Dynamics of Spiral Structure

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Master's Seminar Course

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Context:

0. Introduction

1. Material Arms vs Kinetic Density Waves

2. Dispersion Relation

   2.1 LS and LSK Dispersion Relations

   2.2 Stability Criterion

   2.3 Wave Propogation

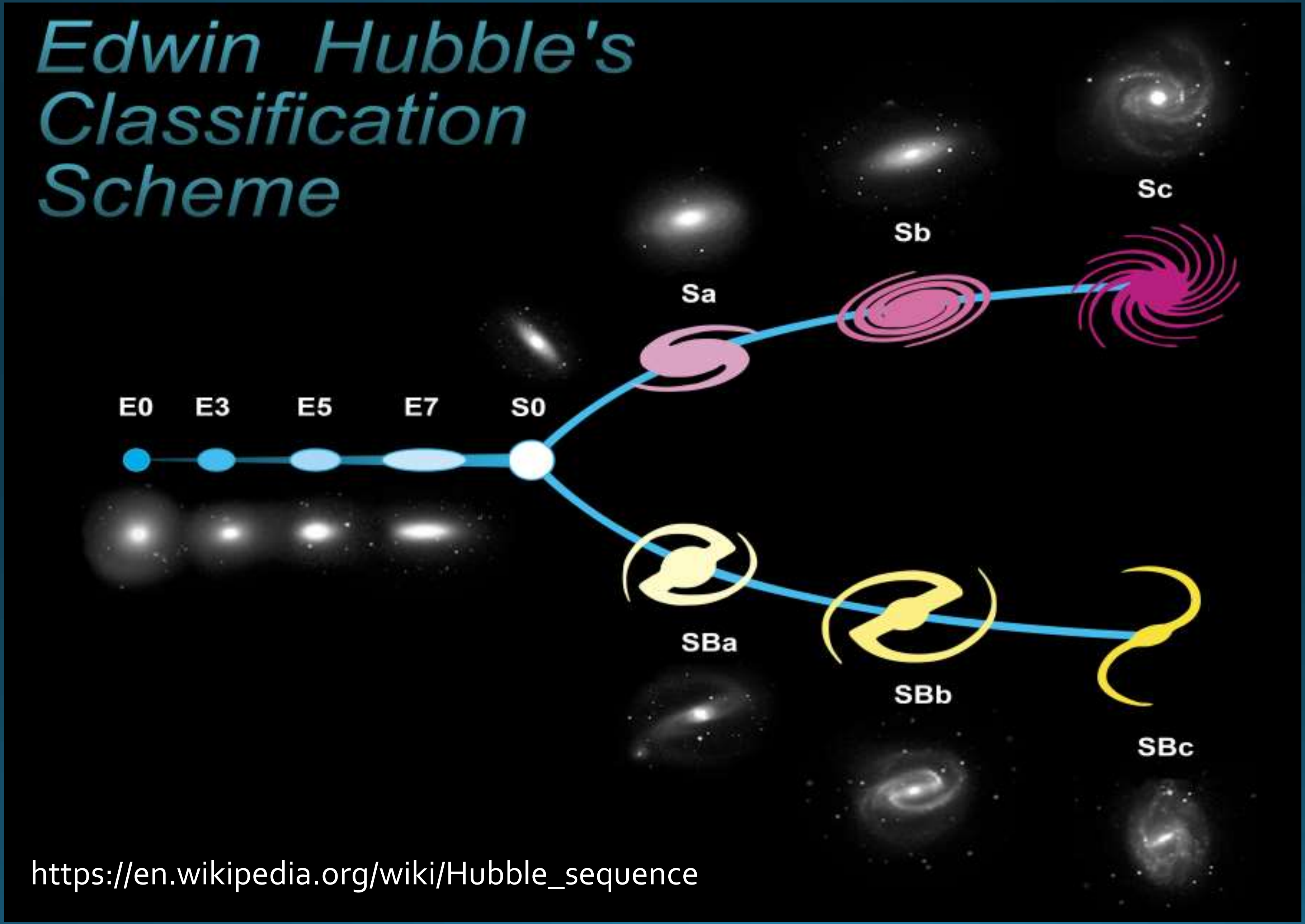
3. Swing Amplification

4. Bar-Driven Spirals

5. Tidal-driven Spirals

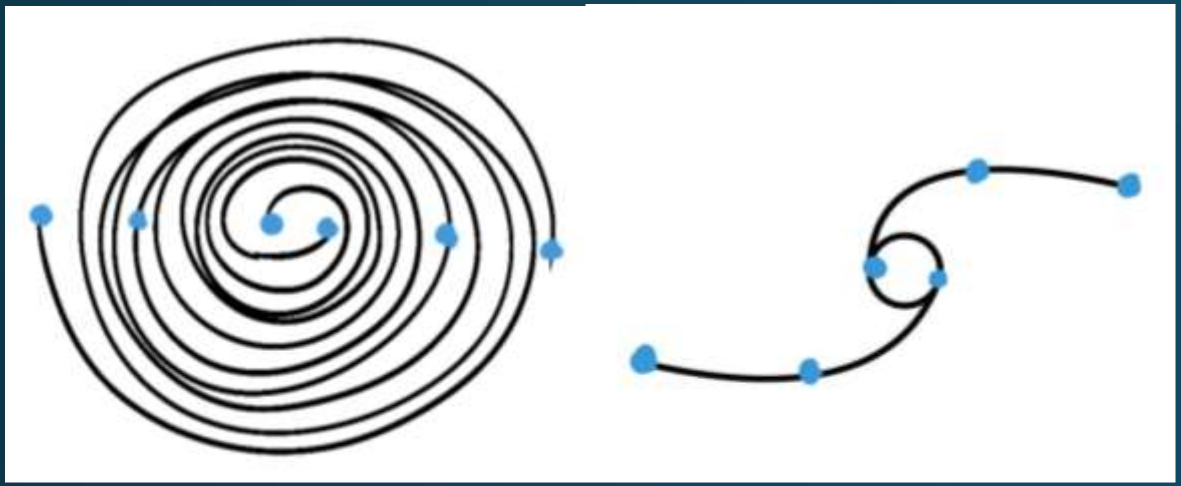
6. Summary

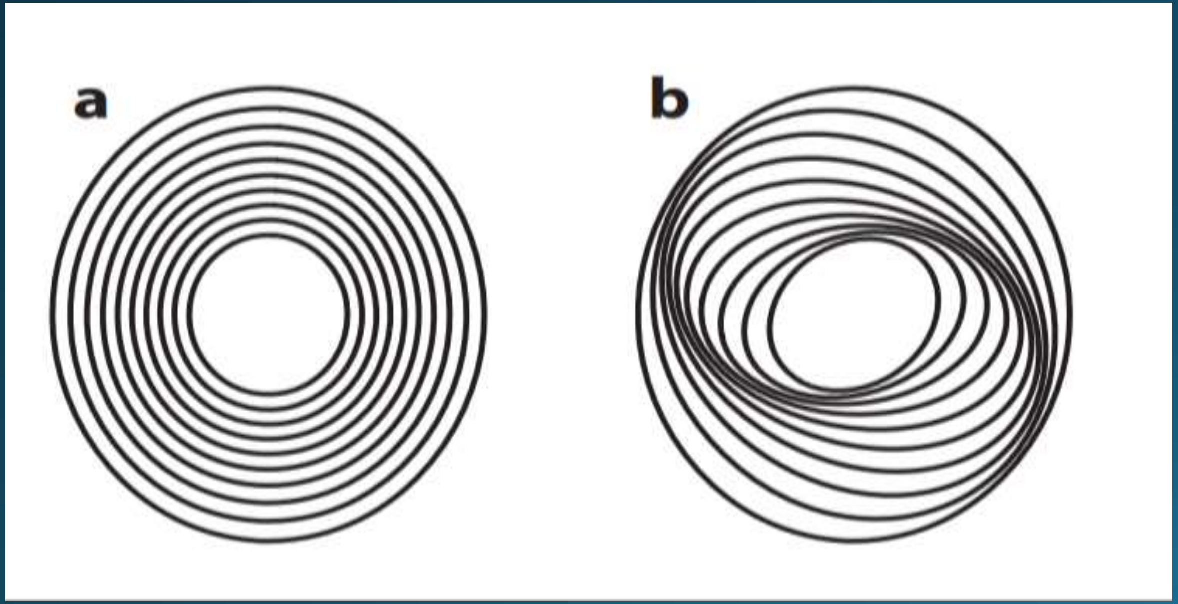
0. Introduction



https://en.wikipedia.org/wiki/Hubble_sequence

1. Material Arms or Kinetic Density Waves





Material Arms

$$\Omega_p = const.$$

Kinetic Density Waves

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

Not constant → open orbits

Winds slower

Sellwood & Masters (2022)

2.1- LS & LSK Dispersion Relation

- Lin-Shu (LS) Dispersion Relation (fluid)

$$(\omega - m\Omega)^2 = \underbrace{\kappa^2}_{\text{Rotation Effect}} + \underbrace{c_s^2 k^2}_{\text{Pressure}} - \underbrace{2\pi G|k|\Sigma_0}_{\text{Self-Gravity}}$$

- Lin-Shu-Kalnajs (LSK) Dispersion Relation (disc of stars)

$$(\omega - m\Omega)^2 = \kappa^2 - 2\pi G|k|\Sigma_0 F$$

Reduction factor:
Weakening of self gravity by random motion
$F \leq 1$

2.2 Stability Criterion

$$(\omega - m\Omega)^2 = \kappa^2 + c_s^2 k^2 - 2\pi G|k|\Sigma_0$$

$$k_\pm = \frac{\pi G \Sigma_0}{\kappa c_s^2} \pm \sqrt{\frac{\pi^2 G^2 \Sigma_0^2}{c_s^4} - \frac{\kappa^2}{c_s^2}} \Longrightarrow Q = \frac{\kappa c_s}{\pi G \Sigma_0}$$

Toomre Parameter

$\Longrightarrow$ $Q > 1: stable$

$\Longrightarrow$ $Q < 1: unstable$

$$(\omega - m\Omega)^2 = \kappa^2 - 2\pi G|k|\Sigma_0 F$$

$$\Longrightarrow Q = \frac{\kappa \sigma_R}{3.358 G \Sigma_0}$$

$$\boxed{\begin{array}{l} \pi \rightarrow 3.358 \\ c_s \rightarrow \sigma_R \end{array}}$$

Cold disk: $c_s = 0 \rightarrow (\omega - m\Omega)^2 = 0 \rightarrow stable\ if: \lambda < \lambda_{crit} = \frac{2\pi}{k_{crit}} = \frac{4\pi^2 G \Sigma_0}{\kappa^2}$

2.3 Wave Propagation

$$v_g = \frac{\partial \omega}{\partial k} = \pm \frac{c_s^2|k| - \pi G \Sigma_0}{\omega - m\Omega}$$

