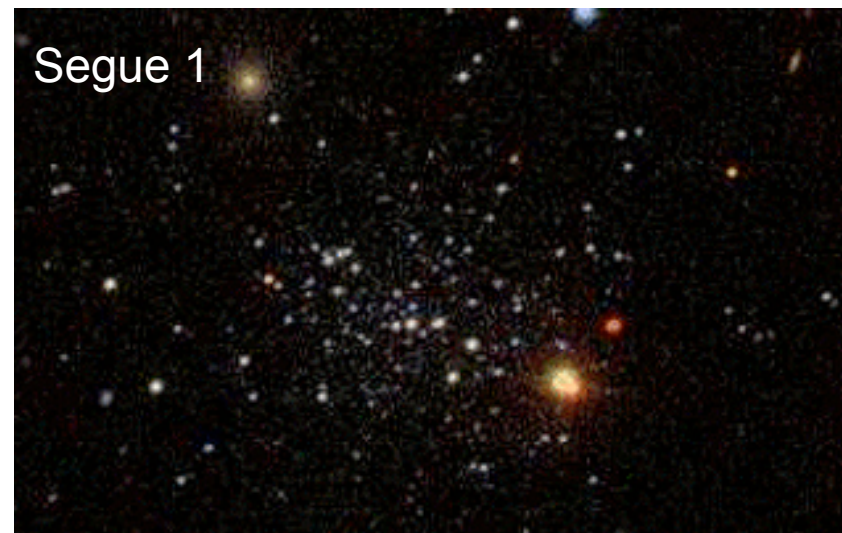
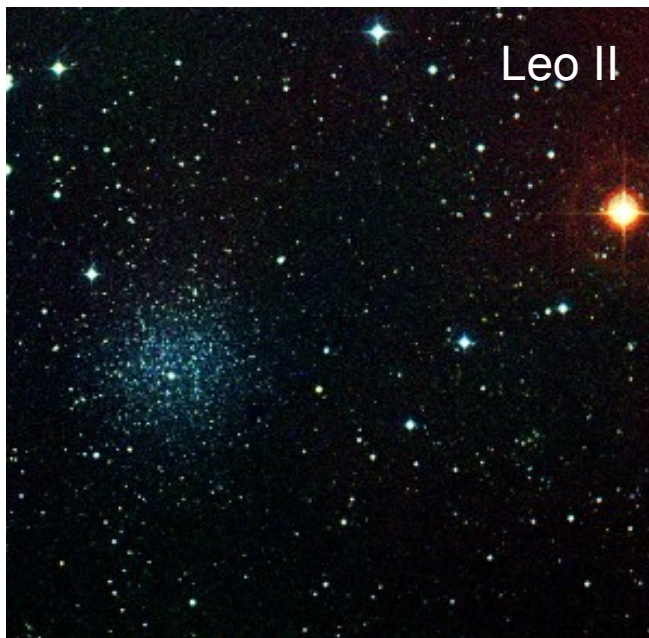
Members of the Local Group

- These are the main members of the Local Group. Newest members are missing : the “ultra-faint” dwarf companions of the Milky Way



Ultra-Faint Galaxies

- Latest estimates (after the book was published) suggest that the Milky Way may be surrounded by hundreds of yet undetected satellites.
- Indeed, the Sloan Digital Sky Survey has made possible the discovery of several of these objects
- These systems are so faint that only the ones nearest to the Sun can be found in current surveys—the “ultra-faint satellites” of the Milky Way
 - Some are so faint that if one single star became a red giant the luminosity of the whole galaxy would double!
- Here are some examples:

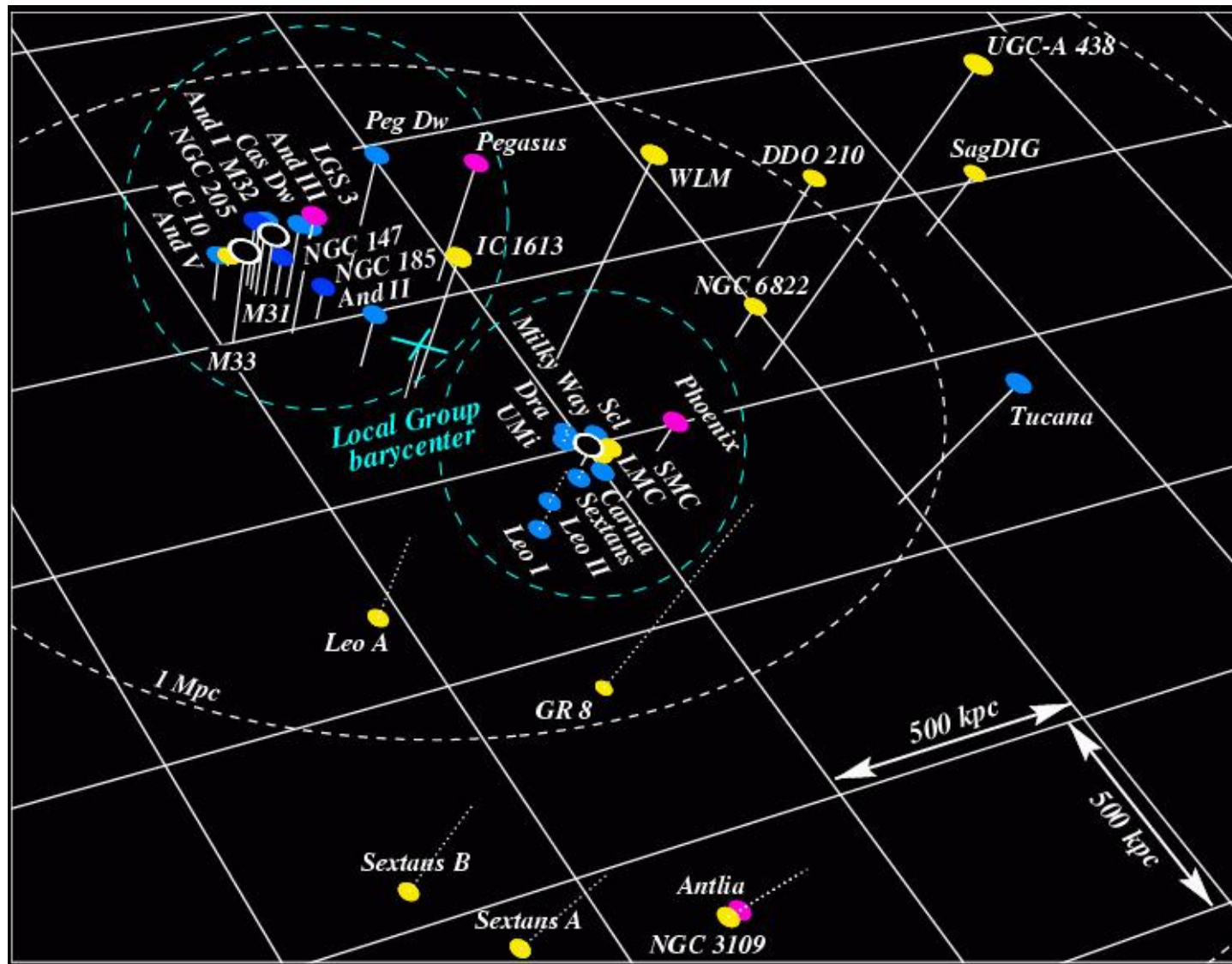


CDM substructure: the
sites of dwarf galaxy
formation?



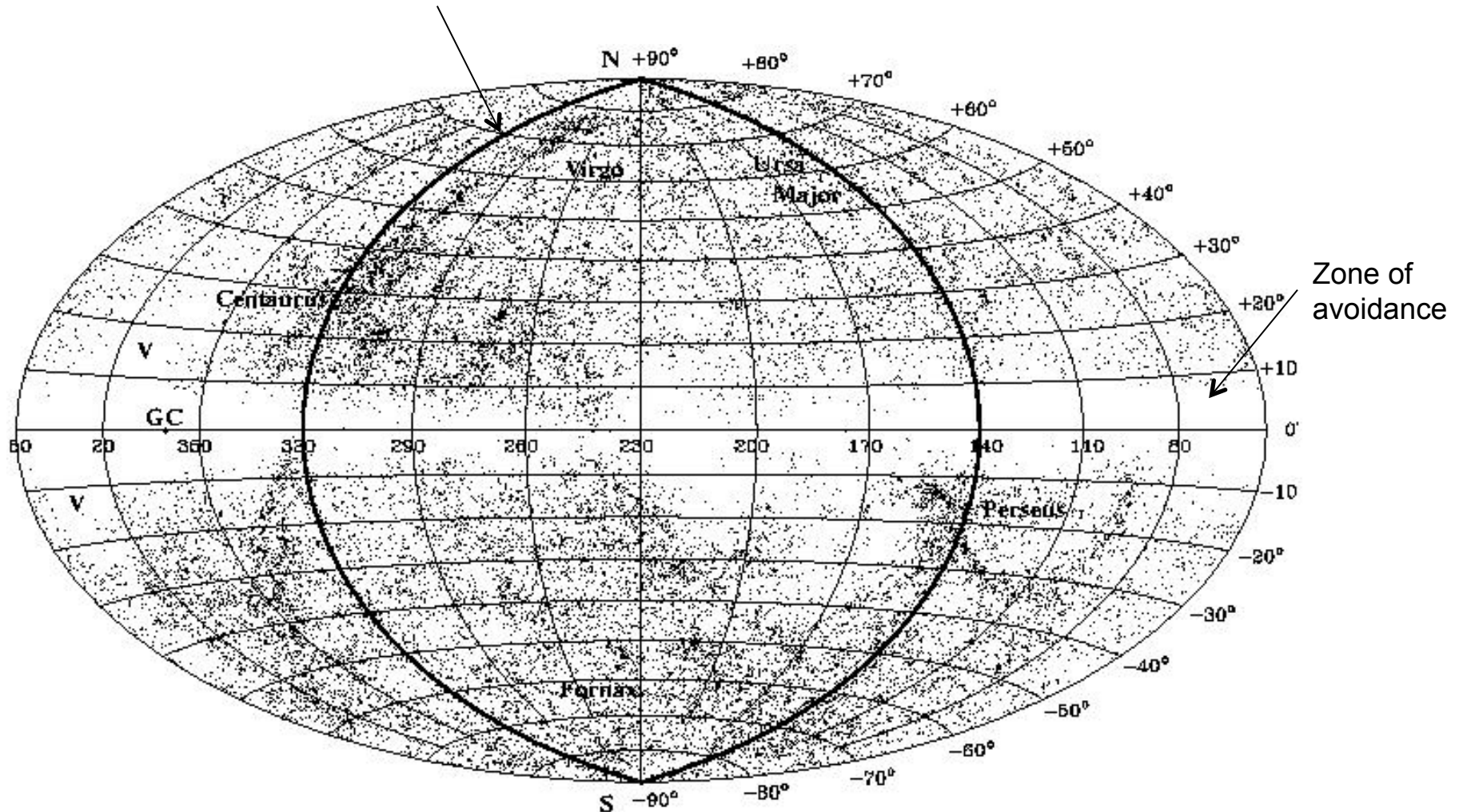
A 3D-view of the Local Group

- Galaxies **cluster**: most dwarf satellites inhabit the vicinity of the two giant spirals, M31 (Andromeda) and the Milky Way (MW)



Beyond the Local Group

- The large-scale distribution of galaxies is highly inhomogeneous. Most galaxies around the Local Group are roughly in a 2D “sheet” called the SuperGalactic Plane



The Magellanic Clouds

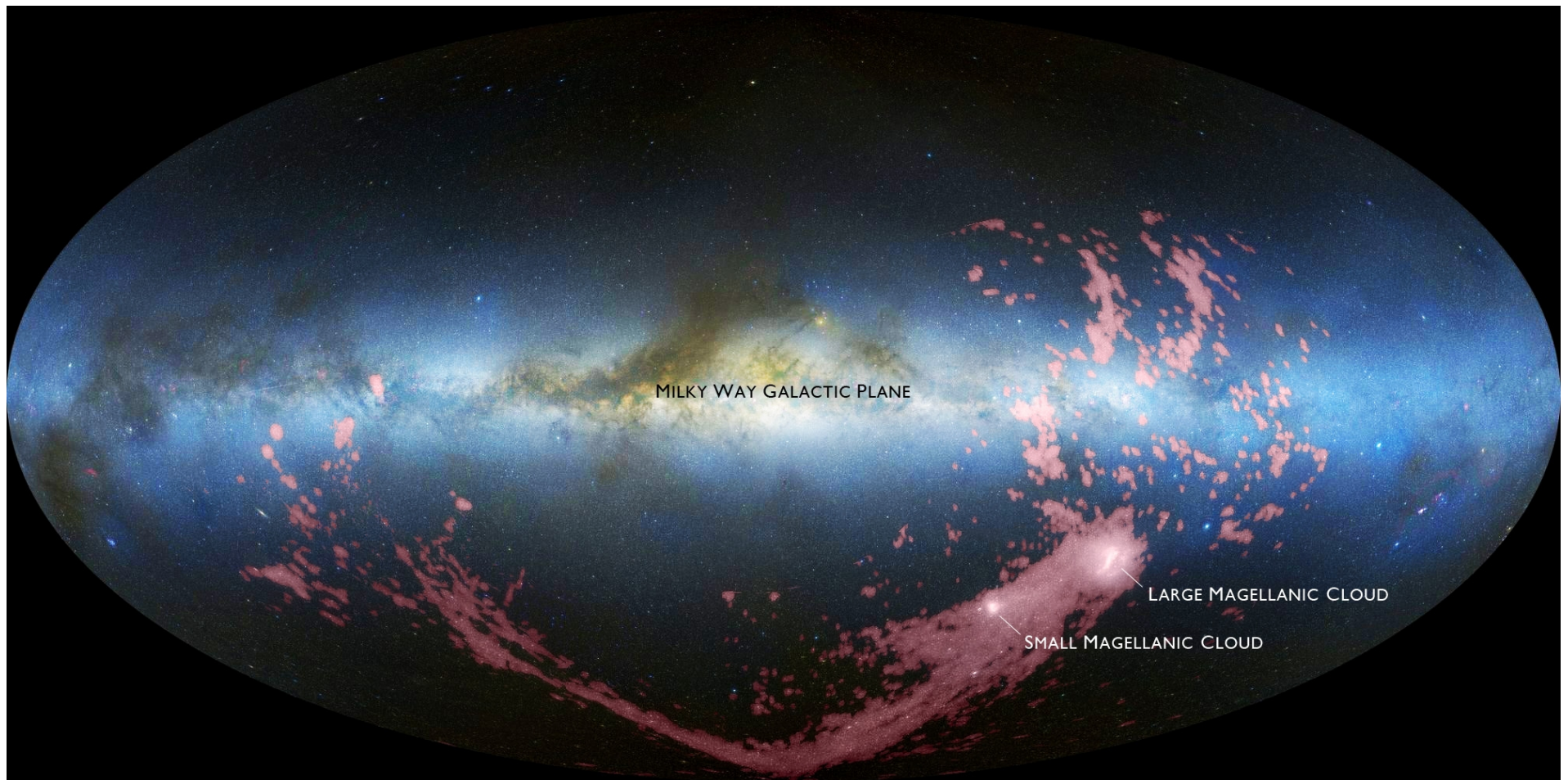
- The Large Magellanic Cloud (LMC): a small galaxy actively-forming stars, at about 50kpc from the Milky Way. Forms a pair with the Small Magellanic Cloud (SMC). Near the pericenter of their orbit around the Milky Way



