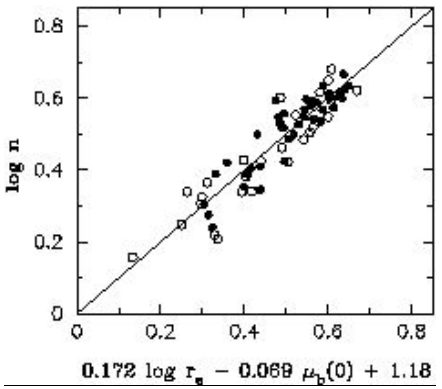
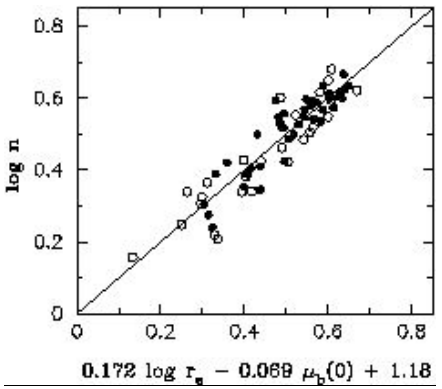
Hello!

Galaxy Morphology, SuperMassive Black Holes and all that



Ajit Kembhavi
IUCAA, Pune

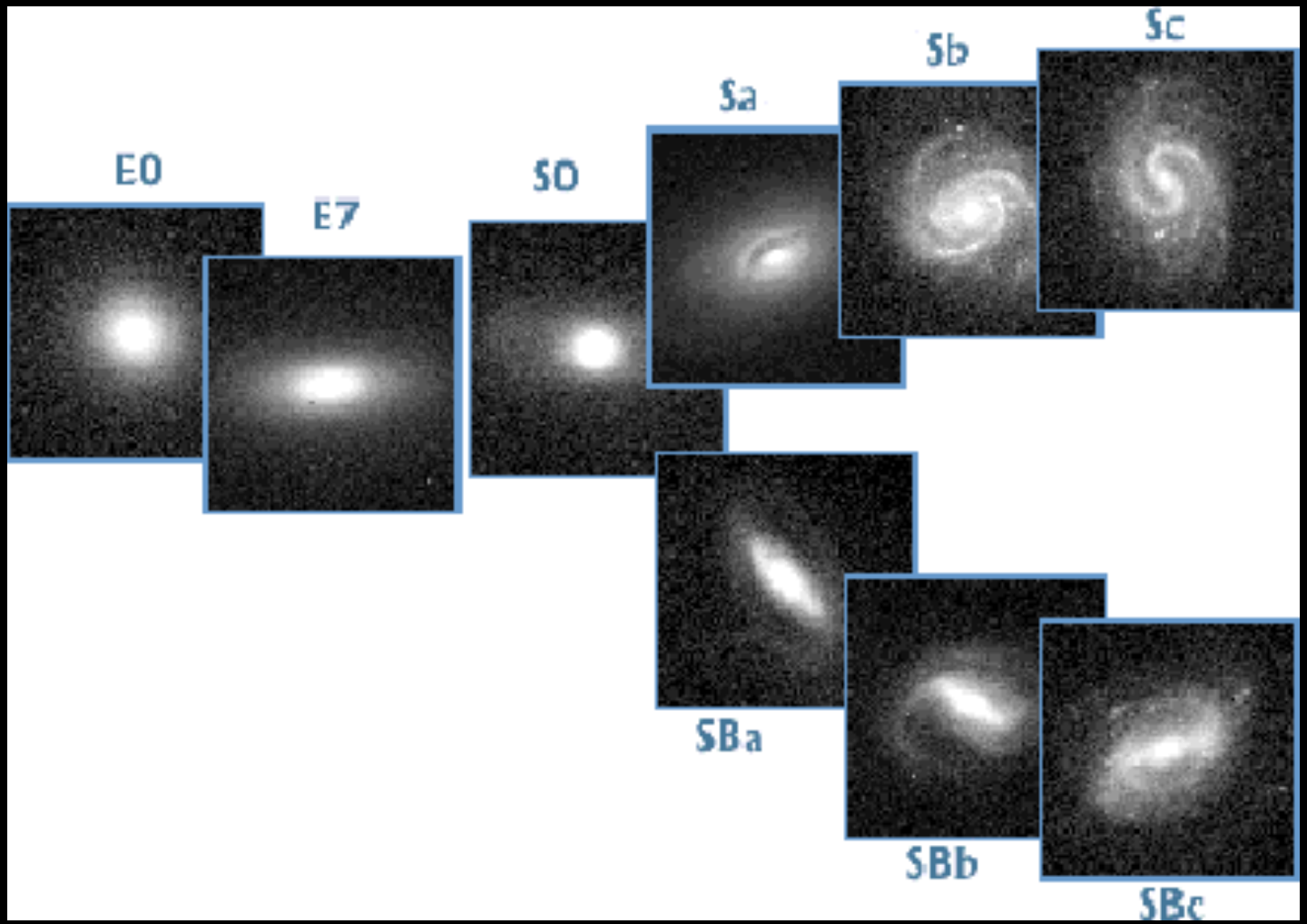
Galaxy Morphology, SuperMassive Black Holes and all that



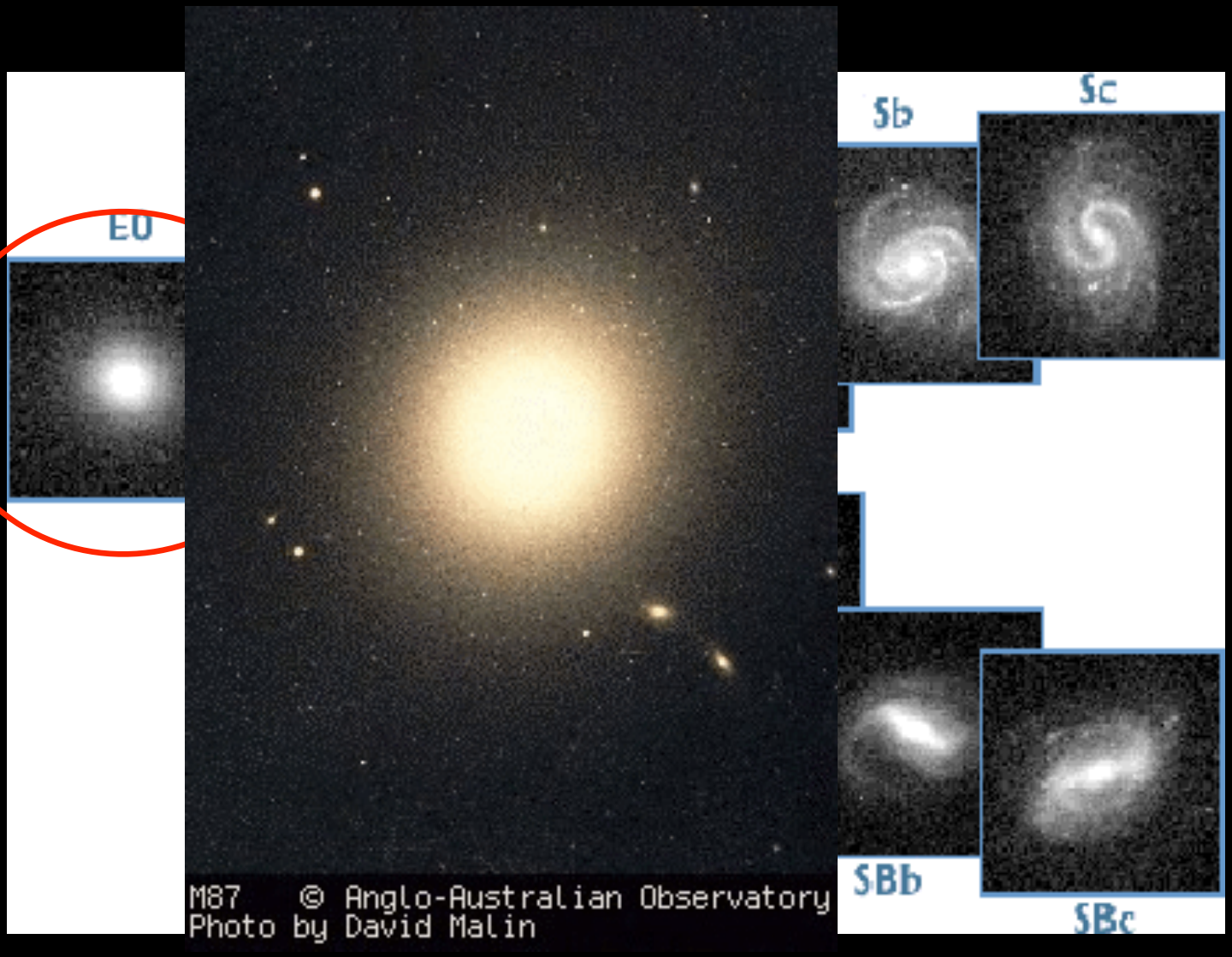
Ajit Kembhavi
IUCAA, Pune

Sudhanshu Barway
Kaustubh Waghmare
Yogesh Wadadekar

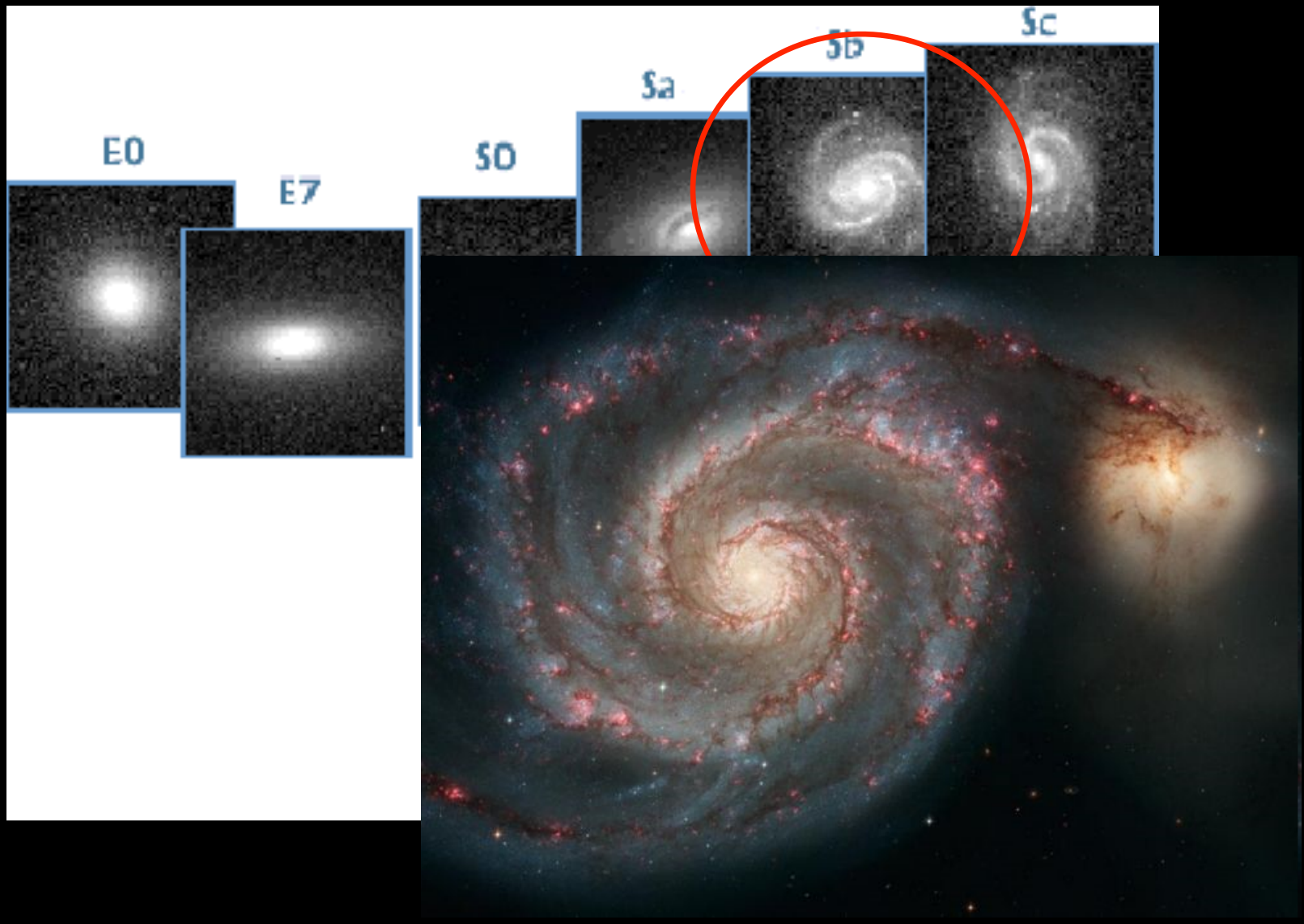
Hubble's Tuning Fork



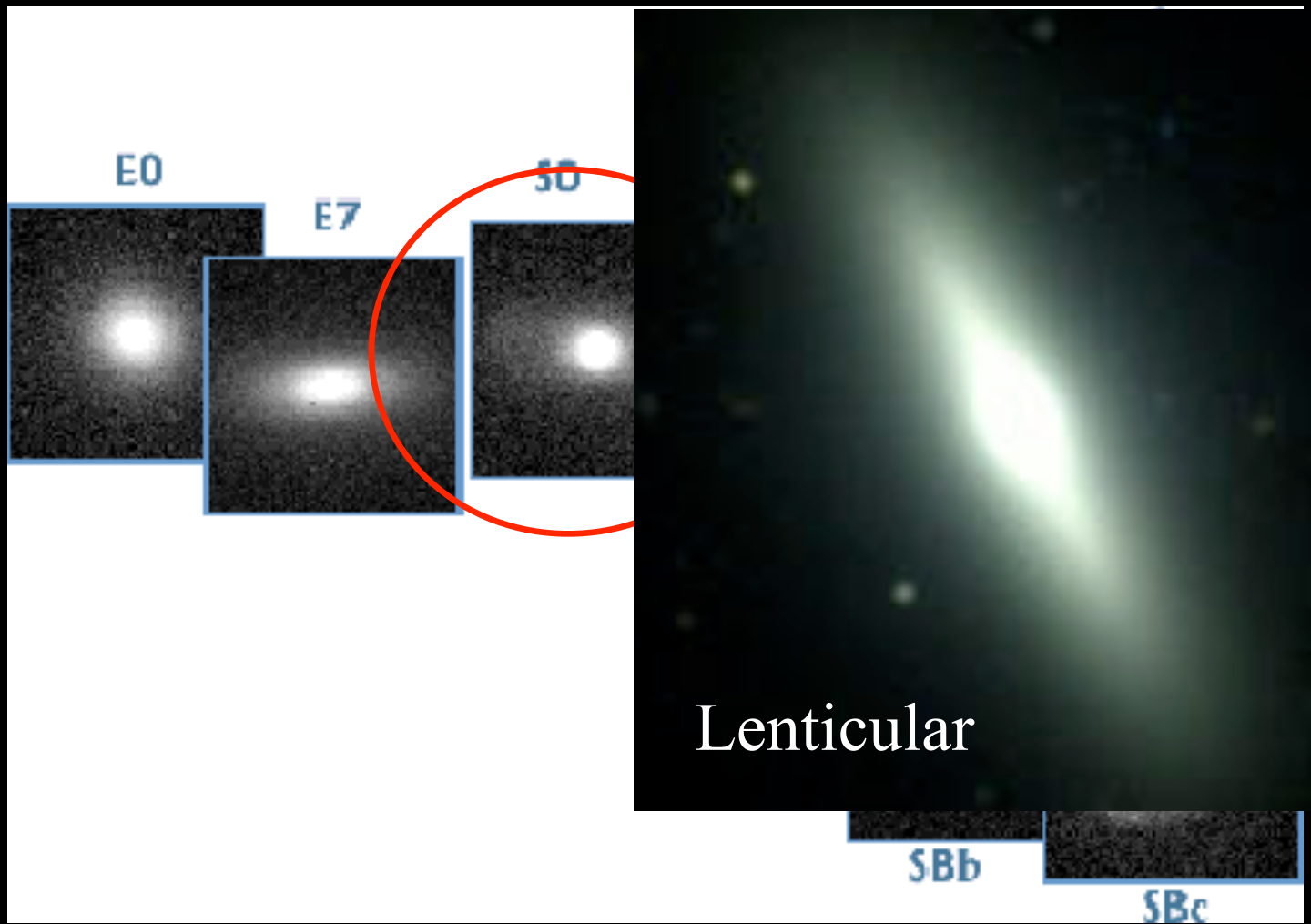
Hubble's Tuning Fork



Hubble's Tuning Fork



Hubble's Tuning Fork



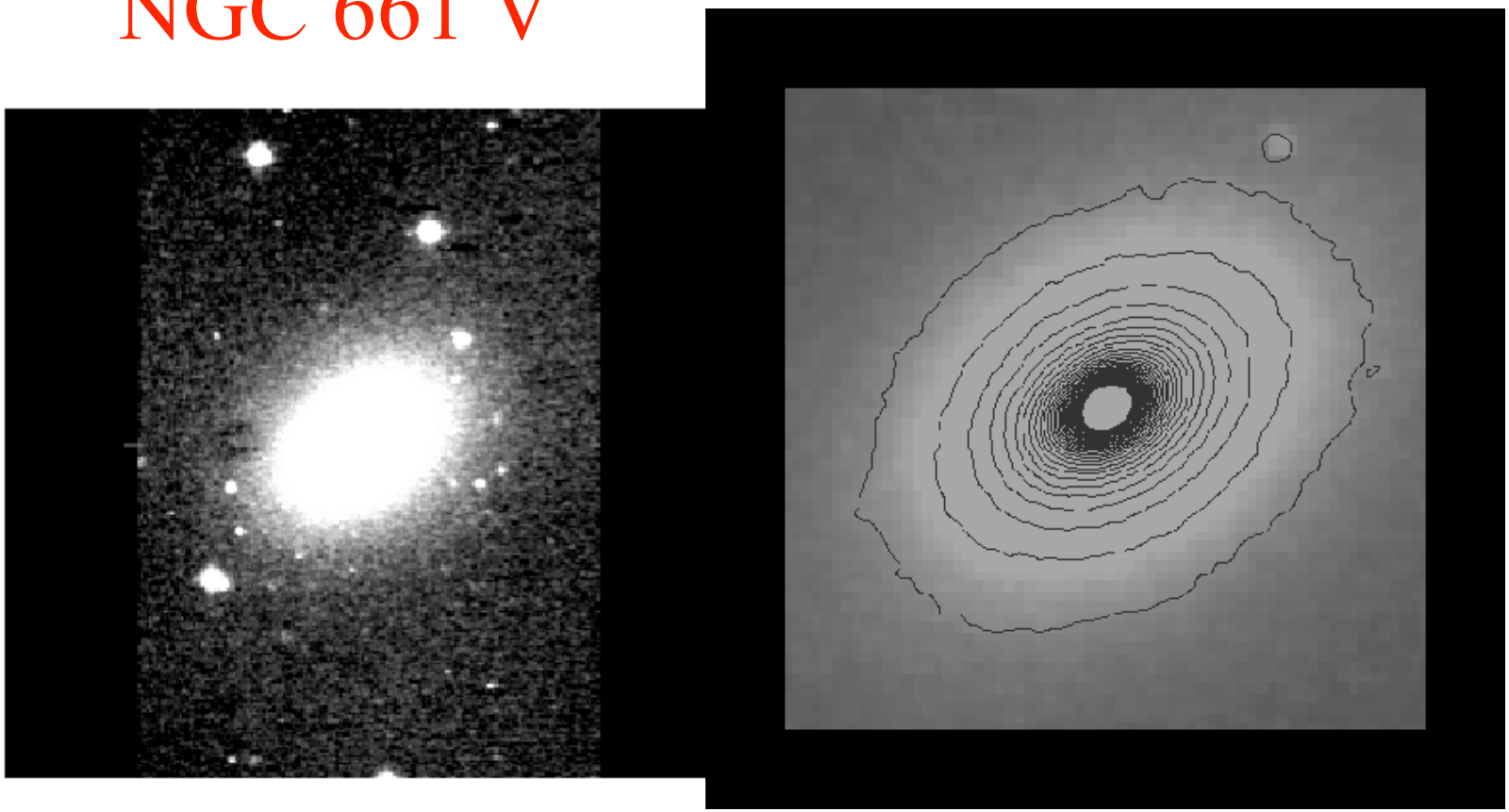
Bulges of lenticulars are very similar to ellipticals. Their disk are similar to those of early type spirals, but they have no spiral arms.

B/T ratios, colors and spectral properties, neutral and molecular gas fraction, star formation rate, average luminosity, M/L ratio are intermediate to ellipticals and spirals.

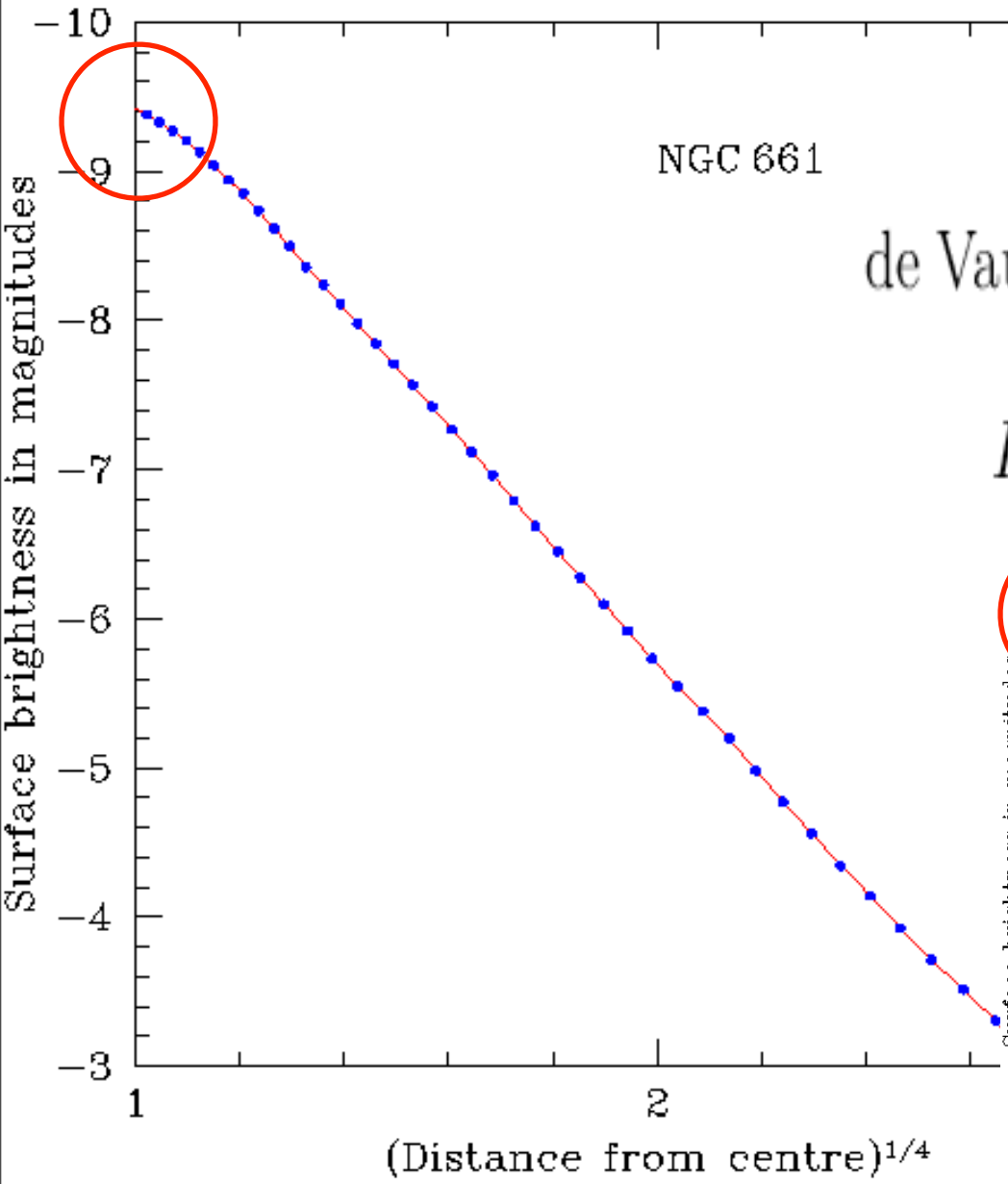
Lenticular galaxies are a morphological transition class between ellipticals and early type spirals.

Surface Brightness Distribution

NGC 661 V

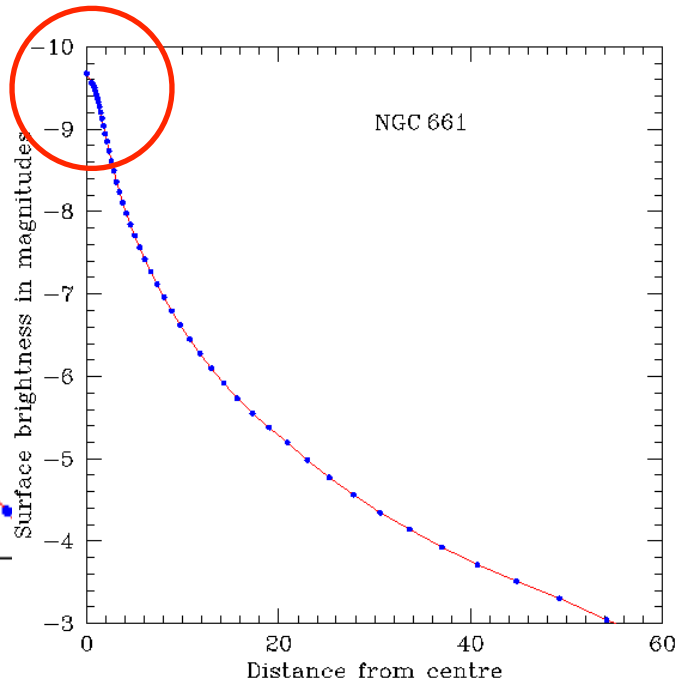


Surface Brightness Profile



de Vaucouleurs' law:

$$I_b(r) = I_b(0)10^{-3.33(r/r_e)^{1/4}}$$



Galaxy Surface Brightness

Surface Brightness

$$I(r) = \delta(r) + I_{\rm b}(r) + I_{\rm d}(r)$$

de Vaucouleurs' law:

$$I_{\rm b}(r) = I_{\rm b}(0) 10^{-3.33(r/r_{\rm e})^{1/4}}$$

Sersic law:

$$I_{\rm b}(r) = I_{\rm b}(0) 10^{-c_n\left(\frac{r}{r_{\rm e}}\right)^{1/n}}$$

Disk surface brightness:

$$I_{\rm d}(r) = I_{\rm d}(0) e^{-(r/r_{\rm d})}$$

Galaxy Surface Brightness

Surface Brightness

$$I(r) = \delta(r) + I_{\rm b}(r) + I_{\rm d}(r)$$

de Vaucouleurs' law:

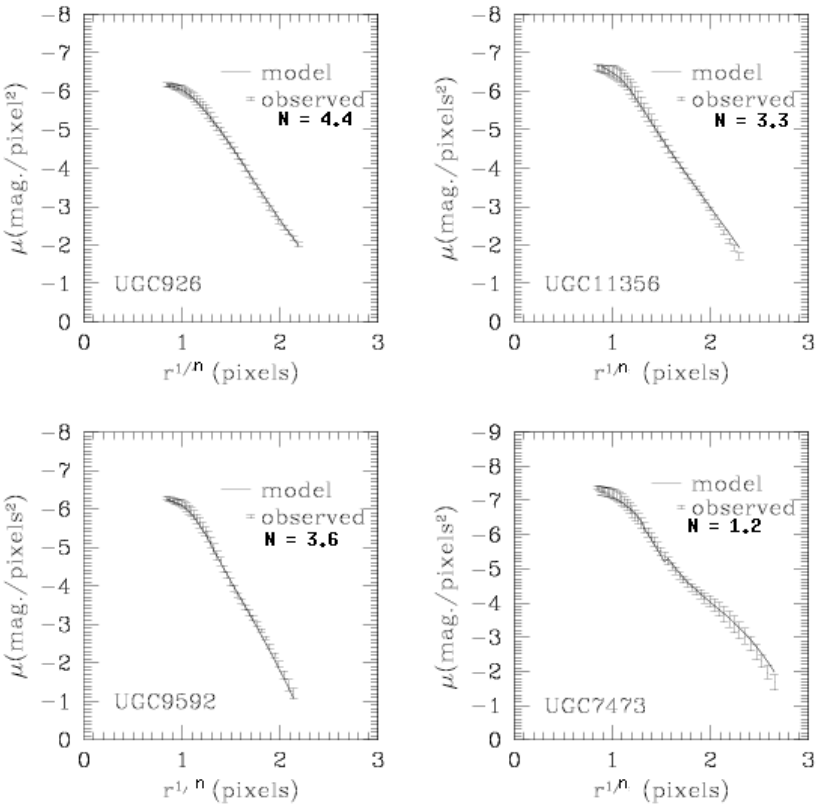
$$I_{\rm b}(r) = I_{\rm b}(0) 10^{-3.33(r/r_{\rm e})^{1/4}}$$

Sersic law:

$$I_{\rm b}(r) = I_{\rm b}(0) 10^{-c_n\left(\frac{r}{r_{\rm e}}\right)^{1/n}}$$

Disk surface brightness:

$$I_{\rm d}(r) = I_{\rm d}(0) e^{-(r/r_{\rm d})}$$



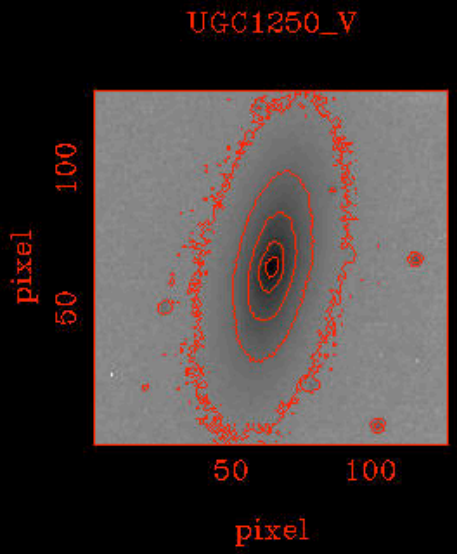
Bulge –Disk Decomposition

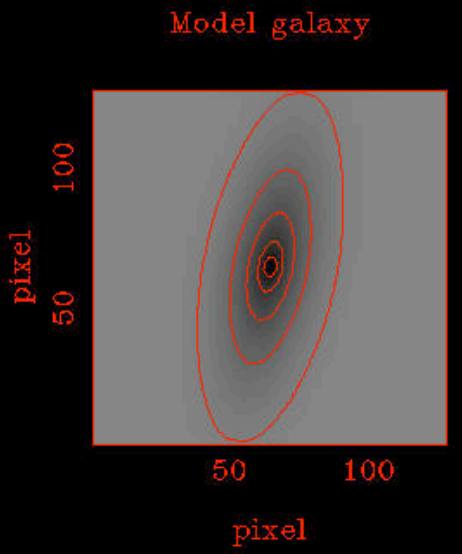
UGC 1250

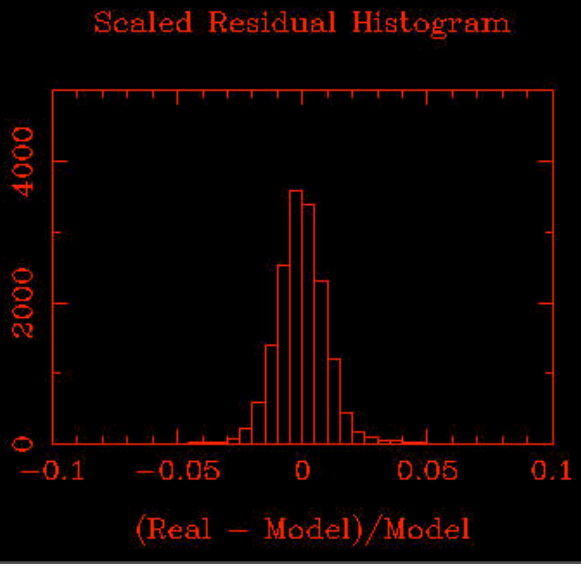
Bulge –Disk Decomposition

$$\chi^2 = \Sigma(o_i - m_i)^2/\sigma_i^2$$

UGC 1250





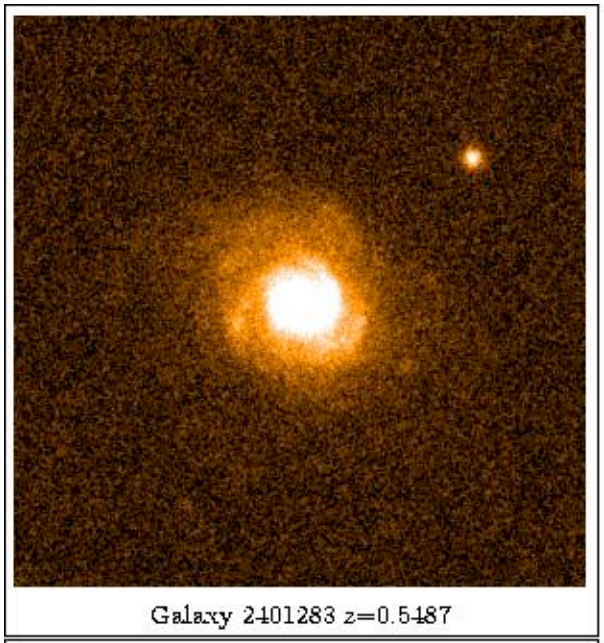


Iteration Number: 910

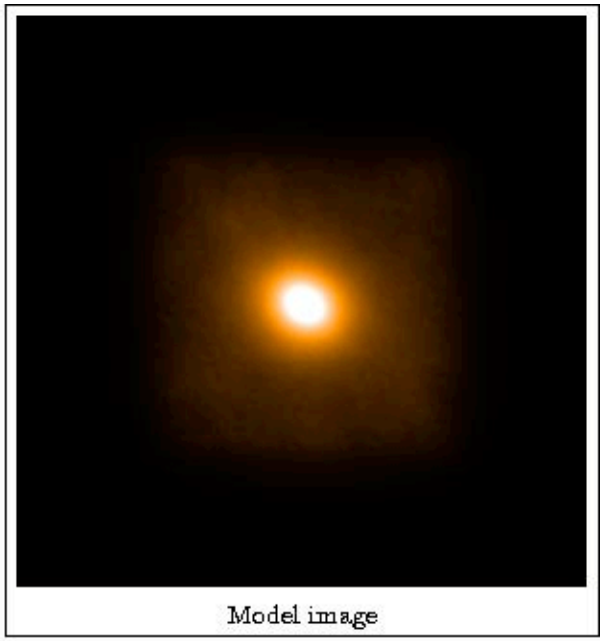
	BULGE	DISK
Intensity:	899380	5681.56
Scale:	12.8185	14.9379
Ellipticity:	0.52	0.67
N:	3.35107	

