7th Korean Astrophysics Workshop: Dynamics of Disk Galaxies
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Dynamics of the ISM in Galactic Spirals

in "isolated" and "non-barred" systems

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A review paper "Spiral Structures in Disk Galaxies": Dobbs & Baba (2014?) PASP

related recent papers:

Baba, KW, Saitoh (2012)

KW, Baba, Saitoh (2011)

Fujii, Baba, Saitoh, Makino, Kokubo, KW (2011)

modeling MW => **Baba, Saitoh, KW (2010)**

Baba, Asaki, Makino, Miyoshi, Saitoh, KW (2009)

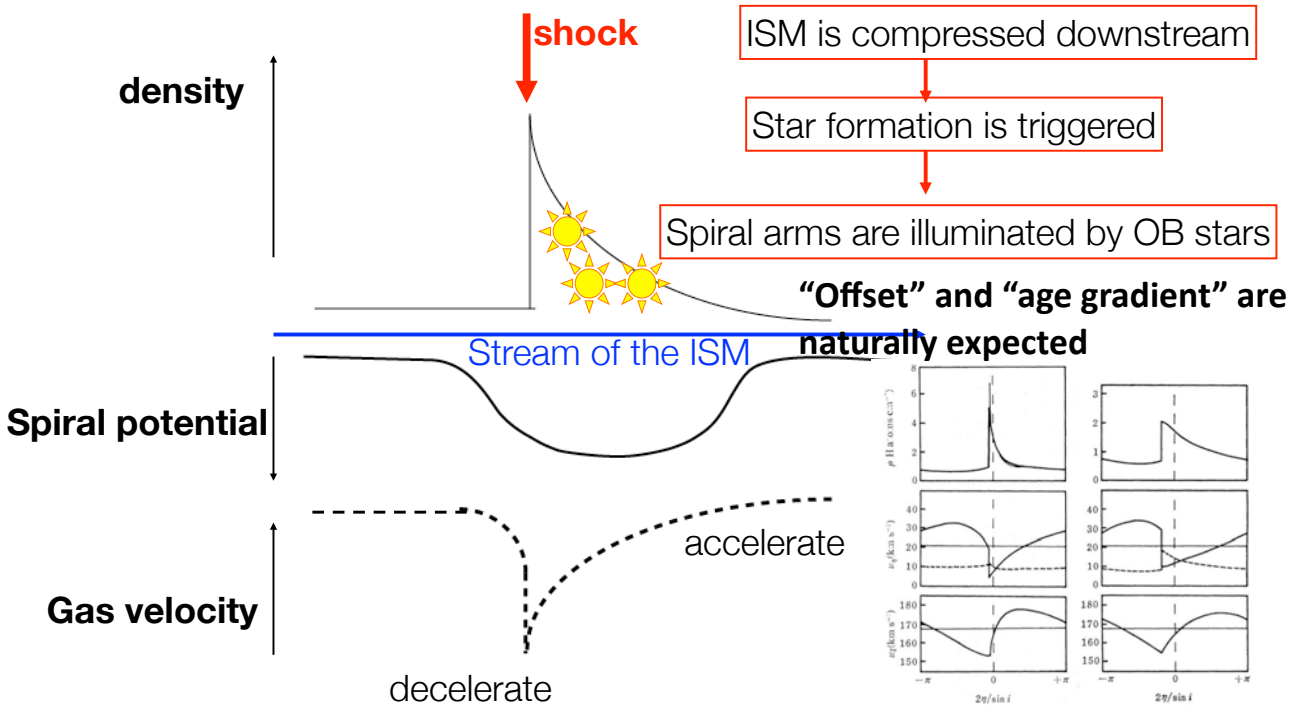
KW (2008)

Outline

1. Conventional pictures of galactic shocks and a more realistic case in a fixed potential
2. Stellar Spirals as structures in dynamic equilibrium
3. ISM in non-steady stellar spirals ≠ galactic shock
4. Observational test: "offset" between stellar and gas spirals

Galactic shock in a tight winding spiral potential

(Fujimoto 1968; Roberts 1969; and many papers in 70s and 80s)

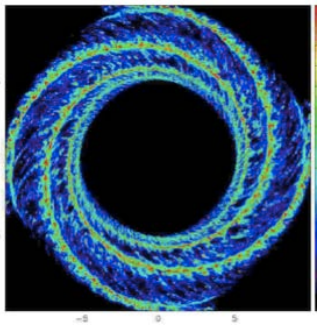


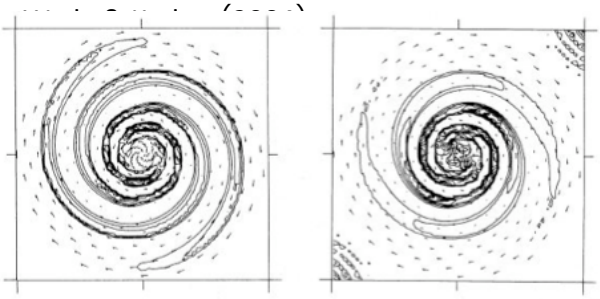
Ishibashi & Yoshii 1984

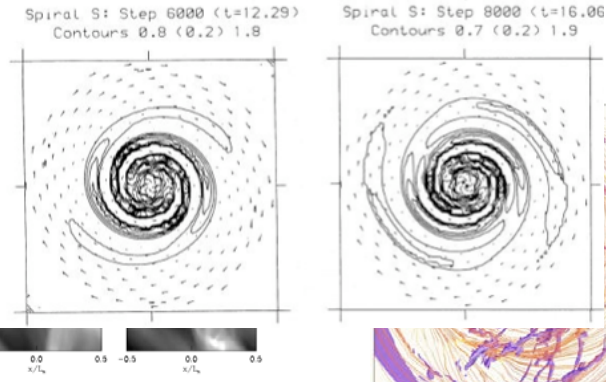
2D/3D Spiral shocks are neither smooth nor stable

