How Do Galaxies Grow Their Bulges?

The View from TNG50

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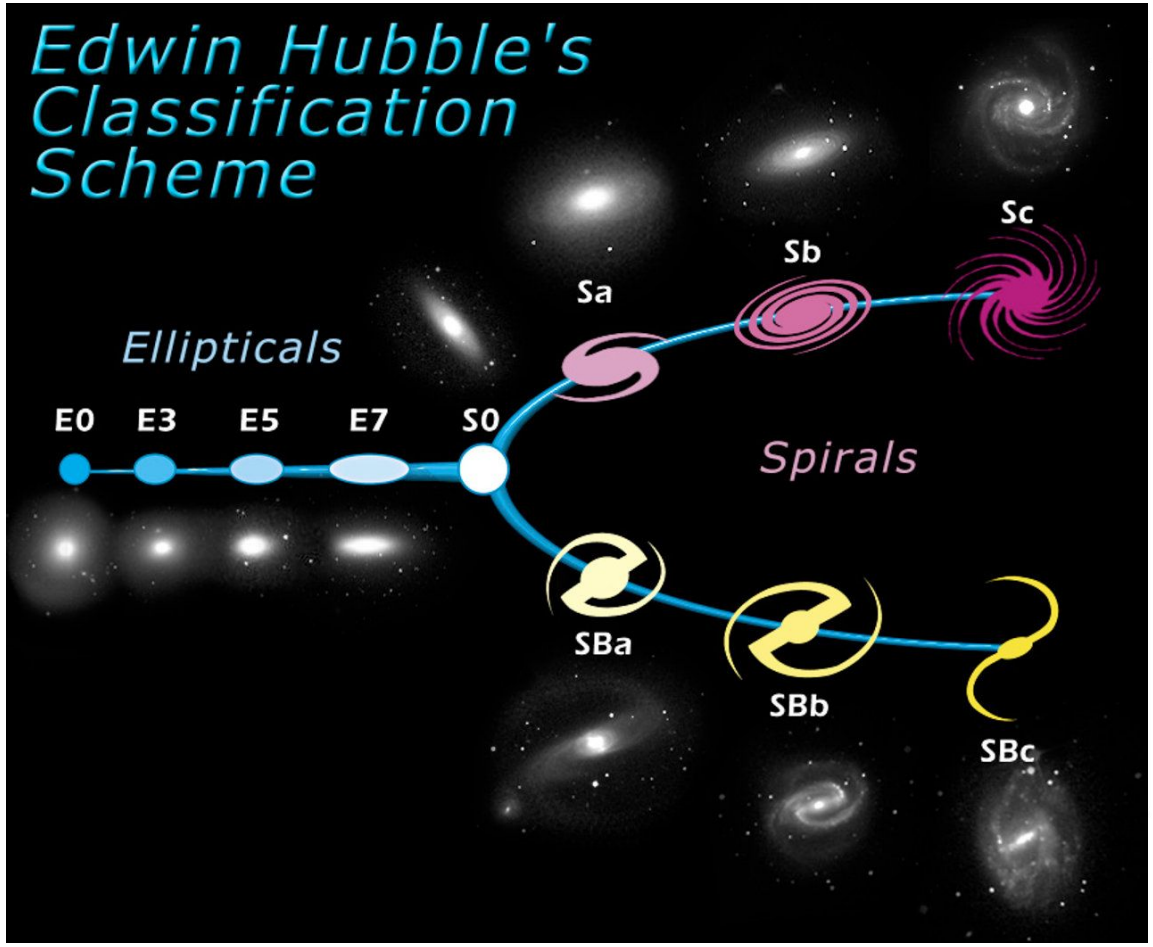
Galaxy bulges in the Hubble sequence

What is a bulge, and where does it sit in the morphological zoo?

- **Two main structural components**
  - Disc — flat, rotation-supported, star-forming
  - Bulge — central, dispersion-supported, often older stellar population

- **Bulges themselves split in two**
  - Classical bulges ($n \geq 2$) — pressure-supported, merger-built
  - Pseudo-bulges ($n \leq 2$) — rotating, boxy/peanut, secular

- **Hubble sequence rising B/T**
  - Spirals → S0 → Ellipticals



Hubble's classification Sequence: Credit NASA & ESA

Formation pathways — two channels

Mergers and disc instabilities leave very different signatures

Mergers

- Violent relaxation turns discs into spheroids
- Major mergers ($\mu > 1/4$) $\rightarrow r^{1/4}$ profile, classical bulge
- Minor mergers $\rightarrow$ stripped stars deposited at large radii

Tracer: *Ex-situ content in the galaxy*

Toomre & Toomre 1972 · Hopkins+ 2009 · Rodriguez-Gomez+ 2016

Disc instabilities

- Bars and global instabilities drive gas inflow
- Vertical buckling produces boxy/peanut pseudo-bulges
- In-situ central star formation grows $\Sigma_{1\mathrm{kpc}}$

Tracer: *Toomre Q*

Kormendy & Kennicutt 2004 · Athanassoula 2005 · Buck+ 2019

Question for this talk: Do these channels leave distinct, *measurable* signatures across the Hubble sequence?

This work — TNG50 sample and visual classification

Three questions, 502 central galaxies, four morphological types

Q1

How does the morphological B/T compare to the kinematic B/T across cosmic time?

Q2

Does merger frequency, mass ratio, or accreted mass drive present-day morphology?

Q3

Are bulges built in situ or ex situ, and does it depend on Hubble type?

Sample

TNG50-1

Highest-resolution IllustrisTNG run; $m_{baryon} \approx 8.5 \times 10^4\ M\odot$, $\varepsilon = 0.288$kpc

Selection at z = 0

Centrals with $M_\star(2R_{half\text{-}stellar\text{-}mass}) > 10^{10}\ M_\odot$, $N_\star > 10^4$
→ 502 galaxies after fit-quality cuts

Tracked from redshift 6 to 0 on the SubLink main branch

Visual classification at z = 0

Classified by eye from face-on, edge-on and mass surface-density projections

Elliptical	S0	Unbarred spiral	Barred spiral	Peculiar
36	42	190	197	6

→ *used as the morphological axis throughout the talk*

Methods — kinematic decomposition

MORDOR (Zana+ 2022) — five components from orbit space

Per-particle orbital diagnostics

- Binding energy E and circularity $\eta \equiv j_z / j_{circ}(E)$
- j_p / j_{circ} tested to remove unbound or counter-rotating outliers

Five components

- Classical bulge, pseudo-bulge, thin disc, thick disc, stellar halo
- Energy-minimum search splits bound / less-bound populations

Definitions used here

- $M_{bulge} \equiv M_{classical} + M_{halo}$
- $M_{disc} \equiv M_{thin} + M_{thick} + M_{Pseudo\text{-}bulge}$

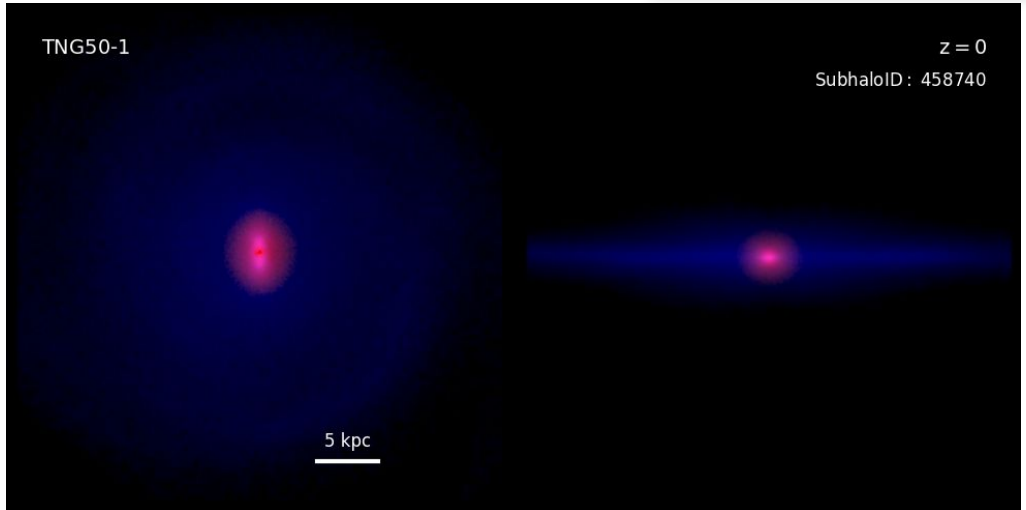
Assignment of particles

$\eta < 0$
→ classical bulge

$\eta > 0.7$
→ thin disc

$0 < \eta \lesssim 0.7$
→ pseudo-bulge (after symmetric η-cut)

Less-bound particles → halo + thick disc



Methods — morphological decomposition

1-D Sérsic + exponential fit → probabilistic per-particle assignment

$$\Sigma(R) = \Sigma_{\rm bulge}(R) + \Sigma_{\rm disc}(R)$$

Sérsic (bulge)

