Secular Evolution of Galaxy Disks: Our Milky Way as a Case Study

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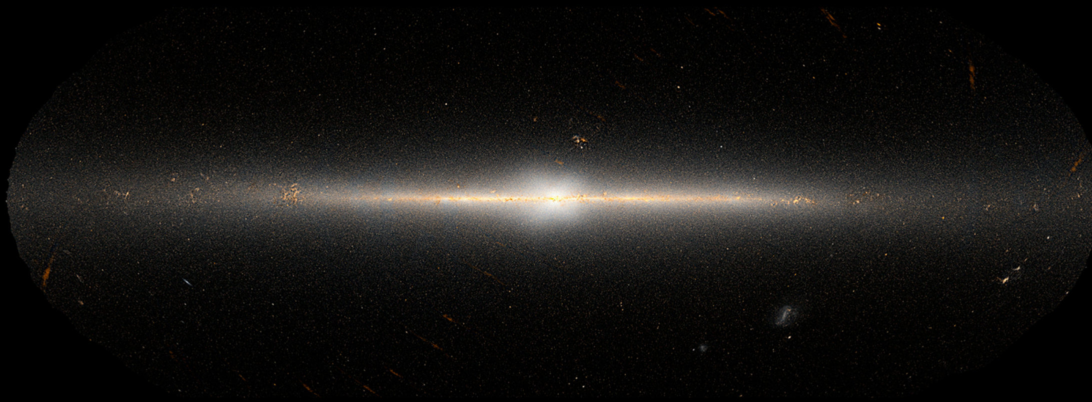


Milky Way history is dominated by gentle hierarchical clustering of fragments and by disk secular evolution & growth of 2 pseudobulges (boxy & disky).

Close analogs of the Milky Way are SB(r)b NGC 4565 and NGC 5746.

The boxy structure
= almost-end-on bar
has exponential minor-axis profile
(e. g. Launhardt et al. 2002).

Plot boxy pseudobulge parameters = mean from Launhardt et al. 2002 and from Bland-Hawthorn & Gerhard 2016, ARA&A, 54, 520.

Plot disk parameters = mean from Portail, Gerhard et al. 2016, arXiv 1608.07954 and from Bland-Hawthorn & Gerhard 2016, ARA&A, 54, 520.

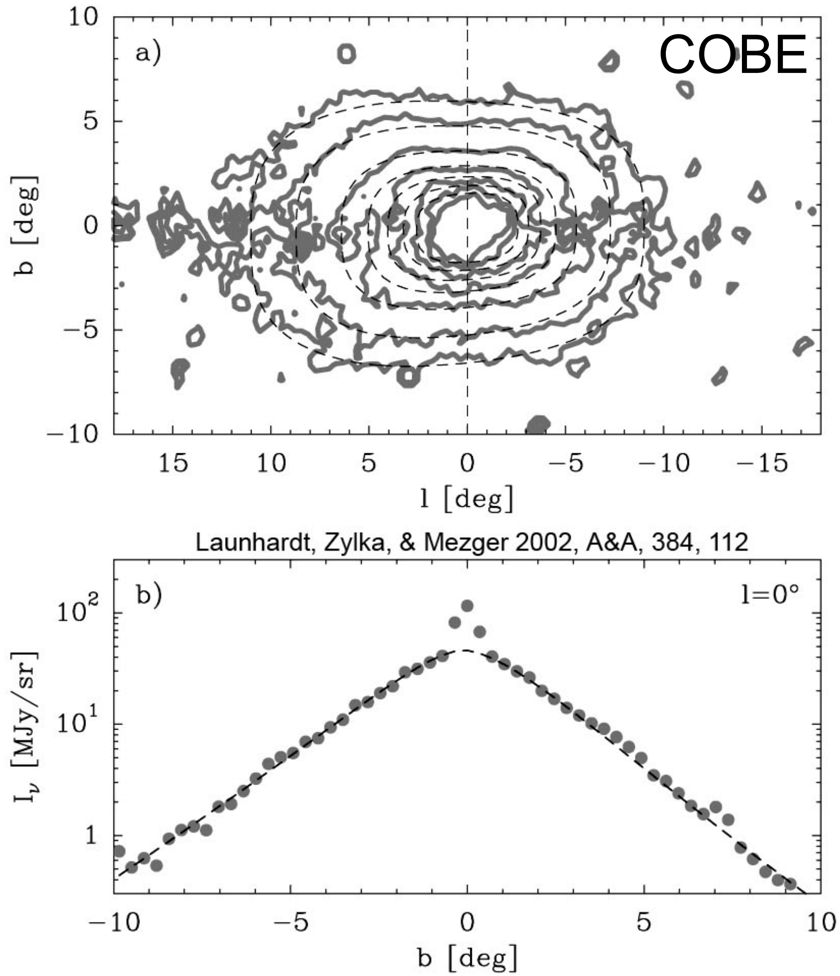
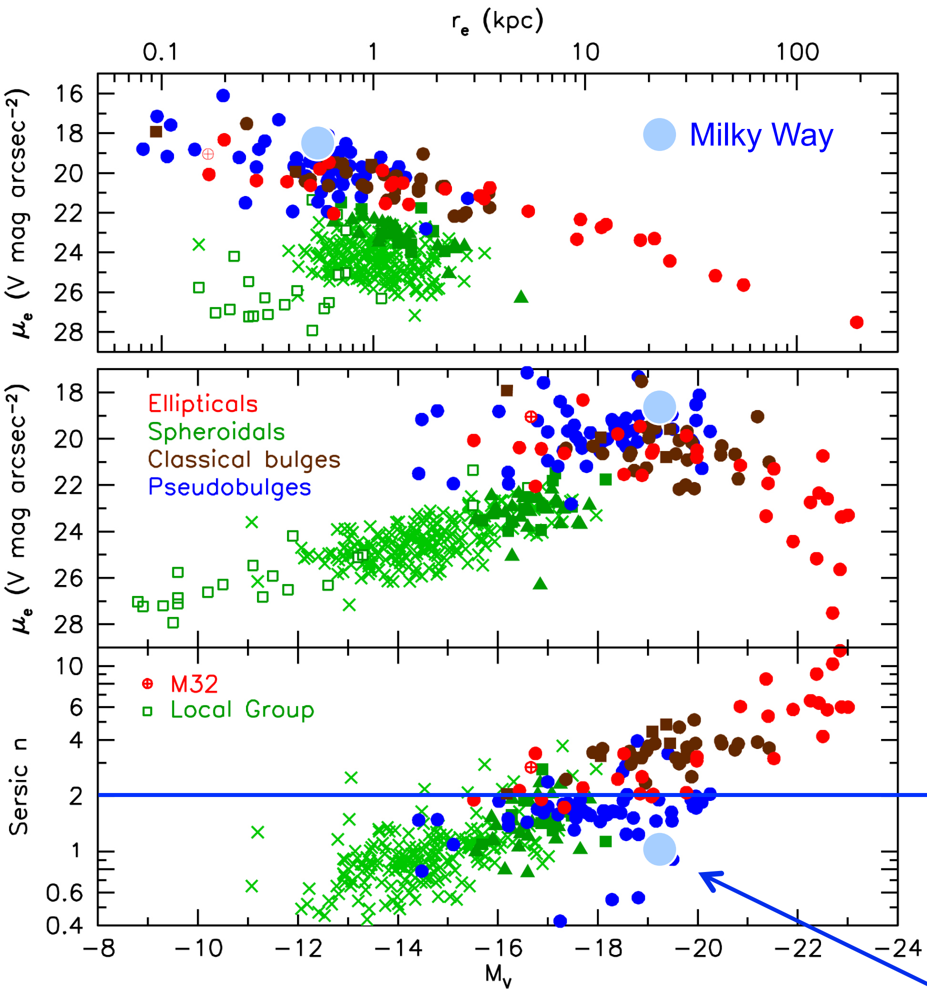


Fig. 5. 2.2 μm surface brightness distribution of the Galactic and Nuclear Bulge. In order to achieve the best signal-to-noise ratio, a weighted average of the 2.2, 3.5, and 4.9 μm maps, scaled to the 2.2 μm surface brightness, is shown. Contributions from the Galactic Disk are subtracted and the emission is dereddened for extinction by foreground dust. **a)** Contour maps of the observed dereddened (thick grey lines) and modeled (dashed lines) NIR surface brightness distribution. Levels are at 5, 10, 20, ..., 60% of modeled peak surface brightness. **b)** Latitude profile at $l = 0°$ of the observed dereddened (grey dots) and modeled (dashed line) NIR surface brightness distribution of the GB.

The Parameters of our Galaxy's Boxy Pseudobulge are Normal



Bulge and pseudobulge parameters from Fisher & Drory (2008);
Ellipticals from Kormendy et al. 2009, ApJS,182, 216 ("KFCB")

This figure is from Kormendy & Fisher (2008), in Formation & Evolution of Galaxy Disks, ed. Funes et al. (SF: ASP 396), p. 297

Classical bulges and ellipticals have n ≥ 2.
Pseudobulges have n ≤ 2.

The boxy structure = almost-end-on bar has exponential minor-axis profile (e. g. Launhardt et al. 2002).

The Parameters of our Galaxy's Boxy Pseudobulge are Normal

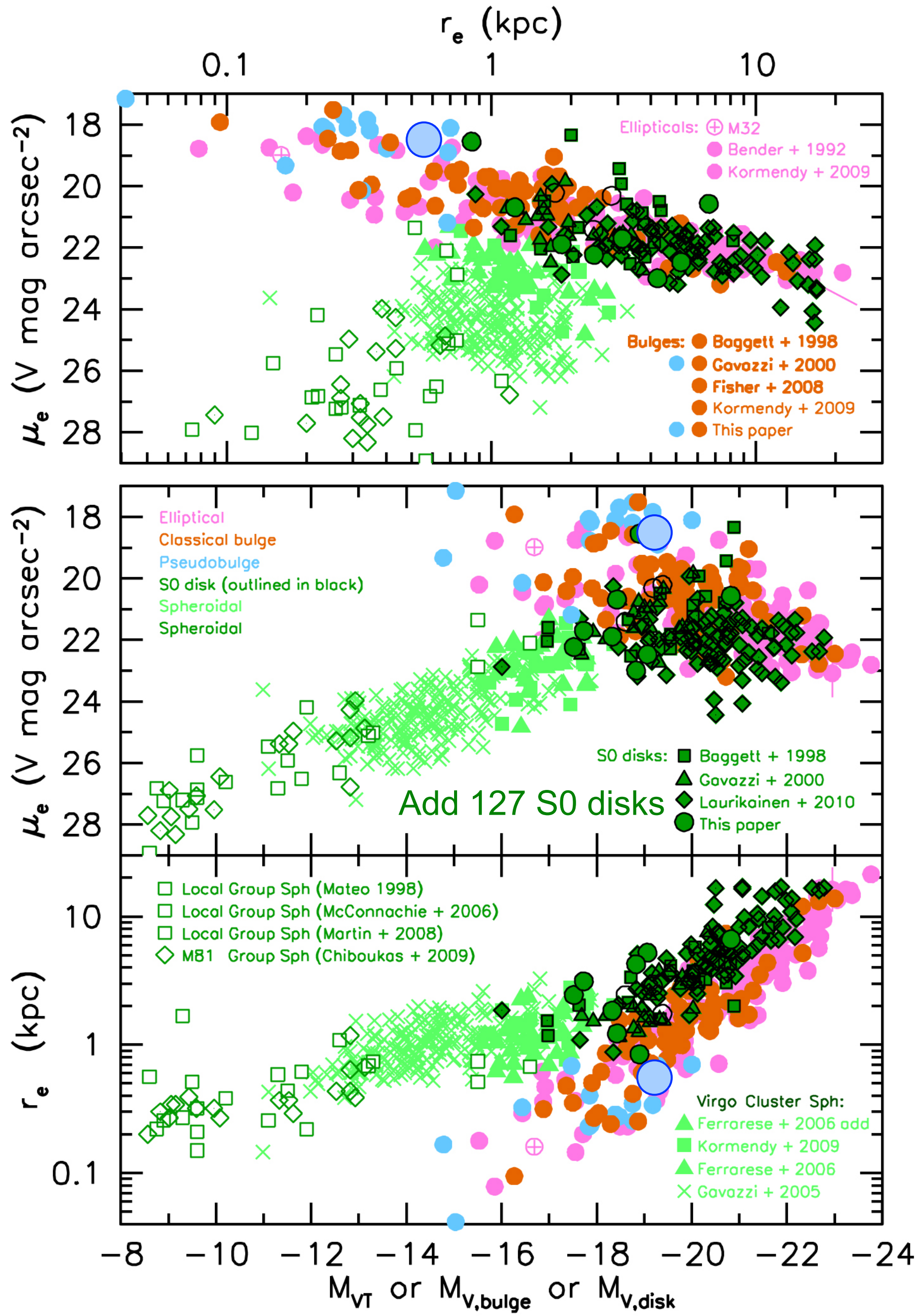
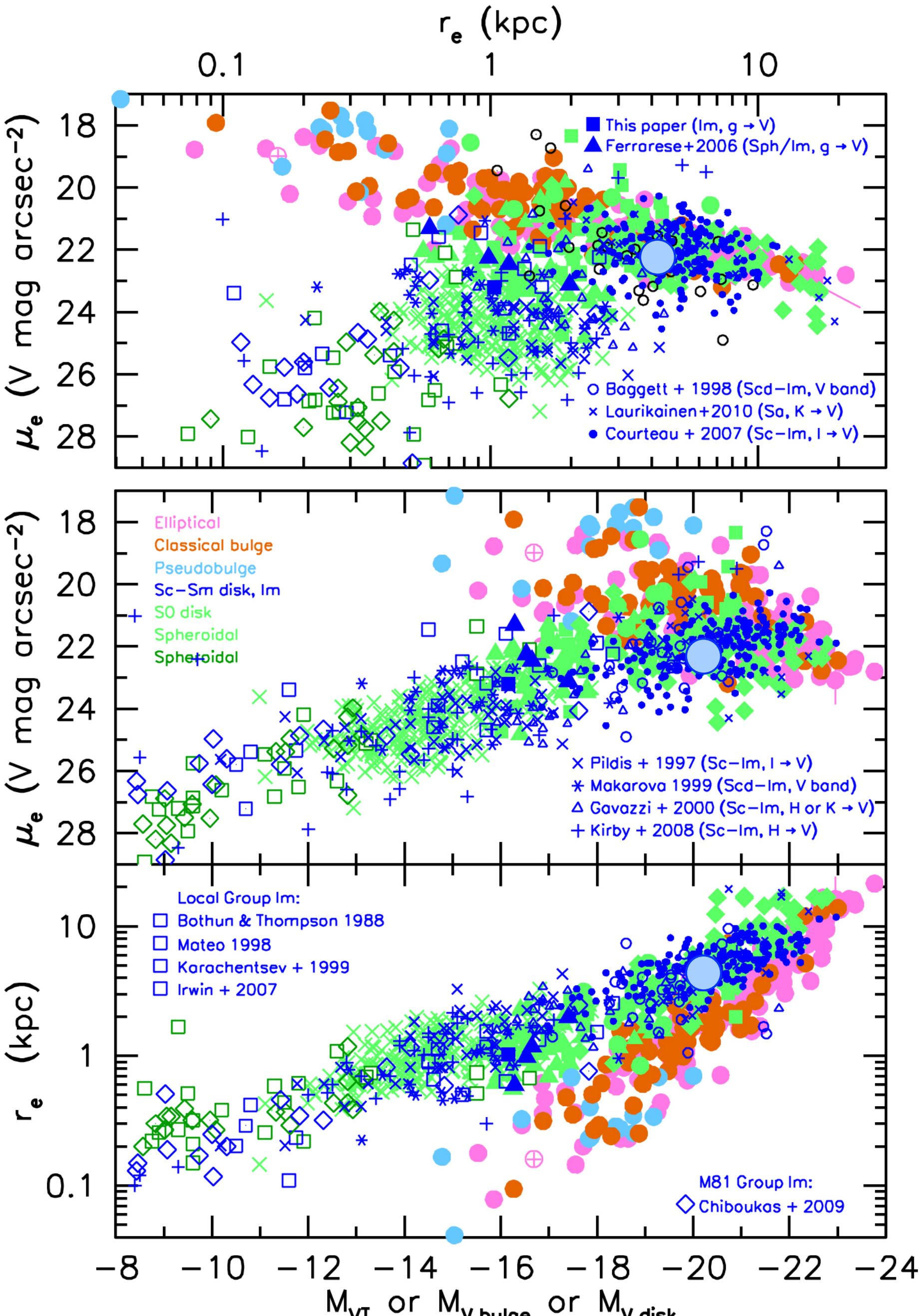


Figure:
Kormendy & Bender 2012, ApJS, 198, 2

The Parameters of our Galaxy's Disk are Normal



Add parameters

for 407 S+Im disks from 14 independent sources.

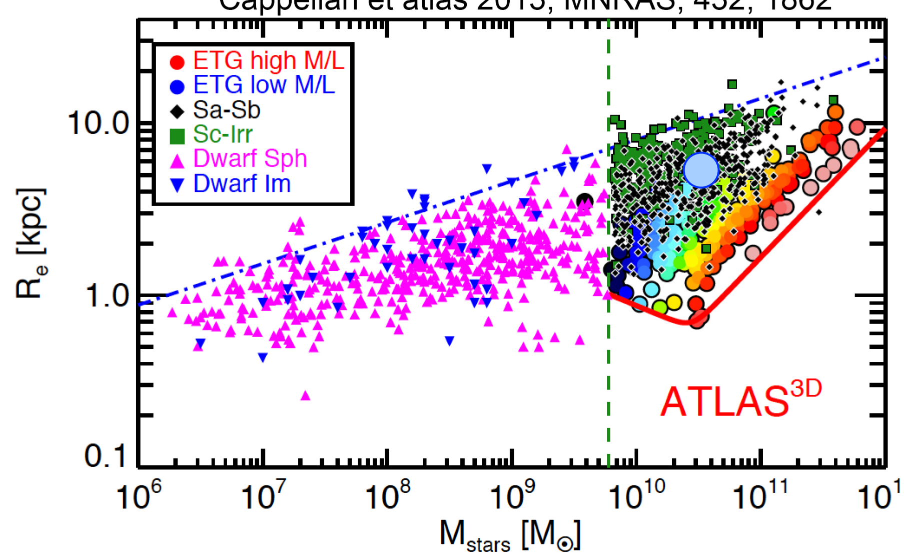
Milky Way Long bar + thin disk + thick disk

Figure:

Kormendy & Bender 2012, ApJS, 198, 2

ATLAS^{3D} team
gets closely similar results.
But, without B-D decomposition,
pure disks look continuous with pure Es.

Cappellari et atlas 2013, MNRAS, 432, 1862



Our Galaxy as similar in scale to NGC 4565 and slightly smaller than NGC 5746.

