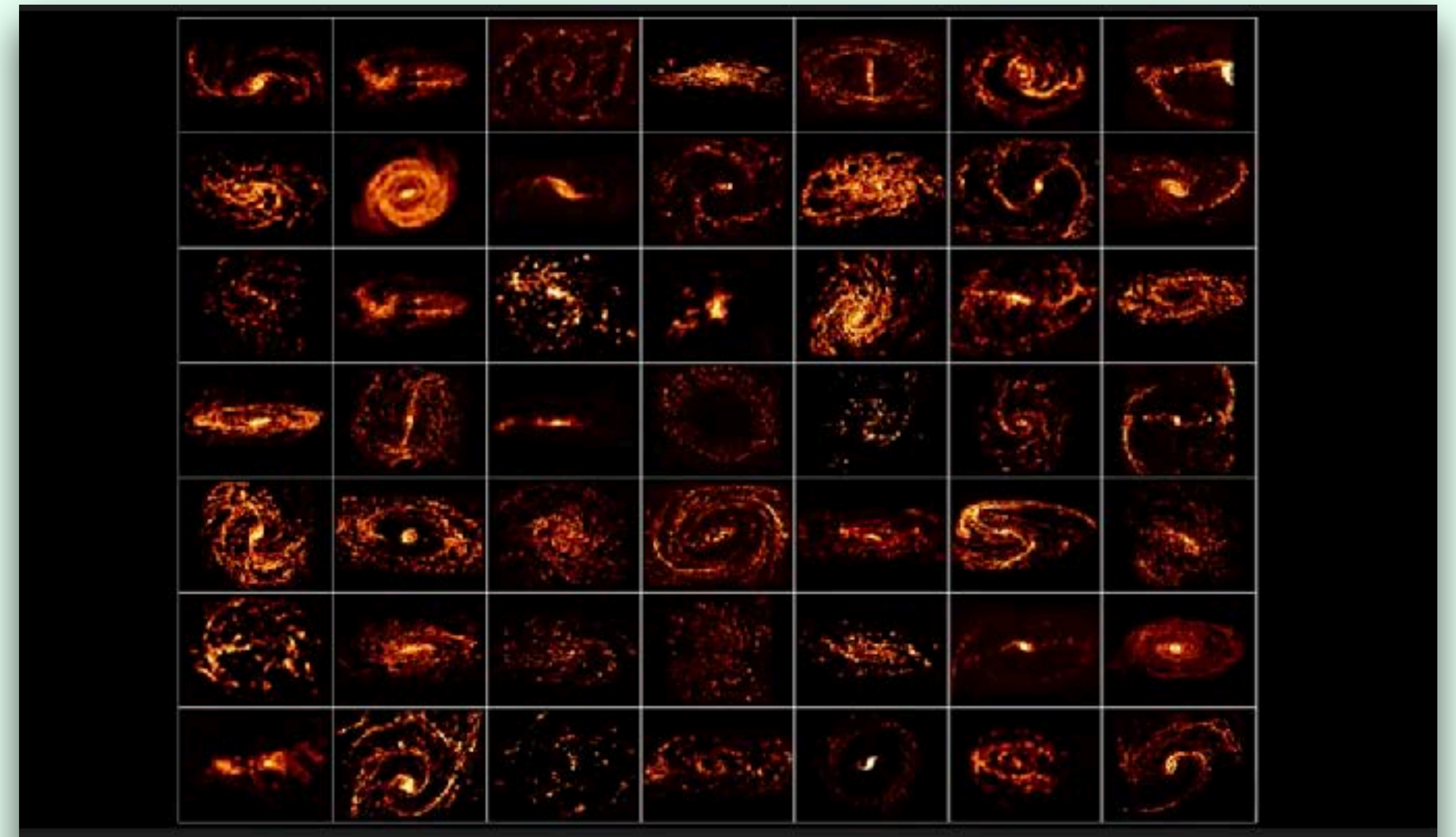
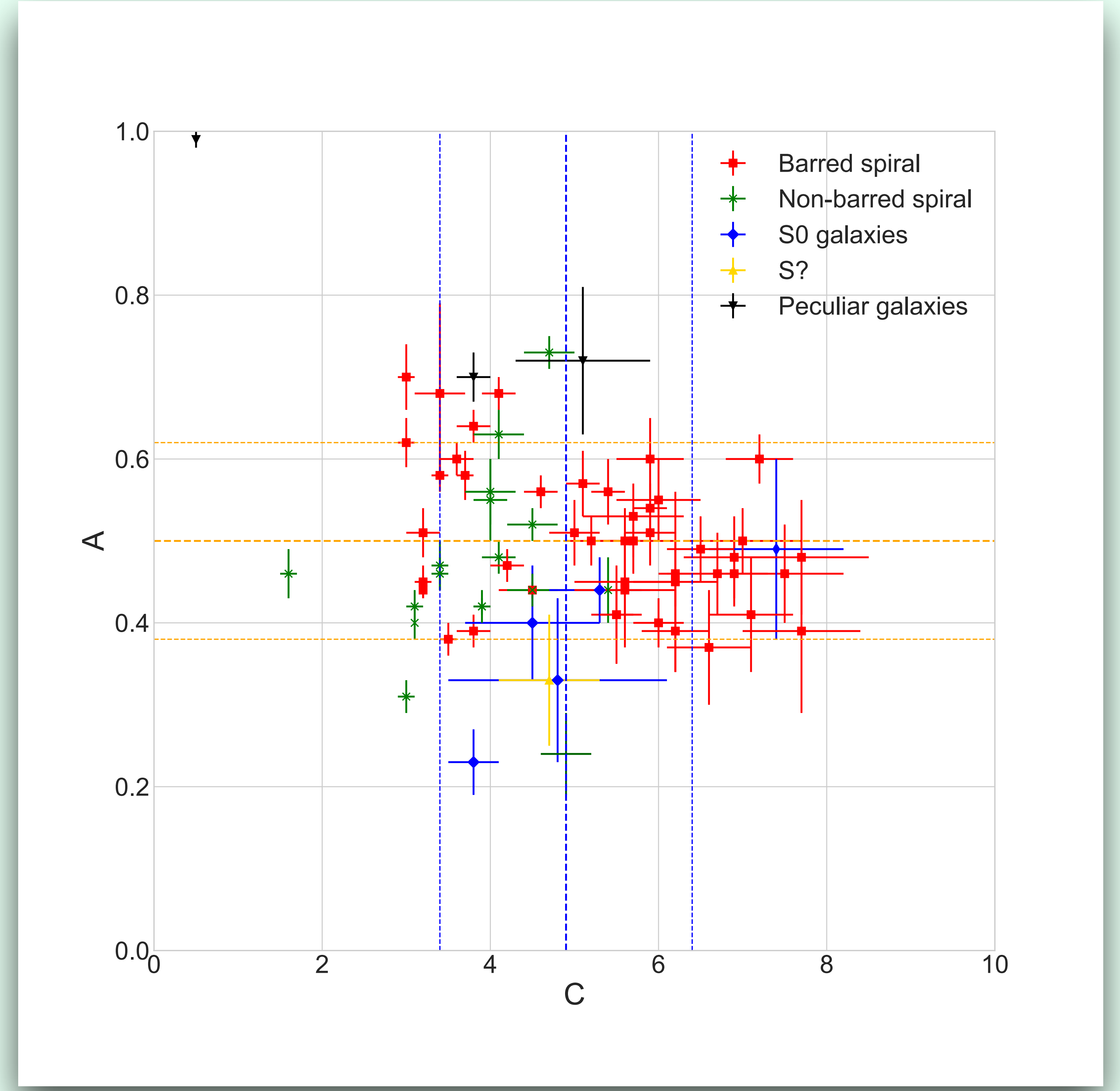
Quantitative and statistical analysis of the molecular gas morphology in the nearby star-forming galaxies



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



Credit: ALMA (ESO/NAOJ/NRAO), A. Marinkovic/X-Cam

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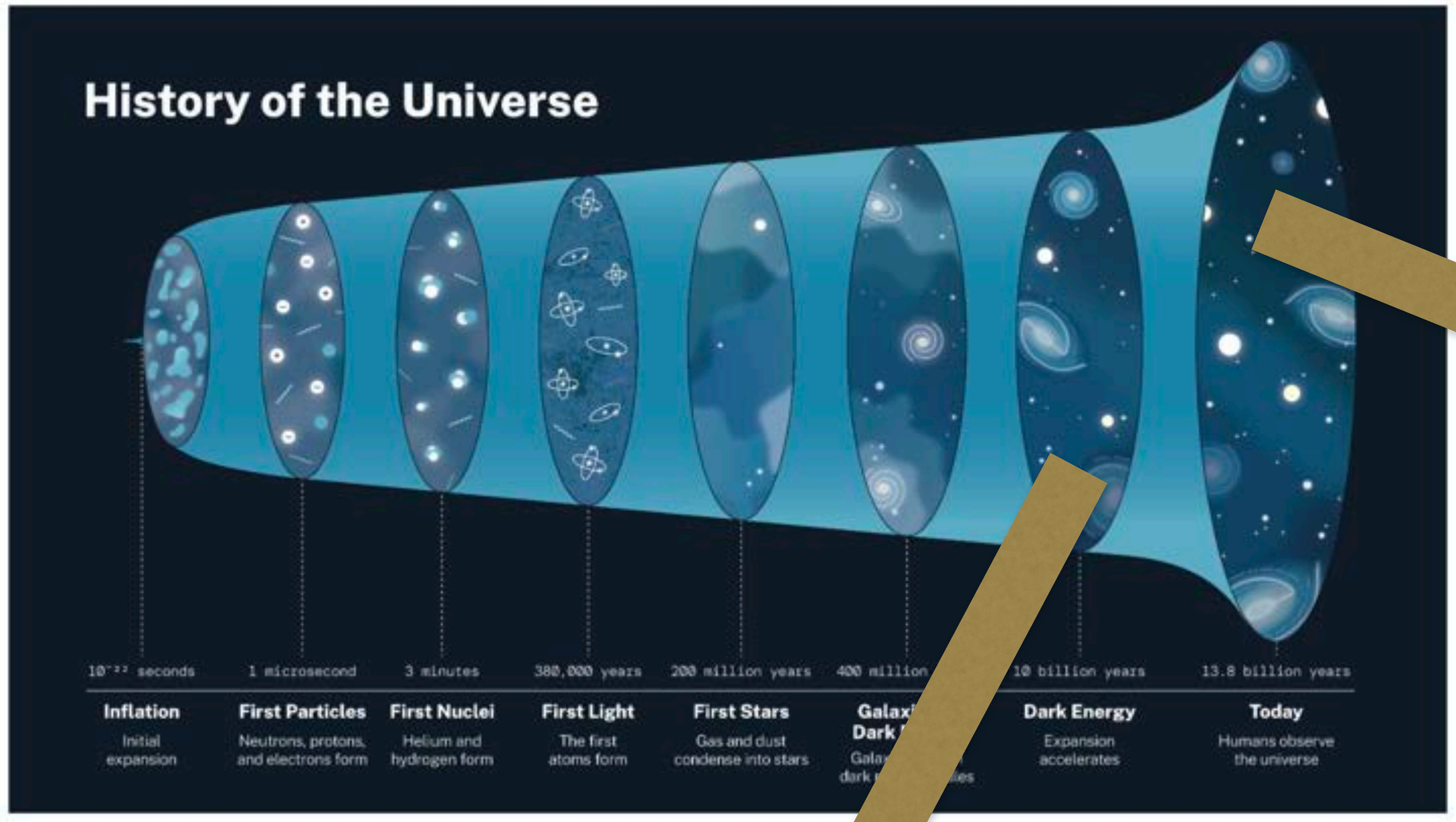
Tomonaga Center for the History of the Universe

December 18, 2023

The process of galaxy evolution remains unresolved.

