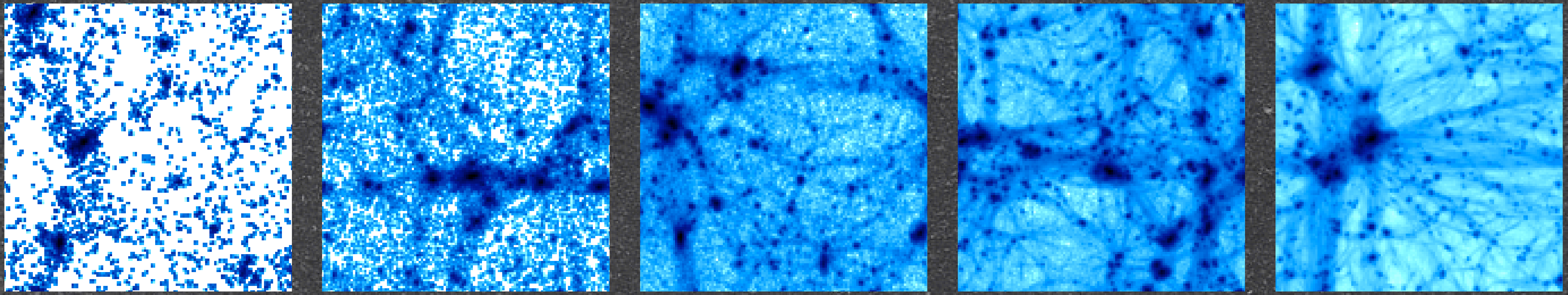

Shedding light on *j*

The specific angular momentum of disc galaxies and its connection with galaxy morphology, bar structure and disc gravitational instability

Alessandro Romeo

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Tack, Oscar! Merci, Florent!

- ➤ You are not only my closest collaborators and dearest friends, but also part of my family ❤️ ❤️

- ➤ And many thanks to all of you for participating in such an amazing workshop! GRAZIE !!

The specific angular momentum

- $j \equiv J/M$ is one of the most fundamental galaxy properties!

➤ Measuring and analysing j allows relating the dynamics of present-day galaxies to models of galaxy formation and evolution (see, e.g., Combes 2020; Obreschkow 2020).

j for the 'baryons' (= stars + atomic gas)

- j_b has been measured for disc galaxies of all morphological types: from lenticulars to blue compact dwarfs.

➤ We use high-quality data with a wide dynamic range from the SPARC and the LITTLE THINGS galaxy samples (Read et al. 2017; Posti et al. 2018, 2019; Mancera Piña et al. 2021).

j for the dark matter halo

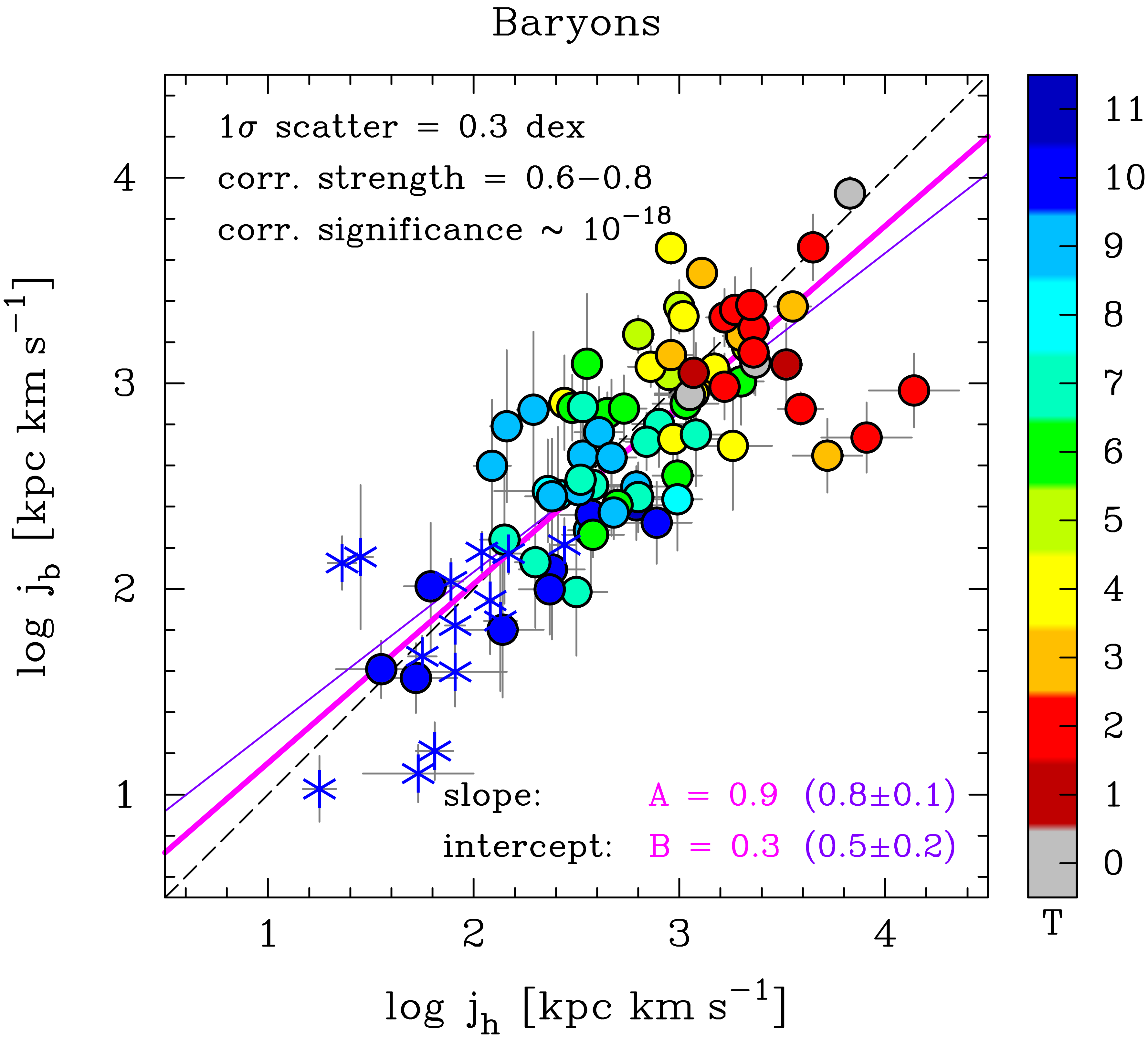
- j_h is not a truly observable galaxy property, but we 'measure' j_h via two fundamental relations:

➤ $j_\mathrm{h} \propto \lambda\, M_\mathrm{h}^{2/3}$ (e.g., Romanowsky & Fall 2012)

➤ $$p(\lambda)\,\mathrm{d}\lambda = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{(\ln\lambda - \ln\lambda_0)^2}{2\sigma^2}\right] \frac{\mathrm{d}\lambda}{\lambda}$$

$$\lambda_0 \approx 0.035$$
$$\sigma \approx 0.50 \;\; (0.22\,\mathrm{dex})$$
(e.g., Bullock et al. 2001)

Our analysis: a first view of j_b vs j_h



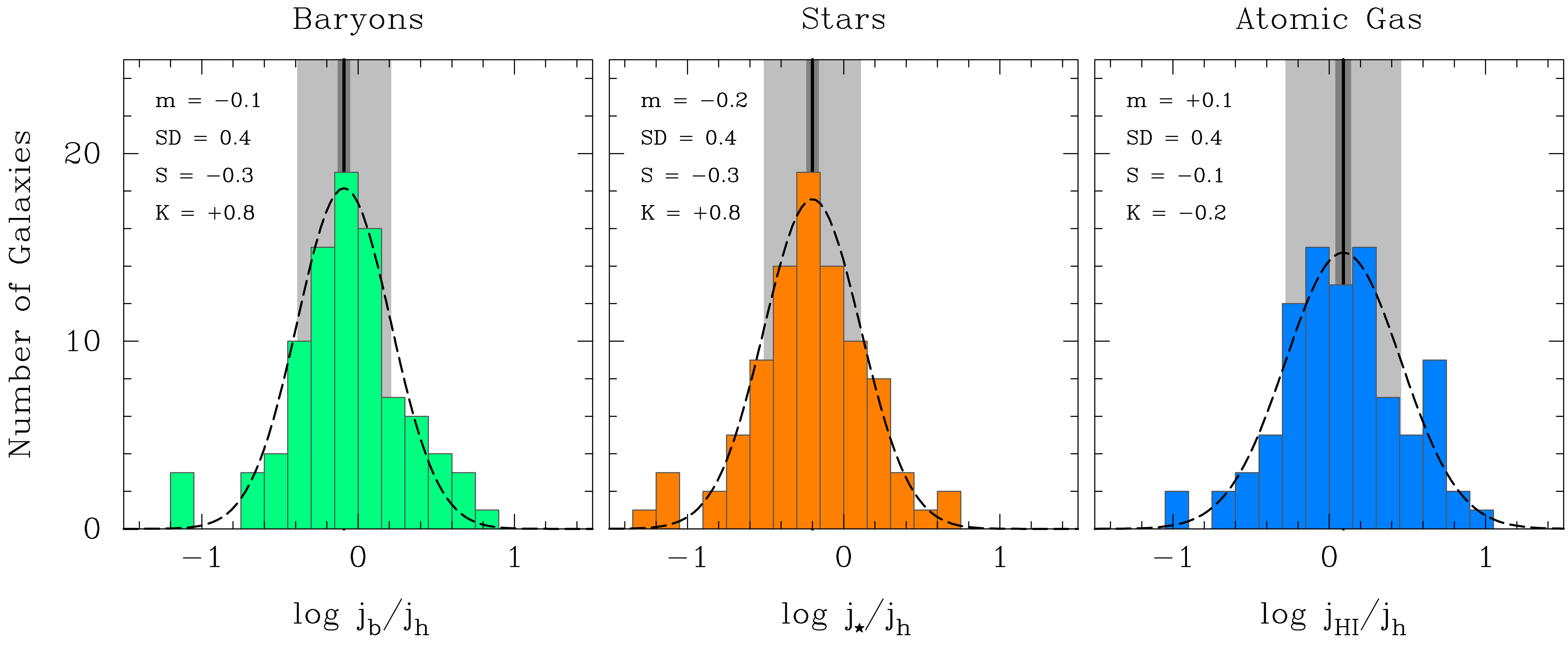
Romeo, Agertz & Renaud (2023), MNRAS, 518, 1002

The baryonic-to-halo *j* ratio

- $j_{\rm b}/j_{\rm h}$ is thus a quantity of great theoretical importance!

➤ $j_{\rm b}/j_{\rm h}$ measures the fraction of j retained by baryons, i.e. how well j is conserved in the process of galaxy formation and evolution (see, e.g., Cimatti et al. 2020).

