Spiral Arms

M81 : **Grand Design Spiral**
(Spitzer, IR data)

SA(s)ab

M33: **Flocculent Spiral**
(Spitzer, IR in red)
(Galaxy Explorer, FUV in blue)
SA(s)cd

NED: http://ned.ipac.caltech.edu/

Recall: De Vaucouleurs 1963 system

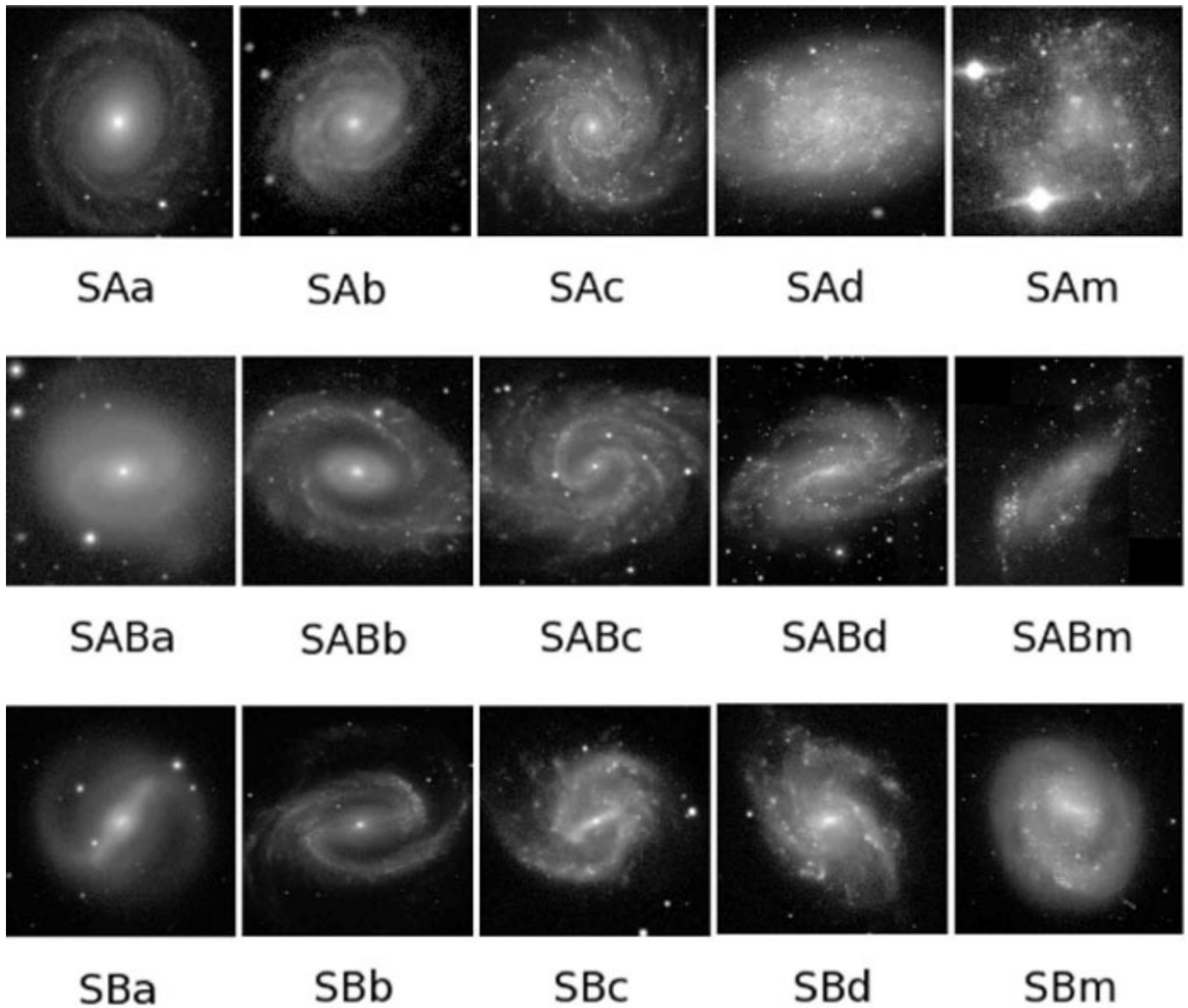
(r) = Ring

(s) = no ring

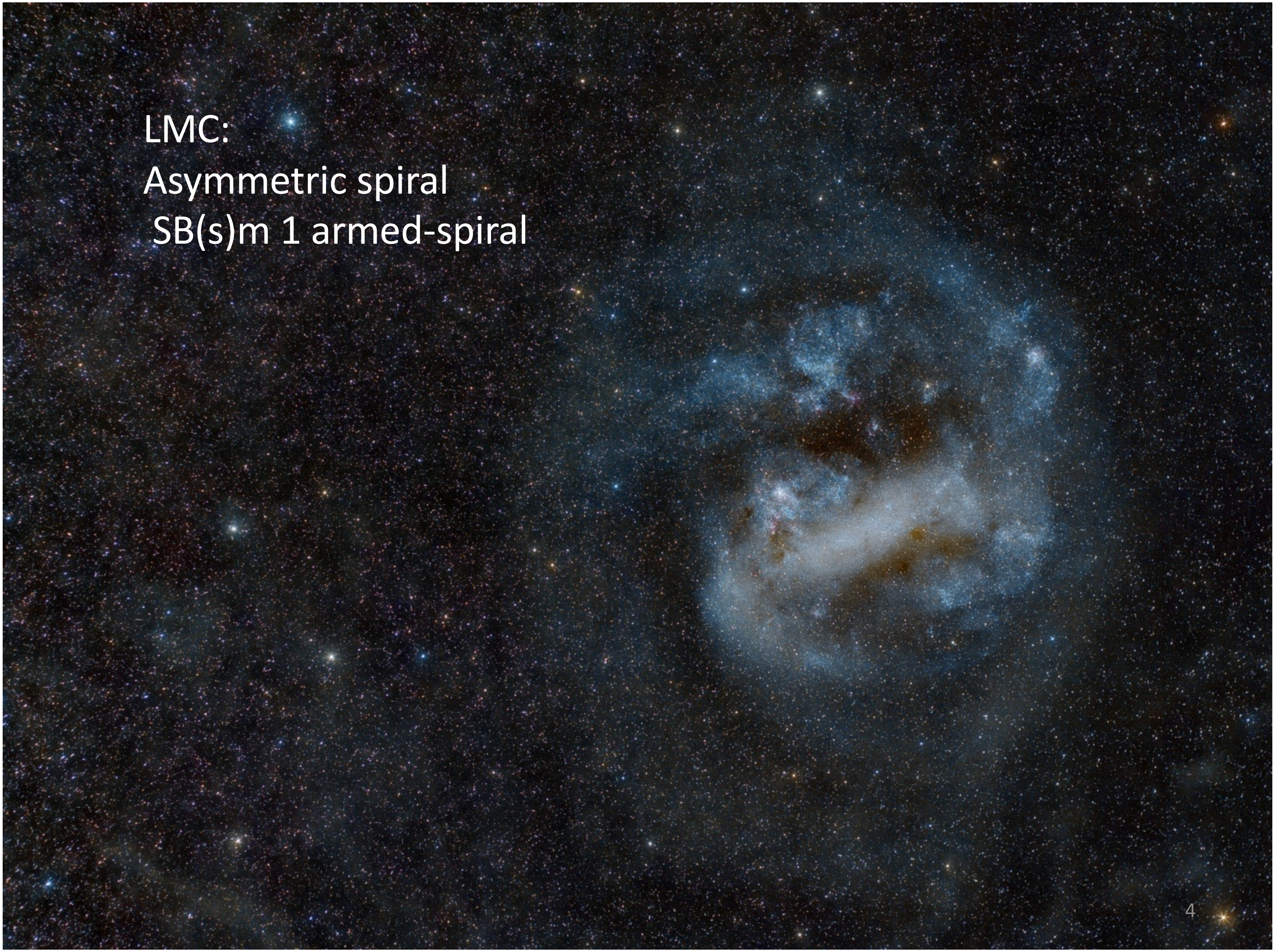
No bar

In between

Barred

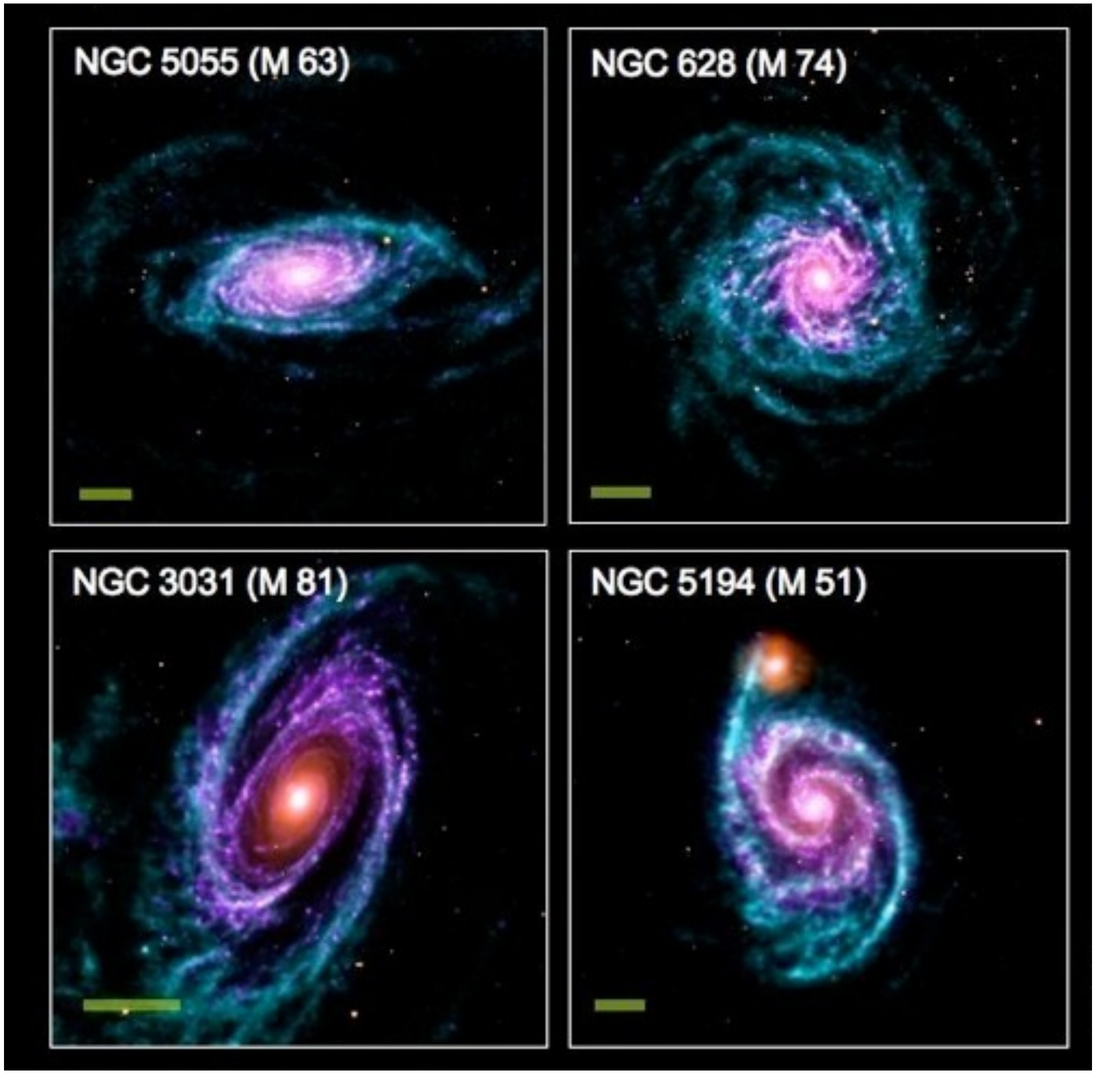


NGC 3100
Barred Spiral
SB(rs)bc



LMC:
Asymmetric spiral
SB(s)m 1 armed-spiral

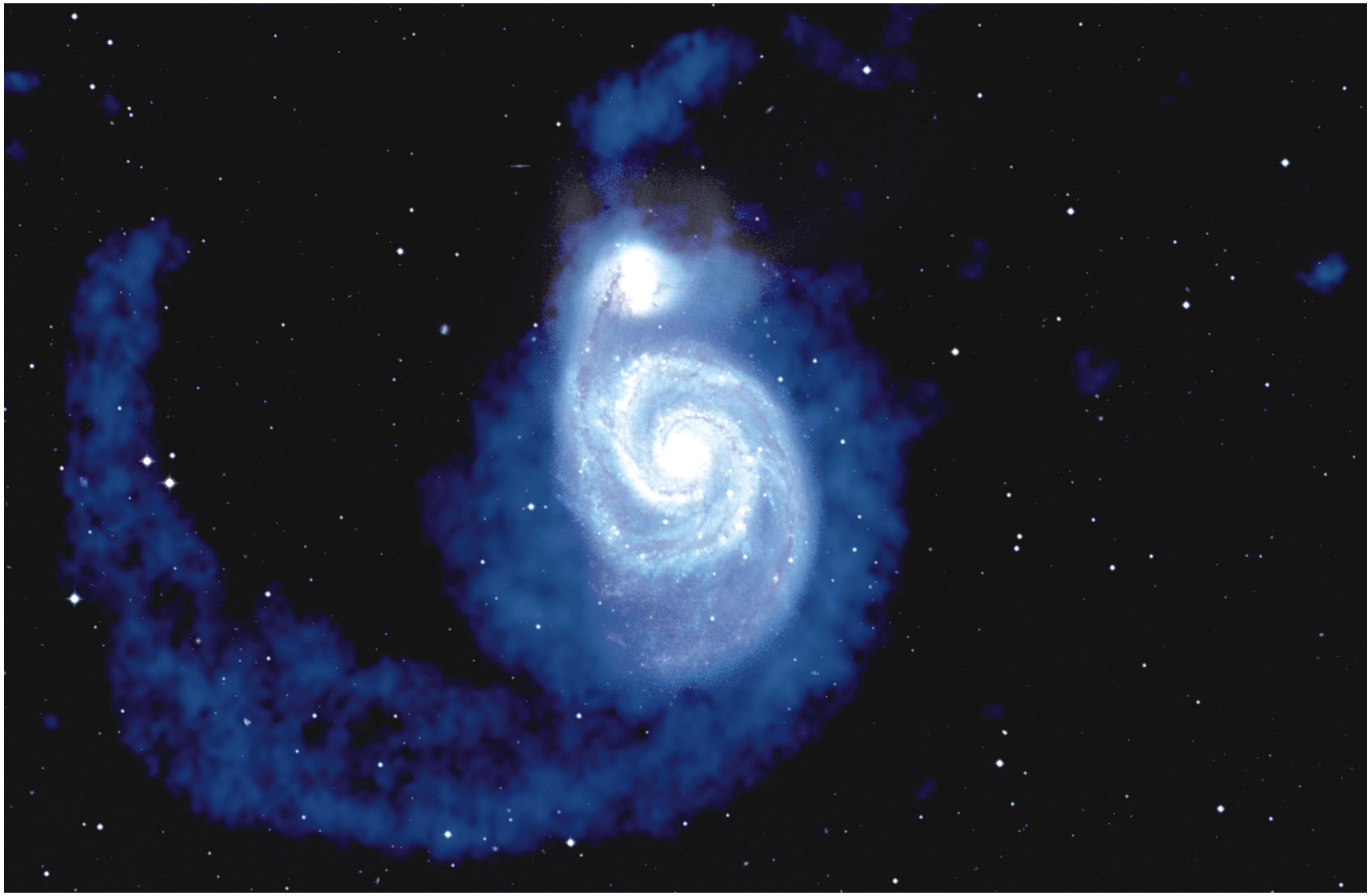
Spiral structures contain gas, young stars, old stars…



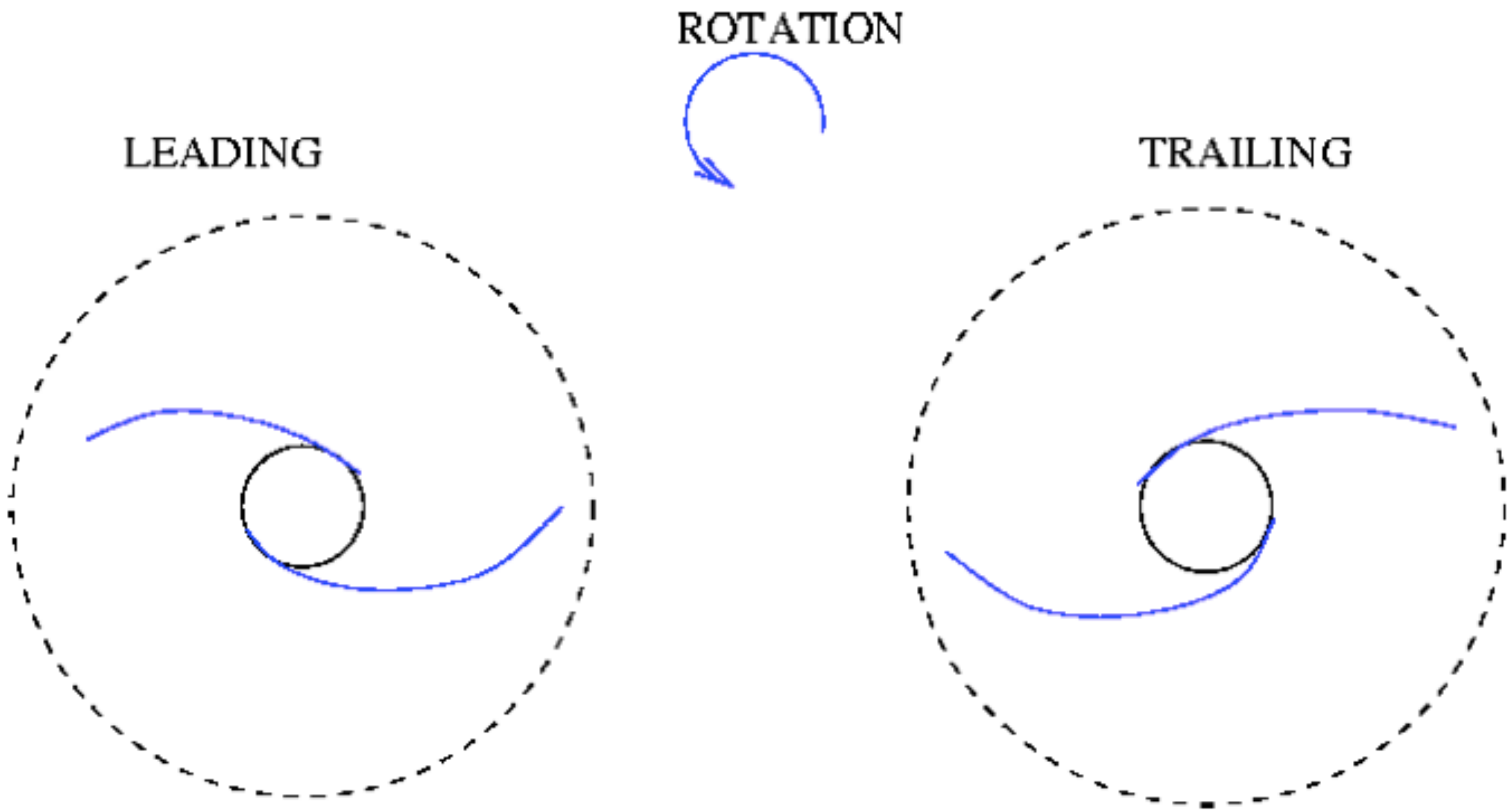
In the outer parts of disks, the spiral arms are mainly observed in neutral Hydrogen

Hydrogen gas
Old Stars (IR)
Young Stars (UV)

M51: Stars vs Gas



Credit: NRAO/AUI/NSF, Image copyright J. M. Uson, observers A. H. Rots, A. Bosma, J. M. Van der Hulst, E. Athanassoula, P. C. Crane



Most Common

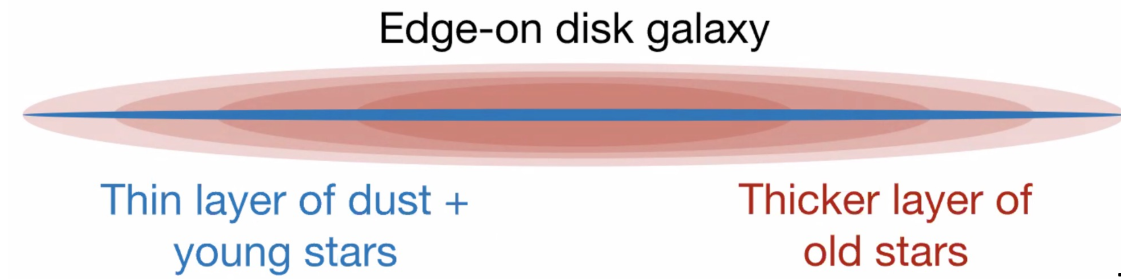
Spiral structures contain gas, young stars, old stars… and dust

Likely CCW rotation

Likely CW rotation

Dust typically concentrated on the inner side of the arm — is being compressed there.