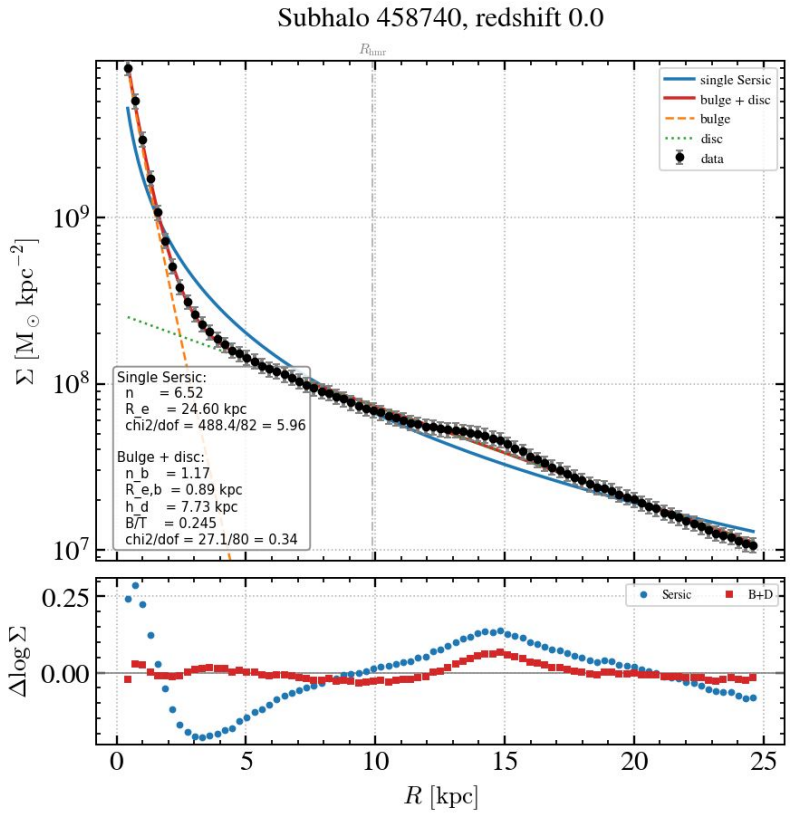
$$\Sigma(R) = \Sigma_e \exp\left\{-b_n\left[\left(\frac{R}{R_e}\right)^{1/n} - 1\right]\right\}$$

Exponential (disc)

$$\Sigma_0 \exp\left(-\frac{R}{R_d}\right)$$

Fit to $R \leq 2.5\ R_{\star,\rm half\ mass}$

Single Sérsic seeds the two-component fit;
asymmetric Gaussian prior on n=4;
quality cut $0.1 < \chi^2_\nu < 2$



$B/T_{\rm morphological} = 0.24$, $n_{\rm bulge} = 1.17$ $\qquad$ $B/T_{\rm kinematic} = 0.26$

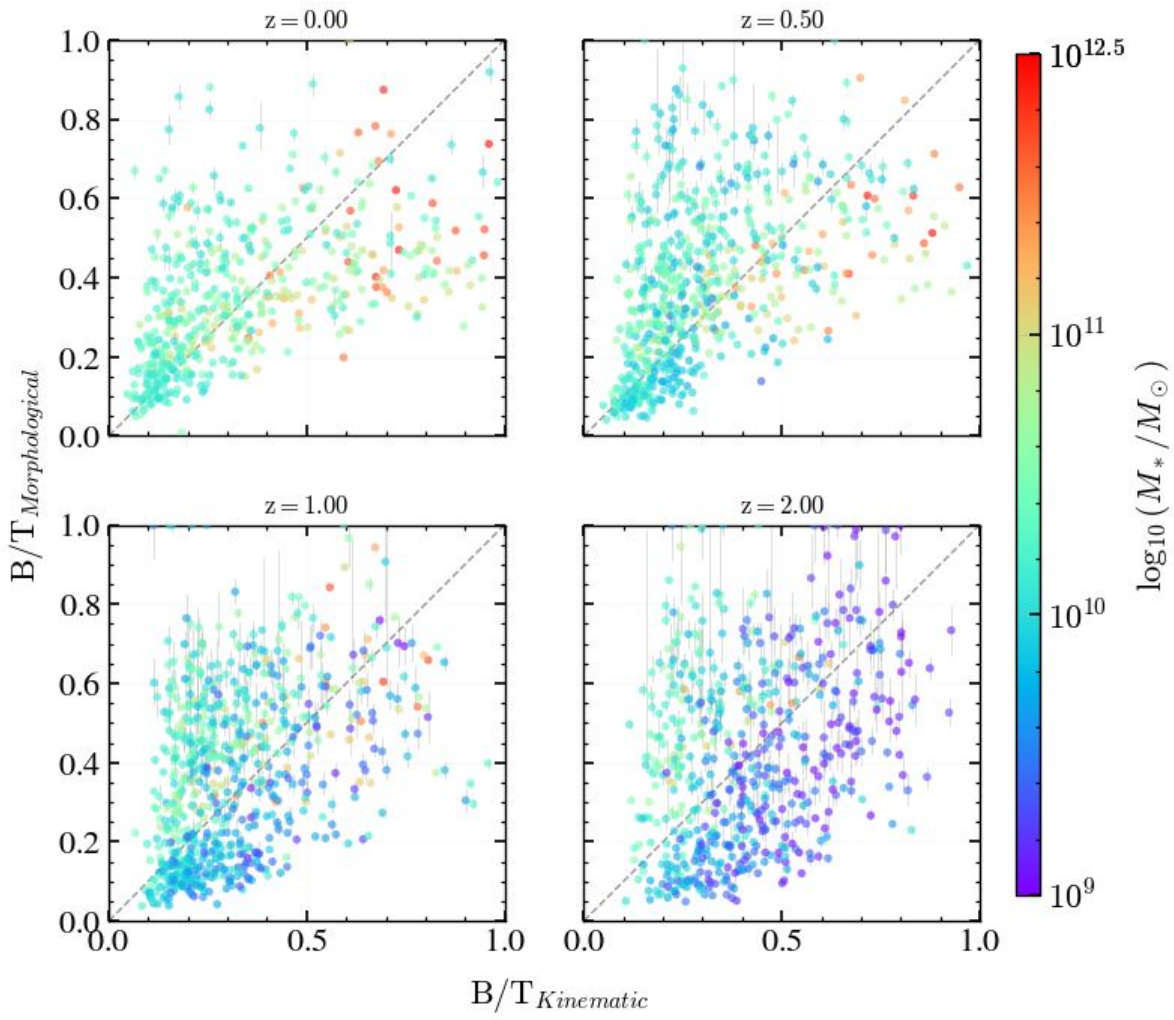
Result I — morphological and kinematic B/T

Systematic disagreement at every redshift

- Below $\mathrm{B/T_{kin}} \approx 0.4$ the Sérsic+exp over-fits the centre
- Above $\mathrm{B/T_{kin}} \approx 0.4$ it saturates — the Sérsic absorbs both bulge and halo

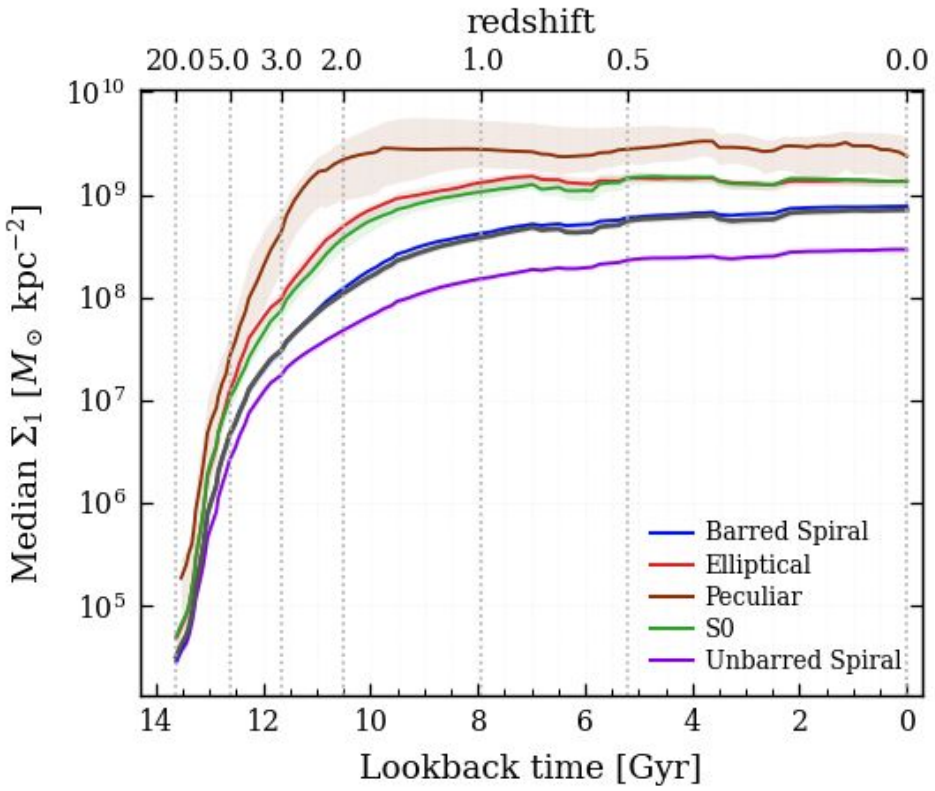
- Both regimes are present at $z = 0, 0.5, 1$ and 2
- $\longrightarrow$ *a structural bias of the parametric fit, not a redshift effect*

