Probing Seed Black Holes and Intermediate Mass Capture Sources with ET

Jonathan Gair (IoA, Cambridge)
Ilya Mandel (NW), Alberto Sesana (PSU), Alberto Vecchio (U. B'ham)

Seed black hole paper - arxiv:0903.????
(submitted to ApJ, on astro-ph tomorrow)

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
- Different models predict very similar event rates for massive BH mergers detected by LISA. If seeds are light, a detector in the 1-50Hz range could detect first epoch of mergers.

Einstein Telescope event rates

- Estimate ET event rate 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.

Einstein Telescope event rates

- Estimate ET event rate 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

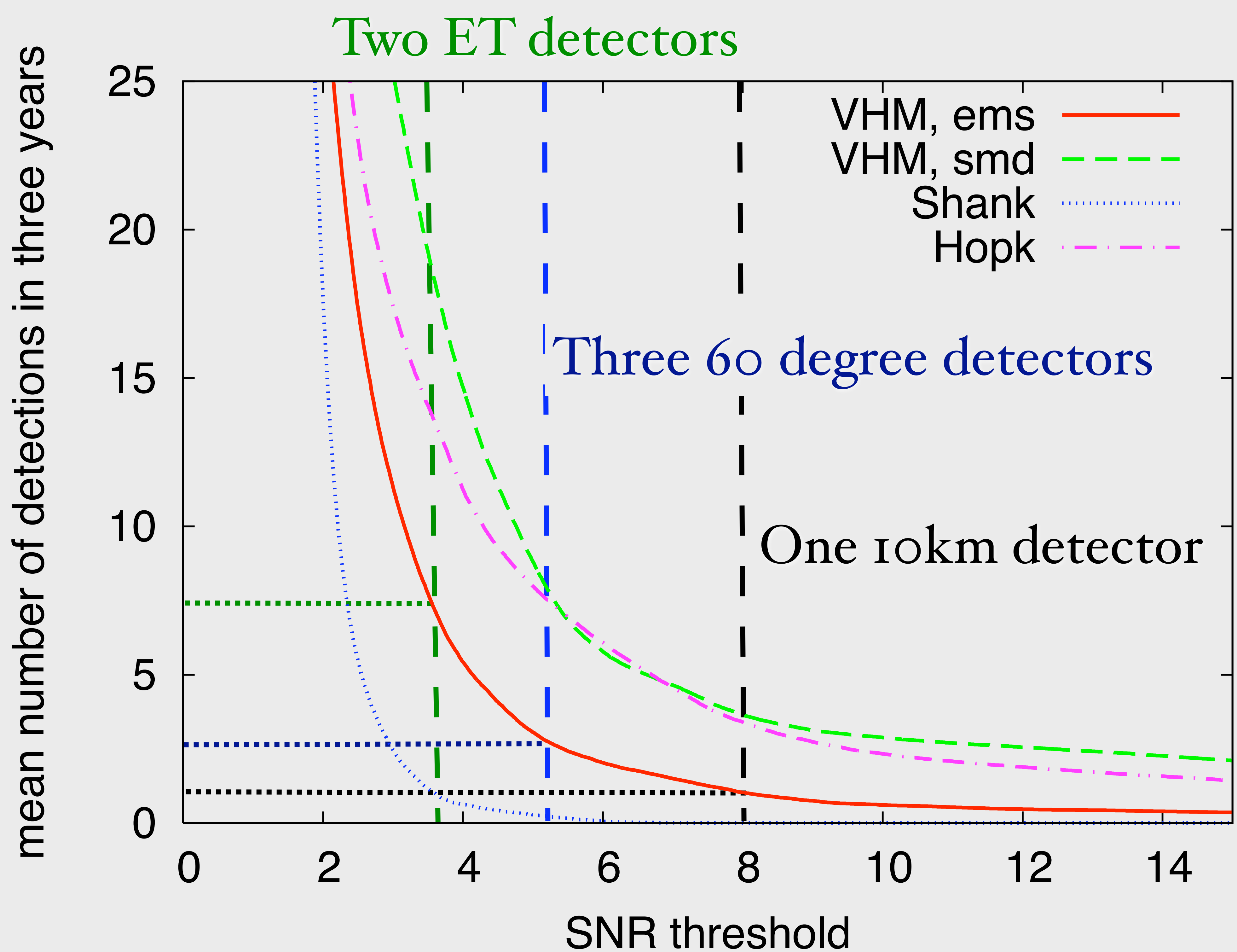
- Compute SNRs for ET using the inspiral/merger/ringdown waveform model of Ajith et al. (2008).

