# NUMERICAL SIMULATIONS OF DISK GALAXIES

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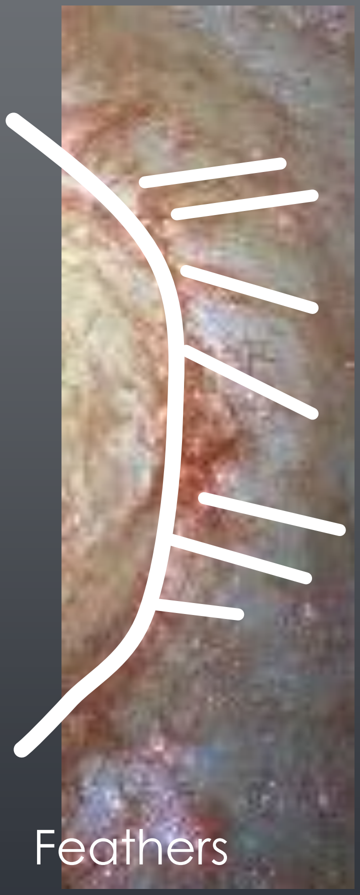
@EAYAM FEB 11, 2015

# OUTLINE

- Background:
  - Spiral shock and its substructure in the spiral arm (galactic feathers)
- Local Simulations of A Spiral Arm
  - Setup
  - Feathering Instability vs Wiggle Instability
- Global Model and Magnetic Fields

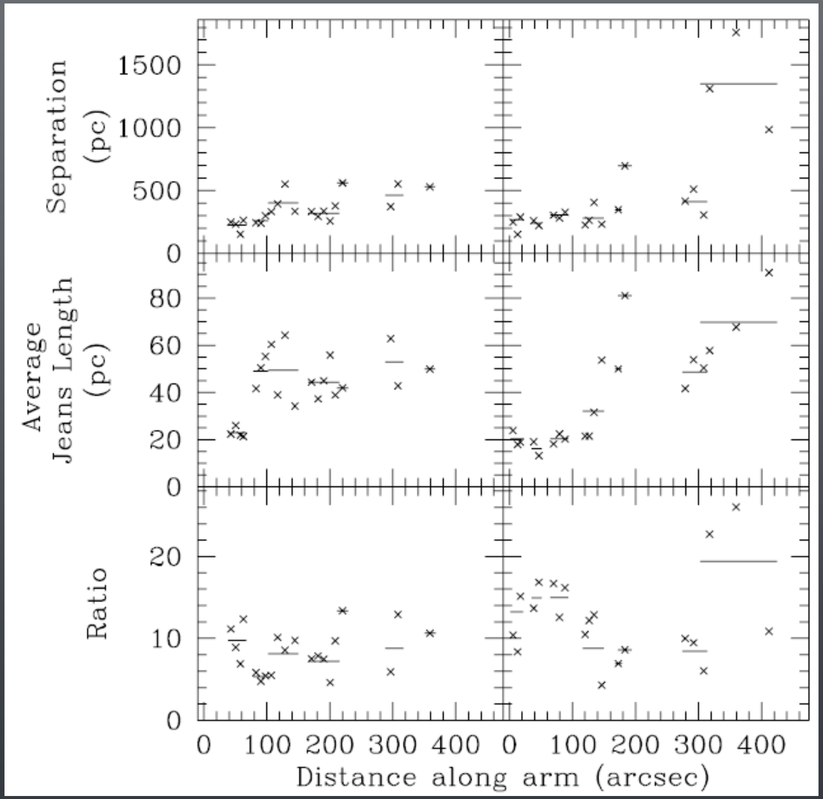
# SPIRAL ARM SUBSTRUCTURE




HST Image of M51

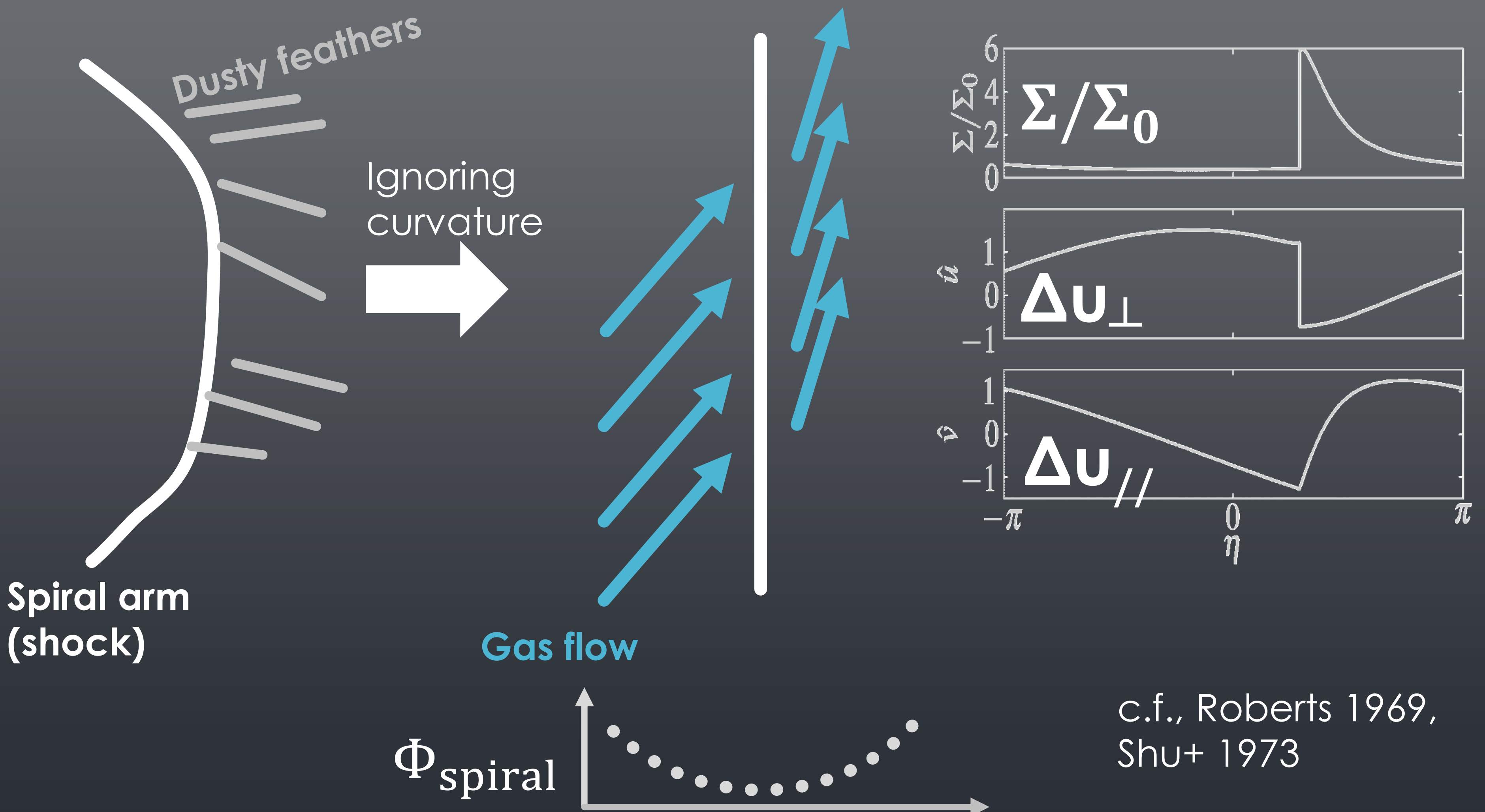

w/ star formation, feathers not clear

Spacing measurement




Reference: La Vigne+ 2006
Spacing ~ 500 pc

# GASEOUS SHOCK ACROSS THE SPIRAL ARM (THEORY)



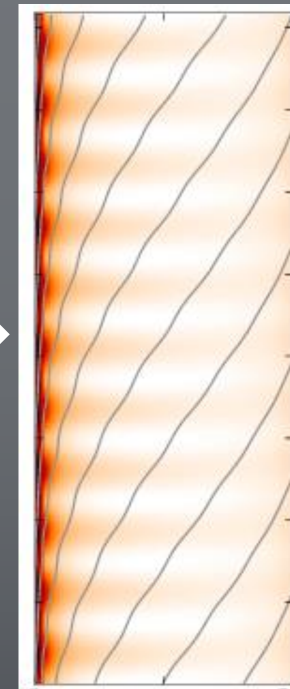

c.f., Roberts 1969, Shu+ 1973

# SPIRAL ARM SUBSTRUCTURE

perturbations

Gas flow

Stability analysis

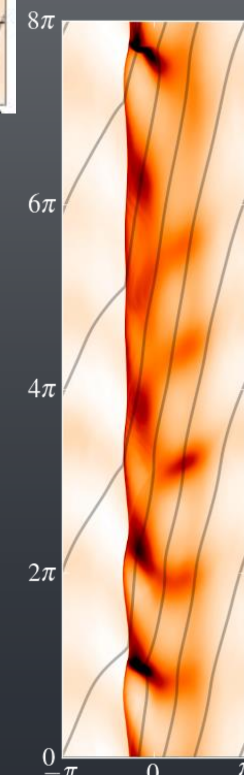


Normal-mode

(Lee 2014)

Numerical simulations

(e.g., Kim+'02,'06)

