

# 銀河円盤星間ガスの大局構造と力学

Global structures and dynamics of ISM in galactic disks

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## 結論的なこといくつか

1. (たとえ弱くても) **非軸対称ポテンシャル(bar, spiral)があると、大局構造が全然変わる**
  - ・ barは剛体回転でいいけど、spiralは非定常 (←現代的な描像)
2. **自己重力、銀河回転 (と熱的不安定) が重要**
  - ・ local近似な計算は非現実的 (←場所によってかなり違う)
3. **磁場は”あまり”関係ない (←和田の仕事じゃないけど…)**
4. **SNeは大局的な非一様性に必須ではない (← LMCの例)**
5. **星間ガス ≠ ”離散的なcloudの集まり” (← 密度の薄いガスも重要)**

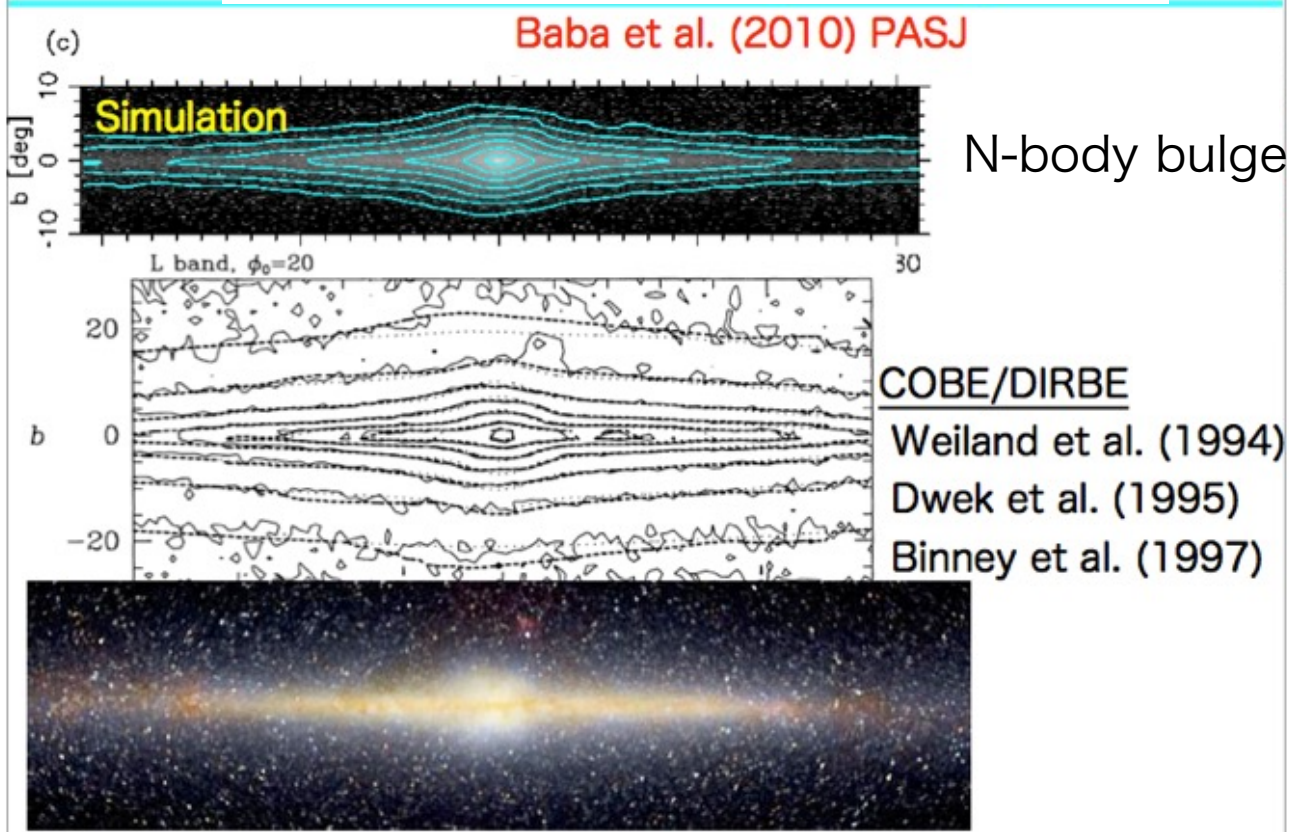
there are bars and spirals in the Galaxy (& most galaxies)

therefore, ISM=circular motion (+random motion) is a wrong assumption

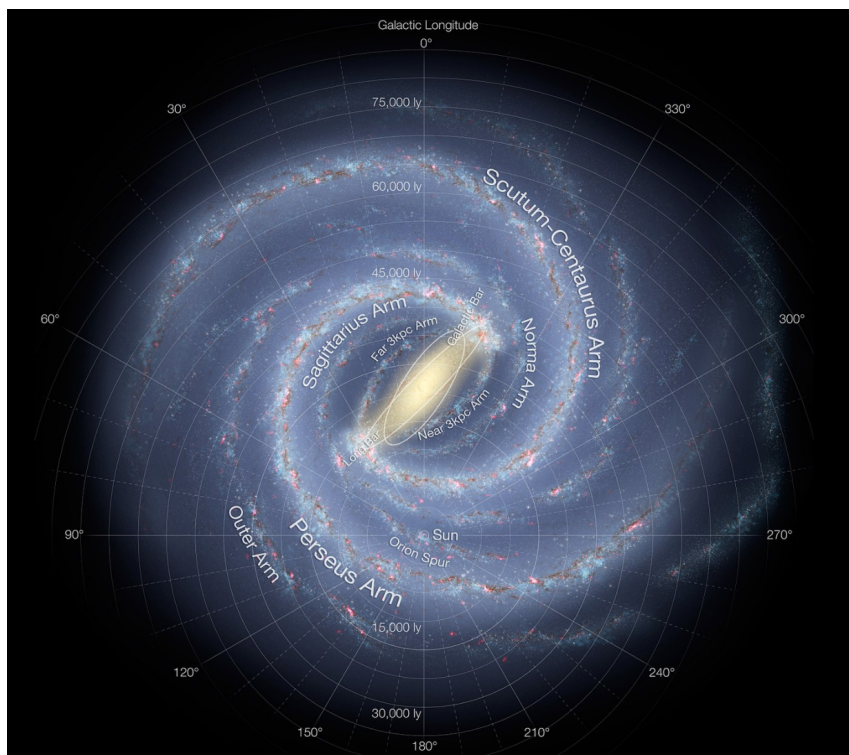
ということを観測屋さんに言うと、  
「そんなことはわかってる！」と怒られます…

Results

# Edge-on View of the 'bulge'

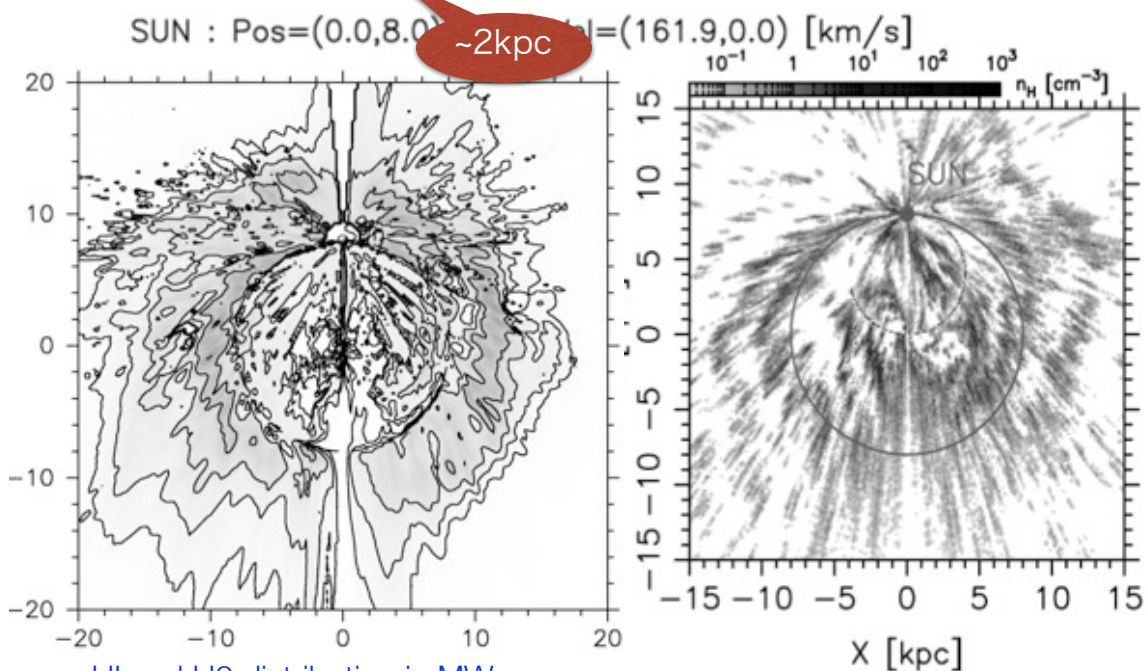


この”絵”に観測データを乗せるのは（少なくとも日本の研究者は）止めましょう



# How does the Galaxy look like?

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



5

犬塚先生

「バーの話しろ」

なんで今頃…

和

## bar影響下のガス運動の基本

… 20数年前にやっていたことなので、  
パワポファイルがない…

6



銀河天文学と

スペースアストロメトリ研究会

2/124, 1994  
洞爺湖

24 yrs ago

Gas 運動 から 知る

edge-on 銀河 中の バー構造

北海道大 情報処理教育センター

和田 桂一

- I. Bar Potential 中の Gas の  
特徴的 なふるまい  
resonant orbit model から  
hydrodynamical simulation
- II. Our Galaxy = Barred Spiral ?  
HI, CO の観測を説明するモデル
- III. Numerical PV diagram  
もし、バーが存在するとどう見えるか?

7

### GASDYNAMICAL APPROACH TO A FACE-ON VIEW OF THE MILKY WAY

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Received 1994 July 19; accepted 1994 October 6