Short waves: Positive
Long waves: Negative

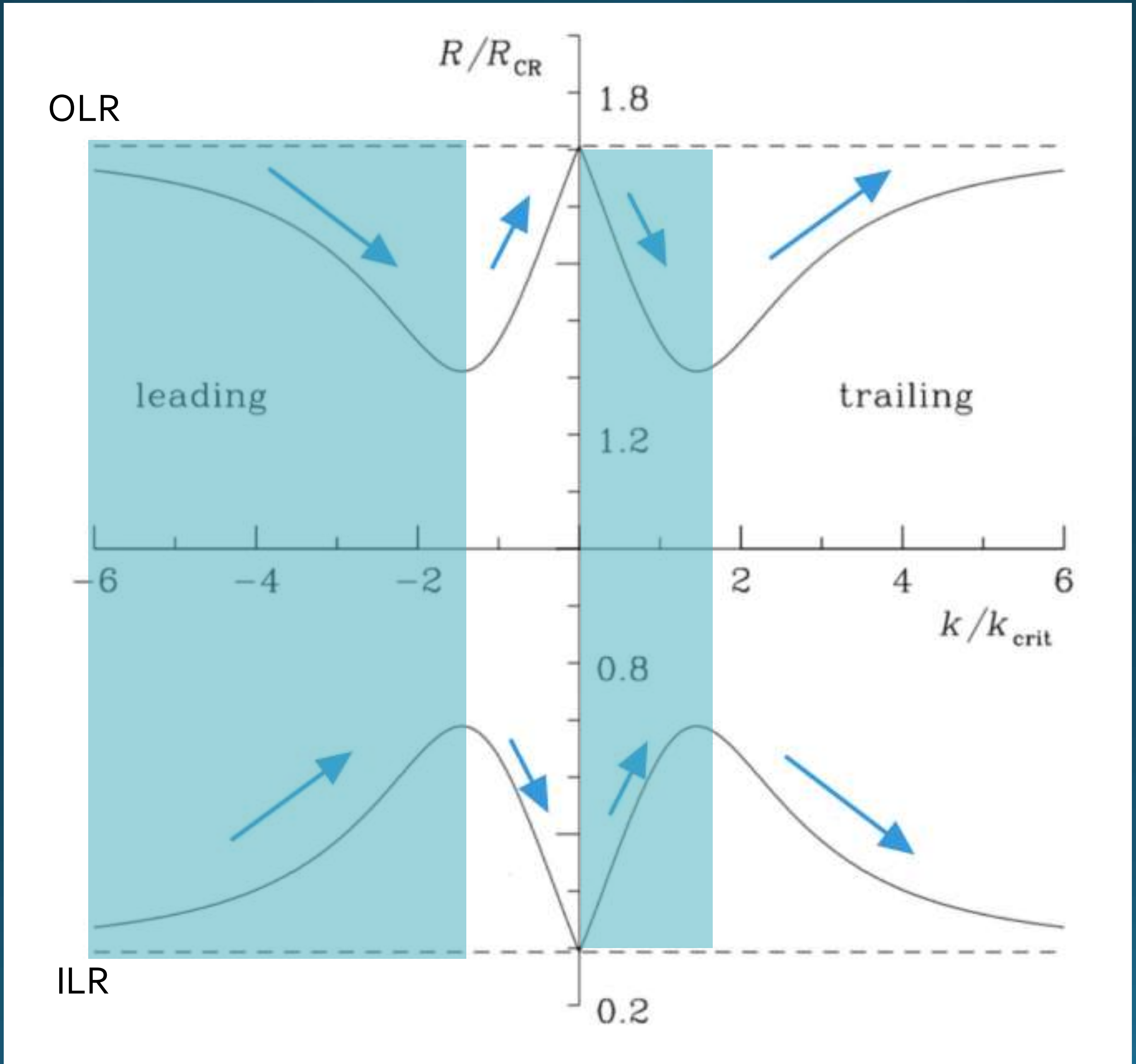
Trailing: Positive
Leading: Negative

$R > R_{CR}$: Positive
$R < R_{CR}$: Negative

Short trailing And Long leading propagates away from the CR

Short Leading And Long Trailing propagates Toward the CR

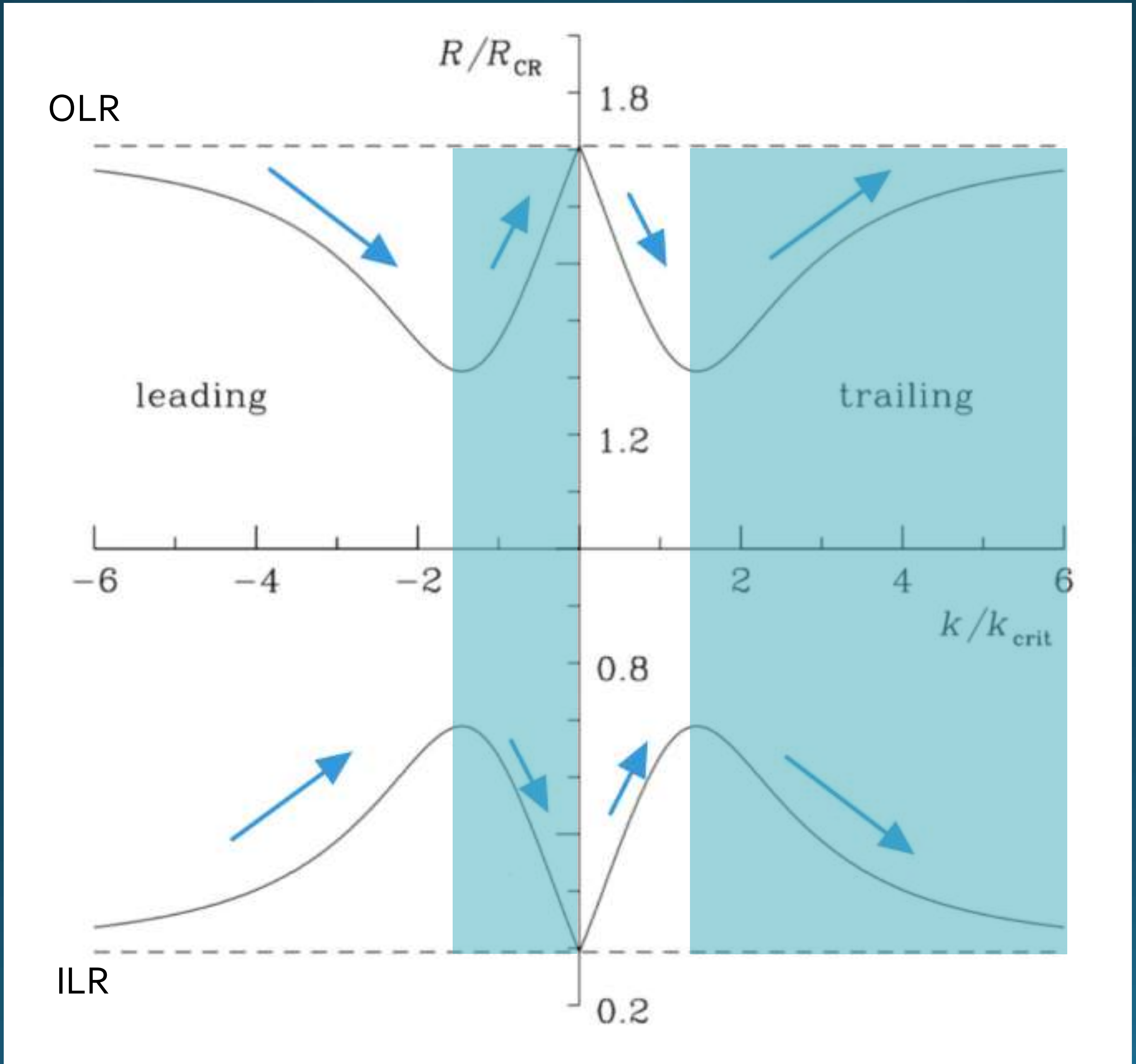
2.3 Wave Propagation



Binney & Tremaine (2008)

Short Leading and Long Trailing propagates Toward the CR

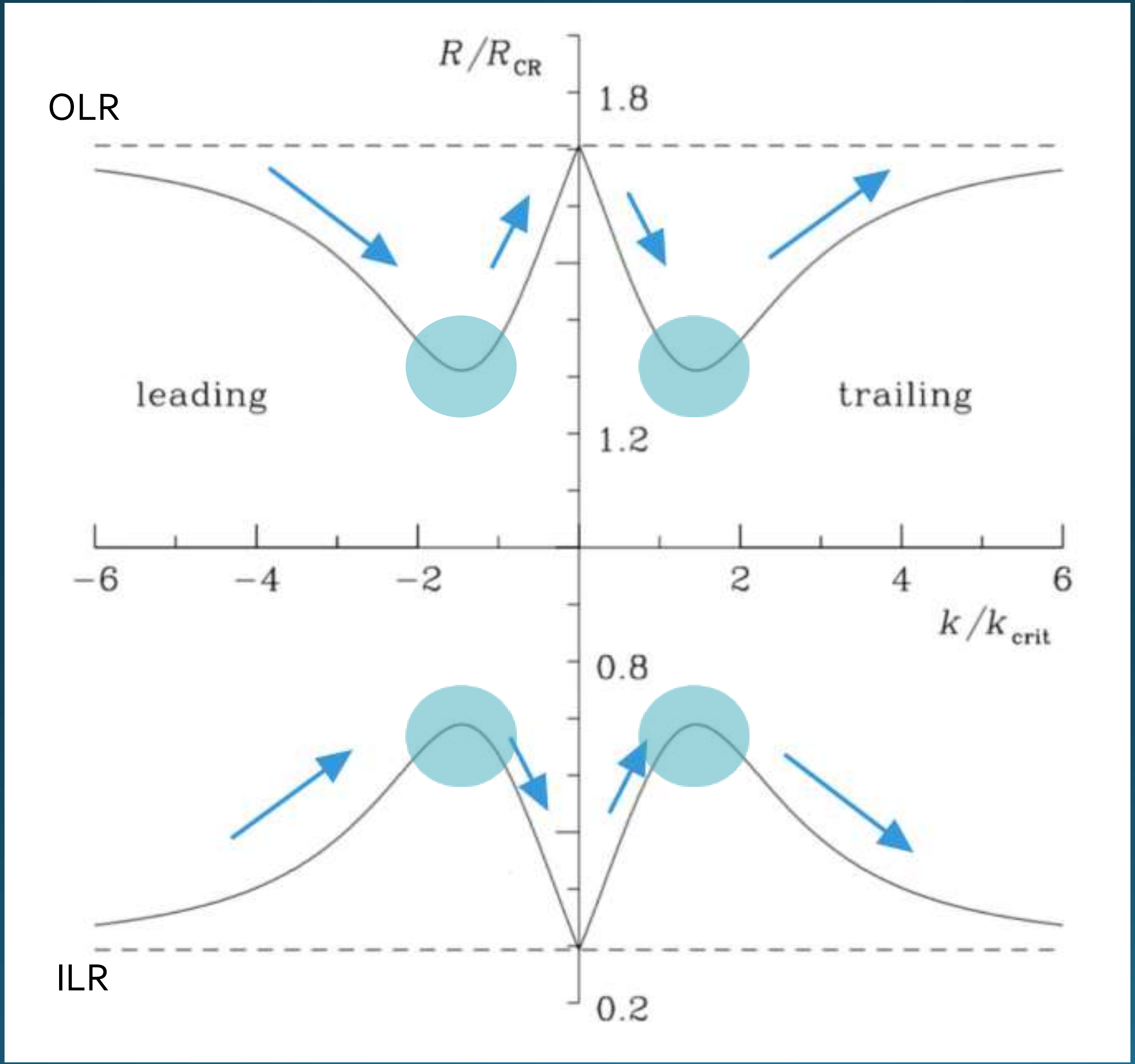
2.3 Wave Propagation



Short Trailing and Long Leading propagates away from the CR

Binney & Tremaine (2008)