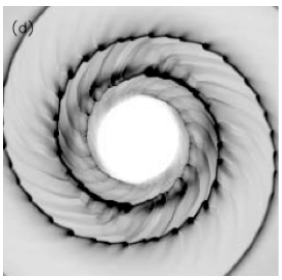
cf. the first 2D simulations of the galactic shocks (Johns&Nelson 1986)

Two-component, SPH Dobbs (2008)









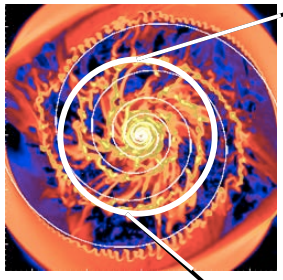
Shetty & Ostriker 2006

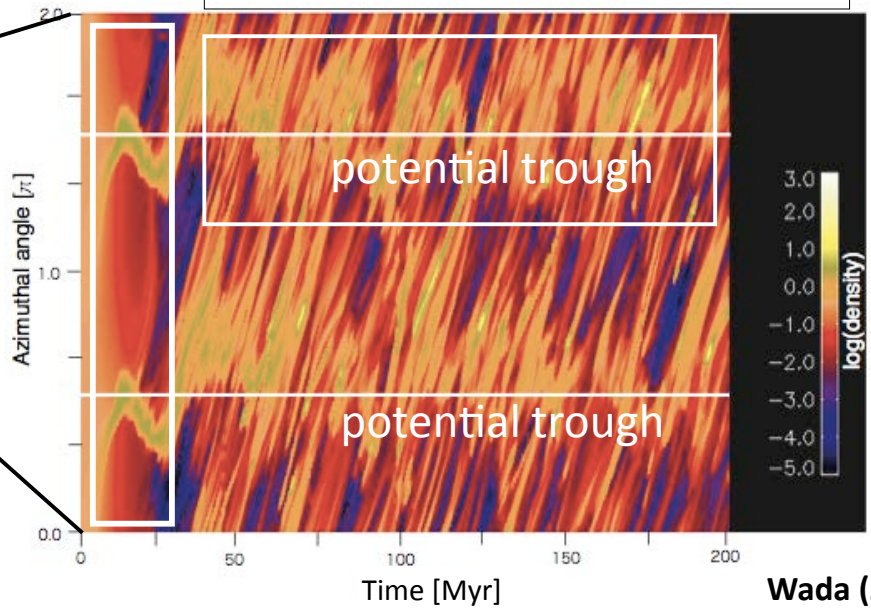
Kim & Ostriker 2006
3D, MHD, self-graivty

Wada (2008)

3D, selfgravity + cooling and heating in steady 2-arm spiral

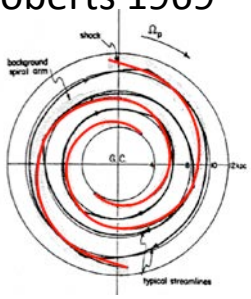
Classic 'galactic shocks' → evolve → inhomogeneous quasi-steady arms + inter-arm substructures





Wada (2008)

Roberts 1969

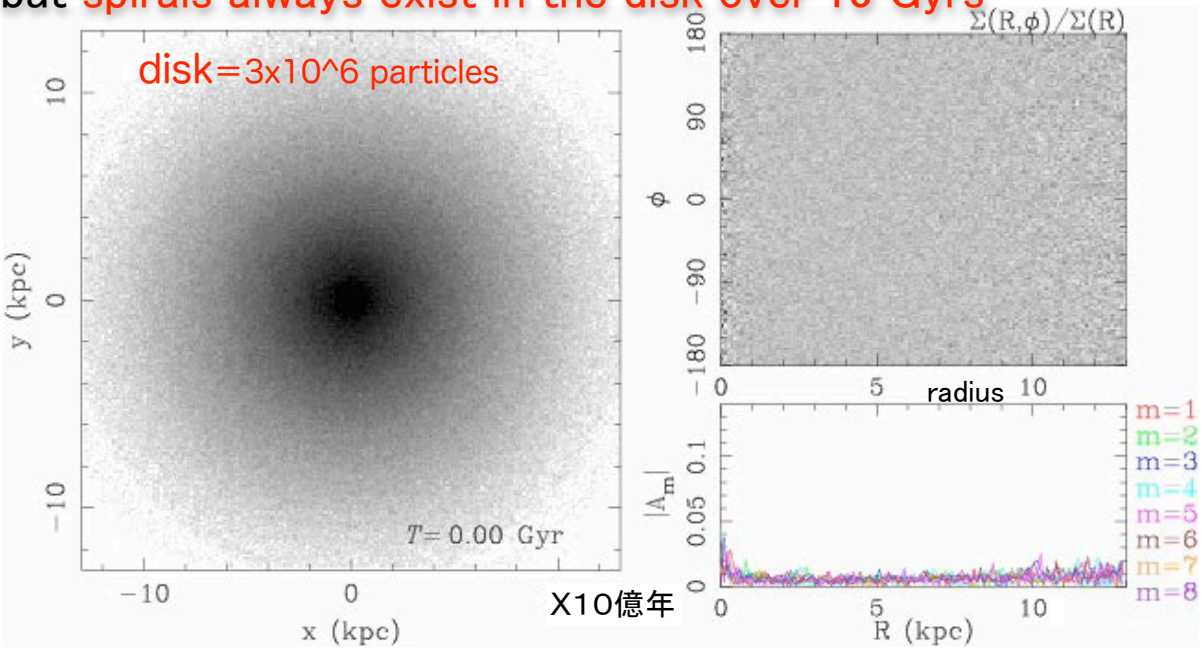


Inhomogeneous arms are loosely associated with the background spiral potential.

3D pure N-body simulations (Fujii et al.)

