Periodicity makes galactic shocks unstable

(mnras submitted)

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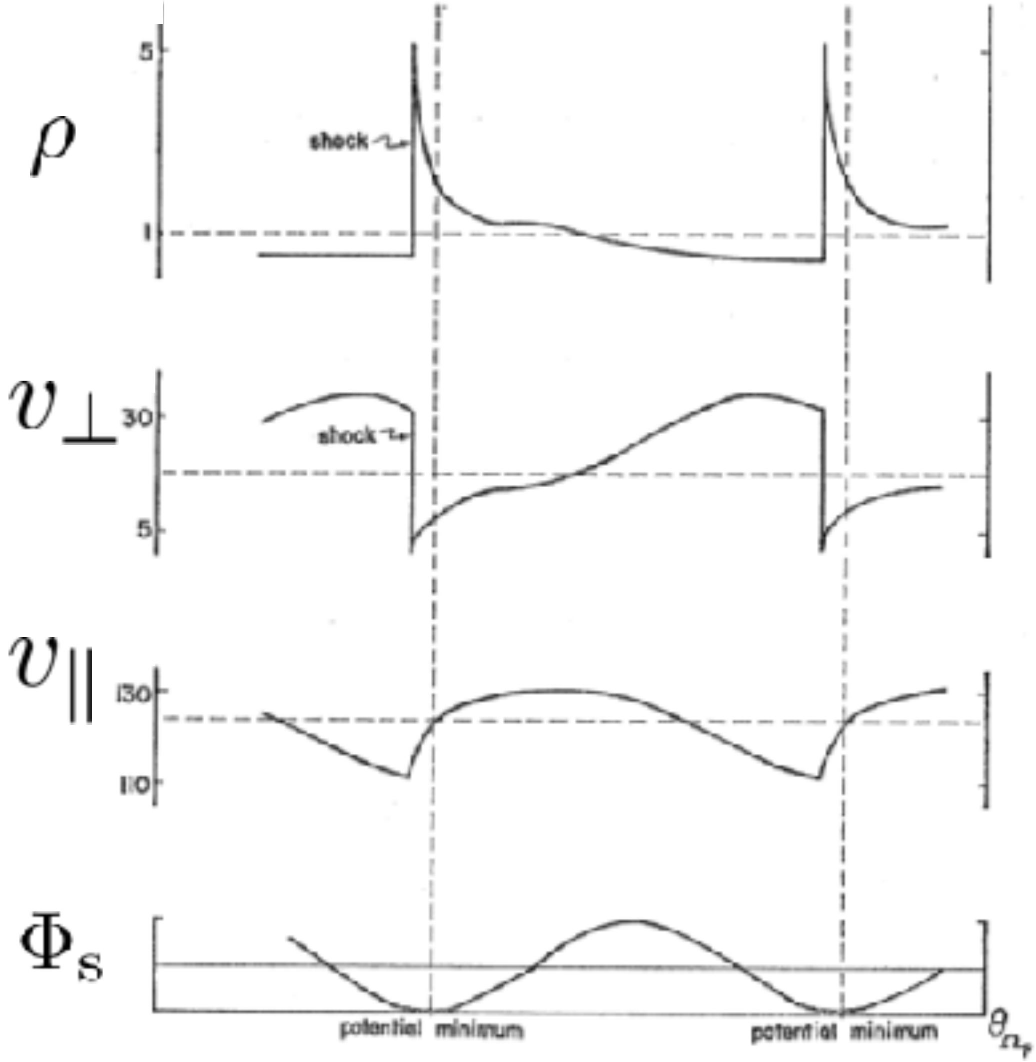
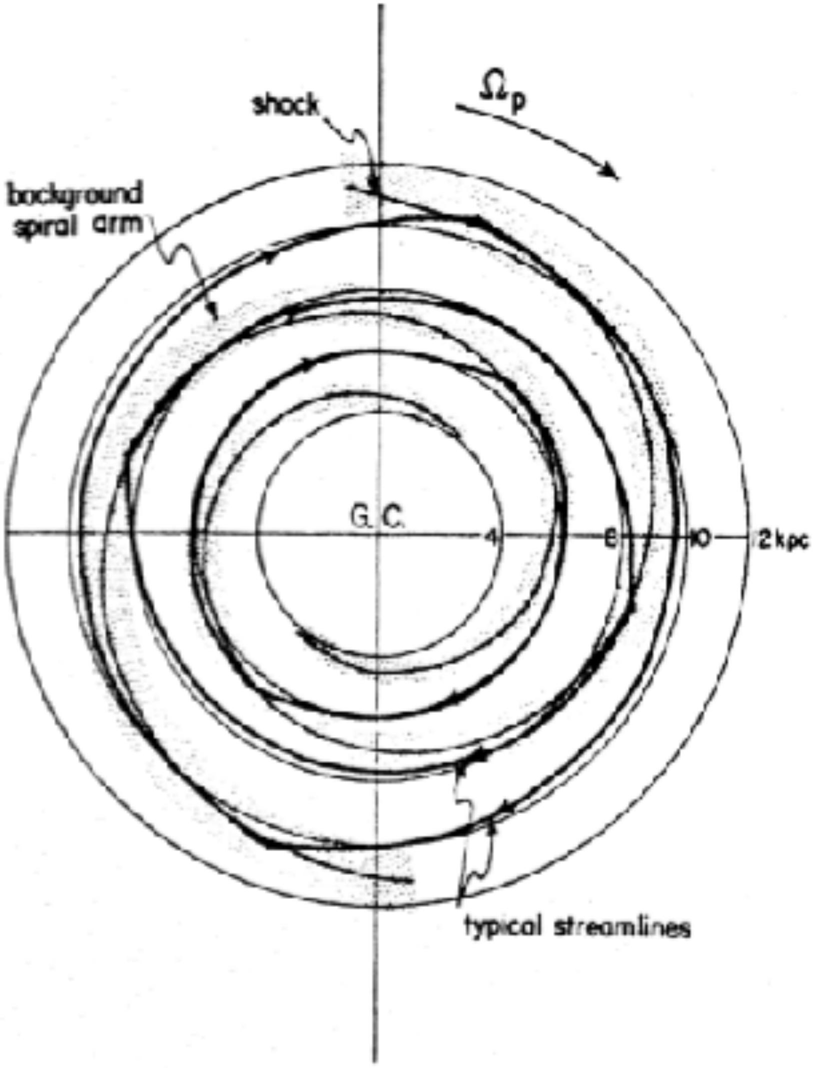
Roberts1969

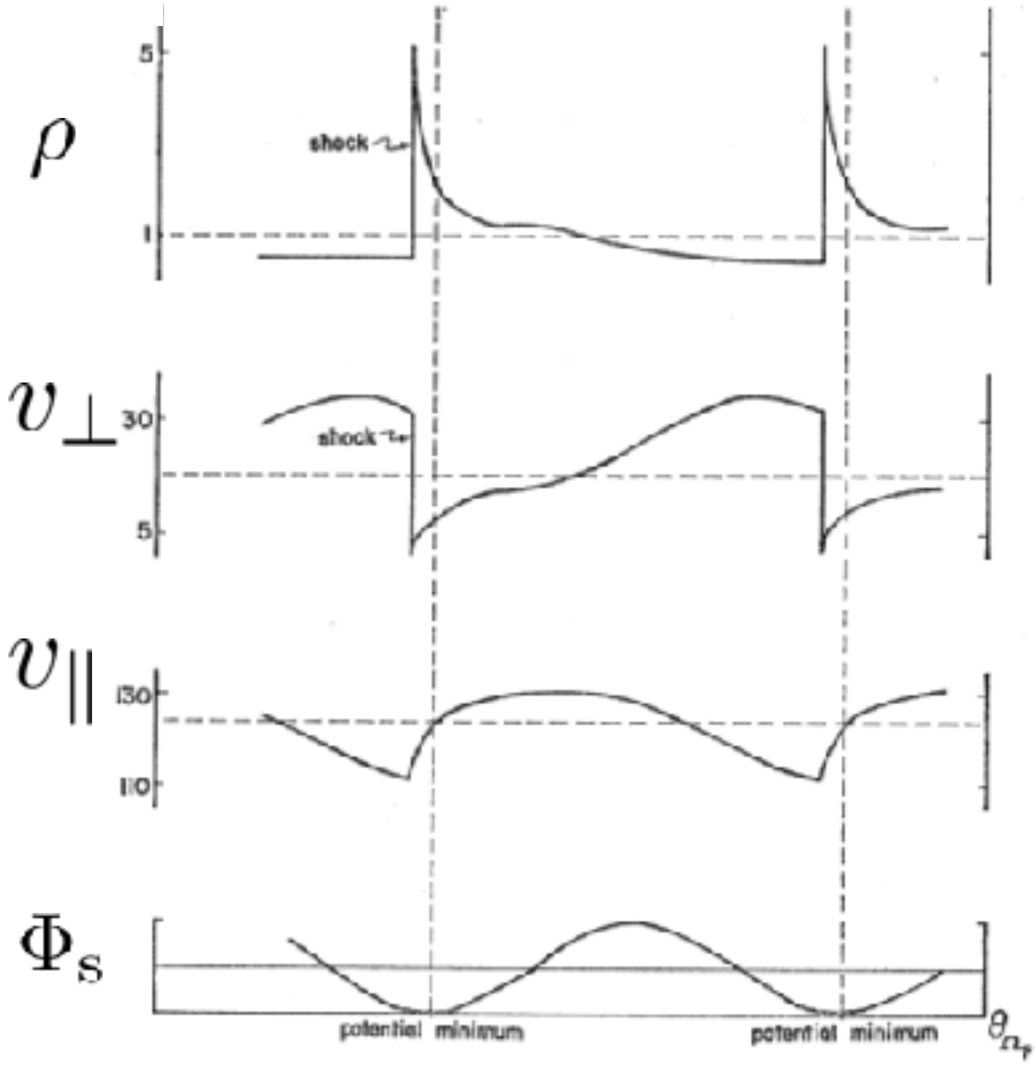
- **Stationary spiral shocks** can result as gas response to externally imposed spiral potential
- **No self-gravity**
- **Isothermal gas**



