Intermediate Mass Ratio Inspirals in ET

Jonathan Gair (IoA, Cambridge)

work done with: Eliu Huerta (Cambridge)

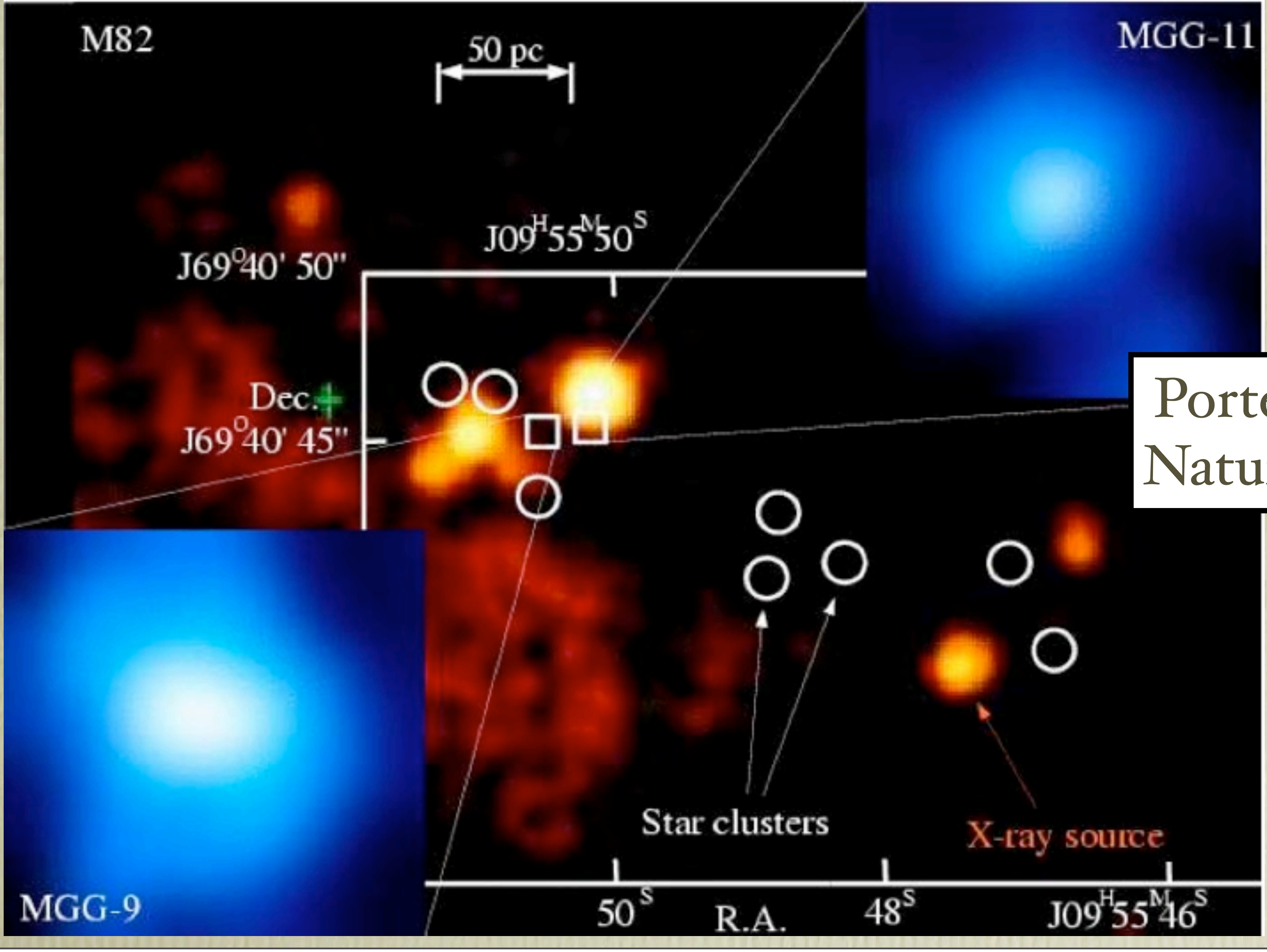
Based on arxiv:1009.1985 and arxiv:1011.0421

IMBH sources for ET

- Black holes of intermediate mass could form through two separate channels
  - Direct collapse of low metallicity population III stars at high redshift could form low-mass 'seed' black holes from which galactic black holes then grow. Would be found in dwarf galaxies today.
  - Runaway stellar collisions in the dense environments of globular clusters could form single or binary intermediate mass black holes.
- ET could detect gravitational waves from two classes of system containing intermediate mass black holes (IMBHs)
  - Mergers of two comparable mass IMBHs.
  - Mergers of stellar mass compact objects with IMBHs (intermediate mass ratio inspirals [IMRIs]). Focus of this talk.

