*The Galactic Center: Feeding and Feedback in a Normal Galactic Nucleus*
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# Young stars in the Galactic center

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**Abstract.** The central parsec of our Galaxy hosts not only a supermassive black hole, but also a large population of young stars (age <6 Myr) whose presence is puzzling given how inhospitable the region is for star formation. The strong tidal forces require gas densities many orders of magnitude higher than is found in typical molecular clouds. Kinematic observations of this young nuclear cluster show complex structures, including a well-defined inner disk, but also a substantial off-disk population. Spectroscopic and photometric measurements indicate the initial mass function (IMF) differs significantly from the canonical IMF found in the solar neighborhood. These observations have led to a number of proposed star formation scenarios, such as an infalling massive star cluster, a single infalling molecular cloud, or cloud-cloud collisions. I will review recent works on the young stars in the central parsec and discuss connections with young nuclear star clusters in other galaxies, such as M31, and with star formation in the larger central molecular zone.

**Keywords.** star formation, Galactic center

## 1. Introduction

The center of our Galaxy hosts three massive ($\sim 10^4$ $M_\odot$), young (<8 Myr) star clusters, including the young nuclear cluster (YNC) that surrounds the supermassive black hole. Detailed studies of the Arches, Quintuplet, and YNC allow us to address a number of open questions about star and cluster formation in the Galactic center environment. First, these clusters are ideal laboratories for studying how the star formation process changes when initial conditions are quite different from the Galactic disk. In this context, it is important to fully understand where and when the clusters formed. Second, the fate of the Arches and Quintuplet clusters is not yet clear. Will they dissolve at large radii and join the larger nuclear cluster or will they spiral in and have a significant impact on the black hole? Lastly, if the YNC formed *in situ*, then the events leading up to its formation were likely unique when compared to all other clusters. We would like to understand the YNC's formation in order to learn about the interplay between star formation and black-hole accretion in nuclear clusters and the dynamical processes that are important to the cluster's evolution. In this proceeding, I review recent work on these three massive young clusters based on Keck adaptive optics imaging and spectroscopy.

