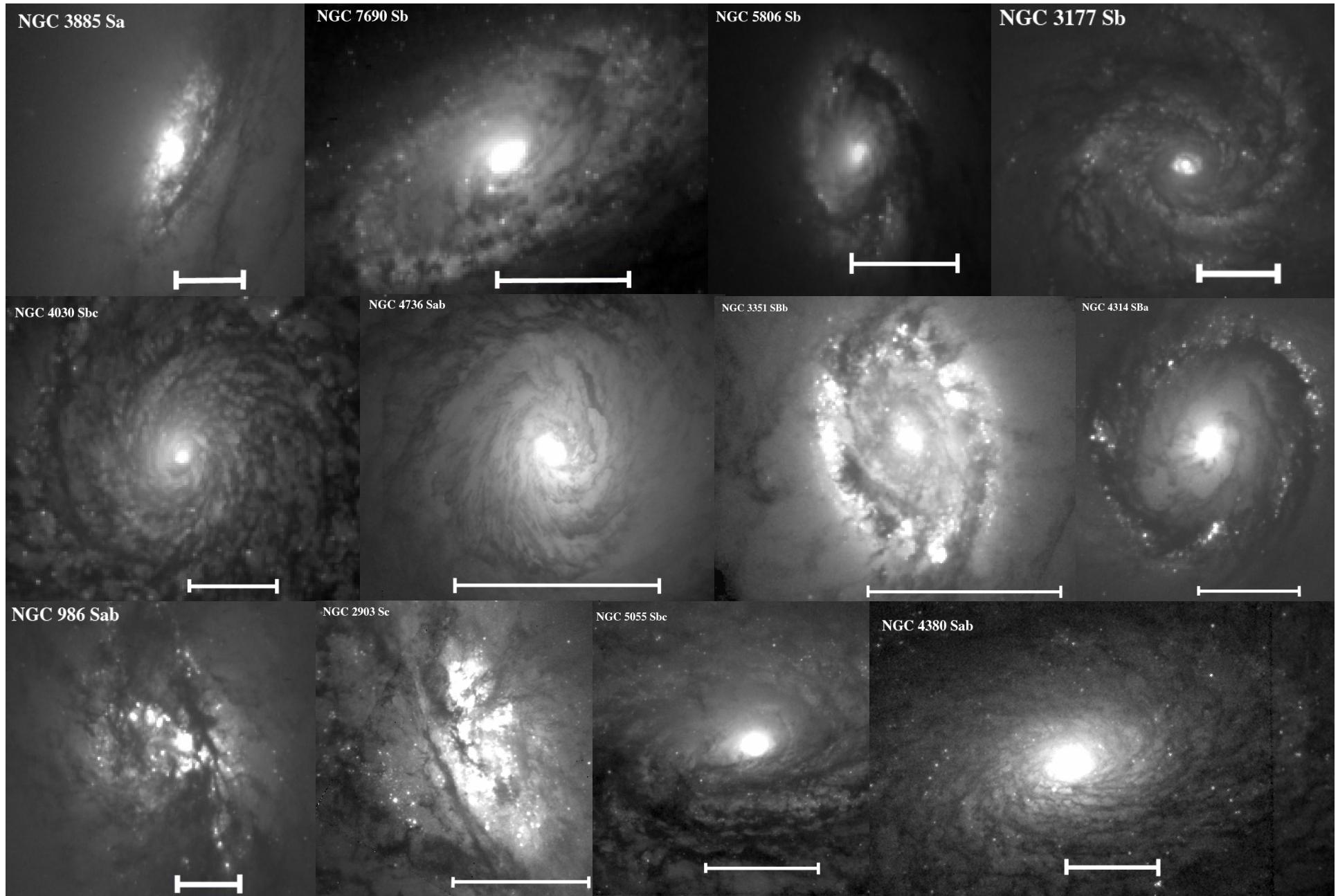


“What are pseudobulges, and
why should I care?”

David B. Fisher

Swinburne University

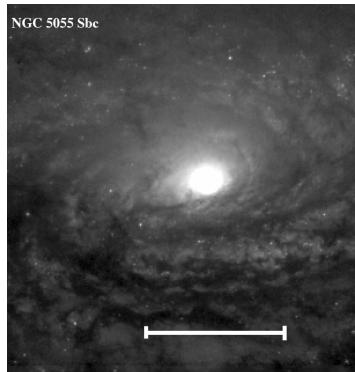
Many bulges look nothing like elliptical galaxies



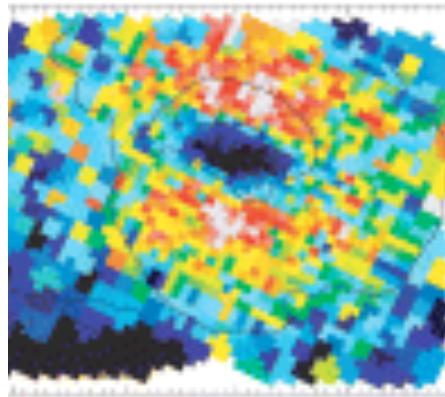
We Observe 2 Kinds of Bulges

Pseudobulge

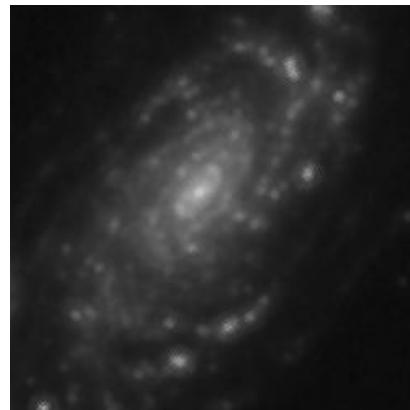
Morphology



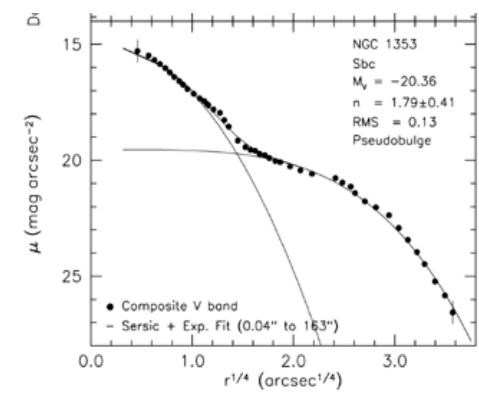
Kinematics



Star Formation
and ISM

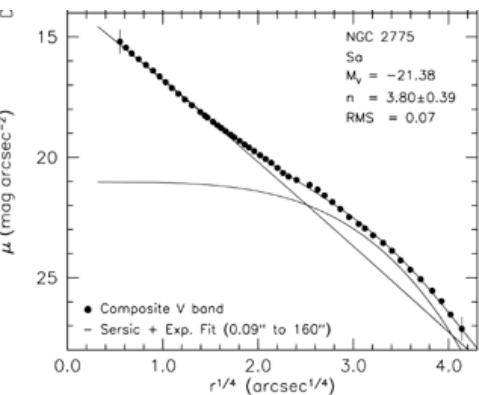
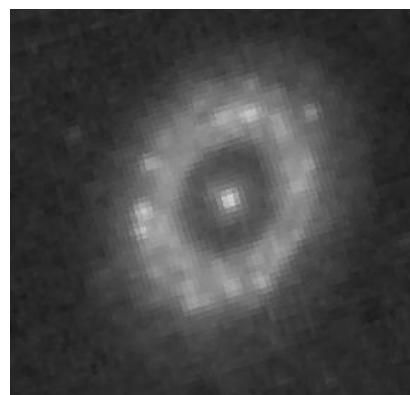
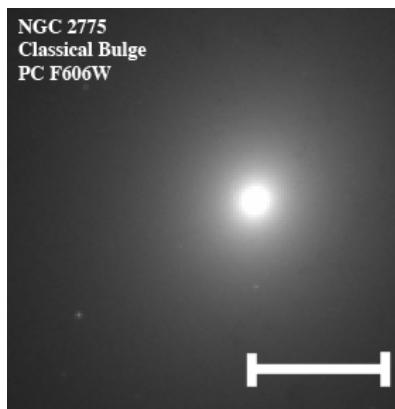


Structure



Classical

NGC 2775
Classical Bulge
PC F606W



Morphology: Carollo et al. 1997; Kormendy & Kennicutt 2004

Kinematics: Fabricius et al. 2012, Falcon-Barroso 1996, Kormendy 1993,

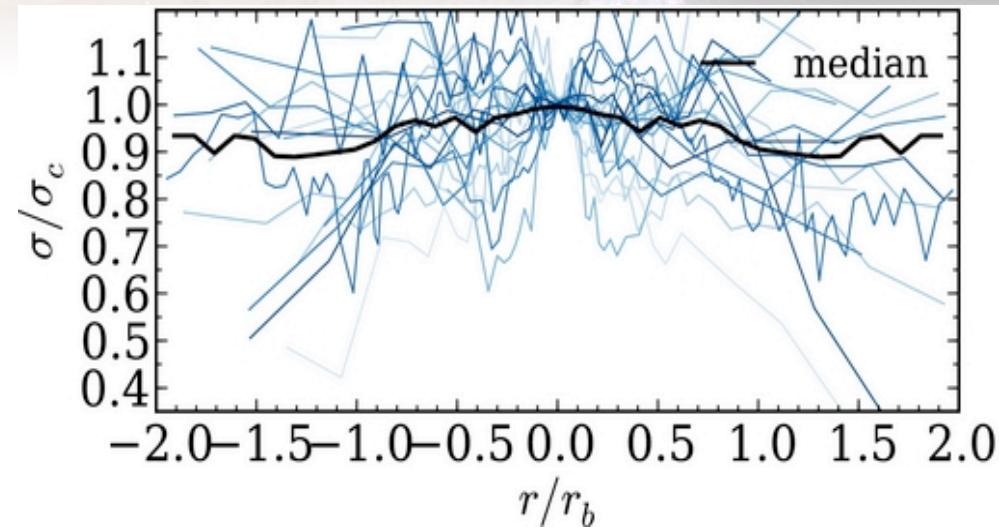
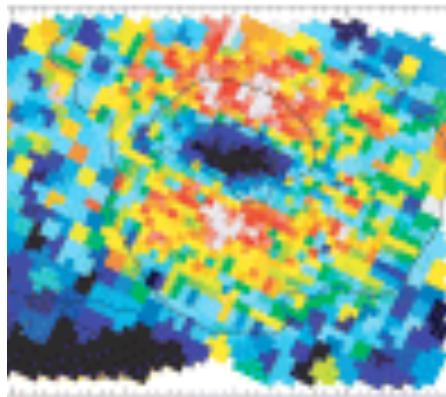
SFR : Fisher 2006; Fisher et al 2009, 2013; Peletier & Balcells 1996; Gadotti & dos Anjos 2001

Sersic Index & Structure: Fisher & Drory 2008, 2010; Gadotti 2009

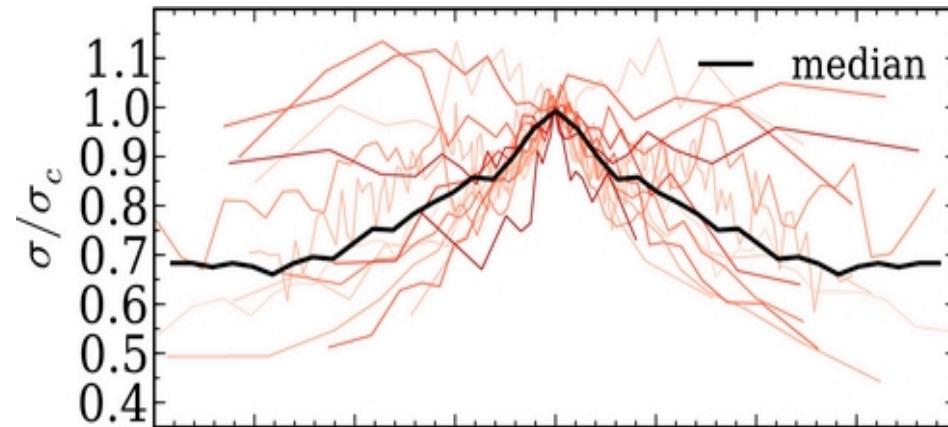
Pseudobulge kinematics are more like disks.

Pseudobulge

Kinematics



Classical

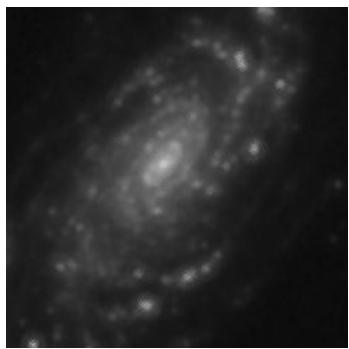


Kinematics: Fabricius et al. 2012, Falcon-Barroso 1996, Kormendy 1993,

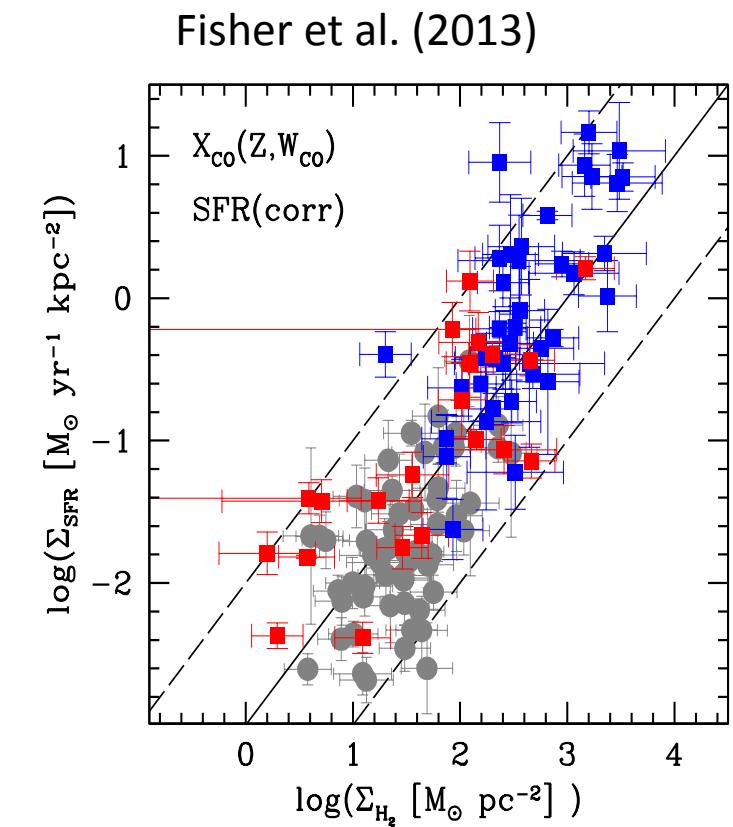
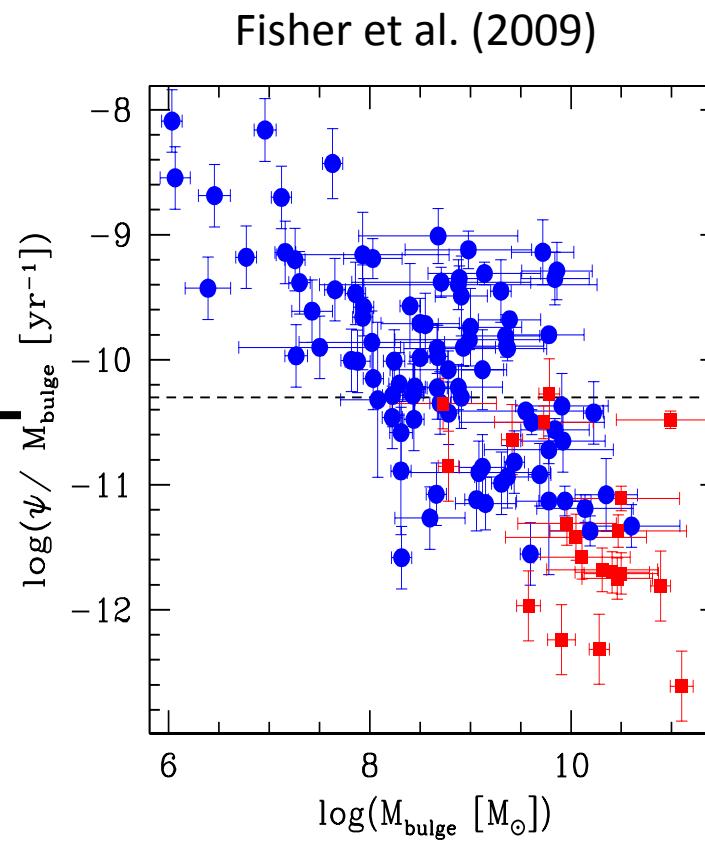
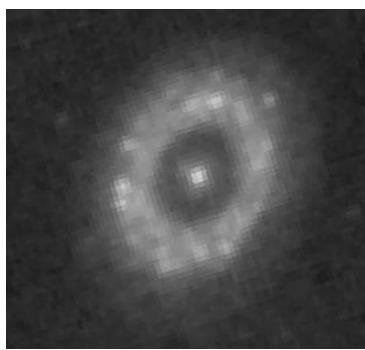
Pseudobulges are actively forming stars

Star Formation and ISM

Pseudobulge



Classical

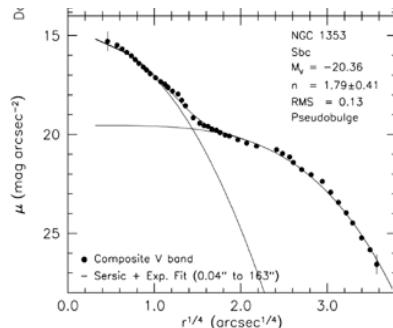


SFR : Fisher et al 2013, Fisher et al 2009, Fisher 2006

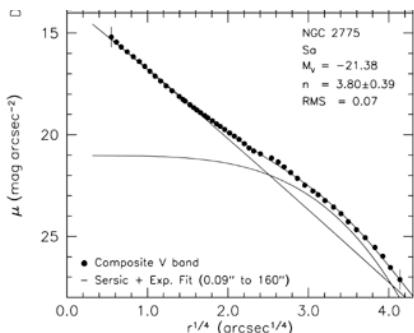
Pseudobulges have smaller Sersic index.

