

# Dynamical Picture of the ISM associated with Spiral Arms

Keiichi Wada

Kagoshima University, Japan

related recent papers:

**Baba, KW, Saitoh (2012)**

**KW, Baba, Saitoh (2011)**

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

**Baba, Saitoh, KW (2010)**

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

**KW (2008)**

## Contents

### 1. Conventional pictures of galactic spirals

stability of “galactic shocks” in static spirals

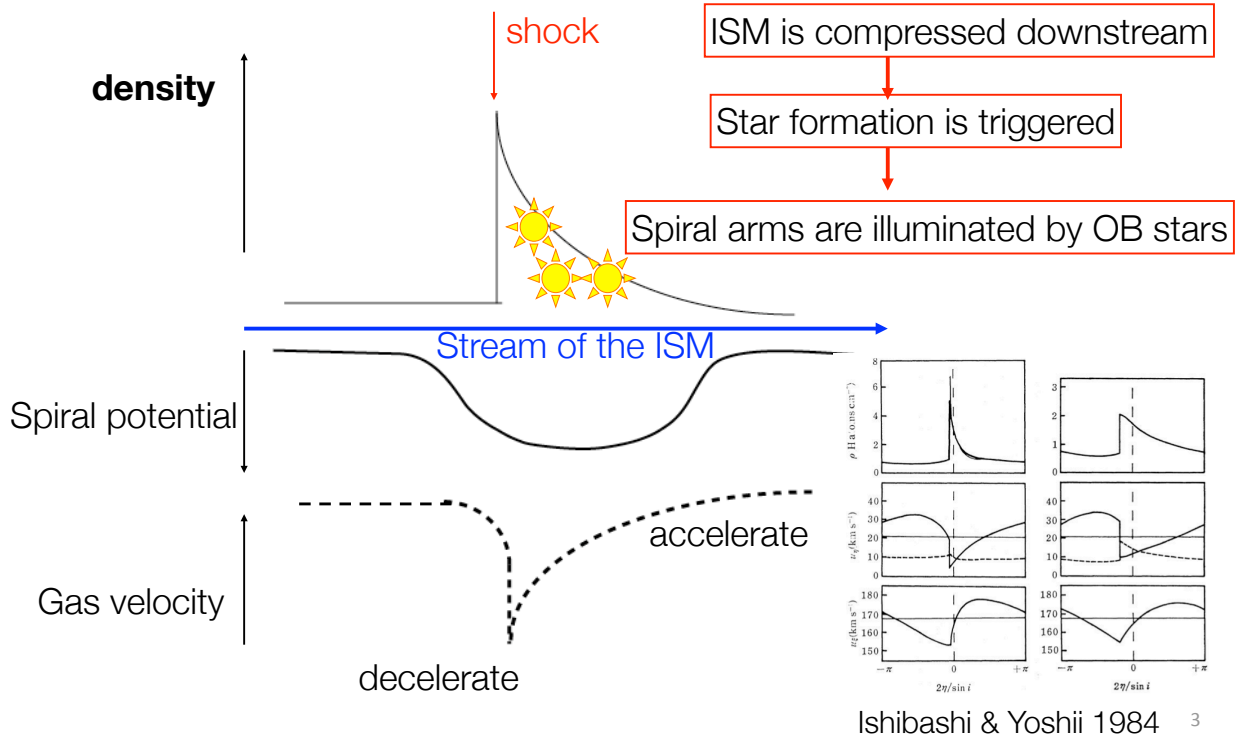
### 2. Stellar Spirals as structures in dynamic equilibrium

### 3. ISM in non-steady stellar spirals

a model for MW

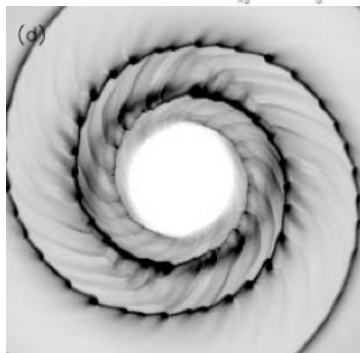
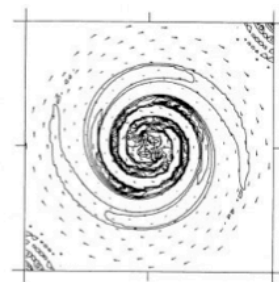
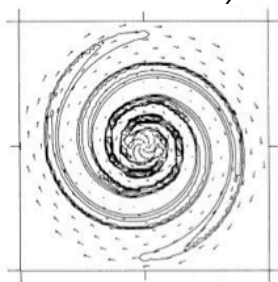
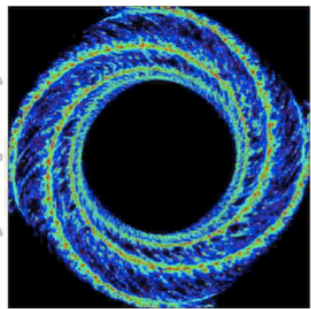
### 4. “offset” between stellar and gas spirals

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

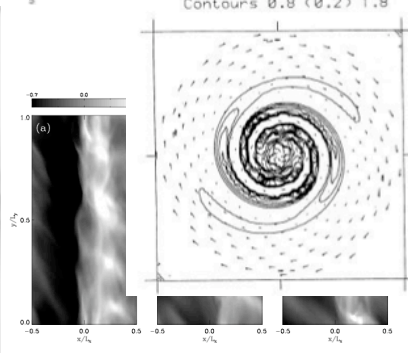


## 2D/3D Spiral shocks are neither smooth nor stable cf. the first 2D simulations of the galactic shocks (Johns & Nelson 1986)

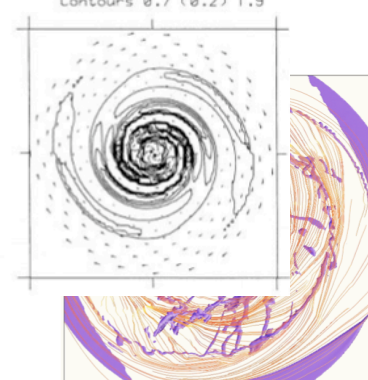
Two-component, SPH Dobbs (2008)



