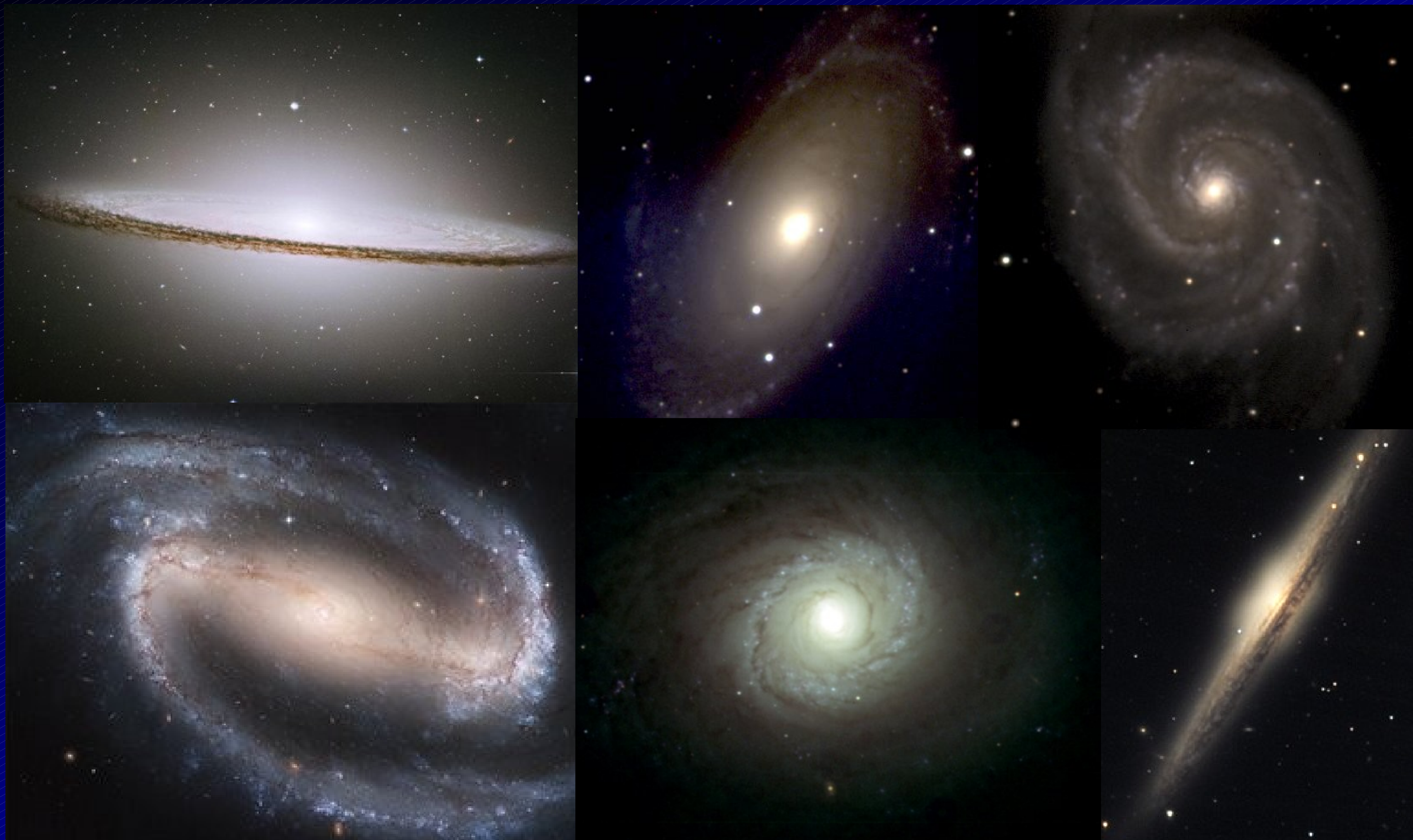
Properties and Origin of Bulges in High Mass Spirals

(Weinzirl et al. 2008, ApJ submitted, arXiv:0807.0040)



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Motivation

- Bulges provide important clues about galaxy formation, but the absence of bulges is likewise interesting!

- Bulges are often absent locally:
  - 15% of edge-on SDSS galaxies are bulgeless (Kautsch et al. 2006)
  - 20% of i<60° low-mass disks appear bulgeless (Barazza, Jogee, & Marinova, 2008)
  - 11/19 galaxies with D<8 Mpc and V_c>150 km/s have pseudobulges (Kormendy & Fisher 2008)

- Must compare distribution of bulge-to-total mass (B/T) and bulge index to ΛCDM-based models for high and low masses

Kautsch et al. 2006

Barazza, Jogee, Marinova (2008)

Weinzirl et al. 2008 (ApJ submitted, arXiv:0807.0040) has two goals:

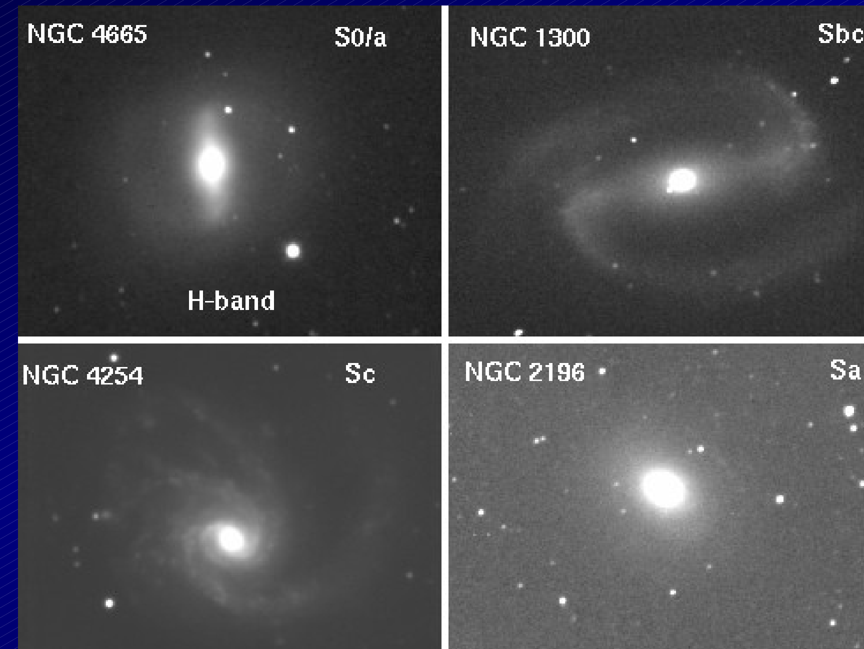
- Quantify B/T and bulge index for nearby high mass galaxies
- Make a detailed quantitative comparison with ΛCDM-based models