Pseudobulge

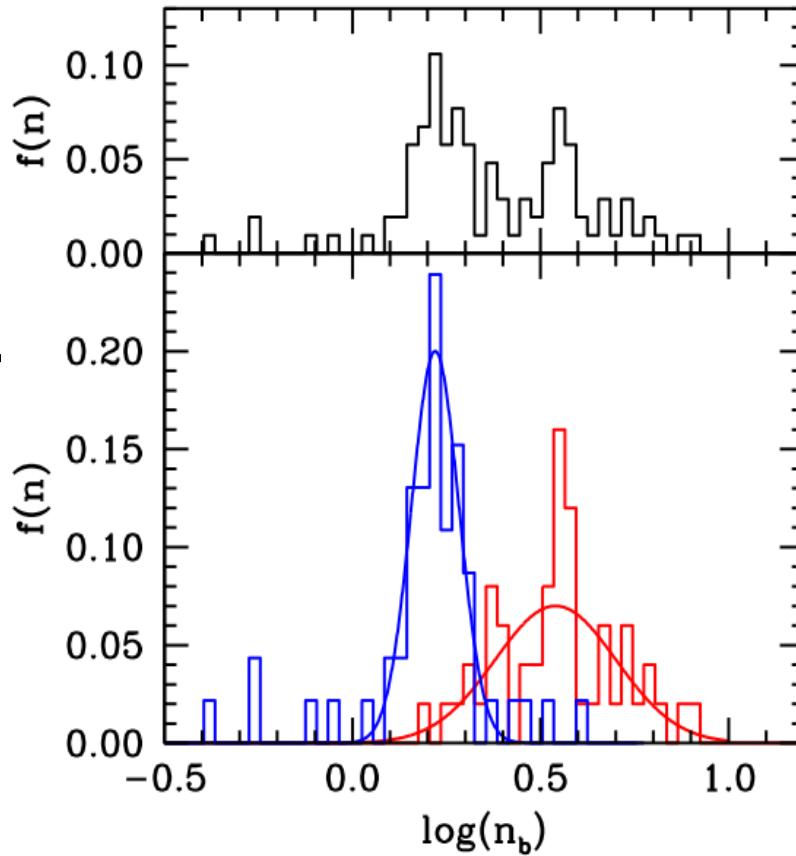
Structure



Classical



Fisher & Drory (2008)

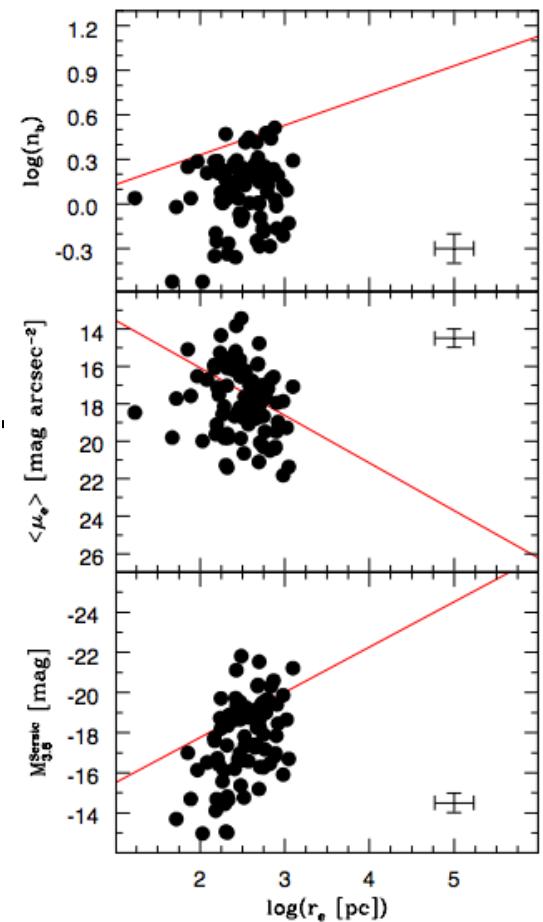
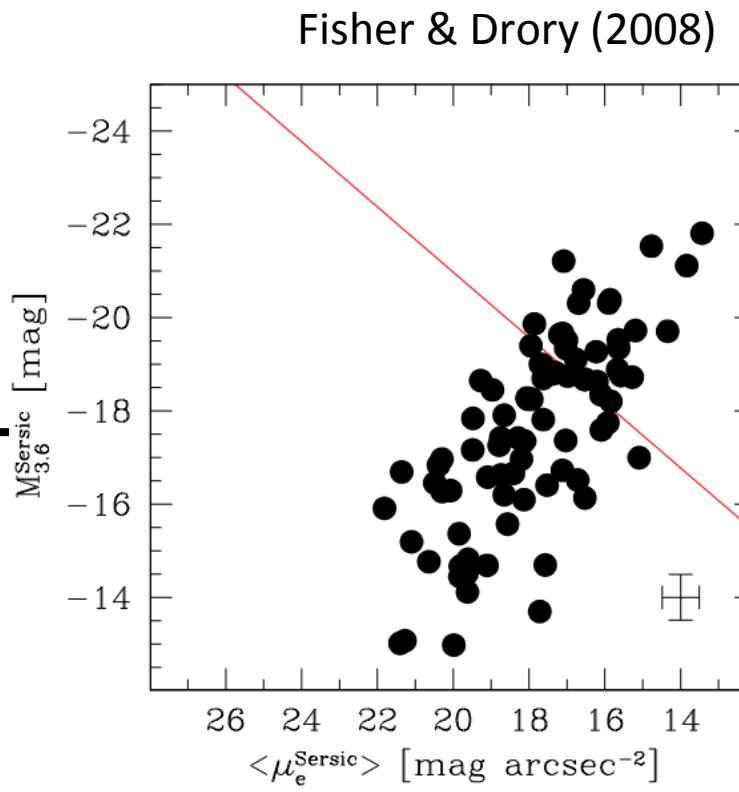
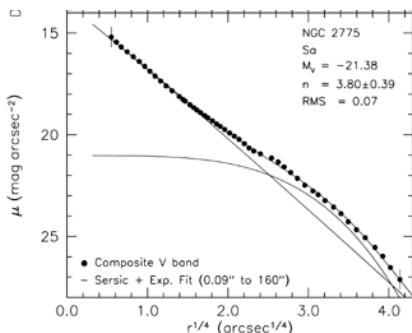
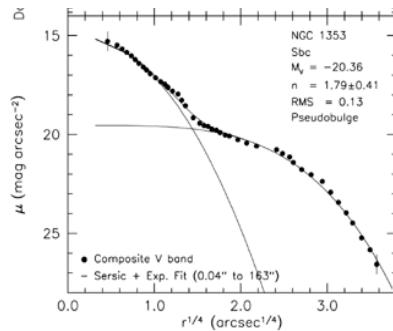


Sersic Index & Structure: Fisher & Drory 2008, Fisher & Drory 2010; Gadotti 2009

Pseudobulges are not on the fundamental plane.

Classical Pseudobulge

Structure



Sersic Index & Structure: Fisher & Drory 2008, Fisher & Drory 2010; Gadotti 2009

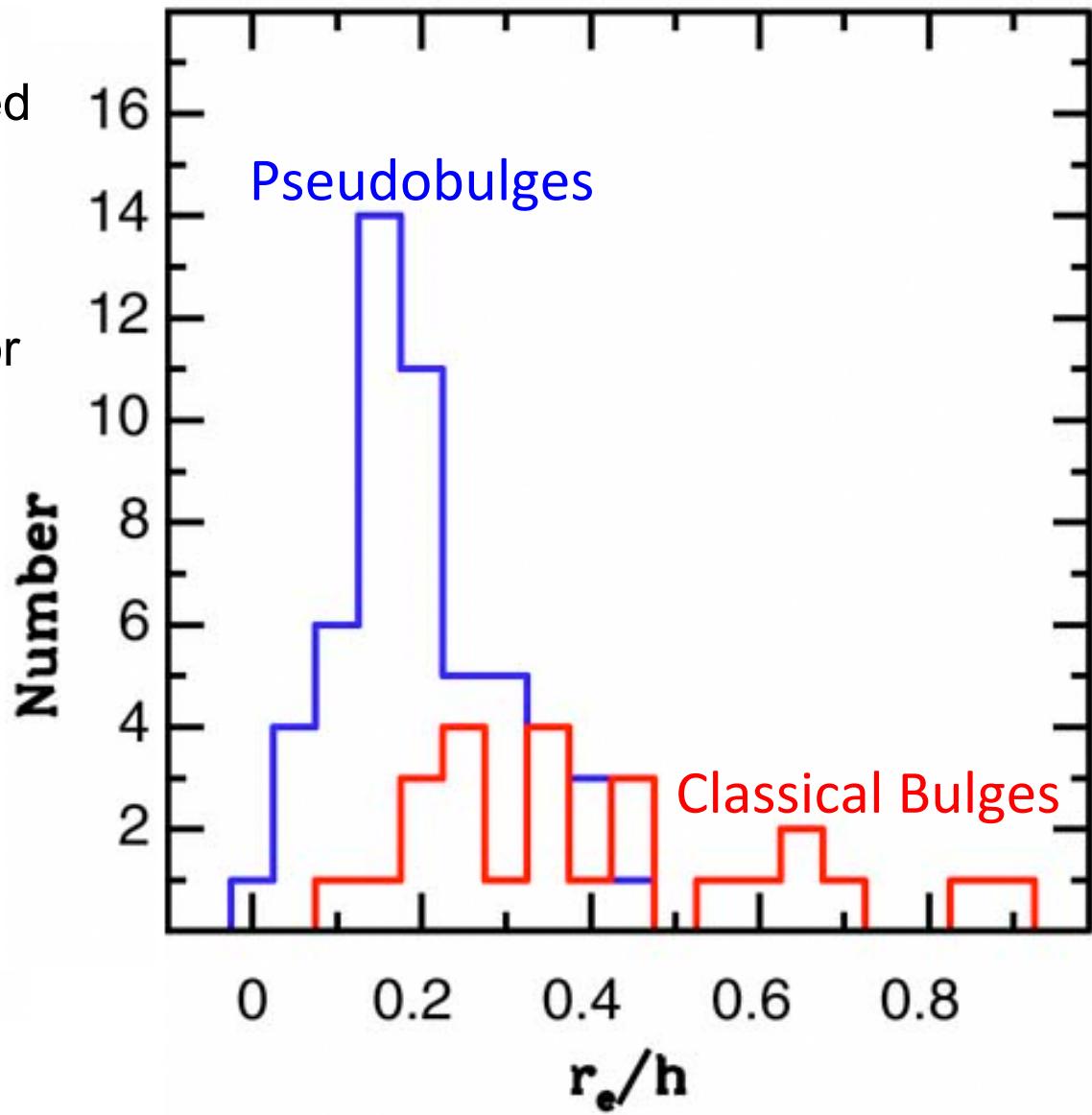
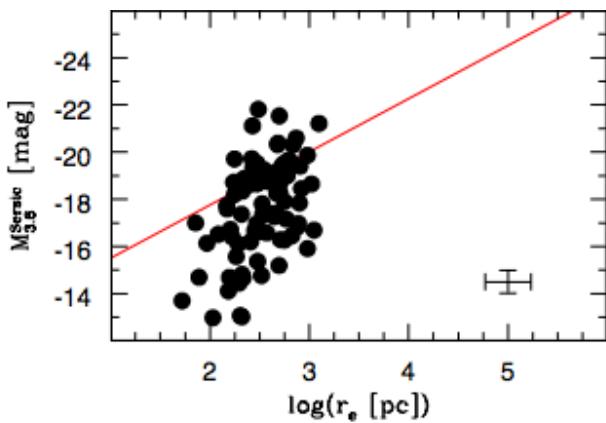
Pseudobulges sizes are correlated with disk size (only?)

Courteau (1996): scale lengths of bulges is connected to disks.

Fisher & Drory (2008):
The connection only exists for pseudobulges.

$$r_e \sim 0.2h$$

Recall ...



Pseudobulges are VERY common

Fisher & Drory (2011):

Bulge-Disk Galaxies:

~75% have
pseudobulges

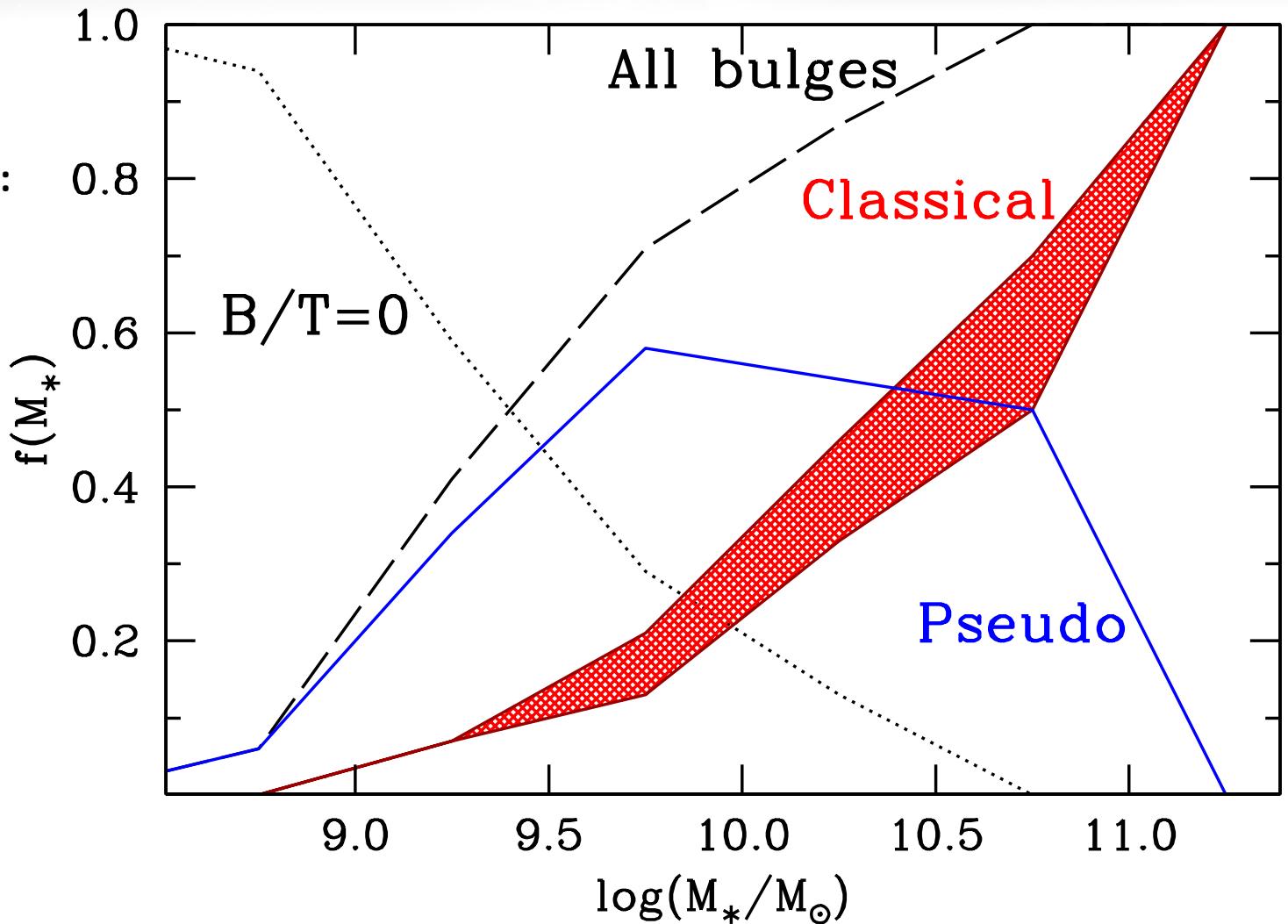
All bright galaxies

($>10^9 M_\odot$):

42% pseudobulges

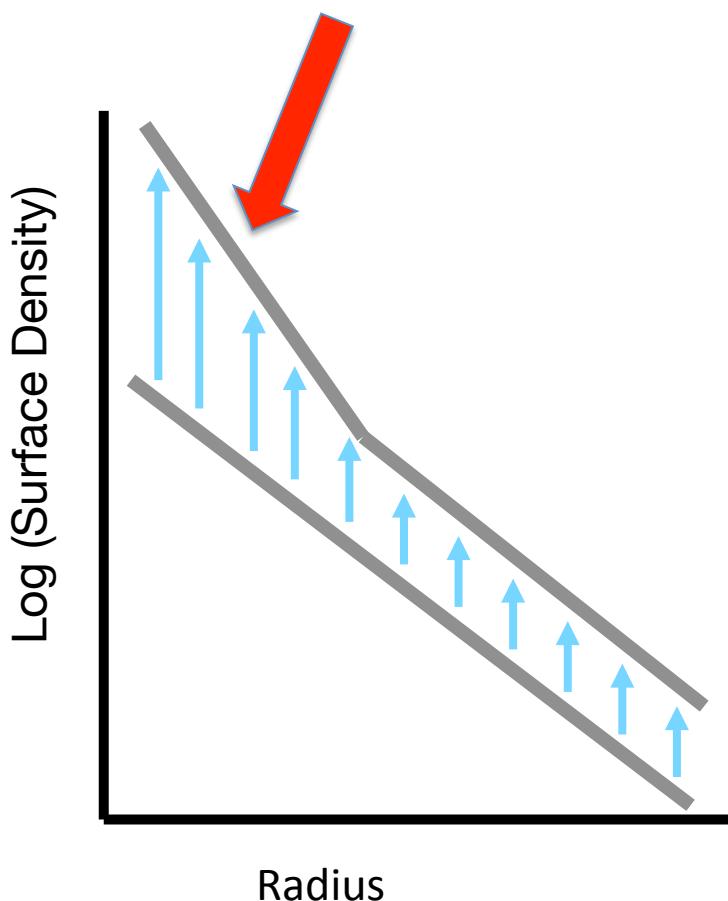
38% bulgeless

17% classical



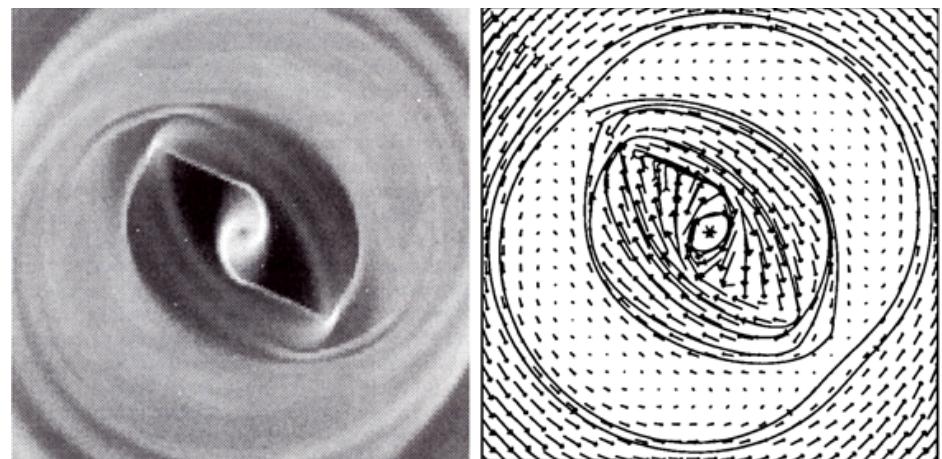
Can Internal Gas Flows Grow Bulges?