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

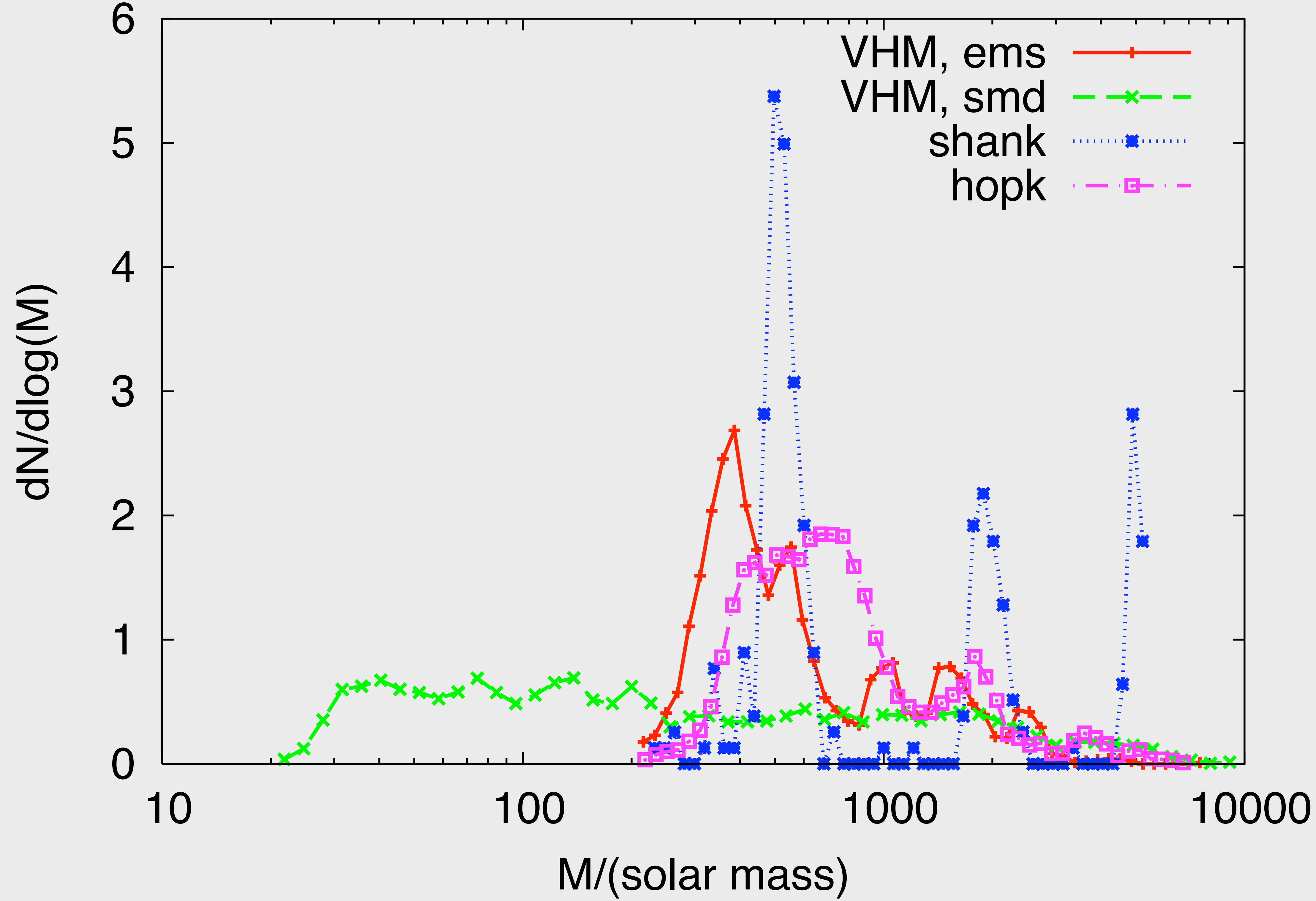
$$A_{\rm eff}(f) \equiv \frac{M^{5/6}}{D\,\pi^{2/3}\,f_{\rm merg}^{7/6}}\sqrt{\frac{5\eta}{24}}\begin{cases} (f/f_{\rm merg})^{-7/6} & \text{if } f < f_{\rm merg} \\ (f/f_{\rm merg})^{-2/3} & \text{if } f_{\rm merg} \le f < f_{\rm ring} \\ \frac{\sigma^2}{4(f_{\rm ring}/f_{\rm merg})^{2/3}((f-f_{\rm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

- 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.

