OVERVIEW OF CLUSTER DYNAMICS

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TWO VIEWS

- globular clusters are clean realizations of the classical N-body problem

- clusters are a complex, messy mixture of stellar and binary evolution, stellar interactions and collisions, gas dynamics, tidal fields, and many other competitive physical processes

OUTLINE

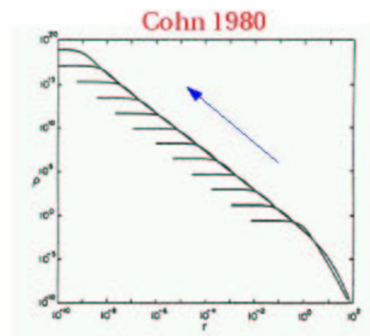
- basic dynamics
- modeling
- deep core collapse
- black holes in cluster centers

INITIAL CONDITIONS

- standard choices of IMF, density profile, binary parameters, etc.
- current studies almost universally assume:
  - clusters are gas-free (but see Kroupa et al. 2001)
  - clusters are virialized
  - there is no initial mass segregation (in stars or binaries)
  - stars are coeval
  - stars are all on ZAMS at time $t = 0$
  - no rotation (but see Einsel & Spurzem 1999, Baumgardt et al. 2003)

Key Dynamical Processes

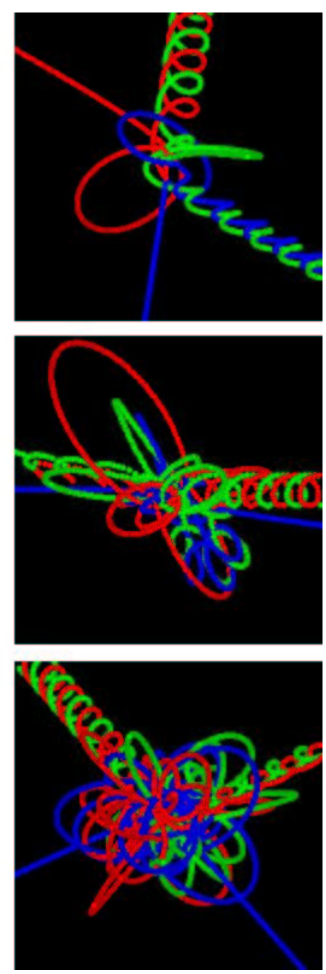
- thermalization/relaxation (time scale t_{Rh} ~ Gyr)
- equipartition/mass segregation (time scale ~ $\langle m \rangle t_R / m$)
- core collapse (time scale ~ few t_{Rh})
- tides/evaporation (time scale ~ 10–100 t_{Rh})
- binary dynamics
- stellar evolution and mass loss