We do observe the signature that would lead to bulge growth.



Gas Inflows

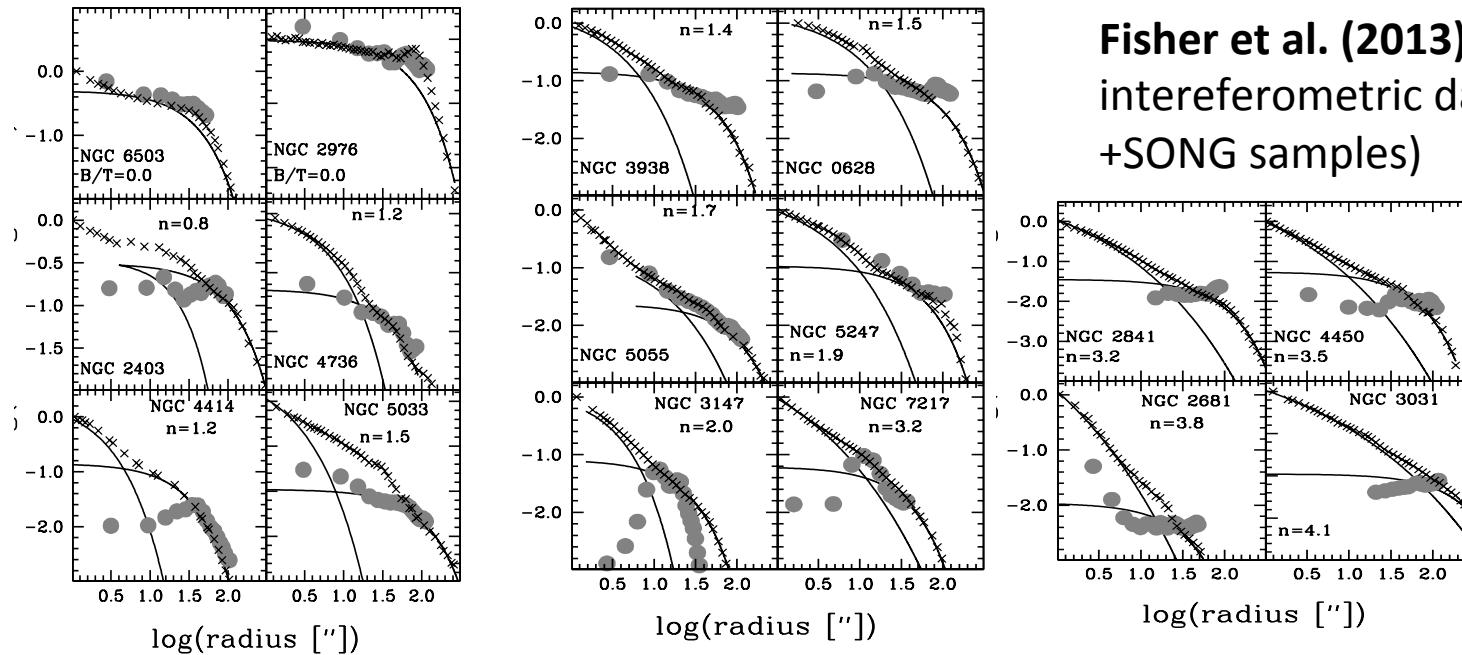
- Bars drive gas inward (Athanassoula 1992, Simkin 1980, Heller+2007, etc.)
- We observe high density gas preferentially in the center of barred disks.
- Bars are very common
- Inflow rates are enough to build a bulge in a few gigayears. (Haan+2009)



Athanassoula (1992), Shlosman et al. (1989), Combes & Gerin (1985), Heller et al. (2007)

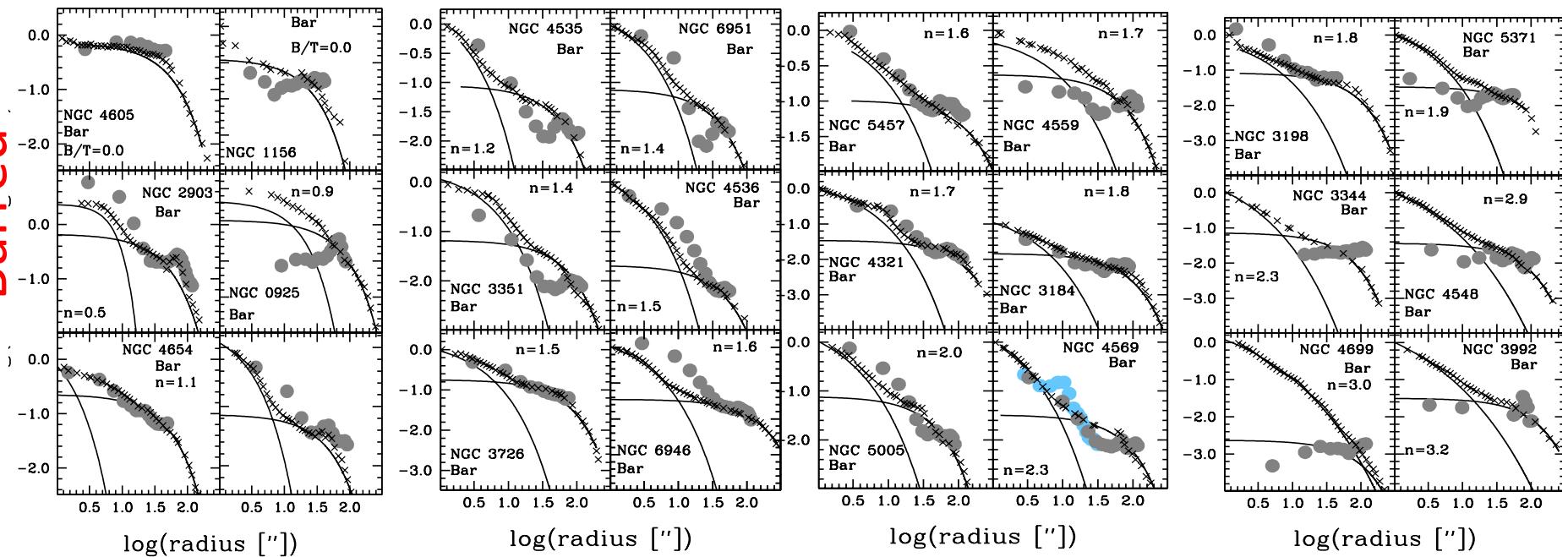
Reviews: Kormendy & Kennicutt (2004), Athanassoula (2005), Combes (200N)

Unbarred



Fisher et al. (2013): 60 galaxies with interreferometric data (STING+NUGA +SONG samples)

Barred



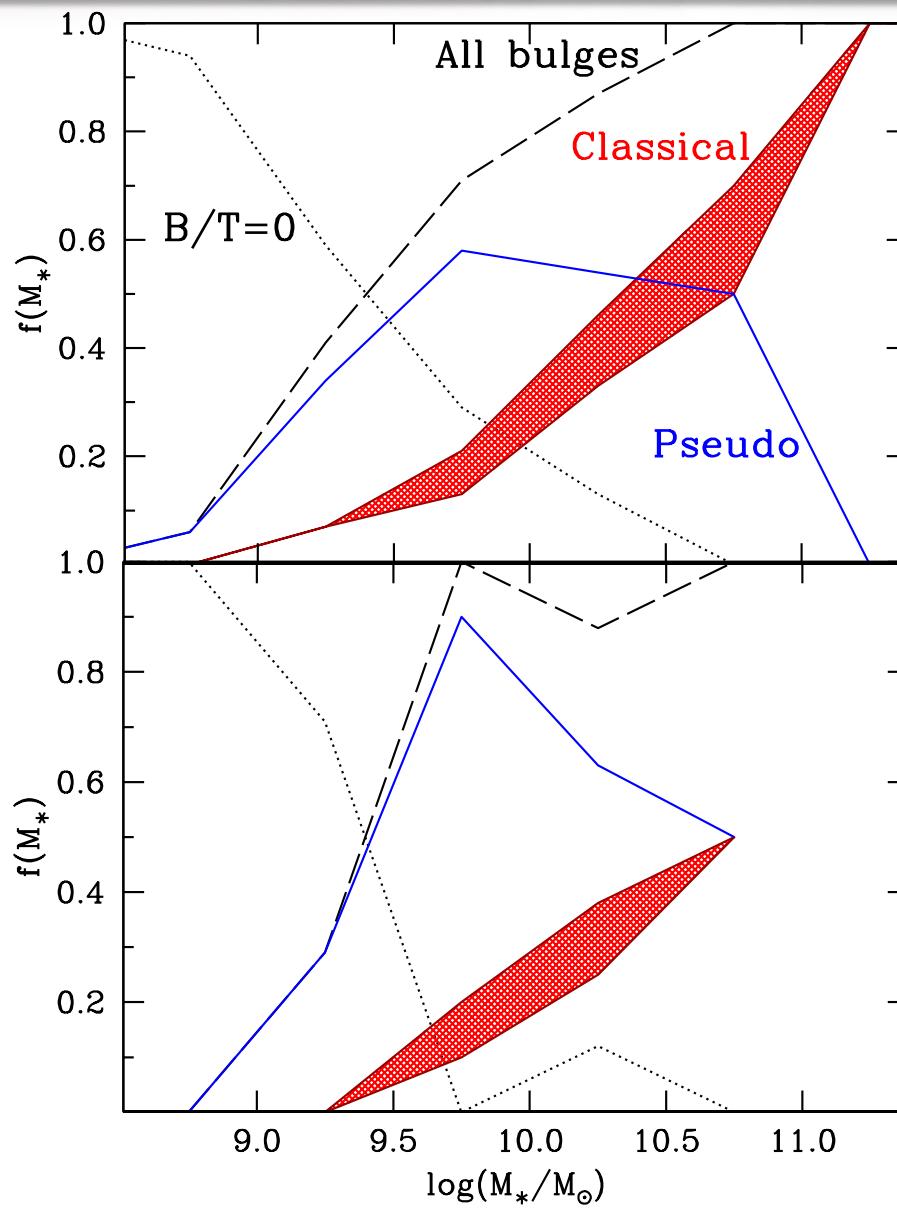
Also ... Sakamoto et al. (1998), Sheth et al. (2005), Jogee et al. (2005), Komugi et al. (2008), NUGA survey

Pseudobulges Are More Common in Barred Galaxies

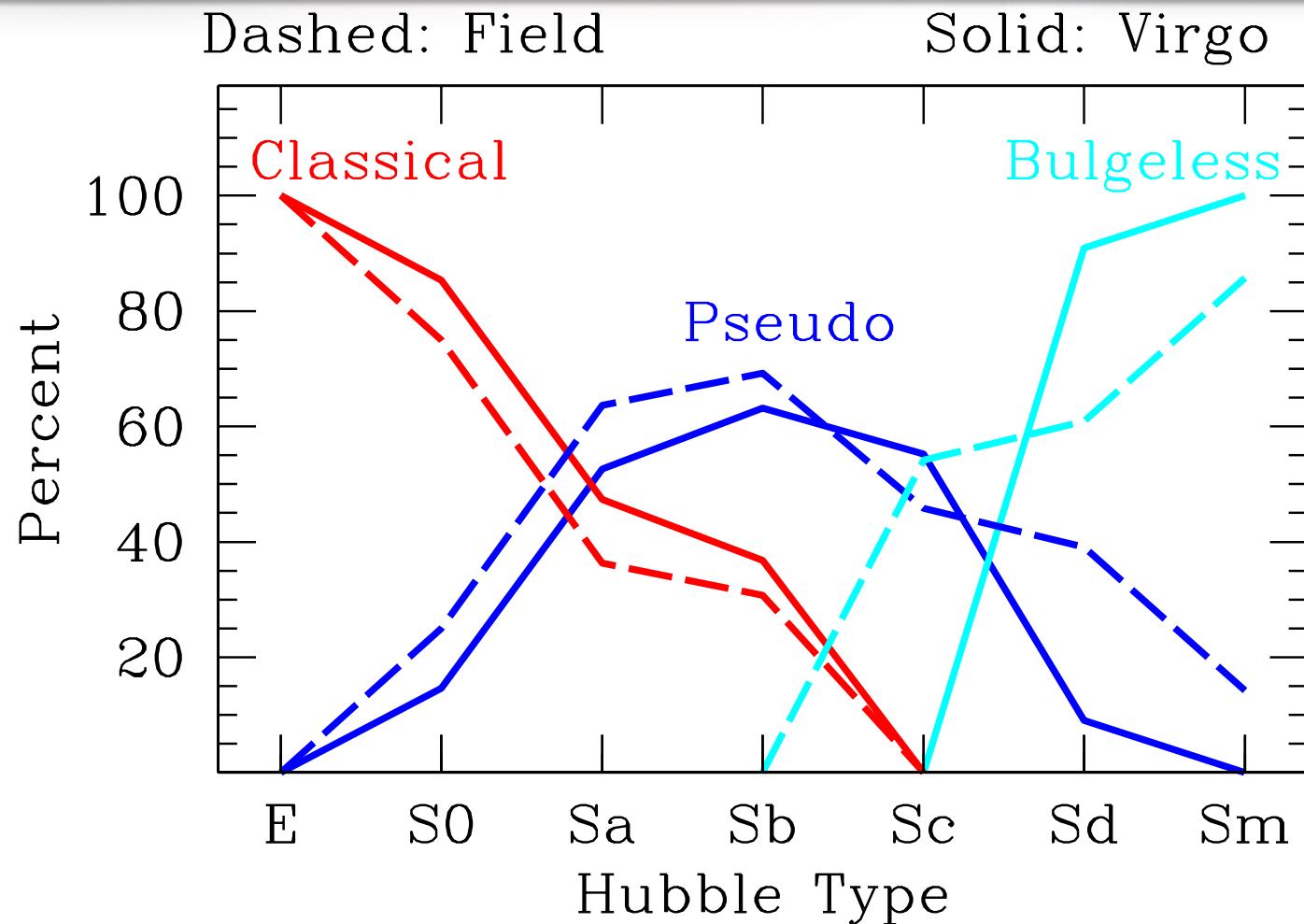
All Galaxies

Barred Galaxies

Fisher & Drory (2011)



Pseudobulges dominate Sa-Sc galaxies.



Pseudobulges are far less common in clusters (<30% of bright galaxies). This seems to be due to morphology-density relationship.