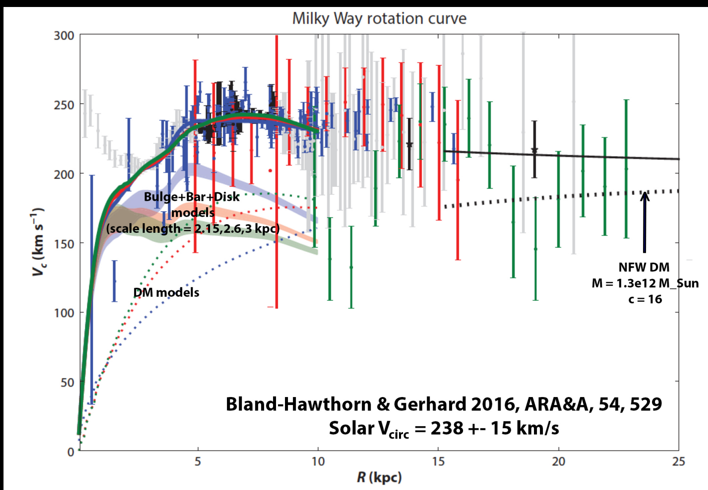
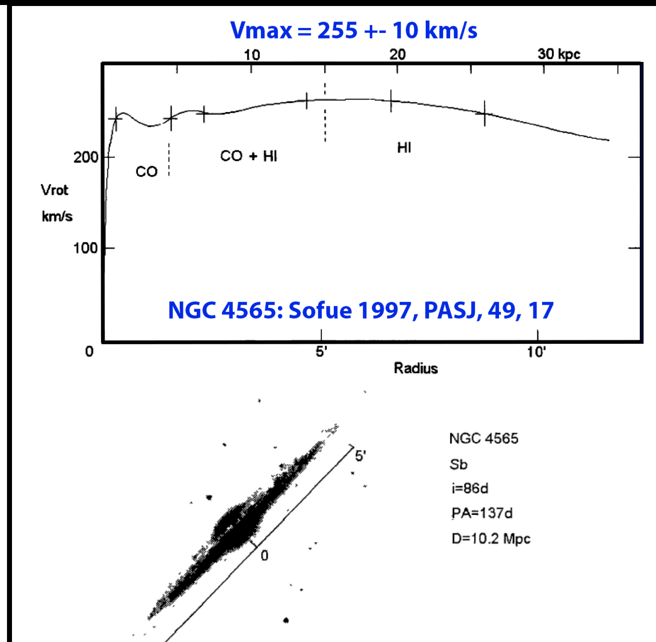
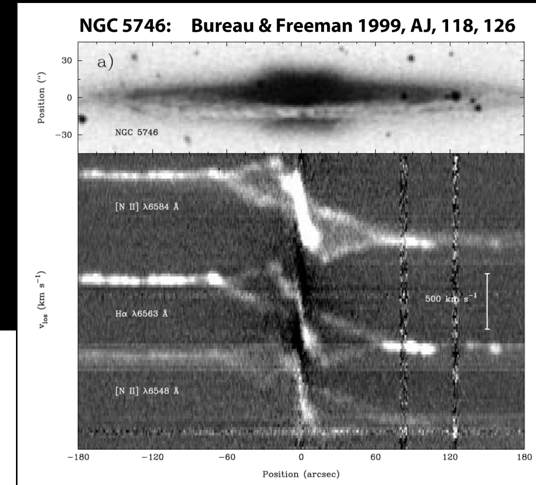


Figure 16

Galactic rotation curve. Sources for data points are: maser proper motions (PMs) and radial velocities (RVs) associated with high-mass disk stars (Reid et al. 2014, *blue*), inner Galaxy terminal velocities and outer disk velocities collected by Sofue et al. [2009, *black* (5 kpc $< R < R_0$) and *gray* (elsewhere)], PMs of disk red clump giants (RCGs) from López-Corredoira (2014, *red*), Jeans-equation converted RV data for blue horizontal branch (BHB) stars (Kafle et al. 2012, *green*), and stream modeling for GD-1 and Pal-5 (Koposov et al. 2010 and Küpper et al. 2015, *black stars*. All data were approximately converted to ($R_0 = 8.2$ kpc, $\Theta_0 = 238$ km s^{-1}). The colored bands show azimuthally averaged circular velocities for illustrative dynamical models with bulge, long bar, disk, and dark halo (Portail et al. 2016).





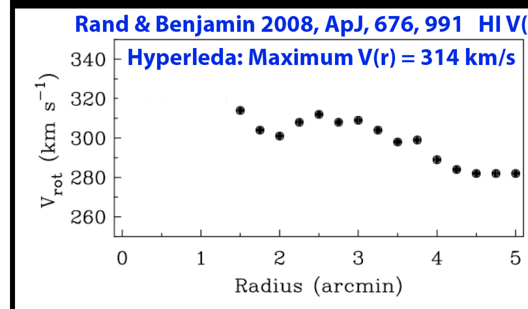
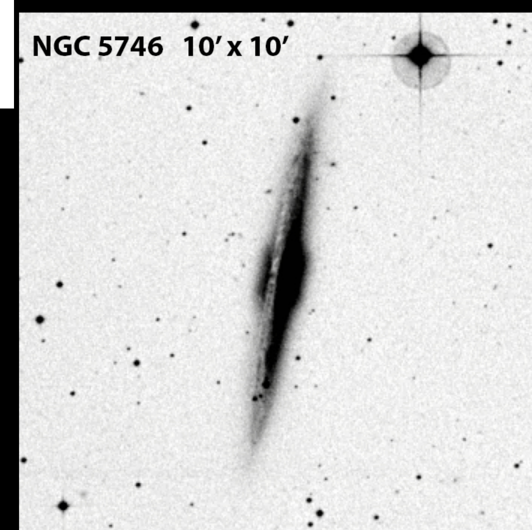
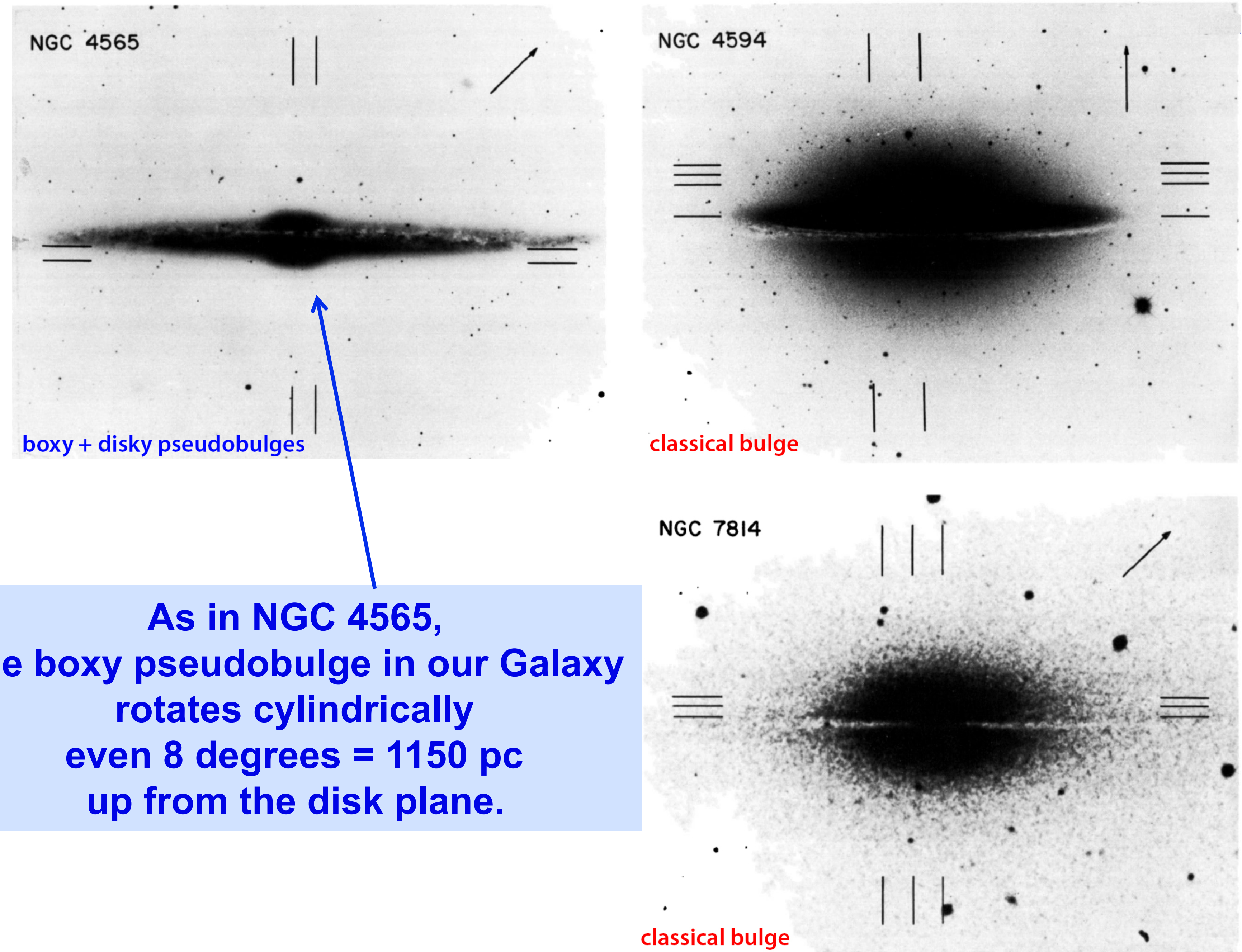


FIG. 8.—Filled circles show the rotation curve for NGC 5746 derived from envelope fitting.



Note re: NGC 5746:
Bureau & Freeman interpret the "figure 8" V(r) near the center as the signature of an almost-end-on bar.
Dark inside of "8" ⇒ almost no gas inside inner ring of circular-V gas.

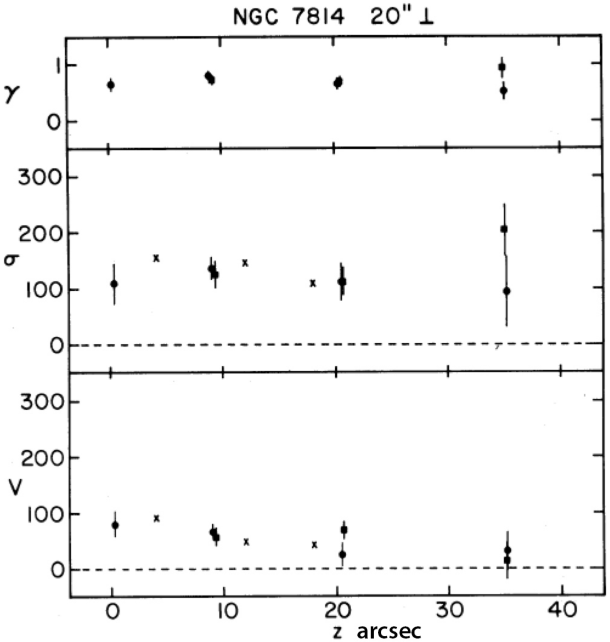
Does our Galaxy show this behavior? Caution:
H I velocity fields in our Galaxy are usually interpreted as circular motion.

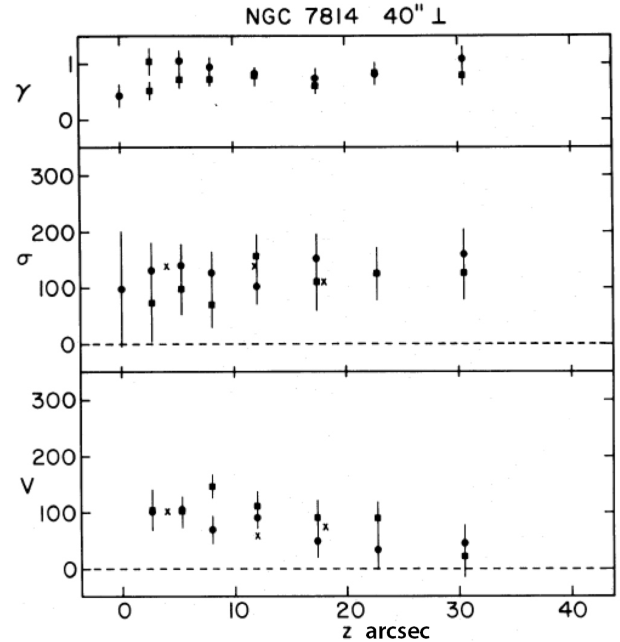


As in NGC 4565,
the boxy pseudobulge in our Galaxy
rotates cylindrically
even 8 degrees = 1150 pc
up from the disk plane.

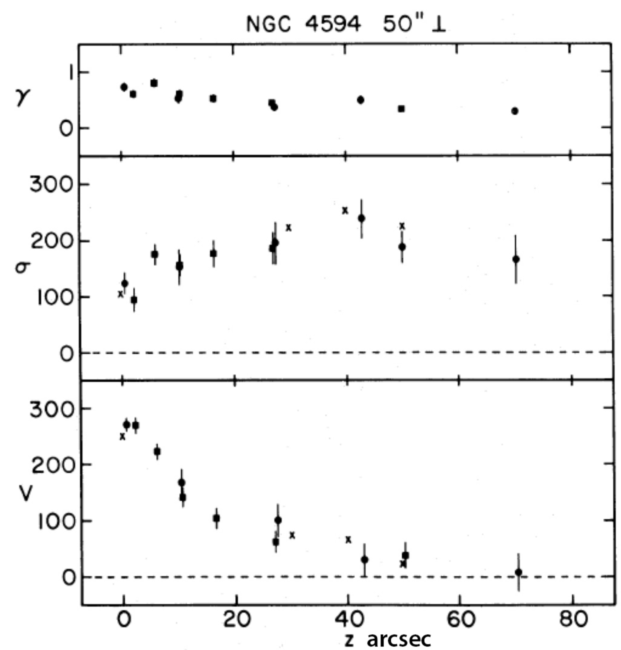
FIG. 1.—The four S0–Sb galaxies studied. Arrow indicates north in each case. East is counterclockwise in the usual sense. The length of the arrow is 95″, 62″, 16″, and 43″, respectively, in NGC 4565, 4594, 5866, and 7814. Horizontal and vertical bars show the slit positions for the offset spectra (see Fig. 2 and Table 3 for the actual offsets).

Kormendy & Illingworth 1982, ApJ, 256, 460 slit positions



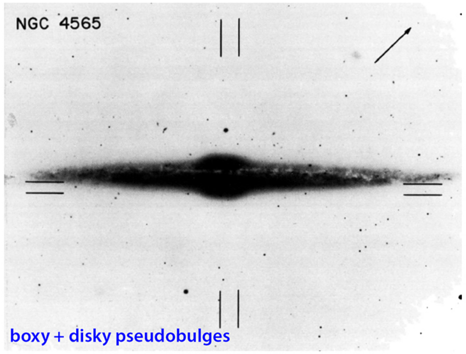


Kormendy & Illingworth 1982, ApJ, 256, 460



The classical bulges of NGC 7814 and NGC 4594 do not rotate cylindrically:

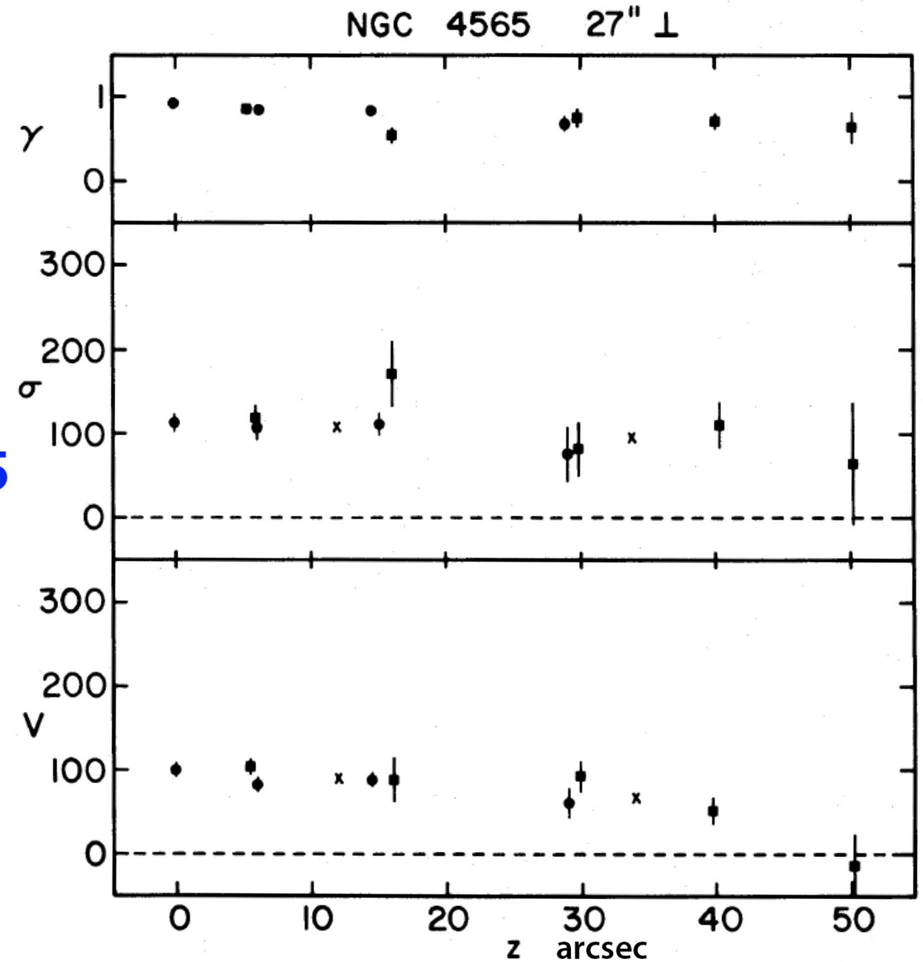
V(r) decreases at increasing height z above the disk plane.



The boxy pseudobulge of NGC 4565 rotates cylindrically:

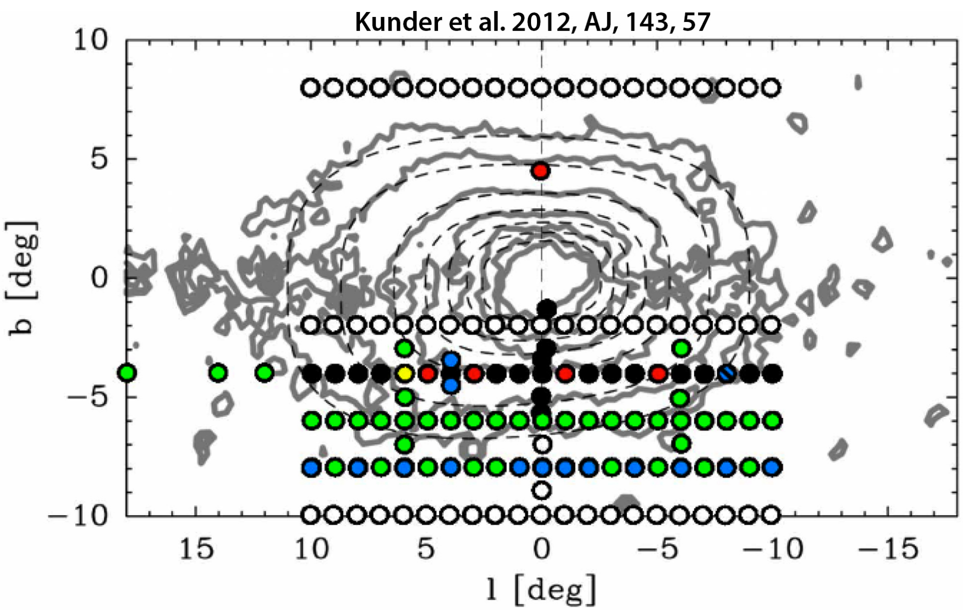
V(r) is almost constant with increasing height z above the disk plane.

