Composite Bulges: The Coexistence of Classical Bulges and Pseudobulges

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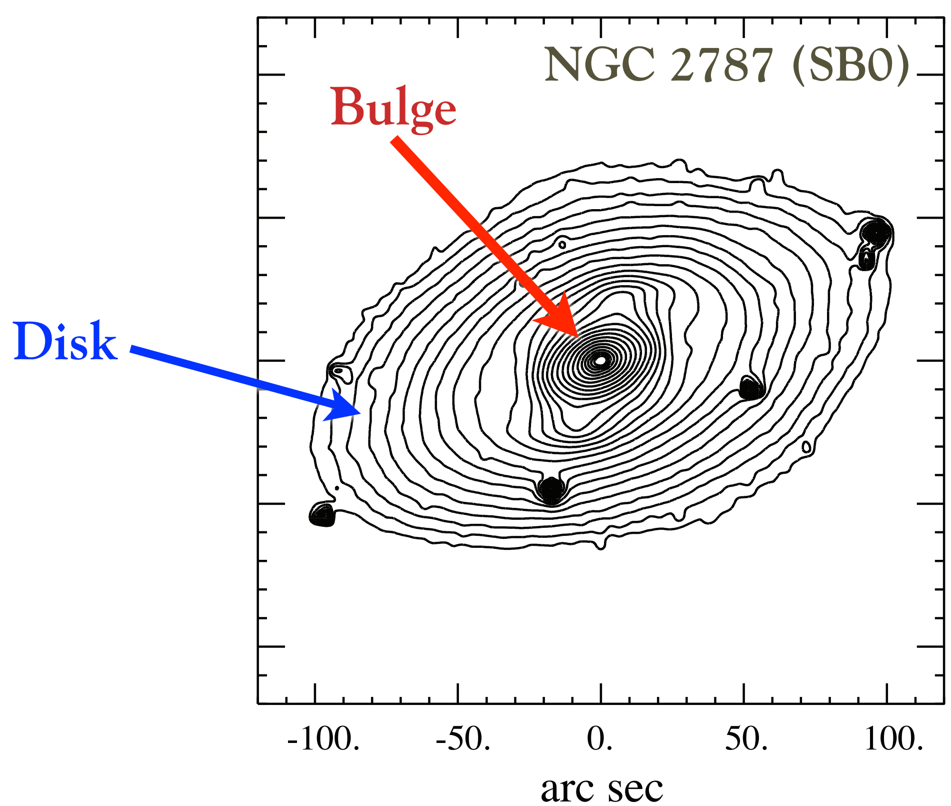
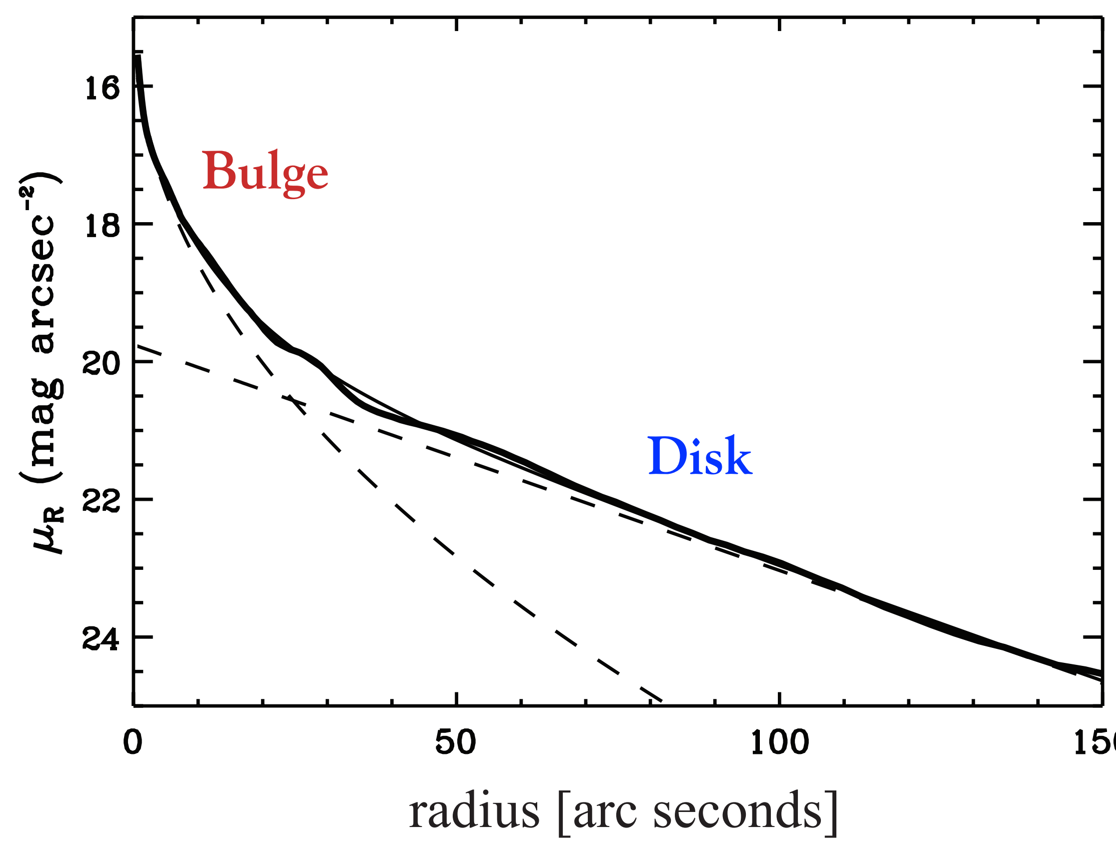
Bulges in Disk Galaxies: The Traditional Picture

The Main (Stellar) Components of Disk Galaxies

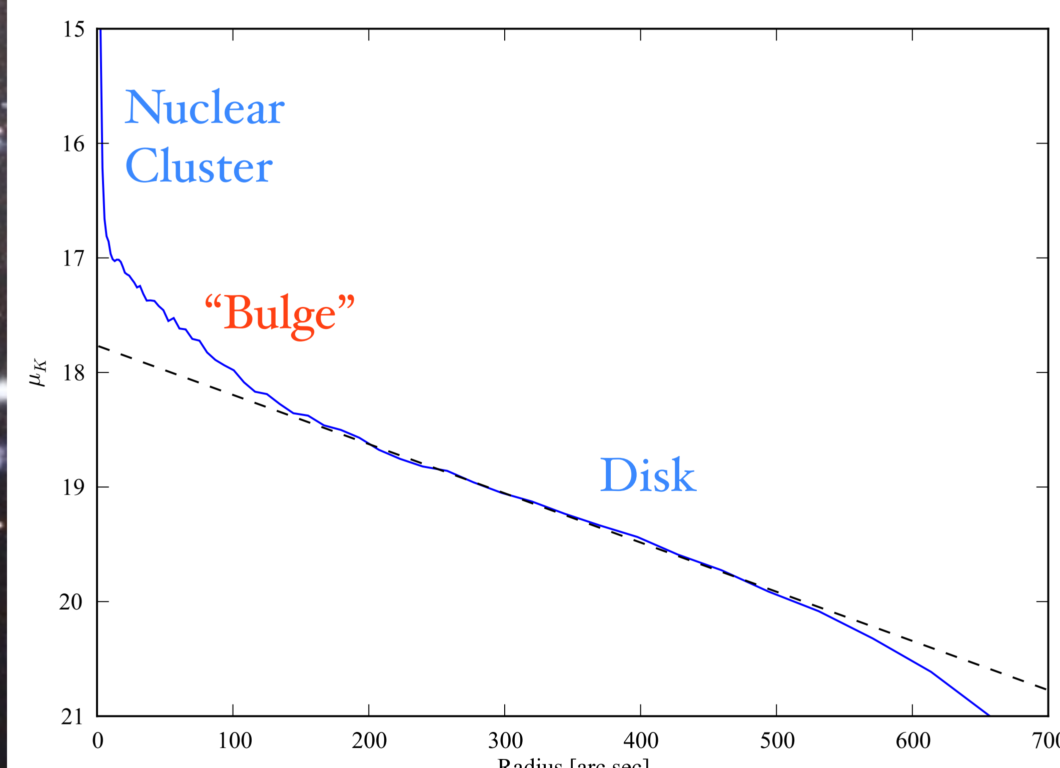
- **Disk** — round & flat, exponential profile, young + old stars, gas, dust
  - Kinematically cool (stars in ordered, nearly circular motion)
- **Central Spheroid ("Bulge")** — spheroidal or mildly triaxial, old stars with de Vaucouleurs $R^{1/4}$ (or Sérsic $R^{1/n}$) surface-brightness profile. Forms via early mergers.
  - Kinematically hot (some rotation, but dominated by random motions)
  - Bulge assumed to be visible as excess light in inner part of galaxy — **"photometric bulge"** — over & above disk light





But not all “bulges” look like small elliptical galaxies

M33: inner few hundred pc = spiral arms, star formation, flattened isophotes, rapid rotation — just like rest of disk!



(2MASS Large Galaxy Atlas *K*-band profile)

So some “bulges” may be “pseudobulges”...

- Kormendy (1982, 1993): some “bulges” are disk-like (e.g. Kormendy & Kennicutt 2004 and references therein):
  - Exponential or near-exponential SB profiles
  - Younger stellar populations (more like disk stars)
  - Spirals, rings, bars, and other disk phenomena
  - Highly flattened geometry (bulges supposed to be “spheroids”)
  - Disk-like stellar kinematics — rotation dominates over velocity dispersion
- Different formation mechanism: Supposed to form via some secular evolution process from the disk (e.g., bar-driven gas inflow + central star formation), instead of mergers?

WARNING:

A Simple “Classical bulge vs. Pseudobulge” Dichotomy Is Probably Not Be the Whole Picture!

Some Working Definitions

- **Photometric bulge:** Excess light in center of galaxy, above the outer exponential. (Standard assumption behind "bulge-disk" decompositions.)

- **Classical bulge:** *Spheroidal* (or weakly triaxial) and *kinematically hot* — like a low-luminosity elliptical galaxy, surrounded by a disk. (Probably from mergers, but I'll ignore speculations about formation.)

- **(Disky) Pseudobulge:** When the photometric bulge region appears to be morphologically and kinematically *disklike*:

  - *Morphology*: geometrically thin like a disk or clearly dominated by disky structures (nuclear rings, spirals, bars, etc.)

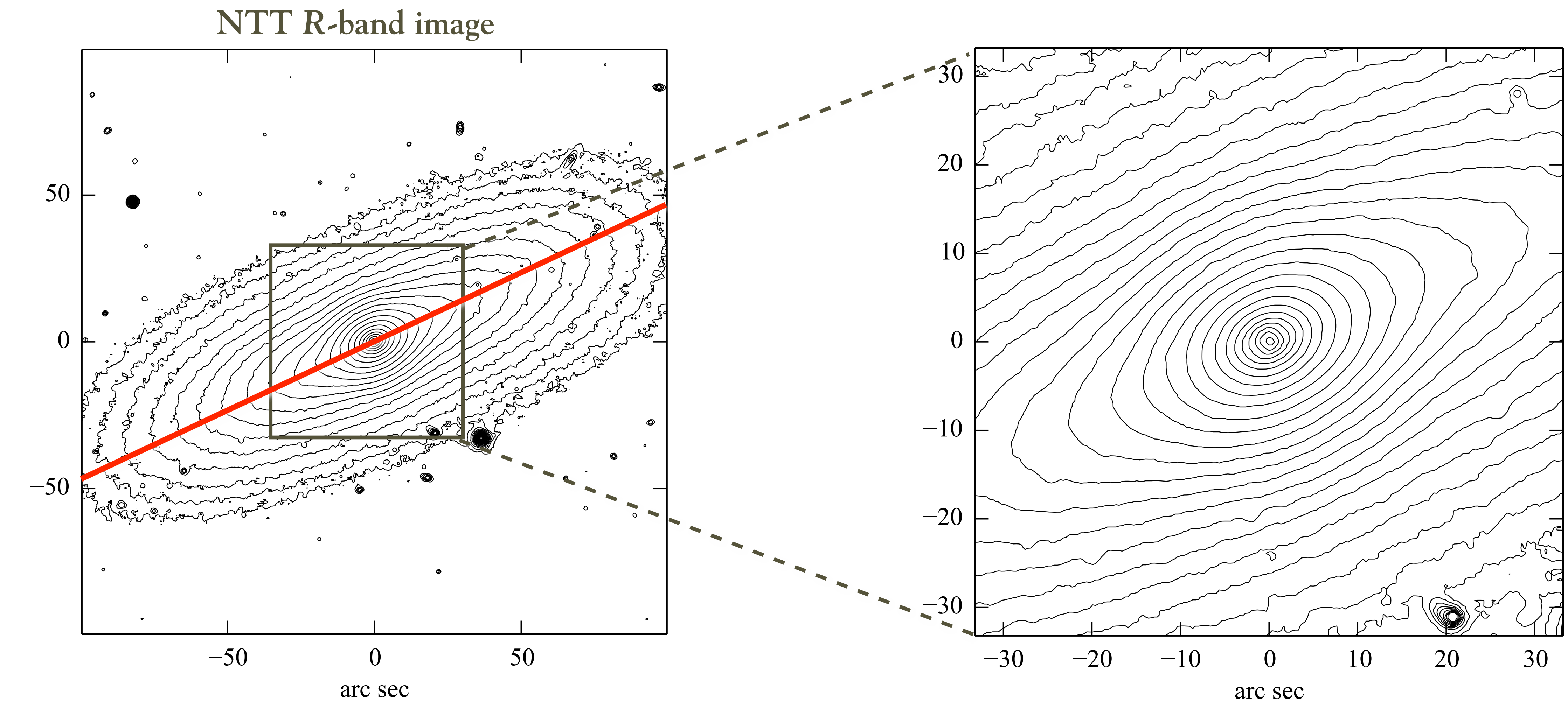
  - *Stellar Kinematics*: dominance of rotation over velocity dispersion