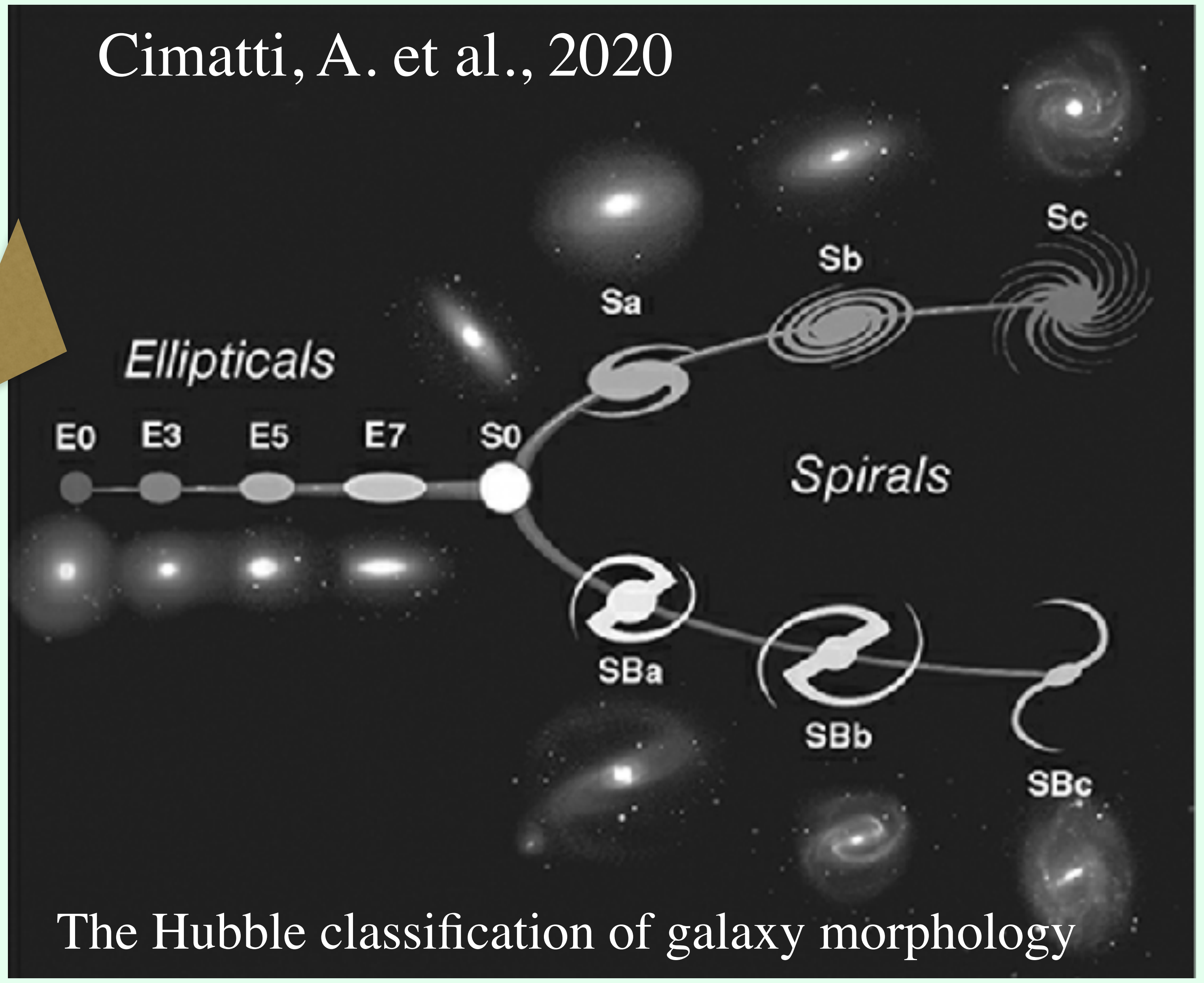
Introduction



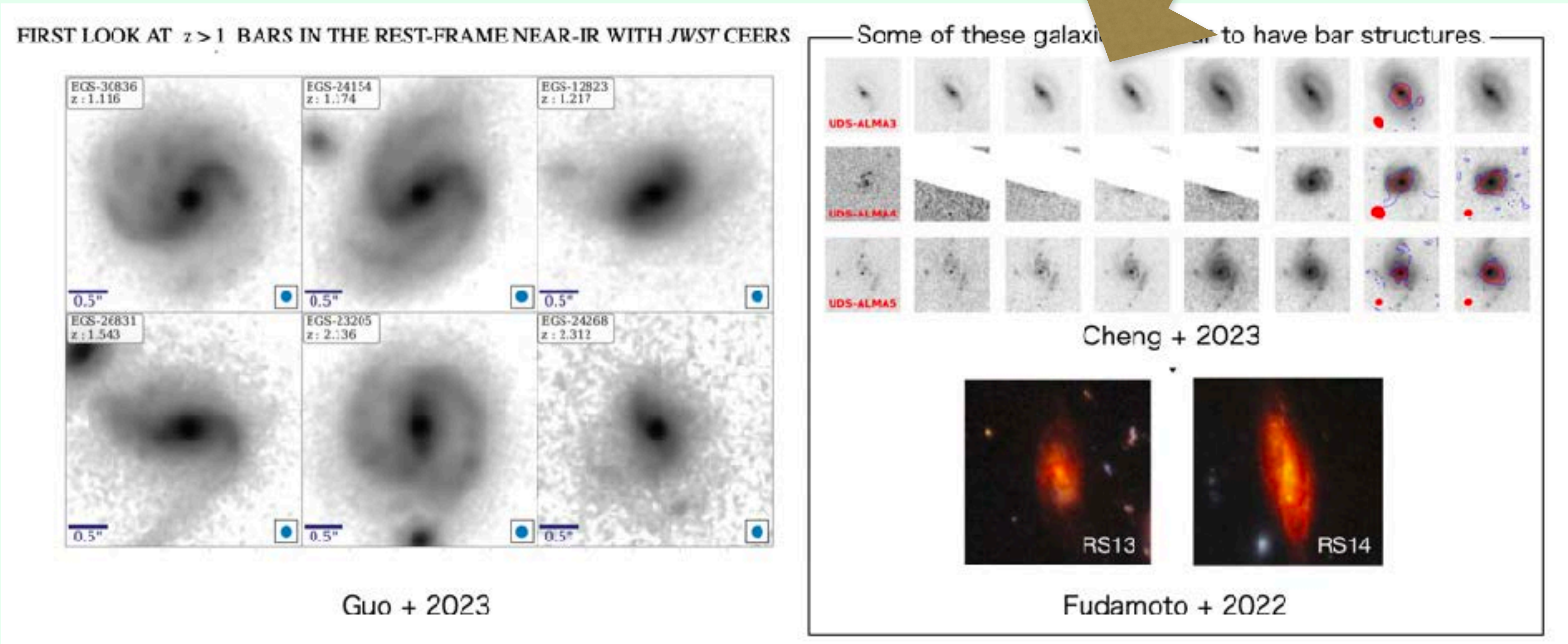
Credit: NASA

Published: December 20, 2022

$z \sim 0$



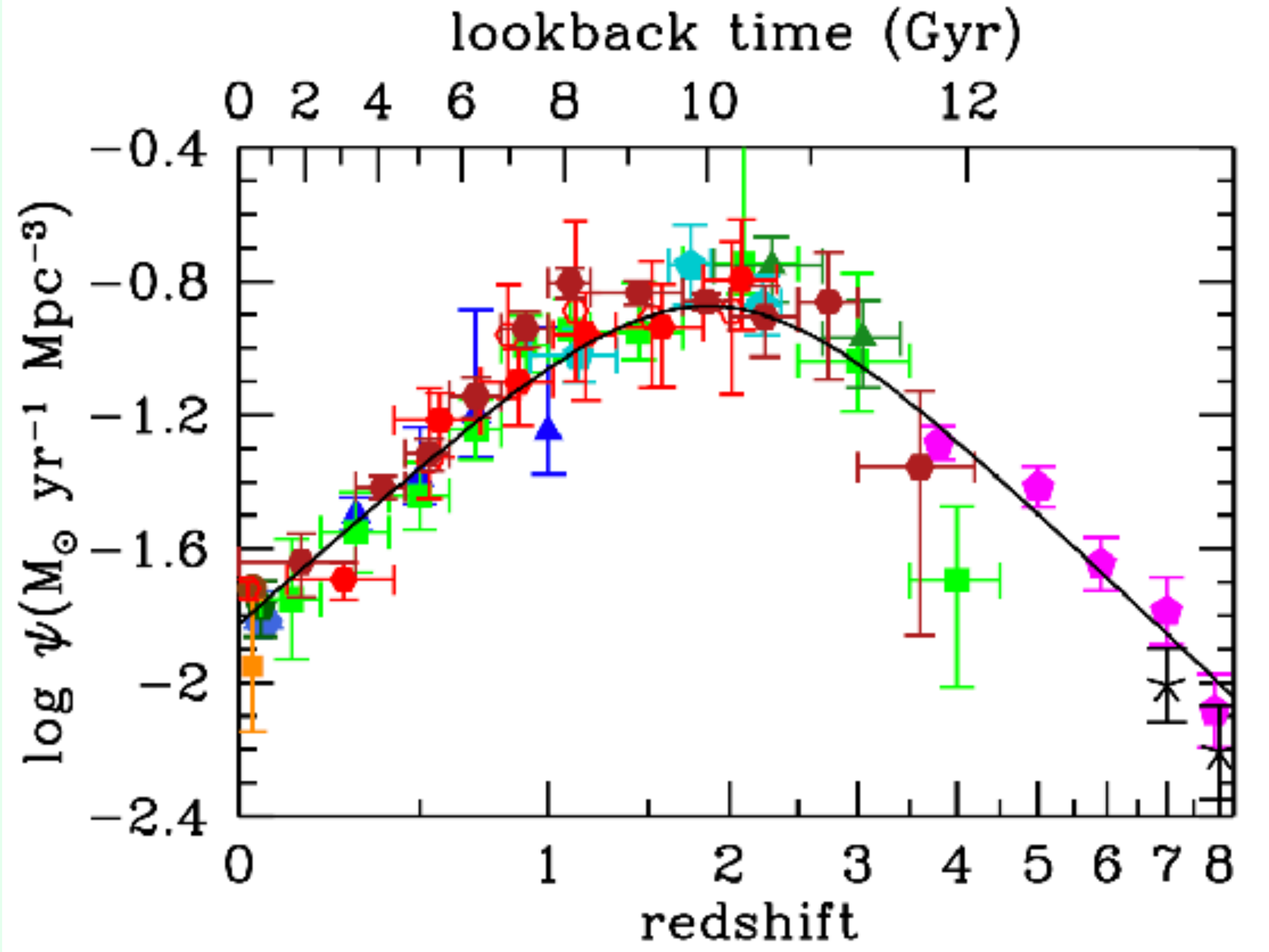
$1 < z < 3$



Guo + 2023

Cheng + 2023

Fudamoto + 2022

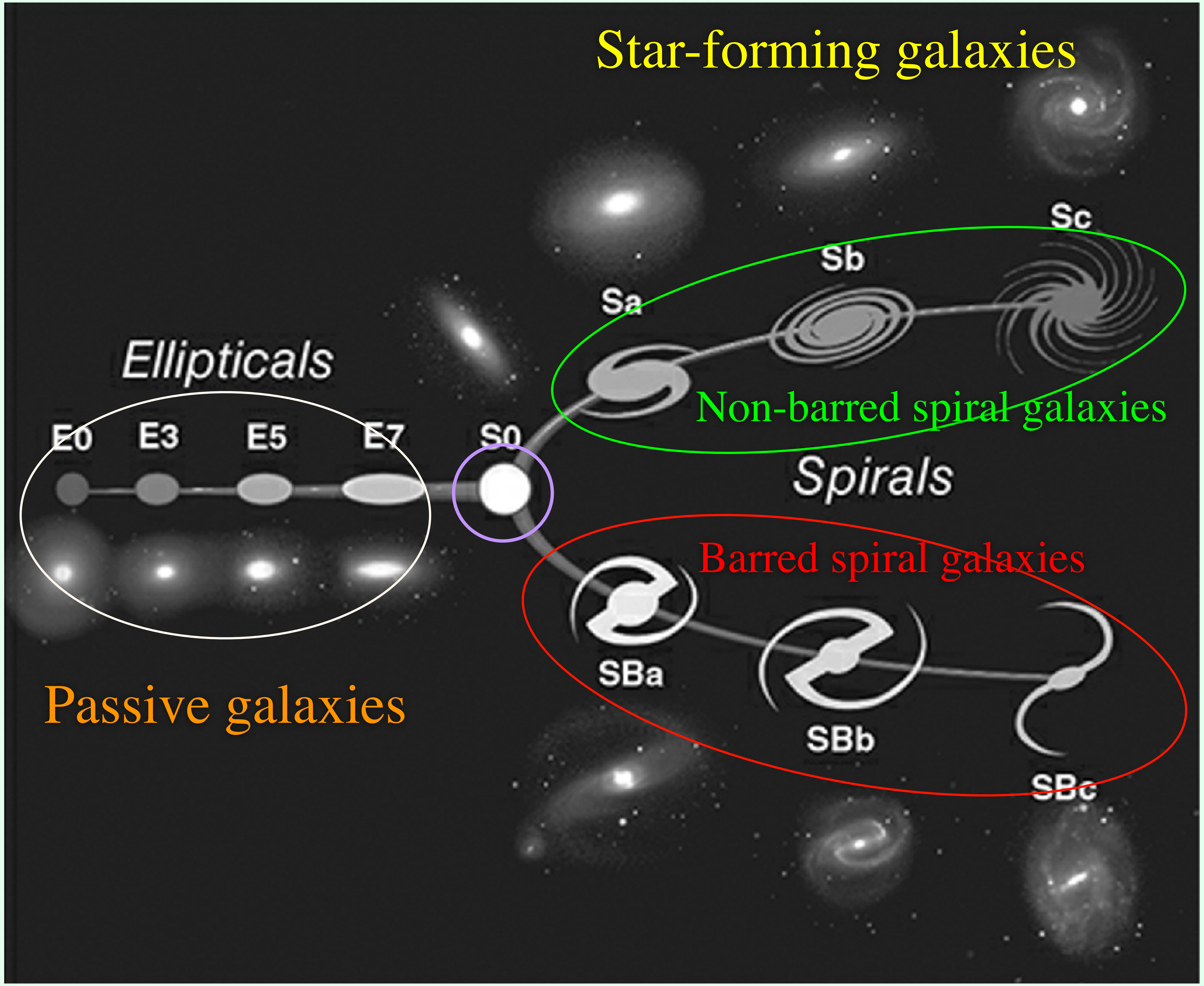


Madau & Dickinson 2015

The Age of JWST in Astronomy

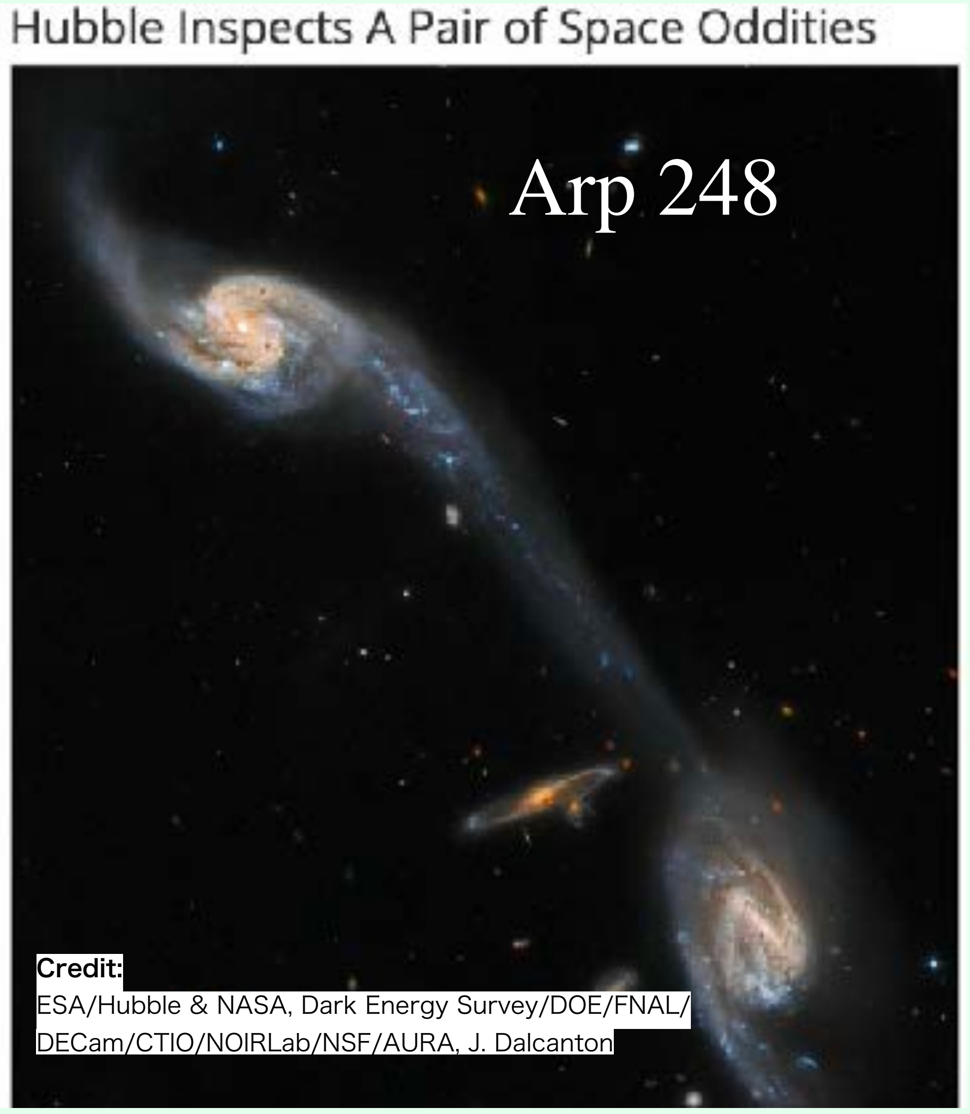
Introduction

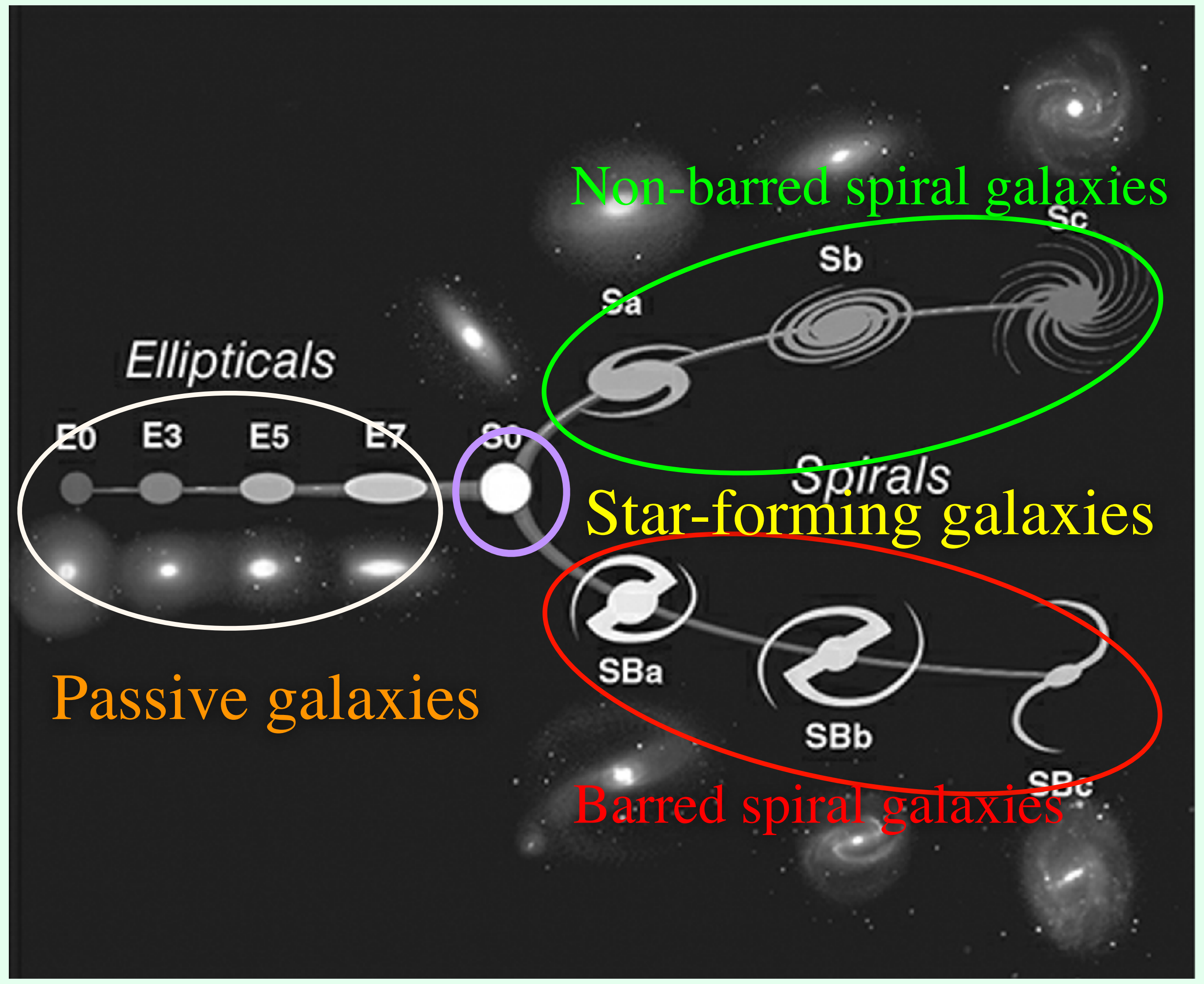
The process of galaxy evolution remains unresolved.



Introduction

The diverse shapes of the galaxy tell a lot of information.





Qualitative morphology is not sufficient to explore galaxy evolution.
Quantitative morphology is needed.

> We want to understand how galaxy populations are related to each other and to their formation histories (right panel).

Introduction

Can we classify them more quantitatively?

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

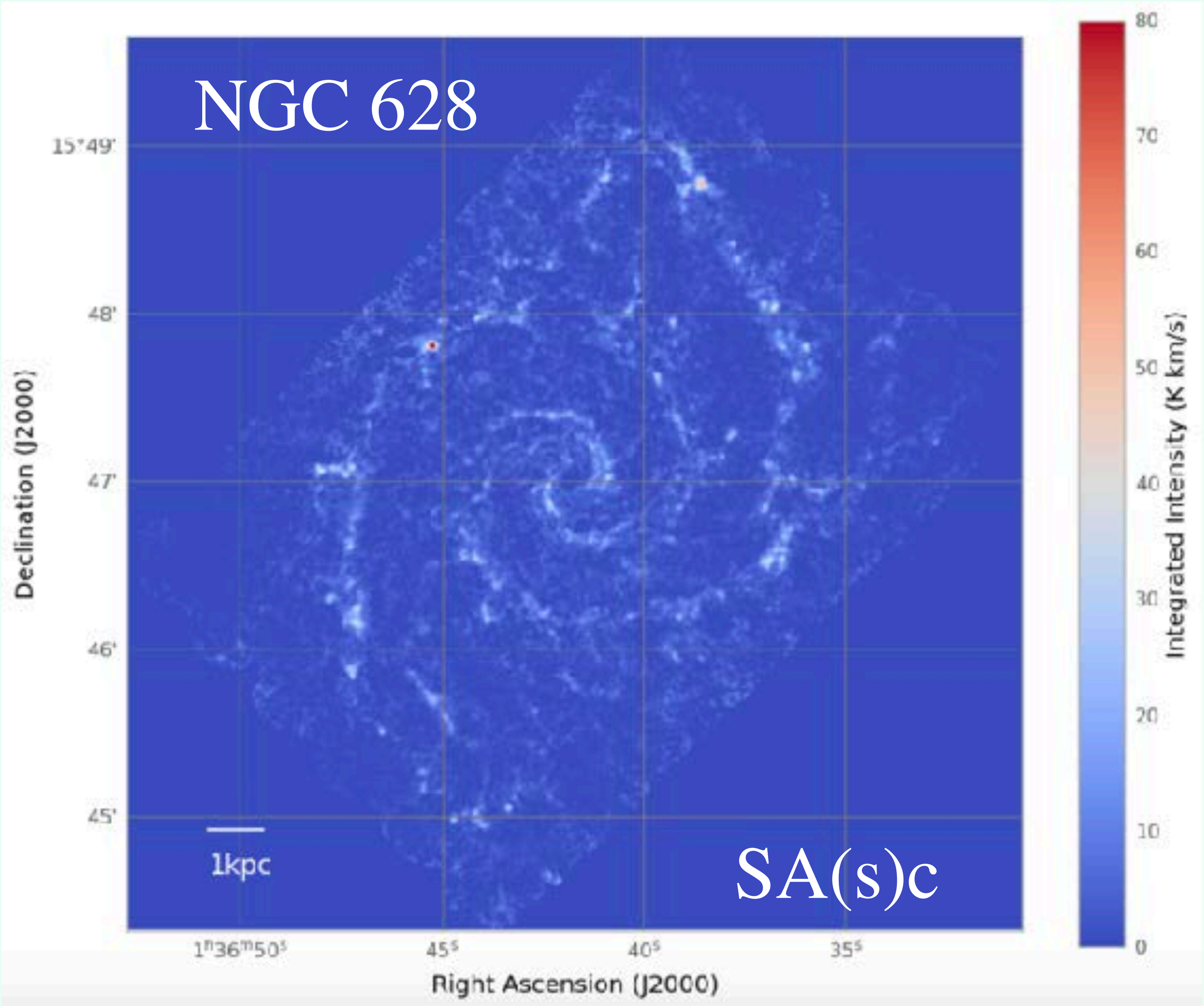
> On the other hand, quantitative analysis of the distribution morphology of molecular gas in nearby galaxies using radio data essential for the study of galaxy evolution has not been sufficiently carried out due to the lack of spatial resolution.

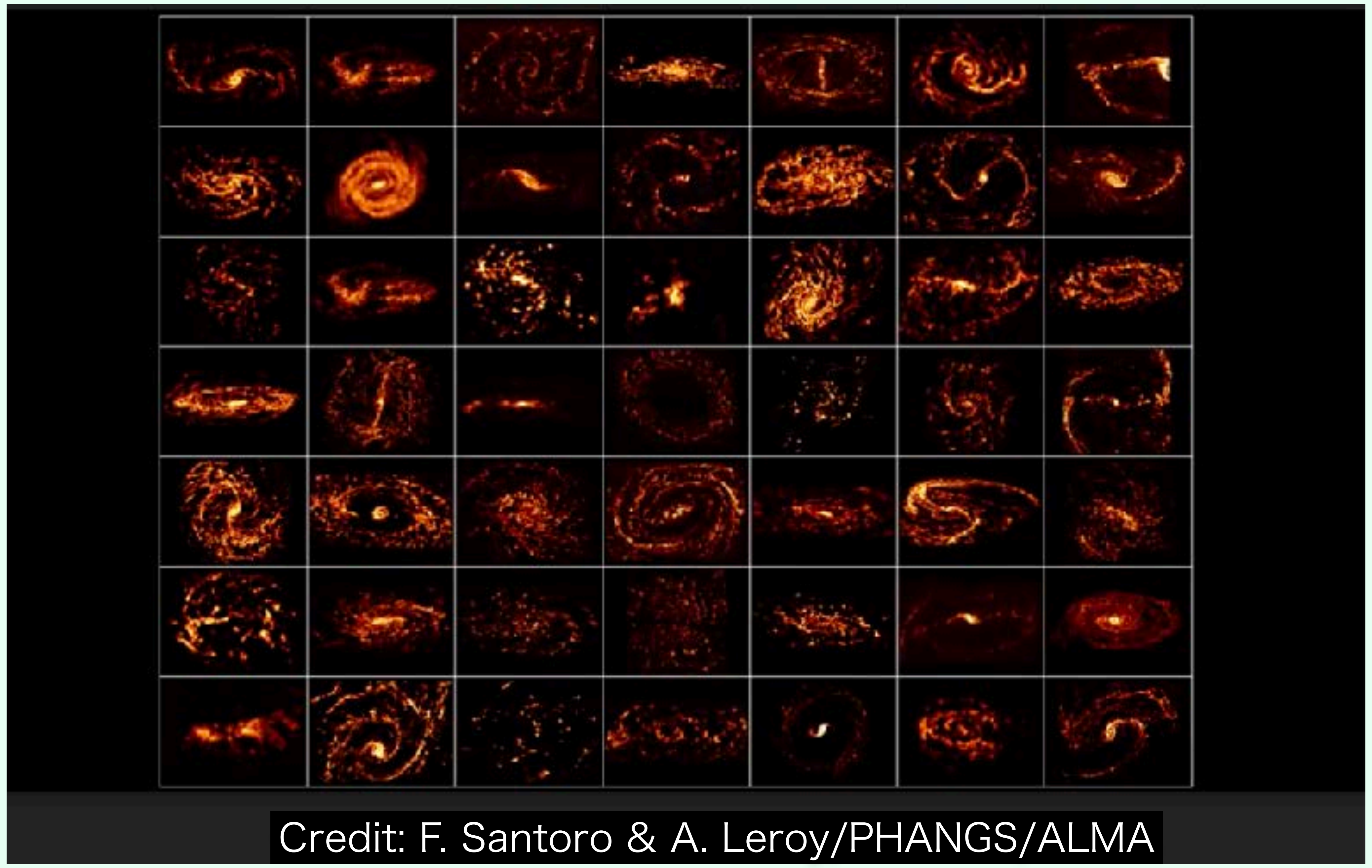
>However, with the operation of ALMA, a large amount of high-resolution molecular gas observation data has been accumulated. This has made it possible to do equivalent to Conselice's research in radio astronomy.

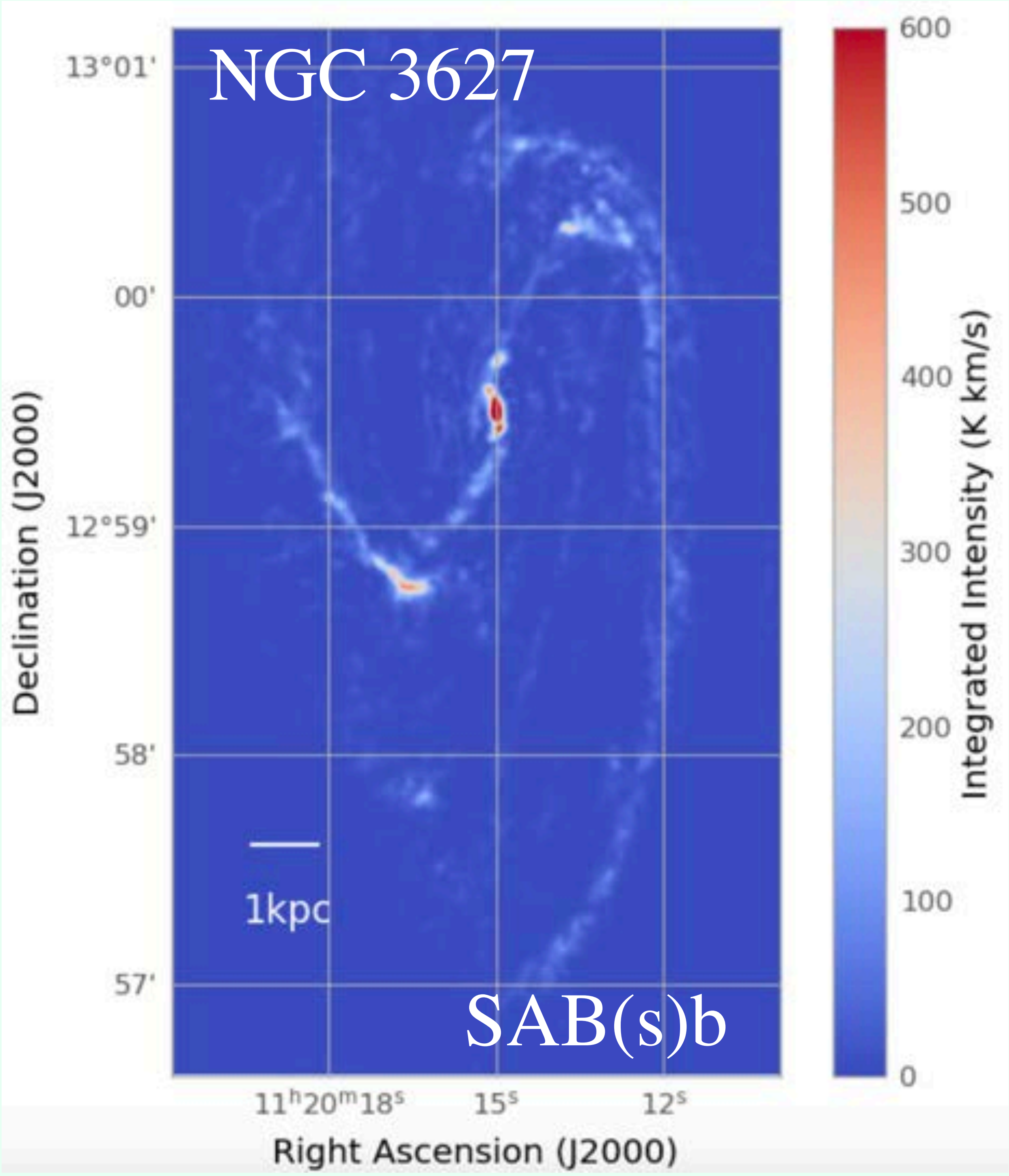
Introduction

We want to obtain clues to the evolutionary process of nearby galaxies.
For this purpose, quantitative classification of morphology by **molecular gas** is essential.

This is because star formation is a principal factor in the formation and evolution of galaxies, and molecular gas is the material for star formation.