Sample and Method

Sample

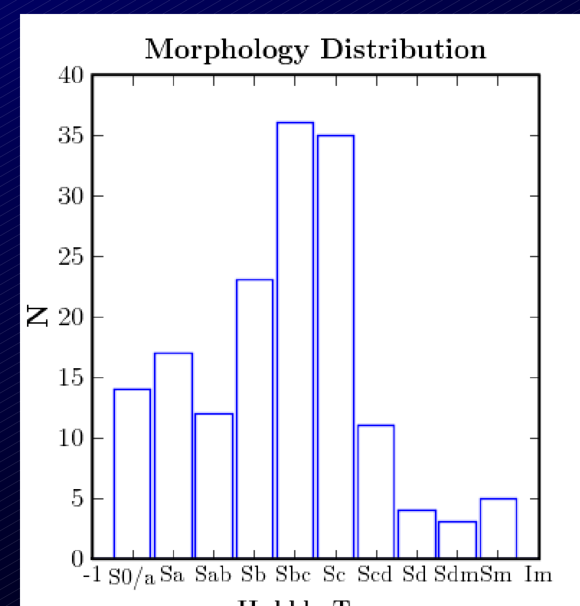
- Drawn from OSU Bright Spiral Galaxy Survey:
  - Bright local field galaxies with $m_B \leq 12$
  - Reference sample for bars in the local Universe (Eskridge 2000; Marinova & Jogee 2007)

- Use H-band light to trace stellar mass



Main sample is 146 $i<70^\circ$ galaxies, complete for $M_* \geq 10^{10} M_\odot$ and $M_B \leq -19.3$

Sample peaks at intermediate Hubble types Sbc-Sc



Luminosity Decomposition

- Galaxy light is emitted from physically and dynamically distinct components:

$$I(r,\theta) = I_{Bulge}(r,\theta) + I_{Disk}(r,\theta) + I_{\mathrm{Bar}}(r,\theta) + I_{Spiral}(r,\theta) + \ldots$$

- Most previous 2D decompositions have used only bulge-disk models (e.g., Allen et al. 2006)
- Inclusion of the bar in 2D bulge-disk-bar decomposition is important:
  - B/T and bulge index are overstated in 2D bulge-disk decomposition of barred galaxies (Laurikainen et al. 2005)
  - 60% of galaxies are barred in H-band (Marinova & Jogee 2007)
  - Optical bar fraction is higher in galaxies without prominent bulges (Odewahn 1996; Barazza, Jogee, Marinova 2008; Marinova et al. 2008; Aguerri et al. 2008)

We perform 2D bulge-disk and bulge-disk-bar decomposition with GALFIT (Peng et al. 2002)

Decomposition With GALFIT

Stage 1:
One Component

Input guesses for
single Sersic component

→ Fit single Sersic profile

Stage 2:
Two Components
(bulge+disk or bar+disk)

Stage 1 outputs are
input guesses for bulge
(disk b/a, PA fixed to pre-determined values)

→ Fit Sersic profile + exponential disk

Stage 3:
Three Components
(bulge+disk+bar)

Stage 2 outputs are
input guesses for bulge and disk
Include guesses for bar parameters.
(disk b/a, PA fixed to pre-determined values)

→ Fit Sersic bulge +
exponential disk + Sersic bar

Choose the best fit from Stage 2 and Stage 3 based on:

χ^2
Residuals
Model parameters
Data image

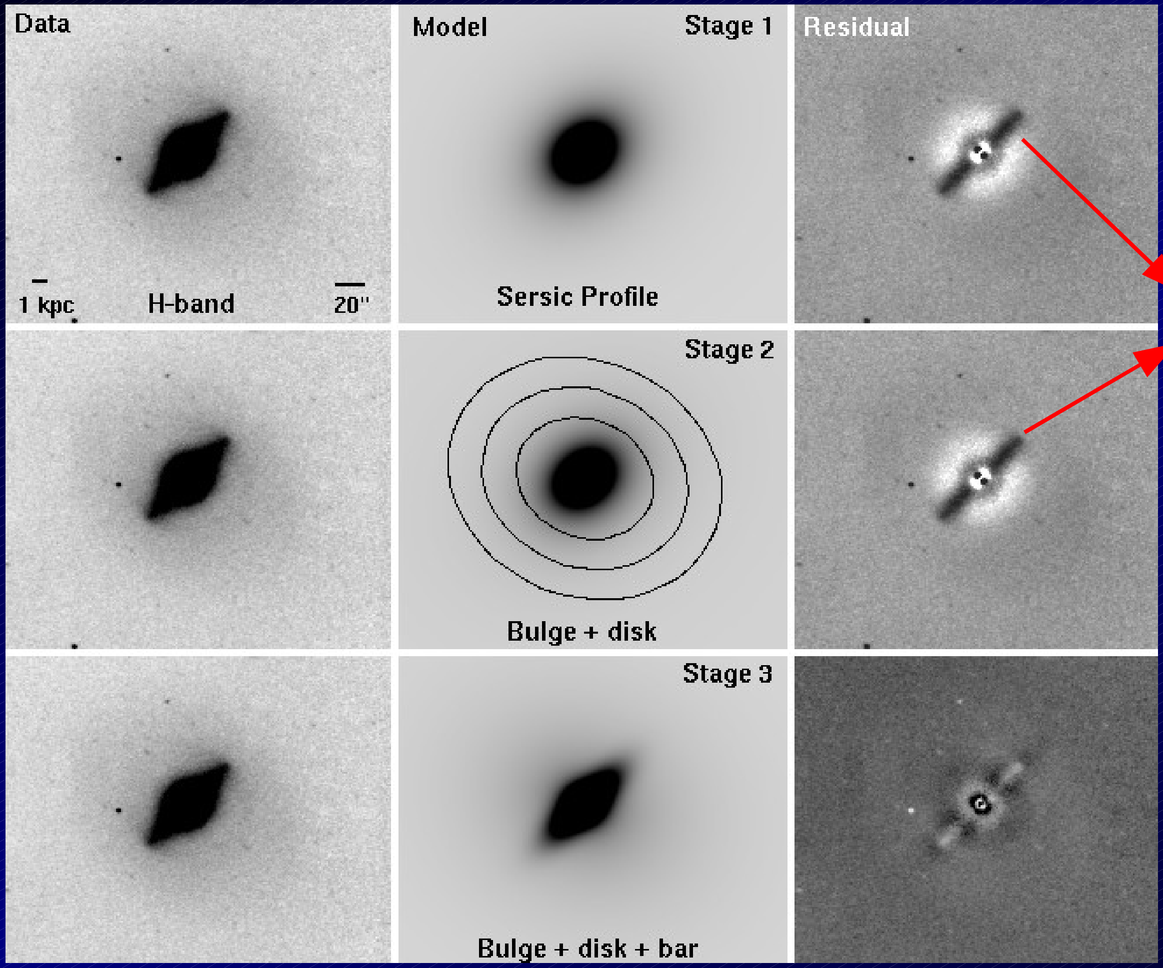
For 78% of galaxies, nuclear point sources were added to the best model
(to account for AGN, HII nuclei, nuclear star clusters)

Sample Decomposition For NGC 4643

Stage 1:
One Component

Stage 2:
Two Components
(bulge+disk or bar+disk)