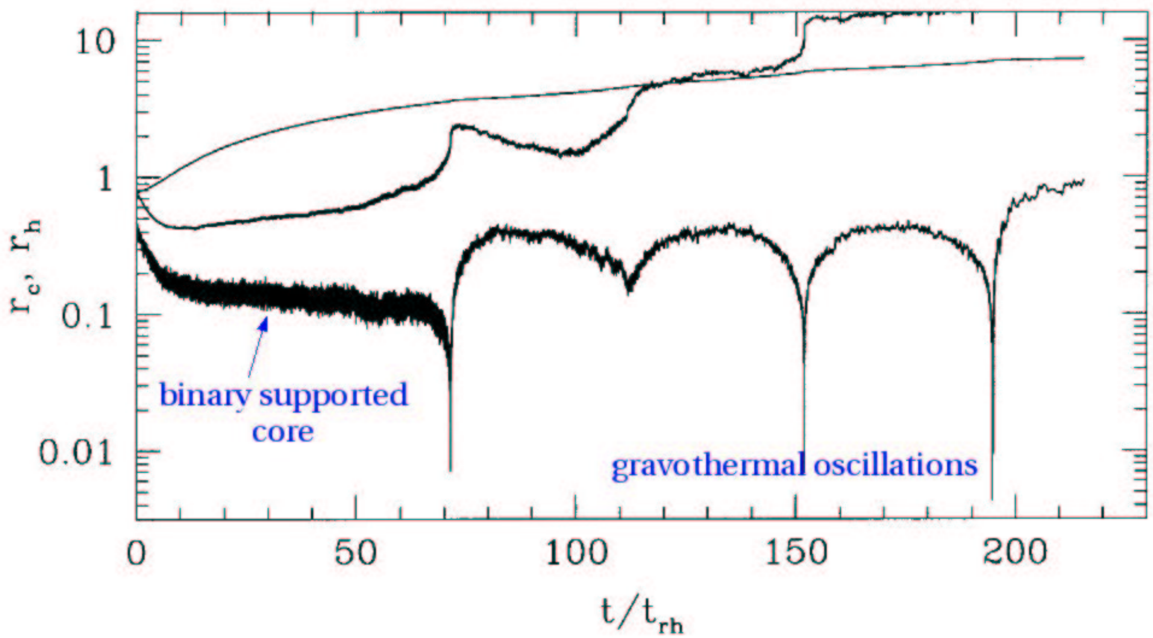


$\Rightarrow$ clusters concentrate interesting objects in regions of high stellar density

Binary Dynamics

- Heggie's law (1975)
  median $\langle \Delta E_b / E_b \rangle \sim$ 20% for $E > kT$
- binary heating and ejection (> ~100 kT)
- binary destruction
  - binary-binary interactions
  - binary mediated collisions and mergers
- exchange interactions
- binaries stall core collapse until most are gone or dynamically insignificant
  (Goodman & Hut 1989, Gao et al. 1990, McMillan et al. 1990, Fregeau et al. 2003)





Fregeau et al. (2003)

Stellar Evolution

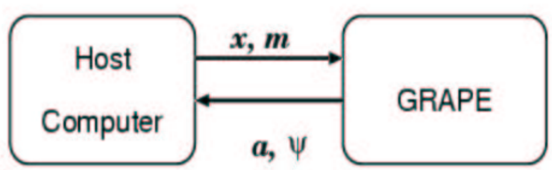
- the "kitchen sink"
- early mass loss may destroy the cluster (e.g. Applegate 1986, Chernoff & Weinberg 1990)
- mass loss may soften/prevent core collapse in tidally limited clusters (Fukushige & Heggie 1995, Portegies Zwart et al. 1998)
- reverse interaction: core collapse drives collisions, mergers, stripping, etc.

Modeling Cluster Dynamics

- basic approaches
  - continuum methods
    - gas sphere (Larson, Bettwieser & Sugimoto, Spurzem & Dieters)
    - direct Fokker-Planck (Cohn, Takahashi)
  - particle methods
    - N-body ("brute force") (Aarseth; NBODY6++; Starlab)
    - direct Monte-Carlo (Hénon, Spitzer; Giersz, Freitag, Rasio++)
    - hybrid Monte-Carlo (Giersz & Spurzem)
- inclusion of stellar physics
- use of special-purpose hardware

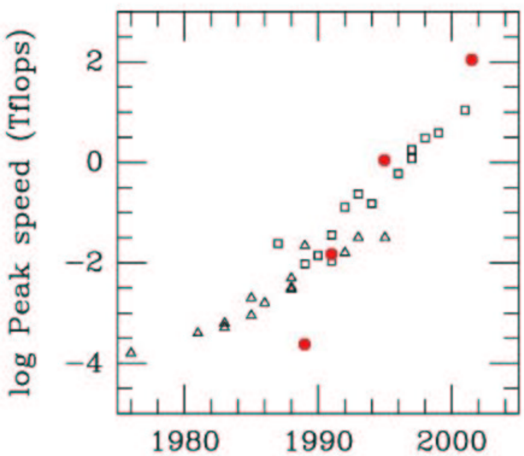
The GRAPE Project

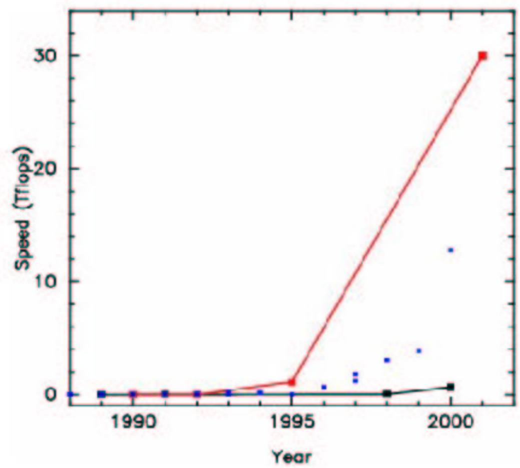
- current state of the art: GRAPE-6 (Makino 2001)
  - single chip: 30 Gflops
  - single board: ~1 Tflops
  - full system: ~100 Tflops