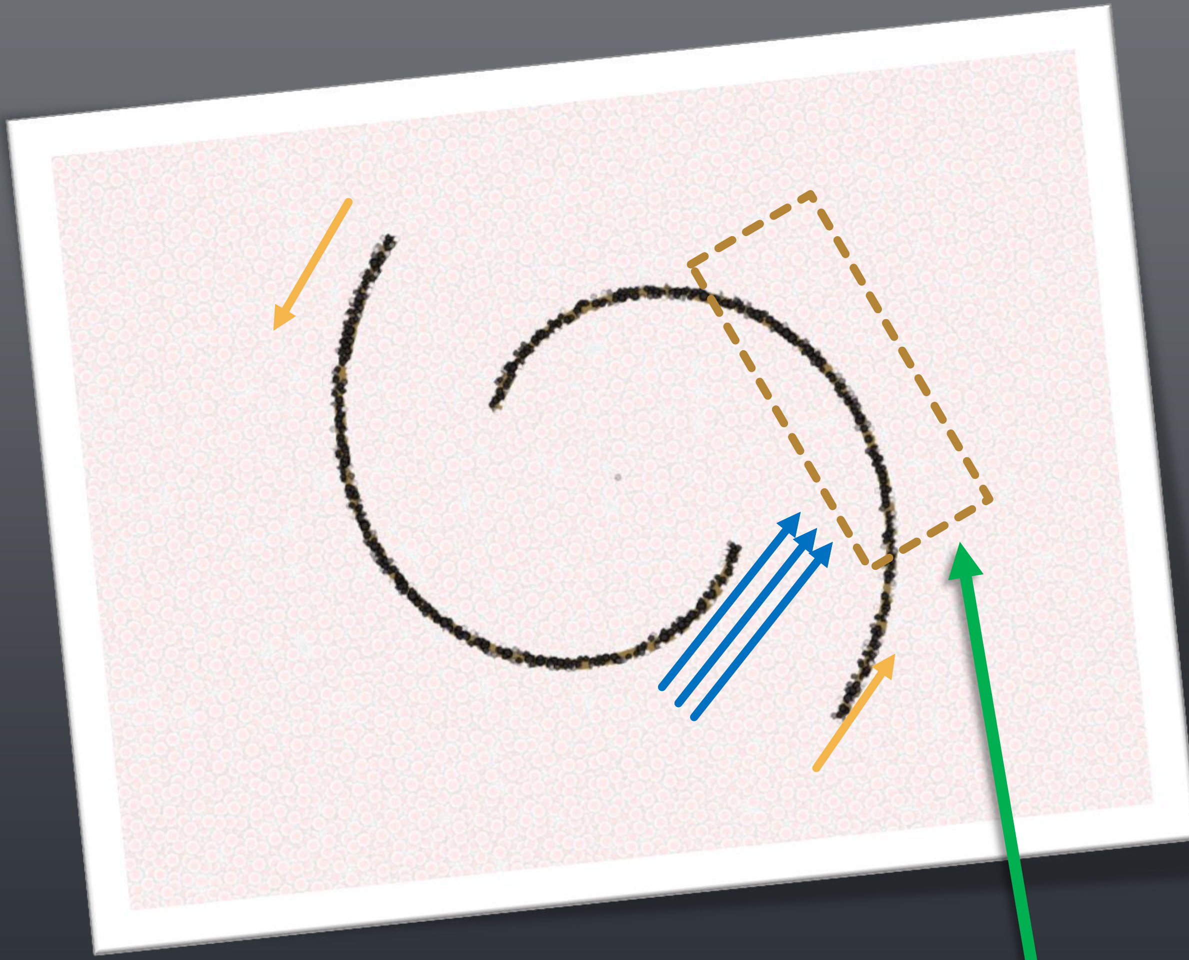



Stable or Unstable?

# LOCAL BOX

e.g., Kim & Ostriker '02, '06, Kim+ 2014

Ignore curvature in a tight-winding galaxy



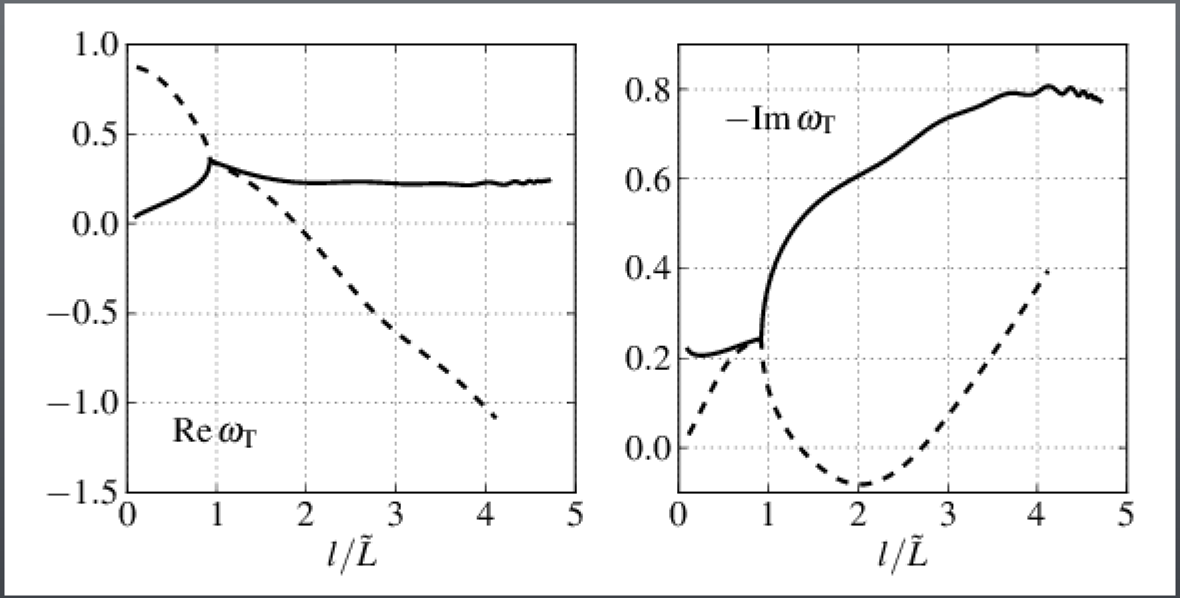
Circular Flow (blue)

Pattern Rotation (orange)

Computation domain

# NORMAL MODE ANALYSIS (FEATHERING INSTABILITY)

- Nonlinear background of the 1D spiral shock model
- **Numerical** dispersion relation of the linear instability



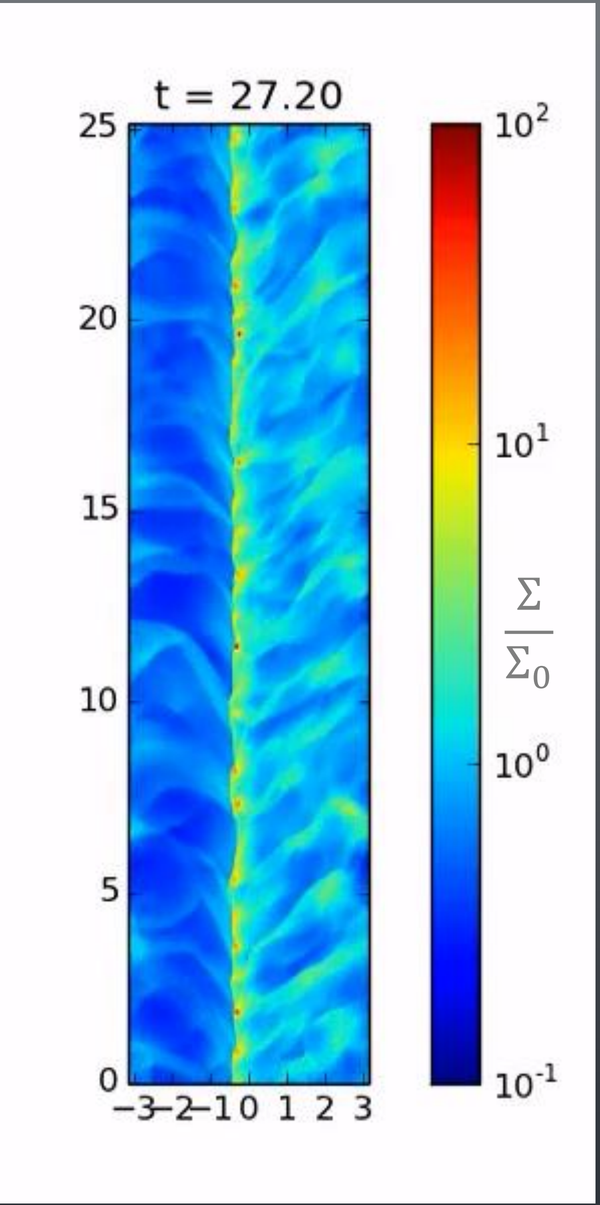

- $\omega_T$ is the (complex) Doppler-shifted frequency
- non-zero real part (left) indicates group velocity along the arm
- Peak of imaginary (right) indicates preferred scale (~ a few 100pc)

