Exploring Intermediate and Massive Black Hole Binaries with ET

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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.
  - 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 (CIMMs).
  - Mergers of stellar mass compact objects with IMBHs (intermediate mass ratio inspirals [IMRIs]).

Pop III black holes

- Current understanding is that galactic black holes grow via two mechanisms: 1) accretion, 2) mergers following galaxy mergers.

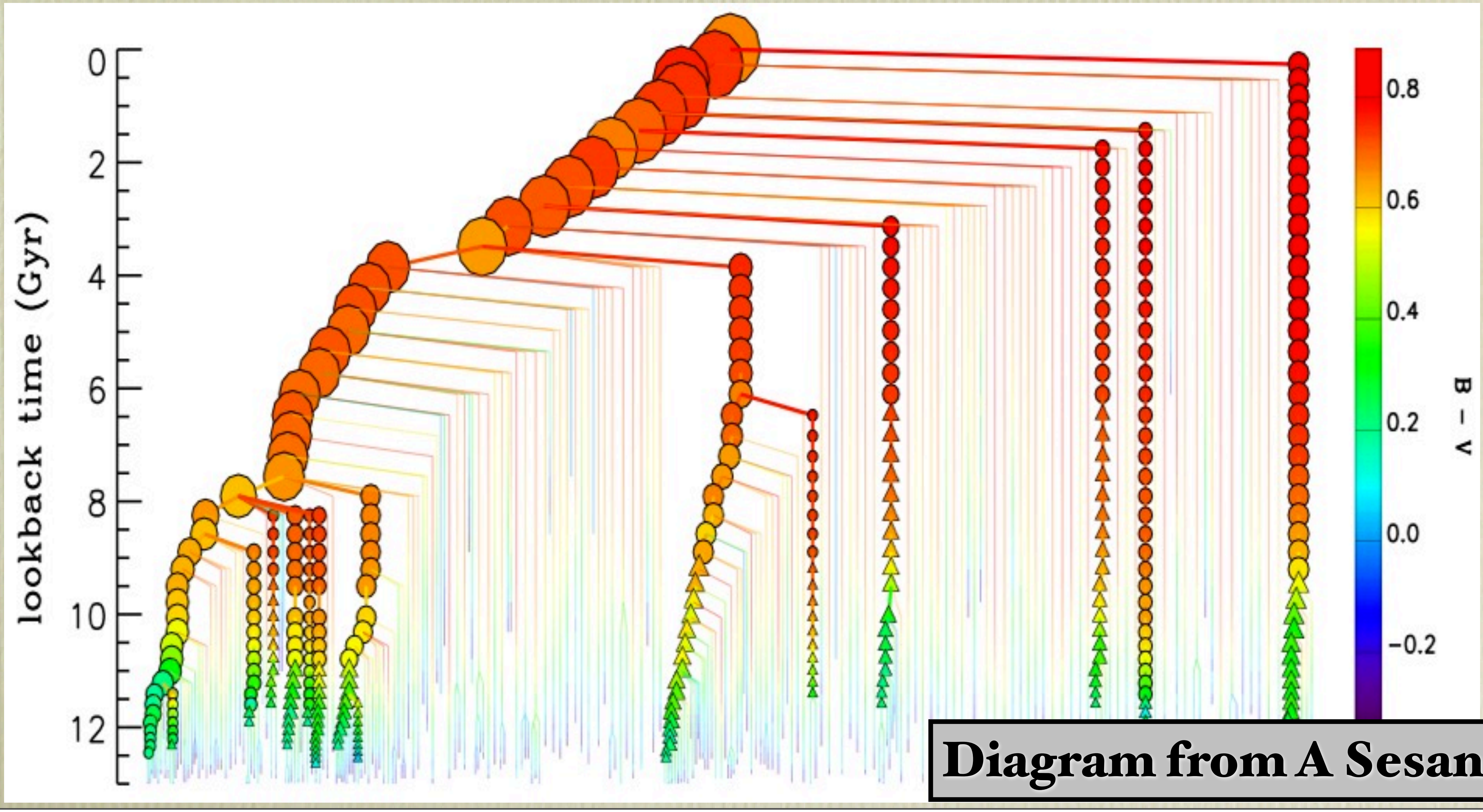


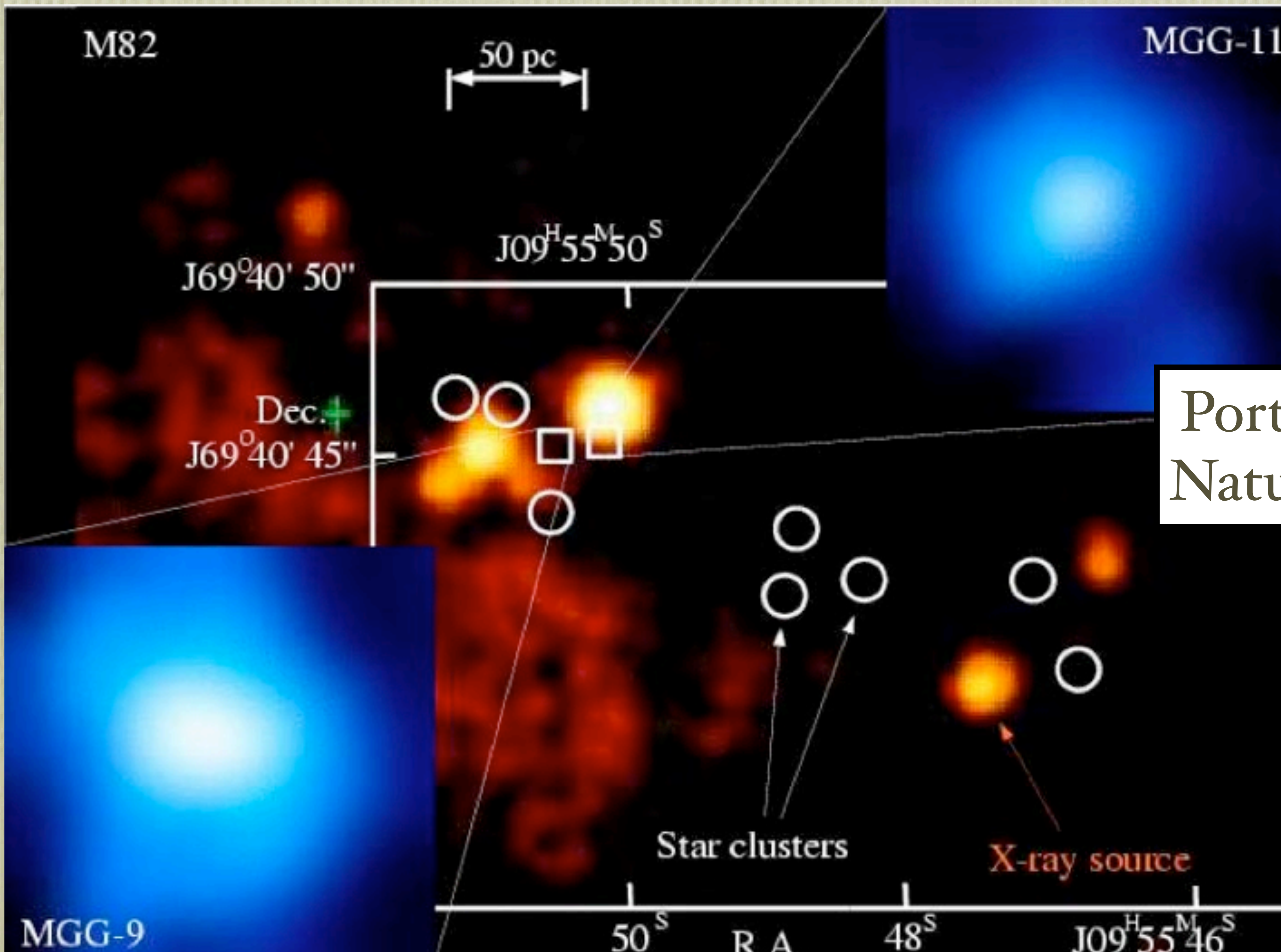
Diagram from A Sesana

Pop III black holes

- Current understanding is that galactic black holes grow via two mechanisms: 1) accretion, 2) mergers following galaxy mergers.