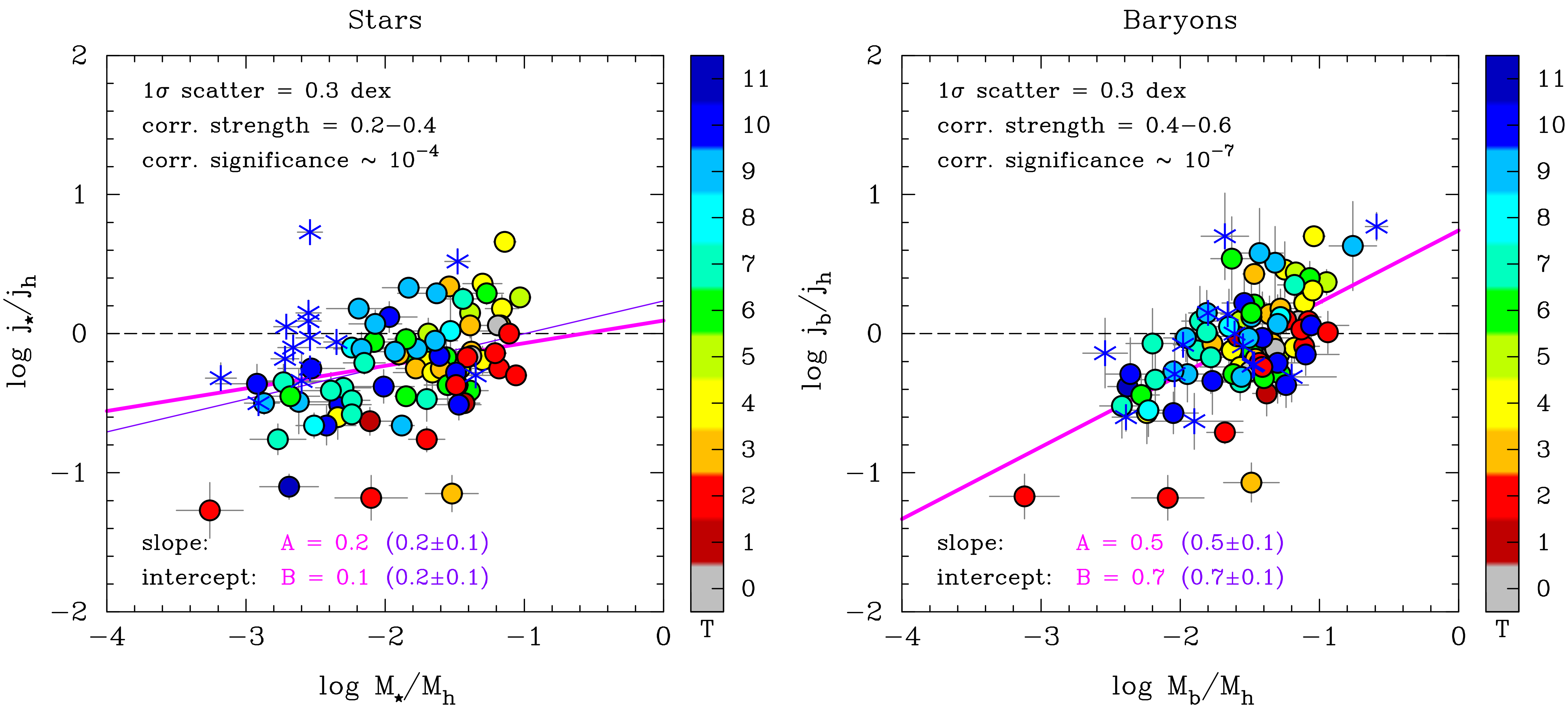
Our analysis: basic constraints



$\Delta j/j \approx$ -20% $\Delta j/j \approx$ -40% $\Delta j/j \approx$ +20%

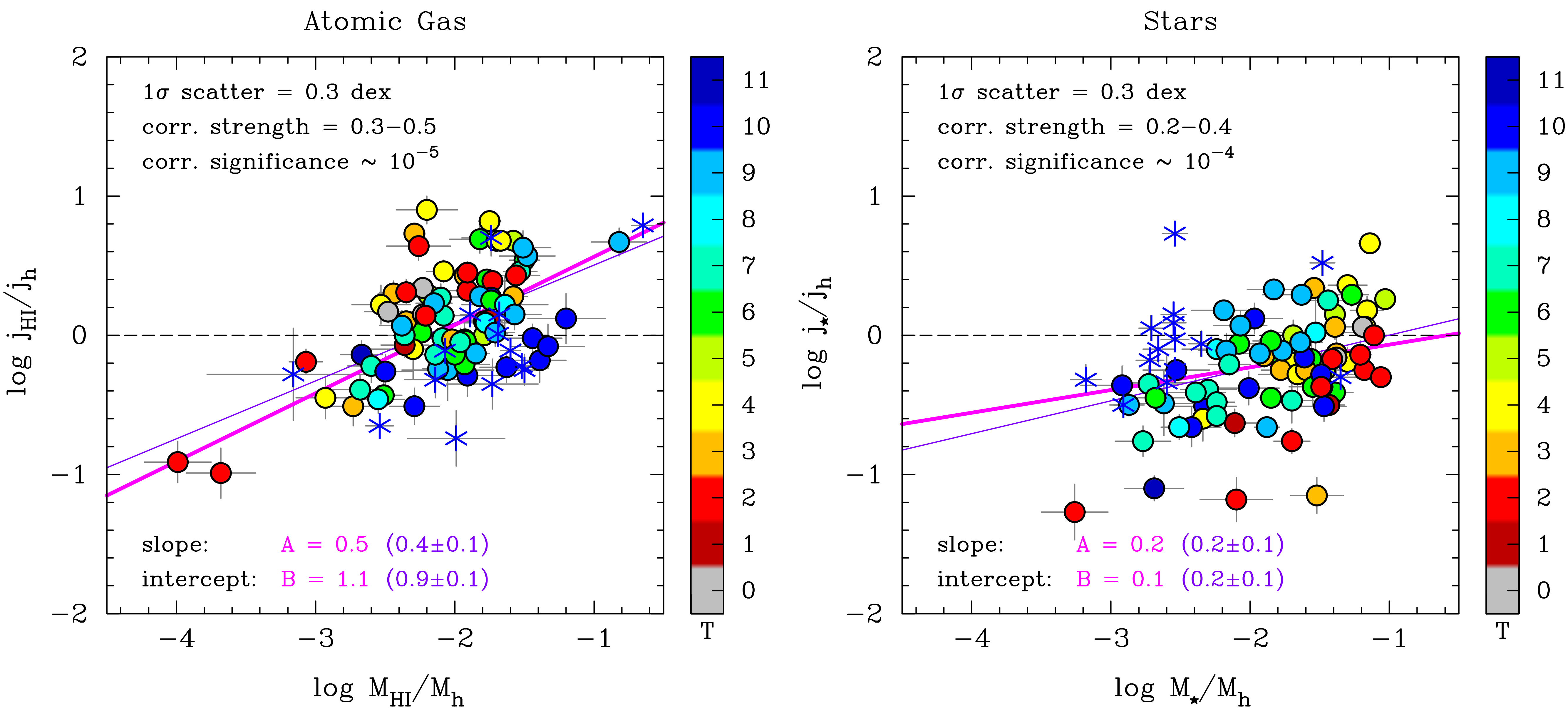
Romeo, Agertz & Renaud (2023), MNRAS, 518, 1002

Our analysis: systematic trends



Romeo, Agertz & Renaud (2023), MNRAS, 518, 1002

Our analysis: systematic trends



Romeo, Agertz & Renaud (2023), MNRAS, 518, 1002

BARRED versus NON-BARRED galaxies

- The core of the problem:

Are barred galaxies characterized by values of *j* that are systematically different from those of non-barred galaxies?

➤ Observational test of the Efstathiou, Lake & Negroponte (1982) bar instability criterion

➤ Self-regulation of galaxy discs driven by local gravitational instabilities

The ELN criterion

$$\mathcal{E} \equiv \frac{V_{\rm max}}{(GM_{\rm d}/R_{\rm d})^{1/2}} \lesssim 1$$ Efstathiou et al. (1982)

$$\mathcal{E}^2 \approx \lambda \frac{(j_{\rm d}/j_{\rm h})}{(M_{\rm d}/M_{\rm h})} \lesssim 1$$ Mo et al. (1998)

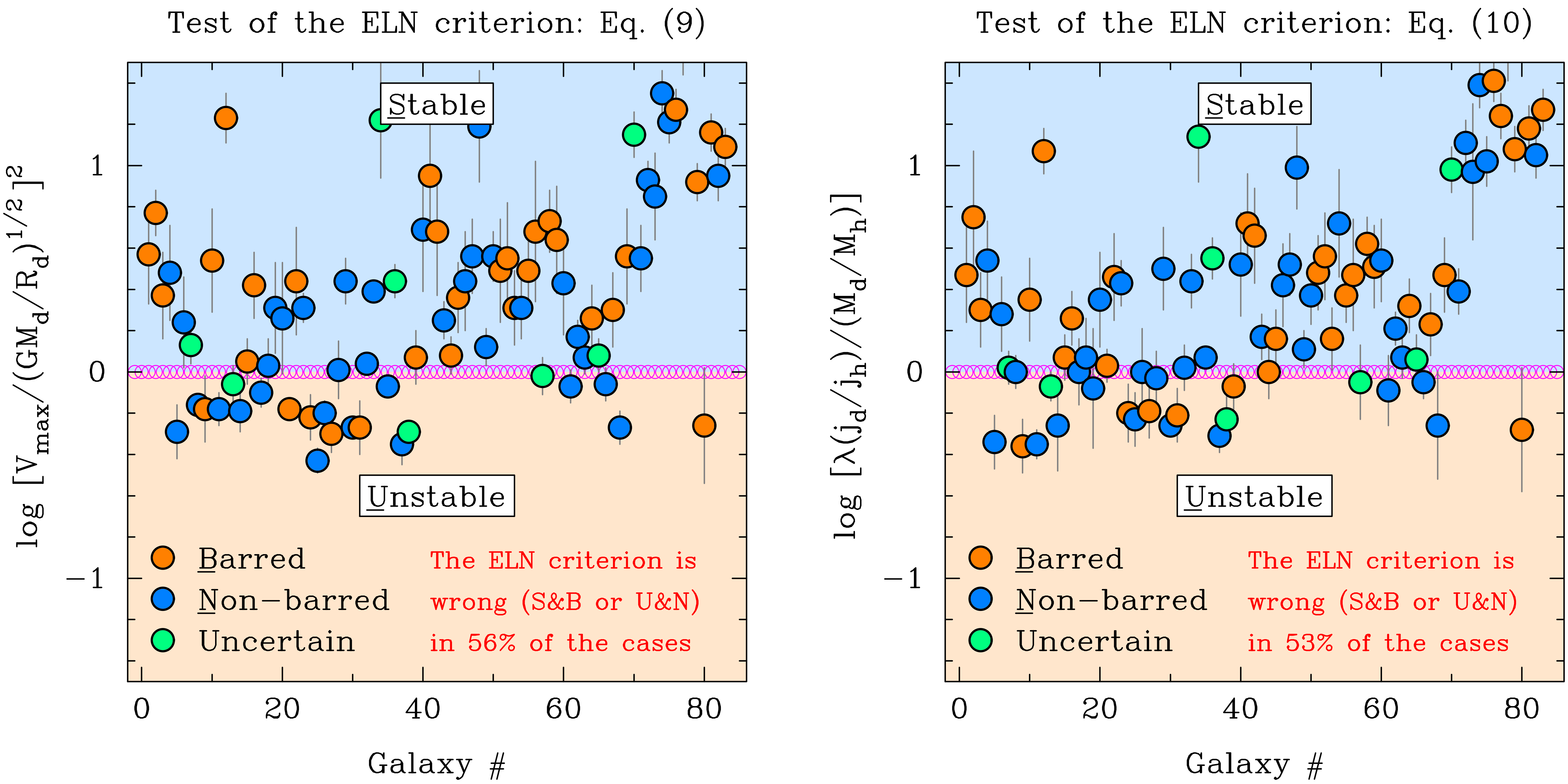
Observational test of the ELN criterion

- Motivations behind such a test:

➤ The ELN criterion is used by all current semi-analytic models of galaxy formation and evolution to ‘create’ bulges in disc galaxies that are predicted to be bar unstable.

