Feathering Instability in Spiral Arms

Wing-Kit Lee

University of California, San Diego

June 27, 2013

The Lin-Shu Symposium: 50 Years of Spiral Density Waves

Outline

Introduction to the galactic spiral shock

Feathering Instability (Formulation)

Some results from the parametric study

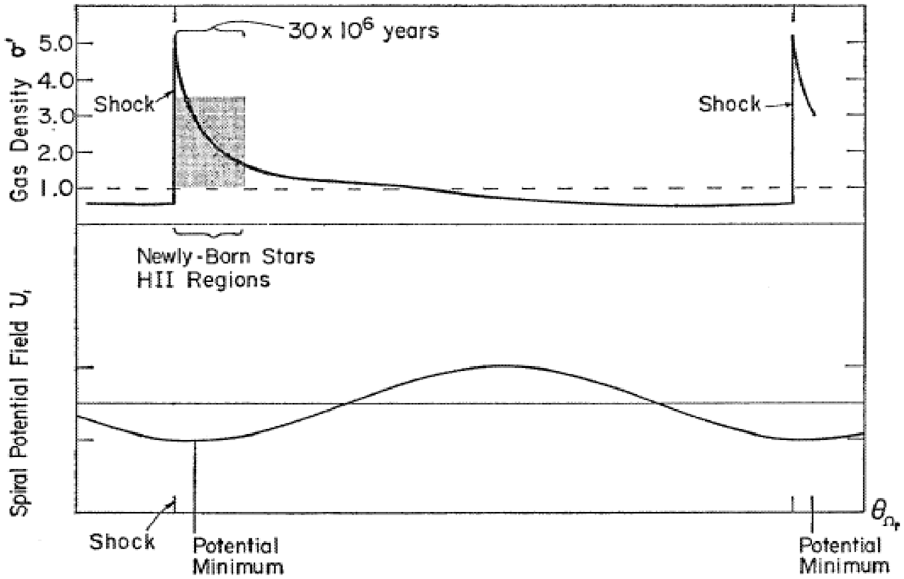
Spiral Shock

Gas flow across the spiral arm:

Acceleration due to the gravitational potential of the stars in the spiral arm

The effective sound speed of the gas ~ 10 km/s, which is comparable to the perturbation due to the stellar spiral

Spiral shock is formed

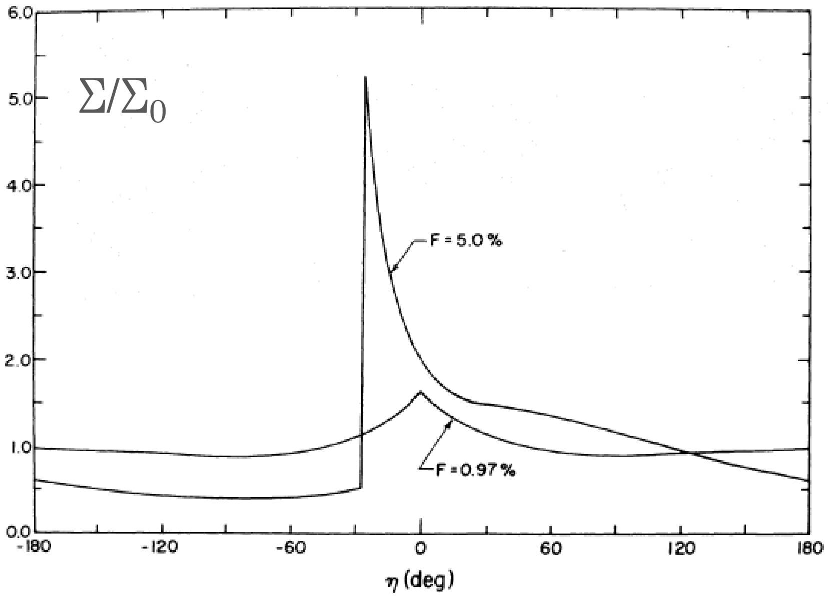


“Large-Scale Shock Formation in Spiral Galaxies and its Implications on Star Formation”, Roberts 1969

Spiral Shock

Since the velocity perturbation and the effective sound speed are comparable, the amplitude of the spiral field can be only a few percent of the axisymmetric field:

$$F = \frac{|k_\varpi|A}{\varpi\Omega^2} = 1\sim10\%$$



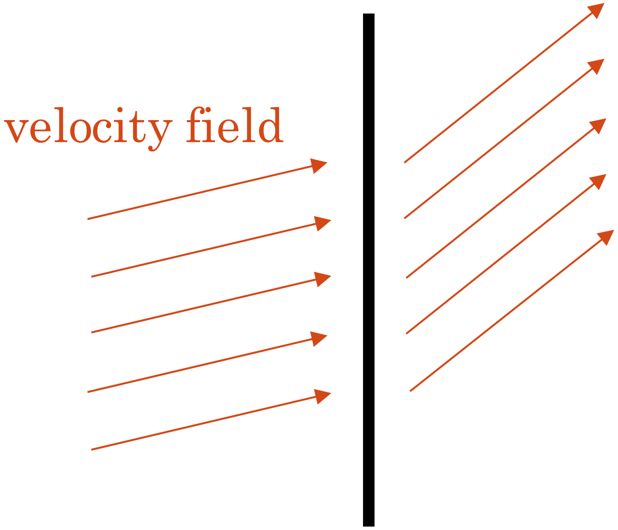
Shu, Milione and Roberts, 1973

A shock (*F*=5%) versus a cusp (*F*=0.97%)