Coordinate perpendicular to spiral arm

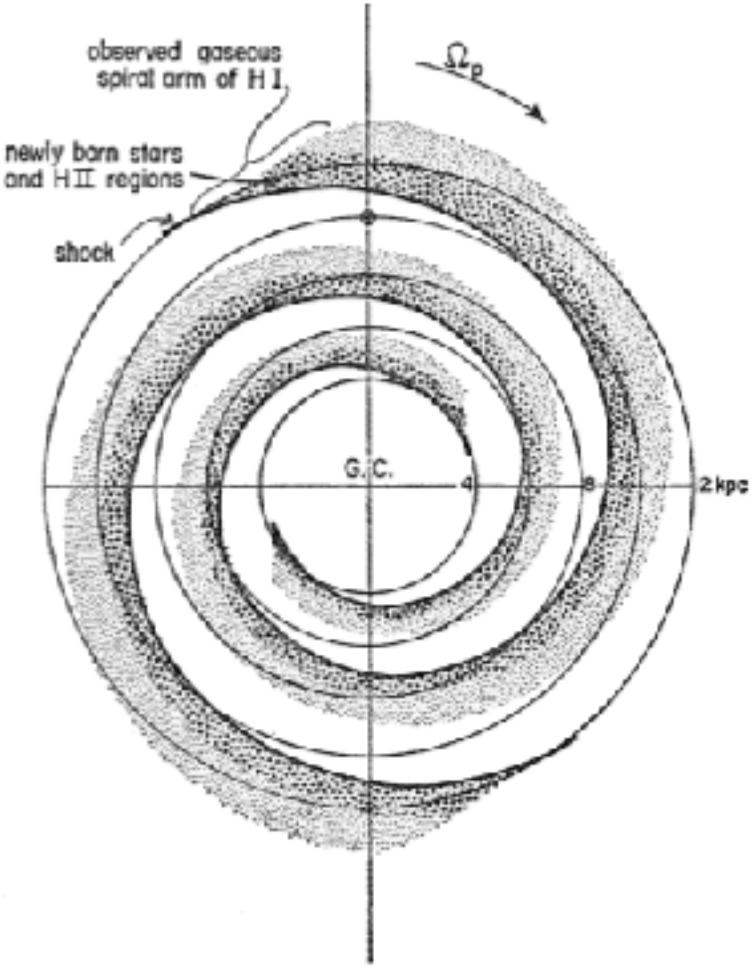
Roberts1969

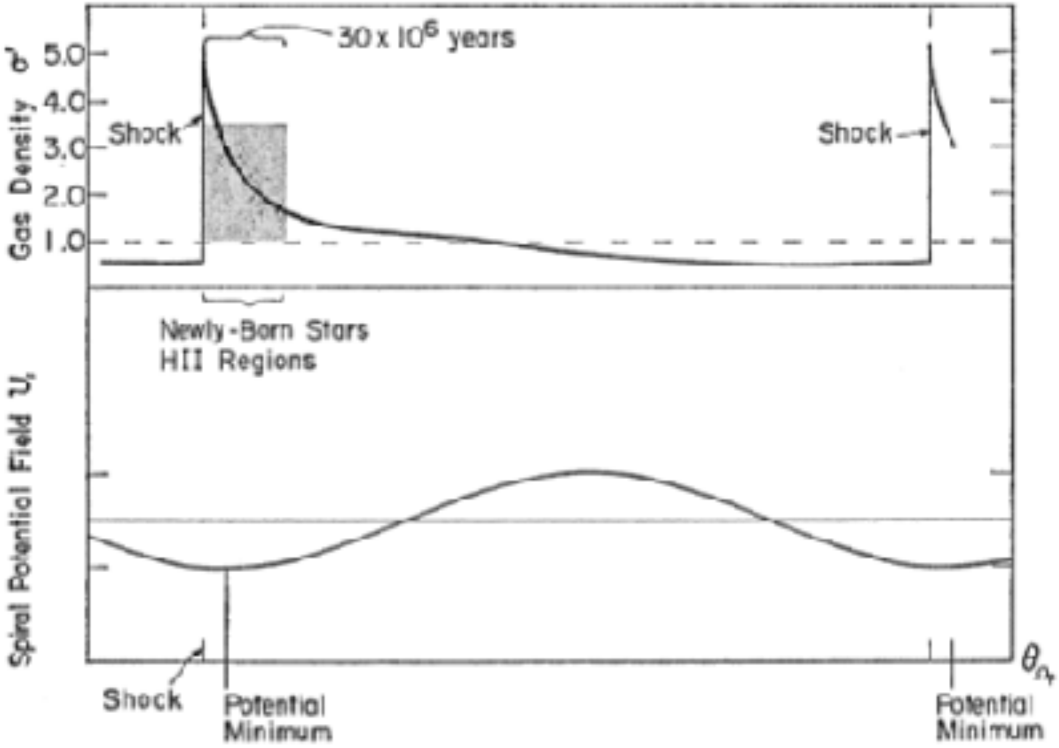




Coordinate perpendicular to spiral arm

Implications for star formation

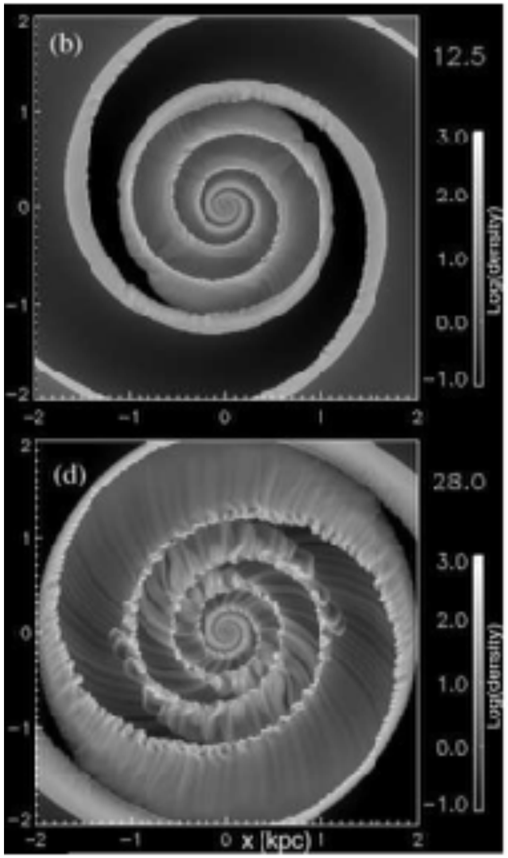




Coordinate perpendicular to spiral arm

Are these shocks stable?