IMBHs in Globular Clusters

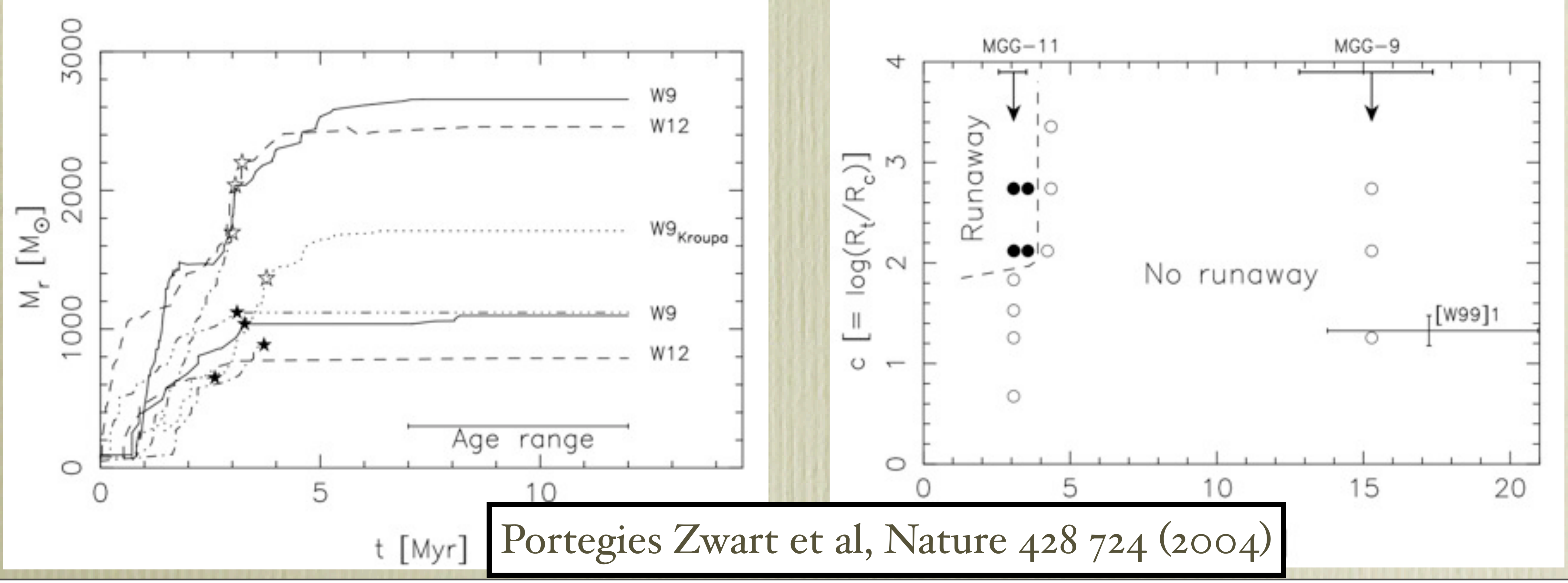
- There is some observational evidence suggestive of the existence of IMBHs in globular clusters, e.g., ULXs.



Portegies Zwart et al, Nature 428 724 (2004)

IMBHs in Globular Clusters

- There is some observational evidence suggestive of the existence of IMBHs in globular clusters, e.g., ULXs.
- Single IMBHs could form in globular clusters via
  - Runaway collisions of massive stars on timescales too short for stellar evolution ($\lesssim$ 3Myr) (Portegies Zwart et al. 2004). May be limited by winds in non-metal-poor systems (Glebbeek et al. 2009).



Portegies Zwart et al, Nature 428 724 (2004)

IMBHs in Globular Clusters

- There is some observational evidence suggestive of the existence of IMBHs in globular clusters, e.g., ULXs.
- Single IMBHs could form in globular clusters via
  - Runaway collisions of massive stars on timescales too short for stellar evolution ($\lesssim 3\mathrm{Myr}$) (Portegies Zwart et al. 2004). May be limited by winds in non-metal-poor systems (Glebbeek et al. 2009).
  - Mergers of stellar-mass black holes in dense subclusters in the cores of globular clusters (O'Leary et al. 2006).
- If the stellar binary fraction is high ($\gtrsim 10\%$), binary IMBHs could also form in globular clusters (Gurkan et al. 2006) as a consequence of stellar collisions that take place during binary scattering interactions.

Intermediate Mass Ratio Inspirals

- An IMBH in a globular cluster will readily swap into a binary as it is the most massive object present. Three-body interactions will harden the binary leading to merger. This mechanism should dominate over direct capture or other processes.

- IMRI - inspiral of a stellar mass compact object (neutron stars or black holes) into IMBHs. Analogue of EMRIs for LISA.

- For IMBHs with mass of ~100-500 solar masses, detection requires a detector sensitive to gravitational waves in the 1-10Hz band - Einstein Telescope.

- But, a network of 3 Advanced LIGO detectors could see a few events, to distances of ~0.7/2 Gpc (NSs/BHs) (Mandel, Brown, JG & Miller ApJ **681** 1431 (2008)).

Compact object capture rates

- Estimate rate by finding the time, $T_{\rm min}$, that minimizes the sum of the hardening time and merger time due to GW emission

$$T_{\rm harden} \approx 2 \times 10^8 \frac{10^{5.5}\text{pc}^{-3}}{n_*} \frac{10^{13}\text{cm}}{a} \frac{\sigma}{10\text{km/s}} \frac{0.5M_\odot}{m_*}\text{yr}$$

