Dynamic Evolution of Globular Clusters

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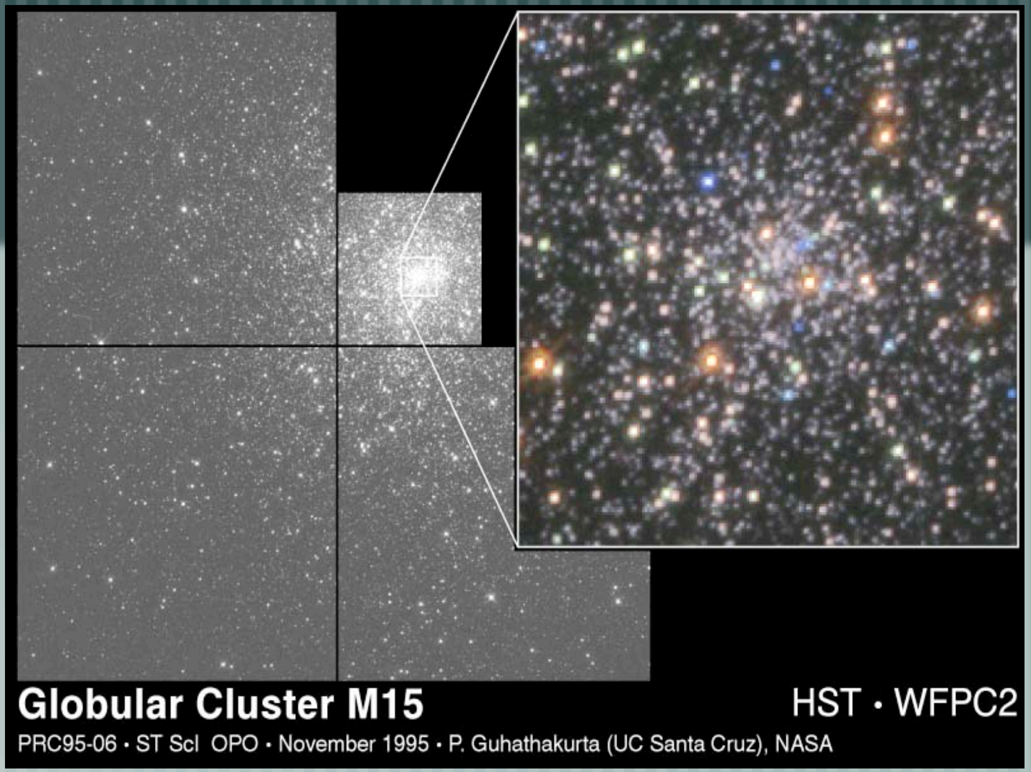
Outline

- Globular Clusters Conditions:
  - multiple stellar populations, a shift of paradigm
- Thermodynamics to the rescue:
  - Evolution on the two-body relaxation timescale
- Primordial Binaries
- Mass Segregation

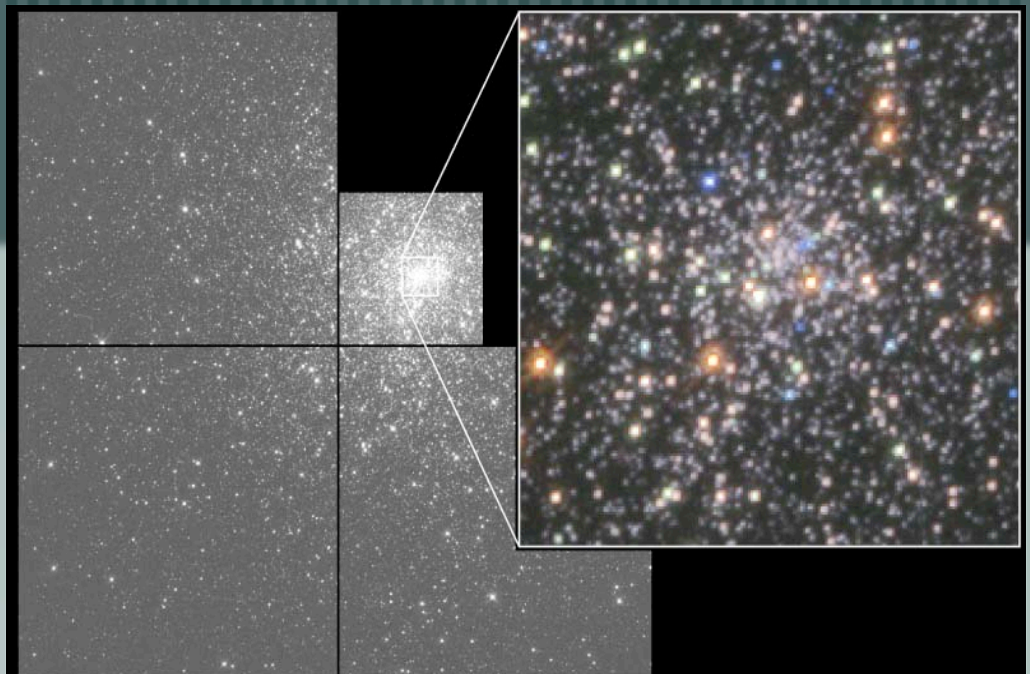
Globular Clusters



The picture before ≈2007

- Compact stellar systems
  - ≈10^5-10^6 old stars
  - high concentration: typical dimension of a few pc
- Live in and around galaxies
- Simple stellar population
  - Uniform age & chemical composition

Globular Clusters



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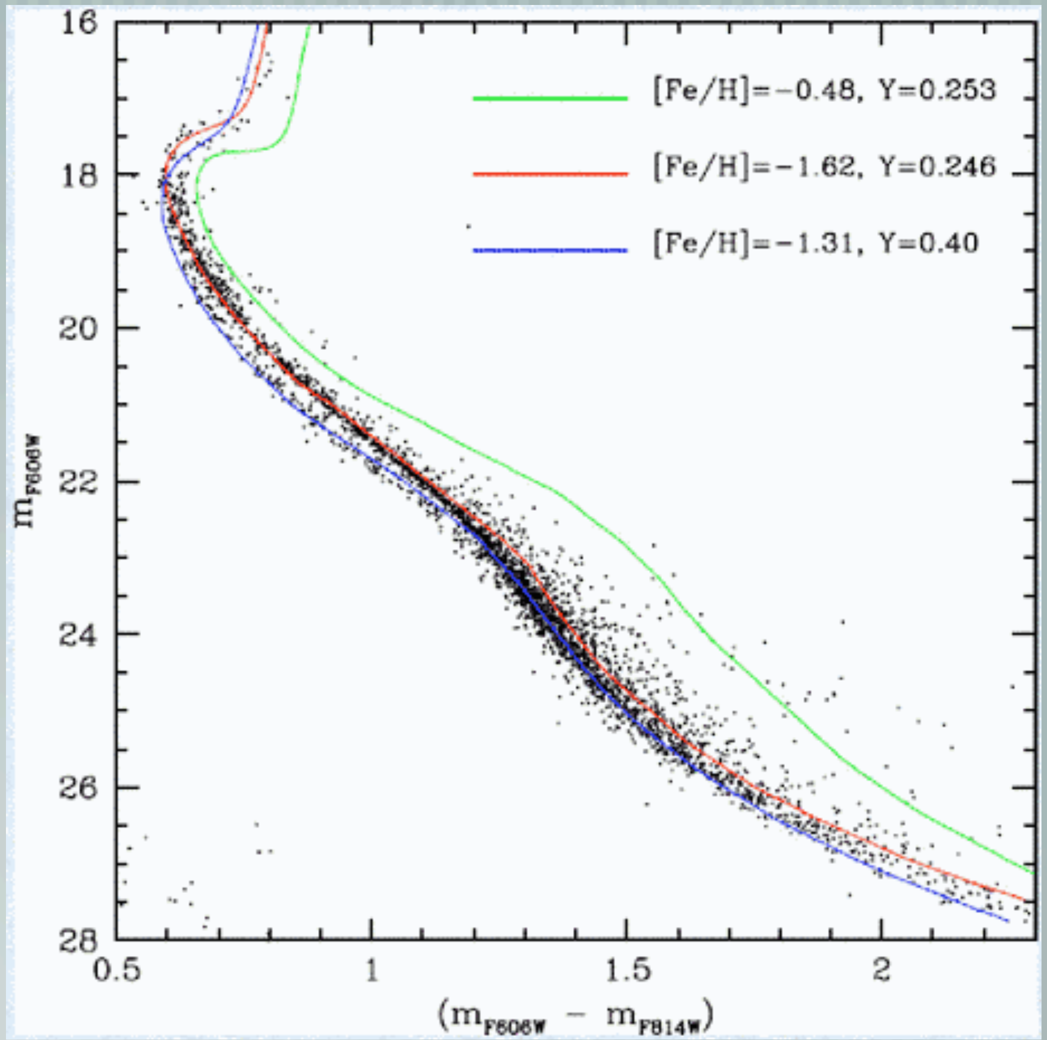
  - ~~Uniform age & chemical composition~~

Globular Clusters

The picture today

- GCs have Multiple Stellar Populations
- They imply different helium abundance
- Can be explained with a complex dynamic formation history
  - Very significant mass loss in the first generation (Vesperini et al. 2008)