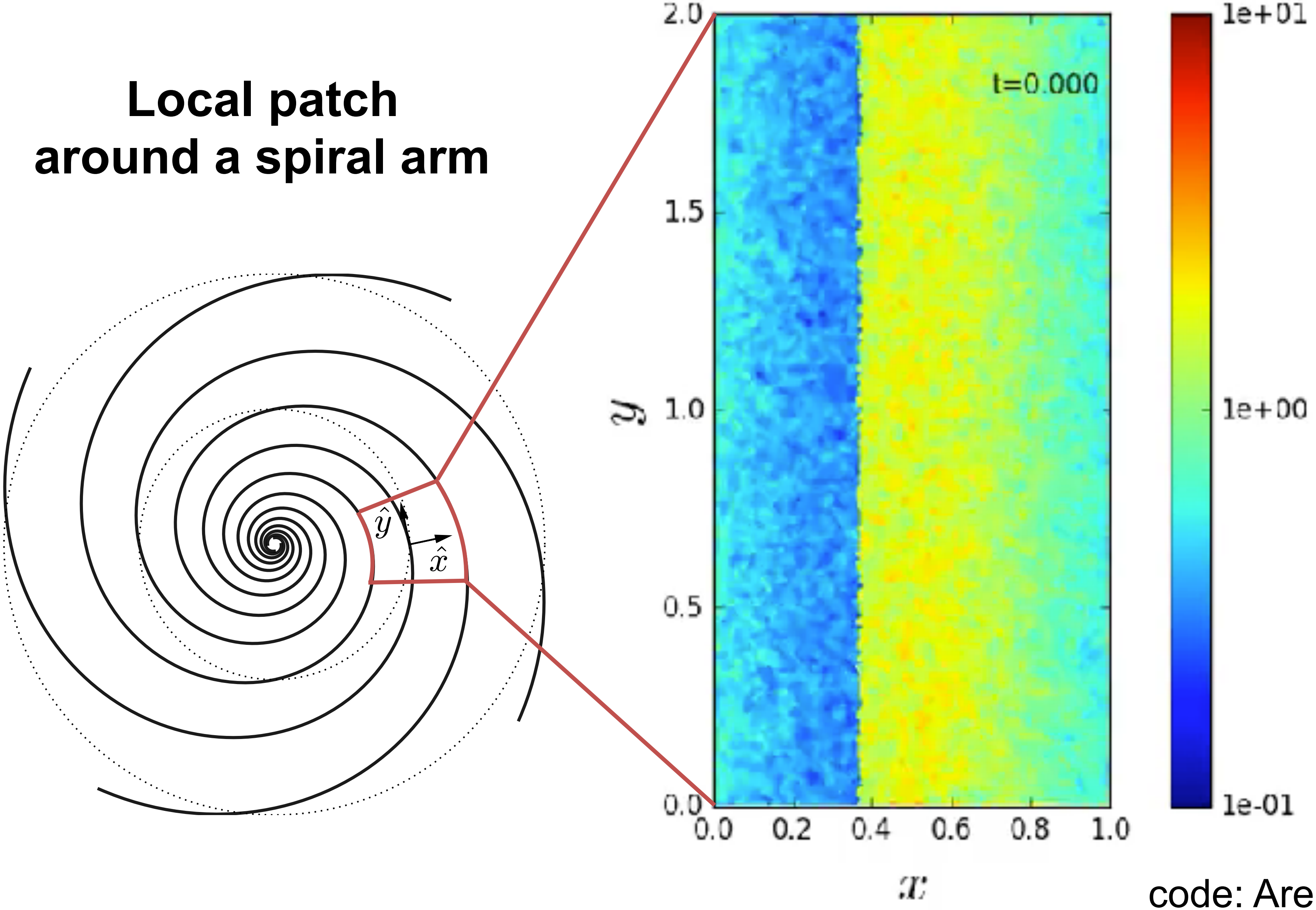
- **Shocks are usually stable** against corrugation of surface **(**D'yakov&Kontorovich classic result)
- Hence, people argued if instabilities are present is because:
    - **self-gravity** (because of high compression at shocks)
    - **shear** in the post-shock region.
- **70s, 80s, 90s**: several papers find **no evidence of instability.** Topic was thought to be dead…until
- **2000s**: Wada&Koda2004 revitalise the question. They run isothermal, 2D, non-self gravitating simulations and find "**wiggle instability**". Interpret as KH. Some say is numerical artefact.
- **2010s:** New studies appear and **this time they find shocks to be unstable**.
  (e.g. Lee&Shu2012, KimKimKim2014)



1. **Contradictory results**: new&old papers study the same problem but obtain different results! Why?? Who is right?
2. **Is it just Kelvin-Helmholtz as some say (e.g. review by Shu2016) or is there more?**

Zoom

Local patch around a spiral arm

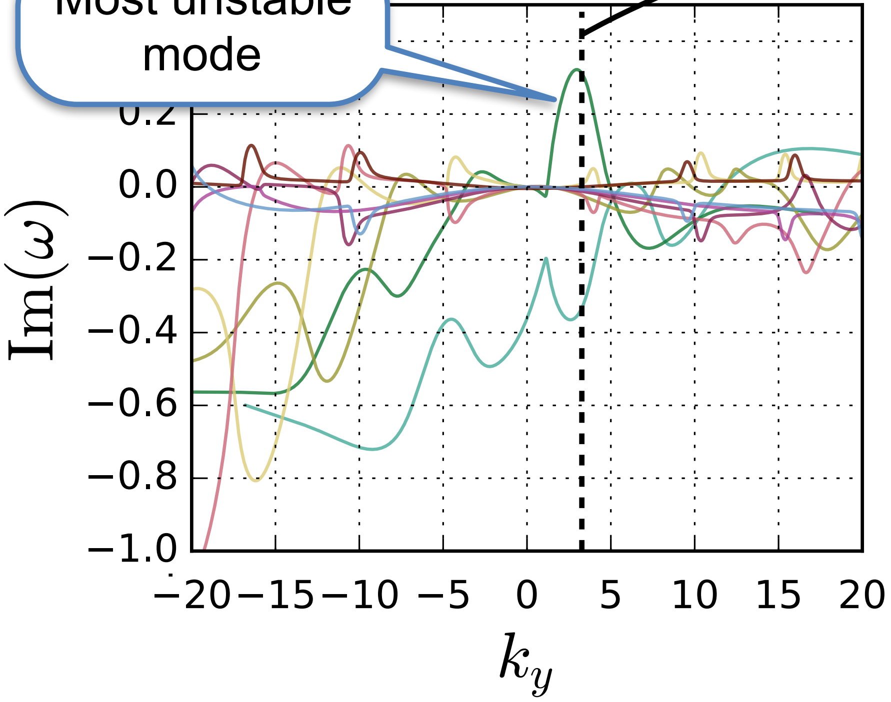


code: Arepo

Confirmed by linear analysis

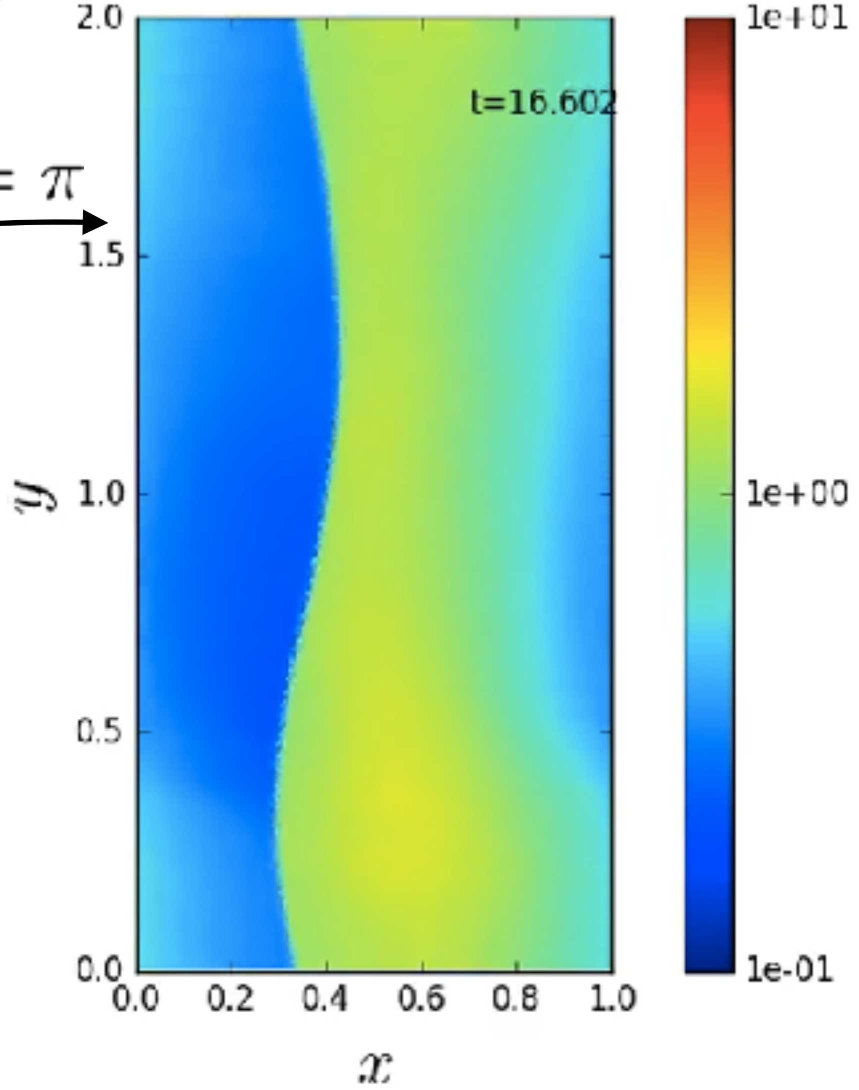
$$\rho = \rho_0(x) + \rho_1(x) \exp(ik_y y - i\omega t)$$
$$\mathbf{v} = \mathbf{v}_0(x) + \mathbf{v}_1(x) \exp(ik_y y - i\omega t)$$