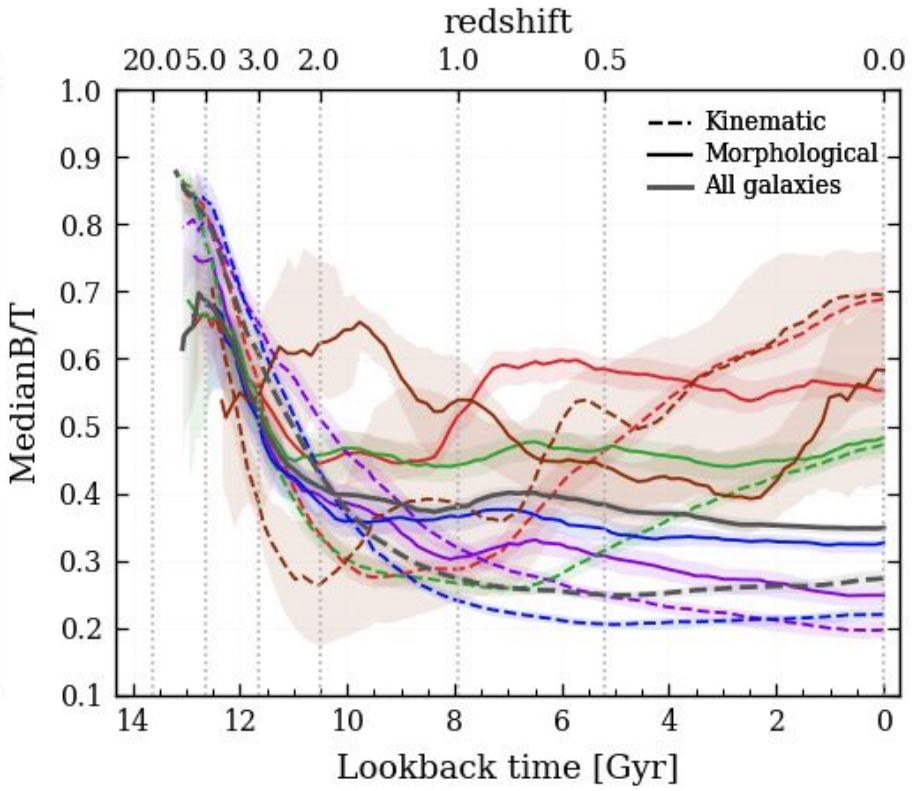
- *Reproduces and extends Gargiulo+ 2022 across cosmic time*



Result III — B/T evolution along the Hubble sequence

Visual classes diverge by z ≈ 2





Kinematic vs. morphological

Solid: morphological.
Dashed: kinematic.

- Ellipticals: $B/T_{kin} \approx 0.7$ by $z = 0$; built up since $z \approx 1$
- S0s: intermediate track; bulges set early but plateau
- Unbarred & barred spirals: $B/T \lesssim 0.3$ throughout

Morphological tracks are flatter — the parametric fit hides real evolution.

Σ_1

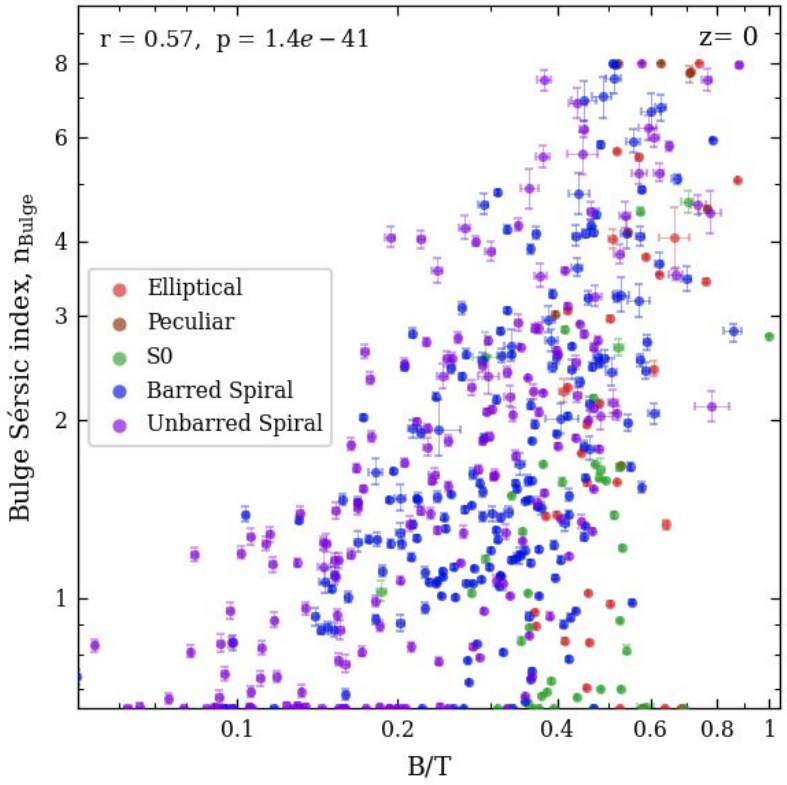
- S0, Peculiar & Elliptical share same evolution
- Unbarred spirals, less dense bulges than Barred

B/T

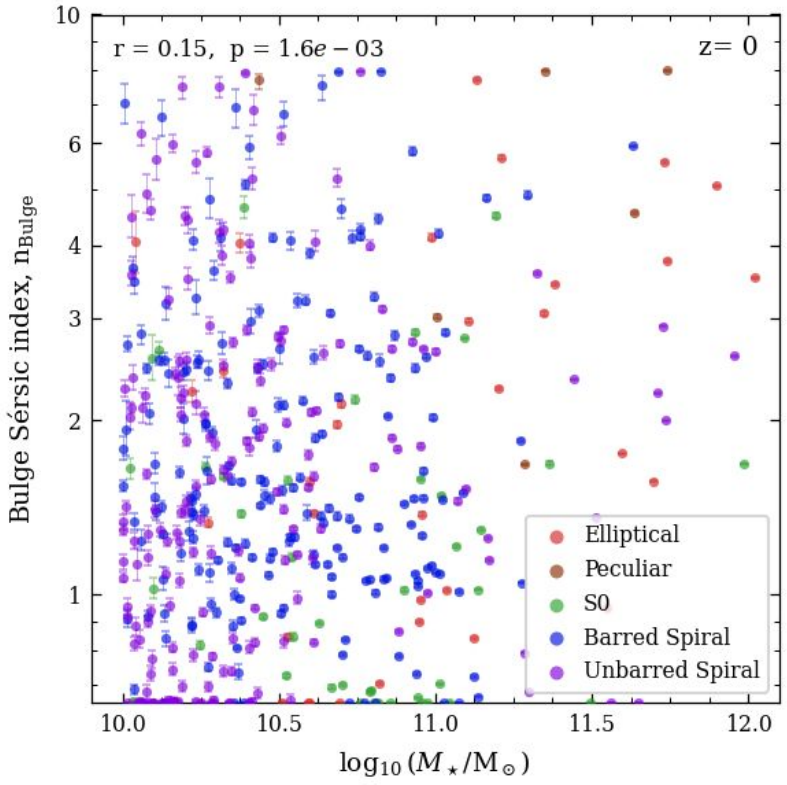
- Separates evolution paths by Hubble types
- Evolutions

Result II — Sérsic index as a diagnostic

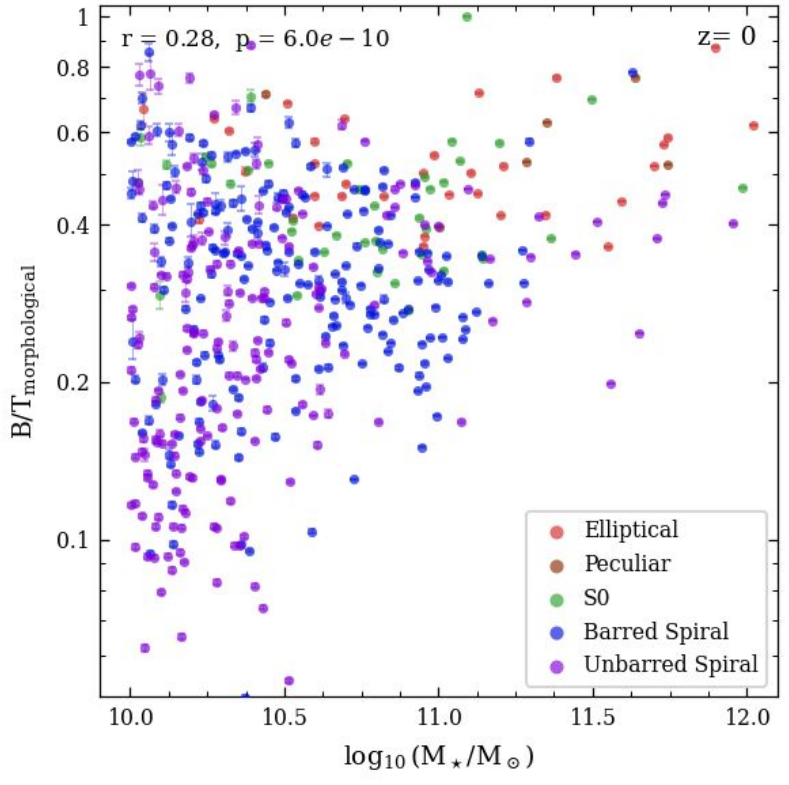
n correlates with B/T but only weakly with stellar mass



n vs. B/T — r = 0.51 ($p \approx 10^{-34}$)



