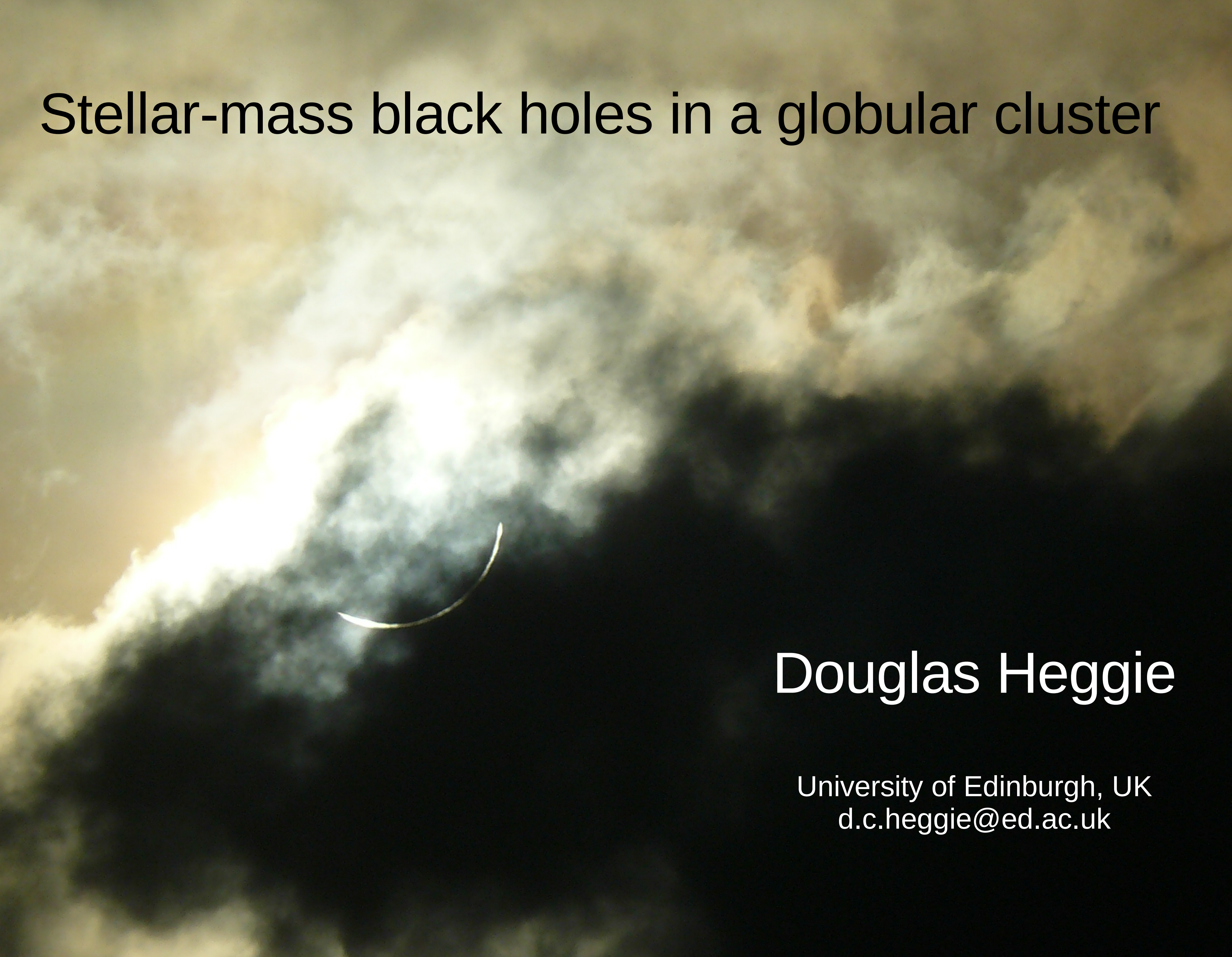

Stellar-mass black holes in a globular cluster

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How many stellar-mass black holes do you expect to find?

Example: M4

- Assume: initial conditions as in Heggie & Giersz (2008)
- **Initial number of stars: ~ 500 000**
- IMF: two-part power law ((lower: 0.9; upper: 2.3) to $50M_\odot$
- Stellar evolution: Hurley, Pols, Tout (2000)
- **Then about 1000 stellar-mass black holes (BH)**

How many will remain at the present day?

- 80% of stars have escaped (H&G 2008), so 200?
- But BH are centrally segregated, and so perhaps the number is much greater...
- Did natal kicks eject most BH at birth?

The traditional view

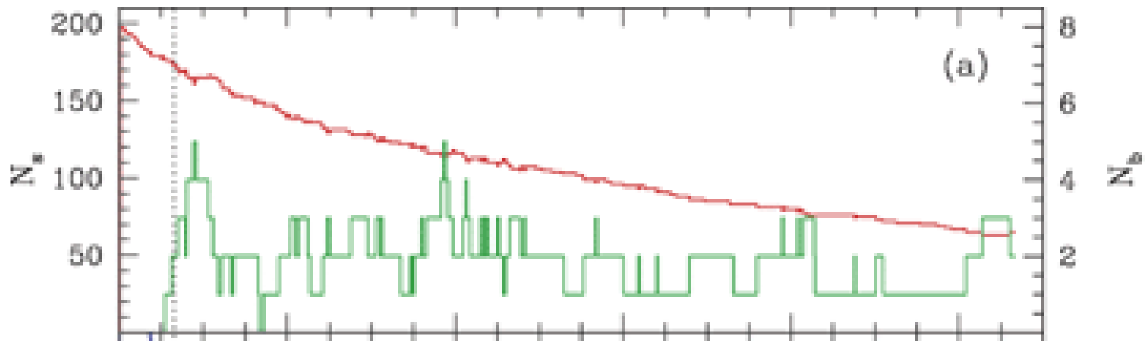
Theory: Kulkarni, Hut & McMillan (1993), Sigurdsson & Hernquist (1993)

1. By two-body encounters (relaxation) BH try to achieve equipartition. The result is that the BH mass-segregate.
2. Cluster is Spitzer-unstable (Spitzer 1969): BH subsystem cannot achieve equilibrium
3. BH subsystem forms a compact, almost isolated subsystem at centre of cluster
4. BH subsystem evaporates on Spitzer-Ambartsumian time scale (Ambartsumian 1938, Spitzer 1940) ~ 100 relaxation times, i.e. the relaxation time of the very compact BH subsystem.
5. Thereafter, star cluster evolves without BH: **essentially none at present day**

But....