93年頃の野辺山スパコン?のプリントアウト

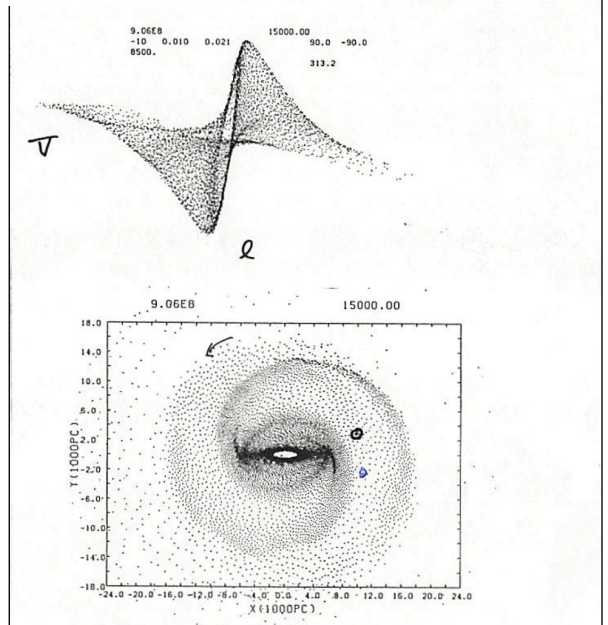
$$\Omega_p = 30 \text{ km/s kpc}^{-1}$$

$$\theta_p = -10^\circ$$

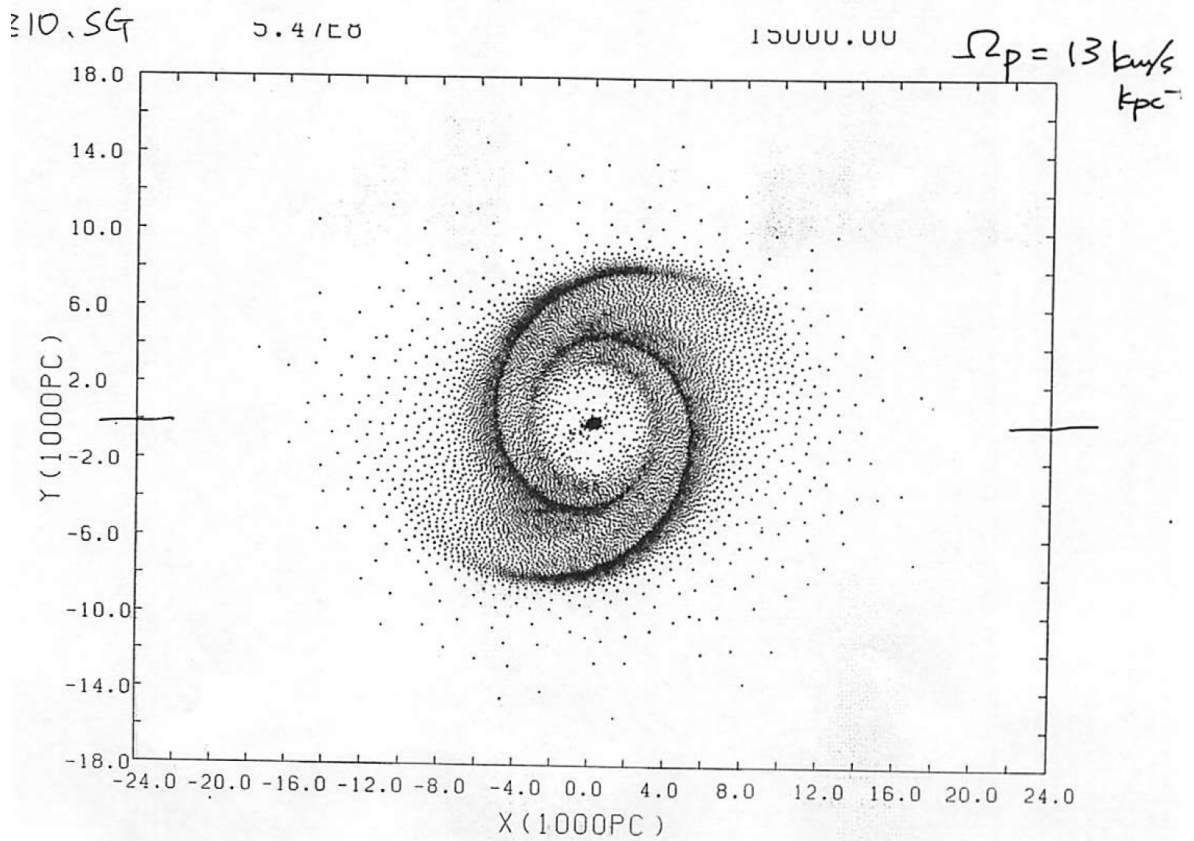
ApJ437,L123 (1994)



これらのちゃんとしたやつ  
Baba, Saitoh, KW (2010)



“wobble instability & spur”が!



バーポテンシャル中の粒子軌道  
(エピサイクル近似、 $R = R_0 + R_1, R_0 \gg R_1$ )

$$\Phi_0 \gg \Phi_1$$

弱いバーポテンシャル:  $\Phi_1(R, \phi) = \Phi_b(R) \cos 2\phi_0$

半径方向の摂動  $R_1$  のふるまい (bar 回転系)

$$\ddot{R}_1 + \kappa_0^2 R_1 = f_0 \cos 2(\Omega_0 - \Omega_b)t$$

↓

$\Omega_b$ : バーの  
ポテン

周期的外力 (振動数  $2(\Omega_0 - \Omega_b)$ ) が働く、  
調和振動子 (振動数  $\kappa_0$ )

エピサイクルの振動数

閉軌道解:

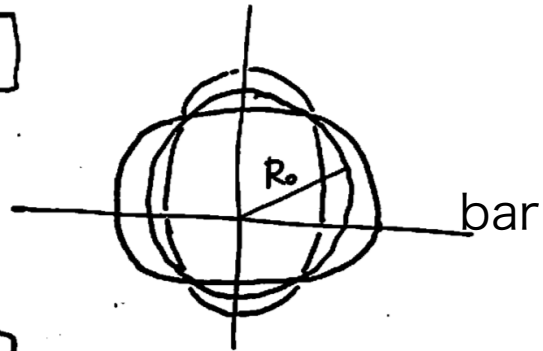
$$R_1(\phi_0) = -\frac{f_0}{\kappa_0^2 - 4(\Omega_0 - \Omega_b)^2} \cos 2\phi_0.$$

$$R(\phi) = R_0 + R_1$$

$$R_1 = c \cdot \cos 2\phi_0$$

X1 (x4)  $c > 0$   
軌道

$$c = 0$$



X2 (x3)  $c < 0$   
軌道

Lindblad resonanceを境に、  
楕円軌道の向きが90°変わる

$$c \equiv 4(\Omega_0 - \Omega_b)^2 - k_0^2 \quad \begin{matrix} > 0 \\ < 0 \end{matrix}$$

10

当時 (90年頃?)、x1, x2 orbitで  
ガス運動の議論をしていた



気持ち悪いし、SPH計算の結果と合わない

11

ガス軌道

圧力、粘性の効果を「摩擦項」として、  
強制振動子の運動方程式に取り入れる。

$$\ddot{R}_1 + 2\lambda \dot{R}_1 + \kappa_0^2 R_1 = f_0 \cos 2(\Omega_0 - \Omega_b)t$$

→ 「 $R_0$  のまわりの半径方向減衰強制振動」

一般解：

$$R_1(t) = \underbrace{Ae^{-\lambda t} \cos(\omega t + \alpha)}_{\text{減衰項}} + \underbrace{B \cos[2(\Omega_0 - \Omega_b)t + \delta_0]}_{\text{特解}}$$

(減衰振動の解)

↓  
閉軌道を表す

Closed damped Orbits:

$$R_1(\phi_0) = B_0 \cos(2\phi_0 + \delta_0)$$

$B_0, \delta_0$  は  $R_0$  の関数

振幅：

$$B_0 \equiv \frac{f_0}{\sqrt{\{\kappa_0^2 - 4(\Omega_0 - \Omega_b)^2\}^2 + 16\lambda^2(\Omega_0 - \Omega_b)^2}}$$

位相差：

$$\delta_0 = \arctan \left[ \frac{2F\Lambda}{F^2 - 1} \right],$$

$$F \equiv 2(\Omega_0 - \Omega_b)/\kappa_0, \Lambda \equiv \lambda/\kappa_0.$$

epicycle approximation

$$\ddot{R}_1 + \left[ \frac{d^2\Phi_0}{dR^2} - \Omega^2 \right]_{R_0} R_1 - 2R_0\Omega_0\dot{\phi}_1 = - \left[ \frac{\partial\Phi_1}{\partial R} \right]_{R_0}, \quad (1)$$

$$\ddot{\phi}_1 + 2\Omega_0 \frac{\dot{R}_1}{R_0} = - \frac{1}{R_0^2} \left[ \frac{\partial\Phi_1}{\partial\phi} \right]_{R_0}, \quad (2)$$

位相差  $\delta_0 = \arctan \left[ \frac{2F\Lambda}{F^2 - 1} \right]$  の重要な性質

(1)  $\delta_0$  は  $F$  の減少関数、  $F \equiv \frac{2(\Omega_0 - \Omega_b)}{\kappa_0}$

常に負 (if  $F > 0 \Leftrightarrow R < R_{CR}$ )

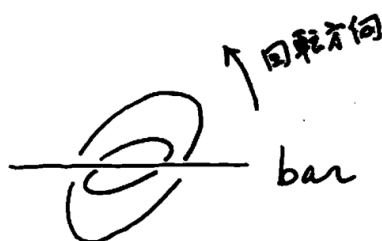
↓

corotation より内側では  
楕円軌道はバーポテンシャルに対して常に先行する

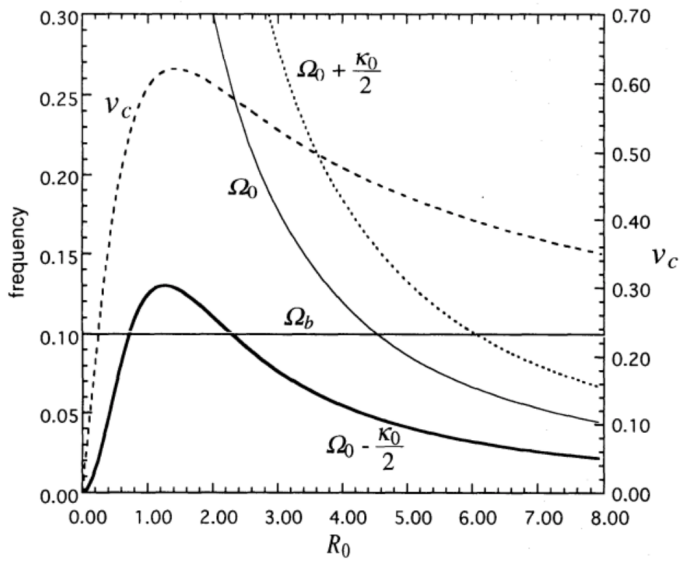
強制減衰振動の  
特徴

(2)  $\delta_0 = \pm\pi/2$  at  $F^2 = 1$   
(Lindblad resonances で軌道は 45 度傾く)

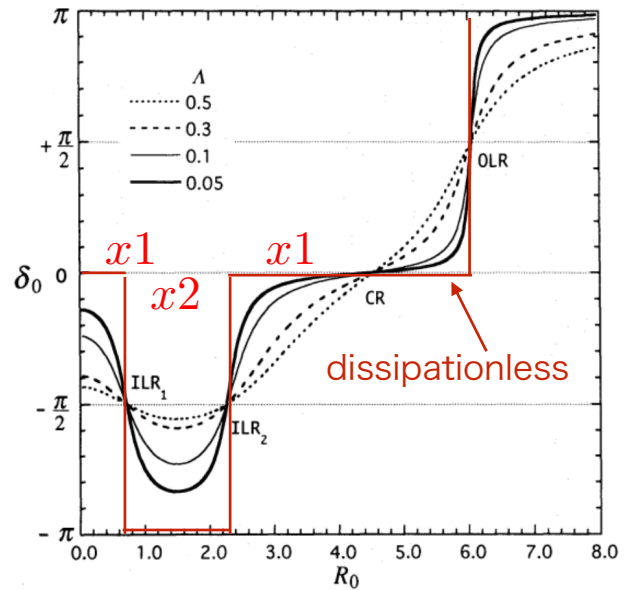
$$R_1(\phi_0) \propto \cos(2\phi_0 + \delta_0)$$



bar pattern speedと resonance の位置



位相差 (つまり軌道の傾き) の半径依存性



Wada (1994)

14

Wada (1994)

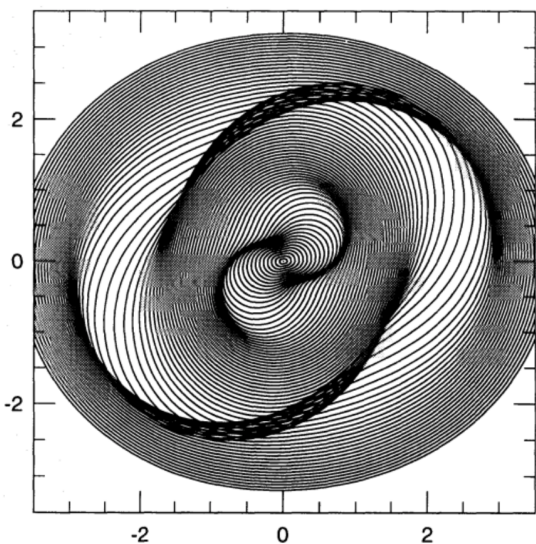
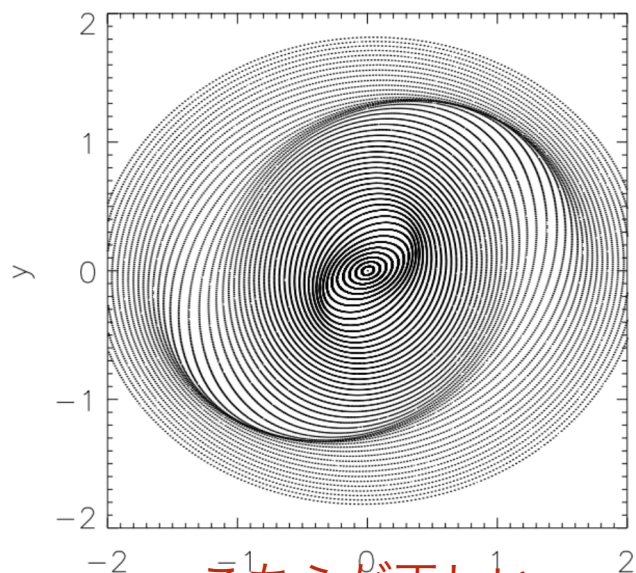


Fig. 4. Damped oval orbits represented by equations (13), (10), and (11) in the case of  $\Omega_b = 0.10$ ,  $\Lambda = 0.05$ , and  $\varepsilon = 0.05$ . The major axis of the bar potential is horizontally fixed in this figure.

