Stellar-mass black holes in star clusters: gravitational waves and the “dark cluster remnants”

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Stellar-mass black holes in star clusters

- Black Holes (BH) in star clusters form in early evolutionary phase (~ 10 Myr) through supernovae of $\gtrsim 20M_\odot$ stars — stellar mass BHs $\sim 10M_\odot$ (for low metallicity clusters). BH-MF

- Evidences from recent X-ray observations — several Globular Cluster (GC) BH-candidates, *e.g.*, NGC4472 X-ray source, Maccarone et al. 2007; CHANDRA candidates, Brassington et al. 2010; ULX systems (likely stellar BH-WD candidates, Ivanova et al 2010).

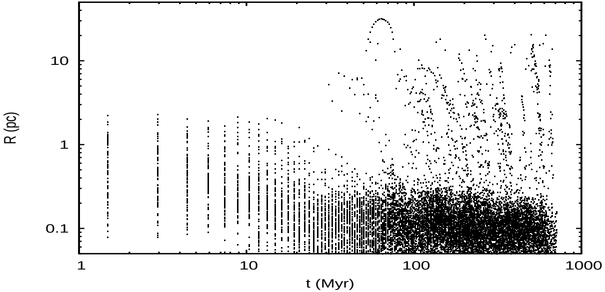
- Dynamically significant: Mass-stratification/Spitzer instability — *pure BH-core formation* due to runaway sinking.

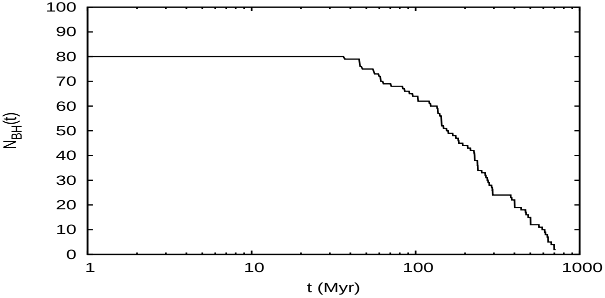
- Potential consequences: *dynamical formation of tight BH-BH binaries* — promising sources of GW for ground-based detectors; *modification of dynamical evolution*.

- BH-normal star encounters: potential formation of BH X-ray binaries.

Segregation of BHs (and their self-depletion)

N-body integration of Plummer cluster: $N(0) = 45K$, $N_{BH} = 80$, $r_h(0) = 1$ pc





Gravitational waves from star clusters

Dynamical BH - BH binaries

How BH - BH binaries form from a population of single BHs?

- In *close encounter among three BHs*, two get bound as third escaping BH carries away excess K.E.

  BH + BH + BH —> (BH + BH) + BH

- *Multiple exchanges* — BHs being more massive replace binary members in successive exchange encounters (important when primordial binaries present).