P. Intensity: 2.66454e−15
D/B: 1.51627

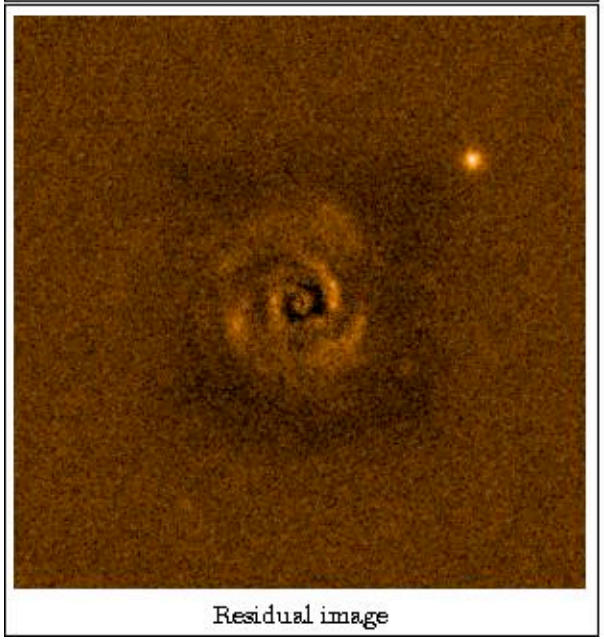
Reduced χ^2 0.900344



Galaxy 2401283 z=0.5487



Model image

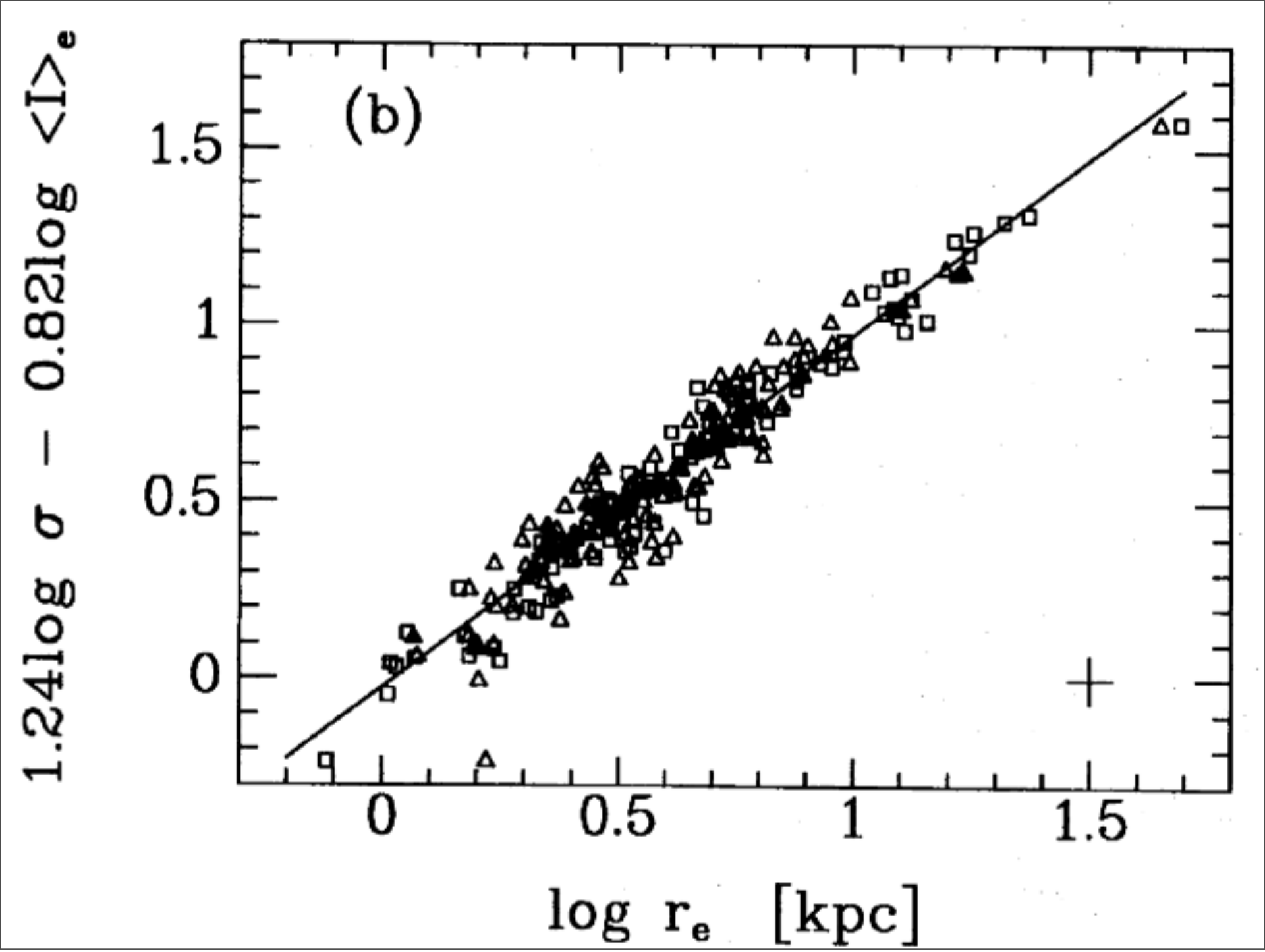


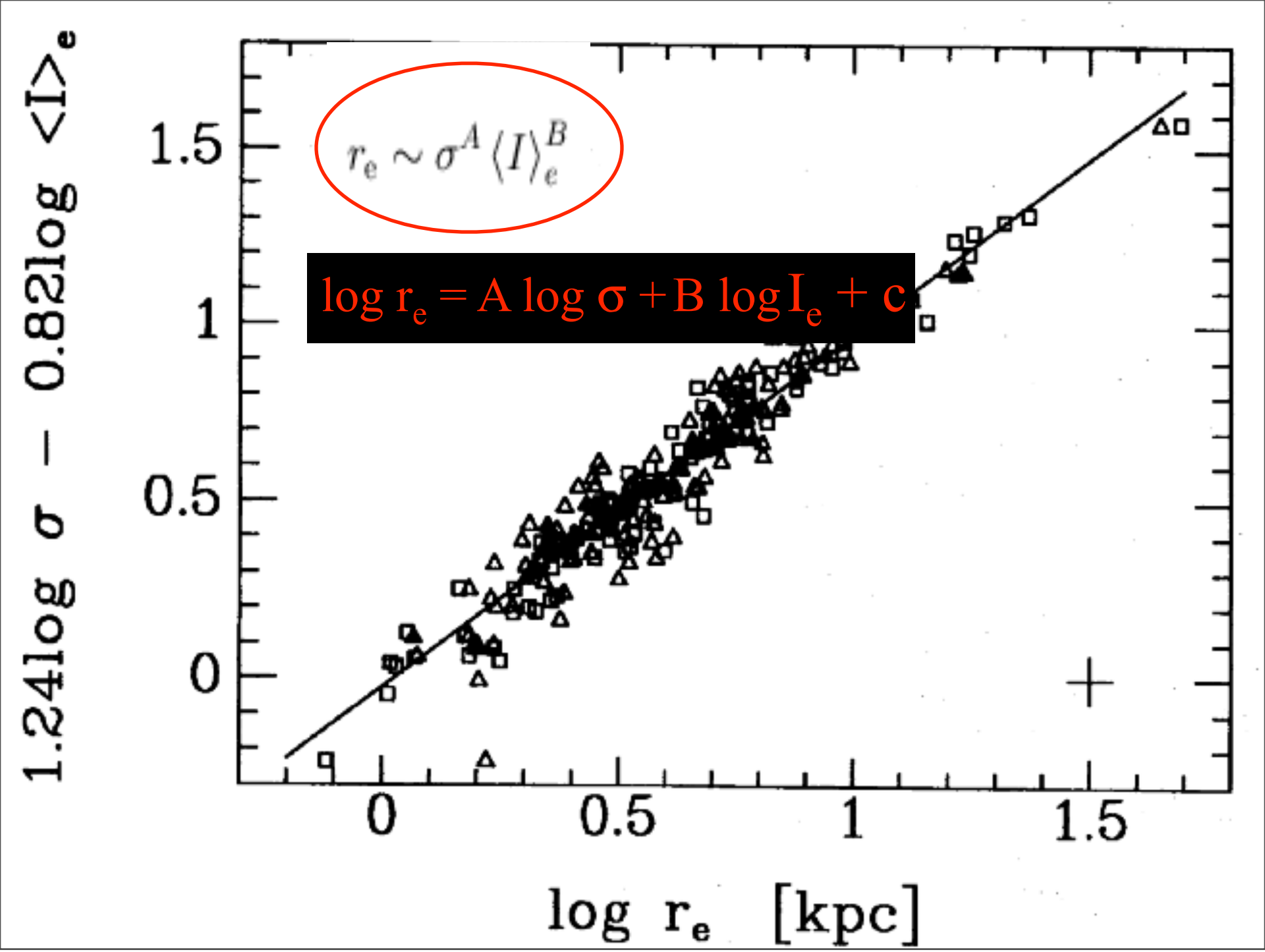
Residual image

Bulge-Disk Decomposition

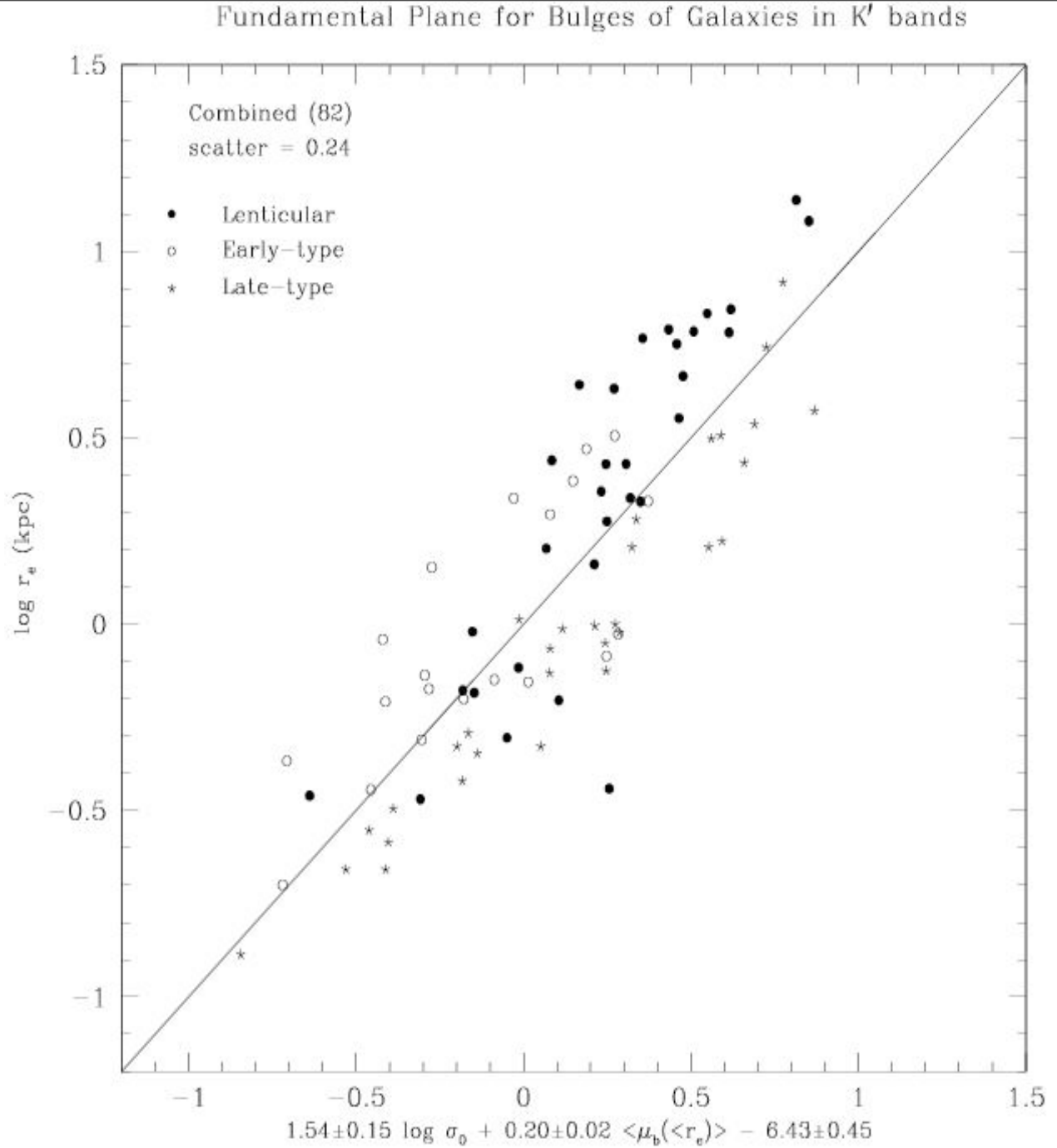
Morphological Parameter Correlations

The Fundamental Plane


(b)
1.5
1
0.5
0
0
0.5
1
1.5
1.24log σ − 0.82log <I>e
log re [kpc]

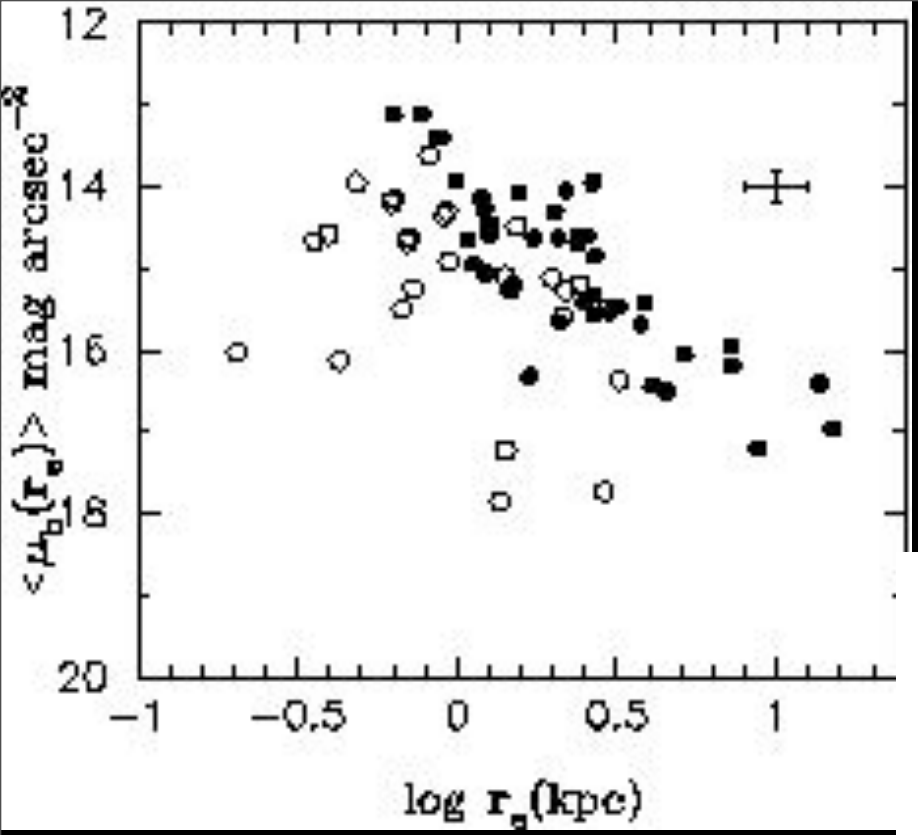

$r_e \sim \sigma^A \langle I \rangle_e^B$
$\log r_e = A \log \sigma + B \log I_e + c$
1.24log σ − 0.82log <I>e
log r_e [kpc]
1.5
1
0.5
0
0
0.5
1
1.5

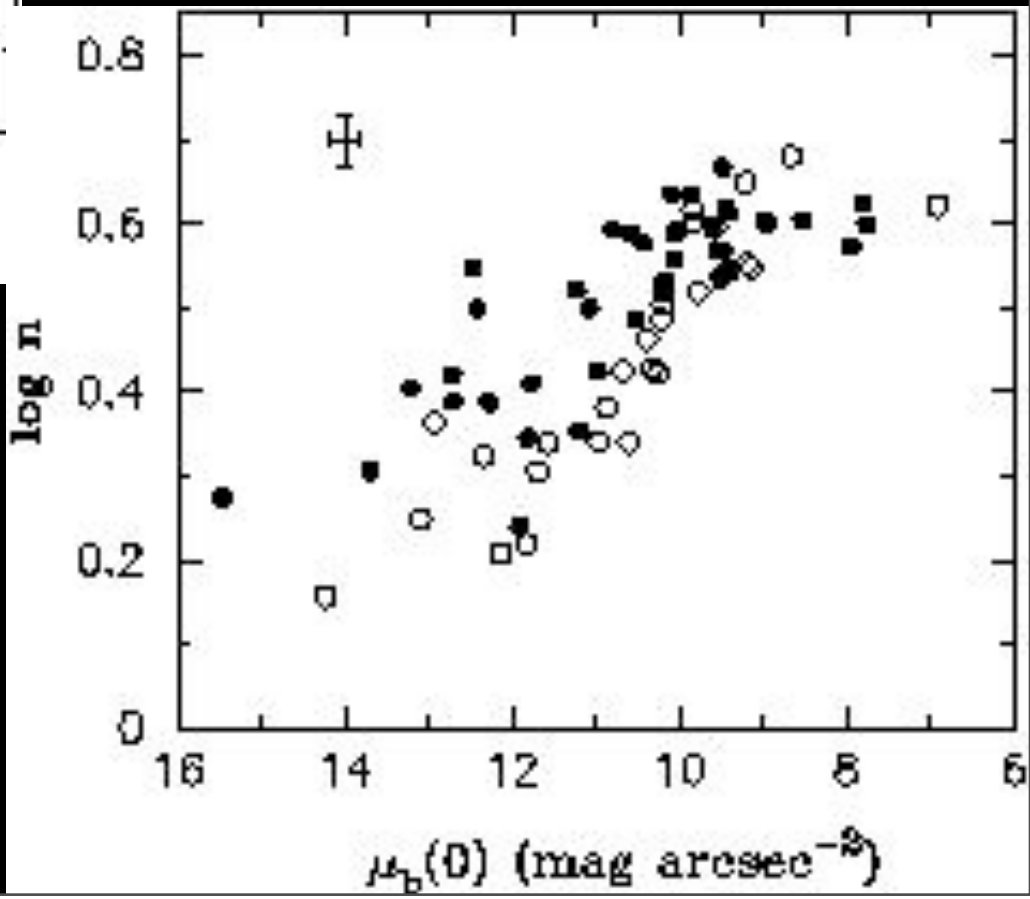
Fundamental Plane for Morphological Mix of Galaxies



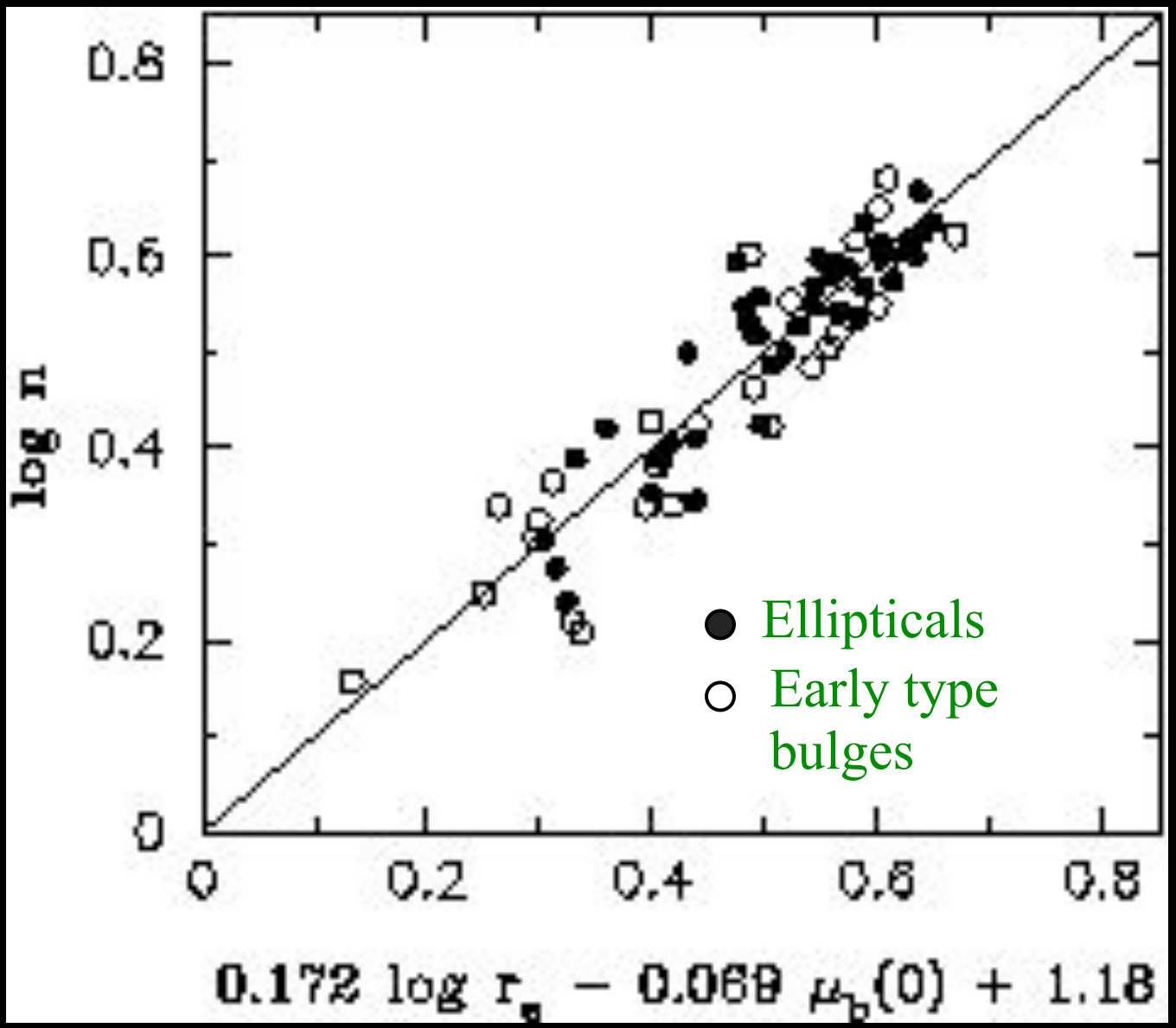
The Photometric Plane

2-D Correlations





Ellipticals and Early Type Bulges



Photometric Plane

Ellipticals and Early Type Bulges

Khoshroshahi etal ApJL 2000

Bulge-Disk Correlations in Lenticular Galaxies

Barway etal ApJL 2007
Barway etal MN 2009
Barway etal MN 2010
Barway MN etal 2011
Wadadekar etal 2013
Vaghmare etal 2013

- *N-body simulations indicate that the bulge component of massive (luminous) lenticulars formed from major mergers.*

- *But bulges in the less luminous elliptical probably formed from minor mergers or accretion events. Stripping of gas from the halo and disk lead to a change in morphology.*

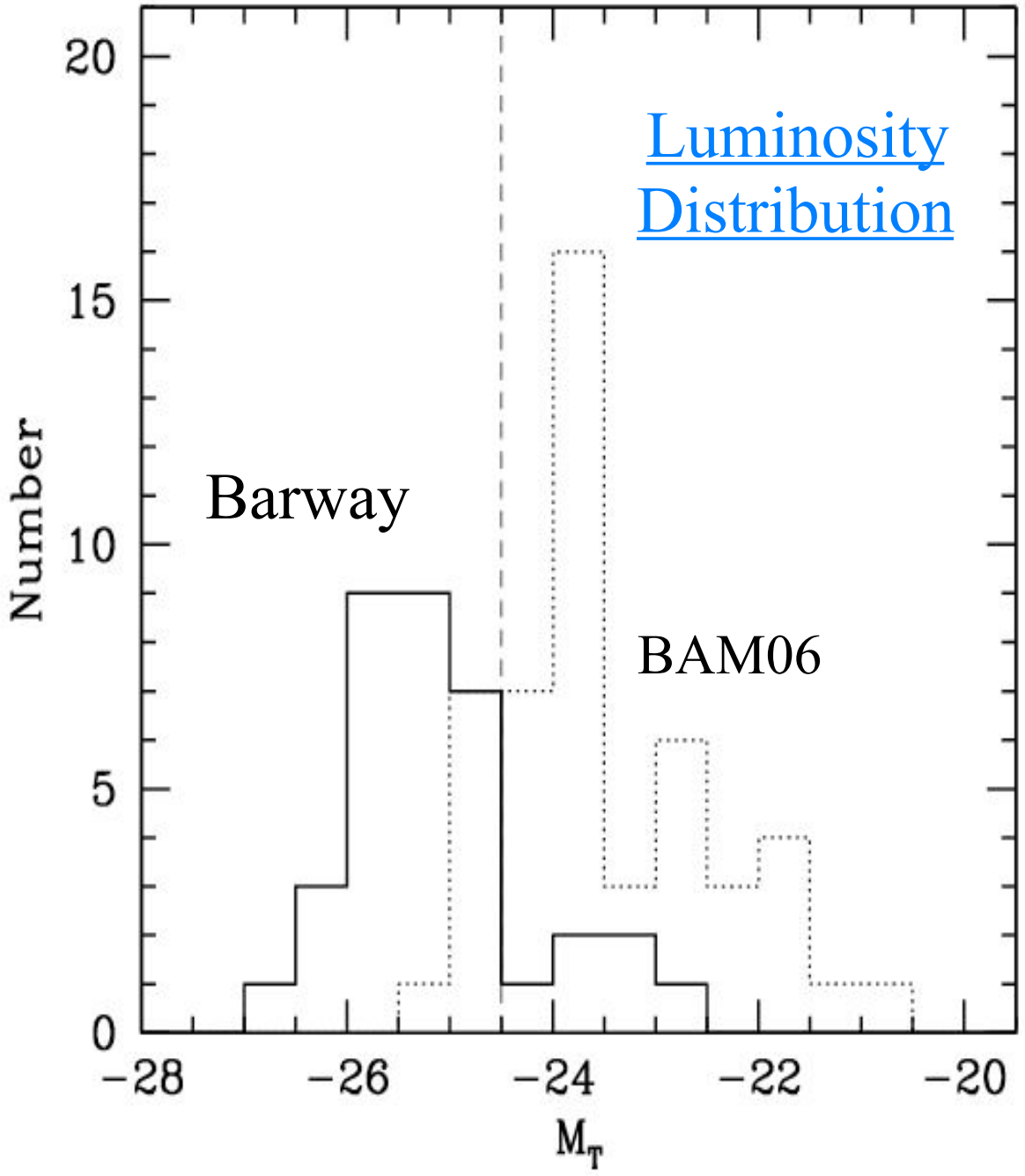
- *Correlation between photometric parameters can be a signature of the formation mechanism.*

Bright field lenticulars observed in the K band: 35

Barway etal 2006

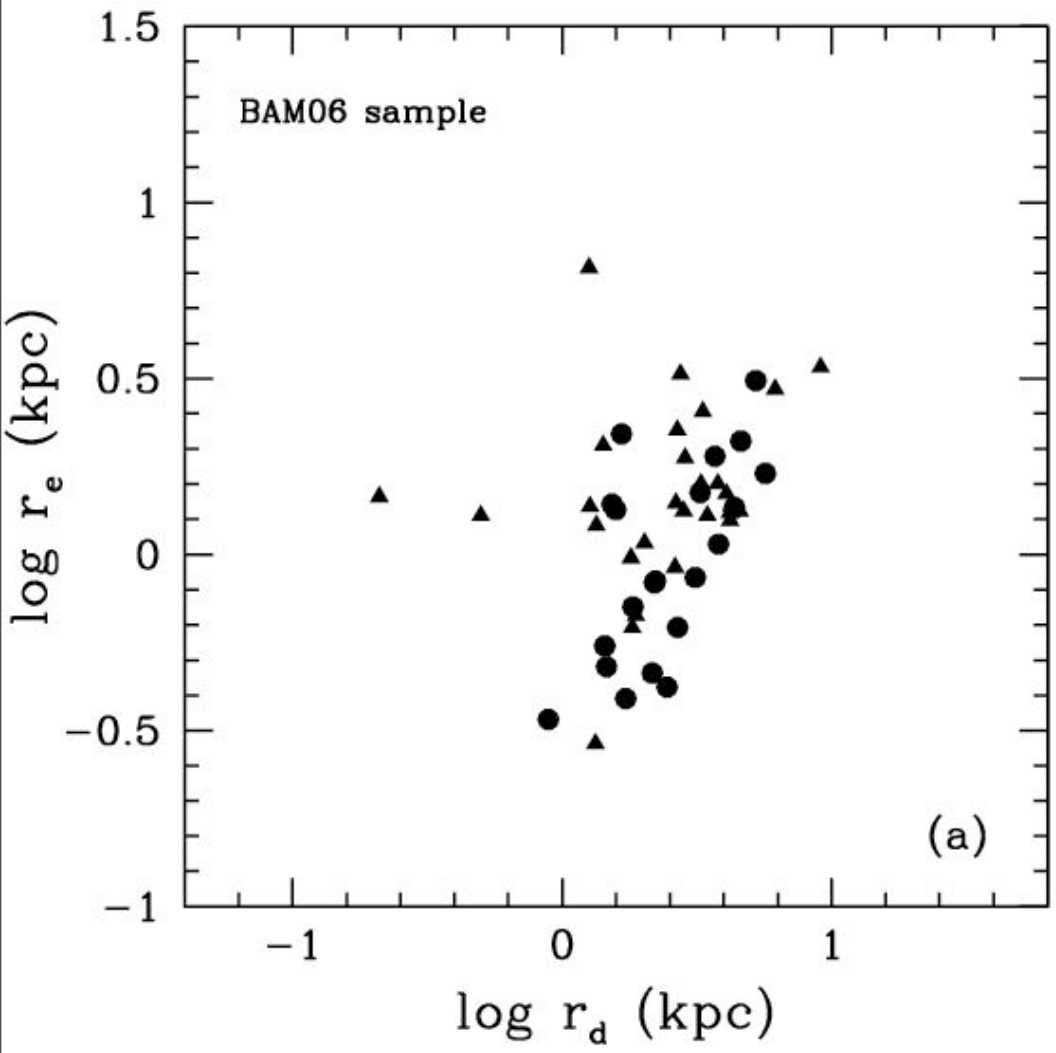
Less luminous field and cluster lenticulars with 2MASS data: 49

