Intermediate Mass Black Holes in Globular Clusters

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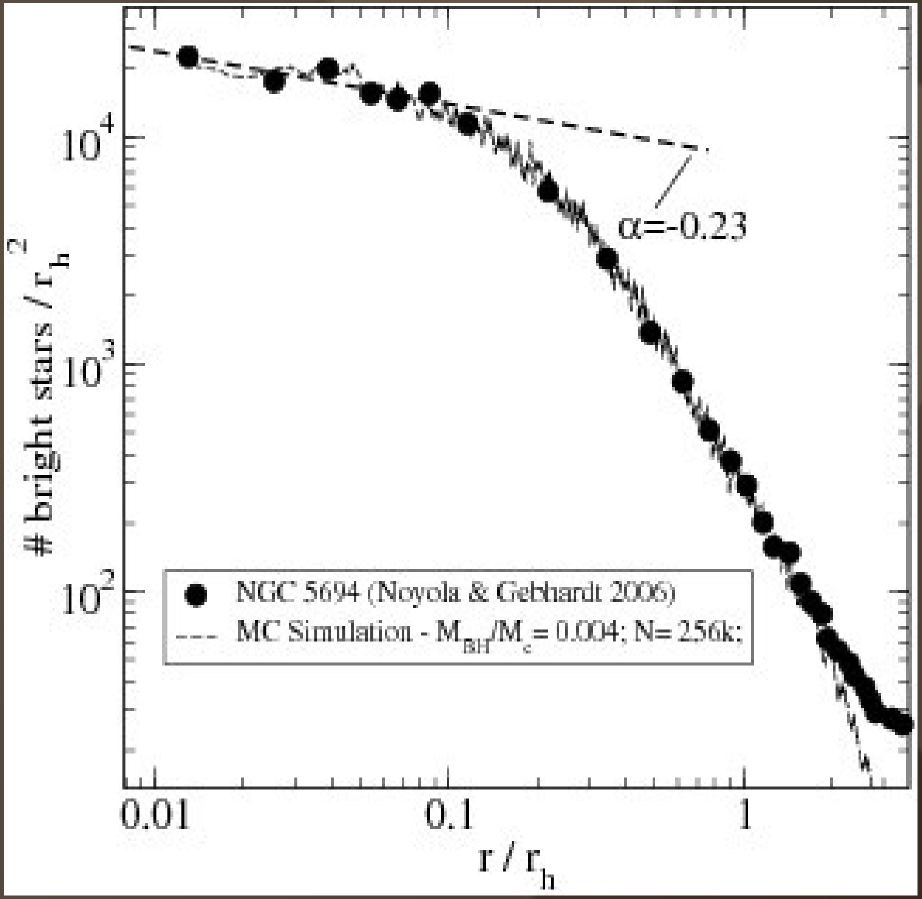
CIERA

GC Simulations with Central IMBHs - Monte-Carlo Method

- Can be thought of as randomized N-body method
  - Star-by-star description of GC
  - Therefore easy to add additional physical processes
  - Resolves orbital evolution on relaxation time scale
    - $$t_{relax} = \frac{N}{\log \gamma N} t_{cr} \gg t_{cr}$$
    - Makes it much faster than direct N-body
    - Can simulate cluster with realistic number of stars
- Includes tidal disruption of stars by IMBH (loss-cone) (analogous to Freitag et al. 2002)
- stellar evolution: BSE code (Hurley et al.. 2002)
- strong binary interactions: Fewbody (Fregeau 2004)

Imprints of IMBHs on the Structure of GCs



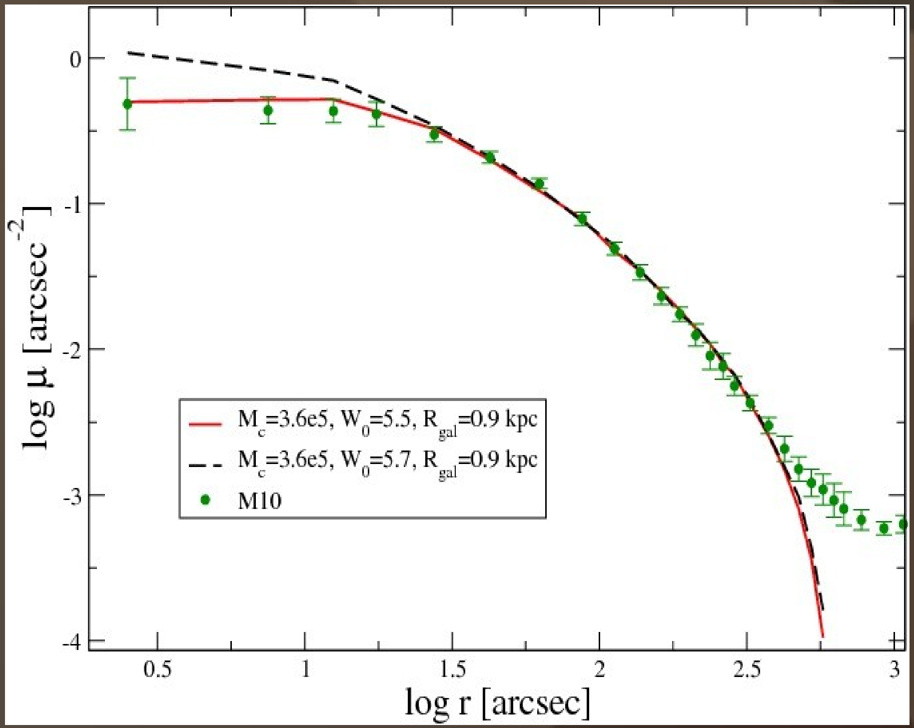
- cusp in surface density and velocity dispersion
  - Observed projected density cusp shallow
  - GC center dominated by dark remnants
  - only a few bright stars within the influence radius of IMBH to determine velocity dispersion cusp
- denisty cusp of bright stars follows a power-law slopes of 0.1-0.3
- based on cusp slopes Baumgardt et al. (2005) identified 9 candidate clusters with IMBH

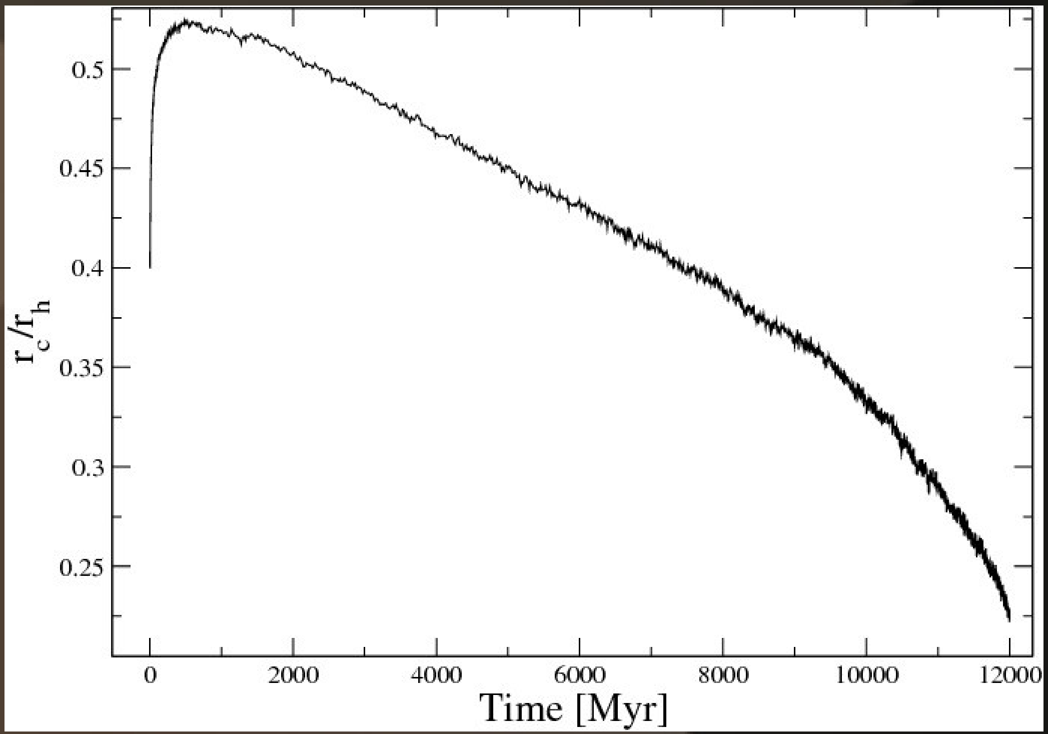
To what extent does the absence of cusps constrain IMBH mass?

