Intermediate-Mass Black Holes and Gravitational Radiation

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Evidence for $10^{2-4}\,M_\odot$ black holes.

Black holes in dense stellar clusters.

Evidence for current IMBH binaries.

Eccentricities and spins.

Information from waveforms.

Kicks during black hole mergers.

Observations of $10^{2-4}\,M_\odot$ BH

Density, velocity cusps in globulars.

- Fits $M-\sigma$ relation of SMBH!
- But current evidence is marginal.

Odd point sources seen in many galaxies:

- Off-center, strongly variable$\Rightarrow$ BH.
- Debate about beaming, super-Eddington.
- If $\sim$isotropic, $L<L_E$, then $M\gtrsim 100\,M_\odot$.

Associated with dense stellar clusters.

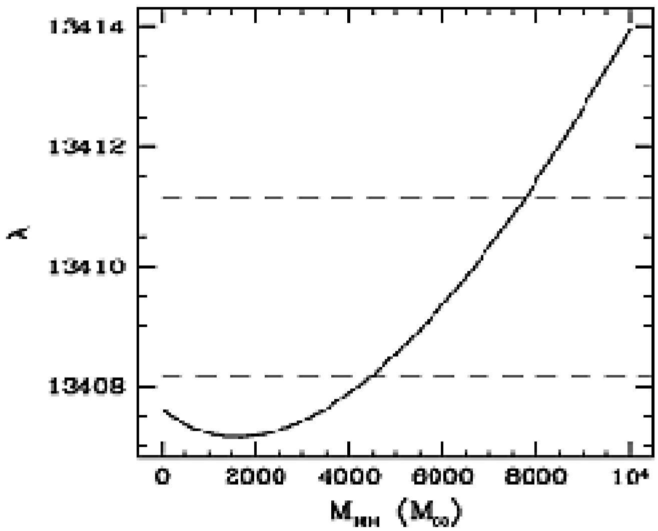
- Globulars and young star clusters.

Formation mechanism is debated.

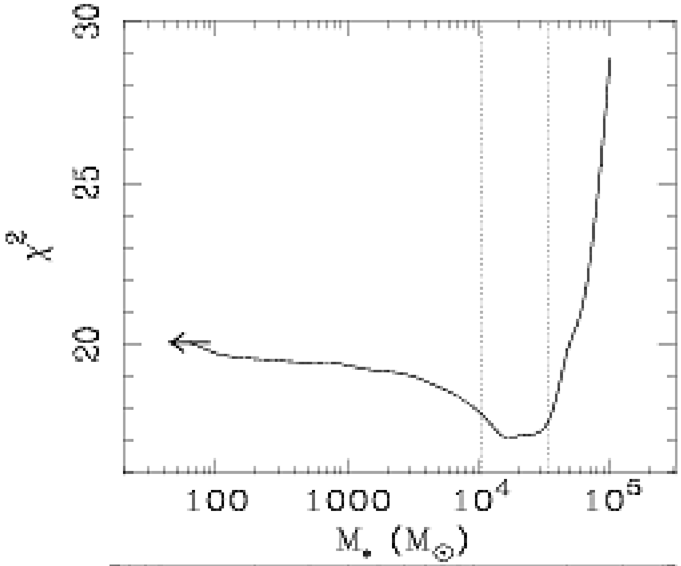
- Remnants of first stars?
- Rapid collisions in young clusters?
- Dynamical formation in globulars?

Hubble Observations of G1, M15

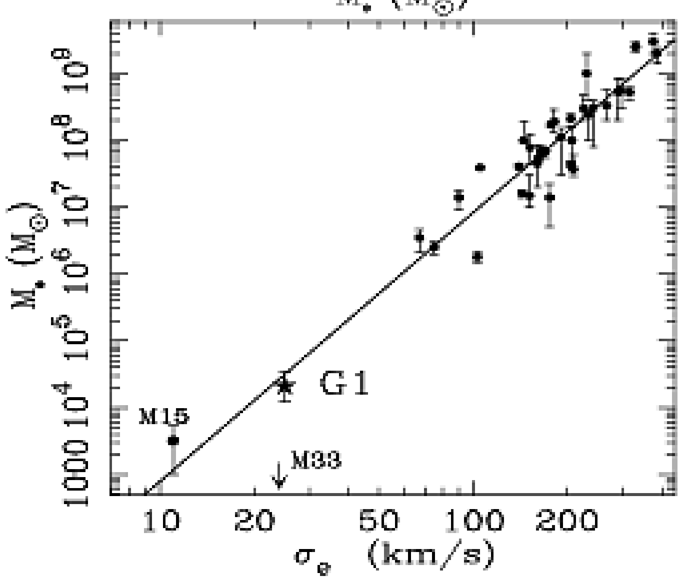
Gebhardt et al., van der Marel et al.