- First generation of black holes probably created by collapse of very massive, zero metallicity "population III" stars.
- There are various freedoms in galaxy merger models
  - Seed black hole masses
  - Seed black hole abundance
  - Seed black hole formation mechanism
  - Massive black hole accretion prescription
- 'Light seed' models predict the existence of IMBHs that can be sources for ET when 1) they merge at moderate to high redshift; 2) they reside in dwarf galaxies today (IMRIs).

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)

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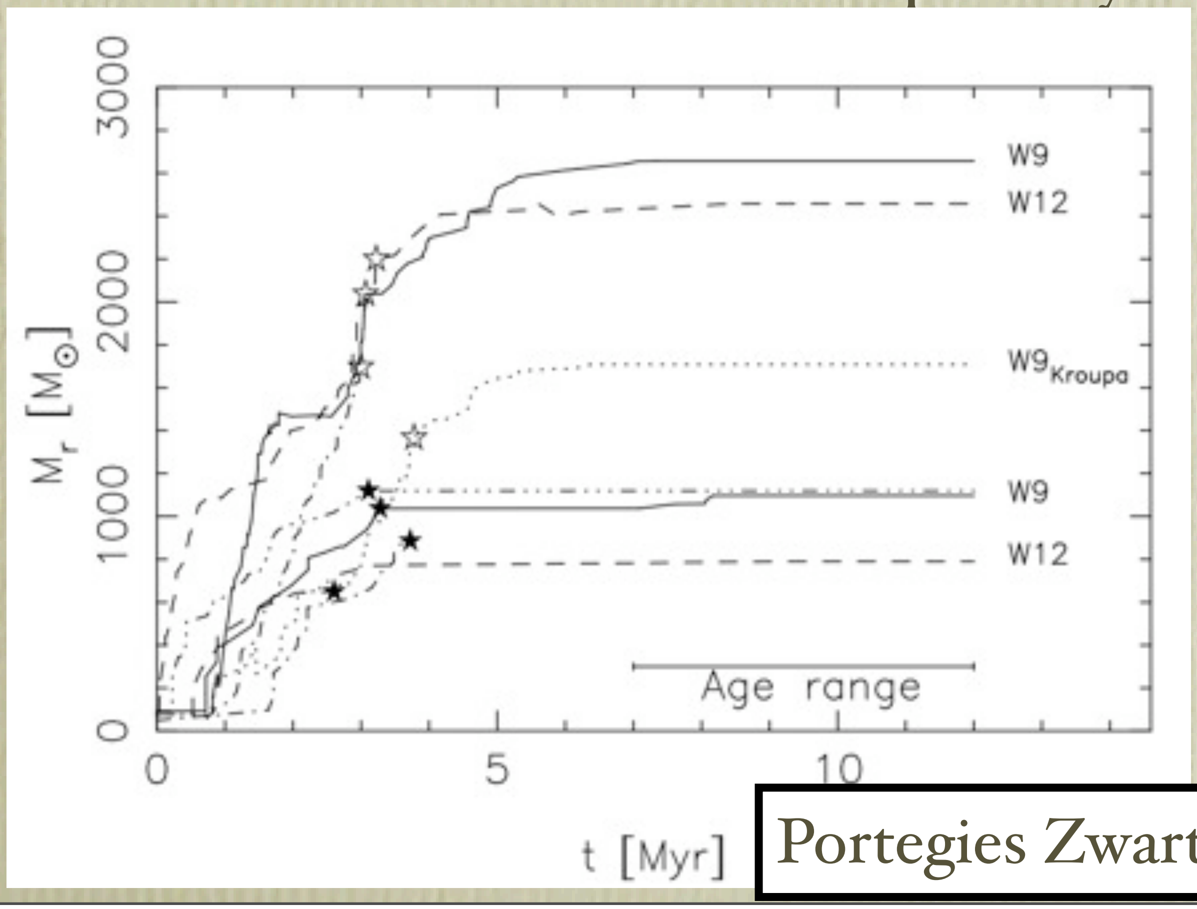
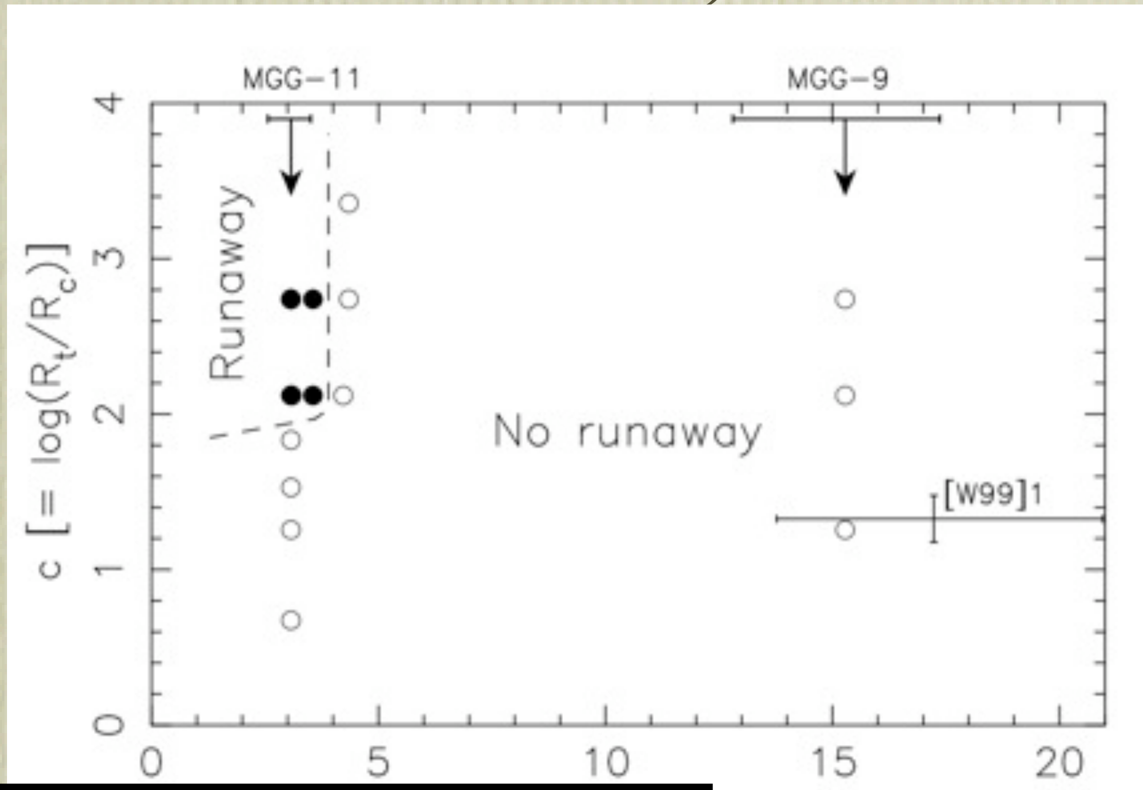
- Single IMBHs could form in globular clusters via