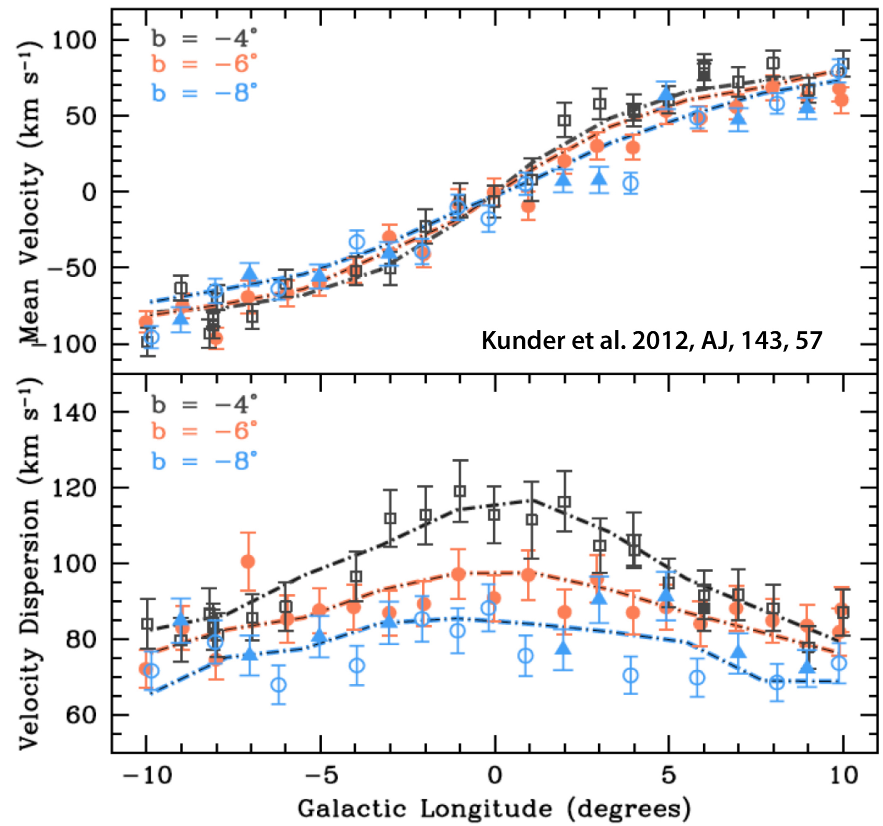
Kormendy & Illingworth 1982, ApJ, 256, 460



Like other boxy pseudobulges, the one in our Galaxy rotates cylindrically even 8 degrees = 1150 pc up from the disk plane.

Major Axis showing cylindrical rotation (Fit is Shen et al. 2010)





See also:

ARGOS: Ness, Freeman et al. 2013, MNRAS, 432, 2092 -- All 16,600 stars in “bulge region”

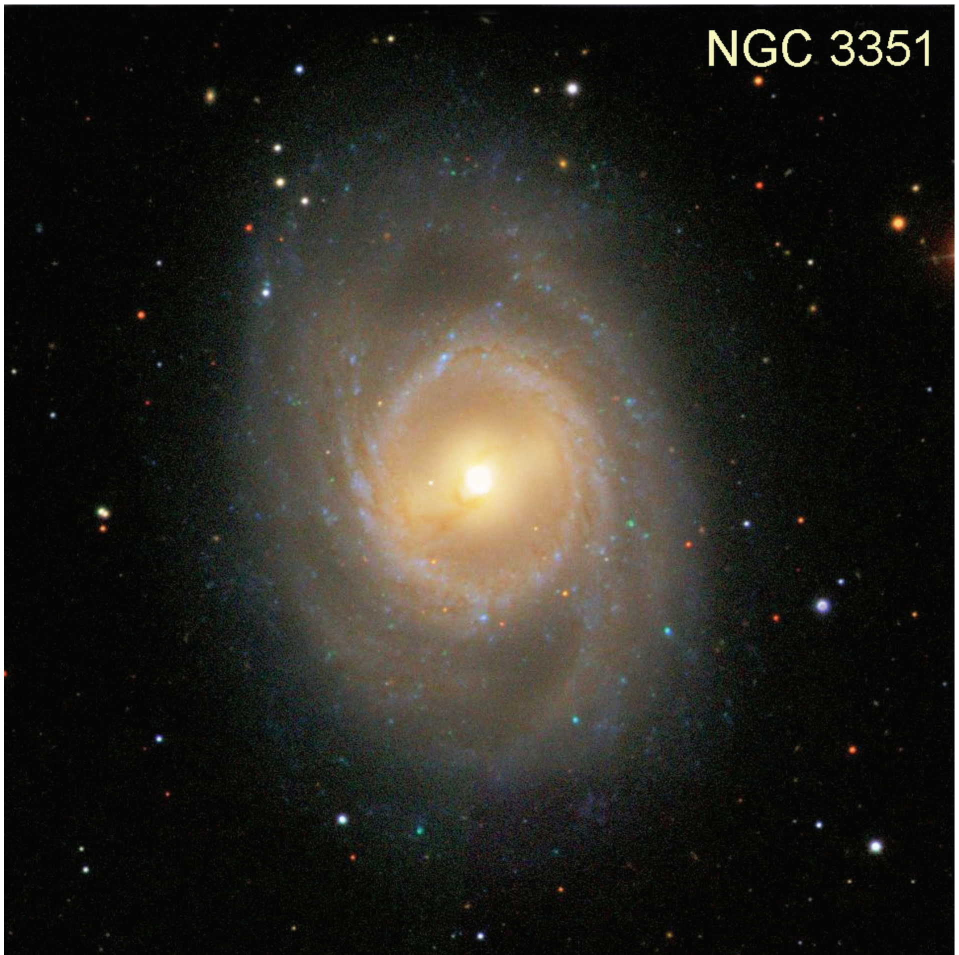
DETECTION OF A PSEUDOBULGE HIDDEN INSIDE THE "BOX-SHAPED BULGE" OF NGC 4565

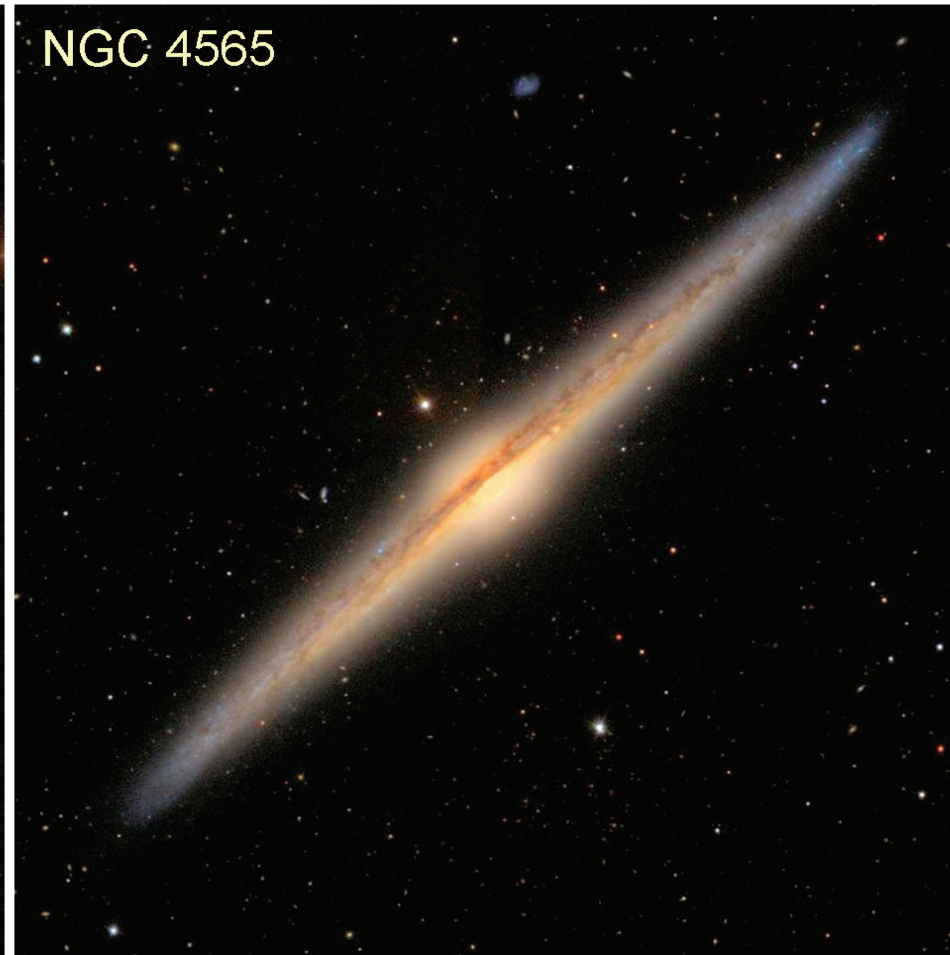
JOHN KORMENDY AND JOHN C. BARENTINE

THE ASTROPHYSICAL JOURNAL LETTERS, 715:L176–L179, 2010 June 1

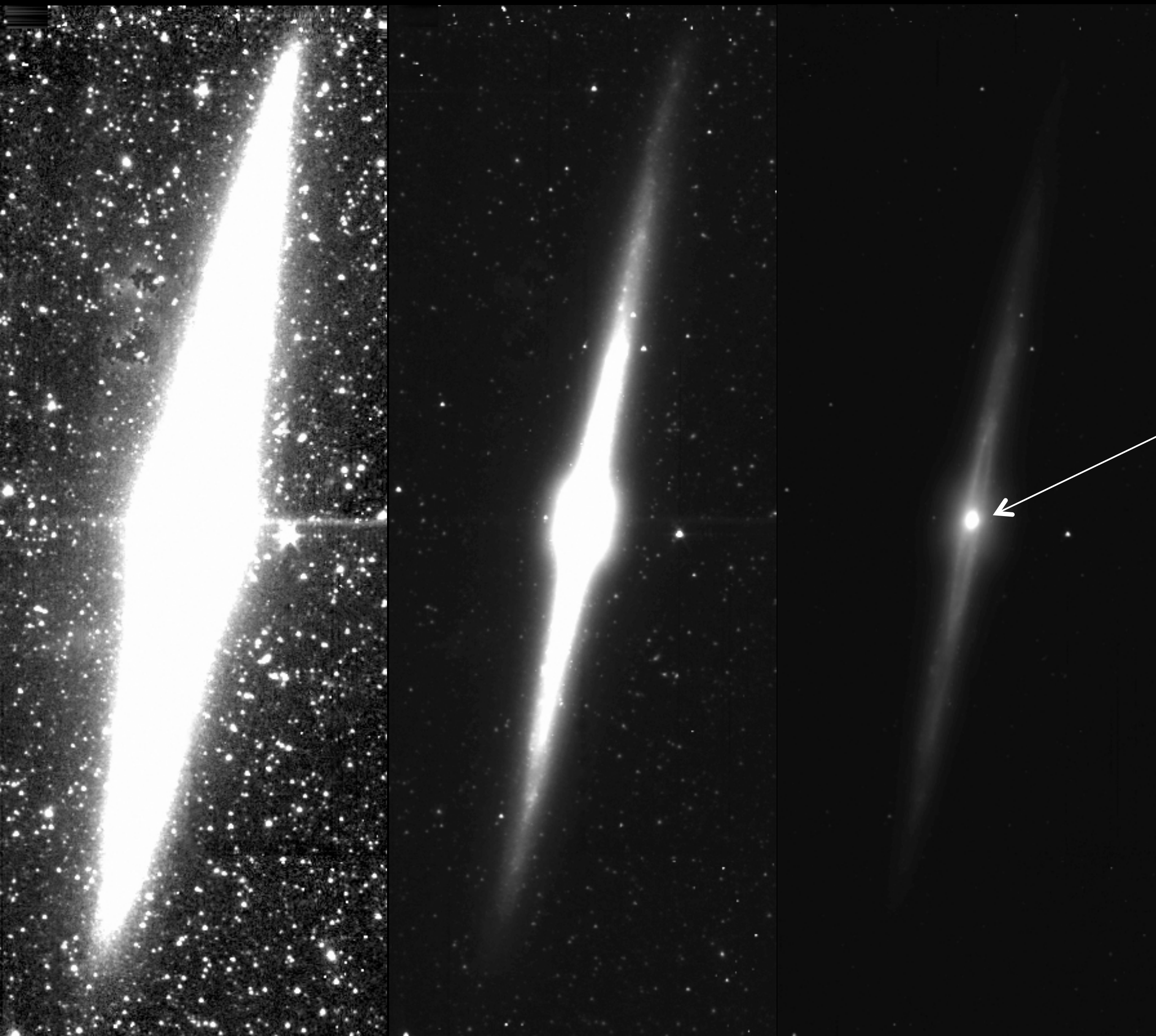
ABSTRACT

Numerical simulations show that box-shaped bulges of edge-on galaxies are not bulges: they are bars seen side-on. Therefore, the two components that are seen in edge-on Sb galaxies such as NGC 4565 are a disk and a bar. But face-on SBb galaxies always show a disk, a bar, and a (pseudo)bulge. Where is the (pseudo)bulge in NGC 4565?





Where is the bulge in NGC 4565?

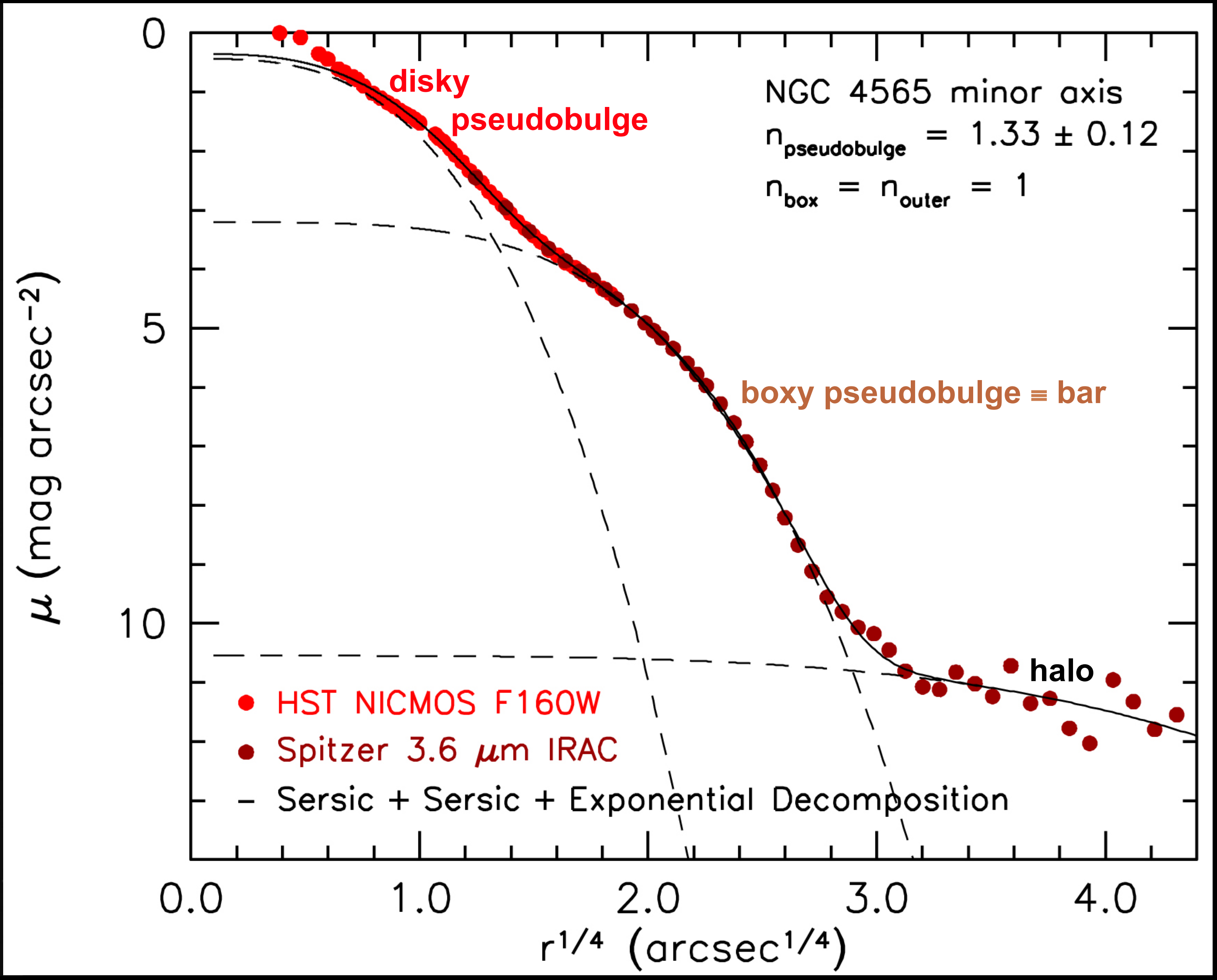


Spitzer Space Telescope 3.6 μm IRAC images and HST NICMOS penetrate dust but still show starlight.

⇒ clearly defined but tiny <u>central component</u> with B/T « 0.4, well differentiated from the box = bar structure (Kormendy & Barentine 2010, ApJ, 715, L176).