M15



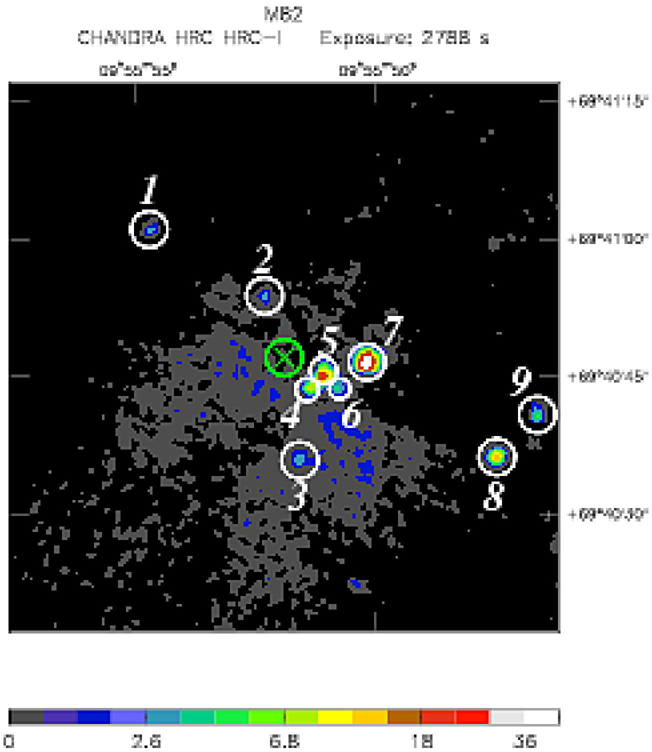
G1



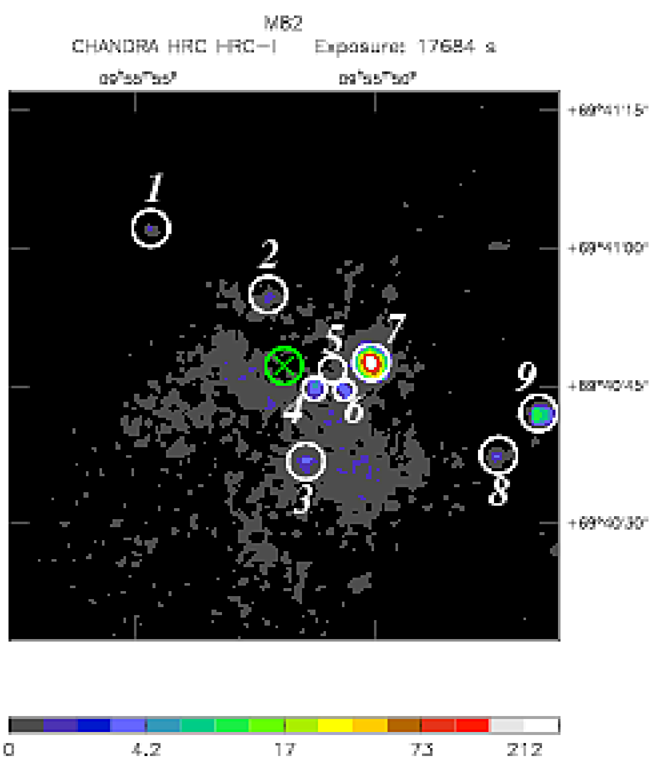
M vs. σ

Chandra Observations of M82

Matsumoto et al. (2000)



28 October 1999



20 January 2000

Interactions of Black Holes in Dense Clusters

More massive objects sink to center.