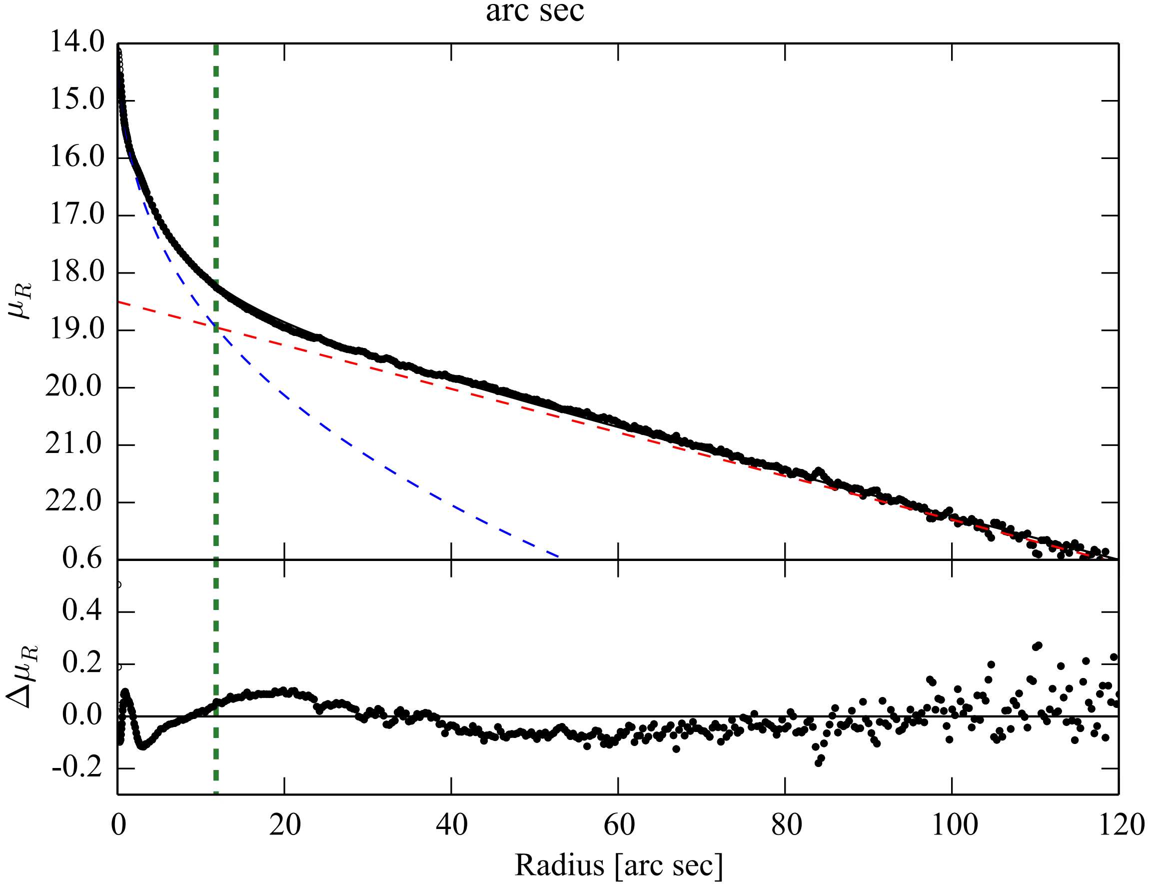
  - (Things I'm agnostic about: dust and star formation, color, Sérsic index)

  - (Things I'm mostly ignoring: box/peanut structures in bars)

Let's start with a simple case:
Disk + classical bulge

NGC 1332: SA0 with Classical Bulge





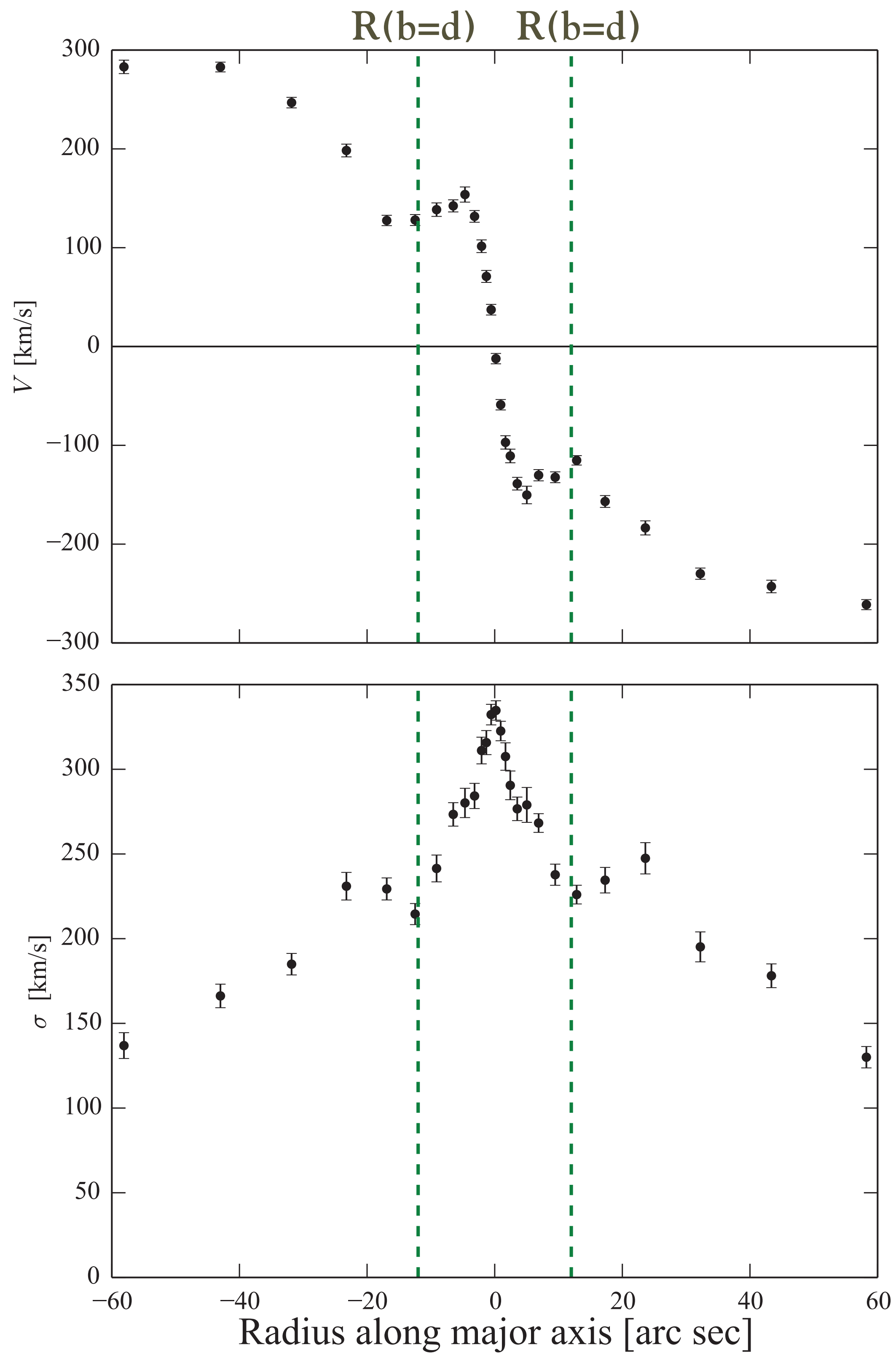
Isophotes become rounder in center: consistent with rounder structure embedded in disk

Bulge-disk Decomposition (Sérsic + exponential functions):
B/T = 0.43

R(b=d) = 12 arcsec (1300 pc)
"Photometric bulge region"

Major-axis Stellar Kinematics: Kinematically Hot Bulge

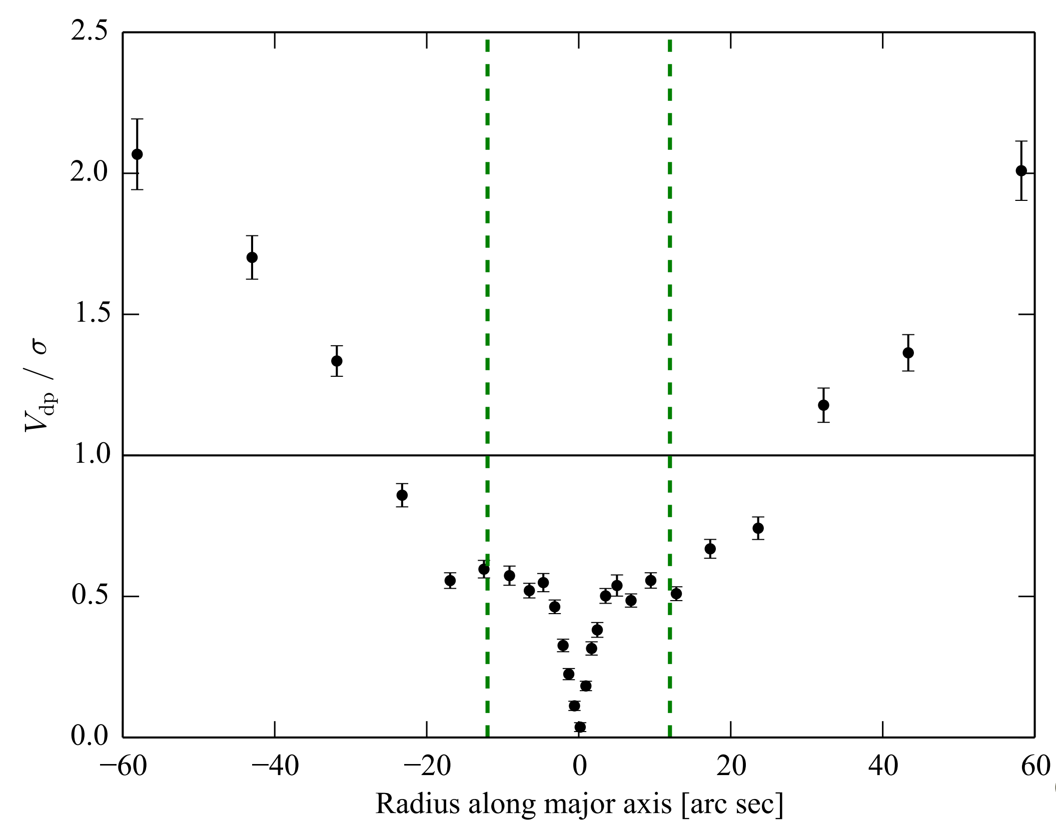
Major-axis spectroscopy (Rusli+2011)



Ratio of in-plane velocity to dispersion:

Deproject observed V_{rot} to in-plane value (V_{dp}), divide by velocity dispersion
= Local measure of relative importance of rotation vs. pressure support

$V_{dp}/\sigma < 1$ within photometric-bulge region ⇒
Bulge of NGC 1322 is *kinematically hot*



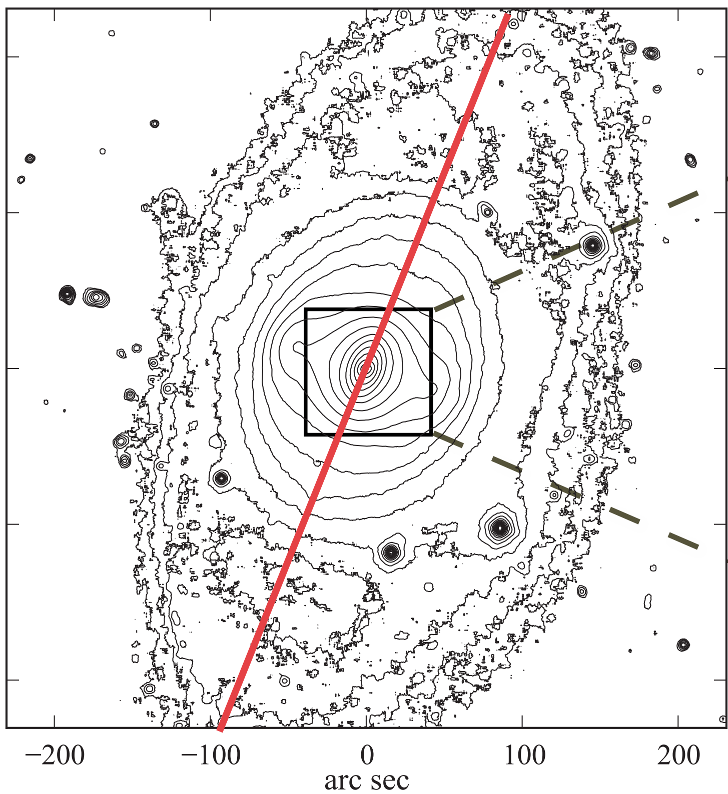
That was too easy—let’s get more complicated…

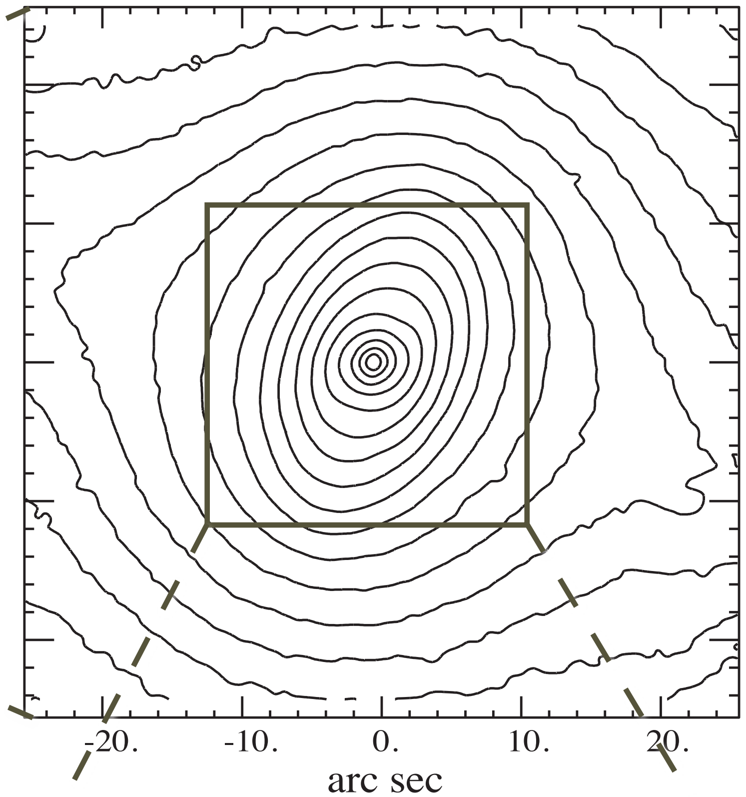
NGC 3945 and NGC 4371: S0 Galaxies with Multiple "Bulges"


NGC 3945 (SDSS)

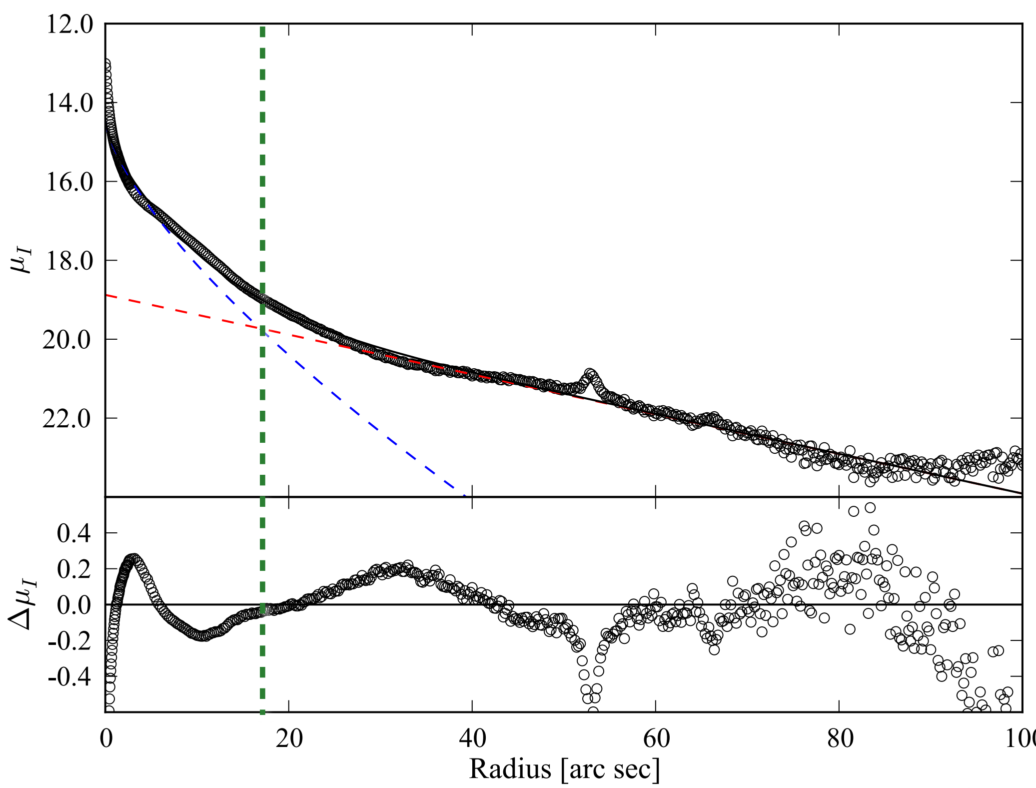

NGC 4371 (SDSS)