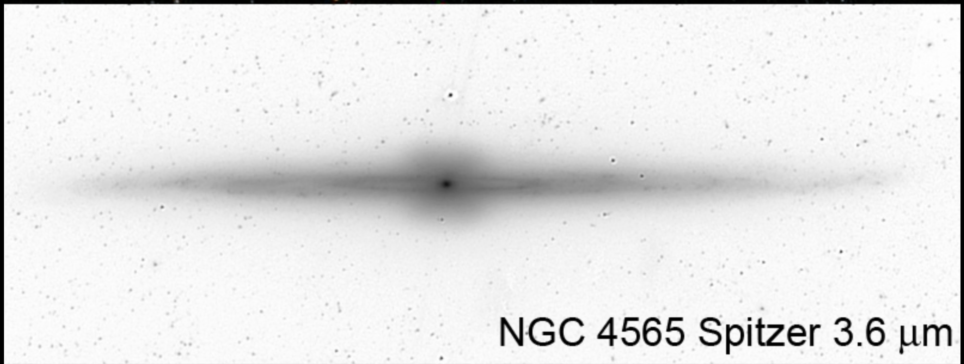
Is it a classical bulge or is it a pseudobulge? Answer: Pesudobulge (Sérsic n = 1.33 ± 0.12)

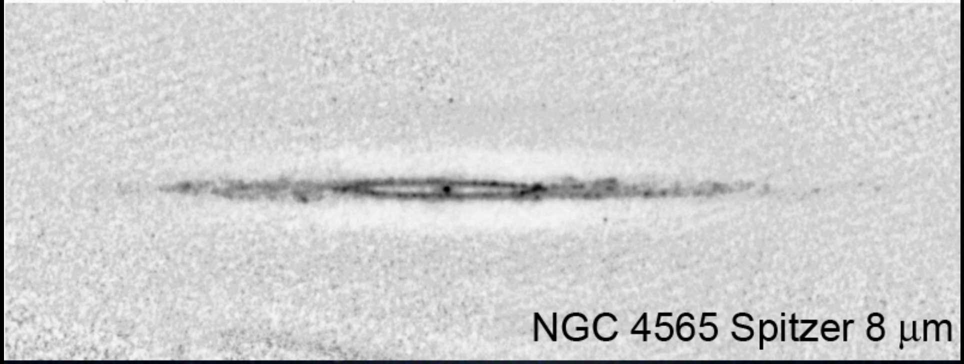
NGC 4565 contains a disky pseudobulge + ("Boxy bulge" ≡ bar)
⇒ no sign of a merger-built bulge. But V_{circ} = 255 ± 10 km s^{-1} (Rupen 1991).

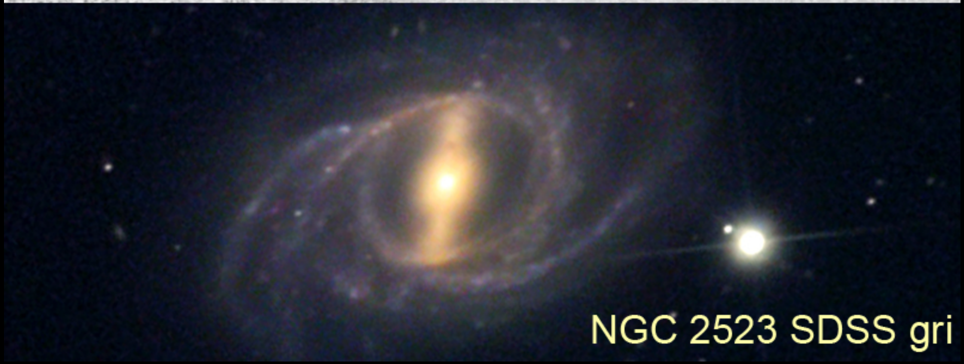


If NGC 4565 were seen face-on,
it would be the most spectacular
SB(r) galaxy
in the sky.

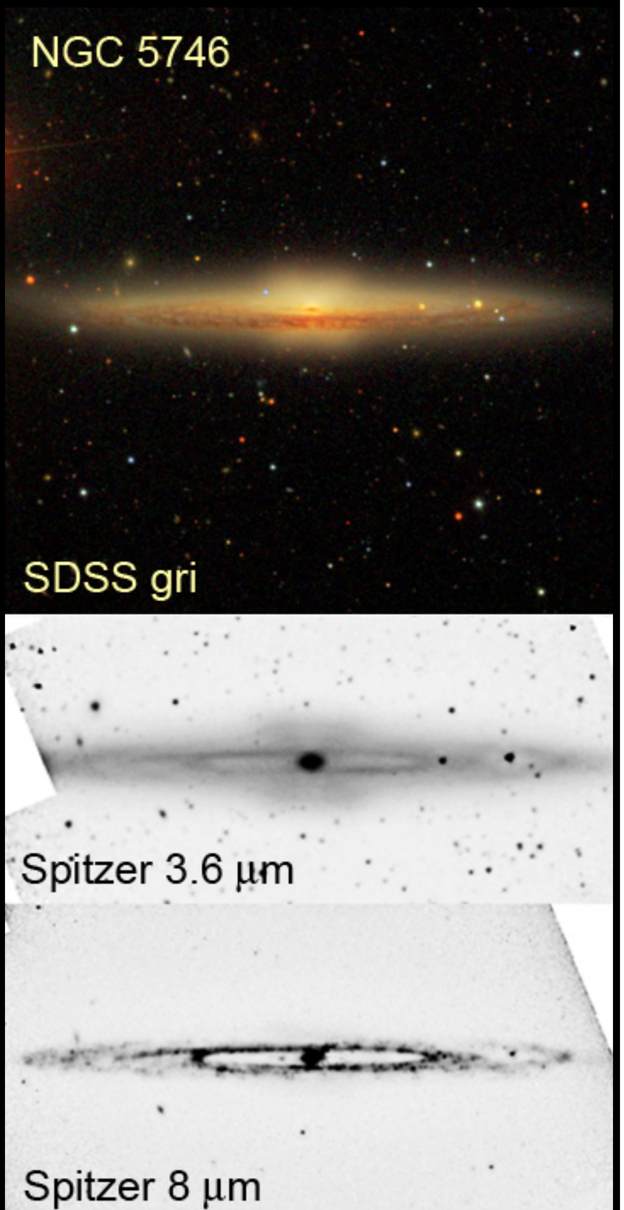
Is our Milky Way Galaxy
also an SB(r)bc ?







NGC 5746 contains a disky pseudobulge + ("Boxy bulge" ≡ bar)
⇒ no sign of merger-built bulge.



Barentine & Kormendy 2012 Astrophysical Journal, 754:140

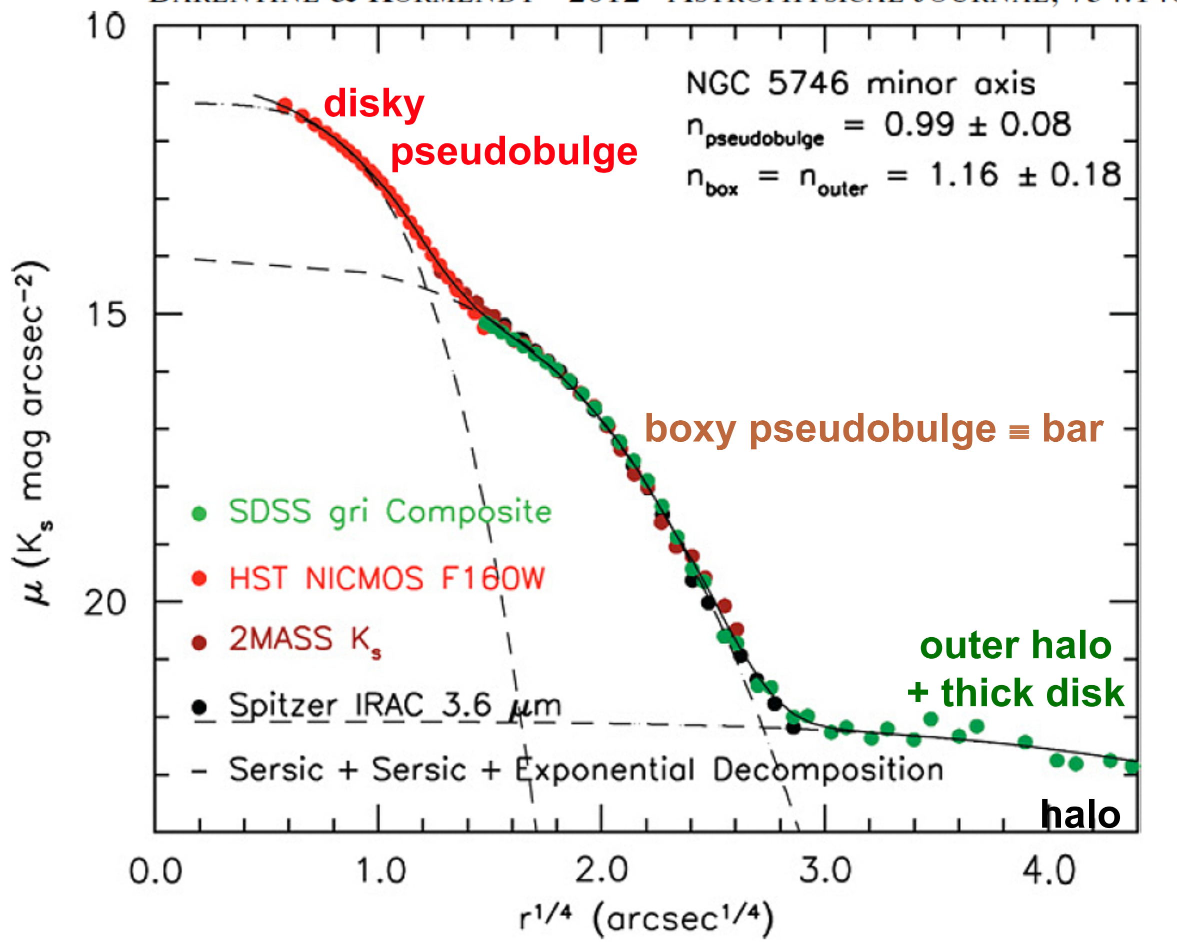
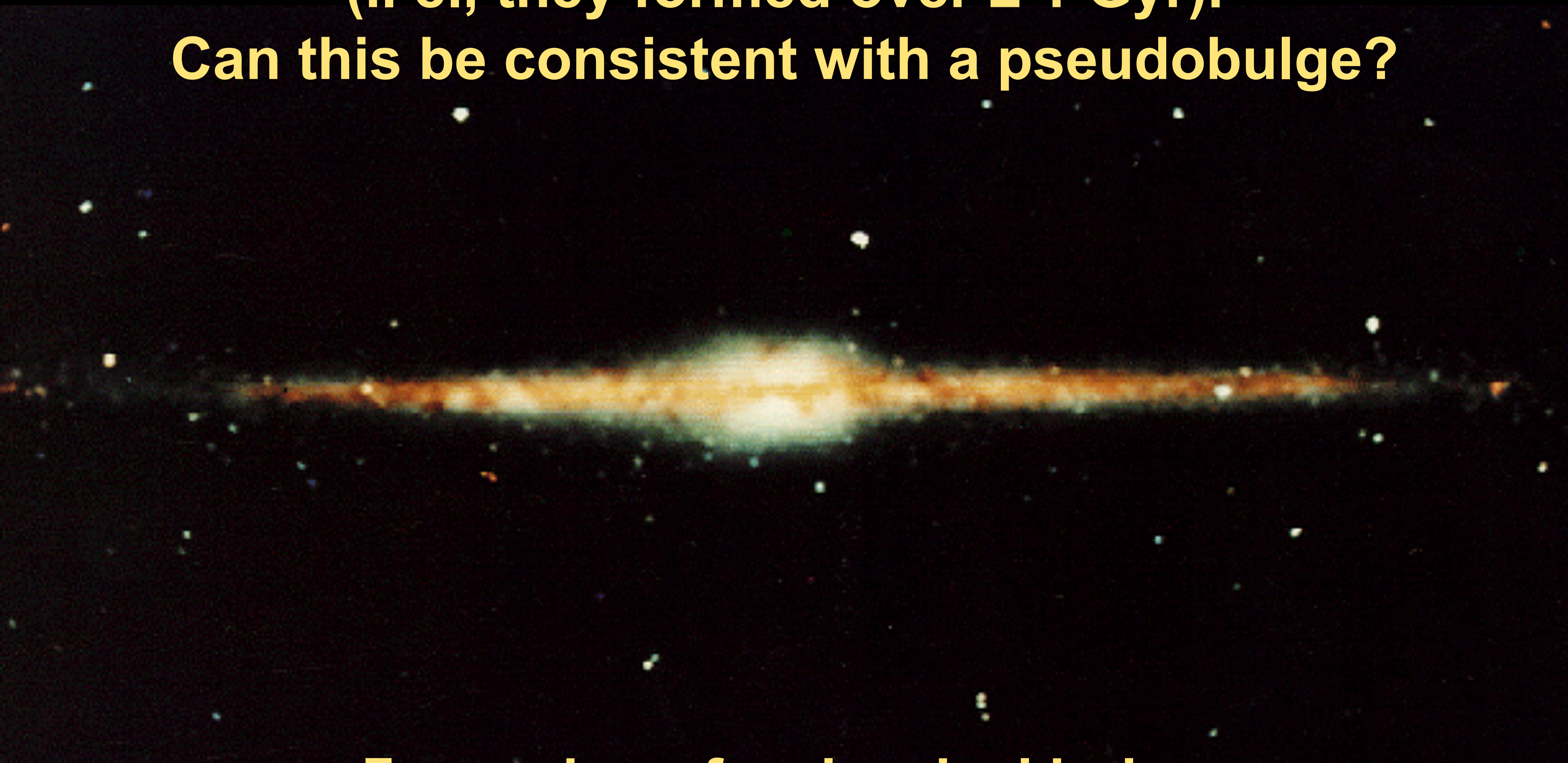


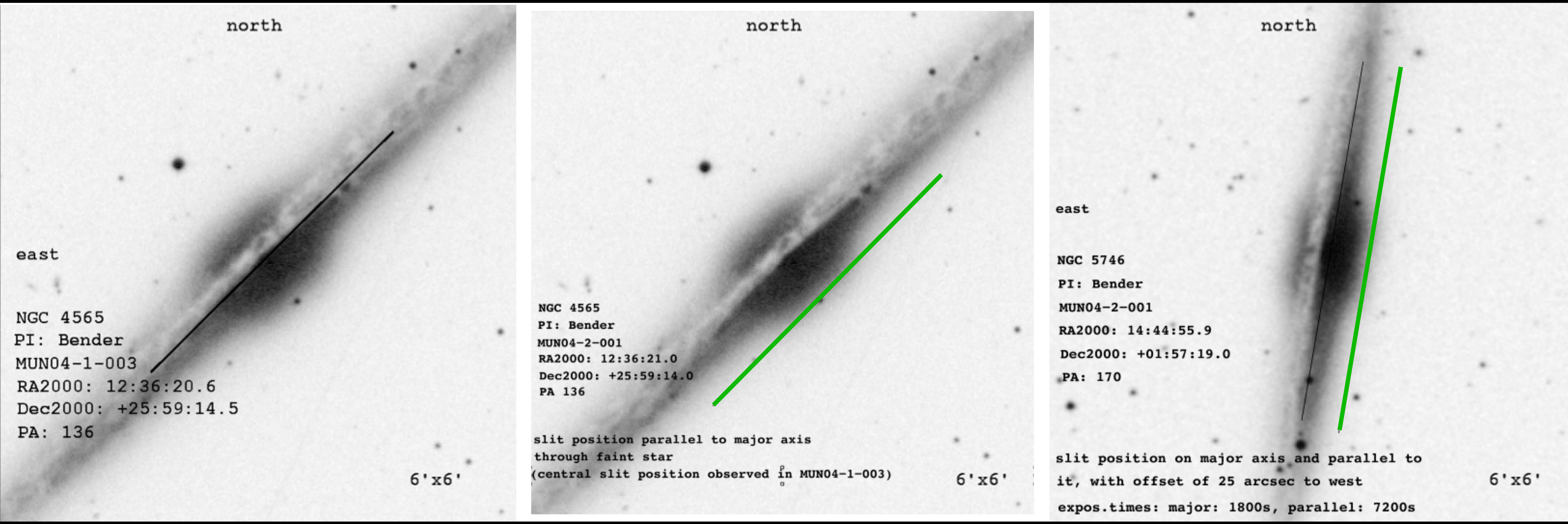
Figure 3. Minor-axis light profile of NGC 5746 from the following data sources: combined SDSS *gri* (green points), *HST*/NICMOS F160W (red points), 2MASS K_s (brown points), and *Spitzer*/IRAC 3.6 μm (black points). A Sérsic–Sérsic-exponential decomposition is overplotted as dashed lines, representing the inner pseudobulge, boxy bar, and outer halo, respectively. The solid line represents the sum of these three components.

Our Galaxy has a boxy bulge (COBE), but most of its stars are old and α-element-enhanced (i. e., they formed over $\leq$ 1 Gyr). Can this be consistent with a pseudobulge?



$\exists$ no sign of a classical bulge (Freeman 2007, IAU245; this paper).

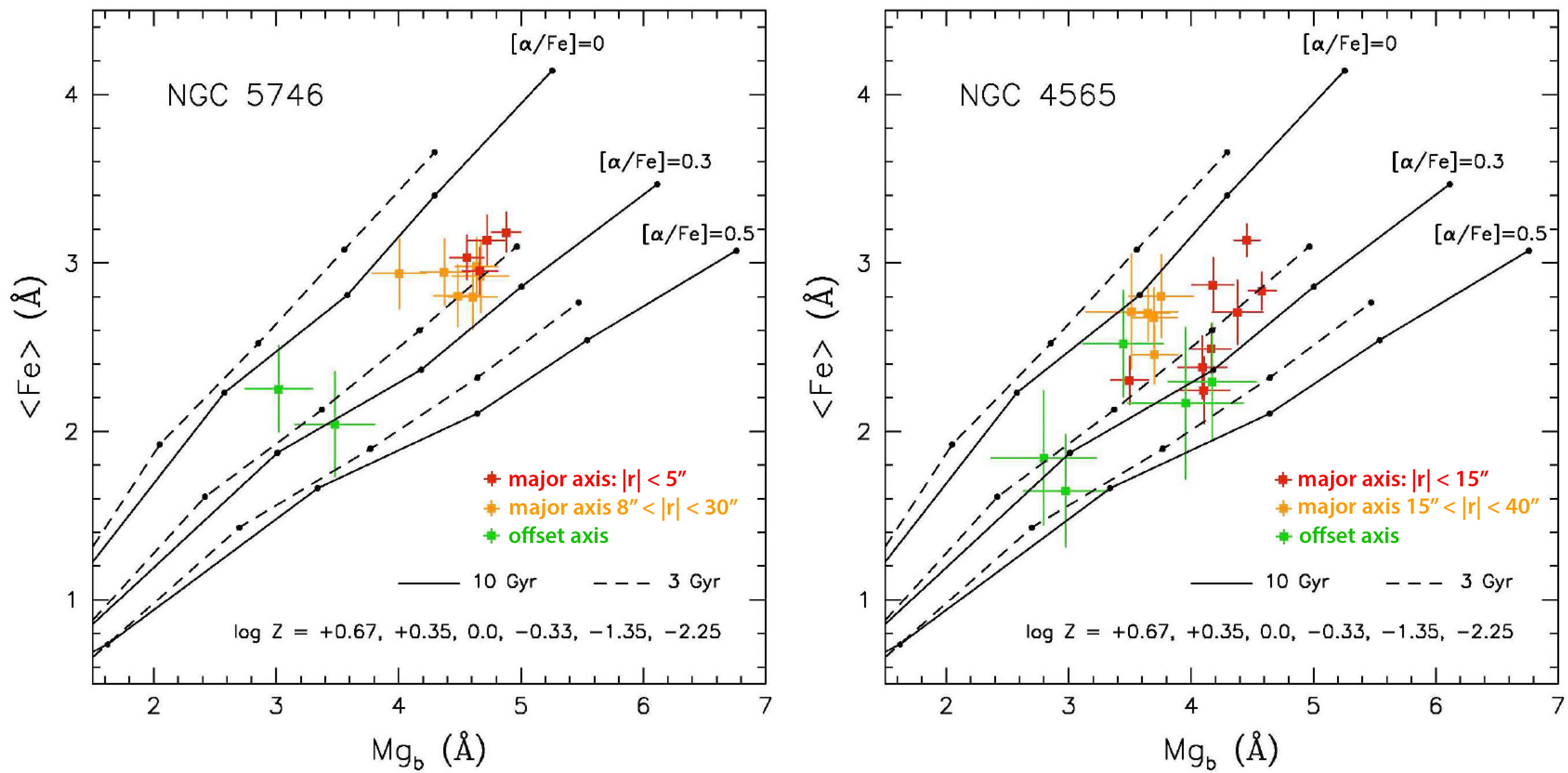
We measured [α/Fe] along the major axis
and in the boxy pseudobulges of NGC 4565 and NGC 5746
using the LRS Spectrograph on the Hobby-Eberly Telescope.



