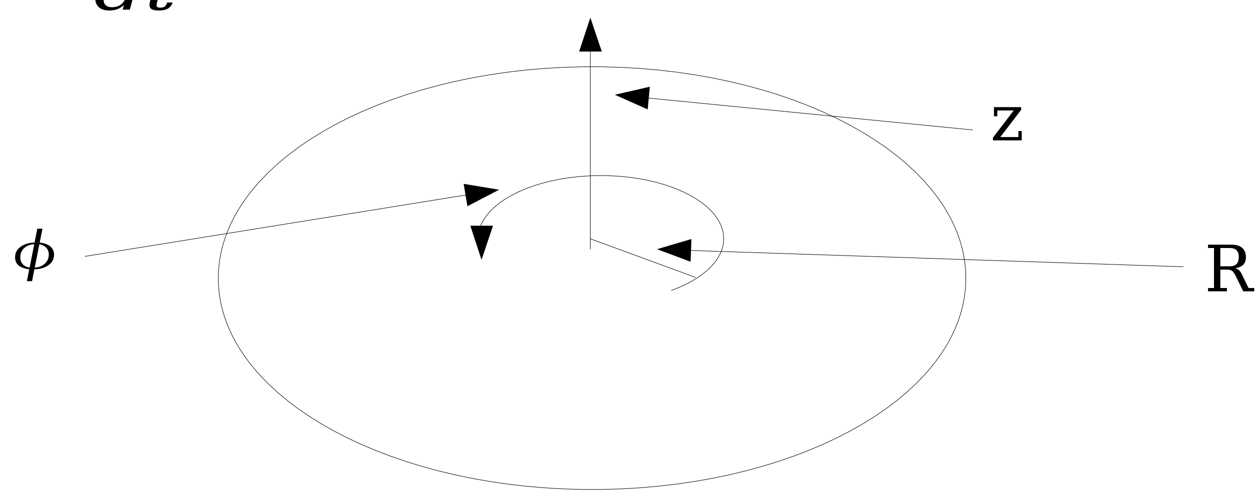
Stellar Orbits

Galactic Potentials and Epicycles

Detailed orbital properties for a star orbiting the galaxy. The angular momentum L_z is conserved

$$\frac{d R^2 \dot{\phi}}{dt} = 0 \quad \text{so} \quad L_z \equiv R^2 \dot{\phi} = const$$



If Φ is not changing with time we can write the equation of motion as

$$\ddot{R} - R\dot{\phi}^2 + \frac{\partial \phi}{\partial R} = 0$$

We can rewrite this as

$$\ddot{R} = R\dot{\phi}^2 - \frac{\partial \phi}{\partial R} = -\frac{\partial \Phi_{eff}}{\partial R}$$

$$\Phi_{eff} = \Phi(R, z) + \frac{L_z^2}{2\mathrm{R}^2}$$

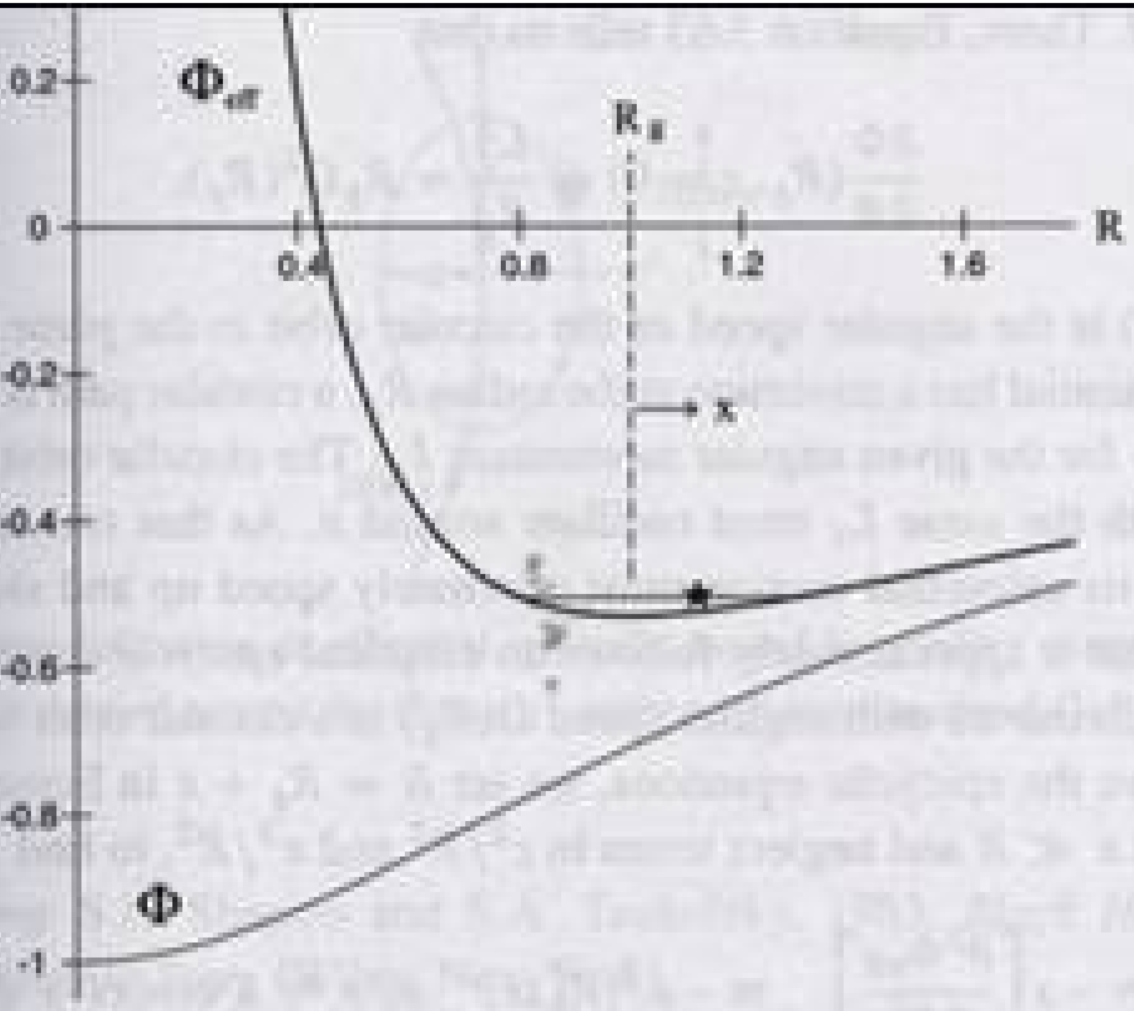


Figure 3.7 Effective potential Φ_{eff} (upper curve) for a star with angular momentum $L_z = 0.595$, orbiting in a Plummer potential Φ_P (lower curve). The scale length $a_P = 1$; L_z is in units of $\sqrt{G\mathcal{M}a_P}$; units for Φ and Φ_{eff} are $G\mathcal{M}/a_P$. The vertical dashed line marks the guiding center R_g; the star oscillates about R_g between inner and outer limiting radii.

Lets pick a specific model: the Plummer sphere

First used by H.C. Plummer in 1911 to fit observations of globular clusters.

The potential is

$$\Phi_p(r) = -\frac{GM}{\sqrt{r^2+b^2}}$$

To get the density associated with the potential

$$\nabla^2 \Phi_p(r) = \frac{1}{r}\frac{d}{dr}\left(r^2 \frac{d\Phi_p}{dr}\right) = \frac{3\mathrm{GMb}^2}{(r^2+b^2)^{5/2}}$$

But from Poisson's eqn

$$\nabla^2 \Phi(r) = 4\pi G \rho(r)$$ we know

the density is

$$\rho(r) = \frac{3\mathrm{b}^2}{4\pi} \frac{M}{(r^2 + b^2)^{5/2}}$$

And the projected surface brightness is

$$\Sigma_p(R) = \int_{-\infty}^{+\infty} \rho \sqrt{R^2 + z^2}\, dz = \frac{M}{\pi} \frac{b^2}{(R^2 + b^2)^2}$$

In the vertical direction

$$\ddot{z} = -\frac{\partial \Phi(R,z)}{\partial z} = -\frac{\partial \Phi_{eff}(R,z)}{\partial z}$$

In this case the potential is symmetric in z

$$\Phi(R,z) = \Phi(R,-z) \quad \text{and} \quad \Phi(R,0) = 0$$

Expand this in a Taylor series around z=0

$$\ddot{z} = -\Phi_{eff}(R,0) - \frac{\partial}{\partial z}\frac{\partial \Phi_{eff}(R,z)}{\partial z}\, z$$

$$\ddot{z} = -\left[\frac{\partial^2 \Phi_{eff}(R, z)}{\partial z^2}\right]_{z=0} z = -\nu^2 z$$

Which is the equation for a harmonic ocillator with angular frequency ν and z = Z cos(νt+θ).

A star with a given angular momentum will only follow a circular orbit if it is at a specific radius R_G. R_G is the “guiding radius” and everywhere else we can write the radius in terms of R = R_G + x. If x << R we can again expand this, so in the radial direction we have

$$\ddot{x} = -x\left[\frac{\partial^2 \Phi_{eff}}{\partial R^2}\right]_{R_g} = -\kappa^2(R_g)x$$

This has solutions of the form

$$x = X\cos(\kappa t + \phi)$$

Where X and ψ are constants of integration. κ^2 is the epicyclic frequency if $\kappa^2>0$. If $\kappa^2<0$ the orbit is unstable.

You can show that

$$\kappa^2(R) = \frac{1}{R^3}\frac{d}{dR}(R^2\Omega^2) = -4\mathrm{B}\Omega$$

Where B is Oort's constant we derived earlier. Recall that B = -12.4 km/s/kpc. Since B<0 then $\kappa^2>0$ so stars near the sun are in stable orbits.

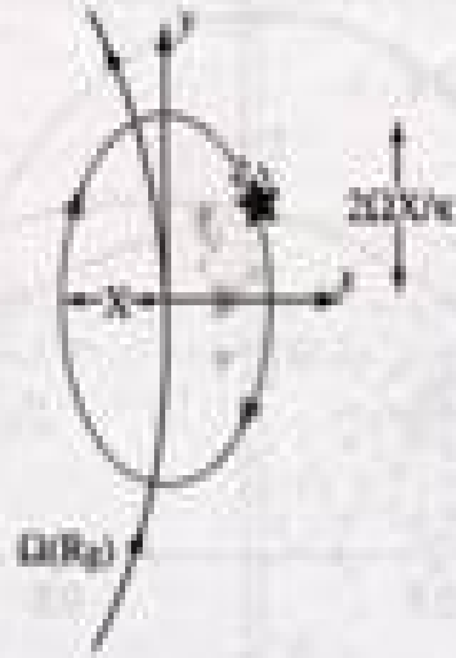


Figure 3.8 A star following an elliptical epicycle around its guiding center at ($x = 0$, $y = 0$), which is carried around the Galactic center with angular speed $\Omega(R_g)$.

So relation to a star in a circular orbit star appear to oscillate around this point, and epicycle. In the Galactic potential near the sun $\kappa = 1.4\Omega$, where Ω is the angular speed, so...

For the sun we make 1.4 epicycles for every orbit of the Galaxy. This means that the suns orbit is not closed.