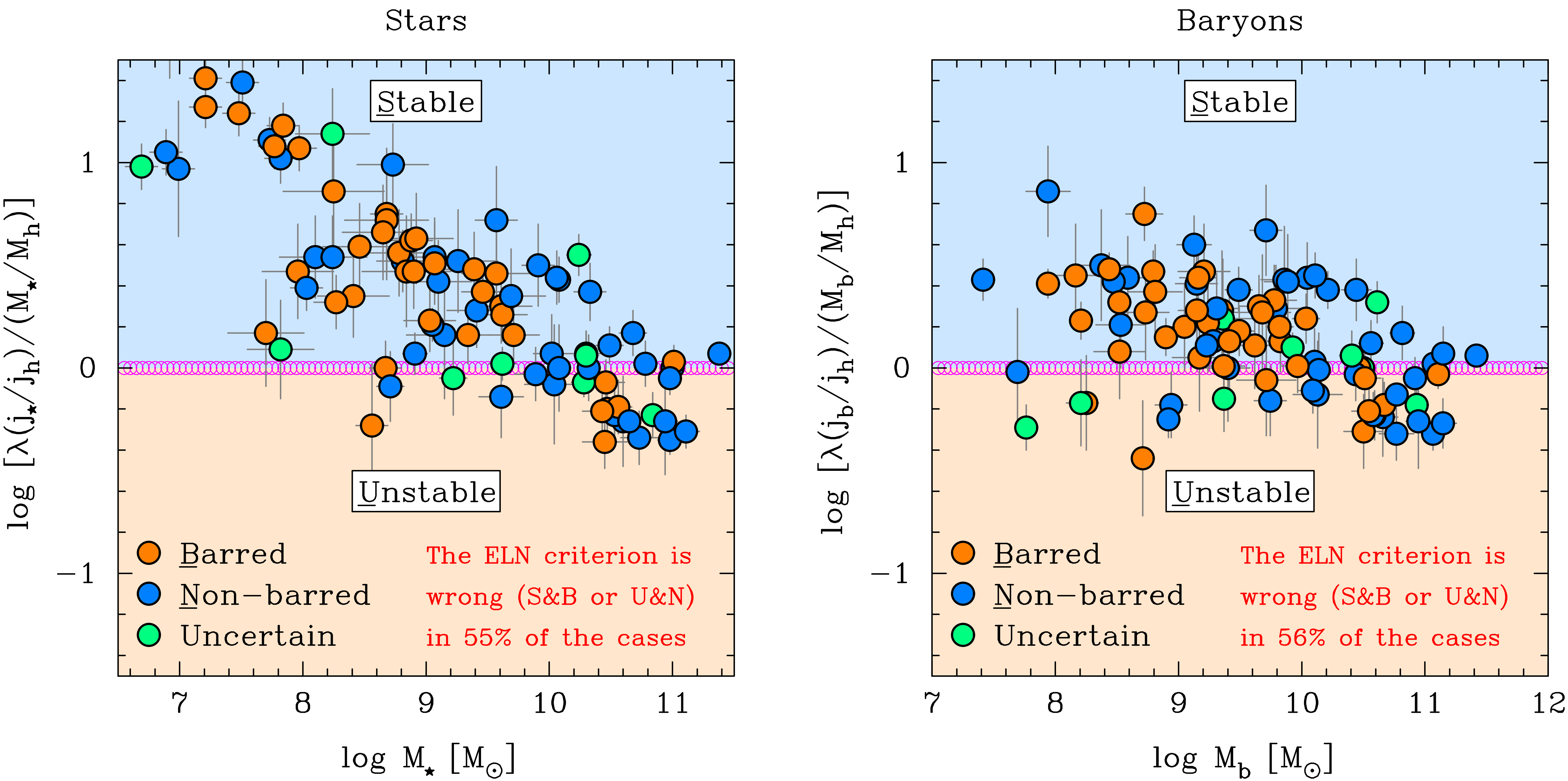
➤ This is the first observational test performed on the ELN criterion; and it is statistically unbiased.

Our analysis: overall accuracy



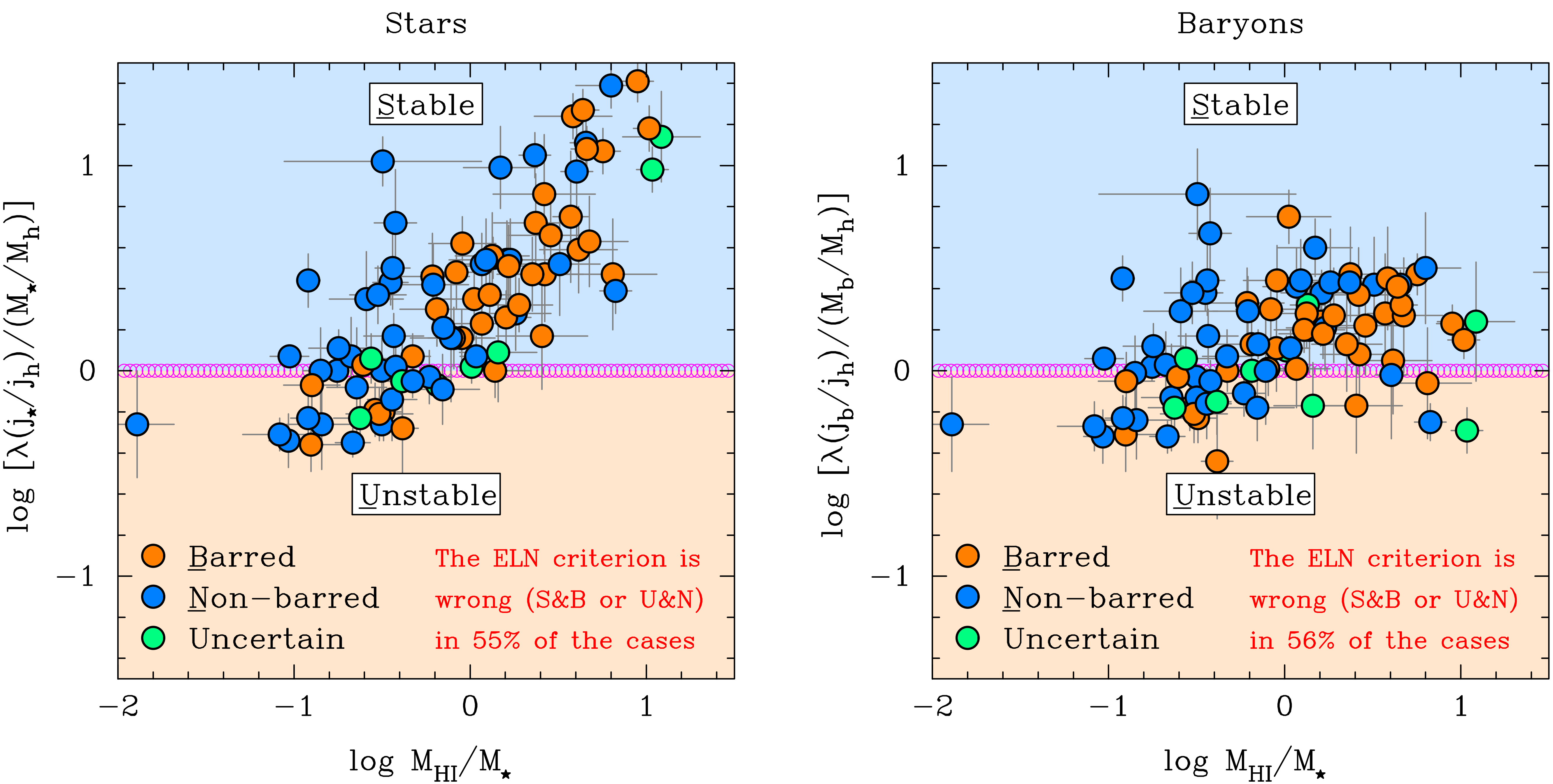
Romeo, Agertz & Renaud (2023), MNRAS, 518, 1002

Our analysis: systematic trends



Romeo, Agertz & Renaud (2023), MNRAS, 518, 1002

Our analysis: systematic trends



Romeo, Agertz & Renaud (2023), MNRAS, 518, 1002

Self-regulation of galaxy discs

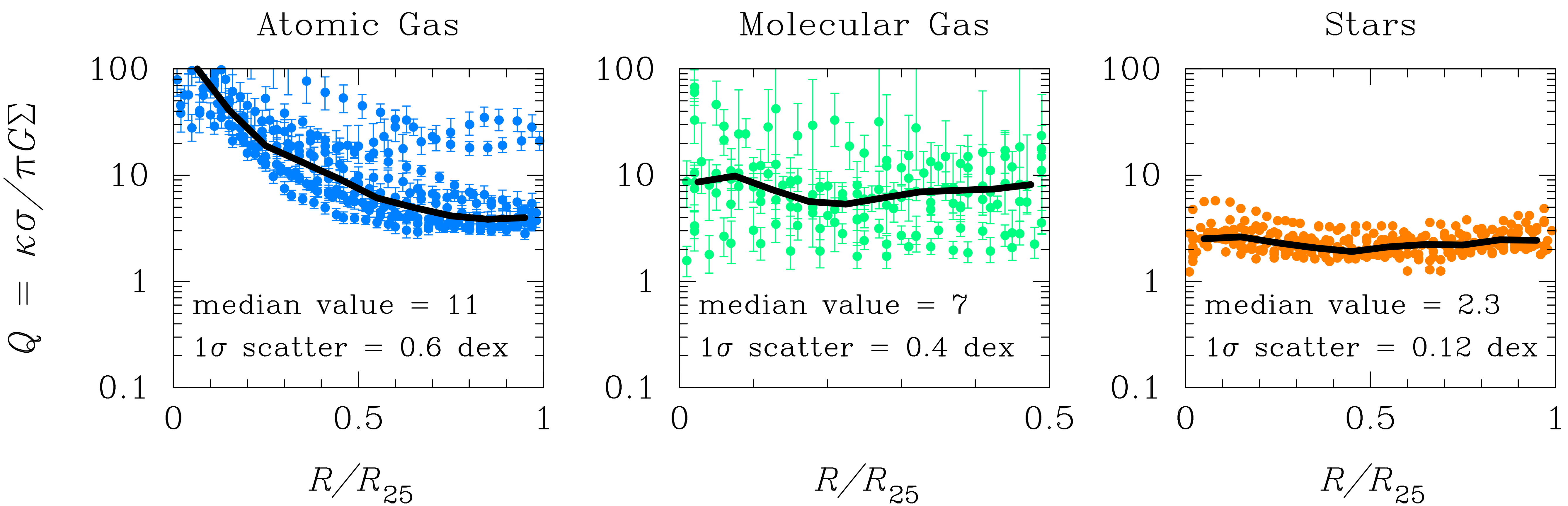
- A fundamental physical process that constrains how gravitationally (un)stable galaxy discs are.

What is the constraint?

➤ $$Q \equiv \frac{\kappa\sigma}{\pi G\Sigma}$$ Toomre (1964)

$Q \approx 1$? No: theoretically motivated BUT mostly inconsistent with observations!