  (S + S) + BH —> (S + BH) + S
  (S + BH) + BH —> (BH + BH) + S

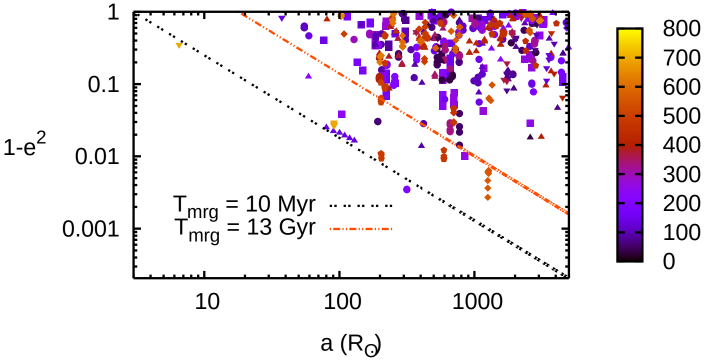
N-body computations

- Concentrated *Plummer clusters* of single stars with $r_h(0) \leq 1.0$ pc, $N(0) \leq 10^5$ low-mass ($0.5M_\odot \leq m \leq 1.0M_\odot$) stars.
- $M_{BH} = 10M_\odot$ BHs added with same distribution as stars — the number N_{BH} of BHs added consistent with a Kroupa IMF with full/half retention fraction.
- Isolated clusters without primordial binaries — BHs mostly unaffected by tidal field.
- BH-BH binary evolution due to GW radiation using *Peters' formula*: applied for *individual* binaries and *hierarchies*.
- GW emission-recoil during final merger phase likely to eject merged BH — *arbitrary large velocity kick* ~ 100 Km s^{-1} *applied* to eject merged BH from cluster.
- All computations using state-of-the-art `NBODY6` direct N-body integrator (Sverre Aarseth) on GPUs.

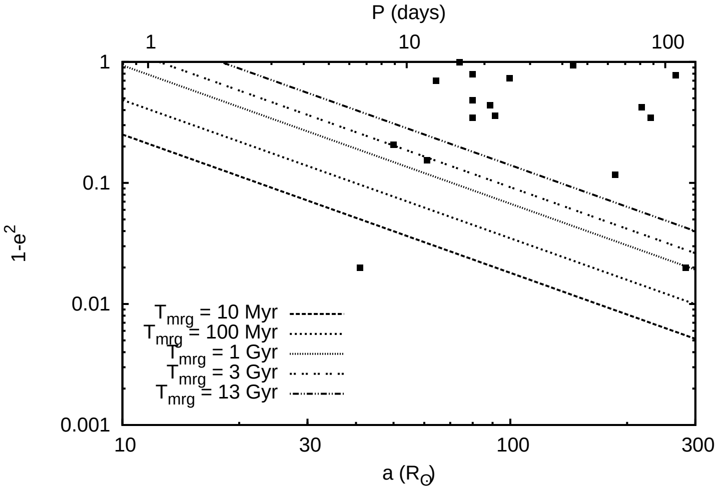
Can dynamical BH-binaries merge via GW?

Dynamical BH-BH binaries shrink due to *encounter hardening (Heggie's law).* ▸ BH hardening

Few BH-binaries near $T_{mrg} = 10$ Myr *line* — "potential" candidates for mergers. Typical for simulations with medium to large *N*. ▸ Runs



Escaping BH-binaries



For model C65K110 ▸ Runs

Models

Model name	$N(0)$	N_{sim}	$r_h(0)$ or R_s (pc)	$N_{BH}(0)$	N_{mrg}	t_{mrg} (Myr)	N_{esc}	$\mathscr{R}_{\text{AdLIGO}}$
Isolated clusters								
C5K12	5000	10	1.0	12	0	— —	— —	— —
C10K20	10000	10	1.0	20	0	— —	— —	— —
C25K50	25000	10	1.0	50	0	— —	3 1 1	— —
C50K80	45000	1	1.0	80	1	698.3	3 1 0	$28(\pm 14)$
C50K80.1	45000	1	0.5	80	2	217.1, 236.6	3 2 1	$35(\pm 15)$
C50K40.1	45000	1	0.5	40	0	— —	1 1 1	$7(\pm 7)$
C50K200	50000	1	1.0	200	2	100.8, 467.8	0 0 0	$14(\pm 10)$
C65K110	65000	1	1.0	110	1	314.6	4 2 1	$35(\pm 15)$
C65K110.1	65000	1	0.5	110	0	— —	4 3 1	$28(\pm 14)$
C65K55.1	65000	1	0.5	55	1	160.5	1 0 0	$14(\pm 10)$
C100K80	100000	1	1.0	80	2	219.4, 603.2	5 2 1	$42(\pm 15)$
C100K200	100000	1	1.0	200	0	— —	5 4 4	$28(\pm 14)$
Reflective boundary								
R3K180	3000	1	0.4	180	1	1723.9	5 3 1	$35(\pm 15)$
R4K180A	4000	1	0.4	180	1	3008.8	2 2 1	$21(\pm 12)$
R4K180B	4000	1	0.4	180	2	100.2, 1966.5	2 1 0	$28(\pm 14)$
R3K100	3000	1	0.4	100	2	3052.8, 3645.9	1 1 0	$18(\pm 10)$
R4K100A	4000	1	0.4	100	2	104.4, 814.2	3 3 1	$28(\pm 14)$
R4K100B	4000	1	0.4	100	1	1135.3	3 3 3	$28(\pm 14)$

▸ Reflect ◂ Mergers ▸ IMCs ▸ Detection

Which clusters are best candidates?

