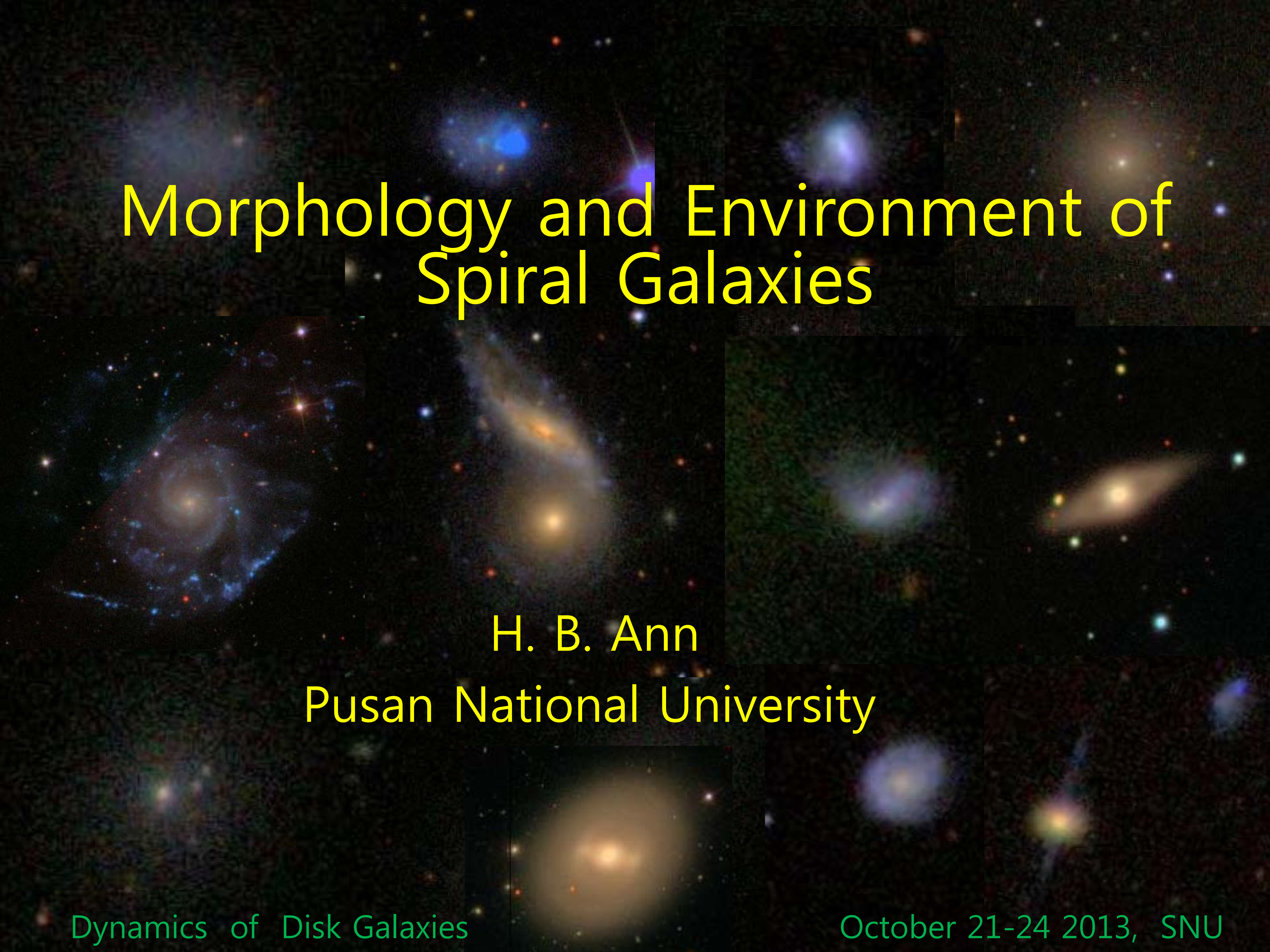

Morphology and Environment of Spiral Galaxies

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Dynamics of Disk Galaxies October 21-24 2013, SNU

Contents

- Part 1: Brief review of disk morphology
- Part 2: Environment dependence of disk morphology

Why morphology?

Morphology is an integrated property of a galaxy that reflects the formation and evolution history of galaxy.

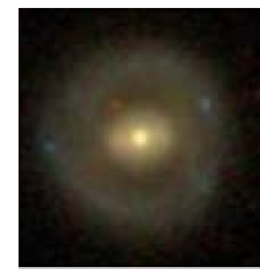
Why environment?

Environment is one of the most important parameters that affect the life of a galaxy. Nature vs nurture controversy is still on-going. Since morphology is closely related to dynamical structures and star formation history of a galaxy, understanding the relationship between morphology and environment is one of the main steps toward understanding galaxies.

Morphology of Spiral Galaxies

1. Nuclear features
   nuclear rings and spiral arms

2. Bulge
   classical bulge vs pseudo bulge



3. Disk
   bars, spiral arms (Hubble stage, arm class)
   cf. lens, inner and outer rings

4. Vertical structure
   thick disk and warps

Nuclear morphology of spiral galaxies

- There are rings, bars , spiral arms and disk in the inner kpc regions.

NGC 6782

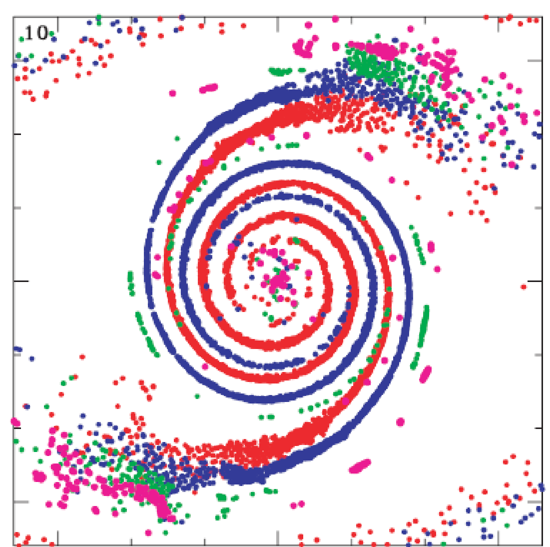
NGC 1300

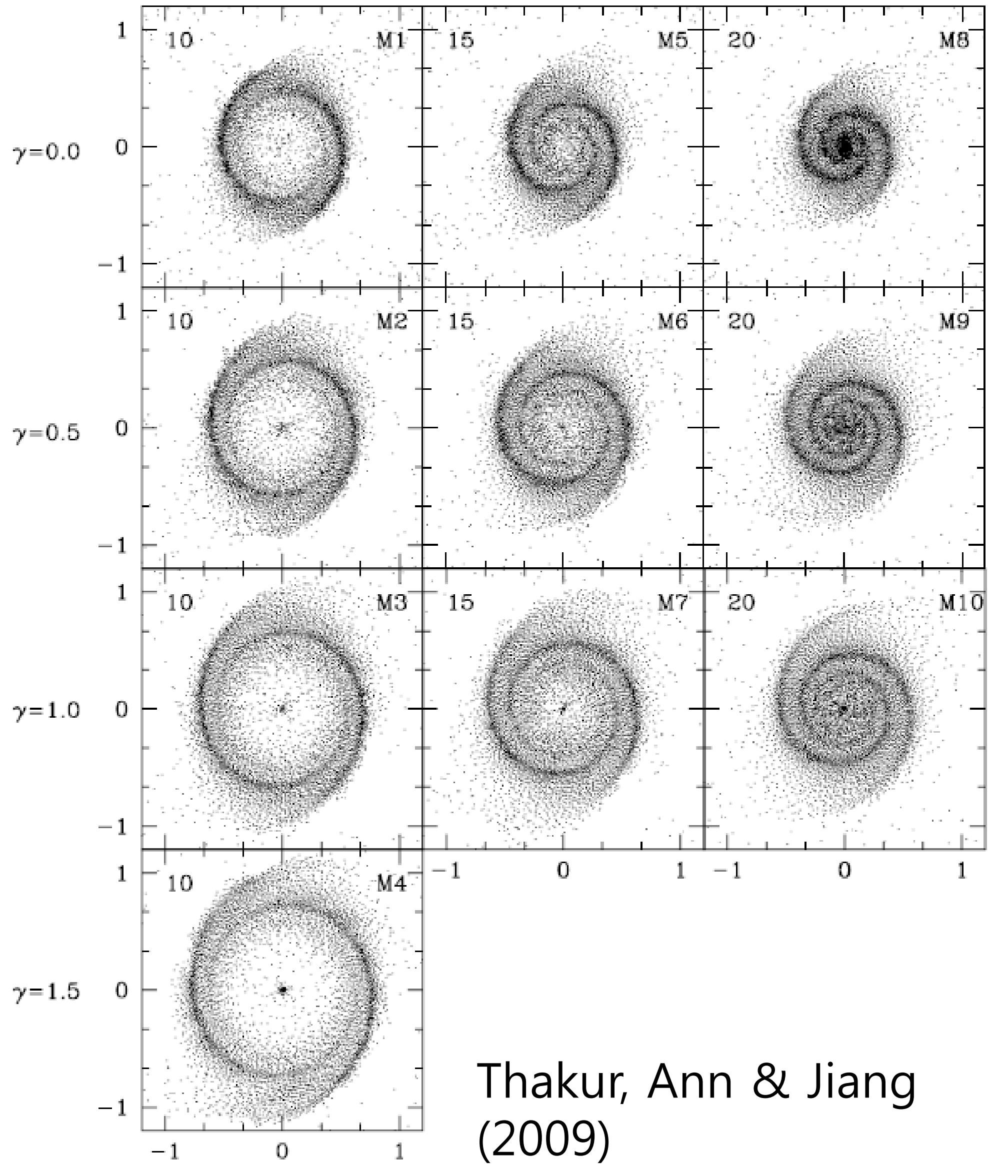
They are formed by bar driven gas inflow and their detailed morphology depends on the B/D, cs, Msmbh, bar strength (a/b, Mbar/M) as well as mass of the galaxy.

Maciejewski et al. (2004), Ann & Thakur (2005)

Dependence of the morphology of nuclear ring/spiral on the central mass concentration and sound speed.