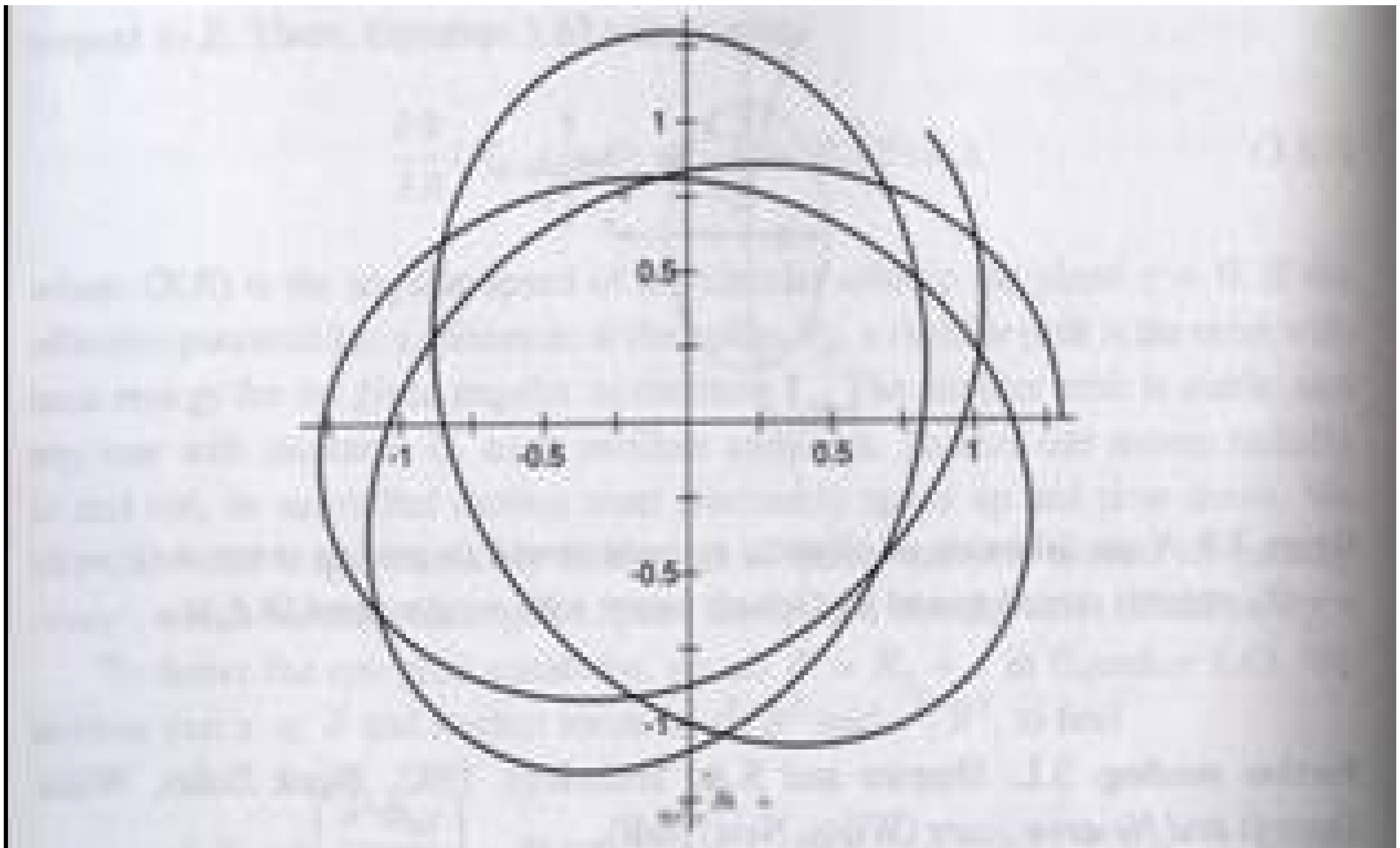
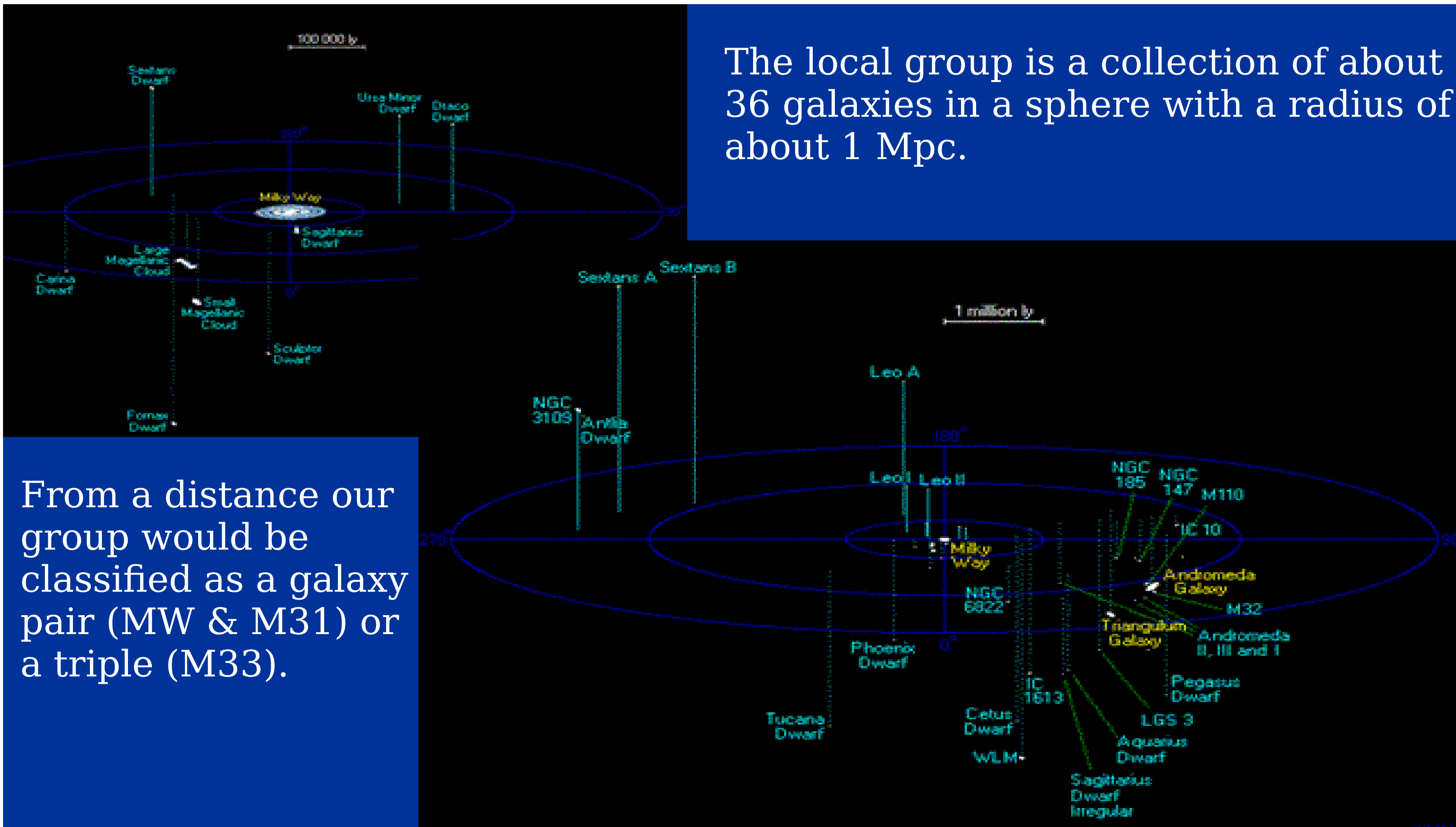


Figure 3.9 Path of the star of Figure 3.7, viewed from above the Galactic plane; the orbit started with ($R = 1.3$, $\phi = 0$) and ($\dot{R} = 0$, $R\dot{\phi} = 0.4574$).

Beyond our Galaxy: The local group

The local group is a collection of about 36 galaxies in a sphere with a radius of about 1 Mpc.



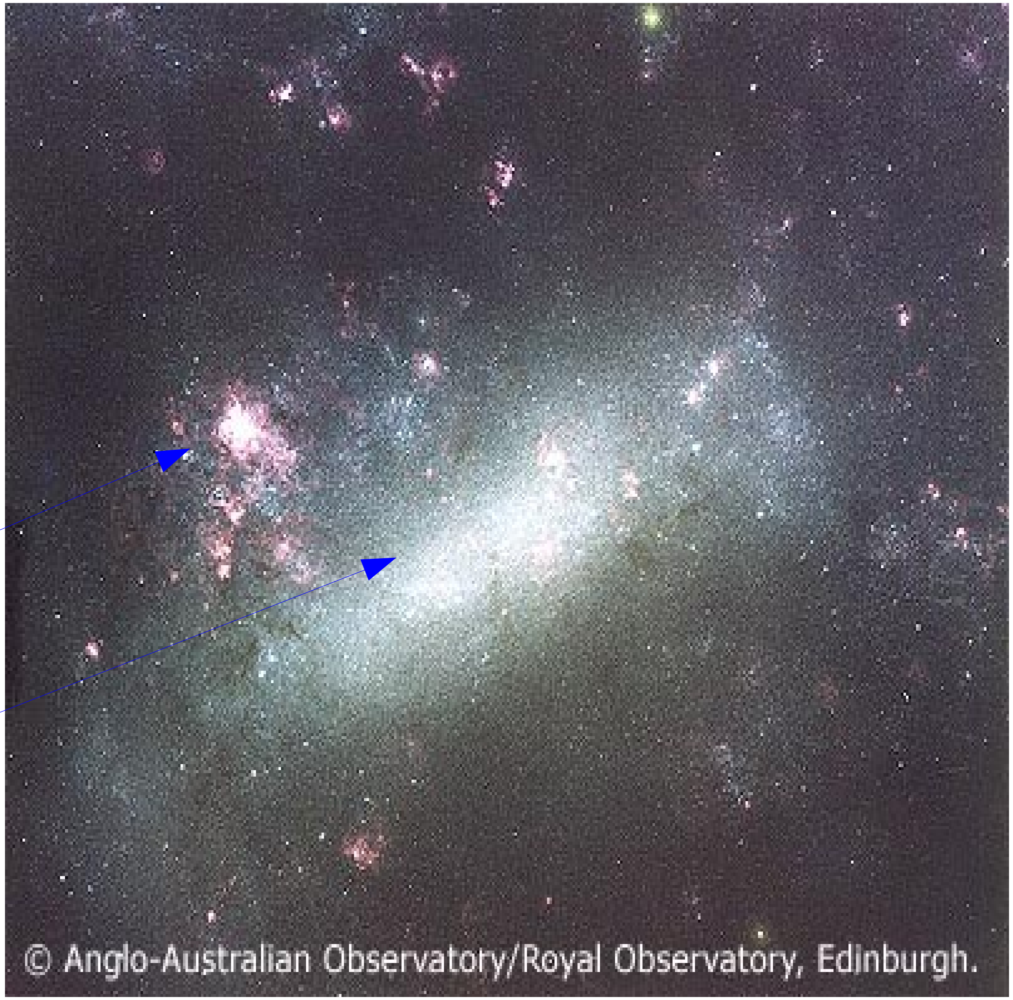
From a distance our group would be classified as a galaxy pair (MW & M31) or a triple (M33).

Most prominate satellites of our Milkyway are the Magallanic Clouds.