Comet McNaught seen from Patagonia

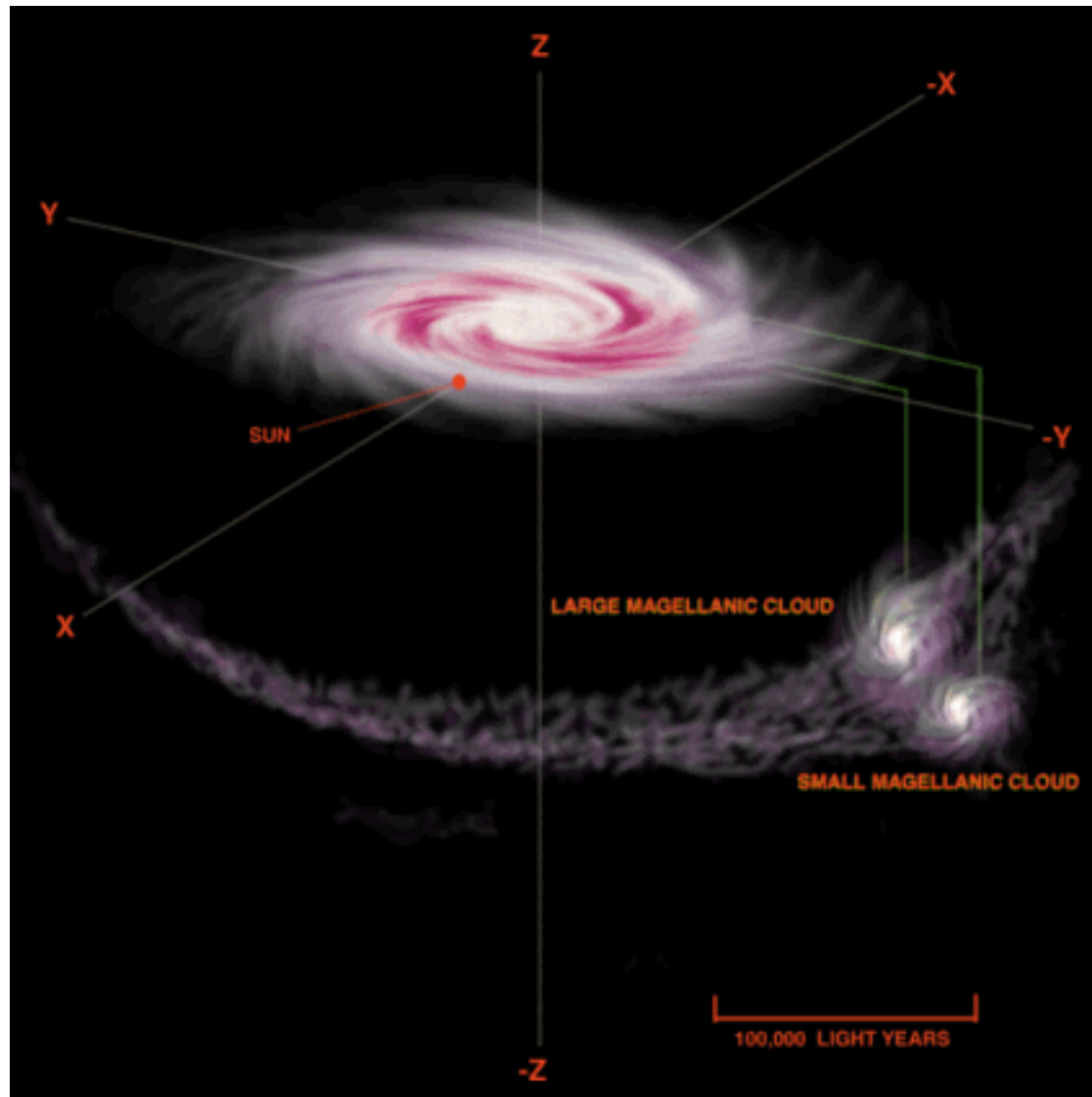
The Magellanic Stream

- The best evidence for interaction between the LMC and the SMC is the presence of the Magellanic Stream. Theories about the origin of the stream are still evolving. Both the orbit, the extent of the stream, the morphologies of the arms are being constantly revised—even as recently as 2010!



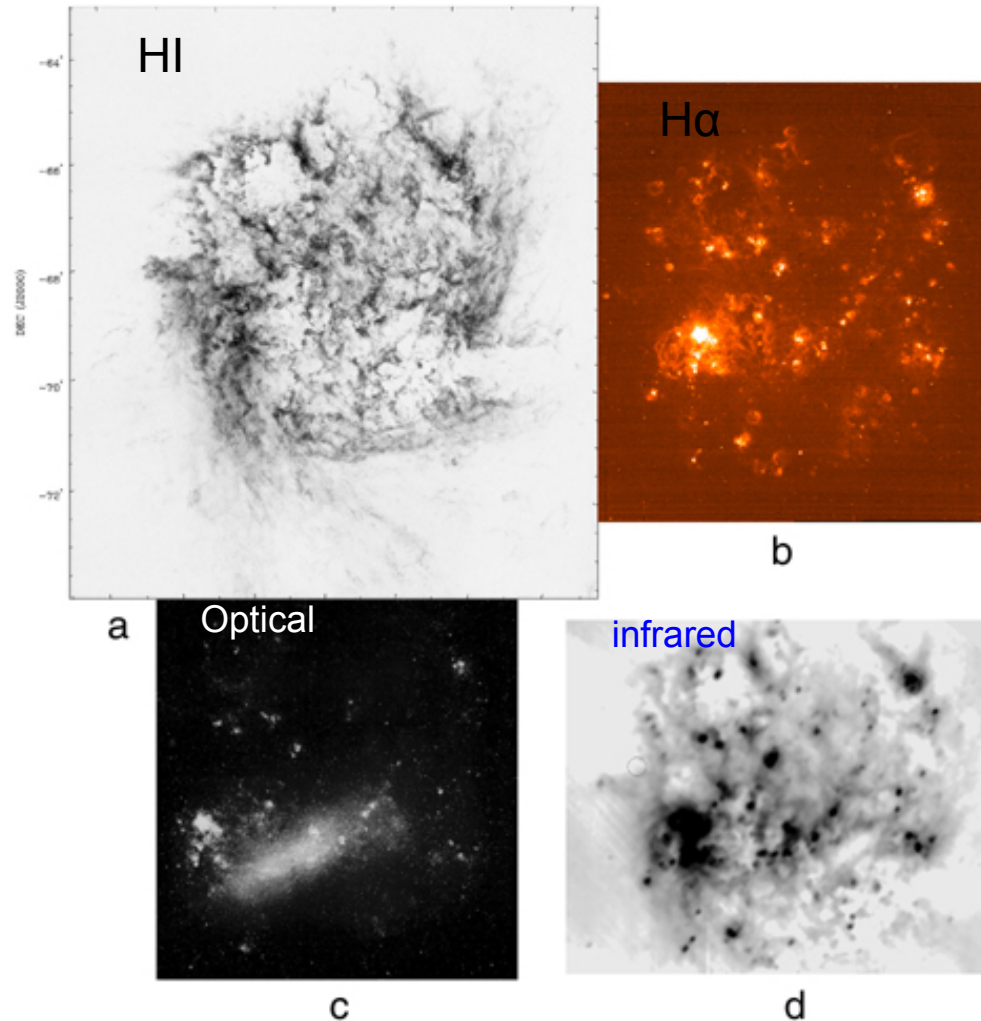
The Magellanic Stream

- The best evidence for the interaction between the LMC and the SMC is the presence of the Magellanic Stream



The Large Magellanic Cloud

- The Large Magellanic Cloud (LMC): a small galaxy actively-forming stars, at about 50kpc from the Milky Way. An inclined, thin rotating disk of stars with a prominent bar, lots of gas and dust, and HII (ongoing star-forming) regions.



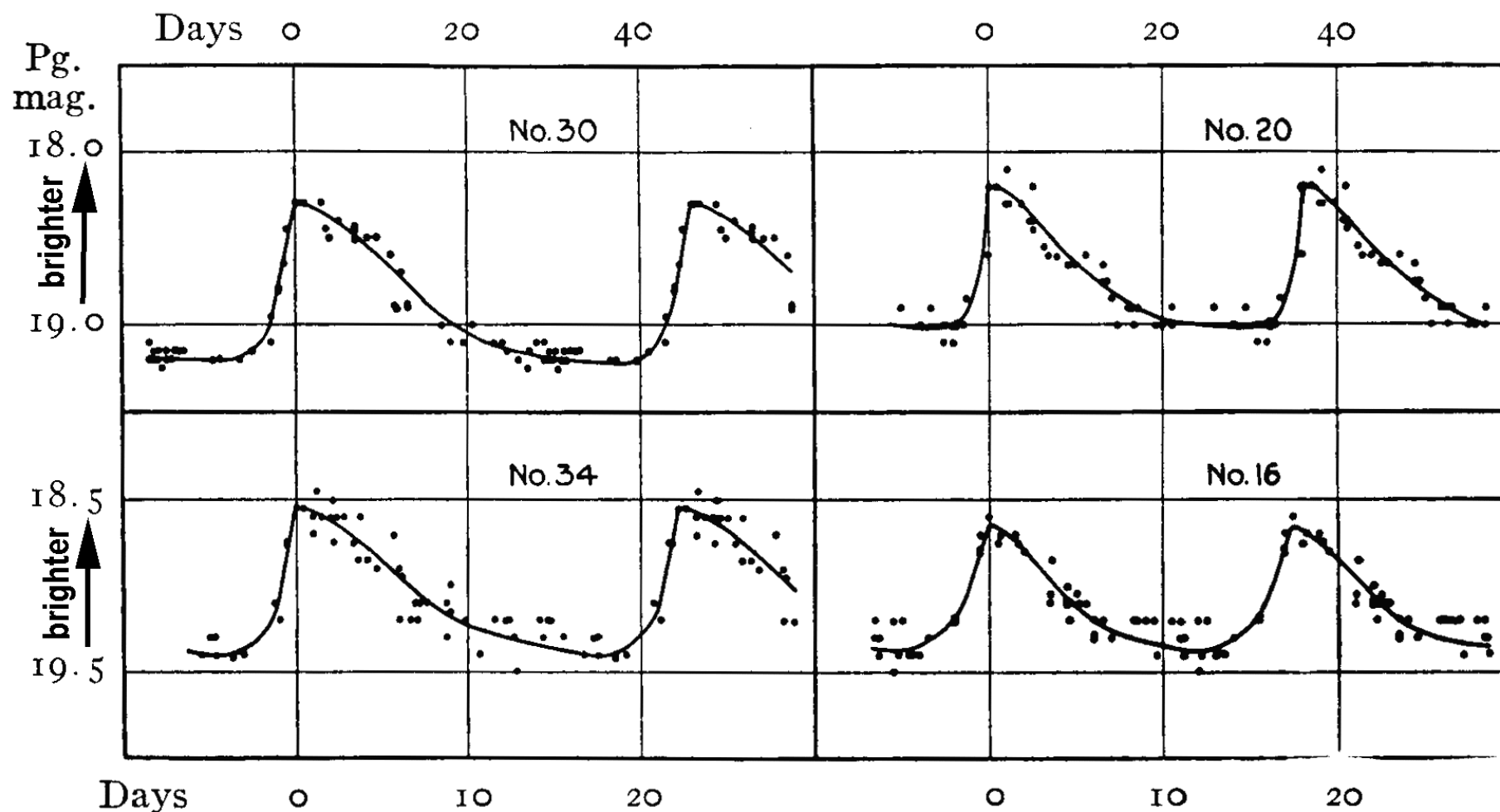
The Small Magellanic Cloud

- The Small Magellanic Cloud (LMC): also actively-forming stars, fainter and a bit further than the LMC from the Milky Way. Prolate, end-on inclined “cigar” with no obvious sense of rotation.



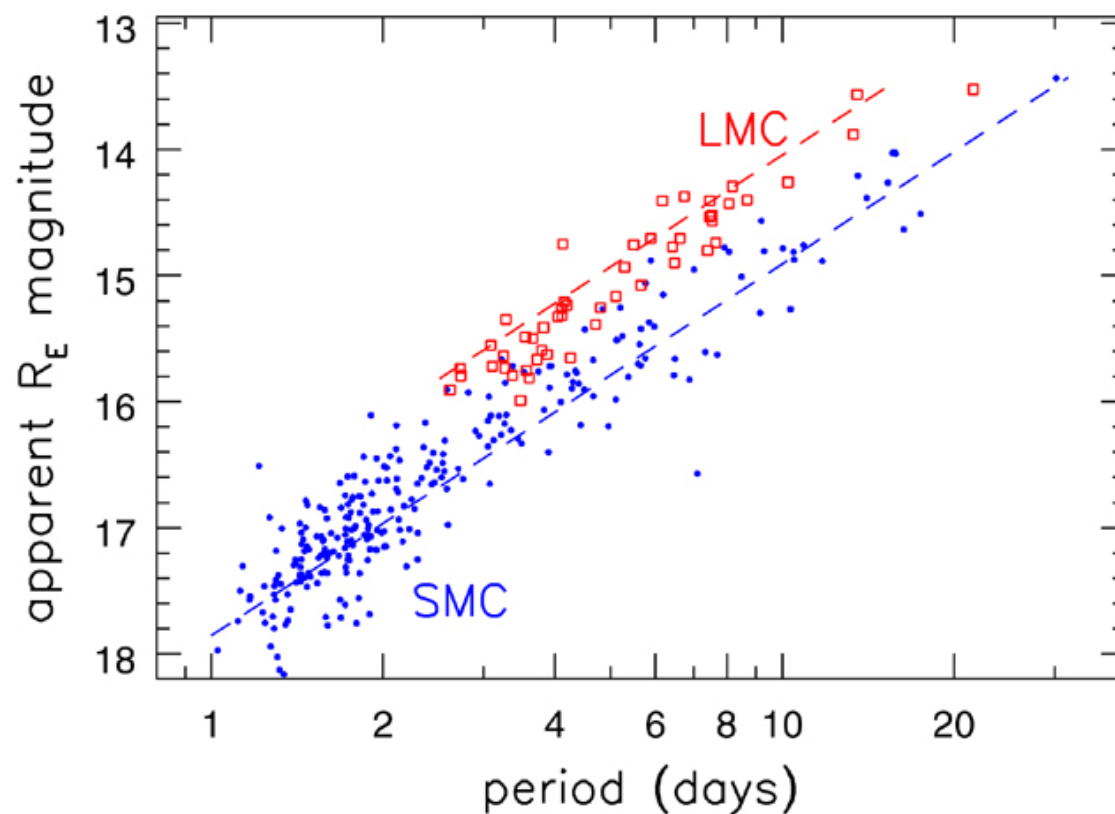
Cepheids in the Magellanic Clouds

- The Magellanic Clouds were instrumental in developing our best distance estimator for extragalactic objects—the Cepheid period-luminosity relation



Cepheids in the Magellanic Clouds

- The Magellanic Clouds were instrumental in developing our best distance estimator for extragalactic objects—the **Cepheid period-luminosity relation**
- Henrietta Leavitt measured them on photographic plates and started the whole field of *distance estimation from standard candles*
- History is fraught with examples of why the use of *secondary* distance estimators is fraught with peril



The Andromeda Galaxy

- Messier 31 is more luminous ($\sim 1.5x$) than the Milky Way. Its gas rotates more rapidly about the center than the MW (250 km/s). There are recent revisions to the MW rotation speed that may change that!). It has a more prominent bulge and roughly twice as many satellites as the MW. One of its satellites (M32) is the only elliptical galaxy in the nearby Universe (albeit a faint one)