Bedregal etal 2006



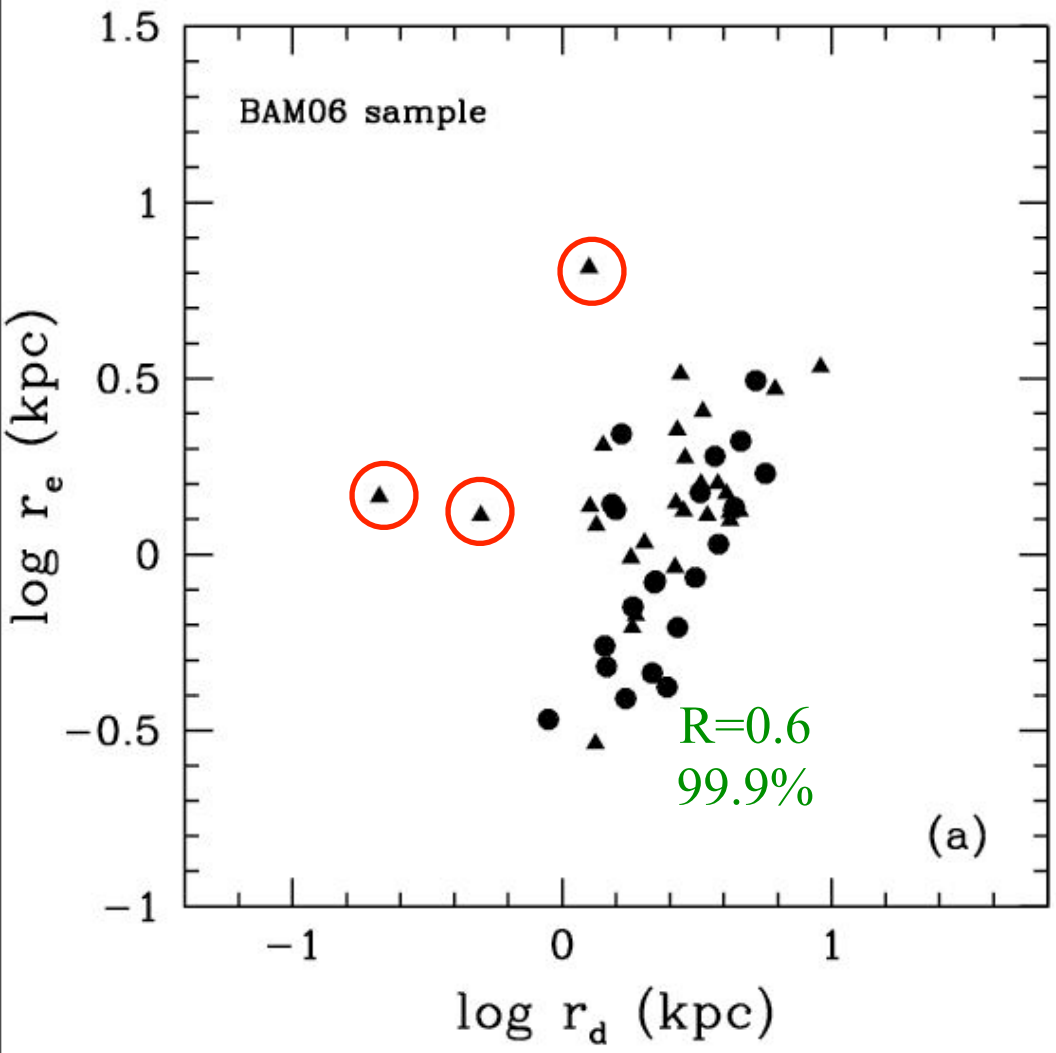
Bulge-Disk Correlation

- field
- ▲ cluster



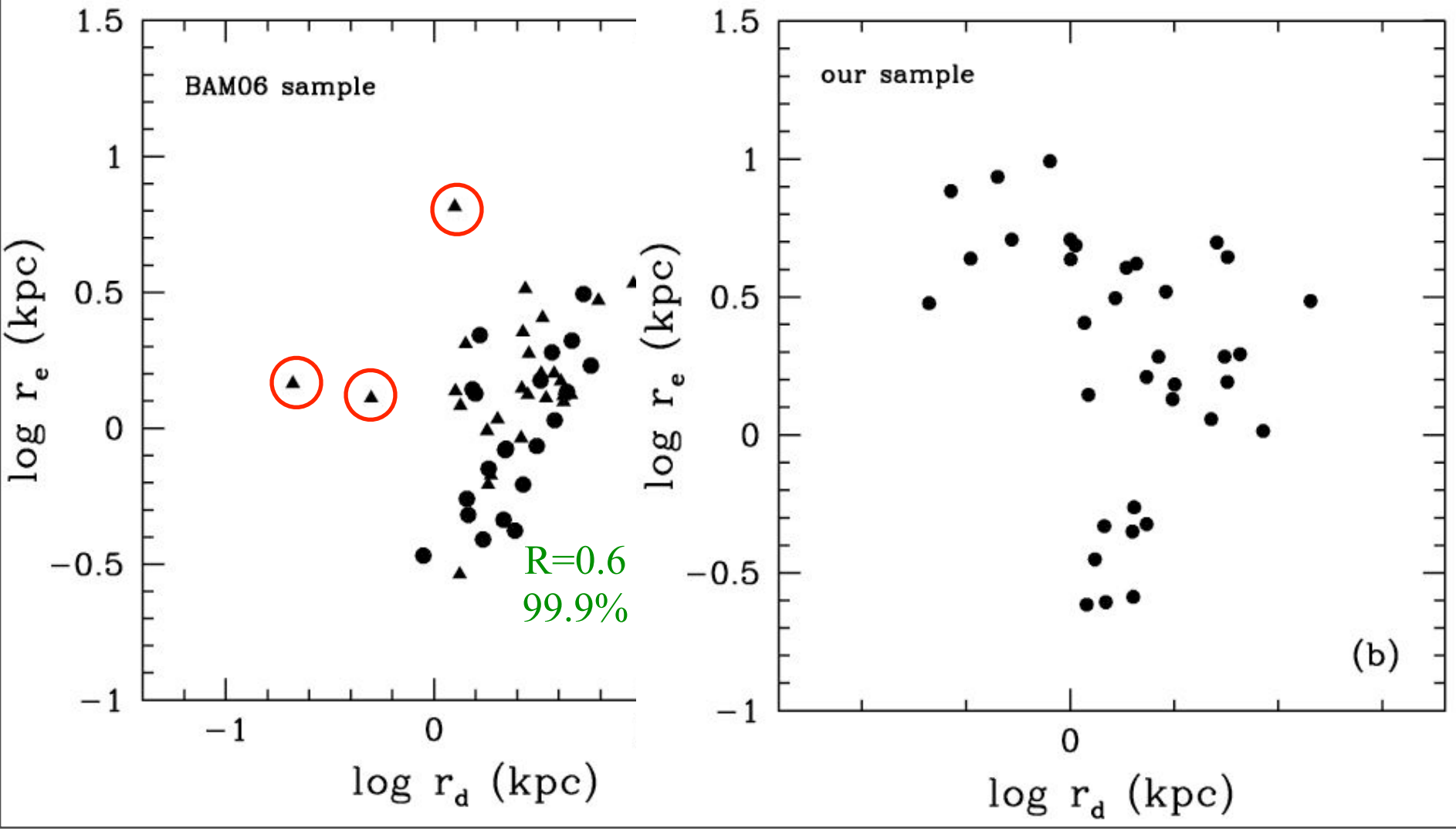
Bulge-Disk Correlation

- field
- ▲ cluster



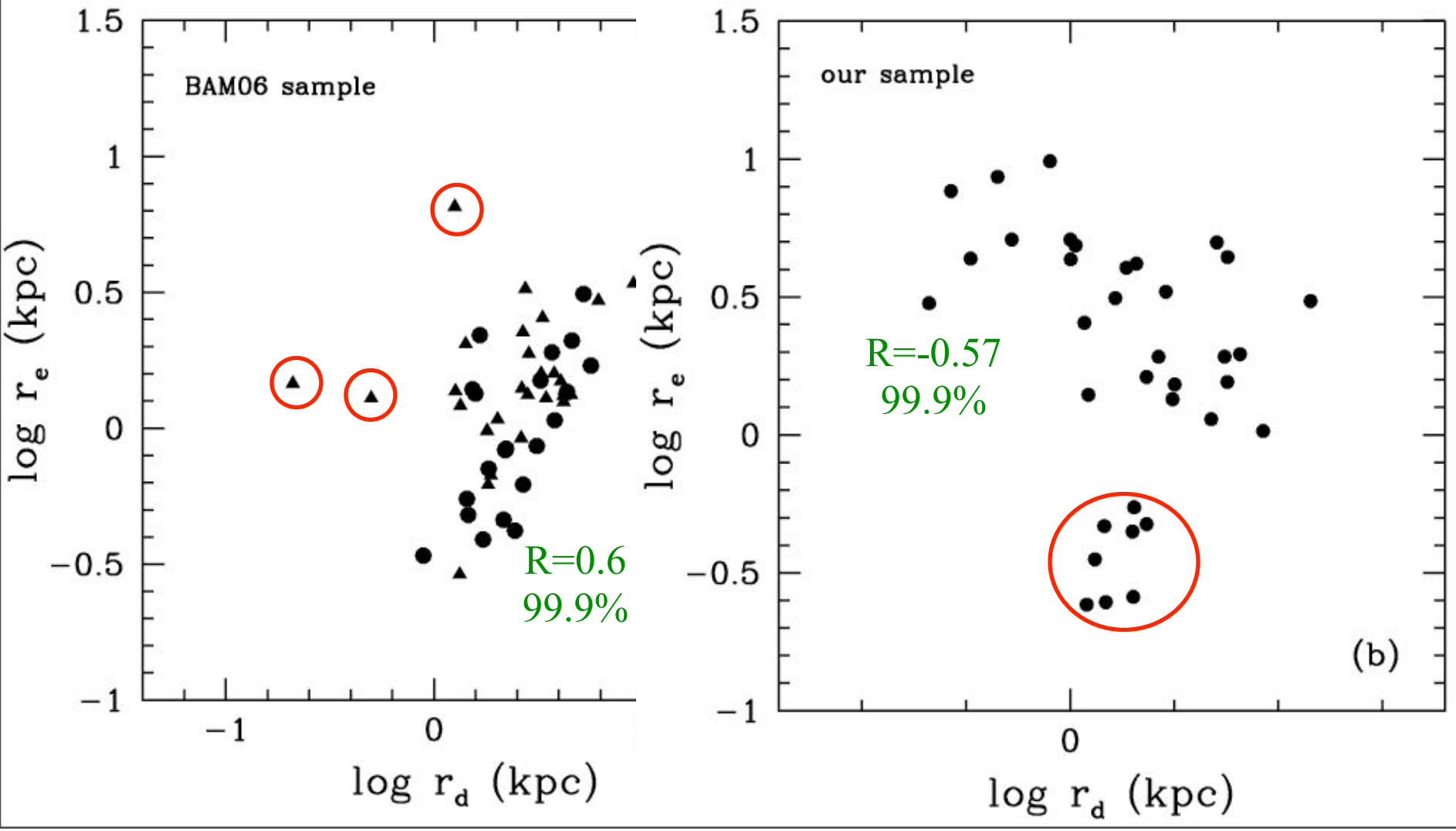
Bulge-Disk Correlation

• field
▲ cluster



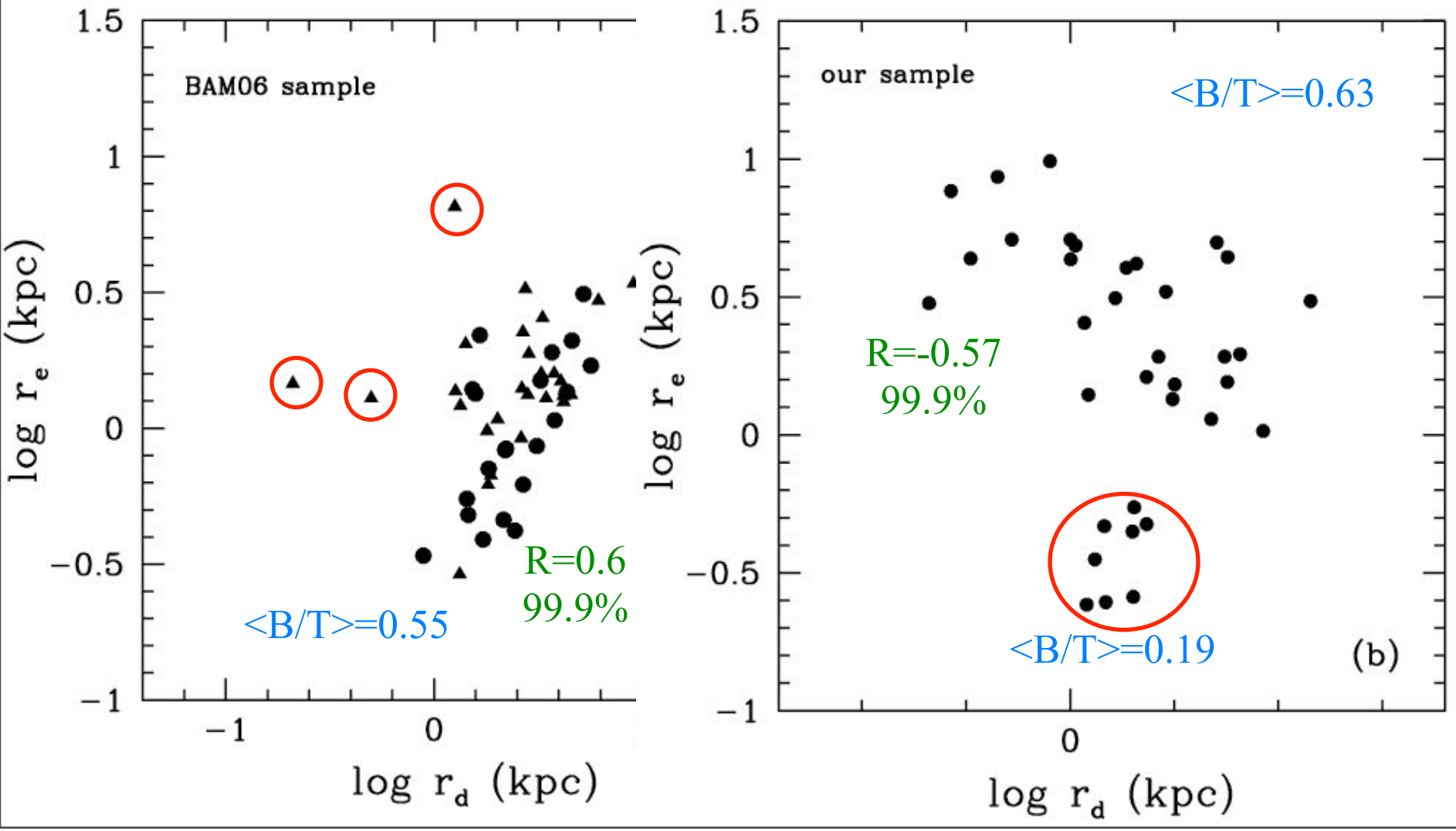
Bulge-Disk Correlation

• field
▲ cluster

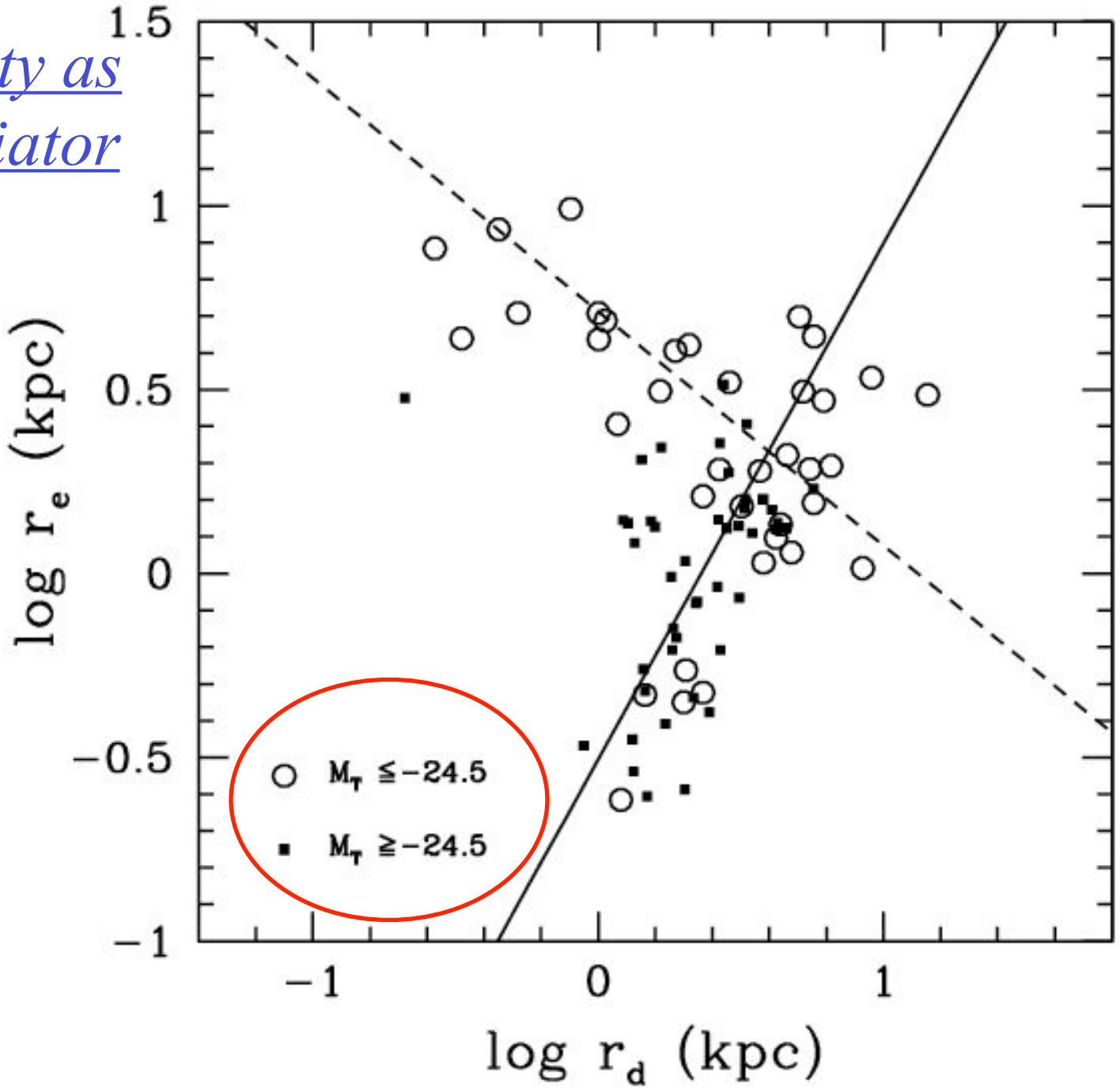


Bulge-Disk Correlation

- field
▲ cluster

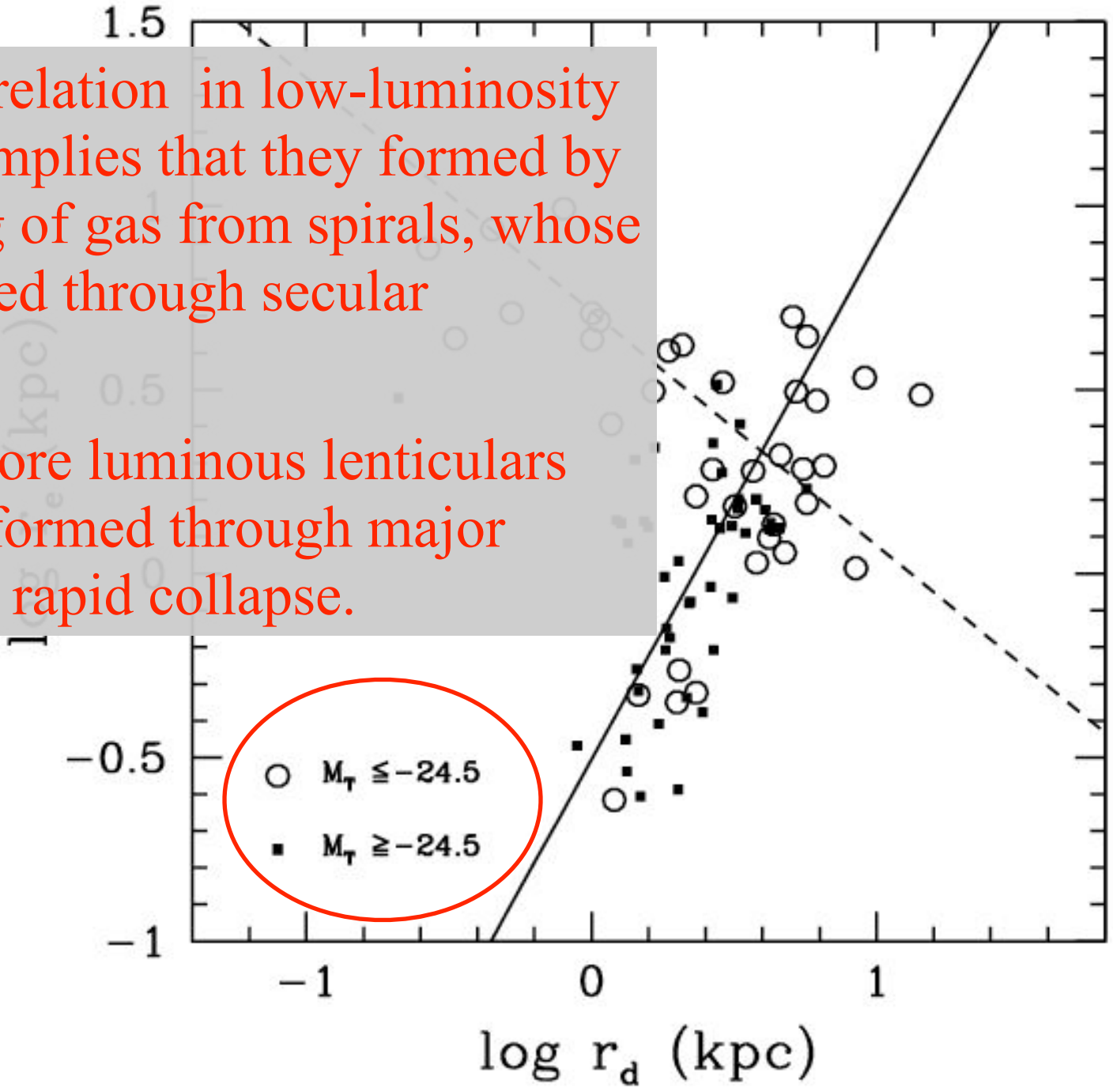


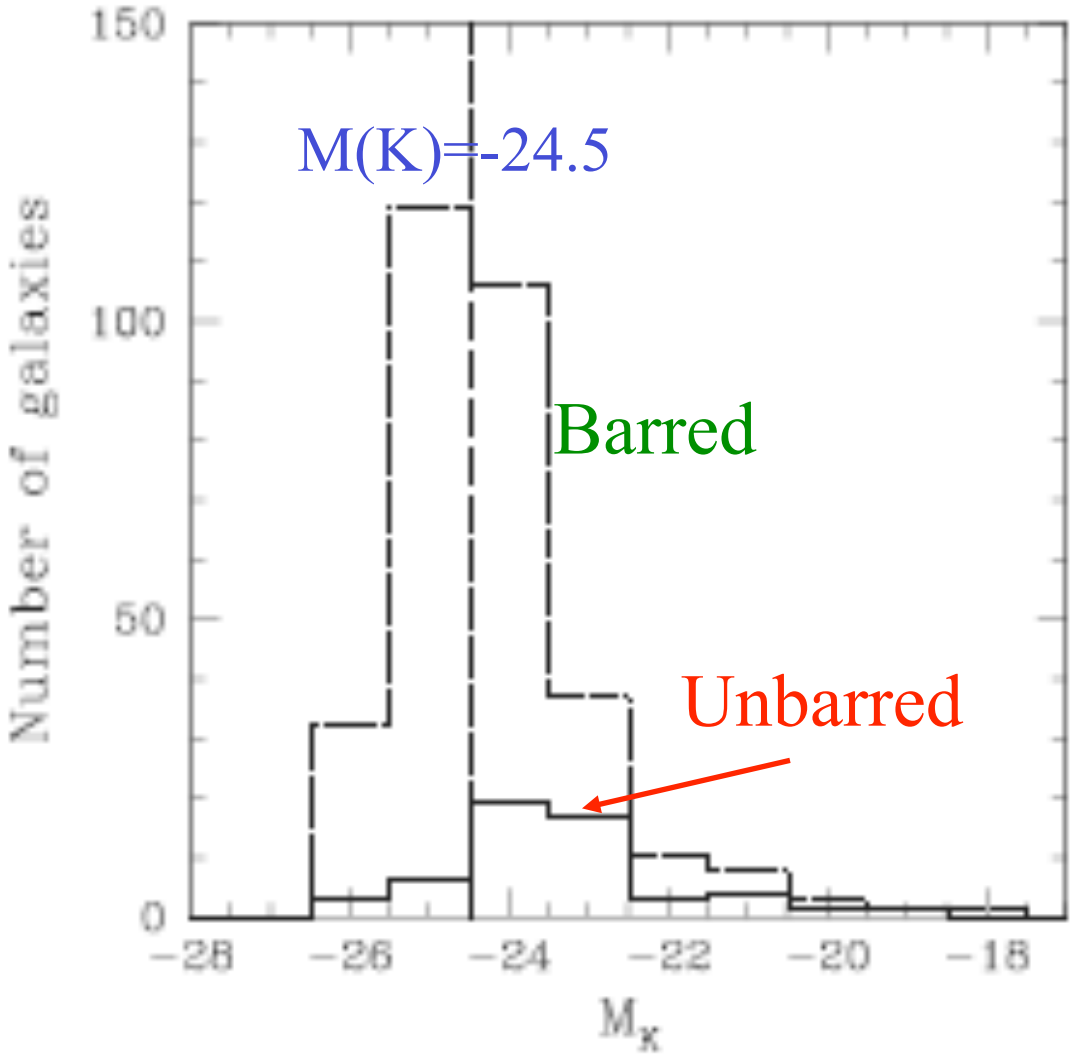
Luminosity as Differentiator



Positive correlation in low-luminosity lenticulars implies that they formed by the stripping of gas from spirals, whose bulges formed through secular evolution.

Bulges of more luminous lenticulars have likely formed through major mergers and rapid collapse.



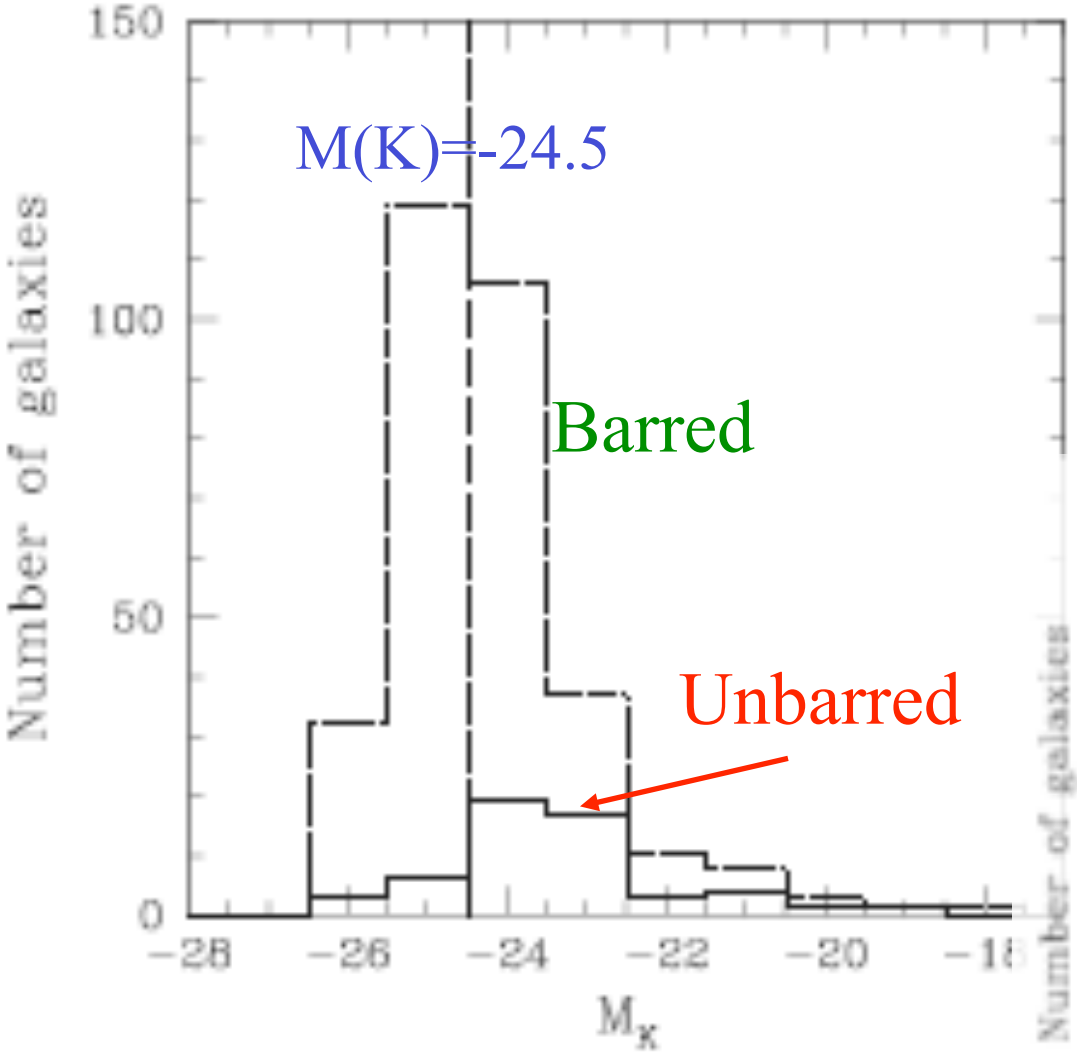


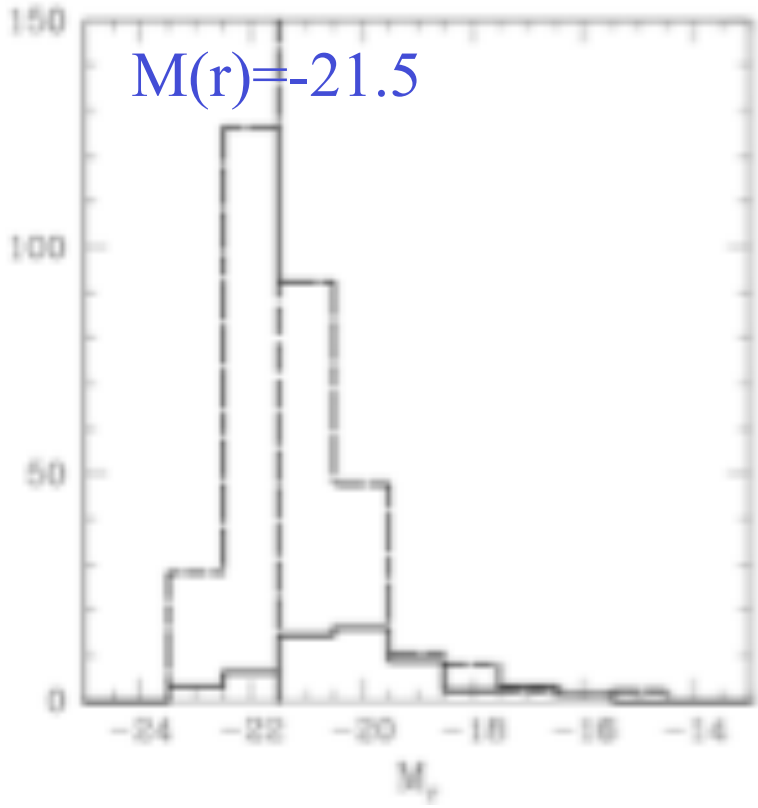
Bar Fraction and Luminosity

UGC + SDSS + 2MASS + Hyperleda, 385 galaxies

Bar Fraction and Luminosity

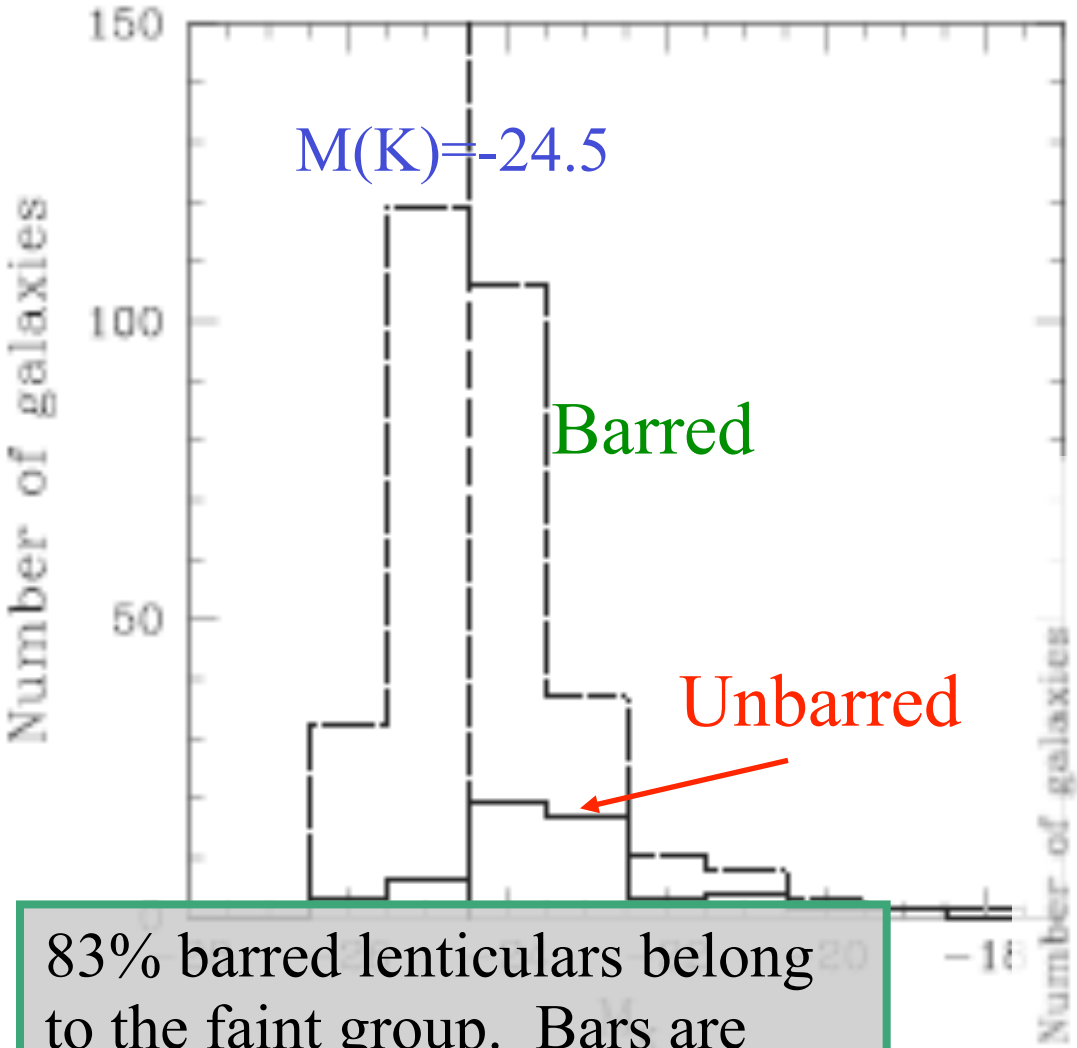
UGC + SDSS + 2MASS + Hyperleda, 385 galaxies

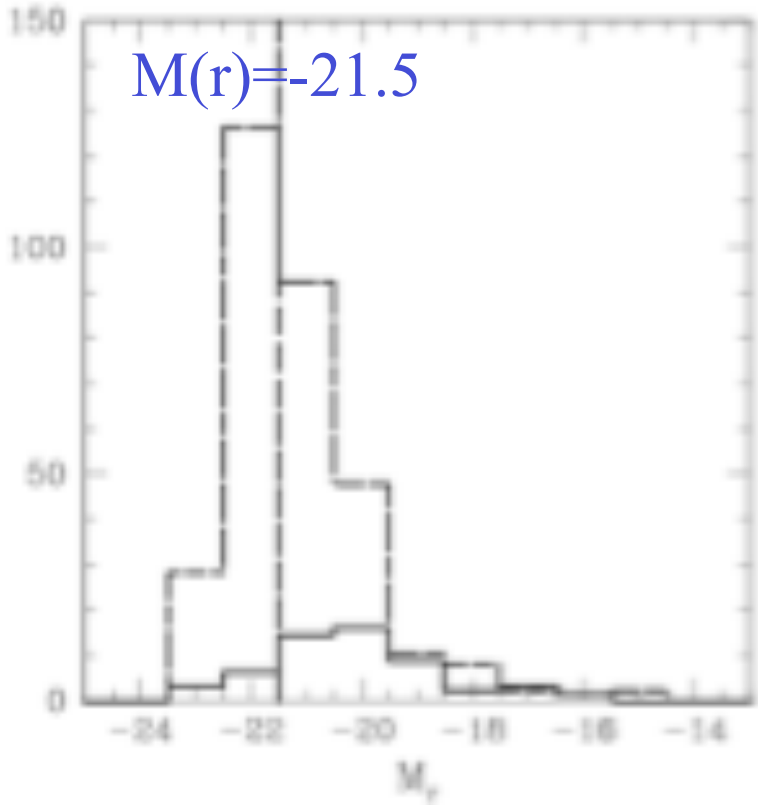




Bar Fraction and Luminosity

UGC + SDSS + 2MASS + Hyperleda, 385 galaxies

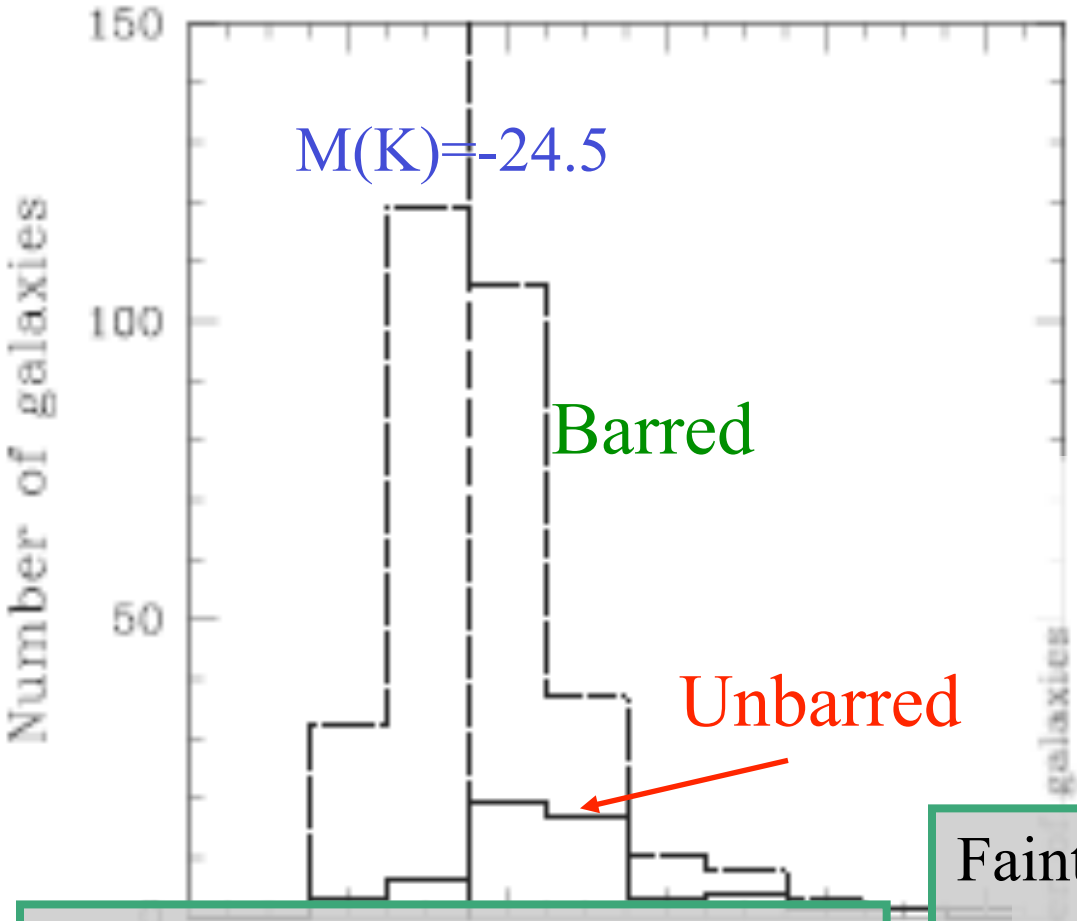


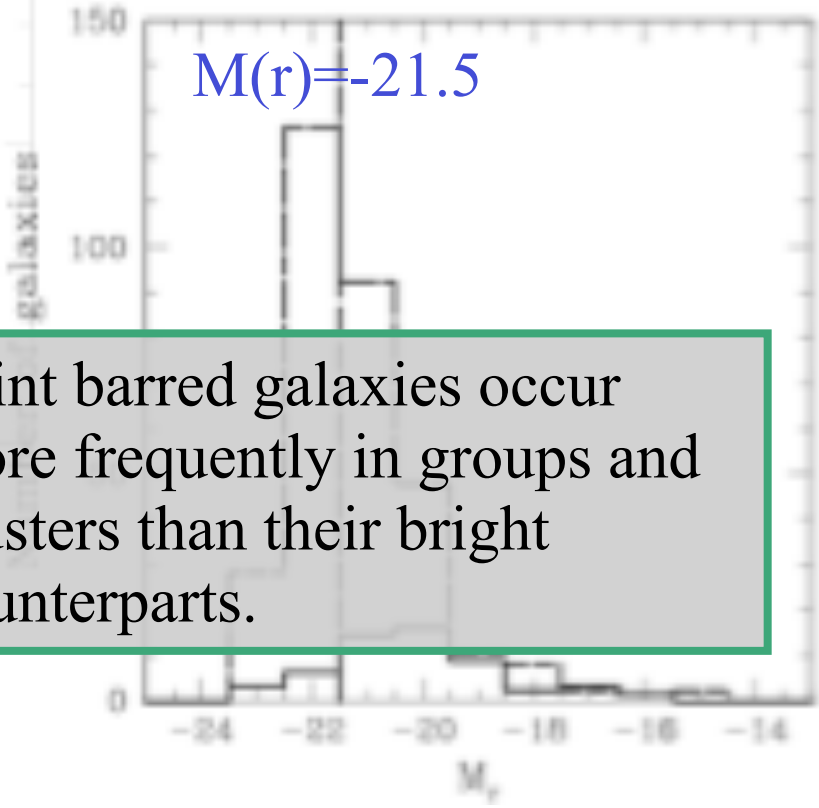


83% barred lenticulars belong to the faint group. Bars are found in 21% of the faint group, but in only 6% of the bright group.