Modelling M10

- Nearby cluster: 4.4 kpc
- Galactic distance: 4.1 kpc
- Tidal radius (profile): 26 pc
- Concentration: 1.4 (W0=6.5)
- Mass: 10^5 Msun
- surface brightness profile:
  - R< 1.7pc: Noyola & Gebhardt (2006) (HST/WFPC2)
  - R> 1.7pc: Trager (1995) (various ground based data)
- star count data for stars <19mag:
  - Lanzoni (priv comm.) ACS/HRC
  - cover the whole radial range

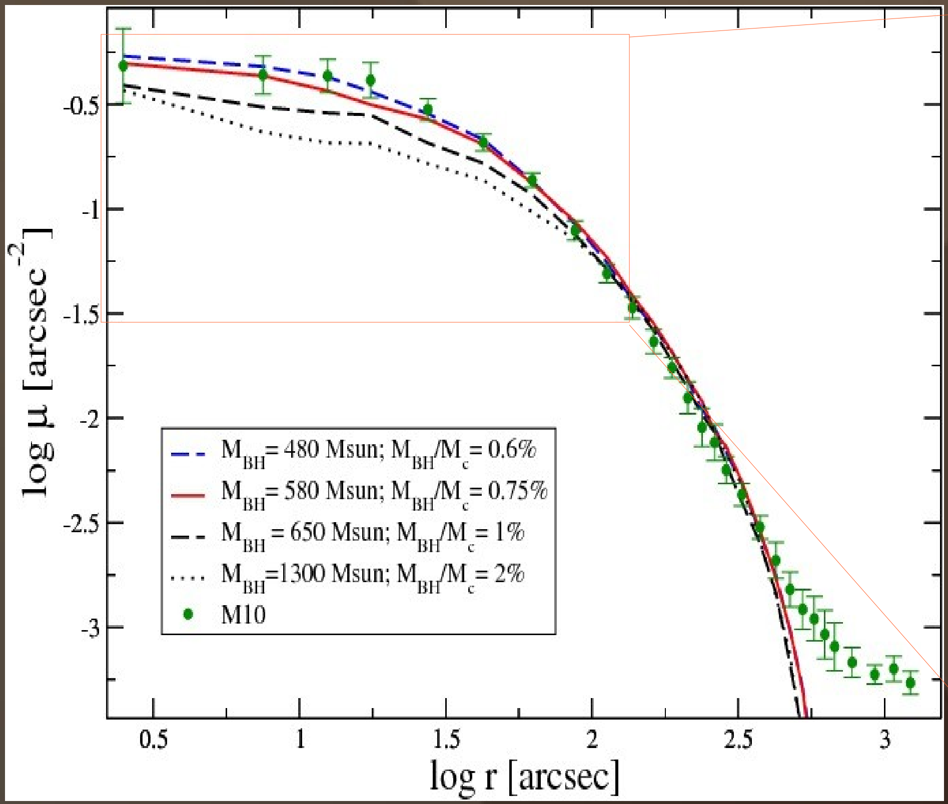
Results w/o IMBH

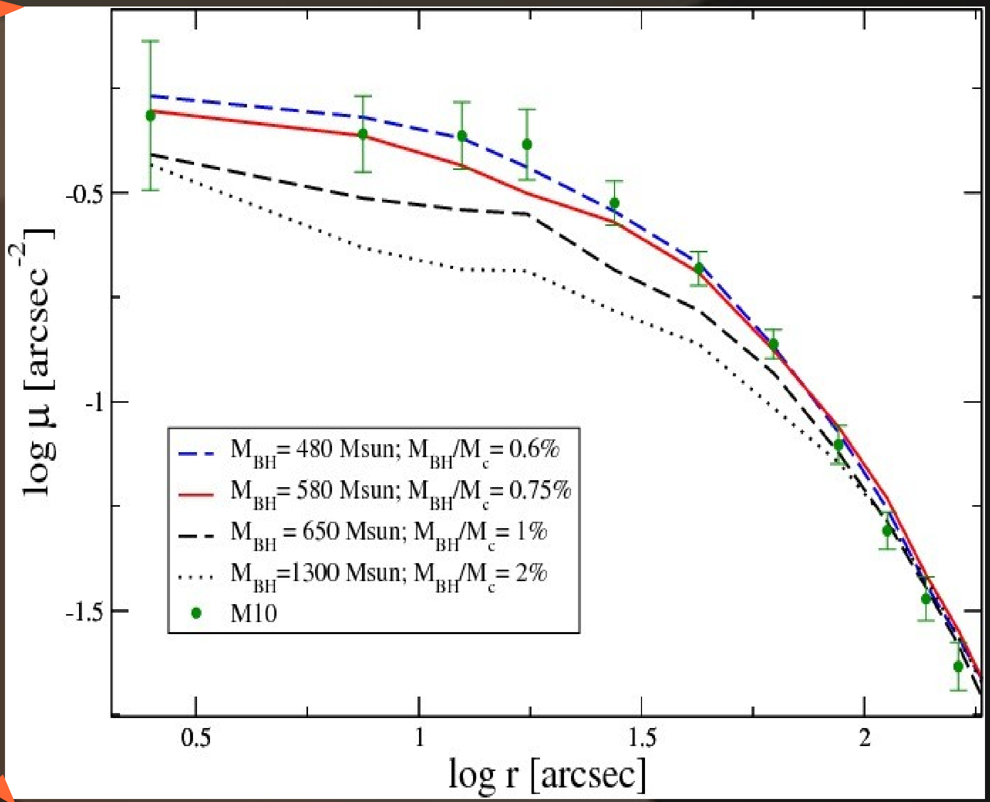




- Model: W0=5.5, initial Mc= 360 000 Msun; circular orbit at 0.9kpc
- fits observed SDP reasonably well
- find also good agreement for galactic distances up to 1.1kpc
- cluster still in core contraction, not in binary burning stage

