Work shop on Galaxy Evolution
@ Ehime University
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COMING
CO Multi-line Imaging of Nearby Galaxies

Physical Properties of Molecular Gas in Nearby Barred Spiral Galaxies

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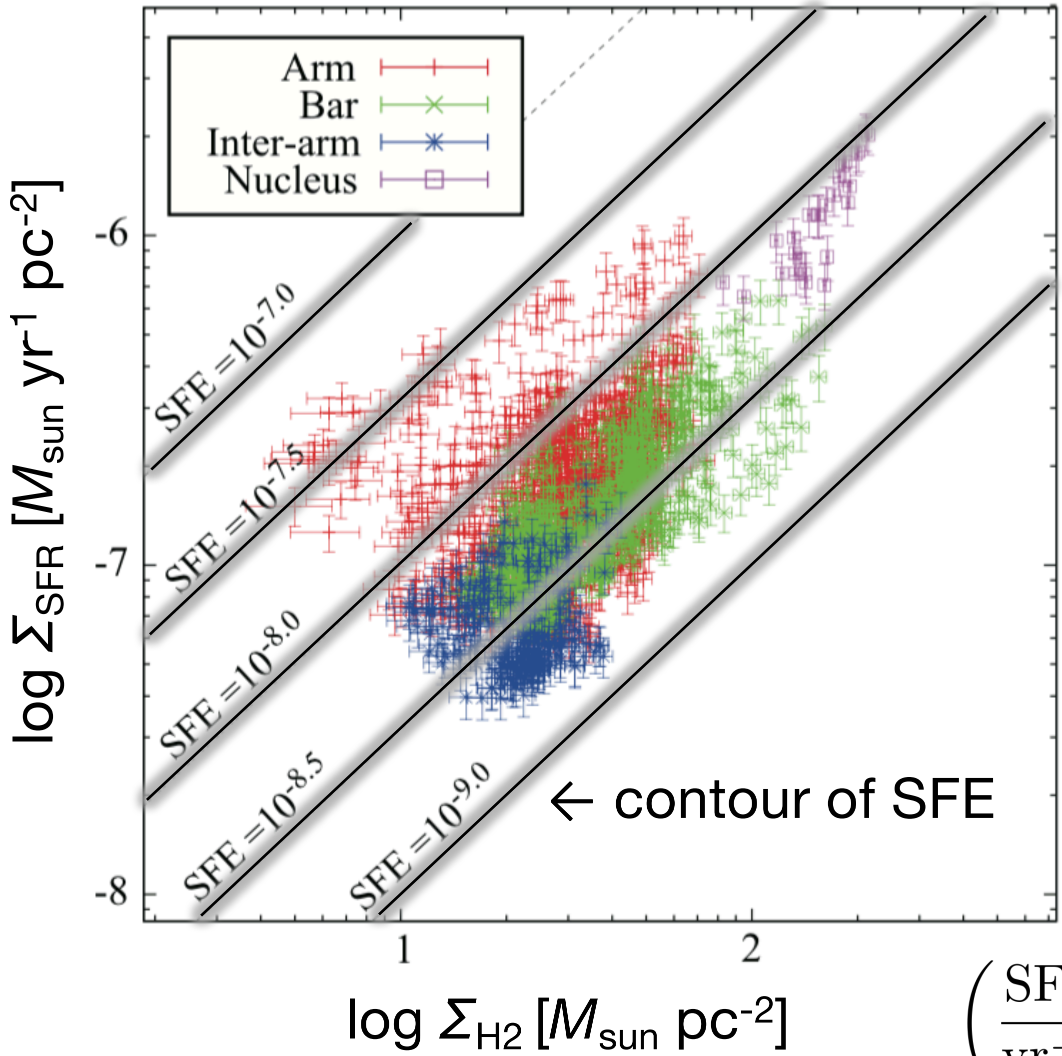
Star Formation in a Barred Spiral Galaxy

spatially resolved K-S plot
(Momose+ 2010)



In the bar,

- plenty molecular gas
- little newborn stars (lower star formation rate; SFR)

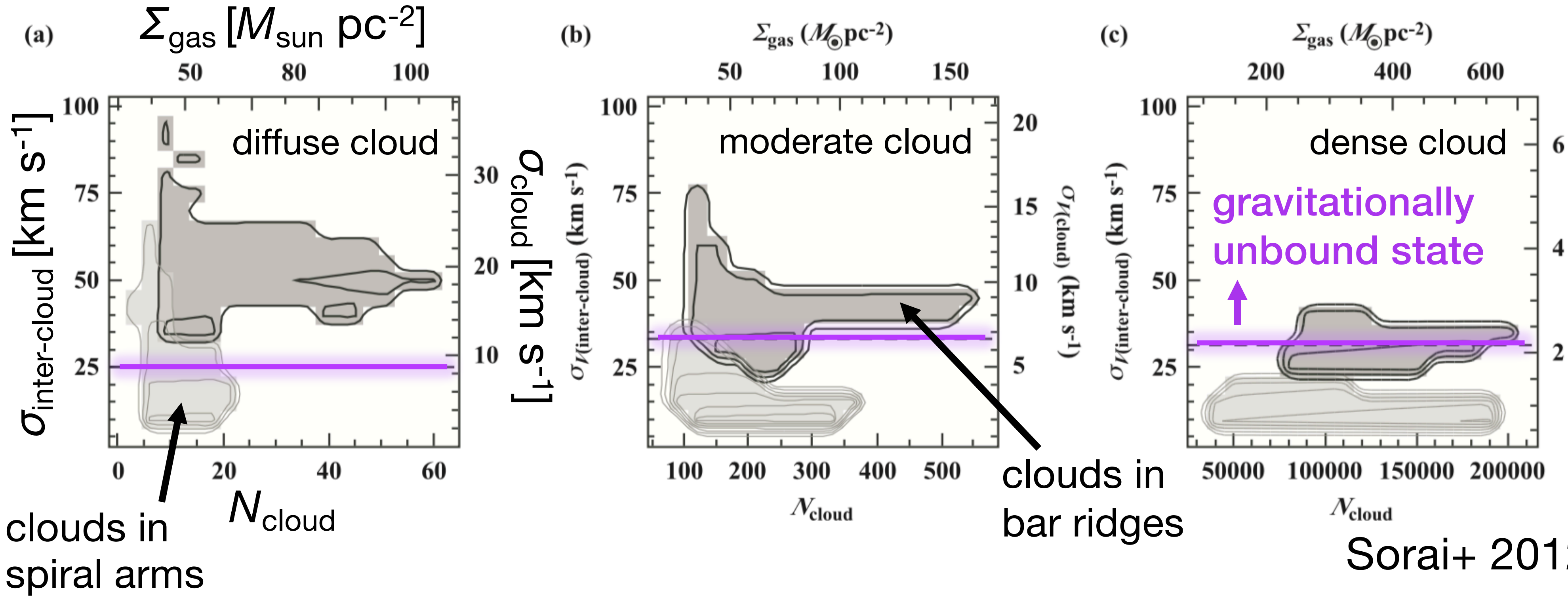
↓

- difficult to form stars **(lower star formation efficiency; SFE)**

the definition of SFE

$$\left(\frac{\mathrm{SFE}}{\mathrm{yr}^{-1}}\right) = \left(\frac{\Sigma_{\mathrm{SFR}}}{M_\odot\ \mathrm{yr}^{-1}\ \mathrm{pc}^{-2}}\right) \Big/ \left(\frac{\Sigma_{\mathrm{gas}}}{M_\odot\ \mathrm{pc}^{-2}}\right)$$

Molecular Gas in Ridges of the Bar



Sorai+ 2012

✓Molecular clouds in bar ridges may be gravitationally unbound

✓There are few studies derived physical properties of molecular gas in the bar because of difficulty

→ Does lower density condition of molecular clouds in the bar suppress star formation? (cause lower SFE?)

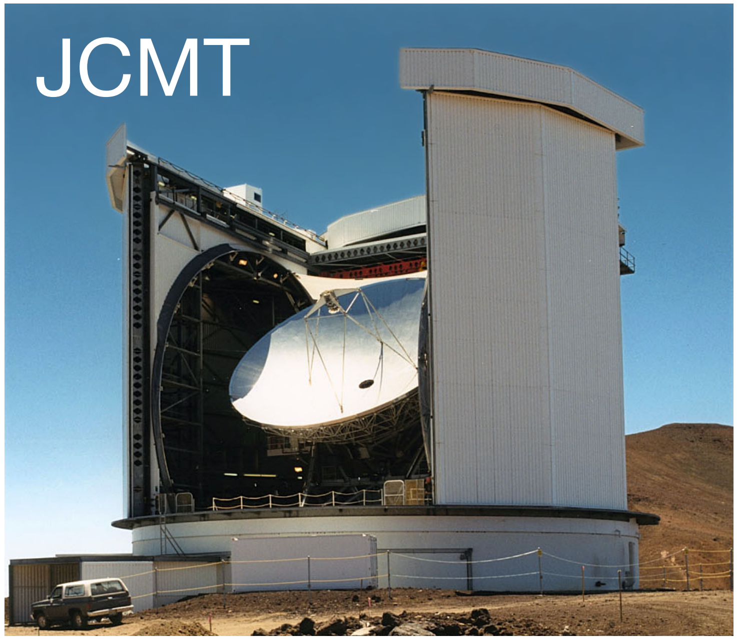
Our observation - COMING project

- CO Multi-line Imaging of Nearby Galaxies
  Sorai+ 2018 in prep
- A NRO Legacy Project
- Observation period Mar., 2014 – Apr., 2018
- Number of observed galaxies
  # > 140 with NRO 45-m telescope, FOREST receiver
- Observed emission lines
  ^{12}CO (J=1→0), ^{13}CO (J=1→0), C^{18}O (J=1→0)
  with simultaneous observation
- Spatial resolution
  17”.4 (^{12}CO (J=1→0)), 17”.9 (^{13}CO (J=1→0), C^{18}O (J=1→0))
- Velocity resolution
  10 km/s