2.3 Wave Propagation

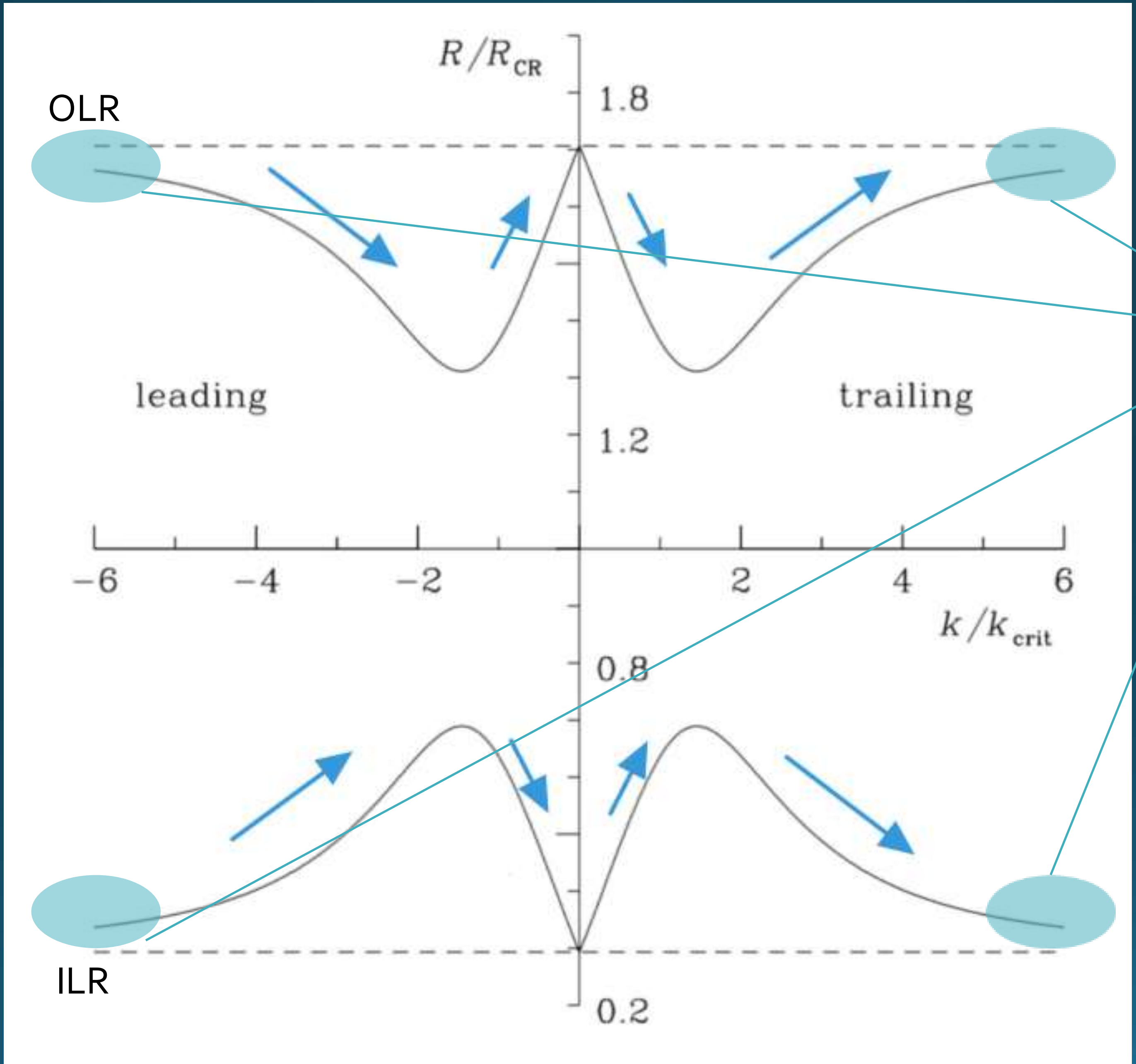


Binney & Tremaine (2008)

Forbidden Regions

No real solutions

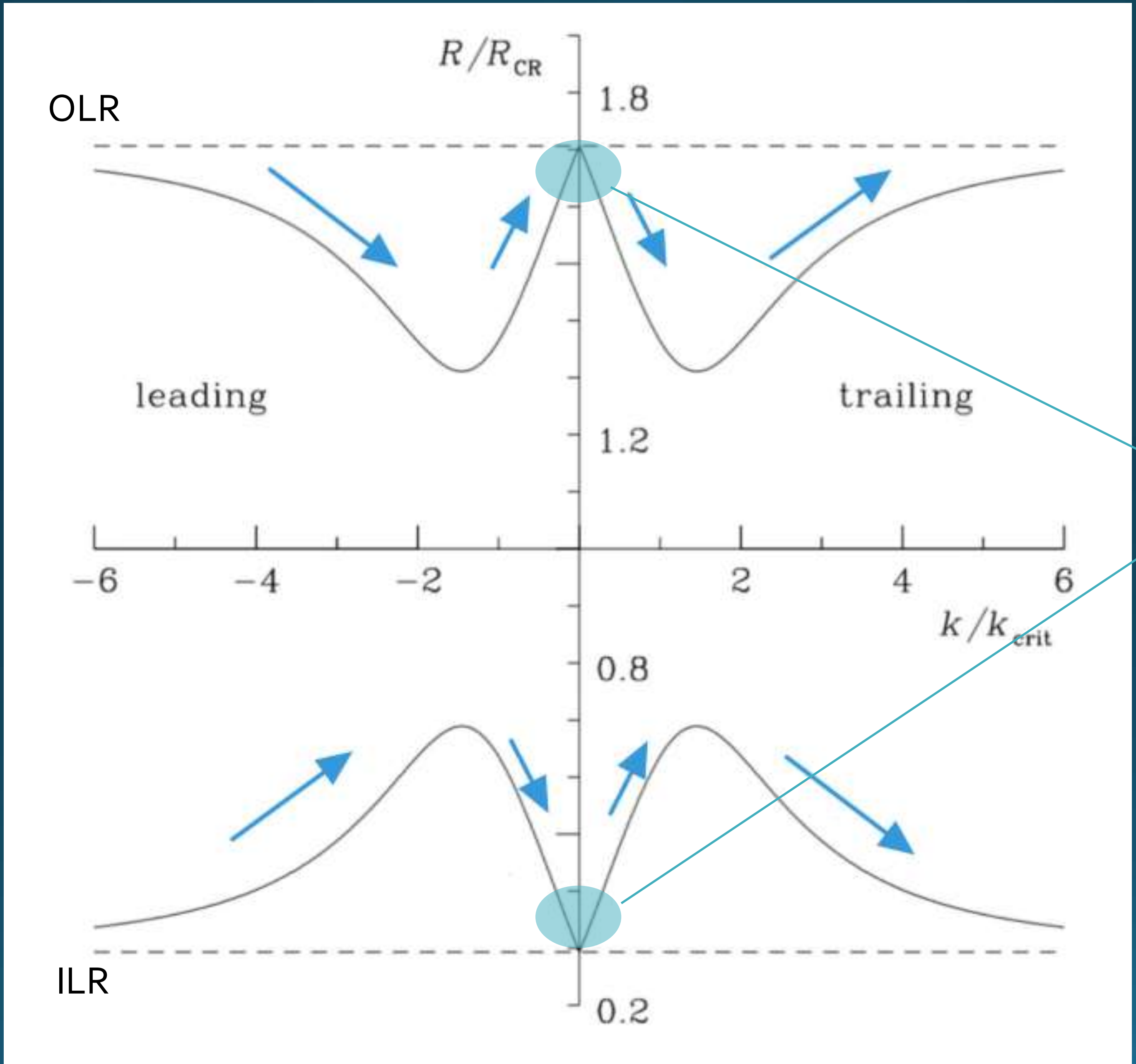
2.3 Wave Propagation



short waves absorbed due to Landau damping

Binney & Tremaine (2008)

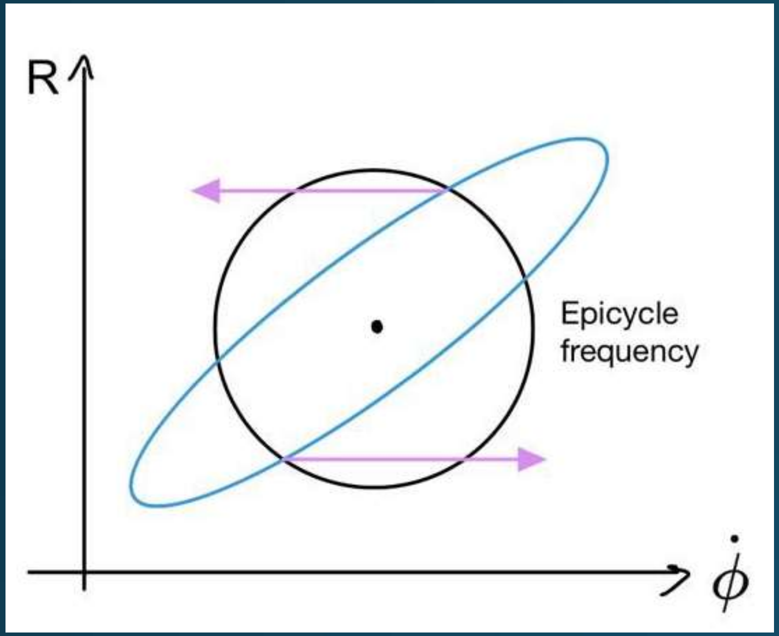
2.3 Wave Propagation

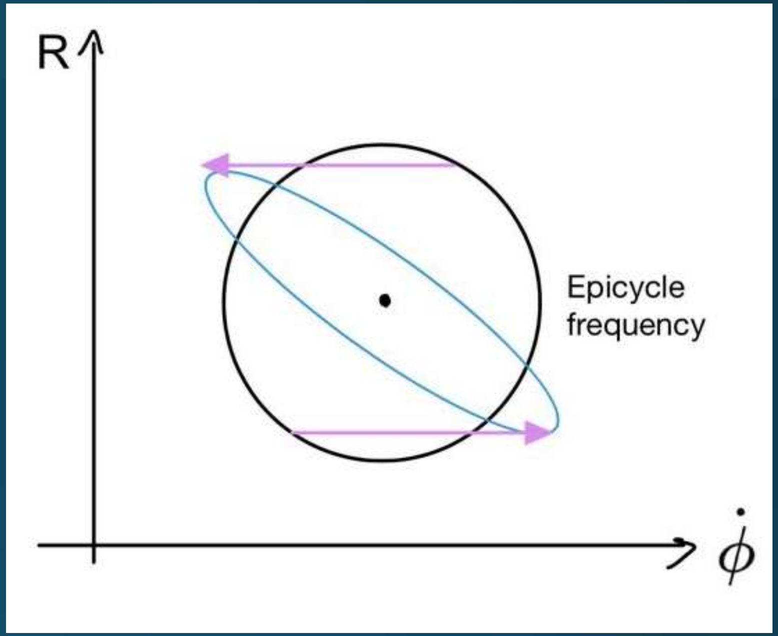


long waves are reflected at Lindblad resonances

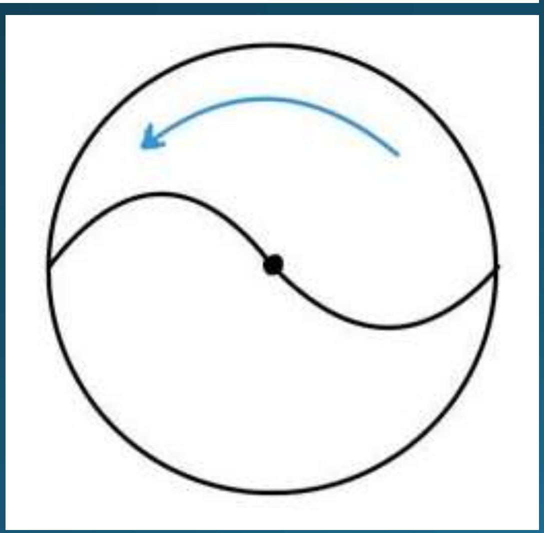
Binney & Tremaine (2008)

