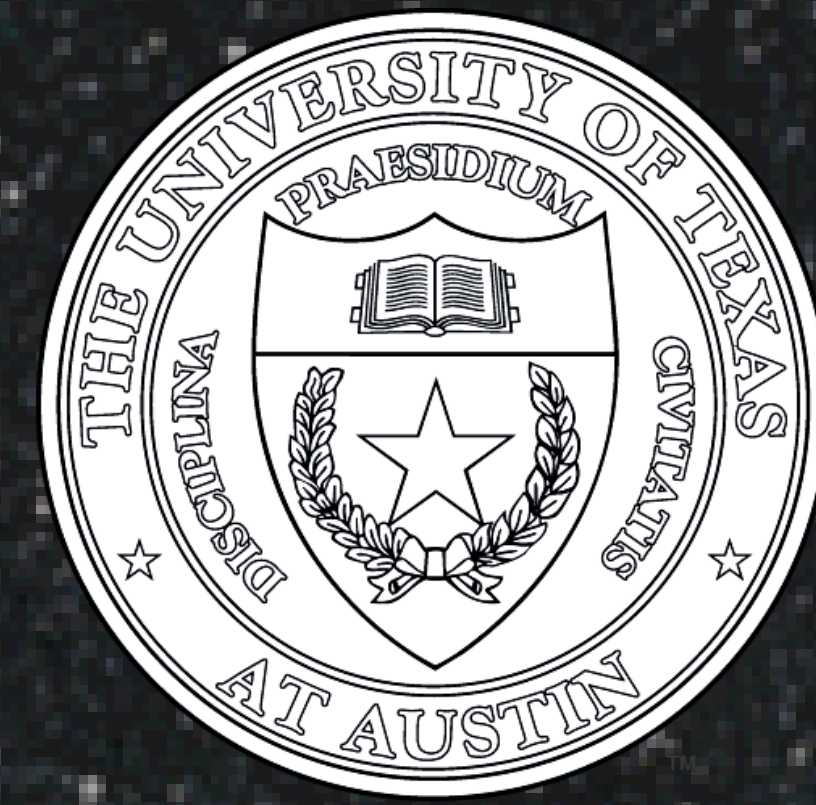


# DETECTION OF A DISTINCT PSEUDOBUULGE HIDDEN INSIDE THE "BOX-SHAPED BULGE" OF NGC 4565



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## MOTIVATION

Hierarchical clustering of galaxies dominated their evolution in the early Universe but is currently giving way to internal, slow ("secular") evolution. This evolution of galaxies via interactions with collective phenomena like bars and spiral structure is well-established (Kormendy and Kennicutt 2004). *N*-body simulations suggest that bars heat up in the axial direction and explain the morphology of so-called "box-shaped" bulges of some edge-on galaxies (Combes & Sanders 1981). These secular processes drive gas toward the galactic center, building to high densities and often triggering starbursts. In the process, bulge-like ("pseudobulge") structures are produced mimicking "classical" (i.e., merger-built) bulges. To what extent are these components (disk, box-shaped bulge, and pseudobulge) actually seen in edge-on galaxies?

An iconic edge-on galaxy with a box-shaped bulge we can use to check is NGC 4565. Optical and near-infrared images (Figure 1) of this galaxy show the disk and the edge-on bar manifesting as a box-shaped bulge. In this picture, a pseudobulge is not found in this galaxy. Short wavelength imagery shows a prominent dust lane in NGC 4565 that may hide interior structures due to the shallow viewing angle. Using infrared data from the *Spitzer Space Telescope* and *Hubble Space Telescope*, we set out to (1) search for the underlying pseudobulge—our picture of secular evolution tells us should exist and (2) determine the scale heights for the various components of the galaxy.

## METHOD

In edge-ons, extinction at optical and shorter wavelengths is large along the sightline through the highly-inclined disk. Observations in the near- to mid-infrared solve this problem. We used 3.6  $\mu\text{m}$  *Spitzer*/IRAC archive images to see through the dust and probe the central regions of NGC 4565 and its measure minor axis light profile. The imagery is shown in Figure 1 with two stretches emphasizing the box-shaped bulge (top) and the central pseudobulge (bottom). We supplemented the *Spitzer* data at small radii with NICMOS F160W imagery from the *HST* archive; the higher spatial resolution of the NICMOS data allowed us to measure the Sérsic index of the pseudobulge. Profiles were measured by taking vertical-cuts along the minor axis of NGC 4565 after registering the *HST* and *Spitzer* images. Surface photometry was done using these cuts from which we performed a three-component decomposition into a central Sérsic function for the pseudobulge, another Sérsic function for the boxy bulge, and an outer exponential. The data and fits are shown in Figure 2.