⇒ each spiral is non-steady, short-lived

but spirals always exist in the disk over 10 Gyrs



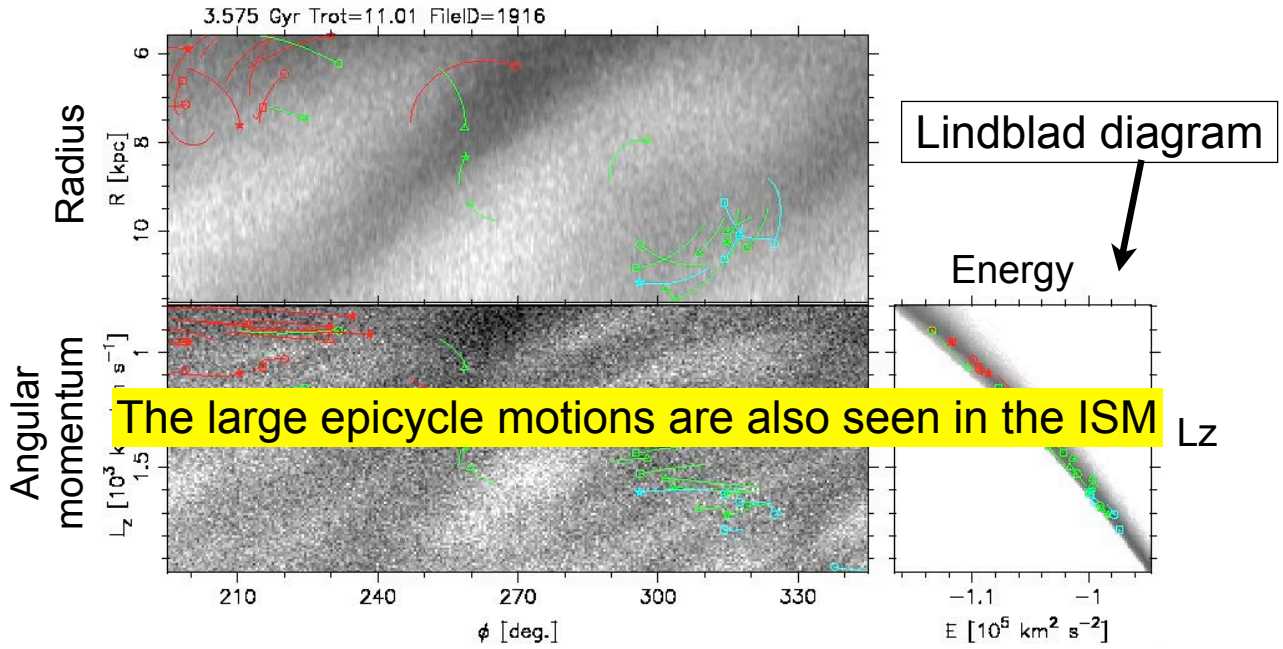
All spiral modes are time-dependent

Baba, Wada,Saitoh (2013)

Swarming stars causes the non-steady spirals:

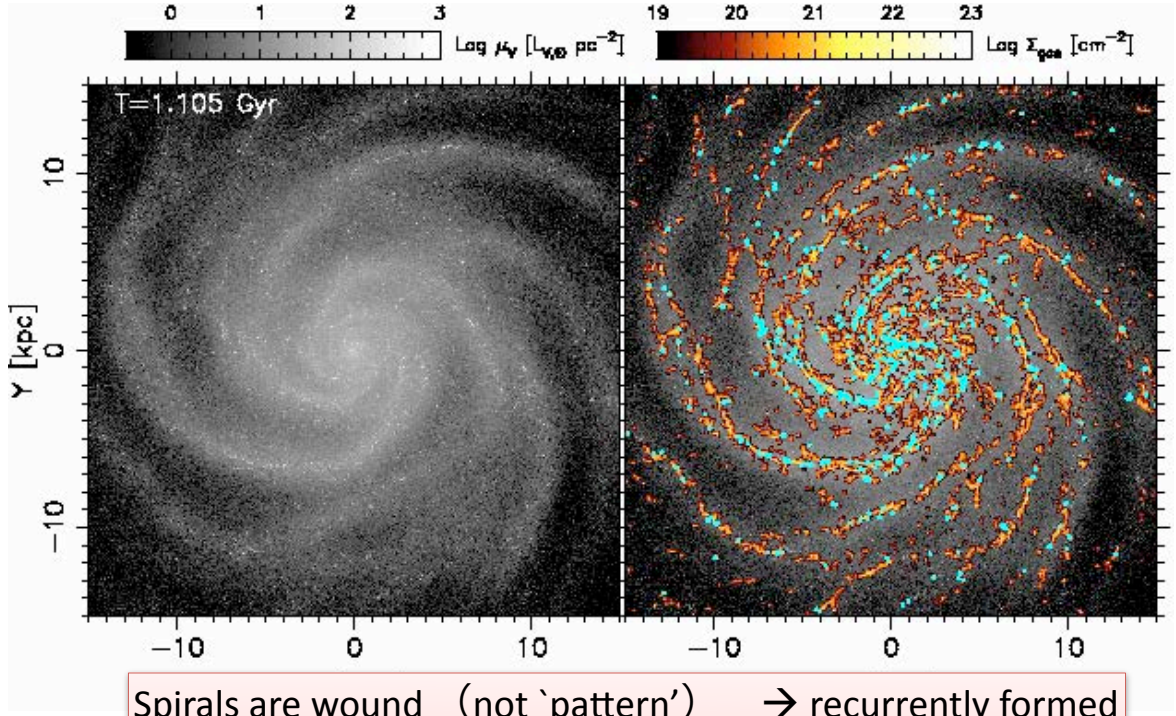
"epicyclic motion", but with a kpc scale travel,
oscillation on angular momentum space

⇒ guiding center moves (L, E are no longer constant) in the non-linear stage ⇒
"swarm" of stars ⇒ non-steady spirals