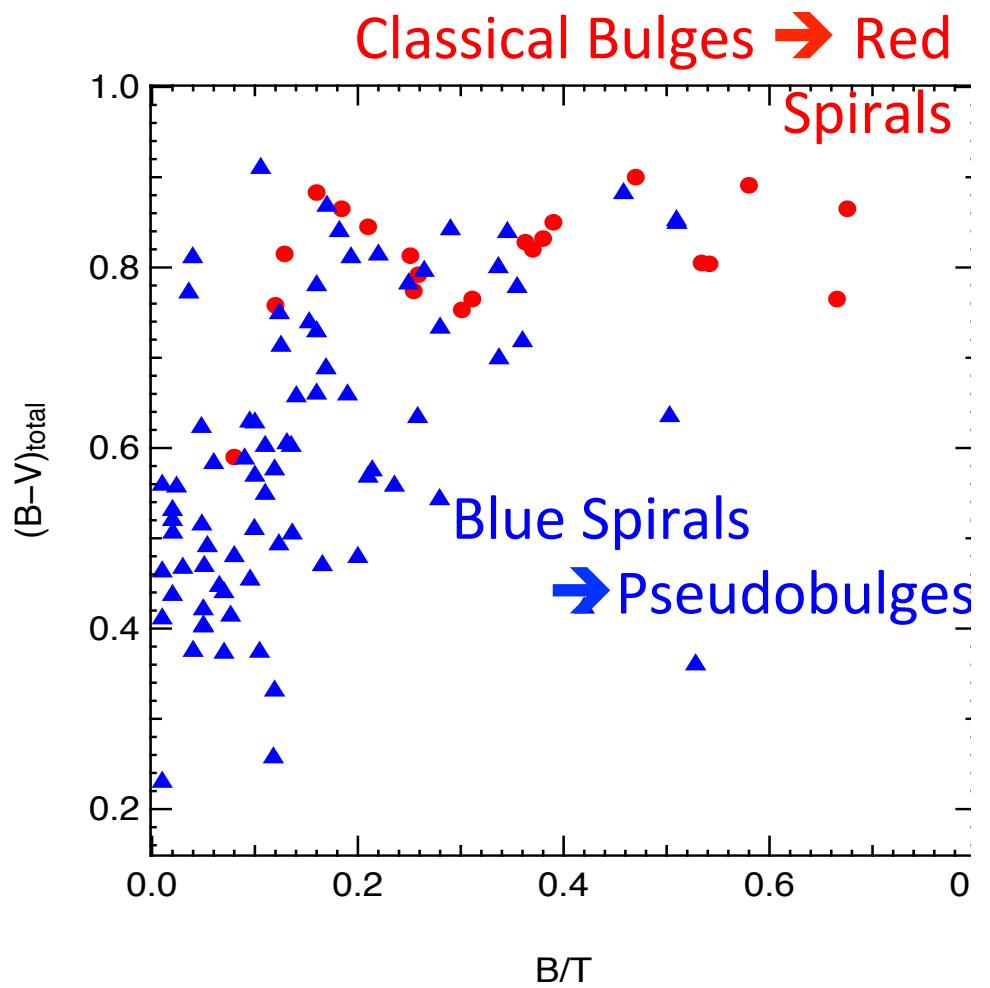
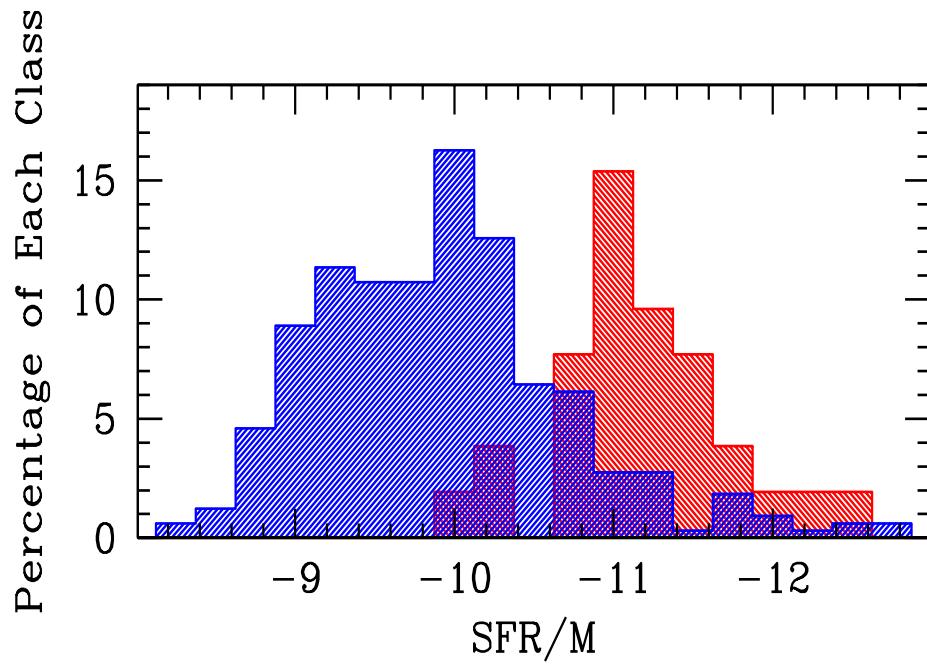
Observational Definition of Pseudobulge

Pseudobulge – a bulge observed to have “disk-like” properties

- **Morphology** : spiral structures, nuclear rings, etc.
 - **Brightness Profile**: Sersic index of the bulge is below $n_b \approx 2$
seems to correlate very well with all properties.
 - **Kinematics**: velocity dispersion is comparable to the associated disk
caution: Saha & Gerhard (2013) show bars can increase rotation in classical bulges
-
- **ISM & Star Formation**: pseudobulges are often have more gas and star forming
 $SFR/M \geq 5 \times 10^{-11} \text{ yr}^{-1}$
 $f_{\text{gas}} \geq 5\%$
 - **Scaling relations**: pseudobulges are often low density outliers to Kormendy relation, size-luminosity correlation, and surface brightness-luminosity
 - **Flatness**: the flattest bulges are pseudobulges

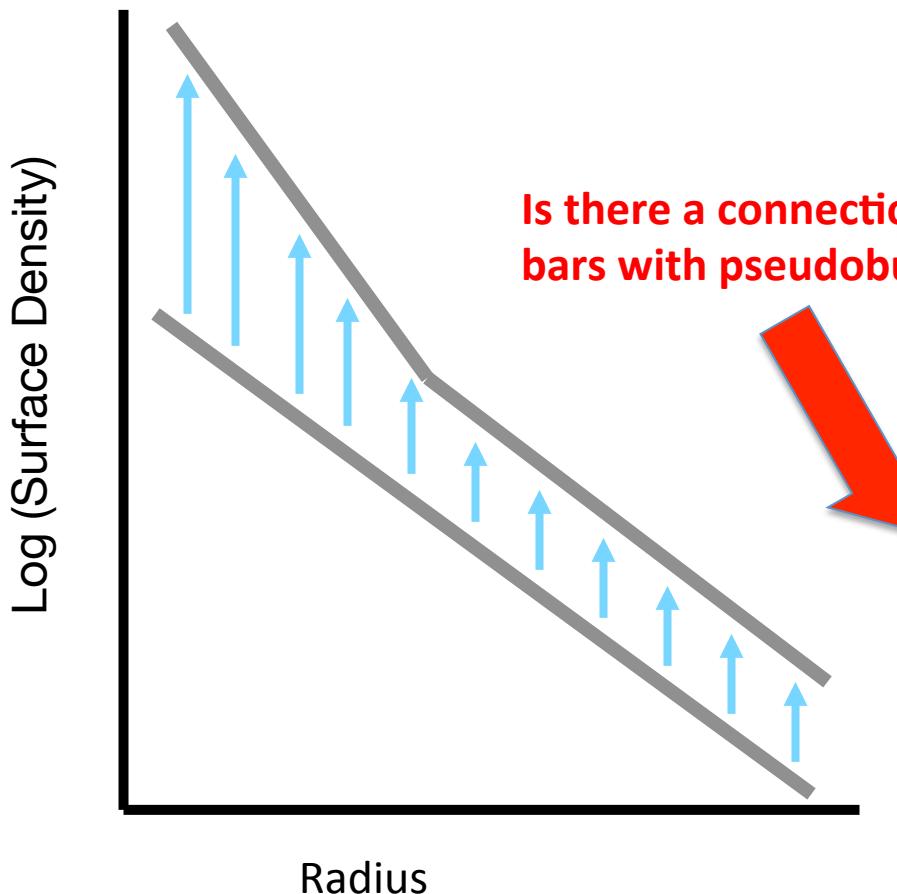
May Not Select
All Pseudobulges

Pseudobulges are in blue spirals.



Drory & Fisher (2007)

Can Internal Gas Flows Grow Bulges?



Gas Inflows

- Bars drive gas inward (Athanassoula 1992, Simkin 1980, Heller+2007, etc.)
 - Bars are very common (Eskridge+2000)
- Inflow rates are enough to build a bulge in a few gigayears. (Haan+2009)
- Bulges in barred disks are the locations of intense star formation (Fisher et al. 2013).

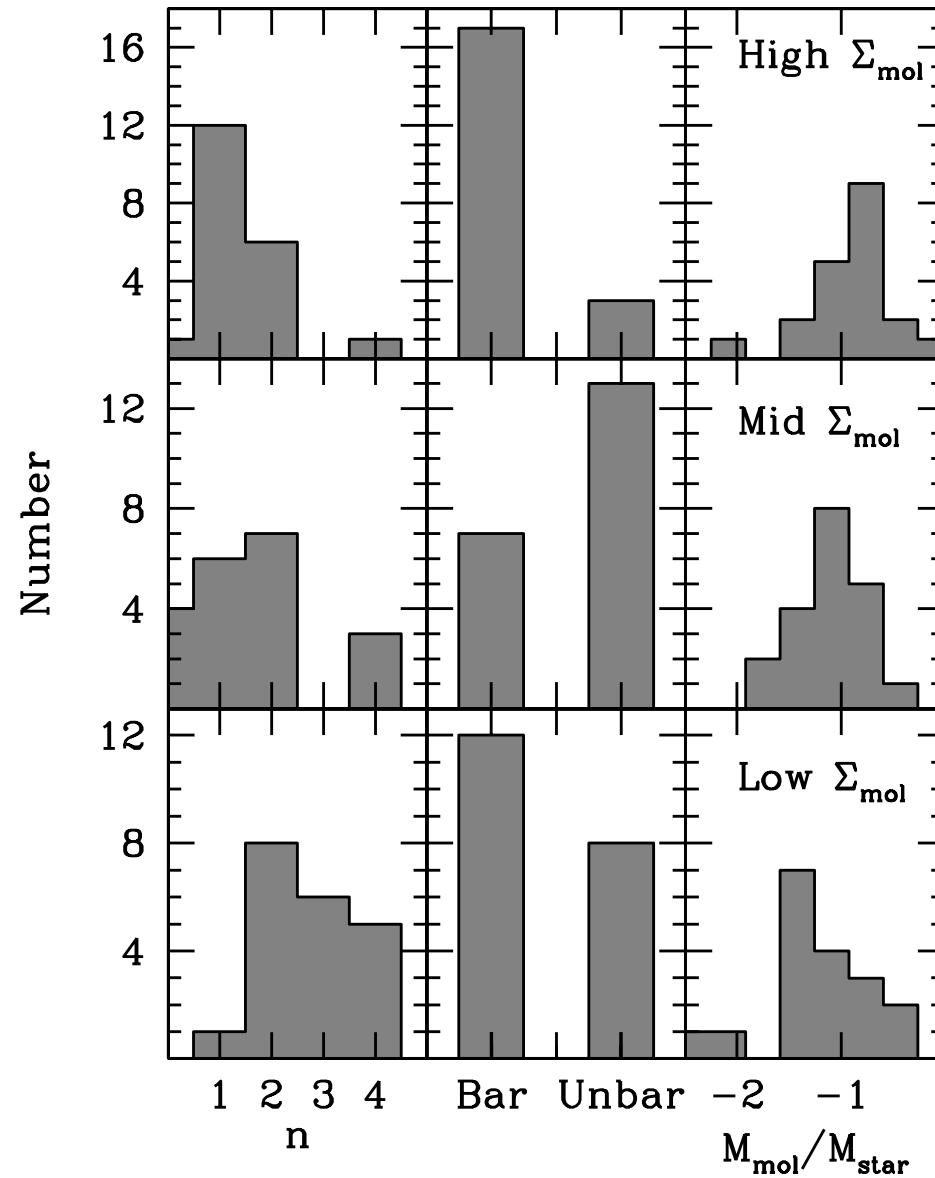
Bulge Growth:

- Gas forms stars in thin disk. (Garcia-Burillo +1999)
- Resulting structure of stars is cold, and high concentration compared to a disk.
- Stars may be heated by resonant phenomena later (but maybe not)

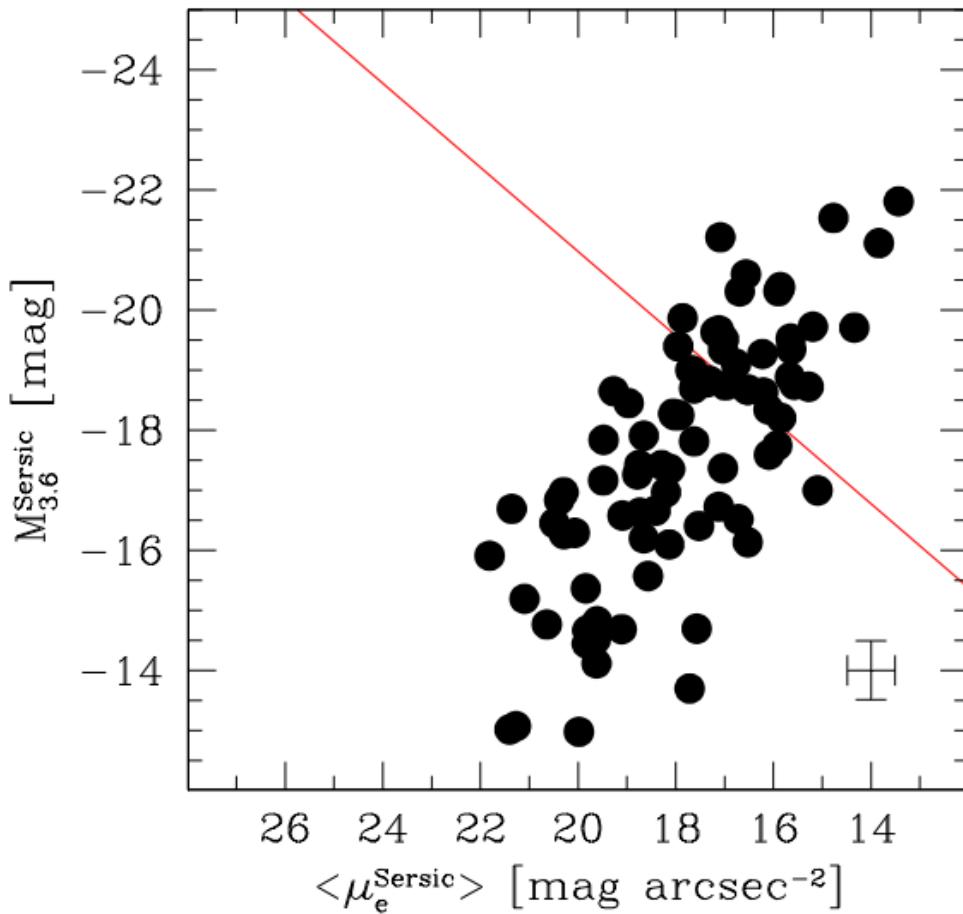
Bars Are Necessary To Have the Highest Central Gas Density

Fisher et al. (2013): 60 galaxies with interreferometric data (STING +NUGA+SONG samples)

Coelho & Gadotti (2011) find similarly that bulges in barred disks have more young stars.



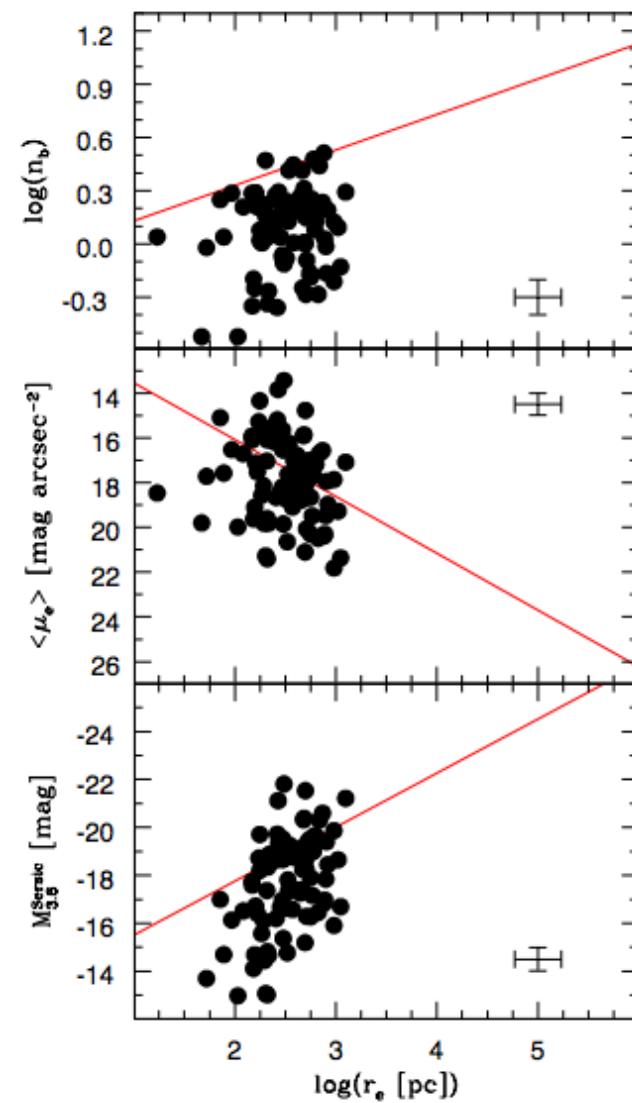
Pseudobulges are not on the Fundamental Plane



Fisher & Drory (2010)

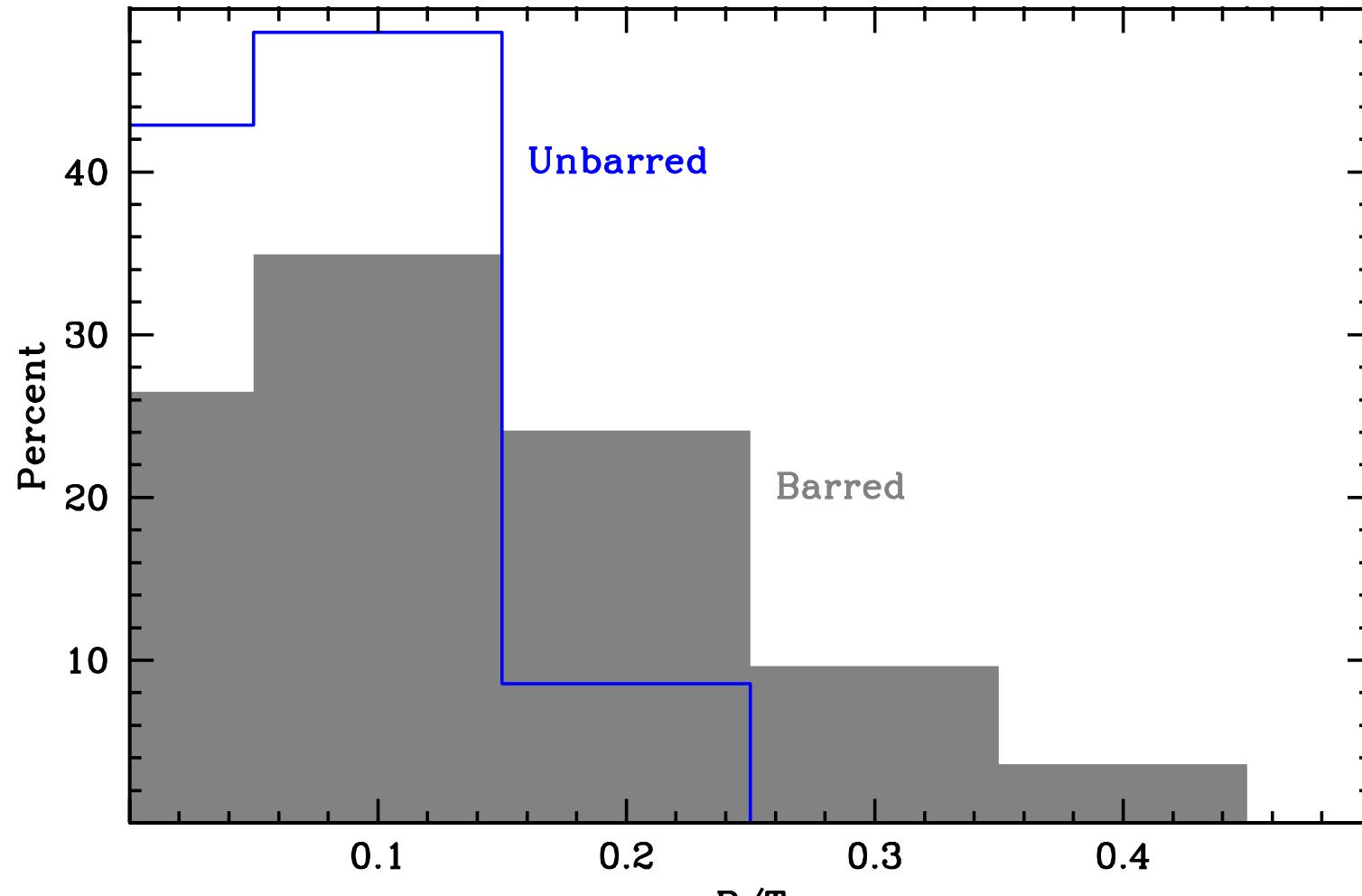
Gadotti (2009)

