Intermediate Mass Black Hole Binaries in ET

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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, since LISA is most sensitive to higher mass systems.

Computing Merger Rates

- Construct semi-analytic merger trees by following mergers of dark matter halos (e.g., Volonteri, Haardt & Madau 2003).

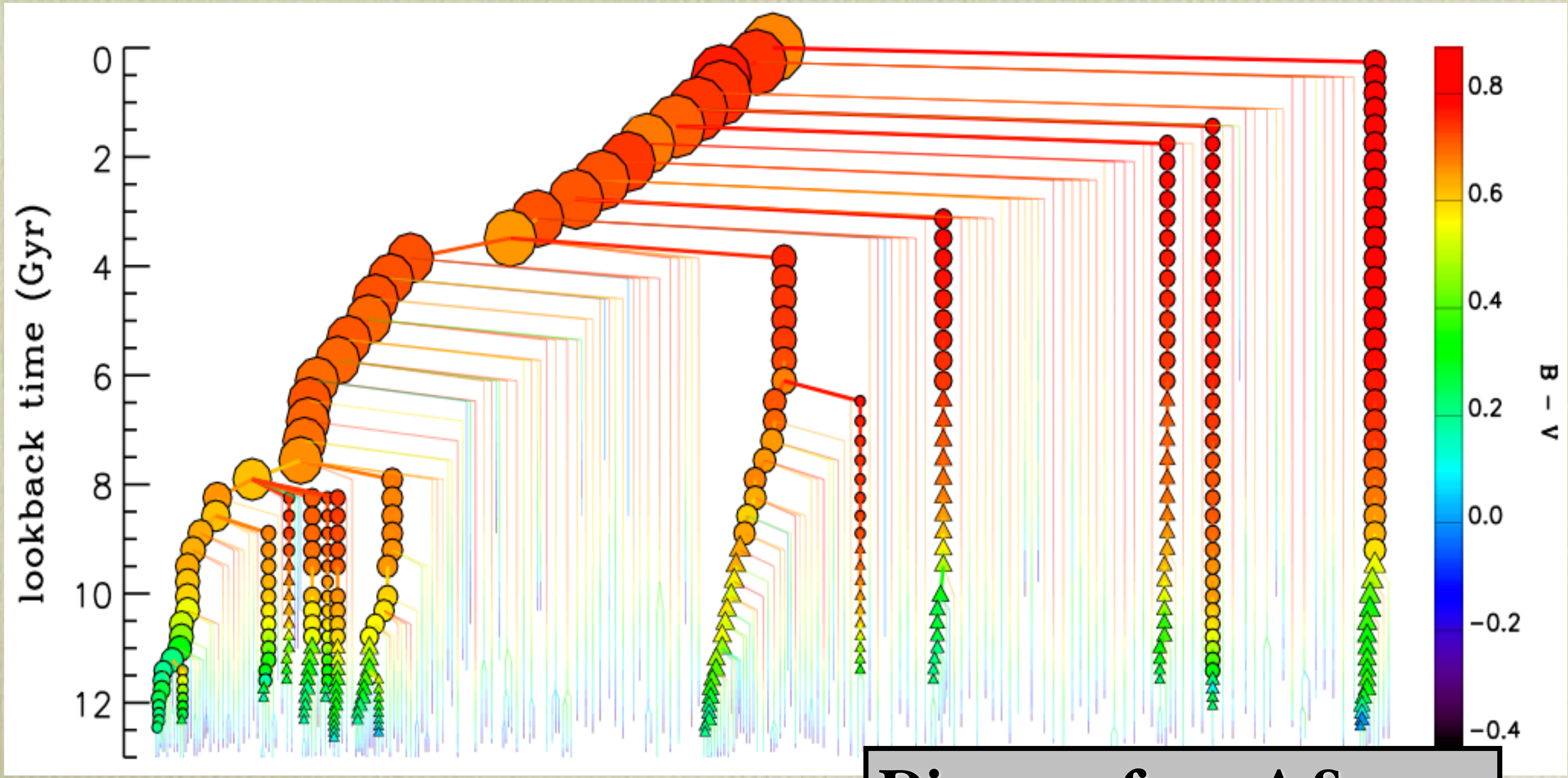
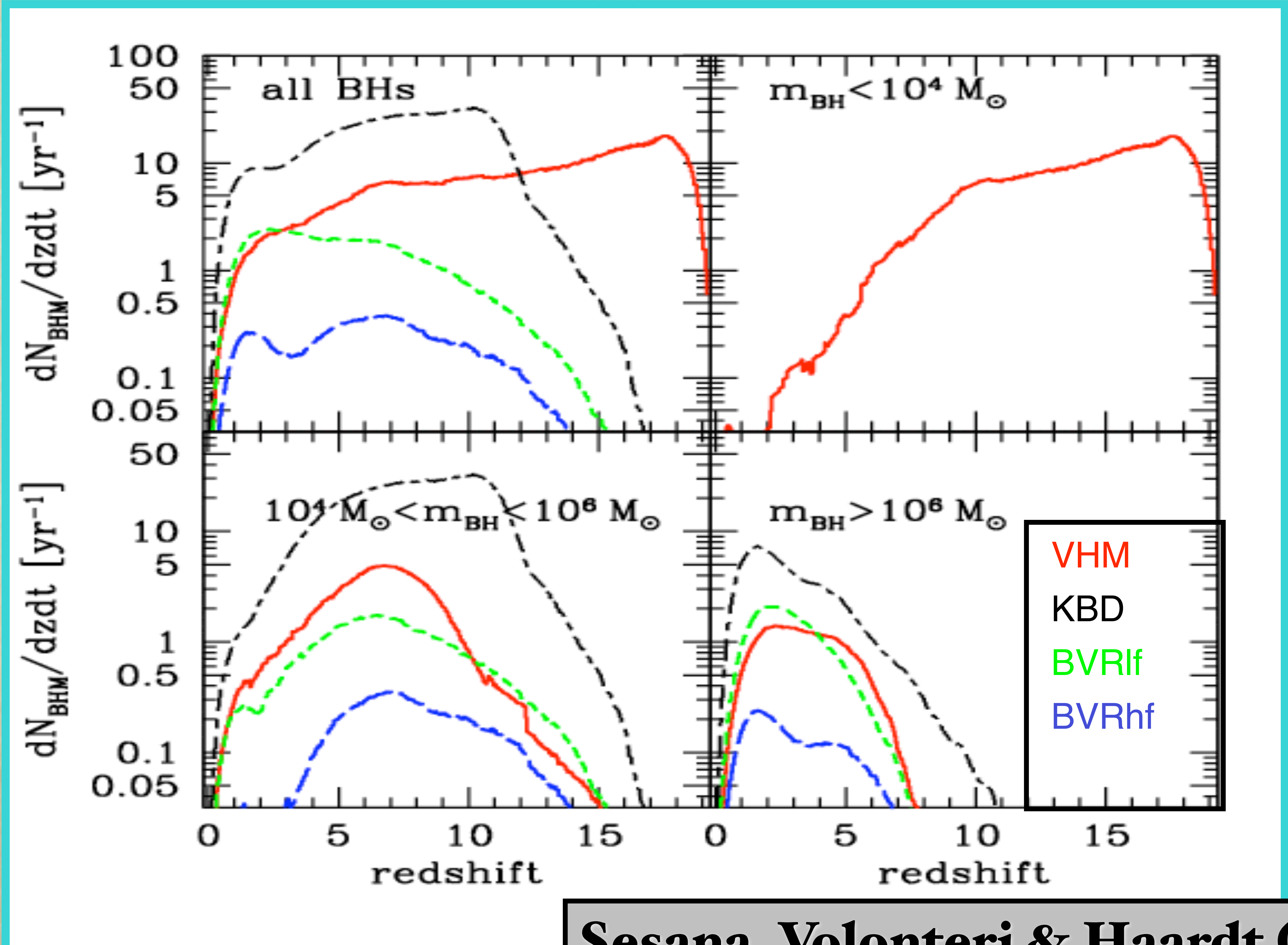


