The transition from low-mass stars to planets

Chair: **G. BONO**

Galaxy bulges

Chair: **M. ZOCCALI**

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Pseudo-bulges, classical bulges and elliptical galaxies – I

A Tale of Two Bulges and One Misnomer

Dimitri Gadotti (ESO)

Initial Considerations

1. Bulges are complex; a difficult, quickly evolving subject

2. Semantics is (unfortunately) important; some people use the same word to describe different things; there is confusion in the literature, be sure about what authors really mean

3. There is still too much room for subjective judgment, so it's important to look at the physics and separate what data tell you from speculation

4. Previous important references:

    - IAU Symp. 153, Ghent, Belgium – '92
    - Wyse et al. ('97)
    - Kormendy & Kenniccutt ('04)
    - Athanassoula ('05)
    - IAU Symp. 245, Oxford, UK – '07

5. All we want is to understand how stellar systems form and evolve

Outline – Lecture One

1. Bulge definitions

2. Bulge types: classical, pseudo and box/peanuts

3. Identifying pseudo-bulges

    a. morphology
    b. the Sérsic index
    c. the Kormendy relation

4. Structural parameters and scaling relations (e.g. the fundamental plane)

5. The stellar mass budget at redshift zero

Outline – Lecture Two

6. Composite bulges

7. Host galaxies and environment

8. Elliptical galaxies and two dichotomies

    a. core-depleted vs. extra-light
    b. giants vs. dwarfs

9. Supermassive black holes and their scaling relations

10. Bulge formation models

11. Some thoughts on future research

Bulge Definitions

What is a bulge? It's not an easy question and, in fact, we still lack a definition for what is a galaxy (Forbes & Kroupa '11).

I. From morphology

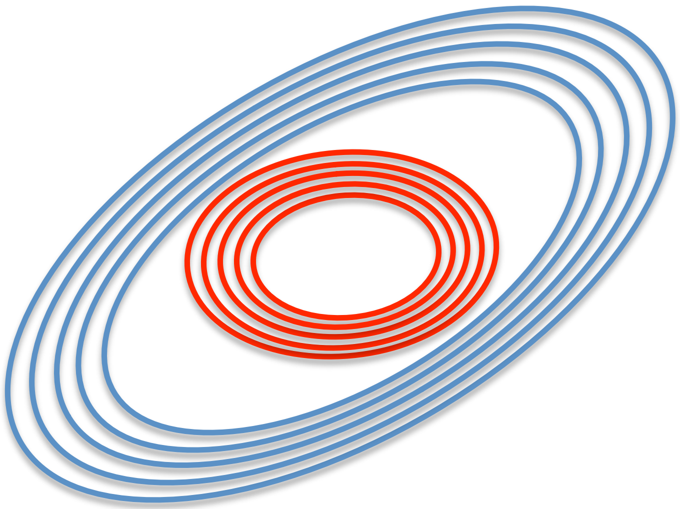
One of the criteria in the Hubble ('26) classification of disk galaxies:

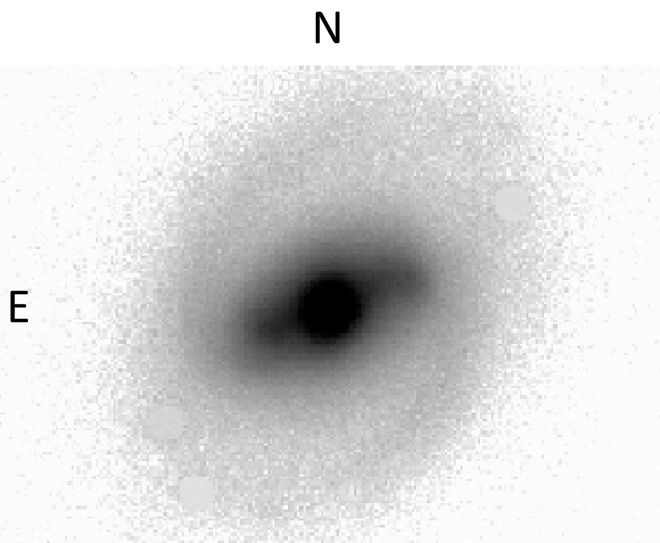
> "relative size of the unresolved nuclear region", elliptical-like, changes monotonically along the sequence

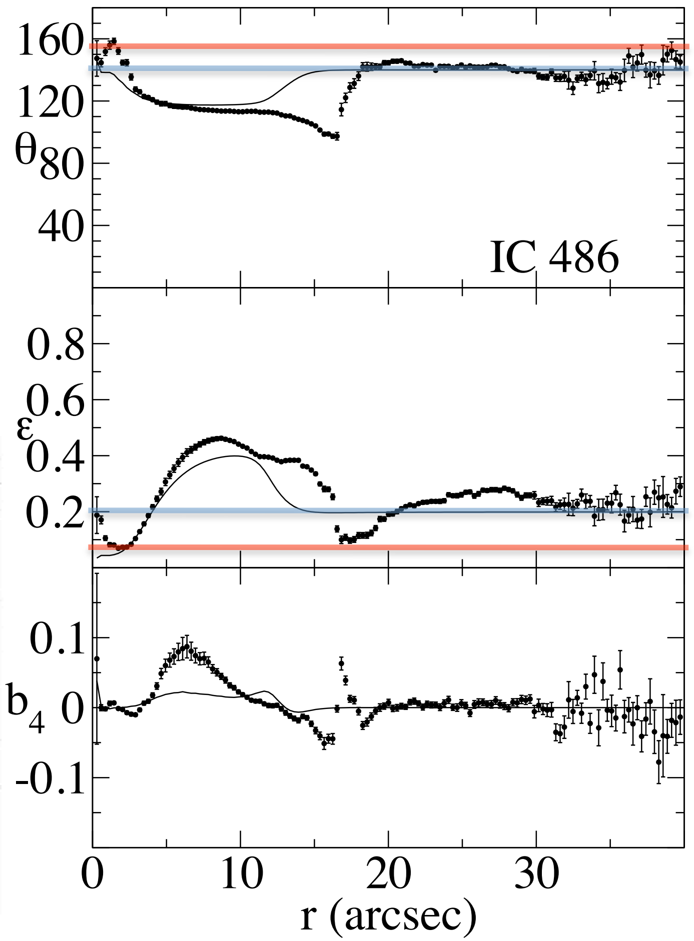
led to the concept that disk galaxies are like elliptical galaxies (the bulge) surrounded by disks.

Bulge Definitions

I. From morphology (isophotal maps; ellipse fits in IRAF – Jedrzejewski '87)







Gadotti '08

Bulge Definitions

I. From morphology

Pros:

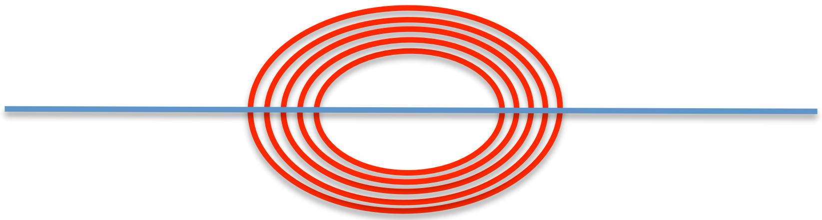
1. Physical

Cons:

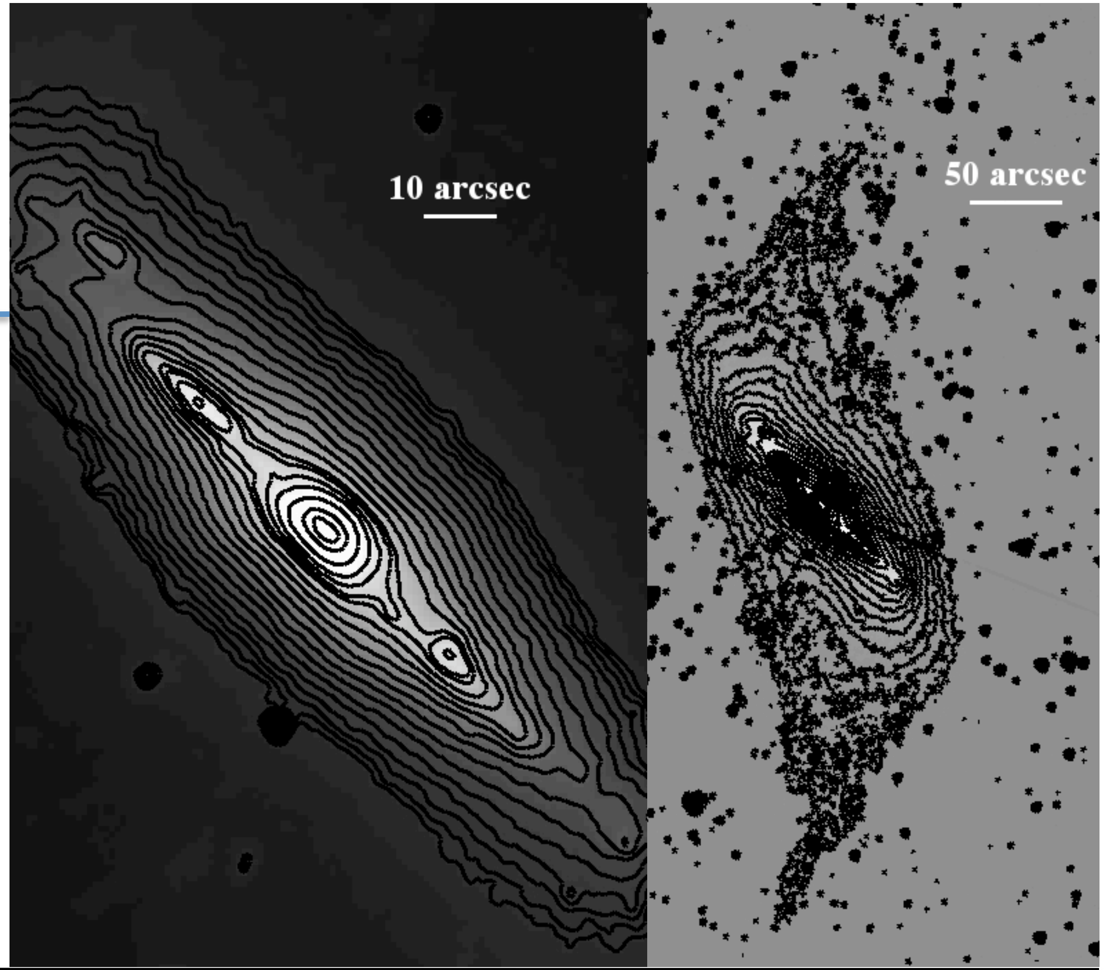
1. Somewhat subjective; arbitrary (how much difference in θ or ε is enough?)
2. “Bulge” can be a lot of different things

Bulge Definitions

II. From geometry (everything above the disk plane)



thick disk?



Gadotti et al., in prep. – Spitzer 3.6μm S^4G image of NGC 660

Bulge Definitions

II. From geometry

Pros:

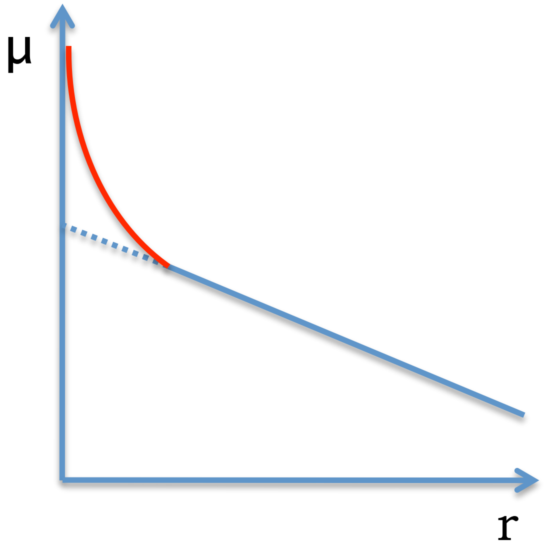
1. Easy, can be objective

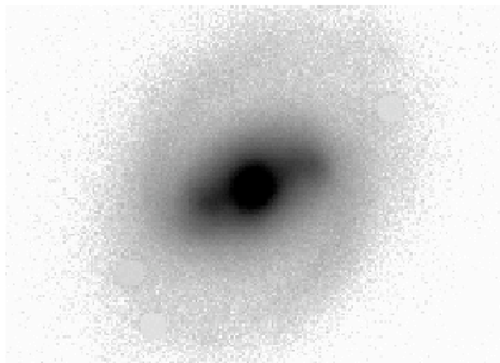
Cons:

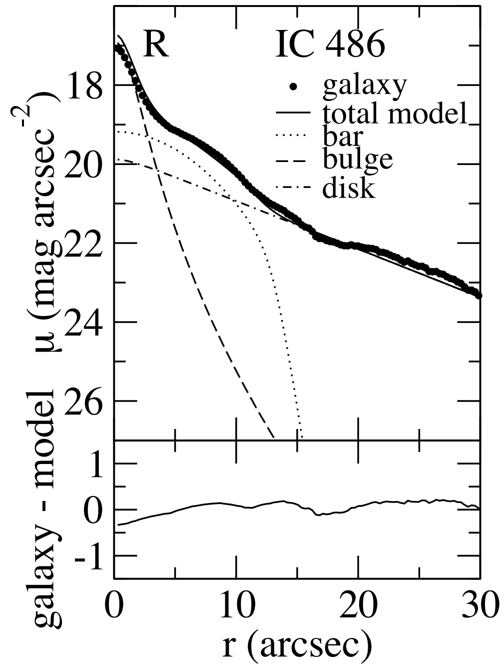
1. Only works for very inclined galaxies
2. Somewhat arbitrary
3. “Bulge” can be a lot of different things

Bulge Definitions

III. From photometry (excess above inner extrapolation of disk intensity radial profile)







disks seem to be well described with at least 1 exponential

Gadotti '08

Bulge Definitions

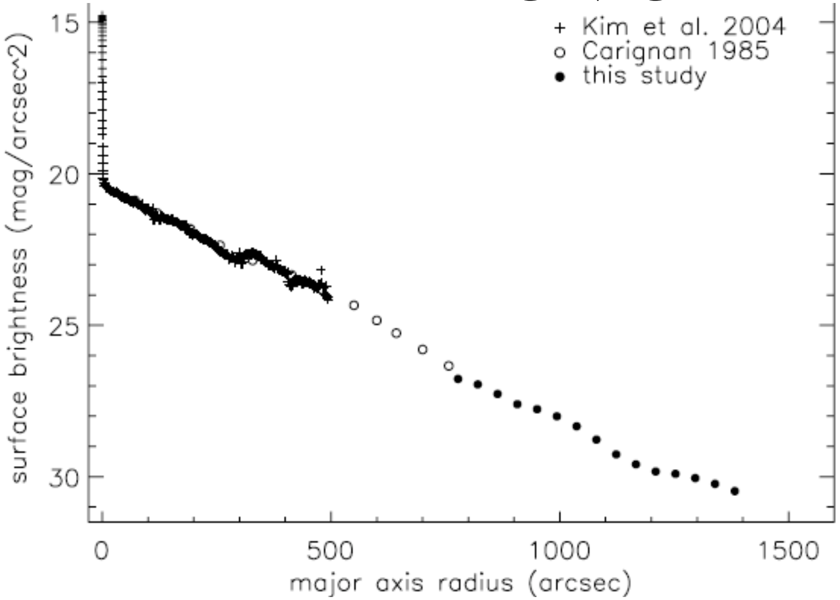
III. From photometry

Pros:

1. Objective, can be reproduced (most times)

Cons:

1. “Bulge” can be a lot of different things (e.g. nuclear cluster in NGC 300)



Bland-Hawthorn et al. ‘05

Bulge Definitions

Bulges seem to be everything but the disk!