Omega Cen

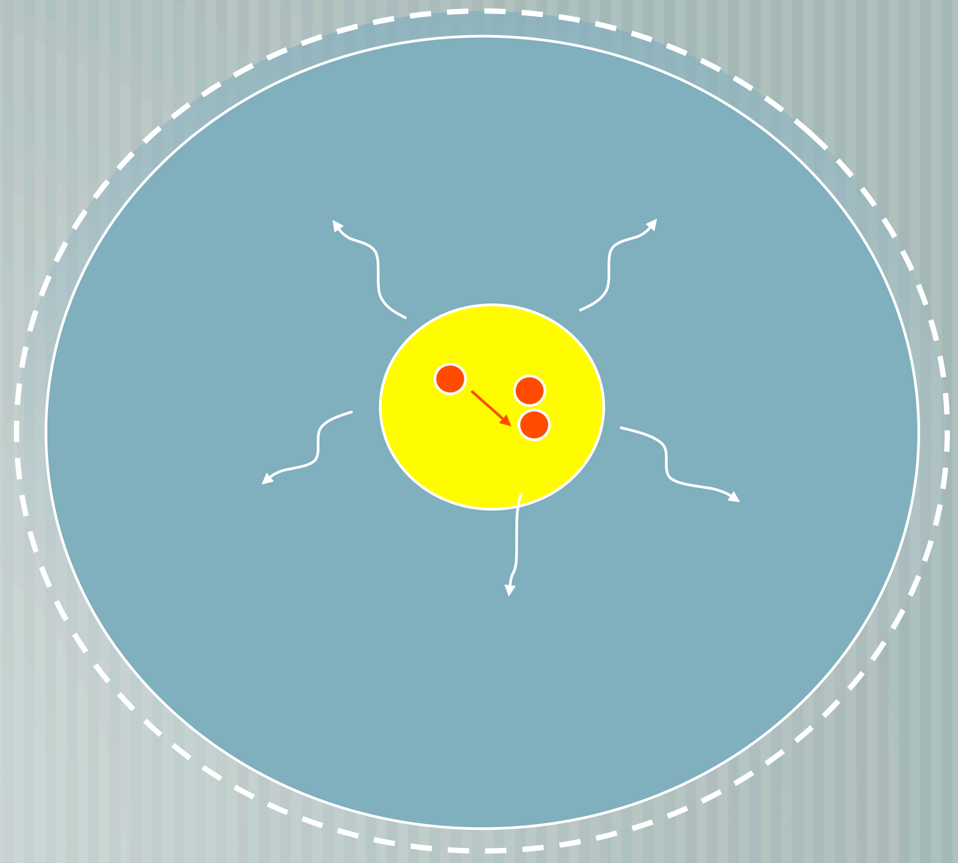


Piotto 2009 KITP conference

Globular Clusters: long term evolution

- Evolution on the two-body relaxation timescale (~10^9 yr for globulars)
- Details of initial conditions are erased
- Energy flux generated in the core through gravitational encounters
- Equilibrium established:
  - core flux is equal to half mass radius flux
  - this fuels global expansion

Thermodynamics to the rescue

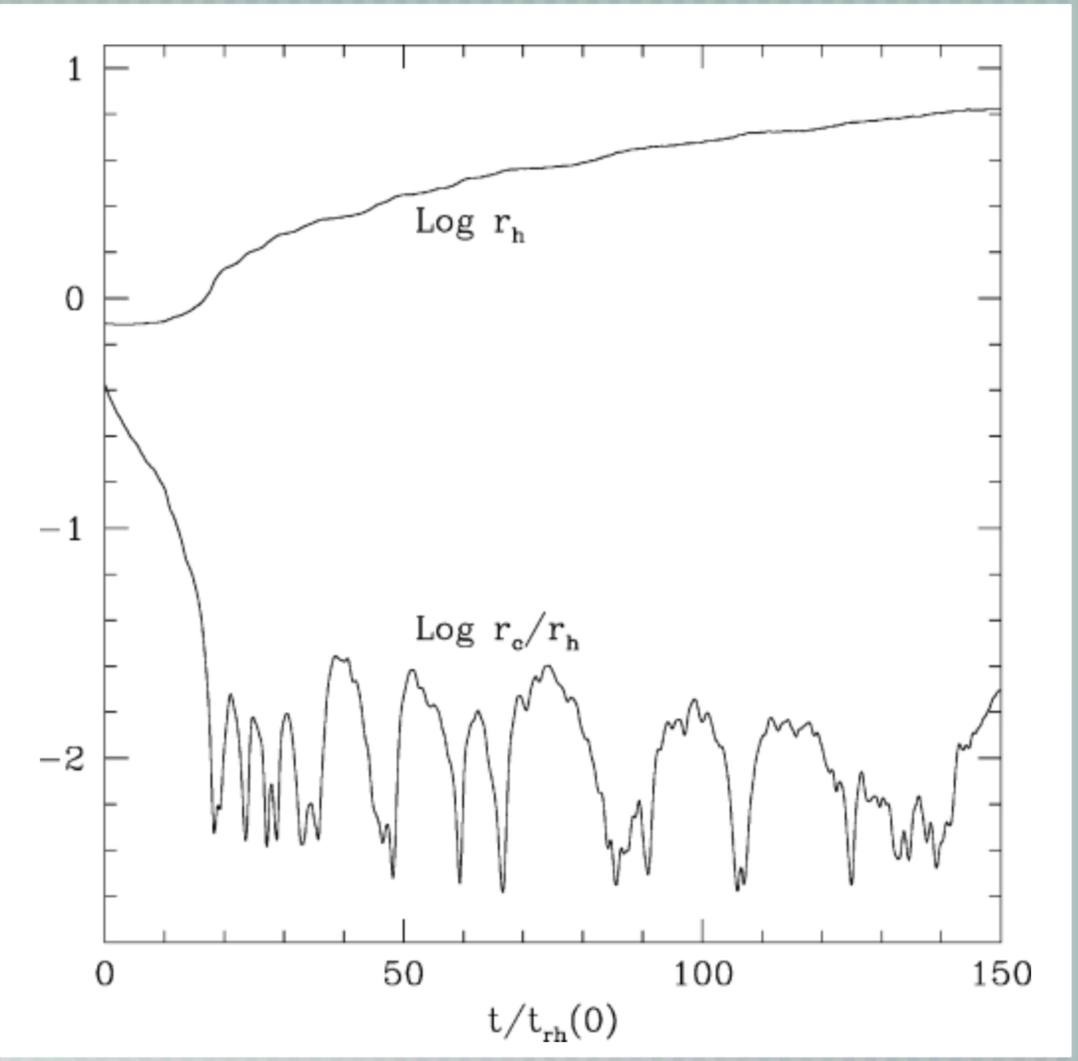


Our Modeling

- Direct N-body simulations with Aarseth's NBODY6:
  - NO softening
  - Exact treatment of all strong interactions (KS+chain regularization)
  - Up to N=32768 for the results here; 64K&128K currently running on Lincoln
- Large Grid of Initial Conditions/Runs (embarrassingly parallel)
  - "Late Time" Mass function, Primordial Binary Fraction, Tidal Field, Concentration, central IMBH
- Runs carried out until tidal dissolution (typically >15 t_{rh})

The classical core collapse

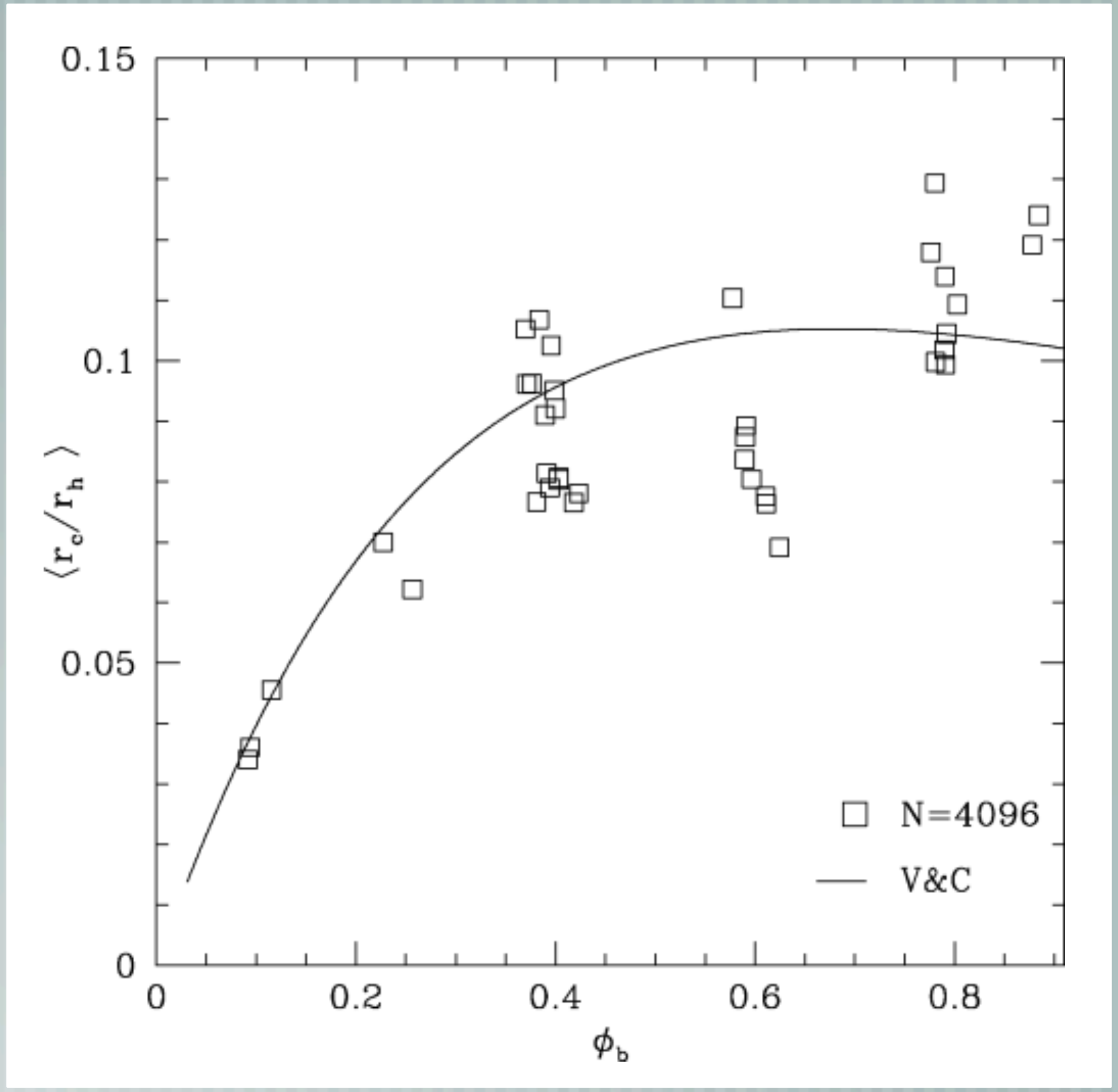
- Direct N-body simulations
  - single stars only, equal mass
  - core collapse (negative specific heat)
  - 3-body binaries formed
  - gravothermal oscillations + cluster expansion



Heggie, Trenti & Hut (2006)

