Density Waves and Chaos in Spiral Galaxies

Frank Shu
NTHU Physics Department

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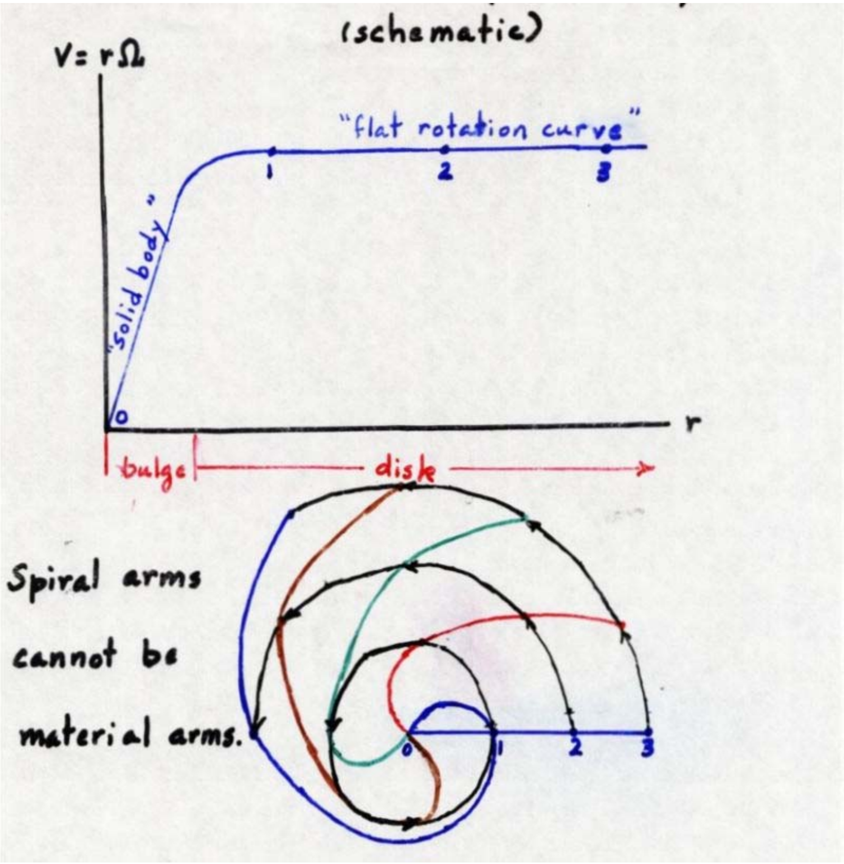
Outline of Talk

- Elements of Spiral Density-Wave Theory
- Theory of Spiral Substructure:
  - Feather Formation by Gravitational Instability Behind Galactic Shocks
  - Branch Formation by Ultraharmonic Resonances
  - Spur Formation by Reflection of Leading Waves Off Sharp Features Induced by Nonlinear Dredging
  - Flocculence Arising from Overlapping Resonances
- Summary

The Winding Dilemma of Galactic Spirals



After about 10^8 yr, material arms would add about 1 turn,
but spiral galaxies are about 10^{10} yr old, yet don't have 100 turns.

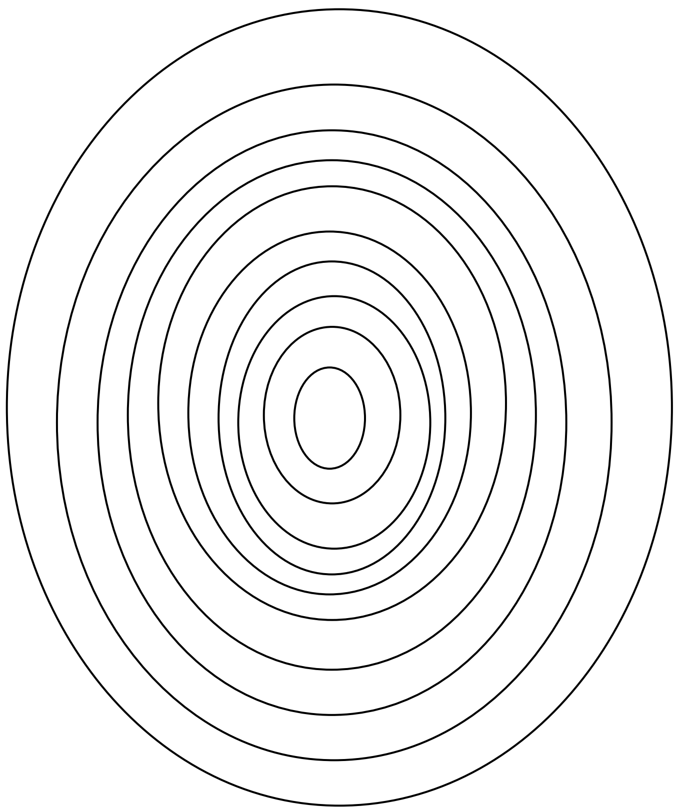
M51 in Visible and Near-Infrared

Famous simulation by Toomre & Toomre suggests grand-design spirals result from interactions.

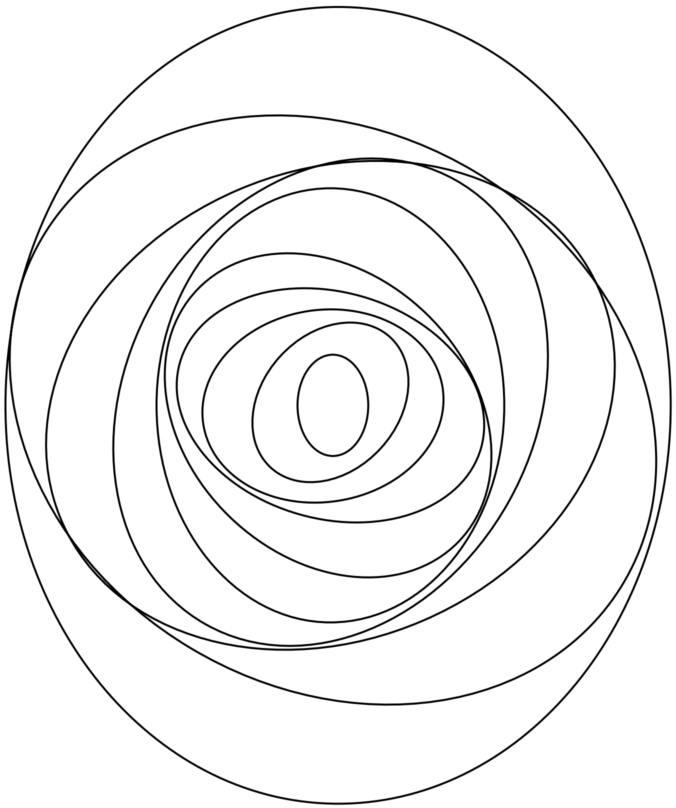
Frequency of infrared grand-designs → Quasi-stationary normal modes (Block et al. 1994, 1996).

Why does visible/blue image have so much substructure when infrared image looks so smooth?

Infrared Barred and Spiral Galaxies as Stellar Density Waves



Disk Galaxy with Oval Distortion

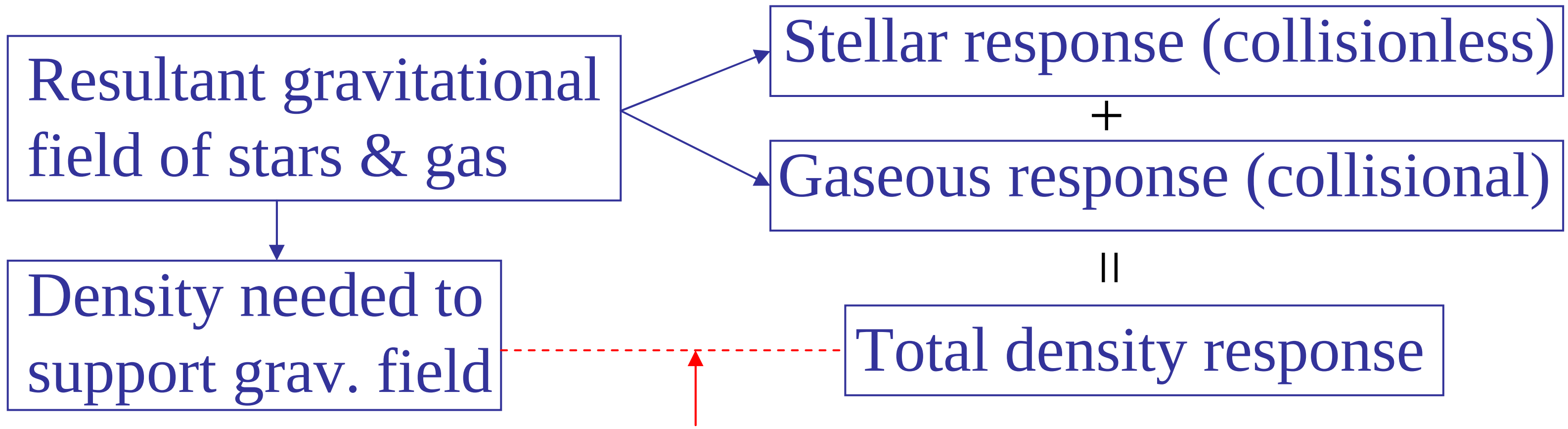


Disk Galaxy with Spiral Structure

Orbits are closed, even on average, only in a frame rotating at Ω_p.

Same Ω_p at different radii only if self-gravity can organize pattern of orbits.