Diagram from A Sesana

Computing Merger Rates

- Four different popular models
  - **VHM Model** (Volonteri et al. 2003) - light seeds (-100 solar masses), formed in high sigma density peaks at $z=20$.
  - **KBD model** (Koushiappas et al. 2006) - massive, abundant seeds formed in halos with efficient molecular hydrogen cooling at $15 < z < 20$.
  - **BVRhf model** (Begelman et al. 2007) - massive rare seeds, formed in halos with efficient atomic hydrogen cooling at $18 < z < 20$.
  - **BVRlf model** (Begelman et al. 2007) - massive rare seeds, formed in halos with efficient cooling at $15 < z < 20$.
- All predict similar event distributions for LISA, but ET can distinguish these models by probing the first round of pop III mergers.

LISA event distribution



Sesana, Volonteri & Haardt (2007)

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

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

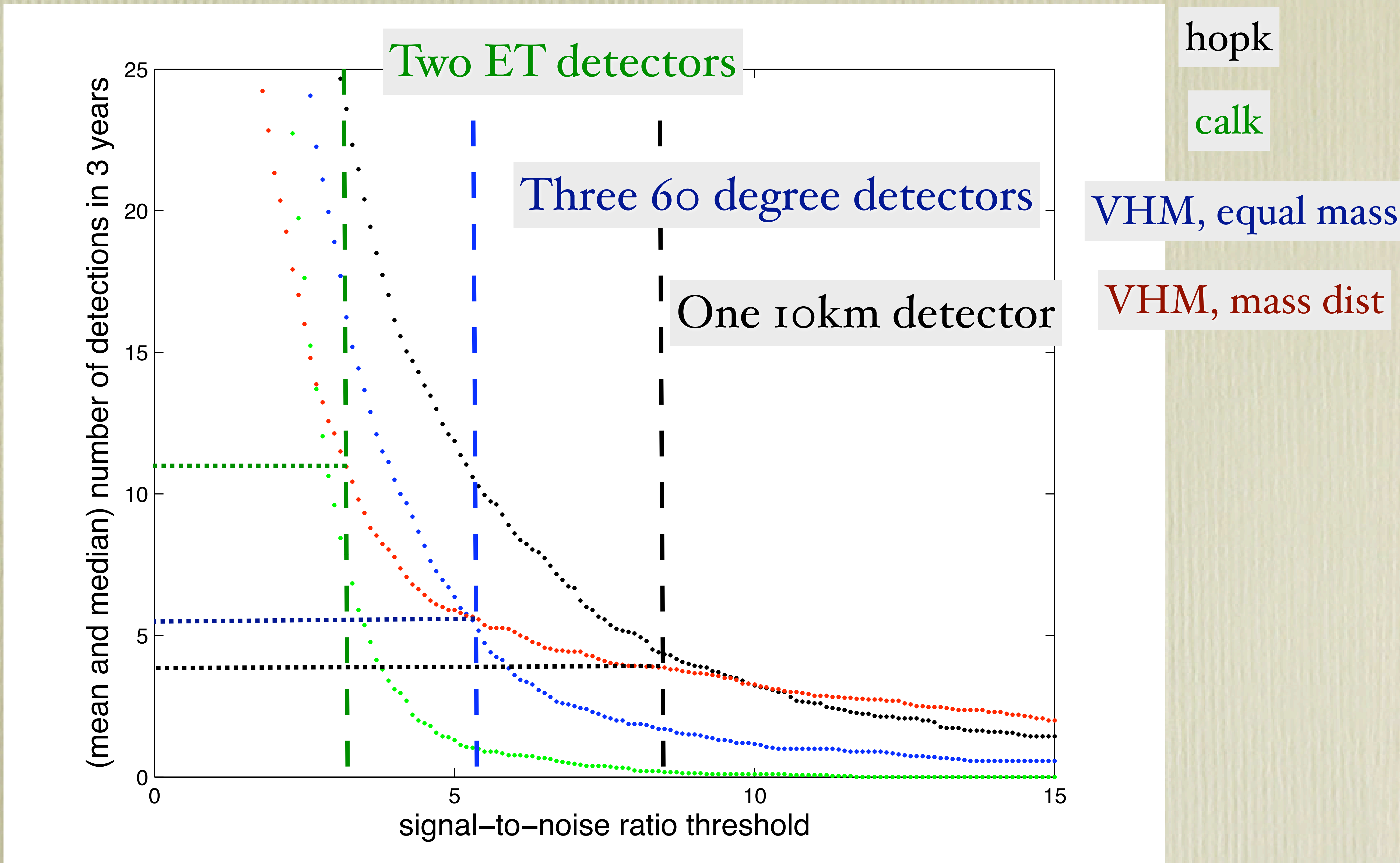
$$\tilde{h}(f) = A_{\rm eff}(f)\exp\left[i\Psi(f)\right]$$

