Astronomy 537

Lecture 10: Spiral structures II

Color gradients

Individual galaxies have *color gradients,* i.e. color depends on location. Bulges are redder than disks:

- Star formation
  - less ongoing star formation
  - agrees with more gas available in disk than in spheroidal components
- Metallicity
  - more electrons per atom

    -> more electrons to cause opacity effects

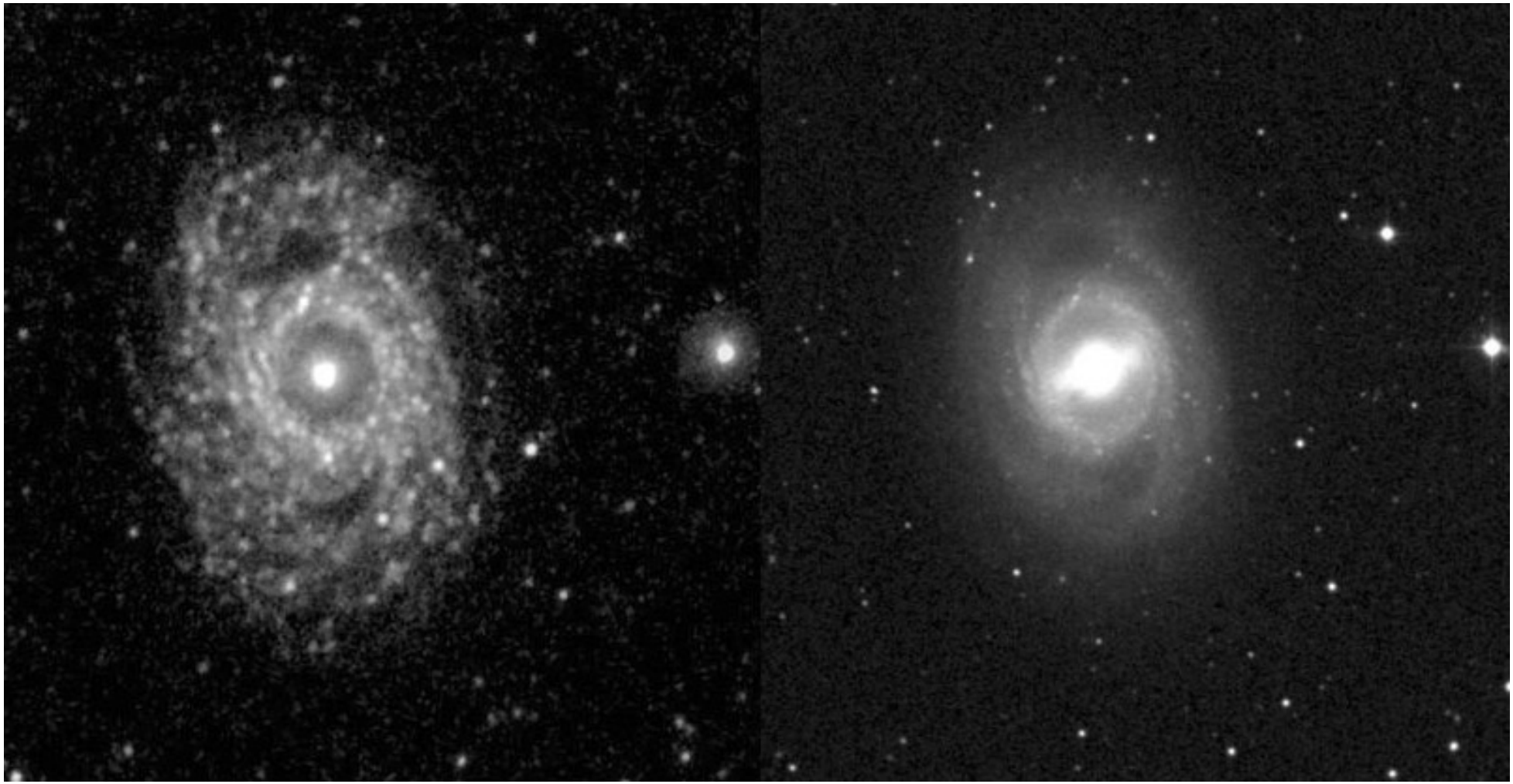
    -> less radiation escape star

    -> pushes layers outwards somewhat

    -> decreasing surface temp

    -> redder

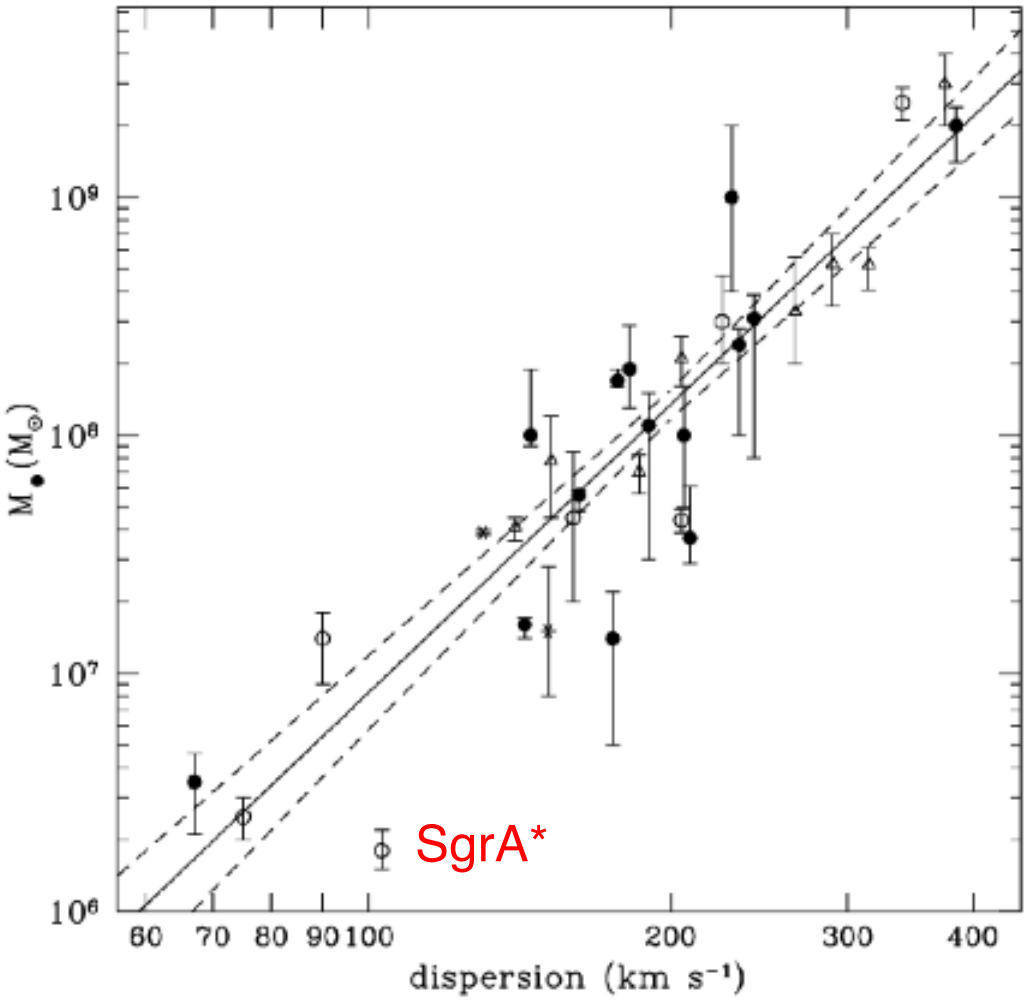
Effect of Color Gradients in M95



Ultraviolet

Visible

Supermassive black holes (M-sigma relation)



Correlation between black hole mass and velocity of bulge components. Indicates formation of galaxy is linked to formation of supermassive black hole.

Journal Class

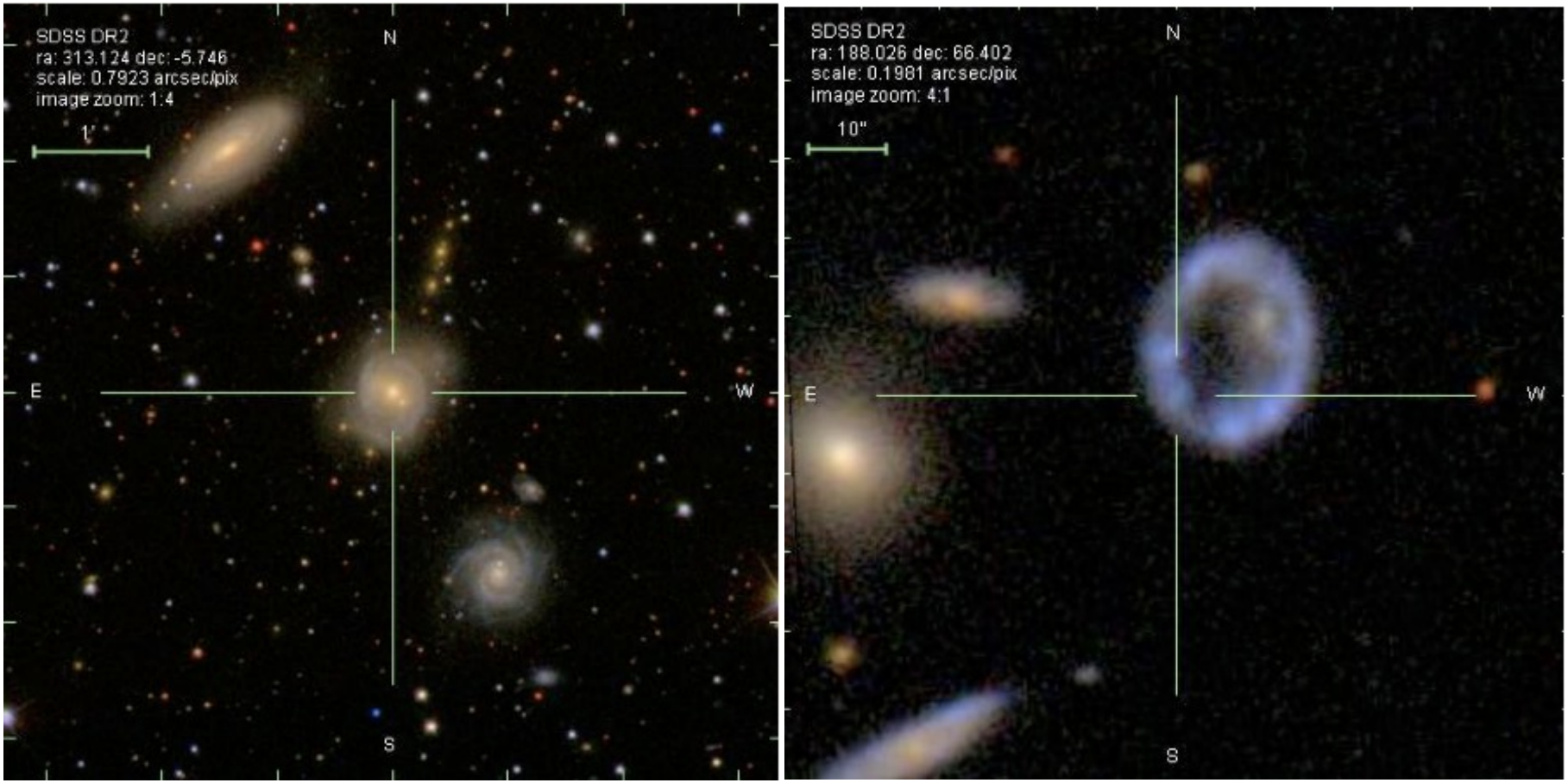
- **The Case for the Fundamental**

M_{BH}- σ Relation

- Marsden et al. 2020

Discussion leader: **Mark Burch**

Note: To encourage discussion everybody must pose at least one question during the group discussion



