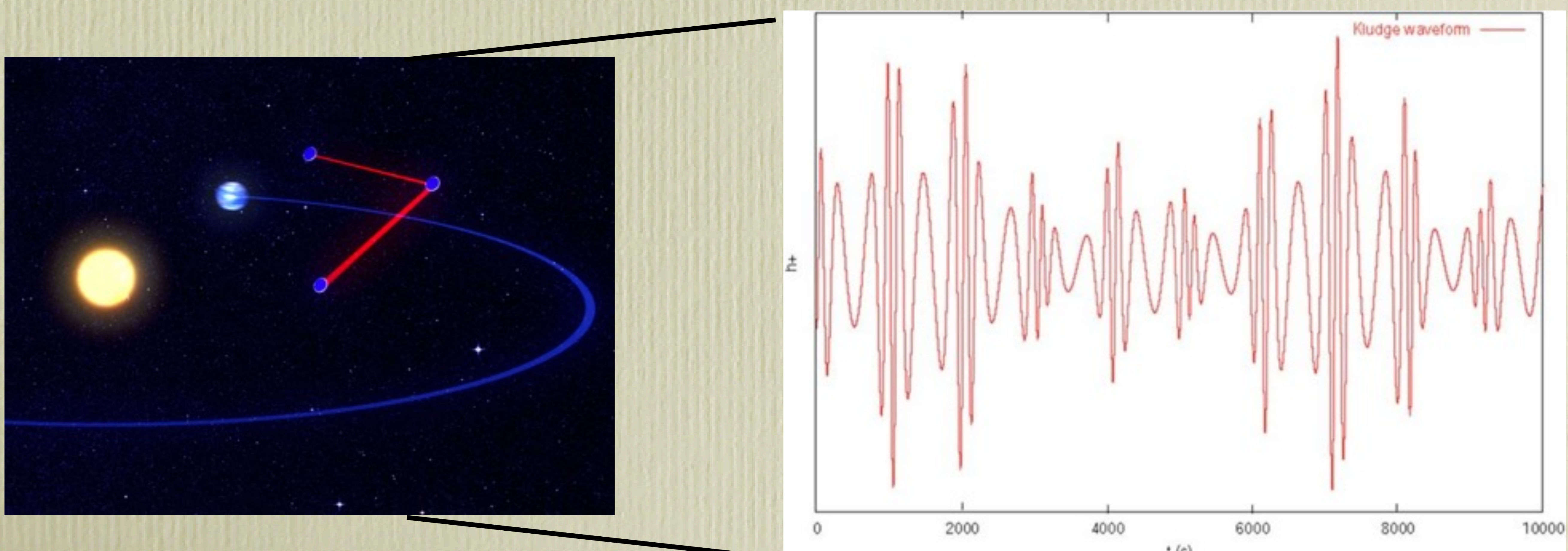
Impact of LISA design on EMRI science

Jonathan Gair (University of Edinburgh)
LISA Symposium, Zurich, September 2016



Acknowledgements

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  - Emanuele Berti
  - Christopher Berry
  - Alberto Sesana
  - Carlos Sopuerta

Talk outline

- Introduction to EMRIs
- EMRI event rates
- EMRI parameter estimation precision
- Impact of eLISA configuration on EMRI measurements
- EMRI science
  - astrophysics
  - fundamental physics
  - cosmology

Extreme-mass-ratio inspirals

- An extreme mass ratio inspiral (EMRI) is the inspiral of a compact object (a white dwarf, neutron star or black hole) into a SMBH. Not main sequence stars, as these will be tidally disrupted before gravitational radiation becomes significant.
- Originate in dense stellar clusters through direct capture, binary splitting, tidal stripping of giant stars or star formation in a disc.
- For black holes with mass in the range $10^4 M_\odot \lesssim M \lesssim 10^7 M_\odot$, EMRIs will generate gravitational waves detectable by eLISA.
- In "standard" picture, EMRIs begin when an object is captured by the central black hole on a very eccentric orbit. Expect EMRI orbits to be both eccentric and inclined in eLISA band.
- Complex gravitational waveforms include three fundamental frequencies - orbital frequency, perihelion precession frequency and orbital plane precession frequency.

