Galaxy Masses as Constraints of Formation Models
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Massive Elliptical Galaxies: BH Scouring or a Bottom-Heavy IMF?

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Abstract. We present indirect constraints on the stellar initial-mass-function (IMF) in nine massive elliptical galaxies with $\sigma \approx 300$ km/s, via a comparison of dynamical and stellar-population based stellar masses. We use adaptive-optics assisted, high resolution kinematical data from the SINFONI Search for Supermassive Black Holes that allow us to constrain the dynamical stellar mass-to-light ratio in the very centre of each galaxy. Hence we measure the IMF in a galaxy region where the stellar mass dominates over dark matter, minimising any potential degeneracy between the two mass components. In six of our galaxies – those which have depleted stellar cores – we find an IMF consistent with the one measured in the Milky-Way via direct star counts. The three remaining, power-law galaxies have instead stellar masses about a factor of two times larger than expected from a Milky-Way type IMF, indicating either a more bottom-heavy IMF (like, e.g., the Salpeter IMF) or a dark-matter distribution that is degenerate with the stellar mass down to the very centres of these galaxies. The bottom-light IMF in our core galaxies is surprising in view of previous studies that suggested a systematic IMF variation where early-type galaxies with $\sigma \approx 300$ km/s have a Salpeter or even more dwarf-dominated IMF. Core galaxies are particularly important since their unique central orbital structure offers an independent crosscheck for the dynamical models. Our models with a bottom-light IMF are consistent with the distribution of orbits predicted by SMBH-binary core-formation models. This indicates that spatially well resolved central kinematical data are important for determining unbiased dynamical stellar mass-to-light ratios. Our results imply either that the IMF in massive galaxies varies over a wider range than previously anticipated, and is not the same in core and power-law ellipticals, or else that there are systematic variations in the distribution of dark matter among massive early-type galaxies.

Keywords. galaxies: elliptical and lenticular, cD - galaxies: evolution - galaxies: formation

1. Introduction

Several recent studies have investigated whether the IMF systematically varies with galaxy mass, in particular among elliptical galaxies. These analyses are mostly based on two independent approaches. The first is an indirect method, where galaxy stellar masses are determined from stellar population synthesis models that actually do not resolve the IMF: the IMF is adjusted until the population-synthesis mass-to-light ratio matches independent constraints from dynamics and/or lensing. The second, direct method uses features in galaxy spectra that are particularly sensitive to the presence of, e.g., dwarf stars to determine the IMF directly from spectroscopic observations. Both approaches come to the same result: although there is significant galaxy to galaxy scatter, lower mass early-type galaxies (with dispersions $\sigma \approx 200$ km/s) seem to be roughly consistent with a Milky-Way type IMF (e.g. a Kroupa or Chabrier IMF). In high-dispersion elliptical galaxies, however, stellar mass-to-light ratios are about a factor of 2 times higher than expected from a Kroupa IMF. Direct studies specifically indicate that the IMF in massive

