Distances to Spiral Galaxies

- Distance can be computed from Hubble Law ($D=H_0v$)
  - But that is only *after* we can calibrate the relation
  - For nearby galaxies we can determine the distance using
    - Cepheids
    - Brightest supergiants
    - Supernova

- Peaks in the HI velocity profile shows where the galaxies has the maximum rotation velocity (los)

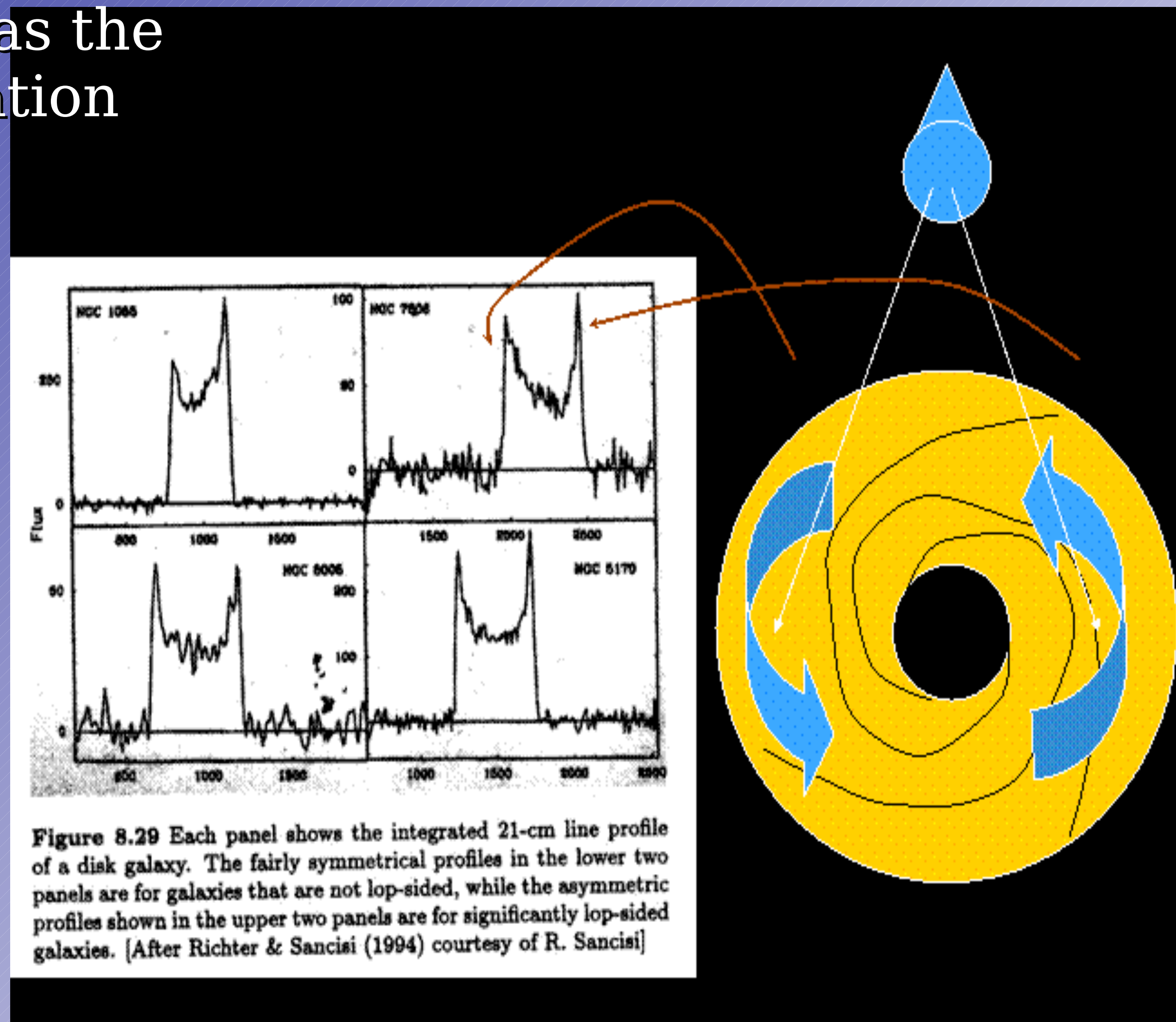


Figure 8.29 Each panel shows the integrated 21-cm line profile of a disk galaxy. The fairly symmetrical profiles in the lower two panels are for galaxies that are not lop-sided, while the asymmetric profiles shown in the upper two panels are for significantly lop-sided galaxies. [After Richter & Sancisi (1994) courtesy of R. Sancisi]

Tully-Fisher Relation

- They noticed that when you plotted the absolute magnitude of a spiral galaxy vs the width of the HI profile you had a linear correlation (Tully & Fisher 1977)

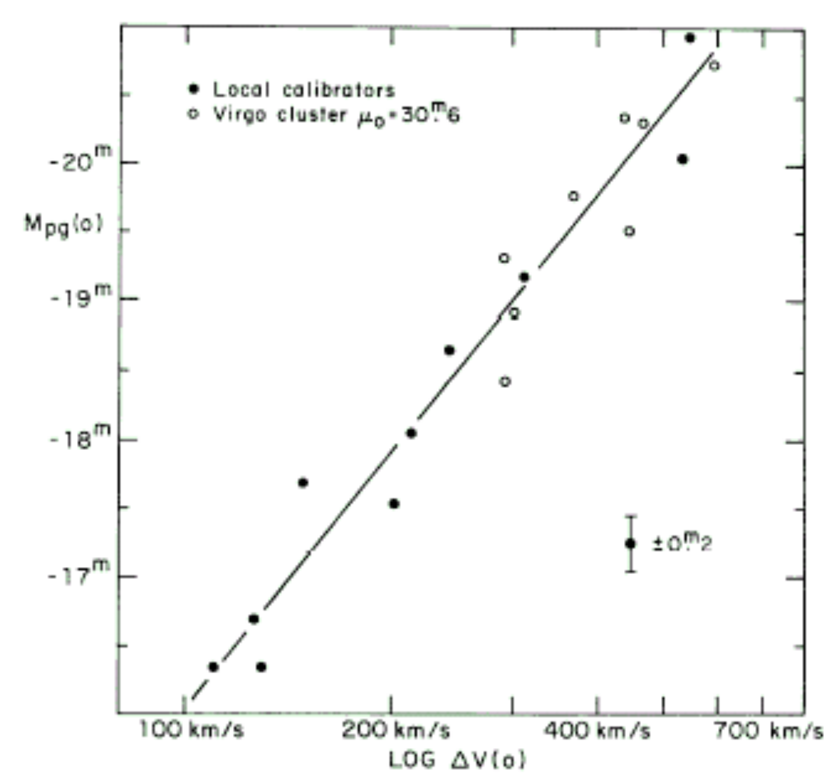


Fig. 5 (a) Absolute magnitude – global profile width relation produced by overlaying Figure 3 on Figure 1, adjusting Figure 3 vertically to arrive at a best visual fit with a distance modulus of $\mu_0 = 30^m.6 \pm 0^m.2$

Tully-Fisher Relation (cont)

- Find that $L \sim V^{\alpha}$, where α depends on the wavelength, $\alpha \sim 4$.
- $M = b \log(W) + a$
  - W is the width of the 21 cm HI line
    - Note: Must correct for inclination: $W = W_{obs}/\sin(i)$
  - Constants a & b are found using nearby galaxies

Tully-Fisher Relation (cont)

Why does this work?
We know that $V^2 = GM/R$ or $M \sim V^2 R$
and that the surface brightness
$\Sigma = L/R^2$ or $R \sim (L/\Sigma)^{1/2}$