NGC 4565 offset slit was at z = 35″ = 2.5 kpc @ D = 14.5 Mpc.

NGC 5746 offset slit was at z = 25″ = 3.3 kpc @ D = 27.5 Mpc.

We find that [α/Fe] is enhanced with respect to Solar values in the boxy pseudobulges of NGC 4565 and NGC 5746 as it is in the boxy structure of our Galaxy .



Bender & Kormendy 2016, in preparation

FIG. 2.— The points show Fe and Mg equivalent widths as a function of galactocentric radius r using red points near $r = 0$ and bluer points farther out. For two stellar population ages (key), the lines show [α/Fe] values in log Solar units. Both box-shaped bulges are α-element enhanced, indicative of short star formation timescales (∼ 1 Gyr).

The disk of NGC 4565 has more nearly Solar [α/Fe].

The boxy structure
= almost-end-on bar has
exponential minor-axis profile,
like the boxy psedubulges
of NGC 4565 & NGC 5746.

The Launhardt et al. 2002
minor-axis K-band profile
allows us to check
how much classical bulge
could be hidden
in our Galaxy.

Recall: Fundamental Plane
correlations ⇒ We do not have
the freedom to tinker
classical bulge profiles
to make them easy to hide.

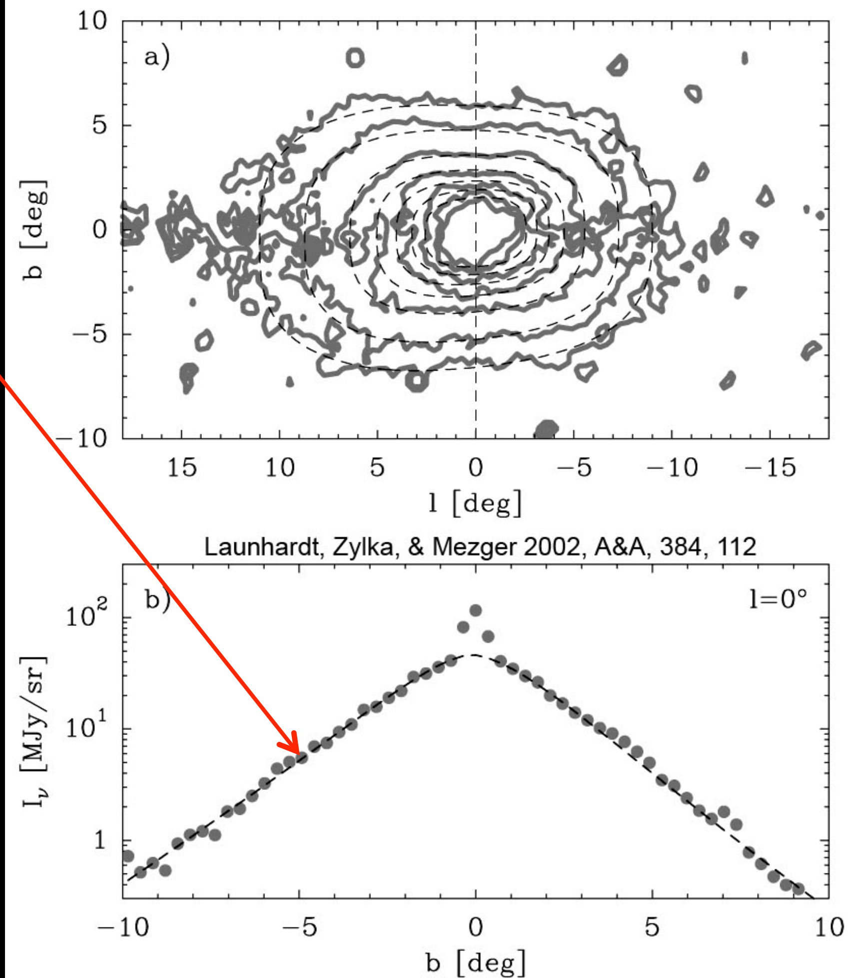
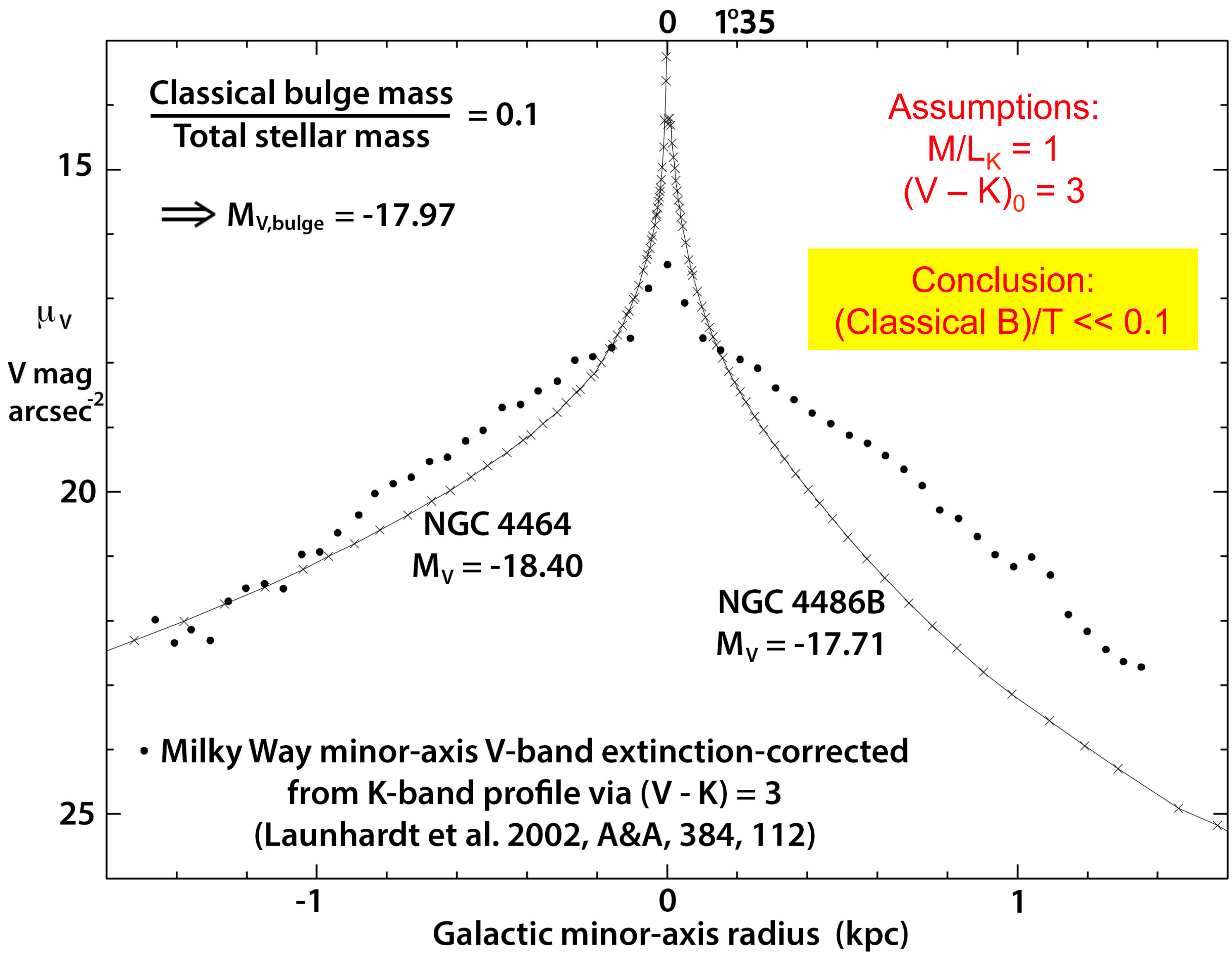


Fig. 5. 2.2 μm surface brightness distribution of the Galactic and Nuclear Bulge. In order to achieve the best signal-to-noise ratio, a weighted average of the 2.2, 3.5, and 4.9 μm maps, scaled to the 2.2 μm surface brightness, is shown. Contributions from the Galactic Disk are subtracted and the emission is dereddened for extinction by foreground dust. **a)** Contour maps of the observed dereddened (thick grey lines) and modeled (dashed lines) NIR surface brightness distribution. Levels are at 5, 10, 20, ..., 60% of modeled peak surface brightness. **b)** Latitude profile at $l = 0°$ of the observed dereddened (grey dots) and modeled (dashed line) NIR surface brightness distribution of the GB.

Could (Classical B)/T = 10 % by stellar mass?
Compare Galactic minor axis profile to 2 Virgo Es (Kormendy + 2009, ApJS, 182, 216) that bracket 10 % of the Milky Way stellar mass.



Comparison of Structural Components in Milky Way, NGC 4565, and NGC 5746

⇒ Cannot hide even a small classical bulge in our Galaxy.

(Quote: Stellar mass ratios of Milky Way, light ratios of NGC 4565 & NGC 5746)

Parameter	Milky Way	NGC 4565	NGC 5746
Nuclear cluster/T	0.00036	0.00011	…
Disky pseudobulge/T	0.04 ± 0.01	0.06 ± 0.01	0.136 ± 0.019
Box/T	0.27	~ 0.4	~ 0.4
Nuclear cluster r_e	4.2 ± 0.4 pc	unresolved	unresolved
Disky pseudobulge z_0	45 pc	90 pc	100 ± 13 pc
Boxy pseudobulge z_0	0.22 kpc	0.74 kpc	0.76 ± 0.15 kpc
Boxy pseudobulge n	~ 1	1	1.16 ± 0.18
Thin, thick disk z_0	0.30, 0.90 kpc @ $r_\odot$	0.56, 1.03 kpc	…, 1.2 kpc

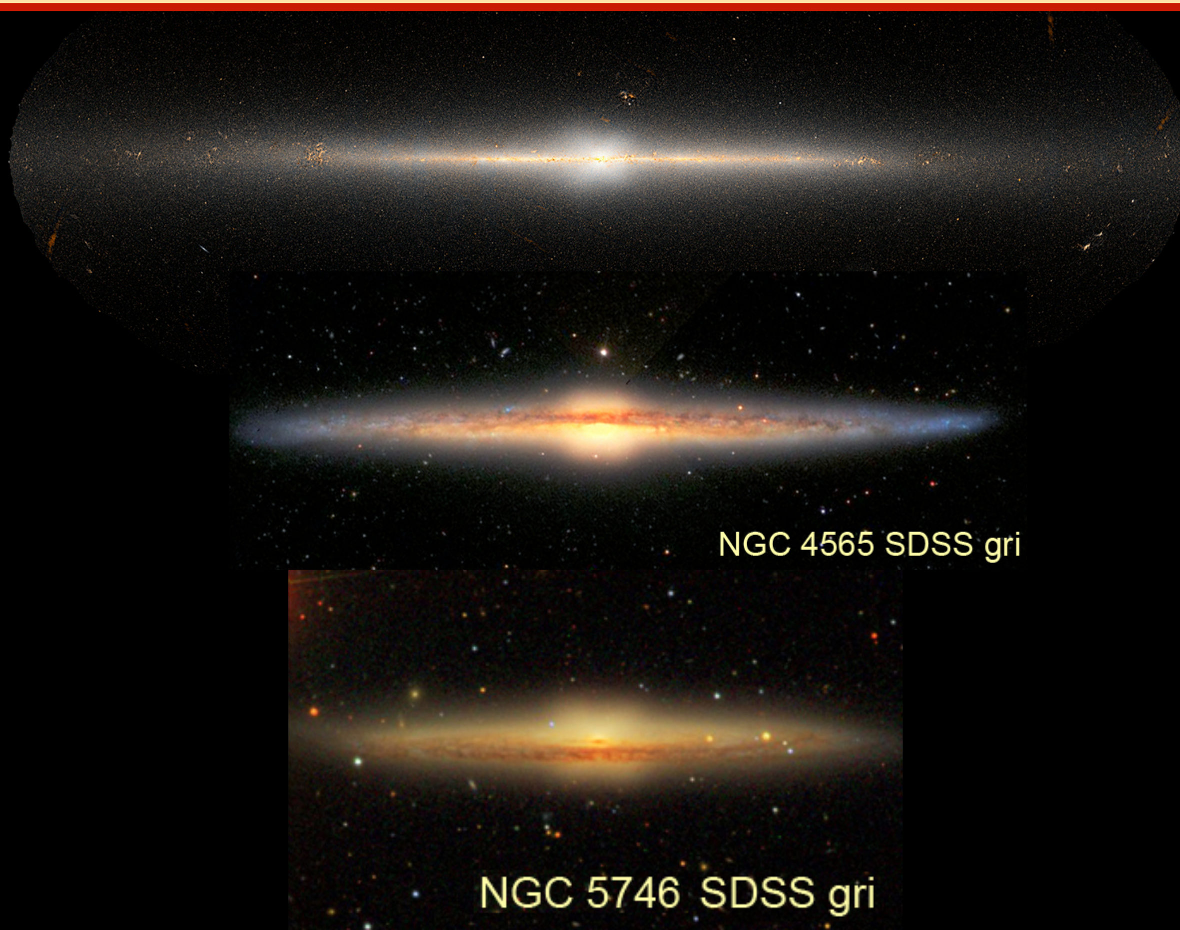
Classical bulge r_e

if B/T = 0.02 — 100 – 200 pc, corresponding to $M_V \approx -16.3$ (M32: -16.7)

if B/T = 0.01 — 60 – 150 pc, corresponding to the faintest Es known.

All three galaxies have $B/T = 0$ and (Disky PB) / $T \lesssim 0.1$.

NGC 4565 & NGC 5764 As Milky Way Analogs



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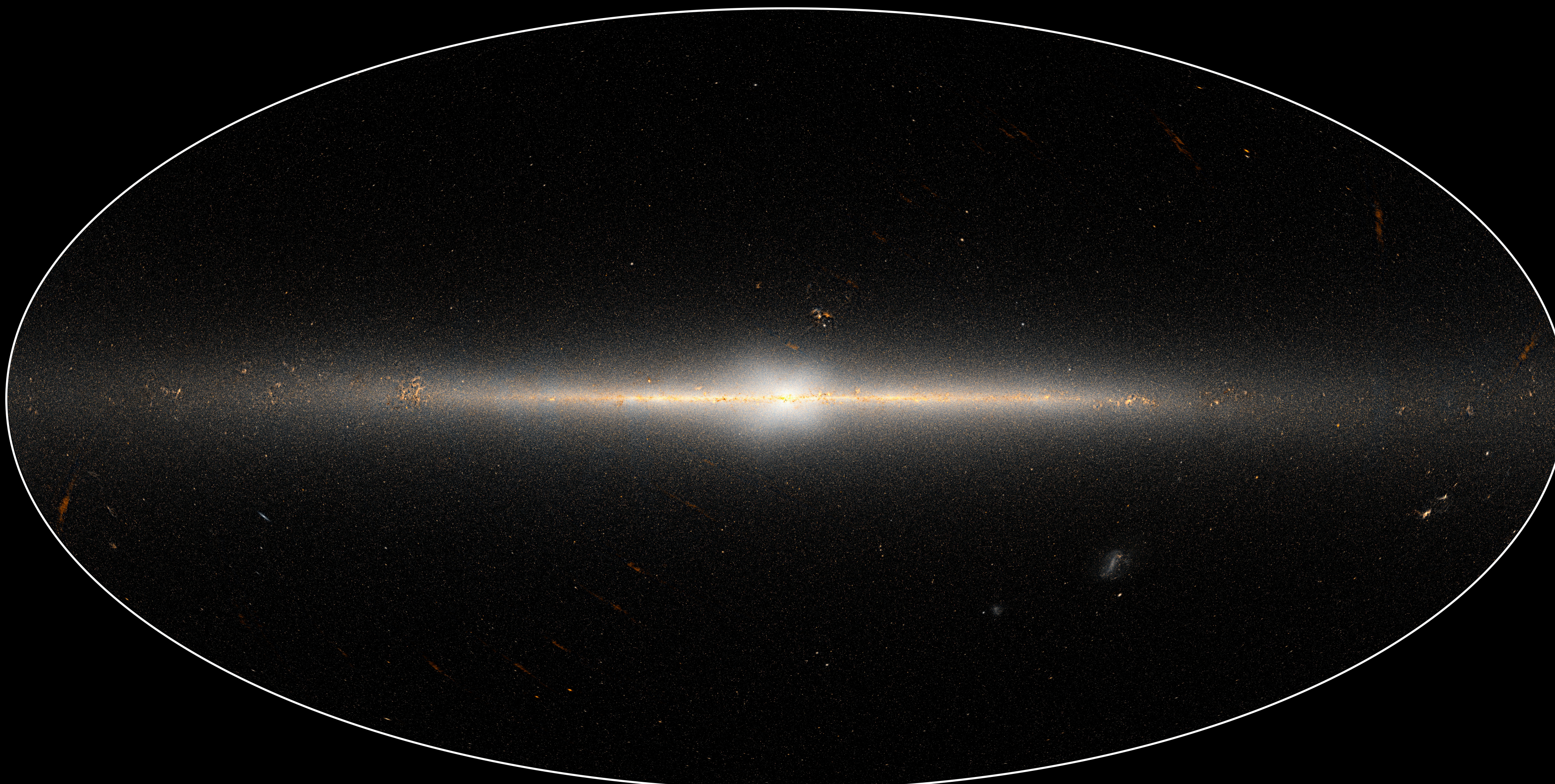


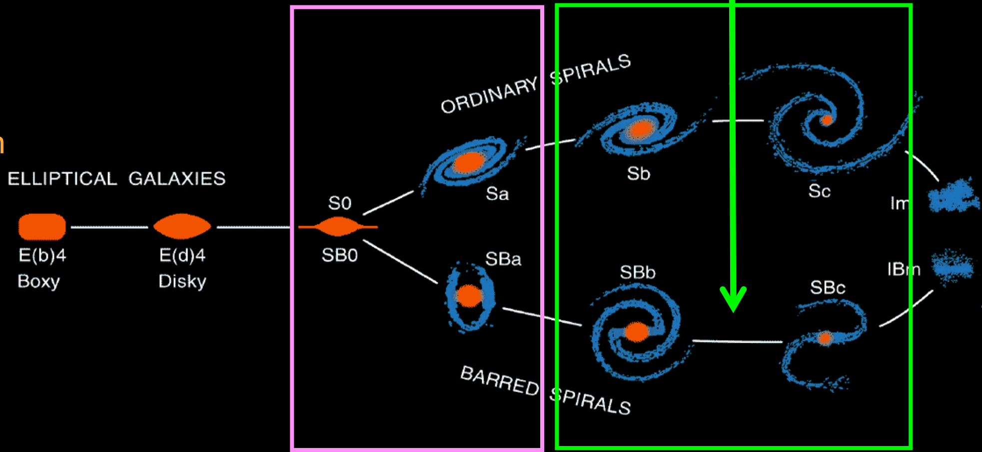
Kormendy & Kennicutt 2004, ARA&A, 42, 603;
Kormendy 2013, 23rd Canary Islands Winter School review, arXiv:1311.2609

At what Hubble types does secular evolution happen?