- "easily" integrated into existing programs
  - replaces `get_force()` by hardware call
  - effectively reduces gravitational computational bottleneck: $O(N) \rightarrow O(1)$
- $N > 100$k now feasible with single PC front-end

GRAPE SPEEDUP HISTORY





Makino (2001)

THE BINARY BOTTLENECK

- significant challenge to all modeling techniques
  - binary dynamics
  - binary evolution
- split: simulations with and without binaries
  (few) (many)
- are the binaries we see the binaries that drove the dynamics?
- were there primordial *multiples*?? ☹

The State of the Art

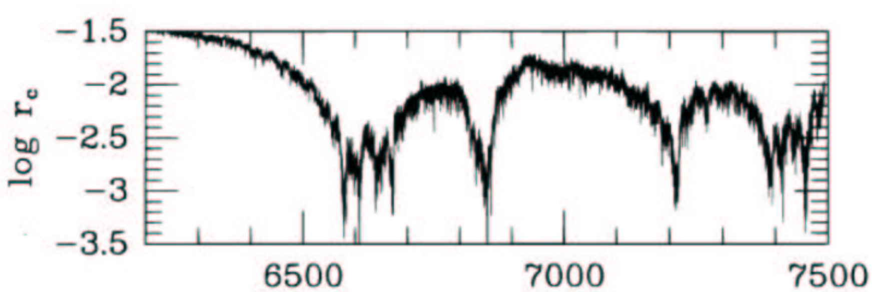
- small clusters ($N <$ few $\times 10^4$)
  - full "kitchen-sink" N-body simulations
  - binary dynamics
  - stellar and binary evolution
  - arbitrary tidal and orbital geometry
- large systems ($N > 10^5$)
  - N-body to $N \sim 1$–2×10^5, Monte-Carlo to $N > 10^6$
  - limited binary dynamics in both
  - limited stellar/binary evolution in Monte-Carlo

Deep Core Collapse

- 20% "core-collapse" clusters
- assume binaries all burned, or at least dynamically insignificant
- assume that the single-star population leads to the same final state as a population processed through binary evolution and dynamics
- stellar remnants in cluster cores
- gravothermal oscillations?

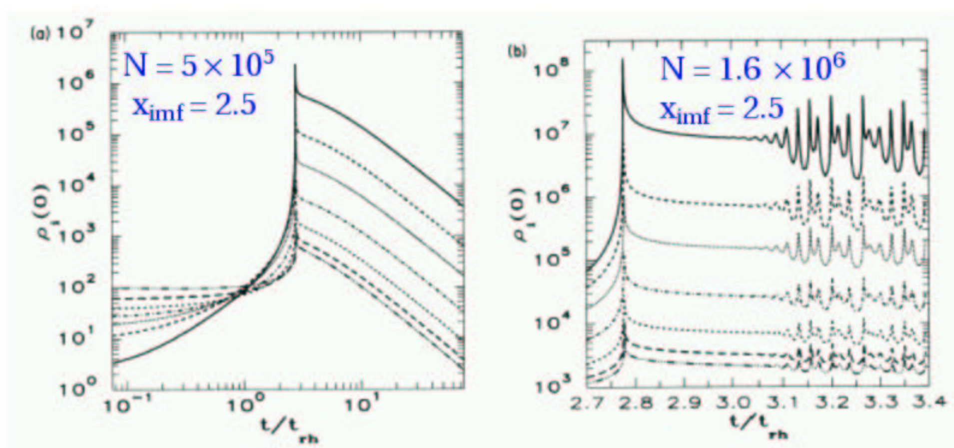
GRAVOTHERMAL OSCILLATIONS

- proposed by Bettwieser & Sugimoto (1984), based on gas-sphere cluster models
- criteria clarified analytically by Goodman (1987)
  - $N > 20{,}000$ required
- subsequently observed in Fokker-Planck, Monte-Carlo, and N-body cluster models
- GRAPE systems built in part to demonstrate the point
- suppressed by primordial binaries (Gao et al. 1990; McMillan et al. 1991; Fregeau et al. 2003)
- suppressed by stellar mass spectrum (Murphy et al. 1990)