Stage 3:
Three Components
(bulge+disk+bar)



Residual bar light

Weinzirl et al. 2008

Median B/T change between Stage 2 and Stage 3 is a factor of 3.3

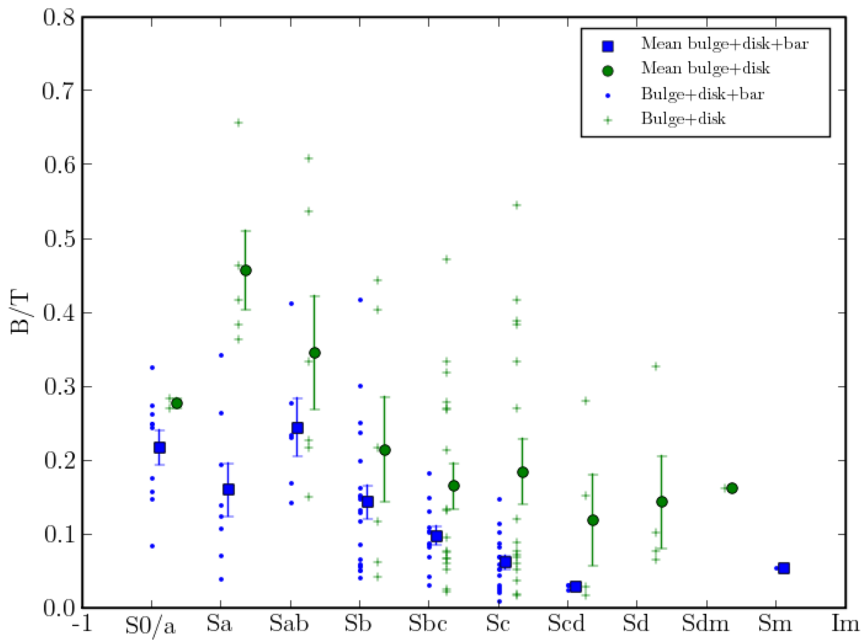
Fit		r_e or h (")	n	b/a	PA	Luminosity (%)
Stage 1	Sersic	27.9	4.44	0.80	-51.0	100
Stage 2	Bulge Disk	23.9 338.9	4.16 1.00	0.90 0.84	-51.1 66.9	34.6 65.4
✓ Stage 3	Bulge Disk Bar	5.43 48.2 21.3	2.53 1.00 0.62	0.90 0.84 0.37	60.5 66.9 -45.8	25.0 54.1 20.9

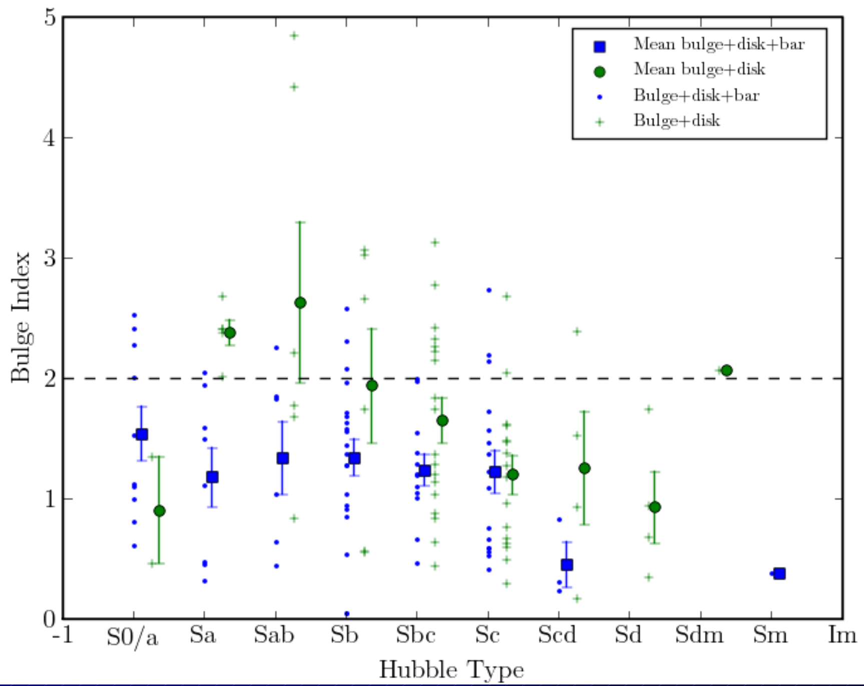
Light redistributed from bulge & disk to bar

~~Sample and Method~~

Results

Distribution of B/T and Bulge Index





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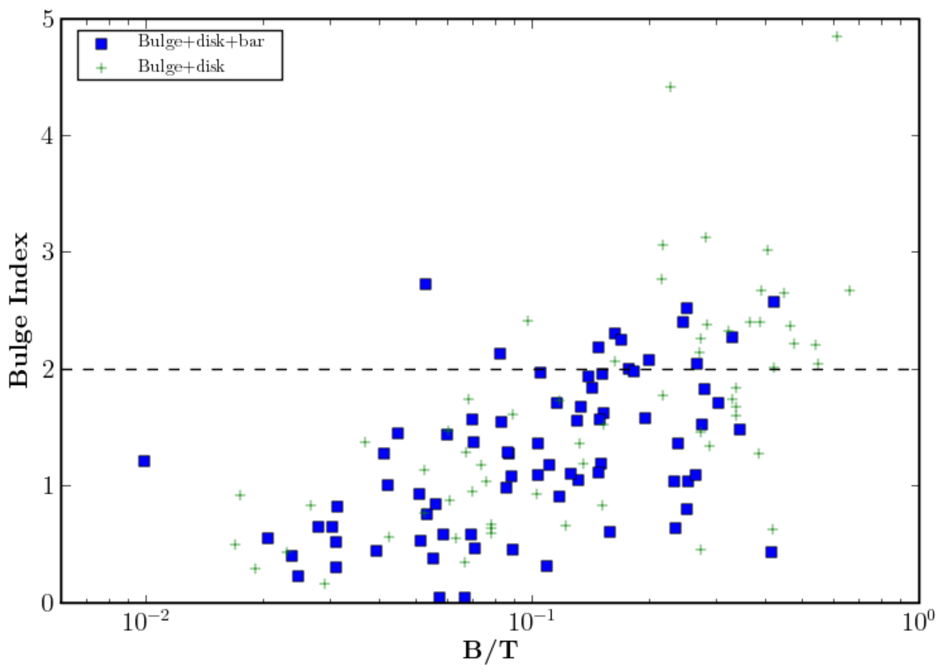


Weinzirl et al. 2008

Mean B/T, bulge index are consistent with other work (e.g., Laurikainen et al. 2007; Graham & Worley 2008).

66% of bulges have B/T≤0.2; 74% have n≤2

Such bulges exist in barred and unbarred galaxies across a wide range in Hubble type!