実は正しくない図

phi方向のdampingも考慮すべき

Wada & Koda (2001)



$$R_1(\phi_0) = B \cos(2\phi_0 + \delta_0)$$

and

$$\phi_1(\phi_0) = -\frac{\Omega_0 B}{R_0(\Omega_0 - \Omega_b)} [\sin(\delta_0) - \sin(2\phi_0 + \delta_0)]$$

$$-\frac{\Phi_b(R)}{2R_0^2(\Omega_0 - \Omega_b)^2} \sin(2\phi_0).$$

5

和田のD論(1993)とほぼ同じ

Gas flow in barred potentials – II. Bar-driven spiral arms

Mattia C. Sormani,<sup>1★</sup> James Binney<sup>1</sup> and John Magorrian<sup>1,2</sup>

間違いが再生産されている！

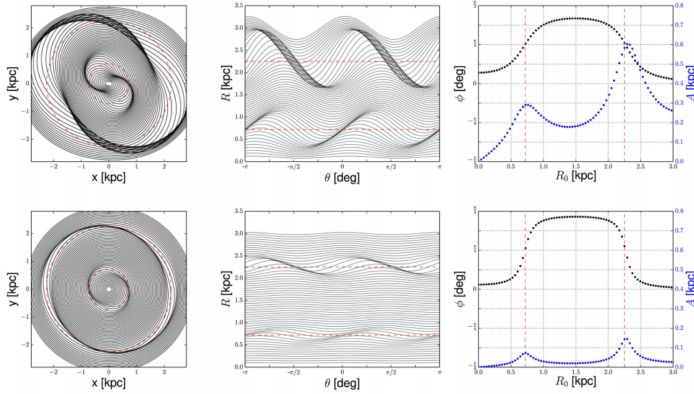
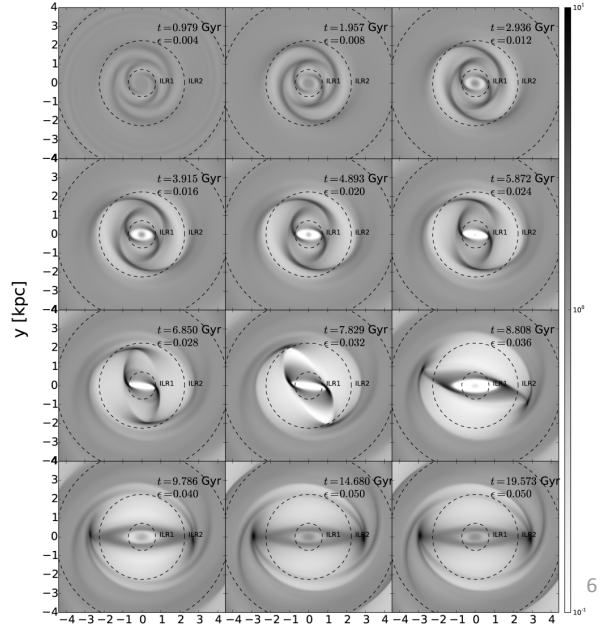
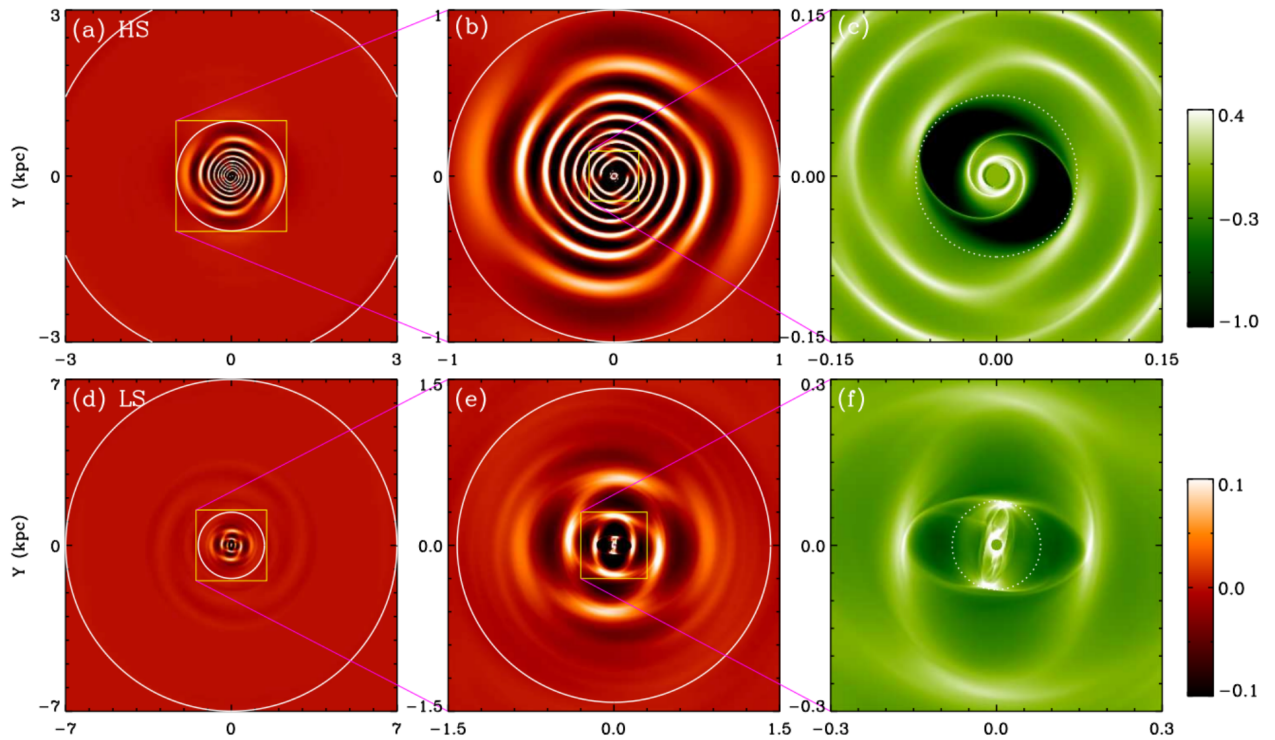


Figure 4. Top: reproduction of Wada (1994) predictions for a bar strength of  $\epsilon = 0.05$ . The damping parameter is  $\Lambda = 0.05$ . Bottom: another model produced using Wada (1994) theory, for  $\epsilon = 0.005$  and  $\Lambda = 0.02$ .



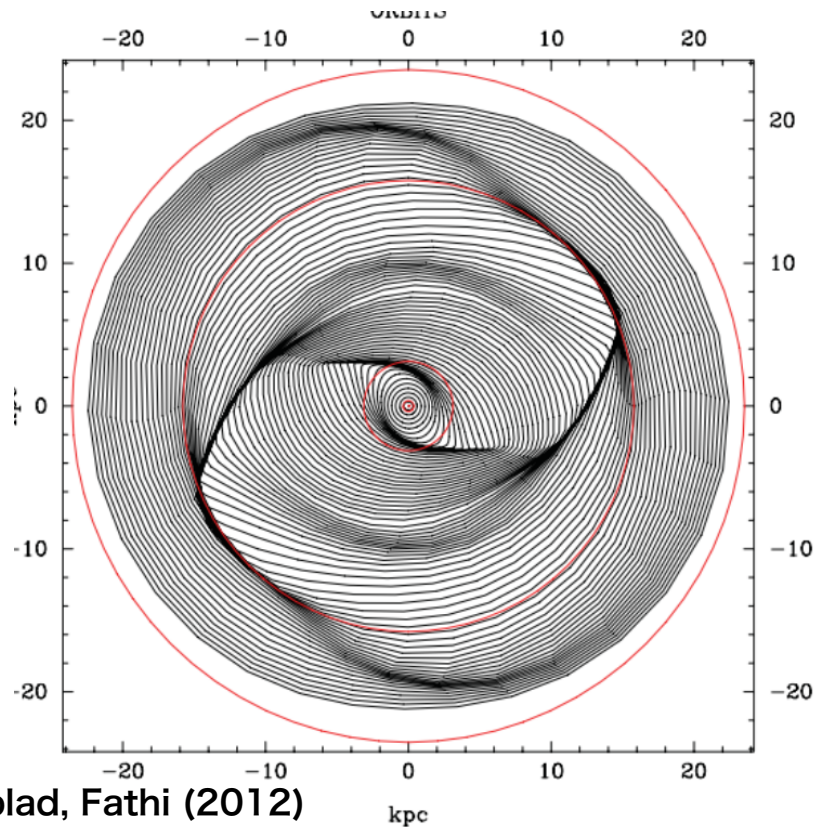
Kim, Ostriker (2017)