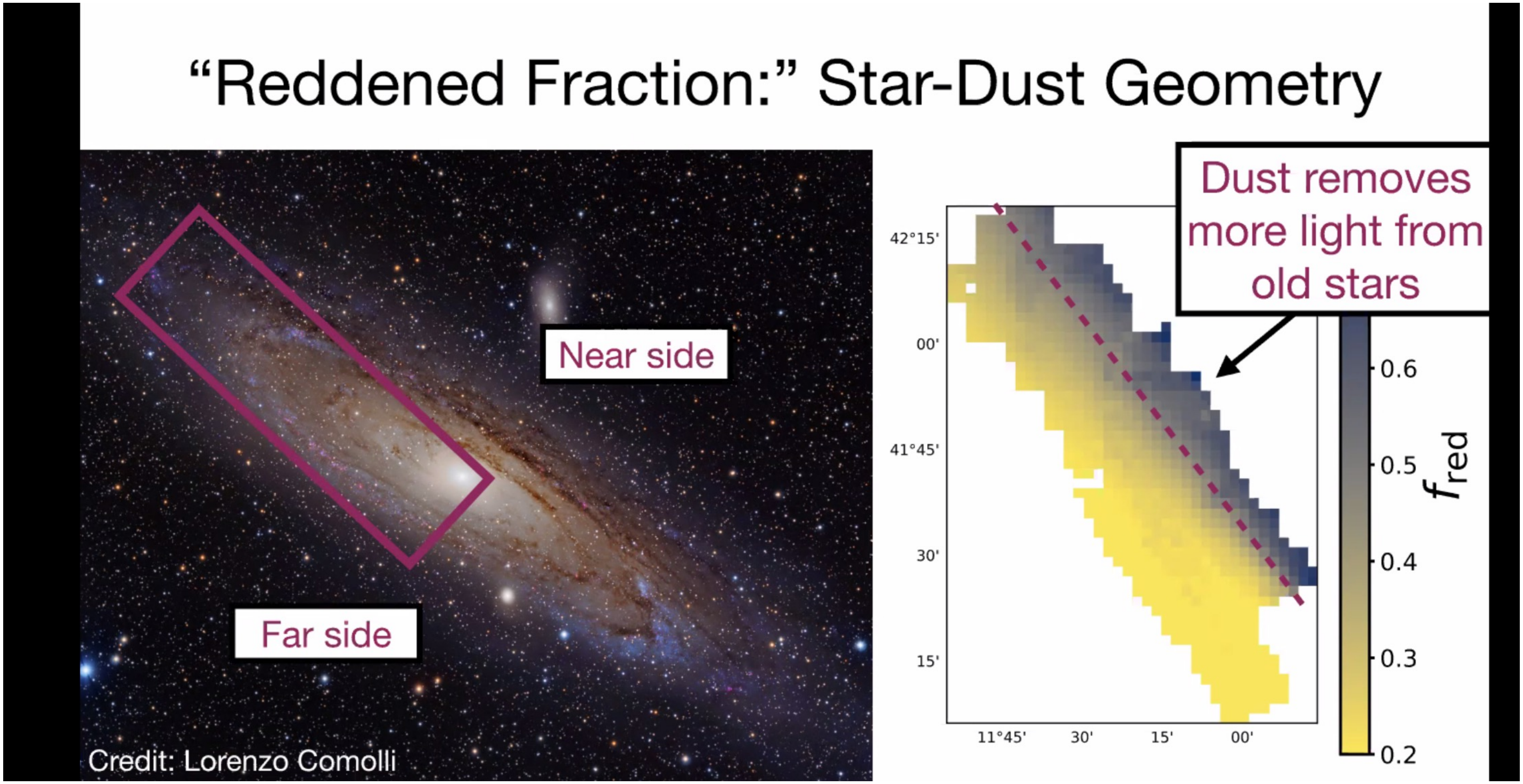
Complication: Galaxy Inclination

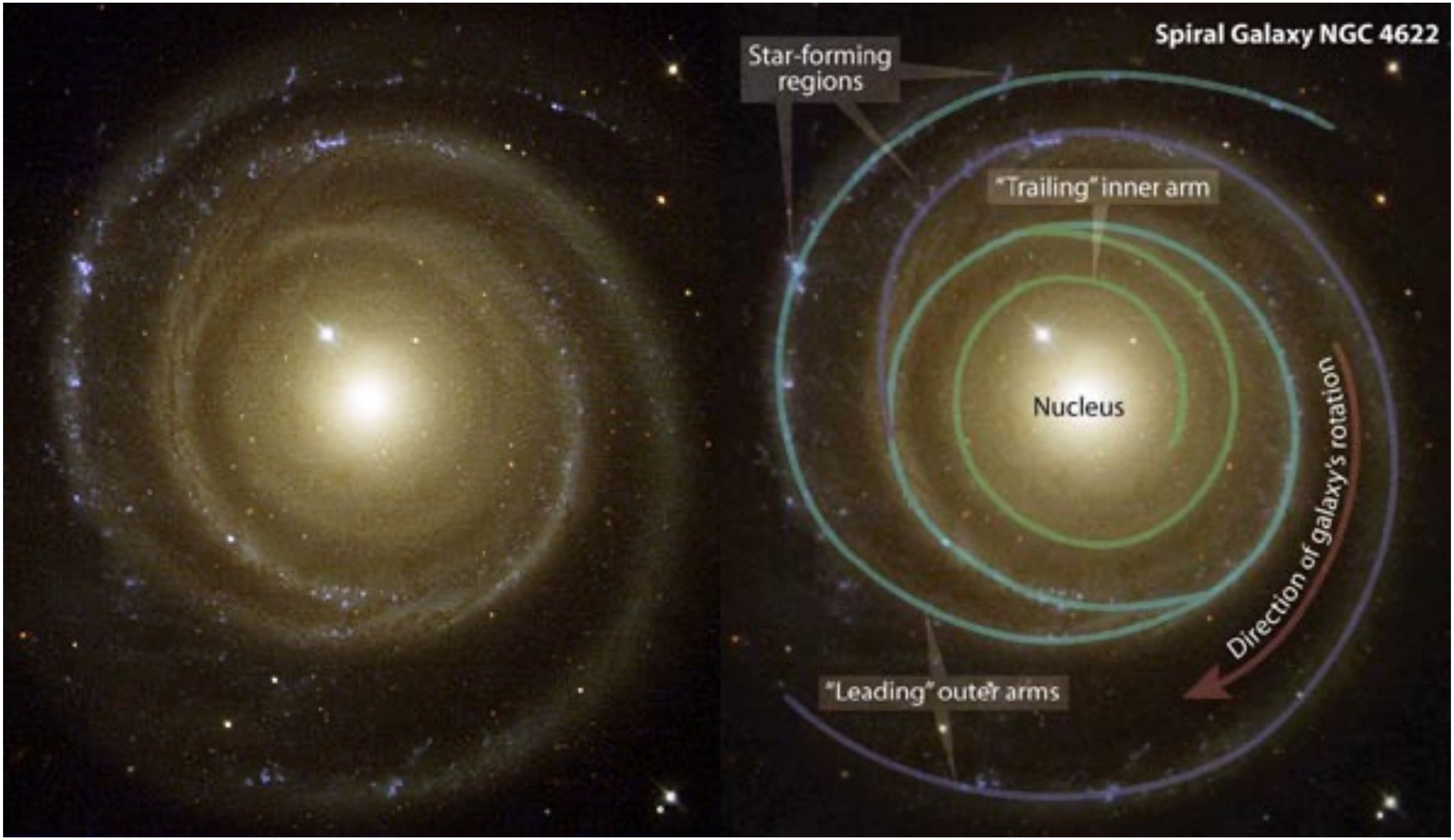


Dalcanton+2015
Telford+2020

Complication: Galaxy Inclination

Dalcanton+2015
Telford+2020





NGC 4622: The "Backward Galaxy"

Pitch angle

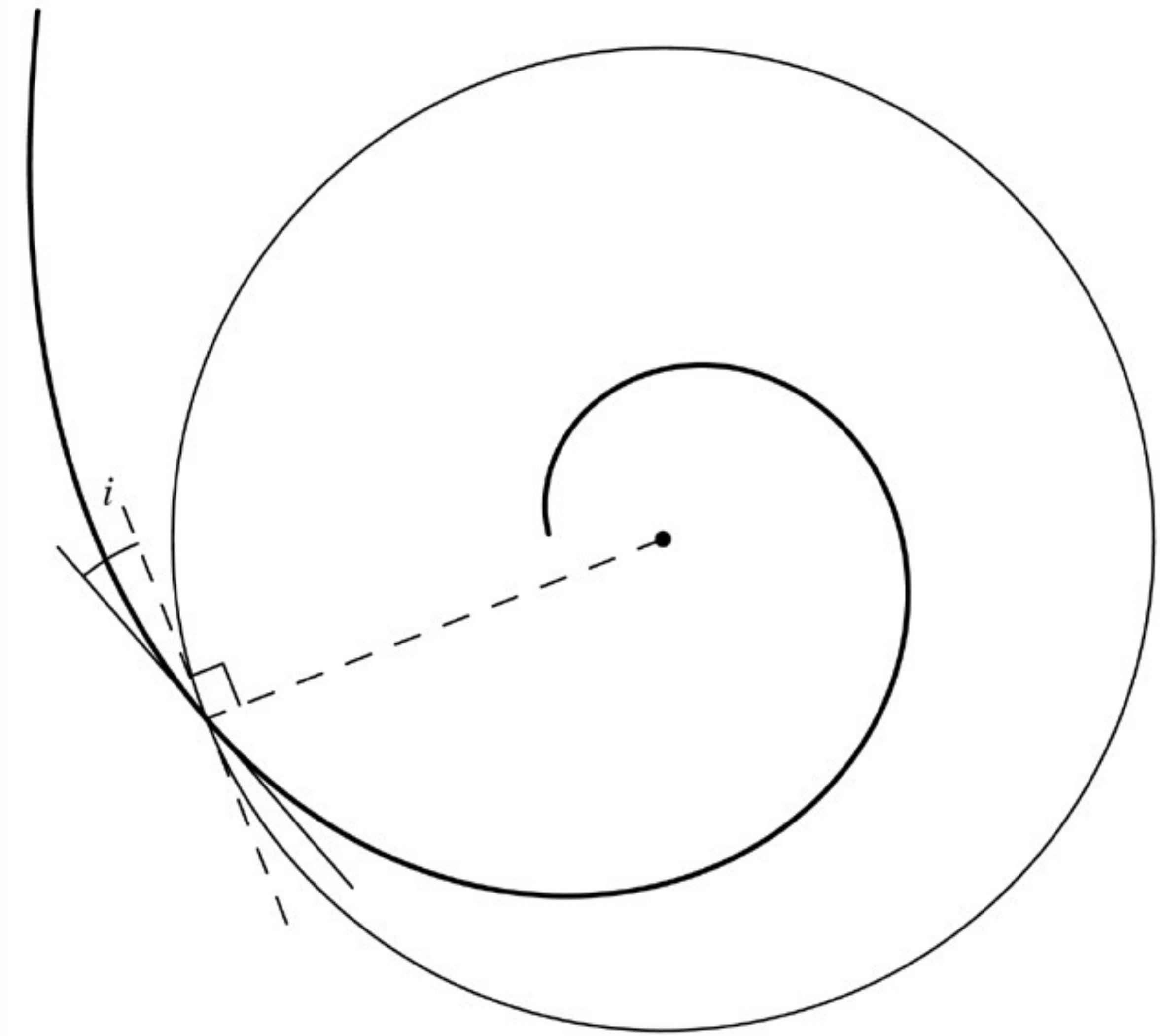


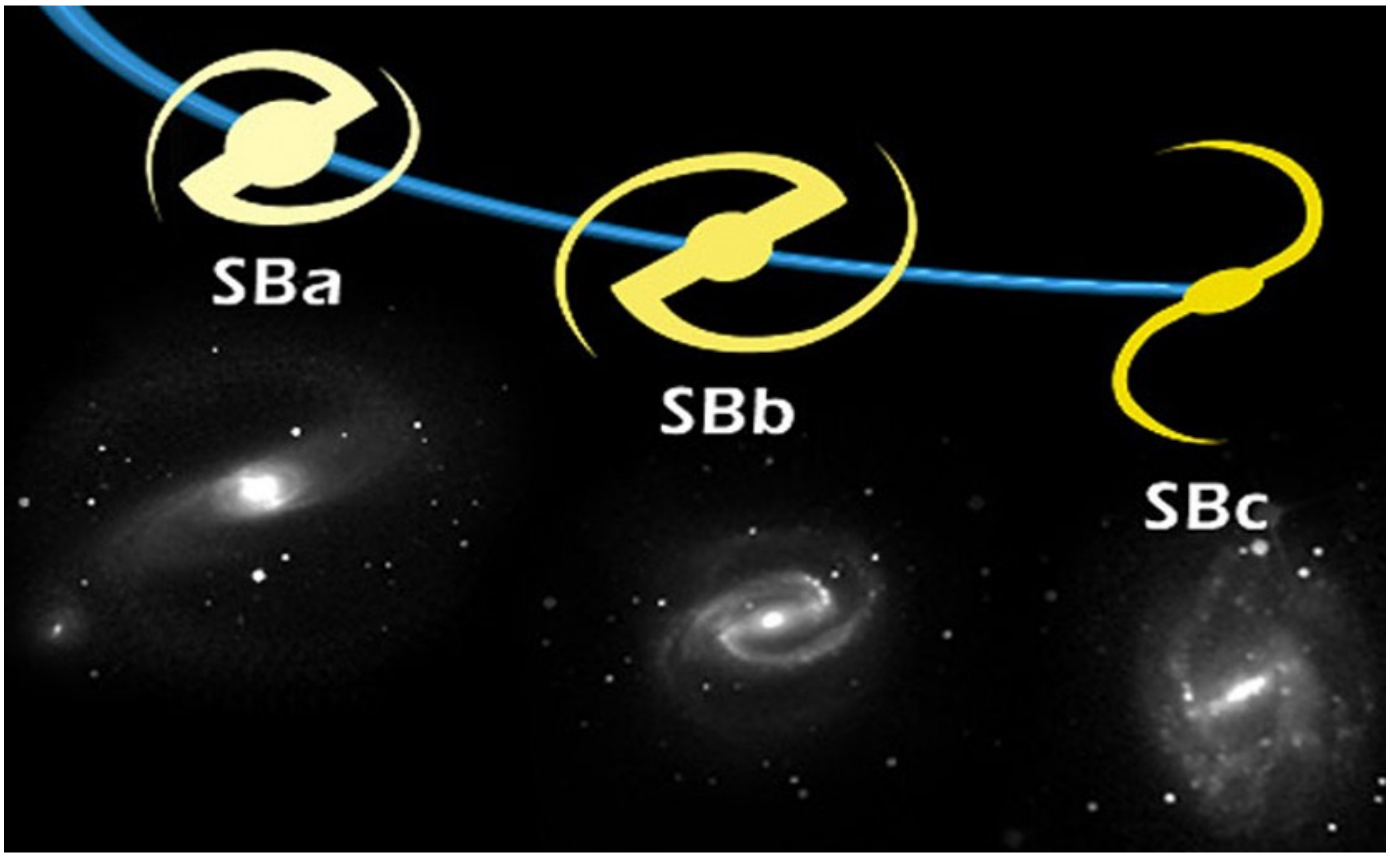
Fig 5.28 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

In a disk rotating anticlockwise, where the rotation rate falls with radius, stars that initially lie along a radial line are wound into a trailing spiral; the angle *i* is the pitch angle of the spiral.