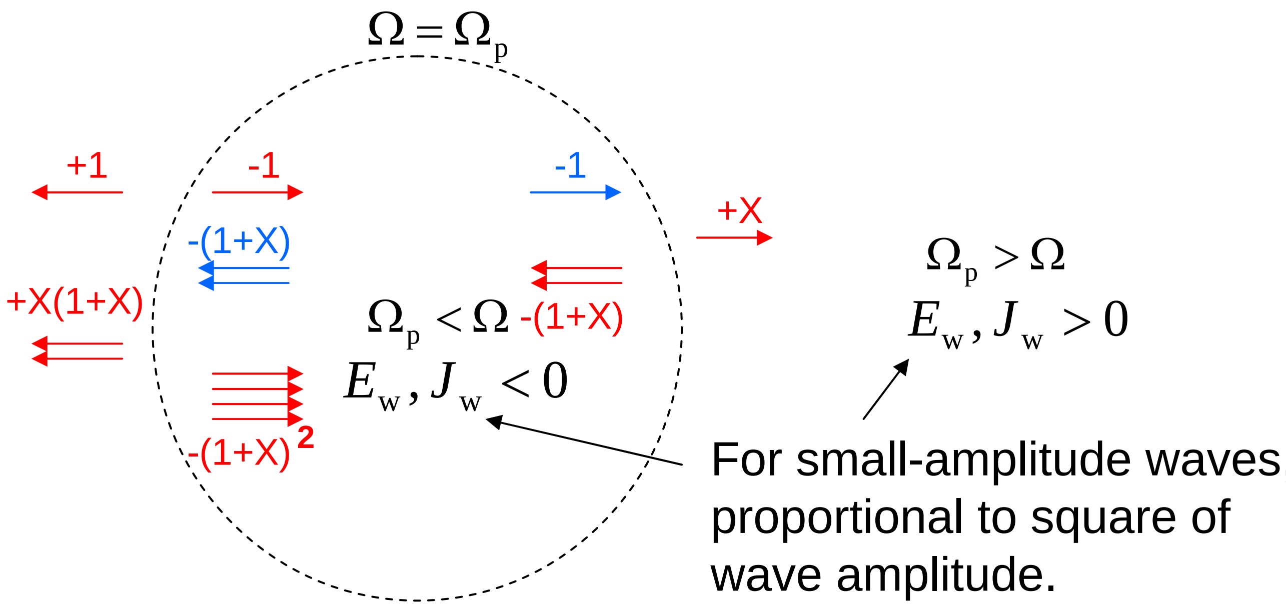
Outline of Density WaveTheory (Lin & Shu 1964; Lin, Yuan, & Shu 1969)



This equation determines properties of spiral density waves, in particular, Ω_p as an eigenvalue of the problem.

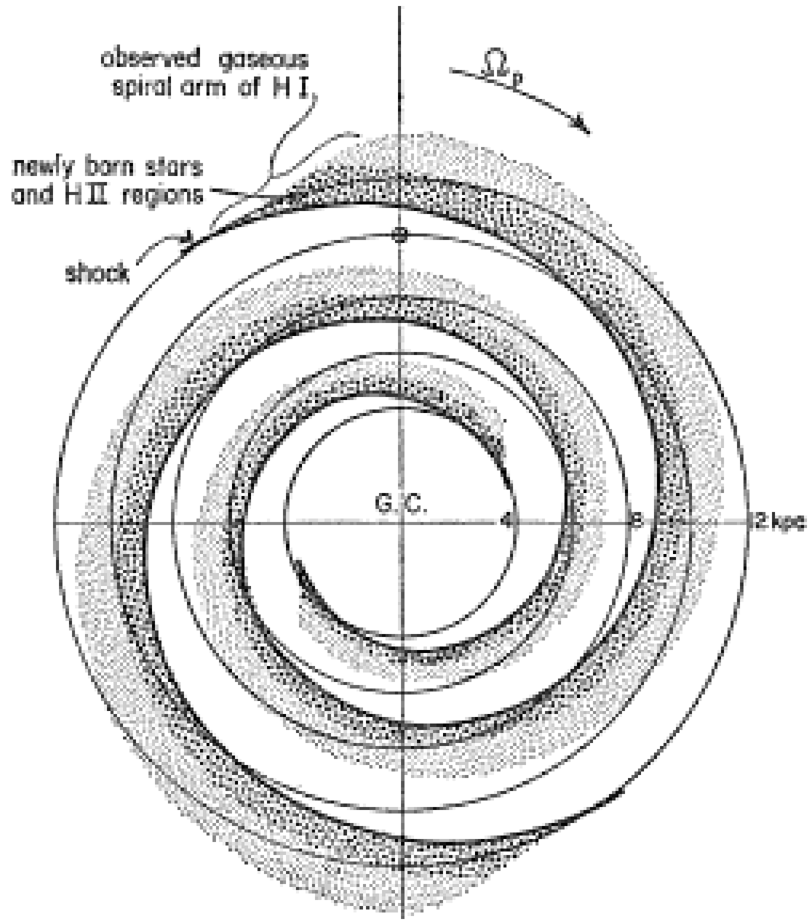
- Depending on the galaxy model, disturbances of a spiral or barred form can grow spontaneously in the disk (a self-excited normal mode).
- This basic tendency arises because a transfer of angular momentum outwards (by gravitational torques) is energetically favorable for the system (Lynden-Bell & Kalnajs 1972). Nonlinear dissipation is essential element of quasi-stationary structure (Zhang 1996).
- New dynamical component – active dark-matter halo.

Swing Mechanism for Instability and Wave Growth (WKBJ Interpretation)

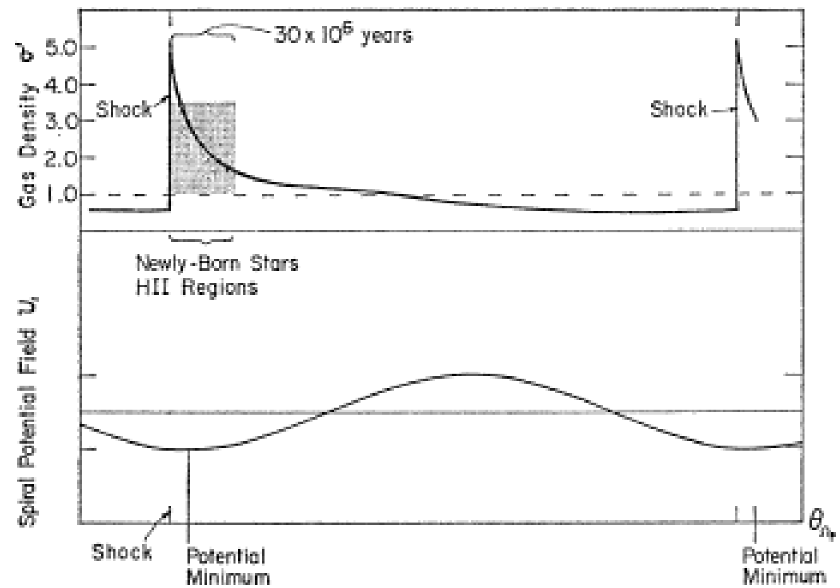


Arrows indicate group velocity of trailing and leading spiral waves. Each round trip across corotation circle increases by (1+X)-fold the interior density of wave energy and angular momentum (globally zero). Condition waves inside CR add constructively in phase yields eigenvalue determination for Ω_p. Example of getting something from nothing made popular later by idea of cosmic inflation in modern cosmology.

Spiral Shockwave in Visible/Blue Light as Nonlinear Response of Gas



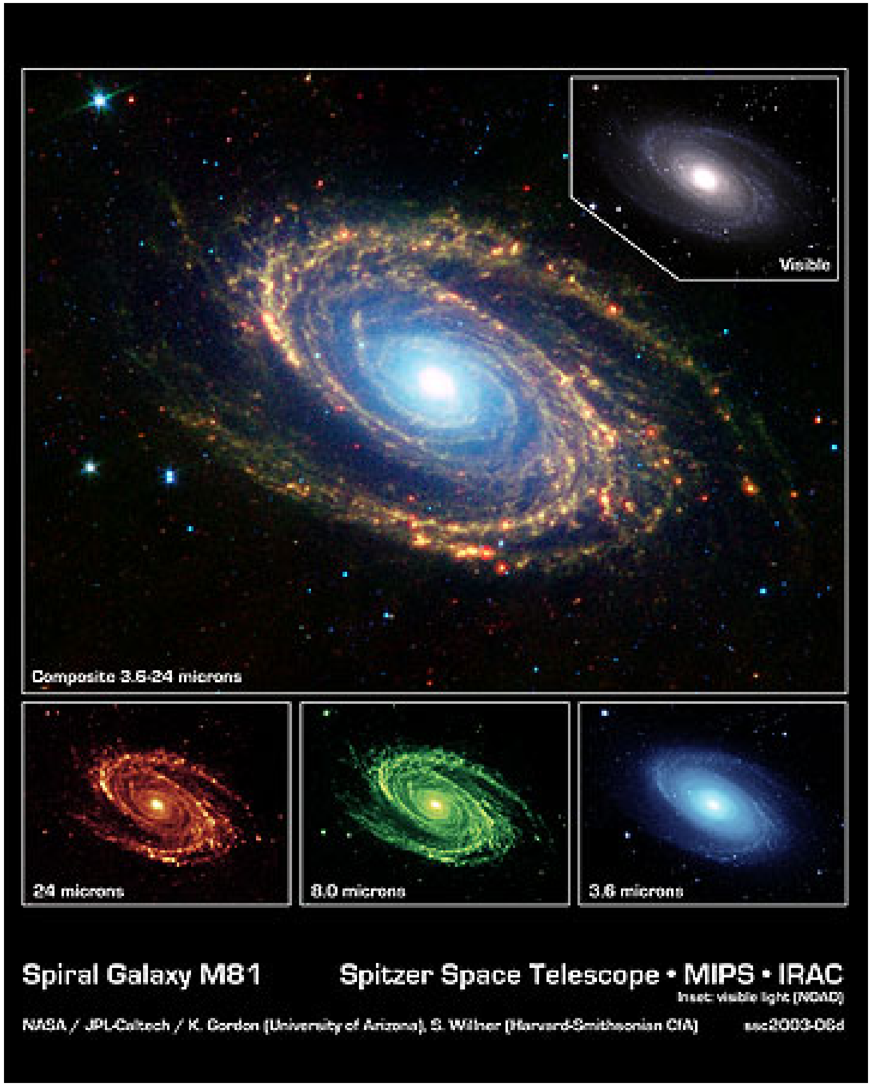
Roberts (1969)