We can also measure the mass using a mass-to-light ratio $M = L(M/L)$

so now

$L(M/L) \sim V^2 (L/\Sigma)^{1/2}$

$L^2(M/L)^2 \sim V^4 (L/\Sigma)$

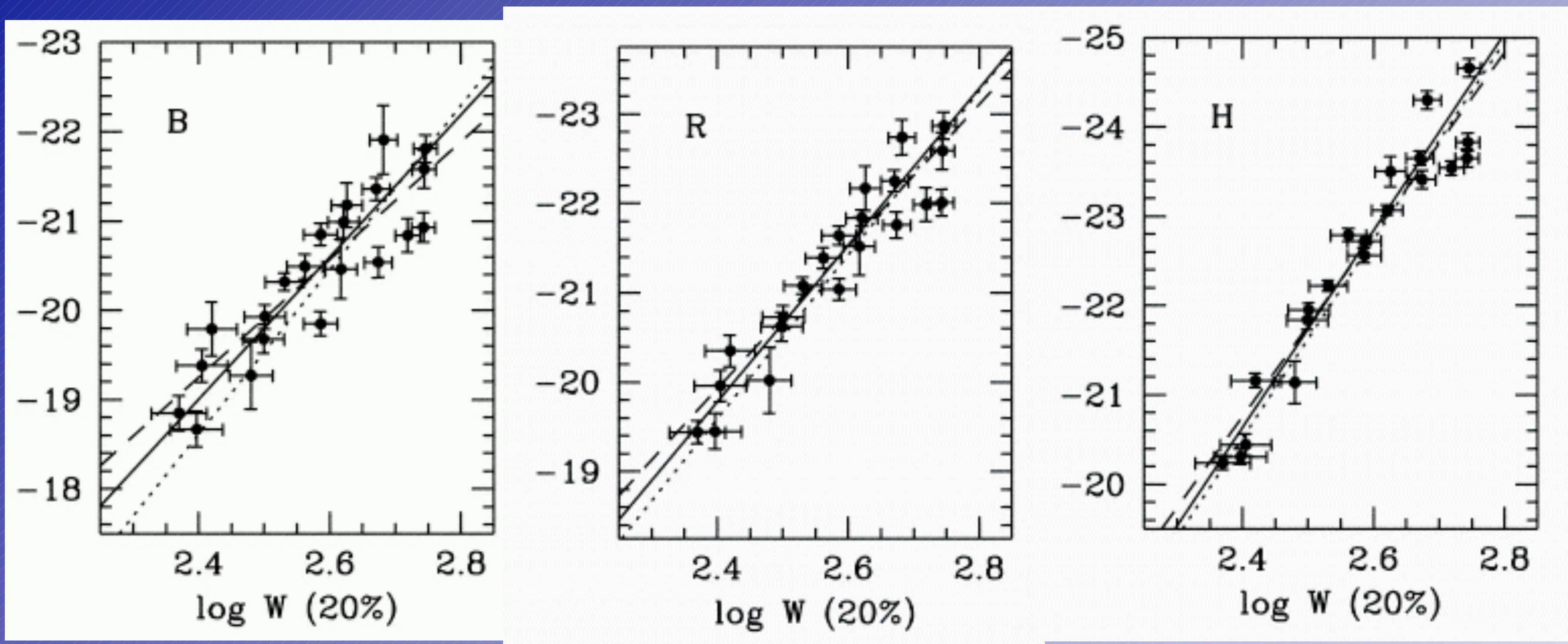
Tully-Fisher Relation (cont)

$L^2 (M/L)^2 \sim V^4 \; (L/\Sigma)$

$L \sim V^4 / \{ \Sigma (M/L)^2 \}$

This is where we've hidden the unknowns. This relation only works if the surface brightness and the M/L ratio is a constant. So somehow the mass (including the DM) and the stars "know" about each other!

We don't know how this works but it must be explained by any galaxy formation theory!



α=3.2 with a scatter of 0.25 mag

α=3.5 with a scatter of 0.25 mag

α=4.4 with a scatter of 0.19 mag

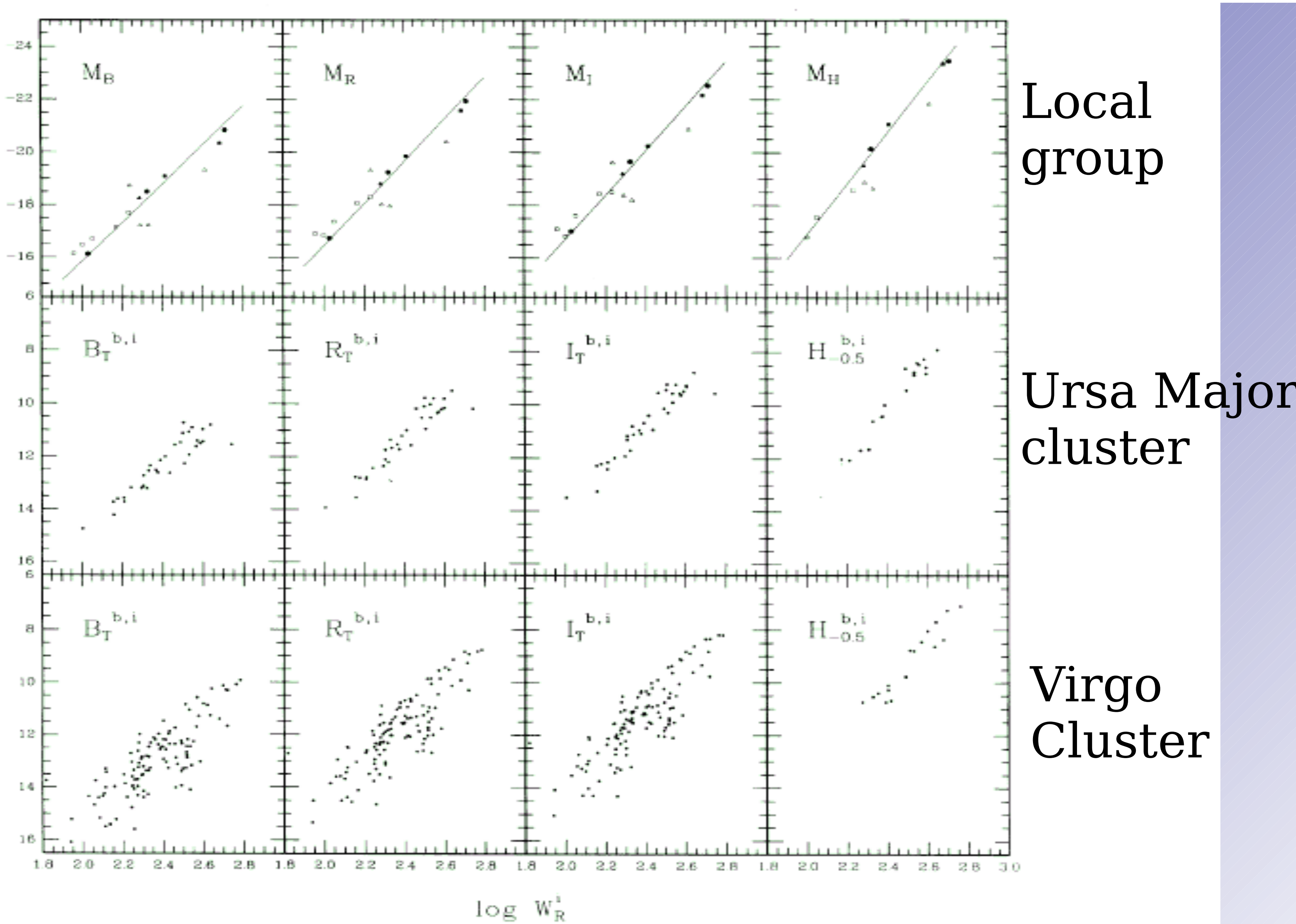


FIG. 11—*B*-, *R*-, *I*-, and *H*-band Tully–Fisher relations for the Local Calibrators (top), Ursa Major cluster members (middle), and Virgo cluster members (bottom). It is apparent from the figures that the slope of the relations increases going to longer wavelengths and the dispersion decreases. The variation in slope is thought to arise from the differing contributions to the observed bandpass made by greater fraction of young stars found in the lower-luminosity systems. The smaller dispersion at longer wavelengths is likely due to a reduction in the sensitivity to these effects, as well as those expected from extinction variations. Note the much larger dispersion found for the Virgo cluster data.