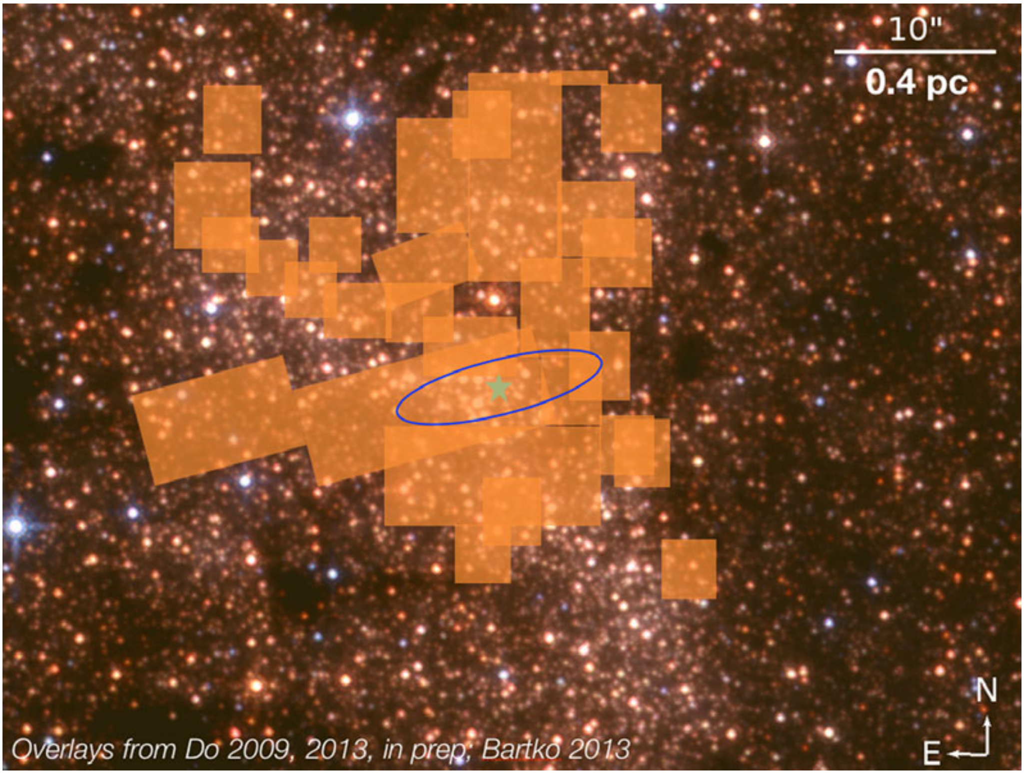


**Figure 1.** Spectroscopic coverage with adaptive optics fed integral field unit spectrographs on Keck (OSIRIS) and VLT (SINFONI) as published in Do *et al.* (2009, 2013); Bartko *et al.* (2009) and Do *et al.* in preparation. The IFU fields of view (*orange*) are overlayed on a a *Hubble* Space Telescope image centered on the black hole (*green star*). The *blue ellipse* shows the orientation of the disk of young stars. The colors in the RGB image correspond to *Hubble* WFC3-IR filters with red for F153M, green for F139M, and blue for F127M. [A COLOR VERSION IS AVAILABLE ONLINE.]

## 2. The young nuclear cluster

A young (4-8 Myr) nuclear cluster (YNC) surrounds our Galaxy's supermassive black hole and extends out to a radius of ∼0.5 pc. Over 120 members of the YNC have been identified via spectroscopy showing either hydrogen and helium lines or featureless blue continuum characteristic of hot Wolf-Rayet (WR) or OB stars (Allen *et al.* 1990; Krabbe *et al.* 1991, 1995; Blum *et al.* 1995; Tamblyn *et al.* 1996; Najarro *et al.* 1997; Ghez *et al.* 2003; Paumard *et al.* 2006; Bartko *et al.* 2010; Do *et al.* 2013). The current generation of surveys utilize adaptive optics fed integral field spectroscopic instruments such as OSIRIS on Keck or SINFONI on VLT. These surveys are deep enough to identify B main-sequence stars; however, they have very small fields of view (∼2"), which has led to incomplete spatial coverage (Figure 1). Proper motions and radial velocities of the young stars have revealed coherent dynamical structures, including one well-defined inner disk (Genzel *et al.* 2000; Levin & Beloborodov 2003; Paumard *et al.* 2006), and there is continued discussion on the possibility of a disk warp or a second disk (Genzel *et al.* 2003; Bartko *et al.* 2009; Lu *et al.* 2009; Yelda *et al.* 2013).

The strong tidal forces in this region will shear apart typical molecular clouds; thus, any *in situ* star formation must occur under very extreme conditions. The presence of a disk has led to several possible models for the origin of the YNC that overcome this tidal shear in different ways. First, the cluster may have formed *in situ* in a gas disk that