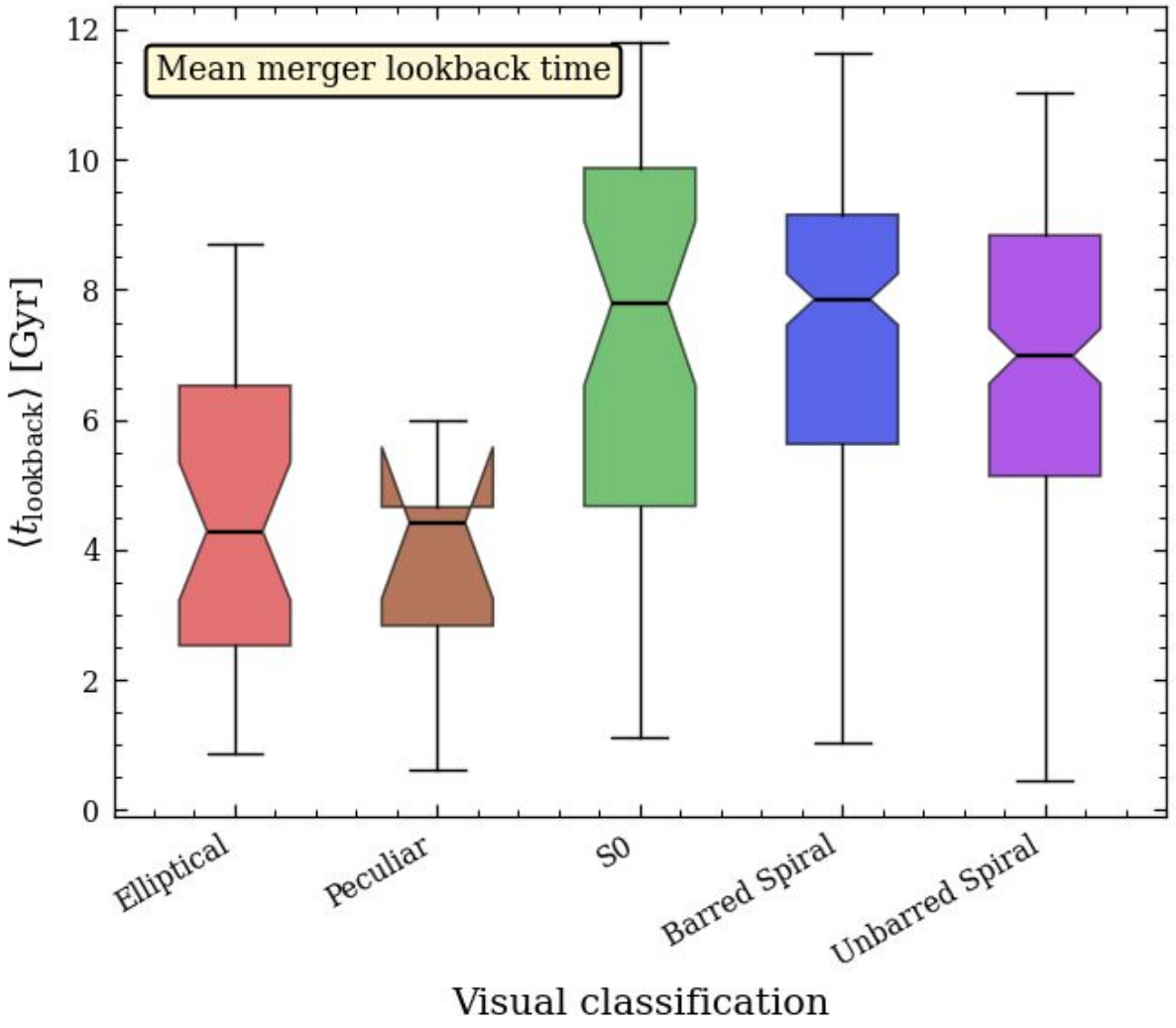
n vs. log M* — r = 0.13 ($p \approx 10^{-3}$)

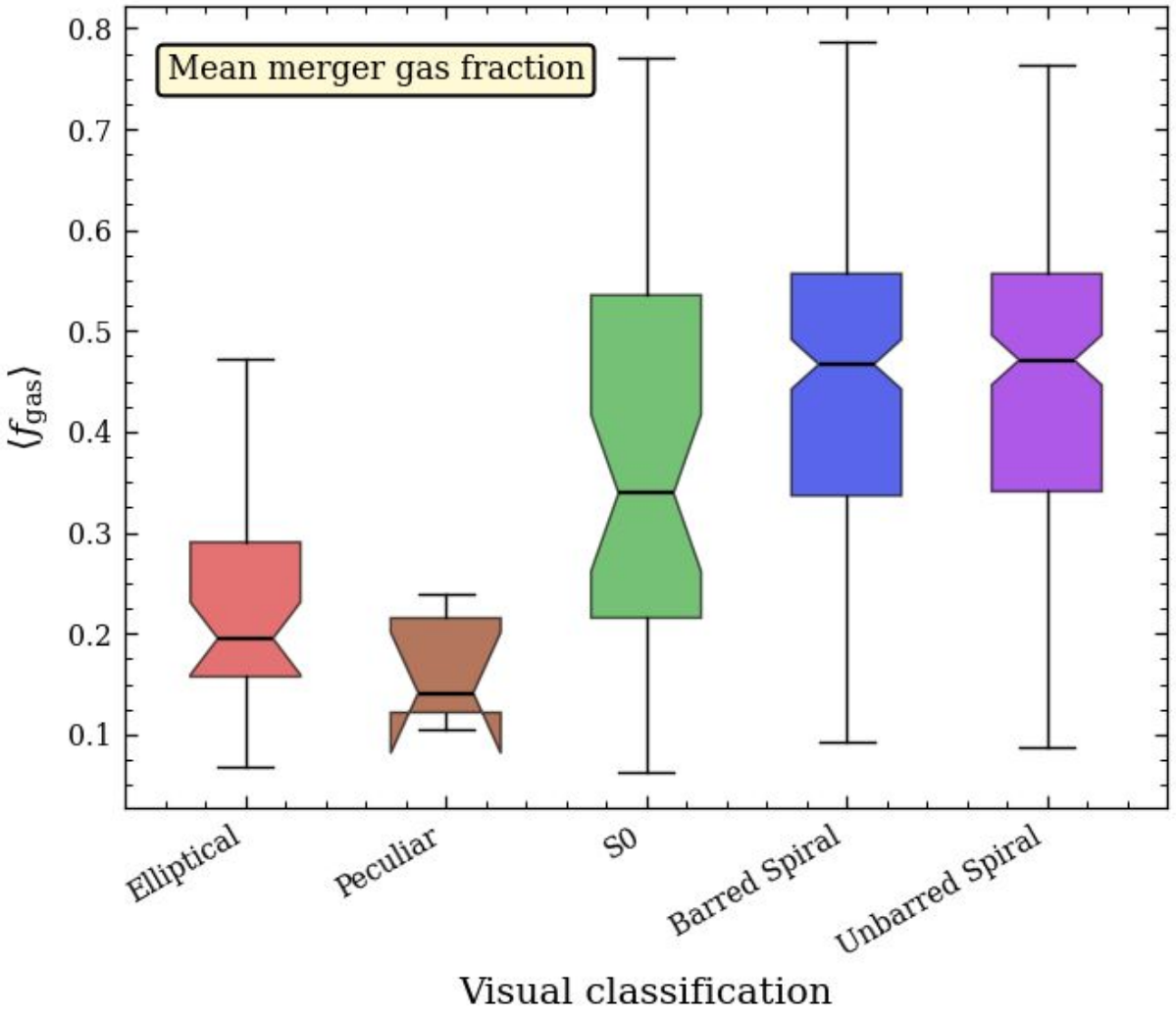


B/T vs. log M* — r = 0.19 ($p \approx 10^{-5}$)

Result IV — Do mergers drive B/T?