1. After core collapse an isolated system expands, and the evaporation time scale is much longer (half-life about 2000 $t_{rh}(0)$ for N = 2000 (Baumgardt, Hut & Heggie 2002)
2. The potential well is much deeper than for an isolated system, and evaporation is much harder

Results from *N*-body simulations

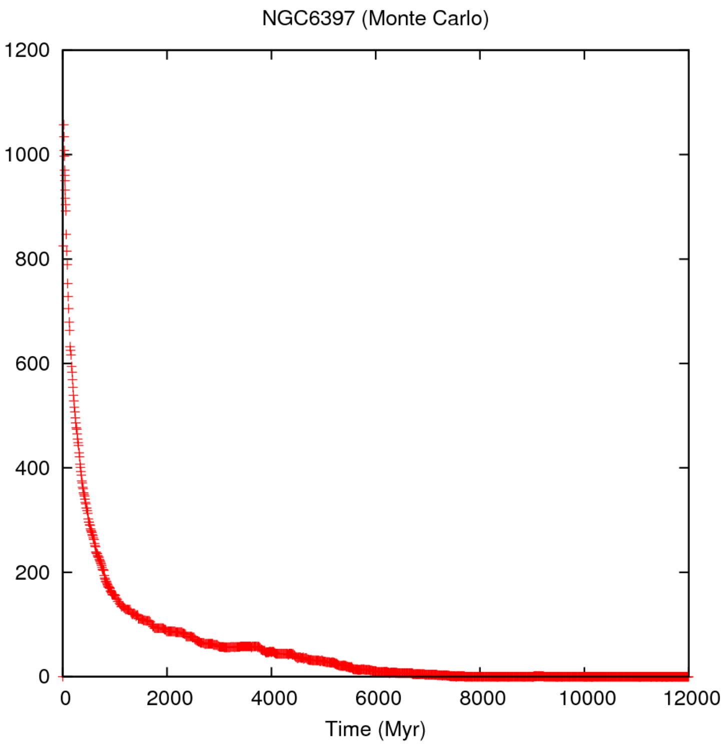


1. Mackey+ 2008: N = 10^5, $\rho_c = 200 M_\odot pc^{-3}$, 100% retention of BH
   Plot shows evolution of number of single and binary BH up to 10.6Gyr
2. Merritt+ 2004: N = 10^3, 100% retention of BH
   “Majority” ejected after ~$5t_{rh}(0)$
3. Aarseth 2012: N = 10^5, R_{vir} = 1pc, ~10% retention fraction
   ~50% escape by 1Gyr
4. Banerjee+ 2010: N $\leq$ 10^5, $R_h \leq$ 1pc, 50-100% retention fraction, no tide
   ~0 after 800Myr for 50% retention
5. Heggie (unpub): N ≈ 4.9×10^5, R_h = 0.58 pc, ~50% retention fraction
   9 after 6.76Gyr
6. Sippel & Hurley 2012: N = 2.5×10^5, R_h = 6.2 pc, 10% retention fraction
   16 at 12 Gyr (see later)
7. Hurley & Shara 2012: N = 2×10^5, R_h = 4.7 pc, retention fraction ?
   4 at 11.5 Gyr

Results from Monte Carlo simulations

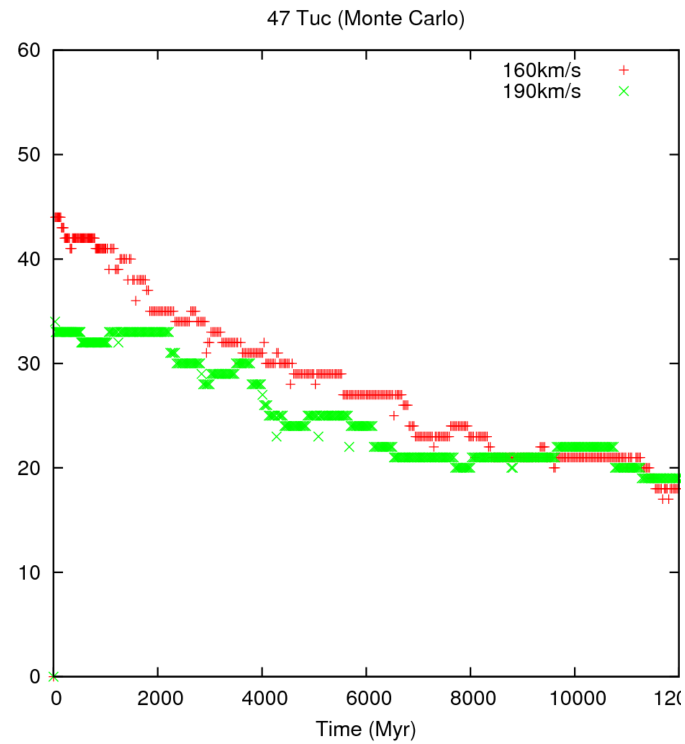
- Numbers of stellar-mass BH against time
- These models are designed to resemble stated cluster at the present day
- All results from papers by Giersz & Heggie