- Average stellar mass $\sim 0.4\, M_\odot$.
- Black holes, neutron stars, binaries in core.

In binary-single encounter, two most massive form final binary.

- Many BH expected in binaries.

Hard binaries are hardened.

- $10\, M_\odot$ BH kicked out before merger.
  - (Sigurdsson & Hernquist 1993)
- $> 50\, M_\odot$ BH stays, grows by mergers.

Might form $10^{2-4}\, M_\odot$ BH this way.

Current IMBH binaries in clusters?

For detection of gravitational radiation, it matters whether mergers happen now or only $\sim 10^{10}$ yr ago!

Evidence for rotation in globular cores.

Should isotropize in $t_{\rm relax}$, $\sim 10^7$ yr in core.

Needs recent deposit of angular momentum.

F. Rasio: IMBH binary? Companion would have to be $10-20\,M_\odot$ black hole.

Caution: hairy edge of observations.

Cluster center? Resolution issues?

Colpi et al. (2003): dynamics of NGC 6752 millisecond pulsars implies binary black hole?

N5824 Rotation Profile

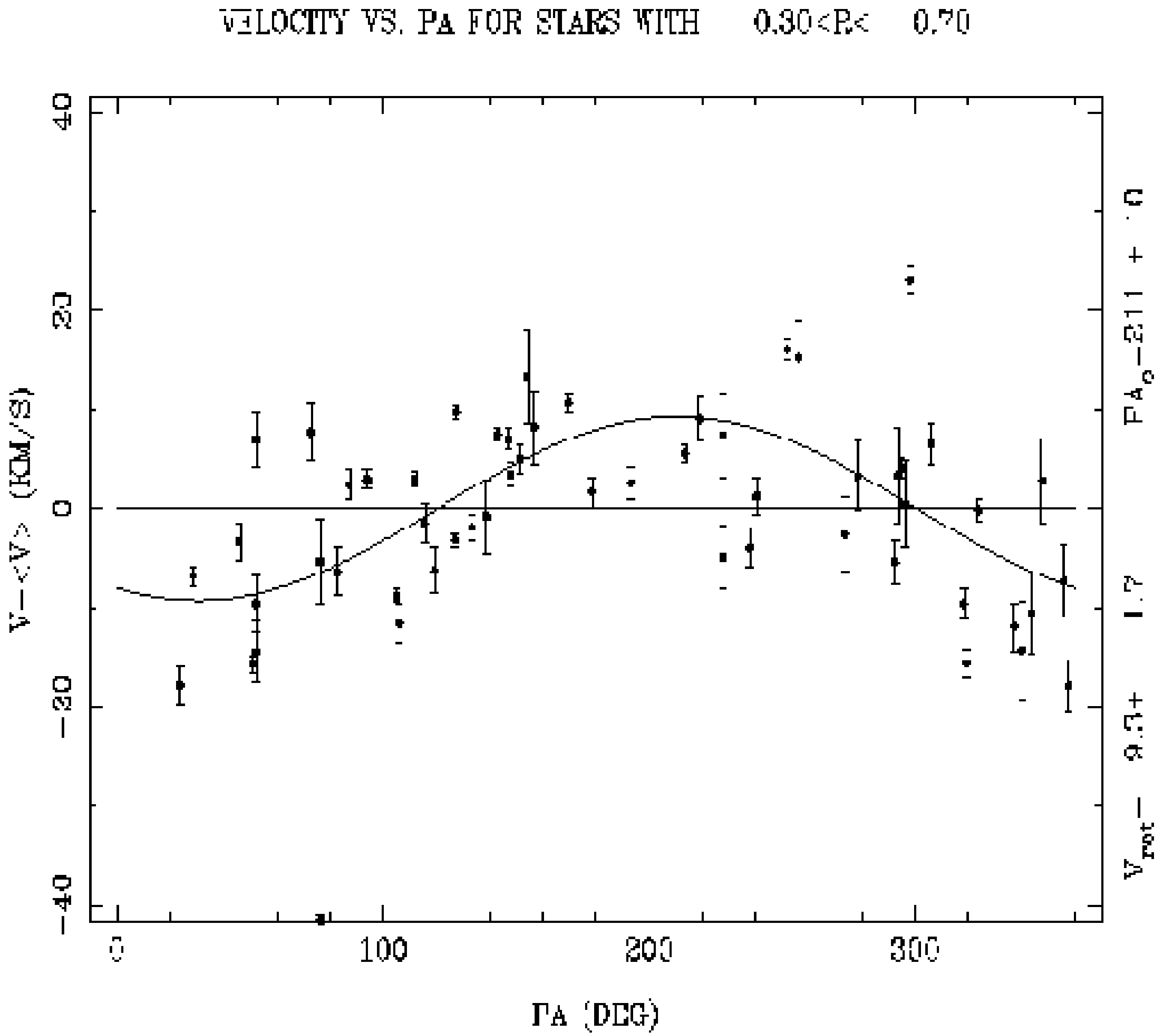


Fig. 1.— Line of sight speeds versus position angle in sky, for stars near the core of the globular cluster NGC 5824. An isotropic velocity distribution would give a uniform spread in speeds, independent of the position angle. The solid line shows the best-fit curve assuming systematic rotation in the center. Without a continued supply of angular momentum, rotation signatures such as this would be erased in a core relaxation time, $\sim 10^7$ yr for a dense cluster. Much additional work needs to be done to assure the reality of rotational signatures in NGC 5824 and other clusters. Figure provided by Karl Gebhardt.

Distribution of Eccentricities

Gravitational radiation merger time:

$\tau_{\rm merge} \propto (\mu M^2)^{-1} a^4 (1-e^2)^{7/2}$.

Thus, eccentricity matters a lot.

Detectability of pericenter advance.

For equal-mass binary, thermal dist: $P(e) = 2e$.

What about for higher mass ratios?

Simulations by Kayhan Gültekin.

Key: inspiral after last encounter.

Resulting strong bias towards high e.