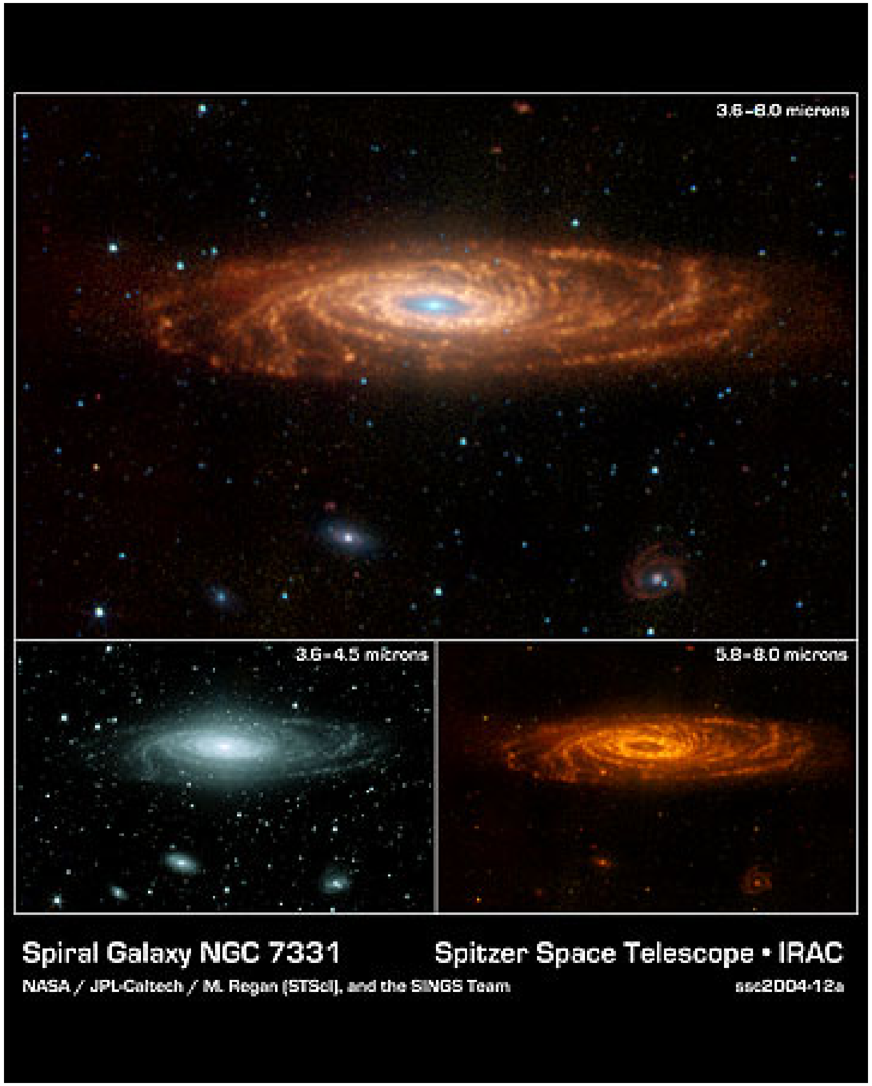
Out-of-phase gaseous response damps stellar spiral density-wave (Kalnajs 1972). Presence of shockwave guarantees non-closure of streamlines (accretion inside CR) and saturates growth of stellar density wave (Roberts & Shu 1972).

Pop I Features Not Explained by Roberts (1969) Picture: Branches, Spurs, & Feathers