Carollo et al. (1997)



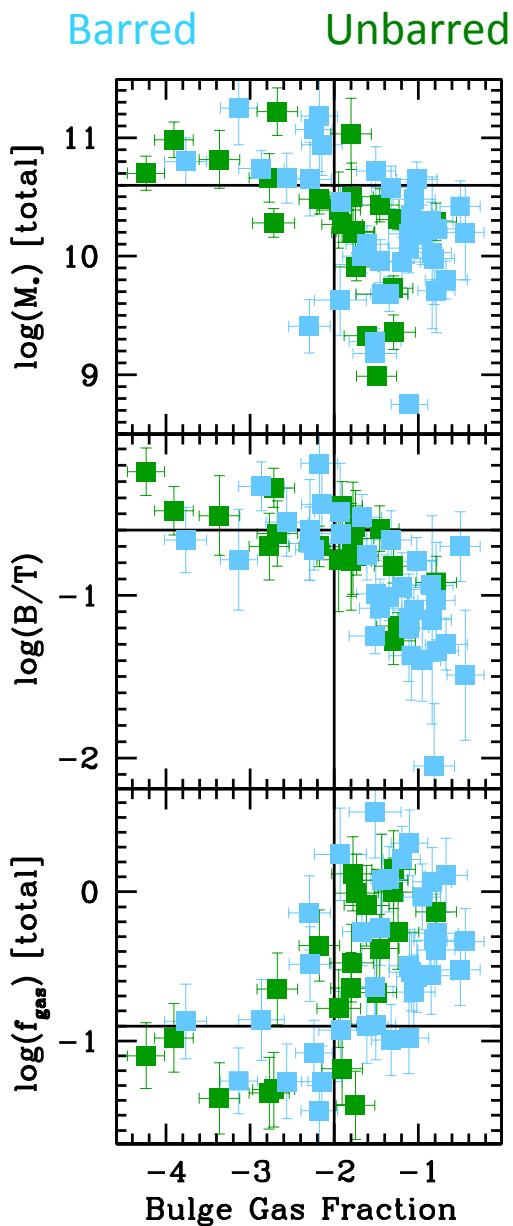
Pseudobulges in Barred Galaxies Are Bigger

Pseudobulges Only



Fisher (*in prep*)

Ingredients to Make a Pseudobulge



- Galaxy stellar mass between $10^9 - 3 \times 10^{10} M_\odot$
- High total gas fraction
aka blue sequence galaxy
- Does not have a large bulge $B/T \leq 1/3$
consistent with B/T vs bar torque

Bars are not necessary, but they help.

- 35% of pseudobulges are in unbarred disks, similar to unbarred galaxies in general.
- Bars definitely increase both the amount of gas and B/T of pseudobulges.

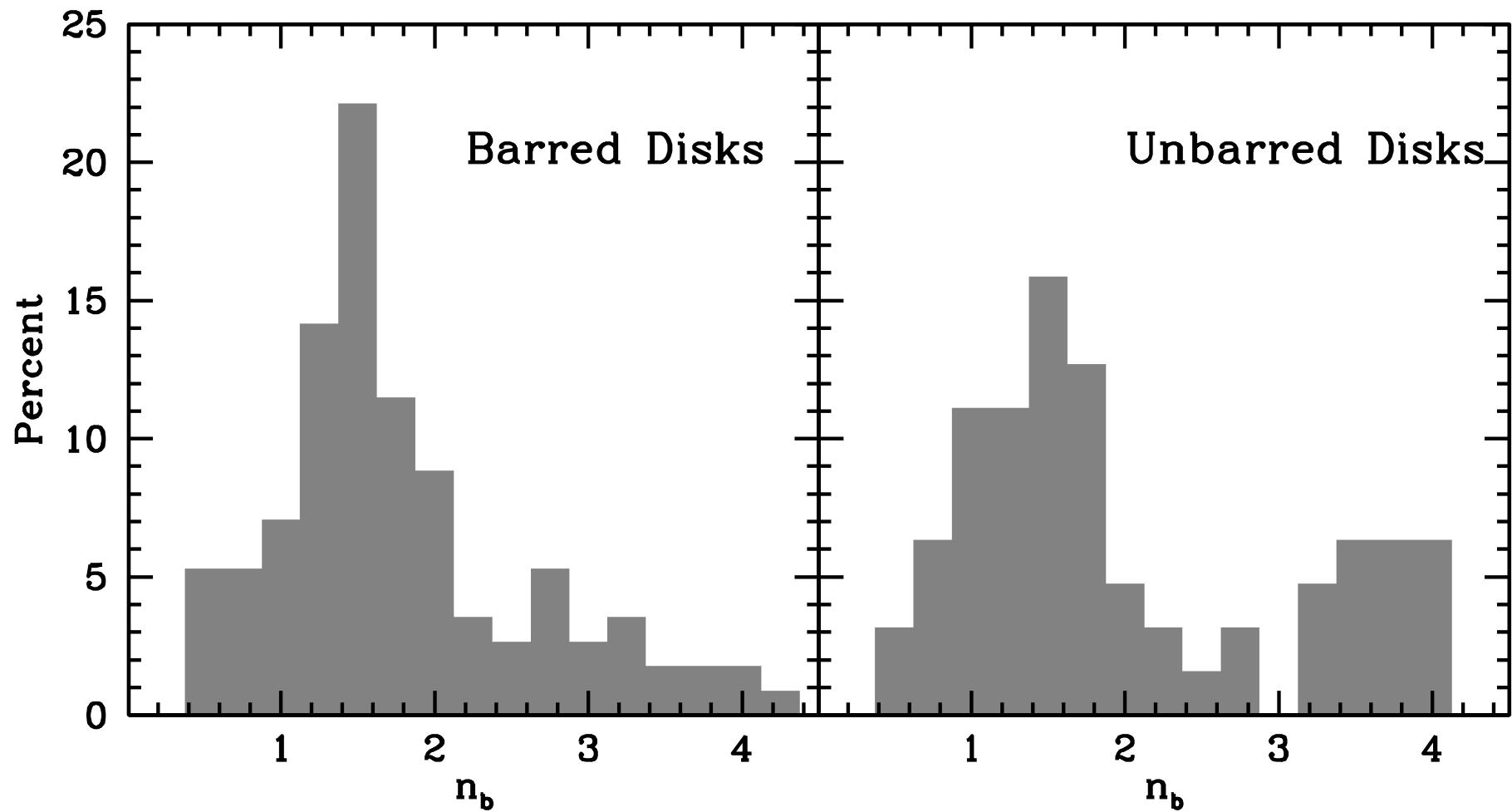


Summary

- **Gas density profiles are consistent with bulge growth.**
 - > Profiles are NOT exponential in the centers of bulge-disk galaxies
 - The high density gas in galaxy centers is associated with barred disks.
- **Pseudobulges are consistent with what we expect bar evolution.**
 - Pseudobulges are very common, especially at intermediate masses
- **There is a strong observable connection between pseudobulges and barred disks.**
 - Pseudobulges are more common in barred disks.
 - Pseudobulges in barred disks have higher B/T and higher surface densities of gas (both consistent with secular formation of pseudobulges).

80% of barred galaxies* have pseudobulges

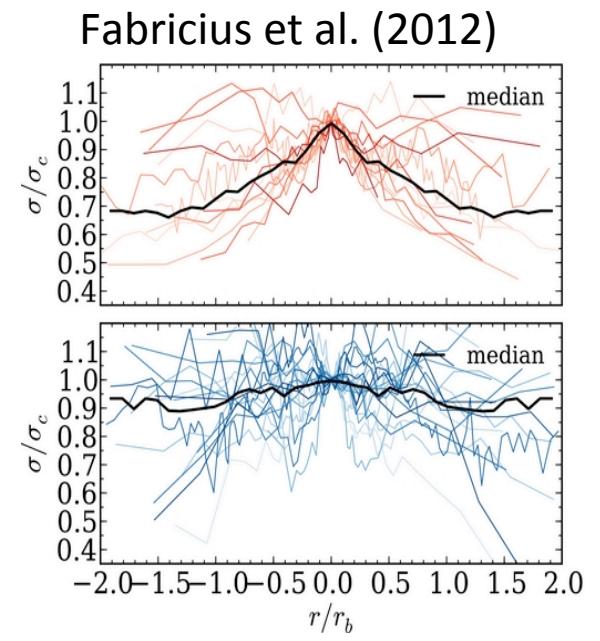
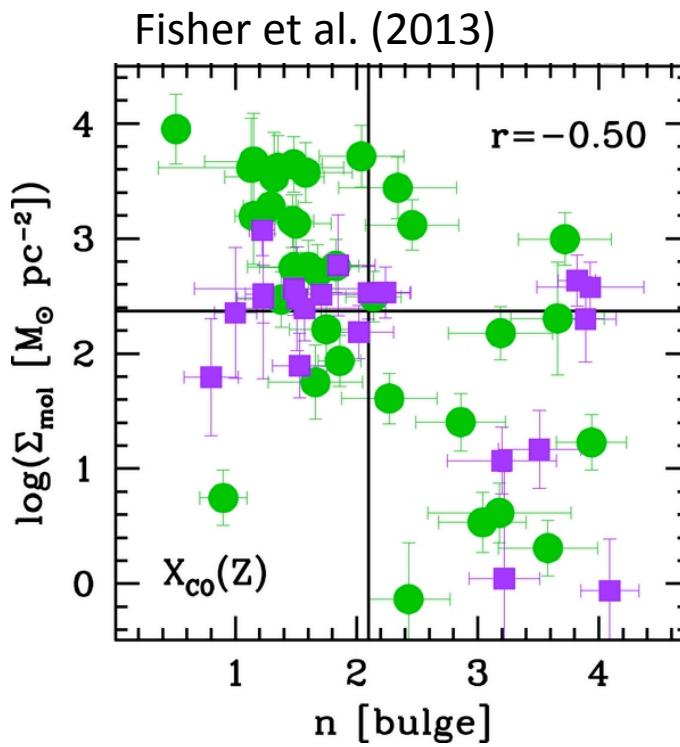
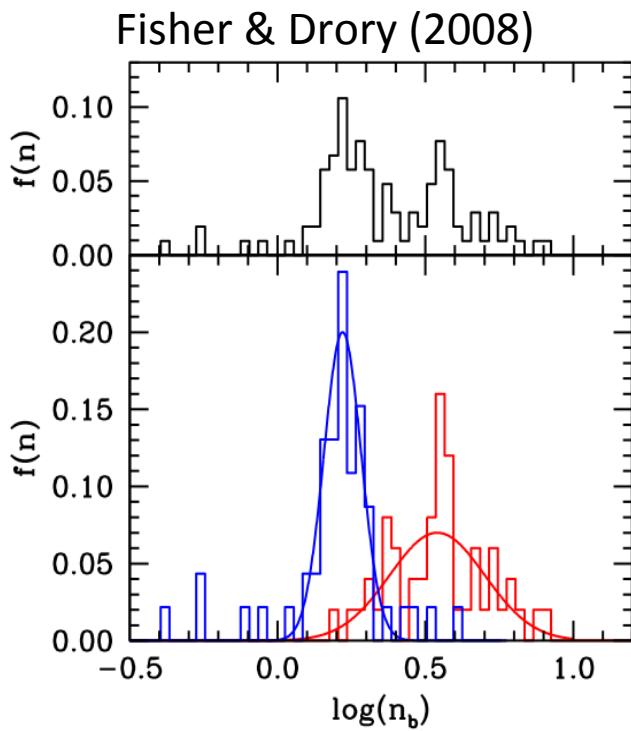
* with $M_{\text{star}} > 10^9 M_{\odot}$



Sérsic Index Correlates with Many Bulges Properties

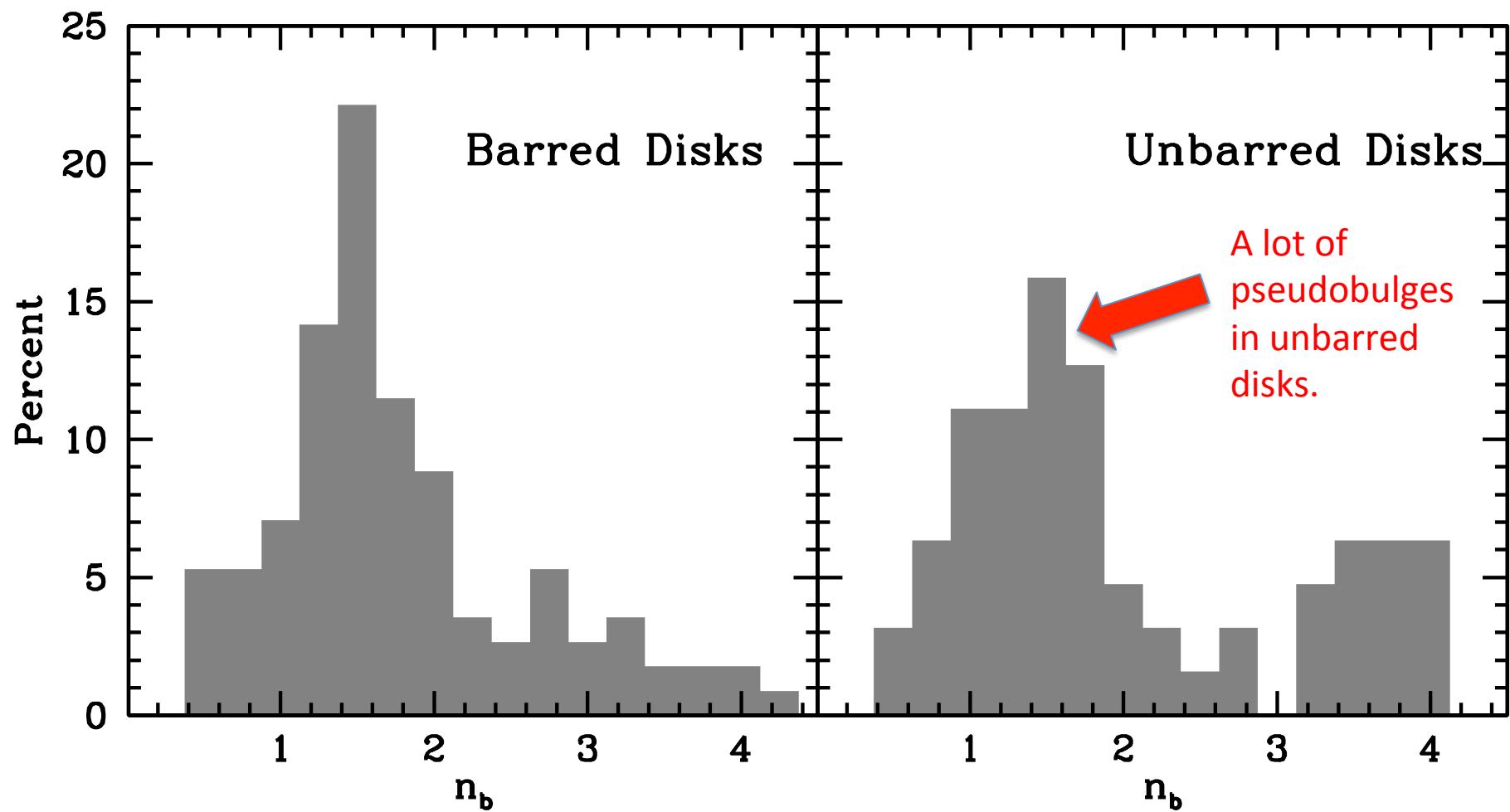
When a bulge has low Sérsic Index it also has...