Shetty & Ostriker 2006

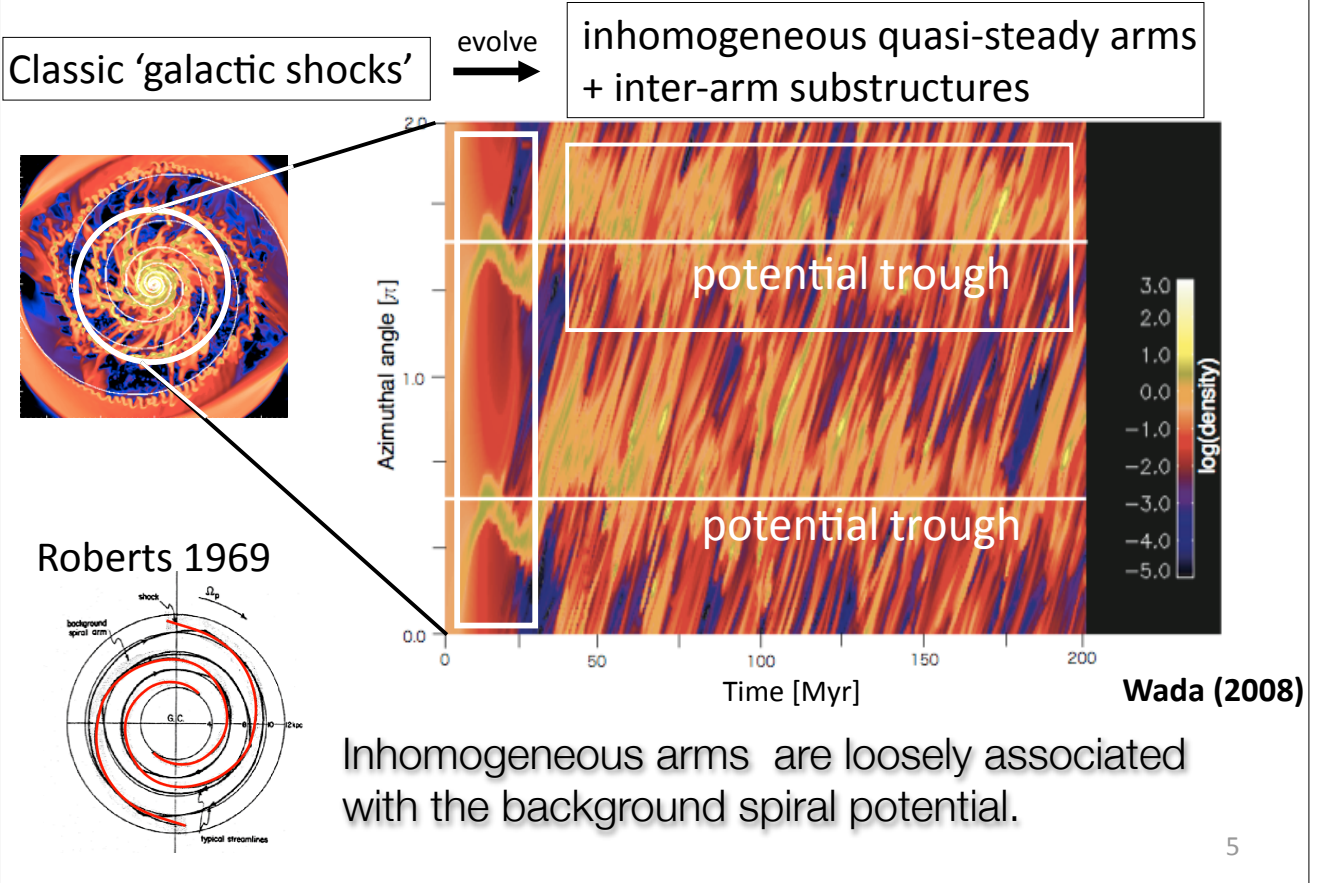


Kim & Ostriker 2006  
3D, MHD, self-gravity



Wada (2008)

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



## Are galactic spirals stationary?

--> controversy over 50yrs

ON THE SPIRAL STRUCTURE OF DISK GALAXIES

C. C. LIN AND FRANK H. SHU

Department of Mathematics, Massachusetts Institute of Technology

Received March 20, 1964



ApJ 140, 640 (1964)

**Toomre: spirals = material arms, destroyed by differential rotation, reformed by gravitational instability**

Toomre tends to favor the first of the possibilities described above. In his point of view, the material clumping is periodically destroyed by differential rotation and re-generated by gravitational instability. It is somewhat difficult to see how this mechanism alone can account for the relatively regular spiral pattern over the whole disk in most of the flat galaxies. The present authors favor the second point of view, i.e., that the matter in the galaxy (stars and gas) can maintain a density wave through gravitational interaction in the presence of the differential rotation of the various parts of

**Lin&Shu: steady density wave**

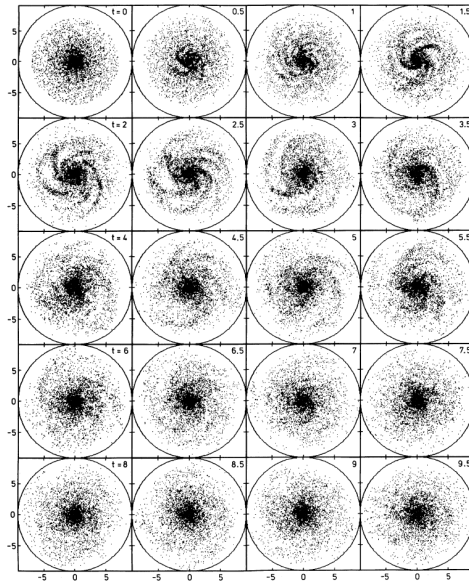
**Toomre(1969) : energy of waves is radially transferred, and it is absorbed at resonances  $\rightarrow$  some other mechanism is necessary to keep steady waves.**

Toomre was probably right.

we have never seen  
tightly wound, stationary spiral waves with a single  
pattern speed  
in N-body (or N-body+gas) simulations (e.g. J.  
Sellwood, M. Fujii)

N-body spirals are not  
stationary, but evolving.

2D  
Sellwood, Carlberg (1984)