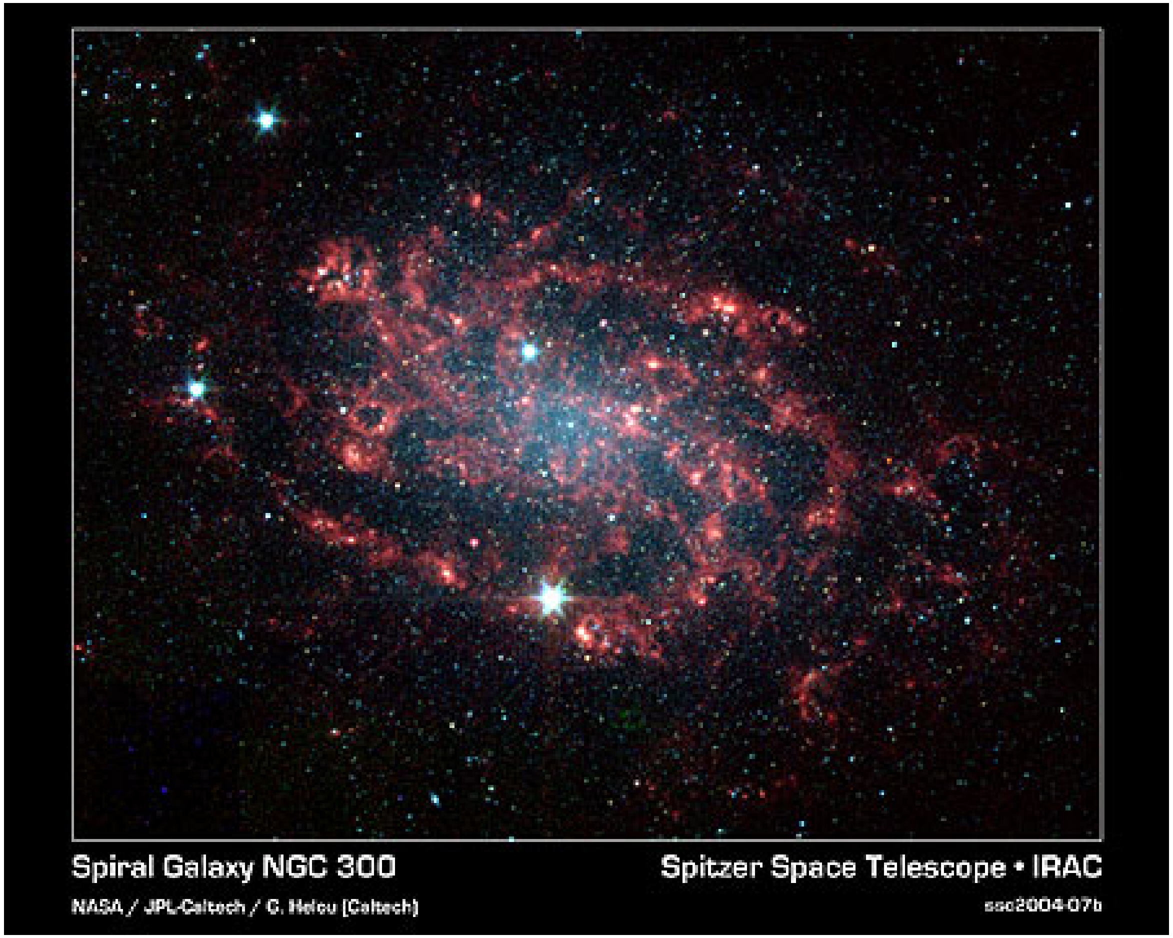
Spitzer Composite Image of M81



Spitzer Image ofMilky Way Twin



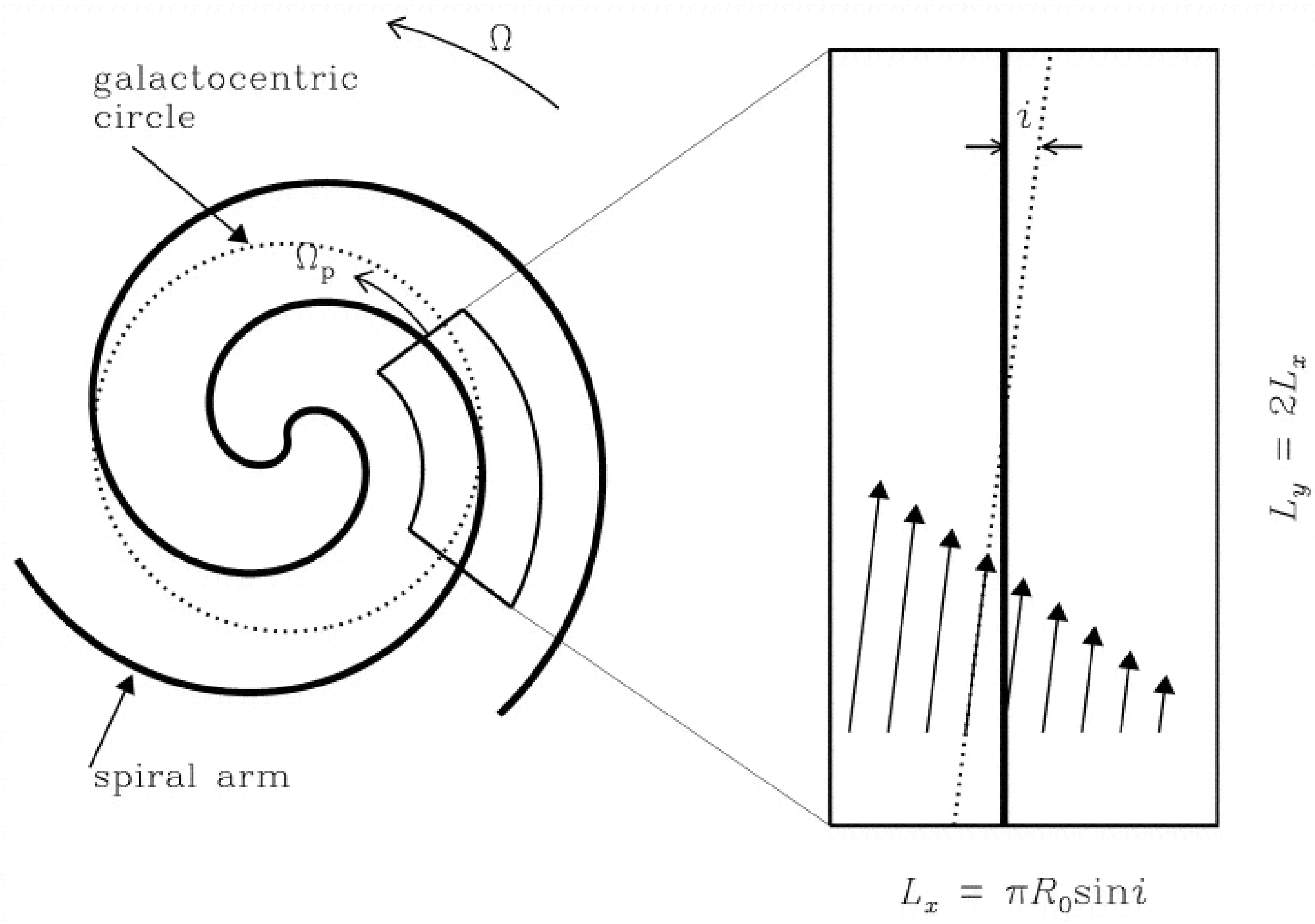
Spitzer Image of NGC 300



Possible Causes of Substructure

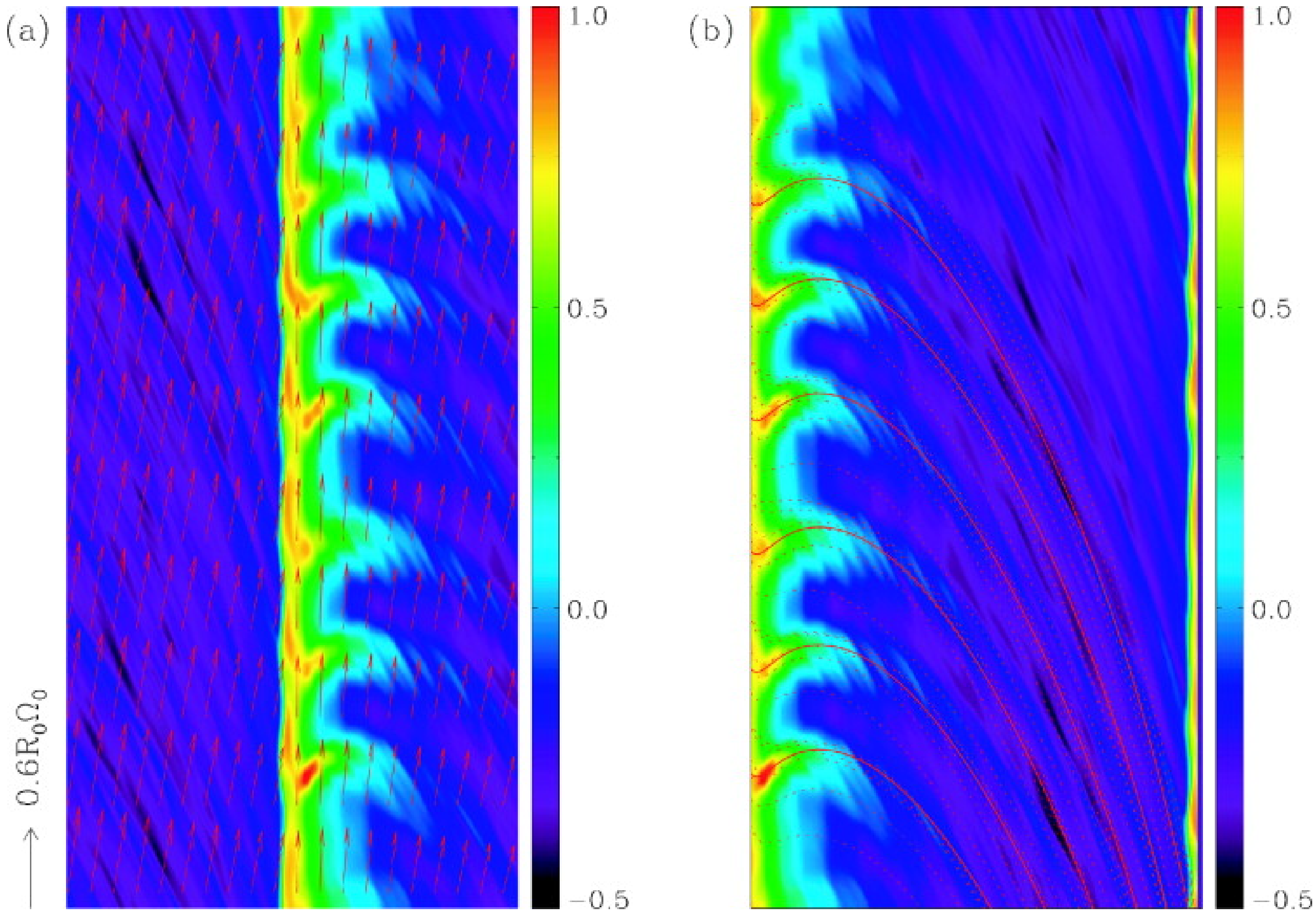
- Irregular structures have irregular causes.
  - Shearing (swinging) bits and pieces (Goldreich & Lynden-Bell 1965, Julian & Toomre 1966)
  - Stellar explosions (Seiden & Gerola 1982, Roberts & Hausman 1984).
  - Decoupled dynamics of stars and gas (Block et al. 1994, 1996).
- Irregular structures can arise from regular causes:
  - Gravitational instability behind galactic shocks (Roberts 1969)
    - Non-magnetic (Balbus & Cowie 1985, Balbus 1988)
    - Magnetic (Lynden-Bell 1965, Elmegreen 1994, Kim & Ostriker 2002).

Transient Gravi-Magneto Instabilities Behind Galactic Shocks: Local Analysis



Kim & Ostriker (2002)

Magnetically Mediated Feather Formation Behind Galactic Shocks



Kim & Ostriker (2002)

Possible Causes of Substructure

- Irregular structures can arise from regular causes (cont.):
  – Branch formation at ultraharmonic resonances (Shu, Milione, & Roberts 1973; hereafter SMR)
  – Branch, spur, & feather formation as result of nonlinear dynamics (non-magnetic simulation: Chakrabarti, Laughlin, & Shu 2003; hereafter CLS).
- Speculation: flocculence as chaos induced by overlapping ultraharmonic resonances (CLS).

Ultraharmonic Resonances

- Slightly nonlinear response (SMR):

Lindblad (linear response)
Nonlinear response

$$\frac{m(\Omega_p - \Omega)}{\kappa} \equiv \nu = \pm\left(\frac{1}{n^2} + x\right)^{1/2}, \quad n = 1, 2, 3, \ldots$$

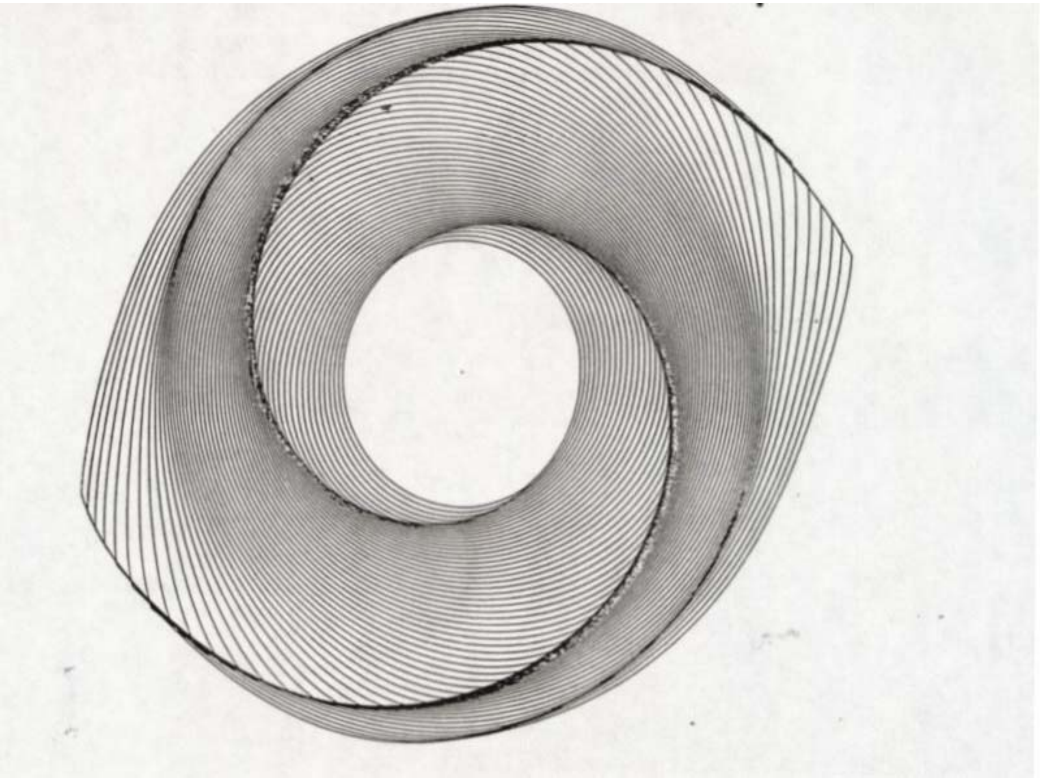
Base flow is sonic at $n = \infty$.

where $x \equiv k^2 c_g{}^2 / \kappa^2$ and linear forcing (single m).

Major branching at n = 2 (so-called 4:1 resonance if m = 2 because only mn = 4 enters if x = 0).

- Nonlinear forcing (CLS): $m \rightarrow mj$, j = 1, 2, 3, …
- Observed infrared spirals are periodic but nonsinusoidal (fractional surface-density amplitudes are not small). Nevertheless ratio of spiral field to axisymmetric field F may be small because rigid dark-matter halo helps to support axisymmetric field.

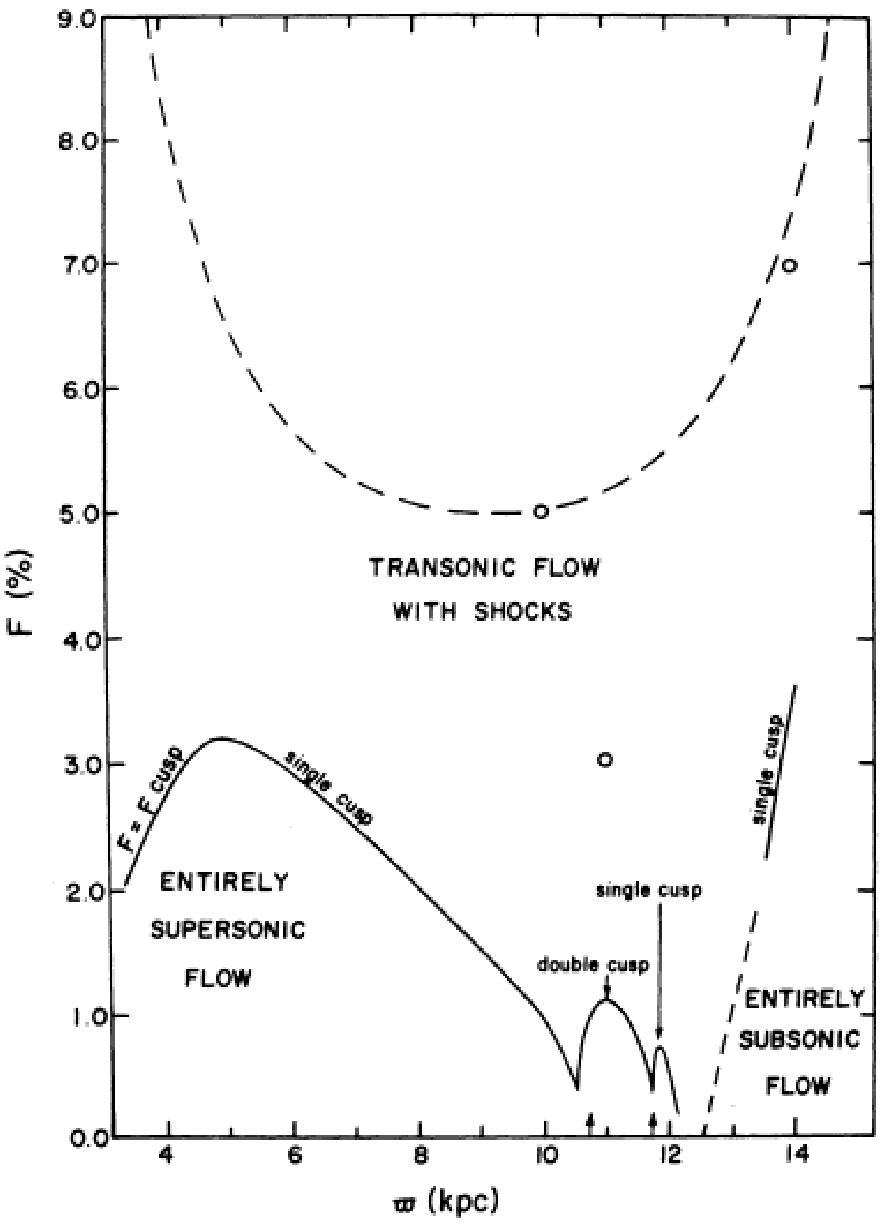
Branching at n = 2 Ultraharmonic



Model of M81 by Visser (1980)
using WKBJ steady-flow code of SMR
which ignores self-gravity of gas.