- S type morphology
- High gas density
- Lower dispersion kinematics
- Flatter

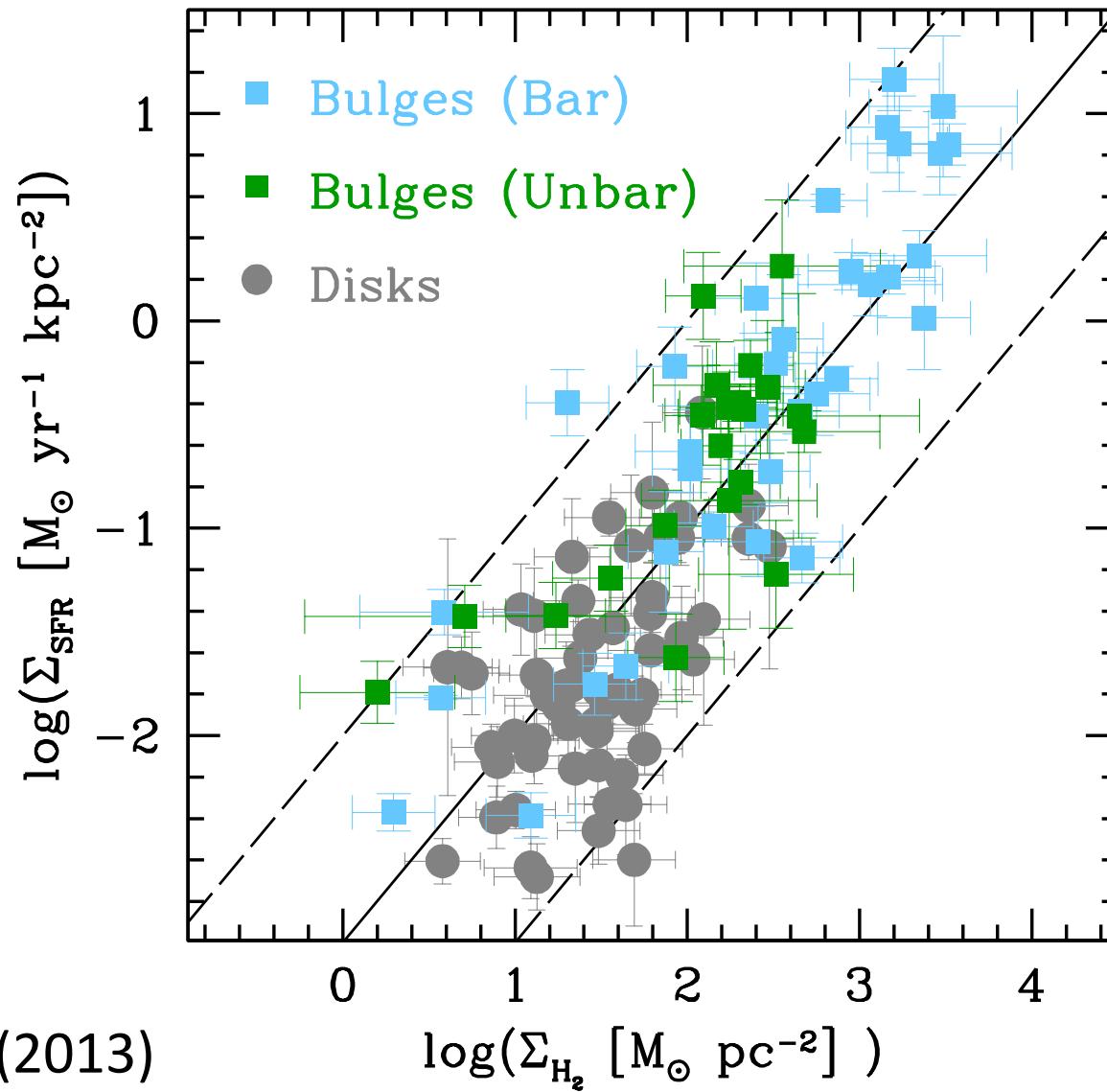


80% of barred galaxies* have pseudobulges

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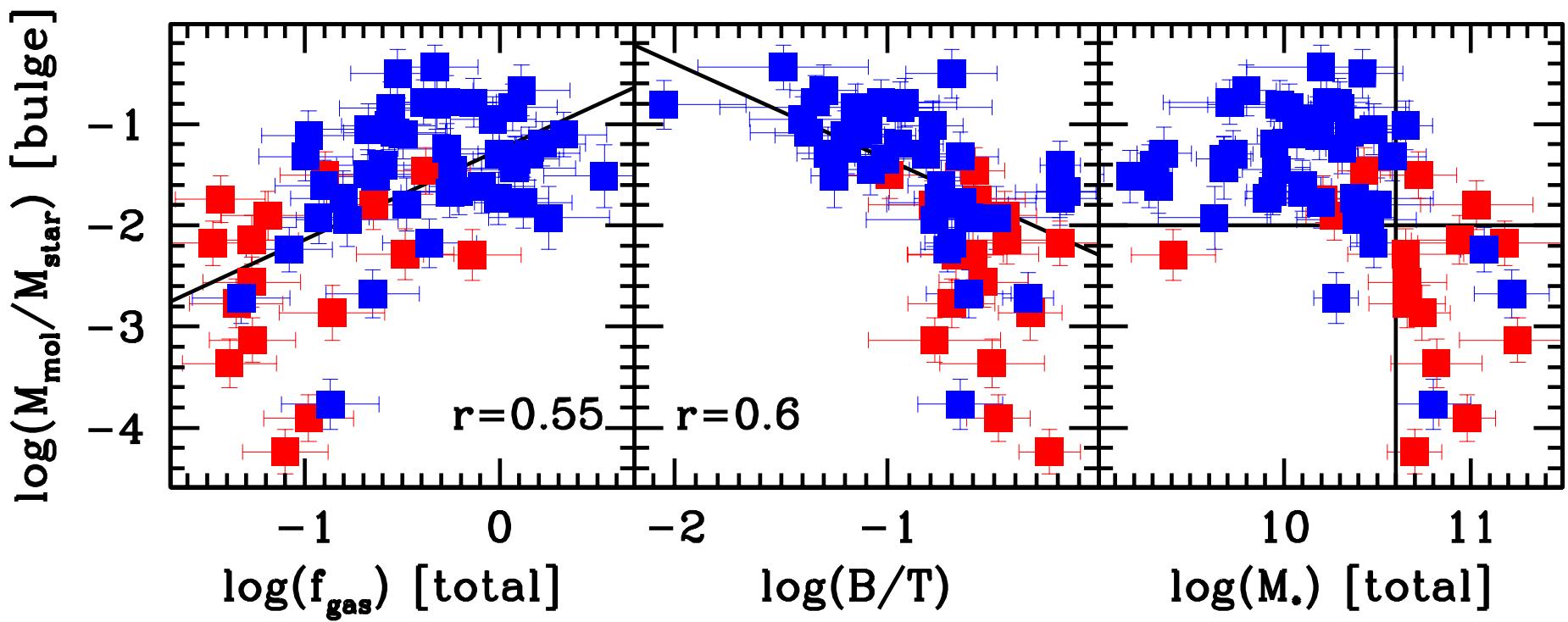


Bulges Surrounded by Bars are VERY Actively Making Stars



Fisher et al. (2013)

Using bulges to Constrain Bar Evolution

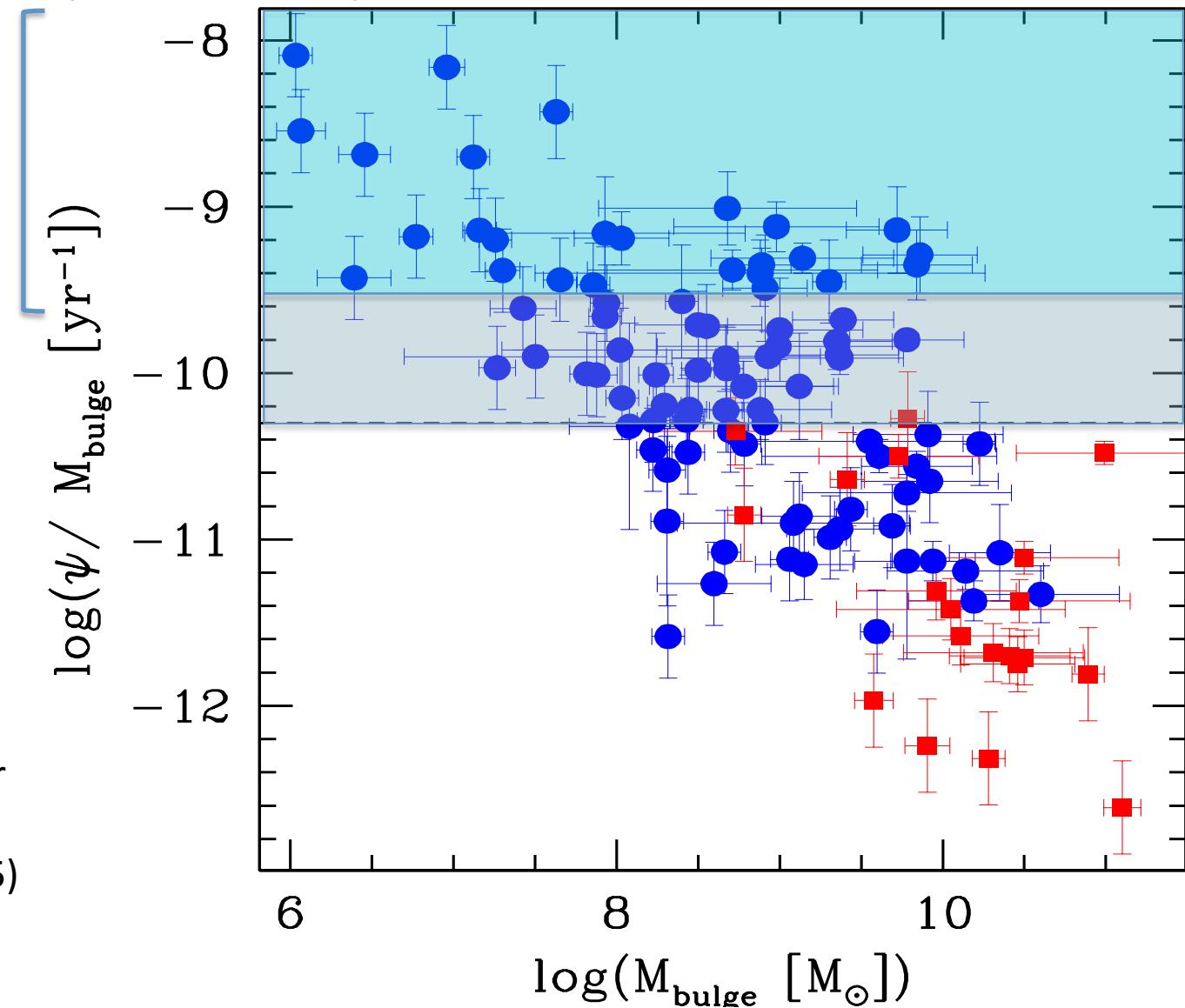


The Star Formation in Pseudobulges is Large Enough to Account for The Mass of Bulges.

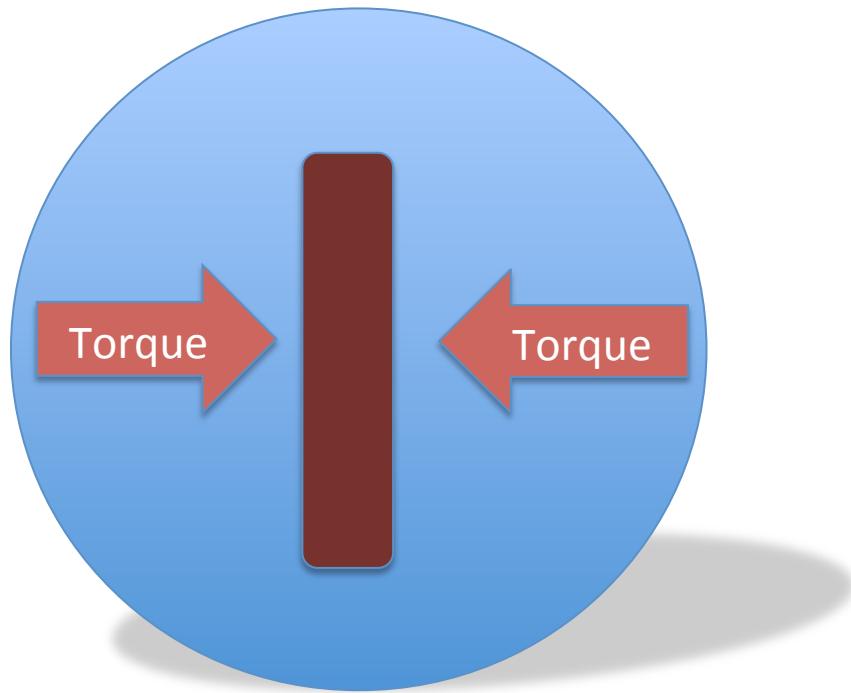
Fisher (2006); Fisher et al. (2009,2010,2013)

Can double mass in less than the time than bars have been around.

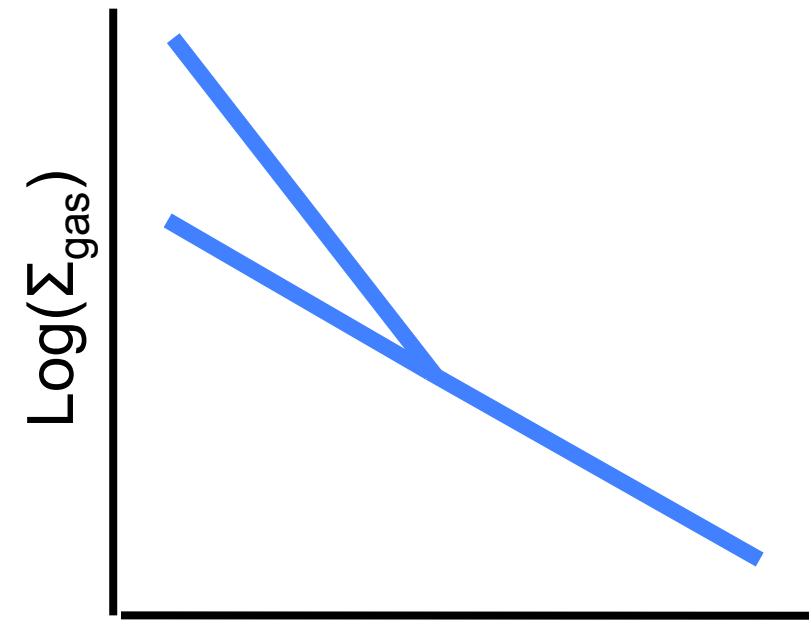
Similar results for stellar populations
Peletier & Balcells (1995)



Bars Drive Gas Inward



Gas Disk+Bar



In disks... $\Sigma_{\text{SFR}}^{\alpha} \Sigma_{\text{mol}}$

CO Surveys

BIMA SONG: CO(1-0) survey of 44 IR bright galaxies.

Regan et al. (2000), Helfer et al. (2003), Sheth et al. (2005)

PdBI NUGA: CO survey of 12 galaxies targets Seyferts, results useful for bulges.

Garcia-Burillo et al. (2003) (many papers)

PI: Garcia-Burillo & Combes

CARMA STING: CO(1-0) survey of 23 galaxies out to D25.

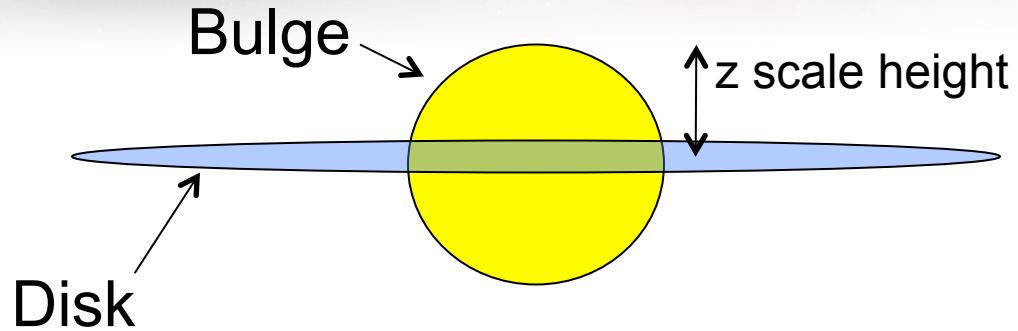
Rahman et al. (2011), Fisher et al. (2012)

PI: Bolatto

- 60 galaxies
- Representative of bright Sa-Scd type disks



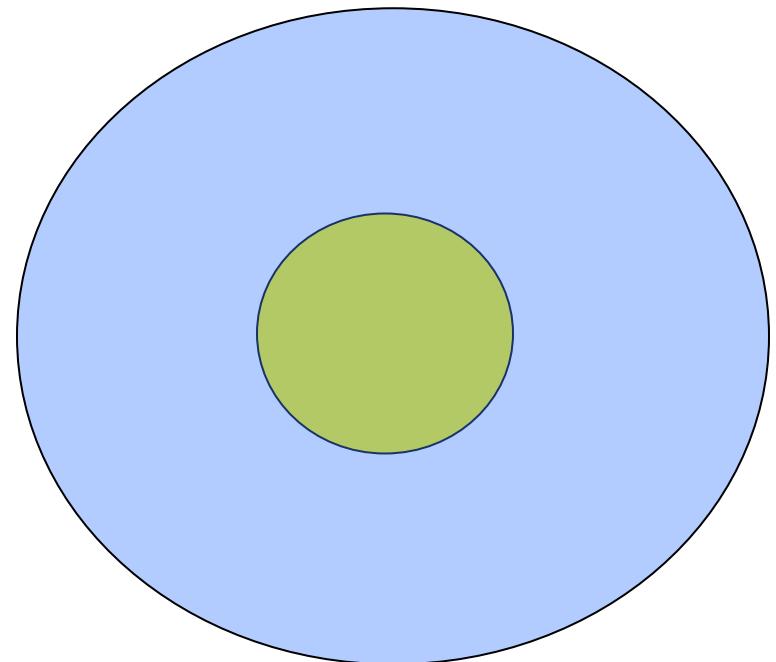
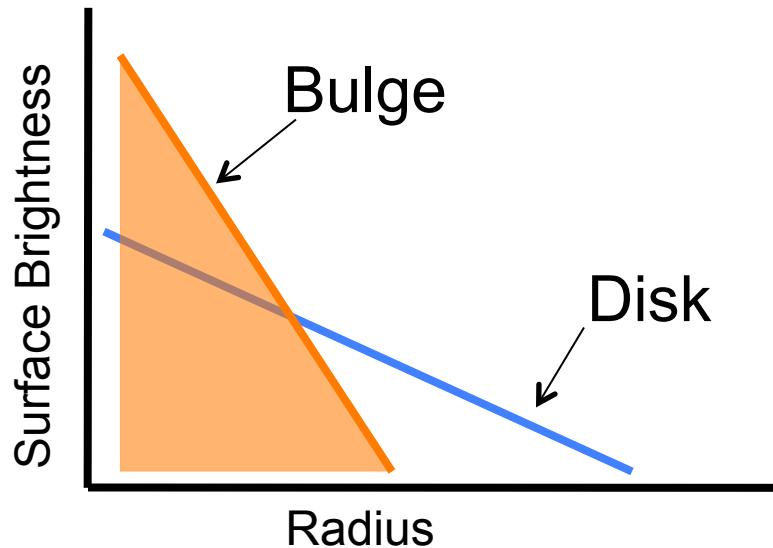
What is the “bulge”?