The large epicycle motions are also seen in the ISM

V-band surface density Gas surface density + young stars



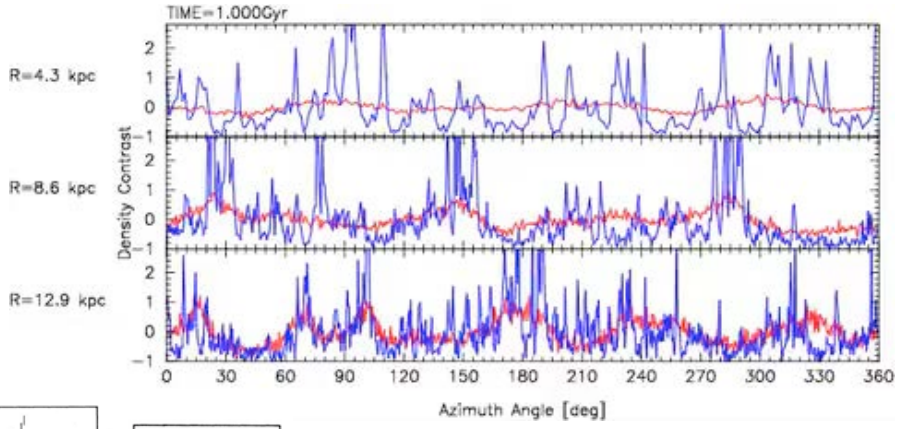
Spirals are wound (not `pattern') → recurrently formed

Non-stationary: stretching/bifurcating/merging

Gas arms are associated with stellar arms with substructure

Amplitude of stars and gas at different radii on their rotating frames

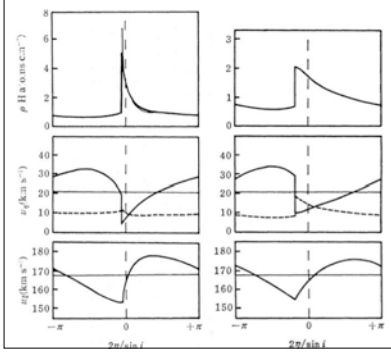
Gas clouds are associated with non-steady stellar arms, without clear offset.



Stellar density

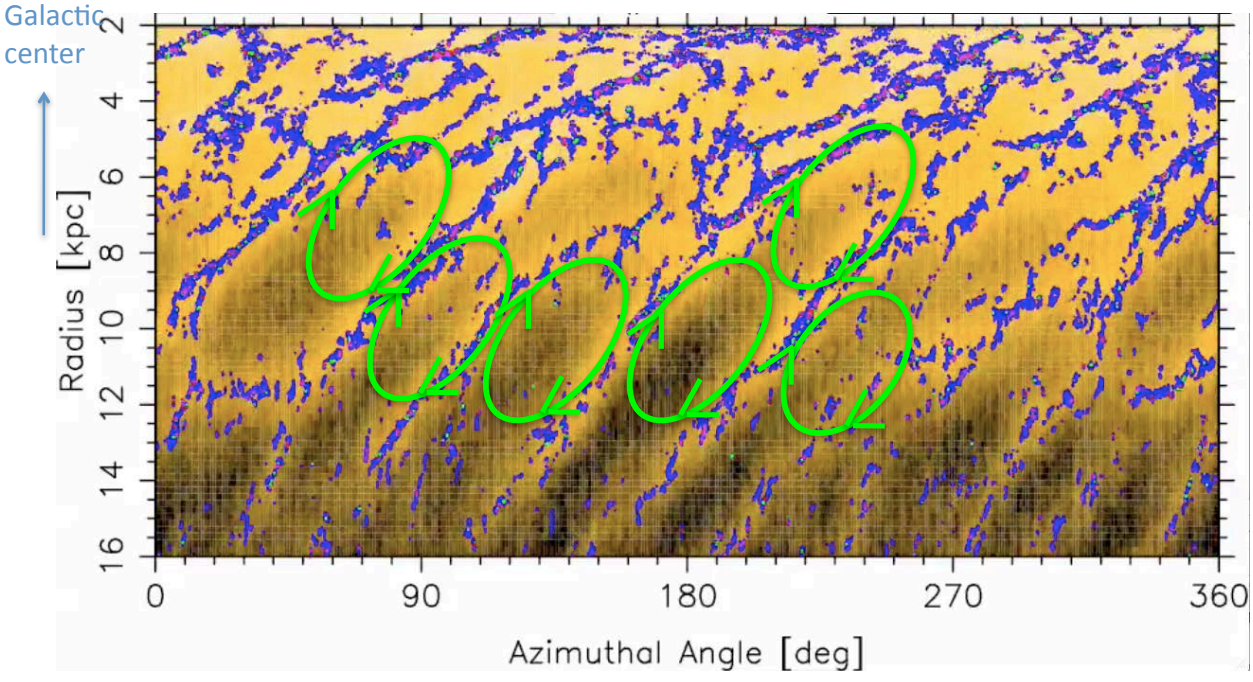
Gas density

KW, Baba, Saitoh (2011)



← steady galactic shock (Ishibashi &Yoshii 1984)