NGC 3945: Photometric Bulge is Flattened

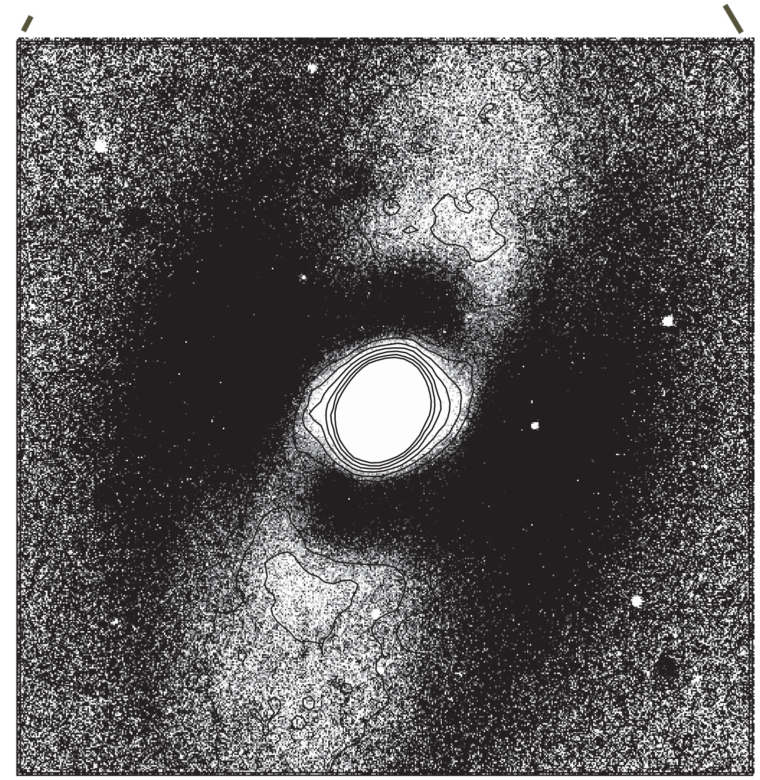




"Bulge" isophotes very elliptical (similar to outer disk)



Photometric bulge: r < 17 arcsec (1.6 kpc)



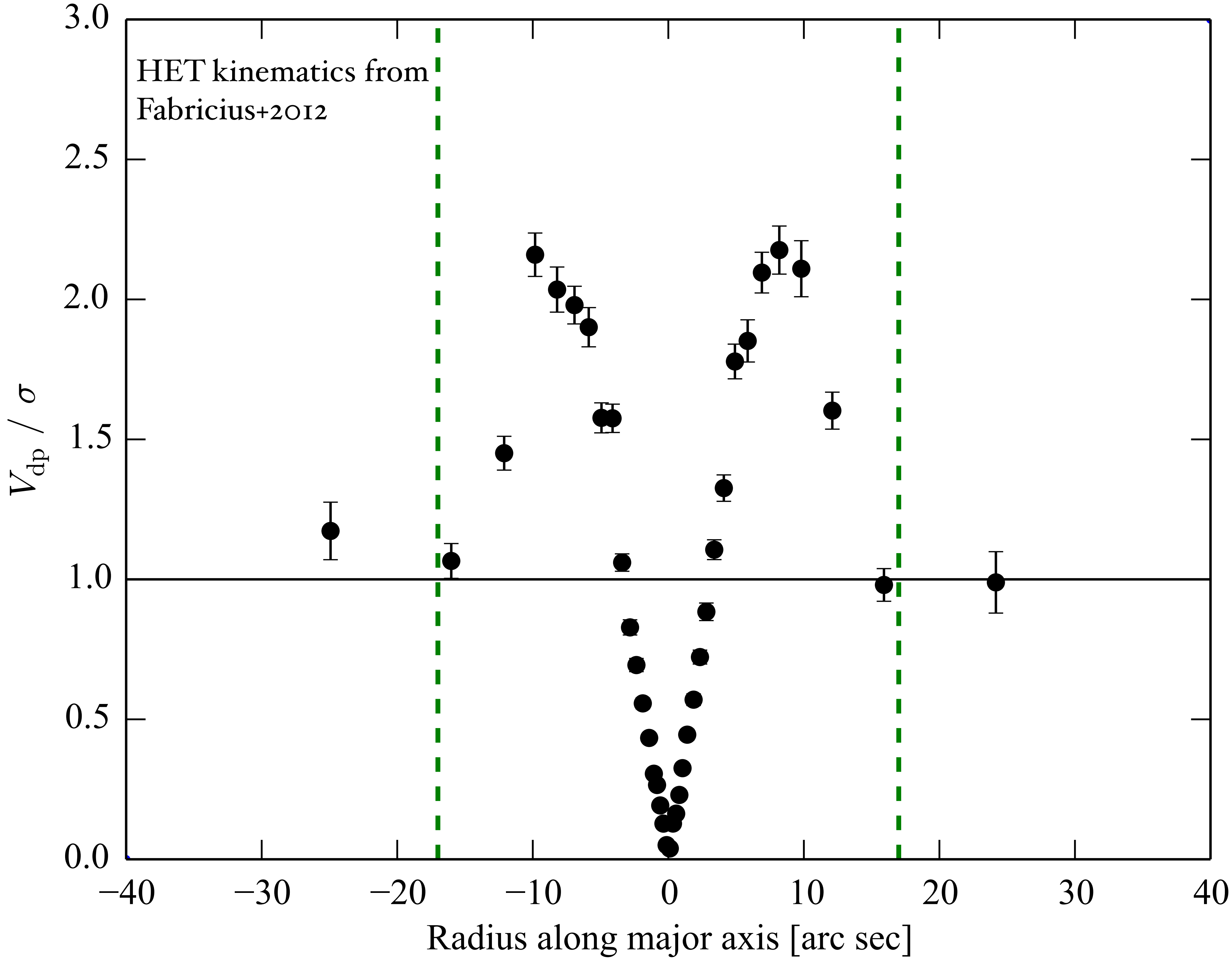
unsharp mask

Partial nuclear ring + inner (nuclear) bar

Photometric bulge has same flattening as disk; disky substructure (nuclear bar + ring)

Pseudobulge?

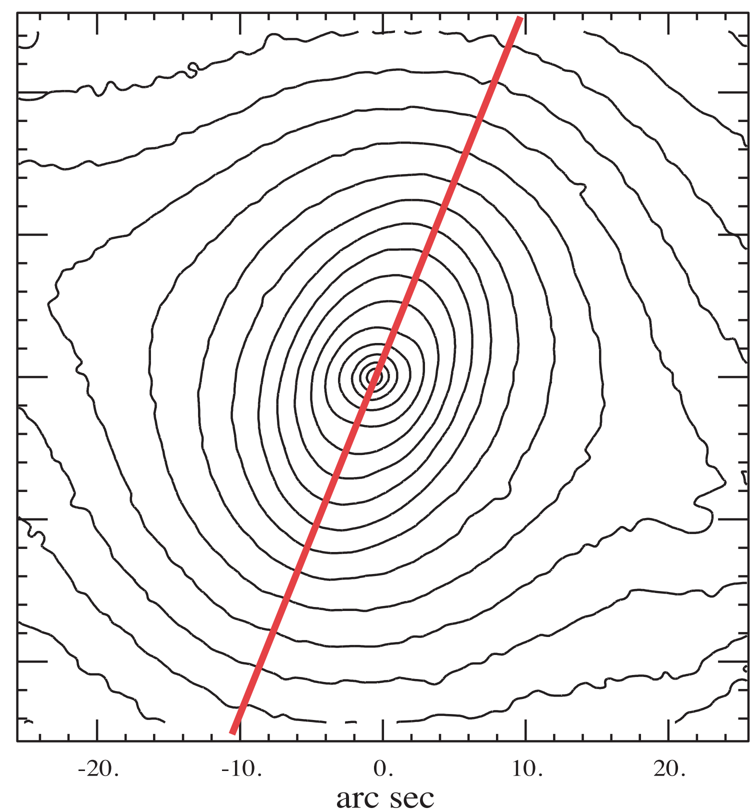
NGC 3945: Kinematics in Photometric Bulge

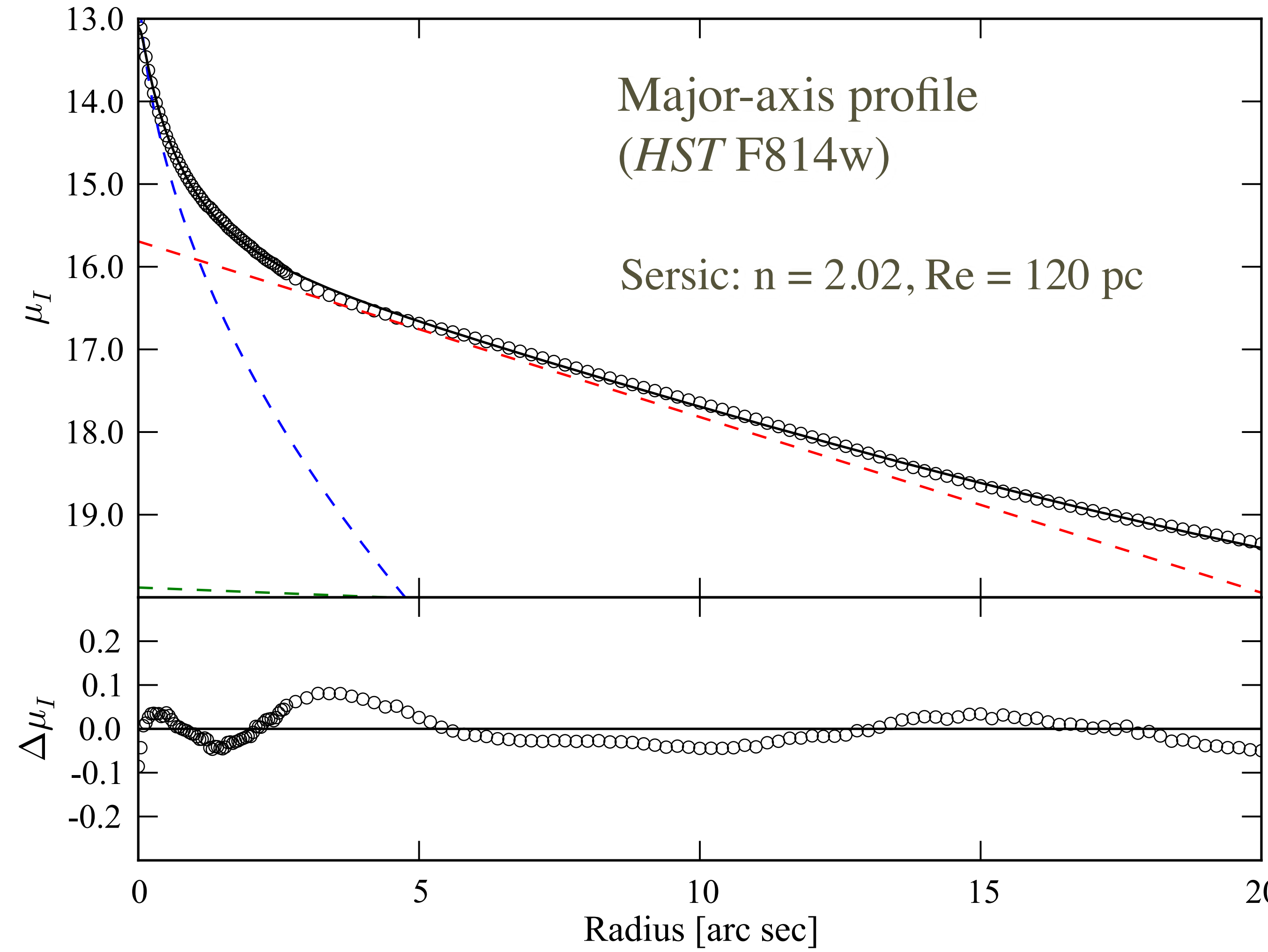


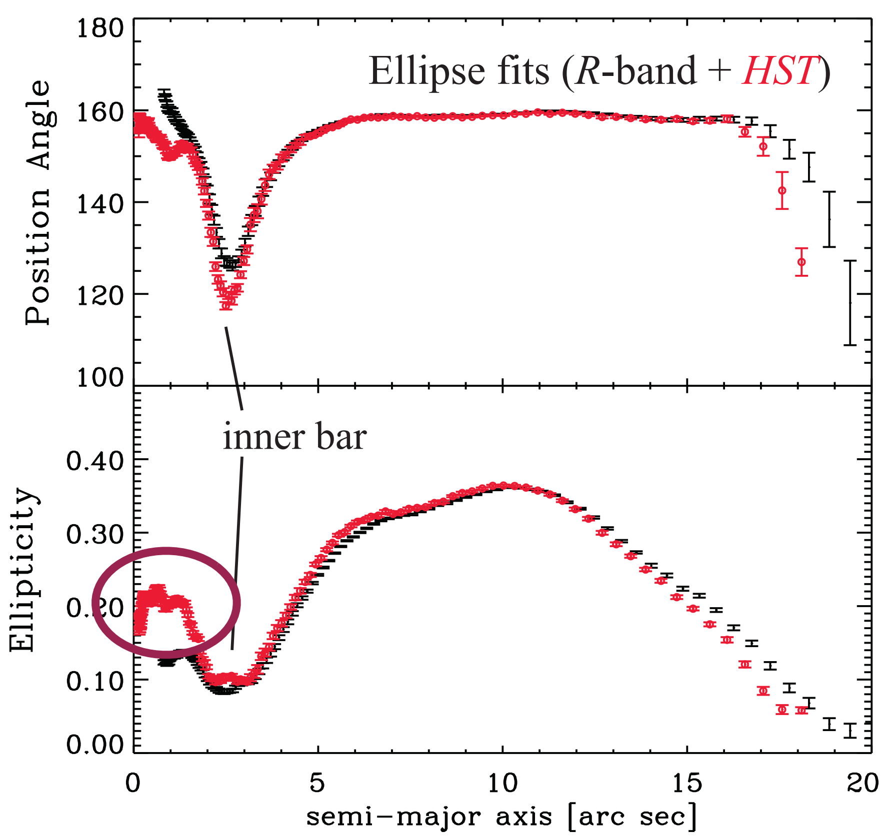
V_{dp}/σ rises to > 2 in photometric bulge region: kinematically cool, *not* a classical bulge!

But wait — there's more!