Pitch angle increases along the Hubble Sequence

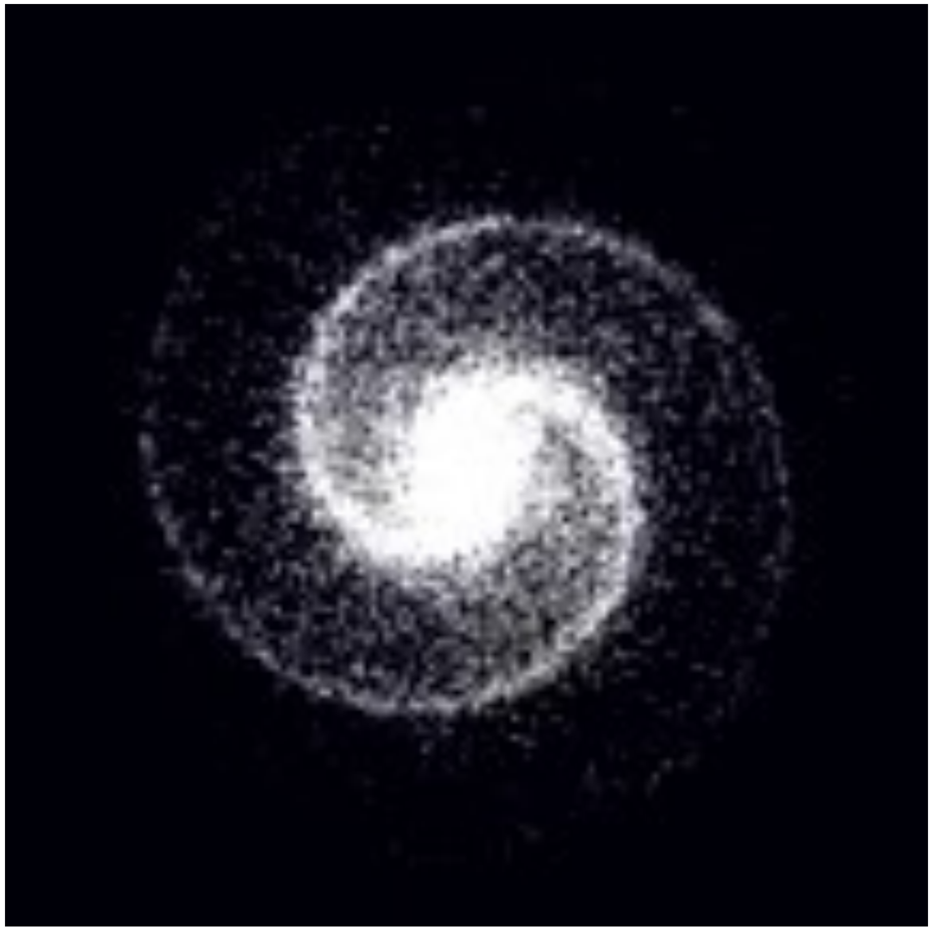
a i~5 degrees

c :10 < I <30 degrees

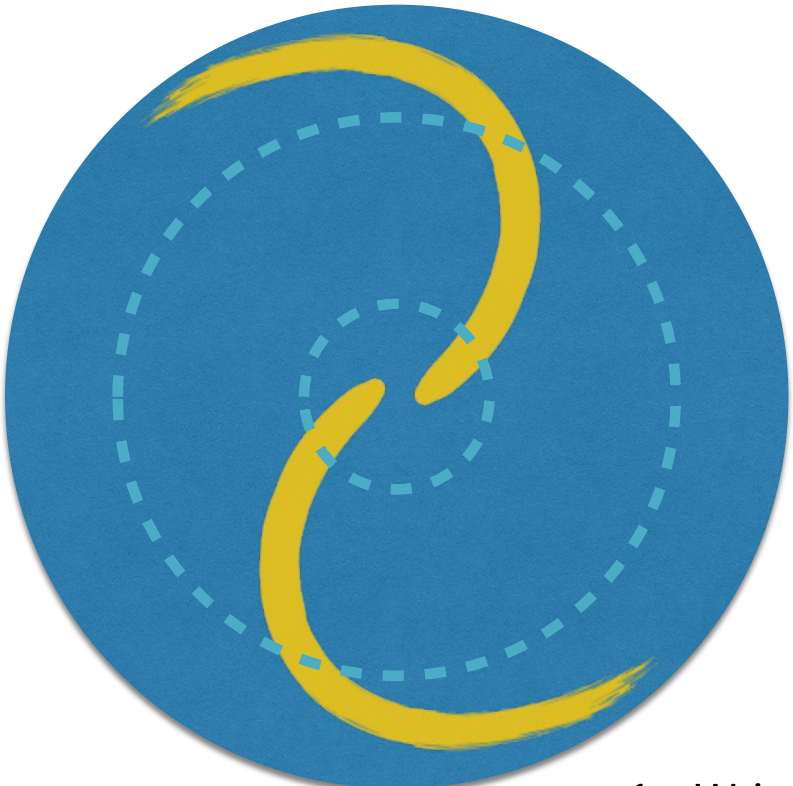


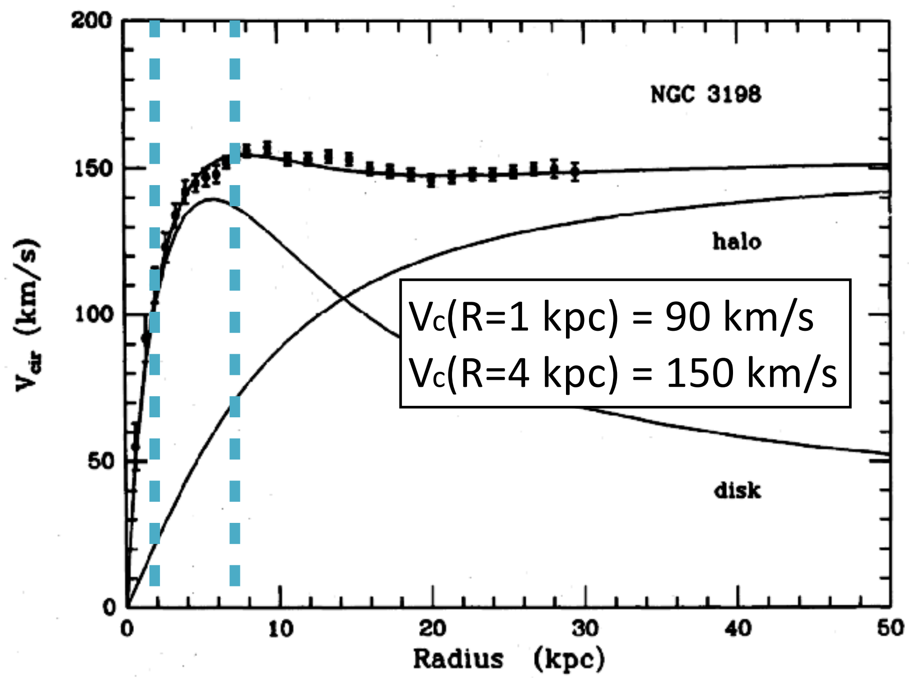
Are spiral structures static?

- Rigid Rotation



Are spiral structures static?

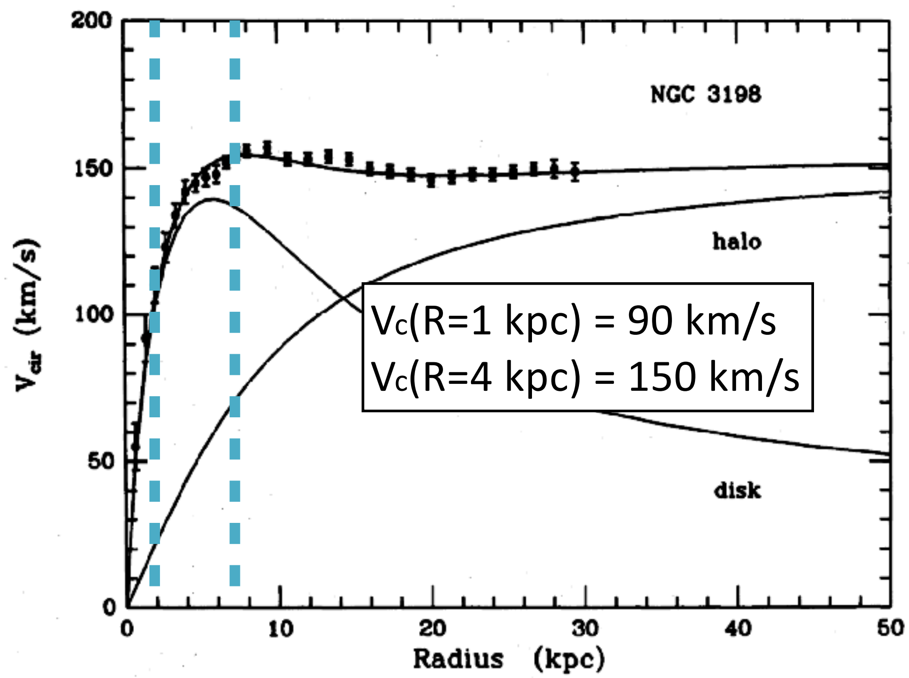




1. Write an equation for the orbital period as a function of V_c and R.
2. How many orbits will the R=1 kpc material have made during 1 orbit of the R=4 kpc material?
3. Sketch what the spiral pattern would look like after one full orbital time for the R=4 kpc materal.

From Karin Sandstrom

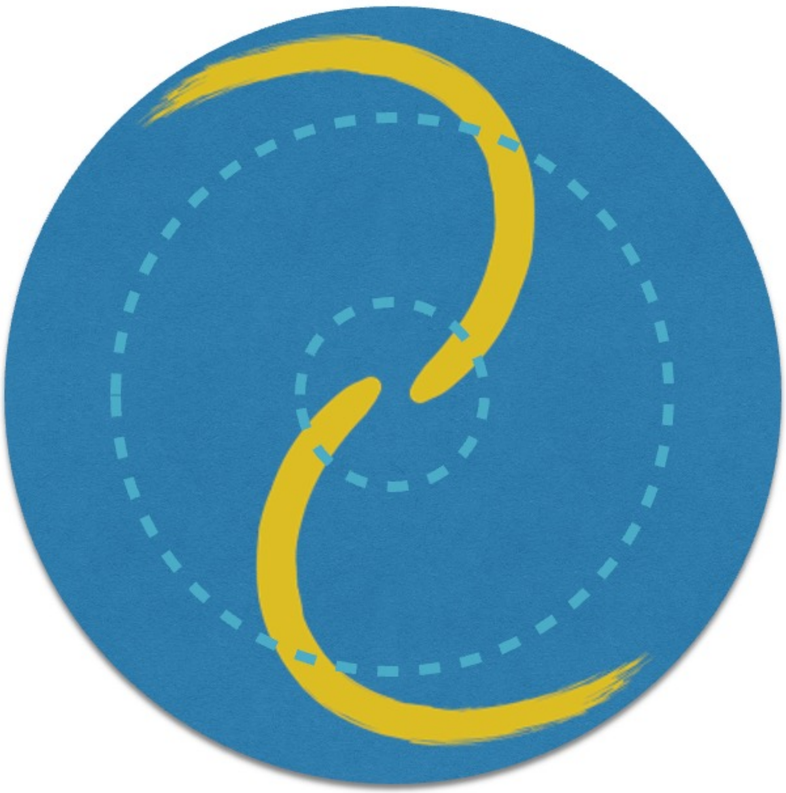
Are spiral structures static?

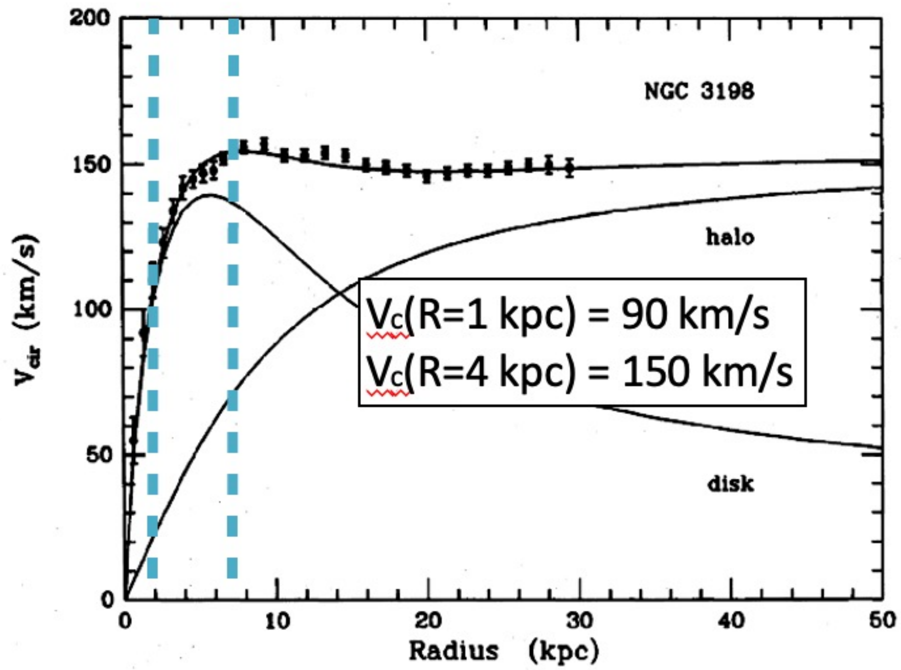


$$T_{orb}(R) = 2\pi R/V_c$$

From Karin Sandstrom

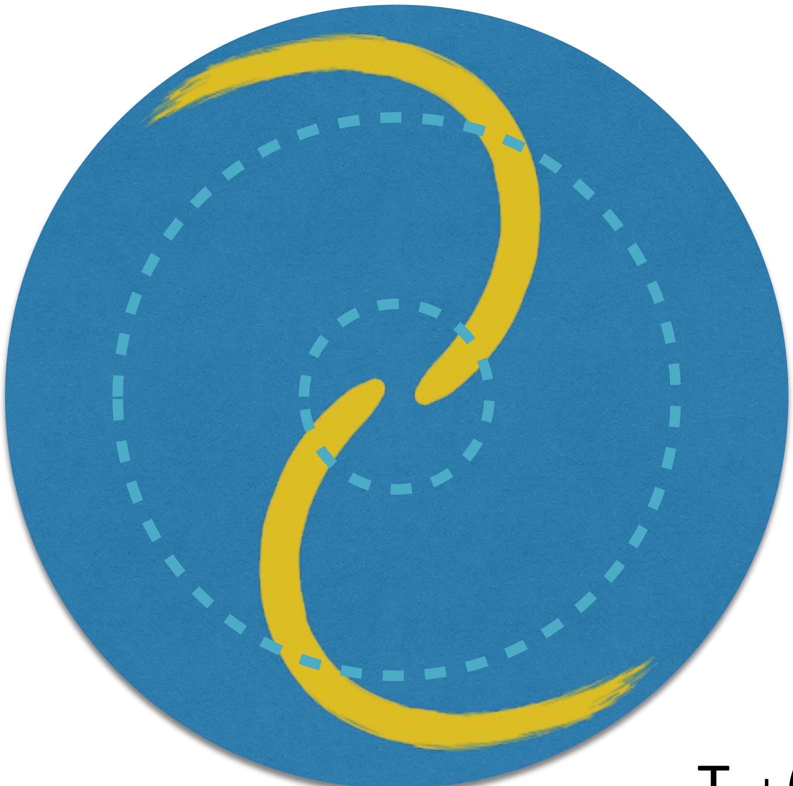
Are spiral structures static?

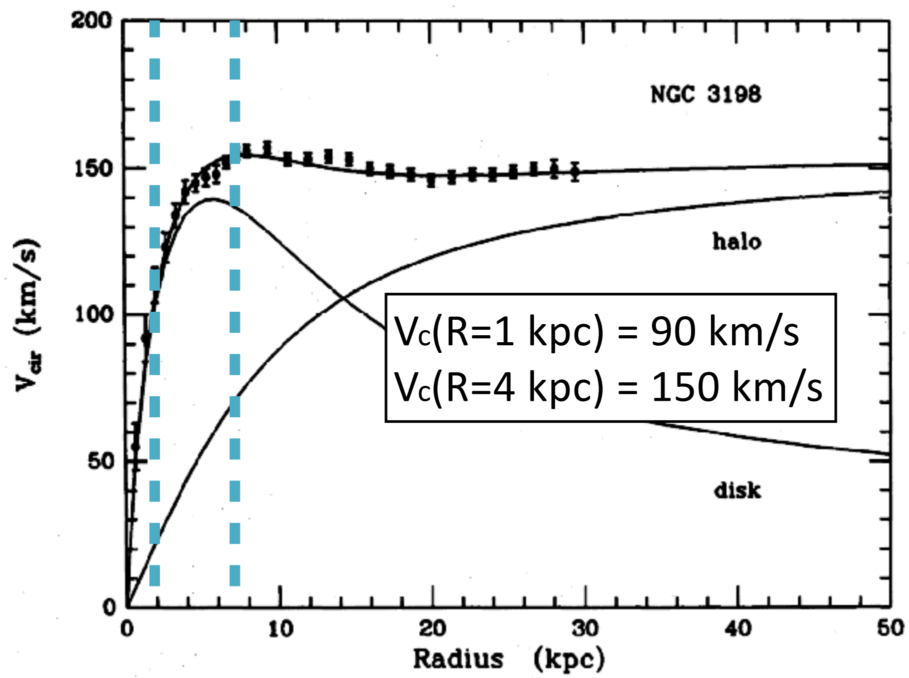




$$\frac{T_{orb}(R=1\ \mathrm{kpc})}{T_{orb}(R=4\ \mathrm{kpc})} = \frac{2\pi R_{1kpc}/V_{c,1kpc}}{2\pi R_{4kpc}/V_{c,4kpc}} = \frac{R_{1kpc}}{R_{4kpc}}\,\frac{V_{c,4kpc}}{V_{c,1kpc}} = \frac{1}{4}\,\frac{150}{90} \sim 0.4$$

Are spiral structures static?