  - 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).





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  - 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.

Comparable mass mergers - SNRs

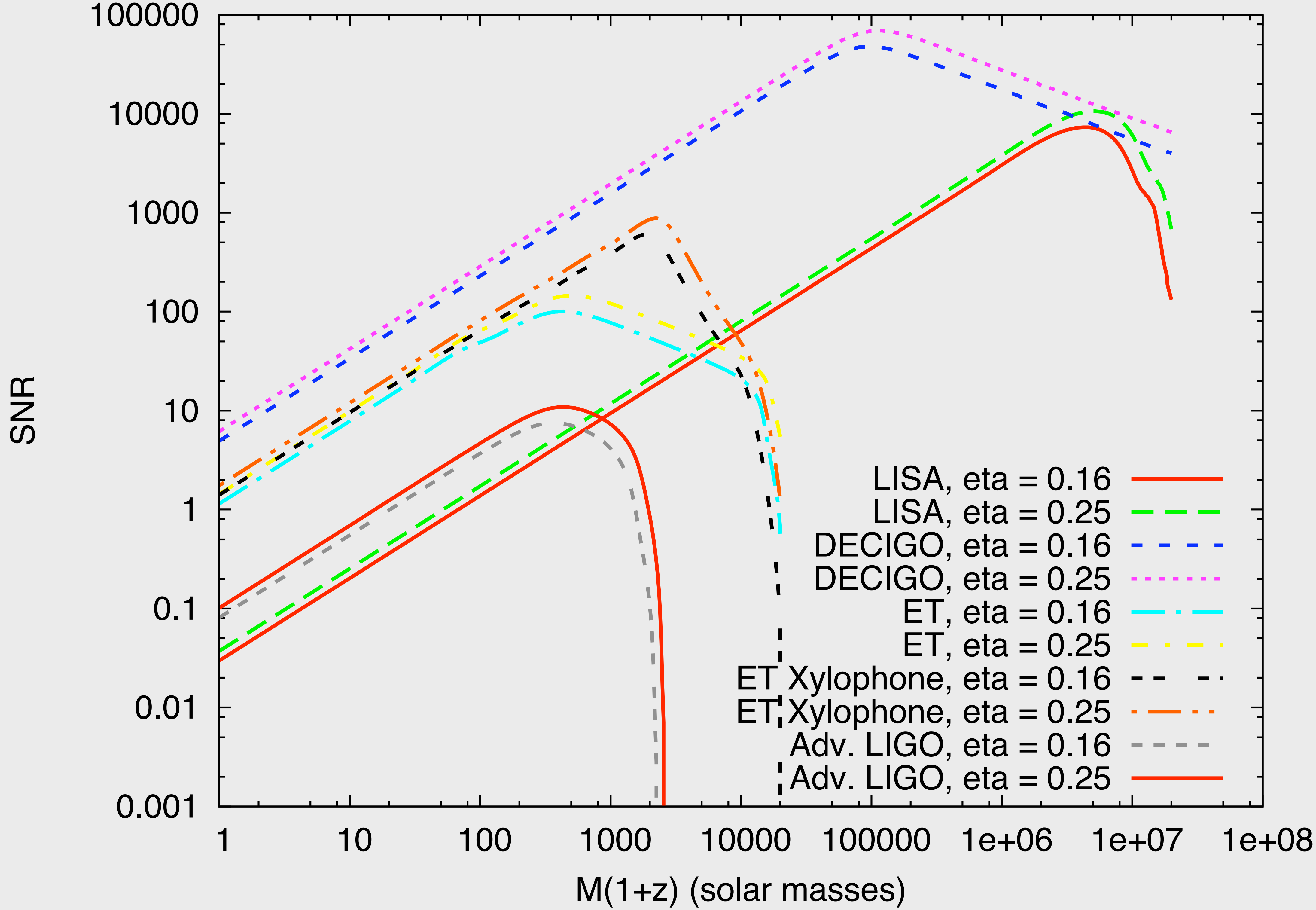
- Compute SNRs for ET using the inspiral/merger/ringdown waveform model of Ajith et al. (2008).