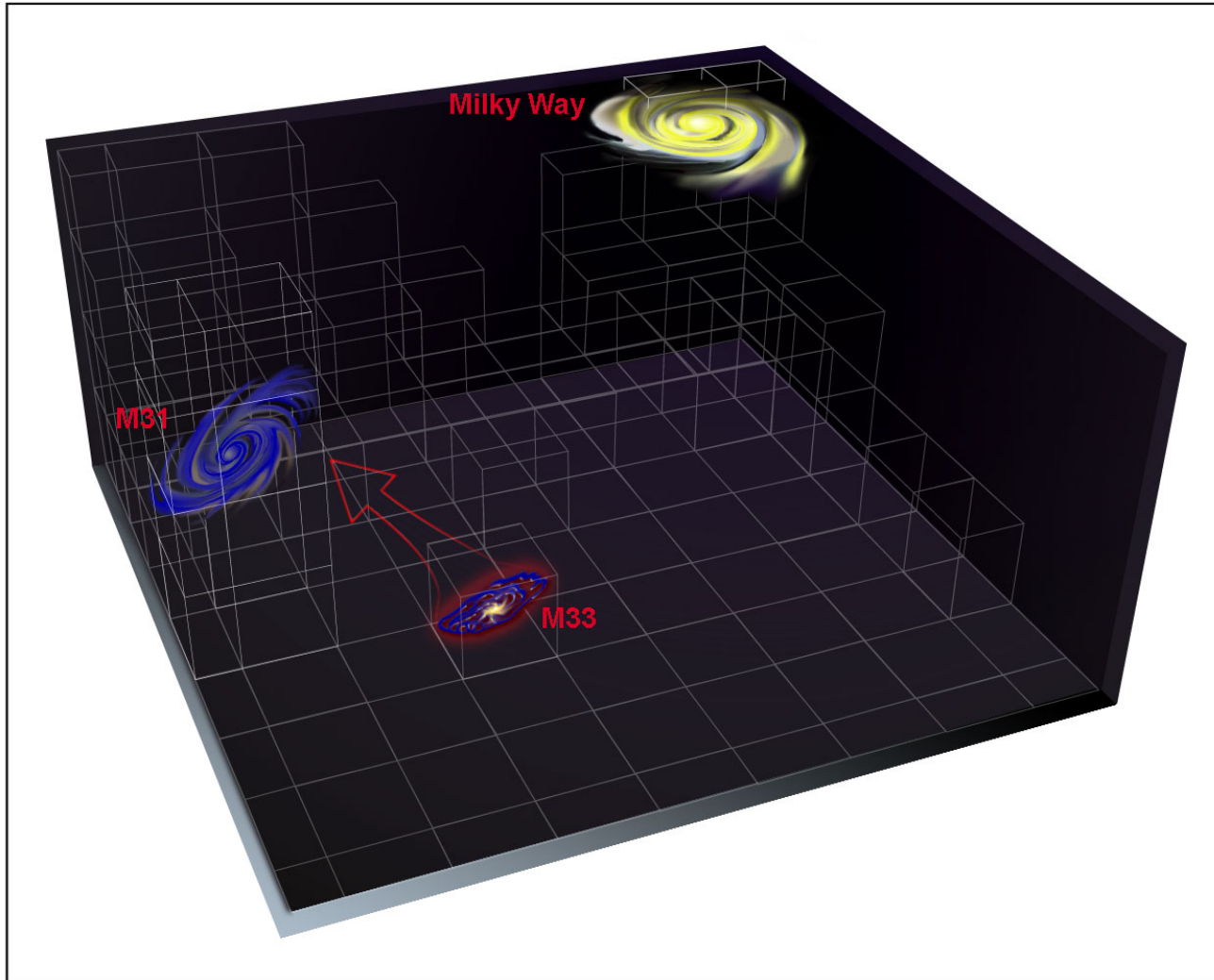
The Andromeda and Triangulum Galaxies

- Messier 31 and 33 form a bound pair of galaxies. Recent *proper motion* measurements of masers in M33 have allowed measurement of its *transverse* motion on the sky. This is an astonishing measurement, made possible by the VLBA array of radio telescopes.



The Andromeda and Triangulum Galaxies

- Messier 31 and 33 form a bound pair of galaxies. Recent *proper motion* measurements of **masers** in M33 have allowed measurement of its *transverse* motion on the sky. This is an astonishing measurement, made possible by the VLBA array of radio telescopes.



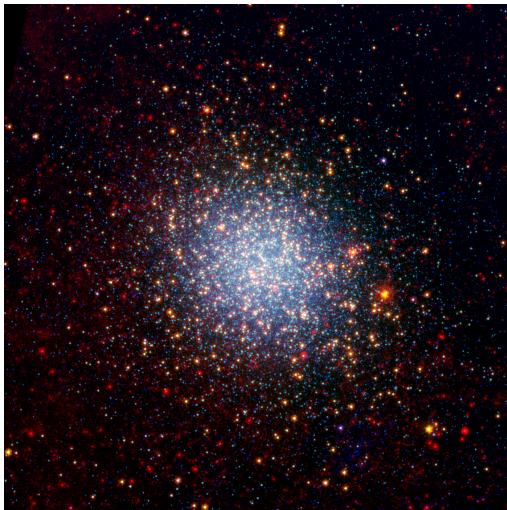
The Triangulum Galaxy

- Messier 33 (the Pinwheel Galaxy) was long thought to be a “pristine” disk galaxy, with no bulge, no halo, and an undisturbed disk component.



The Triangulum Galaxy

- Evidence for a previous encounter between M31 and M33 is, however, emerging. Most compelling evidence comes from the warp in the HI disk and from the appearance of its outer stellar halo
- M33 also has a nuclear star cluster, which many astronomers believe it may be the analog of some of the most massive globular clusters in our galaxy, like ω Centauri



omega Centauri



The PAndAs Survey
PI: Alan McCannachie (HIA)

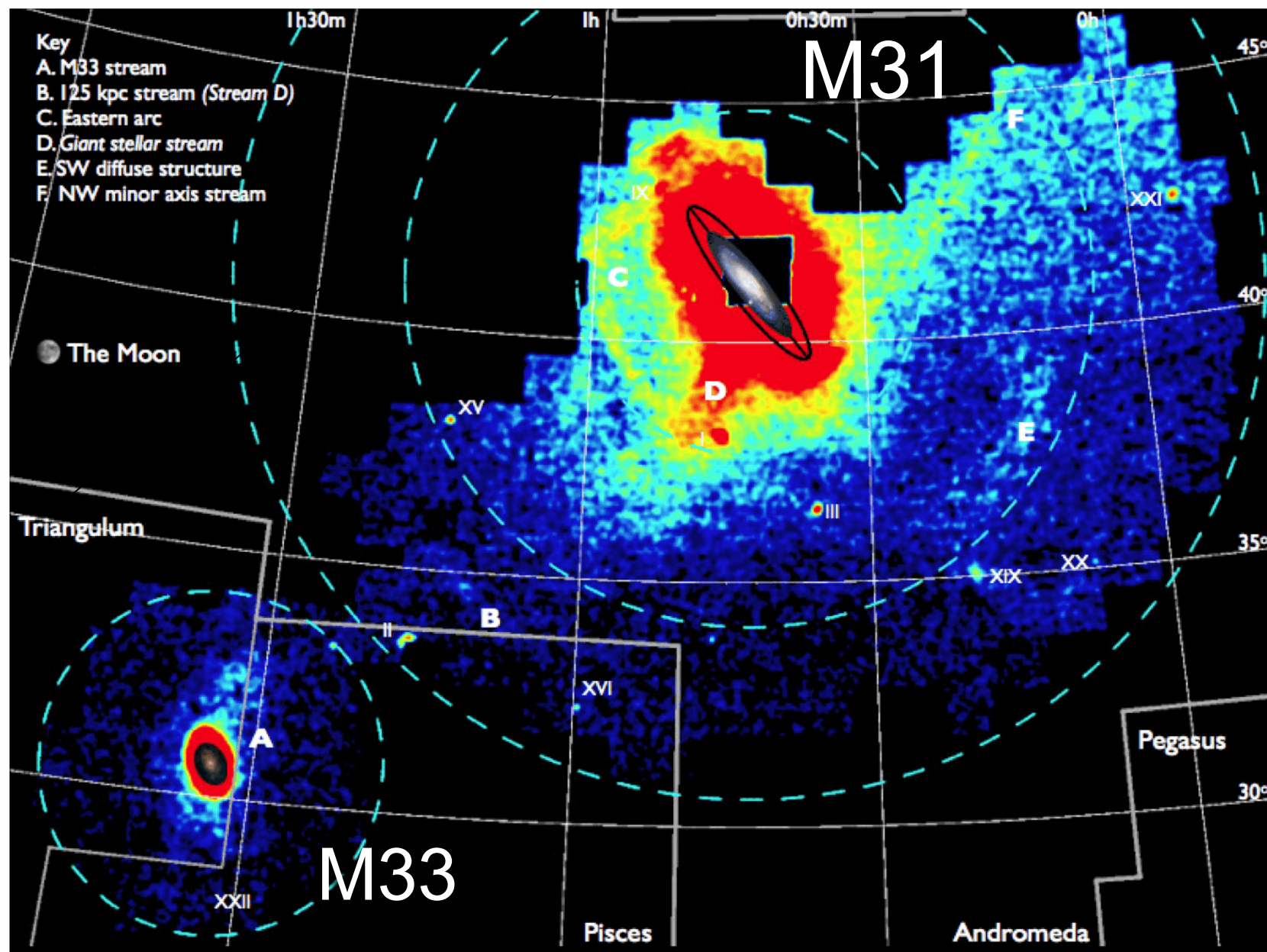
M31



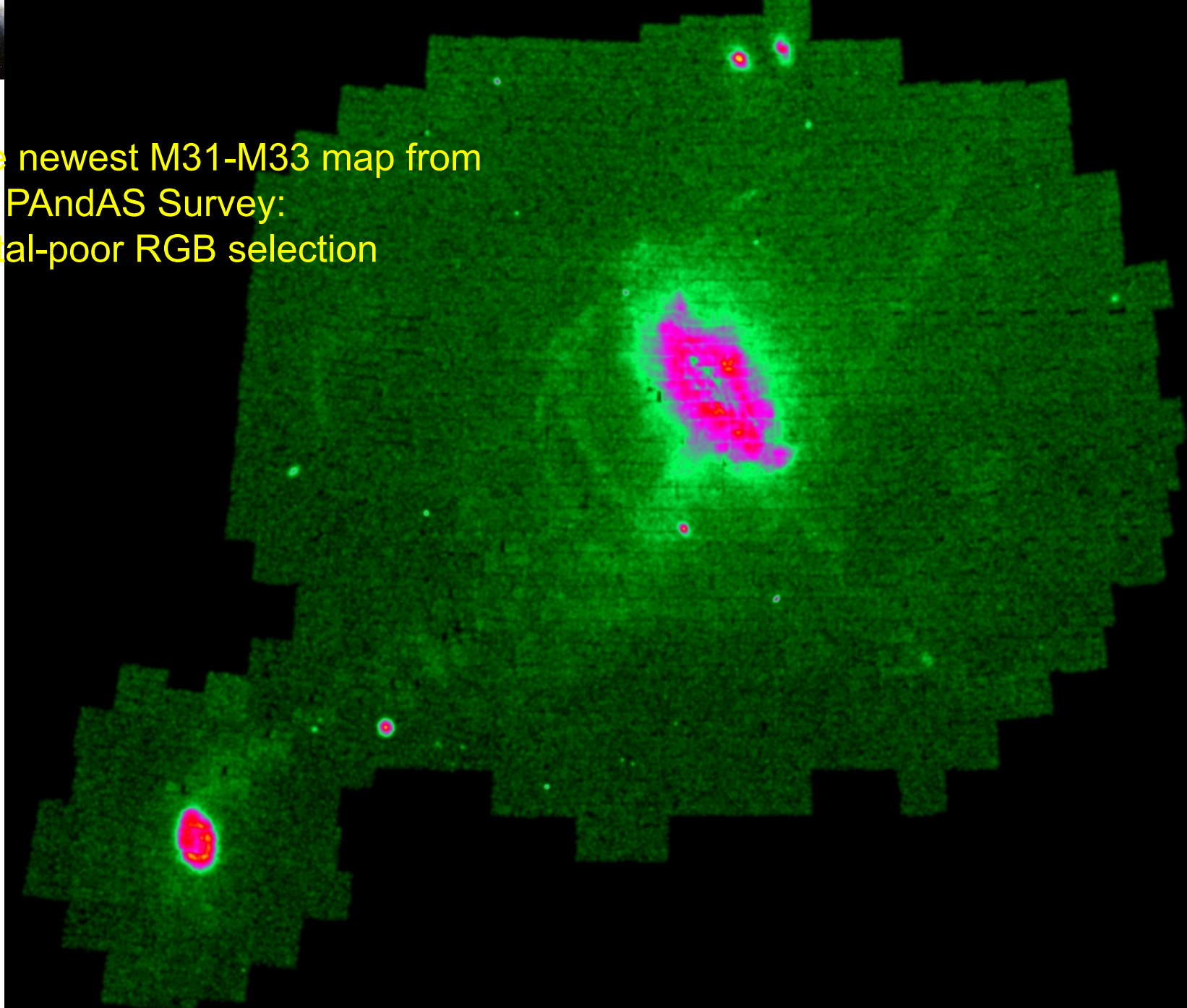
200 kpc



M33



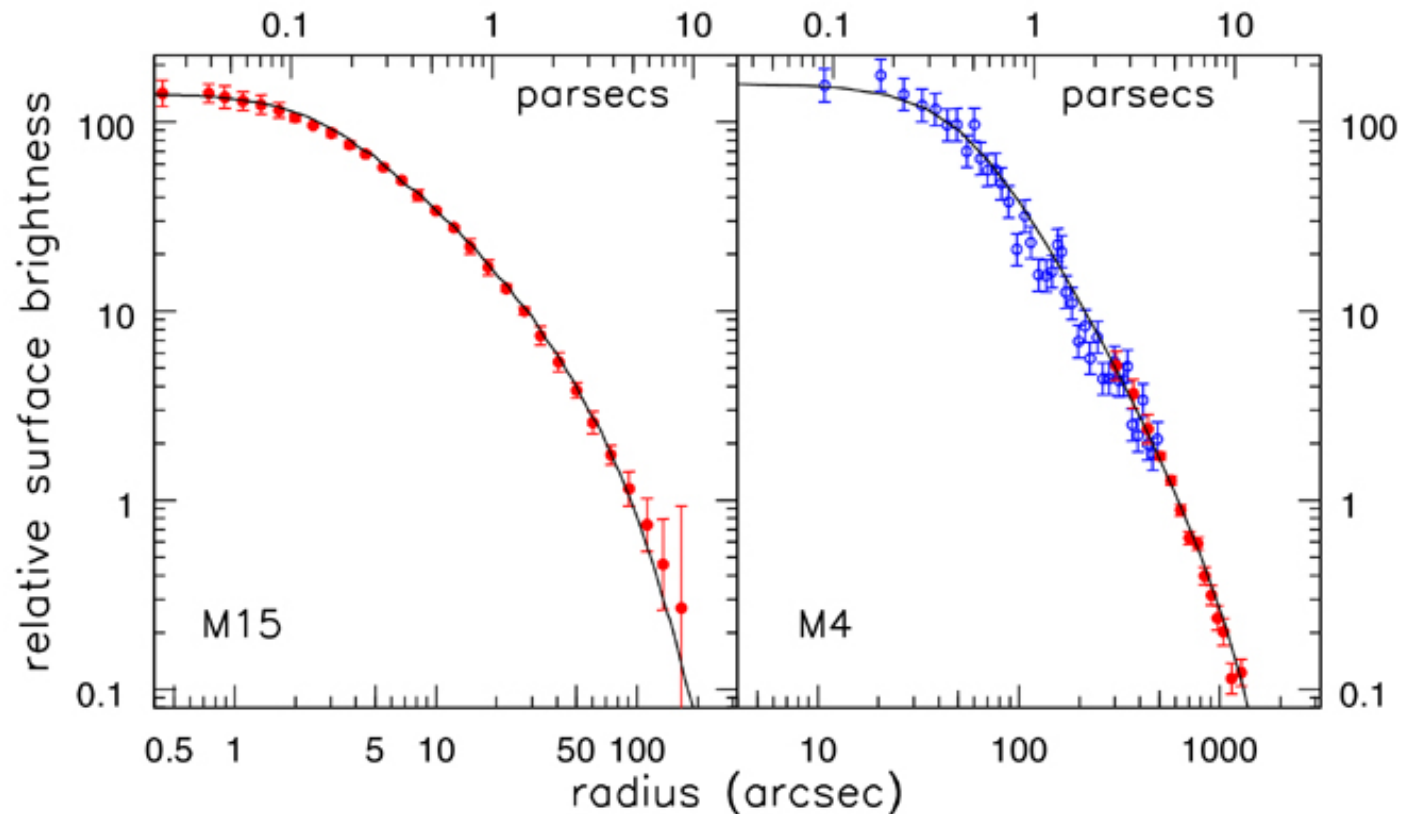
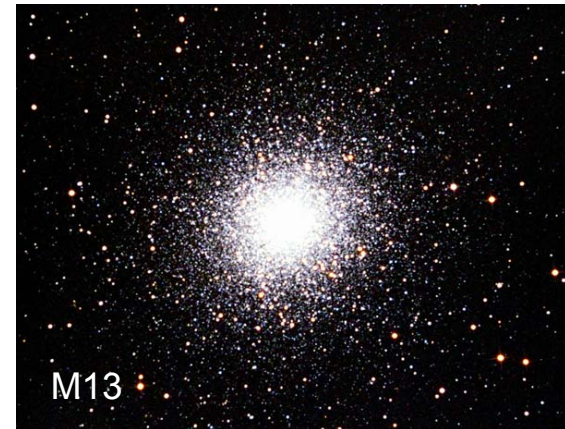
The newest M31-M33 map from
the PAndAS Survey:
metal-poor RGB selection