# STABILITY OF SPIRAL SHOCK

# Hydrodynamic Simulations with Self-Gravity

- With Self-Gravity (Toomre's Q~2)
- No Magnetic Field
- Results:
  - Shearing-Type Instability
  - Overall linear structure of spiral shock is maintained
  - Instability starts from small scale
  - No particular length scale in the late stage
  - High-Density clumps only in the spiral arm (red blobs)

$$Q = \frac{\kappa c}{\pi G \Sigma_0}$$

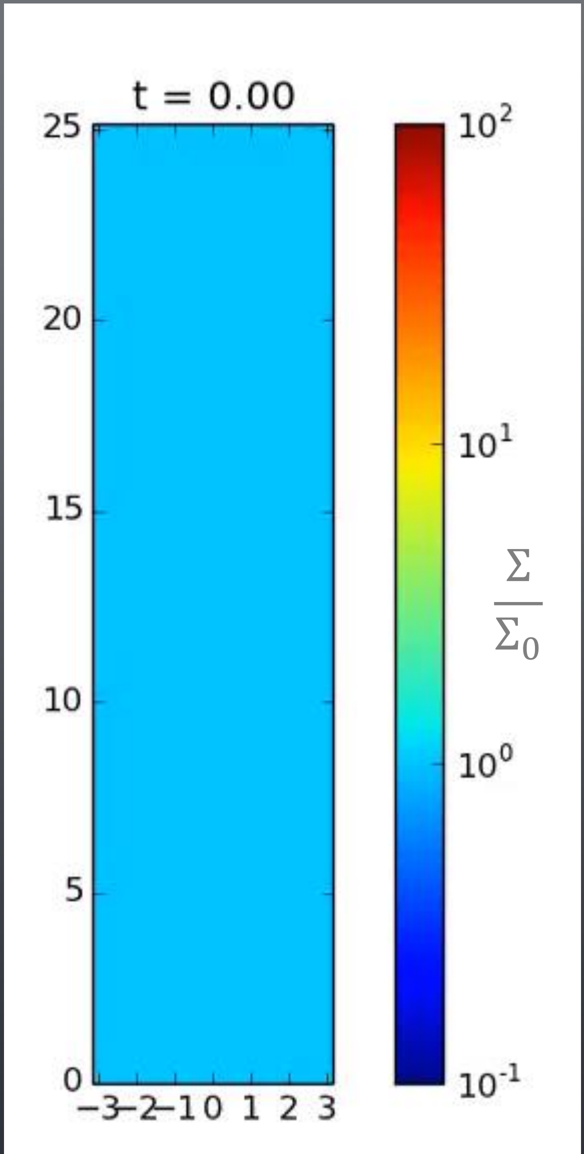



Crossing time ~ 8.9 computational unit

Lee, in prep.

# MAGNETO-HYDRODYNAMIC SIMULATIONS WITH SELF-GRAVITY

- Self-gravity (Toomre's Q~2)
- Magnetic Field ($\beta = 1$)
- Results:
  - Feathering Instability
  - Feather spacing ≤ 1 arm-arm distance




Crossing time ~ 8.9 computational unit

Lee, in prep.

# SUMMARY OF RESULTS*

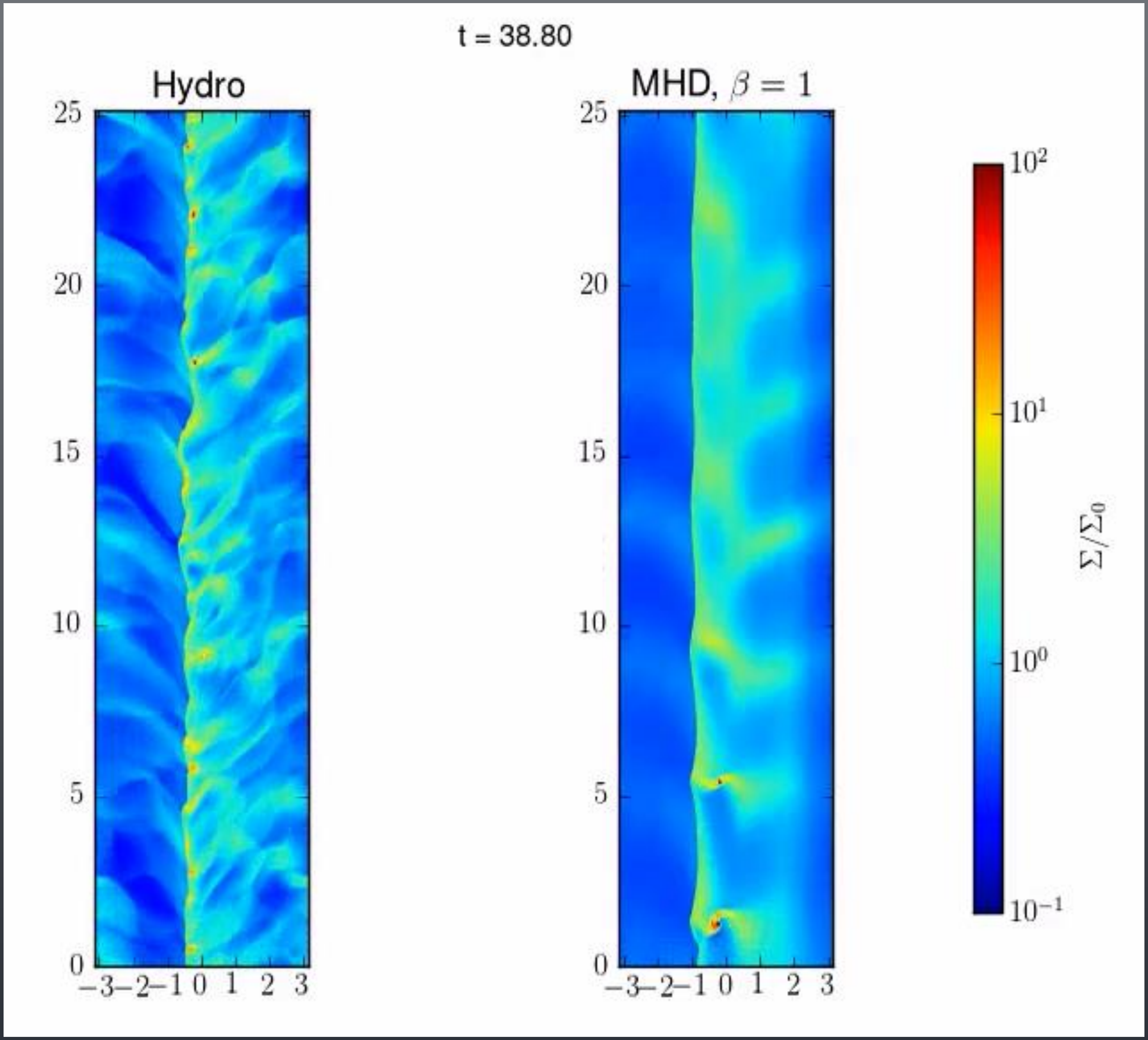
*STRONG SPIRAL POTENTIAL (F~10%)

| Hydro/ MHD | Self-Gravity | Stable? | Spiral Shock Maintained? | Characteristic Length Scale | Type of Instability |
|---|---|---|---|---|---|
| Hydro | No | No | Yes | Small initially, many other modes in the nonlinear stage | Wiggle Instability |
| Hydro | Q~2 | No | Yes | Same as above | Wiggle Instability |
| MHD | No | Yes | Yes | NA | NA or 1D instability? |
| MHD | Q~2 | No | No | ~1 arm-arm distance | Feathering Instability |

# RECAP..
# Q~2

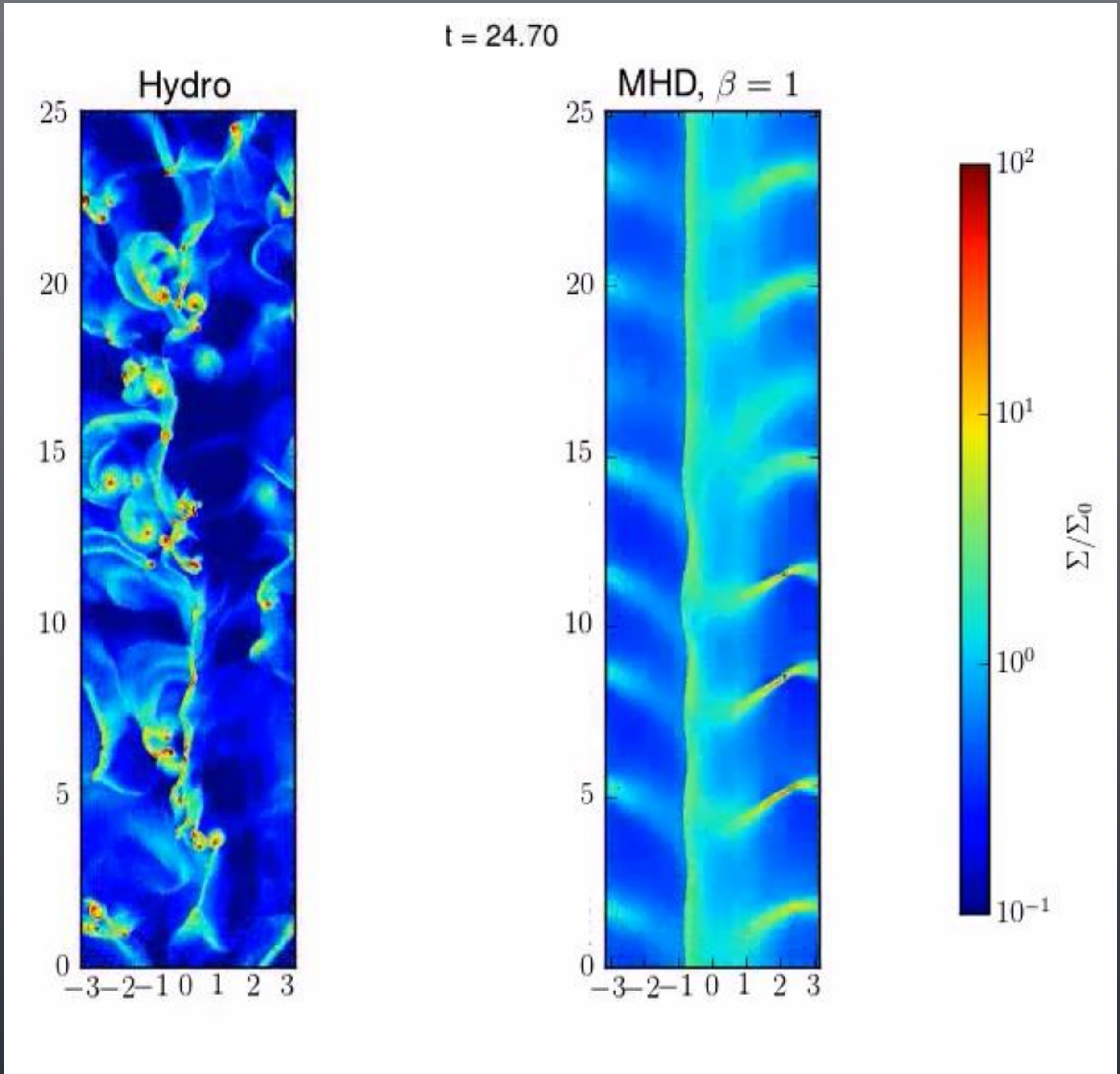
Effectively Q is higher for MHD case with the magnetic pressure.