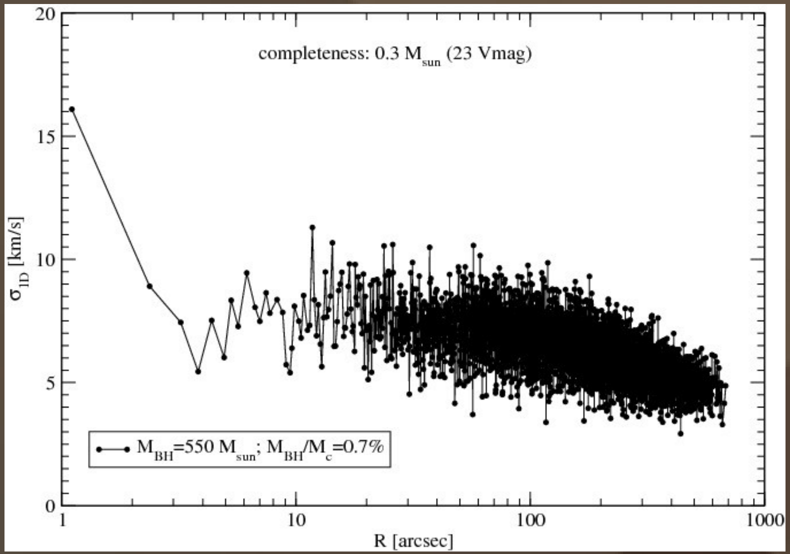
Surface Densities with IMBHs

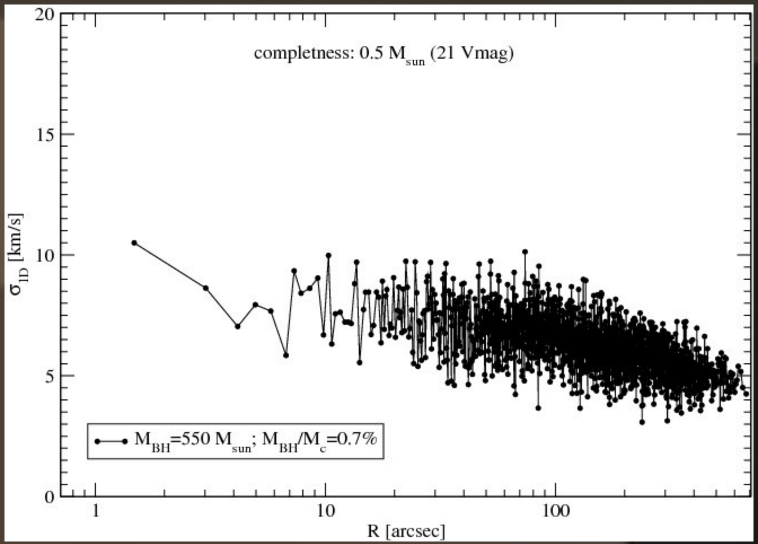


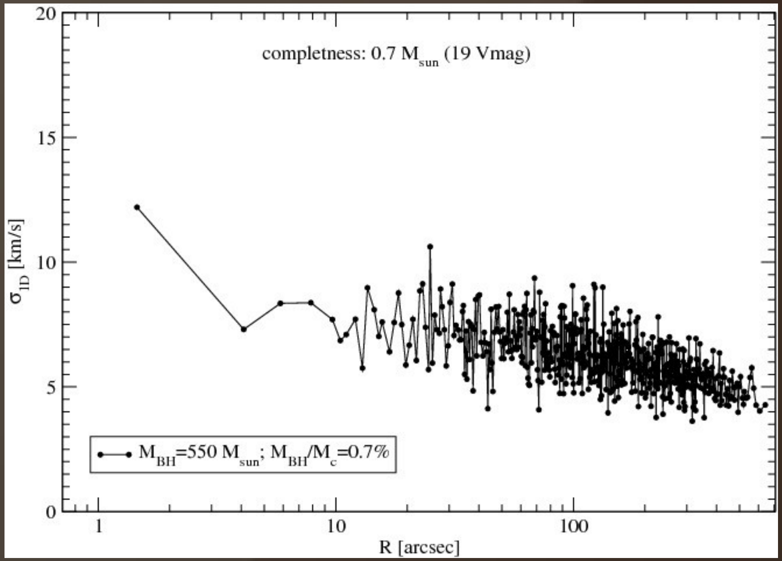


- Models with M < 0.75% Mc fit observed SDP reasonably well
- Models with M > 0.75% Mc do not

Kinematic Signature

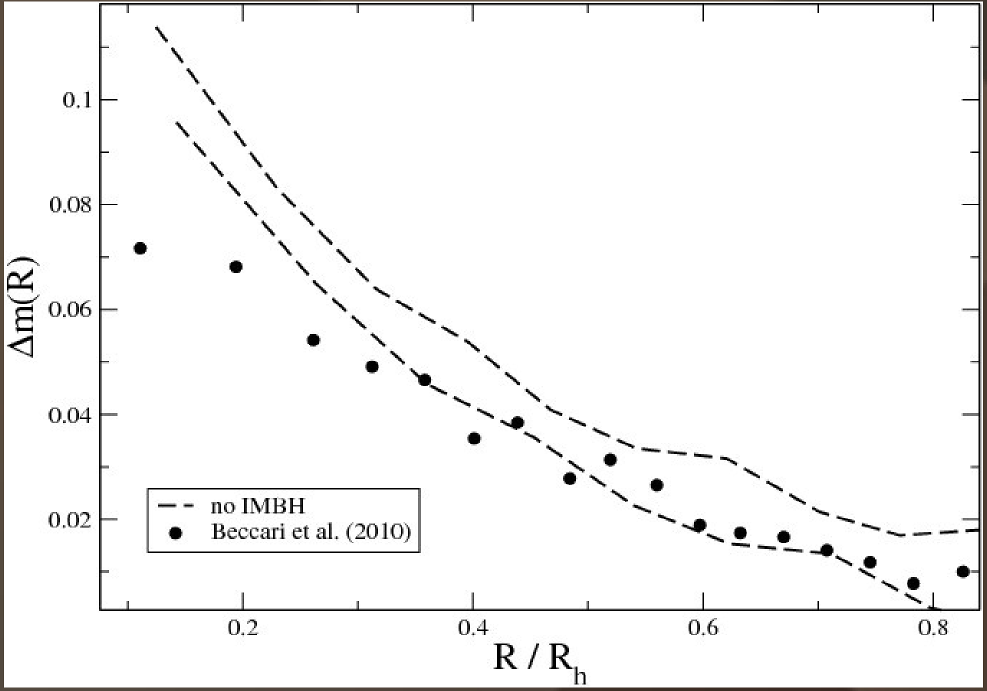




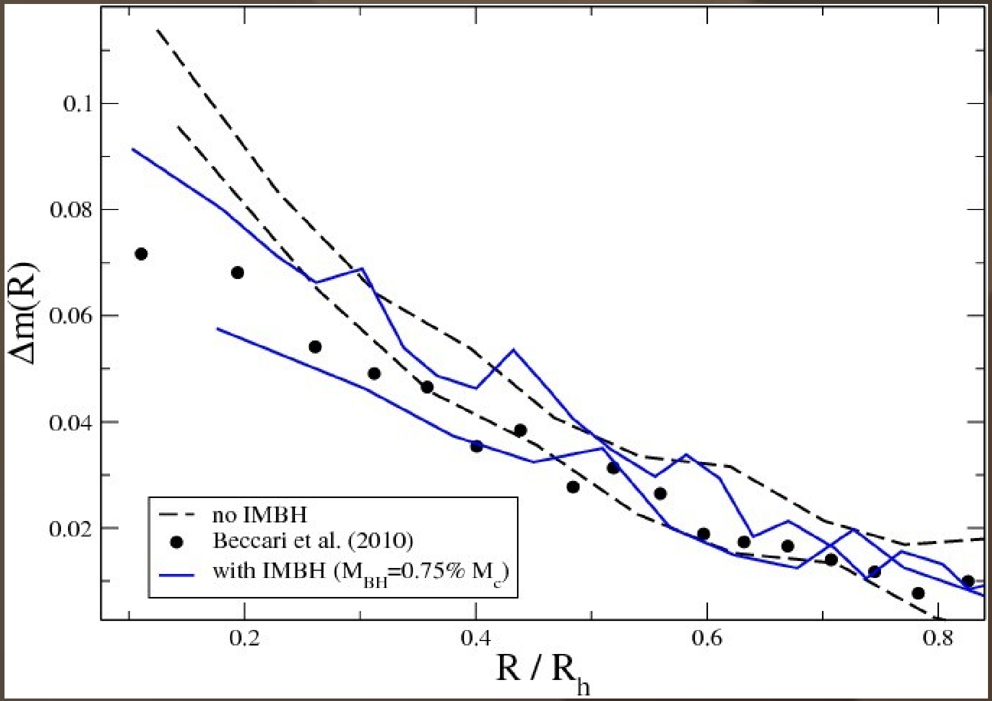


- Velocity dispersion cusp within 2-3 arcsec
- Could be easily resolved
- BUT: only about 10-20 MS stars have significantly larger velocities
- might be difficult to reliably infer the presence of an IMBH

Mass Segregation Signature



Mass Segregation Signature



- noticable mass segregation quenching with IMBH
- cluster with IMBH agrees with mean mass profile
- also, no significant quenching through binaries alone
  - since cluster is still in core contraction
  - IMBH only explanation?