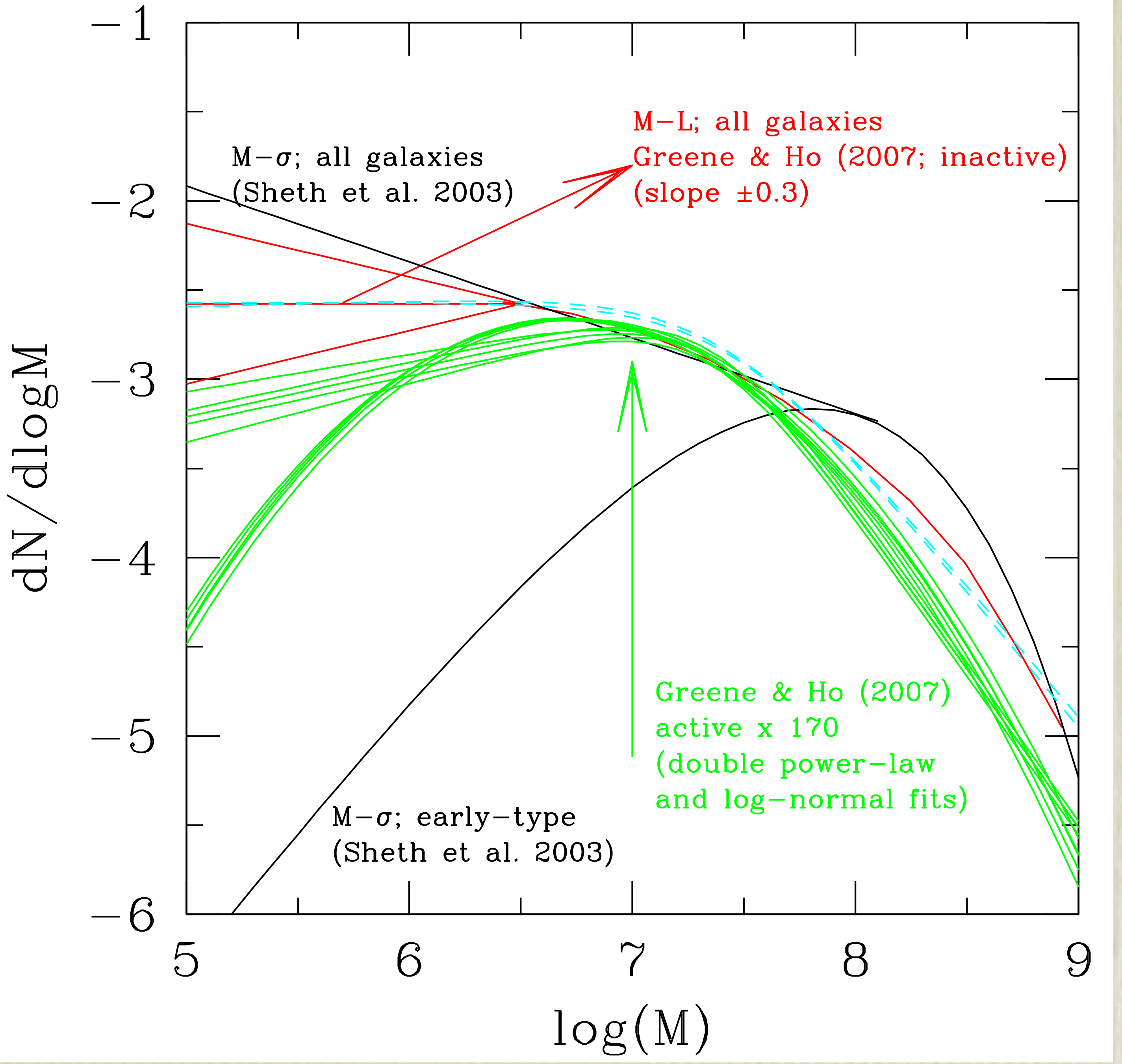
EMRIs - Event Rates

- To estimate EMRI event rates need several ingredients

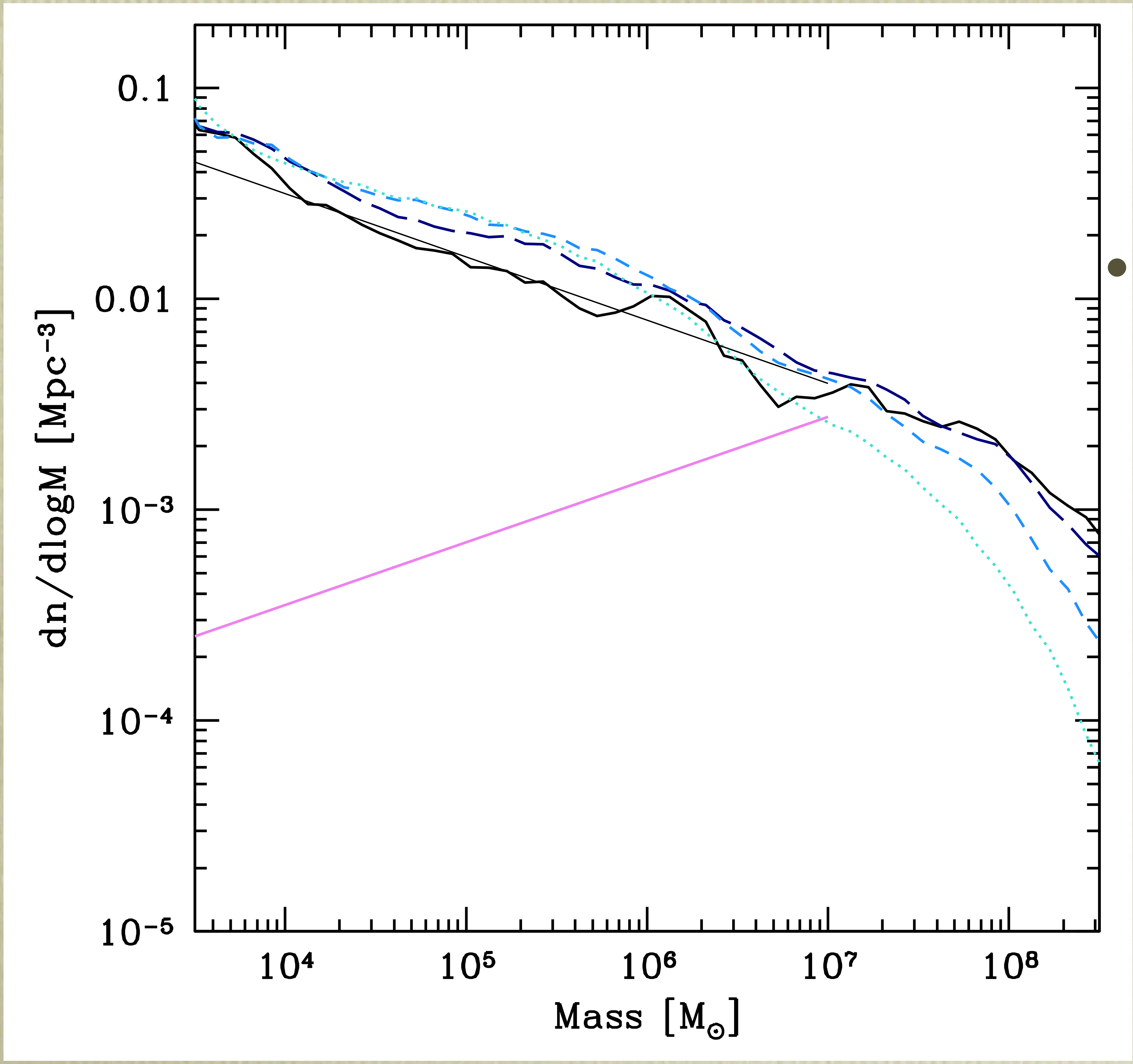
- **Mass function of black holes**: for $10^4 M_\odot \lesssim M \lesssim 10^7 M_\odot$ the BH mass function is not well constrained observationally.
- Traditionally have assumed a flat distribution

$$\frac{\mathrm{d}N}{\mathrm{d}\ln M} = 0.002\,\mathrm{Mpc}^{-3}$$

- Uncertainty in slope +/-0.3. Models for MBH mergers favour slopes close to -0.3.