We infer,

- (a) *Concentrated star clusters with $N(0) \gtrsim 5.0 \times 10^4$ and significant BH-retention produce dynamical BH-BH binaries that merge within Hubble time.*

- (b) *Most mergers occur within first few Gyr cluster evolution (for both in-cluster & escaped BH-binaries).*

▸ Merger time dist.

Star clusters with *initial mass* $M_{cl}(0) \gtrsim 3 \times 10^4 M_\odot$ that are *few Gyr old* seem best candidates — represent *Intermediate-age Massive Clusters* (IMC). ▸ Cluster MF

◂ Runs

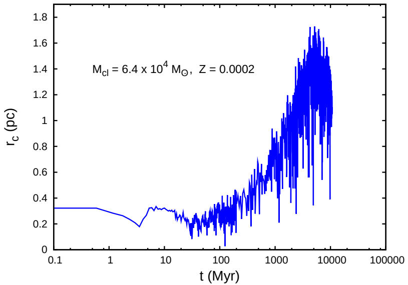
Which clusters are best candidates? (cont)

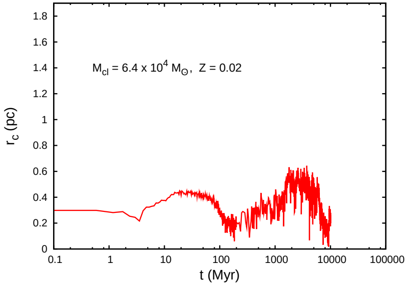
- GCs *too old* ($\sim$ 10 Gyr): most BH-BH pairs already merged. $N_{BH} - t$
- Young massive clusters (age $<$ 50 Myr) are *too young*. Generally mergers happen much later.

IMCs appear most likely candidates for dynamically forming present-day BH-BH mergers.

Runs

Heating of cluster core: effect of metallicity





Ejected BHs returning to core via dynamical friction deposit K.E. in central region — *expansion of cluster core*.

Lower Z yields more massive BHs, hence core expansion stronger.

Also, lower Z tends to produce more BH-BH mergers: low Z computation: *3 mergers* within Hubble time; high Z computation: *1 merger*

[Work in progress, also see Mackey et al. (2008)]

MC Age-r_c

BH-BH merger Detection rate

- Total LIGO/AdLIGO detection rate of BH-BH mergers from IMCs

$$\mathscr{R}_{\rm GW} = \frac{4}{3}\pi D^3 \rho_{cl} \mathscr{R}_{mrg}. \quad (1)$$

$D =$ max. distance for compact-binary inspiral detection. For $10 M_\odot$ BH-pair $D \approx 1500$ Mpc (AdLIGO). $\rho_{cl} \approx 1.4\ {\rm Mpc}^{-3}$ (density of young populous clusters, Portegies Zwart & McMillan (2000)). ▸ Range ◂ Runs

- Isolated clusters with full BH retention and *power-law IMC mass function with* $\rm index = -2$ (ICMF in spiral/starburst galaxies) $\Rightarrow \mathscr{R}_{\rm AdLIGO} \approx 31(\pm 7)\ {\rm yr}^{-1}$

- *Dynamical BH-BH binaries may constitute dominant contribution to stellar mass BH-BH merger events in the Universe.*

- See `Banerjee, S., Baumgardt, H. and Kroupa, P., 2010, MNRAS, 402, 371` for further details.