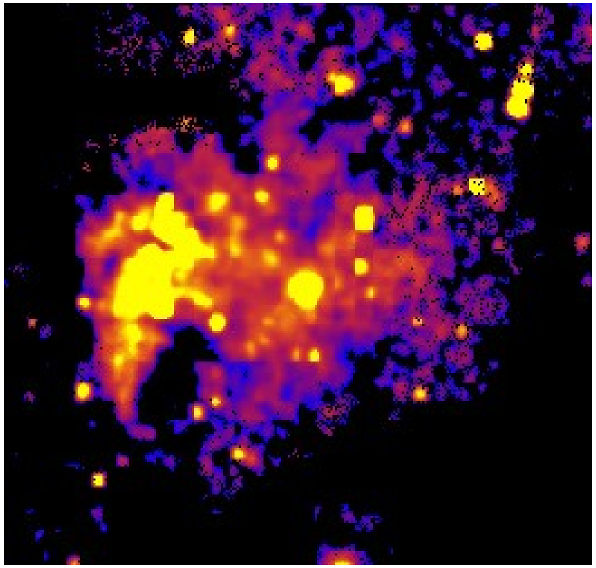
Image credit: Bill Keel

The LMC

- Distance 50kpc
- Dwarf Irregular
  - Type Sm
- Tarantula Nebula
  - active star forming region
- Barred galaxy
- $L \approx 1.7 \times 10^9 L_\odot$

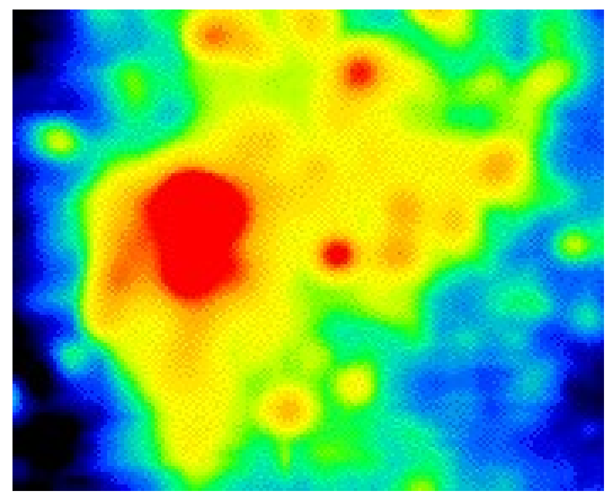


Xray: ROSAT



AAO optical 3 color

IRAS (Jason Surace)

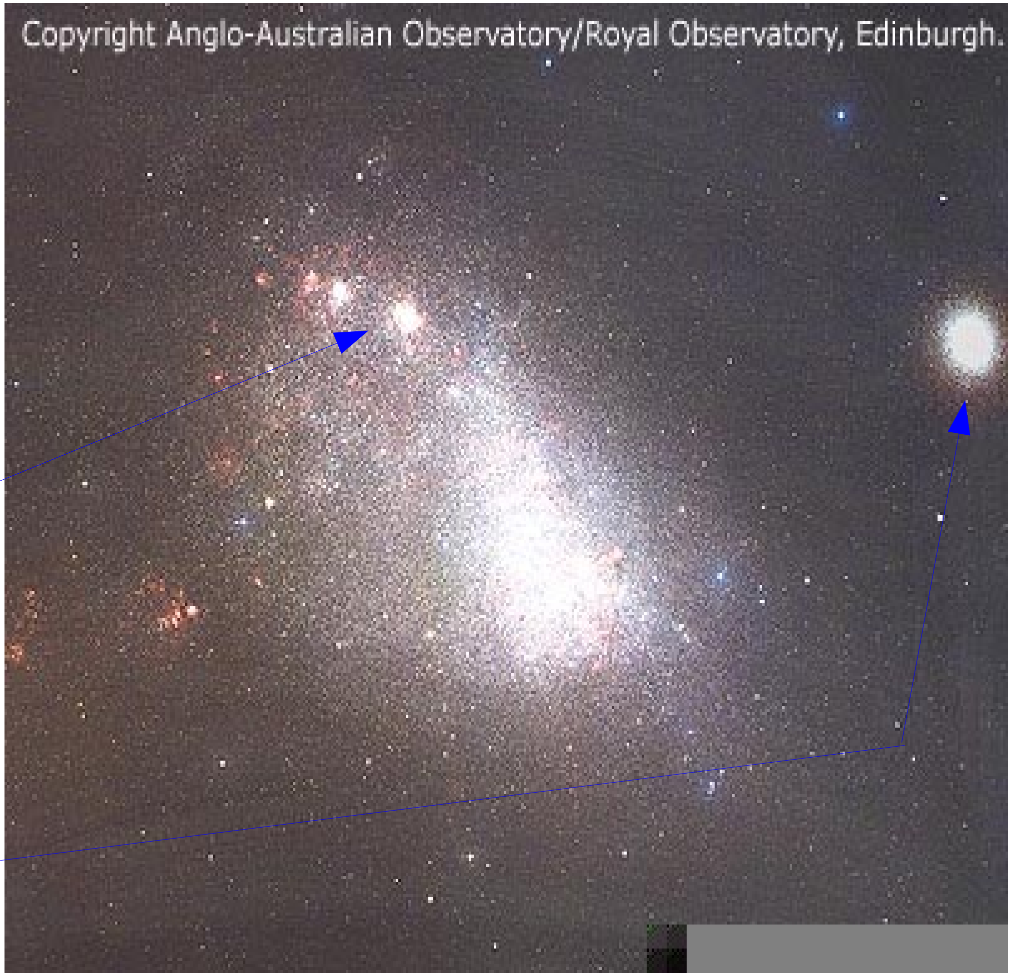


Radio (RAIUB/MPIFR Bonn

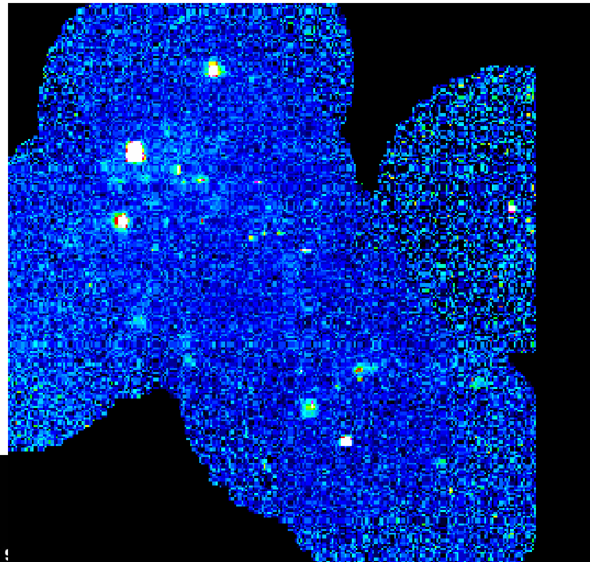
Each image is about 4°.5 on a side (9x moon's diameter)

The SMC

- Distance 58 kpc
- Dwarf Irregular
  - Type Irr
- NGC1978
  - Active star forming region
- $L \approx 3.4 \times 10^{8}\ L_{\odot}$
- 47 Tucanae
  - MW Globular Cl



Xray: ROSAT



AAO optical 3 color

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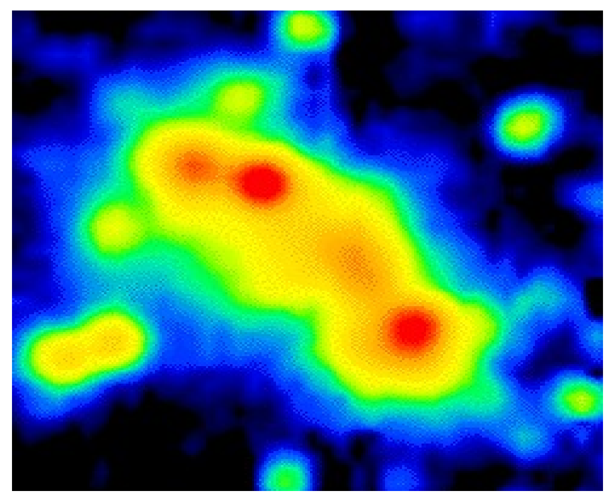
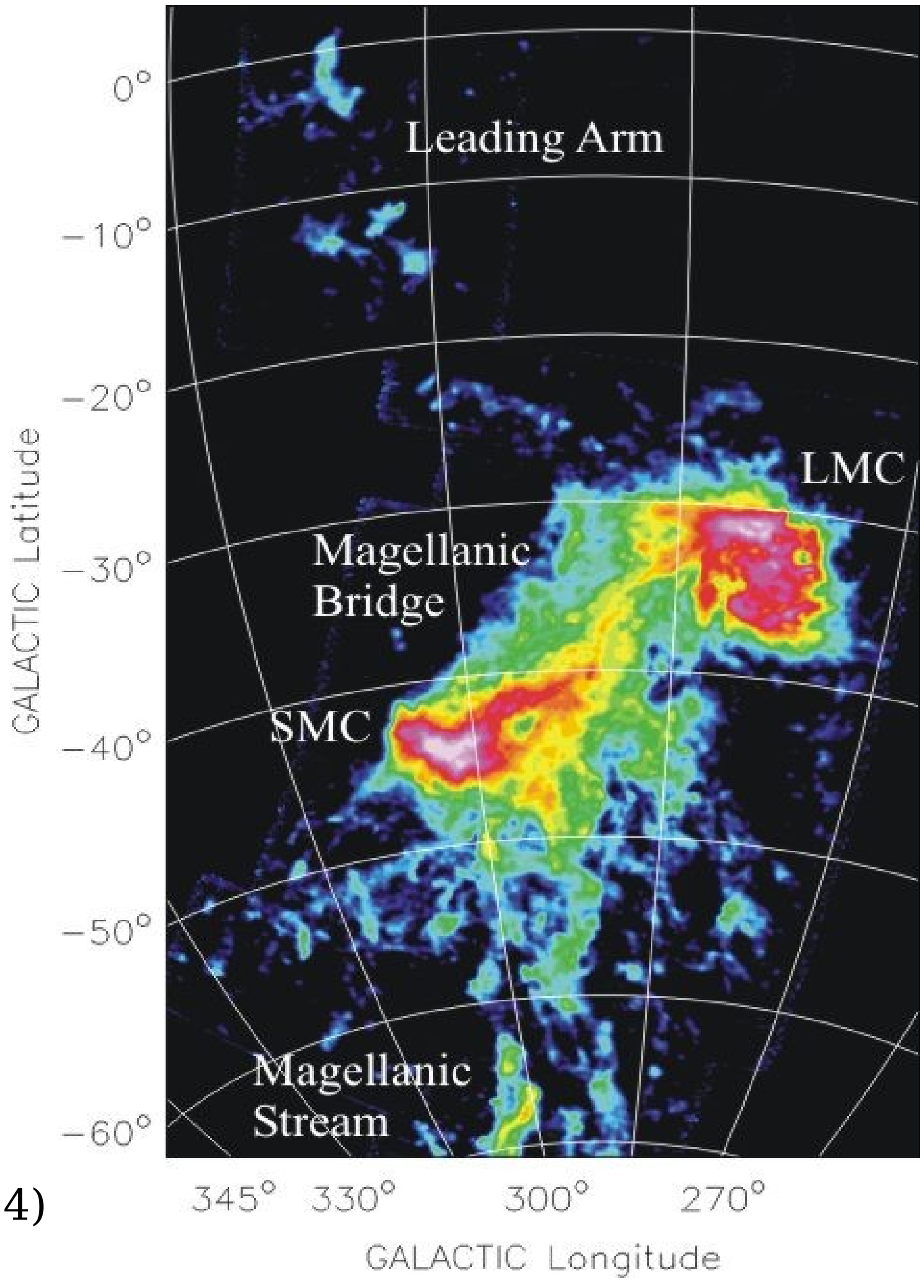


Radio (RAIUB/MPIFR Bonn)

Each image is about 4°.5 on a side (9x moon's diameter)

- Clues to the MC's dynamics
  - Common HI envelope
  - Stream of gas “following” the MC's