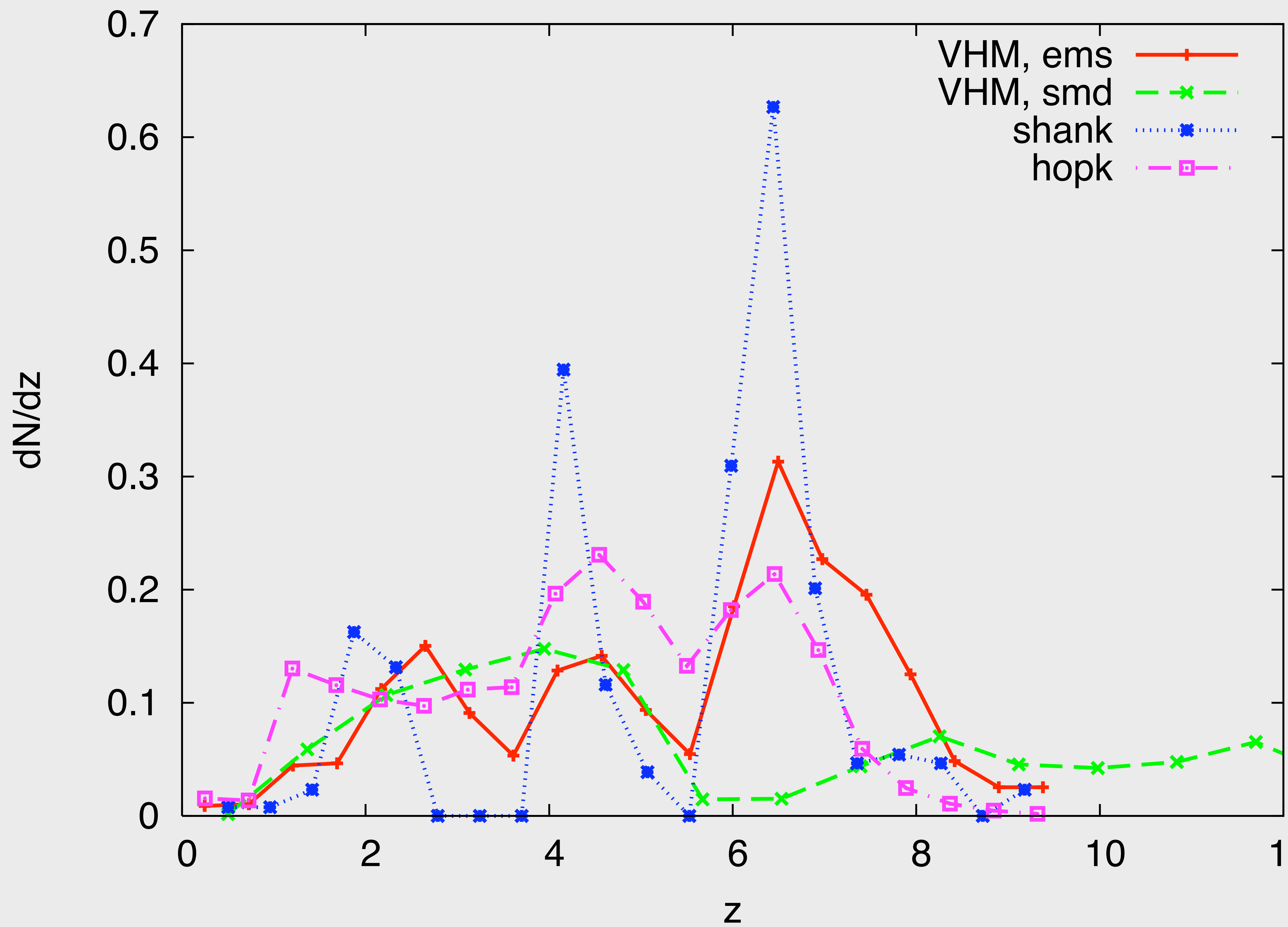
ET event rate



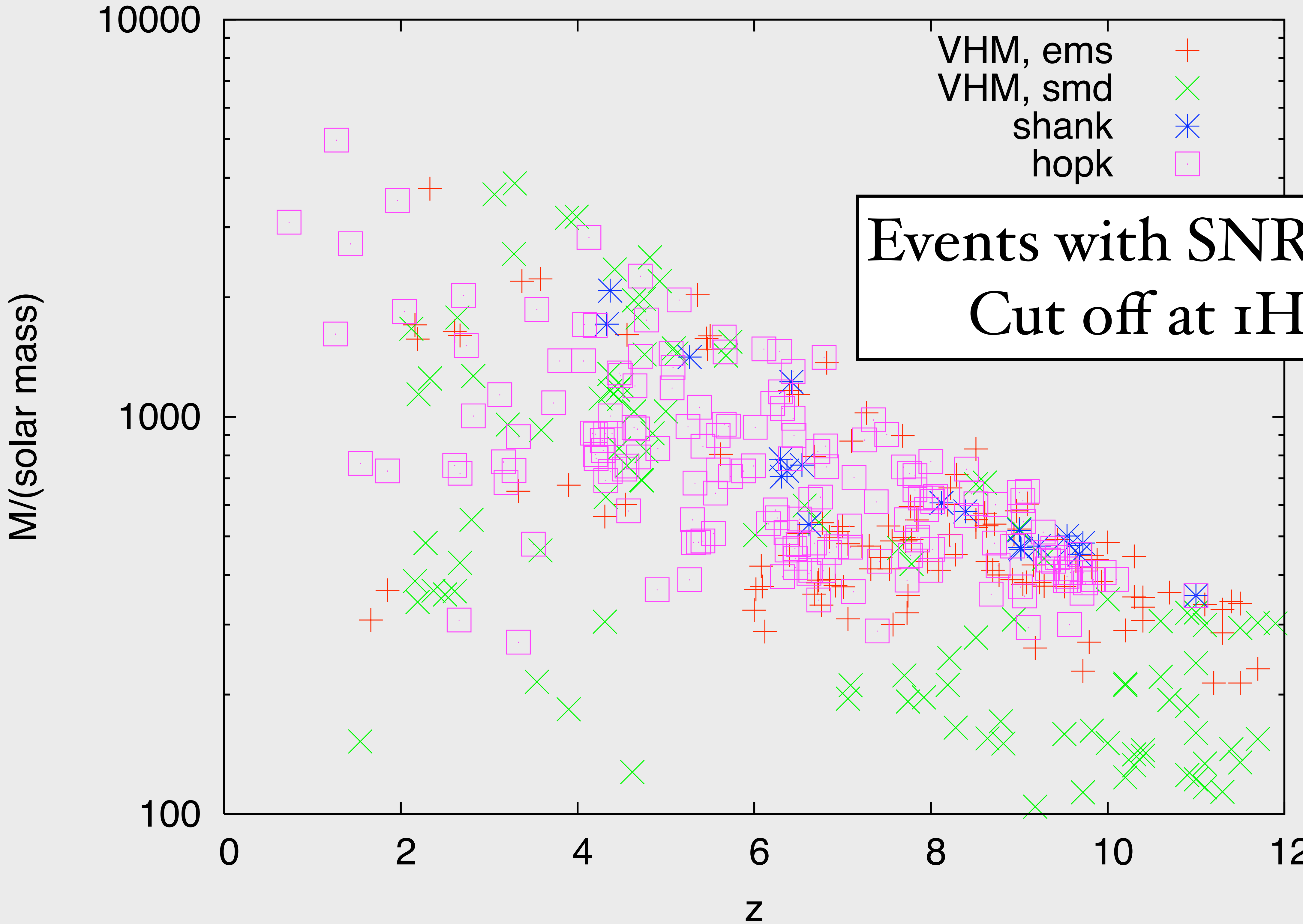
ET event mass distribution



ET event redshift distribution

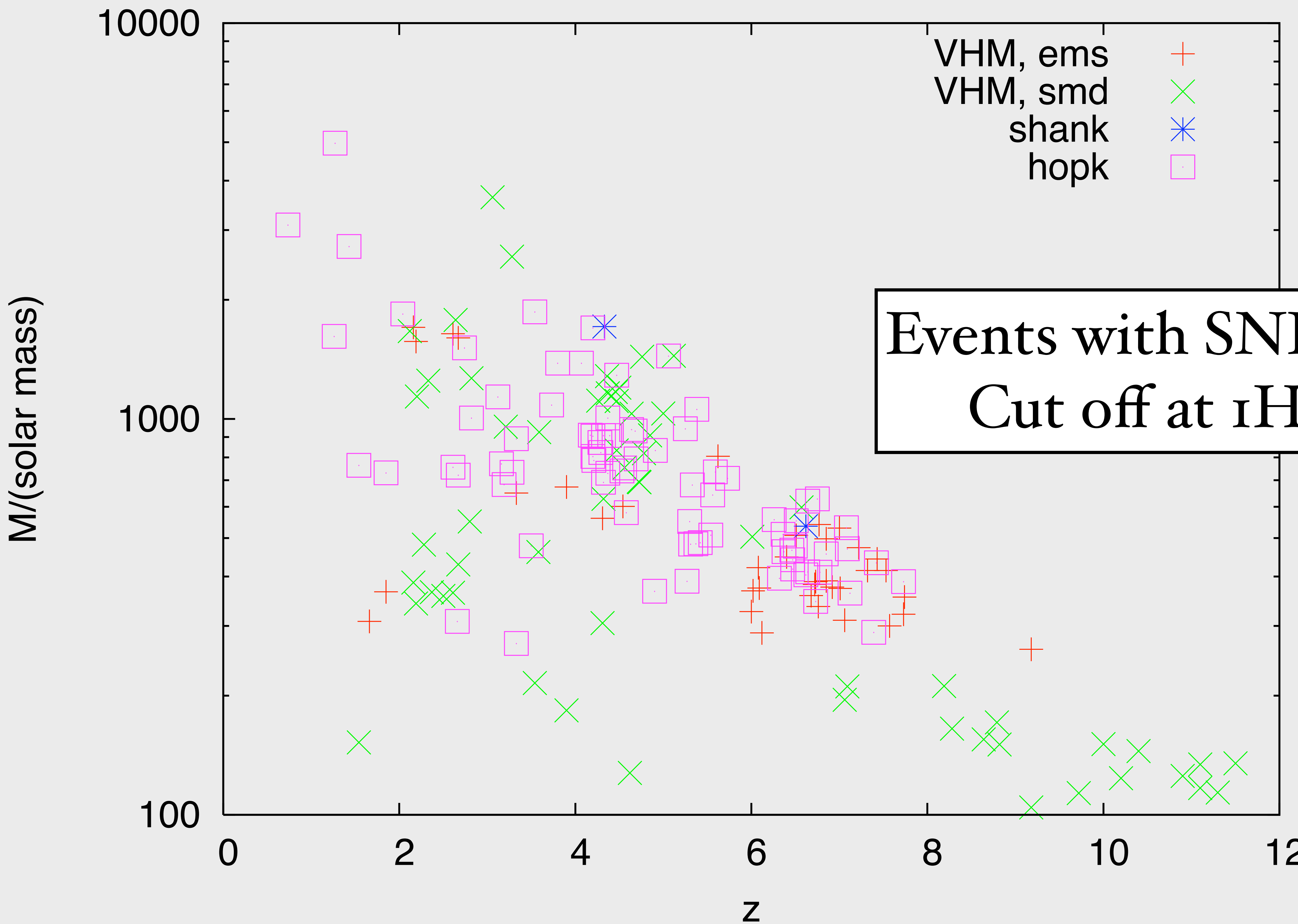


Event Distribution - SNR>3.1



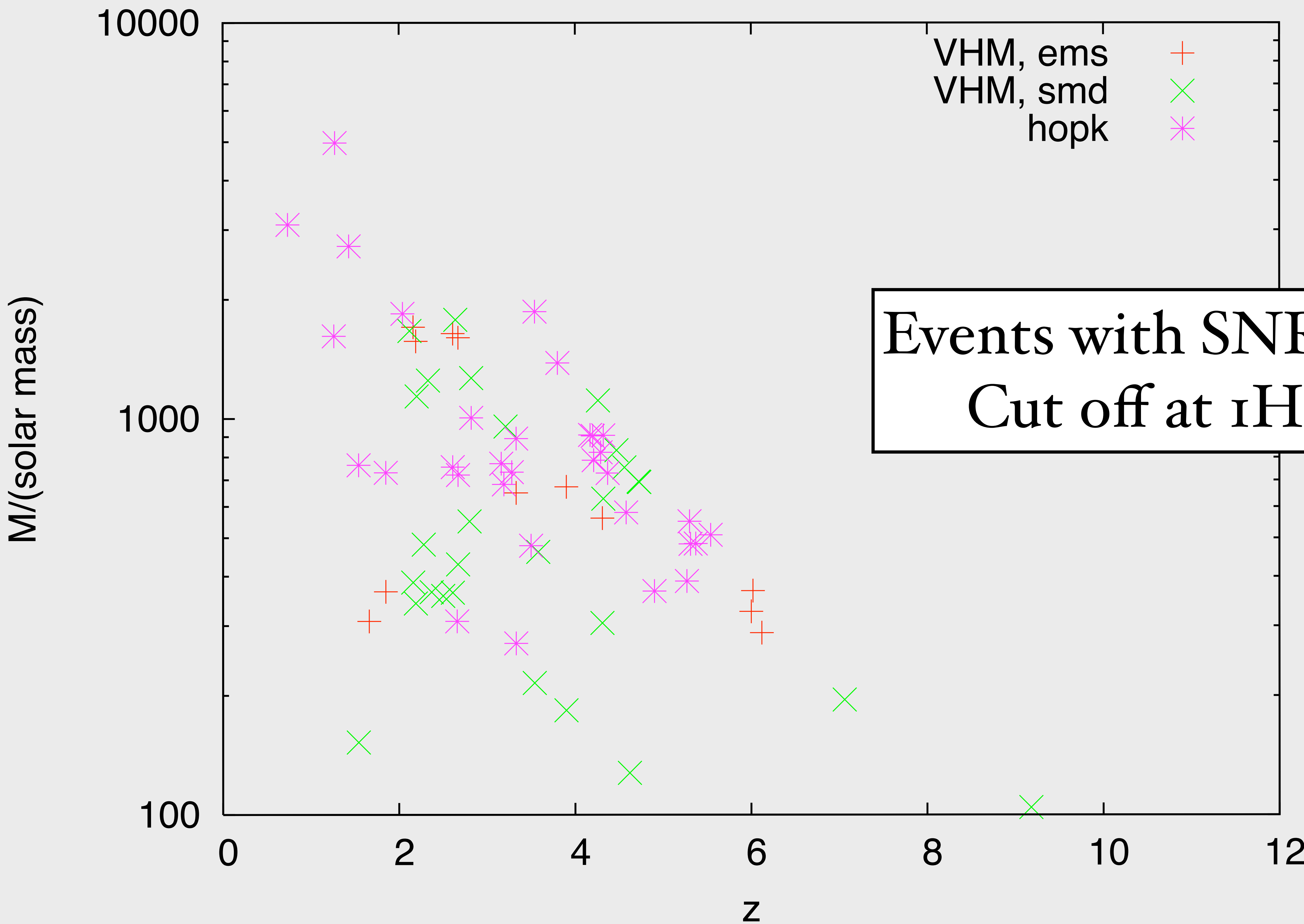
Events with SNR > 3.1
Cut off at 1Hz