The “dark cluster remnants”

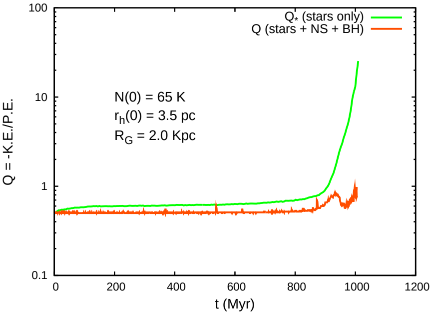
Existence of BH-core or “dark core” potential for a variety of phenomena, gravitational waves, delay of core-collapse, X-ray binaries — direct observational evidences?

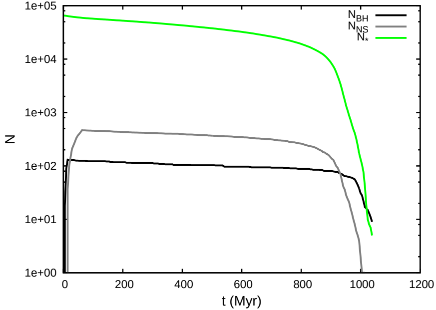
MC Age-r_c

The “dark cluster remnants”

- The BH-core depletes in $\tau_{\mathrm{BH}} \sim 700 - 1000$ Myr through ejections due to dynamical encounters (O’Leary et al. 2006, Banerjee et al. 2010).
- Galactic tidal field preferentially remove low-mass stars and retain heavier BHs (also neutron stars).
- Rapid tidal dissolution close to Galactic center in timescale shorter or comparable to τ_{BH} form cluster remnants containing few stars orbiting around a cluster of BHs.
- Observationally appear as *highly super-virial or large mass-to-light ratio star clusters bound by invisible mass:* the “**dark cluster remnants**”.
- Comprise *predicted new class of objects*.
- Their existence implies significant survival of BHs in star clusters following formation via supernovae — *constraint on supernova natal kicks*. (Banerjee, S. & Kroupa, P., in preparation)

Cluster evolution in strong tidal field: remnant formation ▸ r_c





Direct N-body computation (NBODY6) of Plummer clusters in circular orbits around point-mass Galactic bulge.

Remnant formation from stellar evolution: all BH/NS retained assuming low natal kicks in general; supports BH-core formation.

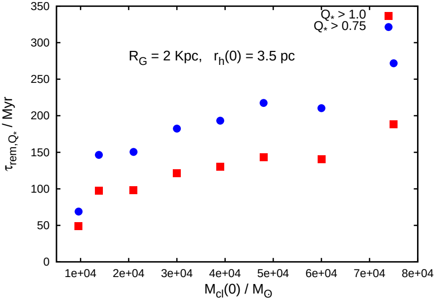
Virial coefficient ($Q = -\mathrm{K.E}/\mathrm{P.E}$) *of only luminous stellar members* continually rises during final dissolving phase although cluster remains bound as a whole.

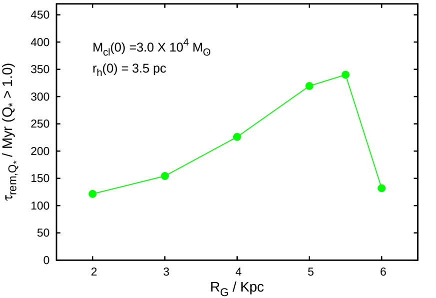
Lifetime of dark cluster remnants: estimated population

Lifetime in remnant phase ~ 100 Myr $(Q_* > 1.0)$, about twice for $Q_* > 0.75$.

Plausible parameter range for remnant formation: $M_{cl}(0) \gtrsim 10^4 M_\odot$, $R_G \lesssim 5$ Kpc (taking full NS/BH retention).

Estimated present population ($R_G \lesssim 5$ Kpc): $N_{\rm rem} \approx 50/80 (Q_* > 1.0/0.75)$. Assuming uniform average cluster formation $0.16 M_\odot$ yr^{-1} & Schechter cluster mass function (see, *e.g.*, Larsen 2008).





