
The central region of spiral galaxies
Winter school, January 12 - 23 2015

# Bulge families and elliptical galaxies

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# Initial Considerations

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

2. Semantics is 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 conjectures

4. Important references:

    - IAU Symps. 153, Ghent – '92 & 245, Oxford – '07
    - Wyse et al. ('97); Kormendy & Kenniccutt ('04); Athanassoula ('05); Graham ('13)
    - Galactic Bulges (ed. by Laurikainen, Peletier & Gadotti, '15)

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

# Outline

1. Bulge definitions

2. Bulge families: classical, disky and box/peanuts + barlenses

3. Identifying disky bulges (or inner disks)

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

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

5. The stellar mass budget at redshift zero

# Outline

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. Formation of disky bulges by bars

# 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

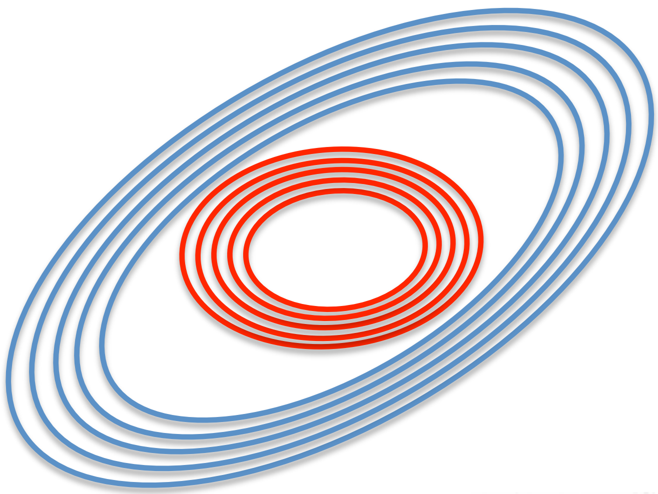
One of the criteria in the Hubble ('26) classification of disk galaxies:

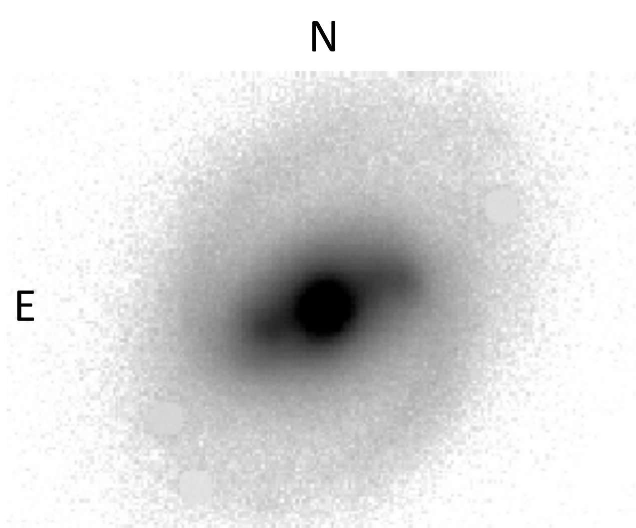
> "relative size of the unresolved nuclear region", elliptical-like, changes monotonically along the sequence

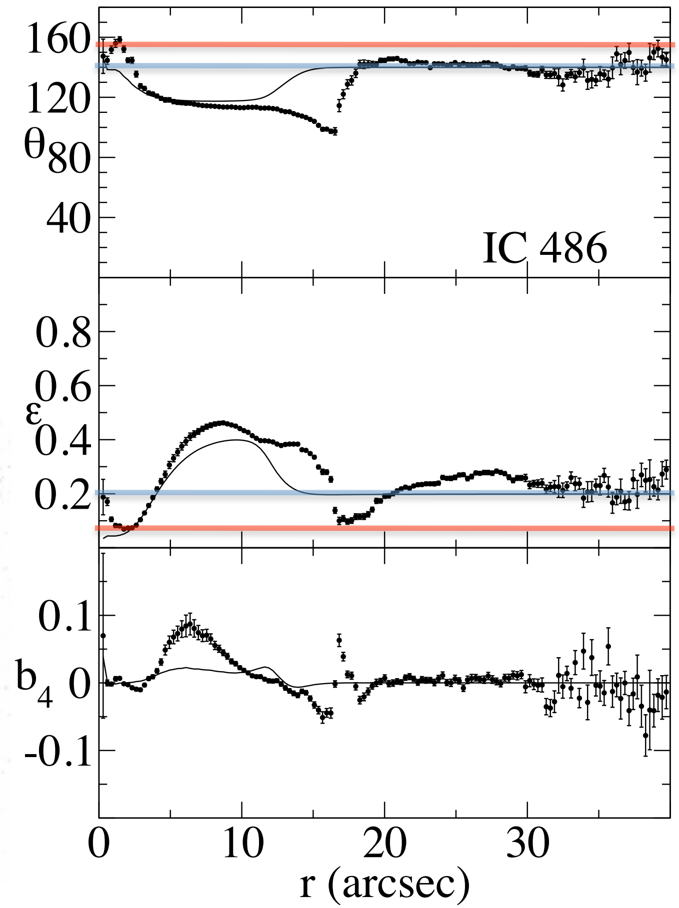
led to the concept that disk galaxies are like elliptical galaxies (the bulge) surrounded by disks.

# Bulge Definitions

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






Gadotti '08

# Bulge Definitions

I. From morphology

Pros:

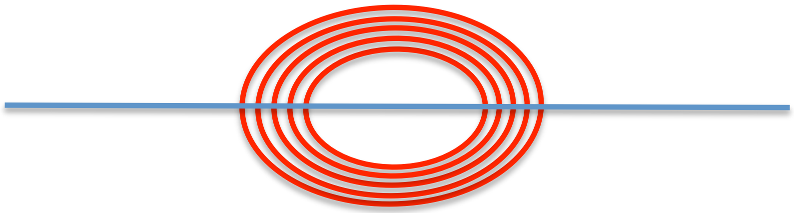
1. Physical

Cons:

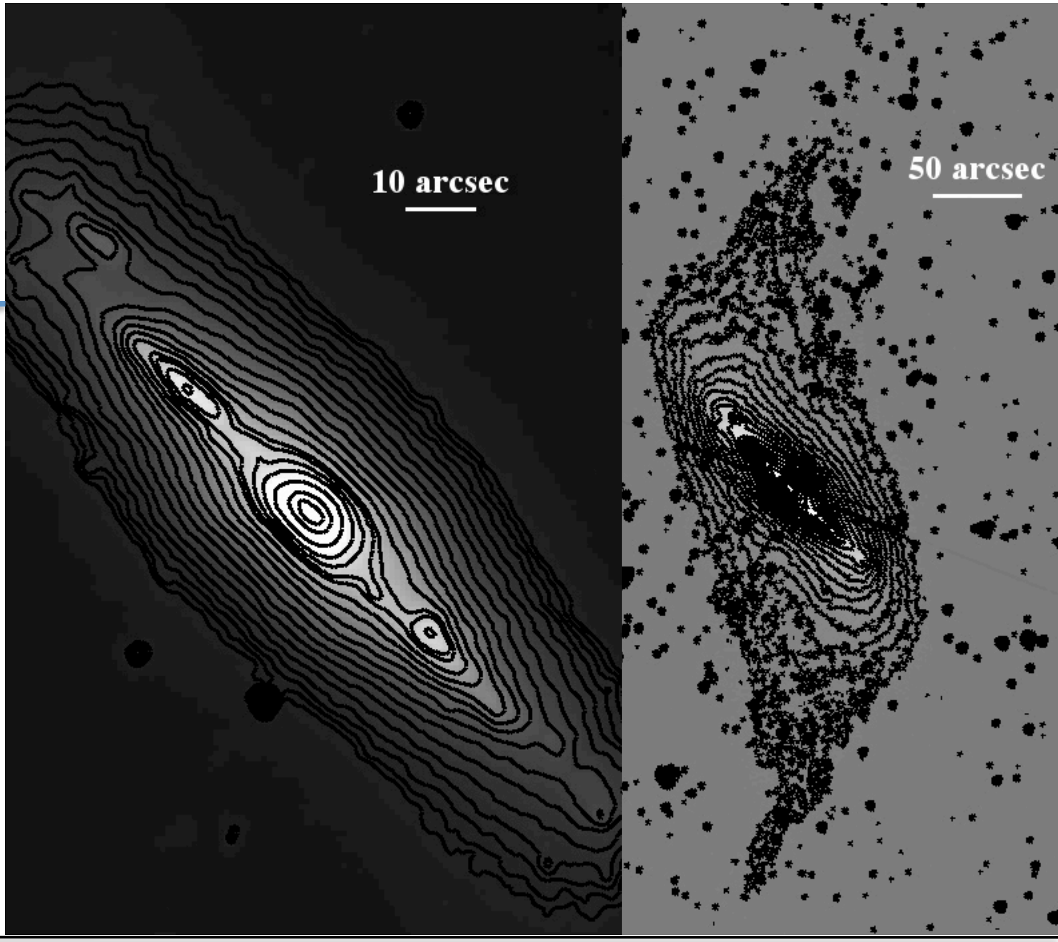
1. Somewhat subjective; arbitrary (how much difference in $\theta$ or $\varepsilon$ is enough?)
2. “Bulge” can be a lot of different things

# 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:

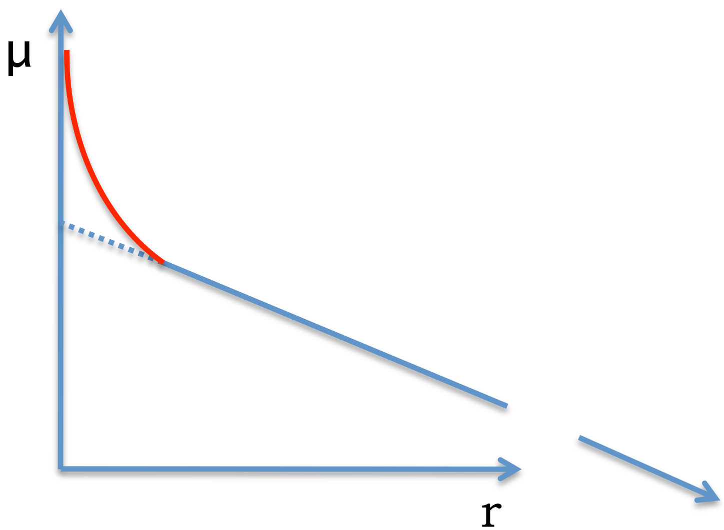
1. Easy, can be objective

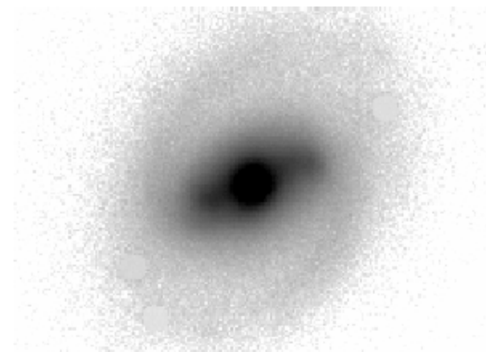
Cons:

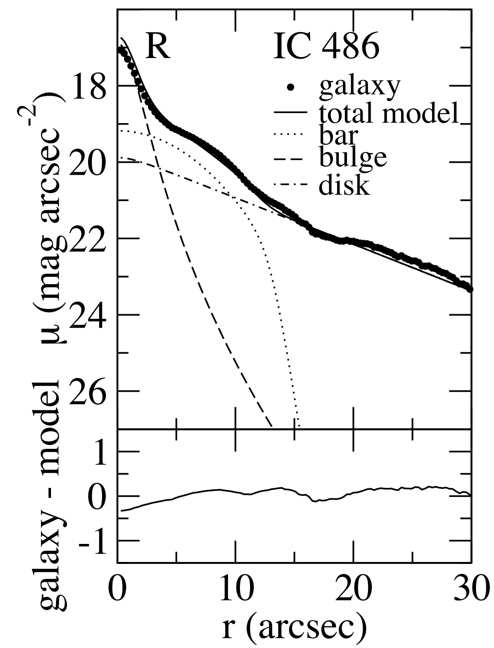
1. Only works for very inclined galaxies
2. Somewhat arbitrary
3. “Bulge” can be a lot of different things

# 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

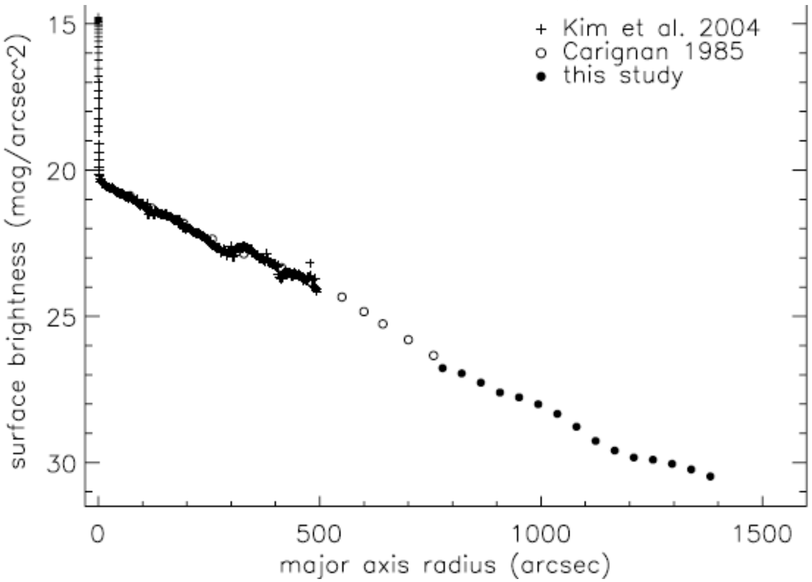
III. From photometry

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 major 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 Families

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 (this is currently the best understood scenario, but not the only one)

# Bulge Families

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

# Bulge Families

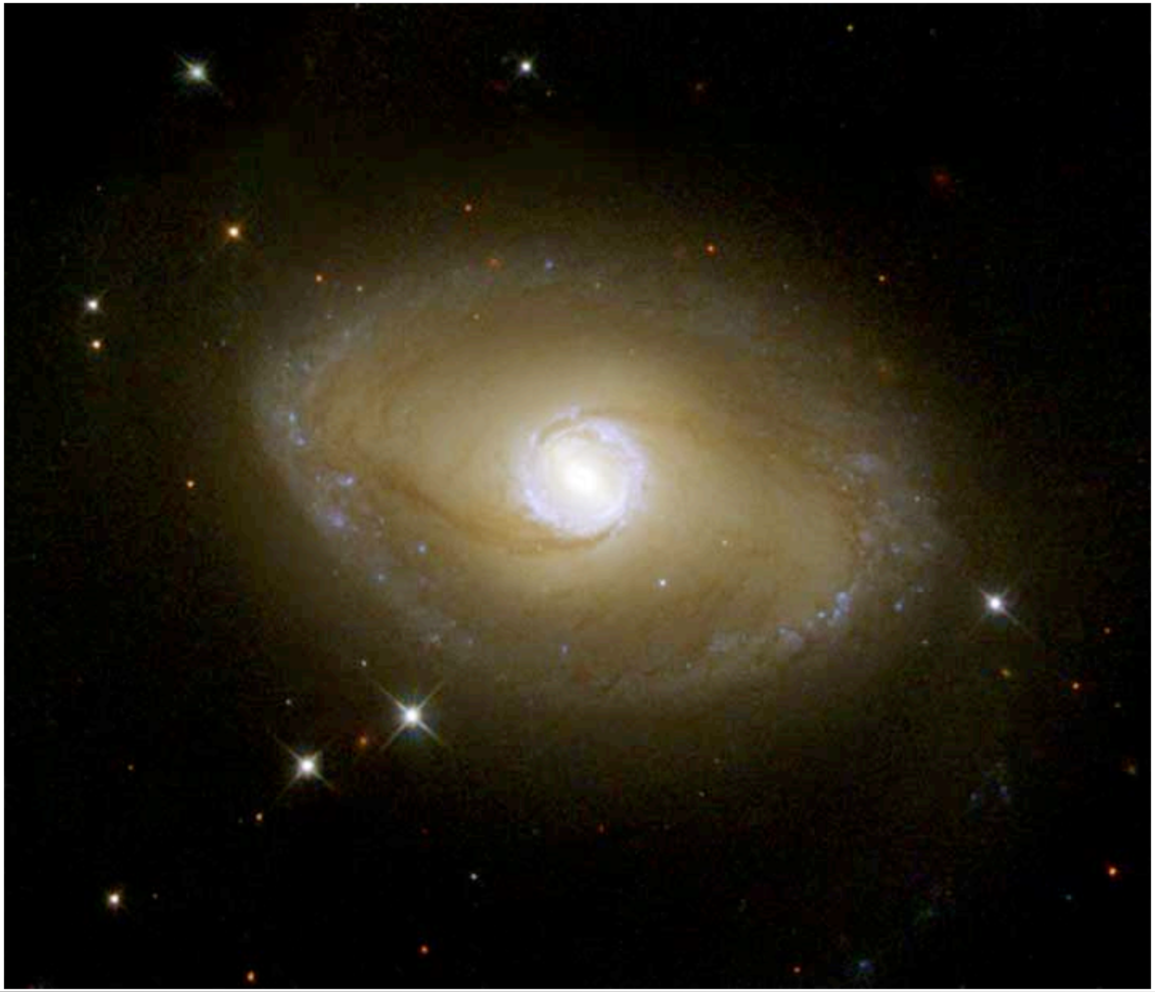
II. Disk-like – or disky – bulges (aka pseudo-bulges)

- as flat (or almost as flat) as the disk (not easy to see in very inclined galaxies)
- may contain/be sub-structures such as nuclear bars, spiral arms, rings…
- may 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 – seem to be simply inner disks

# Bulge Families

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



# Bulge Families

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)
- usually do 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 in the classical sense (i.e. merger-built) but the inner parts of bars, seen at an edge-on projection

# Bulge Families

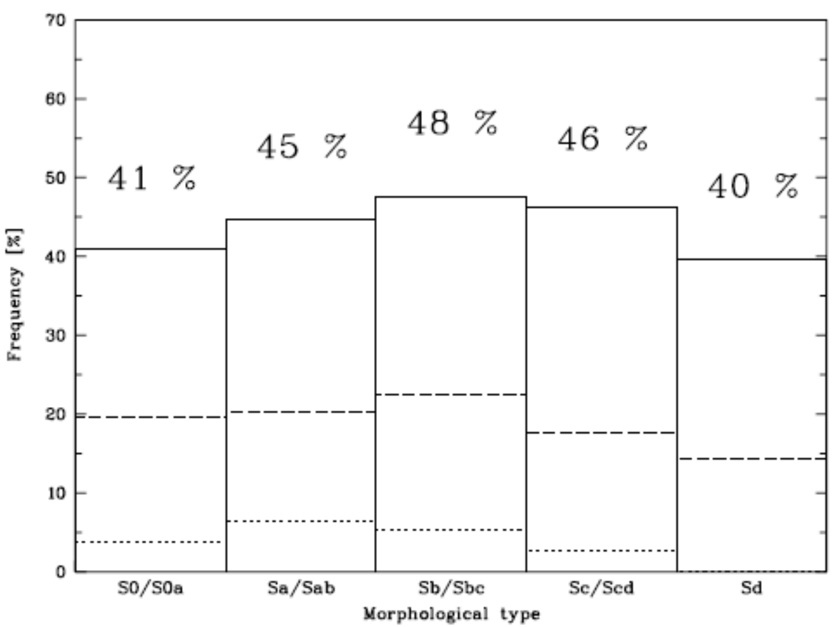
III. Box/Peanut bulges (aka pseudo-bulges): e.g. ESO 597-G 036 [NASA, ESA and the Hubble Heritage Team (STScI/AURA)]

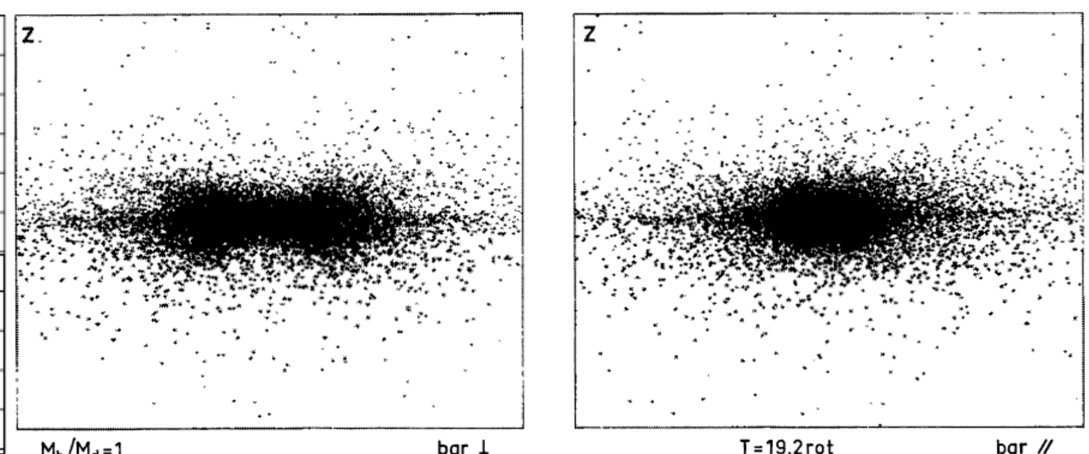
- Boxy or Peanut morphology depend on strength and projection

# B/Ps and Bars

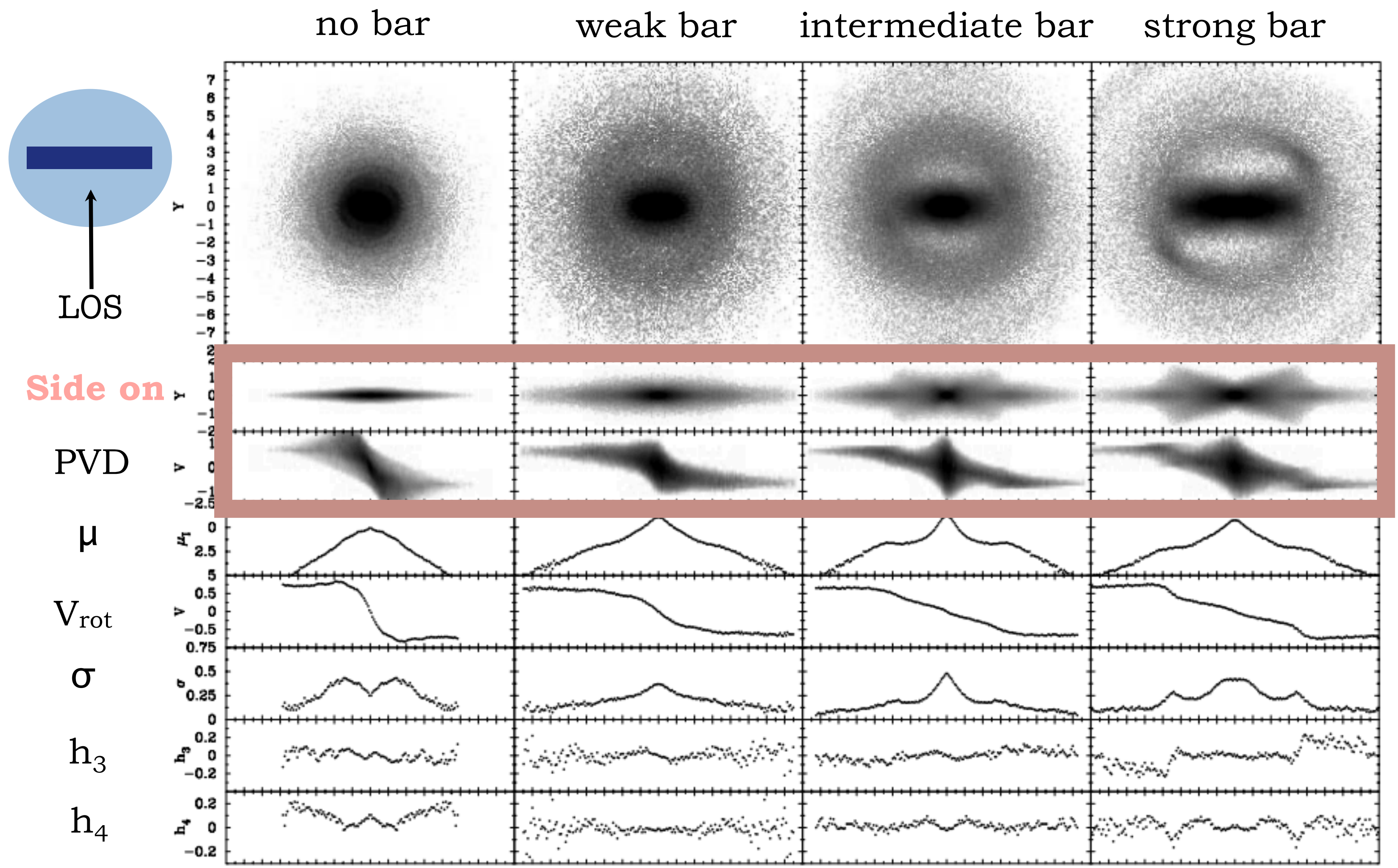
Suggestive evidence that box/peanuts are associated with bars, from statistical considerations, go at least as far as the 80's (e.g. de Souza & dos Anjos '87; see also Luetticke et al. '00). Distribution of bps in morphological types in edge-on galaxies is similar to the corresponding distribution of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