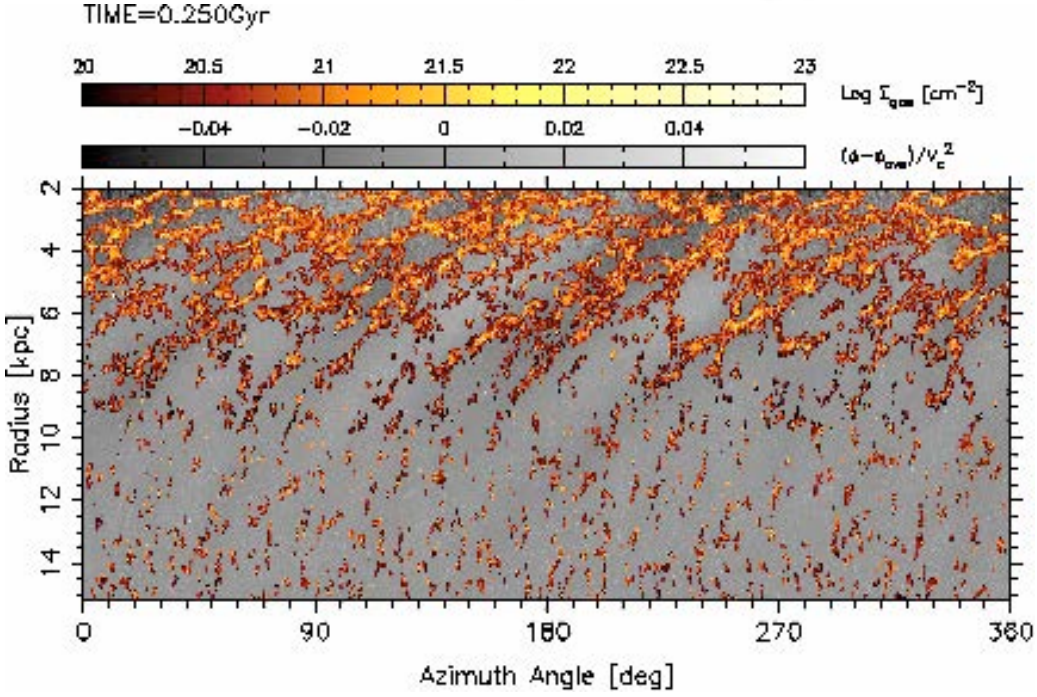
On a local galactic galactic rotating frame,
Cold gas clouds have large (2-3 kpc) "epicycle" motions,
collide near the stellar spirals, forming massive associations.



'GMAs' have **strong shear motion**. → **source of turbulence**?

Dynamics of cold gas and stellar spirals

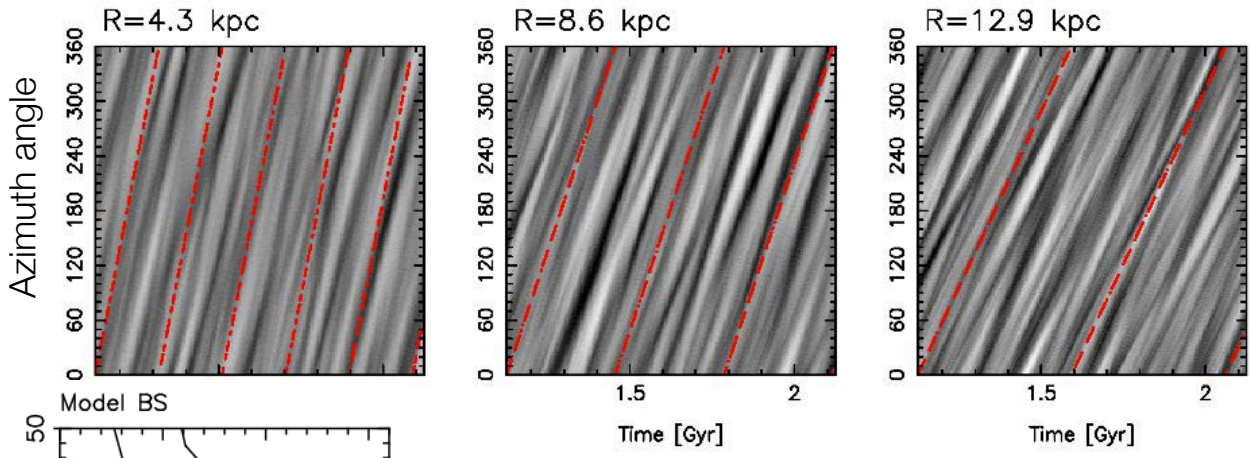
* Cold gases collide near the stellar arms on the rotating frame
* Kpc scale radial motions
* Hard to define "life time of clouds" (=> Dobbs & Pringle)

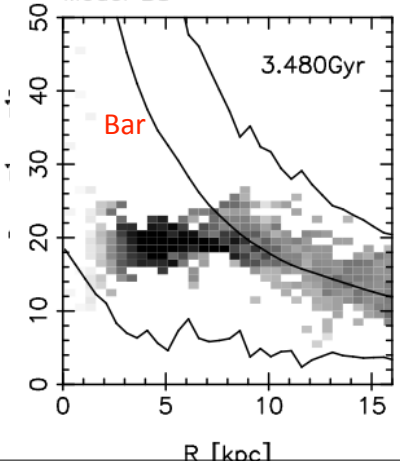


difference between steady & global density waves and non-steady, N-body spirals

Each portion of spiral moves following the galactic rotation

⇒ Not “global waves” with a constant pattern speed



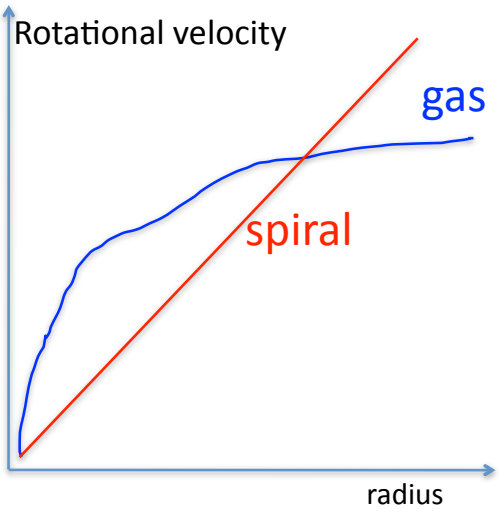


← Angular velocity of m = 4 spirals

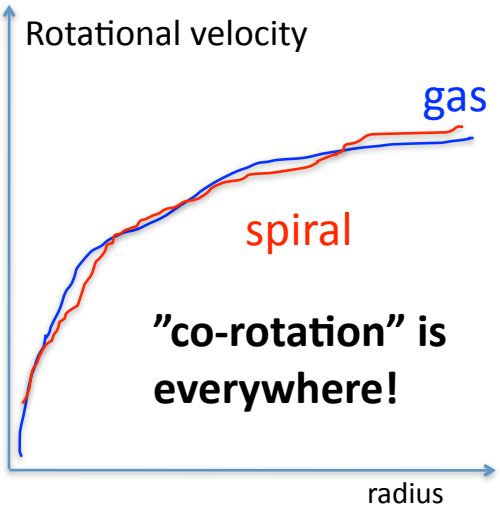
→ High density regions of stars move slower in the outer part

→ The spiral arms are in fact wound!