Ellipticals and Peculiars merger more recently, and experience gas poor mergers





Result IVa — Ex-Situ mass

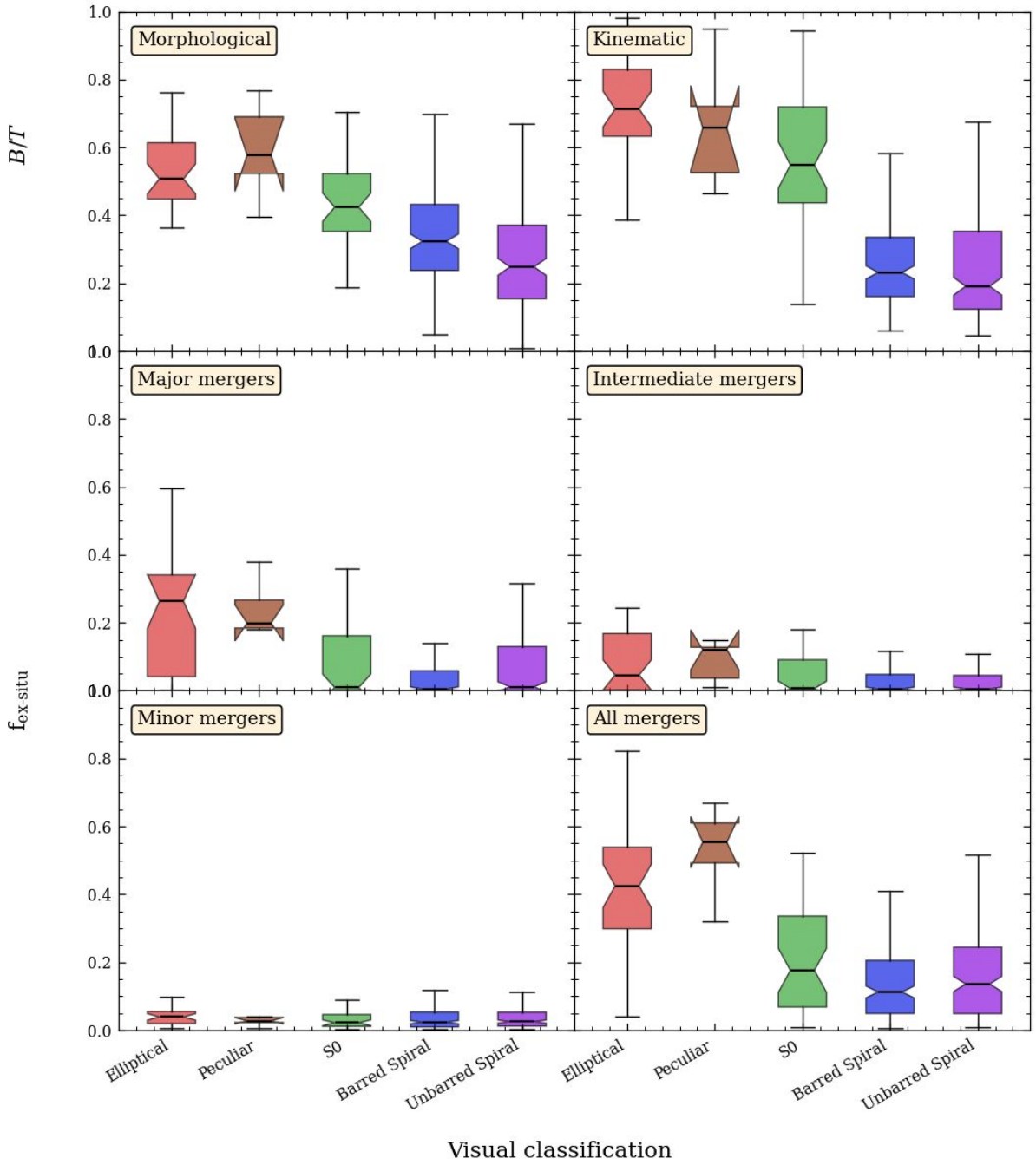
Rodriguez-Gomez+ 2015,2016a,2016b

Mergers definition

- Major: $\mu > 1/4$
- Intermediate: $1/10 < \mu < 1/4$
- Minor: $\mu < 1/10$

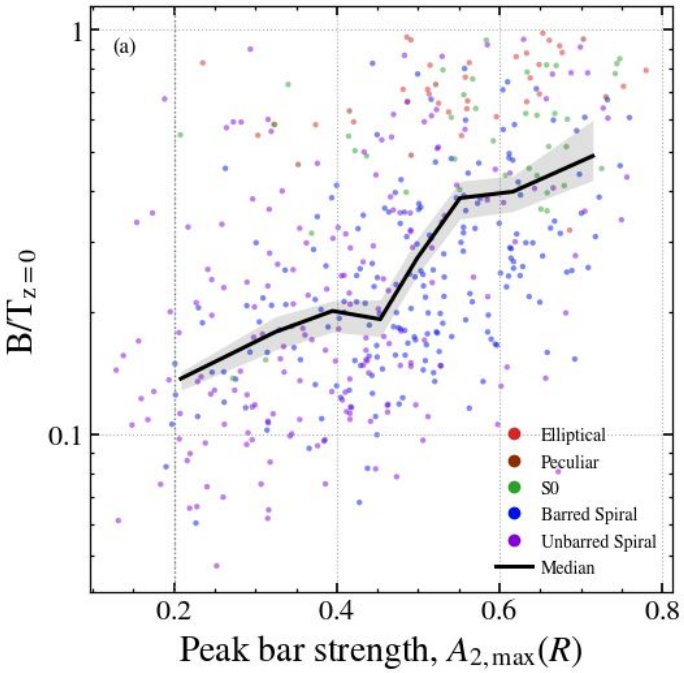
Ex-situ mass

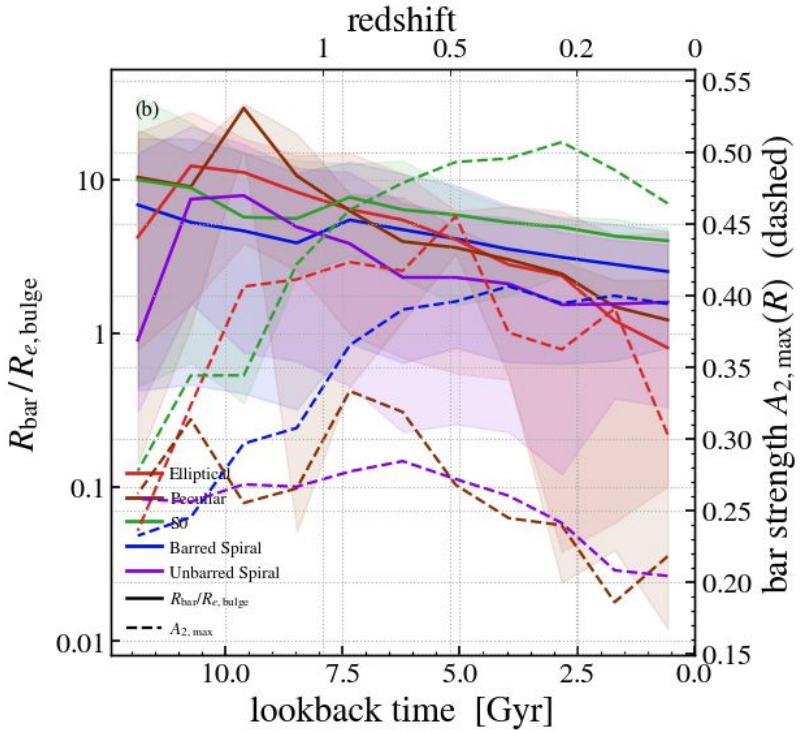
- Major mergers are transport the majority of gas into Elliptical and S0 galaxies
- S0 galaxies and Unbarred spirals contain same about of Ex-Situ mass from major mergers
- Peculiar galaxies are merging at present



Results V – Disc instabilities

Do bulges evolve with their bars?





Bar strength → Bulge growth

- Stronger historical bars → higher $z=0$ B/T
- Bar strength tracks morphological type
- Bulge density grows toward $z=0$
- Ellipticals: high B/T, weak present-day bars
- S0s: strongest bars at low redshift

Results VI Environment — Nearest Neighbours and their proximity

Nearest neighbour data provided by Flores-Freitas+ 2024)

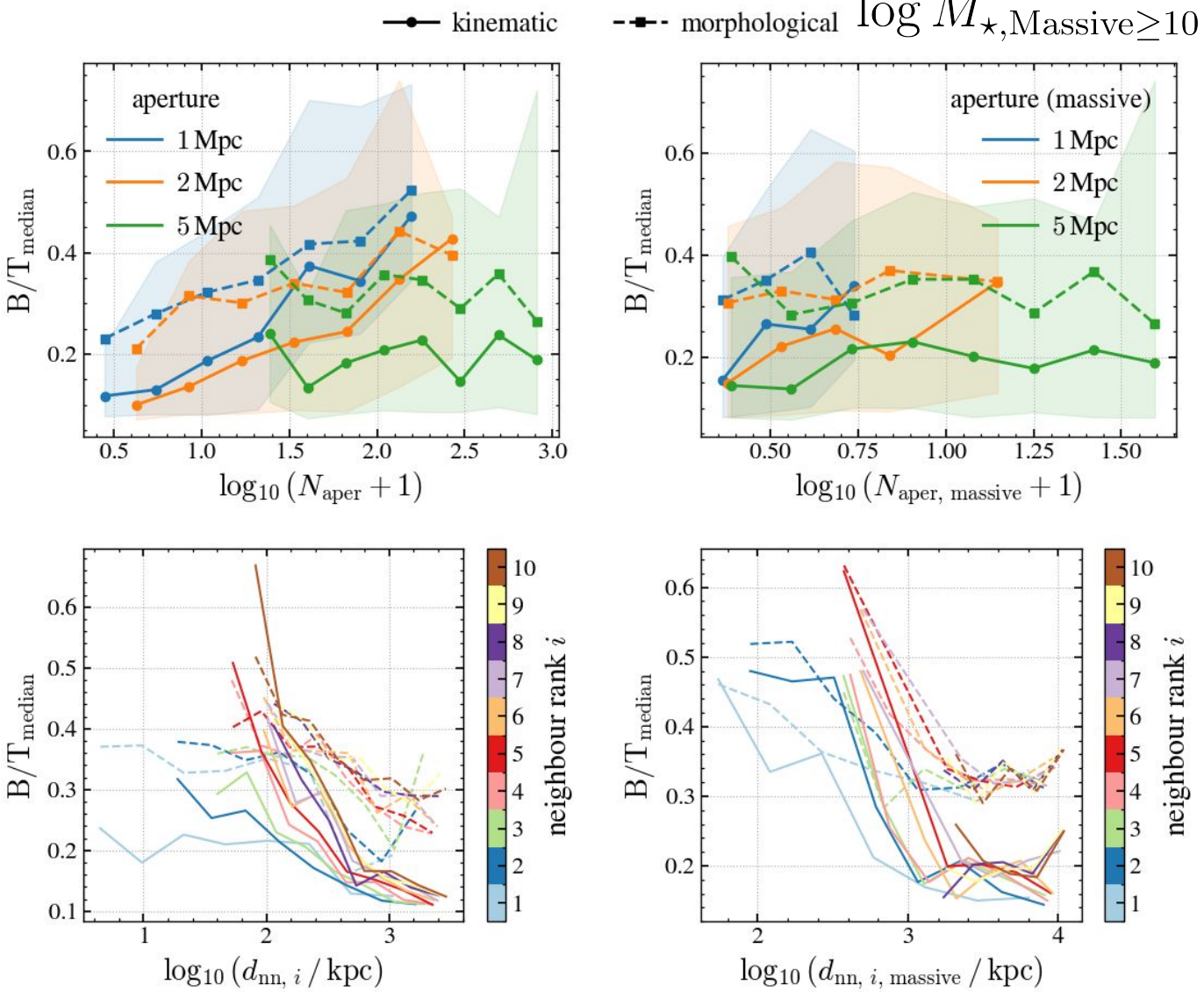
Number of Nearest Neighbours

- High mass bulges live in denser environments
- Big spread accounts for isolated galaxies that form via disc instabilities

Distance to Nearest Neighbour

- Bulges exist in galaxies who's neighbours are closer
- If the closest nearest neighbour is not massive bulges don't reach $\mathrm{B/T} > 0.5$

Board agreement between morphological and kinematic bulges



Conclusions

1

Parametric B/T is biased

Morphological B/T over-fits at low bulge dominance and saturates at high B/T — a structural bias of the Sérsic+exp model, present at every redshift probed.