NGC 3945: Inner Morphology





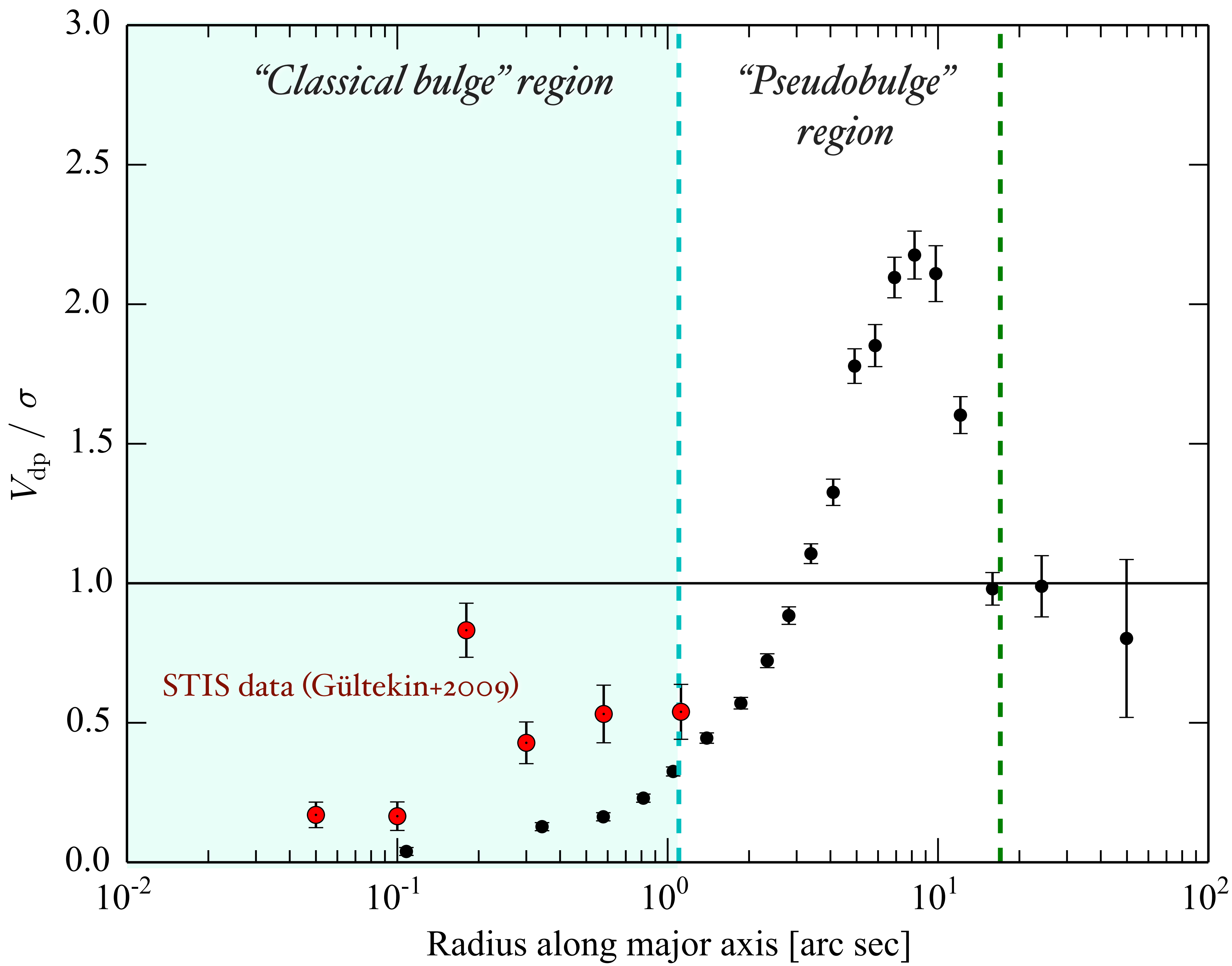


Rounder isophotes (ell = 0.2) inside disky/ring isophotes (ell = 0.35): **r < 1.5 arcsec**

Central photometric excess:
B/D decomposition ⇒ Sérsic component dominates for **r < 1 arcsec**

What are the kinematics of this inner region?

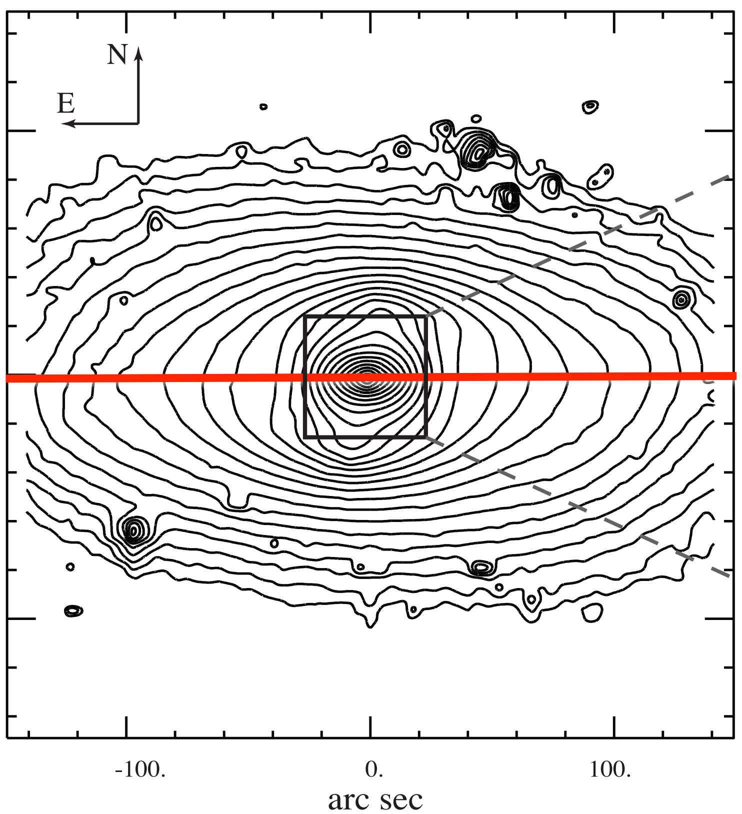
Kinematics of the Central Region

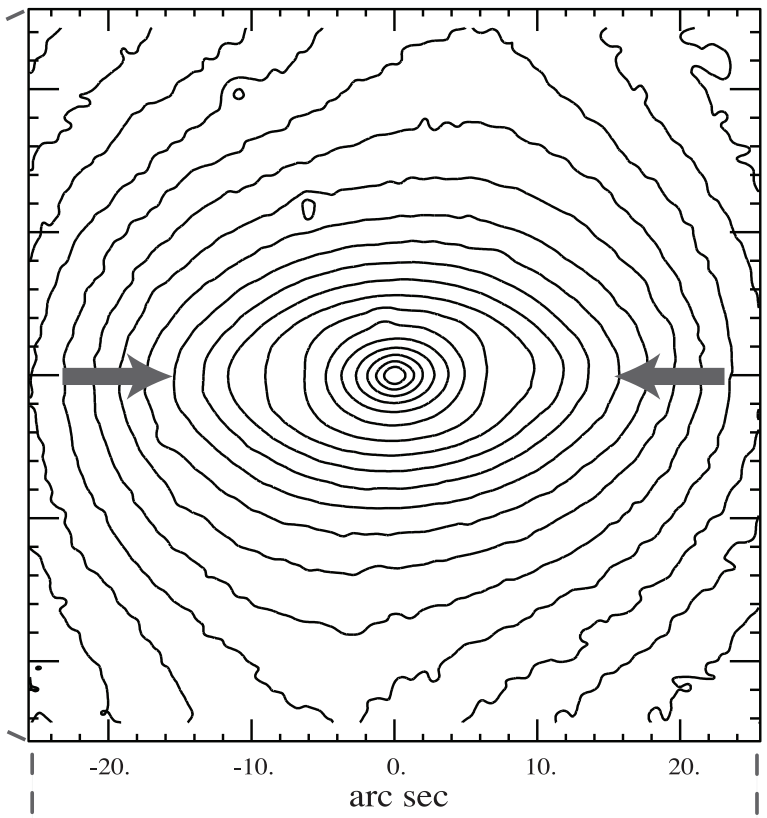


$V_{dp}/\sigma < 1$ in central bulge region: kinematically hot!

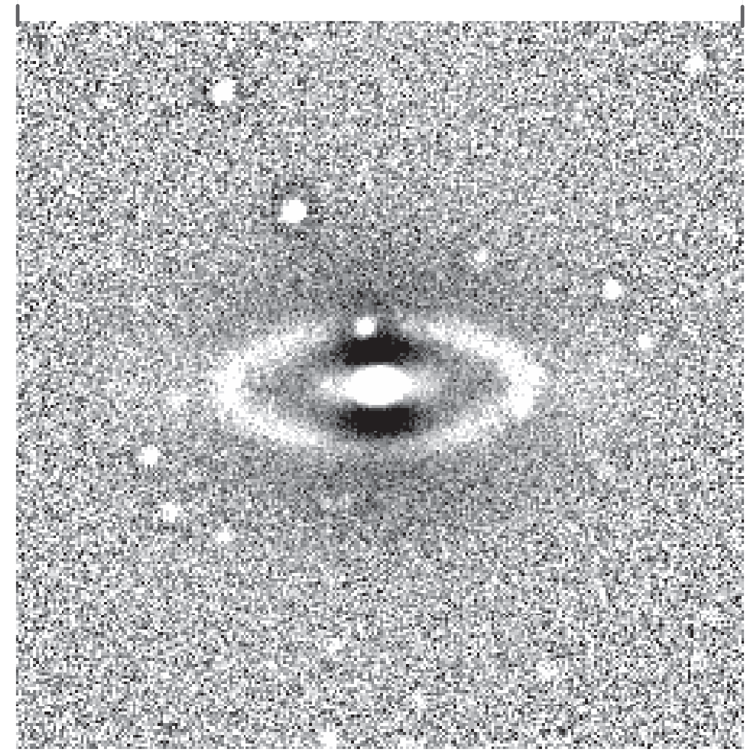
NGC 4371: Photometric Bulge is Flattened

R-band contours





"Bulge" isophotes very elliptical (similar to outer disk)

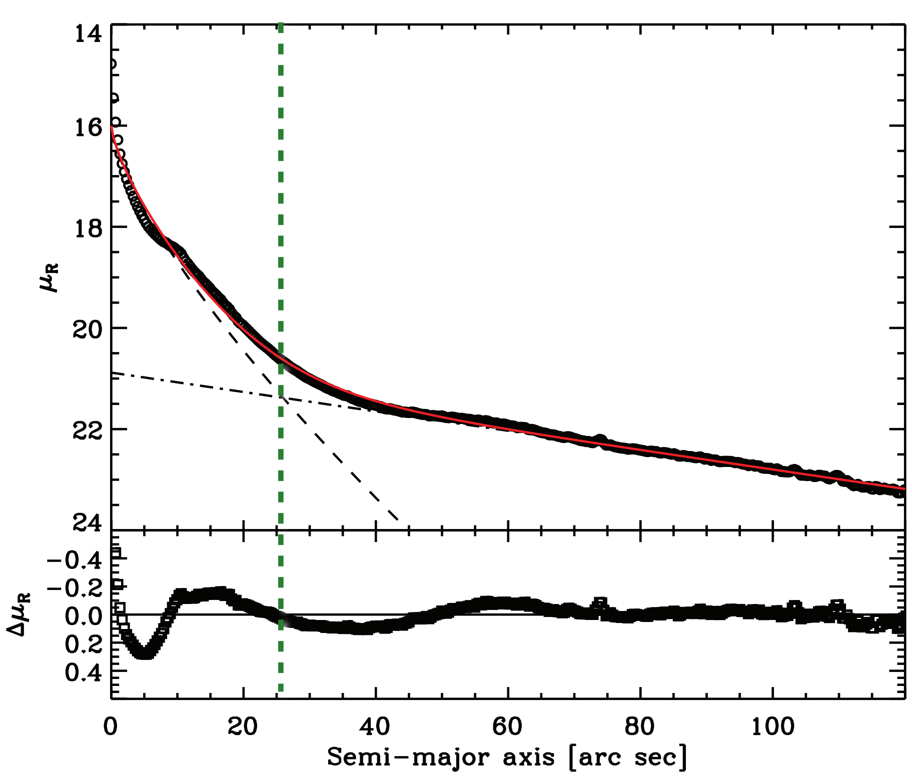


unsharp mask

Nuclear ring with r = 10″ (750 pc)
Slightly blue, no dust
= mix of young & old stars

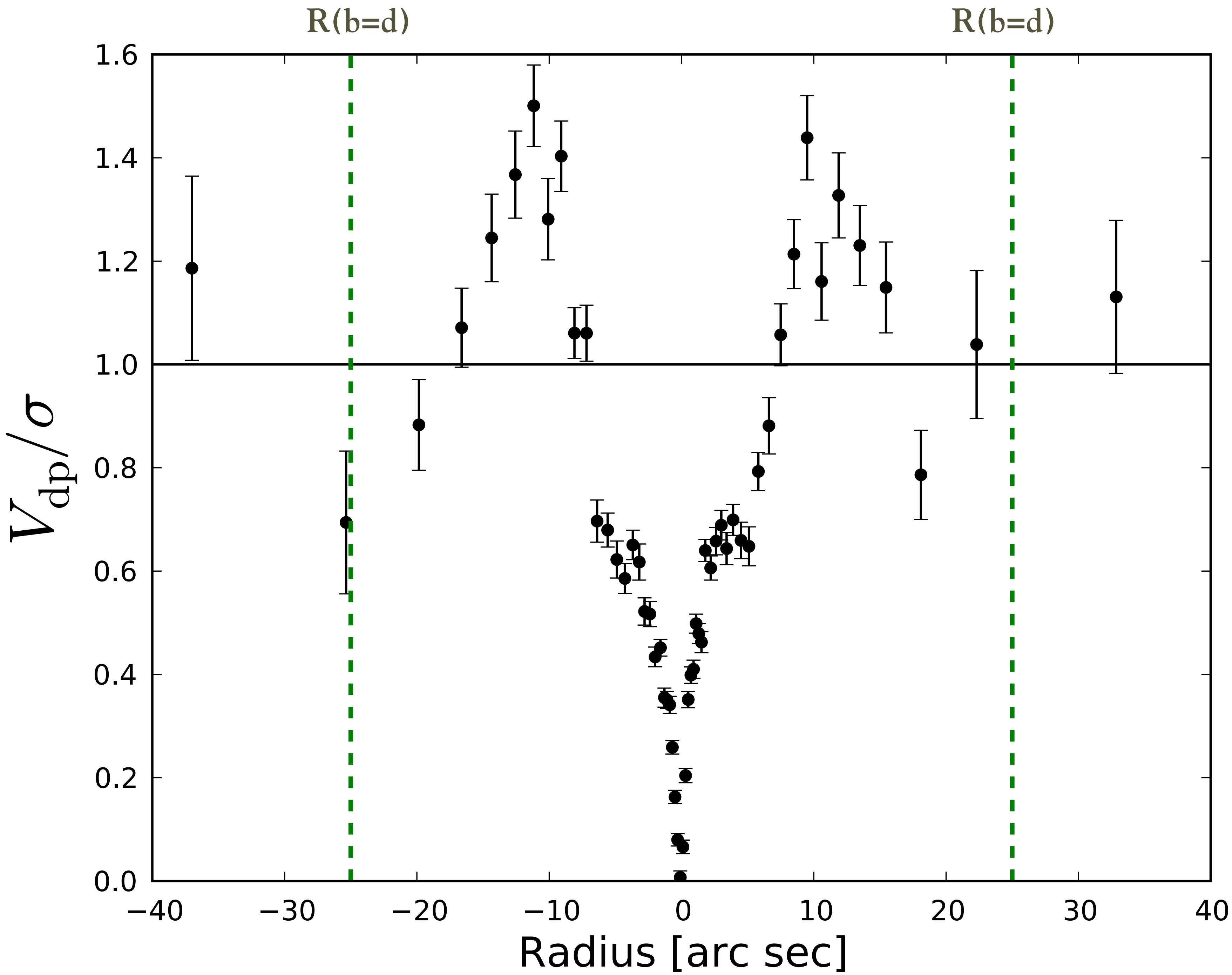
Photometric bulge has same flattening as disk; disky substructure (nuclear ring)

Pseudobulge?