Essential difference between rigid, global density waves vs. `live’ spirals in a dynamical equilibrium

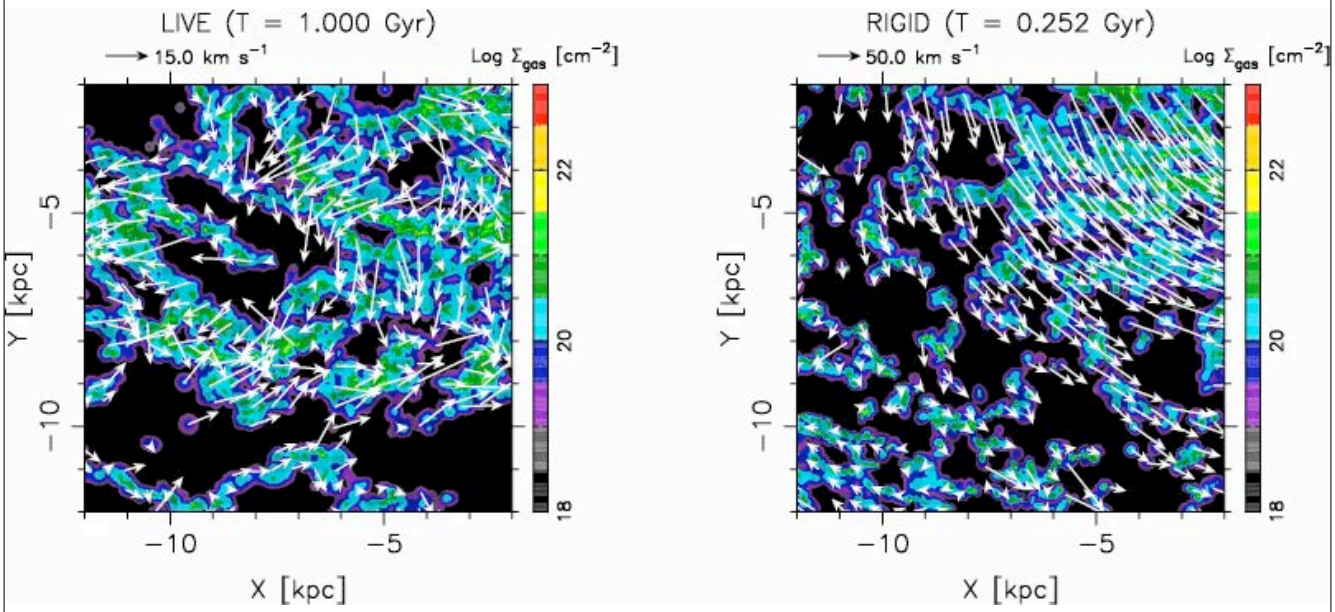


Gas can be ‘supersonic’ for the spiral potential



Gas is ‘subsonic’ (random velocity ~ relative velocity to the stellar potential).