2

B/T evolution traces the Hubble sequence

Visual classes diverge by $z \approx 2$; ellipticals build $B/T_{kin} \approx 0.7$ since cosmic noon, S0s plateau, spirals stay disc-dominated.

3

It's complex

Mergers build classical bulges and ex-situ envelopes; Bars are linked to the growth of the general B/T; Environment matters. All these things are needed to explain diverse bulges across the Hubble sequence.

Thank you · Questions?

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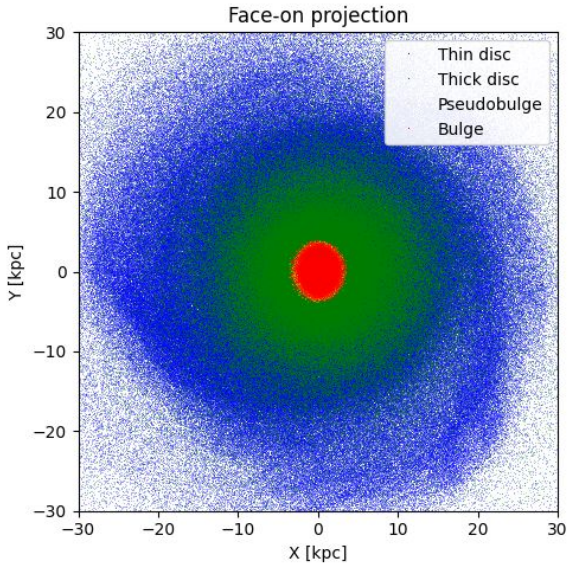
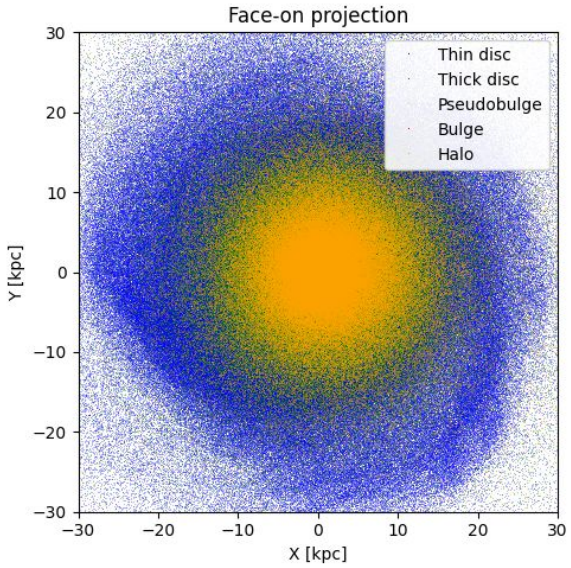
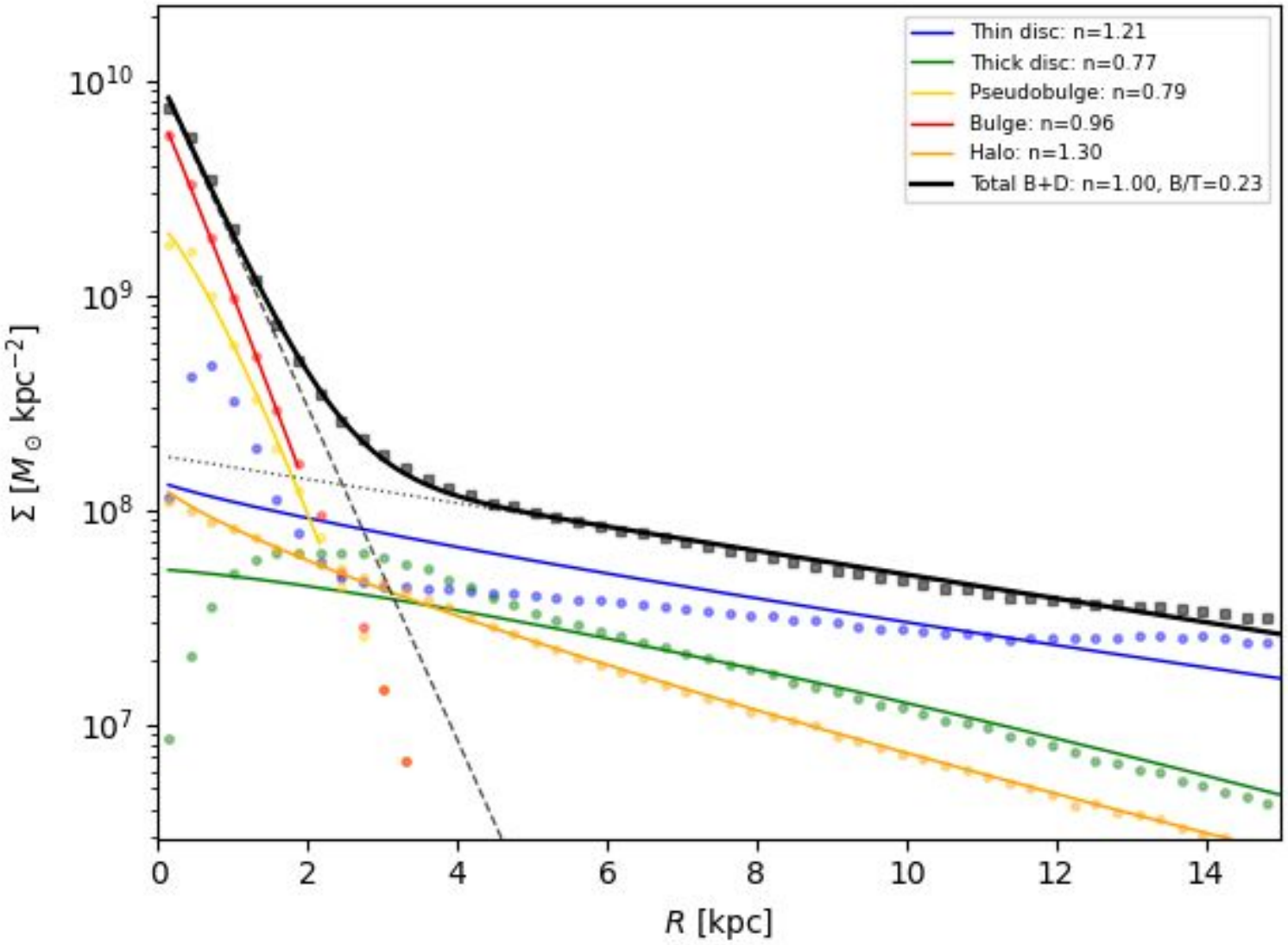
Kinematic decomposition

BACKUP

MORDOR Zana et al. 22

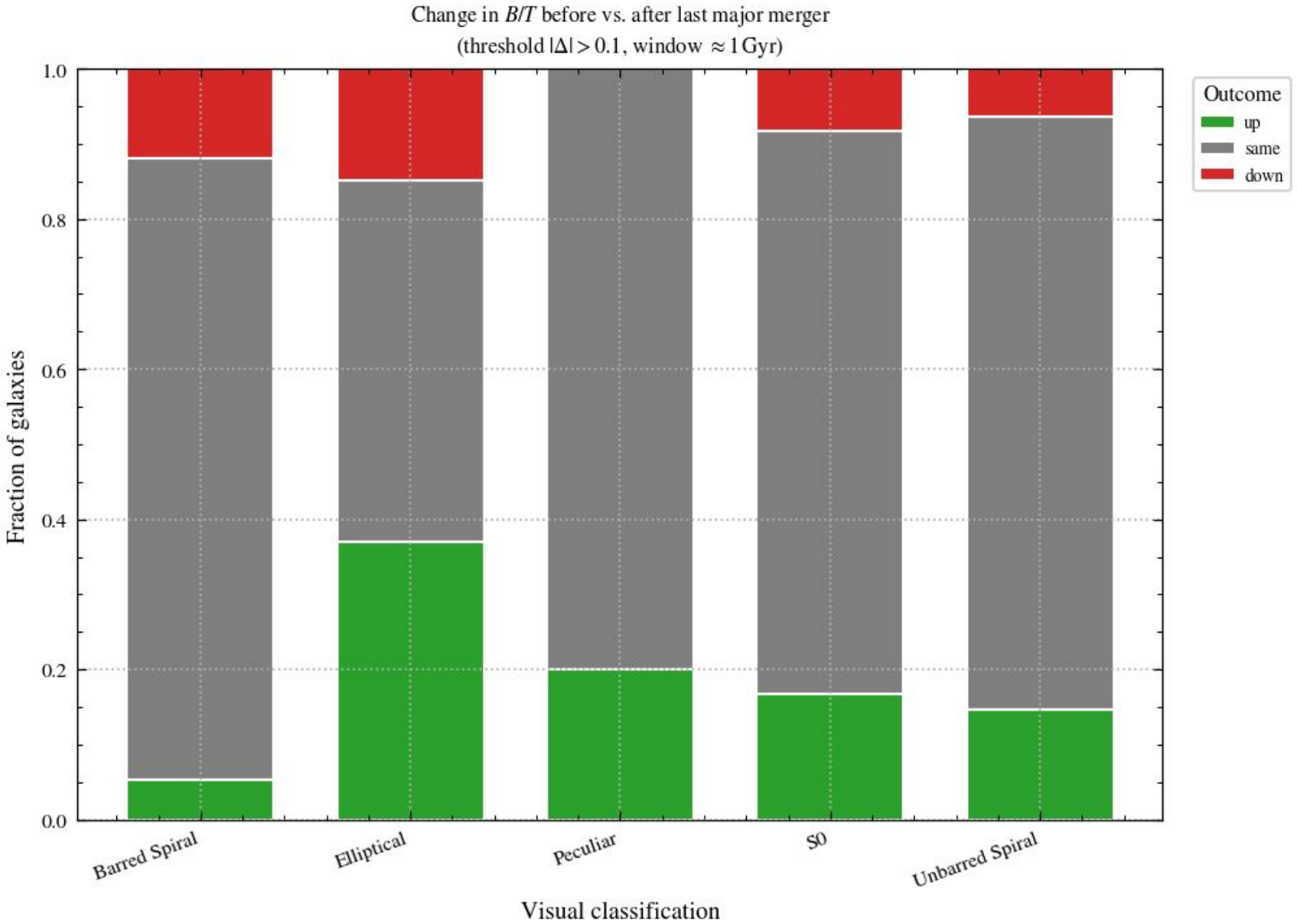






How many galaxies grow a bulge after the last major merger?