Bar Fraction vs B/T and Bulge Index

- H-band bar fraction is 58% (84/146), in agreement with other studies on the same data (Marinova & Jogee 2007; Laurikainen et al. 2004; Eskridge et. al 2000)
- Does H-band bar fraction change with B/T and bulge index?

Bar fraction with bulge $B/T \leq 0.2$	67.6% ± 5.44%
Bar fraction with bulge $B/T > 0.2$	35.9% ± 7.68%

Bar fraction with bulge $n \leq 2$	64.3% ± 4.53%
Bar fraction with bulge $n > 2$	35.3% ± 8.20%

H-band bar fraction is greater by a factor of two for low B/T and low bulge index galaxies!

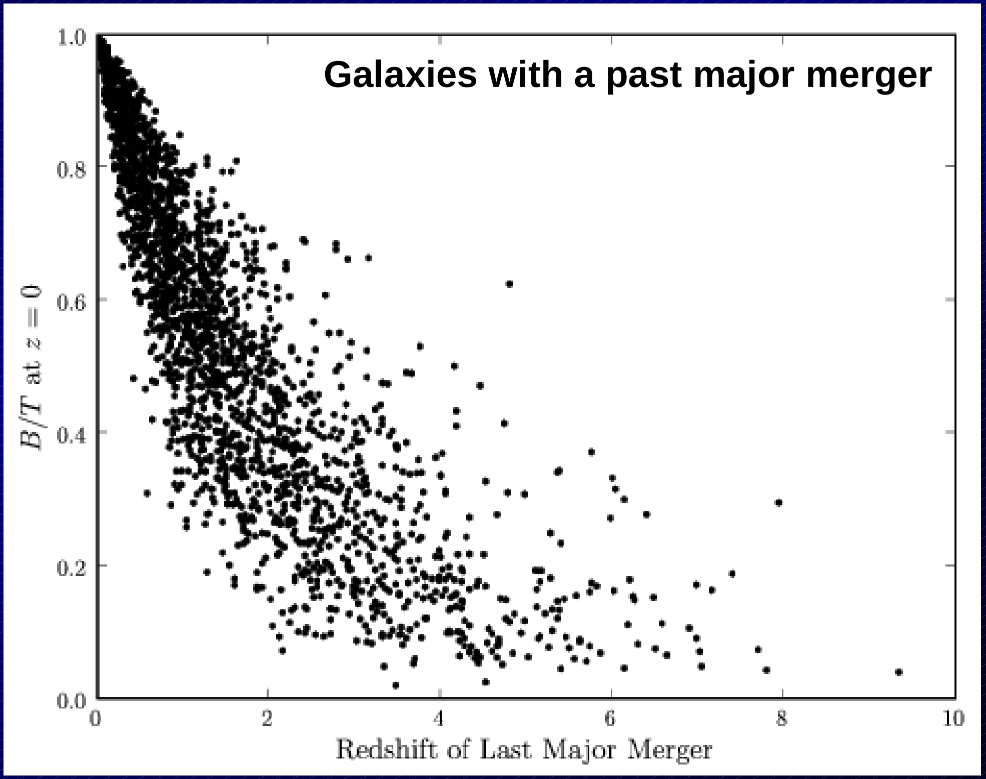
- Is there a relationship between bulges and bars?
  - Secular evolution may build low-B/T, disky bulges
  - Or, low-B/T galaxies with no ILR are more susceptible bars induced by swing amplification with a feedback loop (Julian & Toomre 1966; Toomre 1981; Binney & Tremaine 1987)

Comparing with Hierarchical Models

- Make a quantitative comparison with the predicted B/T distribution from ΛCDM-based models (Khochfar & Burkert 2005; Khochfar & Silk 2006)
- DM halo merger trees from the extended Press-Schechter formalism (Somerville & Kolatt 1999)
- Baryonic physics from semi-analytic prescriptions for SF, cooling, supernovae feedback

Major merger ($M_1/M_2 \geq 1/4$) dynamics:

- Major mergers set B/T to 1; B/T declines after major mergers due to disk buildup by cold accretion
- A galaxy with a past major merger can have B/T$\leq$0.2 at z=0 only if $z_{last} \geq 2$



Courtesy of Khochfar & Burkert

Minor Mergers and Secular Evolution

Bulge formation mechanisms include major mergers ($M_1/M_2 \geq 1/4$), minor mergers ($1/10 < M_1/M_2 < 1/4$), and secular evolution

Contribution of minor mergers:

- Satellite deposits stars in central region of the primary
- Gas inflow from tidally induced bars and tidal torques

Included in model
Neglected in model

Contribution of secular evolution:

- Bar-driven inflow between mergers
- Boxy/peanut bulges from bar bending/buckling

Minor mergers add all stellar mass in satellite to bulge of primary

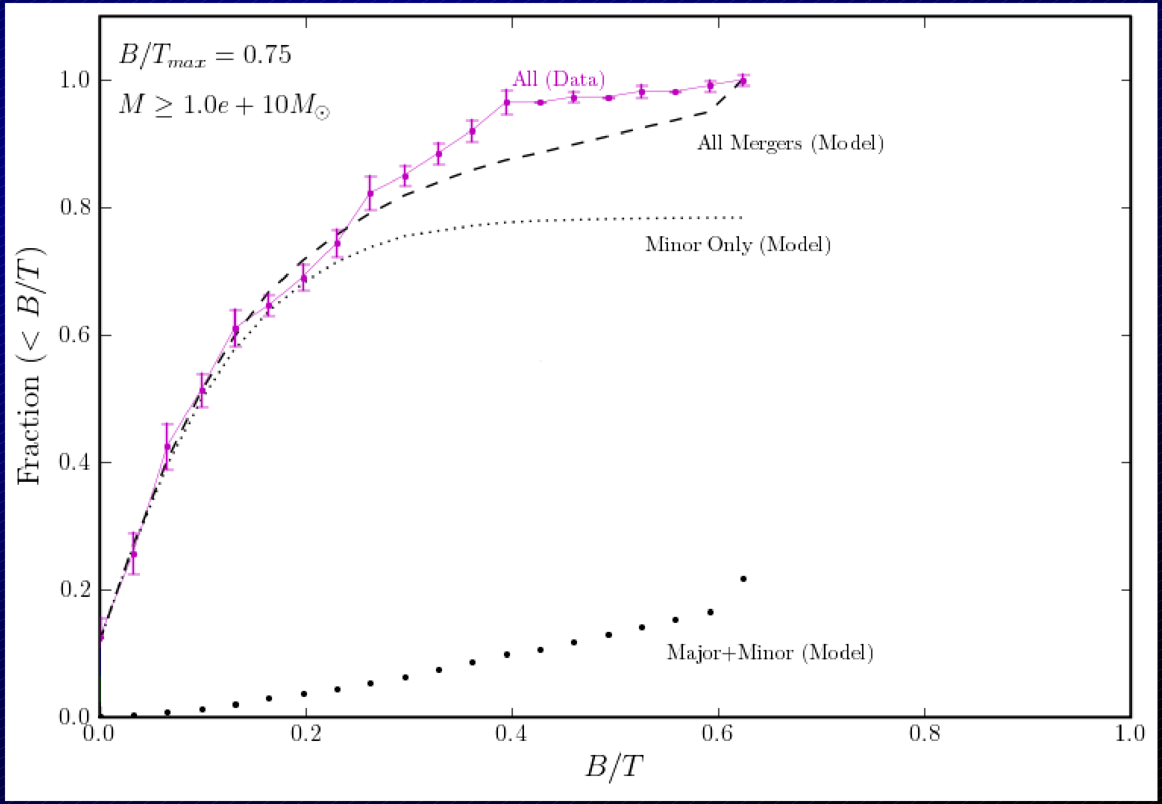
Secular processes are neglected

Distribution of B/T: Data vs Model

	Data	Model (Major + minor)	Model (Minor only)	Model (All mergers)
B/T ≤ 0.2	65.5%	3.09%	64.1%	67.2%
B/T > 0.2	34.5%	18.6%	14.3%	32.9%