Photometric definition is better suited most times, leading to the concept of ‘photometric bulge’, as a separate entity from the disk. Further analysis might reveal what the photometric bulge is consisted of physically.

Bulge Types

I. Classical bulges

- stick out of disk plane, i.e. not as flat as the disk (when seen at sufficient inclinations)
- more or less spheroidal (hard to see at low inclinations)
- featureless (no spiral arms, bars, rings…)
- mostly old stars (no much dust or star-forming regions)
- kinematically hot, i.e. dynamically supported by stellar velocity dispersion σ

- seem to be built mostly by mergers (accretion of usually smaller exterior units), in violent events, inducing fast bursts of star formation if gas is available

Bulge Types

I. Classical bulges: e.g. M81 [NASA, ESA and the Hubble Heritage Team (STScI/AURA)]

Bulge Types

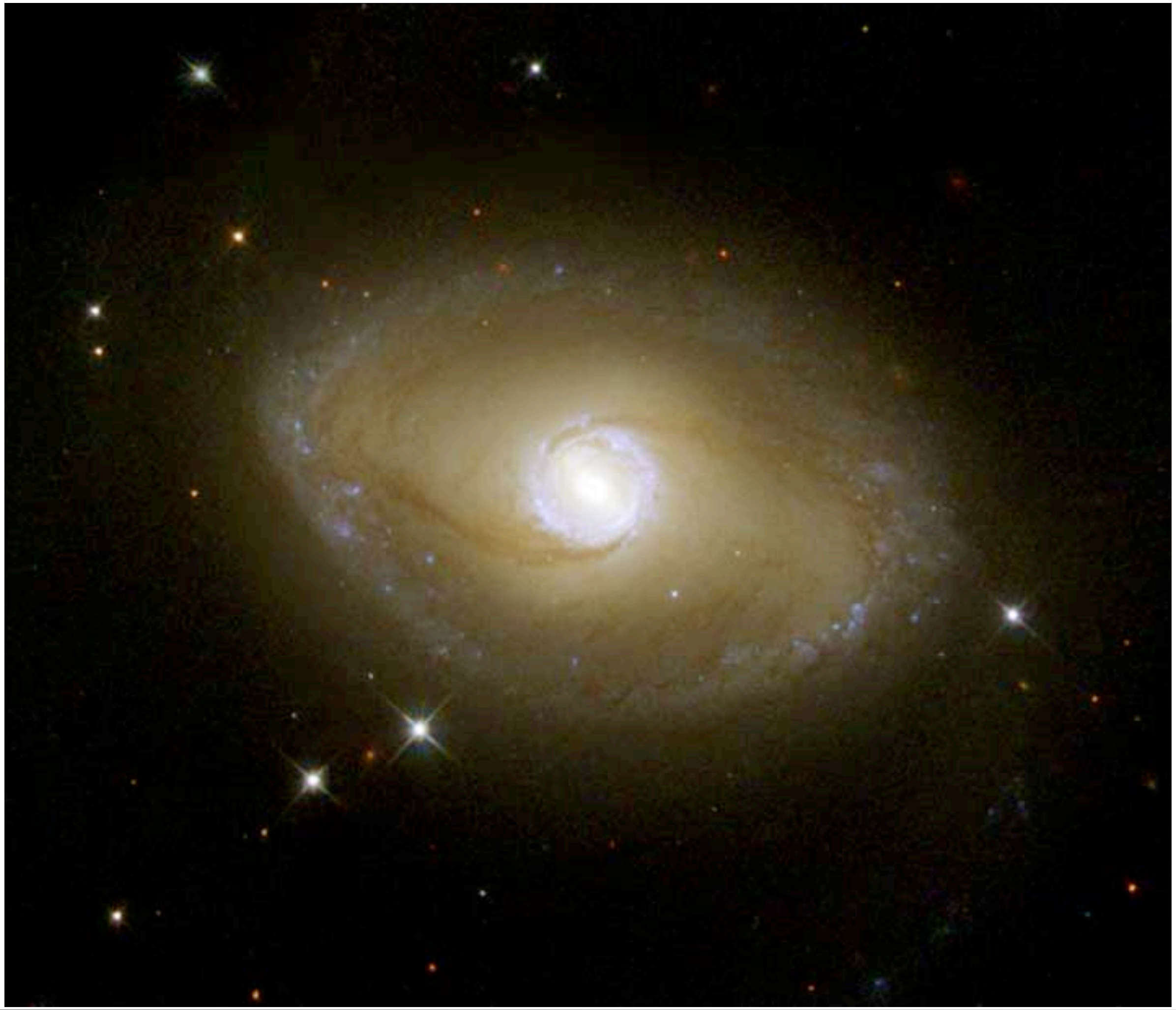
II. Disk-like bulges (aka pseudo-bulges)

- as flat (or almost as flat) as the disk (not easy to see in very inclined galaxies)
- may contain sub-structures such as nuclear bars, spiral arms, rings…
- usually show signs of dust obscuration, young stellar populations or ongoing star formation
- kinematically cold, i.e. dynamically supported by rotation of its stars V_{rot}

- seem to be built mostly via disk instabilities (mainly bars but also possibly spiral arms and ovals) in a relatively continuous, smooth process

Bulge Types

II. Disk-like bulges (aka pseudo-bulges): e.g. NGC 6782 [NASA, ESA and the Hubble Heritage Team (STScI/AURA)]



Bulge Types

III. Box/Peanut bulges (aka pseudo-bulges)

- stick out of the disk plane (not easy to see at low inclinations)
- show a boxy or peanut-like morphology
- usually featureless (no sub-structures, such as spiral arms, bars or rings)
- usually does not show signs of dust obscuration, young stellar populations or star-forming regions
- kinematically cold, i.e. dynamically supported by rotation of its stars V_{rot}

- are not bulges but the inner parts of bars

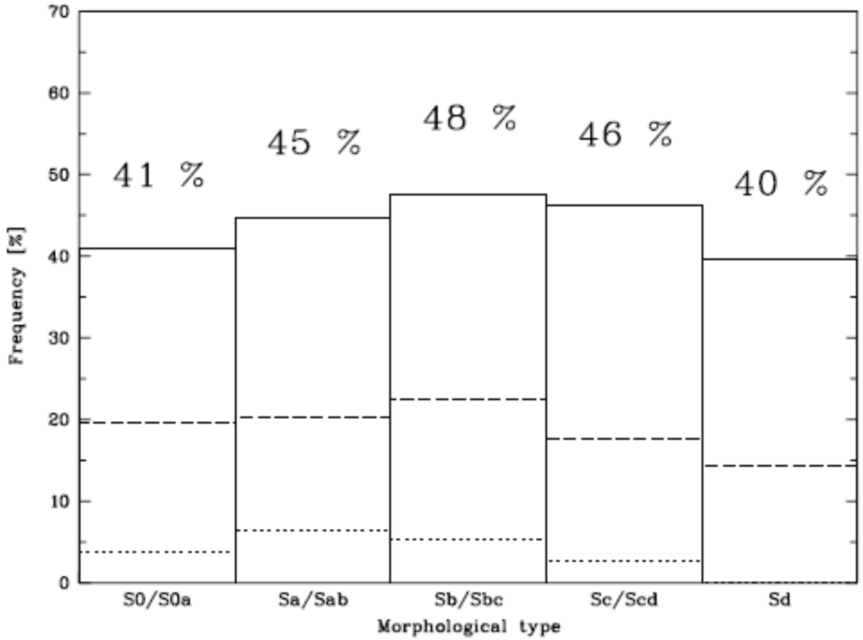
Bulge Types

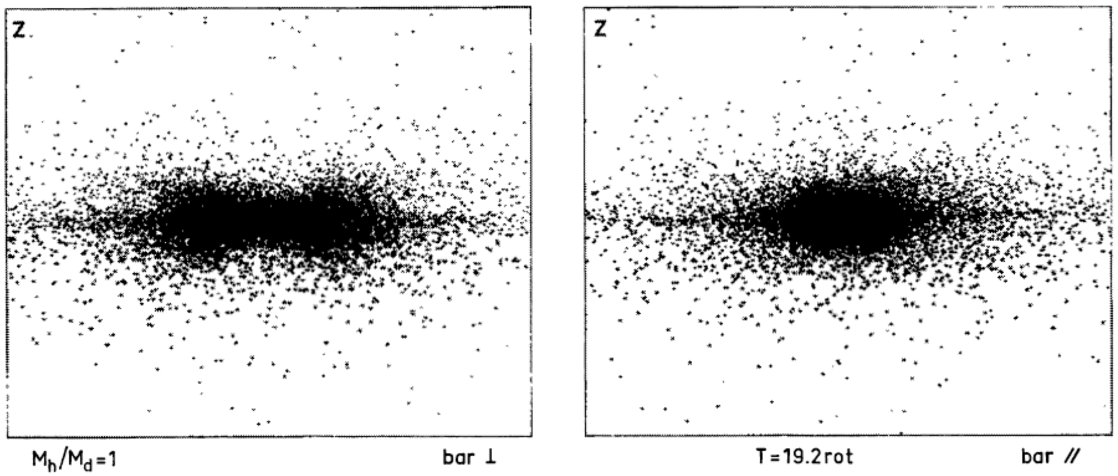
III. Box/Peanut bulges (aka pseudo-bulges): e.g. ESO 597-G 036 [NASA, ESA and the Hubble Heritage Team (STScI/AURA)]

B/Ps and Bars

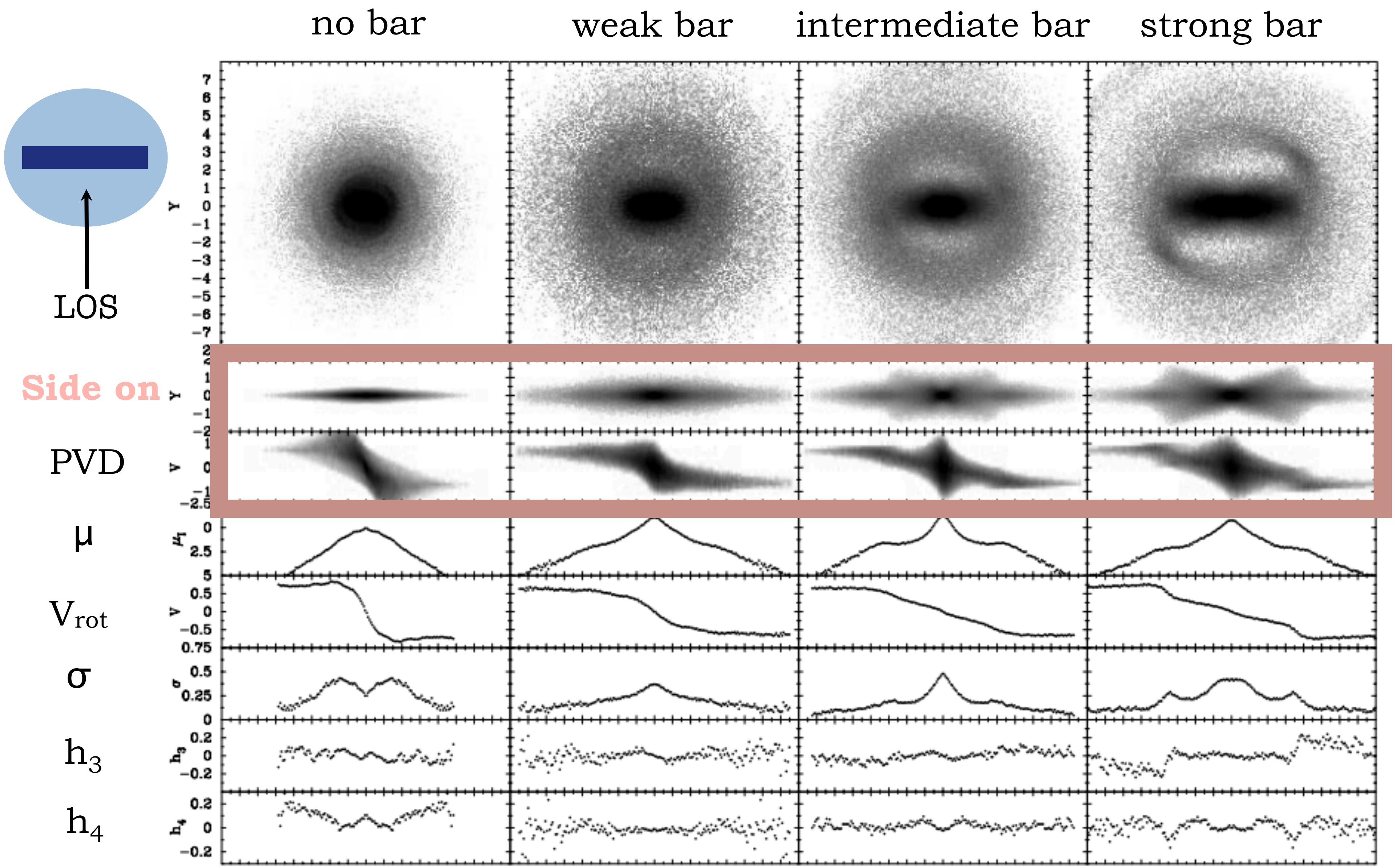
Suggestive evidence that box/peanuts are associated with bars, from statistical considerations, go at least as far as the 80's (e.g. de Souza & dos Anjos '87; see also Luetticke et al. '00). Distribution of bps in morphological types in edge-on galaxies is similar to the corresponding distribution of strong bars in face-on galaxies.