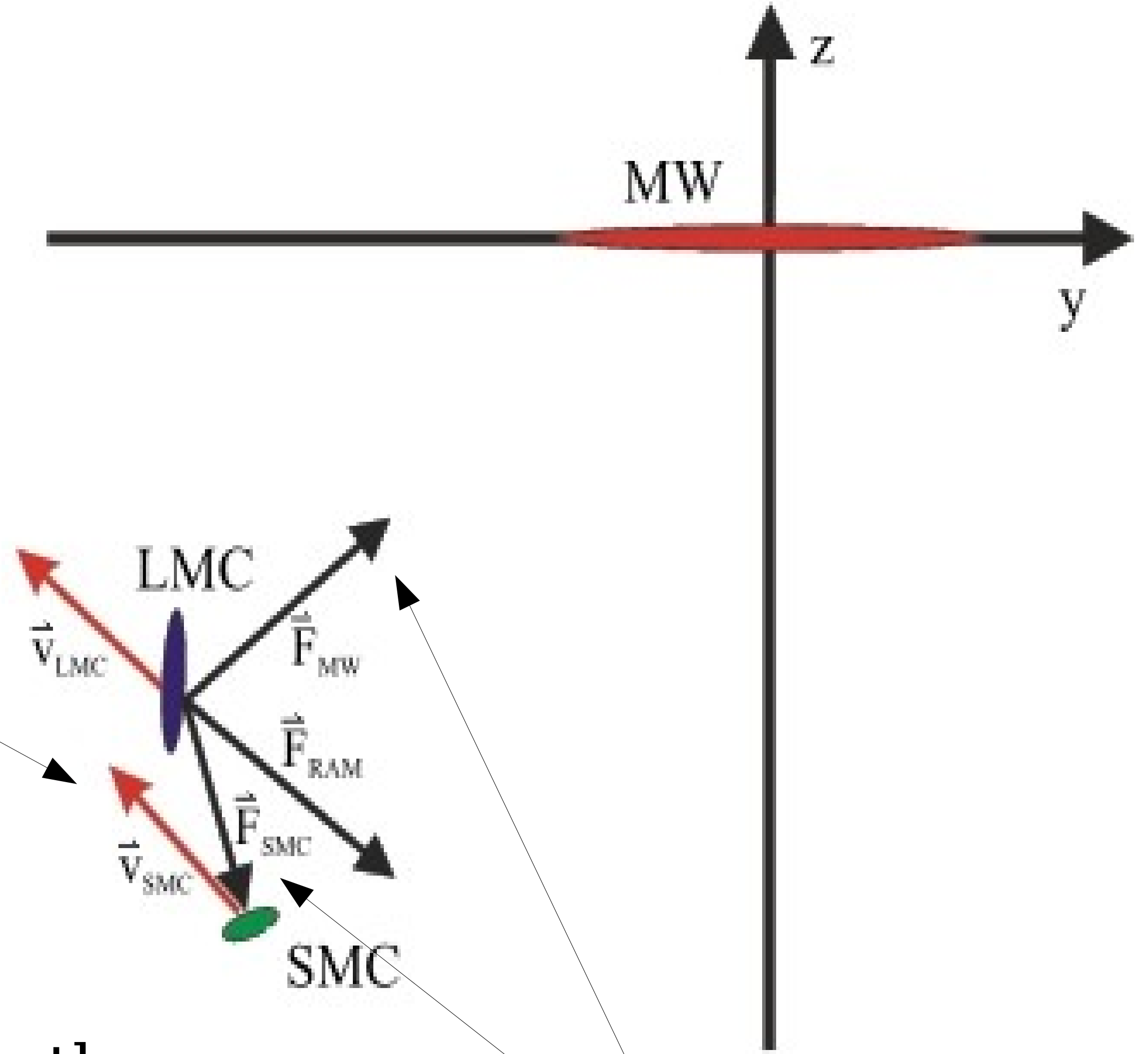
Magellanic Bridge (Hindman 1961)
Magellanic Stream (Mathewson et al. 1974)
Leading Arm (Putman et al. 1998)



(RAIUB/MPIFR Bonn)Brüns et al 2004 A&A

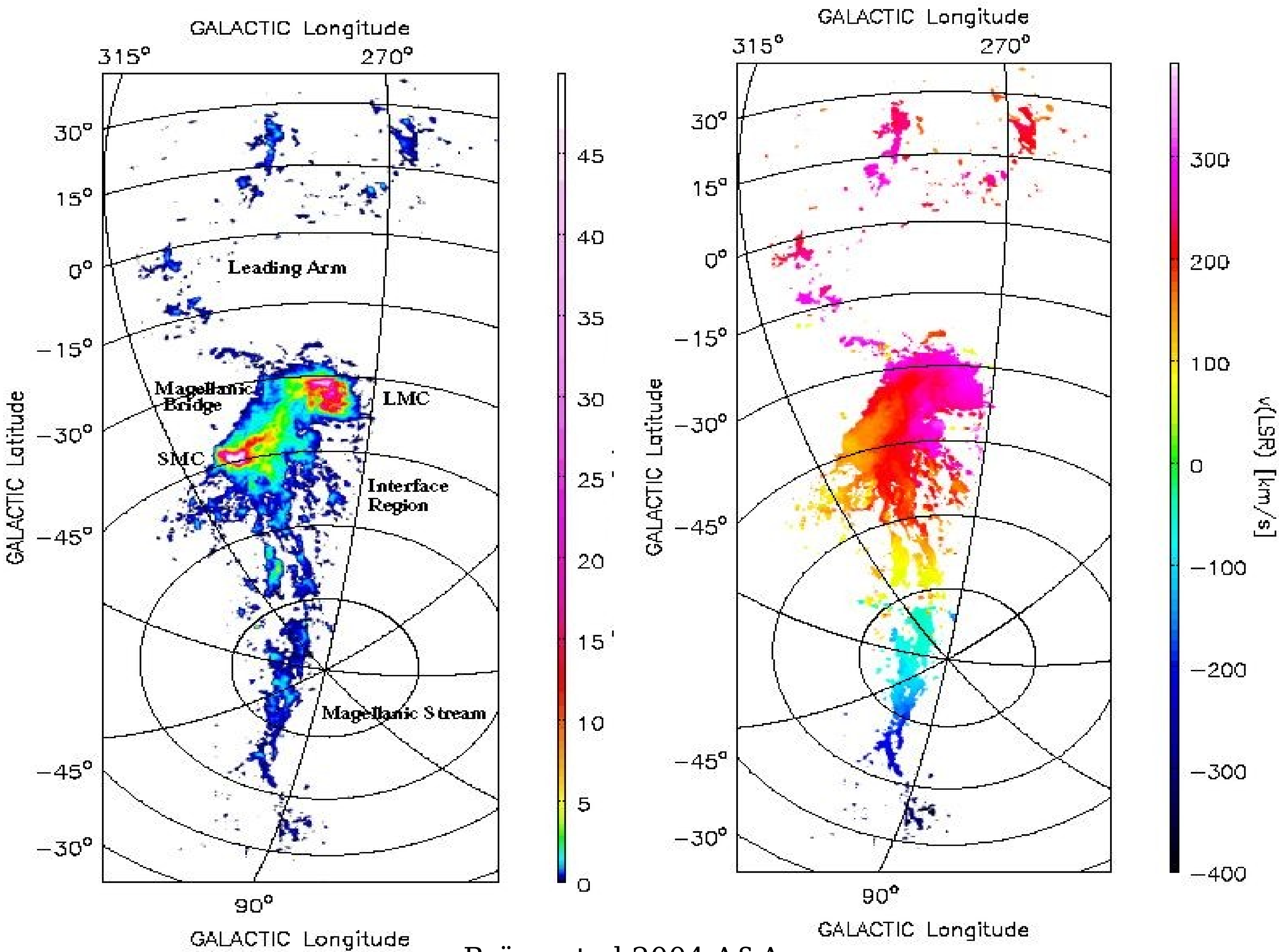
Forces on the Magellanic Clouds

Space Velocity



Ram Pressure is the force on the gas from the gaseous halo of the MW.

Gravitational Force



Brüns et al 2004 A&A

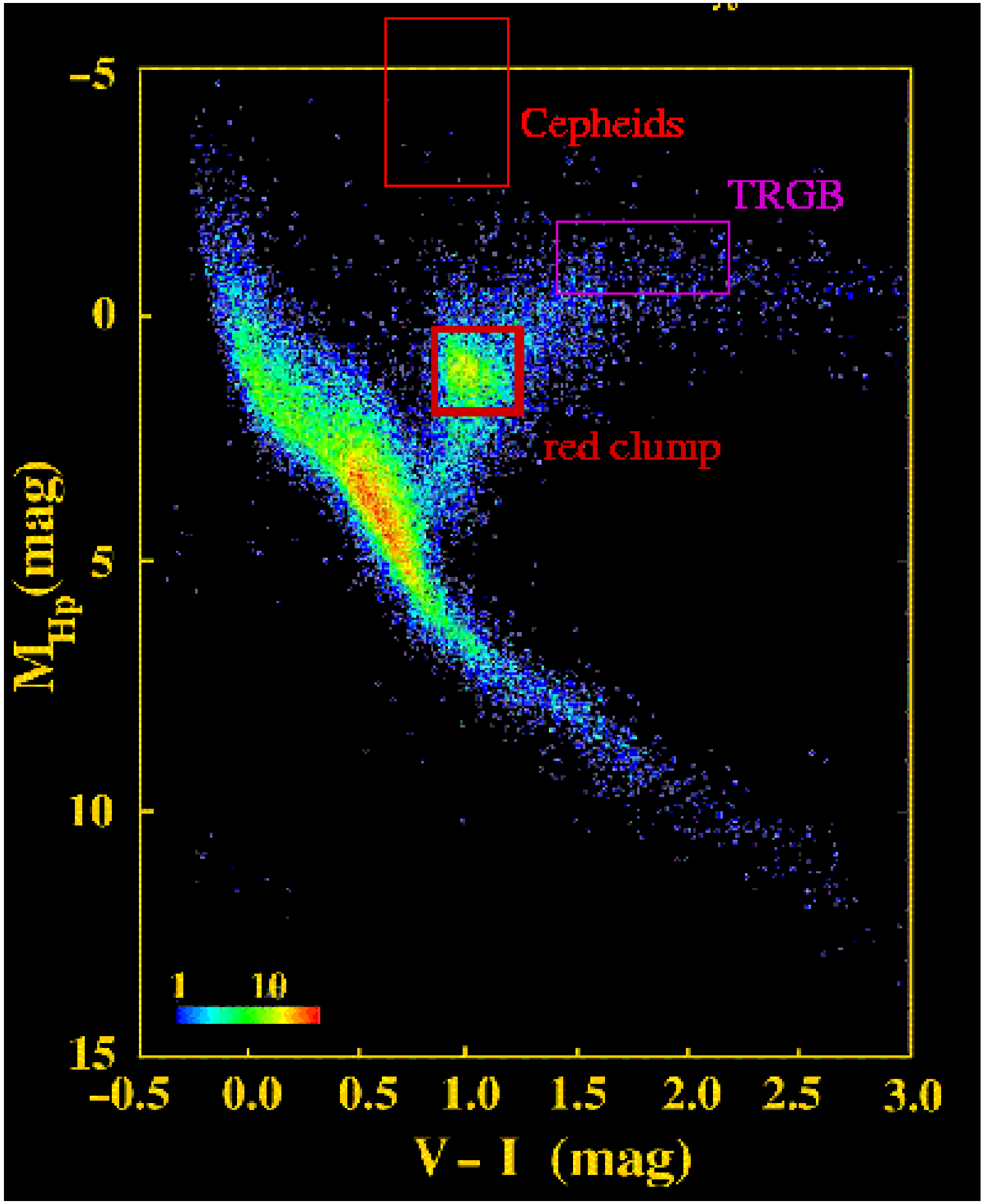
To accurately determine the orbit for the MC's we need the position (x,y,x) and the velocity v_x,v_y,v_z. We can measure the position and the *radial* velocity very accurately but determining the tangent velocity for objects at the distance of the MC's is very uncertain.

v_x, v_y, v_z [km/s] 41±44, -200±31, 169±37
Kroupa & Bastian (1997)

v_x, v_y, v_z [km/s] -56±39, -219±23, 186±35
van der Marel et al. (2002)

We also need the distance to the LMC

- Distance Indicators
  - Cepheid Variables
    - Very accurate
    - Very rare
  - RR Lyrae variables
    - Only one close Enough to be Measured accurately