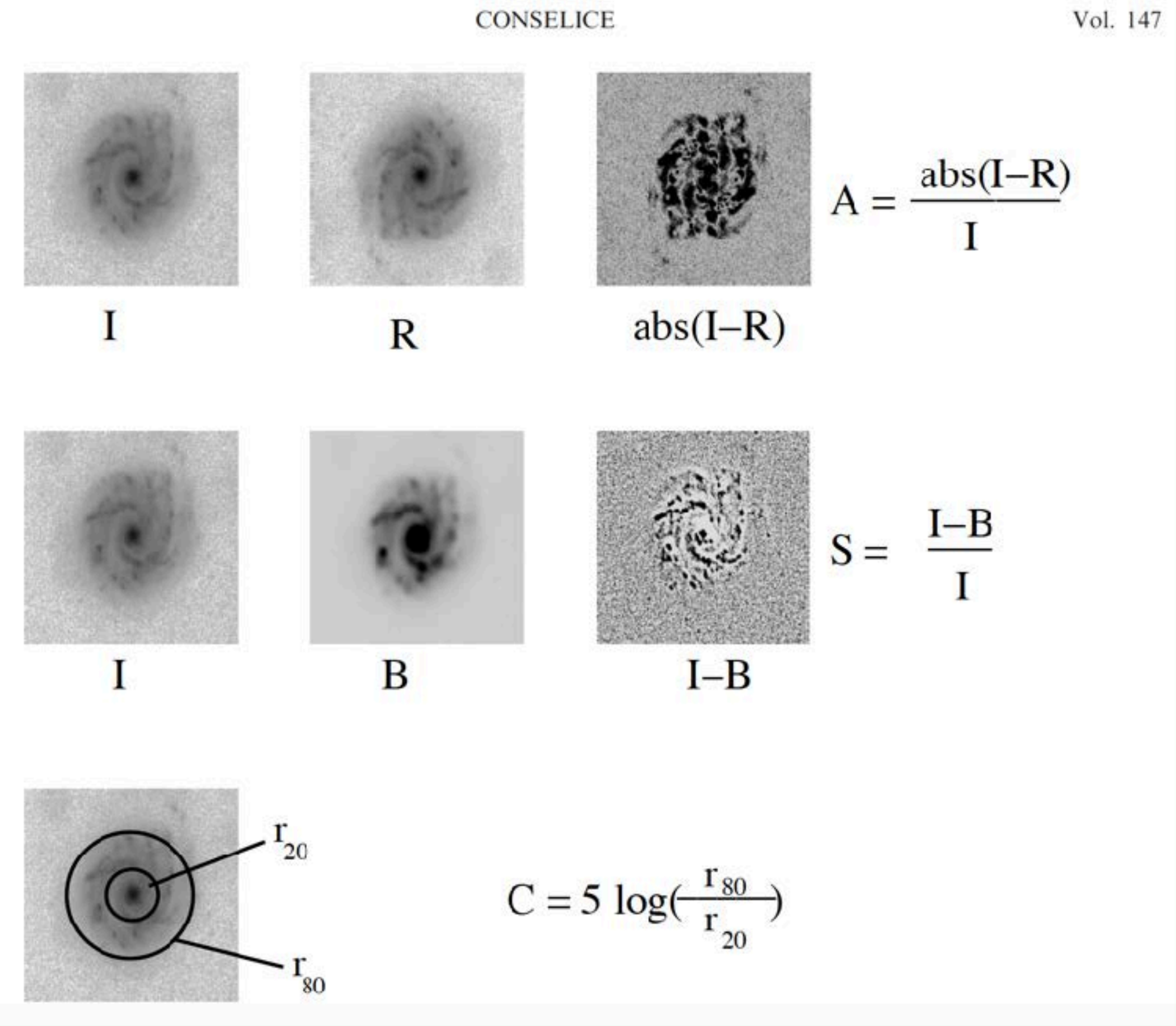
Method

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)

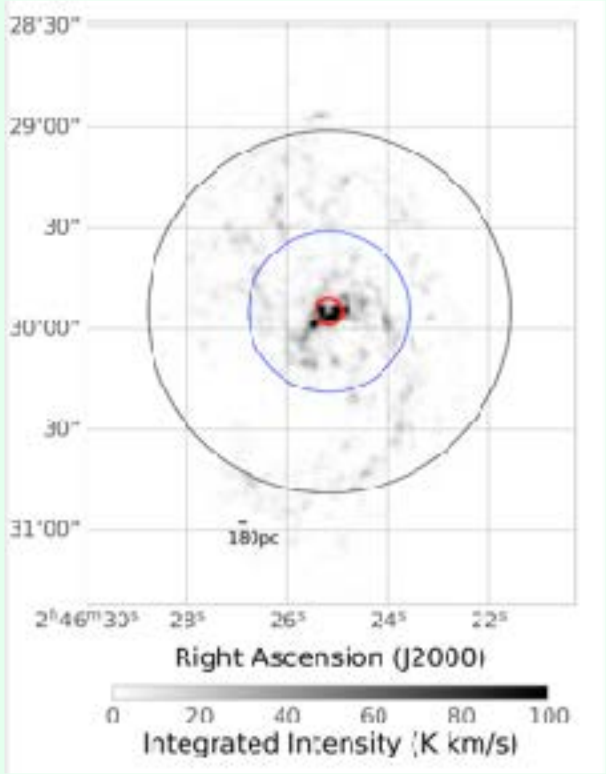
$$S = \frac{10 \times (I - I^{\sigma})}{I}$$

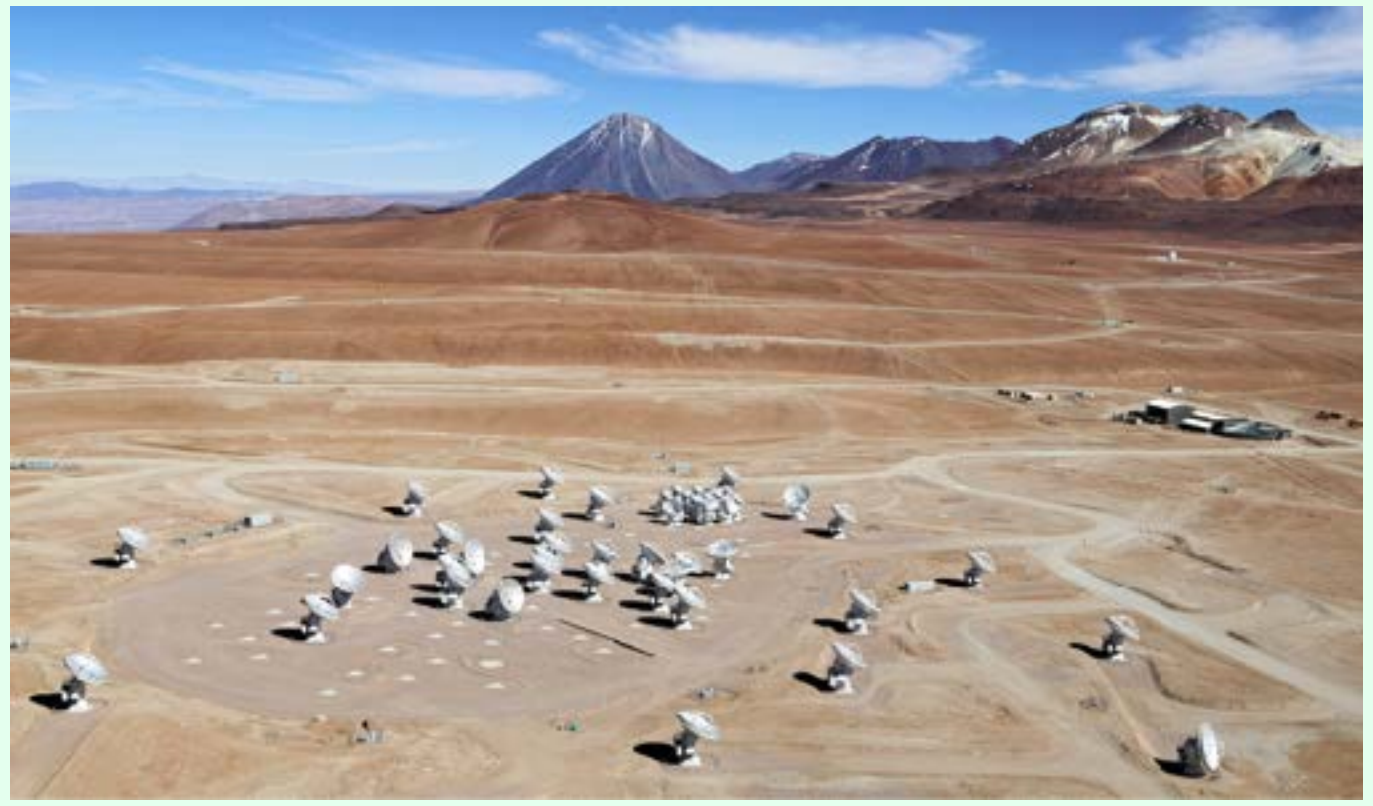
$$\sigma = 0.3 \times r \ (\eta = 0.2)$$

r : Petrosian radius

Method

Modified CAS (Conselice 2003) parameters





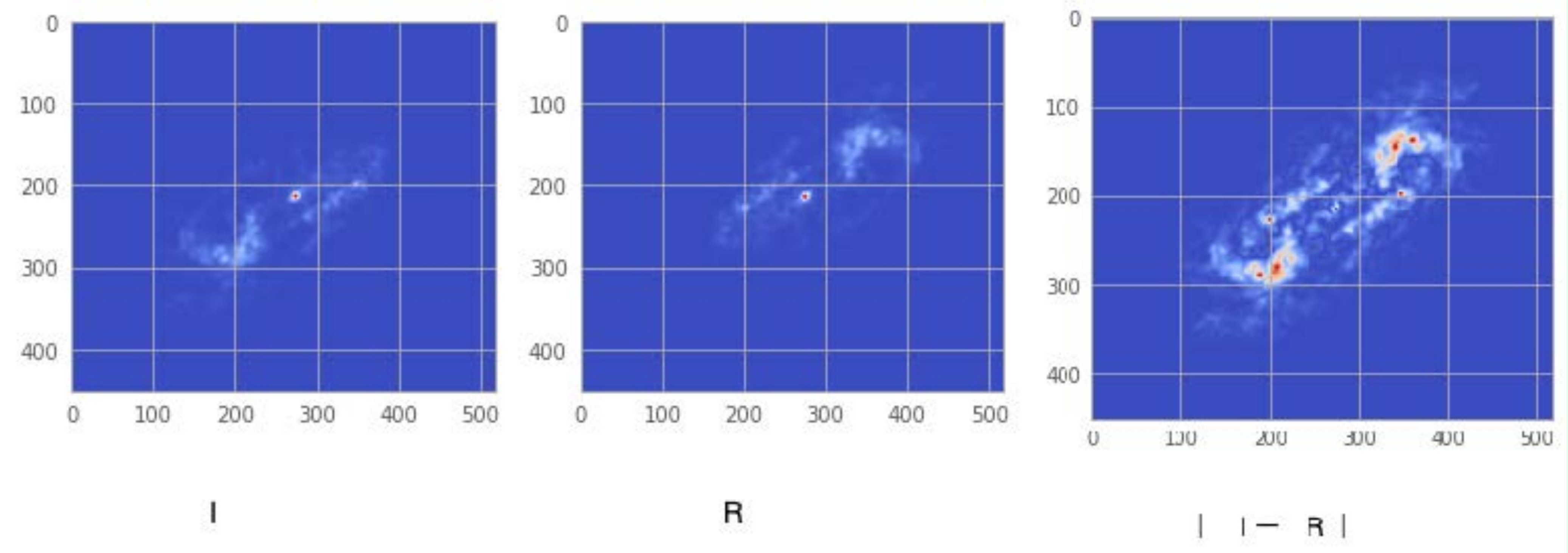
Concentration (C)

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

Central concentration of molecular gas

Asymmetry (A)

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

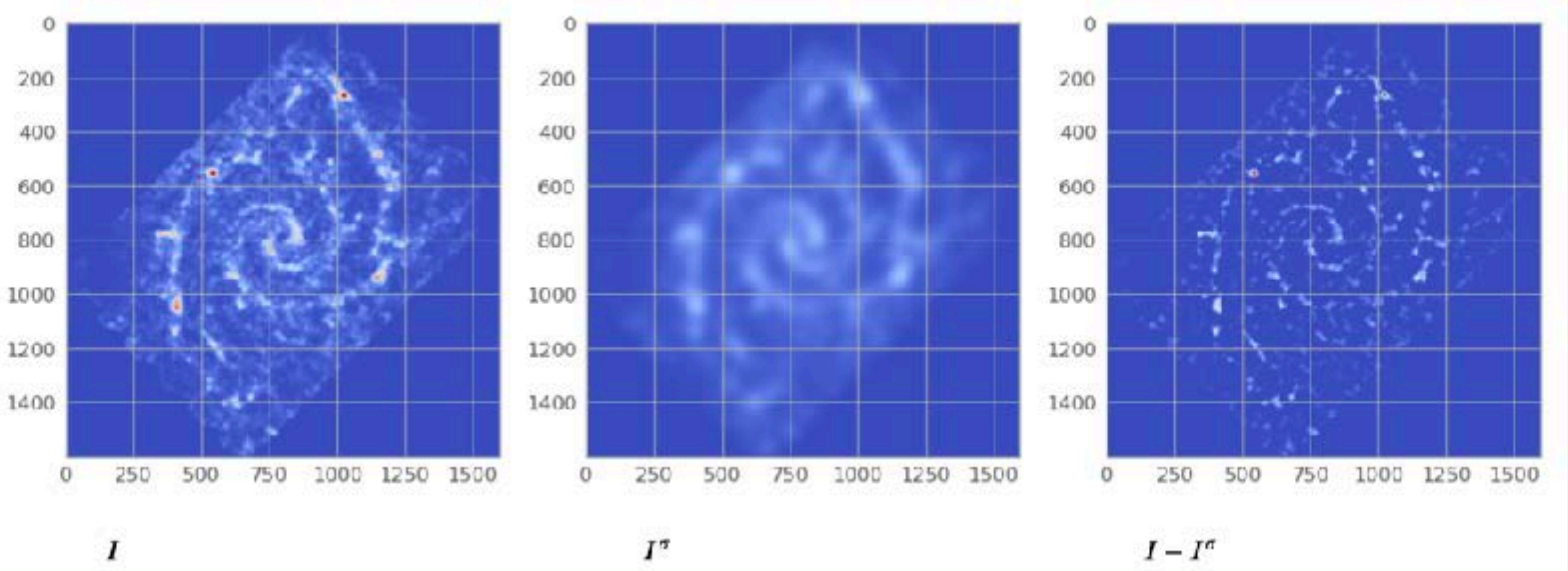


Distortion of molecular gas distribution

Clumpiness(S)

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

$\sigma = 0.3 \times R_{\mathrm{e}}$



The ratio of GMAs in molecular gas

GMAs; The Giant Molecular cloud Associations

Data

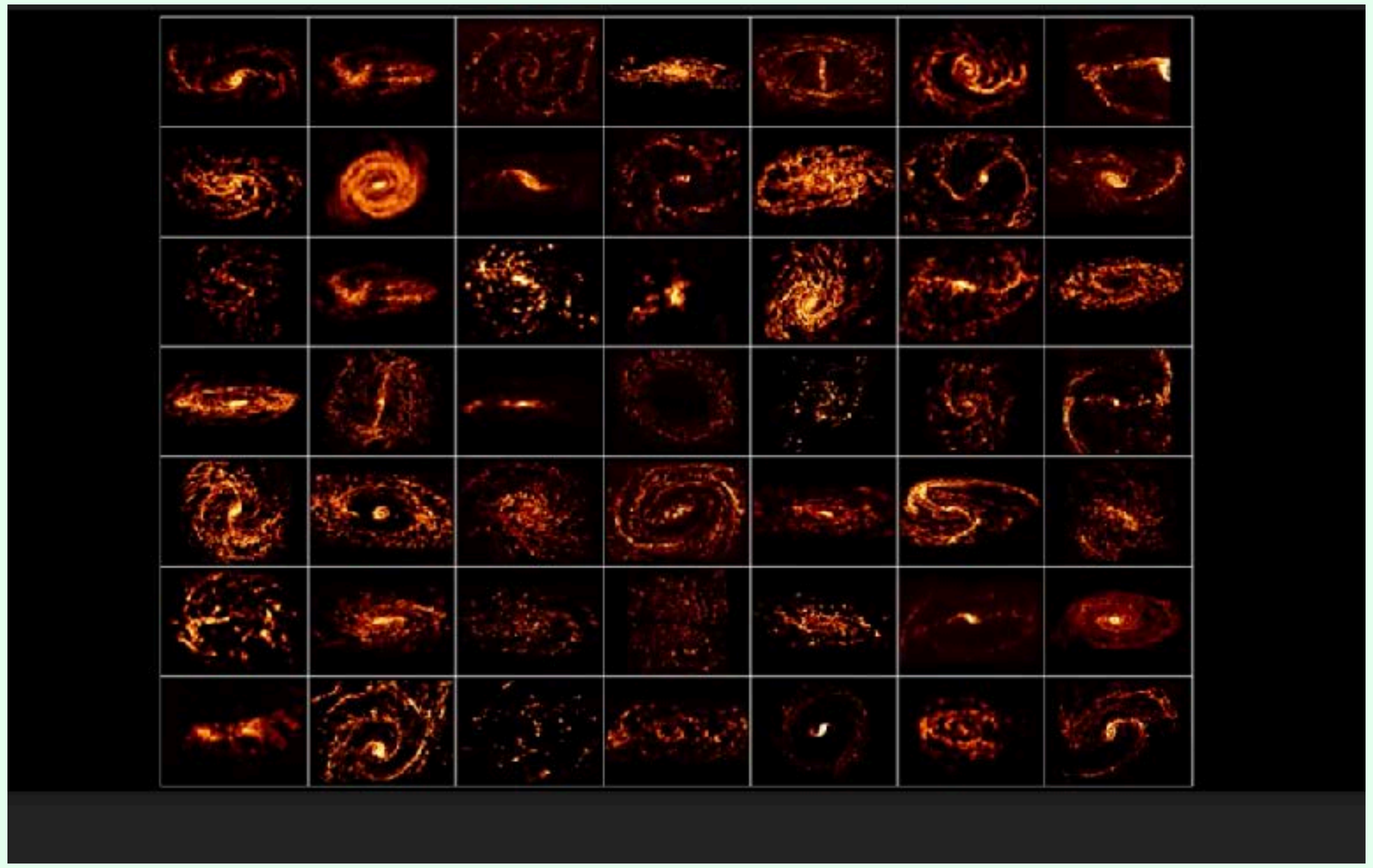
73 galaxies
From PHANGS-ALMA
Archive data

The Physics at High Angular resolution in Nearby Galaxies (PHANGS)

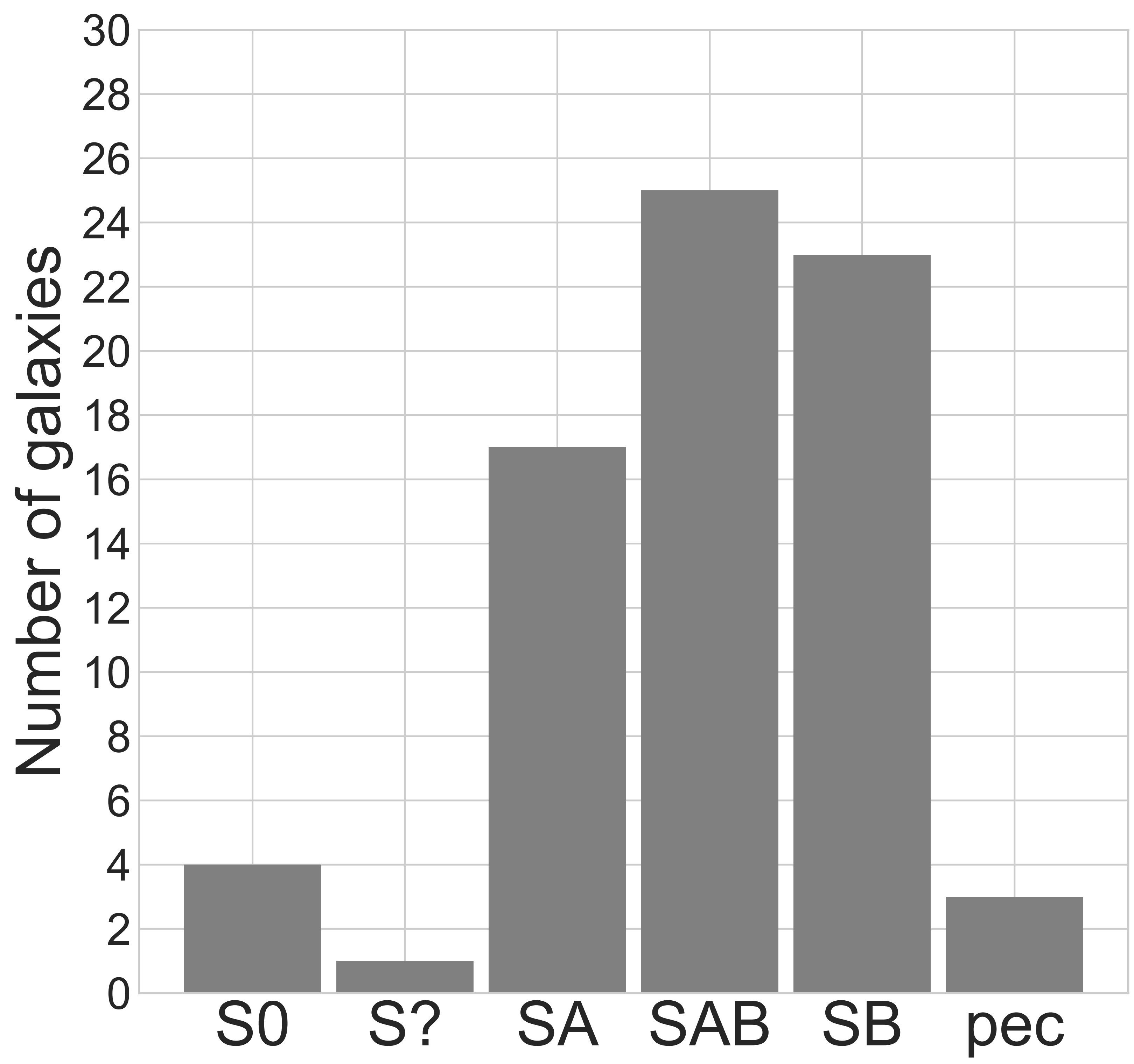
Table 1. PHANGS–ALMA Selection

Quantity	Value
Selection criteria for main sample[a]	
Declination	$-75° < \delta < +25°$
Inclination	$i < 75°$
Distance	$d < 17$ Mpc
$\log_{10} M_\star [\mathrm{M}_\odot]$	> 9.75
$\log_{10} \mathrm{SFR}/\mathrm{M}_\star [\mathrm{yr}^{-1}]$	> -11
Main sample selection[b]	75 galaxies
Extensions[c]	15 galaxies