Photometric bulge = inner 25 arcsec [2.1 kpc]

Stellar Kinematics in Photometric Bulge

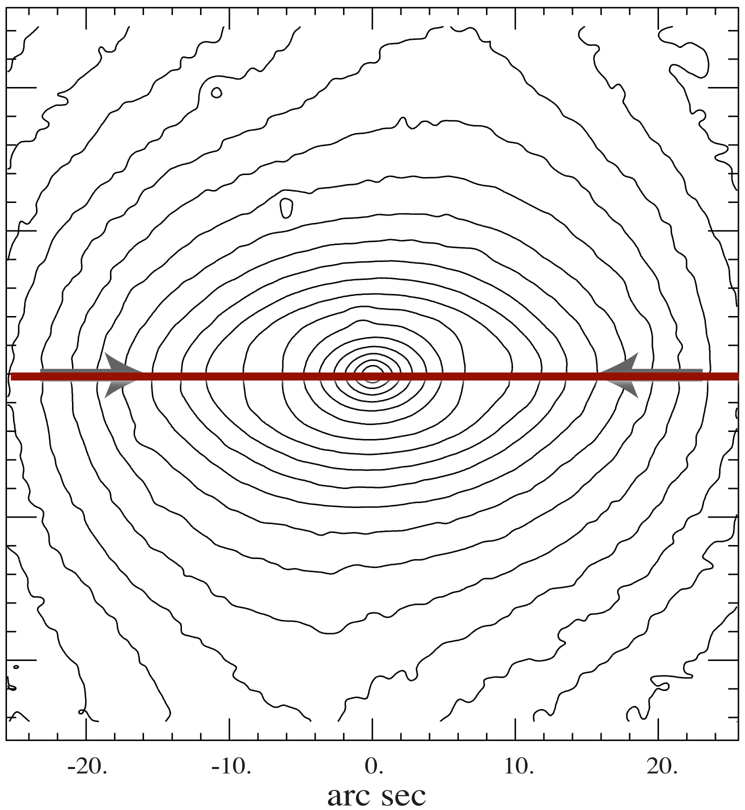


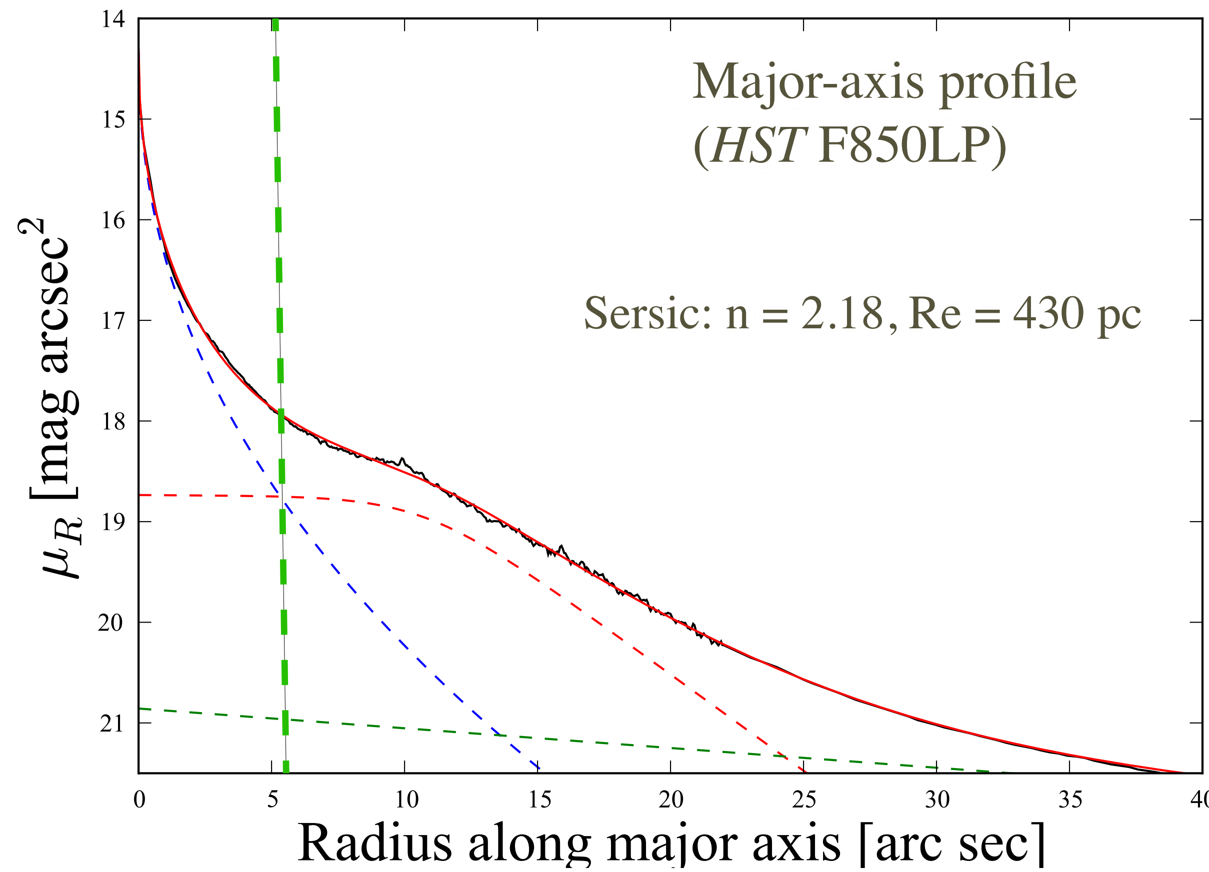
Major-axis spectroscopy (WHT-ISIS)

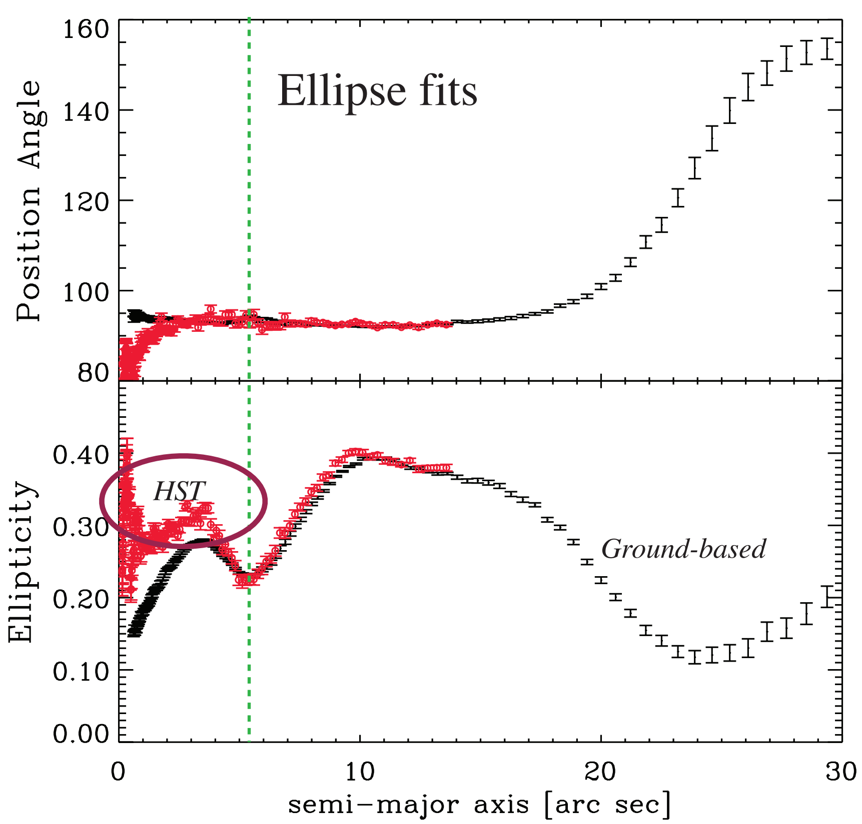
V_{dp}/σ rises to ~ 1.5 in photometric bulge region.
Again, kinematically cool, *not* a classical bulge!

(Yes, there's more ...)

Central (rounder) structure inside pseudobulge!







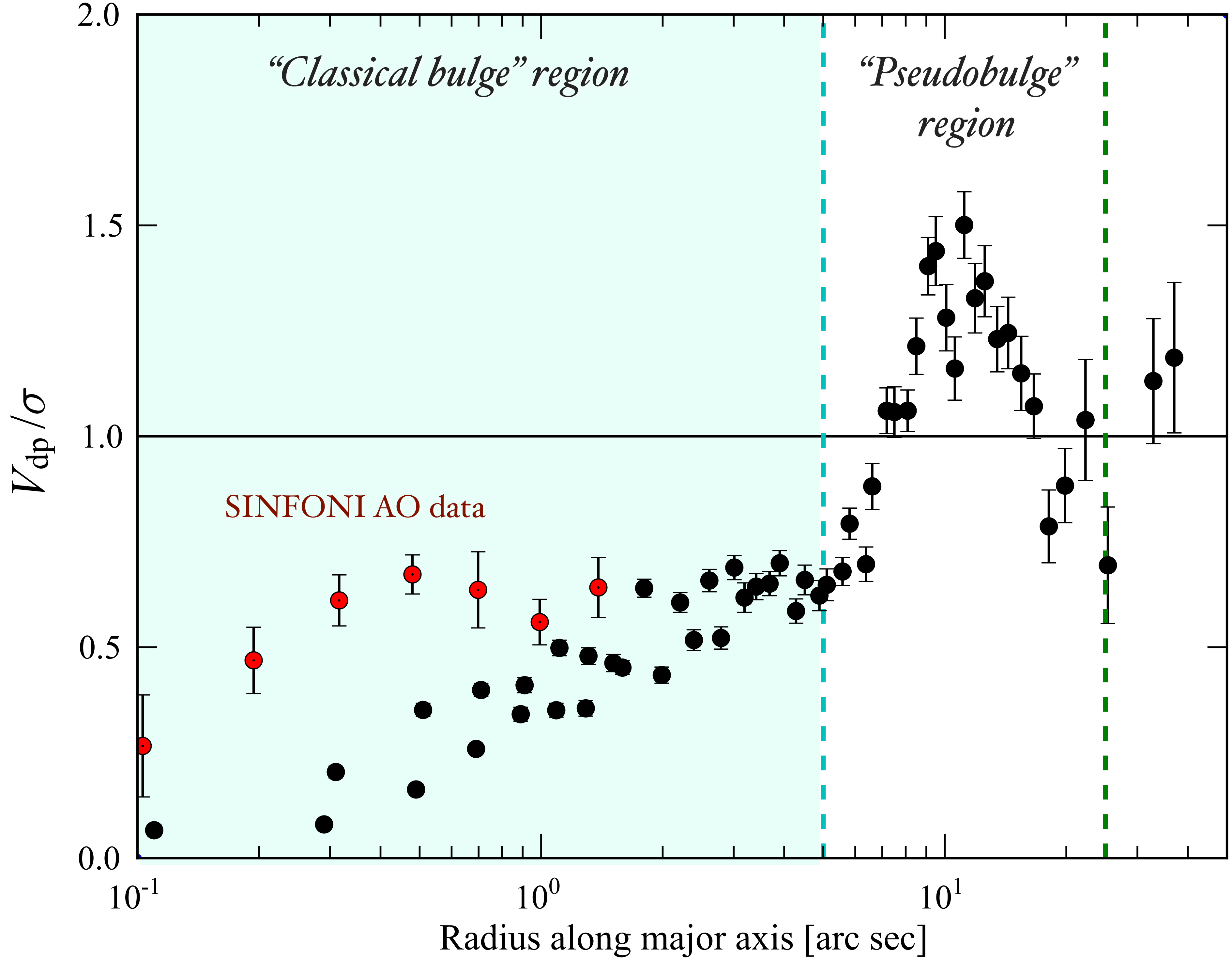
Rounder isophotes (ell = 0.3) inside disky/ring isophotes (where ell = 0.4): r < 5 arcsec

Central photometric excess:
B/D decomposition (+ nuc.ring), with Sérsic component dominating for r < 5 arcsec

Like a small classical bulge inside the pseudobulge…

What are the kinematics of the central 5 arcsec?