Bars seen edge-on in N-body simulations were known to show bp structure from dynamical processes (e.g. Combes & Sanders '81).

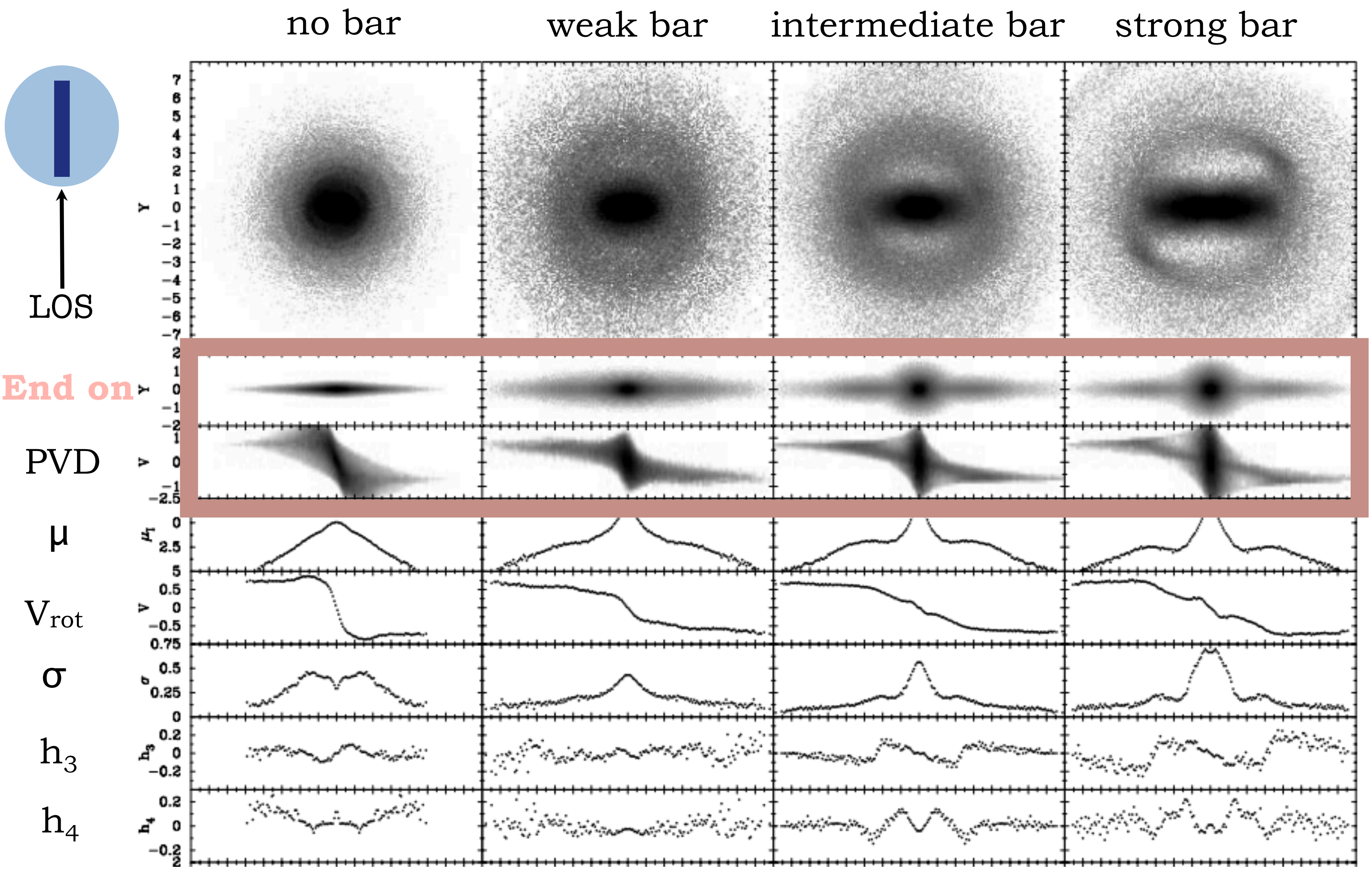




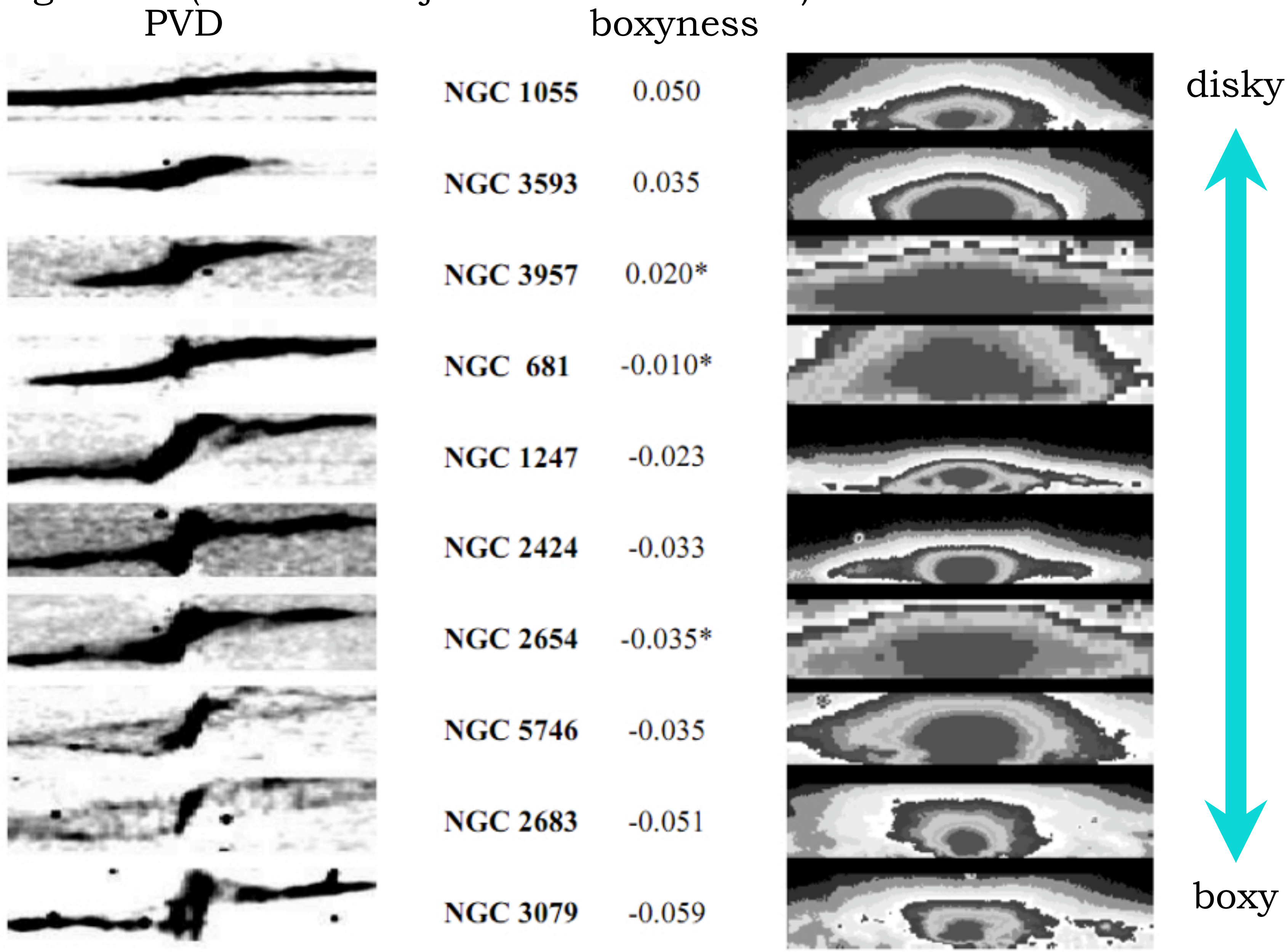
Bureau & Athanassoula ’05: state-of-the-art N-body simulations reveal bar signatures that can be tested with observations of galaxies showing bp.



Bureau & Athanassoula '05: state-of-the-art N-body simulations reveal bar signatures that can be tested with observations of galaxies showing bp.

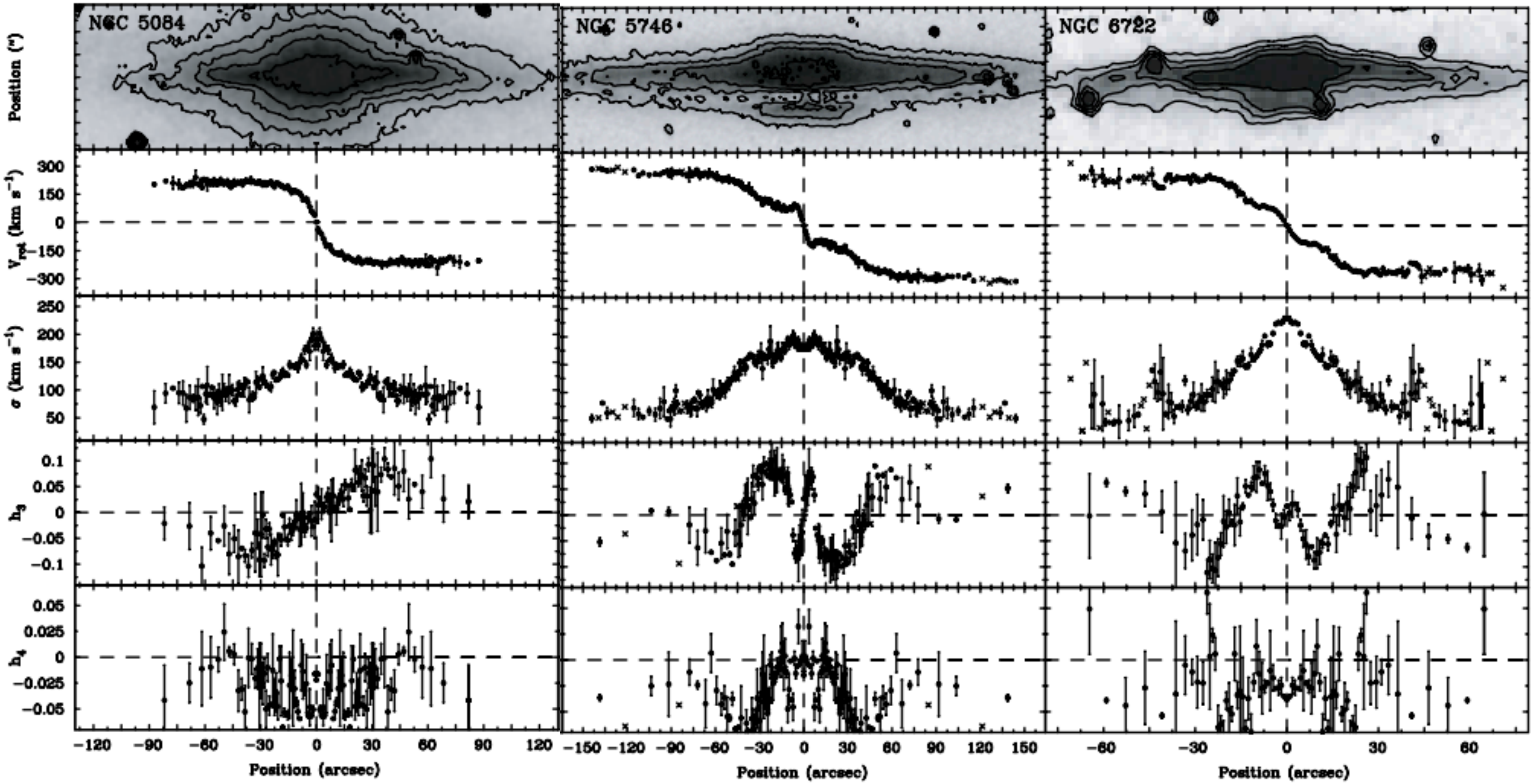


Merrifield et al. '99: use (gas) [NII] 6584Å emission to find evidence for the connection between bps and bars. Position-velocity diagrams of bps show clear bar signature (see also Kuijken & Merrifield '95).



B/Ps and Bars

Chung & Bureau '04 use stellar kinematics and find further evidence.



B/Ps and Bars

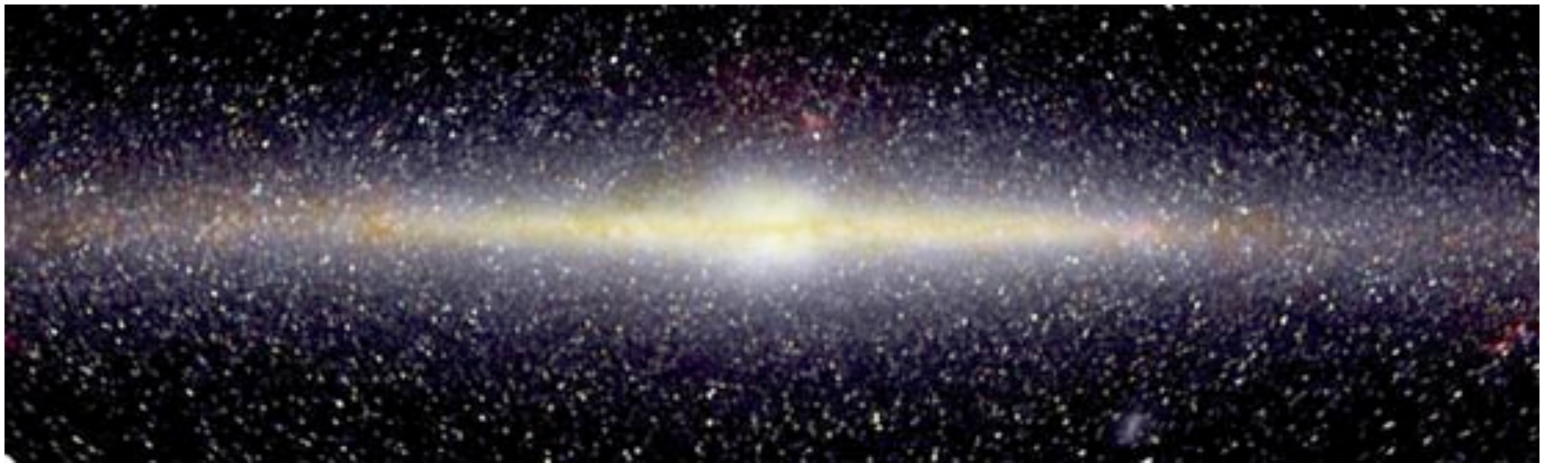
Box/Peanuts are the inner parts of bars, vertically thickened by dynamical processes.