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

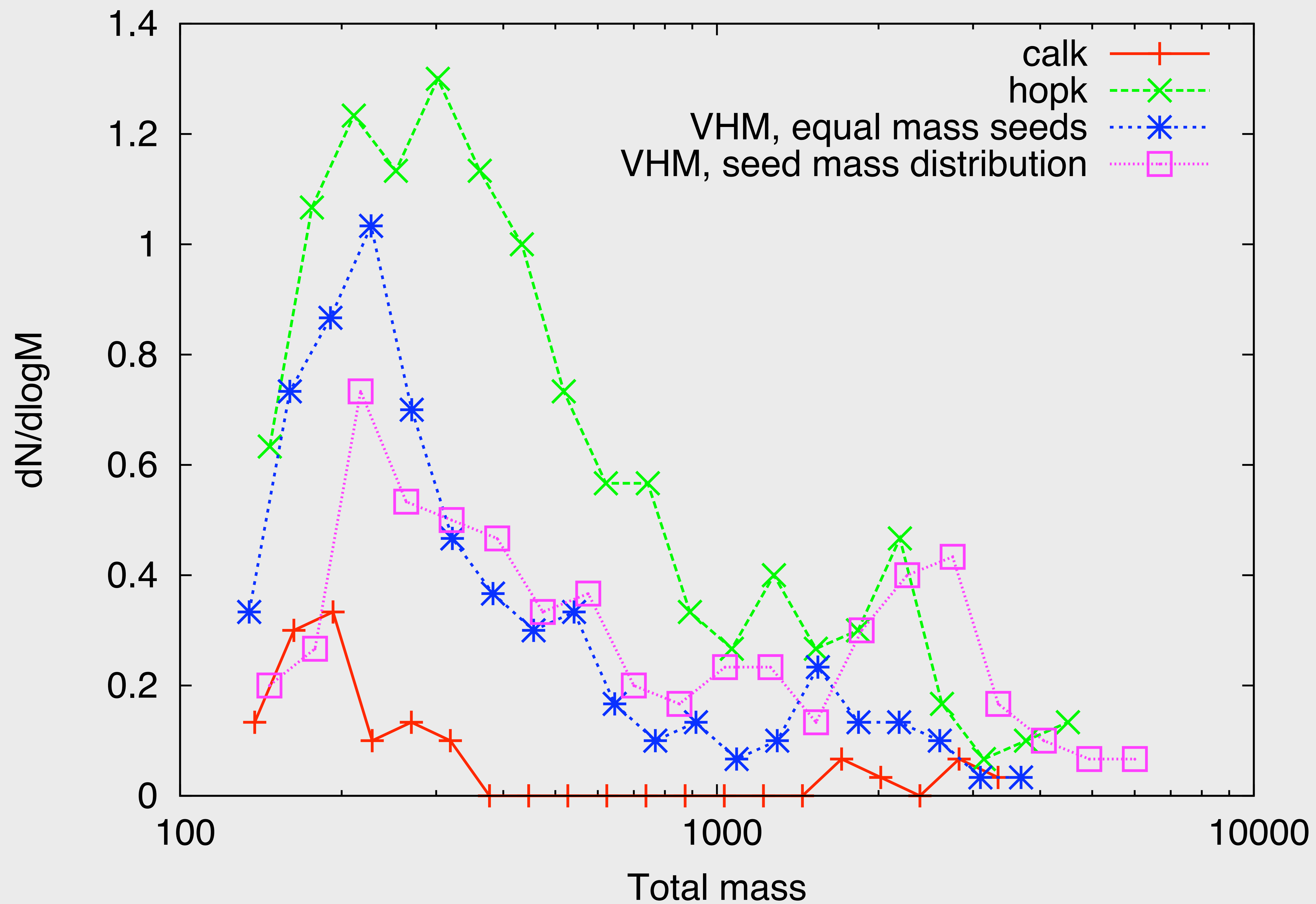
- Average SNR over sky positions and orientations in the usual way. Compute SNR using noise curve for a single 10km detector. Triangle configuration is equivalent to two $(3/2\sqrt{2}) \times 10$km detectors.

- Assume a network SNR threshold of 8. Threshold in one 10km detector is then 8, 5.33 or 3.77 for one detector, one triangular detector or two triangular detectors respectively.