Spiral Shock

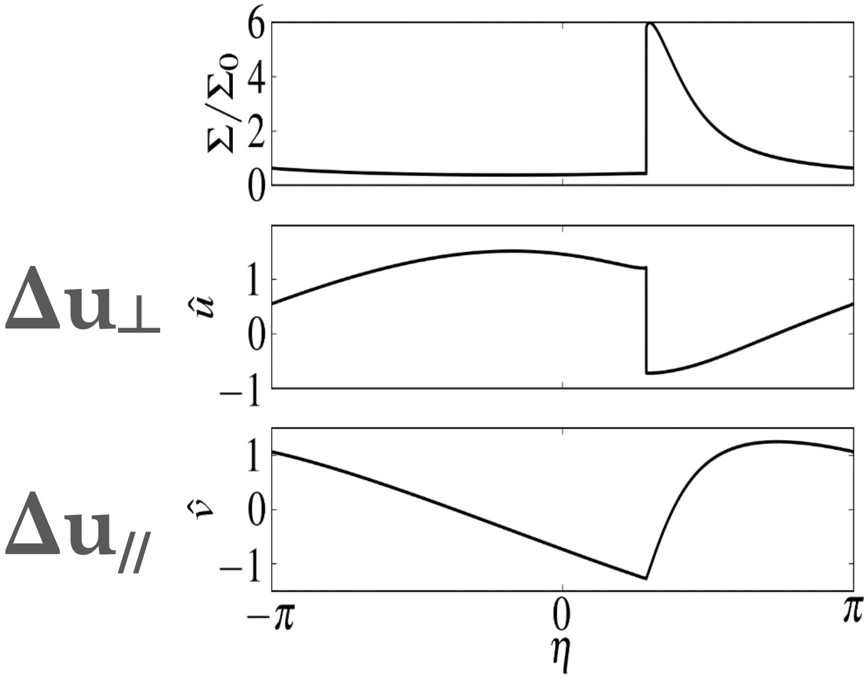
In general, the magnitude of the velocity does not change much along a streamline (dominated by the circular component).

However, the perpendicular component of the velocity changes rapidly across the spiral arm (and so changes the direction).

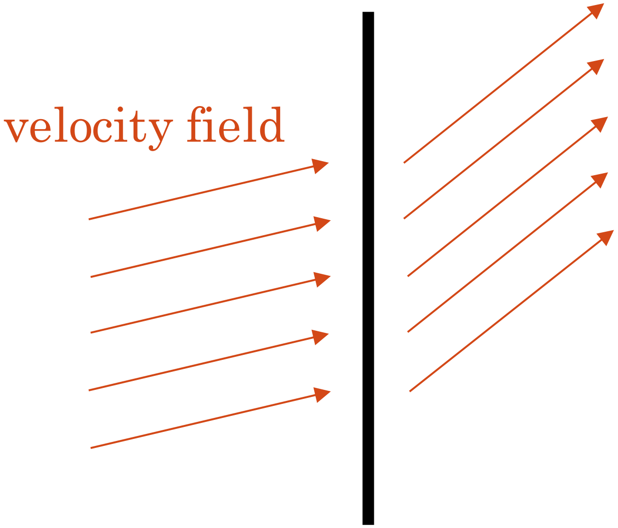


Spiral shock
(static in the pattern frame)

Spiral Shock

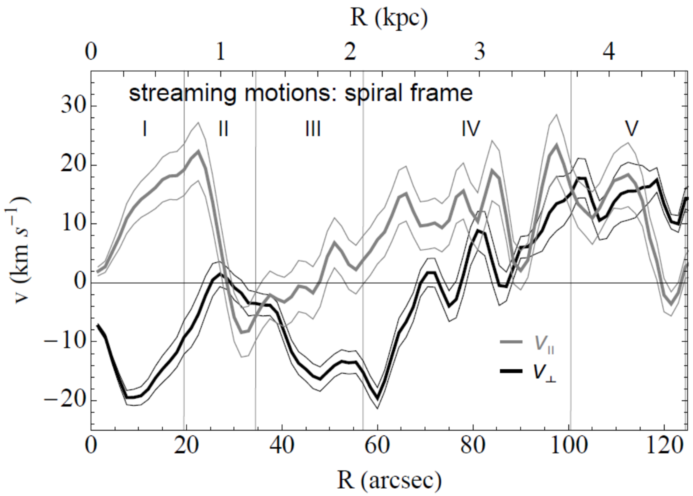


Typical profile in the direction perpendicular to the spiral arm

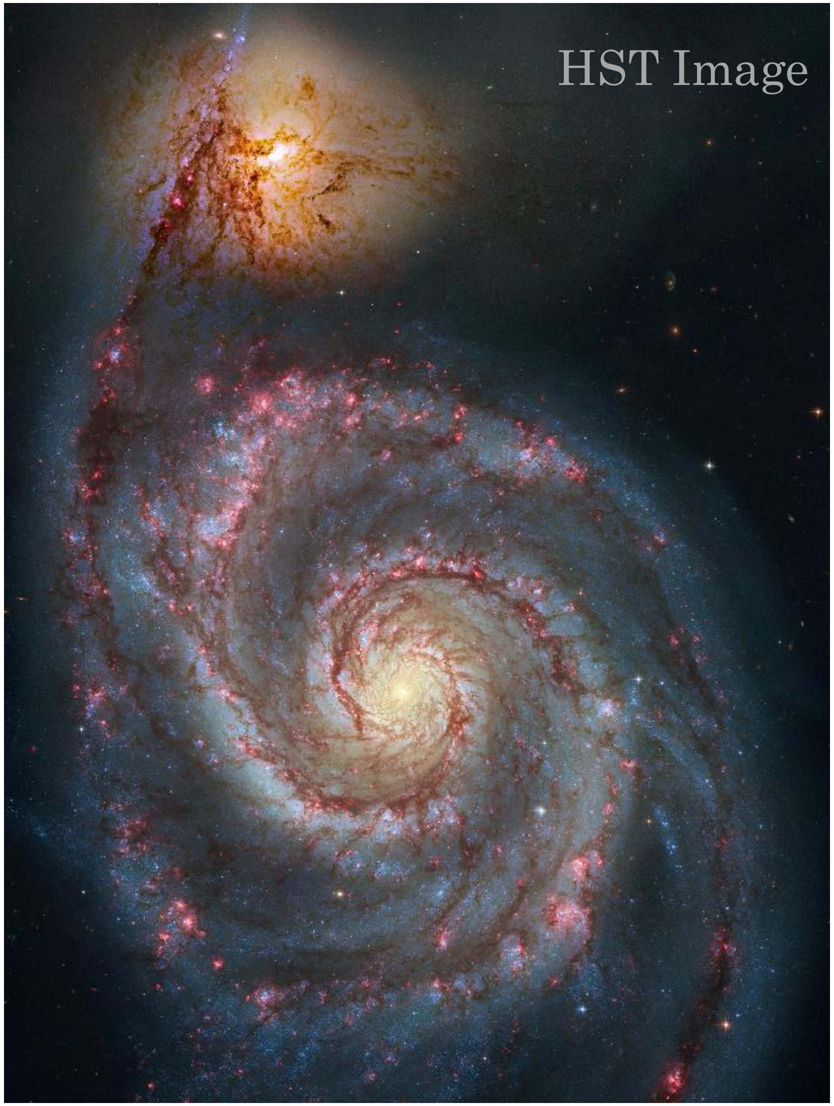


Spiral shock
(static in the pattern frame)