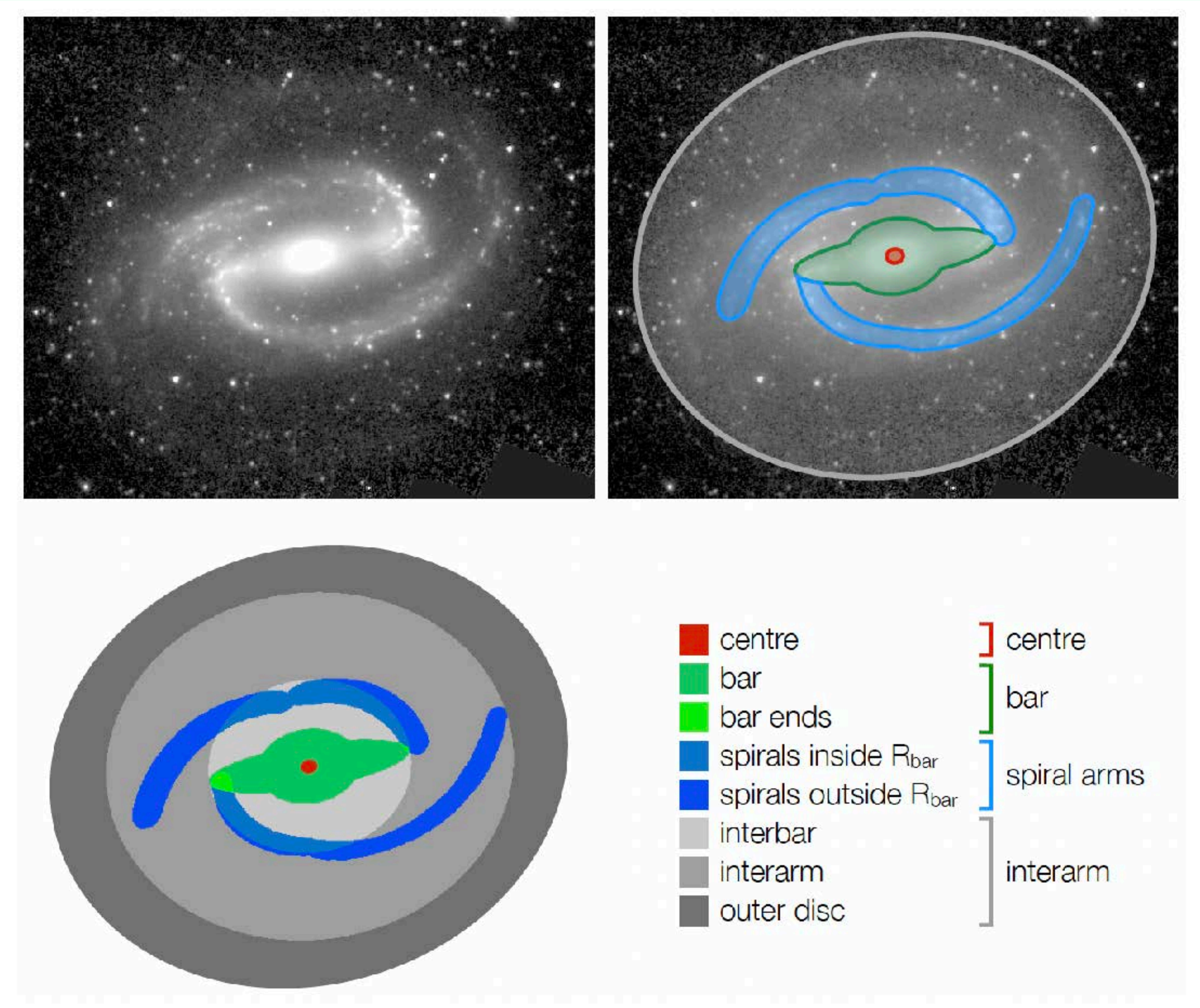
Leroy et al., 2021a



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



Spatial resolution ~ 180 pc



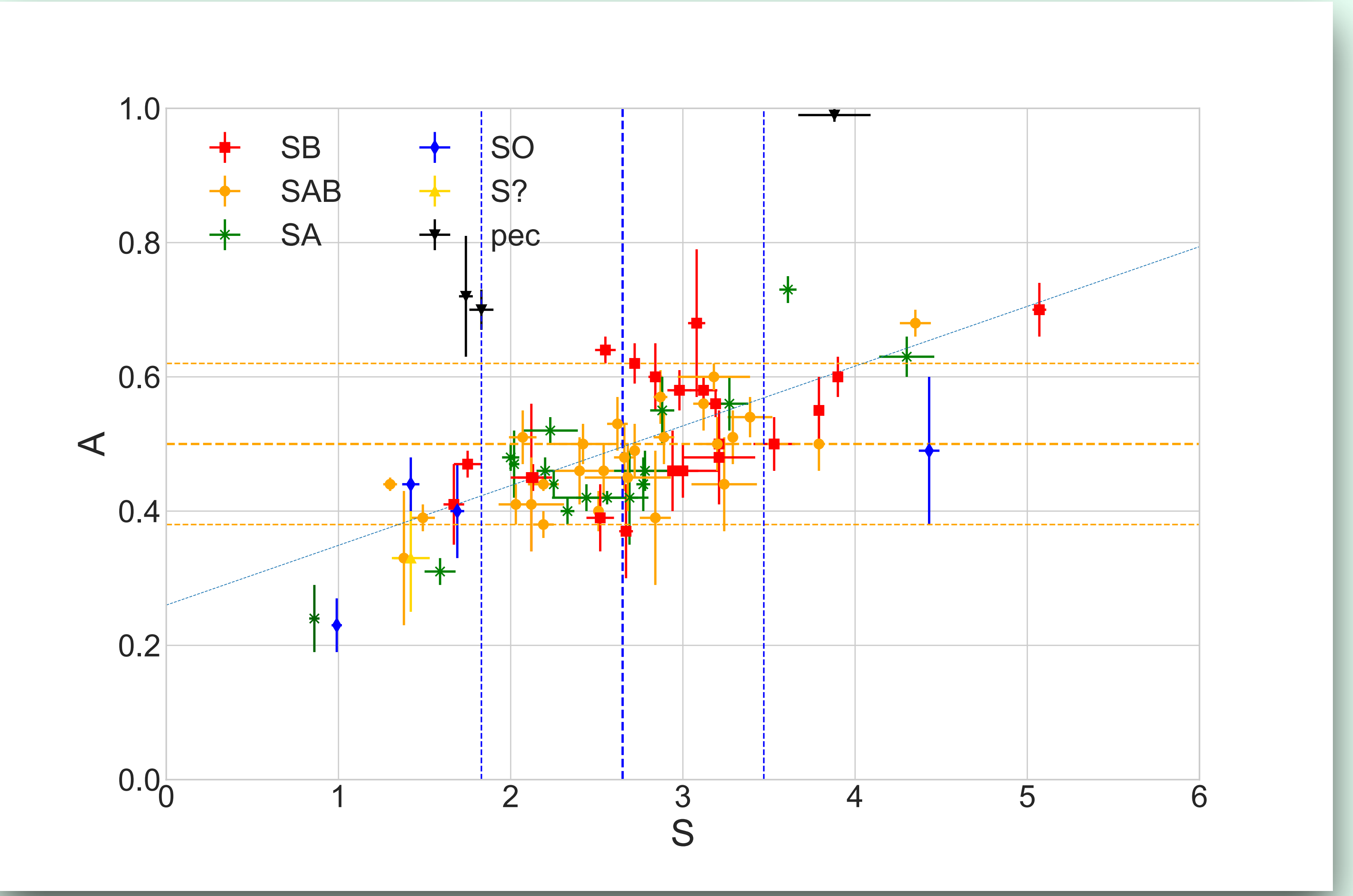
Querejeta et al. 2021

Result

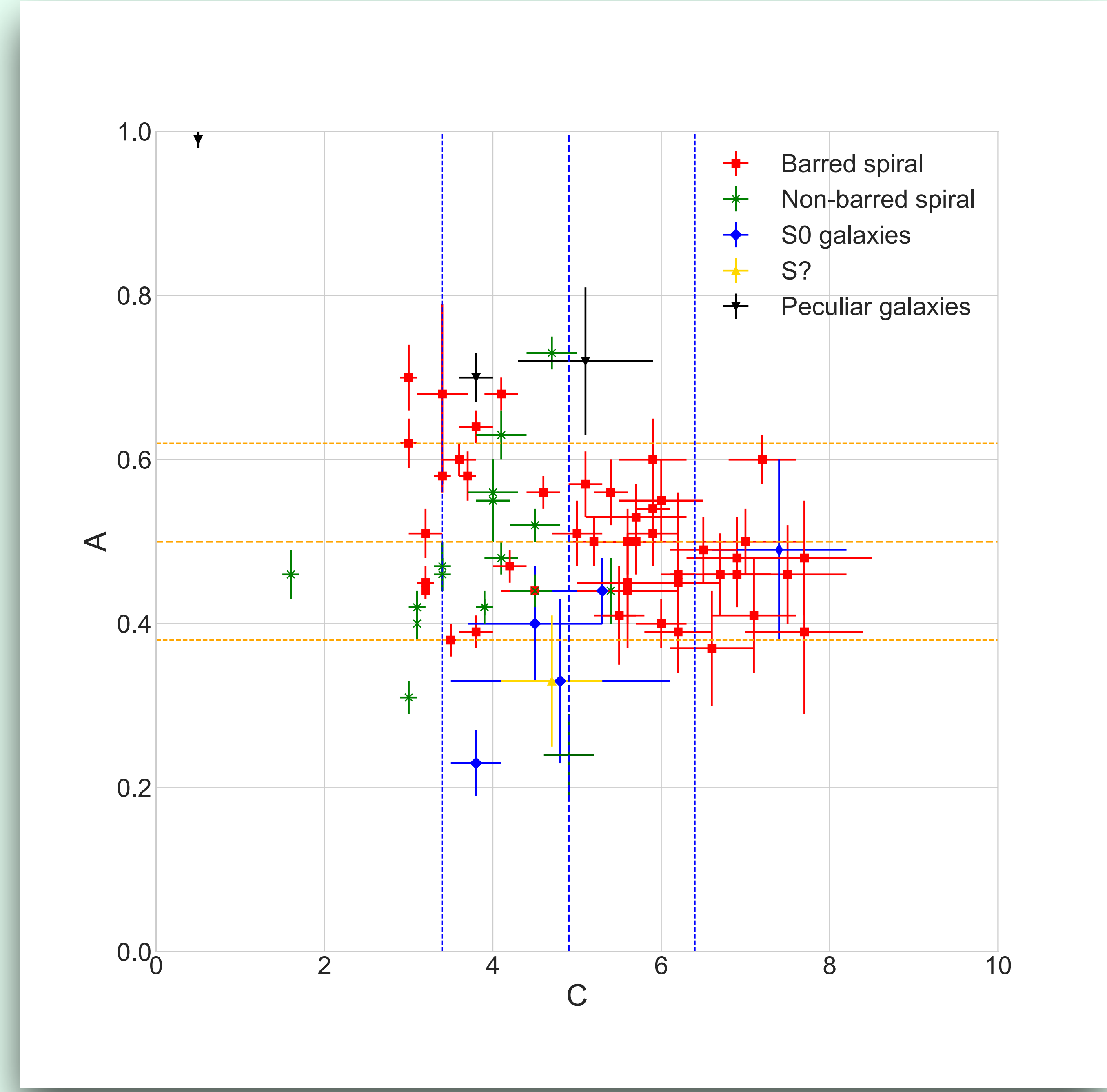
This is the first study to examine molecular gas distribution using all three model-independent CAS parameters from Conselice (2003).

As a result of this analysis, we made several important findings, as shown in the figure below.

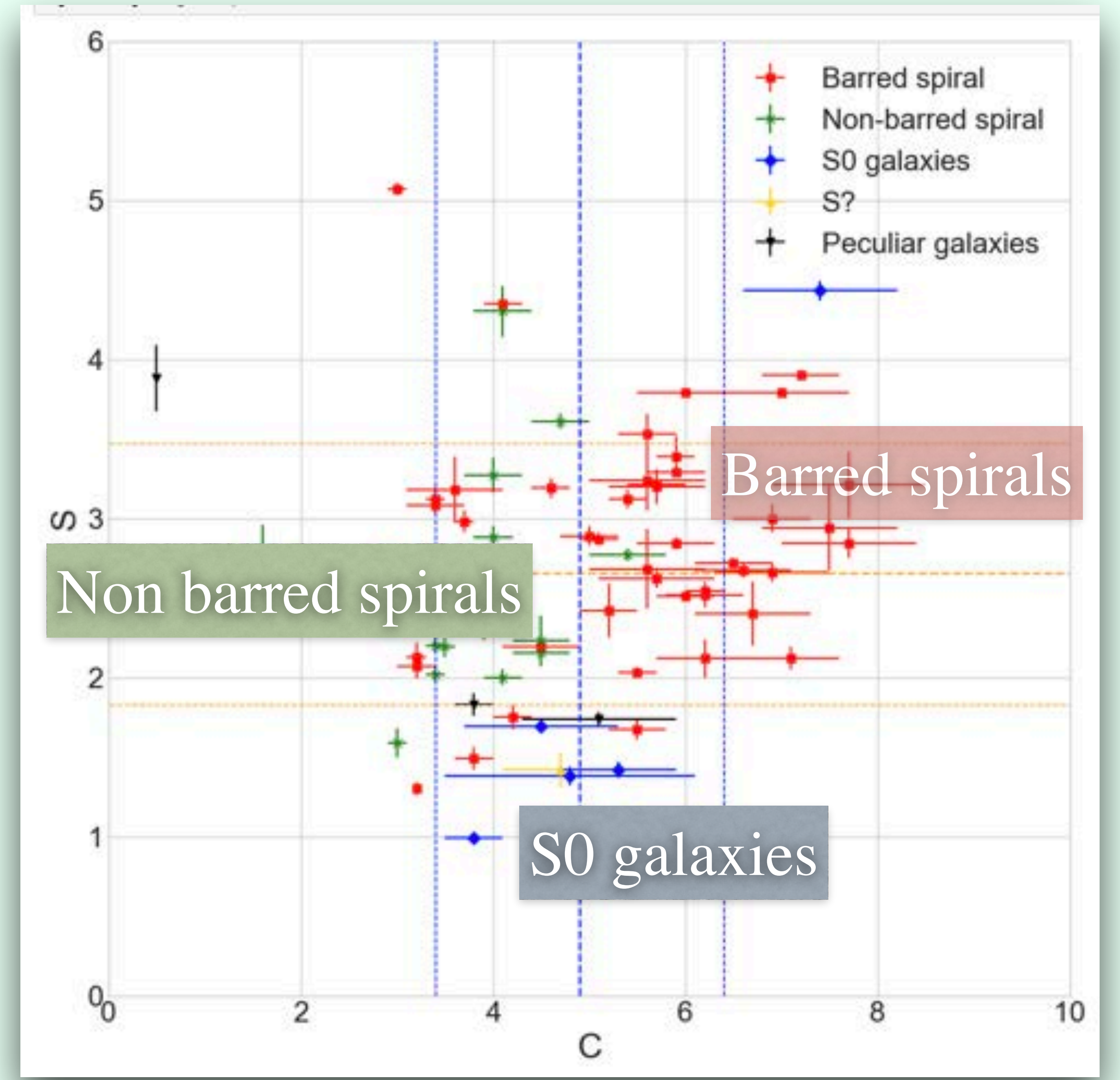
The clear correlation between Asymmetry(A) and Clumpiness(S)



The bar structure increases the central concentration of molecular gas.



Barred spiral galaxies, non-barred spiral galaxies, and lenticular galaxies are plotted in characteristic positions on the CAS space.



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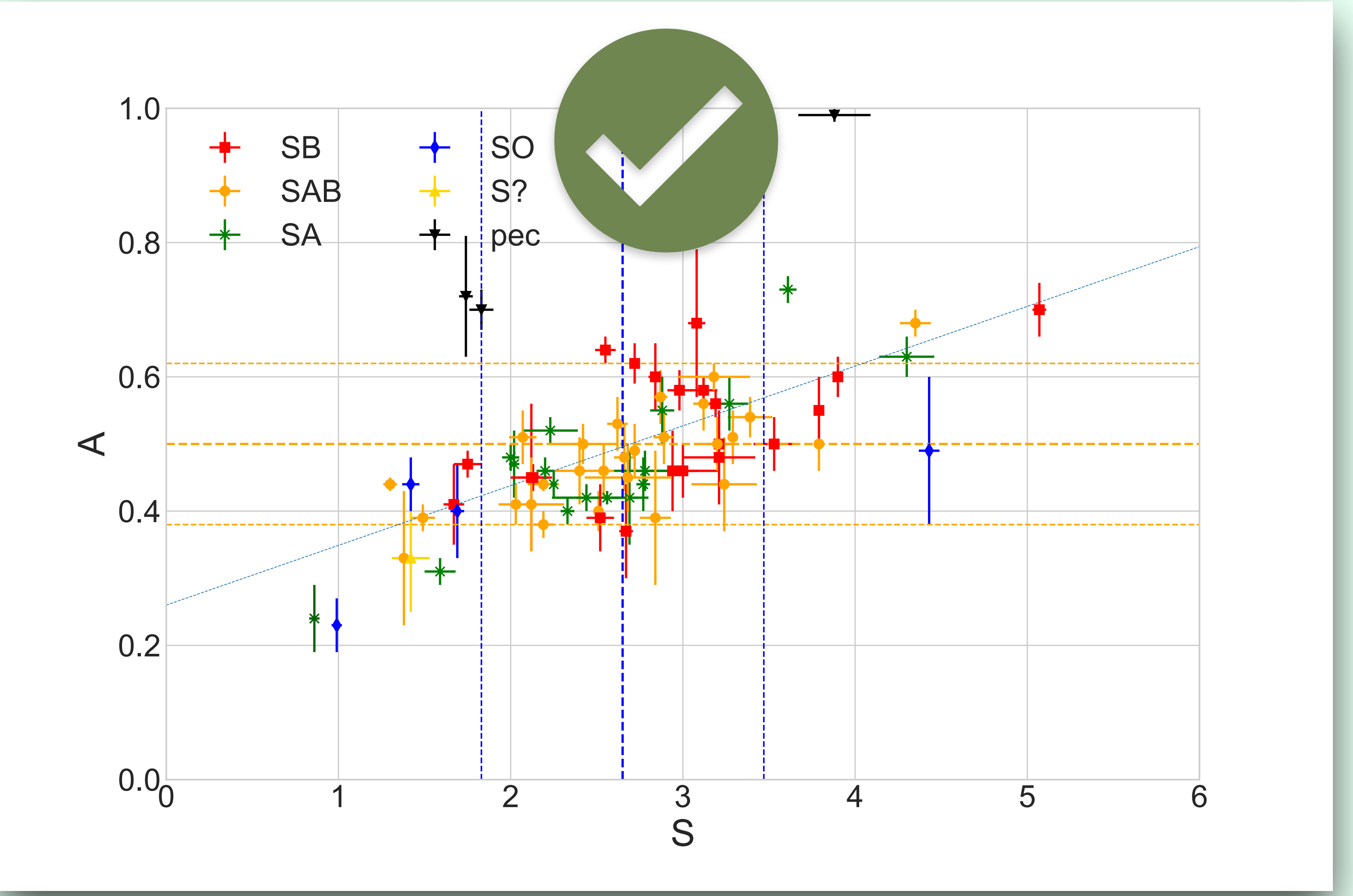

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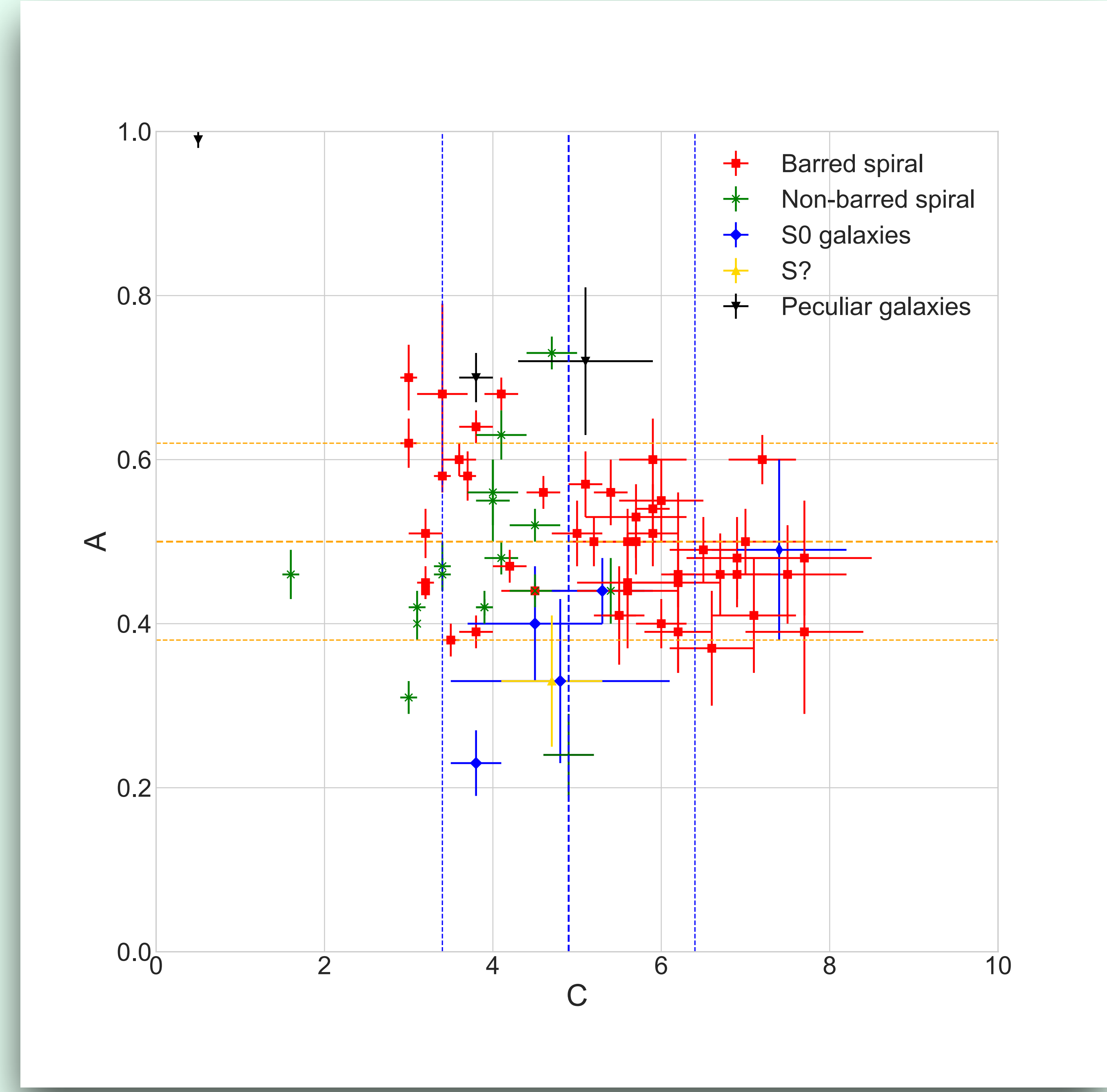

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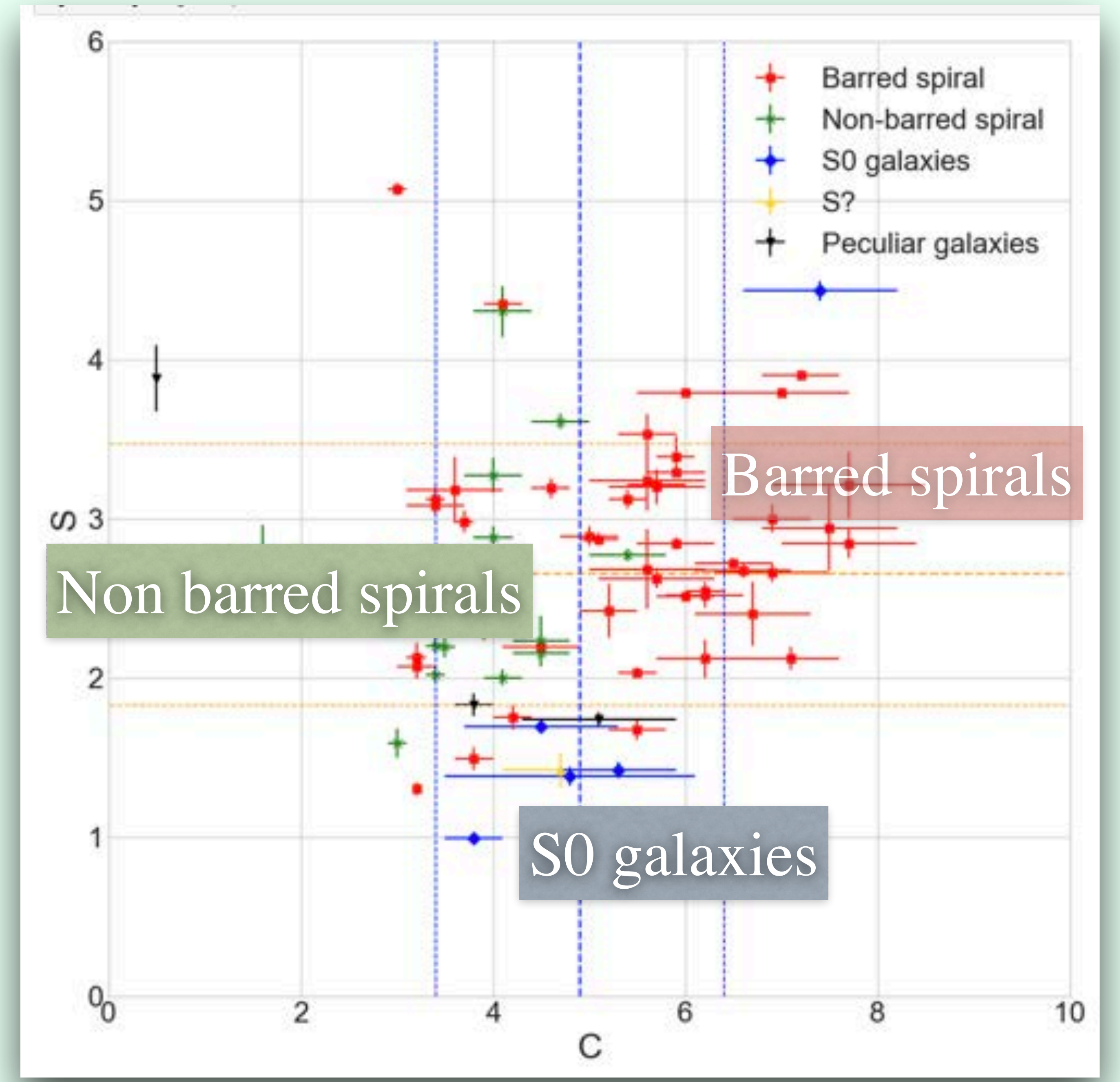
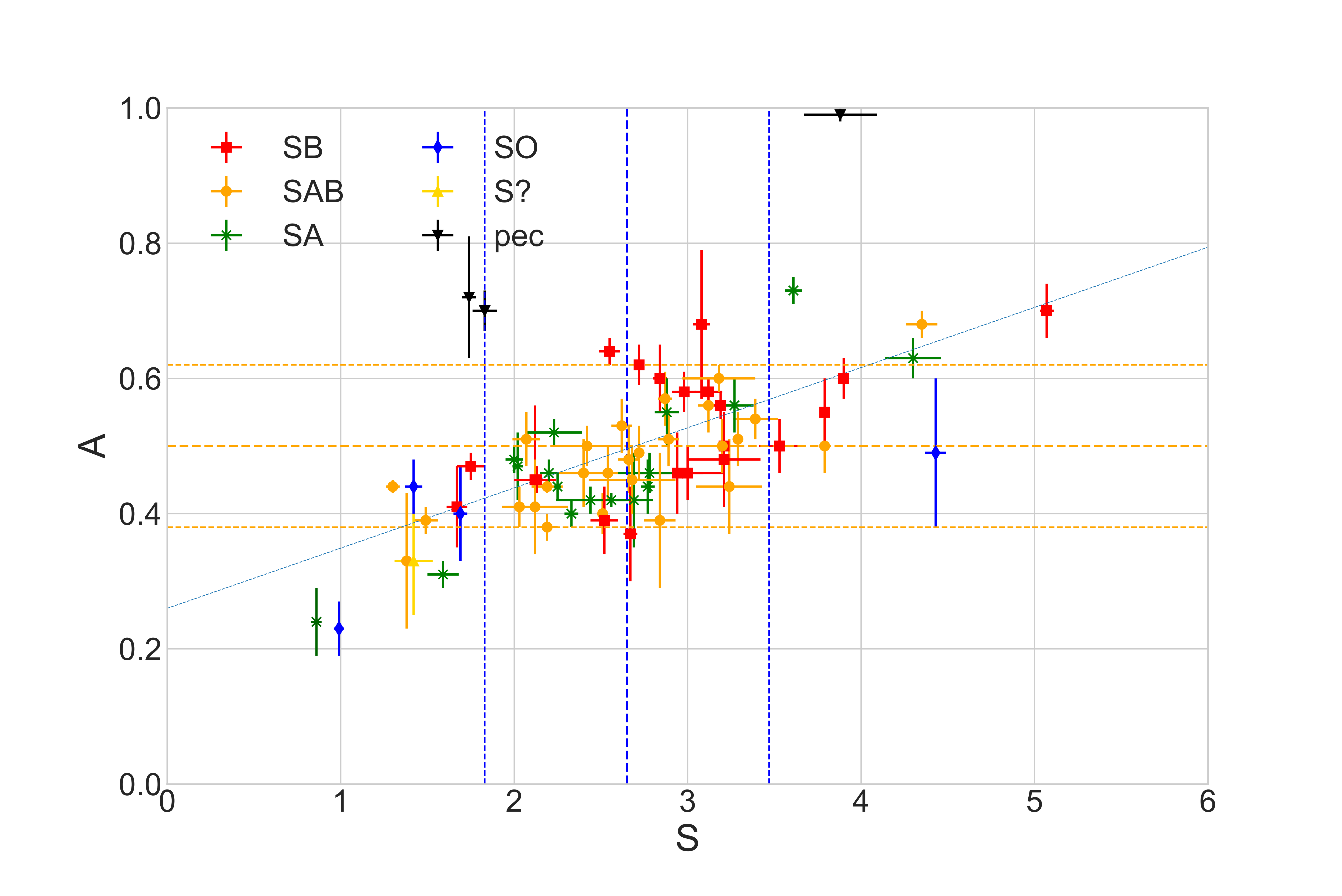


Result & Discussion

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

(1) One of the results is that Clumpiness (S) and Asymmetry (A) showed a clear correlation. It suggests that galaxies with a more distorted distribution of molecular gas are more likely to form GMAs.