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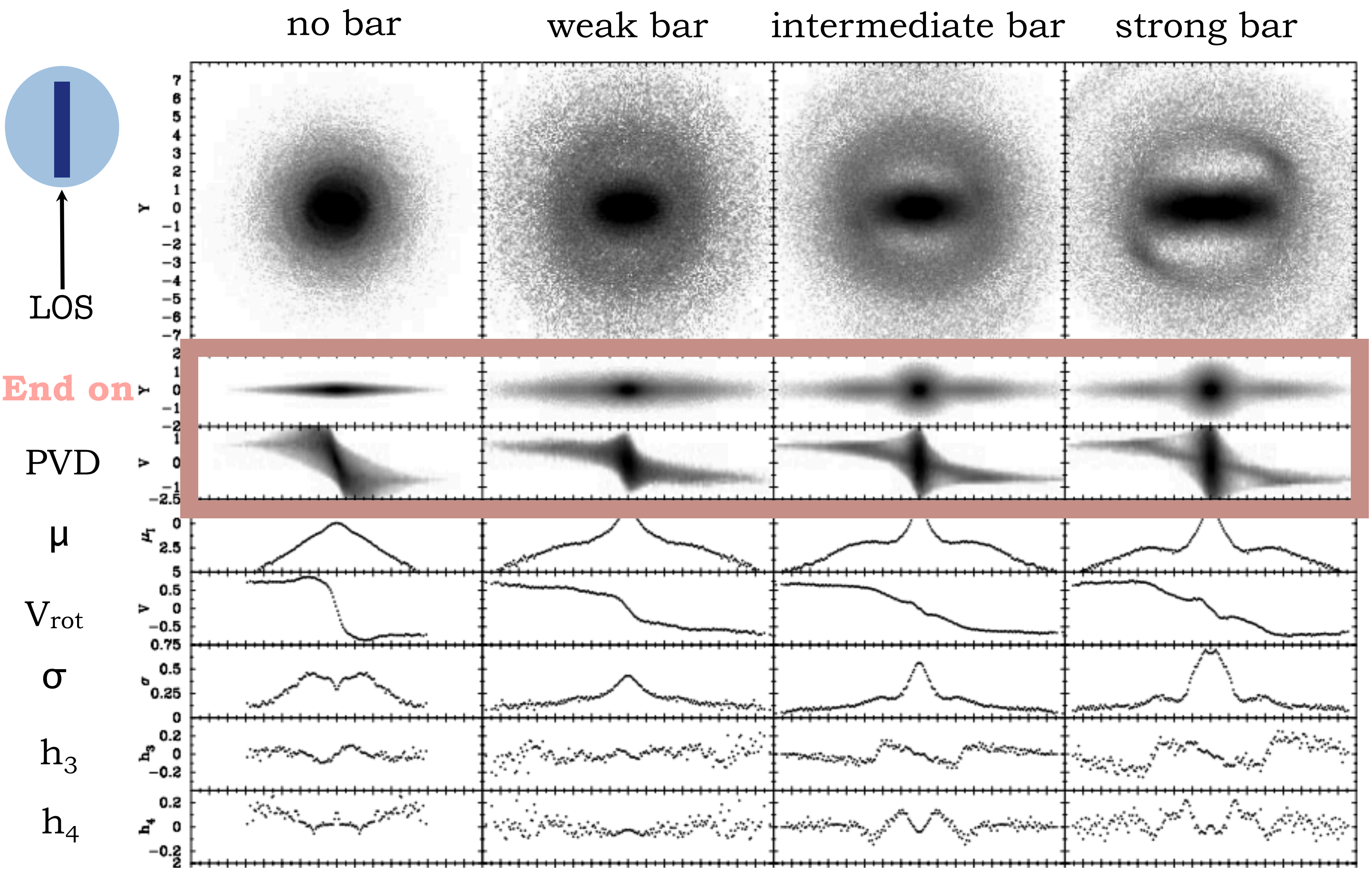
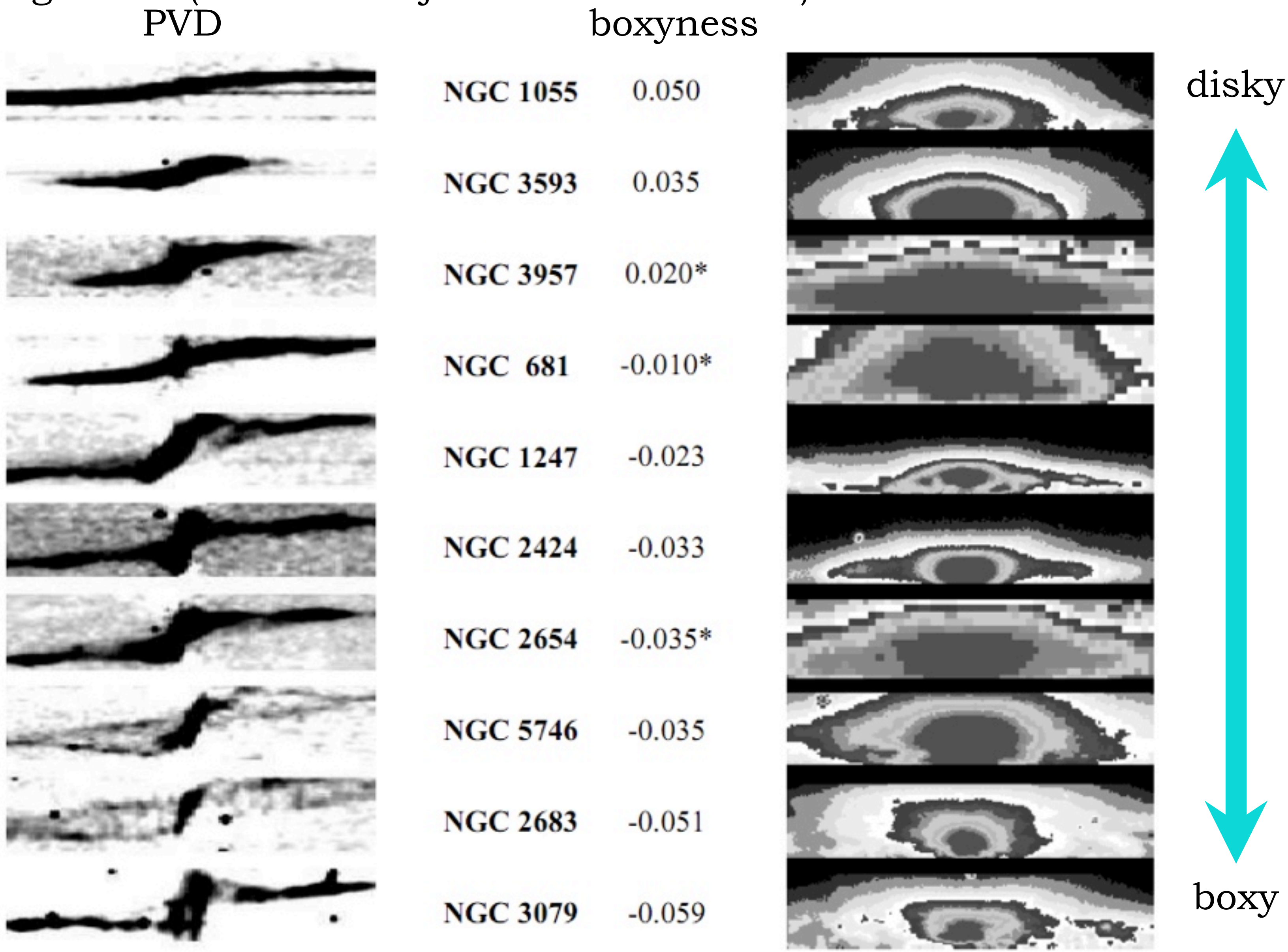
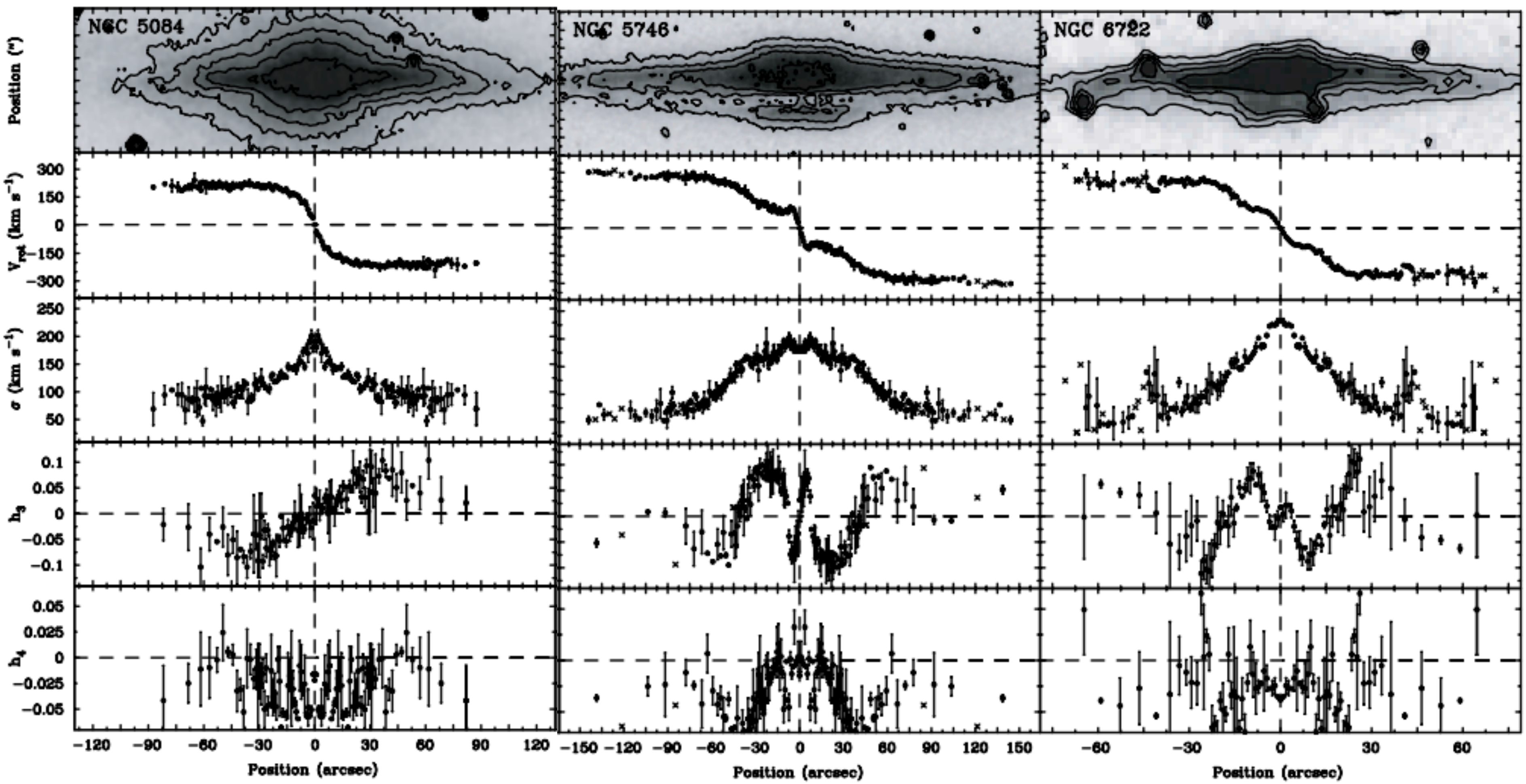


Merrifield et al. '99: use (gas) [NII] 6584Å emission to find evidence for the connection between bps and bars. Position-velocity diagrams of bps show clear bar signature (see also Kuijken & Merrifield '95).



# B/Ps and Bars

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

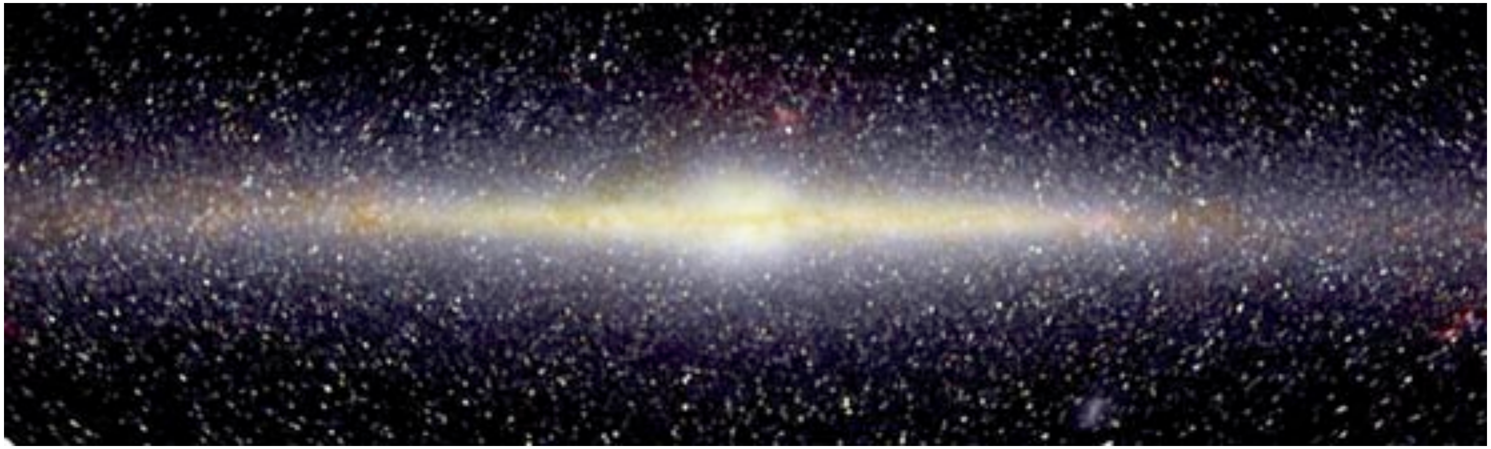


# B/Ps and Bars

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

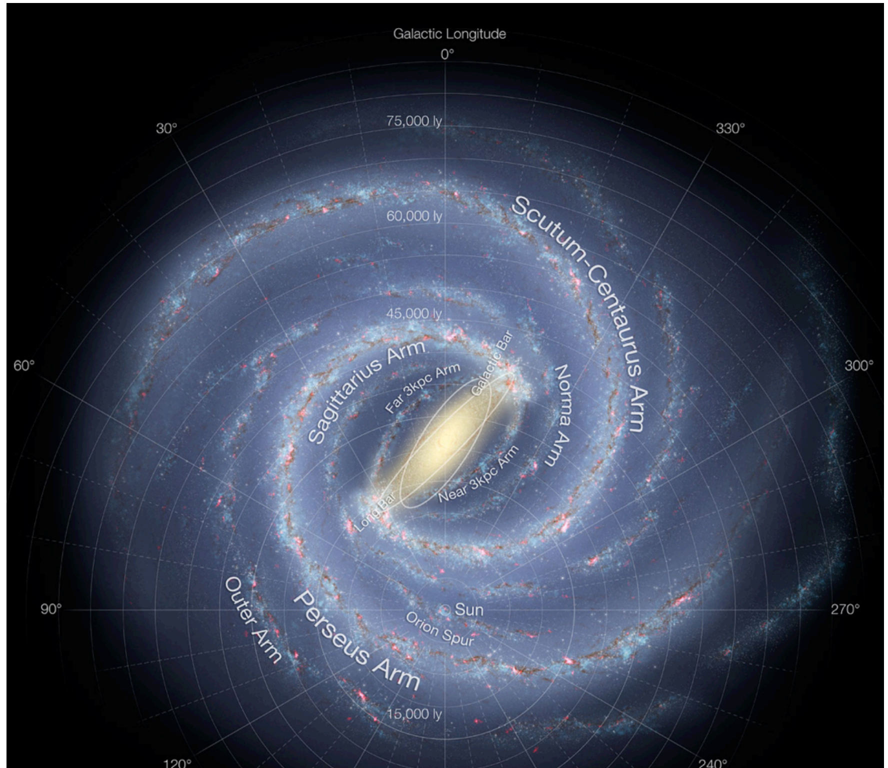
Milky Way "bulge" is known to show bp morphology since the 90's, e.g. with COBE.

The COBE Project, DIRBE, NASA



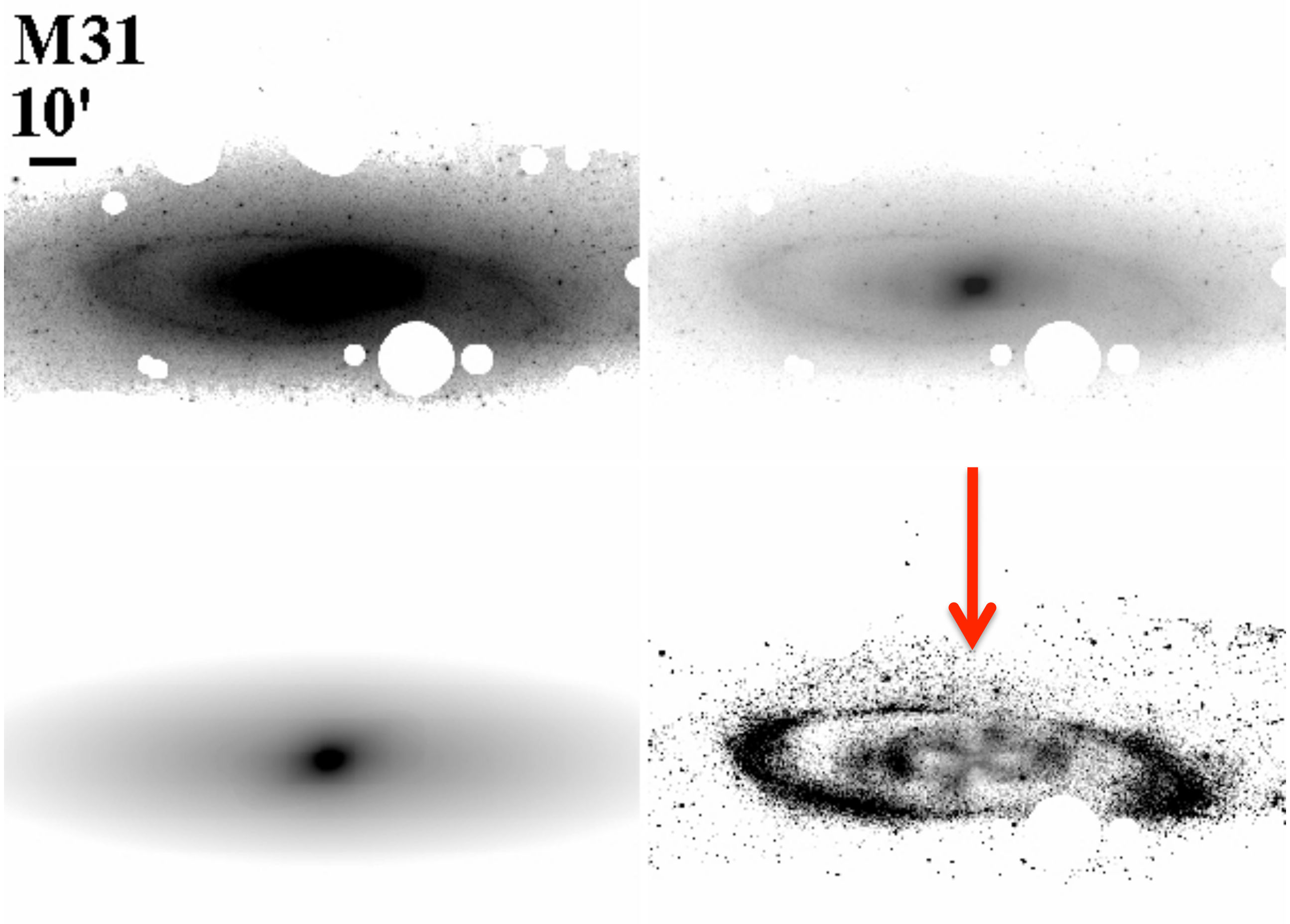
# B/Ps and Bars

# B/Ps and Bars


Galactic Longitude
0°
30°
330°
60°
300°
90°
270°
120°
240°
75,000 ly
60,000 ly
45,000 ly
15,000 ly
Scutum-Centaurus Arm
Sagittarius Arm
Far 3kpc Arm
Galactic Bar
Norma Arm
Near 3kpc Arm
Long Bar
Outer Arm
Perseus Arm
Sun
Orion Spur

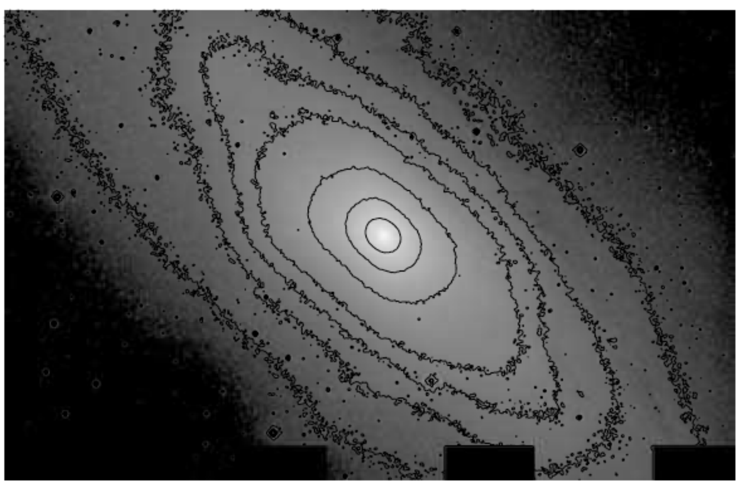
# B/Ps and Bars

M31 is another 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.

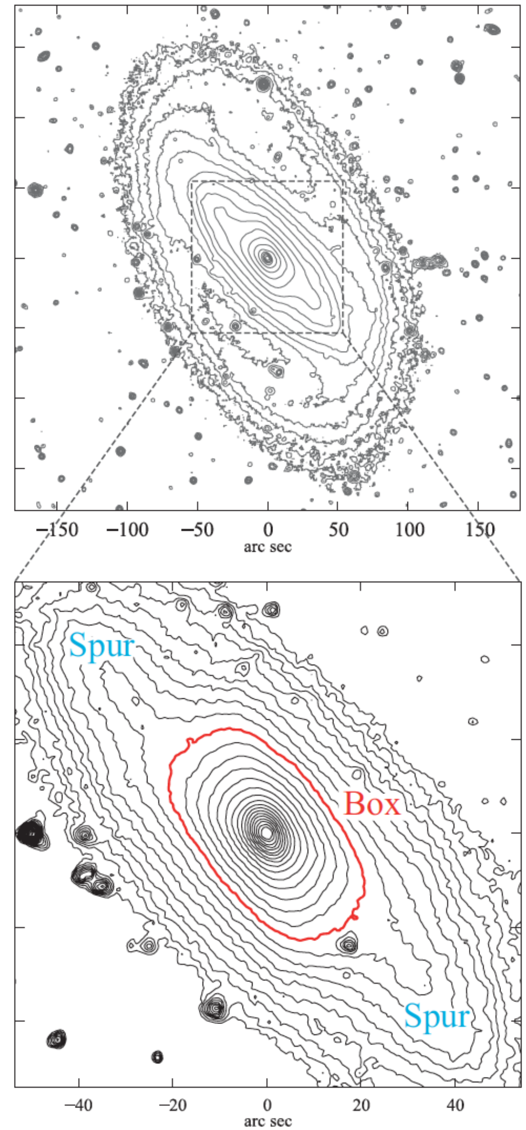


# B/Ps and Bars

Bars are easier to see in more face-on projections, whereas bps are easier to see in more edge-on projections. At some favorable projections, however, both can be identified.



Athanassoula & Beaton '06




Erwin & Debattista '13

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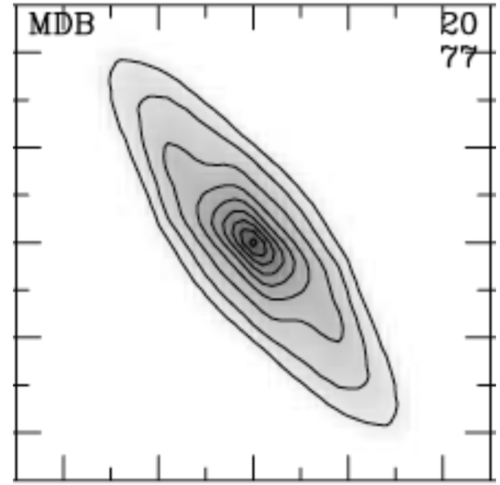
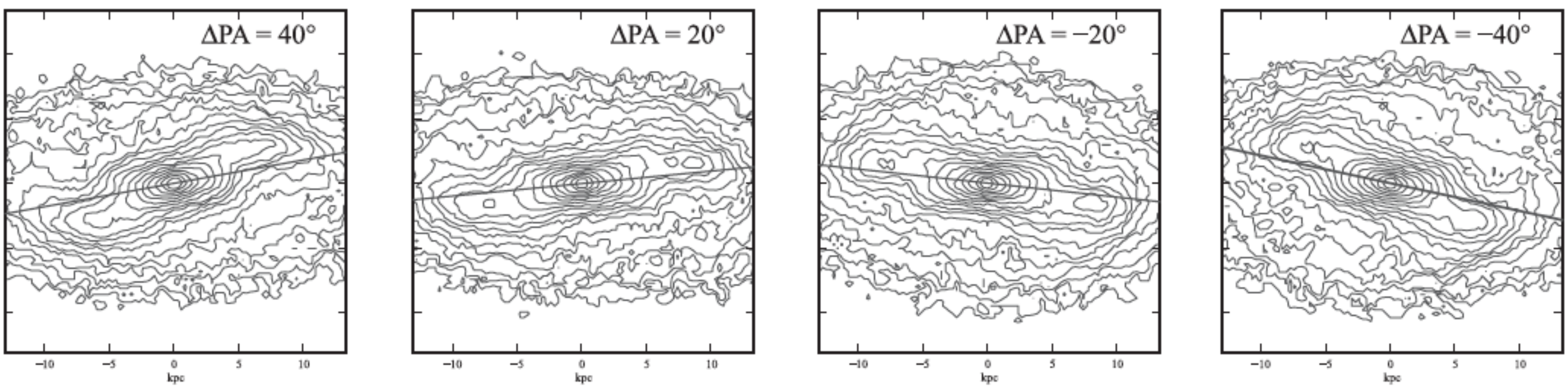
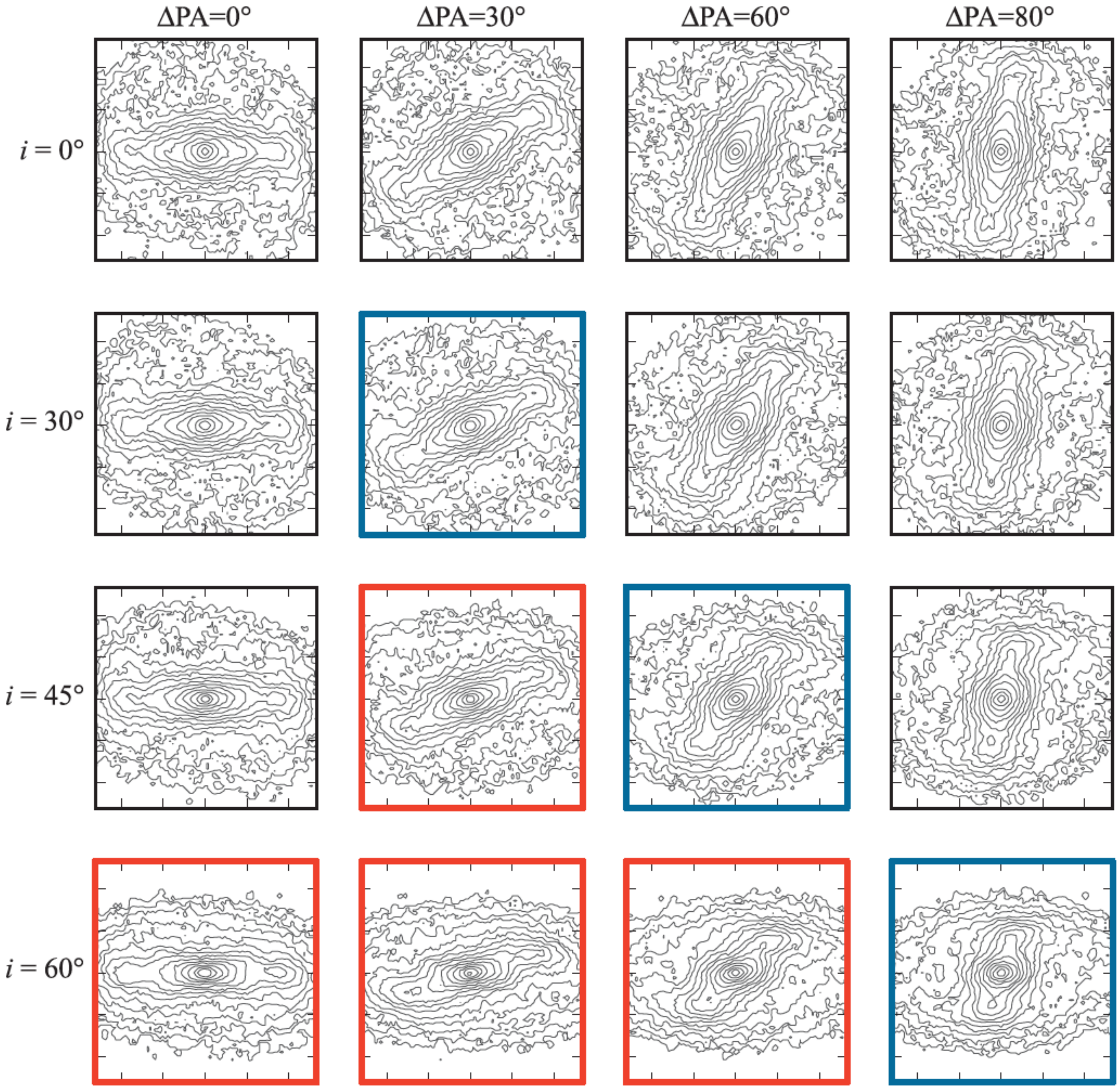



Athanassoula & Beaton '06




Erwin & Debattista '13

# B/Ps and Bars




Erwin & Debattista '13

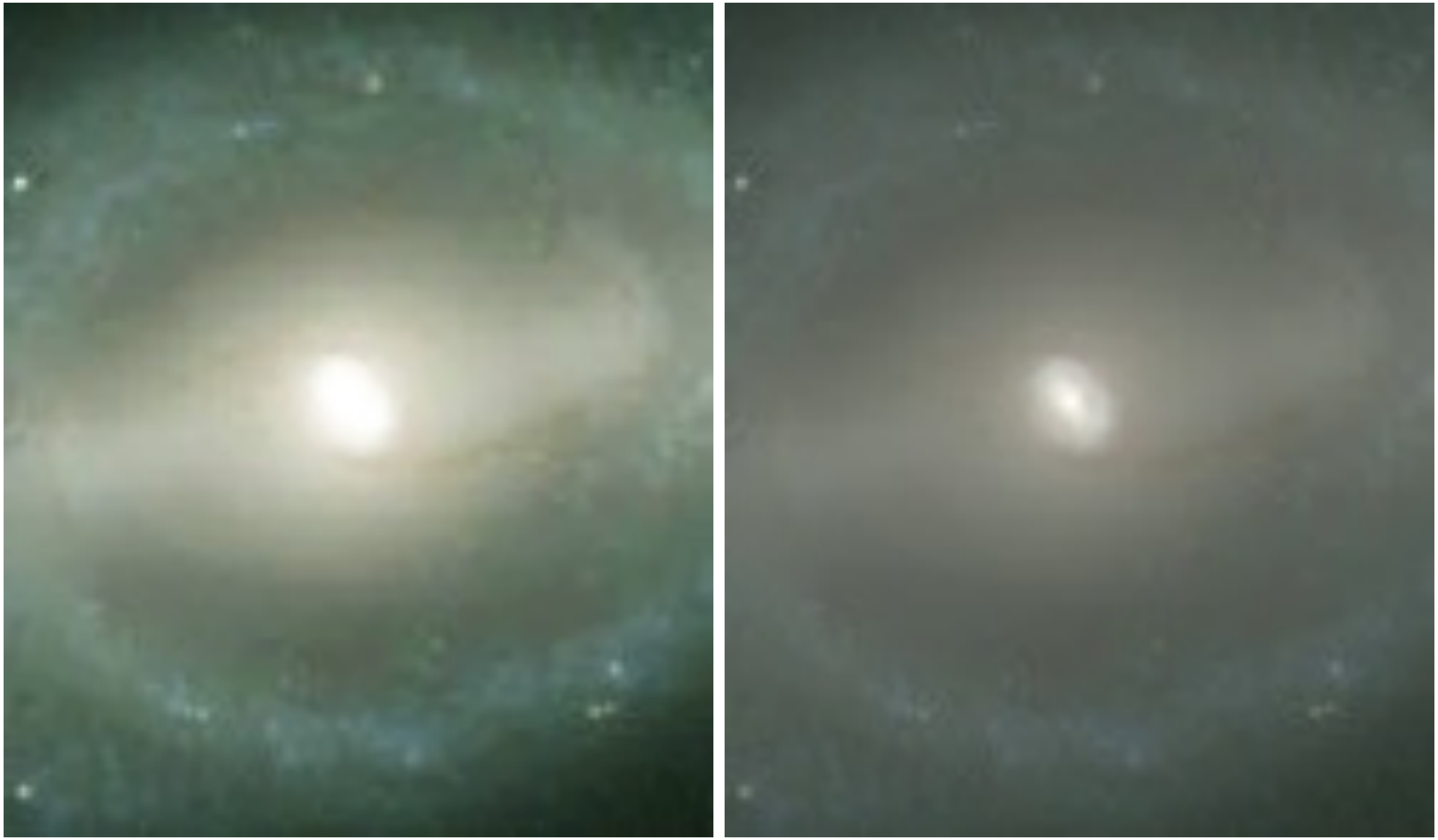
# B/Ps and Bars

Erwin & Debattista ‘13 find that bps have a mean size of 1.5 kpc, or 0.38 of the bar length. Their measures range from 0.4 to 3.8 kpc, or 0.26 to 0.58 of the bar length. This is consistent with numerical simulations.