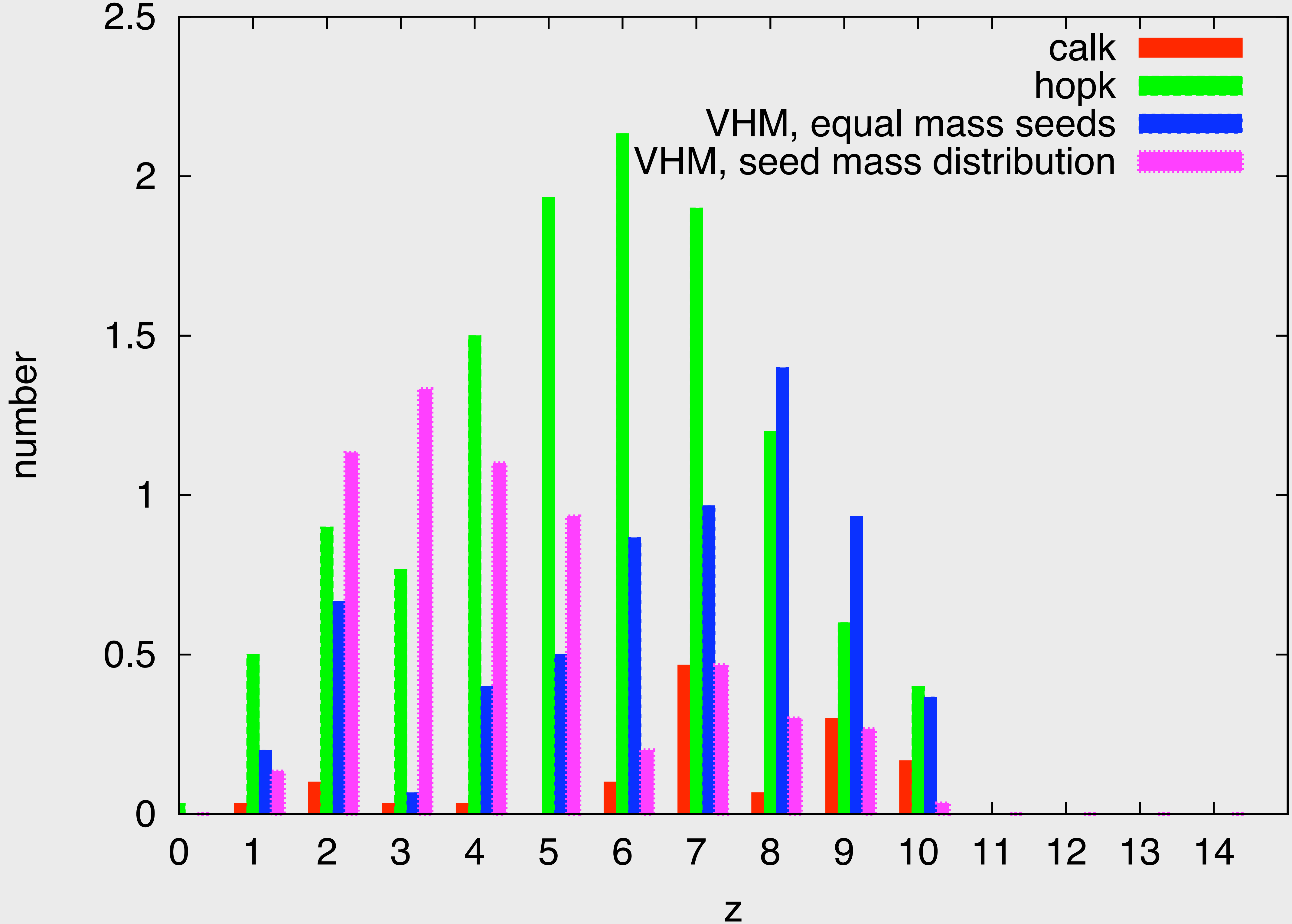
ET event rate



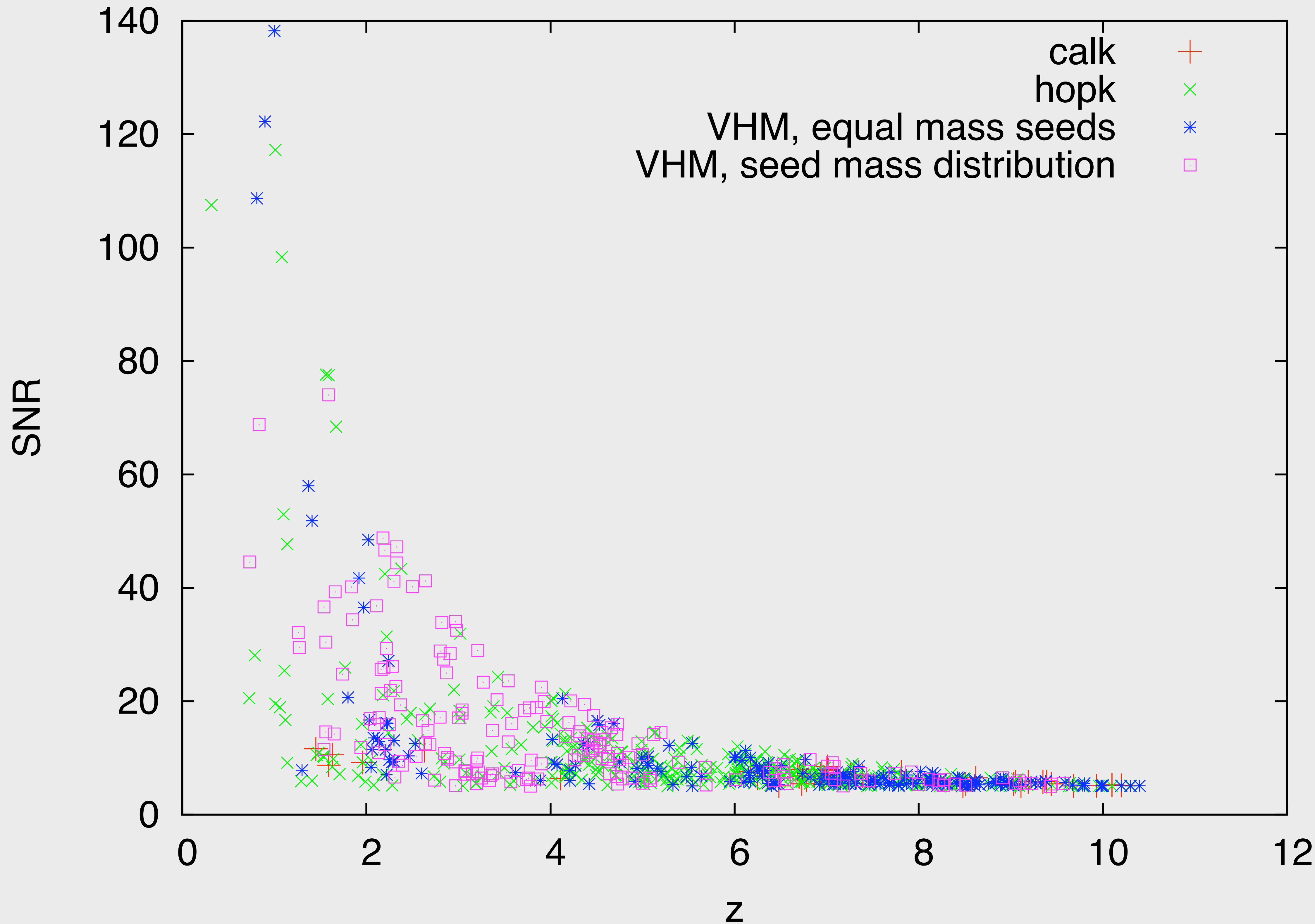
ET event mass distribution



ET event redshift distribution



ET SNRs vs redshift



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 detector exists, so the extrinsic parameters are not unknowns. Also consider two colocated detectors, with some extrinsic parameters known.