Event Distribution - SNR>5



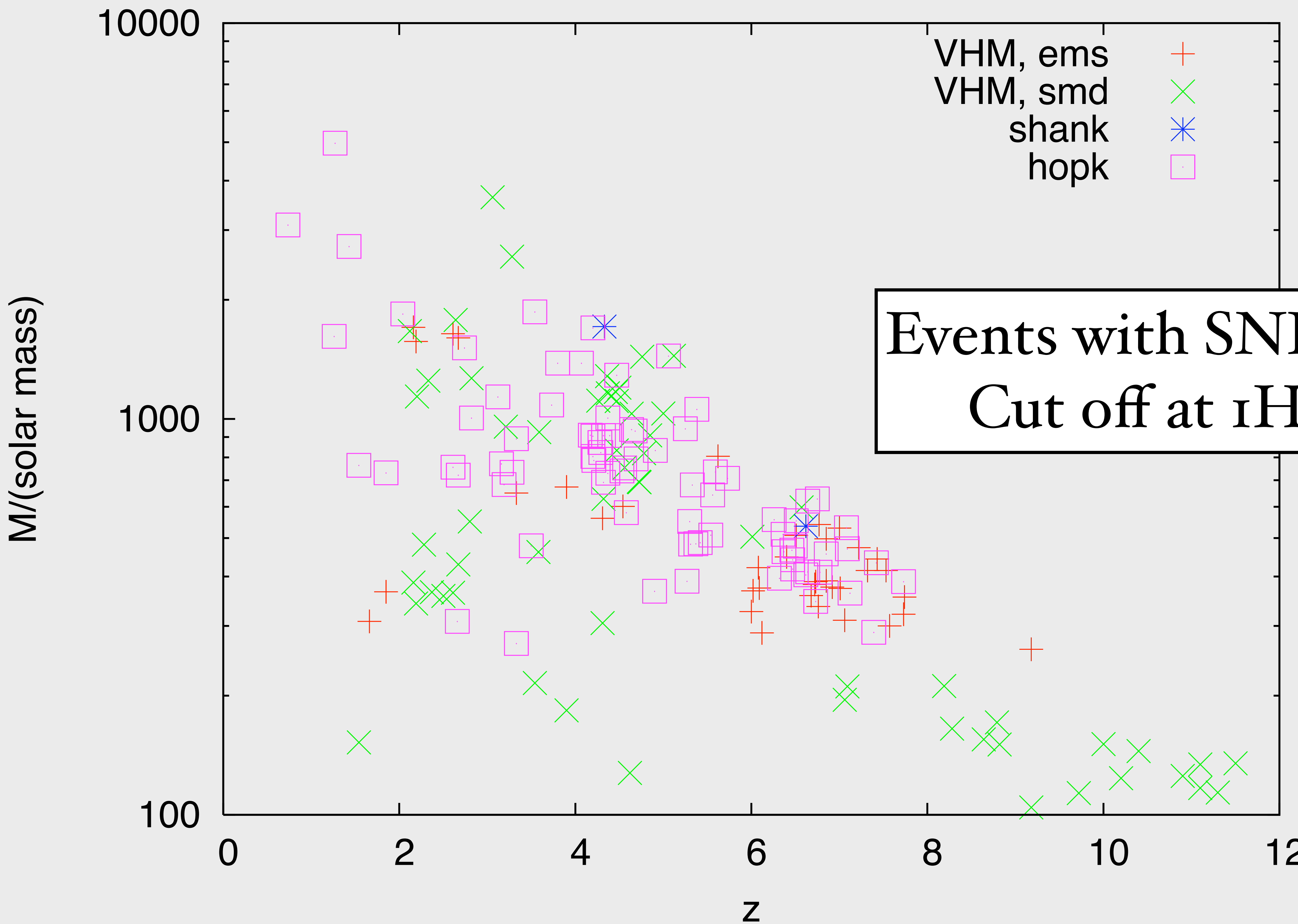
Events with SNR > 5
Cut off at 1Hz

Event Distribution - SNR>8



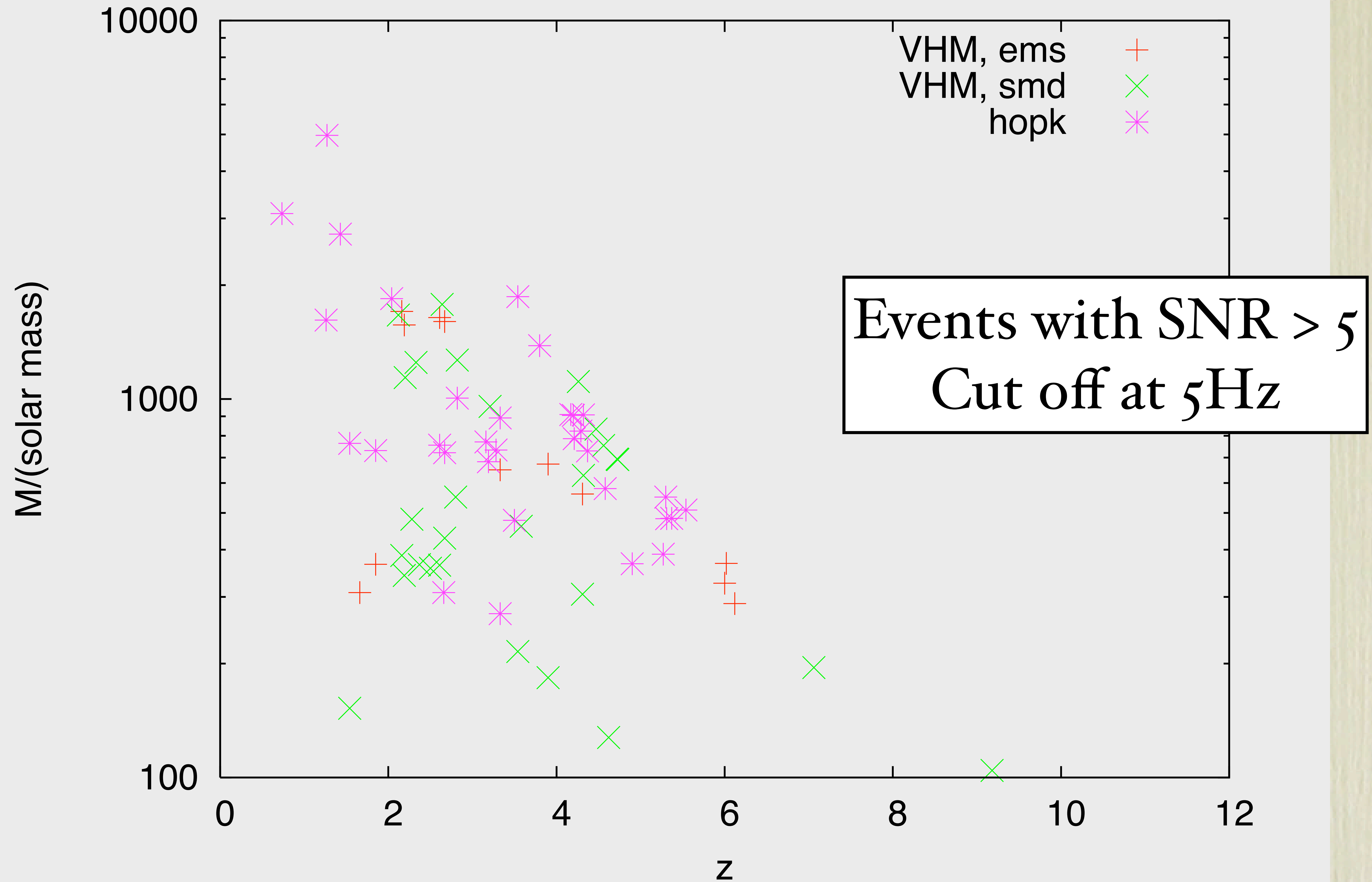
Events with SNR > 8
Cut off at 1Hz

Event Distribution - SNR>5



Events with SNR > 5
Cut off at 1Hz

Event Distribution - cut off



Parameter estimation accuracy

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

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

- Waveform depends 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 another ET detector exists and estimate ability of network to measure parameters.