Jacoby et al. 1992

Tully-Fisher Relation (cont)

- Pros
  - Once calibrated can be used at large distances
  - Can measure the HI linewidth very accurately
  - Can work in the IR band with little dust extinction
  - Measure distances to groups and clusters
- Cons
  - Not sure why it works
    - Hidden systematic effects
  - L can be affected by dust
  - Scatter in the relation so its difficult to measure distances to a single galaxy

Spiral Structure

- There are three basic types of spiral galaxies (ignoring detailed classification)
  - Grand design spirals (~10%)
  - Multi-arm spirals (~60%)
  - Flocculent spirals (~30%)
- Basic questions:
  - What are the arms?
  - Are spiral arms leading or trailing?

Grand Design Spirals

Arms are well defined

Can be traced at least once around the galaxy

About 10% of all spiral galaxies

M100 © Anglo-Australian Observatory
Photo by David Malin

Grand Design Spirals

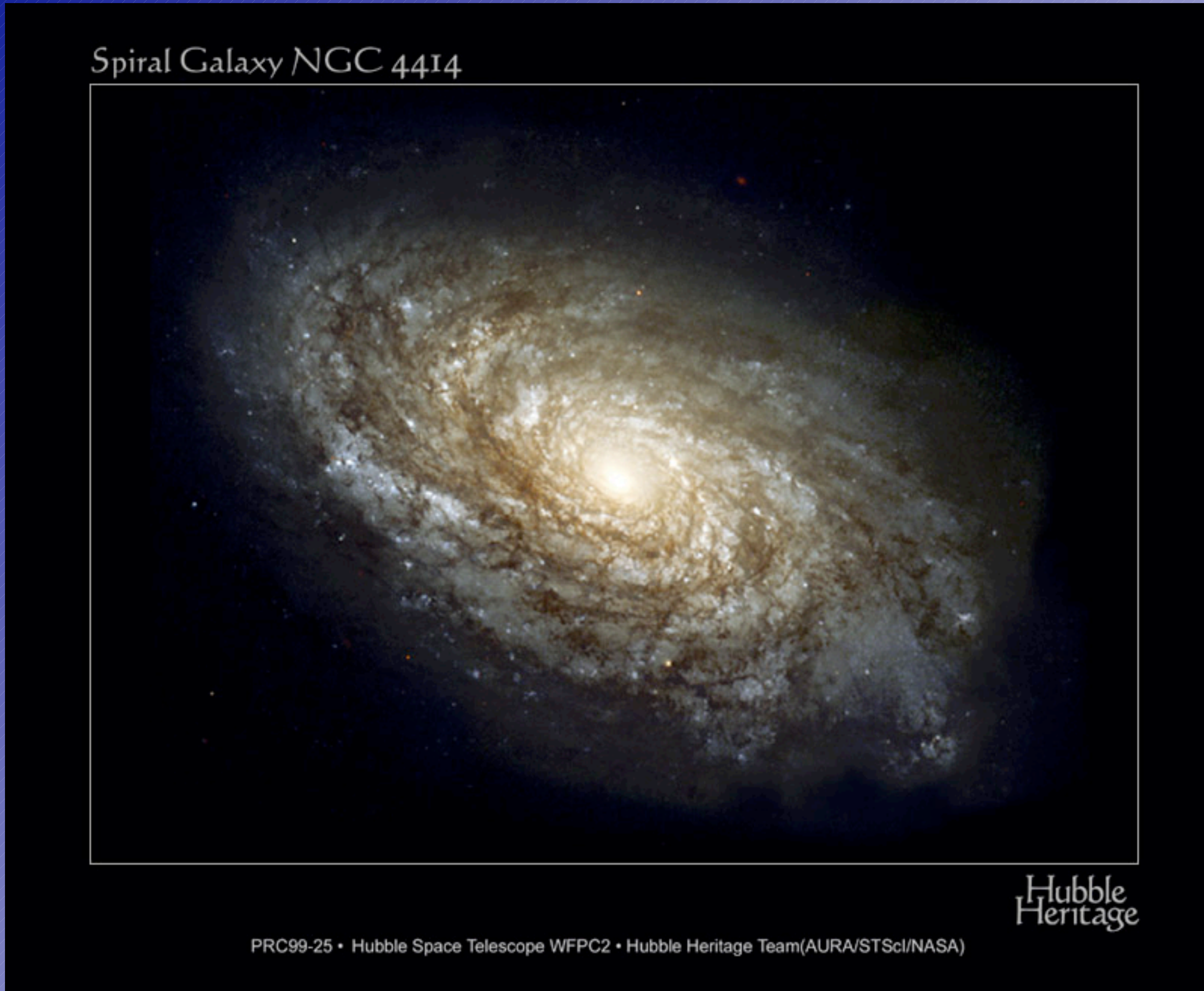
Arms are well defined

Can be traced at least once around the galaxy

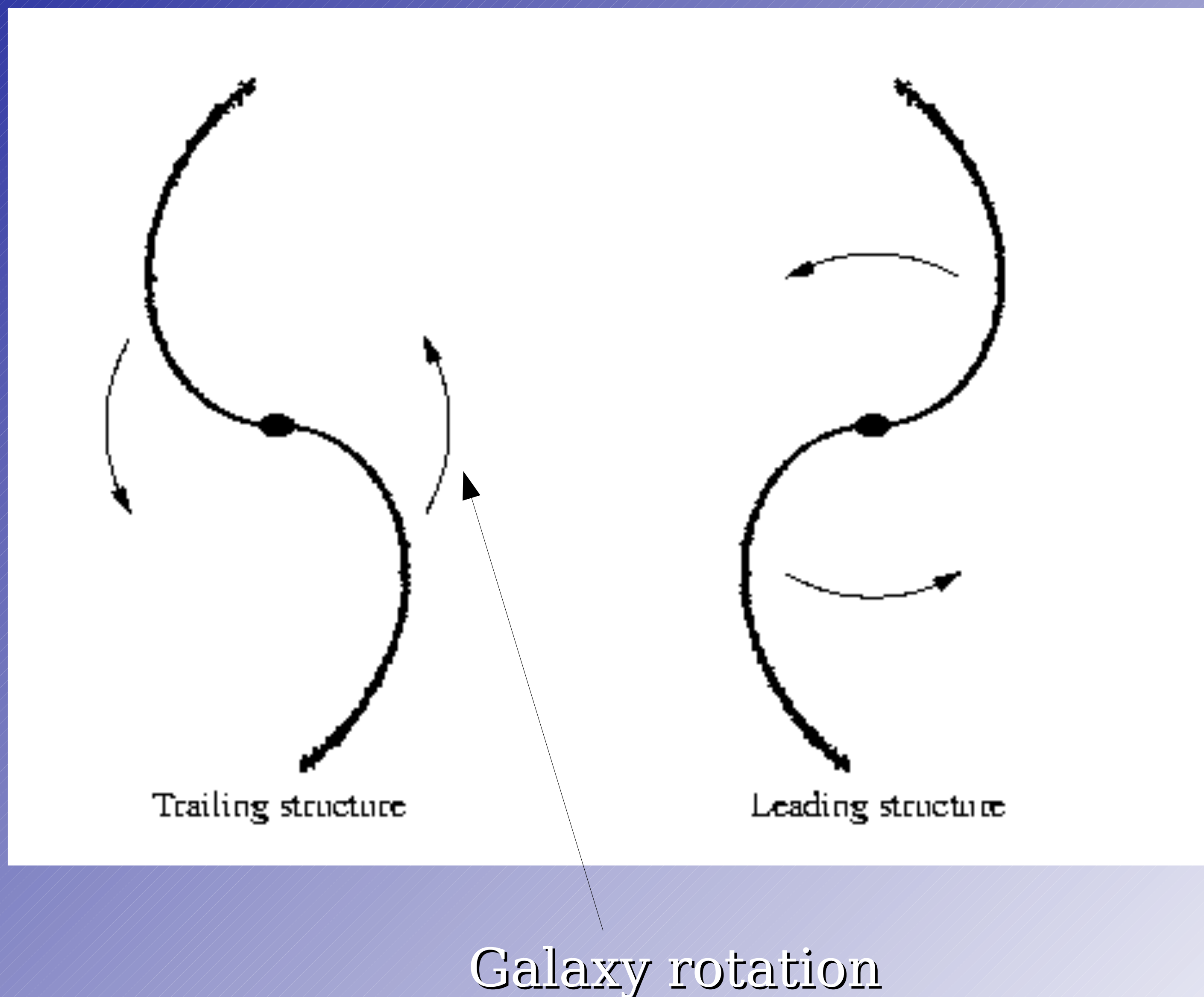
About 10% of all spiral galaxies


M100 © Anglo-Australian Observatory
Photo by David Malin

NGC 6946 a multi-armed spiral:
Arms have various lengths and definition
The majority of spirals are multi-armed.



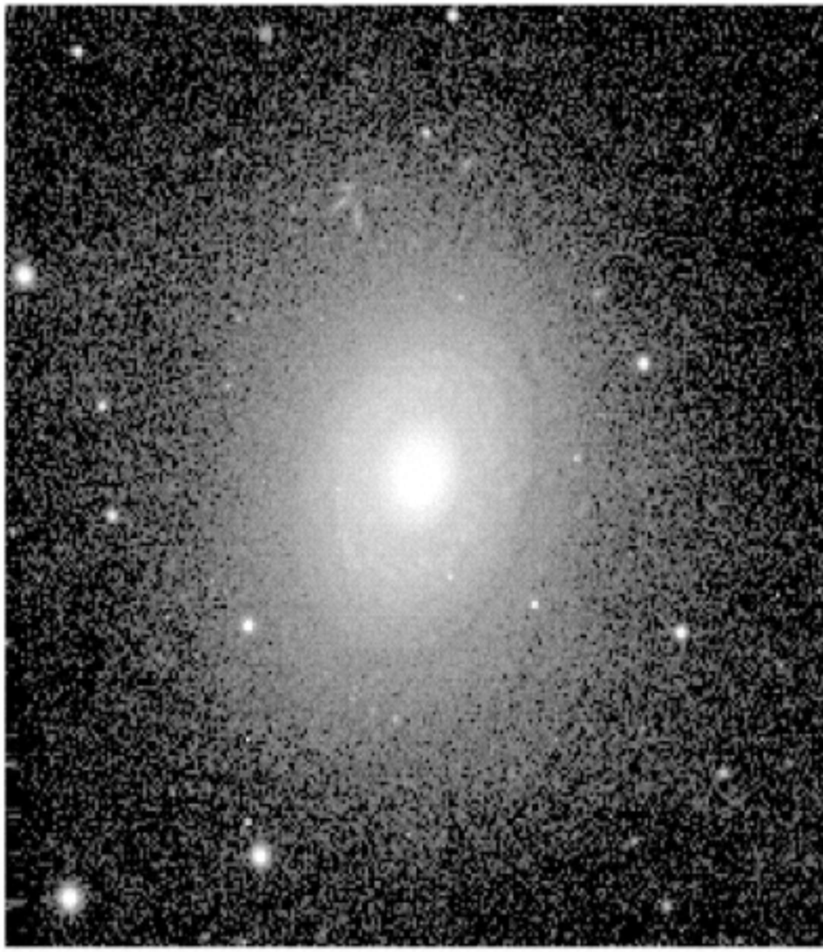
Arms are poorly defined and often segmented

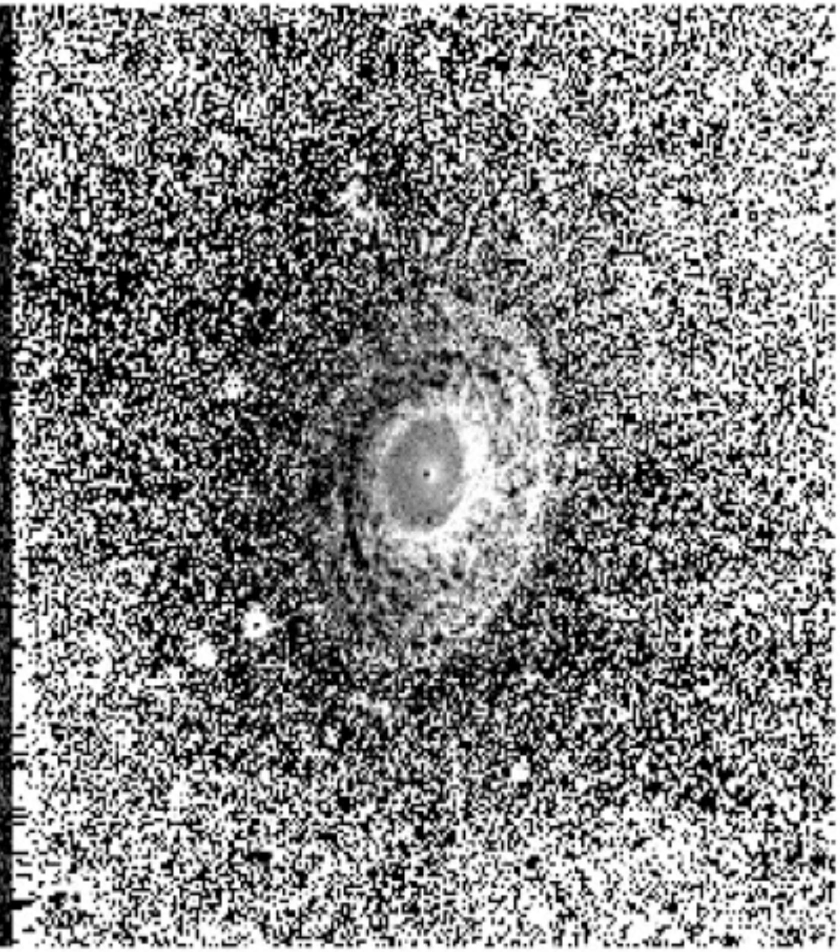

Trailing structure
Leading structure
Galaxy rotation

How do we tell is arms are leading or trailing.
We need two bits of information:

1) the direction of rotation
2) Which side of the galaxy is closer to us!

#1 can do done using spectroscopy but #2 is much more tricky. The basic idea is to try and determine which side of the galaxy is dimmer. If its dimmer we must be seeing it through more dust and it must be further away!