THINGS, HERACLES and SINGS



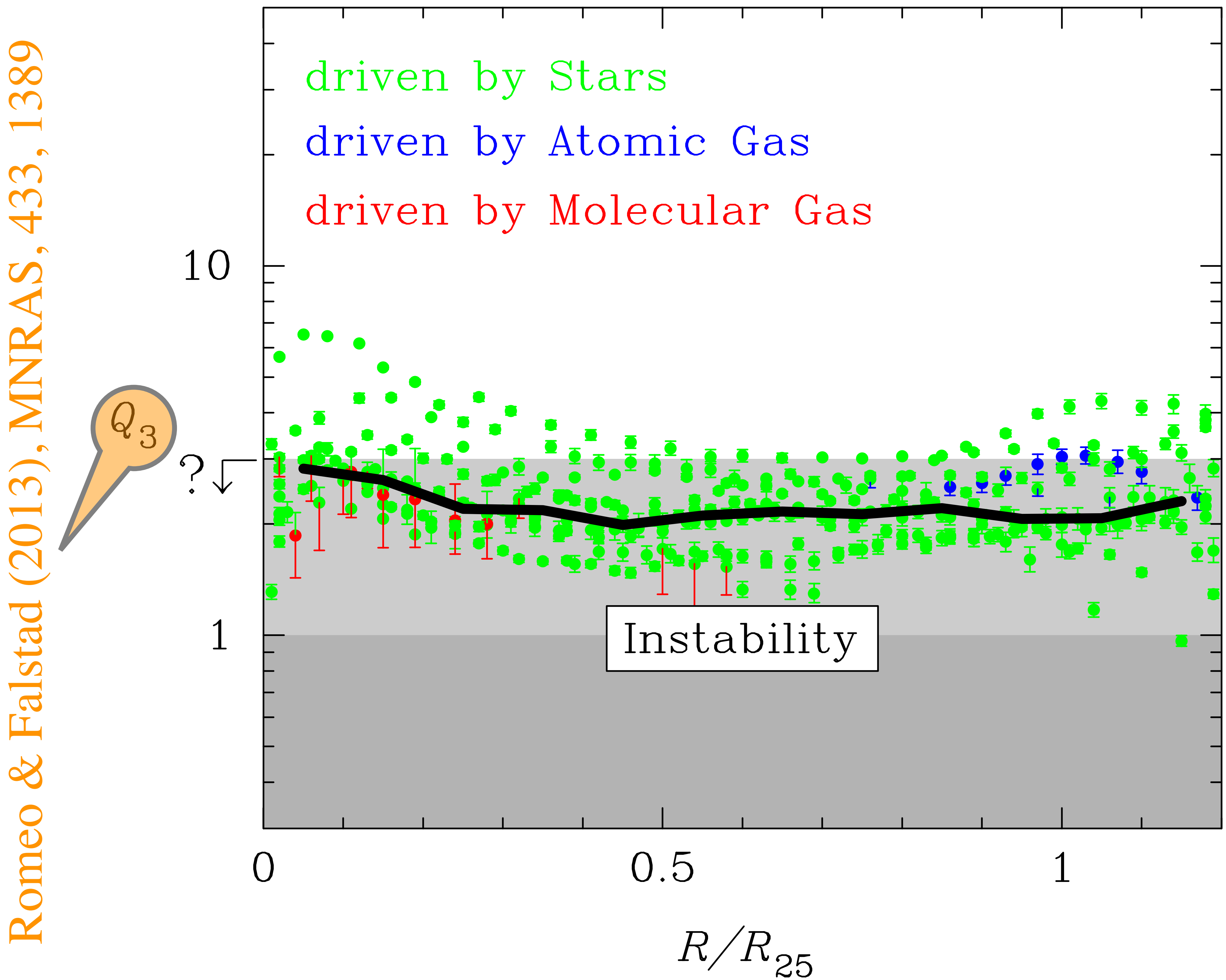
Romeo (2020), MNRAS, 491, 4843

The constraint on the disc as a whole

➤ $$\frac{1}{\mathcal{Q}_{\mathrm{RF}}} = \sum_{i=1}^{N} \frac{W_i}{T_i Q_i}$$ Romeo & Falstad (2013)

$\mathcal{Q}_{\mathrm{RF}} \approx$ 2-3: theoretically motivated AND fully consistent with observations!

THINGS, HERACLES and SINGS



Romeo & Mogotsi (2017), MNRAS, 469, 286

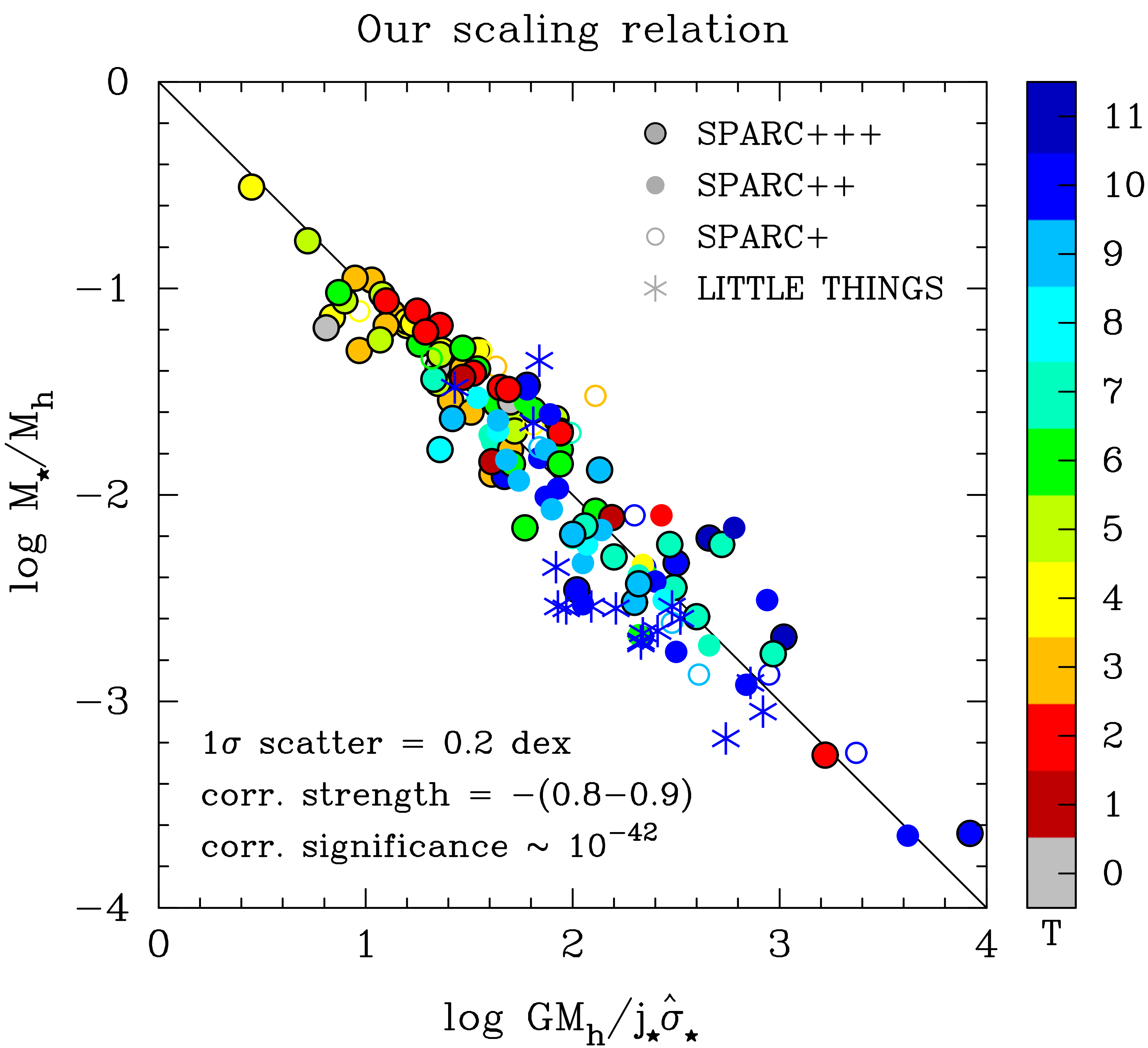
The constraint on each disc component

➤ $$\frac{j_i \hat{\sigma}_i}{G M_i} \approx 1 \quad \text{for } i = \star, \text{H I}, \text{H}_2$$ Romeo (2020)

☞ $\langle Q_\star \rangle \approx$ 2-3, $\langle Q_{\rm HI} \rangle \sim$ 10, $\langle Q_{\rm H2} \rangle \sim$ 10:

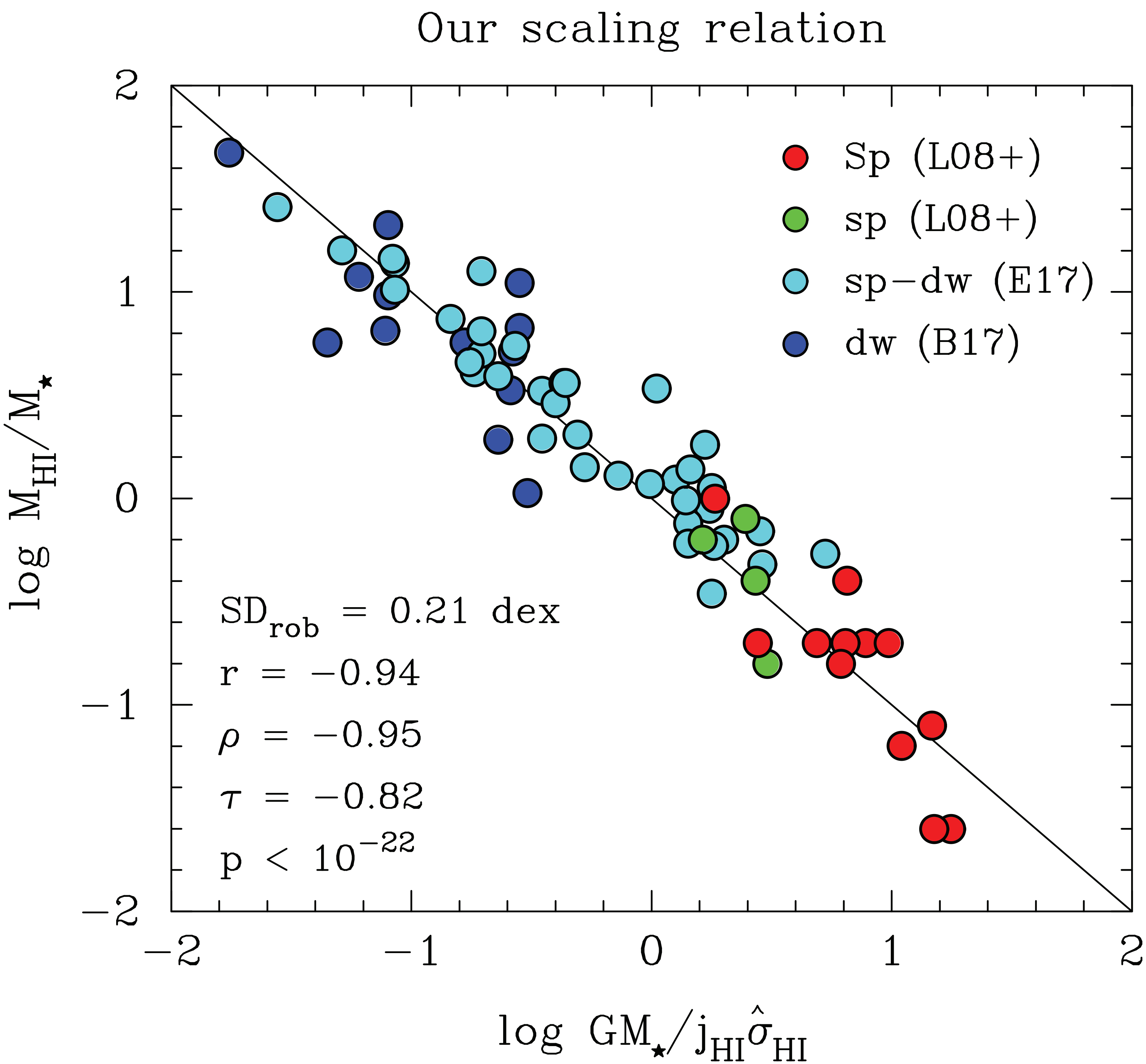
fully consistent with observations AND
more predictive than $Q_{\rm RF} \approx$ 2-3!