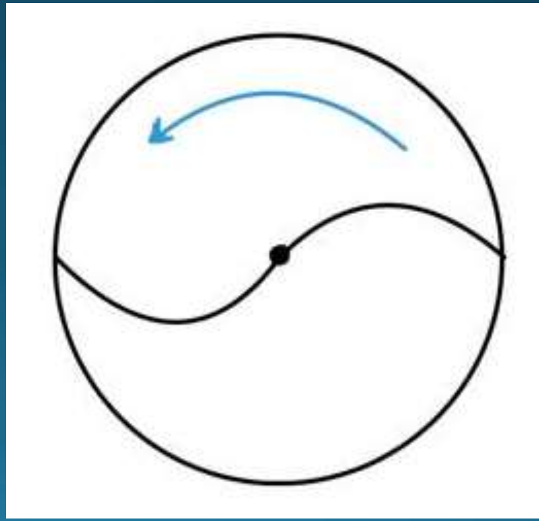
3. "Swing" Amplification





LEADING





TRAILING

3. Swing "Amplification"

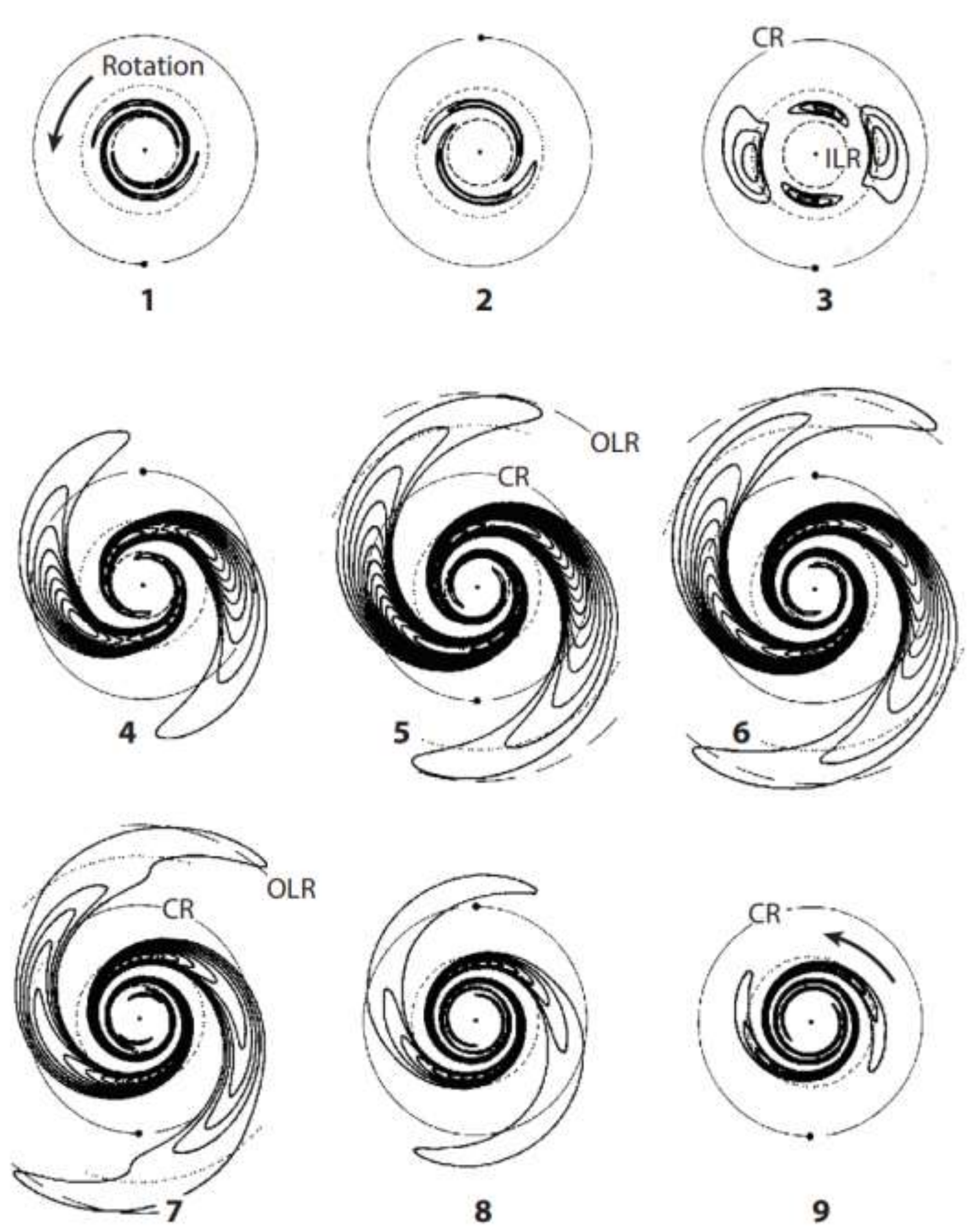
Normal displacement of stars

$$\ddot{\xi} + S(\gamma)\xi = 0$$

$$S(\gamma) = \left(1 - \frac{2\Gamma}{2-\Gamma}\cos^2\gamma + \frac{3}{2}\frac{\Gamma^2}{2-\Gamma}\cos^4\gamma - \frac{F}{X}\sec\gamma\right)\kappa^2$$

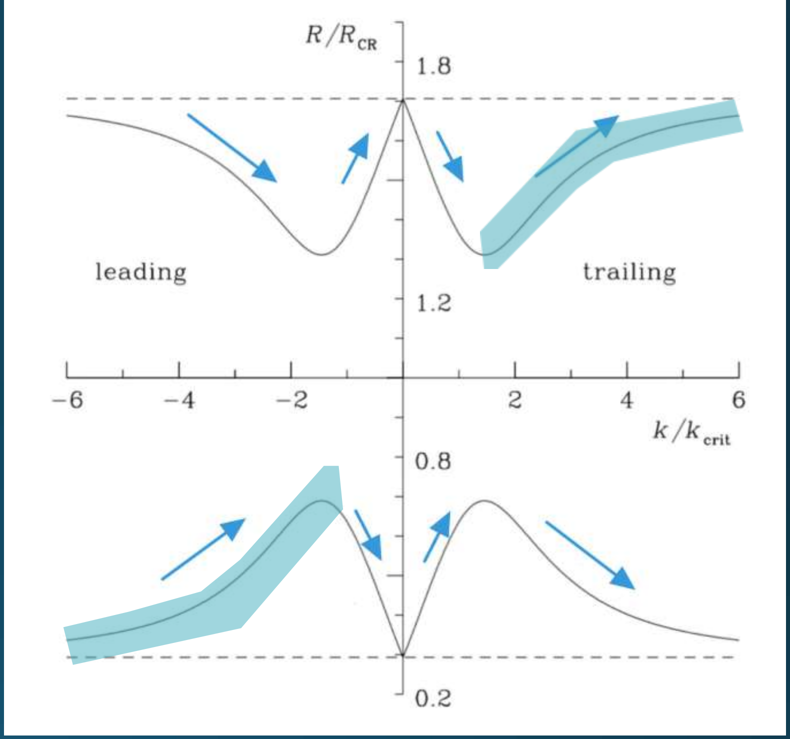
$$effectivenes\colon\ X = \frac{k_{crit}R}{m} \rightarrow efficient\ 1 \leq X \leq 2.5\ \rightarrow X \approx 2\ \rightarrow m = \frac{\kappa^2 R}{4\pi G\Sigma_0}$$

$$\text{shear rate: } \Gamma = -\frac{d\ln\Omega}{d\ln R} \rightarrow\ \Gamma = 0\ \rightarrow rigid\ body\ \rightarrow S(\gamma) > 0\ \rightarrow spiral\ arms\ don't\ amplify$$



3. Swing Amplification

- Leading wave packet with m=2
- Initially leading (1)
- Unwind (2)
- Open pattern (3)
- Passing CR (4)
- Trailing pattern(4)
- Amplifies (4-6)
- Winds (7-9)



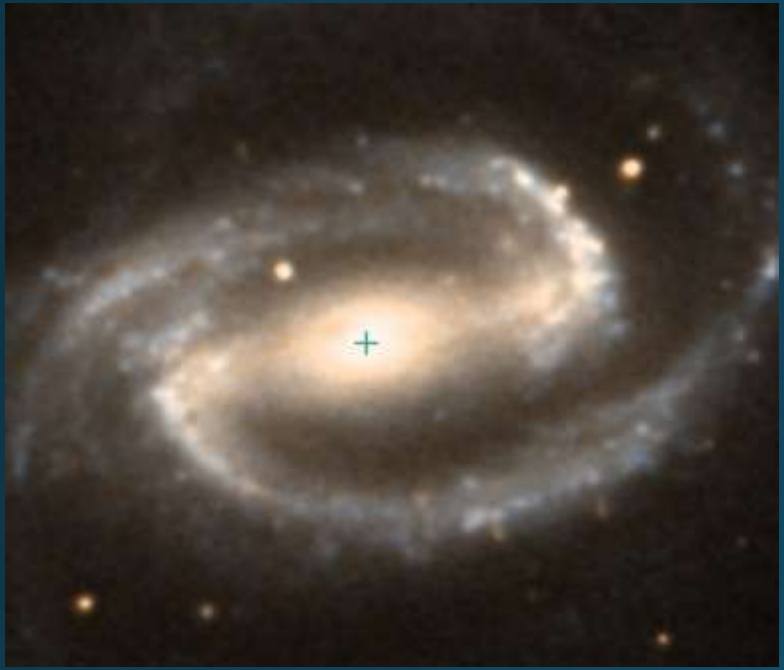
- ➢ Swing amplification: short leading to short trailing
- ➢ Self-gravity increases density contrast
- ➢ Transient and keeps recurring over time

Toomre (1981)

4. Bar-Driven Spirals

NGC1300

SDSS (SIMBAD)



- ❑ 2 armed barred spiral galaxies
- ❑ Same pattern speed in the spirals and the bar
- ❑ Long-lived pattern

NGC2336

SDSS (SIMBAD)

~~2 armed~~

M83

~~2 armed~~

2MASS (SIMBAD)