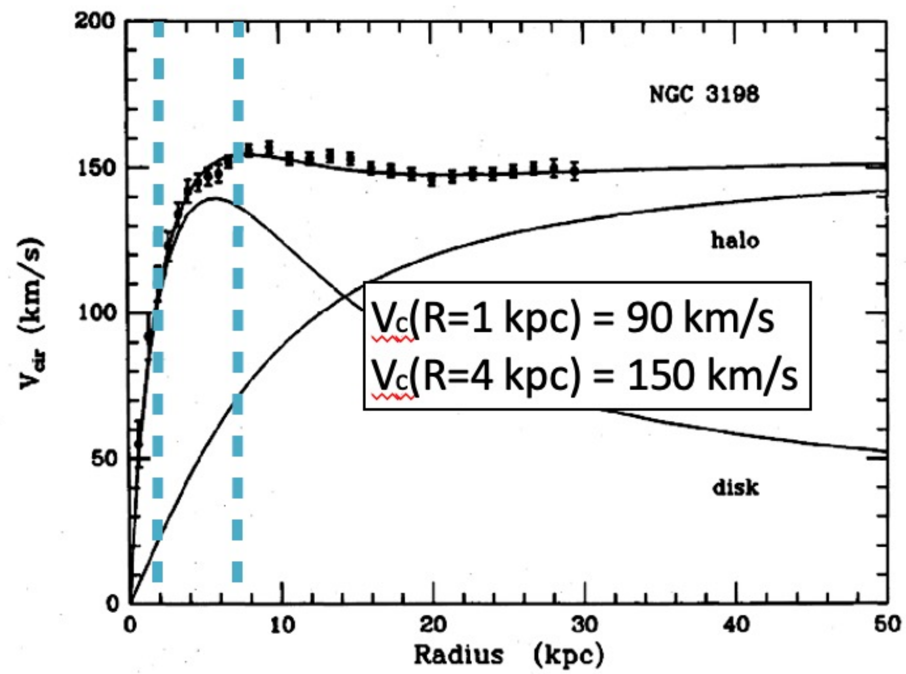


T_{orb}(R=1 kpc) ~ 0.4T_{orb}(R=4 kpc)

For every orbit of the 4 kpc material, the 1 kpc material orbits (1/0.4) ~ 2.5 times.

From Karin Sandstrom

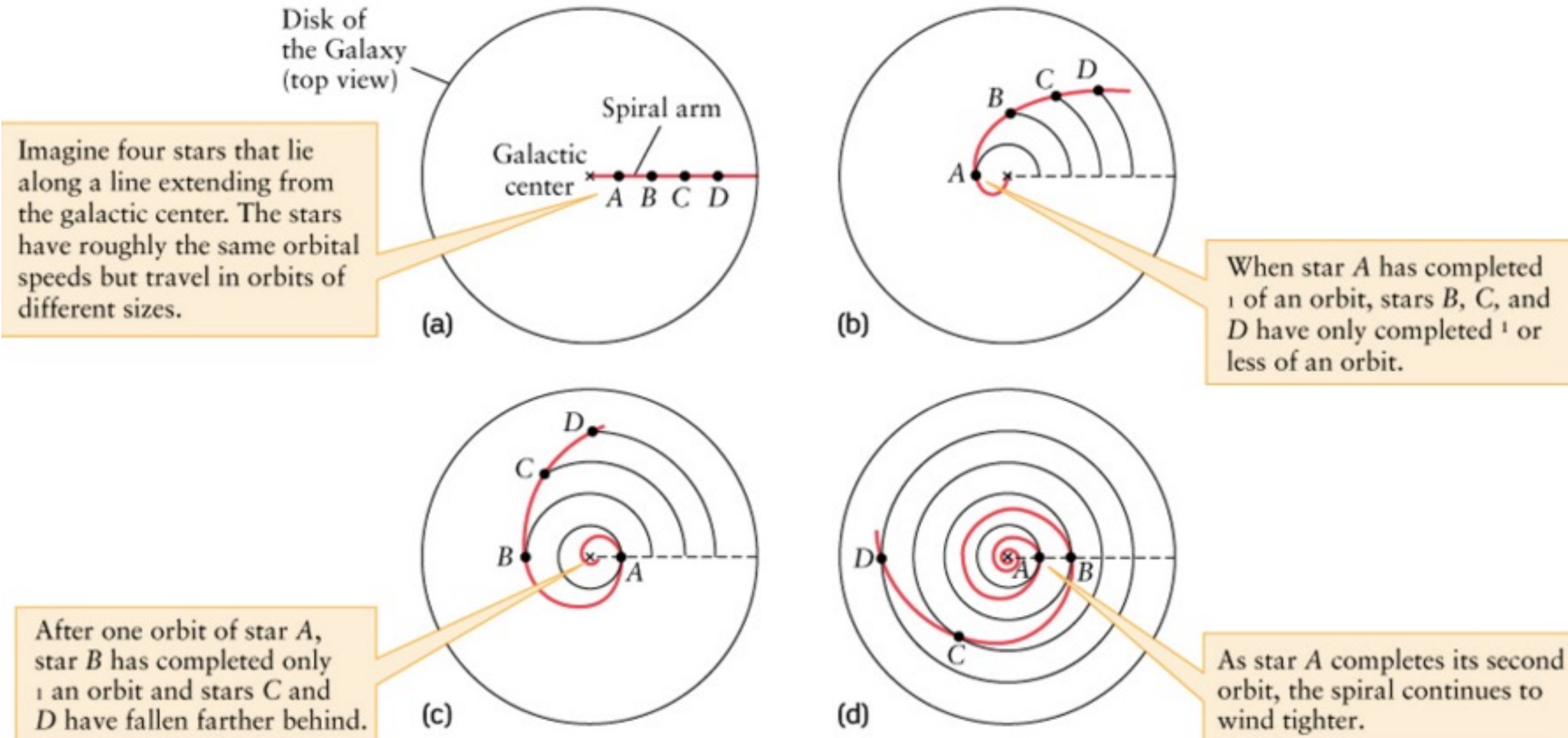
Are spiral structures static?



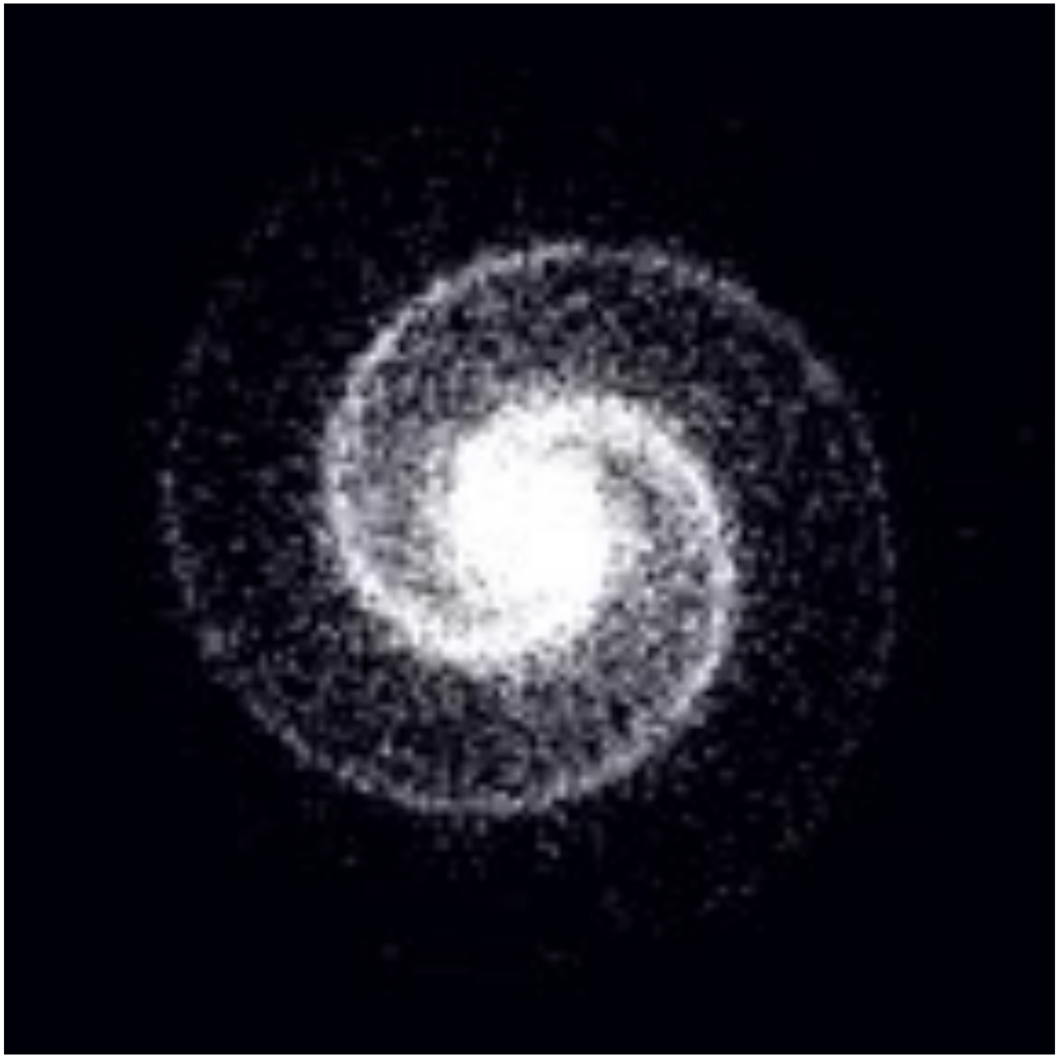
T_{orb}(R=1 kpc) ~ 0.4T_{orb}(R=4 kpc)

For every orbit of the 4 kpc material, the 1 kpc material orbits (1/0.4) ~ 2.5 times.

Winding Problem



Winding Problem

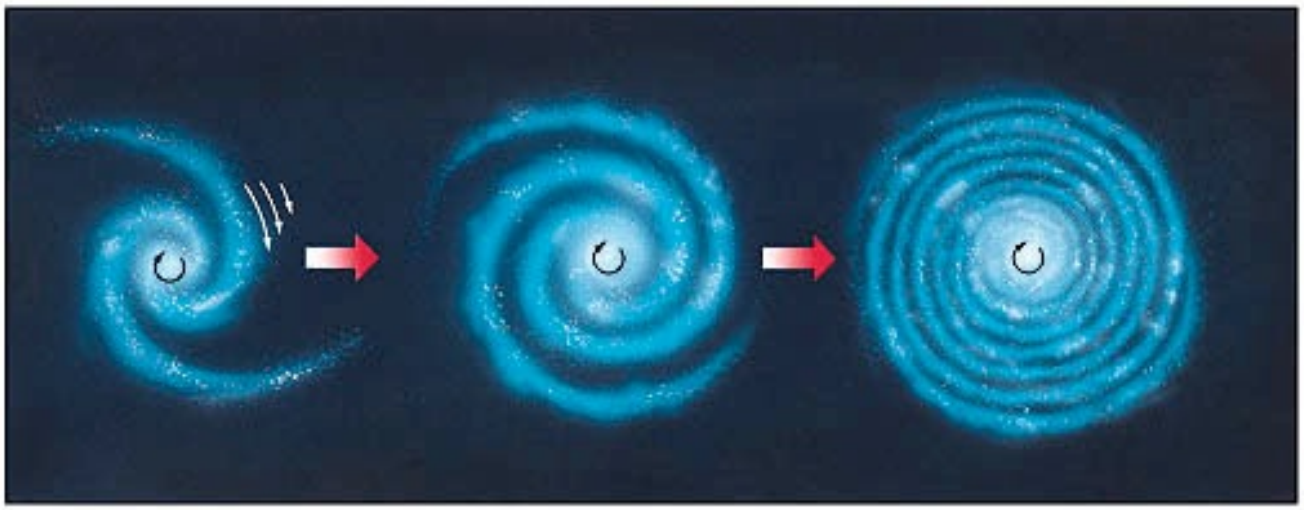


Ingo Berg

Hypothesis 1: stars born in spiral arms stay in spiral arms. Spiral structures are "static" (unchanging).

NO!

Differential rotation would cause a spiral pattern to wind up over time as the inner regions completed more revolutions than the outer ones



This would quickly (within a few 100 Myr) destroy spirals. The fact that we see so many suggest that spiral structures are not static

MW has made ~70 rotations: 13.8 Gyr / T, [T= (2*8kpc*pi)/ (240 km/s ~ kpc/Gyr) = 0.2 Gyr]

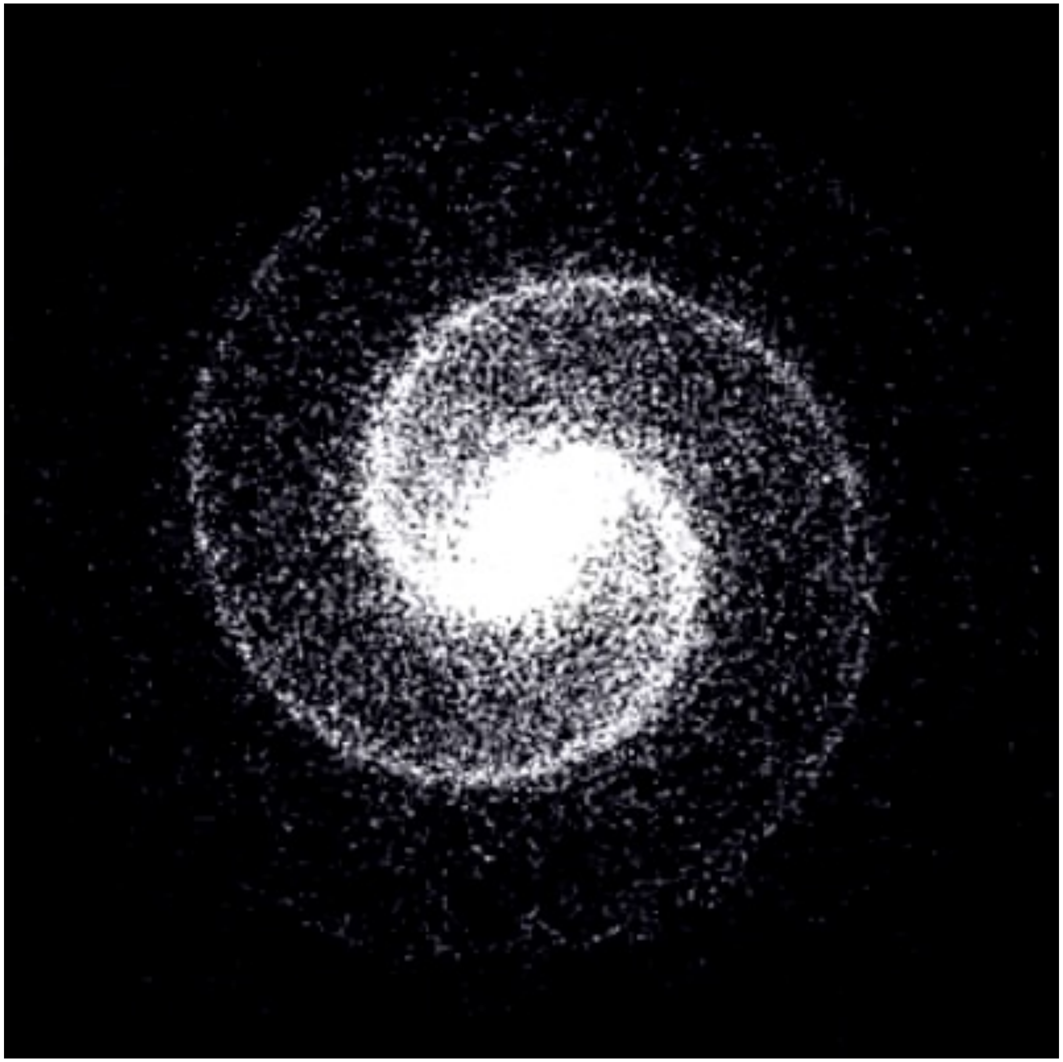
Hypothesis 2: Spiral arms are the result of density waves – Spiral arms are not rotating with the stars.

In this picture orbiting stars and molecular clouds *pass through the spiral arms* and *linger* a bit longer there due to the gravitational attraction of the extra matter in the arm.

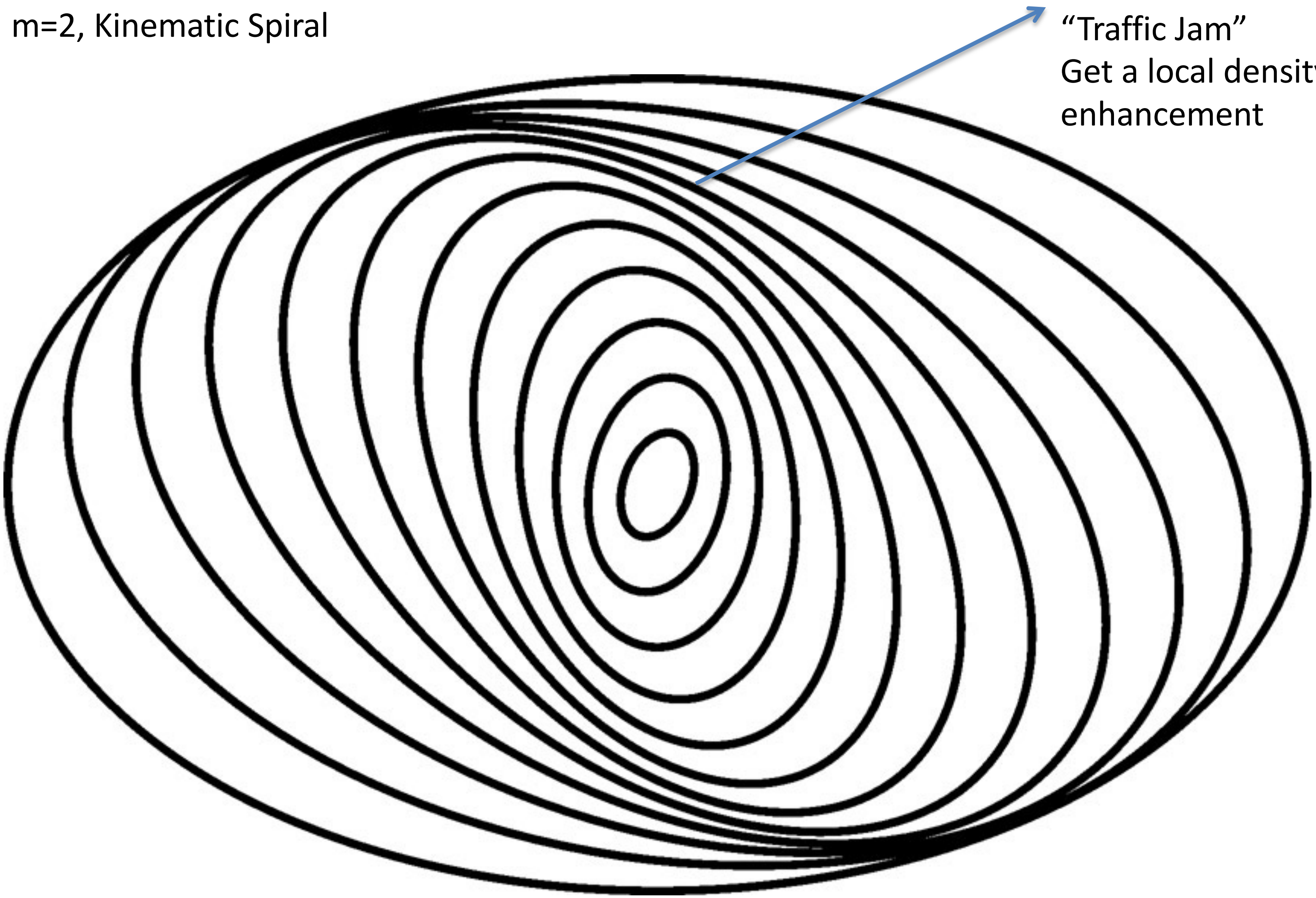
Density Waves are like stellar traffic jams:

So spiral arms are locations where the stellar orbits cause the stars to temporarily be more densely packed.