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*N*-body simulations show that "box-shaped bulges" of edge-on galaxies are not bulges at all: they are bars seen side-on. Therefore the two components that we readily see in edge-on Sb galaxies like 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? We use archival Hubble Space Telescope K-band images and Spitzer Space Telescope 3.6 micron wavelength images to penetrate the dust in NGC 4565. We find a high-surface-brightness, central stellar component that is clearly distinct from the boxy bar and from the galaxy's disk. Its minor-axis profile has a Sérsic index of  $1.33 \pm 0.12$ , so it is a pseudobulge, not a classical bulge. The pseudobulge has the smallest scale height ( $\sim 90$  pc) of any component in the galaxy. This is in contrast to a scale height ( $\sim 740$  pc) of the boxy bar plus thin disk. The diskly pseudobulge is also much less luminous than the boxy bar, so the true pseudobulge-to-total luminosity ratio of the galaxy is much less than the value  $\sim 0.4$  that was previously published. We infer that the (pseudo)bulge-to-total luminosity ratios of edge-on galaxies with "box-shaped bulges" have generally been overestimated. Therefore more galaxies than we have recognized contain little or no evidence of a merger-built classical bulge. This presents a challenge to our picture of galaxy formation by hierarchical clustering, because it is difficult to grow big galaxies without also making a big classical bulge. Solving the puzzle of the "missing pseudobulge" in NGC 4565 further increases our confidence that we understand "box-shaped bulges" correctly as edge-on bars. This in turn supports our developing picture of the formation of pseudobulges -- both edge-on bars and diskly central components -- by secular evolution in isolated galaxies.