Face On:

-Lose z information

Use surface brightness profile



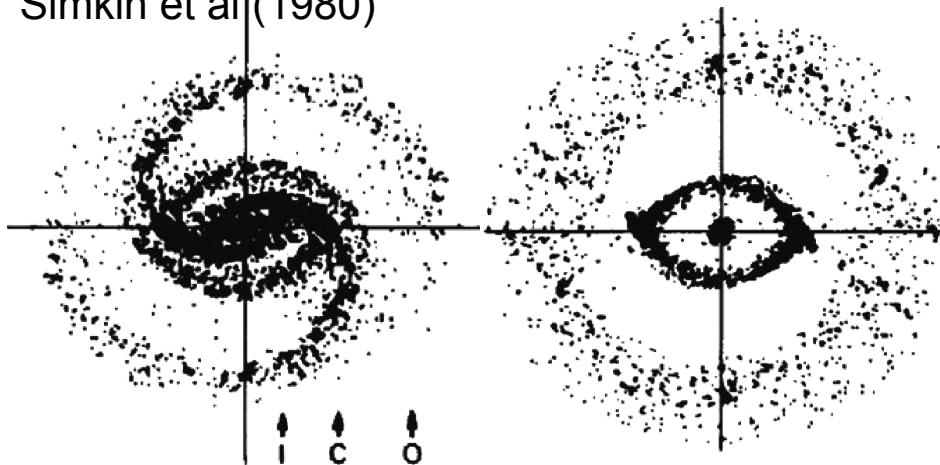
Bulge - (bəlj)- noun -

1. centrally concentrated component extending above the plane of a disk.
2. centrally concentrated density enhancement over an exponential disk (that is not a bar component).

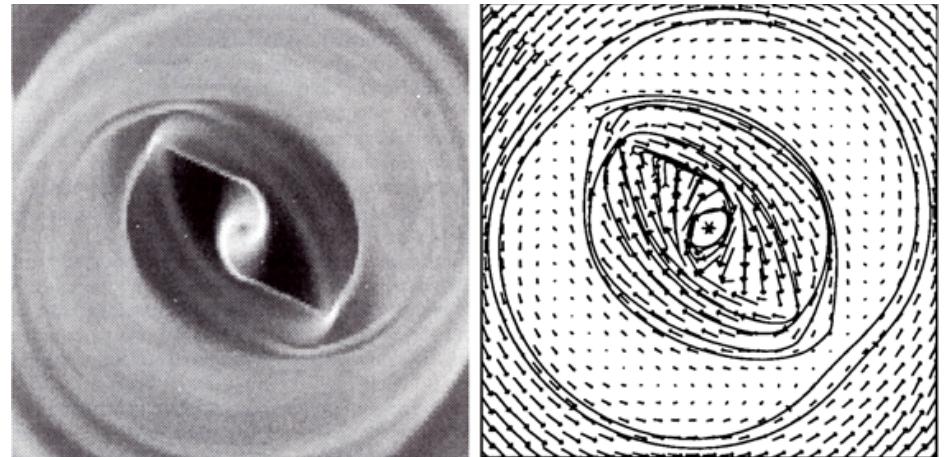
Bars Drive Gas Inward

Simulations show that bars drive gas to the center of disks.

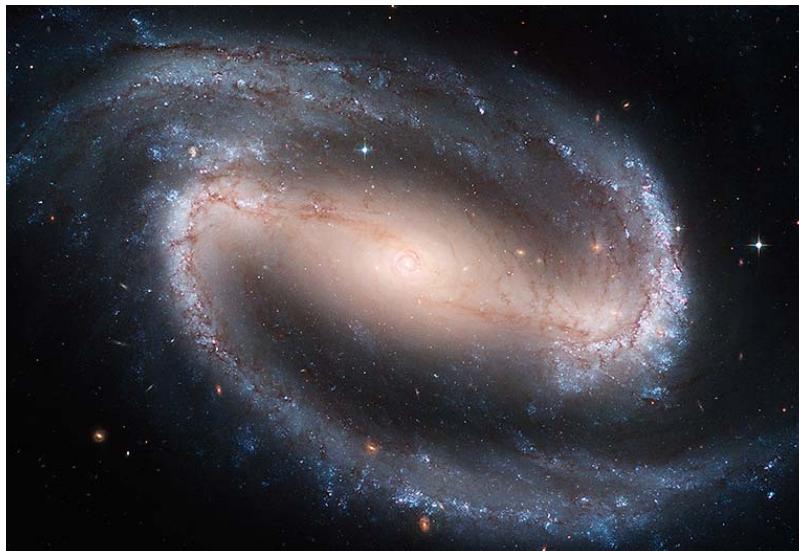
Simkin et al (1980)



Athanassoula (1992)

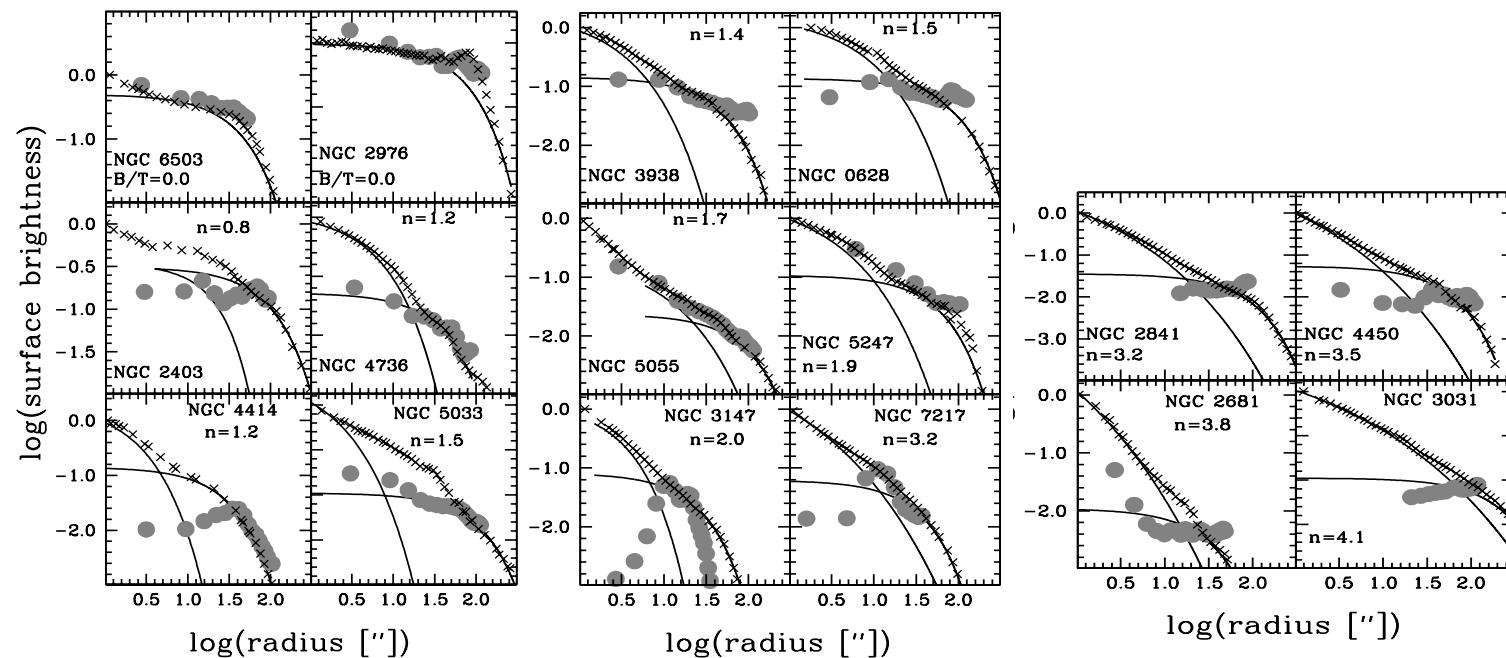


Also Shlosman et al. (1989), Combes & Gerin (1985), Heller et al. (2007) ...



In Unbarred Disks the Gas is Not Inside the Bulge

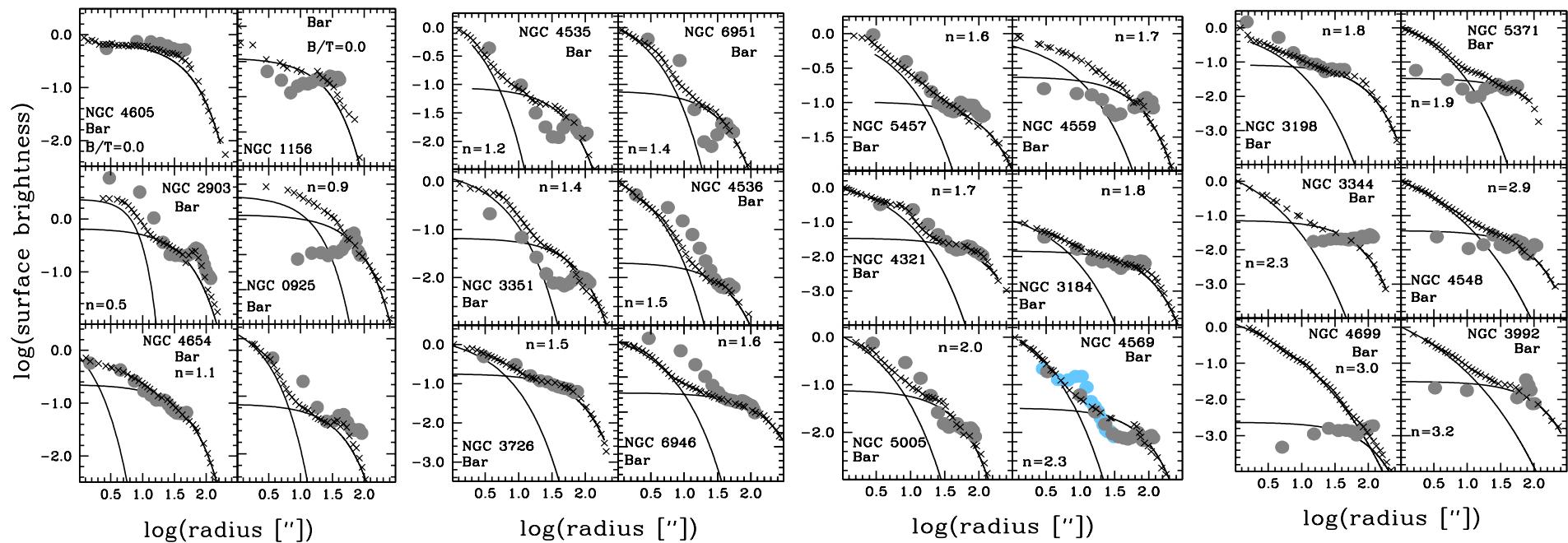
Fisher et al. (2013): 60 galaxies with interreferometric data (STING+NUGA+SONG samples)



**Steep profiles of CO gas in unbarred galaxies
is the exception, not the rule.**

Barred Disks Have Higher Central Gas Density

Fisher et al. (2013): 60 galaxies with interreferometric data (STING+NUGA+SONG samples)



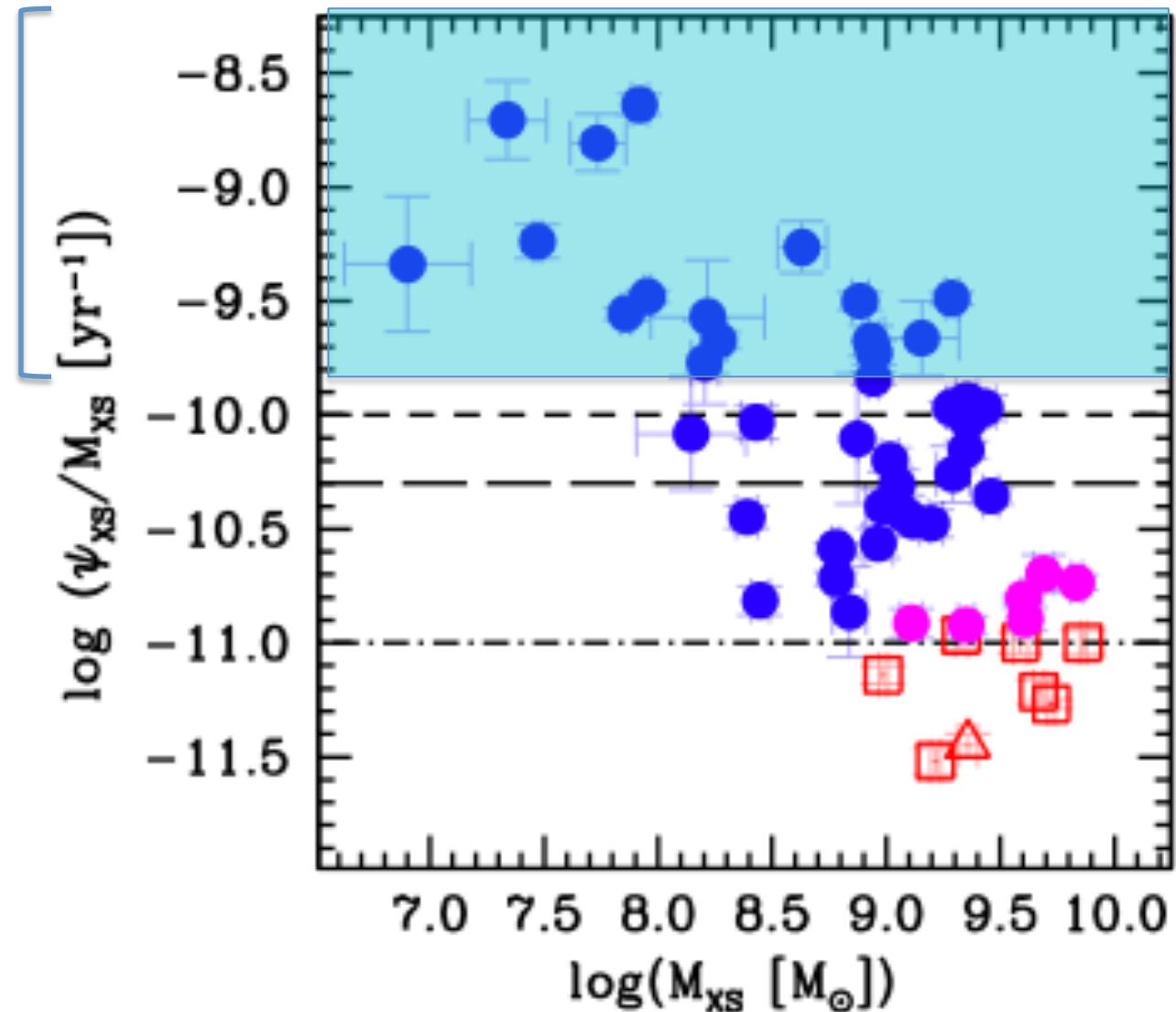
Gas in the center of barred disks is almost always as steep as the star light.

Sakamoto et al. (1998), Sheth et al. (2005), Jogee et al. (2005), Komugi et al. (2008),
NUGA survey papers

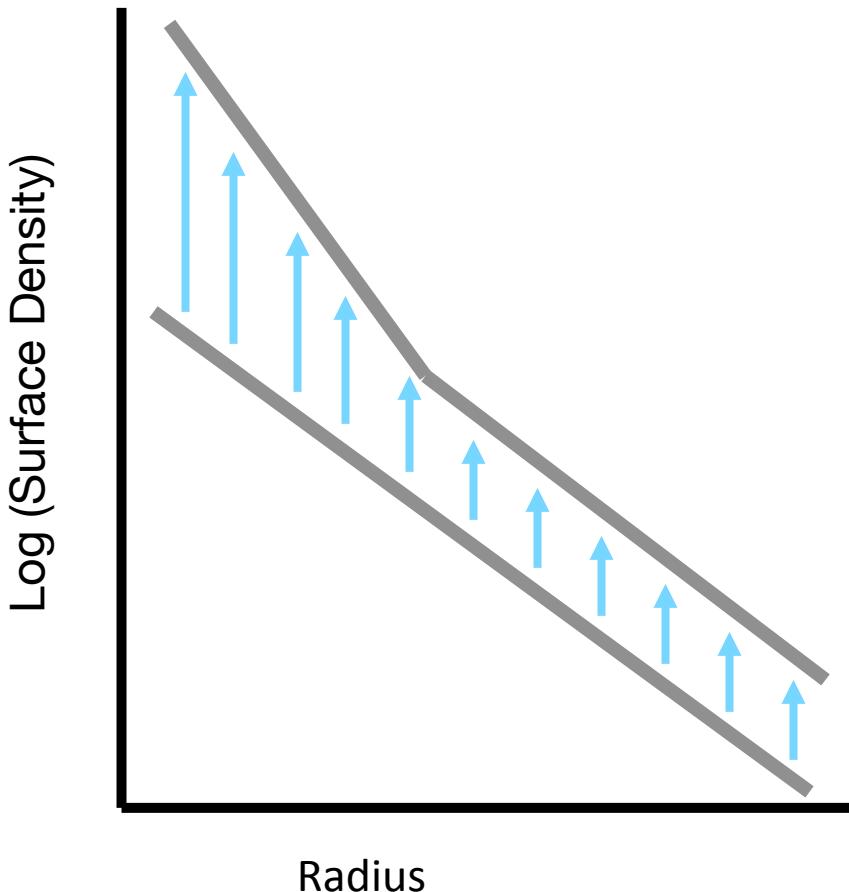
The Star Formation in Pseudobulges is Large Enough to Account for The Mass of Bulges.