Gas motion: Live vs. Rigid spiral



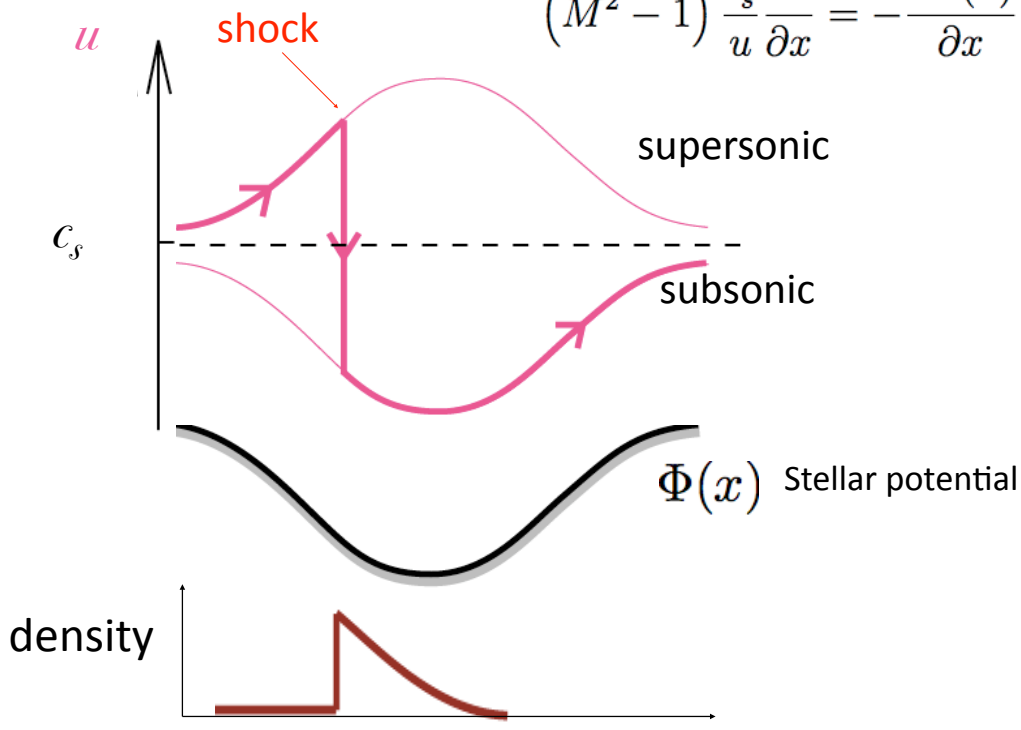
Random or converging flows

Regular flows typically seen in galactic shock

Conventional galactic shock

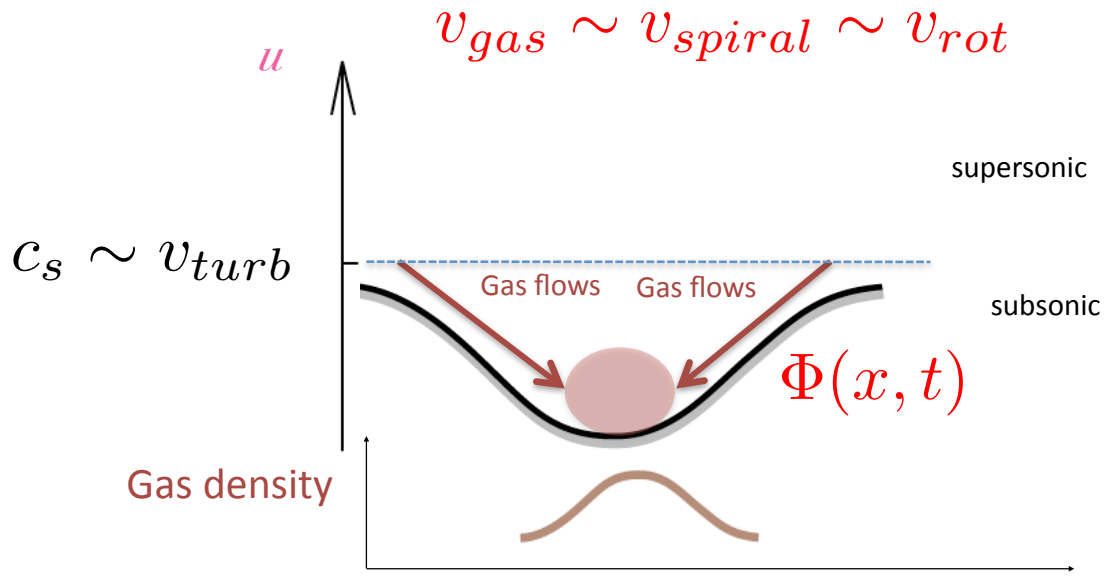
If ISM is supersonic relative to a stationary potential, a shock could be formed.

$$\left(M^2-1\right)\frac{c_s^2}{u}\frac{\partial u}{\partial x}=-\frac{\partial \Phi(x)}{\partial x}$$



new picture of galactic spiral

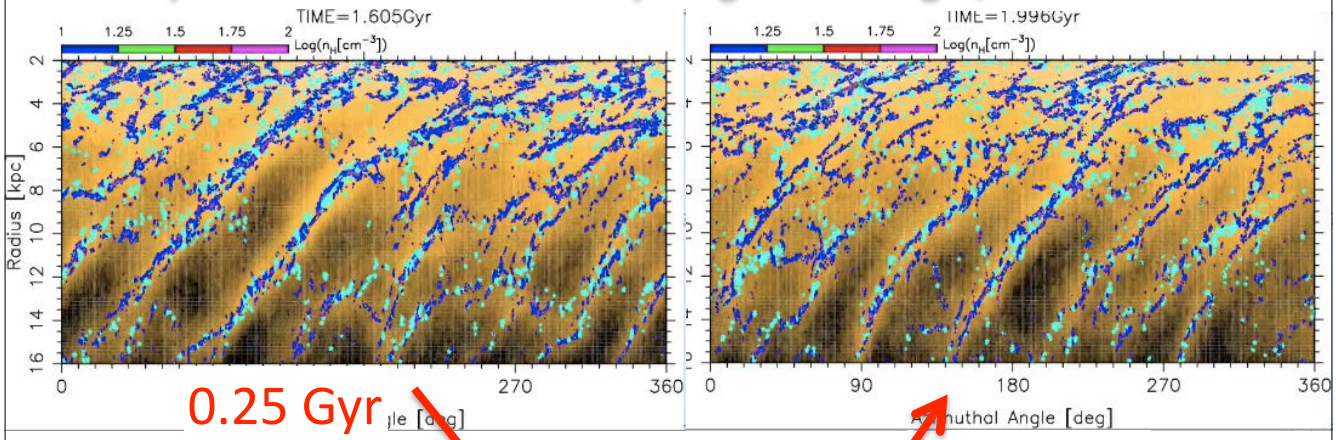
Both ISM and spiral potential follow galactic rotation

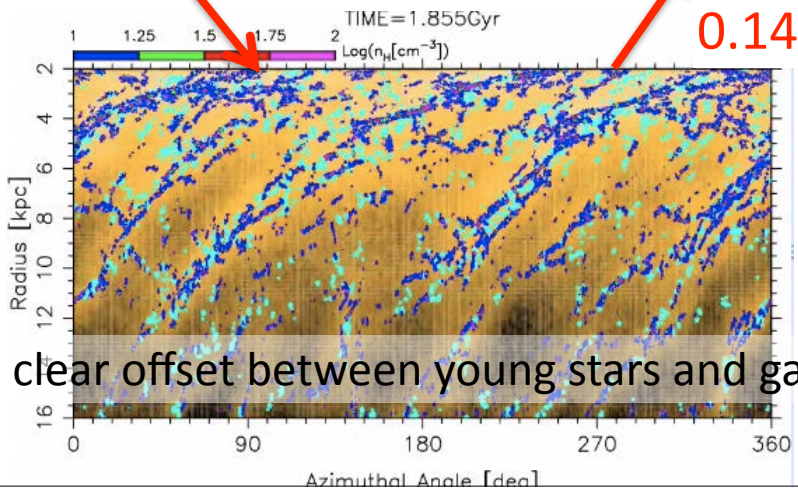


Spiral potential itself is time-dependent
→ This makes the bound-clouds unbound.