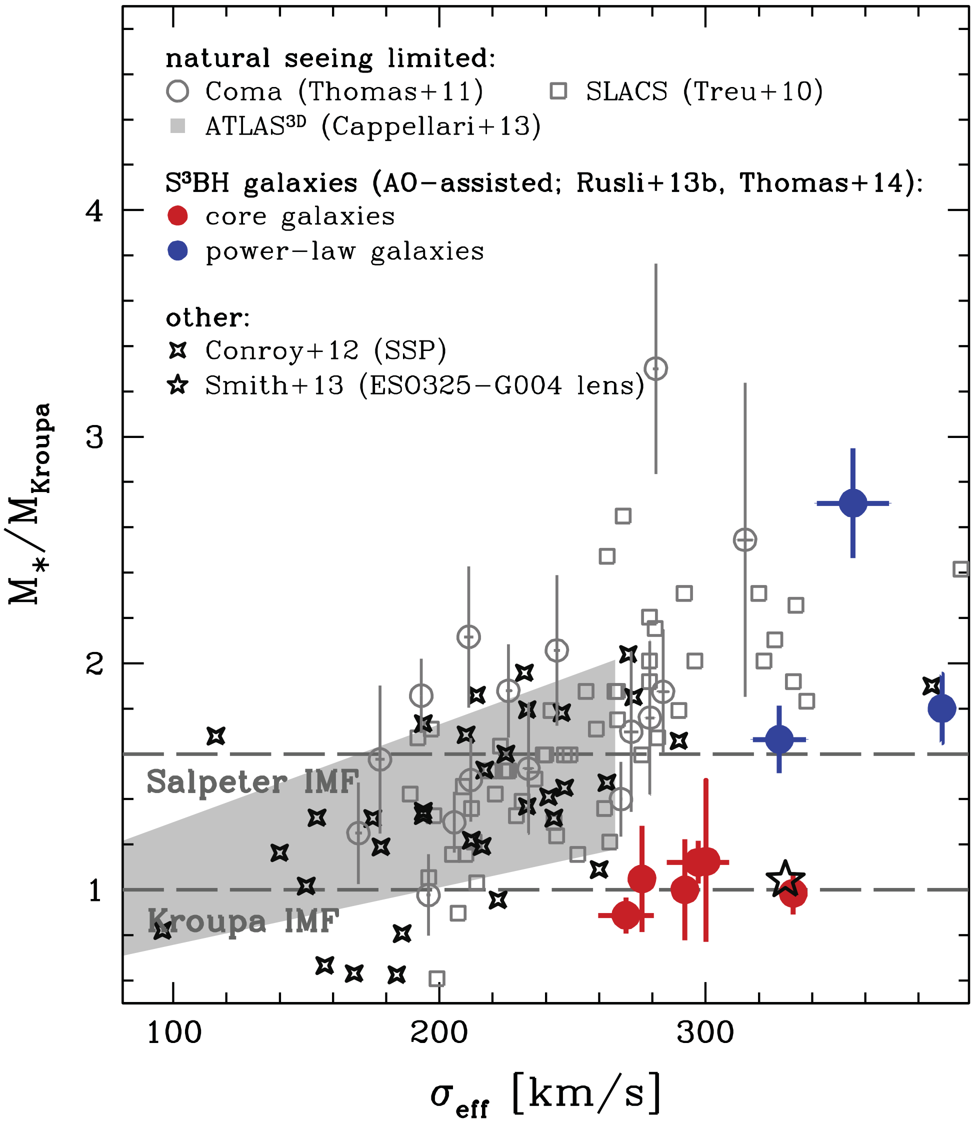

Figure 1. The IMF parameter $M_*/M_{\rm Kroupa}$ as a function of galaxy velocity dispersion $\sigma_{\rm eff}$. Grey: M_* from kinematical and/or lensing data that do not resolve the central SMBH (Treu *et al.* 2010; Thomas *et al.* 2011; Cappellari *et al.* 2013); colored: new M_* from adaptive-optics assisted kinematics in S^{3}BH (Rusli *et al.* 2013b; Thomas *et al.* 2014); open diamonds: M_* from stellar population models with variable IMF constrained from dwarf-star sensitive spectral features (Conroy & van Dokkum 2012); open star: M_* from gravitational lensing (Smith & Lucey 2013).

galaxies seems to be more dwarf dominated than in the Milky-Way (and can be described, e.g., by a Salpeter IMF).

Neither of the two approaches is free of systematics. While direct methods may suffer from not-yet-understood abundance effects on the IMF sensitive spectral features, dynamical and/or lensing masses in general can only determine the total gravitating mass of a galaxy – its decomposition into the contribution of the stars and of the dark matter halo is degenerate and model dependent. So far, indirect IMF measurements from stellar dynamics have been based on kinematical data that do not resolve the sphere of

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influence of the central supermassive black hole (SMBH). Here, we present new constraints on the IMF in massive ellipticals from the SINFONI Search for Supermassive Black Holes (S^3BH). S^3BH is a K-band spectroscopic survey of about 30 disk and elliptical galaxies, using the SINFONI IFU at the VLT to obtain adaptive-optics assisted central stellar kinematics (≈ 0.15 arcsec resolution). Together with larger-scale kinematical data this allows us to dynamically constrain the mass of the central SMBH, the stellar mass-to-light ratio Υ and the mass in the dark matter halo at the same time, using Schwarzschild orbit superposition models (Rusli *et al.* 2013b; Thomas *et al.* 2014). The high spatial resolution of our data further allows us to constrain Υ in the innermost regions of the galaxies, where any possible degeneracy between the stars and the dark matter halo is least significant.

2. Results

Fig. 1 shows our constraints on the IMF for the subsample of nine high-σ early-type galaxies in S^3BH. This sample is identical with the one described in Thomas *et al.* (2014), except for two galaxies that we here omit for their low σ (< 250 km/s). Fig. 1 shows, as a function of galaxy velocity dispersion σ, the ratio of the dynamically derived stellar mass M_* and a stellar population estimate $M_{\rm Kroupa}$ using the models of Maraston (2005) and assuming a Kroupa IMF. Galaxies from S^3BH are shown by the filled colored circles. Six of the nine galaxies have depleted stellar cores and are shown in red (cf. Rusli *et al.* 2013a), while the remaining three (power-law) galaxies are shown in blue. We find a marked difference between core and power-law ellipticals: while core galaxies, in contrast to the trend implied by previous works, are consistent with a Milky-Way like (e.g. Kroupa) IMF, power-law galaxies have stellar masses about a factor of two times larger than expected from a Kroupa IMF.

The formation of depleted stellar cores in the centres of the massive elliptical galaxies is most likely a consequence of dissipationless merging: the two black holes of the progenitor galaxies form a binary, which ejects stars from the core through gravitational slingshot. This process leaves a unique fingerprint in the central orbital structure of core galaxies: only stars on radial orbits pass the centre close enough to get ejected by the interaction with the SMBH binary, while stars on tangential orbits remain unaffected. Core galaxies are therefore of particular importance, since their unique central orbital structure allows an independent crosscheck of the dynamical models. In Thomas *et al.* (2014) we show that our best-fit dynamical models for the core ellipticals are in very good agreement with the predicted tangential anisotropy in the centres of these galaxies. Higher mass-to-light ratios, as indicative for a bottom-heavy IMF are not only ruled out by the kinematical data, but would also require an orbital structure in contradiction with the core scouring picture.

The bottom-light IMF in our high-σ core ellipticals causes tension with the statistical trend implied by previous studies, from which a Salpeter or even more dwarf dominated IMF had been expected. Previous dynamical studies, however, were based on kinematical data with lower spatial resolution that did not resolve the central SMBH. Our findings suggest that kinematic data with high central spatial resolution may be essential to derive unbiased dynamical stellar mass-to-light ratios. Smith & Lucey (2013) recently also reported evidence for a bottom-light IMF in a nearby, high-σ (lensing) galaxy. The range of the stellar IMF in massive galaxies may therefore be larger than anticipated thus far. The data is also consistent with a non-variable, Kroupa IMF in all galaxies, if part of the central mass in the power-law galaxies is a component of dark matter that is degenerate with the stellar mass distribution at the resolution limit of present-day kinematical observations.

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