NGC 6397



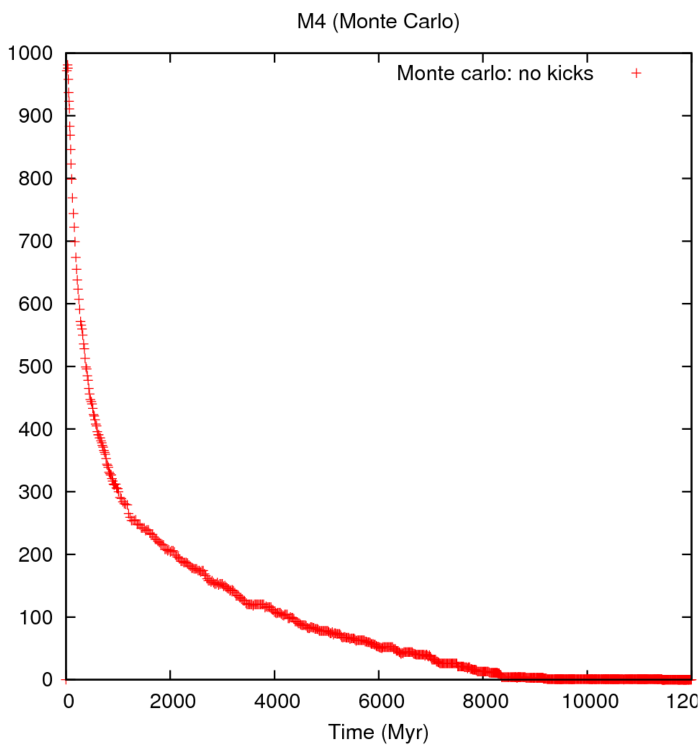
Retention factor 100%

47 Tuc



Natal kicks, σ = 160/190 km/s

M4



Retention factor 100%

See also Morscher+ 2012: N = $3\text{x}10^5$, r_h = 2.44pc, retention factor 86%. ~400 at 12 Gyr

The number remaining depends as much on the cluster as on the retention factor

Finding initial conditions

~~Method 1. By trial and error~~
Method 2. Automatically

Technique:

- Specify initial conditions by N (number of stars), r_h, r_t, initial King parameter W_o, three parameters specifying the piecewise power-law IMF. Call the parameter vector **x**
- Devise a measure of goodness of fit of the evolved model (e.g. at 12Gyr) to the desired cluster. This is on χ^2 lines, and involves the surface brightness profile, the velocity dispersion profile, the local luminosity function(s), pulsar accelerations, ... Call this **A**
- Optimise **A(x)** using the downhill simplex method (Nelder & Mead 1965, Press+ 1994)

Notes:

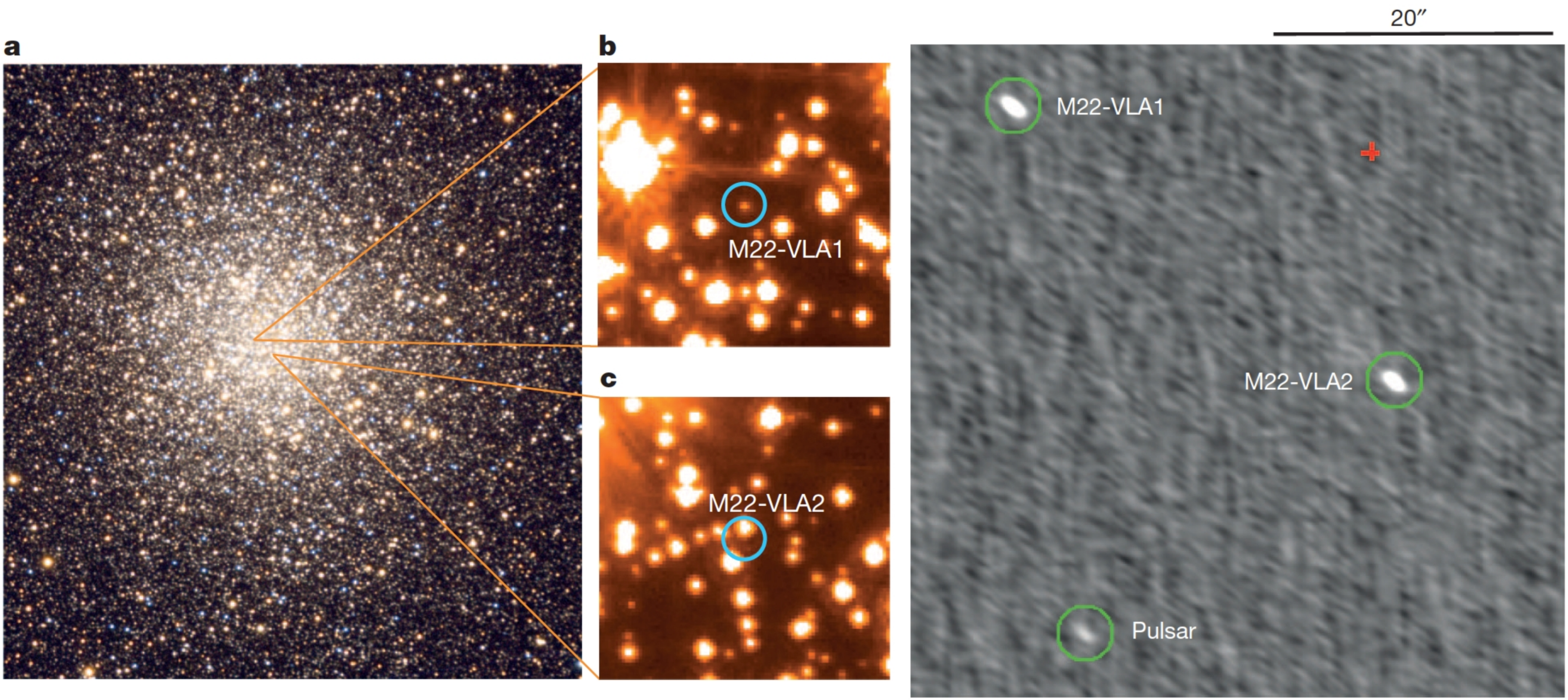
- Each evaluation of **A(x)** requires running a Monte Carlo simulation
- We use a previous version of the code for speed
- We scale the results, i.e. use smaller N than in the cluster, and scale the results in such a way as to preserve the relaxation time.
- Typically N = 10^5. Initial conditions optimised after about 100 models. Total time ~1-2 days
- Result checked with full-size model (correct N) using latest version of code (Giersz+ 2011)

