Intermediate-mass black holes in globular clusters

the mass-segregation tracer

Mario Pasquato

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Globular Clusters in short

- Among the oldest objects known
- About 200 objects in the Milky Way
- Size: $\approx 1 - 10$ pc
- Mass: $\approx 10^5 M_\odot$
- Considered simple...
  - stellar evolutionary lab
  - truncated maxwellian models
- ...actually surprising
  - multiple populations

    [e.g. Bedin et al. 2004, Piotto et al. 2007]
  - exotica (e.g. blue stragglers)
  - cuspy profiles

    [Noyola & Gebhardt 2006, 2007]

M 15 (POSSII J image)

Globular Clusters may host the elusive IMBHs

- Intermediate Mass Black Holes (IMBHs) are black holes with masses in the $10^2 - 10^5\ M_\odot$ range
- Expected from theoretical predictions, but still not firmly detected
- Detection claims date back at least to the seventies

  [e.g. Bahcall, Ostriker 1975; Silk, Arons 1975; Newell et al. 1976]
- Globular clusters are an high density environment
- Stellar runaway merging or stellar-mass black-hole merging could produce IMBHs
- A definitive detection would have momentous implications on different fields

If found in Globular Clusters, IMBHs then would...

If found in Globular Clusters, IMBHs then would...

- ...be dragged to the Galactic center by dynamical friction, contributing to super-massive black-hole formation
- ...accrete neutron stars and stellar-mass black-holes, emitting gravitational radiation
- ...probably be produced in the cluster environment: how?
- ...explain some X-ray emission, expecially ULXs
- ...influence the dynamical evolution of host clusters

Unfortunately no definitive detection yet!

Suggested evidence that an IMBH is present:

- Luminosity density profile cusps [see Bahcall & Wolf 1976; Noyola & Gebhardt 2006, 2007]
- Velocity dispersion cusps [Noyola et al. 2008]
- Larger cluster core [Baumgardt 2005, Trenti 2007]
- Ultra Luminous X-ray sources ($L_X > 10^{39} erg/s$)
- Millisecond pulsars [D'Amico et al. 2002]
- High-velocity stars [Yu & Tremaine 2003]

Many claims but no undisputed detection.

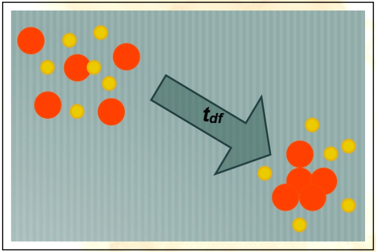
So, what did we do?

- Developed a new, model-independent method to obtain globular cluster structural parameters
- Applied extensive visualization, exploratory data analysis tools to the resulting dataset
- Developed a framework to test for IMBH presence based on a new indicator: mass segregation

Mass segregation: a promising indirect tracer for IMBHs

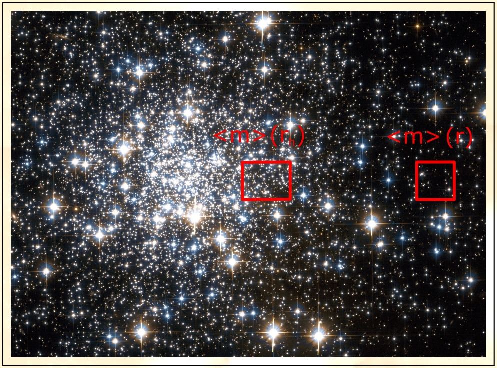
Mass segregation fingerprint:

- Massive stars segregate towards the center of a stellar system, lighter stars move outside and preferentially evaporate
- An IMBH quenches mass segregation [Baumgardt et al. 2004, Trenti et al. 2007, Gill et al. 2008]
- The effect can be measured in well relaxed GCs



Measuring mass segregation

- feasible with detailed star counts
- mass segregation → average mass $\langle m \rangle$ of MS stars higher in center wrt half-mass radius
- *we measure* $\langle m \rangle(r) - \langle m \rangle(r_h)$