Spiral Shock



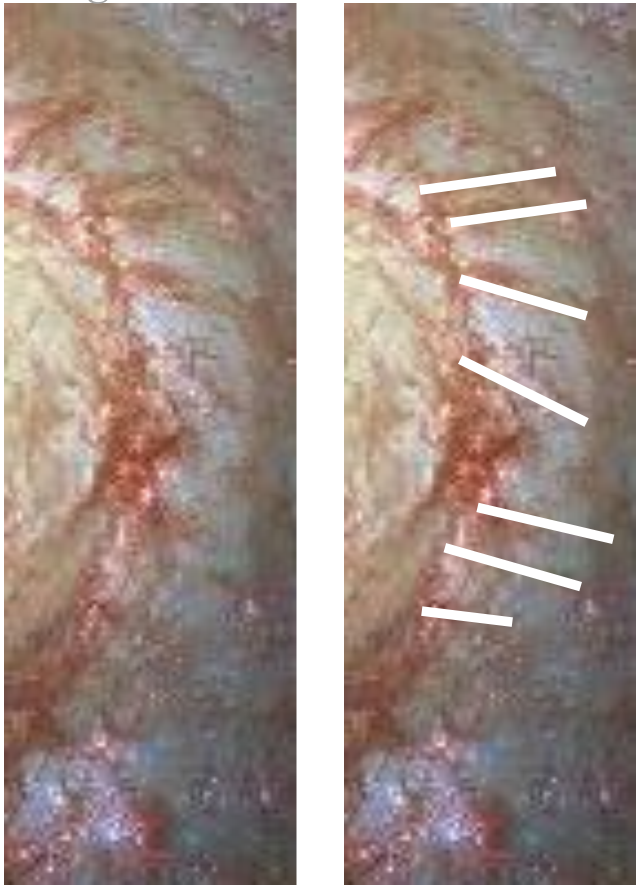
Meidt+ (2013) arxiv
1304.7910
M51, PAWS Survey


HST Image

Streaming motion (i.e., non-circular velocity) has been measured.

Galactic Feathers

HST images

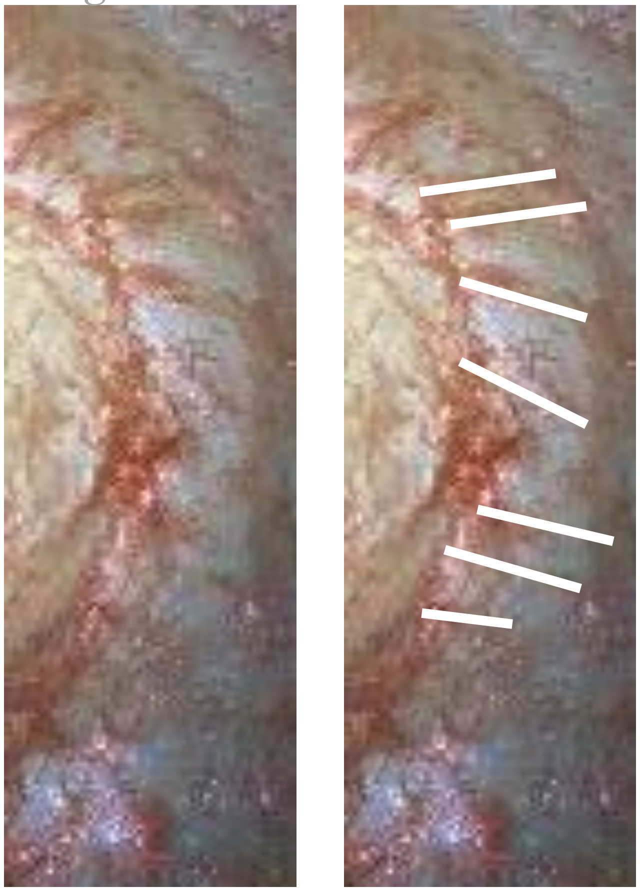


Note the dust lanes in the inter-arm regions

w/ SF, feathers not clear

Galactic Feathers

HST images



Note the dust lanes in the inter-arm regions

Feathering Instability

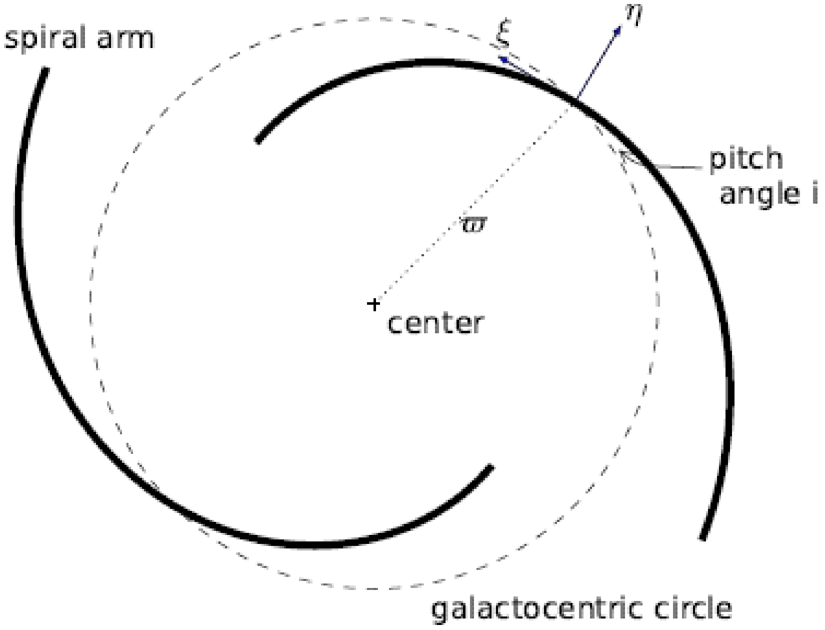
One-dimensional spiral shock as the basic state