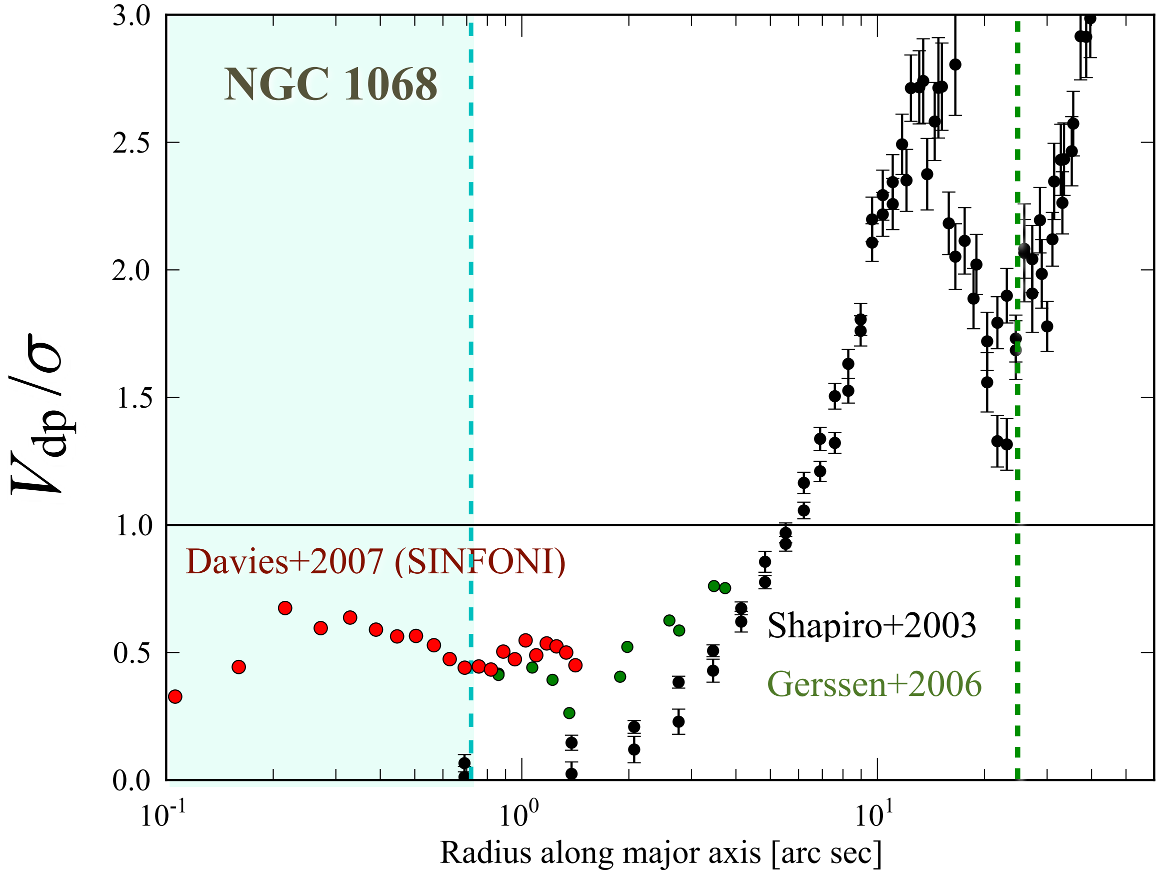
Kinematics of the Central Region

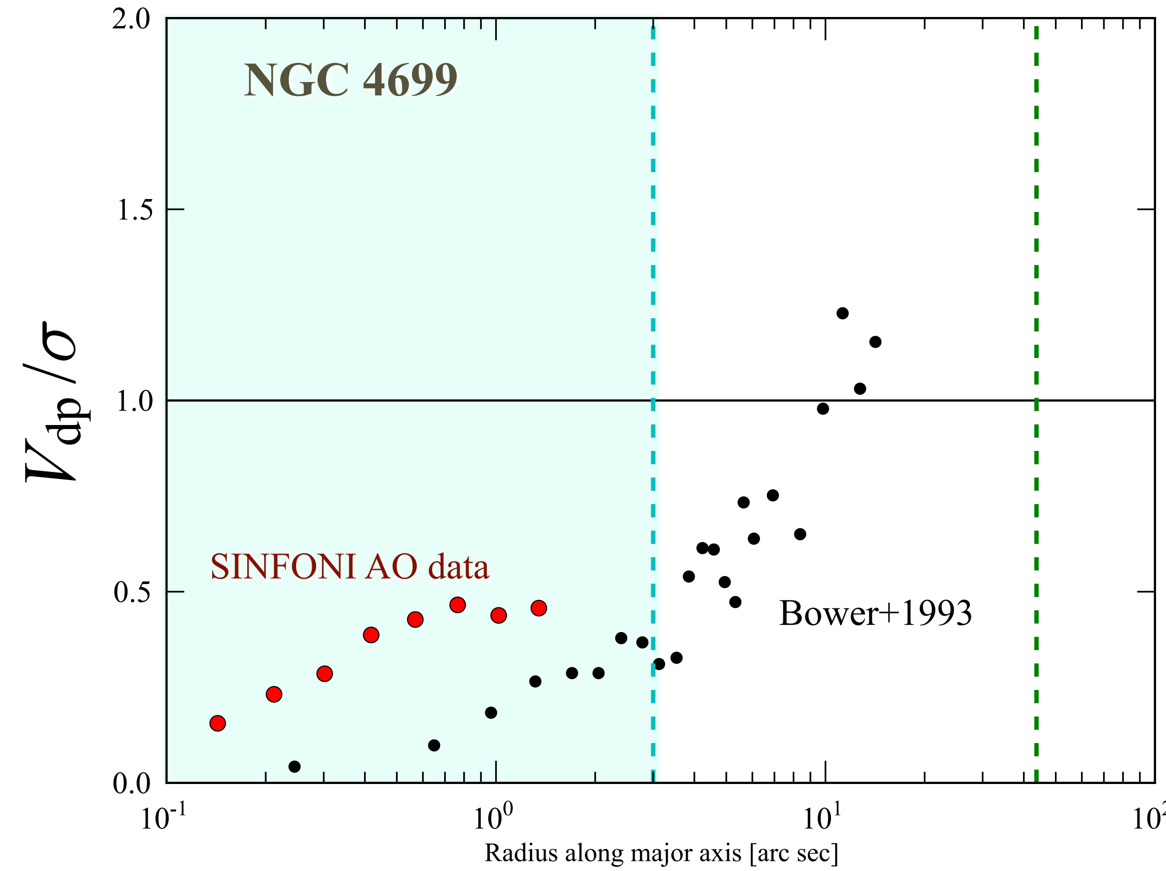


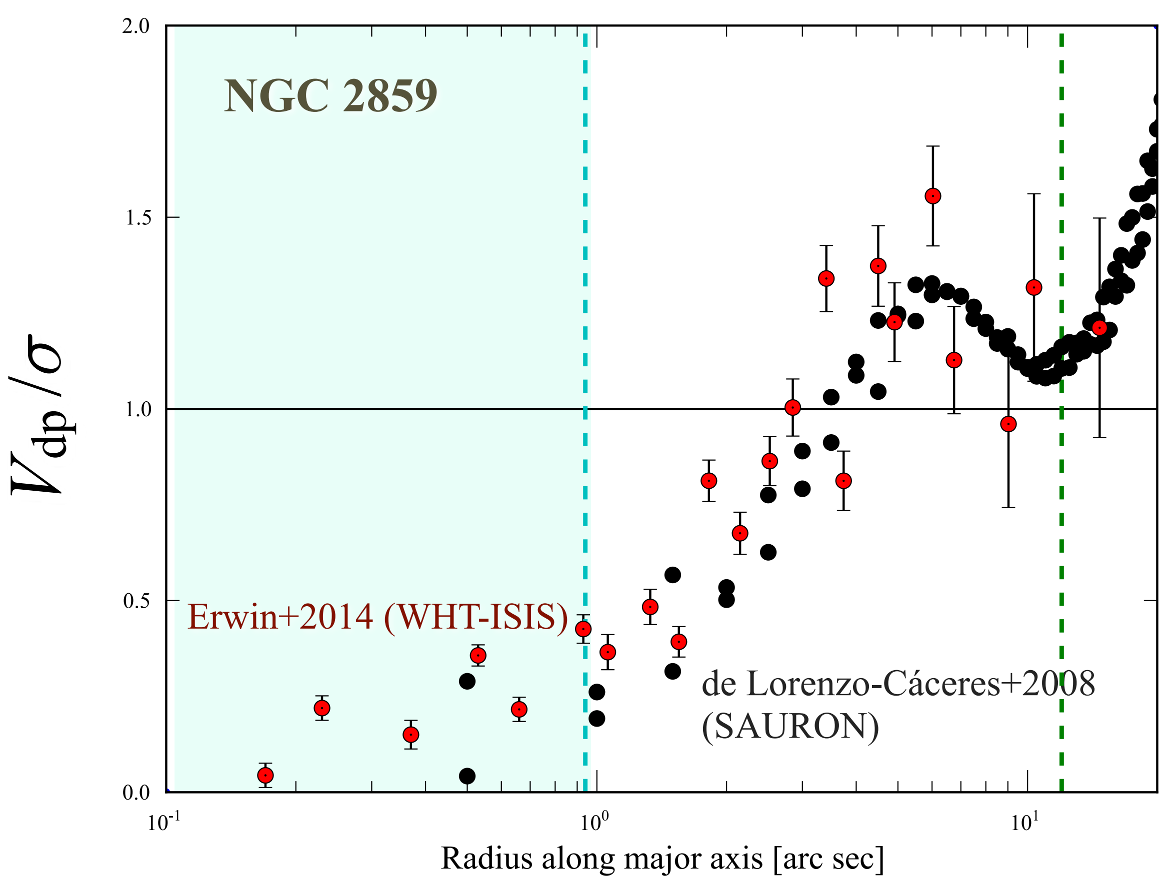
Central region (r < 5 arcsec):

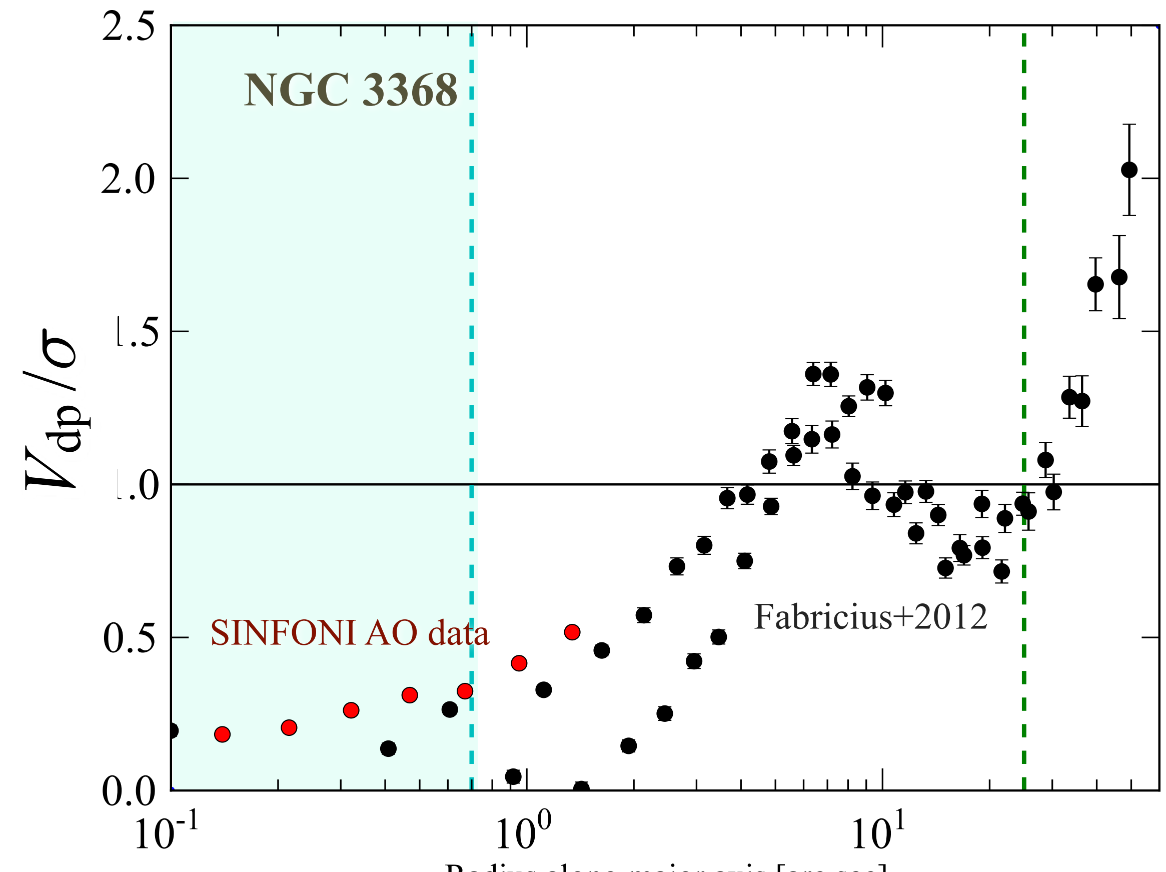
V_{dp}/σ inner plateau, clearly < 1: kinematically hot!

Other Examples: NGC 1068, 2859, 3368, and 4699





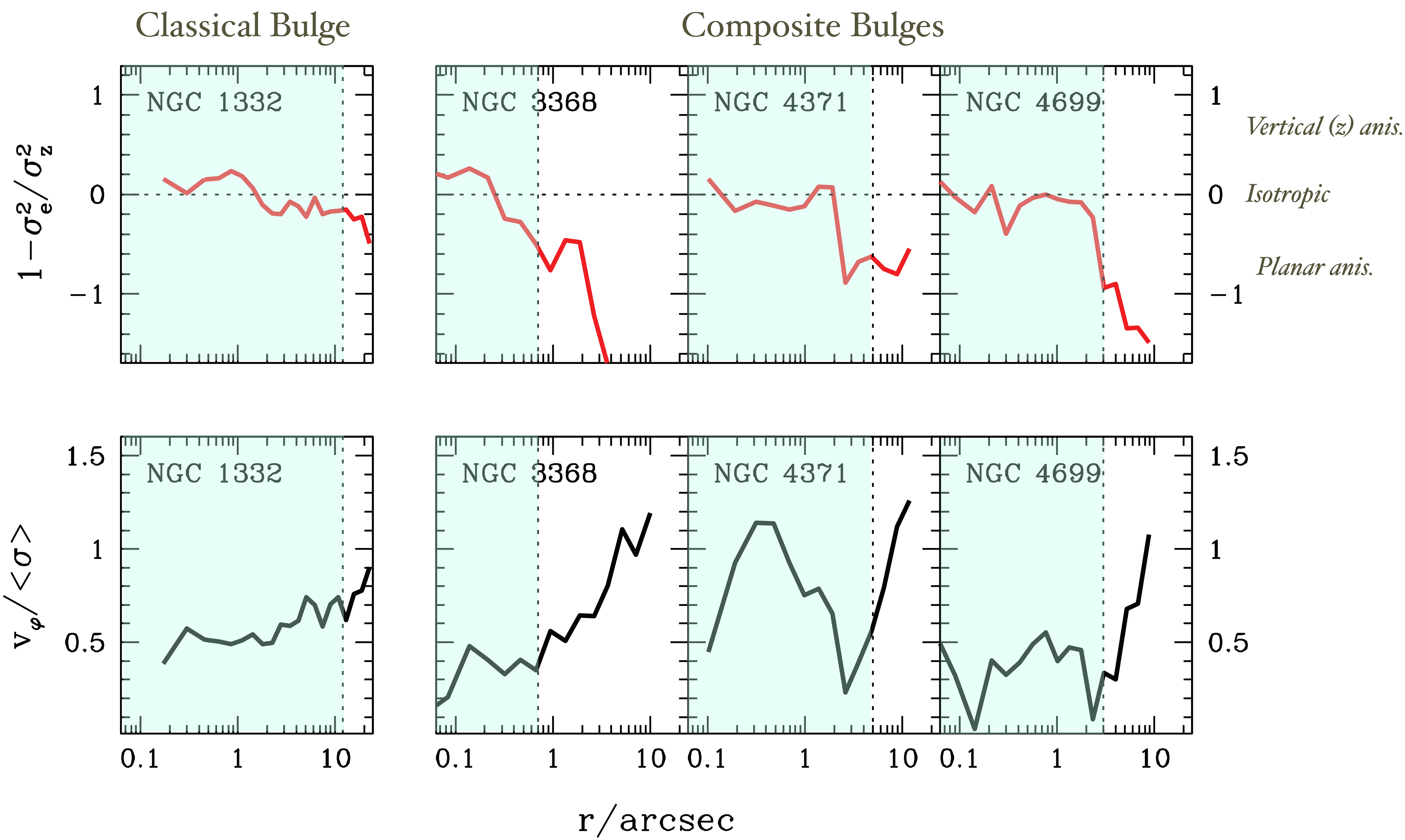




Dynamical Modeling

- For 3 of these composite-bulge galaxies (+ NGC 1332), we have SINFONI AO data
- Dynamical modeling to get SMBH masses
  - Nowak+2010, Rusli+2011, Erwin+2014 (in prep)
- Gives us stellar orbital structure as a byproduct
- What do our models tell us about the stellar kinematics in these structures?