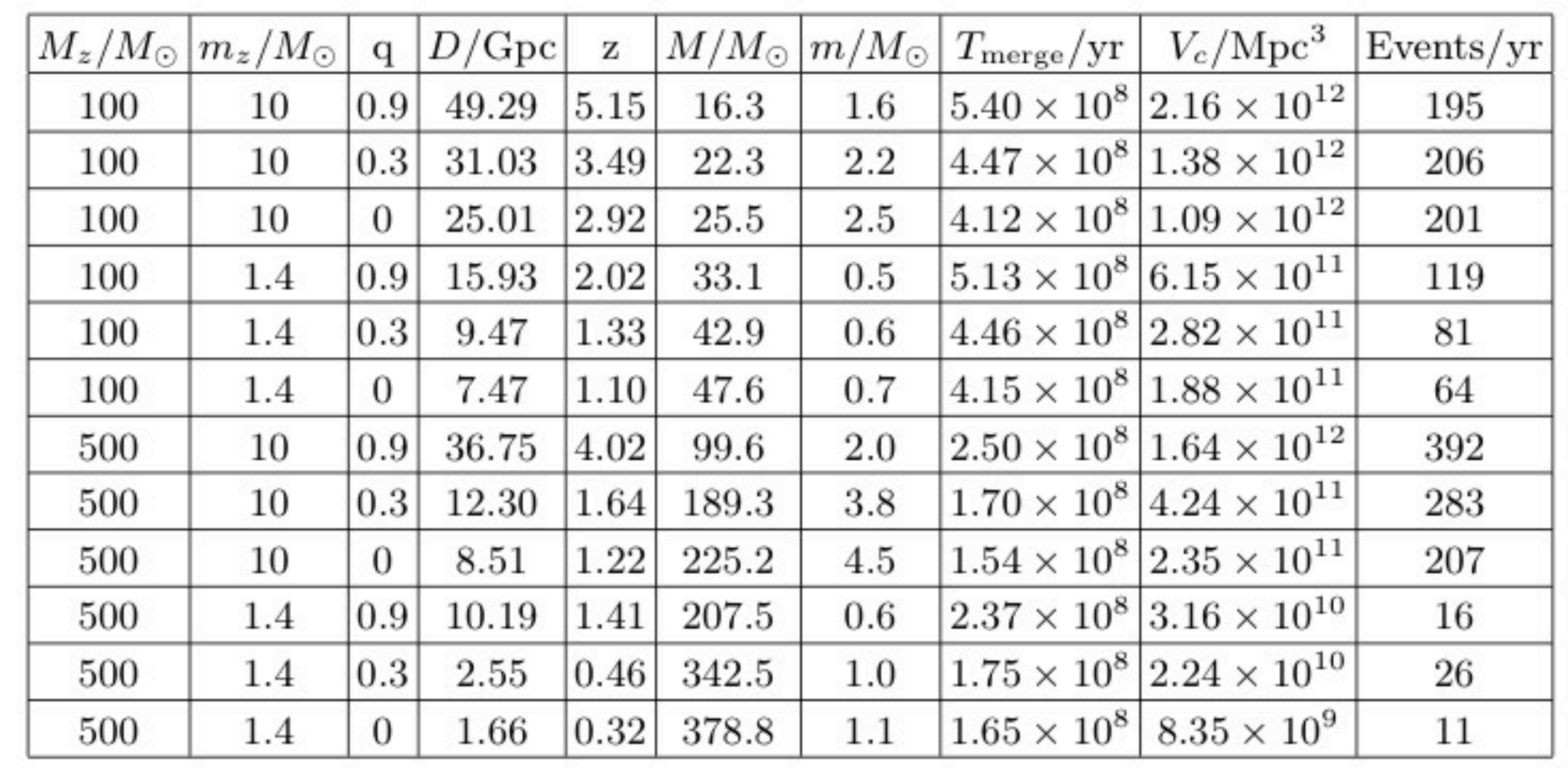
$$T_{\rm merger} \approx 10^8 \frac{M_\odot}{m} \left(\frac{100M_\odot}{M}\right)^2 \left(\frac{a}{10^{13}\text{cm}}\right)^4 \text{yr}$$

- The capture rate from three-body hardening scales with the typical stellar density of the environment as $n_*^{\frac{4}{5}}$.

- Typical densities for Dwarf galaxies are $n_* \sim 10^{-3}\text{pc}^{-3} - 1\text{pc}^{-3}$, e.g. $n_* \approx 10^{-3}\text{pc}^{-3}$ for Sagittarius and $n_* \approx 10^{-1}\text{pc}^{-3}$ for Fornax. These are much smaller than typical densities of globular clusters, $n_* \sim 10^{5.5}\text{pc}^{-3}$. We don't therefore expect to see IMRIs occurring into pop III black holes in Dwarf galaxies if three-body capture is dominant.

ET IMRI Event Rate

- Assuming a comoving density of GCs of $8.4h^3\mathrm{Mpc}^{-3}$ and that ~10% of GCs will form an IMBH, we can estimate the ET rate as $\sim 0.3(V_c/\mathrm{Mpc}^3)/T_{\mathrm{min}}$, where V_c is the comoving volume within which IMRI events can be detected.
- Compute V_c and T_{min} for several different canonical systems to estimate an approximate rate.