I suggest:
Our Galaxy plausibly is
SB(r)bc ⇒
secular evolution
should be important.

Some S0 – Sa galaxies
evolved secularly in the past:
they contain pseudobulges.

Ellipticals: Any secular evolution
in progenitor disks
got scrambled by mergers.
Ellipticals have
different secular processes
not discussed here.



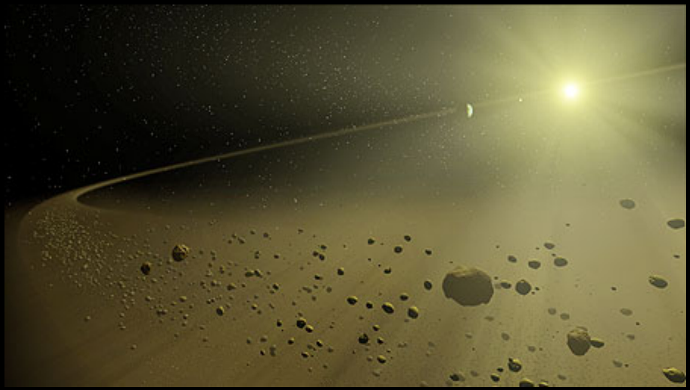
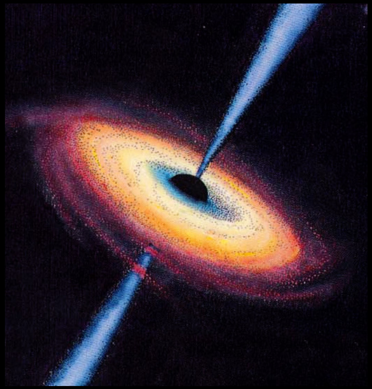
Sd – Im galaxies have
little internal secular evolution
because
it is not energetically favorable
to transport angular momentum
outward.

This is where internal
secular evolution is
most important now.

Tremaine (1989), Lynden-Bell & Kalnajs 1972; Lynden-Bell & Pringle 1974:
d(total energy) / d(angular momentum) = $\Omega(r) = V(r)/r$
⇒ Secular evolution by inward transport of gas ⇒ pseudobulge growth should be
most rapid at Hubble type ~ Sbc.

Self-gravitating systems evolve by spreading — they form a denser core and a more diffuse halo.

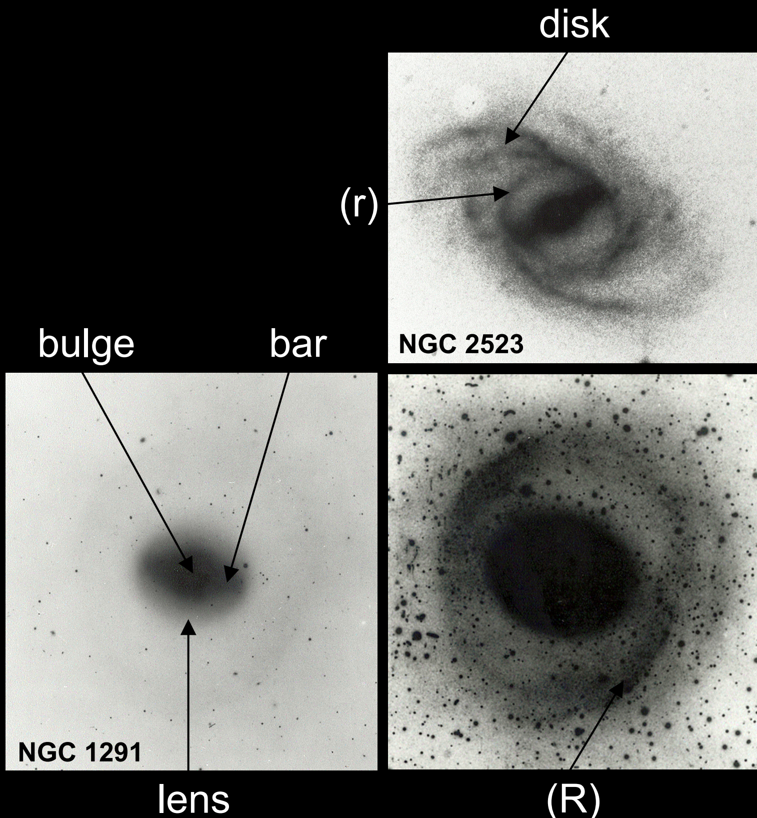

Systems that are supported by random motions evolve by transporting energy outward.

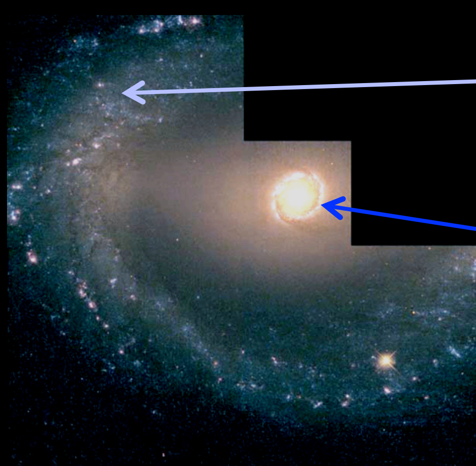




Systems that are supported by rotation evolve by transporting angular momentum outward.

Pseudobulge growth in a galaxy disk is analogous to growth of a star from a protostellar disk and growth of a black hole from a quasar accretion disk.

Secular ≡ Slow Evolution of Galaxies





Evolution happens via angular momentum exchange between (especially) gas and nonaxisymmetric components such as bars and oval disks (timescale » dynamical time).

This is believed to rearrange disk gas into <u>inner rings</u> (r), <u>outer rings</u> (R), and <u>pseudobulges</u>.

Duus & Freeman 1975; Simkin + 1980

Kormendy 1979; 1981; 1982; 1993; 2013, … .

Kormendy 1979; Simkin + 1980

Inner rings have the same (young) stellar population as the disk, not the old stellar population of the bar.

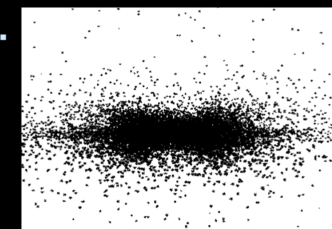
Pseudobulges are grown slowly out of disks that are always nearly in dynamical equilibrium.

This slow evolution happens on time scales of billions of years (the galaxy rotates many times while it changes; evolution is gentle; galaxy is always in gravitational equilibrium).

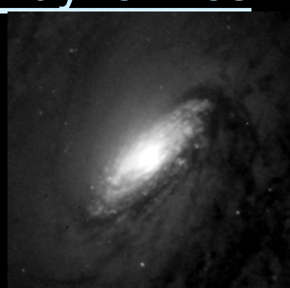
SB(spiral) galaxies like NGC 1300 are "dynamically younger" than SB(ring) galaxies like NGC 2523.

Secular evolution grows pseudobulges – central, dense gas+star subsystems – out of disks.

Stellar-dynamical bar formation: bars heat and buckle in the axial direction and look box-shaped when seen edge-on.
Box-shaped pseudobulge = edge-on bar
(e. g., Combes & Sanders 1981, A&A, 96, 164;
Combes et al. 1990, A&A, 233, 82)


Combes & Sanders 1981

Gas-dynamics: Angular momentum transport by bars drives gas to center where it starbursts and makes disky pseudobulges (see Kormendy 1993; Kormendy & Kennicutt 2004; Kormendy 2013, Canary Islands school for reviews).



Nuclear bars – like their associated main bars – are disk phenomena ⇒ pseudobulges.

Many barred galaxies have dark “dust lanes” on the front side (as they rotate) of bars. They are signatures of gas shocks.

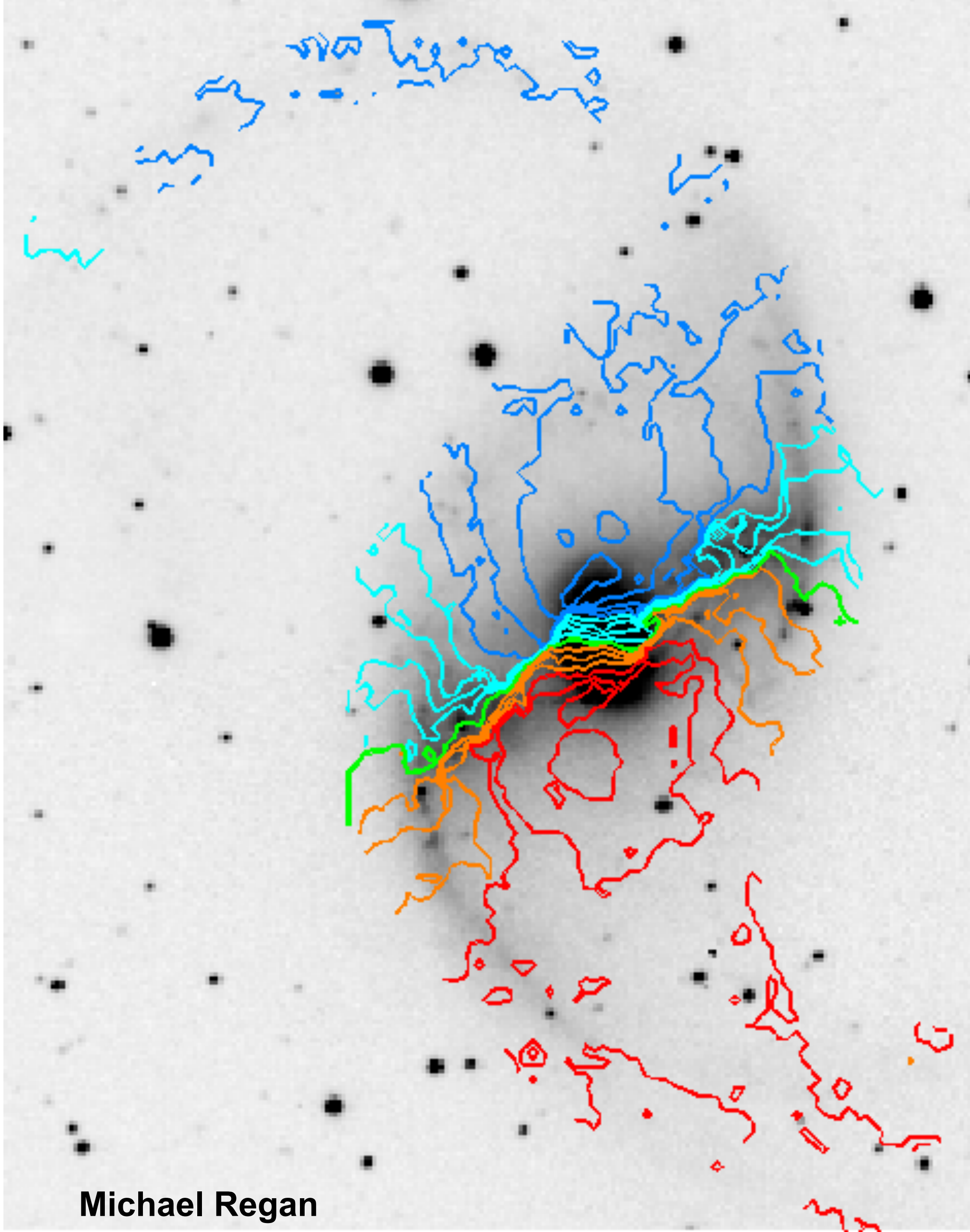
They are predicted by computer simulations (e. g., Athanassoula 1992, MNRAS, 259, 345).

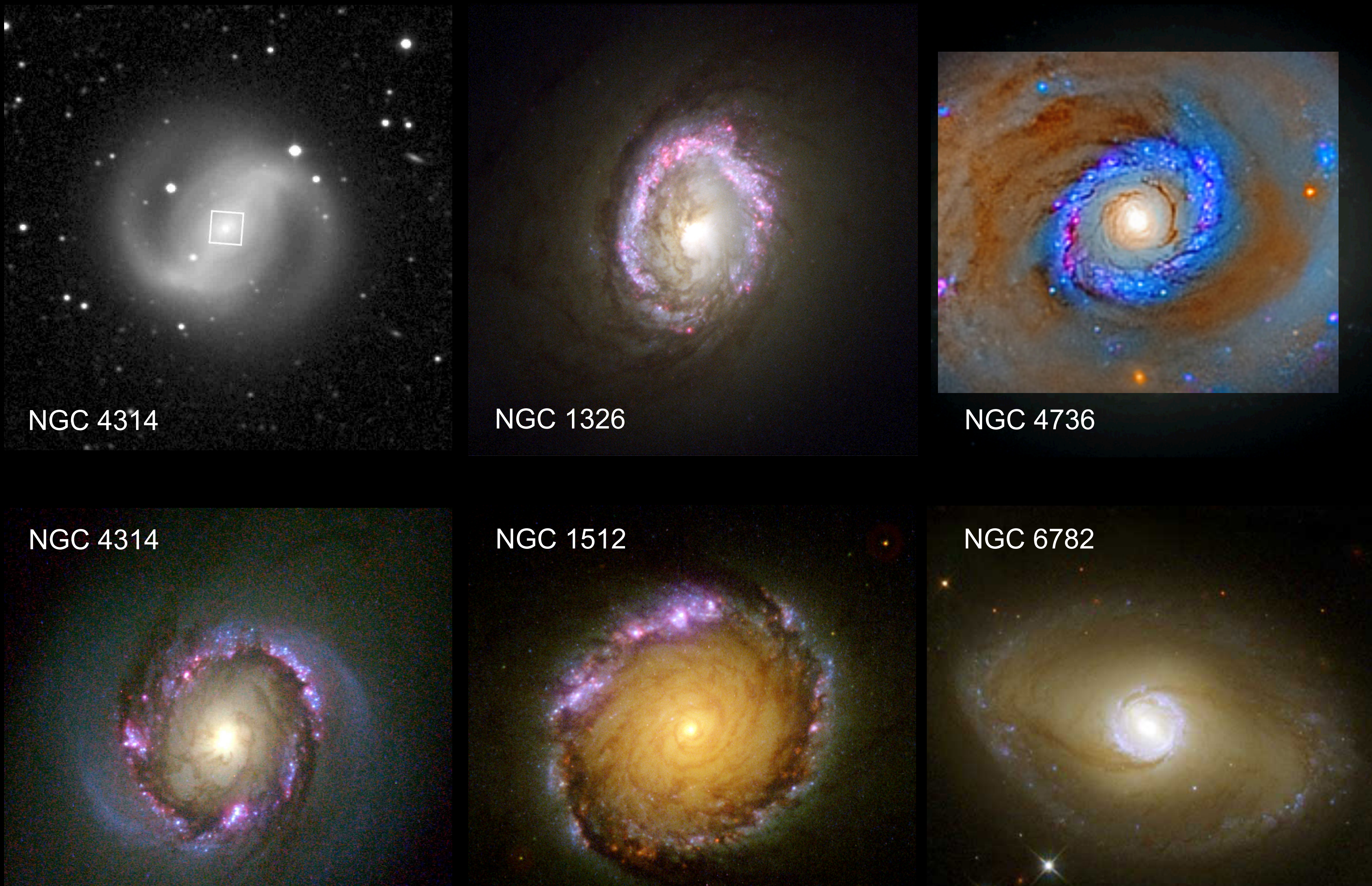
Gas flow toward the center is inevitable.

Regan, Vogel & Teuben 1997, ApJ, 482, L143:

H I velocity contours crowd in the dust lanes of NGC 1530 consistent with gas shocks.

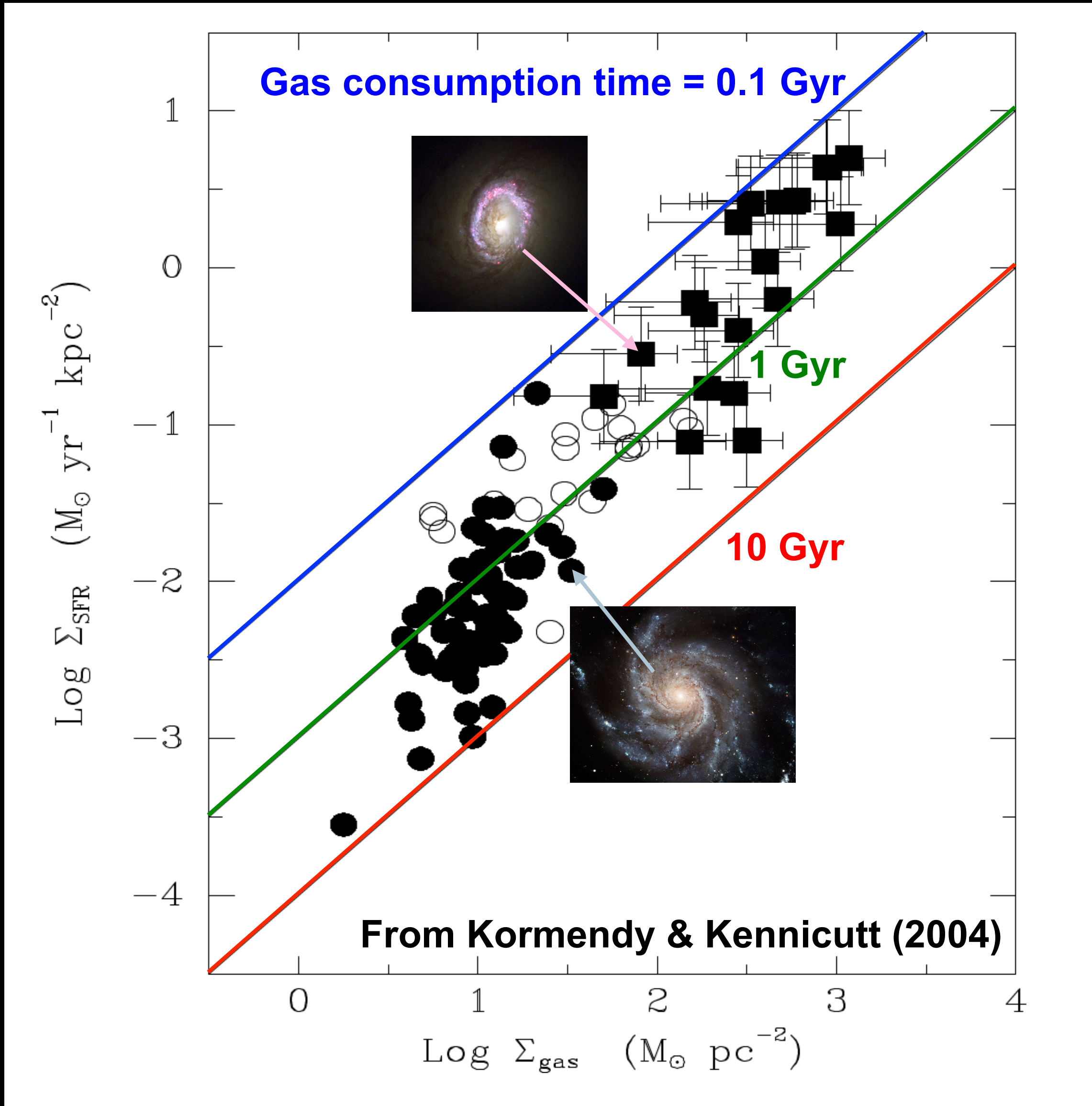
Gas flow toward the center is inevitable.