Application: M22

(Work in progress with Mirek Giersz [Warsaw])

Motivation: discovery of two stellar-mass BH (Strader+ 2012)

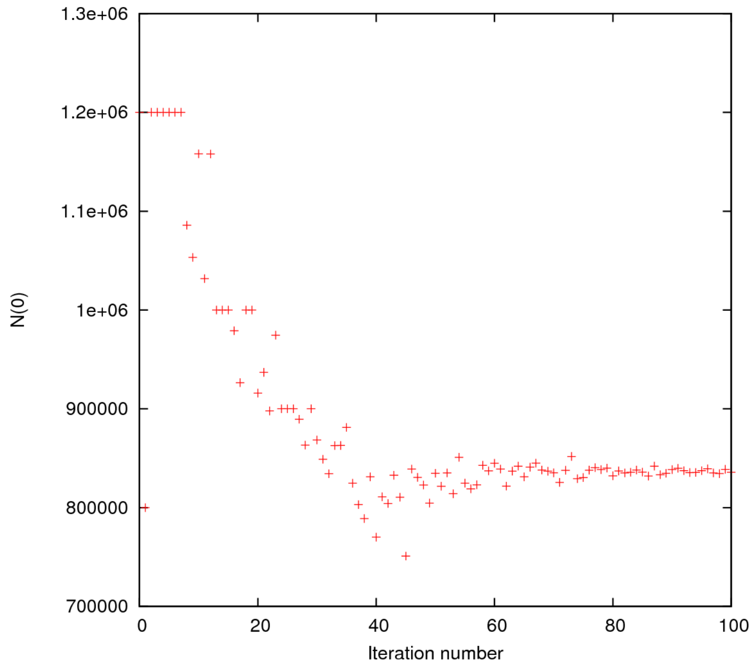
- Strader talk at MODEST 12 (Kobe, Japan, August 2012)
- Total population ~5-100 (assuming accretion from white dwarf companion)

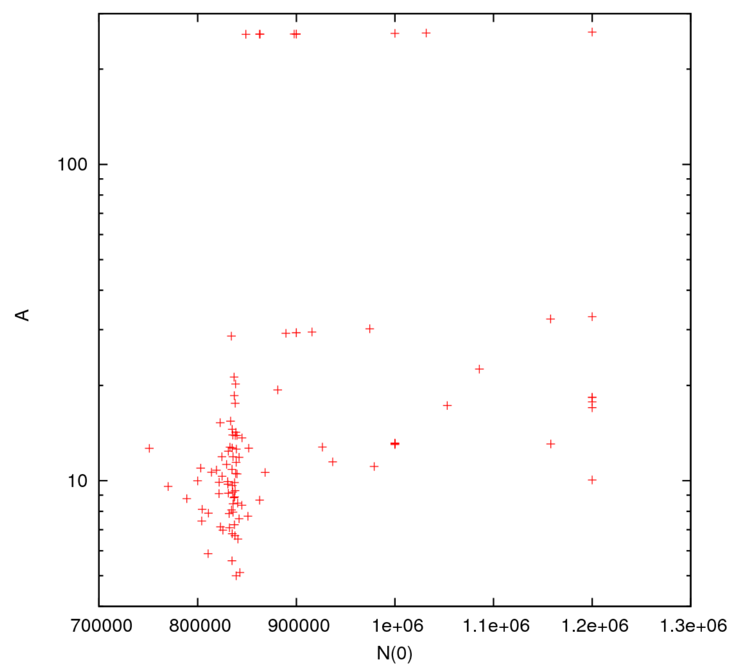


optical

radio

Finding initial conditions for M22





Convergence of N(0)

Goodness of fit v. N(0)

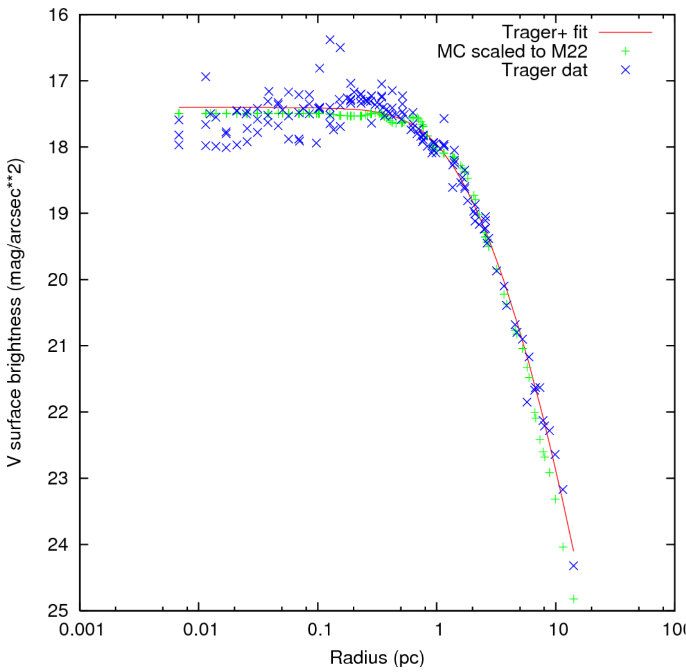
Best initial conditions (100% retention of BH)