COMING
CO Multi-line Imaging of Nearby Galaxies

Archival data

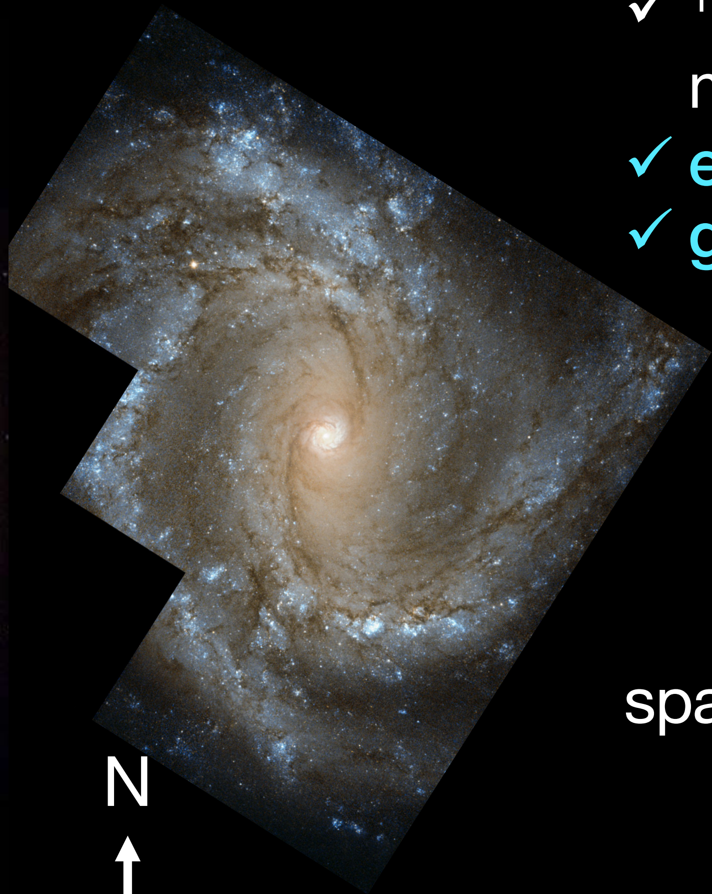
Line, Band	Telescope, Instrument
^{12}CO (J=3→2) line	James-Clerk-Maxwell Telescope (JCMT), HARP
Far UV (λ=1350-1750Å) band	GALEX
24μm mid-IR band	Spitzer Space Telescope, MIPS

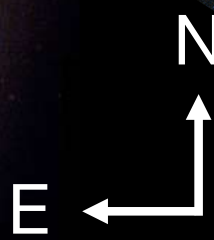


Samples of barred spiral galaxies

NGC 3627

NGC 4303





images by *HST*

✓ ^{12}CO(J=3→2) archival mapping data is available

✓ easy to recognize the bar

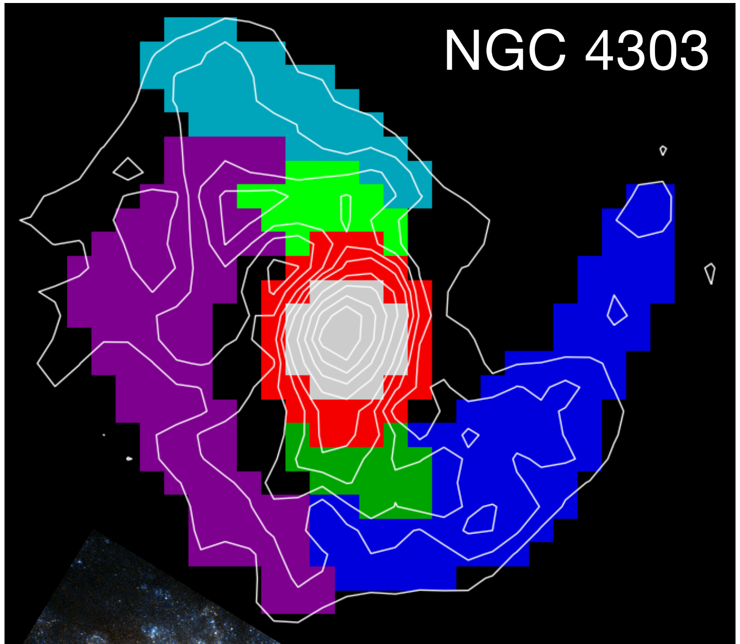
✓ gas rich in the bar

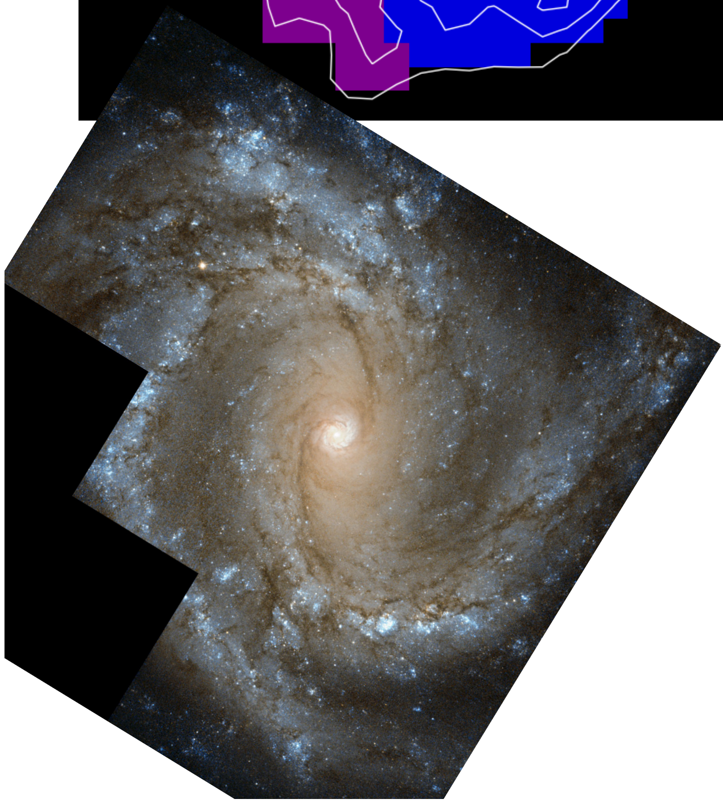
→ make it easy to discuss properties of molecular gas in the bar

spatial resolution 17”.4

→ 0.76 kpc for NGC 3627
1.6 kpc for NGC 4303

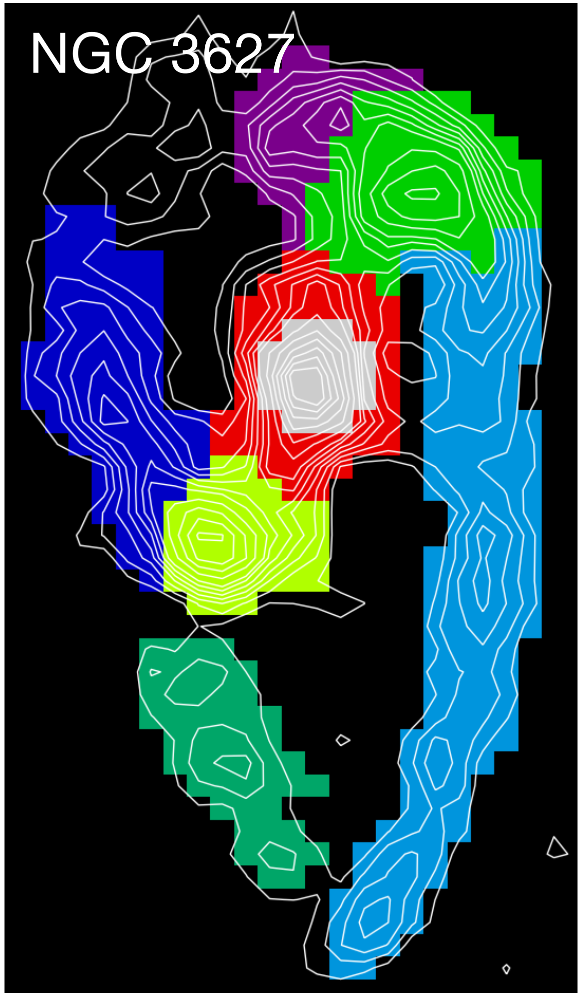
Region separation





Arms, bar-ends & bar region are defined

We measured SFE, $I_{12CO(1-0)}/I_{13CO(1-0)}$, $I_{12CO(3-2)}/I_{12CO(1-0)}$ for each region