Dispersion relation



Most unstable mode

$k_y = \pi$



Assumptions: 2D, isothermal

Physical interpretation

- In D’yakov-Kontorovich analysis in which the upstream flow is left unperturbed, the shock is stable but can oscillate and emit small waves at some **characteristic frequencies**.
- However, if in the DK problem one sends **incident waves from upstream towards the shock**, these can be greatly amplified or even blow everything up if sent with the proper frequencies of the system.
- What happens if spontaneously emitted waves are somehow allowed to re-enter the shock from upstream? This is what happens with periodic boundary conditions. The shock can **``resonate with itself”**

Conclusions

- **Stability depends on boundary conditions.** This explains apparently contradictory results
- **Galactic shocks are always unstable** because they are essentially periodic
- **The periodic shock instability is distinct from KH** otherwise it would not disappear by switching boundary conditions
- Relevant for **feathering/spurs of spiral arms.** (e.g. M51) and **Galactic centre bar shocks**
- For strong spiral potentials a **parasitic KH** can also be present on top of the periodic shock instability

Thank You!

Extra

Consider the following problem

$$\partial_t \mathbf{v} + (\mathbf{v}\cdot\nabla)\,\mathbf{v} = -\frac{\nabla P}{\rho} - \nabla\Phi - 2\Omega\times\mathbf{v} + \mathbf{F}$$

$$\partial_t \rho + \nabla\cdot(\rho\mathbf{v}) = 0$$

external pot.

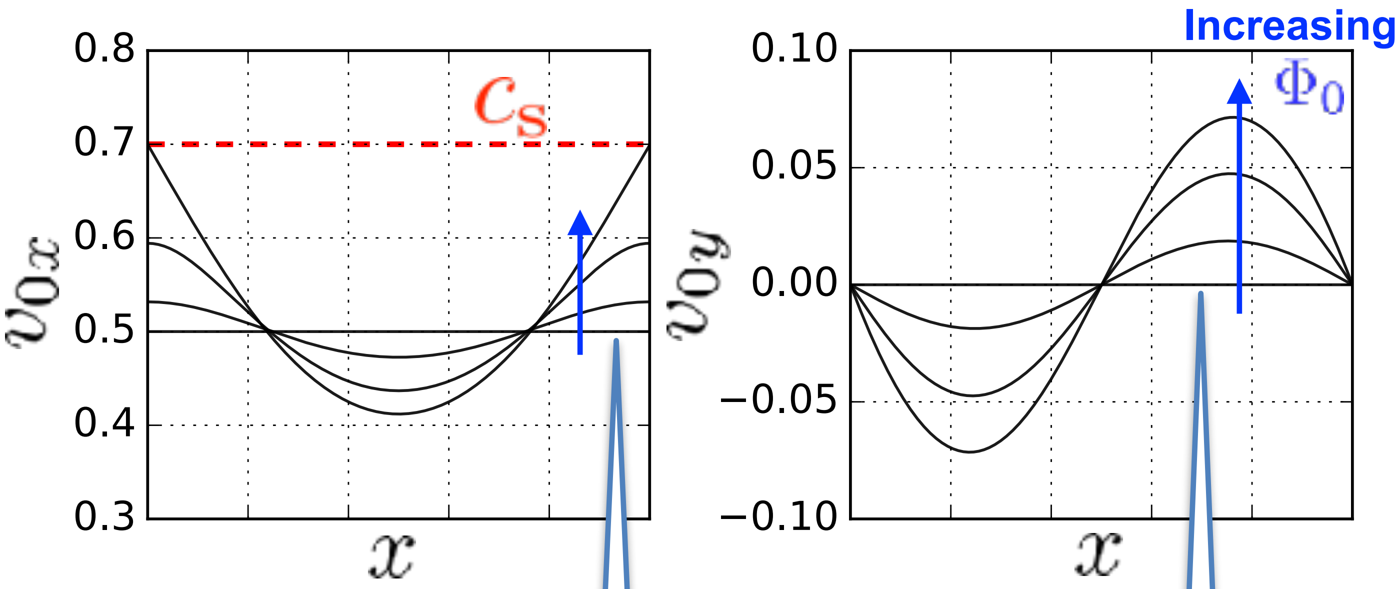
Coriolis

constant force

$$P = c_s^2 \rho$$

$$\Phi(x) = \Phi_0 \cos\left(\frac{2\pi x}{L}\right)$$

Steady states



$$\Phi_0 = 0 \;\Rightarrow\; \mathbf{F} = 2\Omega\times\mathbf{v}$$

- **Periodic in x**
- **Do not depend on y**

Consider the following problem

$$\partial_t \mathbf{v} + (\mathbf{v}\cdot\nabla)\,\mathbf{v} = -\frac{\nabla P}{\rho} - \nabla\Phi - 2\Omega\times\mathbf{v} + \mathbf{F}$$
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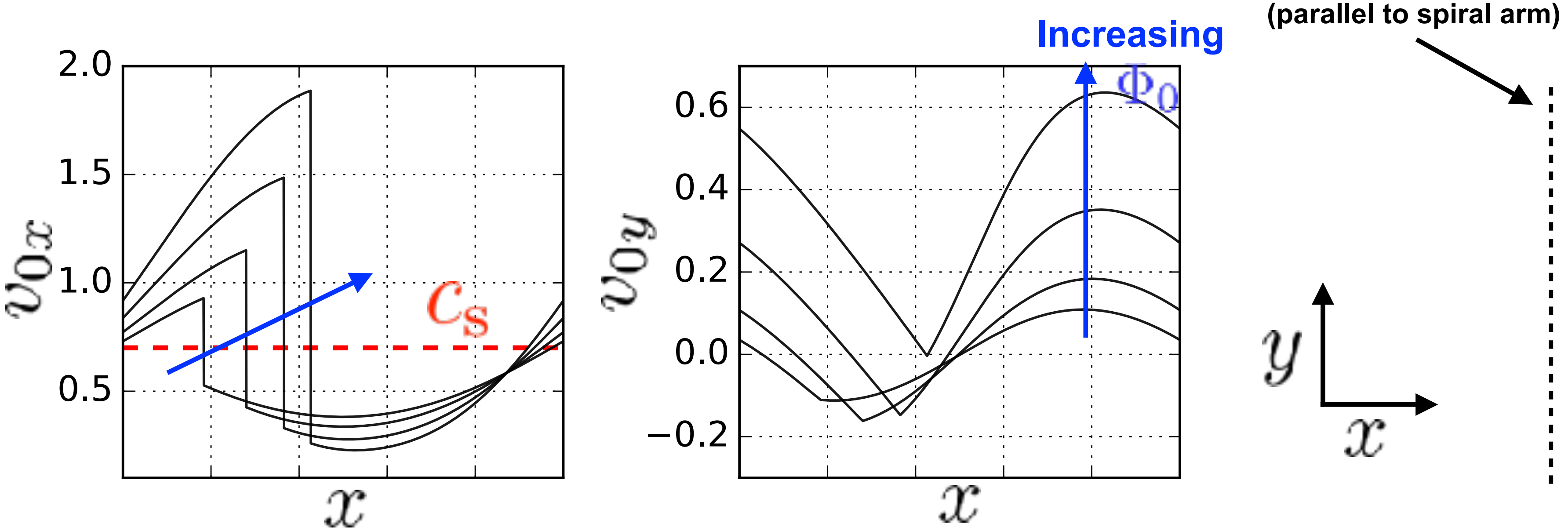
Steady states