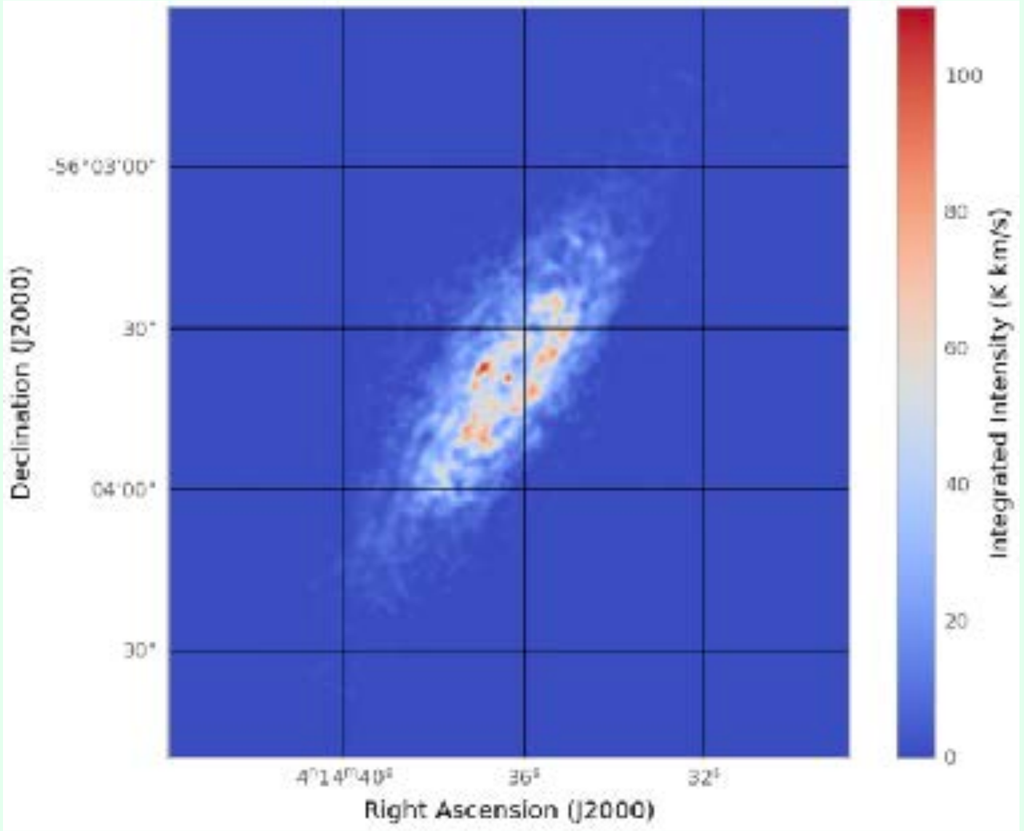


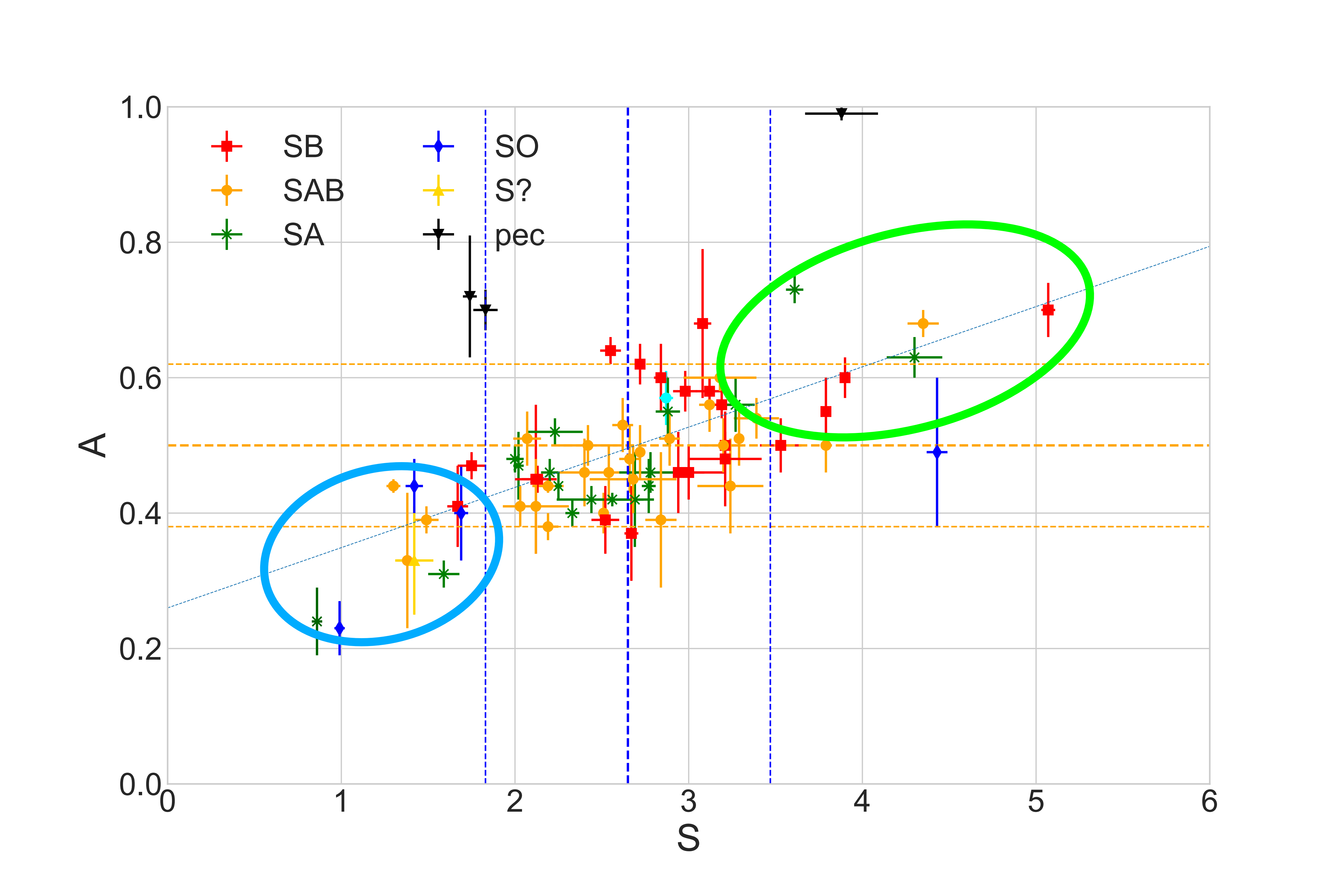
Spearman's rank correlation coefficient is 0.62, with the associated p-value of 4×10^{-9}

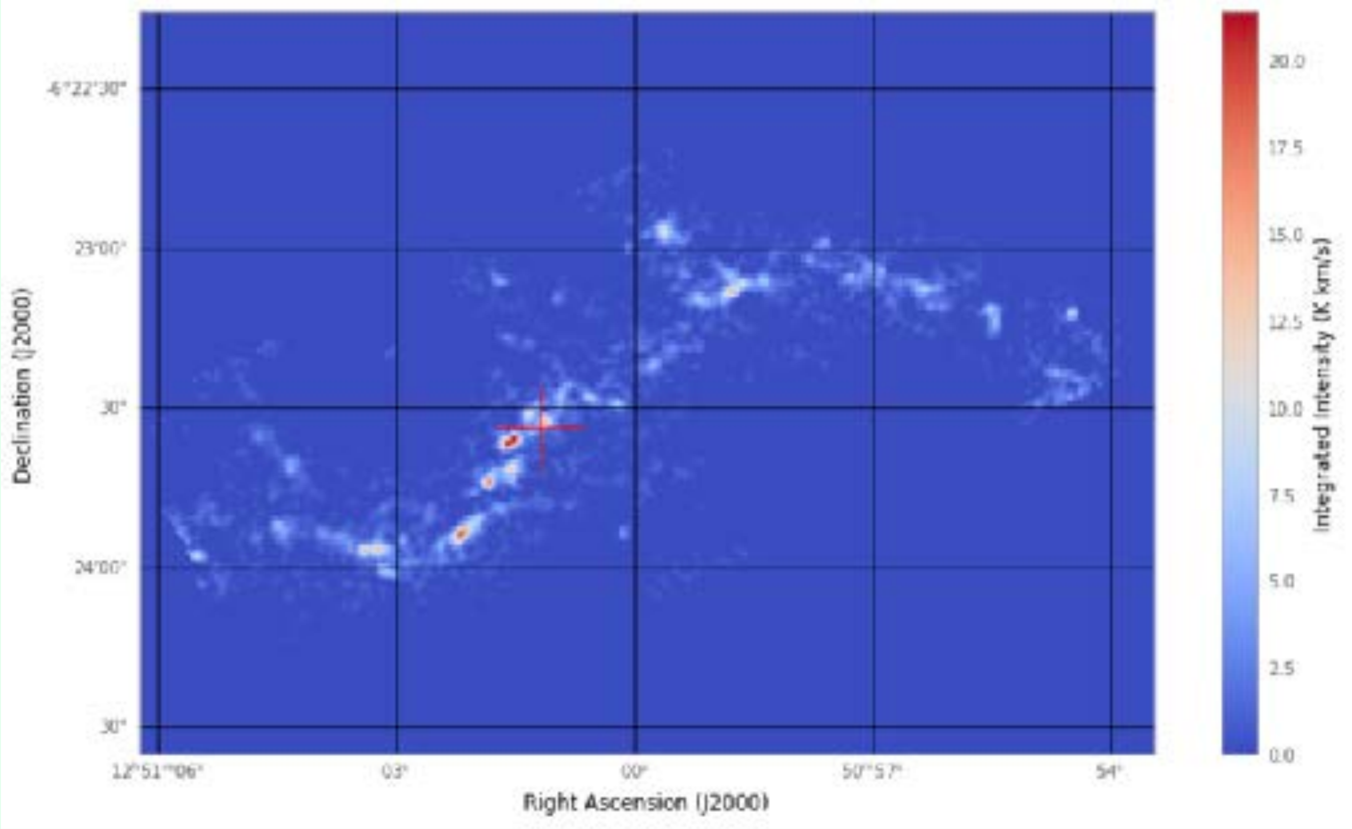
Result & Discussion

Asymmetric galaxies affected by past interactions are more likely to form giant molecular cloud associations due to repeated collisions between gas clouds caused by perturbations of molecular gas clouds.

NGC 1546







NGC 4731

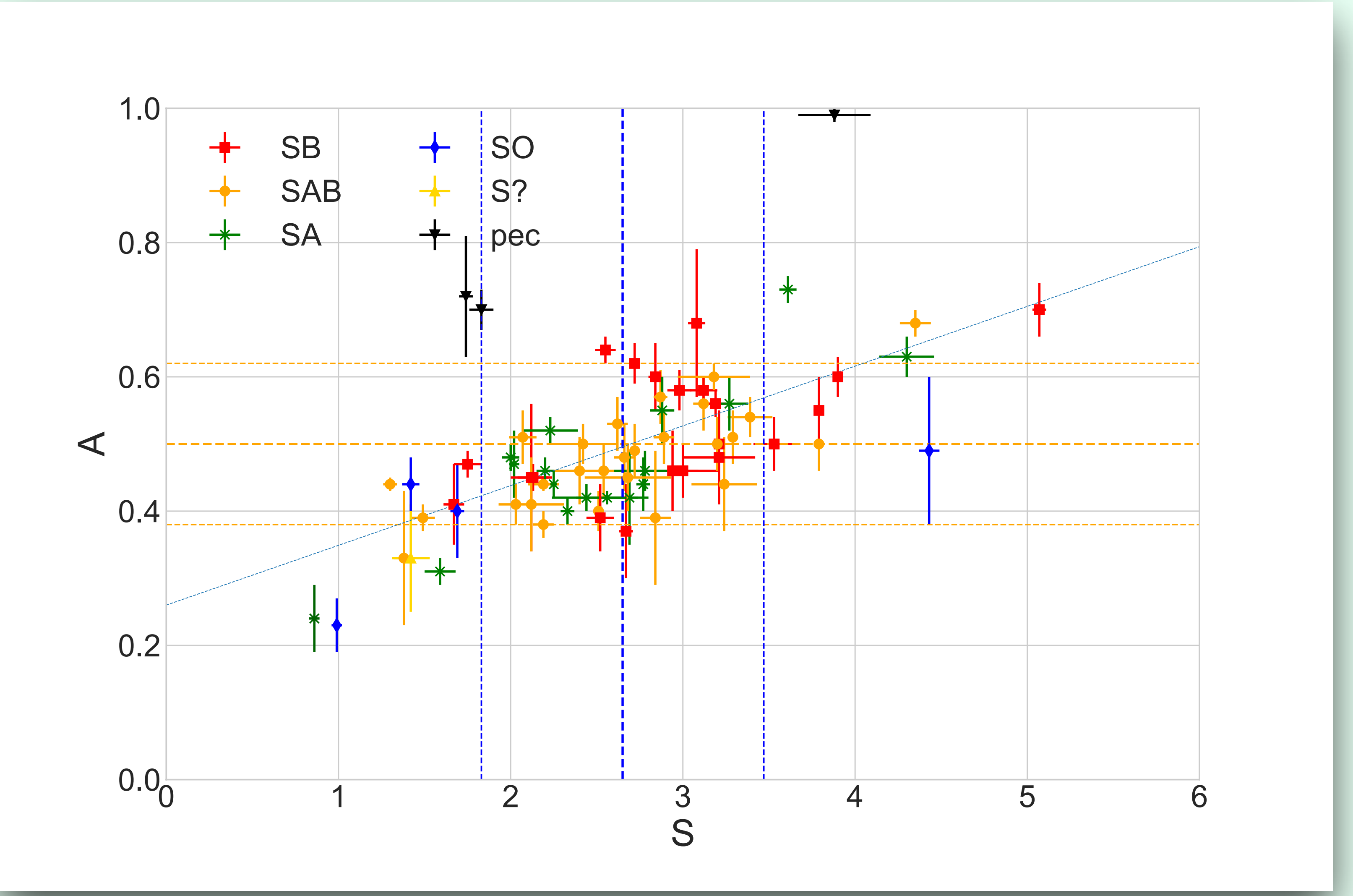
Symmetric galaxies, such as S0 galaxies, have an extended distribution of molecular gas in the galactic bulge and are less likely to form GMAs.

Result

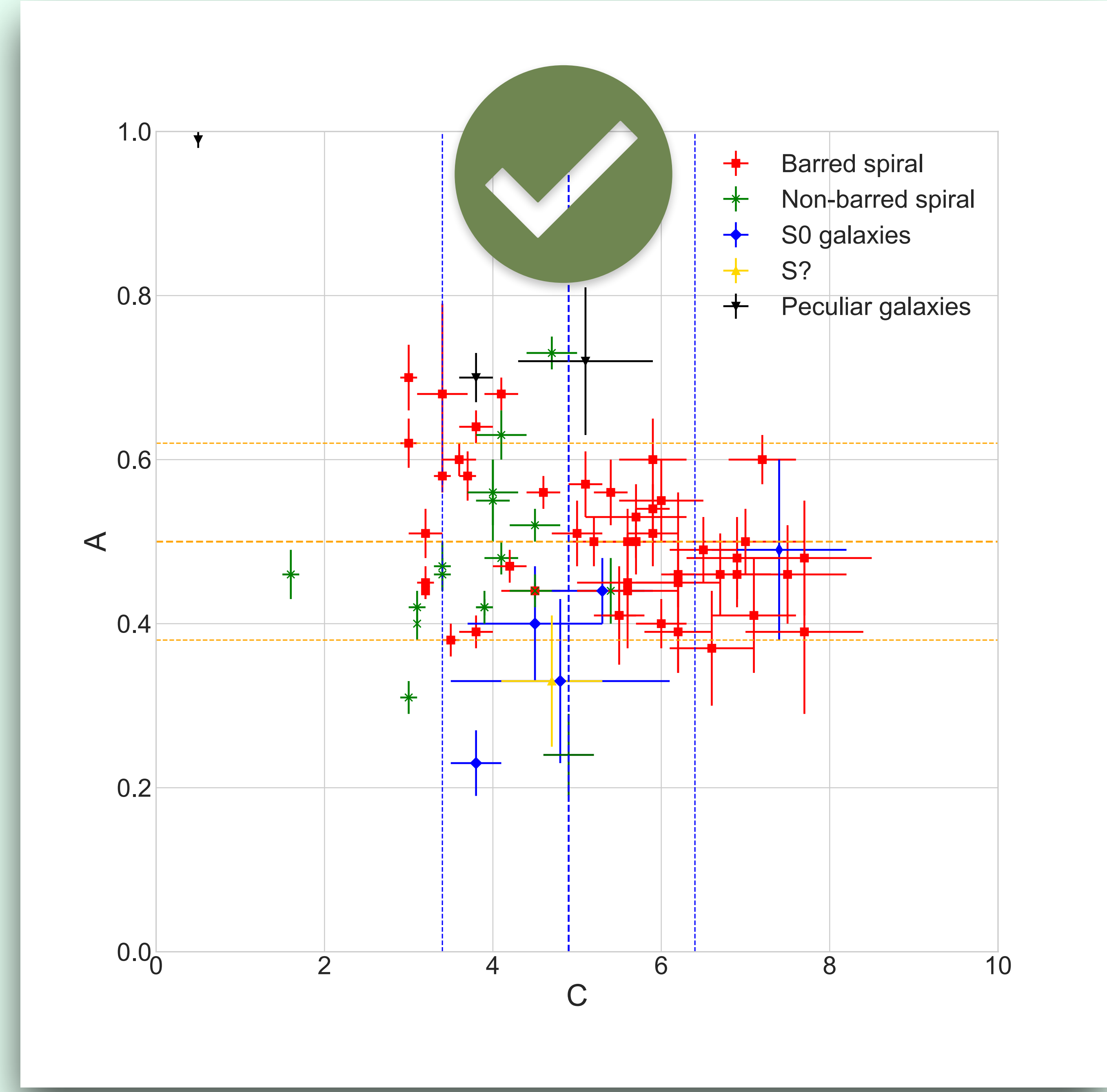
This is the first study to examine molecular gas distribution using three model-independent CAS parameters from Conselice (2003).

As a result of this analysis, we made several important findings, as shown in the figure below.

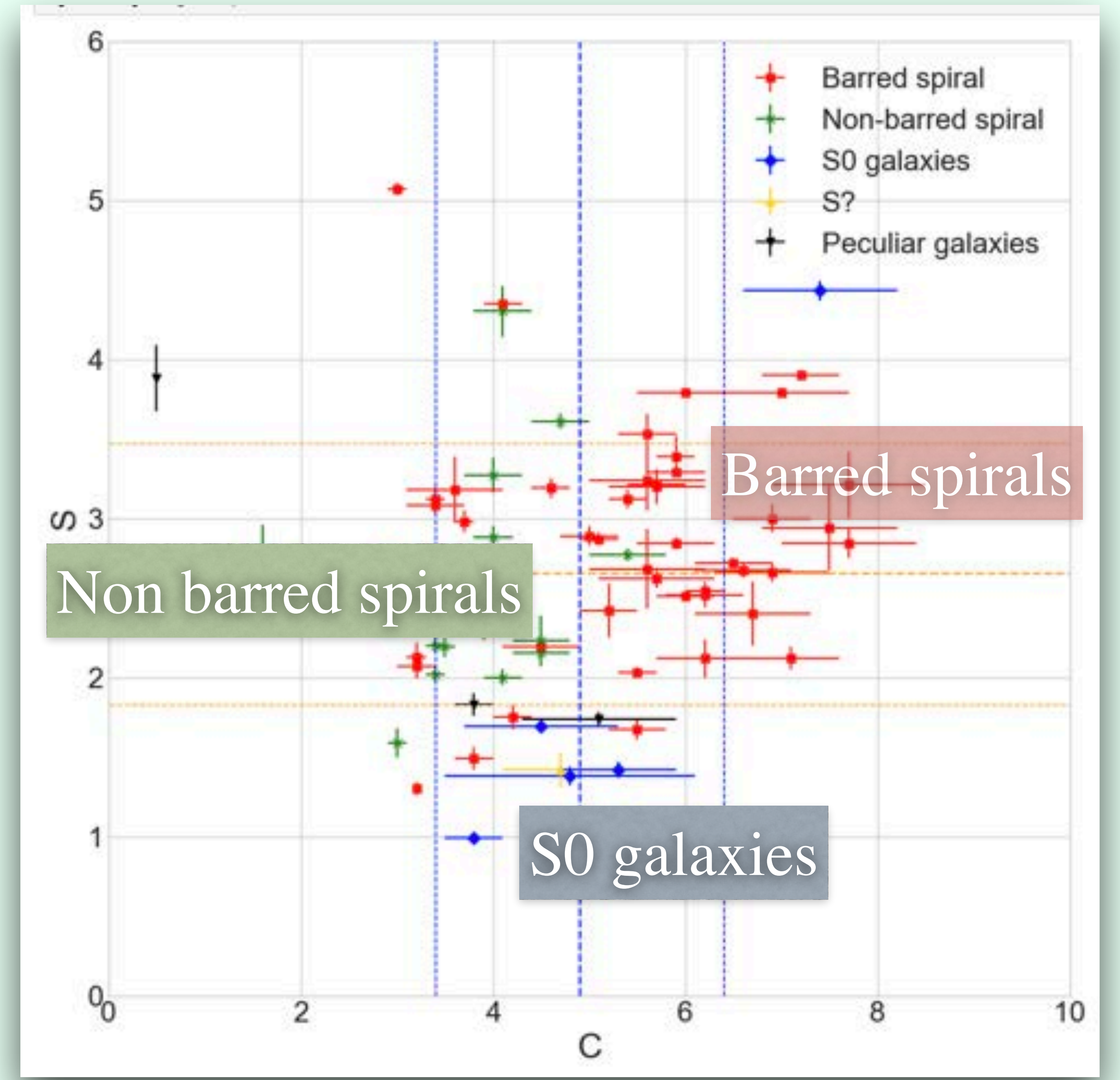
The clear correlation between Asymmetry(A) and Clumpiness(S)



The bar structure increases the central concentration of molecular gas.