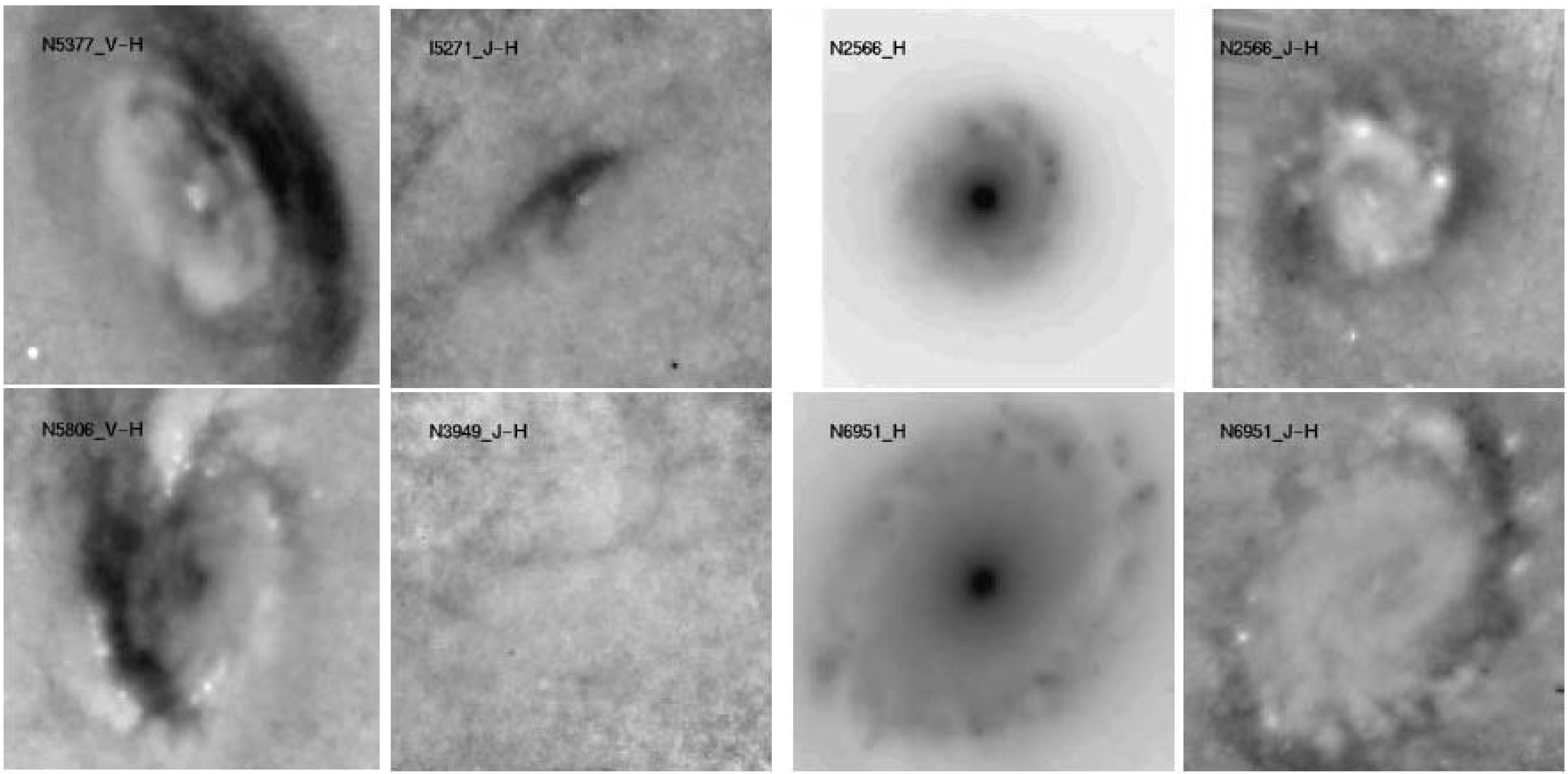
- Nuclear spiral arms open out as the gas sound speed increases.
- Models with high central mass concentrations and with low gas sound speed allow a larger nuclear disk than those with low central mass concentrations and high sound speed.
- It seems clear that shocks play a major role to transport gas toward nucleus of galaxy because shocked particles spiral in toward the cnter.



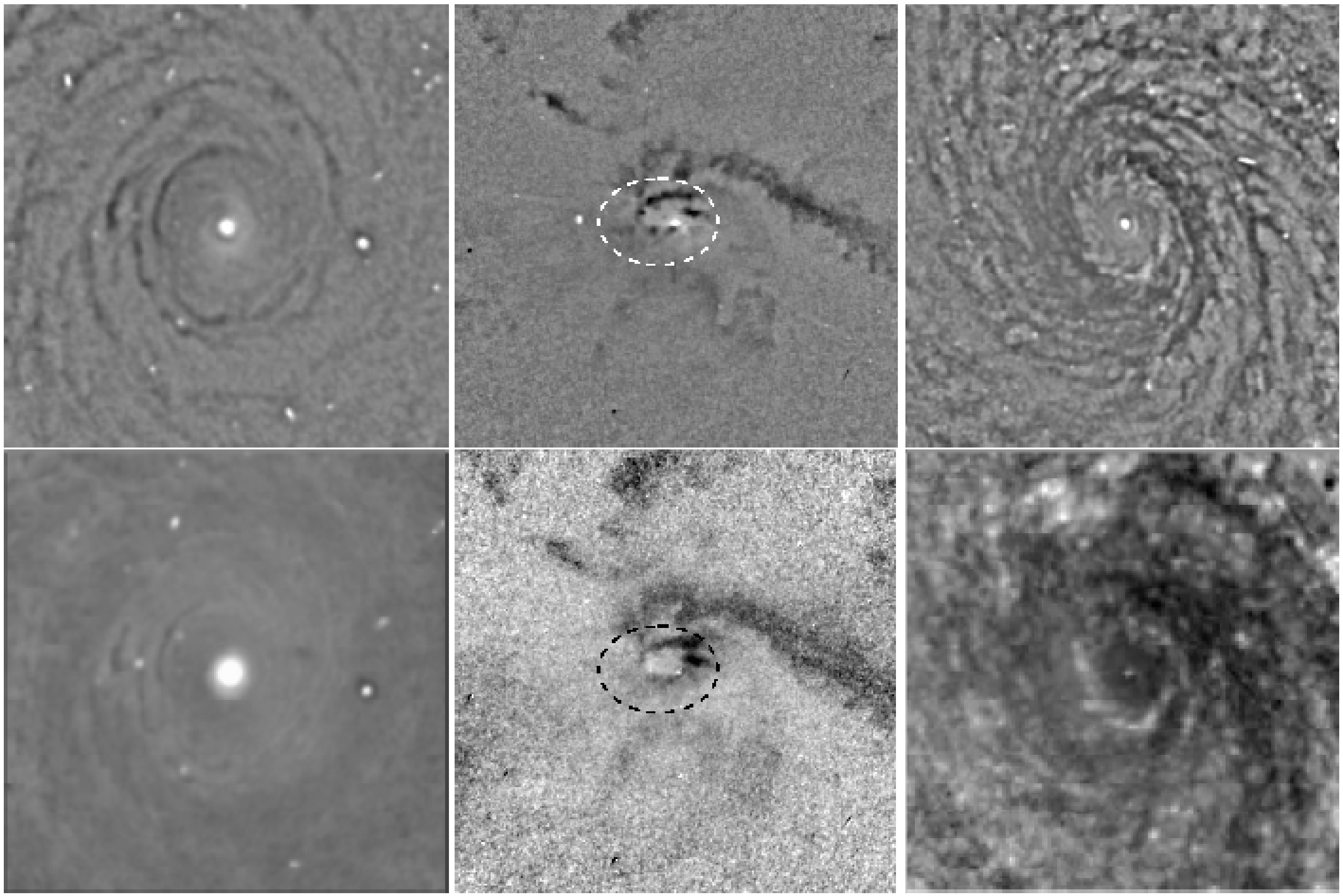


Thakur, Ann & Jiang (2009)

HST/NICMOS imgaes (Carollo et al. 2002)

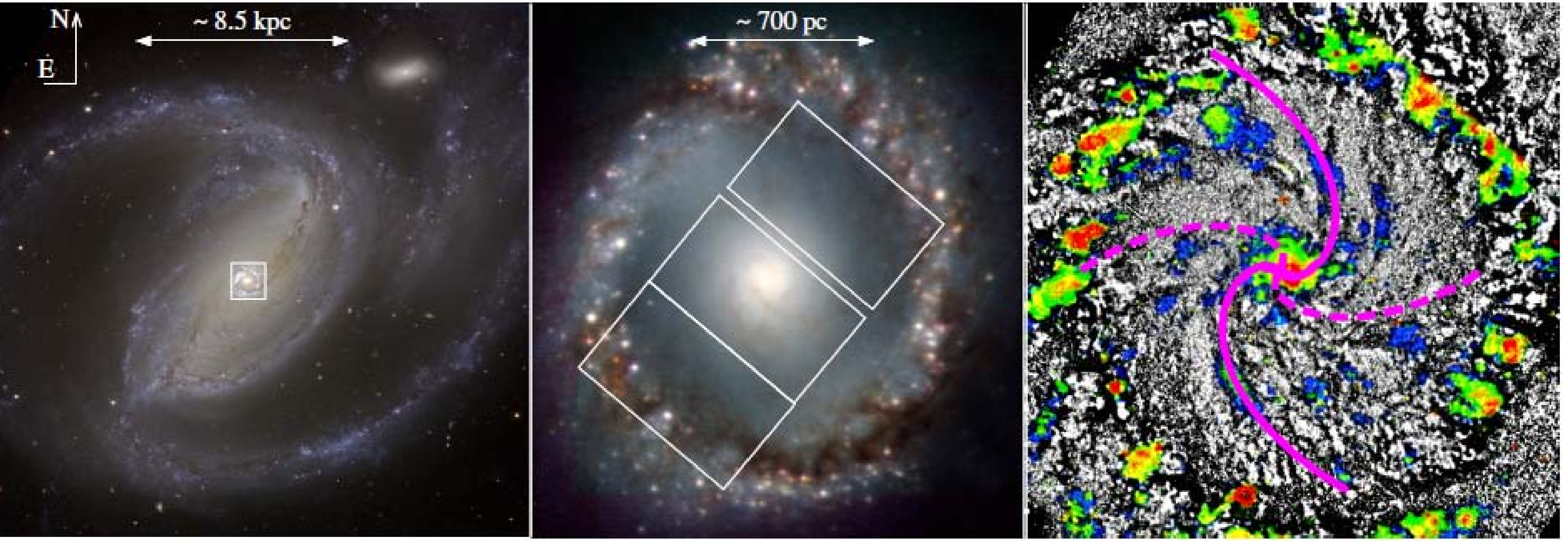


Ultra-compact nuclear rings
(Comerón et al. 2008)