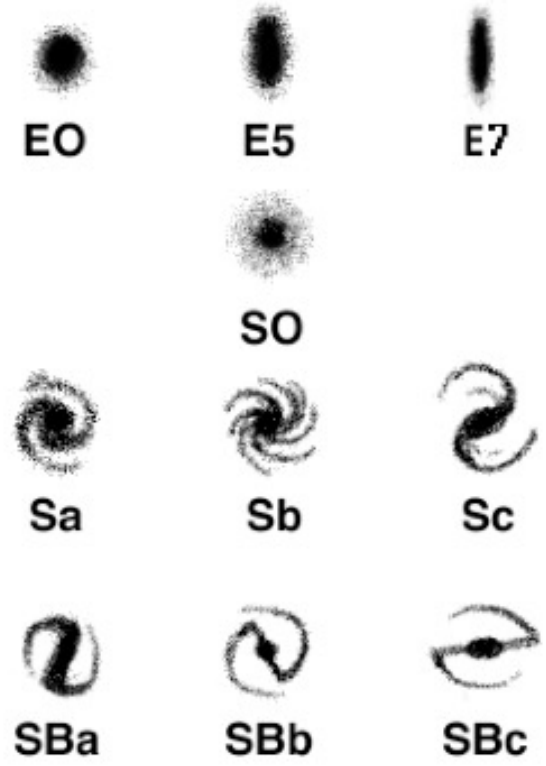
Disk instabilities comes in different forms - spiral structure is one of them.

M83 - a pinwheel structure???

Recall Hubble classification:

- a, b or c classification refers to size of nucleus and the tightness of the spiral arms.
- Sc has smaller nucleus and less tightly wound spiral arms than an Sa.
- Number of arms, and how tightly they are wound are correlated with large scale properties:
  - Bulge/disk luminosity ratio
  - Amount of gas

  Implies global processes are involved in the spiral arm structure.



In addition to the Hubble types, there are different types of spirals:

- *Grand design spirals* with clear spiral arms, well organized

- *Flocculent spirals* with fluffy structure, and many short, globally uncorrelated spiral arms.

Spiral structure theories

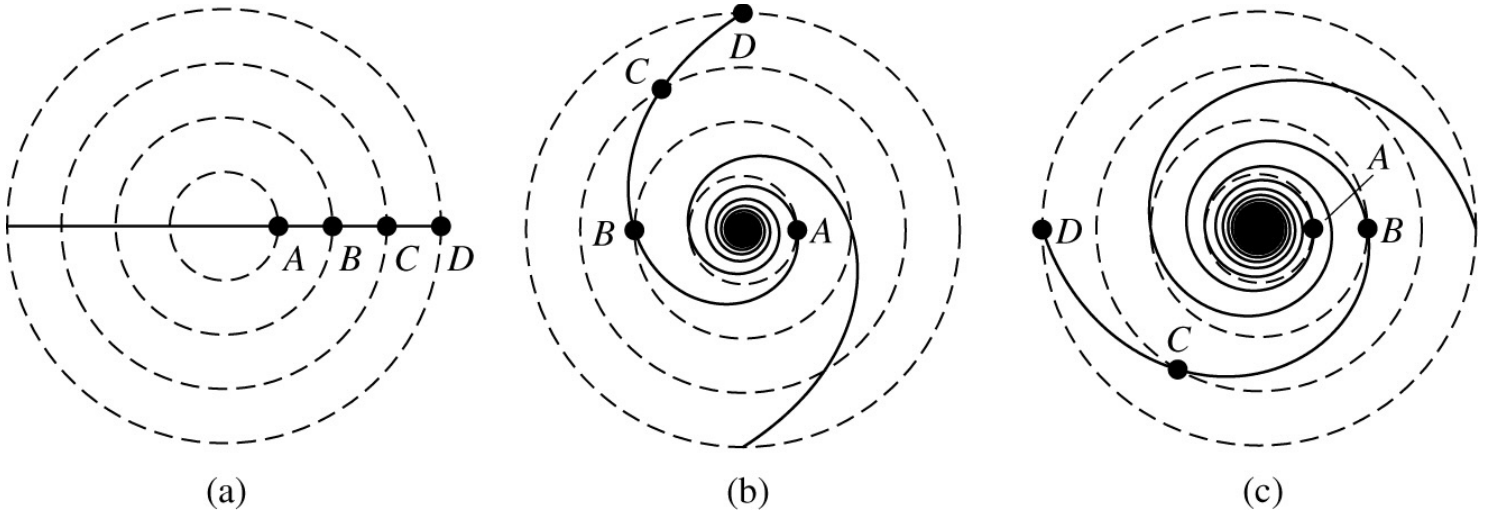
- Still not very well understood after ~60 years of research.

- Differential rotation is a key component of the theories. There are also global instabilities, shock patterns from bars etc that may play a role.

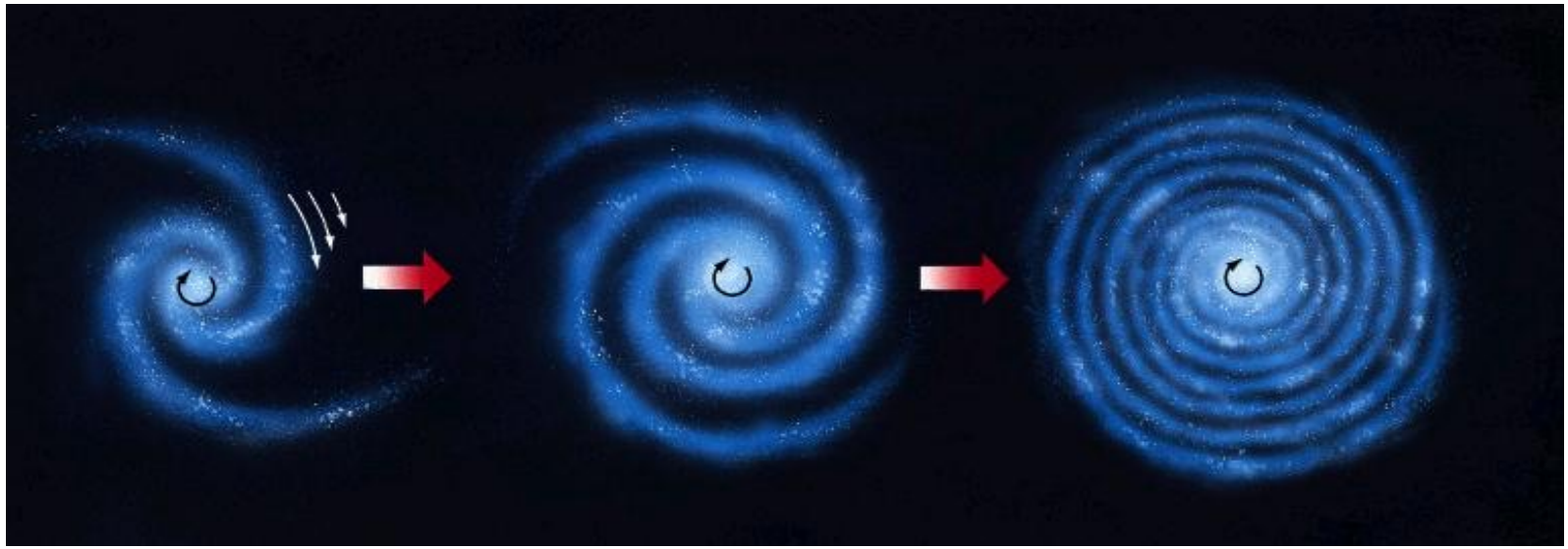
- Two main theories, one for grand design spirals and one for flocculent spirals.

Let's first look at the so called *winding problem.*

The winding dilemma

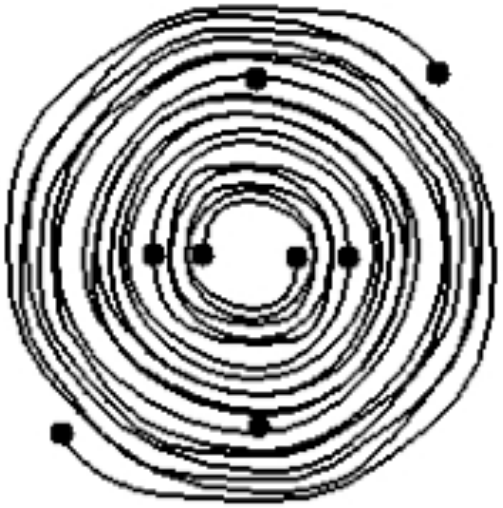


Assuming flat rotation curves, the arms rapidly get tightly wound.