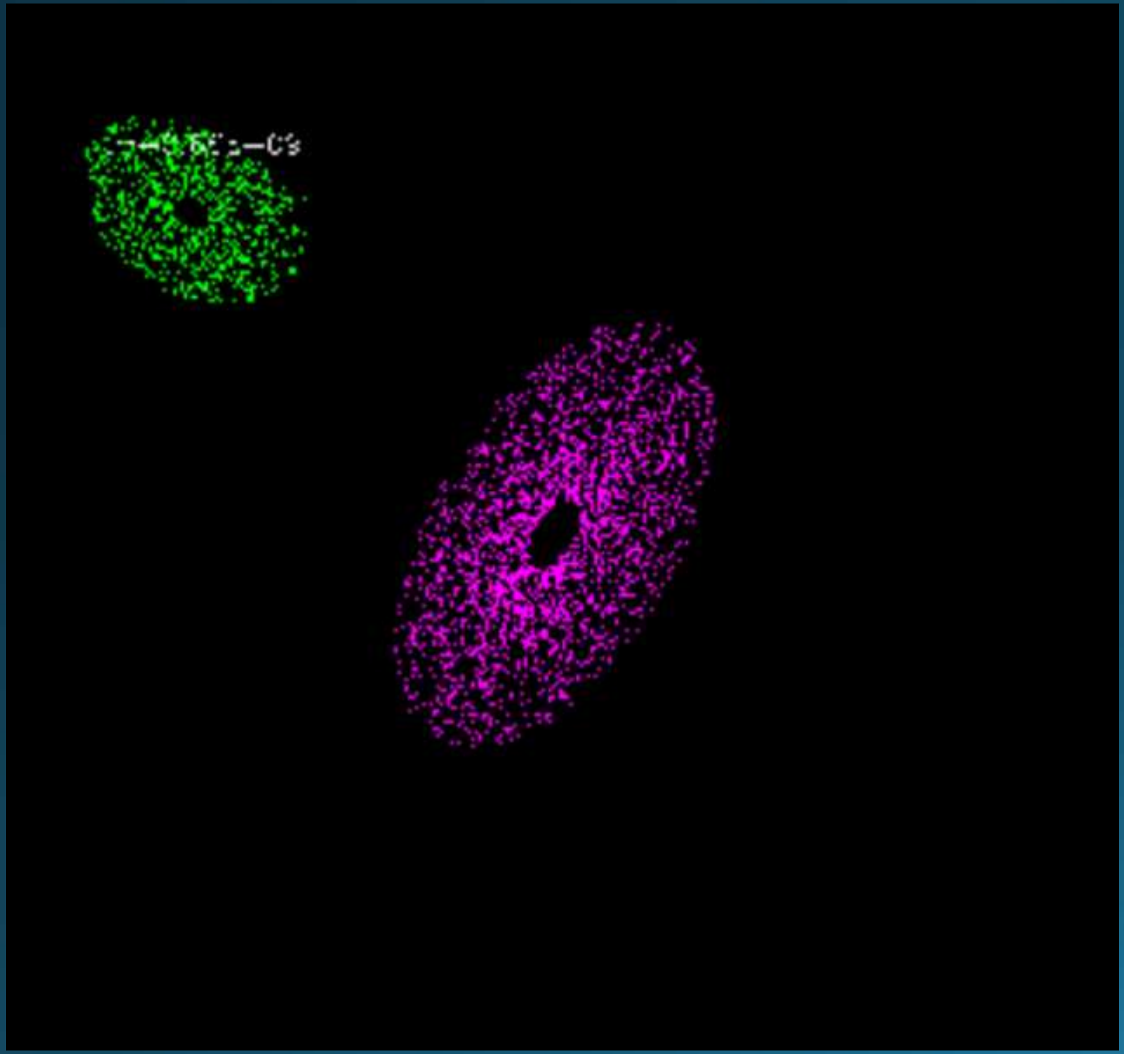
NGC1365

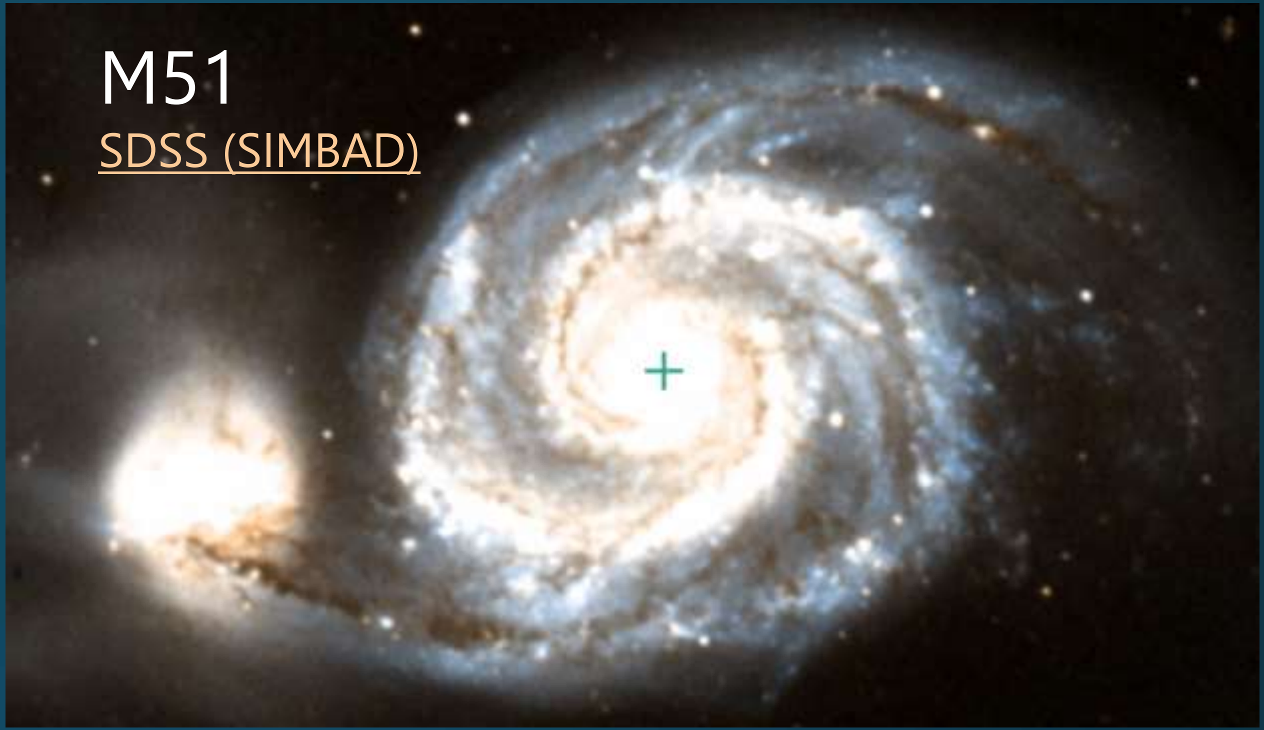
SDSS (SIMBAD)

~~same pattern speed~~

5. Tidal-Driven Spirals

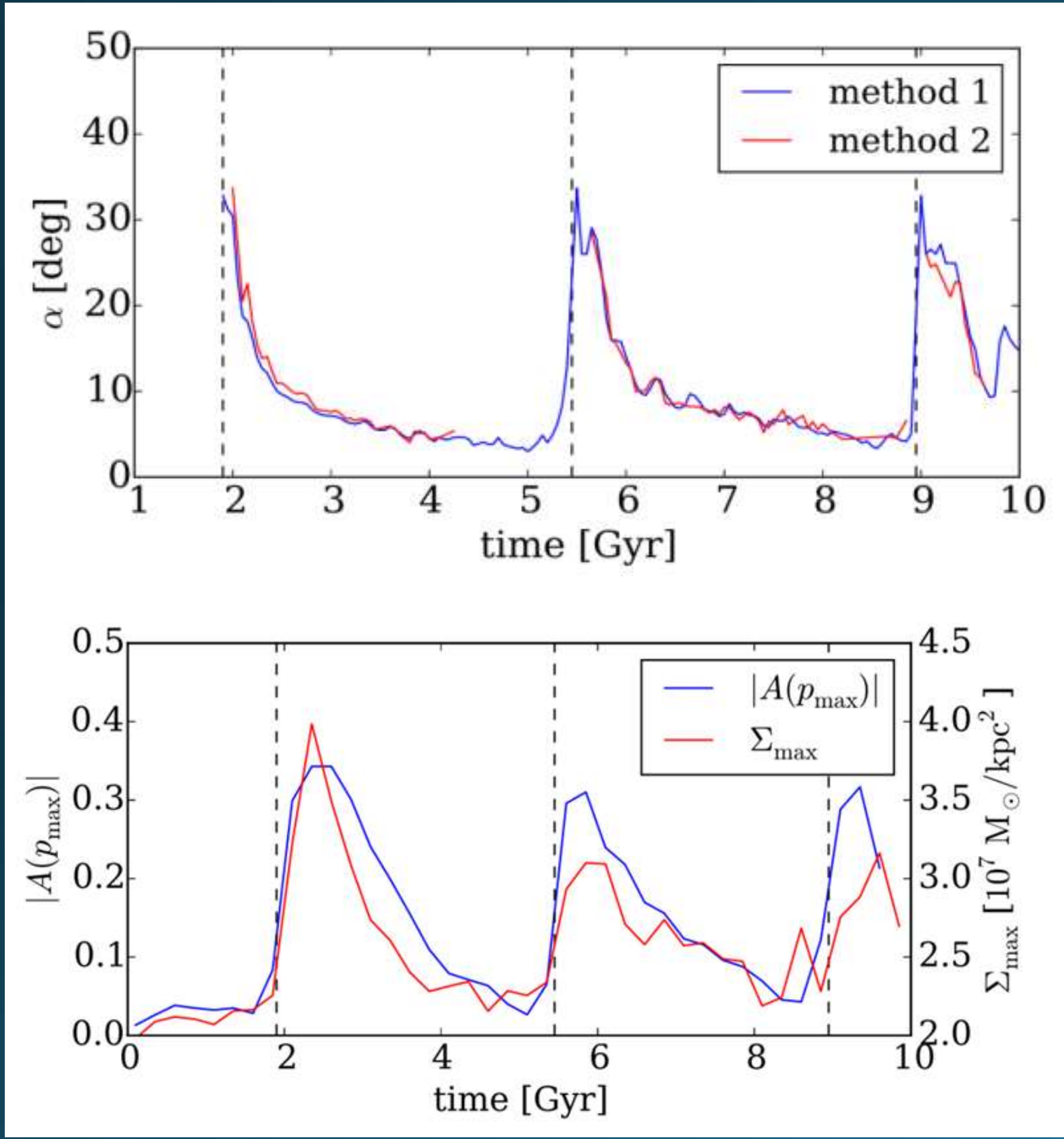
- ❑ Close passage triggering spirals
- ❑ Two-armed grand-design pattern





- ☒ Only grand design
- ☒ Spirals without any satellites → DM Halo?

M81
https://people.astro.umass.edu/~myun/movie.gif



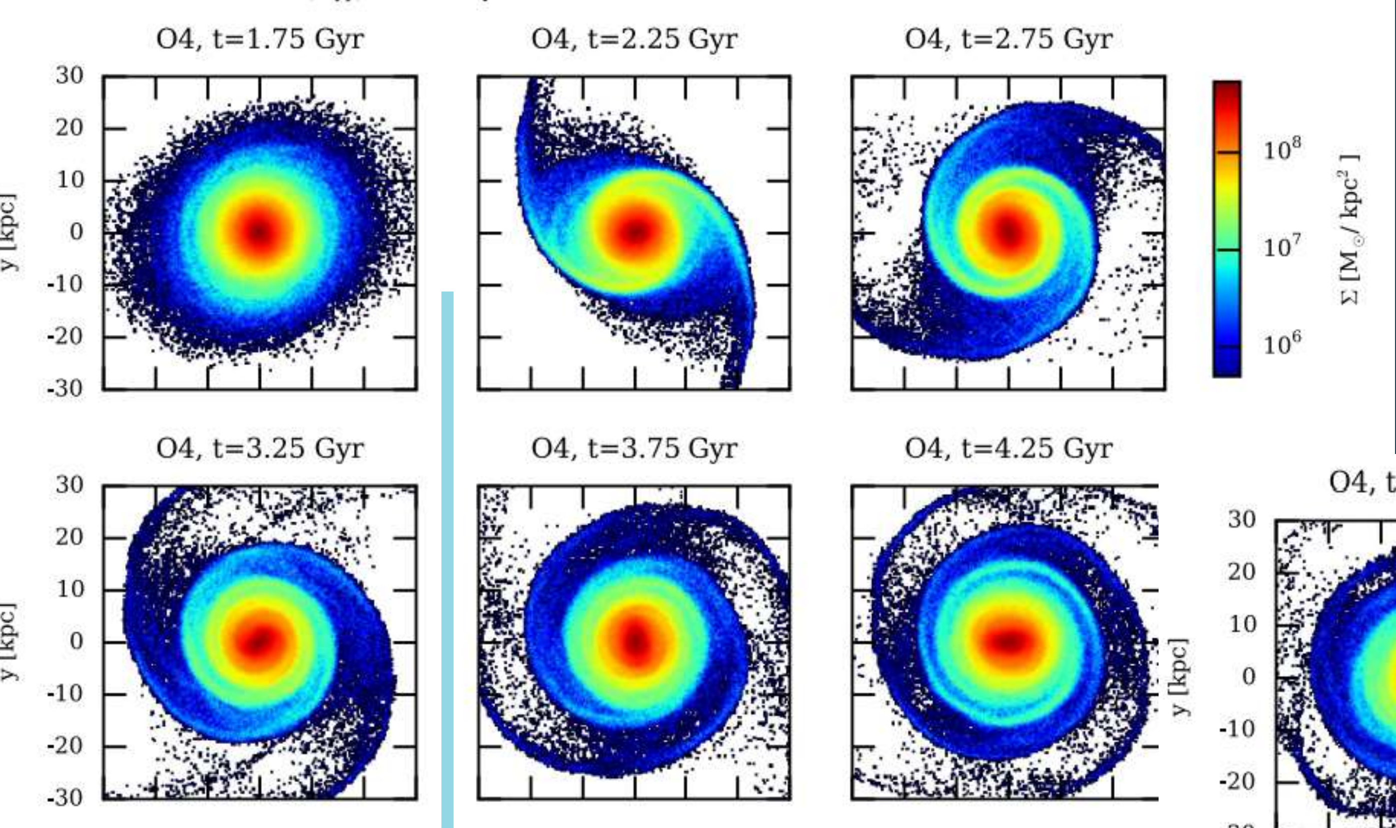
5. Tidal-Driven Spirals

- Strongest arm formation after passage
- 0.5 Gyear of difference between the maximums

$A(p_{max})$: Strength of the arms
Σ_{max}: Max. surface density distribution of the stars at certain radius