Box/Peanuts are NOT bulges, in the sense that they are not a distinct physical component.

I am NOT going to talk about them here.

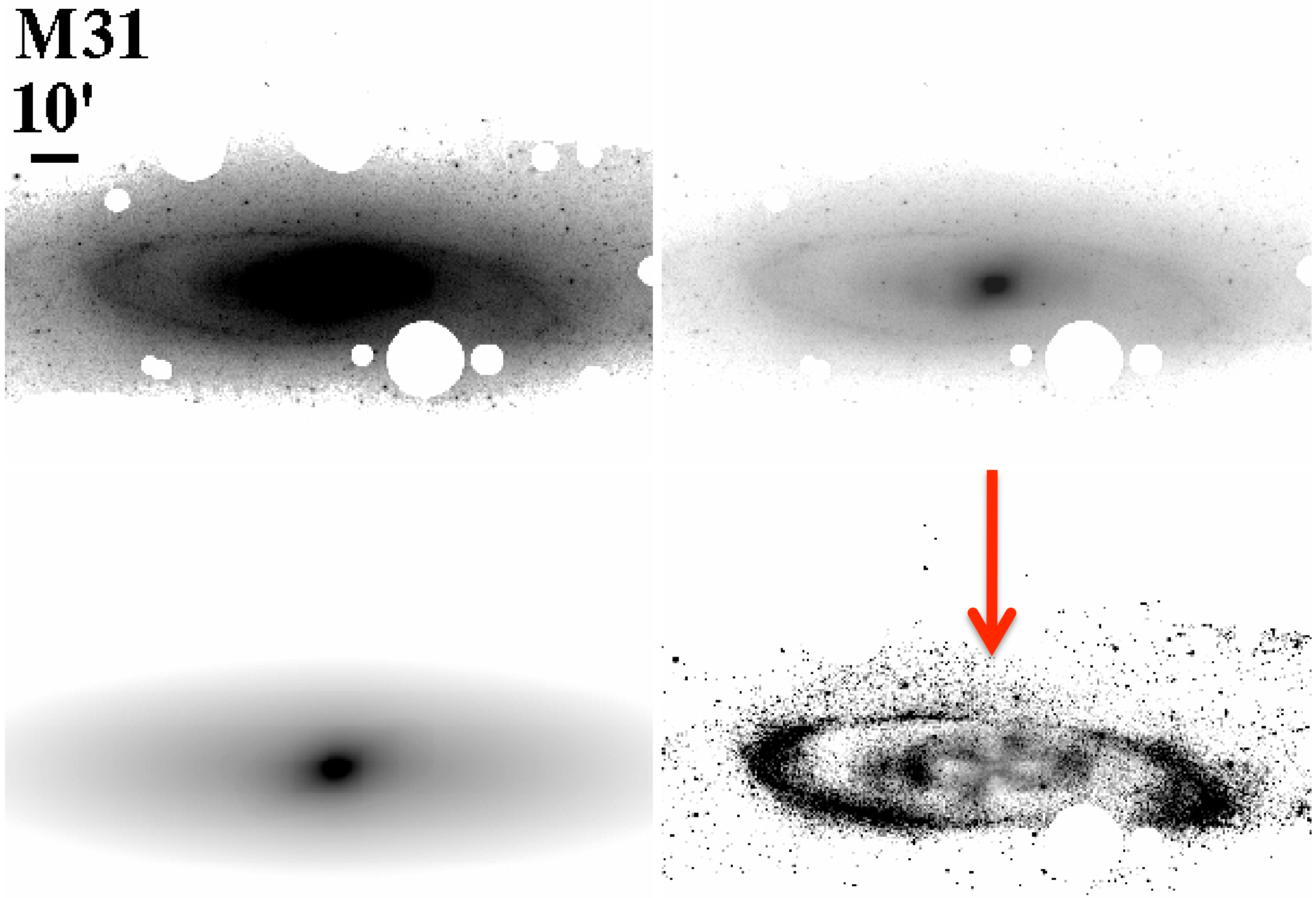
Milky Way "bulge" is known to show bp morphology since the 90's, with COBE.

The COBE Project, DIRBE, NASA



B/Ps and Bars

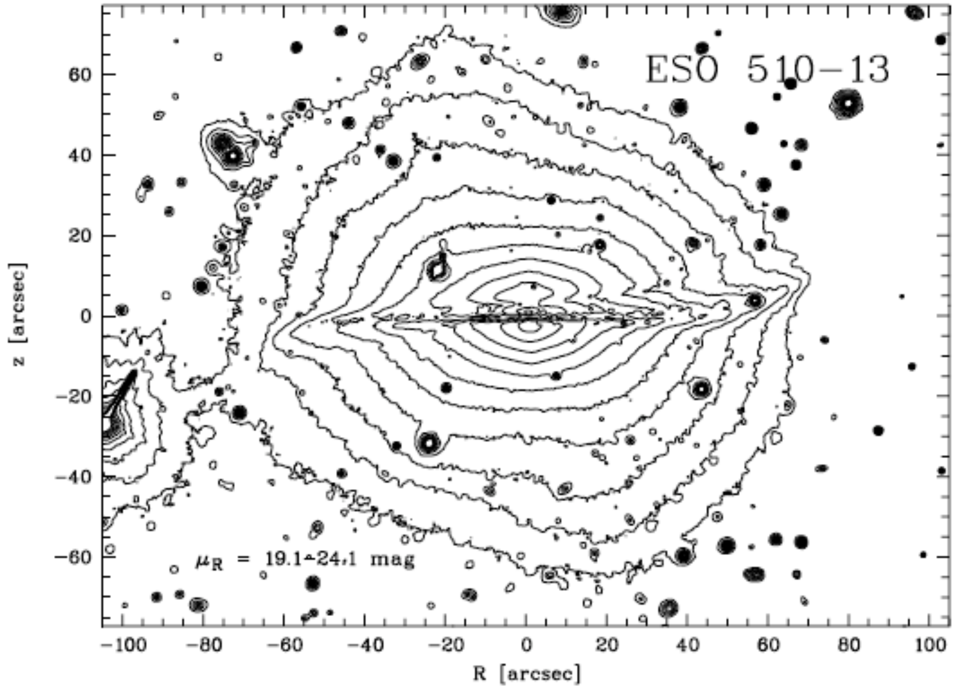
M31 is a remarkable case (see e.g. Athanassoula & Beaton '06). Erwin & Gadotti (in prep.) show a BUDDA (de Souza et al. '04; Gadotti '08) decomposition of M31, using a Spitzer 3.6μm image. The X-shape, clear signature of the bp, is evident in the residual image.



B/Ps and Bars

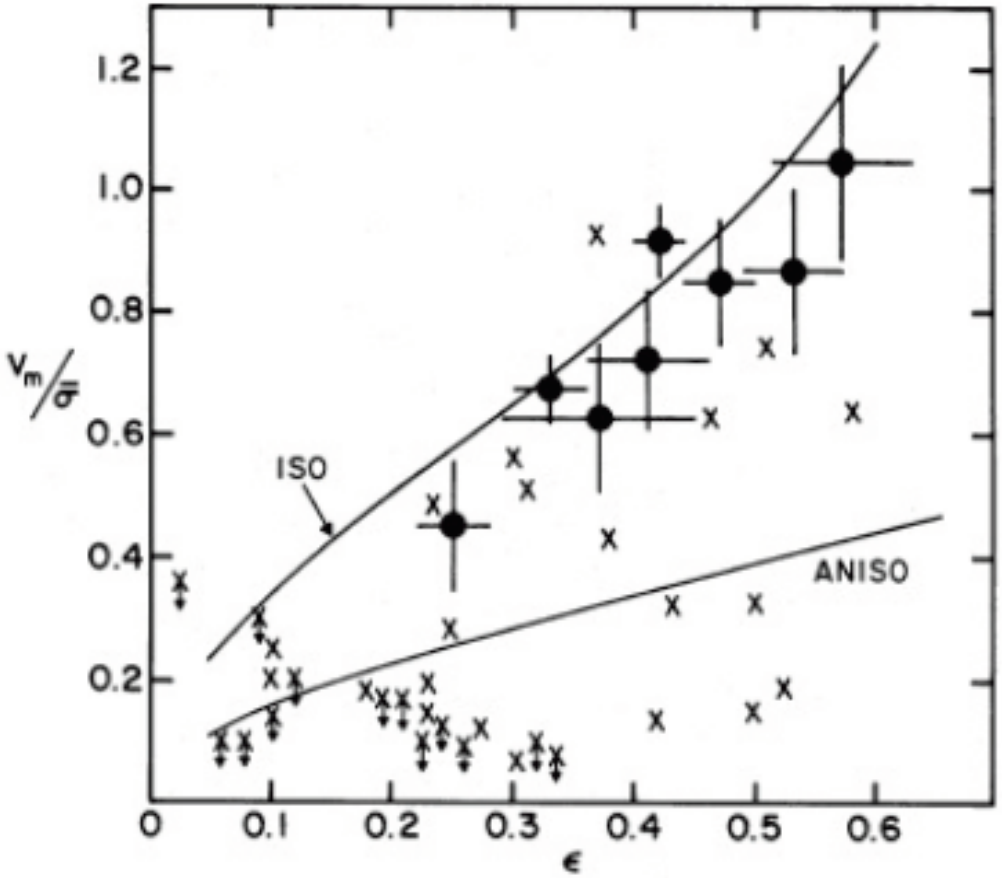
A caveat: some bulges with boxy morphology might be in fact classical bulges built by mergers (see Luetticke et al. '04).

NASA, ESA and the Hubble Heritage Team (STScI/AURA)



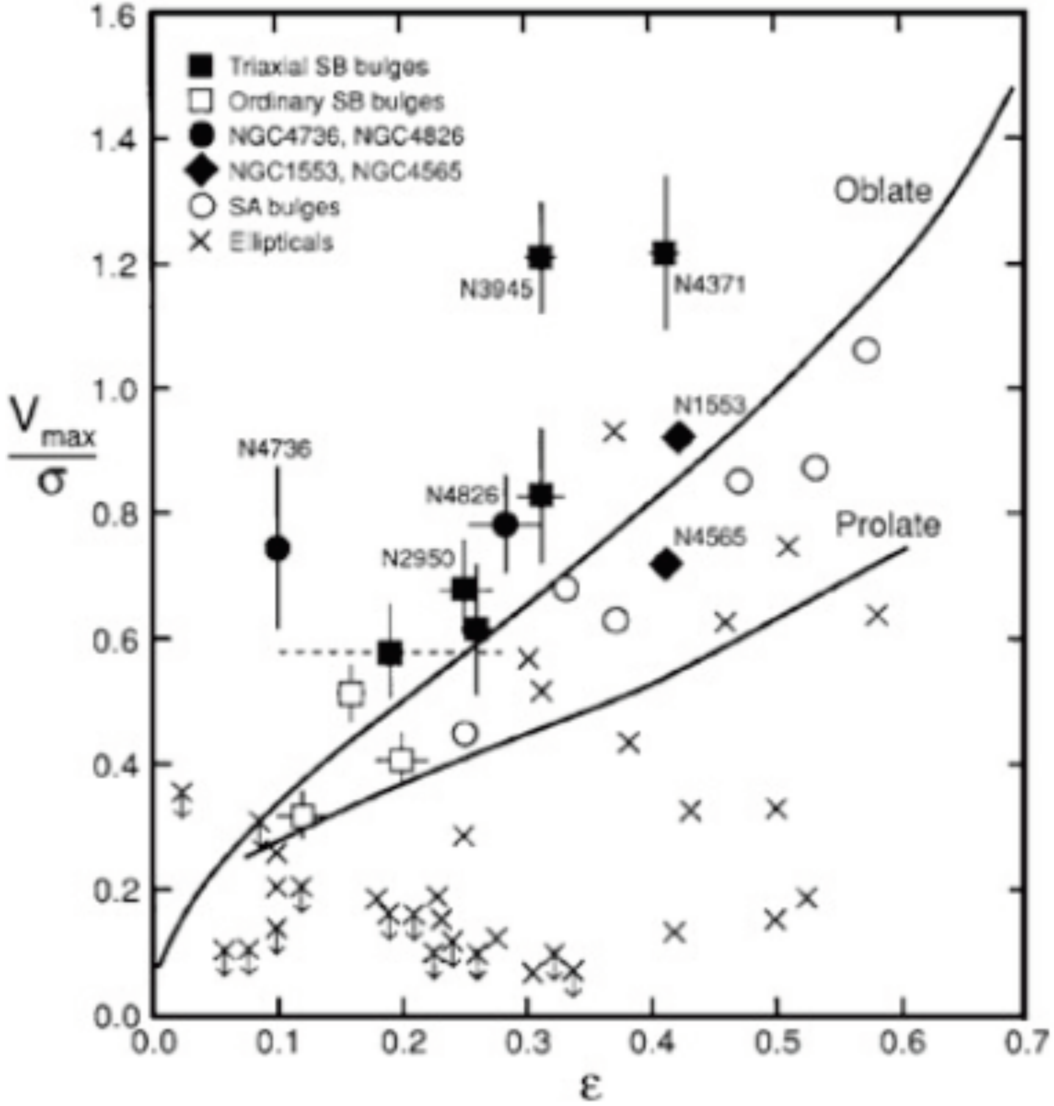
The Dynamical Support of Bulges

Kormendy & Illingworth ‘82: bulges are isotropic, oblate rotators, unlike (massive) ellipticals. Some bulges appear to have dynamical support similar to ellipticals, but many (classical) bulges seem to have more rotational support.