Fisher (2006); Fisher et al. (2009,2010,2013)

Will double mass in less than the time that bars have been around (Kartik's talk, also a number of simulations).



Can Internal Gas Flows Grow Bulges?

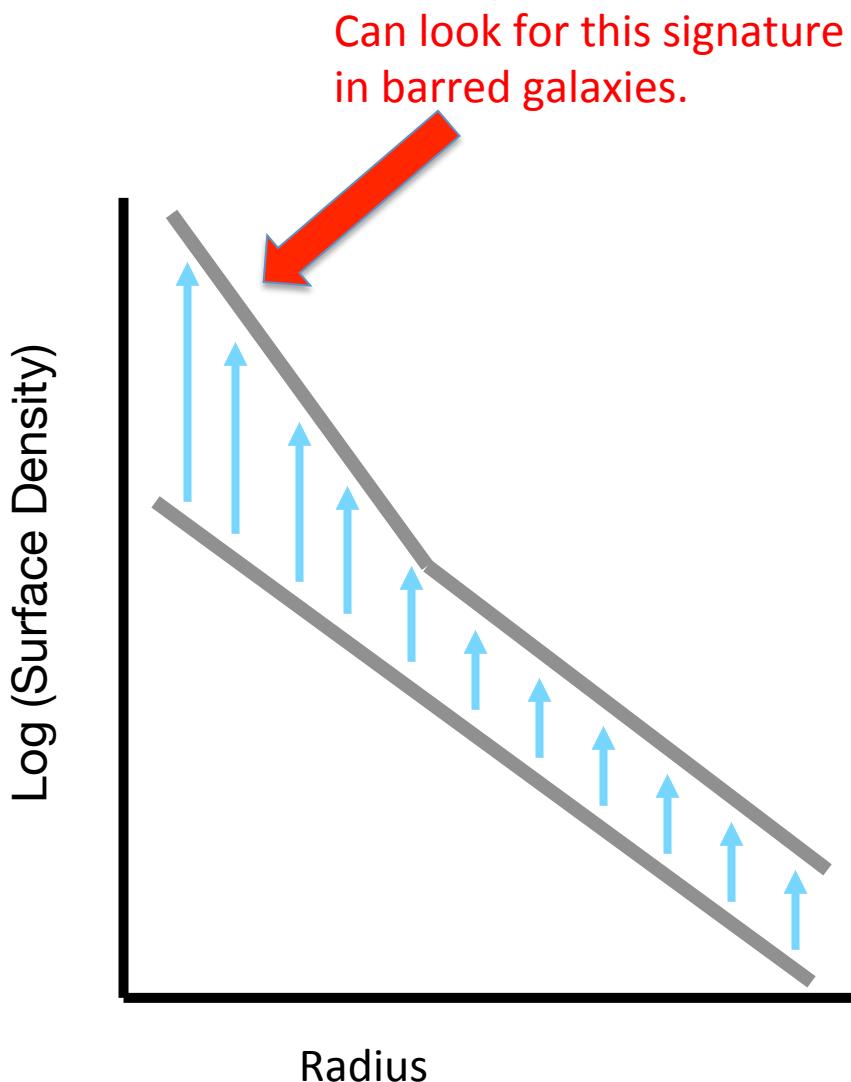


Gas Inflows

- Bars drive gas inward (Athanassoula 1992, Simkin 1980, Heller+2007, etc.)
- Bars are very common
- Inflow rates are enough to build a bulge in a few gigayears. (Haan+2009)

Reviews:
Kormendy & Kennicutt (2004),
Athanassoula (2005), Combes (200N)

Can Internal Gas Flows Grow Bulges?



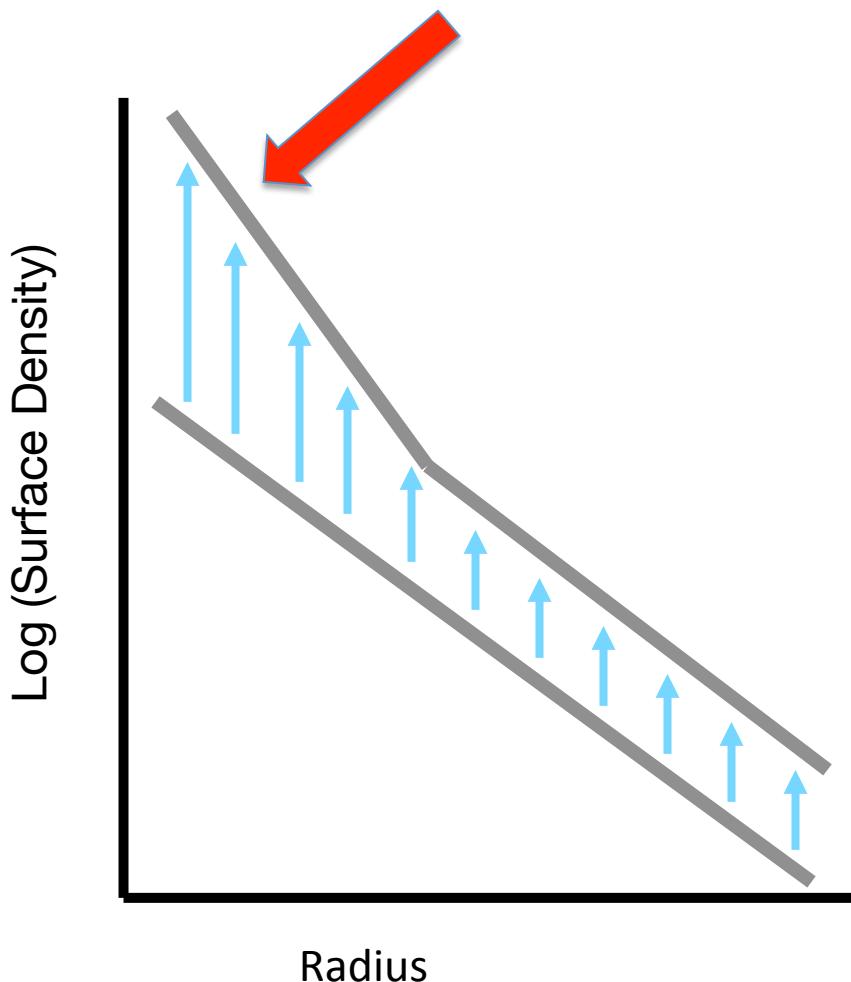
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Can Internal Gas Flows Grow Bulges?

We do observe the signature that would lead to bulge growth.



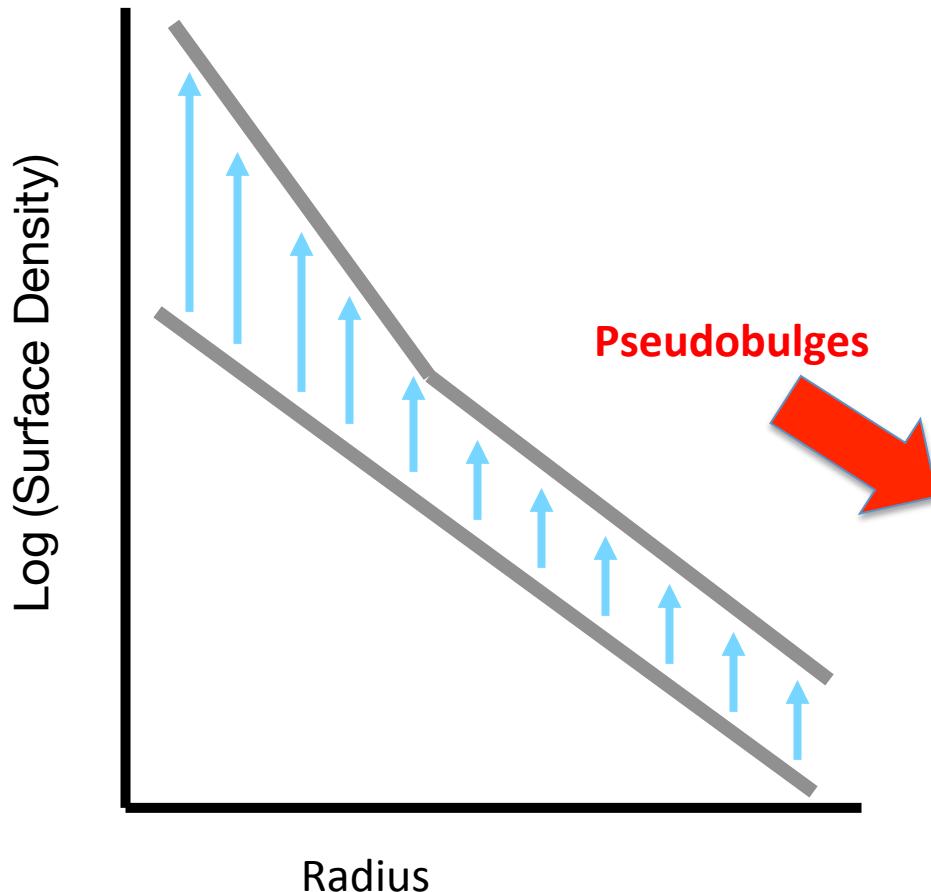
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- We observe high density gas preferentially in the center of barred disks.
- Bars are very common
- Inflow rates are enough to build a bulge in a few gigayears. (Haan+2009)
- Bulges in barred disks are the locations of intense star formation (recently shown in Fisher et al. 2013 but also many others).

Reviews:

Kormendy & Kennicutt (2004),
Athanassoula (2005), Combes (200N)

Can Internal Gas Flows Grow Bulges?



Gas Inflows

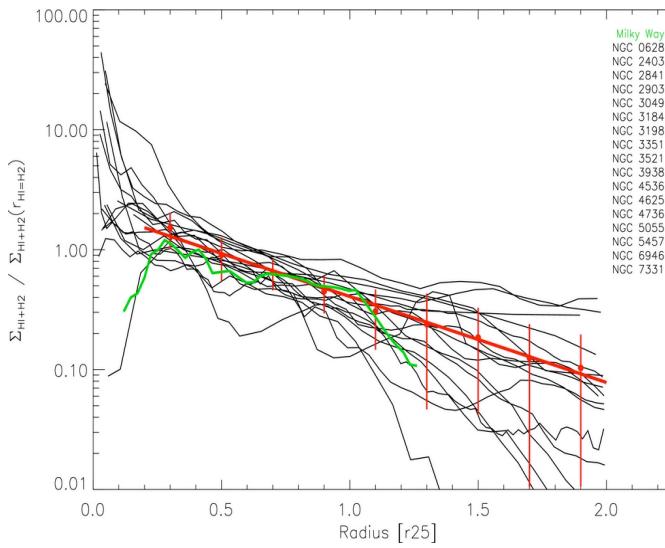
- Bars drive gas inward (Athanassoula 1992, Simkin 1980, Heller+2007, etc.)
- Bars are very common (Eskridge+2000)
- Inflow rates are enough to build a bulge in a few gigayears. (Haan+2009)
- Bulges in barred disks are the locations of intense star formation (Fisher et al. 2009, 2013).

Bulge Growth:

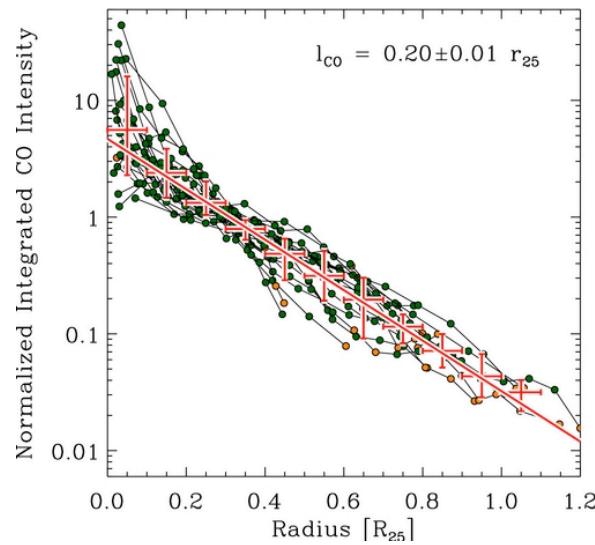
- Gas forms stars in thin disk. (Garcia-Burillo +1999)
- Resulting structure of stars is cold, and high concentration compared to a disk.
- Stars may be heated by resonant phenomena later (but maybe not)

The Gas is Often at High Density in Galaxy Centers

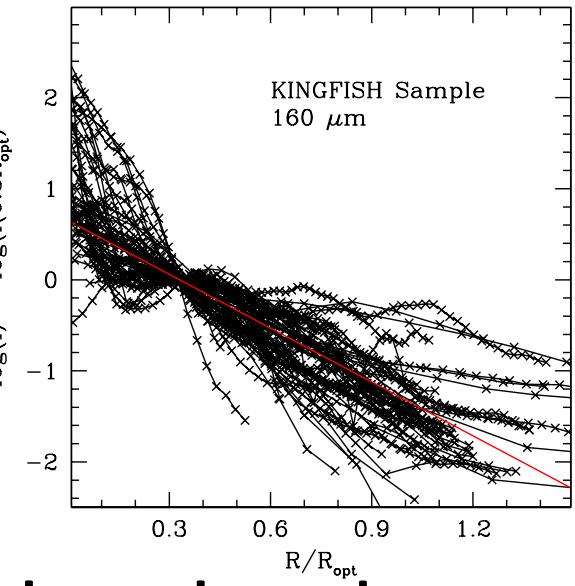
Bigiel & Blitz (2012):
Total Gas



Schruba et al. (2011):
Molecular

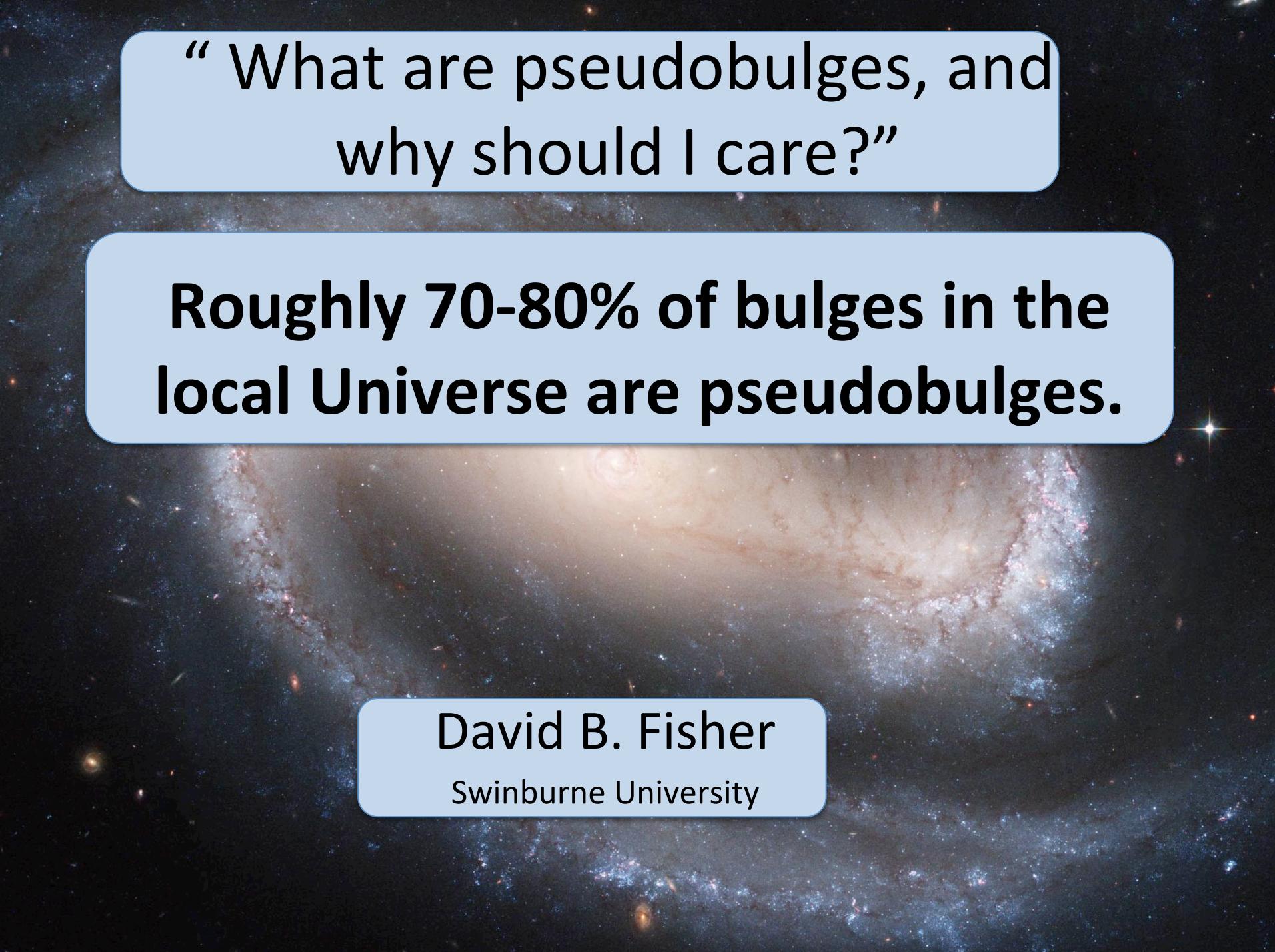


Fisher et al. (in prep):
Dust



In each these samples about 2/3 of the disks are barred.

Regan et al. (2001)



“ What are pseudobulges, and
why should I care?”

Roughly 70-80% of bulges in the
local Universe are pseudobulges.

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Classical Picture of Bulges

Renzini (1999) describes bulges as “little elliptical galaxies surrounded by a disk”