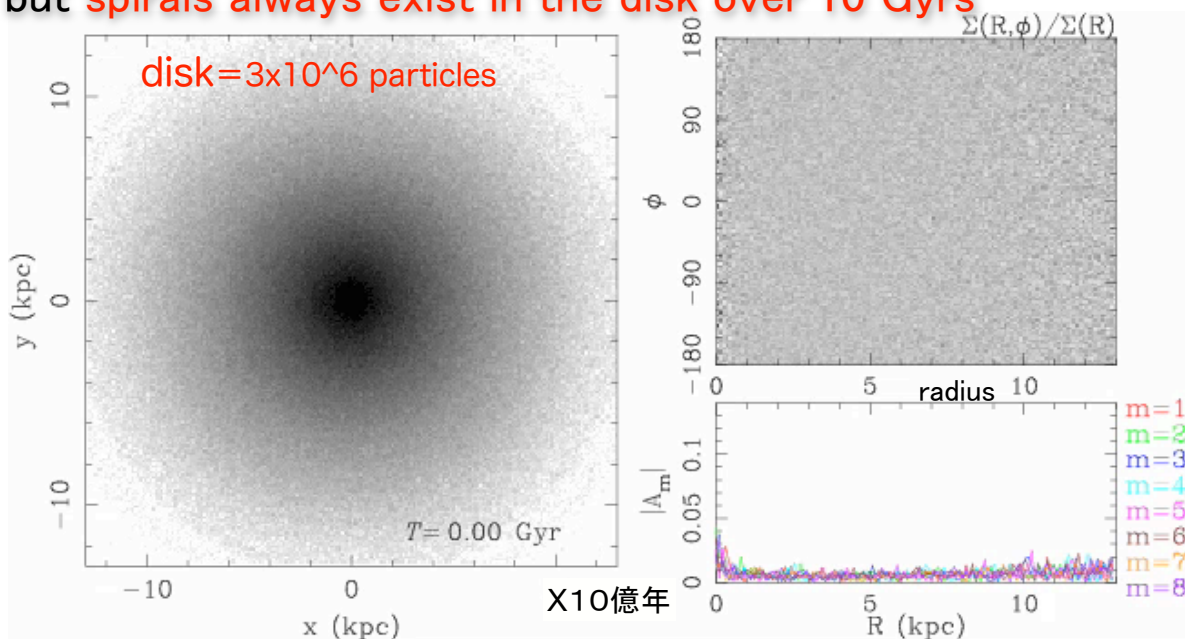


7

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

⇒ each spiral is **non-steady**,

but **spirals always exist in the disk over 10 Gyrs**

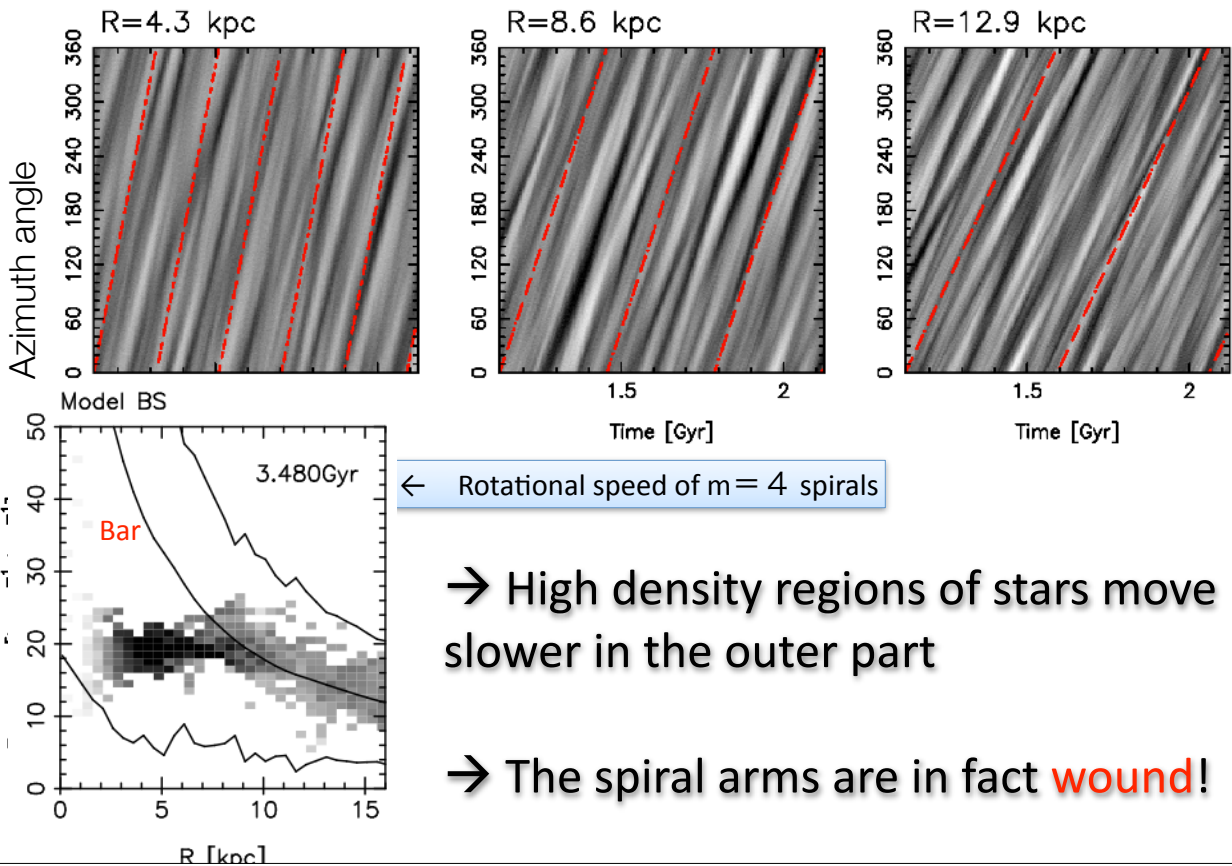


All spiral modes are time-dependent



Each portion of spiral moves following the galactic rotation

⇒ Not “waves” with a constant pattern speed

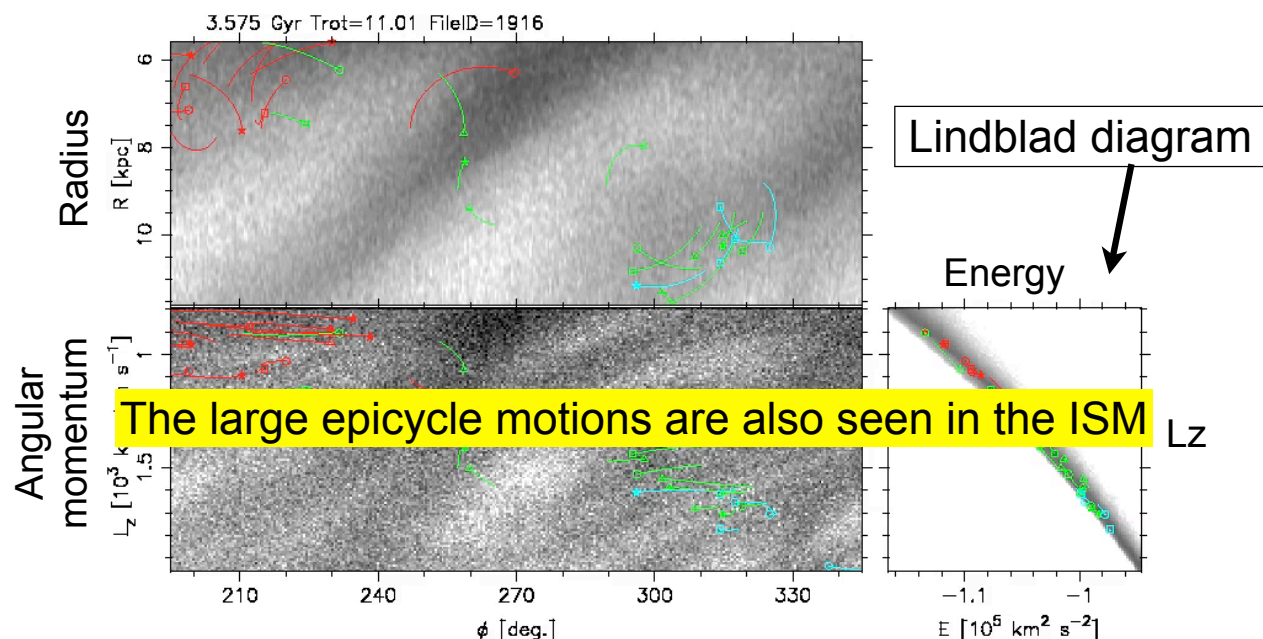


### Particle motions in the non-steady spirals:

Baba, Wada, Saitoh (2013)

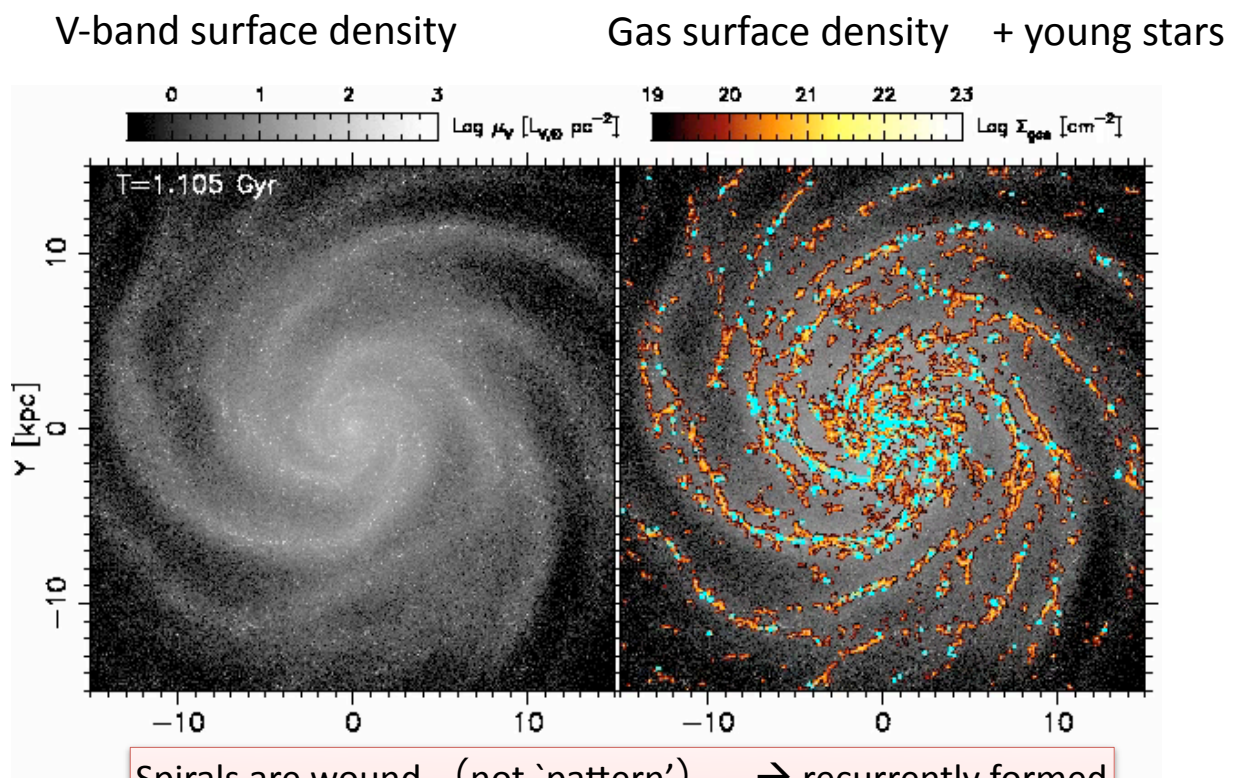
“epicyclic motion”, but with a **kpc scale travel**,  
oscillation on angular momentum space

⇒ **guiding center moves** ( $L$ ,  $E$  are no longer constant) in the non-linear stage ⇒  
**non-steady spirals**