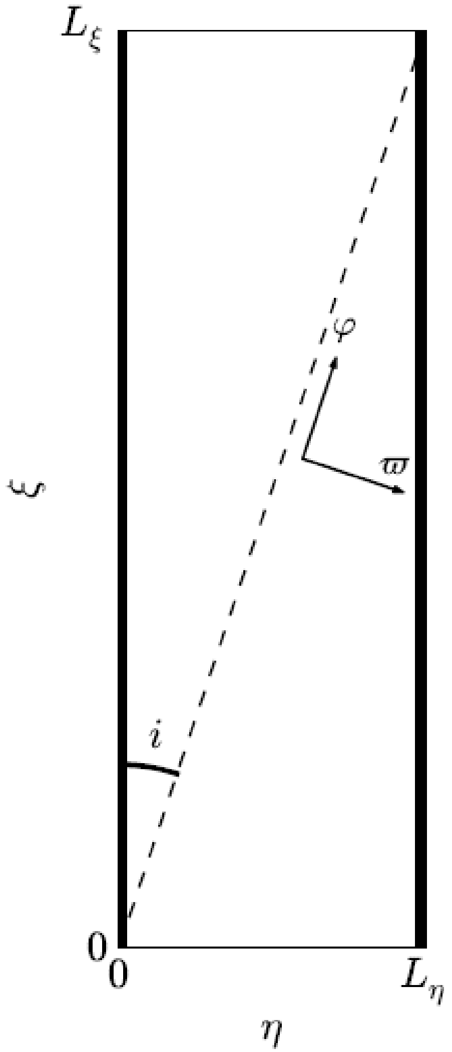
Two-dimensional, time-dependent, linear perturbation:

- Look for unstable modes

Assumptions

1. Tight-winding approximation
2. No “back-reaction”, only response of the gas to the stellar spiral
3. No (background) shear in the box (i.e., same Ω)



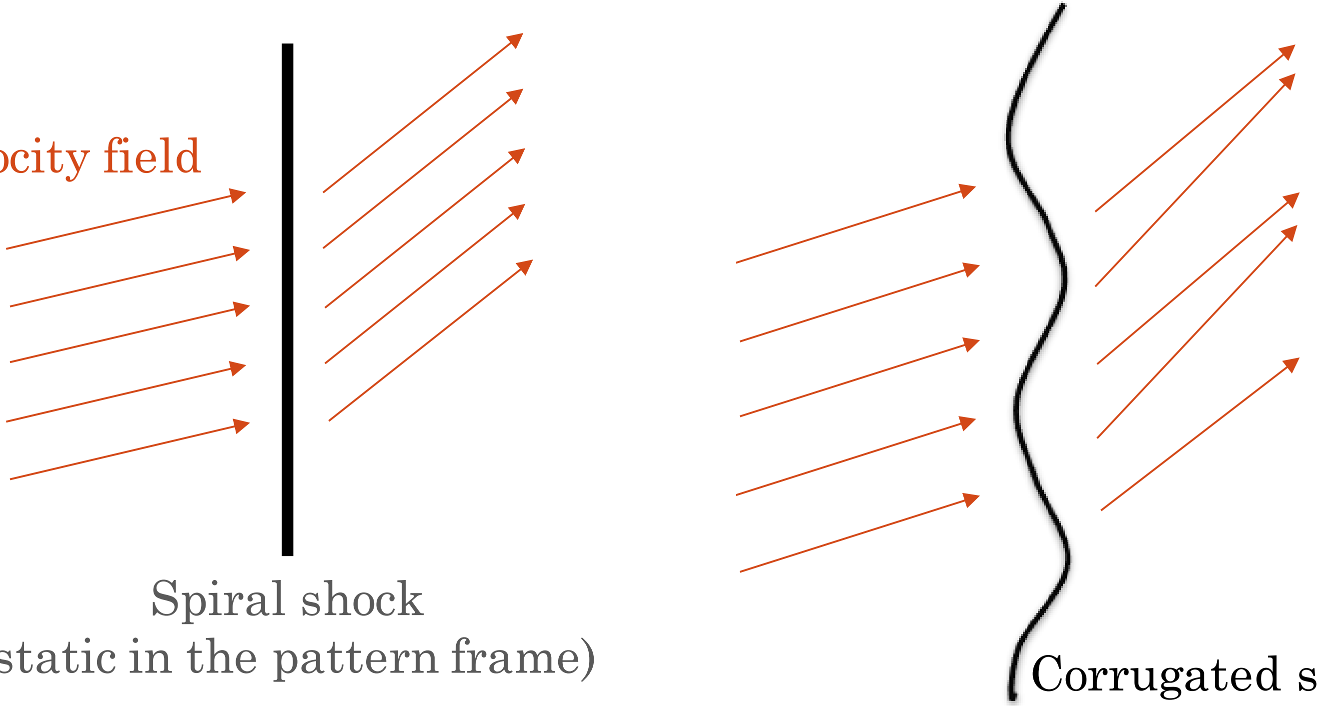


Lee & Shu 2012

Feathering Instability

1D spiral shock (in η direction) as the basic state

2D feathering perturbation(in both η and ξ directions): corrugation of the shock front; distorted post-shock flows



Spiral shock
(static in the pattern frame)

Corrugated shock front

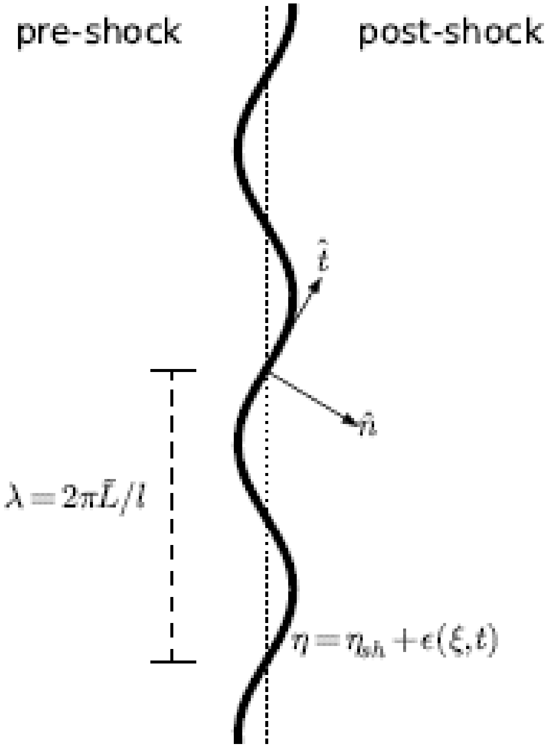
Normal mode analysis:

- Perturbation takes the form $e^{i(\omega t - \frac{l\xi}{L})}$, l/L being an effective wave-number

Six equations to solve:

- Continuity, momentum equations (2D), induction equation (2D magnetic field), Poisson equation of the gas
- Closed with an EOS: $\Pi_g \propto \ln(\frac{\Sigma}{\Sigma_0})$