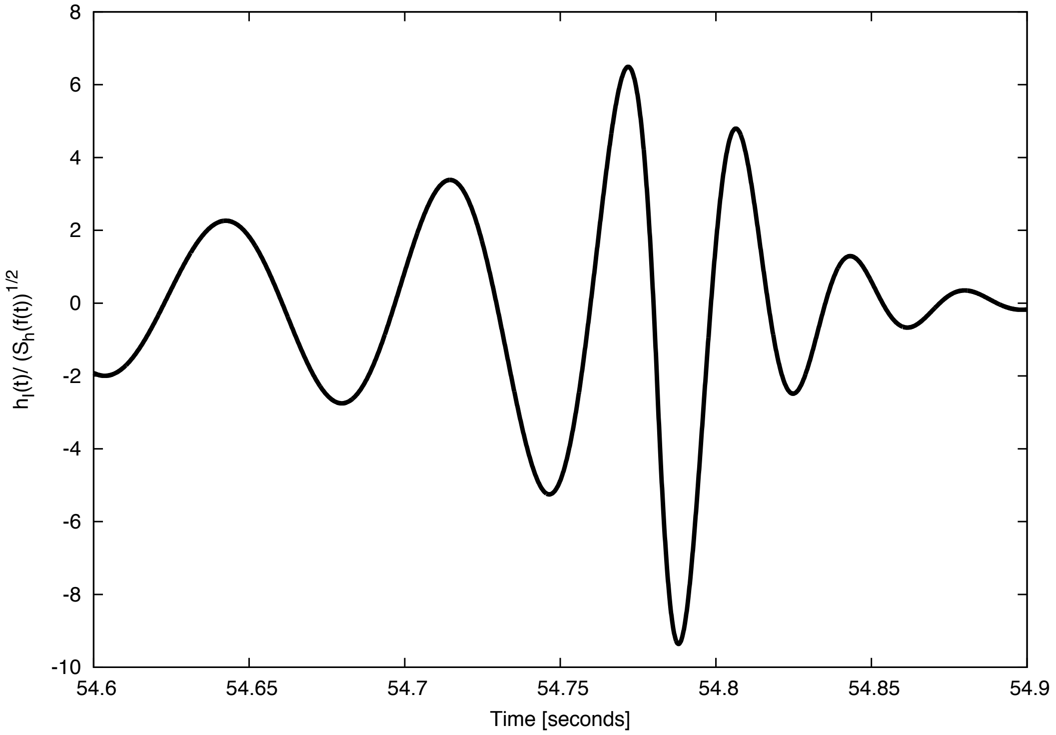


$M_z/M_\odot$	$m_z/M_\odot$	q	D/Gpc	z	$M/M_\odot$	$m/M_\odot$	T_{merge}/yr	V_c/Mpc^3	Events/yr
100	10	0.9	49.29	5.15	16.3	1.6	5.40×10^8	2.16×10^{12}	195
100	10	0.3	31.03	3.49	22.3	2.2	4.47×10^8	1.38×10^{12}	206
100	10	0	25.01	2.92	25.5	2.5	4.12×10^8	1.09×10^{12}	201
100	1.4	0.9	15.93	2.02	33.1	0.5	5.13×10^8	6.15×10^{11}	119
100	1.4	0.3	9.47	1.33	42.9	0.6	4.46×10^8	2.82×10^{11}	81
100	1.4	0	7.47	1.10	47.6	0.7	4.15×10^8	1.88×10^{11}	64
500	10	0.9	36.75	4.02	99.6	2.0	2.50×10^8	1.64×10^{12}	392
500	10	0.3	12.30	1.64	189.3	3.8	1.70×10^8	4.24×10^{11}	283
500	10	0	8.51	1.22	225.2	4.5	1.54×10^8	2.35×10^{11}	207
500	1.4	0.9	10.19	1.41	207.5	0.6	2.37×10^8	3.16×10^{10}	16
500	1.4	0.3	2.55	0.46	342.5	1.0	1.75×10^8	2.24×10^{10}	26
500	1.4	0	1.66	0.32	378.8	1.1	1.65×10^8	8.35×10^9	11

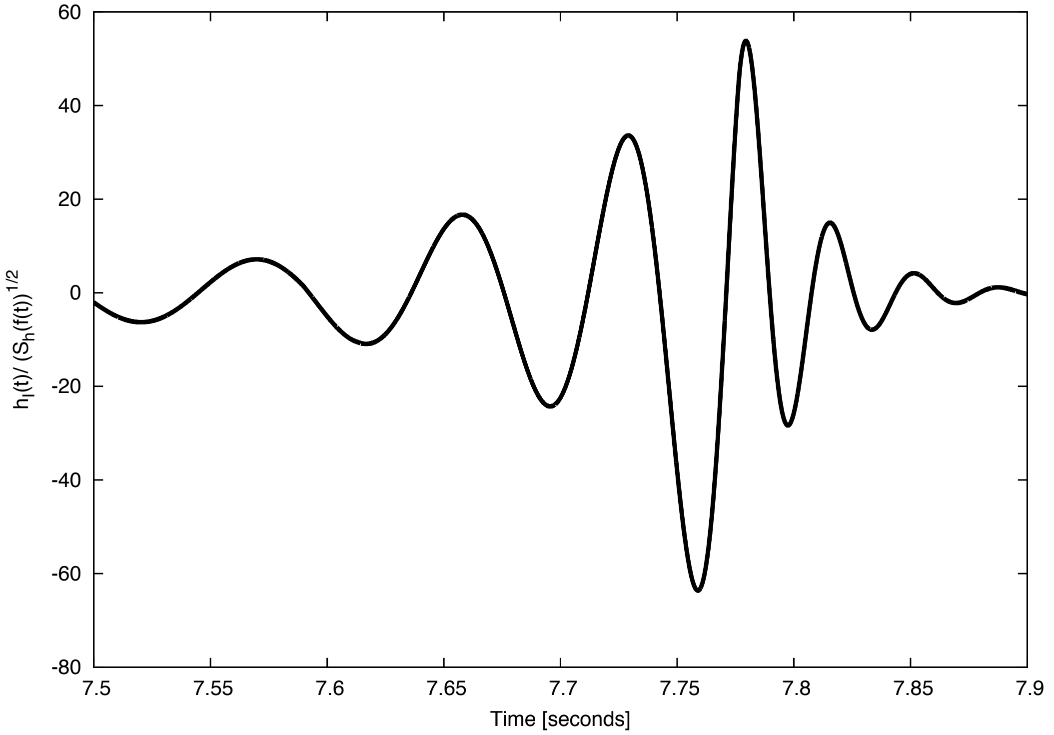
IMRI waveform modelling

- Modelling of IMRIs is not well developed
  - Object generates too many cycles in regime with v/c~1 for post-Newtonian theory or numerical relativity to be used.
  - Mass ratio is too large for perturbation theory. Need second-order corrections. Spin of small object also important.
- Make progress by using an approximate model constructed from
  - 'Numerical kludge' inspiral waveform.
  - Two models for plunge and merger waveform
    - 'Transition model' of Ori and Thorne (arbitrary spin).
    - Effective-One-Body (EOB) model (for q=0 only).
  - Ringdown waveform matched onto merger waveform at light-ring.
- Use of two models allows us to perform consistency checks that provide greater confidence in the results.