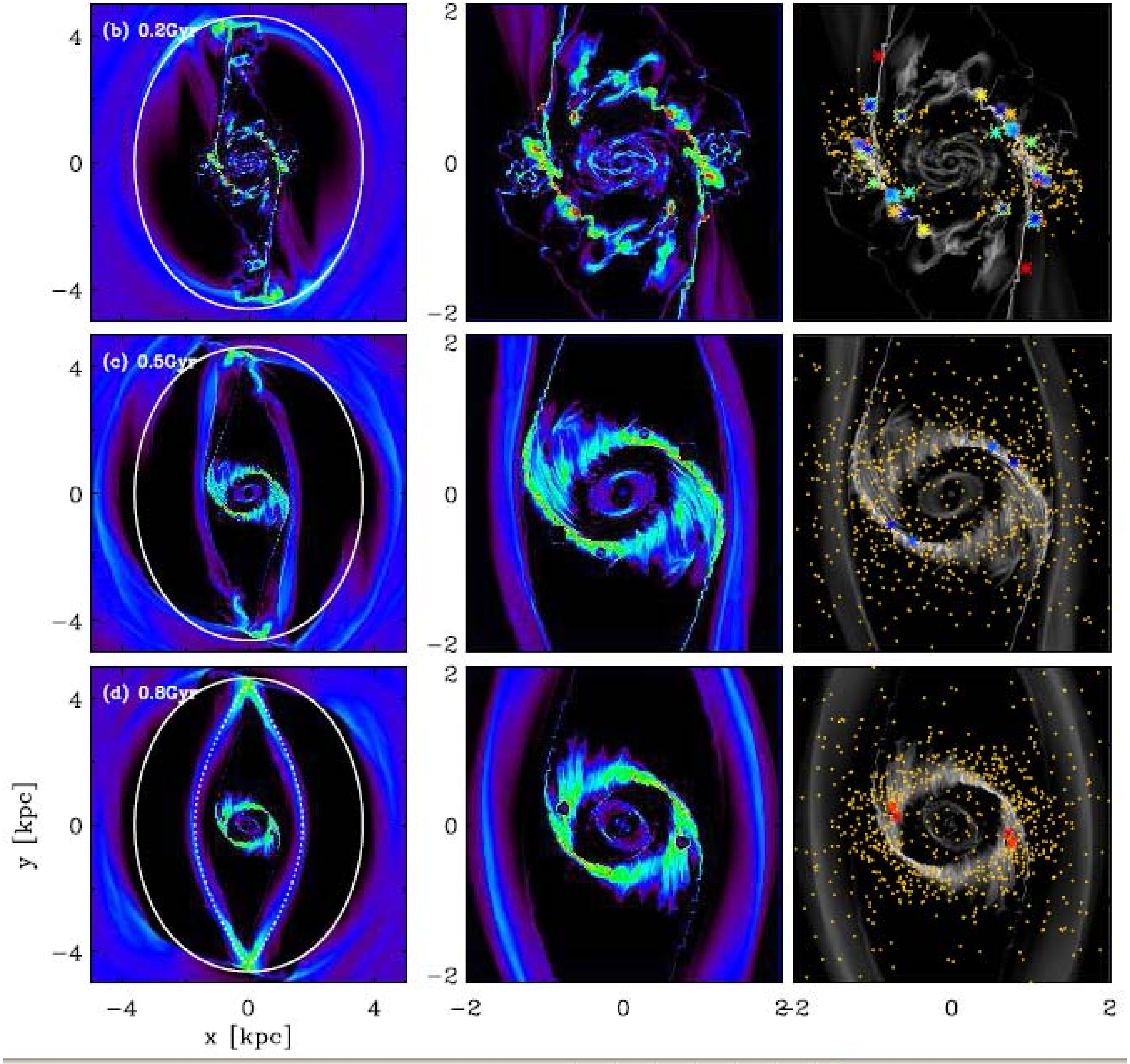
NGC 2985 NGC 4579 NGC 4800,

Nuclear spiral
(van de Ven & Fathi 2010)



NGC 1097

Seo & Kim (2013)



Lens, inner and outer rings

Bulges

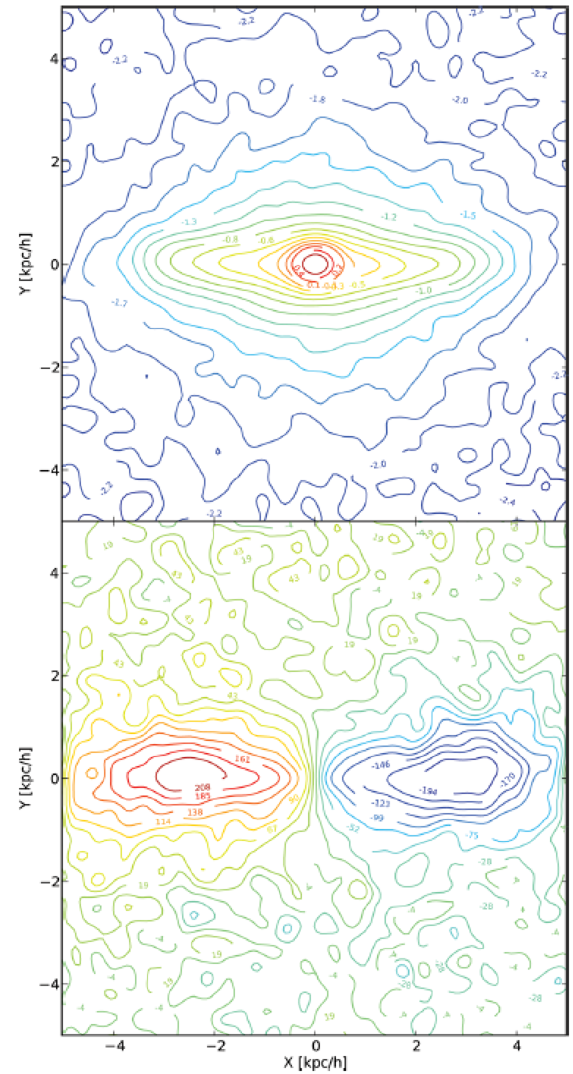
Classical bulges:
r^1/4 profiles, not flattened, slow rotation, formed from violent mergers of protogalactic fragments in the early stages of galaxy formation.

Pseudo-bulges:
Exponential profiles, fast rotation , flattened, formed through internal (secular) evolution from the disk, mediated by a bar.

Pseudo-bulge formation via major mergers
(Keselman & Nusser 2012)

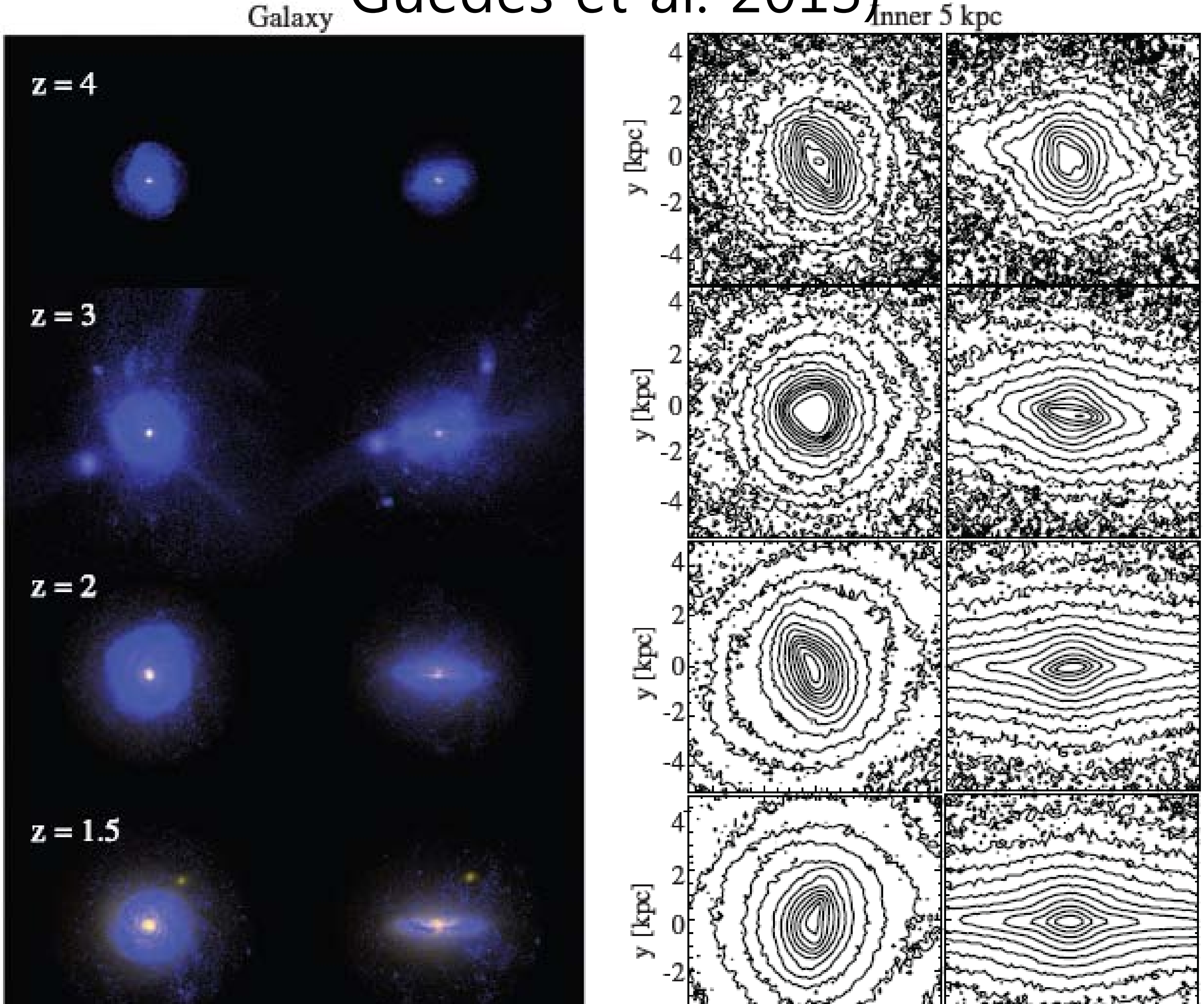
Or

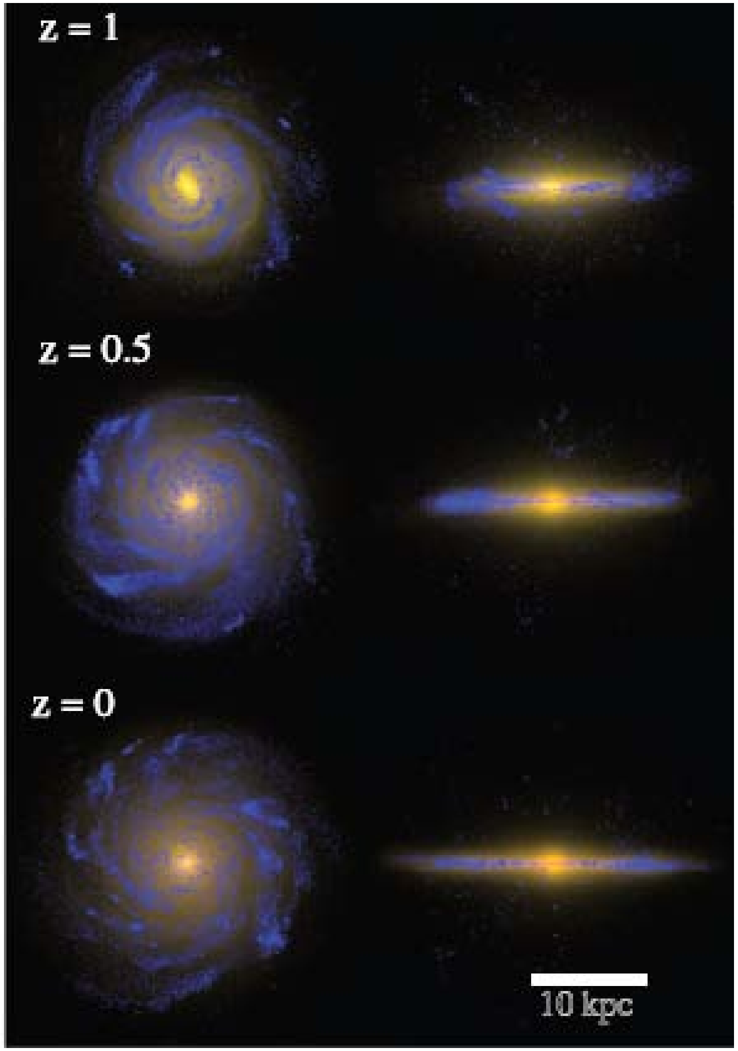
Pseudo-bulge formation by a dynamical process
(Guedes et al. 2013)