Boundary conditions:



$$[\rho \delta u_\perp + u_\perp \delta \rho]_1^2 = 0, \tag{71}$$

$$\left[u_\perp^2 \delta\rho + 2\rho u_\perp \delta u_\perp + \left(\frac{\partial P}{\partial \rho} \right) \delta\rho + \frac{B_\parallel}{4\pi} \delta B_\parallel \right]_1^2 = 0, \tag{72}$$

$$[u_\perp u_\parallel \delta\rho + \rho u_\perp \delta u_\parallel + \rho u_\parallel \delta u_\perp \\ - \frac{B_\perp}{4\pi} \delta B_\parallel - \frac{B_\parallel}{4\pi} \delta B_\perp]_1^2 = 0, \tag{73}$$

$$[\delta B_\perp]_1^2 = 0, \tag{74}$$

$$\left[B_\perp \delta u_\parallel - B_\parallel \delta u_\perp + u_\parallel \delta B_\perp - u_\perp \delta B_\parallel \right]_1^2 = 0, \tag{75}$$

Lee & Shu, ApJ (2012)

Dimensionless Parameters

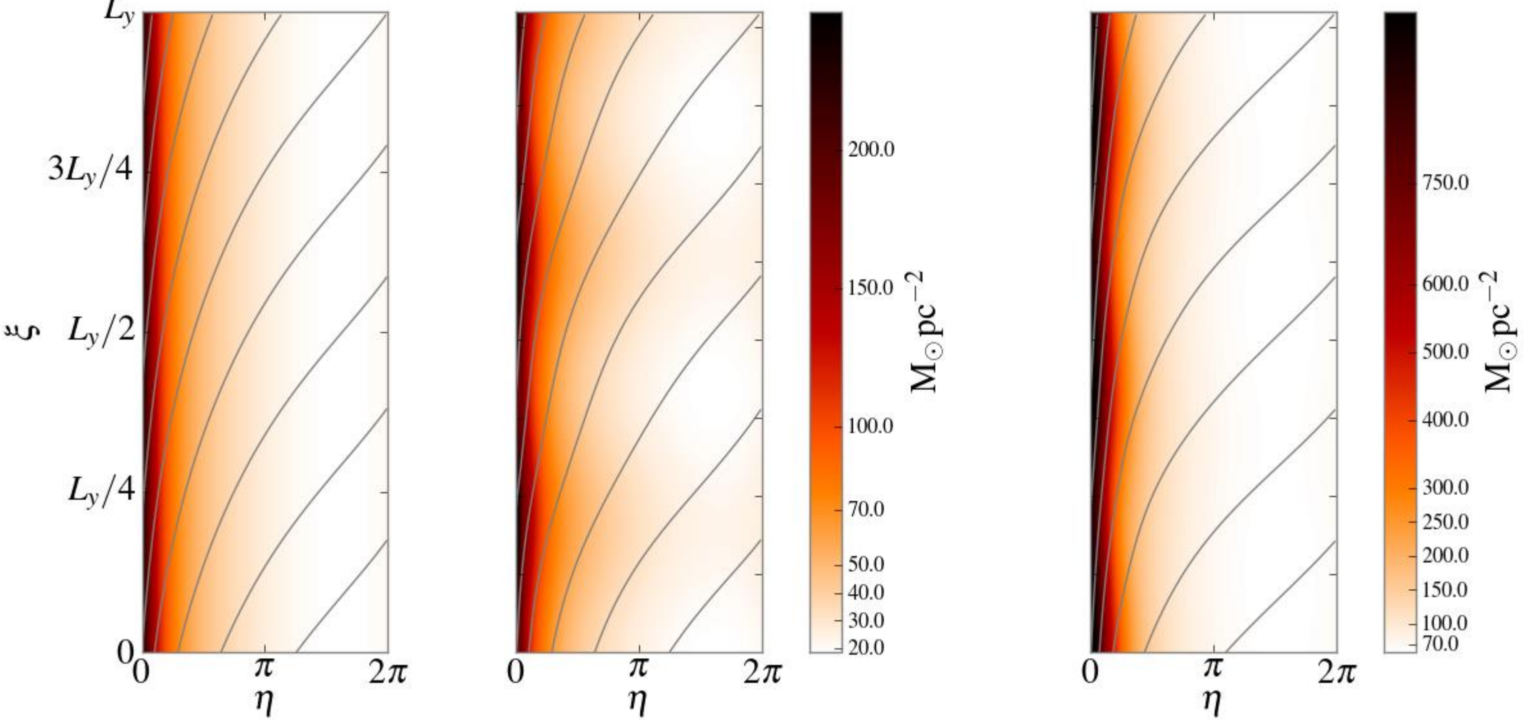
Basic state:

- Circular Flow of the galaxy
- Stellar Spiral Potential
- Turbulence/Thermal Pressure
- Magnetic Field
- Self-gravity of the gas

Perturbation:

- Pitch angle
- Ratio of the rotational and epicyclic frequency

Lee (in prep.)