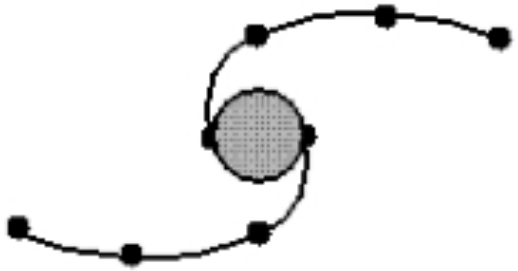


The rotation curves of spiral galaxies are flat:

- Ω=V/R
- Stars and gas at larger R have longer periods
- Outskirts of a galaxy may only have rotated a few times since formation
- Thousands of rotations near center



Prediction: 500 million years



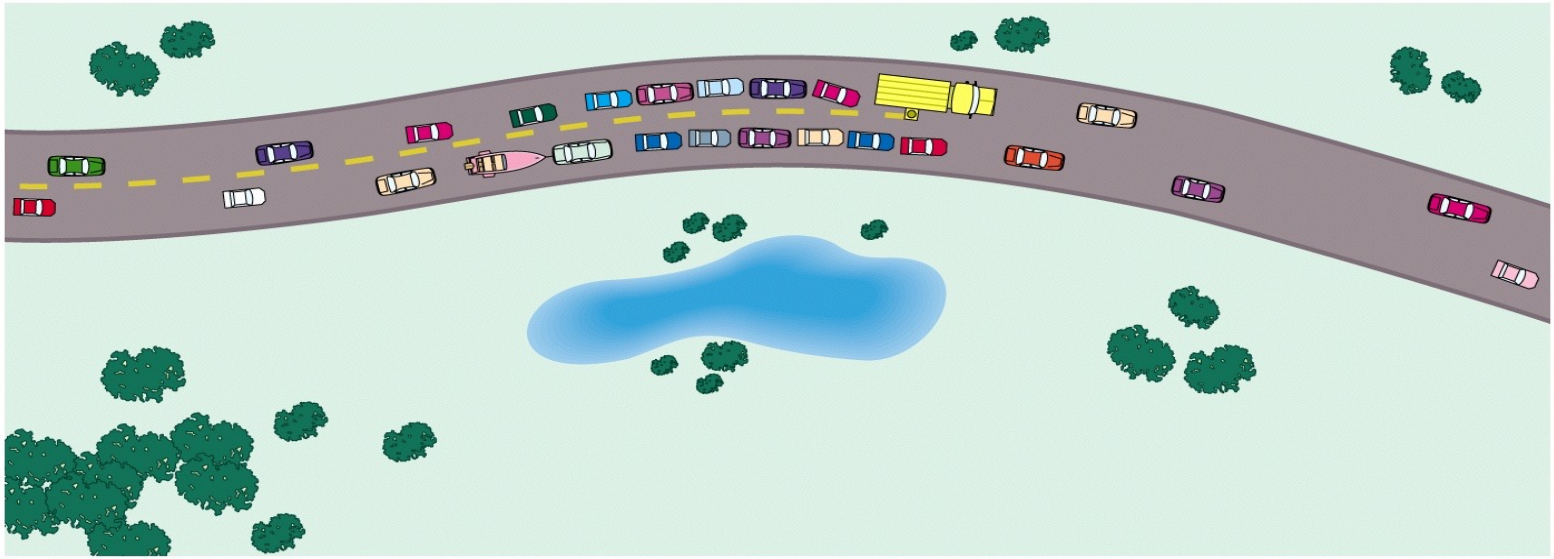
Observation: 15,000 million years

Proposed solution:

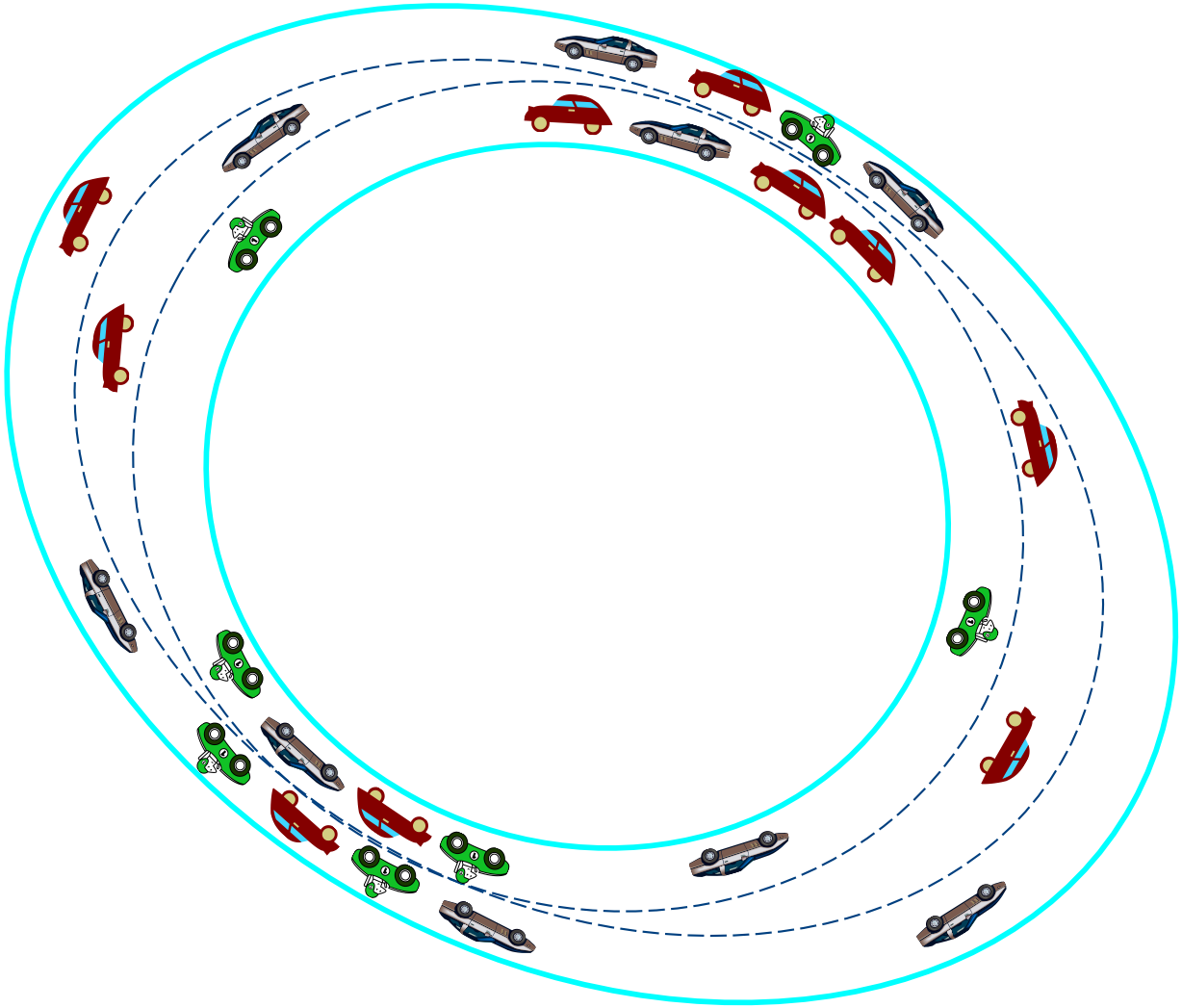
Arms are not material moving together, but mark peak of a compressional wave circling the disk:

A Spiral Density Wave

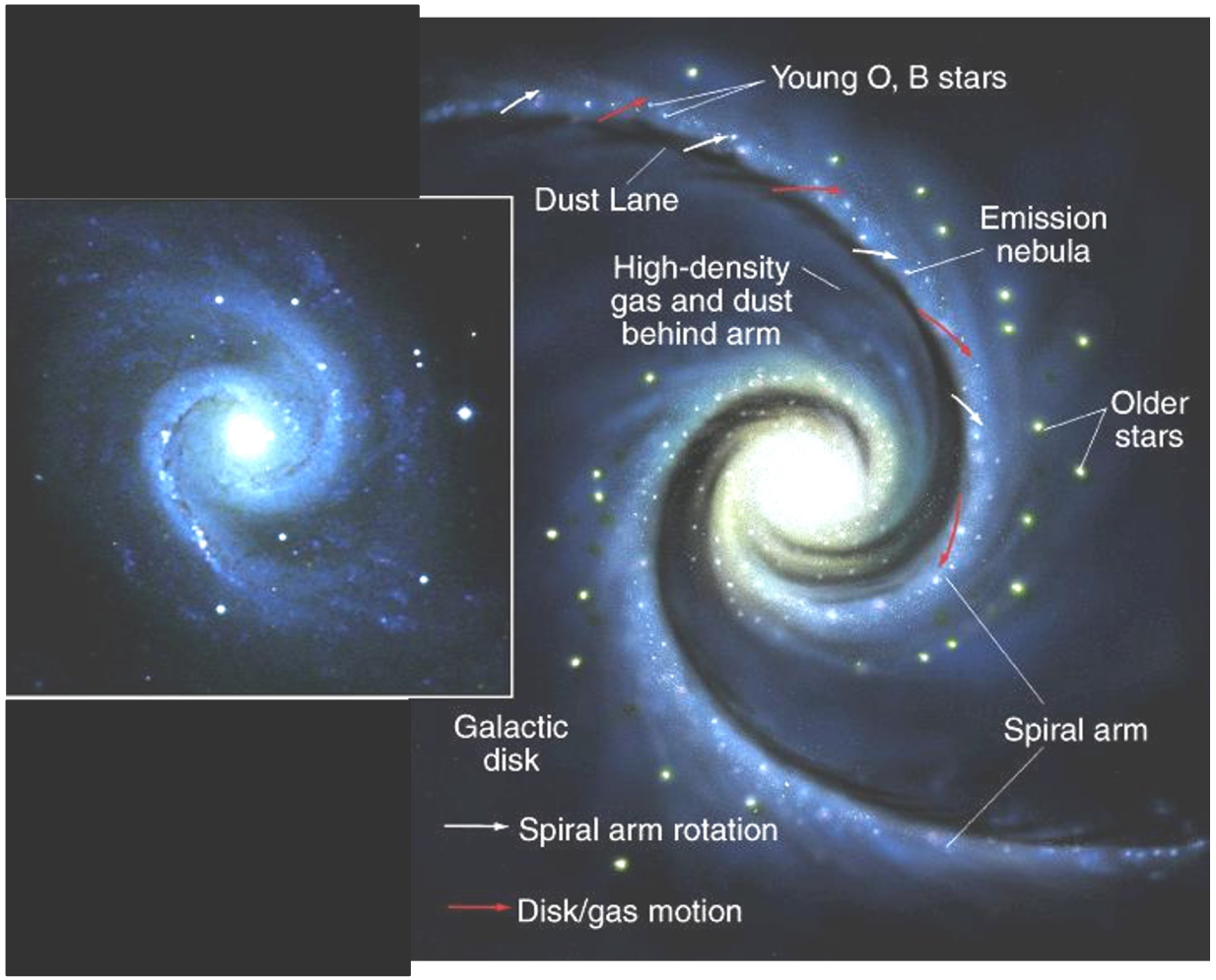
Traffic-jam analogy:



Traffic jam on a loop caused by merging



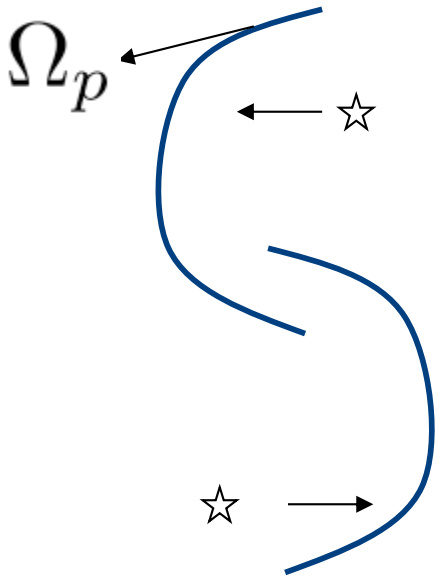
Now replace cars by stars and gas clouds. The traffic jams are actually due to the stars' collective gravity. The higher gravity of the jams keeps stars in them for longer. Calculations and computer simulations show this situation can be maintained for a long time.