Without any feedback, most gas accretes into the clumps

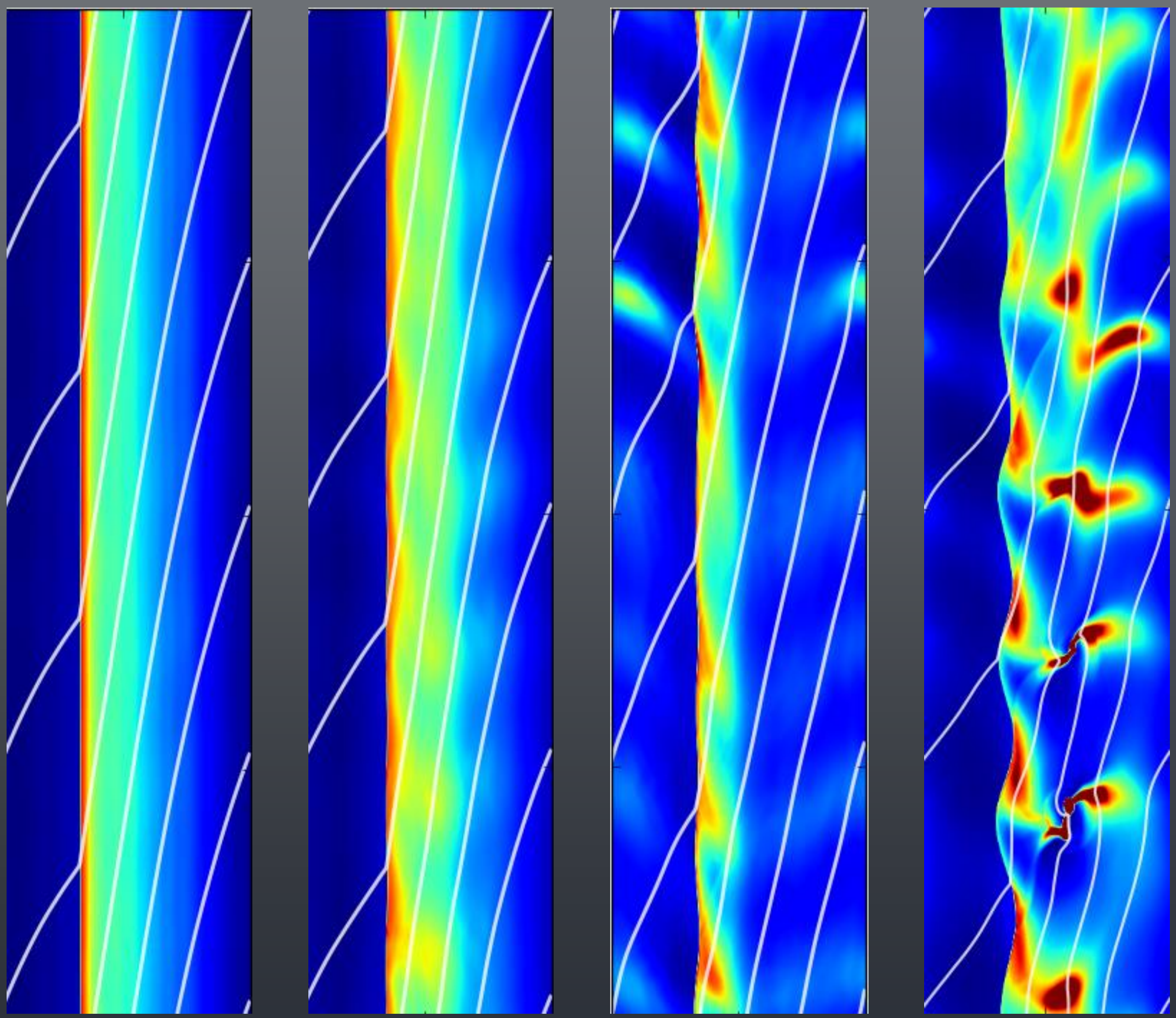


# MORE..
# Q~1

Unstable to axis-symmetric perturbations (for Hydro case)

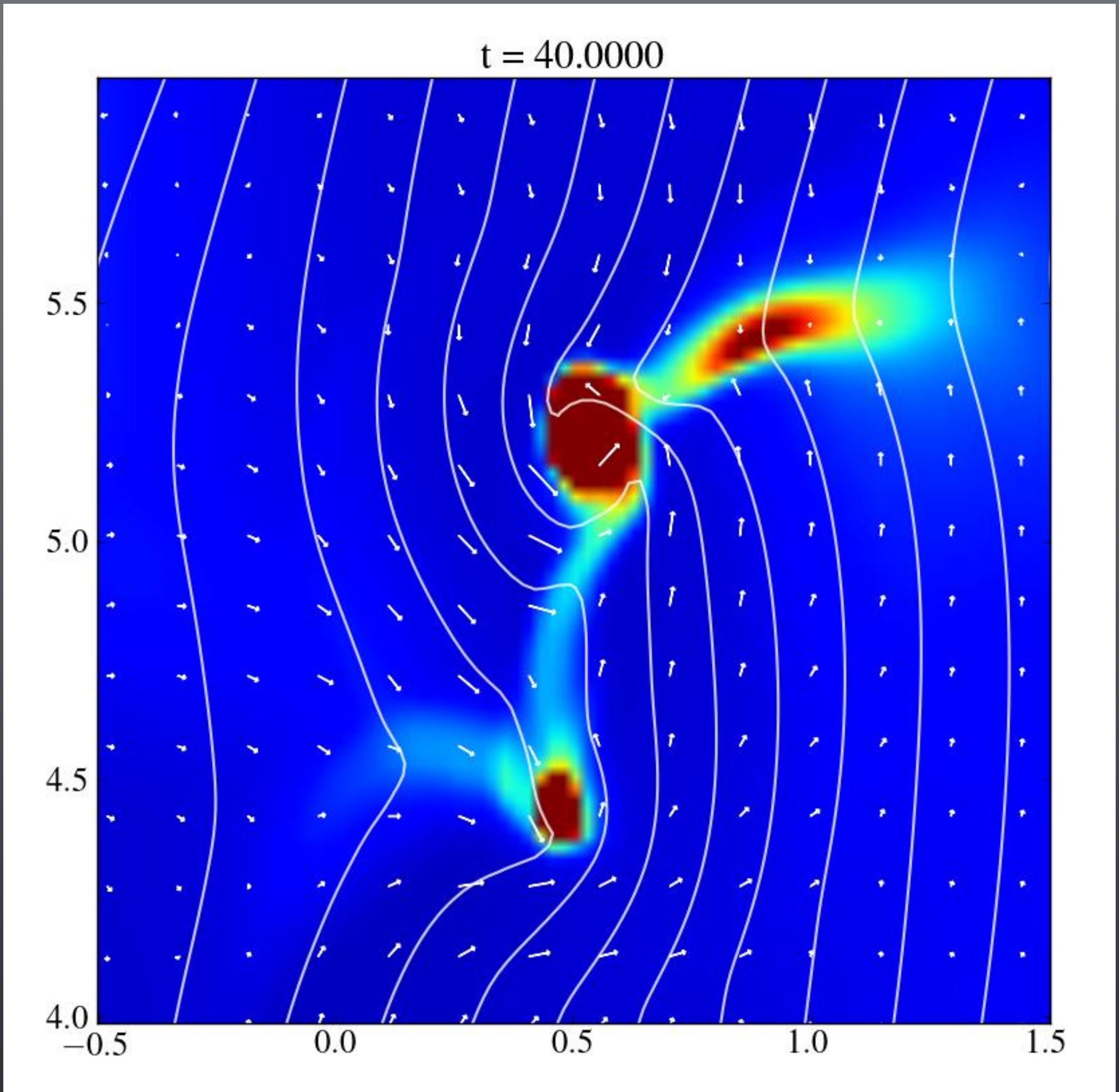


# MAGNETIC FIELDS



Characteristic spacing / growth rate may be calculated using normal mode analysis (Lee 2014)

time




Color background:

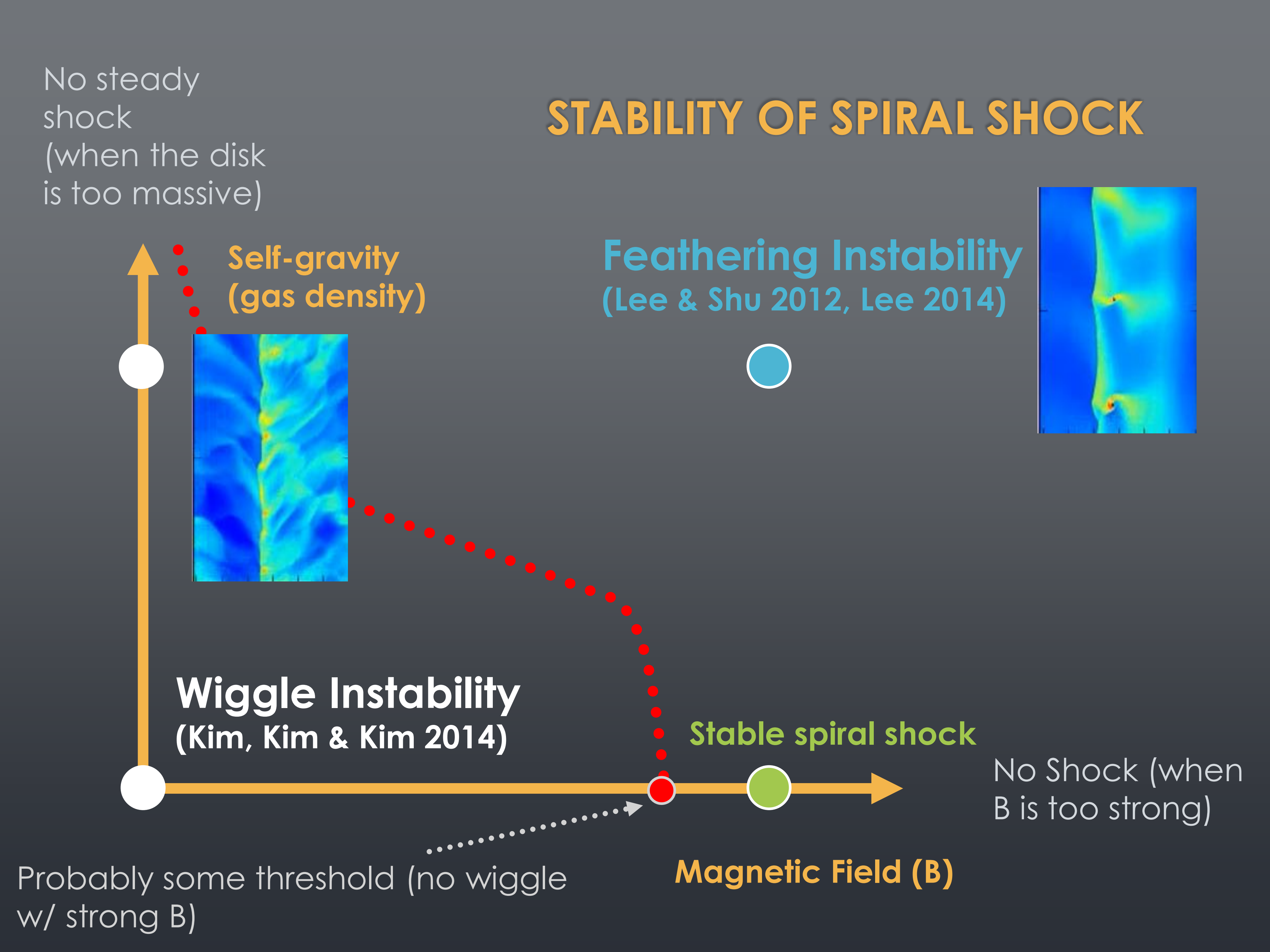
**Surface density** *contrast*

Arrows: **Velocity** *difference*

Contour: **Magnetic field lines**

**Gravitational collapse along the field lines**

Dark red: over-density>3



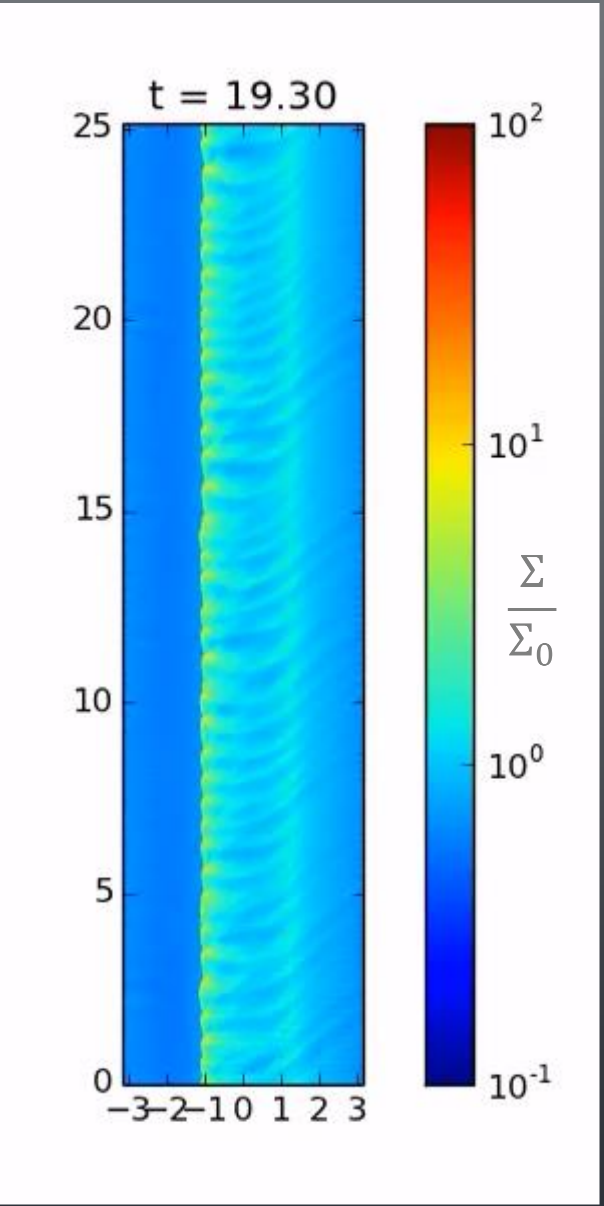
STABILITY OF SPIRAL SHOCK
No steady shock (when the disk is too massive)
Self-gravity (gas density)
Feathering Instability
(Lee & Shu 2012, Lee 2014)
Wiggle Instability
(Kim, Kim & Kim 2014)
Stable spiral shock
No Shock (when B is too strong)
Magnetic Field (B)
Probably some threshold (no wiggle w/ strong B)

# Summary

- Theory of Spiral Arm Substructure
  - Able to predict gas dynamics / Magnetic fields near the arm
  - Spacing may be used to constraint magnetic fields and other factors
- Future work
  - 3D model (weaken the shocks and effects of gas self-gravity)
  - Multiphase ISM and Stellar Feedback (affect the evolution of dense structure of dense structure and "Clouds")
  - High resolution (turbulence, GMCs etc )
  - Global model (Effects of curvature and background galactic shear)

# HYDRODYNAMIC SIMULATIONS

- **NO SELF-GRAVITY**
  - IGNORE POISSON'S EQUATION
- **NO MAGNETIC FIELD**
- RESULTS:
  - SHEARING-TYPE INSTABILITY
  - OVERALL LINEAR STRUCTURE OF SPIRAL SHOCK IS MAINTAINED
  - INSTABILITY STARTS FROM SMALL SCALES
  - **NO PARTICULAR LENGTH SCALE IN THE LATE STAGE (Y-DIRECTION)**

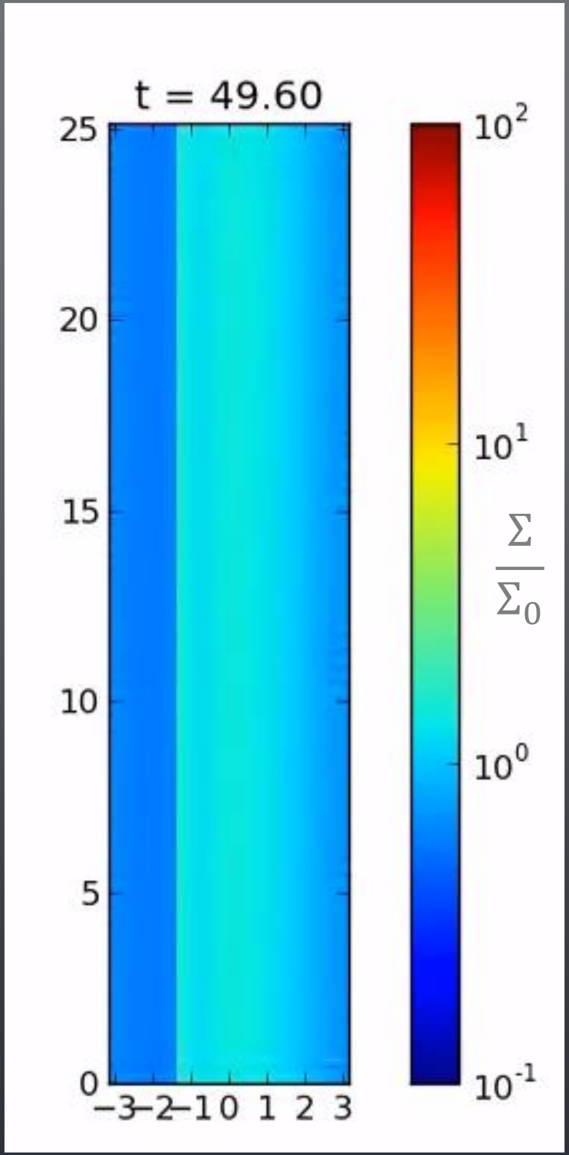



Crossing time ~ 8.9 computational unit

Lee, in prep.