The Dynamical Support of Bulges

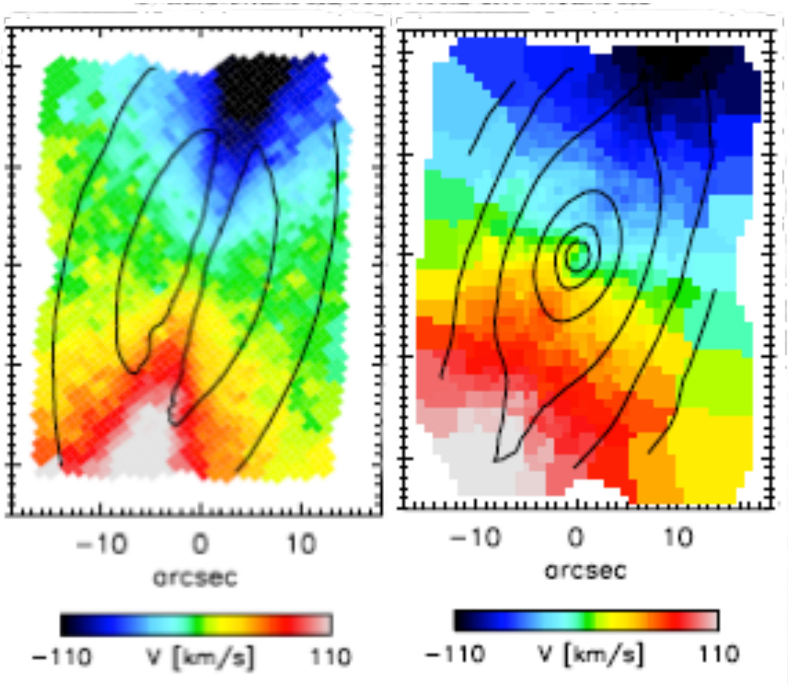
Kormendy '93: some bulges are really disks! Some of these are box/peanuts. They are more rotationally supported than pressure supported.



The Dynamical Support of Bulges

More recently, the SAURON team (e.g. Emsellem et al. '04; Falcon-Barroso et al. '06; Ganda et al. '06) obtained 2D kinematical data and found examples of usual bulge rotation, as well as cylindrical rotation in bars.

usual rotation



cylindrical rotation

Identifying Disk-like Bulges

1. From morphology, i.e. looking for signatures of sub-structures, such as inner bars, spiral arms or rings, or dust obscuration or star formation regions. A vertically thin bulge can also be a disk-like bulge. This is of course subjective (see e.g. Fisher & Drory '10).

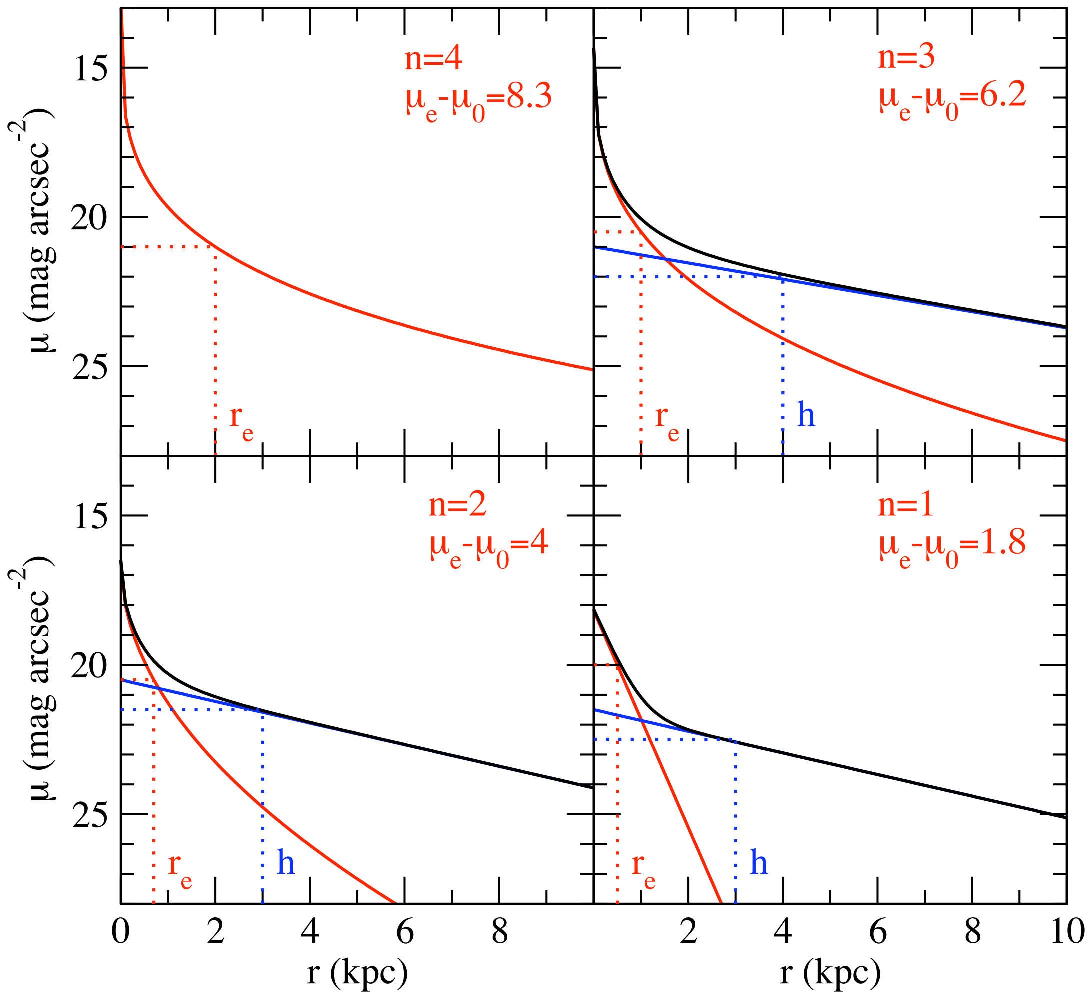
2. From the Sérsic index. There is evidence that disk-like bulges, as disks, have intensity radial profiles well described by an exponential function, which translates to a Sérsic index n = 1. The Sérsic function is:

$$\mu_b(r) = \mu_e + c_n[(r/r_e)^{1/n} - 1]$$

   where μ_e is the effective surface brightness, c_n depends on n, r_e is the effective radius, and n is the Sérsic index. Thus, Fisher & Drory ('08), among others, use a threshold at $n < 2$ to define such bulges as pseudo-bulges. It is not well understood physically why it should be so. Also, the uncertainty in n is typically about 0.5 (see Gadotti '08; '09), which can lead to many misclassifications.

Identifying Disk-like Bulges

Usually, elliptical galaxies have higher values of n (n = 4 is the famous de Vaucouleurs '48 profile). Bulge parameters can be obtained via decomposition.

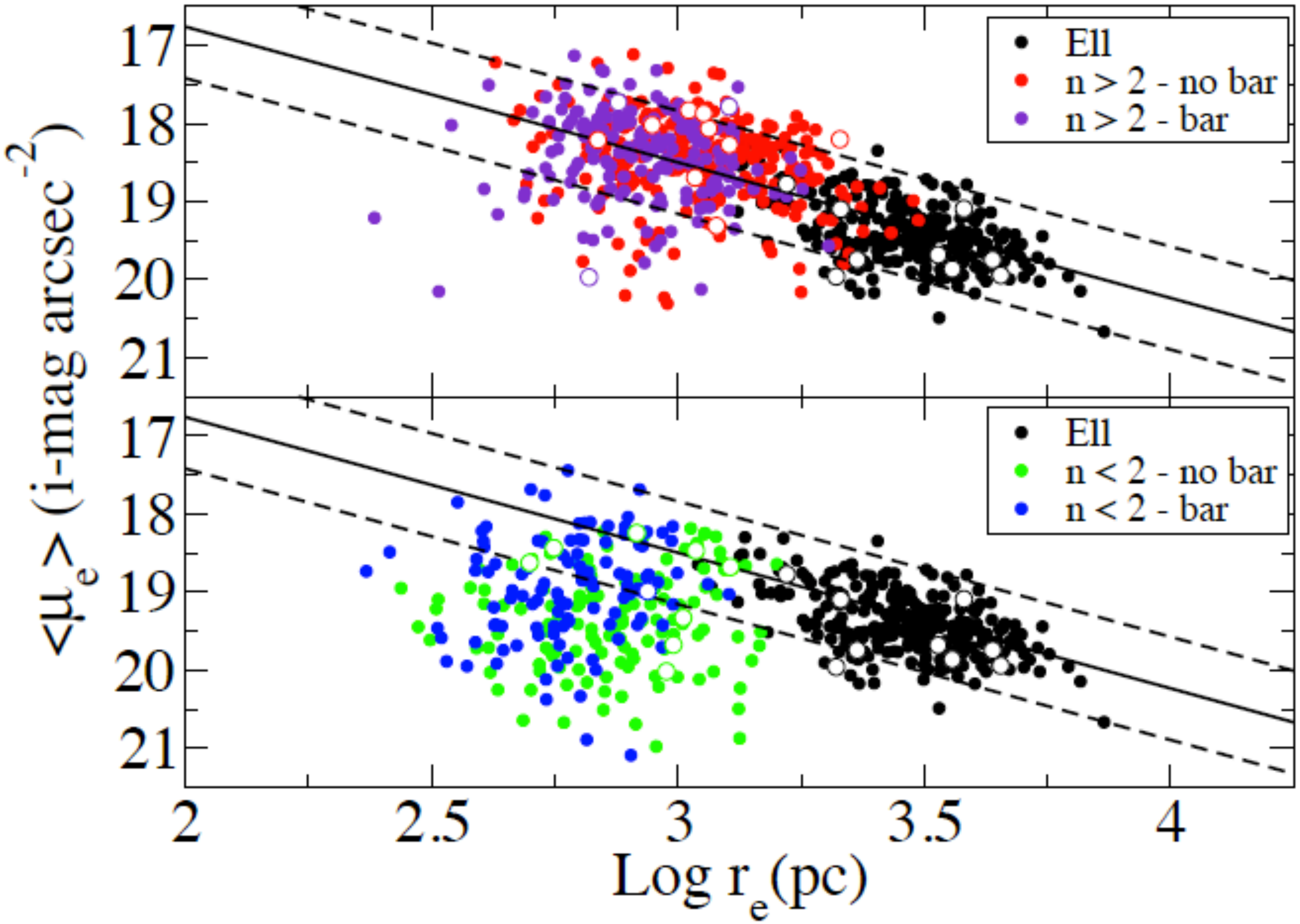


classical

disk-like

Identifying Disk-like Bulges

3. From the Kormendy ('77) relation, a projection of the fundamental plane followed by ellipticals. Disk-like bulges can be identified as outliers (Gadotti '09). This is more physically motivated.



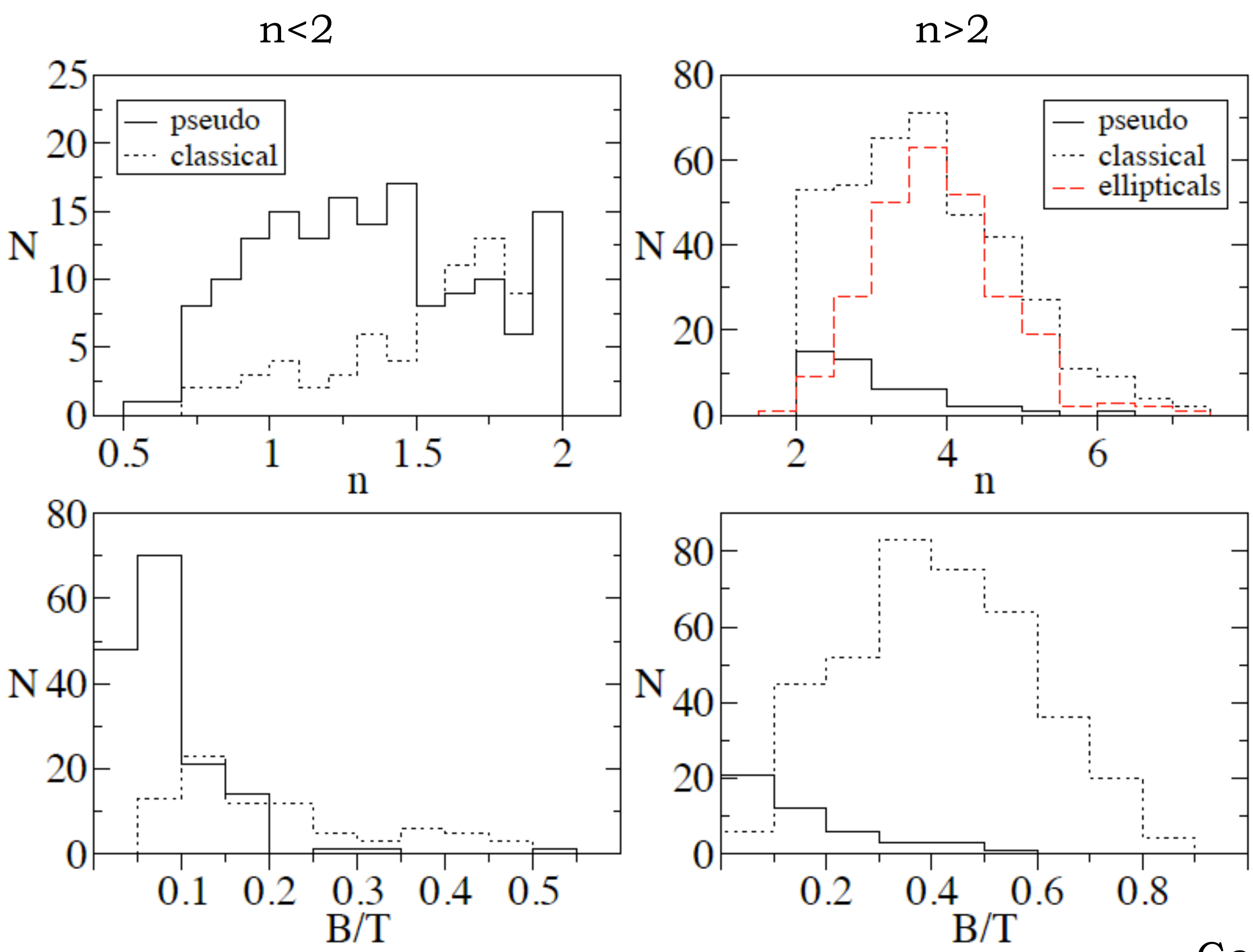
Identifying Disk-like Bulges

3. From the Kormendy ('77) relation, a projection of the fundamental plane followed by ellipticals. Disk-like bulges can be identified as outliers (Gadotti '09). This is more physically motivated.