Bar Fraction and Luminosity

UGC + SDSS + 2MASS + Hyperleda, 385 galaxies





83% barred lenticulars belong to the faint group. Bars are found in 21% of the faint group, but in only 6% of the bright group.

Faint barred galaxies occur more frequently in groups and clusters than their bright counterparts.

A Spitzer Study of Pseudobulges

Vaghmare, Barway, Kembhavi

Sample Selection

S0 galaxies from RC3 -3 ≤ T ≤ 0, B_T ≤ 14.0,

1031 galaxies

Cross-correlate with 3.6μ Spitzer-IRAC data, delete galaxies with poor S/N, disturbed morphology

Sample: **185** galaxies

Pre-processing using MOPEX

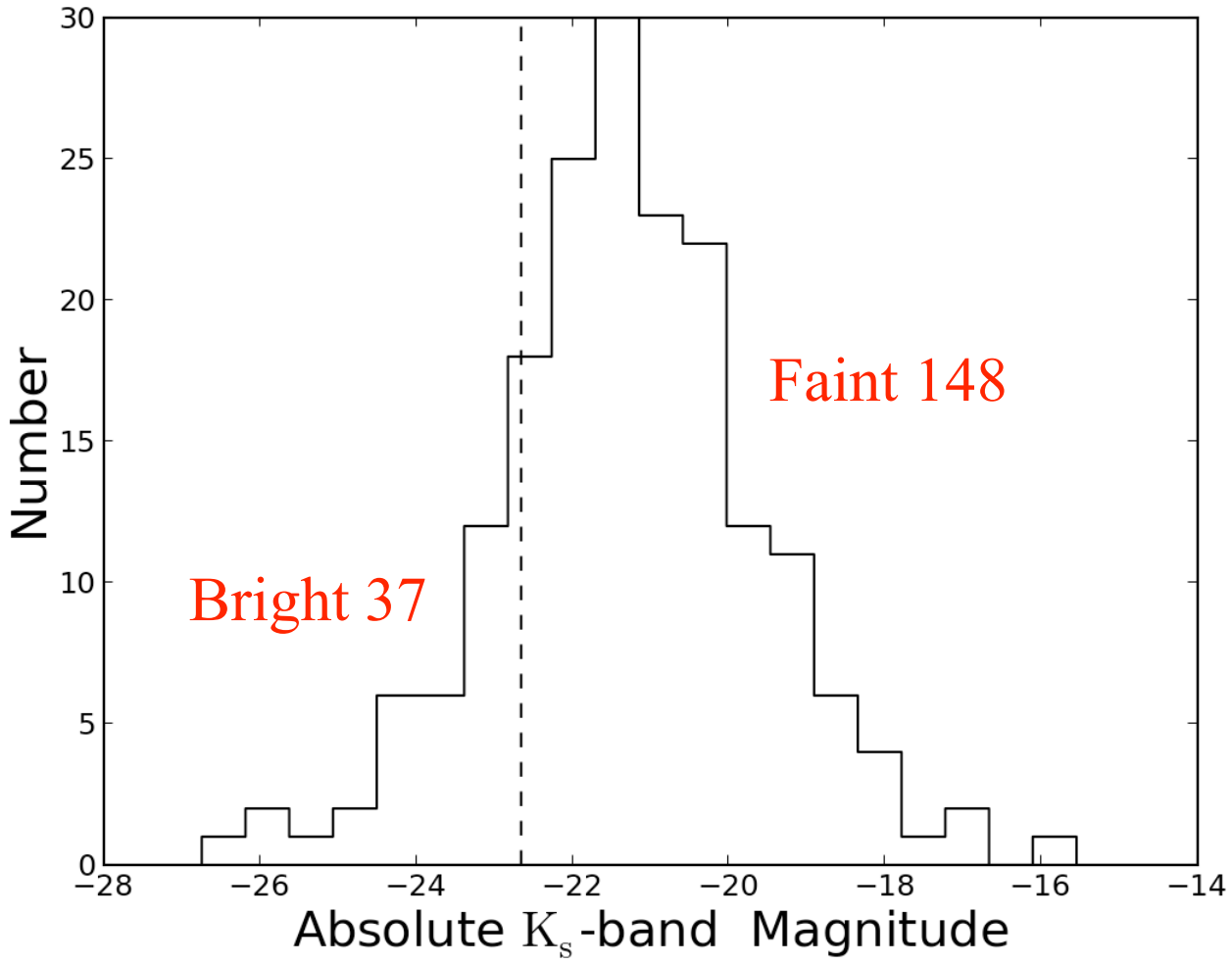
2-dimensional bulge-disk decomposition using GALFIT

Sample Selection

S0 gala

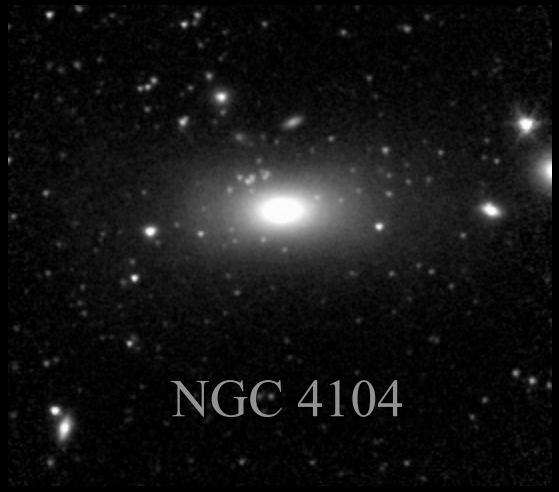
Cross
ga

2-dimer



NGC 936

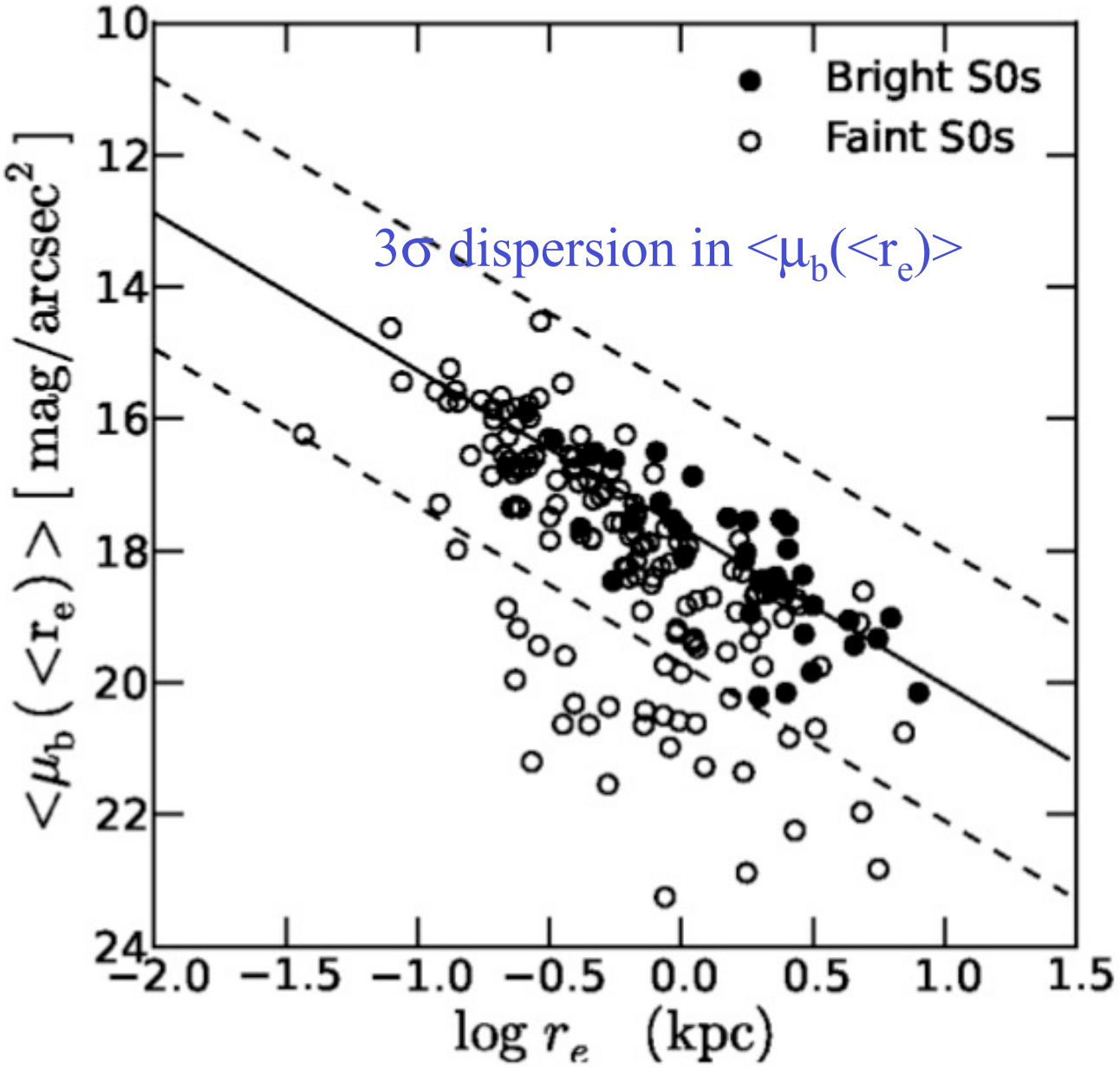
NGC 1023


NGC 4104

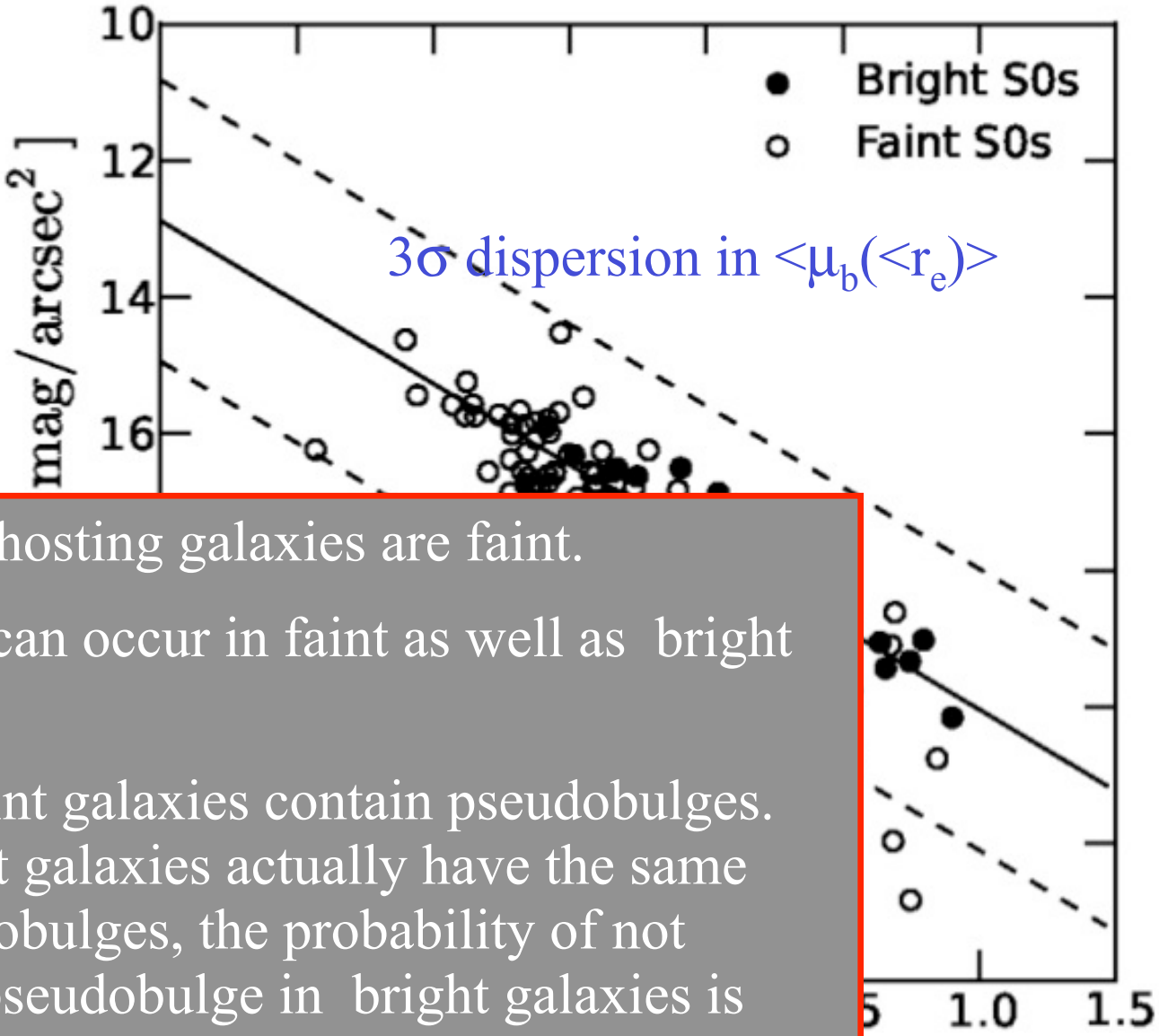
NGC 1326

Pseudobulge Selection from Kormendy Diagram

Superior to n<2, n>2 criterion



Pseudobulge Selection from Kormendy Diagram

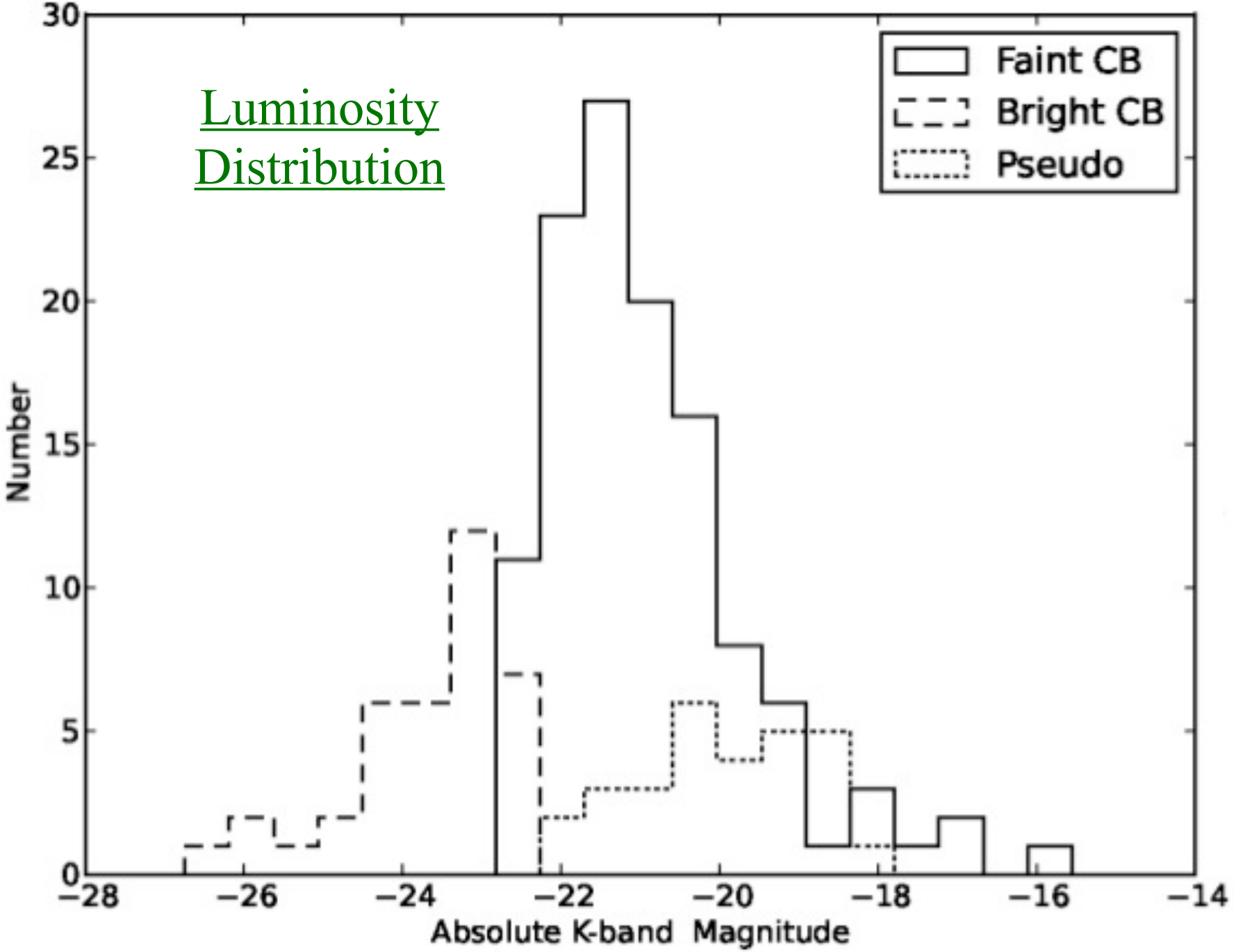


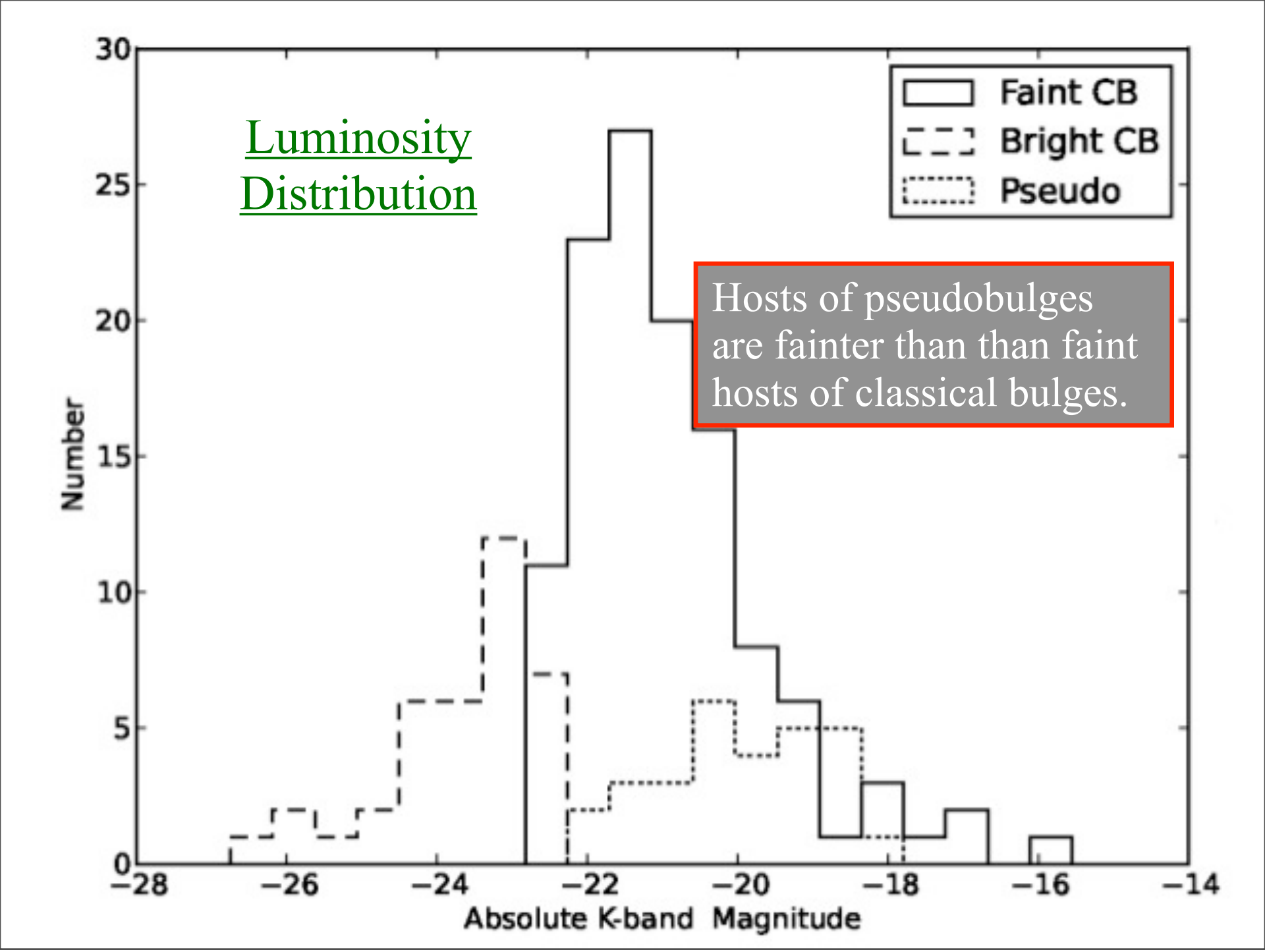
All pseudobulge hosting galaxies are faint.

Classical bulges can occur in faint as well as bright galaxies .

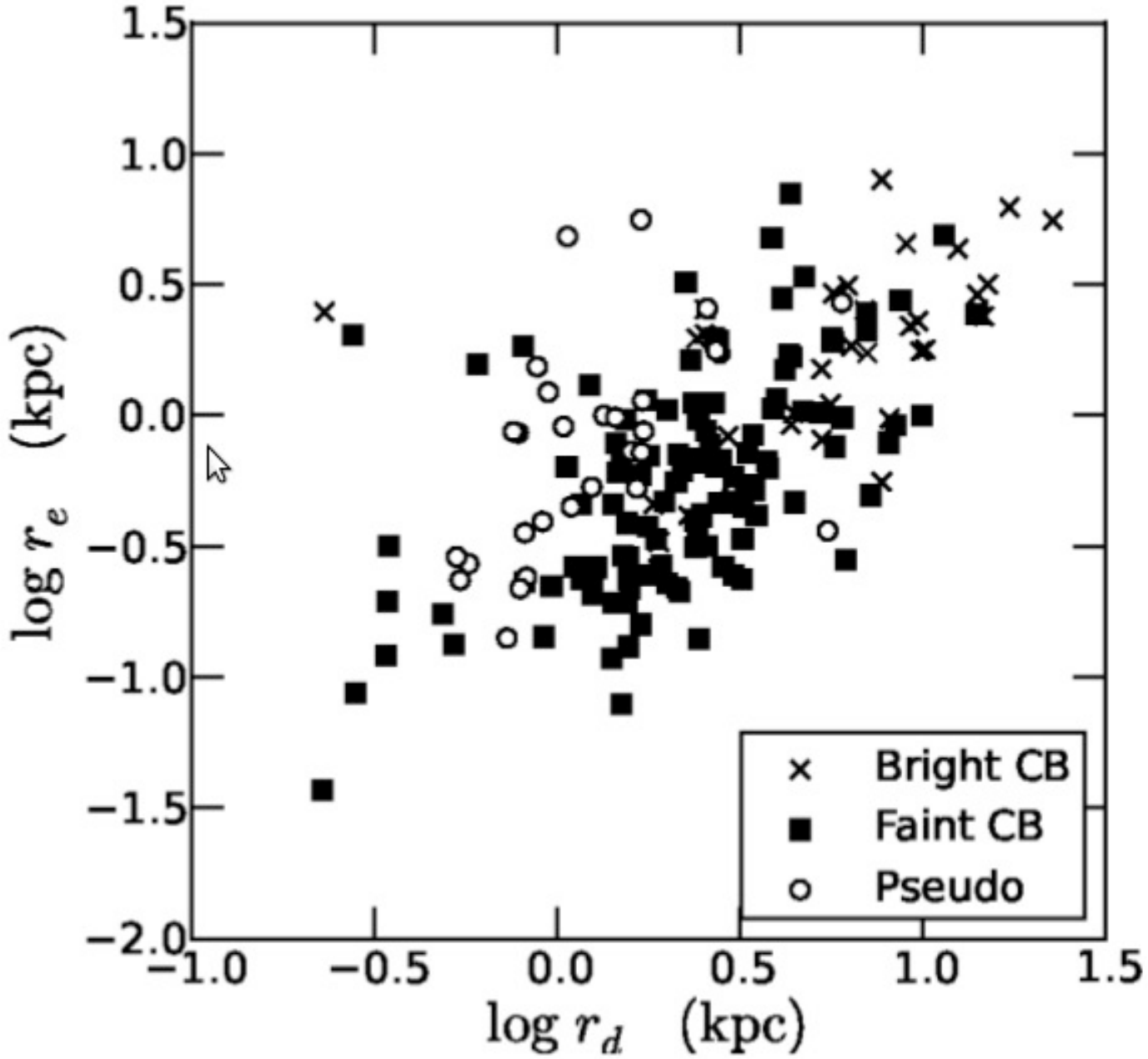
About 20% of faint galaxies contain pseudobulges. If bright and faint galaxies actually have the same fraction of pseudobulges, the probability of not finding a single pseudobulge in bright galaxies is $\sim 10^{-4}$.

Luminosity Distribution

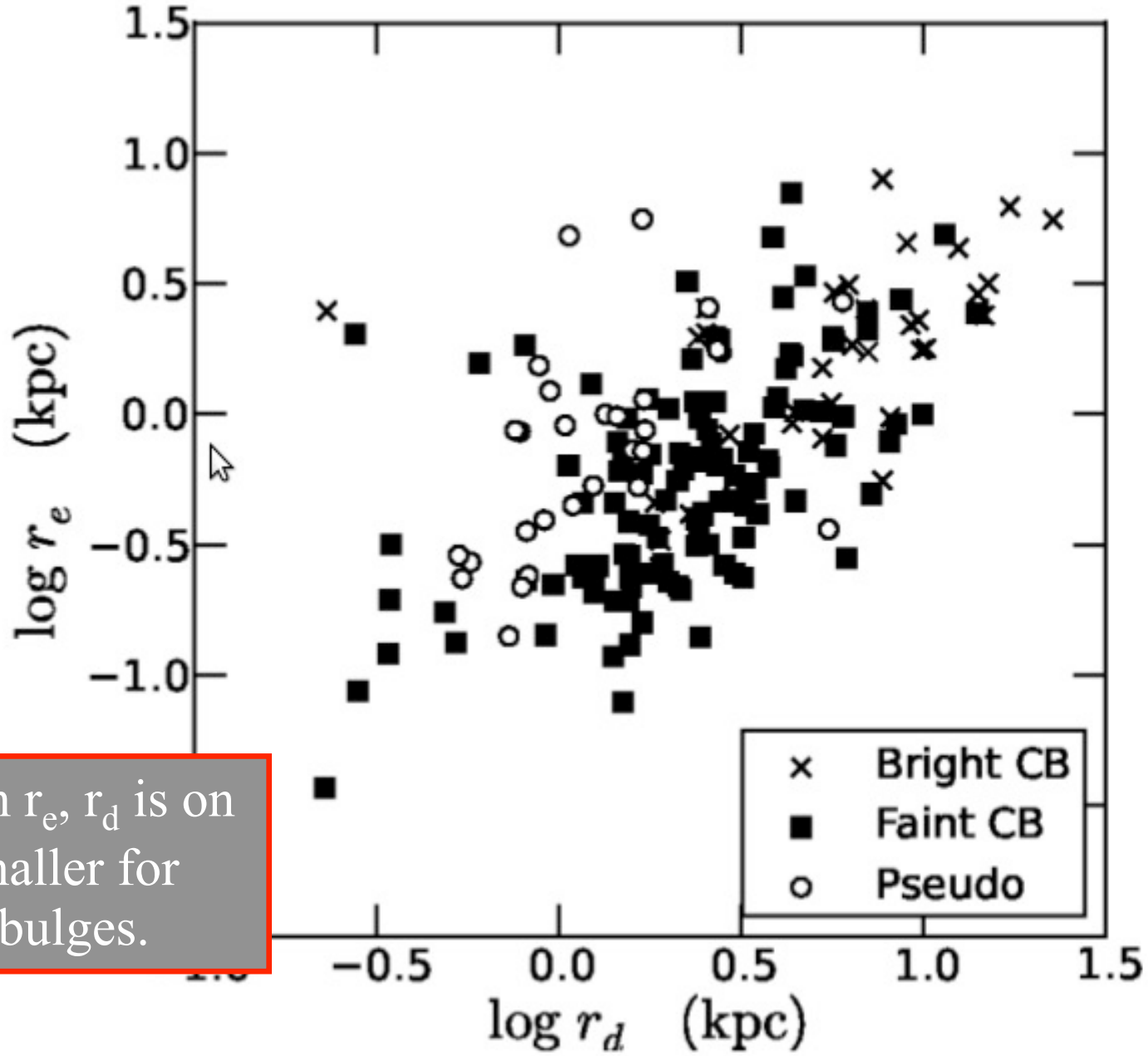



Luminosity Distribution
Faint CB
Bright CB
Pseudo
Hosts of pseudobulges are fainter than than faint hosts of classical bulges.
Number
Absolute K-band Magnitude
30
25
20
15
10
5
0
−28
−26
−24
−22
−20
−18
−16
−14