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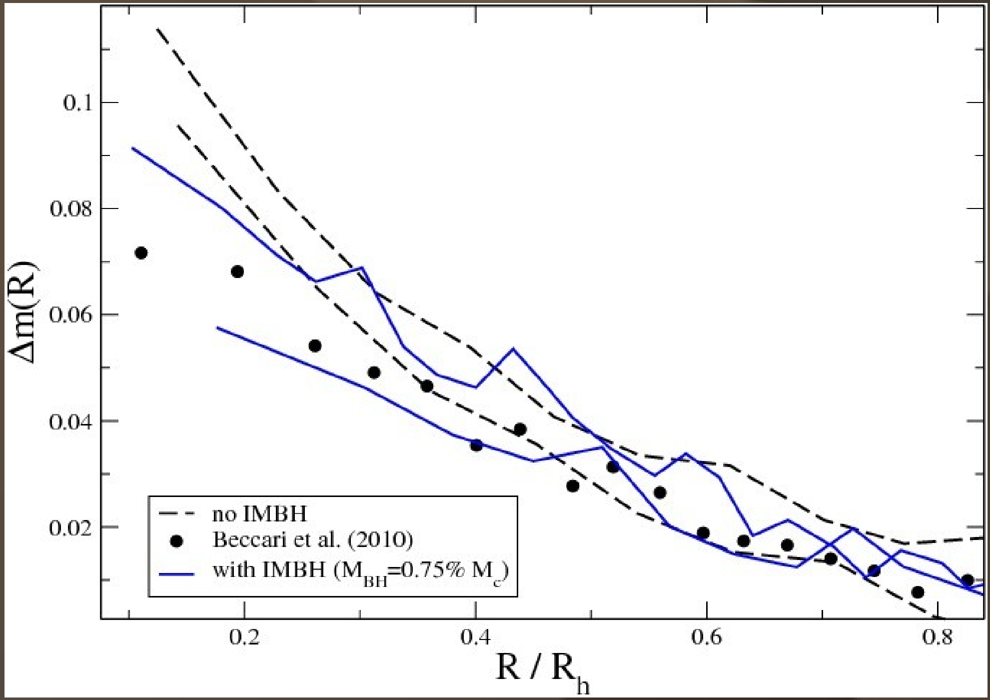

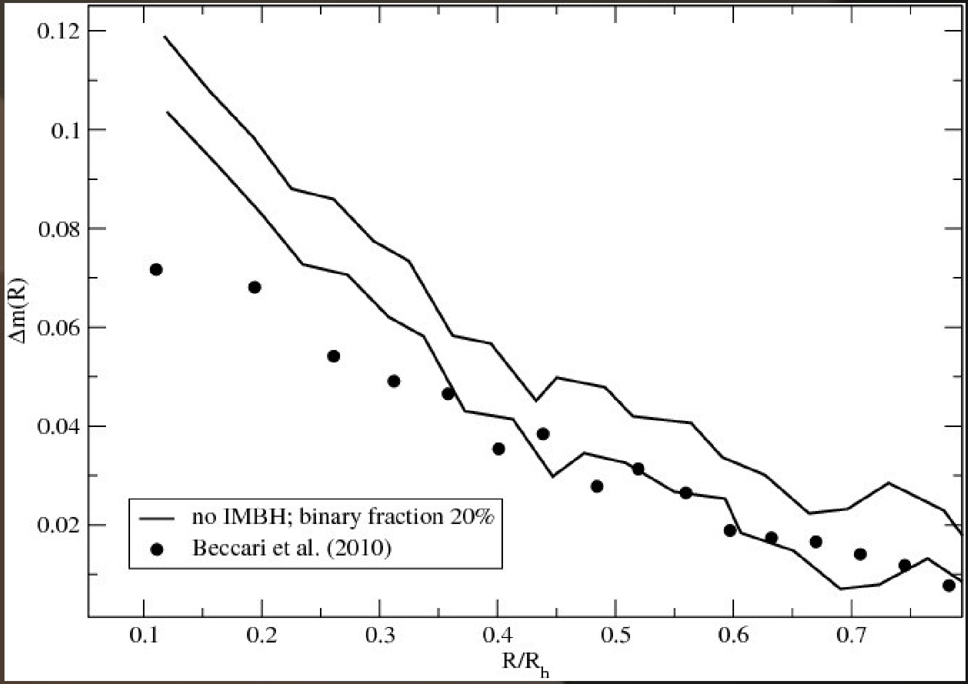

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Escaped Stars

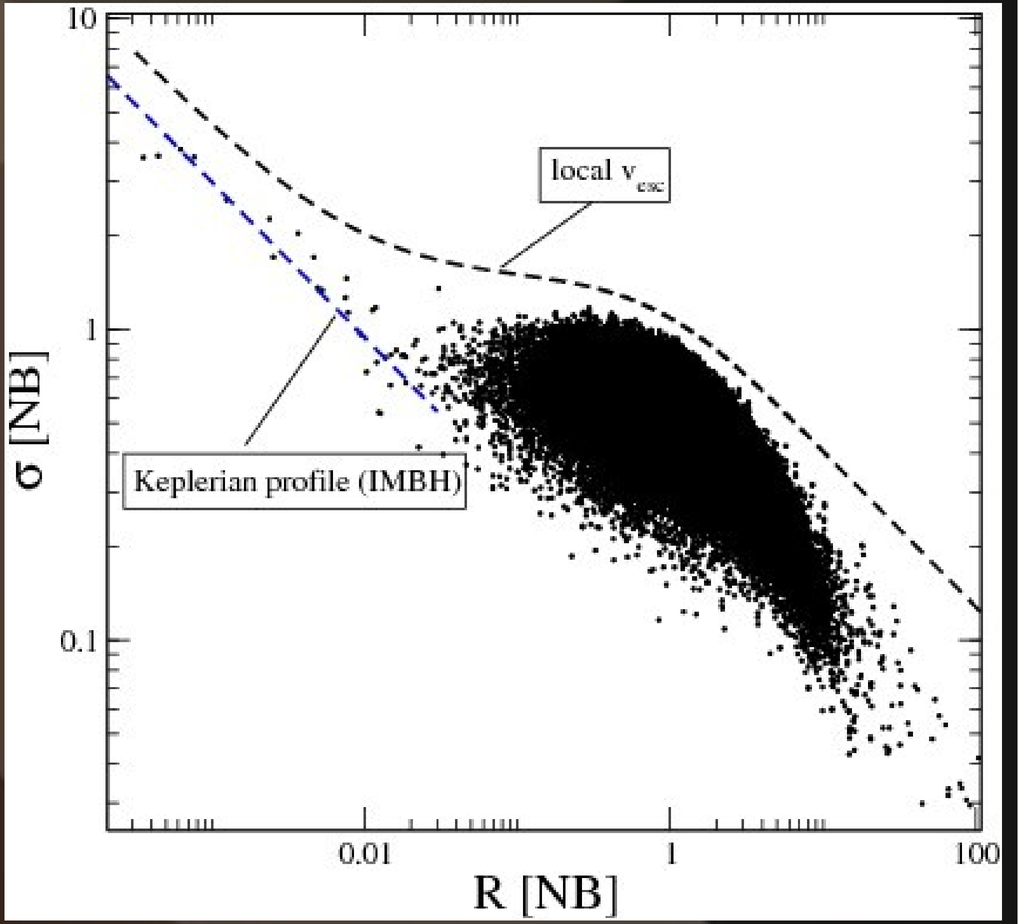
- due to presence of IMBH

  → increase in velocity dispersion

  → vesc/sigma lower

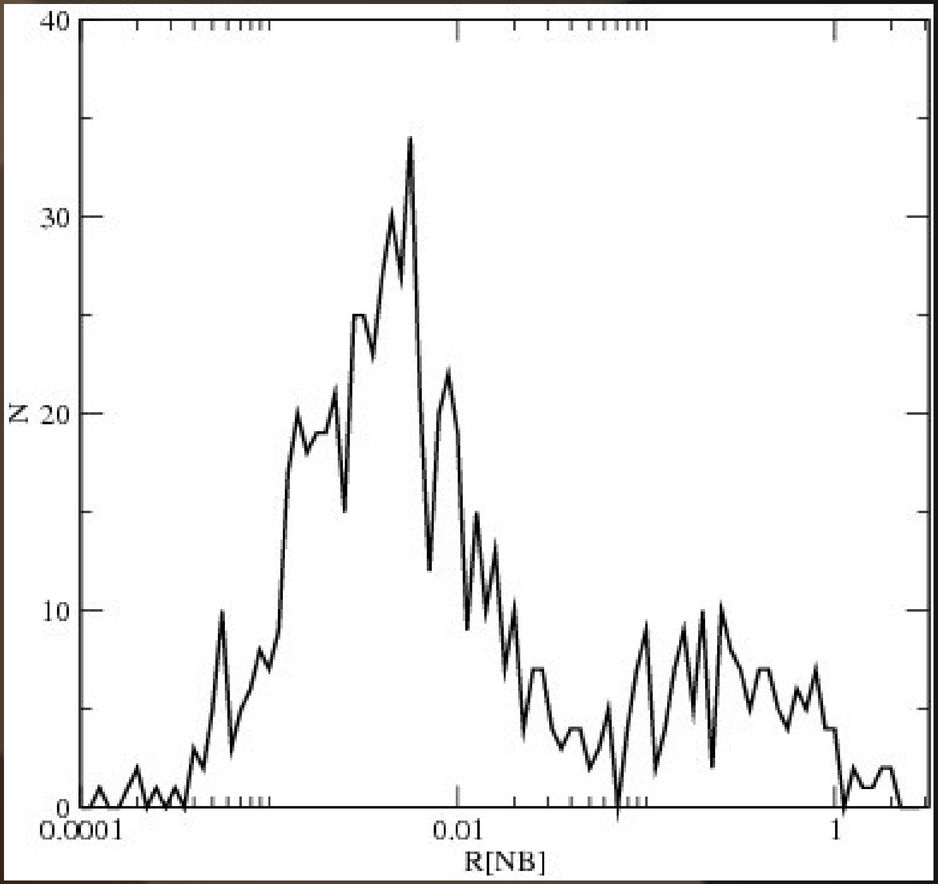
  → stars escape more easily as they strive towards Maxwellian vel. distribution