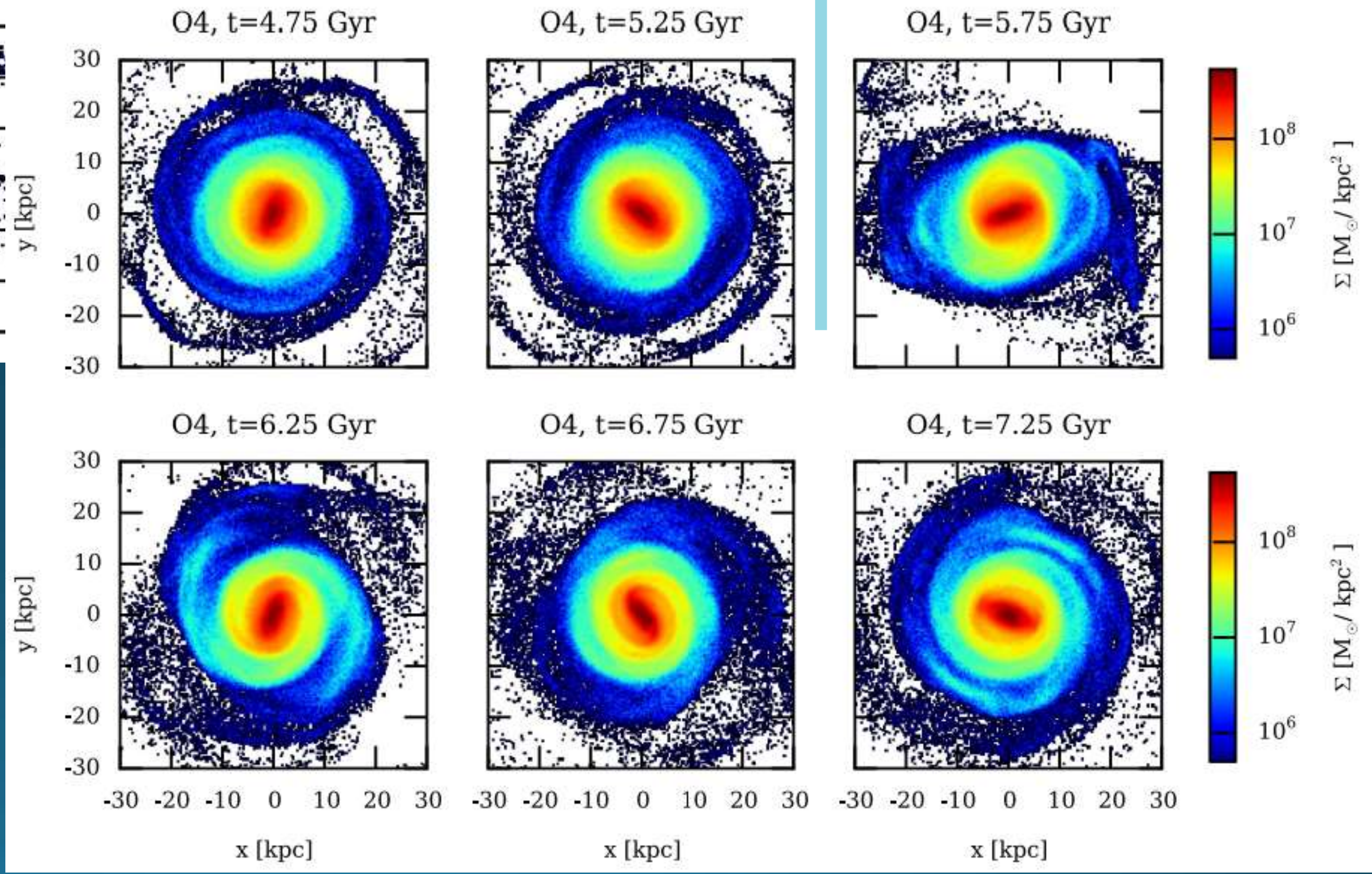
Semczuk et al. (2017)

5. Tidal-Driven Spirals



2^{nd} pericenter passage at 5.4 Gyear

1^{st} pericenter passage at 1.9 Gyear

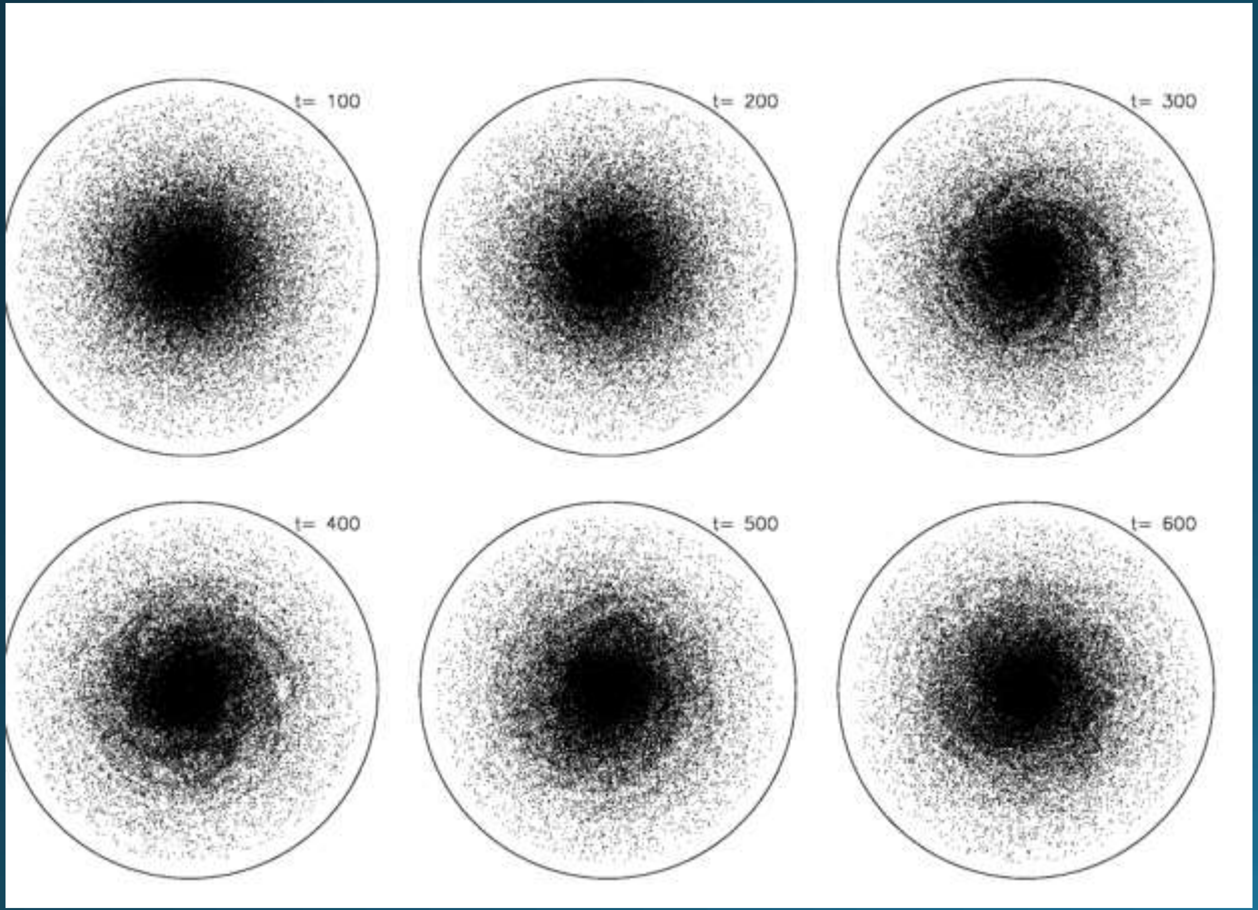


The recurrent pattern, explains why we still see grand-design spirals even though they have short-life

Semczuk et al. (2017)

6. Lifetime of Spirals

- Simulations by Sellwood (2011):
  - For m=2: stable disc over 40 disc rotations
  - For m≥2: multi-arm short-lived spiral patterns



$$X = \frac{k_{crit} R}{m}$$

- For m ≥4 → $1 < X < 2.5$ → vigorous swing amplification
- For m =2 → swing amplification is not effective

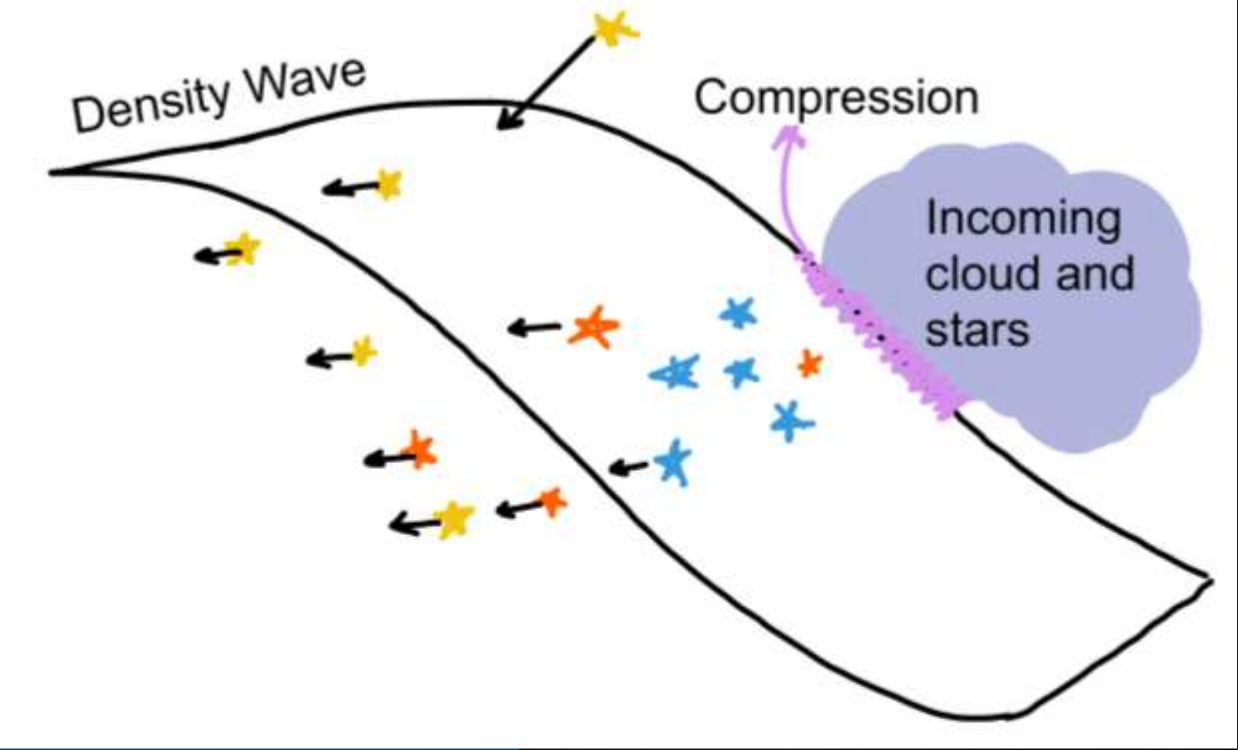
Sellwood (2011) Sellwood, J. A. 2011, MNRAS, 410, 1637

6. Lifetime of Spirals

- Angular momentum from inner to outer parts → scattering stars and mixing materials

Transient spirals:

- Scatter disc stars
- Random motion $\uparrow$ → heat up → $Q\uparrow$
- No cooling → spirals will disappear
- cooling → fresh stars on circular orbits
- Lenticular (S0) galaxies: no gas → no spirals



NGC 2787
https://en.wikipedia.org/wiki/Lenticular_galaxy

- Radial Mixing: different metallicities for the same age
- Stars moving in and out in their radii

6. Summary

Swing Amplification

- Driven by differential rotation and self-gravity of the disk
- Turning short leading waves to short trailing waves as they pass the CR and amplifying them in the process
- Transient nature and continuous generation

Tidal Interactions:

- A satellite or a DM subhalo (possibly)
- Only grand-design spirals
- Transient spiral due to multiple passages