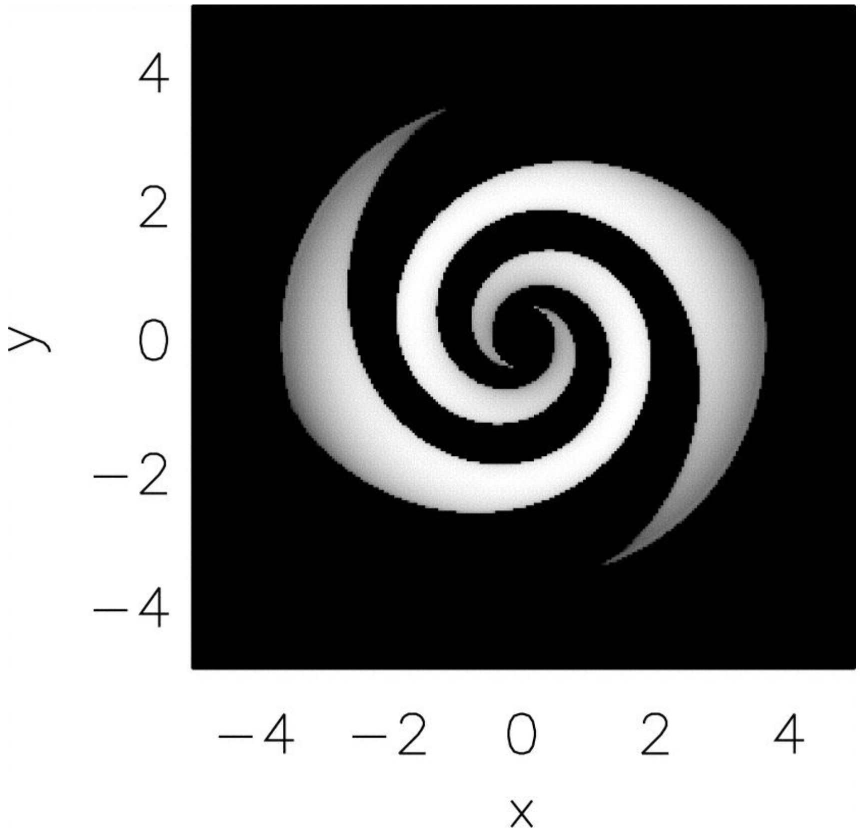
Resonances & Chaos

- Nonlinear saturation by alignment or anti-alignment of response to forcing in case of one resonance (e.g., X1 and X2 orbits in case of bars).
- Nonlinear resonances have finite width even in the absence of dissipation.
- General impossibility of alignment in two or more different directions if there are overlapping resonances.
- Result is chaos ("go crazy if have two bosses").

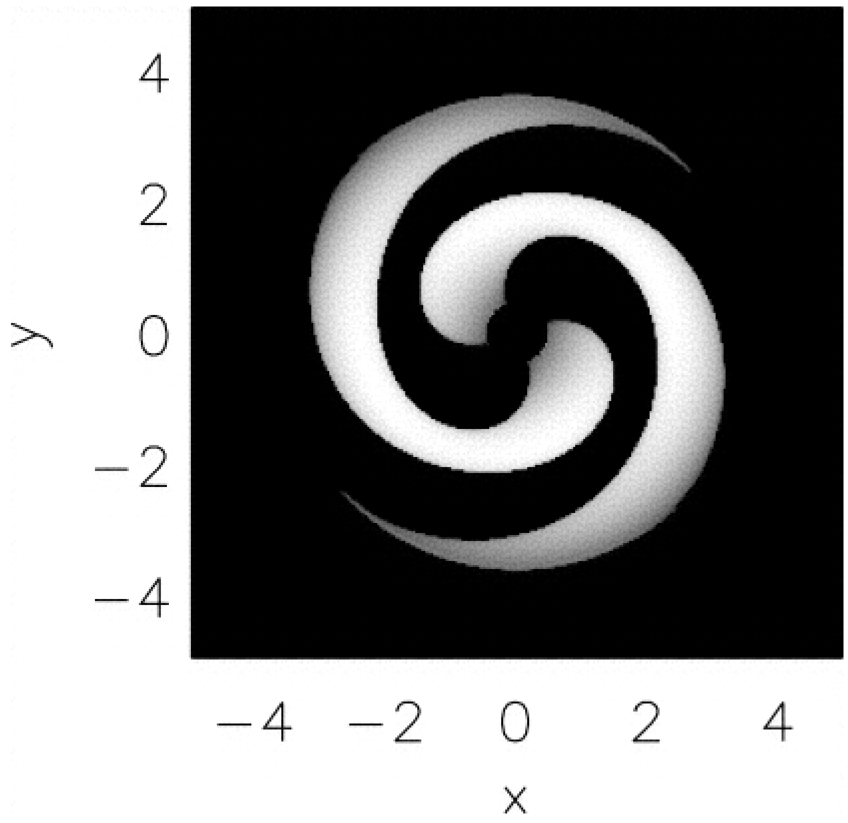


Shu, Milione, & Roberts (1973)

Whole-Disk Simulations with Background Stellar Spiral Planforms



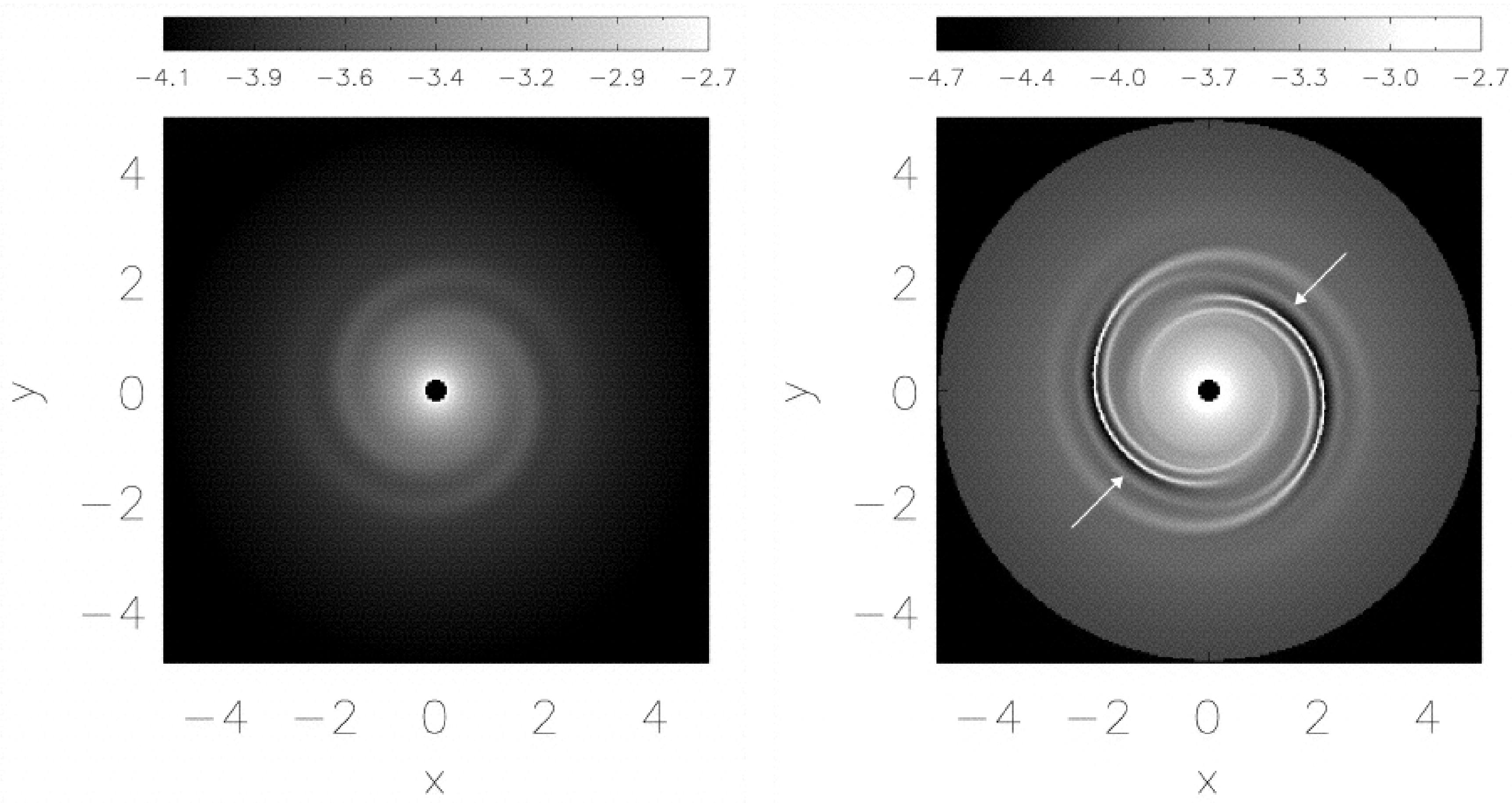
Tapered logarithmic spiral



Nonlinear long SDW

(Shu, Yuan, & Lissauer 1985)