SPARC and LITTLE THINGS



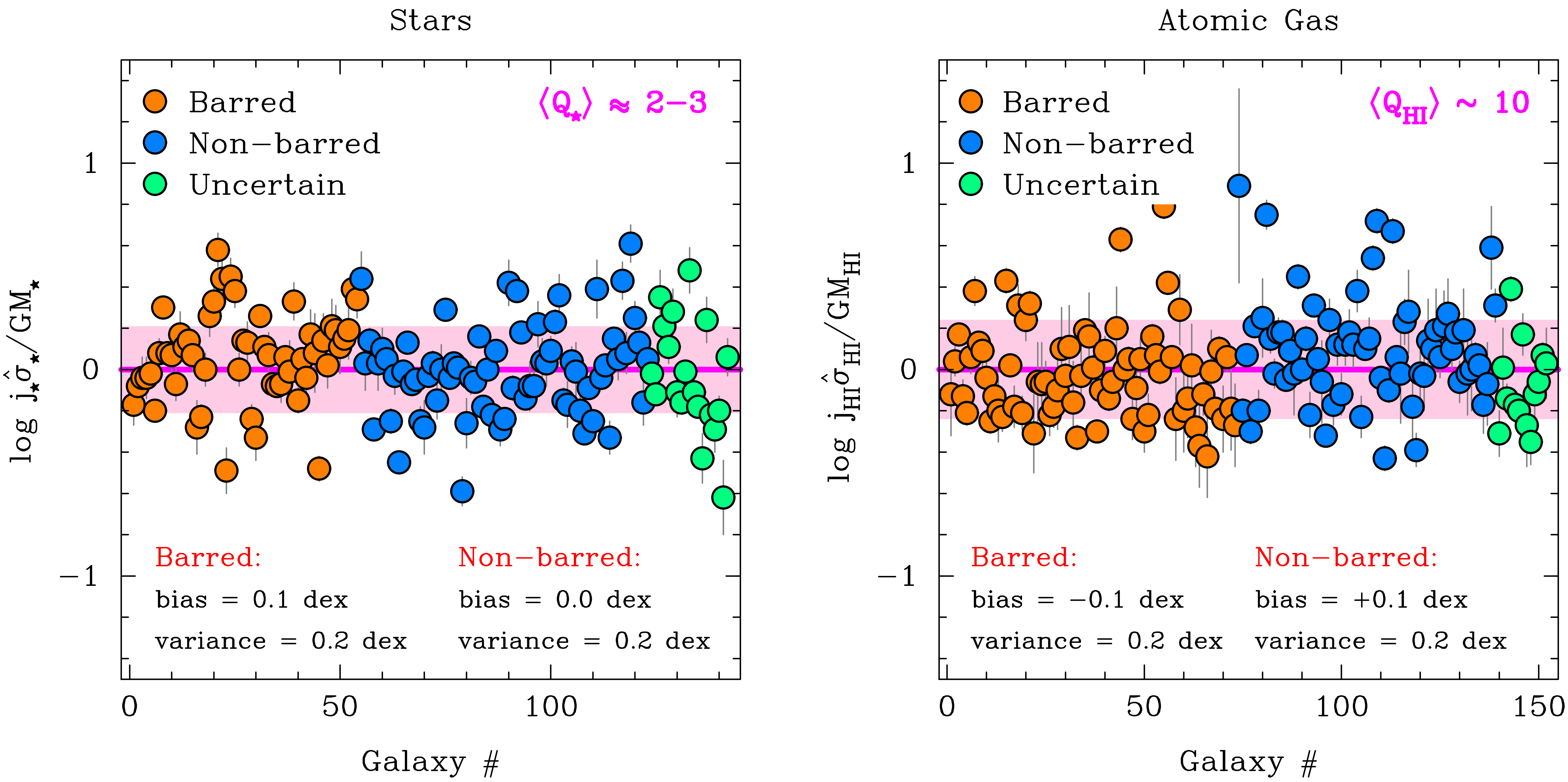
Romeo, Agertz & Renaud (2020), MNRAS, 499, 5656

THINGS, WHISP and LITTLE THINGS



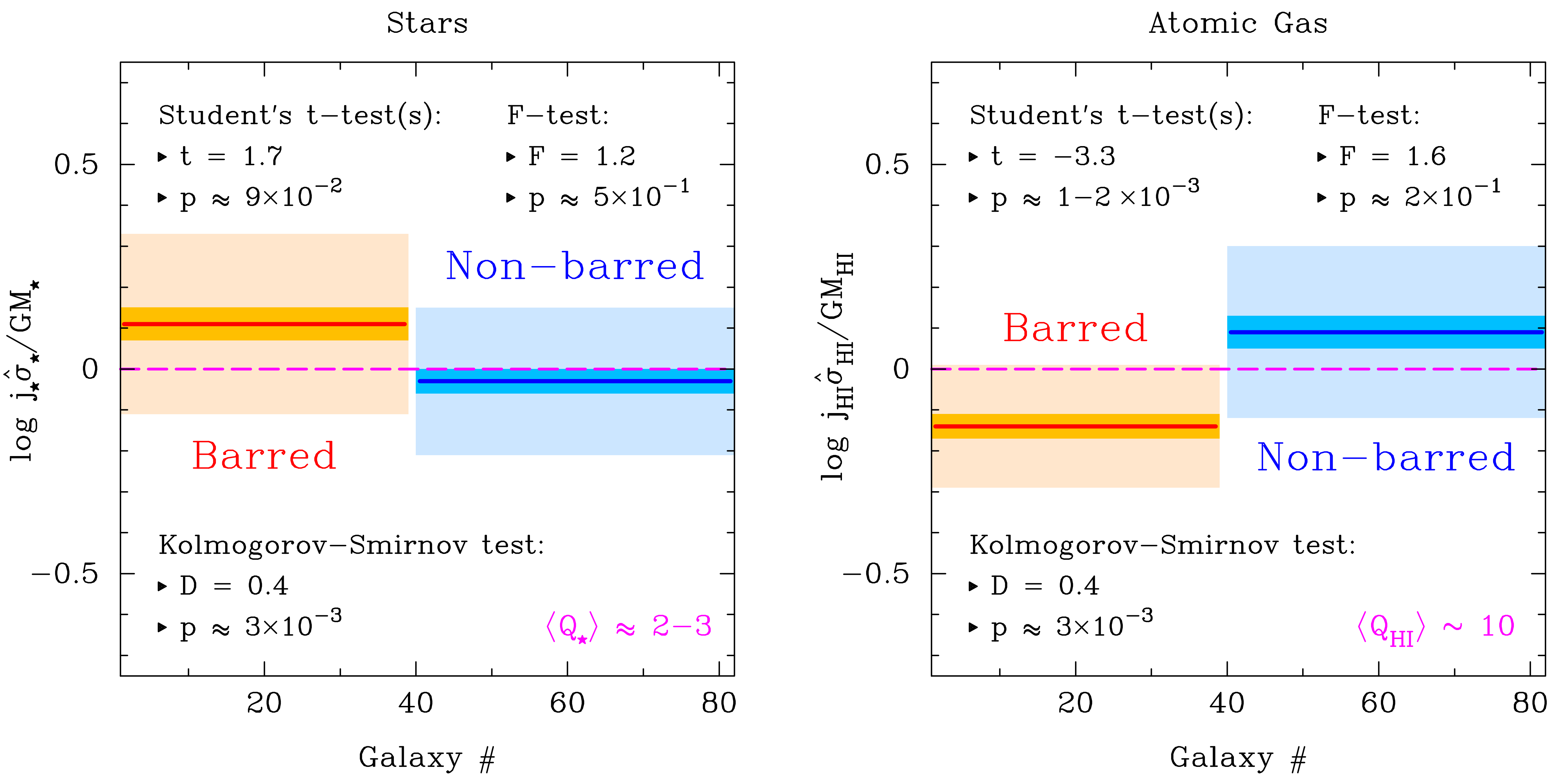
Romeo (2020), MNRAS, 491, 4843

Our analysis: systematic trends



Romeo, Agertz & Renaud (2023), MNRAS, 518, 1002

Our analysis: further tests



Romeo, Agertz & Renaud (2023), MNRAS, 518, 1002

What do we learn?

➤ It is amazingly challenging to characterize barred galaxies from a gravitational instability point of view!

➤ This has important implications especially for semi-analytic modelling of galaxy formation and evolution.

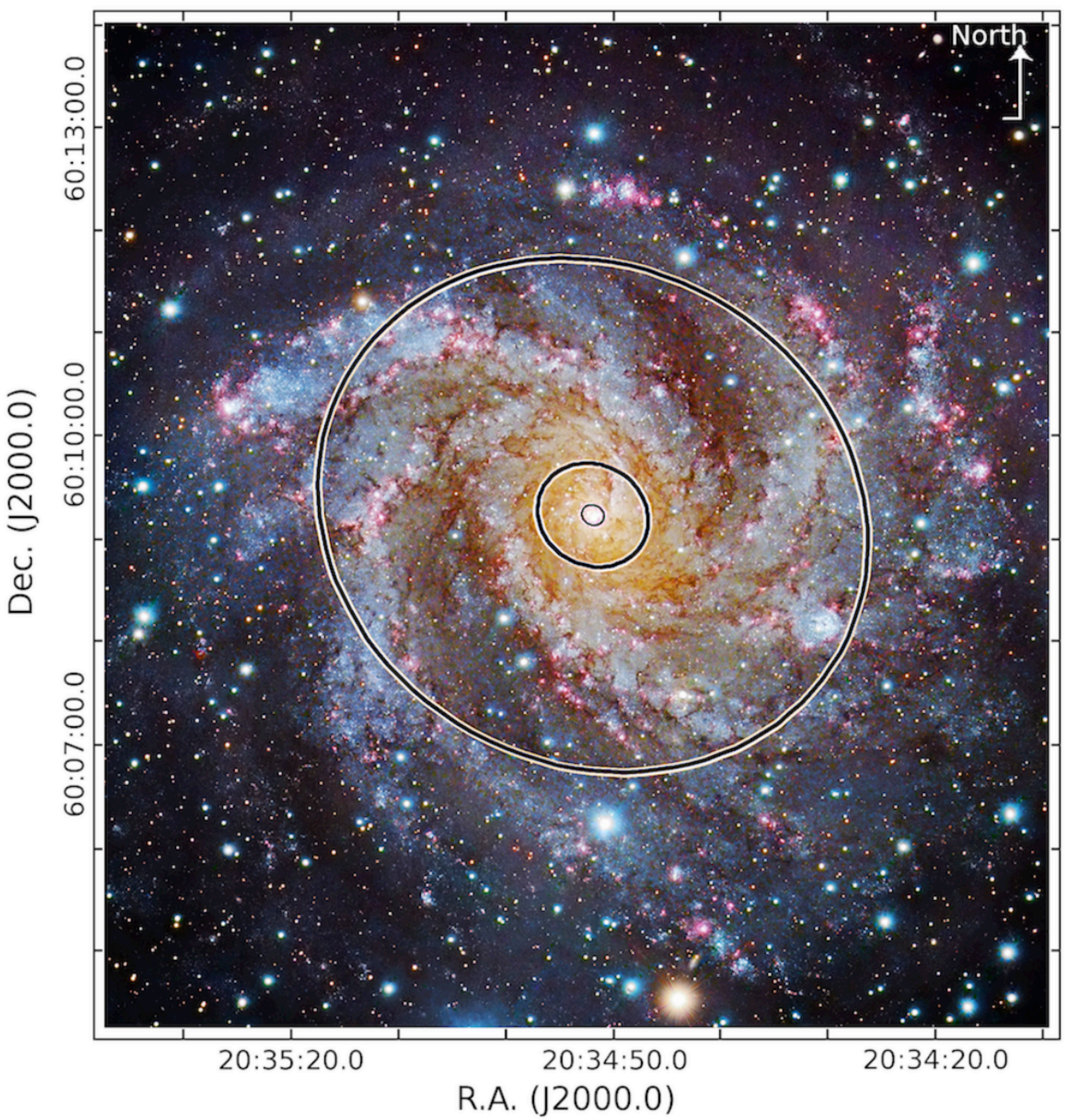
But this is not the end of the story!