- vesc/sigma also lower in outer core region



Escaped Stars

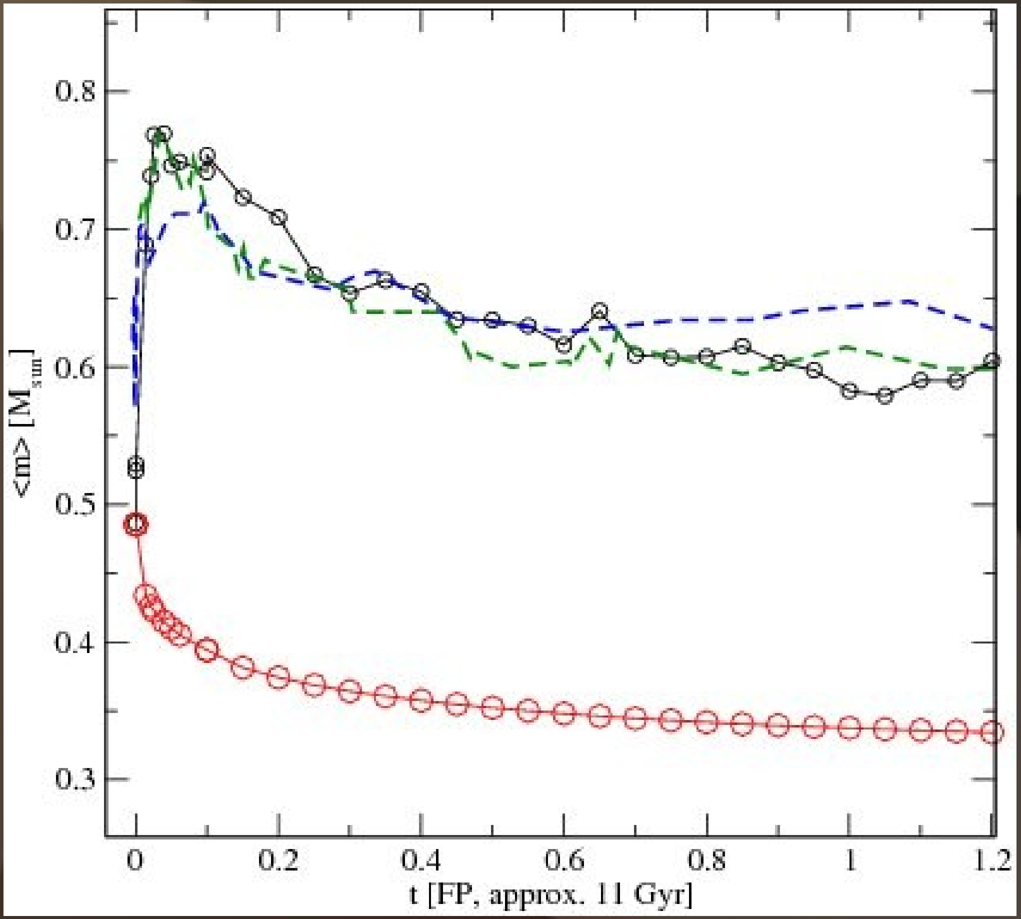
- two distinct escape zones
  - outer core region (r> 0.1)
  - cusp region (r<0.01)
  - "zone of avoidance" (0.01<r<0.1)
- reflects low vesc/sigma regions



Conclusions

- We created Monte Carlo models of the globular cluster M10
  - results suggest that M10 is still in its core contraction phase
  - although it shows no clear sign of an IMBH in its center (cuspy SBP), could still harbor one with M<=580 Msun
  - Velocity dispersion cusp easily resolvable
  - But: only 10-20 MS stars available that have significantly larger velocities
  - IMBH **might** turn out to be only explanation for mass segregation quenching
    - could mean M10 strong GC candidate with IMBH
- Mass segregation quenching **not only** due to strong binary encounters:
  - low vesc/sigma in cusp region and outer core
  - stars escape through tail of Maxwell velocity distribution

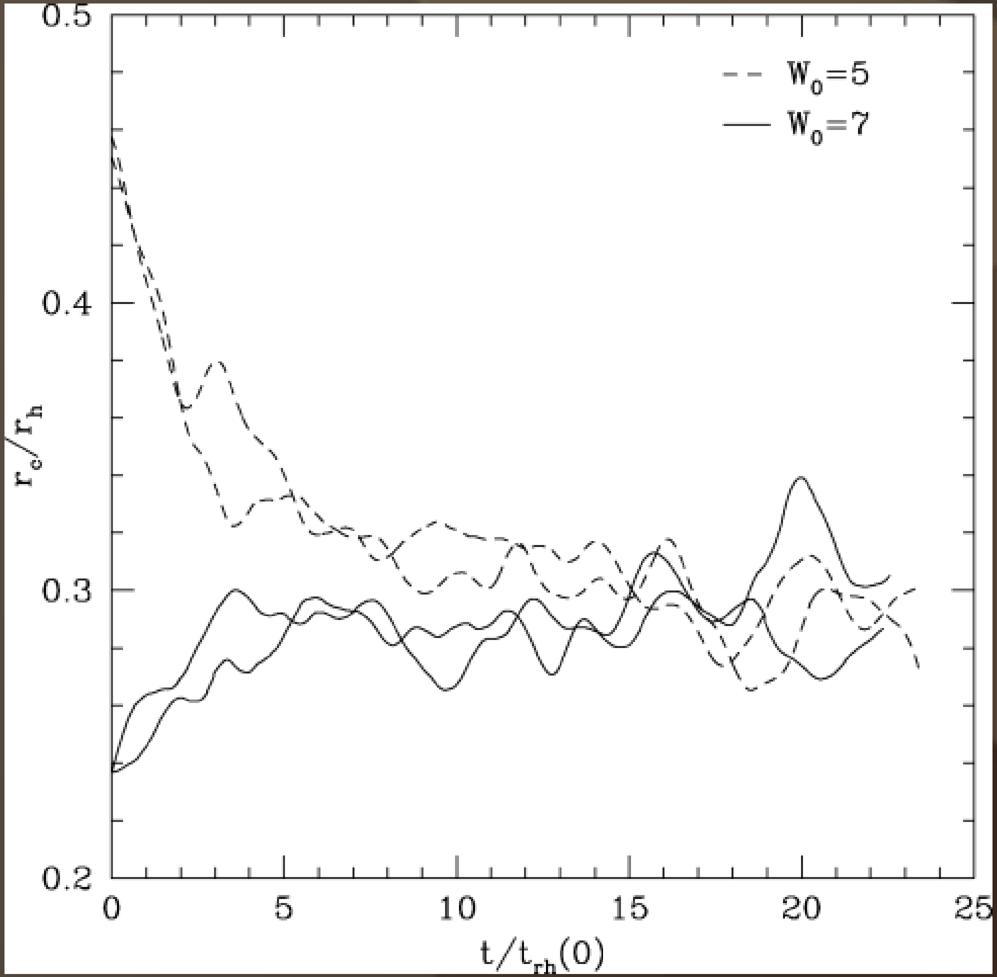
Mass Segregation with IMBH



M(BH)= 500 Msun; Rvir= 4.8 pc; W0= 7;
N=128k; Mcl= 68300 Msun

- noticable quenching of mass-segregation
- despite binary interactions with IMBH not included