Summary

Gravitational waves from star clusters:

- BH-only subcluster dynamically potential for a wide variety of physical phenomena — GW emission, cluster core expansion, formation of BH X-ray binaries.
- Star clusters with *initial* mass $M_{cl}(0) \gtrsim 3 \times 10^4 M_\odot$ dynamically produce BH-BH mergers (inside cluster or escaped) within *few Gyr*.
- *IMCs seem best candidates* for present-day BH-binary mergers.
- Preliminary estimate of merger rate for "AdLIGO" ≈ 30 yr^{-1} — dynamical BH-BH merger might dominate stellar mass BH-BH merger events in the Universe.

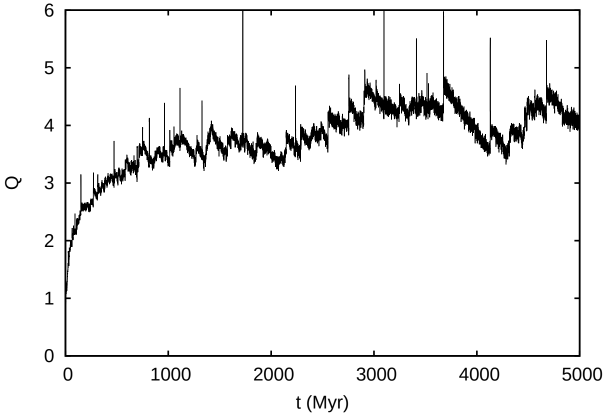
Dark cluster remnants:

- Rapid tidal stripping of stars from clusters close to Galactic center results remnants that appear *highly super-virial clusters bound by unseen mass — predicted new type of objects.*
- Can form as remnants of initially $M_{cl}(0) \gtrsim 10^4 M_\odot$ clusters within $R_G \sim 5$ Kpc Galactocentric distance (taking full NS/BH retention) — expected in significant numbers ($N_{\rm rem} \sim 50$).
- Detection can provide *constraint on supernova natal kicks*.

N-body computations: reflective boundary

- Star-clusters confined within perfectly reflecting sphere.
- *Mimics only core* of a cluster.
- Fewer stars needed, much faster than full cluster computation: we use $N = 3000 - 4000$ stars within $R_s = 0.4$ pc giving $\rho \sim 10^4 M_\odot \, \mathrm{pc}^{-3}$.
- Stars faster than $v_{esc} \approx 24$ Km s^{-1} allowed to escape — *inhibits runaway heating*. Models Q – t

Virial coefficient Q for reflective boundary



Initial heating caused by super-elastic encounters, followed by saturation of the heating curve. Latter caused by enhanced escape rate of stars due to the heating. Reflective