EMRIs - Event Rates



- Consider two cases
  - a numerically simulated population, evolved consistently from pop III seeds: slope ~ -0.3
  - a pessimistic analytic model: slope = 0.3

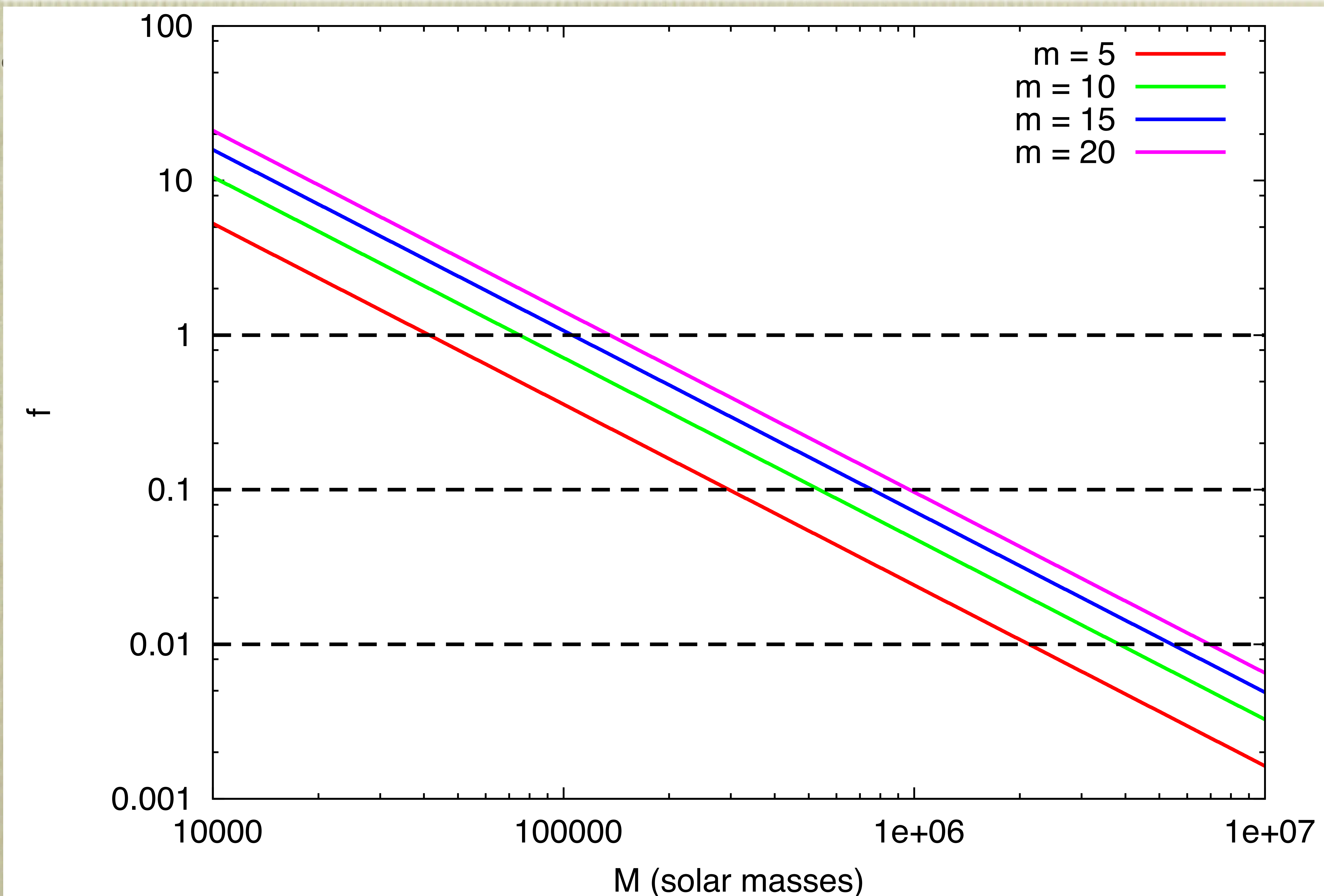
EMRIs - Event Rates

- To estimate EMRI event rates need several ingredients
  - **EMRI rate per galaxy** numerical simulations suggest rate of black hole mergers (Hopman 2009, Amaro-Seoane & Preto 2011)

$$\rho = 400\text{Gyr}^{-1}\left(\frac{M}{3\times 10^6 M_\odot}\right)^{-0.19}$$

  - **But** cannot have such a high rate over whole cosmic history for light massive black holes to avoid overgrowth. Assume maximum of one e-fold of mass from EMRI accretion.