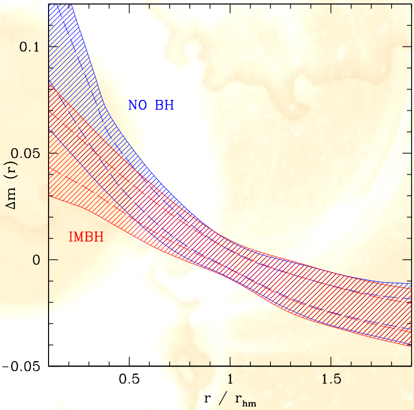


Pasquato et al. 2009, Beccari, Pasquato et al. 2010

Mass-segregation: simulations

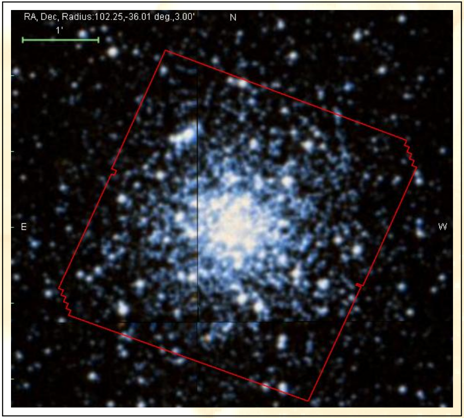
- Direct N-body (NBODY6), 16k to 32k particles, *no softening*, galactic tidal interaction
- IMBH with $M \approx 0.01 M_{GC}$ in half of the simulations
- Broad array of initial conditions:
  - Different IMFs (Miller & Scalo, Salpeter)
  - Different primordial binary fractions
- *a differential measurement, robust against IMF change*
- 2σ shaded areas at relaxation

Pasquato et al. 2009



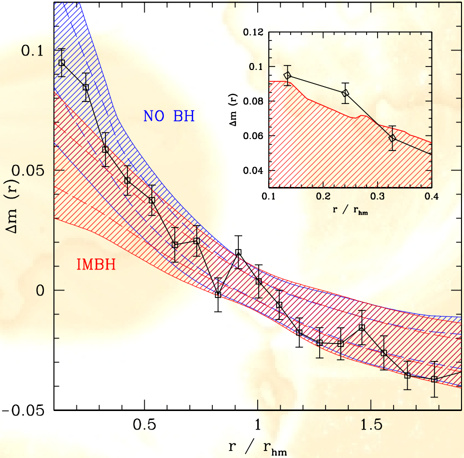
Mass-segregation: observations

- NGC 2298 chosen for deep ACS photometric data
- Small size, almost 1:1 star-to-simulated particle ratio
- HST/ACS field contains $\approx 2r_h$
- Data reduction [de Marchi & Pulone 2007] gives detailed star counts
- 0.2 $M_\odot$ stars still have 50% completeness in the core
- Low background contamination
- *Is relaxed:* $t_h < 1$ *Gyr*



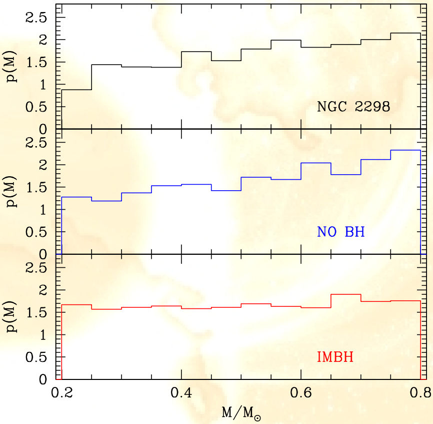
Comparing simulations to observations

- Only projected simulation data is used
- Finite FOV effects are imposed when ”observing” simulations
- NGC 2298 data overlap with NO IMBH confidence area
- 3σ upper limit on IMBH mass is 300 $M_\odot$