The fraction of model galaxies with a past major merger and B/T≤0.2 is 3%, more than 20 times smaller than the observed fraction (66%).

B/T≤0.2 bulges cannot have been built by major mergers!



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Summary & Future Work

- **Sample:** 146 $i < 70^\circ$ galaxies; complete for $M_* \geq 10^{10}\ M_\odot$ and $M_B \leq -19.3$
- **Modeling:** Hierarchical ΛCDM-based models from Khochfar, Burkert, & Silk
- **Results ($M_* \geq 10^{10}\ M_\odot$):**
  - Low $B/T \leq 0.2$ bulges are found in 66% of spirals; $n \leq 2$ bulges are found in 74%
  - Fraction of model galaxies with past major mergers and $B/T \leq 0.2$ is more than 20 times smaller than the observed fraction
- **Future theoretical work for modelers:**
  - More realistic treatment of minor mergers and secular processes. Suggestions welcome!
- **Future observational work:**
  - Measure ages of bulges relative to bars and disks with IFU spectroscopy
  - Ongoing decomposition of the dense Coma cluster (ACS Coma Cluster Treasury Survey; Carter et al. 2008)
  - Study properties of massive disks at $1.5<z<3$ from the GOODS NICMOS survey (Conselice et al. 2008)

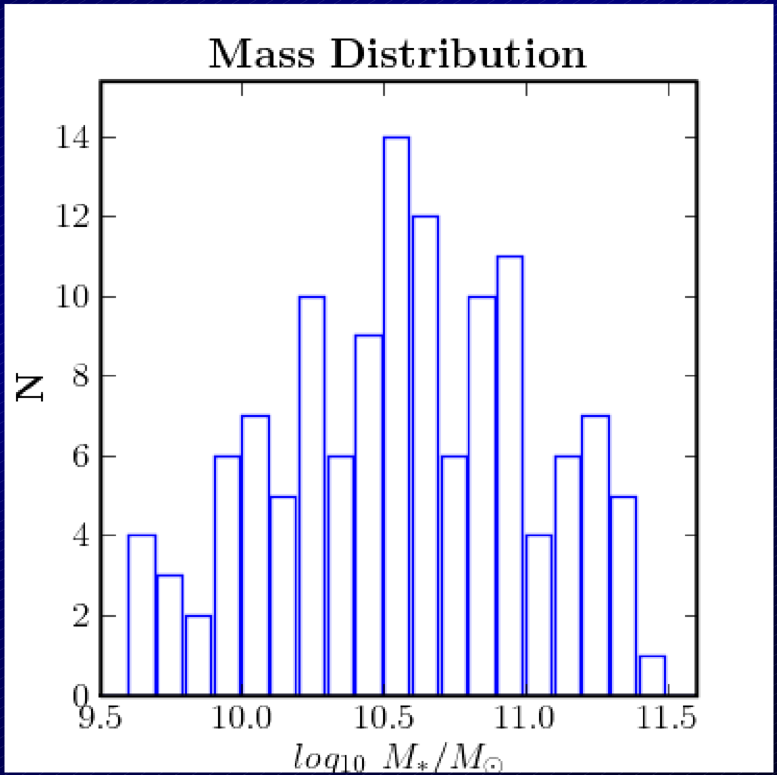
Stellar Masses

- Photometric masses calculated based on Bell et al. (2003)

$$M_* = v_{lum} 10^{-0.628 + 1.305(B-V) - 0.10}$$

$$v_{lum} = 10^{-0.4(V-4.82)}$$

- We calculate stellar masses for 127 (87%) of objects
- Several studies note good agreement between photometric and dynamical masses (Bell et al. 2003; Drory et al. 2004; Salucci, Yegorova, & Drory 2008). Typical errors are within factors of 2-3



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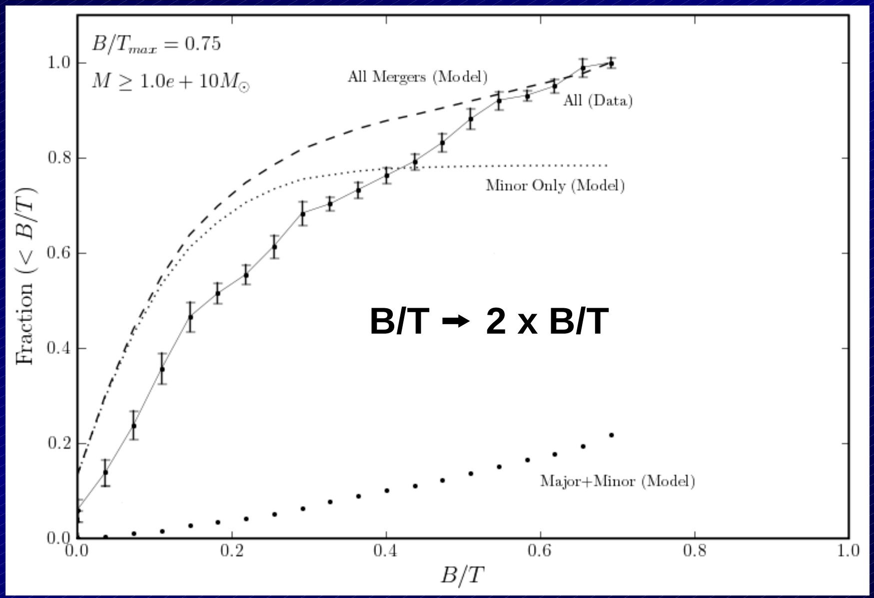
M/L Ratio