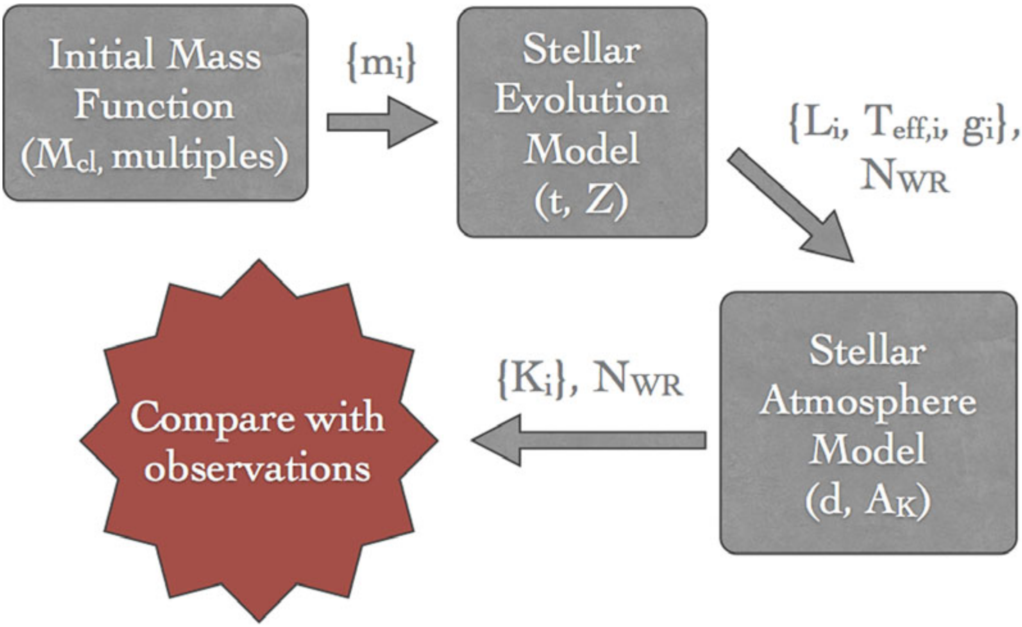


**Figure 2.** Flow chart showing how synthetic clusters are generated and compared with observations. [A color version is available online.]

was massive enough ($> 10^4$ $M_\odot$) that vertical self-gravity resulted in collapse and star formation before shearing could occur (Levin & Beloborodov 2003). Alternatively, the cluster may have formed far from the black hole and migrated in via dynamical friction (Gerhard 2001). Current observations favor *in situ* formation based on the steep fall off in the number of young disk stars at larger radii. The observed radial density profile is consistent with $\rho(r) \propto r^{-2}$ as predicted for *in situ* gas disks and is much steeper than the $\rho(r) \propto r^{-0.75}$ predicted for in-falling cluster scenarios (Lin & Pringle 1987; Berukoff & Hansen 2006; Levin 2007; Lu *et al.* 2009; Bartko *et al.* 2009). The simplest *in situ* formation scenarios initially produce circular orbits since gas that flows in at low or moderate rates circularizes prior to the onset of star formation (Nayakshin & Cuadra 2005; Alexander *et al.* 2007; Löckmann *et al.* 2009). The observed eccentricity distribution peaks at e=0.3 (Lu *et al.* 2009; Yelda *et al.* 2013). Scenarios invoking more rapid gas inflow, such as the infall of a single molecular cloud or the collision of two molecular clouds, could produce disk stars with large initial eccentricities and have the added bonus of producing a large population of young stars off the disk (Bonnell & Rice 2008; Wardle & Yusef-Zadeh 2008; Hobbs & Nayakshin 2009; Mapelli *et al.* 2012), similar to what has been observed (Paumard *et al.* 2006; Bartko *et al.* 2009; Lu *et al.* 2009; Yelda *et al.* 2013). However, the evolution of an initially circular disk over 4-6 Myr depends on the initial mass function (IMF) of the stars and it is possible to evolve to today's observed distribution for moderately top-heavy IMFs (Yelda *et al.* 2013). In summary, current observations support *in situ* formation; but the specific details of the initial conditions of the gas, including whether it was in a stable disk or was rapidly dumped into the central parsec, are still uncertain.

The initial mass function of the YNC is particularly interesting given the cluster's apparent *in situ* formation. These models predict extreme gas conditions compared to the disk of the Milky Way with higher temperatures, pressures, densities, and ambient radiation fields (Nayakshin 2006; Alexander *et al.* 2007, 2008; Cuadra *et al.* 2008; Mapelli *et al.* 2012). Analysis of the observed luminosity function of the spectroscopically identified young stars and careful correction for incompleteness has resulted in two different estimates for the IMF. Bartko *et al.* (2010, henceforth B10) derives an IMF with a power-law index of $\alpha = 0.45$ (where a Salpeter mass function has a slope of $\alpha = 2.35$); while Lu *et al.* (2013, henceforth L13) derives $\alpha = 1.7$ (Figure 3). There are small differences in the analysis methods and modeling between these two works such as the inclusion of multiplicity and the special treatment of Wolf-Rayet stars by L13 and different assumptions about the star formation history (single starburst in L13 versus exponential decay in B10). Figure 2 shows the detailed modeling that is performed in L13 to derive the cluster's properties via Bayesian inference methods. The major differences between B10 and L13 that may explain the IMF discrepancy revolve around the observed vs. completeness corrected luminosity functions. In particular, the luminosity function presented in Do *et al.* (2013) and L13 *before* completeness correction agrees with the luminosity function presented in B10 *after* completeness correction. The fields of view of the two studies are slightly different with L13 going along the plane of the young-star disk and B10 going orthoganal to it. So while it is clear that the IMF in the YNC is top-heavy, azimuthally complete spectroscopic coverage and detailed sample comparisons in overlap regions are essential to resolving exactly how top-heavy the IMF is in the Galactic center.