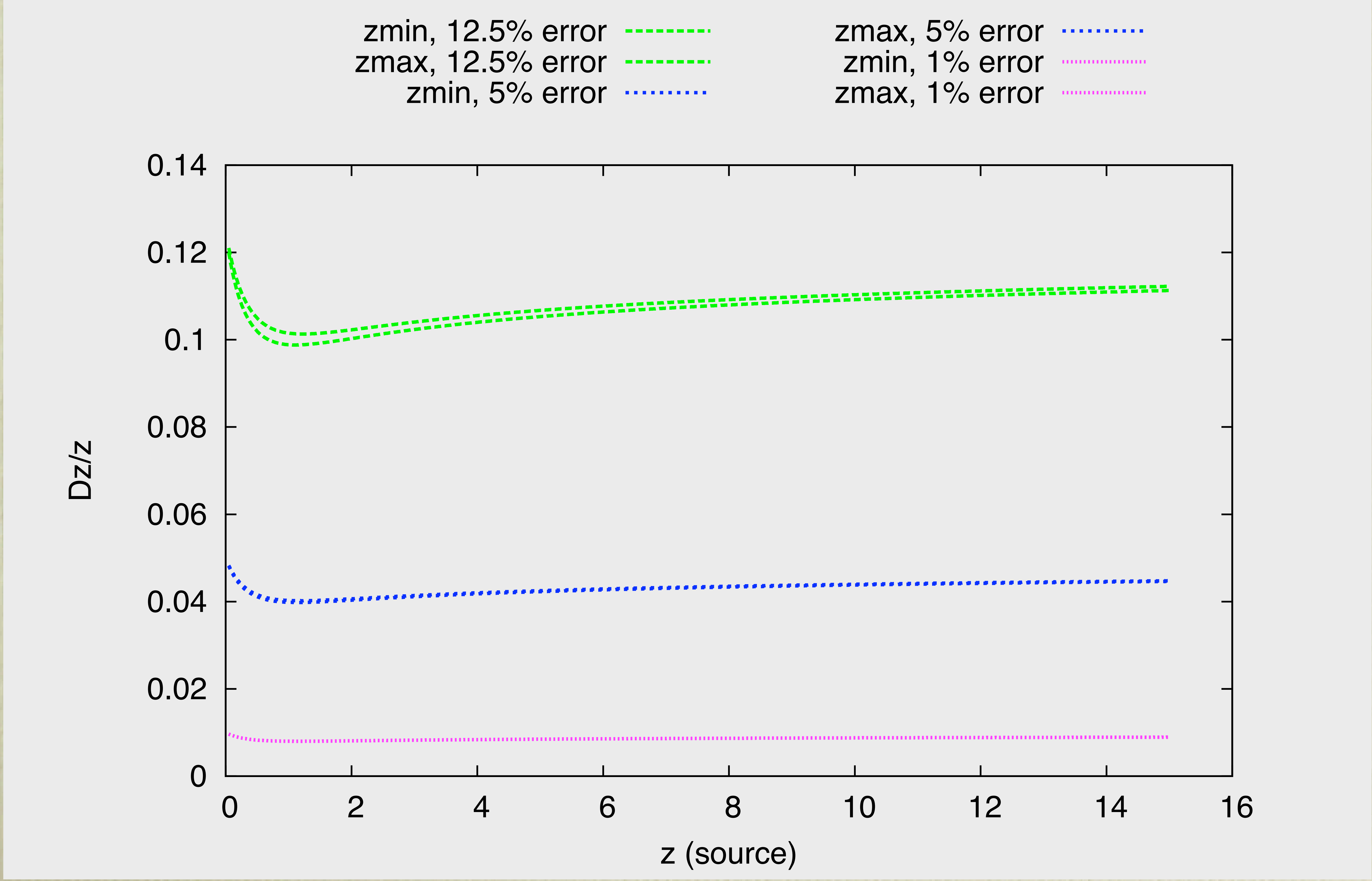
Optimistic Parameter Errors

- Assuming all extrinsic parameters are known, one detector returns good parameters and achieves theoretical limit in determination of distance -$\Delta(\ln D_L) \sim 1/(SNR)$.

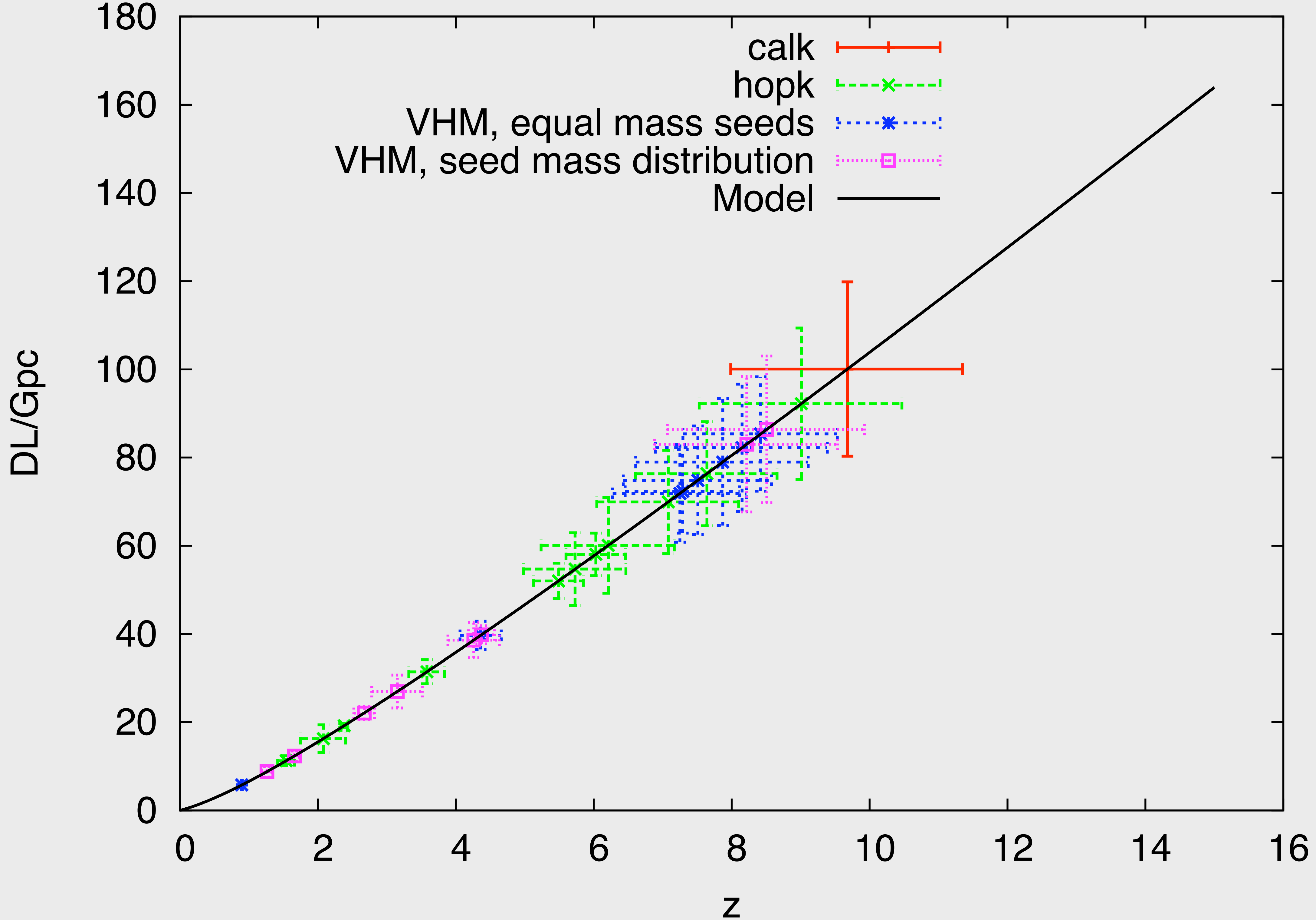
$(1+z)M_{\text{tot}}$	η	$\Delta(\ln M)$	$\Delta(\eta)/\eta$	$\Delta(\ln D_L)$
100	0.25	0.04%	0.003%	12.5%
100	0.2	0.03%	0.003%	12.5%
500	0.25	0.08%	0.006%	12.5%
500	0.2	0.055%	0.005%	12.5%
1000	0.25	0.09%	0.006%	12.5%
1000	0.2	0.06%	0.006%	12.5%

- First column is the redshifted mass, and all events have been renormalised to an SNR of 8.