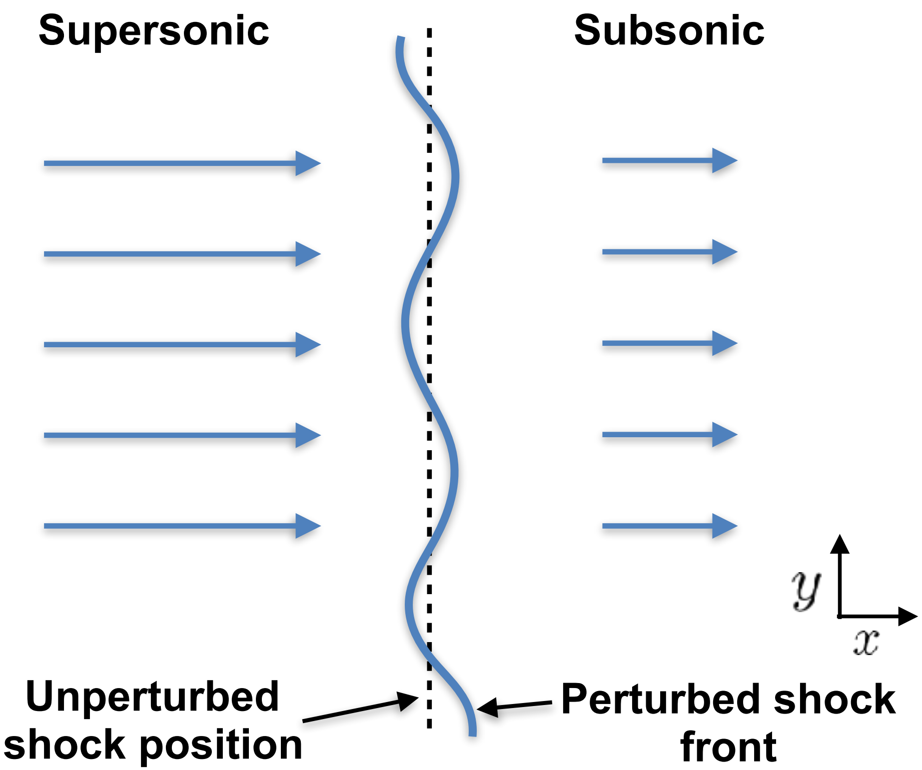
Linearise around steady state and find eigenmodes

$$\rho = \rho_0(x) + \rho_1(x)\exp(ik_y y - i\omega t)$$

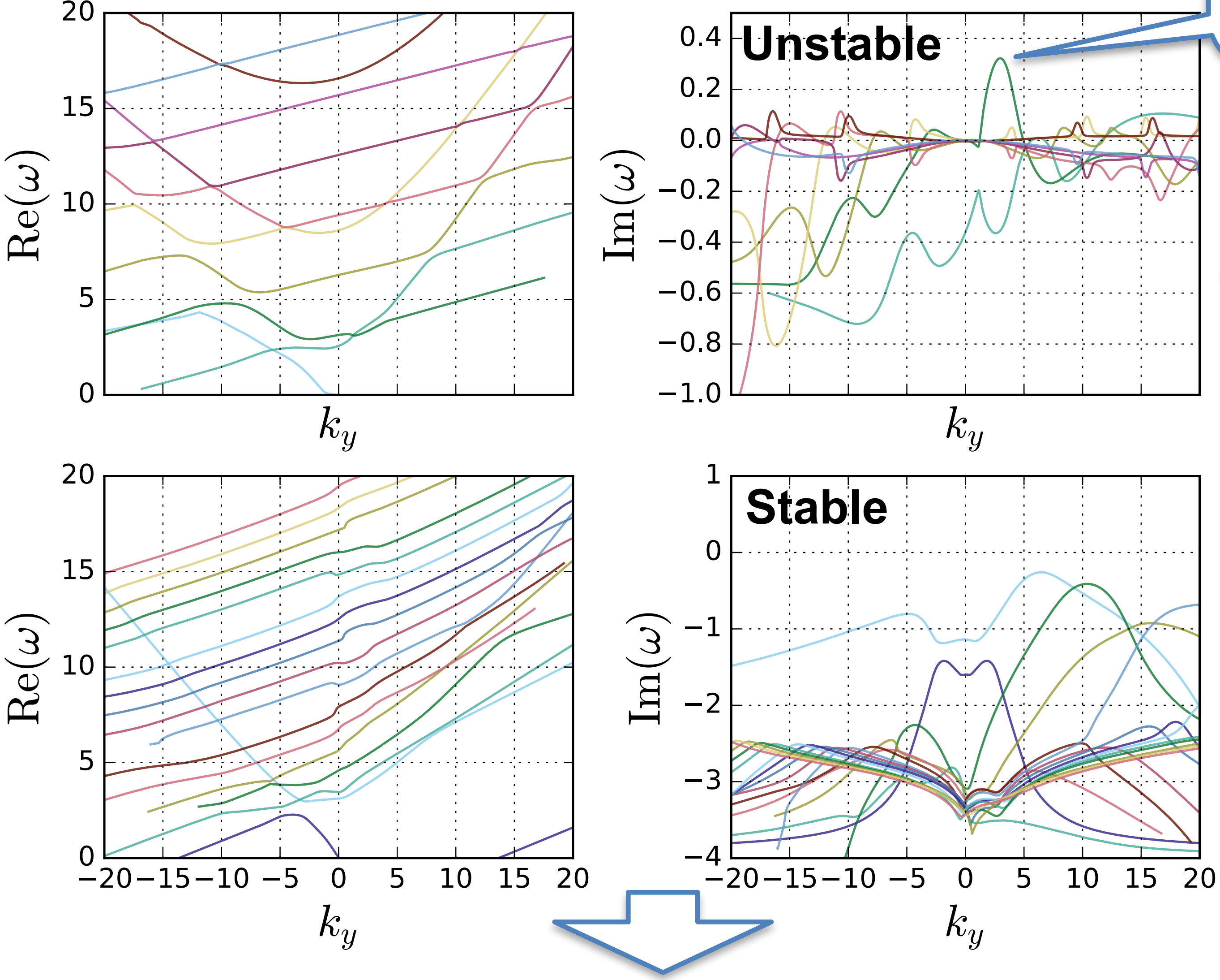
$$\mathbf{v} = \mathbf{v}_0(x) + \mathbf{v}_1(x)\exp(ik_y y - i\omega t)$$

Two types of boundary conditions

1. **Periodic**
2. **D'yakov-Kontorovich** (upstream flow unperturbed because supersonic)



Dispersion relation



Most unstable mode

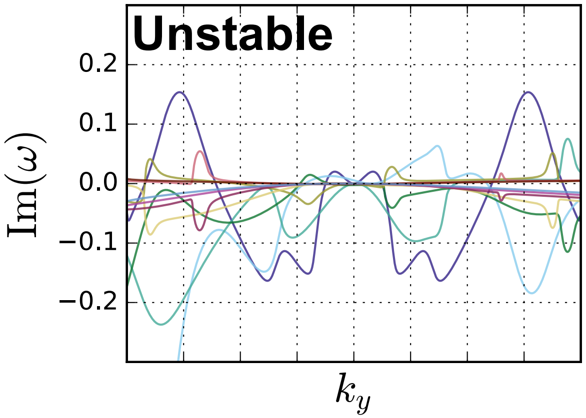
$\Phi_0 = 0.25$
periodic b.c.

$\Phi_0 = 0.25$
DK b.c.

Changing boundary conditions can make the instability disappear!

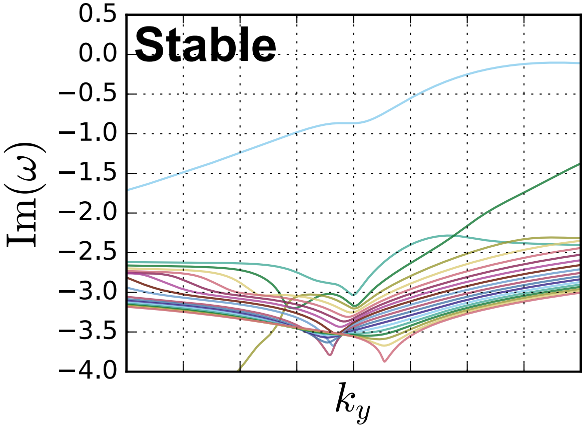
Dispersion relation

Weak/Moderate spiral potential



$\Phi_0 = 0.025$

periodic b.c.