N-body

Makino (1997)



Fokker-Planck

Murphy et al. (1990)

Stellar Remnants

- dynamical models $\Rightarrow$ heavy remnants in cluster cores (Dull et al. 1997, Murphy et al. 1998, Gerssen et al. 2003, Baumgardt et al. 2003)
- dark component dominates the central density
  - heavy white dwarfs?
  - neutron stars?
  - black hole(s)?
- issues:
  - neutron star retention
  - black hole formation

Stellar Black Holes

- massive stars: $\sim 5 \times 10^{-4} N$ have $M > 20$–$25\ M_\odot$
  $\rightarrow$ black holes in 1–10 Myr, $m_{BH} \sim 10\ M_\odot$
- <u>short</u> mass segregation time scale $\sim \langle m \rangle\, t_R \,/\, m_{BH}$
  $\sim t_R/20$, typically
- competition between rapid mass segregation and short stellar lifetimes

PROMPT STELLAR MERGERS

⇨ progenitors do sink to cluster center before supernovae

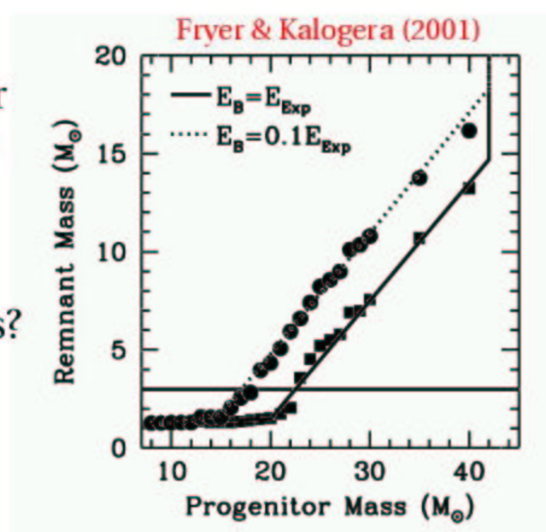
- dynamical formation of massive binaries
- possibility of runaway collisions (Portegies Zwart et al. 1999)
- terminated after ~ 5 Myr by the supernova of the runaway

- IMBH formation? (Ebisuzaki et al. 2001, Portegies Zwart & McMillan 2002)
- subsequent growth by collisions