Core size & Thermodynamics

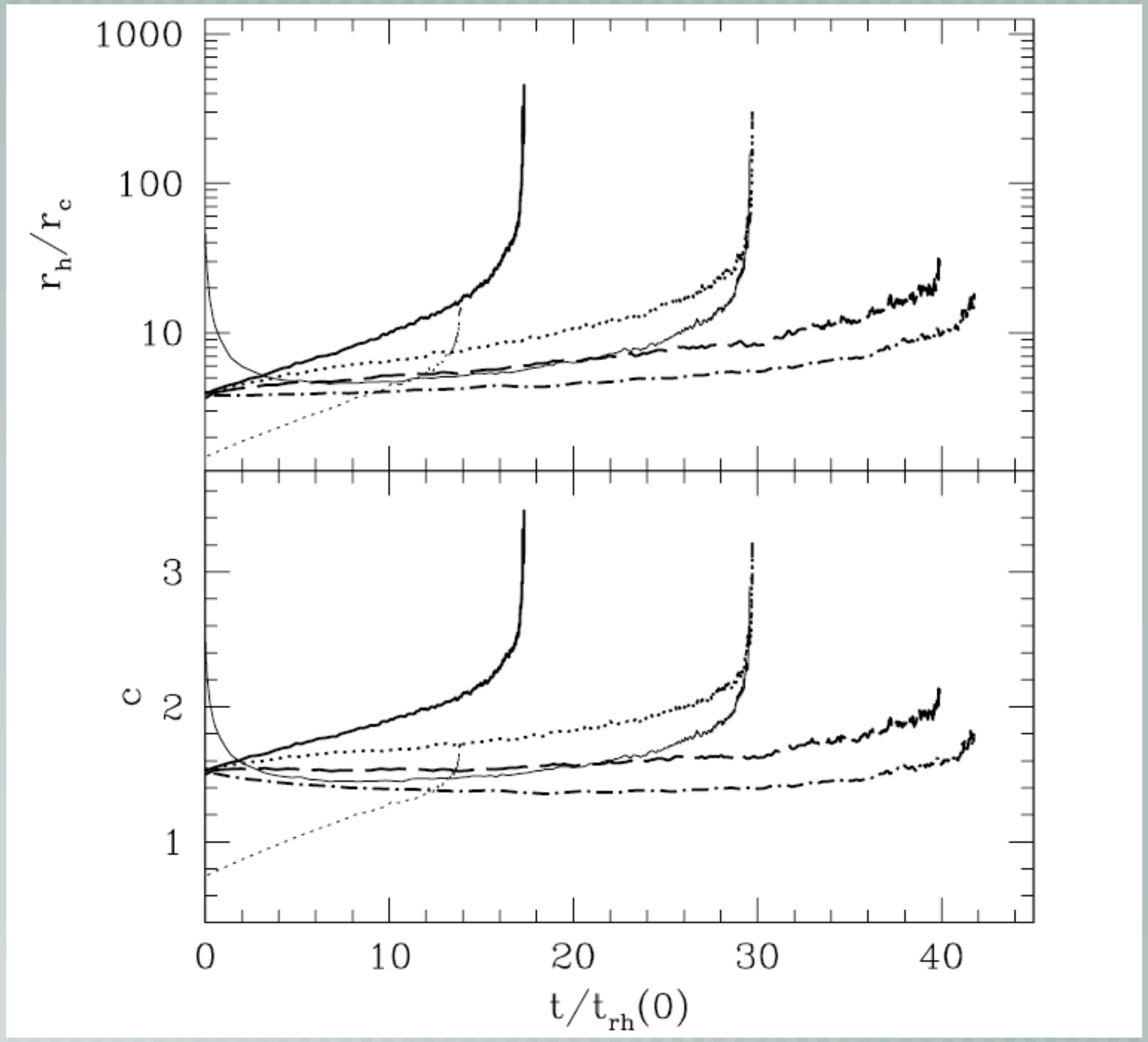
- Vesperini & Chernoff (1994) model: core size with central energy source (binaries)
    - Initial core size does not affect the model
    - Excellent match to idealized simulations (equal mass, isolated, Plummer ICs)
    - Saturation of binaries efficiency



Heggie, Trenti & Hut (2006)

Core size & Thermodynamics

- Fregeau et al. (2003):
  - Initial conditions appear important!
  - Different binary fractions and tidal fields lead to a different evolutionary history
  - (Monte Carlo code based)

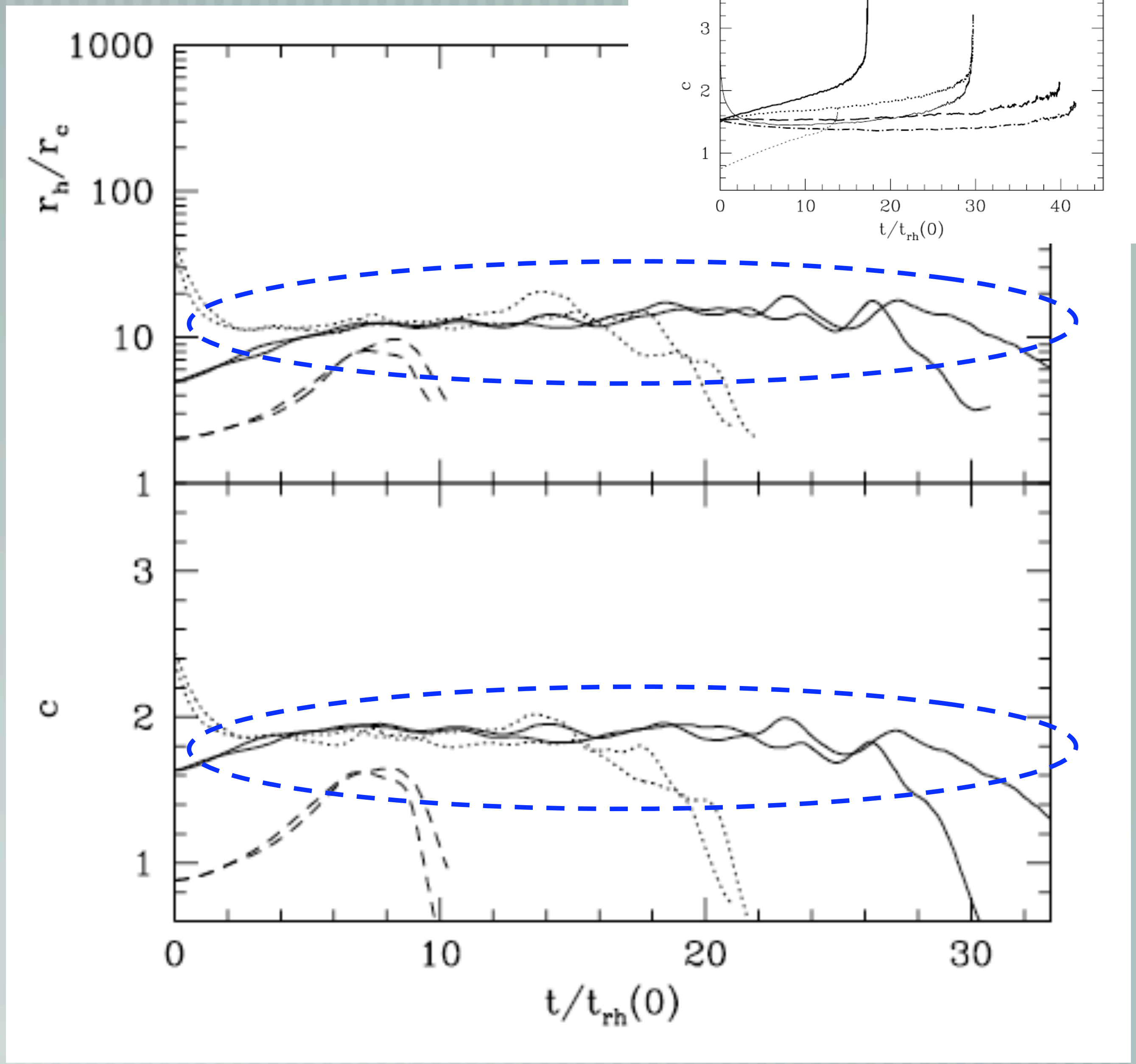


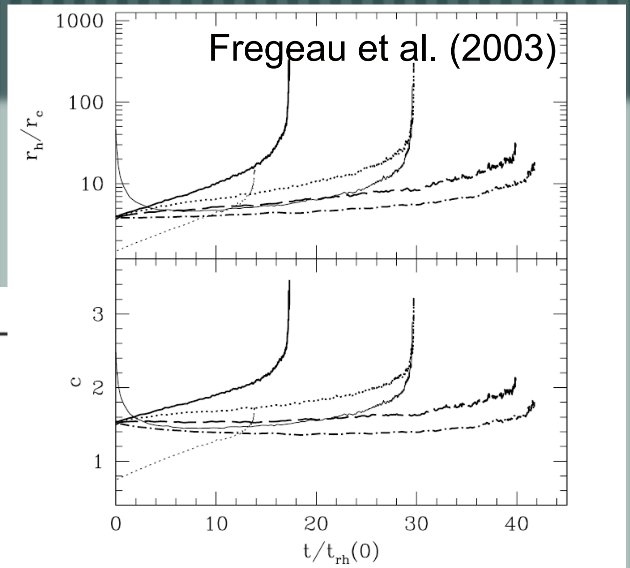
Fregeau et al. (2003)

Core size & Thermodynamics

The direct N-body point of view:

- Different ICs evolve toward universal rc/rh and concentration until shortly before tidal dissolution
- Fully consistent with theoretical expectation from thermodynamic
- (MC code by Fregeau & Rasio (2007) has improved agreement with direct integration)





Trenti , Heggie & Hut (2007)