## 3. The Arches and Quintuplet clusters

The Arches and Quintuplet clusters are massive ($\sim 10^4$ $M_\odot$) clusters located ~30 pc in projection from the black hole (Figure 4). The Arches cluster is younger (age ~2.5 Myr, Najarro *et al.* 2004; Martins *et al.* 2008) and more centrally concentrated than the Quintuplet cluster (age ~4 Myr, Liermann *et al.* 2012). Both clusters have been studied extensively with near-infrared imaging and spectroscopy (e.g. Nagata *et al.* 1995; Cotera *et al.* 1996; Figer *et al.* 1999; Stolte *et al.* 2005; Espinoza *et al.* 2009). However, many of the cluster properties derived from these works have been limited by lack of membership information. Below, we review some of the more recent work that has benefited from the addition of proper motions used to distinguish between cluster members and contaminating field stars.

The first proper motions of Arches cluster members were measured from high spatial resolution adaptive optics images from Keck and VLT (Stolte *et al.* 2008). By combining the cluster's position, proper motion, and radial velocity, the Arches' orbit was partially constrained (depending on the unknown line of sight distance) and several possible orbits trace back to an origin in the outer periphery of the central molecular zone (Figure 8 of Stolte *et al.* 2008). Proper motions also provided membership information and a number of proto-planetary disk-bearing stars were revealed, yielding a disk fraction of 6% (Stolte *et al.* 2010), similar to other massive young clusters throughout the Milky Way (e.g. Haisch *et al.* 2001; Stolte *et al.* 2006; Hernández *et al.* 2007; Harayama *et al.* 2008). This low disk fraction at 2.5 Myr shows that proto-planetary disk evolution, and possibly planet formation, are strongly modified in the environment of a massive cluster. Increased precision in the proper motions of Arches cluster members has more recently allowed us to measure an internal velocity dispersion of $5.4 \pm 0.4$ km s$^{-1}$ (Clarkson *et al.* 2012). The resulting dynamical mass, assuming a virialized cluster, is 9,000 $M_\odot$ within a radius of 0.4 pc (Figure 5, blue horizontal band). The observed luminosity function extends down to ~3 $M_\odot$ and when it is extrapolated down to lower masses using a "normal" (e.g., Kroupa) mass function (Espinoza *et al.* 2009), the total mass exceeds the dynamical mass (Figure 5). A non-standard, present-day mass function seems necessary, at least within a radius of 0.4 pc, and must either have a flatter power-law index (top-heavy)