BACKUP



Distribution of Visual types in B/T and Mas

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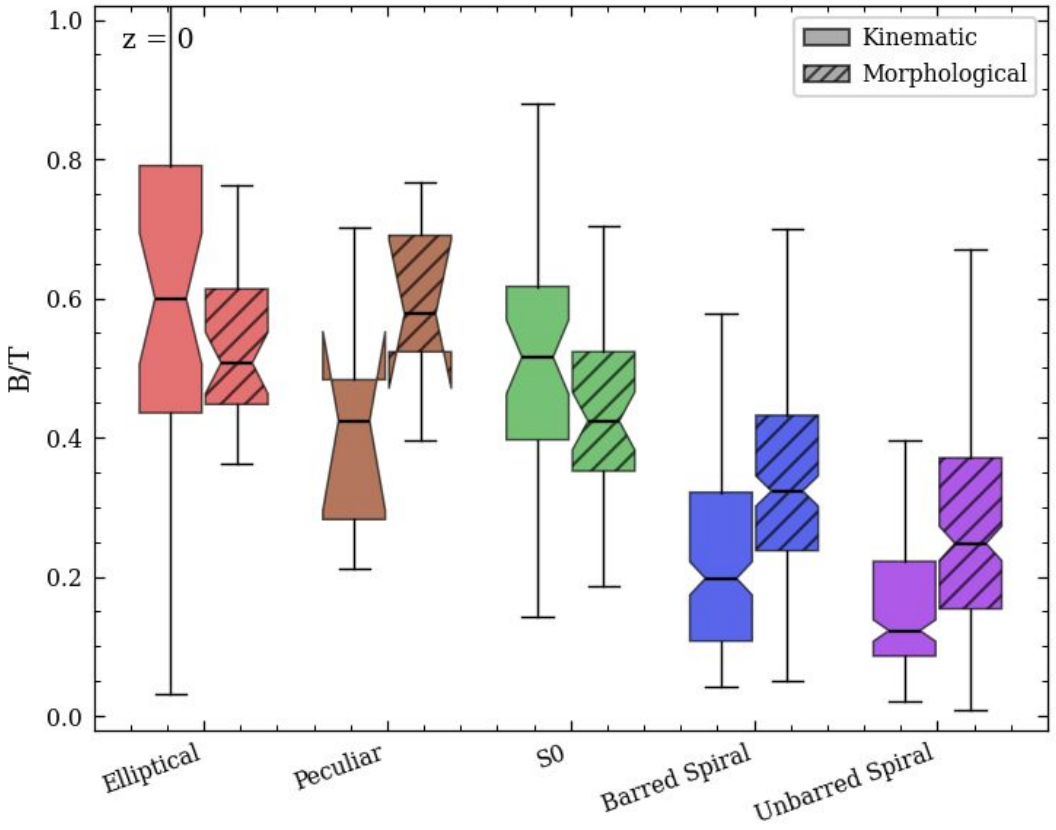
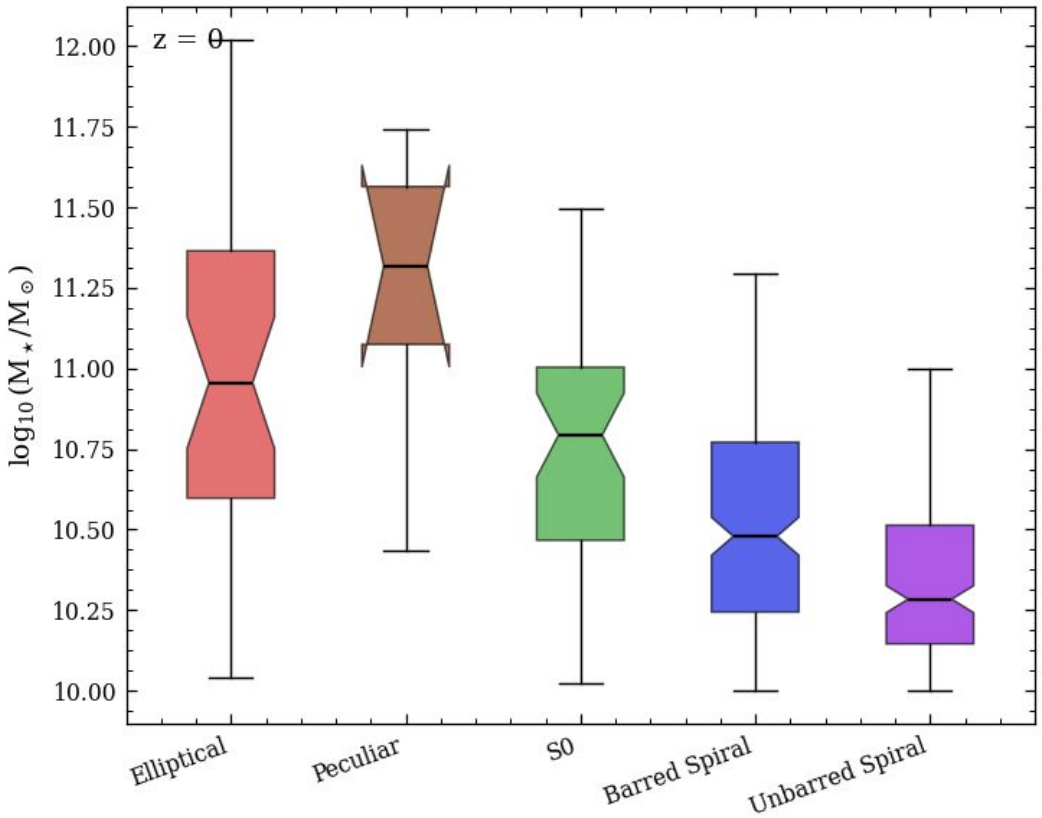


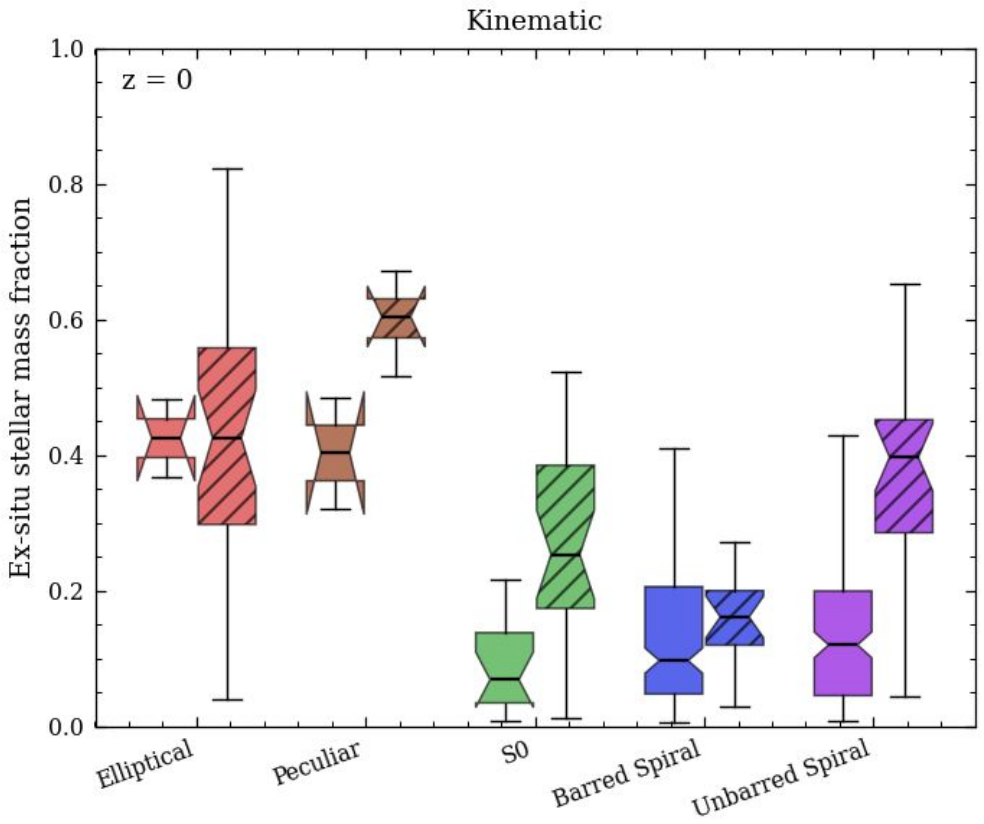
Bulge fraction fraction by visual class.