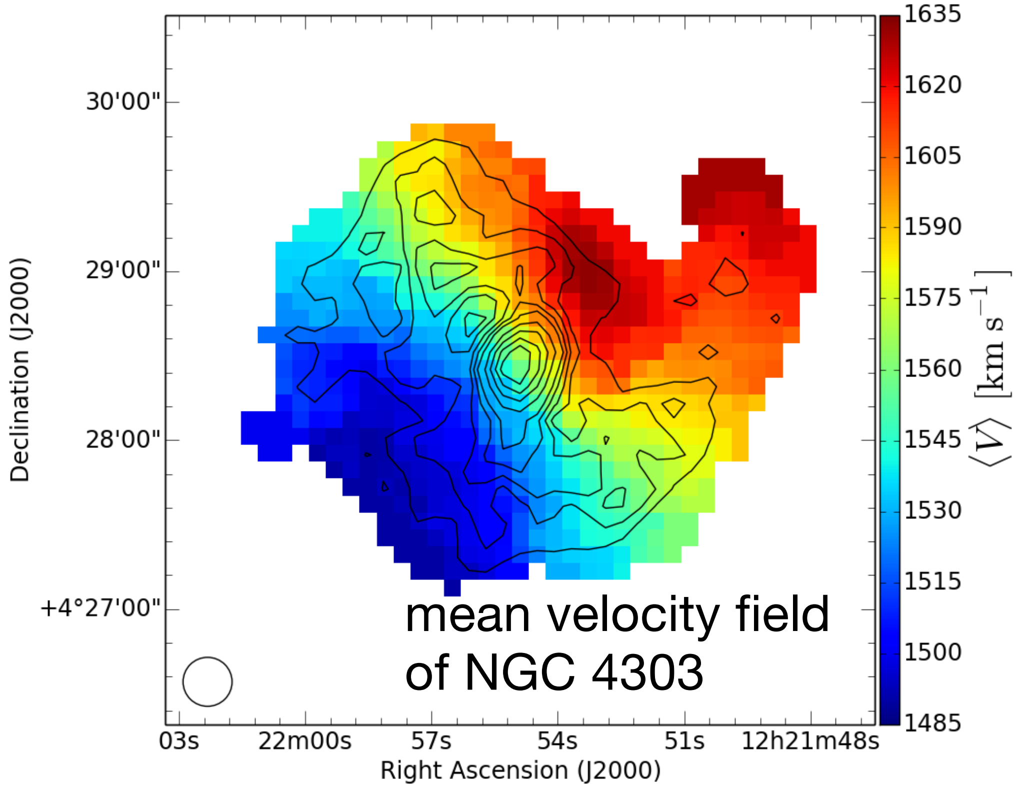
Stacking analysis

^{13}CO(J=1→0) spectrum is
too noisy to measure $I_{13CO(1\text{-}0)}$

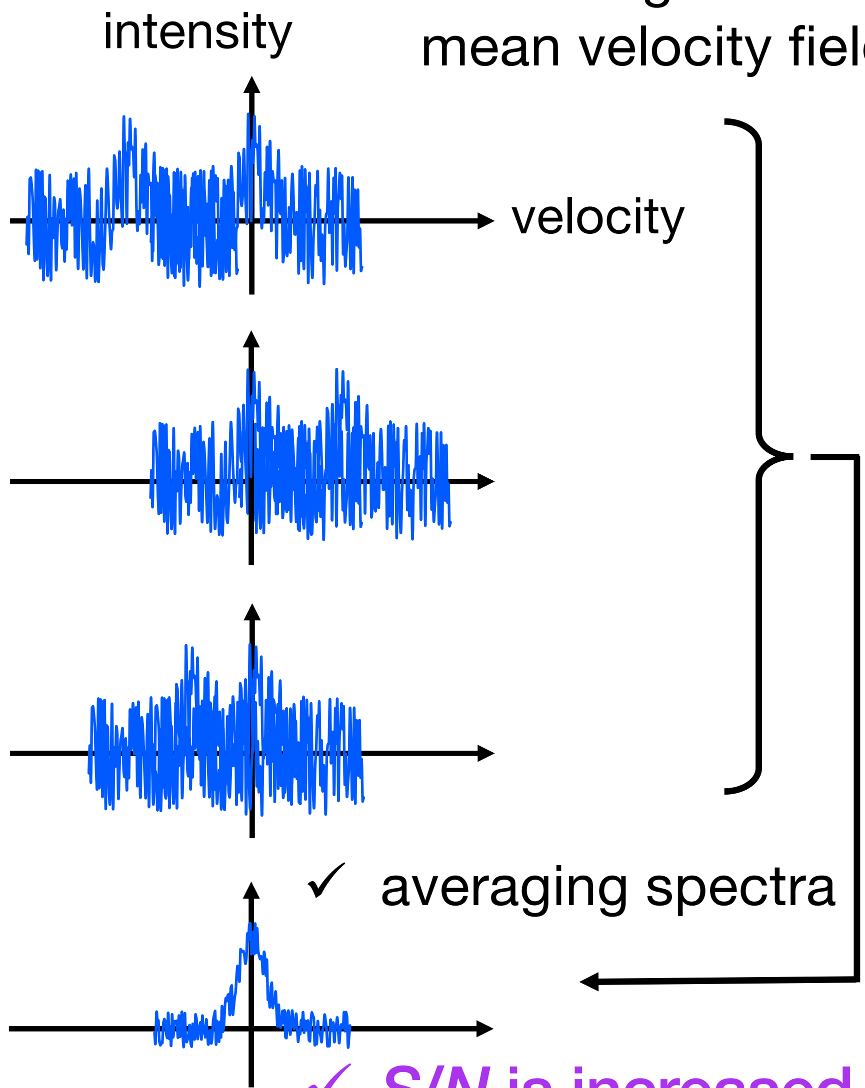
↓

performed 'stacking analysis'
(Schruba+ 2011)

$$\langle V \rangle = \int vT(v)dv/I$$



✓ shifting velocity according to mean velocity field



✓ averaging spectra

✓ ***S/N* is increased**

Deriving molecular gas density & temperature

integrated intensity ratios

$I_{\text{12CO(1-0)}}/I_{\text{13CO(1-0)}}$

$I_{\text{12CO(3-2)}}/I_{\text{12CO(1-0)}}$

↓

a code 'RADEX'
(van der Tak+ 2007)
for **non-LTE analysis**

↓

number density $n(H_2)$

kinetic temperature T_{kin}

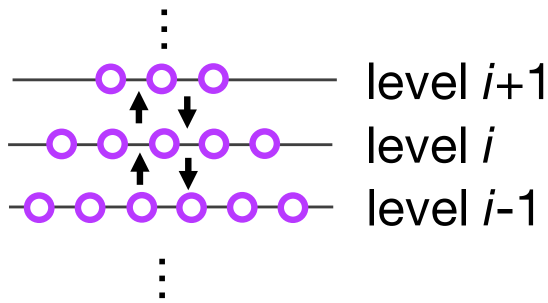
of molecular gas

(LTE: Local Thermodynamic Equilibrium)

iteratively solve

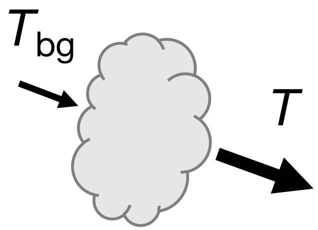
- level population of the molecule at static state

$$\frac{dn_i}{dt} = 0$$
$$= \sum_{i>j} \left[n_j (B_{ji}\bar{J} + C_{ji}) - n_i (A_{ij} + B_{ij}\bar{J} + C_{ij}) \right]$$
$$+ \sum_{i<j} \left[n_j (A_{ji} + B_{ji}\bar{J} + C_{ji}) - n_i (B_{ij}\bar{J} + C_{ij}) \right]$$



- radiative transfer

$$\frac{dT}{d\tau} = -T + S$$



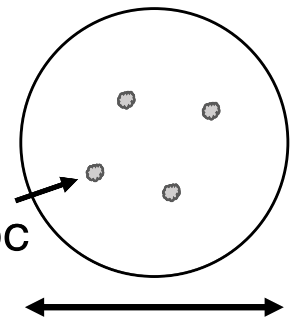
Correction for ‘*beam dilution*’ effect

For RADEX calculation, ^{12}CO column density of **one cloud** is necessary

- an usual method for deriving column density

$$\left(\frac{N_{^{12}\mathrm{CO}}}{\mathrm{cm}^{-2}}\right) = \left(\frac{I_{^{12}\mathrm{CO}(1-0),\mathrm{obs}}}{\mathrm{K\ km\ s}^{-1}}\right) \cos i \times \left\{\frac{X_{\mathrm{CO}}}{\mathrm{cm}^{-2}\ (\mathrm{K\ km\ s}^{-1})^{-1}}\right\} \times \frac{[^{12}\mathrm{CO}]}{[\mathrm{H}_2]}$$

$\Omega_c << \Omega_{beam}$



However,

$$T_{\mathrm{obs}} \simeq \frac{\Omega_{\mathrm{c}}}{\Omega_{\mathrm{mb}}} T_{\mathrm{c}} < T_{\mathrm{c}}$$ ← so-called **‘beam dilution’**

column density will be **underestimated**

Hence,

$$\left(\frac{N_{^{12}\mathrm{CO}}}{\mathrm{cm}^{-2}}\right) = \left(\frac{I_{^{12}\mathrm{CO}(1-0),\mathrm{obs}}}{\mathrm{K\ km\ s}^{-1}}\right) \cos i \times \frac{1}{\eta_{\mathrm{f}}} \times \left\{\frac{X_{\mathrm{CO}}}{\mathrm{cm}^{-2}\ (\mathrm{K\ km\ s}^{-1})^{-1}}\right\} \times \frac{[^{12}\mathrm{CO}]}{[\mathrm{H}_2]}$$

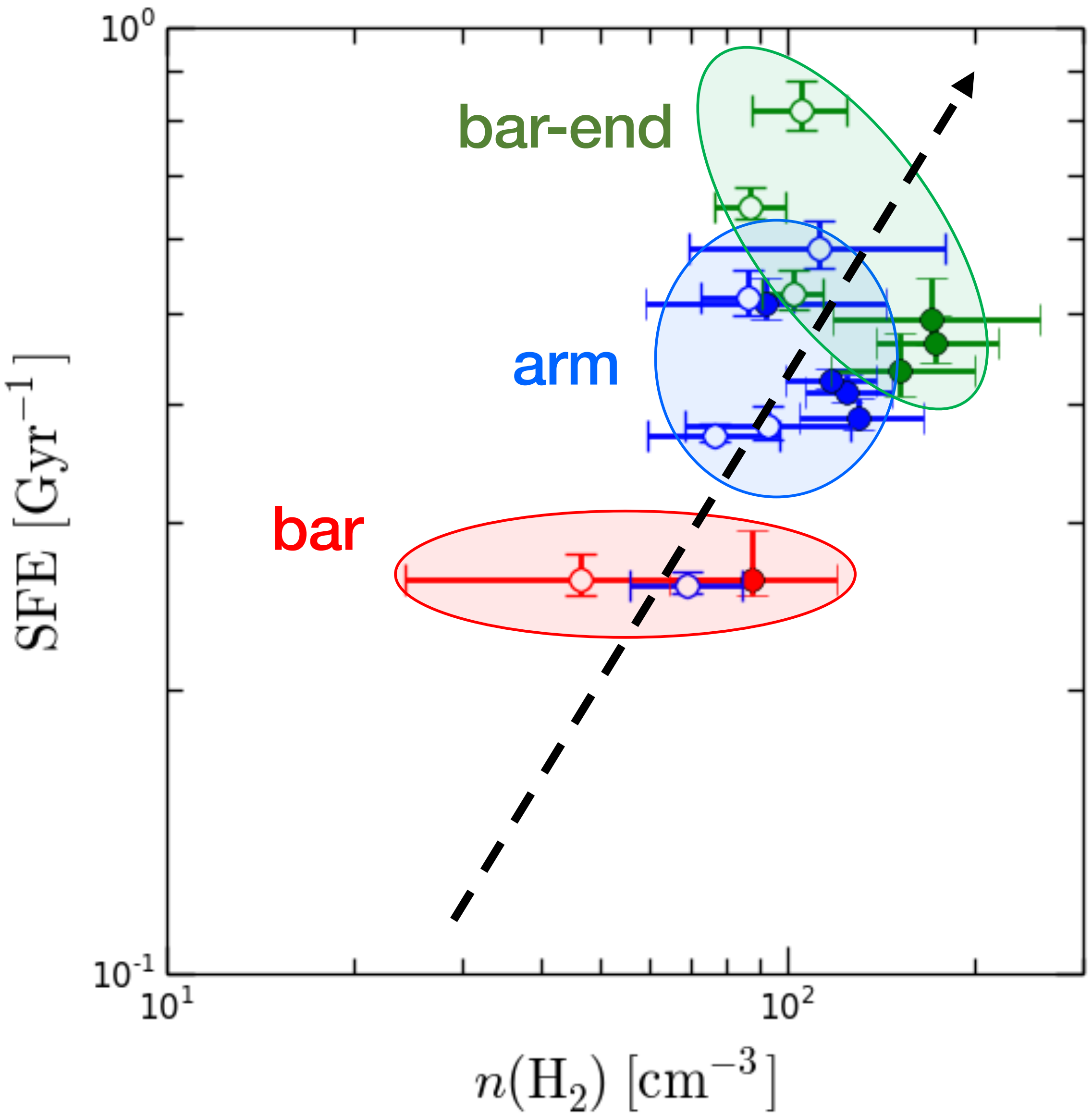
$\eta_{\mathrm{f}} \equiv \Omega_{\mathrm{c}}/\Omega_{\mathrm{mb}}$; beam filling factor