BINARY BLACK HOLES

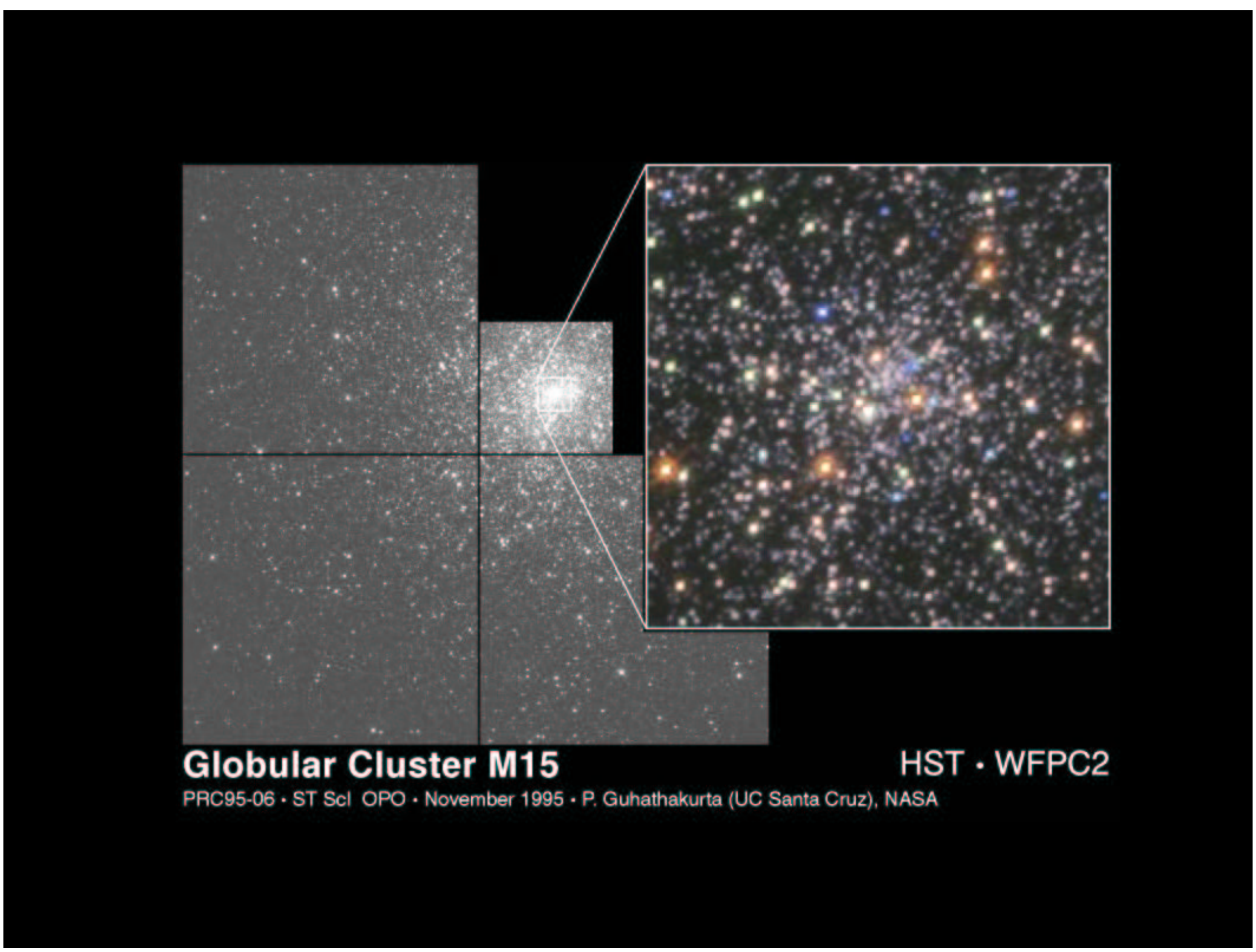
⇨ progenitors don't sink to center before supernovae