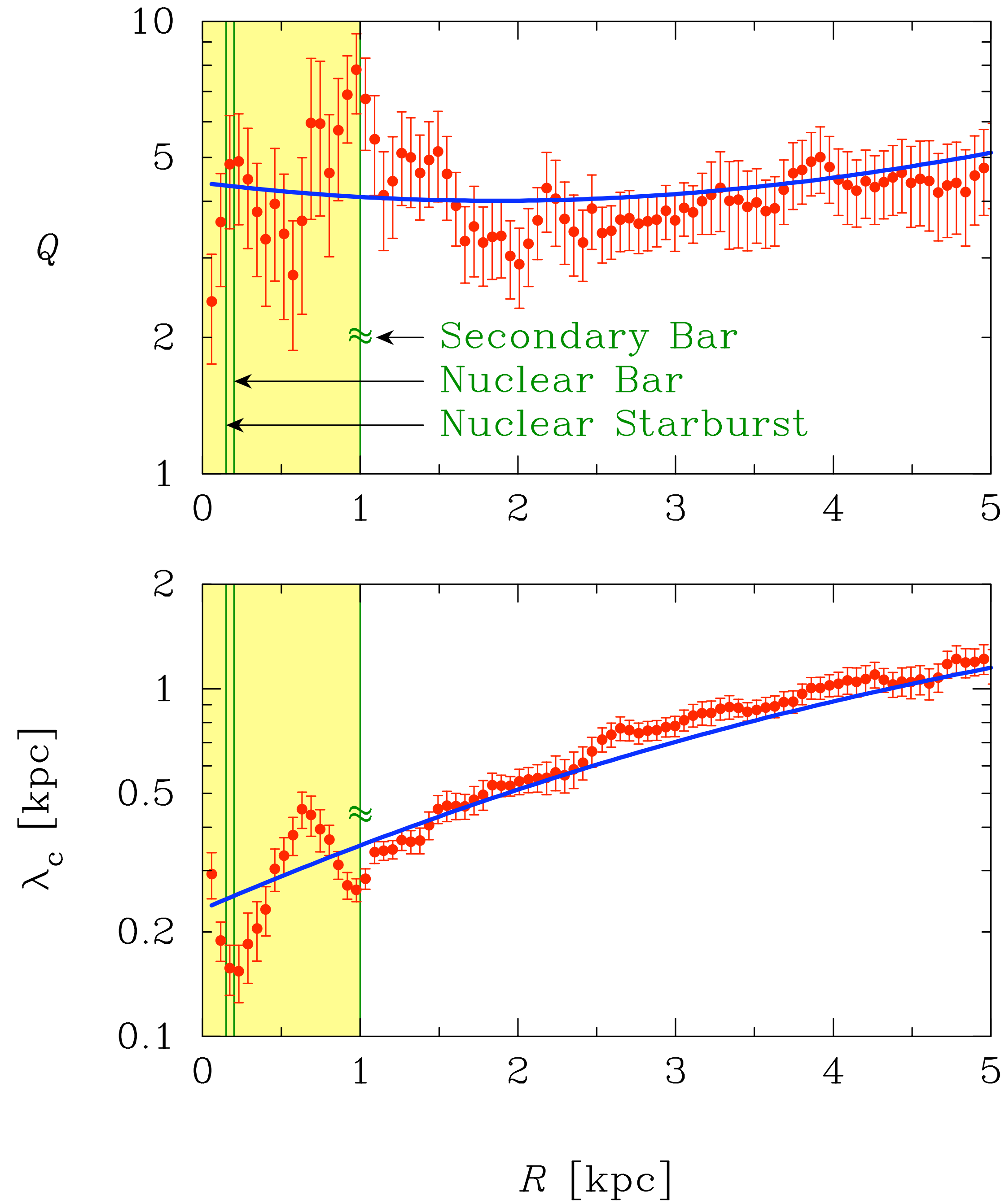
➤ Amazingly, `bars within bars´ are easier to characterize …

➤ not as global, but as local gravitational instabilities,

➤ using not the Q stability parameter, but the characteristic instability scale: $\lambda_c = 2\pi\,\sigma/\kappa$!

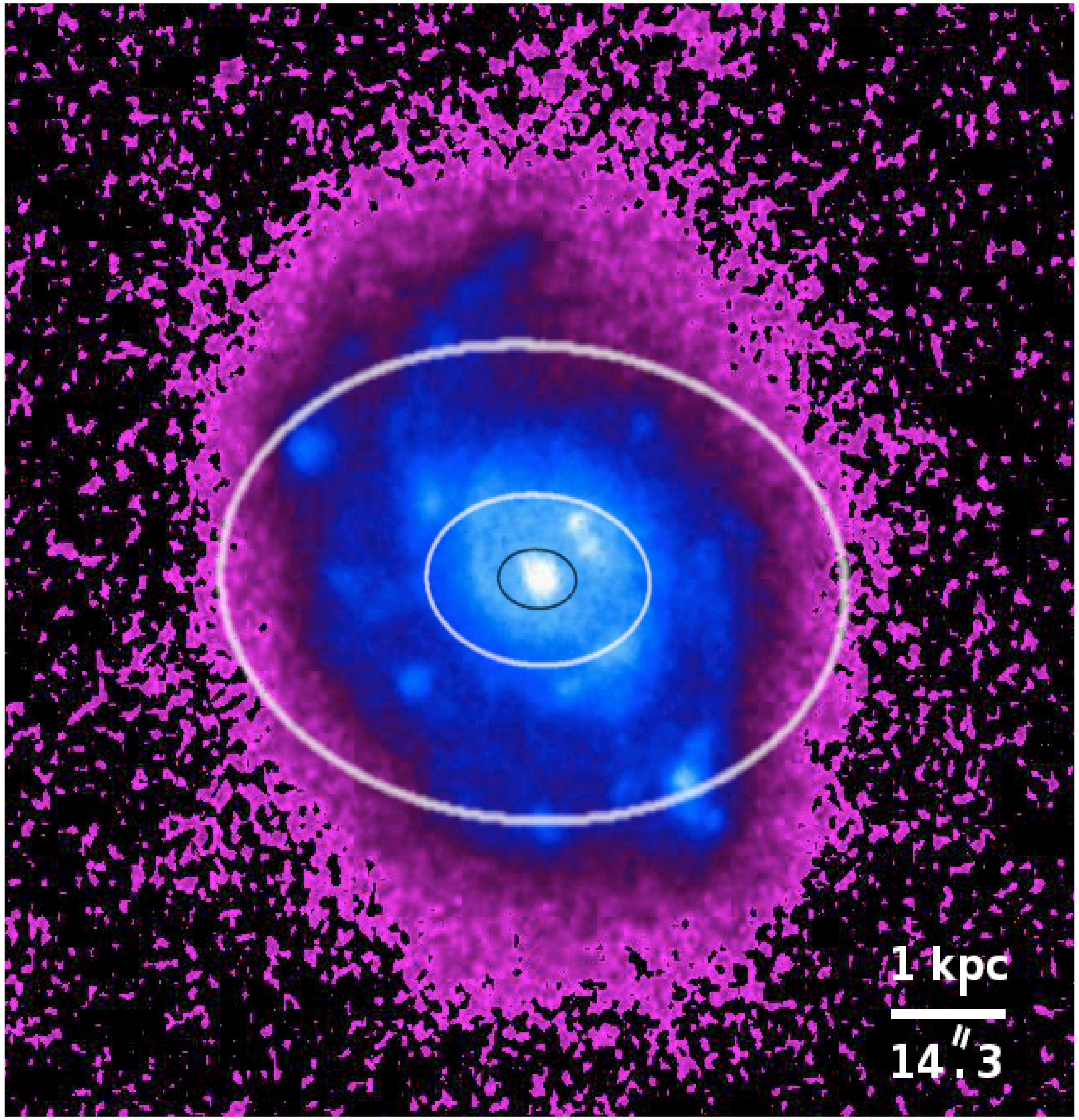
NGC 6946: a triple-barred galaxy

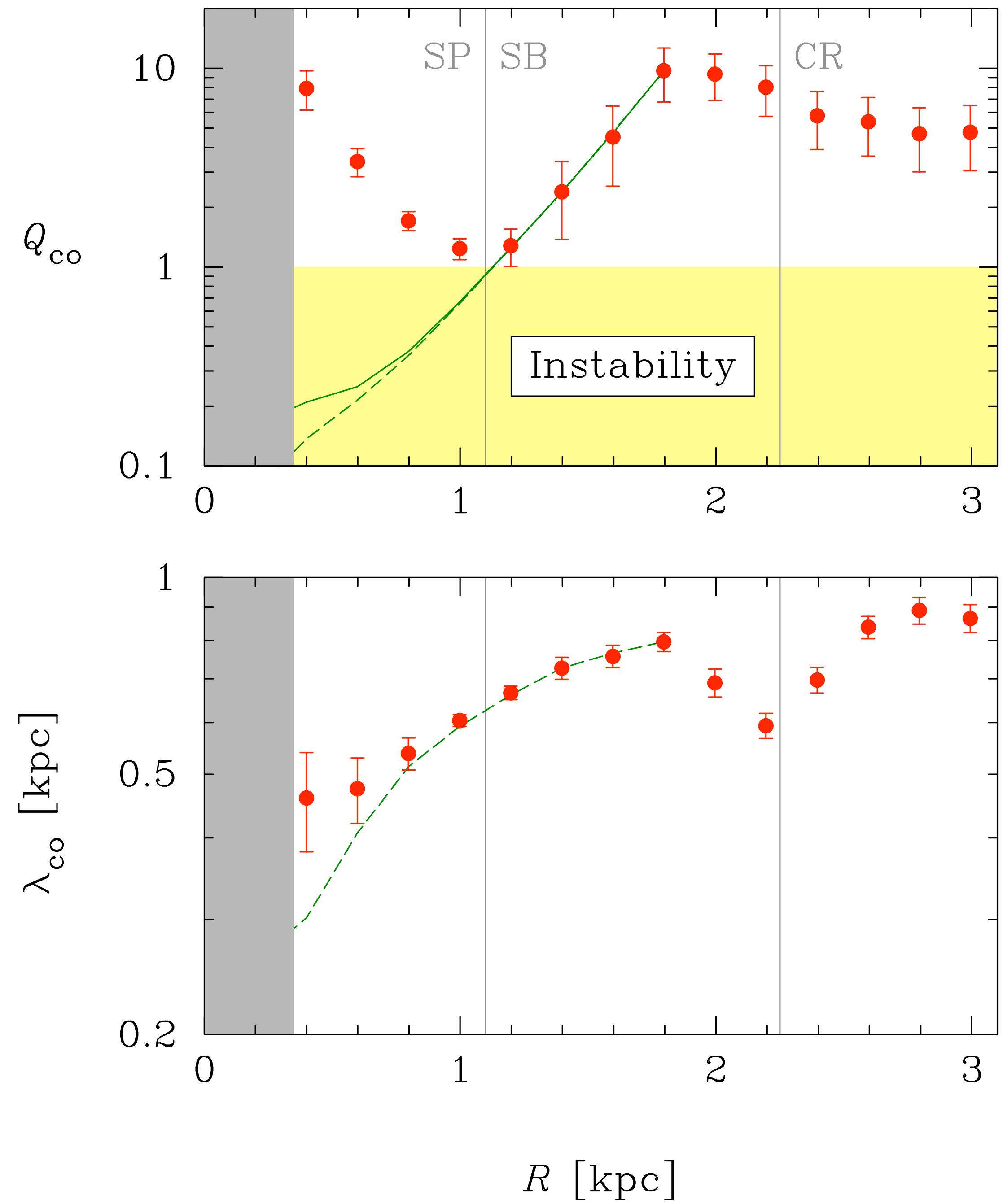




Romeo & Fathi (2015), MNRAS, 451, 3107

NGC 1068: a double-barred galaxy





Romeo & Fathi (2016), MNRAS, 460, 2360

CONCLUSION

● Our analysis solves important aspects of the angular momentum problem, and imposes tight constraints not only on *j* itself but also on its connection with galaxy morphology, bar structure and disc gravitational instability.