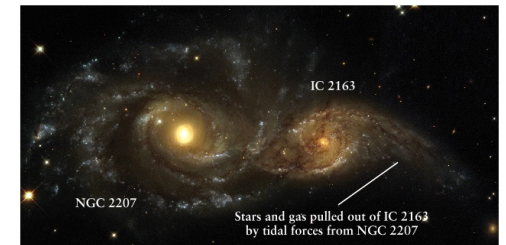
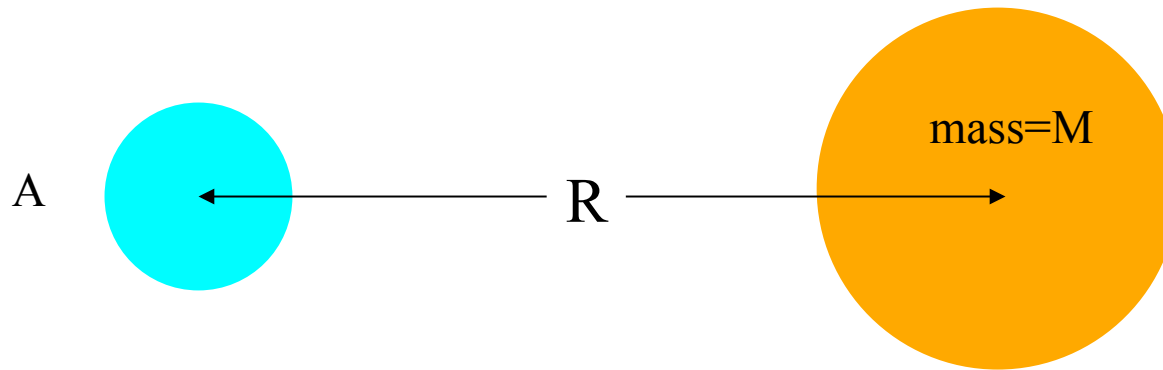


The Importance of Tides

- The sharp outer “cutoff” in the surface brightness profile of globular clusters is usually attributed to the effect of tides, which remove loosely-bound stars from the outskirts of the cluster



The Importance of Tides



- One simple example considers the orbits of stars in a system made of two objects locked in a **circular** orbit.
- In such cases, the potential is static in a **rotating frame of reference** that turns with the angular speed of the objects
- The equations of motion of a star in such non-inertial reference frame are

$$\ddot{\mathbf{r}} = -\nabla\Phi - 2(\boldsymbol{\Omega}_b \times \dot{\mathbf{r}}) - \boldsymbol{\Omega}_b \times (\boldsymbol{\Omega}_b \times \mathbf{r}),$$

including the familiar Coriolis and “centrifugal” forces

- If we take the dot product of this with $\dot{\mathbf{r}}$ we see that the resulting equation may be written as

$$\frac{dE_J}{dt} = 0,$$

The Importance of Tides

- The quantity E_J is called the “Jacobi integral”

$$E_J \equiv \frac{1}{2}\dot{\mathbf{r}}^2 + \Phi - \frac{1}{2}|\boldsymbol{\Omega}_b \times \mathbf{r}|^2.$$

- And may be shown to be

$$E_J = E - \boldsymbol{\Omega}_b \cdot \mathbf{L}.$$

- In an rotating potential neither the energy nor the angular momentum is conserved but a combination of the two is.
- We may define an “effective potential”

$$\Phi_{\text{eff}} = \Phi - \frac{1}{2}\Omega_b^2 R^2,$$

- Then the equations of motion are

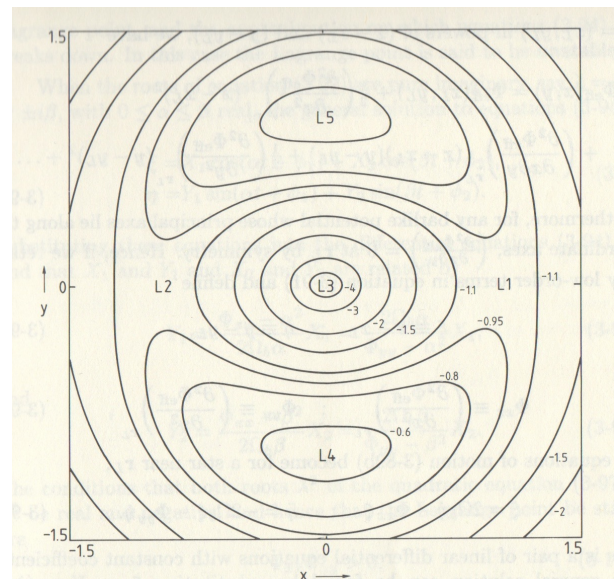
$$\ddot{\mathbf{r}} = -\nabla\Phi_{\text{eff}} - 2(\boldsymbol{\Omega}_b \times \dot{\mathbf{r}}),$$

The Importance of Tides

- And the “Jacobi integral” is

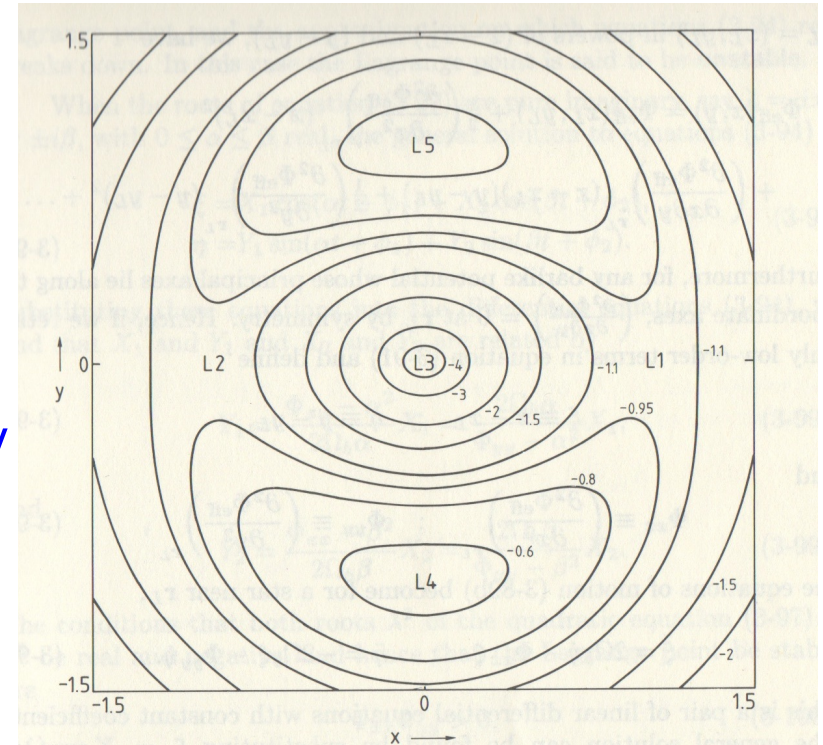
$$E_J = \frac{1}{2}|\dot{\mathbf{r}}|^2 + \Phi_{\text{eff}}.$$

- The surfaces $\Phi_{\text{eff}} = E_J$ are called “zero-velocity surfaces” and regions where $\Phi_{\text{eff}} > E_J$ are forbidden to a bound star.
- This is valid for any rotating reference frame. For example, contour maps for the effective potential of a barred (the bar pattern rotates) galaxy look like this:



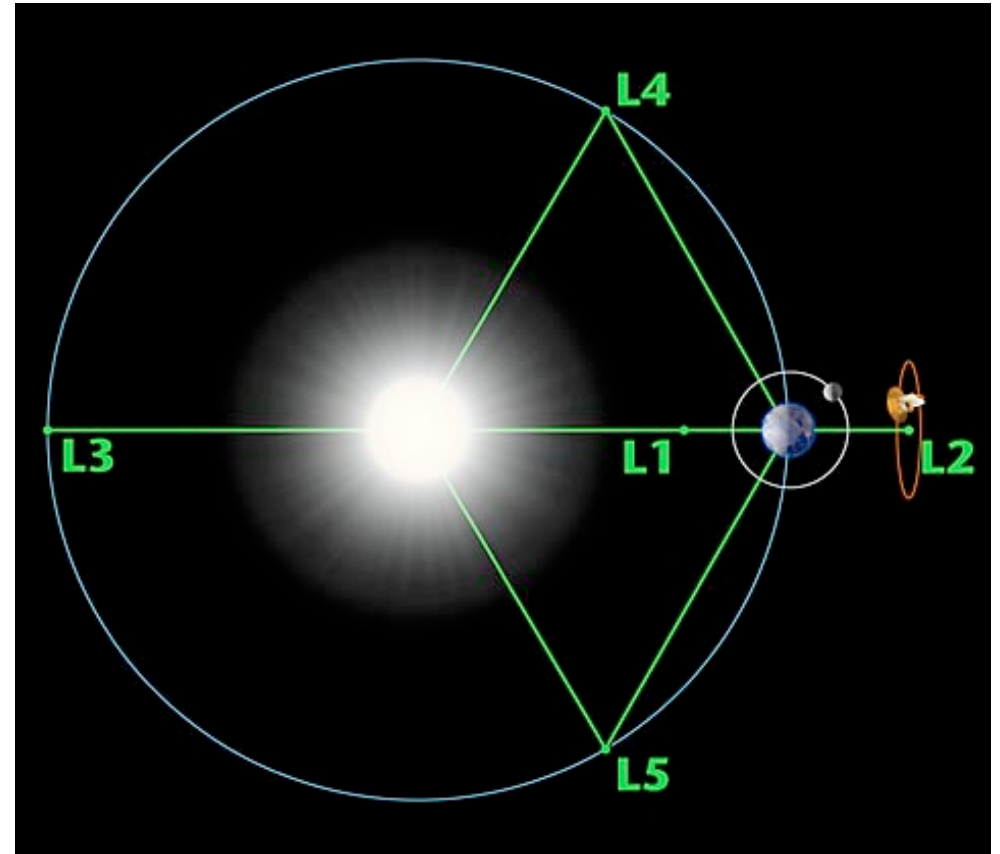
The Lagrange points

- The five stationary points, L1 to L5, are called “**Lagrange points**” for their resemblance to the analogous points that appear in analytic treatments of the restricted three-body problem
- They are the location where the derivatives of the effective potential vanish
- L3 is a minimum of the potential
- L1, L2, L4 and L5 are the points where it is possible for a star to travel on a circular orbit while appearing stationary in the rotating frame
- L4 and L5 are **maxima** of the effective potential
- L1 and L2 are **saddle** points and are unstable---stars originally near L1 or L2 will drift away from their original location
- The stability of L4 and L5 depends on the details of the potential—they can be stable even if they are maxima of the effective potential



Use of the Lagrange points

- L2 is often used to place satellites in orbit, since it “faces” the Sun and is not too far away from Earth.
- The **WMAP** satellite (Wilkinson Microwave Anisotropy Probe) is located at L2.
- Note that the notation sometimes changes ($L1 \Leftrightarrow L3$)!
- Other satellites also orbit at Lagrange points, such as **SOHO** (at L1), **Herschel**, **Planck**, and, in the future, the James Webb Space Telescope (**JWST**), and **GAIA**.



Tidal Radii

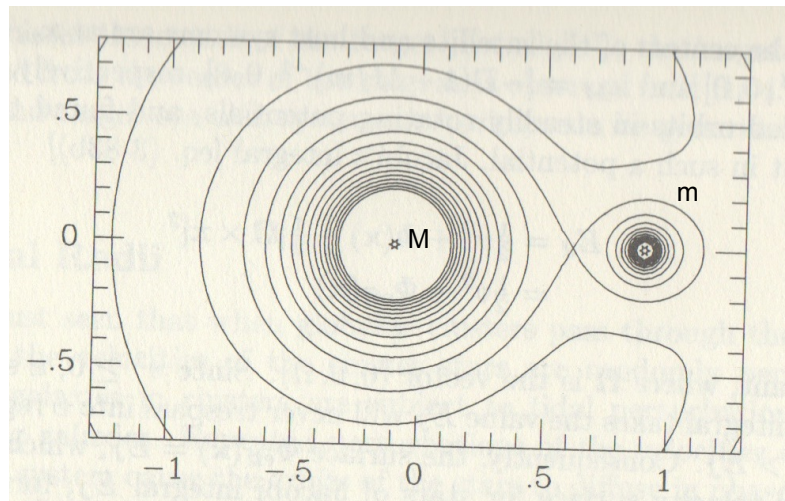
- For a potential given by two spherical masses M and m on a circular orbit and separated by a distance D , the angular speed is

$$\Omega = \sqrt{\frac{G(M + m)}{D^3}}.$$

- And Jacobi's integral is

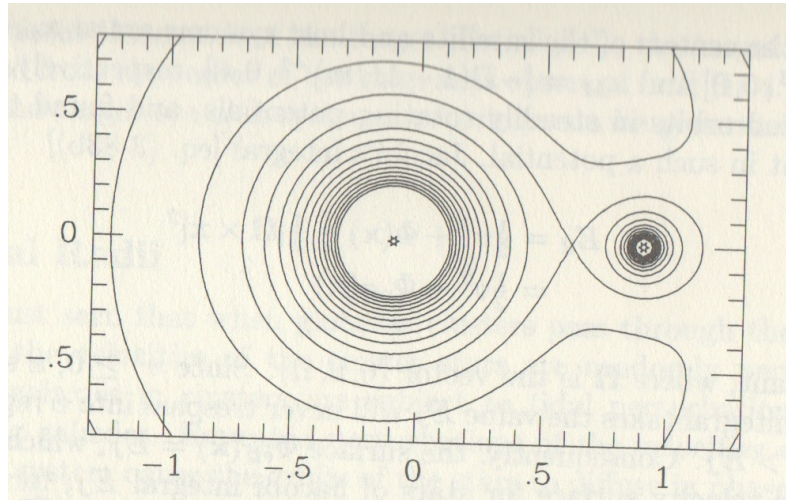
$$\begin{aligned} E_J &= \frac{1}{2}v^2 + \Phi(\mathbf{x}) - \frac{1}{2}|\boldsymbol{\Omega} \times \mathbf{x}|^2 \\ &= \frac{1}{2}v^2 + \Phi_{\text{eff}}(\mathbf{x}) \end{aligned}$$

- With effective isopotential contours as in the following example for $M=9m$ and $D=1$



Tidal Radii

- Note that the effective potential has a saddle point between the two masses



- Which occurs at a distance r_J from m . Particles outside that contour are in principle free to wander away from m
- This may be found by imposing the condition:

$$\left(\frac{\partial \Phi_{\text{eff}}}{\partial x} \right)_{x=x_m - r_J} = 0.$$

- Where we have assumed that $x_m = D/(1+m/M)$ and $x_M = -D/(1+M/m)$.

