

# Using 3D Spectroscopy to Probe the Orbital Structure of Composite Bulges

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**Abstract.** Detailed imaging and spectroscopic analysis of the centers of nearby S0 and spiral galaxies shows the existence of “composite bulges”, where both classical bulges and disk pseudobulges coexist in the same galaxy. As part of a search for supermassive black holes in nearby galaxy nuclei, we obtained VLT-SINFONI observations in adaptive-optics mode of several of these galaxies. Schwarzschild dynamical modeling enables us to disentangle the stellar orbital structure of the different central components, and to distinguish the differing contributions of kinematically hot (classical bulge) and kinematically cool (pseudobulge) components in the same galaxy.

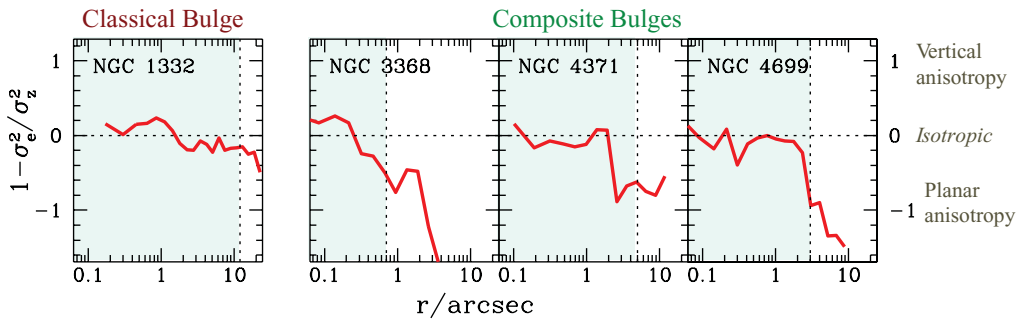
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## 1. Introduction

Although the standard picture of the stellar structure of disk galaxies combines a disk and a central bulge, recent studies have suggested a dichotomy between galaxies which host *classical* bulges – round, kinematically hot, and presumed to originate from violent mergers at high redshift – and those with *pseudobulges*, where the central excess stellar light is from a flattened, kinematically cool structure, presumed to originate from some long-term, internal (“secular”) processes.

We have recently found evidence that some disk galaxies can harbor both a classical bulge *and* a disk pseudobulge (we use the term “disk pseudobulges” to distinguish them from bar-derived box/peanut structures, which are sometimes also called pseudobulges). Evidence for this includes a combination of highly flattened isophotes, disk substructures (spirals, nuclear rings, nuclear bars), and stellar kinematics dominated by rotation in the disk pseudobulge, and rounder isophotes and stellar kinematics dominated by velocity dispersion in the classical-bulge region; see Nowak *et al.* (2010) and Erwin *et al.* (2014) for details.

As part of our SINFONI Search for Supermassive Black Holes (S<sup>3</sup>BH), we observed approximately 30 disk and elliptical galaxies with the SINFONI IFU on the VLT, using natural- or laser-guide-star adaptive optics to obtain 3D *K*-band spectroscopy of the galaxy centers; our sample includes three well-defined examples of composite-bulge galaxies. We combine the high-resolution stellar kinematics derived from this data with larger-scale, ground-based spectroscopy and *HST* and ground-based imaging to measure SMBH masses via Schwarzschild dynamical modeling (e.g., Nowak *et al.* 2007, 2008, 2010; Rusli *et al.* 2011, 2013).



**Figure 1.** Results of Schwarzschild modeling for classical-bulge S0 galaxy NGC 1332 (Rusli *et al.* 2011, left) and three composite-bulge galaxies, based on VLT-SINFONI AO data. The plots, based on mass-weighted averages of stellar orbits within  $\pm 23^\circ$  of the equatorial plane for each galaxy, show equatorial-vs-vertical stellar anisotropy as a function of radius; the equatorial term combines radial and tangential dispersions:  $\sigma_e^2 = (\sigma_R^2 + \sigma_\phi^2)/2$ . Vertical dashed lines mark the approximate photometric transition between the classical bulge and the disk (for NGC 1332) or between the classical bulge and the disk-like pseudobulge (other three galaxies), with the shading indicating the classical-bulge region. For all four galaxies, the classical bulge is dominated by isotropic velocity dispersion, while the disk or disk-like pseudobulge regions show planar-dominant anisotropy.

As part of the Schwarzschild modeling process, we obtain weighted libraries of stellar orbits for the central galaxy regions; these can be used to explore the relative contributions of ordered (rotational) and random stellar motions within classical and disk-like pseudobulge regions. Fig. 1 shows part of this analysis, plotting the planar/vertical anisotropy of 3D stellar orbits as a function of radius for an S0 with a purely classical bulge (NGC 1332) and for three composite-bulge galaxies. The anisotropy term measures the relative amounts of “equatorial” dispersion (that is, radial and azimuthal dispersions added in quadrature) versus vertical dispersion (with respect to the equatorial plane). In all four galaxies, the dispersion is approximately isotropic within the classical-bulge region, and shifts to an equatorial-dominant state in the disk outside (for NGC 1332) or in the disk-like pseudobulge region (for the composite-bulge galaxies). This is additional evidence supporting the argument that what we identify as “classical bulges” in the composite-bulge systems are isotropic, pressure-supported components similar to low-luminosity ellipticals, while the disk-like pseudobulges have stellar kinematics similar to those of large-scale disks.

Full details of this study are presented in Erwin *et al.* (2014).

## References

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