$$\tilde{h}(f) = A_{\rm eff}(f) \exp\left[i\Psi(f)\right]$$

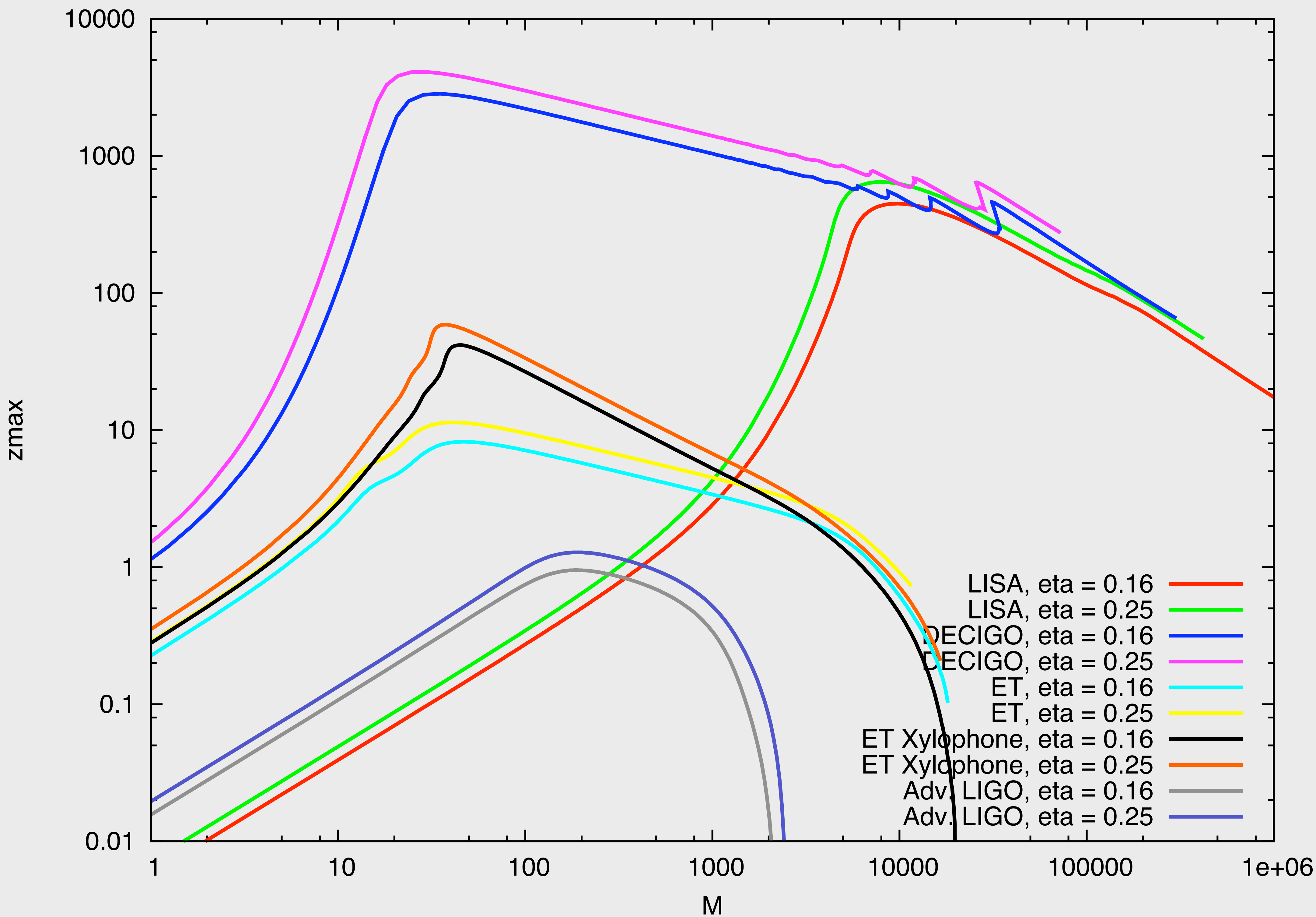
$$A_{\rm eff}(f) \equiv \frac{M^{5/6}}{D\,\pi^{2/3}\,f_{\rm merg}^{7/6}}\sqrt{\frac{5\eta}{24}}\begin{cases} (f/f_{\rm merg})^{-7/6} & \text{if } f < f_{\rm merg} \\ (f/f_{\rm merg})^{-2/3} & \text{if } f_{\rm merg} \le f < f_{\rm ring} \\ \frac{\sigma^2}{4(f_{\rm ring}/f_{\rm merg})^{2/3}((f-f_{\rm ring})^2+\sigma^2/4)} & \text{if } f_{\rm ring} \le f < f_{\rm cut} \end{cases}$$

- Average SNR over sky positions and orientations in the usual way. Compute SNR using noise curve for a single 10km detector. Triangle configuration is equivalent to two $(3/2\sqrt{2}) \times 10$km detectors. Assume a network SNR threshold of 8 - threshold in one 10km detector is then 5.33 or 3.77 for one or two ETs.

Comparable mass mergers - SNRs



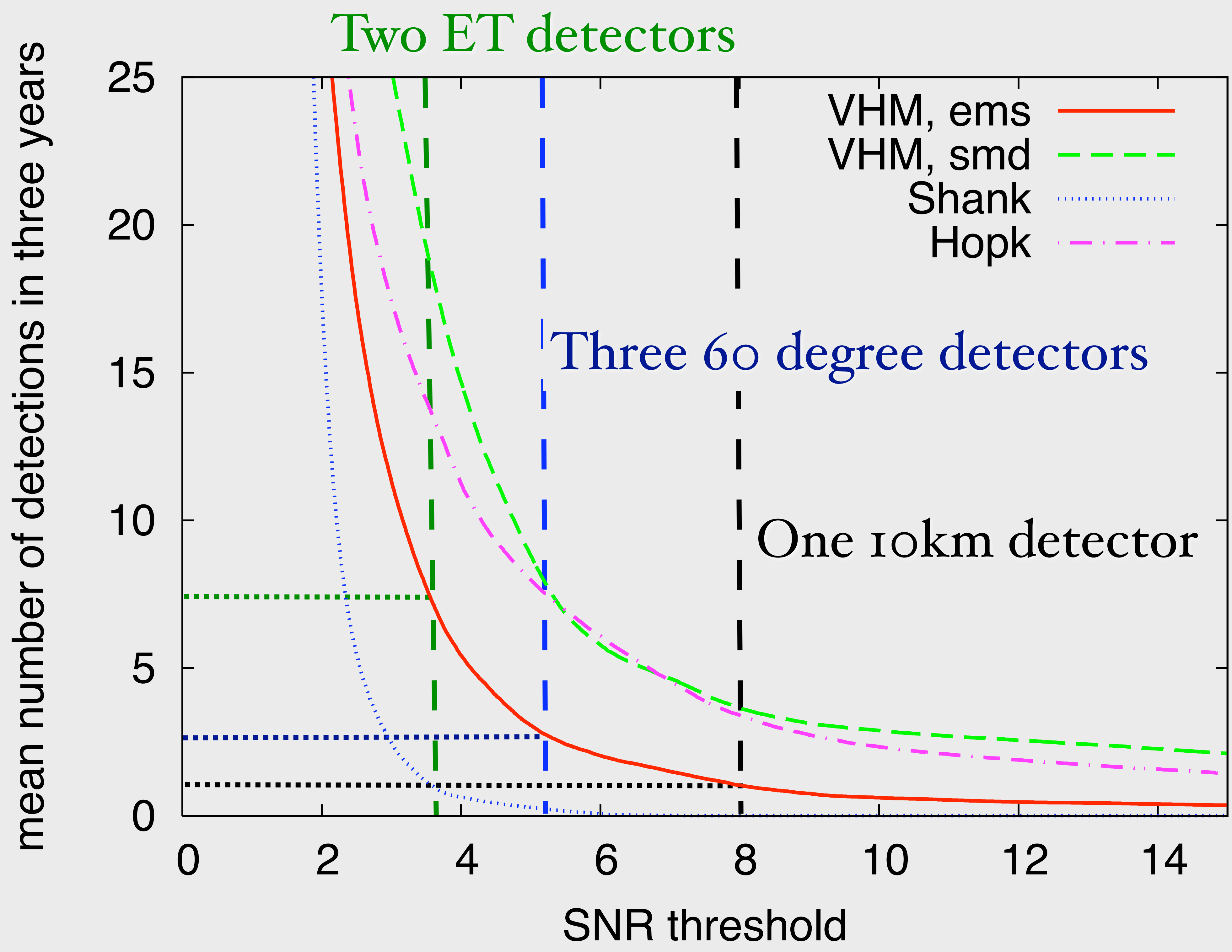
Comparable mass mergers - SNRs



ET seed merger event rates

- Estimate ET event rate for seed black hole mergers using galaxy merger trees. Assume BH seeds form in 3.5σ density peaks at z=20. Use four different models for mass distribution and accretion history (see Volonteri, Salvaterra & Haardt 2006):
  - **VHM, equal mass seeds**: all BHs have mass M=150 solar masses and accrete at Eddington rate a mass that scales as the fifth power of the halo circular velocity.
  - **VHM, seed mass distribution**: as above, but now BH seeds have a flat distribution of masses from 30-600 solar masses.
  - **calk**: Eddington rate varies with redshift.
  - **hopk**: Eddington rate varies with AGN luminosity.

