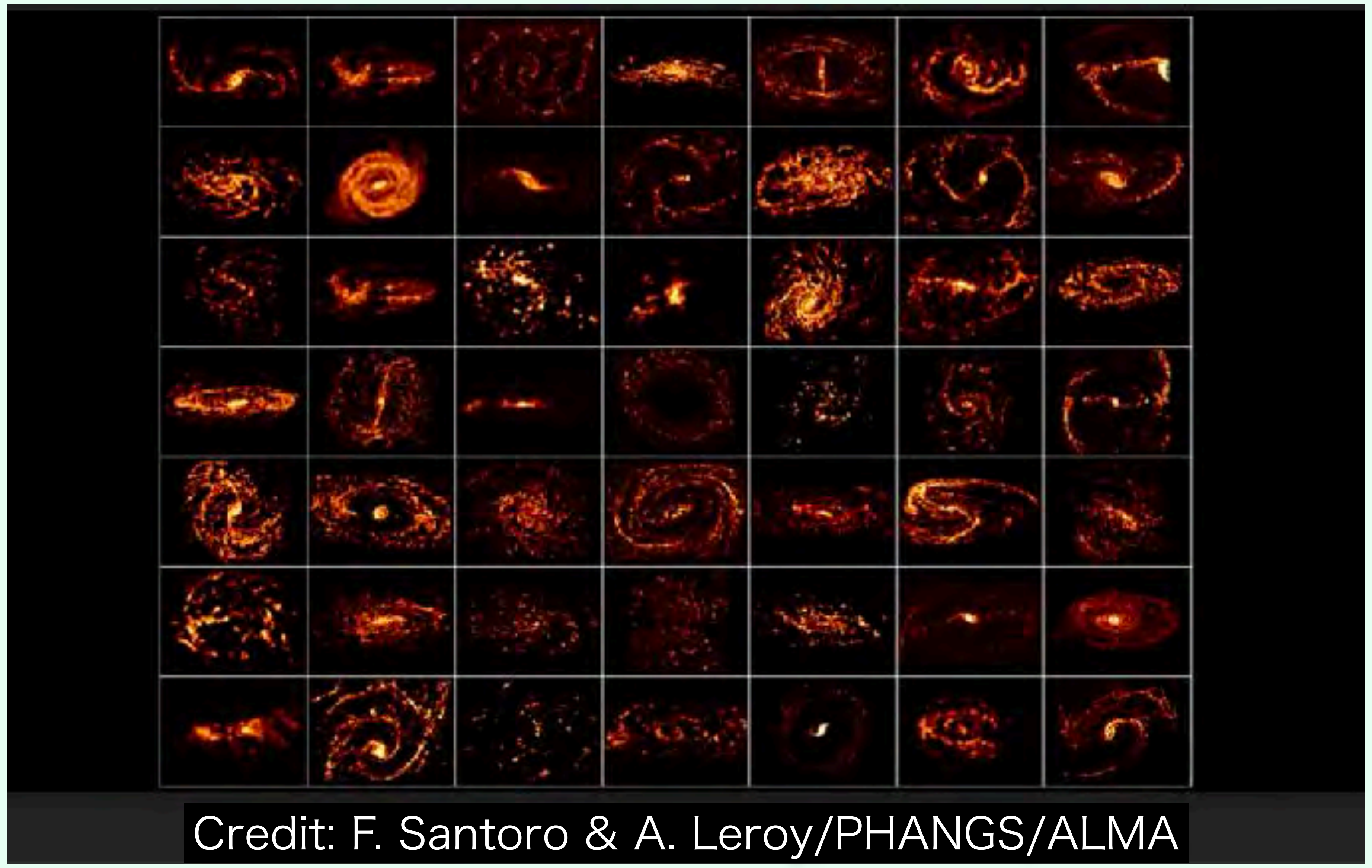
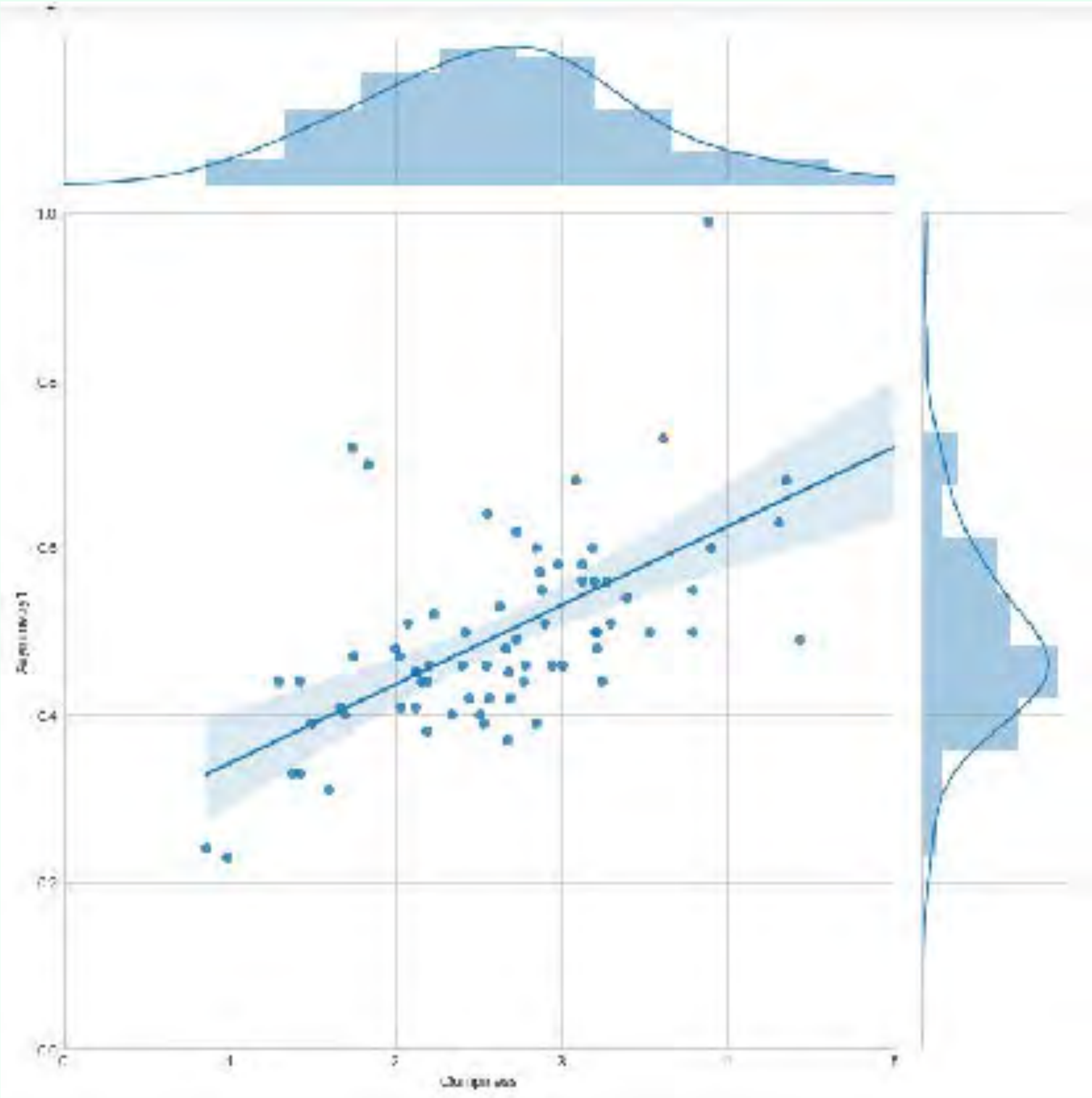
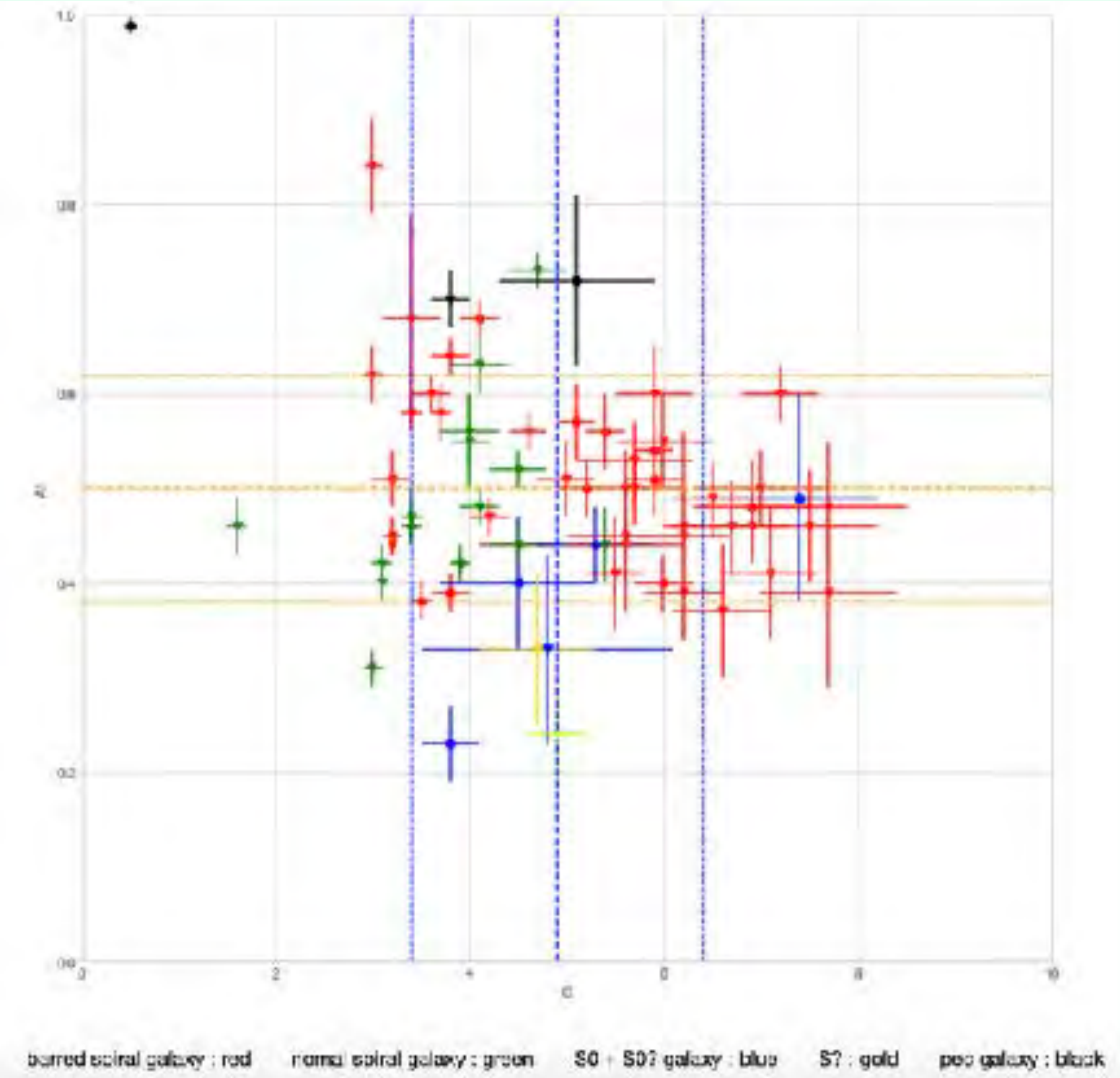
Quantitative and statistical analysis of the molecular gas morphology in the nearby star-forming galaxies



Credit: F. Santoro & A. Leroy/PHANGS/ALMA





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August 10, 2022

Motivation

> Quantitative analysis of the morphology of galaxies using optical and infrared data has been extensively studied by Conselice (2003) and others.

> On the other hand, quantitative analysis of the distribution morphology of molecular gas in nearby galaxies using radio data essential for the study of galaxy evolution has not been sufficiently carried out due to the lack of spatial resolution.

>However, with the operation of ALMA, a large amount of high-resolution molecular gas observation data has been accumulated. This has made it possible to do equivalent to Conselice's research.

Motivation

>Through quantitative and statistical analysis of the morphology of the distribution of molecular gas, we aim to understand the physics of the star formation process and gain a more realistic understanding of the evolutionary history of galaxies.

> This study is not limited to nearby galaxies. It has the potential to be applied to high-redshift galaxies as well, depending on future spatial resolution.

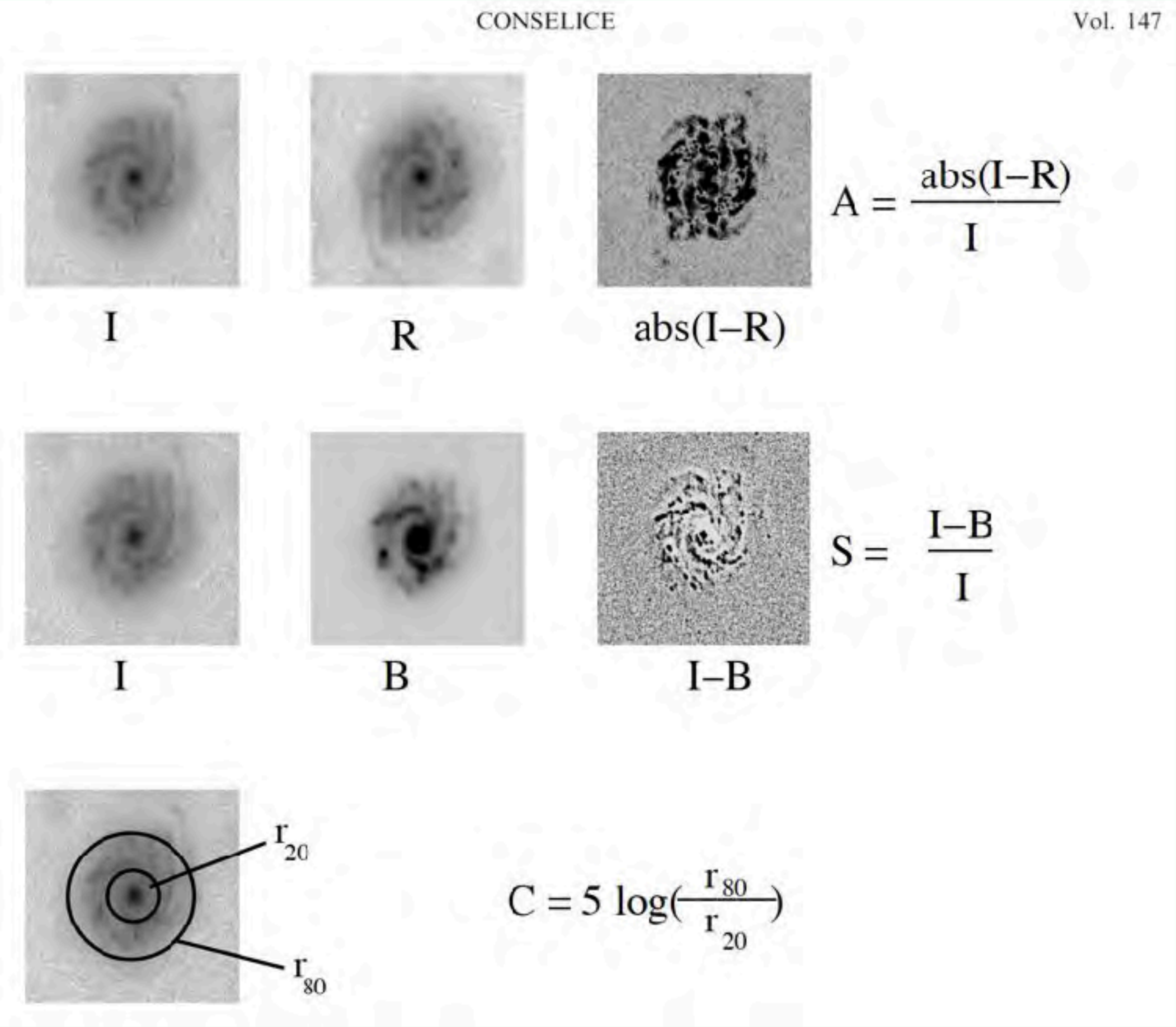
Method

The CAS Parameters

By C. J. Conselice(2003).

Many attempts have been presented in the literature to define the quantitative method.

The CAS physical morphology parameters have been the most widely used among them.



Concentration (C)

$$C = 5 \times \log\left(\frac{r_{80\%}}{r_{20\%}}\right)$$

Asymmetry (A)

$$A = \frac{|I - R|}{I}$$

Clumpiness(S)

$$S = \frac{10 \times (I - I^{\sigma})}{I}$$

$$\sigma = 0.3 \times r \ (\eta = 0.2)$$

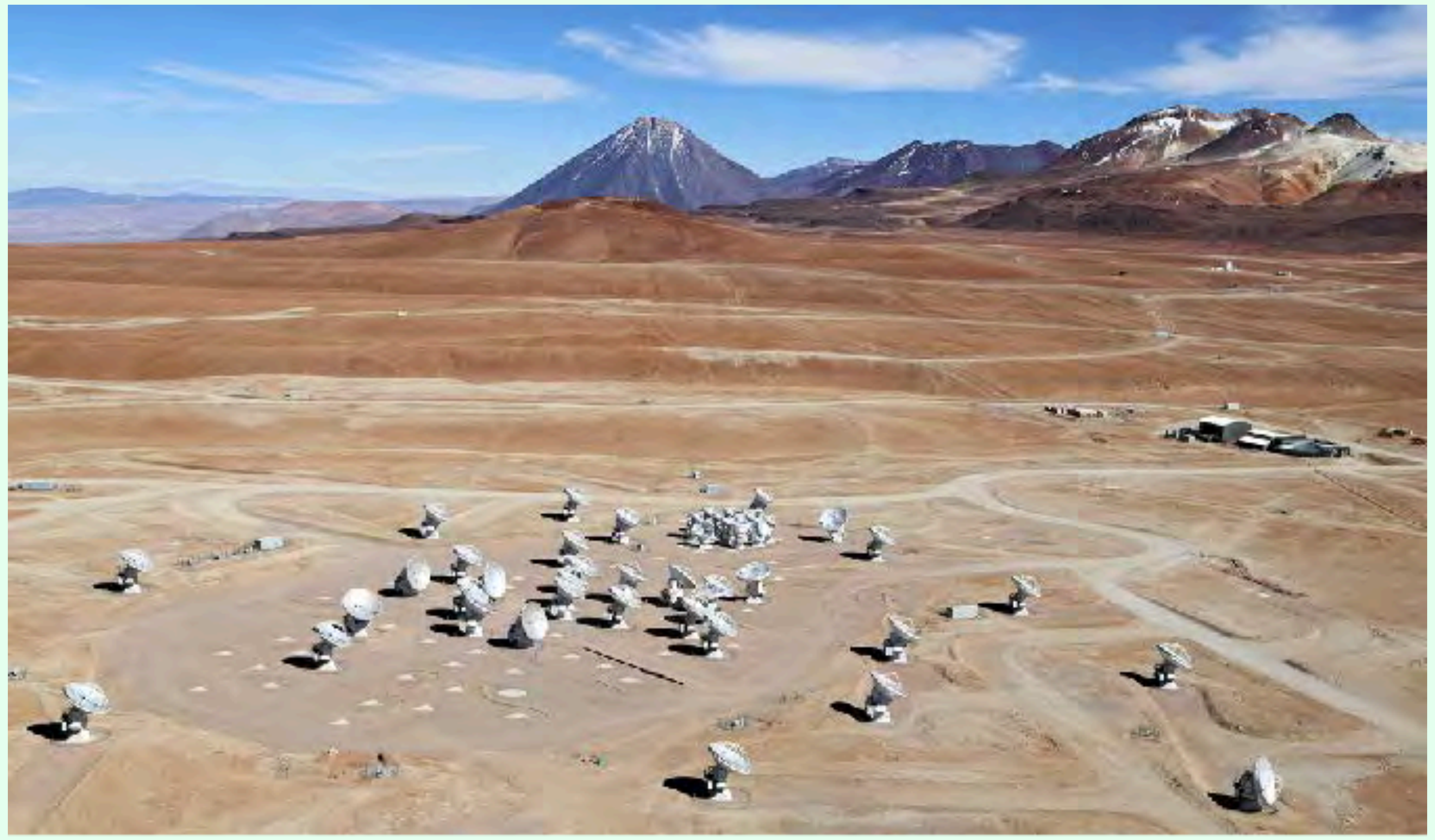
r : Petrosian radius

Method

Modified CAS parameters

Concentration (C)

$$C = 5 \times \log\left(\frac{r_{90\%}}{r_{10\%}}\right)$$



Asymmetry (A)

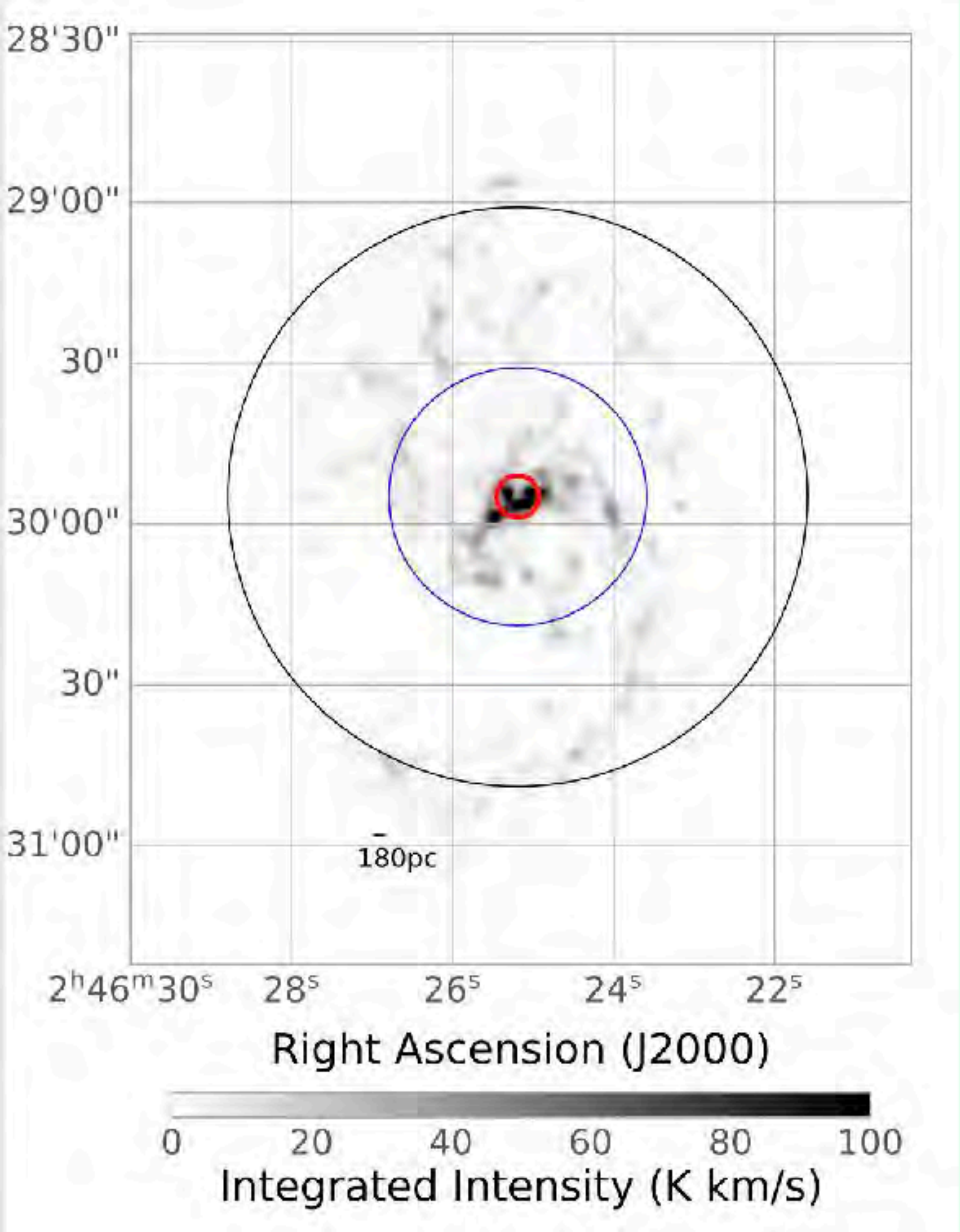
$$A = \frac{|I - R|}{2I}$$

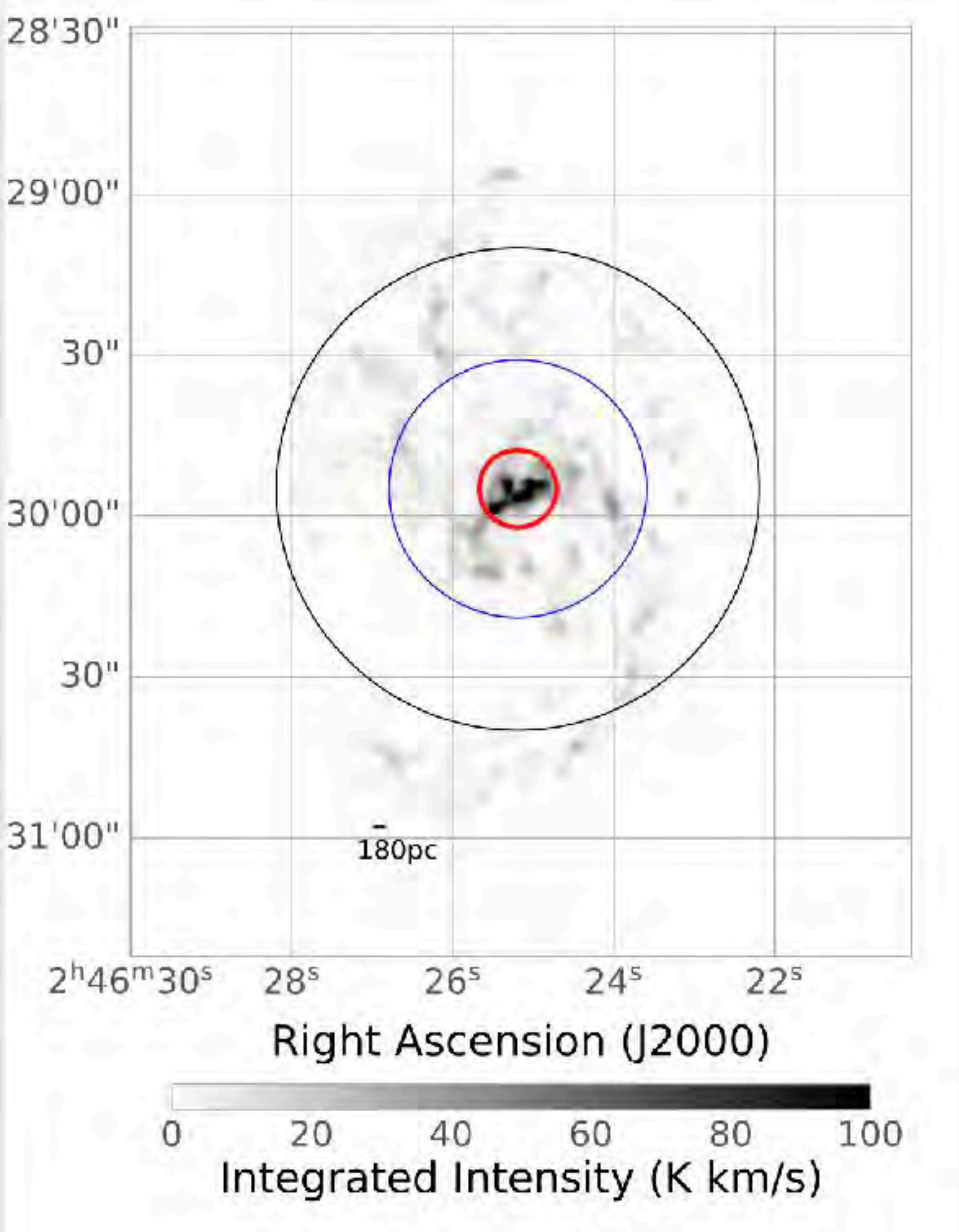
Clumpiness(S)