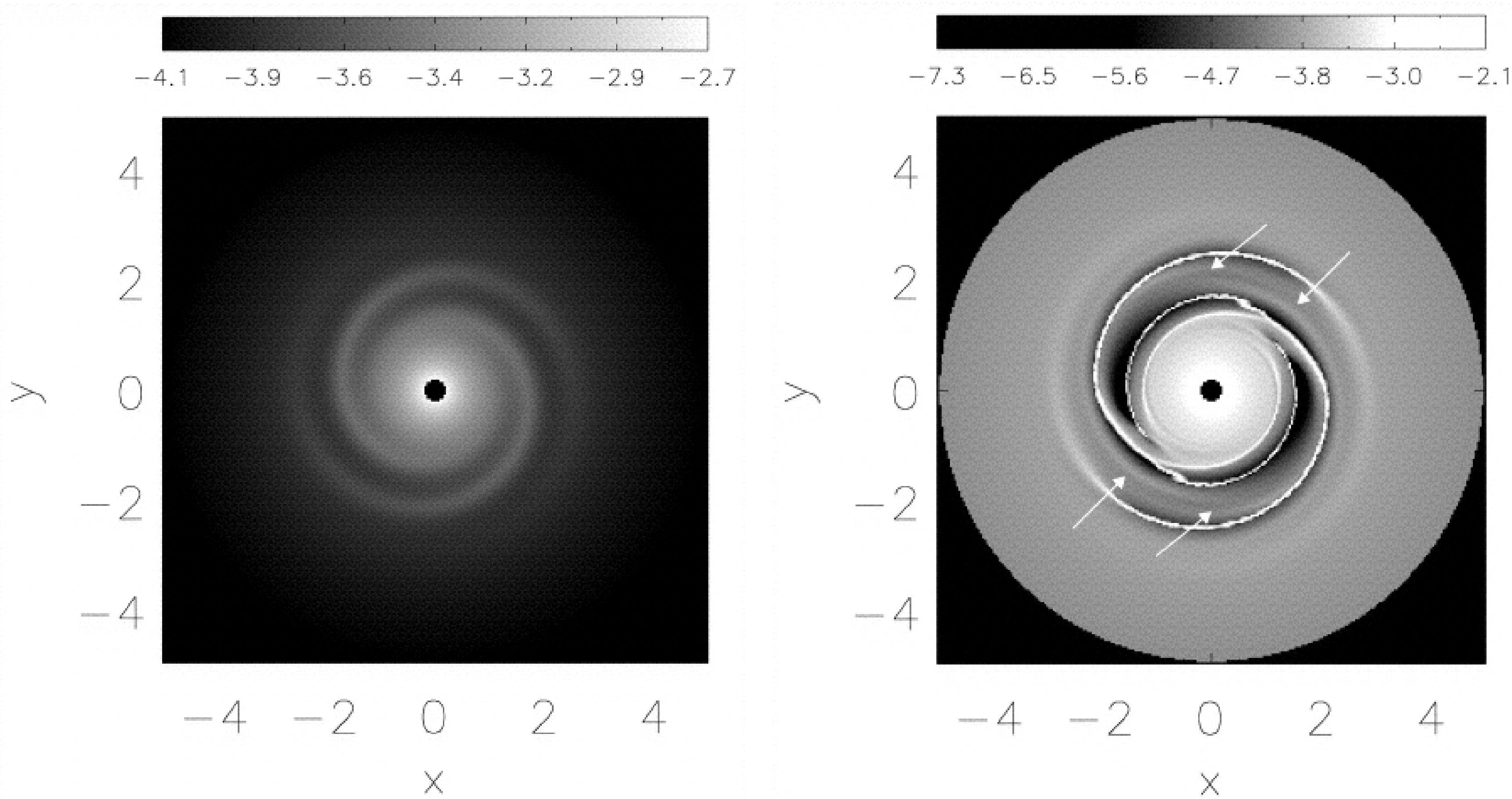
$Q = \kappa\, c_g / \pi G \Sigma_g = 1.3$, f=0.1, F= 2.5%, logarithmic spiral bkgd