Density Wave Theory



m=2, Kinematic Spiral



“Traffic Jam”
Get a local density enhancement

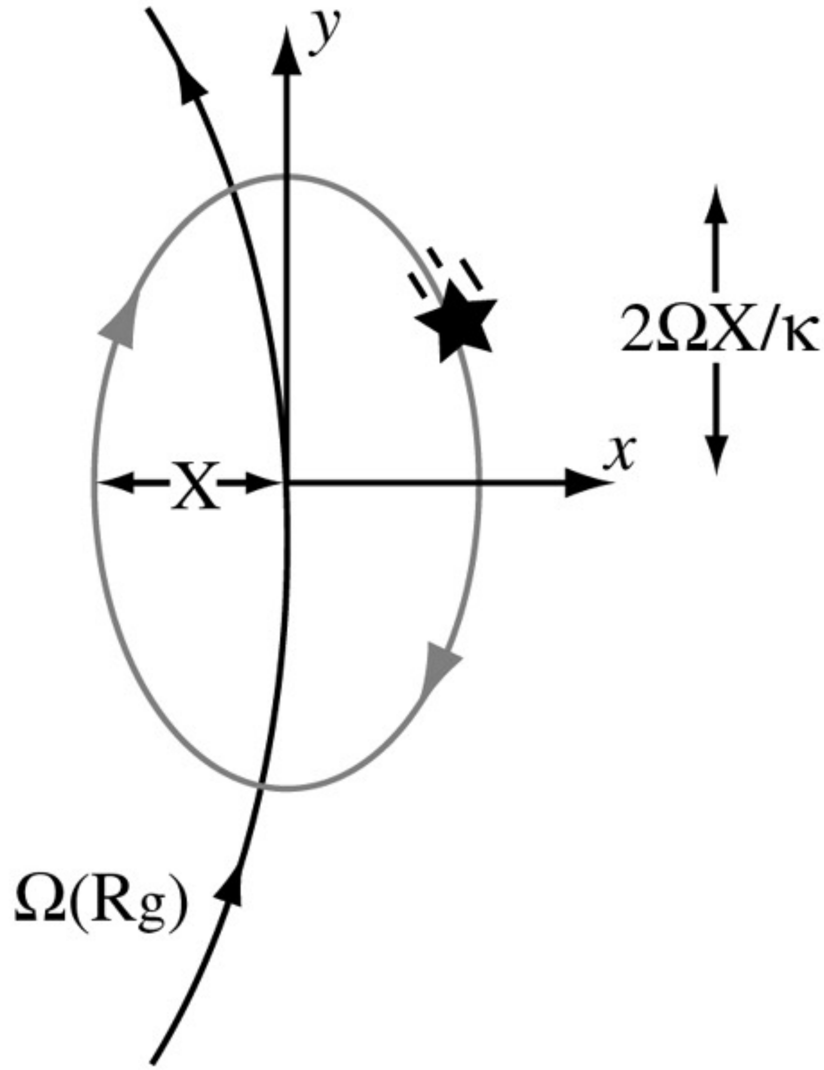
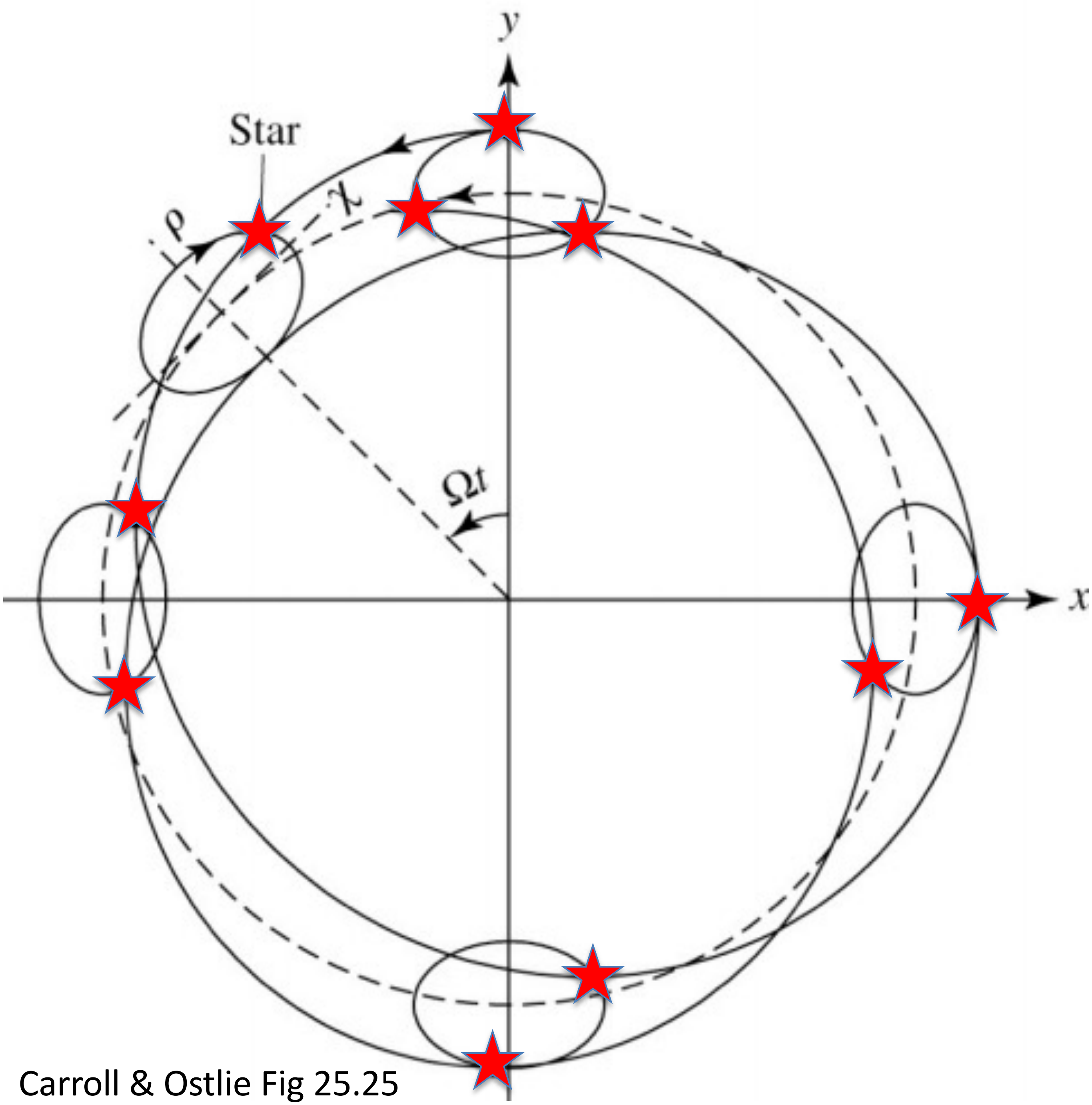


Fig 3.9 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Star moves in an elliptical epicycle around its guiding center, which is carried around the Galactic center with angular speed Ω(Rg)



Carroll & Ostlie Fig 25.25

In an inertial reference frame a star's orbital motion in the disk forms a non-closing rosette pattern. The motion can be imagined as being the combination of a retrograde orbit about an epicycle with the prograde orbit of the center of the epicycle about a perfect circle (dashed line)

Orbital path of a star in the disk, seen from above.

2. In general the ratio κ/Ω is irrational, so the orbit is unclosed and forms a rosette figure;

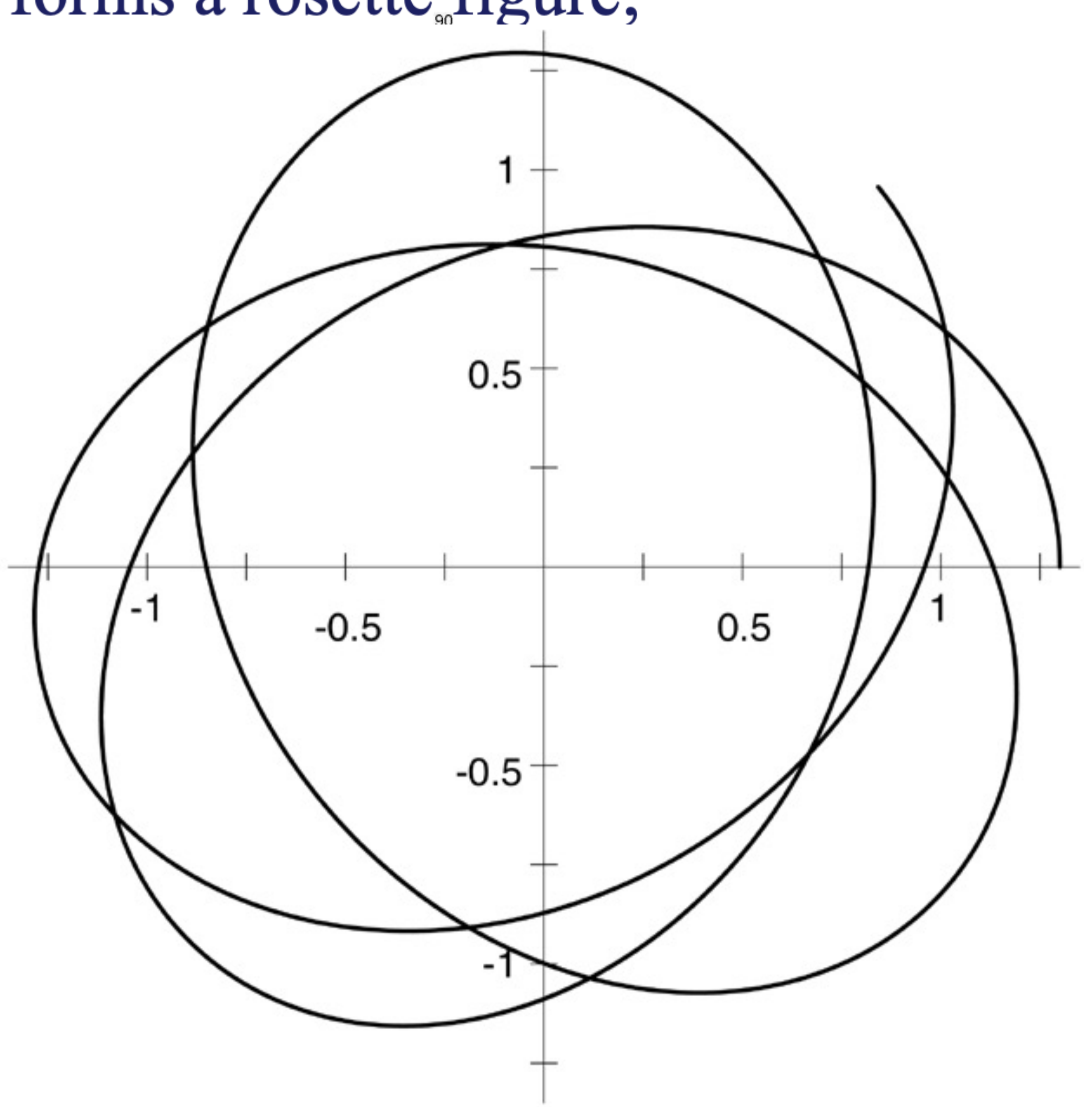
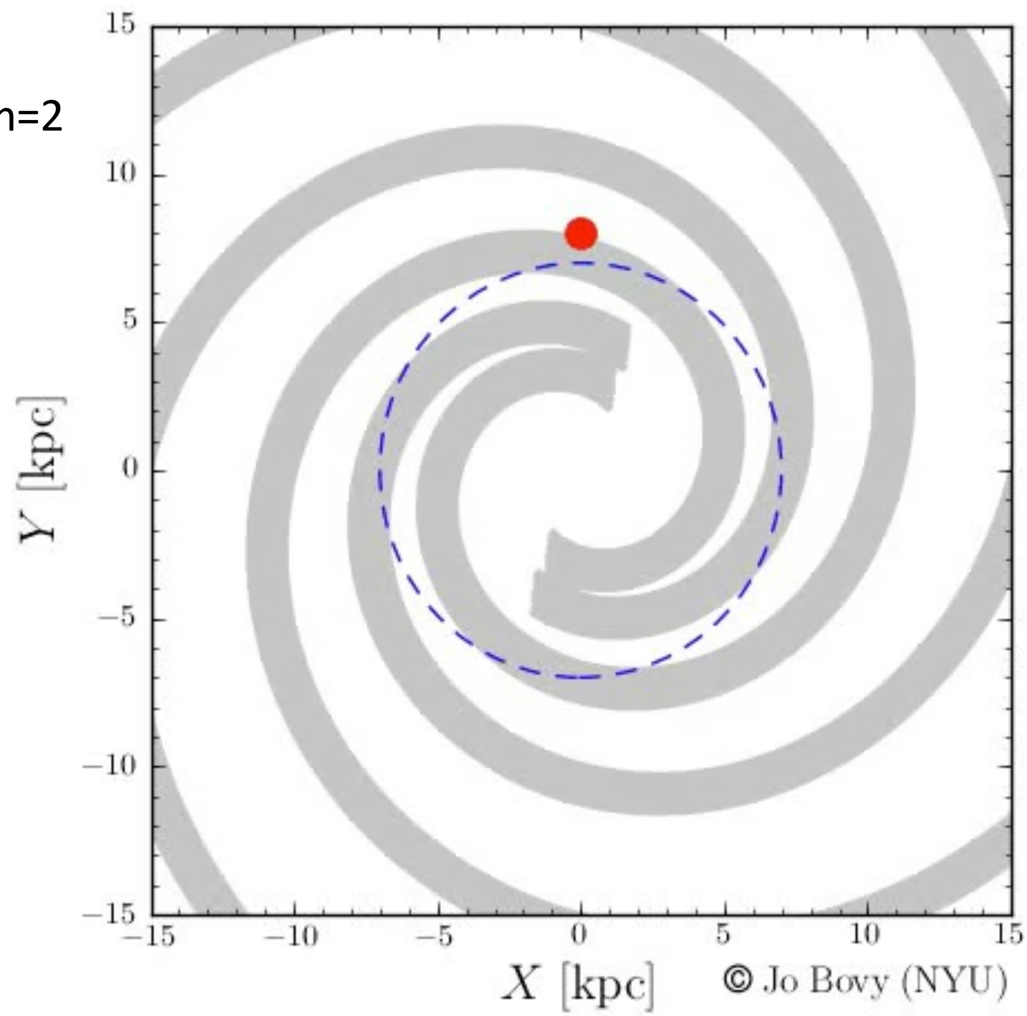


Fig 3.10 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

View the motion in a rotating frame at a proper angular speed Ωp – the orbits are then closed

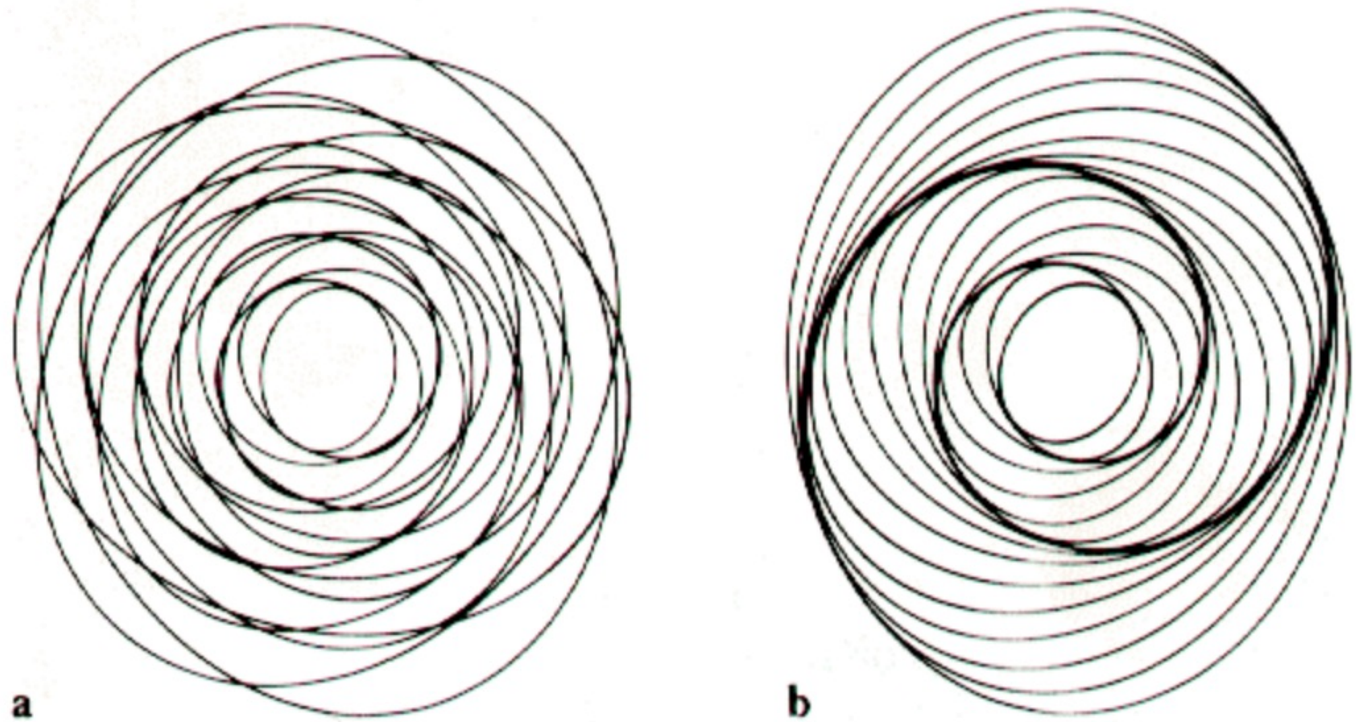
n=1, m=2



$$\Omega_p = \Omega - \frac{n\kappa}{m}$$

Pattern Speed Ωp : The pattern made up by stars with a given guiding center will return to its original state after a time T=2Pi/ Ωp

Why m=2 ? Why not random ?