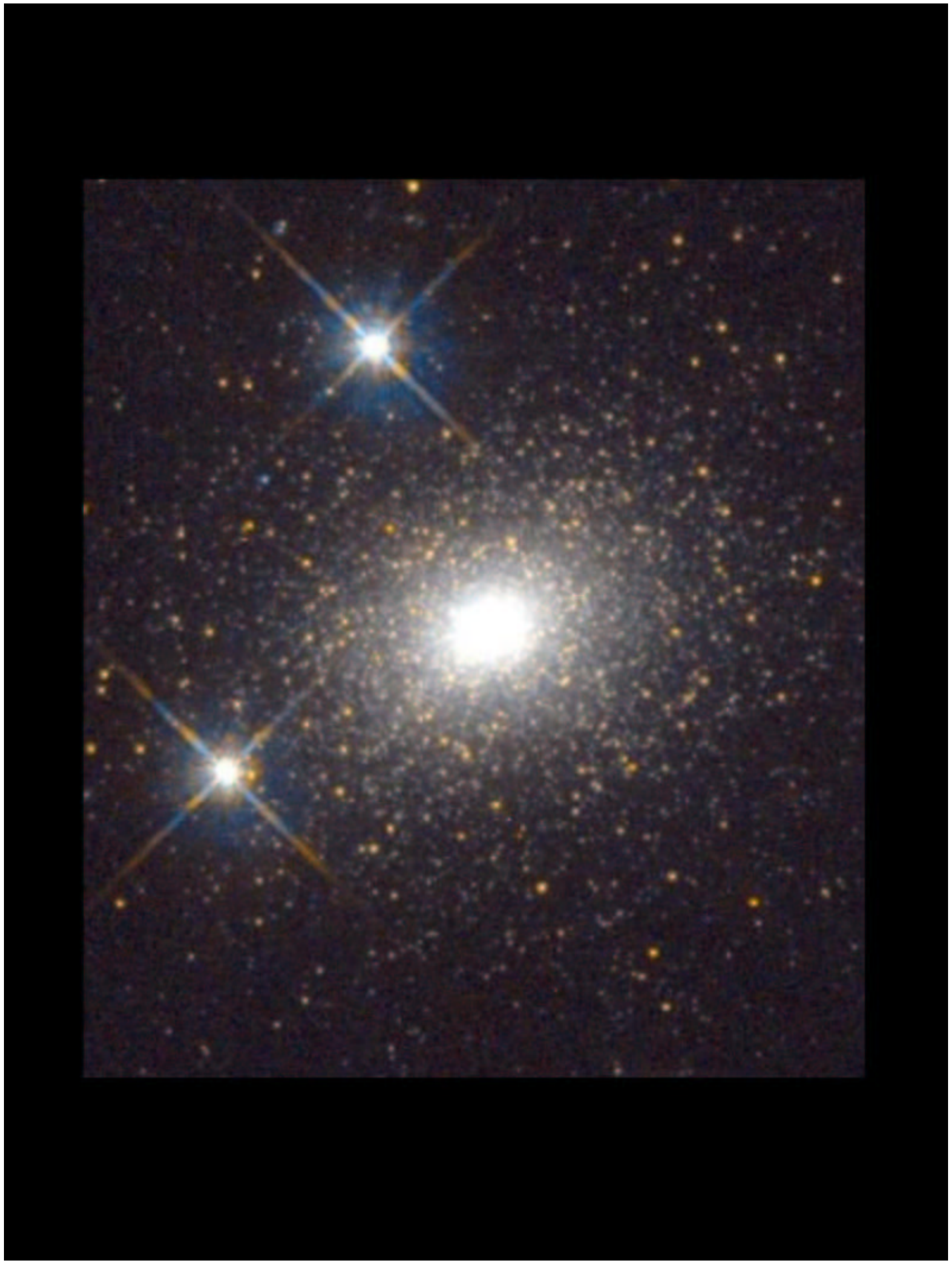
- black hole binary formation and dynamics
  (Kulkarni, Hut, & McMillan 1993, Sigurdsson & Hernquist 1993)
- ejection time scale ~ 0.1–1 Gyr
  (Portegies Zwart & McMillan 2000)
- massive binary or single black hole left behind
- long-term growth by collisions?
  (Miller & Hamilton 2002)
- black-hole mass spectrum?
- black hole kick velocities?