$$S = \frac{10 \times (I - I^{\sigma})}{I}$$

$$\sigma = 0.3 \times \mathrm{R_e}$$

Method Concentration(C) NGC 1087 SAB(rs)c

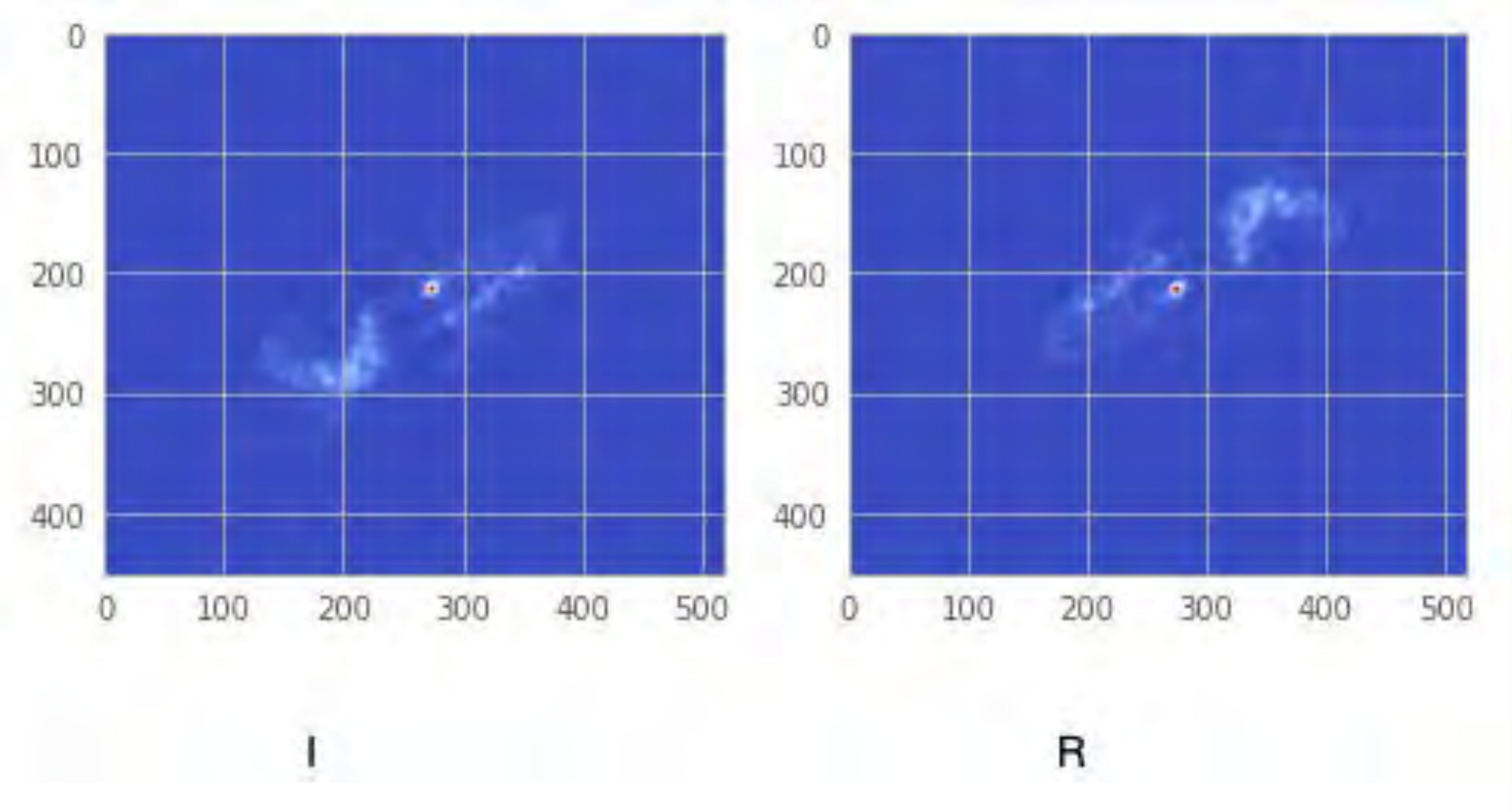


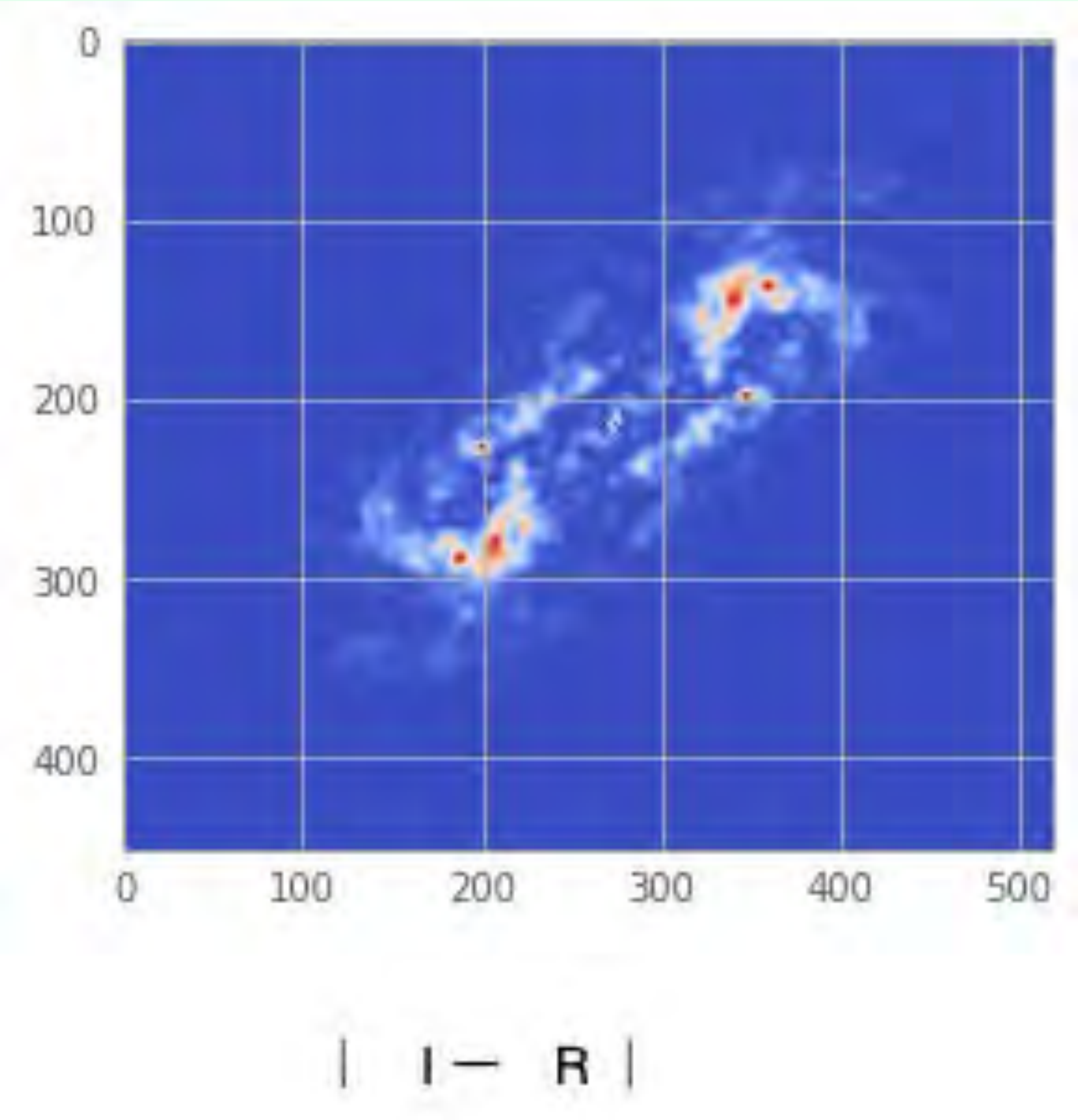


$$C_W = 5 \times \log\left(\frac{r_{90\%}}{r_{10\%}}\right) \qquad C_W = 5.7 \pm 0.6$$

$$C_C = 5 \times \log\left(\frac{r_{80\%}}{r_{20\%}}\right) \qquad C_C = 4.0 \pm 0.2$$

Method Asymmetry(A) NGC151 1 SAa pec

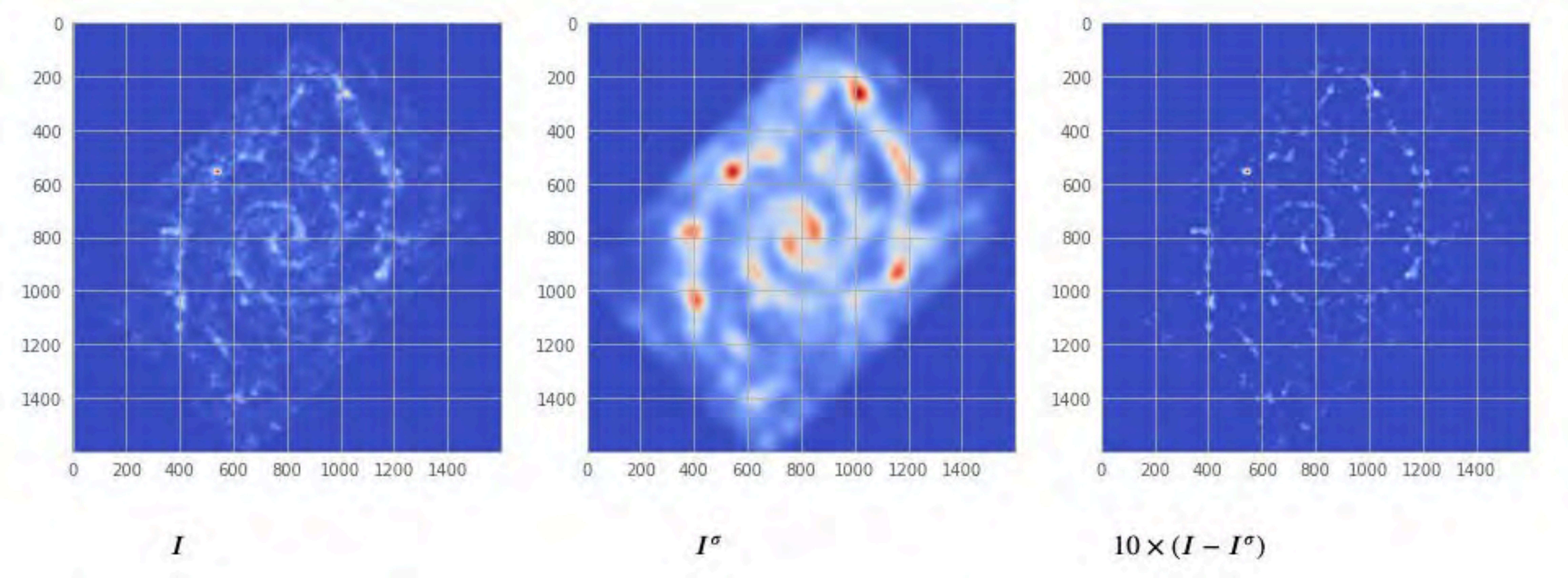




$$A = \frac{|I - R|}{2I}$$

$$A = 0.70 \pm 0.03$$

Method | Clumpiness(S) | NGC 628 | SA(s)c



$$S = \frac{10 \times (I - I^{\sigma})}{I}$$

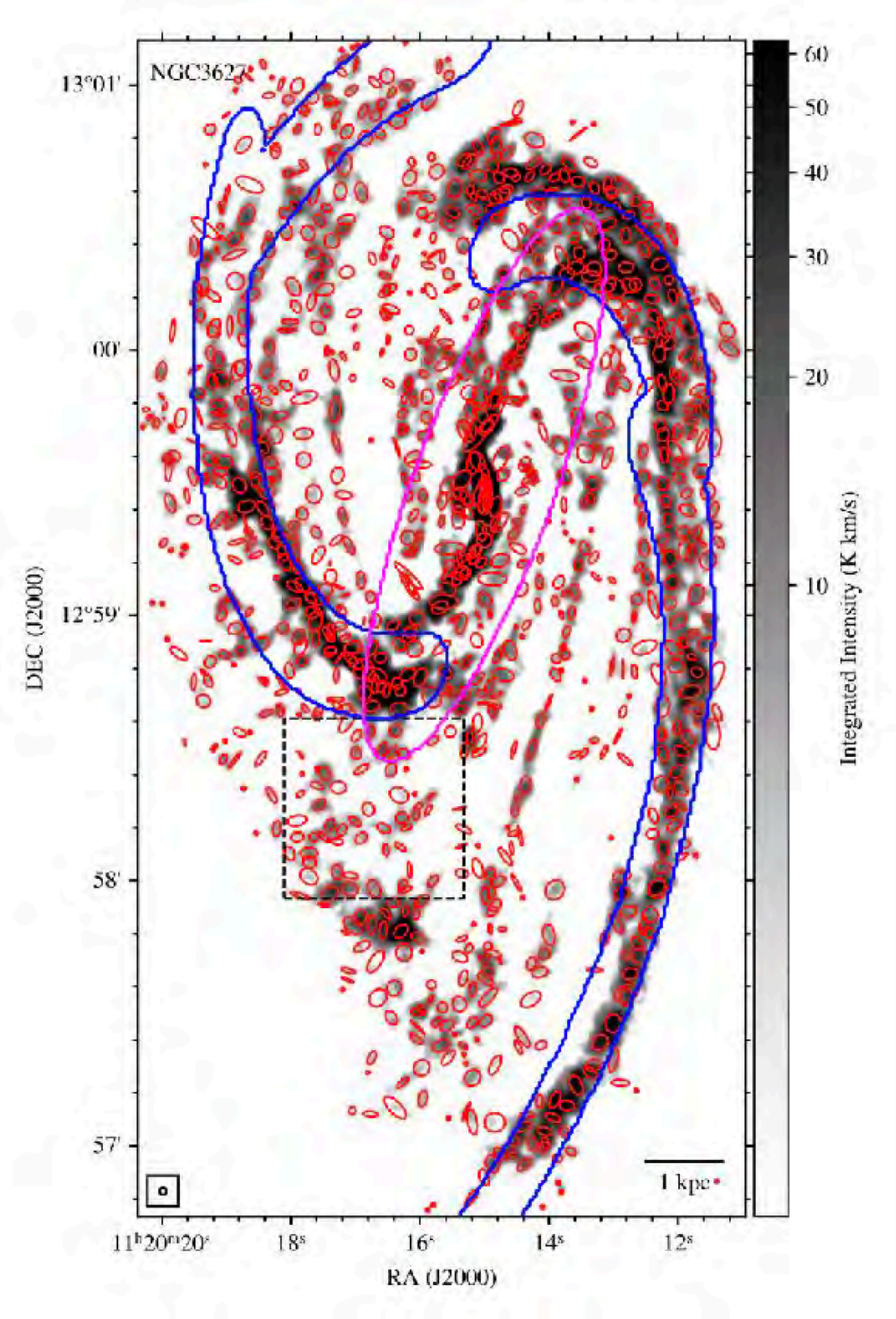
$$S = 2.33 \pm 0.04$$

Method

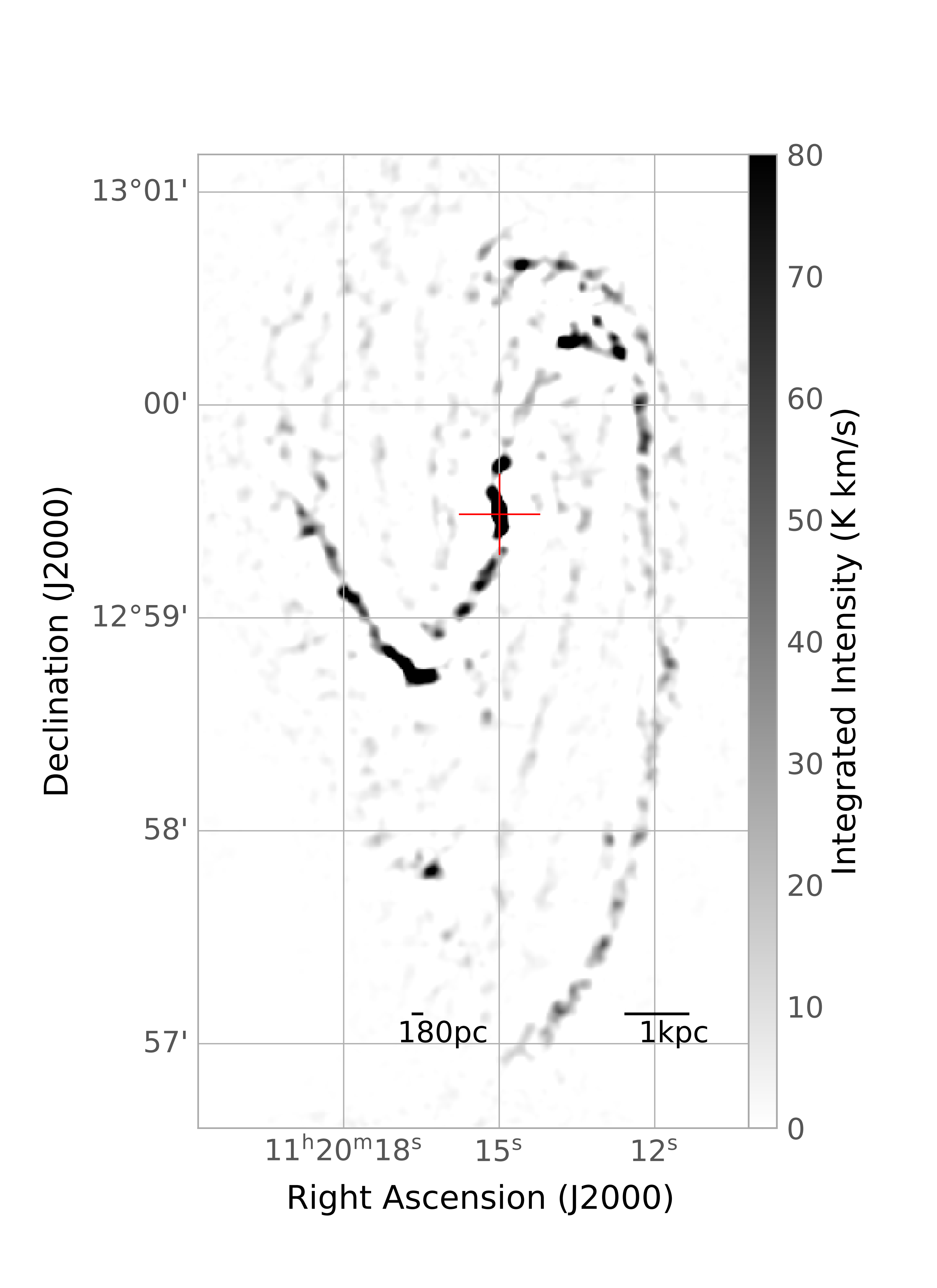
Clumpiness(S)

NGC 3627

SAB(s)b

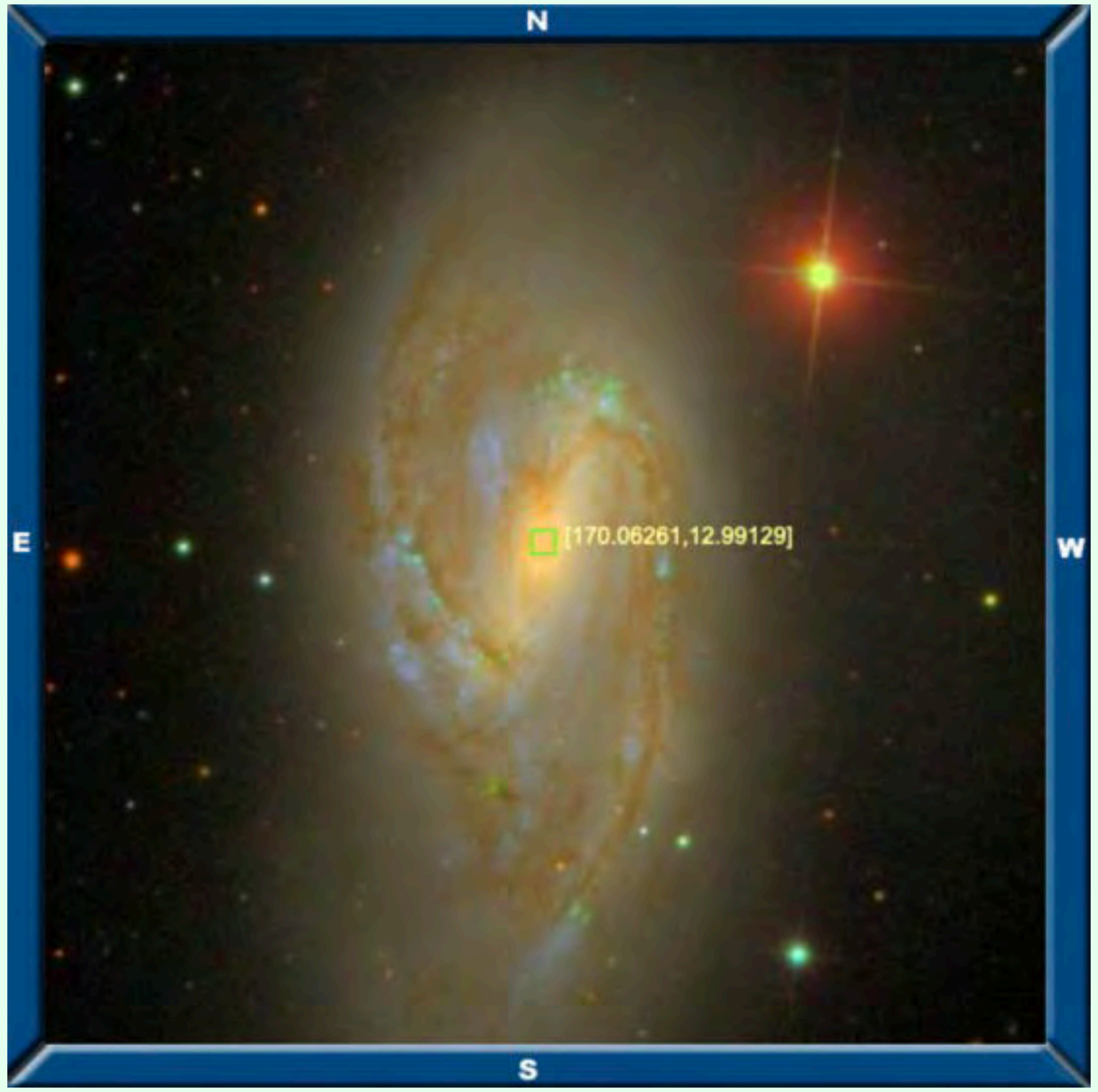


Rosolowsky et al. 2021 ~ 90pc



~ 180pc

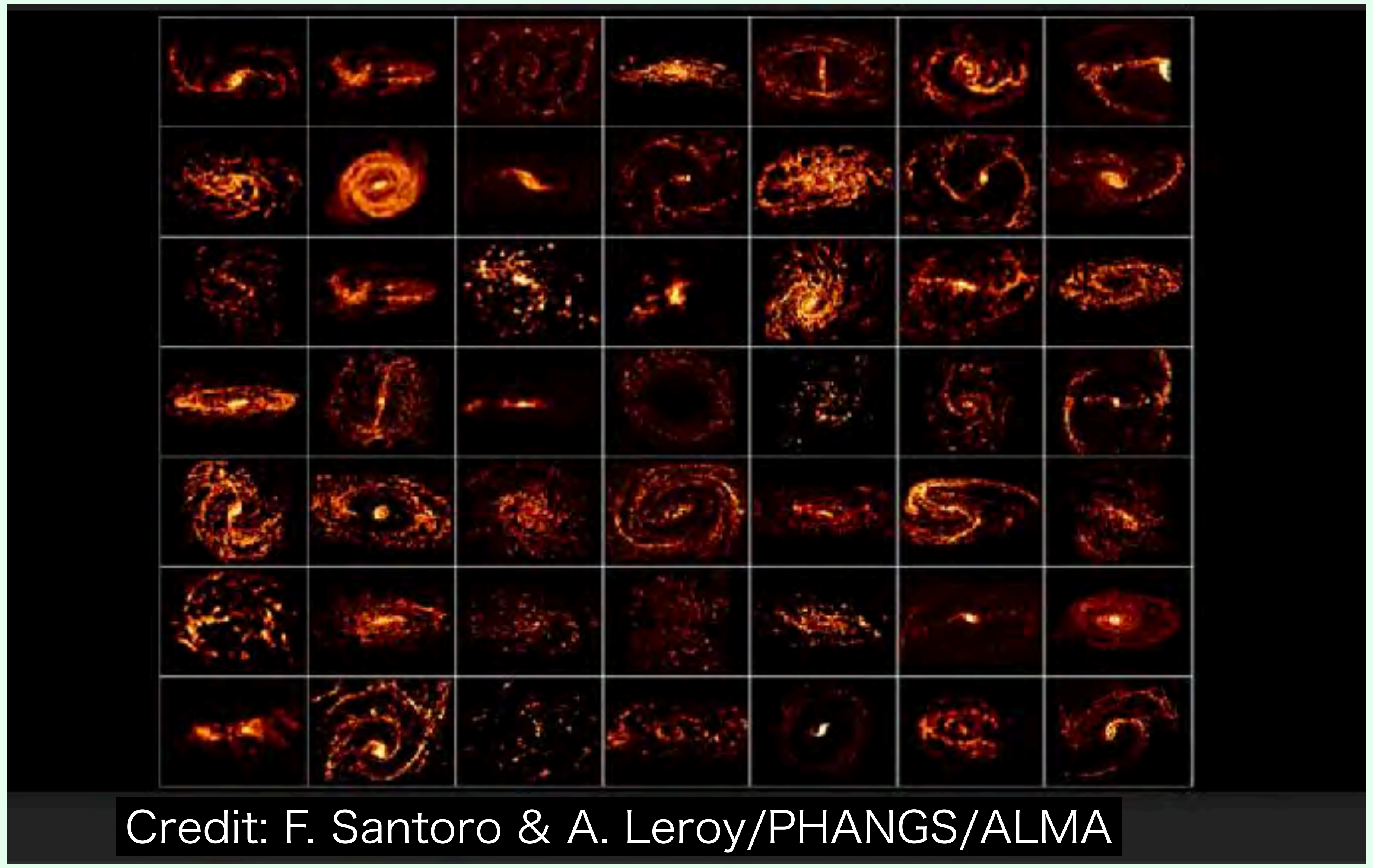
$S = 2.87 \pm 0.04$



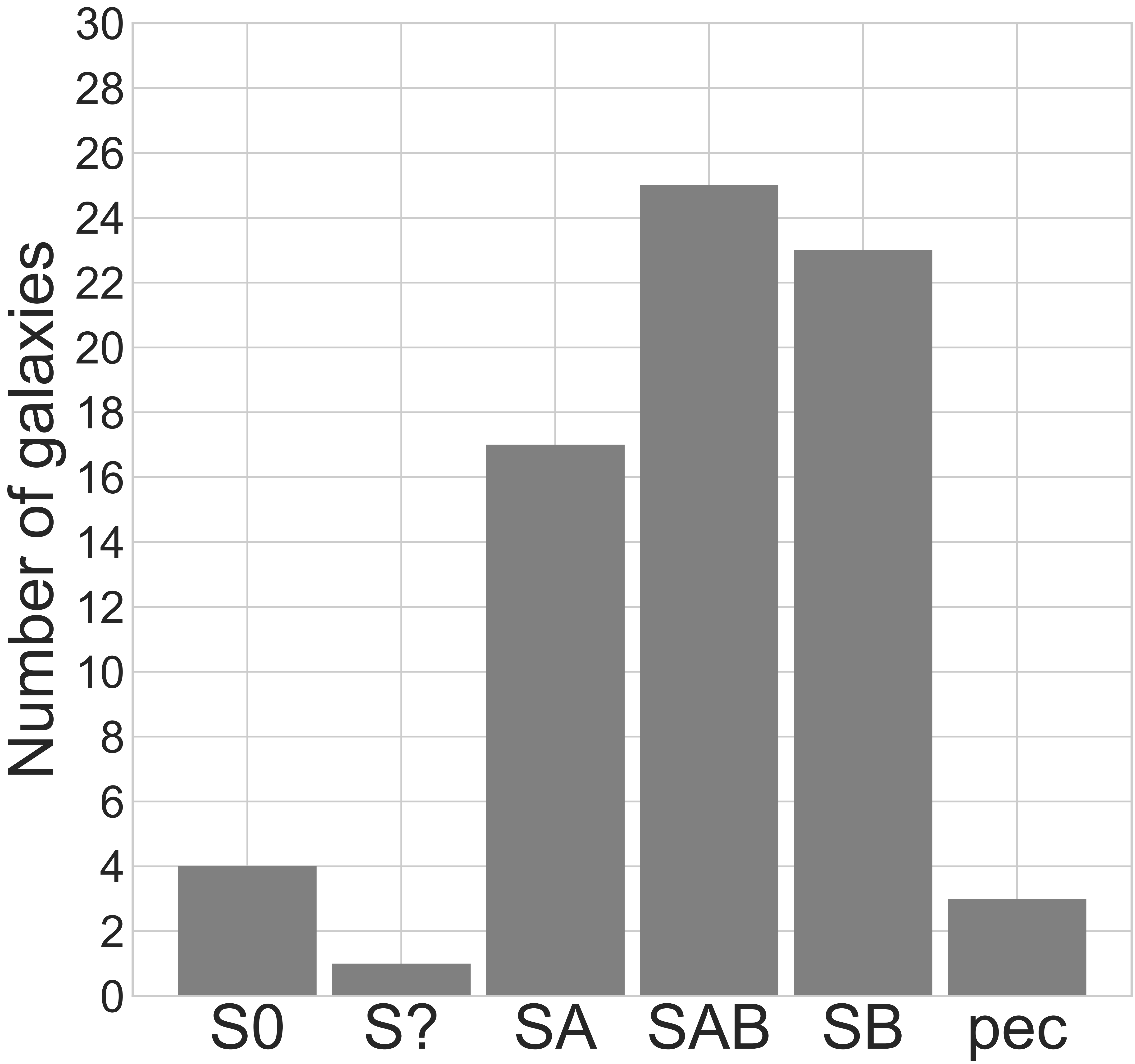
SDSS DR16

Result

73 galaxies
From PHANGS-ALMA
Archive data



Spatial resolution ~ 180pc



Result

Table 3. Correlation measurements*

Correlation	Sr	p	$p < 0.05$
S vs. A	0.63	2.9×10^{-9}	√
C vs. A	-0.12	0.30	...
C vs. S	0.23	0.05	...
$\log_{10} \mathrm{M}_*$ vs. C	0.45	7.4×10^{-5}	√
$\log_{10} \mathrm{M}_*$ vs. A	-0.21	0.07	...
$\log_{10} \mathrm{M}_*$ vs. S	0.12	0.30	...
$\log_{10} (\mathrm{M}_{\mathrm{H}_2}/\mathrm{M}_*)$ vs. C	0.25	0.03	√
$\log_{10} (\mathrm{M}_{\mathrm{H}_2}/\mathrm{M}_*)$ vs. A	-0.03	0.83	...
$\log_{10} (\mathrm{M}_{\mathrm{H}_2}/\mathrm{M}_*)$ vs. S	-0.15	0.20	...
$\log_{10}$ sSFR vs. C	-0.04	0.73	...
$\log_{10}$ sSFR vs. A	0.30	0.01	√
$\log_{10}$ sSFR vs. S	0.05	0.70	...
$\log_{10}$ SFE vs. C	-0.11	0.35	...
$\log_{10}$ SFE vs. A	0.45	7.0×10^{-5}	√
$\log_{10}$ SFE vs. S	0.29	0.01	√

Table 5. Correlation measurements*

Correlation	Sr	p	$p < 0.05$
$\log_{10} \mathrm{M}_*$ vs. C	0.45	7×10^{-5}	√
$\log_{10} \mu_*$ vs. C	0.26	0.03	√
$\log_{10} \mu_*$ vs. A	-0.48	2×10^{-5}	√
$\log_{10} \mu_*$ vs. S	-0.46	4×10^{-5}	√

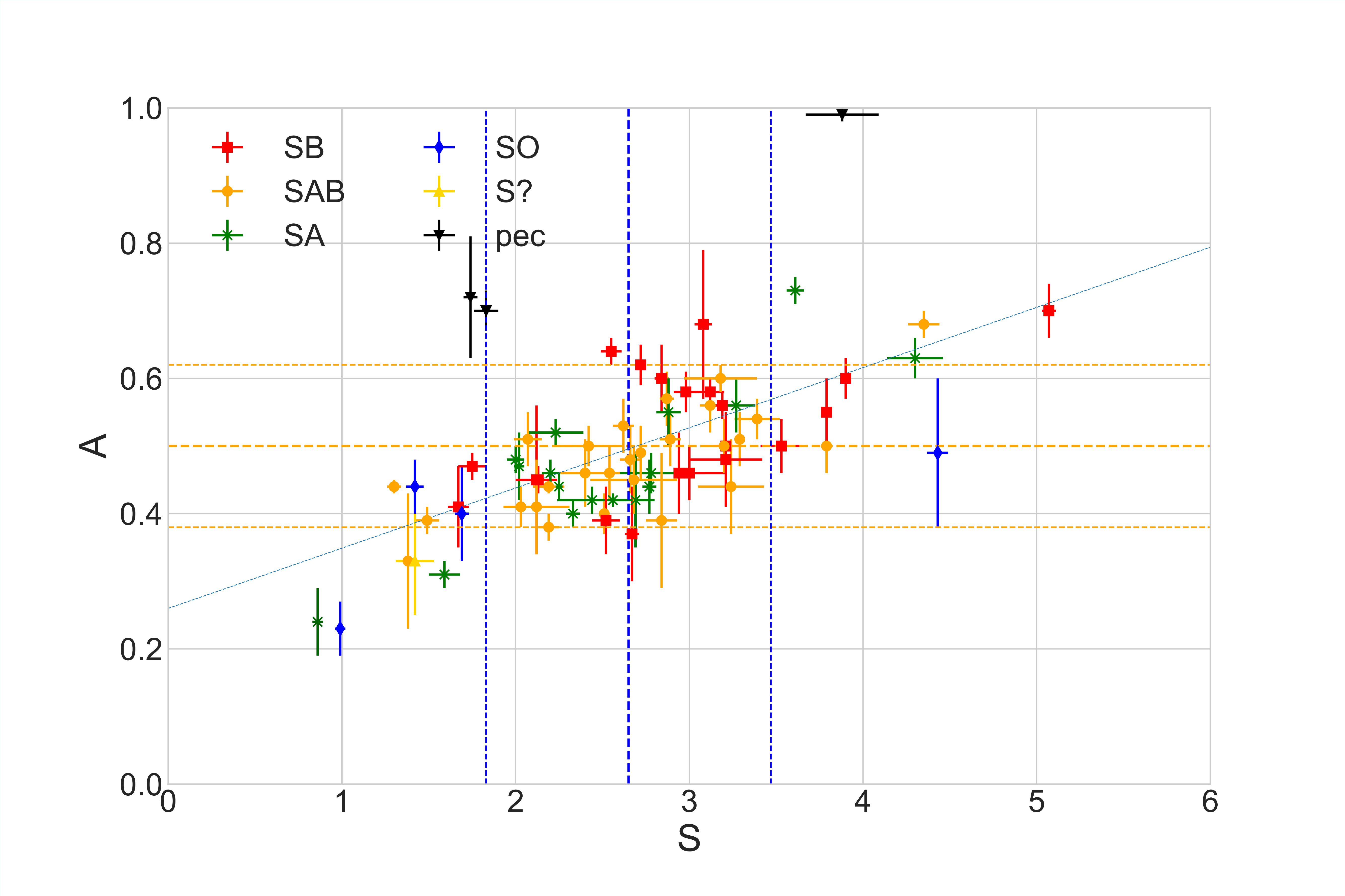
* Spearman's- rank correlation coefficients (Sr) and their associated p -values.

$$\mu_* \equiv \frac{M_*}{2\pi R_e^2}$$

Result 1

The correlation between Asymmetry(A) and Clumpiness(S)

(1) One of the results is that Clumpiness (S) and Asymmetry (A) showed a linear correlation. Higher A values, a measure of galaxy interactions, suggest a tendency for GMA to form more easily.