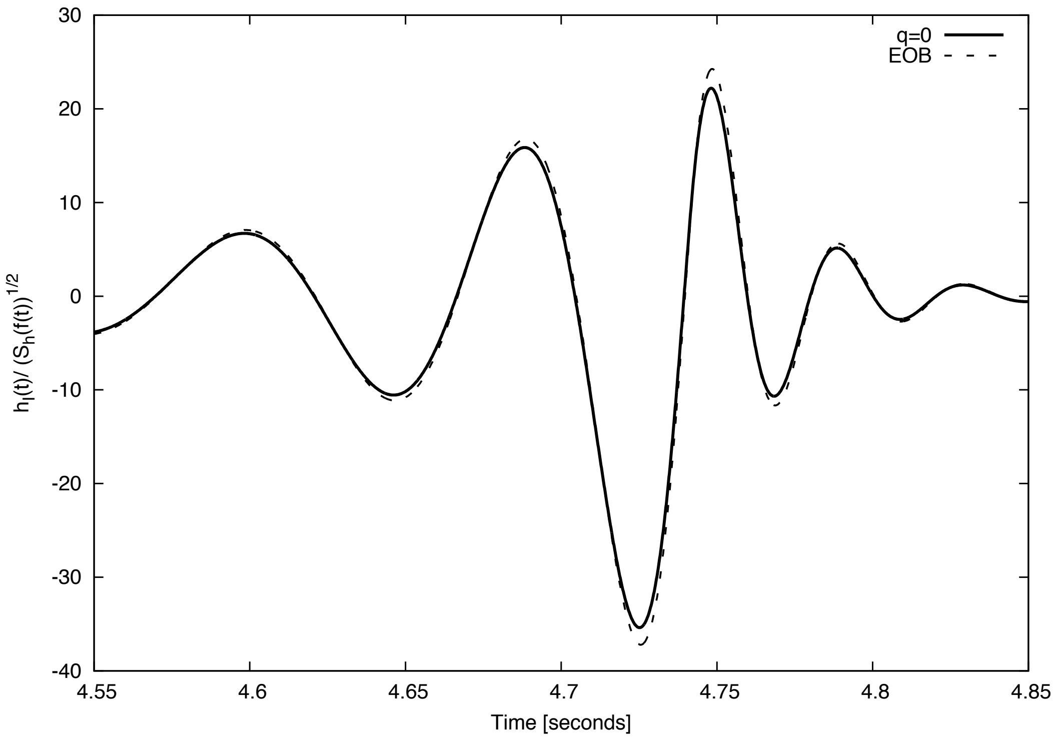
IMRI waveform modelling



$1.4M_\odot + 500M_\odot,\ \ q = 0.3$



$10M_\odot + 500M_\odot,\ \ q = 0.3$



$10M_\odot + 500M_\odot,\ \ q = 0$

Parameter estimation accuracy

- Can compute ET parameter estimation accuracy using Fisher Matrix formalism.

$$\Gamma_{ij} = \langle \frac{\partial \mathbf{h}}{\partial \lambda_i} | \frac{\partial \mathbf{h}}{\partial \lambda_j} \rangle$$

- Waveforms depend on intrinsic parameters - M, m, q and t_0 and also on several extrinsic parameters - distance, sky position and source orientation $D_L, \theta_S, \phi_S, \theta_L, \phi_L$, plus initial phase ϕ_0 .

- Have at most two independent coplanar and colocated detectors - four measurements for six parameters. One ET cannot provide enough information to measure distance.

- Assume one or more other detectors exist and estimate ability of network to measure parameters.

ET Networks

- Consider errors from a 'third-generation network' of detectors, with five different configurations (NB 'one ET' = triangular configuration - three colocated, coplanar 60 degree detectors). Assume the detectors are in Cascina, Livingston and Perth (Australia).

(i) One ET at site 1 (E).

(ii) As (i) plus a right-angle detector at site 2 (EL).

(iii) As (i) plus a second ET at site 2 (EE).

(iv) As (ii) plus a third right-angle detector at site 3 (ELL).

(v) As (iii) plus a third ET at site 3 (EEE).

Parameter estimation results

- Carry out Monte Carlo simulation of SNRs and parameter-estimation accuracies. Fix intrinsic parameters, and Monte Carlo over choices for the extrinsic parameters.
- Consider four canonical mass combinations

$$\begin{array}{ll} 10M_\odot + 100M_\odot \;\; (B1) & 1.4M_\odot + 100M_\odot \;\; (B2) \\ 10M_\odot + 500M_\odot \;\; (B3) & 1.4M_\odot + 500M_\odot \;\; (B4) \end{array}$$

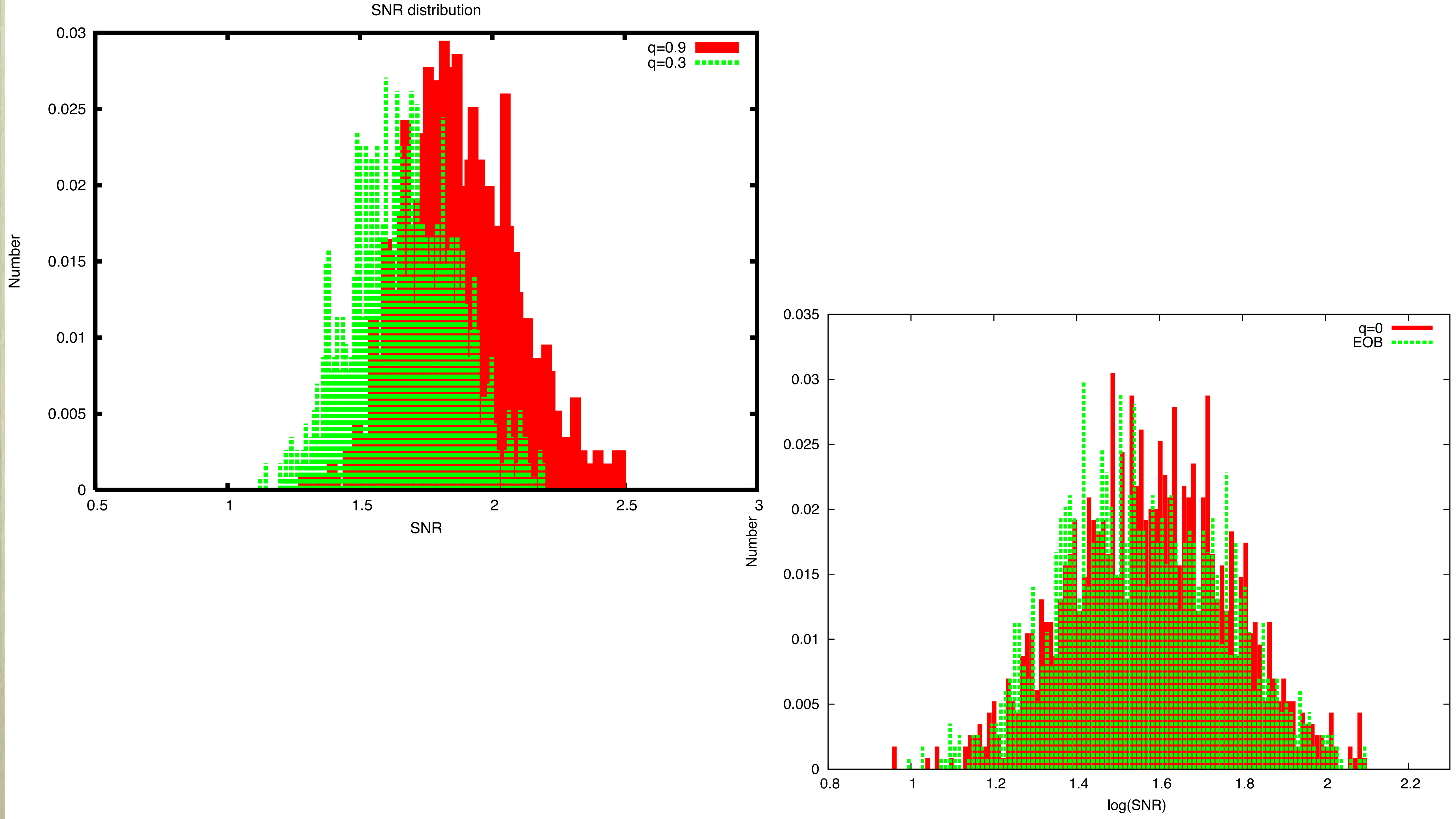
- plus three choices of spin for the central IMBH