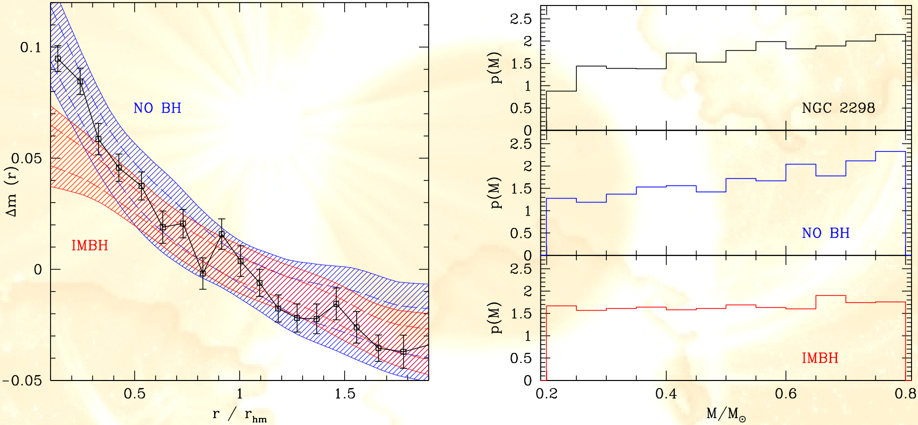


Predicting the mass segregation profile

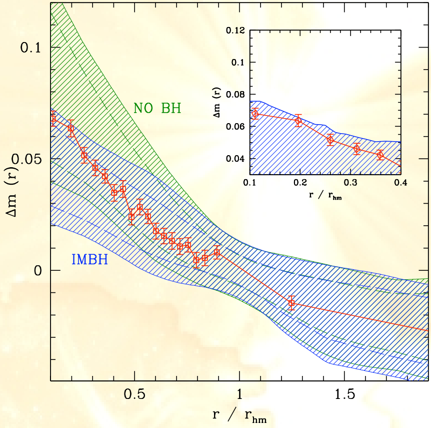
- present day global MF of NGC 2298 has a distinctive shape due to tidal stripping
- our simulations without an IMBH and with Miller & Scalo IMF match it well when $\approx 70\%$ of initial mass stripped
- they must accurately predict NGC 2298 mass segregation profile



Predicting the mass segregation profile

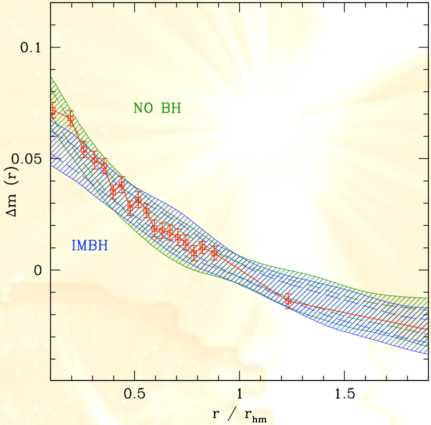


A more promising candidate: M 10



- From Beccari, Pasquato et al. 2010, mass segregation profile of M 10
- This time the mass corresponding to 50% completeness is 0.26 $M_{\odot}$
- In any case the data and the IMBH confidence region overlap
- But also some simulations without an IMBH can explain the data... those with primordial binaries

A more promising candidate: M 10



- From Beccari, Pasquato et al. 2010, mass segregation profile of M 10
- Green shaded area corresponds to 5% primordial binaries
- Binaries visually depress mass segregation (they are heavier but shine as singles)
- Binaries quench mass segregation dynamically, by releasing energy in the core
- A binary - IMBH degeneracy emerges

Conclusions and future prospects

New methods/techniques introduced:

- framework for comparing simulations and observations of mass segregation
- a new preliminary detection method, based on mass segregation

Scientific results:

- NGC 2298 does not contain an IMBH
- M 10 might contain one but there is a IMBH-binary degeneracy

Perspectives:

- Further development of the simulation-observation comparison framework
  - Active collaboration with Giacomo Beccari (ESO) and Guido de Marchi (ESTEC) for studying the mass segregation of binaries
  - Application to several other GCs with resolved stars
  - A study of how mass segregation evolves over time

Back-up slides

Back-up slides - NGC 2298

- RA: 6h 48m 59.2s, Dec: $-36^\circ\ 0'\ 19''$ Harris 2003
- Mass: $3.09 \cdot 10^4\ M_\odot$ McLaughlin & van der Marel 2005
- Half-light radius: $45.4''$ i.e. 2.35 pc McLaughlin & van der Marel 2005
- True distance modulus: 15.15 mag i.e. 12.6 kpc Harris 2003
- Reddening $E(B-V)$: 0.14 mag Harris 2003
- Half-light relaxation time: $2.57 \cdot 10^8$ yr McLaughlin & van der Marel 2005
- Concentration: 1.28 Harris 2003
- Ellipticity: 0.08 Harris 2003
- Metallicity $[Fe/H]$: -1.85 Harris 2003
- Distance from Galactic center: 15.7 kpc Harris 2003

Back-up slides - Our observations

Our data comes from De Marchi & Pulone (2007):

- ACS bands F606W and F814W used
- Size of field covered: $3.4' \cdot 3.4'$
- Completeness calculated in concentric annuli
- 50% completeness for $0.2\ M_\odot$ stars in the GC center
- Half-mass radius consistently computed from star counts
- Mass-luminosity relation used for MS stars from Baraffe et al. (1997) with $[Fe/H] = -1.85$
- $\approx 10^4$ MS stars in our sample