NUCLEAR SPIRAL SHOCKS AND INDUCED GAS INFLOWS IN WEAK OVAL POTENTIALS



damped orbit modelは (ちょっと) 強いバーにも使える

→ ◇型の軌道 → offset shock-like structure

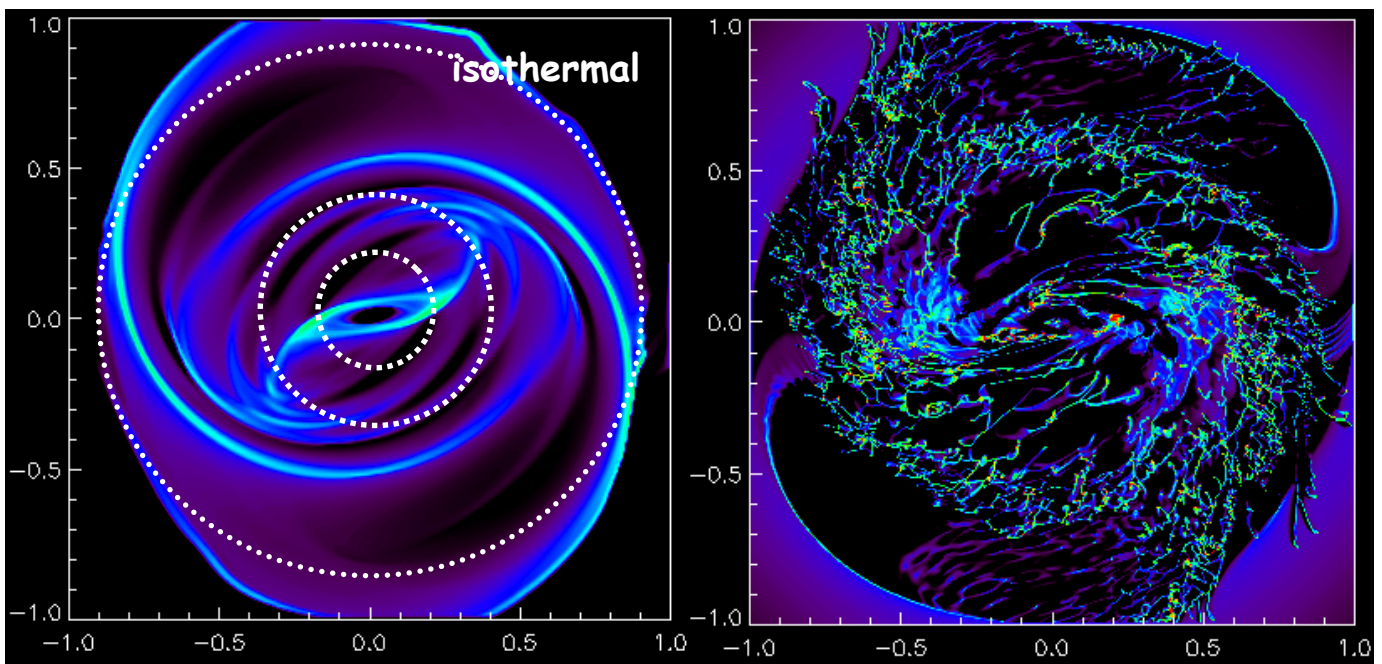


Pinol-Ferrer, Lindblad, Fathi (2012)

KW, Koda (2001)

自己重力, global & cooling/heating  
な計算必須

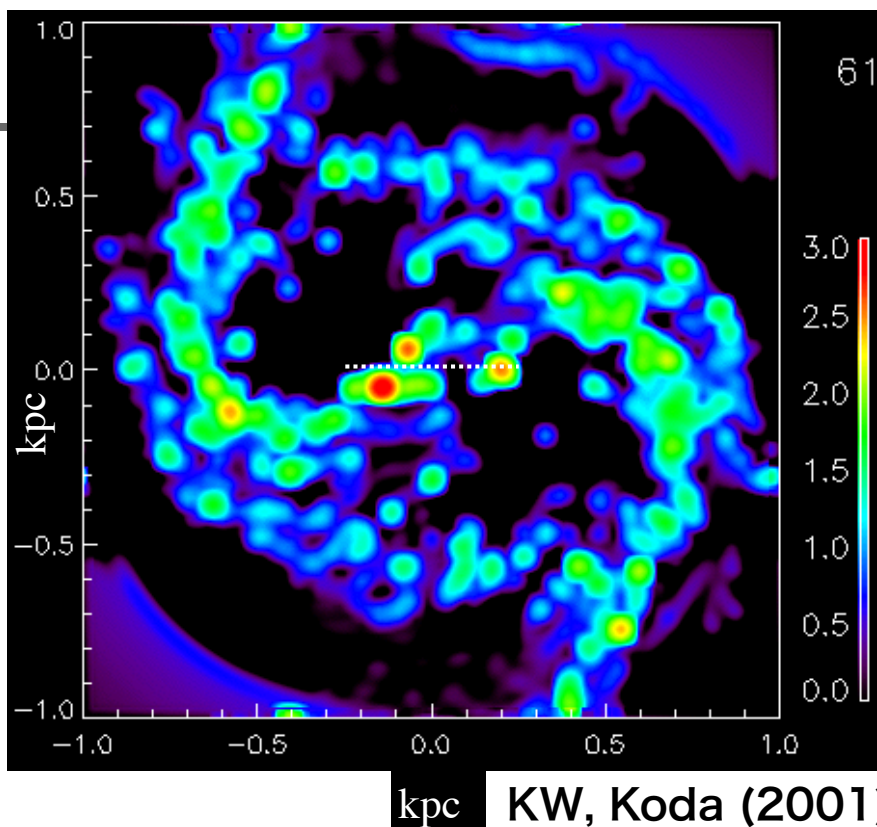
Effect of bar potential:  
Models with and without self-gravity



IILR=200pc, OILR=400pc  
CR= 900pc

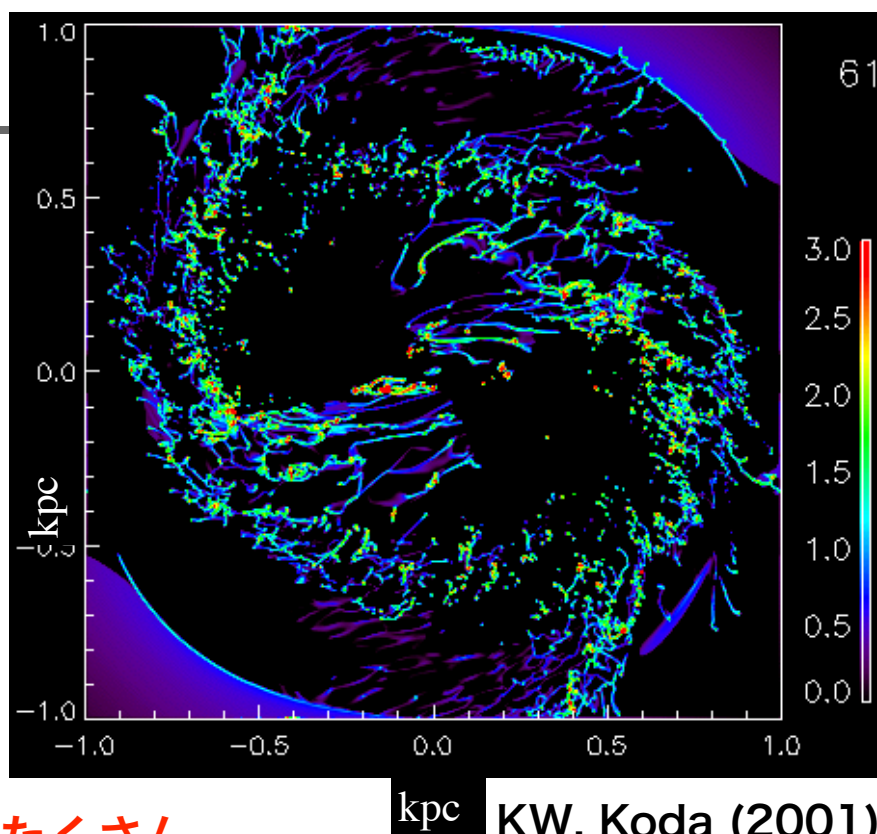
## "molecular gas" in the central kpc region of a bar galaxy

- 100pc Resolution  
e.g. NMA
- Two-arm clumpy spiral
- Pseudo central ring?
- Where are resonances?



## "molecular gas" in the central kpc region of a bar galaxy

- 10pc resolution  
e.g. ALMA
- Spirals are assembly of small clumps/filaments



分子雲っぽいものがたくさん

# 星間ガス=分子雲の集まり、でよいのか？

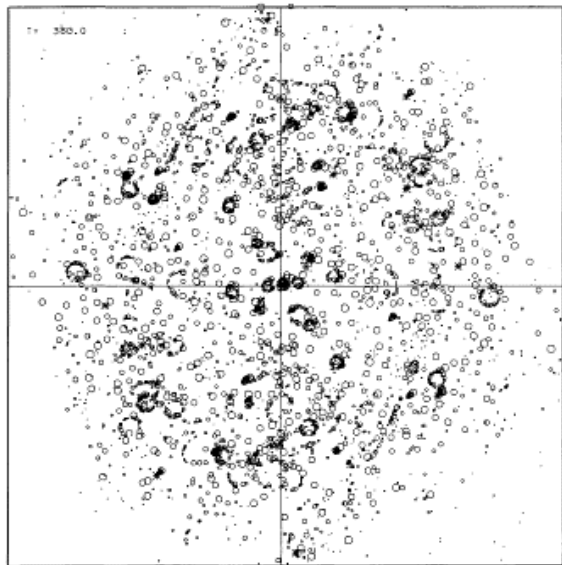
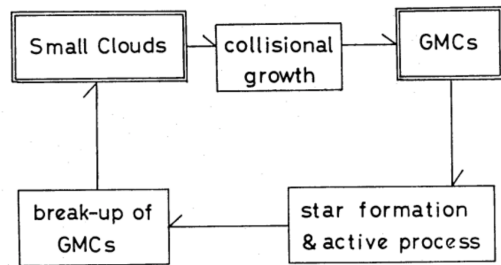
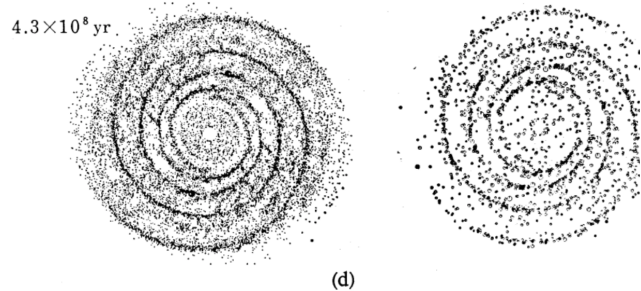


Fig. 2. Simulation of cloud collisions in an axisymmetric potential. Clouds are represented according to their size

Combes & Gerin (1985)

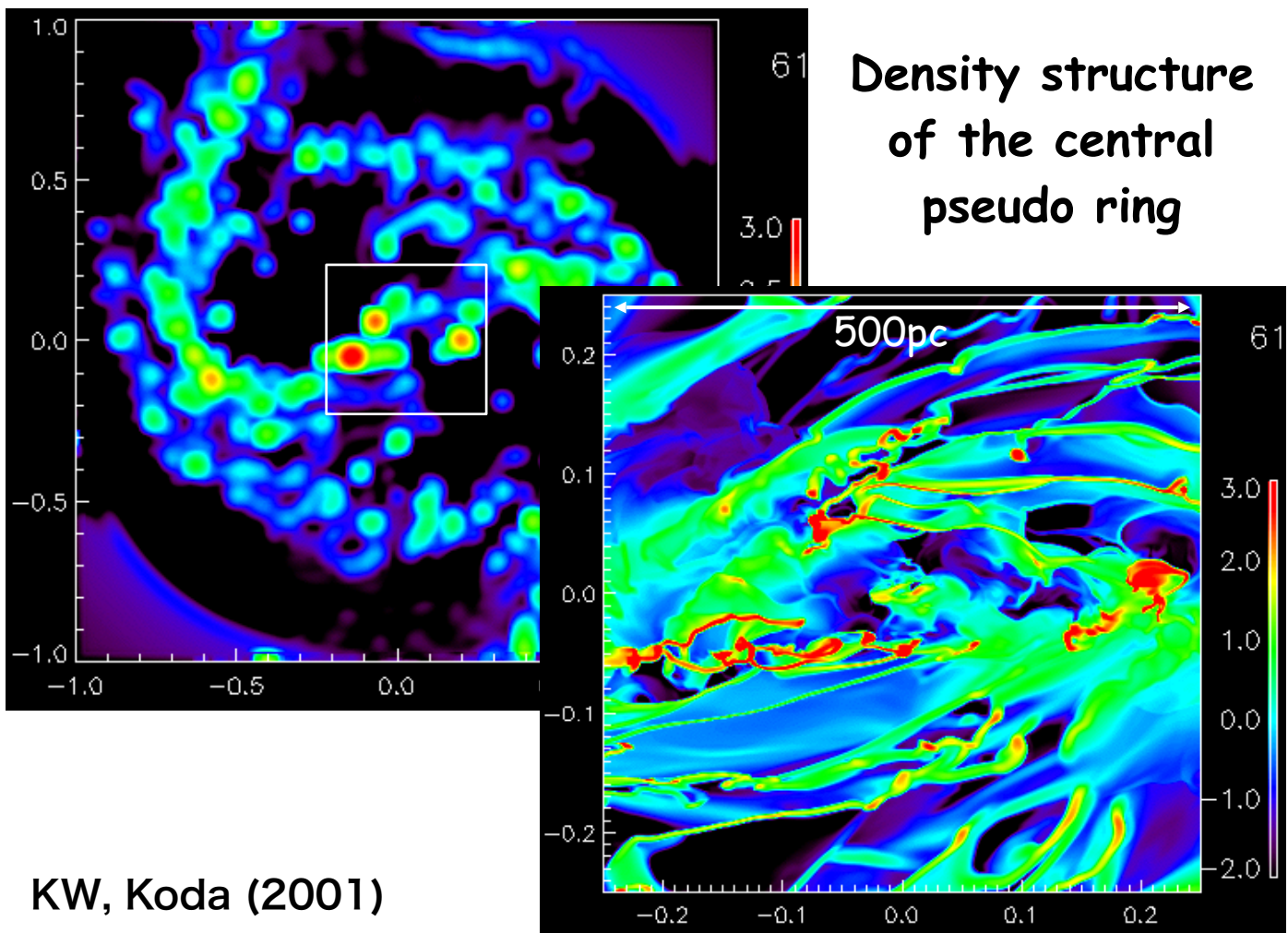


Tomisaka (1986)