Distant close

B band image

B-H band image

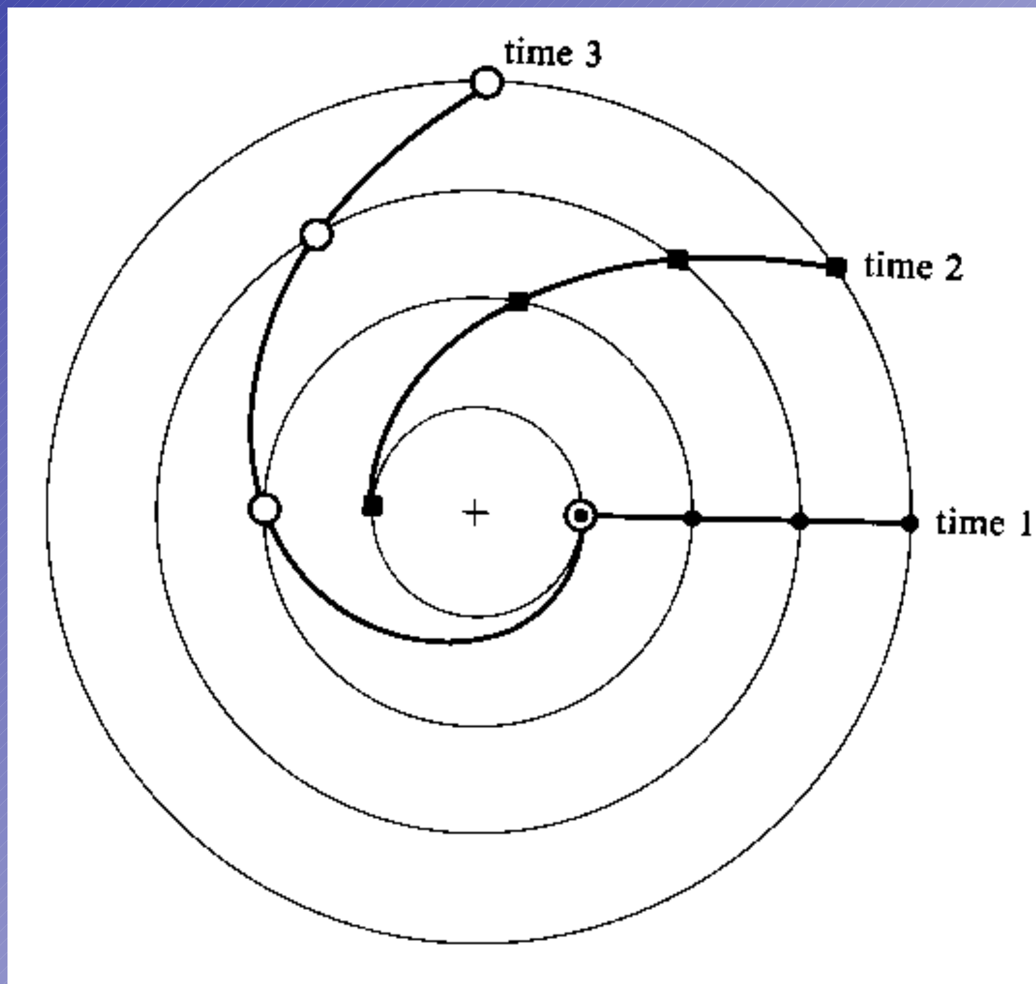
Spiral Arms (cont)

- Early studies of this problem (e.g. Hubble 1943; de Vaucouleurs 1958) showed that all spirals were trailing!
- More recently spirals have been identified with leading edges and spirals that have both types!

NGC 4622 a leading arm spiral (Buta et al 2003)

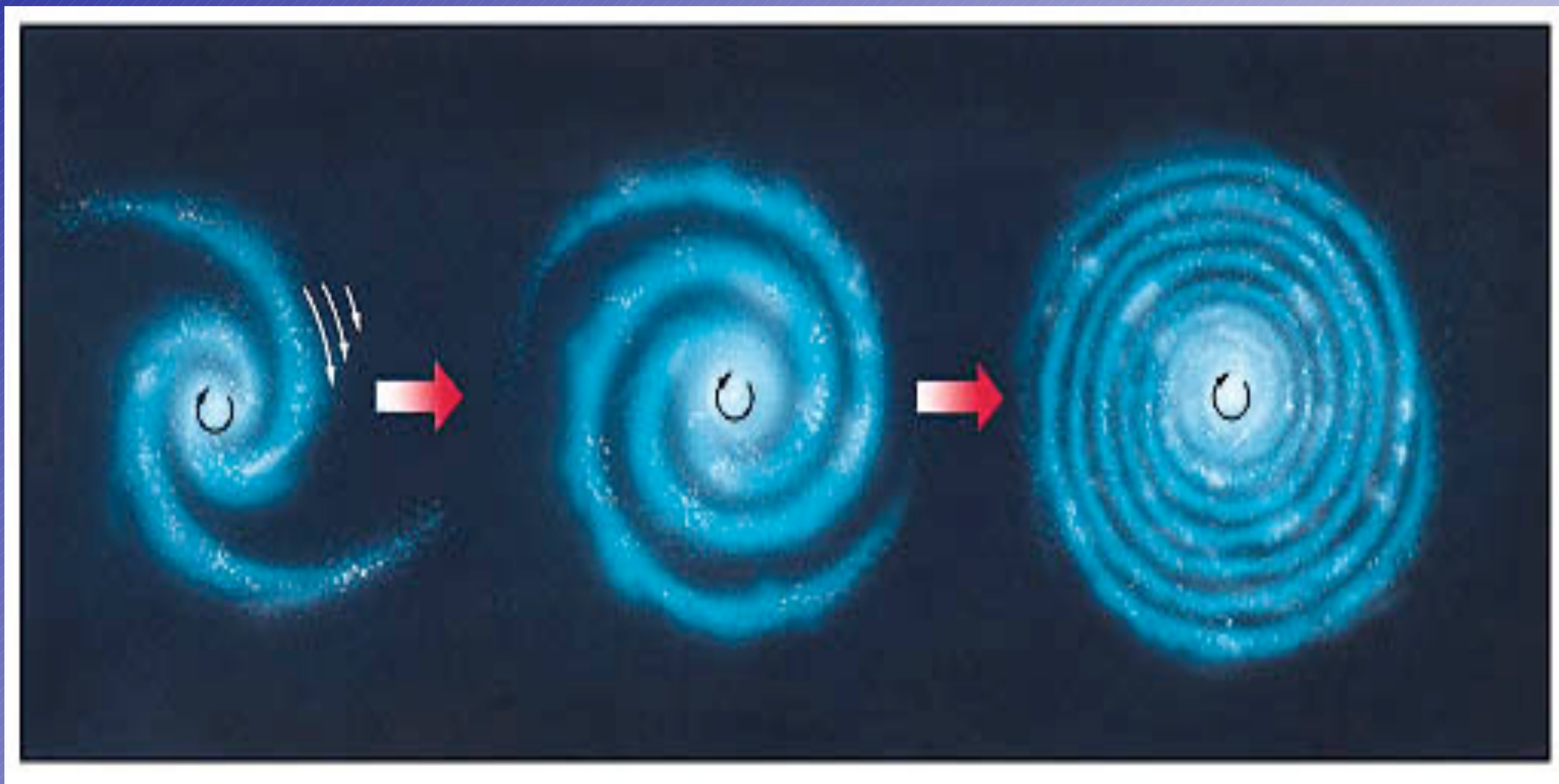
What are spiral arms?

Can they be a physical structure in the disk?



So we can make a spiral-like structure! But what happens as time goes on?

This would only solve the problem for a short time!



What else can we have? Well if it cannot be a physical object then it must be collection of stuff!

What stuff and how do you make a pattern?

Shu proposed that these could be density waves and we see these only because the density wave can concentrate the stars along the wave.

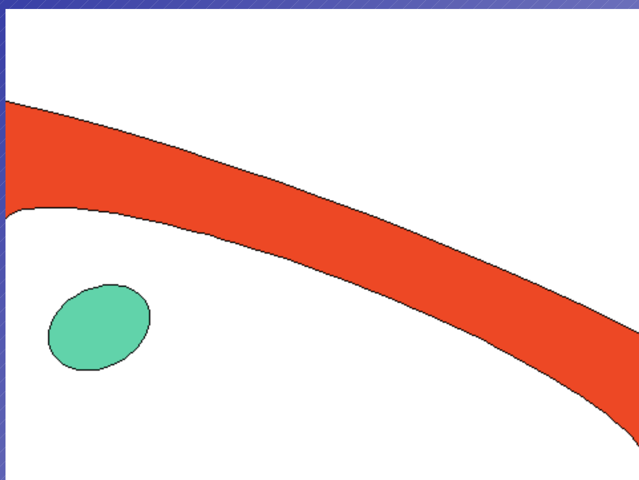
Density Wave Theory

- Think of a density perturbation that moves with a speed unrelated to the speed of the stars
  - Since its not coupled with the stars it doesn't have to wind-up
  - A density wave can rotate like a rigid body
- An analogy is a slow car on the interstate – you can have a much higher density of cars trailing it!