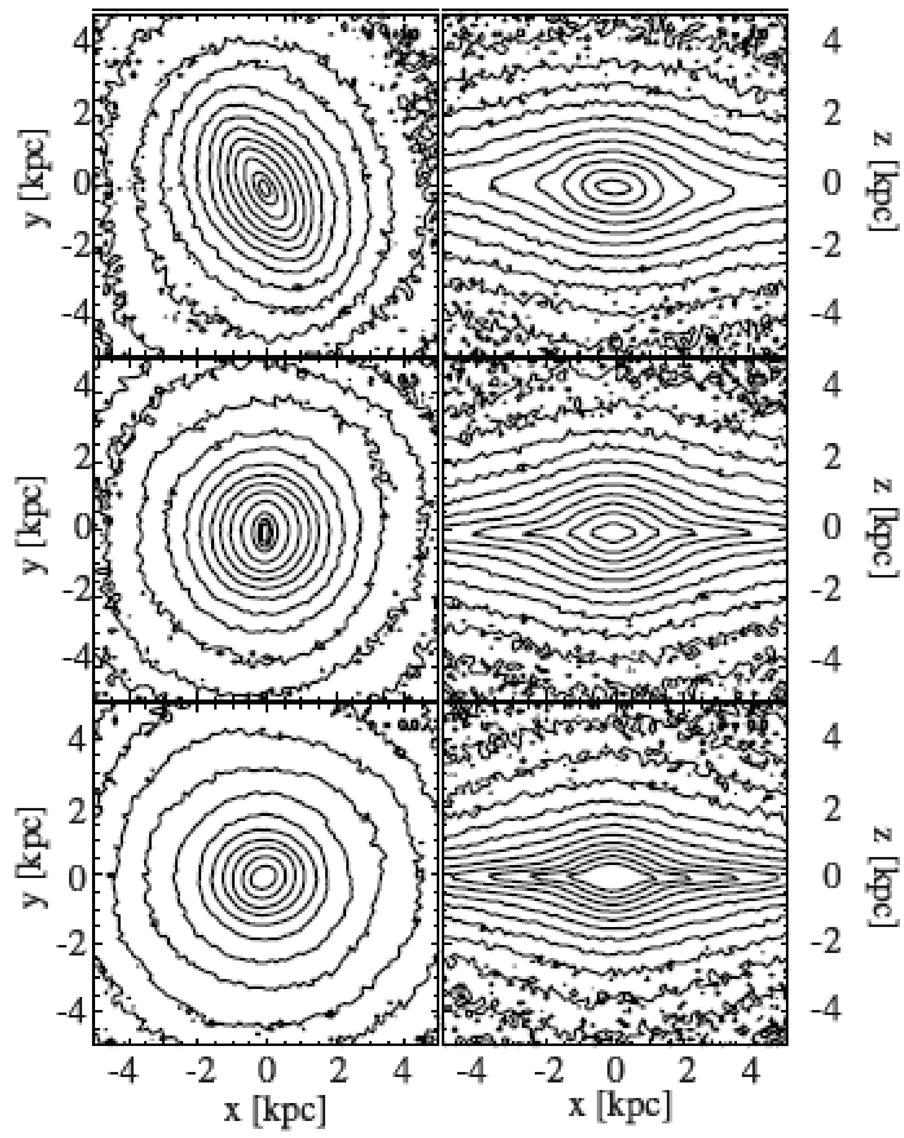


Keselman & Nusser (2012)

Formation of late type galaxies (pseudobulge: Guedes et al. 2013)

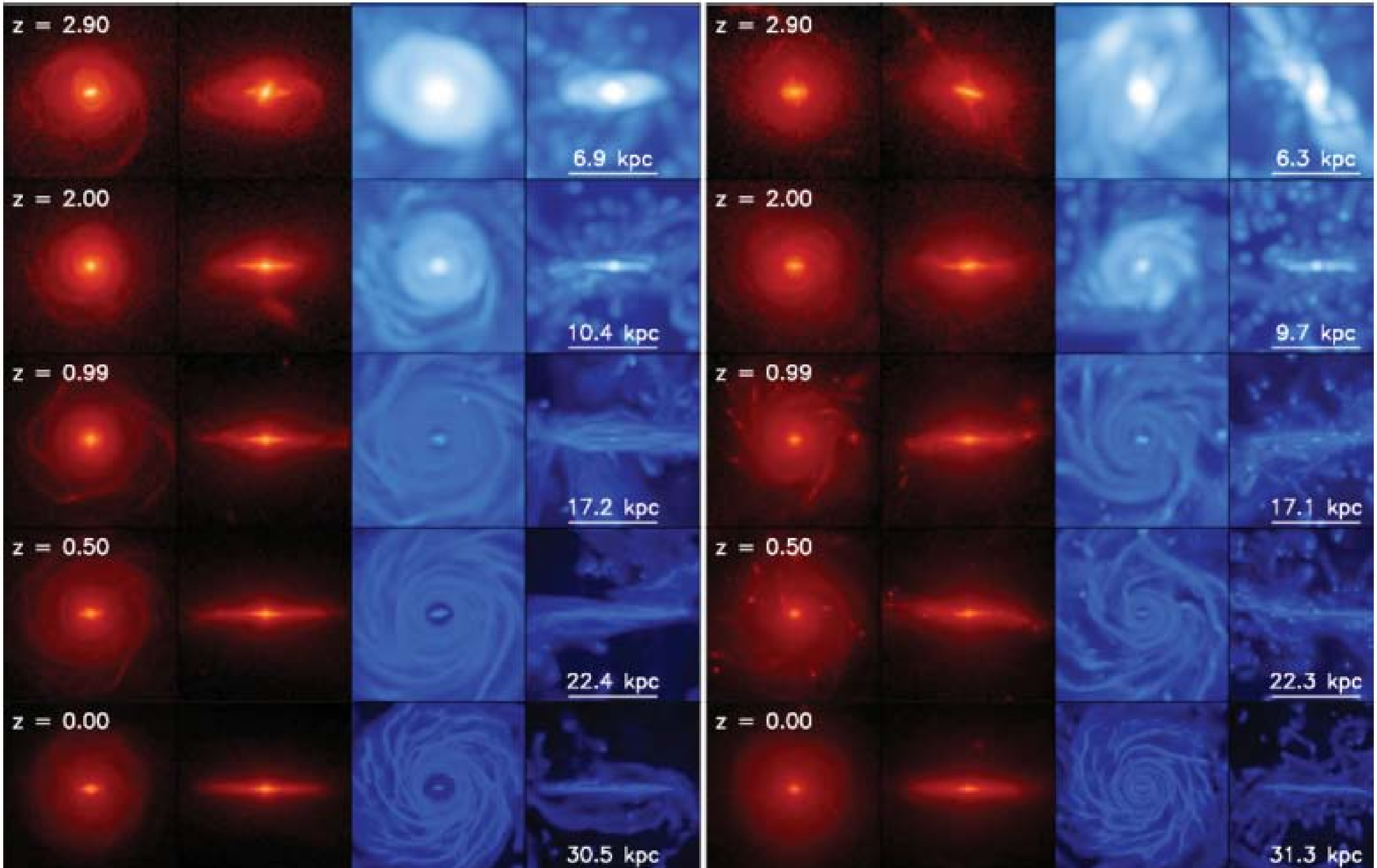






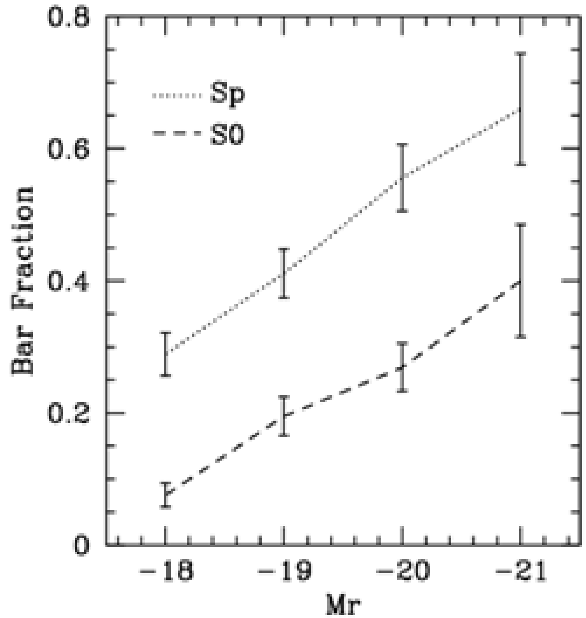
composite *i-band, V, and far-UV rest-frame images*

Pseudo-bulges in cosmological simulations of galaxy formation (Okamoto 2013)