➤ Our results on barred galaxies are of particular interest for semi-analytic modelling of galaxy formation and evolution (see Sect. 5 of Romeo et al. 2023).

This is not yet the end of the story!

• Let me advertise two other possible talks:

➤ Disc gravitational instability has a strong impact on galaxy scaling relations

➤ State-of-the-art diagnostics for detecting gravitational instabilities in galaxy discs

Email me if you are interested!

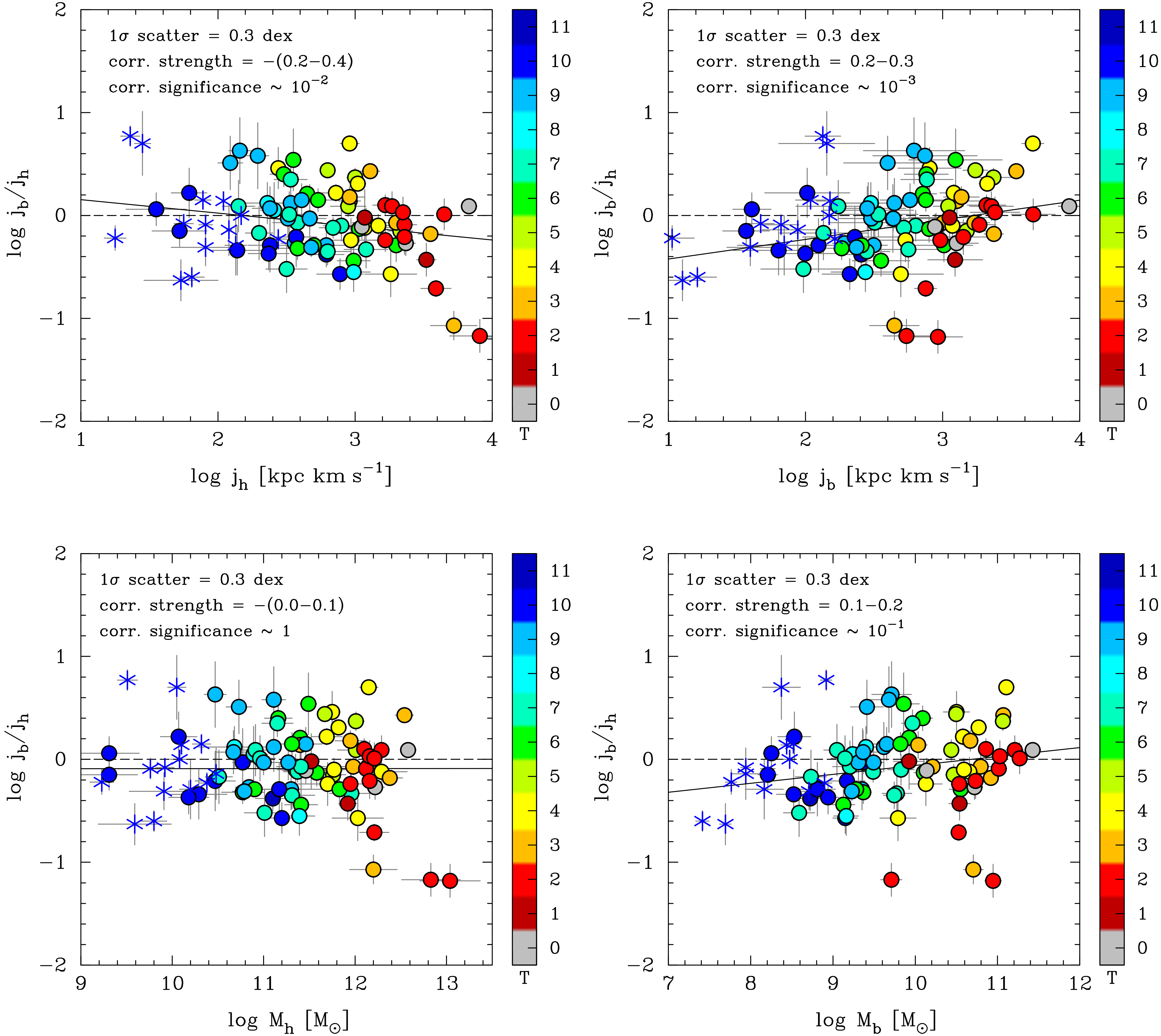
Extra slides

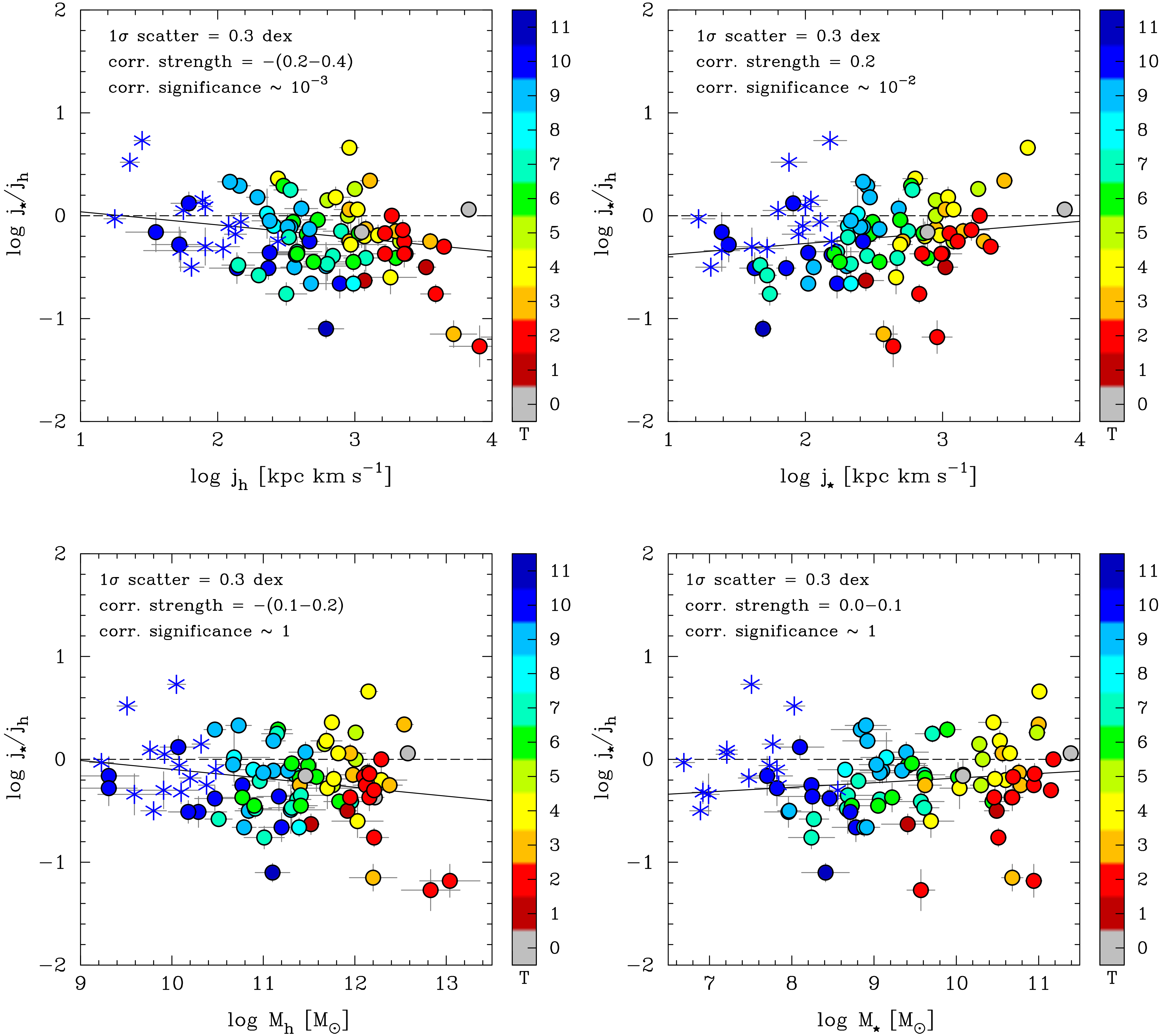
- $<Q>$ versus ELN parameter
- j_b/j_h versus basic galaxy properties
- $j_\star/j_h$ versus basic galaxy properties
- j_{HI}/j_h versus basic galaxy properties
- λ = log-normal versus λ = constant
- Further test of the ELN criterion: HI vs ★