ET seed merger event rate



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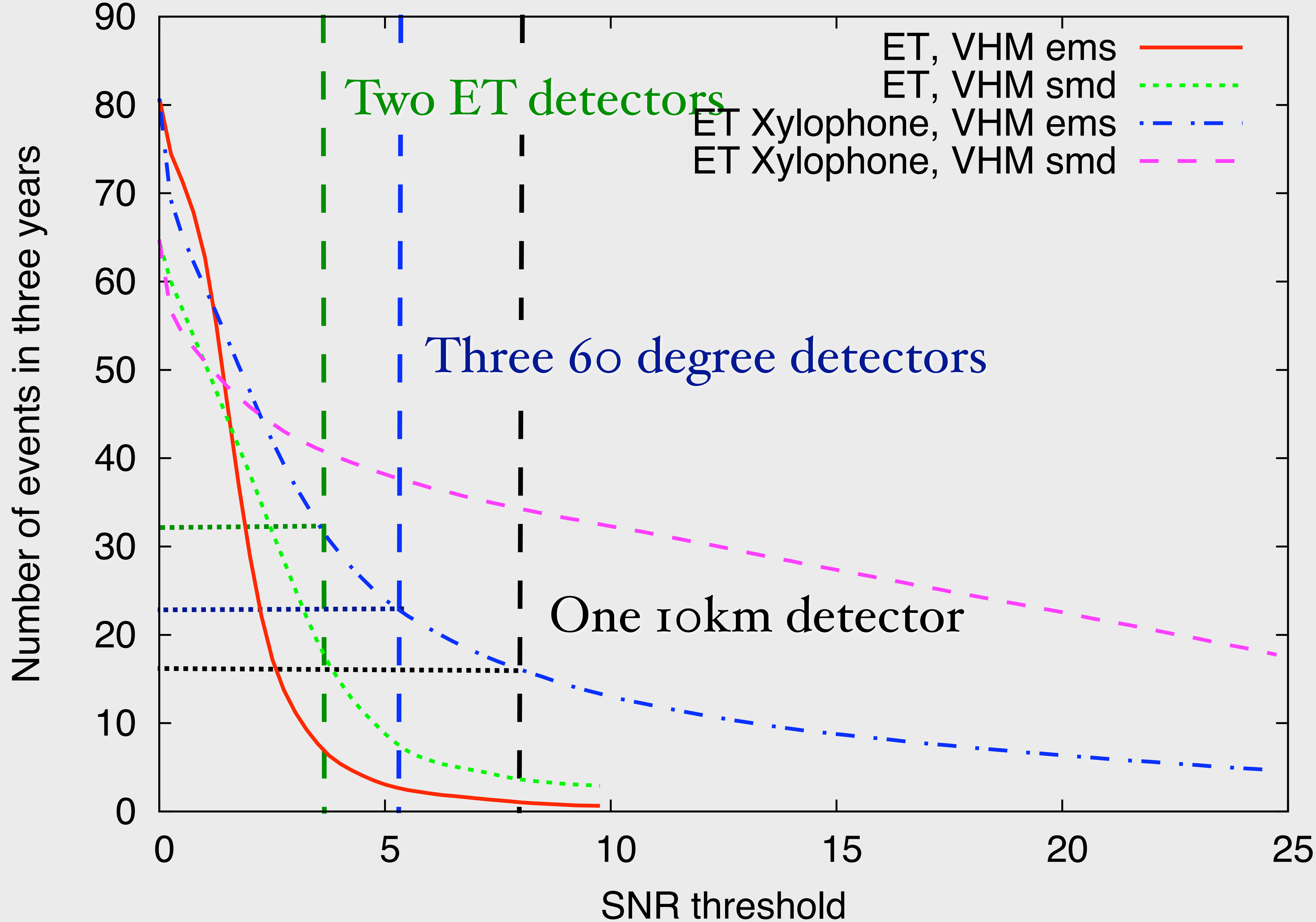