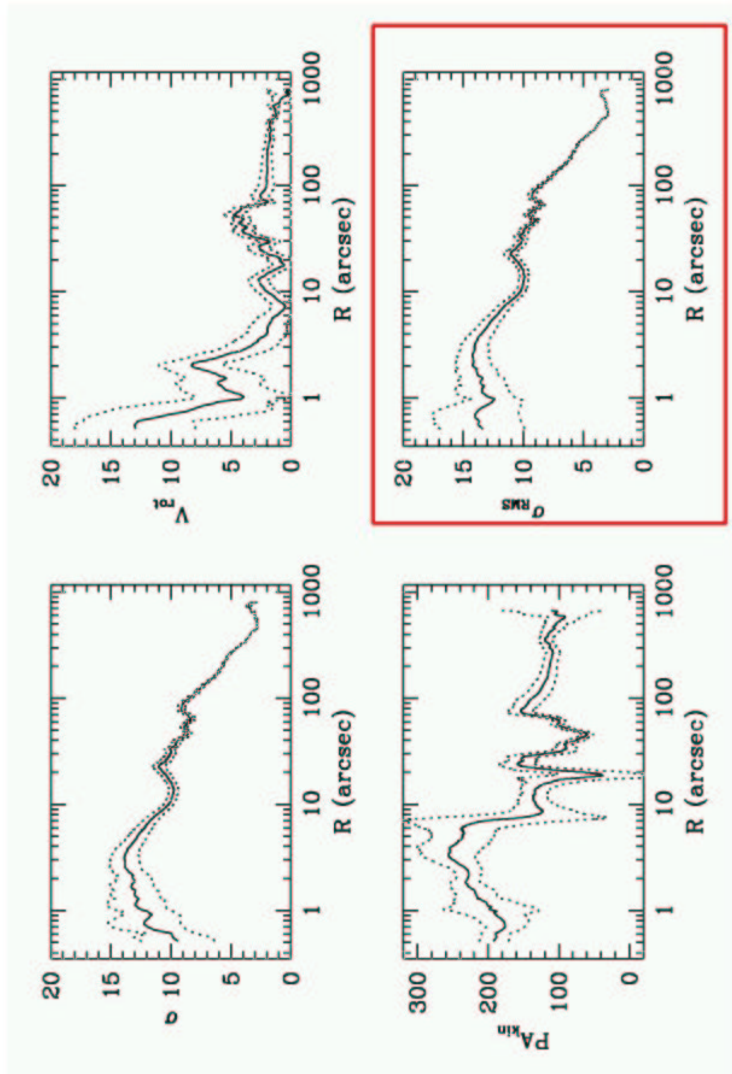


IMBHs in Clusters

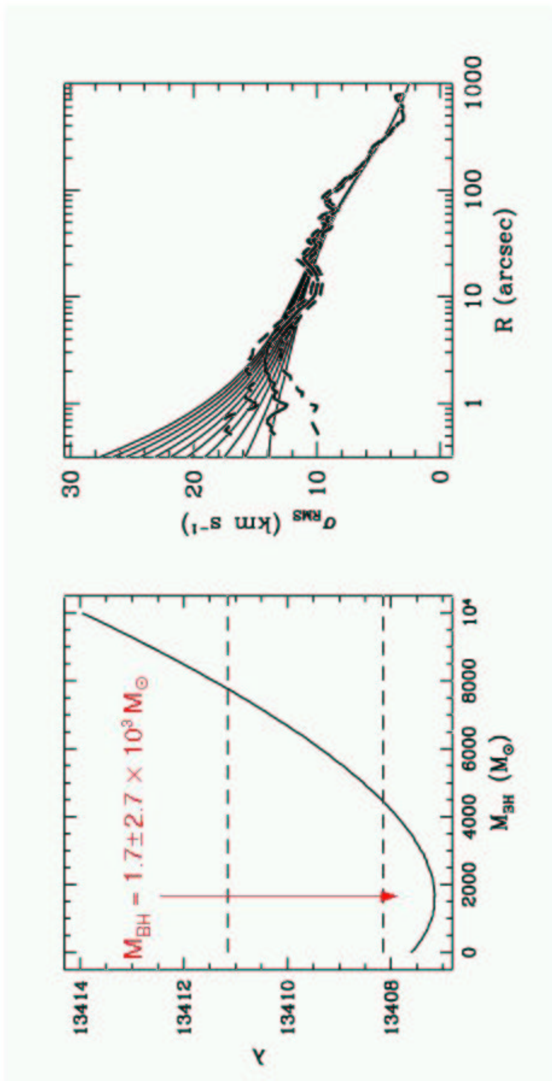
- current candidates:
  - M15 (Gerssen et al. 2003): $1.7 \pm 2.7 \times 10^3\, M_\odot$
  - G1 (Gebhardt et al. 2002): $2.0 +1.4/-0.8 \times 10^4\, M_\odot$
- black holes or heavy remnants?







Gerssen et al. (2002)