Imprints of IMBHs on the GC Structure



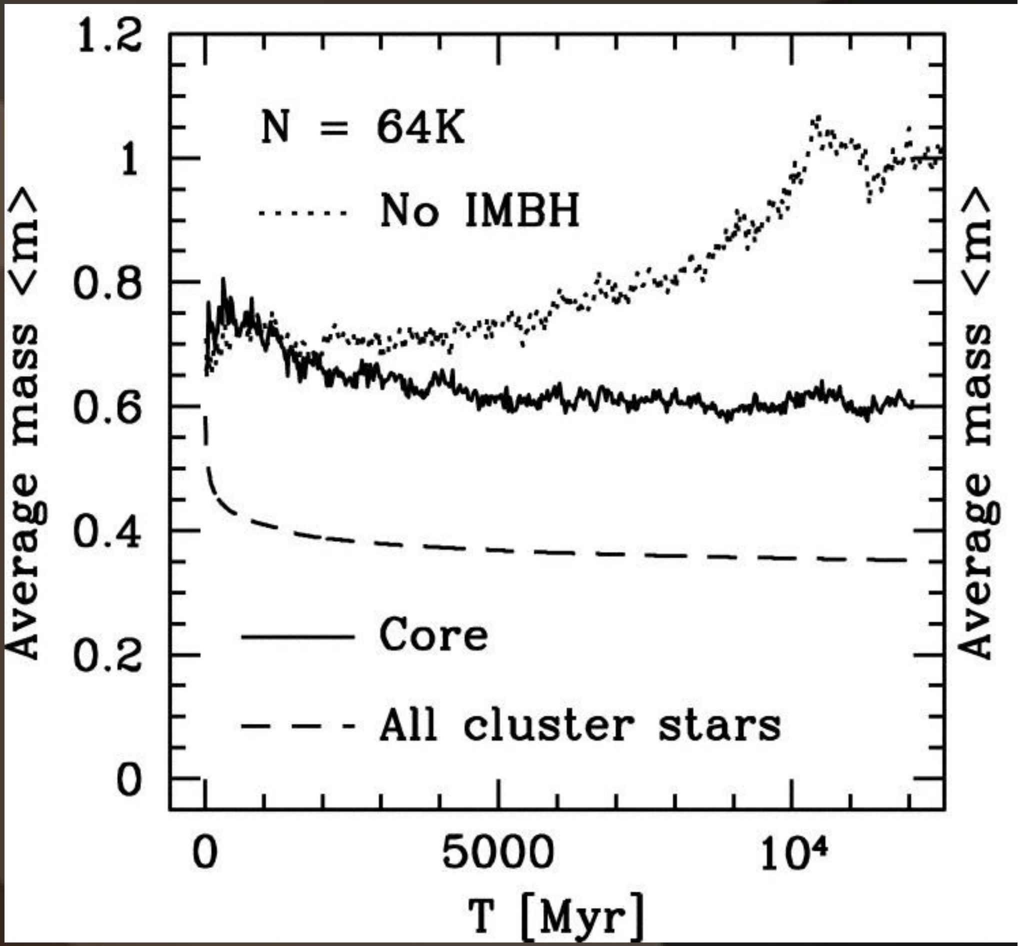
Trenti et al. (2007)

- massive IMBH → large core
- stellar disruption/escape → energy creation in core → core expansion
- for $M_{BH}/M_{clus} \sim 1\%$ $r_c/r_h \sim 0.3$
- relation between cluster concentration, IMBH mass, and inner surface brightness slope (Miocchi 2007):

$$11.6s - 4.85 \lesssim \log\left(\frac{M_{BH}}{M_{clus}}\right) \lesssim -1.14c - 0.694$$

Mass-Segregation in Clusters with IMBHs

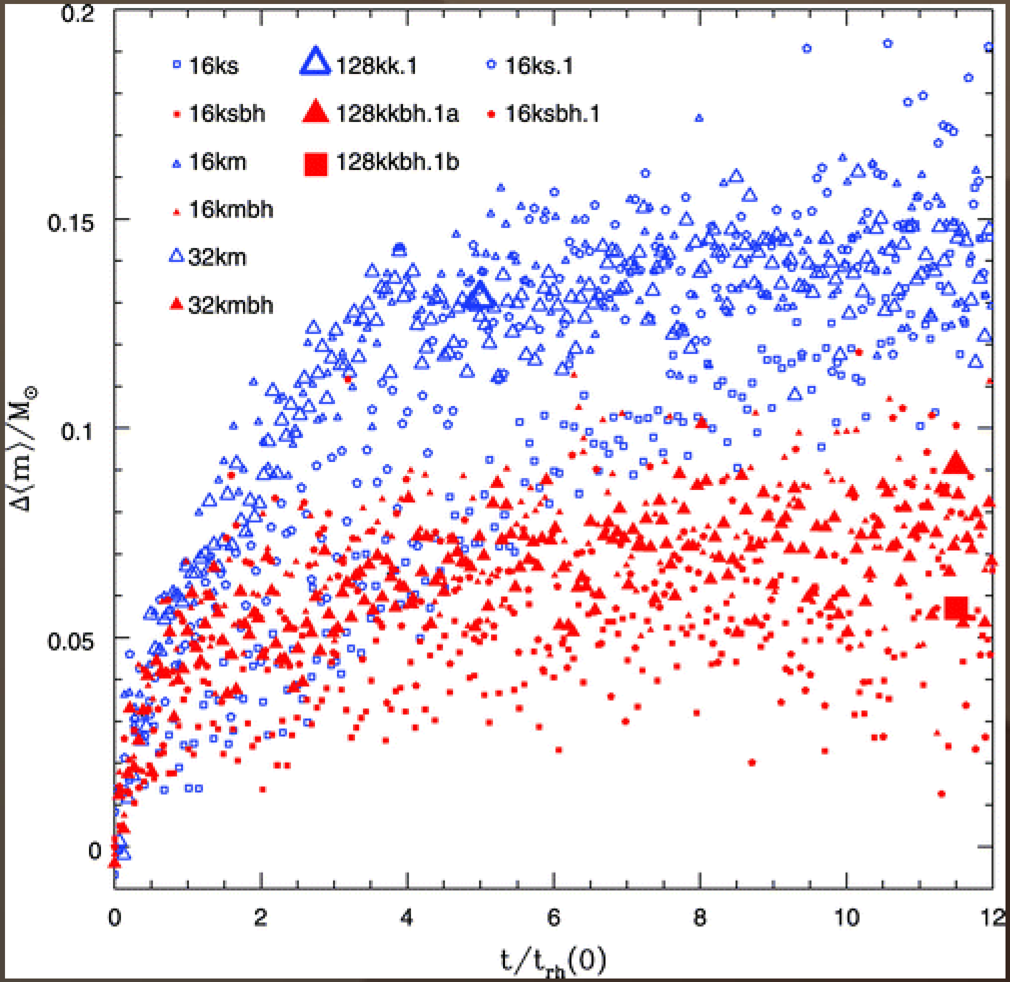
- Mass-Segregation:
  - Massive stars sink to the center
  - Lighter stars pushed further out
- No IMBH:
  - average stellar core mass that of most massive stars/remnants
    - larger than average cluster mass
- With IMBH:
  - Average stellar core mass remains nearly constant
  - massive stars/remnants ejected through strong IMBH-binary interactions



Baumgardt et al. (2004)