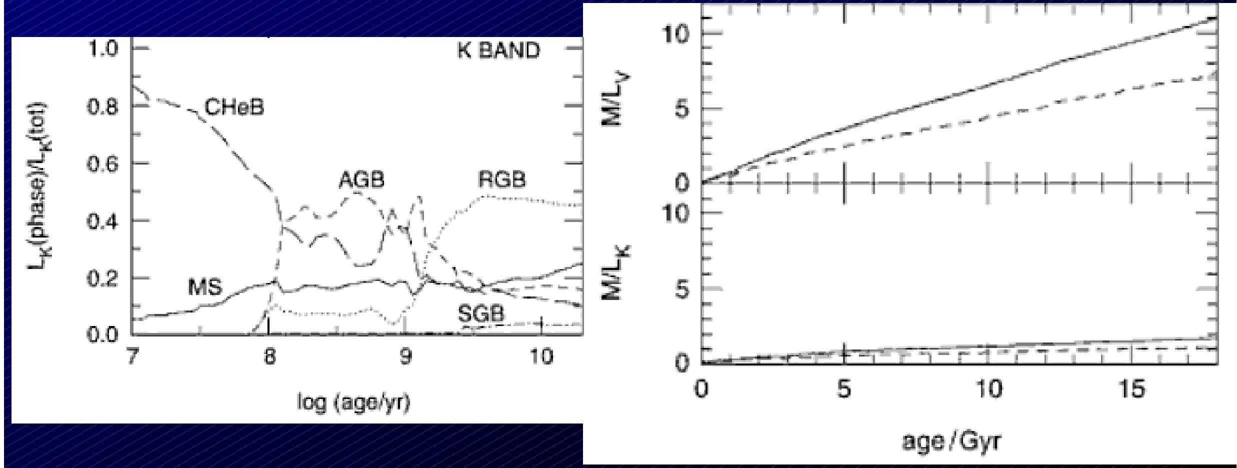
- We assume a constant M/L ratio between bulges, disks, and bars:

$$\left(\frac{B}{T}\right)_{\mathrm{Mass}} = \frac{L_{\mathrm{Bulge}} \times \left(\frac{M}{L}\right)_{\mathrm{Bulge}}}{L_{\mathrm{Bulge}} \times \left(\frac{M}{L}\right)_{\mathrm{Bulge}} + L_{\mathrm{Disk}} \times \left(\frac{M}{L}\right)_{\mathrm{Disk}} + L_{\mathrm{Bar}} \times \left(\frac{M}{L}\right)_{\mathrm{Bar}}} = \frac{M_{\mathrm{Bulge}}}{M_{\mathrm{Bulge}} + M_{\mathrm{Disk}} + M_{\mathrm{Bar}}}$$

- H-band is insensitive to age and dust gradients
- What if this assumption is wrong?
  - If the bulge is older, then $\left(\frac{M}{L}\right)_{\mathrm{Bulge}}$ is larger and bulge mass is underestimated
  - If the disk is younger, then $\left(\frac{M}{L}\right)_{\mathrm{Bulge}}$ is less and bulge mass is overestimated



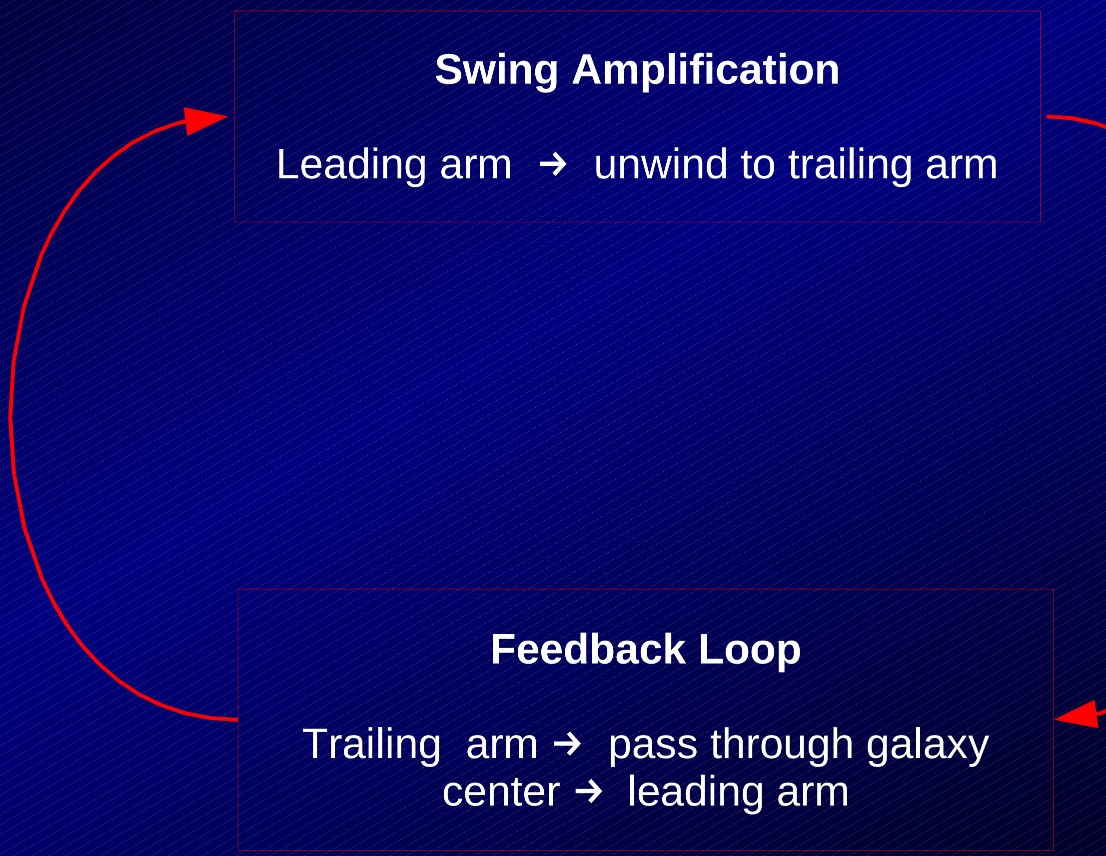
Weinzirl et al. (2008)



Schneider 2006

Swing Amplifier With Feedback Loop

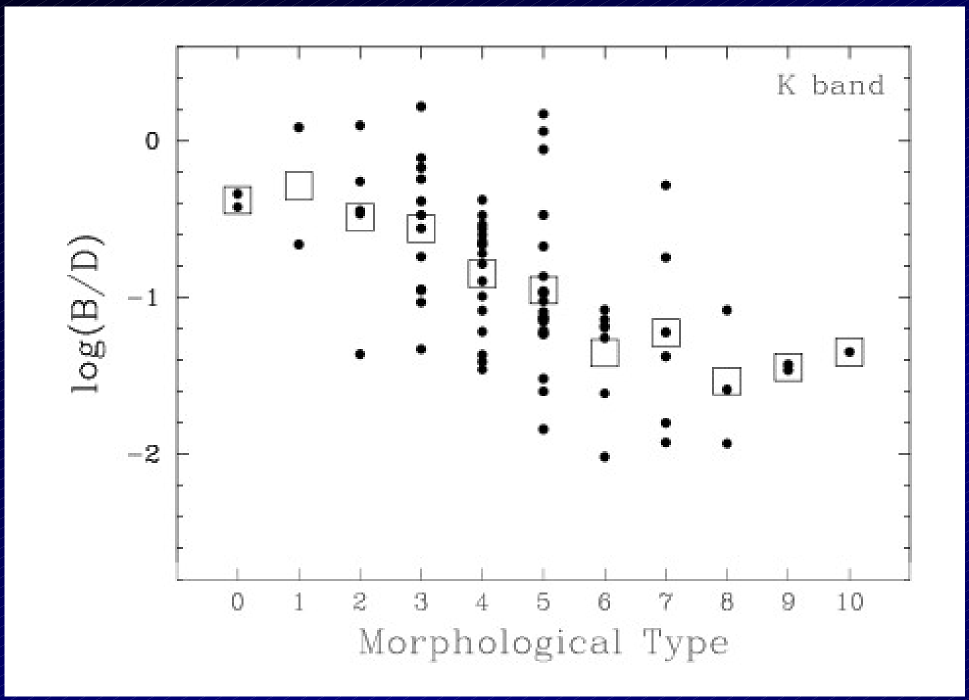
- Swing amplification: Leading spiral arms unwind and swing into trailing arms while gaining a boost in amplitude.
- Feedback loop: In the absence of ILR, the trailing arm is able to pass through the galaxy center and transform into a leading arm