Tidal Radii

- In this case,

$$\Phi_{\text{eff}}(\mathbf{x}) = -G \left[\frac{M}{|\mathbf{x} - \mathbf{x}_M|} + \frac{m}{|\mathbf{x} - \mathbf{x}_m|} + \frac{1}{2} \frac{M+m}{D^3} |\hat{\mathbf{e}}_z \times \mathbf{x}|^2 \right]. \quad (7-81)$$

Hence

$$0 = \frac{1}{G} \left(\frac{\partial \Phi_{\text{eff}}}{\partial x} \right)_{x_m - r_J} = \frac{M}{(D - r_J)^2} \mp \frac{m}{r_J^2} - \frac{M+m}{D^3} \left(\frac{D}{1 + m/M} - r_J \right), \quad (7-82)$$

- This leads to a cubic equation for r_J , which simplifies in the case of $m \ll M$ and $r_J \ll D$. Expanding in powers of (r_J/D) we find

$$0 = \frac{M}{D^2} \left(1 + \frac{2r_J}{D} + \dots \right) \mp \frac{m}{r_J^2} - \frac{M}{D^2} + \frac{M+m}{D^3} r_J.$$

- and

$$r_J = \pm D \left[\frac{m}{M(3 + m/M)} \right]^{\frac{1}{3}} \simeq \pm \left(\frac{m}{3M} \right)^{\frac{1}{3}} D.$$

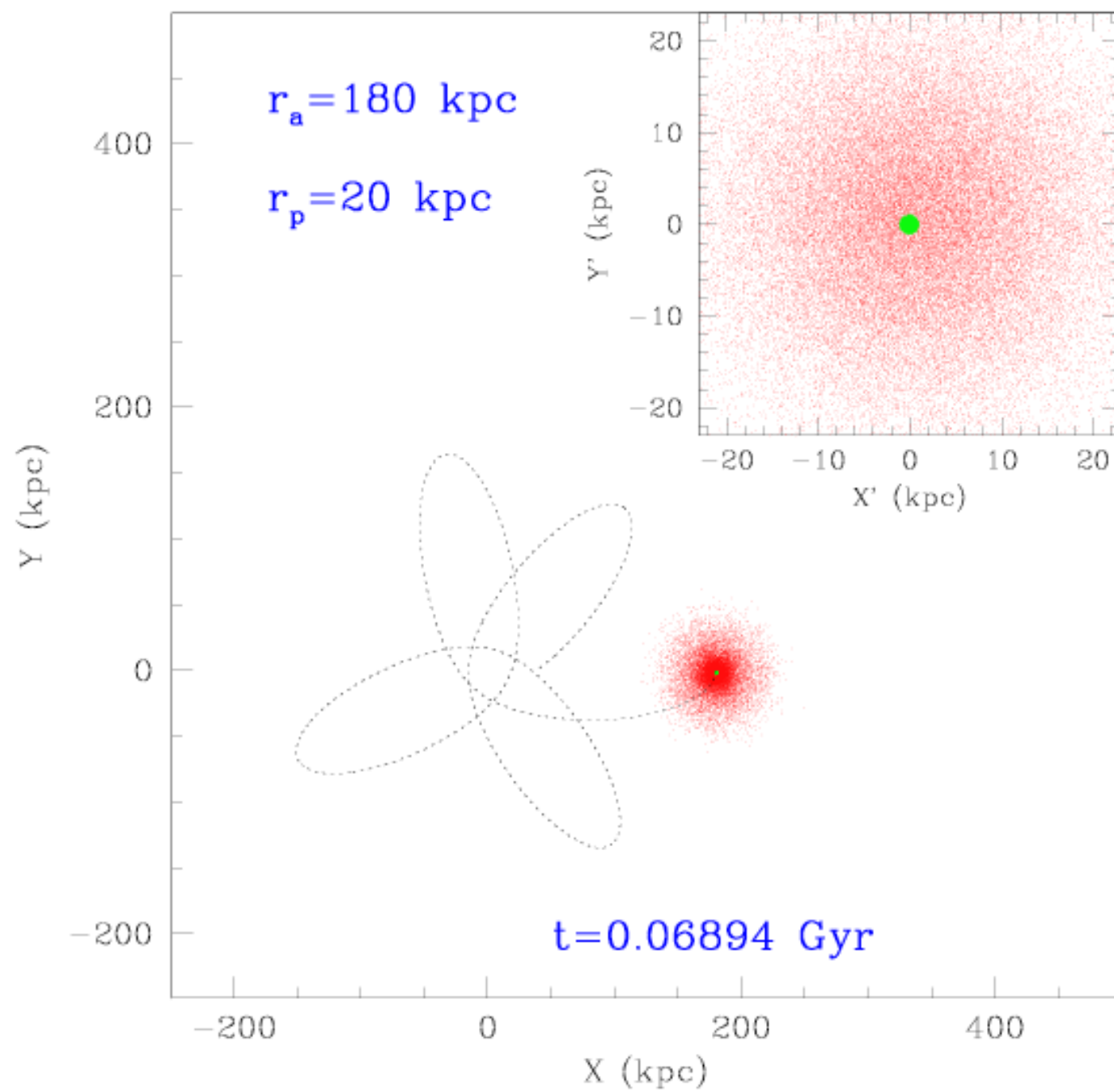
Tidal Radii

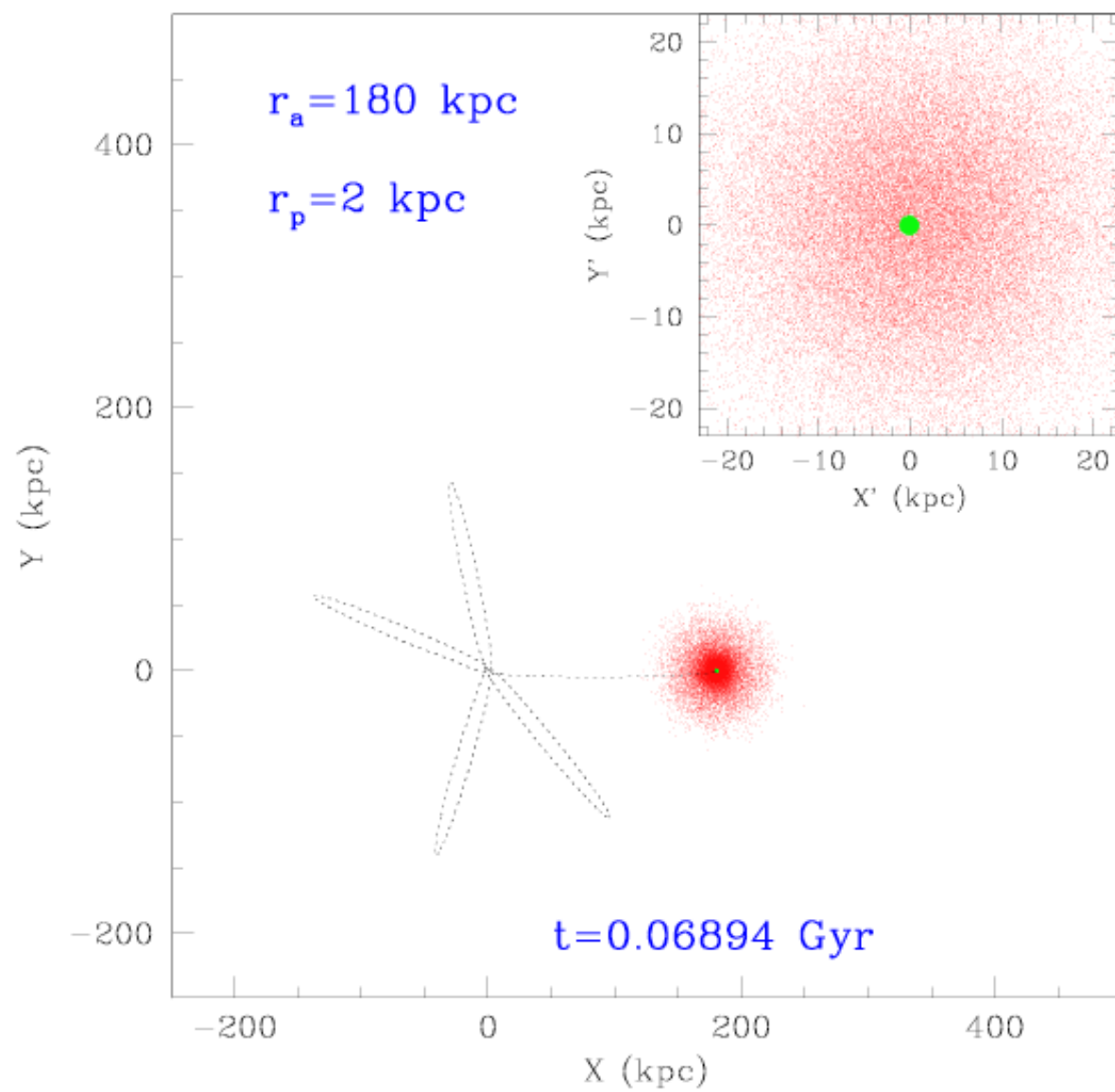
- r_J is usually called the “**Jacobi limit**” of the mass m . A few things worth noting
 - The zero velocity surface is not spherical (we did the calculation on the plane of the orbit)
 - In some cases, stars that are found outside r_J remain attached to the mass m . In other words, being outside r_J is not a guarantee that the star will be “lost” by m
 - In general, systems are not in circular orbits, in that case, replacing D by the pericentric distance usually works well.
 - r_J is just a “rough guide” to what the true tidal limit in a system may be.
- When considering an *extended* system rather than a point mass, Prob 4.5 shows that

$$r_J = D * [m / (2 * M(<D))]^{1/3}$$

An example

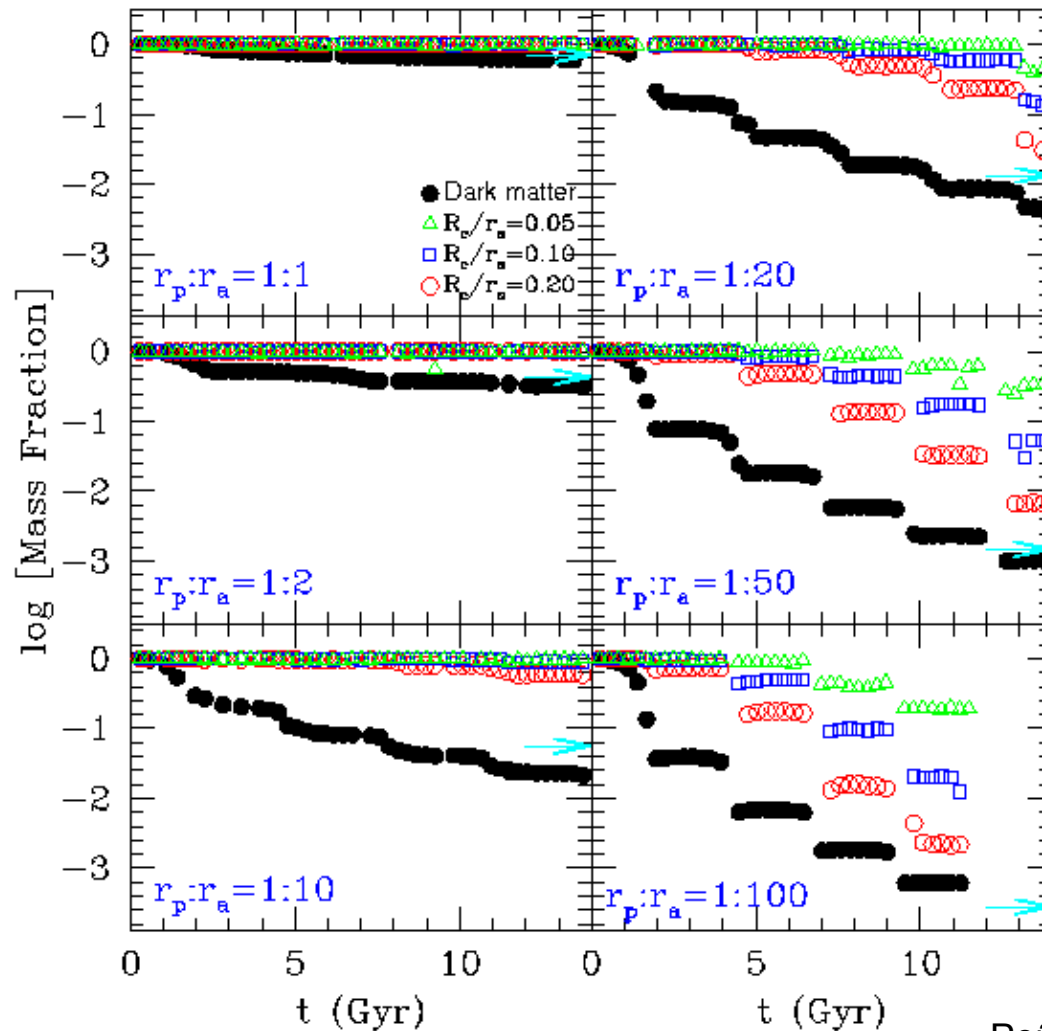
- The evolution of a small galaxy in the potential of a large one—like that of a satellite galaxy in the potential of the Milky Way
- Note that the orbit is a rosette, and that mass is lost continuously, but mainly after each pericentric passage
- Note how stars (which are assumed to populate the central regions of the satellite) are much more resilient to tidal disruption than the surrounding dark matter
- Depending on the orbits and masses of the satellites, tides may have a strong influence in their structure and evolution





The Importance of Tides

- The evolution of the mass bound to the satellite is shown below for various choices of the eccentricity of the orbit
- The arrow marks the prediction of the “Jacobi limit” (at pericenter)

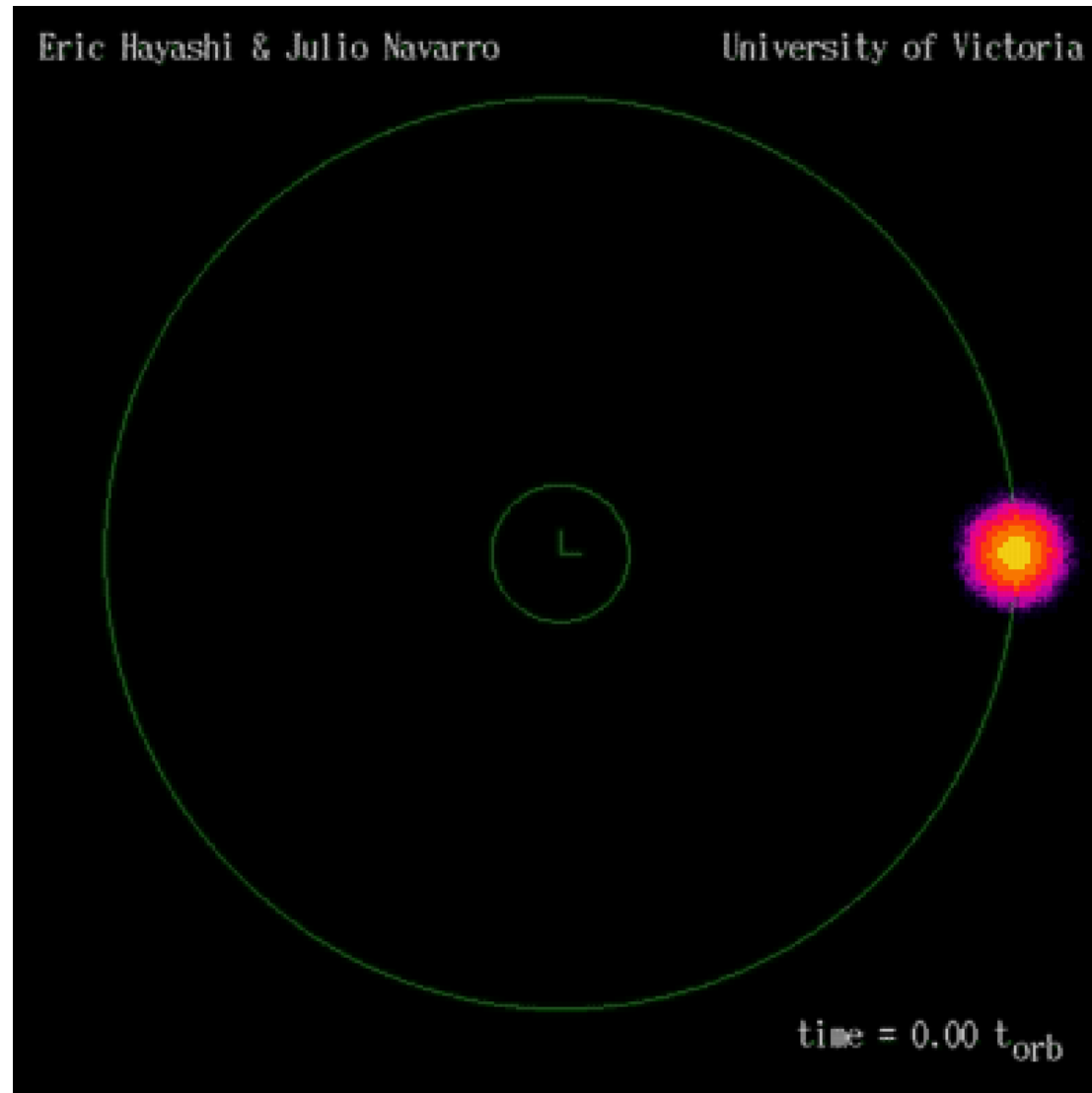


The Sagittarius Dwarf

- The Sagittarius Stream is one of the best examples of the effect of tides.