Result 1

The correlation between Asymmetry(A) and Clumpiness(S)

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WISDOM Project – X. The morphology of the molecular ISM in galaxy centres and its dependence on galaxy structure

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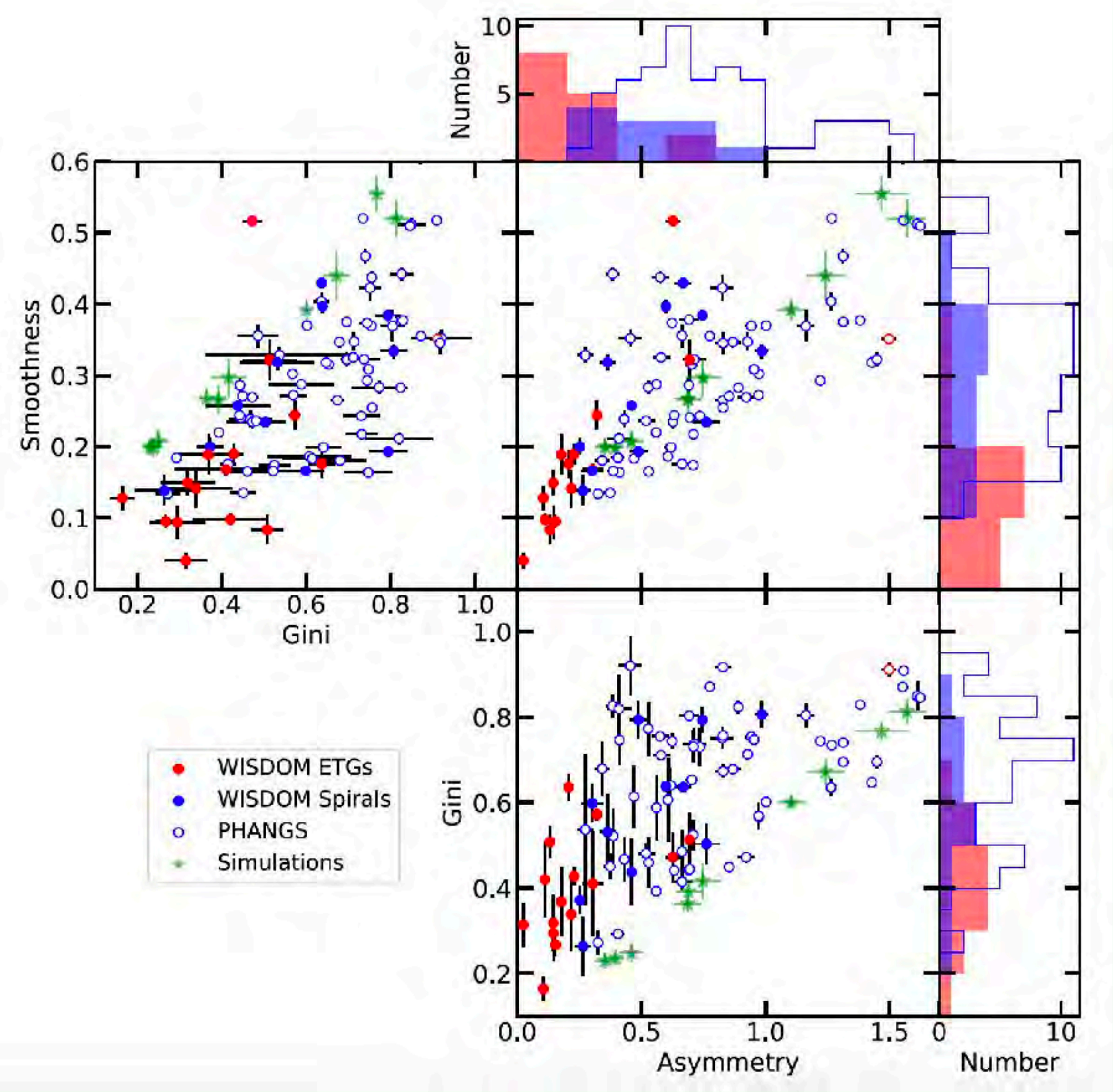
Davis et al. 2022



For example, NGC 3627, one of the Leo Triplet, is considered to have interacted with NGC 3628 and NGC 3623 in the past (e.g., Haynes et al. 1979; Chromey et al. 1998).

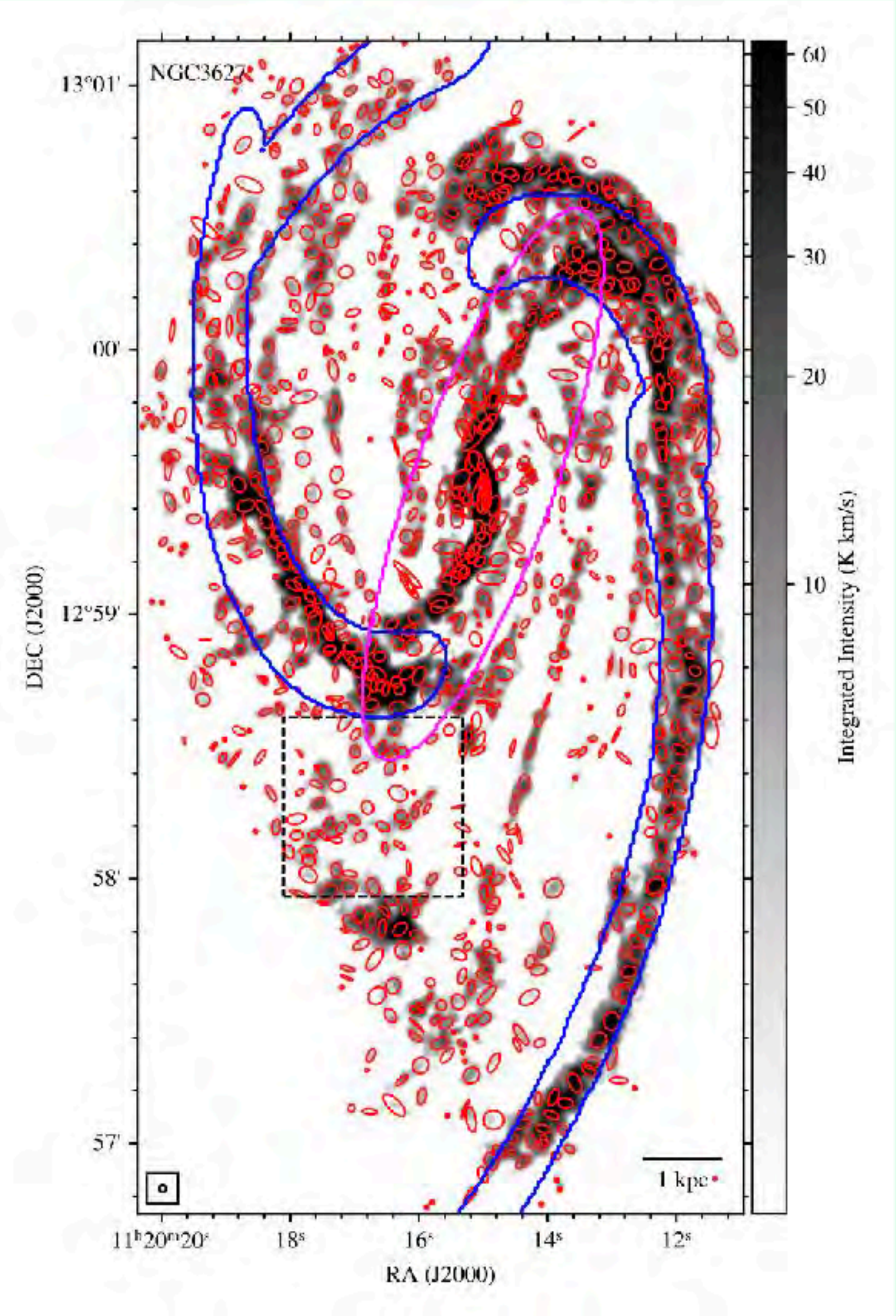
NGC 3627 has a high A value because the two galactic spiral arms have different shapes due to interaction. And the GMAs are also distributed differently in each spiral arm and bar end. And the S value is relatively high.

$$A = 0.57 \pm 0.04$$

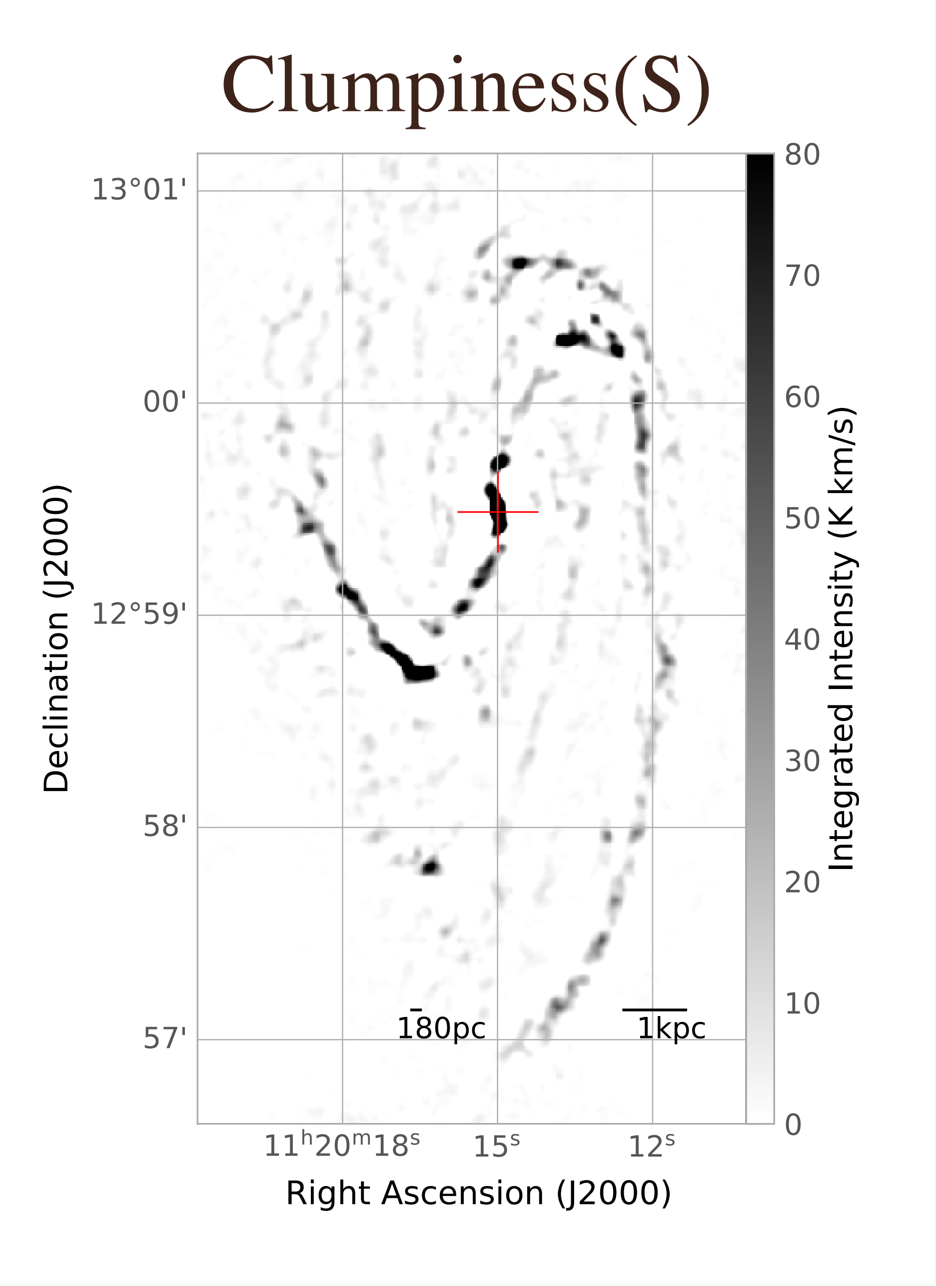
$$S = 2.87 \pm 0.04$$

NGC 3627

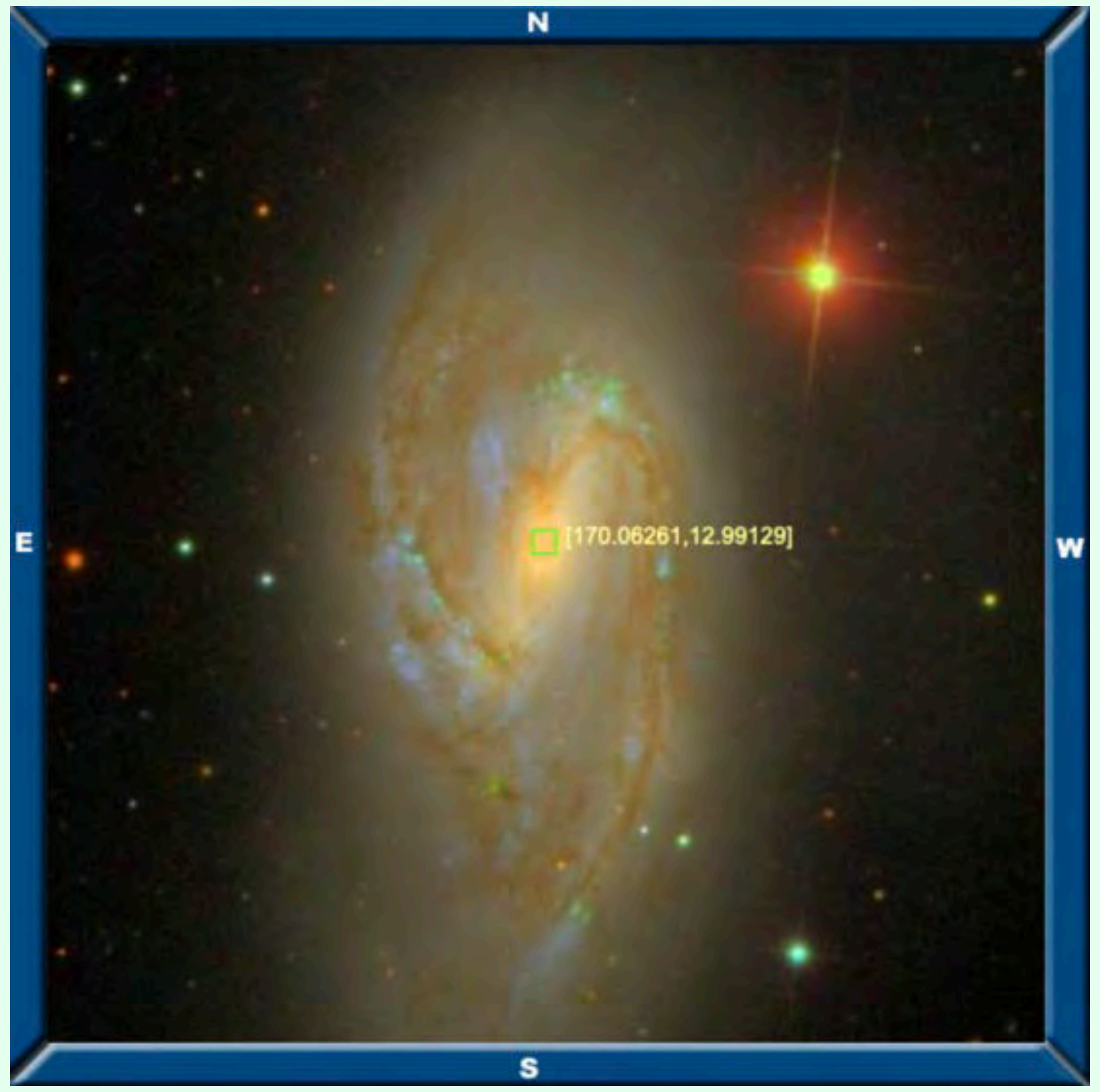
SAB(s)b



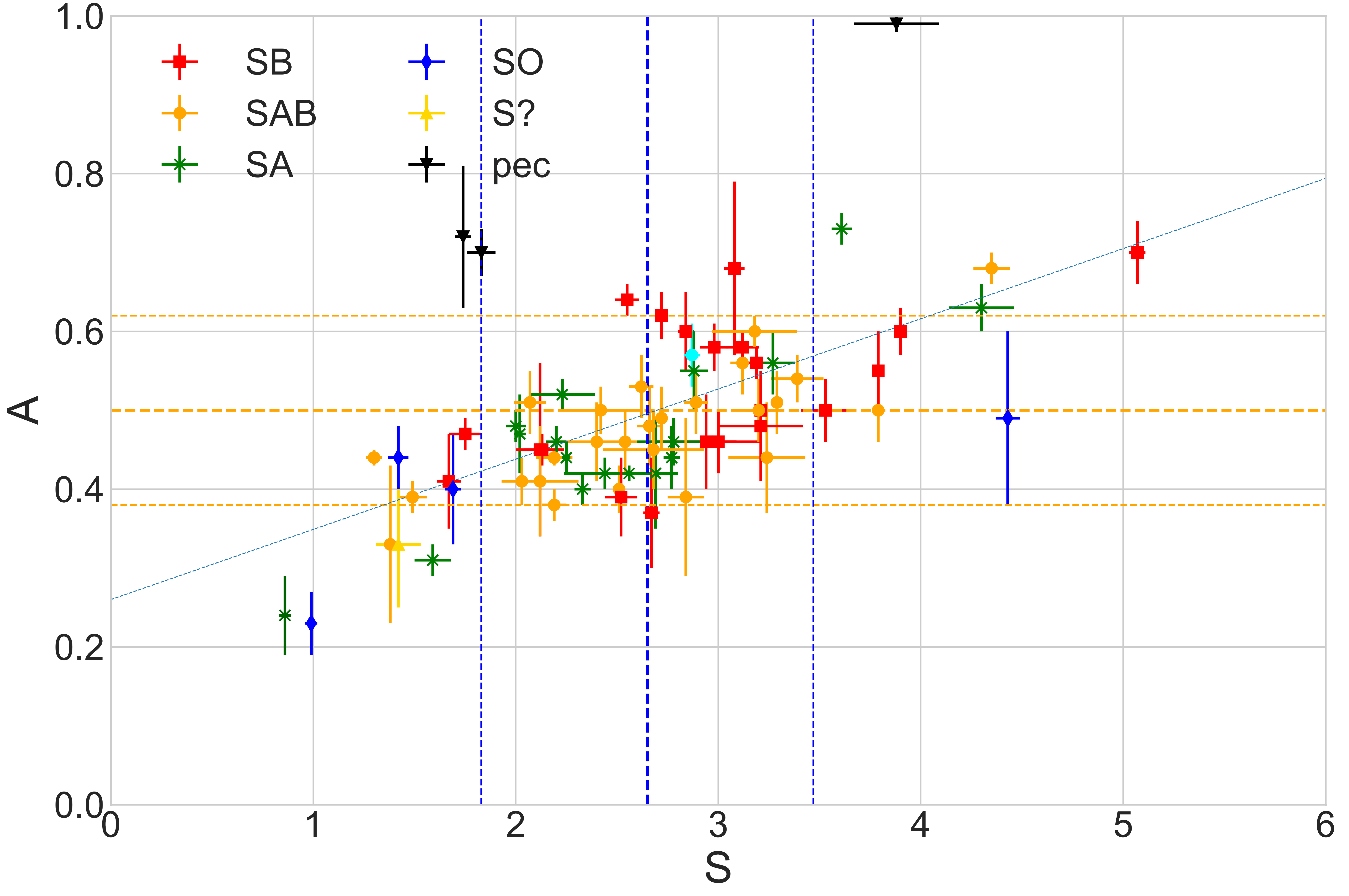
Rosolowsky et al. 2021 ~ 90pc



~ 180pc



SDSS DR16



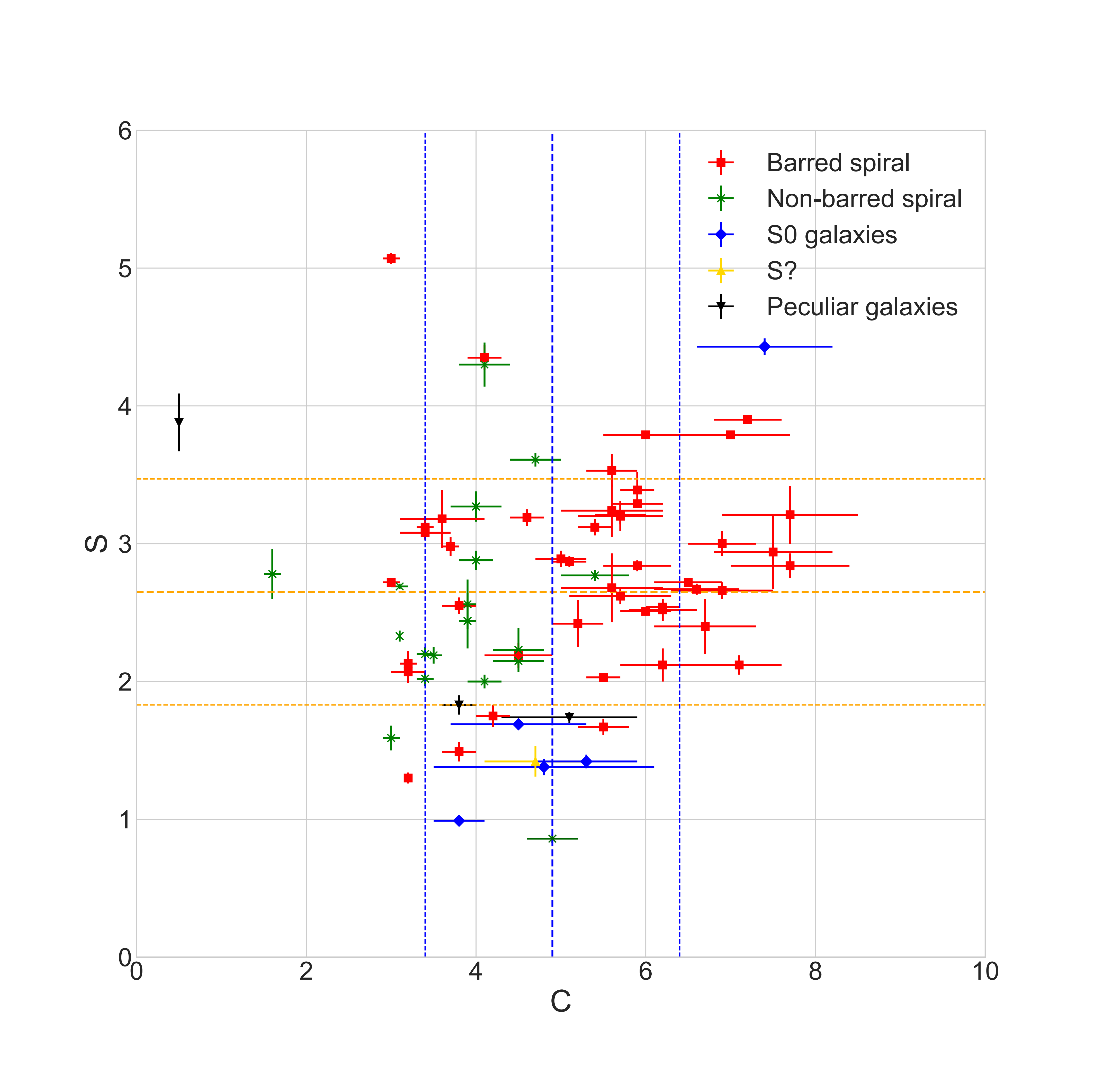
$$A = 0.57 \pm 0.04$$

$$S = 2.87 \pm 0.04$$

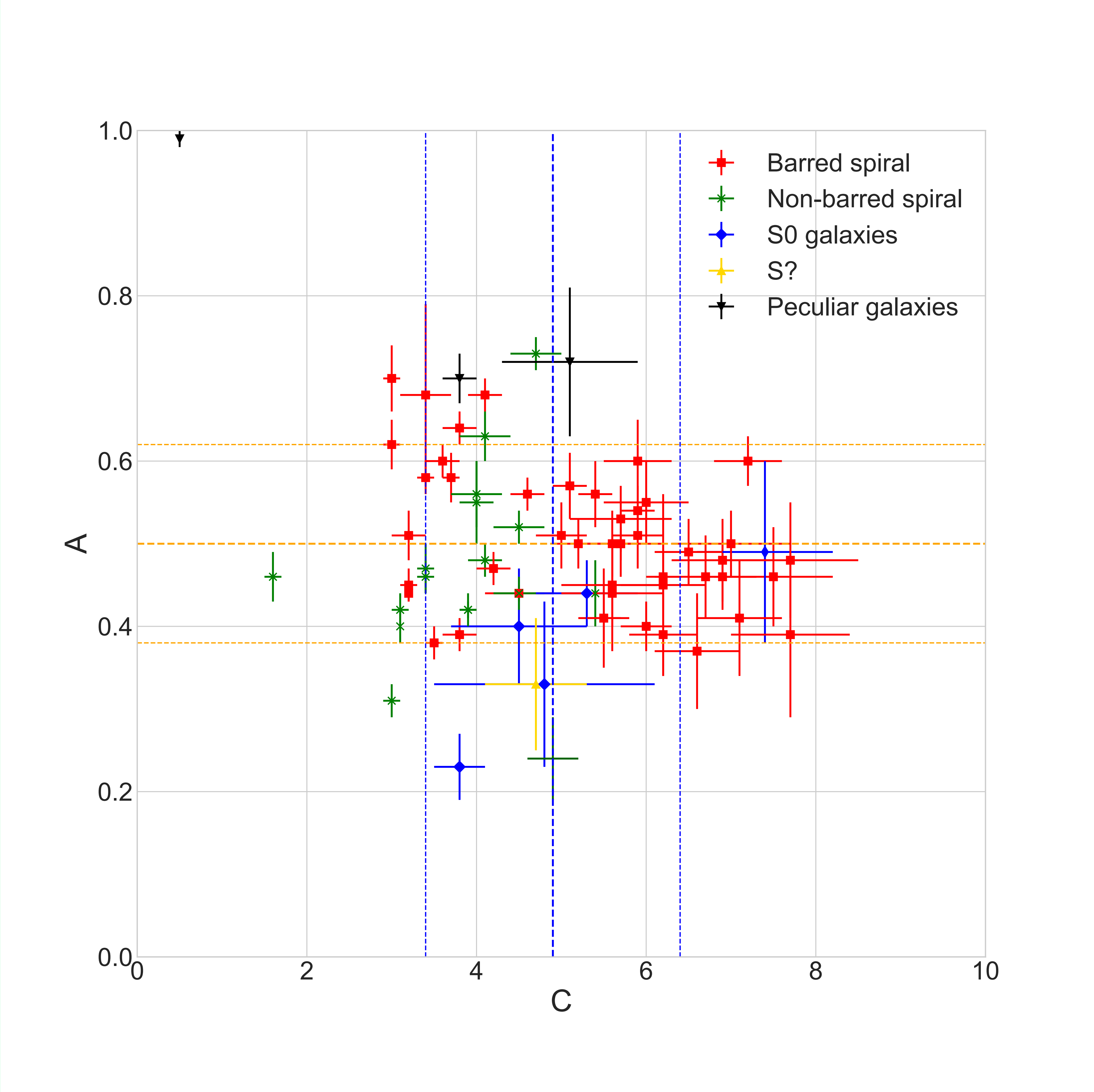
Result 2

The bar structure increases the central concentration of molecular gas.

Concentration(C) vs.Clumpiness(S)

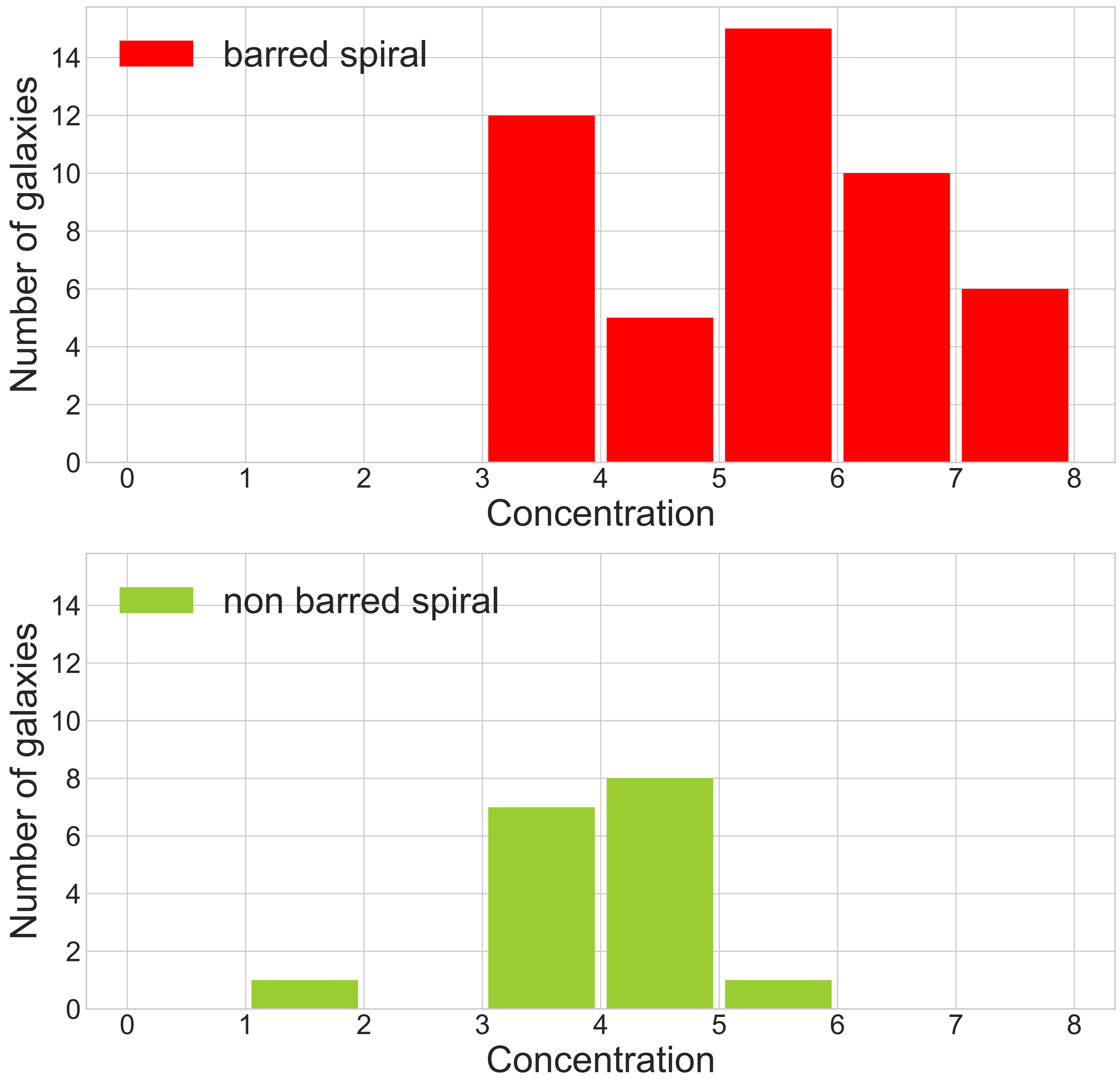


Concentration(C) vs.Asymmetry(A)



Result 2

The bar structure increases the central concentration of molecular gas.