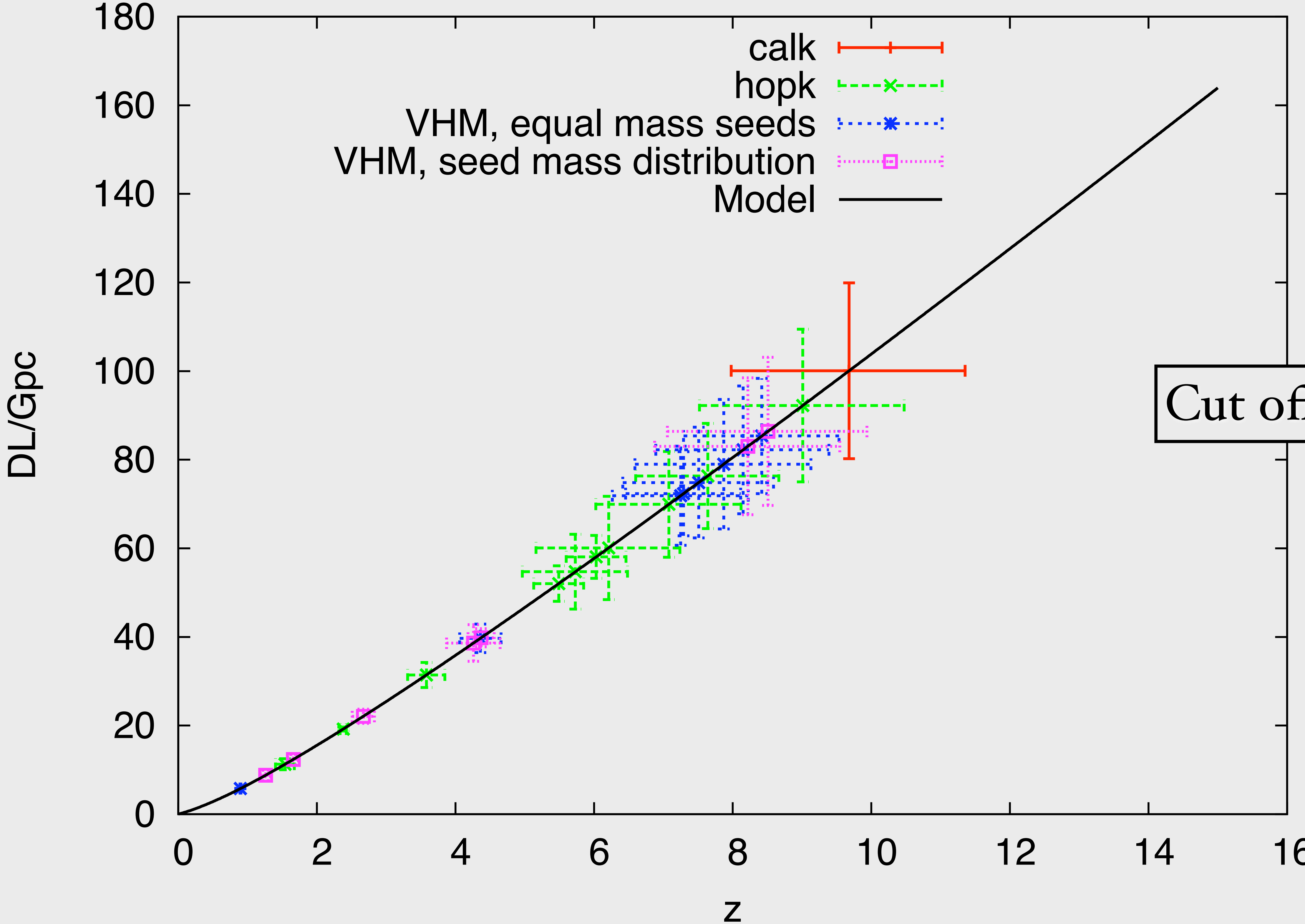
Distance error to redshift error



ET event error bars

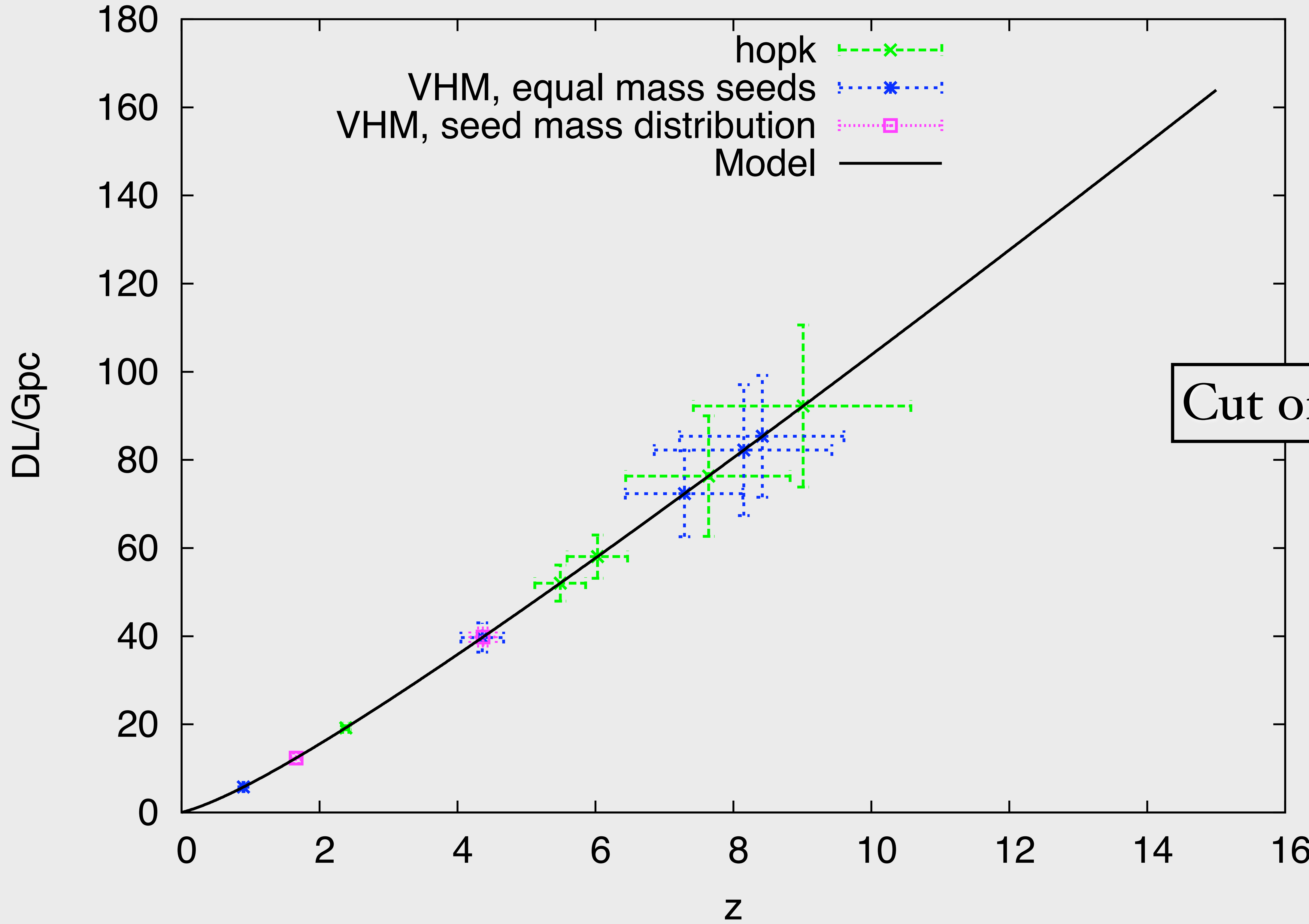


ET events - effect of low-f cutoff



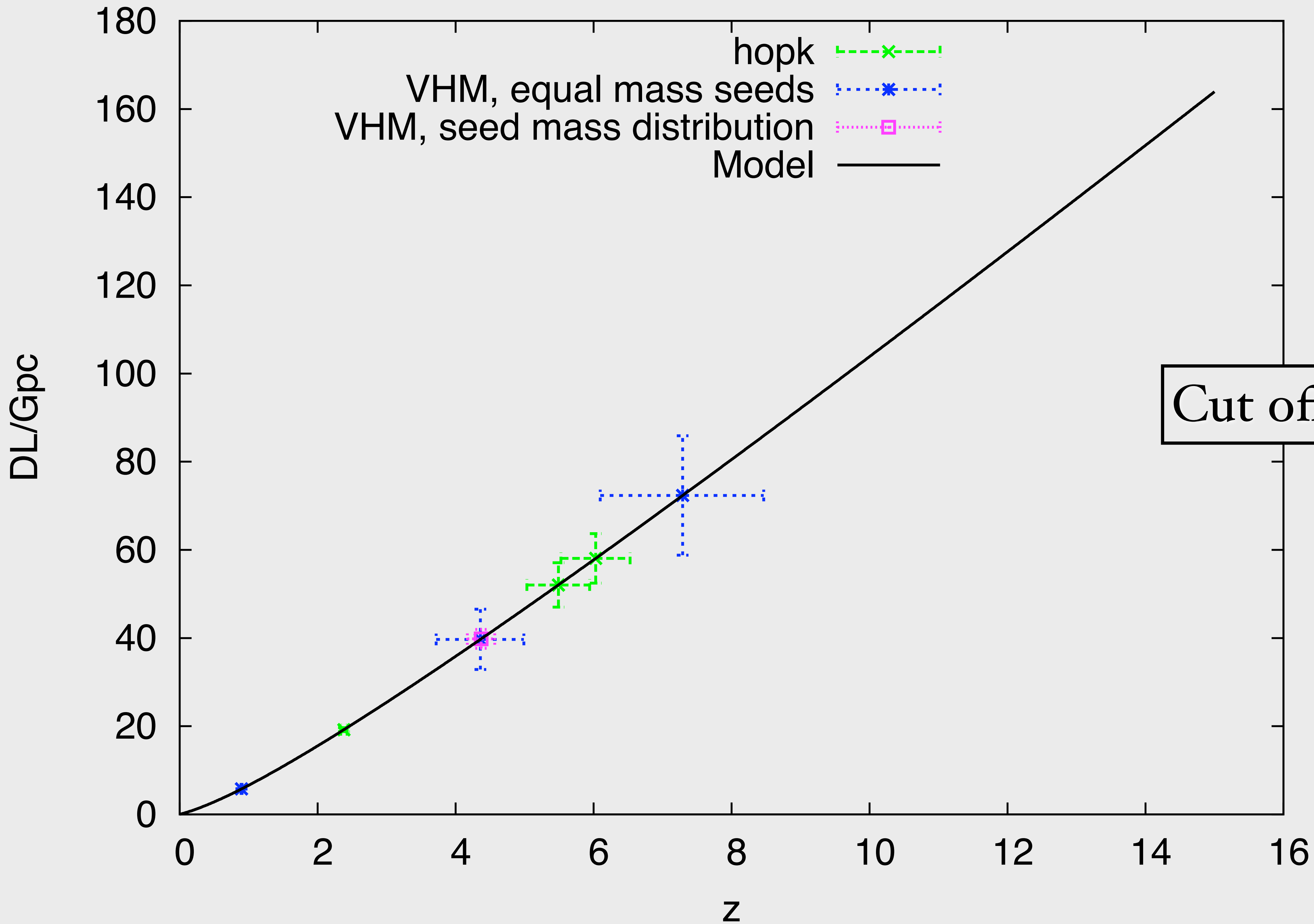
Cut off at 2Hz

ET events - effect of low-f cutoff



Cut off at 5Hz

ET events - effect of low-f cutoff



Cut off at 10Hz

True Parameter Errors

- With two colocated detectors, must still assume some of the extrinsic parameters are known.
- Assuming sky position or source orientation only and adding a second detector at 45 degrees to the first, we find the errors in total mass, mass ratio and distance degrade by a factor of 10 compared to one detector with known extrinsic parameters.
- Distance errors are comparable to redshift errors. Need to know redshift to 50% or better to identify source as population III.
- Science goal requires reasonable distance estimation. Only achievable with a second detector of comparable sensitivity operating in coincidence.