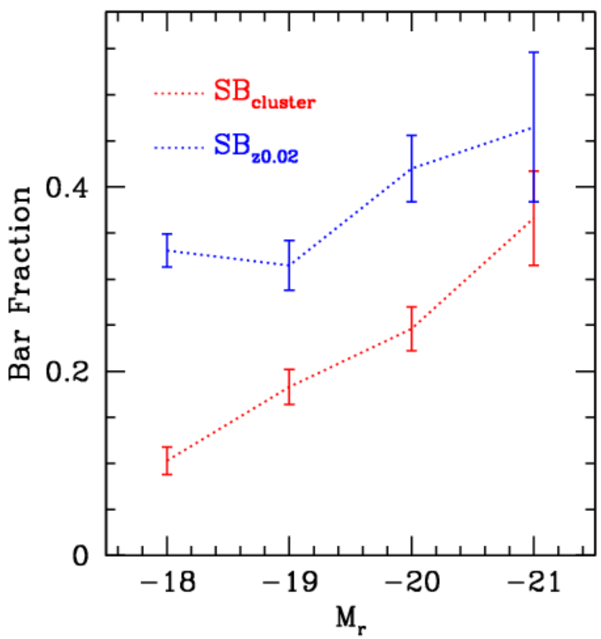


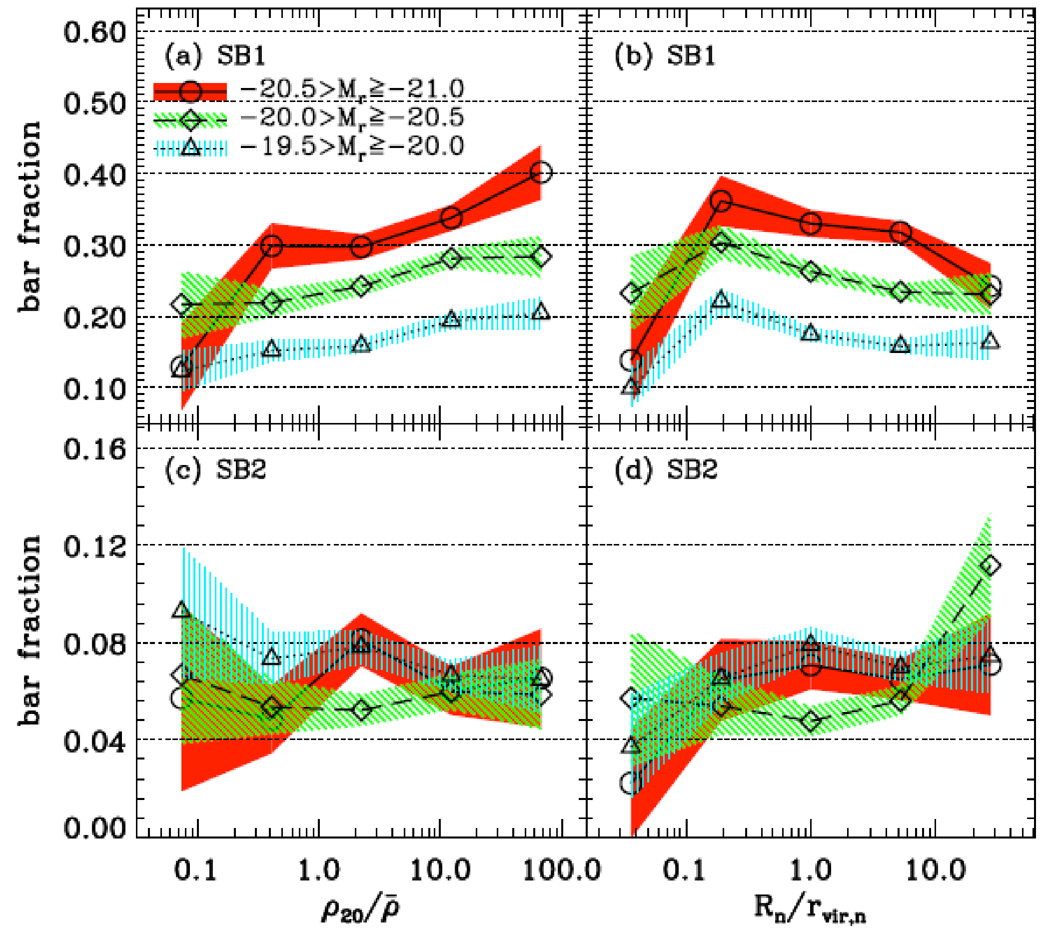
Barred galaxies

Bar fractions of SDSS galaxies



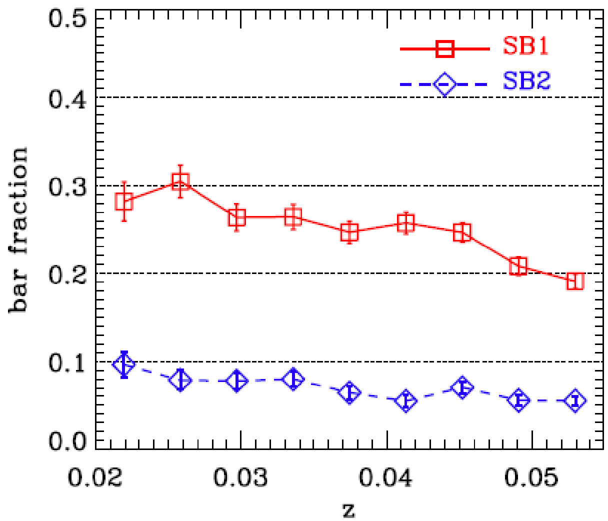
Cluster galaxies
(Choi & Ann 2011)



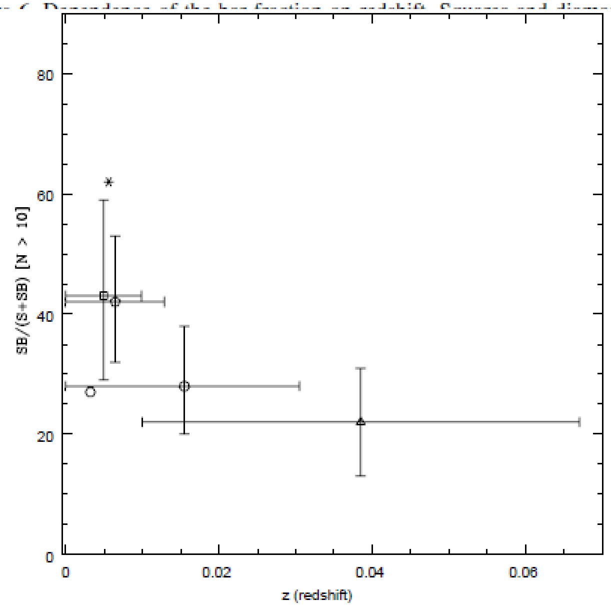


Volume limited sample, 0.02 <z<0.055
(Lee et al. 2012)

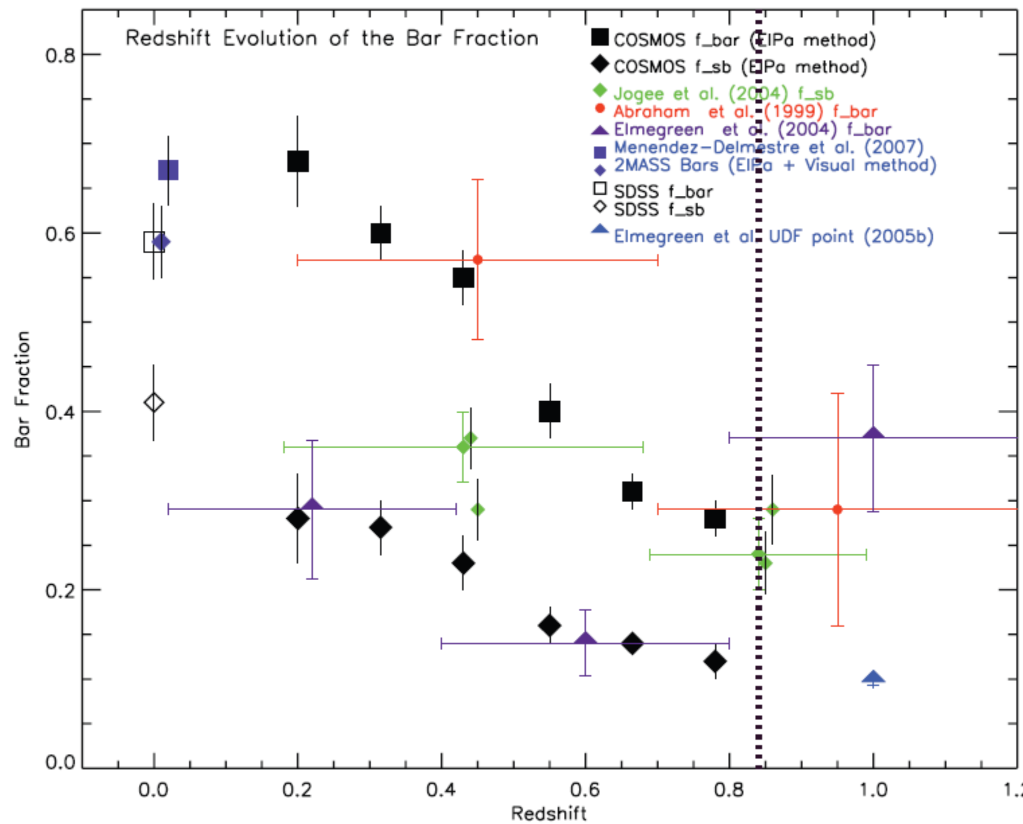
Bar fractions: redshift evolution



Lee et al. (2012)



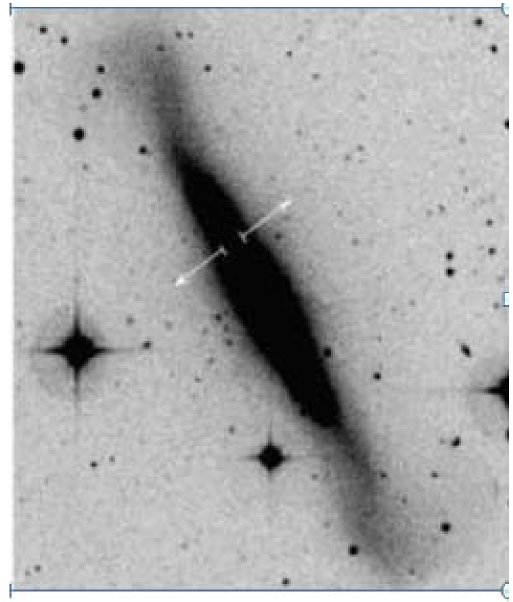
Garc´ıa-Barreto (2011)

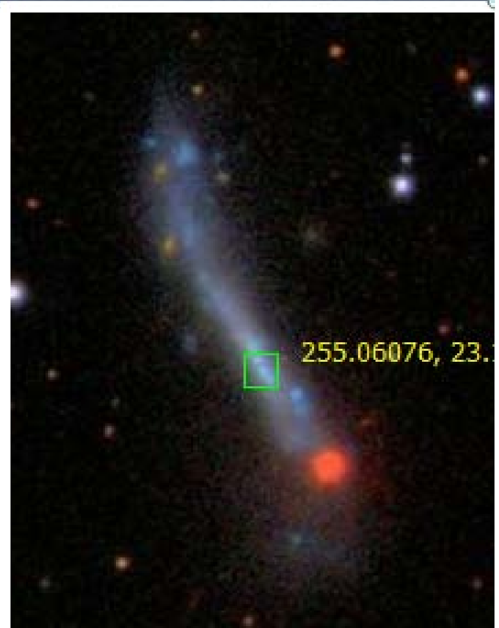


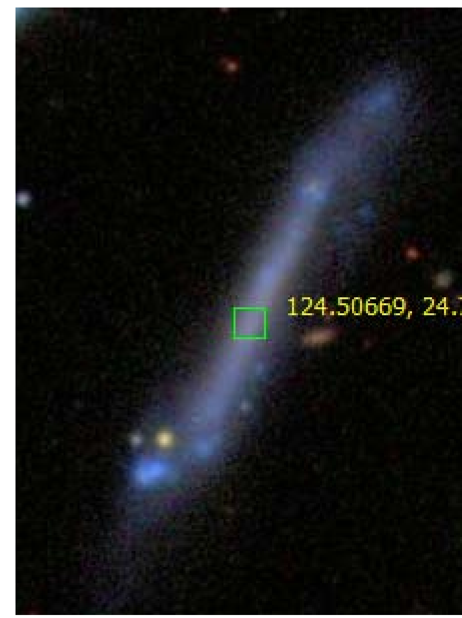
Sheth et al. (2008)

Disk vertical structures

- thick disk
- warps
- thin disk







van der Kruit & Freeman (2011)

Environment dependence of spiral galaxies

Basic Data

- Visually classified morphology (AC, T, Bar) of 2232 Spiral galaxies in X-ray selected Clusters ($0.03 < z < 0.06$,) of Choi & Ann (2011)