# ISM in non-steady stellar spirals

11

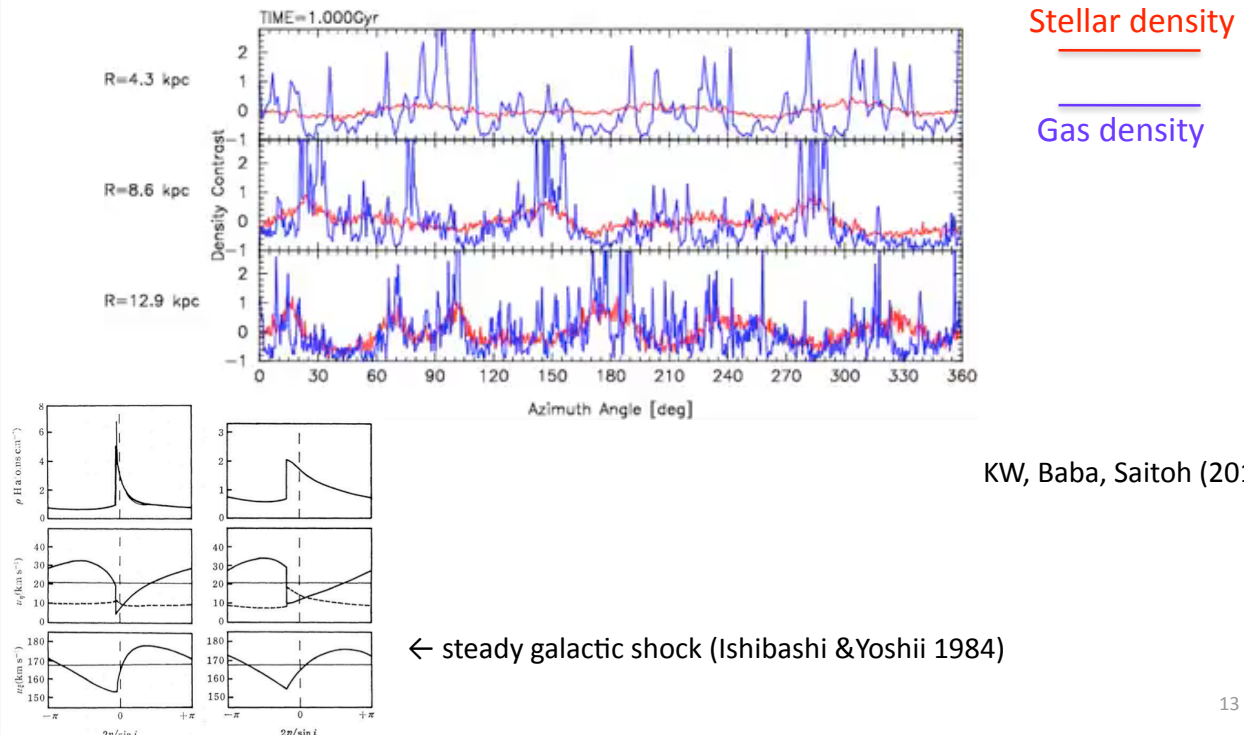


Spirals are wound (not 'pattern') → recurrently formed  
Non-stationary: stretching/bifurcating/merging  
Gas arms are associated with stellar arms with substructure

12

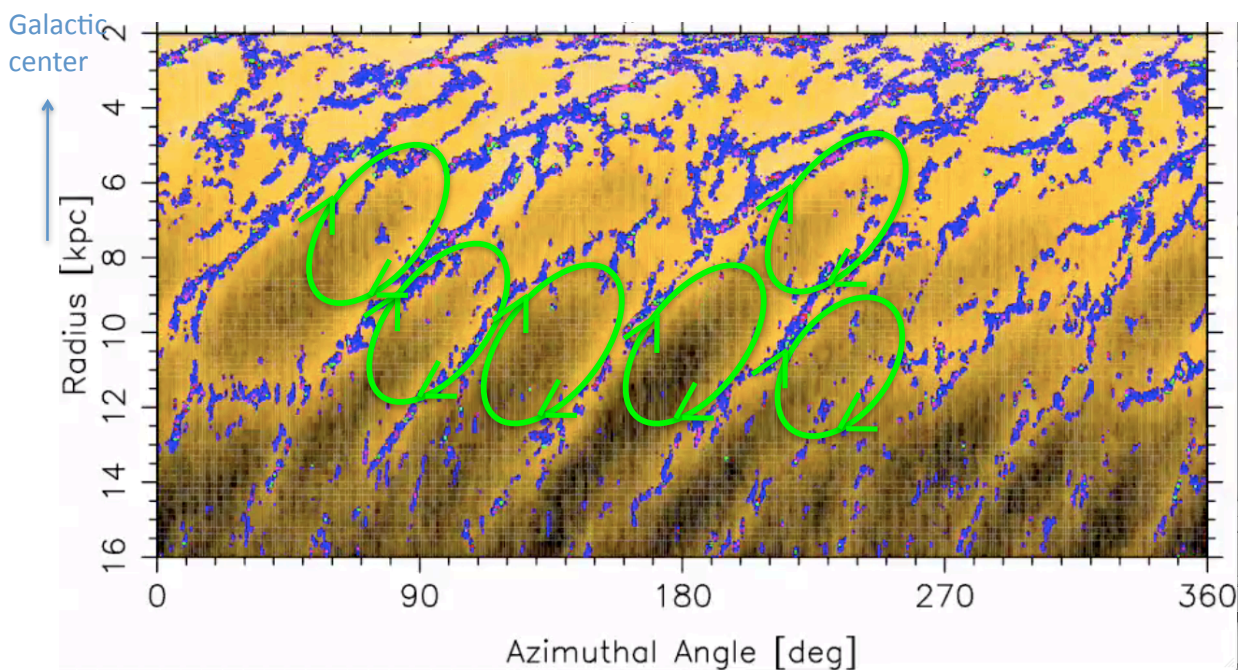
# Amplitude of stars and gas at different radii on their rotating frames

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



13

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



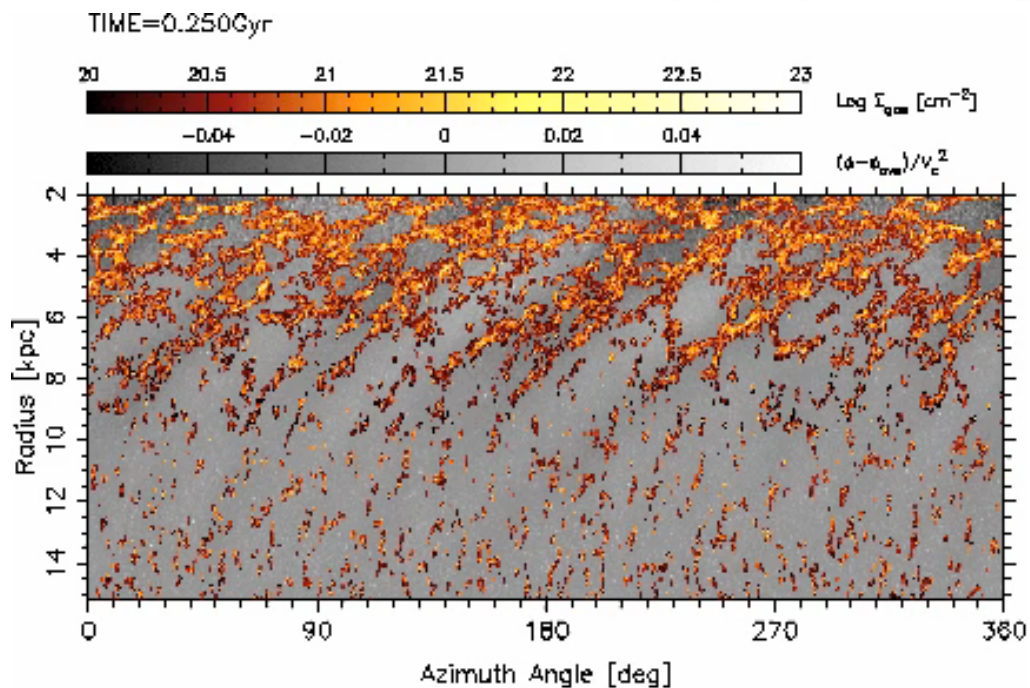
‘GMAs’ show strong shear motion. → source of turbulence?