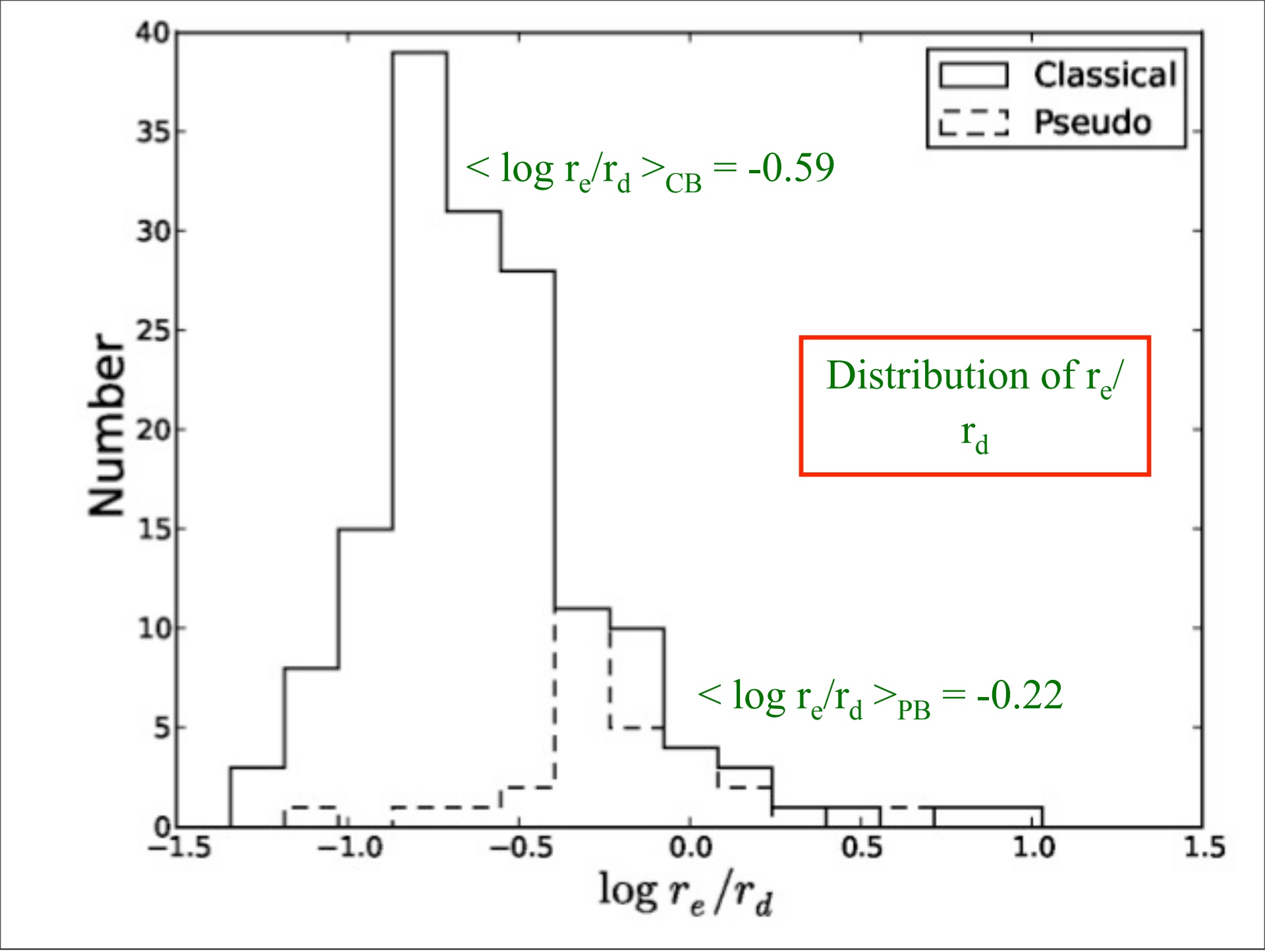
r_e- r_d Correlation



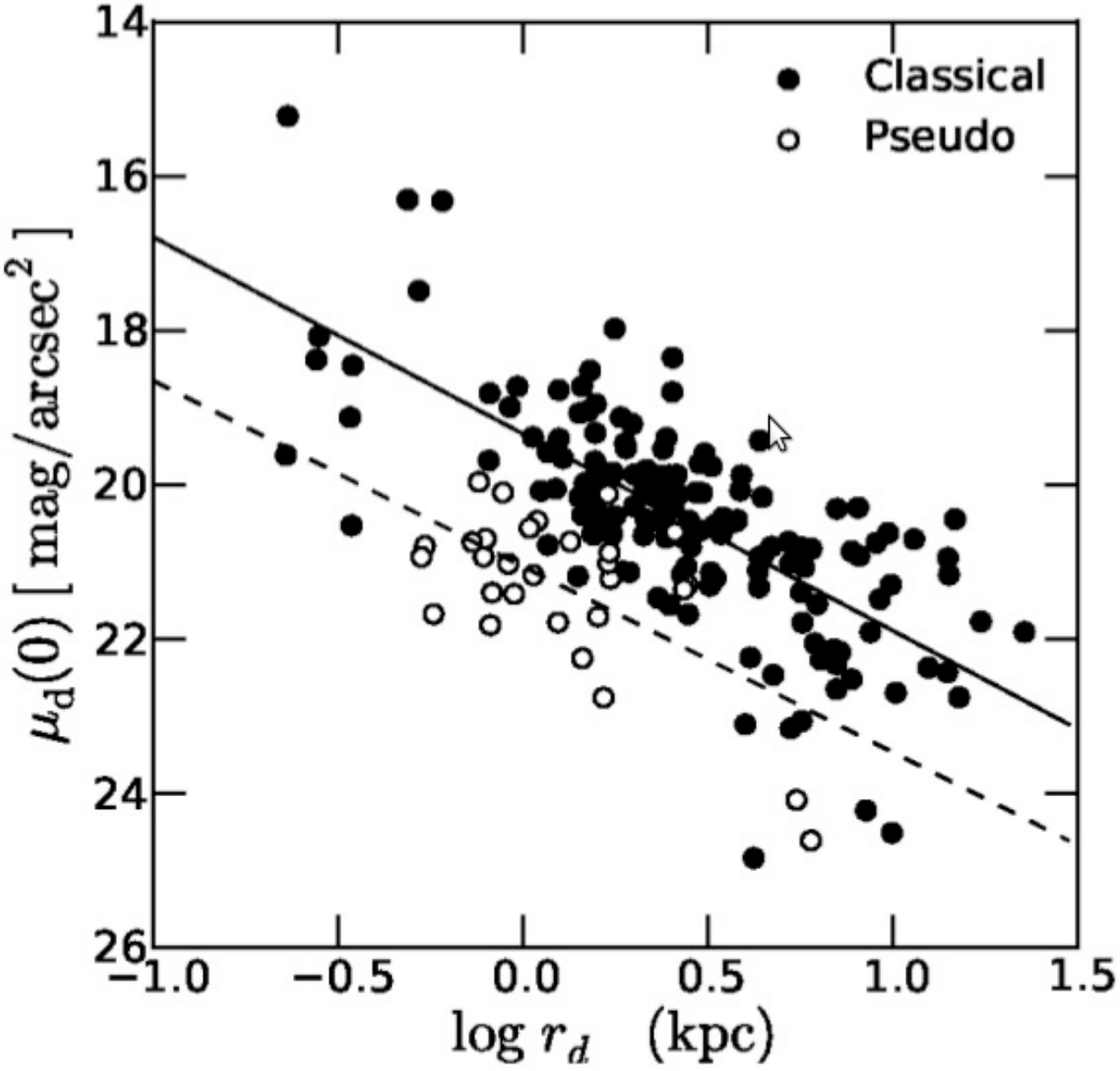
r_e- r_d Correlation



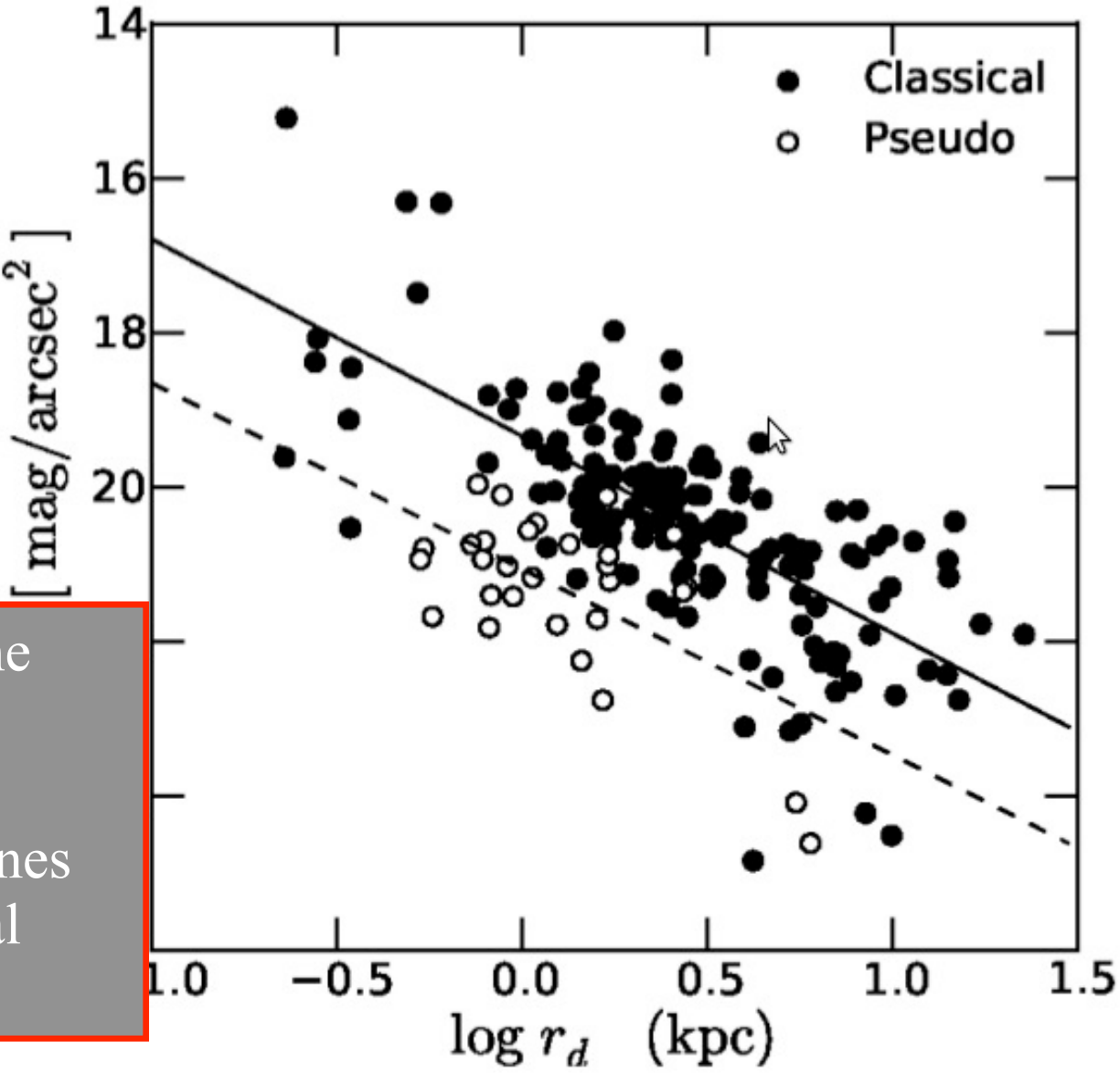
For a given r_e, r_d is on average smaller for the pseudobulges.


Classical
Pseudo
< log r_e/r_d >$_{CB}$ = -0.59
Distribution of r_e/r_d
< log r_e/r_d >$_{PB}$ = -0.22
Number
log r_e/r_d
40
35
30
25
20
15
10
5
0
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5

$\mu_d(0) - r_d$ Correlation



$\mu_d(0) - r_d$ Correlation



For a given r_d , the disks hosting a pseudobulge are fainter than the ones hosting a classical bulge.