ET Network Parameter Errors

- 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

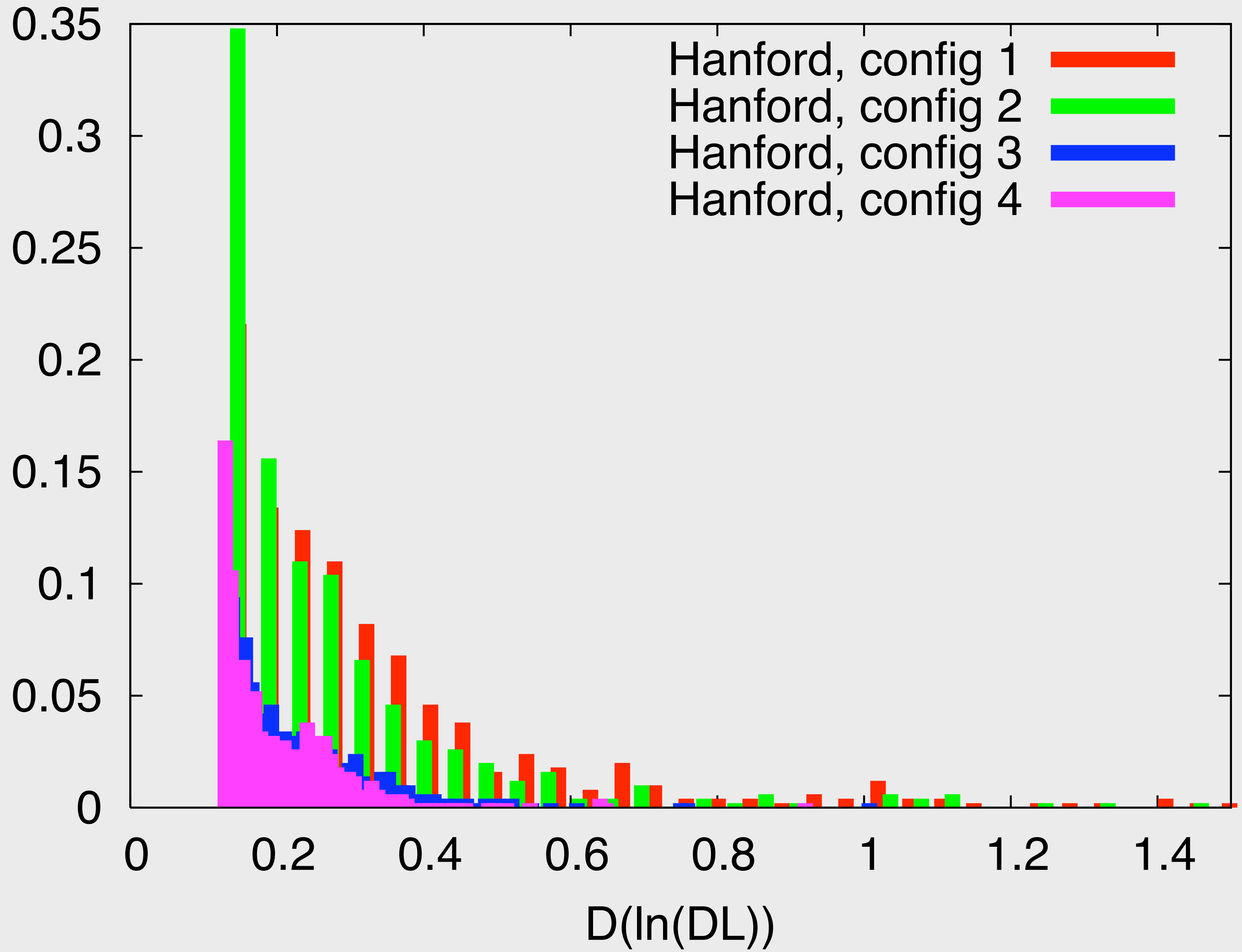
  ➡ 'VPL': sites at VIRGO, Perth (Australia) & LIGO Livingston