Considering $\sigma_{\text{inter-cloud}}$, the best value of η_f is determined when

$$\Delta\eta_{\mathrm{f}} \equiv I_{^{12}\mathrm{CO}(1-0),\mathrm{obs}} \times \cos i / I_{^{12}\mathrm{CO}(1-0),\mathrm{cloud}} - \eta_{\mathrm{f}}$$

becomes 0 with given η_f → best beam filling factor

SFE vs. Molecular Gas Density



open marker: NGC 3627
filled marker: NGC 4303

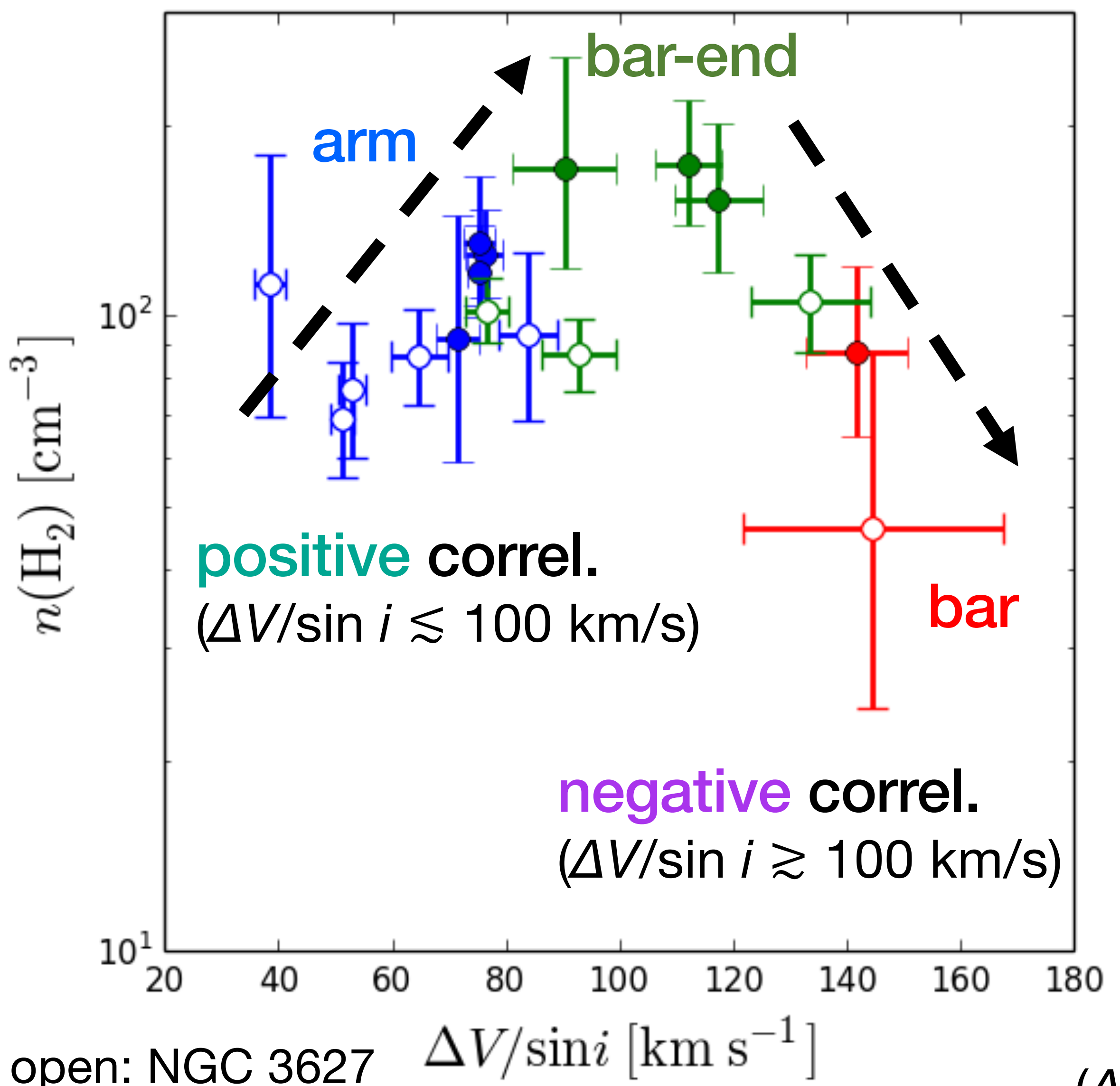
Positive correlation between SFE & $n(H_2)$

lower density of molecular gas

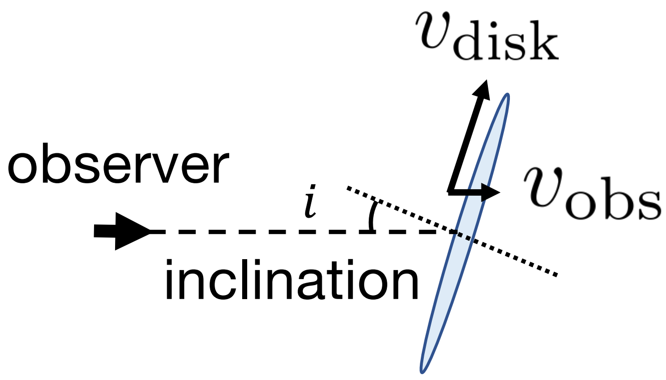
↓

difficult to form stars

Gas Density & Inter-cloud Velocity Dispersion



open: NGC 3627
filled: NGC 4303



$$v_{\rm obs} = v_{\rm disk} \sin i + v_{\rm sys}$$

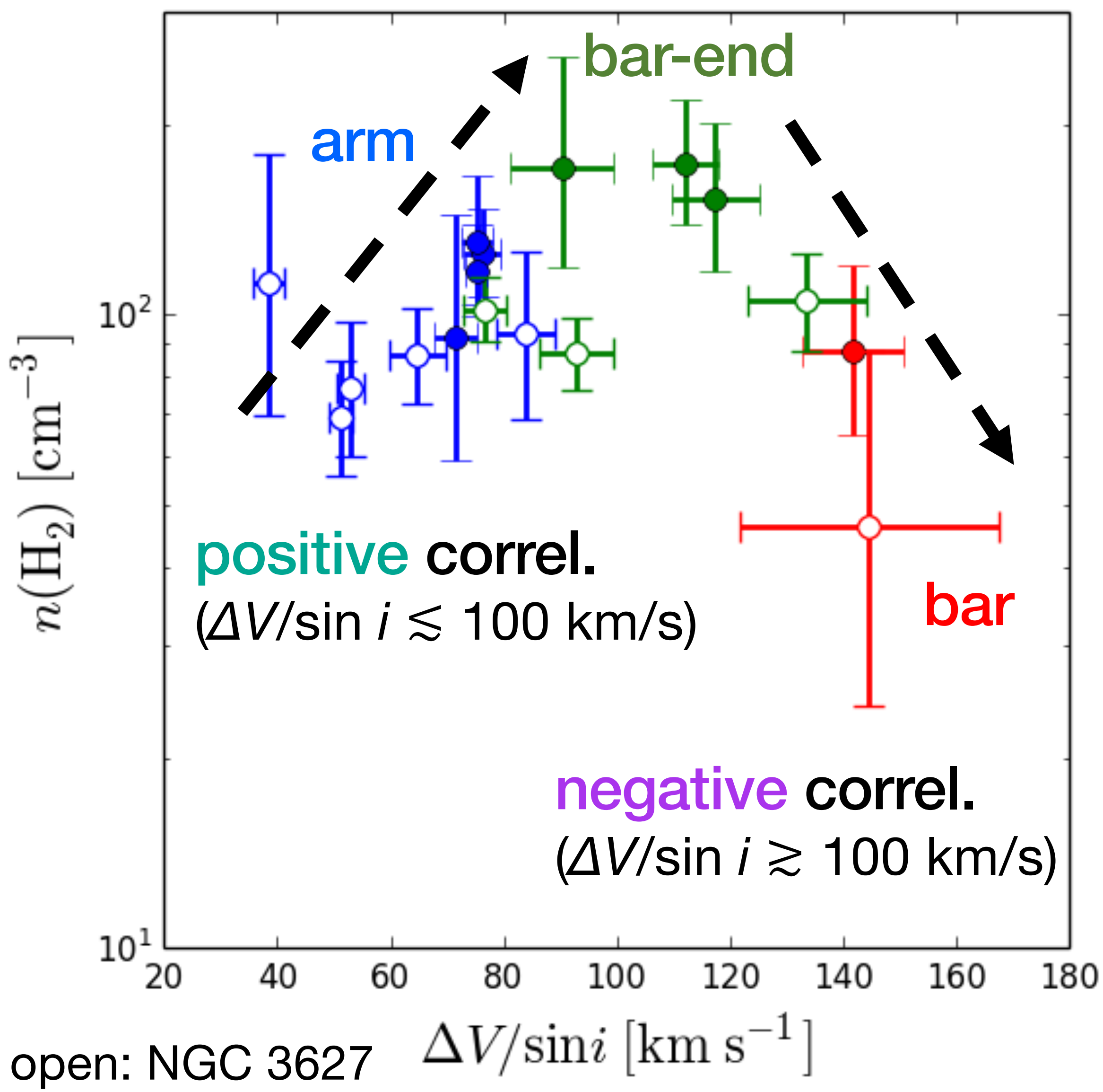
ΔV/sin *i*

~

$\sigma_{\text{inter-cloud}}$ projected galactic plane

(*ΔV*: FWHM of stacked spectrum)

Gas Density & Inter-cloud Velocity Dispersion



open: NGC 3627
filled: NGC 4303

In positive correl. phase
(from arms to bar-ends)

due to moderate $\sigma_{\text{inter-cloud}}$

- cloud-cloud collision is promoted?