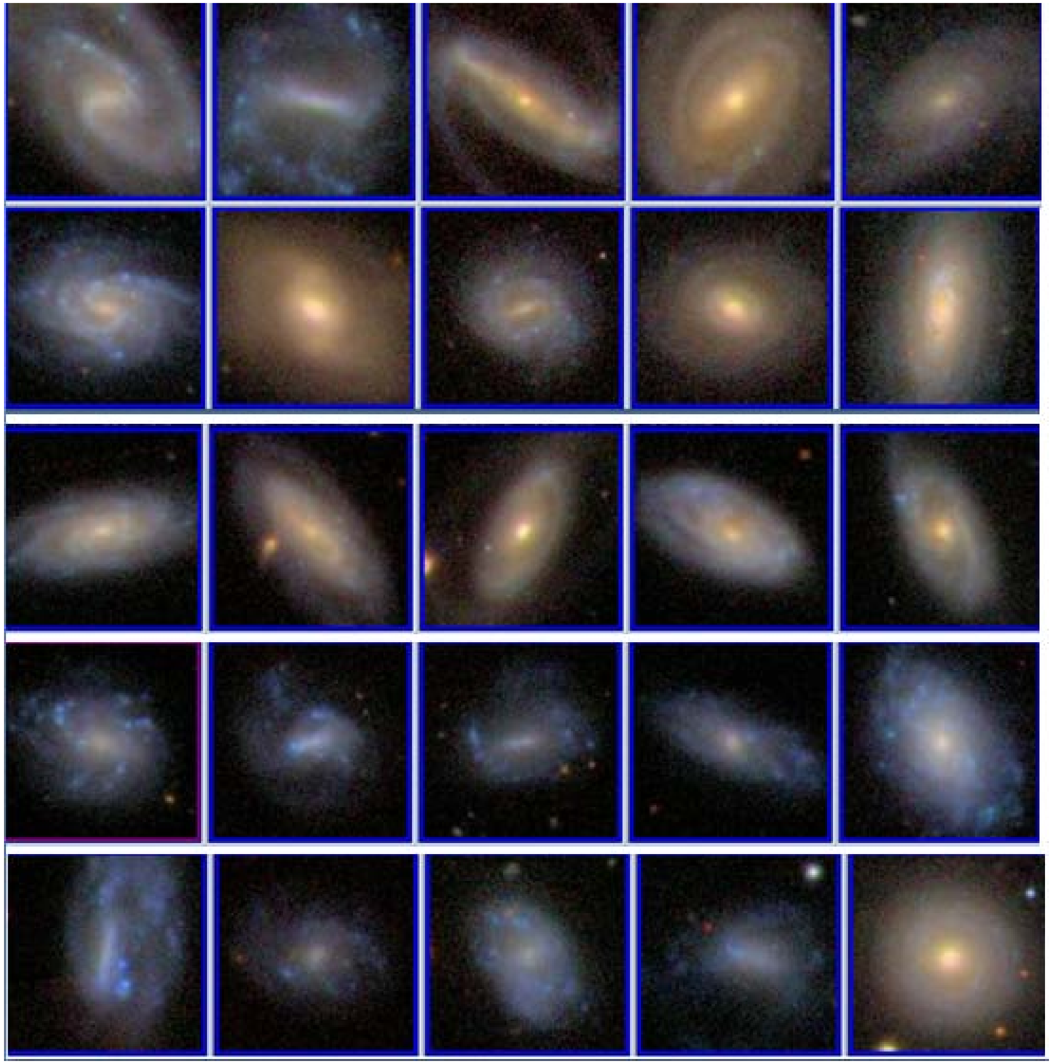
- Visually classified morphology (AC, T, Bar) of 1912 spiral galaxies (Ann & Lee 2013). Densities are derived from ~14,000 galaxies ($z<0.02$) of volume limited sample.

Hubble type (T)
early type (e): 0/a - ab
intermediate (i): b - cd
late type (l): d - m

bar type
SA, SAB, SB

Arm classes (AC)

(Elmegreen & Elmegreen 1982, 1987)



G

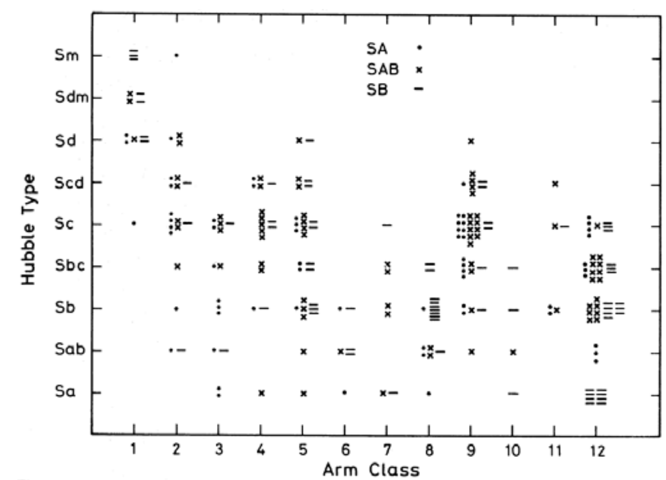
M

M

F

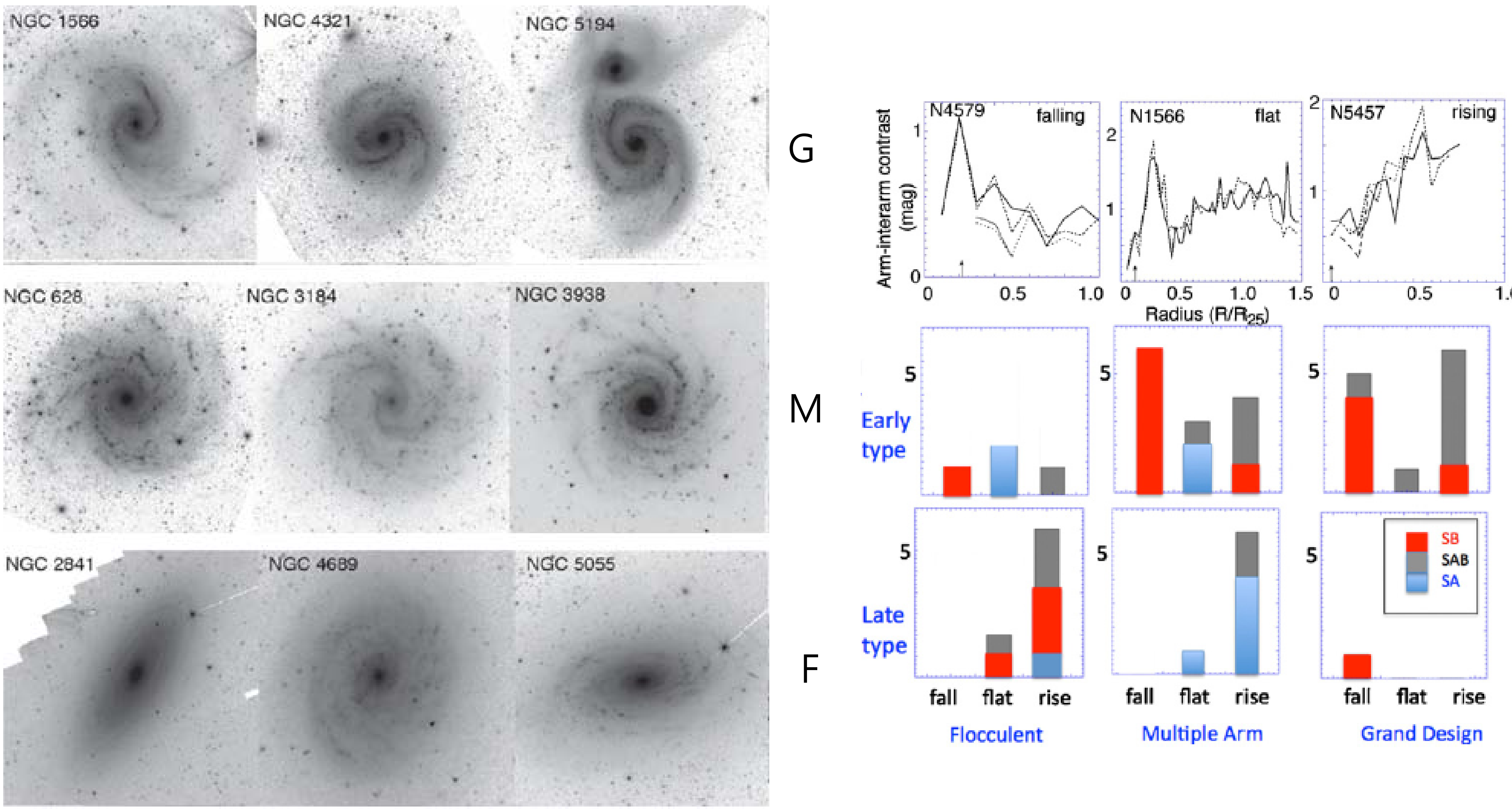
F

Elmegreen & Elmegreen (1982) introduced 12 AC based on continuity, length and symmetry.



G: grand design
M: multiple-arm
F: flocculent

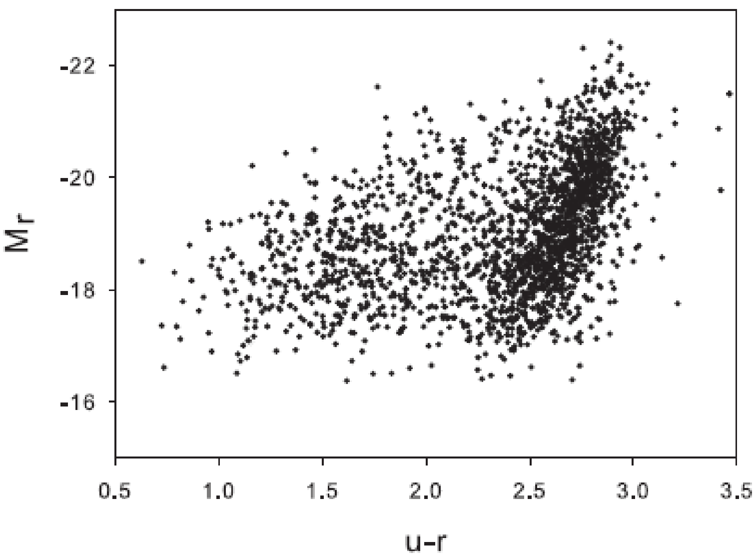
G and F spirals in S4G (3.6μm)