$$q = 0 \qquad q = 0.3 \qquad q = 0.9$$

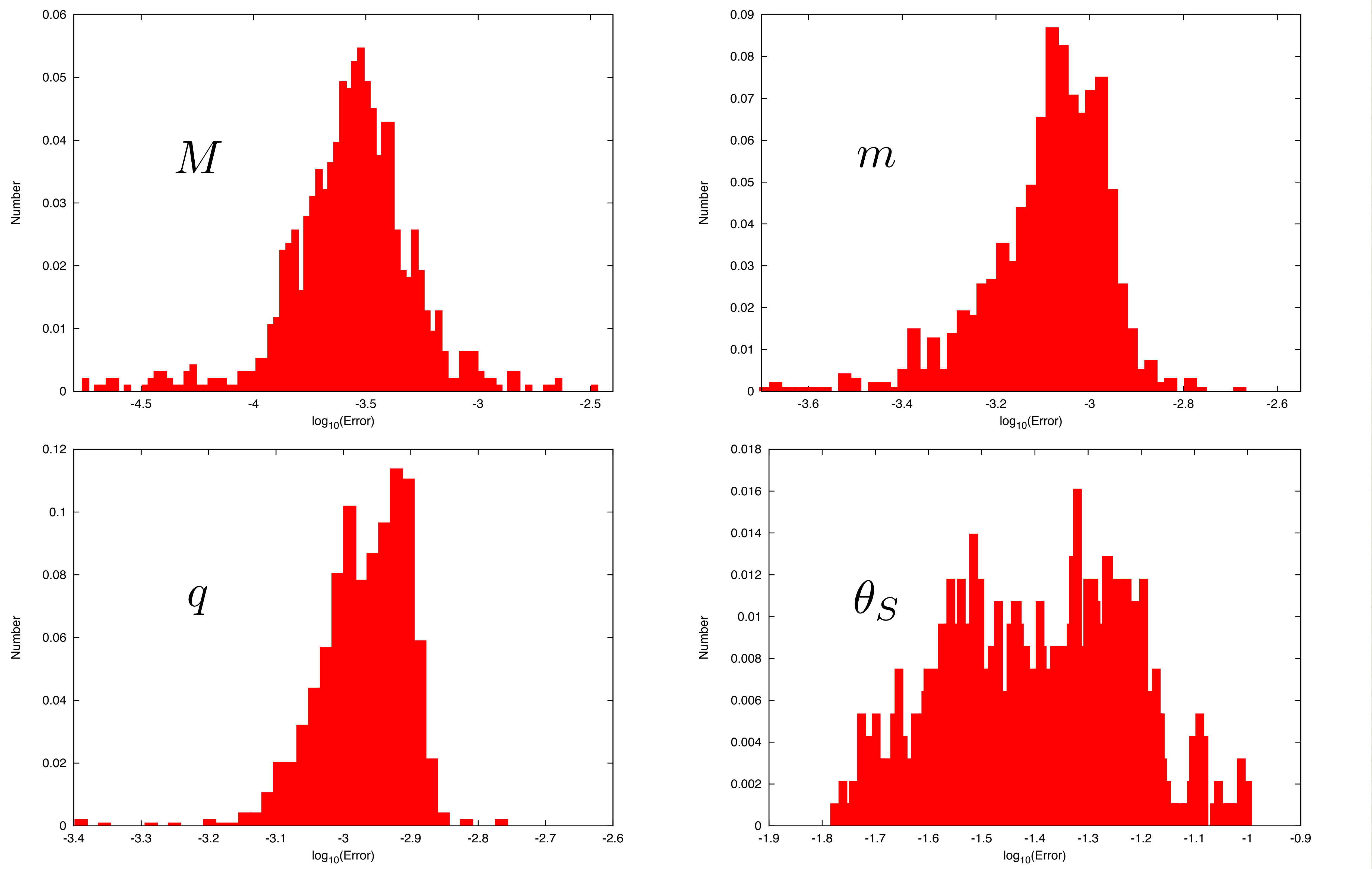
- Repeat for all five network configurations and both waveform models (*q*=0 only).