Back-up slides - Our simulations

Simulations from Gill et al. (2008) $+$ an additional four runs:

- Direct N-Body code: NBODY6 Aarseth 2003, Trenti et al. 2007a
- 16k to 32k stars, simulated to 20 initial relaxation times (tidal dissolution)
- Simulations take days to months to run
- Instantaneous stellar evolution to 12 Gyr using Hurley et al. (2000) tracks
- Stellar mass black holes up to 10 $M_\odot$
- Primordial binary fraction either 0 or 10%, flat distribution in binding energy Heggie et al. 2006
- Miller & Scalo or Salpeter IMF used
- Control runs with invisible *brown dwarfs* (actually 0.1 to 0.2 $M_\odot$ stars)
- Initial conditions from a moderately concentrated $W_0 = 7.0$ King model, control runs with different concentrations

Back-up slides - Formation scenarios for IMBHs

Merging scenarios:

- Runaway merging of massive stars in dense young clusters Portegies Zwart et al. 2004
- Four-body interactions in dense GCs Miller & Hamilton 2002

Non-merging scenarios:

- Population III stars Madau & Rees 2001

The mechanism for forming IMBHs (if any such process ever takes place) is still debated.

Back-up slides - Half-mass relaxation time

The timescale over which two-body encounters between stars attain thermalization of the distribution function is named relaxation time.

In astrophysical units, the half-mass relaxation time is (Djorgovski 1993):

$$t_{rh} = \frac{8.9 \cdot 10^5 yr}{\log(0.4N)} \times \frac{1 M_{\odot}}{\langle m_* \rangle} \times \sqrt{\frac{M_{tot}}{1 M_{\odot}}} \times \frac{r_{hm}}{1pc} \sqrt{\frac{r_{hm}}{1pc}}$$

Back-up slides - Selected references

- Pasquato et al. 2009 ApJ, accepted (astro-ph/0904.3326v1)
- Gill et al. 2008 ApJ, 686, 303
- De Marchi & Pulone 2007 A&A, 467, 107

Homology, scaling laws, the virial coefficient I

GCs are virialized systems:

$$2T + U = 0$$

T and U can be expressed in terms of a scale mass M, scale radius R, scale velocity dispersion σ:

$$T = \alpha M \sigma^2$$

$$U = -\beta \frac{GM^2}{R}$$

Now

$$M = L \cdot \langle \frac{M}{L} \rangle$$

$$SB = -2.5 \log \frac{L}{R^2} + k$$

and we introduce the virial coefficient

$$k_v = \alpha / \beta$$

We get:

$$\log R = 2 \log \sigma + 0.4 SB + \log \frac{k_v}{M/L} + k$$

Homology, scaling laws, the virial coefficient II

A FP then emerges only if

- clusters are virialized
- $\log k_v/(M/L)$ is constant or depends (linearly) on $\log R$ and SB

Naive assumptions:

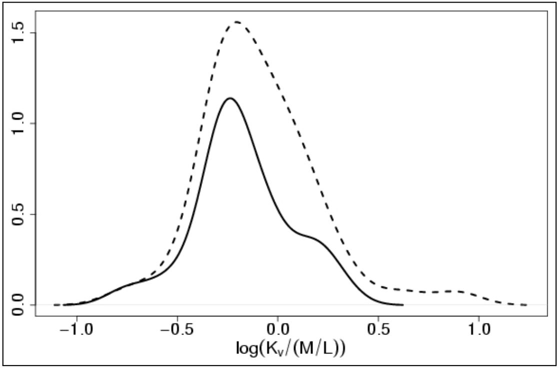
- M/L can be assumed equal for all GCs
- King models with only 1 dimensionless shape parameter c which is one-to-one to k_v describe well GCs
- observationally c depends on SB (Djorgovski & Meylan 1994)

But

- an IMBH introduces a new dimensional scale quantity (e.g. its mass)
- this breaks the one-to-one link between c and k_v
- in eq. $\log R = 2 \log \sigma + 0.4 SB + \log \frac{k_v}{M/L} + k$ then k_v introduces a noise term

Homology, scaling laws, the virial coefficient III

- IMBHs have the potential to add scatter to the FP
- k_v can be measured under the assumption that M/L is constant



- k_v distribution looks bimodal if central σ used