Disk-like bulges satisfy (SDSS i-band):

$$\langle \mu_e \rangle > 13.95 + 1.74 \times \log r_e$$

Identifying Disk-like Bulges

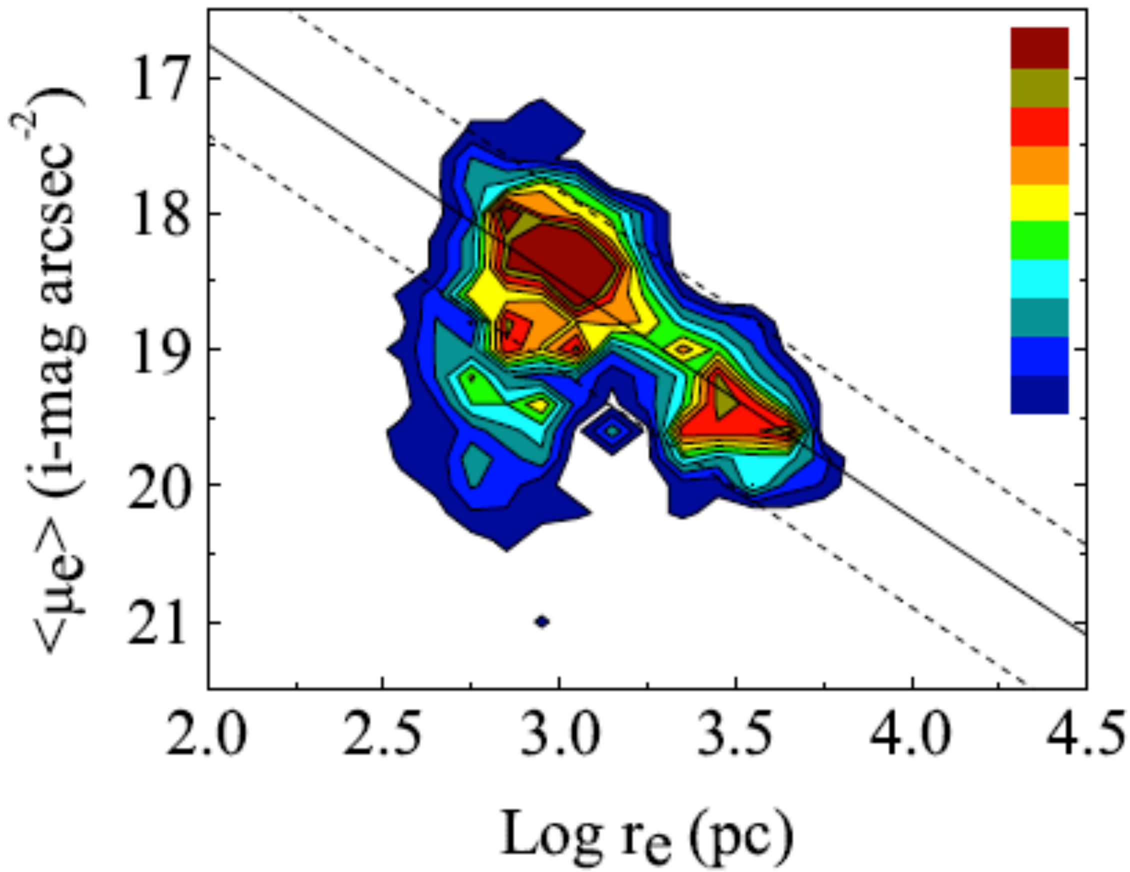


Gadotti '09

Identifying Disk-like Bulges

Disk-like bulges, classical bulges and elliptical galaxies are clearly isolated in this diagram, indicating that the separation is not artificial, but has solid physical grounds.

A section with composite bulges can also be seen between classical and disk-like bulges.



Gadotti '09

Identifying Disk-like Bulges

A promising way to identify disk-like bulges is of course from kinematics, but more work is needed, and it is expensive in terms of telescope time.

The Fundamental Plane

From the Virial Theorem:

$$2\langle T\rangle = -\sum_{k=1}^{N}\langle \mathbf{F}_k \cdot \mathbf{r}_k\rangle$$

average kinetic energy   average potential energy

for any bound system of particles interacting by means of an inverse-square force, and with a number of non-trivial assumptions (see e.g. Zaritsky et al. '06),

$$\sigma^2 \propto GM_e/r_e$$

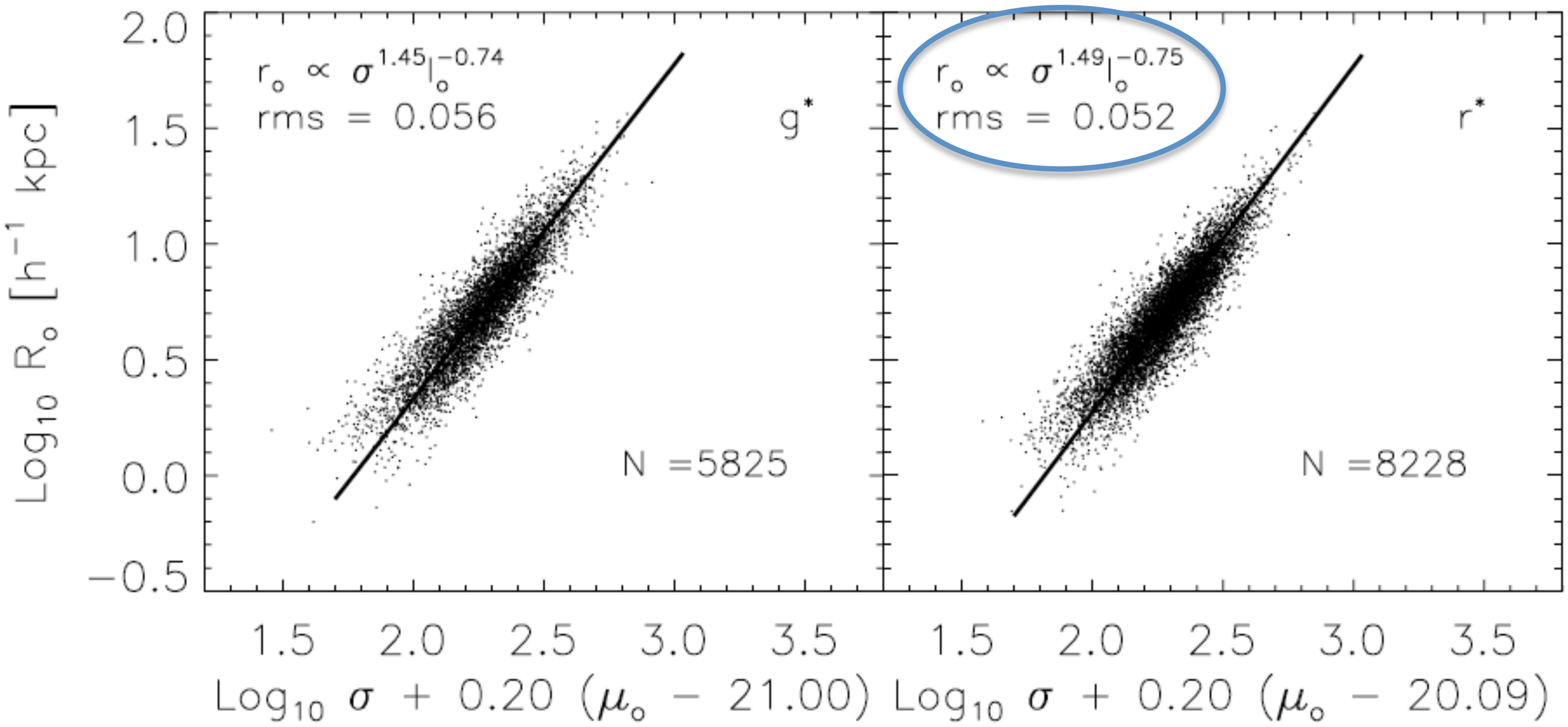
or

$$\sigma^2 \propto (M_e/L_e)(I_e r_e^2)/r_e$$

or

$$\log r_e = 2 \log \sigma - \log I_e - \log (M_e/L_e) + C$$

And this is what we observe for early-type galaxies (Bernardi et al. '03):



The difference between the expected and observed coefficients is called the tilt of the FP.

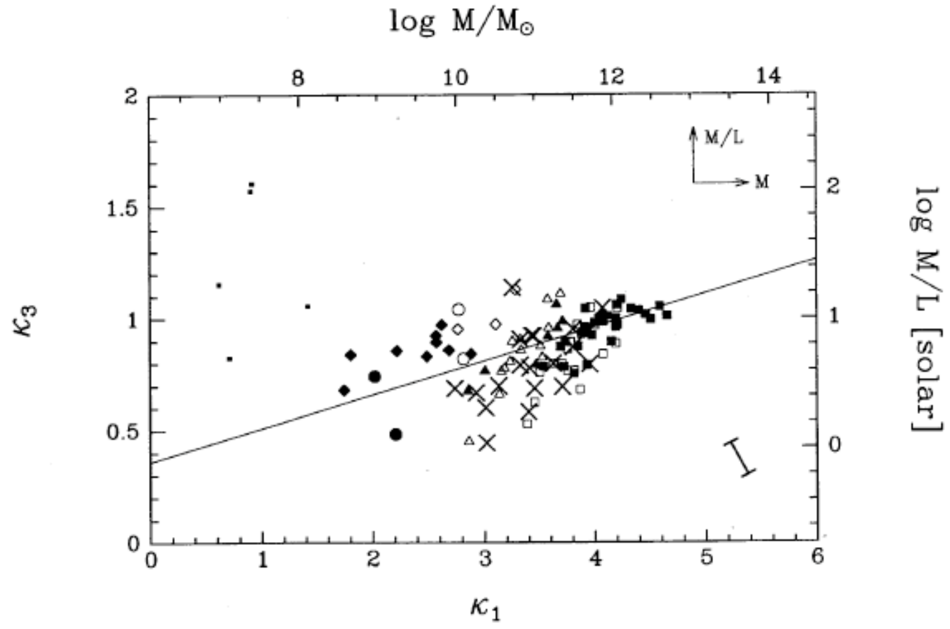
Why is there a tilt (see e.g. Trujillo et al. ‘03)?

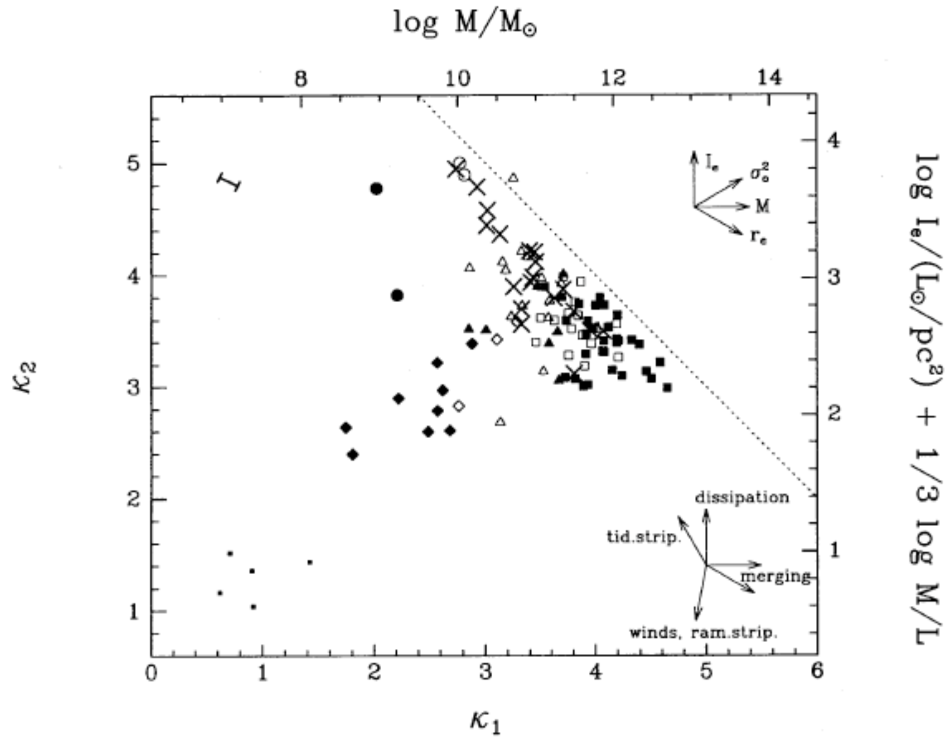
- mostly: systems are not homologous, i.e. the shape of the potential might depend on scale, system size (indeed, the Sersic index varies with galaxy luminosity)

- but also: variations in mass-to-light ratio (also as a function of luminosity)

The FP can also be formulated as (Bender et al. '92):

$$\kappa_1 \equiv (\log \sigma_0^2 + \log r_e)/\sqrt{2} \,,$$
$$\kappa_2 \equiv (\log \sigma_0^2 + 2 \log I_e - \log r_e)/\sqrt{6} \,,$$
$$\kappa_3 \equiv (\log \sigma_0^2 - \log I_e - \log r_e)/\sqrt{3} \,.$$



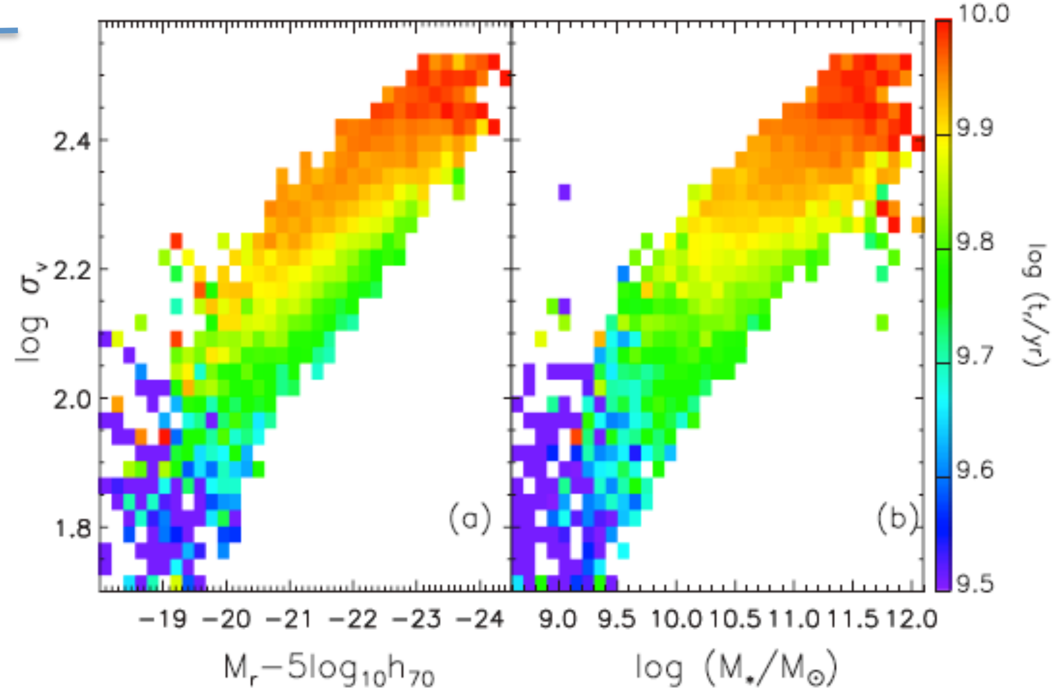


Projections of the FP are also important relations.