Density Wave Theory (cont)

- The density wave will rotate with some speed called the pattern speed (Ω_p)
  - Stars will stream through the wave and "bunch" up
    - As it enters it will speed up slightly
    - As it leaves it will slow down
    - So the stars spend more time in the wave and this enhances the stellar density and we see a spiral arm

- Why do spiral arms appear blue?
  - Think about a gas cloud approaching this density wave
    - It gets squeezed by the wave so it its close to collapsing to form stars this can trigger the collapse
    - Another trigger mechanism may be that since gas clouds may collide as one entering bumps one that is exiting driving a shock wave through the cloud inducing star formation.
  - So young stars -> blue color!



Density Wave Theory (cont)

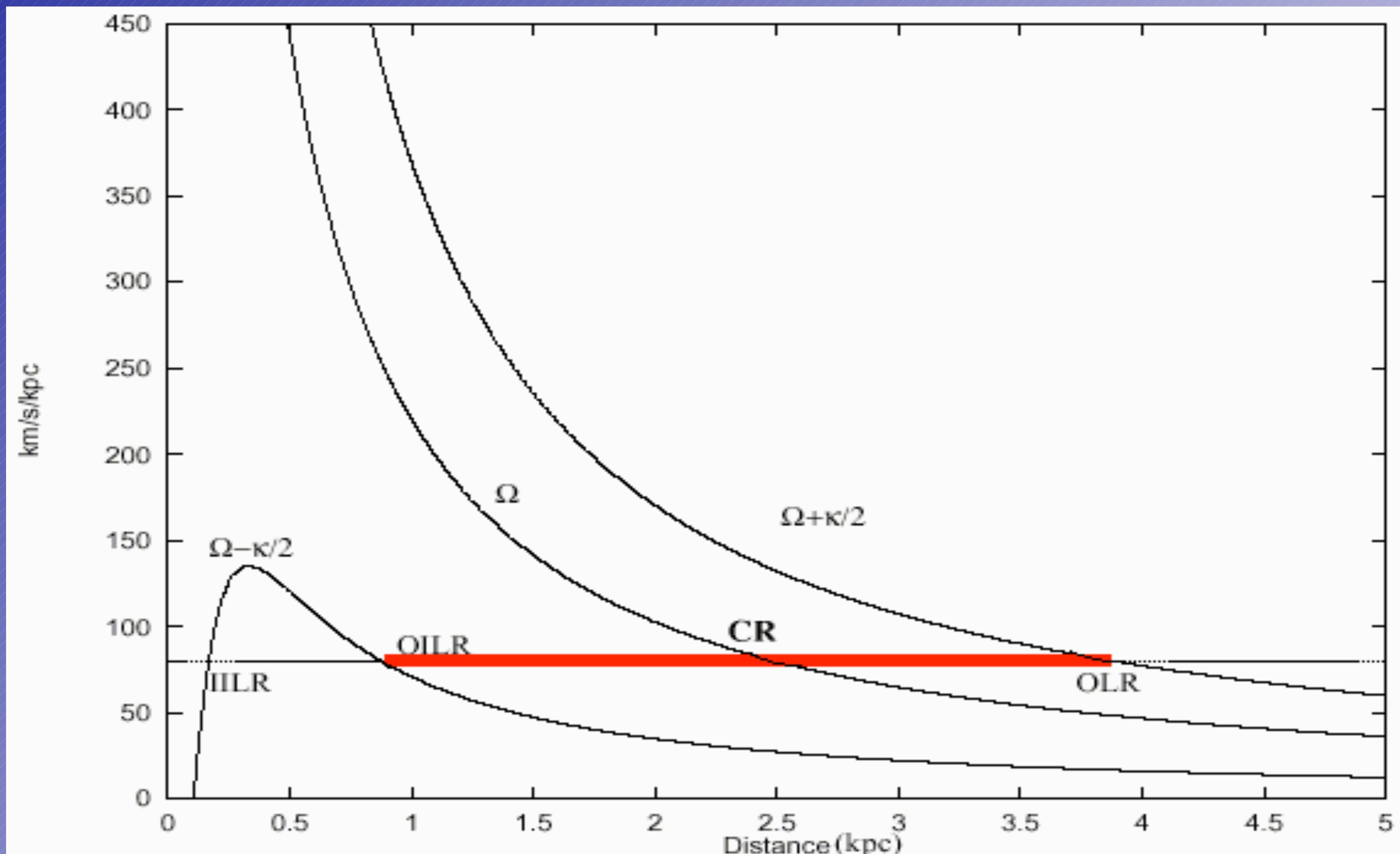
- How do density waves get started?
  - An initial asymetry in the matter or DM distribution?
  - Gravitational encounter?
- Once its started it can sustain itself for about 10^9 yrs.

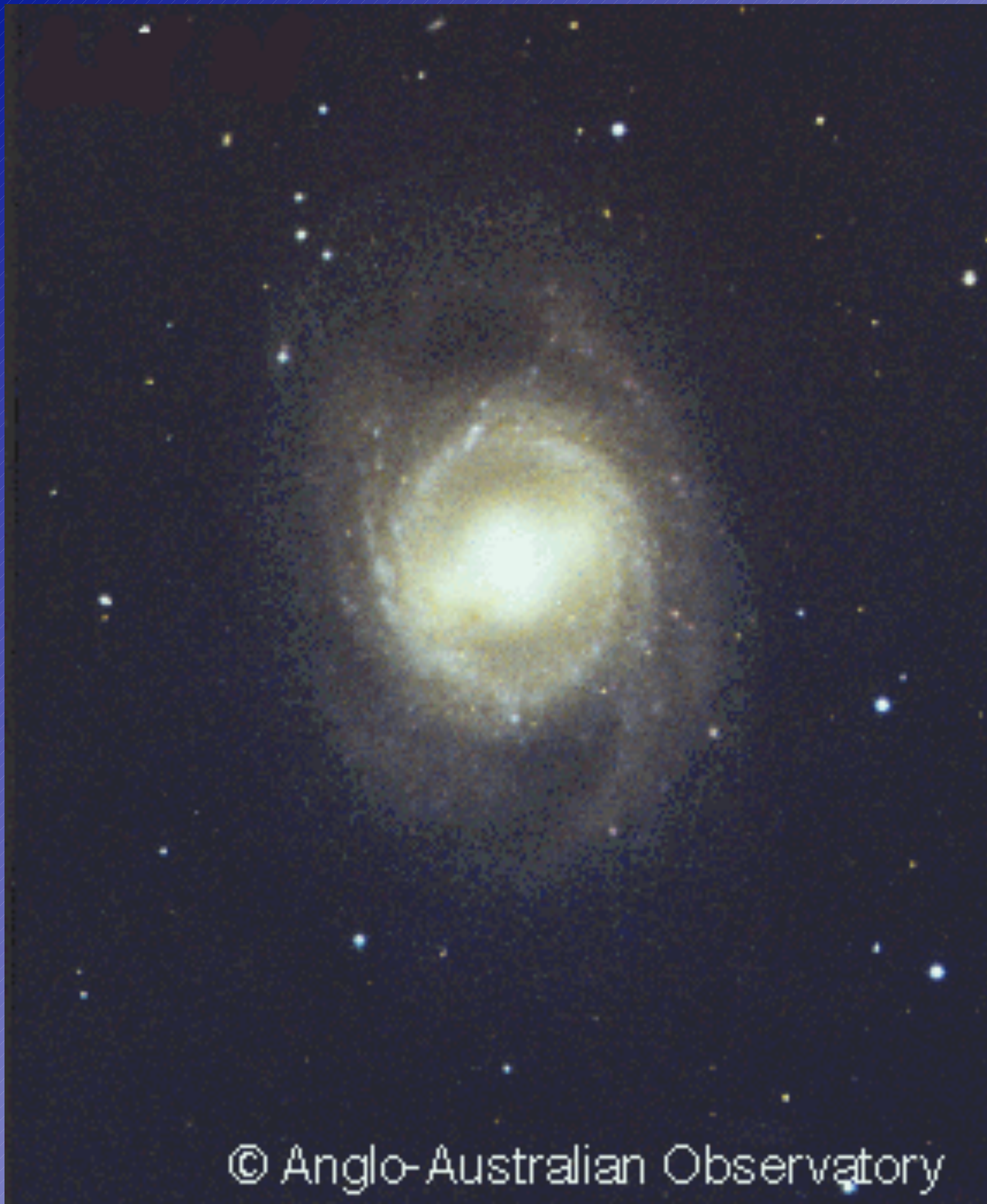
M51: a grand design spiral with a perturber