$N = 7.8 \times 10^5$, $r_h = 2.5$pc, $r_t = 102$ pc, $W_o = 2.9$

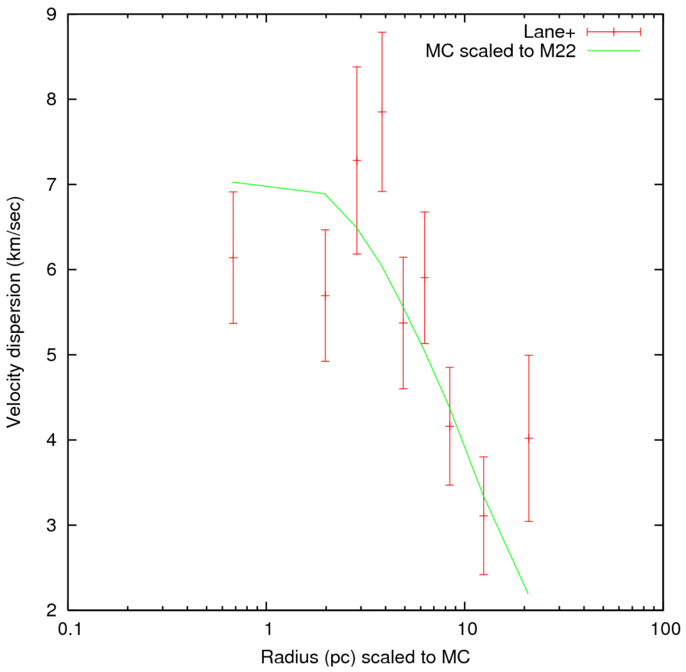
IMF: power law index 0.9/2.7 below/above 0.67 $M_\odot$pc

No technique yet for estimating confidence intervals

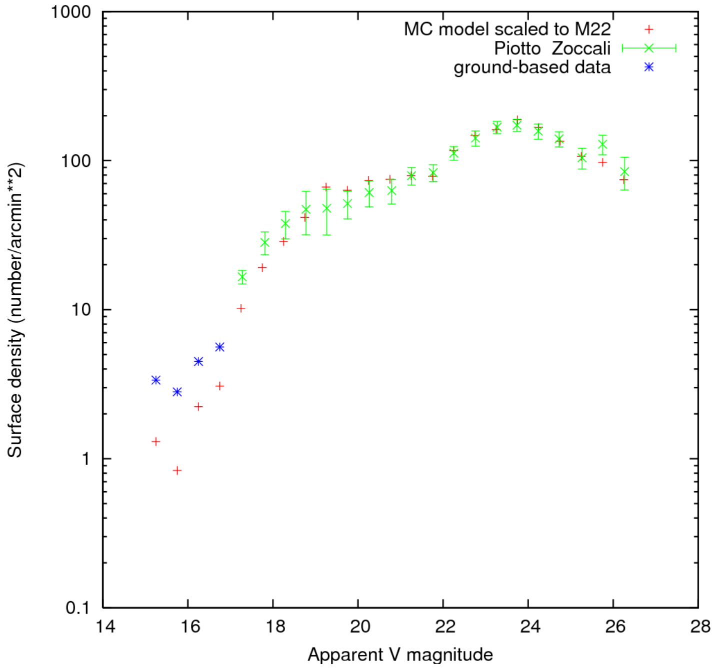
Example of fit



Surface brightness



Velocity dispersion

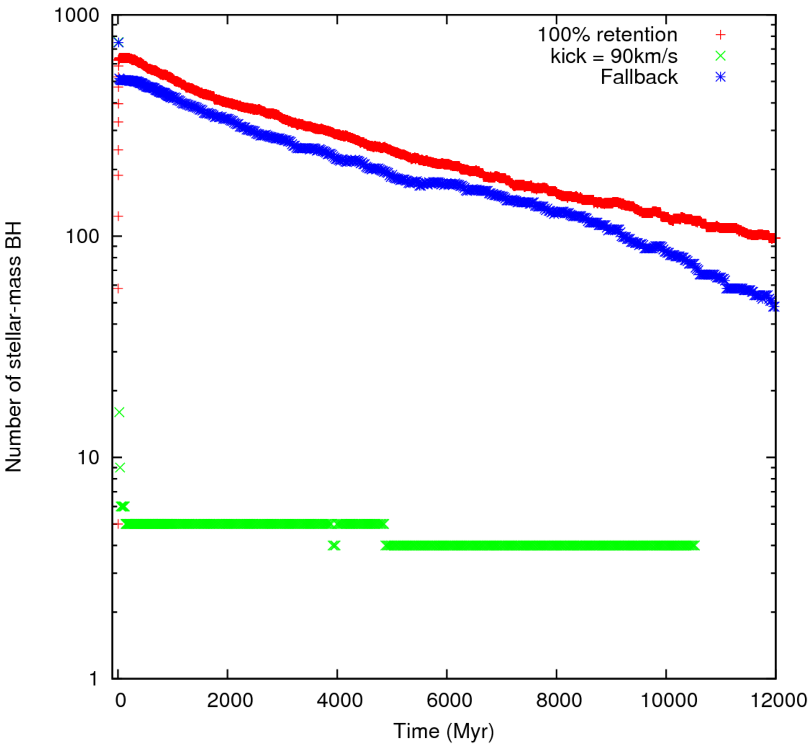


Luminosity function

(Deficient in bright stars)

Bonn Glühwein 2012

Evolution of the number of stellar-mass black holes (Full-size models)



Model	No. of WD/BH binaries at 12 Gyr
100% retention	2
Fallback*	1
kick = 90 km/s	1 (at 10.5 Gyr)

*kick reduced by fraction of envelope mass which falls back onto the remnant

- with kick = 265 km/s no BH remain
- model with kick = 90 km/s not quite complete

Conclusions:

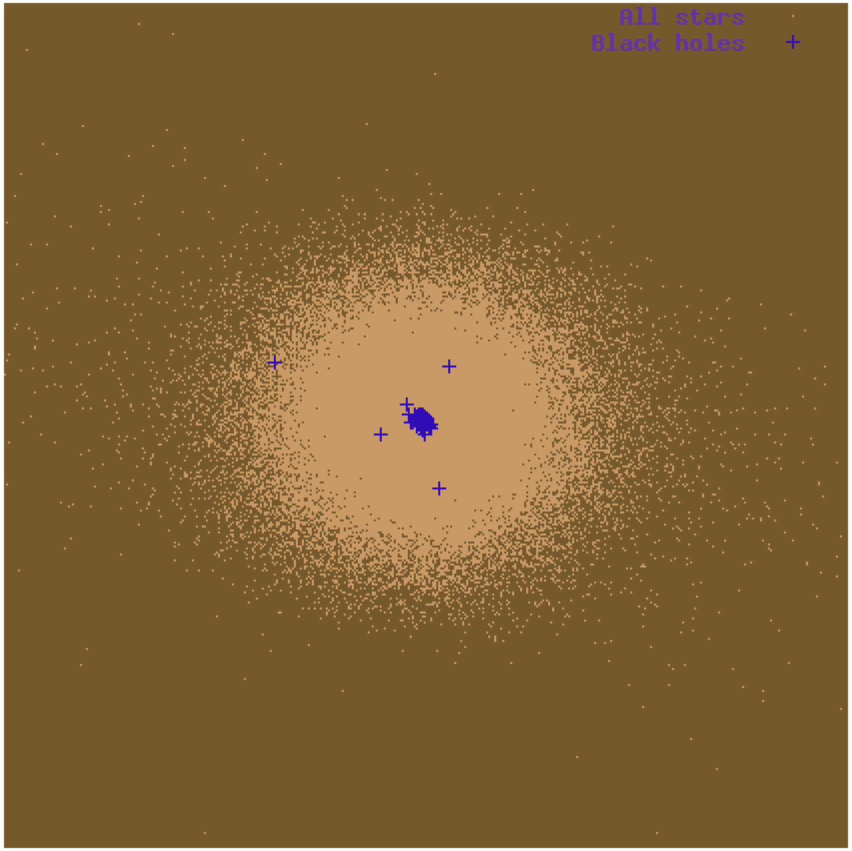
- Up to 100 stellar-mass BH may remain, depending on assumption about natal kicks and high-mass IMF
- Up to two BH-WD binaries

Cf Sippel & Hurley 2012

- N-body, N = 2.5×10^5, retention factor 11%
- t_{rh} and r_h/r_c close to M22 values at 12 Gyr
- 16 BH at 12 Gyr (needs scaling)

A revised theoretical view

Work in progress with Phil Breene (graduate student)



Consider 2-component system:

low-mass stars m_1, total mass M_1;

black holes m_2, total mass M_2;

Consider regime $m_2 >> m_1$ and $M_2 << M_1$

1. *Black holes mass-segregate*
2. *Cluster is Spitzer-unstable (BH subsystem cannot achieve equilibrium)*
3. *The BH subsystem goes into core collapse, forming three-body binaries*
4. *The BH subsystem continues to mass-segregate, but binaries arrest core collapse*
5. BH subsystem reaches balanced evolution powered by
   (a) binary heating,
   (b) heat loss to the low-mass stars
6. The low-mass system is heated by
   (a) heating by BH ejecta from three-body interactions in the BH system
   (b) energy conducted from the BH system
7. Overall thermal balance reached when the energy flux at the half-mass radius of the low-mass system is balanced by 6(a) and 6(b)

Some consequences

Result 1

- *Assume* that, in overall balanced evolution, energy production by BH balances energy flux at half-mass radius of light stars (Hénon's Principle)
- *Assume* total energy associated with loss of mass dM_2 (by escape of BH) is proportional to central potential ϕ_c
- *Assume* that ϕ_c is dominated by potential well of light stars

Then

- dM_2/dt is independent of m_2 and M_2 (recall: “2” means BH); and
- half-life of BH system is proportional to M_2 and independent of m_2; and
- $t_{rh} dM_2/dt \simeq 0.007$ (theory), 0.005 (empirical)
- BH subsystem decays logarithmically with time