# MAGNETO-HYDRODYNAMIC SIMULATIONS WITHOUT SELF-GRAVITY

- No Self-gravity
- With Magnetic Field ($\beta = 1$)
- Results:
  - Shearing-Type Instability is **suppressed**
  - spiral shock is weakened
  - No Instability for long-time evolution (~10 cross-time)

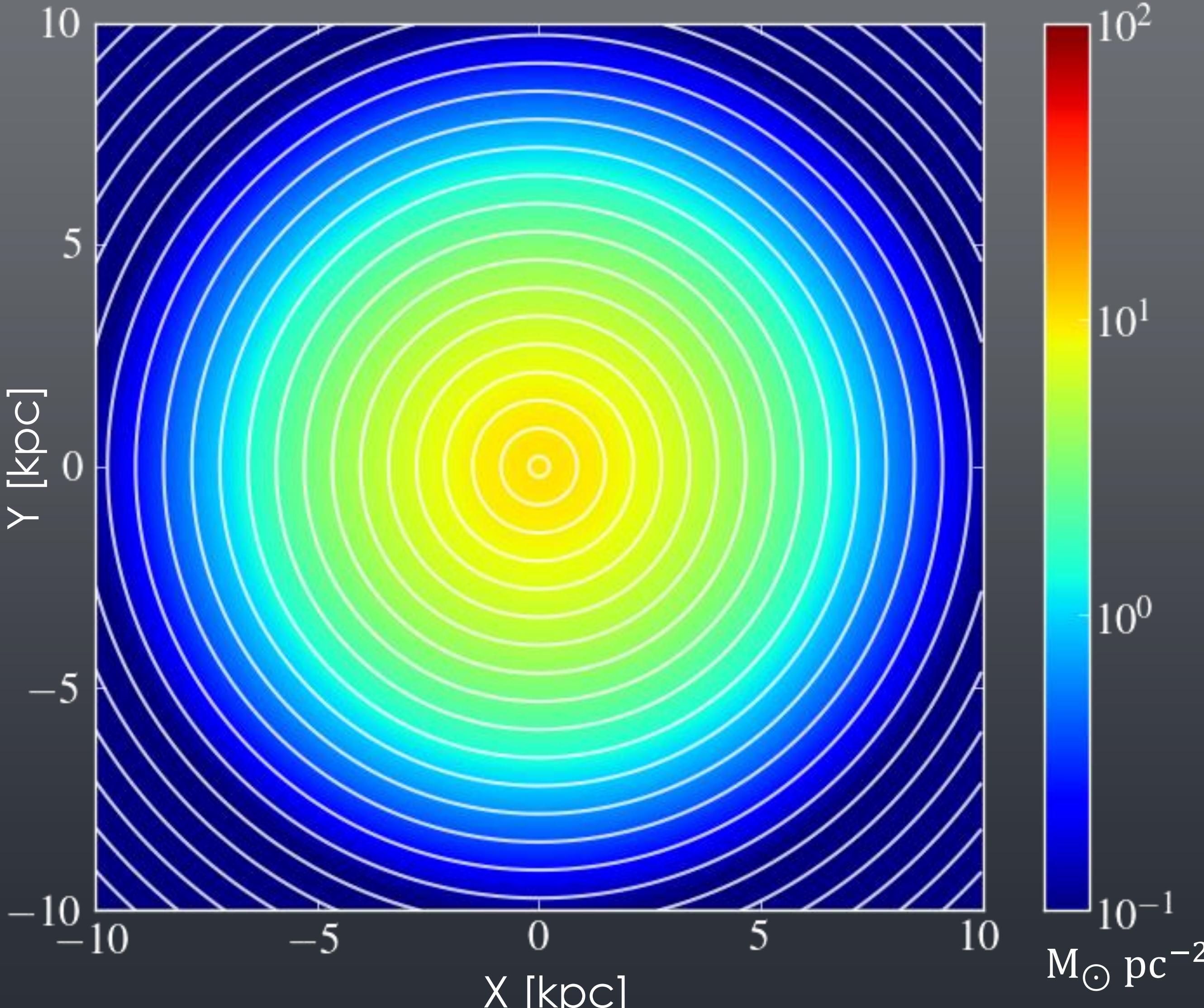



Crossing time ~ 8.9 computational unit

Lee, in prep.

# GLOBAL SIMULATIONS (VERY PRELIMINARY RESULTS)

In collaboration with Hsiang-Hsu Wang



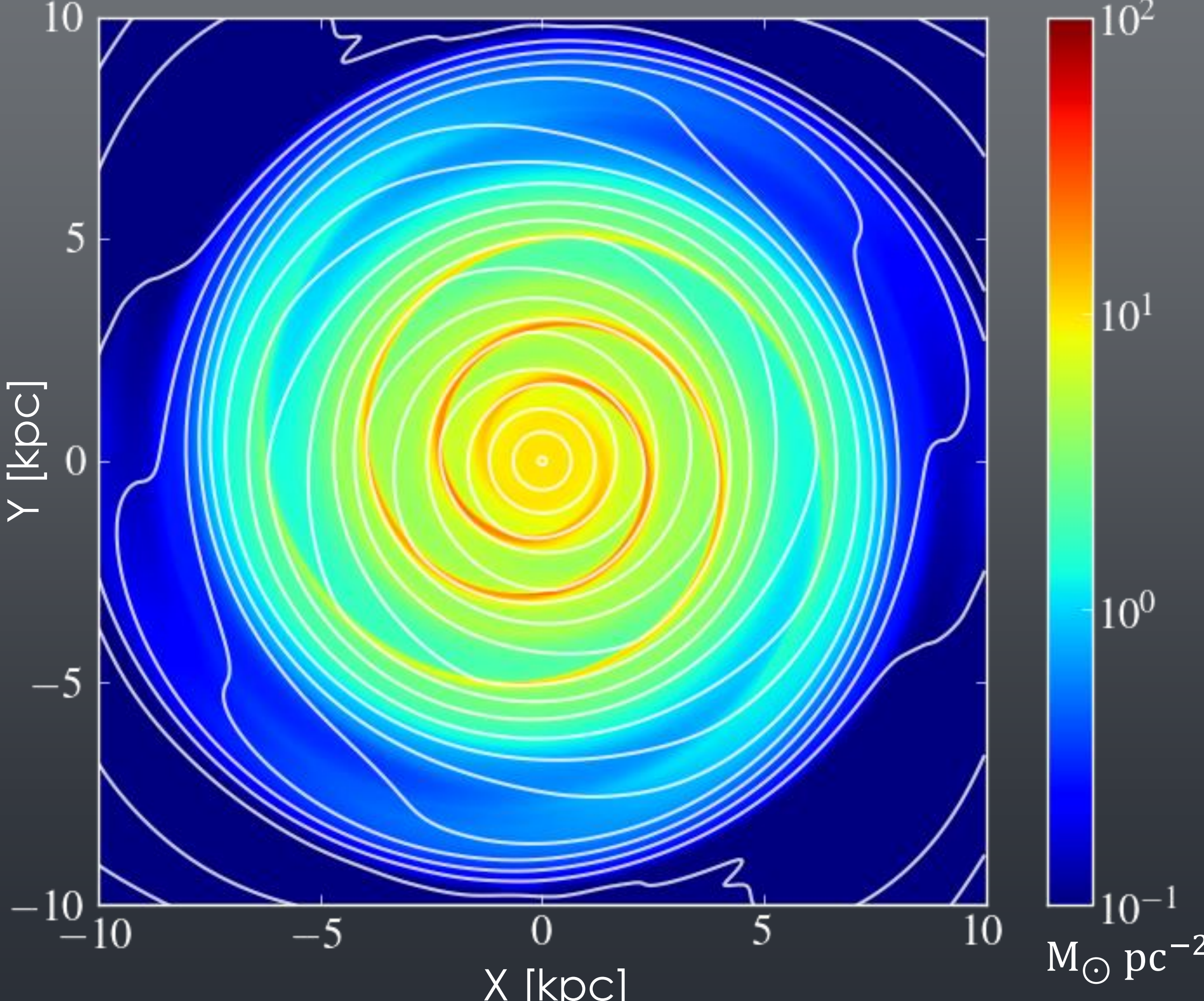

Initial Condition:

Flat rotation curve w/ rising part near center. Corotation at around 8 kpc

Circular Magnetic Field ($\beta = 100$)