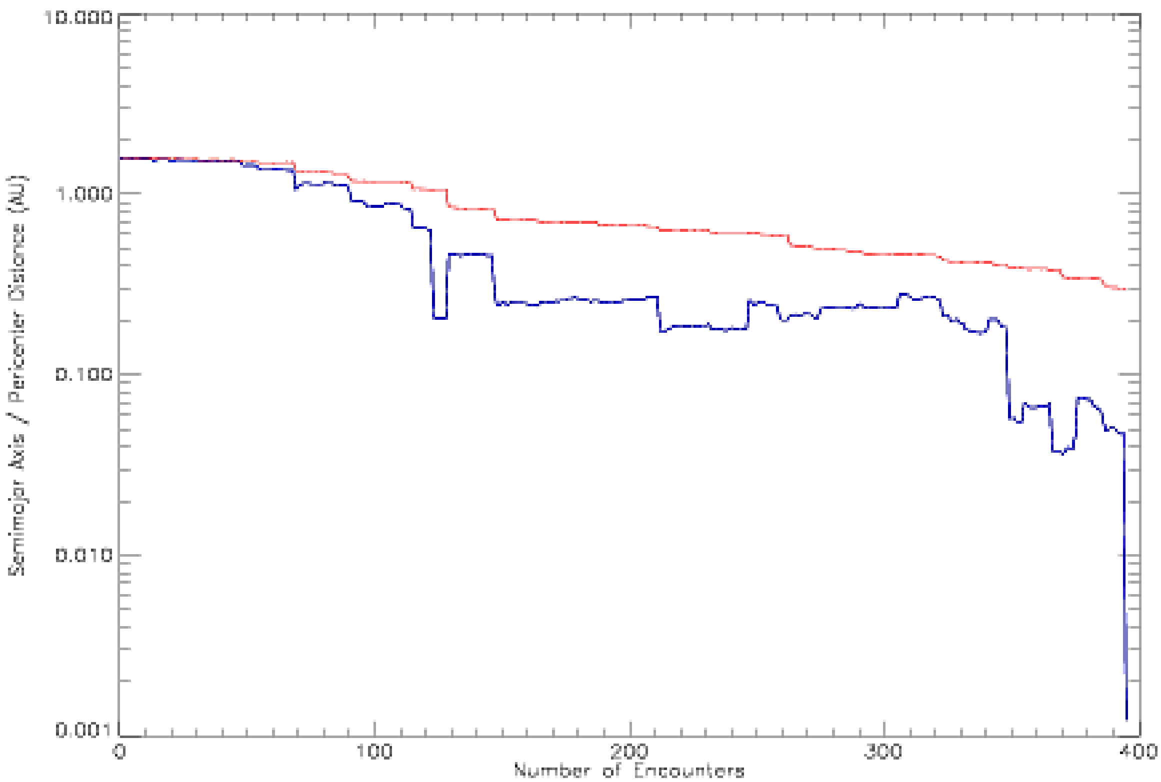


Fig. 2.— Evolution of the semimajor axis (red line) and pericenter distance (blue line) for an intially circular binary. Mass of primary is $1000\,M_{\odot}$, mass of secondary is $10\,M_{\odot}$, and interactions occur with $10\,M_{\odot}$ objects. All encounters are treated in the Newtonian point-mass limit, but are terminated when the two-body gravitational radiation time is less than the time to the next encounter. Evolution of this kind biases the binaries towards high eccentricities. Figure provided by Kayhan Gültekin.

Distribution of Spins

Spin parameter $j = a/M = J/M^2$.

Lense-Thirring precession.

Energy release during merger.

At birth, j may be high.

Accretion of compact objects changes j.

From Blandford & Hughes (2002):

$$|u_{\phi,\mathrm{LSO}}(\iota)| \approx |L_{\mathrm{ret}}| + \tfrac{1}{2}(\cos\iota + 1)\left(L_{\mathrm{pro}} - |L_{\mathrm{ret}}|\right).$$

Damped random walk.

Accretion of masses m, total mass M:

Gaussian, mean $j \approx (2m/M)^{1/2}$.

Detection Statistics

How frequent and strong are detections?

Overall considerations:

- Encounter rates: $\lesssim 10^{-7} - 10^{-6}\,\mathrm{yr}^{-1}$.
- Supply of objects: $\lesssim 10^{-7}\,\mathrm{yr}^{-1}$.
- BH growth rate $\Rightarrow$ $\lesssim 10^{-7}\,\mathrm{yr}^{-1}$.

Detection epochs:

- Inspiral (until last stable orbit).
- Merger (messy non-analytic stuff).