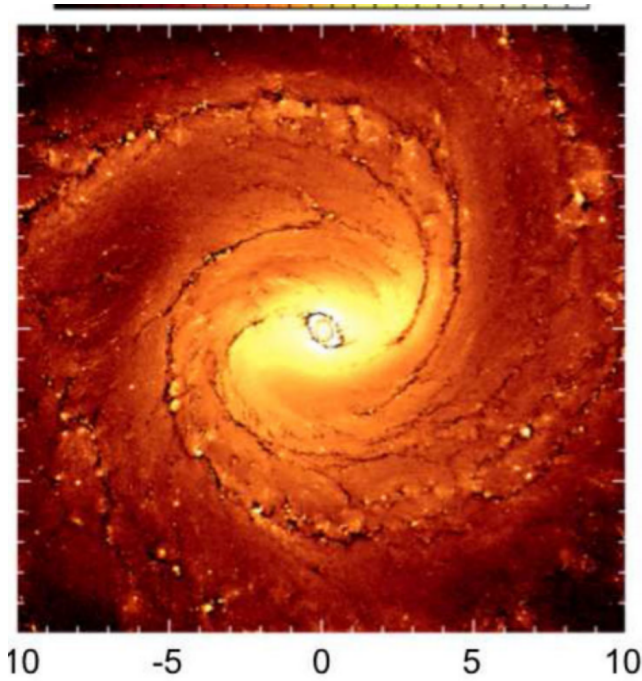


cf. 小林さんのtalk

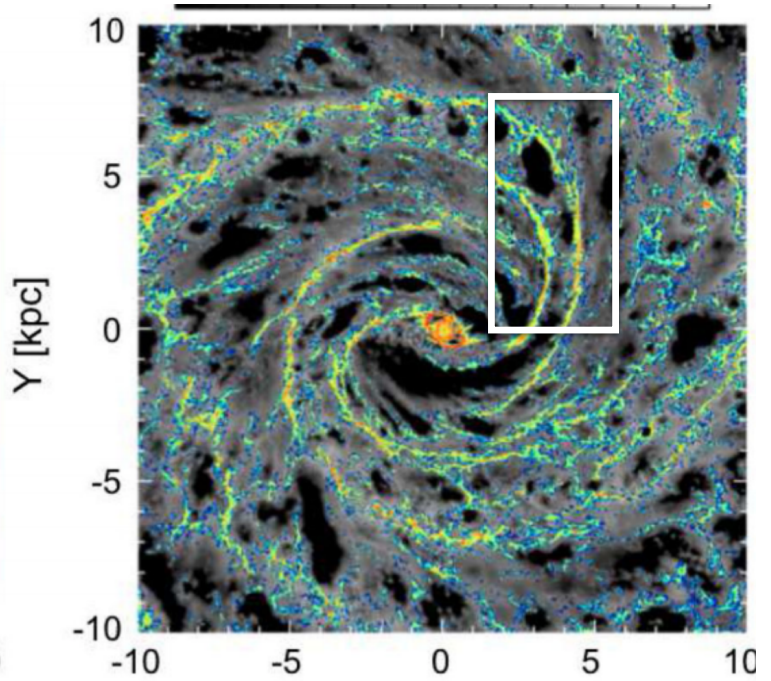
21



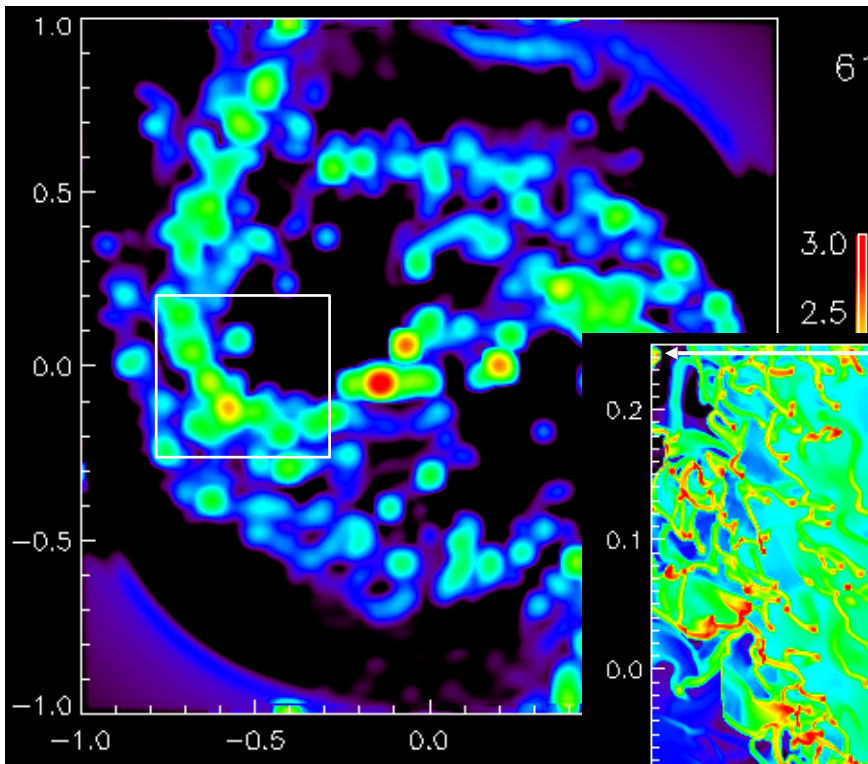
KW, Koda (2001)



R-band

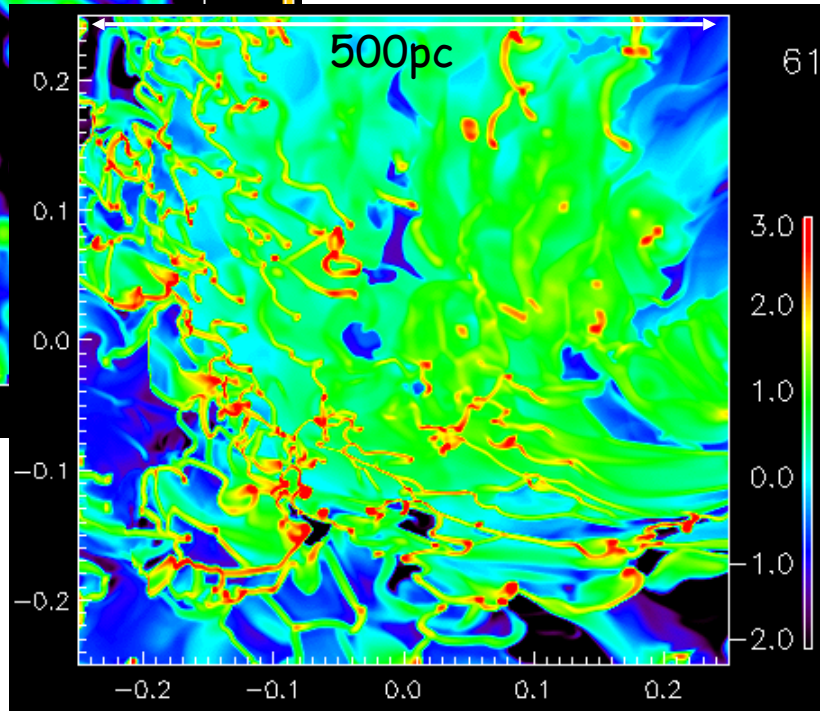


gas density



**Density structure in an arm region**

KW, Koda (2001)

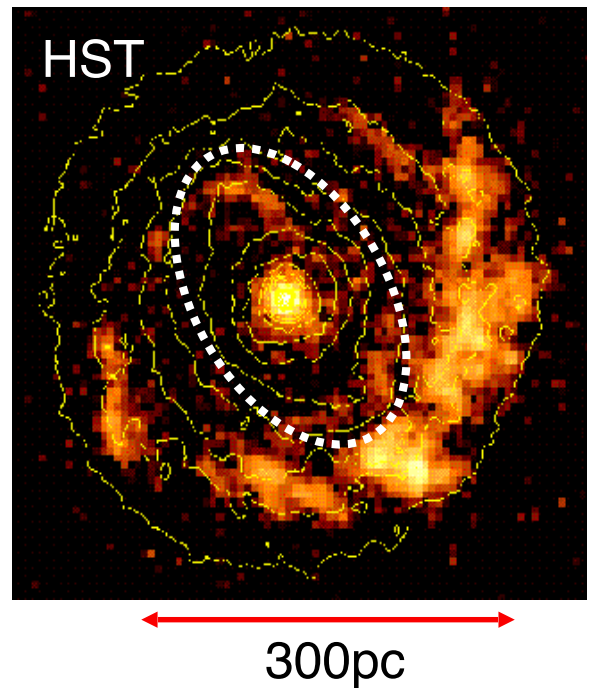


**dense and diffuse gas are NOT independent**  
**⇒ KW&Norman (2007)**

## 現実の銀河への適用

(Seyfert NGC 4303 篇)