# B/Ps and Barlenses

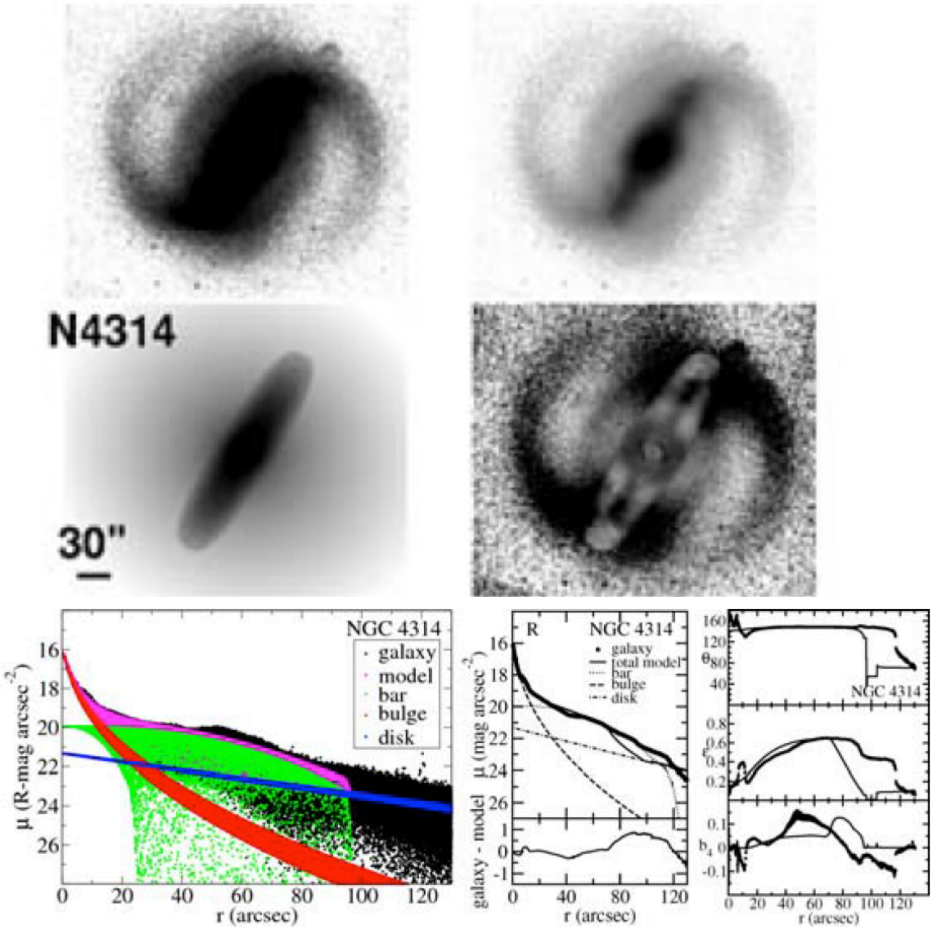
NGC 1433; Ho et al. ‘11; CGS

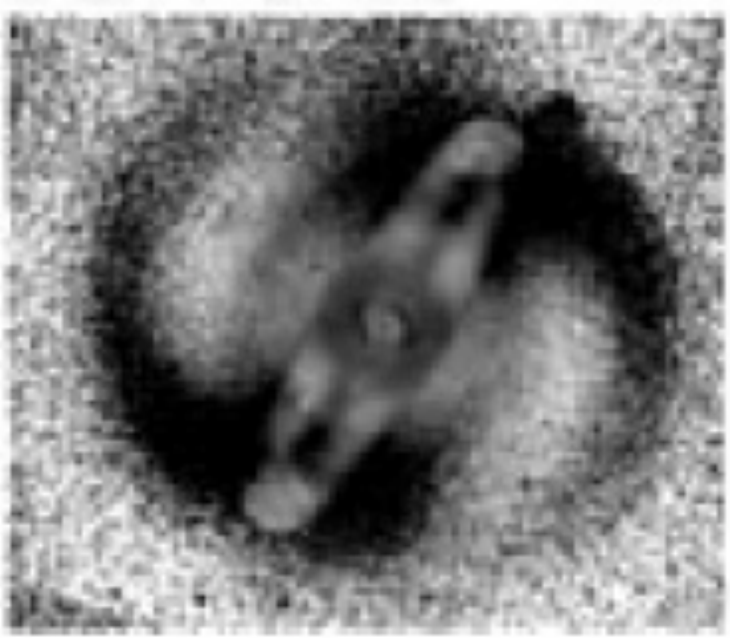
# B/Ps and Barlenses



This central region presents a barlens, an inner disk, a nuclear bar and nuclear spirals (tightly wounded as a ring).

# B/Ps and Barlenses

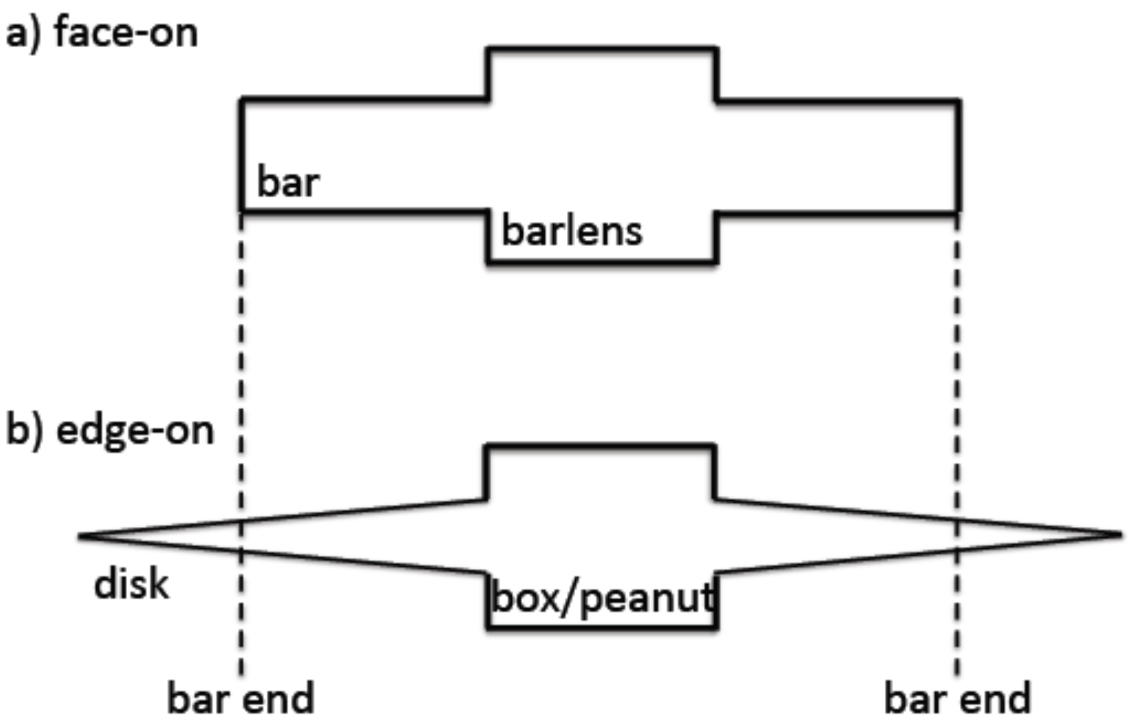


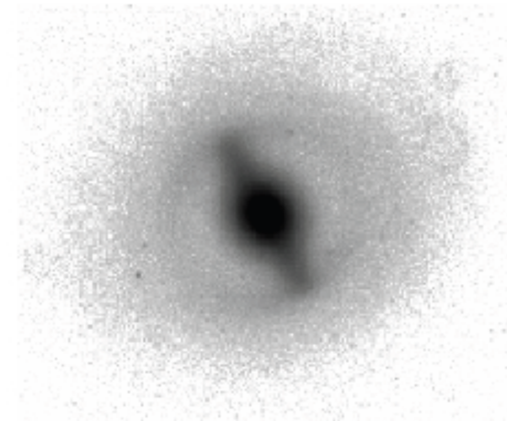
Gadotti ‘08

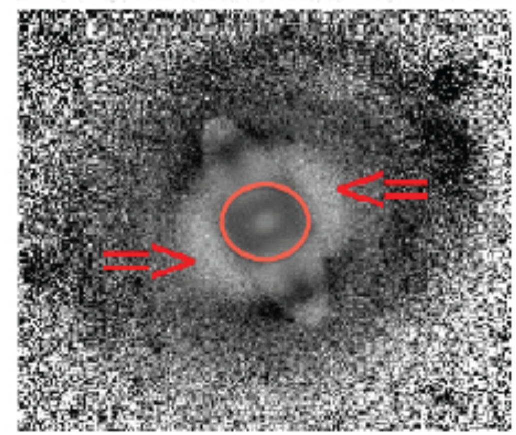
Here one can clearly see the barlens and nuclear spirals in the residual image.

# B/Ps and Barlenses



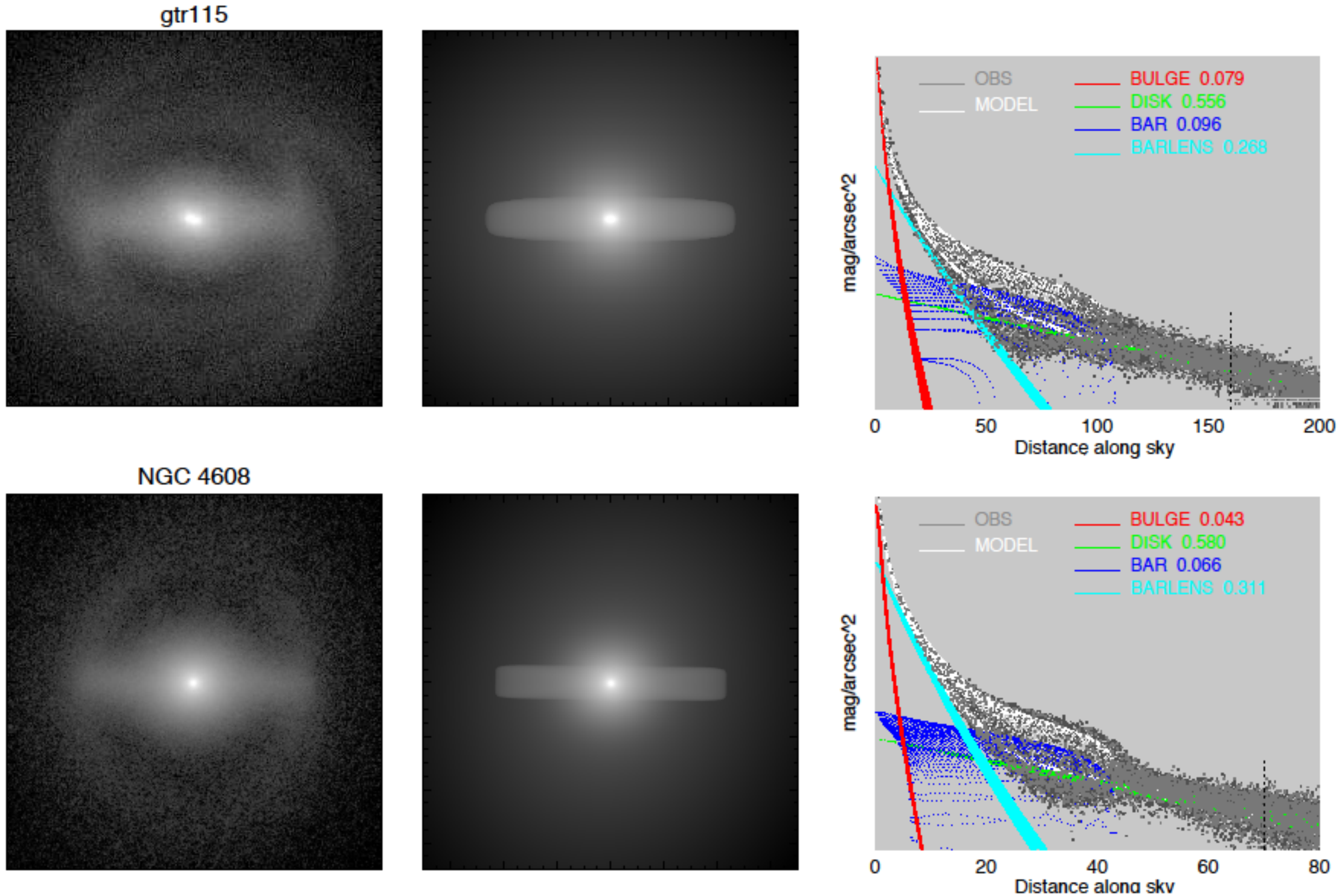

Gonzalez & Gadotti '15





Barlenses are box/peanuts (or the inner parts of bars) seen face-on
(see Laurikainen et al. '14; Athanassoula et al. '14)

# B/Ps and Barlenses

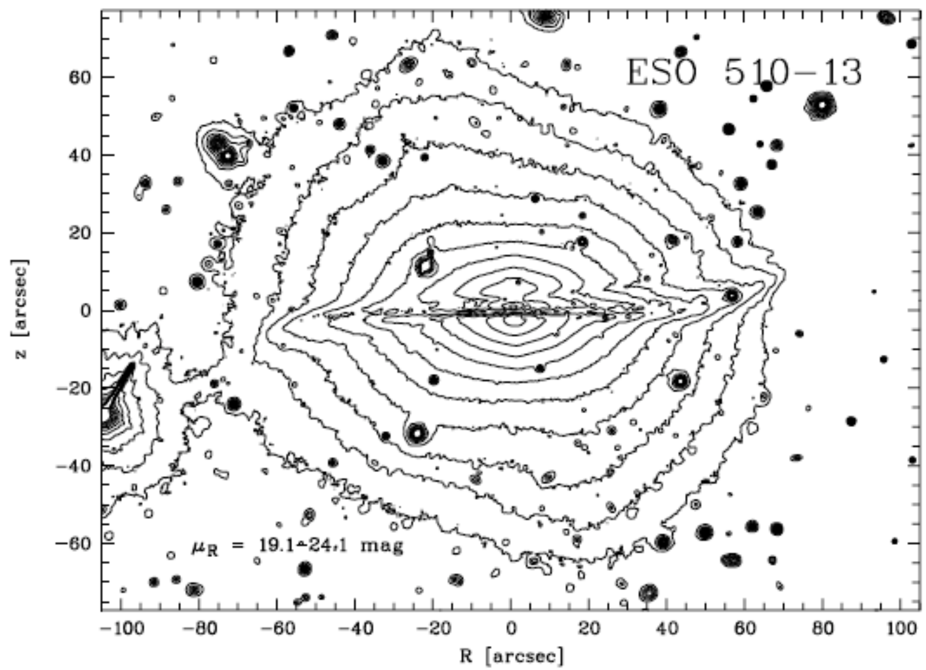



Athanassoula et al. '14

# 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)



# Bulge Families

**Classical bulges**

**Pseudo-bulges**

(Kormendy & Kennicutt '04)

**Disc-like bulges**

**Box/Peanuts**

(Athanassoula '05)

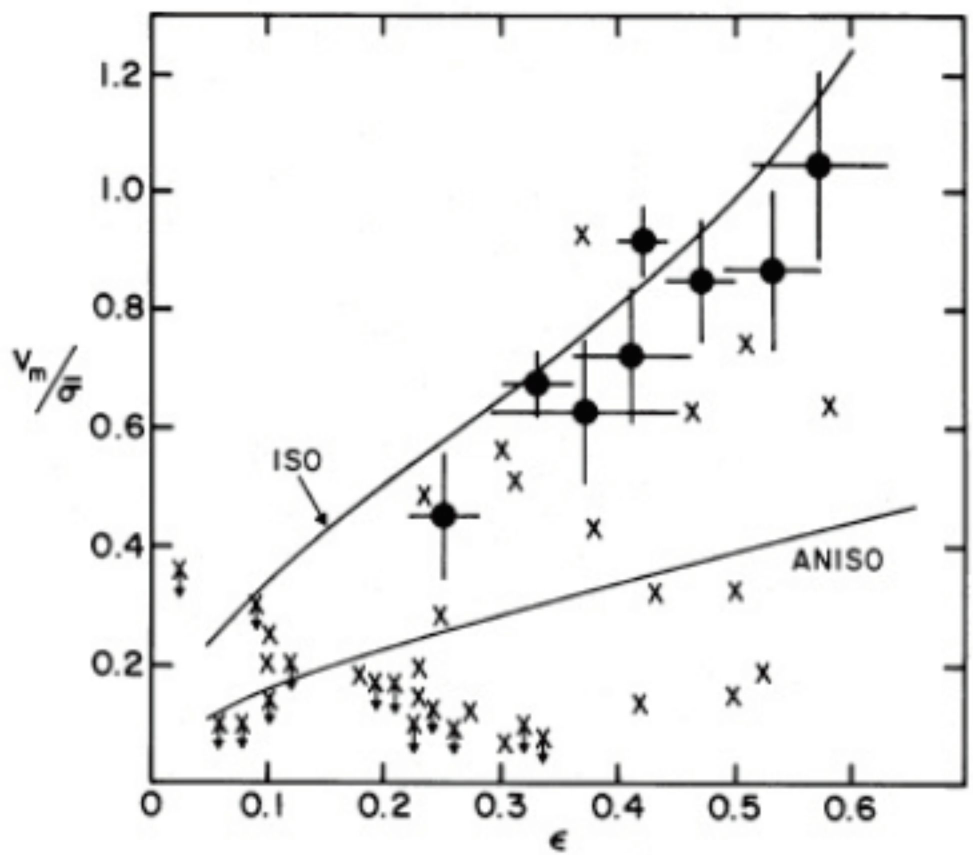
**(Disky bulges/Disc-like pseudo-bulges)**

**Inner Disks**

**Bars**

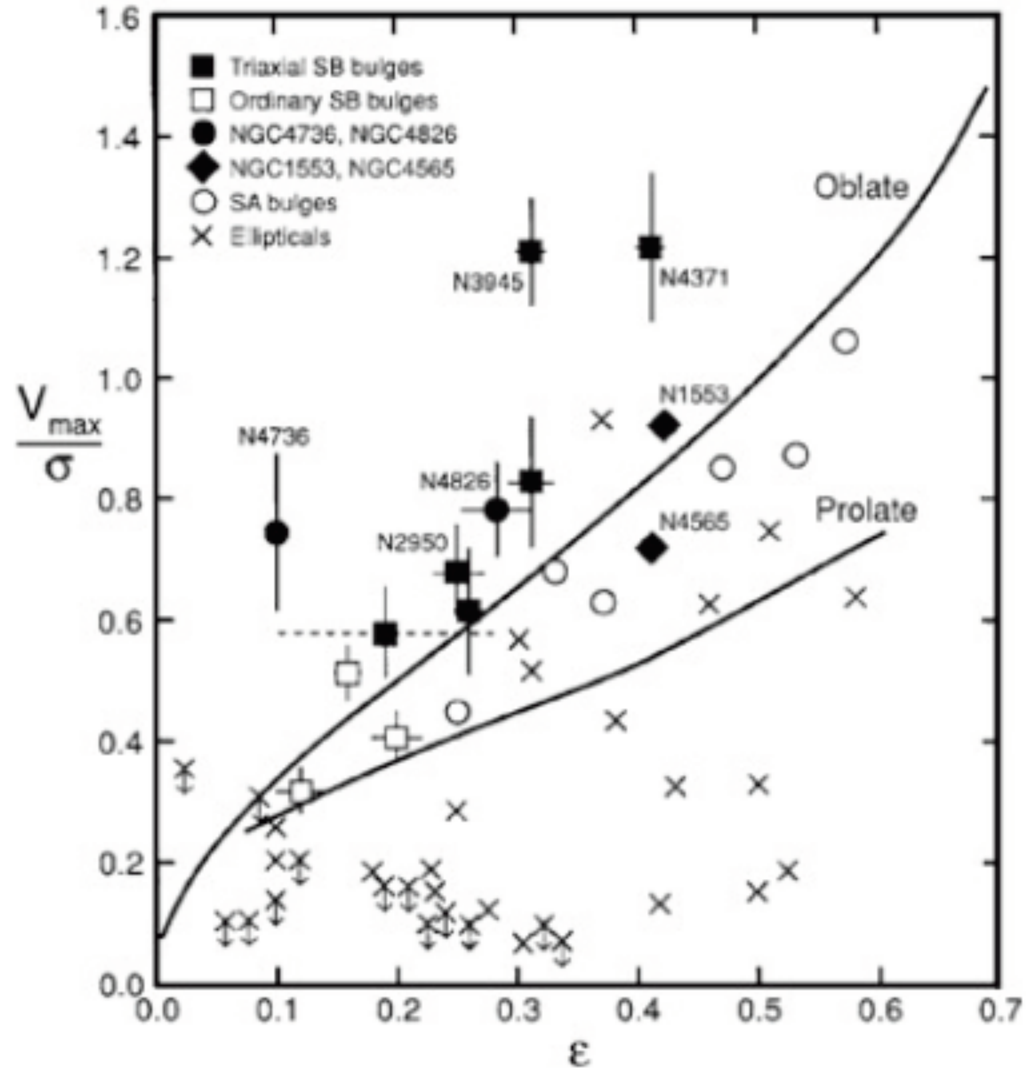
# The Dynamical Support of Bulges

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 (see also Illingworth '77 and Binney '78).



# The Dynamical Support of Bulges

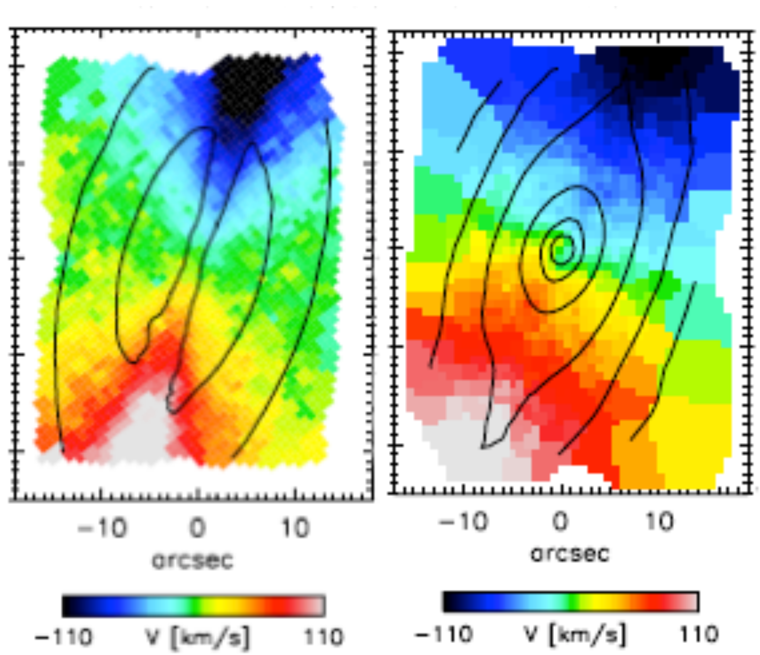
Kormendy '93: some bulges are really disks! Some of these are box/peanuts. They are more rotationally supported than pressure supported.



# The Dynamical Support of Bulges

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.

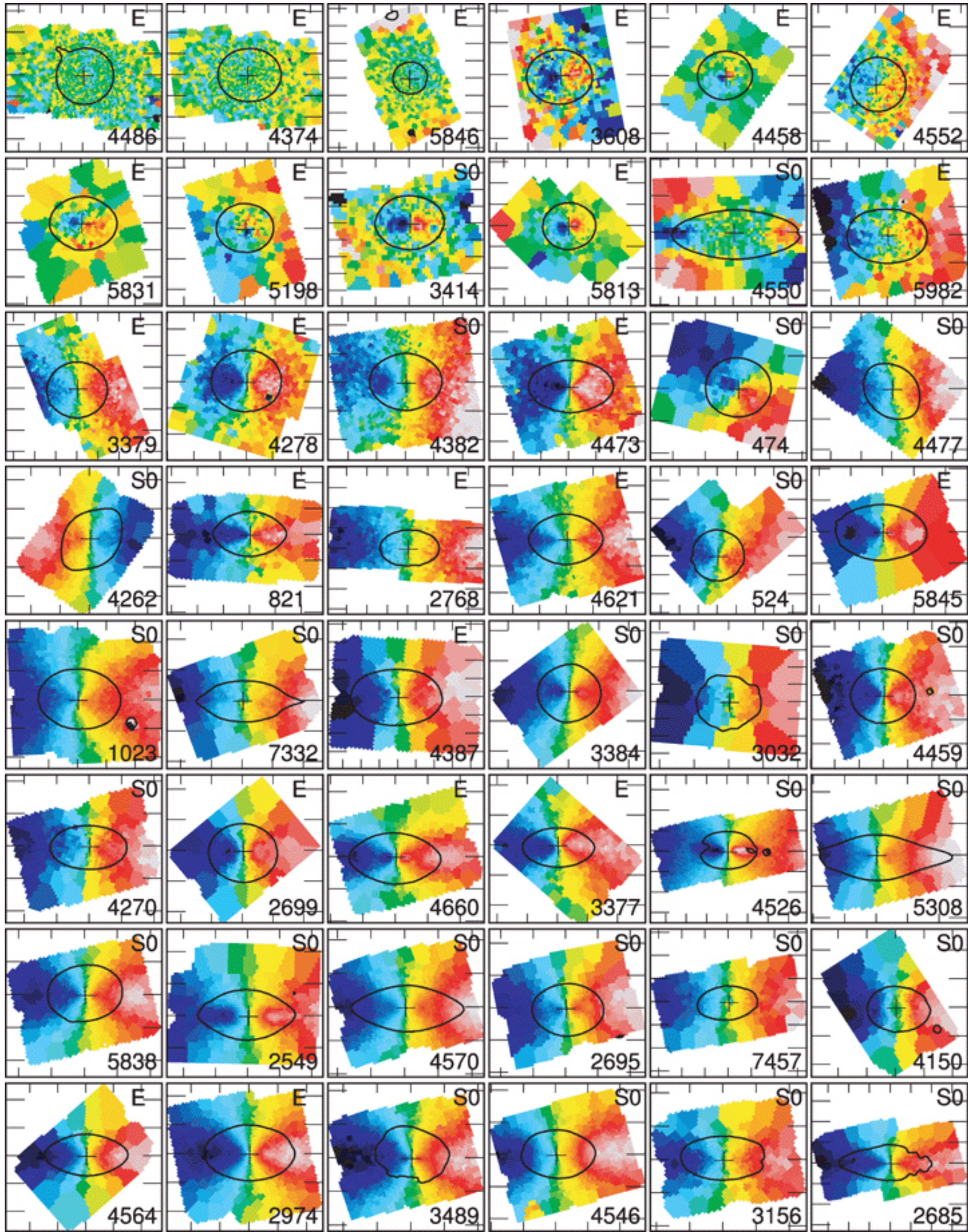
usual rotation




cylindrical rotation

# The Dynamical Support of Bulges

They also find that galaxies can be divided into slow rotators and fast rotators (see Emsellem et al. ‘07).



# The Dynamical Support of Bulges

They define a proxy for angular momentum to separate slow/fast rotators (see Binney ‘05; Emsellem et al. ‘07).

definition:

$$\lambda_R \equiv \frac{\langle R\,|V|\rangle}{\langle R\sqrt{V^2+\sigma^2}\rangle}$$

in practice, with IFU data:

$$\lambda_R = \frac{\sum_{i=1}^{N_\mathrm{p}} F_i R_i |V_i|}{\sum_{i=1}^{N_\mathrm{p}} F_i R_i \sqrt{V_i^2+\sigma_i^2}}$$

# The Dynamical Support of Bulges

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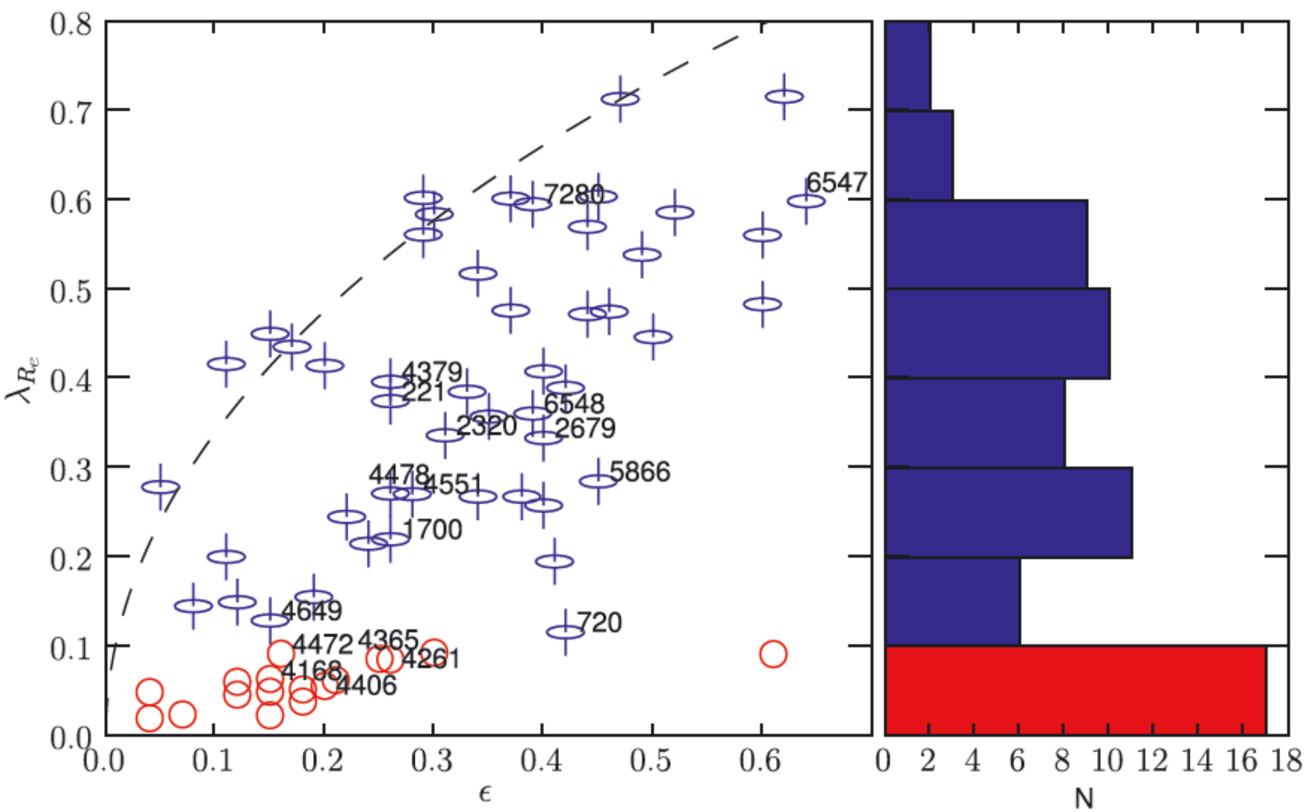
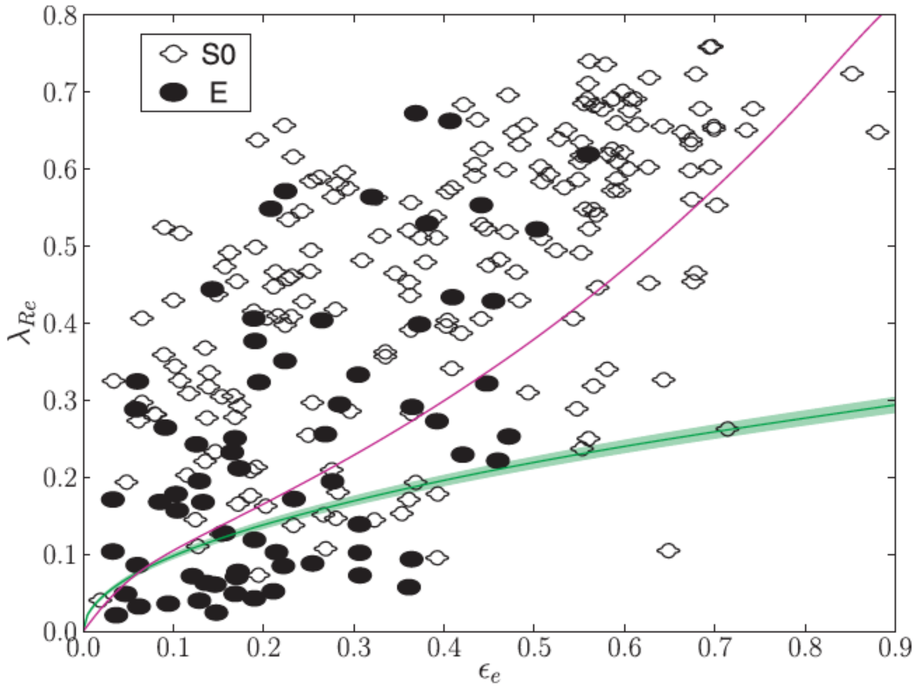



Slow rotators have $\lambda_{Re}$ below 0.1, by definition.