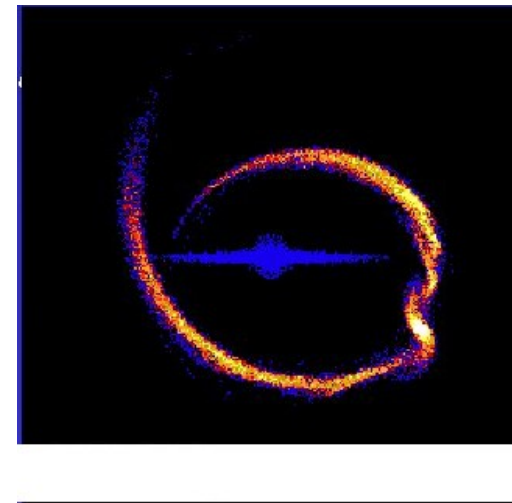
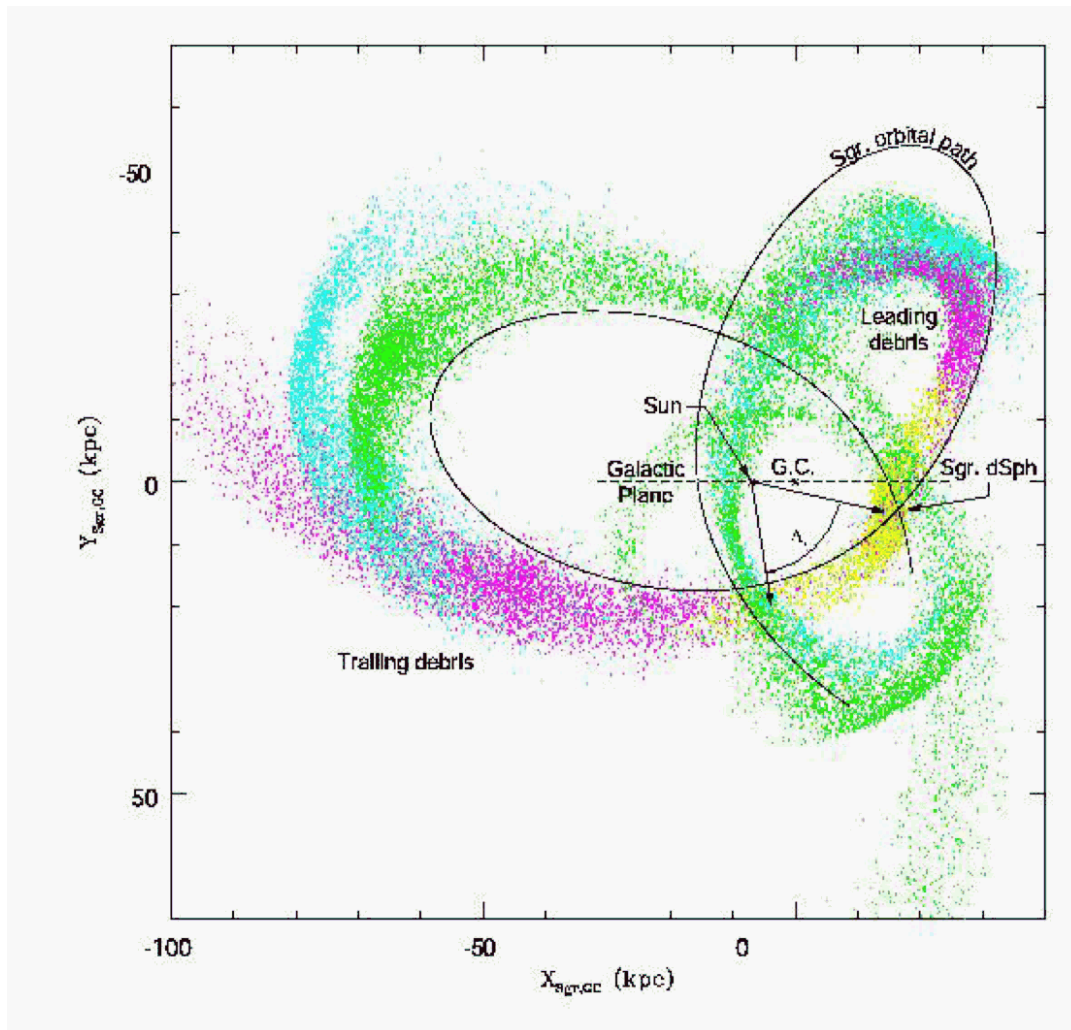


Leading and trailing tidal tails



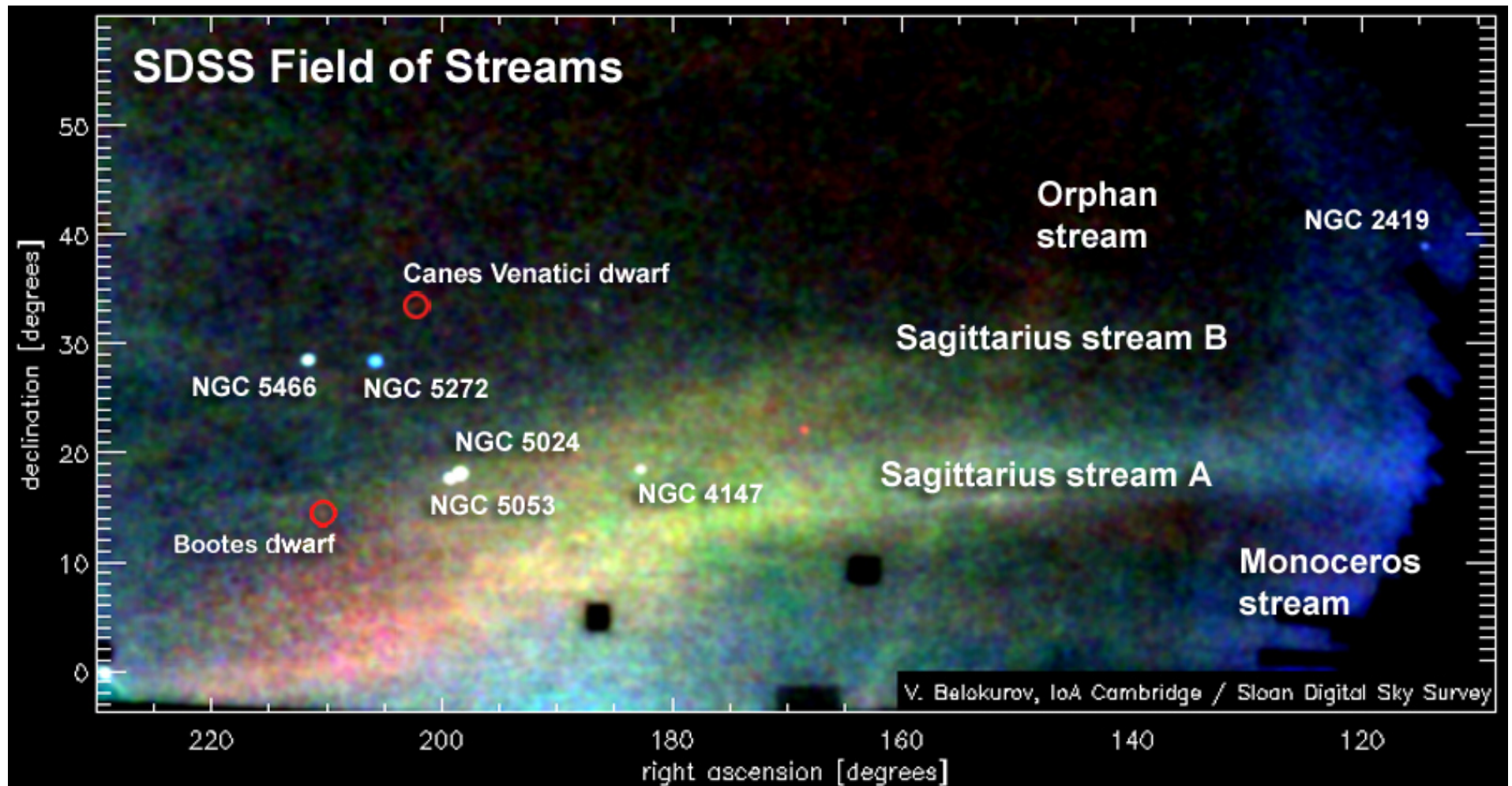
The Sagittarius Stream

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The Field of Streams

- The Sagittarius Stream is not the only stream in the halo of the Milky Way



The Future of the Local Group

- The Milky Way and M31 are separated by ~770 kpc and are approaching each other at roughly 120 km/s.
- One may combine this with the fact that we have a very good estimate of the age of the Universe (~13 Gyrs) to derive an estimate of the total mass of the MW-M31 system
- You will show in Prob 4.12 that the distance between two point masses may be expressed as

$$r = a(1 - e \cos \eta), \quad t = \sqrt{\frac{a^3}{G\mathcal{M}}}(\eta - e \sin \eta) \text{ for } a = \frac{L_z^2}{G\mathcal{M}(1 - e^2)}. \quad (4.24)$$

- And therefore

$$\frac{dr}{dt} = \frac{dr/d\eta}{dt/d\eta} = \sqrt{\frac{G(m + \mathcal{M})}{a}} \frac{e \sin \eta}{1 - e \cos \eta} = \frac{r}{t_0} \frac{e \sin \eta (\eta - e \sin \eta)}{(1 - e \cos \eta)^2}.$$

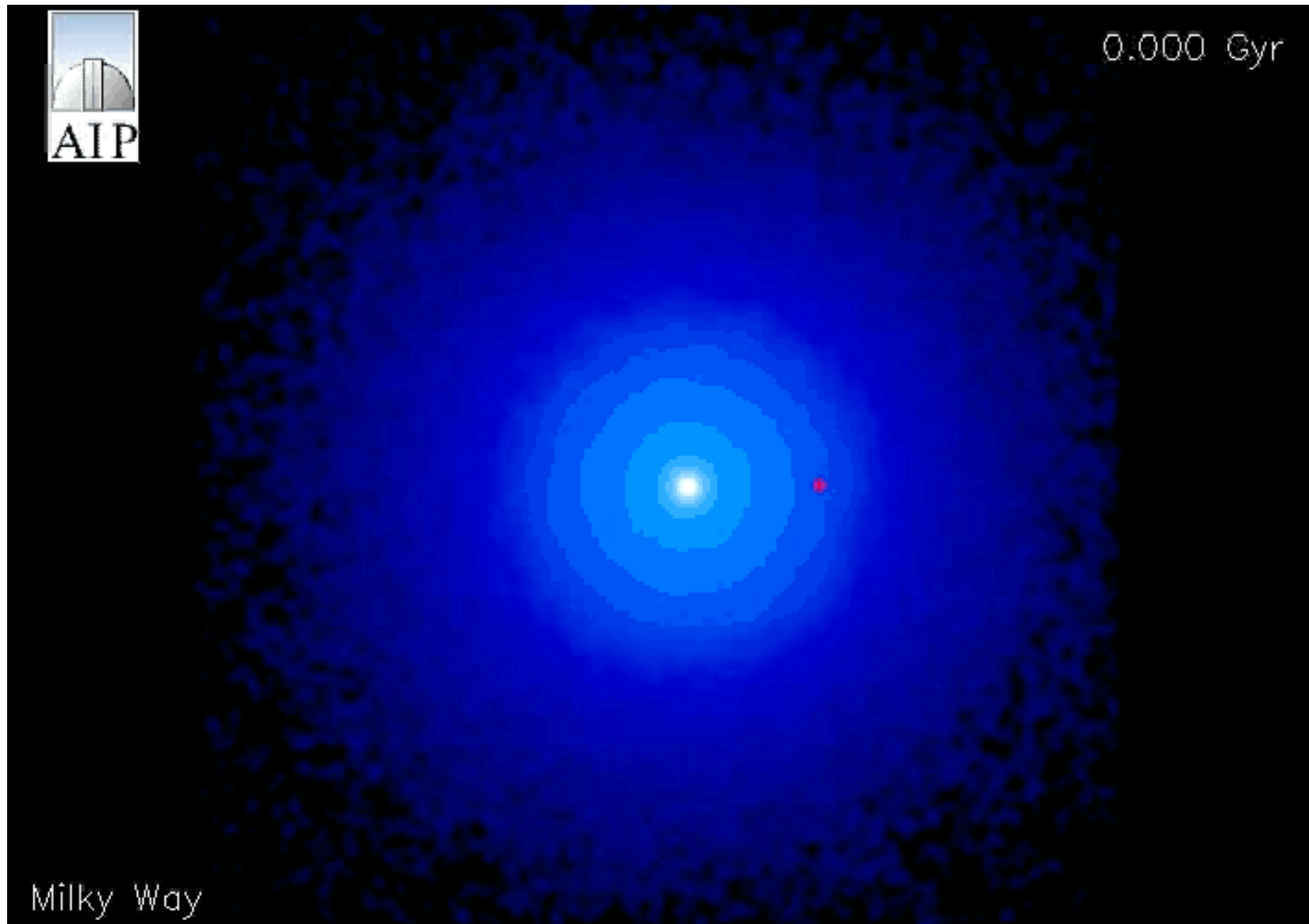
The Future of the Local Group

- Substituting the observed values, assuming a radial orbit, one may obtain an estimate for $M+m \sim 4-5 \times 10^{12} M_{\text{sun}}$. This is much larger than the mass in gas and stars in both galaxies.
- Further evidence for the presence of dark matter!
- This is sometimes referred to as “the timing argument”

$$\frac{dr}{dt} = \frac{dr/d\eta}{dt/d\eta} = \sqrt{\frac{G(m + \mathcal{M})}{a}} \frac{e \sin \eta}{1 - e \cos \eta} = \frac{r}{t_0} \frac{e \sin \eta (\eta - e \sin \eta)}{(1 - e \cos \eta)^2}.$$