Density Wave Theory (cont)

- The spiral arm pattern can be amplified by resonances between the epicyclic frequencies of the stars (deviations from circular orbits) and the angular frequency of the spiral pattern
    - Spiral waves can only grow between the inner and outer Lindblad resonances ($\Omega_p = \Omega - \kappa/m$; $\Omega_p = \Omega + \kappa/m$) where κ=the epicyclic frequency and m is an integer (the # of spiral arms)
  - Stars outside this region find that the periodic pull of the spiral is faster than their epicyclic frequency, they don’t respond to the spiral and the wave dies out
  - Resonance can explain why 2 arm spirals are more prominent
- We observe resonance patterns in spirals

Lindblad Resonance





We see these resonances as ring structures in spiral galaxies.

NGC 3351 with an inner resonance (ring).

Outer ring

Inner ring

NGC 6872

Kinematic Spiral

From the lecture on orbits recall that...

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

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

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

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

Solar Orbit

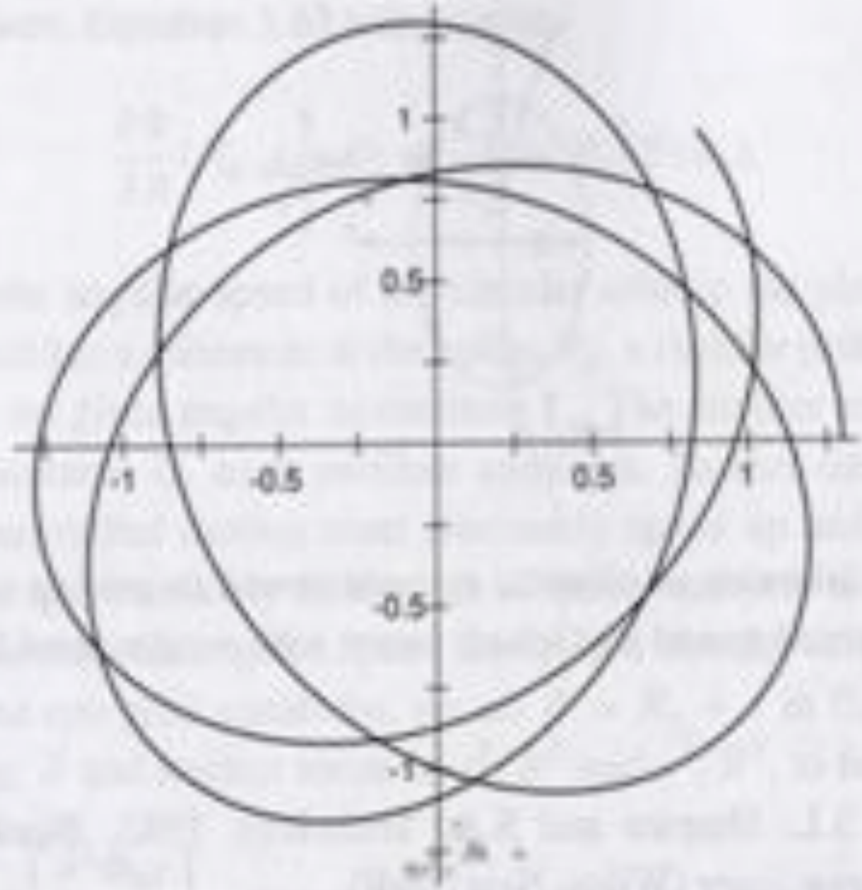
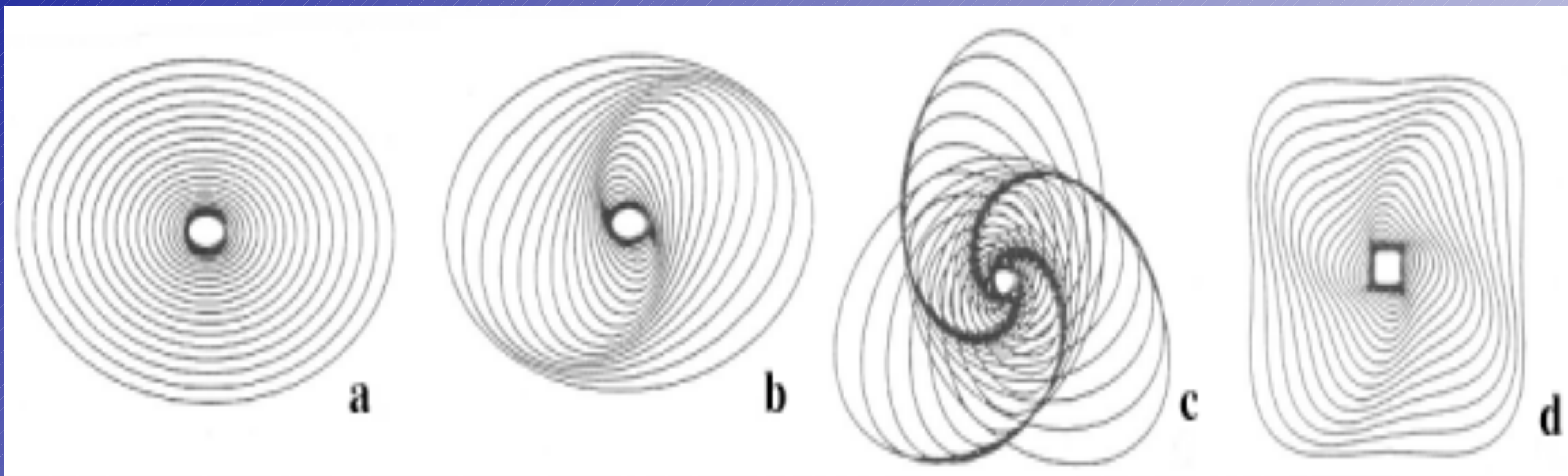