Also, squeezing of clouds initiates collapse within them => star formation. Bright young massive stars live and die in spiral arms. Emission nebulae mostly in spiral arms.

So arms always contain same types of objects, but individual objects come and go.

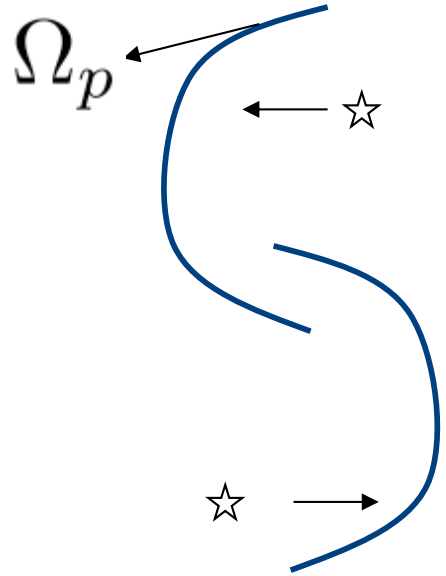
- Bertil Lindblad (1963) proposed spiral arms rotate as a solid body:
  - Same angular speed Ω_p (pattern speed) from the center to the edge
  - The material rotates *faster* than the spiral near the center.
  - The material rotates *slower* than the spiral at large R.
  - The pattern is maintained by self-gravity of stars.



If V_{rot} is constant, then for stars with

$$R < \frac{V_{rot}}{\Omega_p} \rightarrow \Omega_{rot} > \Omega_p$$

$$R > \frac{V_{rot}}{\Omega_p} \rightarrow \Omega_{rot} < \Omega_p$$

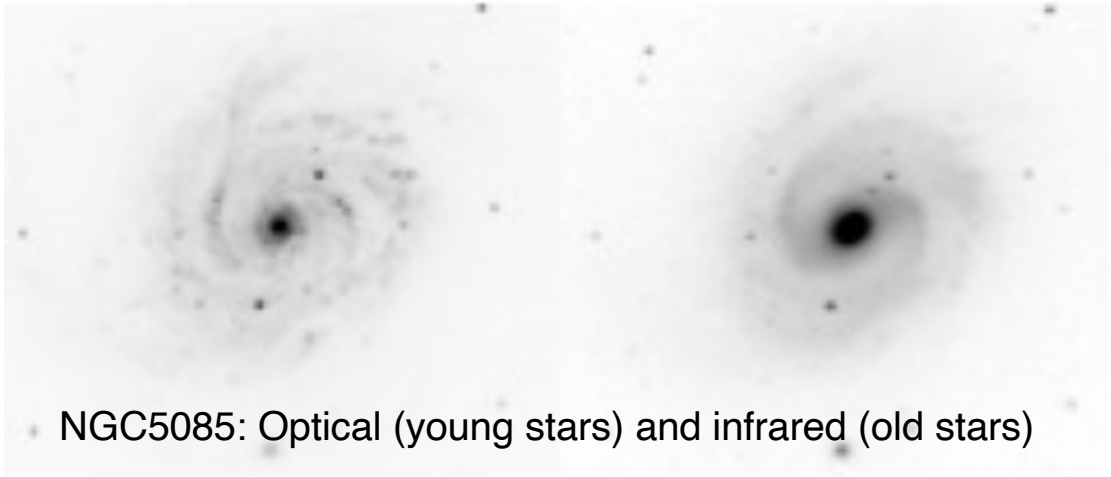


$$R = \frac{V_{rot}}{\Omega_p} = R_c \equiv \text{corotation radius}$$

Long-lived Spiral Density Waves (SDW)

After Lindblad, the SDW theory was further developed by Lin & Shu 1964-70.

- Explains the presence of the grand design spirals
- Spiral arms regarded as waves, propagating like waves in the sea.
- Must maintain pattern for many mean rotations of a galaxy: observations of old & young stars show spiral arms contain both
    - Young stars expected: stars form along arms
    - Old stars live in the disk and are just passing through



NGC5085: Optical (young stars) and infrared (old stars)

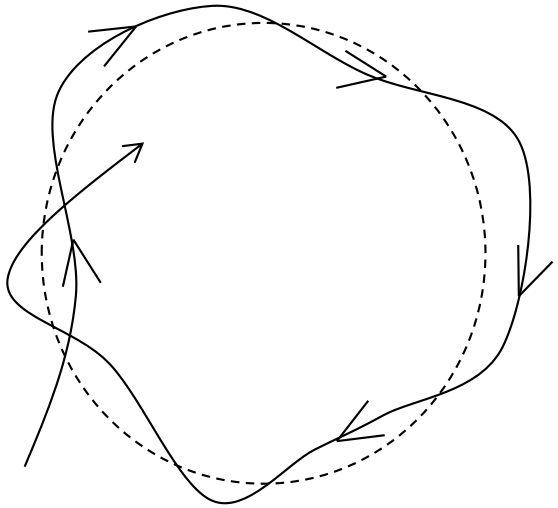
- To be long-lasting, it must be self-sustained. How does it get started? Not clear. A few mechanisms proposed.

Nevertheless, we can investigate prospects for long-lived SDWs, and some of their basic features:

- Stars in a disk galaxy need not move far from their unperturbed orbits to create a spiral density wave.

- To describe *local* motions of stars in a disk we study the equations of motion for small perturbations from a circular orbit.
  - a description of stellar motion in terms of *epicycles*.

Real stellar orbits are not perfectly circular, they show epicycles.



Can think of as:

- Circular orbit of angular frequency Ω(R)
- With epicycles of angular frequency of κ(R) superimposed.
- Position of star varies as

$$r = r_{circ} + A\cos(\kappa t + \psi)$$

What is $\kappa(R)$?

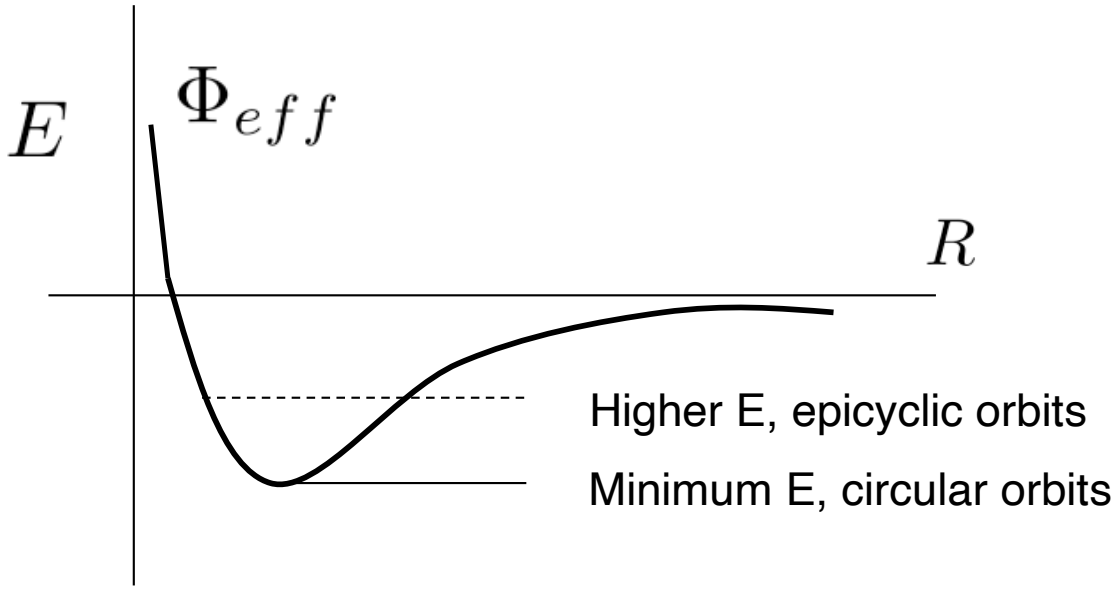
C&O show that for axially symmetric gravitational potential expressed in cylindrical coordinates, the radial and vertical motion can be described as:

$$\ddot{R} = -\frac{\partial \Phi_{eff}}{\partial R} \qquad \ddot{z} = -\frac{\partial \Phi_{eff}}{\partial z}$$

where $\Phi_{eff} = \Phi + \frac{J_z^2}{2R^2}$

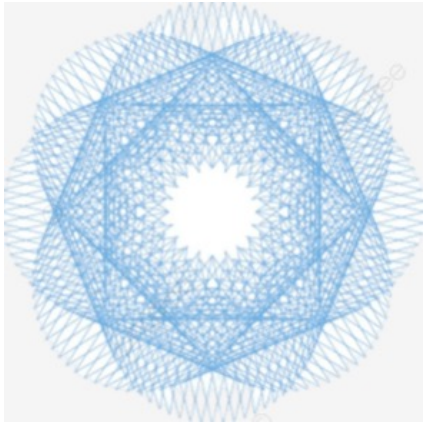
$$J_z = \text{angular momentum per unit mass}$$
$$= \Theta R = \text{constant if no torques}$$

$$\Phi = \text{potential, e.g., if } 2-\text{body}: \quad \Phi = \frac{-GM}{R}$$



C&O show that for small oscillations, the epicyclic frequency is:

$$\kappa = 2\Omega \left[1 + \frac{1}{2} \frac{R}{\Omega} \frac{d\Omega}{dR} \right]^{1/2}$$

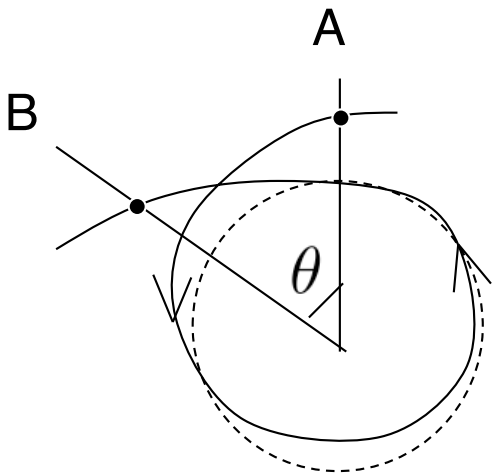


In general: $m\Omega(R) \neq n\kappa(R)$

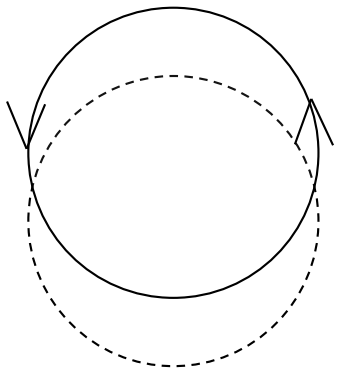
where *m,n* integers => not closed orbit, but 'rosette'.