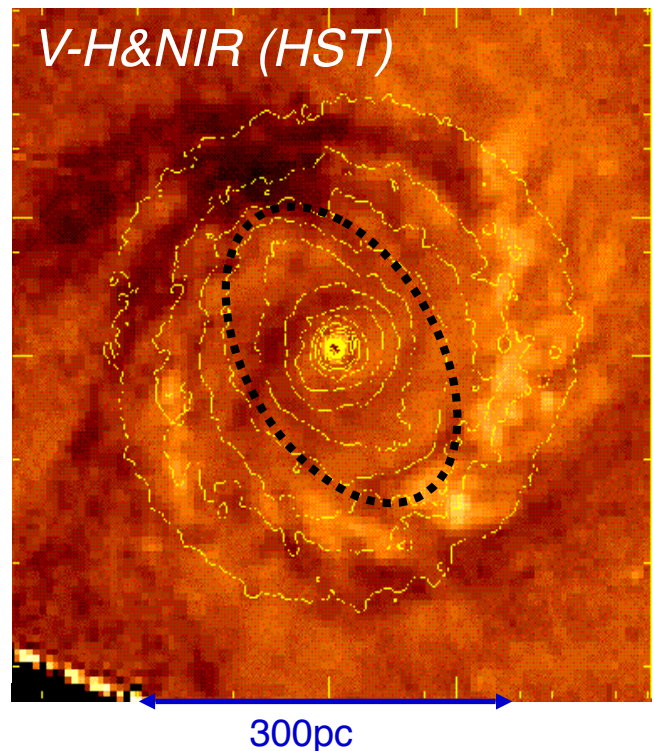
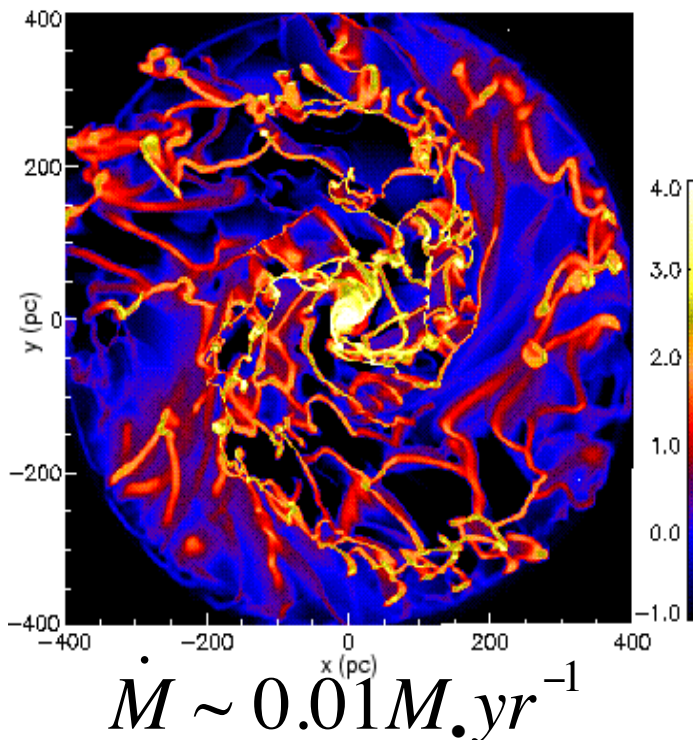
- UV & NIR images (HST)
- 若い星: one-arm spiral
- 中心核領域にbar存在  
– m=1 density waveを作るのは困難



## Effect of Stellar bar

### Seyfert NGC 4303: nuclear region

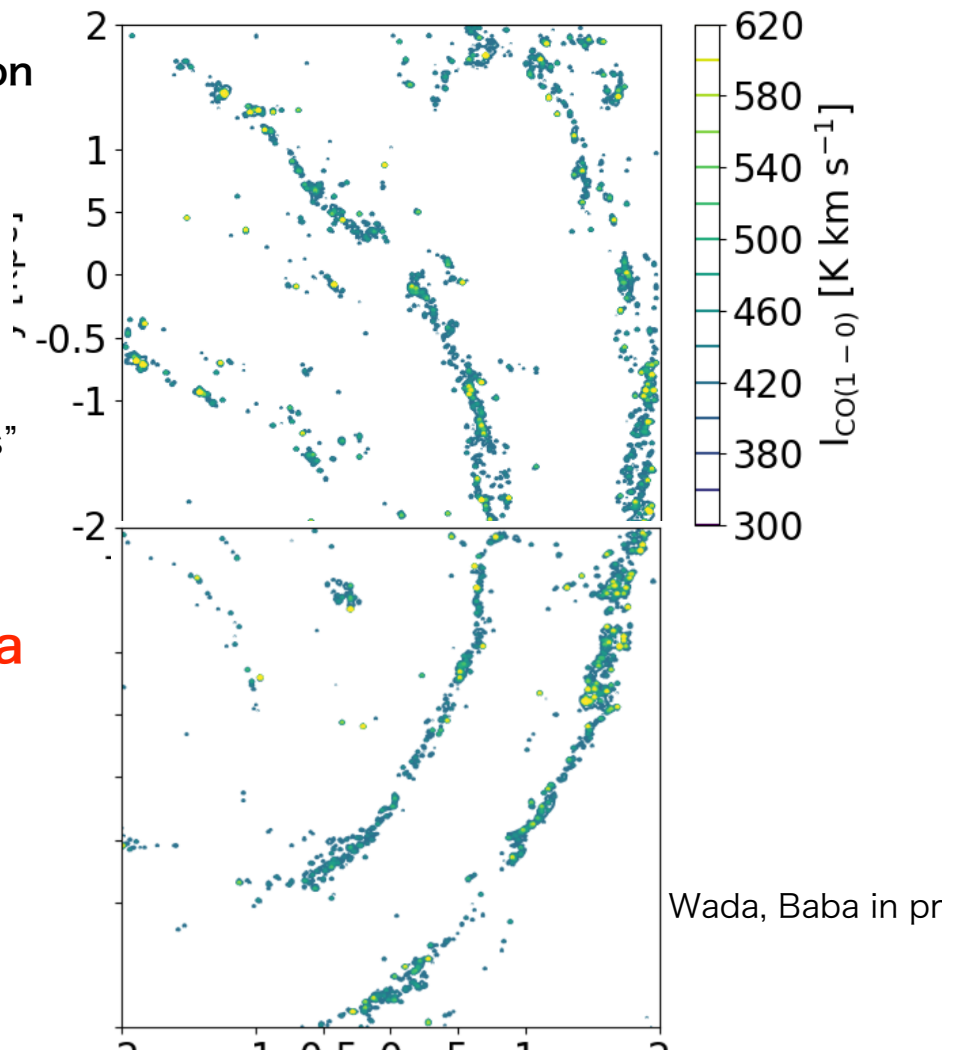
Colina & Wada (2000) ApJ 529, 845



3D non-LTE calculation  
CO(1-0)  
integrated intensity

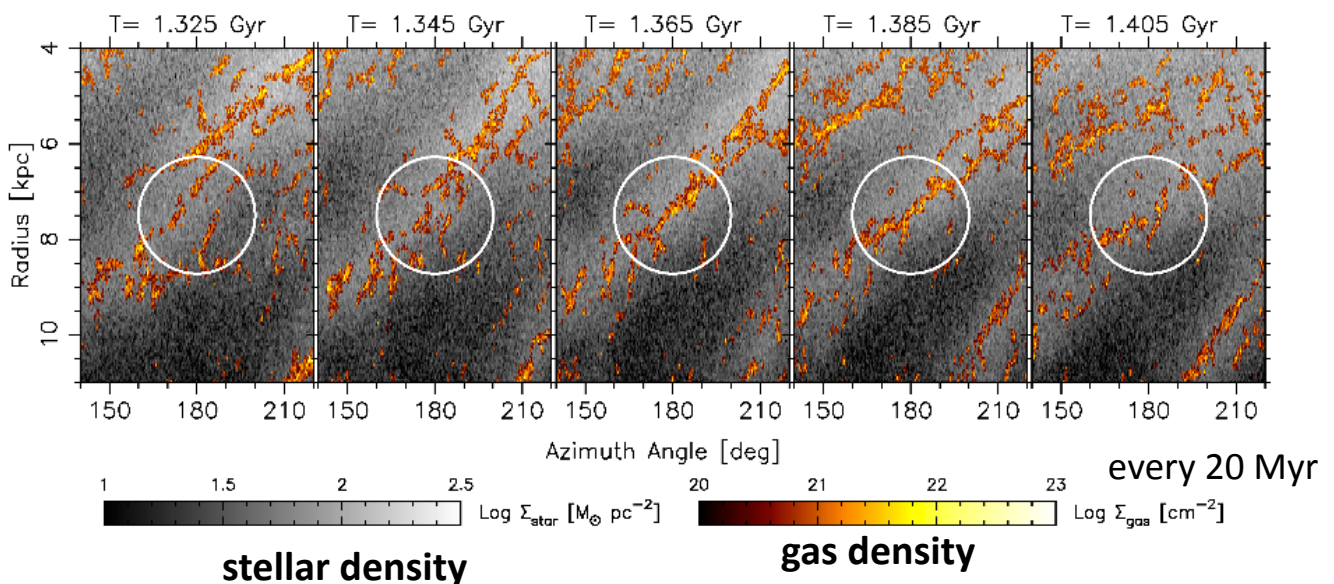
many discrete "GMCs"  
along spirals

⇔ FUGIN data



CCC are expected near spirals ( ≠ galactic shock!)

Gas falls into a spiral potential from both sides → Collision  
between cold gas filaments/clumps → triggering star  
formation → dispersed



KW, Baba, Saitoh (2011)

古屋さん

磁場はどうなってるんだよ！

和

わかりません。やってないんで。

27

## Khoperskov & Khrapov (2017)

MHD, selfgravity, cooling, no SF, no SN

fixed spiral potential ( $m=2, 4$ )