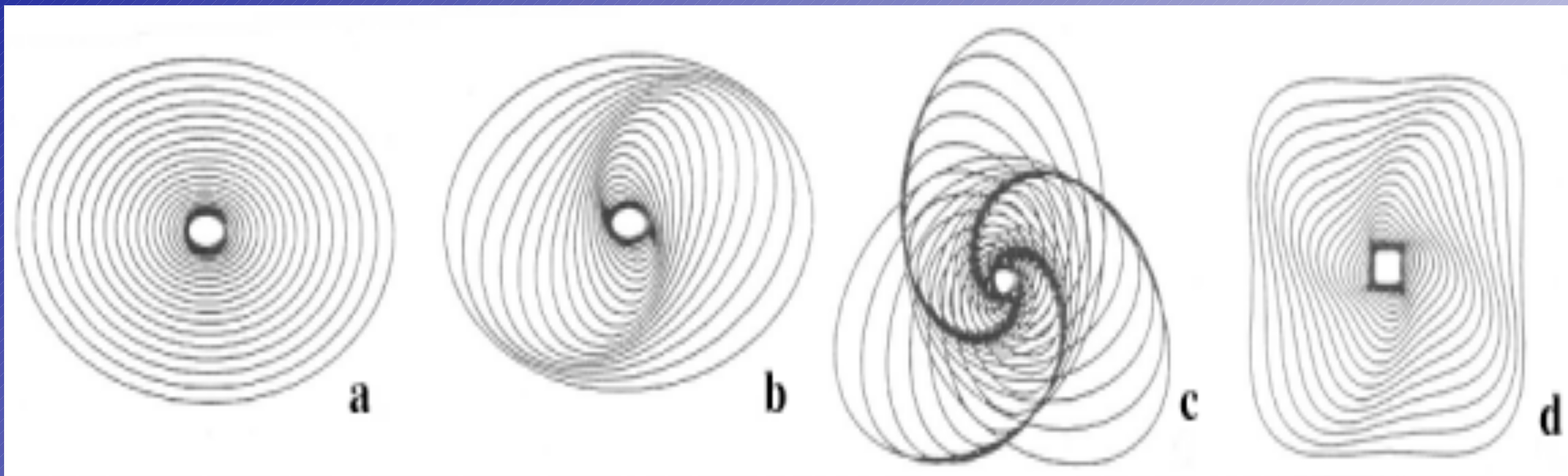
Figure 3.9 Path of the star of Figure 3.7, viewed from above the Galactic plane; the orbit started with ($R = 1.3$, $\phi = 0$) and ($\dot{R} = 0$, $R\dot{\phi} = 0.4574$).

Epicyclic Spirals



For a Keplerian potential, the orbit and epicycle frequencies are the same, $\kappa = \Omega$ The full orbit is closed: we have an off-centered Keplerian ellipse. However, in general Ω and κ are different so orbits don't close

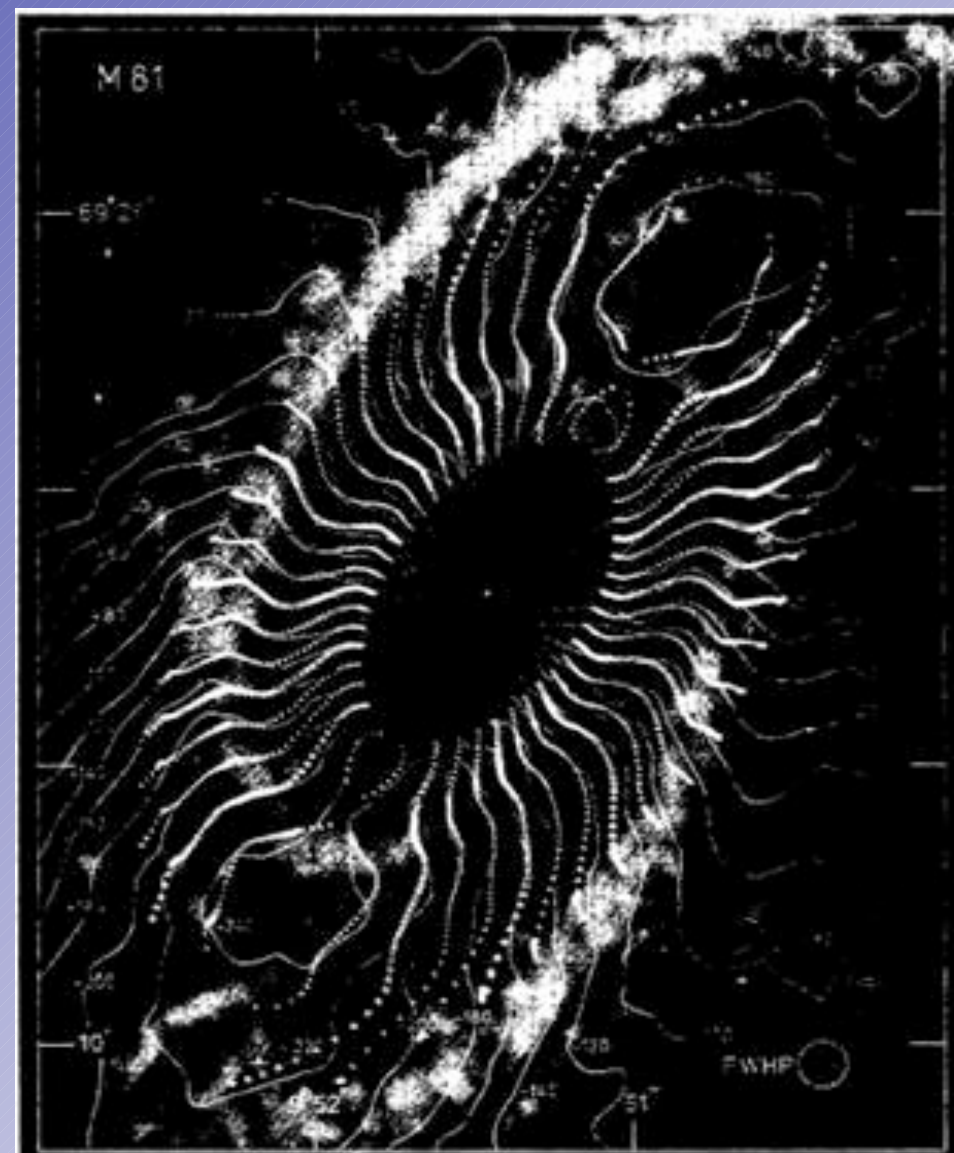
Epicyclic Spirals



If each ellipse is given an azimuthal offset proportional to $r^{1/2}$, the effect is a two armed spiral of orbits (b). A set of (3/2) orbits produces a three armed spiral (c) and (4/1) produces a four armed pattern (d).

Evidence for density waves

- The HI map of M81 with the velocity map (spider diagram) overlayed
- The lines of constant velocity bend as they cross an arm
  - Speeds up and then slows down
- Exactly what we expect for a density wave!



Evidence for Density waves cont.

- Surface density of the disk should vary as
  - $1+ \epsilon\cos(m\phi)$, with ϵ being the amplitude and < 1.
- But for dust and gas ϵ is 2 – 3, why?
  - Gas clouds are collisional and can be compressed! (Fujimoto 1968; Roberts 1969)
- Predicts that the dust and gas arms are narrower than the stellar arms.

M51 and M101

Arm Width

- The width of the arms must be related to the angular speed (Ω) and the lifetimes of the young blue stars (t_*).
- $\Delta\theta = |\Omega - \Omega_p|\, t_*$
  - $\Omega = 2\Omega_p$, $\Omega_p = 10$ km/s/kpc
  - B3 star has $t_* = 2 \times 10^7$ yrs
- So $\Delta\theta$ is about 12^o, close to what we observe

Stochastic Spirals

- Many short fragmented arms
- No clear symmetry
- Star formation by local instabilities
- Sheared into long arcs by differential rotation

Possible Spirals

- Kinematic spirals
  - Arms are “families” of orbits.
- Density Wave spirals
  - Self gravity of the disk drives and maintains the pattern.
- Stochastic (Chaotic) spirals
  - Caused by differential rotation of star forming regions.

Stochastic Spirals cont

- Arm lengths are predicted to be ~0.2kpc
  - Similar to what is observed
- Arms fade quickly but are replaced by new arms from fresh star formation
  - This implies a carful regulation of the star formation rate.
- This model predicts no underlying arms from the older disk stars.