14



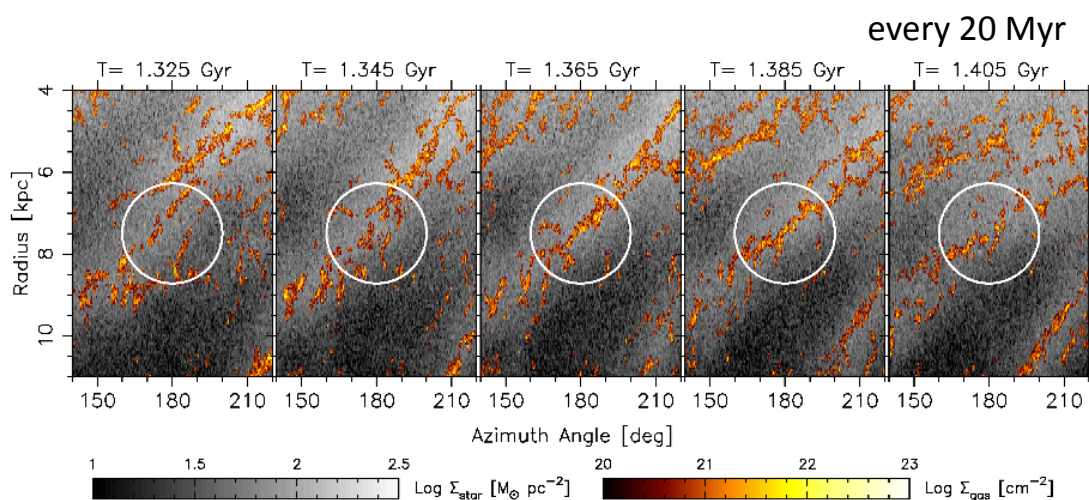
# Dynamics of cold gas and stellar spirals

- \* Cold gases collide near the stellar arms on the rotating frame
- \* Kpc scale radial motions
- \* Hard to define “life time of clouds” (cf. recent papers by Dobbs & Pringle)



15

Collision between cold gas filaments/clumps  
 → triggering star formation → dispersed

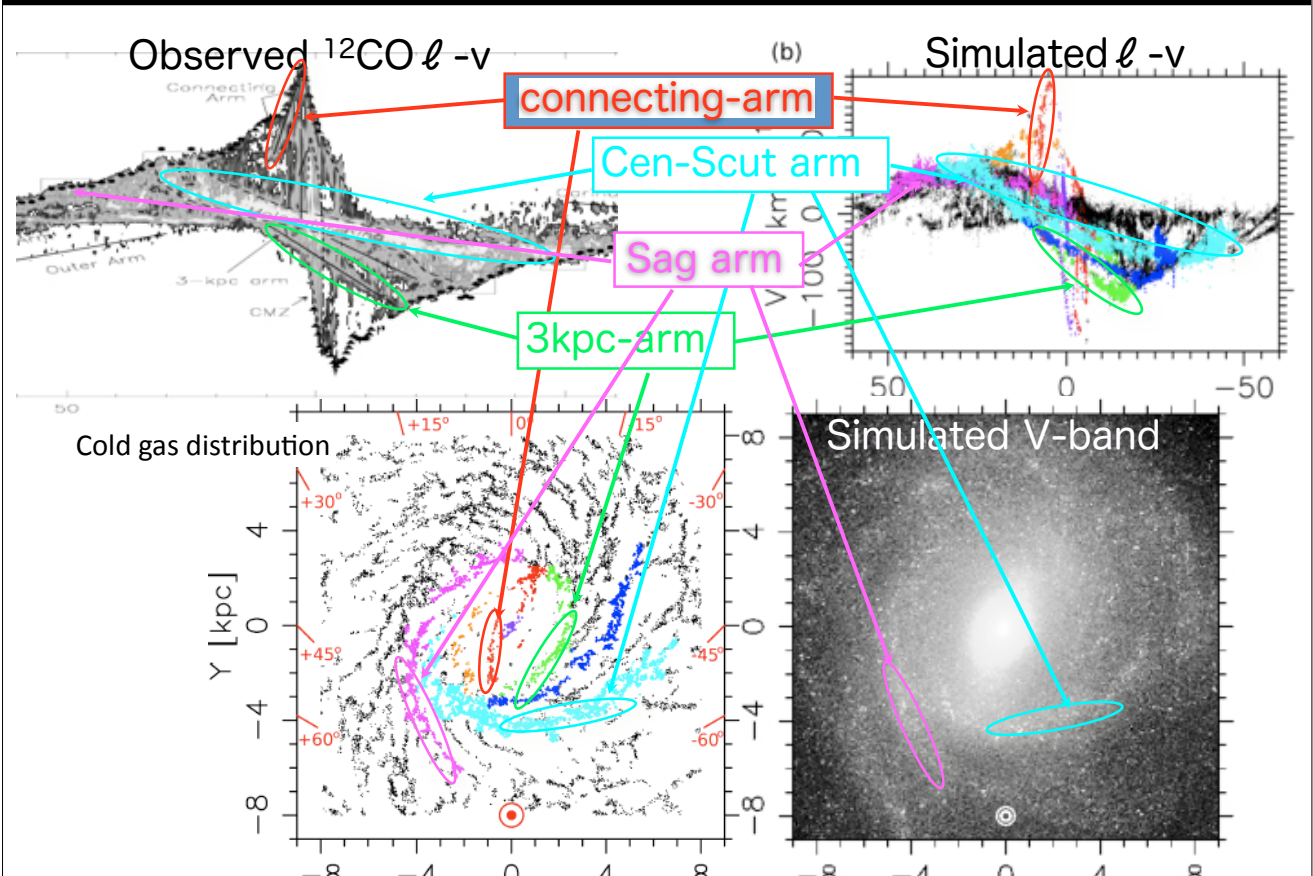


Wada, Baba, Saitoh (2011)

16

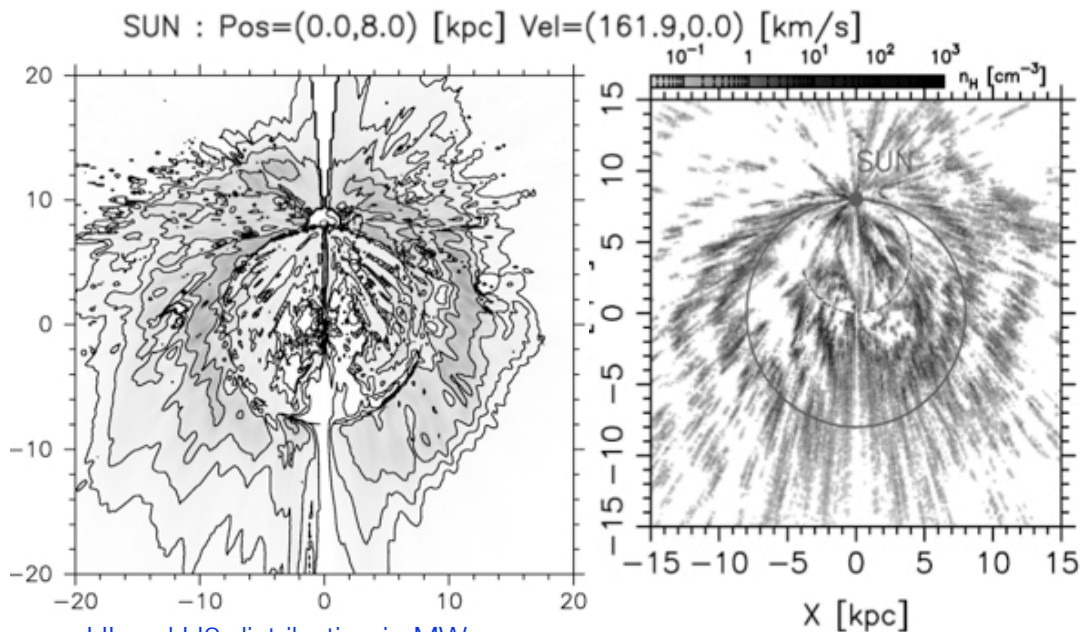


# Link $\ell$ - $v$ to Face-on



How does the Galaxy look like?

**Kinematic Distance based on an assumption of circular rotation has large errors -> 'radial features'**

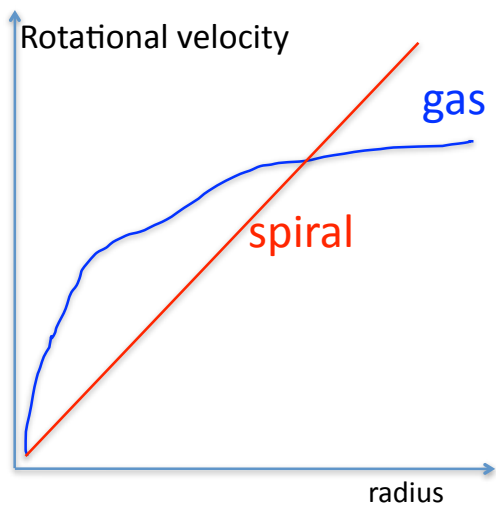


HI and H2 distribution in MW:  
Nakanishi & Sofue 2003

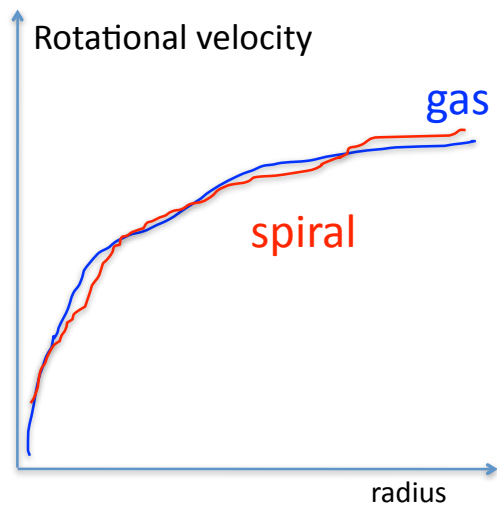
## Difference from the steady(rigid) spirals