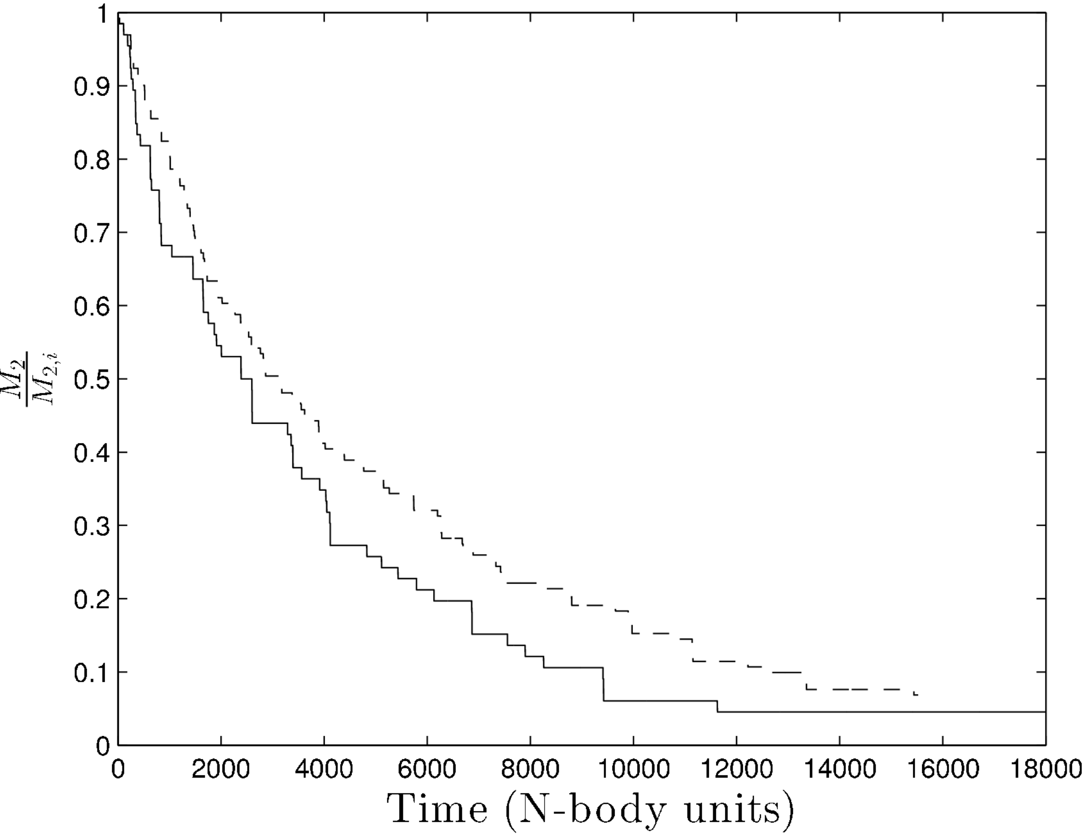
Result 2

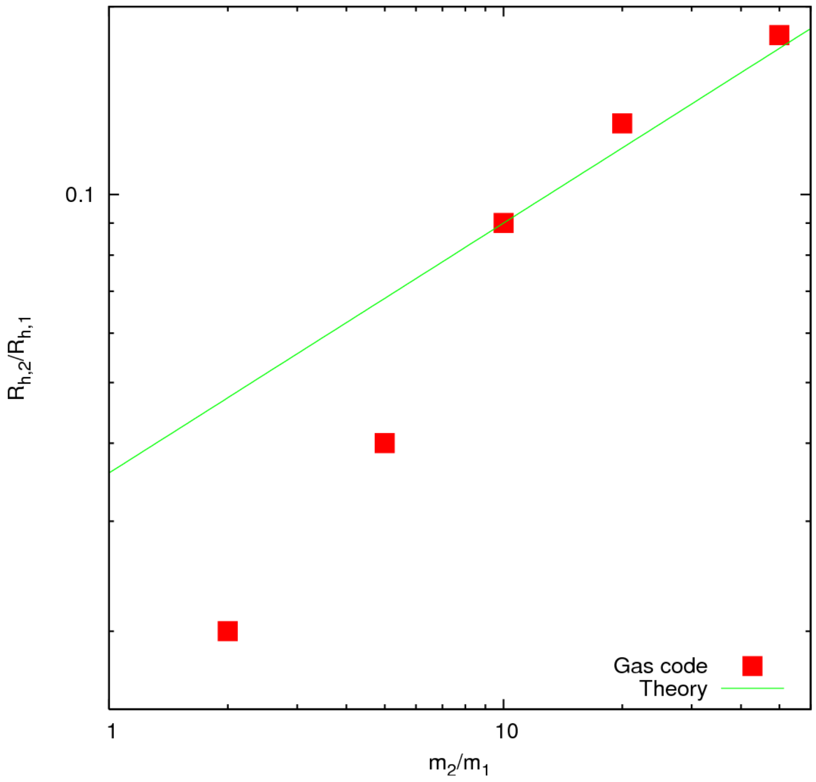
- *Assume* in addition that heating of lights is dominated by conduction from BH
- *Assume* that the BH are in balanced evolution

Then

- The ratio of half-mass radii of the two populations is $R_{h2}/R_h \propto (m_2/m_1)^{0.4}$

Numerical illustrations





Fractional mass loss in the heavy component:

$M_2/M_1 = 0.02$, $m_2/m_1 = 20$ (solid), 10 (dashed)

N-body

Relative half-mass radii in the two components

$M_2/M_1 = 0.02$

gas model

Some consequences (continued)

Result 3

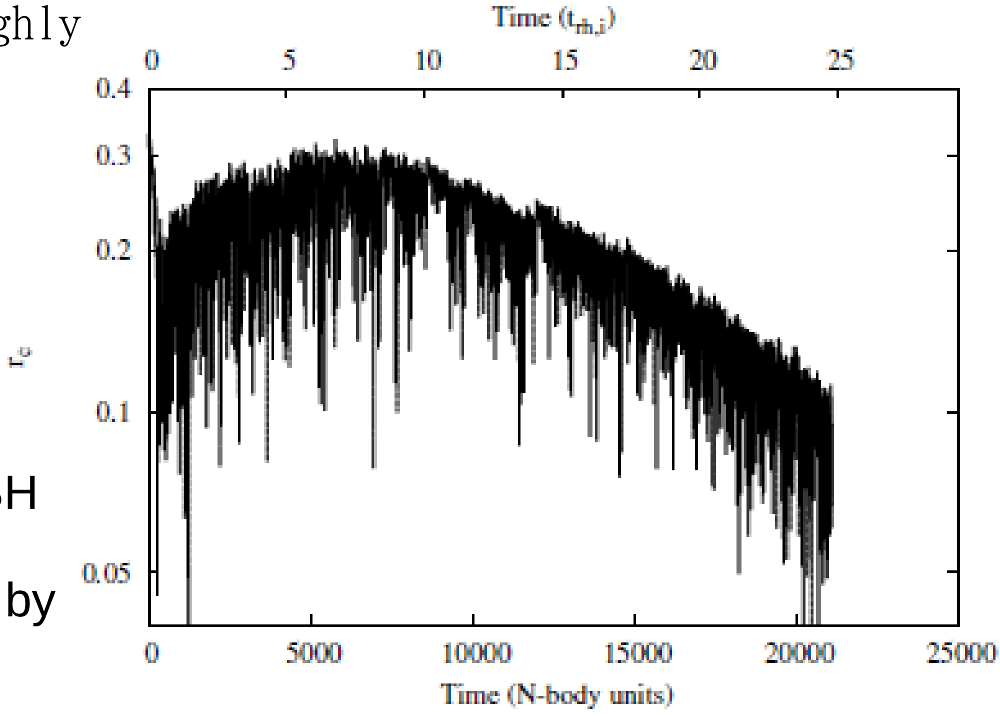
- *Assume* usual formulae for rate of formation of 3-body binaries in BH subsystem