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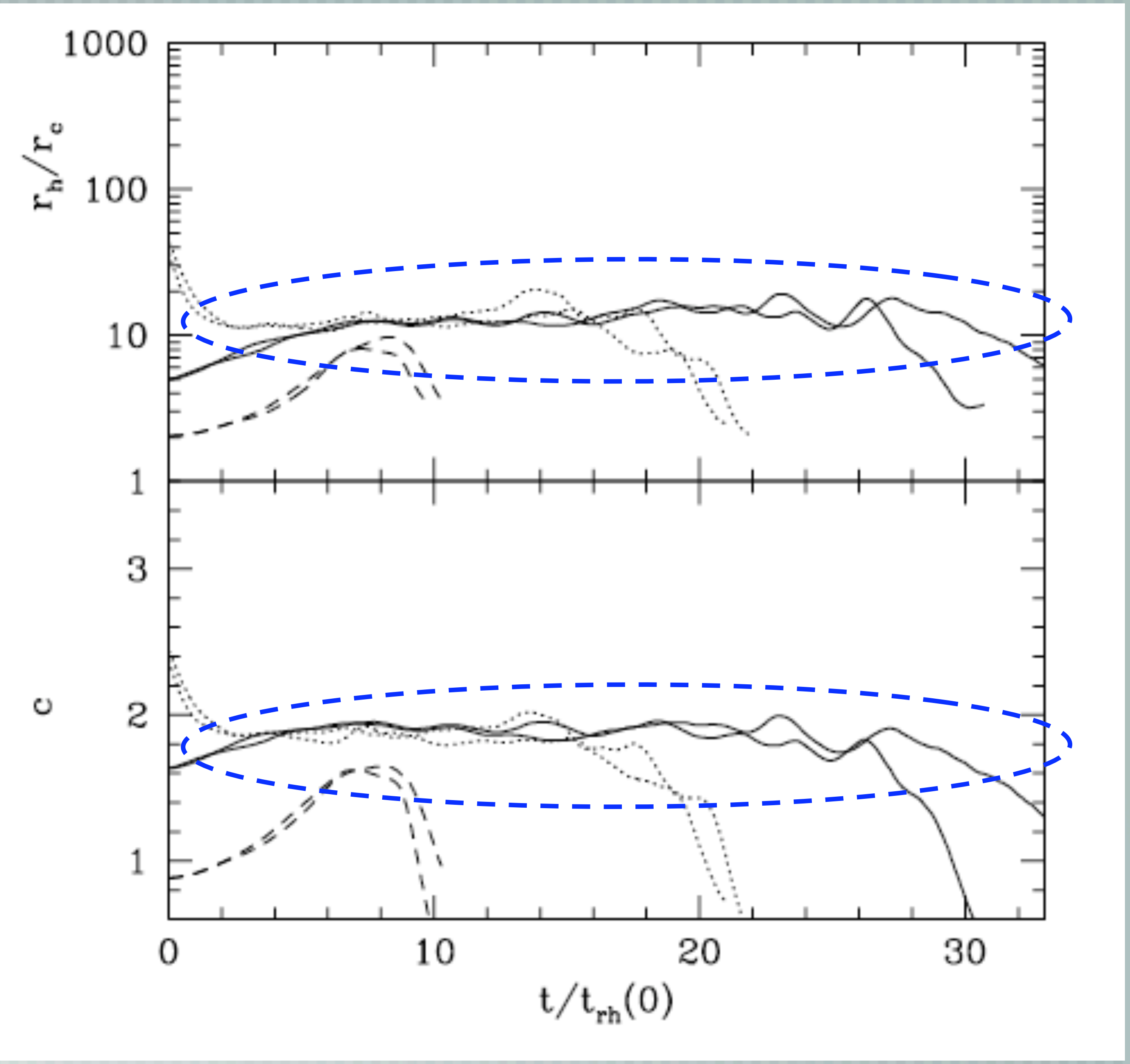
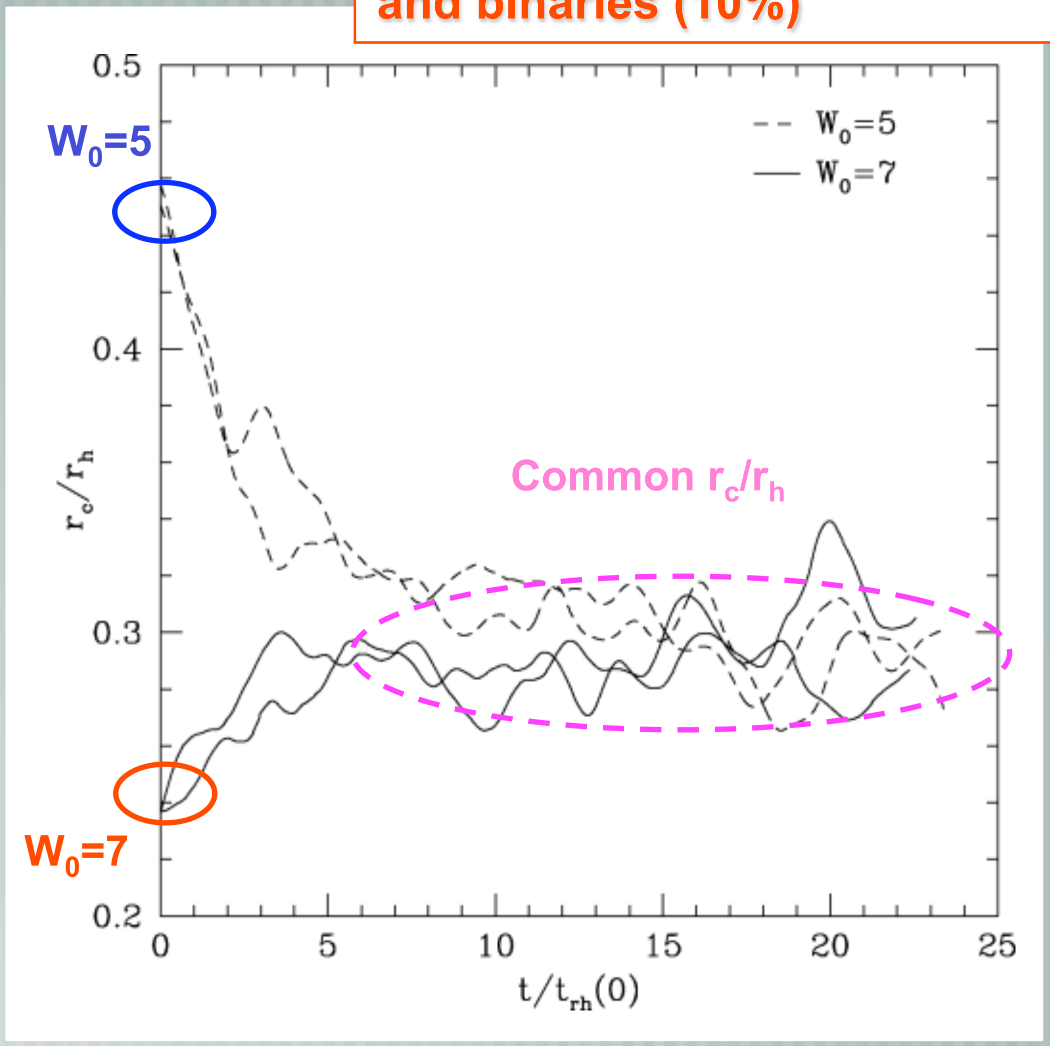


Trenti , Heggie & Hut (2007)

More universal evolution: IMBH runs

- Efficient IMBH heating leads to
  - Universal large rc/rh after a few relaxation times
- There are other efficient heating sources besides binaries & IMBHs
  - Stellar evolution (Hurley 07), WD kicks (Fregeau et al. 09), Stellar collisions (Chatterjee et al.09), Stellar BHs (Mackey et al. 08)

r_c/r_h with IMBH (m_{BH}/m_{tot}=0.014) and binaries (10%)

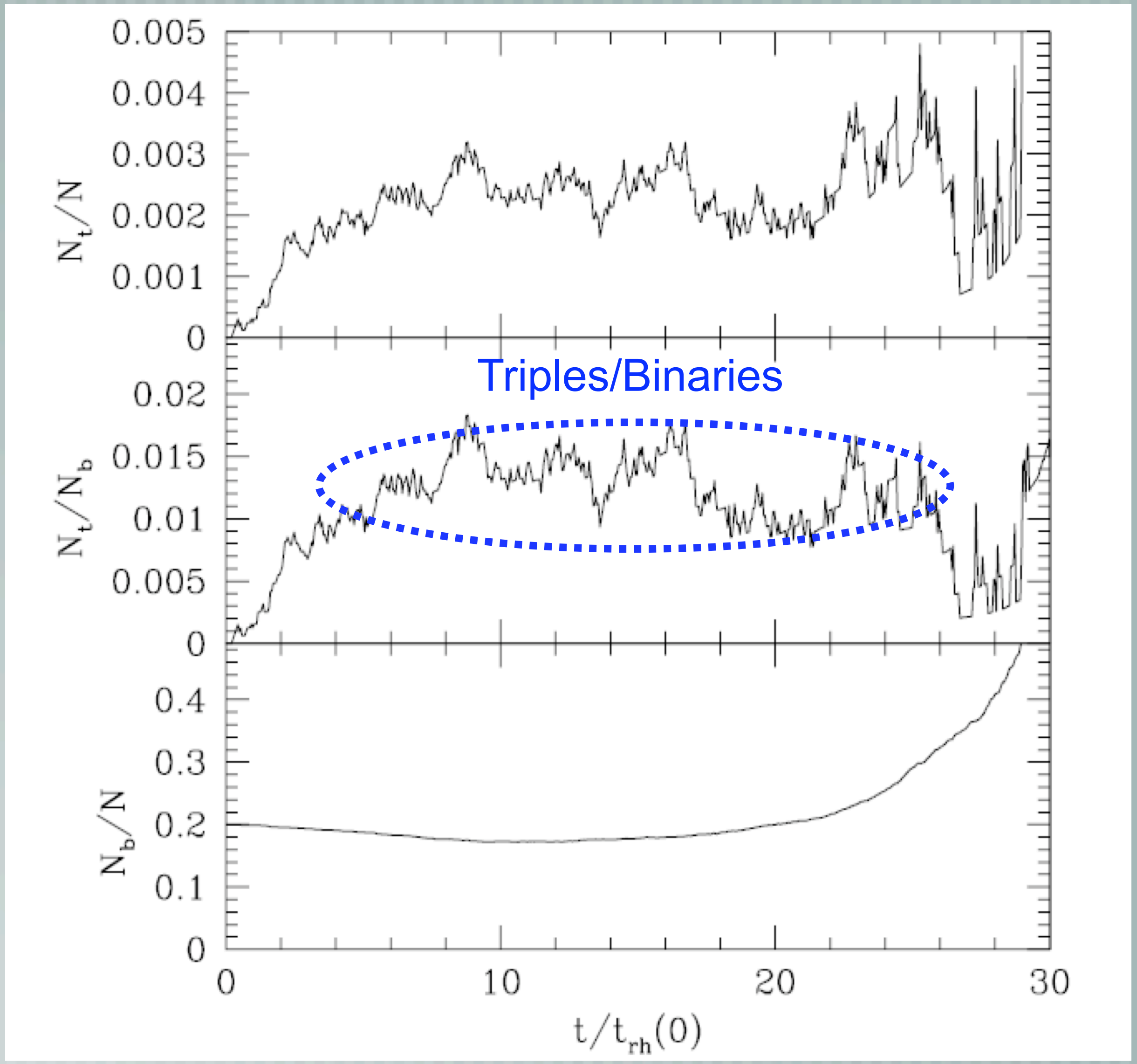


Trenti et al. (2007)