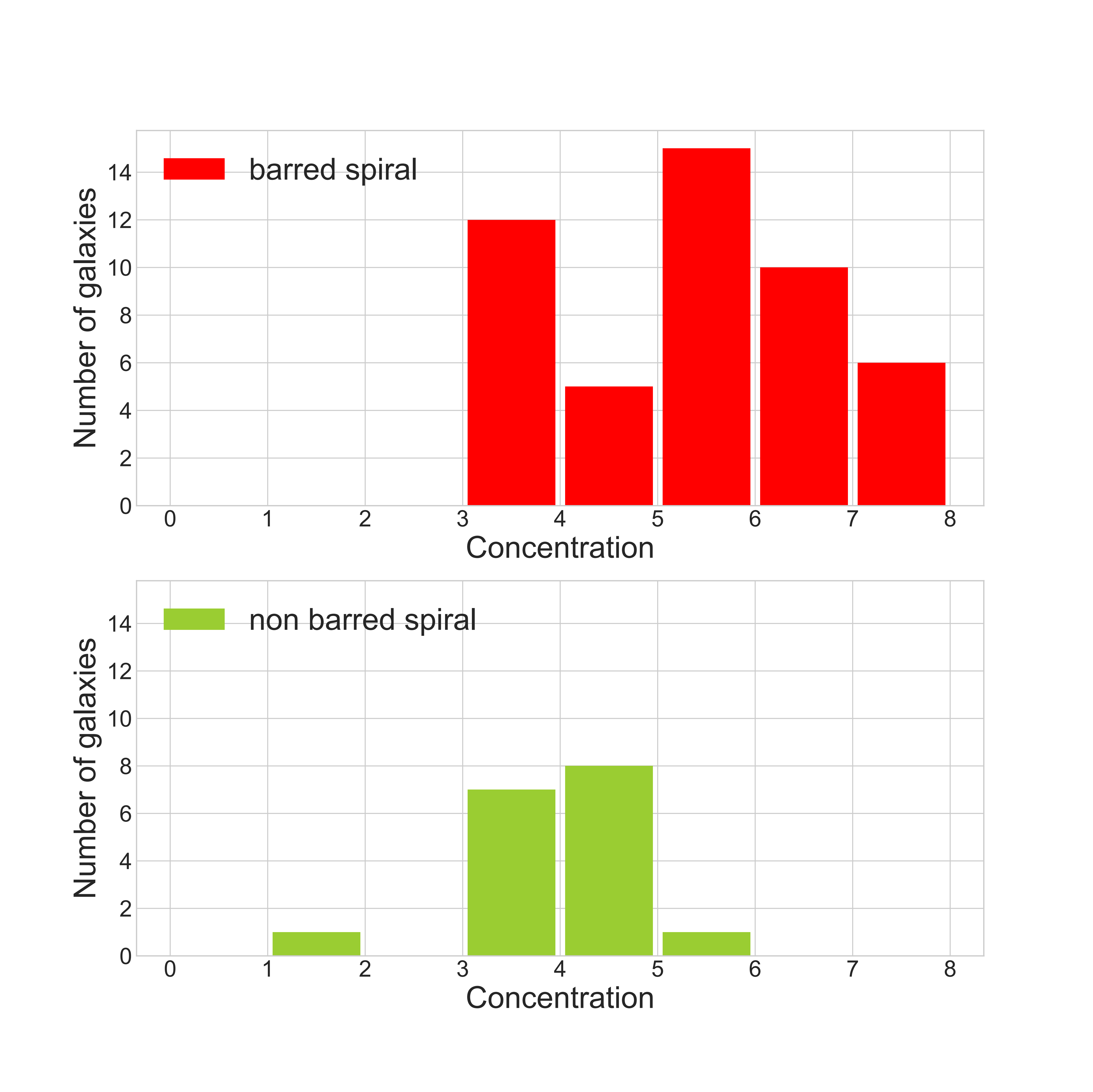


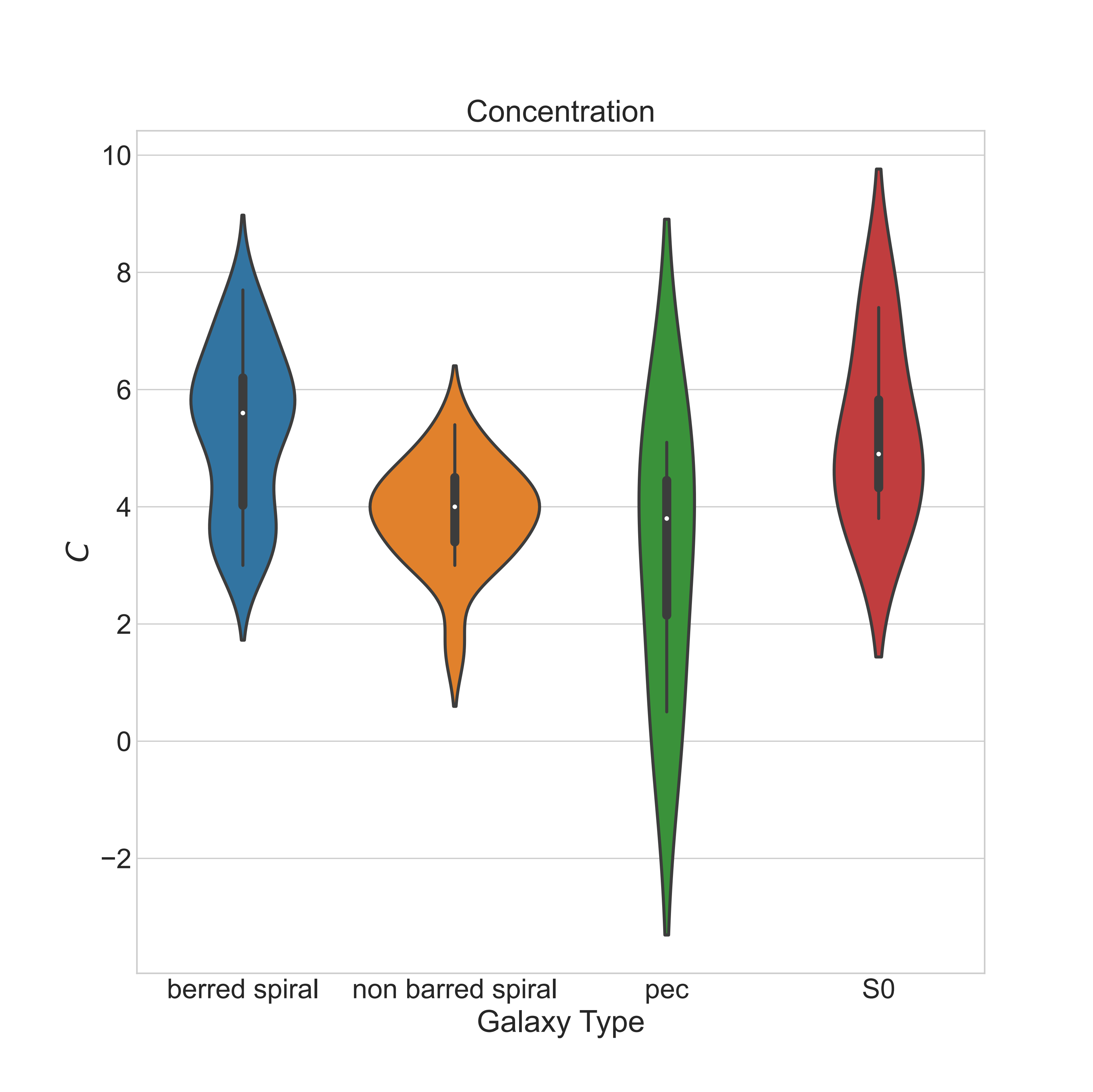
Barred spiral galaxies, non-barred spiral galaxies, and lenticular galaxies are plotted in characteristic positions on the CAS space.



Result & Discussion

The bar structure increases the central concentration of molecular gas.





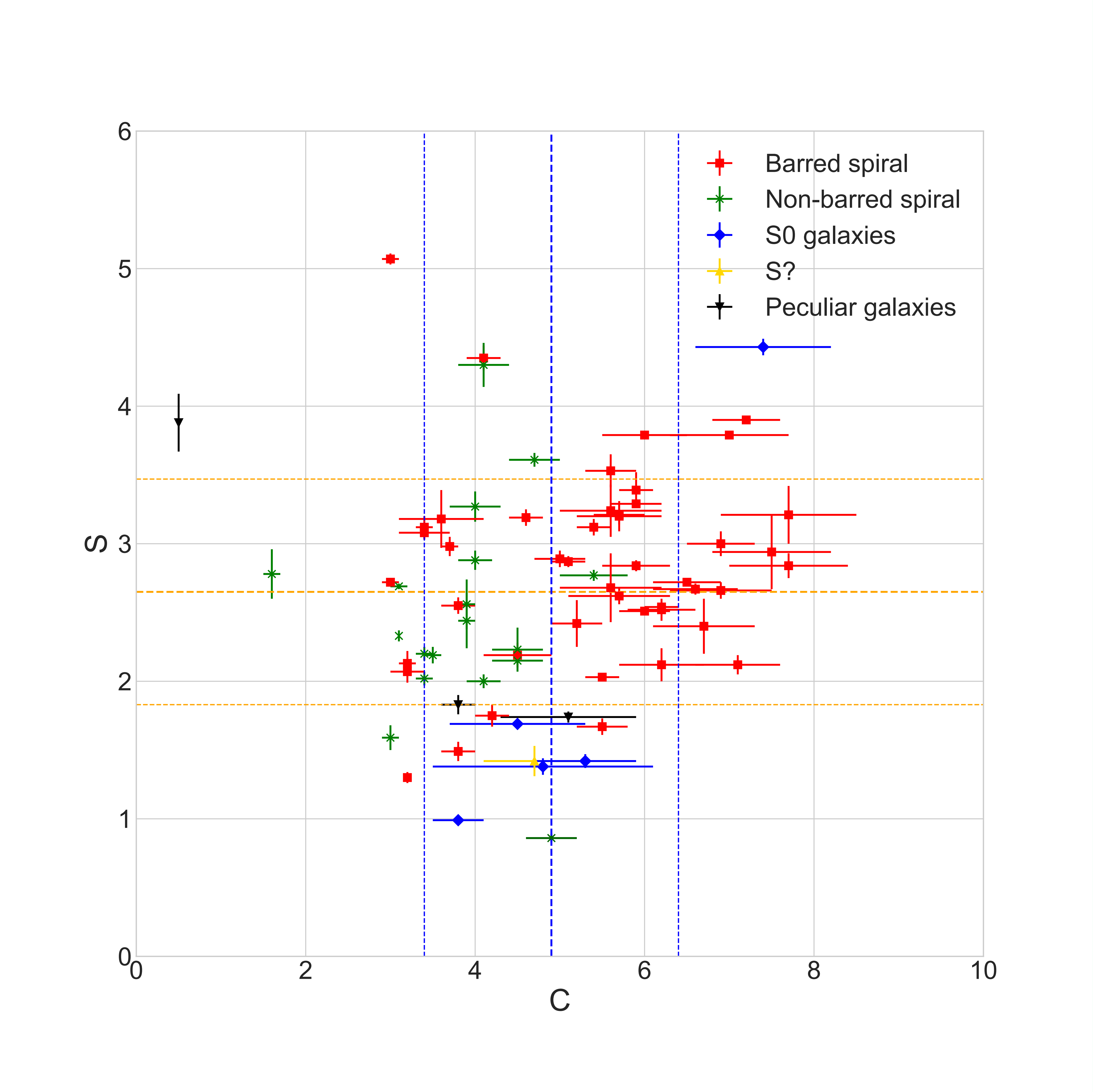
We used the Kolmogorov-Smirnov (KS) test for two samples, SA galaxies and SB+SAB galaxies.

KS probability value is 1.46×10^{-4}

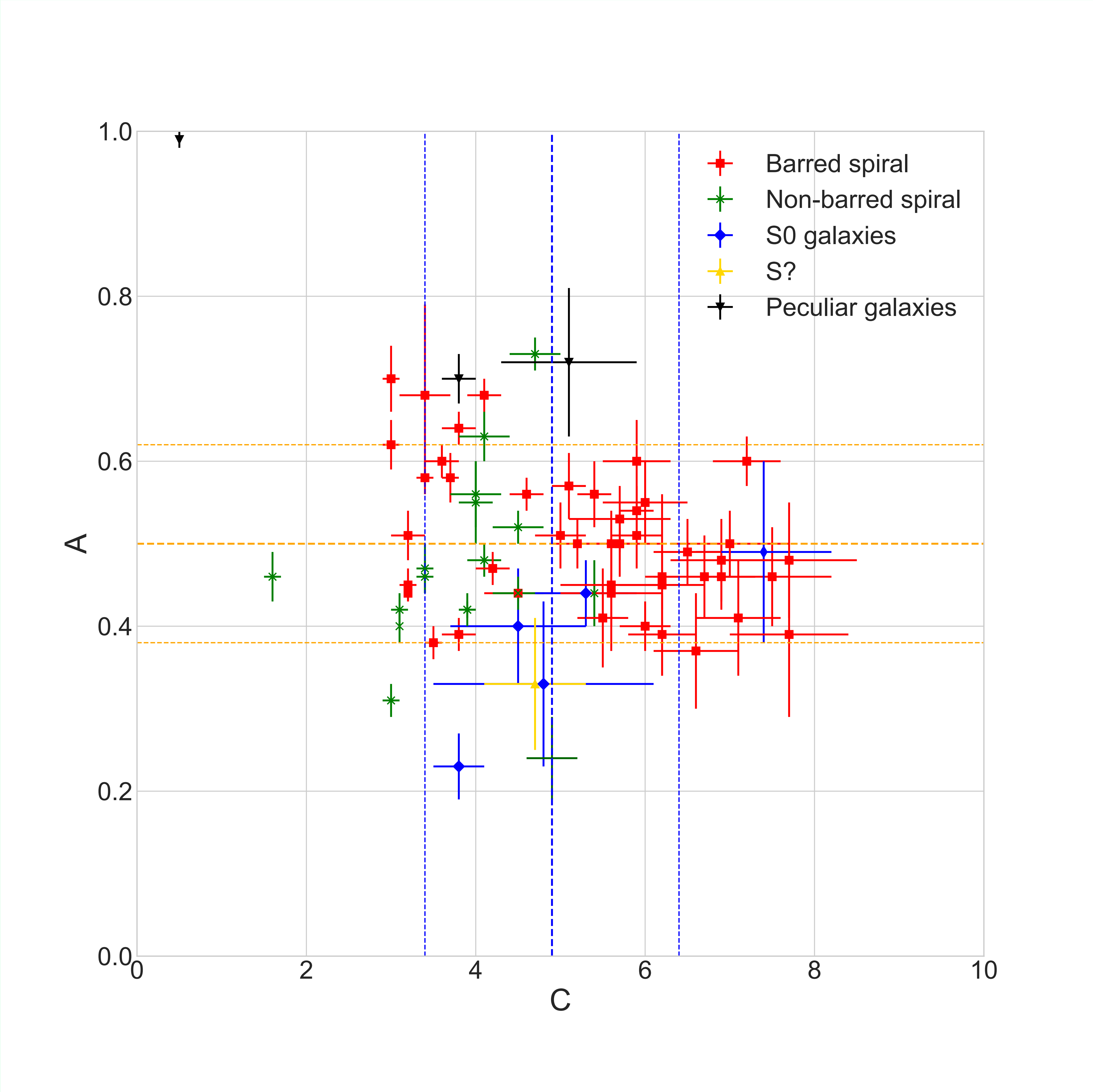
Result & Discussion

The bar structure increases the central concentration of molecular gas.

Concentration(C) vs.Clumpiness(S)



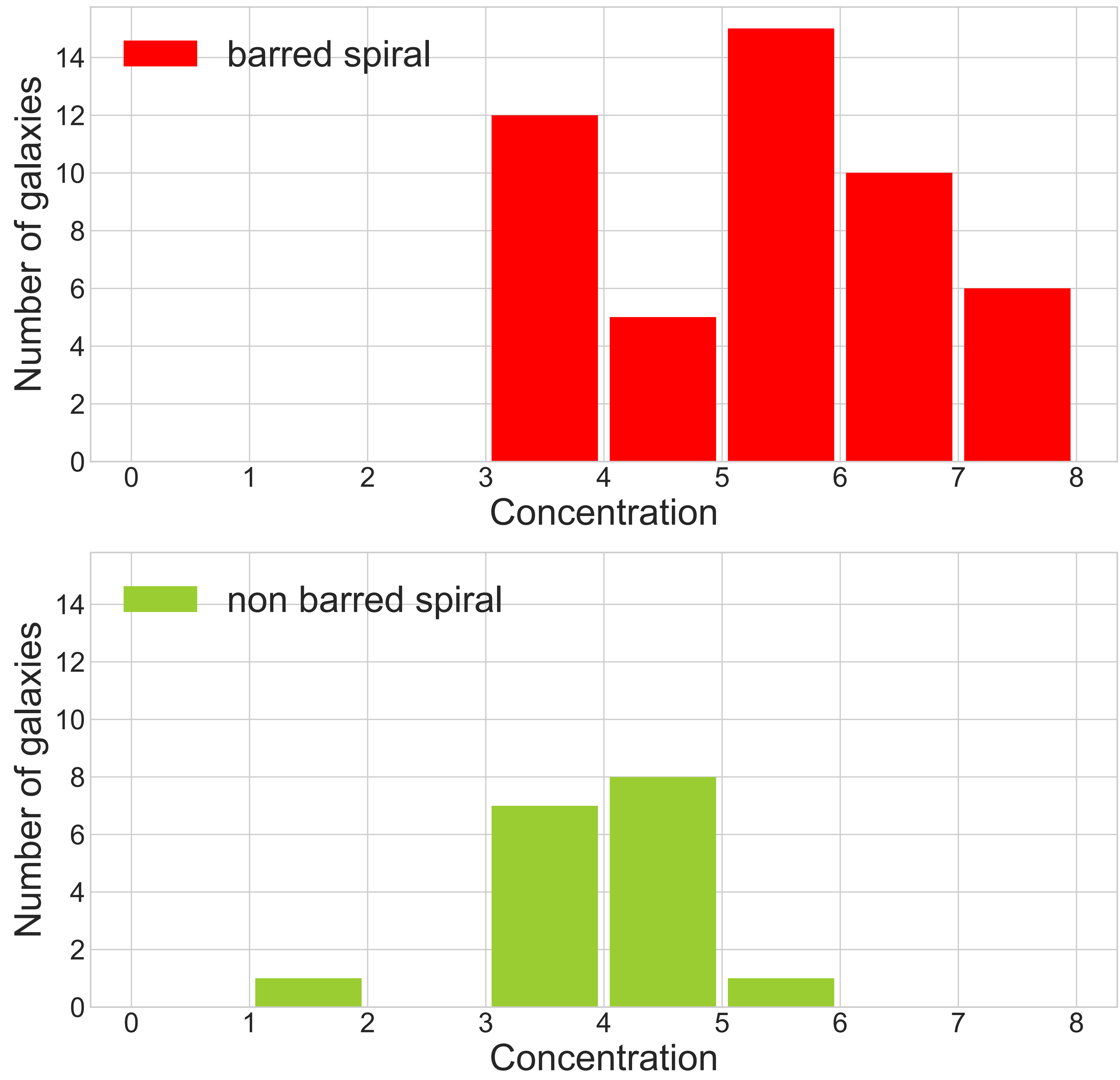
Concentration(C) vs.Asymmetry(A)



Result & Discussion

The bar structure increases the central concentration of molecular gas.

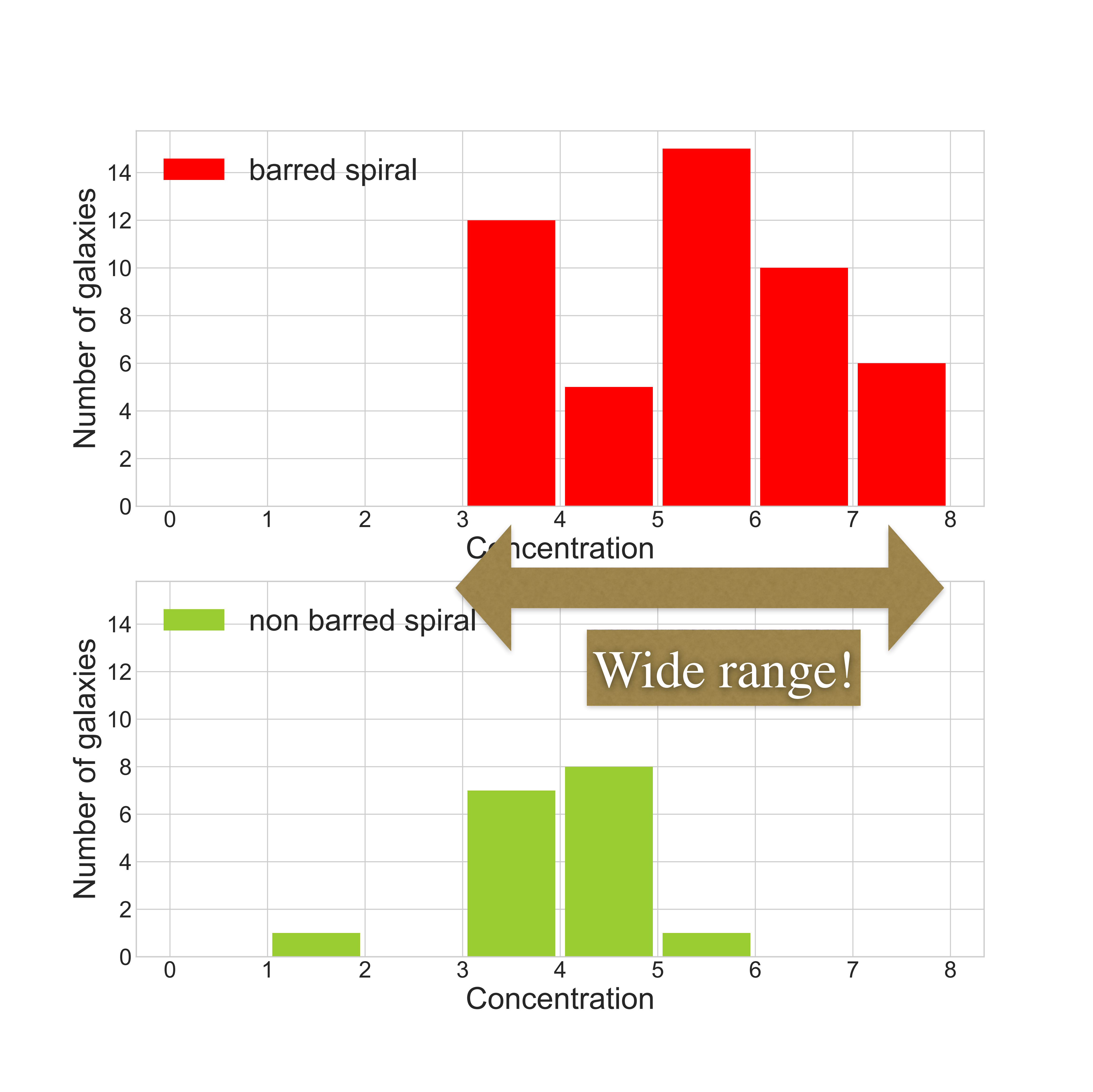
The mean C value for all galaxy samples in this analysis is 4.9. The mean C value for barred spiral galaxies is 5.4, while the mean C value for non-barred spiral galaxies is 3.9. This is consistent with the results of previous studies (e.g., Sakamoto et al. 1999; Sheth et al. 2005; Kuno et al. 2007).



It is also consistent with many previous theoretical studies on the physical processes that cause molecular gas to fall into the center of galaxies due to bar structures (e.g., Wada et al. 1995; Baba et al. 2022).