Stellar Dynamics from Schwarzschild Modeling of SINFONI Data



Classical bulges are isotropic; disky pseudobulges are anisotropic (as expected for flattened disk)

Composite-Bulge Galaxies

- 9 clear cases (so far): NGC 1068, 1543, 1553, 2859, 3368, 3945, 4262, 4371, 4699
- Majority are S0; NGC 3368 = Sab, NGC 1068 & 4699 = Sb
- All but 1 are clearly barred
- *Not* an unbiased sample...
- ... but we can estimate a lower limit: at least 20% of barred S0 galaxies have composite bulges

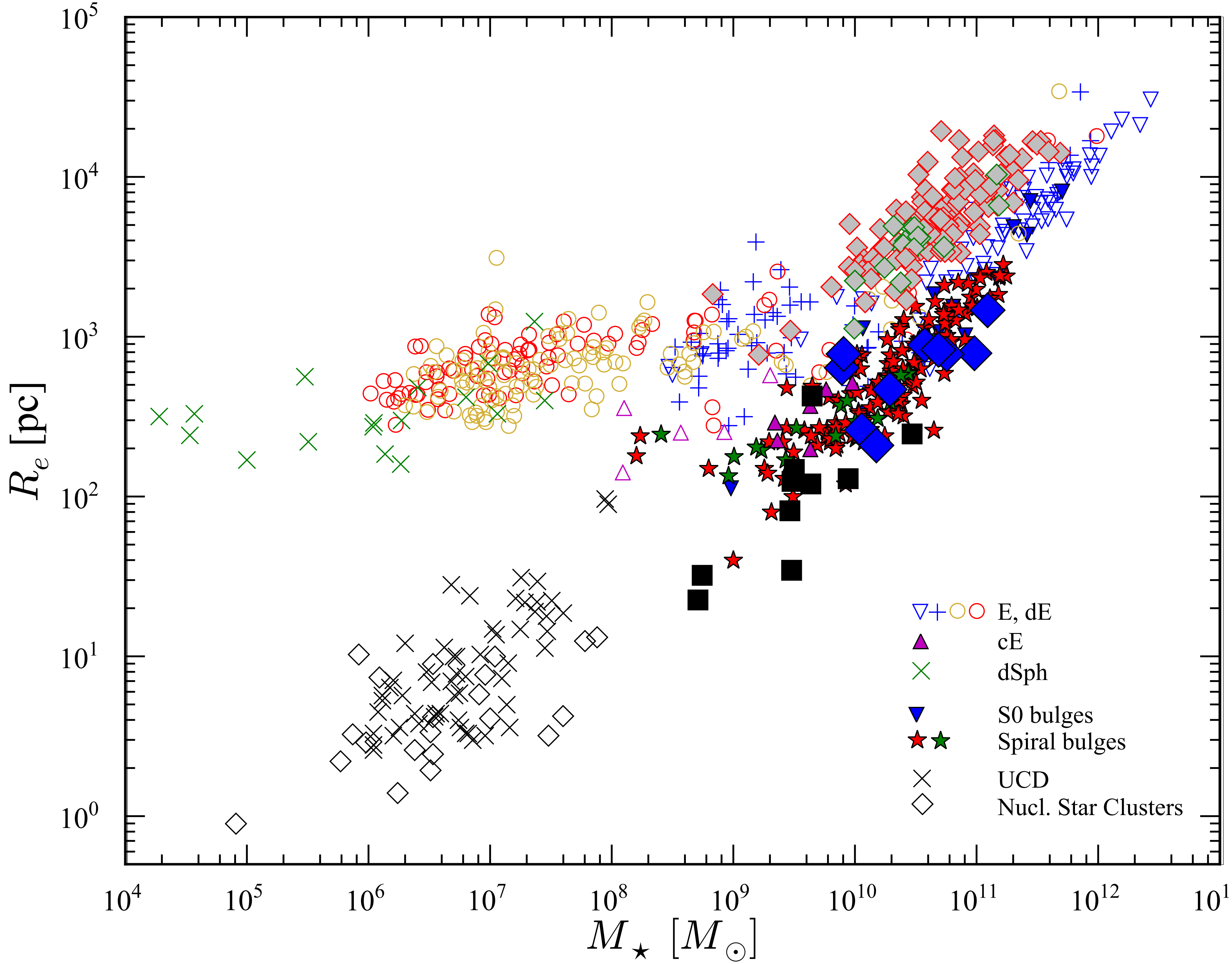
“Disky Pseudobulges”

- Typically flattened, with exponential surf.-brightness profile
  - Scale lengths 130–1300 pc (median = 550 pc)
- Kinematically “cool” (V/sigma > 1)
  - But *not* kinematically cold like outer disk (where V/sigma >> 2)
  - Planar-biased anisotropy similar to large-scale disks
- Anywhere from 40–95% of photometric bulge luminosity (i.e., usually the dominant part of the photometric bulge)
  - 11–59% of total galaxy stellar mass (mean = 33%)
- Often — but not always — has disky substructure: nuclear bar and/or ring

“Classical Bulges”

- Typically oblate (not as flat as outer disk!)
  - Sérsic profiles: n ~ 0.9–2.2 (median = 1.5)
  - Effective radii ~ 25–430 pc (median ~ 120 pc)
- Kinematically “hot”
  - V/sigma < 1
  - (But some rotation *is* present)
  - Evidence for isotropic velocity dispersion
- B/T ~ 2–20% (mean = 6% of galaxy stellar mass)

Composite-Bulge Components in Mass-Radius Plane



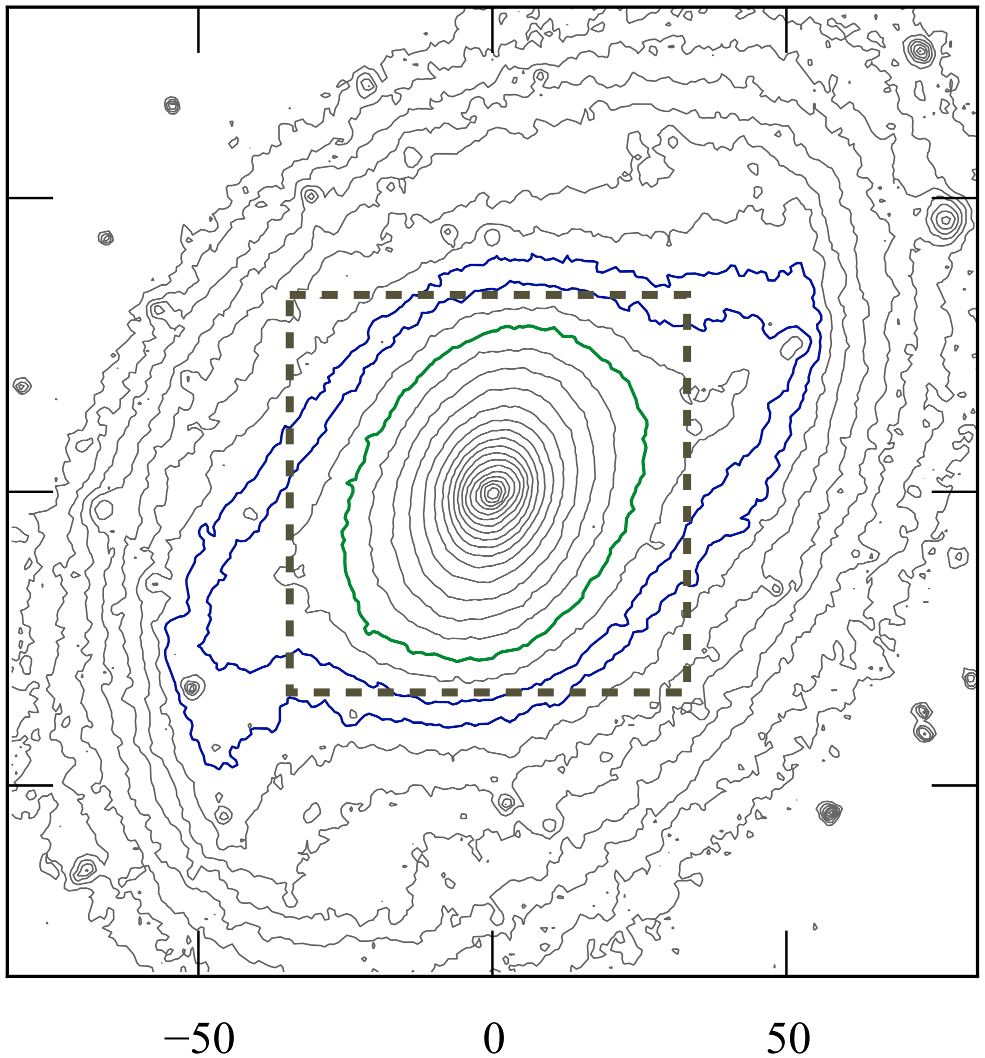
Some of these embedded "classical bulges" are rather small … Are they really nuclear star clusters?

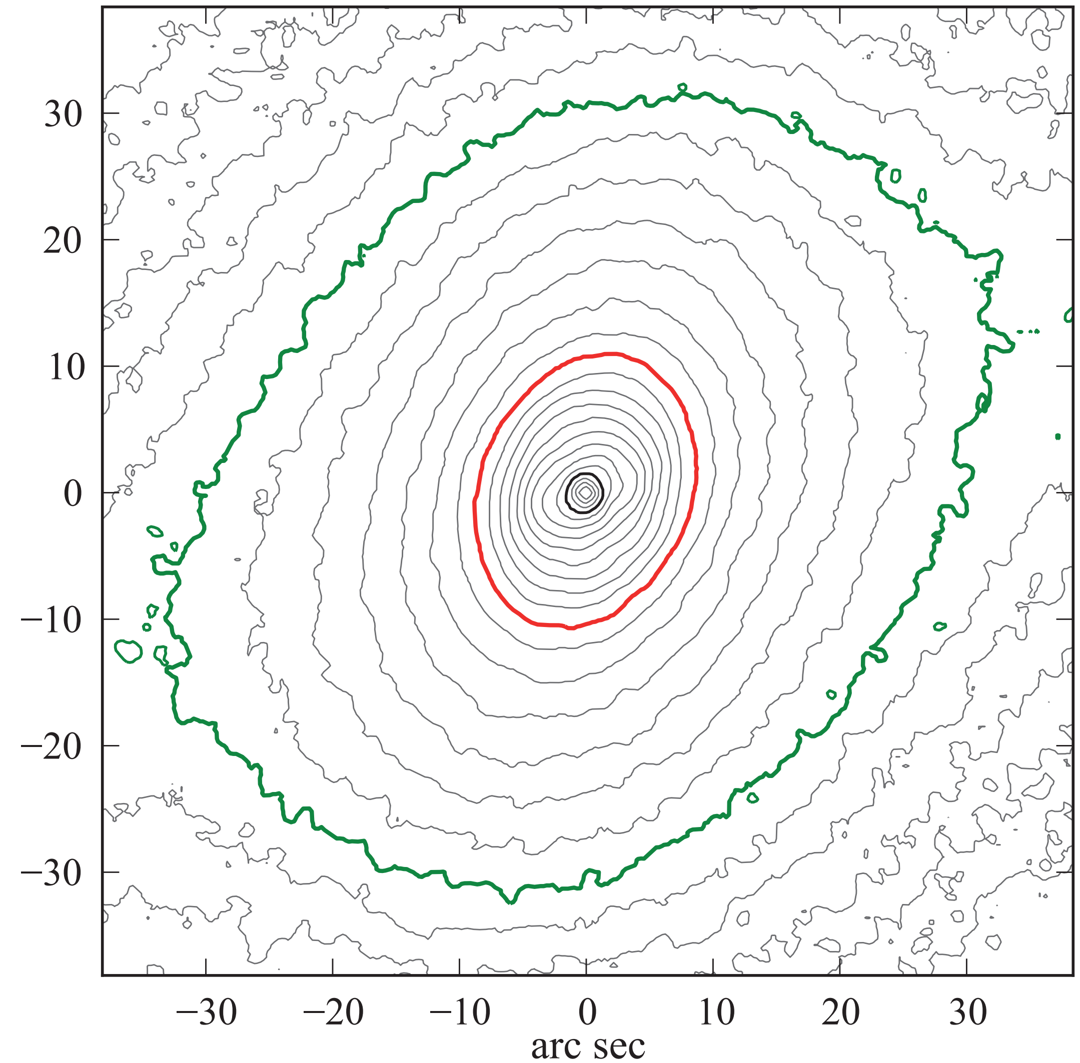
No.

- Even the smallest (r_e ~ 30 pc) are an order of magnitude larger than typical NSCs (r_e ~ 2–5 pc)
- Many have r_e ~ several hundred pc
- Similar mean densities to NSCs, but 2–3 orders of magnitude more massive
- At least one of them has a prominent NSC *inside*

Composite Bulges Coexist with Boxy/Peanut-Shaped Bulges (Another type of "pseudobulge")

NGC 3368: "Box+spurs" morphology
(Erwin & Debattista 2013)





Blue = "spurs" (flat outer part of bar)

Green = "box" (projection of vertically thick inner part of bar = box/peanut bulge)

Red = Disky pseudobulge

(Classical bulge = round innermost isophotes)

Coexistence of classical bulges, pseudobulges, and boxy bulges (Athanassoula 2005)

Black Holes & Composite Bulges

- SINFONI observations for SMBH measurement
- 15 disk galaxies (S0 + spirals)
    - 6 with classical bulges
    - 3 definite composite-bulge galaxies
    - 6 spirals not as well determined
        - mix of pure pseudobulges and composite bulges?
    - 3 already published (Nowak+2010, Rusli+2011); 3 still being modeled
    - Erwin+2014, in prep

Formation of Disky Pseudobulges?

Discussions of pseudobulges often argue that they form from bar-driven "secular evolution" (e.g., Kormendy & Kennicutt 2004)

Usually rather hand-waving

Is there any evidence for this from simulations?

Wozniak & Michel-Dansac 2009:

Isolated galaxy simulation (*n*-body + SPH gas, star formation)

Initial setup: stellar disk + 10% gas

Rigid DM halo

"Nuclear disk" amounting to 34% of galaxy stellar mass formed inside bar, radial extent ~ 500 pc

But: unclear how much this matches our disky pseudobulges

Surface-brightness profile?

Stellar kinematics?

Isolated Galaxy Simulation

Cole, Debattista, Erwin et al. 2014 (*MNRAS*, submitted)

Initial conditions: live DM halo (5M particles) w/ hot gas "corona" (5M SPH particles); *no stars*