Formation of triples

- Dynamical interactions lead to triple formation
  - binary-binary at lowest order
- Within a few relaxation times a steady state is attained
- Triple fraction proportional to binary fraction
  - About 1%

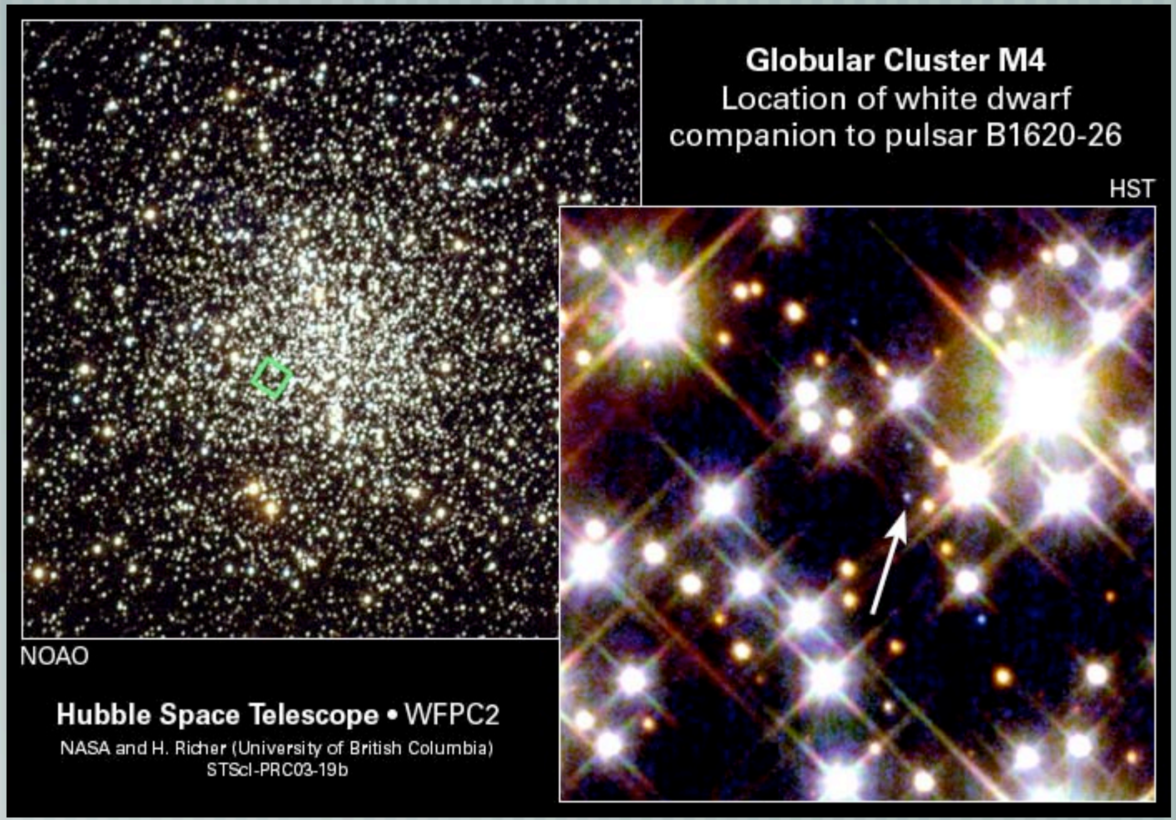
Binaries and triples fraction



Trenti et al. (2008)

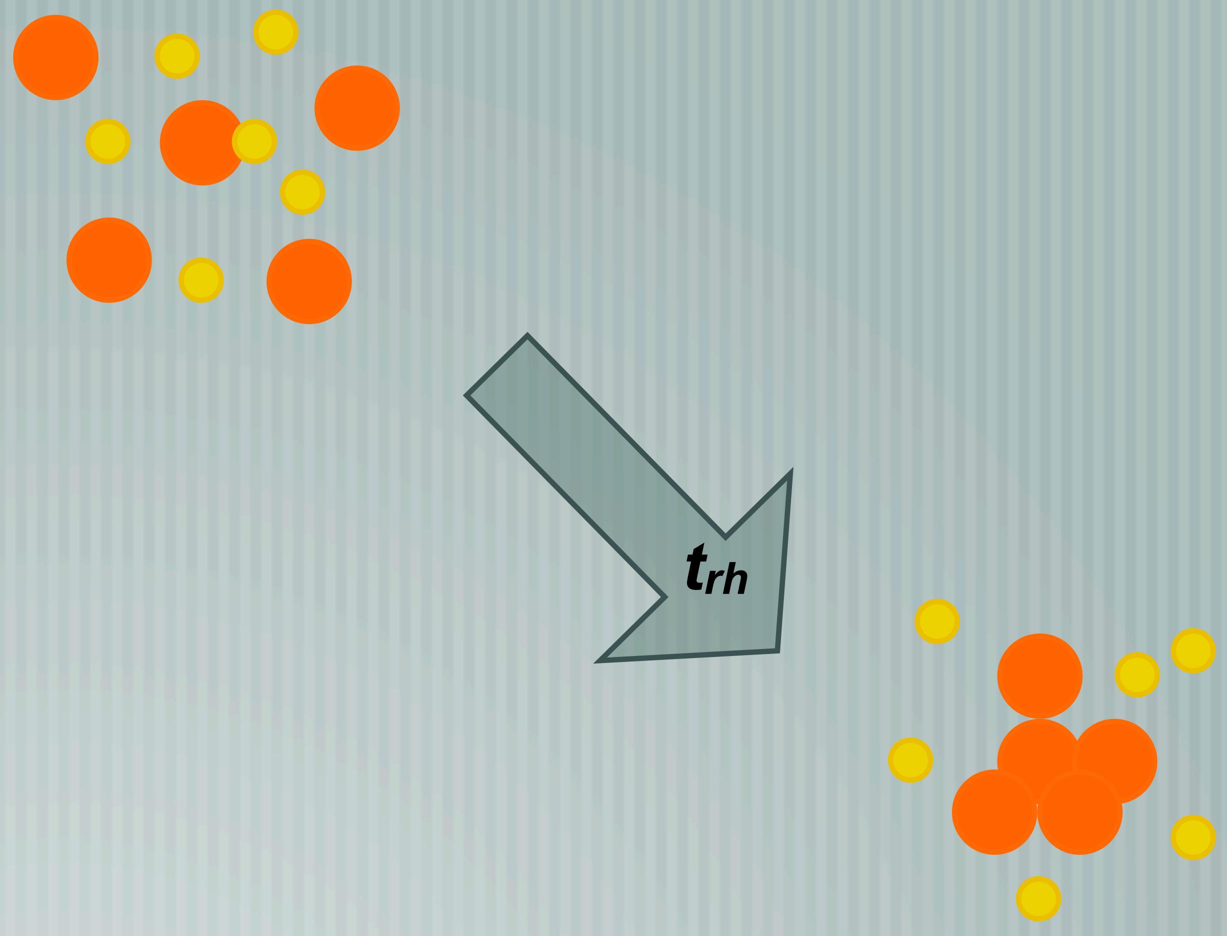
Speculations on triples and planets

- We know about 100 pulsar binaries in GCs
    - O(1) pulsar triple expected from our simulations
- B1620-26 is a pulsar triple with a 2.5 $M_{Jupiter}$ planet at ~ 20 AU
    - *If* the planet was dynamically captured, then planets in clusters are as common as stars!



Thermodynamics & Mass segregation

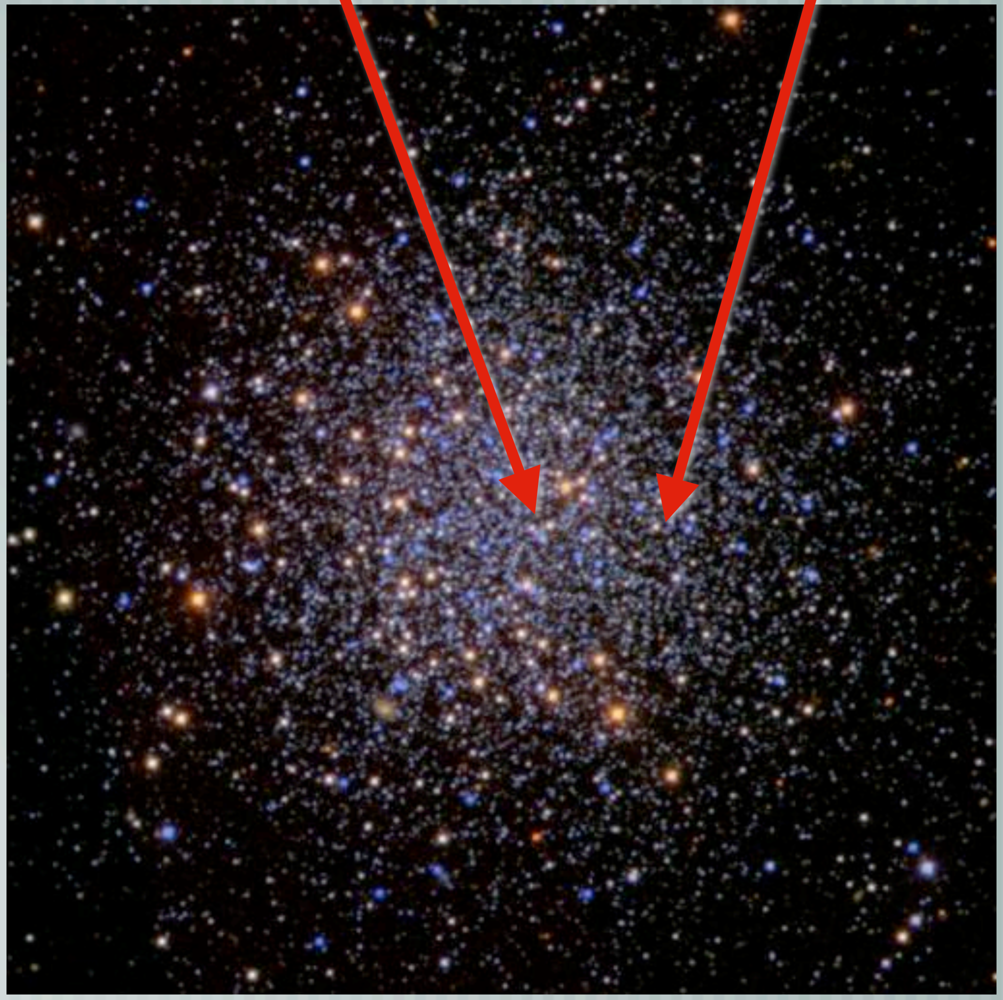
- In a GC the most massive stars segregate toward the center of the system (energy equipartition)
- Can we predict it?
- Does it depend on the initial conditions?
- How can we measure mass segregation?