# The Dynamical Support of Bulges

Emsellem et al. ‘11 propose a variation of the definition that takes into account the apparent ellipticity.

Most slow rotators are massive ellipticals, but many ellipticals do rotate fast. As do massive classical bulges. Disky bulges are expected to have a dynamical support even more dominated by rotation.



# Identifying Disky 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 disky bulge. This is of course subjective (see e.g. Fisher & Drory '10).

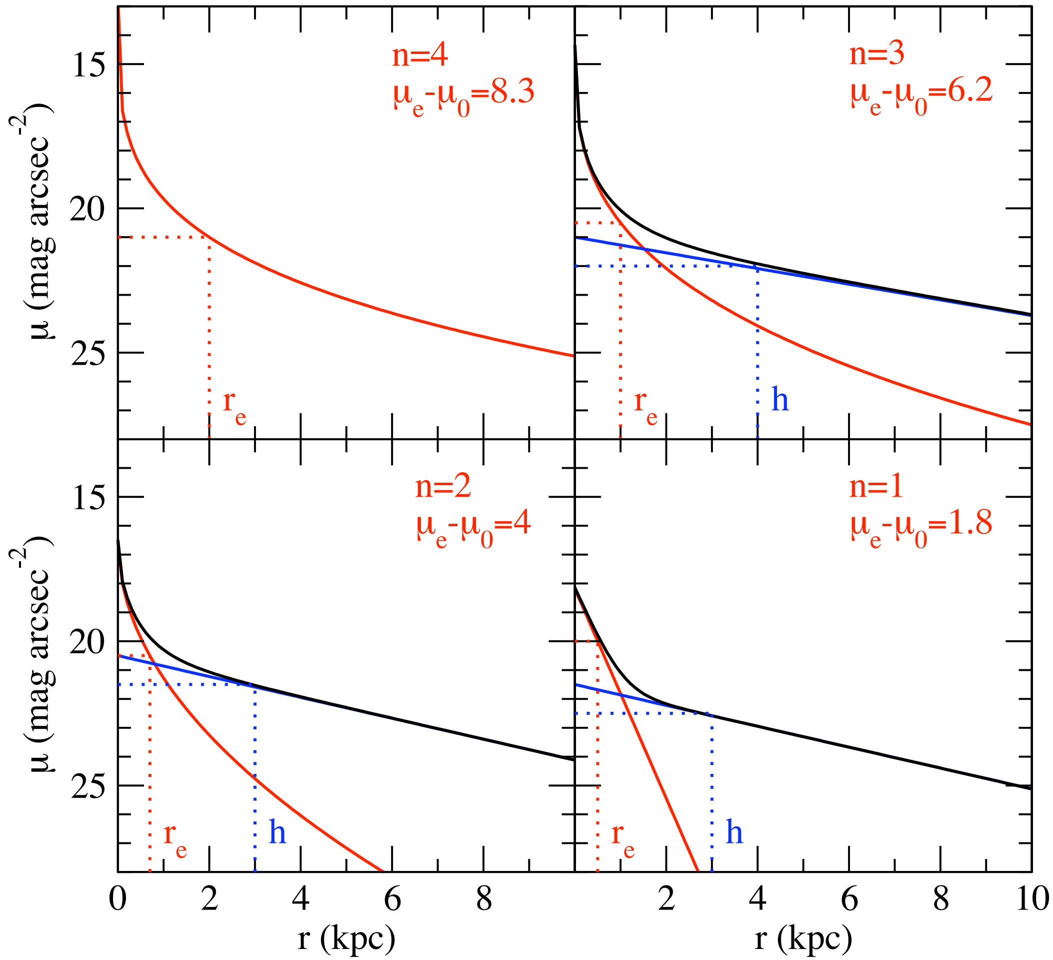
2. From the Sérsic index. There is evidence that disky bulges, as disks, have intensity radial profiles well described by an exponential function, which translates to a Sérsic index n = 1. The Sérsic function is:

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

   where $\mu_e$ 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 disky 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 Disky 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.

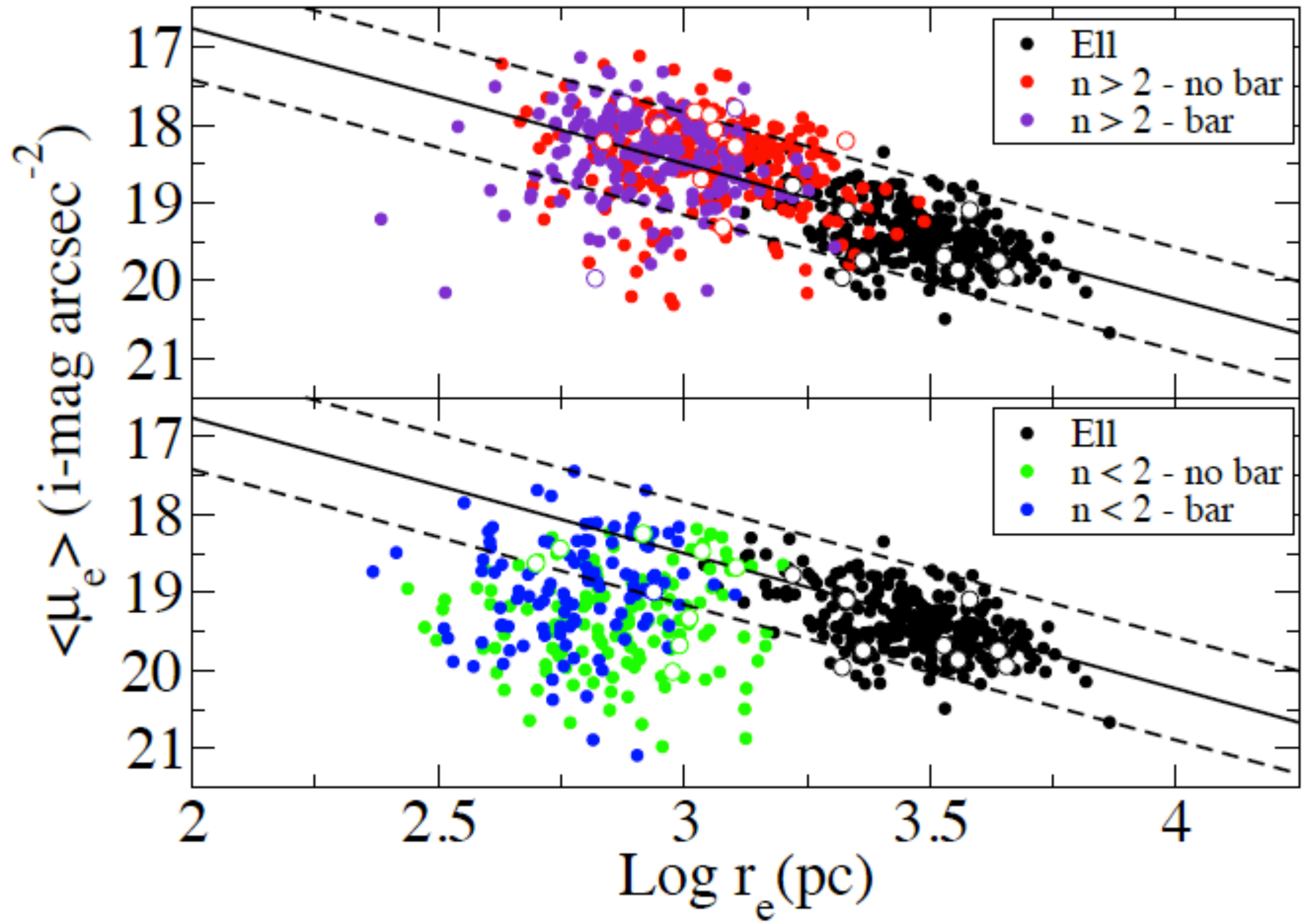



classical

disky

# Identifying Disky Bulges

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



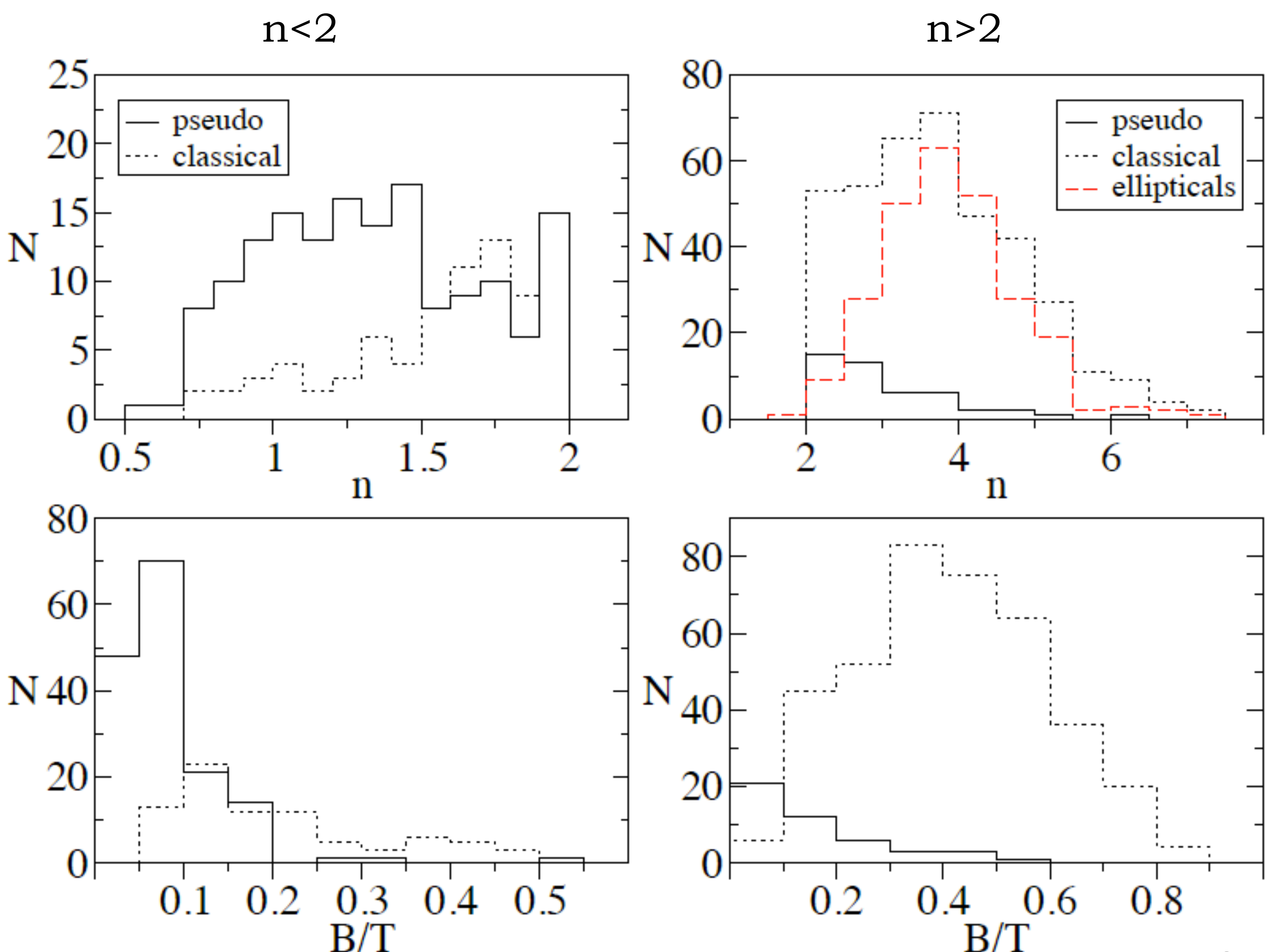
# Identifying Disky Bulges

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

Disky bulges satisfy (SDSS i-band):

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

# Identifying Disky Bulges

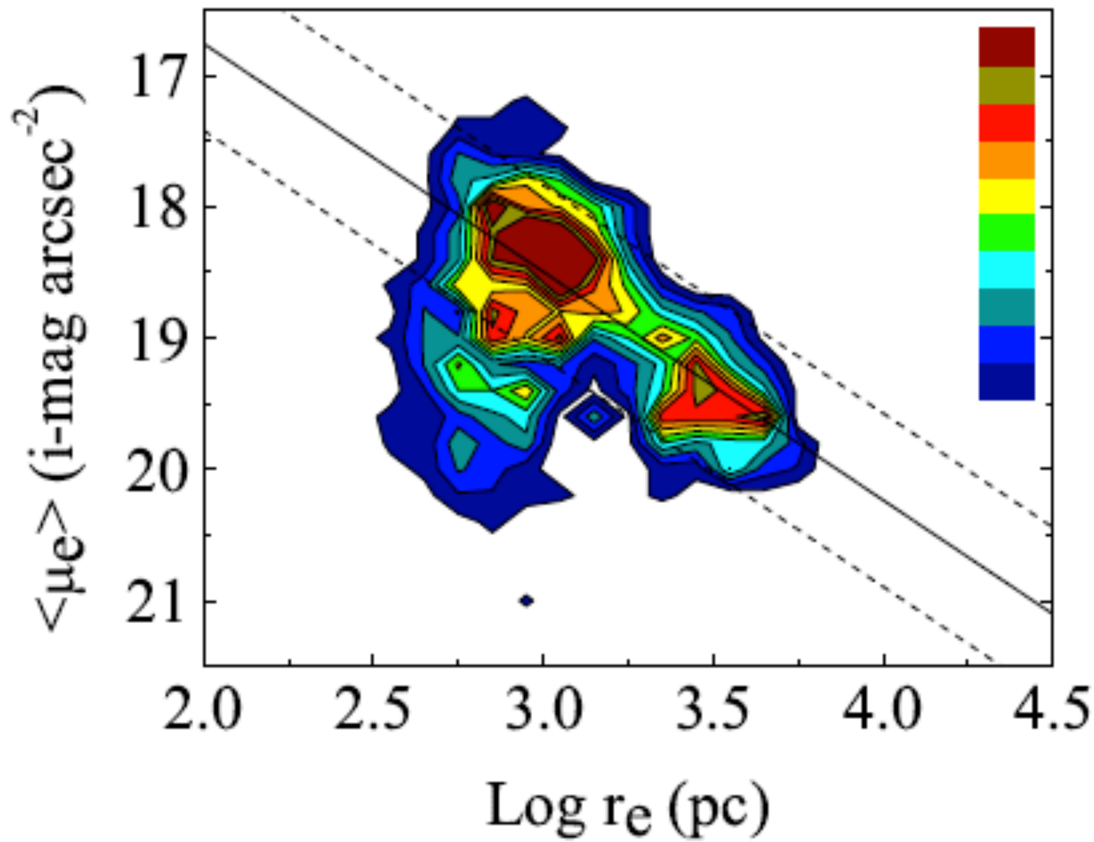



Gadotti '09

# Identifying Disky Bulges

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

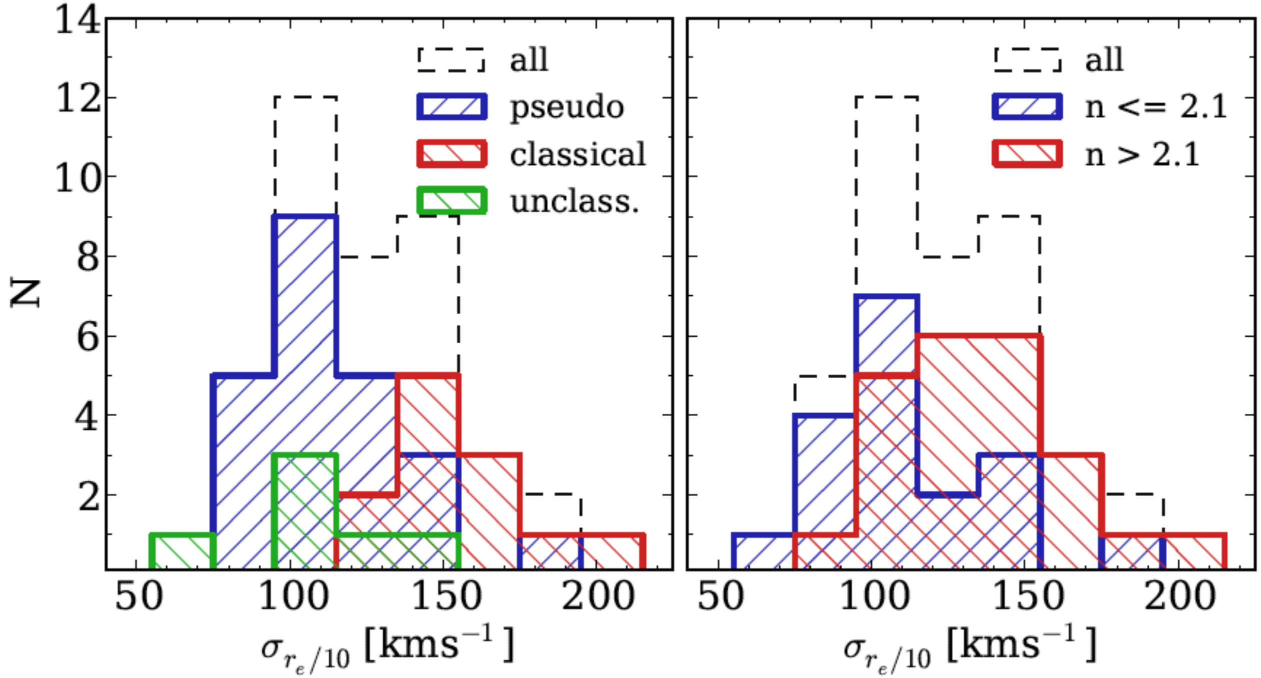
A section with composite bulges can also be seen between classical and disky bulges.




Gadotti '09

# Identifying Disky Bulges

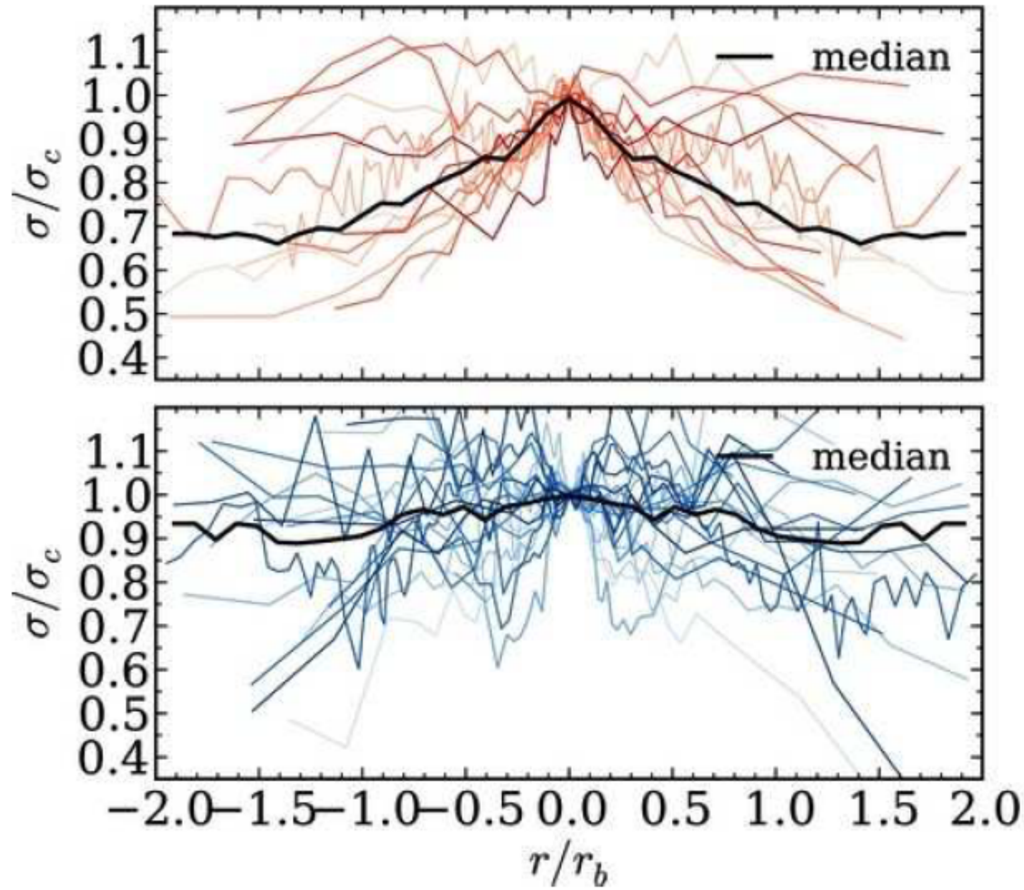
A promising way to identify disky bulges is of course from kinematics, but more work is needed, and it is expensive in terms of telescope time. Fabricius et al. ('12) combined different criteria to identify disky bulges, including kinematics.




Disky bulges usually have lower velocity dispersion than classical bulges.

# Identifying Disky Bulges

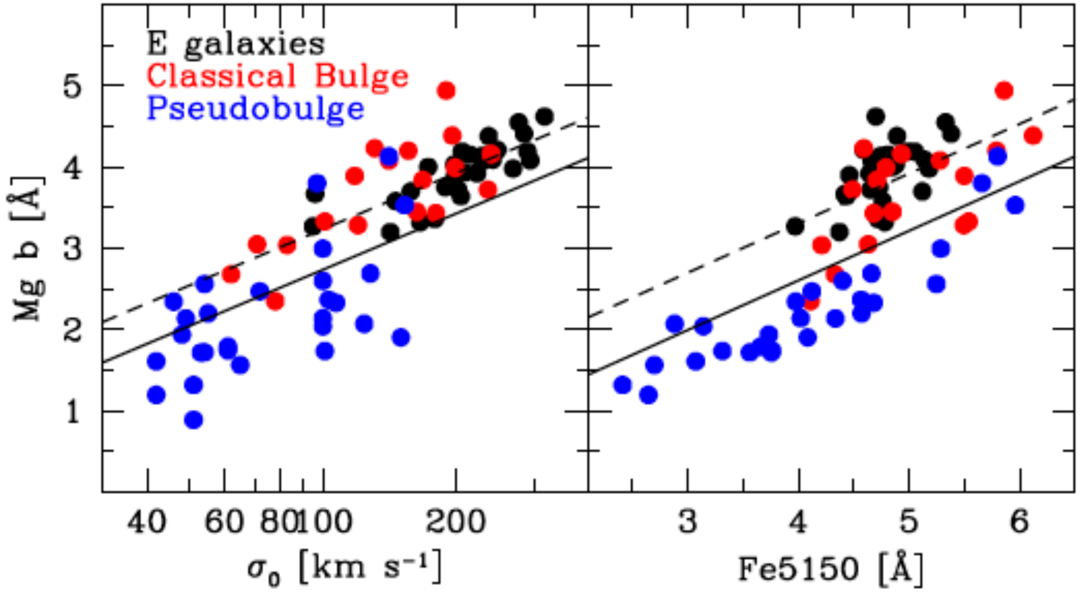
Disky bulges also tend to have flatter radial profiles of velocity dispersion.



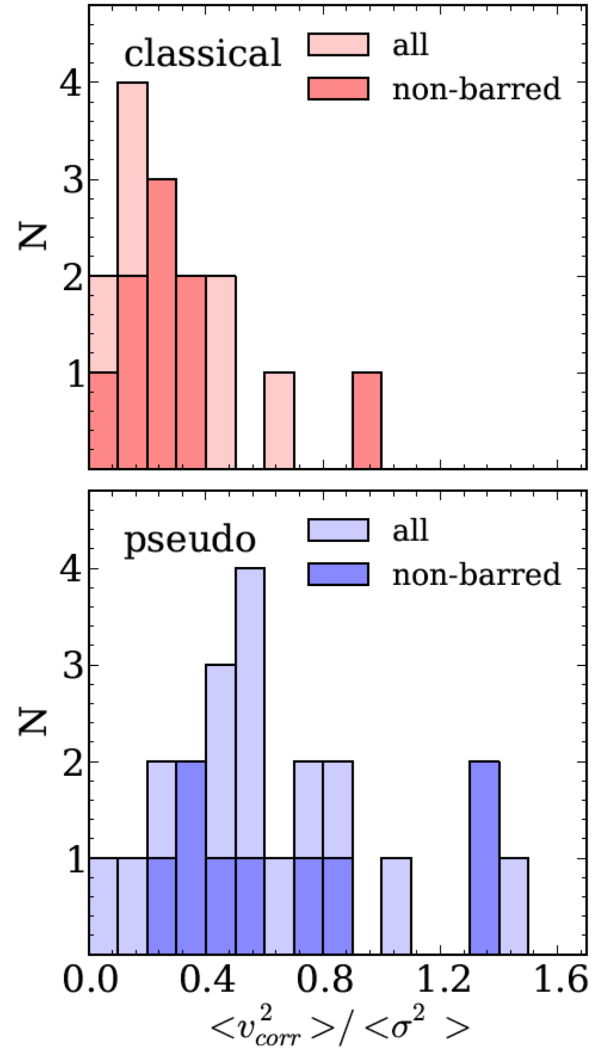

Fabricius et al. '12

# Identifying Disky Bulges

Disky bulges also tend to be more rotationally supported and have different correlations with Lick indices.



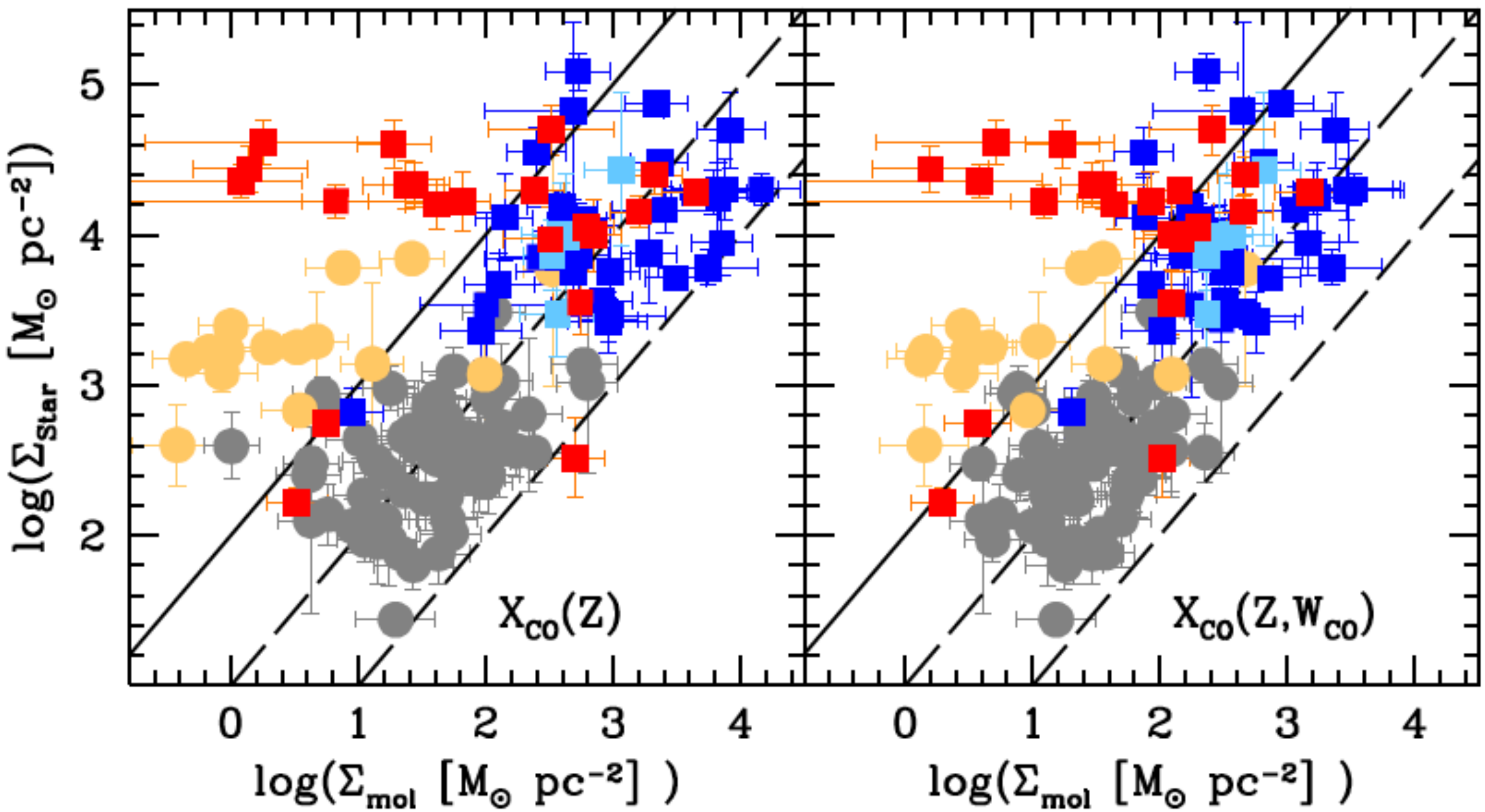

Fisher & Drory ‘15




Fabricius et al. ‘12

# Identifying Disky Bulges

Disky bulges have higher gas surface density (Fisher et al. ‘13).