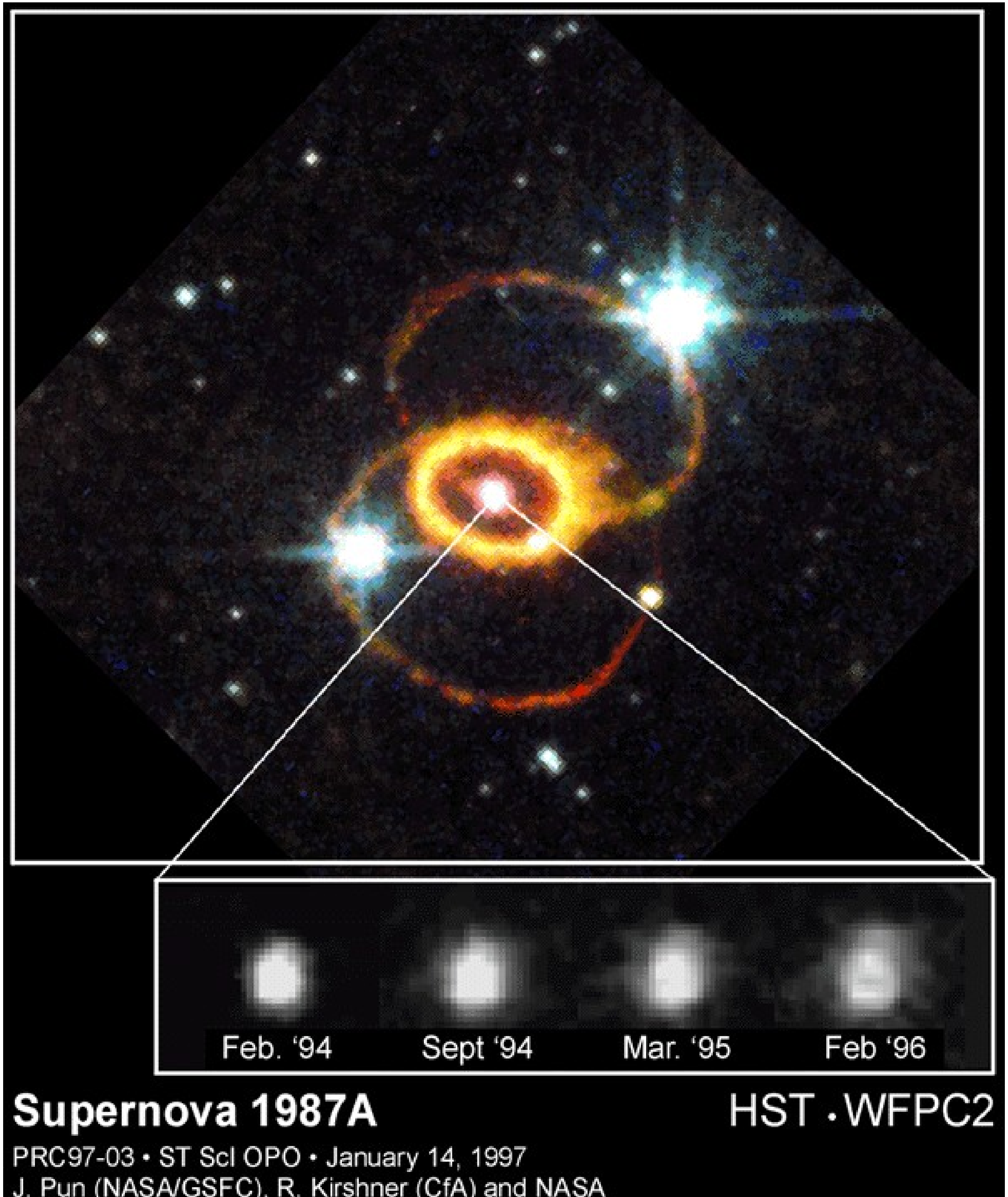


- Main Sequence Fitting
  - Compares HR diagram for stars in clusters – can get accurate relative distances
    - Problem – the LMC has a different chemical composition than the MW so we have to also apply a theory to do the comparison
- Tip of the Red Giant Branch
  - Many of these type stars are close enough for Hipparcos to measure their distance in our Galaxy and get absolute magnitudes.
    - Problem – Chemical composition again

- The Red Clump
  - Stars burning He -> Carbon tend to lie in one area of the HR diagram
    - Problem – astronomers cannot agree if all red clump stars are the same or do their properties vary from galaxy to galaxy
- Supernova 1987a

Supernova 1987A

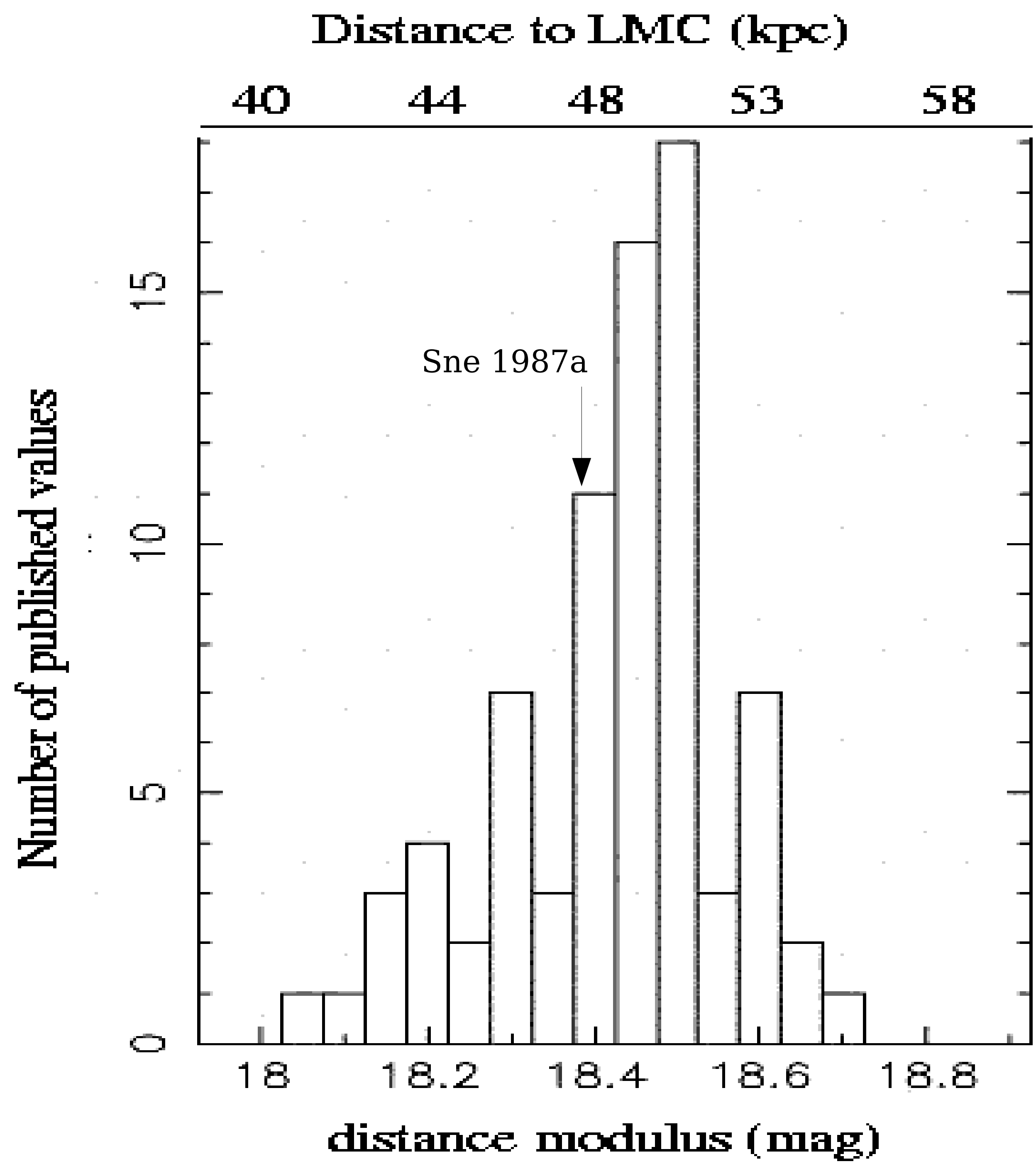
PRC99-04 • Space Telescope Science Institute • Hubble Heritage Team (AURA/STScI/NASA)



We know when then Sne exploded and when the rings lit up from the explosion. Thus the distance is d = t/c. We can measure the spectum of the rings and derive a velocity and if they were ejected from the star the two distance measurements match. So we think we know the absolute size of the rings and thus the distance to the Sne and the LMC!

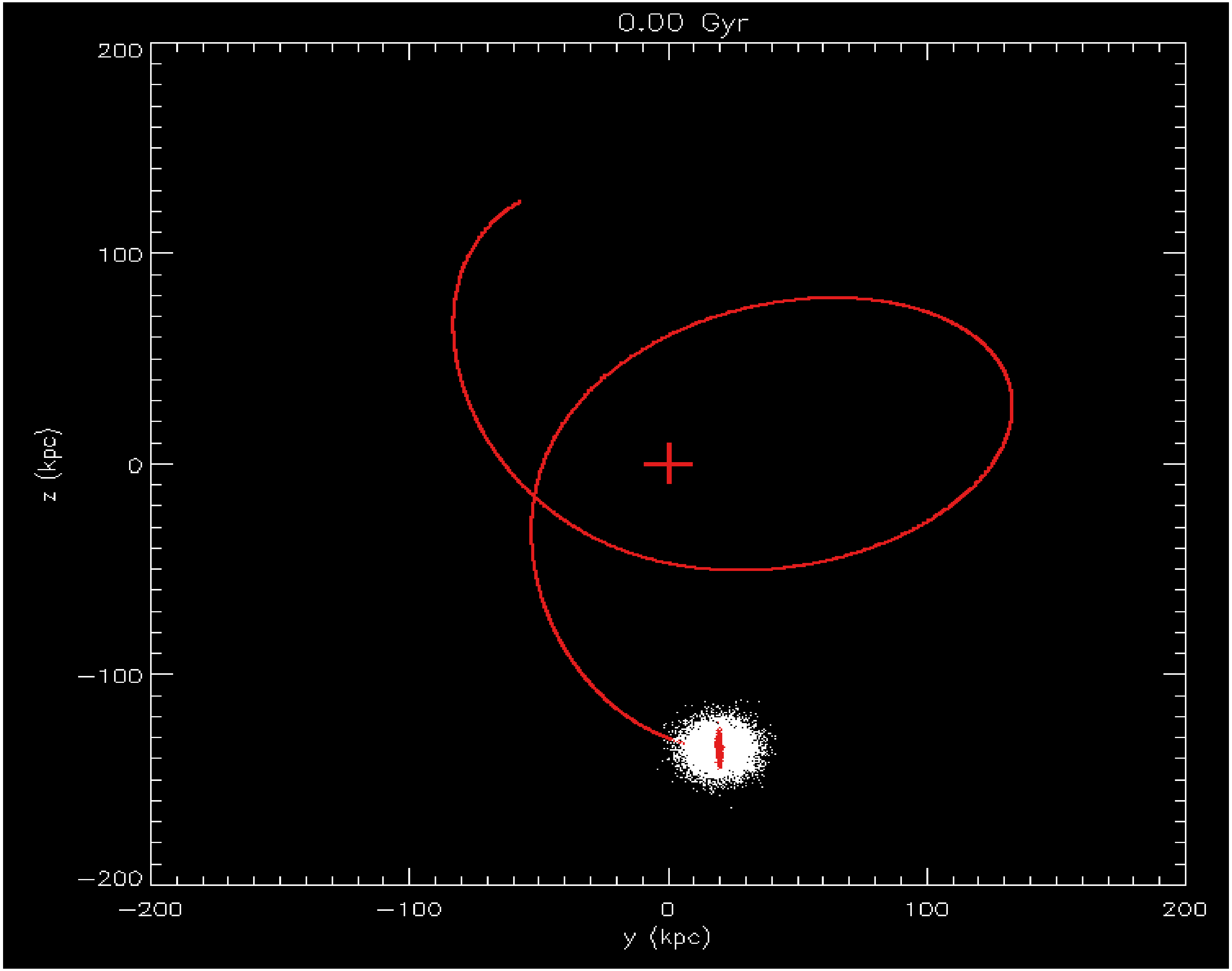
Distance Measurements to the LMC

Method	LMC Distance (kpc)		
RR Lyrae	45 +/- 7		
	46 +/- 4		
	51 +/- 10	Kovacs (2000)	
MS Fitting	52 +/- 3		
Binaries	48 +/- 3	Nelson et al. (2000)	Same system
	44 +/- 6	Udalski et al. (1998)	VV2274
	41 +/- 13		
TRGB	52 +/- 5		
	51 +/- 6	Cioni et al. (2000)	
Red Clump	44 +/- 6		
	52 +/- 5		
Mira type	50 +/- 9		
SN 1987a	52 +/- 4		
	47 +/- 2		