95 Myr Rotation period at radius = 1 is 250 Myr 477 Myr

ILR = 0.33, CR = 1.14, OLR = 1.93

Q =1.3, f= 0.1, F = 5%, log

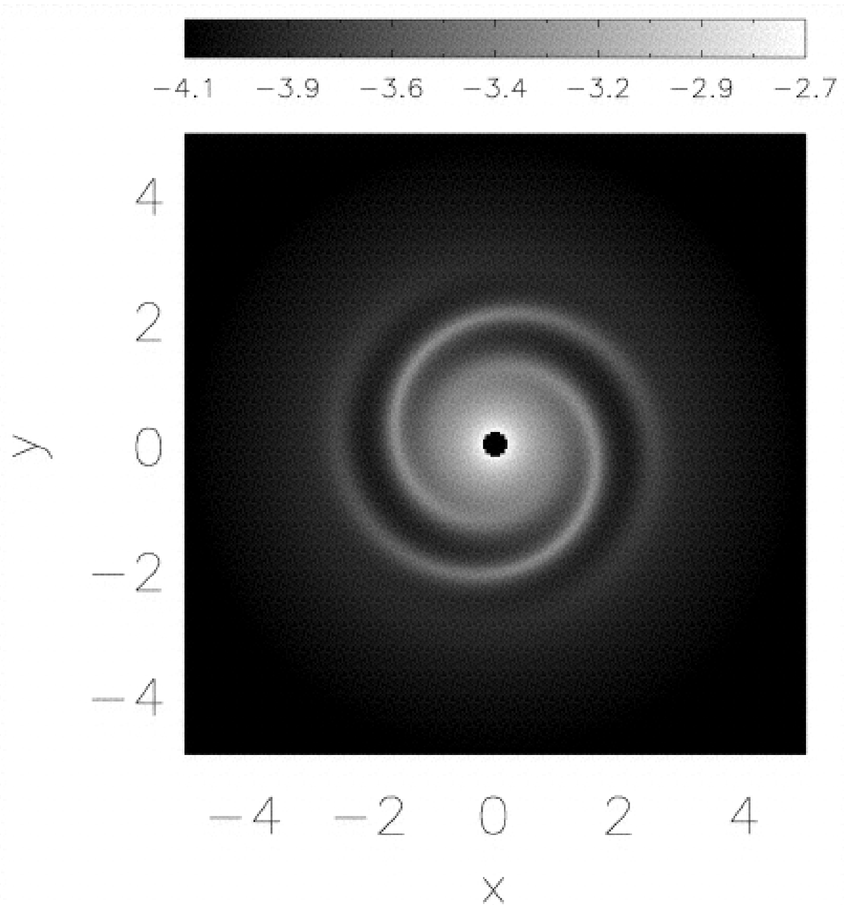


95 Myr

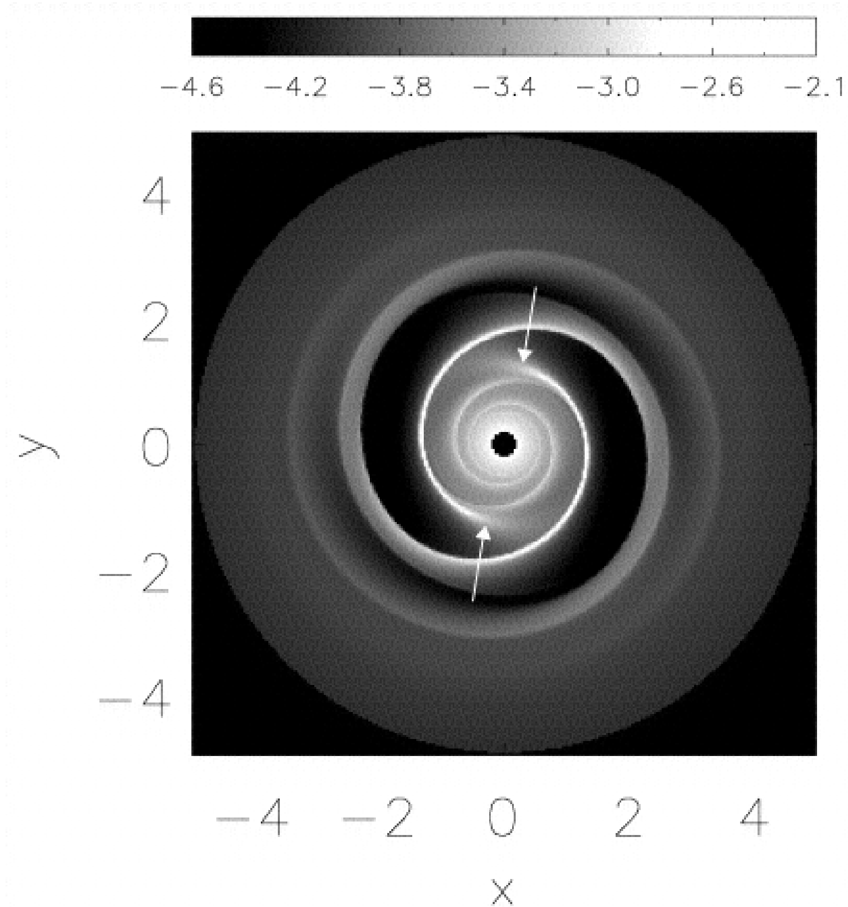
477 Myr

ILR = 0.33, CR = 1.14, OLR =1.93

Q=2.48, f=0.1, F=15%, log



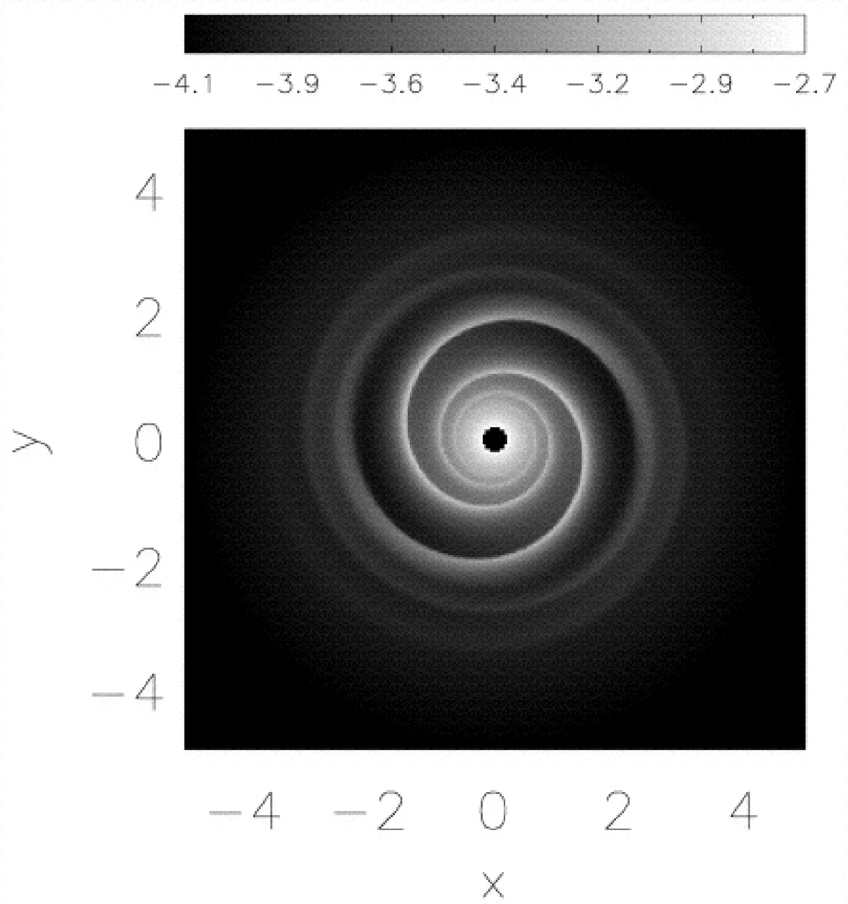
95 Myr



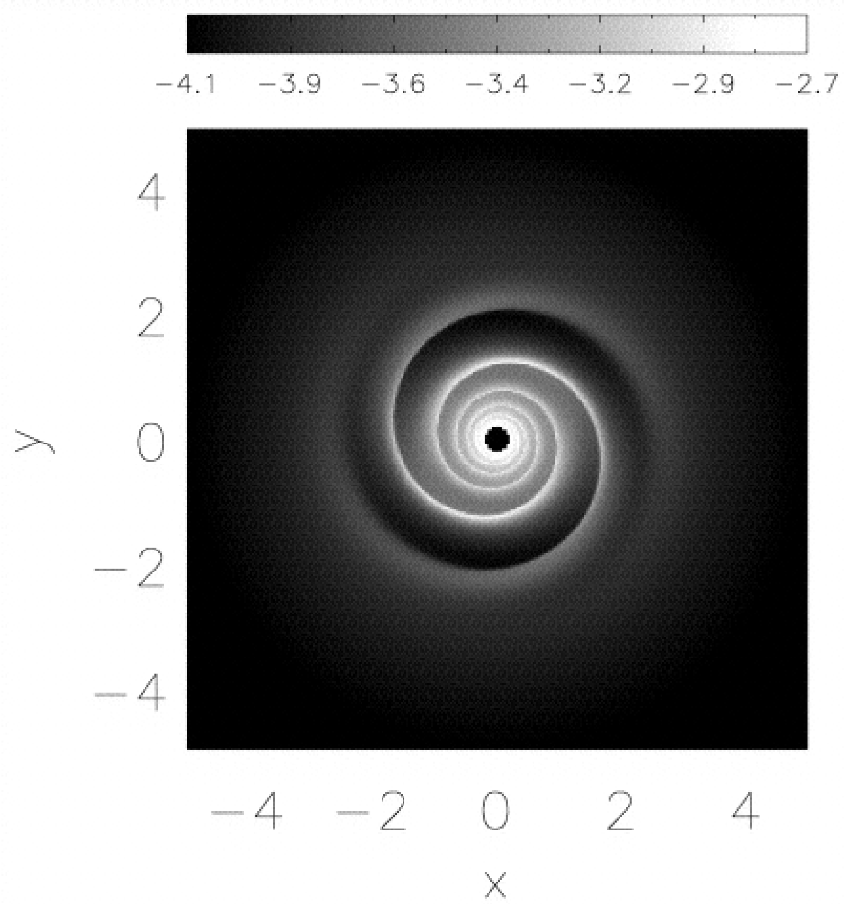
477 Myr

ILR = 0.62, CR = 2.13, OLR = 3.63

Q=2.48, f=0.1, F = 3.5%, log



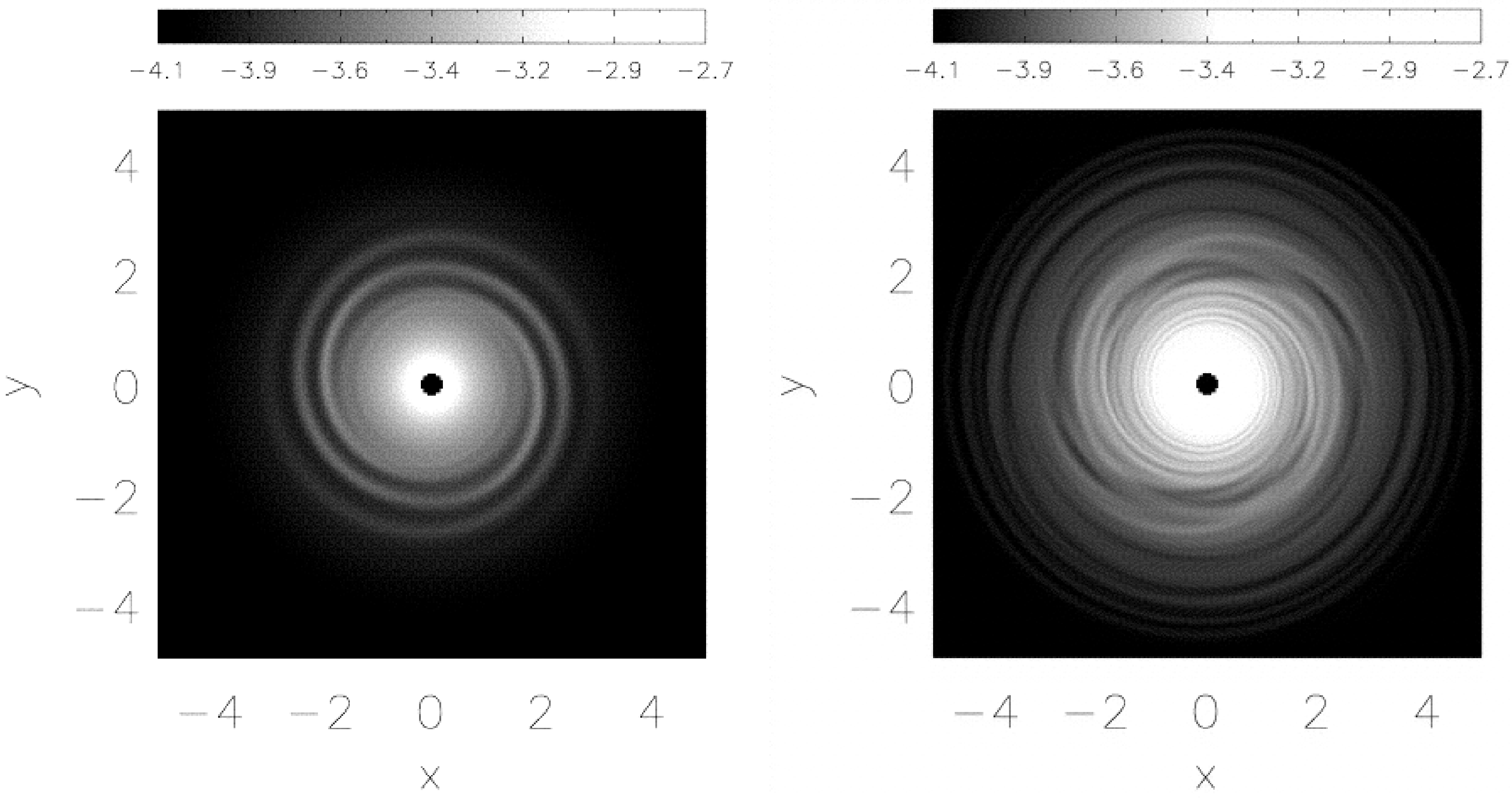
576 Myr



2870 Myr

ILR = 0.62, CR = 2.13, OLR = 3.63

Q=2.48, f=0.1, F=3.5%, SYL

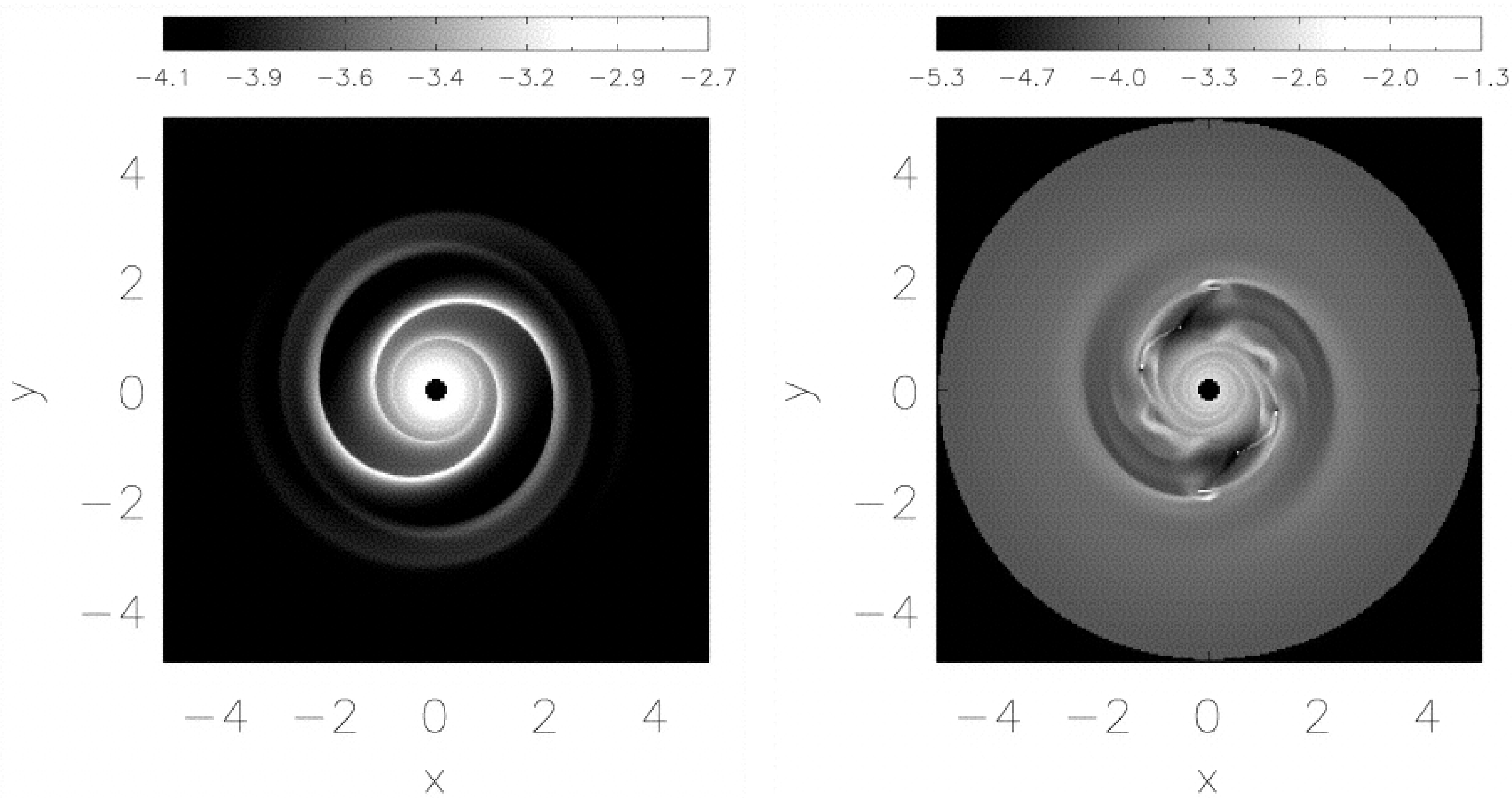


576 Myr

2870 Myr

ILR = 0.62, CR = 2.13, OLR = 3.63

Q=2.48, f=0.1, F=5%, SYL



576 Myr

2870 Myr

ILR = 0.62, CR = 2.13, OLR = 3.63

Summary

Feathers form by transient gravitational instability behind galactic shocks.
In purely hydrodynamical simulations of long term, need either high *Q* or low *F* to prevent continued collapse of spiral arms.
In reality, near free-fall collapse on large and small scales (i.e., rapid star formation) is prevented by interstellar magnetic field.