Hardening of BH-binaries

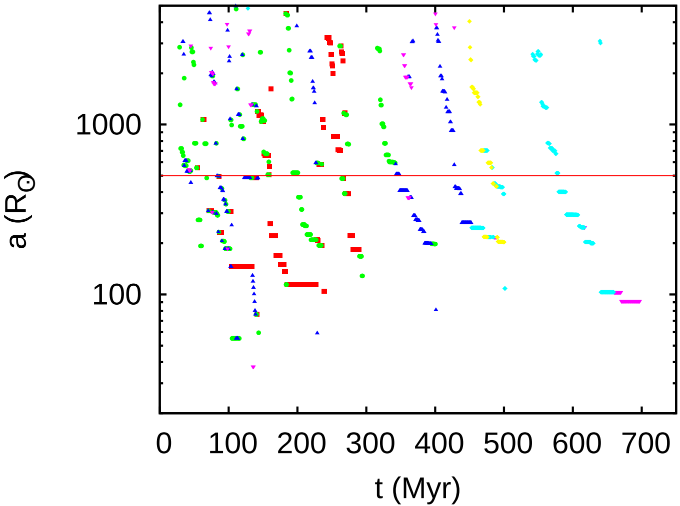


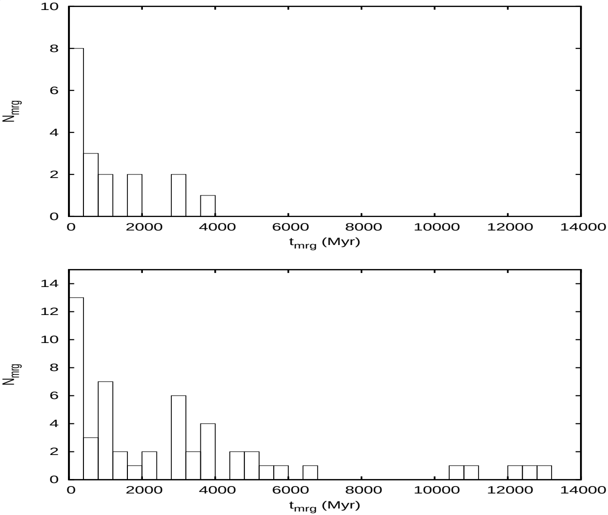
Figure for model C50K80

Mergers

Merger-time distribution

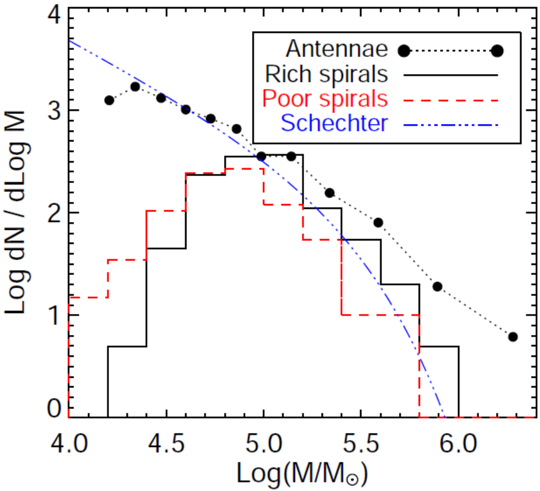
Top: mergers within clusters, **bottom:** escaped BH-binaries

Infer



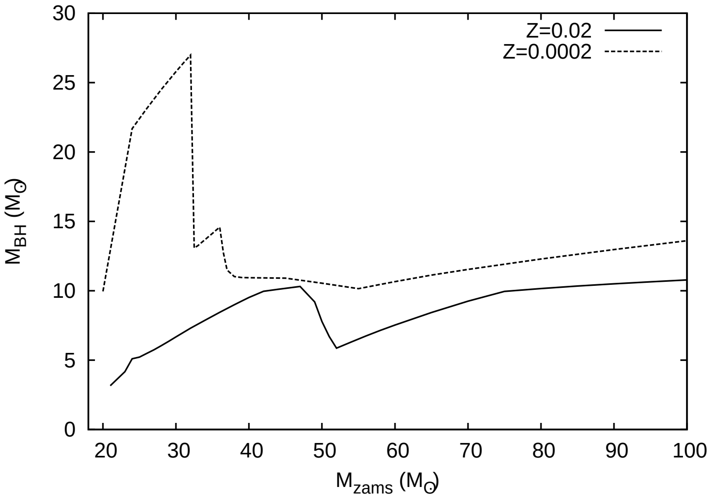
Most mergers (in-cluster & escapers) happen within first few Gyr.