Luminosity Dependence of Star Formation-History of SO Galaxies

Sample Selection

S0 galaxies from Barway et. al. 371

SDSS data in u, g, r, I, z for full sample

2MASS data in J, H, K for full sample

GALEX data in FUV and NUV for 242 galaxies

WISE mid-IR data at 3.4, 4.6, 12μ for 242 galaxies

Sample Selection

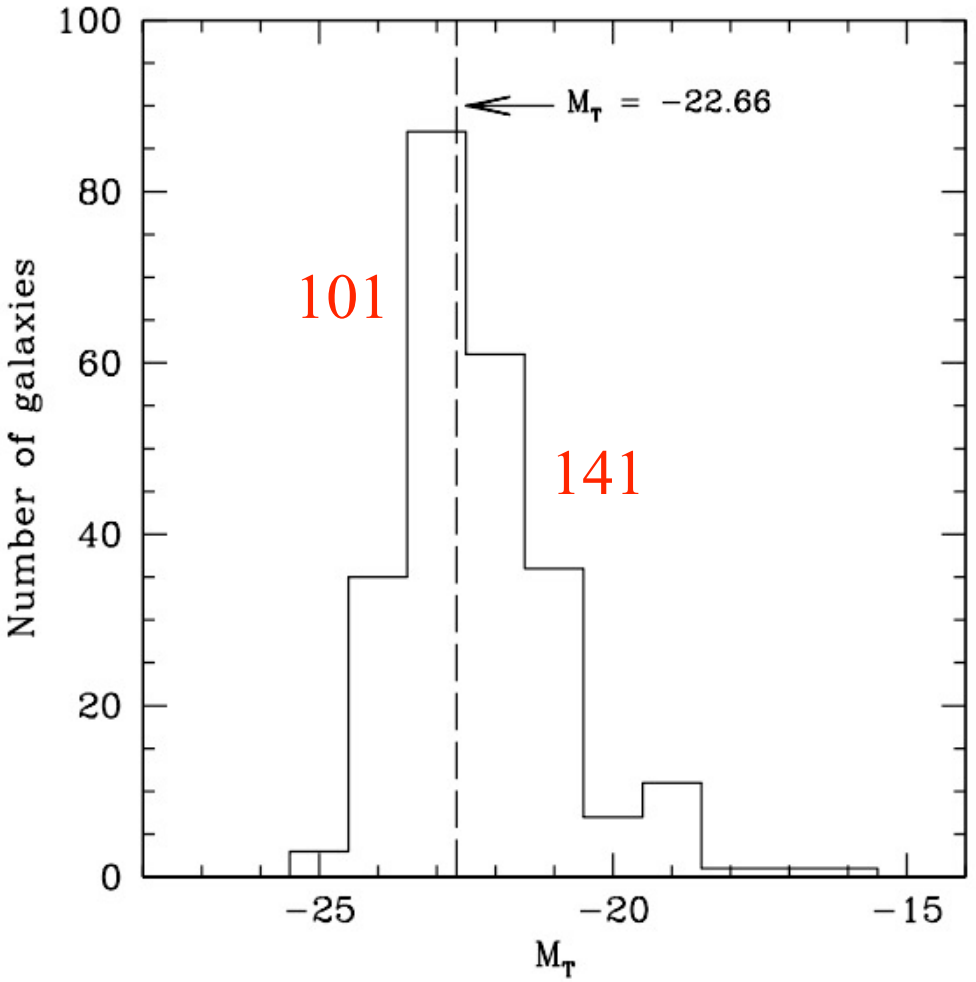
S0 galaxi

SDSS data

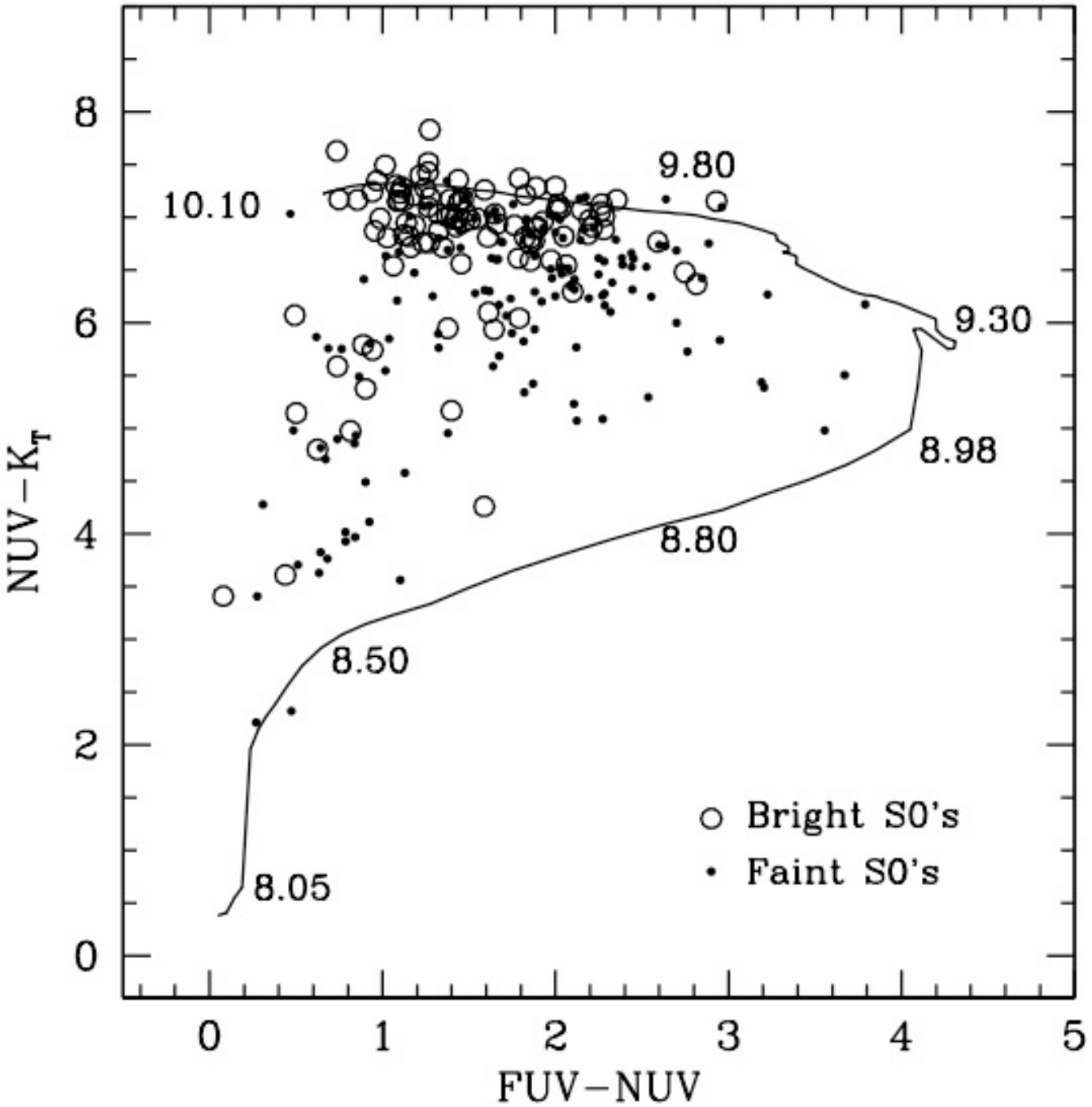
2MASS da

GALEX data in

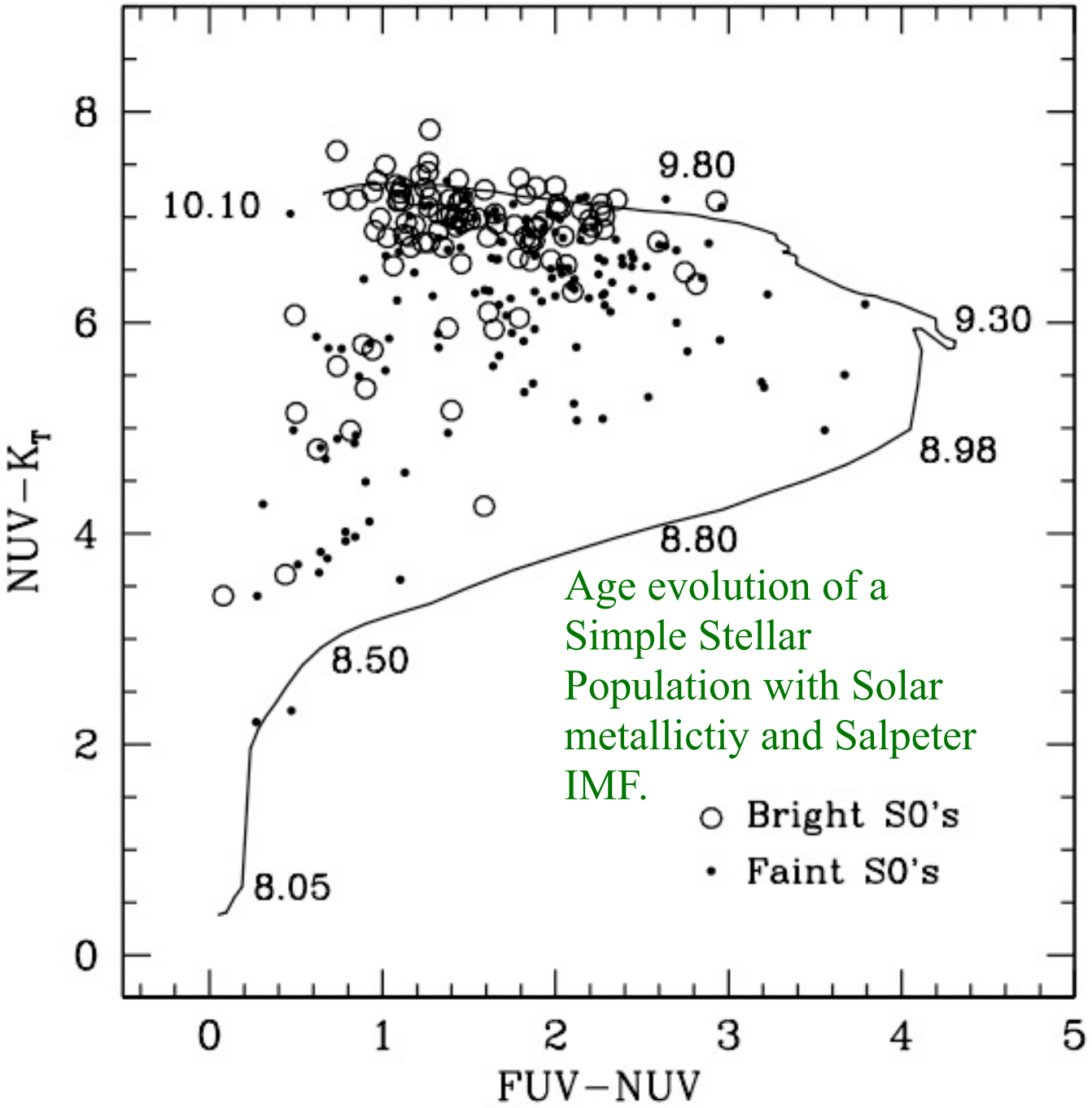
WISE mid-IR dat

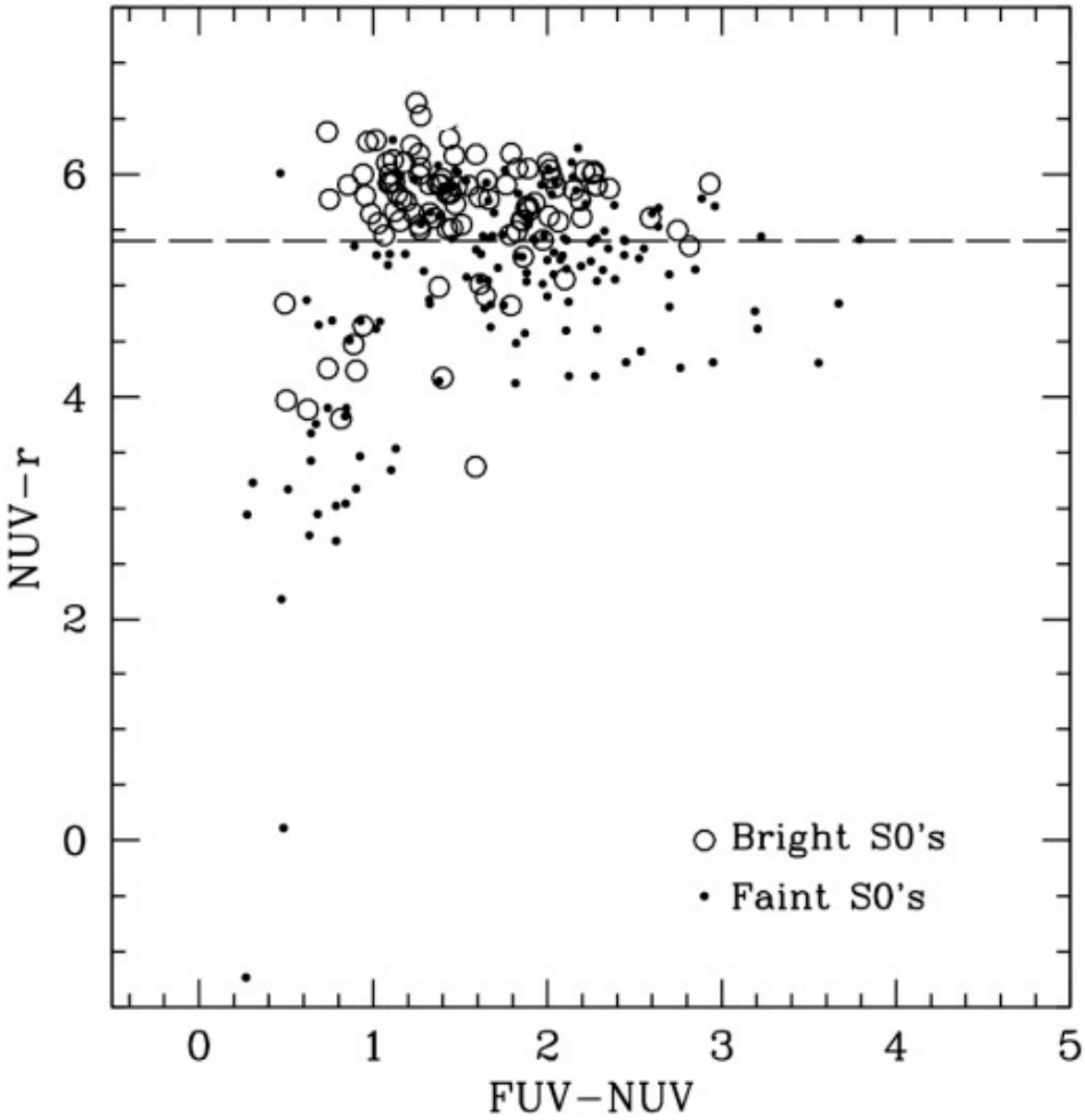


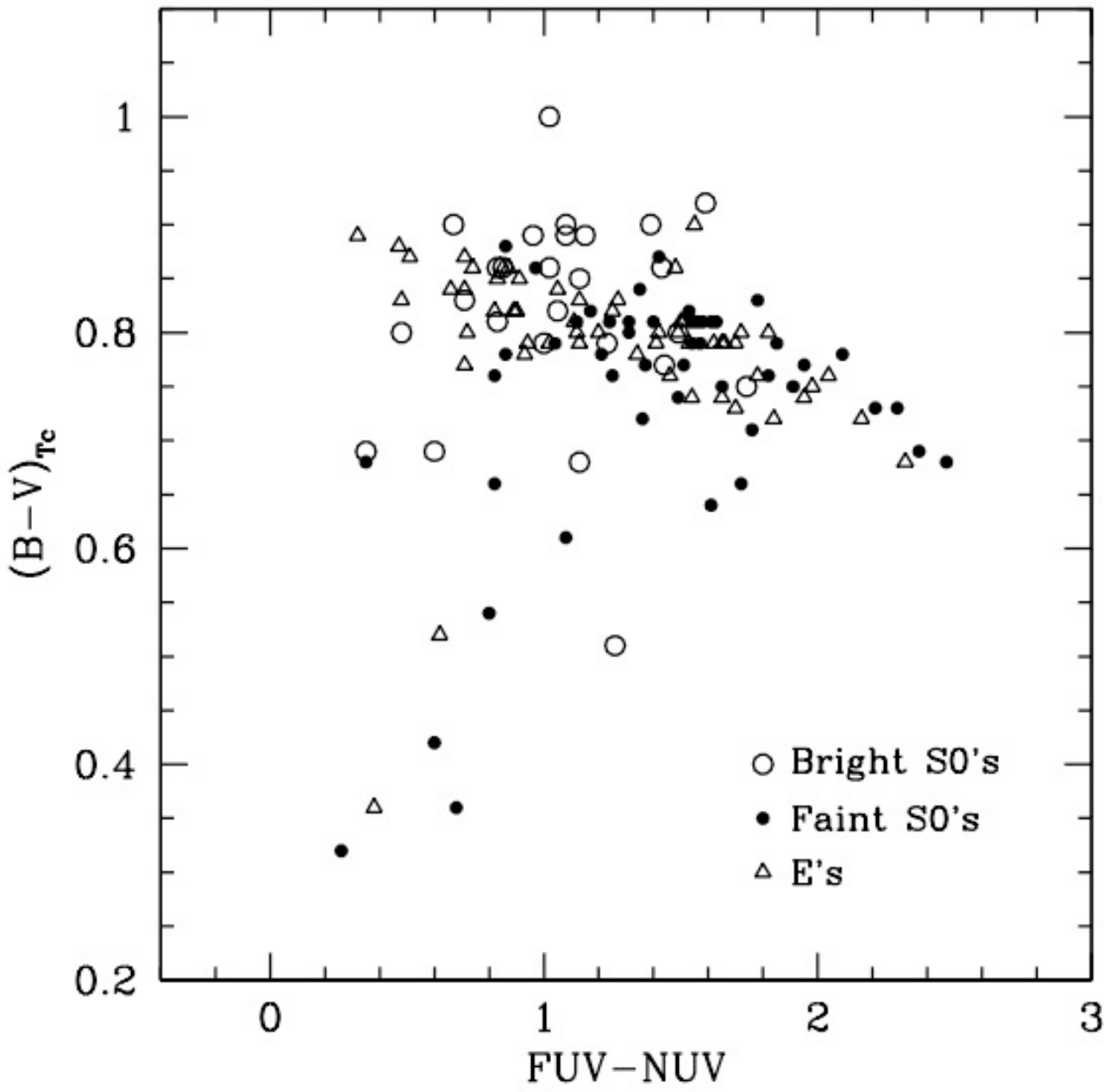
Colour-Colour Diagram

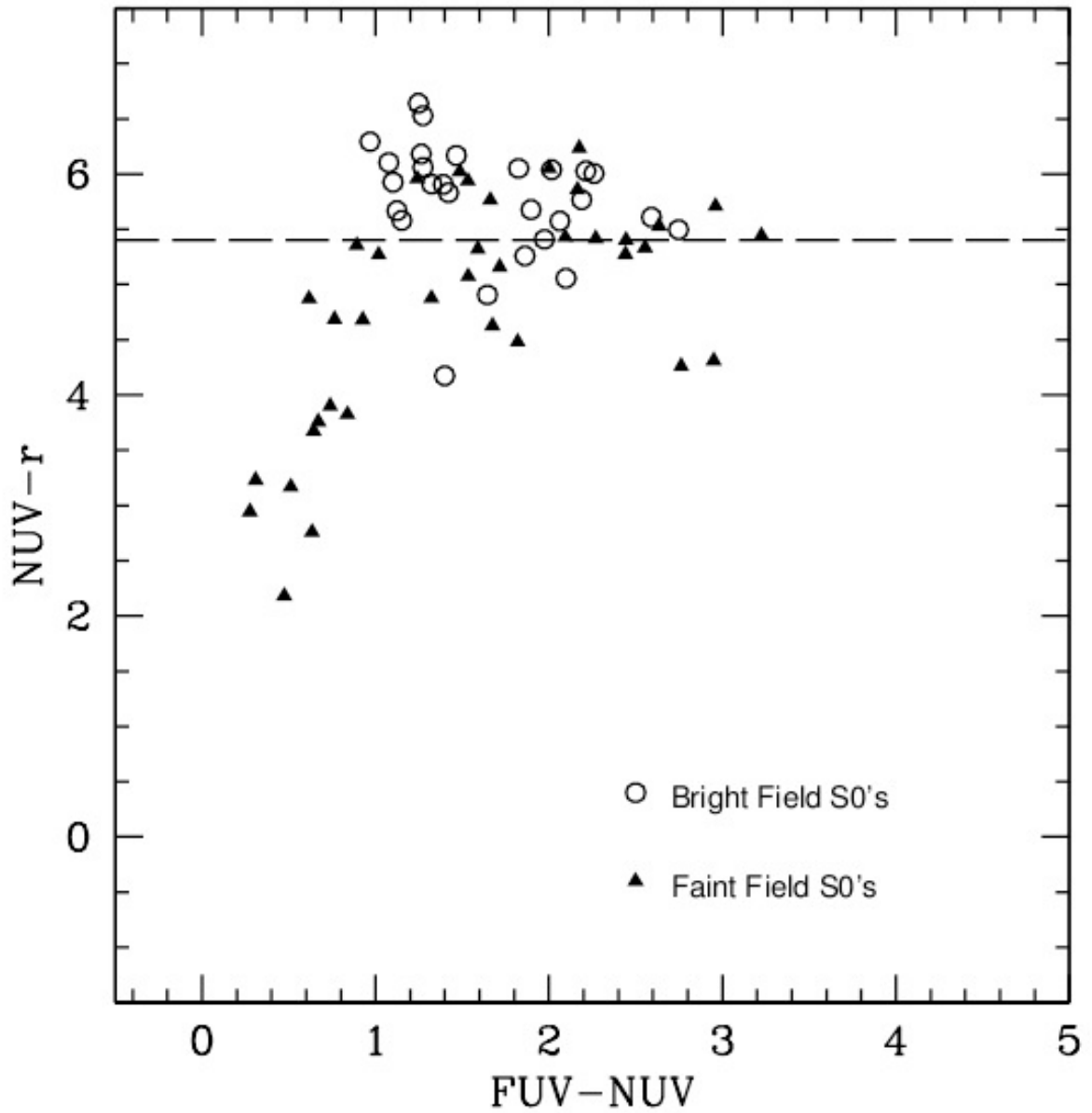


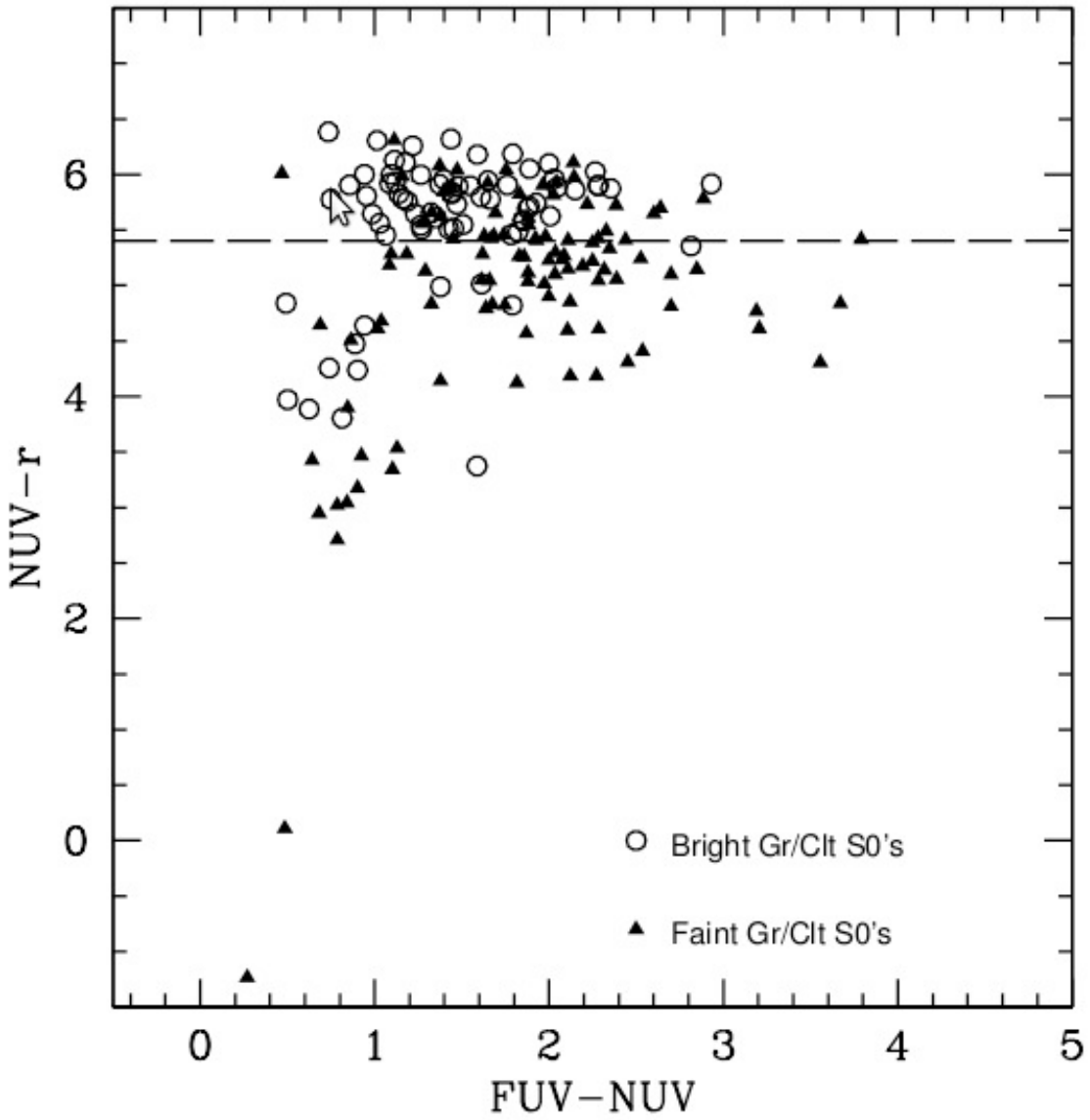
Colour-Colour Diagram

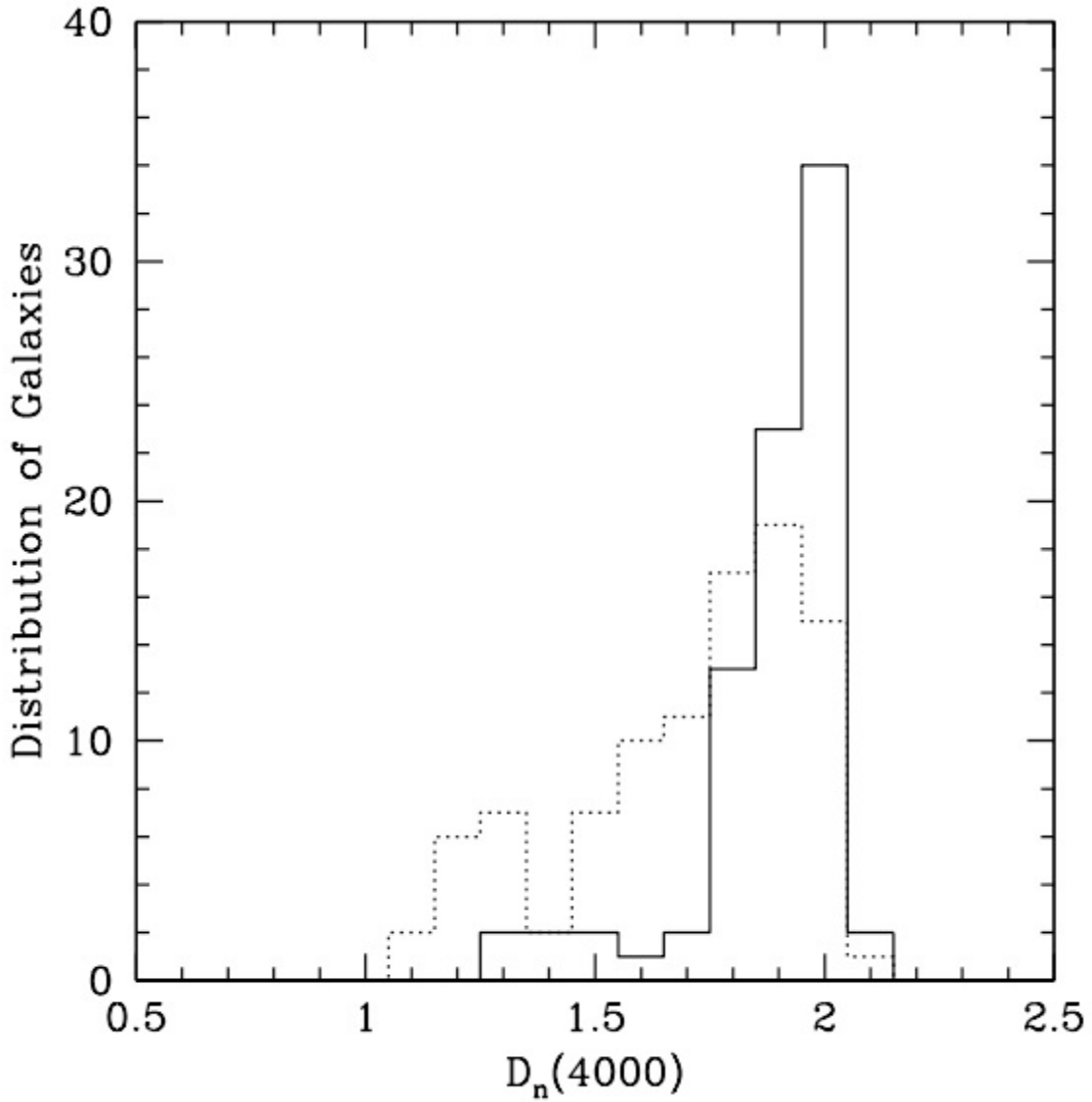


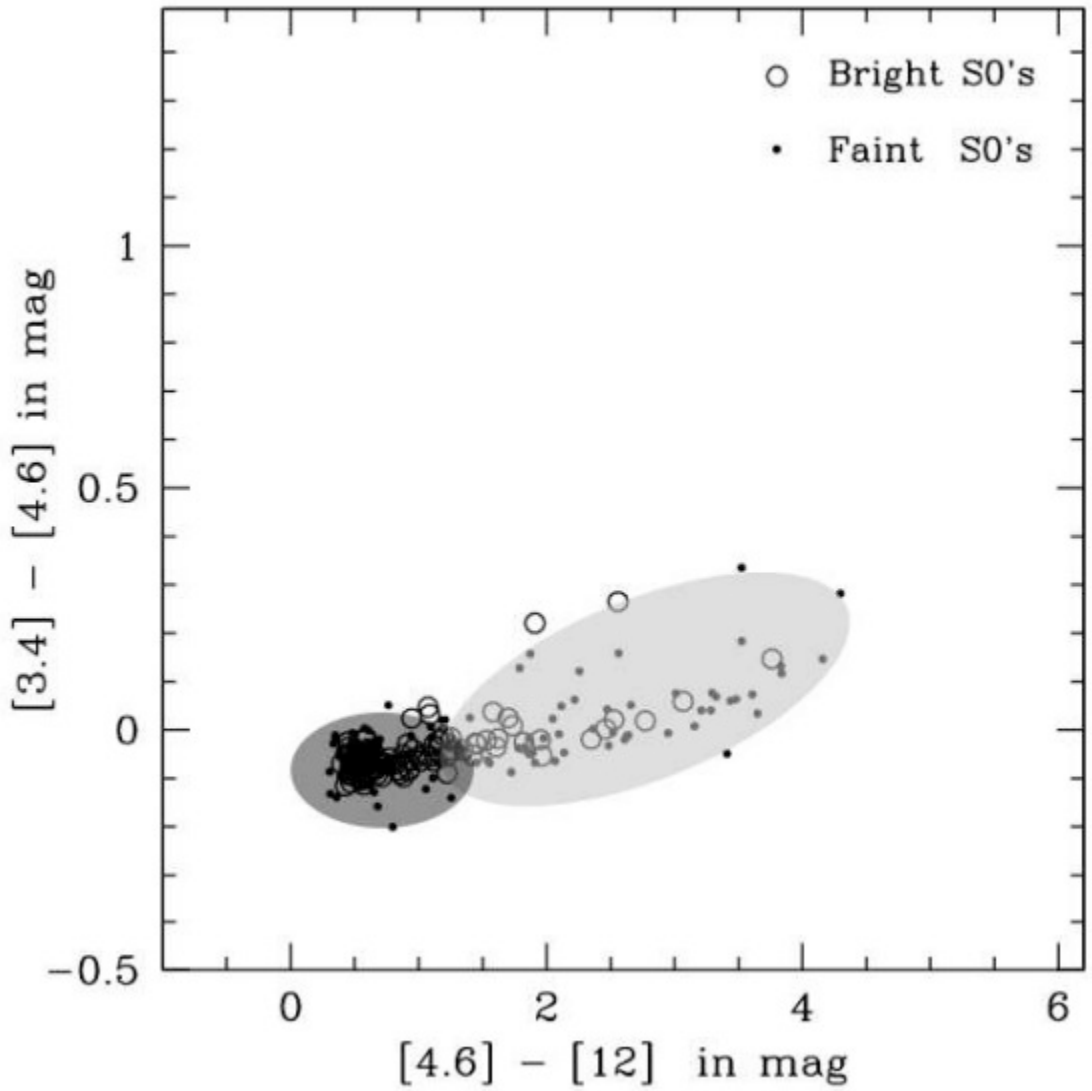

NUV−r
FUV−NUV
0
2
4
6
0
1
2
3
4
5
Bright S0's
Faint S0's


1
0.8
0.6
0.4
0.2
$(B-V)_{Tc}$
0
1
2
3
FUV−NUV
Bright S0's
Faint S0's
E's


NUV−r
FUV−NUV
0
2
4
6
0
1
2
3
4
5
Bright Field S0's
Faint Field S0's

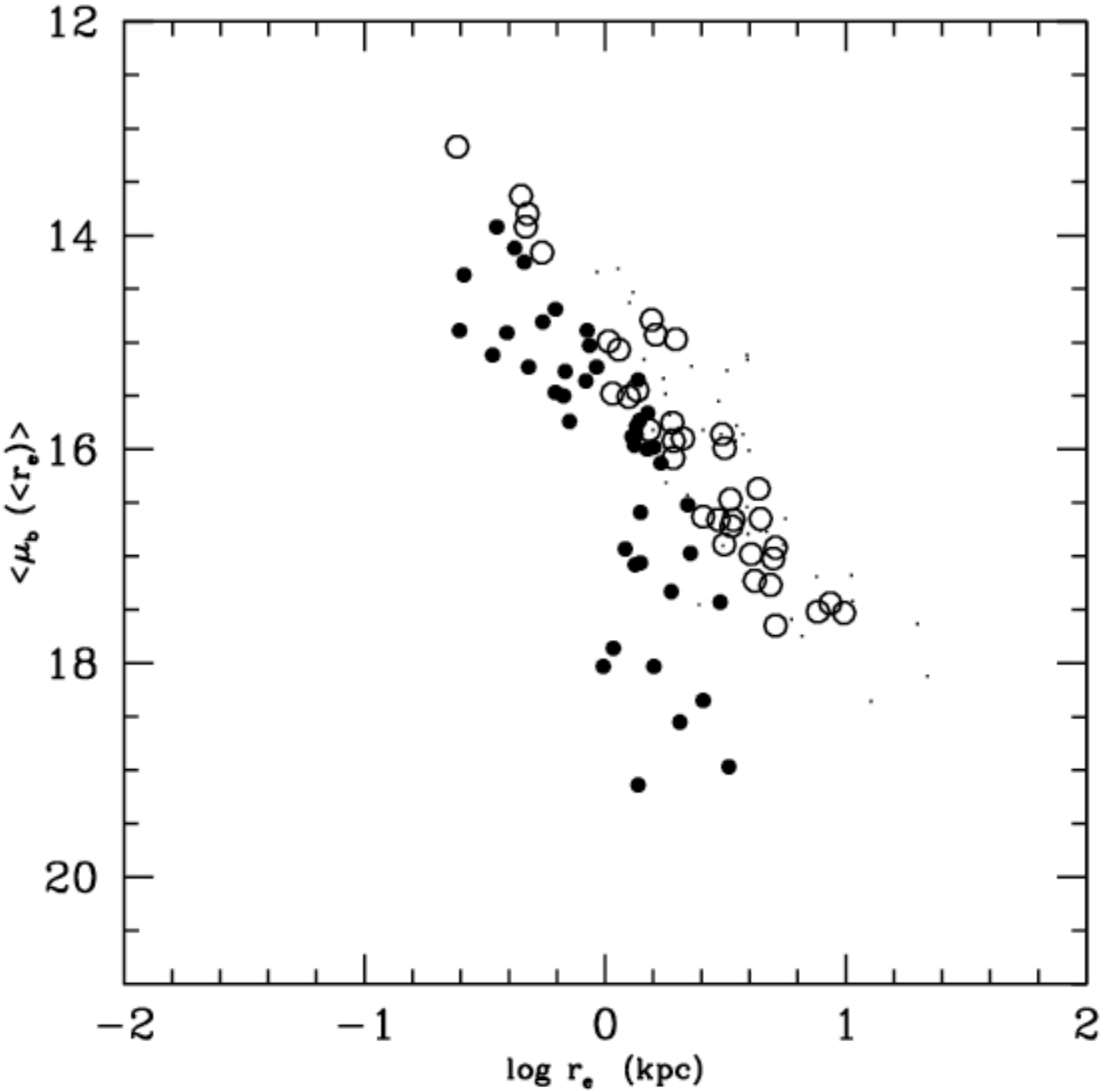

NUV−r
FUV−NUV
0
2
4
6
0
1
2
3
4
5
Bright Gr/Clt S0's
Faint Gr/Clt S0's


Distribution of Galaxies
0
10
20
30
40
0.5
1
1.5
2
2.5
$D_n(4000)$

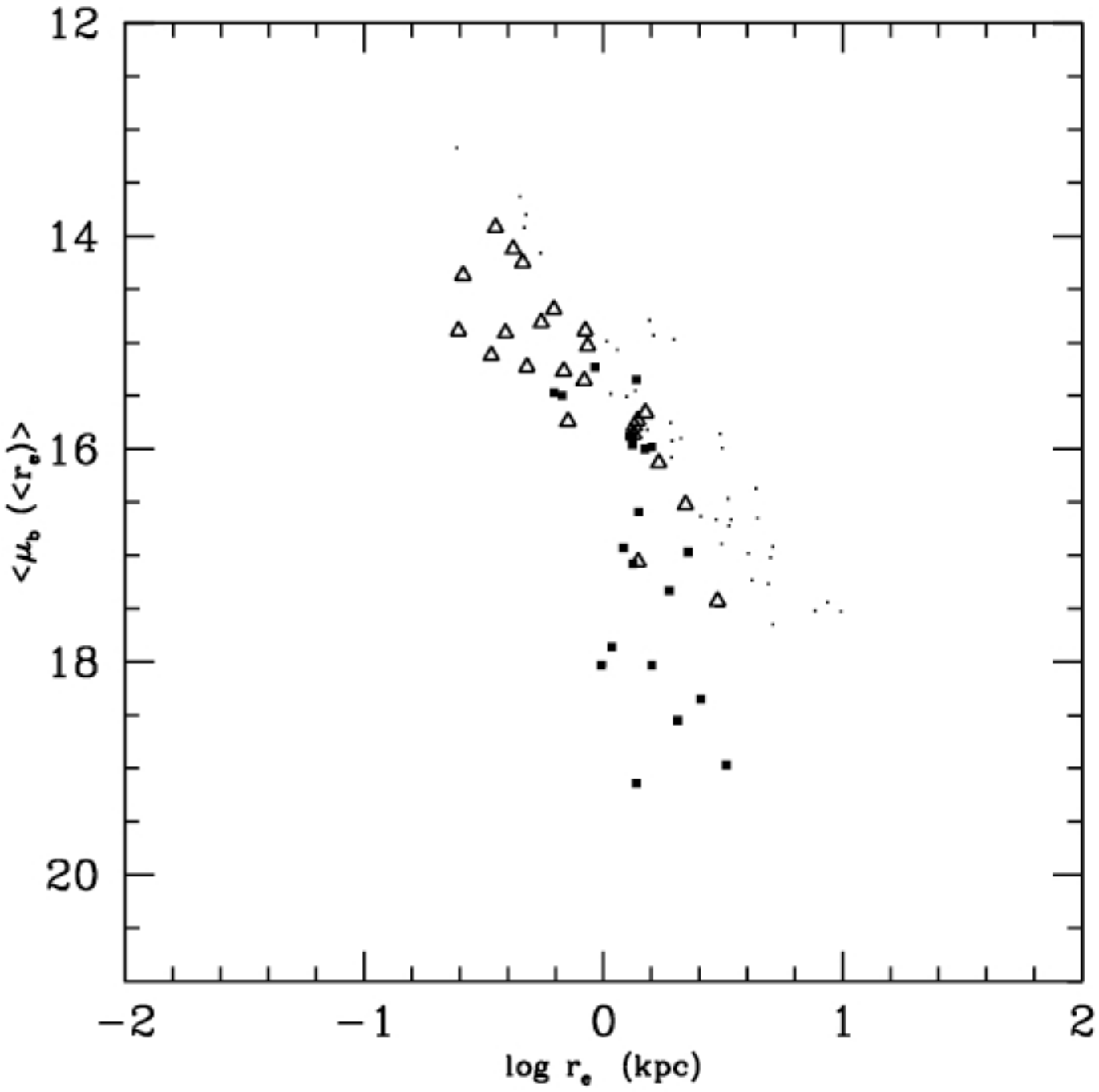

Bright S0's
Faint S0's
[3.4] – [4.6] in mag
1
0.5
0
−0.5
0
2
4
6
[4.6] – [12] in mag

Thank You

Kormendy Relation for SMBH Galaxies



Kormendy Relation – Luminosity Classes



Virial Theorem & Fundamental Plane

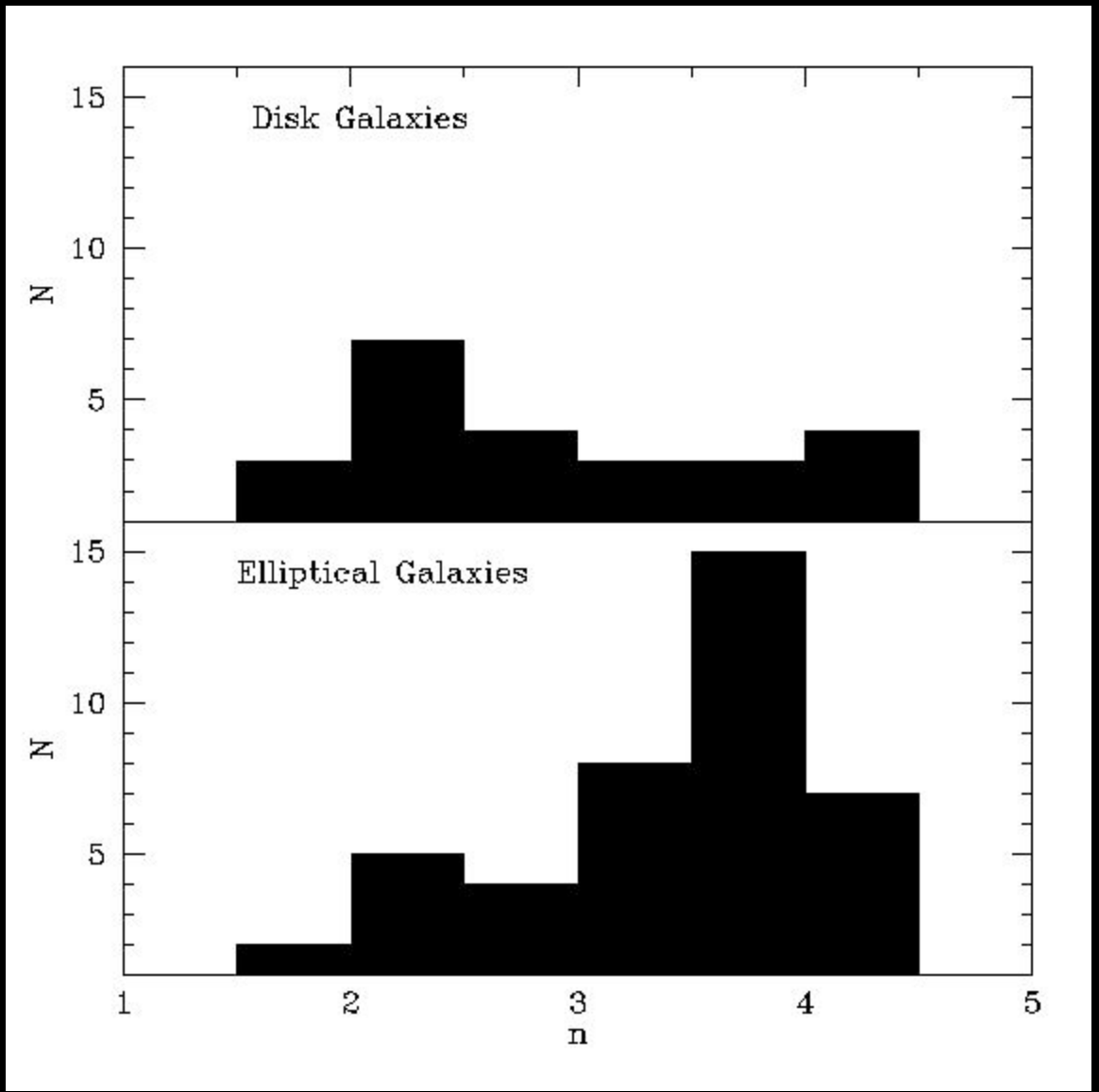
$$\frac{GM}{\langle R \rangle} = \left\langle V^2 \right\rangle$$

$$R = k_R \langle R \rangle, \quad \sigma^2 = k_V \left\langle V^2 \right\rangle, \quad L = k_L I R^2$$

$$R = K \sigma^2 I^{-1} \left(\frac{M}{L}\right)^{-1}, \quad K = (G k_R k_L k_V)^{-1}$$

$$k_R, k_V, k_L \sim \text{constant}, \quad R \sim \sigma^A I^B$$

$$\left(\frac{M}{L}\right) \sim \frac{\sigma^{2+A/B}}{R^{1+1/B}} \sim R^{0.22} \sigma^{0.49} \sim \frac{M^{0.24}}{R^{0.02}}$$



Distribution of Sersic Index n

Ellipticals and Early Type Bulges

Khosroshahi et al
ApJL 2000
ApJ 2001

Morphological Mix

Abell clusters ellipticals 34

Coma ellipticals 42

UGC field lenticulars 37

Bulges of early type spirals 26

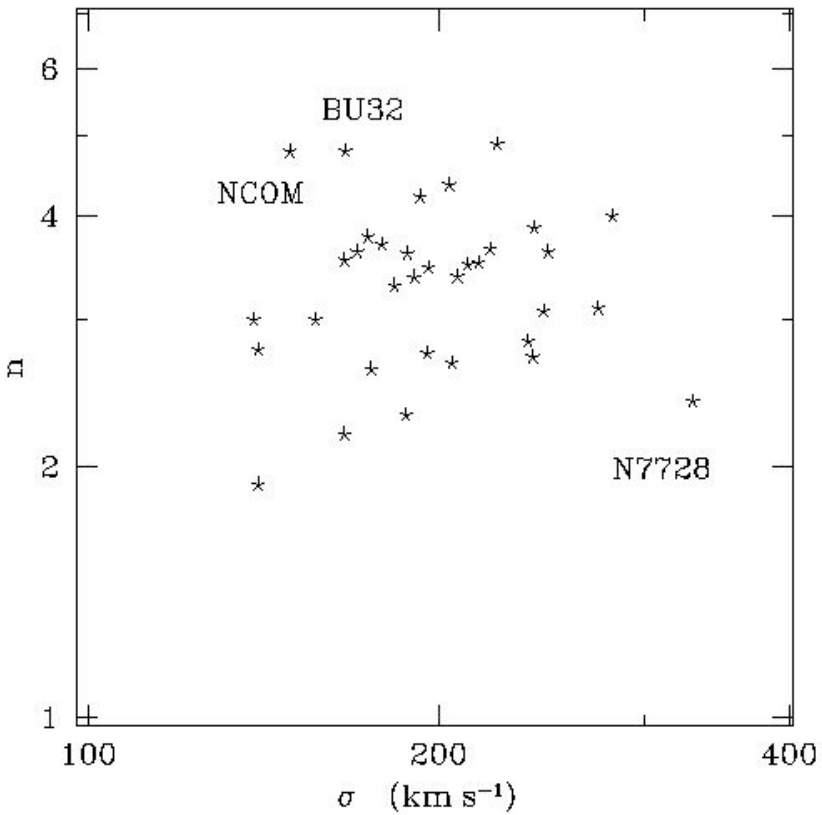
Bulges of late type spirals 40

Early type dwarf galaxies 128

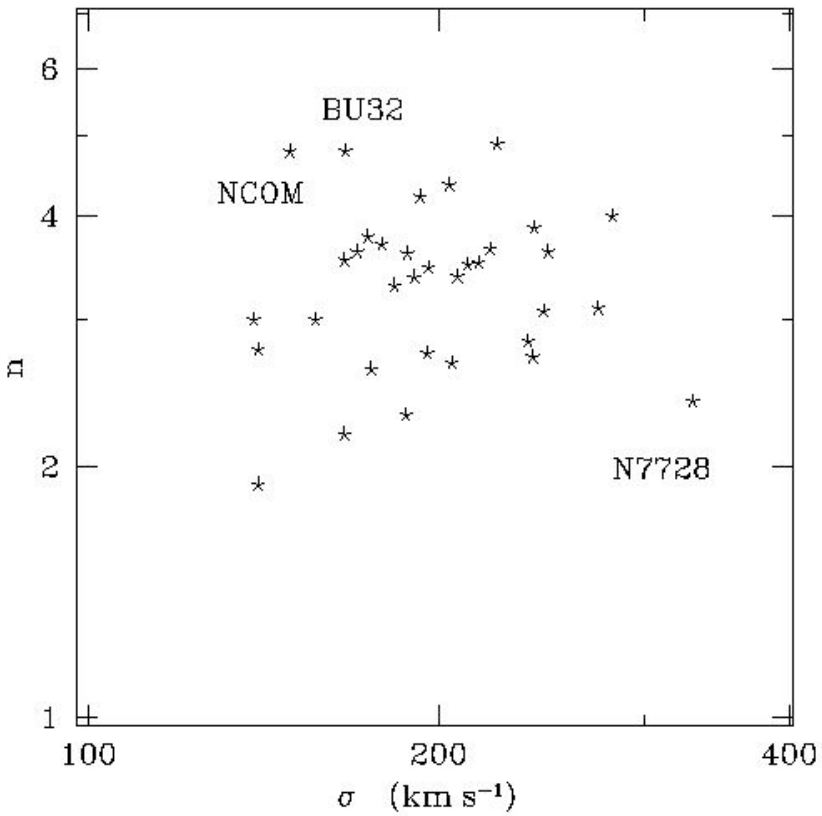
Morphological Mix of Galaxies

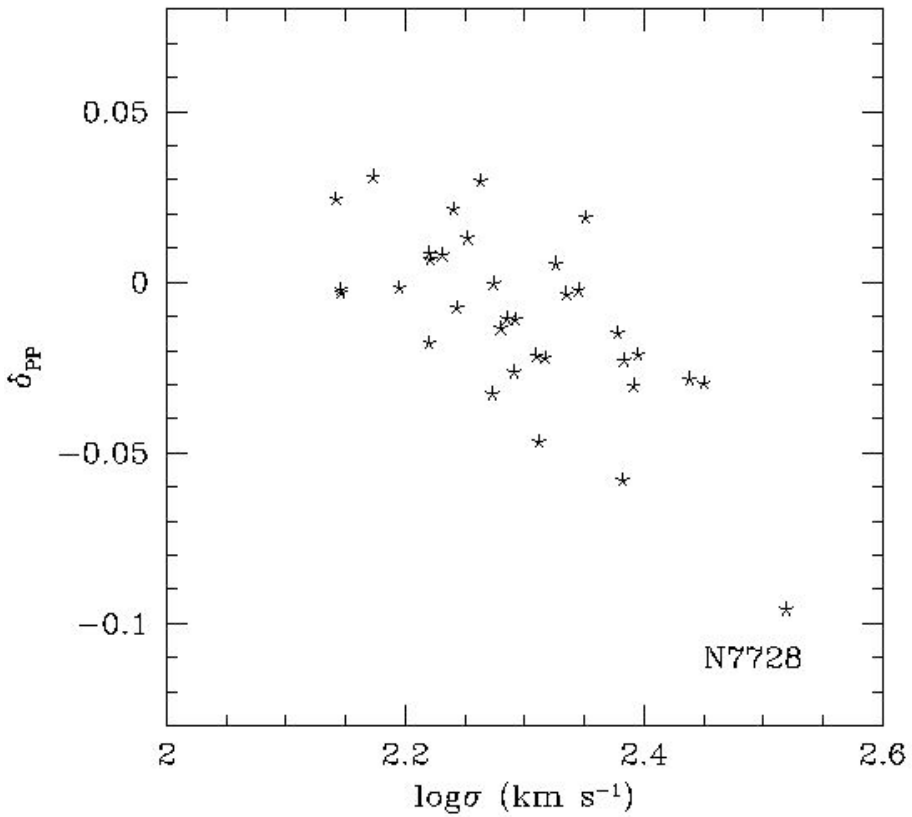
Ravikumar et al 2006

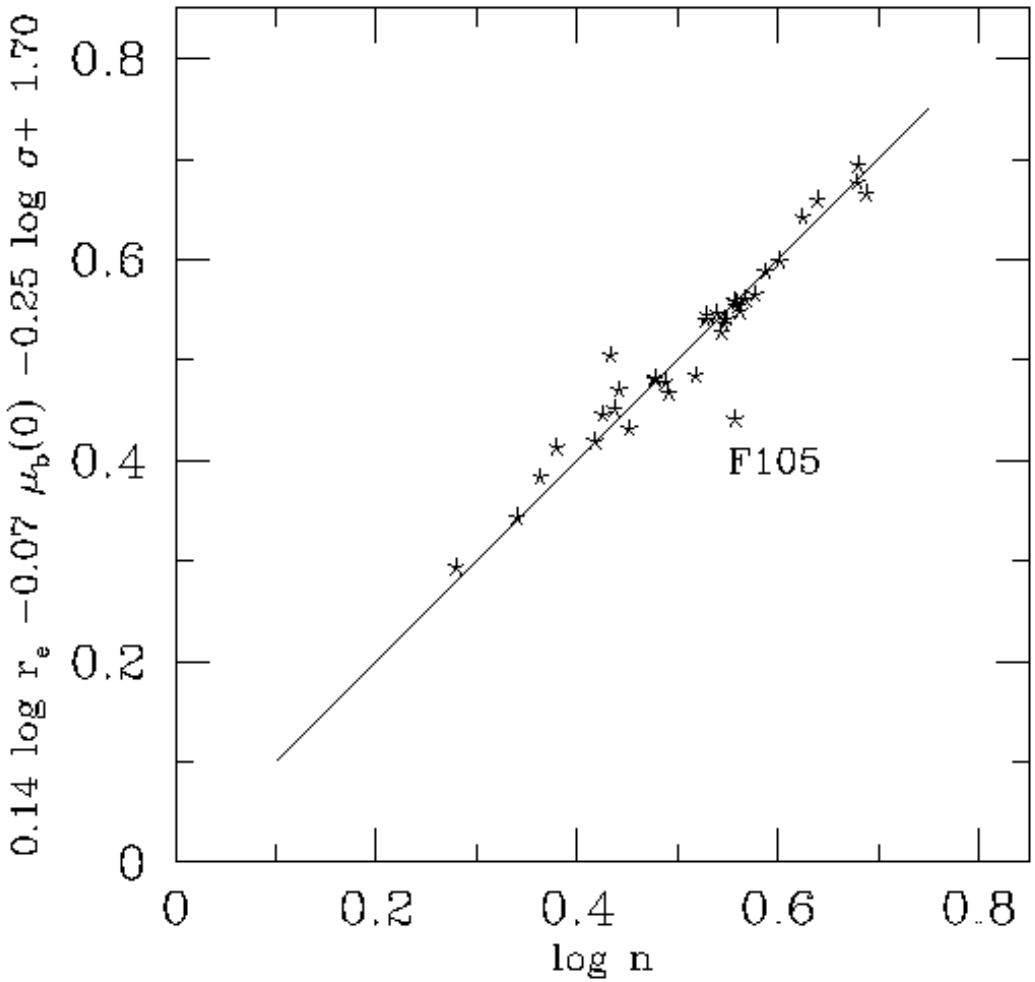
The Photometric Plane and Dispersion Velocity