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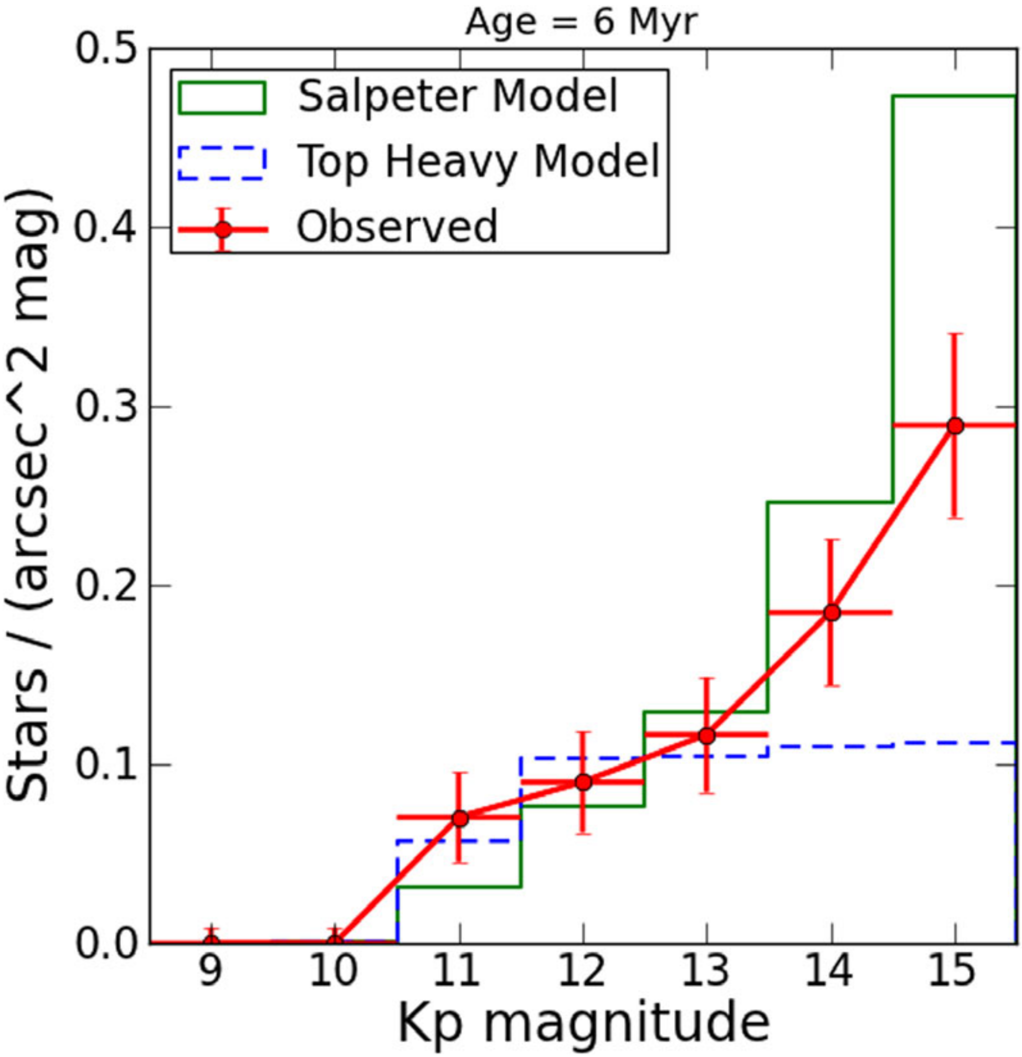


**Figure 3.** The observed $K$p-band luminosity function (*red*) for the young nuclear cluster after completeness-correction as presented in Lu *et al.* (2013). Two model KLFs are shown with a normal power-law index of $\alpha = 2.35$ (*green*) and a very top heavy power-law index of $\alpha = 0.45$ as is reported in Bartko *et al.* (2010). [A color version is available online.]

or a "normal" index with a cut-off at relatively high masses (e.g., 2 $M_\odot$, bottom-light). However, recent results from Habibi *et al.* (2013) covering a much larger cluster extent (but without proper motion membership selection) suggest that the mass-function power-law index steepens dramatically at larger radii. They suggest that this is consistent with a cluster that was originally born with a "normal" and uniform IMF that subsequently evolved through mass-segregation into the present-day, radially-dependent mass function we observe today. Habibi *et al.* (2013) show that the integrated mass above 1 $M_\odot$ and within 0.4 pc extrapolated with a Salpeter IMF only slightly exceeds the dynamical mass reported by Clarkson *et al.* (2012), when an updated radial density profile is used. However, including stars below 1 $M_\odot$ with a "normal" mass-function (which breaks at 0.5 $M_\odot$) may exceed the measured dynamical mass. Further progress requires precise proper motions over a much larger field of view in order to provide membership information,