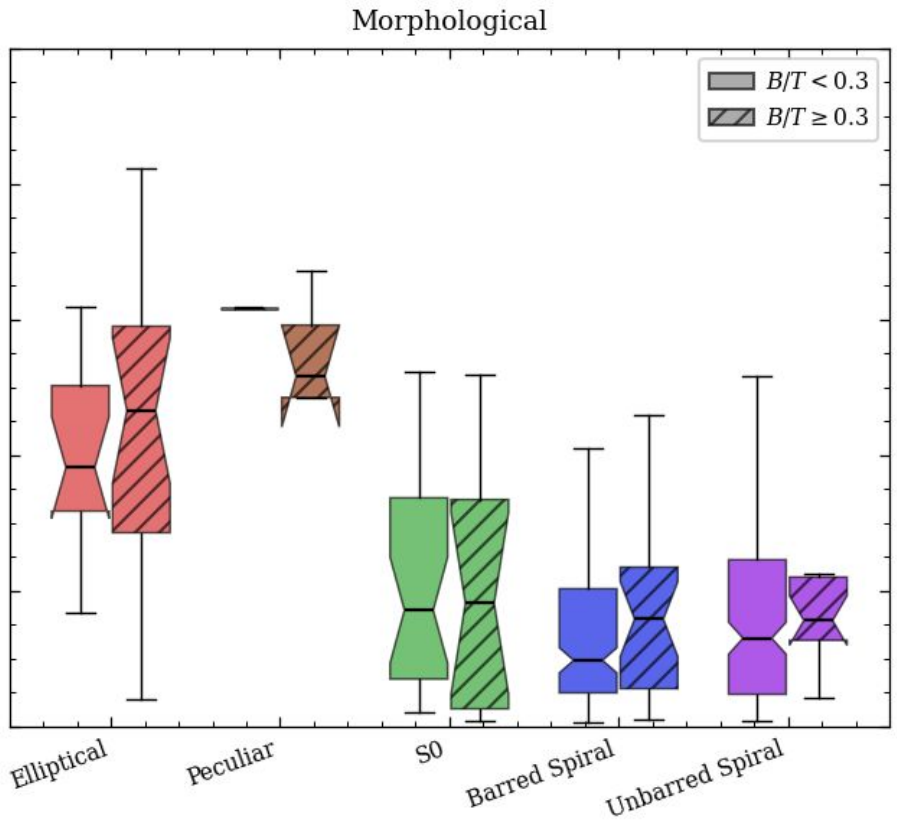
Mass Distribution by visual class

Distribution of Visual types in Ex Situ Mass

BACKUP



Bulge fraction fraction by visual class.

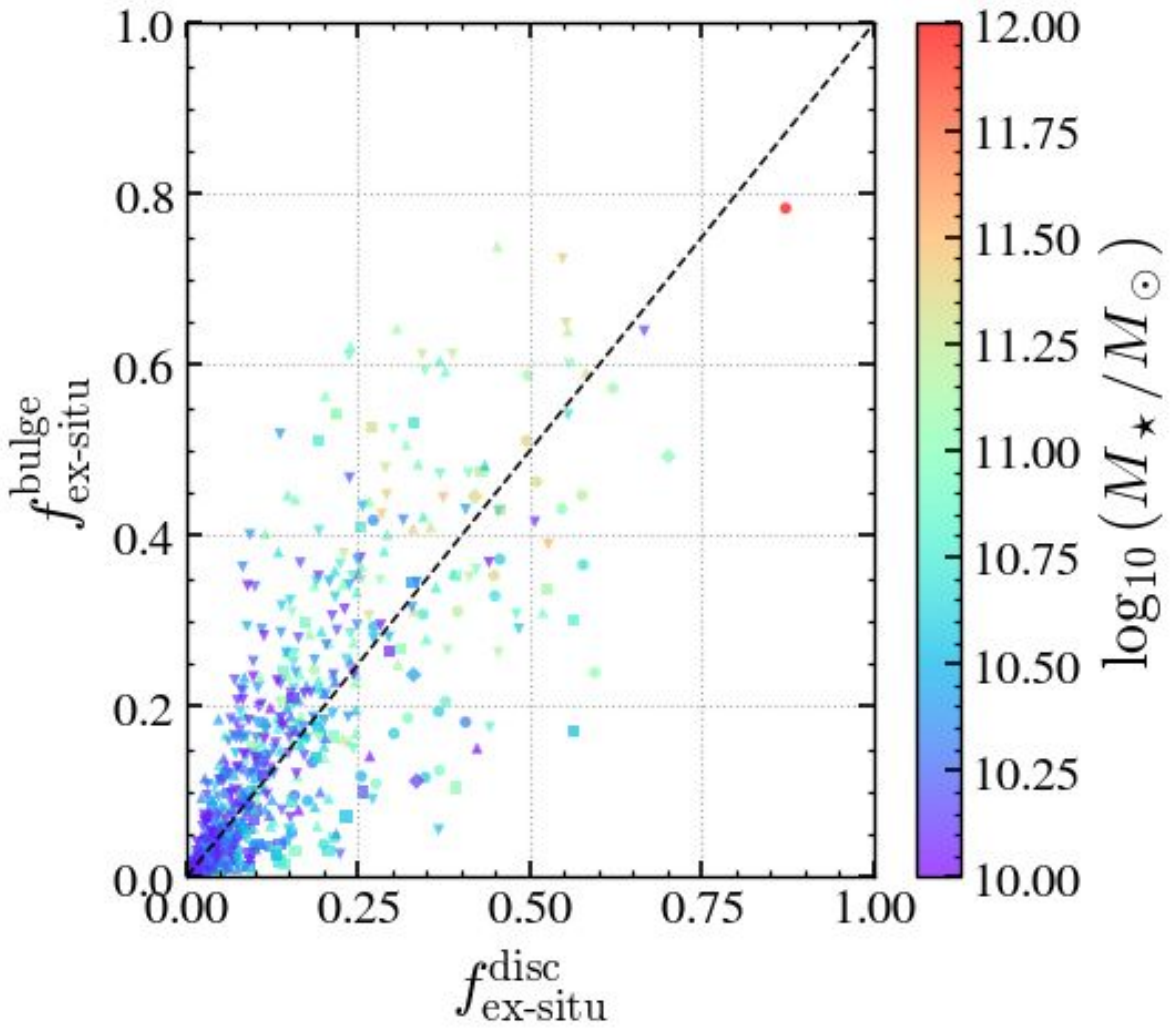


Mass Distribution by visual class

Ex-situ mass distributed proportionally

f_ex,bulge ≈ f_ex,disc ≈ f_ex,galaxy along the 1:1 line

BACKUP



f_ex,bulge

≈

f_ex,disc

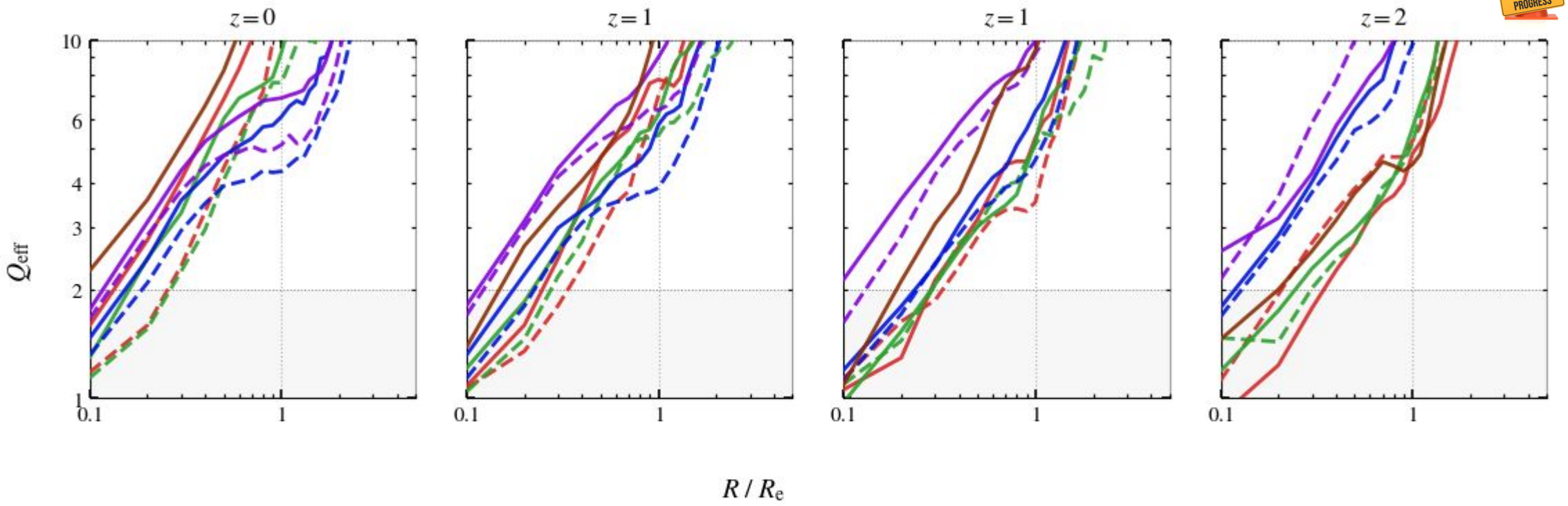
≈

f_ex,galaxy

Accreted material is redistributed in proportion to the in-situ stellar content of each component — not preferentially deposited in the bulge.

Toomre Q - the stability parameter

BACKUP



$$\frac{1}{Q} = \begin{cases} \dfrac{W}{Q_\star} + \dfrac{1}{Q_{\rm g}} & \text{if } Q_\star \geq Q_{\rm g} \\ \dfrac{1}{Q_\star} + \dfrac{W}{Q_{\rm g}} & \text{if } Q_{\rm g} \geq Q_\star \end{cases}$$

$$W = \frac{2\sigma_\star \sigma_{\rm g}}{\sigma_\star^2 + \sigma_{\rm g}^2}\,.$$

Gas and SFR in the Bulge and Disc

BACKUP

$T_{\mathrm{cold-gas}} \leq 10^5 K$