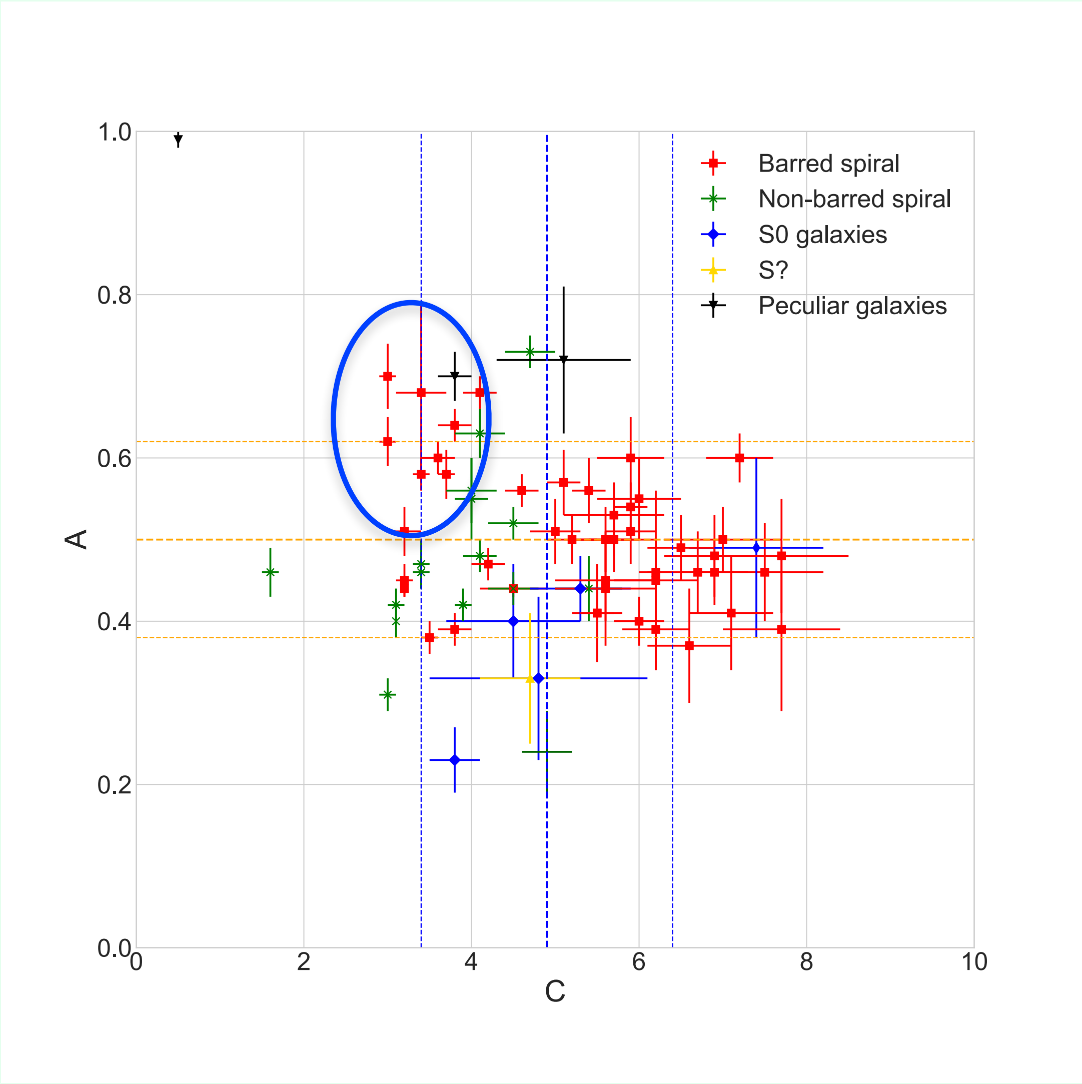


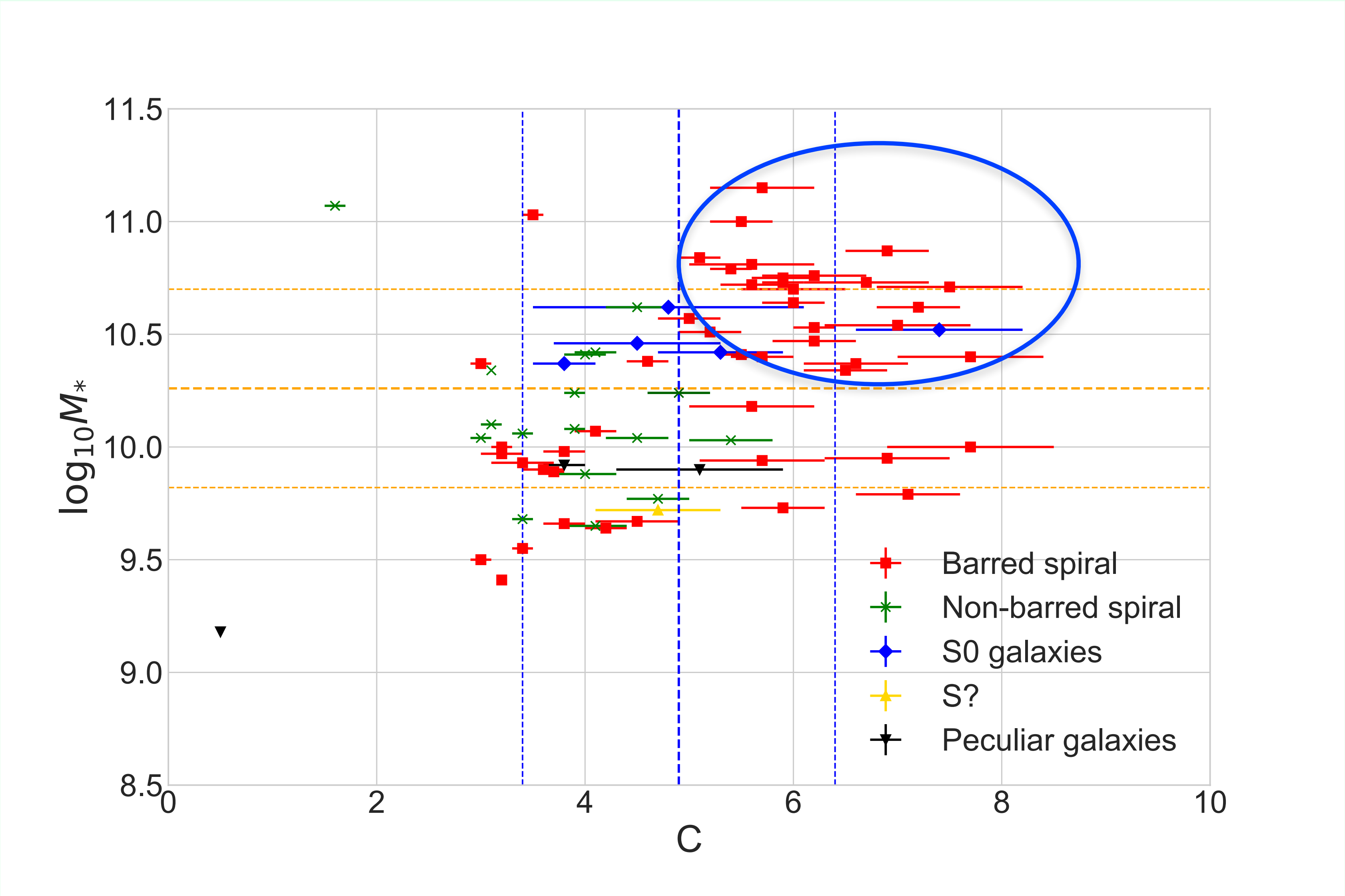
Result 2

The bar structure increases the central concentration of molecular gas.

(2) It is clear that galaxies with barred structures have a concentration of CO gas in their central regions. This result is consistent with previous studies. However, About 30% of the barred spiral galaxies were found to have lower than average C values.

The Concentration may depend on the stellar mass and the A value of the galaxy.





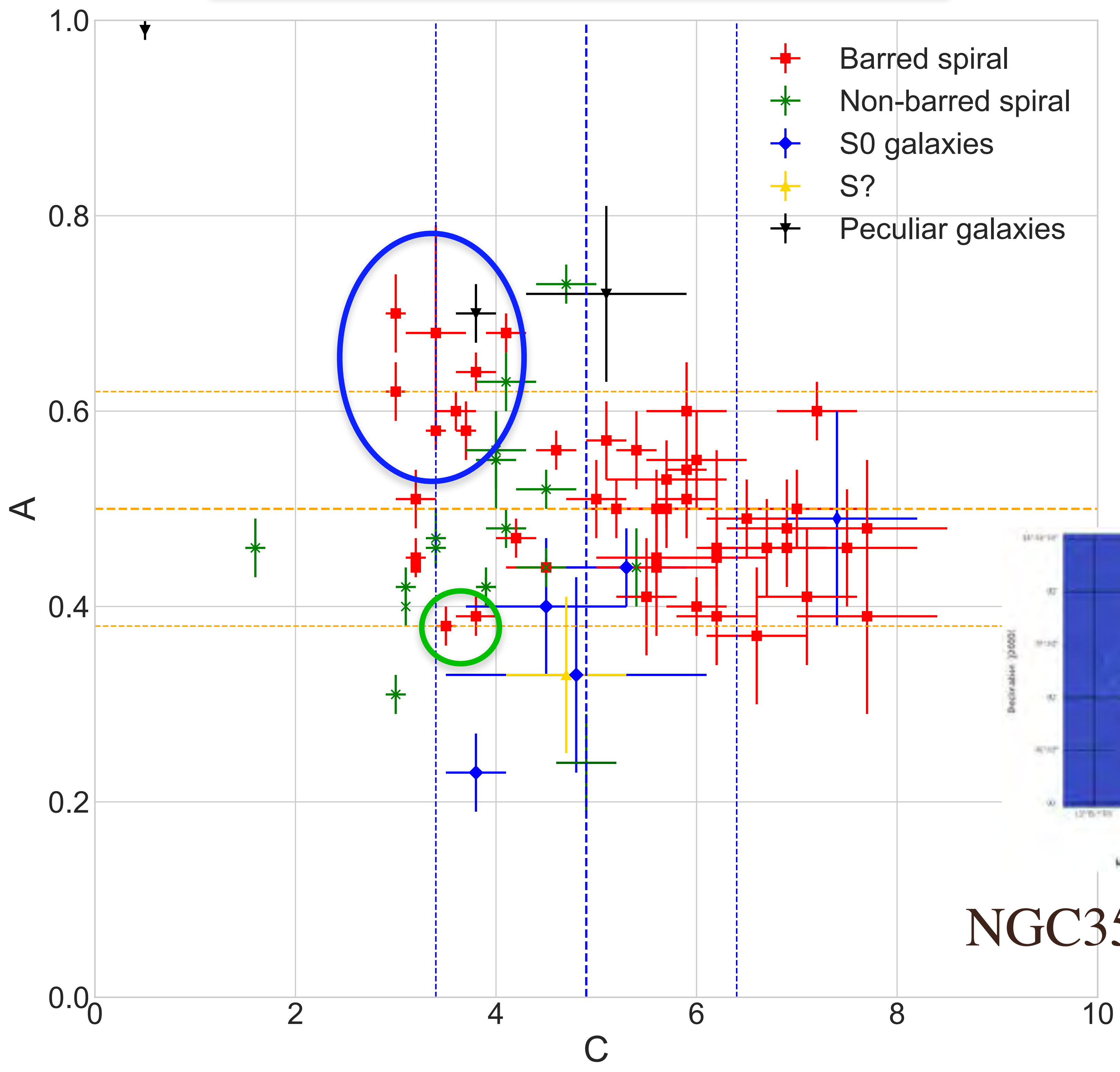
Result 2

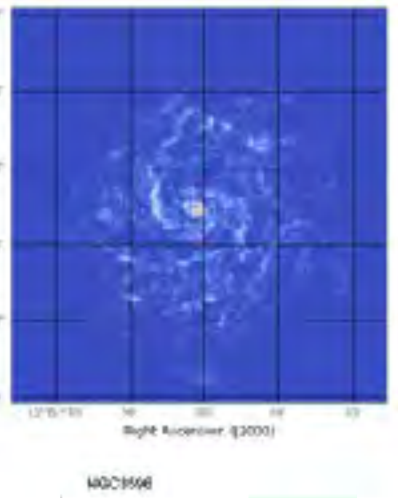
The bar structure increases the central concentration of molecular gas.

About 30% of the barred spiral galaxies were found to have lower than average C values.

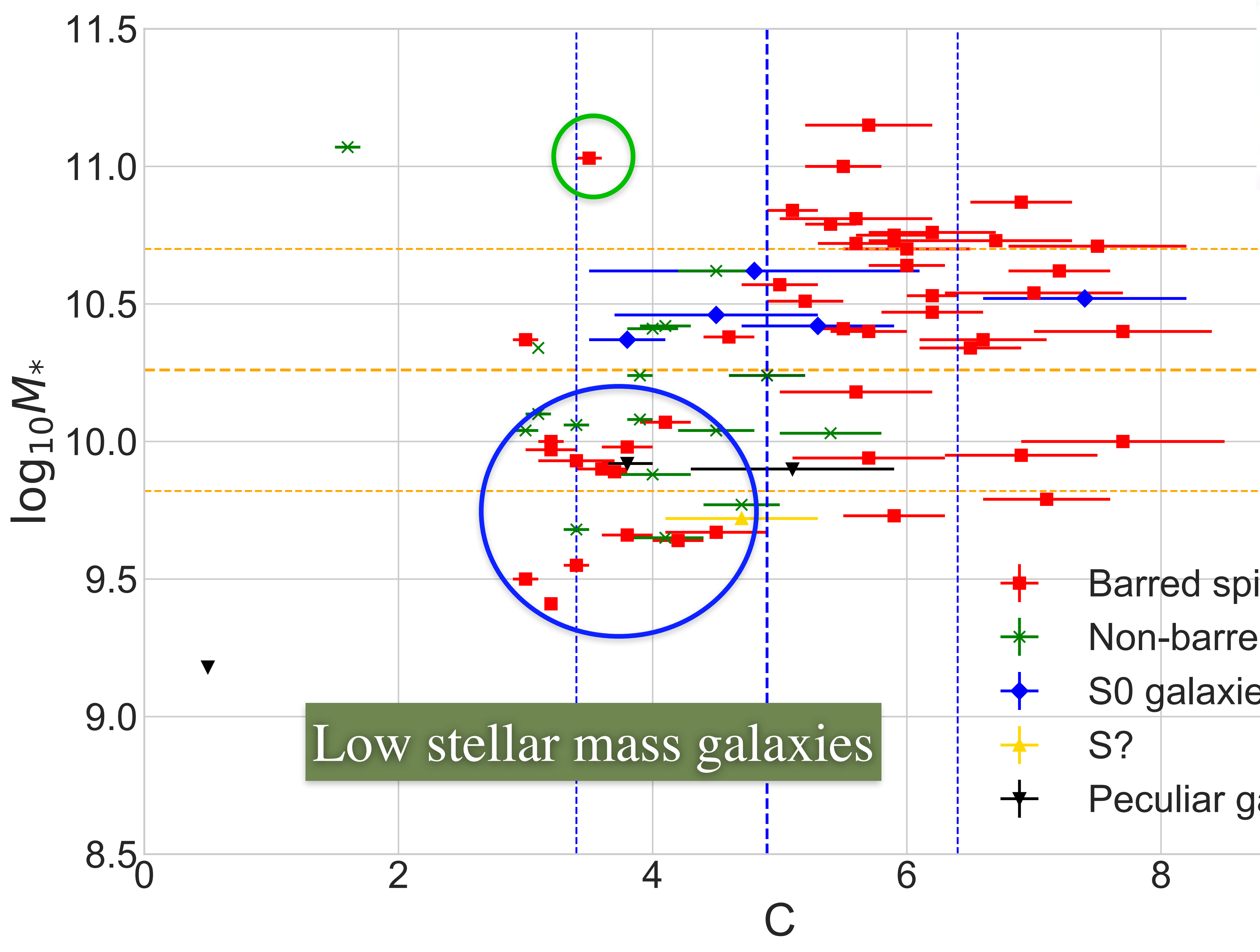
The Concentration may depend on the stellar mass and the A value of the galaxy.

Galaxies with high A values

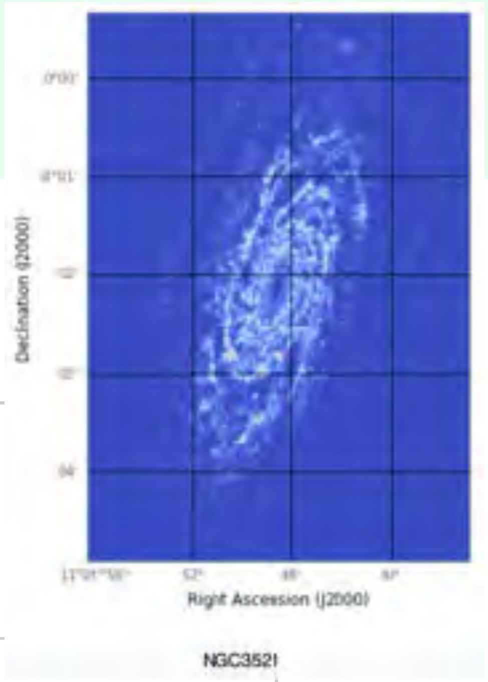




NGC3596



Low stellar mass galaxies



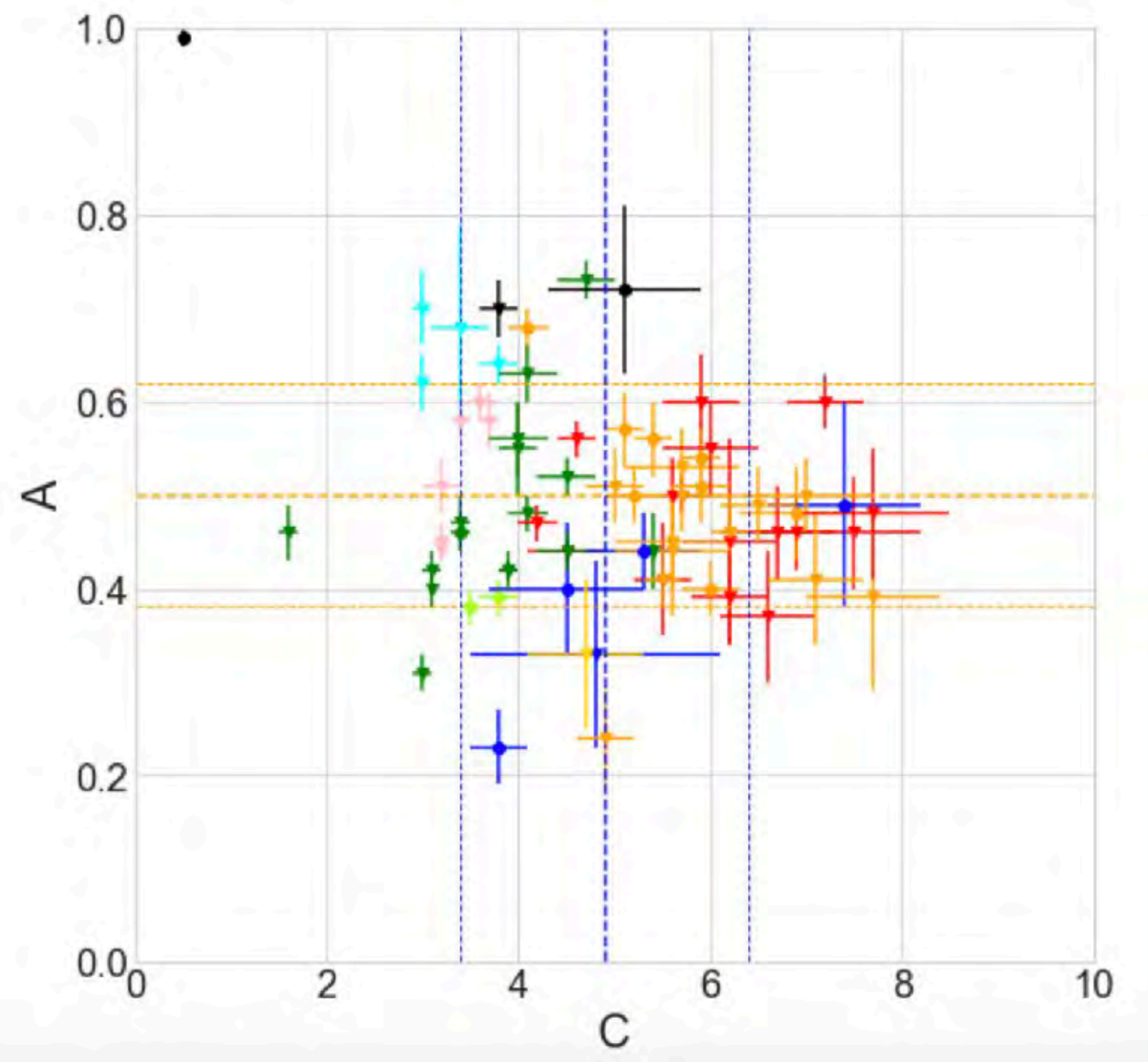
NGC3521

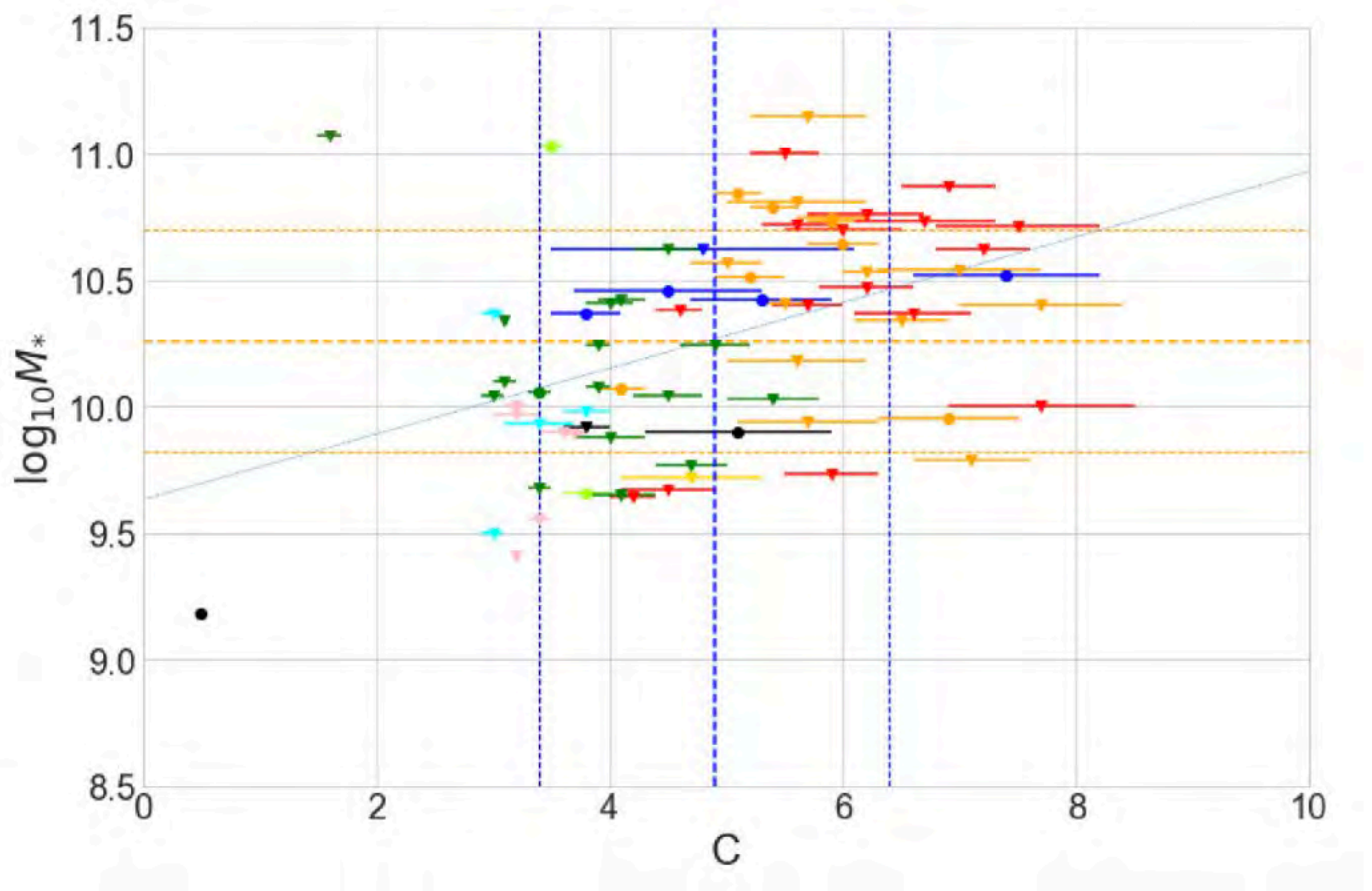
Result 2

The bar structure increases the central concentration of molecular gas.

About 30% of the barred spiral galaxies were found to have lower than average C values.

The Concentration may depend on the stellar mass and the A value of the galaxy.