Measuring Mass Segregation

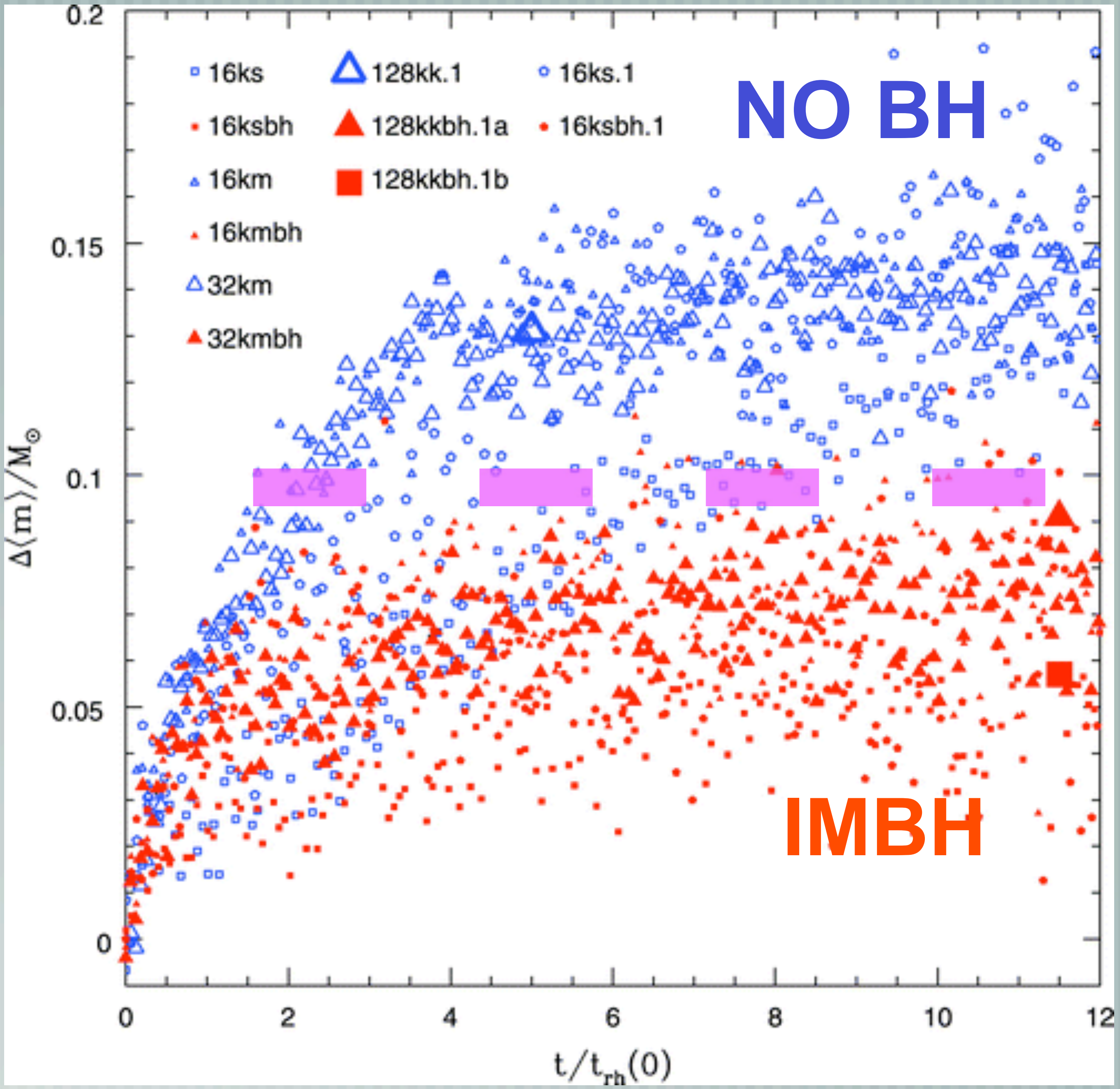
$$\Delta\langle m\rangle = \langle m(r = 0)\rangle - \langle m(r = rh)\rangle$$

- Mass Segregation $\Delta\langle m\rangle$ is measured as the difference in average main sequence mass between the center and the half mass radius
- Differential measure:
  - erases dependence on the IMF
- Mass not light based:
  - less sensitive to fluctuations due to small number of giant stars



Mass Segregation Results: Simulations

- Simulations start with no mass segregation
- After about 5 relaxation times **equilibrium** value of mass segregation is reached
- Quasi-universal amount of mass segregation
- (Good separation of runs with and without an IMBH)

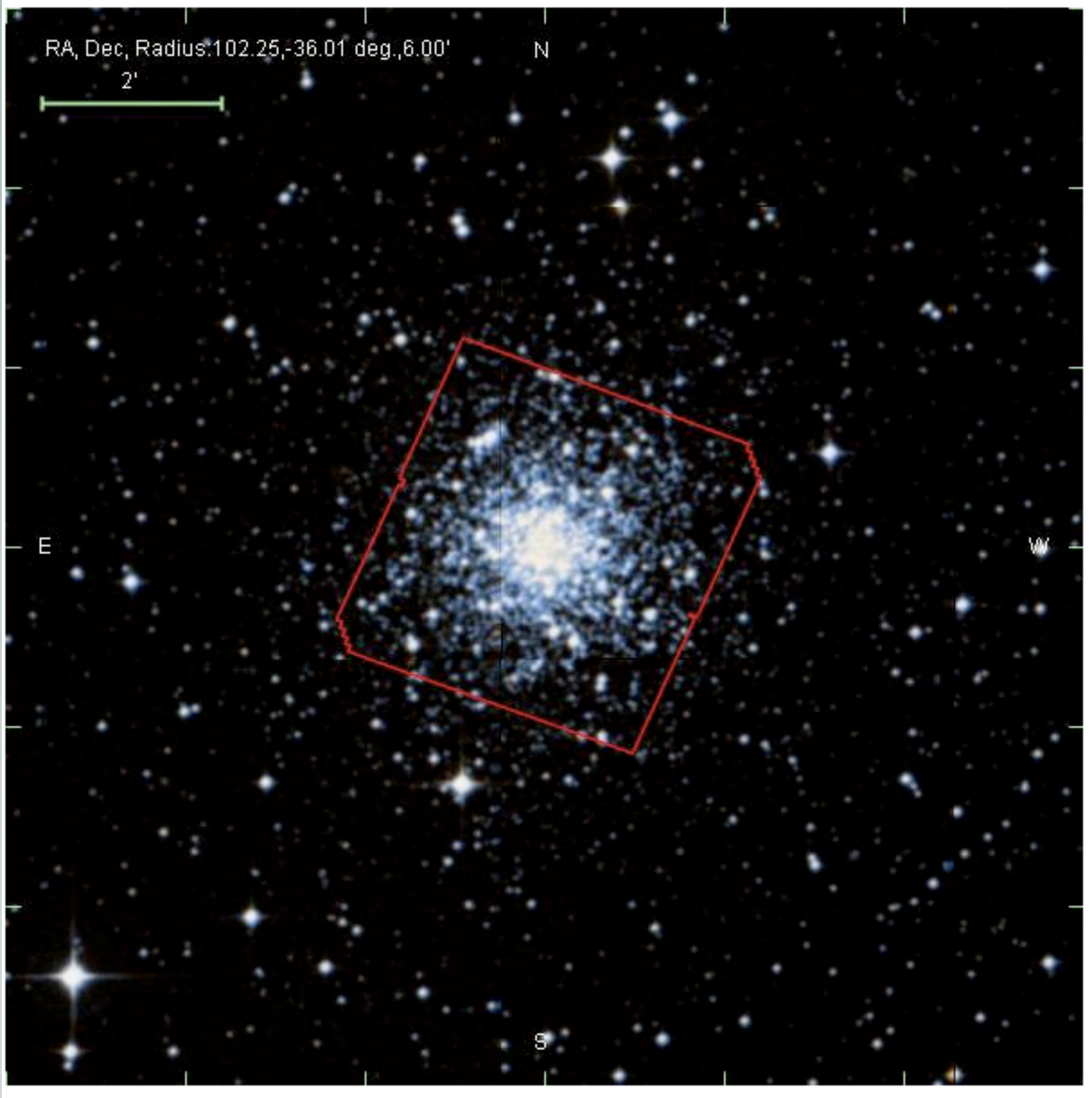


Gill, Trenti et al. (2008)