1. The Faber-Jackson ('76) relation: $L \propto \sigma^{\gamma}$

   where γ should be 4 (from its derivation), but is observed to be ~ 8 for early-type galaxies (Gallazzi et al. '06).

curvature, or a variation in slope with magnitude can indicate different formation histories – more dissipation for fainter galaxies
(see e.g. Desroches et al. '07)

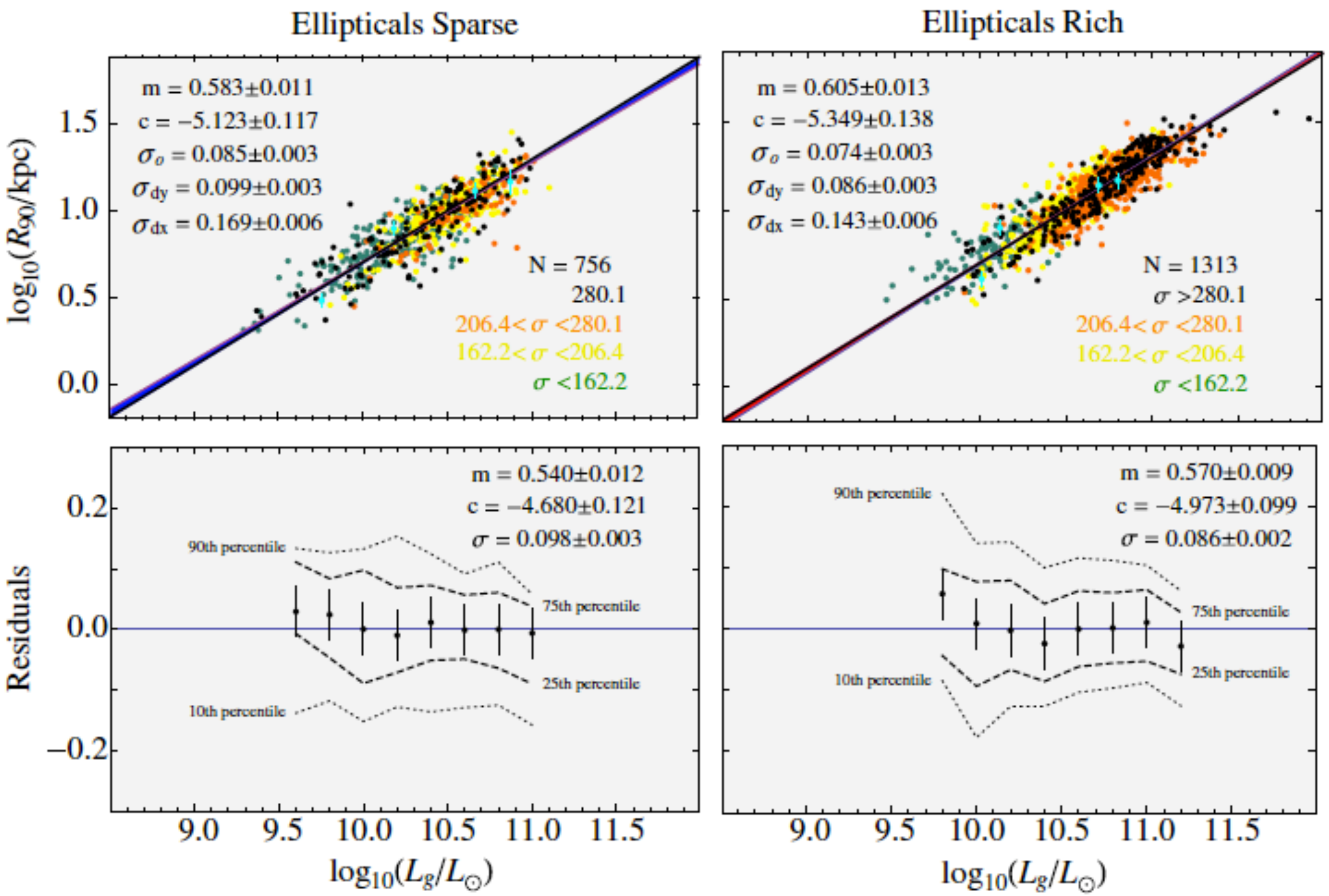


stellar mass
(slope ~ 3.5)

2. The luminosity-size relation

Hyde & Bernardi ('09) find curvature, but Nair et al. ('11) do not. Sample selection by Hyde & Bernardi, based on concentration, includes disk galaxies.

Nair et al. ('11) suggest the scatter is so low, it could be a challenge for building ellipticals through mergers



What these relations tell us?

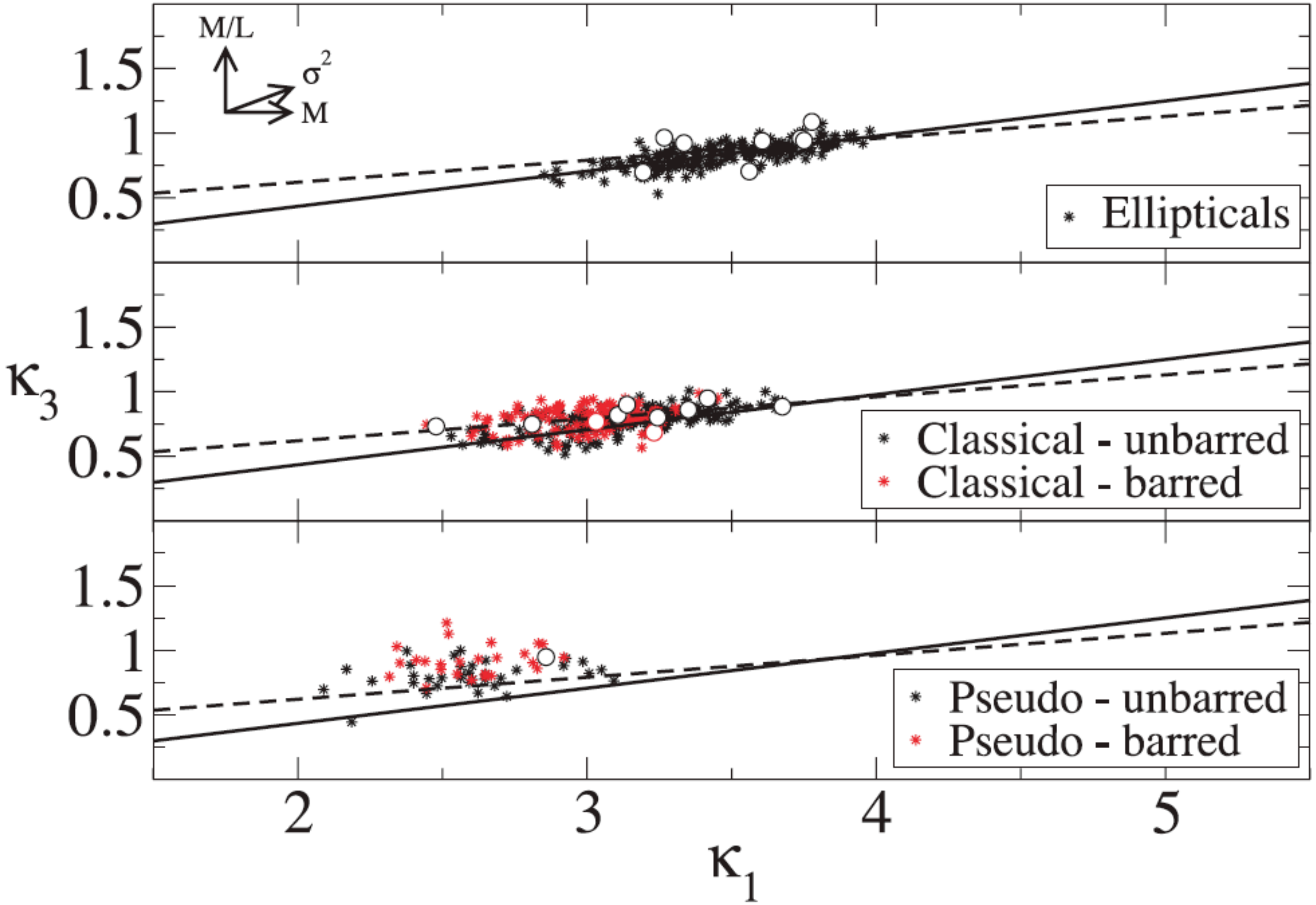
- Systematic properties come from gravity acting

- Deviations are due to other forces, such as gas physics (dissipation, supernovae feedback, AGN feedback…): other formation histories

- Luminosity (Mass)-Size relation indicates how things grow

Where do bulges and ellipticals fall in the edge-on view of the FP?

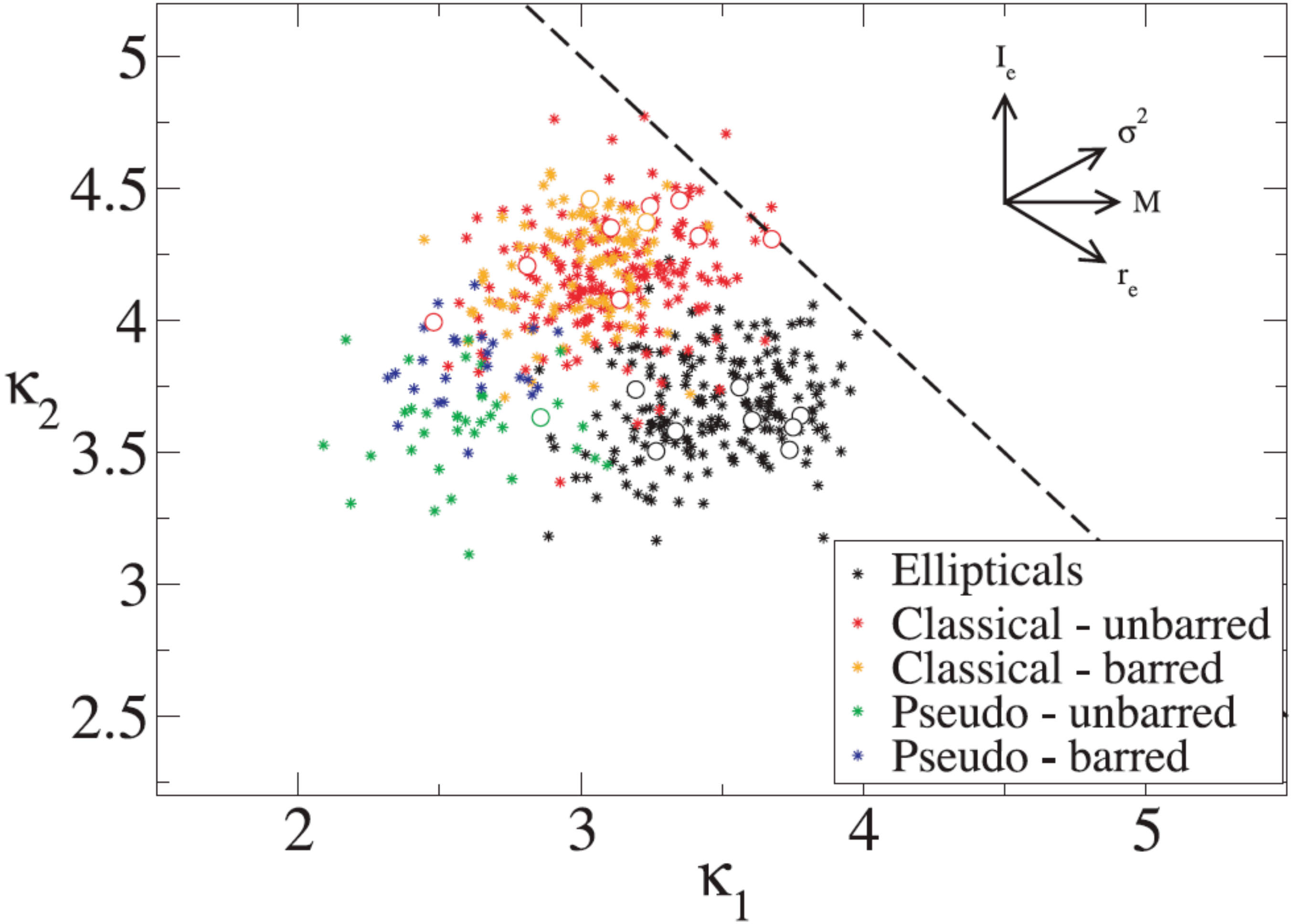
Disk-like bulges and classical bulges deviate from ellipticals, the former more noticeably than the latter (the dashed line is from Bernardi et al. ‘03). There is no clear distinction between barred and unbarred galaxies (although perhaps a slight offset).