In negative correl. phase
(from bar-ends to the bar)

by too large $\sigma_{\text{inter-cloud}}$

- shear becomes effective?
- internal cloud's motion is enhanced?
- clouds are broken?
- cores can't grow?

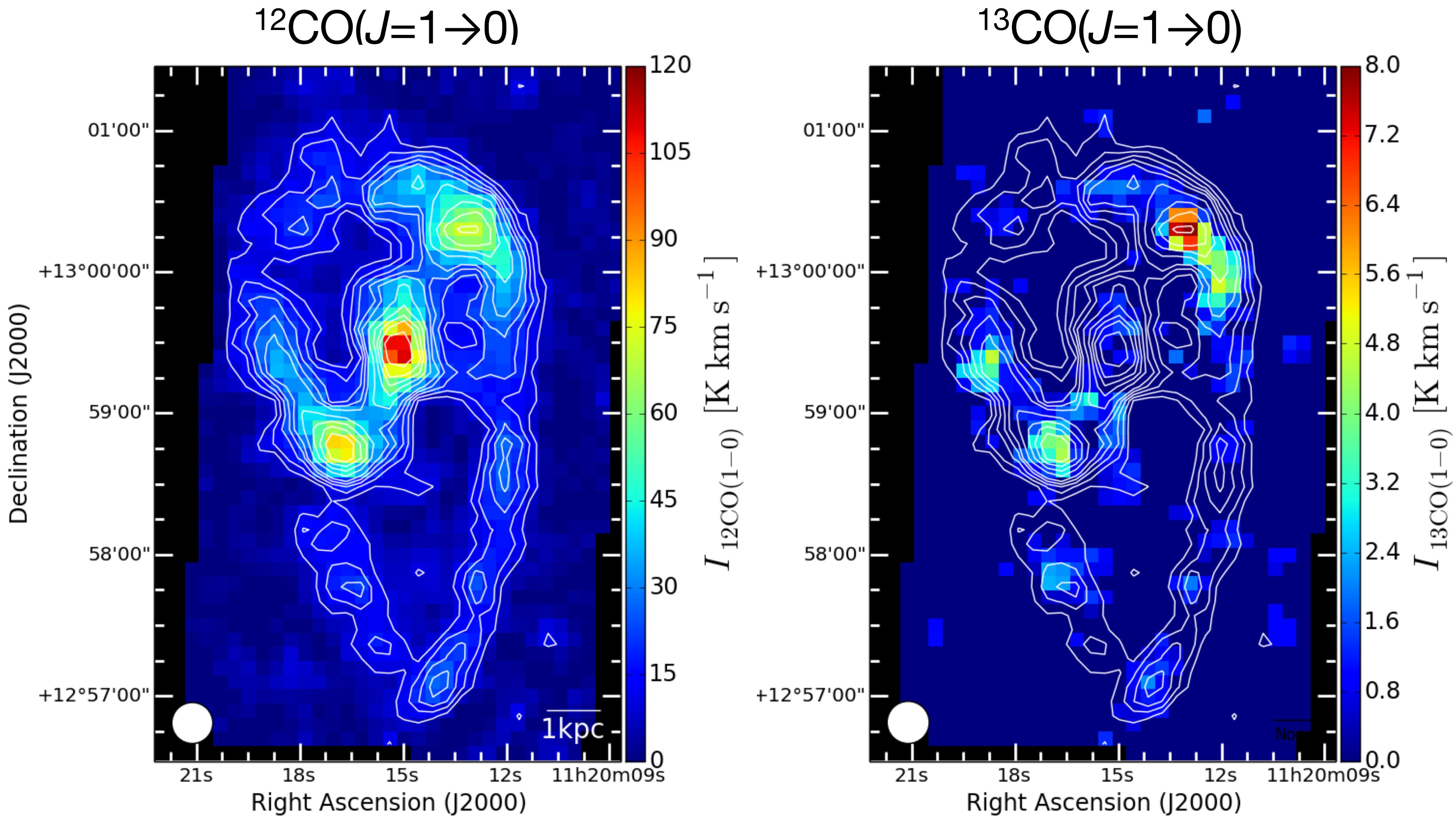
Summary & Conclusions

- Barred spiral galaxies often show that it is difficult to form stars in the bar
- We study about physical properties of molecular gas in barred spiral galaxies NGC 3627, 4303
- Beam dilution correction method is developed for deriving physical properties of molecular gas
- There is positive correlation between SFE & $n(H_2)$
- The relationships between $n(H_2)$ & $\sigma_{\text{inter-cloud}}$ is changing at the boundary $\Delta V/\sin i \approx 100$ km/s
- Star formation in the bar is suppressed by **lower density** of molecular gas &
  lower density is caused due to **strong motion of gas**

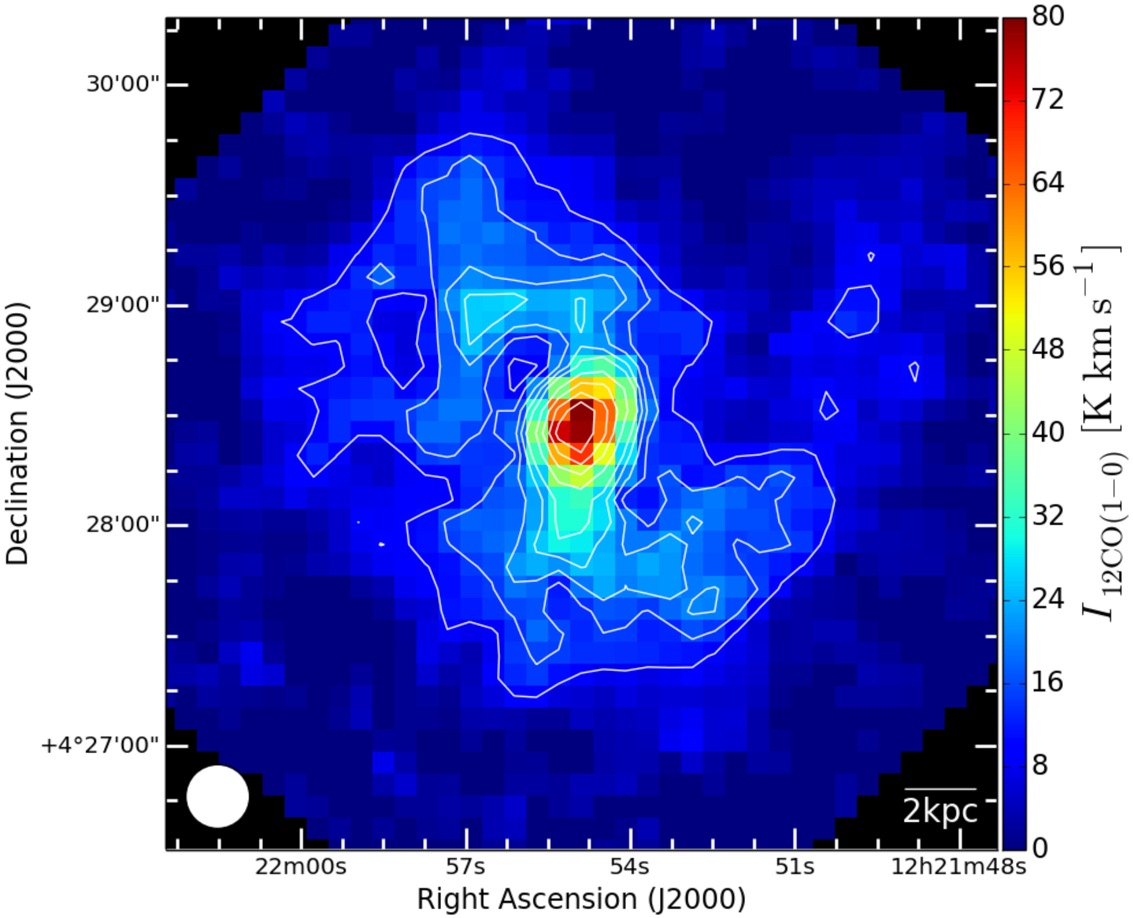
Appendix

CO observation results (NGC 3627)