No systematic "offset" is expected

No systematic offset between young stars and gas/old stars



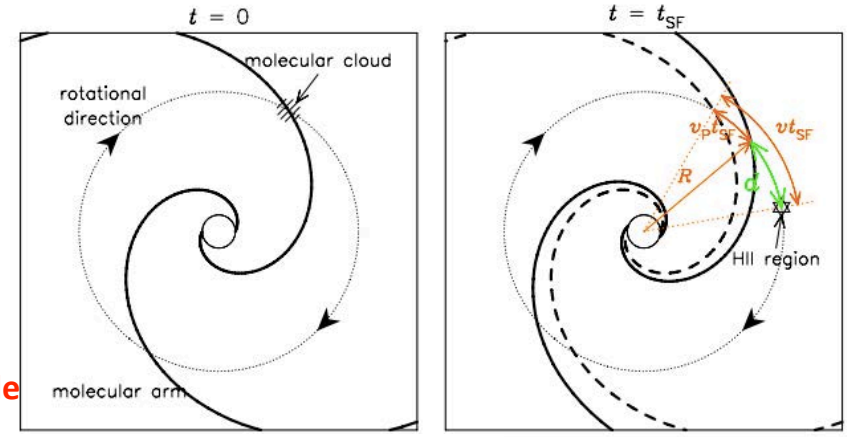


No clear offset between young stars and gas.

Pattern speed of spiral: offset method (Egusa+2009)

Assumptions based on the density wave hypothesis:
1) **spiral pattern is rigid**
2) gas rotates in **pure circular orbits**

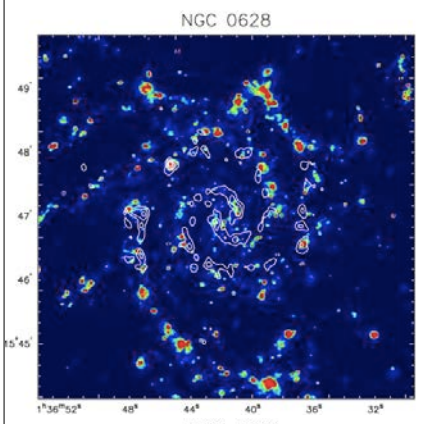
Offset angle is a linear function of Pattern speed and star formation time scale

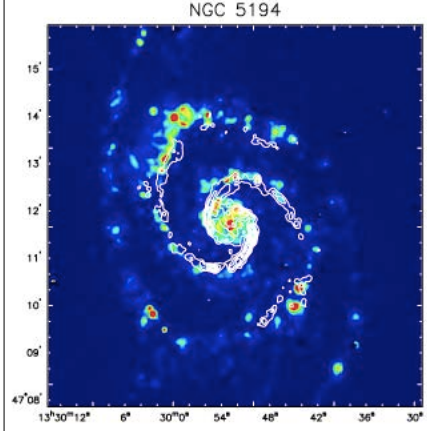


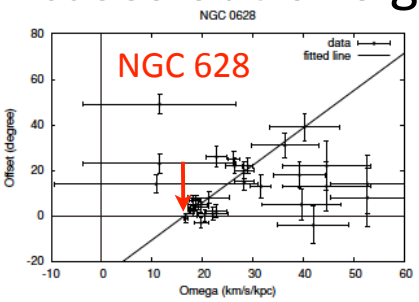
$$\theta = 0.586\left[\left(\frac{\Omega}{\mathrm{km\ s^{-1}\ kpc^{-1}}}\right) - \left(\frac{\Omega_P}{\mathrm{km\ s^{-1}\ kpc^{-1}}}\right)\right] \times \left(\frac{t_{SF}}{10^7\ \mathrm{yr}}\right) \quad \text{(degree)}.$$

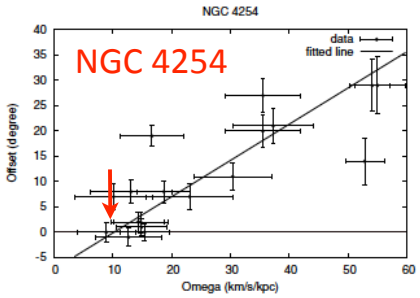
Five "successful" cases out of eight

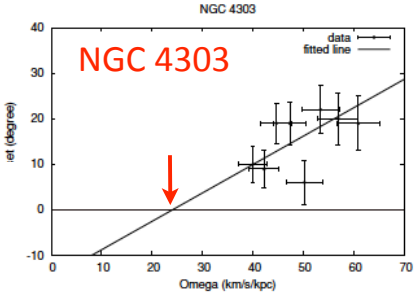
Egusa+2009

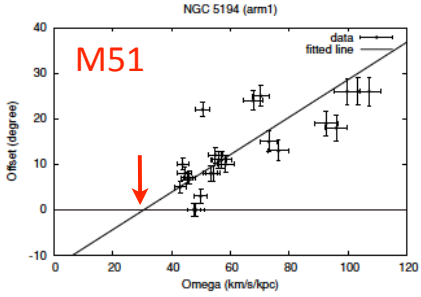


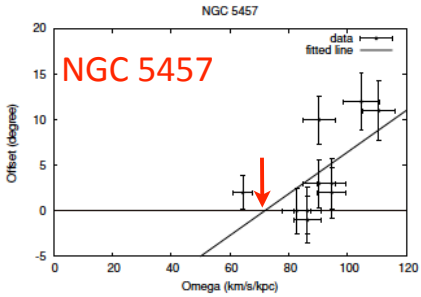












Summary: new picture of multi-arm spirals in an isolated/non-barred galaxies

■ Stellar spirals＝ Dynamic equilibrium structures in a self-gravitating disk

Key physics: **non-linear epicycle motion+ comoving with galactic rotation** (Baba, KW, Saitoh 2013)

■ **Both stellar spirals& ISM move following galactic differential rotation** (KW, Baba, Saitoh 2012)

⇒ ISM falls into the spiral potential from both sides, forming dense regions (⇒ GMCs) ⇒ The dense gas moves into the inter-arm region as the potential changes ⇒ entering other spirals ⇒

■ **Galactic spirals in isolated systems are NOT global, standing galactic shocks.** We do not expect systematic offset between gas and stars (spirals).