The Origin of Spiral Density Waves

Both drawings have exactly the same number of ellipses, each one representing the orbit of a star. (**a**) Randomly oriented ellipses. (**b**) Ellipses with a correlation between the orientations of adjacent ellipses.

Because the Pattern is reinforced by resonances

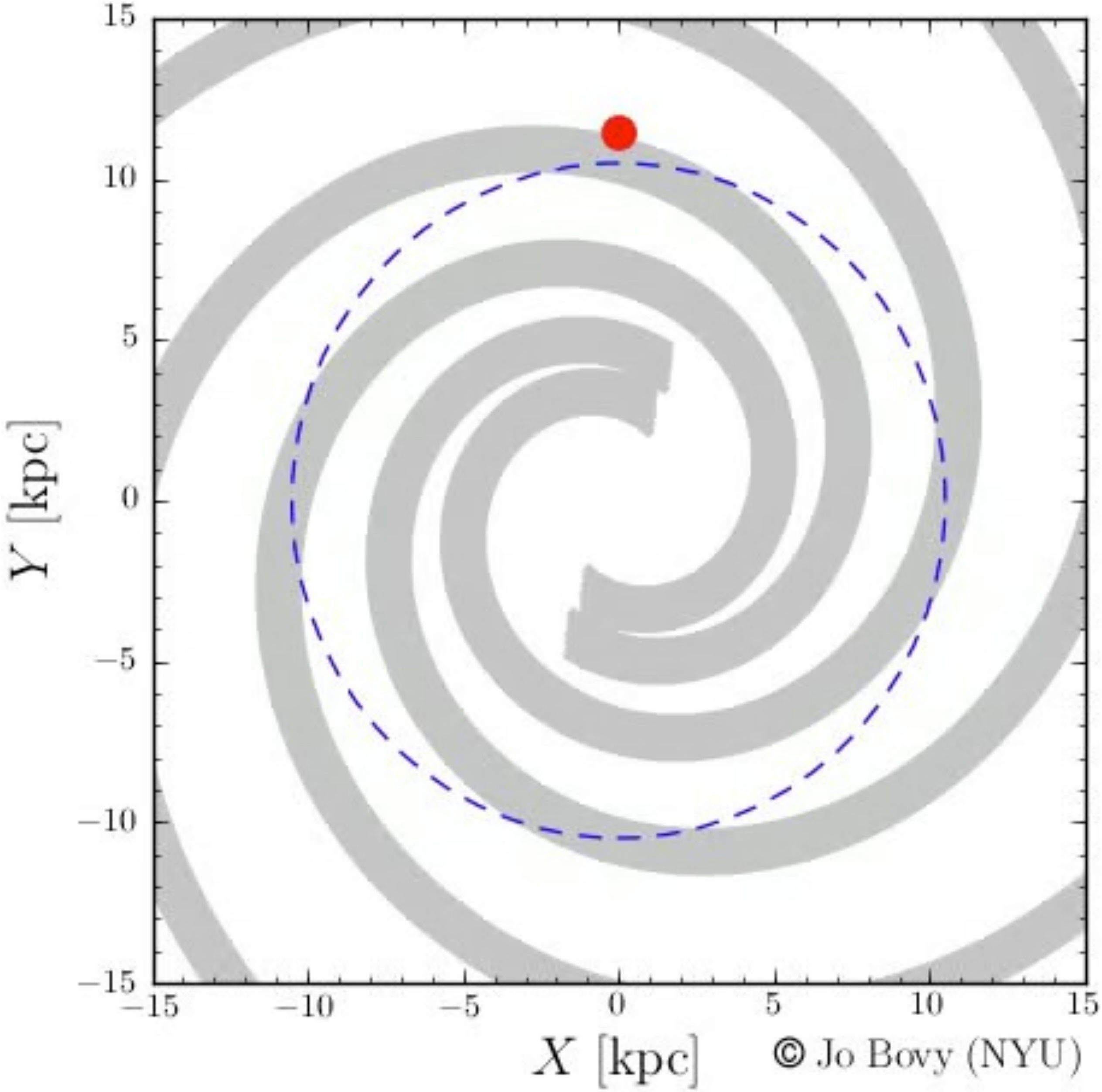
Corotation

Reinforcing the pattern

This resonance occurs when the orbit moves at the same angular speed as the forcing

$\Omega = \Omega_p$

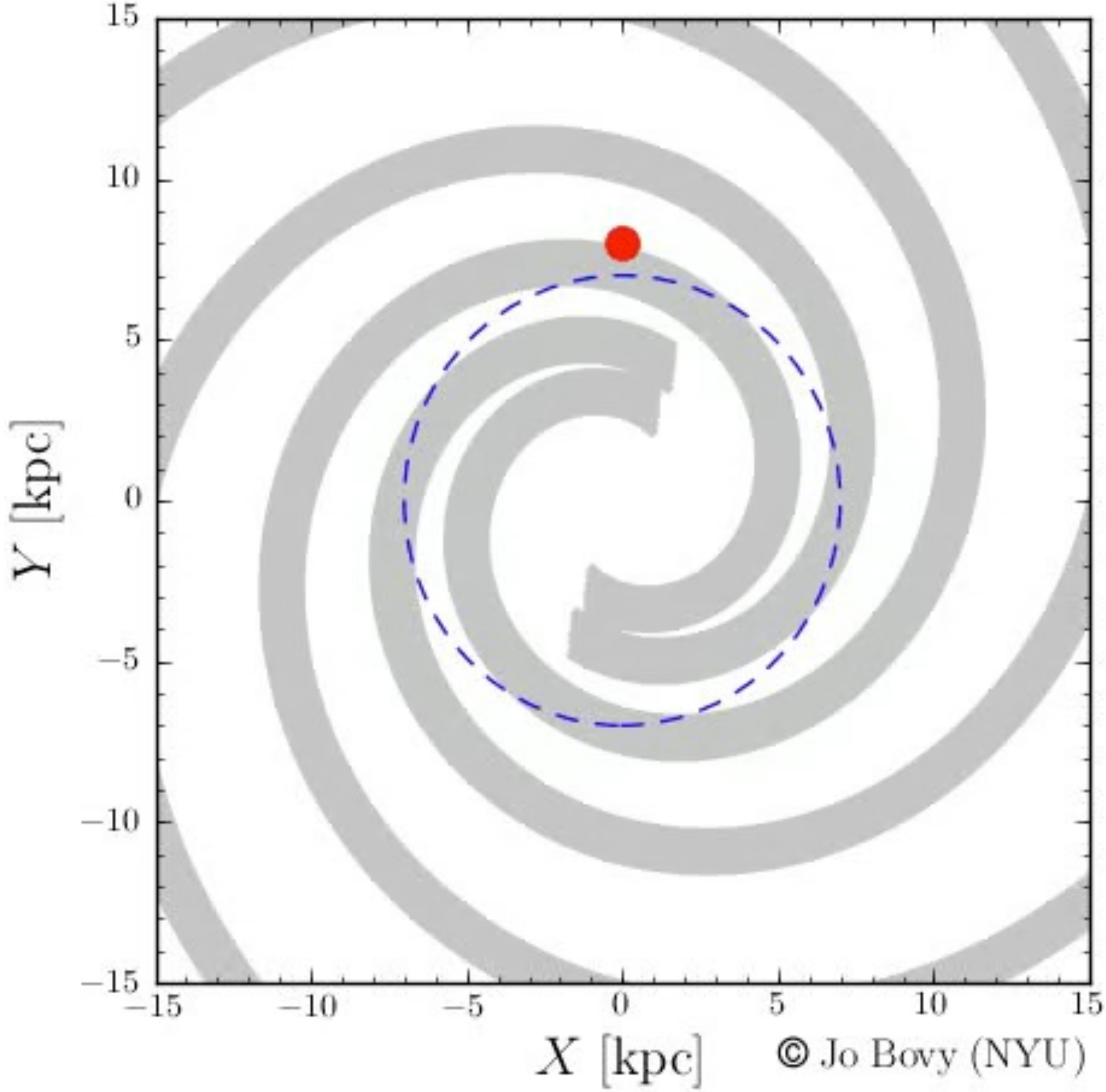
The forcing frequency can be the rate at which an object encounters successive crests of spiral waves



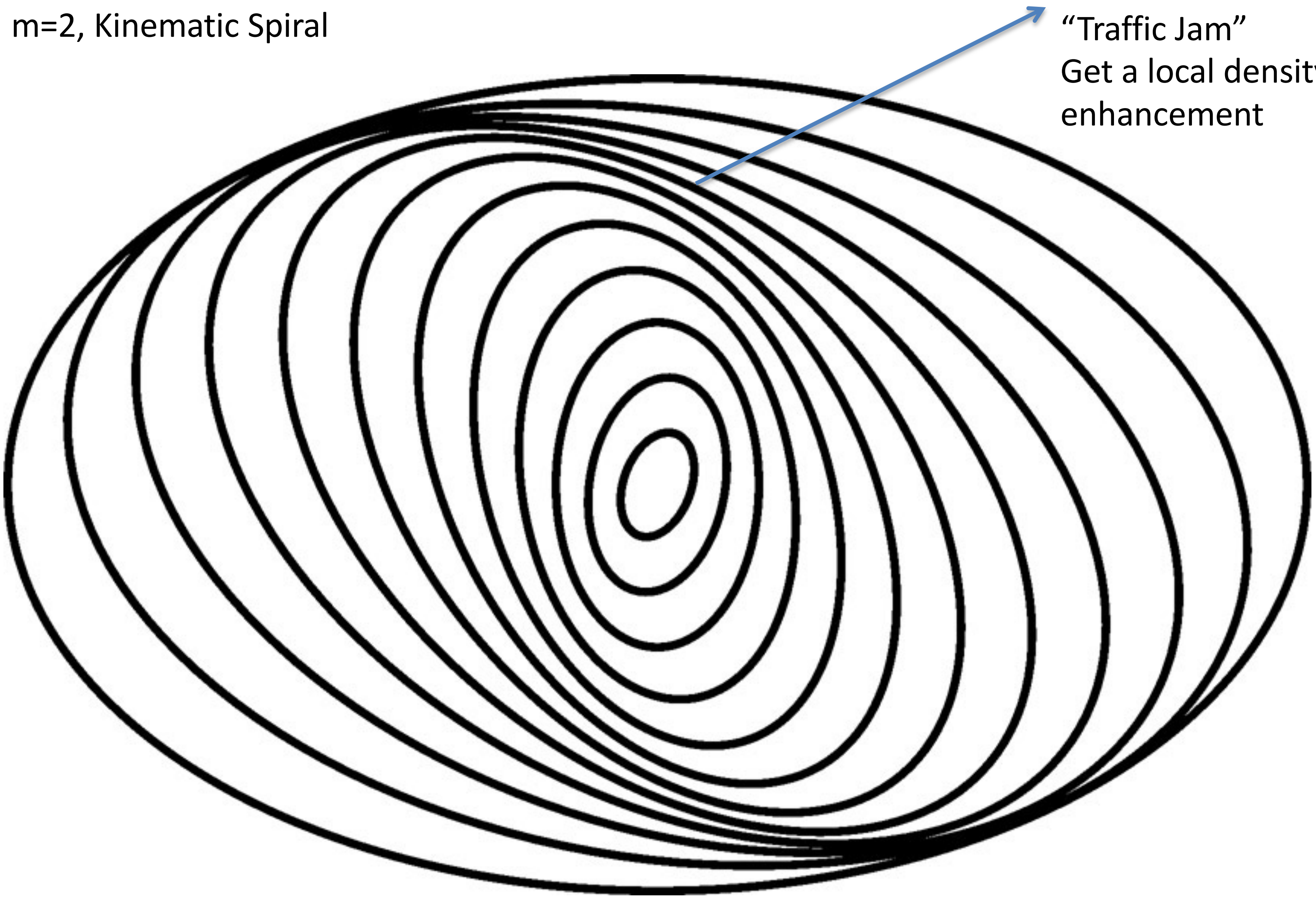
Inner Lindblad Resonance

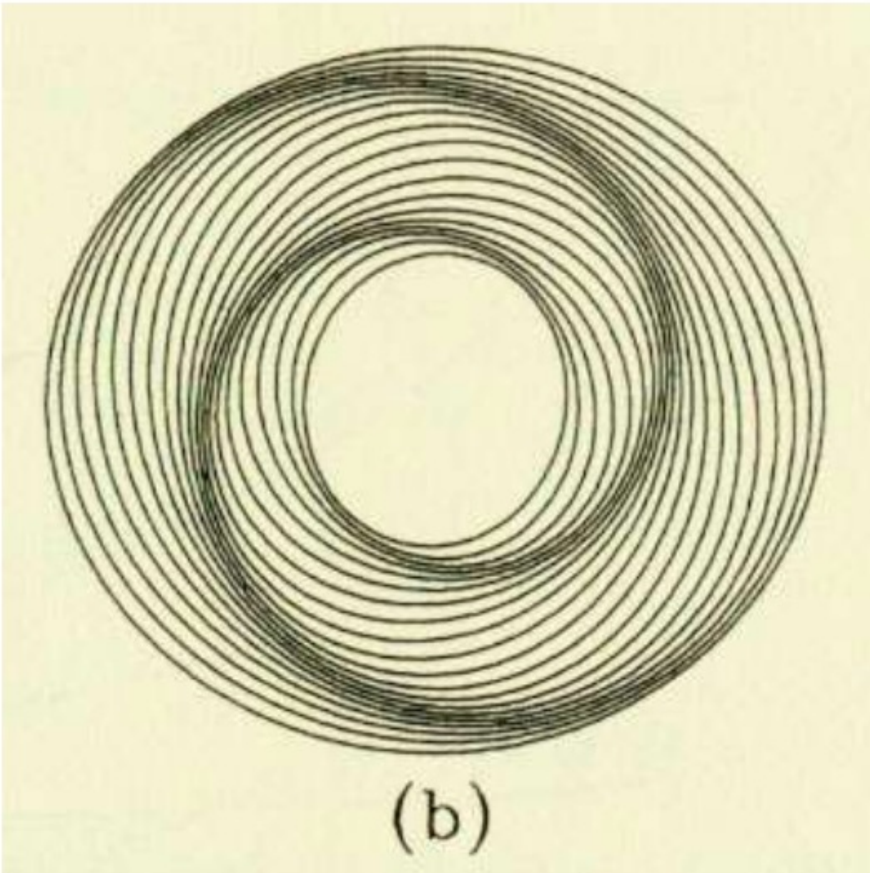
This resonance occurs when the orbit overtakes the forcing periodically.

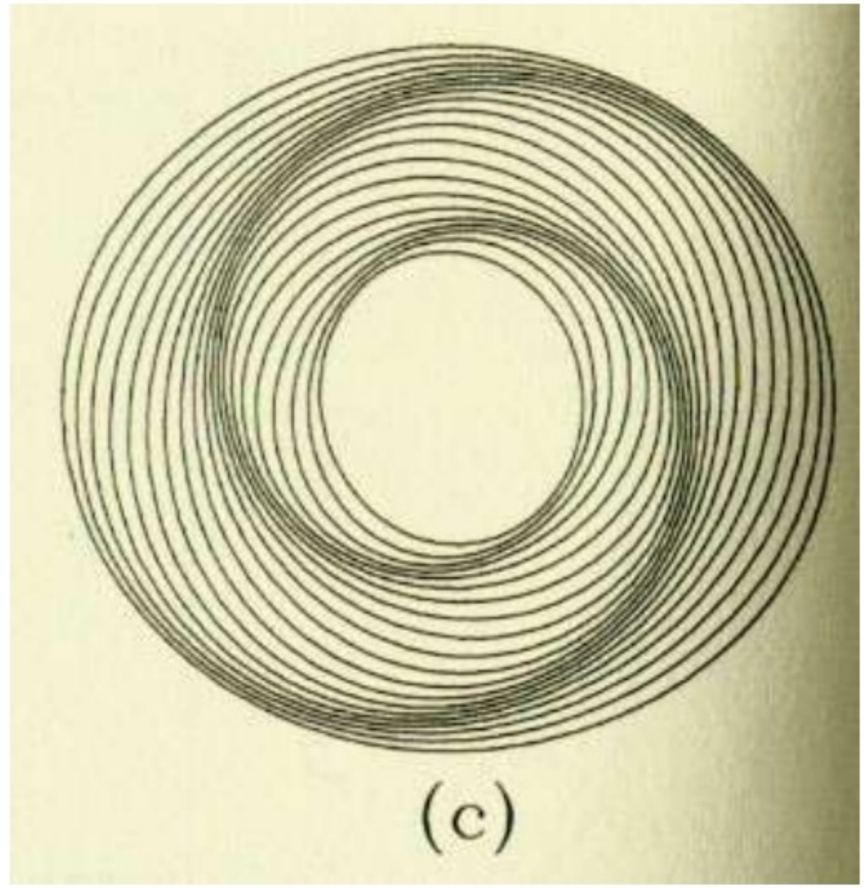
Lindblad Resonance: Stars complete exactly 1 epicycle between the passage of each arm.