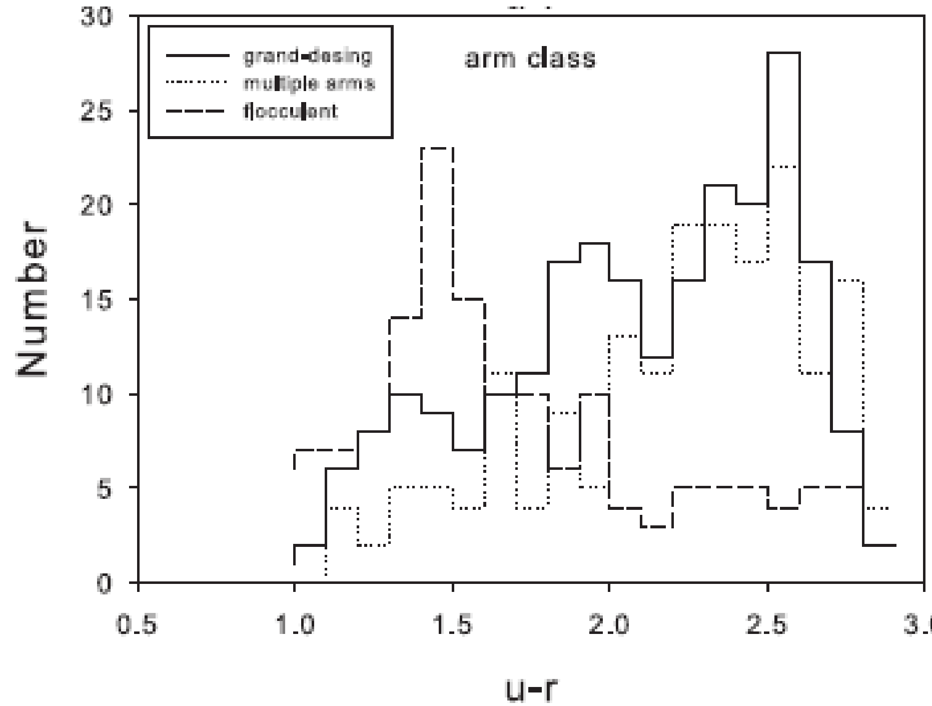


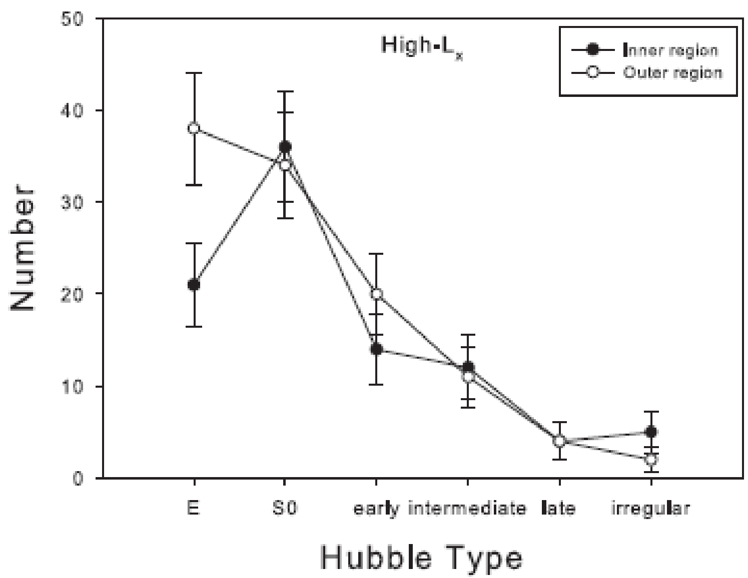
D. Elmegreen et al. (2011)

Spirals in X-ray selected clusters

Choi & Ann (2011)

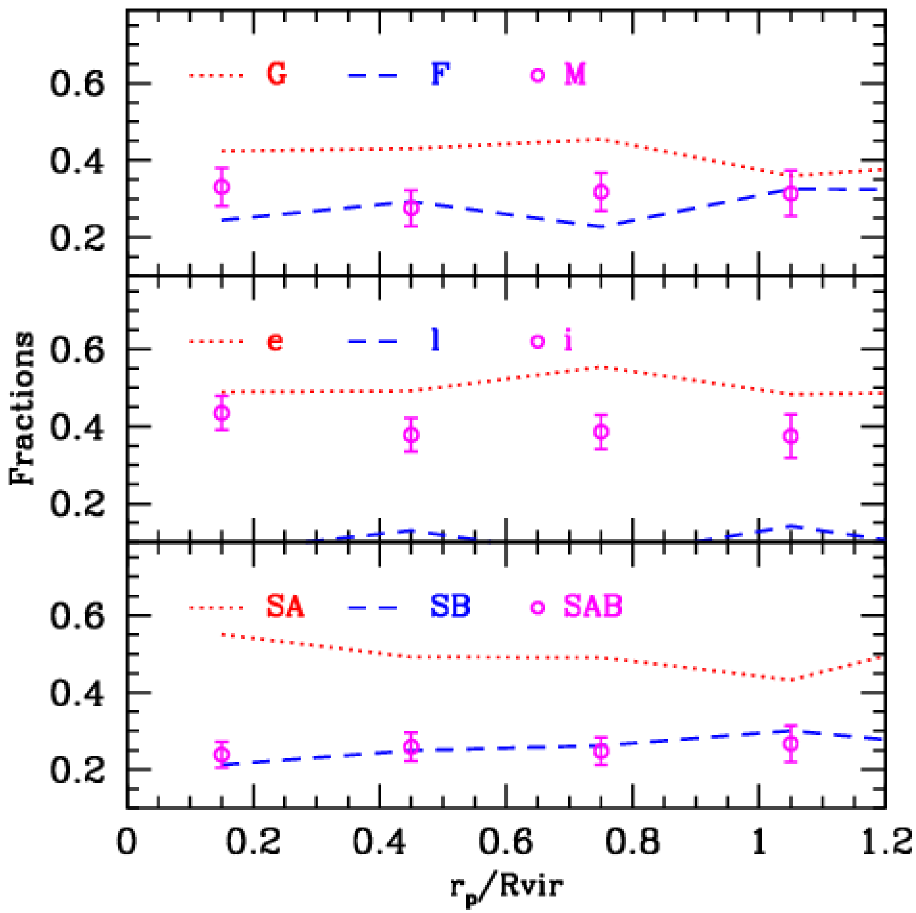






- Early type galaxies are more frequent than late type ones, regardless of the cluster X-ray luminosity..
- Grand design galaxies are likely to be redder than flocculent galaxies.

Spirals in X-ray selected clusters

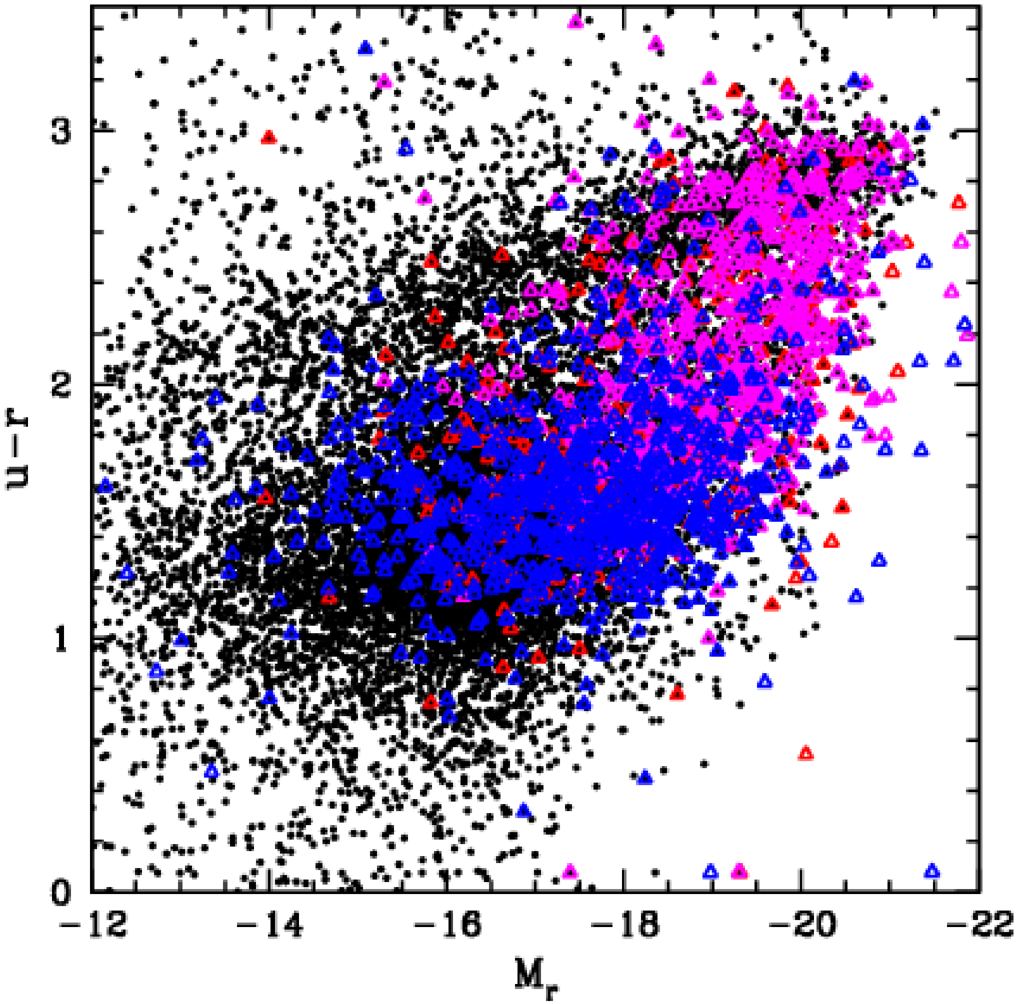


.

- fractions of arm classes is nearly constant along the radius.
- Hubble types of spiral galaxies show nearly constant fraction along the radius and late type spirals are very rare.
- fraction of SB spirals slightly increases with radius while that of SA galaxies decreases

Choi & Ann (2011)

Local galaxies (z < 0.02)



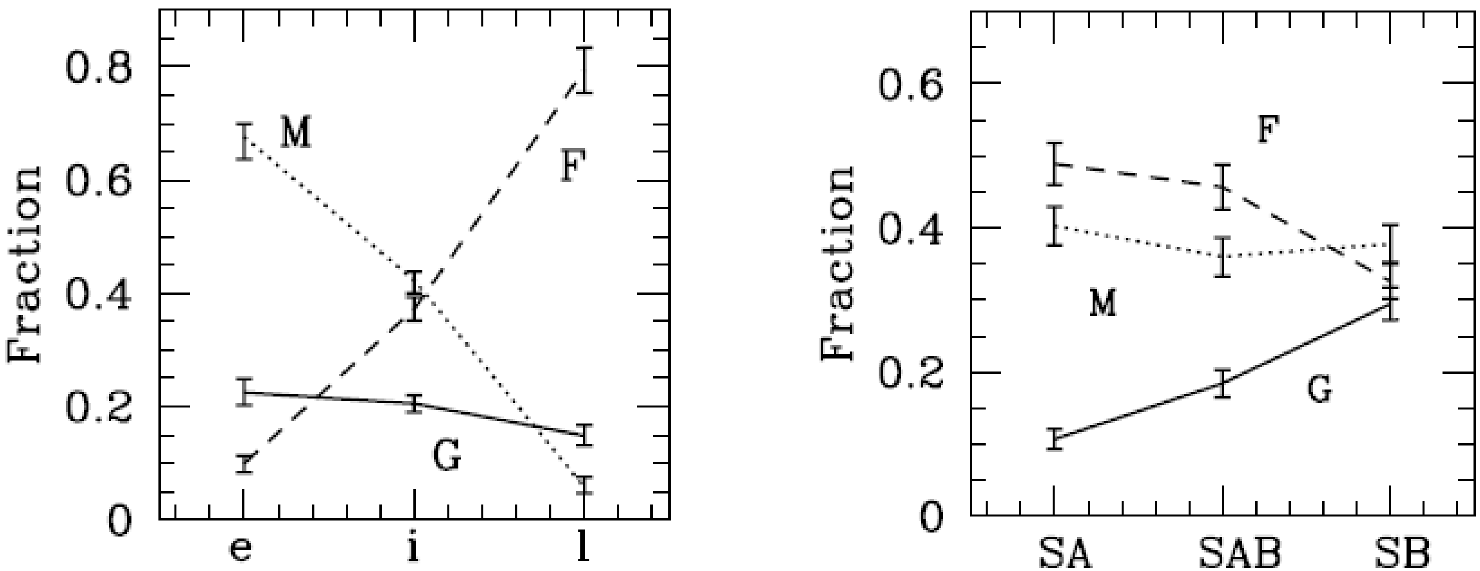
- ~14000 SDSS galaxies
  z < 0.02

- 1912 spiral galaxies:
  i < 65°, Rpet > 10″

- Arm class (1912 galaxies)
  red : grand design
  magenta : multiple-arm
  blue : flocculent

Grand design spirals are redder and brighter than flocculent spirals.