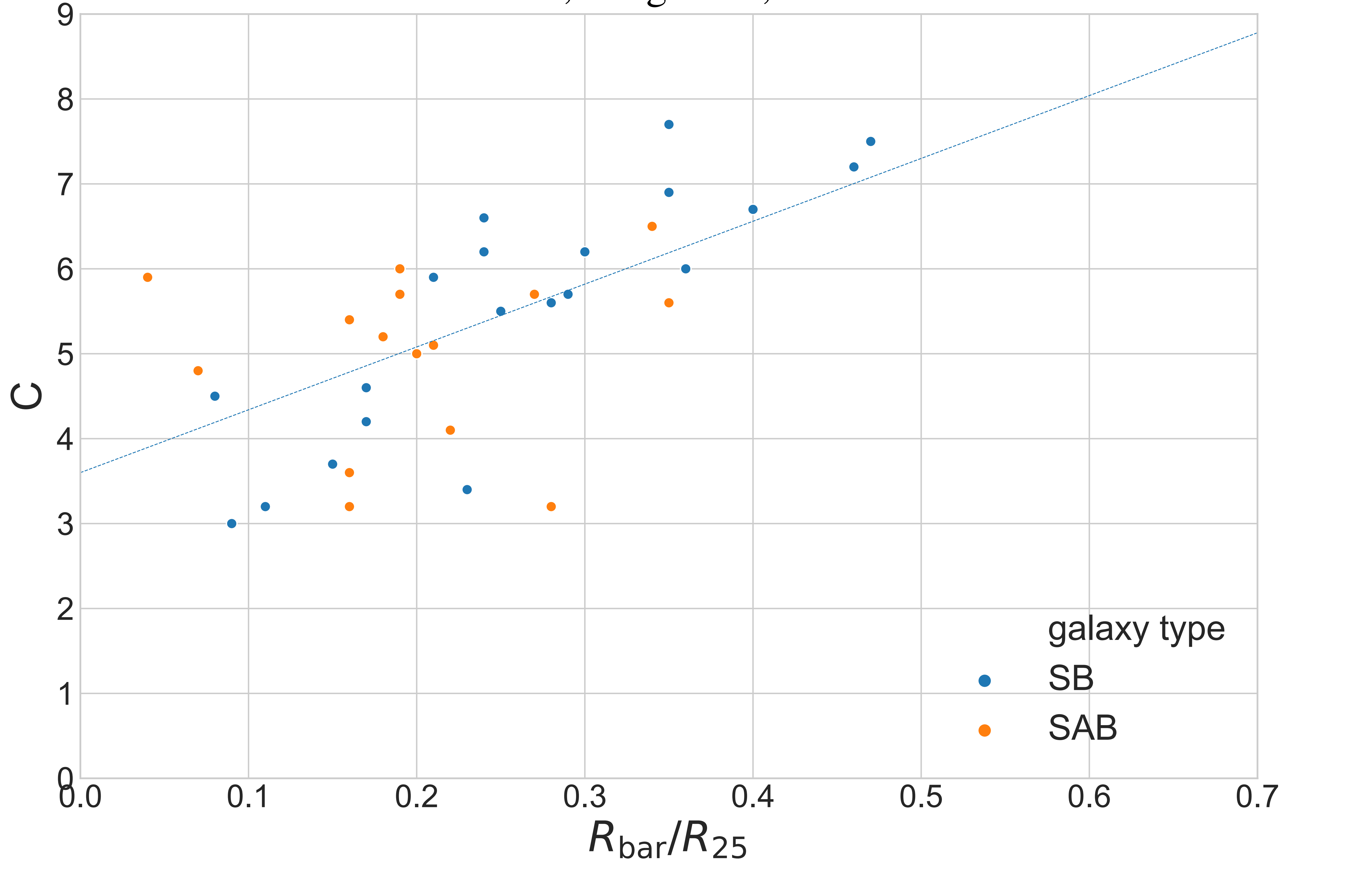
Result & Discussion

However, barred spiral galaxies have a wide range of C values $3.0 \leq C \leq 7.7$. This study found that 25% of barred spiral galaxies with C values are lower than the average C value of non-barred spiral galaxies. What is the cause of this difference in C values?



Result & Discussion

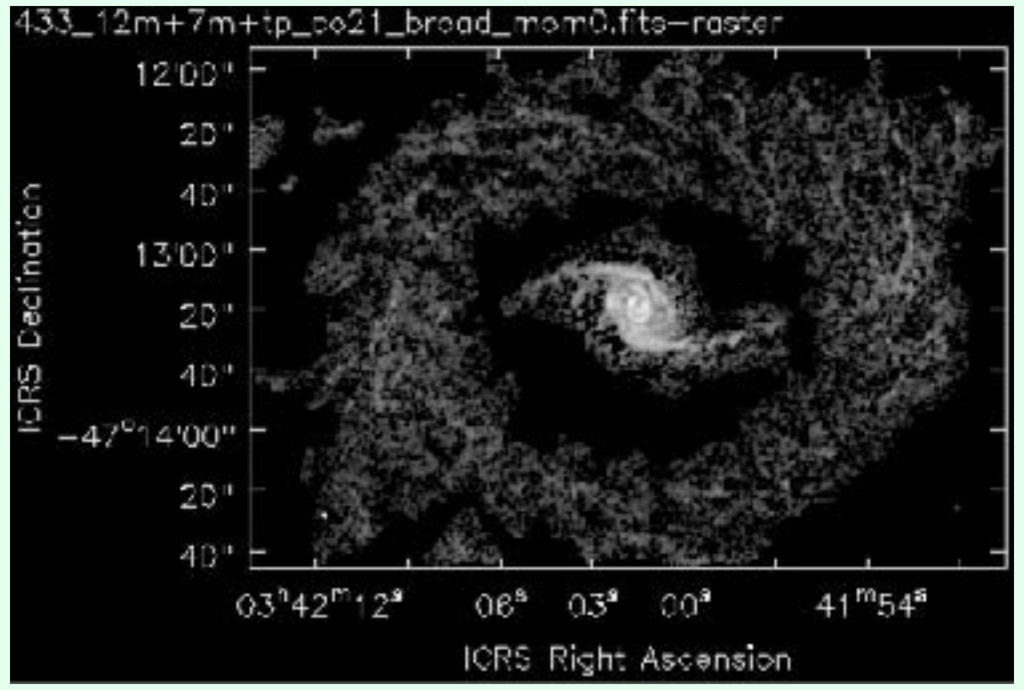
A positive correlation was found between C and Bar length (R_{bar}/R_{25}), as shown in this figure.



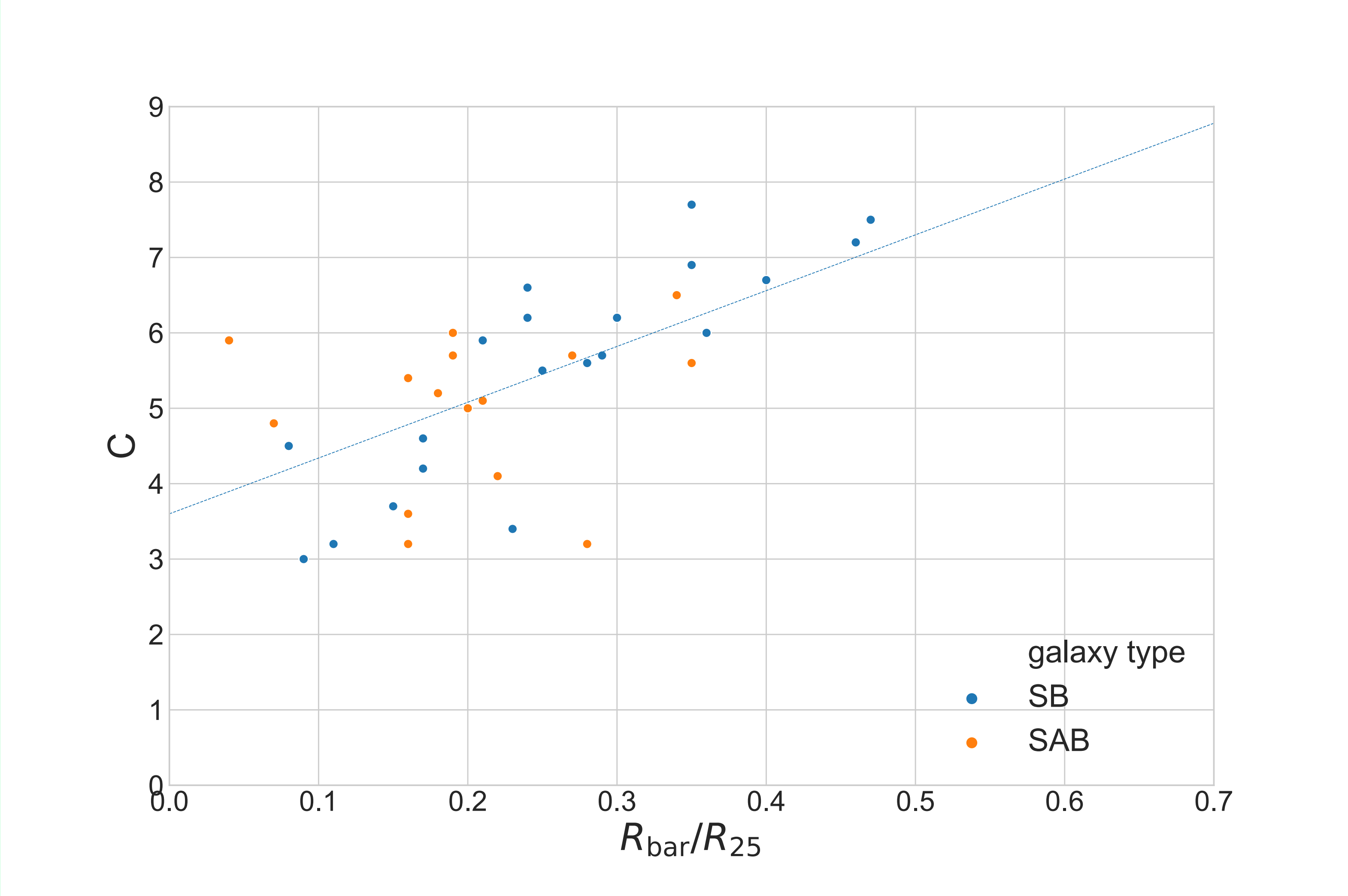
Spearman's rank correlation coefficient is 0.63 with the associated $p-$ value of 3.8×10^{-5})

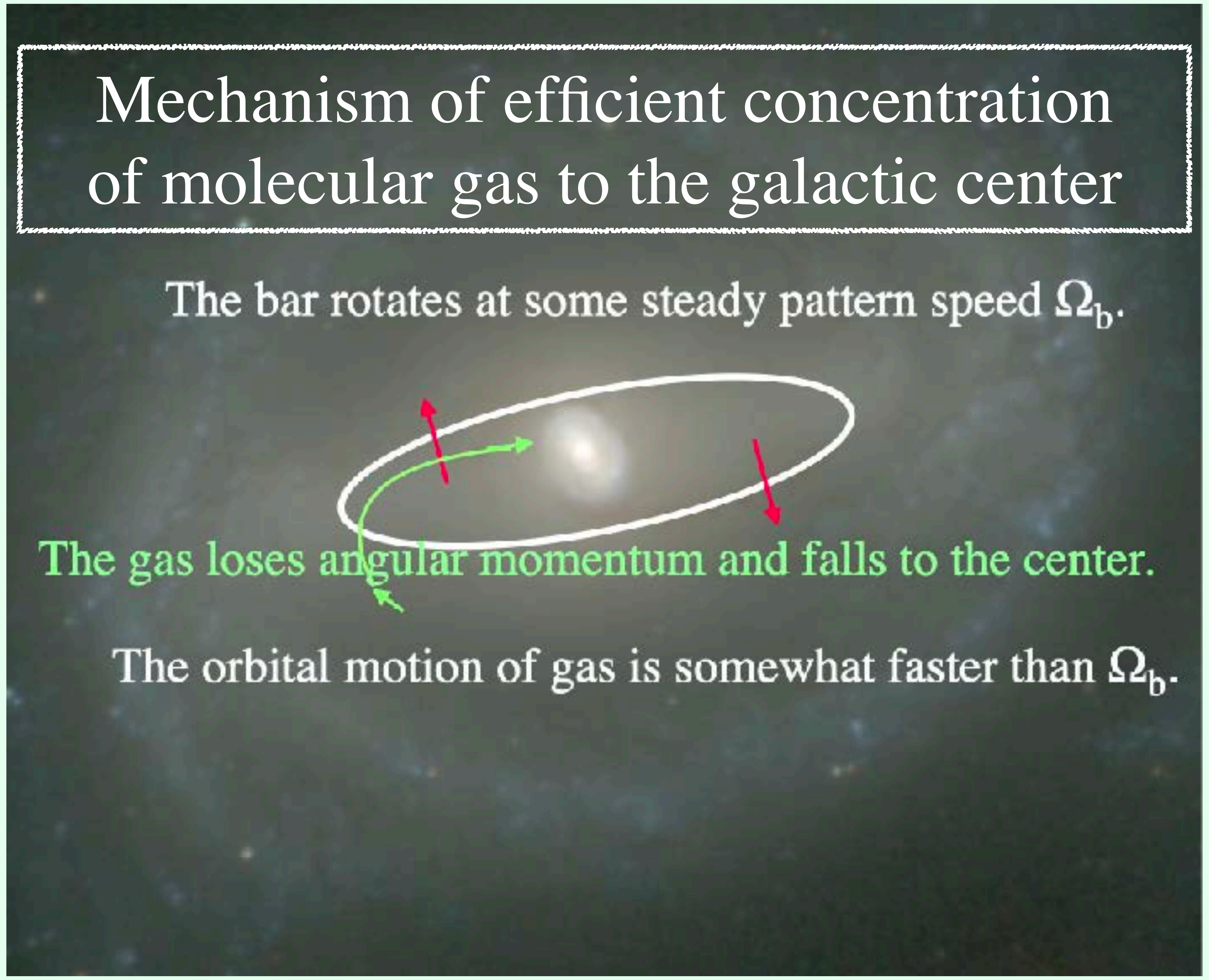
Result & Discussion

This result is consistent with Kuno et al., 2007, which showed that the bar structure efficiently transports molecular gas within the length of the bar toward the center while the role in bringing gas in from the outer parts of the disks is small.



NGC 1433; ALMA, CO (2-1)





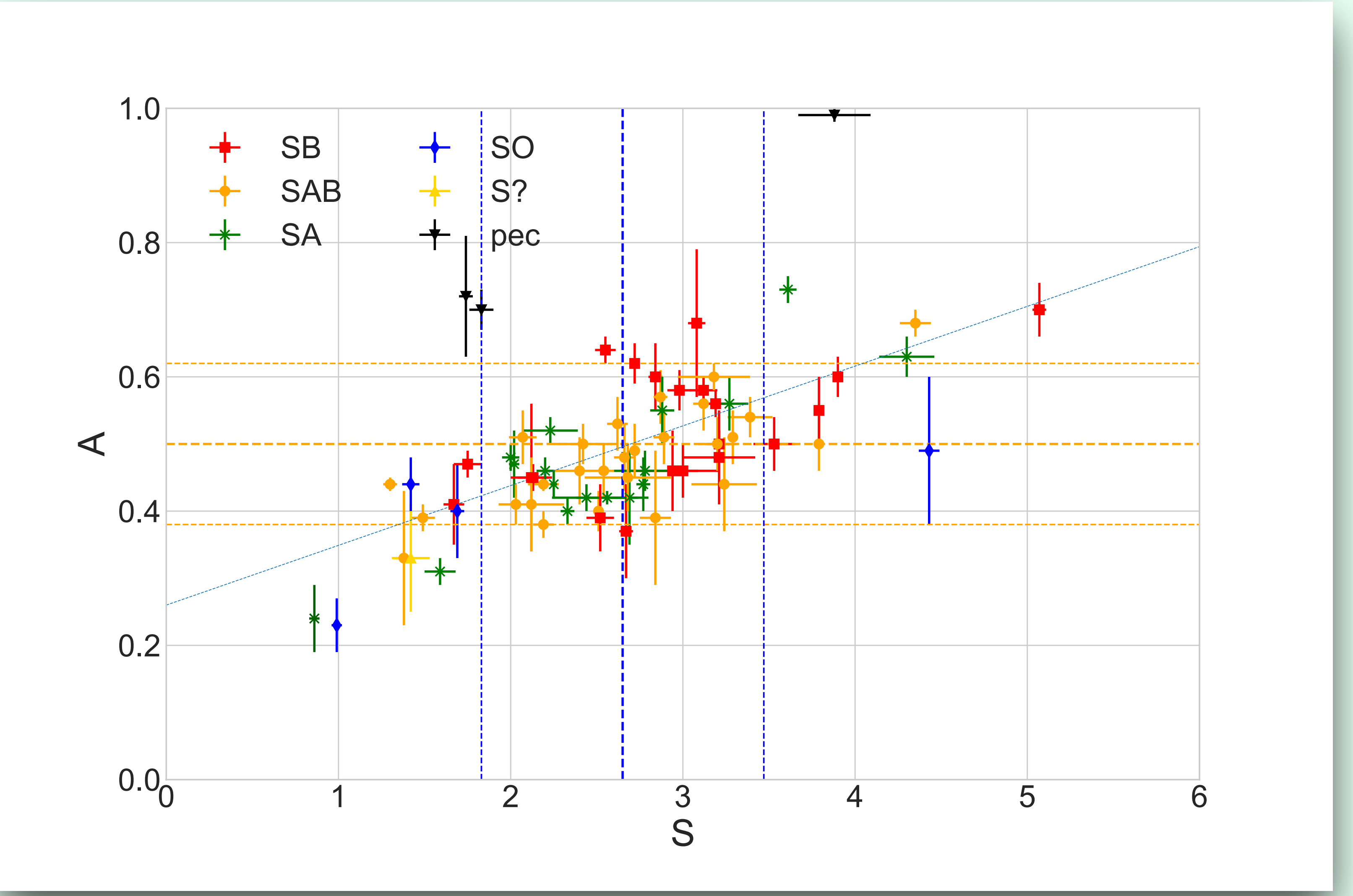
Although the quantitative relationship between the concentration of molecular gas at the Galactic center and the length of the bar structure has not been clarified in Kuno et al., 2007, This study provides quantitative results of this relationship between the two.

Result

This is the first study to examine molecular gas distribution using three model-independent CAS parameters from Conselice (2003).

As a result of this analysis, we made several important findings, as shown in the figure below.

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



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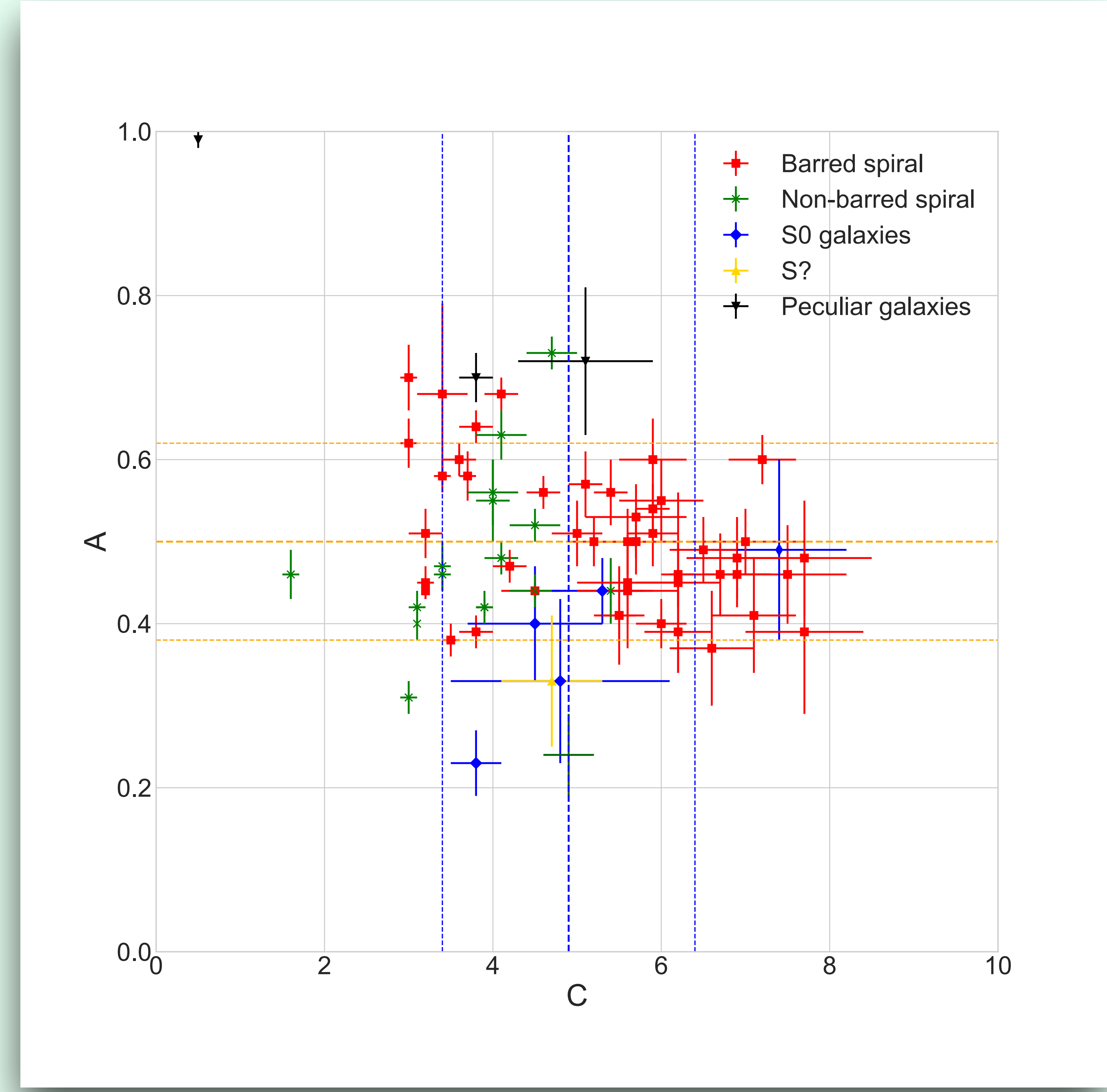
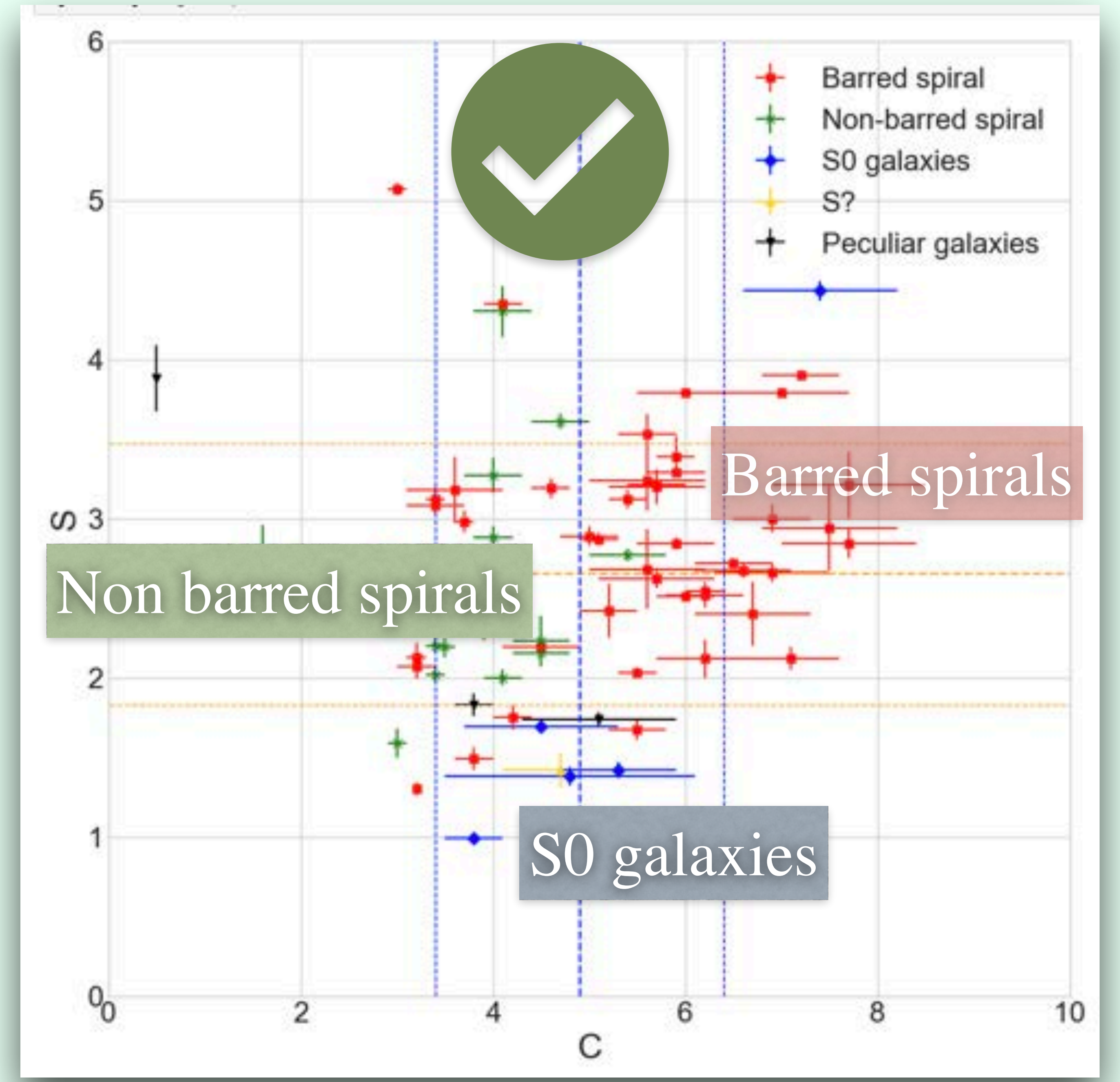
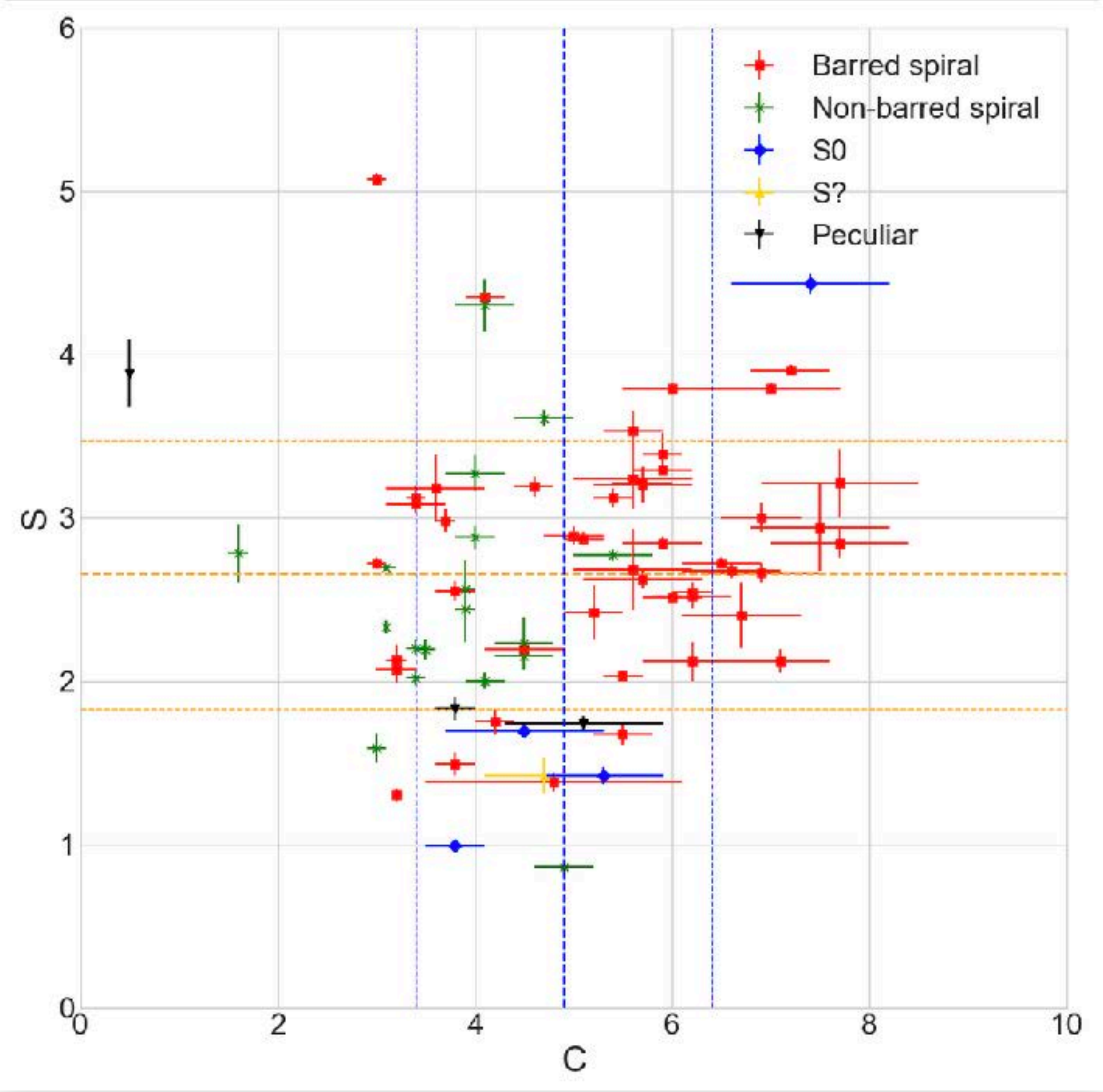