m=2, Kinematic Spiral

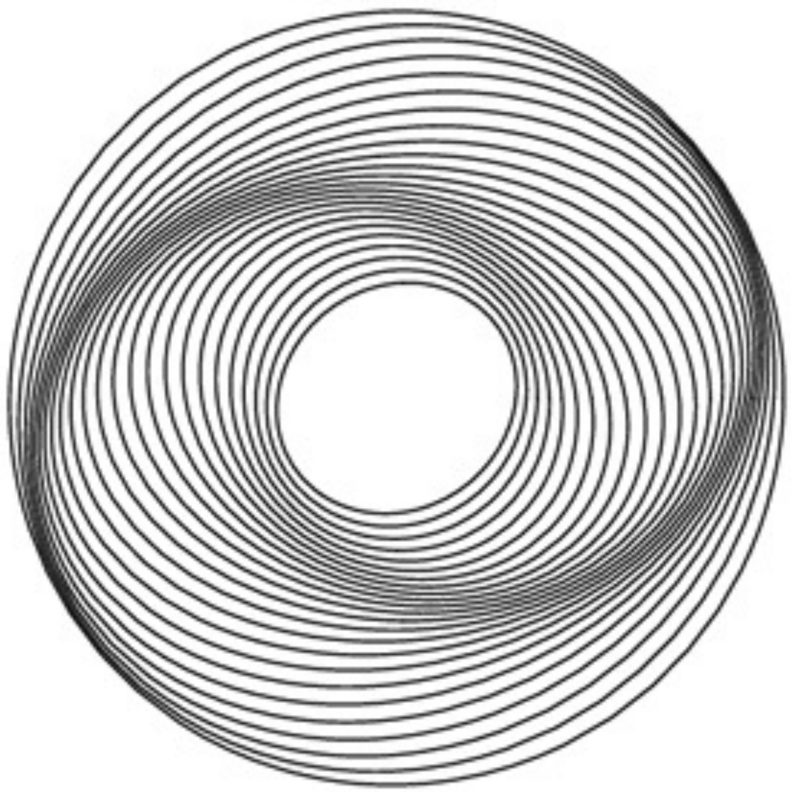






Leading spirals

Trailing spirals



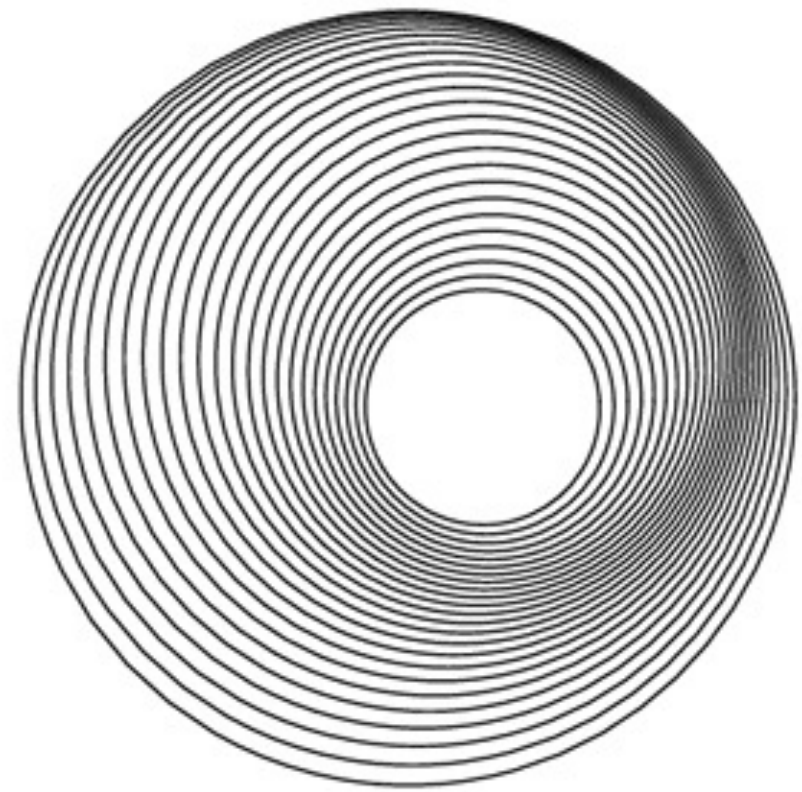
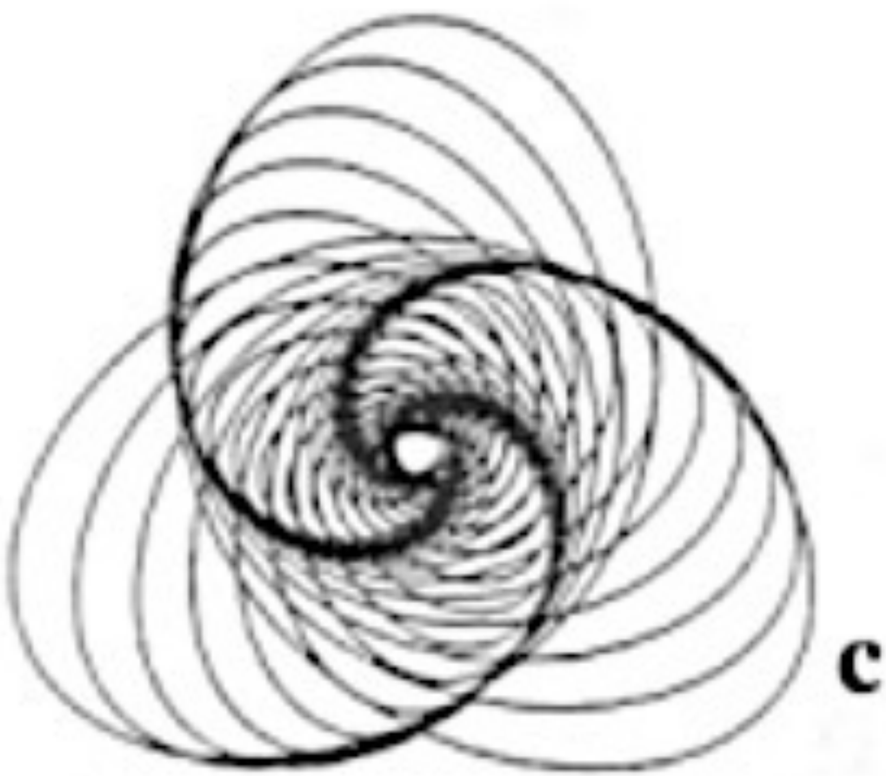


Fig 5.29 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Left: Oval orbits nested to form a 2-armed spiral
Right: A one-armed spiral

Viewed in a frame of reference co-rotating at the pattern speed – spiral looks stationary and the stars travel through it.

3 arms



4 arms

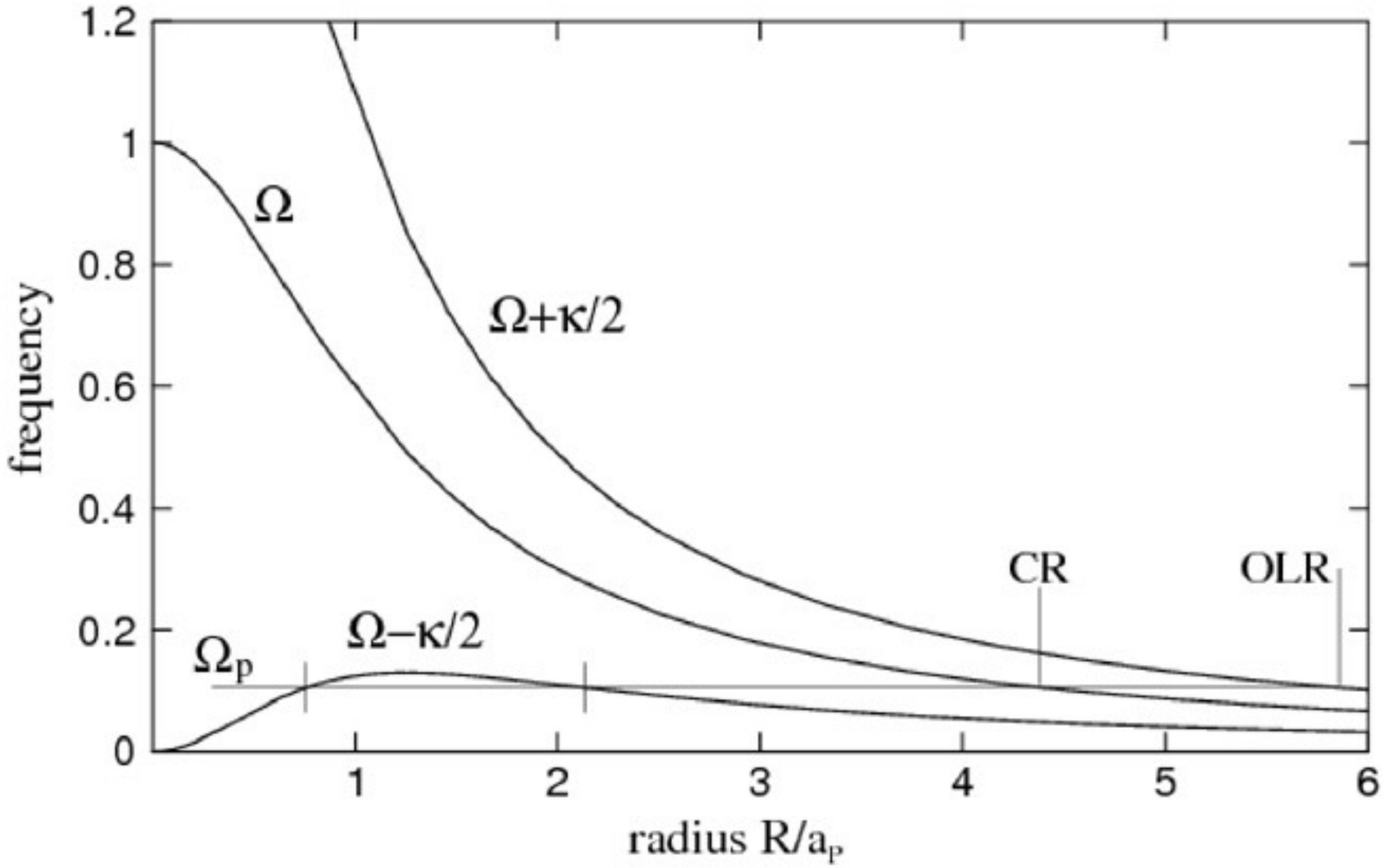
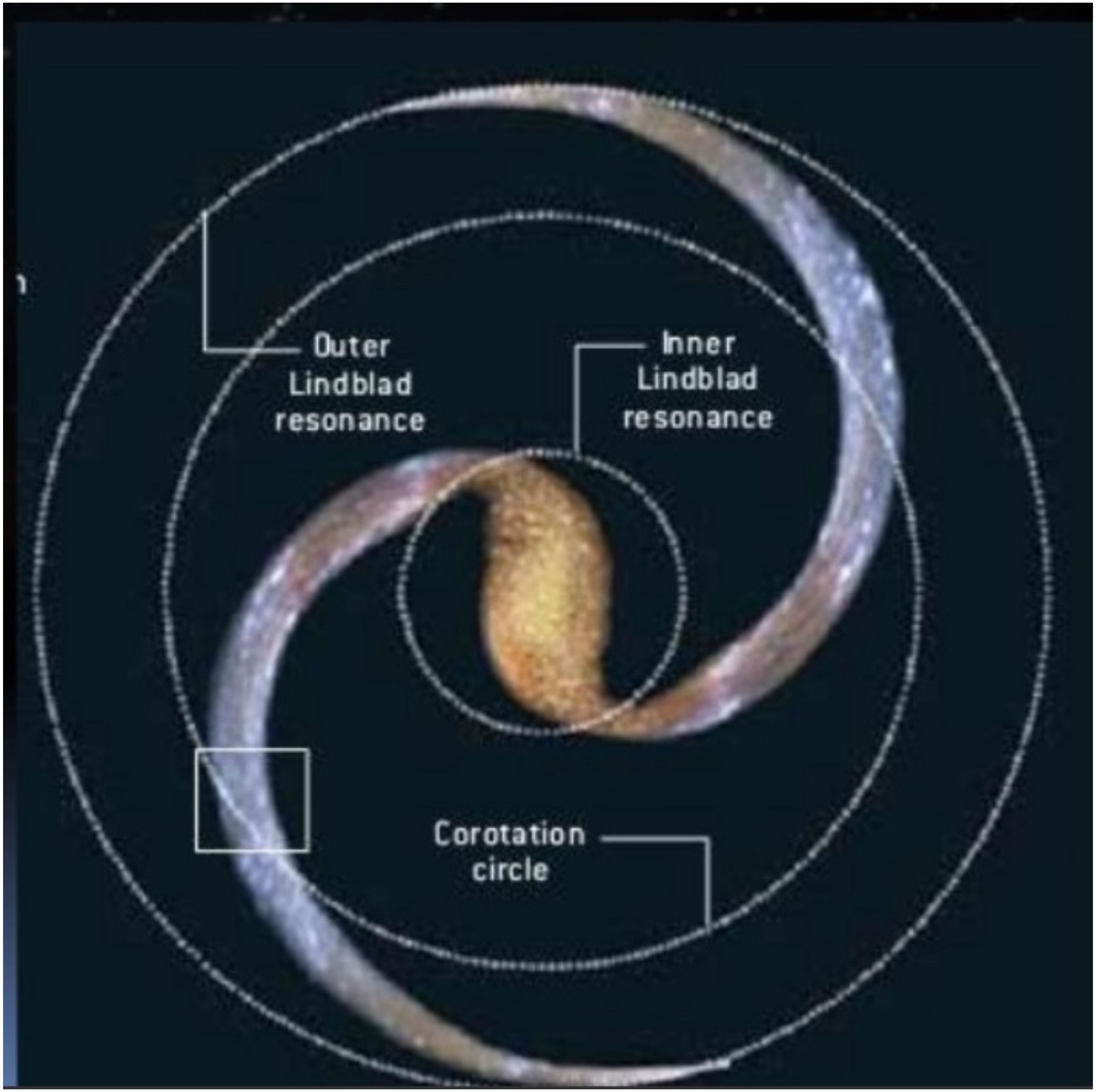


Fig 5.30 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Frequencies Ω(R) and Ω +/- κ/2 in a Plummer potential. For pattern speed Ωp, the m=2 inner Lindblad resonances are marked with vertical ticks.
Corrotation radius is labeled 'CR' (Ω(R) = Ωp) and Outer Lindblad resonance (OLR).
If the pattern speed were twice as large the inner Lindblad resonances would be absent