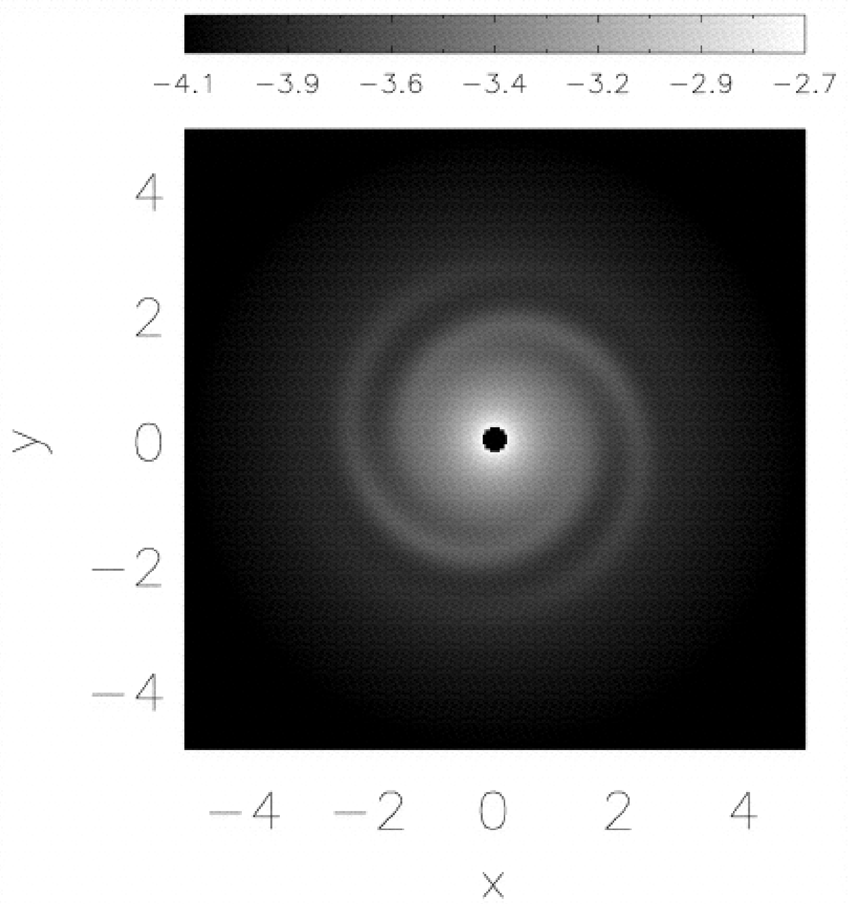
Branches form by action of ultraharmonic resonances.

Spurs can form by reflection of leading waves off sharp features produced by nonlinear dredging.

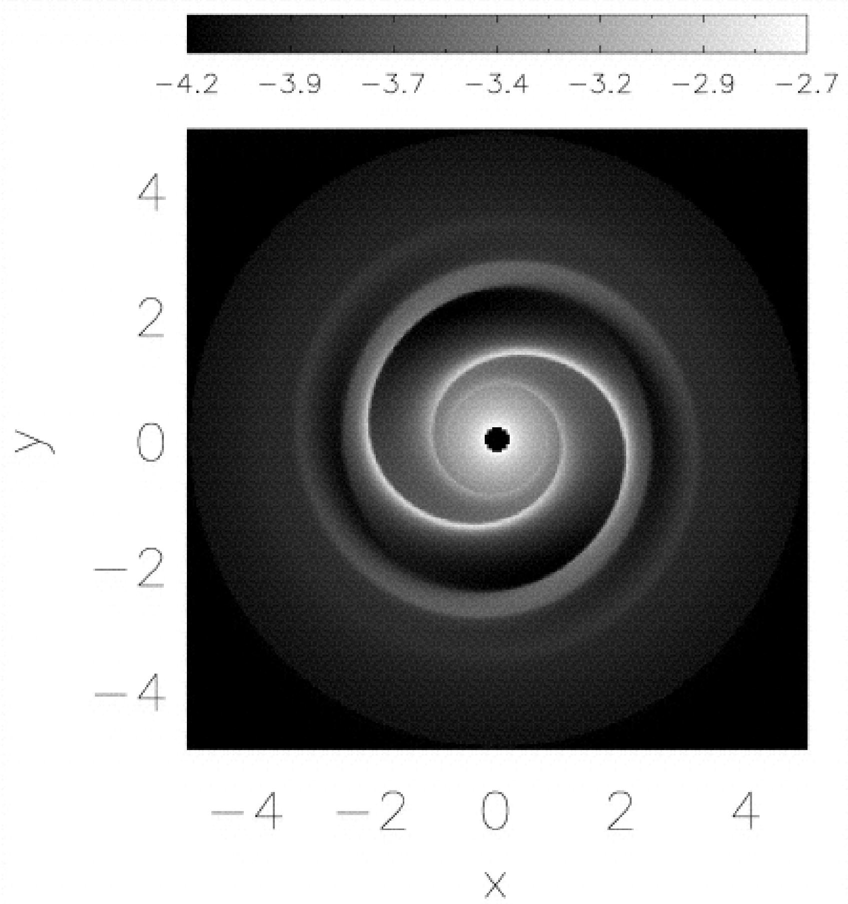
Flocculence may arise from chaos created by overlapping resonances.

Last three processes depend on hypothesis of quasi-stationary spiral structure (Lin & Shu 1964; cf. Binney & Tremaine 1987).

Q=2.48, f=0.1,F=7%, SYL



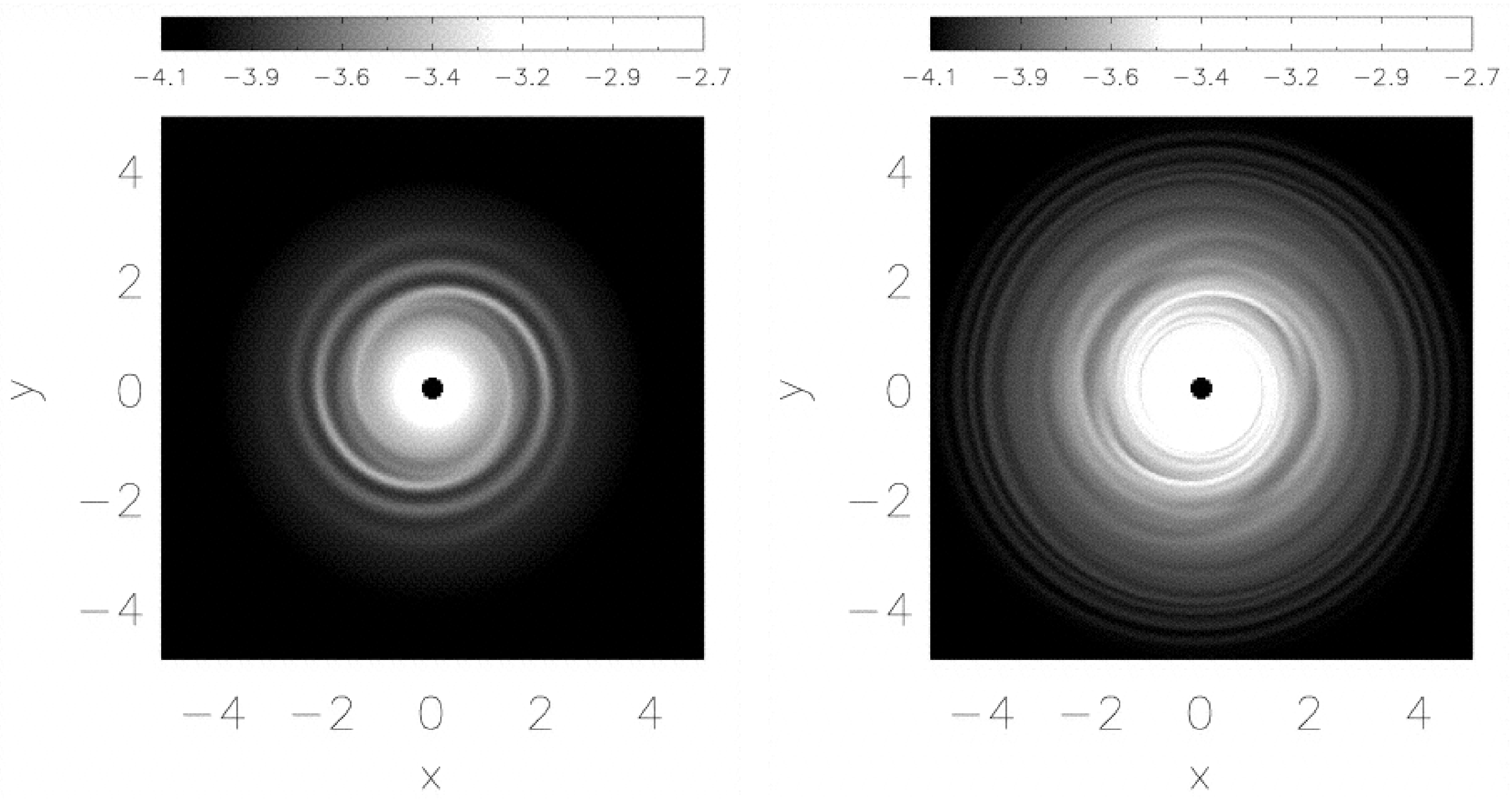
95 Myr



477 Myr

ILR = 0.62, CR = 2.13, OLR = 3.63

Q=1.3, f=0.1, F=1.3%, log



576 Myr

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