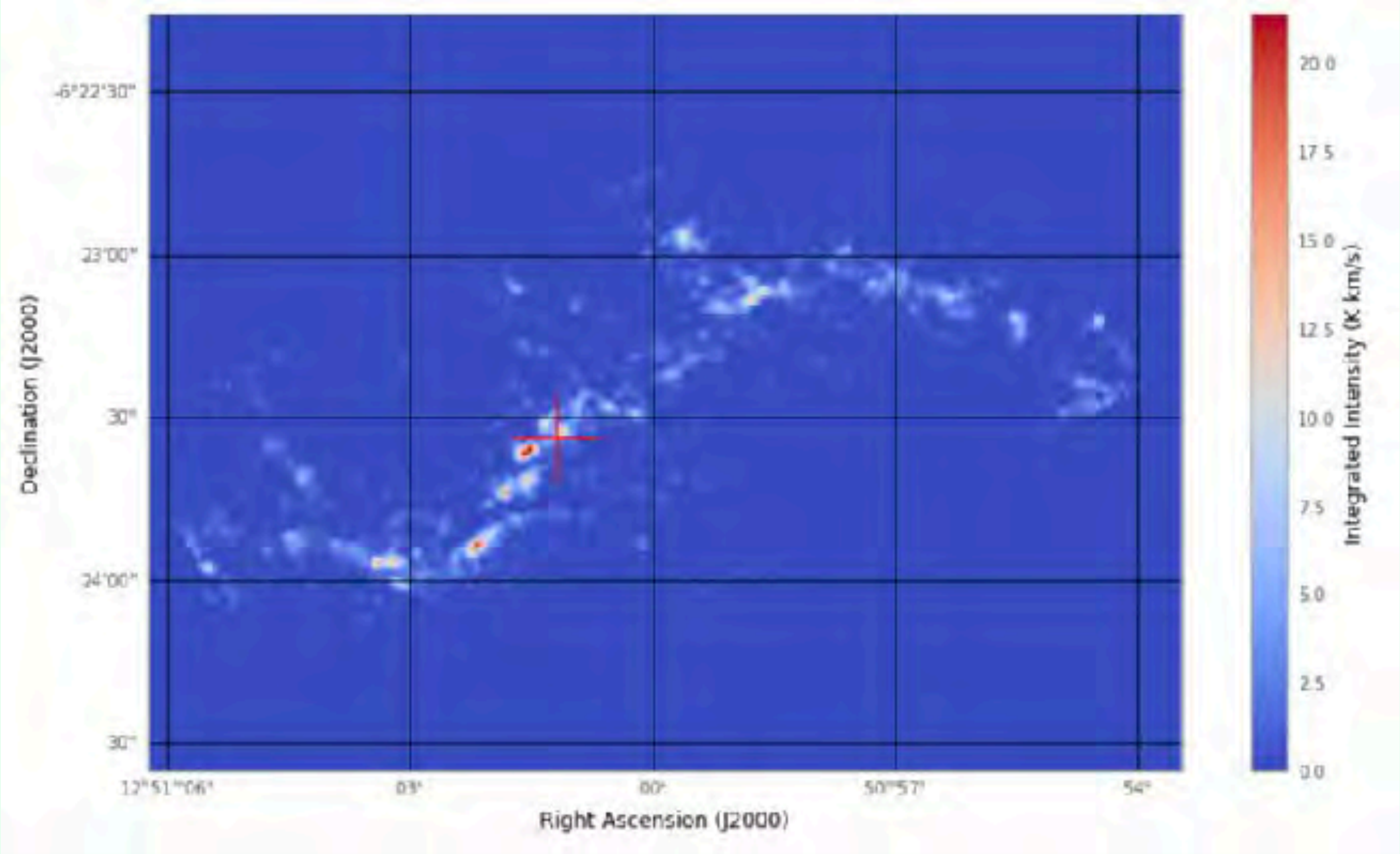




The tidal-induced bar

Galaxies with high A values

NGC 4731 SB(s)cd



The Carnegie-Irvine Galaxy Survey (CGS)

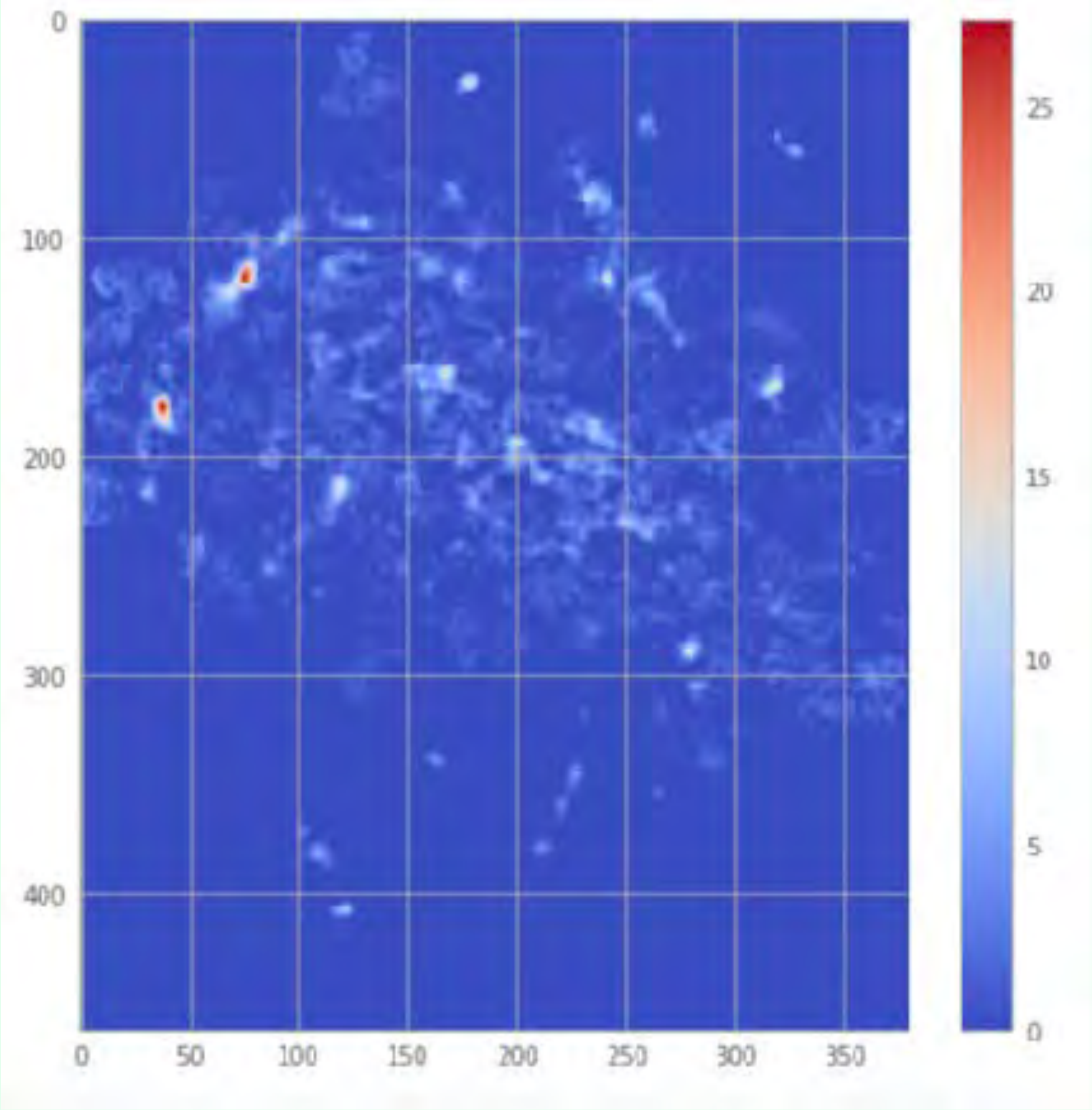
$C = 3.0 \pm 0.1$

$A = 0.70 \pm 0.04$

$S = 5.07 \pm 0.04$

$\log_{10} M_* = 9.50$

NGC 4496A SB(rs)m

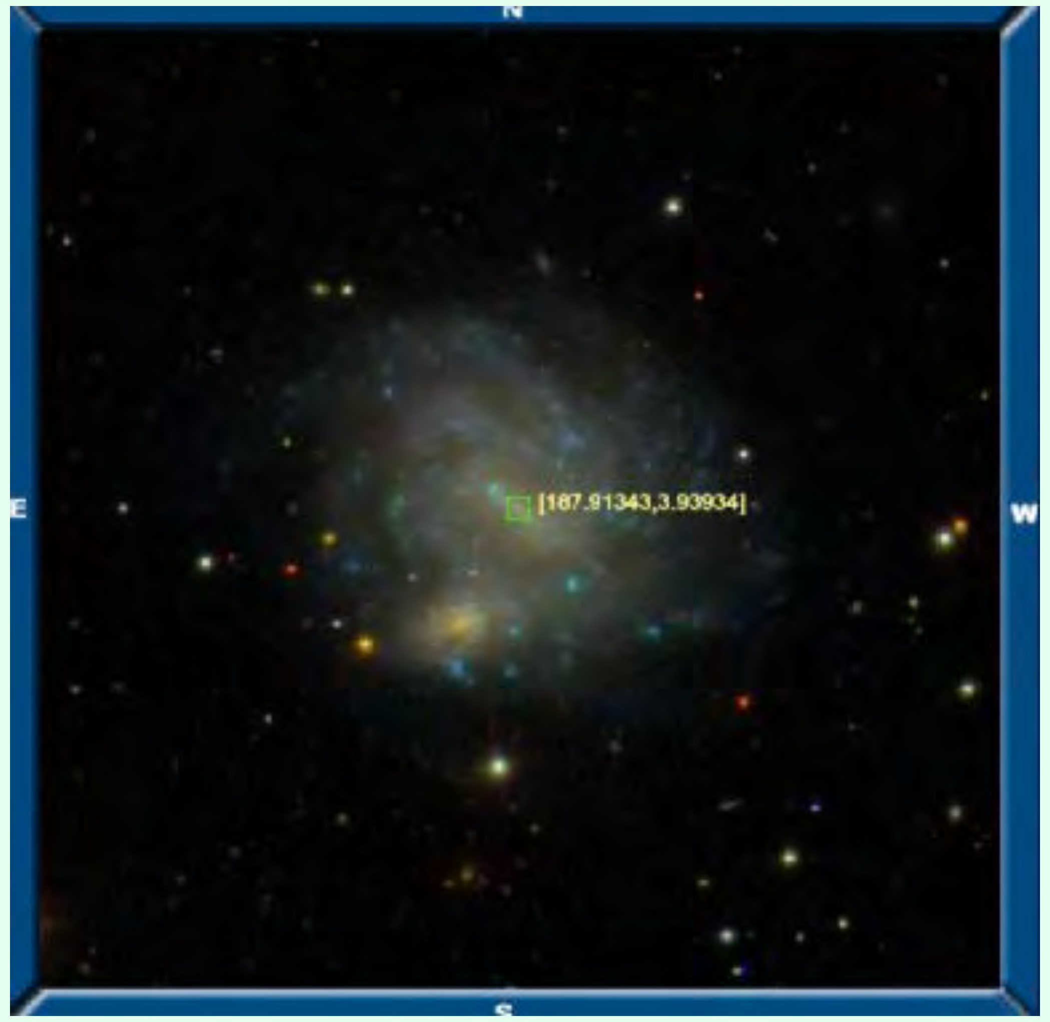


$C = 3.4 \pm 0.1$

$A = 0.58 \pm 0.02$

$S = 3.12 \pm 0.08$

$\log_{10} M_* = 9.55$

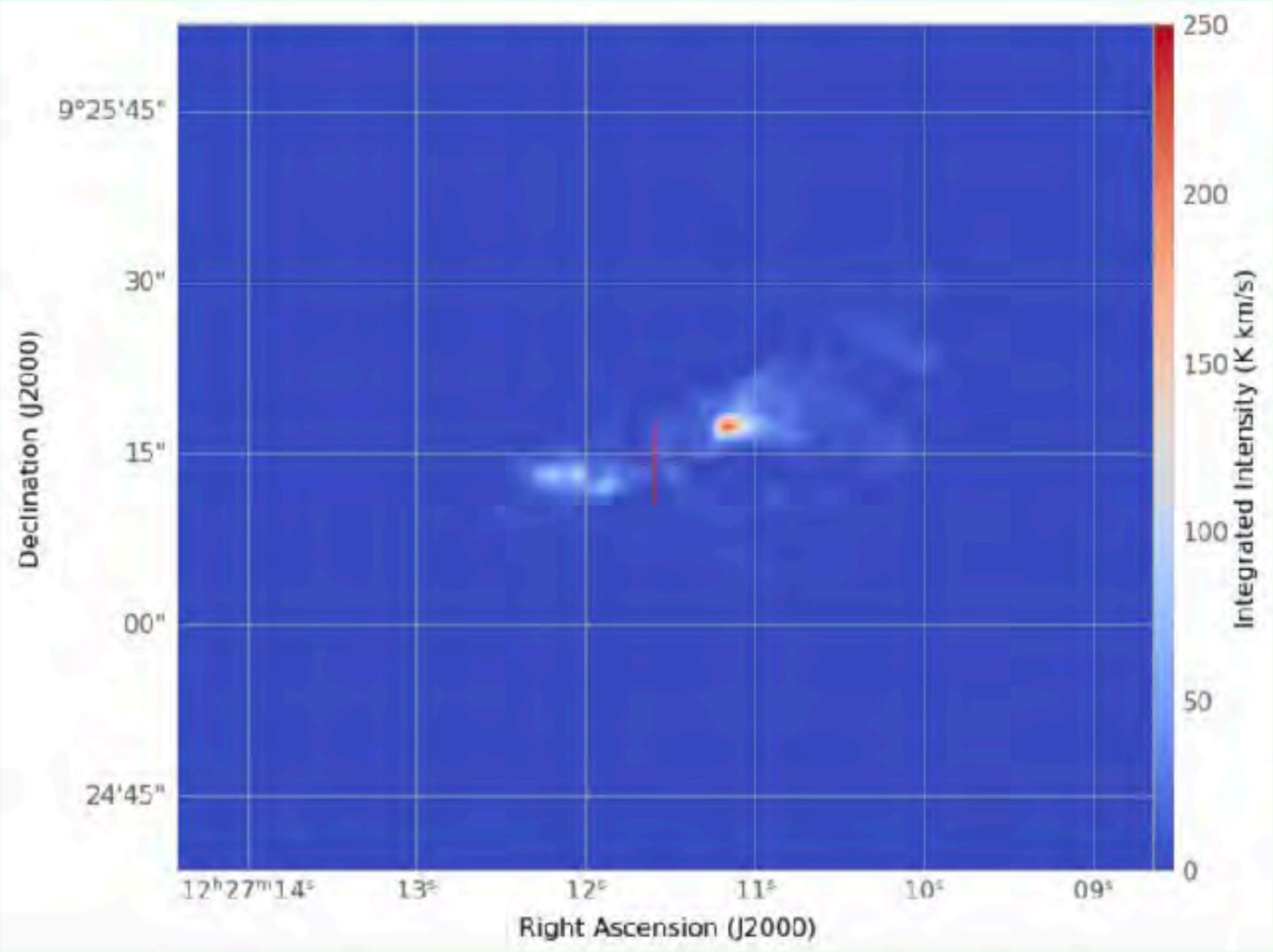


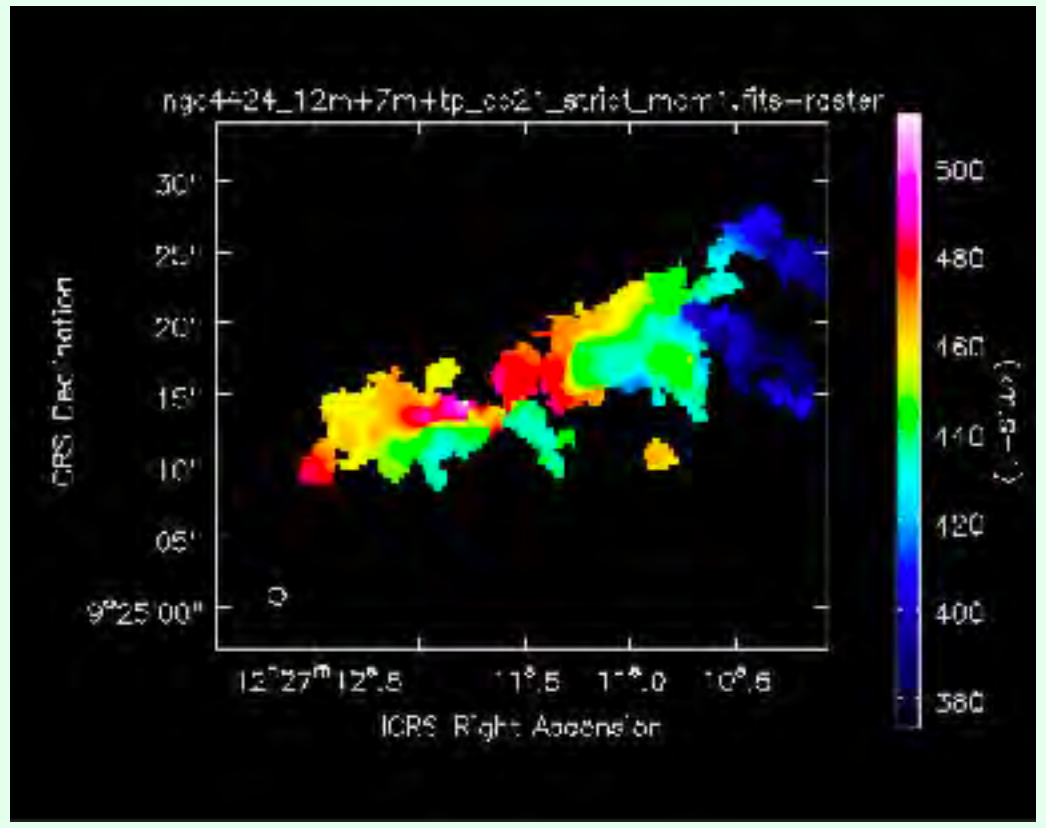
SDSS DR16

The merging galaxy?

Galaxies with high A values

NGC 4424 SB(s)a





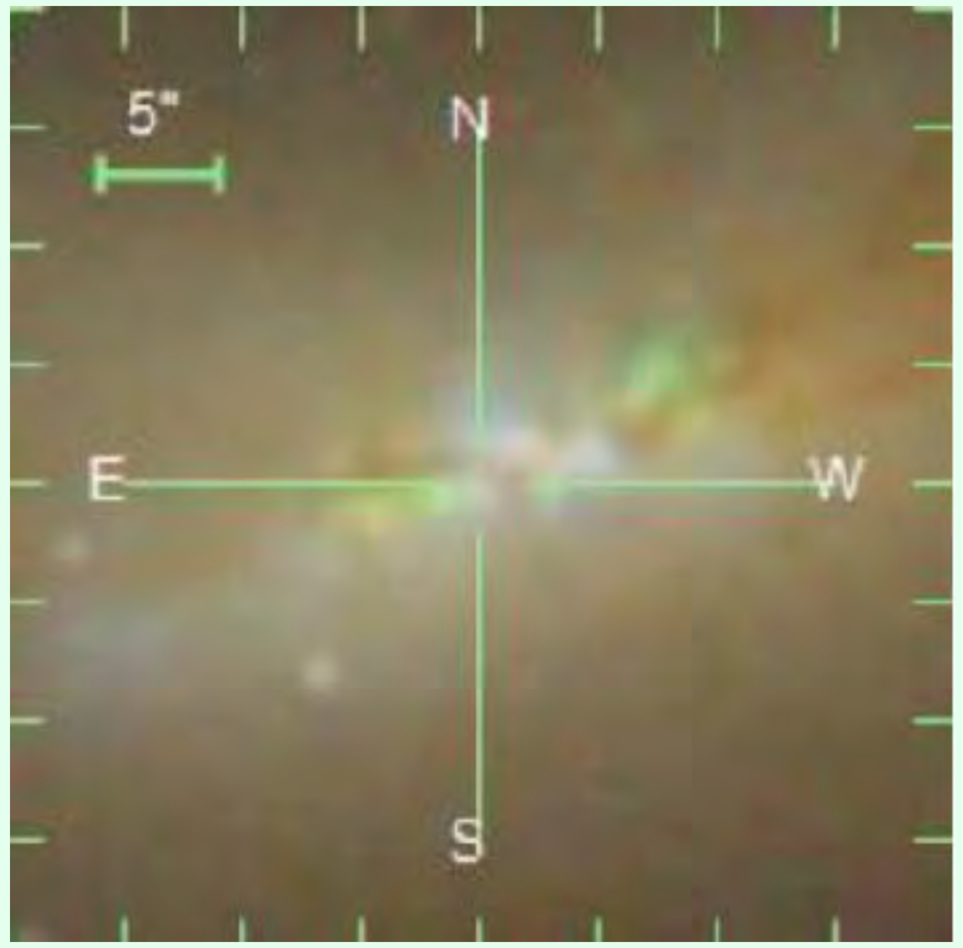
Moment 1 map

$C = 3.4 \pm 0.3$

$A = 0.68 \pm 0.11$

$S = 3.08 \pm 0.05$

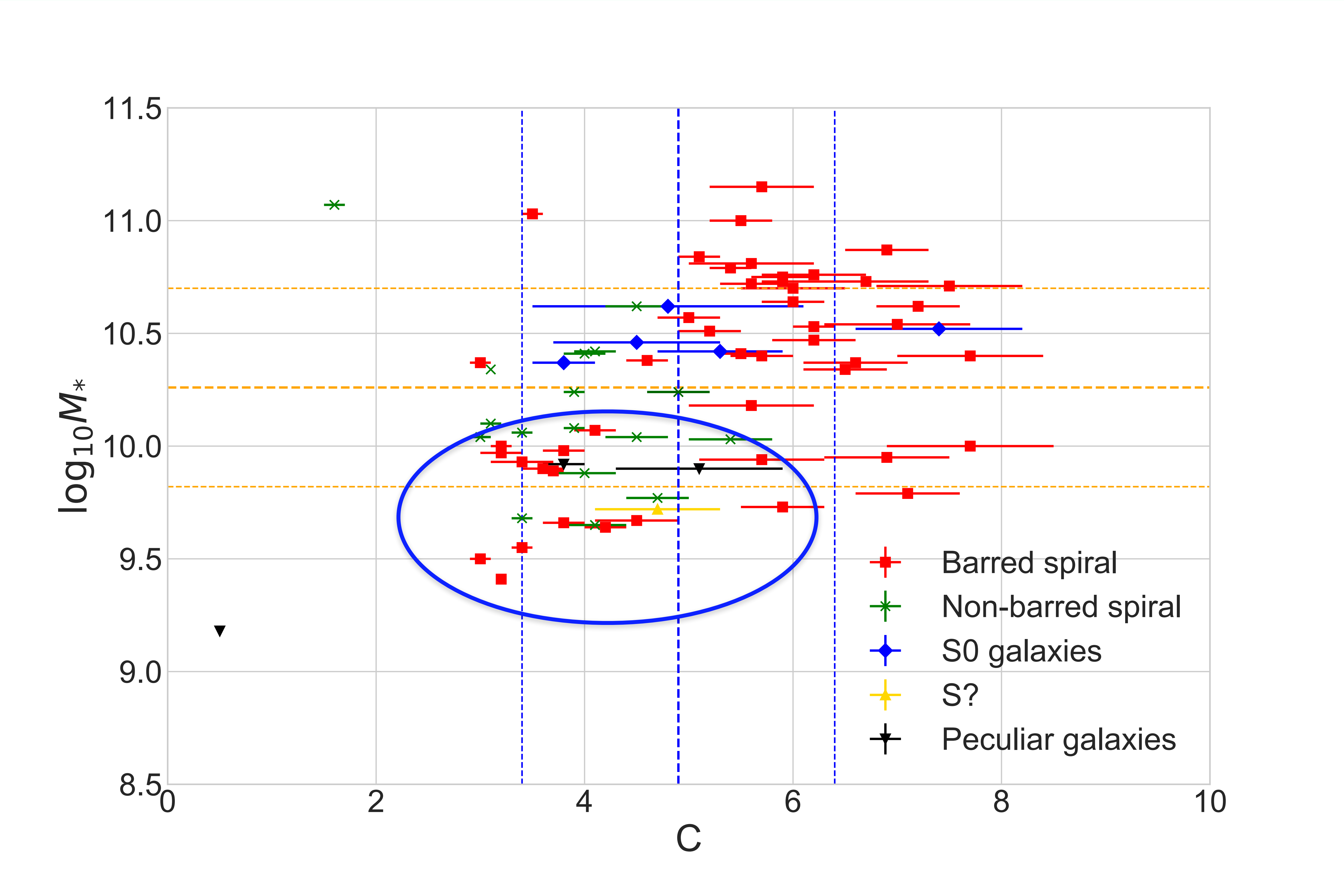
$\log_{10} M_* = 9.93$



Result 2

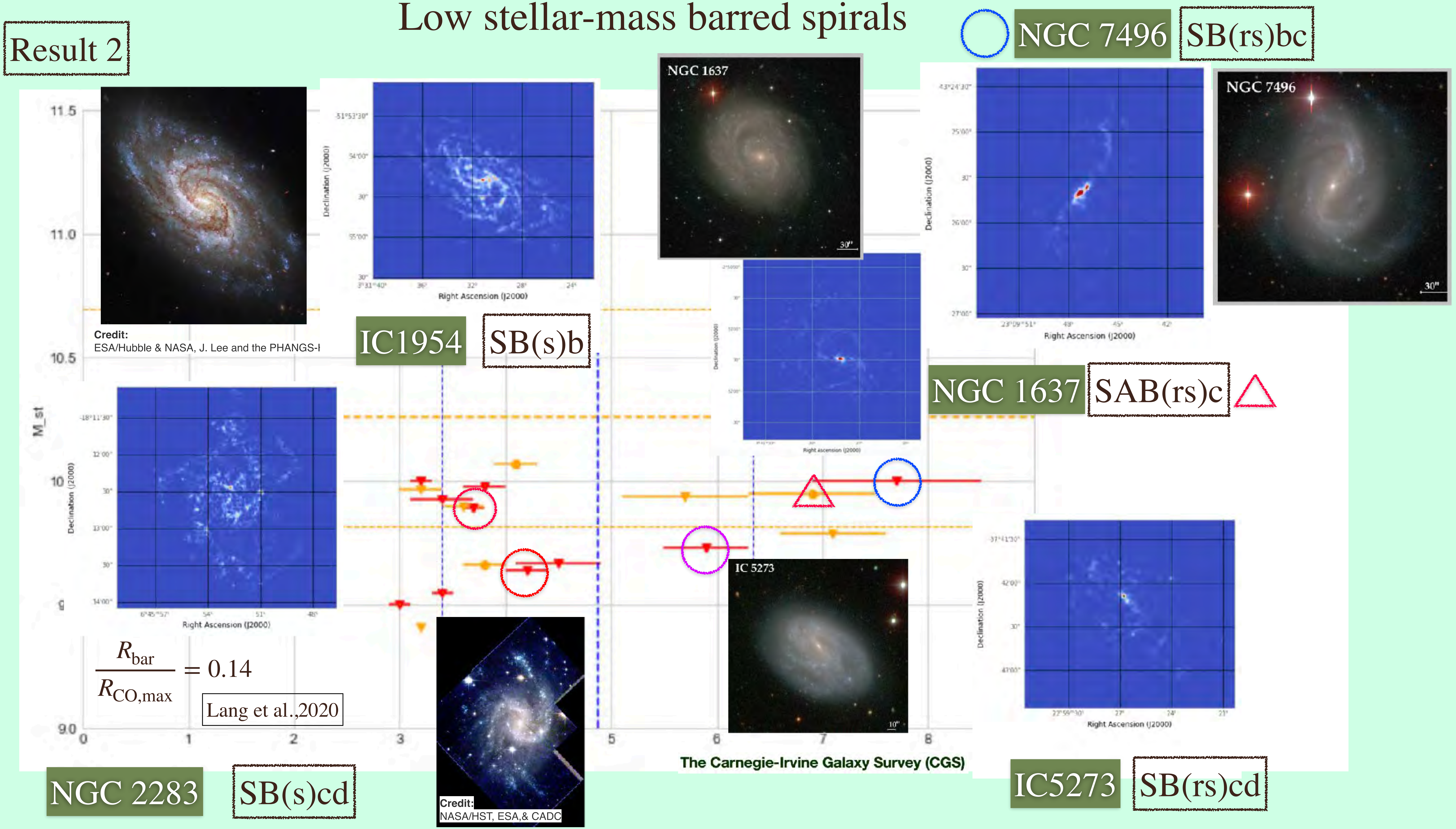
The bar structure increases the central concentration of molecular gas.

Except for galaxies with tidal induced bar,
Barred spiral galaxies with low stellar mass tend to have small bar sizes.