$\Delta x = 15 \text{ pc}$

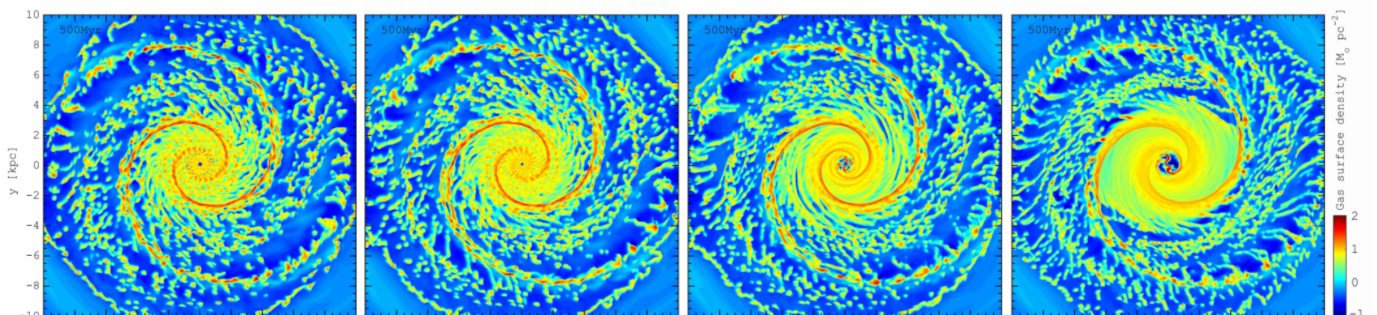
initial B: toroidal or turbulent

磁場なし

$\beta = 10$

$\beta = 1$

$\beta = 0.3$

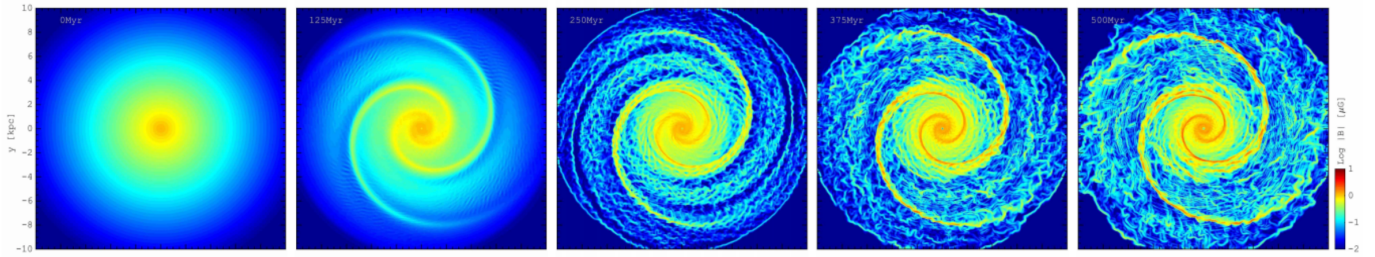


定常状態で大局的な構造はあまり変わらない

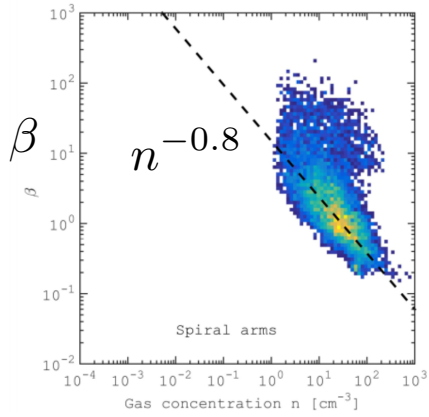
初期磁場の形状にもあまりよらない

28

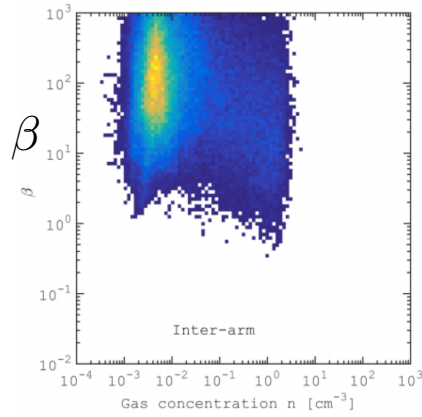
# time evolution of $|B|$ in disk plane



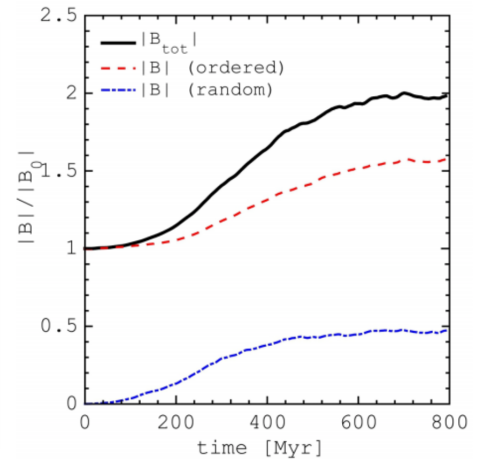
## $\beta$ - density



spiral arm



inter-arm



ランダムな磁場小さい

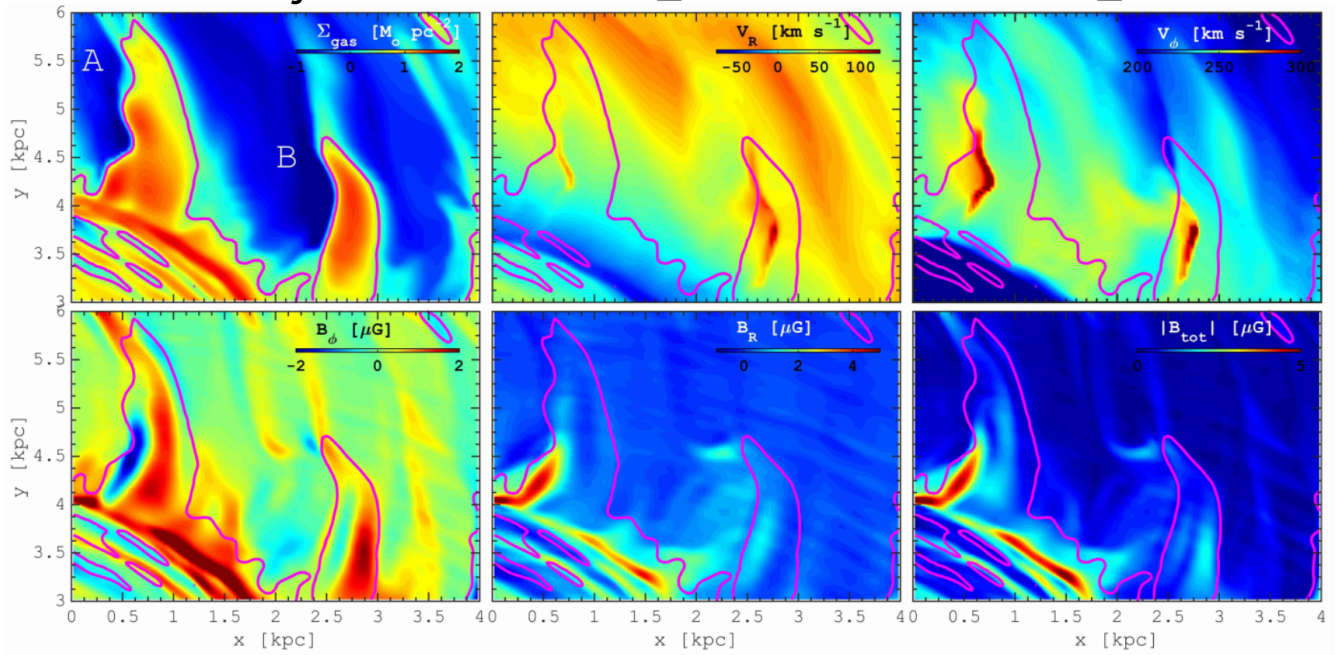
29

# Spur formation

## density

## $V_R$

## $V_\phi$



$B_\phi$

$B_R$

最近の常識！？



## 剛体回転する定常spiral potential

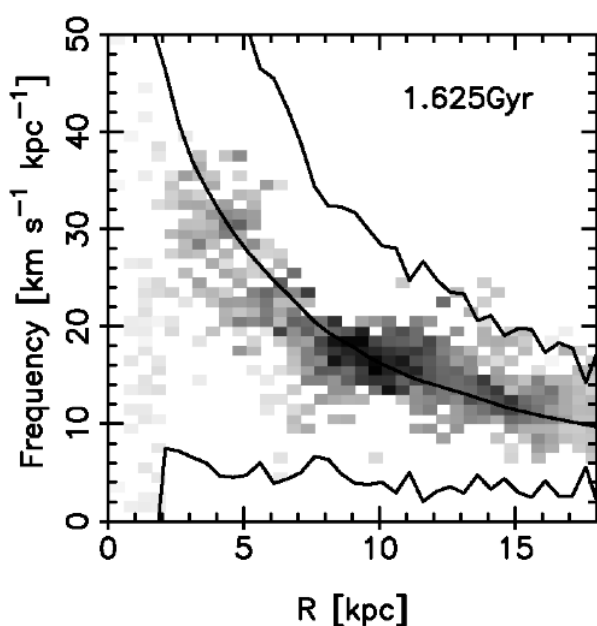
の仮定(Lin & Shu的なdensity wave)は**正しくない**

- “galactic shock”はできない
- MHD simulationでも考慮されるべき

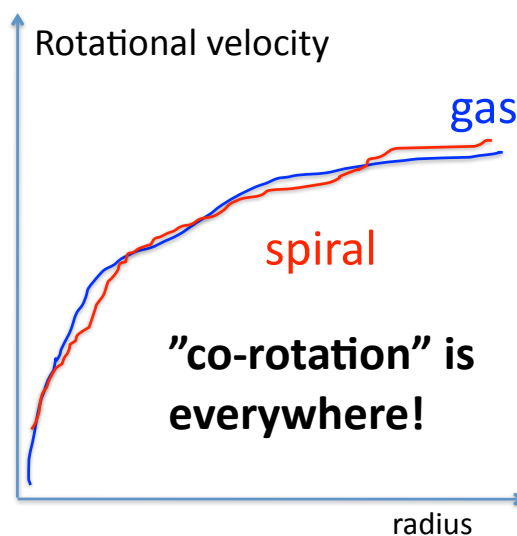
(鹿児島) 工藤さんがやるかも？

30

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



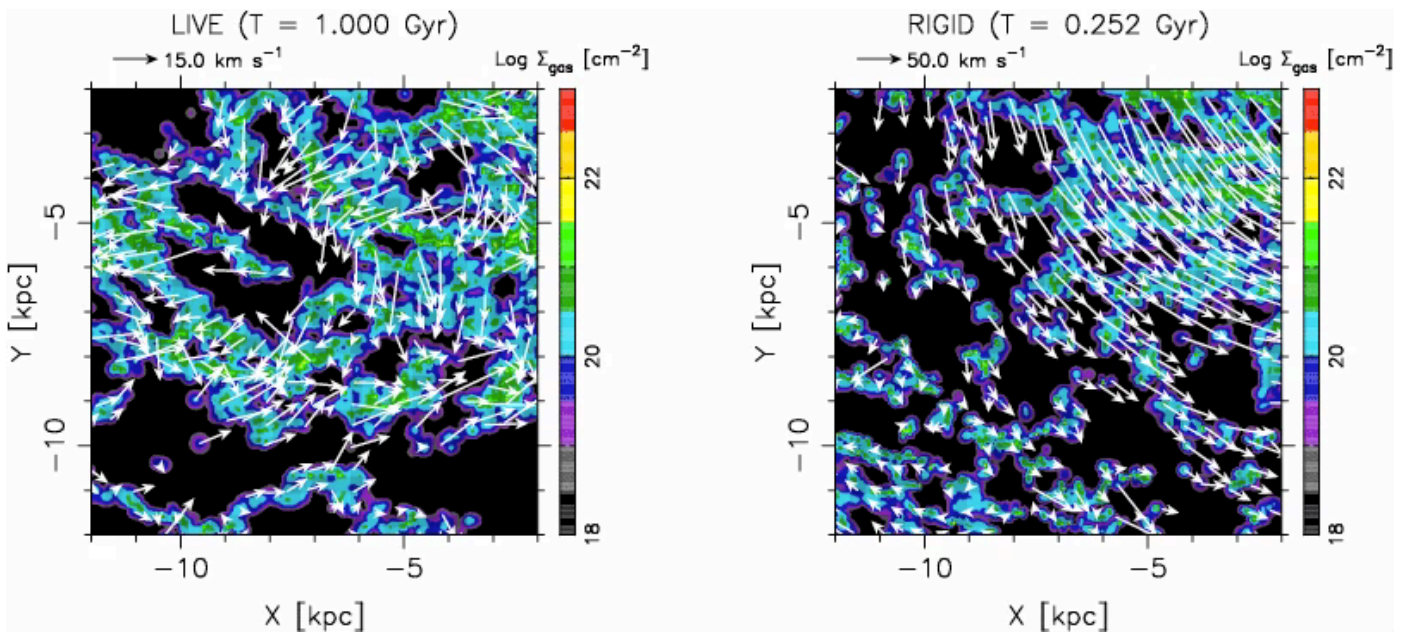
for the spiral potential  
cf. Hasegawa san's talk



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

x

# Gas motion: Live vs. Rigid spiral



Random or converging flows

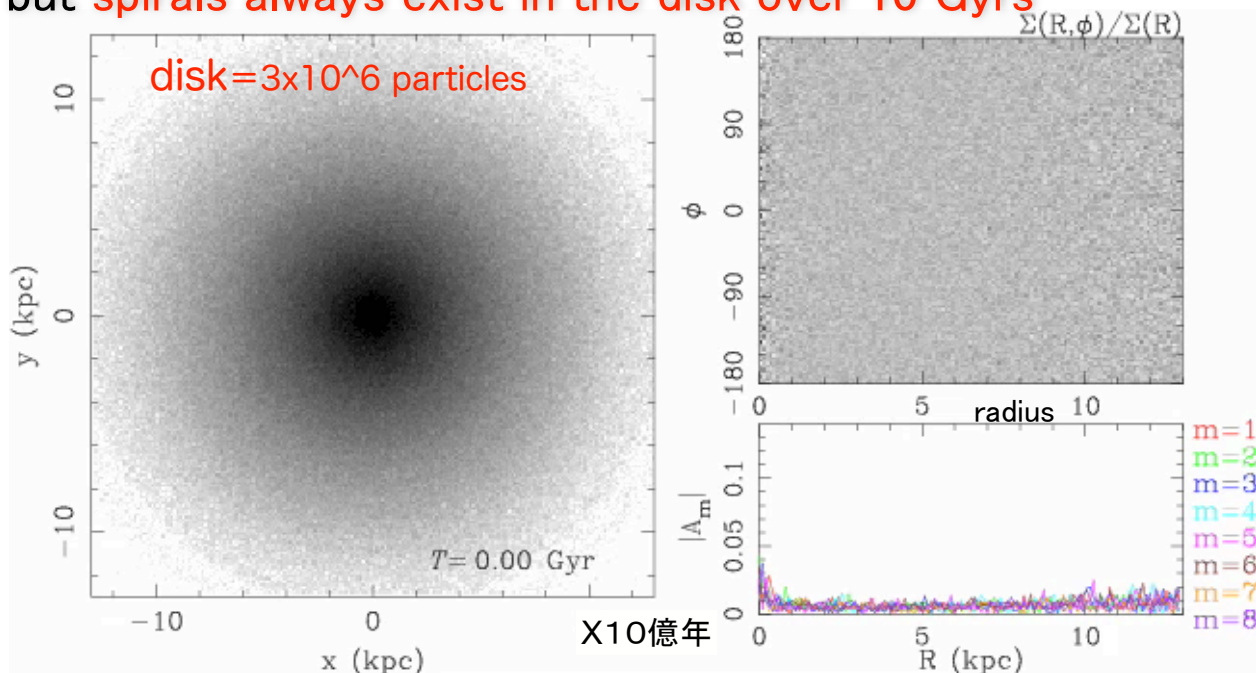
Regular flows typically seen in galactic shock