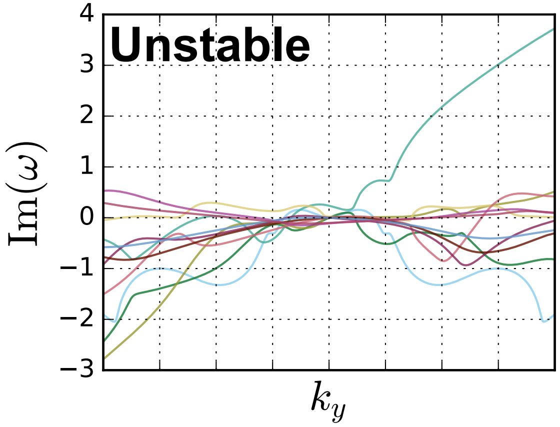


$\Phi_0 = 0.025$

DK b.c.

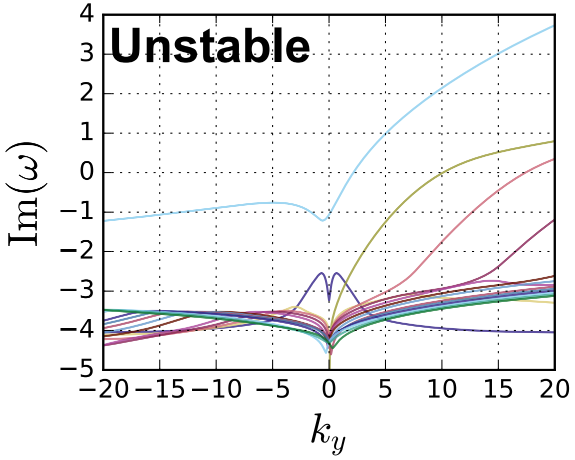
- instability disappears by switching b.c.
- Not KH!

Strong spiral potential



$\Phi_0 = 0.25$

periodic b.c.



$\Phi_0 = 0.25$

DK b.c.

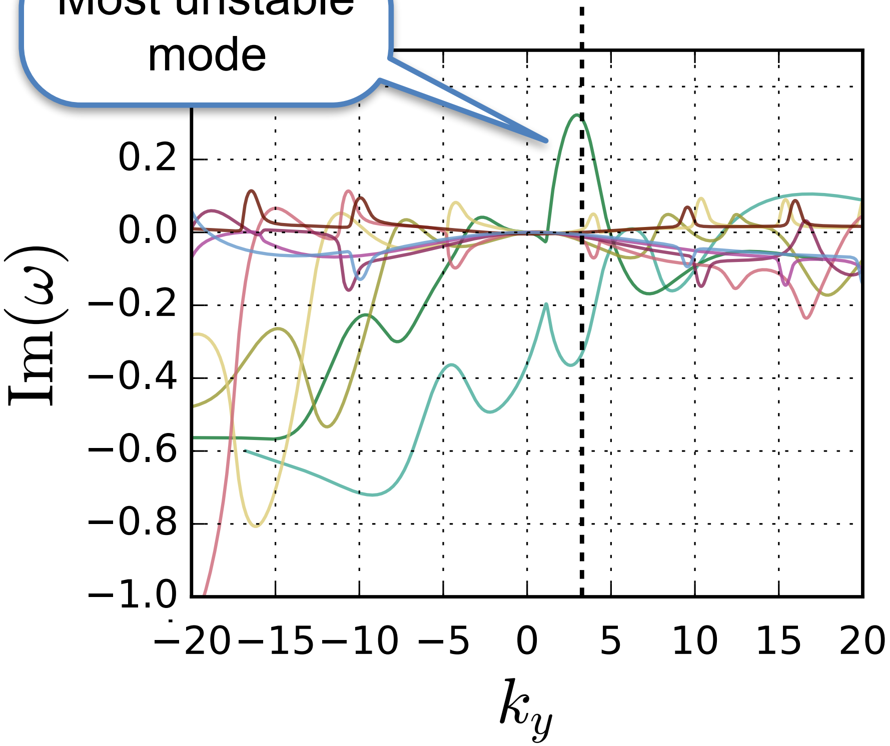
- parasitic KH instability appears on top of periodic shock instability (shear)

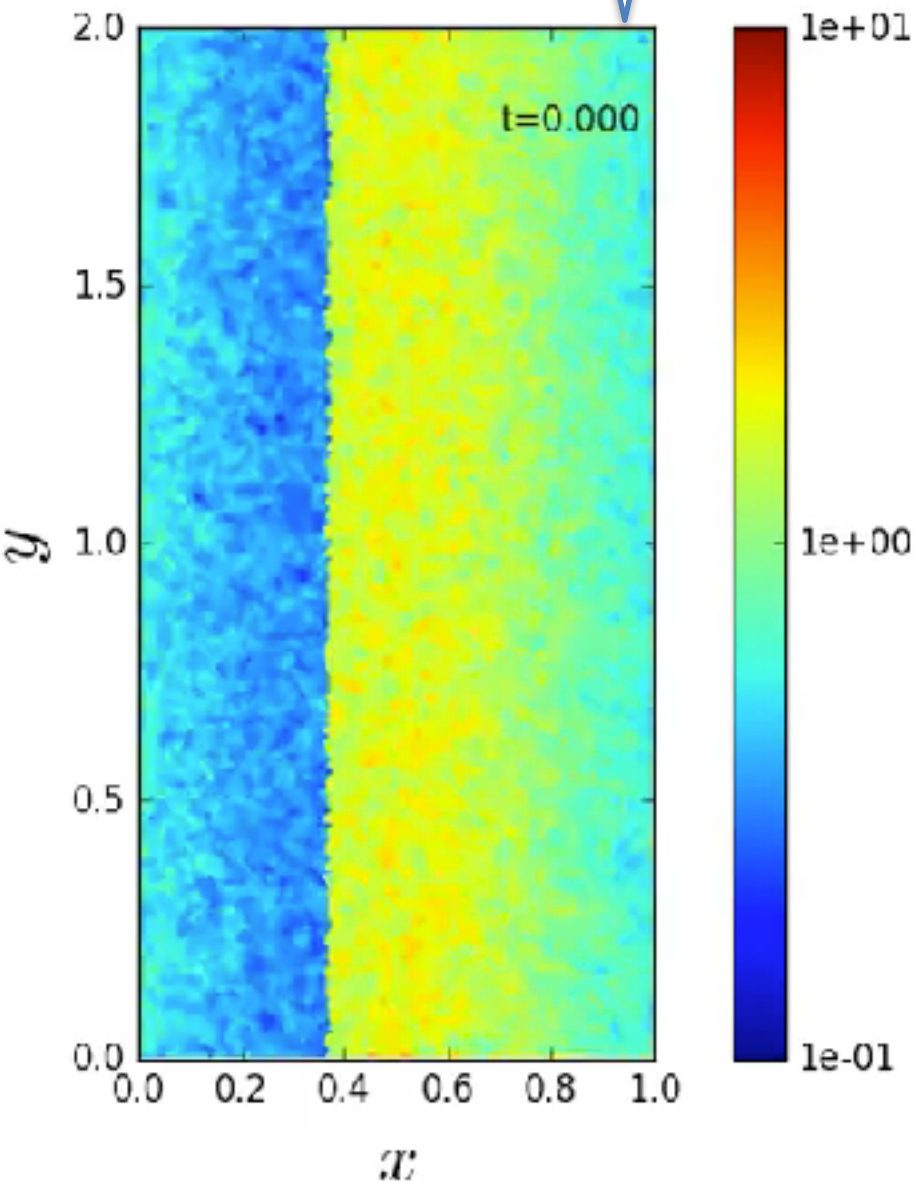
Arepo simulation

- 2D, Isothermal
- **Periodic** b.c.