BUT: orbit is closed in some rotating reference frames (non-inertial), where

$$\Omega_{rf,l} = \Omega(R) - \frac{n}{m}\kappa(R)$$



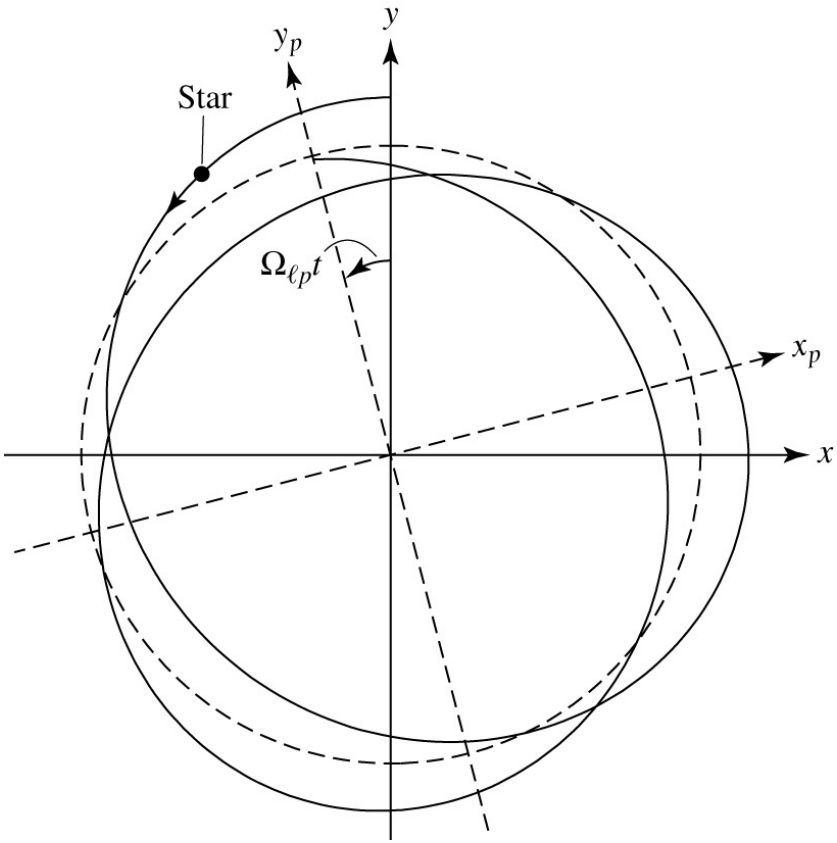
inertial frame

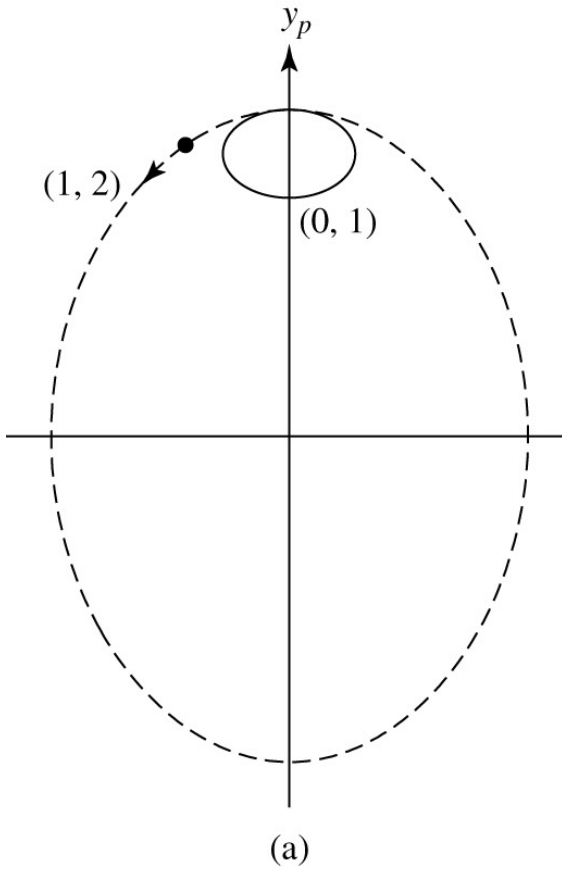


non-inertial frame
(rotating)

In the rotating frame, the stars will appear to trace out an ellipse when n=1, m=2.

$$\Omega_{rf,l} = \Omega(R) - \frac{n}{m}\kappa(R)$$



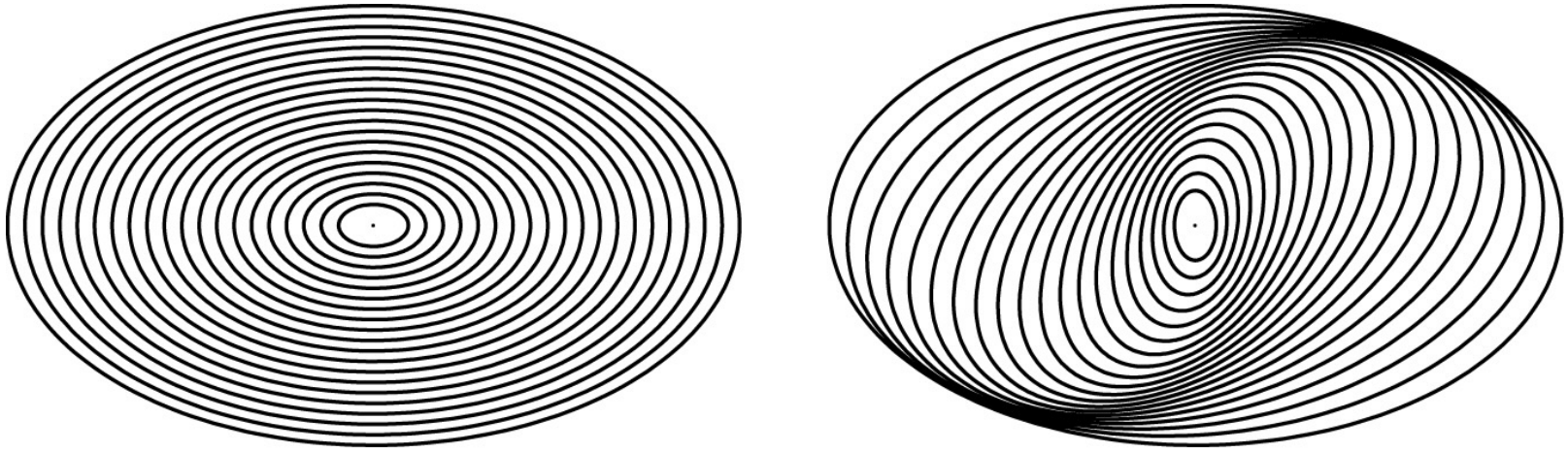


(a)

For n=1, m=2, we get ovals.

$$\Omega_{rf,l} = \Omega(R) - \frac{1}{2}\kappa(R)$$

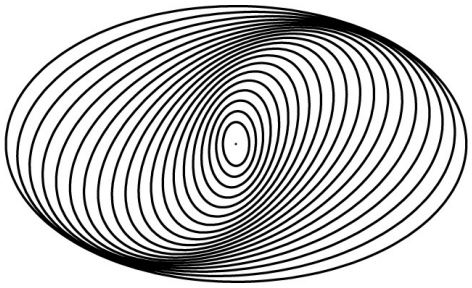
By arranging these ovals, one can make a spiral pattern.



(a) (b)

Kinematic spiral waves

These are so called *kinematic* spiral waves.



(b)

Assume you have a ring of stars, with similar epicyclic orbits, and with equilibrium points at the same radius.

Assume that at the initial phases of the epicycles (at t=0) the stars would define an oval.

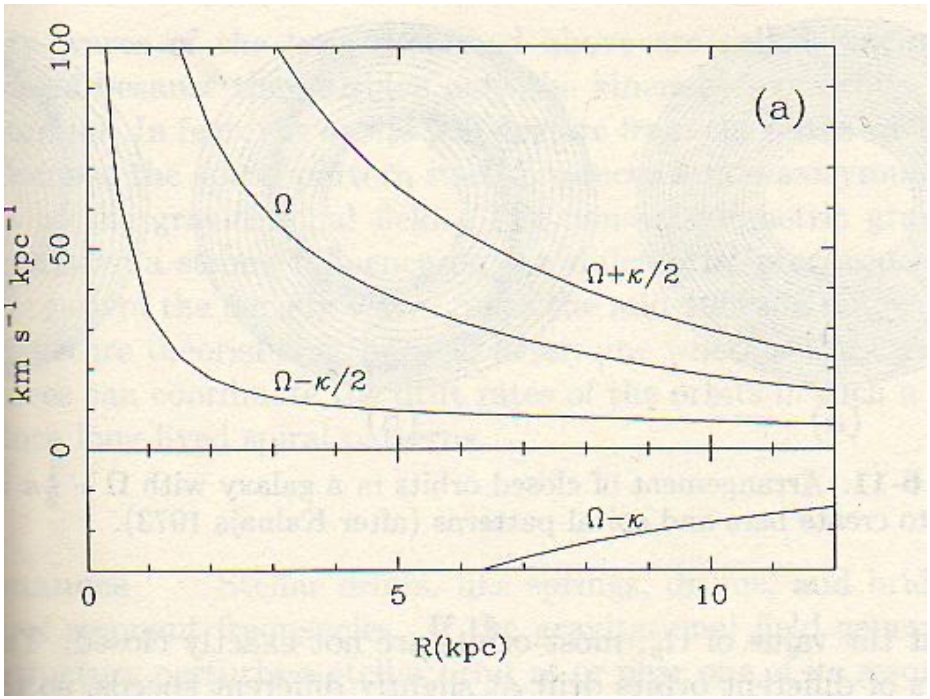
As time increases, the equilibrium points move around the galaxy with an angular speed $\Omega(R_0)$, but stars are moving backward wrt their equilibrium points. Thus the form of the oval is moving slower. The precession rate is the pattern speed of the oval