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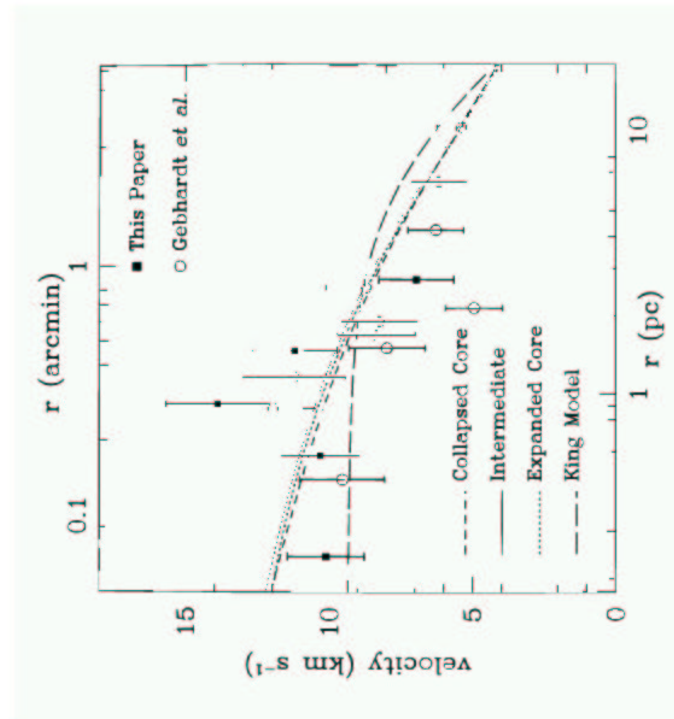

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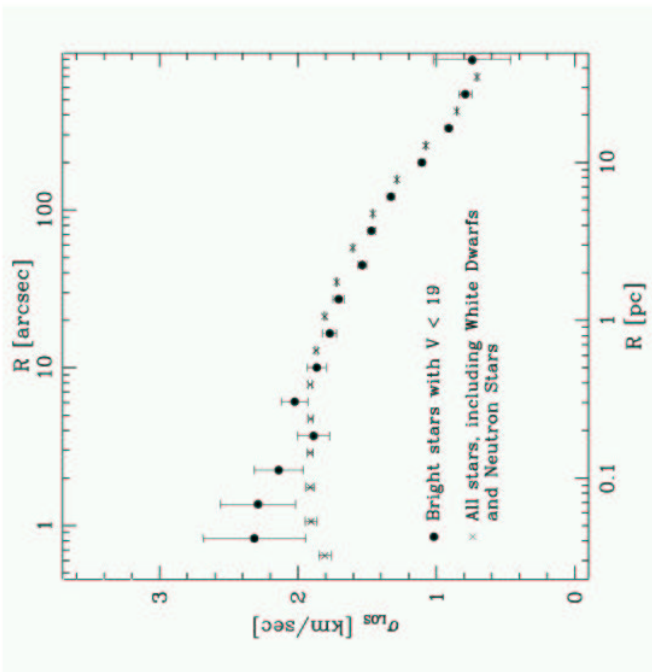
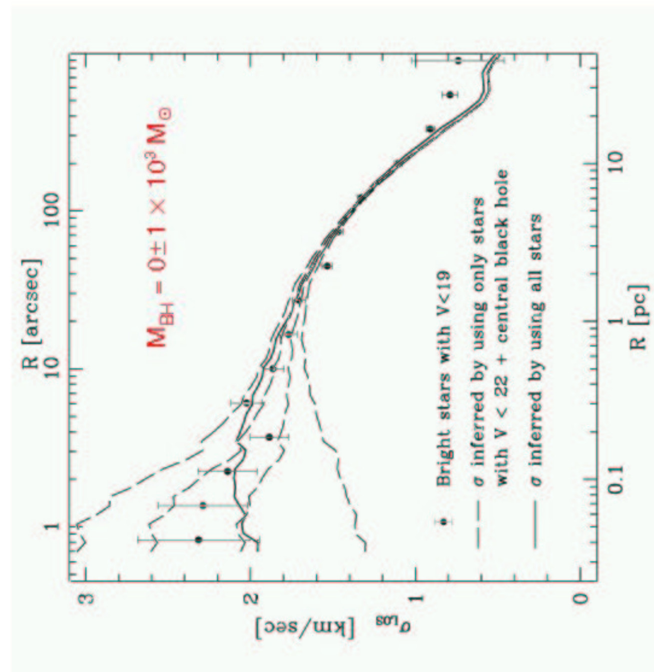


Baumgardt et al. (2003)



Baumgardt et al. (2003)

SUMMARY

- expect dominant dark remnant population in core-collapsed clusters
- several avenues for making IMBHs
- observational evidence for heavy remnant(s) in M15
- jury still out on IMBH interpretation
- what about G1? (Baumgardt et al. 2003)