Results - SNRs

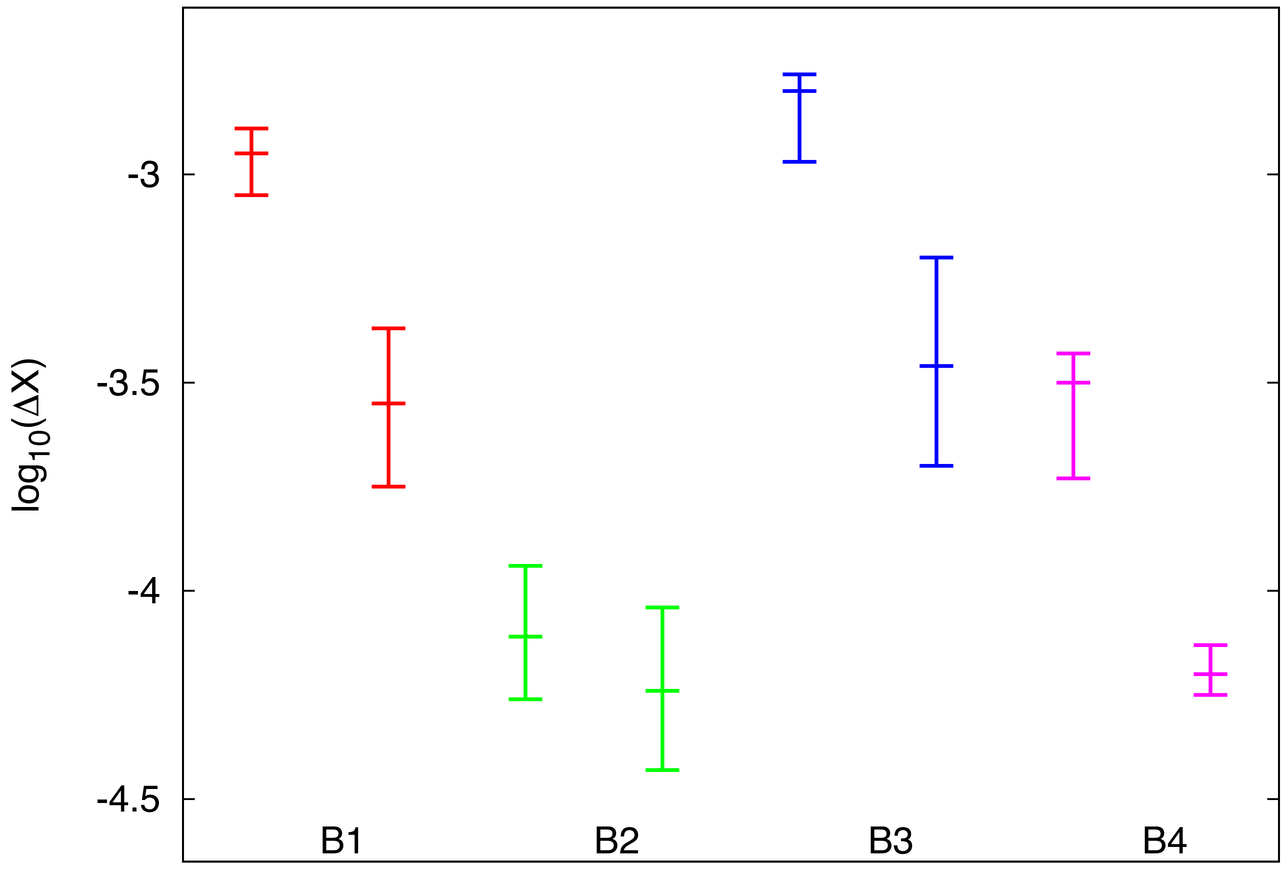
SNR for $10M_\odot + 100M_\odot$ at $D_L = 6.67\text{Gpc}$