Outer
Lindblad
resonance
Inner
Lindblad
resonance
Corotation
circle

Spiral structure is more apparent in blue light

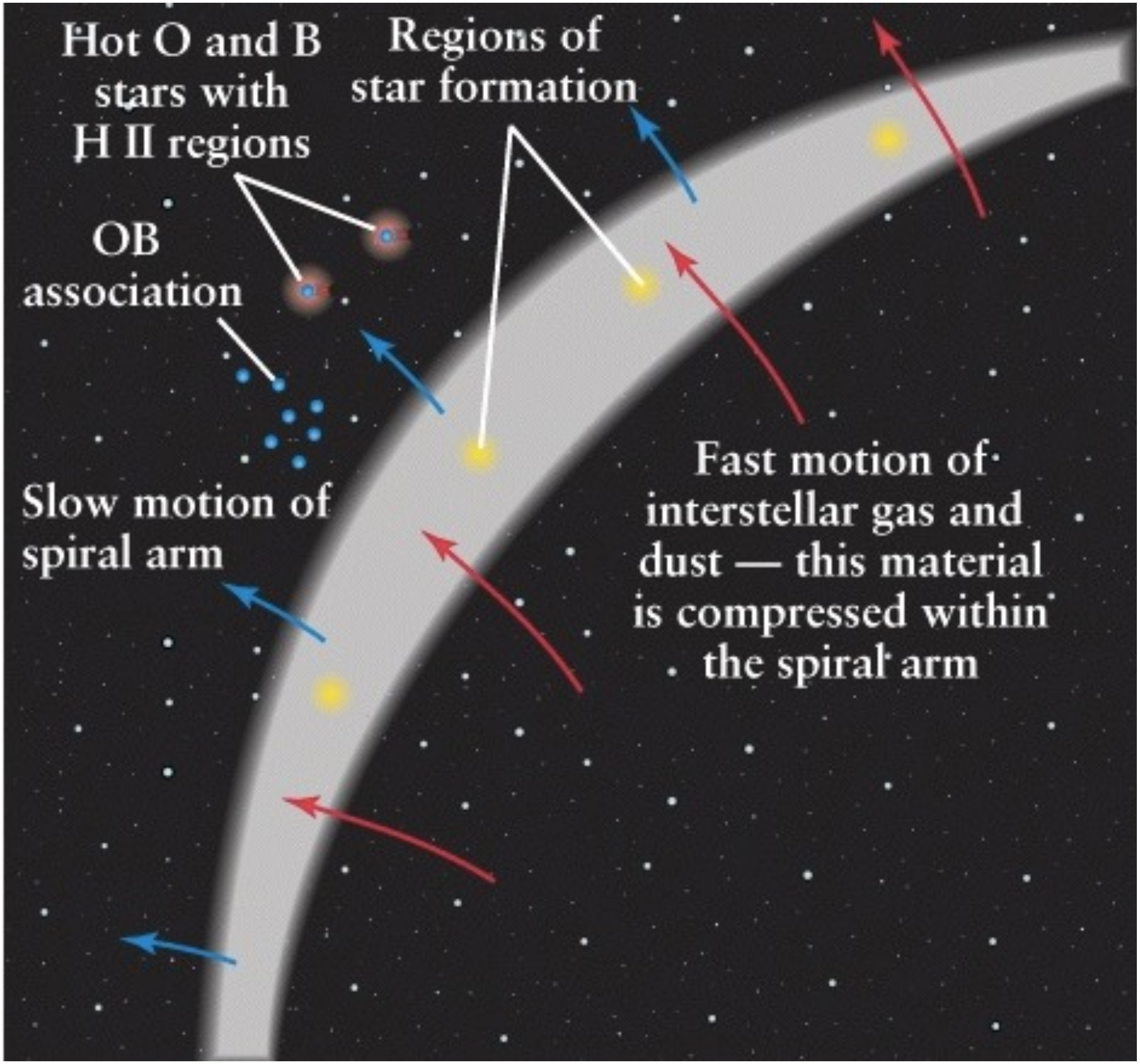
M81: ultraviolet

Light form short-lived massive stars

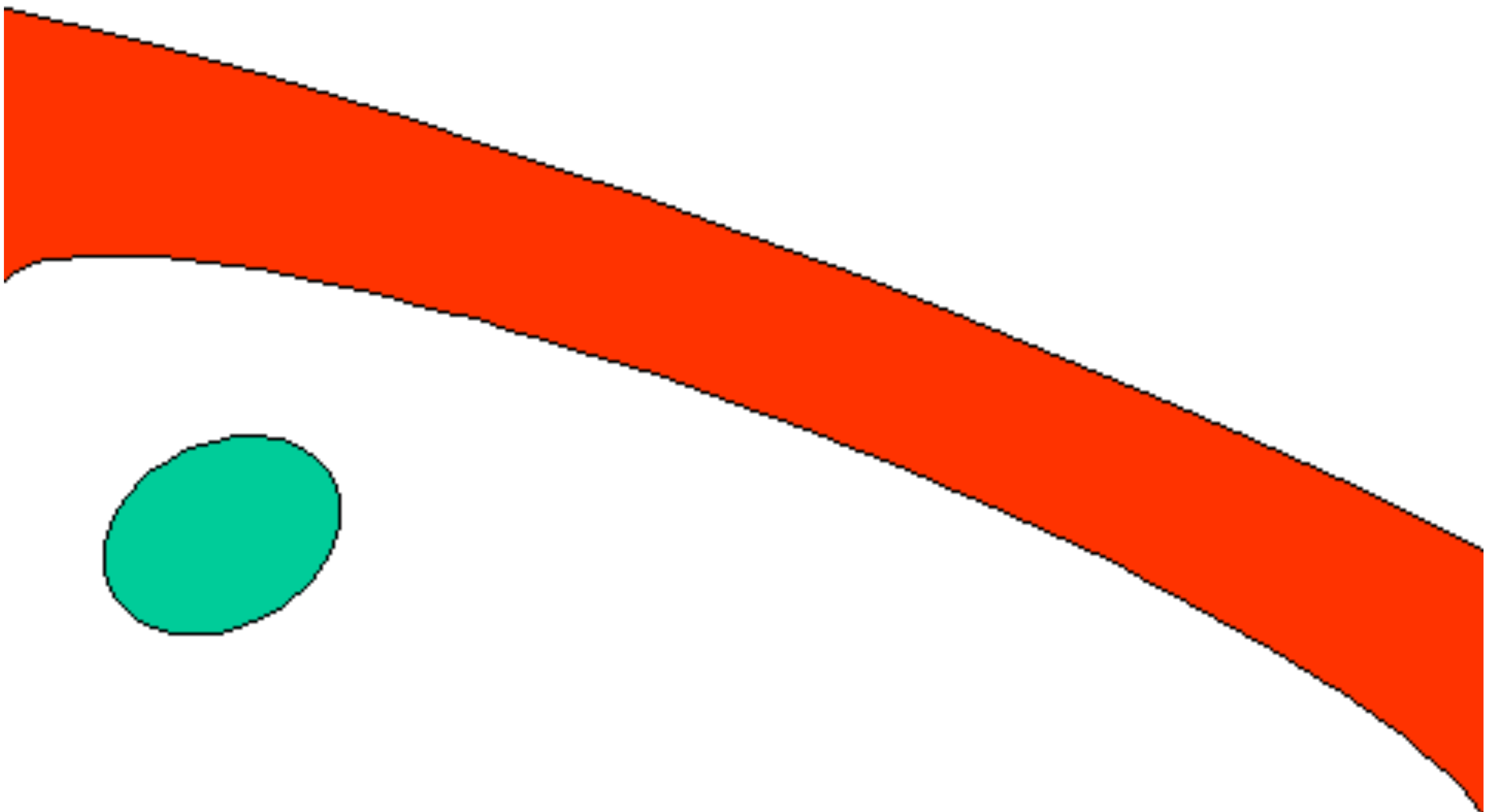
M81: near-infrared

Light form long-lived low-mass stars

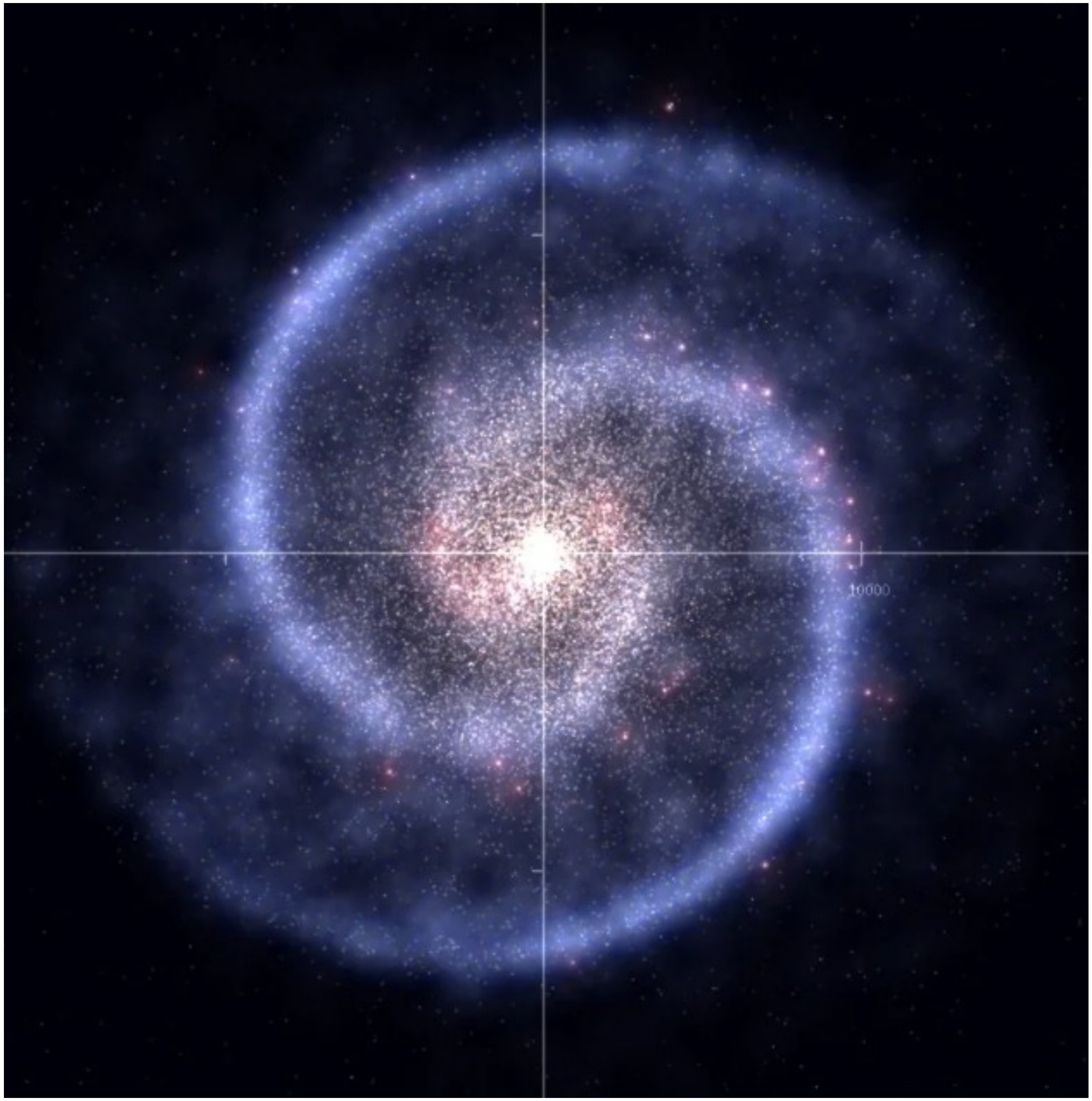
Stars form in the arms due to the compression of gas as it passes through the density wave.



Roberts 1969
Shu 1972

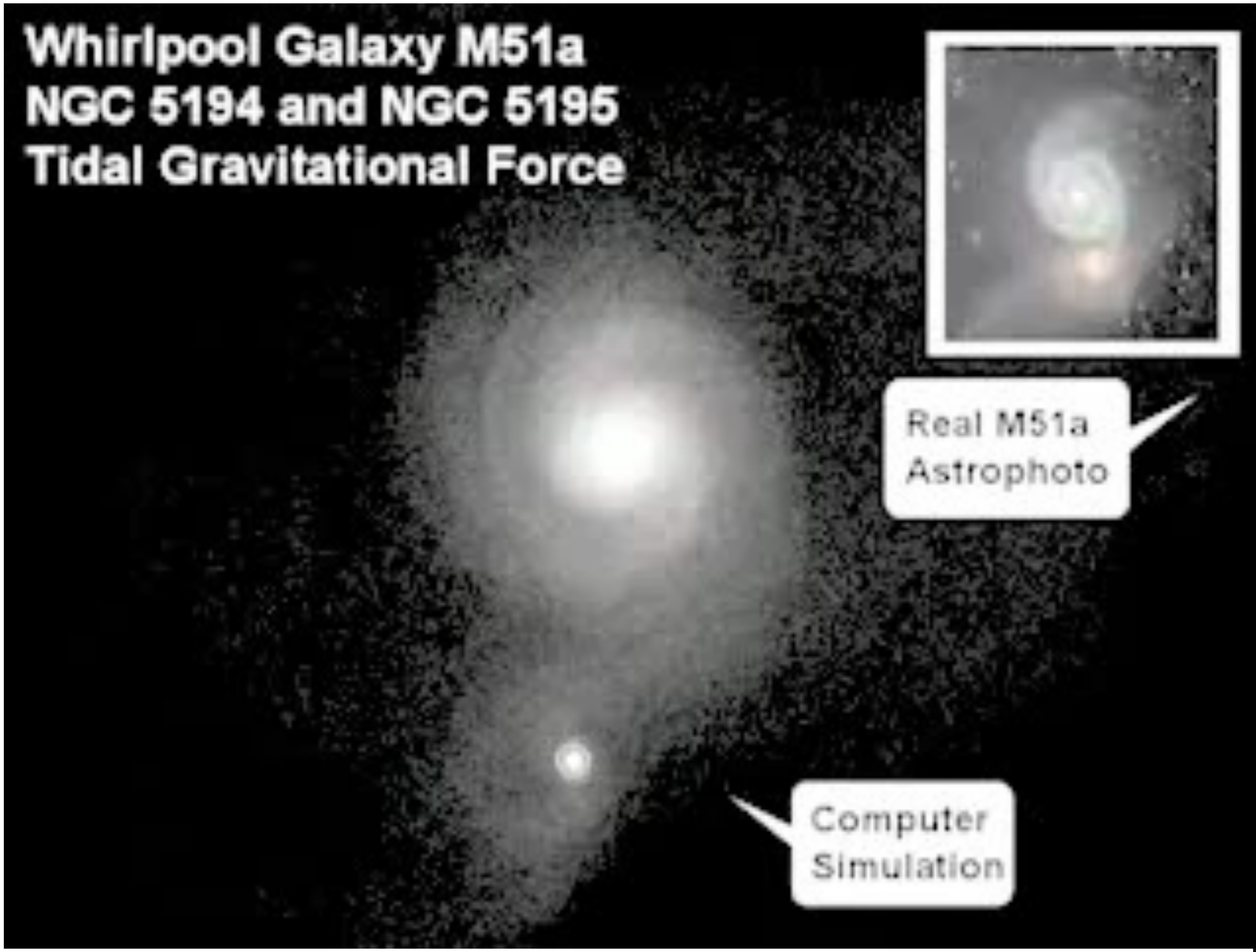


Animation by G. Rieke

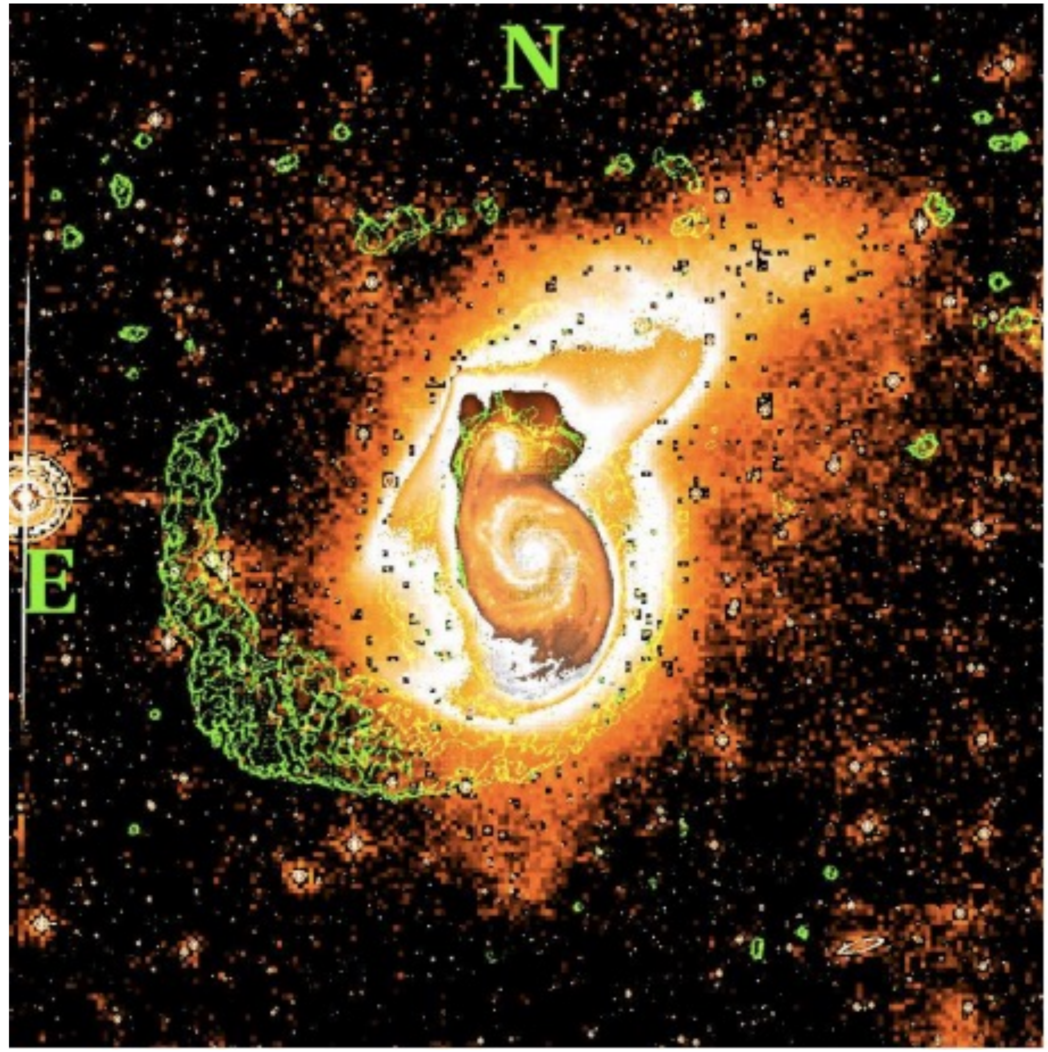


Ingo Berg

Hypothesis 3: Galaxy Interactions: There is an initial "seed" perturbation in the disk. These "seeds" come from either initial asymmetries in the disk and/or halo (galaxy formation processes), or induced via galaxy encounters.


Whirlpool Galaxy M51a
NGC 5194 and NGC 5195
Tidal Gravitational Force
Real M51a Astrophoto
Computer Simulation

Gas: VLA



Gas (green) and Optical (orange)

Watkins + 2015

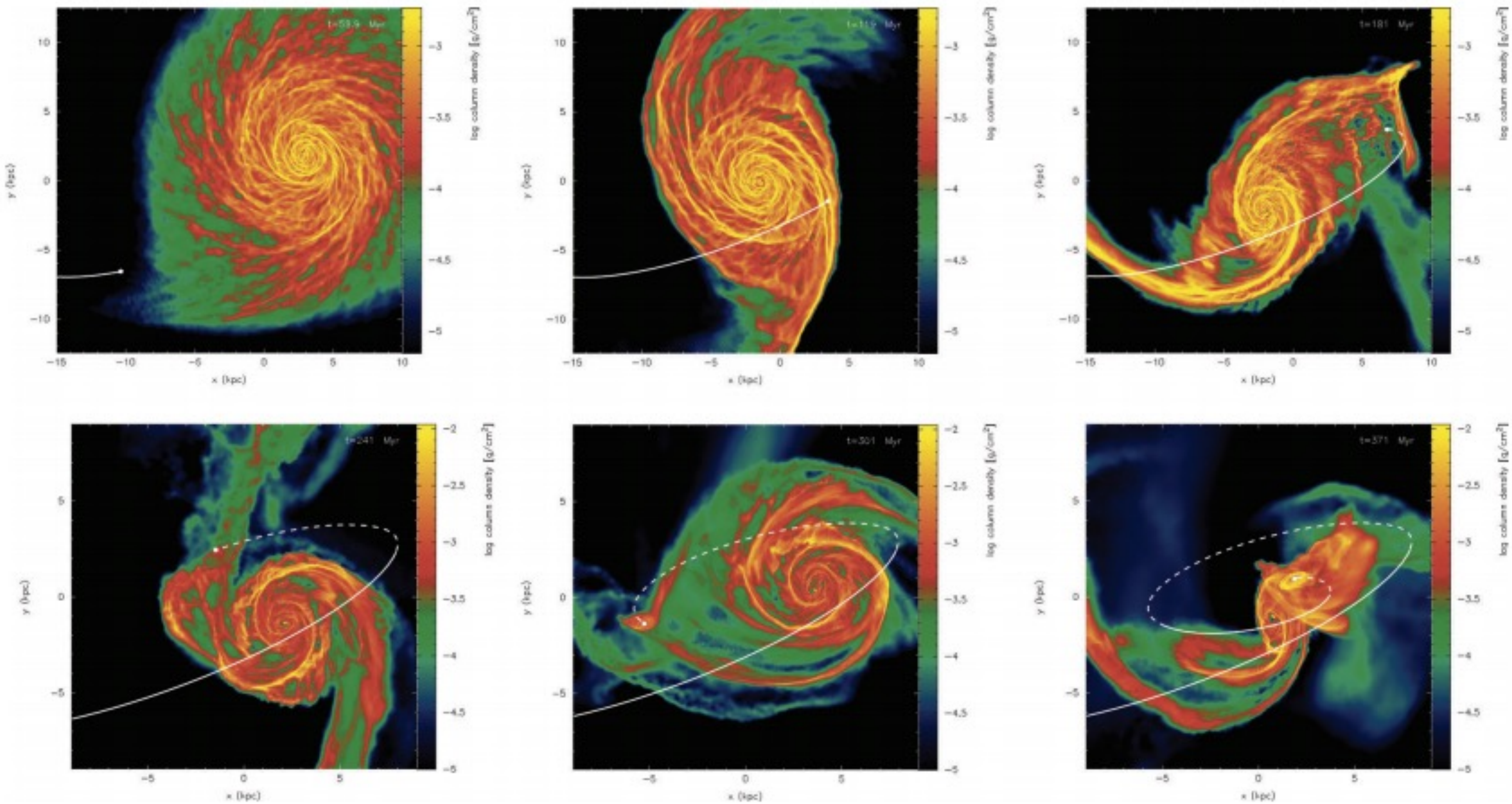


Figure 4. Column density plots show the time evolution of the simulated interaction of M51 and NGC 5195, at times of 60, 120, 180, 240, 300 (corresponding approximately to the present day) and 371 Myr. These plots only show the gas, which represents 1 per cent of the disc by mass, and has a temperature of 10^4 K (model A). We model a galaxy representing M51, whilst the galaxy NGC 5195 (a point mass) is indicated by the white spot. Sink particles are otherwise omitted from the figures (see text). The orbit of the companion galaxy is also shown on the panels (the dashed section indicates that the companion is behind the M51 galaxy). The galaxy undergoes a transition from a flocculent spiral to a grand design spiral during the course of the interaction. At the last time frame (371 Myr), the two galaxies are in the process of merging. Note, both the spatial and density scales differ in the lower three plots.

Dobbs + 2010

Dobbs + 2010