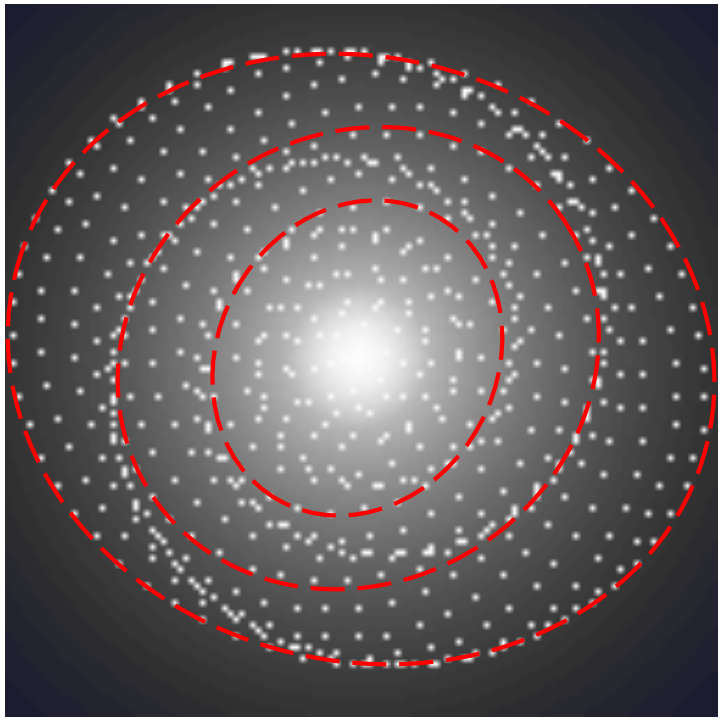
$$\Omega_p = \Omega - \frac{1}{2}\kappa$$

By superimposing ellipses of different sizes, a variety of spiral patterns can be produced.

If $\Omega_p = \Omega - \frac{1}{2}\kappa$ were independent of R, the pattern would be persistent since *all* superimposed ellipses would move at the same angular speed.

Disk galaxy models show circular velocity profiles which yield a pattern speed which is constant over a large range of R.





So, kinematic spirals only exist only to extent that $\Omega(R) - \frac{1}{2}\kappa(R)$ is constant with R

Two issues:

1) Why would orbits want to organize themselves in this way?

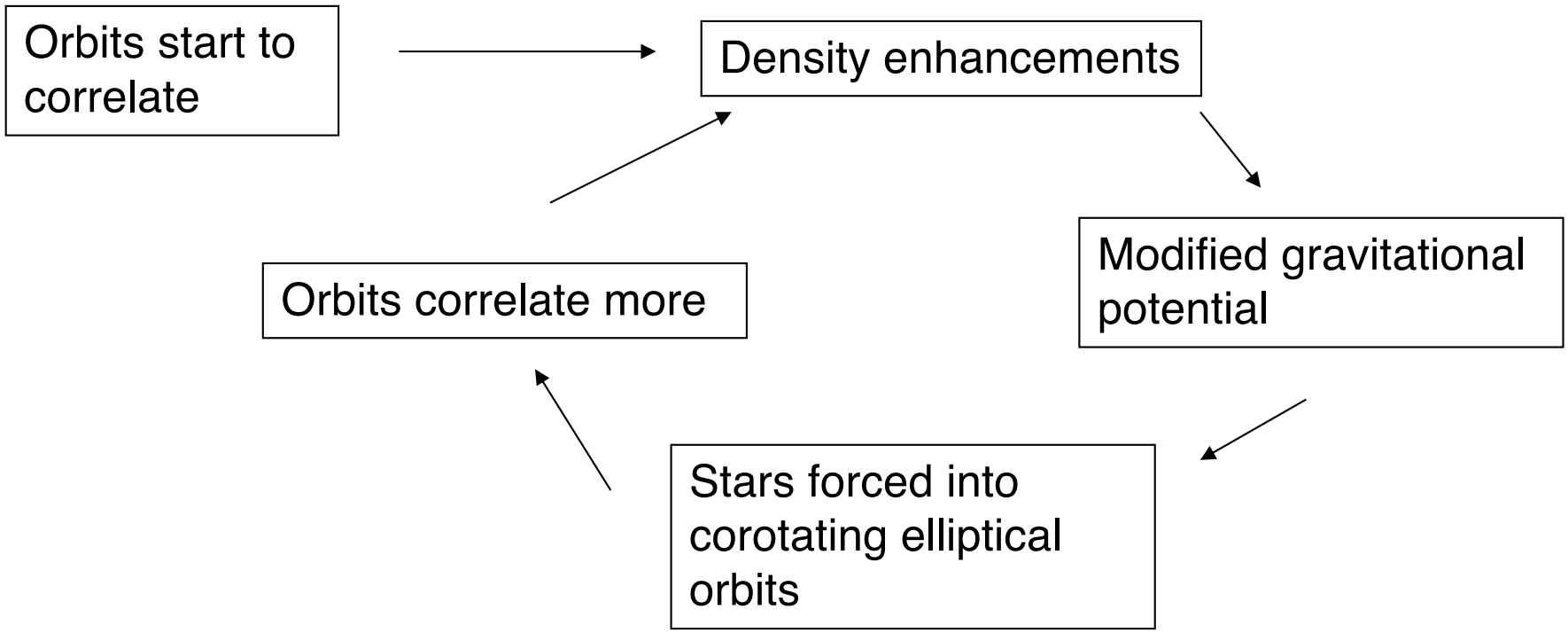
2) Even if they did, $\Omega(R) - \frac{1}{2}\kappa(R)$ is not exactly constant with R, so

   pattern would distort or wind up

   Effect of gravity of arms must be considered! $\Omega(R) - \frac{1}{2}\kappa(R)$
   May cause forced oscillation at frequencies near
   over large range of R => long lived spiral.

Self-gravity and grand design spirals

If the disk is massive enough it can assist in maintaining the SDW:



This is the **Lin-Shu hypothesis:**

1) Spiral properties modifies orbits

2) Modified orbits create spiral density enhancement that reinforces the potential.

3) back to 1) etc

Lin & Shu showed that this could work for a linear spiral perturbation that is fairly tightly wound.

Need mass to be involved in the spiral structure to cause sufficient perturbations to the overall potential:

Sa galaxies have more massive bulges than in Sc, and they do have fewer grand design spirals!

Realities:

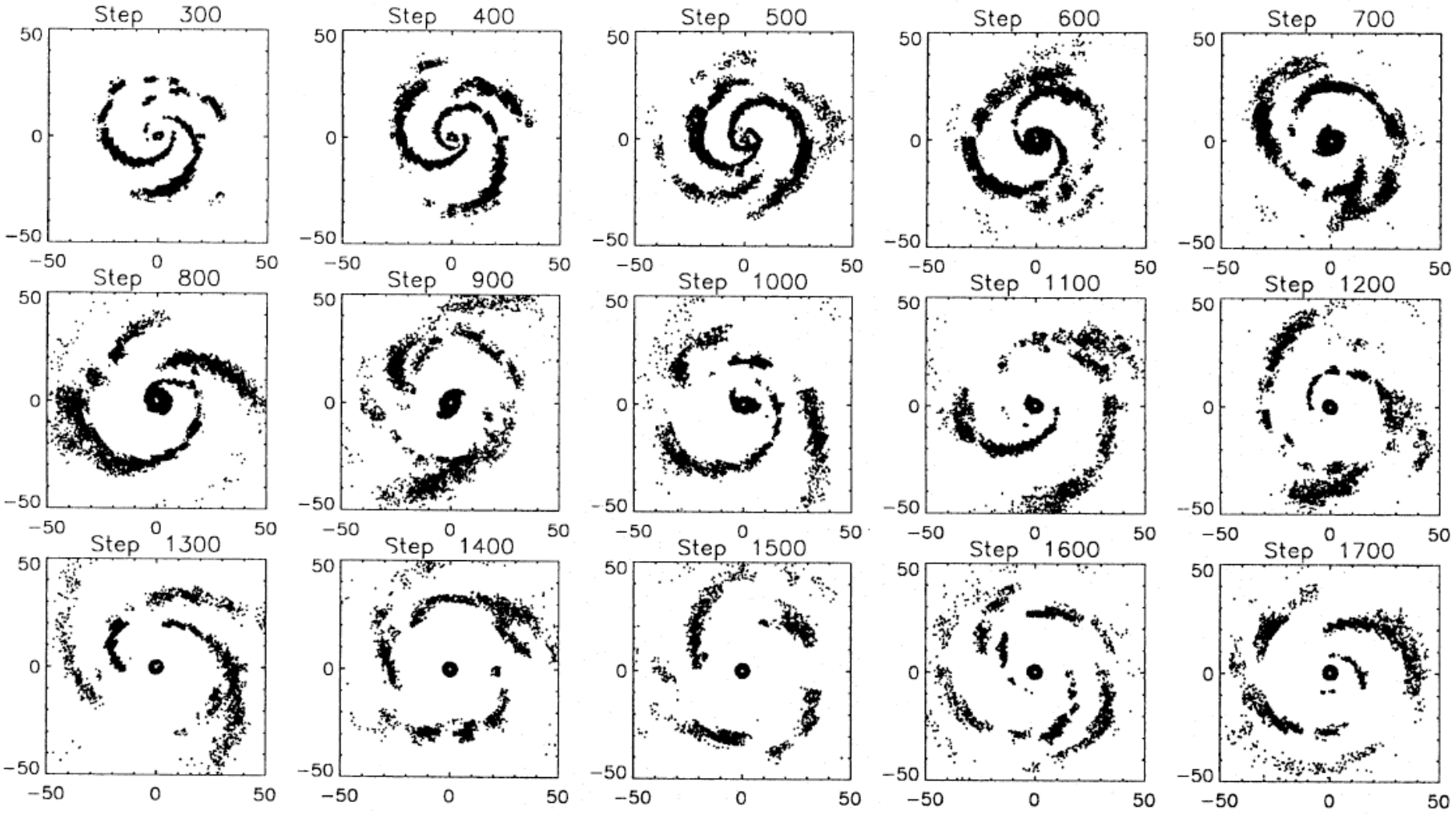
1) Arms not always tightly wound

2) Perturbations probably not linear

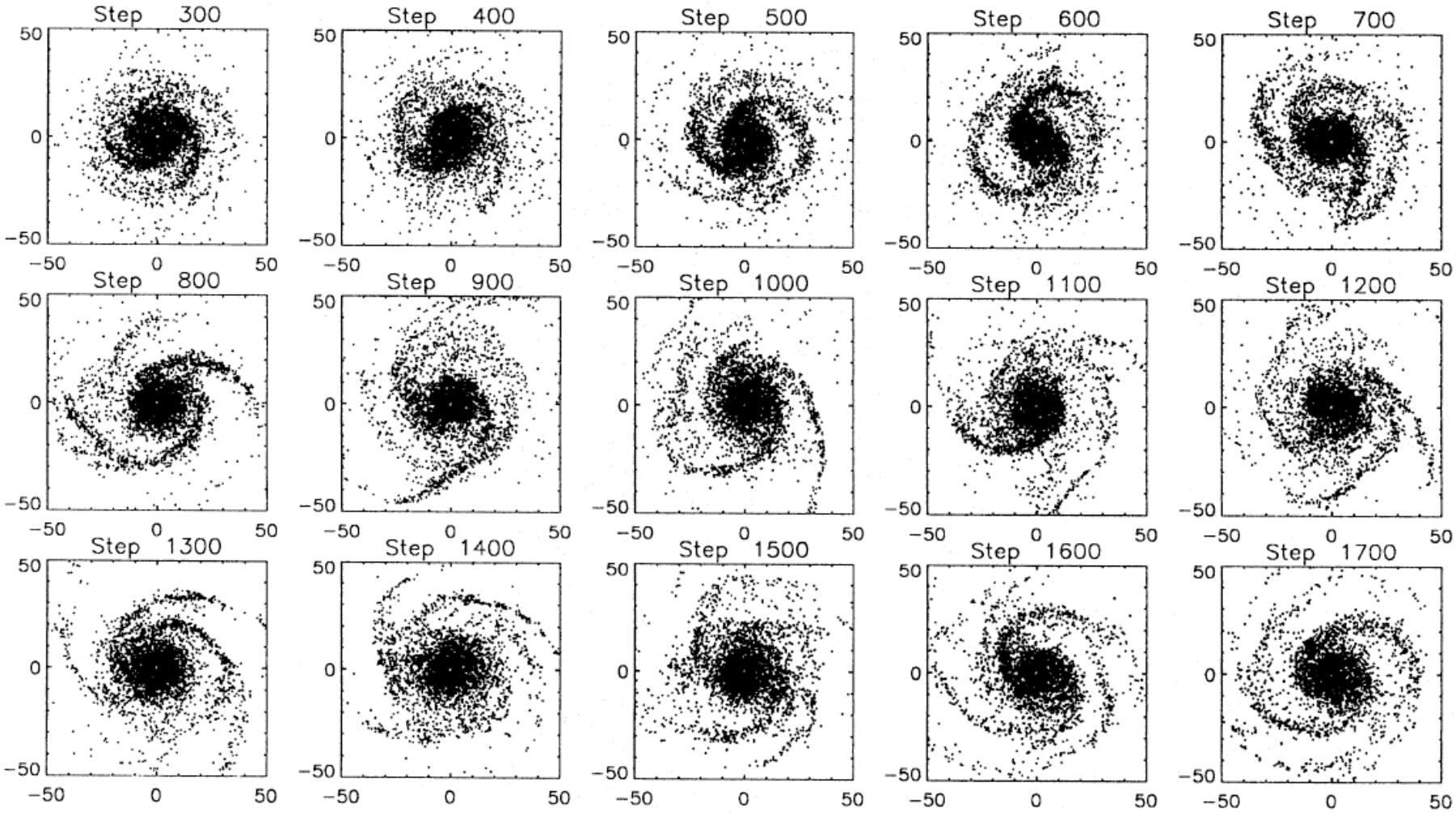
3) 1)+2) => response may not fully reinforce potential, but may partly lead to general increase in *random* motions, eventually destroying wave

4) But effect of gas and newly formed stars must be considered.

Elmegreen & Thomasson (1993) simulations of spiral structure: star formation



Elmegreen & Thomasson (1993) simulations of spiral structure: stars



Spiral wave rotates with an angular frequency Ω_p

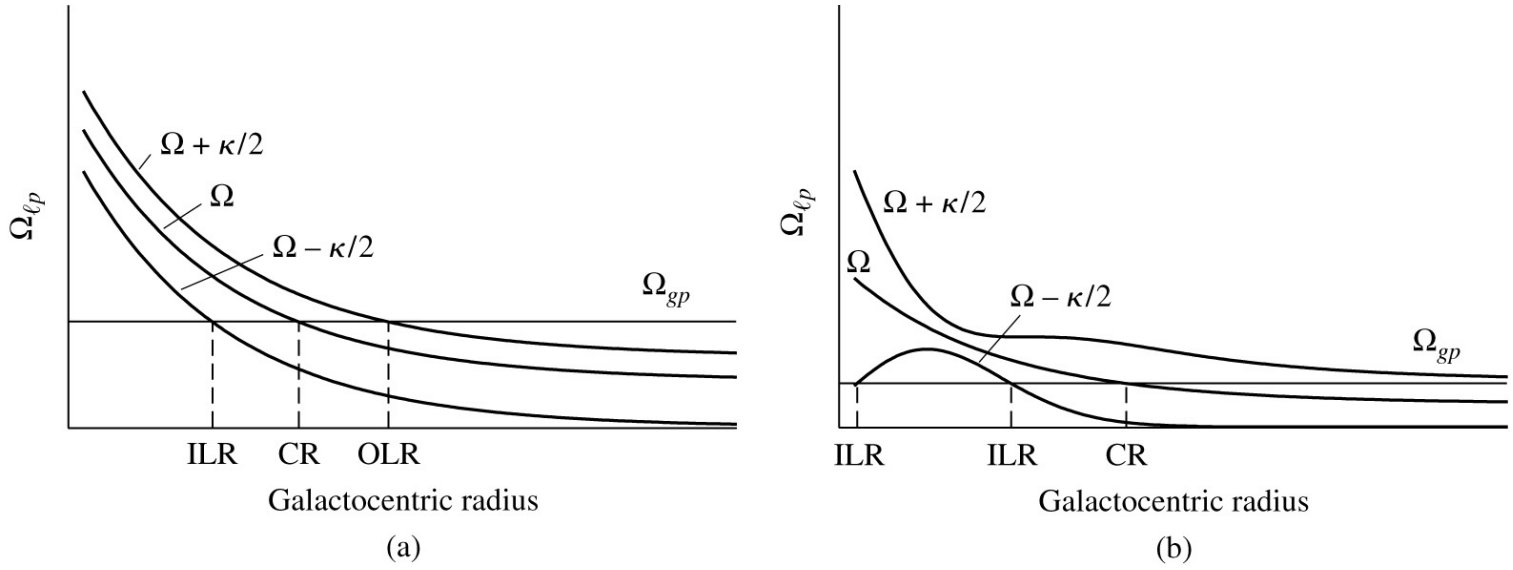
At certain radii, stars are forced at resonant frequency:

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

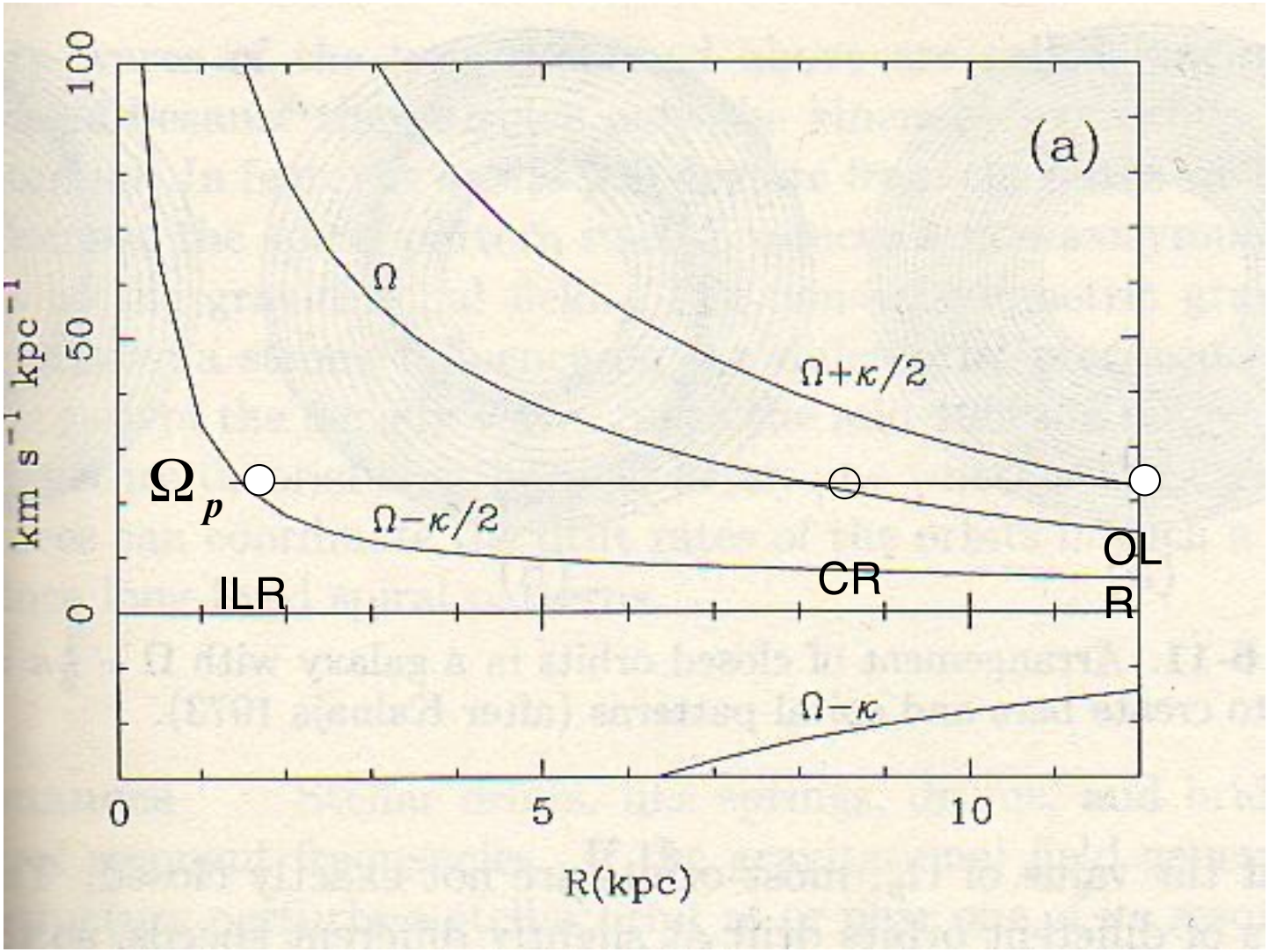
e.g. n=1, m=2: Inner Lindblad resonance

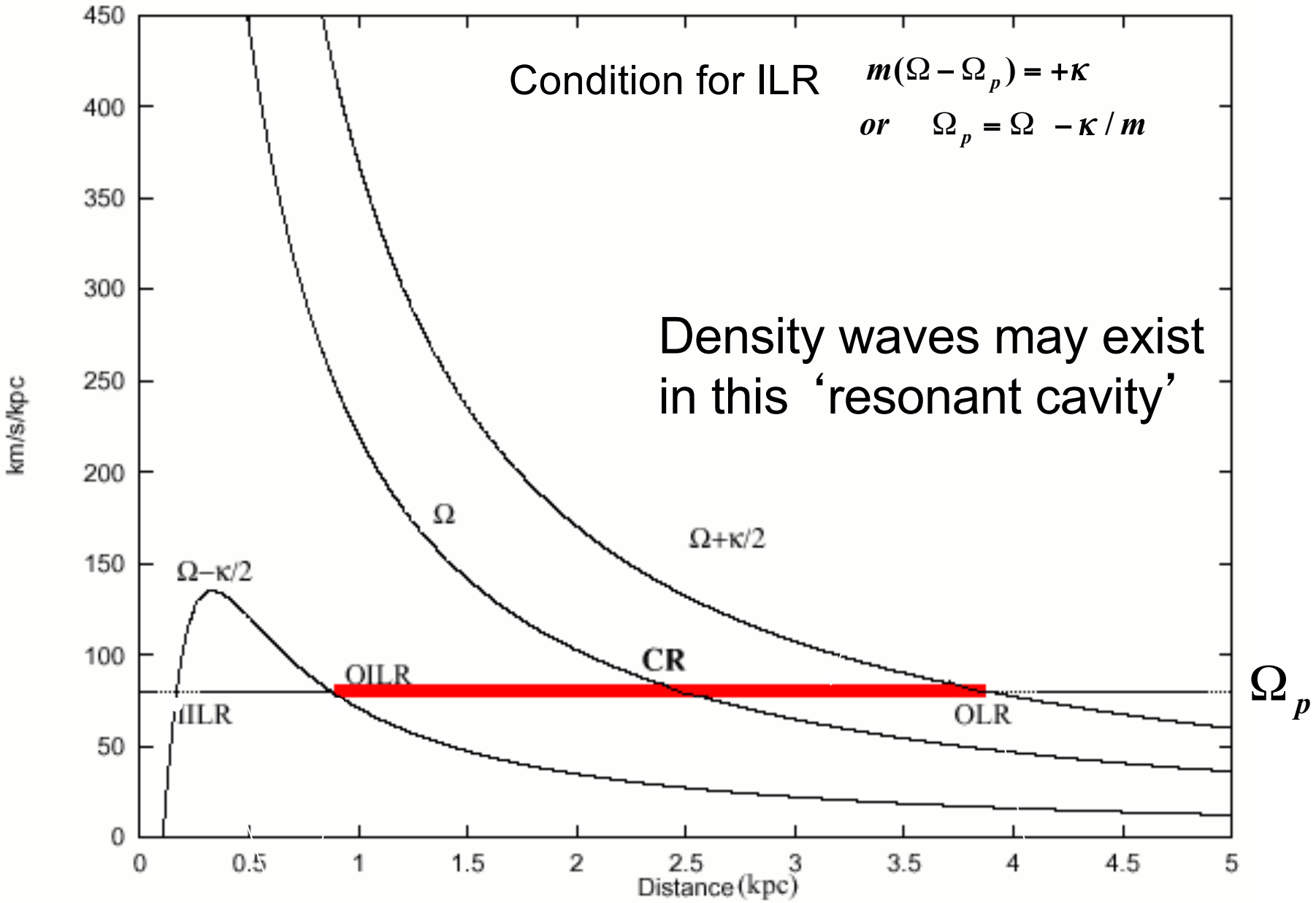
n=-1, m=2: Outer Lindblad resonance

At these radii, stars rob wave of its energy. Two arm spiral can only exist between these resonance radii.



ILR

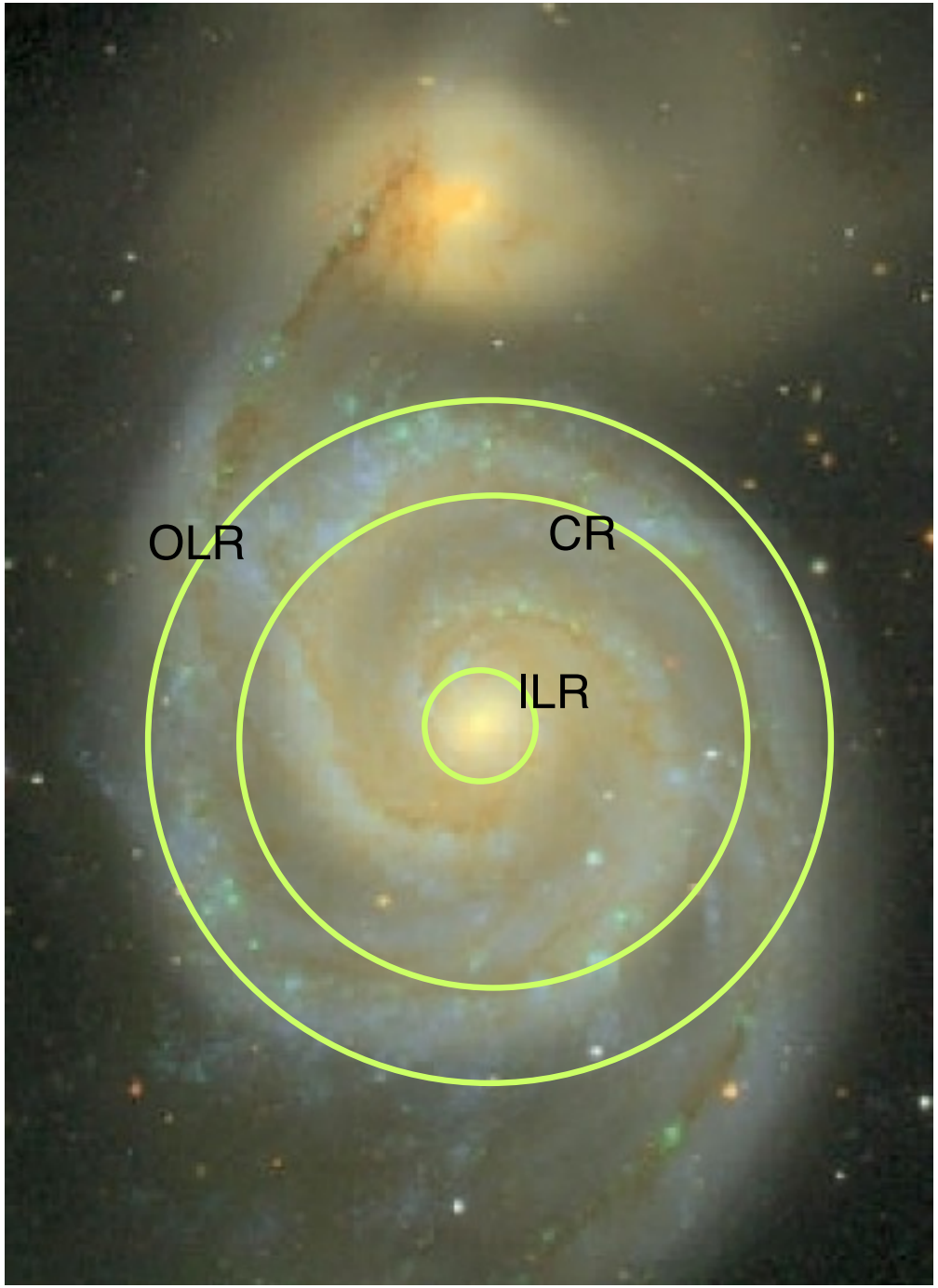




Two ILRs, one inner and one outer.

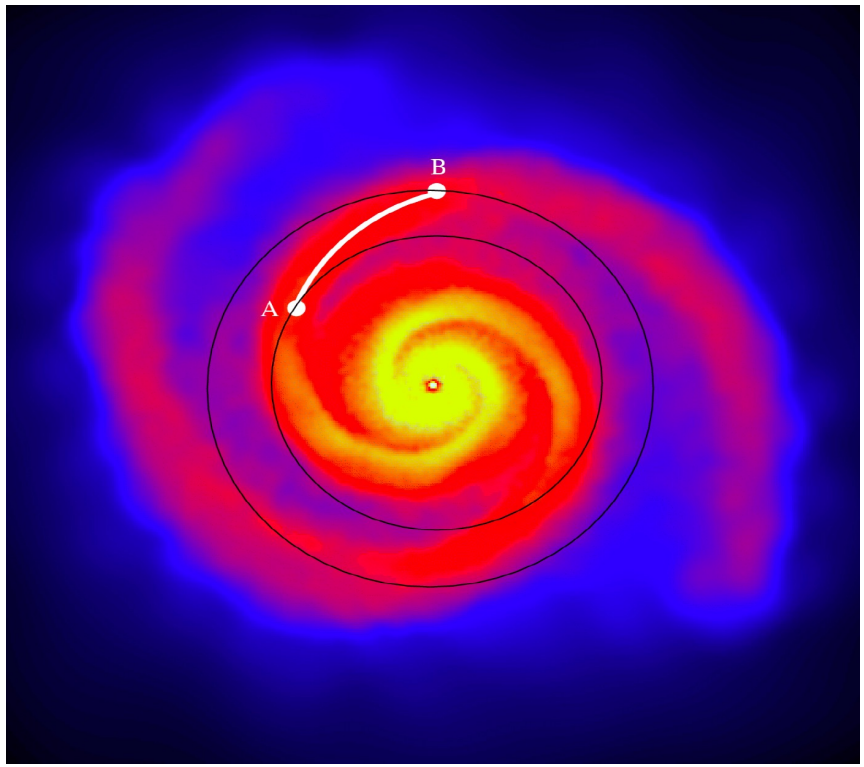
One OLR.

M51: example



Roles of arms

- Essential in the formation and evolution in spiral galaxies
- Most stars, in particular heavy ones are formed in spiral arms
- Spiral arms lead to
  - angular momentum being transported outward in the disc
  - then mass is falling toward the center
    - Galaxy evolution from Sc to Sa
    - Bulge grows
    - Spirals weaker
    - More spirals/tightly wound



Spiral shocks and star formation

Gas will fall down the potential well of the spiral potential

- Compressed in shocks
- Molecular clouds undergo gravitational collapse and form stars
- New stars, HI and HII downstream of shocks

Alternative models:

Stochastic Self-propagating Star Formation

- Doesn't work for grand design spirals, but for flocculent
- Ongoing star formation will trigger star formation in nearby areas. When the galaxy rotates, differential rotation leads to the appearance of a spiral pattern.
- This addition of stars will counteract the increasingly random motions of stars.
- Spiral arms made of short-lived massive blue stars.
- Stars die out before winding dilemma can become a problem