Background with self-gravity

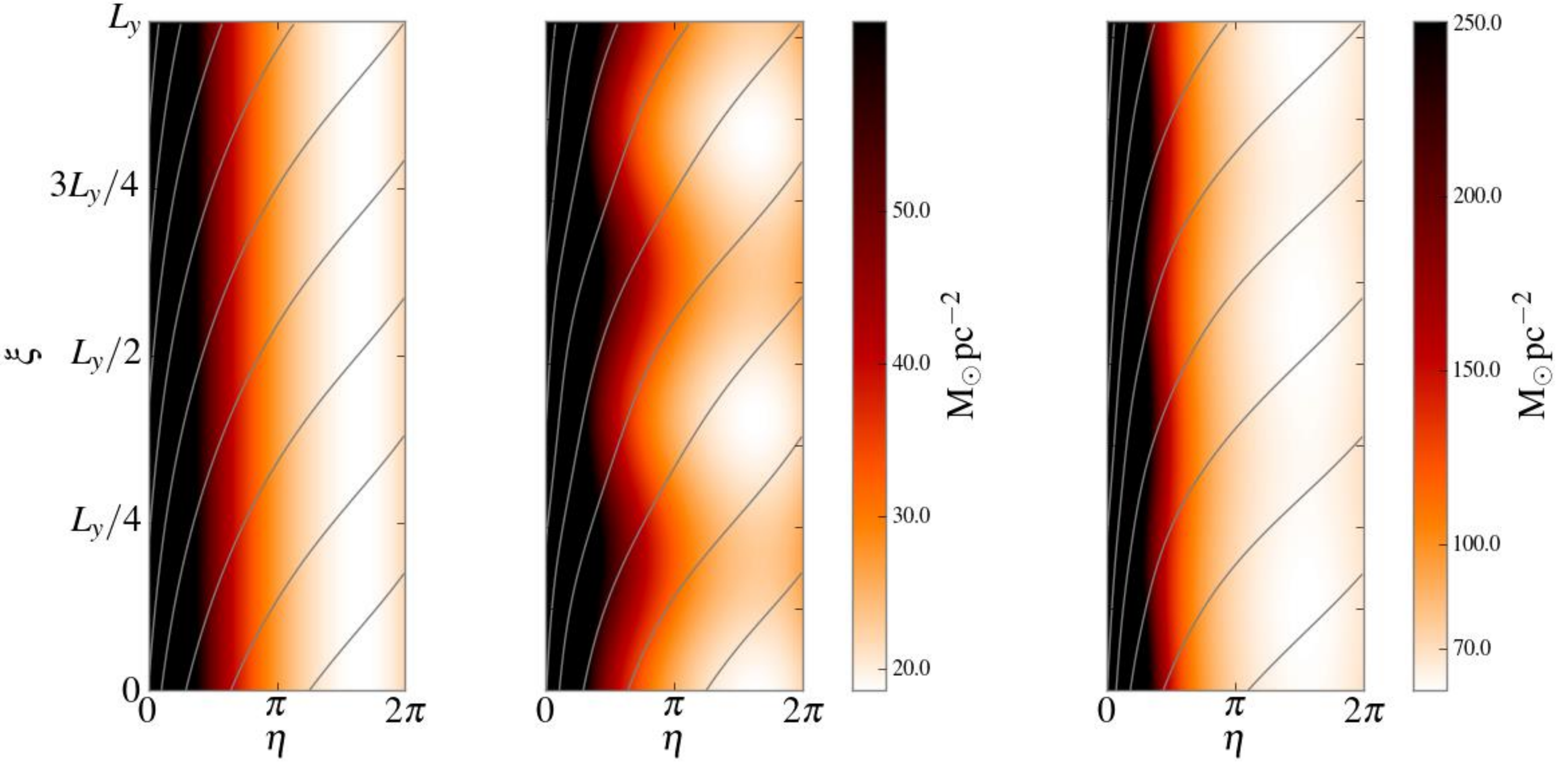
With feathering perturbation

With feathering perturbation; stronger self-gravity

Spiral shocks at the y axes
Color: gas surface density
Gray contours: magnetic field lines
l/L ~ 1 (eigenfunctions)

Black: surface density > ¼ of the peak

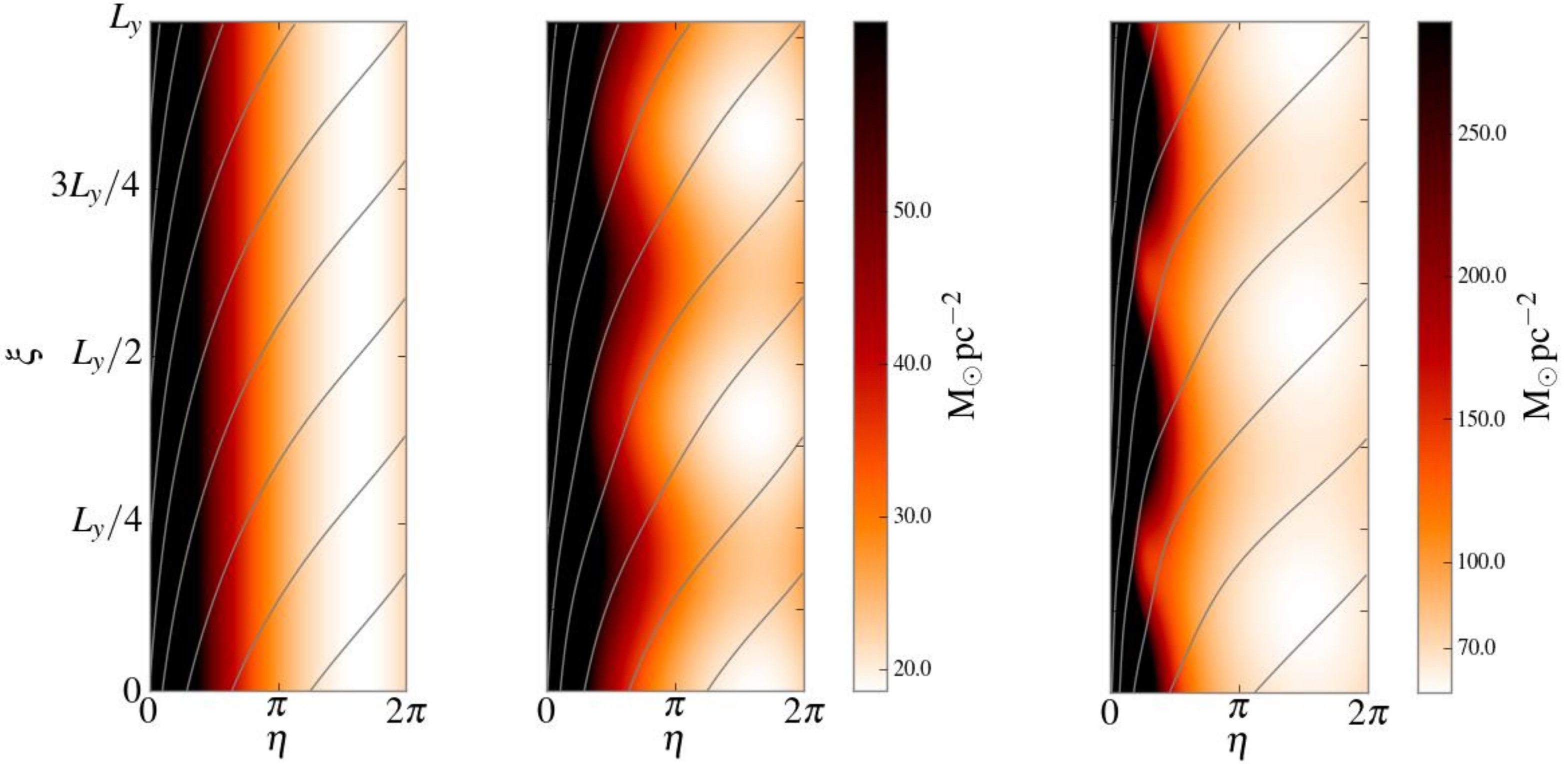
Lee (in prep.)