# 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),

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

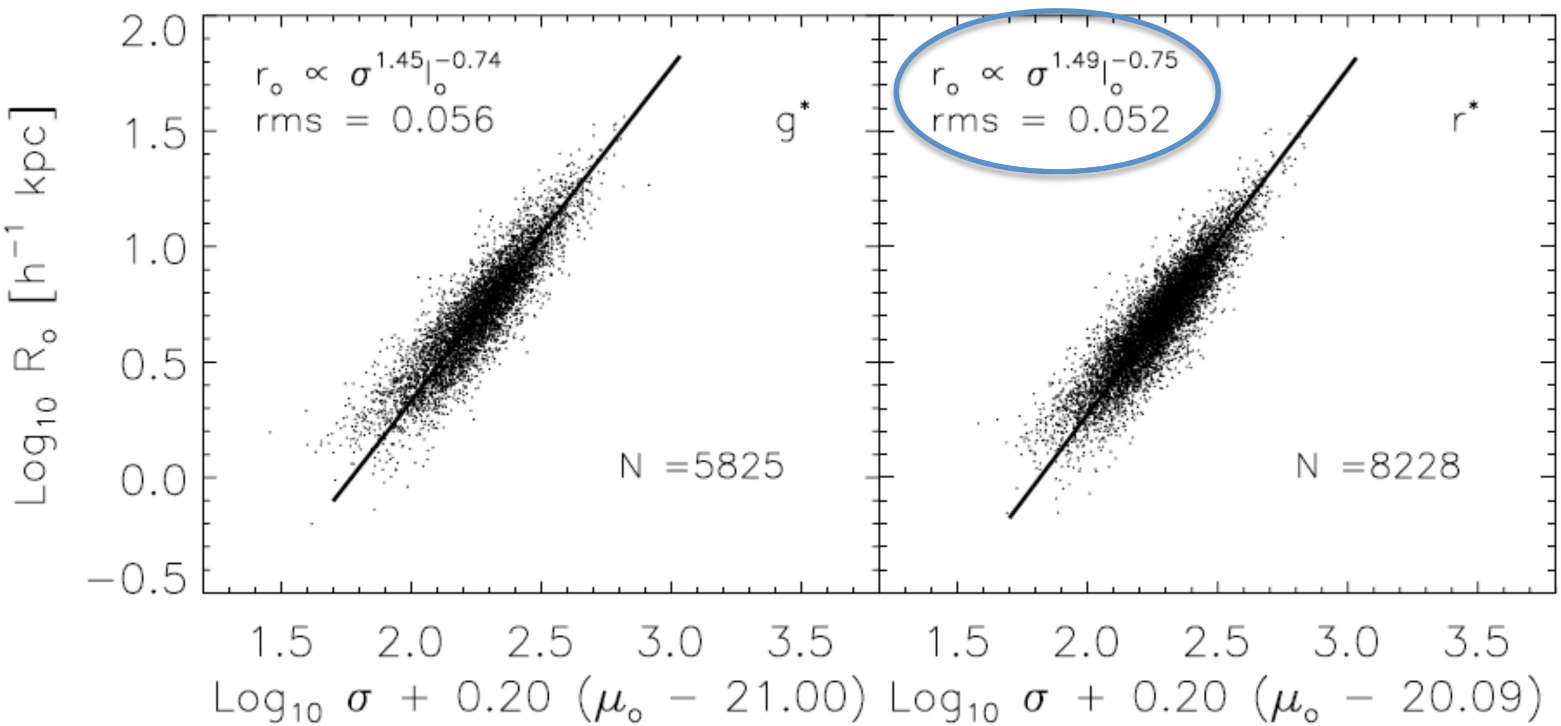
or

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

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.

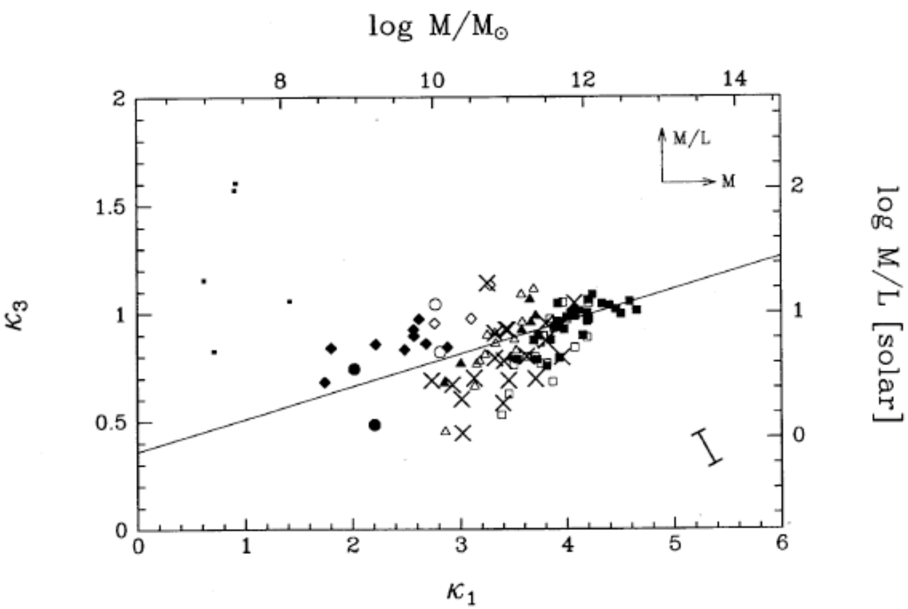
Why is there a tilt (see e.g. Trujillo et al. ‘03)?

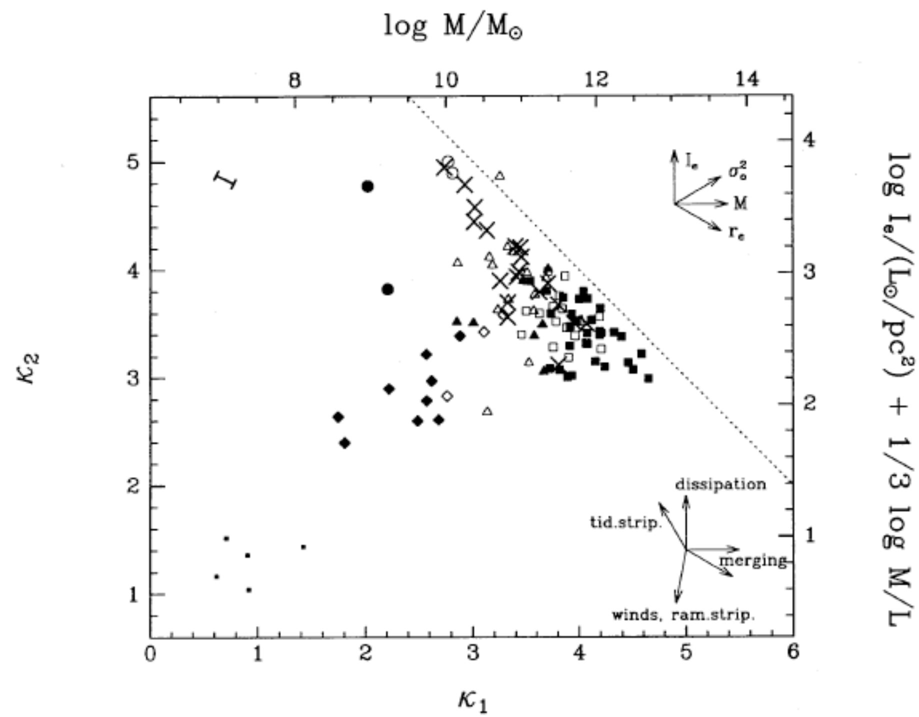
- mostly: systems are not homologous, i.e. the shape of the potential might depend on scale, system size (indeed, the Sérsic index varies with galaxy luminosity)

- 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):

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



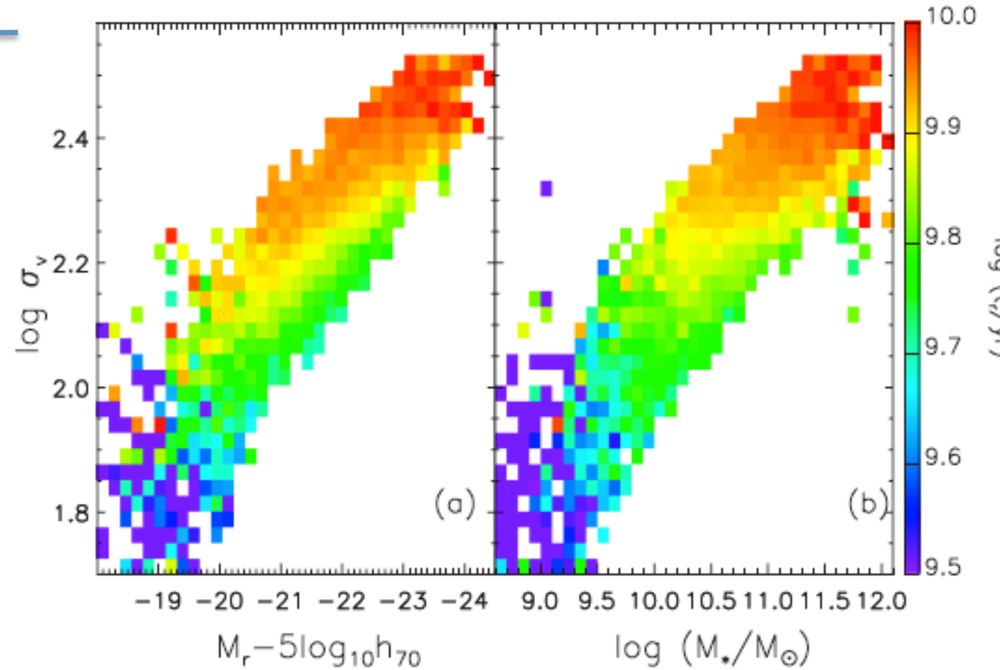



Projections of the FP are also important relations.

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)

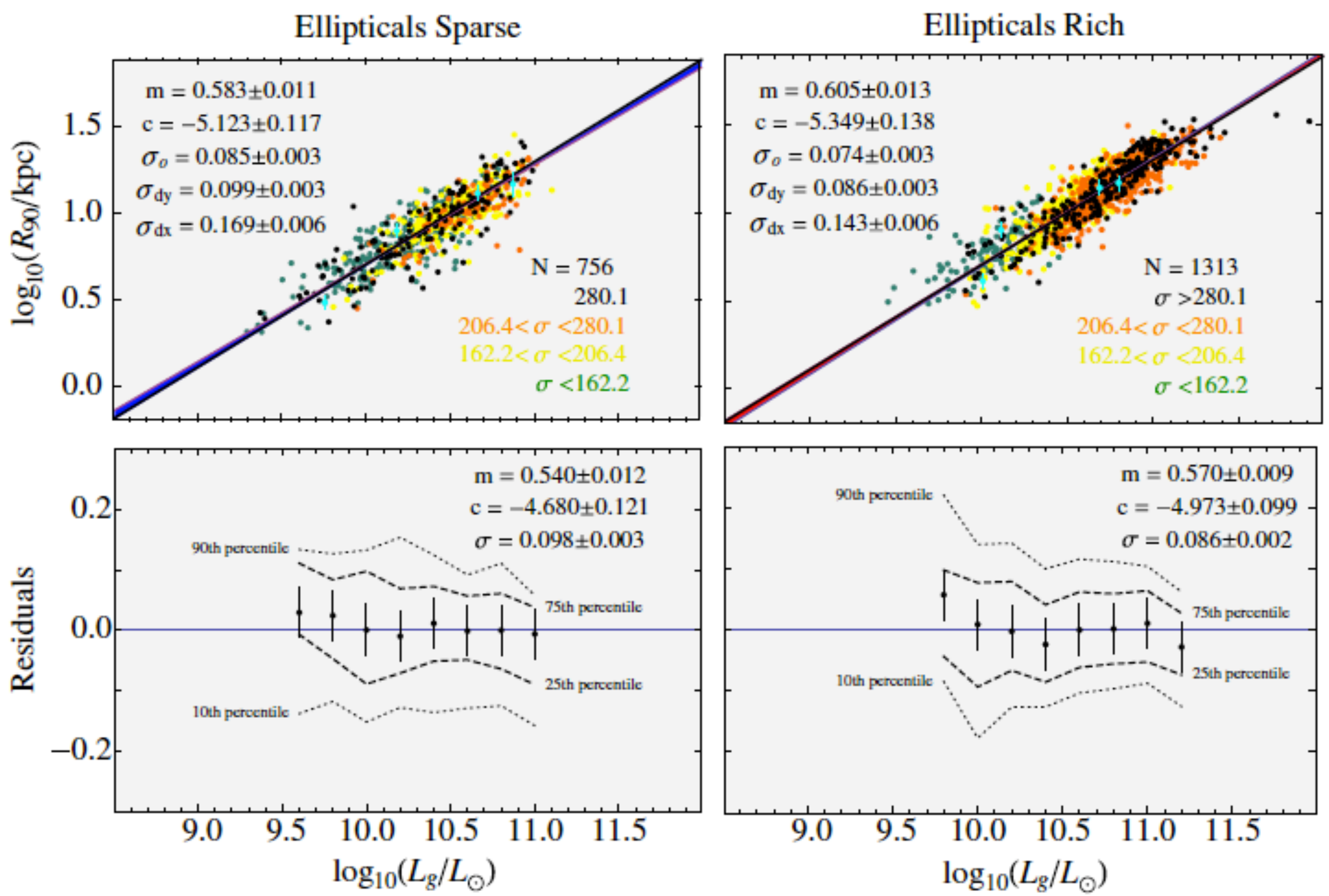



stellar mass (slope ~ 3.5)

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?

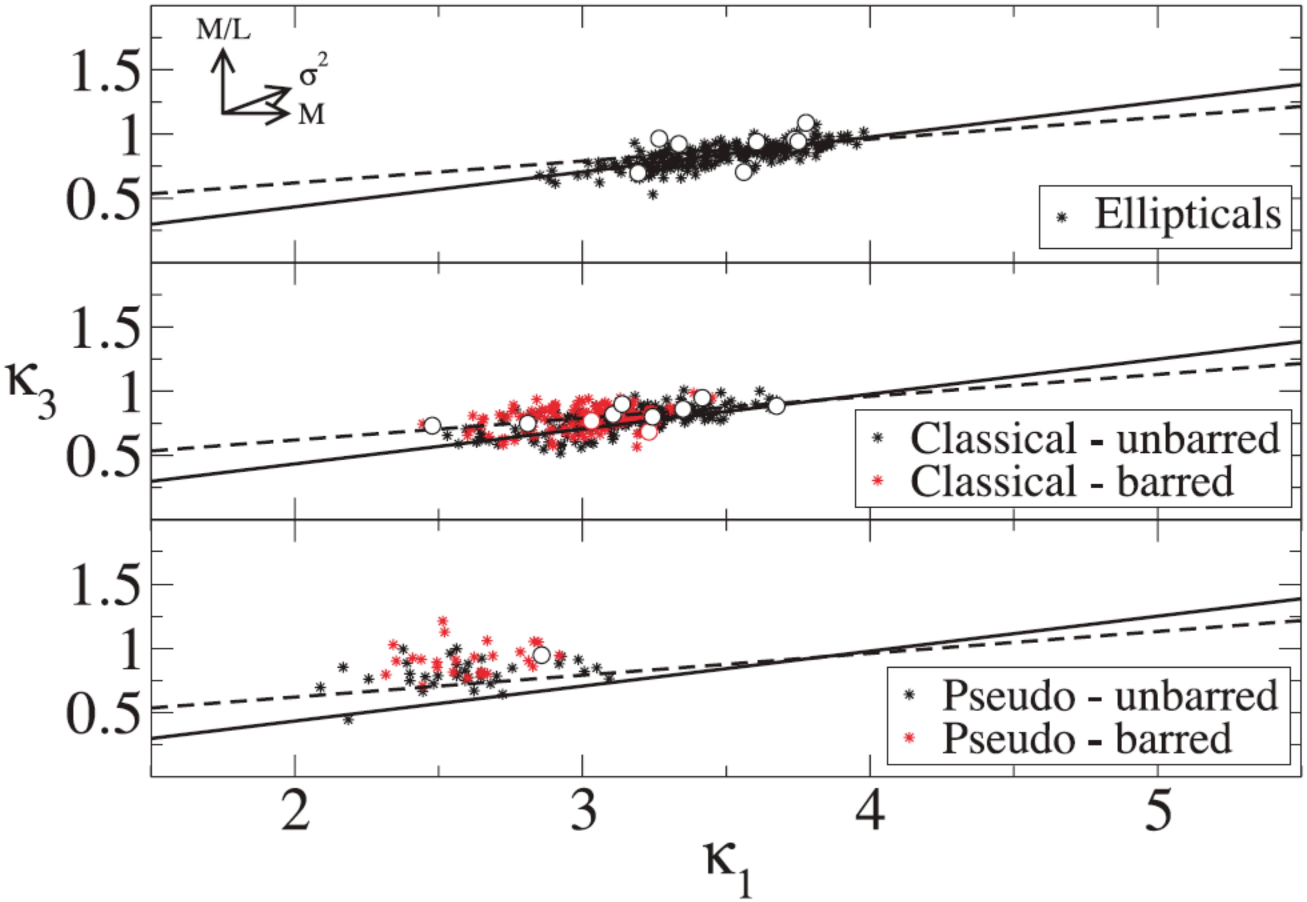
- Systematic properties come from gravity acting

- 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?

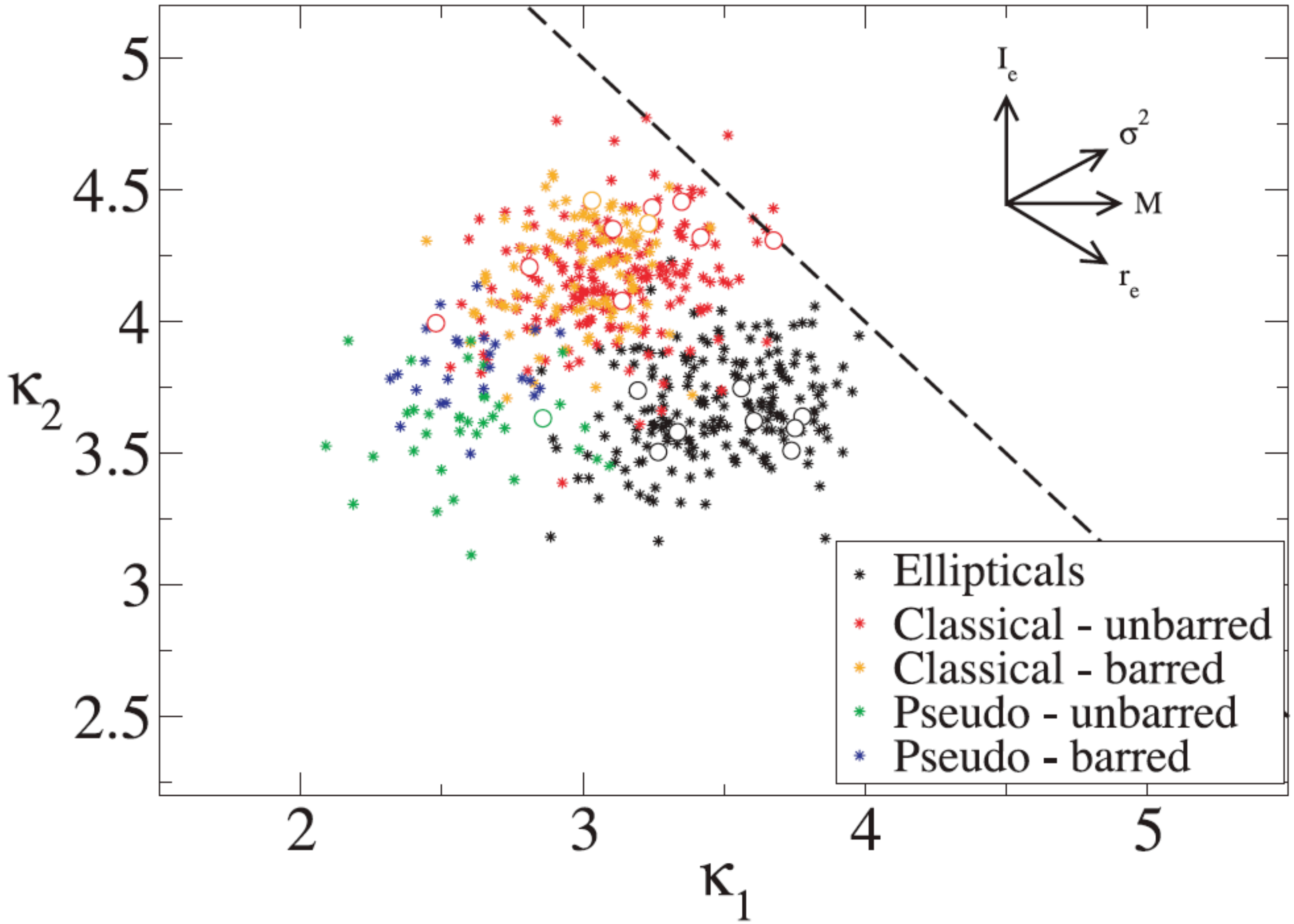
Disky bulges and classical bulges deviate from ellipticals, the former more noticeably than the latter (the dashed line is from Bernardi et al. '03). There is no clear distinction between barred and unbarred galaxies (although perhaps a slight offset).




Gadotti '09

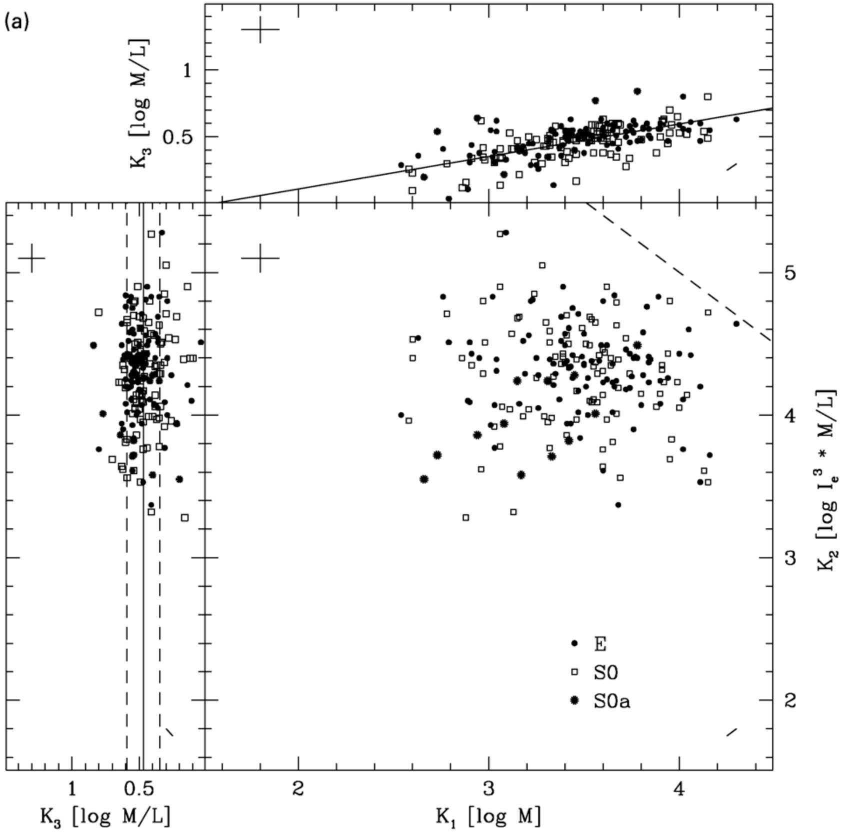
Where do bulges and ellipticals fall in the face-on view of the FP?

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

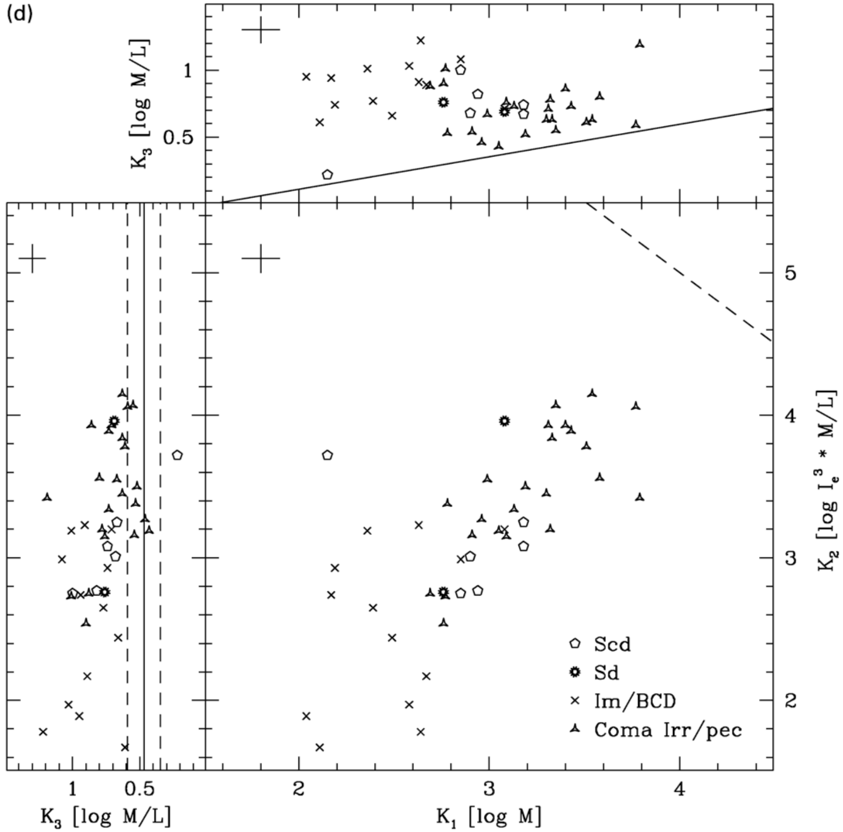



Gadotti '09

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




early-type

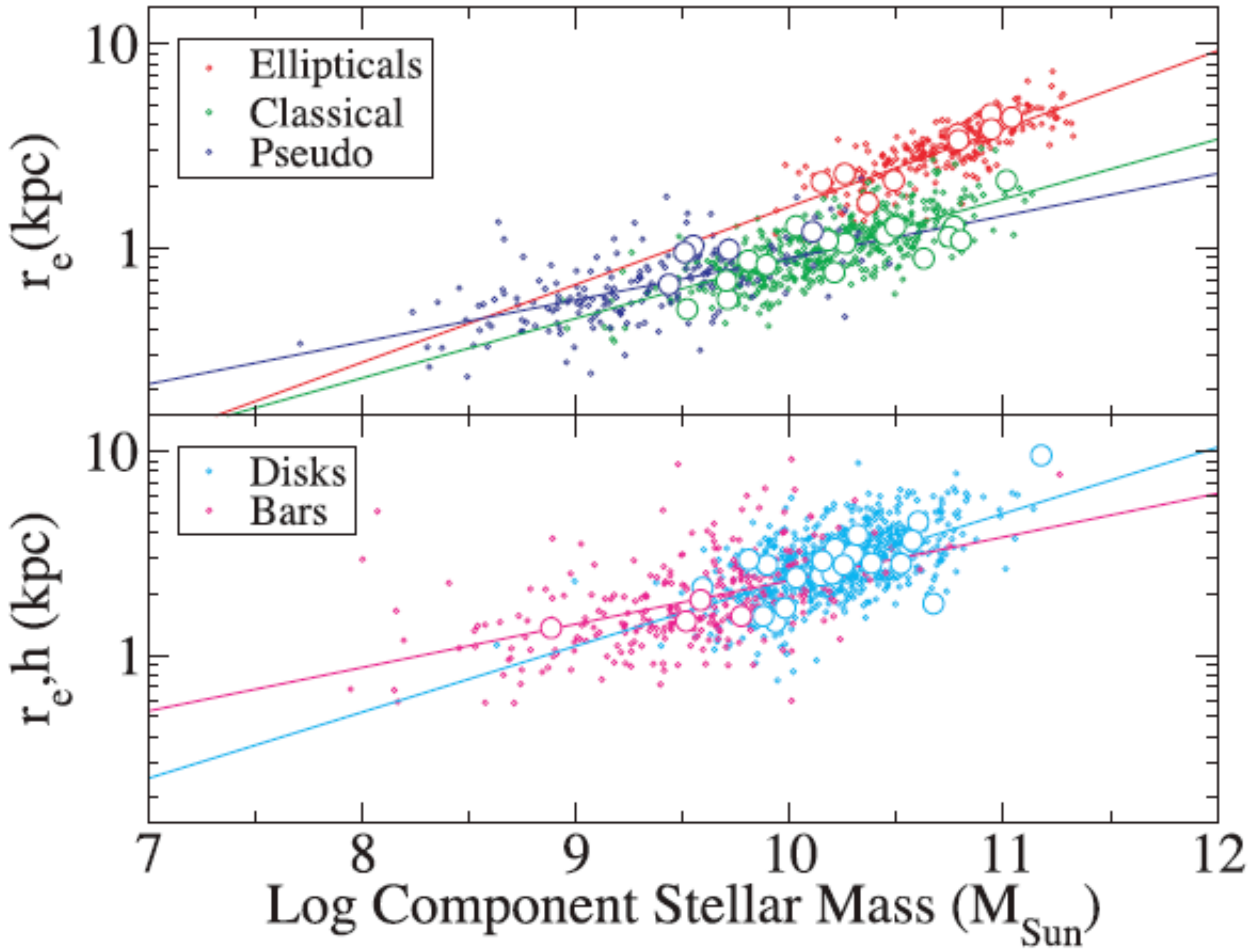



late-type

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

log (size) = alpha × log (mass)

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

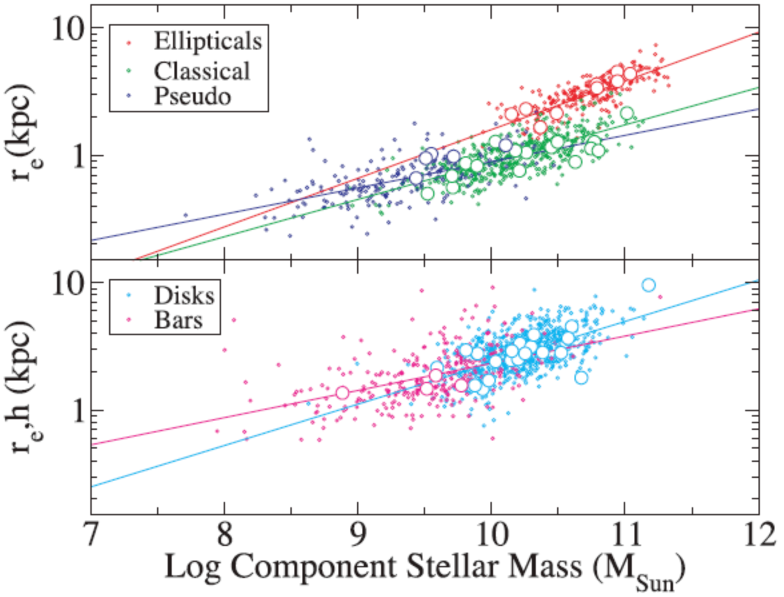


➢ The mass-size relation of disky bulges is different from that of classical bulges by 5σ

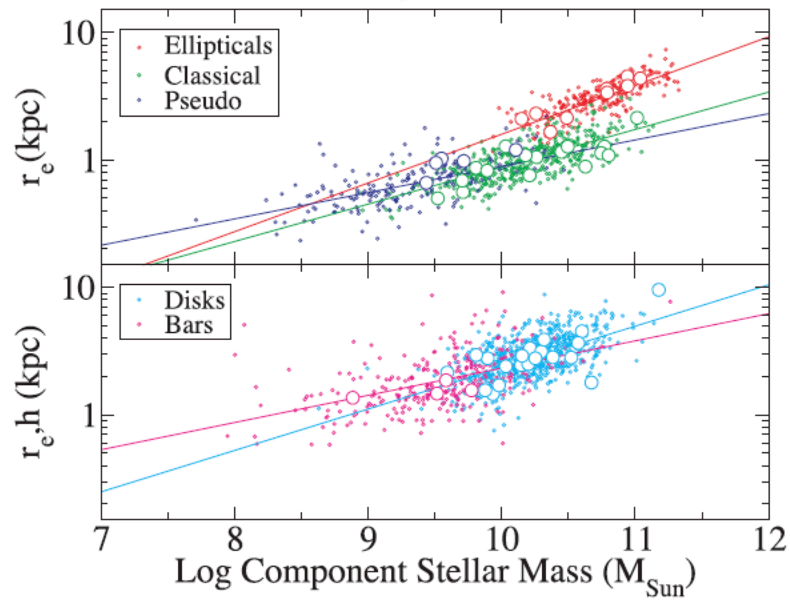
➢ The mass-size relation of classical bulges is different from that of ellipticals by 4σ