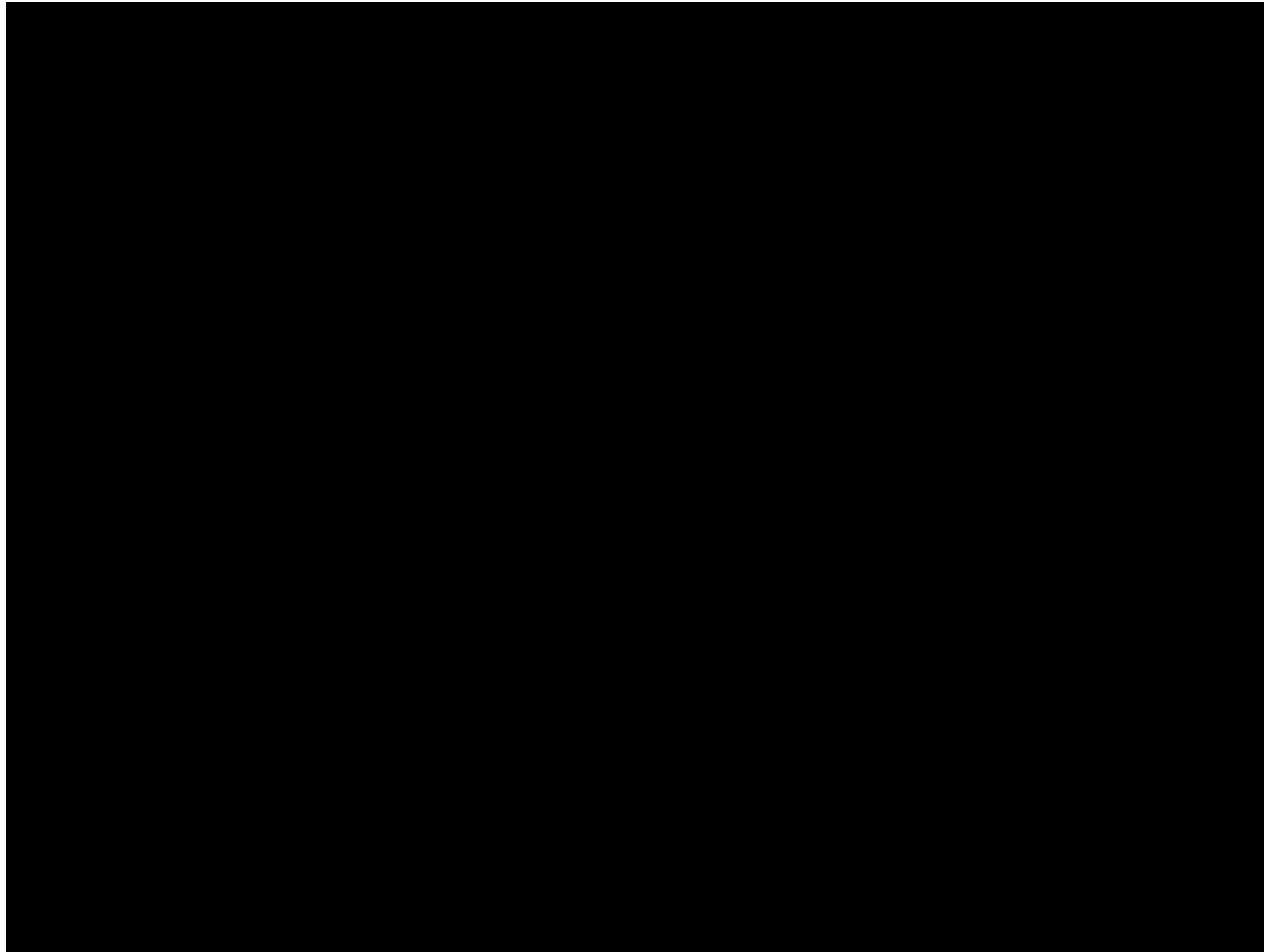
- The following animation shows a possible outcome for the future of the MW-M31 system

The Future of the Local Group



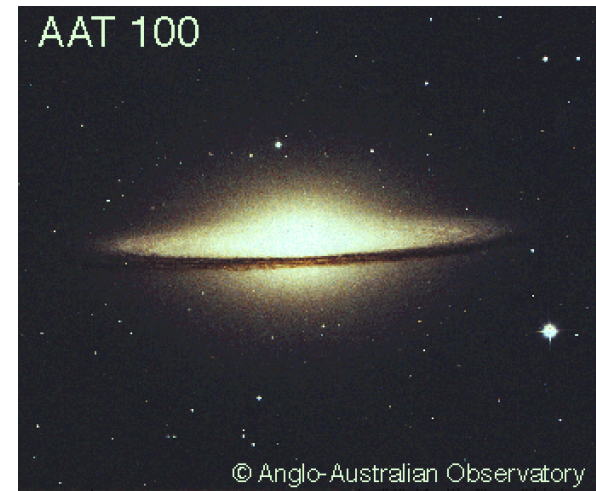
The Future Sky

- The appearance of the night sky as seen from the Sun after the encounter of M31 and MW

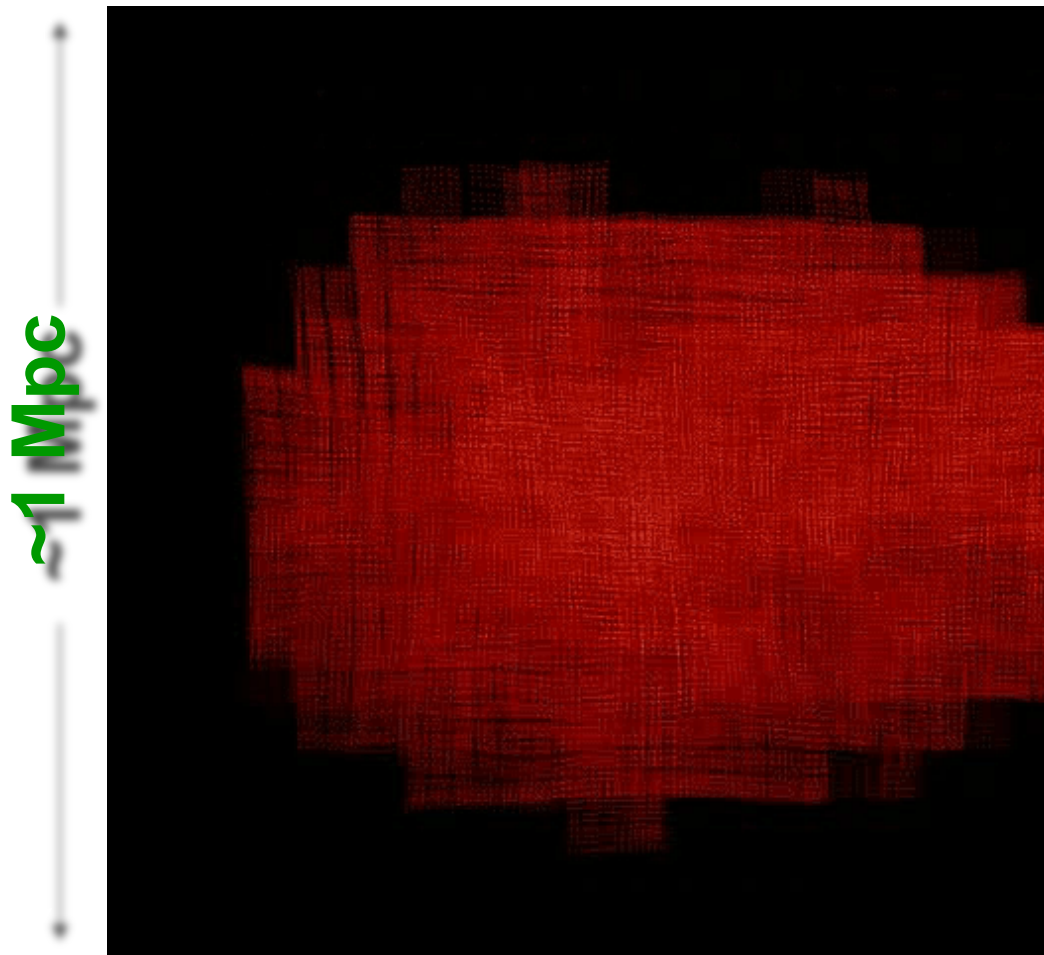


Making Galaxies

- The morphology of a galaxy is a transient, evolving feature dictated by the mass accretion history of its dark matter halo
 - most stars form in disks; spheroids result from subsequent mergers
 - disks result from smooth gas accretion; oldest disk stars are often used to date the last major merger event



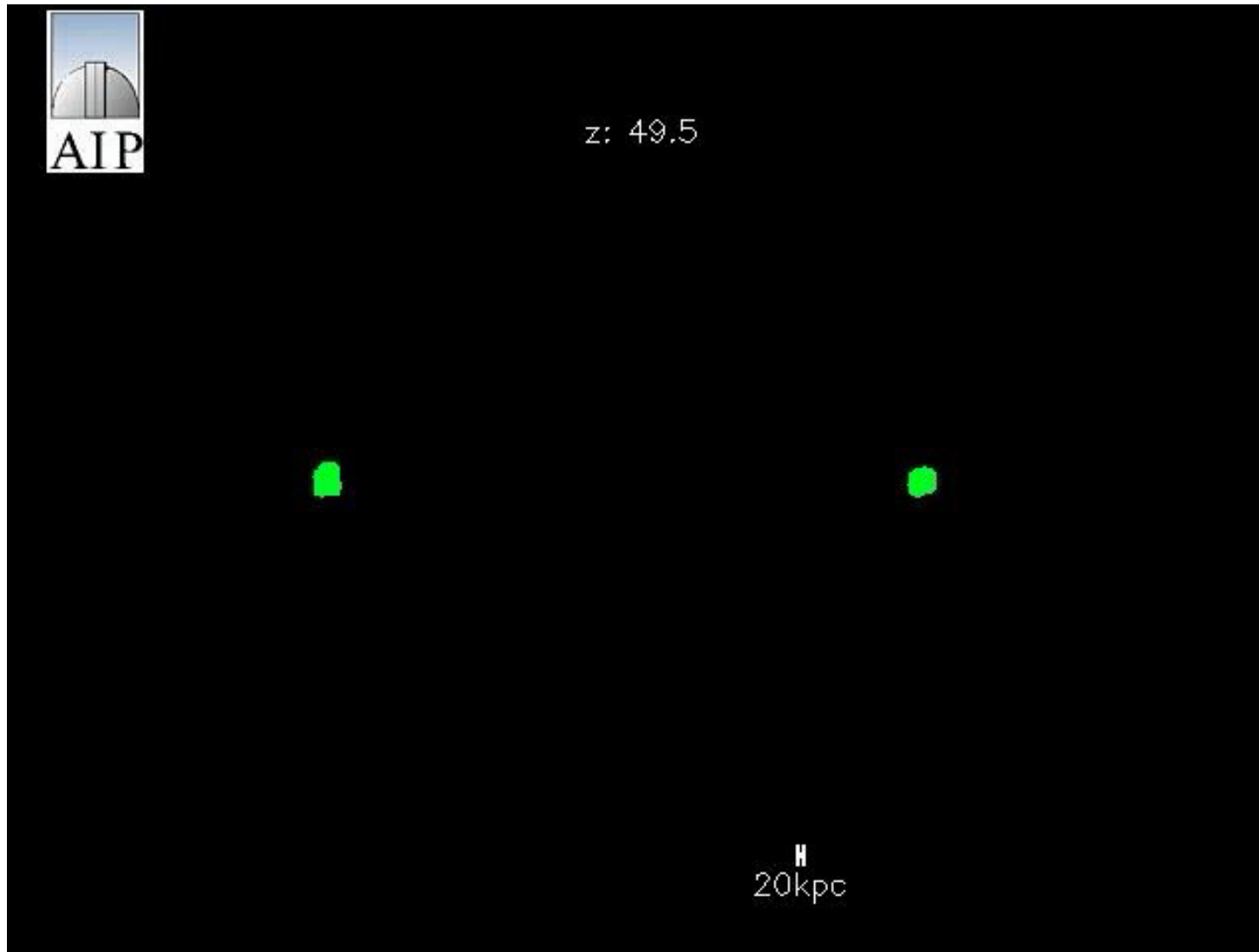
Dark Matter Halos: Galaxy Hosts in CDM Universes



Dark Matter only

- Structure is formed from the bottom-up (i.e. small, dense halos collapse first)
- A substantial fraction of the mass is accreted through mergers.
- A significant amount of substructure remains in the halo at $z \sim 0$.

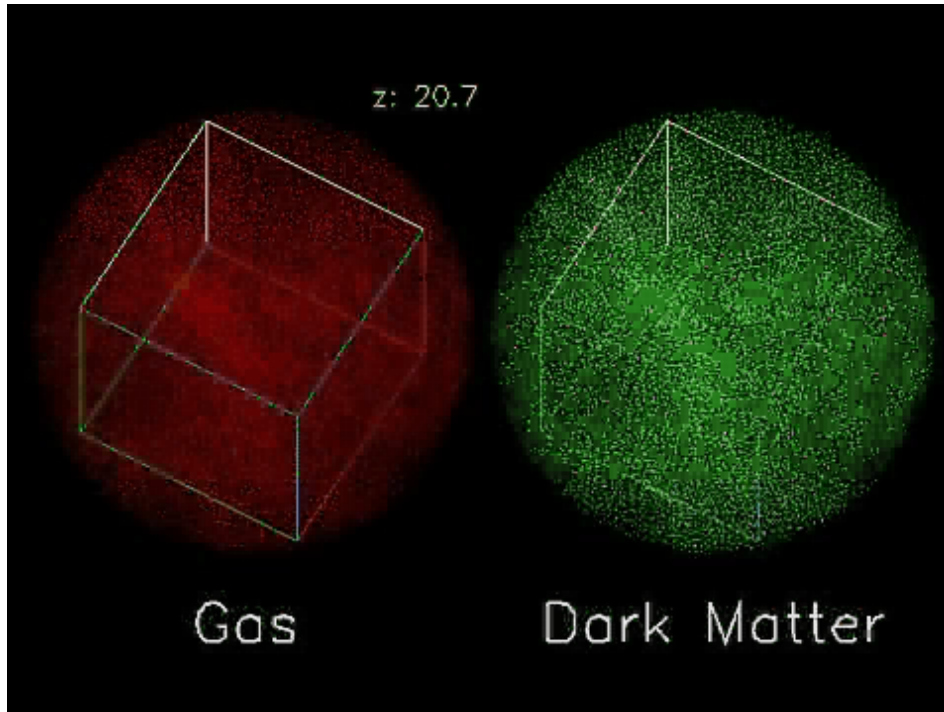
The Hierarchical Formation of a Disk Galaxy



- Stellar disks form after the dissipative collapse of gas onto thin, centrifugally supported structures.
- Spheroids form subsequently as a consequence of mergers.
- Galaxy morphology is a transient, evolving feature in the lifetime of a galaxy.