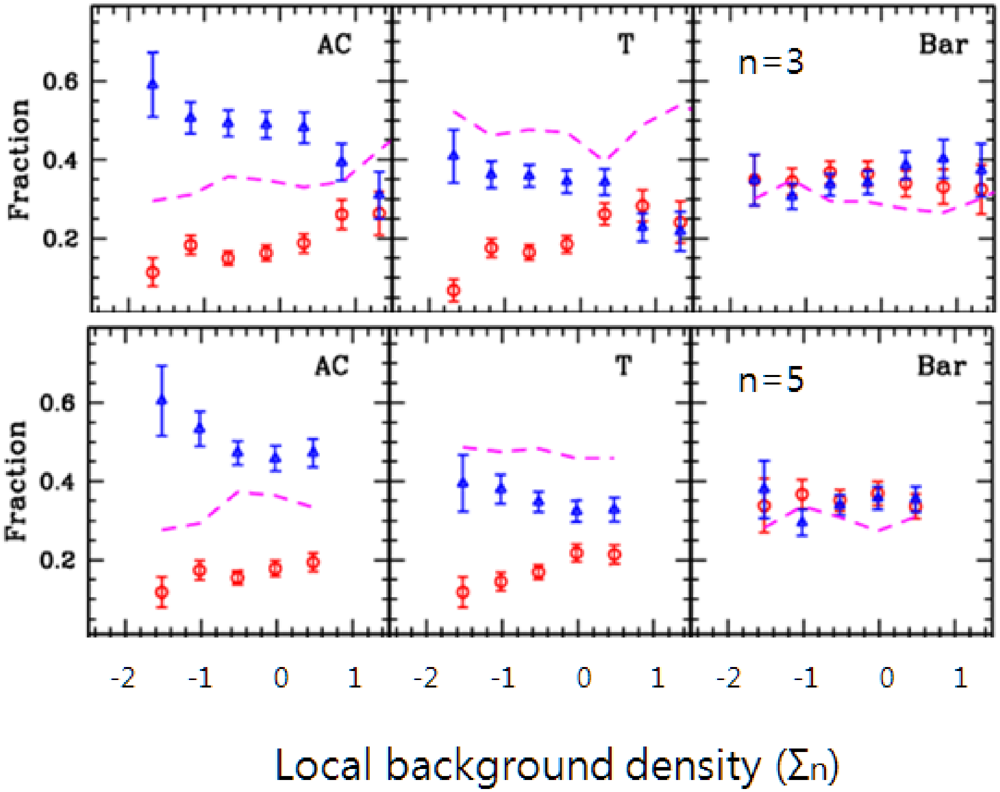
Local spiral galaxies (z < 0.02)



Ann & Lee (2013)

- Multiple-arm galaxies are likely to be found in early-type spirals while flocculent galaxies are dominated in late-type spirals.
- Grand design fractions increase from SA to SAB to SB. Opposite is true for flocculent fractions.

Density (Σn with M*=-16.1 & ΔV=500km/s) dependence of AC, T and bar type

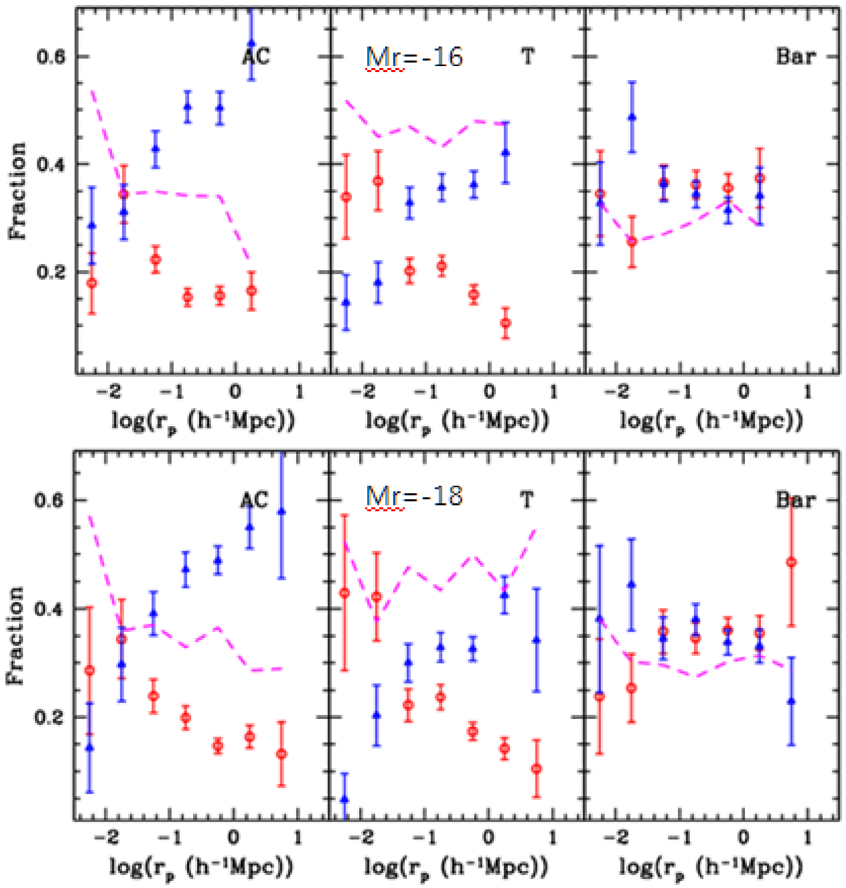


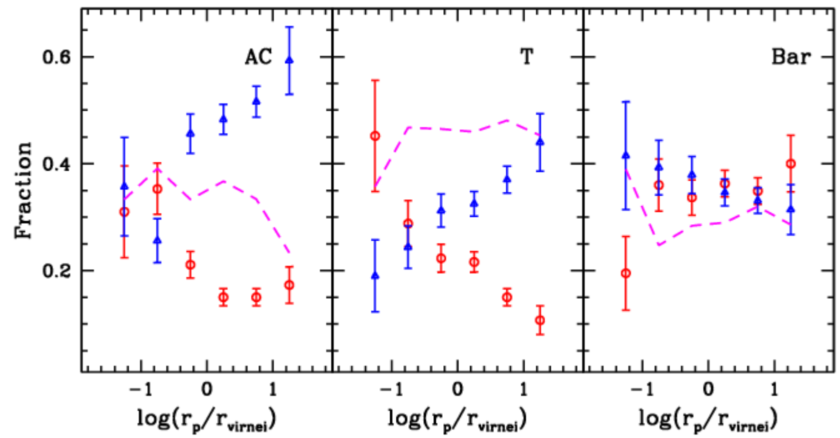
$$\Sigma_n = \frac{n}{4\pi {r_{p,n}}^2},$$

red: grand design, early type, SA
magenta:: multiple-arm, intermediate type, SAB
Blue: flocculent, late type, SB

Grand design and early-type spirals exhibit increasing fractions with Σn while flocculent and late-type spirals show decreasing fractions.
Bar type shows weak dependence on Σn with a trend of high frequency of SB galaxies at high density regions.

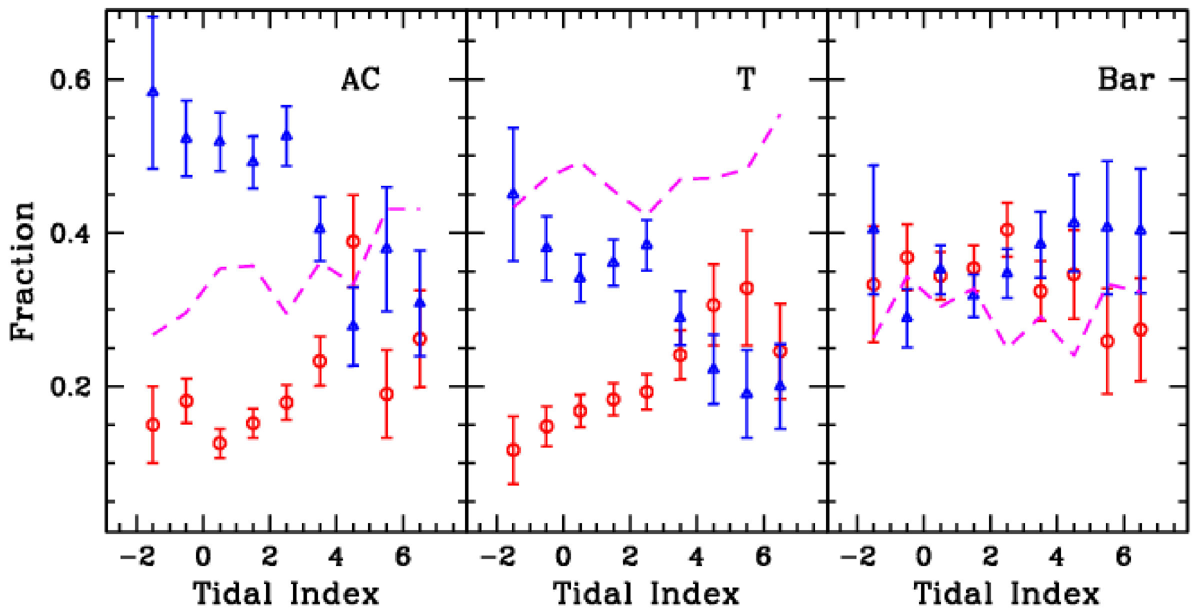
rp (ΔV*=500km/s M*=-18) dependence of AC, T and bar type





- Arm class and Hubble type exhibit strong dependencies on rp (h^{-1}Mpc which is derived by the neighbor luminosity constraint of M*=-18.
- High frequency of SB galaxies at small rp is apparent.
- Hubble type shows a strong correlation with rp normalized by the virial radius of the nearest neighbor.

TI dependence of AC, T and bar type (ΔV^*=500km/s, M^*=-16.1)



Tidal strength represented by TI shows a strong correlation with Hubble type. AC and bar type also show fairly strong dependence on TI.

Conclusions

- Fractions of grand design, early-type spirals increase with Σn, $1/r_p$ and TI while those of flocculent, late-type spirals decrease with them.

- Multiple-arm spirals exhibit the same trend of environmental dependence as grand design arms but much weaker correlation, whereas intermediate-type spirals show nearly constant fractions along Σn , r_p and TI .
- Bar type shows a weak dependence on the environment, but there is a tendency of high frequency of SB galaxies at high density regions where we expect a relatively strong tidal strength and small separations of neighbor galaxies. The opposite is true for non-barred galaxies.

- Arm class exhibits the strongest correlation with r_p when we consider bright neighbors ($M^*=-18$), while the Hubble type shows the best correlation with $\Sigma 5$. It suggests that Hubble type which is mostly determined by the bulge-to-disk ratio is set up during galaxy formation processes while arm class which represents the degree of symmetry and continuity along with arm length is set up by disk instability after disk forms.

Thank you!