ET Network Parameter Errors

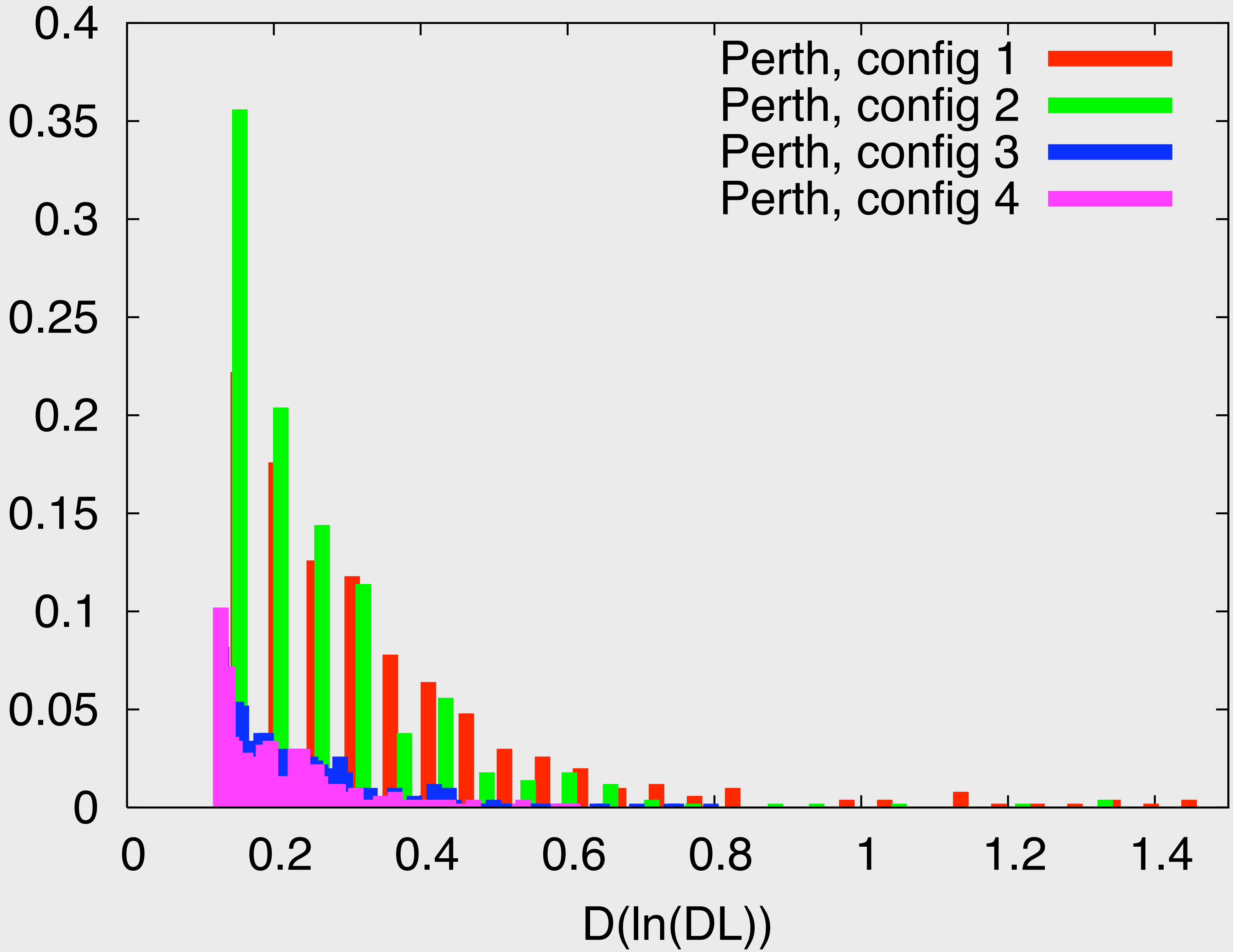
M_z	η	$\Delta\ln M_z$	$\Delta\ln\eta$	$\Delta\ln D_L$ (VHL)				$\Delta\ln D_L$ (VPL)			
				(i)	(ii)	(iii)	(iv)	(i)	(ii)	(iii)	(iv)
100 $M_\odot$	0.15	0.1%	0.05%	37%	27%	25%	23%	36%	27%	25%	23%
100 $M_\odot$	0.25	0.2%	0.06%	37%	28%	24%	22%	36%	26%	24%	22%
500 $M_\odot$	0.15	0.9%	0.4%	41%	31%	29%	25%	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.

Distance Errors - VHL



Distance Errors - VPL



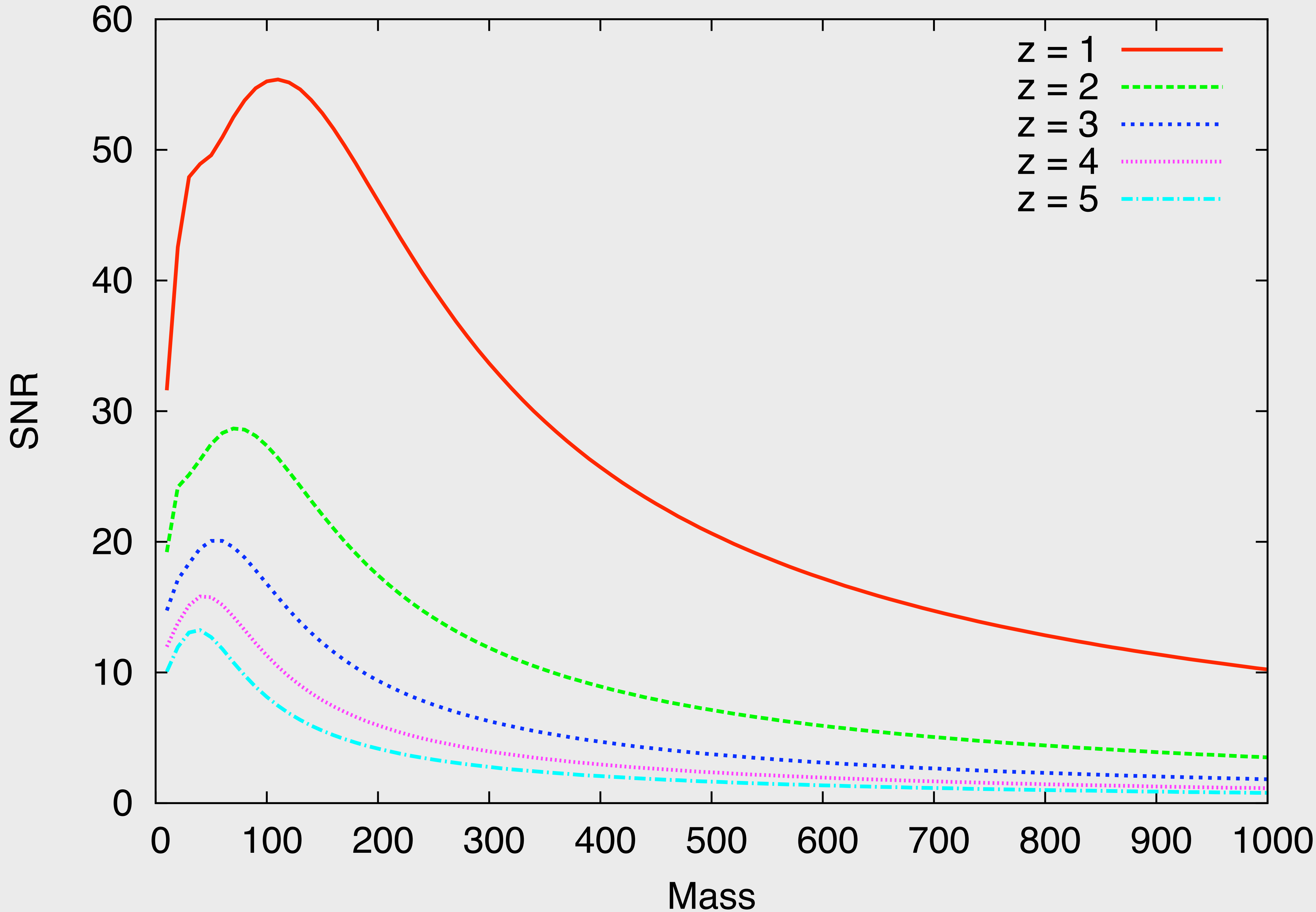
ET discovery space

- If seed BHs do not come from pop III stars, or the initial accretion epoch is very rapid, ET will not see any events, but LISA will in either case. ET probes this seed population directly.
- **Number of events**: we only probe the tip of the population. However, a lot (10-20) of events at z>10 will tell us BH formation is much more efficient than most models assume.
- **Masses**: tell us about seed mass distribution (currently unknown), and early accretion history of pop III black holes.
- **Redshift distribution** is very important. Events at z > 7-8 must be pop III remnants. Events at z < 5 may come from IMBHs formed in clusters. Excess of events at low redshift may probe cluster mergers.