Comparison with NGC2298

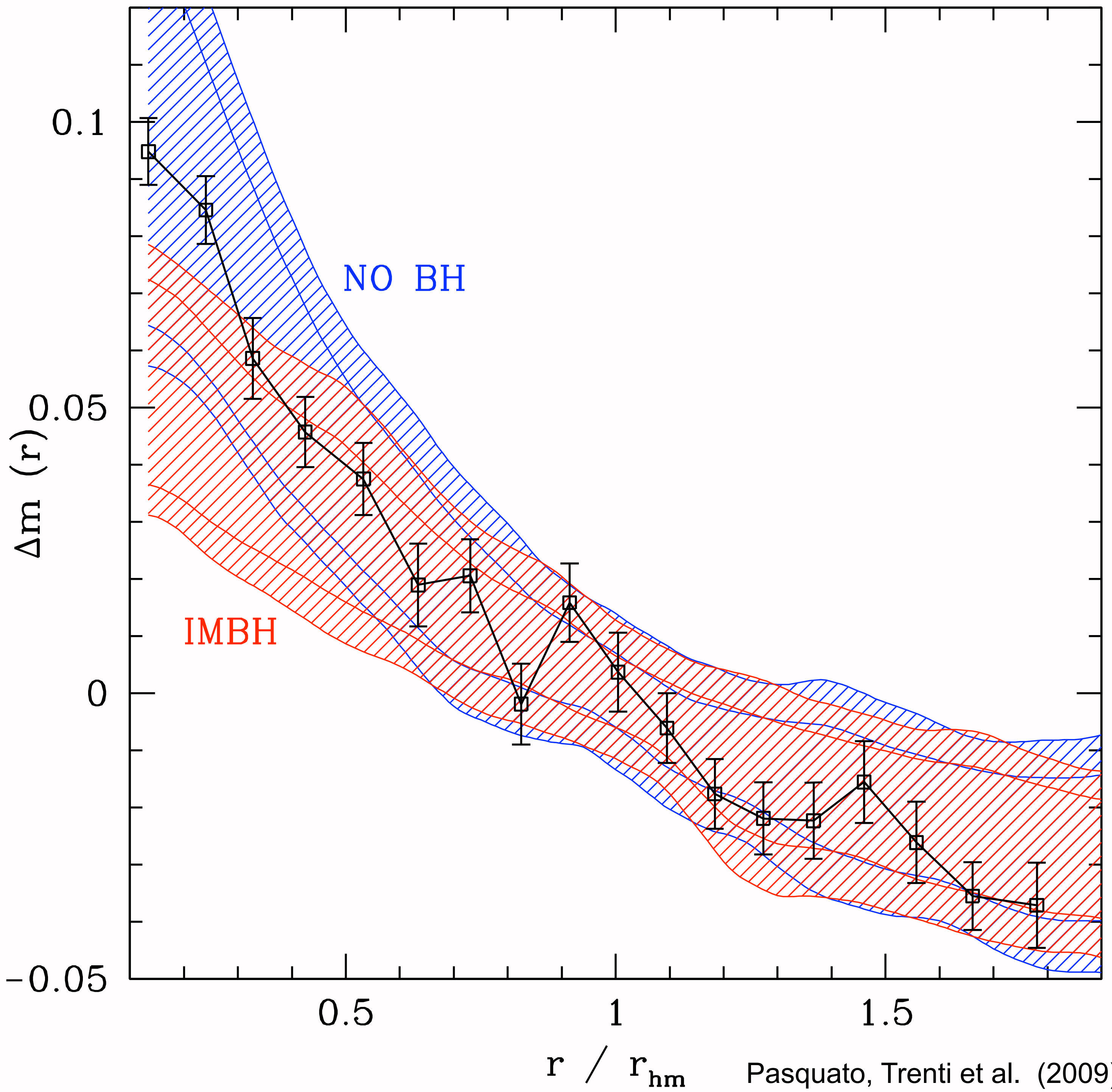
- Cluster properties
  - $t_{rh} = 10^{8.41}$ yr
  - rh = 49″
  - $M_{tot} = 3 \times 10^4$ Msun
- Data Reduction: DeMarchi & Pulone (2007)
- HST-ACS WFC F606W & F814W
  - 10σ limit @ m_{606}=26.5, m_{814}=25.0
  - >50%completeness @ 0.2 Msun

NGC 2298



NGC2298: comparison with simulations

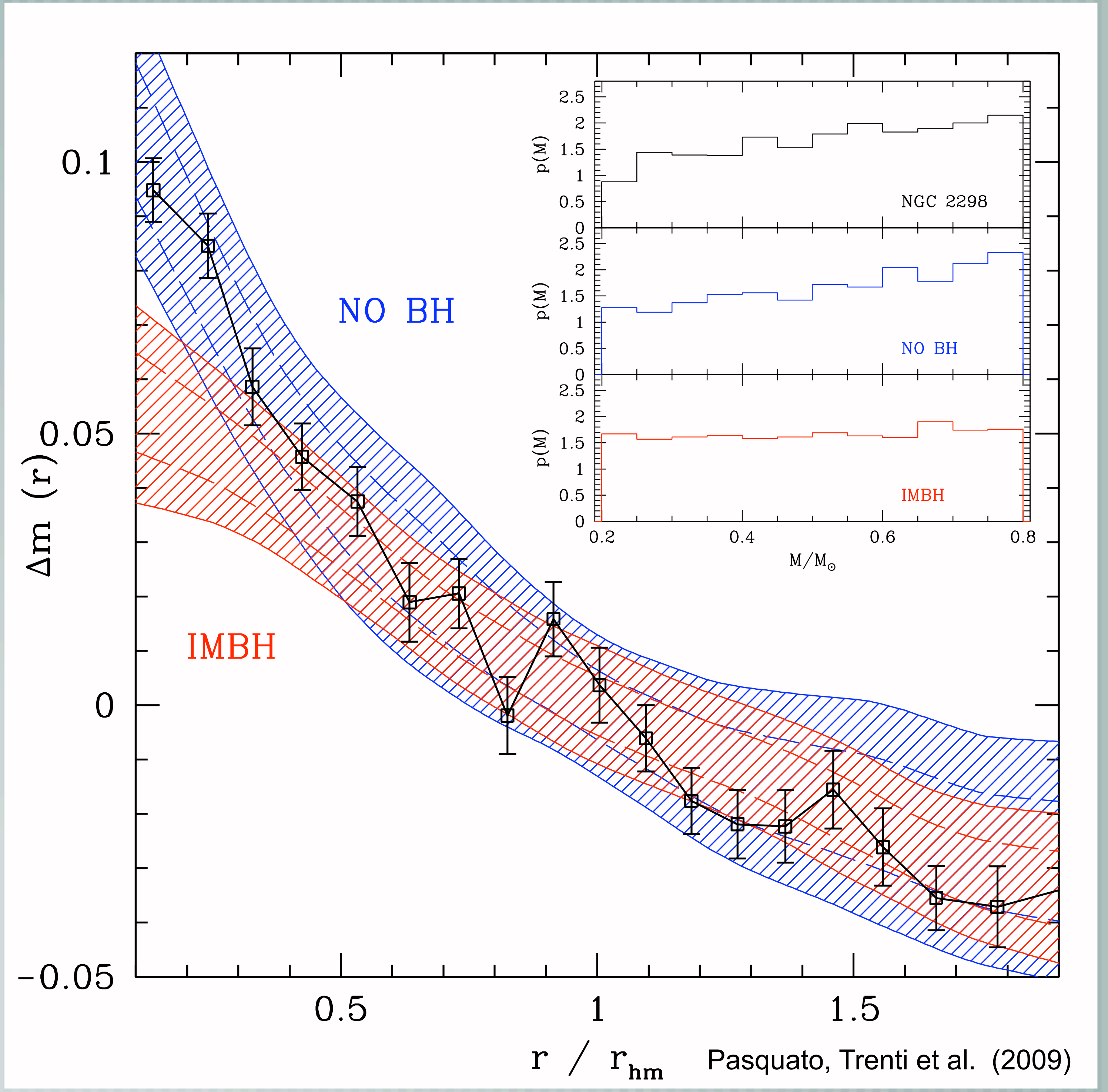
- Predicted quasi universal profile of mass segregation
- Observed mass segregation profile is matched very well by simulations
- Cluster is too segregated to be likely to host an IMBH
  - (Formal limit from the inner two points: >300Msun BH excluded at 3σ CL)



Pasquato, Trenti et al. (2009)

Mass Segregation: testing the predictions

- NGC2298 has a peculiar mass function (very deficient in low mass stars)
- We match the *global* observed mass function & mass segregation profile if we:
  - start with a Miller&Scalo IMF
  - wait until 75% of mass is lost
- Excellent data-model match!



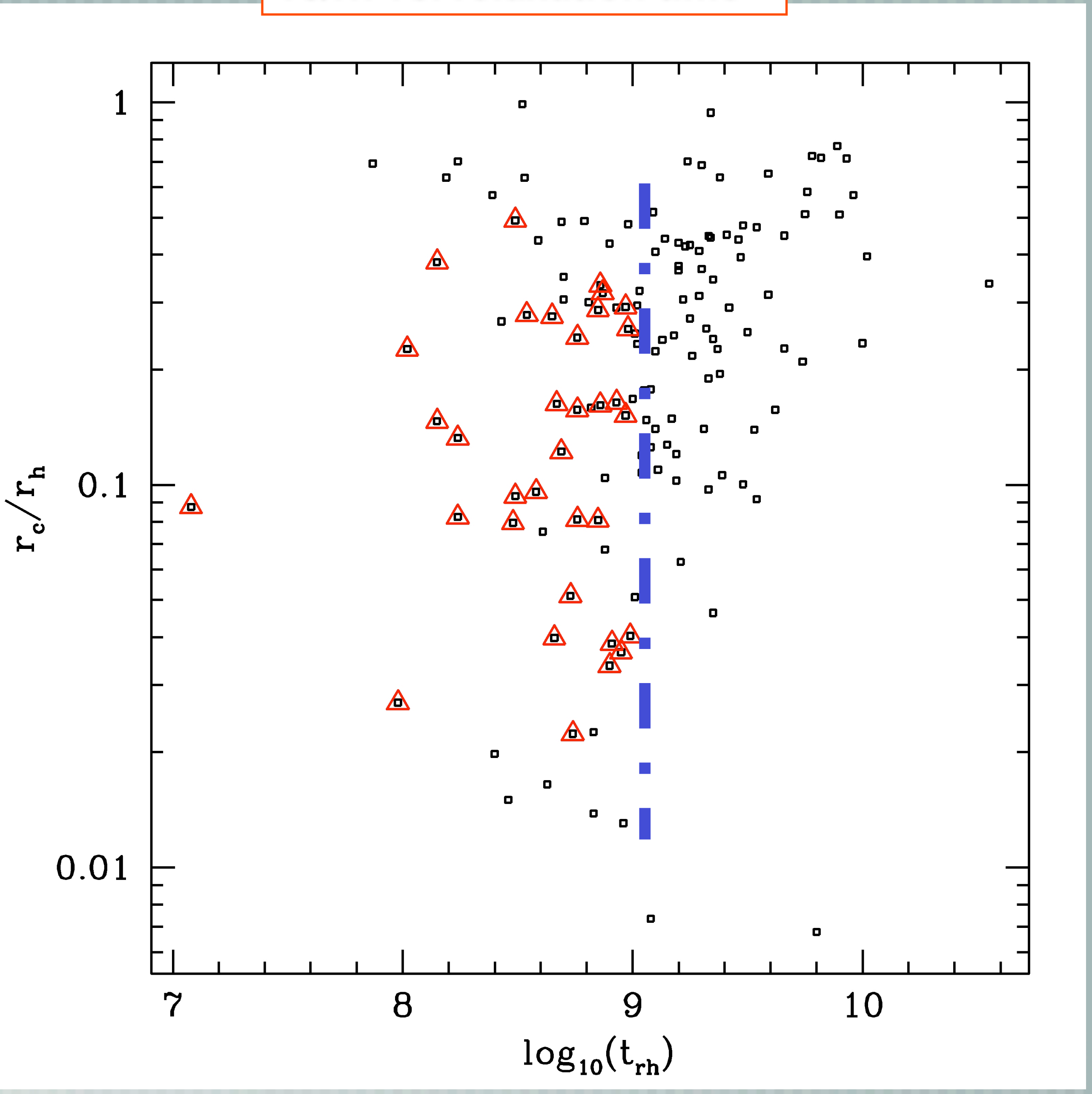
Summary

- GCs had a complicated infancy
  - multiple stellar populations, primordial mass segregation, mass loss
- But the late time collisional evolution of GCs is insensitive to the details of ICs
  - Expected universal behavior of global properties of the system
- Successful data-model comparison:
  - NGC 2298 star counts follow the predicted universal mass segregation profile

Observed rc/rh: any information?