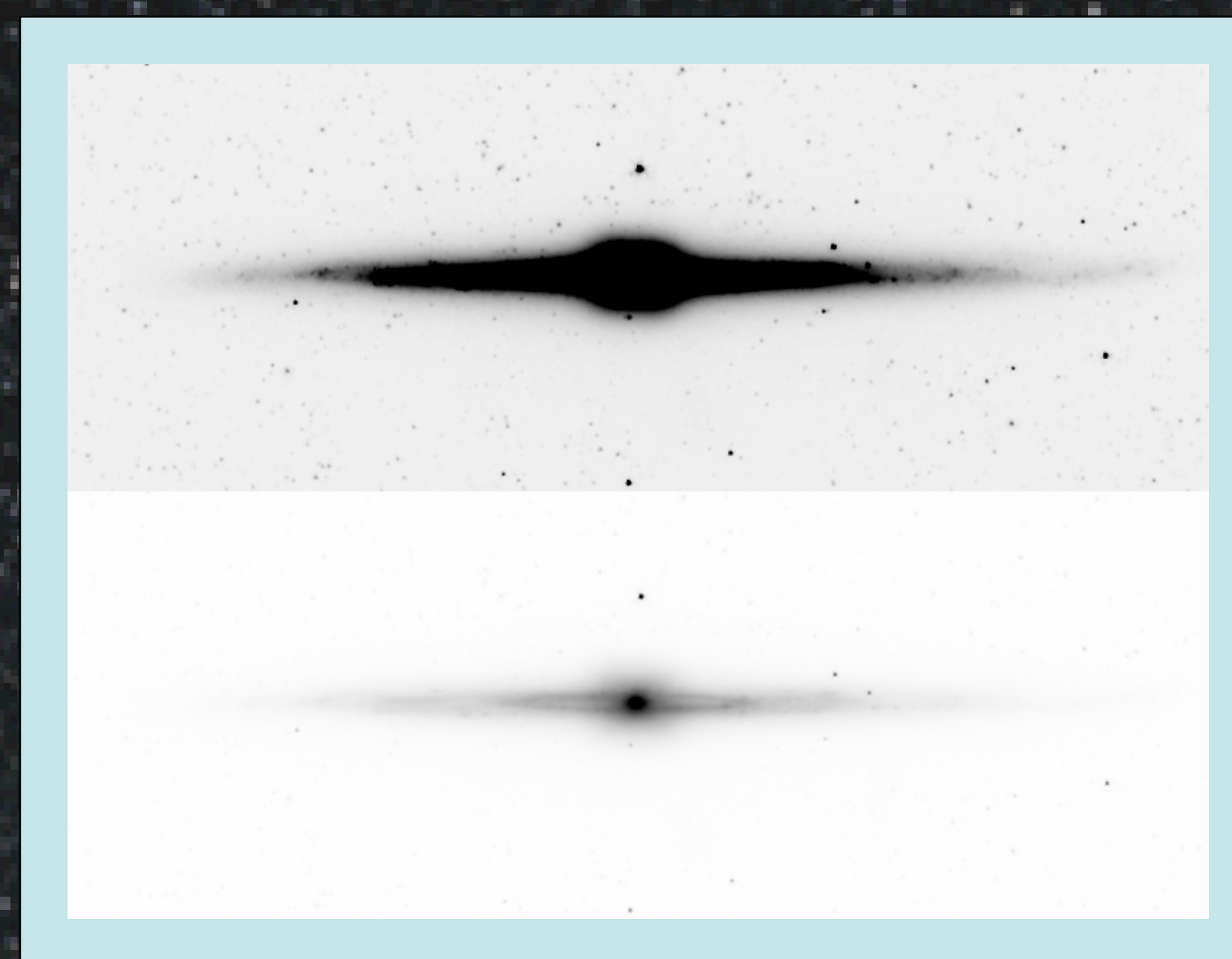


Figure 1: *Spitzer*/IRAC 3.6  $\mu\text{m}$  image of NGC 4565 presented in two different stretches, emphasizing the boxy bar (top) and the inner ring and pseudobulge (bottom). The colors have been inverted to emphasize detail.