Same simulation with **inflow-outflow** on left and right boundaries**: is stable!**

Most unstable mode



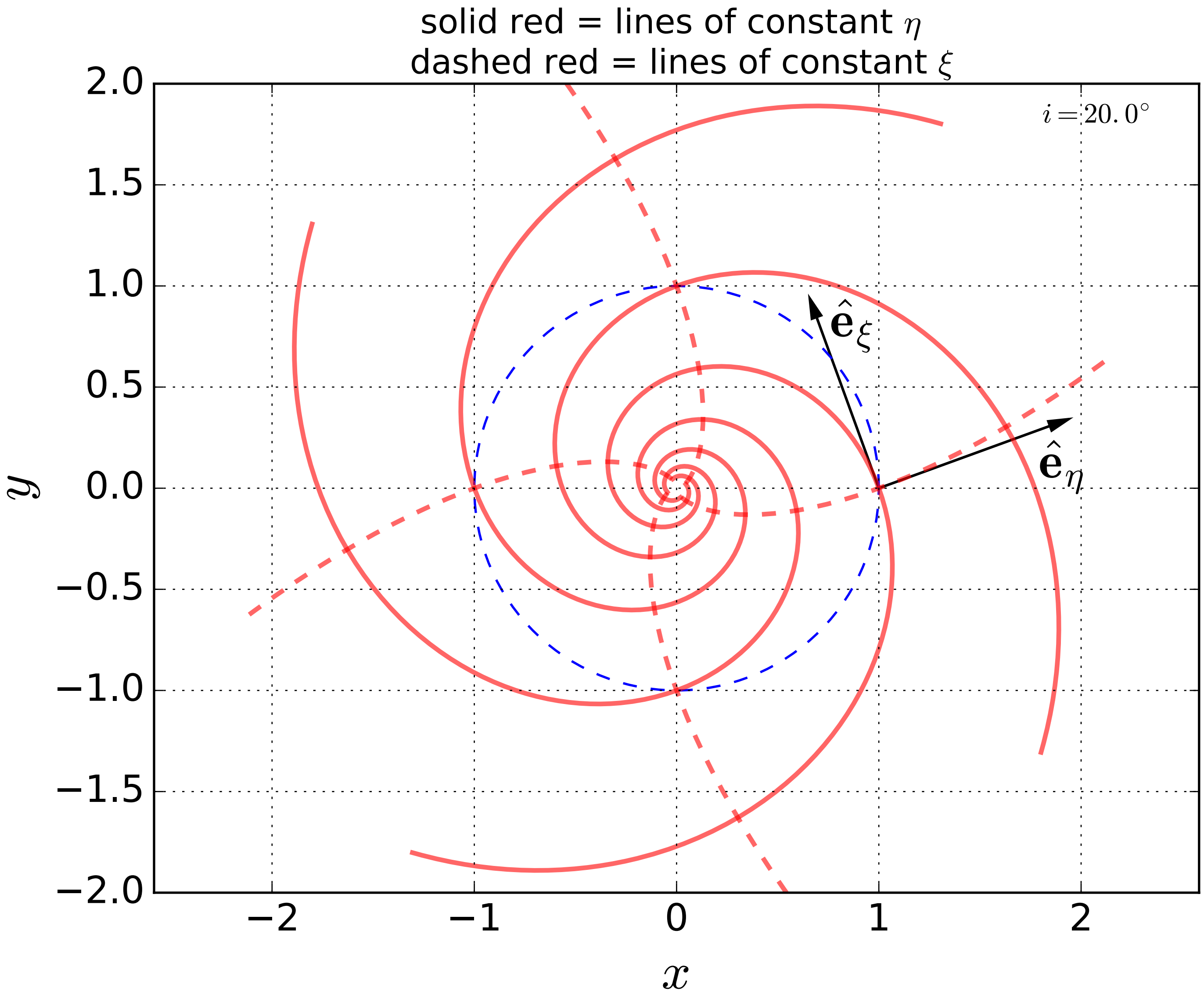


How to derive equations

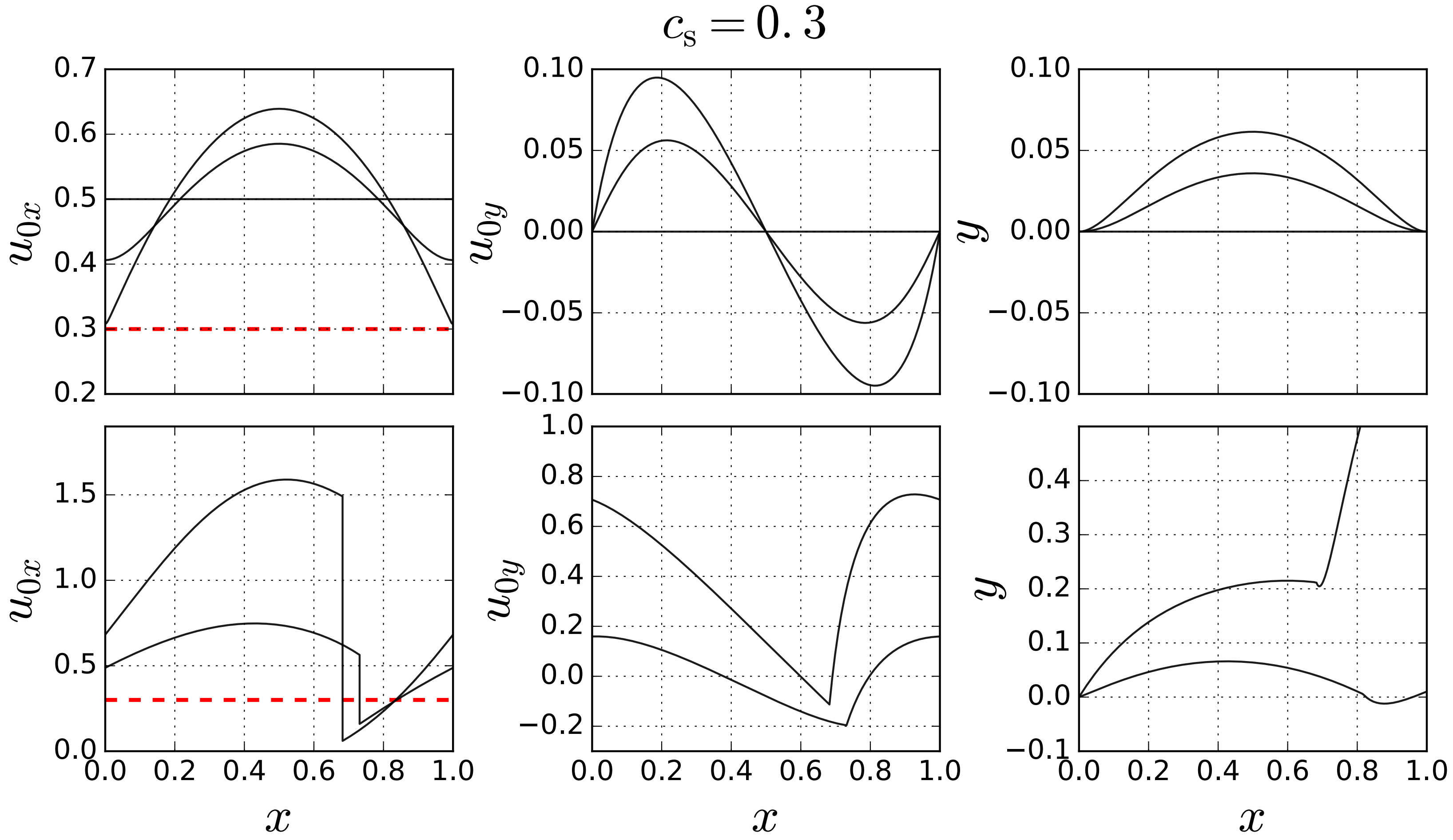
$$\partial_t \mathbf{v} + (\mathbf{v}\cdot\nabla)\,\mathbf{v} = -\frac{\nabla P}{\rho} - \nabla\left(\Phi_0 + \Phi_{\rm s}\right) - 2\boldsymbol{\Omega}_{\rm p} \times \mathbf{v} - \boldsymbol{\Omega}_{\rm p} \times \left(\boldsymbol{\Omega}_{\rm p} \times \mathbf{r}\right)$$

$$\partial_t \mathbf{v} + (\mathbf{v}\cdot\nabla)\,\mathbf{v} = -\frac{\nabla P}{\rho} - \nabla\Phi - 2\Omega \times \mathbf{v} + \mathbf{F}$$