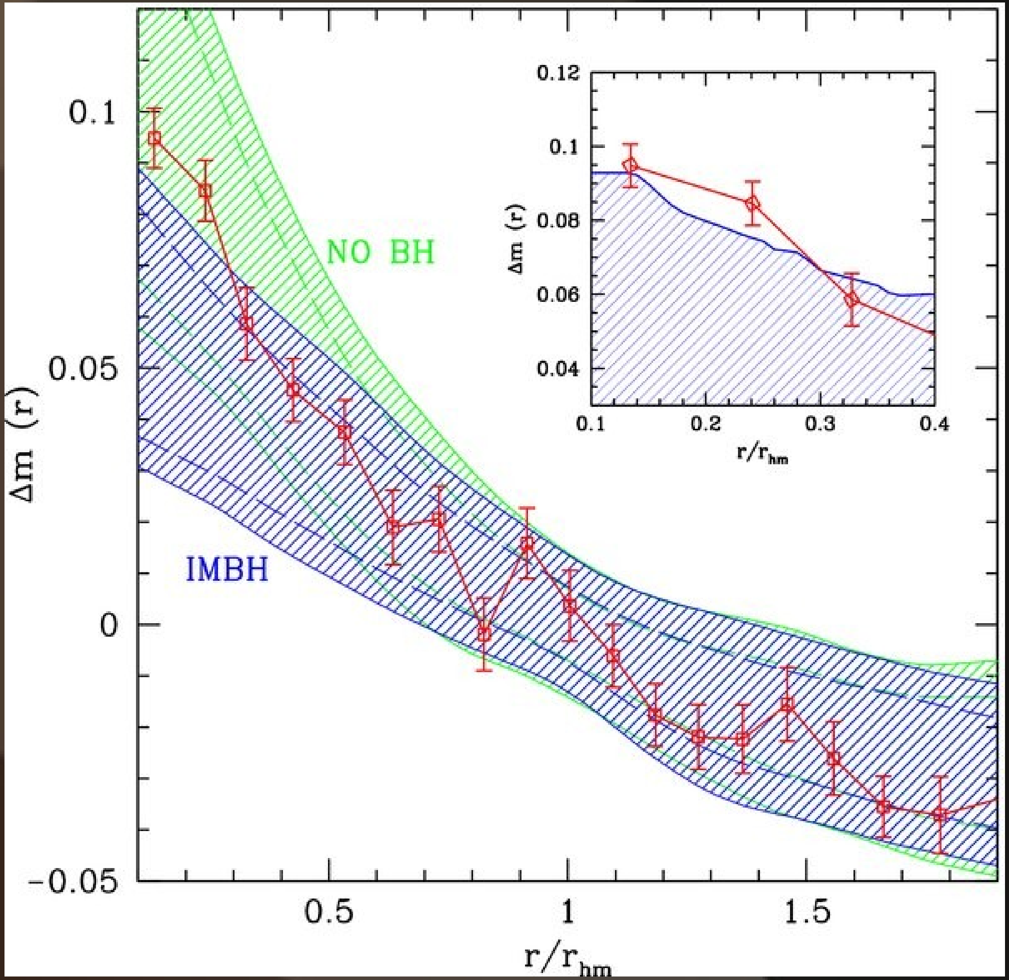
Average Mass Profile and IMBHs

Gill et al. (2008)



$$\Delta \langle m \rangle = \langle m \rangle (r = 0) - \langle m \rangle (r = r_h)$$

Pasquato et al. (2009)

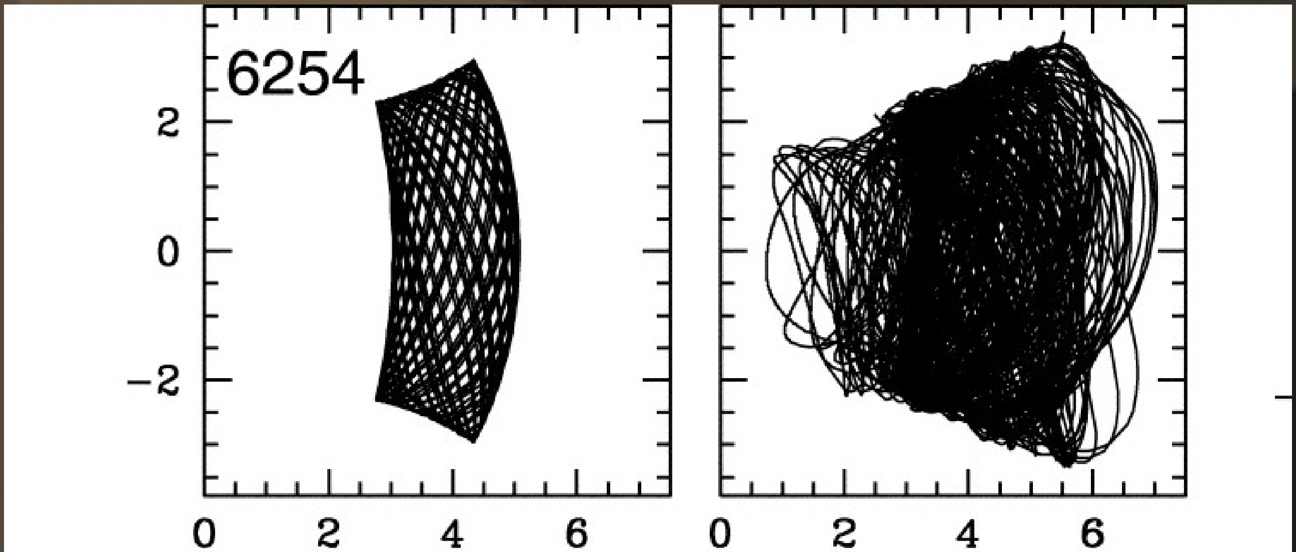


$$\Delta \langle m \rangle = \langle m \rangle (r) - \langle m \rangle (r = r_h)$$

Model Parameters

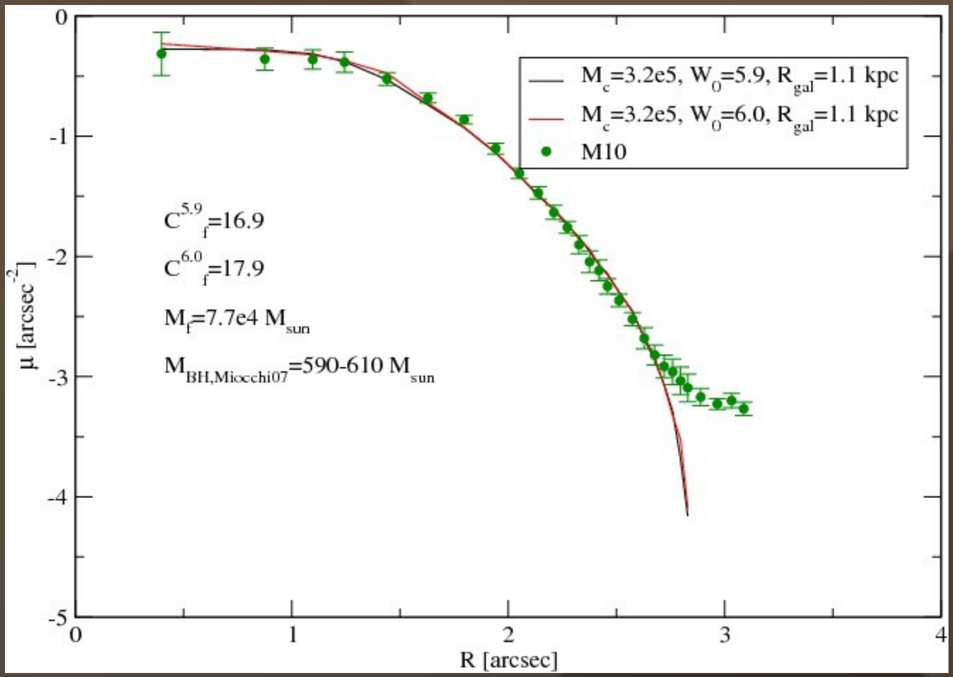
- Initial Mass: 270 000 - 450 000 Msun
- King model with W0= 5, 5.5-6.5, 7 (12 values)
- galactic distances: 0.9 - 1.7 kpc
- IMF:
  - Kroupa et al. (2001)
  - 0.1 – 100 Msun
  - N = 400 000 - 700 000
- IMBH masses: 300 – 2000 Msun
- Z=0.001
- binary fraction: 0 and 20%
- so far approx. 600 runs (each 2 days average runtime)