Central star formation rings grow "fake bulges" or "pseudobulges" with masses $10^6 - 10^9\ M_\odot$ in 1 – 3 billion years (Kormendy & Kennicutt 2004).

Schmidt-Kennicutt Law: $\Sigma_{SFR} \propto \Sigma_{gas}^{1.4}$



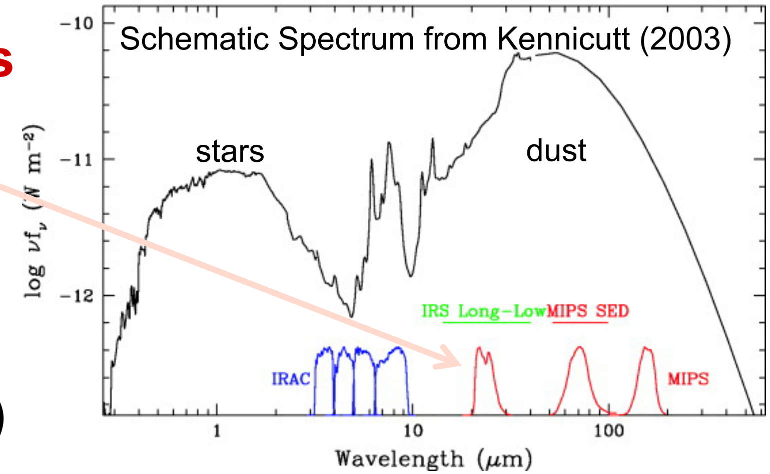
Circumnuclear star formation rings should make pseudobulges of mass 10^7 — 10^{10} $M_\odot$ in ~ 1 — 3 Gyr.

If gas gets replenished by secular evolution ⇒ gas consumption timescales are longer.

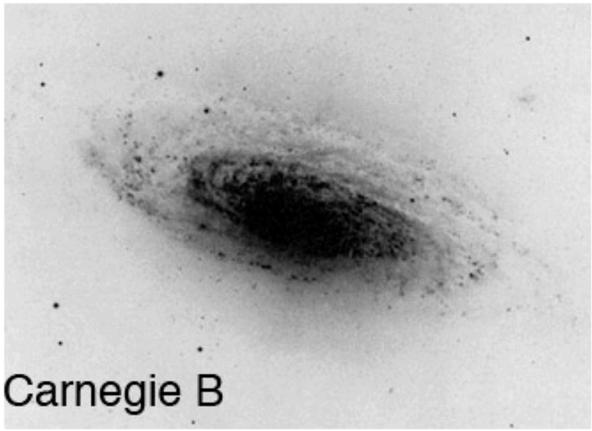
Spitzer MIPS (e. g., 24 μm channel) measures warm dust reradiating light from young stars ⇒ star formation rate (SFR).

SFR is high at the center of the oval and SB galaxies but not in the unbarred NGC 3521.

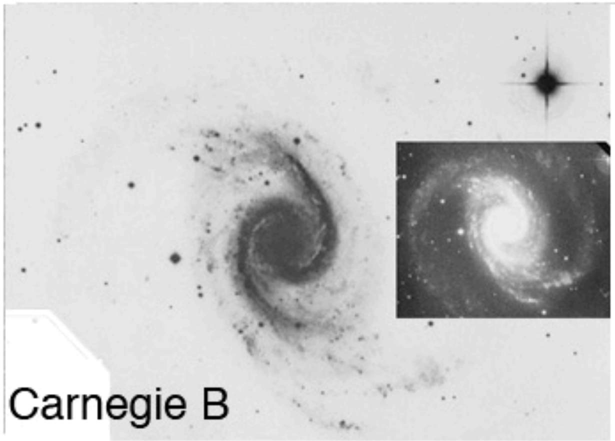
From David Fisher (see 2006, ApJ, 642, L17)



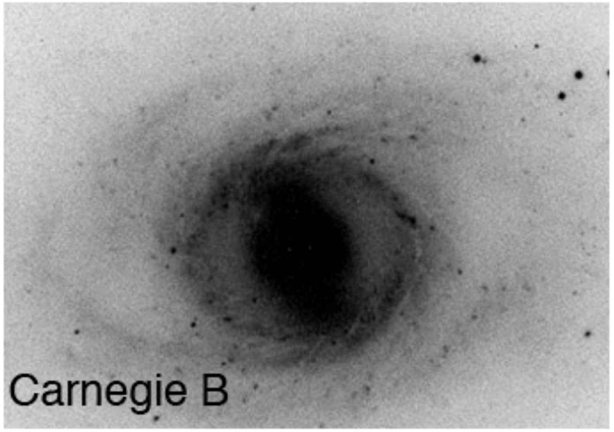
NGC 3521

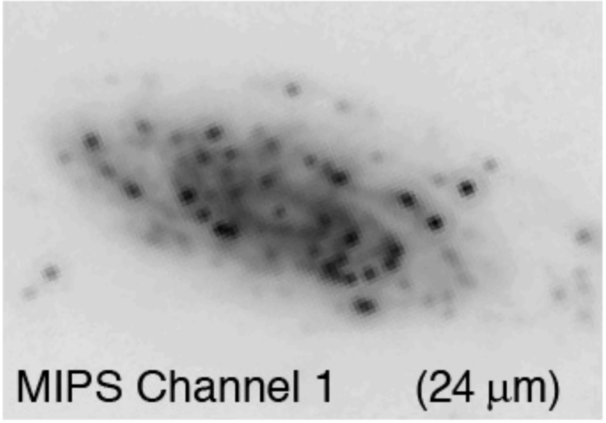


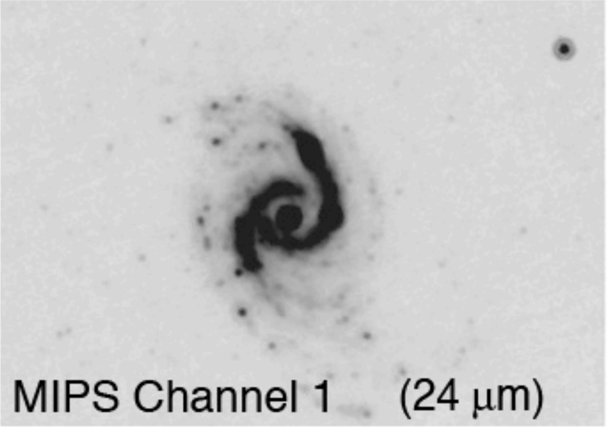
NGC 1566 (oval)

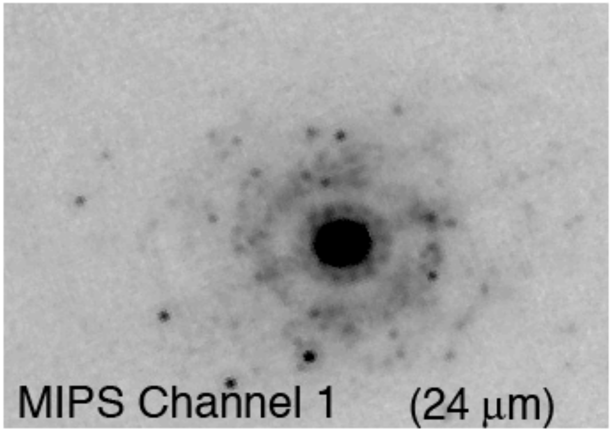


NGC 3351 (barred)







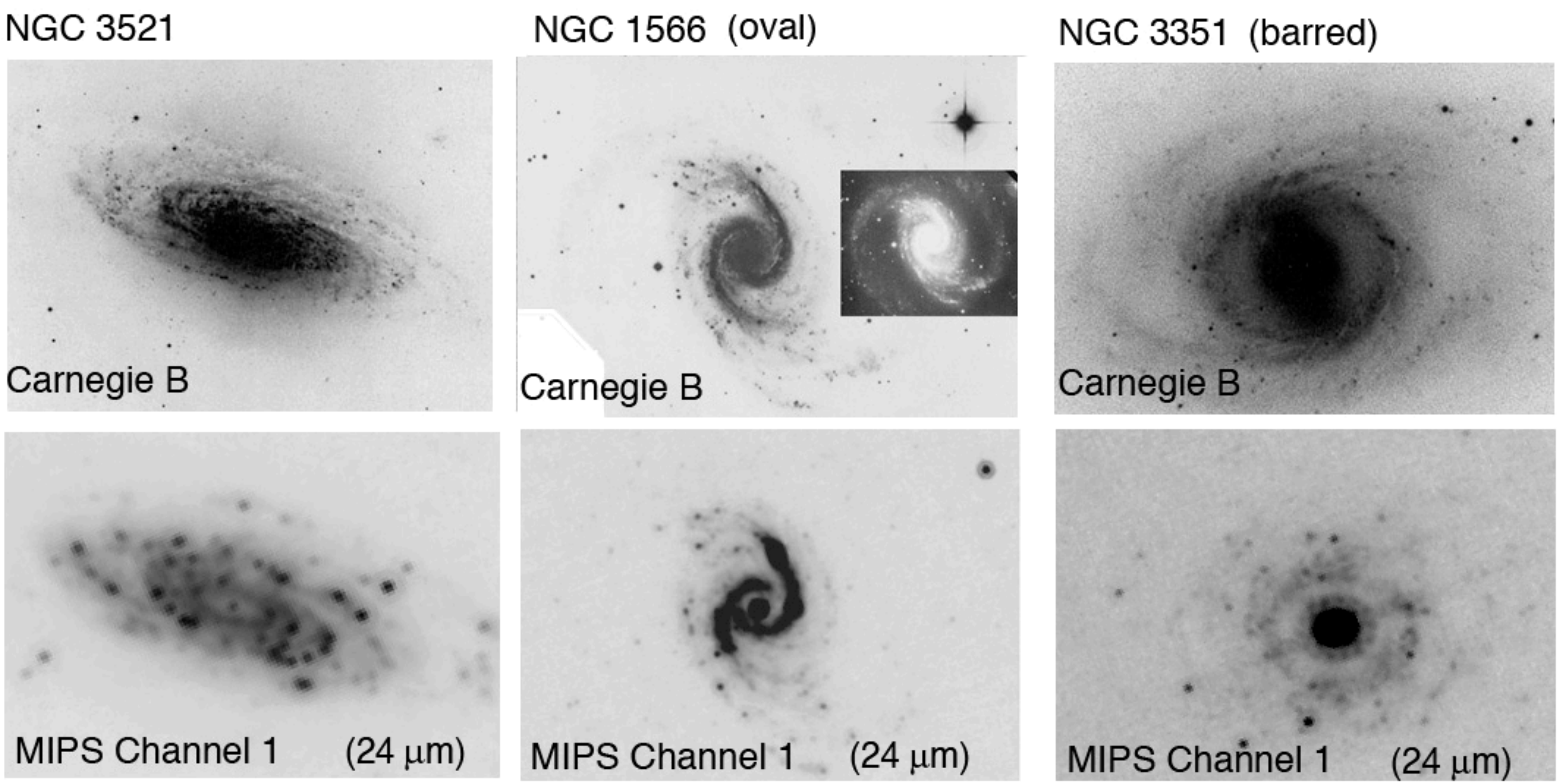


Some people have suggested that pseudobulges are made by minor mergers.

However, at Hubble types Sb – Sbc, pseudobulge properties (especially ubiquitous star formation) are <u>uniquely associated</u> with nonaxisymmetries that drive secular evolution (bars and ovals).

Absent a bar or oval, an Sb – Sbc galaxy has a classical bulge with <u>little star formation</u>.

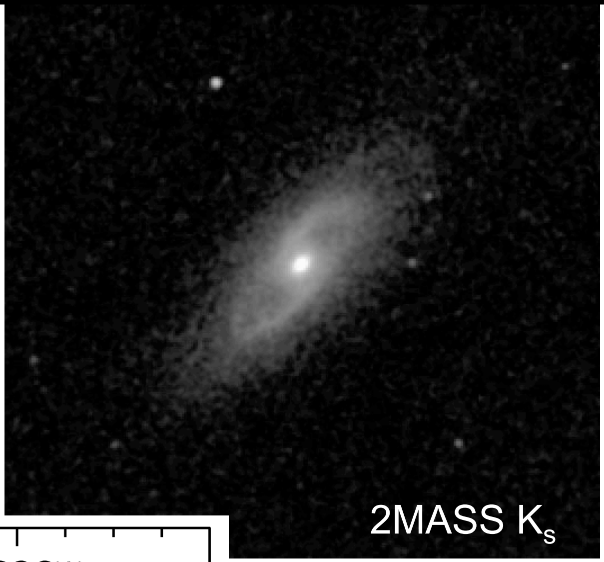
Pseudobulges are made by disk secular evolution, not by minor mergers.