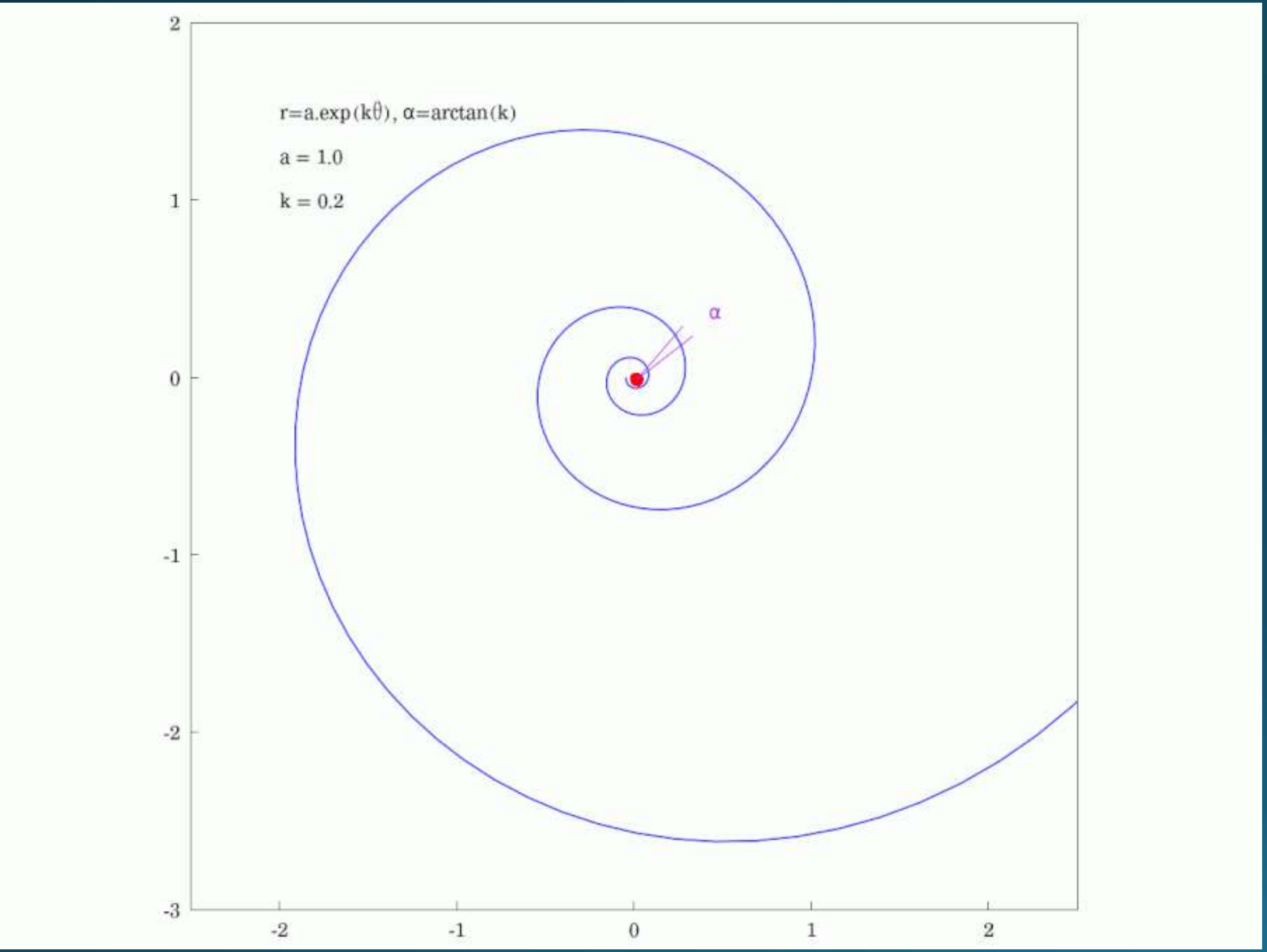
Bar interactions:

- Bar like perturbations
- Long-lived
- Only grand-design
- Common pattern speed

- Simulations and observations point mostly to the transient nature of spiral patterns

Thank you for your attention

Imagining how making the pitch angle smaller will make it more tight/ logarithmics spirals



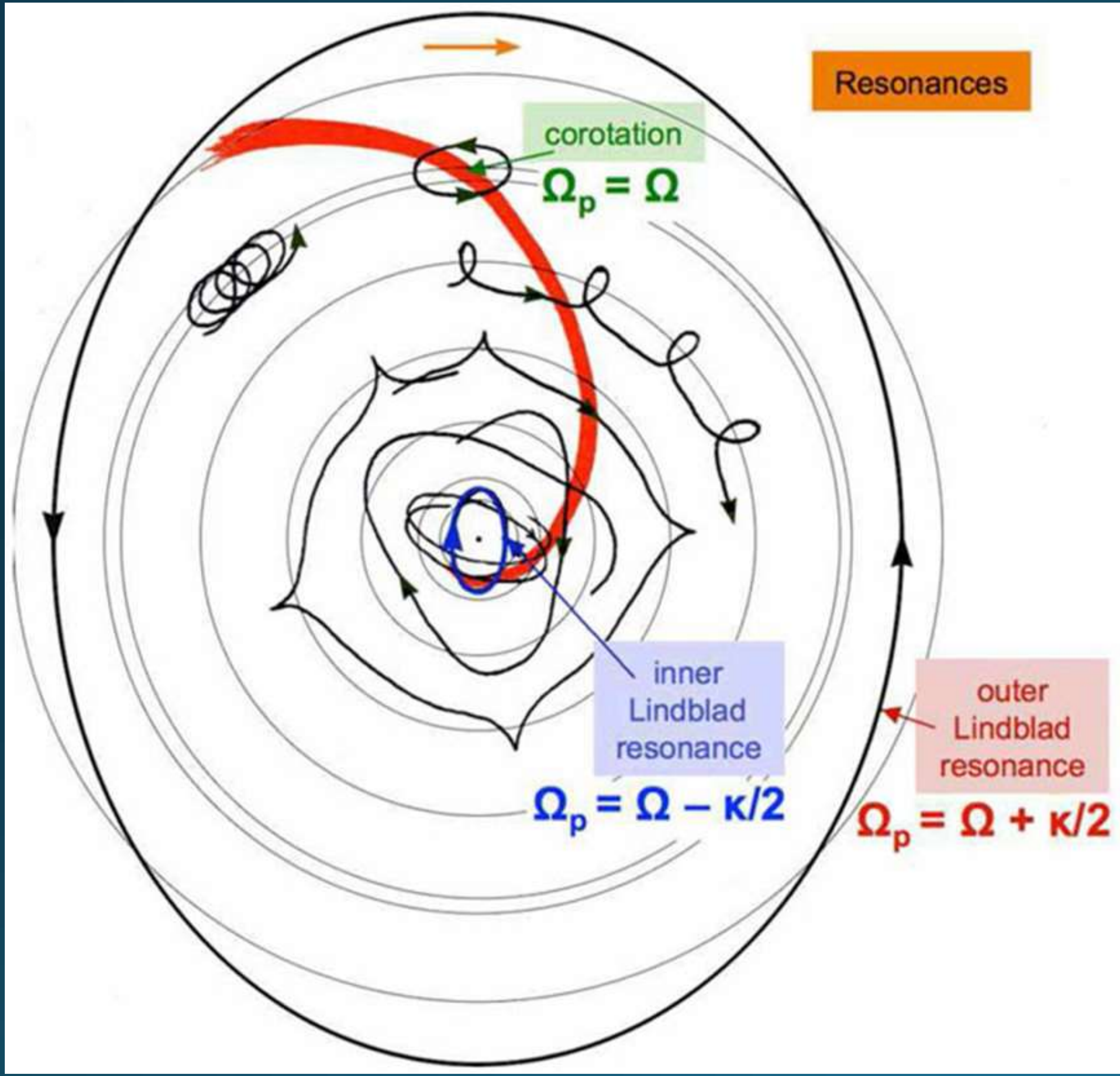
When does the tidal effect happen

$$S = \left(\frac{M_{\mathrm{pt}}}{M_{\mathrm{gal}}}\right)\left(\frac{R_{\mathrm{gal}}}{d}\right)\left(\frac{\Delta T}{T}\right)^3 \tag{27}$$

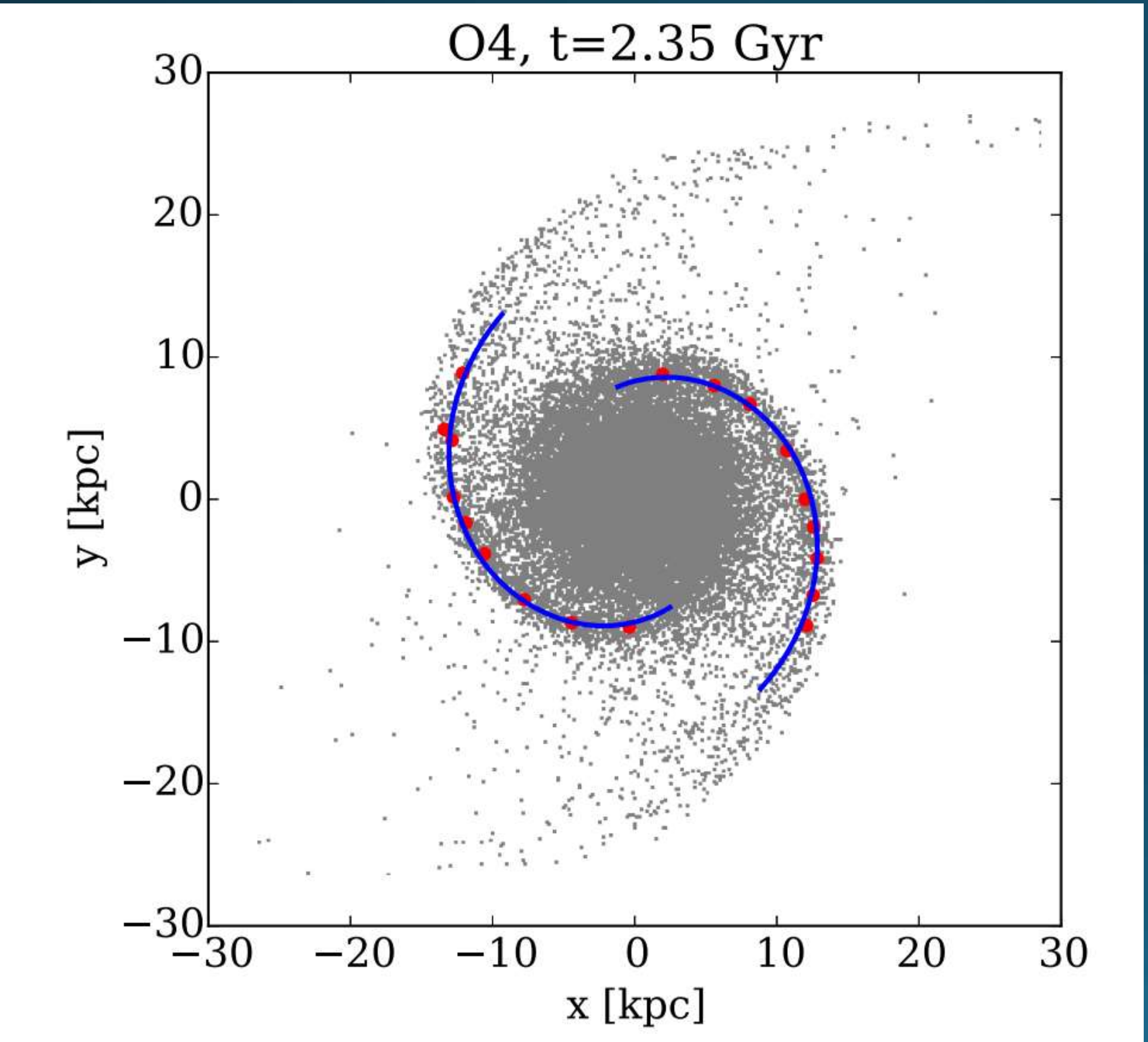
where M_{gal} and R_{gal} are the mass and characteristic size of the perturbed galaxy, M_{pt} is mass of the perturber, d is the closest approach distance between the bodies, ΔT is the interaction time for the perturber to move one radian around the galaxy, and T is the time for stars in the galaxy's outer disk to complete one radian, expressed as $T = \left(R_{\mathrm{gal}}^3/GM_{\mathrm{gal}}\right)^{1/2}$. Semczuk et al. (2017) indicated that spiral arms in galaxies can be triggered by smaller companions when S ranges between 0.01 and 0.25 Semczuk et al. (2017).