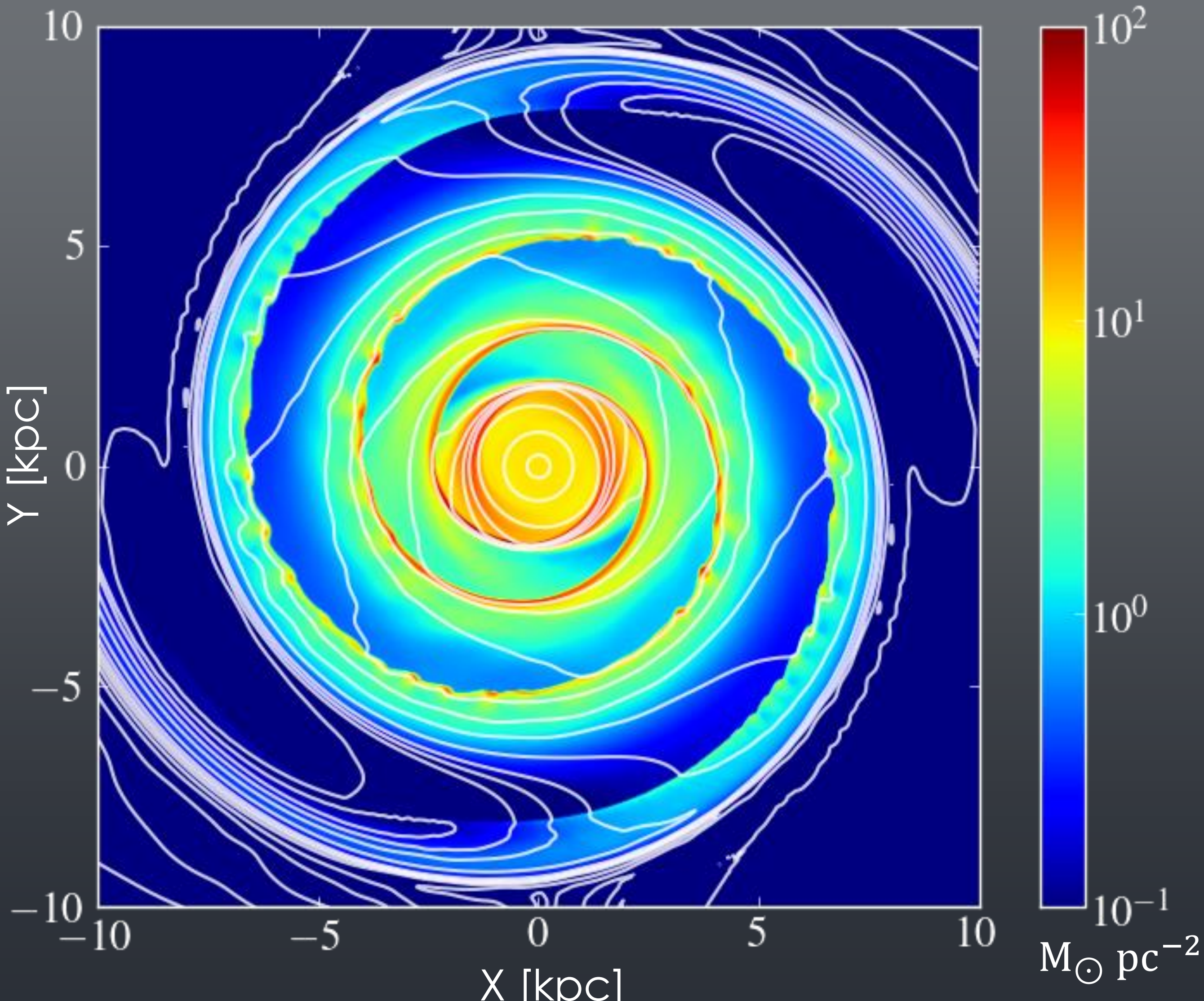
(External) stellar spiral potential grows gradually

Low-res 512x512




Aim to study the same physics in the global model

Spiral shock forms as in the local model




Wiggle instability develops

Similar to previous work, e.g., Wada+ 2004, Shetty+ 2006

Need strong field simulations. Expect more density structure can grow inter-arm.

# Summary

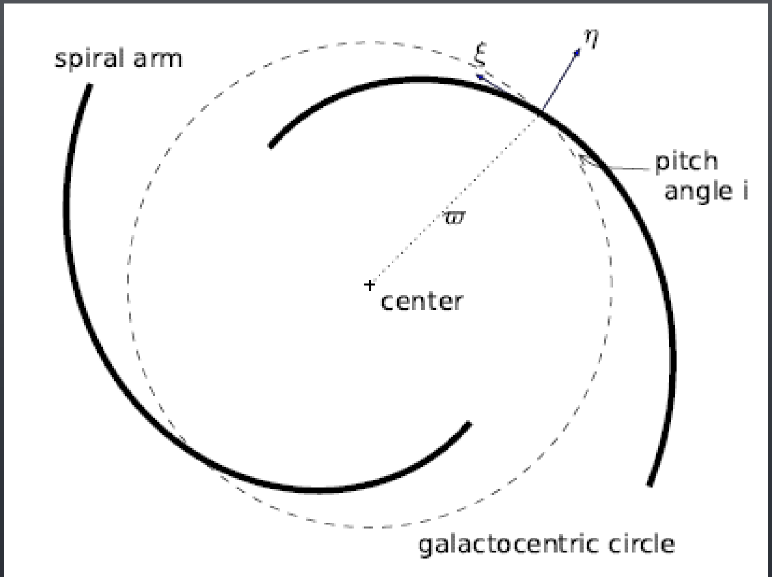
- Magnetic fields act as both stabilizing and destabilizing agent in the system:
  - Stabilize: Weaken the shock, Lower the shear
  - Destabilize: Allow gravitational collapse along the field lines
- Both self-gravity and Magnetic fields are needed to form feathers (spacing large enough to match observations, ~0.1-1kpc)
- In the local model, wiggle (or shearing) instability looks quite different from feathering instability (with self-gravity and B field)
- In the global model, the substructure may look different from the local model (in progress)
- Comparison to the Theoretical calculation of stability is on-going

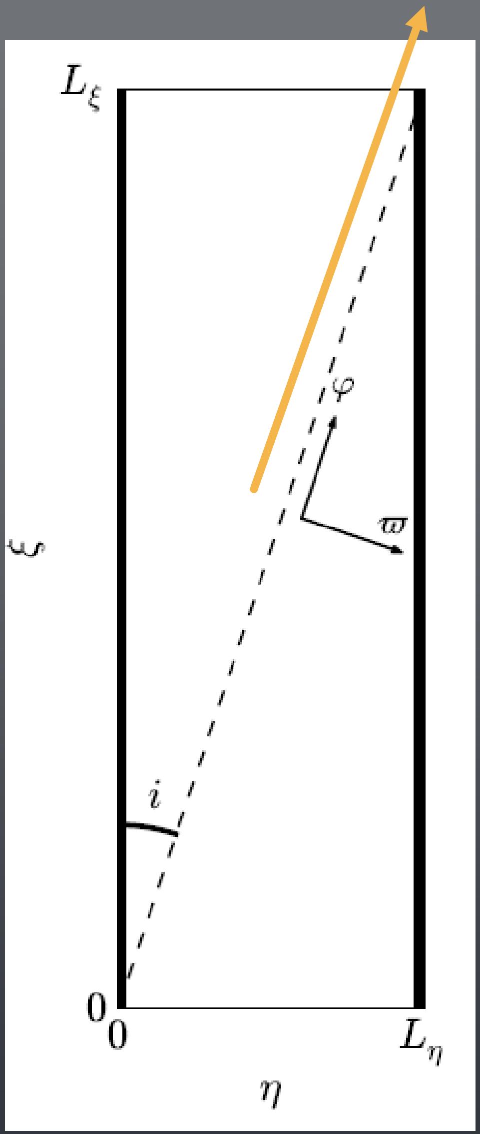
# THANK YOU

# Set-up

Direction of circular flow

1. Tight-winding approximation
2. Defining a local (Cartesian) spiral coordinate system $(\eta, \xi)$ (i.e., ignoring curvature)
3. To construct a doubly-periodic box as the domain of the calculation
4. Assuming no (background) shear in the box (i.e., constant $\Omega$ across)
5. Assuming no "back-reaction": only gaseous response to the stellar spiral




$$\Phi_{spiral} \propto -\cos(\eta)$$

**Lee & Shu 2012**

# SIMULATIONS SETUP

- Antares Code
  - Developed here in IAA (**H.H. Wang**, Lin, Yen, Yuan, etc)
  - Fortran 90 with MPI
- 2D Hydro / MHD Simulations
  - Grid-based Godunov code
- Periodic Boundary Conditions (both x and y)
- Isothermal equation of state
- Poisson Solver For Self-Gravity in thin-disk geometry (FFTW 3)
- Initial conditions:
  - Uniform flow across diagonal (circular direction)
  - Uniform density with 1% random fluctuations (zero vel.)
  - Stellar spiral potential grows slowly in the beginning