velocity-integrated intensity map

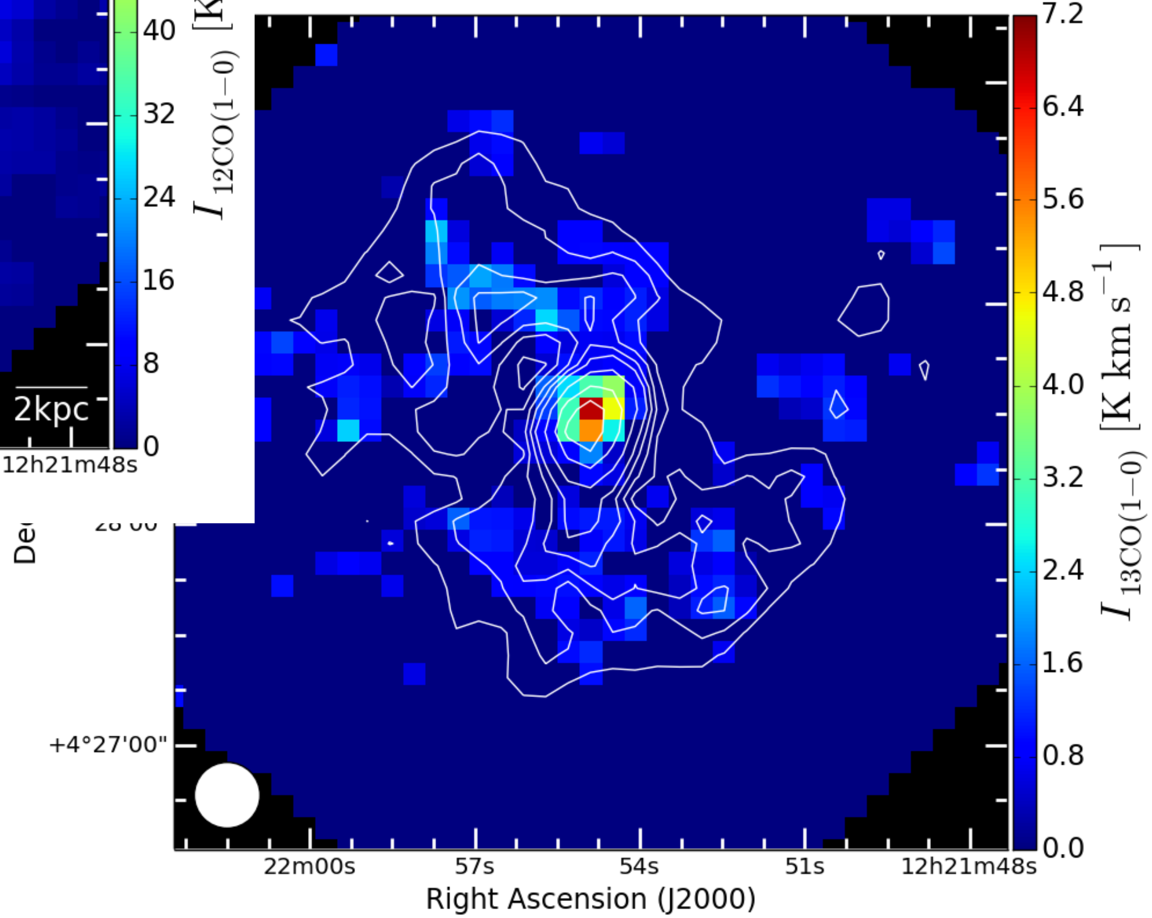


CO observation results (NGC 4303)

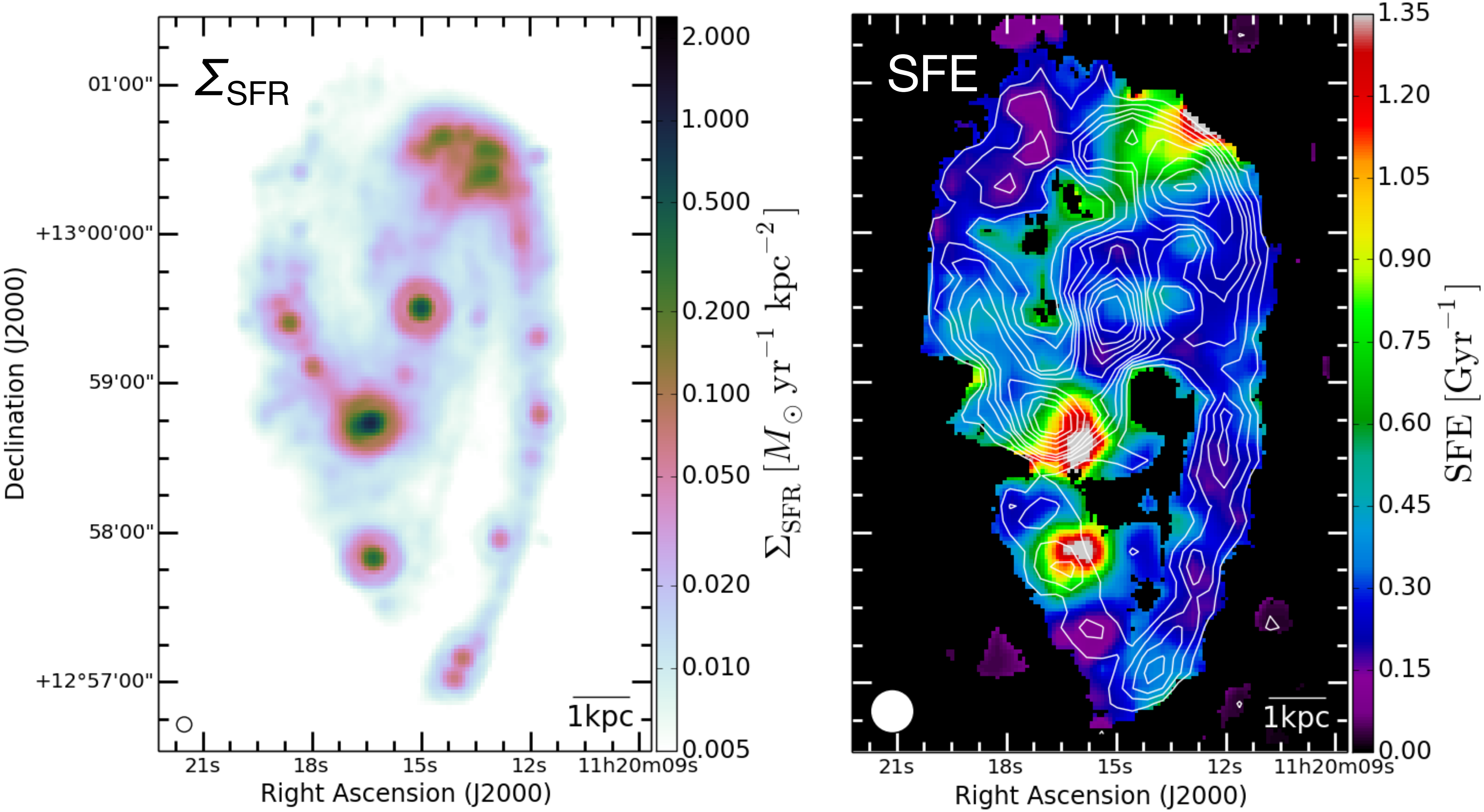


^{12}CO(J=1→0)

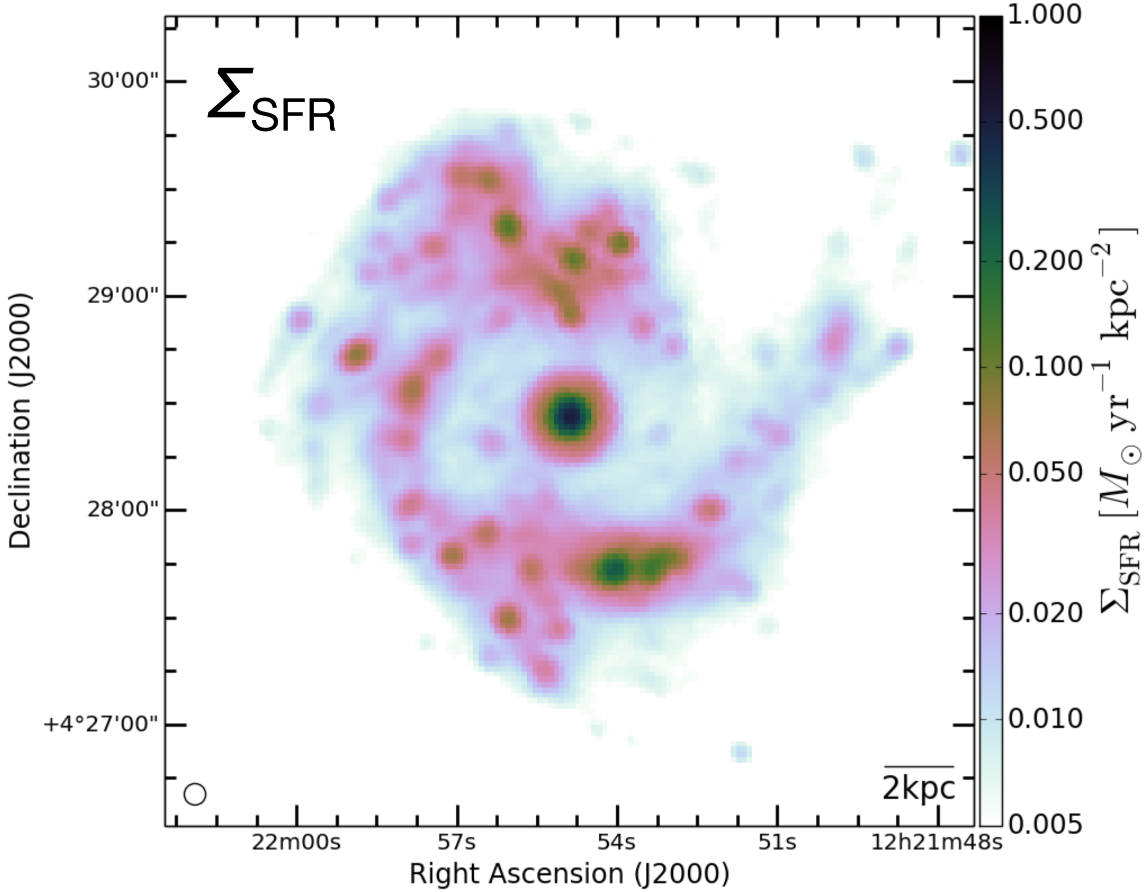
^{13}CO(J=1→0)