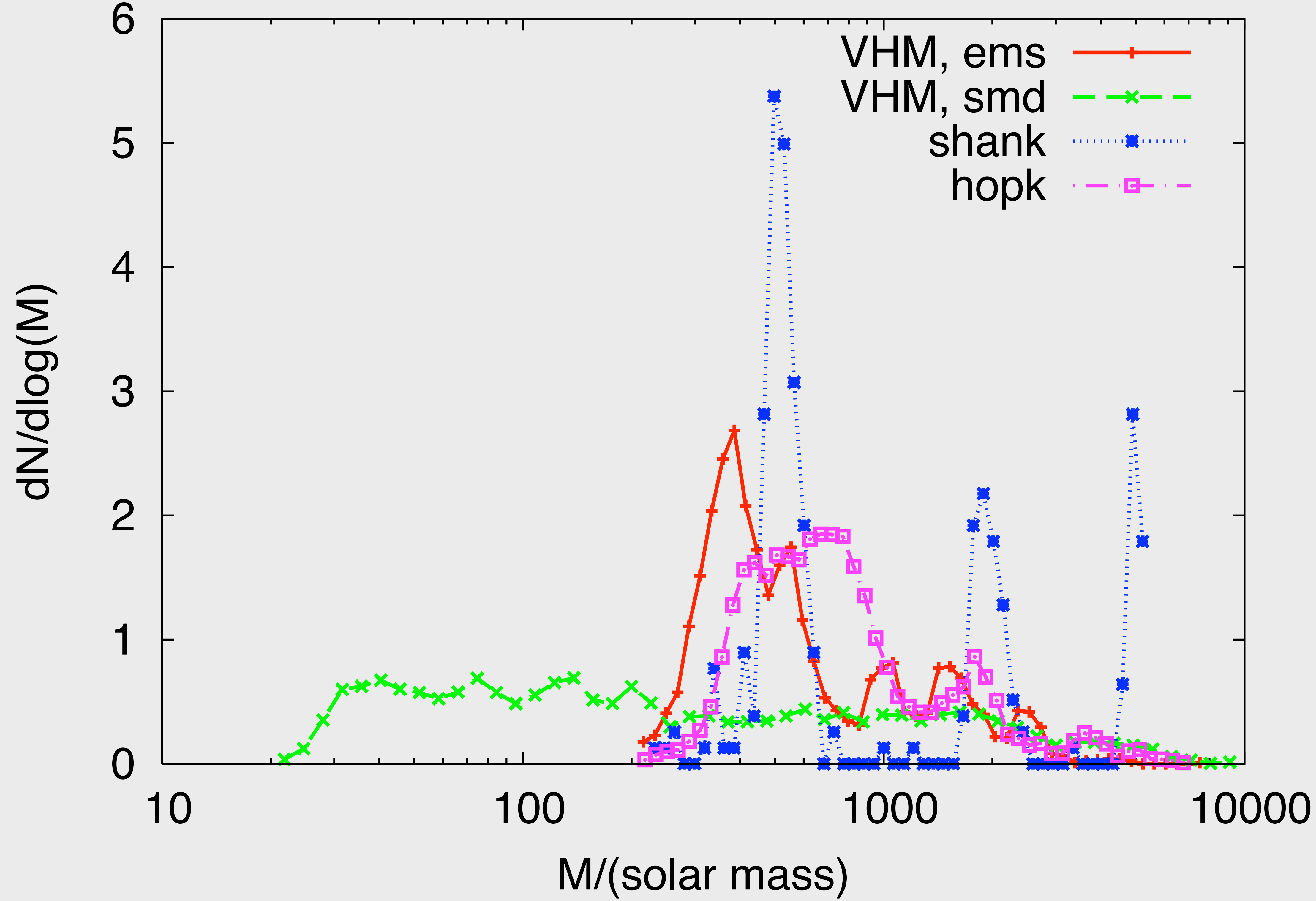
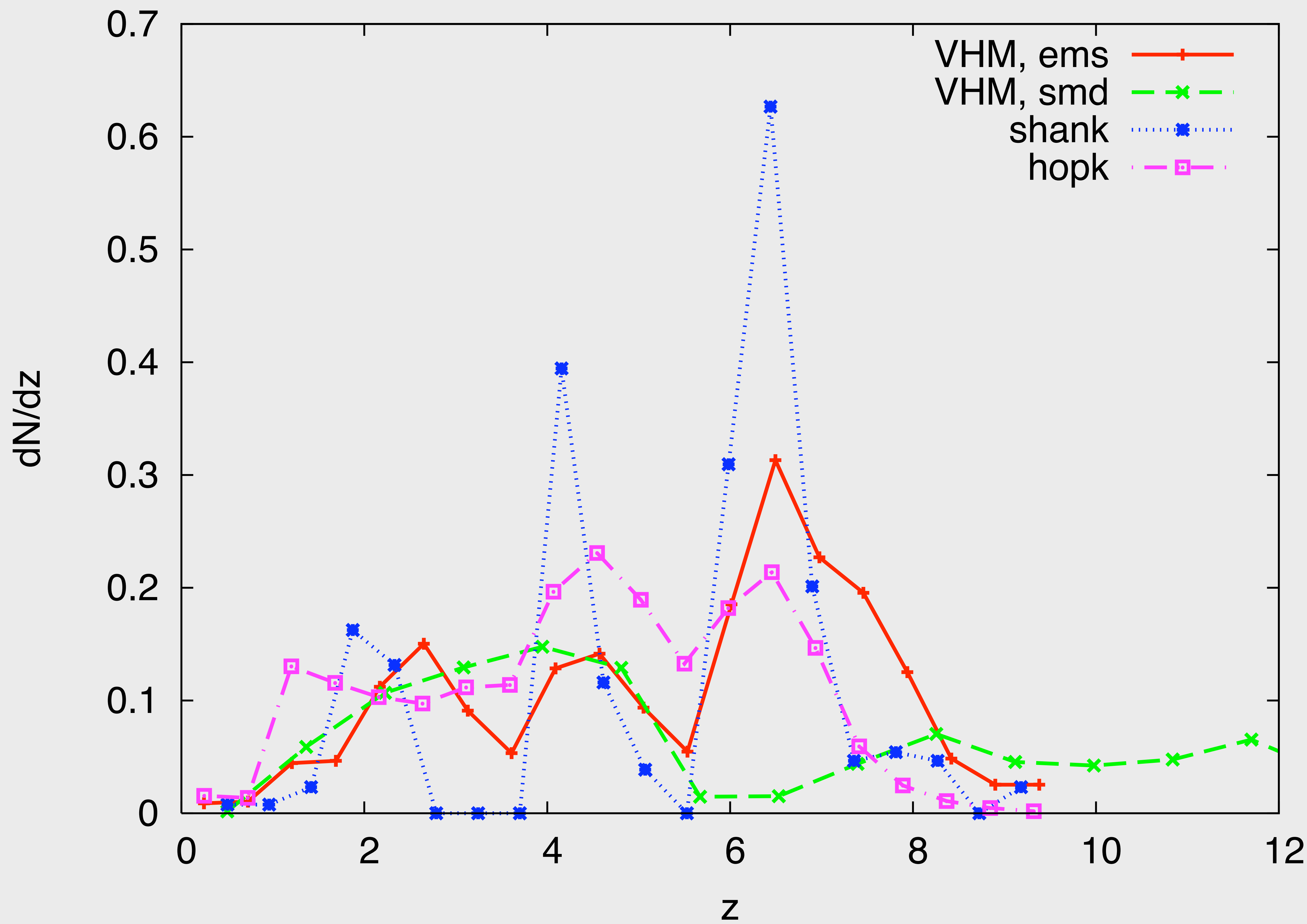