Cluster mass function of spiral galaxies



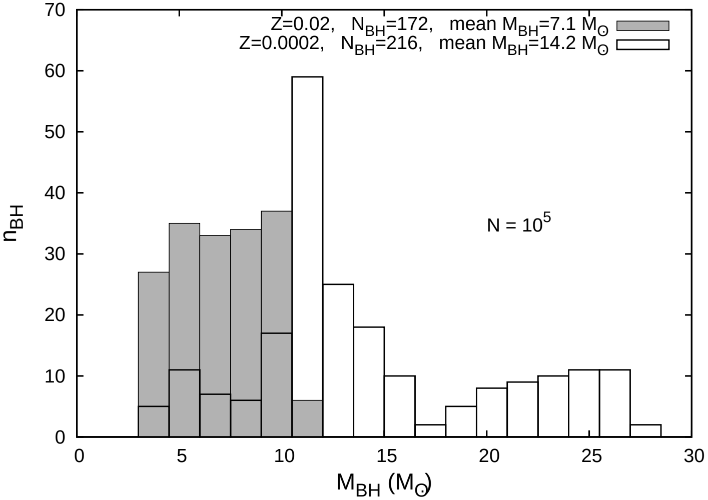
From Larsen, S.S., 2009, A&A, 494, 539 IMCs

Black hole mass function (in NBODY6).I



cf. Belczynski et al. (2008,2009) Outlook First

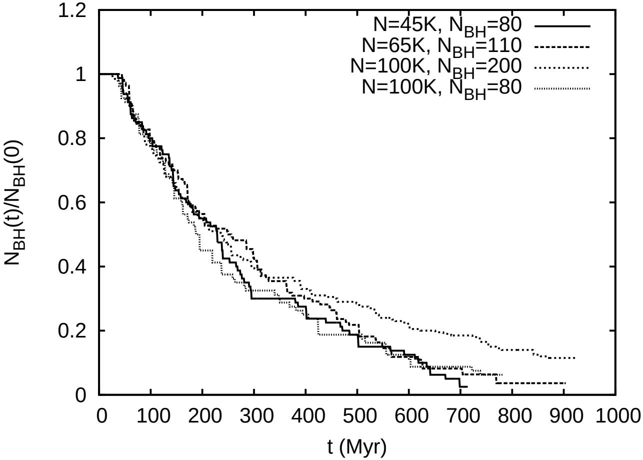
Black hole mass function (in NBODY6).II



BHs formed from $N = 10^5$ star cluster with Kroupa (2001) IMF.

◂ Outlook ◂ First

BH depletion



◂ GCs

Maximum distance for GW inspiral detection

The range of detection of GW from inspiralling compact binary:

$$D = D_0 \left(\frac{M_{ch}}{M_{ch,nsns}} \right)^{5/6}, \qquad (2)$$

$D_0 \approx 300$ Mpc (AdLIGO) ≈ 18 Mpc (LIGO).

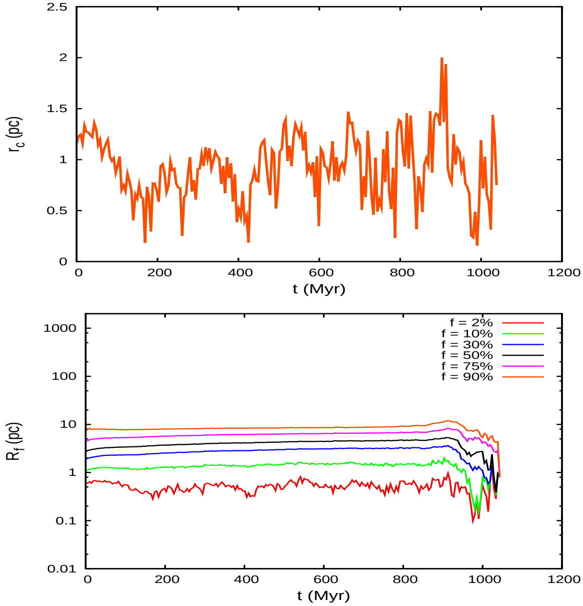
$M_{ch} \Rightarrow$ "chirp mass" for component masses m_1, m_2:

$$M_{ch} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}, \qquad (3)$$

and $M_{ch,nsns} = 1.2 M_\odot$ for a NS-NS binary. For BH-BH pair $M_{ch} = 8.7 M_\odot$.

Detection

Core radius & Lagrange radii ◂ Q – evol



Age - core radius relation in MC (Mackey et al. 2008) ◂ Core exp. ◂ Dark rem.