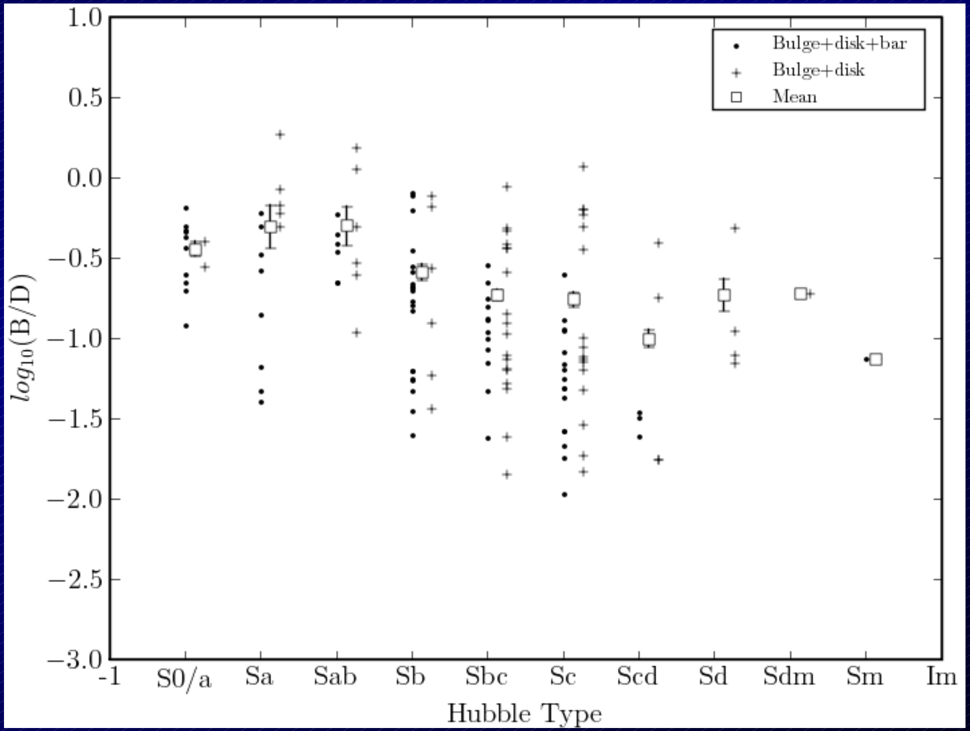
Interference between leading and trailing arms near galactic center makes a bar

Comparison With Independent Results

Comparison with 1D bulge-disk decomposition



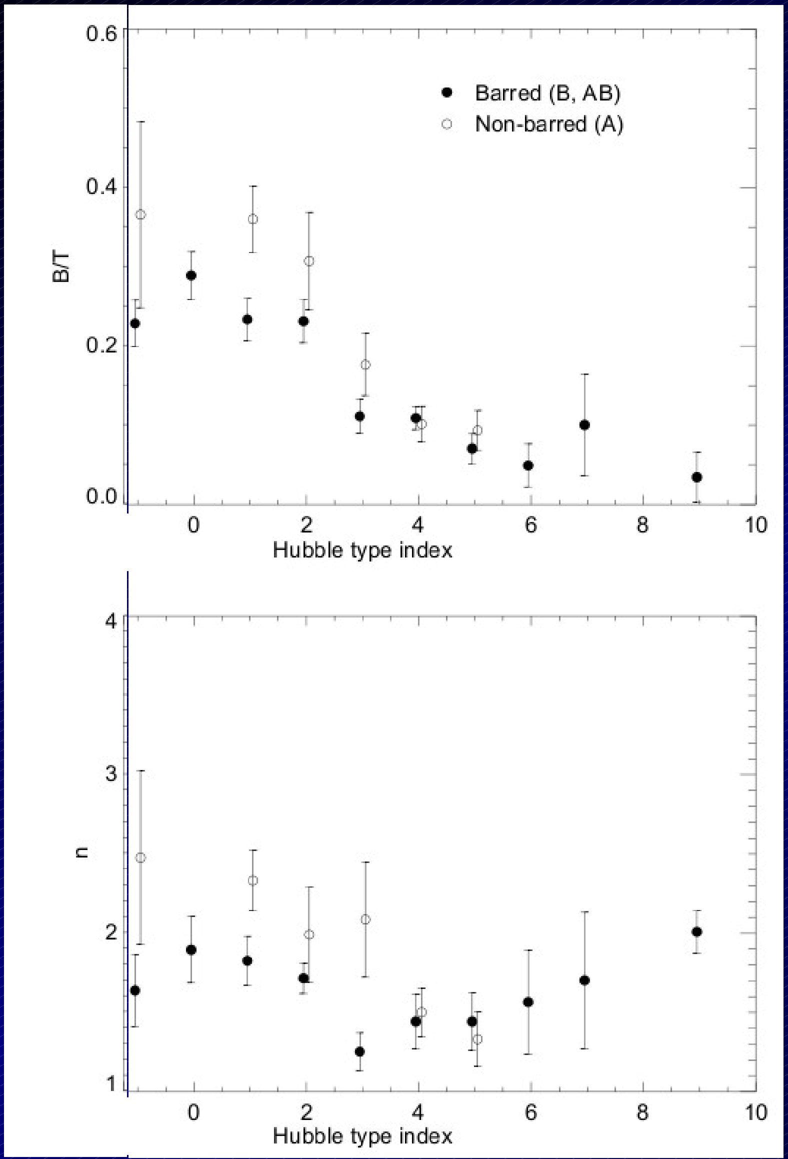
Graham (2001)