31

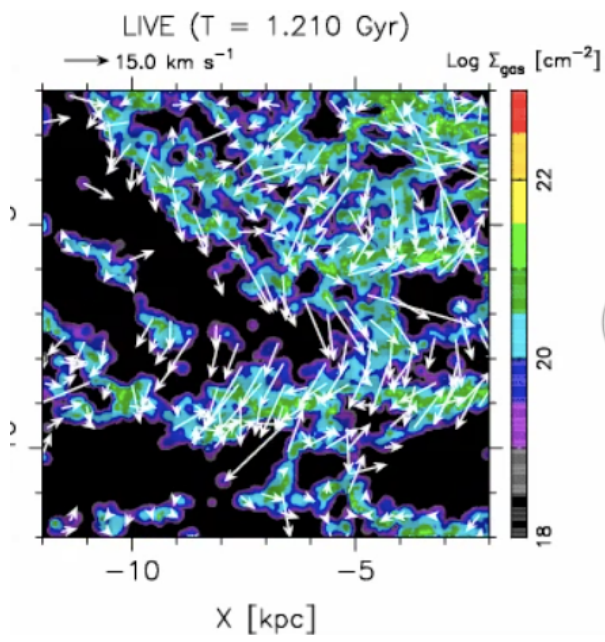
3D pure N-body simulations (Fujii et al.)

⇒ each spiral is **non-steady, short-lived**

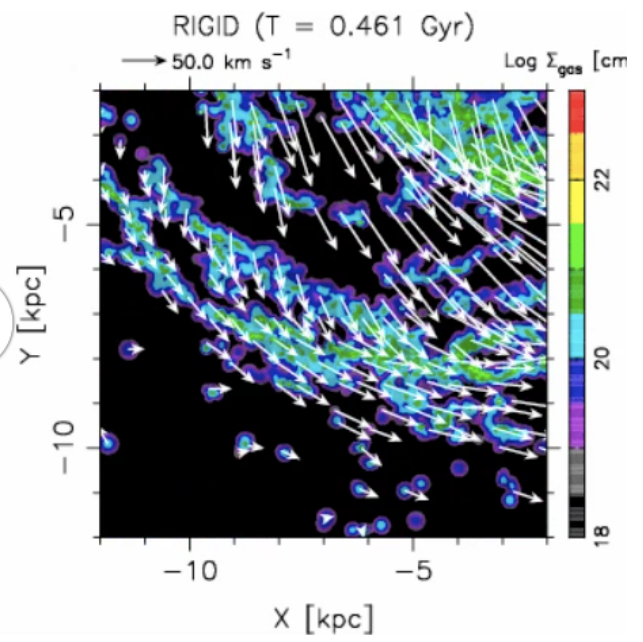
but **spirals always exist in the disk over 10 Gyrs**



All spiral modes are time-dependent, and radially change



Random or converging flows



Regular flows typically seen in galactic shock

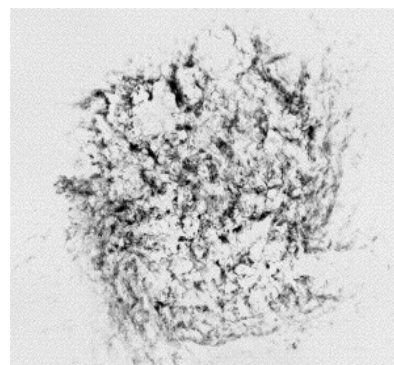
x

銀河円盤の非一様な構造は  
 SNeでできた？

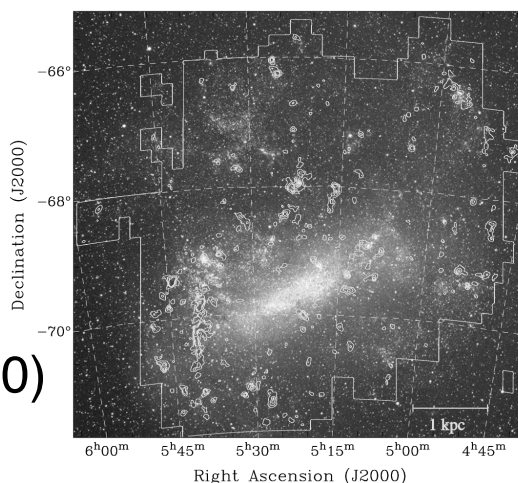
# 現実の銀河への適用 (LMC篇)

- 高分解能全面マップ
  - HI 分布(Kim et al. 1998)
    - 分解能~15pc
  - CO分布(Fukui et al. 1999, 2008; Kawamura+2009)
    - 分解能~40pc
- Simulation: 分解能8pcで全disk領域
  - Wada, Spaans, Kim (2000) ApJ 540, 797

HI

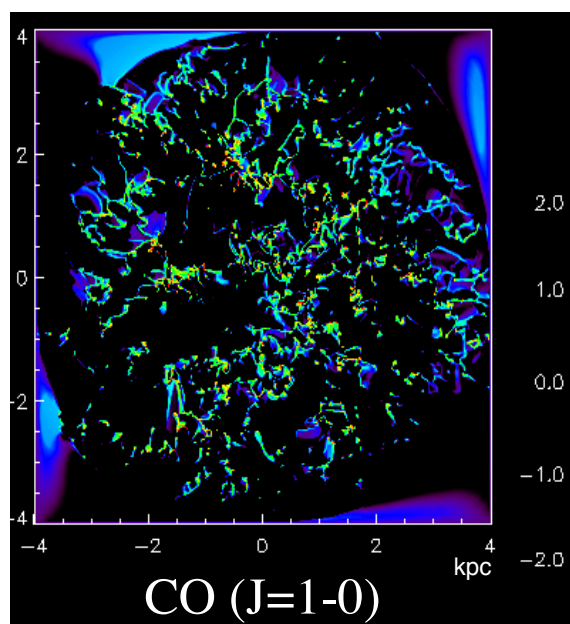
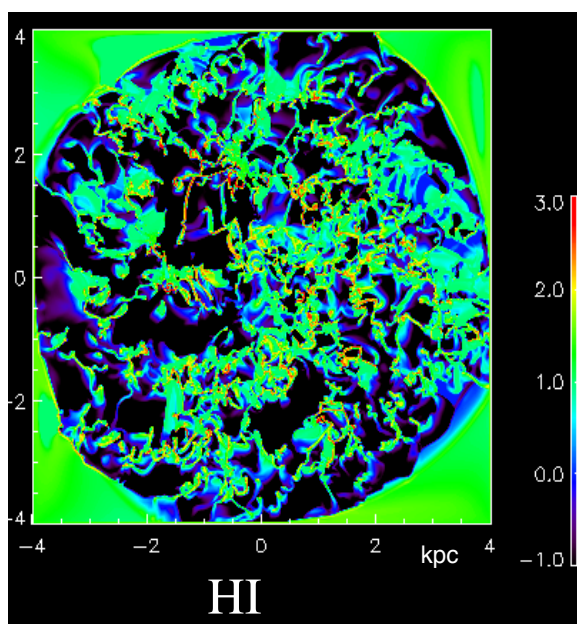


CO(1-0)



KW, Spaans, Kim (2000)

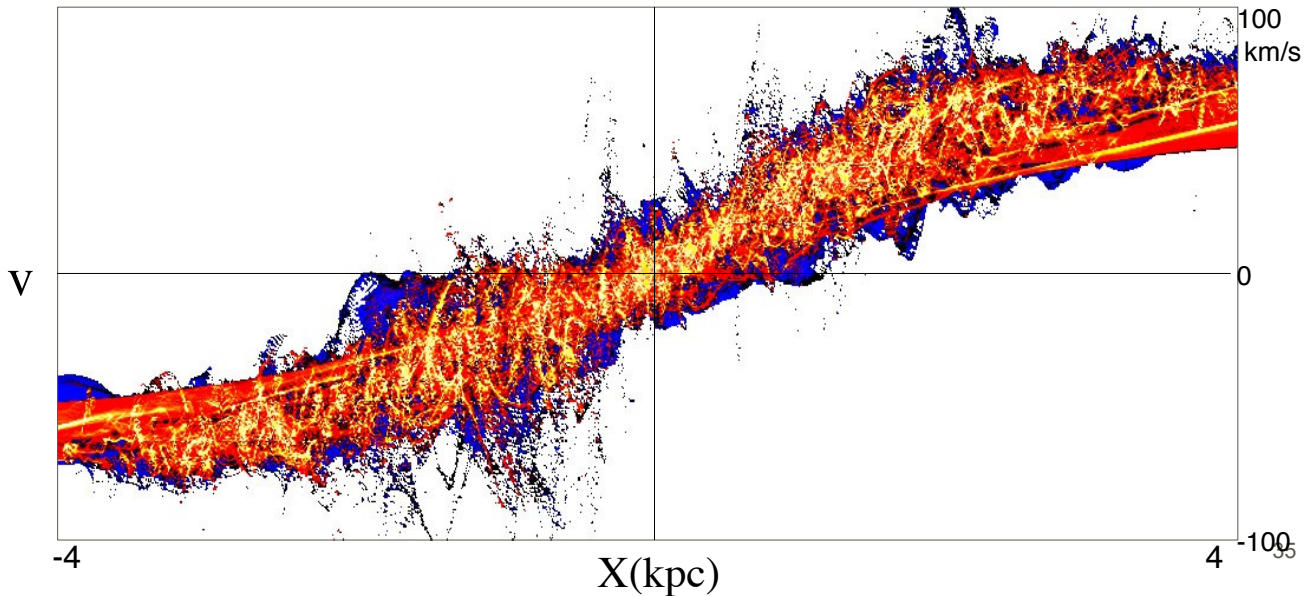
## Large Magellanic Cloud(シミュレーション)



hole/shells, CO非一様分布 <--爆発起源ではない

## PV-diagram for LMC model

*All Shells/Arcs are NOT necessarily due to explosions*



### summary

1. Even weak **non-axisymmetric potential (bar, spiral)** may **change the large-scale structures of the ISM**
  - bar is rigid, spirals should be non-steady (← modern picture)
2. **self-gravity, galactic rotation (&TI)** are important
  - local approximation is not realistic (← theoretically simple, though)
3. **Magnetic field are not essential on galactic structures** (← recent MHD simulations)
4. **SNe feedback is not necessary for large-scale inhomogeneity** (← e.g. LMC)
5. **ISM ≠ "discrete cloudlets"** (← even diffuse gas is important)