Floculent

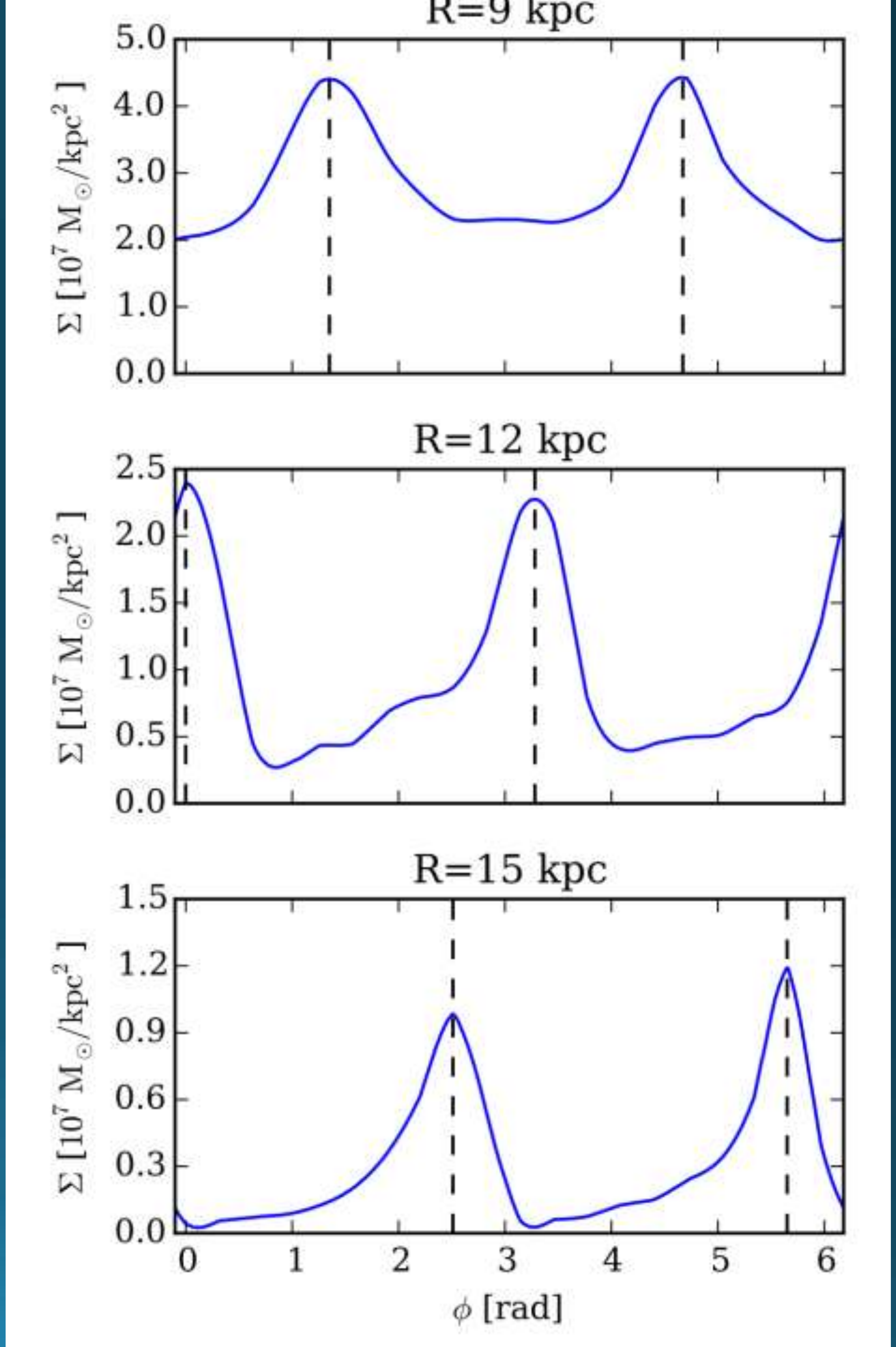

Multi-Armed



Resonances
corotation
$\Omega_p = \Omega$
inner Lindblad resonance
$\Omega_p = \Omega - \kappa/2$
outer Lindblad resonance
$\Omega_p = \Omega + \kappa/2$



$$\phi = B \ln R + C$$



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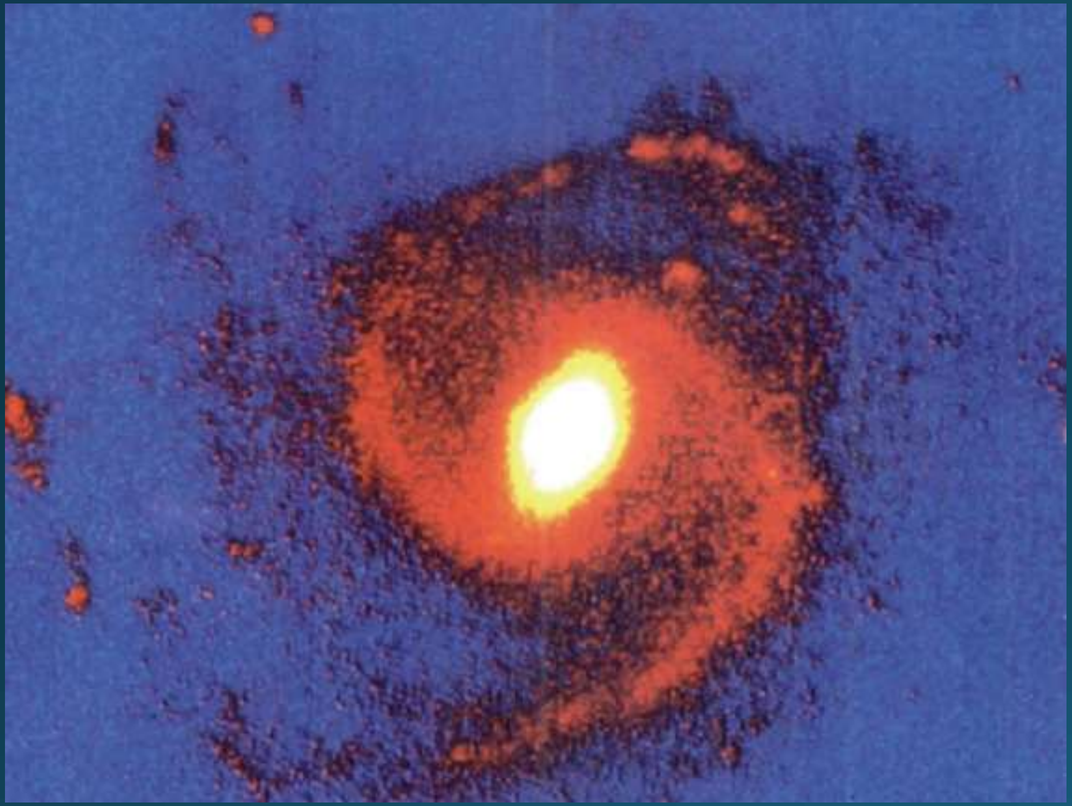
$$A(m, p) = \frac{1}{N_s} \Sigma_j \exp[i(m\phi_j + p \ln R_j)],$$

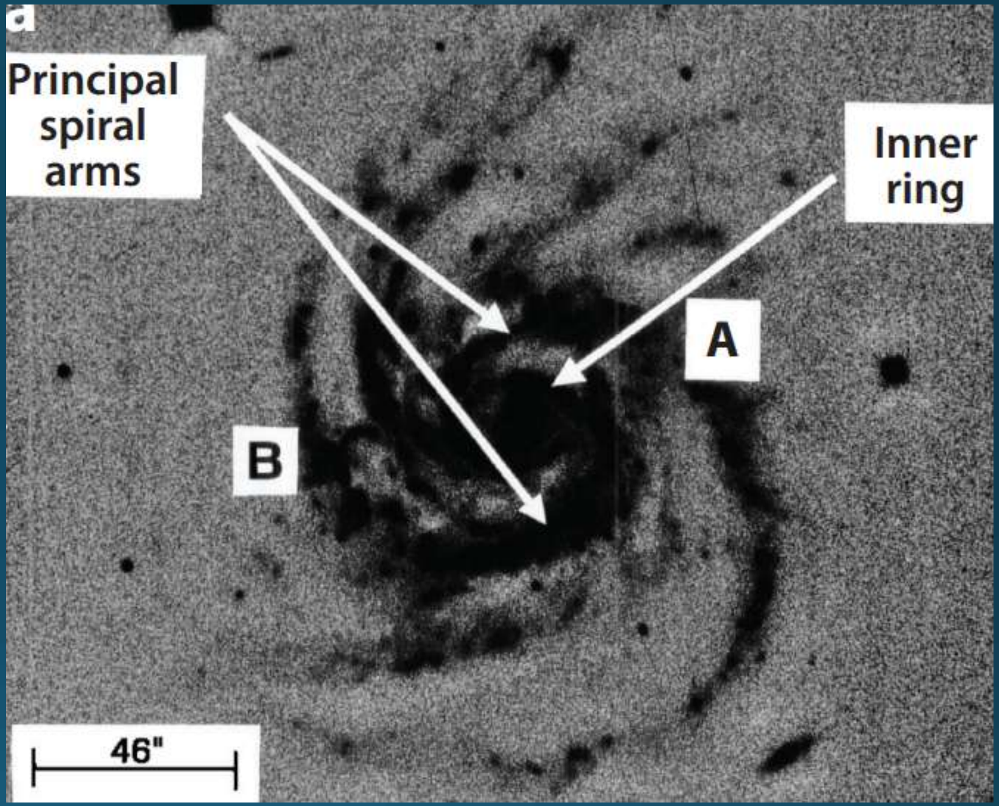
$$\tan a = 2/p_{max}$$

$$\mathcal{F}(s, \chi) \equiv \frac{2}{\chi}(1 - s^2)e^{-\chi} \sum_{n=1}^{\infty} \frac{I_n(\chi)}{1 - s^2/n^2},$$

0. Introduction

Shu (2016) Shu, F. H. 2016, ARA&A, 54, 66



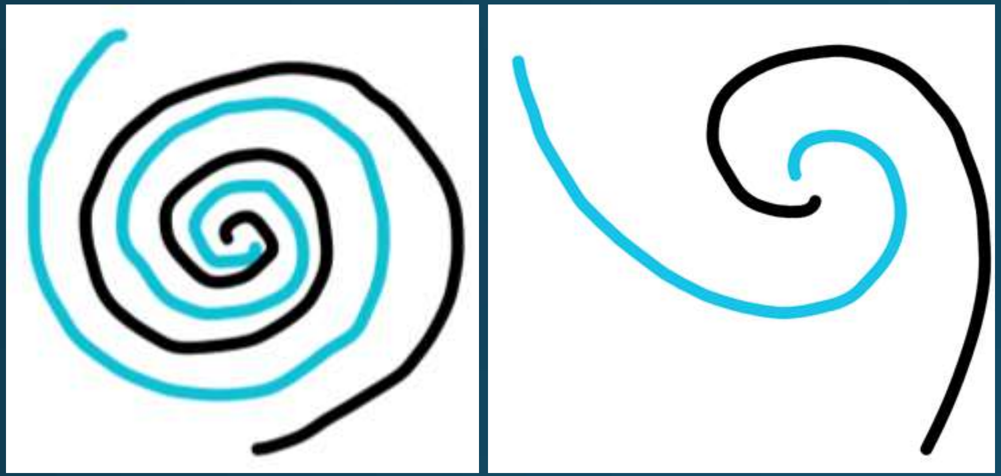


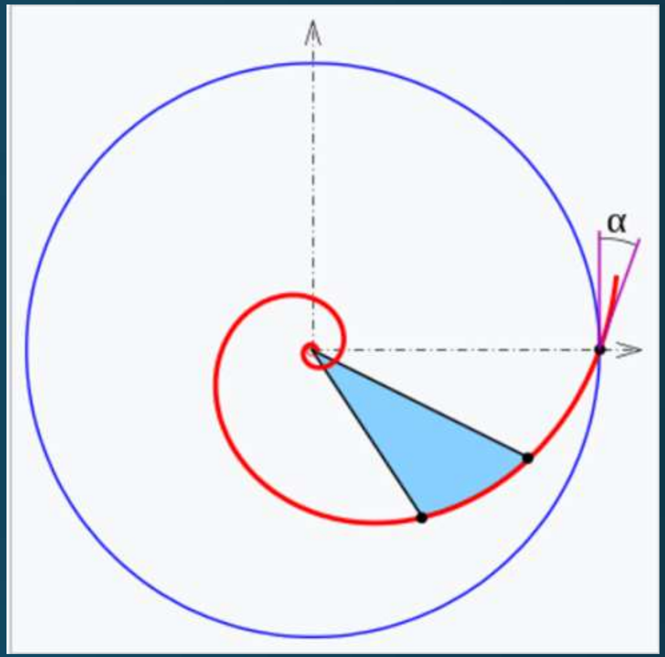
NGC 309
Infrared
Grand-Design

NGC 309
Optical light
Multi-armed almost flocculent

2.1- Dispersion Relation

- Main Hypothesis:
  - ❑ Tight-Winding Spirals





https://en.wikipedia.org/wiki/Pitch_angle_of_a_spiral

  - ❑ Quasi-Stationary Spiral ($\omega = m\Omega_P$)

$$V(r) = \underbrace{V_0(r)}_{} + \underbrace{V_1(r)e^{i(\omega t - m\varphi)}}_{}$$

Stationary
Axisymmetric

Bulge, disc, halo

≫

Non-Stationary
Non-Axisymmetric

Spiral Gravitational Perturbation