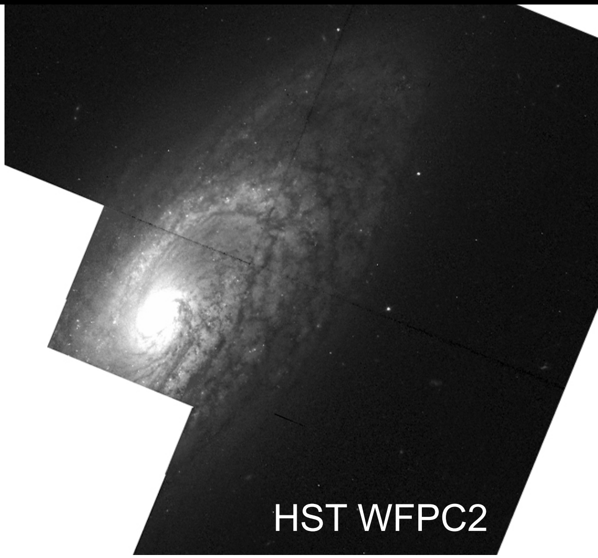


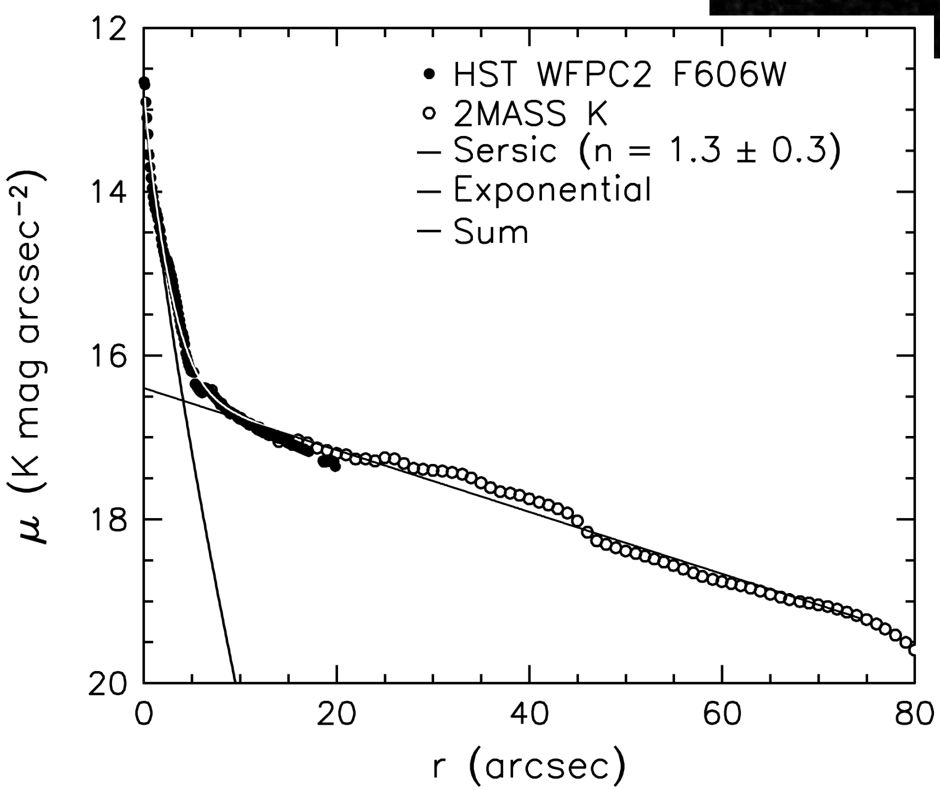
Pseudobulges Are Disk-Like

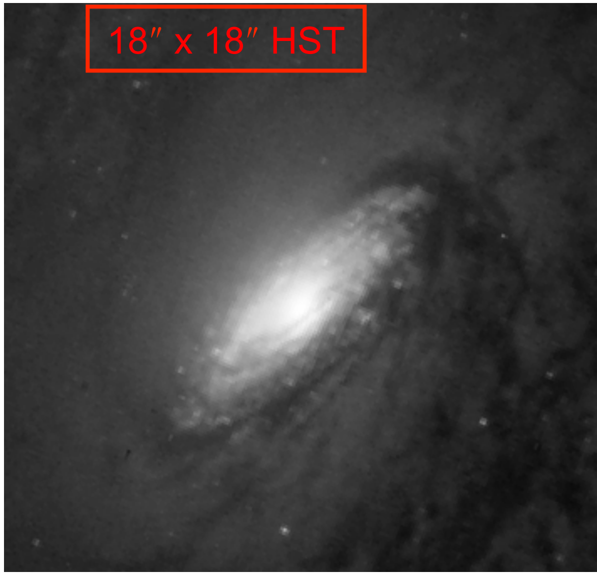
NGC 1353

de Vaucouleurs: SBb







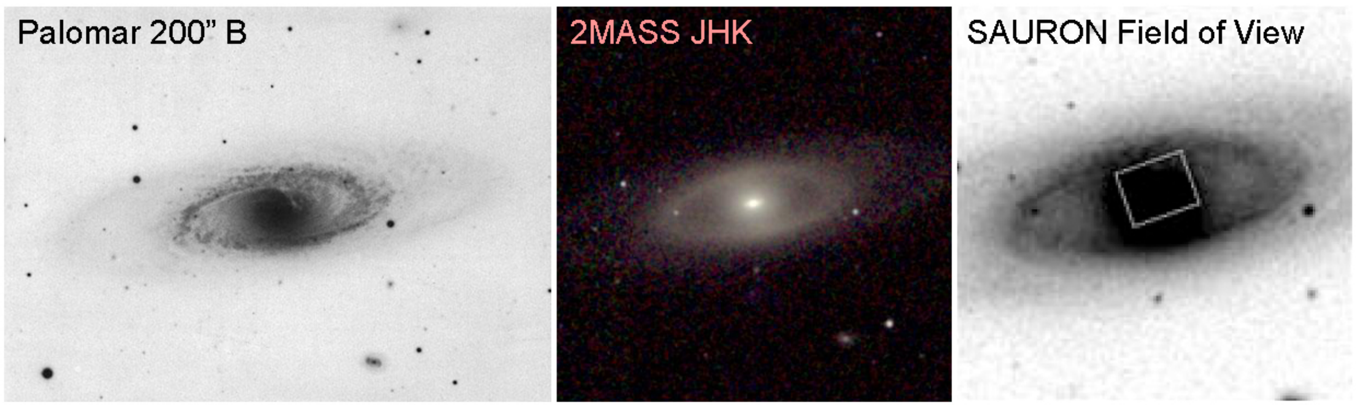


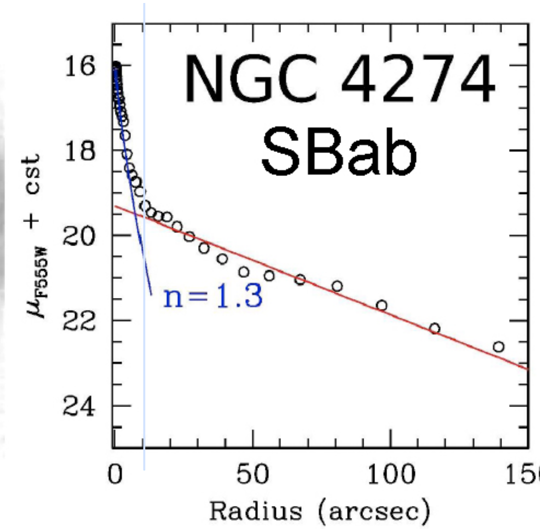
The pseudobulge of NGC 1353 is as flat as its disk.

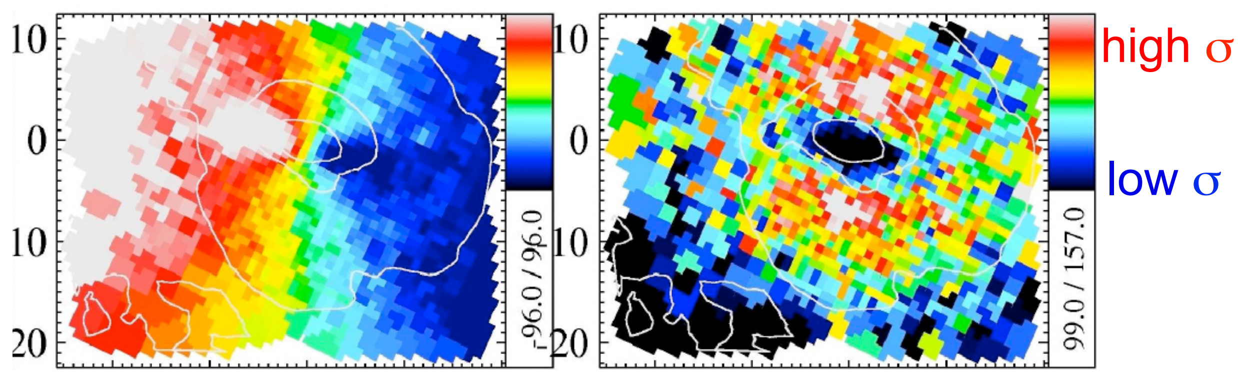
Disky Pseudobulges Are Cold & Rapidly Rotating

Falcón-Barroso et sauron 2006, MNRAS, 369, 529

Peletier et sauron 2008, IAU Symposium 245

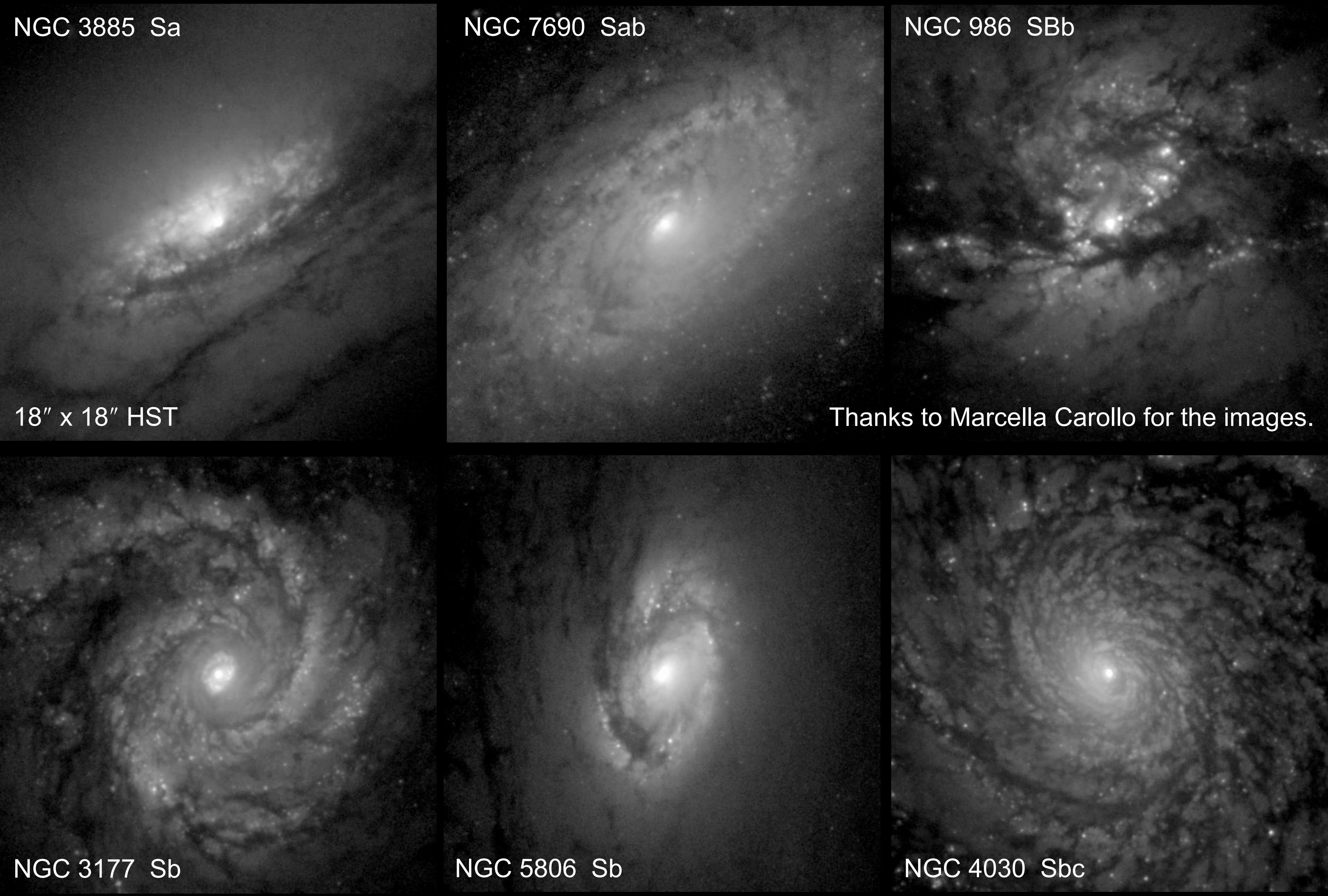






v_stars

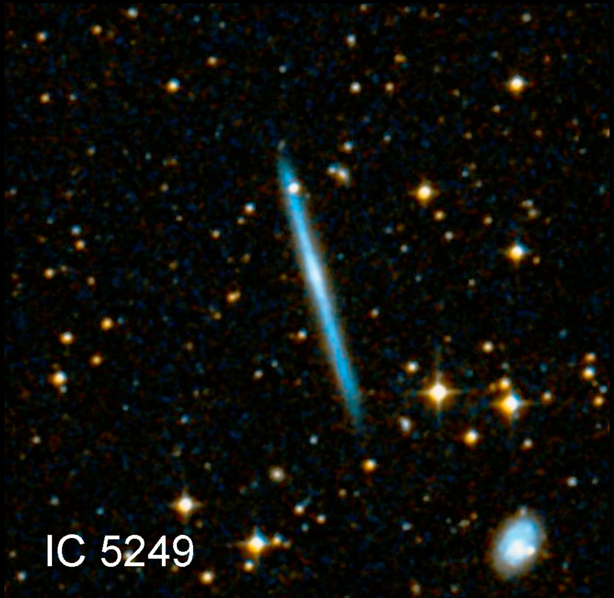
sigma_stars

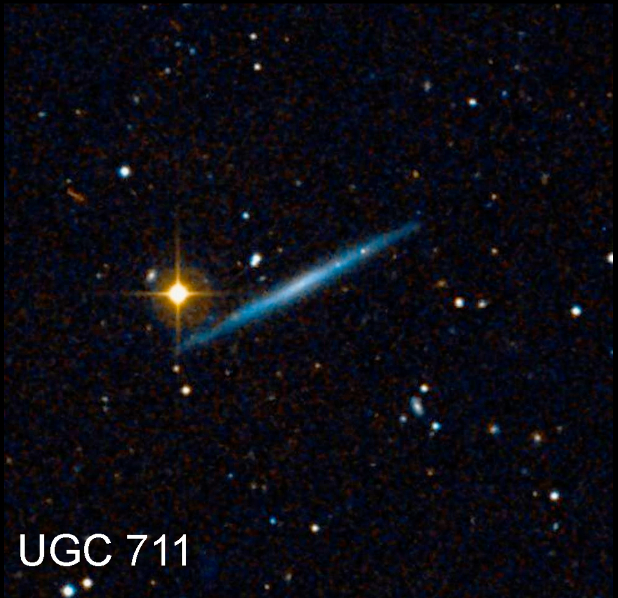


Most "bulges" in Sbc galaxies are pseudo.

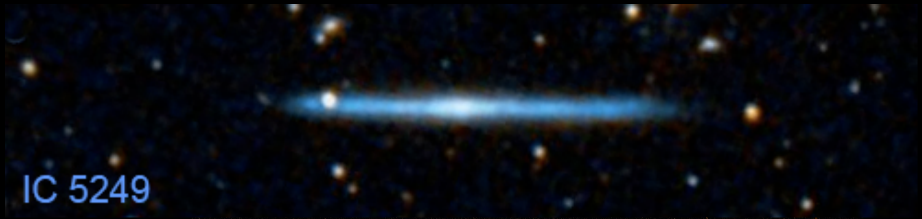
Fundamental Problem for Hierarchical Clustering:

Why are there so many bulgeless disks?



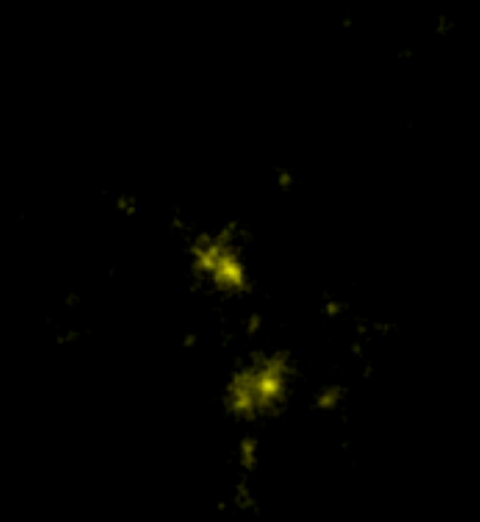


How do you make these:




Our Galaxy

… when halos grow like this?

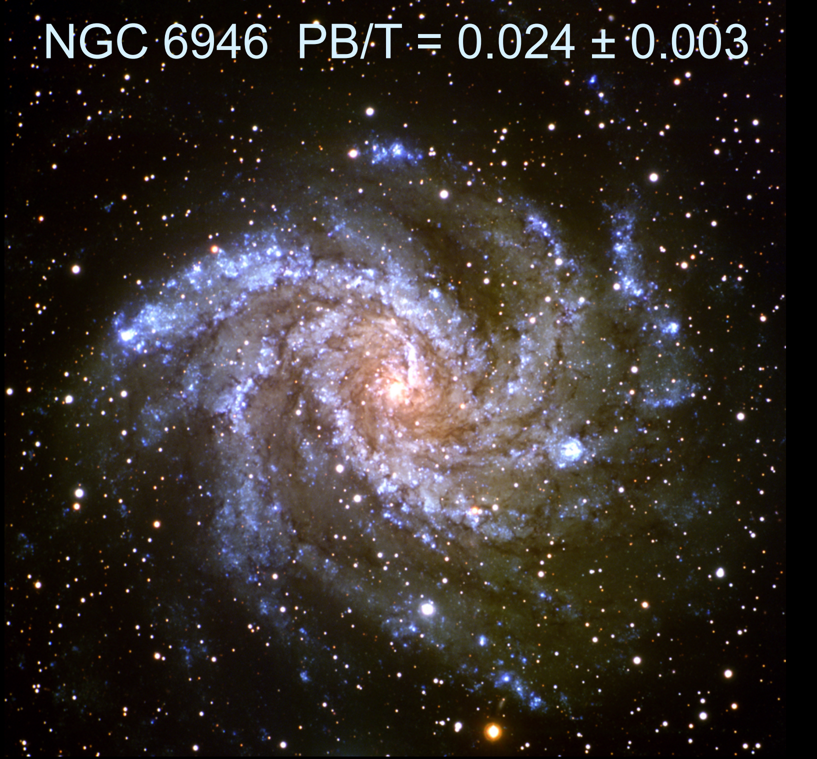


“Preventing bulge formation” is a 2-part problem:

1 – Must not let violent assembly of DM halo over-heat the cold, thin disk.

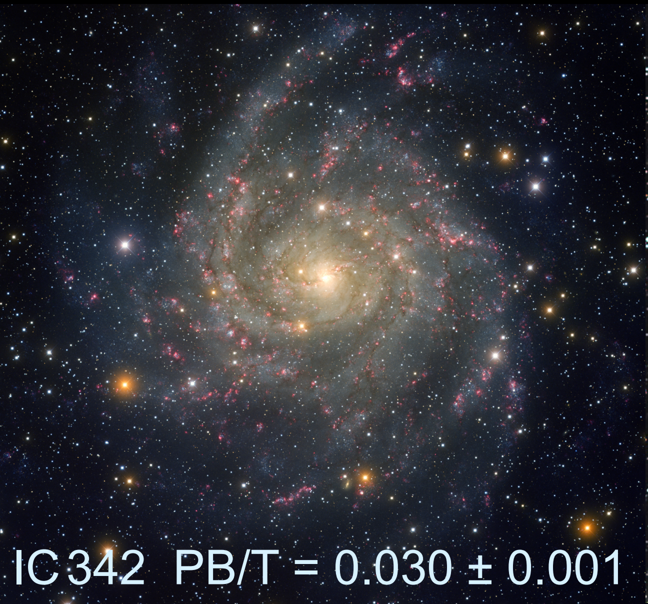
2 – Must not let violent relaxation of already-formed stars that were contributed by merger progenitors build a classical bulge.

M101 PB/T = 0.027 ± 0.008

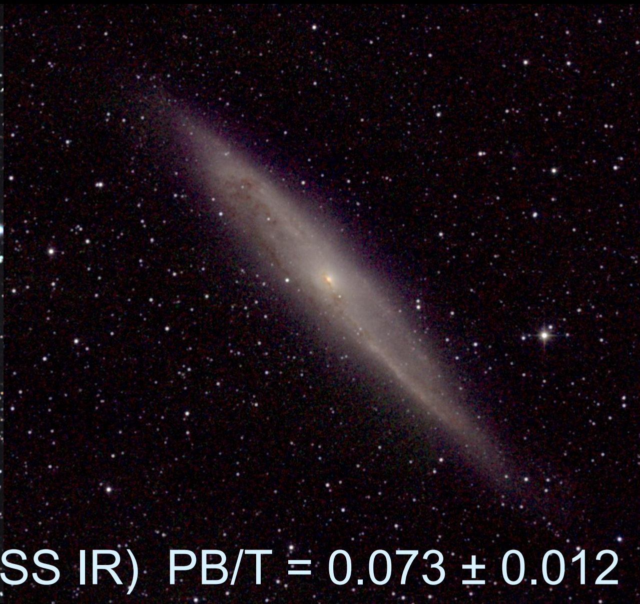


NGC 6946 PB/T = 0.024 ± 0.003

(Kormendy, Drory, Bender, & Cornell 2010, ApJ, 723, 54)



IC 342 PB/T = 0.030 ± 0.001



NGC 4945 (optical and 2MASS IR) PB/T = 0.073 ± 0.012

Giant (V_{circ} > 150 km s^{-1}) Galaxies With Distance < 8 Mpc

Kormendy, Drory, Bender, & Cornell 2010, ApJ, 723, 54

Note: 11 of 19 giant field galaxies with D < 8 Mpc have B/T = 0
(one of these is our Milky Way – it had a very gentle assembly history) ;

4 of 19 have B/T ≤ 0.12 ;

2 of 19 have B/T ~ 1/3 (M31 + M81),

and

only 2 of 19 are ellipticals (Maffei 1 + Centaurus A).

Most giant (V_{circ} > 150 km s^{-1}) galaxies in the local field contain little or no classical bulge = remnant of a major merger.
But in the Virgo cluster, > 2/3 of all stars are in bulges + ellipticals.

Fundamental Question for CDM
and
Hierarchical Clustering:

How did so many bulgeless disks form
<u>in field environments</u>?

Note:

The correct trick is <u>not</u> to use feedback to delay star formation until the halo is built.

Because the <u>thin</u> disk of our Galaxy contains stars that are
at least ~ 9-10 billion years old (from white dwarf cooling).

Correct answer must (I think) involve environment in a fundamental way.
Perhaps: Difference in assembly history – relatively smooth (unlumpy) accretion?