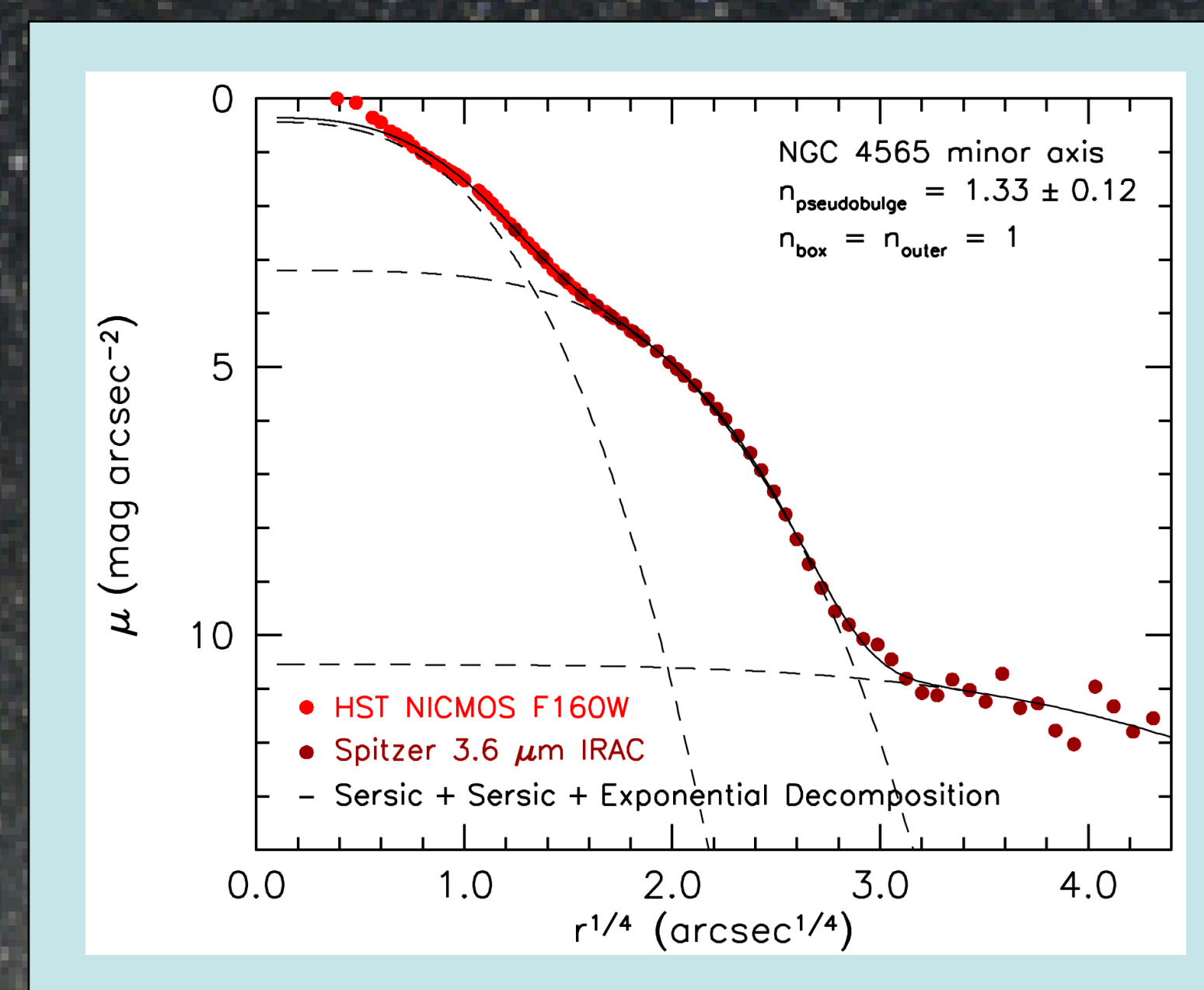


Figure 2: The measured brightness profile of the center of NGC 4565 along the minor axis direction from HST/NICMOS F160W (red points) and *Spitzer*/IRAC 3.6  $\mu\text{m}$  (brown points) data. The dashed lines show the components of a decomposition into the pseudobulge and box-shaped bar (Sérsic) and outer disk (exponential) components. A solid line fits the sum of the components. The Sérsic index of the second component (1) indicates the bar, whereas the first Sérsic index (1.33) suggests a pseudobulge rather than a merger-built, "classical" bulge.

## RESULTS

We find that the innermost component of the decomposition is best fit by a profile with Sérsic index  $n = 1.33 \pm 0.12$ , consistent with a pseudobulge rather than a classical bulge (Fisher & Drory 2007). Excluding the faint thick disk and halo, the thickest parts of the galaxy are in decreasing order of thickness, the edge-on bar, the thin disk, and lastly, the pseudobulge. The boxy bar and thin disk have a combined scale height of 10.5" ( $\sim 740$  pc at a distance of 14.5 Mpc; Wu *et al.* 2002), while the pseudobulge scale height is only 1.2" ( $\sim 90$  pc). Wu *et al.* (2002) fit a profile to the "bulge" in NGC 4565, defining this structure as what remained after subtracting fitted profiles for the disks and halo. Their fitted scale height for the structure we interpret as a pseudobulge is 0.65 kpc. Our value compares favorably with theirs, but they fitted an exponential rather than a Sérsic function to their optical data and claim that photometry alone cannot resolve uncertainty about whether the box structure is a bar or not. We assert that when the "real" bulge in NGC 4565 is revealed to be a pseudobulge, interpretation of the structures becomes more straightforward.

Simien & de Vaucouleurs (1986) find the bulge-to-total light ratio (B/T) = 0.4 in 4565 but B refers to the boxy bar -- not the pseudobulge within. Figure 1 shows that the pseudobulge is clearly less luminous than the boxy structure. If NGC 4565 were seen face-on, light from the apparent box-shaped bulge would be recognized as a bar and would lead to a lower B/T value. Previously measured B/T ratios of edge-on galaxies with box-shaped bulges are probably overestimates, given this reasoning.

## CONCLUSIONS

1. The interpretation of boxy bulges in edge-on galaxies as signature of bars is more believable if we find pseudobulges like those associated with bars in face-on galaxies. Our discovery of the pseudobulge in NGC 4565, distinct from the box-shaped bar previously thought to be the bulge, increases confidence in our picture of secular evolution.
2. B/T ratios in edge-on galaxies with boxy bulges are smaller than previously believed.
3. Published B/T values for most edge-on galaxies must be inconsistent with those derived for their face-on counterparts.
4. Overestimates of B/T in edge-ons present a problem with respect to CDM galaxy formation. The disk of NGC 4565 rotates at  $255 \pm 10$  km/s interior to the outer warp (Rupen 1991). Thus while this galaxy shows no evidence of a major merger in the form of a classical bulge, it has grown to great mass. It is difficult to reconcile these observations in the context of a hierarchically clustering universe.

## ACKNOWLEDGMENTS

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