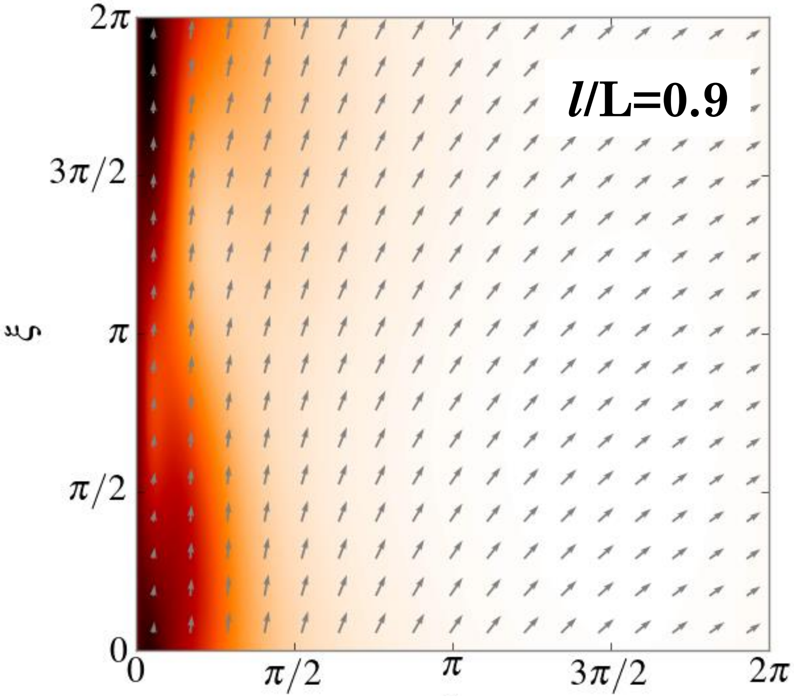
Perturbations for the two cases have the same “amplitude”. It looks much weaker on the right for the stronger background shock.

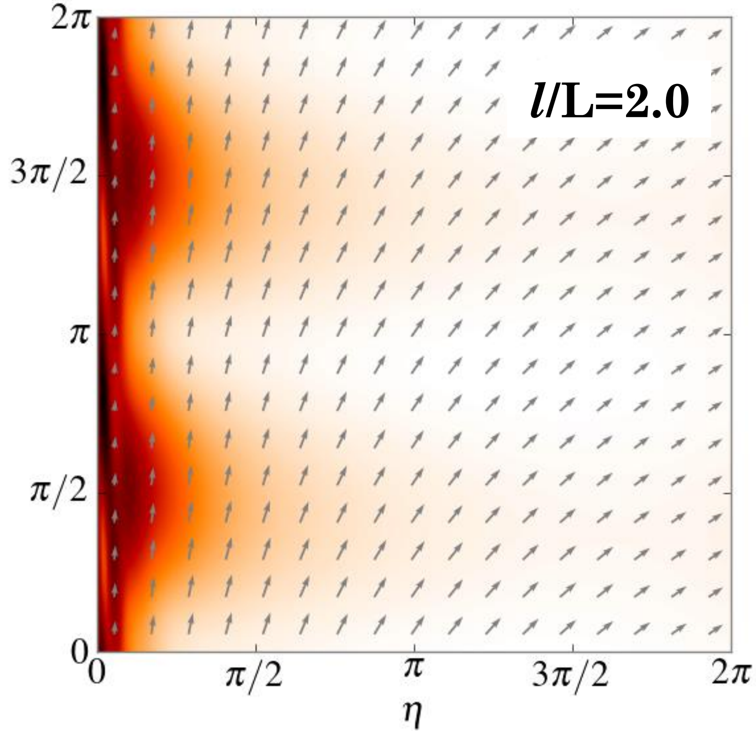
Black: surface density > ¼ of the peak

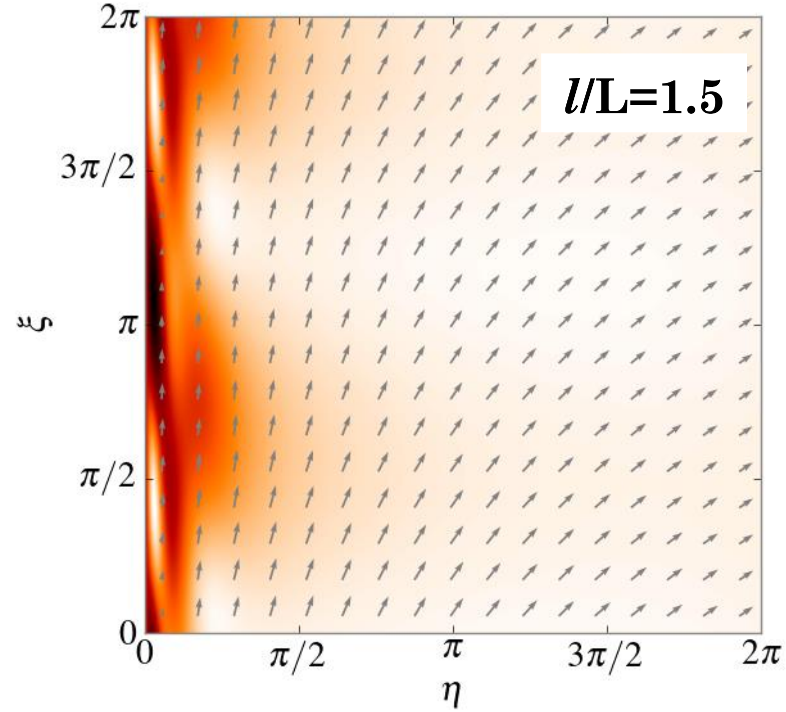
Lee (in prep.)



Perturbation on the right is now 4 times of the original plot.







Y-axis ~ 1/3 L_ξ

Density fluctuates rapidly near the shock with increasing *l*.

Velocity perturbations are small

Not all perturbations look like feathers

Lee (in prep.)