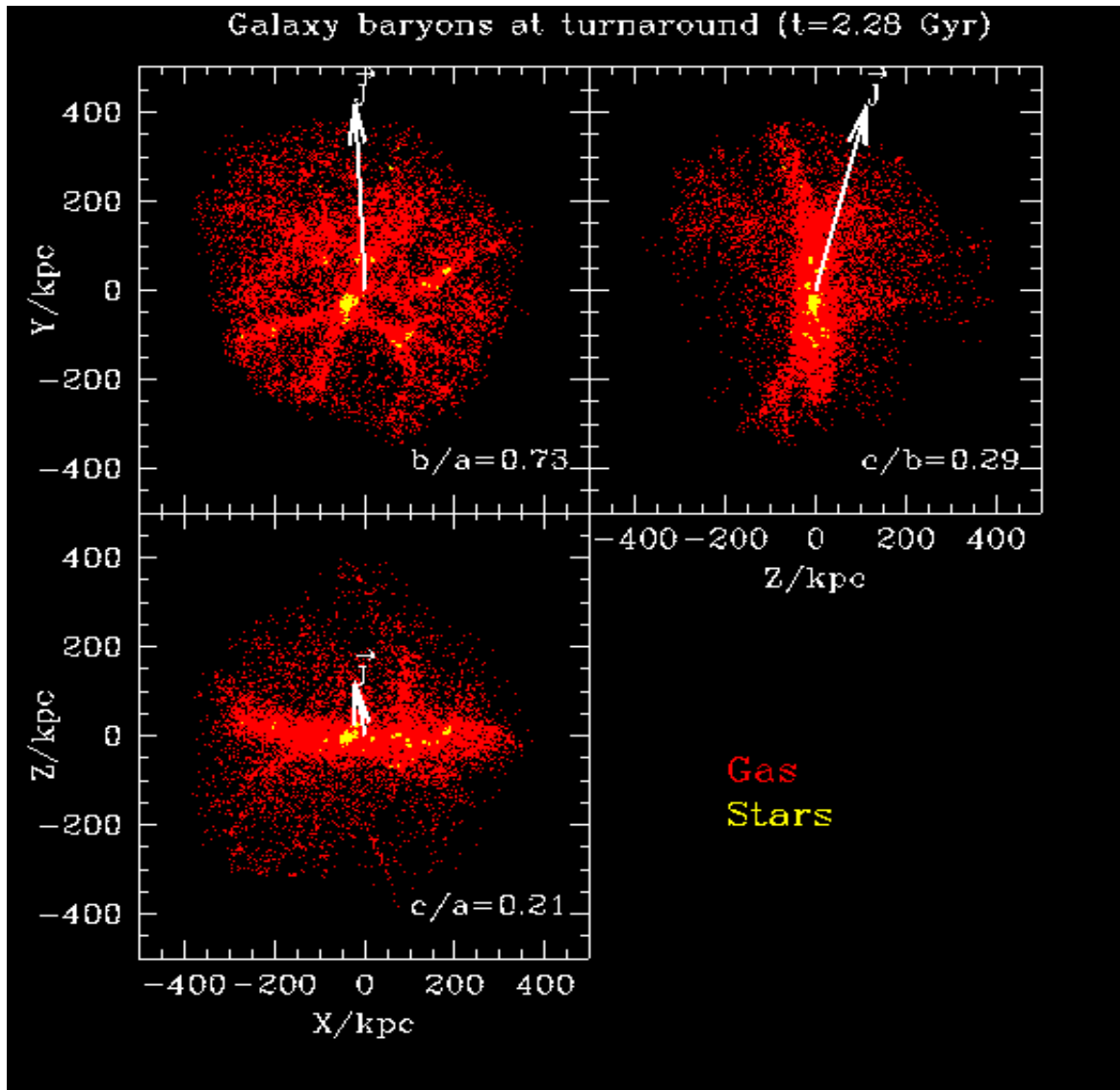
Steinmetz & Navarro 2000

Tidal Torques and Angular Momentum



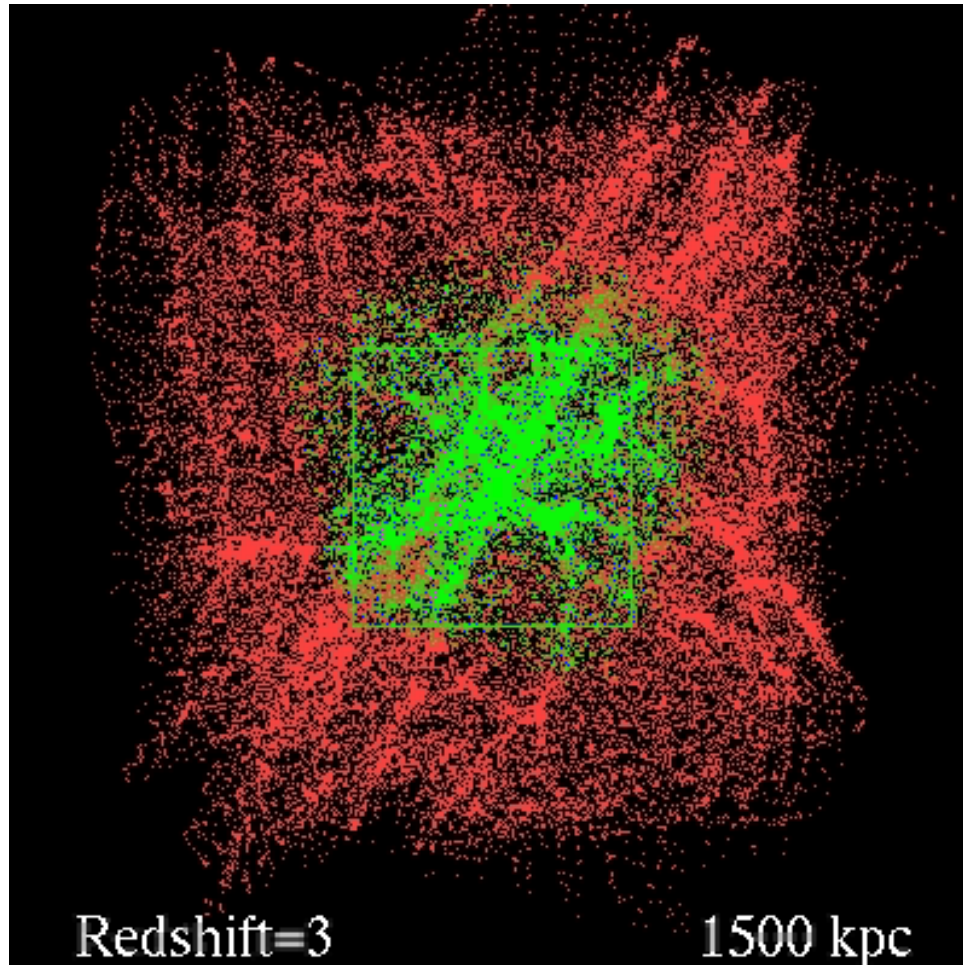
- The angular momentum of galaxies originates in tidal torques exerted by external material during the expansion phase
- It is relatively inefficient ($\lambda \sim 0.05$), implying that dark matter halos must be present to spin up baryonic material during collapse
- The leading cause is a *misalignment* between the principal axes of the inertia momentum tensor (I_{ij}) and of the potential “shear tensor” ($\partial^2\phi/\partial x_i\partial x_j$)
 - $\tau_x = (\partial^2\phi/\partial y\partial z)(I_{yy}-I_{zz})$
 - $\tau_y = (\partial^2\phi/\partial x\partial z)(I_{xx}-I_{zz})$
 - $\tau_z = (\partial^2\phi/\partial x\partial y)(I_{xx}-I_{yy})$
- Most effective near turnaround, when I_{ij} is largest, negligible afterwards.

Tidal Torques and Angular Momentum



- Although a generally accepted scenario, due largely to the lack of a compelling alternative, the tidal torque origin of galactic spins have been remarkably difficult to prove beyond doubt.
- One “natural” prediction of the tidal torque scenario is that the direction of the angular momentum vector should coincide with the intermediate principal axis of the I_{ij} tensor at turnaround.

Tidal Torques and Angular Momentum

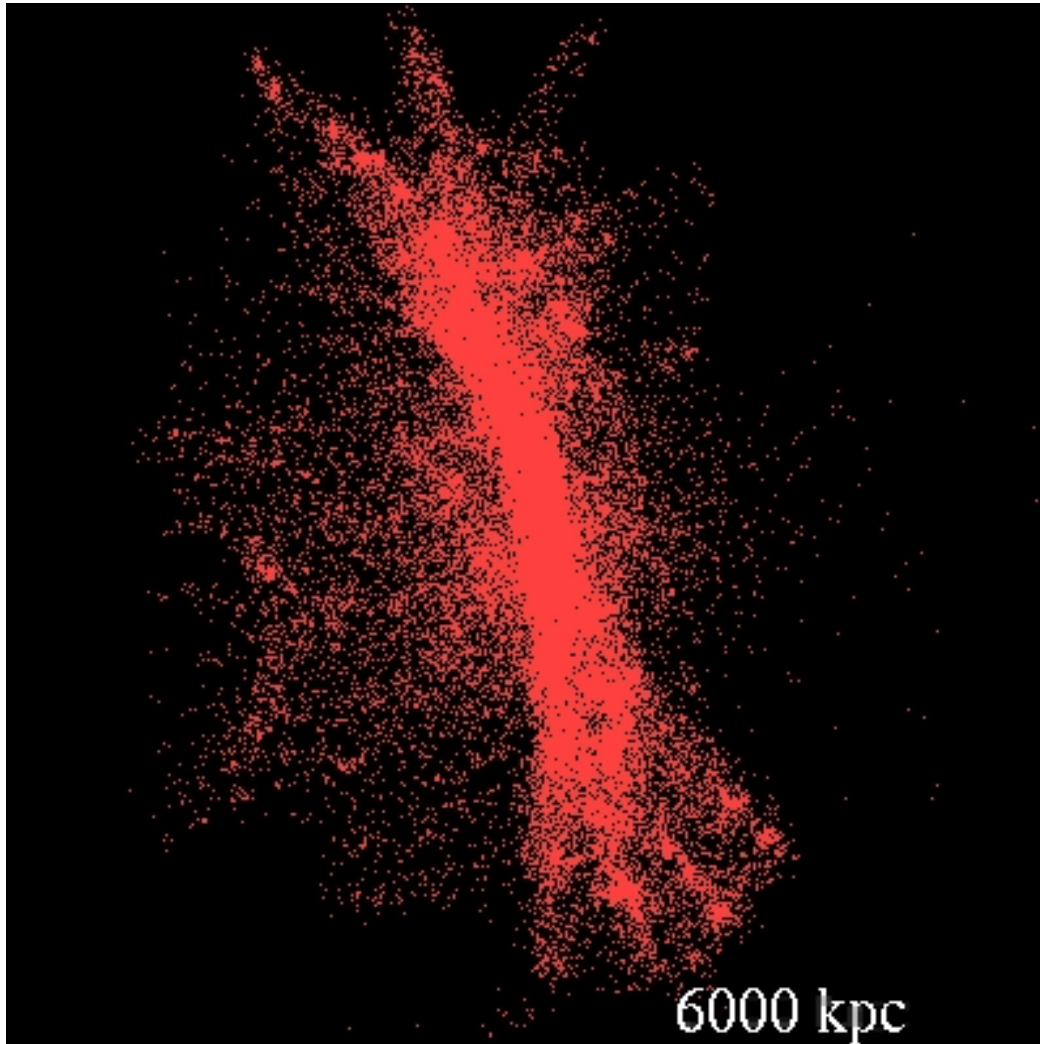


- Given the tendency of matter to collapse on large scale sheets crisscrossed by filaments, this implies that the spin axis should lie on the plane traced by the surrounding large scale structure.

Turn-around time configuration of matter within a 5 Mpc sphere in the initial conditions

Navarro et al 2004

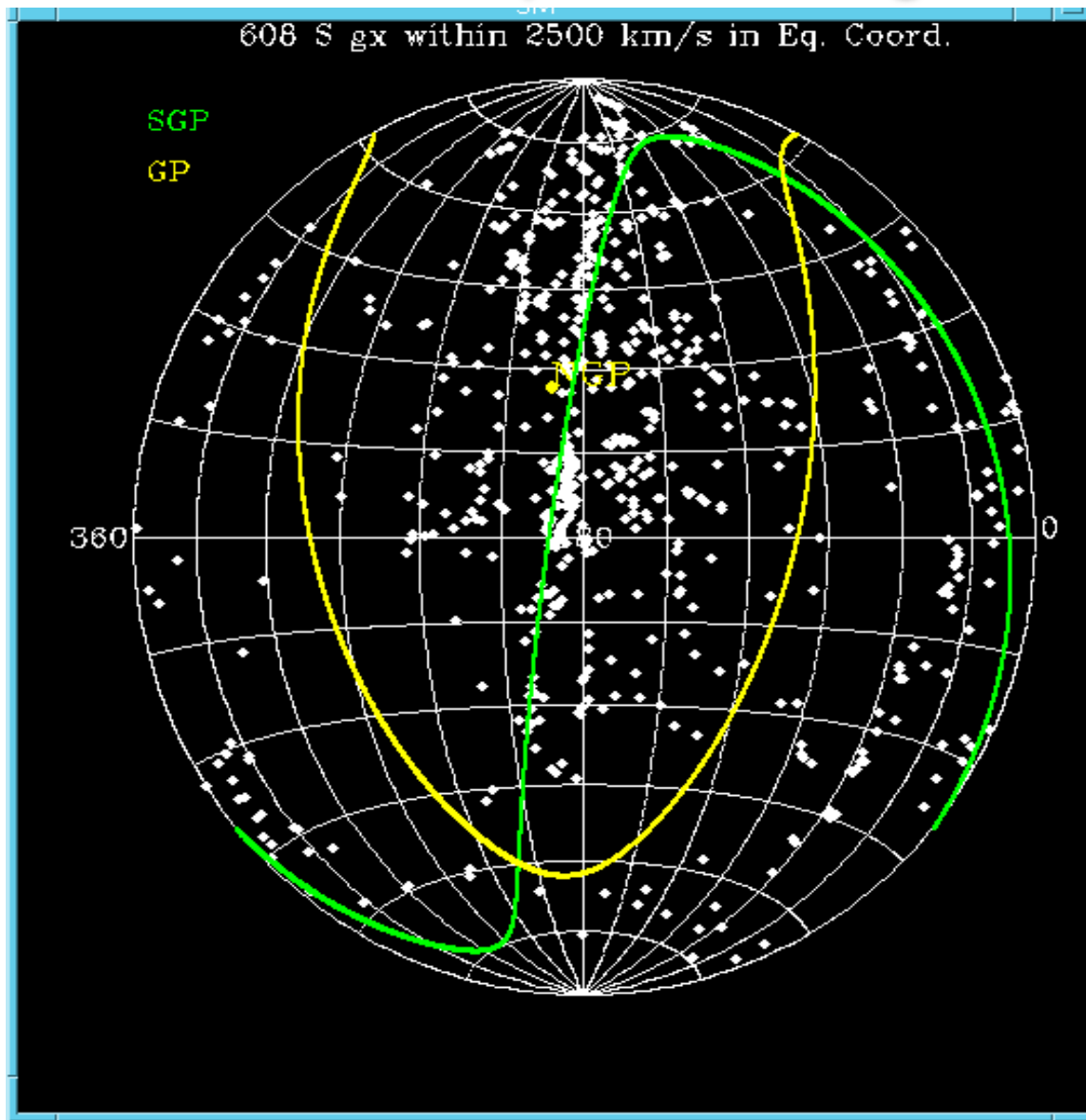
Tidal Torques and Angular Momentum



$z=0$ configuration of matter within a
5 Mpc sphere in the initial conditions

- Given the tendency of matter to collapse on large scale sheets crisscrossed by filaments, this implies that the spin axis should lie on the plane traced by the surrounding large scale structure.

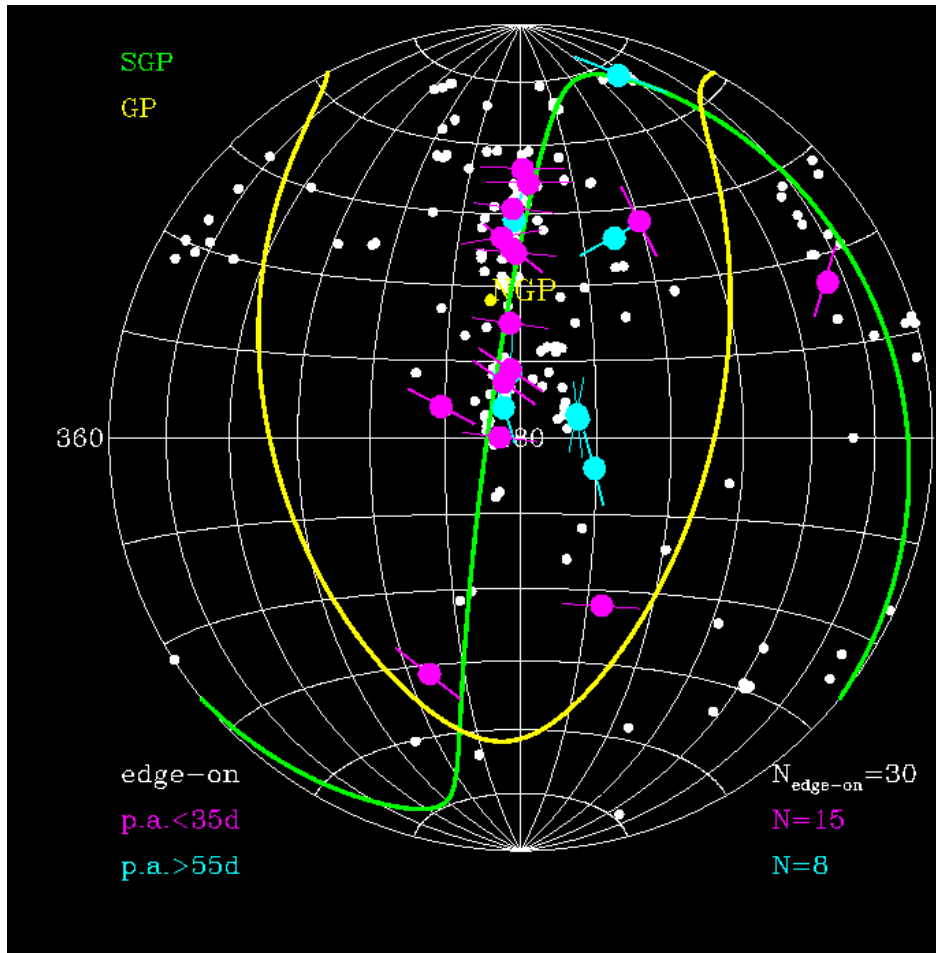
Tidal Torques and Angular Momentum



- The Milky Way provides one clear example of this trend.

- The Galactic Poles lie squarely on the “Super Galactic Plane” where most galaxies within a couple of dozen Mpc arrange themselves.

Galactic Spin Direction and Large Scale Structure



- The direction of galactic spin is easiest to estimate in edge-on spiral disks.
- There is an “excess” of edge-on spirals perpendicular to the SGP in the local Universe!