$$\langle Q \rangle \propto j\sigma/GM \propto \mathcal{E}^2\sigma/V$$

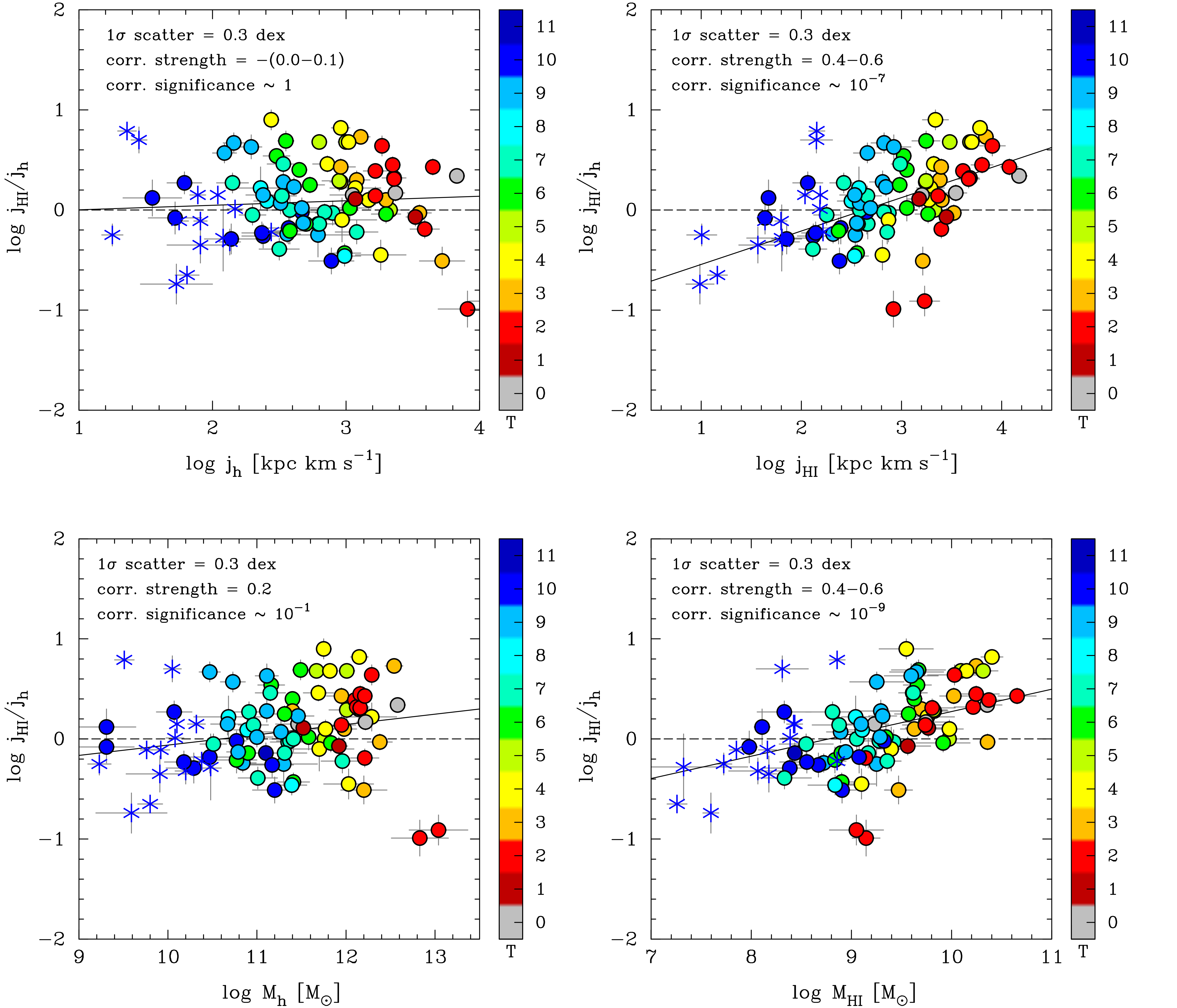
Romeo & Mogotsi (2018), MNRAS, 480, L23

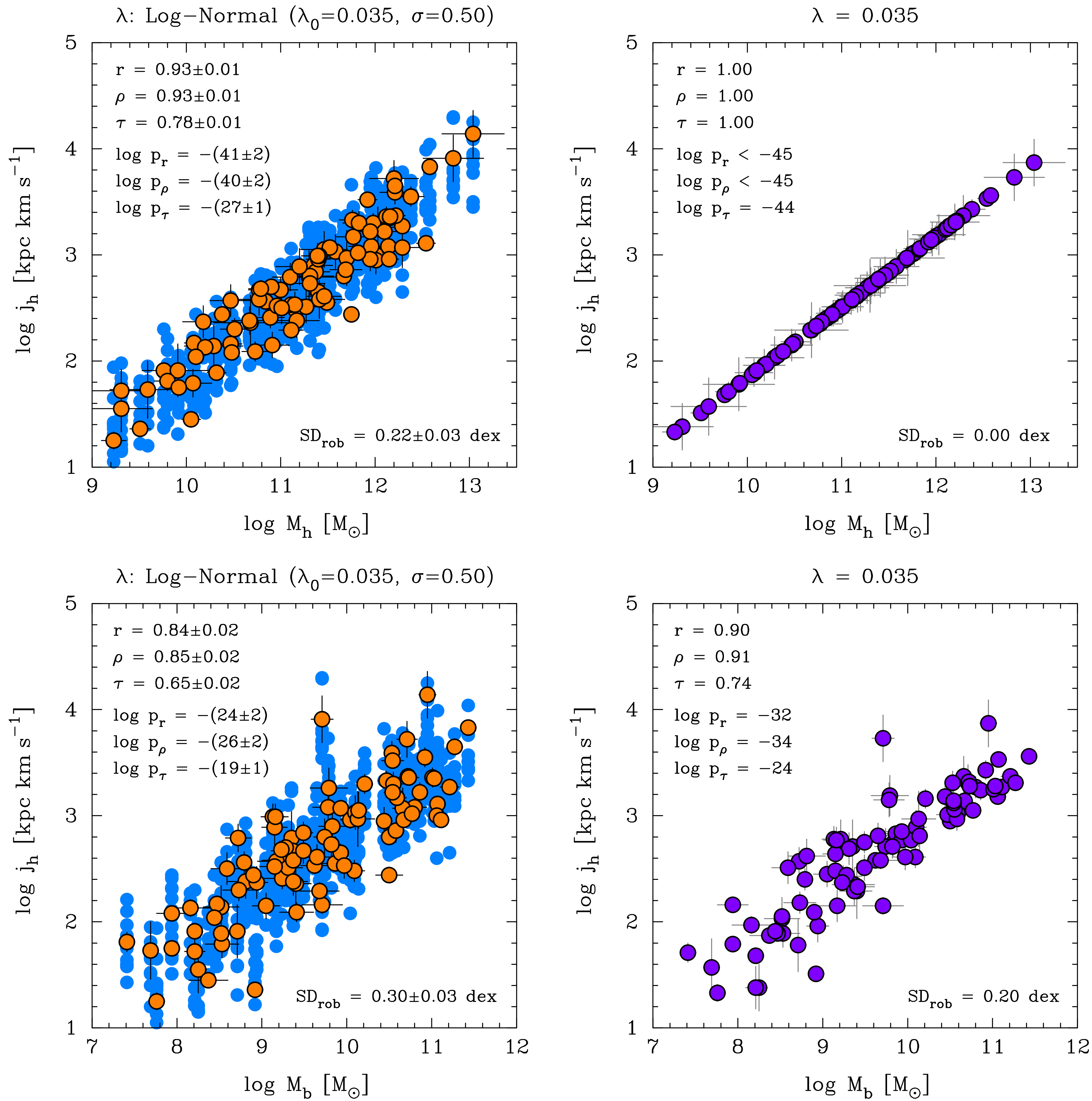
➤ <Q> can be regarded as an improved version of $\mathcal{E}$ that takes into account the disc velocity dispersion, which is an important ingredient missing from $\mathcal{E}$ (Athanassoula 2008).

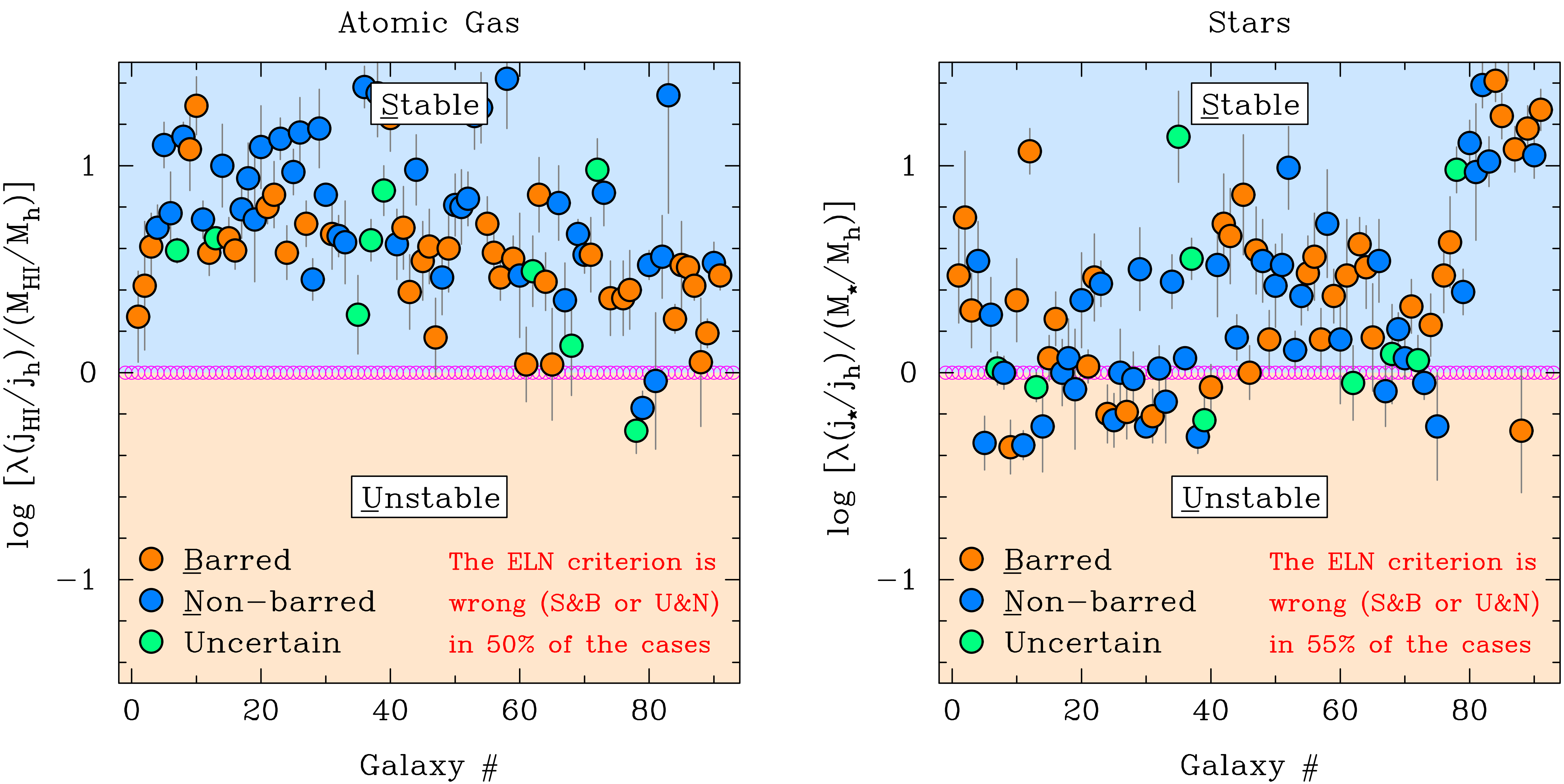

1σ scatter = 0.3 dex
corr. strength = −(0.2−0.4)
corr. significance ∼ 10^−2
log j_b/j_h
log j_h [kpc km s^−1]
1σ scatter = 0.3 dex
corr. strength = 0.2−0.3
corr. significance ∼ 10^−3
log j_b/j_h
log j_b [kpc km s^−1]
1σ scatter = 0.3 dex
corr. strength = −(0.0−0.1)
corr. significance ∼ 1
log j_b/j_h
log M_h [M_⊙]
1σ scatter = 0.3 dex
corr. strength = 0.1−0.2
corr. significance ∼ 10^−1
log j_b/j_h
log M_b [M_⊙]
T



1σ scatter = 0.3 dex
corr. strength = −(0.2−0.4)
corr. significance ~ 10^−3
log j⋆/jh
log jh [kpc km s^−1]
1σ scatter = 0.3 dex
corr. strength = 0.2
corr. significance ~ 10^−2
log j⋆ [kpc km s^−1]
1σ scatter = 0.3 dex
corr. strength = −(0.1−0.2)
corr. significance ~ 1
log Mh [M⊙]
1σ scatter = 0.3 dex
corr. strength = 0.0−0.1
corr. significance ~ 1
log M⋆ [M⊙]
T


1σ scatter = 0.3 dex
corr. strength = −(0.0−0.1)
corr. significance ~ 1
log j_HI/j_h
log j_h [kpc km s^−1]
T
1σ scatter = 0.3 dex
corr. strength = 0.4−0.6
corr. significance ~ 10^−7
log j_HI [kpc km s^−1]
1σ scatter = 0.3 dex
corr. strength = 0.2
corr. significance ~ 10^−1
log M_h [M_⊙]
1σ scatter = 0.3 dex
corr. strength = 0.4−0.6
corr. significance ~ 10^−9
log M_HI [M_⊙]


λ: Log−Normal (λ0=0.035, σ=0.50)
r = 0.93±0.01
ρ = 0.93±0.01
τ = 0.78±0.01
log pr = −(41±2)
log pρ = −(40±2)
log pτ = −(27±1)
SDrob = 0.22±0.03 dex
log jh [kpc km s−1]
log Mh [M⊙]
λ = 0.035
r = 1.00
ρ = 1.00
τ = 1.00
log pr < −45
log pρ < −45
log pτ = −44
SDrob = 0.00 dex
λ: Log−Normal (λ0=0.035, σ=0.50)
r = 0.84±0.02
ρ = 0.85±0.02
τ = 0.65±0.02
log pr = −(24±2)
log pρ = −(26±2)
log pτ = −(19±1)
SDrob = 0.30±0.03 dex
log Mb [M⊙]
λ = 0.035
r = 0.90
ρ = 0.91
τ = 0.74
log pr = −32
log pρ = −34
log pτ = −24
SDrob = 0.20 dex



Atomic Gas
Stars
Stable
Unstable
Barred
Non−barred
Uncertain
The ELN criterion is wrong (S&B or U&N) in 50% of the cases
The ELN criterion is wrong (S&B or U&N) in 55% of the cases
$\log\left[\lambda(j_{HI}/j_h)/(M_{HI}/M_h)\right]$
$\log\left[\lambda(j_\star/j_h)/(M_\star/M_h)\right]$
Galaxy #