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

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

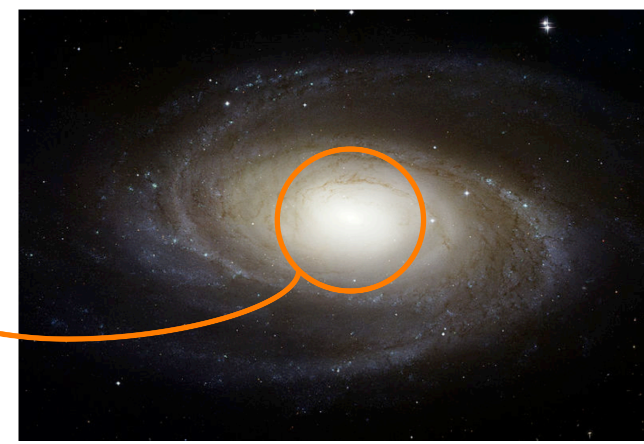
# The Stellar Mass Budget at Redshift Zero

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

- ~ 36% in disks

- ~ 3% in disky bulges
- ~ 4% in bars
- ~ 32% in elliptical galaxies

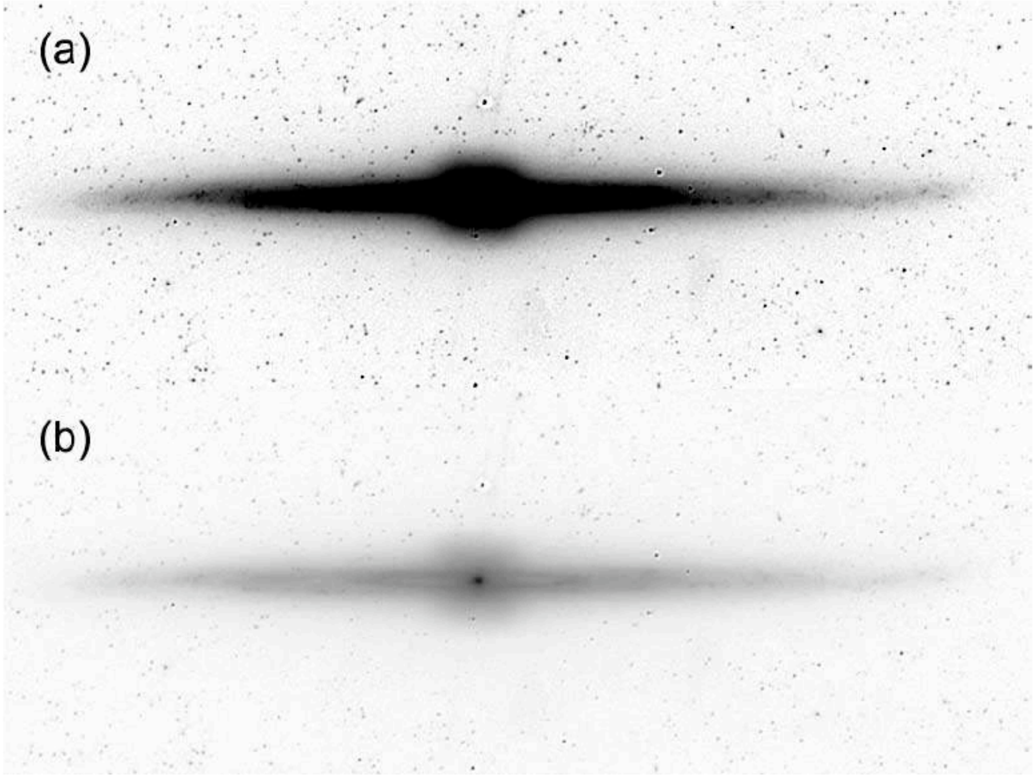
- ~ 25% in classical bulges



Gadotti '09

# Composite Bulges

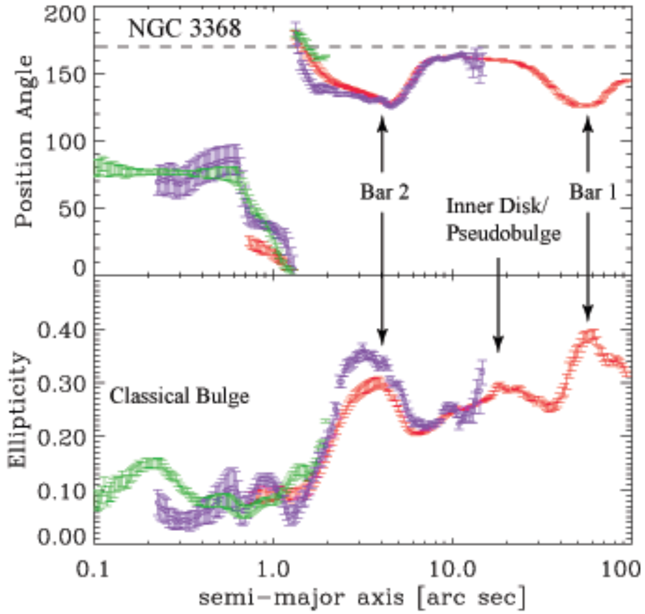
It is evident that a single galaxy can have a classical bulge AND a disky bulge. It can also have a box/peanut (see e.g. Kormendy & Barentine '10).

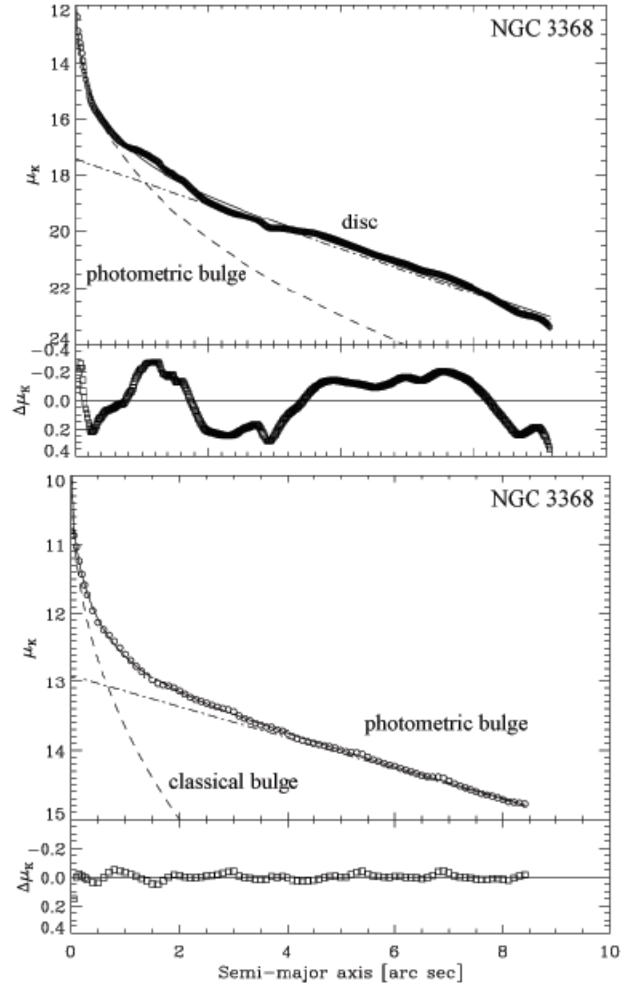



IRAC-1 image of NGC 4565. The disky bulge is the tiny structure in the center.

# Composite Bulges

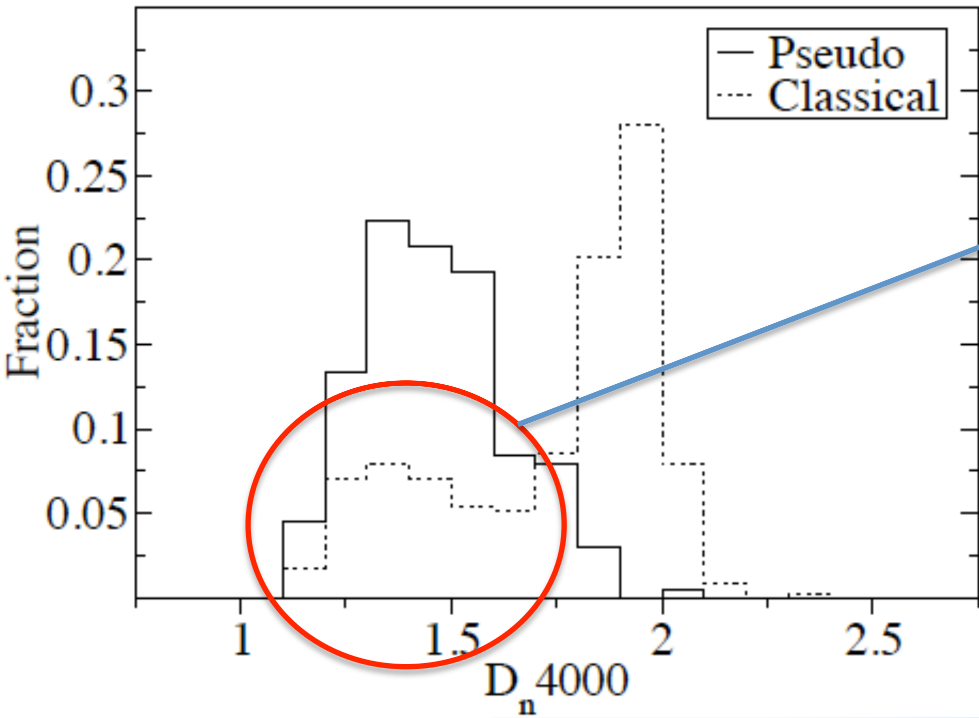
Nowak et al. (‘10) argue that they find two galaxies with a small classical bulge inside a disky bulge.



# Composite Bulges

Gadotti ('09) suggests that the presence of small star-forming disk-like bulges inside classical bulges can be relatively common.




These bulges are structurally like classical bulges, but show high on-going star formation activity, like disky bulges.

low $D_n4000$ means high on-going star formation activity

# Composite Bulges

Mendez-Abreu et al. '14 find only 3/10 galaxies hosting a single bulge (1 classical bulge).

Erwin et al. '14 study 9 galaxies with composite bulges and suggest that a fraction of them hosts bulges from the three different families.

# Host Galaxies and Environment

Having low B/T, galaxies with disky bulges are naturally late-type spirals. Durbala et al. ('08) find them to be predominantly in low density environments.

Mathur et al. ('11) and De Xivry et al. ('11) show evidence that galaxies that are narrow-line Seyferts type 1 (NLS1) host disk-like bulges. High accretion rates might be fuelled by bars.

(NLS1: small black holes, high accretion rates.)

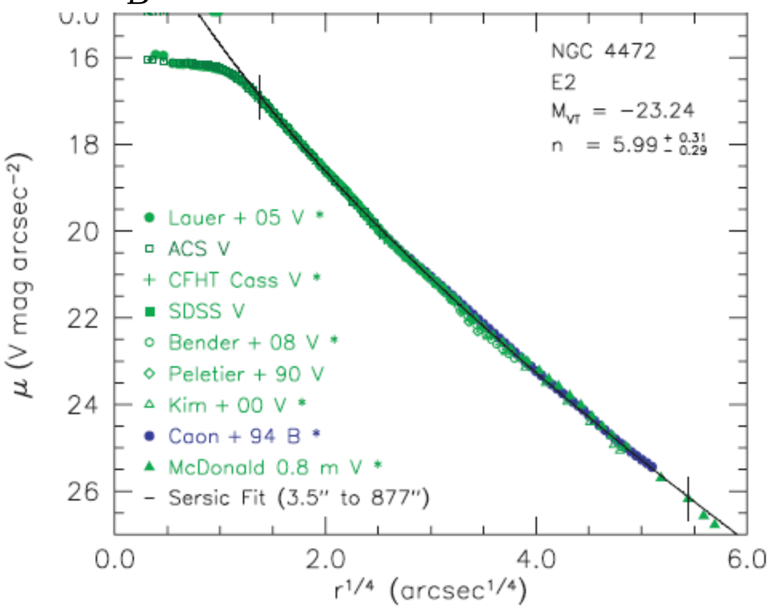
# Elliptical Galaxies

Although there is no consensus in the literature, there are suggestions that elliptical galaxies are characterized by two dichotomies (see e.g. Graham et al. ‘03; Trujillo et al. ‘04; Ferrarese et al. ‘06; Kormendy et al. ’09; Graham ‘11):

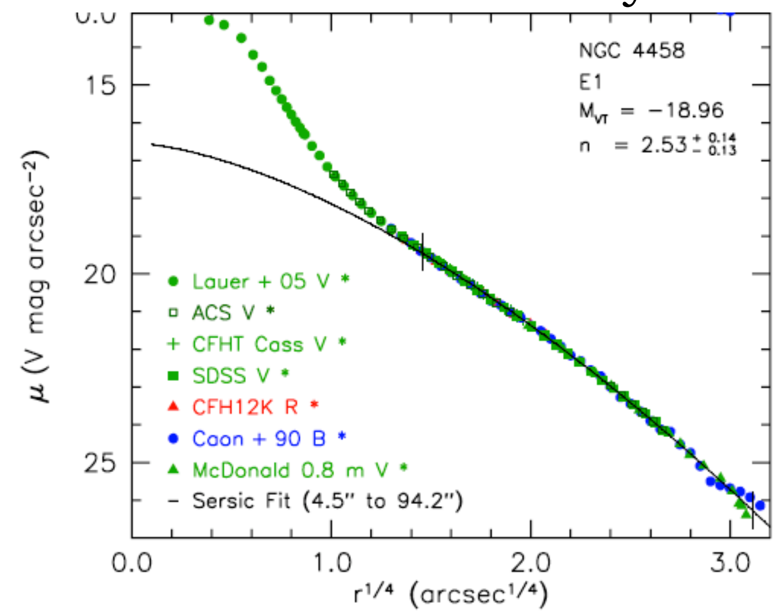
1. core-depleted vs. extra-light (coreless; power-law)

At $M_B$ ~ -20.5

Kormendy et al. ‘09

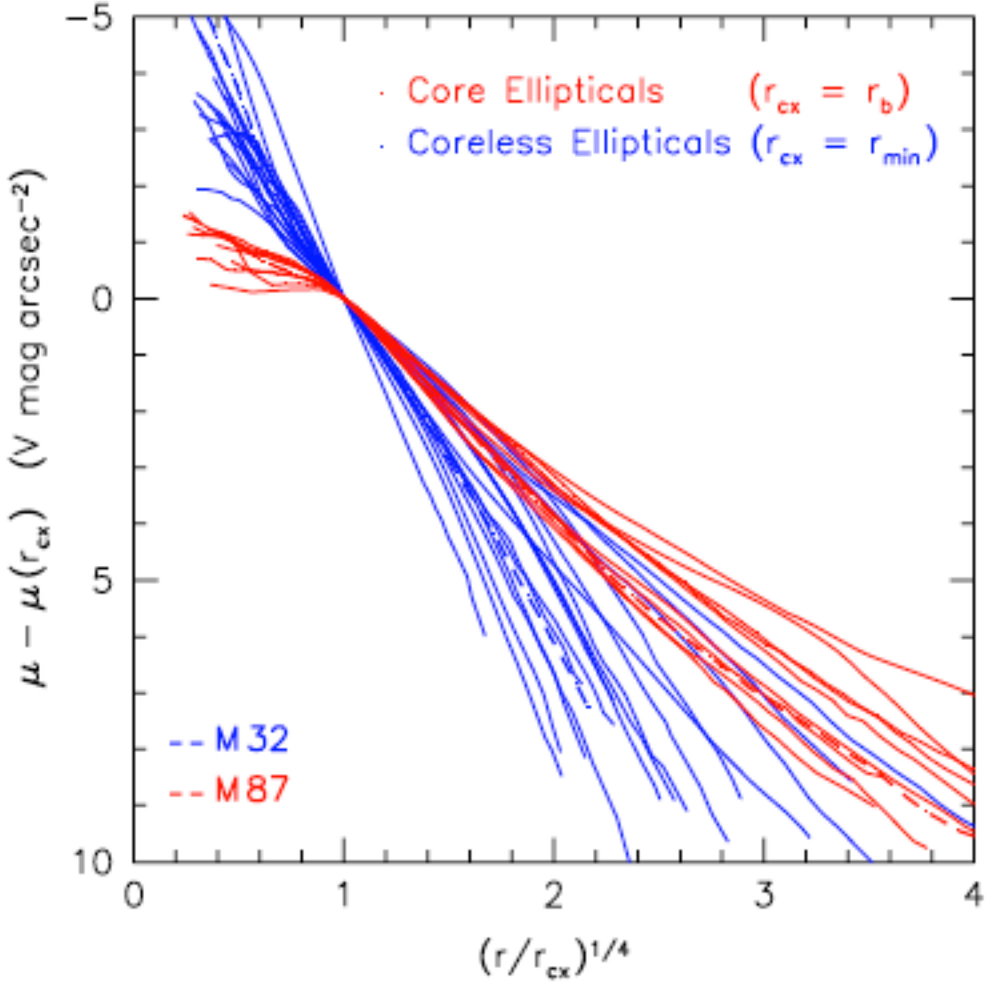



core-depleted




extra-light

# Elliptical Galaxies

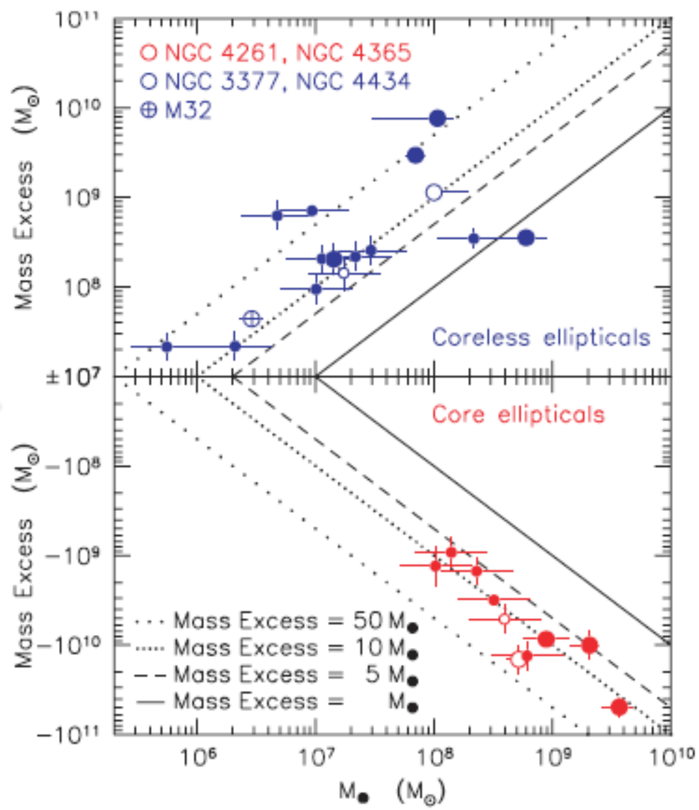



Kormendy et al. ‘09

# Elliptical Galaxies

Mass deficits in core galaxies are probably caused by the slingshot effect of binary supermassive black holes in dissipationless mergers. Stars can even be ejected from galaxy!

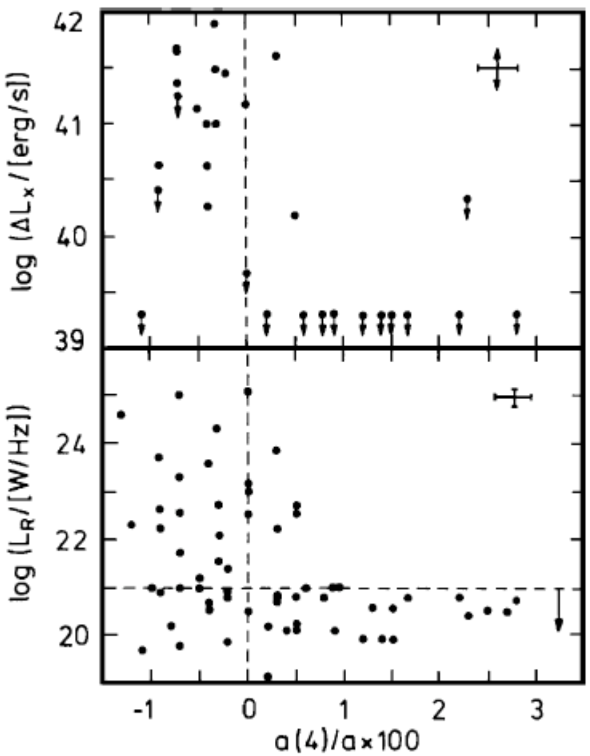
Might give an indication of how many mergers.

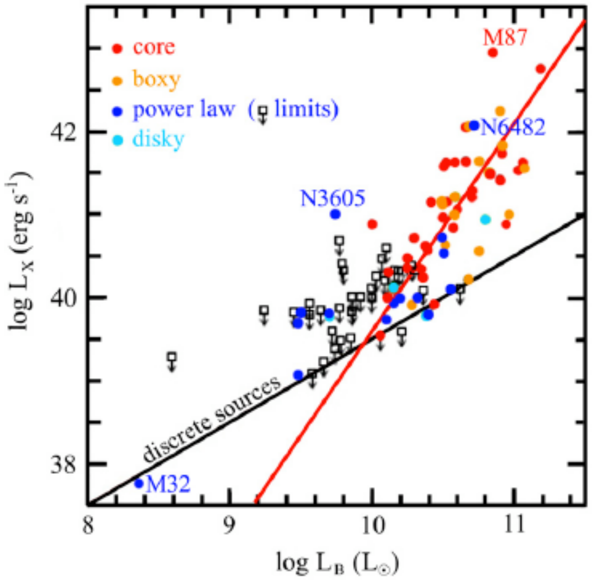


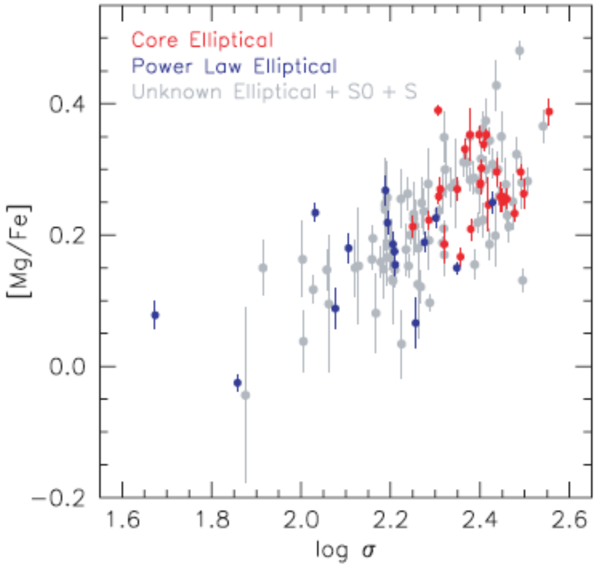

Kormendy et al. ‘09

# Elliptical Galaxies

Core galaxies rotate slowly, have boxy shape, are radio-bright, X-ray-bright and α-enhanced, as compared to extra-light galaxies (Kormendy et al. '09).



# Elliptical Galaxies

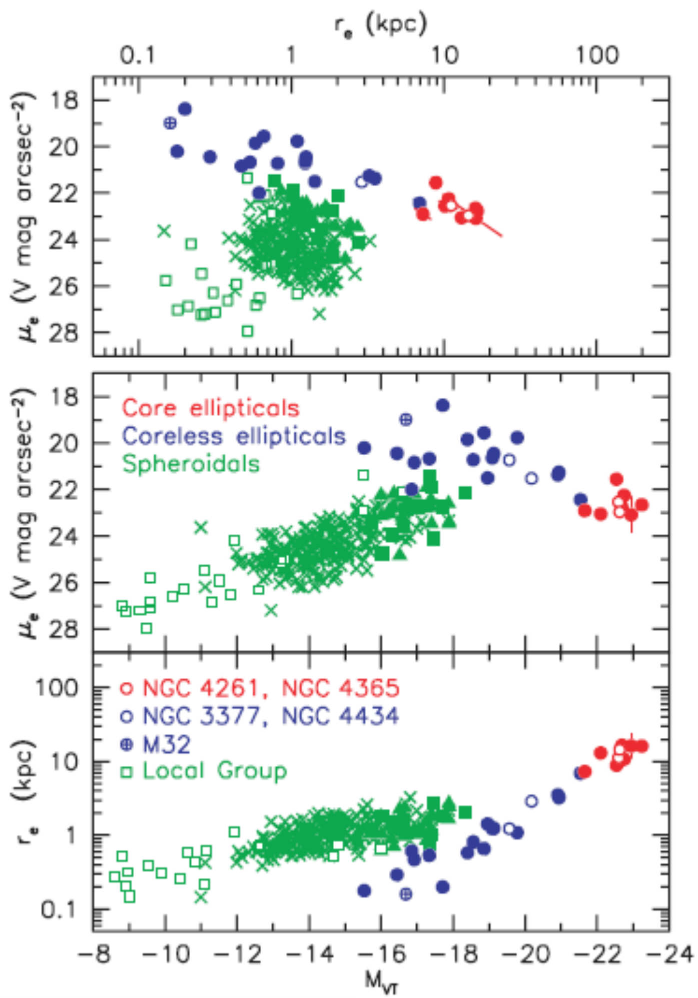
Kormendy et al. ('09) suggest that core ellipticals form via dry, dissipationless mergers. They are also kept with a core due to the heating of external gas through AGN feedback.

Extra-light ellipticals would thus form via wet, dissipative mergers. Starbursts would occur in these mergers and originate the extra component.

# Elliptical Galaxies

2. giants (bright) vs. dwarfs (faint; spheroidals)

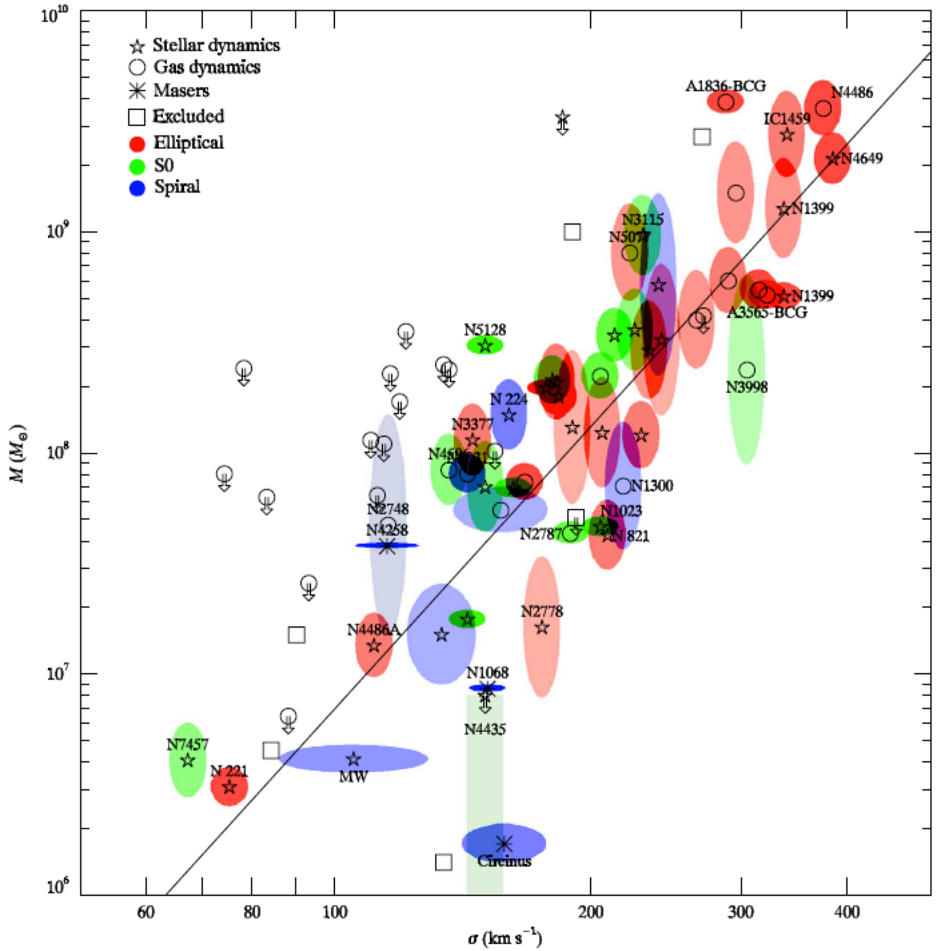
At $M_B$ ~ -18

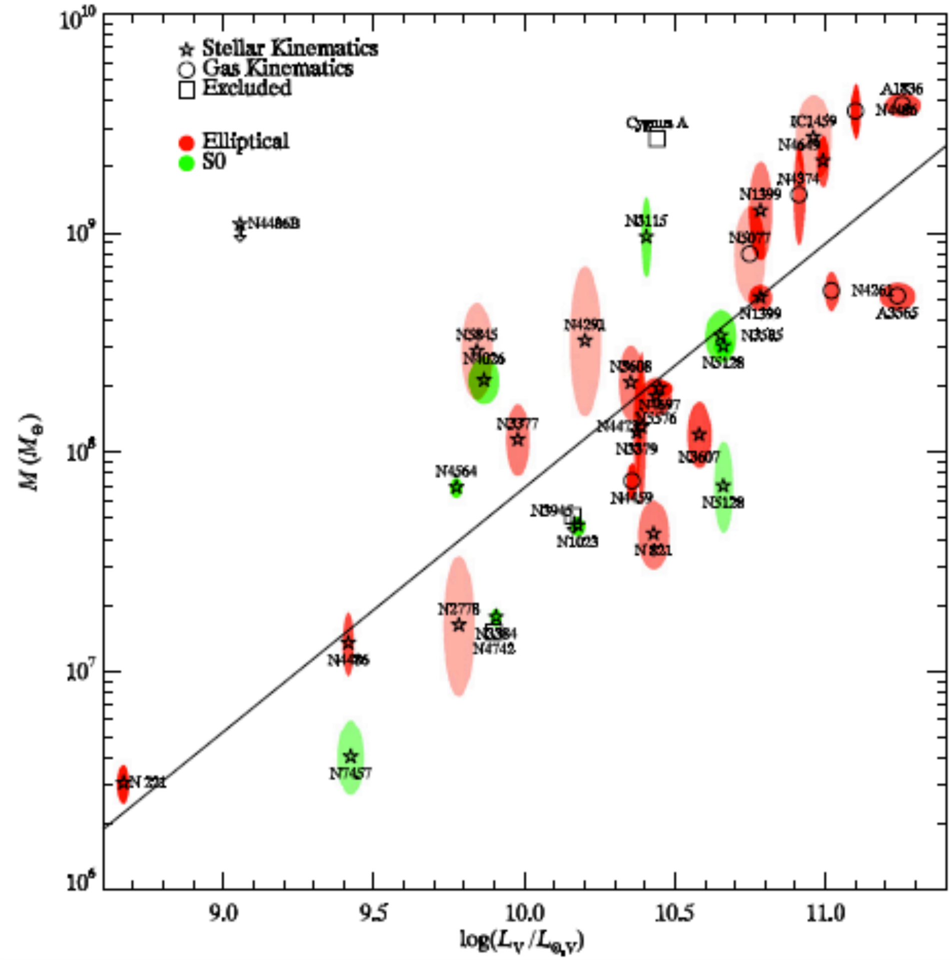



Kormendy et al. ‘09

# SMBHs and their scaling relations

We think that a SMBH resides at the heart of every (massive) galaxy. Their masses are correlated with central velocity dispersion and bulge luminosity (or mass, see e.g. Gueltekin et al. '09).