Low stellar-mass barred spirals

Result 2



$$\frac{R_{\mathrm{bar}}}{R_{\mathrm{CO,max}}} = 0.14$$

Lang et al.,2020

Result 2

High stellar-mass barred spirals

$$\frac{R_{\mathrm{bar}}}{R_{\mathrm{CO,max}}} = 0.68$$

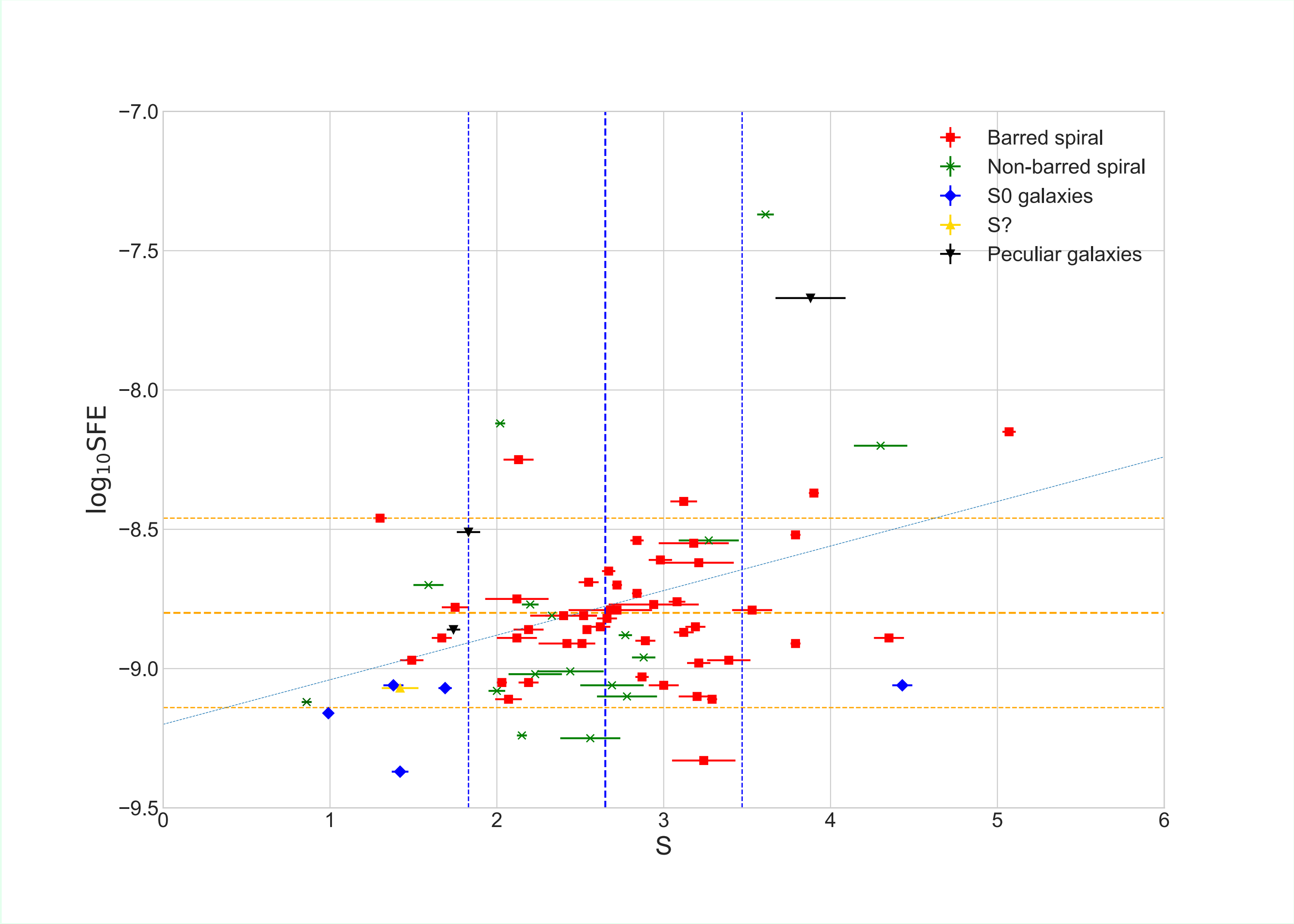
Lang et al.,2020

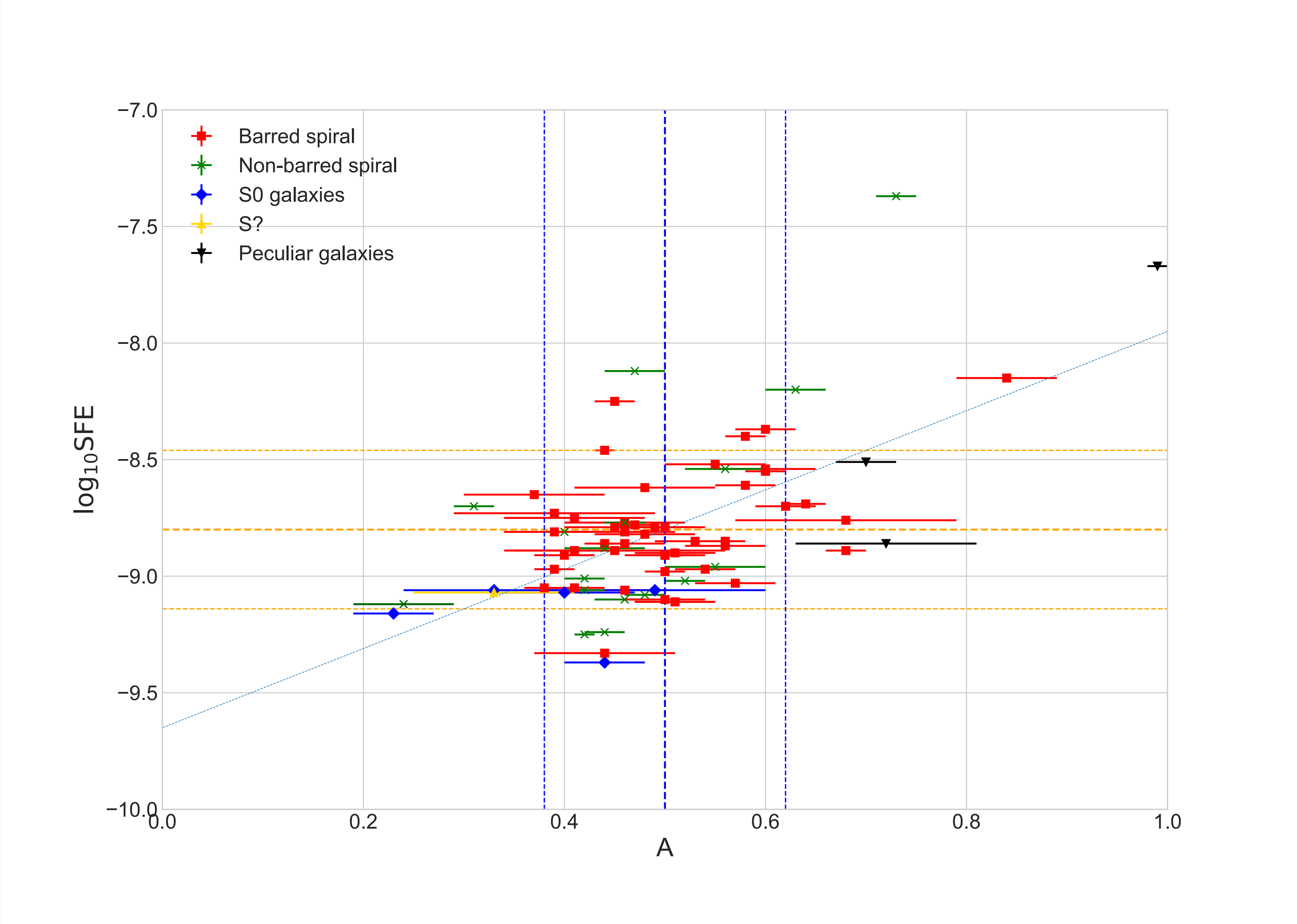
Result 3

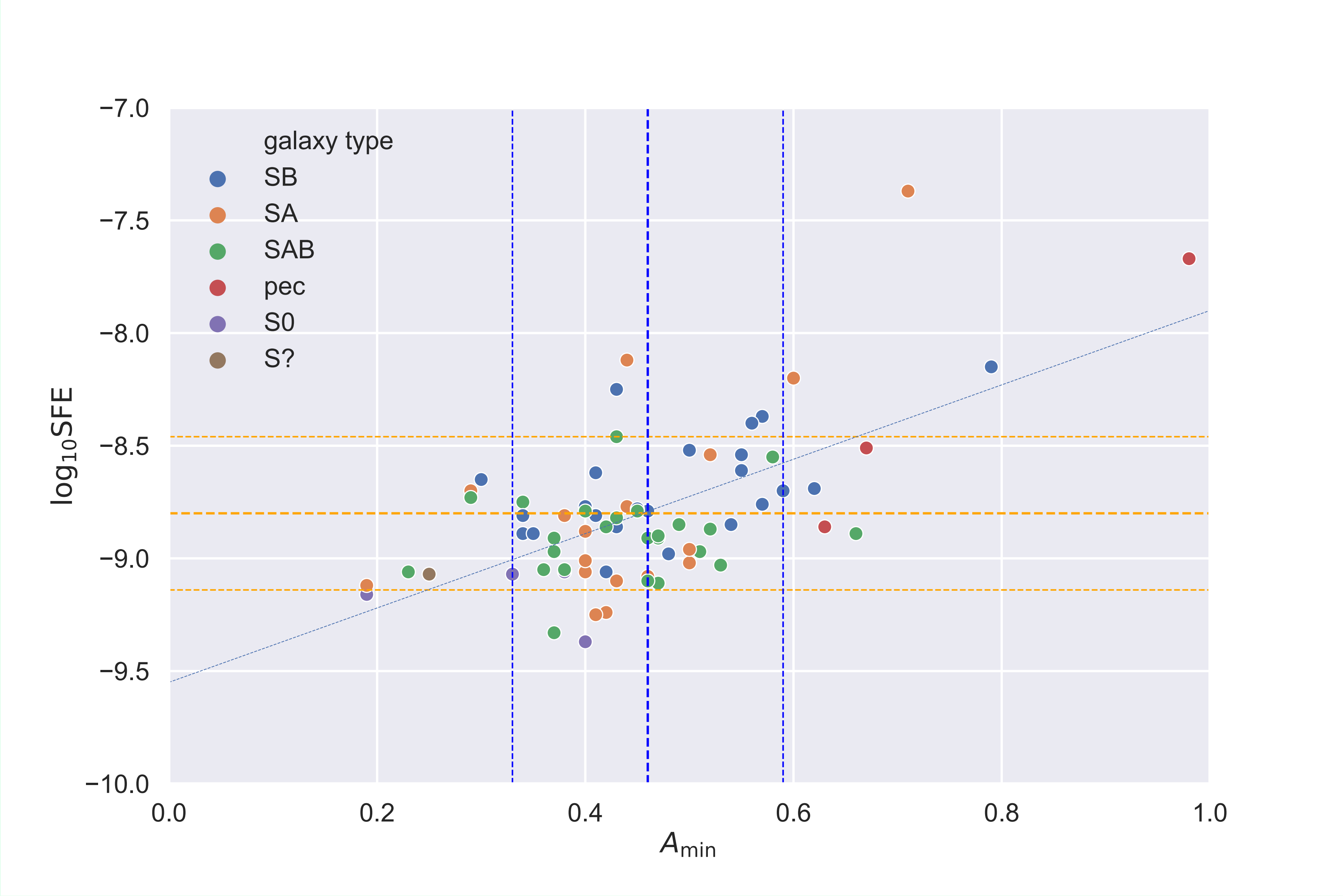
Clumpiness & Asymmetry vs. SFE

(3) The relationship between star formation efficiency(SFE) and clumpiness (*S*) was not as expected, showing only a slight correlation. SFE was somewhat better positively correlated with Asymmetry (*A*).

$\log_{10}$ SFE vs. C	-0.11	0.35	...
$\log_{10}$ SFE vs. A	0.45	7.0×10^{-5}	√
$\log_{10}$ SFE vs. S	0.29	0.01	√



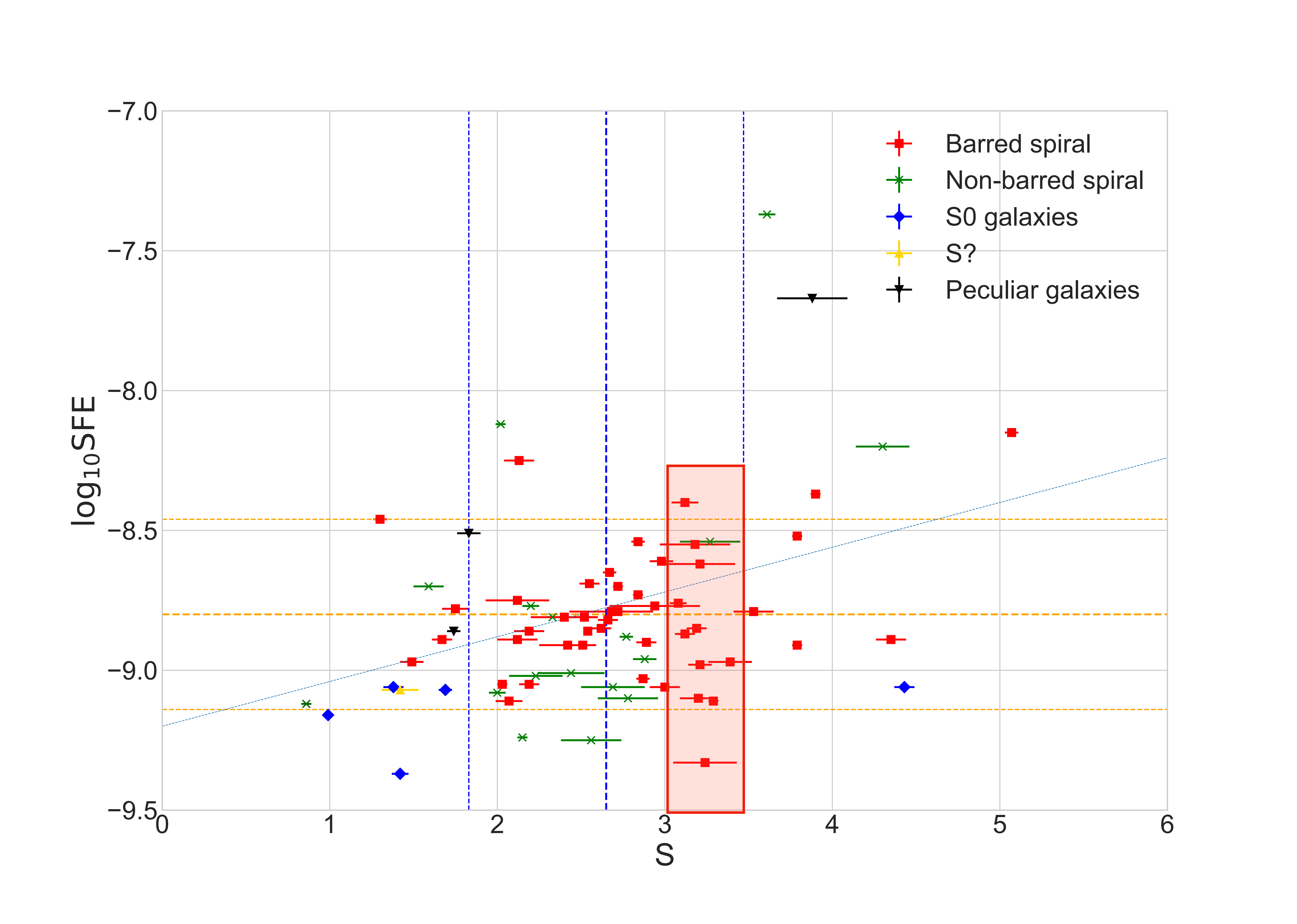




Result 3

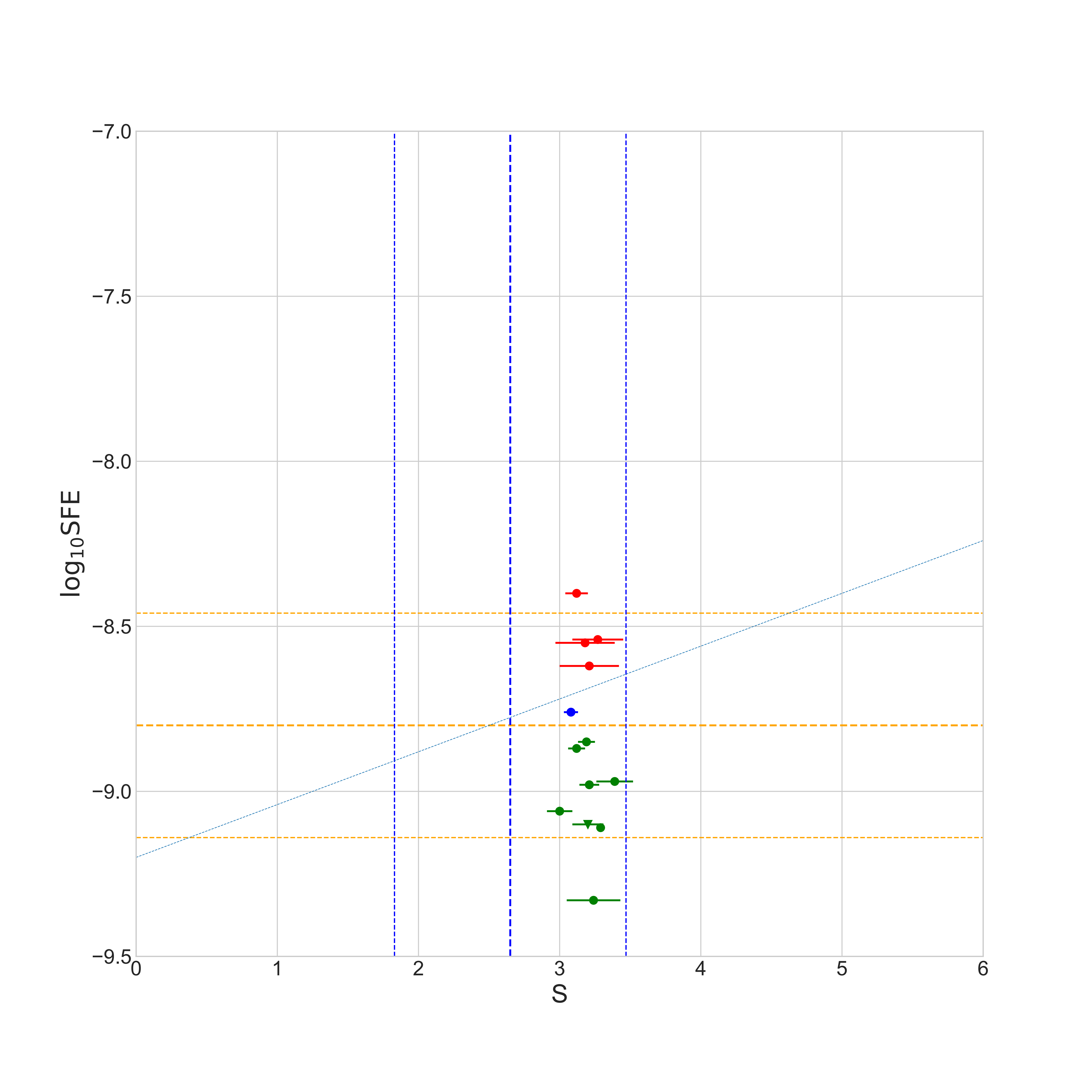
Clumpiness & Asymmetry vs. SFE

The results of this analysis suggest that the physical condition of the GMC, rather than its ratio of GMAs to total molecular gas, contributes to SFE.



Result 3

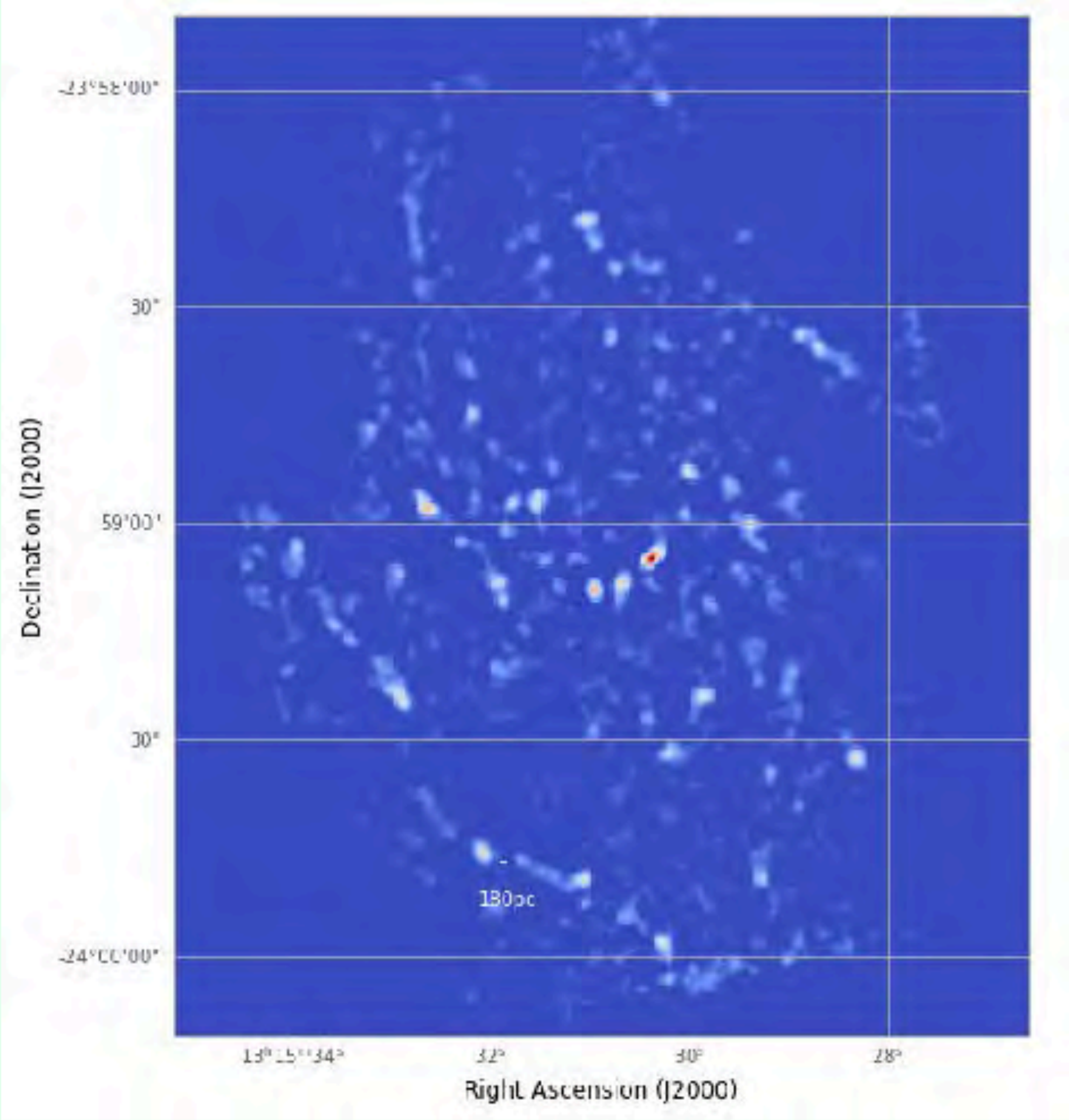
Clumpiness & Asymmetry vs. SFE



Result 3

The star formation efficiency depends on where the GMAs are distributed.

NGC 5042



$C = 3.6 \pm 0.2$

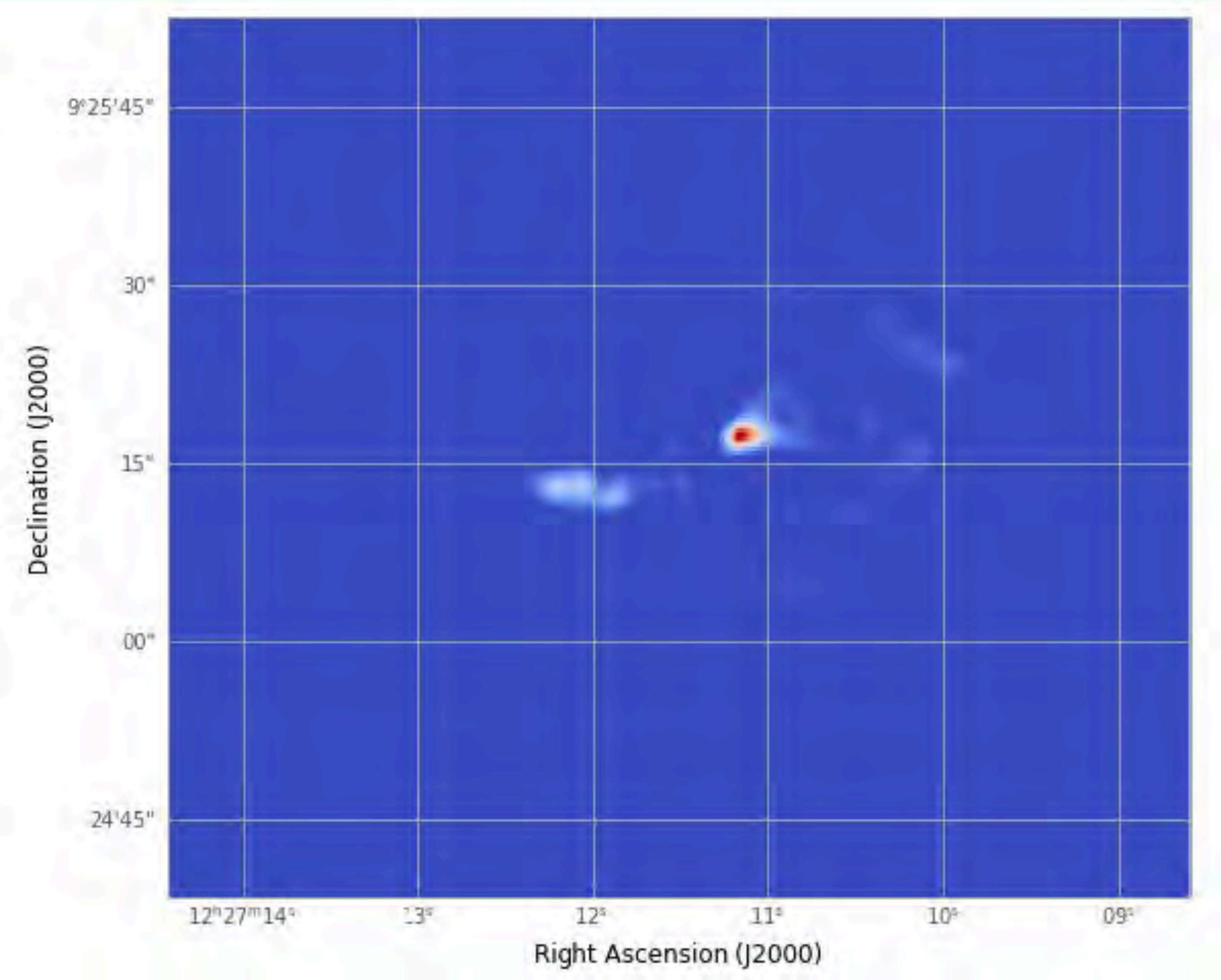
$A = 0.60 \pm 0.02$

$S = 3.18 \pm 0.21$

$\log_{10} M_* = 9.90$

$\log_{10} \mathrm{SFE} = -8.55$

NGC 4424



$C = 3.4 \pm 0.3$

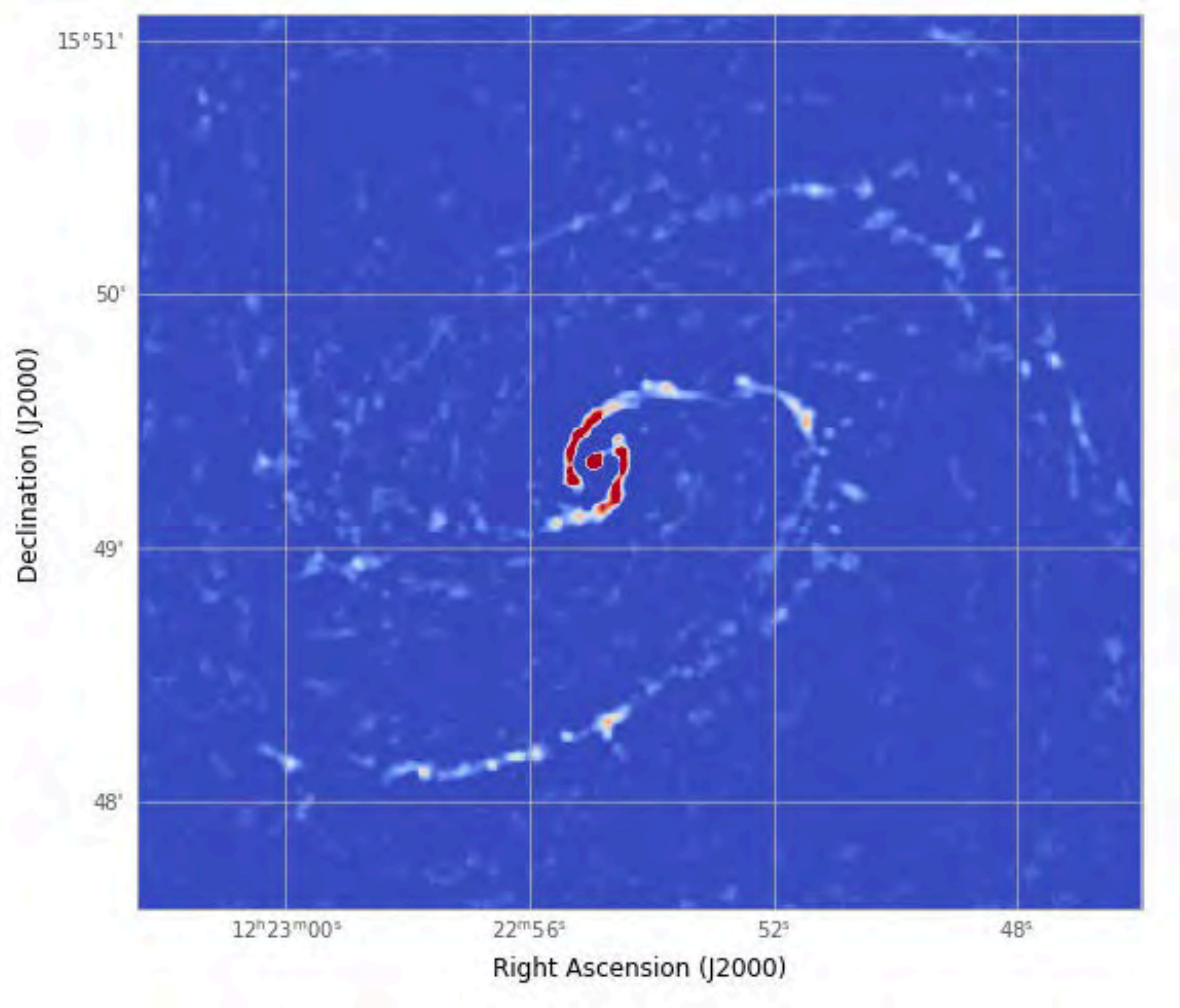
$A = 0.68 \pm 0.11$

$S = 3.08 \pm 0.05$

$\log_{10} M_* = 9.93$

$\log_{10} \mathrm{SFE} = -8.76$

NGC 4321



$C = 5.9 \pm 0.3$

$A = 0.51 \pm 0.04$

$S = 3.29 \pm 0.03$

$\log_{10} M_* = 10.75$

$\log_{10} \mathrm{SFE} = -9.11$

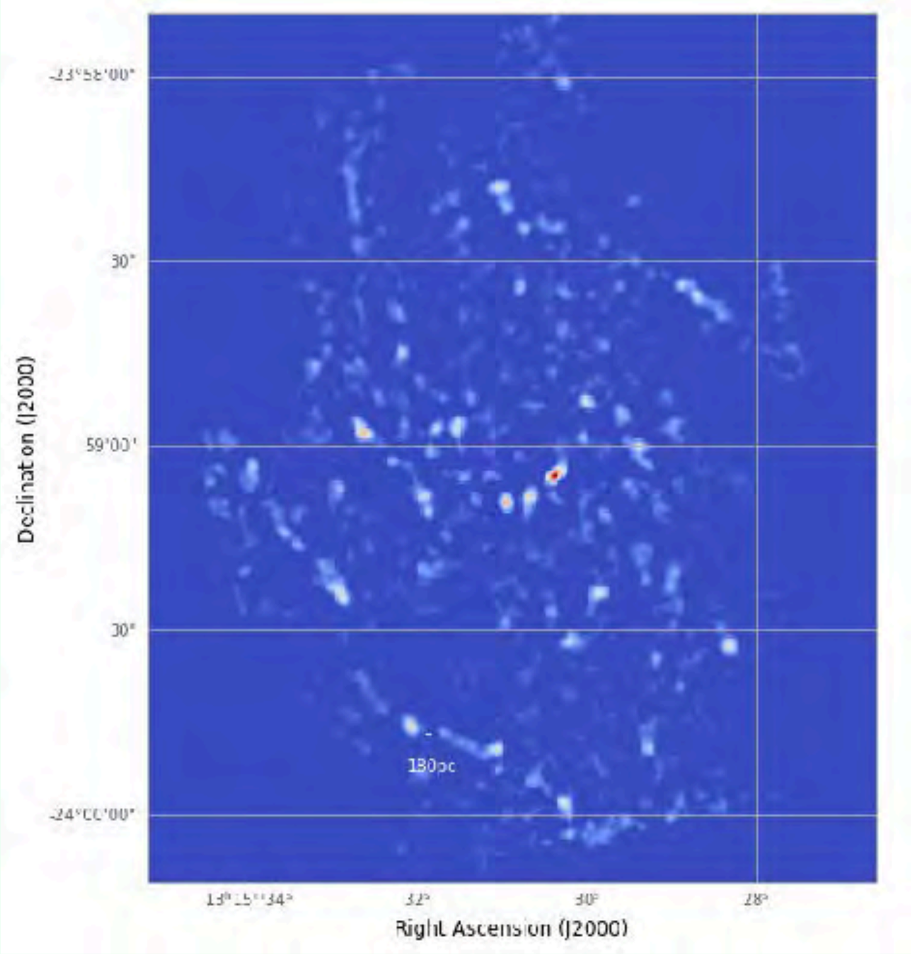
Result 3

The star formation efficiency depends on where the GMAs are distributed.