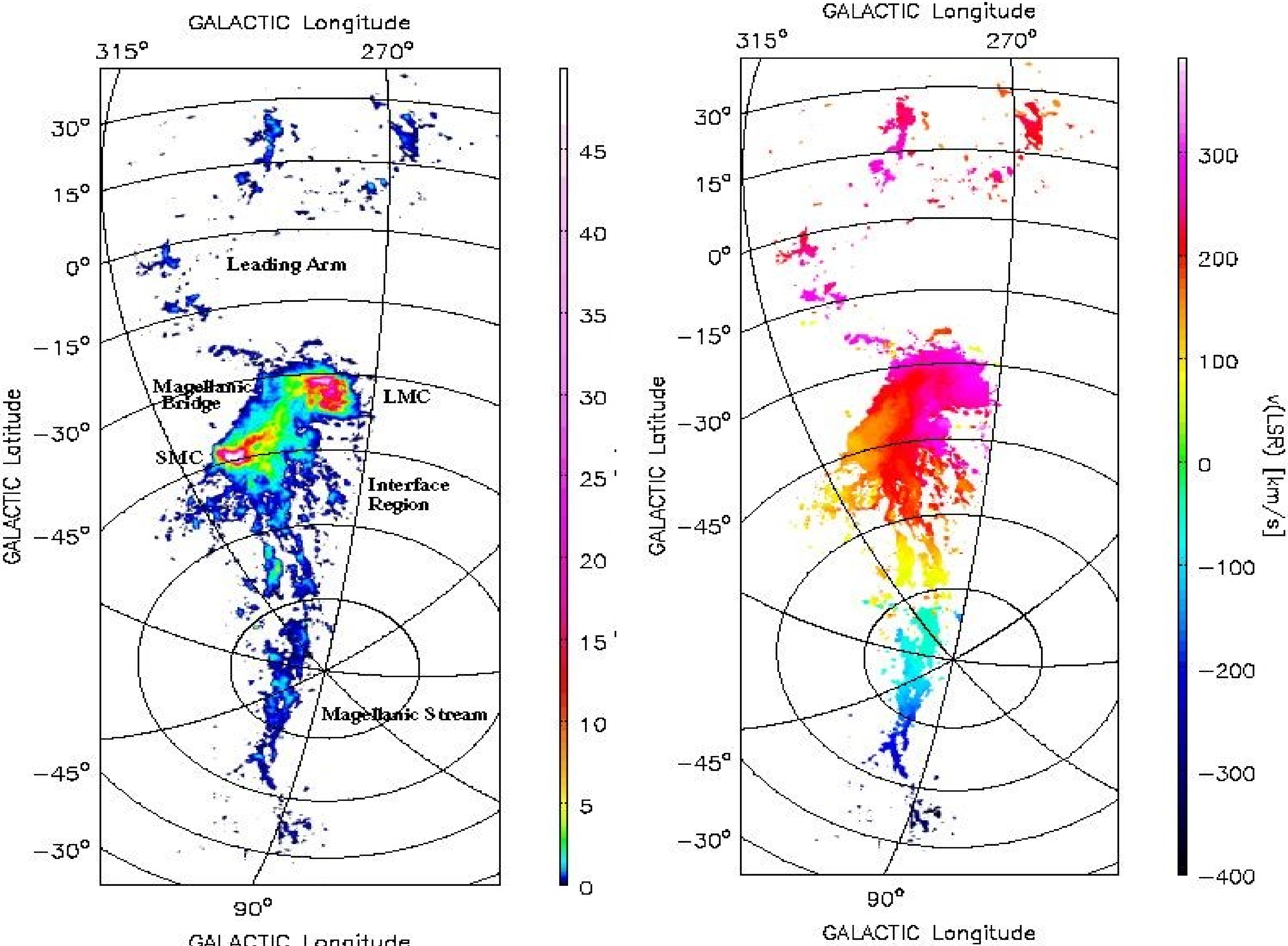


Distance to LMC (kpc)
40
44
48
53
58
Sne 1987a
Number of published values
0
5
10
15
18
18.2
18.4
18.6
18.8
distance modulus (mag)

So now we have all the information we need to model the system and find out the fate of the Magellanic Clouds. The simulation consists of 65k masses. Now the luminosity of the LMC is $L \approx 1.7 \times 10^9\ L_\odot$ so if each star in the LMC was like the sun there would 10^9 stars. So each mass in the simulation represents $\approx 10^4 M_\odot$.

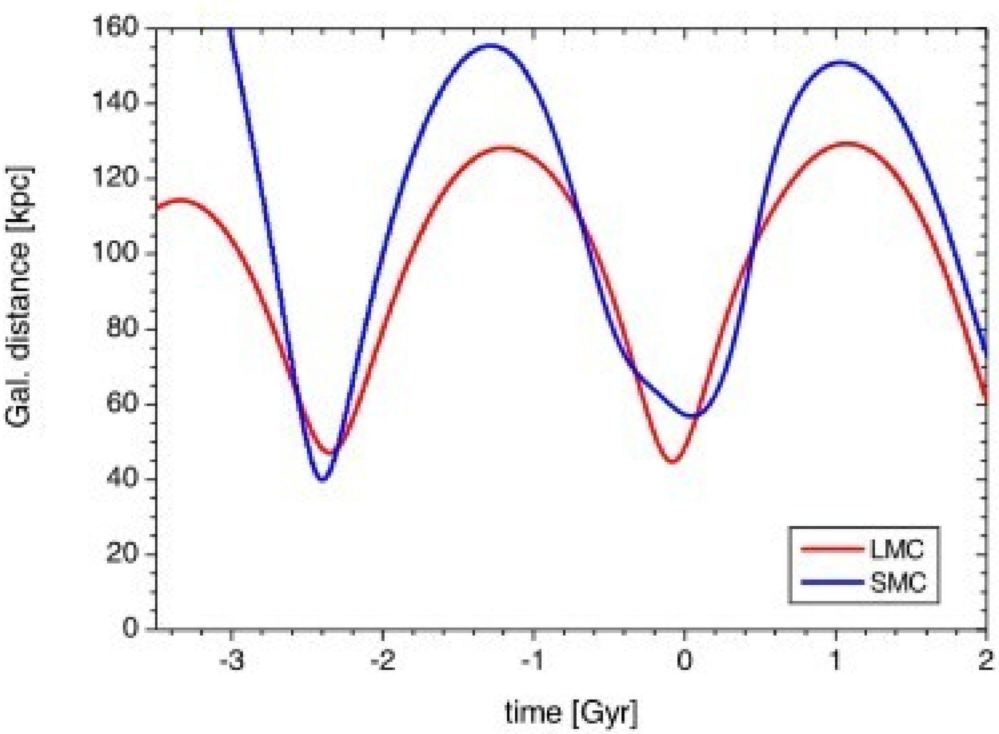


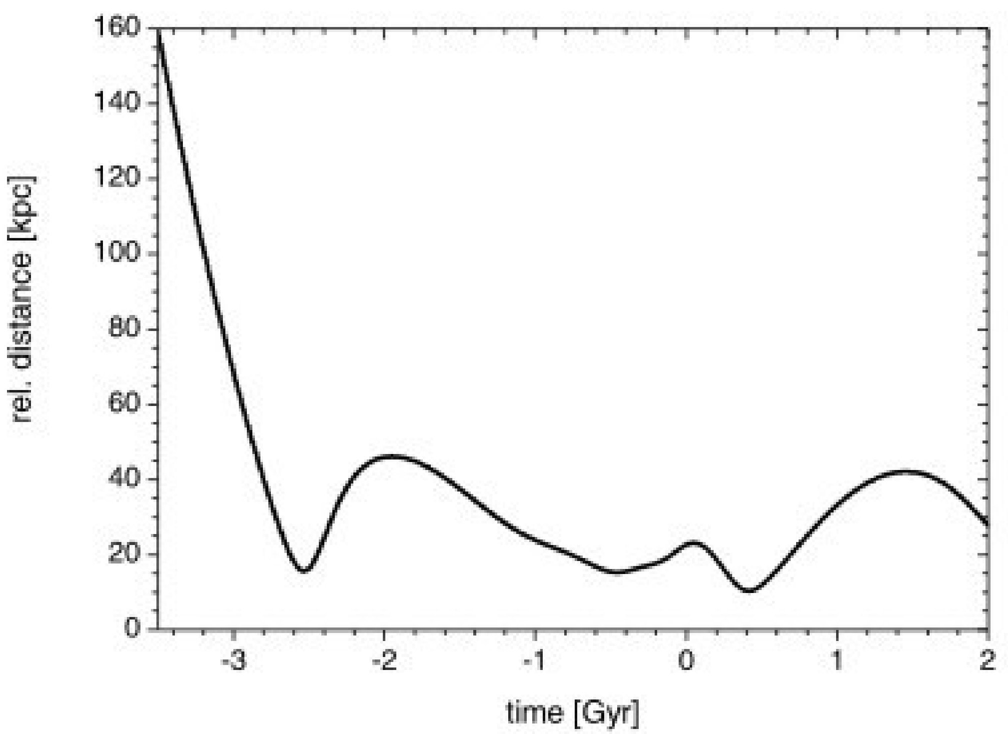
Simulation from R.C. Brüns University of Bonn

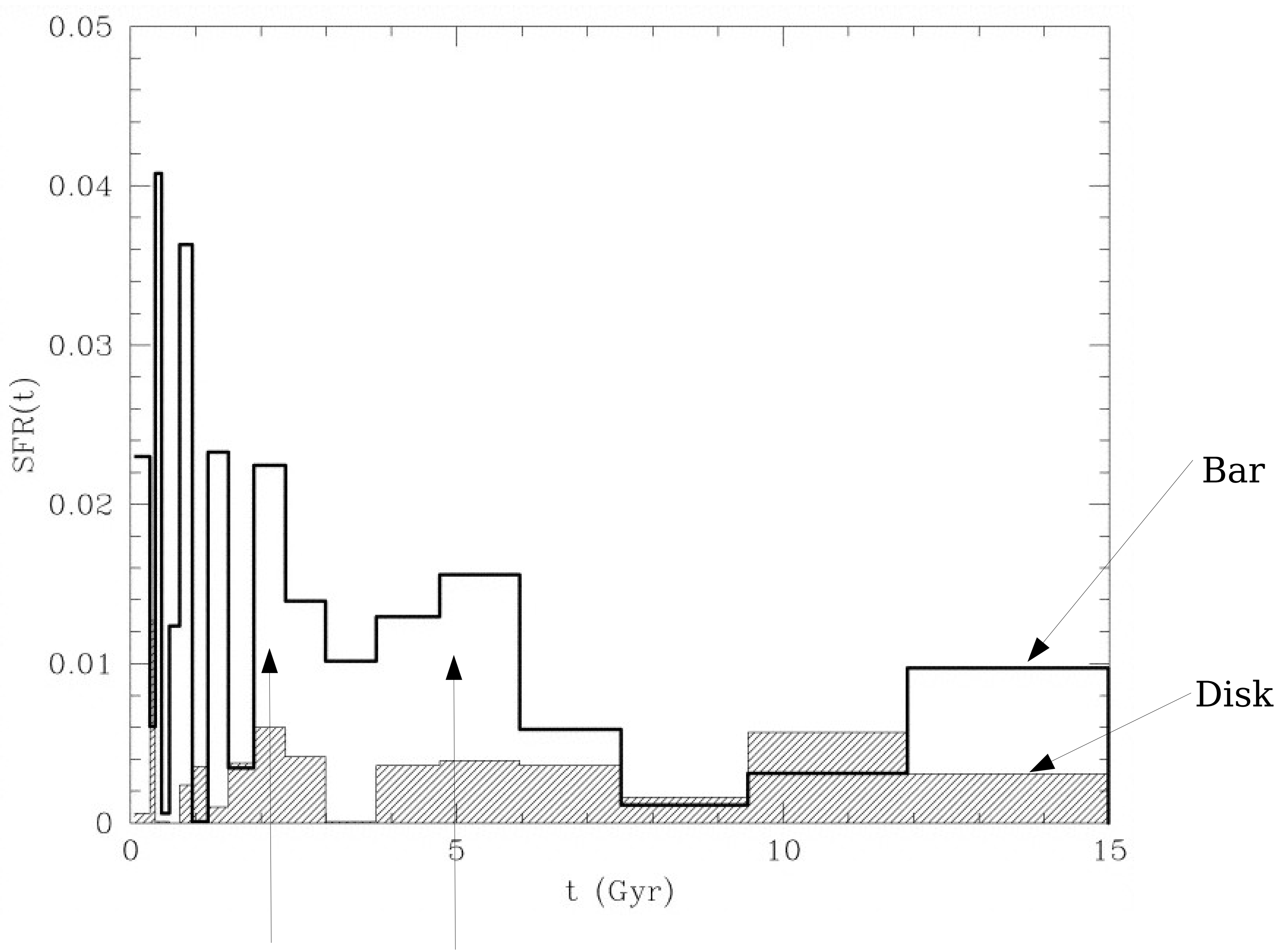


Brüns et al 2004 A&A

In addition to the orbiting the MW the LMC and SMC also orbit each other. On the left you can see that the MC's orbit the Galaxy with distances between ~40 kpc and 150kpc over a 2.5 Gyr period. The two clouds have several close encounters (~15 kpc) but do not merge over the simulation time.