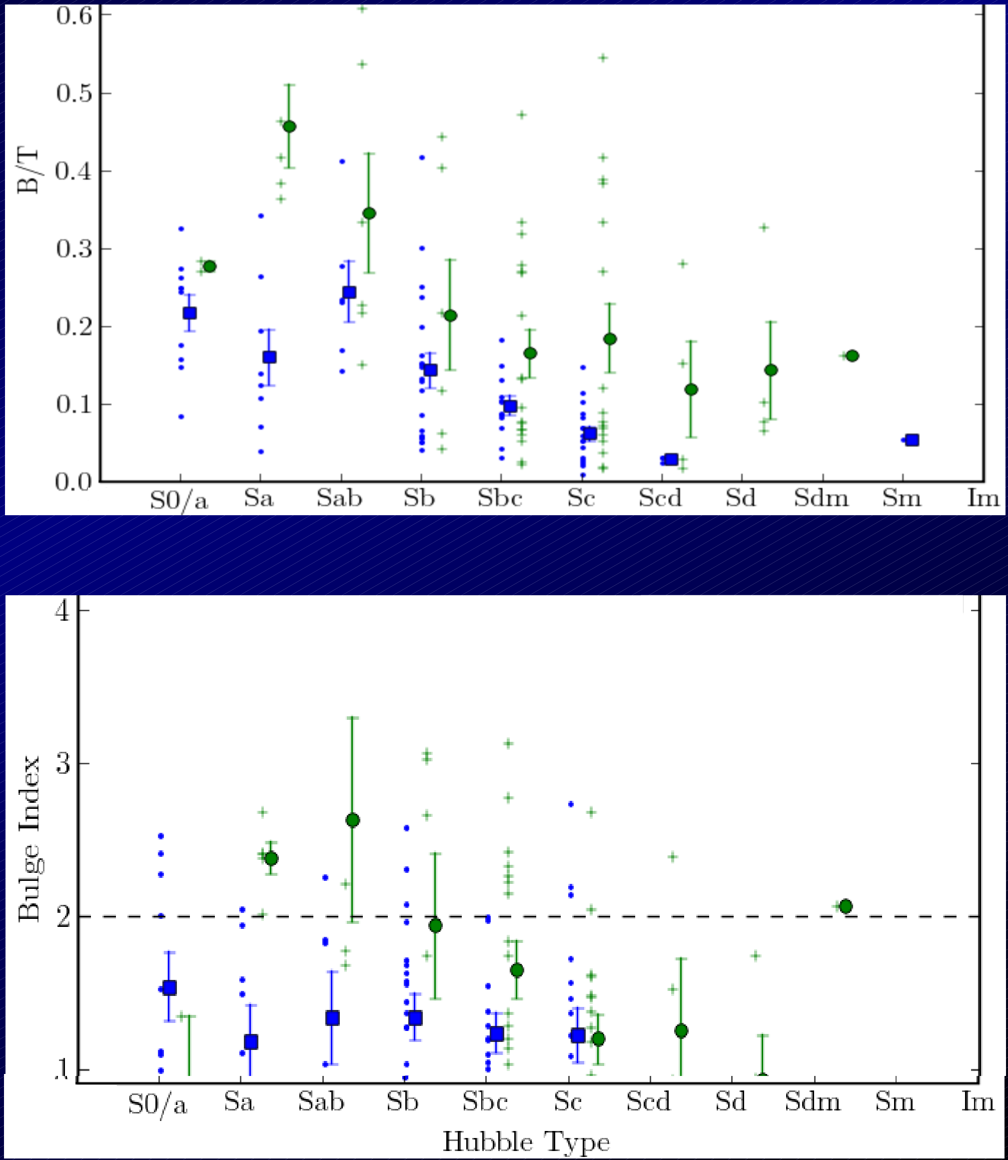
Weinzirl et al. (2008)

Comparison With Independent Results

Comparison with 2D bulge-disk and bulge-disk-bar decomposition

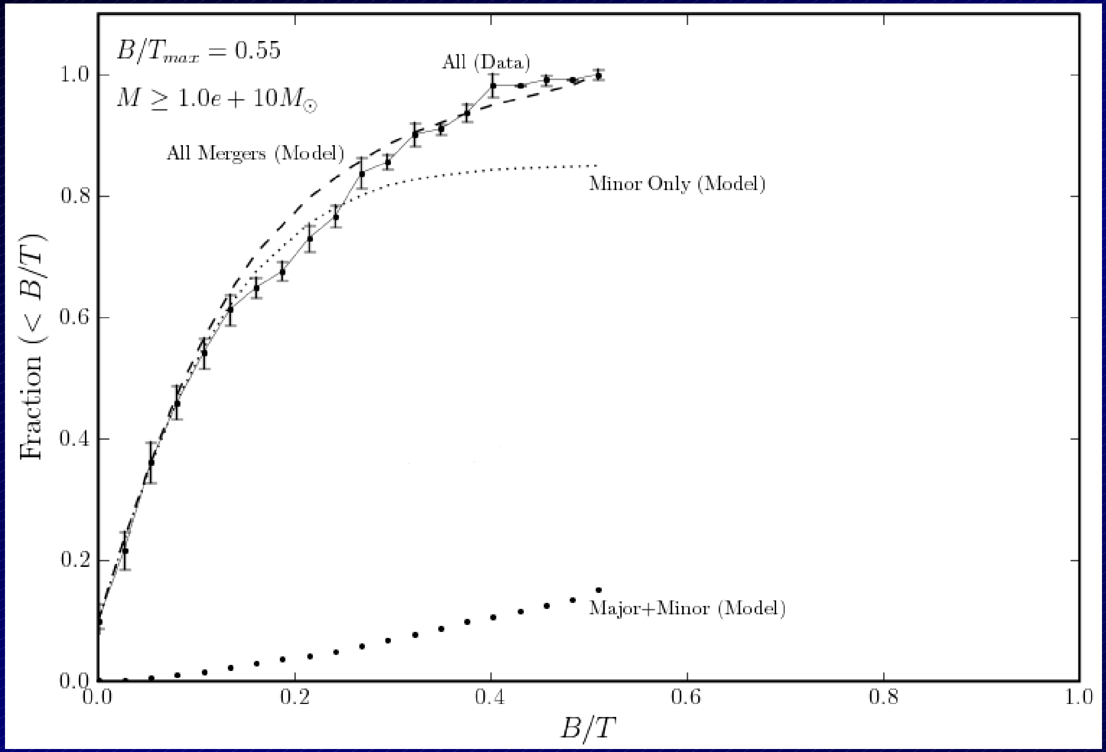


Laurikainent et al. (2007)



Weinzirl et al. (2008)

Sensitivity to Maximum B/T?



Maximum B/T = 0.55

Our conclusions about major mergers do not change when the maximum B/T limit is adjusted

Kinds of Bulges

- Classical bulges:
  - Form in major mergers
  - Miniature elliptical galaxies “that happen happen to have a prominent disk around them” (Renzini, 1999)
  - Dynamically hot, low V/σ
- Pseudobulges:
  - Form from secular processes
  - Disky structures masquerading as bulges
  - Rotationally supported, high V/σ
- Boxy/peanut bulges:
  - Buckling stabilities thickens bars, making them peanut shaped