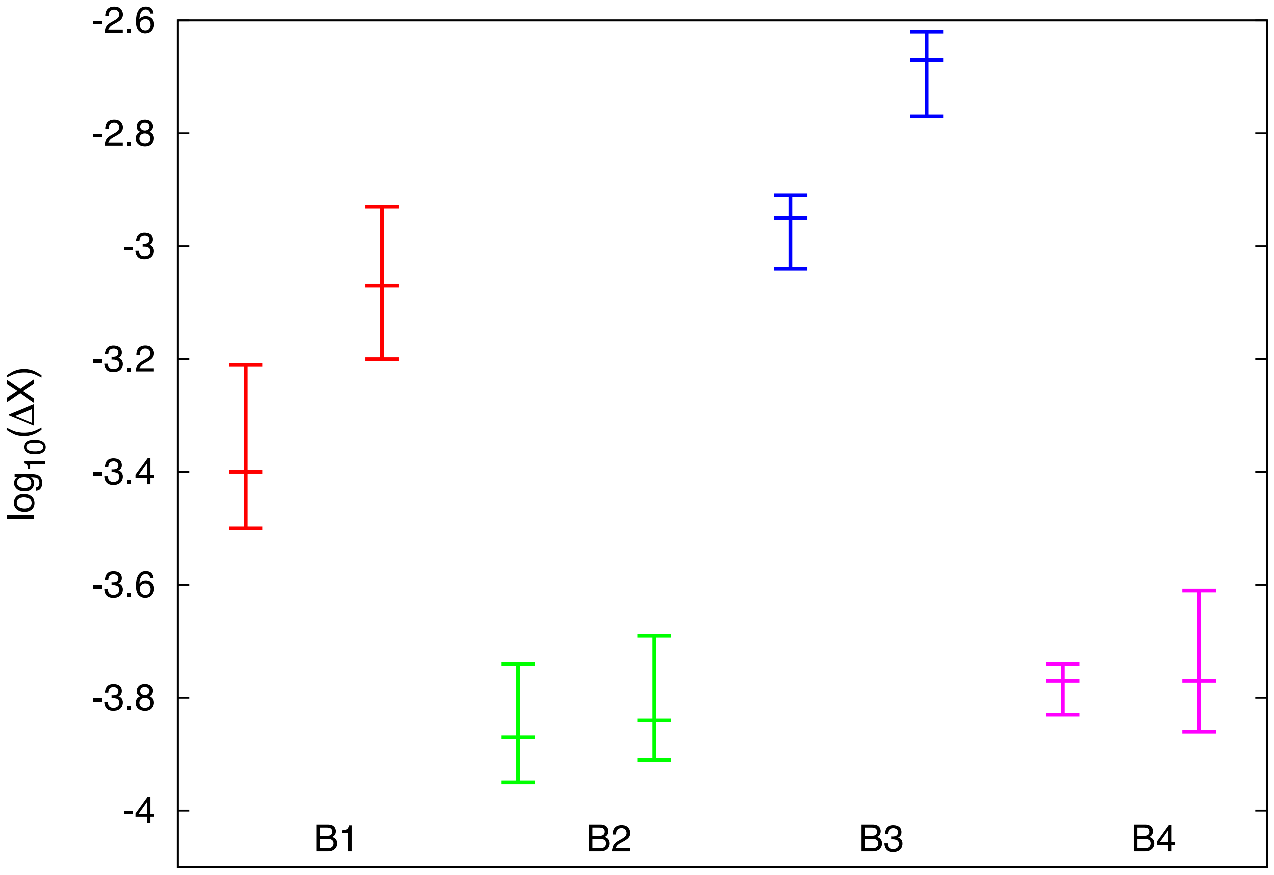
Results - parameter accuracies



Results - parameter accuracies

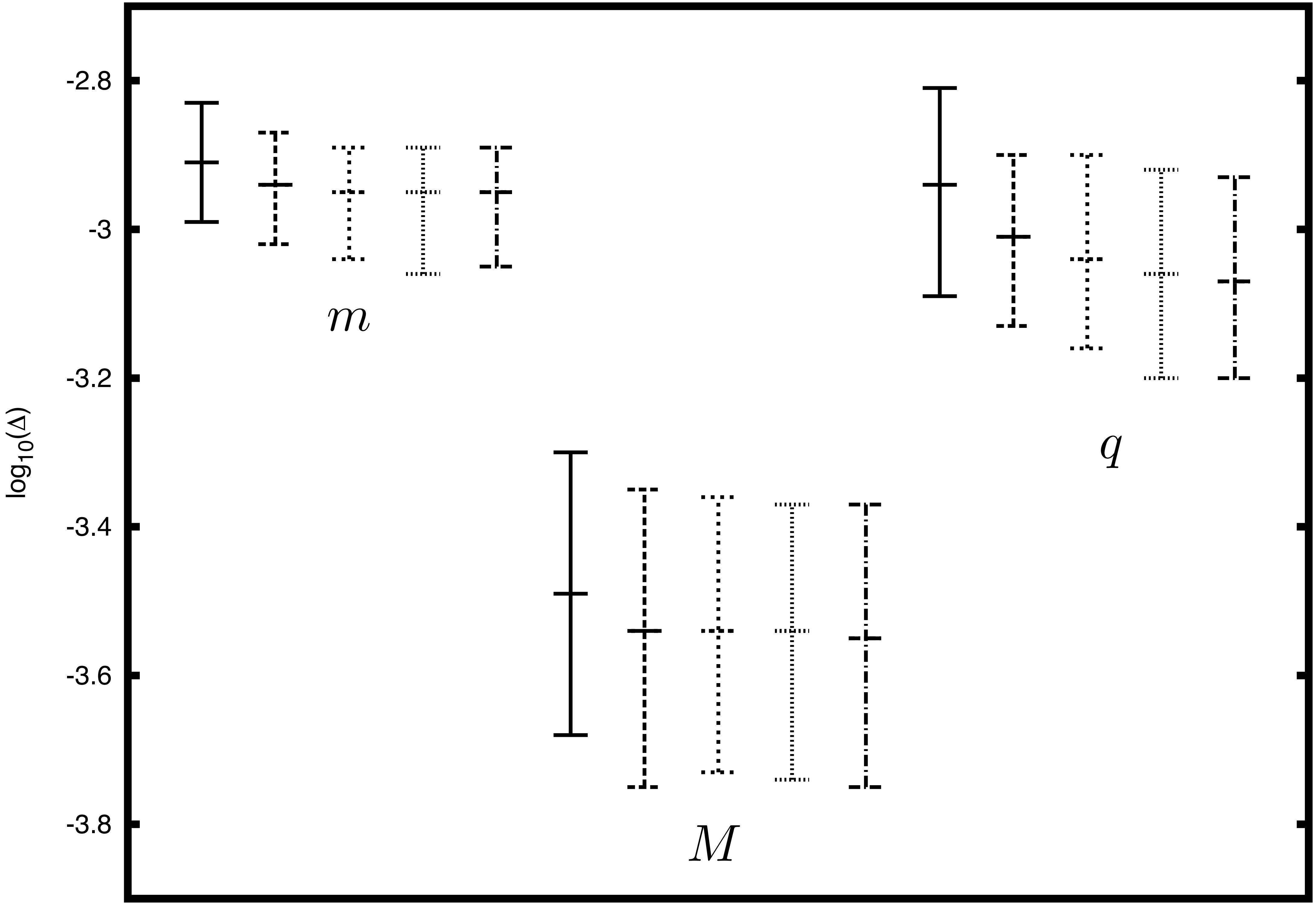


Errors in m (left) and M (right) for $q = 0.3$



Errors in q for systems with $q = 0.9$ (left) and $q = 0.3$ (right) for system $10M_\odot + 100M_\odot$

Results - parameter accuracies



Errors for system: $10M_\odot + 100M_\odot, \;\; q = 0.3$

Results - parameter accuracies

Parameter	Network Configuration				
	E	EL	EE	ELL	EEE
$\ln(m/M_\odot)$	0.0011	0.001	0.001	0.001	0.001
$\ln(M/M_\odot)$	0.00032	0.00028	0.00028	0.00028	0.00028
q	0.0011	0.001	0.001	0.001	0.001
θ_S	>1	0.07	0.05	0.05	0.05
ϕ_S	>1	0.1	0.05	0.05	0.05
$\ln(D_L)$	>1	0.20	0.15	0.15	0.15

All results normalised to a network SNR of 30

Science with IMRIs

- Probe of IMBHs in globular clusters
  - Proof of IMBH existence. Probe of formation efficiency, spin distribution and merger history of IMBHs in clusters
  - Probe of stellar dynamics in globular clusters - processes leading to IMBH formation.
- Test models of cosmological structure formation (indirect).
  - Observed IMRIs likely to involve IMBHs in clusters. IMBH-IMBH mergers might also be observed by ET. Come from two channels.
  - IMRI observations can be used to indirectly decouple pop III black hole and cluster channel in IMBH-IMBH merger observations.
- Use to test 'no-hair' property of central IMBH
  - Measure multipole moments of central object. Test for consistency with Kerr BH. 10% deviations in quadrupole should be detectable.

Summary

- ET is an ideal instrument for probing black holes with mass in the $100M_{\odot} - 1000M_{\odot}$ range. Such black holes could form in the early Universe from Pop III stars, or in globular clusters.
- ET could see several hundred IMBH capture sources out to moderate redshift. Most likely to be in globular clusters.
- A single ET could constrain the intrinsic parameters, m, M and q, of IMRI sources to ~0.1% accuracy.
- Need a detector network to measure distance and sky position. Can achieve ~10% accuracy with one additional right-angle detector. Moderate improvements with second additional right-angle detector, but gain only SNR with further/better detectors.
- IMRI observations have exciting potential for astrophysics and tests of GR. More work necessary to quantify ET capabilities.