# Implications

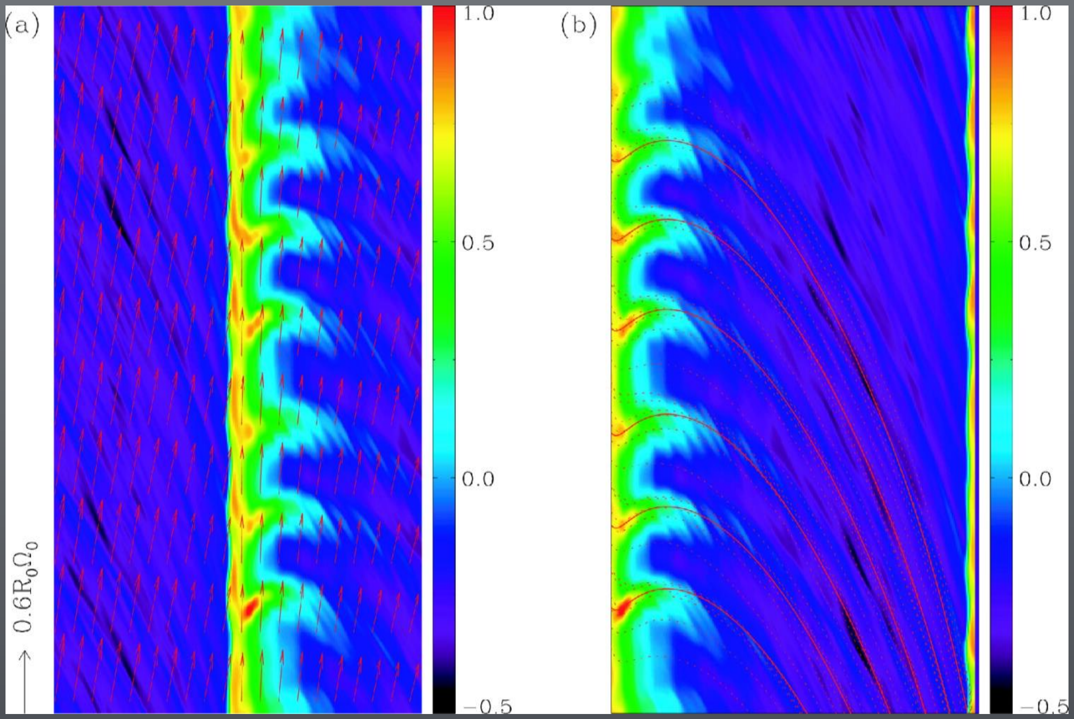
To better understand the formation of feathers and spurs (with star formation)

To explain the "beads on a string" phenomenon (star forming regions along the spiral arms)

To understand different mechanism of the formation of giant molecular clouds (where the star forms), e.g., clouds collision (Tan 2000), collapse of feathers (Kim & Ostriker 2002)

To answer the doubt whether star formation is triggered in the spiral arm (i.e., if $\Sigma_{SFR}$ is related to the amplitude of the spiral arm) (c.f., Elmegreen+ 86, Dobbs+ 09 etc etc)

Kim & Ostriker 2002




Shearing-box simulation (MHD + self-gravity)

Feathers are leading near the shock and trailing when they are farther.

It may be due to nonlinear mode-coupling of linear modes.

# GOVERNING MHD EQUATIONS (I)
## IN THE PATTERN FRAME

CONTINUITY EQUATION:

$$\frac{\partial \Sigma}{\partial t} + \nabla \cdot (\Sigma \boldsymbol{u}) = 0$$

MOMENTUM EQUATION (ON THE PLANE):

$$\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u} \cdot \nabla \boldsymbol{u} = -\frac{1}{\Sigma} \nabla \Pi_{\mathrm{G}} - \nabla \mathcal{V}_{\mathrm{EFF}} + 2\Omega_{\mathrm{P}} \hat{\mathbf{z}} \times \boldsymbol{u} + \boldsymbol{\mathcal{F}}$$

where$(\varpi, \varphi)$ is the polar coordinate on the plane, $\Pi_g$ is the vertically-integrated pressure, $\mathcal{V}_{\mathrm{eff}} = \mathcal{V} + \frac{1}{2}\Omega_{\mathrm{p}}\varpi^2$, and

$$\boldsymbol{\mathcal{F}} = \frac{(\boldsymbol{\nabla} \times \boldsymbol{B}) \times \boldsymbol{B}}{4\pi\Sigma}$$

is Lorentz force per unit mass.

$\Omega_{\mathrm{p}}$: pattern speed of the spiral structure

# GOVERNING MHD EQUATIONS (II)

INDUCTION EQUATION (MHD):

$$\frac{\partial \boldsymbol{B}}{\partial t} + \nabla \times (\boldsymbol{B} \times \boldsymbol{u}) = 0$$

POISSON EQUATION (FOR GAS SELF-GRAVITY):

$$\nabla^2 \phi = 4\pi G \Sigma \delta(z),$$

WHERE WE ASSUME THE RAZOR-THIN DISK GEOMETRY

GRAVITATIONAL POTENTIAL, $\mathcal{V}$ IS A SUM OF THE CONTRIBUTIONS FROM STARS, DARK MATTER, AND GAS $(\phi)$. EXCEPT FOR $\phi$ AND THE STELLAR SPIRAL POTENTIAL, OTHER CONTRIBUTIONS ARE ASSUMED TO BE AXISYMMETRIC. WE ASSUME A ROTATION CURVE $\Omega = \Omega(\varpi)$.

EQUATION OF STATE: $\Pi_{G} = \Sigma_{G} V_{T0}^{2} \, LN(\frac{\Sigma}{\Sigma_0})$

# BOUNDARY VALUE PROBLEM WITH EIGENVALUES

A SET OF FIRST-ORDER ODES

$$\mathrm{A}_{\omega,l}(\eta)\frac{d\boldsymbol{y}_l(\eta)}{d\eta} = \mathrm{B}_{\omega,l}\boldsymbol{y}_l(\eta)$$

WHERE $\boldsymbol{y}_l = \left[\tilde{\sigma}, \tilde{u}, \tilde{\mathrm{v}}, \tilde{A}_1\right]^{\mathrm{T}}$

$\tilde{A}_1$is the z-component of (perturbational) magnetic vector potential

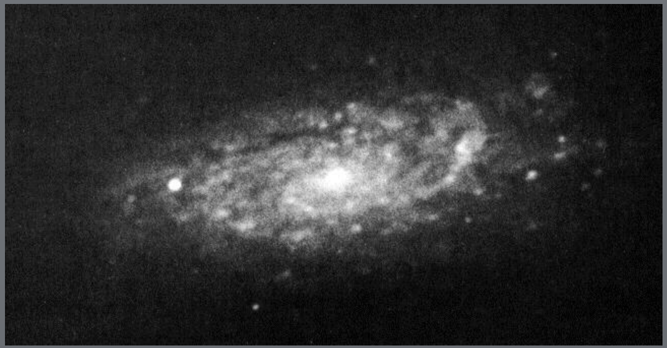
FEATHER SPACING = WAVELENGTH OF THE PERTURBATION

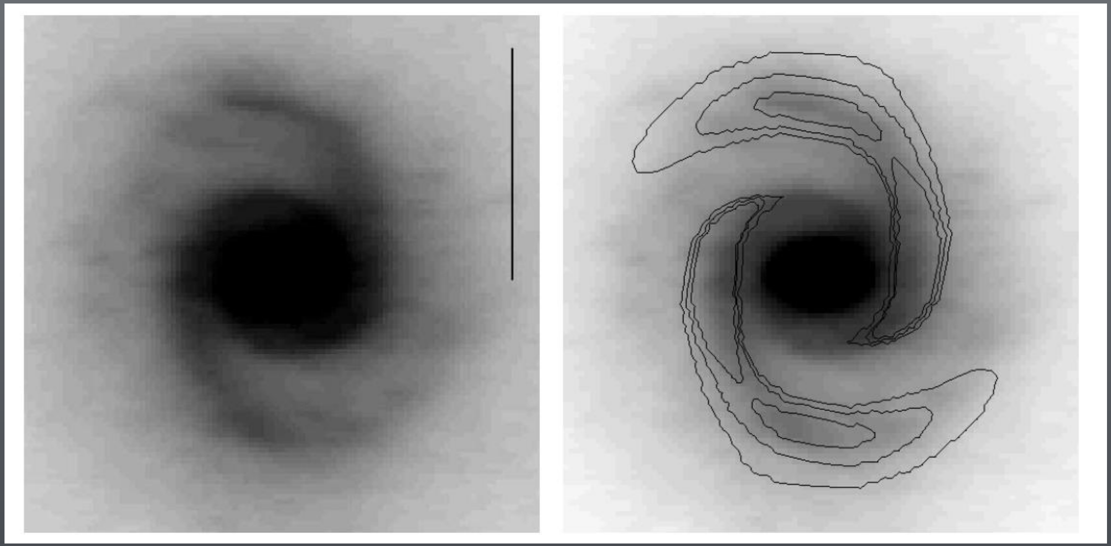
$$\lambda_{\text{FEATHER}} = \frac{\tilde{L}}{|l|} L_{\text{ARM}}$$

USING GALACTIC PARAMETERS FOR M51 AT 2KPC FROM THE CENTER (WITH $\Omega_{\mathrm{P}} = 45\ \mathrm{KMS}^{-1}\mathrm{KPC}^{-1}$)

$$x_{t0} = 0.022, x_{A0} = 0.02, f = 0.5, \alpha = 0.15$$
$$\nu \simeq -0.9$$
$$i = 21^{\mathrm{o}}$$
$$L_{\text{arm}} = 2.1\text{kpc}$$

# FLOCCULENT GALAXIES





NGC 4062

Optically flocculent galaxies also have two-arm spiral structure in their old stellar disk

The bisymmetric radial variation of the arm amplitude matches the prediction from the modal theory of SDW

Optical: http://astronote.org/note/files/objects/ngc05.htm

K-band: Puerari, Block, Elmegreen, Frogel, and Eskridge (2000)

# MOLECULAR HYDROGEN (TRACED BY CO MOLECULES)

PAWS, Schinnerer+2013