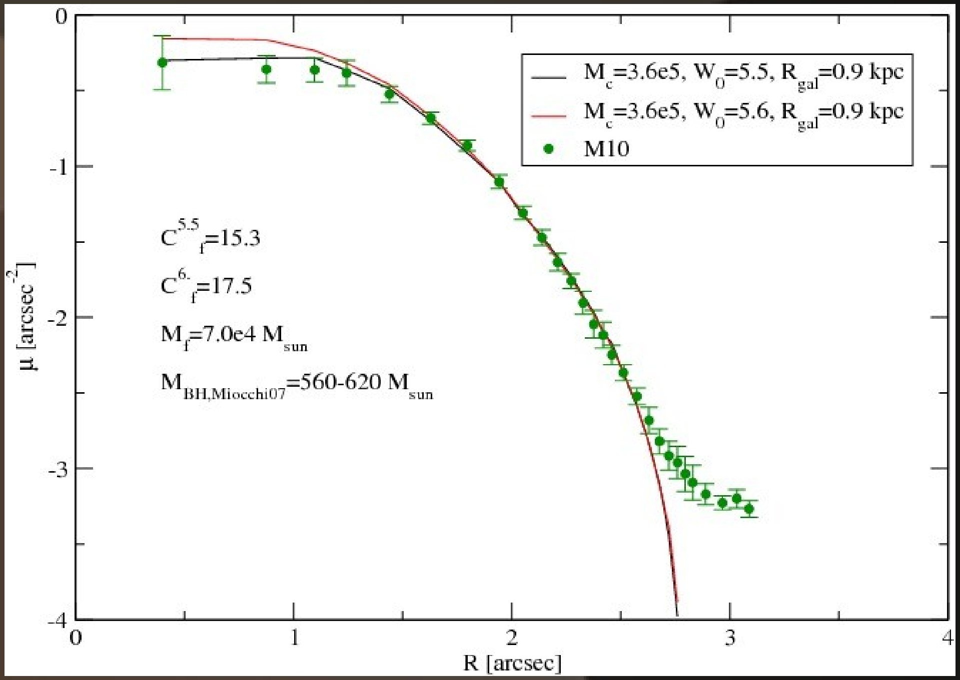
Choice of Tidal Cut-Off Radius



- Assume that cluster fills its Roche lobe initially
- Since orbit of M10 eccentric → SBP most strongly influenced near perigalacticon
- Axis-symmetric Galaxy model (Dinescu et al. 1999; left): rp= 3.4 kpc
- Galaxy model with bar (Allen et al. 2006; right): rp= 0.7 - 3 kpc
- effective galactic distance of about 0.9-1.1 kpc leads to best fit
- results in initial cluster virial radius of about 5 pc (rh = 4 pc)

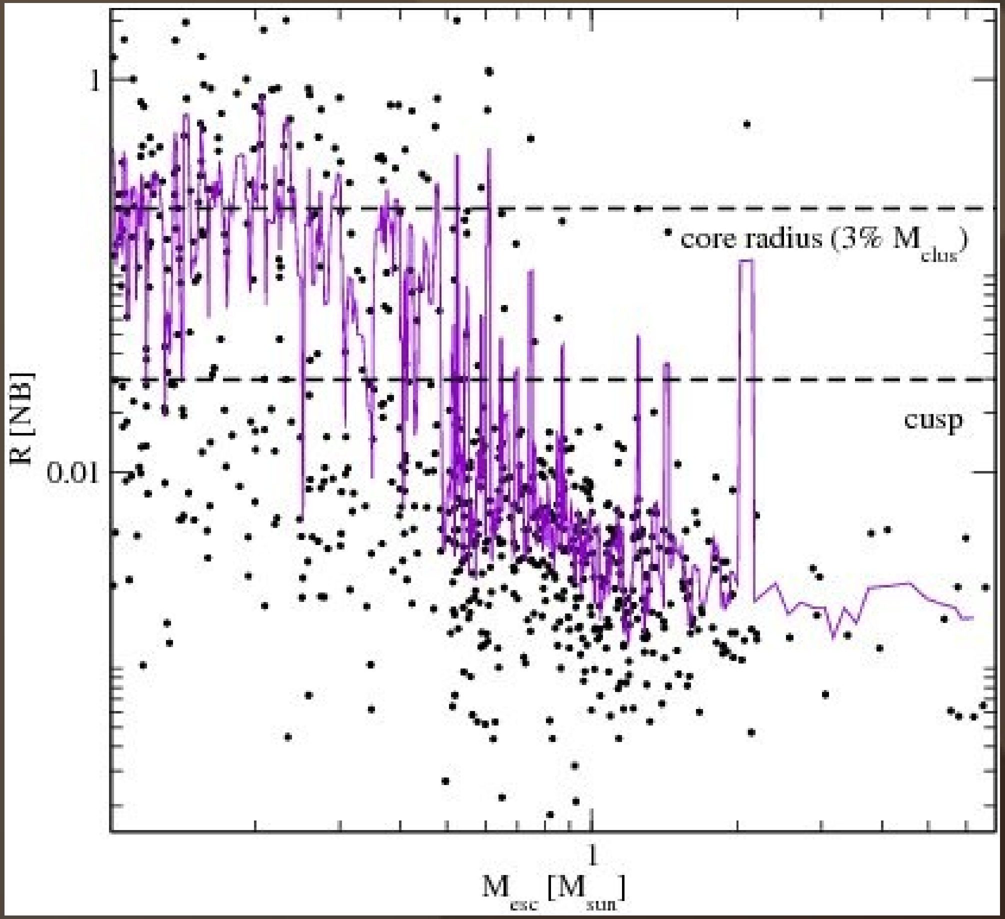
Comparison with Star Count data

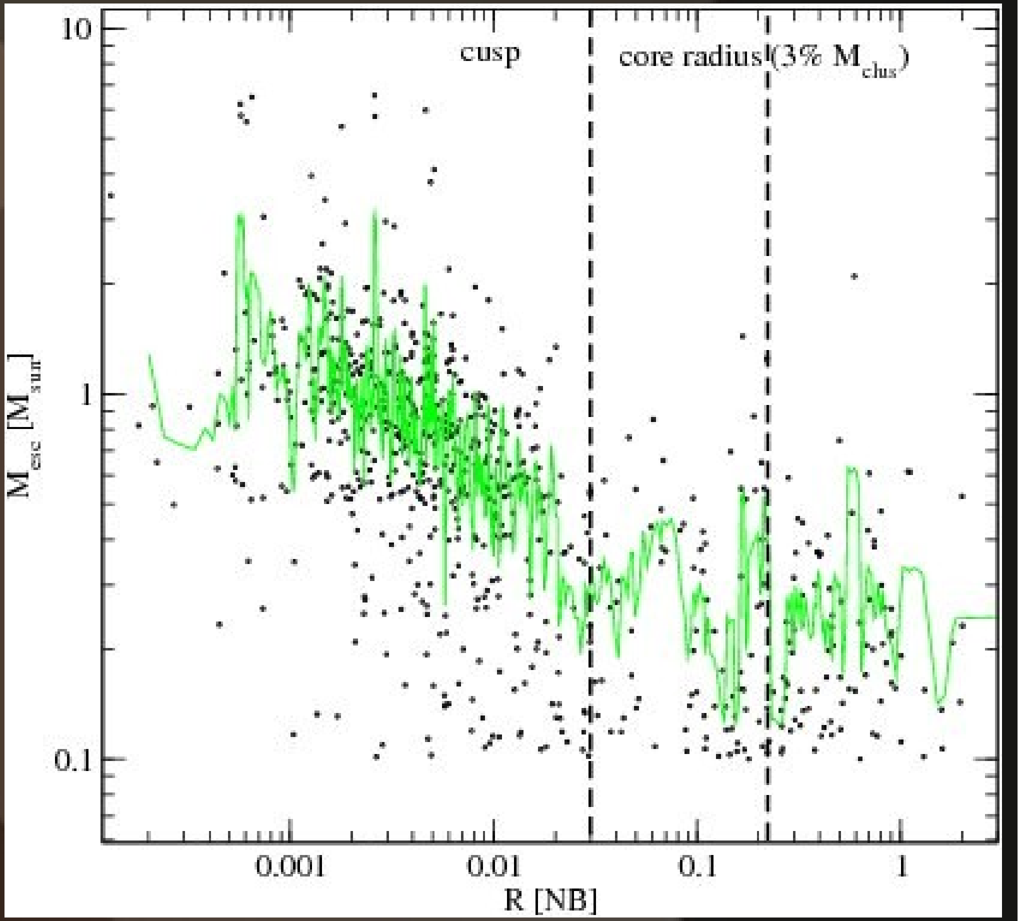




- All final models:
  - in core contraction
  - mass: 7-8x10^4 Msun
  - Trh = 4-4.5 Gyr !! (800 Myr in Harris catalog)
  - expected BH mass: 600 Msun to sustain core.

Escaped Stars





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- more massive stars escape inside IMBH cusp