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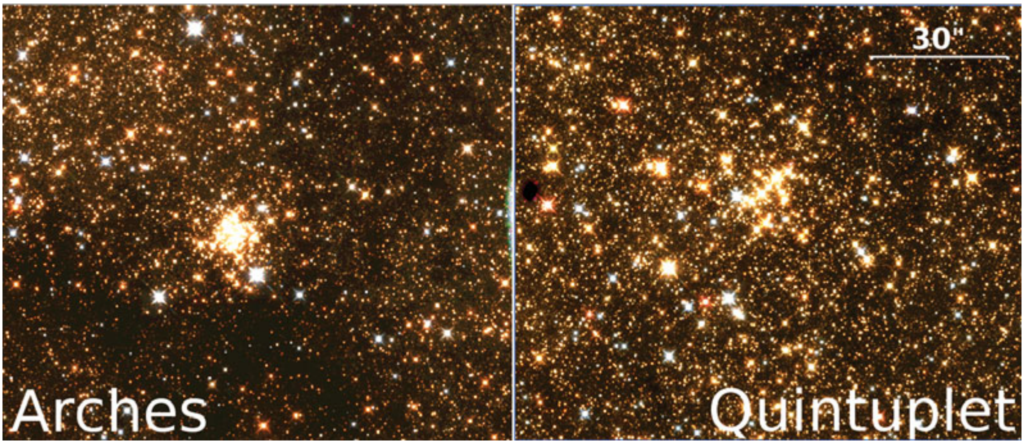


**Figure 4.** The Arches (**left**) and Quintuplet (**right**) clusters as viewed by the *Hubble* Space Telescope. The RGB image colors map to *Hubble* WFC3-IR filters with red for F153M, green for F139M, and blue for F127M. [A color version is available online.]

improve the observed luminosity function, measure the cluster's internal kinematics over its full extent, and determine the cluster's structure and tidal radius. We have a combined Keck and *Hubble* proper motion program underway to make these measurements, which will ultimately yield a complete picture of the Arches' orbit, birth place, and initial mass function.

The Quintuplet cluster has fewer proper-motion-based publications primarily due to its larger spatial extent, older age, and the challenging observations required to accommodate the extremely bright luminous blue variable stars in the cluster. Analysis of cluster members identified by radial velocities shows that the Quintuplet is 3.5 - 4.0 Myr old, although there are some peculiar red supergiant stars (RSGs) that may be associated with the cluster that should have formed 15-30 Myr ago (Liermann *et al.* 2012). The addition of proper motions has shown that many (but not all) of these RSG stars are not cluster members (Hußmann *et al.* 2012) and more precise proper motions may eliminate the problem entirely. The Quintuplet's proper motion is still a work in progress (Stolte *et al.*, in preparation); but preliminary results show that there are possible orbits that trace back to an origin in the outer periphery of the central molecular zone, similar to the Arches (Figure 5.16 of Stolte *et al.* 2011). While not yet definitive, it is interesting to consider whether there is some mechanism that triggers massive cluster formation in this region. The mass function for the Quintuplet appears to have a similar power-law index as the center of the Arches cluster (Hußmann *et al.* 2012). However, the mass function does not steepen with increased radius as rapidly as for the Arches clusters (Hußmann 2014). Recently obtained deep *Hubble* WFC3-IR imaging and proper motions will extend the observed Quintuplet members down to $\sim$1 $M_\odot$ and increase the spatial coverage by a factor of 10, dramatically improving estimates of the cluster's present-day mass function.

## 4. Summary

The Arches, Quintuplet and young nuclear cluster in the Galactic center represent an ideal opportunity to study how stars and clusters form under initial conditions that are very different from those found in the local solar neighborhood. While the Arches and Quintuplet initial mass functions appear to be "top-heavy" in their centers, this may still be explained by mass segregation and more complete spatial coverage of both clusters,