19

## Ground-design rigid density waves vs. N-body spirals



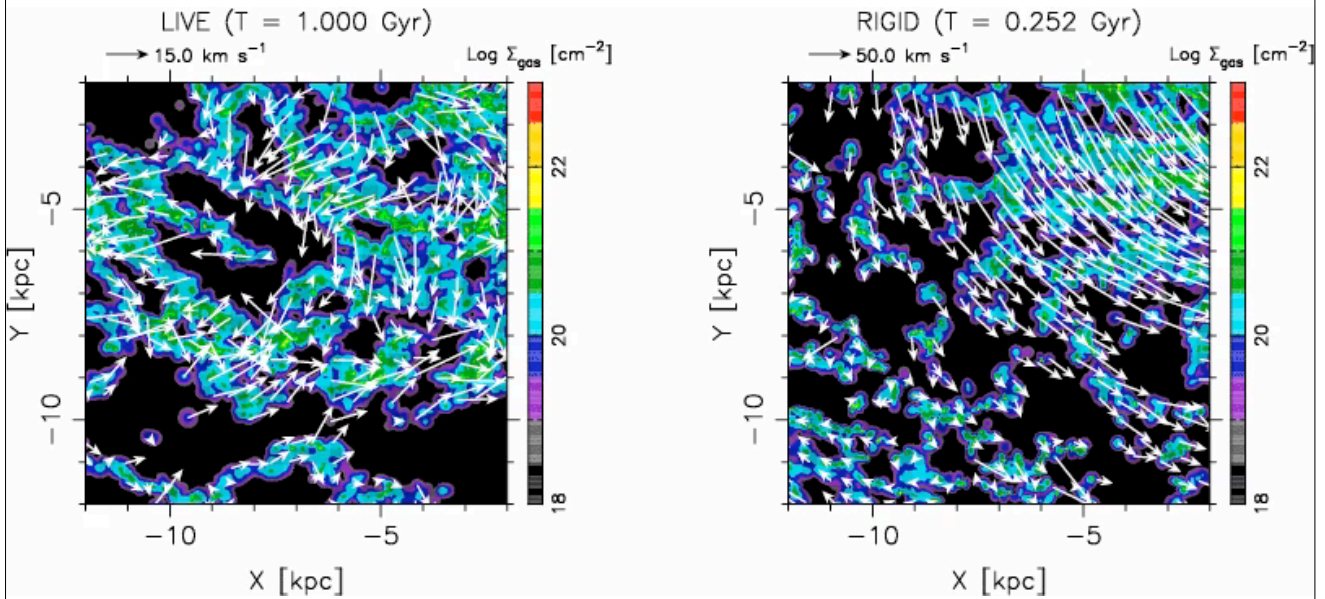
Gas can be 'supersonic' for the spiral potential



Gas is 'subsonic' (random velocity  $\sim$  relative velocity to the stellar potential).

20

# Gas velocities: Live vs. Rigid spiral

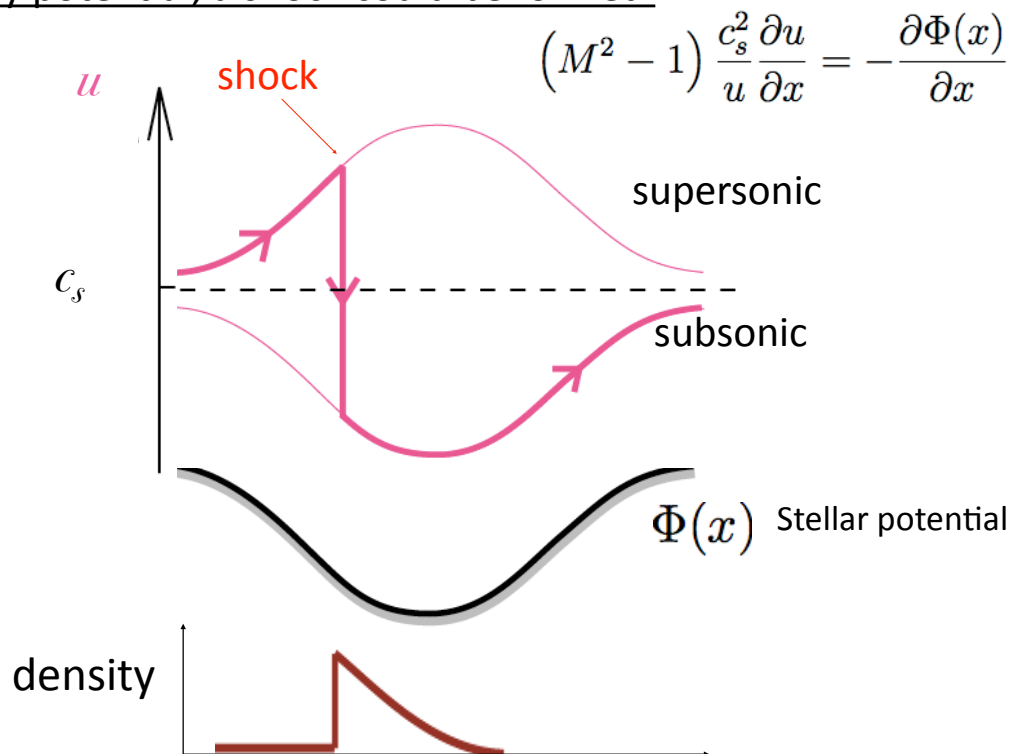


Random or converging flows

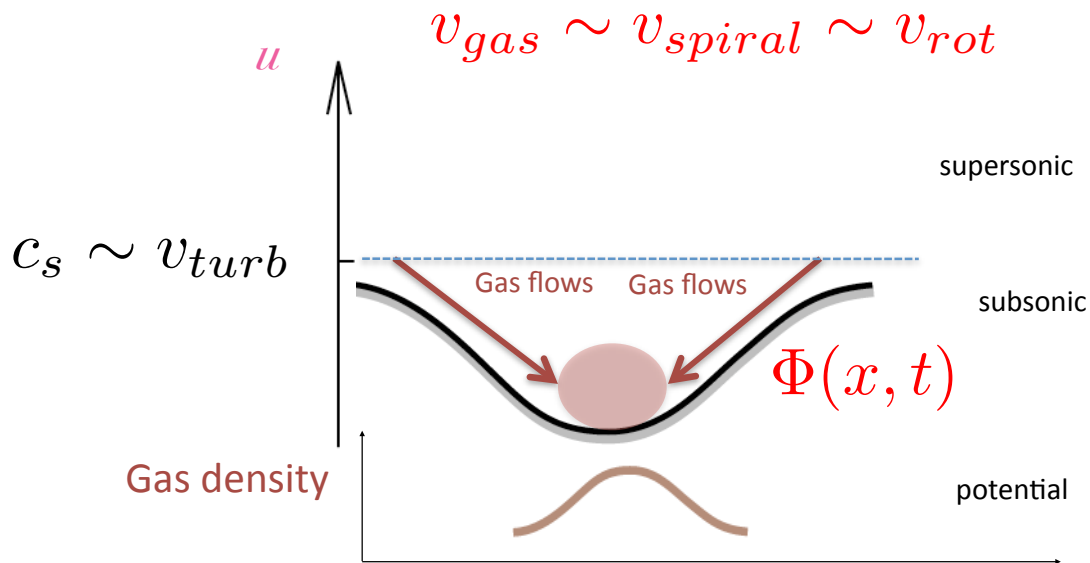
Regular flows typically seen in galactic shock

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

Conventional galactic shock



Both ISM and spiral potential follow galactic rotation



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

Summary: new picture of spiral structures 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)

■ **stellar spirals & ISM move together** ⇒ **winding**  
 ⇒ ISM falls into the spiral potential **from both side, forming dense regions** (could become GMCs) ⇒ The dense gas moves into the inter-arm region as the potential changes ⇒ New spirals

■ **Galactic spirals in galaxies without strong perturbations are NOT global galactic shocks**