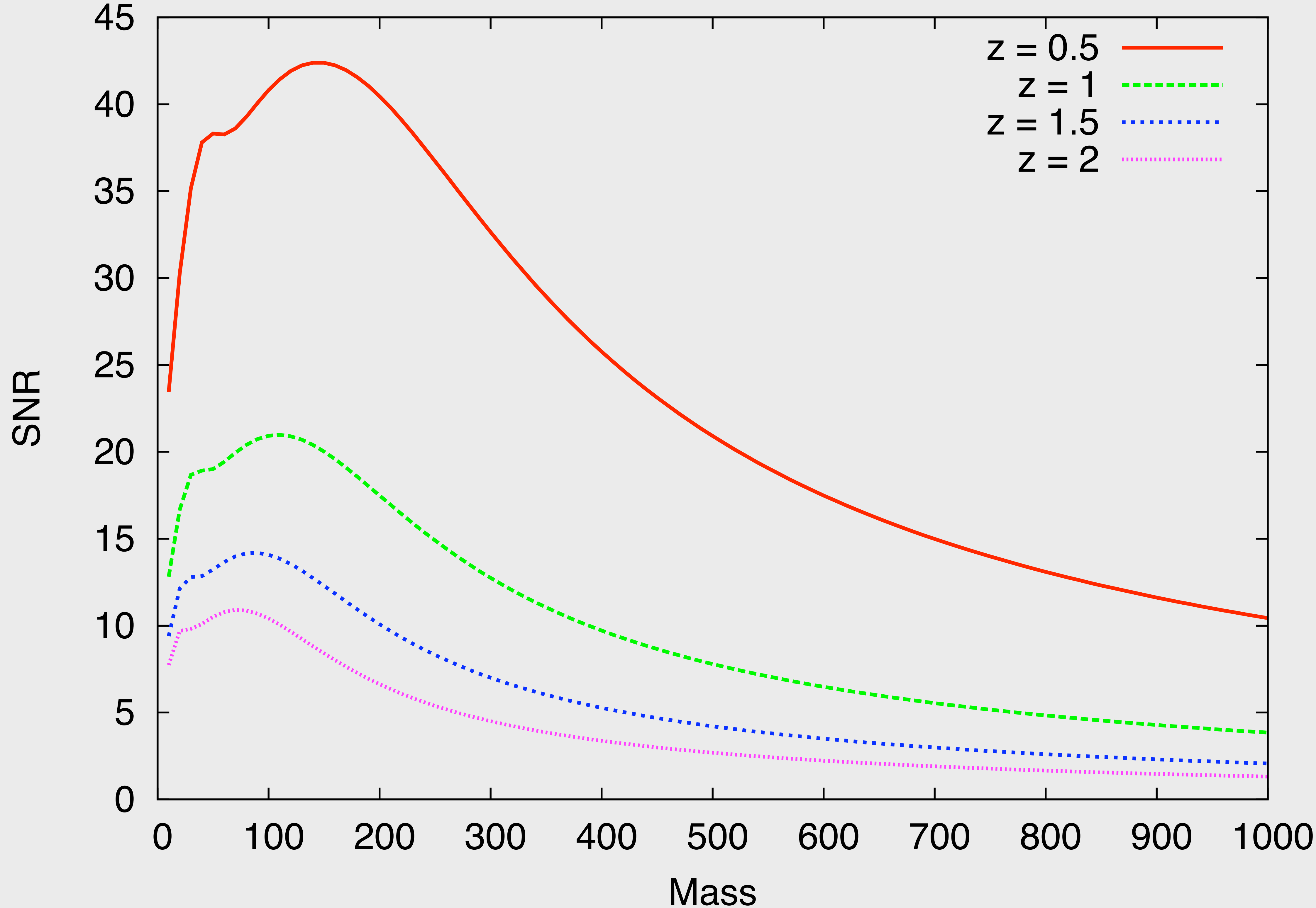
Intermediate Mass Ratio Inspirals

- Inspiral of stellar mass compact objects (neutron stars or black holes) into IMBHs. Analogue of EMRIs for LISA.
- IMBHs may be pop III remnants, or formed by runaway collisions in globular clusters. 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.

BH IMRI signal-to-noise ratio



NS IMRI signal-to-noise ratio



ET IMRI Event Rate

- Number of IMBHs and capture rate is very uncertain, but can get a crude upper limit by assuming some fraction *f* of globular clusters contain IMBH black holes ⇒ IMBH number density,

$$n \sim 0.3(f/0.1)\mathrm{Mpc}^{-3}$$

- Using a standard WMAP cosmology, number of IMBHs available is 4.5×10^{10}(z<1), 1×10^{11}(z<1.5), 1.75×10^{11} (z<2), 3.25×10^{11}(z<3).

- Assume IMBH grows from 50 to 300 solar masses by accreting neutron stars, rate is $2 \times 10^{-8}\mathrm{yr}^{-1}$. Growth from accretion of black holes gives rate of $3 \times 10^{-9}\mathrm{yr}^{-1}$.

- Crude ET rate of $900\mathrm{yr}^{-1}$ (all neutron stars, limit at z=1) or $500\mathrm{yr}^{-1}$ (all black mergers, limit at z=2).

IMRI parameter estimation

- 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

- Determining the mass of the seeds from which galactic black holes grow is very important for understanding galaxy evolution.
- ET is the only proposed instrument with the capability to detect pop III black holes. Whatever the black hole seed mass and growth rate, LISA will see similar numbers of galaxy merger events. ET can probe the first generation of black holes directly.
- An ET network could detect several events per year and determine distance to ~30% accuracy.
- IMBH capture sources could also be seen at moderate redshift. Useful for astrophysics and tests of GR. More work necessary to properly quantify ET capabilities and event rates.