The Photometric Plane and Dispersion Velocity

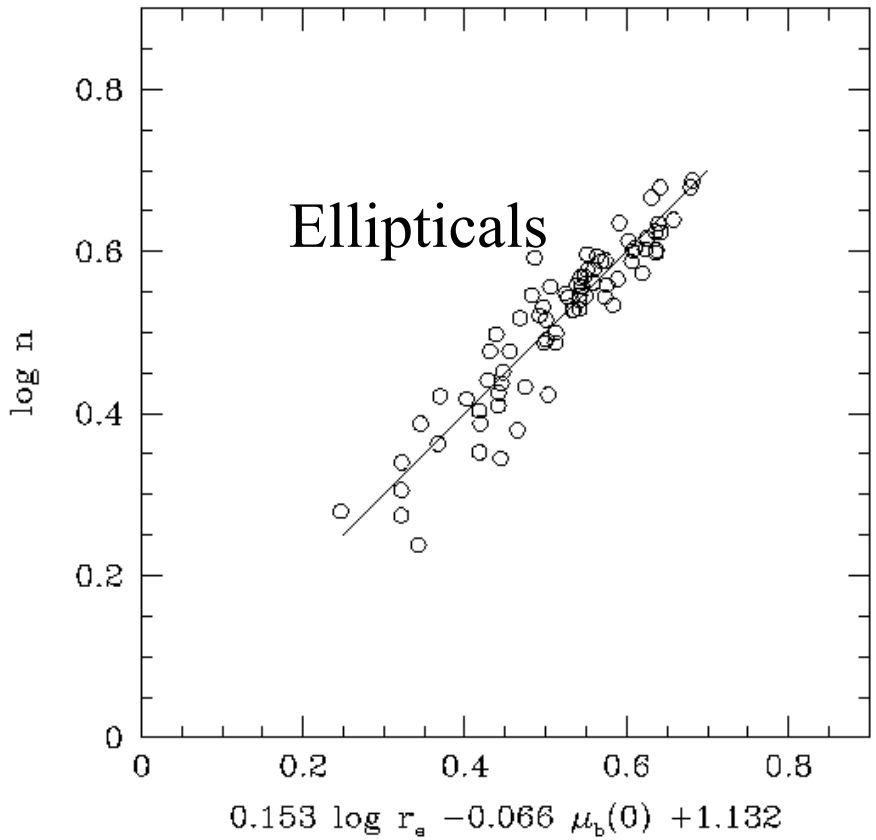


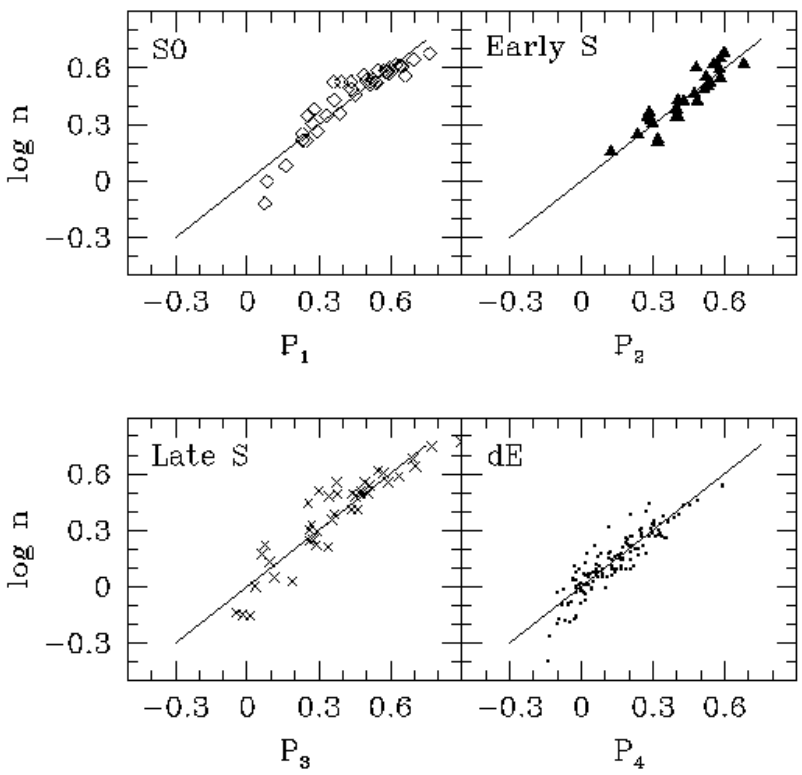


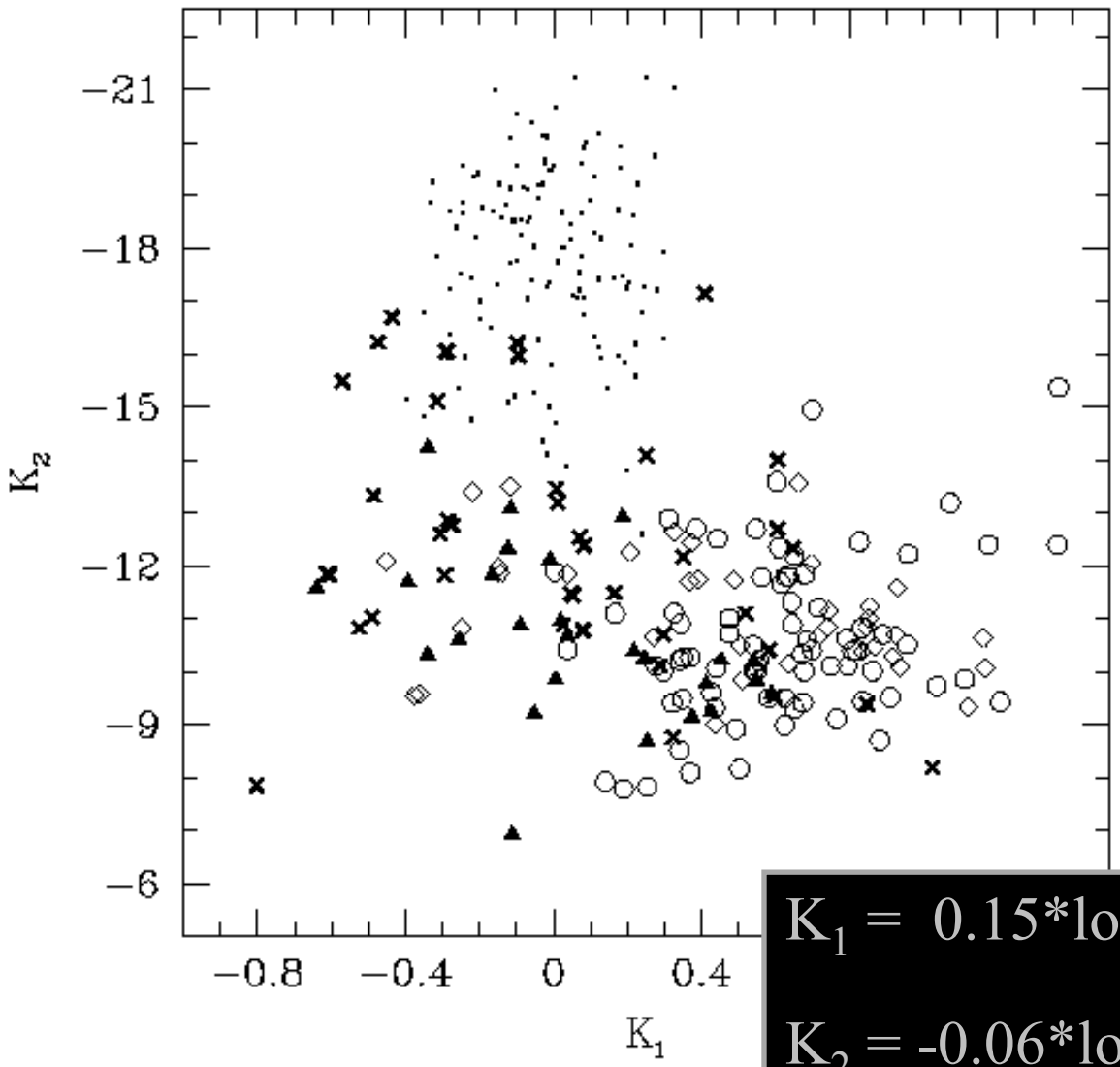


The

Photometric Plane







Photometric Plane

View from the top

$K_1 = 0.15*\log n + 0.99*\log r_e$

$K_2 = -0.06*\log n + 0.01*\log r_e - \mu_b(0)$

Lenticular Galaxies: Morphological Correlations and Formation Mechanisms

Ajit Kembhavi
IUCAA, Pune

Sudhanshu Barway
Yogesh Wadadekar
C.D. Ravi Kumar

Black Hole Search

Black Hole Search

- Stellar Dynamics: Stellar motion indicative of a central massive dark object.

Black Hole Search

- Stellar Dynamics: Stellar motion indicative of a central massive dark object.

  M87, M37, Galactic Centre

Black Hole Search

- Stellar Dynamics: Stellar motion indicative of a central massive dark object.

  M87, M37, Galactic Centre

Black Hole Search

- Stellar Dynamics: Stellar motion indicative of a central massive dark object.

  M87, M37, Galactic Centre

- Gas Dynamics: Rotating gas disk. on various scales

Black Hole Search

- Stellar Dynamics: Stellar motion indicative of a central massive dark object.

  M87, M37, Galactic Centre

- Gas Dynamics: Rotating gas disk. on various scales

  M87, NGC4258

Black Hole Search

- Stellar Dynamics: Stellar motion indicative of a central massive dark object.

  M87, M37, Galactic Centre

- Gas Dynamics: Rotating gas disk. on various scales

  M87, NGC4258

- Relativistic effects close to the dark mass.

Black Hole Search

- Stellar Dynamics: Stellar motion indicative of a central massive dark object.

  M87, M37, Galactic Centre

- Gas Dynamics: Rotating gas disk. on various scales

  M87, NGC4258

- Relativistic effects close to the dark mass.

  MCG 6-30-15

Black Hole Search

- Stellar Dynamics: Stellar motion indicative of a central massive dark object.

  M87, M37, Galactic Centre

- Gas Dynamics: Rotating gas disk. on various scales

  M87, NGC4258

- Relativistic effects close to the dark mass.

  MCG 6-30-15

Black Hole Search

- Stellar Dynamics: Stellar motion indicative of a central massive dark object.

  M87, M37, Galactic Centre

- Gas Dynamics: Rotating gas disk. on various scales

  M87, NGC4258

- Relativistic effects close to the dark mass.

  MCG 6-30-15

- Reverberation mapping and related techniques

Black Hole Search

- Stellar Dynamics: Stellar motion indicative of a central massive dark object.

  M87, M37, Galactic Centre

- Gas Dynamics: Rotating gas disk. on various scales

  M87, NGC4258

- Relativistic effects close to the dark mass.

  MCG 6-30-15

- Reverberation mapping and related techniques

  Seyfert galaxies

Black Hole Search

- Stellar Dynamics: Stellar motion indicative of a central massive dark object.

  M87, M37, Galactic Centre

- Gas Dynamics: Rotating gas disk. on various scales

  M87, NGC4258

- Relativistic effects close to the dark mass.

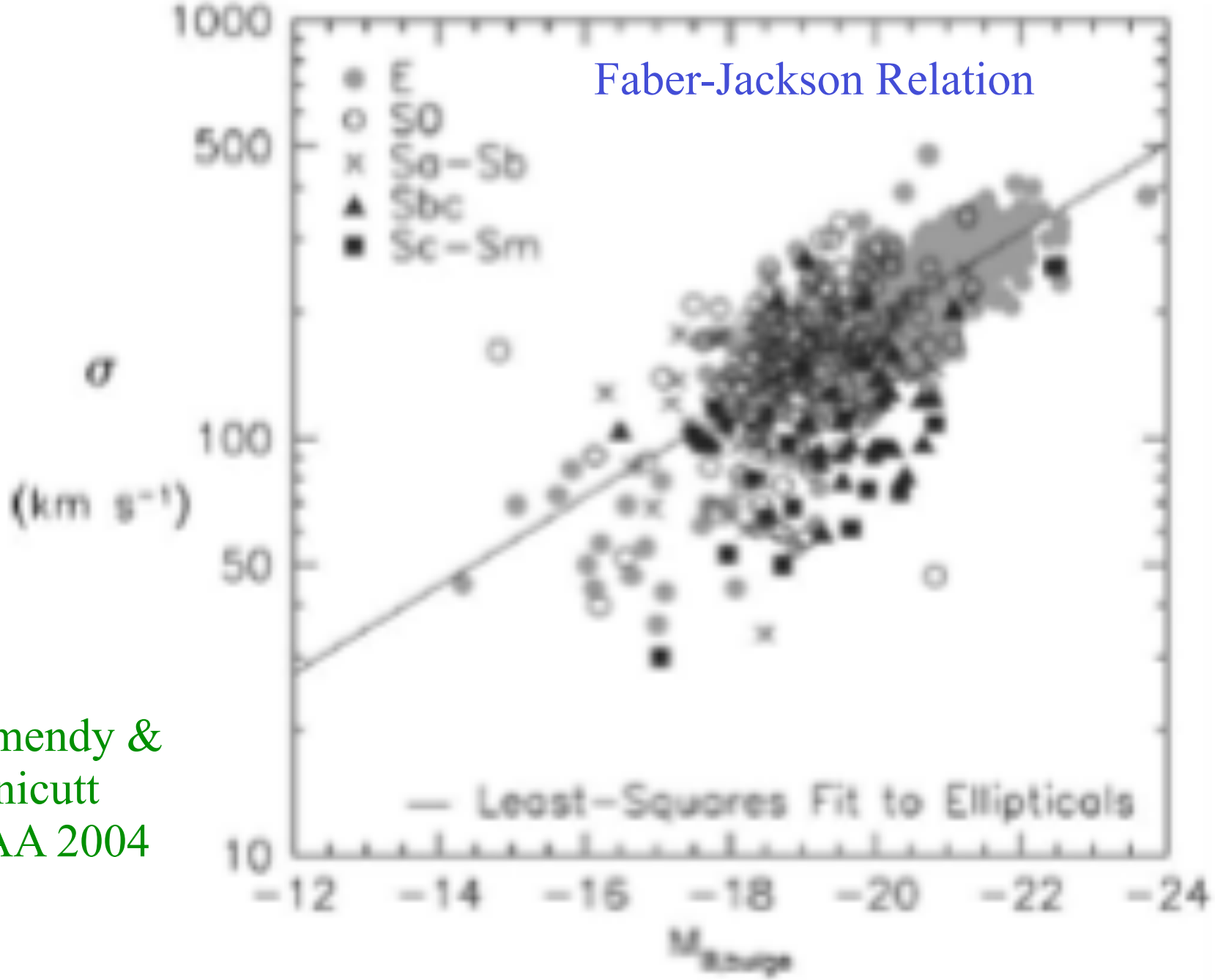
  MCG 6-30-15

- Reverberation mapping and related techniques

  Seyfert galaxies

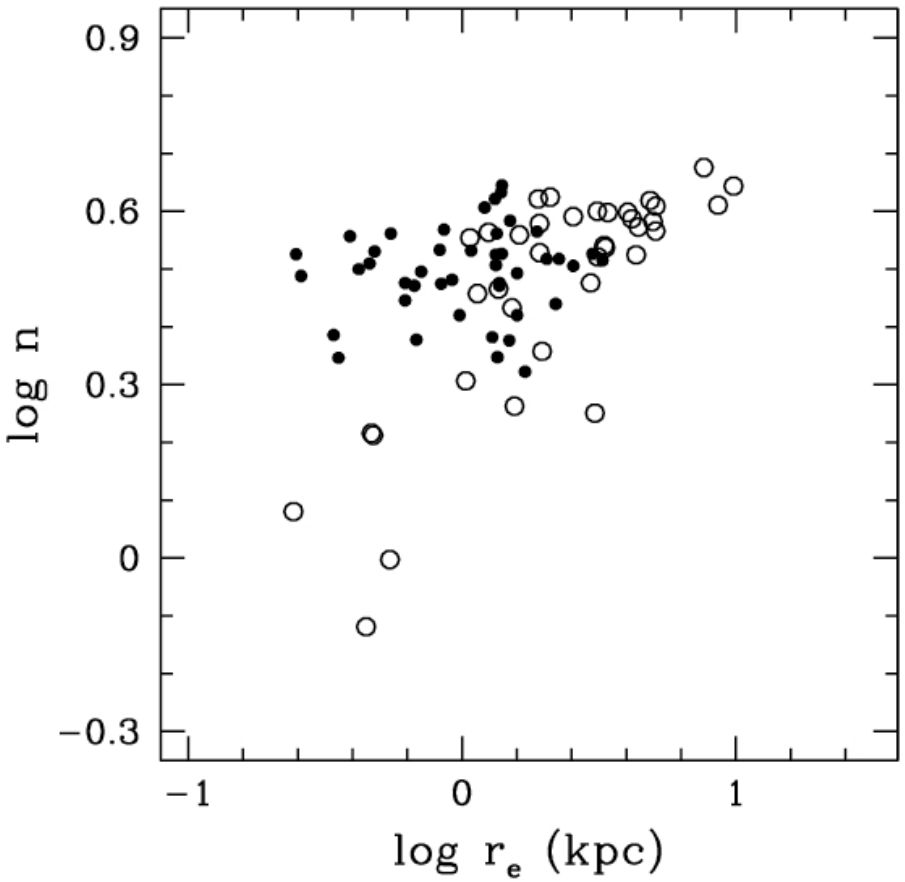
Massive Dark Object or Black Hole?