# SMBHs and their scaling relations

This suggests a connected growth of bulges (and ellipticals) and SMBHs. The latter would accrete mass until AGN feedback regulates the inflow of gas, the growth of the SMBH and the formation of stars in the bulge (or elliptical, see e.g. Younger et al. ‘08).

The building of disky bulges would not be connected with the (bulk of the) growth of the SMBHs. Disky bulges come after.

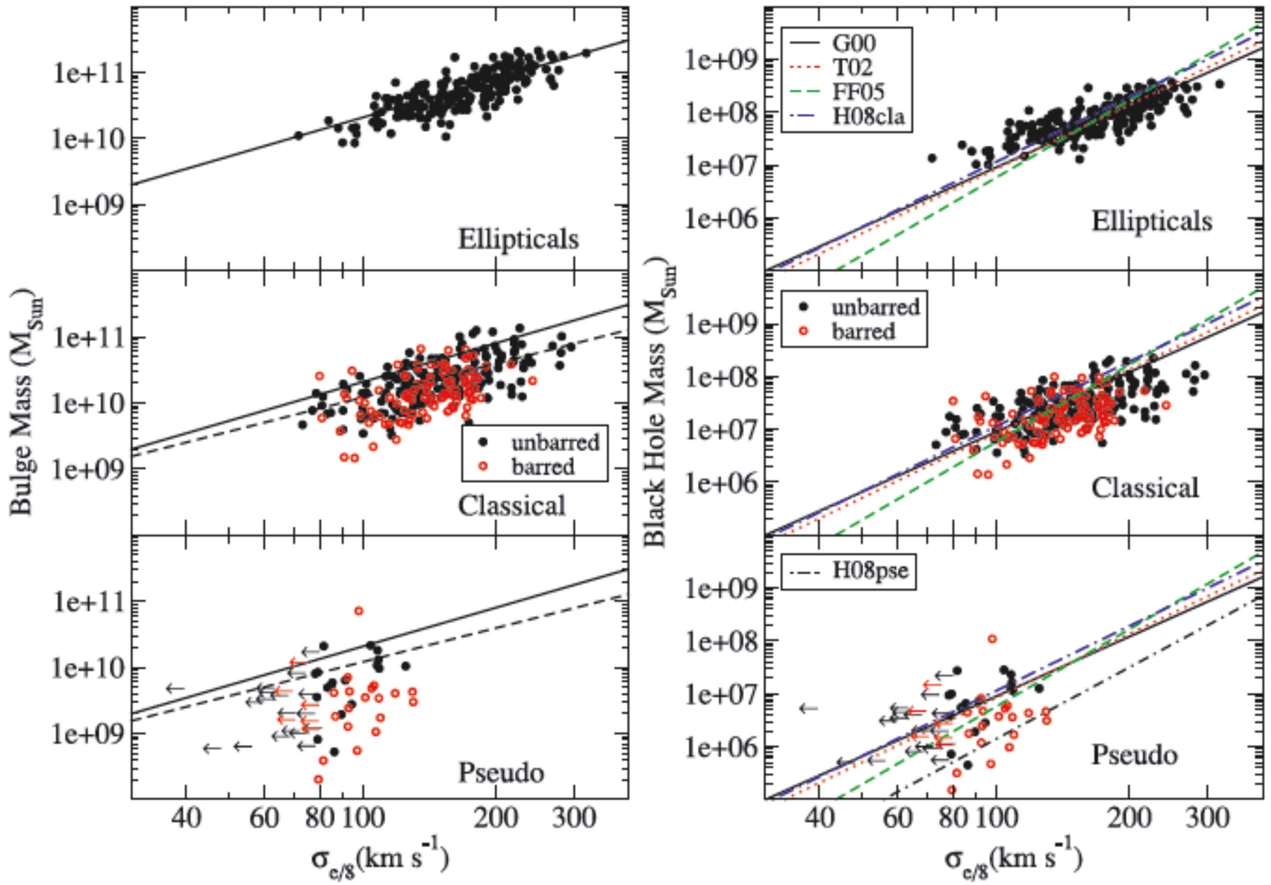
# SMBHs and their scaling relations

Graham ('08) shows evidence that barred galaxies increase scatter in the SMBH scaling relations. Hu ('08) finds different relations for what he classified as pseudo-bulges, a sub-sample which comprises almost exclusively barred galaxies.

# SMBHs and their scaling relations

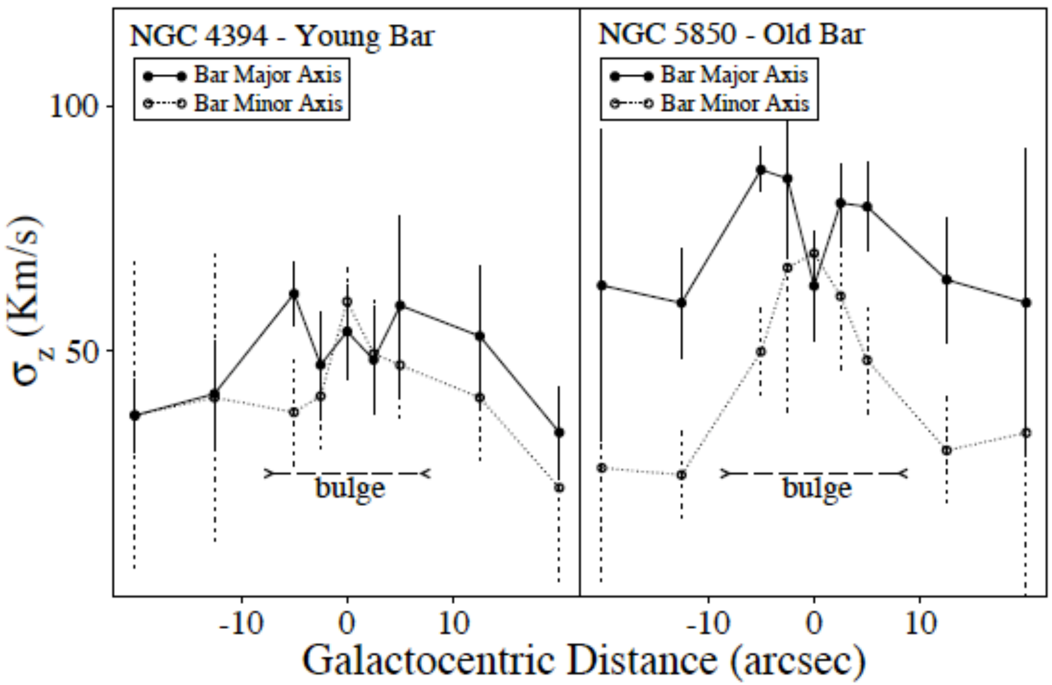
Gadotti & Kauffmann ('09) find that barred galaxies deviate from the $M_{Bulge}$-σ and $M_{BH}$-σ relations ($M_{BH}$ is derived from Haering & Rix '04). Velocity dispersions are too large.

Difference between ellipticals and classical bulges is of 3σ.



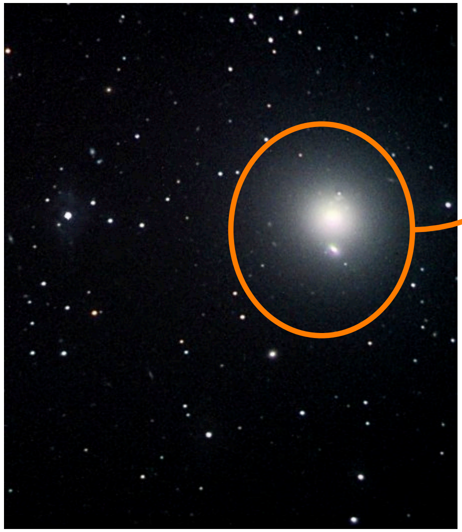
# SMBHs and their scaling relations

In barred galaxies (even if seen face-on), velocity dispersion could increase due to dynamical processes (e.g. Gadotti & de Souza '05).

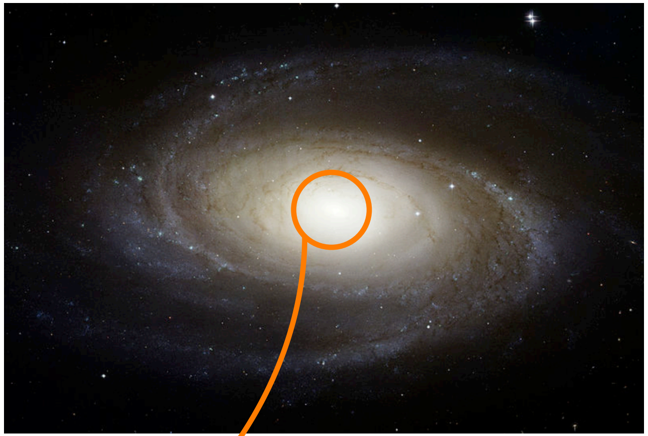


# SMBHs and their scaling relations

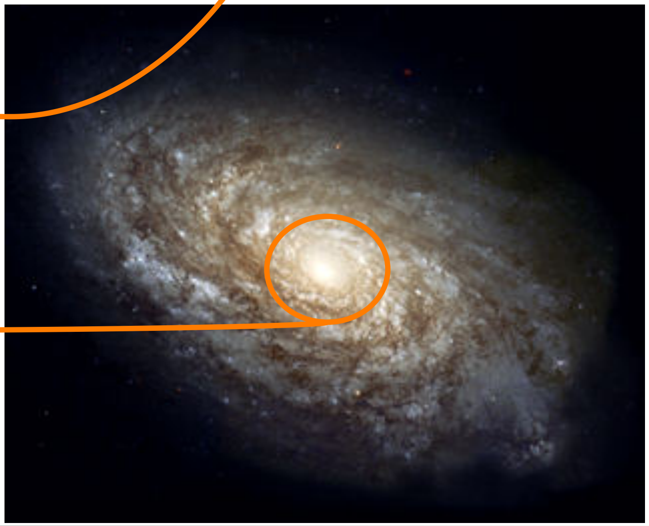
SMBH mass budget at redshift zero (Gadotti & Kauffmann '09) using $M_{BH}$-$M_{Bulge}$ from Haering & Rix ('04)



- ~ 55% in elliptical galaxies



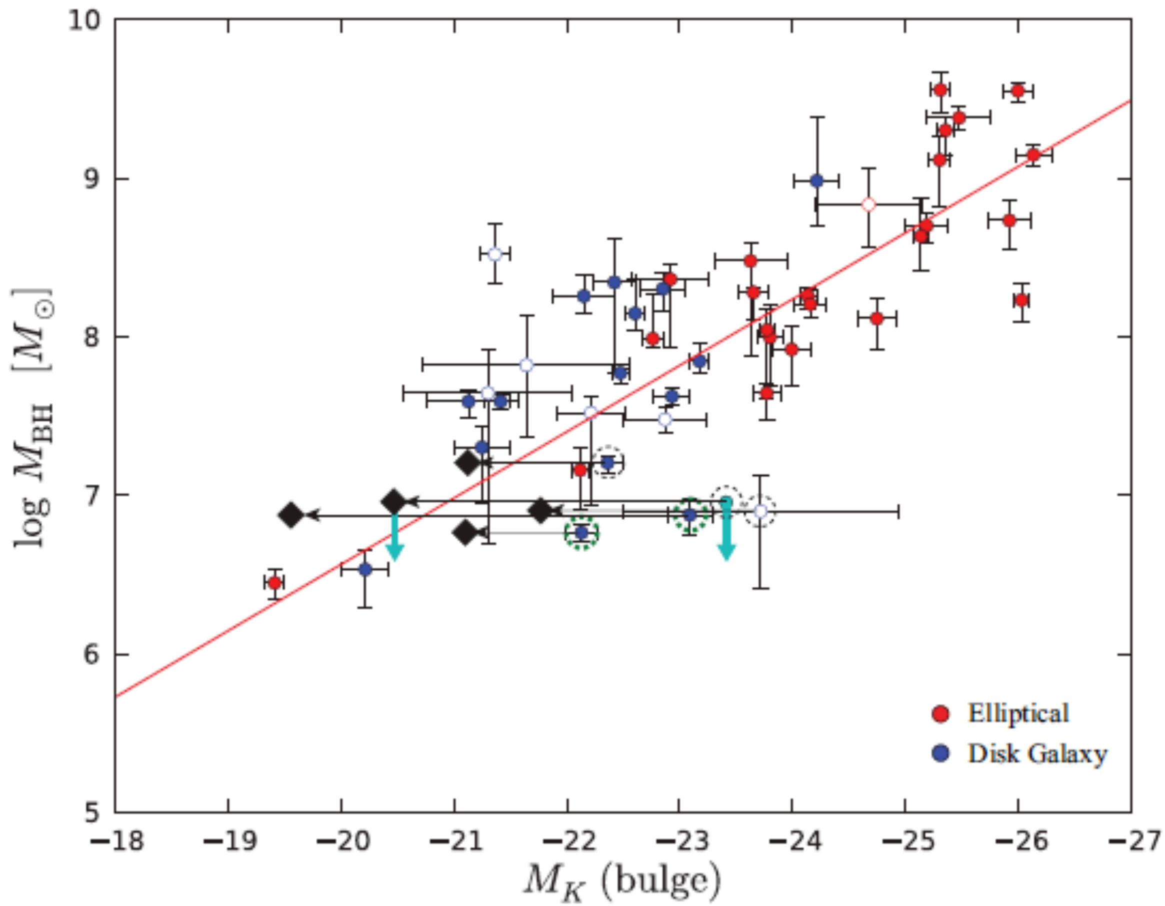
- ~ 41% in classical bulges



- ~ 4% in disky bulges

# SMBHs and their scaling relations

In galaxies with composite bulges, SMBH correlates better with classical bulge mass only (Erwin '10; see also Kormendy et al. '11).




Erwin '10

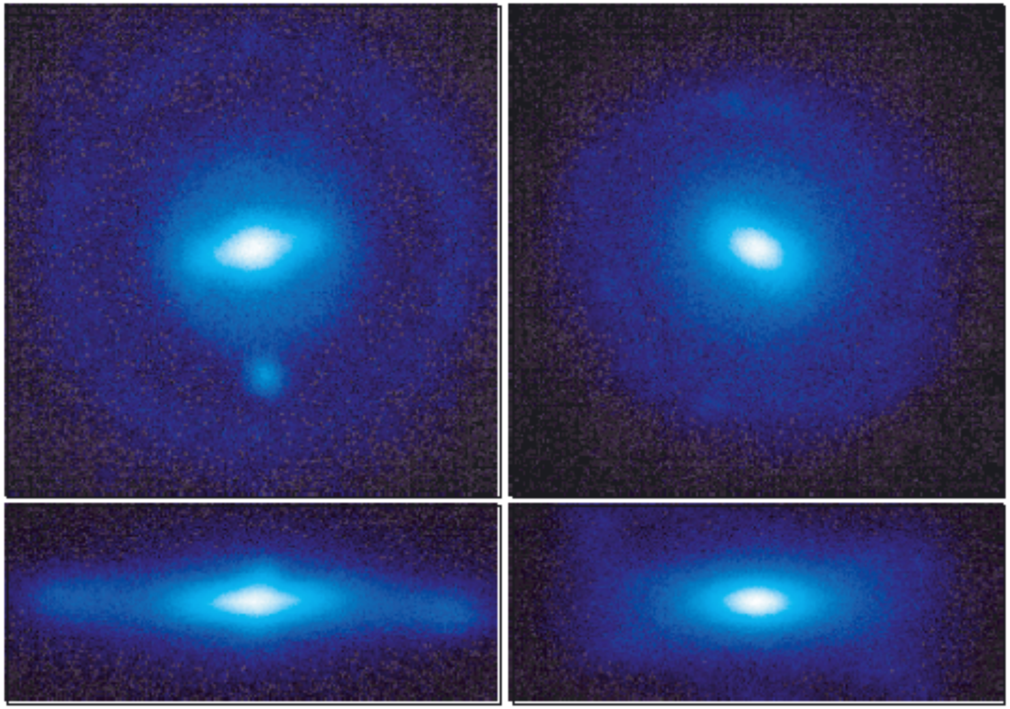
# Bulge Formation Models

The essential idea is that ellipticals would have a formation process that significantly involves the merger of smaller units. Oser et al. ('10,'12) found good agreement with a number of observations, using simulations of the formation of massive galaxies in a two phase process: early dissipation followed by mergers (mostly minor). Time-scales should be shorter for more massive systems (the downsizing scenario, e.g. Cowie et al. '96).

Classical bulges could also form through mergers (see e.g. Aguerri et al. '01), but differences seen between ellipticals and classical bulges suggest different merger histories, in terms of major/minor merger ratio, dry/wet merger ratio and total number of mergers (see e.g. Hopkins et al. '10).

# Bulge Formation Models

Formation of low B/T bulges is a challenge for ΛCDM (e.g. Weinzirl et al. '09), but progress in this direction with N-body simulations is happening. Scannapieco et al. ('10) report the formation, in the Aquarius simulation, through minor mergers, of bulges with low Sérsic indices (~ 1) and B/T (~ 0.1 – 0.2), albeit with excessive effective radii. (See also Governato et al. '09, '10; Brook et al. '11, '12; Aumer et al. '13; Christensen et al. '14).



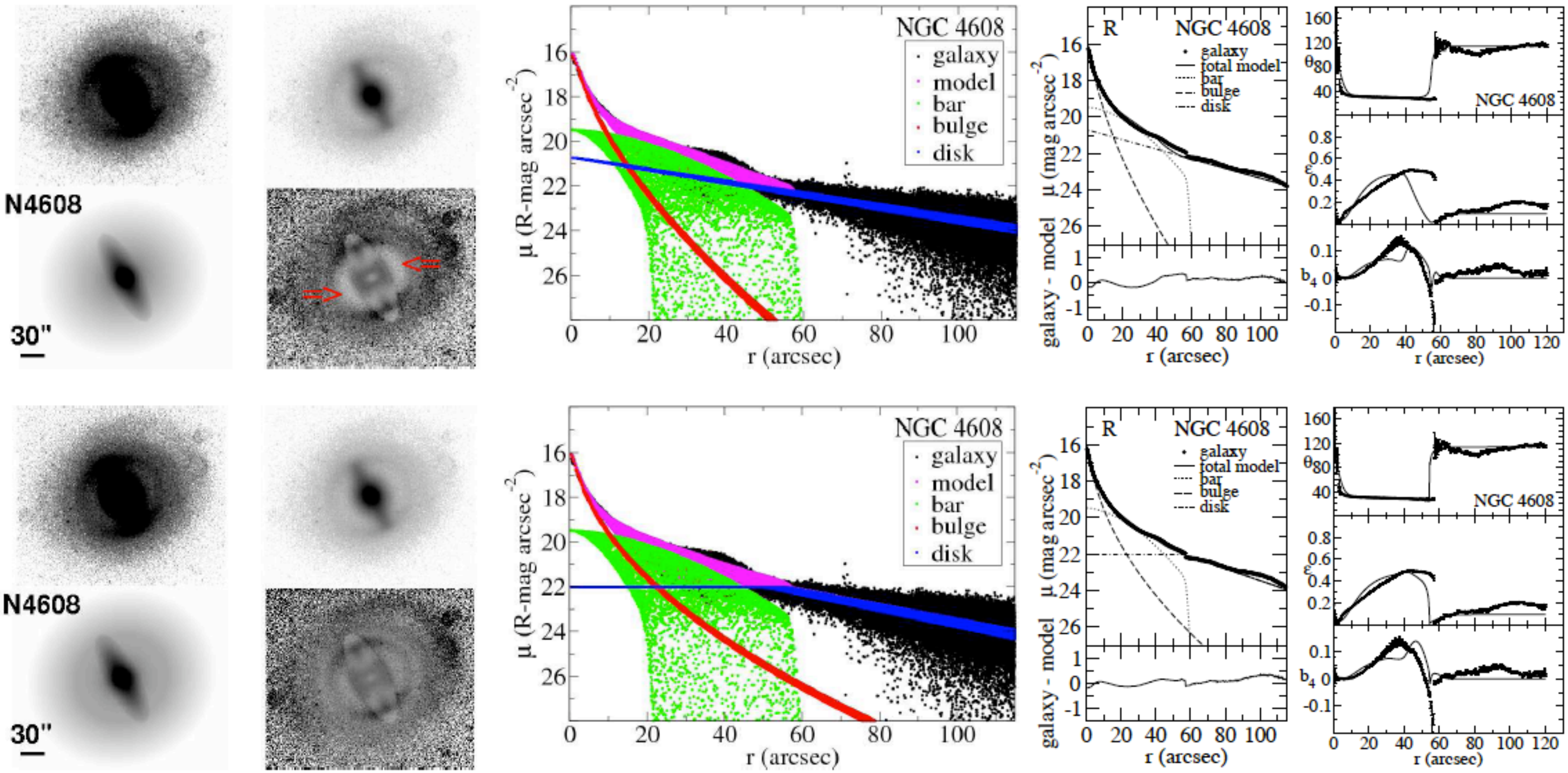
Scannapieco et al. '10

# Bulge Formation Models

Implementation of (disky) bulge building via disk instabilities in semi-analytical models is still very crude (Athanassoula ‘08; De Lucia et al. ‘11; Guo et al. ‘11): a large fraction (half) of the disk mass is transferred to the bulge if a disk is found to be bar-unstable. This is done to stabilize the disk against bar formation, but we see in Nature now at least half of disk galaxies with prominent bars.

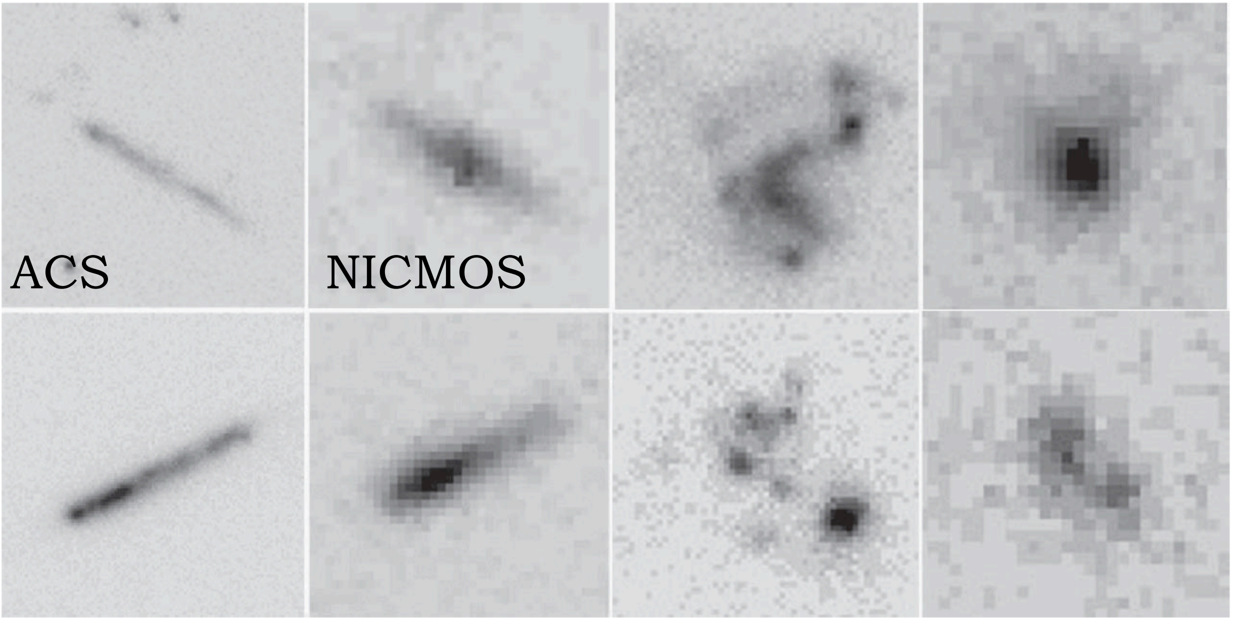
# Bulge Formation Models

In extreme cases, mass transfer is about 13 per cent of disk stars (Gadotti '08).



# Bulge Formation Models

Coalescence of giant clumps in primordial disk galaxies is also a viable way to form (classical) bulges (Bournaud et al. ‘07; Elmegreen et al. ‘08).




Elmegreen et al. ‘08

# Bulge Formation Models

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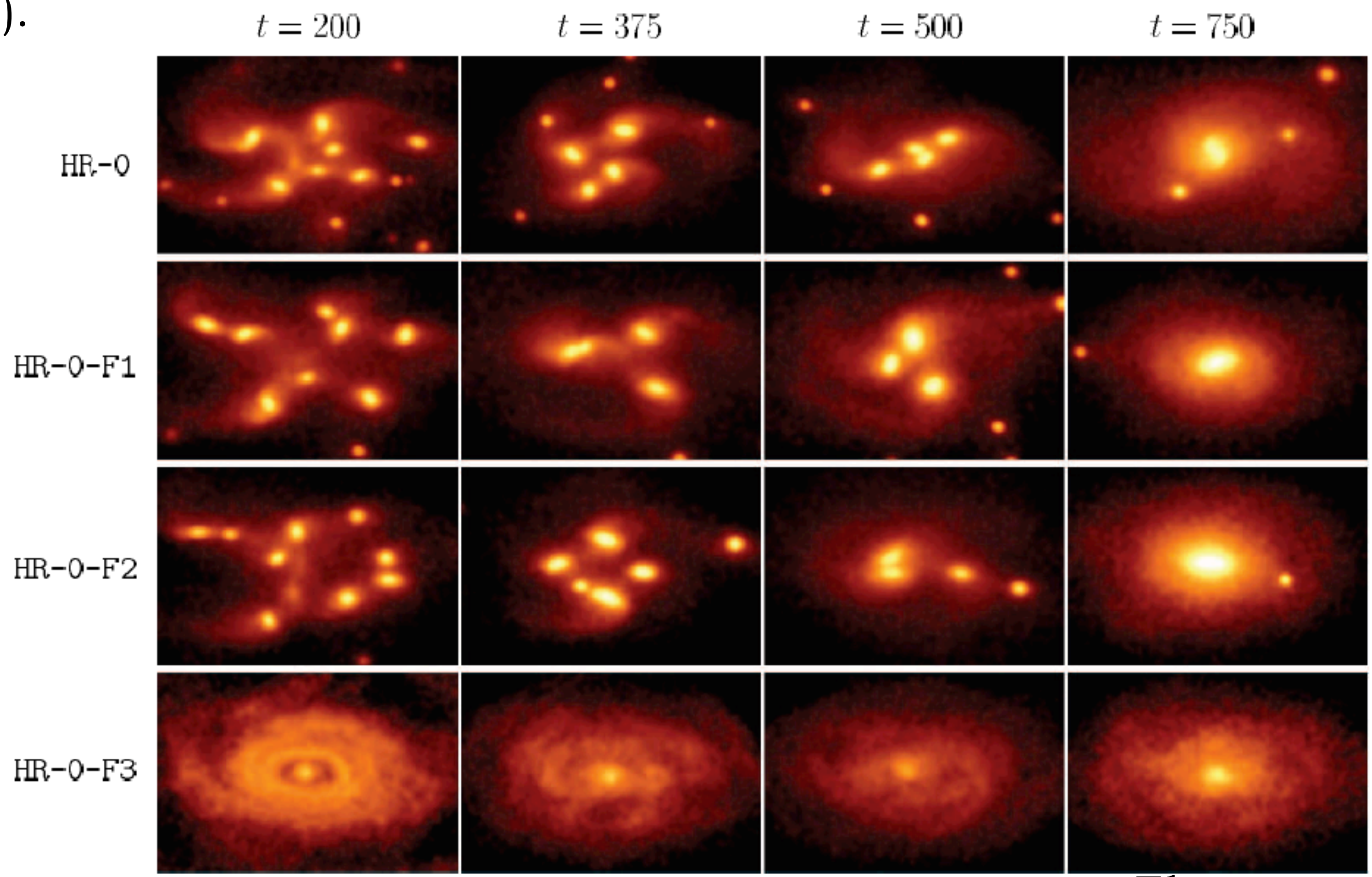



Elmegreen et al. '08

# Bulge Formation Models

Bars are able to drive gas from the outer to the inner disk (Sellwood & Wilkinson ‘93; Athanassoula ‘05; Knapen ‘07; Gadotti ‘09a; Sakamoto et al. ‘99; Sheth et al. ‘05).

# Bulge Formation Models

*Current* formation of stars appears enhanced in the centers of barred galaxies (see Huang et al. '96; Ho et al. '97; Alonso-Herrero & Knapen '01; Ellison et al. '11).

But are stars generally younger in the centers of barred galaxies?

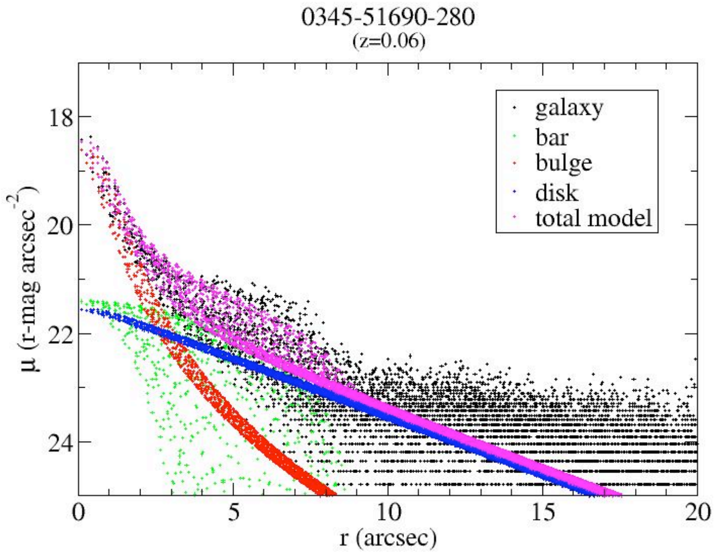
Previous work (Gadotti & dos Anjos '01; Peletier et al. '07; Pérez & Sánchez-Blázquez '11) show difficulties, such as:

- color-metallicity degeneracy, dust
- poor statistics

In Coelho & Gadotti ('11), we aim at comparing mean stellar ages of bulges in matched samples of barred and unbarred galaxies.