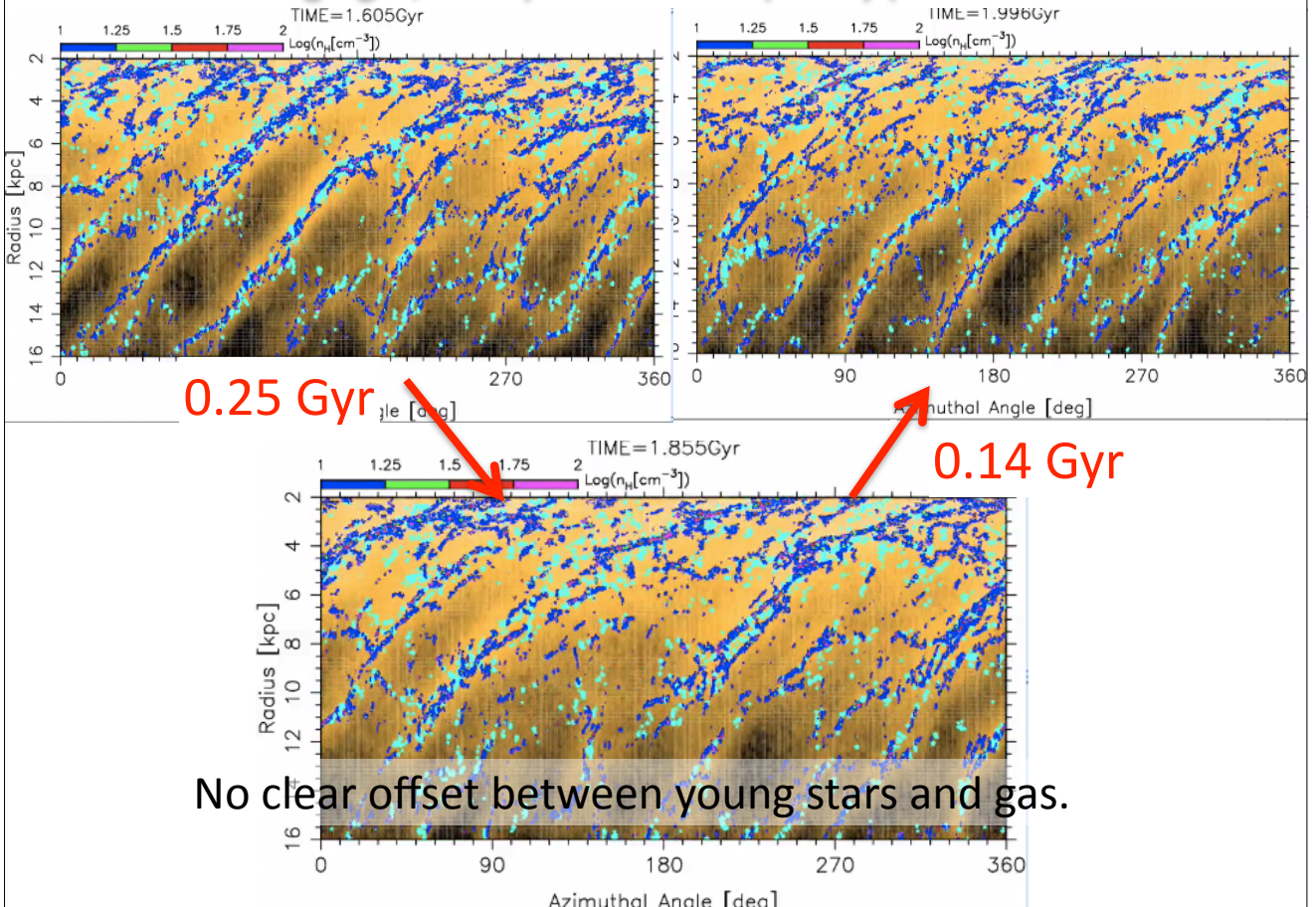


Do we observe offset between gas and stellar spirals, or young and old stars in galaxies?

No, in multi-arm, isolated galaxies, from theoretical prediction

No, from observations?

Ground-design gas/star spirals are temporary phenomena



# A ground-design spiral: consistent with the Galactic Shock/density wave?

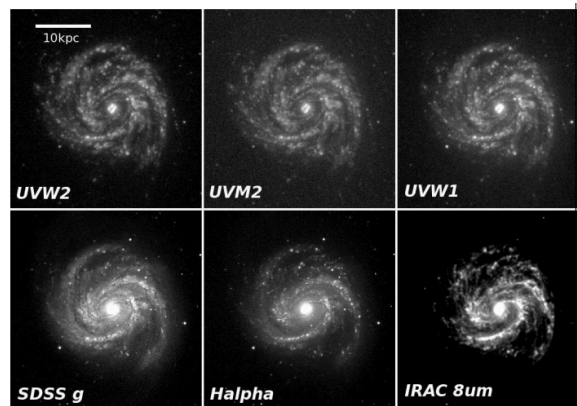
M81 observed by *Spitzer* IRAC Kendall et al. 2008



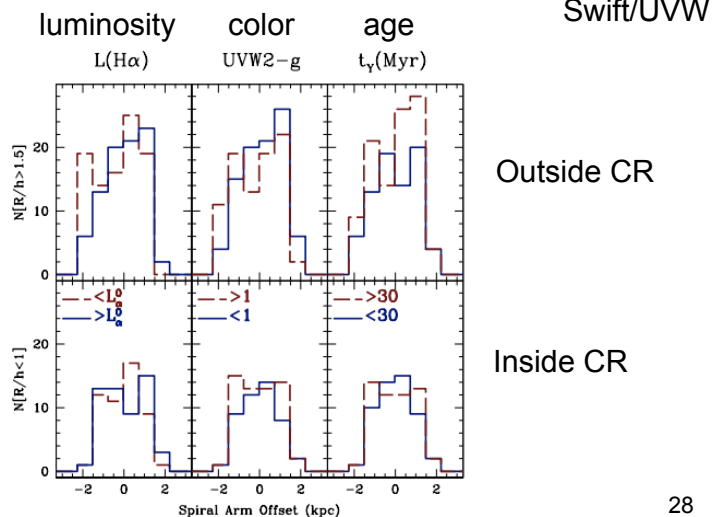
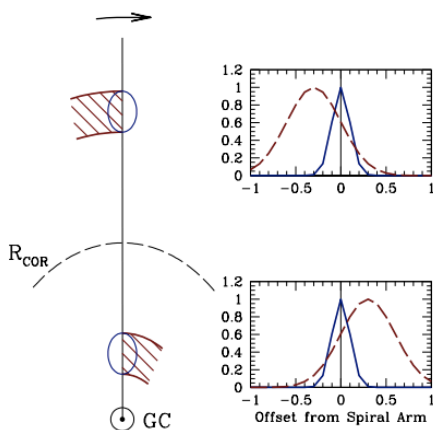
Stellar (K-band) and cold gas/dust (8micron) spirals are **systematically off-set**, as is predicted by **quasi-steady long-lived density wave model and galactic shocks**.

## NGC4321 (Ferreras+2012)

**No systematic offsets in UV arms and H $\alpha$  arms in terms of color, age, luminosity for  $R > CR, < CR$**



Prediction from the classic picture

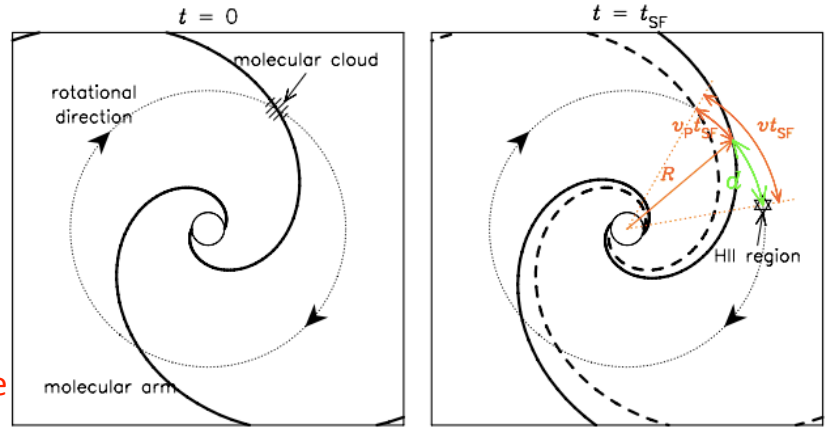


# Pattern speed of spiral: offset method (Egusa+2009)

Assumptions based on the density wave hypothesis:

- 1) spiral pattern is rigid
- 2) gas rotates in pure circular orbits

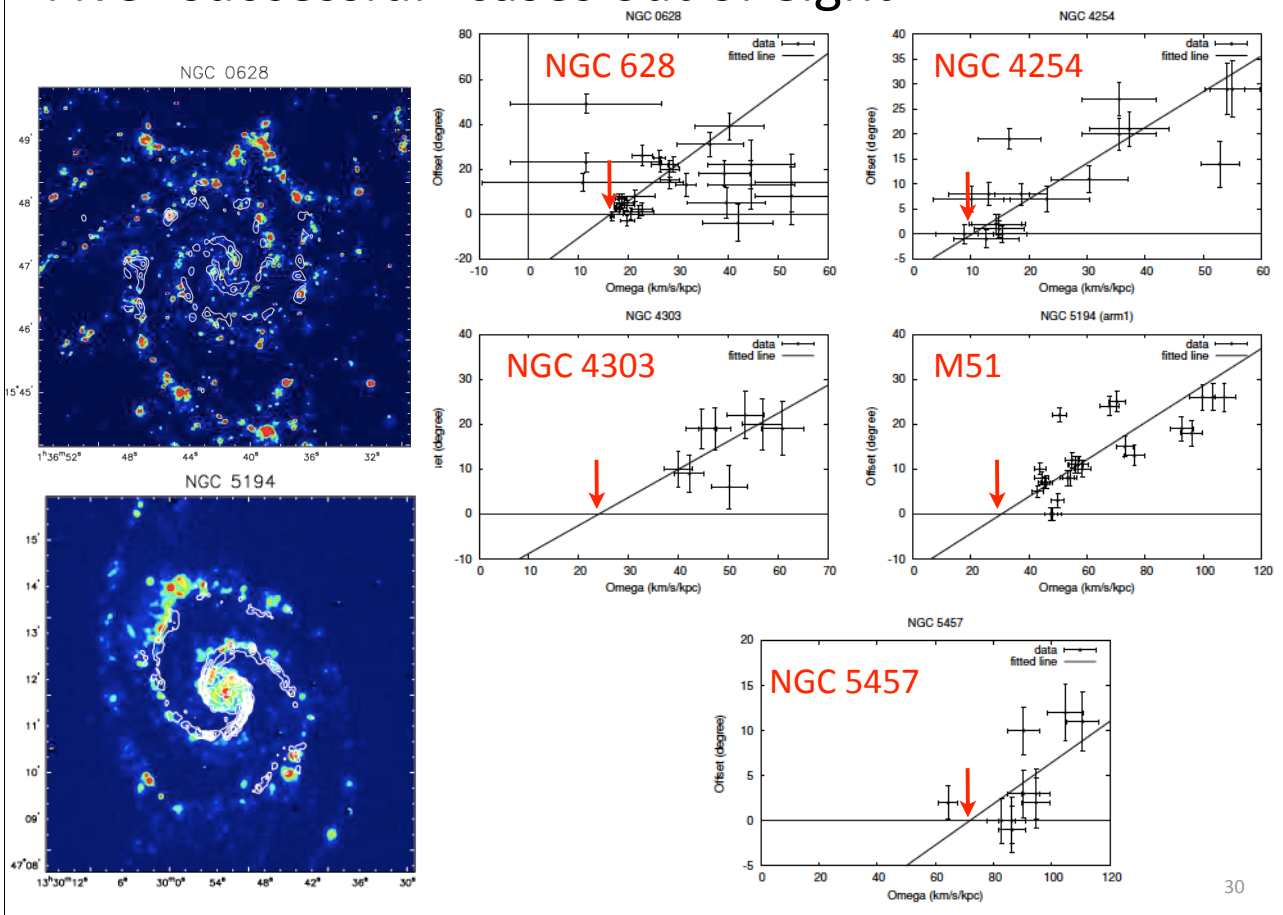
Offset angle is a linear function of  $\Omega$ , and star formation time scale is the slope.



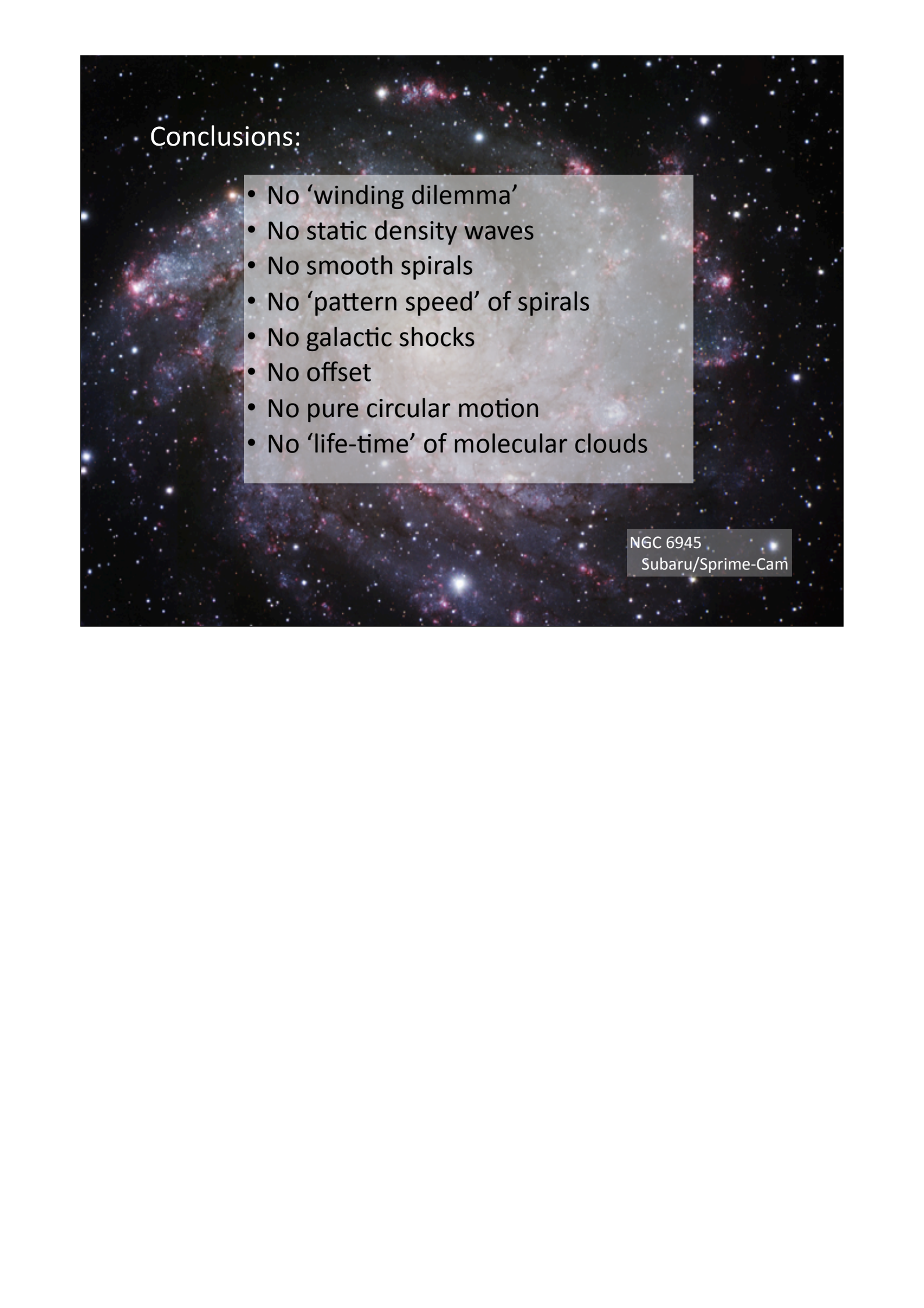
$$\theta = 0.586 \left[ \left( \frac{\Omega}{\text{km s}^{-1} \text{kpc}^{-1}} \right) - \left( \frac{\Omega_p}{\text{km s}^{-1} \text{kpc}^{-1}} \right) \right] \times \left( \frac{t_{\text{SF}}}{10^7 \text{ yr}} \right) \text{ (degree)}$$

## Five "successful" cases out of eight

Egusa+2009







## Conclusions:

- No 'winding dilemma'
- No static density waves
- No smooth spirals
- No 'pattern speed' of spirals
- No galactic shocks
- No offset
- No pure circular motion
- No 'life-time' of molecular clouds

NGC 6945  
Subaru/Prime-Cam