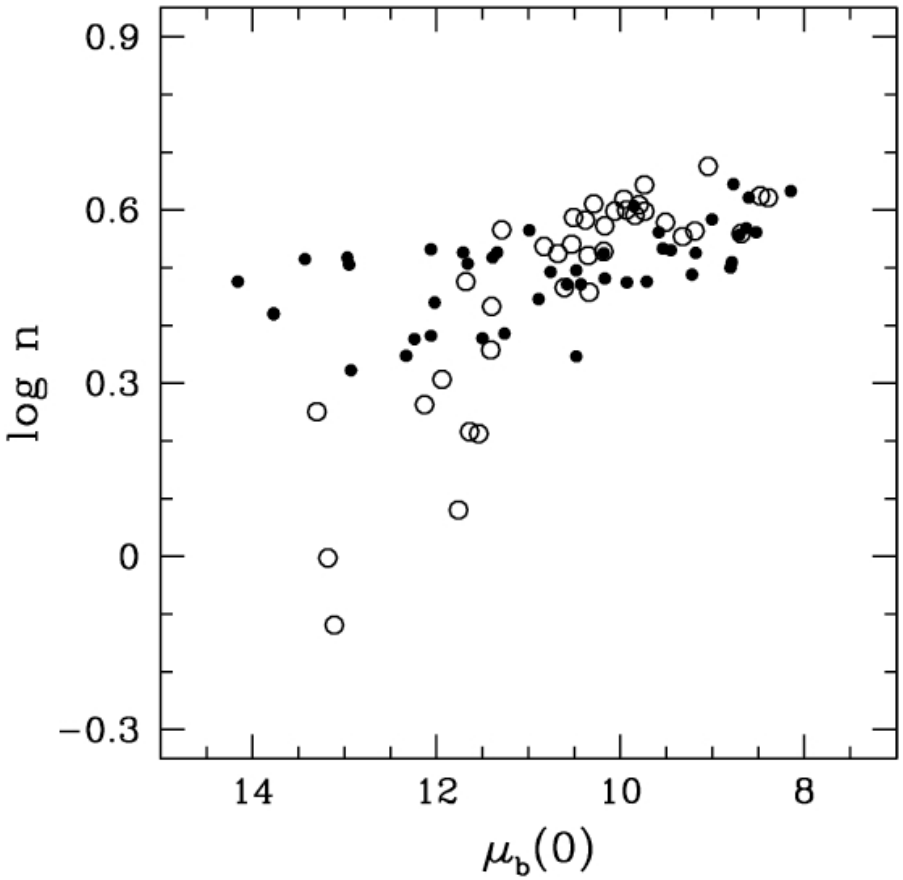
Faber-Jackson Relation



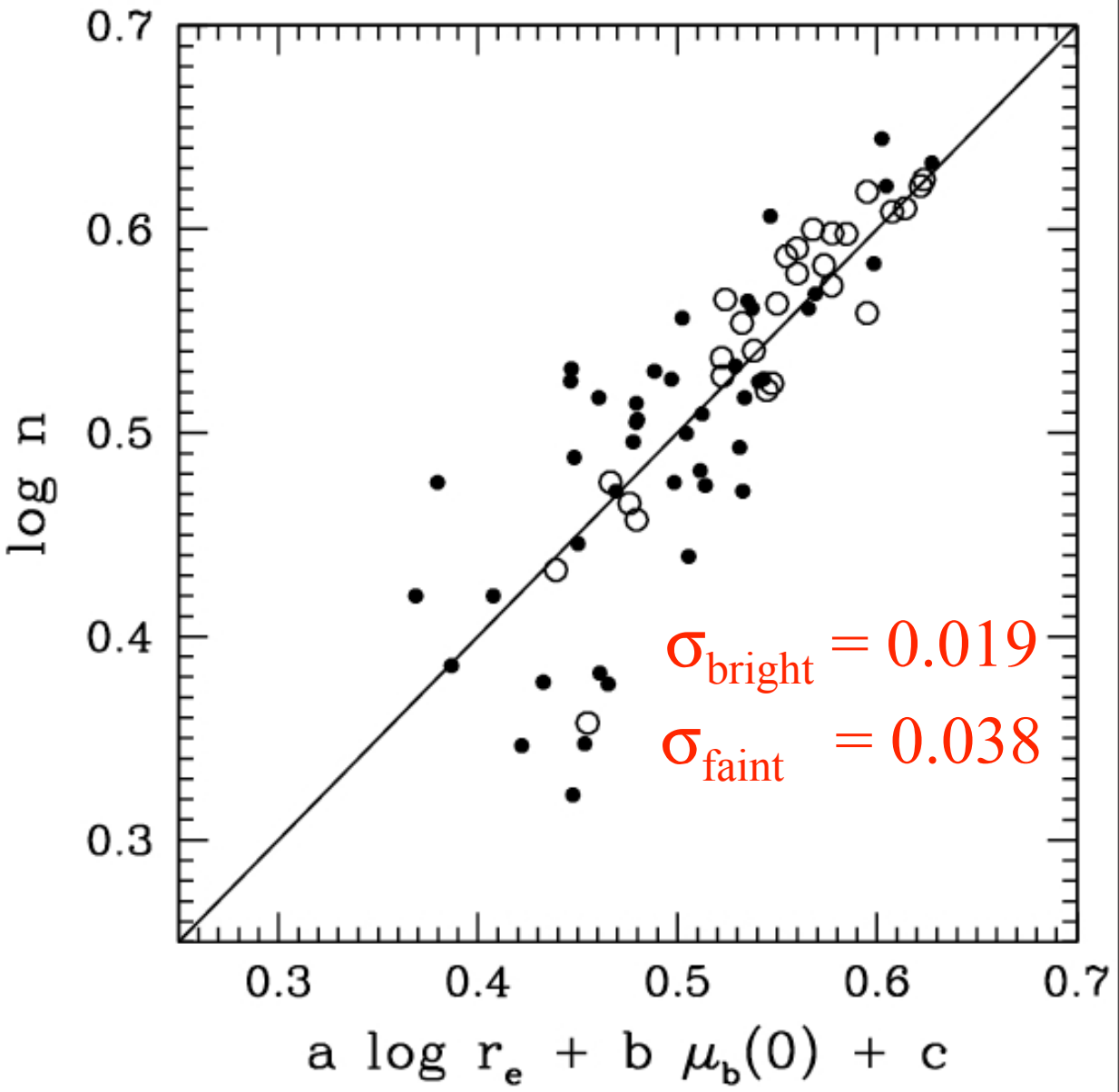
Kormendy & Kennicutt ARAA 2004

Correlations With Sersic Index



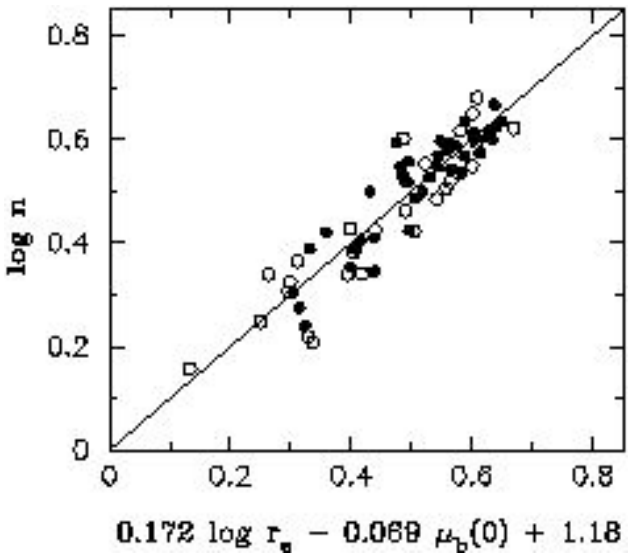


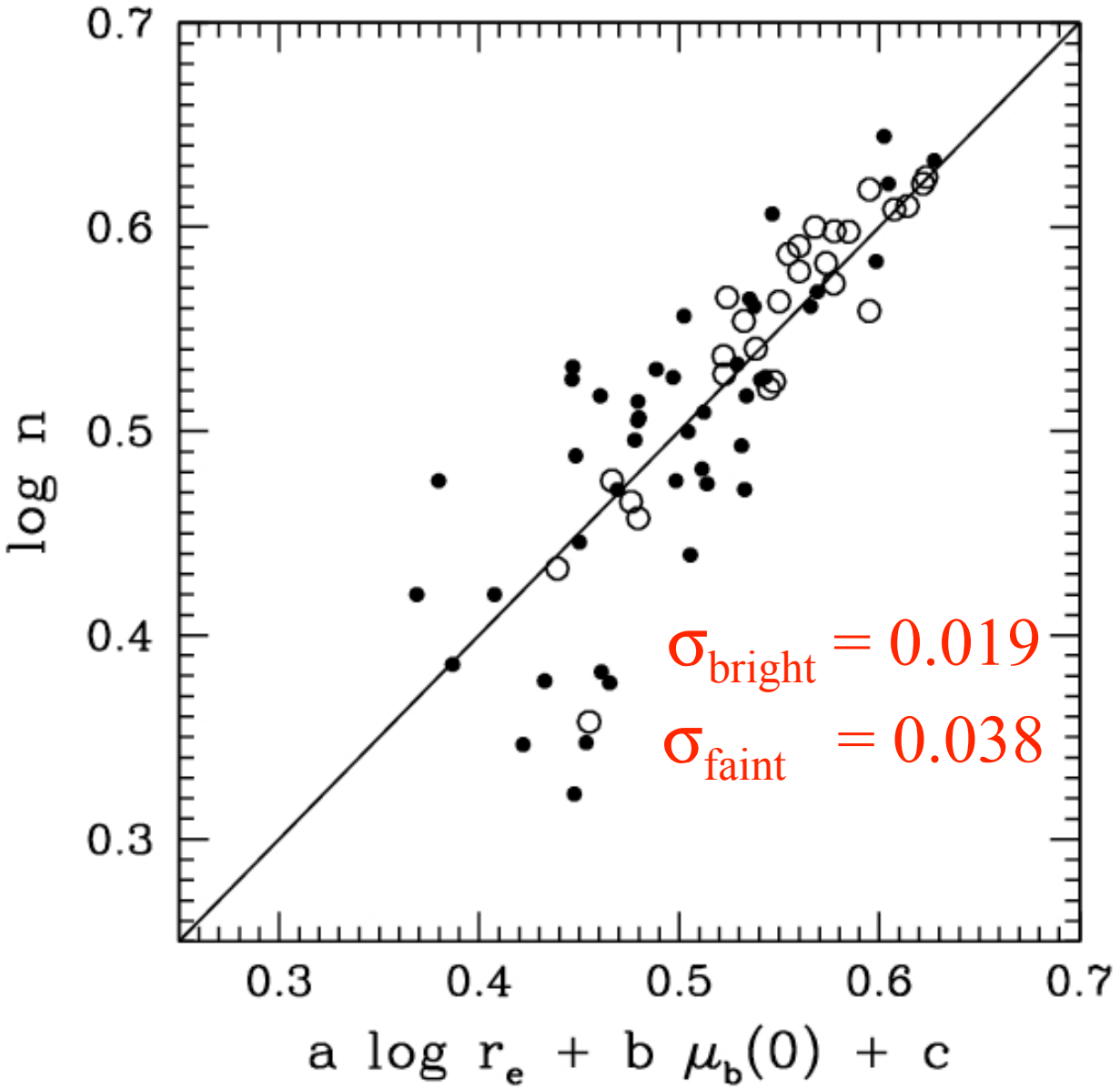
Photometric Plane



Bright lenticulars: $\log n = 0.15 \log r_e - 0.06\mu_b(0) + 1.05$

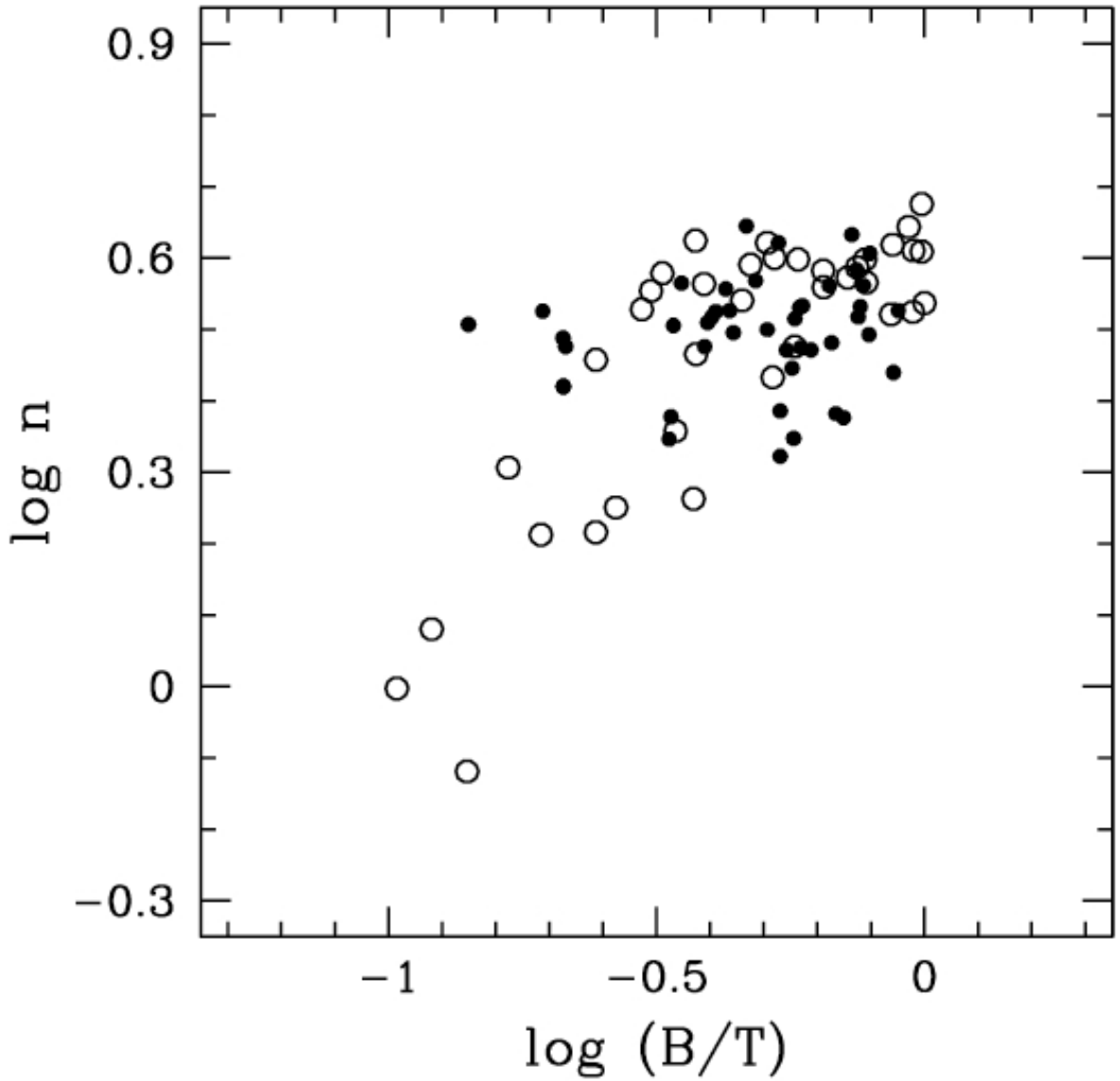
Photometric Plane



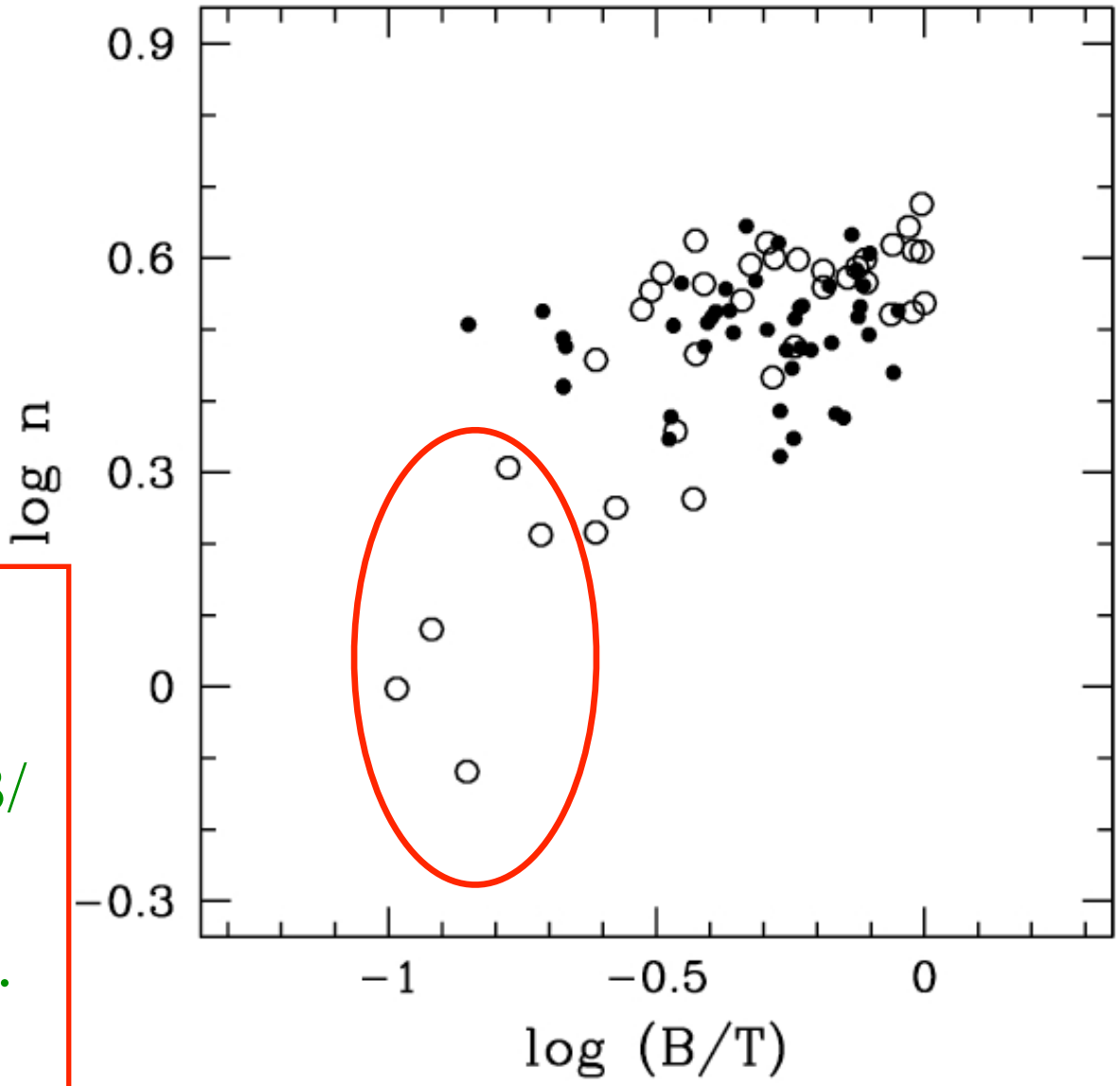


Bright lenticulars: Log n = 0.15 log r_e – 0.06$\mu_b(0)$ + 1.05

Sersic index and B/T ratio



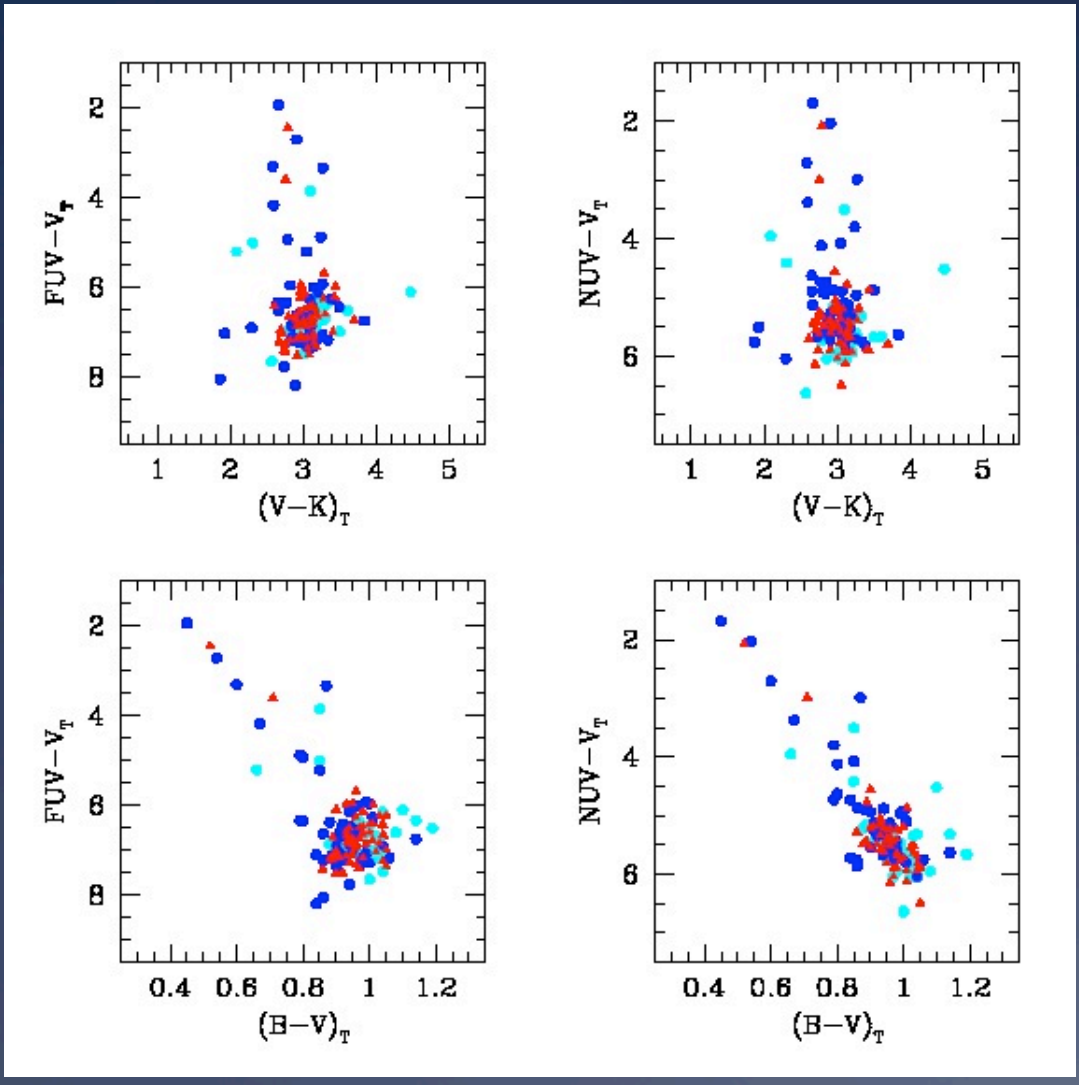
Sersic index and B/T ratio



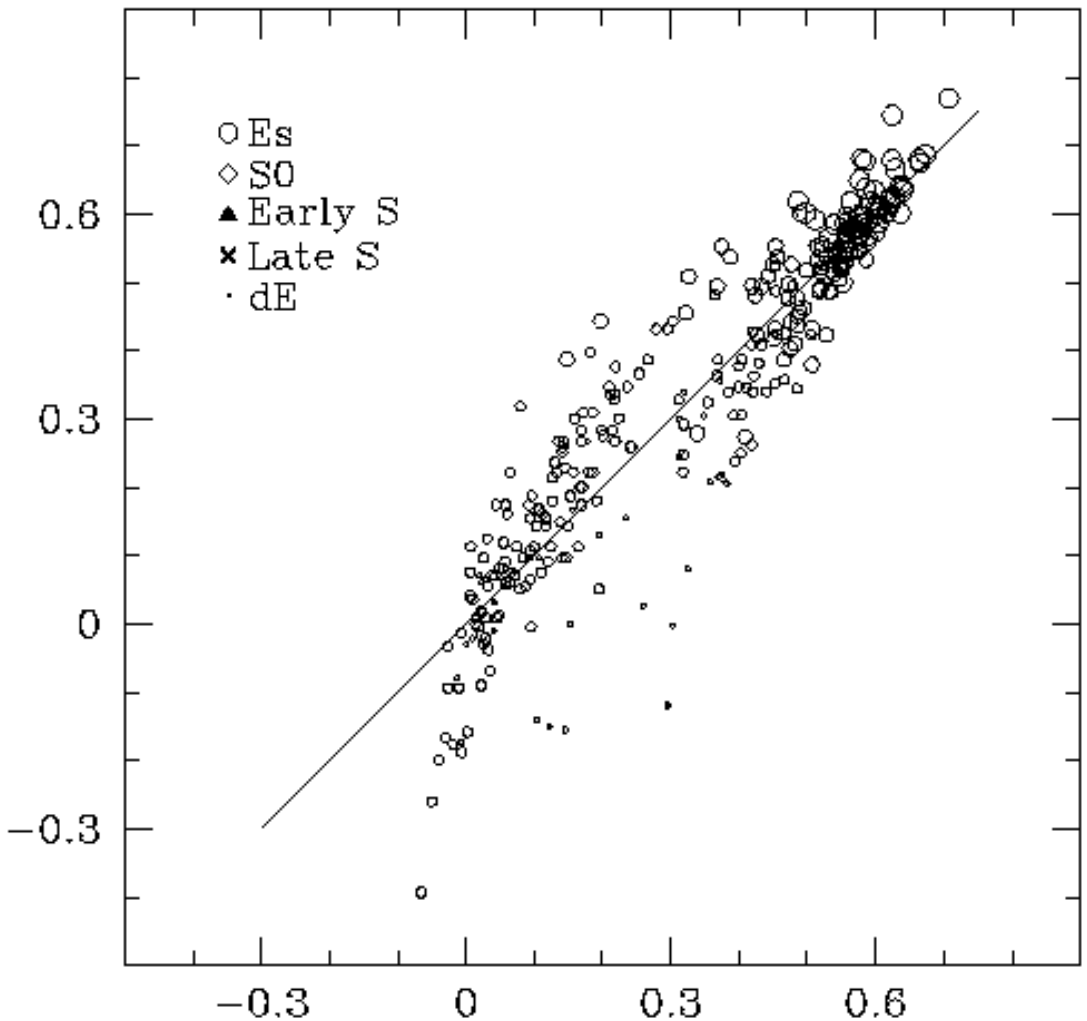
Bright lenticulars with low n, low $\mu_b(0)$, low r_e, low B/T. These are outliers in r_e-r_d plot. but well correlated here.

Color-color relations for S0 galaxies

UV-optical-nir colors



Ellipticals – Δ
Bright S0s – •
Faint S0s – •

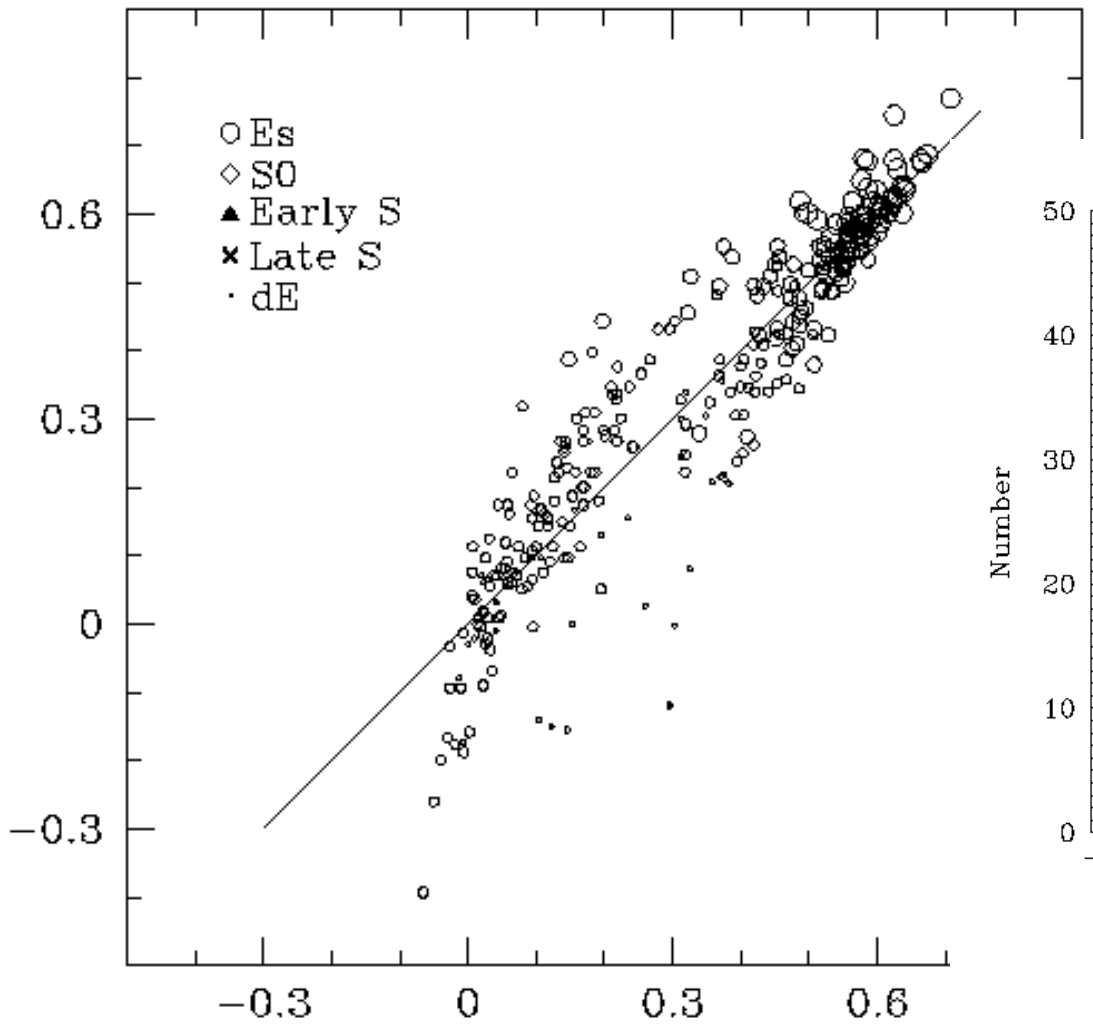


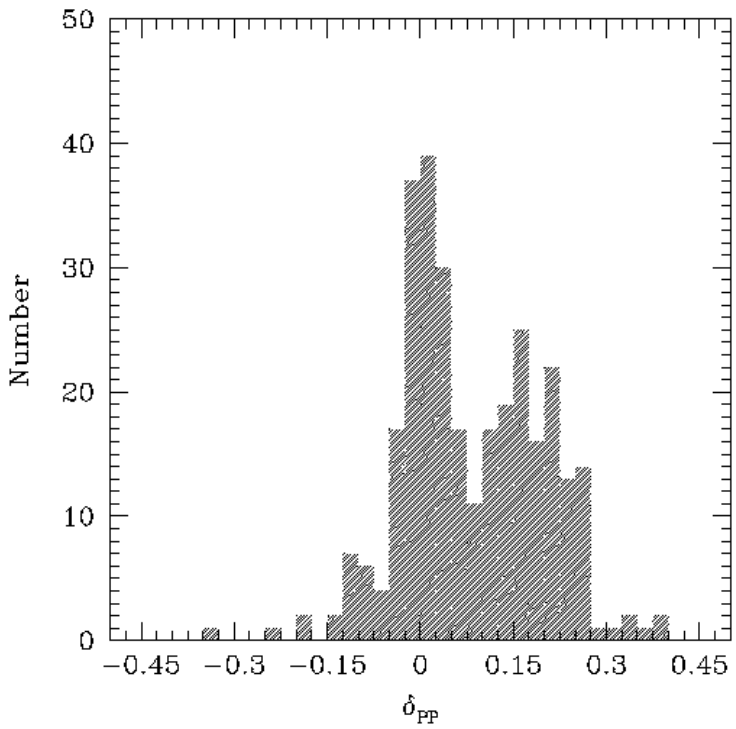
Photometric Plane

Ellipticals
Lenticulars
Dwarf Ellipticals
Bulges

Ravikumar etal
AA 2006

Residuals

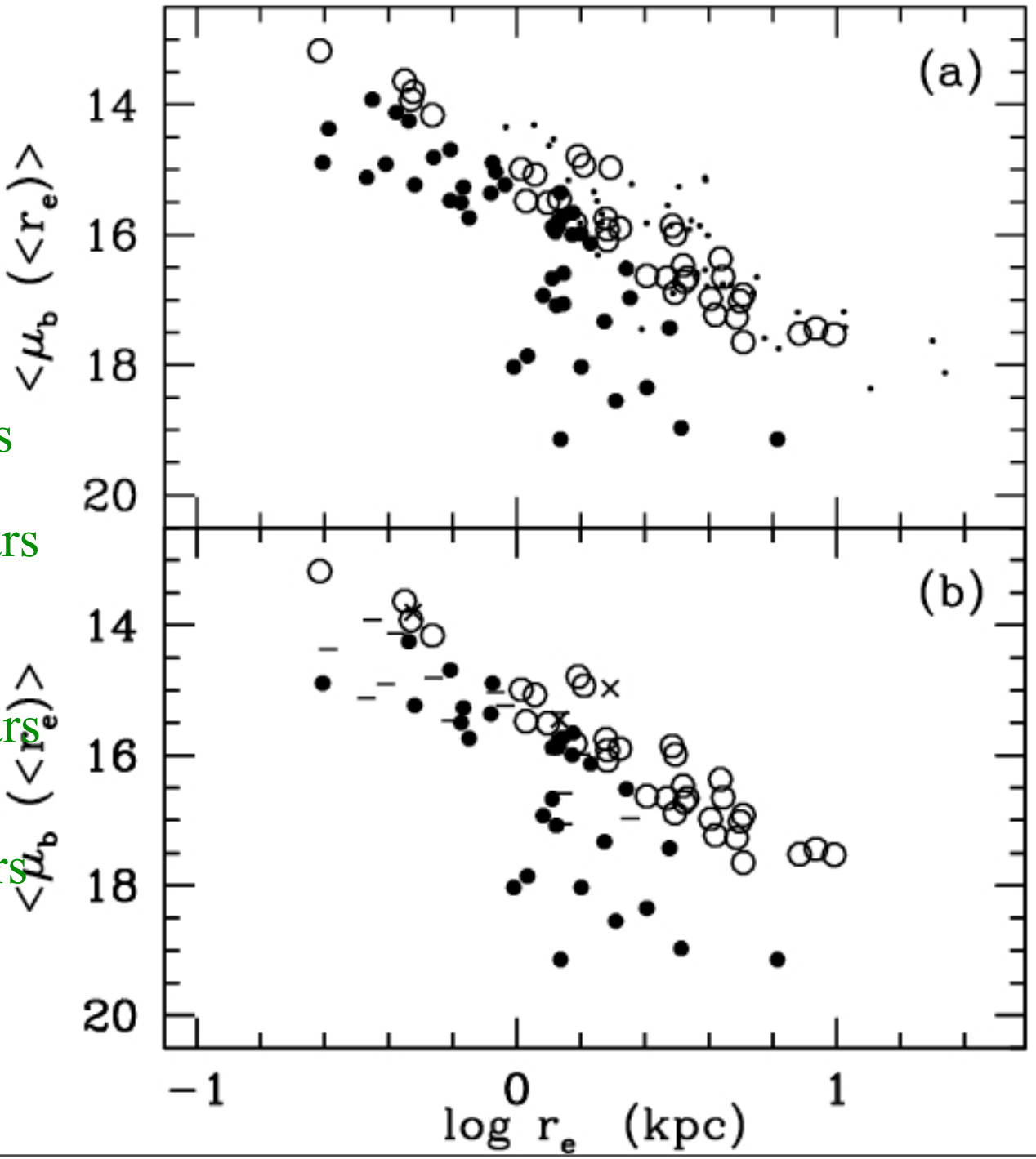




Ravikumar etal
AA 2006

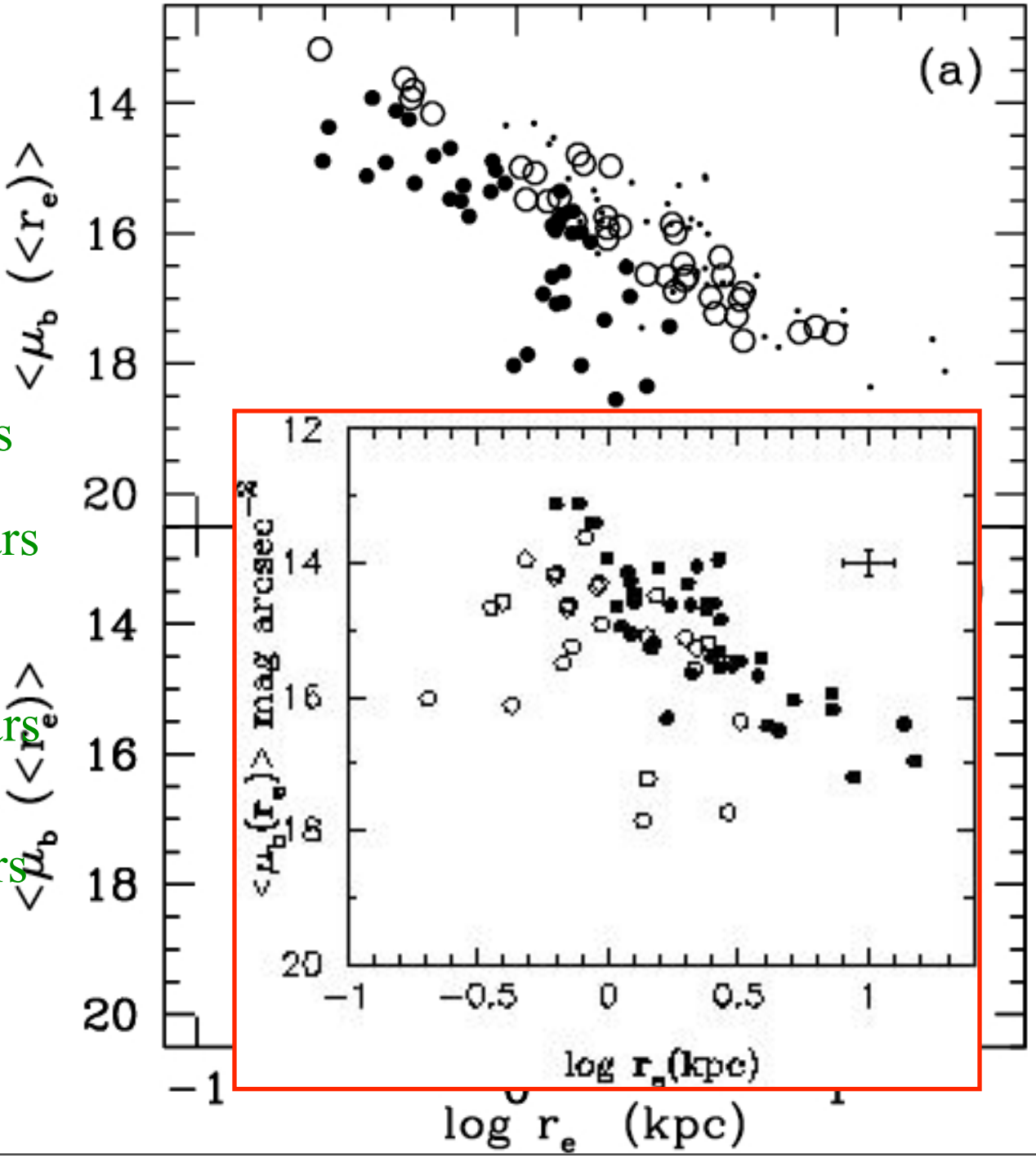
Kormendy Relation

- ● Faint lenticulars
- ○ Bright lenticulars
- • Ellipticals
- x Bright lenticulars with bars
- - Faint lenticulars with bars



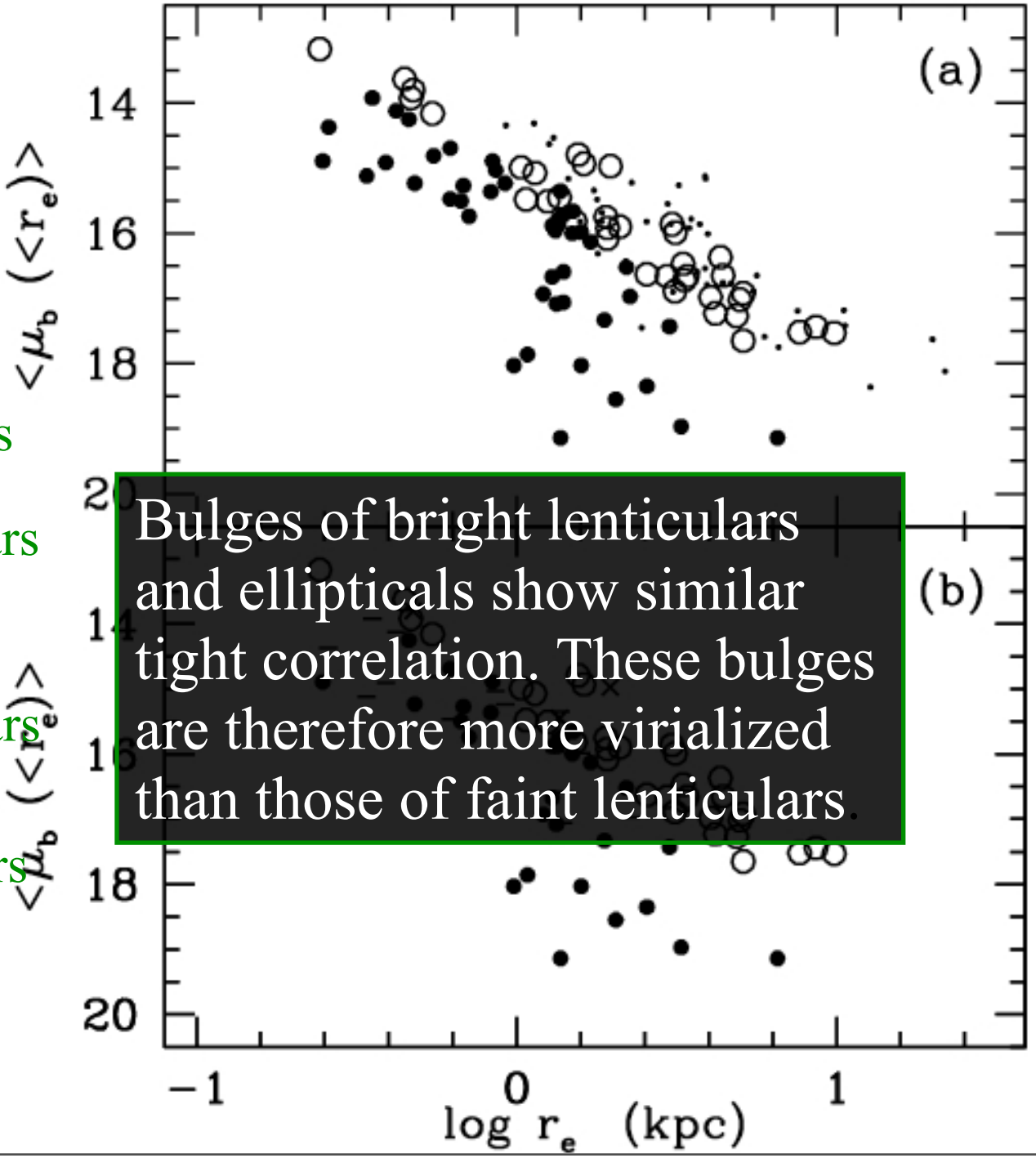
Kormendy Relation

- ● Faint lenticulars
- ○ Bright lenticulars
- • Ellipticals
- x Bright lenticulars with bars
- - Faint lenticulars with bars



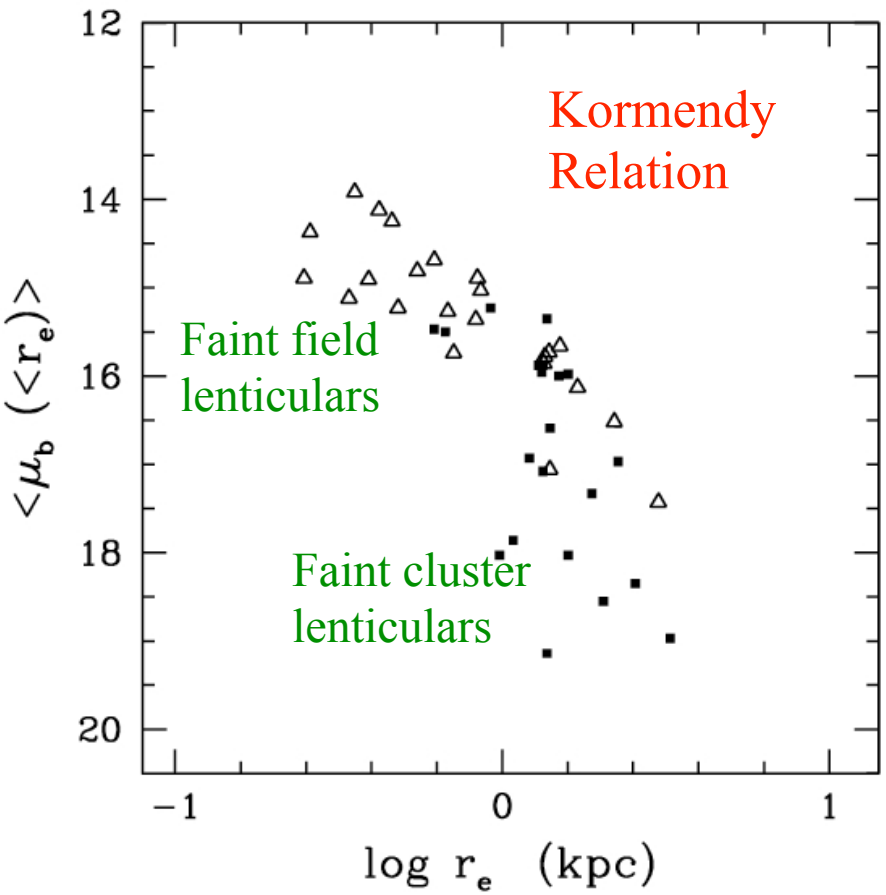
Kormendy Relation

- ● Faint lenticulars
- ○ Bright lenticulars
- • Ellipticals
- x Bright lenticulars with bars
- - Faint lenticulars with bars

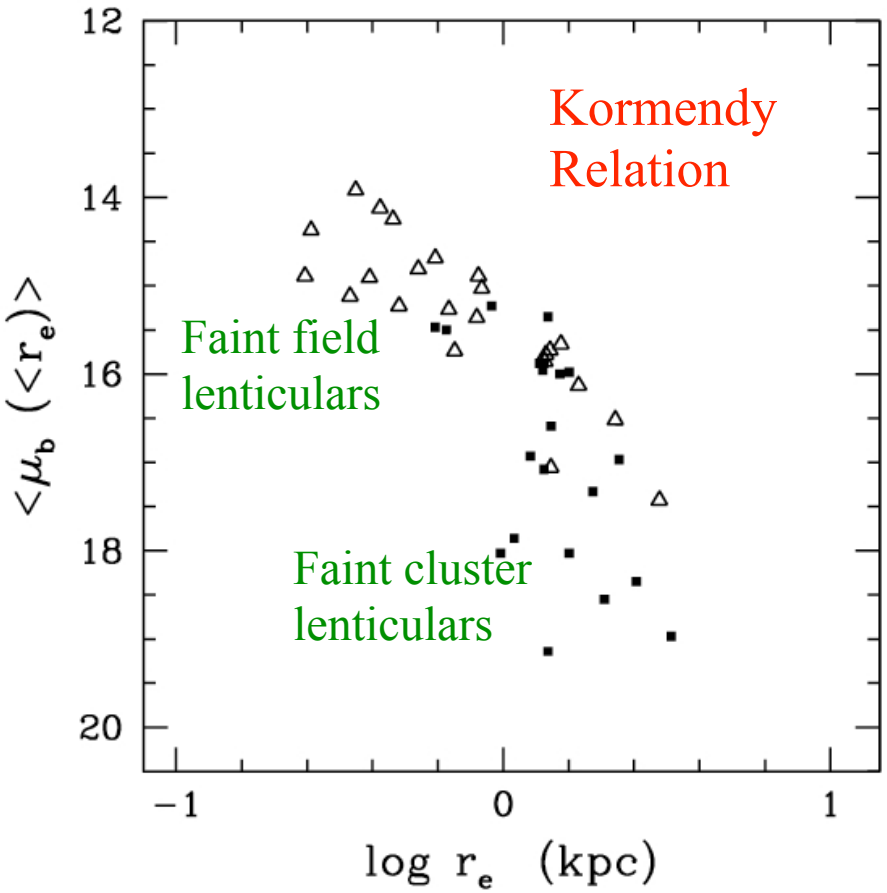


Bulges of bright lenticulars and ellipticals show similar tight correlation. These bulges are therefore more virialized than those of faint lenticulars.

Environmental Dependence

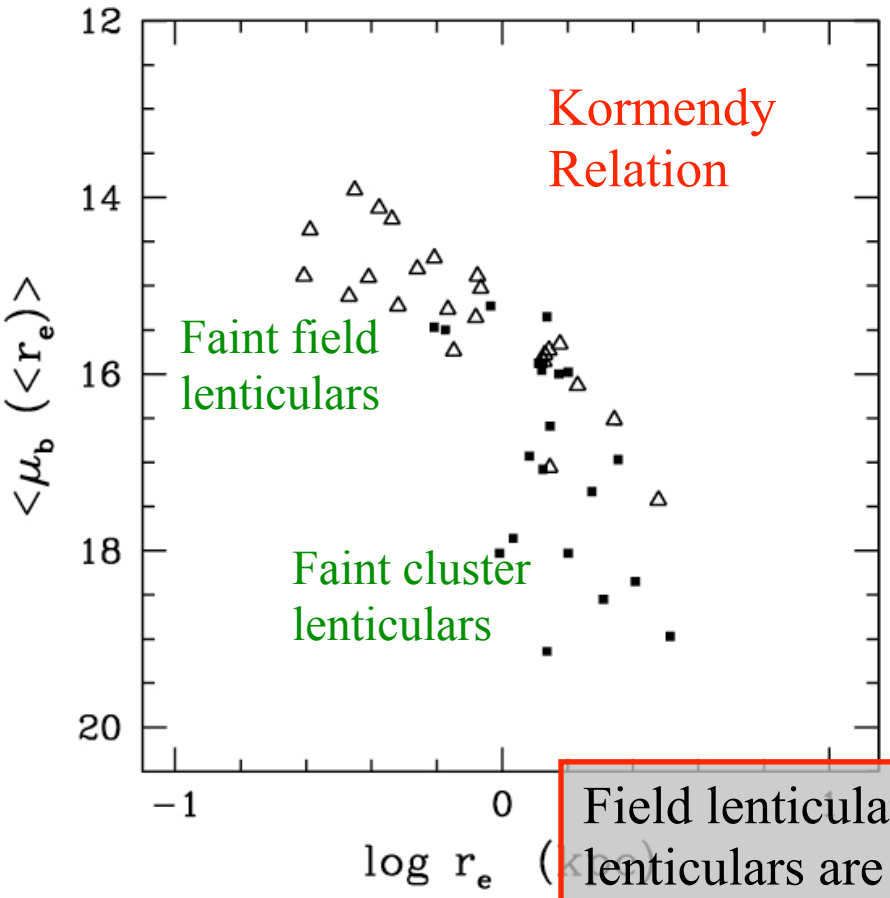


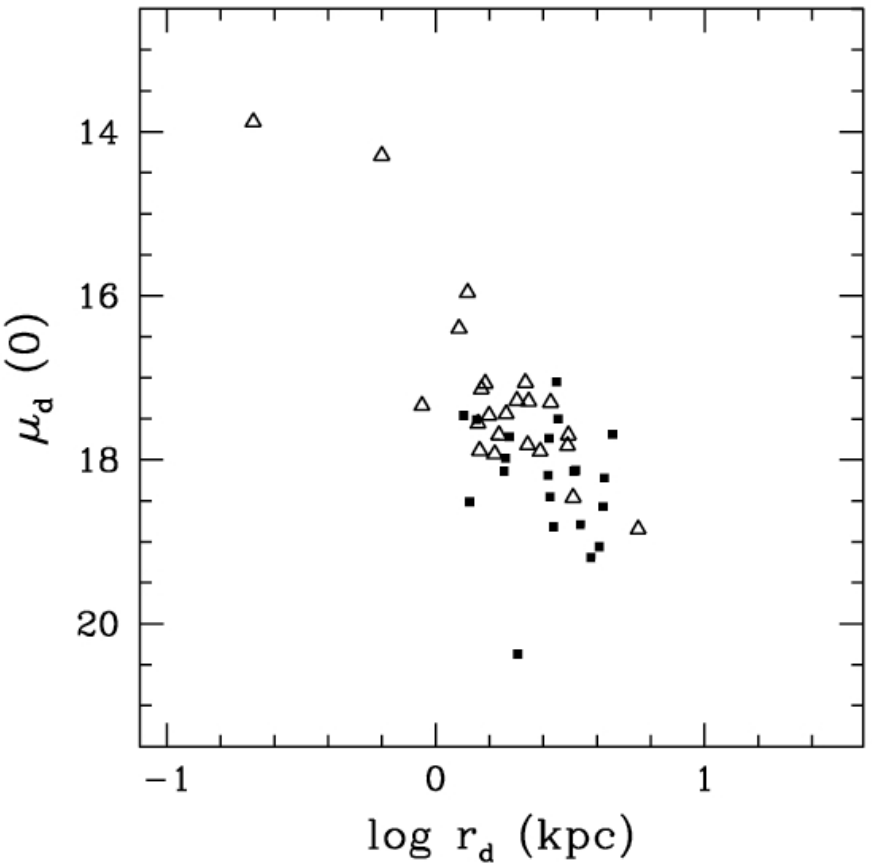
Environmental Dependence



Cluster lenticulars appear to have faded relative to field lenticulars. They could be early type spirals which have lost gas due to ram pressure stripping or galaxy harassment.

Environmental Dependence





Field lenticulars show clear anti-correlation. Cluster lenticulars are restricted to a limited region and show downward scatter. This is consistent with removal of gas from the disk (and bulge) in cluster lenticulars.