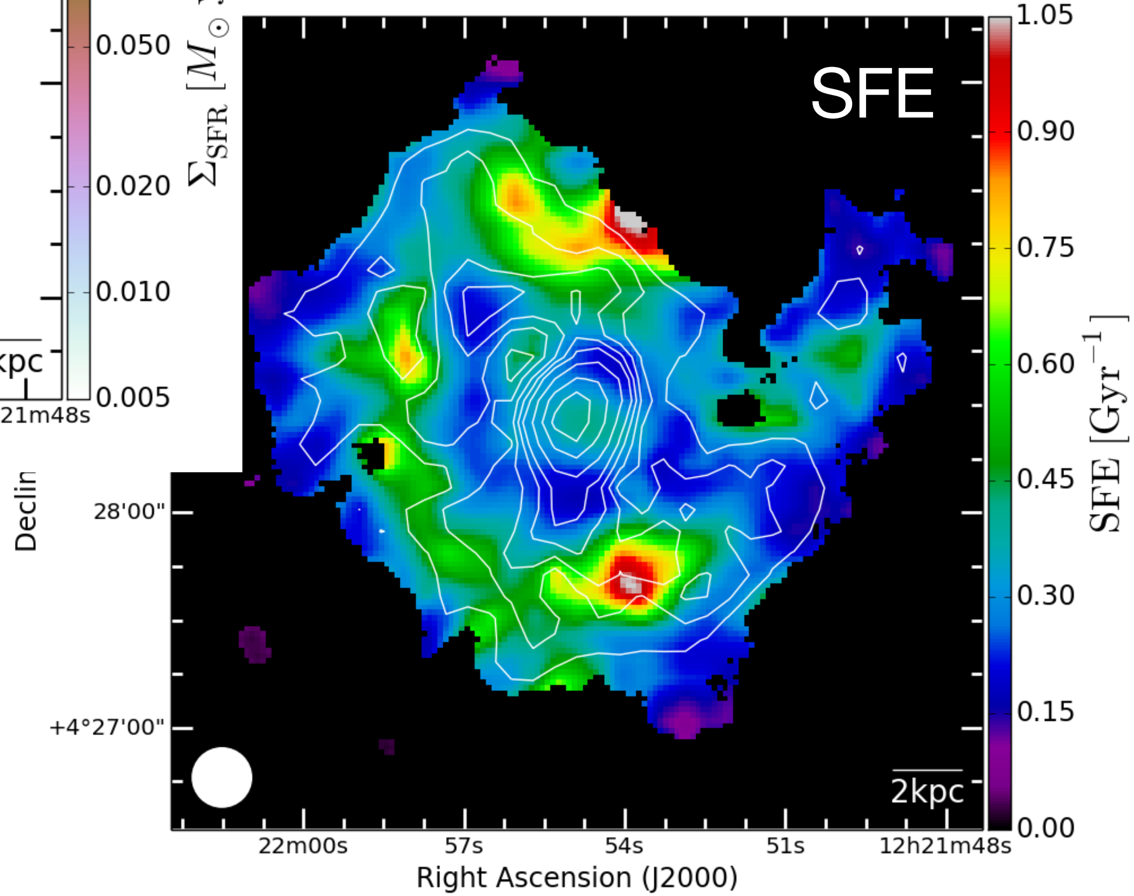


SFR & SFE (NGC 3627)



SFR & SFE (NGC 4303)





NGC 3627 as an interaction galaxy

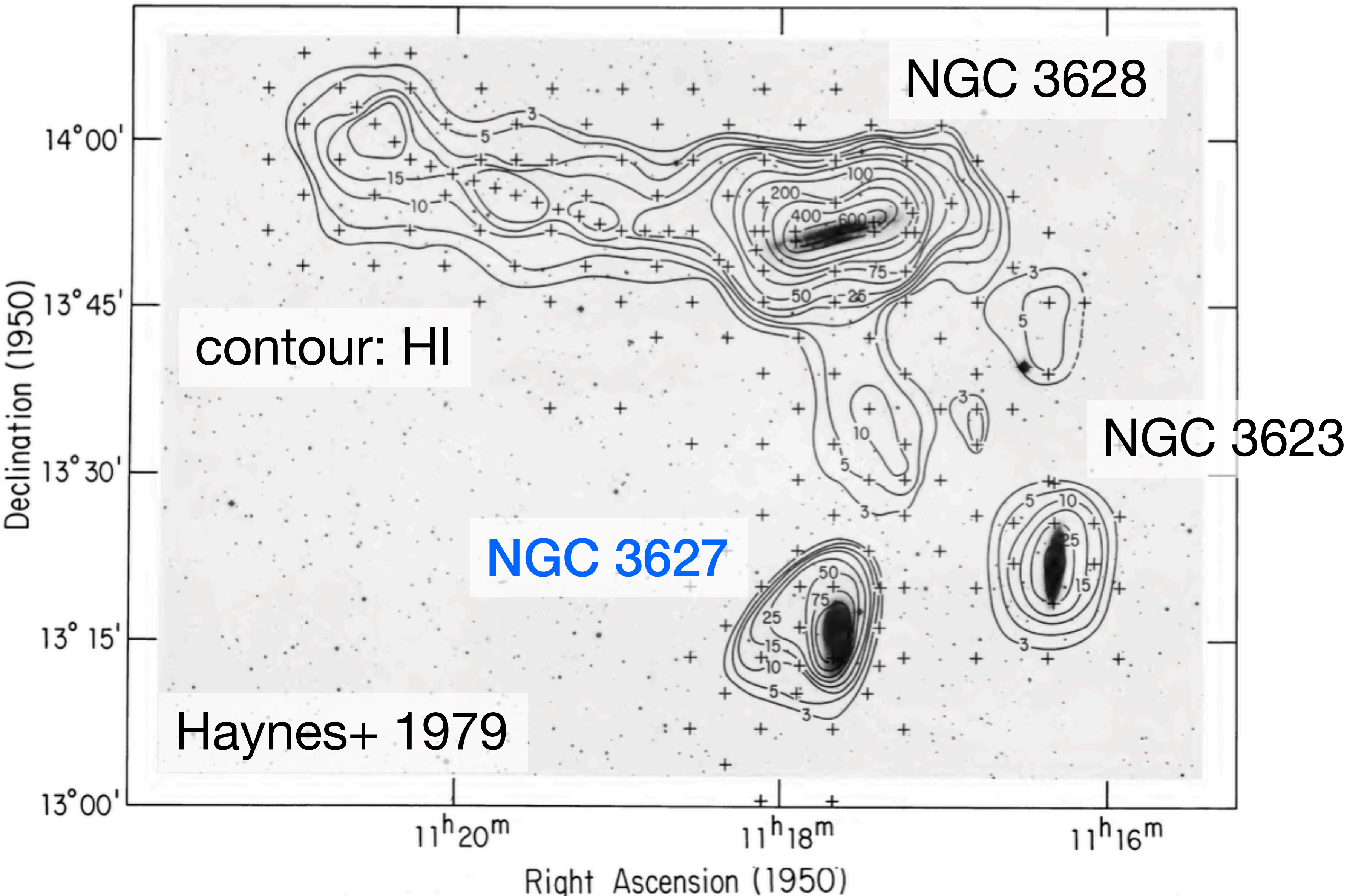


FIG. 1.—Neutral hydrogen contours of $\int T_A dV$ superposed on an enlargement of the Palomar Sky Survey print of the Leo triplet. The northernmost galaxy is NGC 3628; the southernmost is NGC 3627; the westernmost is NGC 3623. Crosses mark the sampling points of the Arecibo observations. The long appendage extending eastward from NGC 3628 is referred to as the plume; the extension in the region between the three galaxies is the bridge.

Input parameters for 'RADEX' code

input parameters

- $I_{12CO(1\text{-}0)} / I_{13CO(1\text{-}0)} \equiv R_{12/13}$
- $I_{12CO(3\text{-}2)} / I_{12CO(1\text{-}0)} \equiv R_{3/1}$
- ^{12}CO column density of a cloud N_{12CO}
- ^{13}CO column density of a cloud N_{13CO}
- FWHM of one cloud's spectrum dv

output parameters

- number density of a molecular cloud $n(H_2)$
- kinetic temperature of a molecular cloud T_{kin}

Setting of input parameters for 'RADEX' code

- column density of ^{12}CO, ^{13}CO

$$\left(\frac{\mathcal{N}_{^{12}\mathrm{CO}}}{\mathrm{cm}^{-2}}\right) = \left(\frac{I_{^{12}\mathrm{CO}(1-0),\mathrm{obs}}}{\mathrm{K\ km\ s^{-1}}}\right) \cos i \times \frac{1}{\eta_{\mathrm{f}}} \times \left\{\frac{X_{\mathrm{CO}}}{\mathrm{cm}^{-2}\ (\mathrm{K\ km\ s^{-1}})^{-1}}\right\} \times \frac{[^{12}\mathrm{CO}]}{[\mathrm{H_2}]}$$

$$\left(\frac{\mathcal{N}_{^{13}\mathrm{CO}}}{\mathrm{cm}^{-2}}\right) = \left(\frac{\mathcal{N}_{^{12}\mathrm{CO}}}{\mathrm{cm}^{-2}}\right) \times \frac{[^{13}\mathrm{CO}]}{[^{12}\mathrm{CO}]}$$

introducing

$[^{12}CO]/[H_2] = 8.0 \times 10^{-5}$ (Langer & Penzias 1993)
$[^{12}CO]/[^{13}CO] = 70$ (Milam+ 2005)
} local ISM value in MW

- FWHM of one cloud's spectrum *dv*

dv = 5 km/s for entire arms region as a standard

For other regions,

$$dv = 5\ \mathrm{km/s} \times \frac{\Delta V}{\Delta V(\mathrm{entire\ arms})}$$

Calculation of non-LTE analysis

At first, assuming optical thin case → excitation is produced by only CMB

$$\bar{J} = \frac{1}{4\pi}\int_{4\pi} d\Omega \int_0^\infty d\nu \; I_\nu(\theta,\varphi)\phi_\nu(\Delta v)$$

Solve the eq. of statistical equilibrium

$$\frac{dn_l}{dt} = -n_l(B_{lu}\bar{J} + C_{lu}) + n_u(A_{ul} + B_{ul}\bar{J} + C_{ul})$$

$$\frac{dn_u}{dt} = n_l(B_{lu}\bar{J} + C_{lu}) - n_u(A_{ul} + B_{ul}\bar{J} + C_{ul})$$

$$\rightarrow \tau_\nu = \frac{A_{ul}}{8\pi k_{ul}{}^3}\frac{\mathcal{N}}{\Delta v}\left(n_l\frac{g_u}{g_l} - n_u\right)$$