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

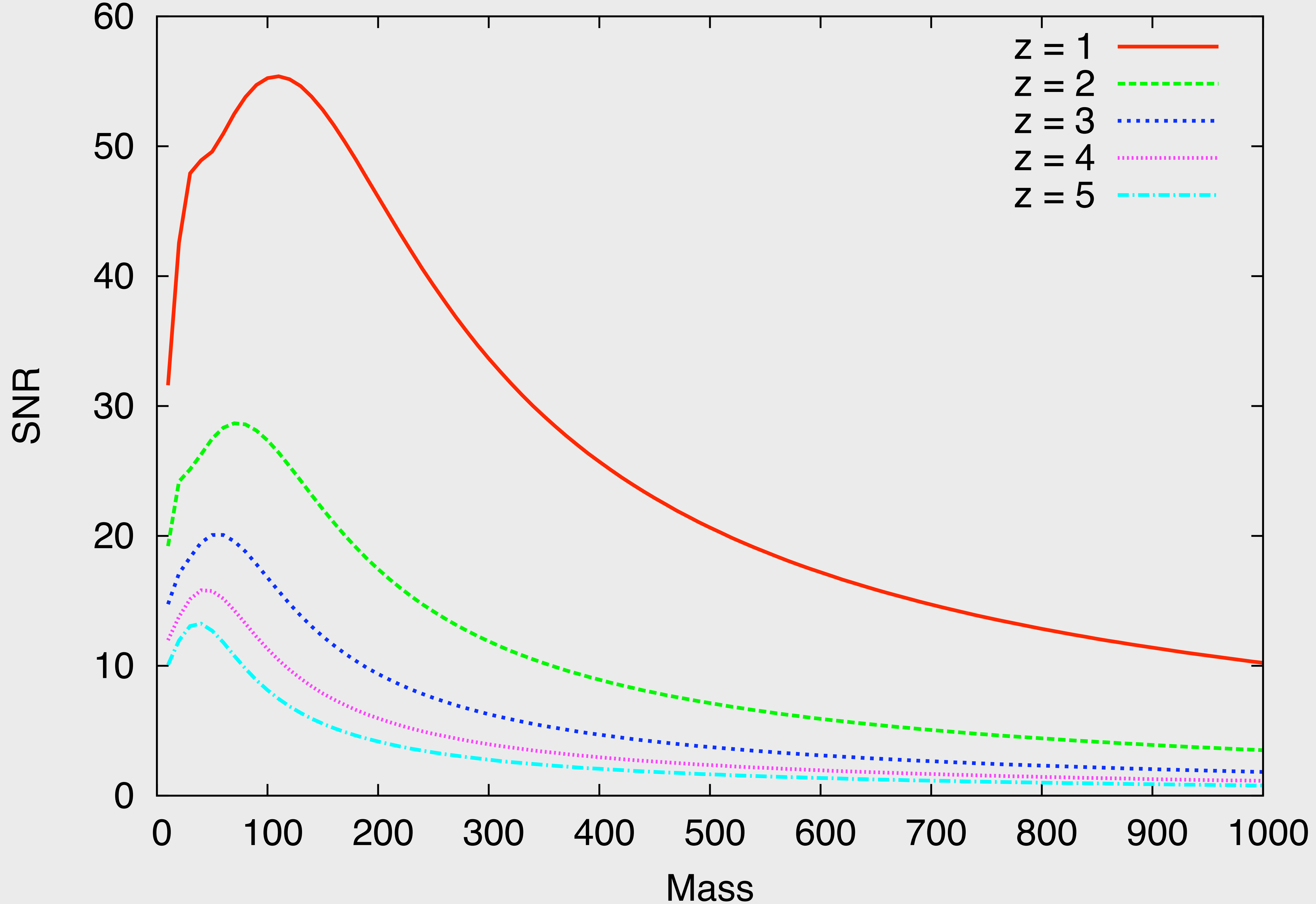
- Inspiral of stellar mass compact objects (neutron stars or black holes) into IMBHs. Analogue of EMRIs for LISA.

- 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)).

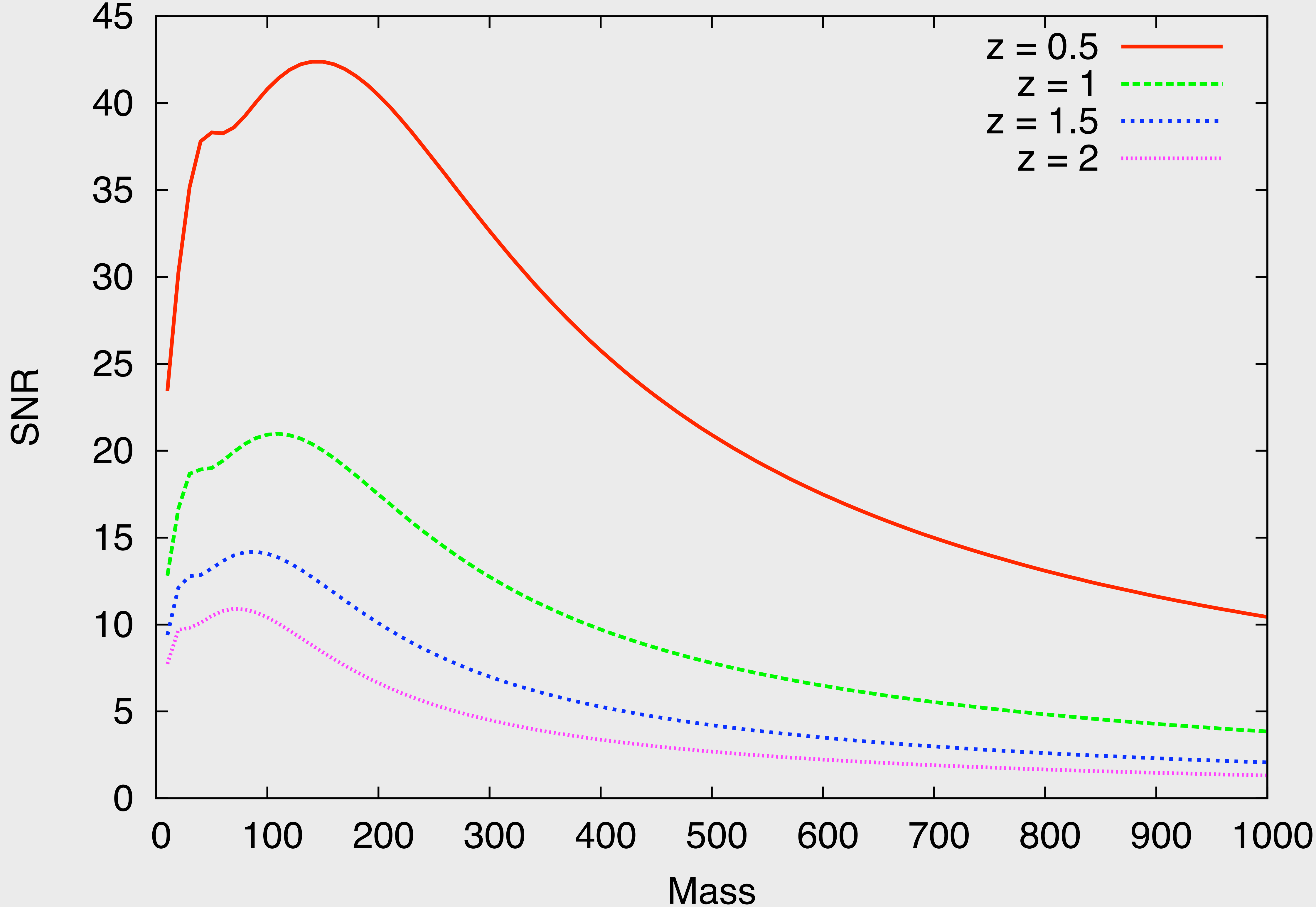
- ET will see these much further - probe of IMBH existence/growth, tests of no-hair theorem etc.

- In this case, may not need multiple detectors for parameter extraction, due to Earth rotation. A 1+100 IMRI takes ~8 hours to proceed from 1Hz to plunge (1+1000 IMRI takes ~2 hours). Higher harmonics also aid parameter extraction.

BH IMRI signal-to-noise ratio



NS IMRI signal-to-noise ratio



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.

- **But** distance estimation is only possible with another, non-colocated detector of comparable sensitivity operating concurrently.

- Intermediate mass ratio inspirals can be detected and analysed, probably without relying on another detector. The event rate is very uncertain but any detections would shed light on IMBH formation and growth in globular clusters.