- Ringdown (Teukolsky formalism).

Advanced LIGO, 10s per year.

- Expect $e < 0.01 - 0.1$ usually (L. Wen).

LISA, 10s of persistent (Galaxy, Virgo).

- $e \sim 0.1 - 0.9$ in most of inspiral.

Information from Waveforms

What could we learn from LISA detections?

Pericenter, Lense-Thirring, orbit decay.

For $m = 10\,M_\odot$ and $M = 100\,M_\odot$:

$t_{\rm obs,peri} \gtrsim 4\tau_6^{5/8}$ yr.

$t_{\rm obs,LT} \gtrsim 100 j^{-1}\tau_6^{3/4}$ yr.

$t_{\rm obs,decay} \gtrsim 30\tau_6^{11/16}$ yr.

Weak dependence on m, M.

All easiest to see from Virgo.

Distance determination?

Get e, $\frac{M+m}{a^3}$, $\frac{M+m}{a}$, $\frac{a^4}{(M+m)Mm}$.

Wave strength then $\Rightarrow d$.

Cepheid distance tests GR consistency.

Kicks During Merger

What could prevent BH buildup in clusters?

- Birth kicks.
- Three-body kicks.
- Merger kicks.

Asymmetric GR emission produces kick.

- Scales as $a_{\rm ISCO}^{-4}$.
- Max for $M/m = 2.6$.

PN calcs suggest few km s^{-1} for $j \ll 1$.

$v_{\rm esc} \sim 50$ km s^{-1}, but:

- Additional energy radiated during merger.
- Strong-gravity calcs needed.

Conclusions

$\sim 10^{2-4}\,M_\odot$ BH seen in growing number of clusters.

Interesting dynamics, GR.

Possibly strong, informative sources.

Significant GR work needed:

- Mergers at 10:1 to 1000:1 mass ratios?
- Recoil kick in strong gravity?

Also need for substantial three-body, four-body simulations (Gültekin).