Solve the eq. of radiative transfer

$$S_\nu = \frac{n_u A_{ul}}{n_l B_{lu} - n_u B_{ul}}$$

$$\rightarrow I_\nu = S_\nu(1 - e^{-\tau_\nu}) + I_\nu^{\rm inc} e^{-\tau_\nu}$$

$$\bar{J}_\nu = S_\nu(1-\beta)$$

β: escape probability

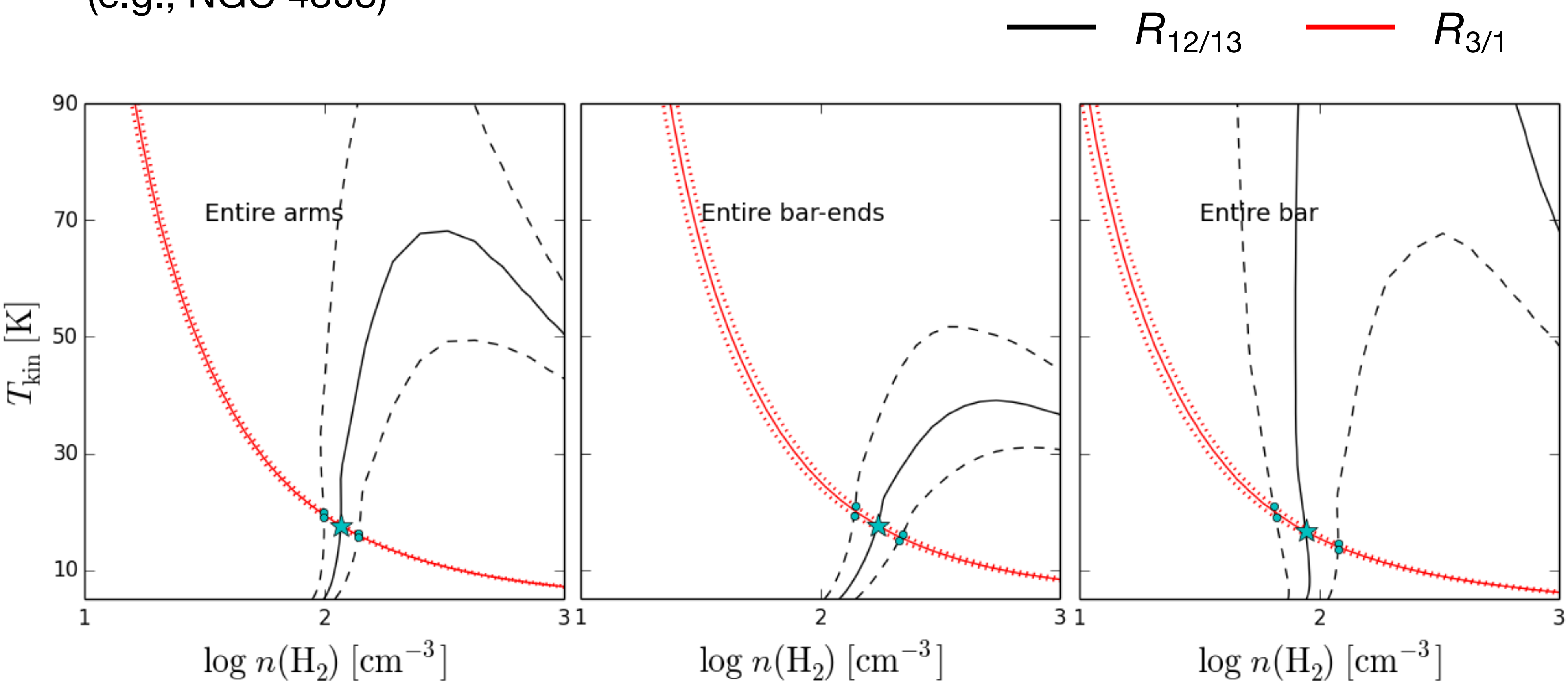
iteration

if $\Delta\tau_\nu < 10^{-6}$

We get I_ν

Example results of 'RADEX' calculation

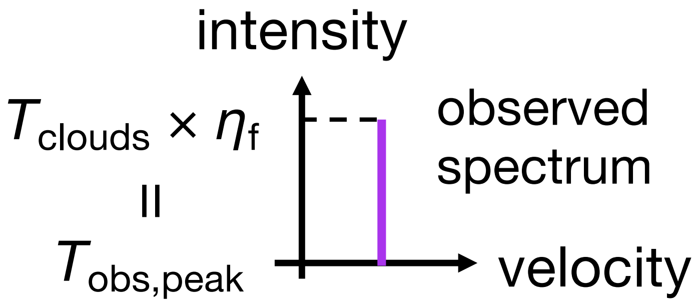
(e.g., NGC 4303)



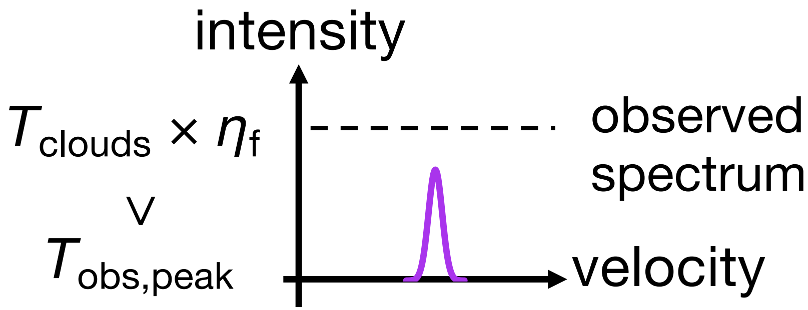
the intersection of black & red lines corresponds to physical properties of molecular gas

How to estimate beam filling factor η_f

If $\sigma_{\text{inter-cloud}} = 0$



However, $\sigma_{\text{inter-cloud}}$ ~ a few 10 km/s



✓ observed peak intensity is **no longer available** for estimating η_f

✓ observed integrated intensity $I_{\text{12CO(1-0),obs}}$ **can be an alternative** to $T_{\text{peak,obs}}$ w/o depending on $\sigma_{\text{inter-cloud}}$

$$\Delta\eta_{\mathrm{f}} \equiv \underline{I_{^{12}\mathrm{CO}(1-0),\mathrm{obs}} \times \cos i} / \underline{I_{^{12}\mathrm{CO}(1-0),\mathrm{cloud}}} - \eta_{\mathrm{f}}$$

I by ensemble of clouds
on galactic plane in the beam
(observed value)

I of a cloud
calculated by RADEX
(theoretical value)

the best η_f value → $\Delta\eta_f = 0$

we evaluate the best η_f value to 2 significant figures

Gas orbit in the bar

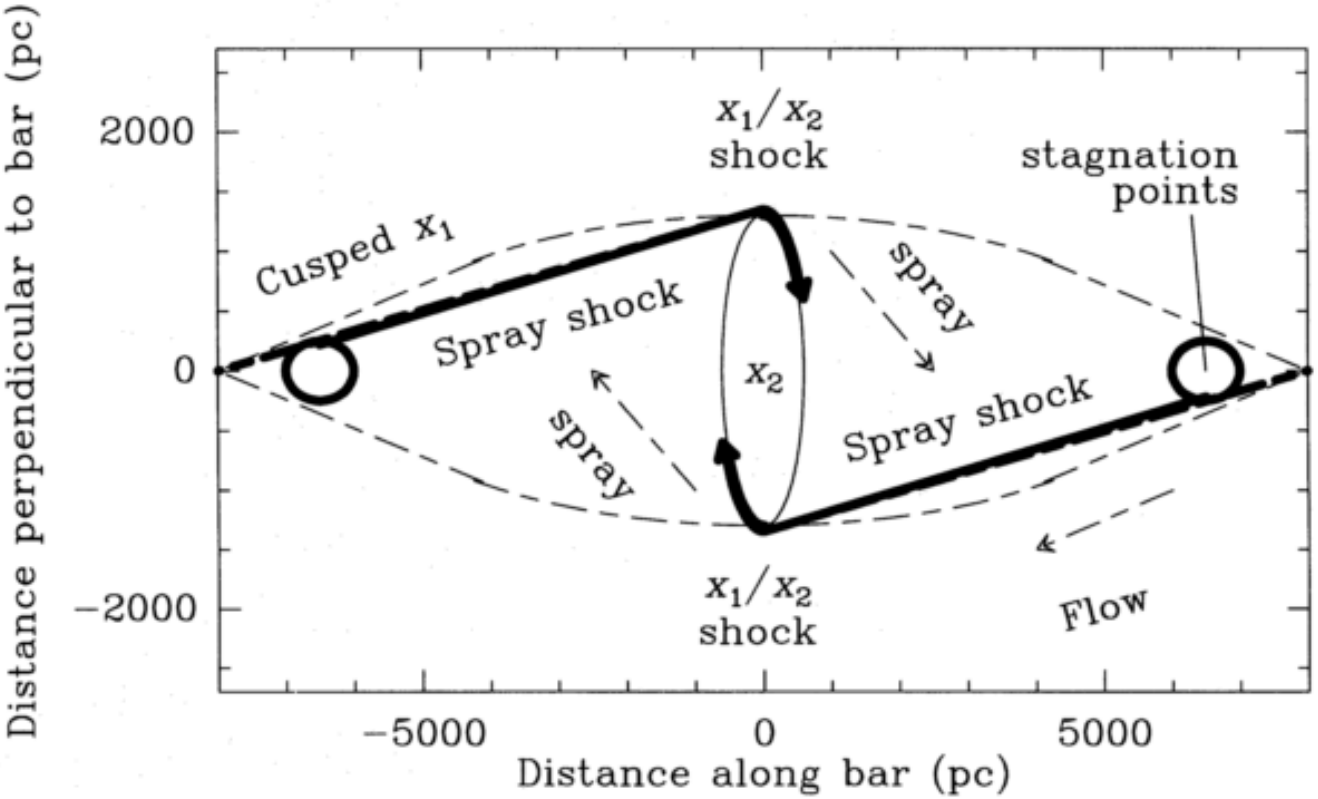


FIG. 10.—Model for gas motions in the bar of NGC 1530. The nuclear ring traces the x_2 orbit. The strong head-tail peaks north and south of the nucleus are standing shocks at the intersections of the x_1 and x_2 orbits. Material emerges from these shocks in a spray, traverses the interior of the bar, and rejoins the x_1 flow at the extended, straight shock fronts. Interior to the cusped orbit, the x_1 orbit family is self-intersecting and forms stagnation points that trap molecular gas near the ends of the bar. In this diagram, the horizontal scale is compressed by cos i to match the galaxy's inclination.

Downes+ 1996