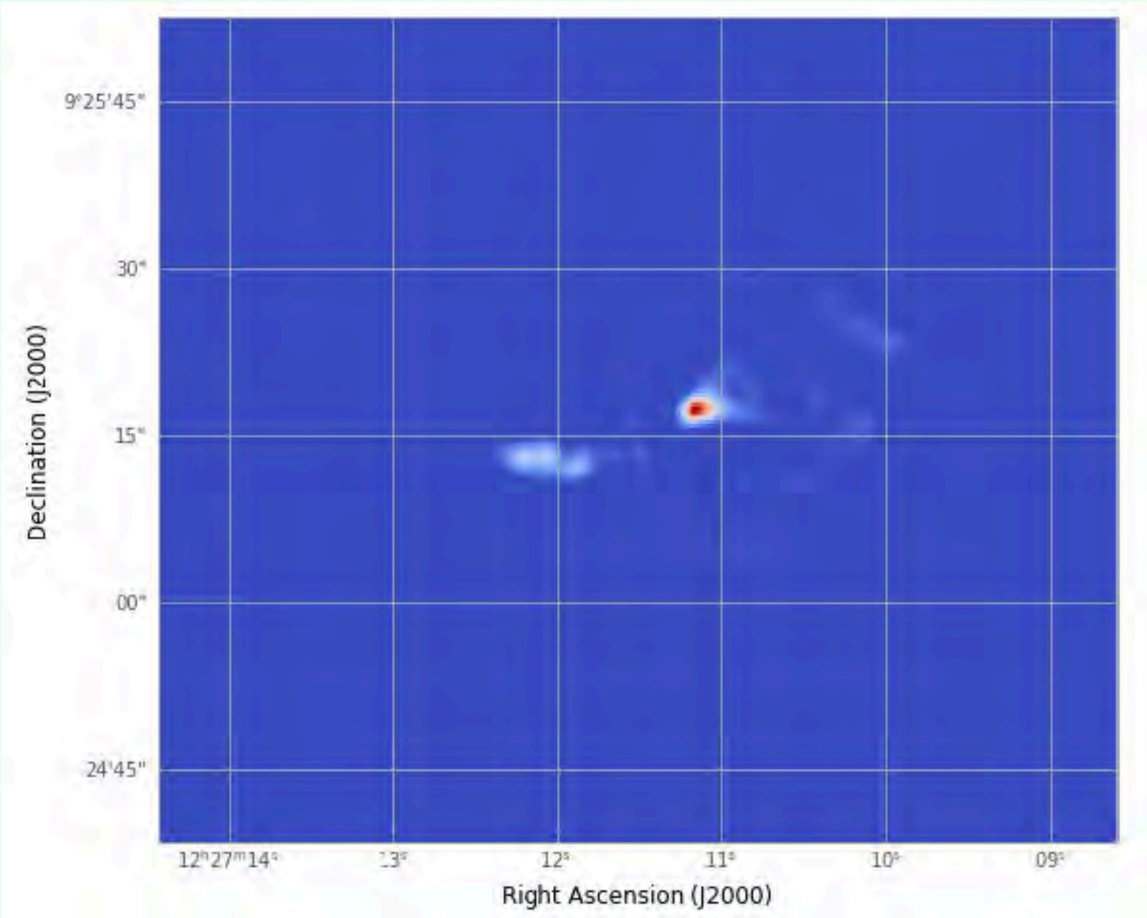
Galaxy	α_{vir}	σ_0 (km s^{-1})
NGC 0628	$1.2^{+1.3}_{-0.5}$	$0.54^{+0.18}_{-0.18}$
NGC 1637	$1.4^{+1.9}_{-0.8}$	$0.57^{+0.28}_{-0.18}$
NGC 2903	$2.0^{+3.3}_{-1.1}$	$0.90^{+0.52}_{-0.30}$
NGC 3521	$1.2^{+1.6}_{-0.5}$	$0.81^{+0.25}_{-0.25}$
NGC 3621	$1.6^{+2.1}_{-0.9}$	$0.81^{+0.32}_{-0.28}$
NGC 3627	$1.6^{+2.5}_{-0.9}$	$0.87^{+0.35}_{-0.26}$
NGC 4826	$4.1^{+4.0}_{-2.0}$	$2.30^{+0.73}_{-0.53}$
NGC 5068	$0.8^{+1.0}_{-0.4}$	$0.54^{+0.24}_{-0.24}$
NGC 5643	$1.5^{+1.8}_{-0.8}$	$0.62^{+0.30}_{-0.22}$
NGC 6300	$1.7^{+2.1}_{-0.9}$	$0.69^{+0.37}_{-0.21}$
Average	$1.5^{+2.1}_{-0.8}$	$0.77^{+0.35}_{-0.27}$
Bar	$2.6^{+4.3}_{-1.5}$	$1.19^{+0.54}_{-0.41}$
Disc	$1.4^{+1.6}_{-0.7}$	$0.71^{+0.29}_{-0.25}$
Arm	$1.2^{+1.2}_{-0.6}$	$0.64^{+0.29}_{-0.21}$
Interarm	$1.4^{+1.7}_{-0.7}$	$0.65^{+0.29}_{-0.24}$

Rosolowsky et al. 2021

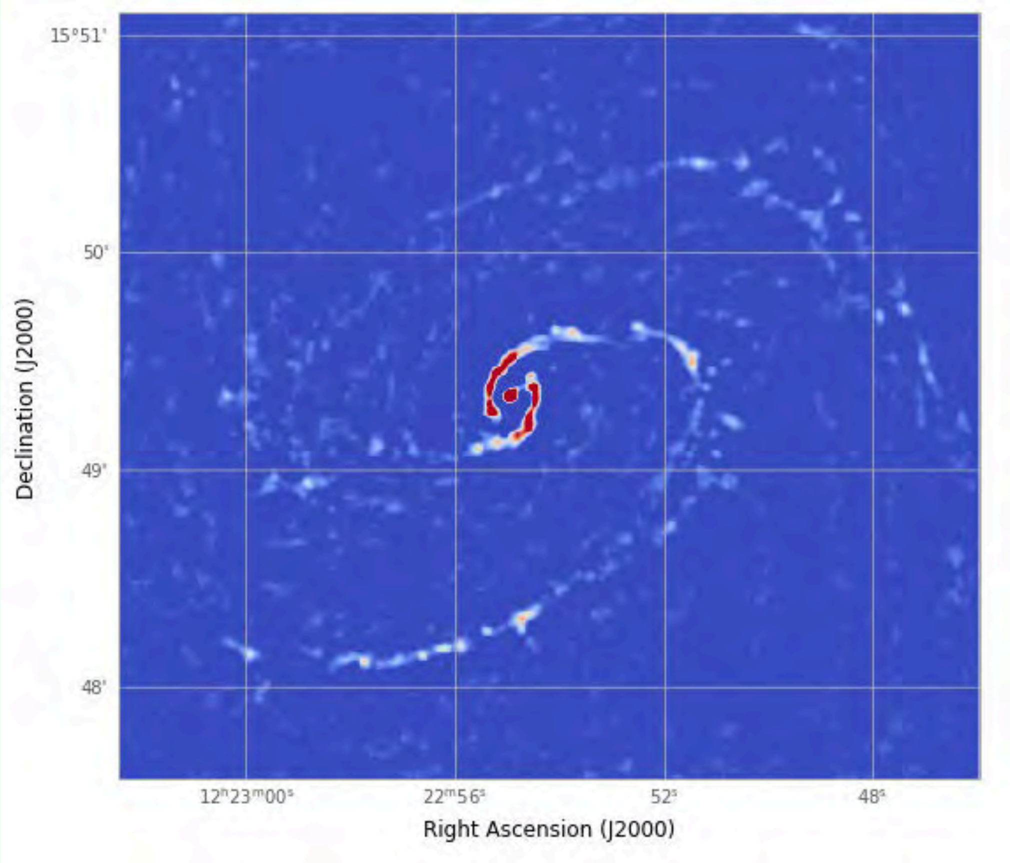
NGC 5042 SAB(rs)c



NGC 4424 SB(s)a



NGC 4321 SAB(s)bc



In the bar structures, both virial parameters (α_{vir}) and velocity dispersion (σ_0) have larger values than in the spiral arms and disks.

For nearly spherical clouds, α_{vir} can be expressed as (Bertoldi & McKee 1992)[20]

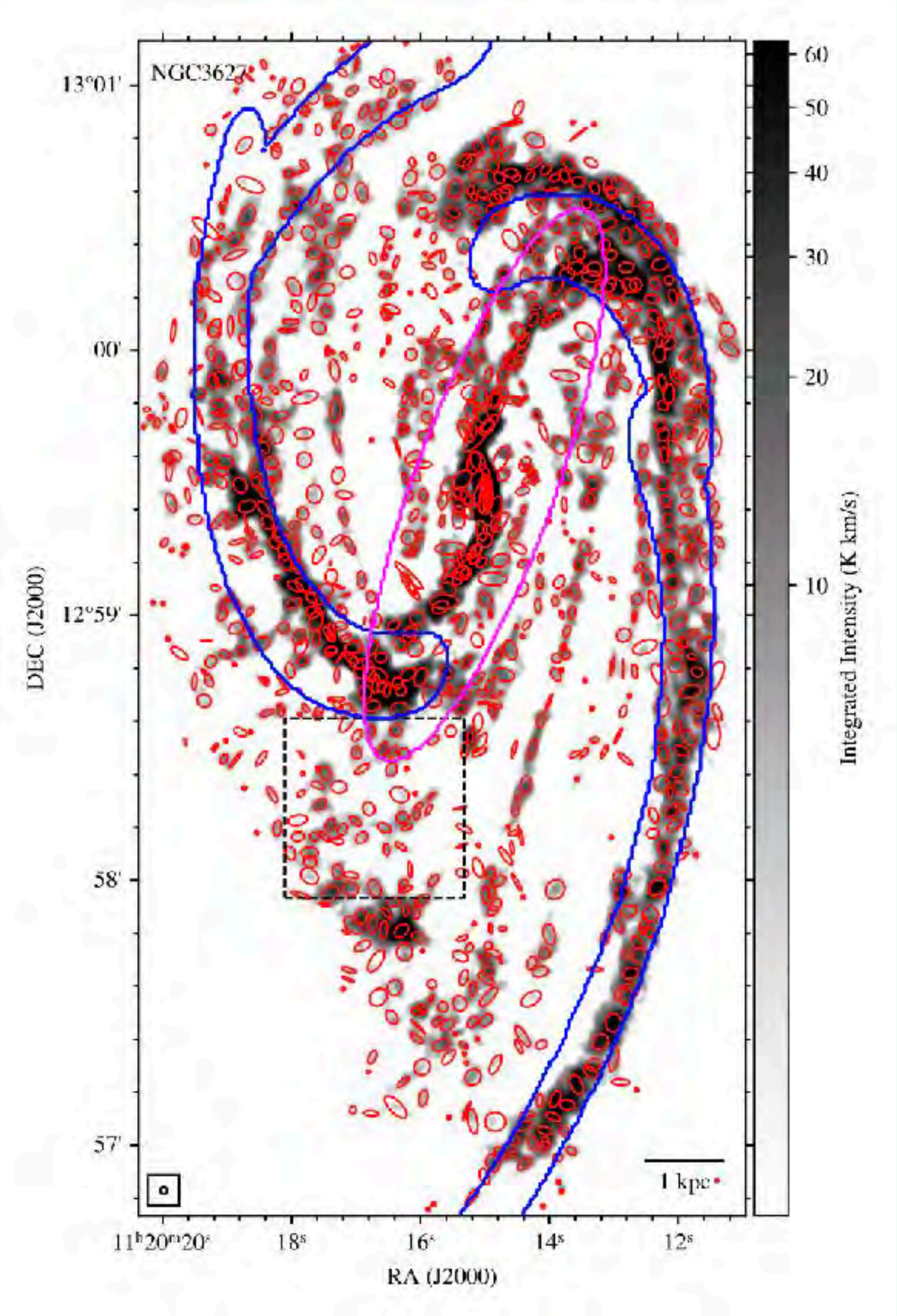
$$\alpha_{vir} \equiv \frac{2K}{U_g} = \frac{5\ \sigma^2 R}{fGM}. \tag{6}$$

NGC 3627 SAB(s)b

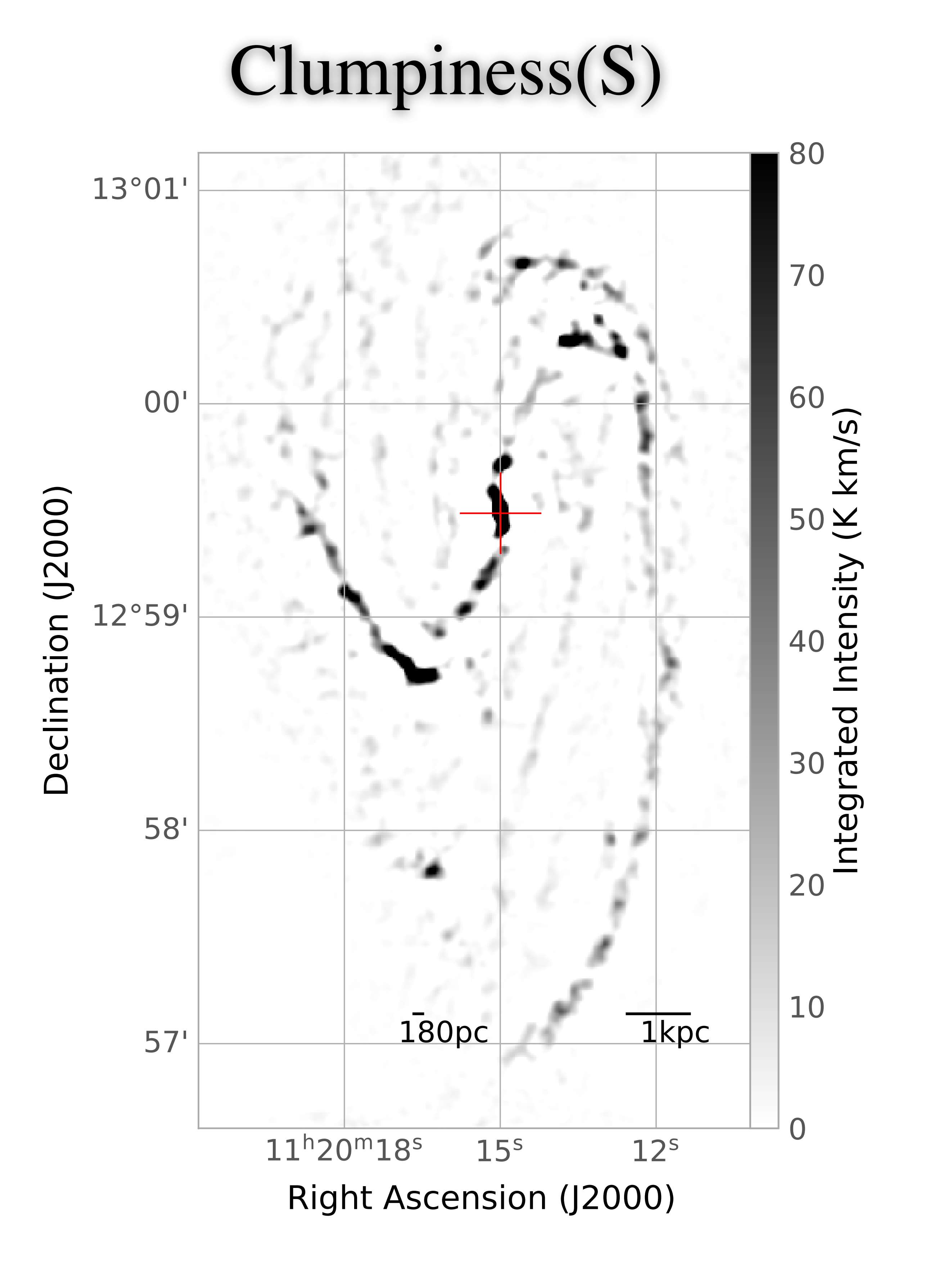
The SFE may differ between the bar and the center due to the higher density of molecular gas in the center.

$$S = 2.87 \pm 0.04$$

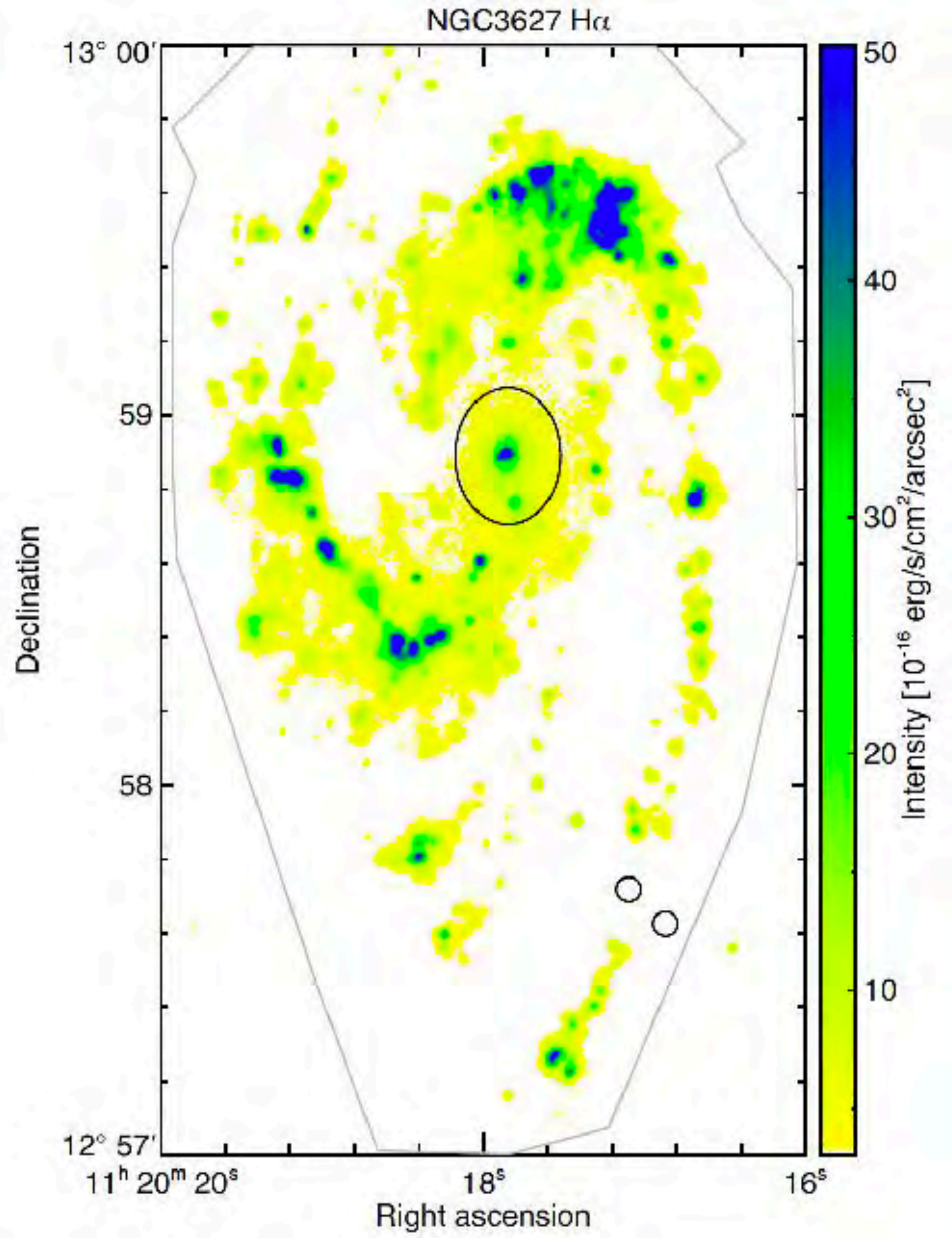
$$\log_{10} \mathrm{SFE} = -9.03$$



Rosolowsky et al. 2021 ~ 90pc



This work ~ 180pc

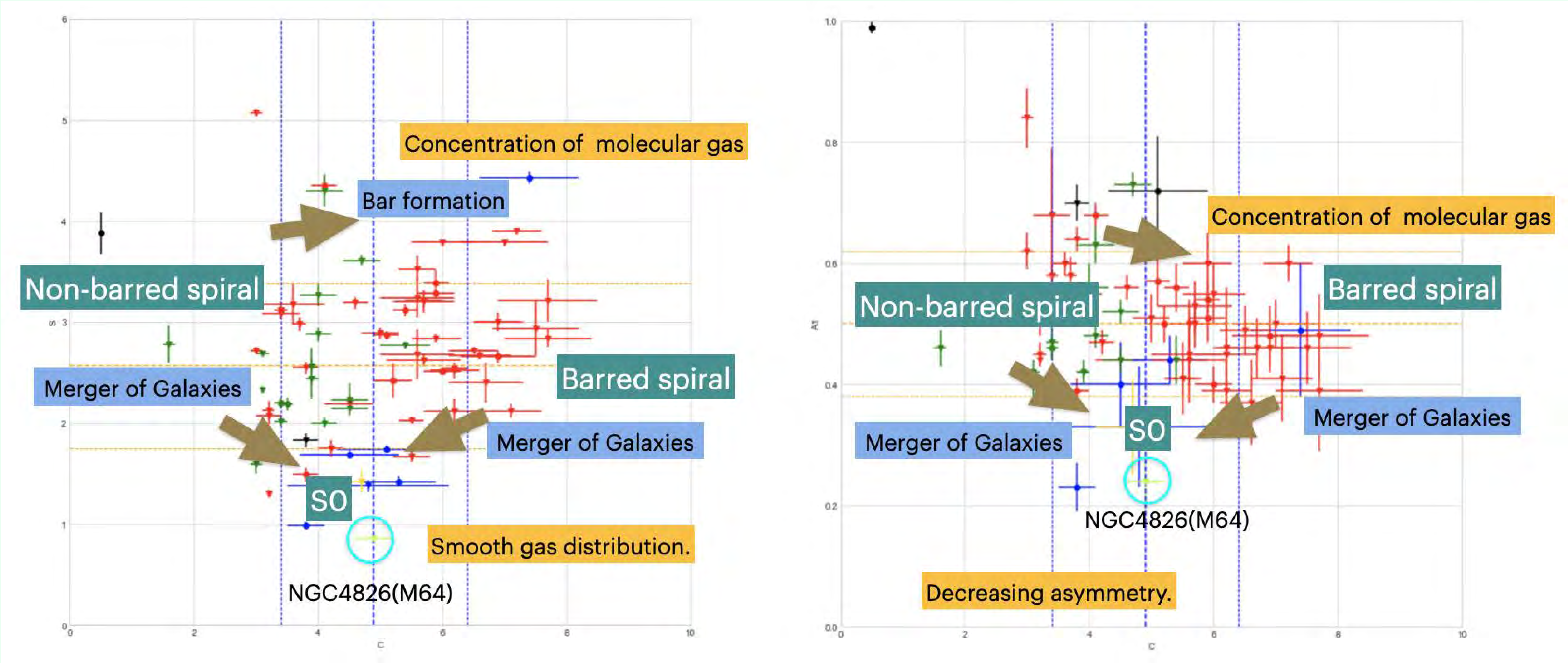


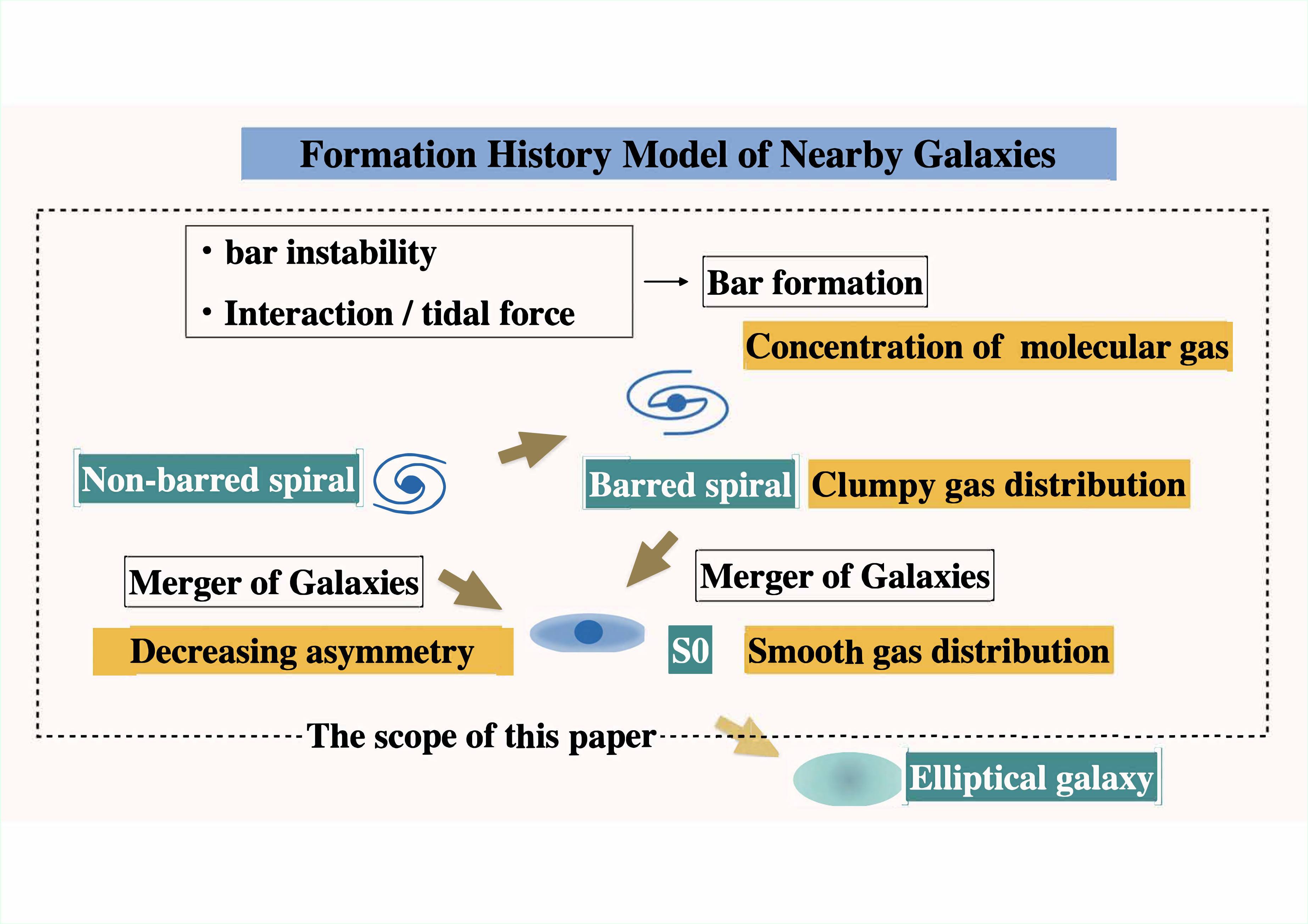
H_α

Chevance et al. 2020

Result 4

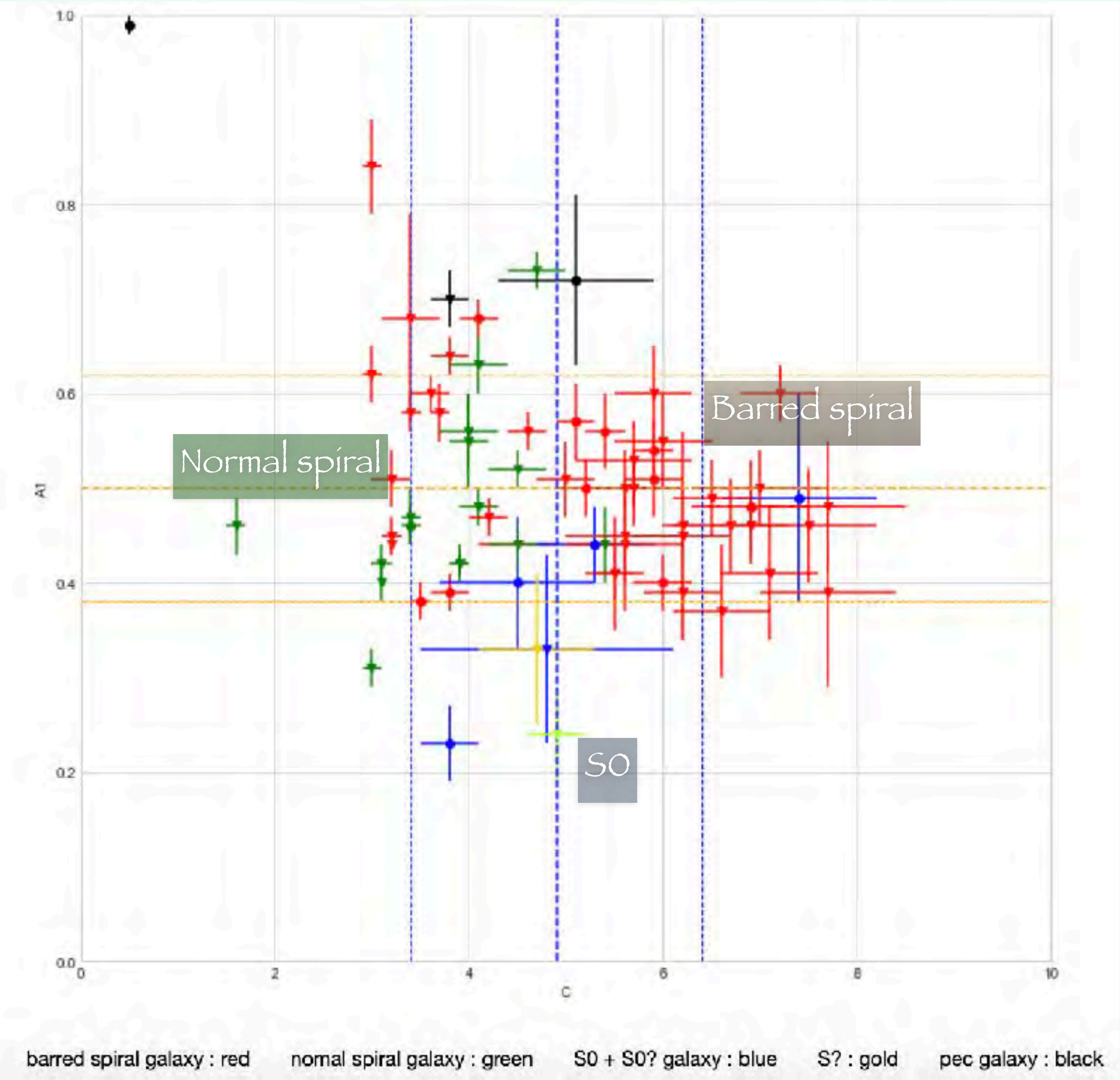
(4) The most interesting result of this study is the history of the distribution morphology of molecular gas in nearby disk galaxies.