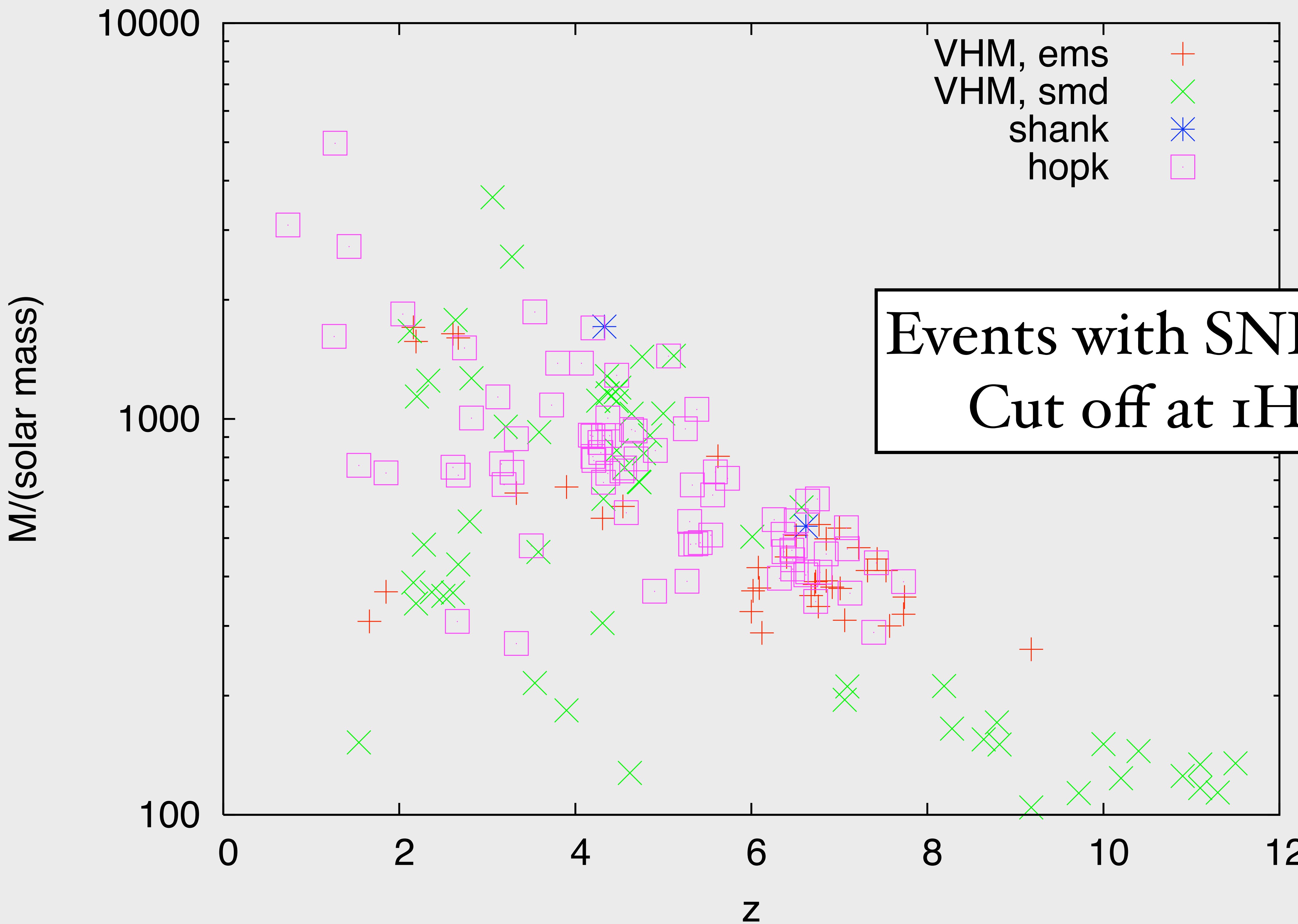
ET seed merger events - masses



ET seed merger events - redshifts

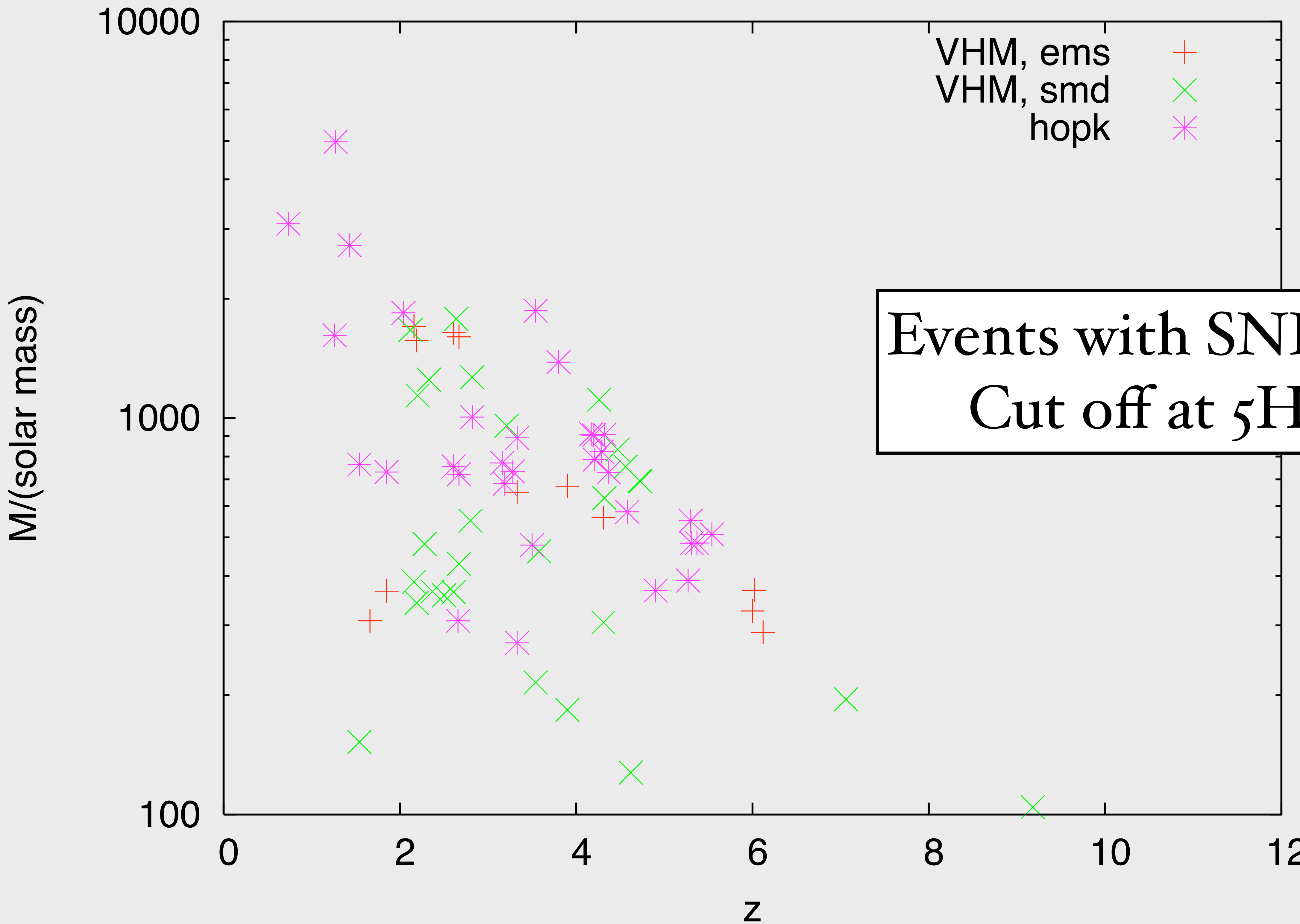


ET seed merger events with SNR>5



Events with SNR > 5
Cut off at 1Hz

ET seed mergers - effect of cut off



Events with SNR > 5
Cut off at 5Hz

CIMMs from globular clusters

- Two formation channels
  - Formation of a binary IMBH in a single globular cluster. Possible if the stellar binary fraction is high enough (Gurkan et al. 2006).
  - Formation of single IMBHs in two separate globular clusters that then merge (Amaro-Seoane & Freitag 2006).
- Rates are comparable between the two channels. Rate for first channel is given by

$$R \equiv \frac{dN_{\rm event}}{dt_o} = \int_{M_{\rm tot,min}}^{M_{\rm tot,max}} dM_{\rm tot} \int_0^1 dq \int_0^{z_{\rm max}(M_{\rm tot},q)} dz \frac{d^4 N_{\rm event}}{dM_{\rm tot} dq dt_e dV_c} \frac{dt_e}{dt_o} \frac{dV_c}{dz}$$

- Here $M_{\rm tot}$ is the total mass of the binary, q is the mass ratio, z is the redshift and $t_{\rm e}, t_{\rm o}$ denote the time at the emitter and observer respectively, with $\mathrm{d}t_{\rm e}/\mathrm{d}t_{\rm o} = 1/(1+z)$.