- Observed rc/rh should carry information on the core energy production for relaxed GCs
- Harris catalog is based on integrated light profiles, possibly very uncertain
- We should define structural parameters on star counts
  - And construct light-based predictions for simulations

rc/rh vs. relaxation time



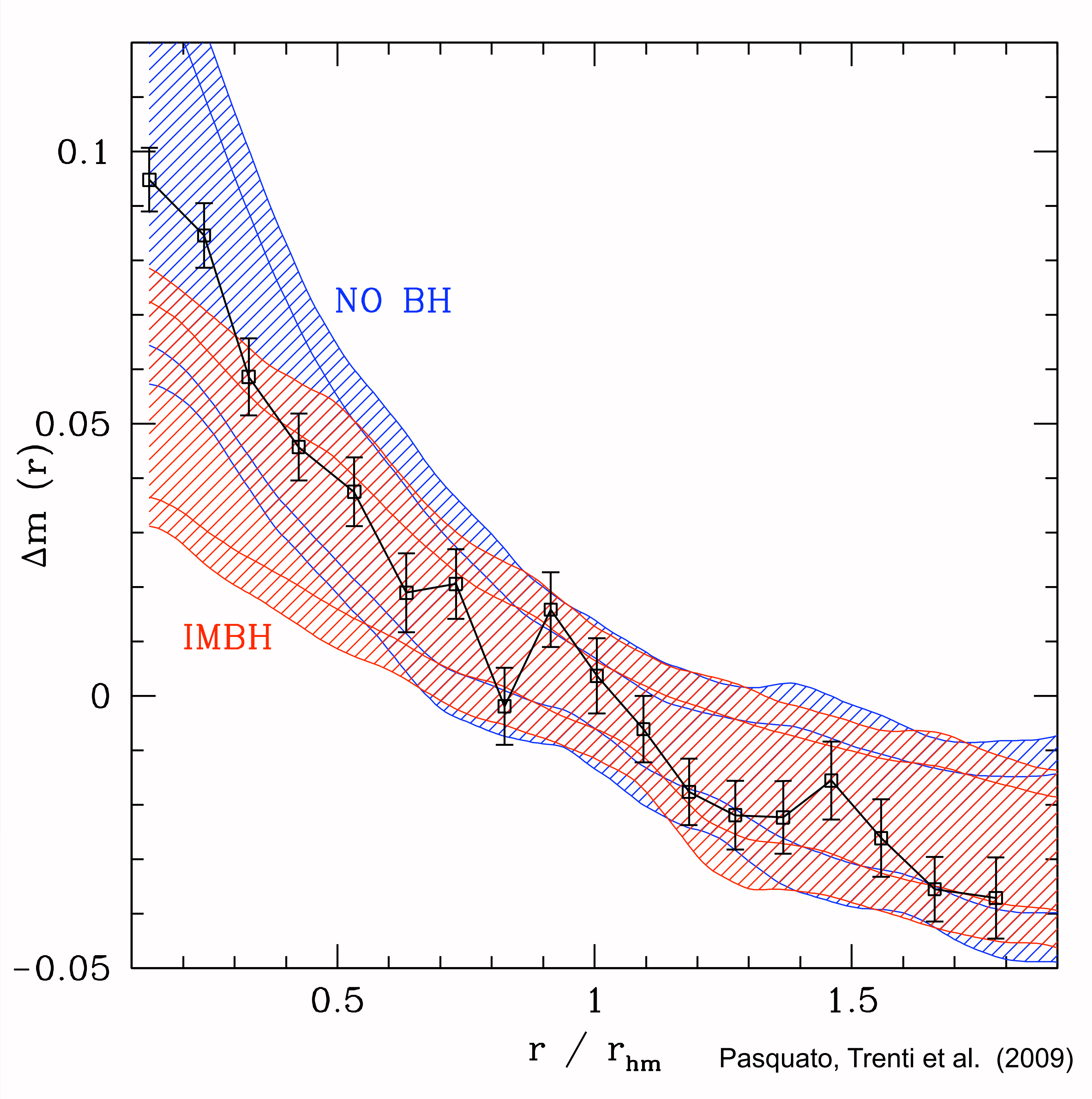
$r_t/r_h>10$ && $t_{rh}<10^9$ yr: relaxed & isolated

The future

- Larger sample of simulations: toward Heggie's Challenge
  - NBODY-6 OpenMP/GPU code on NCSA Lincoln cluster
  - Improved statistics, wider sampling of initial conditions, larger N (64K & 128K)
- HST data for star counts comparison are available in the archive for about 15 relaxed clusters

NGC2298: Error budget

- Poisson errors have been estimated by bootstrap (100 synthetic catalogs)
- Possible systematic errors from determination of
  - Half mass radius. Even a +/- 4″ mis-determination only shifts by less than 1σ Poisson error
  - Center. We use mass, not light based measure, more stable: [0.4″ uncertainty at 1σ] Miscentering only increases BH rejection confidence level



Core size & Thermodynamics

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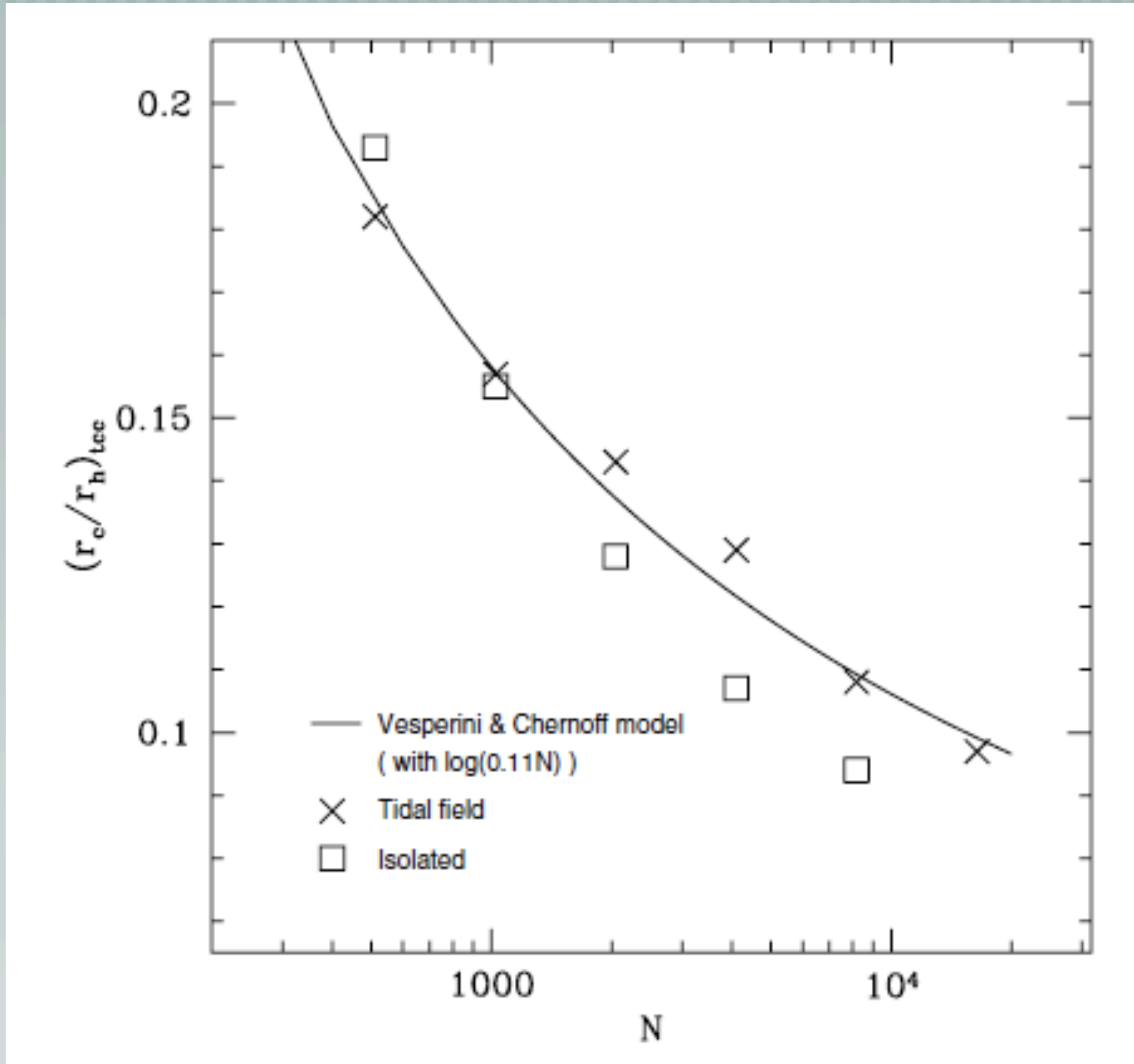
  - Initial core size does not affect the model
  - Core size depends on N
  - Excellent match to simulations results



Trenti, Heggie & Hut (2007)

Quenching of mass segregation

A Cartoon Picture

- IMBH quickly gains at least one tightly bound massive star:
  - A super-scatter machine is born!
- Three body encounters with the BH scatter out incoming stars independently of their mass
  - no strong dependence on BH mass expected or seen in simulations when $m_{BH} >> m_{star}$
  - random walk of the IMBH within the core: loss cone is constantly replenished, high rate of interactions over time