Bar shows two episodes of star formation at 4-6 Gyr and at 1-2 Gyr (Smecker-Hane 2002).

Questions Local Group galaxies can answer

- Is there relationship between dwarf irregular (dIrr) and dwarf spheroidal/dwarf elliptical (dSph/dE) galaxies? The Local Group contains low-luminosity galaxies of both types and this provides some ways to address this question (e.g. Bothun et al 1986, Binggeli 1994, Skillman & Bender 1995).
- Low-luminosity dwarfs tend to be metal poor; thus, the low luminosity dwarfs in the Local Group represent a sample of galaxies that is still largely composed of nearly primordial material.

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- They play an important role in addressing the DM problem, allowing us to map the distribution of DM and placing constraints on the nature of the DM. In fact, dwarf galaxies are among the “darkest” galaxies known.
- There is ample evidence that interactions play an important roll in the evolution of of these systems e.g. The LMC and SMC.
- The large luminosity range of Local Group dwarfs makes them excellent labs to study how other fundamental parameters vary with luminosity, such as DM content, the interstellar medium (ISM) properties, and star-formation history.
- Dwarfs are the simplest galactic systems known. However, Local Group dwarfs also show that simple is a relative term. The star formation history of these systems is complex and the trigger for star formation in these galaxies is still an area of active research.

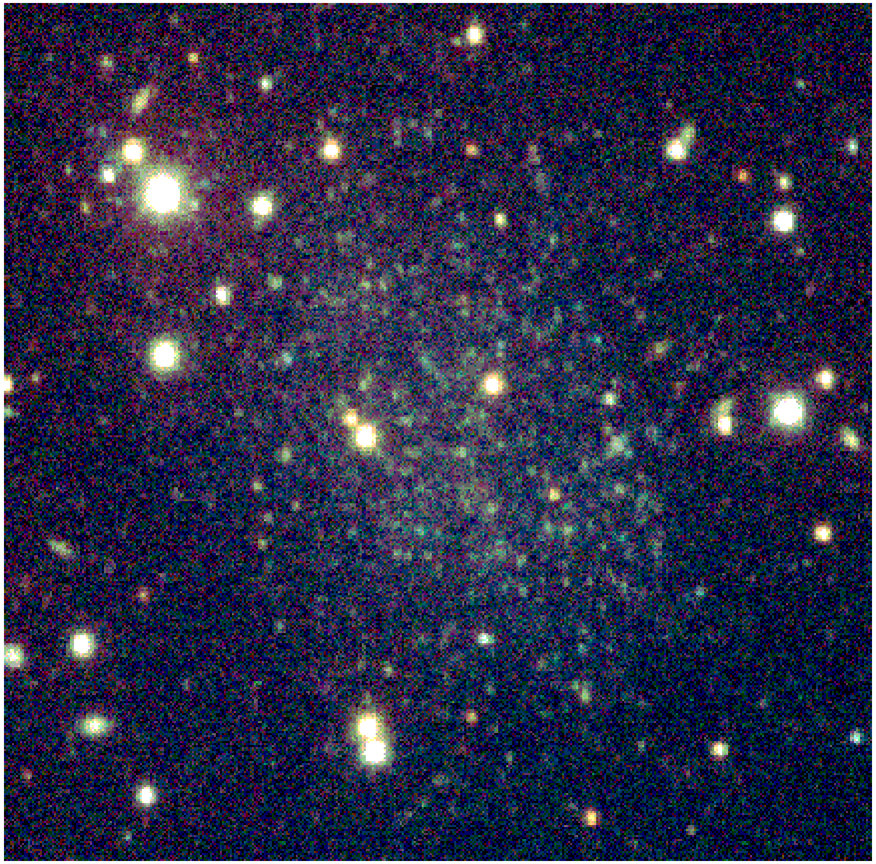


Image NOAO, Antlia dwarf galaxy
D ~ 1.1Mpc and contains only
about 10^6 stars.

Image APOD, AAO
Dwarf galaxy Leo I
D~250 kpc

Image APOD,
Pegasus dSph
D~760 kpc

Image APOD,
NGC 205 Dwarf elliptical near
M31. D~830 kpc

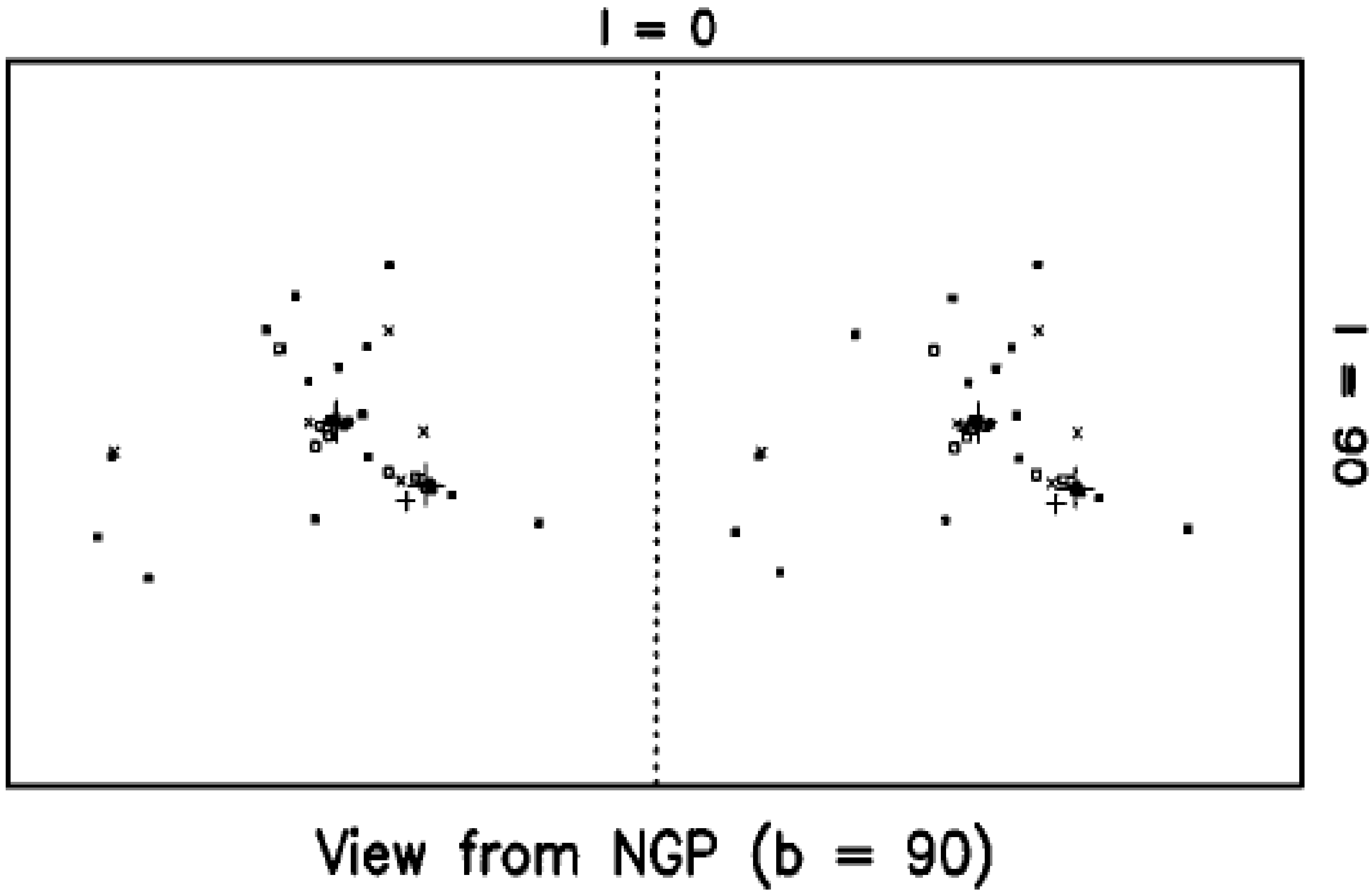
Spatial structure in the local group

The large number of galaxies in the local group we can start to look at the structure of our group.

Two conspicuous concentrations of galaxies are around the MW and M31 and consist of a mixture of dIrr and dSph/dE galaxies.

There is a third “cloud” more diffuse than the ones around the MW and M31 and is mostly dIrr.

The fourth group is relatively isolated from the other three groups and contains NGC 3109 (Irr) as its brightest member.



Stereoscopic of the local group (Mateo ARAA 36,435)

Optically the dIrr galaxies are dominated by bright OB associations and star forming regions with typical diameters of 200 – 300 pc.

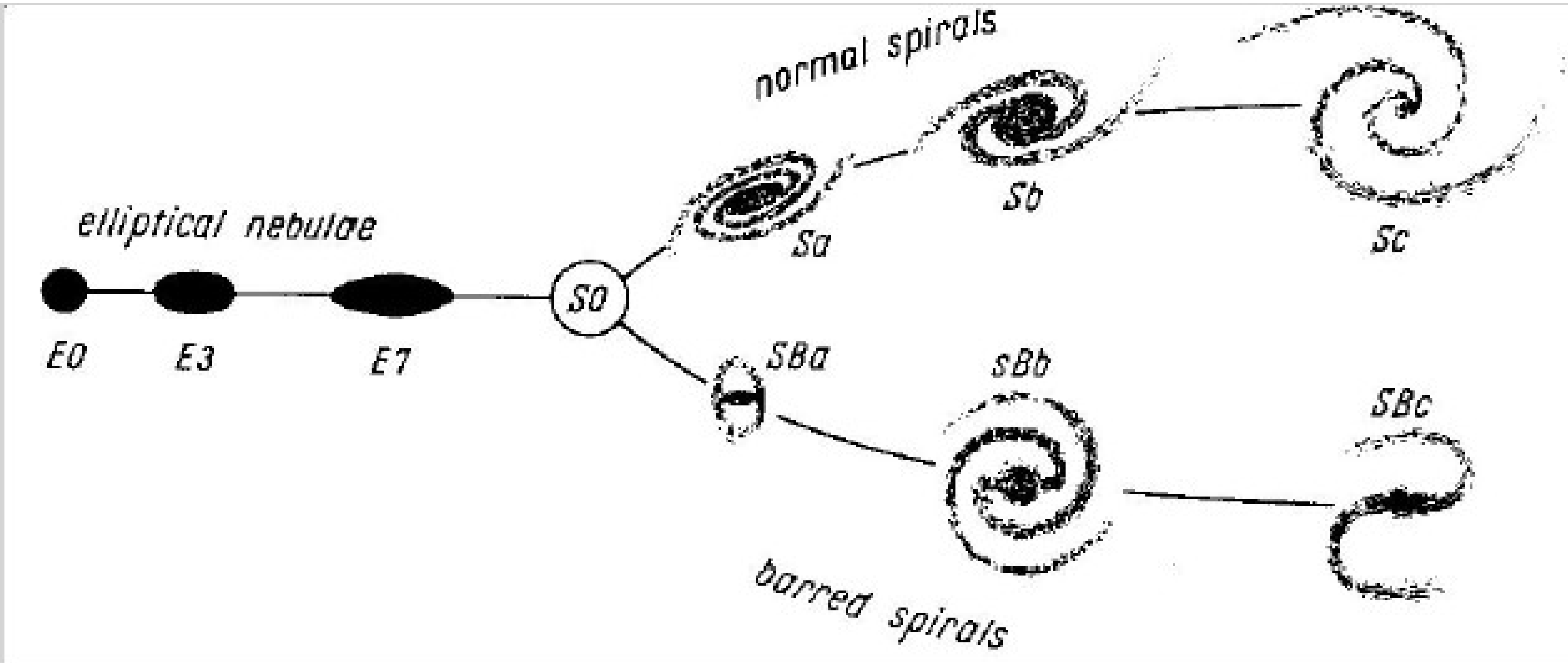
These regions are rarely located at the centers of the system. The dIrr NGC 3109 shows evidence of a faint spiral structure (like the LMC) and all these galaxies have a smooth population of older stars underlying the star forming regions and OB associations.