CIMMs from globular clusters

- Assuming a flat distribution in q, that IMBH binaries form in a fraction, g, of all globular clusters (GCs), that the binary mass is a fixed fraction, 0.002, of the GC mass, the GC mass function is redshift independent and that the total mass of GCs formed is a fixed fraction, $g_{\rm cl}$, of the total stellar mass formed, we find

$$R = \frac{2\times 10^{-3}\; g\; g_{\rm cl}}{\ln(M_{\rm tot,max}/M_{\rm tot,min})} \int_{M_{\rm tot,min}}^{M_{\rm tot,max}} \frac{dM_{\rm tot}}{M_{\rm tot}^2} \int_0^1 dq$$

$$\int_0^{z_{\rm max}(M_{\rm tot},q)} dz\; 0.17 \frac{e^{3.4z}}{e^{3.4z}+22} \frac{4\pi D_H^3}{(1+z)^{5/2}} \times \left\{ \int_0^z \frac{dz'}{[\Omega_M(1+z')^3+\Omega_\Lambda]^{1/2}} \right\}^2$$

- Overall rate (from single cluster channel) is then

$$R \approx 2000 \left(\frac{g}{0.1}\right) \left(\frac{g_{\rm cl}}{0.1}\right) {\rm yr}^{-1}$$

Intermediate Mass Ratio Inspirals

- Inspiral of stellar mass compact objects (neutron stars or black holes) into IMBHs. Analogue of EMRIs for LISA.

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

- ET will see these much further. Various astrophysical applications

  - Probe of IMBH existence, formation efficiency, spin distribution and merger history.
  - Probe of dynamics in globular clusters.
  - Use to test the no-hair property of the central IMBH.

Compact object capture rates

- An IMBH in a GC 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.

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

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

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

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

ET IMRI Event Rate

- Compute V_c and $T_{\min}$ for several different canonical systems

$M_z/M_\odot$	$m_z/M_\odot$	D/Gpc	z	$M/M_\odot$	$m/M_\odot$	T/yr	V_c/Mpc^3	Events/yr
100	10	11	1.5	40	4	3×10^8	3×10^{11}	300
100	2	4.9	0.8	56	1.1	4×10^8	5×10^{11}	70
1000	10	3.2	0.6	640	6.4	9×10^7	1.4×10^{11}	120
1000	2	1	0.2	830	1.7	1×10^8	2×10^9	6

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

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 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, especially for CIMMs which are short-lived.
- Assume another ET detector exists and estimate ability of network to measure parameters.

ET Networks

- Consider errors from a 'third-generation network' of detectors, with four different configurations (NB 'one ET' = triangular configuration - three colocated, coplanar 60 degree detectors):

  (i) An ET at site 1, a 10km third generation detector at site 2.

  (ii) An ET at site 1, plus 10km detectors at site 2 and site 3.

  (iii) An ET at site 1, plus a second ET at site 2.

  (iv) ETs at all three sites.

- Consider two different scenarios for the site locations

  ➡ 'VHL': sites at VIRGO, LIGO Hanford & LIGO Livingston

  ➡ 'VPL': sites at VIRGO, Perth (Australia) & LIGO Livingston

ET Network Parameter Errors - Comparable Mass Mergers

M_z	η	$\Delta\ln M_z$	$\Delta\ln\eta$	$\Delta\ln D_L$ (VHL)				$\Delta\ln D_L$ (VPL)			
				(i)	(ii)	(iii)	(iv)	(i)	(ii)	(iii)	(iv)
100 $M_\odot$	0.15	0.1%	0.05%	37%	27%	25%	23%	36%	27%	25%	23%
100 $M_\odot$	0.25	0.2%	0.06%	37%	28%	24%	22%	36%	26%	24%	22%
500 $M_\odot$	0.15	0.9%	0.4%	41%	31%	29%	25%	41%	30%	28%	26%
500 $M_\odot$	0.25	0.1%	0.1%	37%	32%	28%	24%	35%	30%	28%	26%
1000 $M_\odot$	0.15	2%	1%	53%	33%	31%	26%	43%	33%	32%	27%
1000 $M_\odot$	0.25	0.3%	0.1%	42%	31%	31%	27%	34%	30%	30%	26%

- First column is the redshifted mass, and all events have been renormalised to a network SNR of 8.
- Distance errors are quoted as the 68th percentile of the distribution. Mass and mass ratio errors are statistical errors.

IMRI parameter errors

- Used Fisher Matrix to estimate parameter errors for 1+100 inspiral with a=0 detected by a single ET with SNR=20. Include time-dependence of ET response.
- Conclusion: one ET cannot determine extrinsic parameters - angular errors of order of the whole sky and fractional distance error is of order 1.
- See only a very modest improvement in the Fisher Matrix errors as integration time increased from 10,000s to 30,000s.
- Will again need a network of ETs to pin down location of these sources. **But,** one ET does return accurate measurements of masses and spin, which are more important for these sources to achieve astrophysics goals and tests of GR.

IMRI - typical parameter errors

$m/M_\odot$	$M/M_\odot$	a/M	$\Delta m/m$	$\Delta M/M$	$\Delta(a/M)$
1	100	0.2	0.004	0.007	0.008
1	100	0.9	0.0015	0.0025	0.0025
1	1000	0.2	0.004	0.006	0.007
1	1000	0.9	0.0005	0.0008	0.0008
10	100	0.2	0.04	0.06	0.07
10	100	0.9	0.015	0.025	0.0025
10	1000	0.2	0.035	0.06	0.07
10	1000	0.9	0.005	0.008	0.008

Summary

- ET is an ideal instrument for probing black holes with mass in the $100M_\odot - 1000M_\odot$. Such black holes could form in the early Universe from Pop III stars, or in globular clusters.

- ET could see a handful of mergers between seed black holes, plus as many as several thousand mergers between IMBHs formed in globular clusters.

- ET could also see several hundred IMBH capture sources out to moderate redshift, but these would be in globular clusters only. IMRIs can be used for astrophysics and tests of GR. More work necessary to quantify ET capabilities and event rates.

- A single ET can measure intrinsic (redshifted) source parameters to ~0.1% accuracy. An ET network could constrain distance and hence redshift to a precision of a few tens of percent.