Then

- The BH core radius is given by $r_{c2} \simeq 10\, r_{h2}/(N_2^{\,2} \ln \Lambda_2)^{1/3}$
- Balanced evolution fails if $N_2 \lesssim 10$ roughly

Interpretation of N-body data

Phase 1. Mass segregation of BH
Phase 2. Core collapse in BH subsystem
Phase 3. Balanced expansion powered by BH
Phase 4. Recollapse of the core of the light stars to enhance the energy generation by residual BH
Phase 5: Core collapse of the light stars
Phase 6: Balanced expansion powered by binary activity in the light stars

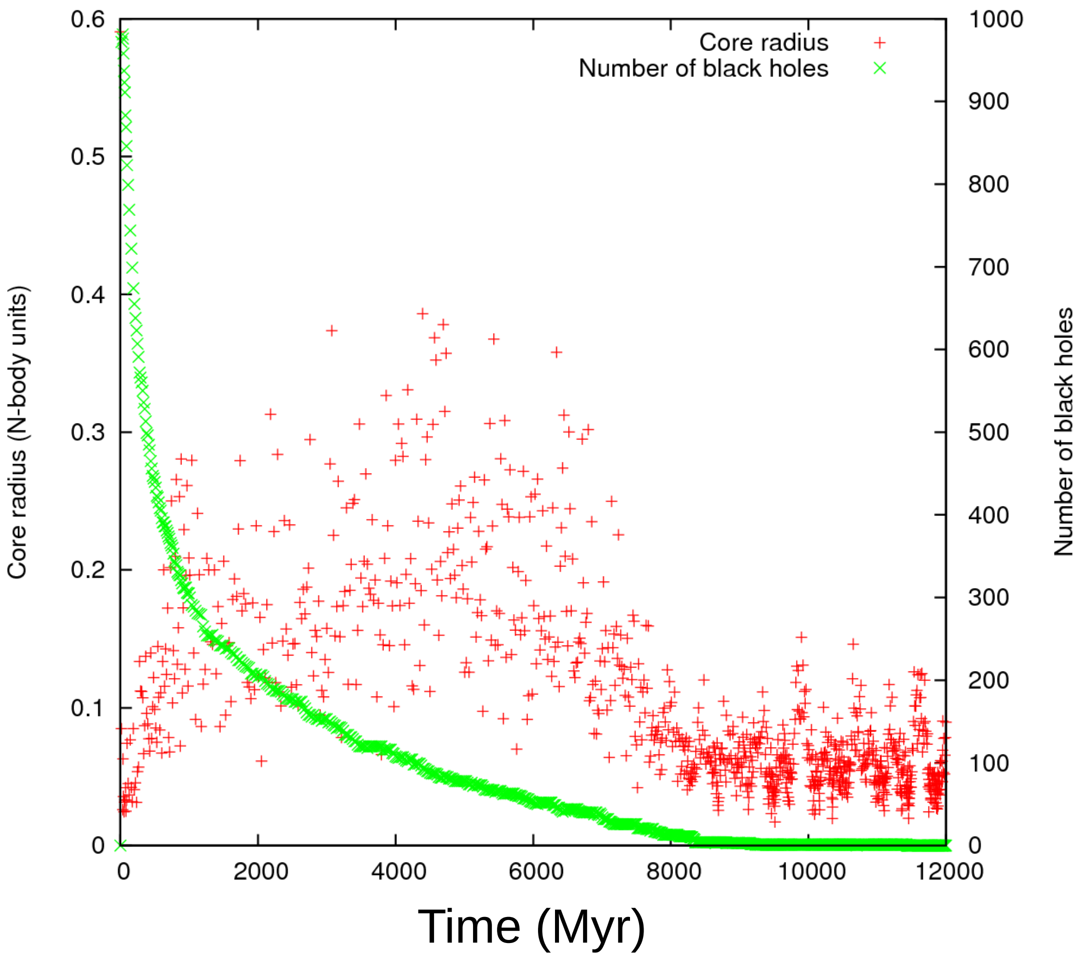


N=64k, $m_2/m_1 = 20$, $M_2/M_1 = 0.02$
Plot shows core radius against time
(Breen & Heggie, in prep)

Illustration: Monte Carlo model of M4

It is no coincidence that the last BH is lost at the time of “core collapse”

Phase 1. Mass segregation of BH
Phase 2. Core collapse in BH subsystem
    ends at about 15Myr
Phase 3. Balanced expansion powered
    by BH for about 2Gyr
Phase 4. Recollapse of the core of the
    light stars to enhance the energy
    generation by residual BH (up to
    8Gyr)
Phase 5: Core collapse in non-BH
Phase 6: Balanced evolution (but
    unstable) with energy generation by
    primordial binaries (8 Gyr to the
    present day)



Model of Heggie & Giersz 2008

Bonn Glühwein 2012

Suggests stellar-mass BH to be found in clusters with large core radii

Summary

1. BH subsystems survive for a few Gyr and maybe a Hubble time depending on the cluster and assumptions on kicks

2. Mass loss and spatial evolution of BH subsystem may be understood on the basis of simple but quantitative arguments

Subversive thought

Could a population of stellar-mass BH account for the “evidence” for an IMBH in ω Cen?