Parameter Study

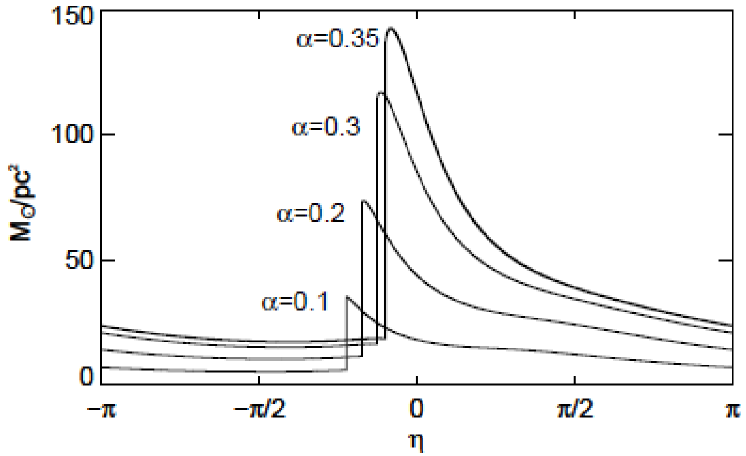
Lots of parameters

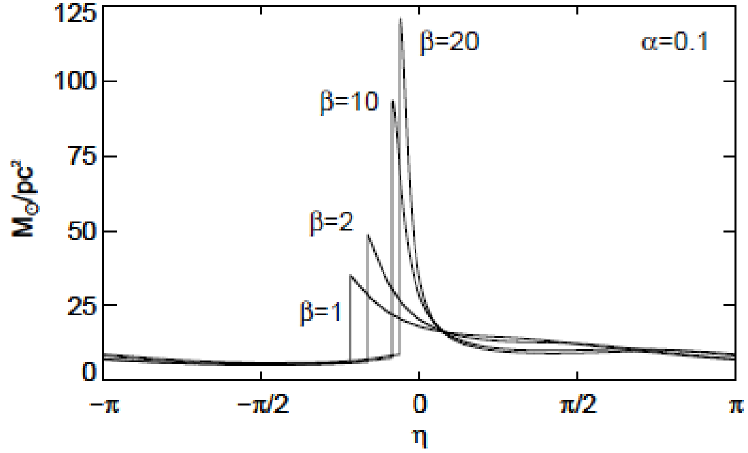
Lots of measurable quantities (e.g., shock location, width of spiral arm, etc.)

Goal:

Have a general idea on how the solutions (both spiral shock and feathering perturbation) depend on parameters

Spiral Shock



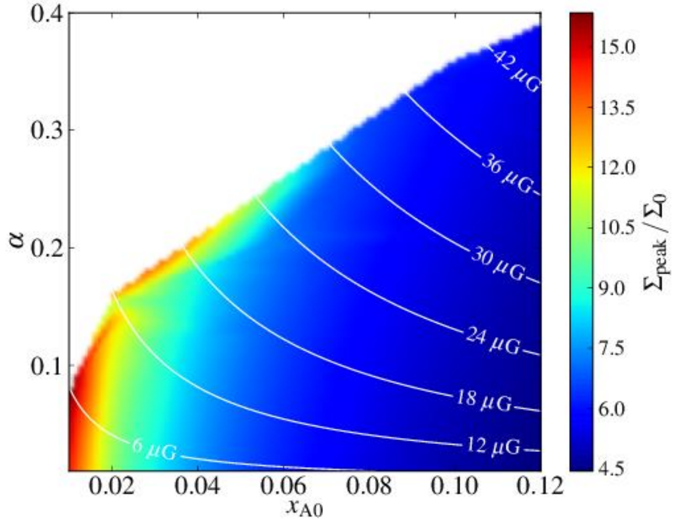


α : dimensionless measure of the self-gravity

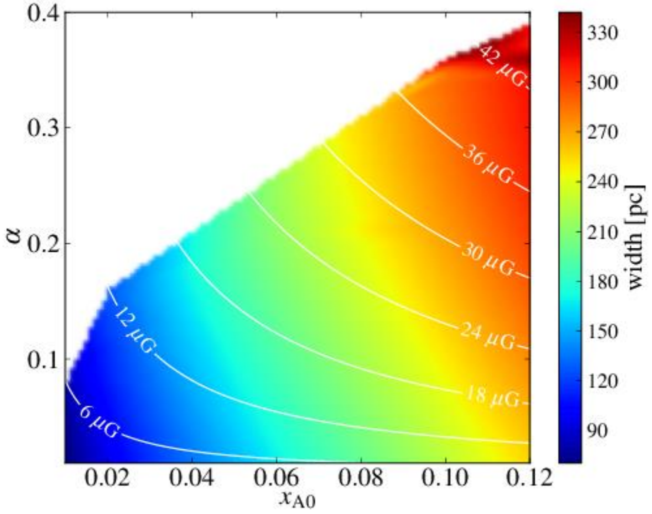
β : ratio of turbulence pressure to magnetic pressure

Lee & Shu, ApJ (2012)

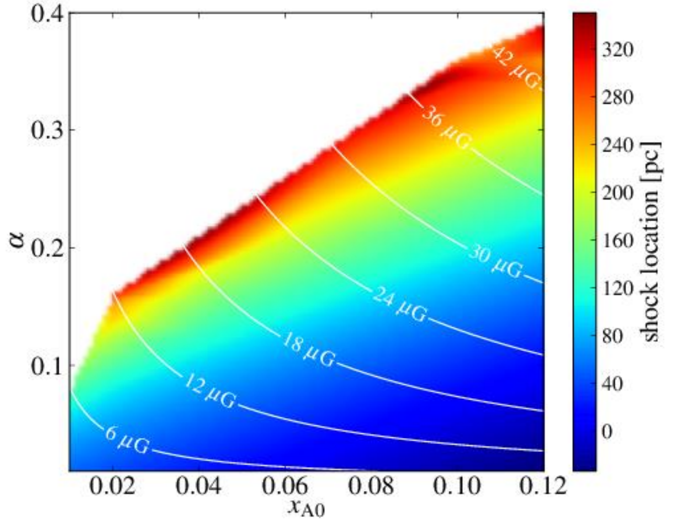
Lee (in prep.)



Relative Peak Surface Density of the gas



Width of the density enhancement



x axes: (dimensionless) square of Alfven's speed

y axes: (dimensionless) measure of self-gravity

Shock location relative to the minimum of stellar spiral potential

Conclusion and Summary

The “modern” spiral shock calculation includes self-gravity, magnetic field. These were done separately (Yuan+ 1970, Lubow+ 1986). Modern observations allow us to revisit the whole problem again.

The feathering instability is able to produce “feathers” along the spiral arm with its unstable mode. While not all perturbations lead to feather-like (density) structure, this also encourages observers to characterize and identify feathers and other substructure.

Normal-mode analysis allows simple and straightforward understanding to the physics for instability (even though in this problem, there is no simple form of "dispersion relation").

Thank you