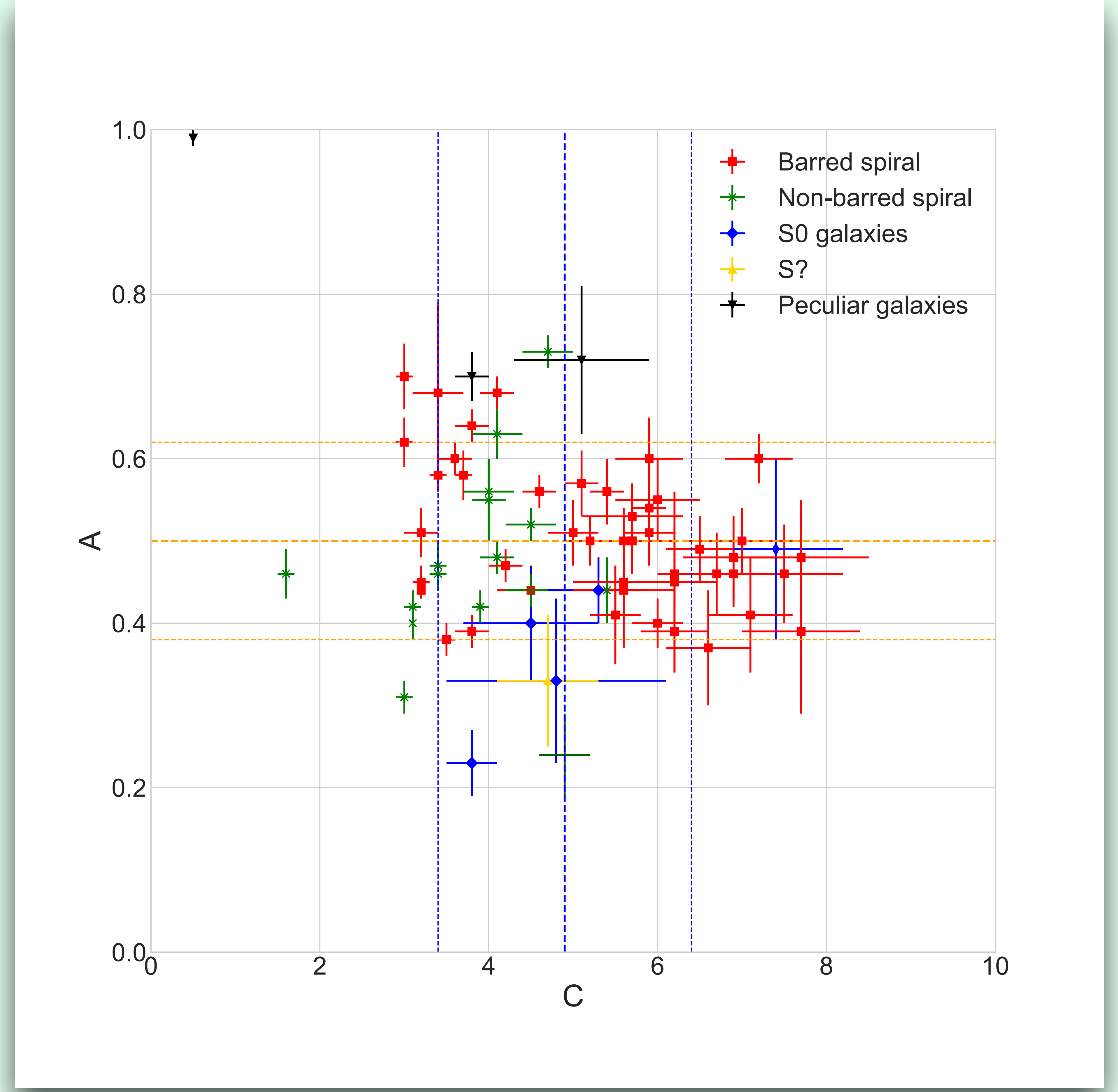
Barred spiral galaxies, non-barred spiral galaxies, and lenticular galaxies are plotted in characteristic positions on the CAS space.



Result & Discussion

The three populations of galaxies, barred spiral galaxies (SB+SAB), non-barred spiral galaxies (SA), and lenticular galaxies (S0), are plotted in characteristic positions on the CAS space.





Result & Discussion

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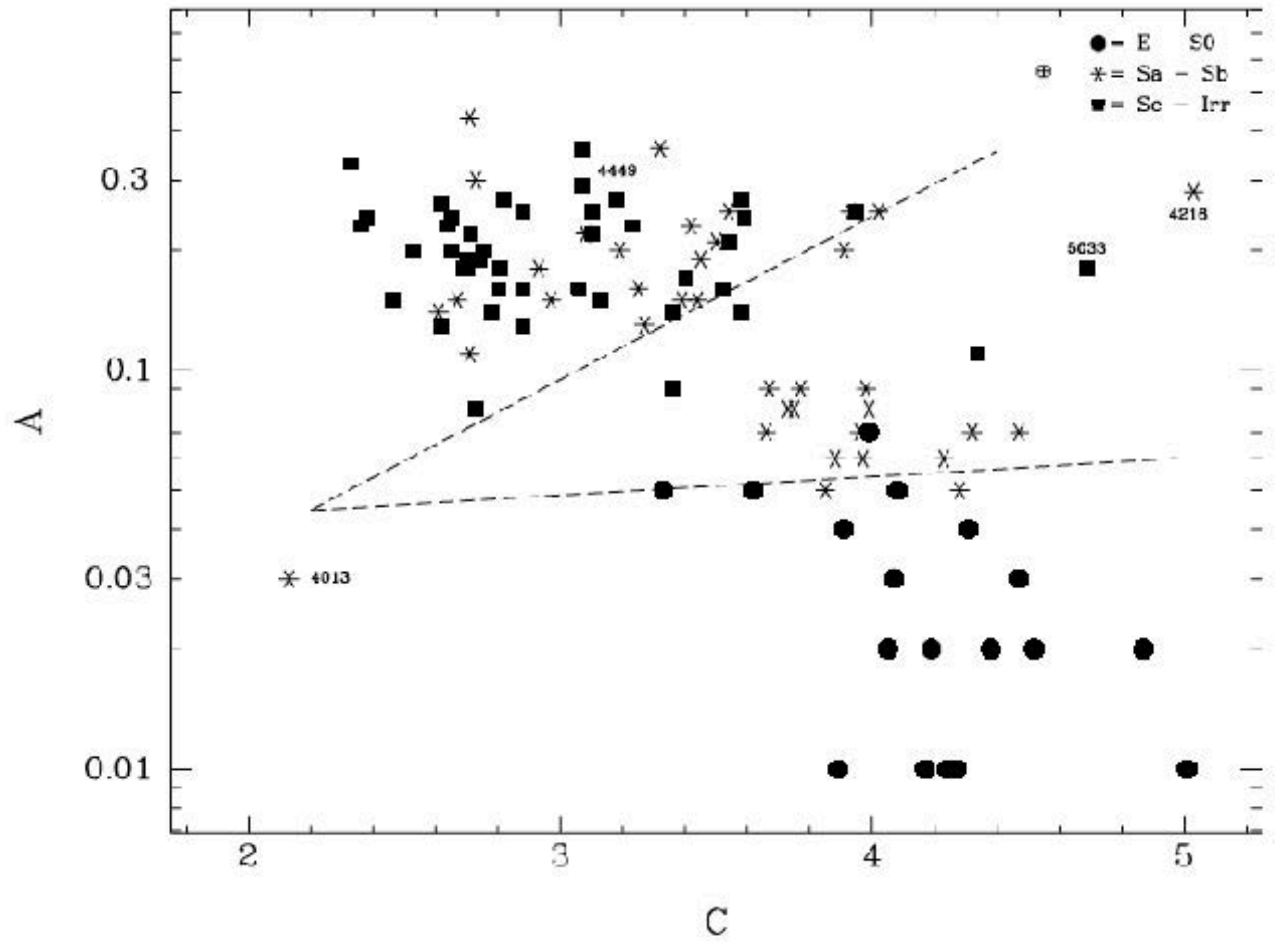
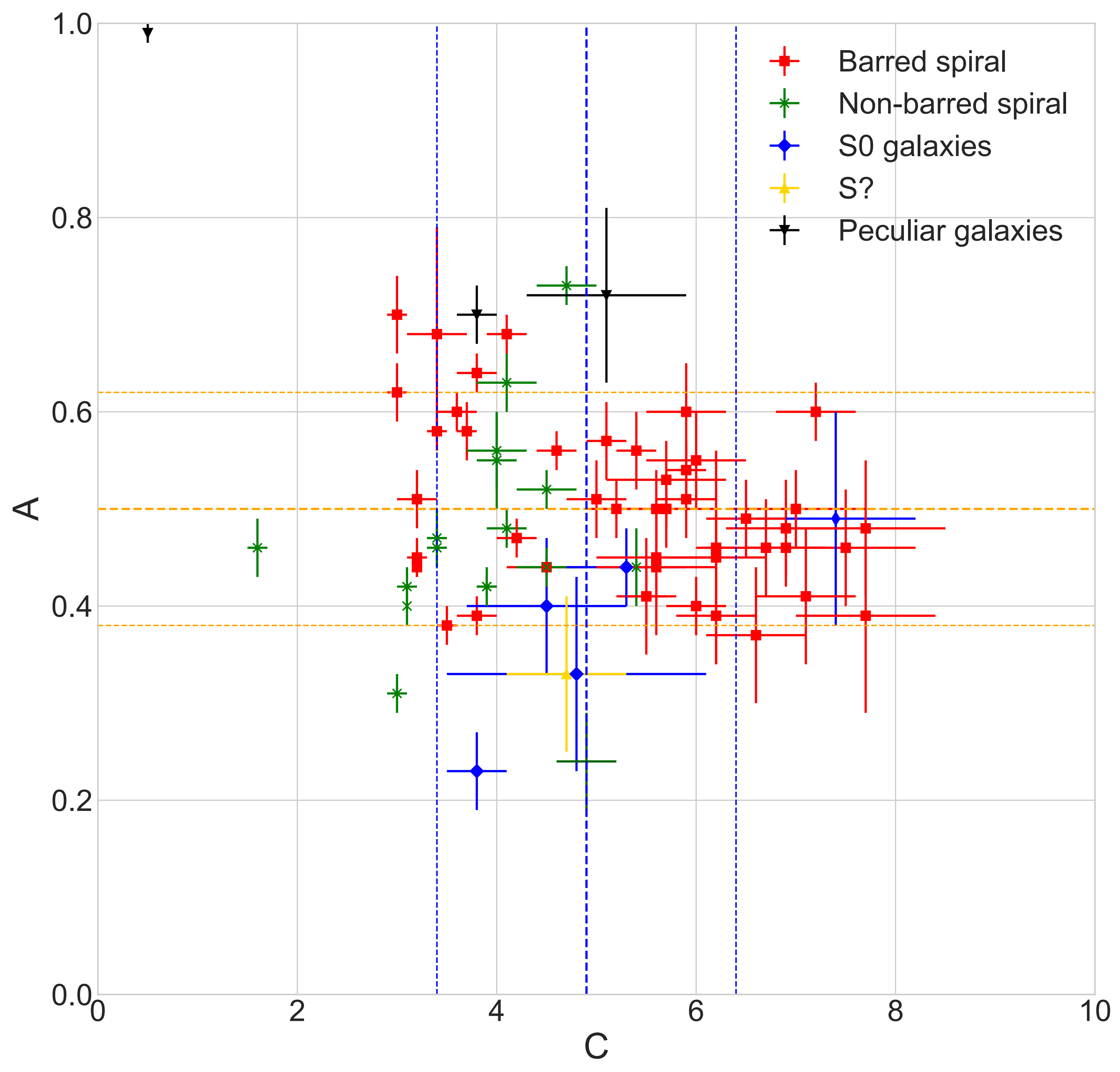


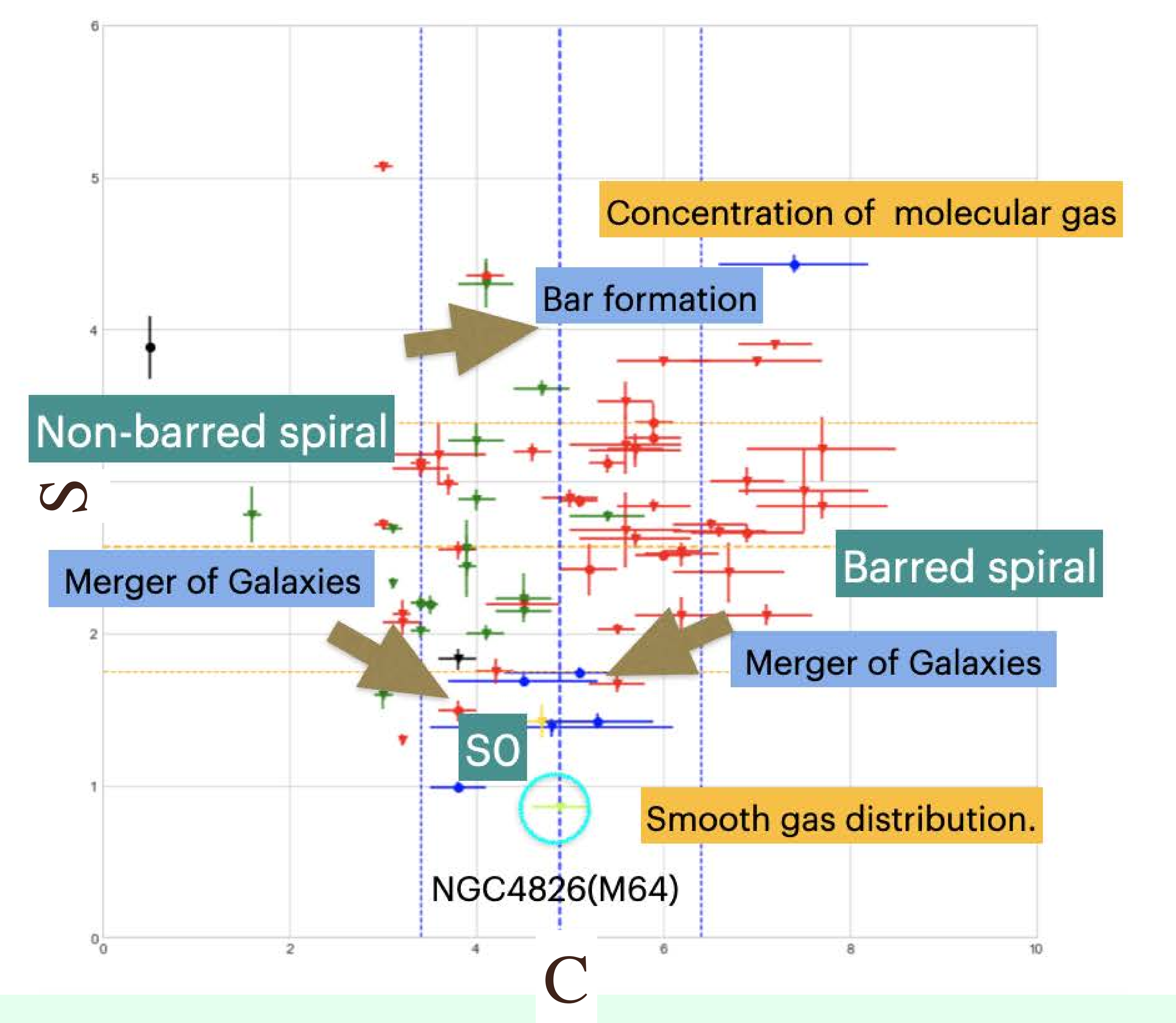
FIG. 5.—Form vs. form parameters for the Frei et al. sample: rest-frame *B*-band image asymmetry (*A*) vs. image concentration (*C*). Outlying objects are labeled and discussed in the text. Dashed lines demark early, intermediate, and late types in our classification scheme. The separation of morphological types is less clear than in Fig. 3, but is comparable with Fig. 4, where the different Hubble types are reasonably segregated.

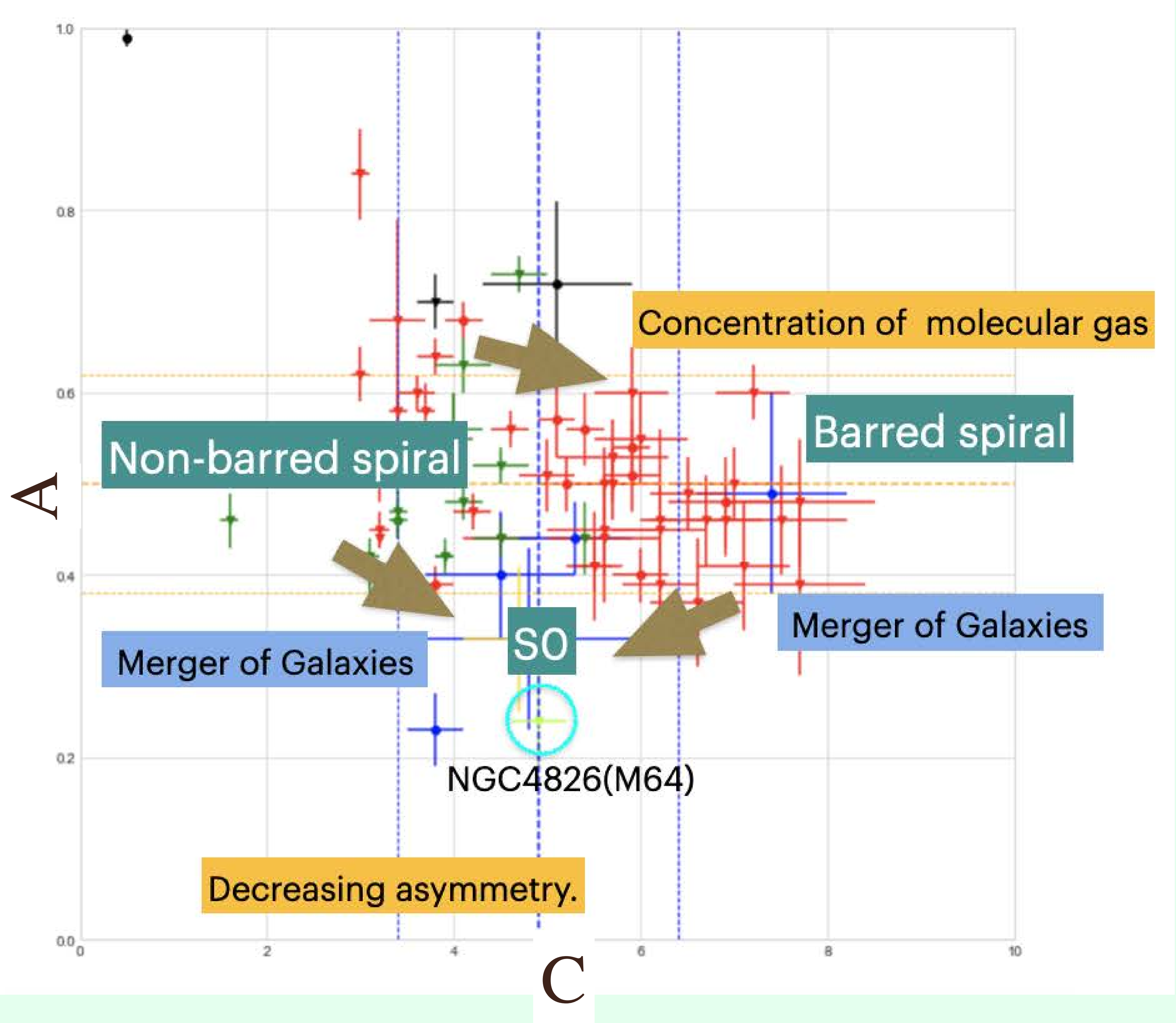
Bershady et al. 2000



Result & Discussion

The most significant result of this study is the history of the distribution morphology of molecular gas in nearby disk galaxies.





The three populations of galaxies, barred spiral galaxies (SB+SAB), non-barred spiral galaxies (SA), and lenticular galaxies (S0), are plotted in characteristic positions on the CAS space.

Summary

✔ Applying CAS methods of quantitative morphometric analysis to the PHANGS-ALMA CO(2-1) data yielded several significant results.

✔ One of the results is that Clumpiness (S) and Asymmetry (A) showed a clear correlation. It suggests that galaxies with a more distorted distribution of molecular gas are more likely to form GMAs.

✔ The results of this analysis indicate that barred spiral galaxies have high central concentrations of molecular gas. This is consistent with the results of previous studies. Our new finding is a positive correlation between C and bar length (R_{bar}/R_{25}).

✔ In this study, we make a remarkable classification of non-barred spiral galaxies and barred spiral galaxies, taking advantage of the characteristics of the CO(2-1) emission line data. Quantitatively and statistically analyzing molecular gas morphology in nearby disk galaxies for the first time classified barred spiral galaxies (SB+SAB), non-barred spiral galaxies (SA), and lenticular galaxies (S0) on CAS space.