The dE systems are dominated by a smooth spherically symmetric component with star forming regions only seen occasionally. The star forming regions in these systems are much closer (but not coincident) with the nucleus.

- Irr galaxies contain a large amount of HI gas
  - 7% - 50% of the total mass
  - HI gas is mostly in clumps 100 - 300 pc
- HI clumps are often associated with star forming regions
- Dust is prevalent and is also clumped D~10-20pc

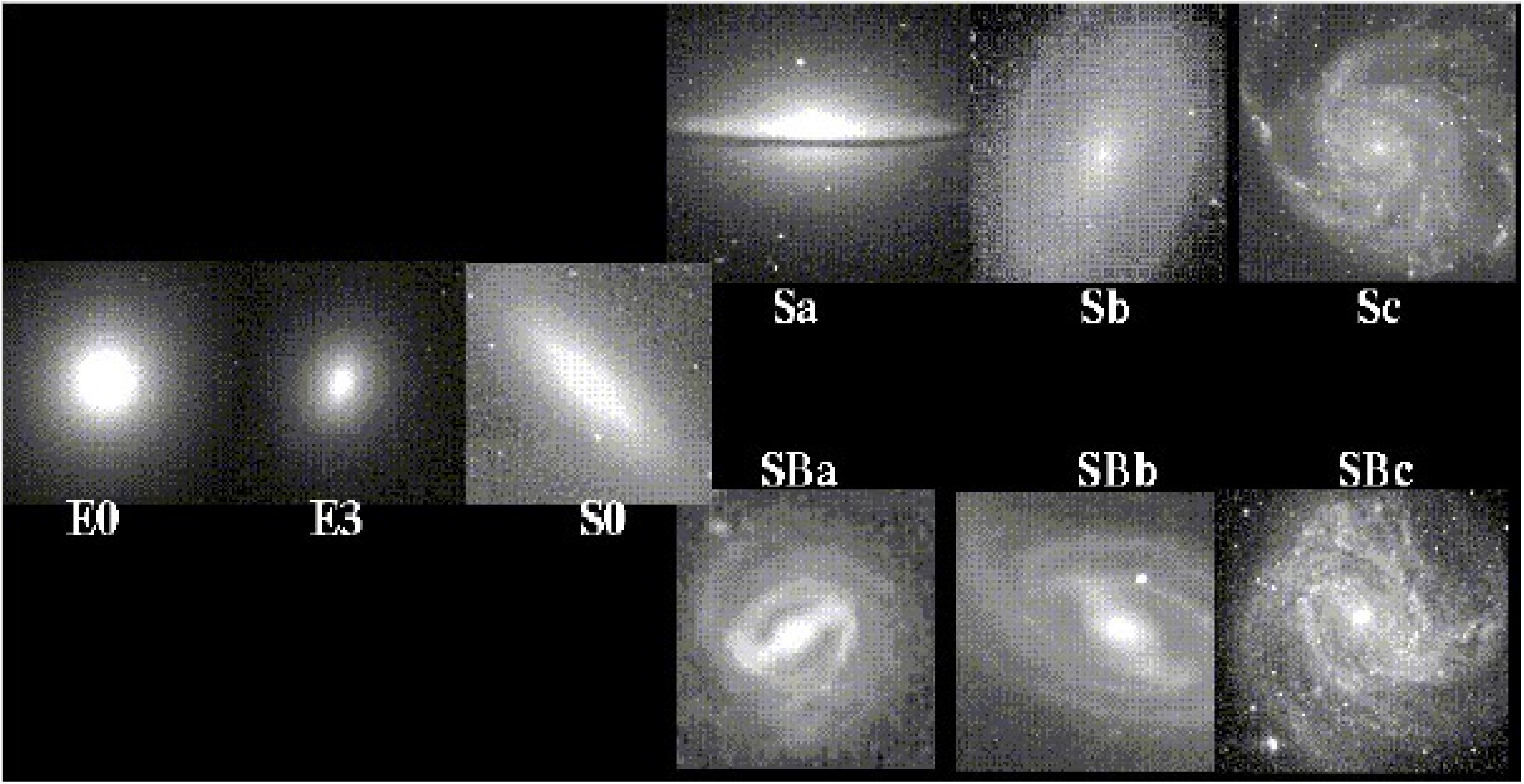
- dE galaxies contian little or no HI gas and most systems only have upper limits.
  - NGC 185 and NGC 205 do have some HI gas
  - 0.05% of the total mass
- HI gas is near the nucleus
- Some dust mostly near the core

Galaxy Classification



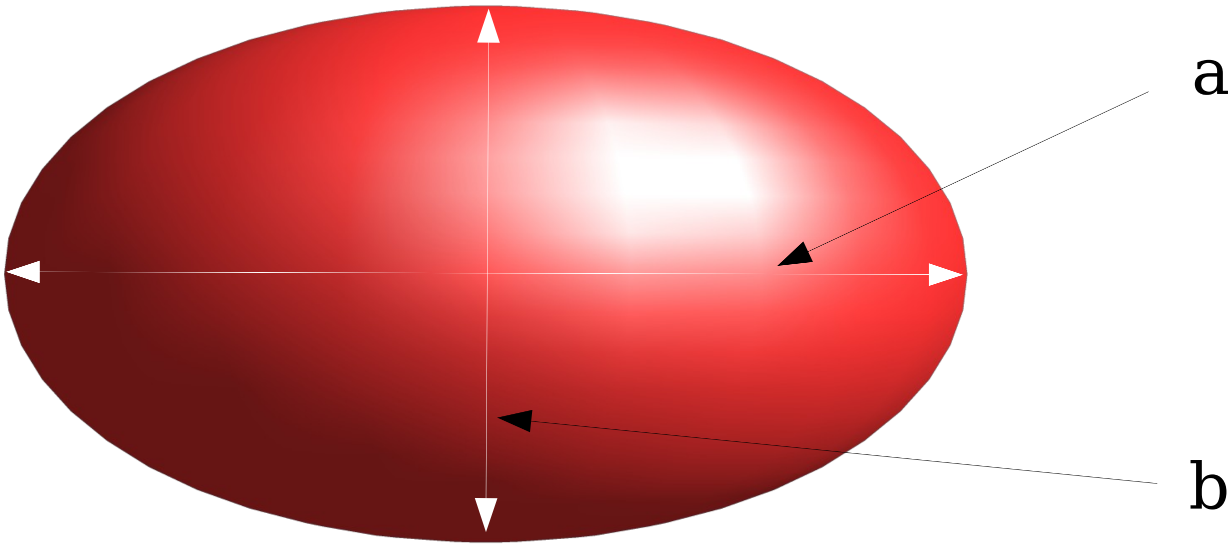
Edwin Hubble (1936) outlined the first widely accepted galaxy classification scheme based on how he thought the different forms evolved. Often called the tuning fork diagram.

Early type ---> Late type

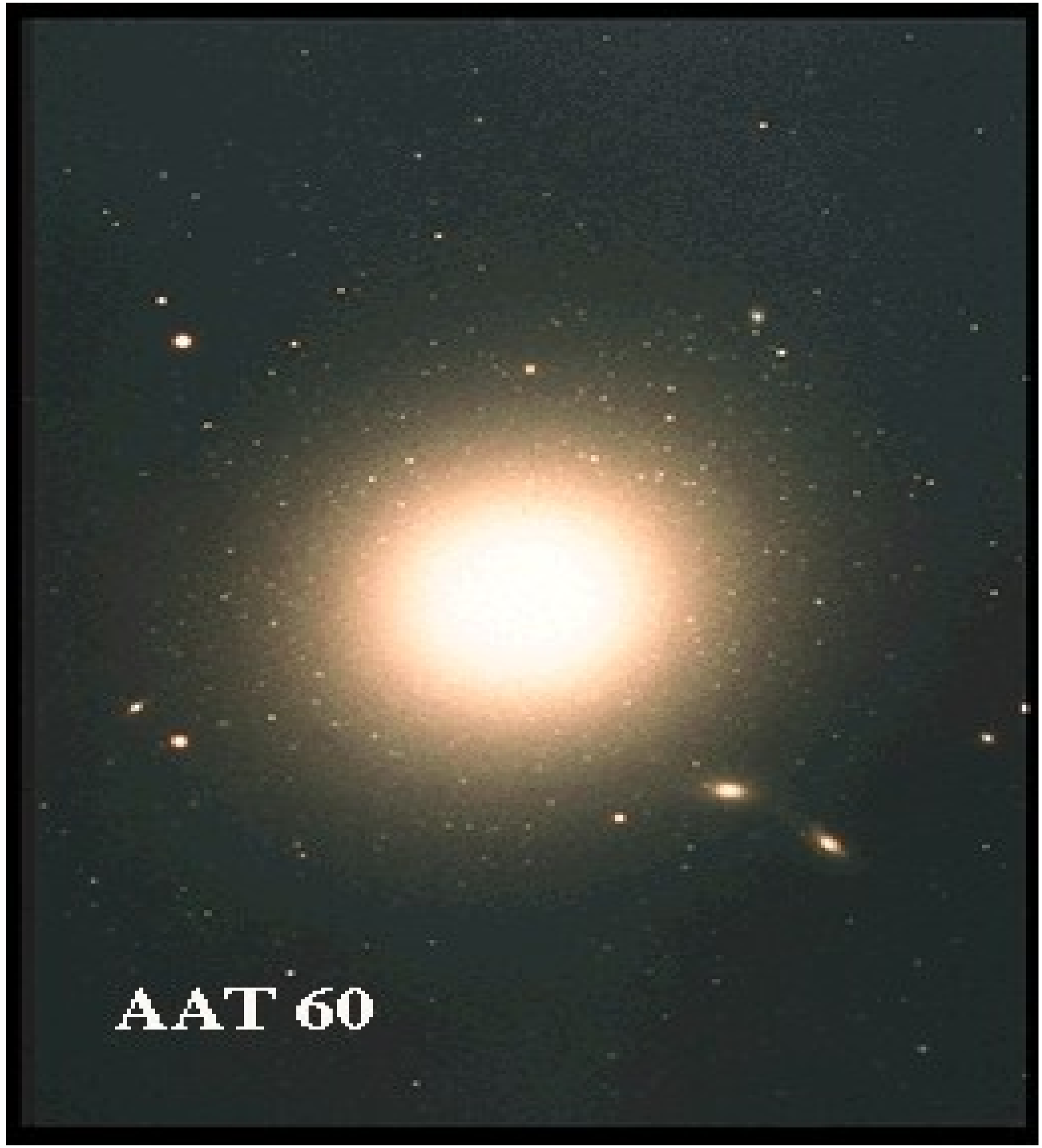


Tuning fork diagram using real galaxies. We now know this is NOT an evolutionary sequence.

Elliptical Classification



Define ellipticity as ϵ = 1 – b/a, this is used in their classification, b/a = 1 – n/10, to get En classification.



M87 (NGC 4486) E3pec

Spiral galaxies are named for their bright spiral arms, which are prominent due either to bright O and B stars (evidence for recent star formation), and/or to dust lanes.

Define two sequences of spiral galaxies:

Sa -> Sb -> Sc -> Sd in order of decreasing bulge size.

And

SBa -> SBb -> SBc -> SBd again in order of decreasing bulge size but with a bar in the center.

M101 HST

NGC 1365 APOD

Transition class between ellipticals and spirals are the S0 galaxies, also called lenticulars. S0 galaxies have a rotating disk in addition to a central elliptical bulge, but the disk lacks spiral arms or prominent dust lanes.

Lenticulars can also have a central bar, in which case they are labeled SB0.

Hubble dubbed galaxies that didn't fit into his scheme irregular Today: irregular galaxies are defined as small blue galaxies lacking any organized spiral structure. Other types of galaxy Hubble called irregular are now identified as starburst or interacting galaxies. These have a disturbed appearance due to recent episodes of violent star formation, or close encounters with other galaxies.