Spiral coordinate system



Steady state - cs03



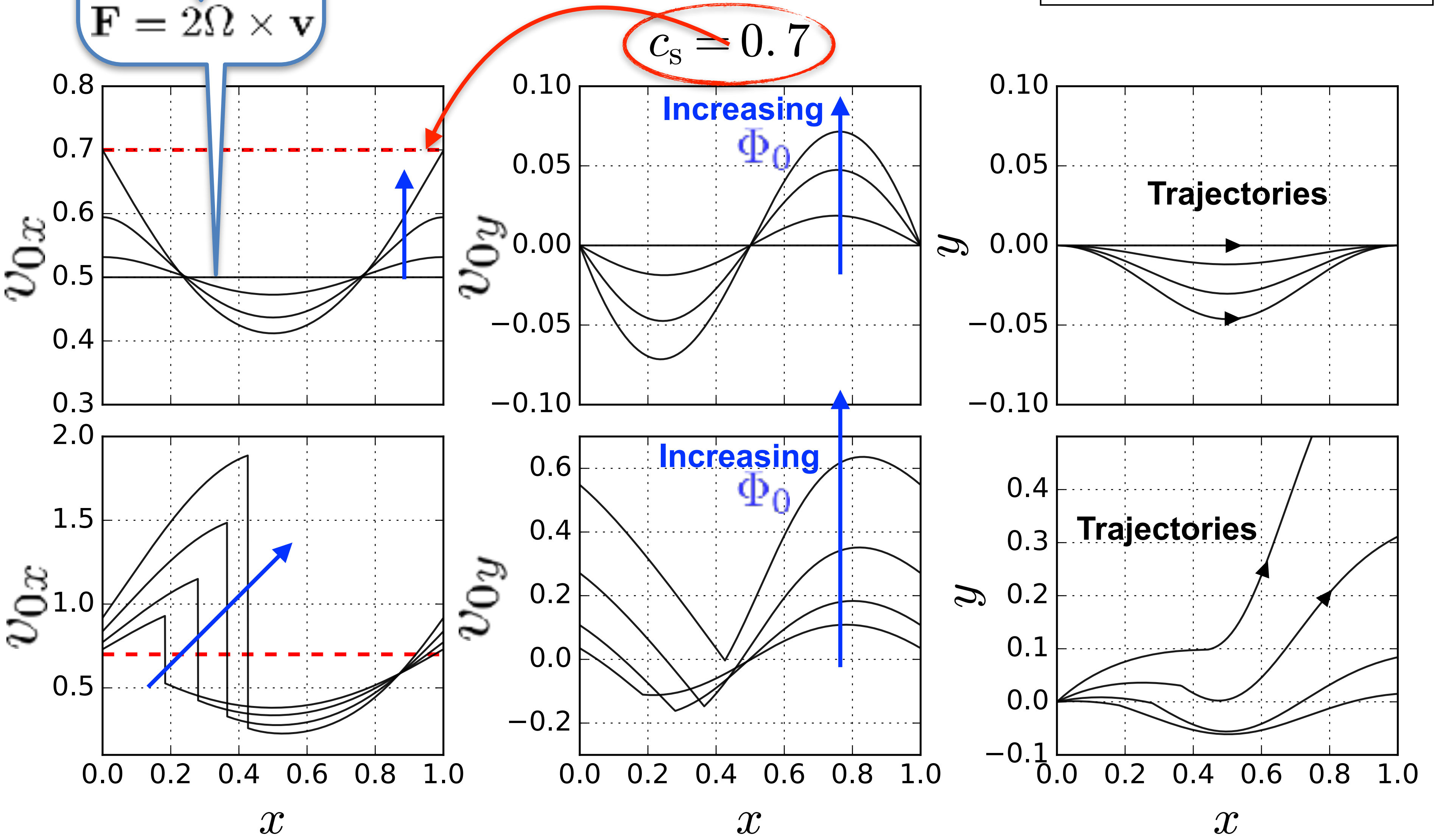
Steady states

- **Periodic in x**
- **Do not depend on y**

$\Phi_0 = 0$

$\Downarrow$

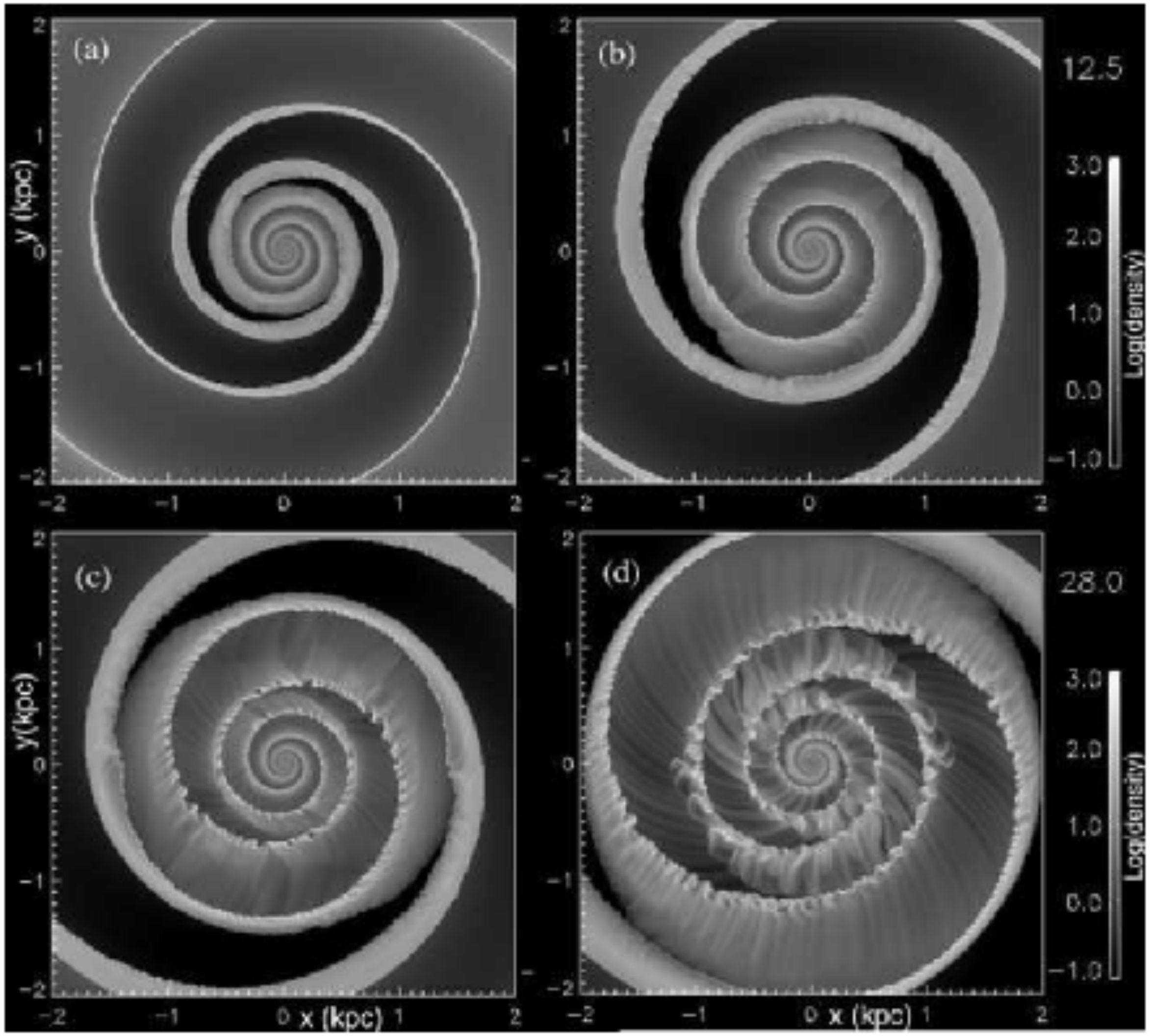
$\mathbf{F} = 2\Omega \times \mathbf{v}$



Wada & Koda 2004

- External spiral potential
- 2D
- Isothermal
- No self-gravity

Why is unstable??



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$$\partial_t \rho + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$P = c_\mathrm{s}^2 \rho$$

$$\Phi(x) = \Phi_0 \cos\left(\frac{2\pi x}{L}\right)$$

Four forces act on the fluid:

- Pressure force $-\nabla P/\rho$
- Coriolis force $-2\Omega \times \mathbf{v}$
- Constant force $\mathbf{F}$
- External potential $-\nabla \Phi$

Take: $L = 1,\ \Omega = 1,\ \mathbf{F} = (0, 1),\ c_\mathrm{s} = 0.3 \,\mathrm{or}\, 0.7,\ \Phi_0 = 0\text{–}0.4$