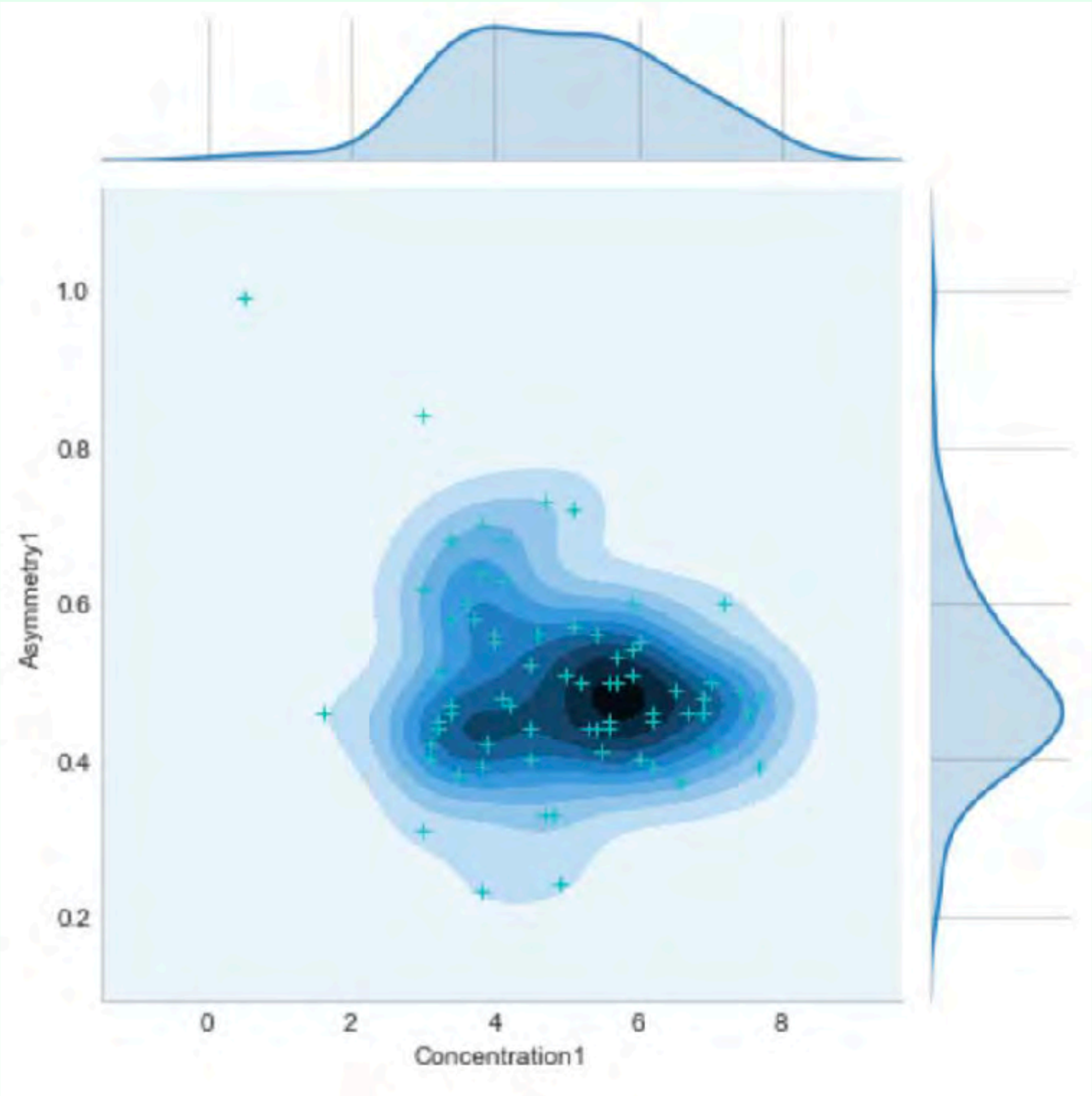




Result 4

Concentration(C) vs.Asymmetry(A)

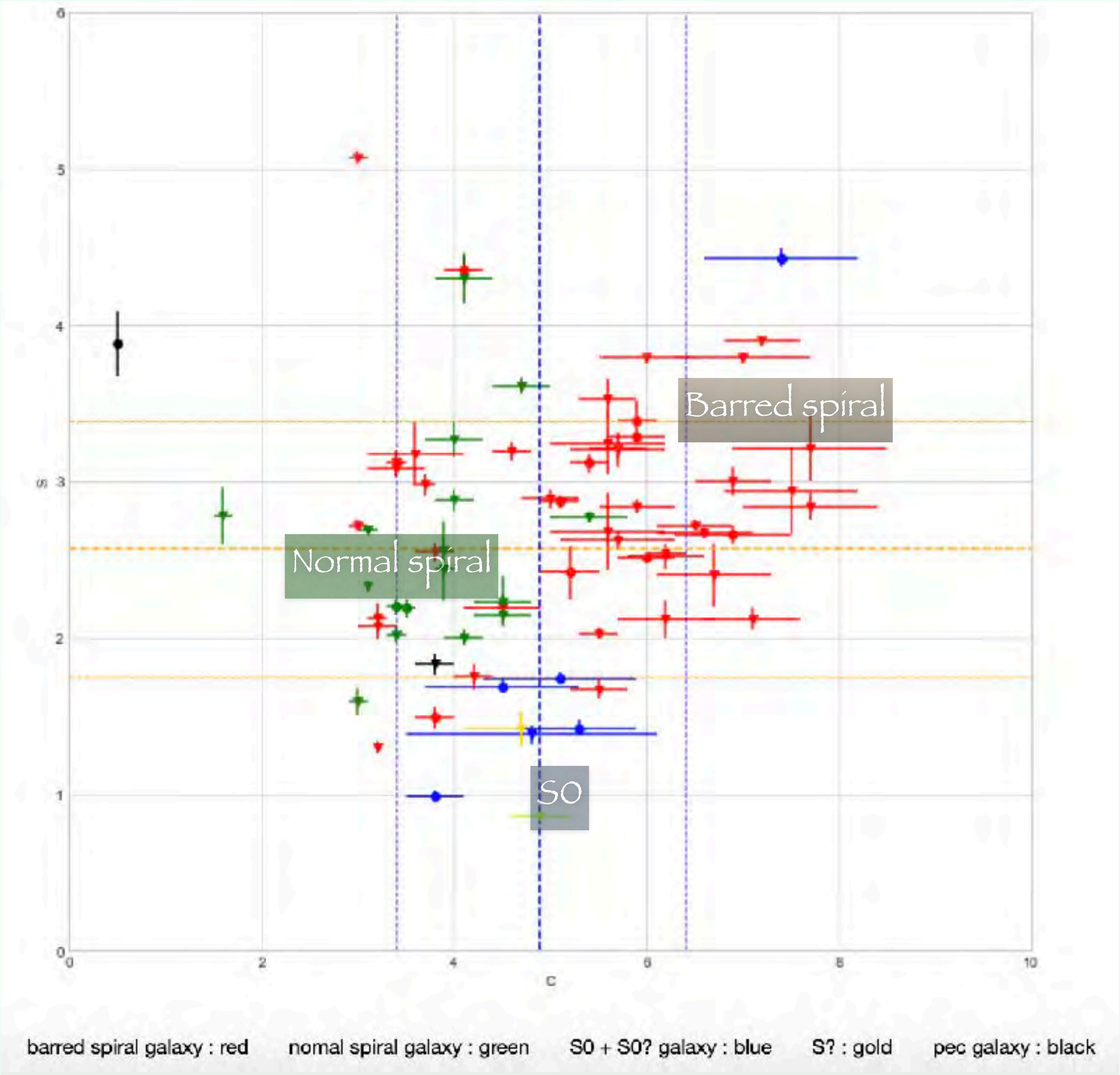


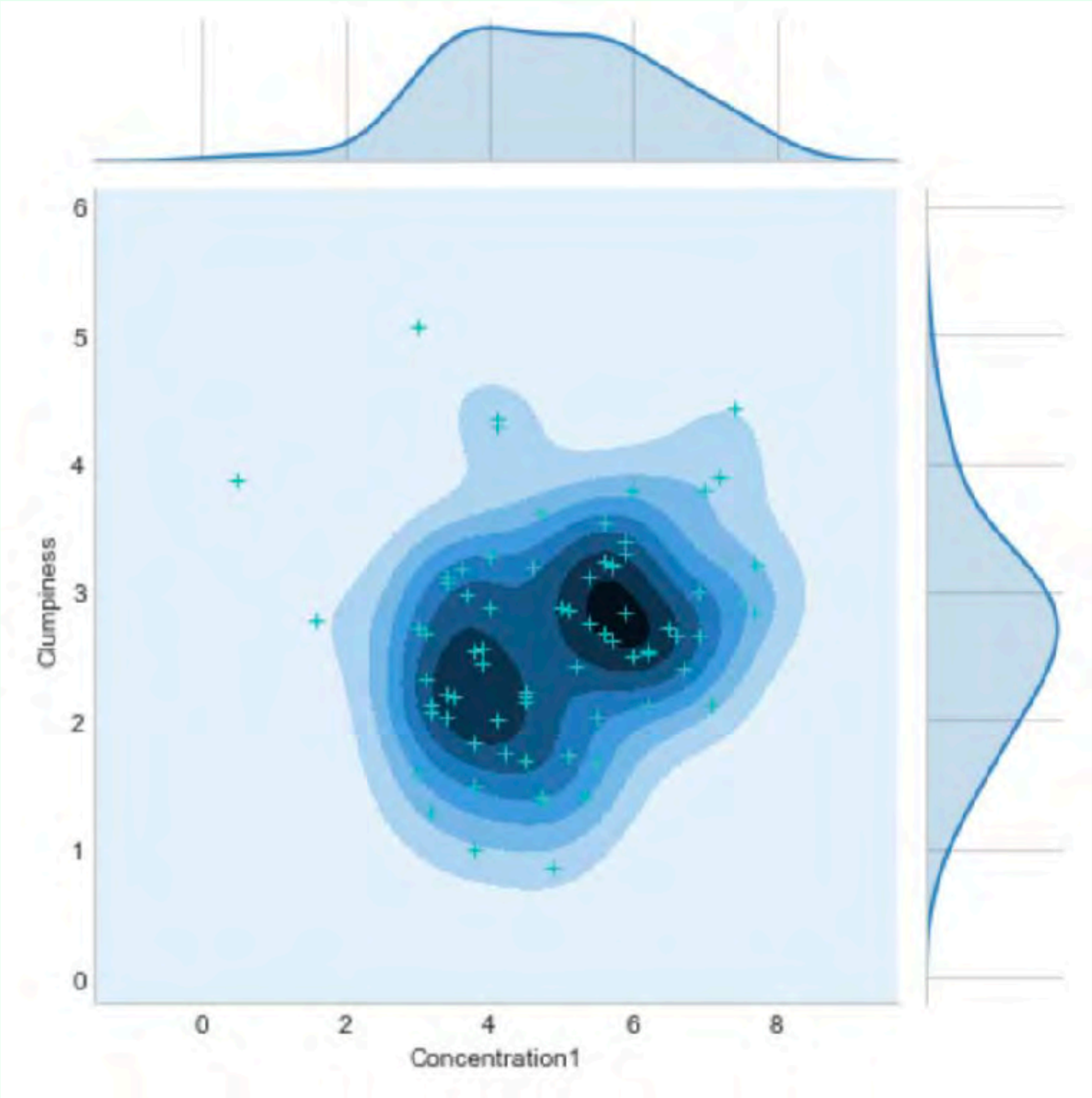


In this scatter plot, the galaxies tend to divide into three populations.

Result 4

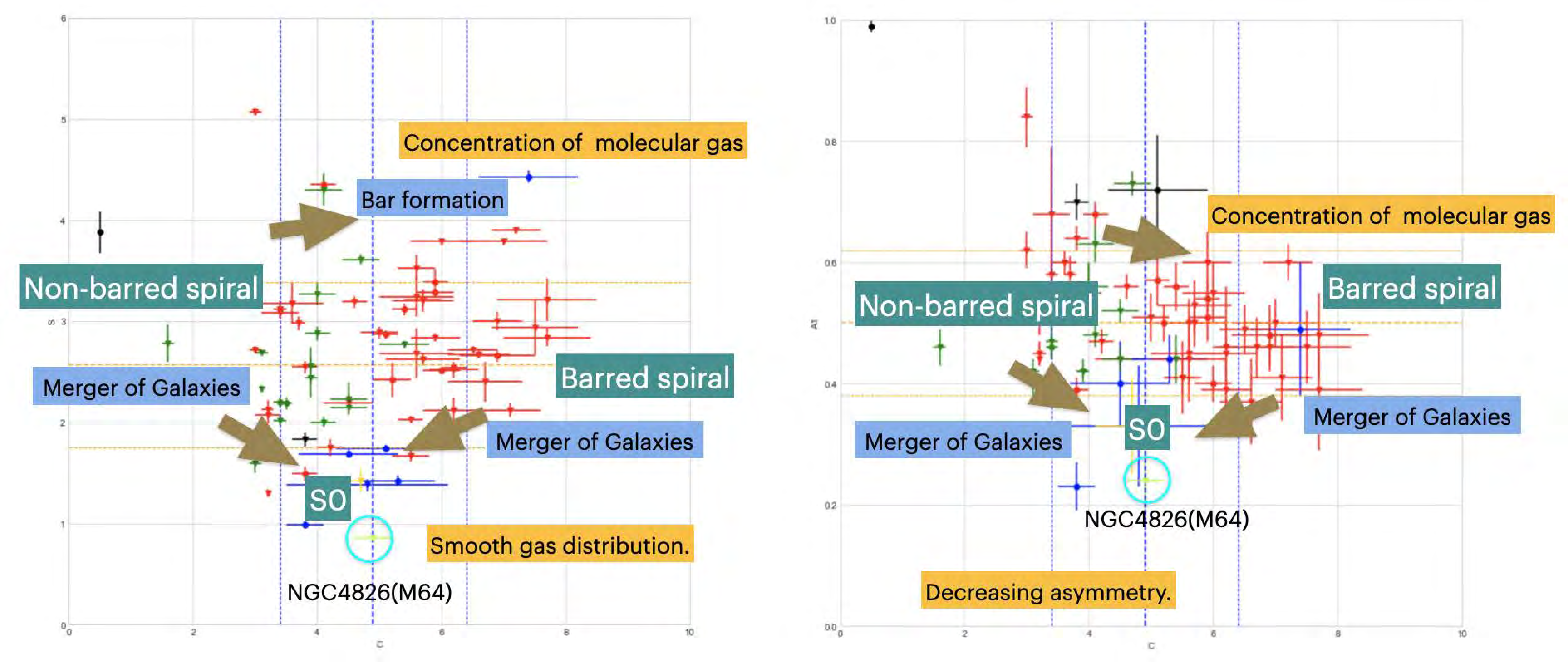
Concentration(C) vs.Clumpiness(S)



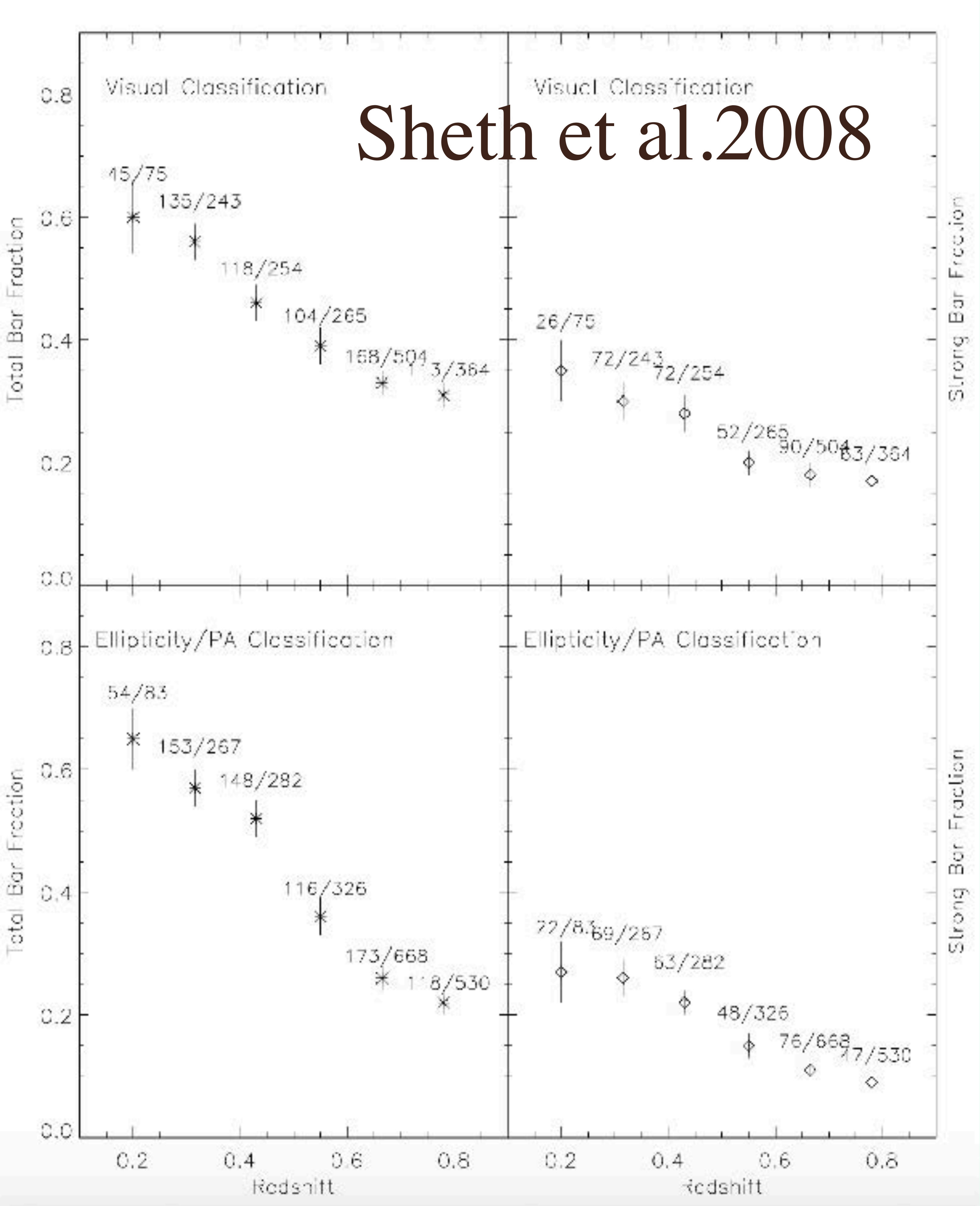


In this scatter plot, the galaxies tend to divide into three populations.

Result 4

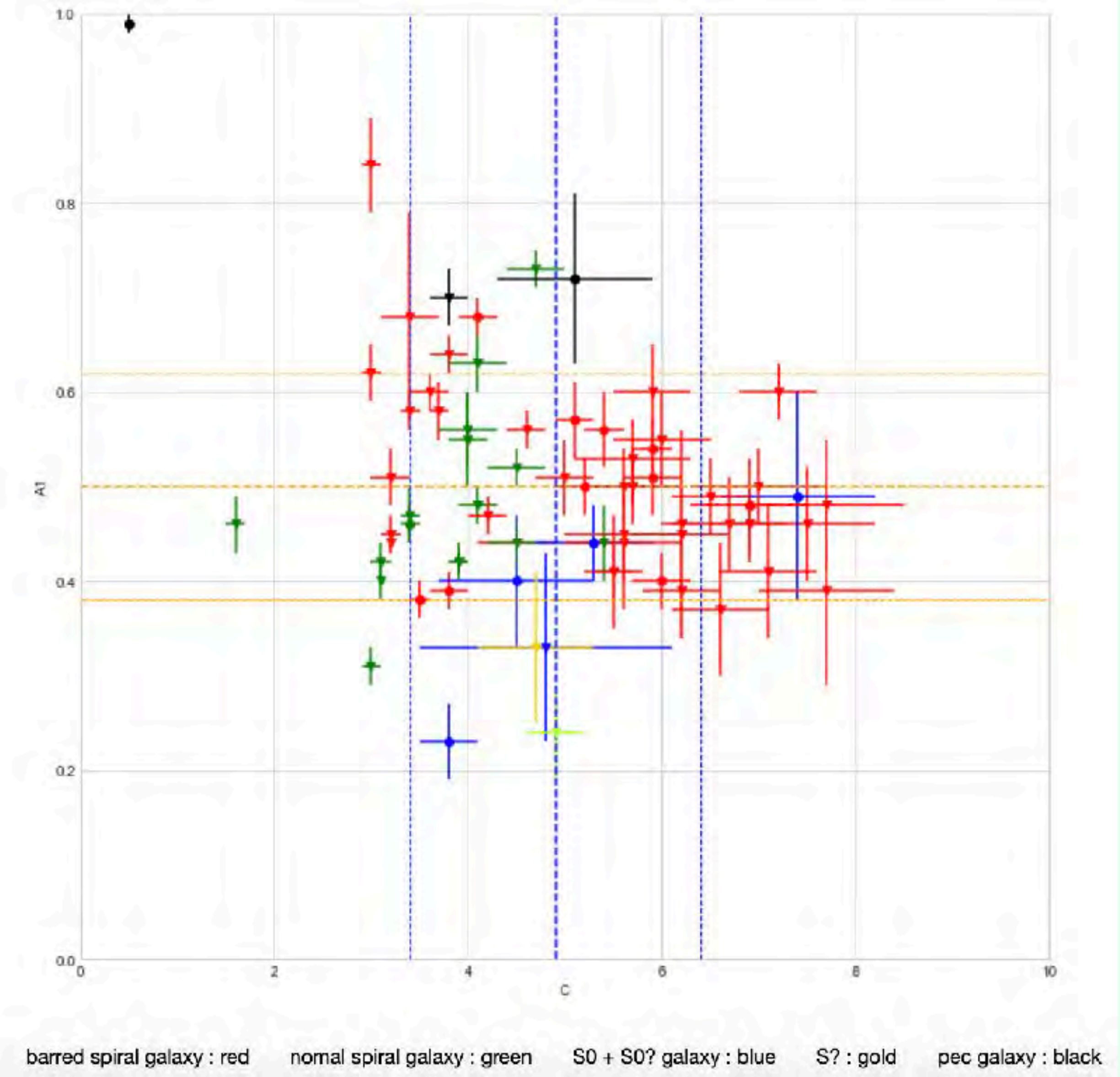

Concentration of molecular gas
Bar formation
Non-barred spiral
Barred spiral
Merger of Galaxies
Merger of Galaxies
SO
Smooth gas distribution.
NGC4826(M64)
Concentration of molecular gas
Non-barred spiral
Barred spiral
Merger of Galaxies
SO
Merger of Galaxies
NGC4826(M64)
Decreasing asymmetry.

Result 4



The number of barred galaxies is increasing with the evolution of galaxies.

The result of our research provides crucial data to consider the strength of the bar structure and its formation factors.



Evolution of the bar fraction as a function of redshift in equal bins from z = 0.0 to z = 0.84, out to a look-back time of 7 Gyr.

Result 4

NGC 4826(M64)

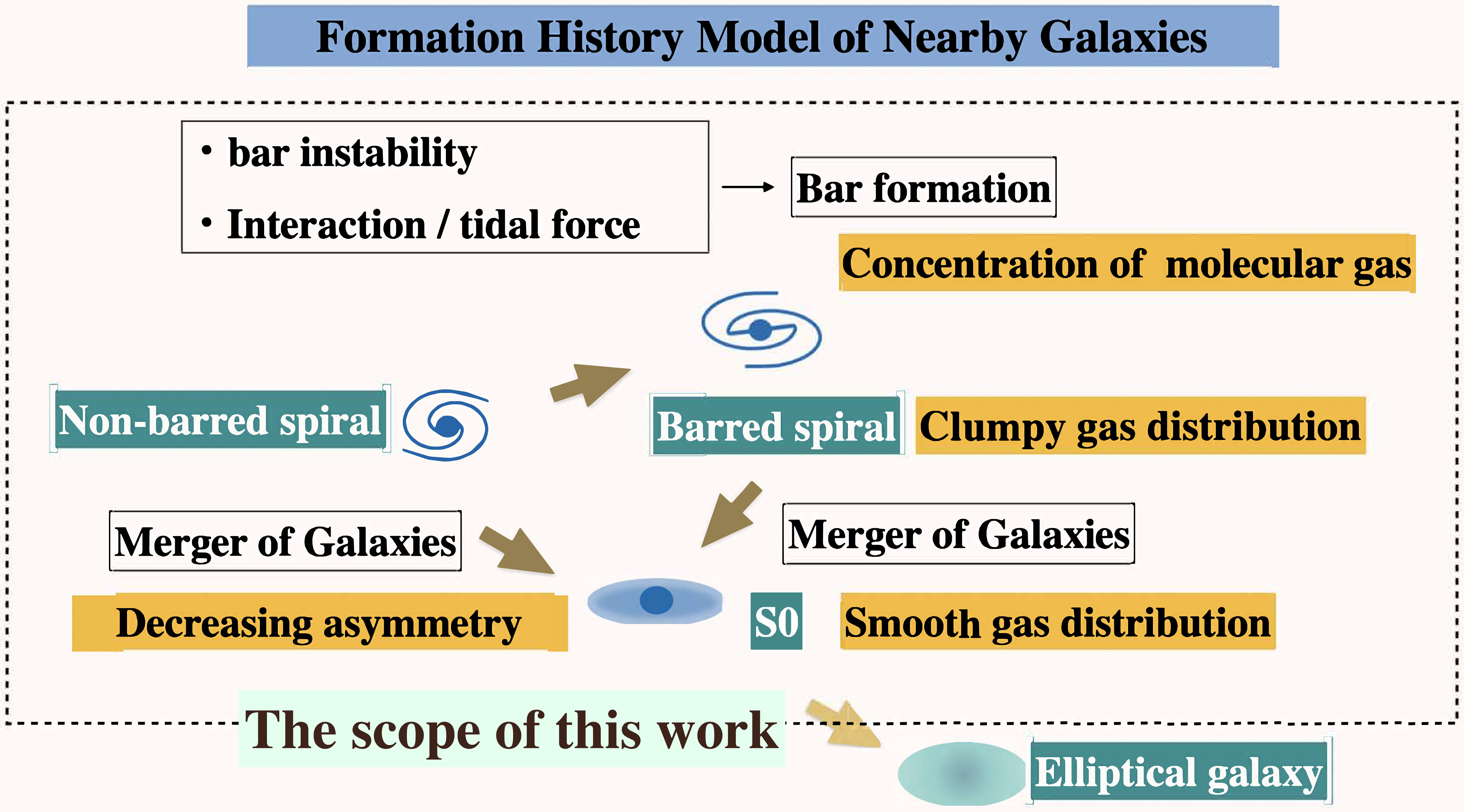
The transition from SA to S0 due to galaxy merger

Several researchers have worked on NGC4826, which has clear evidence of a merger.

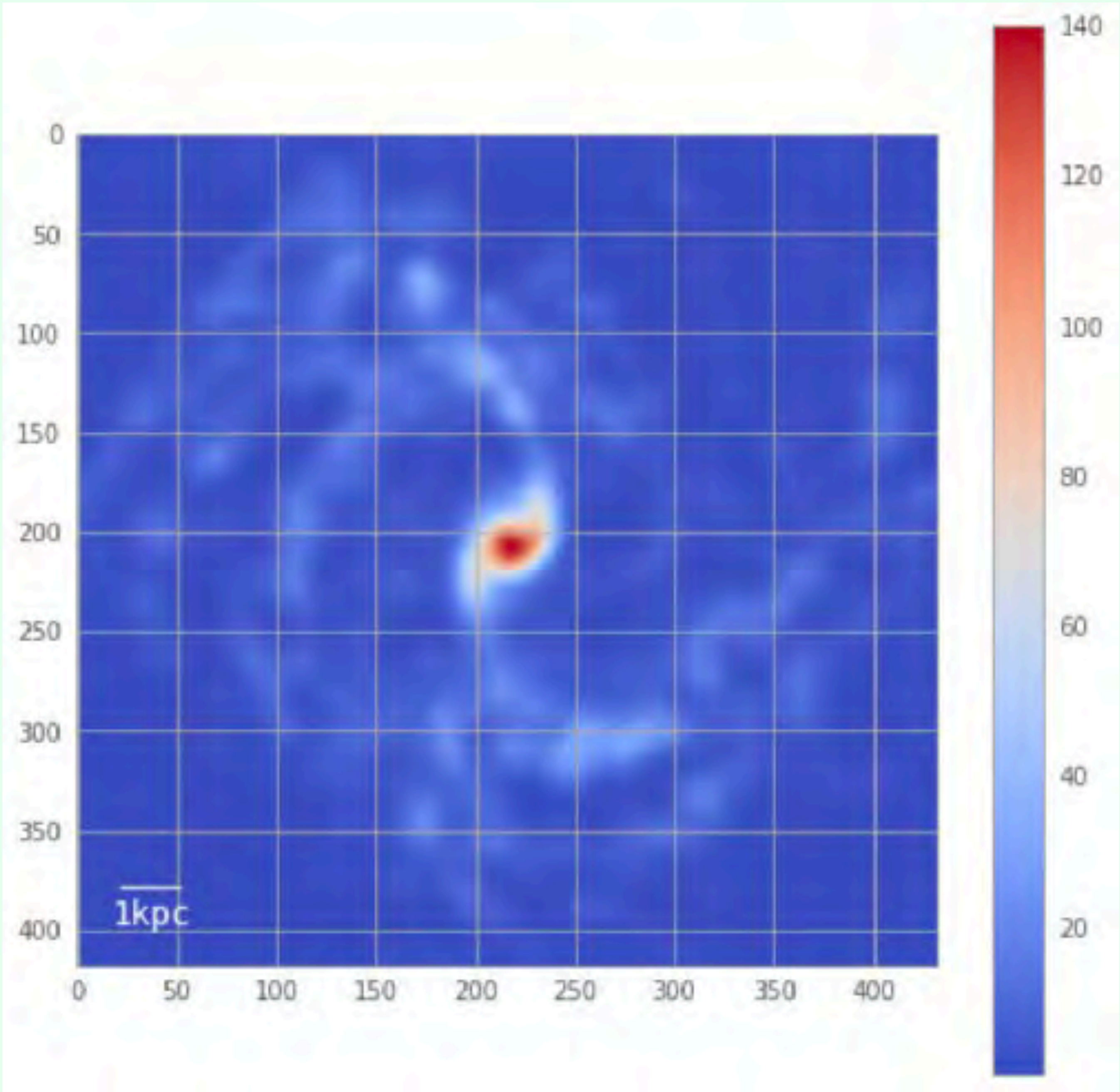
Watkins et al.2016

surface brightness profile. The recent merger event in M64 appears to have disrupted its gas disk and truncated star formation in all but the inner few kiloparsecs, leading to the galaxy's very flat and red color profile. M64 thus appears to be undergoing a transition from a spiral to an S0 galaxy, an interesting example of merger-driven galaxy transformation in an otherwise isolated environment.

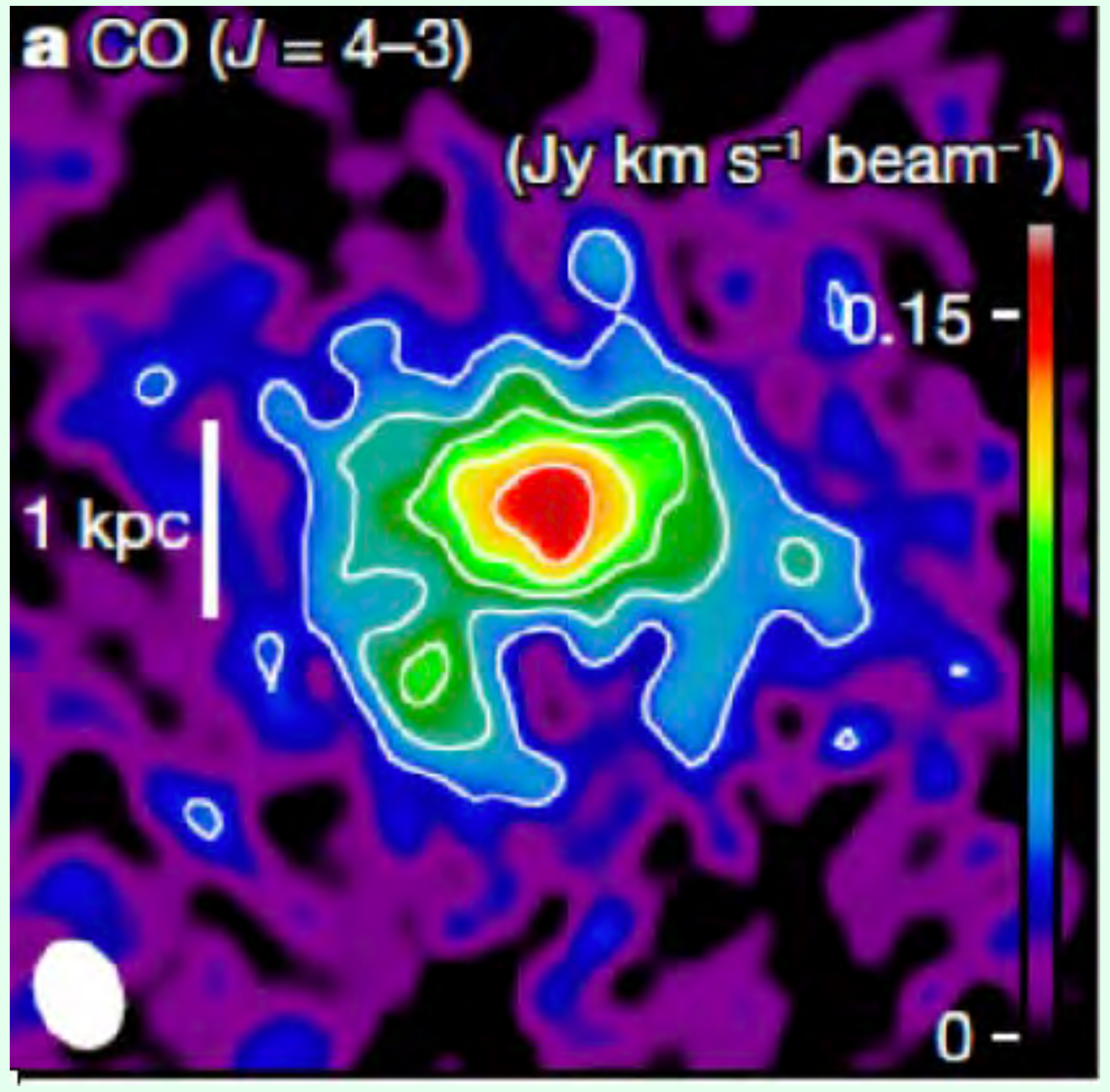
Result 4


Formation History Model of Nearby Galaxies
• bar instability
• Interaction / tidal force
Bar formation
Concentration of molecular gas
Non-barred spiral
Barred spiral
Clumpy gas distribution
Merger of Galaxies
Merger of Galaxies
Decreasing asymmetry
S0
Smooth gas distribution
The scope of this work
Elliptical galaxy

Finally, this study is not limited to nearby galaxies. It has the potential to be applied to high-redshift galaxies as well, depending on future spatial resolution.



600pc



550pc

Tadaki et al. 2018 nature