# Bulge Formation Models

- SDSS data (Gadotti 2009)
  - $0.02 \le z \le 0.07$
  - $M_* \ge 10^{10}\ M_\odot$
  - $b/a > 0.9$
  - nearly 1000 galaxies, of which nearly 300 barred
  - 2D *g*, *r*, *i* bulge/bar/disk – individually checked – decompositions with BUDDA (de Souza et al. '04; Gadotti '08)

# Bulge Formation Models

- Bar classification by visual inspection of image, 2D surface brightness radial profile and isophotal contours

- SDSS fiber spectra

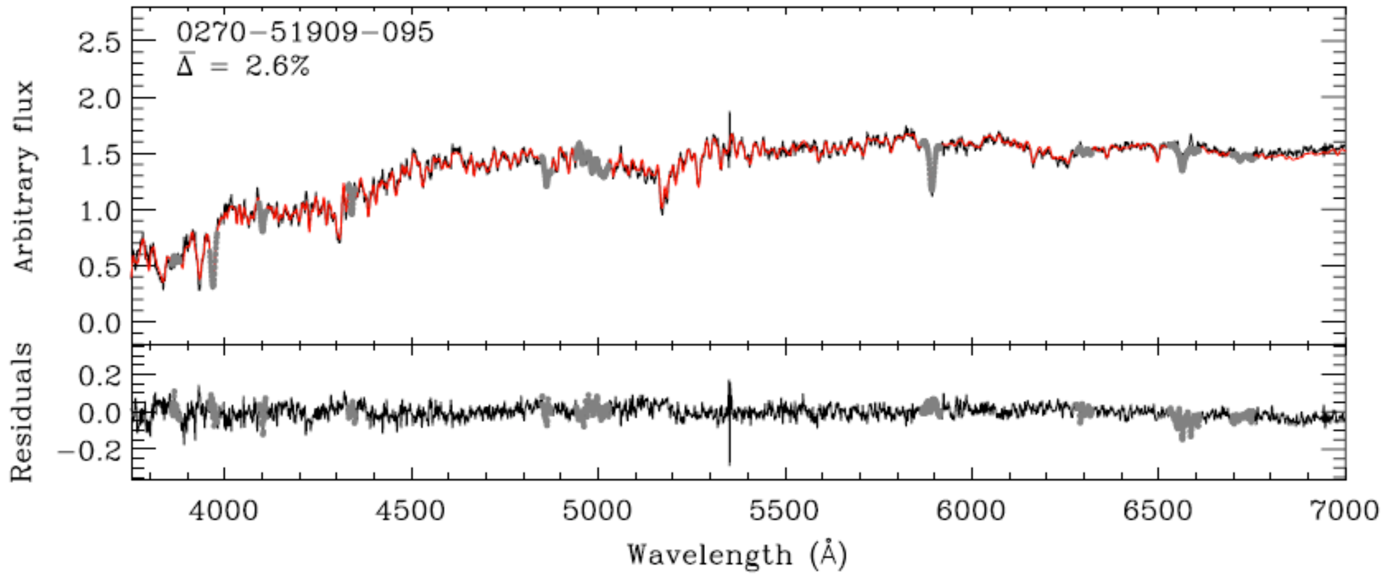
- Bulge stellar masses are determined

- Disk contamination inside the fiber is measured (it's low, typically below 20%)

- Samples of barred and unbarred galaxies are matched in *bulge* mass and disk contamination in the fiber (never done previously)

# Bulge Formation Models

- Spectral fitting w/ STARLIGHT (Cid Fernandes et al. '05)
  - S/N > 10, typically ~ 20

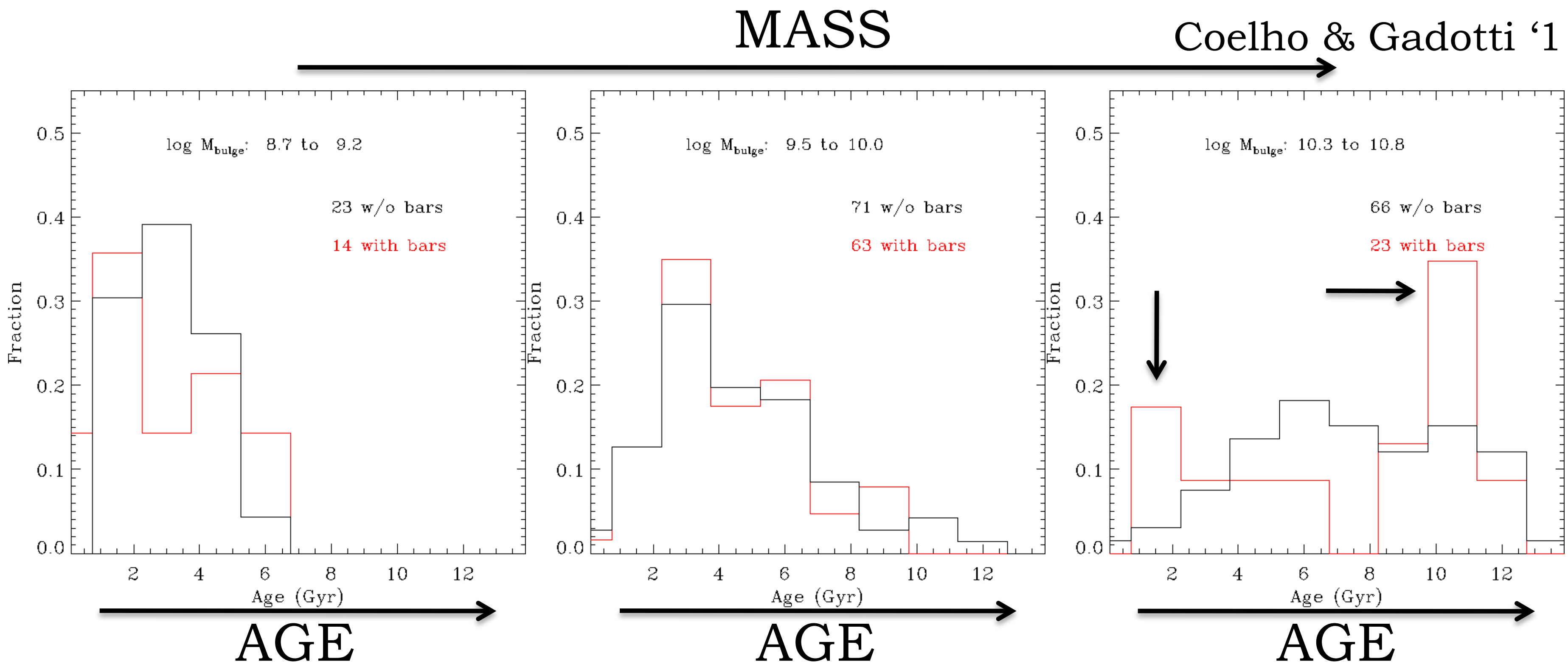


# Bulge Formation Models

➢ Distributions of bulge mean stellar ages for barred and unbarred galaxies in bins of same bulge mass

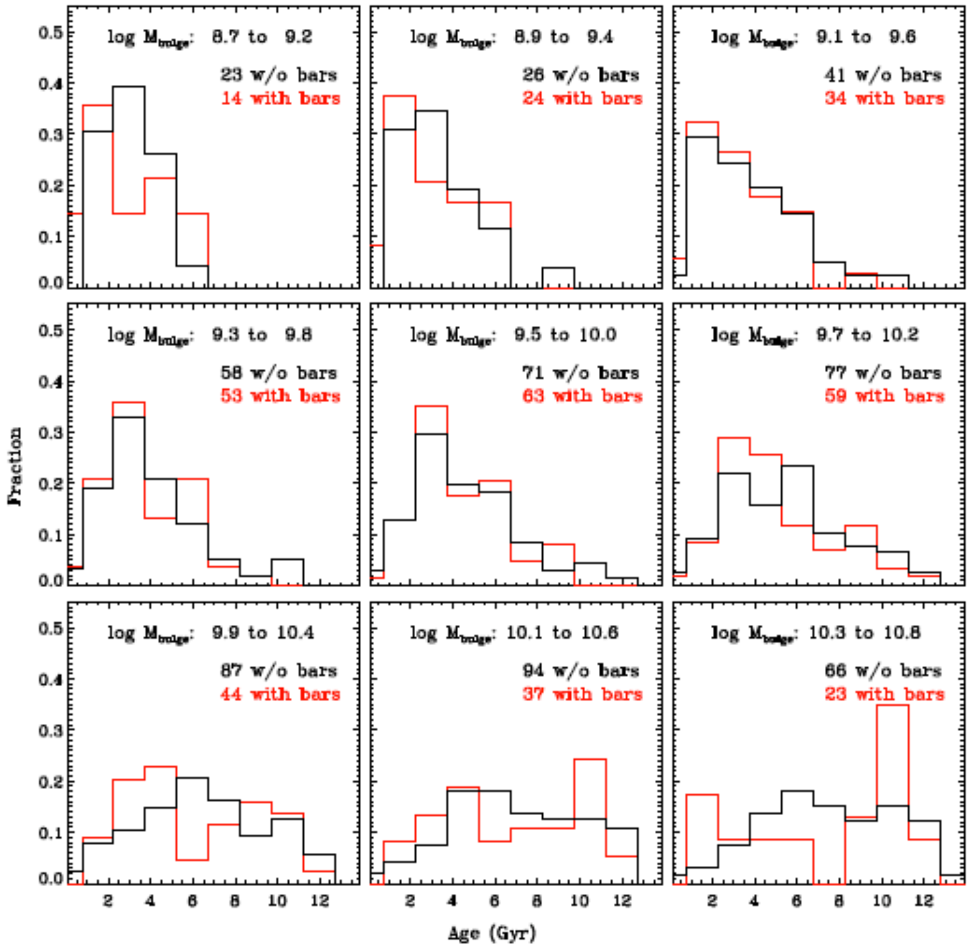
➢ Bulges in non-AGN massive barred galaxies show bimodality and younger component at 4σ!

Coelho & Gadotti '11

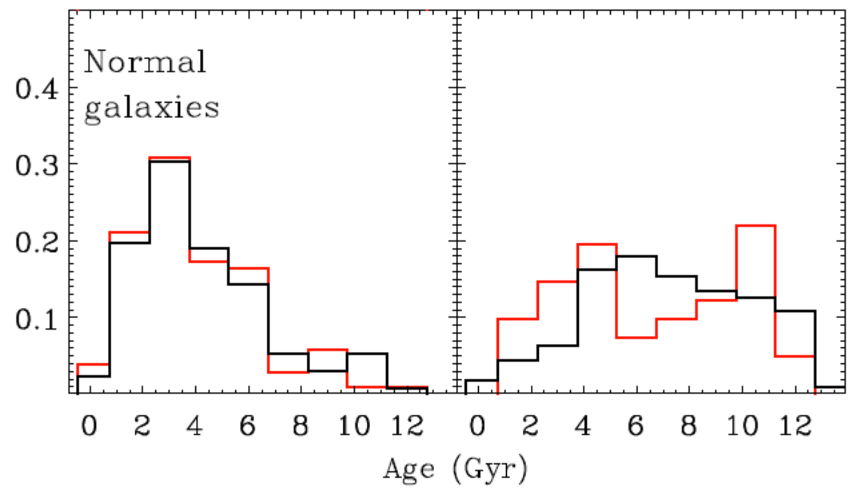


# Bulge Formation Models

Coelho & Gadotti (2011)



# Bulge Formation Models




$\log M_{bul} < 10.1\ M_\odot$ $\log M_{bul} > 10.1\ M_\odot$

- Bars do alter significantly the mean stellar ages of bulges in disk galaxies

Bars can rejuvenate bulges

# Bulge Formation Models

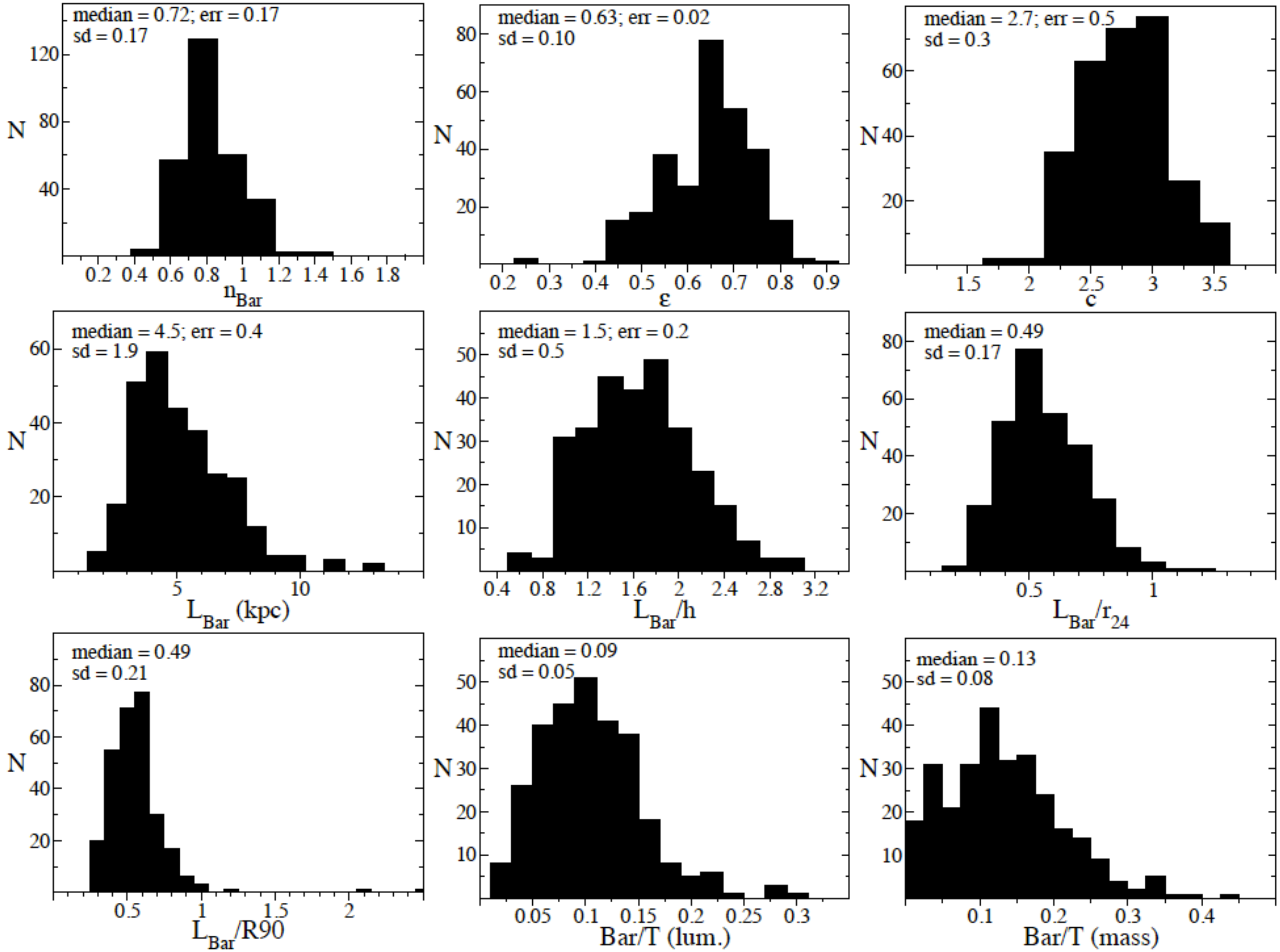
Coelho & Gadotti (2011)

- Bars feeding AGN:

| | |
|---|---|
| low bulge mass bin: | 35% of barred galaxies are AGN |
| | 16% of unbarred galaxies are AGN |
| high bulge mass bin: | 55% of barred galaxies are AGN |
| | 34% of unbarred galaxies are AGN |

- How come we find this?
  - Homogeneous and good data
  - Sample selection
  - Bar and AGN classifications consistent (Gadotti '09b; Kauffmann et al. '03)

# Structural Properties of Bars




Gadotti (2011)

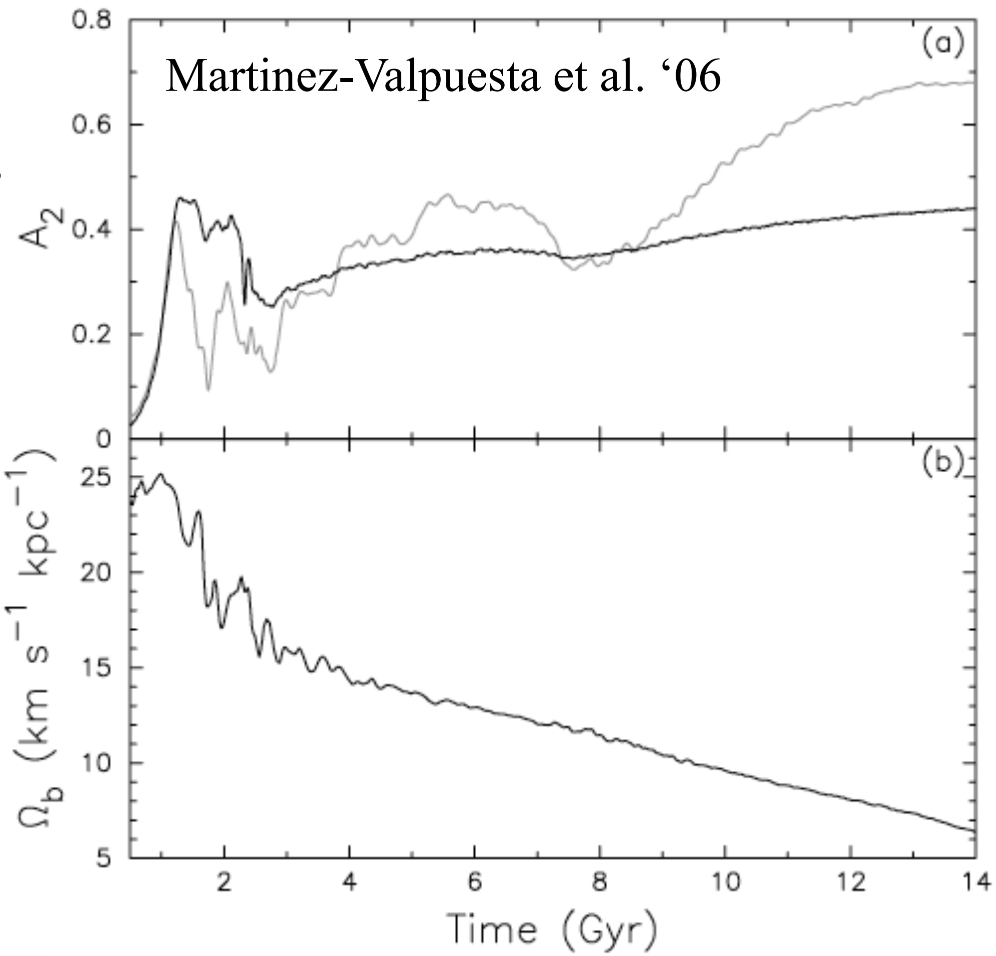
# Bar Length and Strength

• Theory generally predicts that bars grow longer and stronger with time (after an initial "adolescent" phase)

• See also Athanassoula & Misiriotis ('02); Athanassoula ('03); Berentzen et al. ('06)

• A caveat: gas complicates matters (Bournaud & Combes '02; Bournaud et al. '05; Debattista et al. '06; Berentzen et al. '07; but see Kraljic et al. '12; Athanassoula et al. '13)

• Not only gas: halo triaxiality, kinematics, classical bulges etc.



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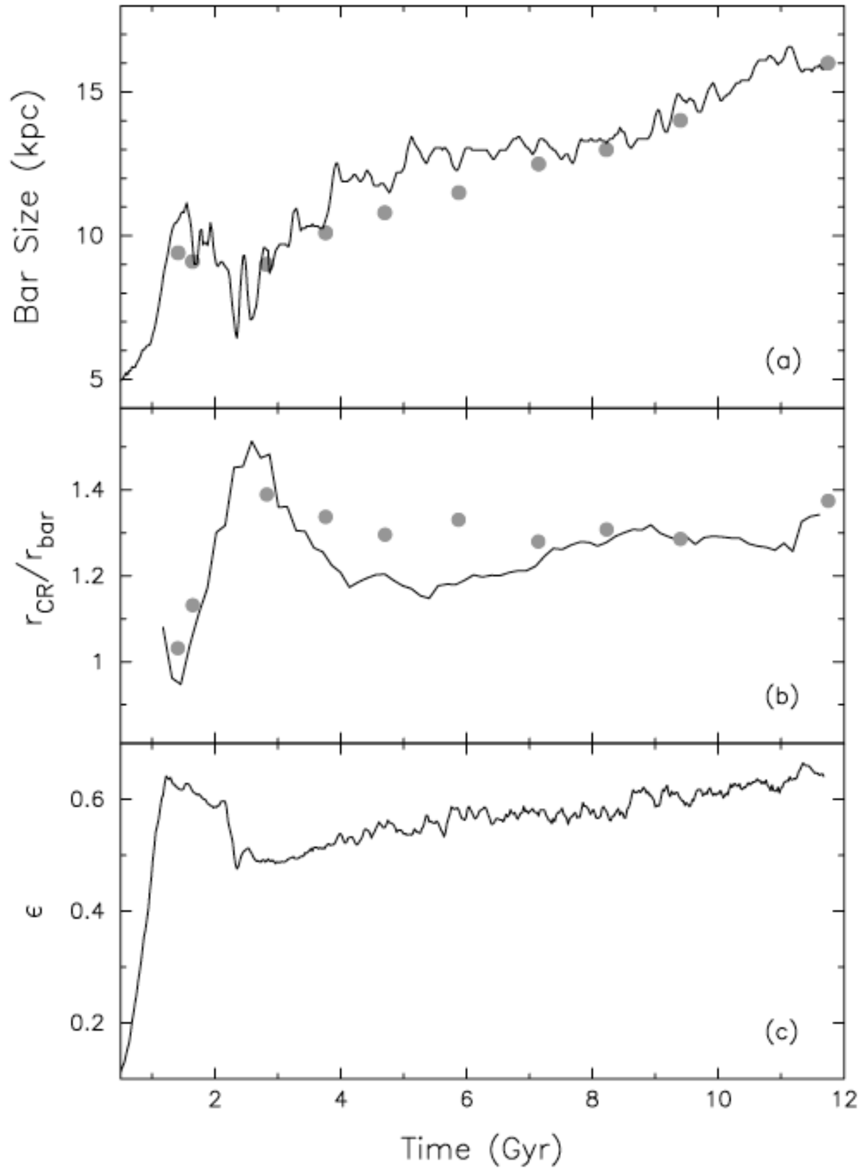
Martinez-Valpuesta et al. '06



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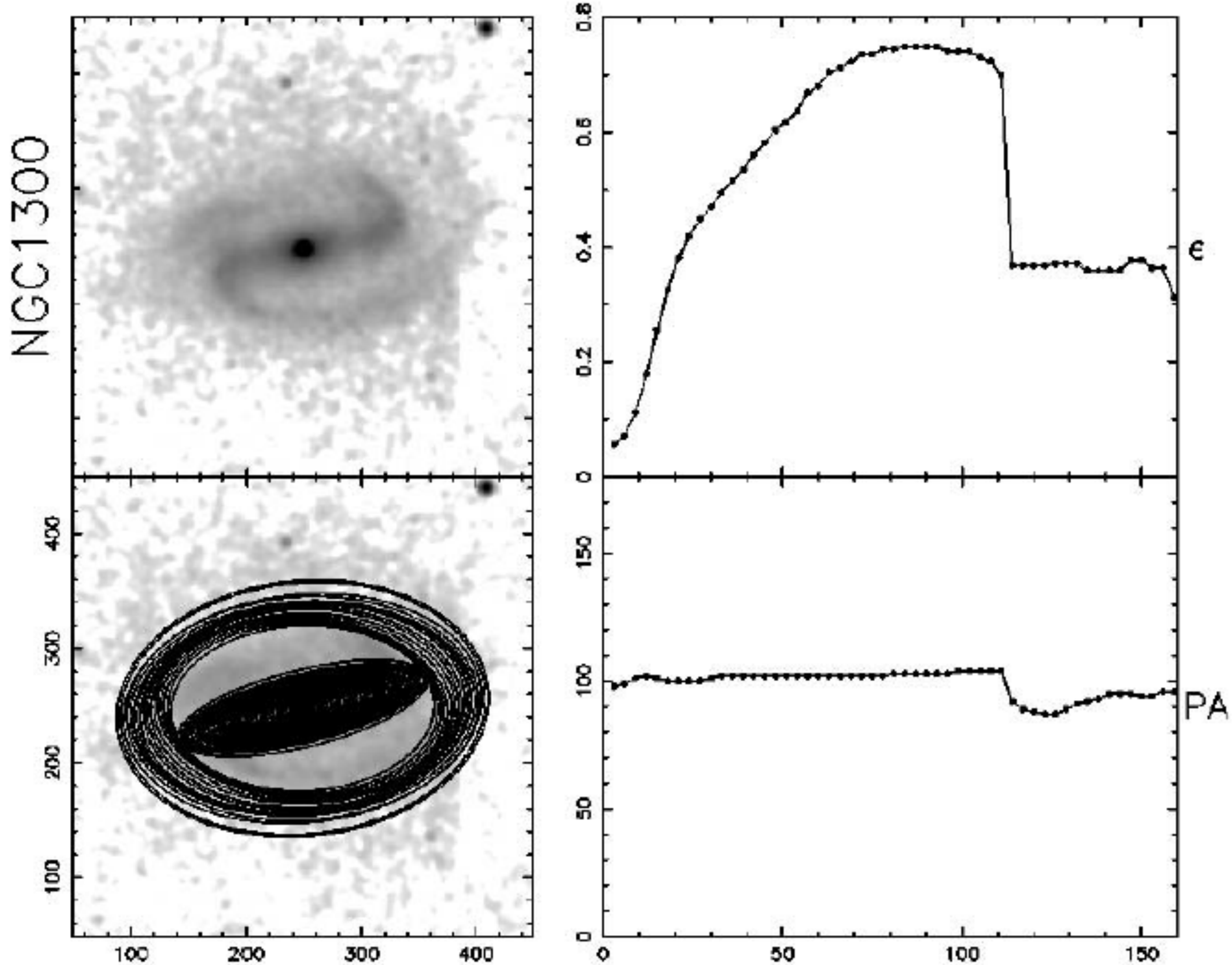
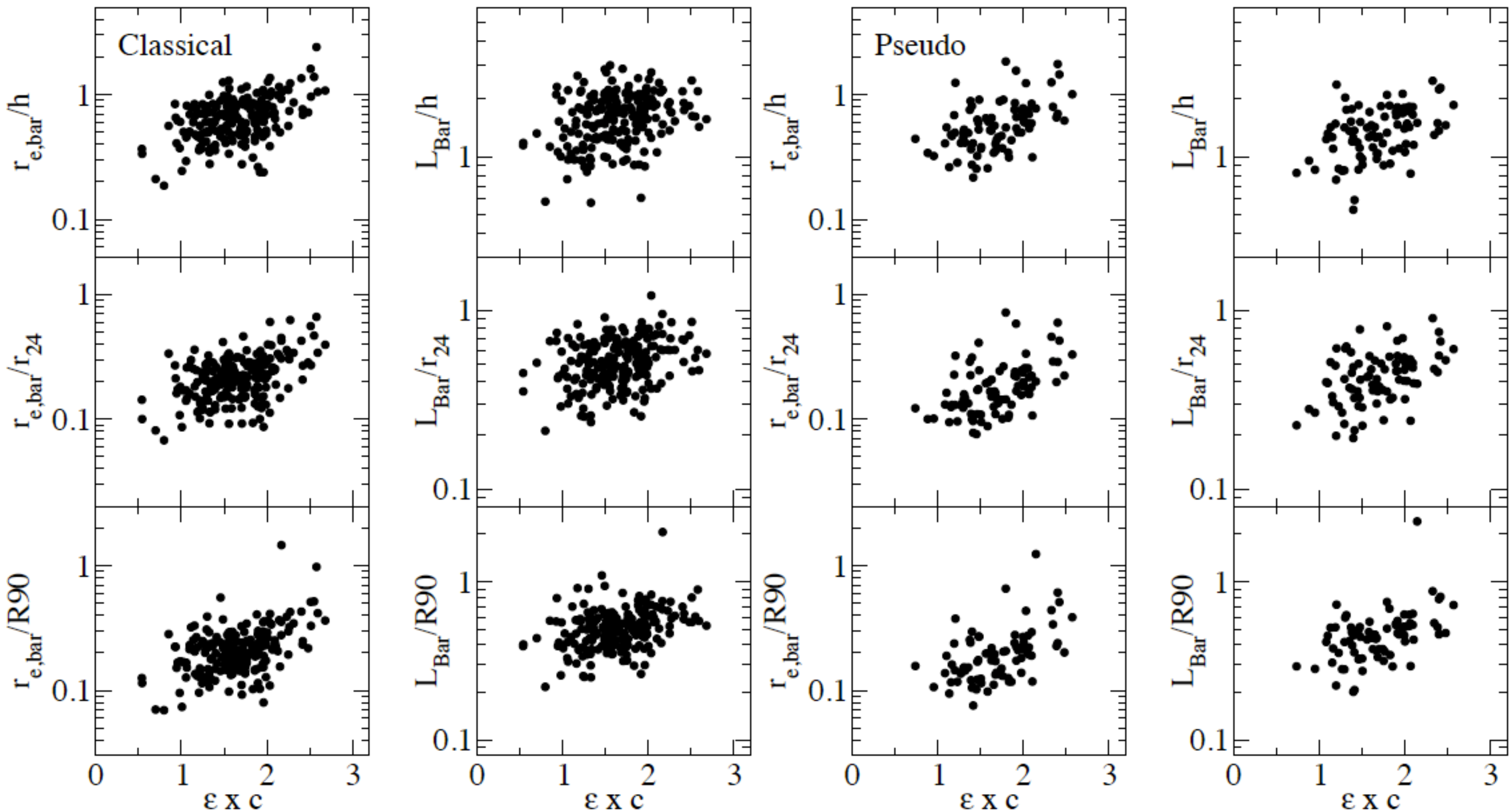



Menéndez-Delmestre et al. ‘07

# Bar Length and Strength




Gadotti (2011)