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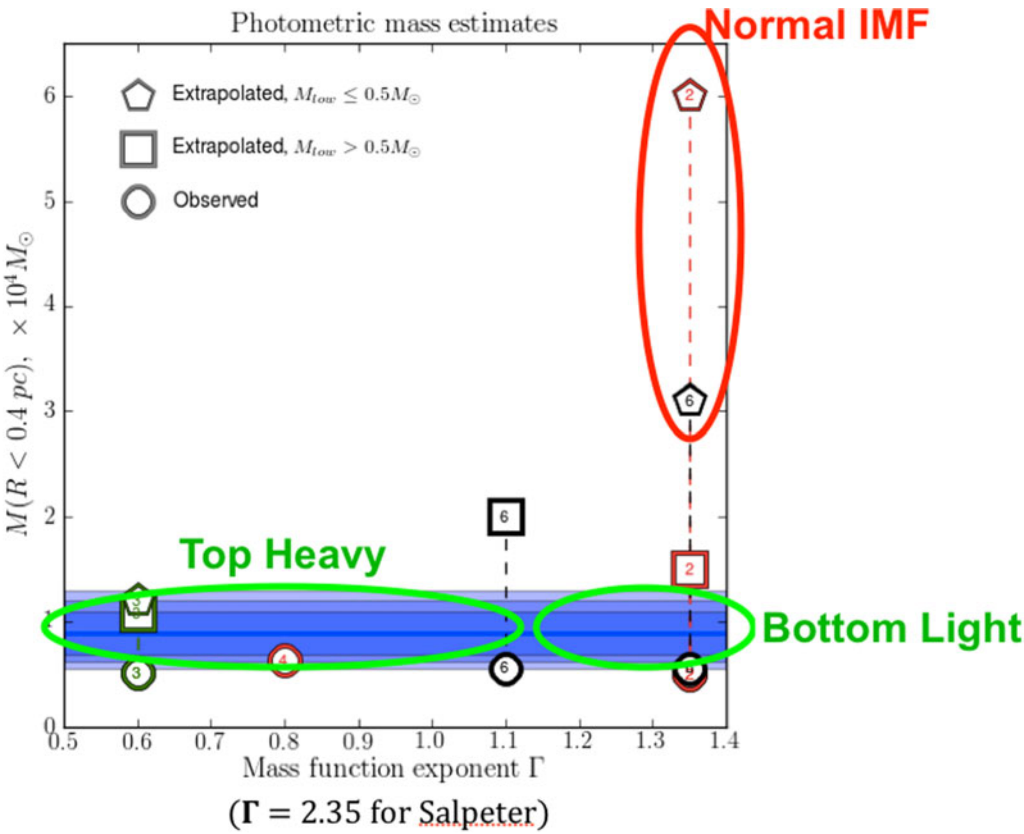


**Figure 5.** The Arches cluster's enclosed mass within a radius of 0.4 pc based on a dynamical mass estimate (*blue band*) from Clarkson *et al.* (2012) and photometric estimates (*symbols*) from the literature. Different symbols show directly observed photometric masses (*circles*), typically for stars above a few $M_\odot$, and extrapolations to lower stellar masses using various power-law indices for the mass functions (*squares, hexagons*). Normal (e.g., Salpeter) mass functions do not agree with the measured dynamical mass. Either bottom-lite or top-heavy mass functions are consistent with the measured dynamical mass and normal (e.g. Salpeter) mass functions are ruled out in the central 0.4 pc of the Arches core. See Figure 11 and Table 9 from Clarkson *et al.* (2012) for more details. [A COLOR VERSION IS AVAILABLE ONLINE.]

including proper motions, is needed. The young nuclear cluster also appears "top-heavy"; but again, larger spatial coverage is essential to determine whether the IMF power-law index is extremely flat ($\alpha = 0.45$) or moderately flat ($\alpha = 1.7$). Improvements in high spatial resolution infrared imaging and spectroscopy over large fields of view on these clusters are already possible with *Hubble* WFC3-IR and Gemini's GeMS today and with *JWST* and the next generation of giant ground-based telescopes (e.g., TMT, E-ELT) in the future. These resources will allow us to probe to much lower masses down below the typical turn-over mass found in local star clusters (~0.5 $M_\odot$), investigate multiplicity, find ejected stars, and investigate the dynamical evolution of the clusters in great detail.

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