Same as model HG1 of Gardner+2014

Evolved with *n*-body+SPH code GASOLINE

gas cooling, SF, stellar feedback as in Stinson+2006

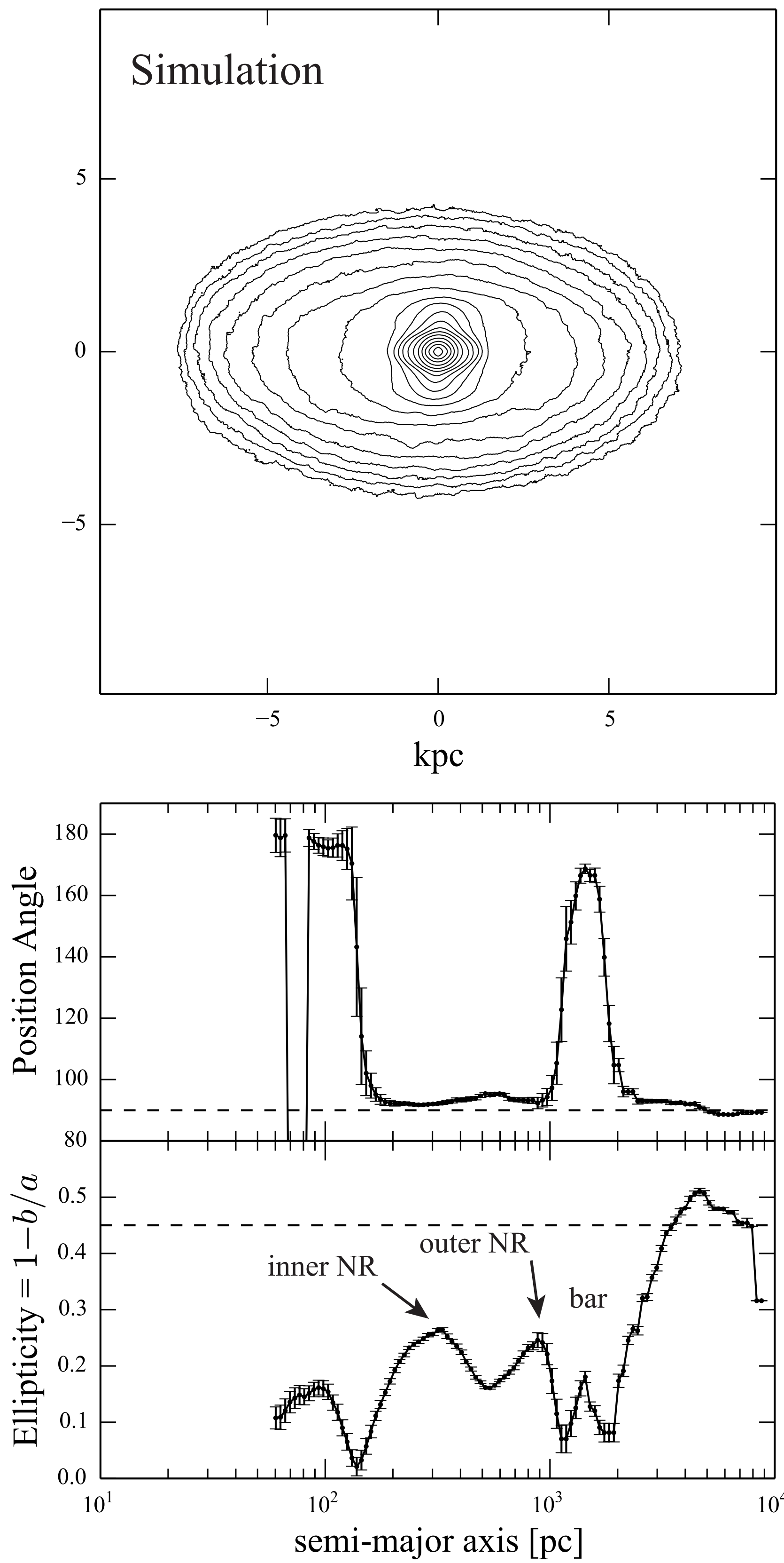
feedback: Type I and II SNe; AGB winds

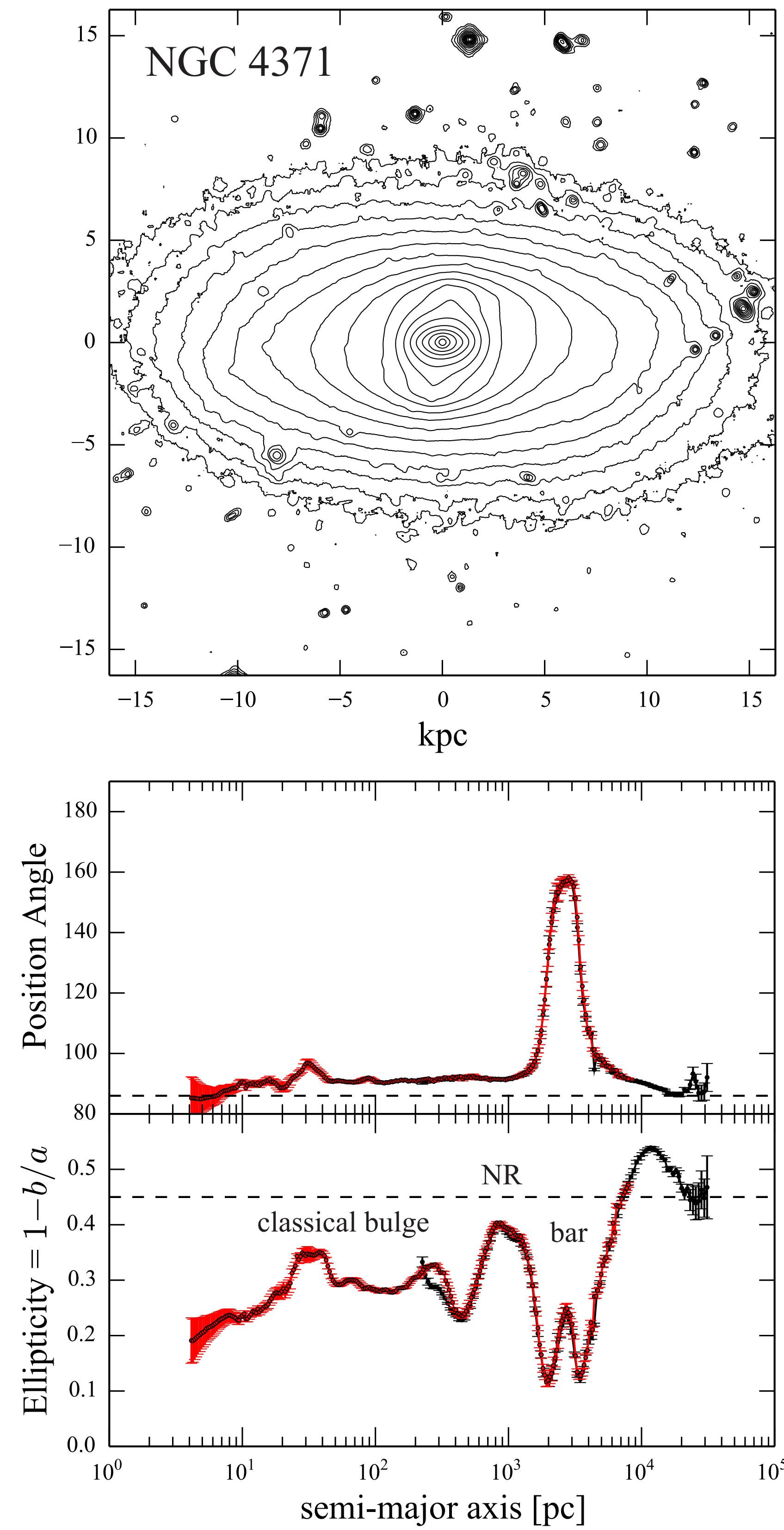
(no SMBH, so no AGN feedback)

Evolved for 10 Gyr ⇒ $6.5 \times 10^{10} M_\odot$ barred spiral

Massive "nuclear disk" with two(!) stellar rings forms inside bar (~ 29% of total stellar mass at end of simulation)

Comparing Simulation with NGC 4371





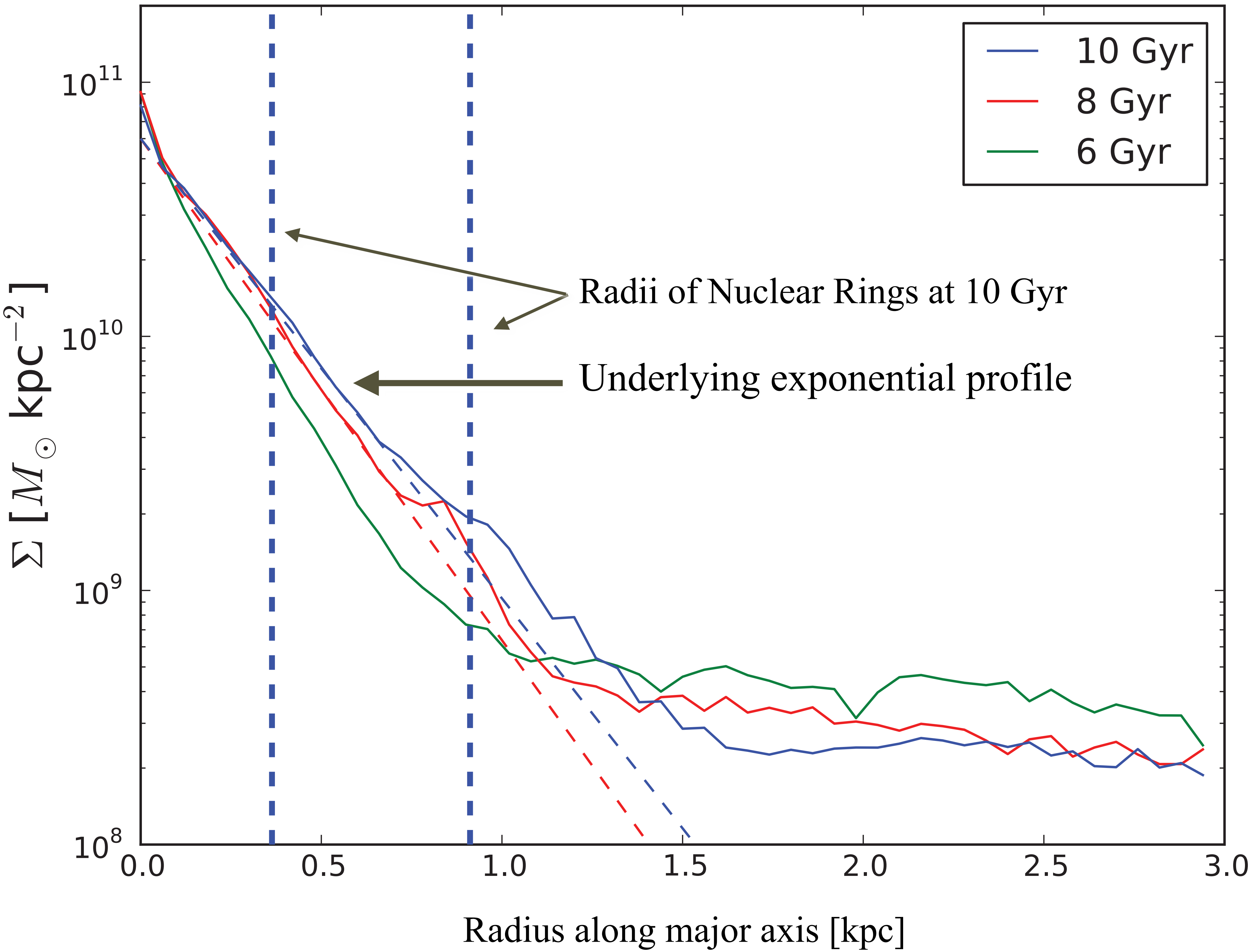
Simulation has disk inside bar (similar to real galaxy!)

Note: disk is slightly *elliptical* (perpendicular to bar) — something to look for in real galaxies?

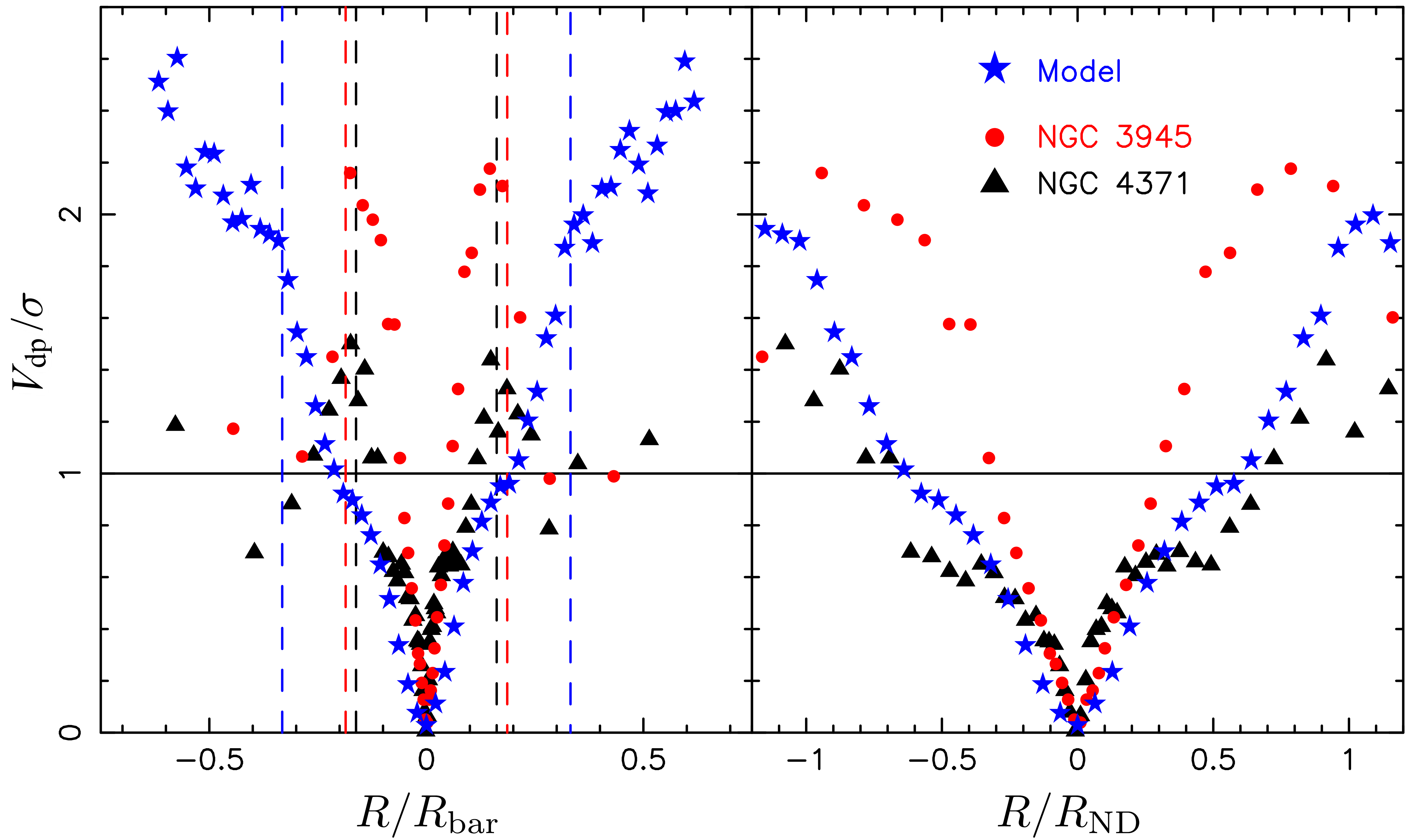
Differences:

1. Simulation's disk is *much larger*
2. *Two* nuclear rings instead of one

Exponential Profile!



Stellar Kinematics



V_{dp}/σ reaches values ~ 2 within "nuclear disk"/disky pseudobulge

But: peak V_{dp}/σ is at larger radii in simulation

No clear *decrease* in V_{dp}/σ at intermediate radii

Some Agreement

Disky structure with exponential profile does form inside bar

Large V_{dp}/σ value where this disk dominates

Nuclear ring(s) coexist with disk

Similar fraction of galaxy stellar mass

Some Disagreement

Observed disky pseudobulges:

are significantly *more compact*
have only 1 (or no) ring
often(?) have nuclear bars

And, of course — no compact classical bulges in simulation

Summary

- At least some "bulges" are ***composite systems***, consisting of:
  - Luminous disky component: disky pseudobulge
    - Usually exponential; disklike kinematics; ~ 30% of stellar mass
  - Embedded, lower-luminosity classical (kinematically hot) spheroid: classical bulge
    - Sérsic n = 1–2; ~ 6% of stellar mass; isotropic dispersions
- Both classical-bulge and disky-pseudobulge components fall on same size-mass relation as ellipticals and (large) classical bulges
- N-body + SPH simulation of isolated disk galaxy forms disky pseudobulge inside bar, though it is *too extended* and has multiple rings instead of 1 or none

Where Next?

- We now have a much better idea of what kinds of structures are found in galaxy centers (and how to measure them!):
  - Nuclear star clusters
  - classical bulges
  - disky pseudobulges
  - box/peanut bulges of bars (Erwin & Debattista 2013) …
- But how common are they, and how much of stellar mass is in each?

Idea for a Survey: Comprehensive Inventory of Central Stellar Structures in (Nearby) Disk Galaxies

- E.g., 30–50+ nearby S0–Sb(Sc?) at moderate inclinations ($D < 25$ Mpc, $30° < i < 70°$)
- Imaging:
    - High-res. optical/near-IR (HST and/or AO)
    - Low-res. optical/near-IR (Spitzer archival; SDSS)
- Spectroscopy:
    - Stellar kinematics (High-res. for classical bulges; lower-res. for pseudobulges & disks)
    - Desirable: Stellar populations (Low-res. only?)
- Comparison with N-body (+ SF) models (V. Debattista)
- Dynamical modeling to determine orbital structure, anisotropy, etc.?