Gadotti ‘09

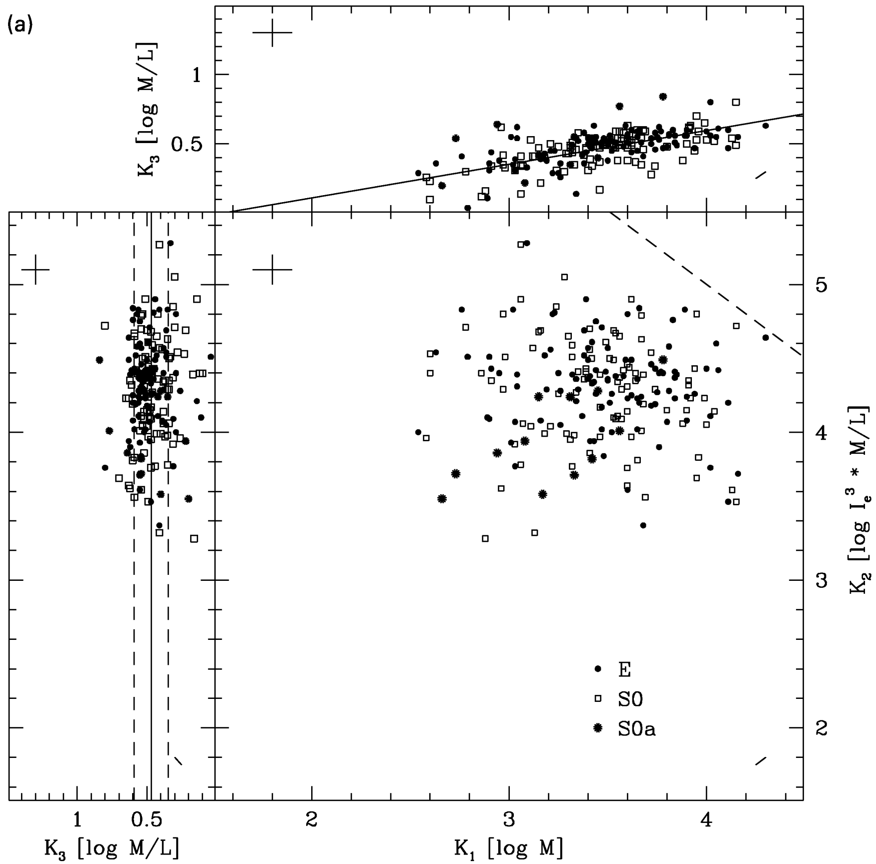
Where do bulges and ellipticals fall in the face-on view of the FP?

The 3 systems occupy very different loci! Again, there seems to be a difference for barred galaxies.

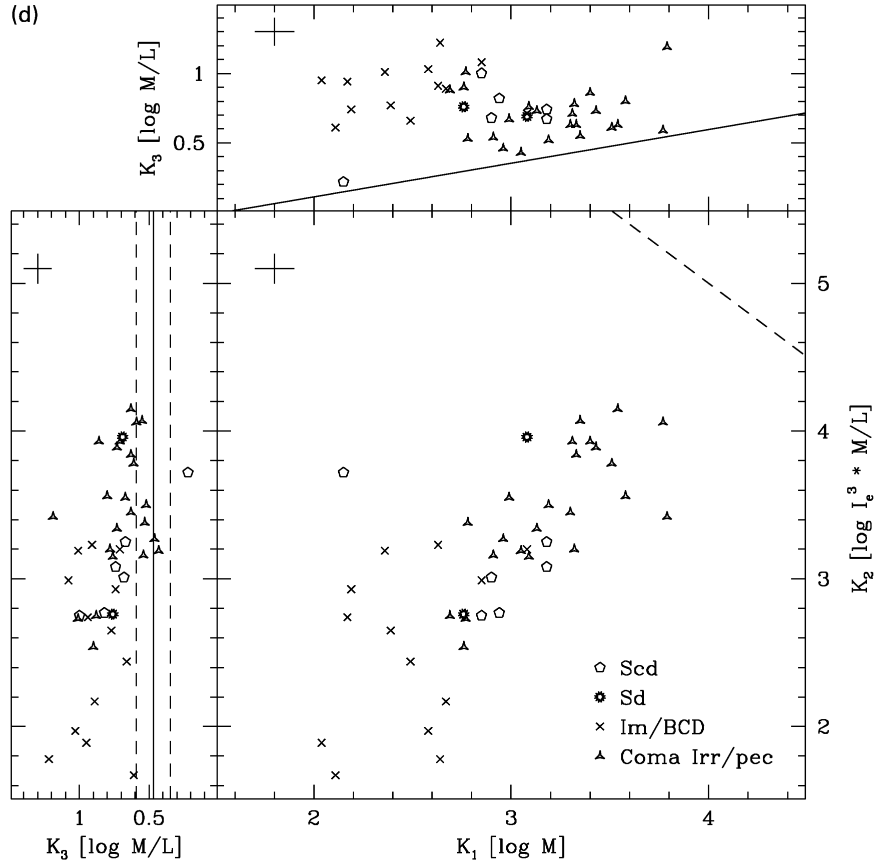


Gadotti ‘09

The locus occupied by disk-like bulges is the same as pure disk systems, as seen in the H-band FP of Pierini et al. ('02).



early-type

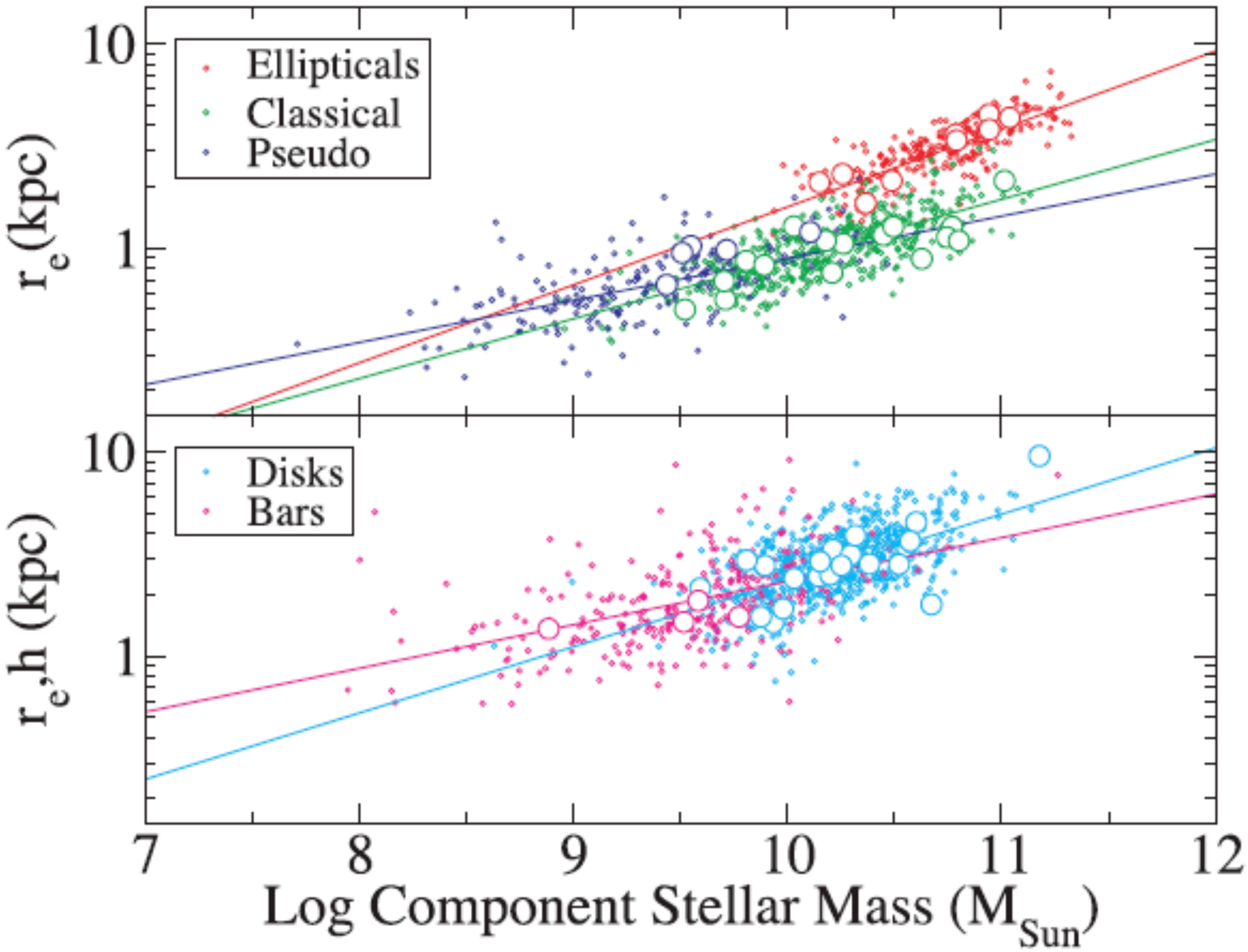


late-type

How the mass-size relation of bulges and ellipticals compare?

$$\log(\text{size}) = \text{alpha} \times \log(\text{mass})$$

bars: α=0.21
disks: α=0.33
disk-like: α=0.20 (±0.02)
classical: α=0.30
ellipticals: α=0.38

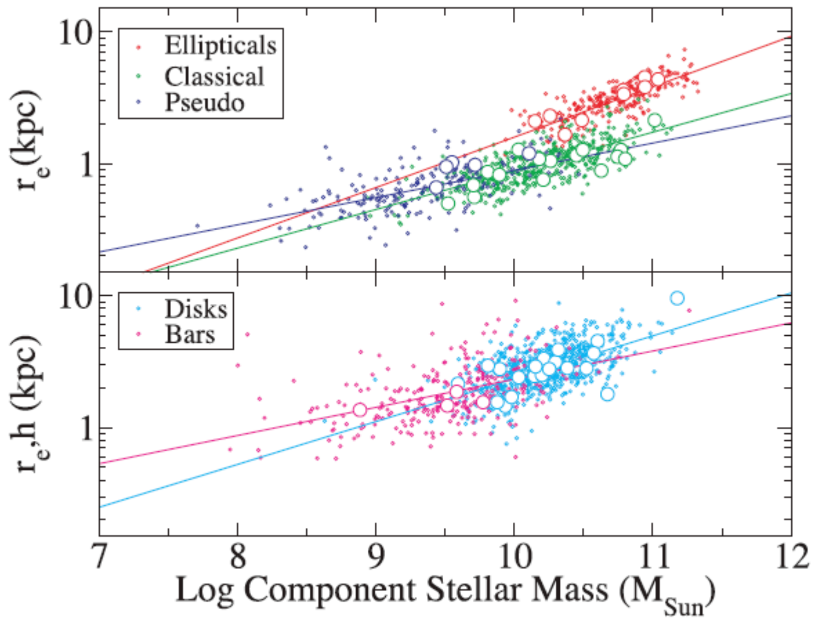


➢ The mass-size relation of disk-like bulges is different from that of classical bulges by 5σ

➢ The mass-size relation of classical bulges is different from that of ellipticals by 4σ

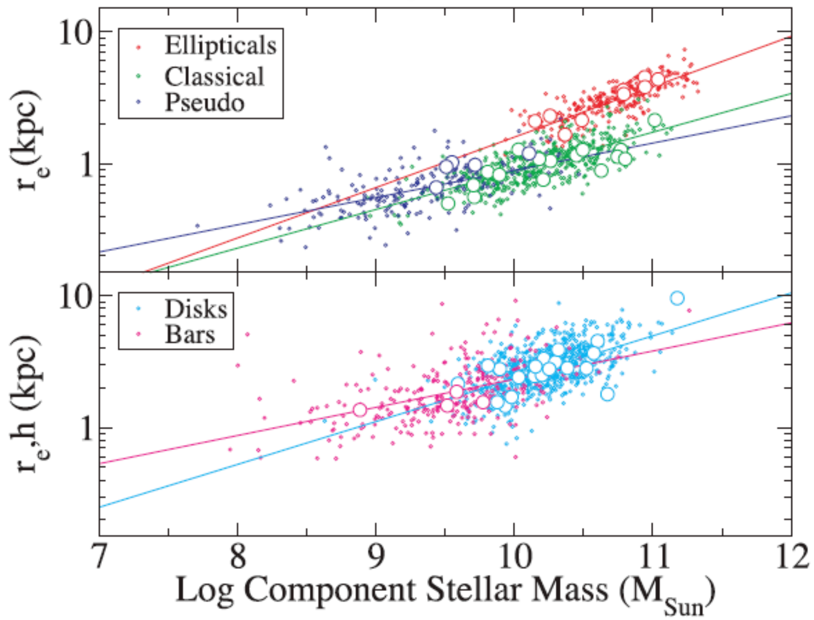
➢ The only pair of components with similar mass-size relations are disk-like bulges and bars

bars: α=0.21
disks: α=0.33
pseudo: α=0.20 (±0.02)
classical: α=0.30
ellipticals: α=0.38



➢ At the high-mass end, classical bulges are not just ellipticals surrounded by disks

bars: α=0.21
disks: α=0.33
pseudo: α=0.20 (±0.02)
classical: α=0.30
ellipticals: α=0.38

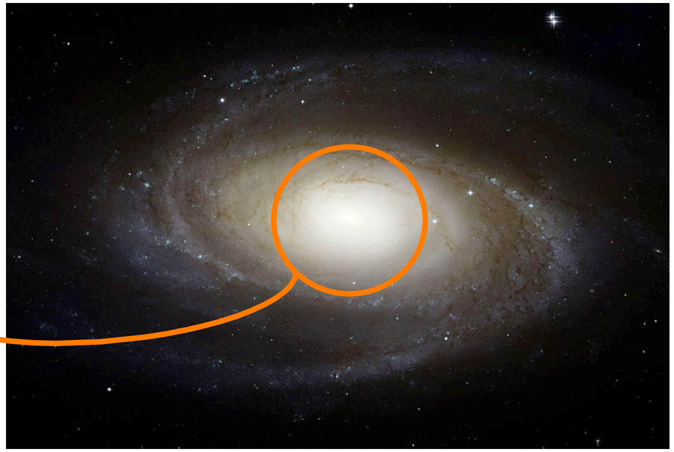


The Stellar Mass Budget at Redshift Zero

For galaxies with stellar mass > 10^{10} M_{Sun}

- ~ 36% in disks
- ~ 3% in disk-like bulges
- ~ 4% in bars
- ~ 32% in elliptical galaxies

- ~ 25% in classical bulges



Gadotti '09