EMRIs - Event Rates



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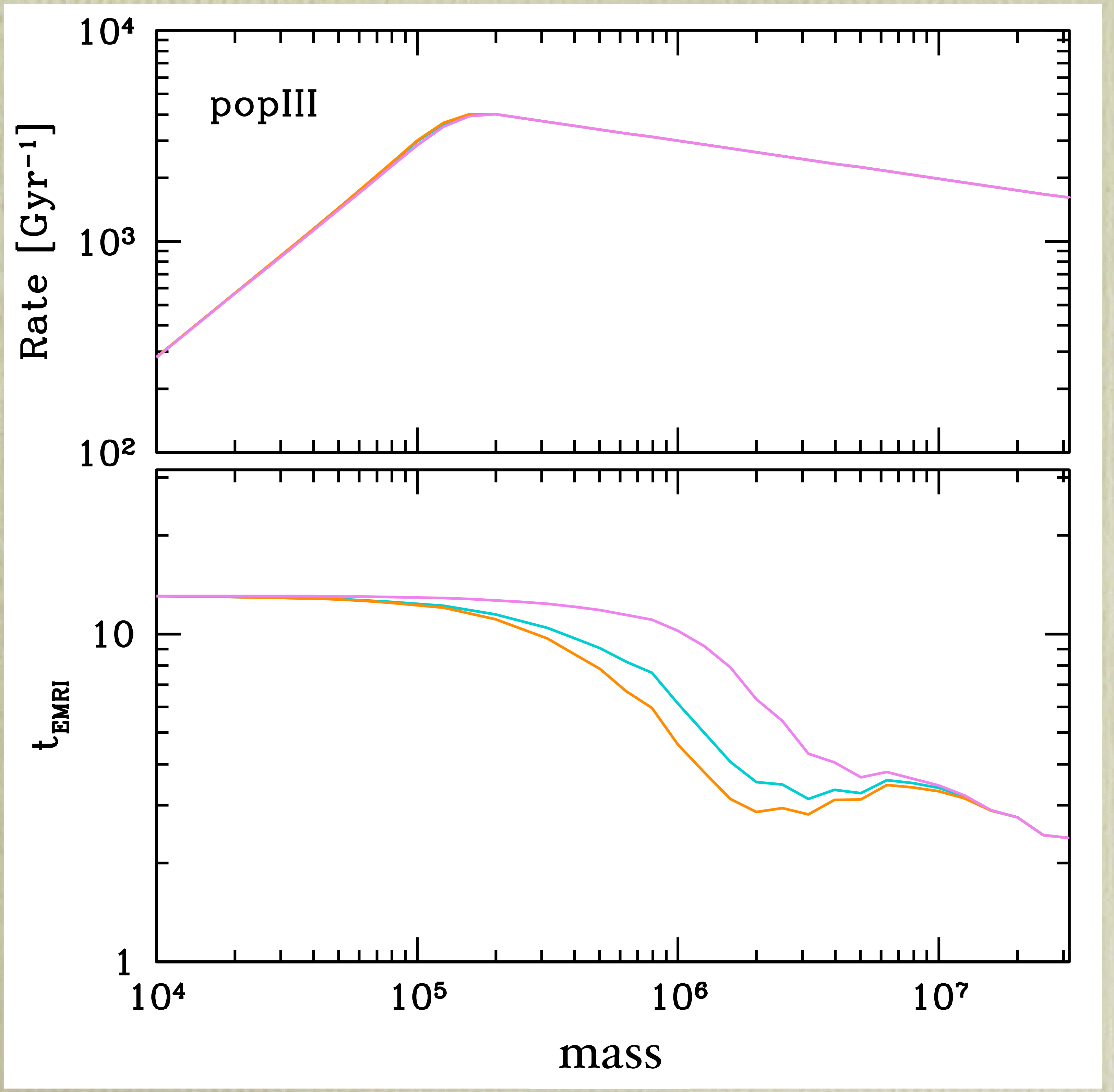
  - **But** cannot have such a high rate over whole cosmic history for light massive black holes to avoid overgrowth. Assume maximum of one e-fold of mass from EMRI accretion.
  - Host galaxy mergers also disrupt stellar cusps - massive black hole is not available as EMRI host until cusp has regrown.
  - Black hole spin/inclination influence capture cross-section - enhanced rate for spinning black holes and prograde EMRIs (Amaro-Seoane et al. 2013).

EMRIs - Event Rates



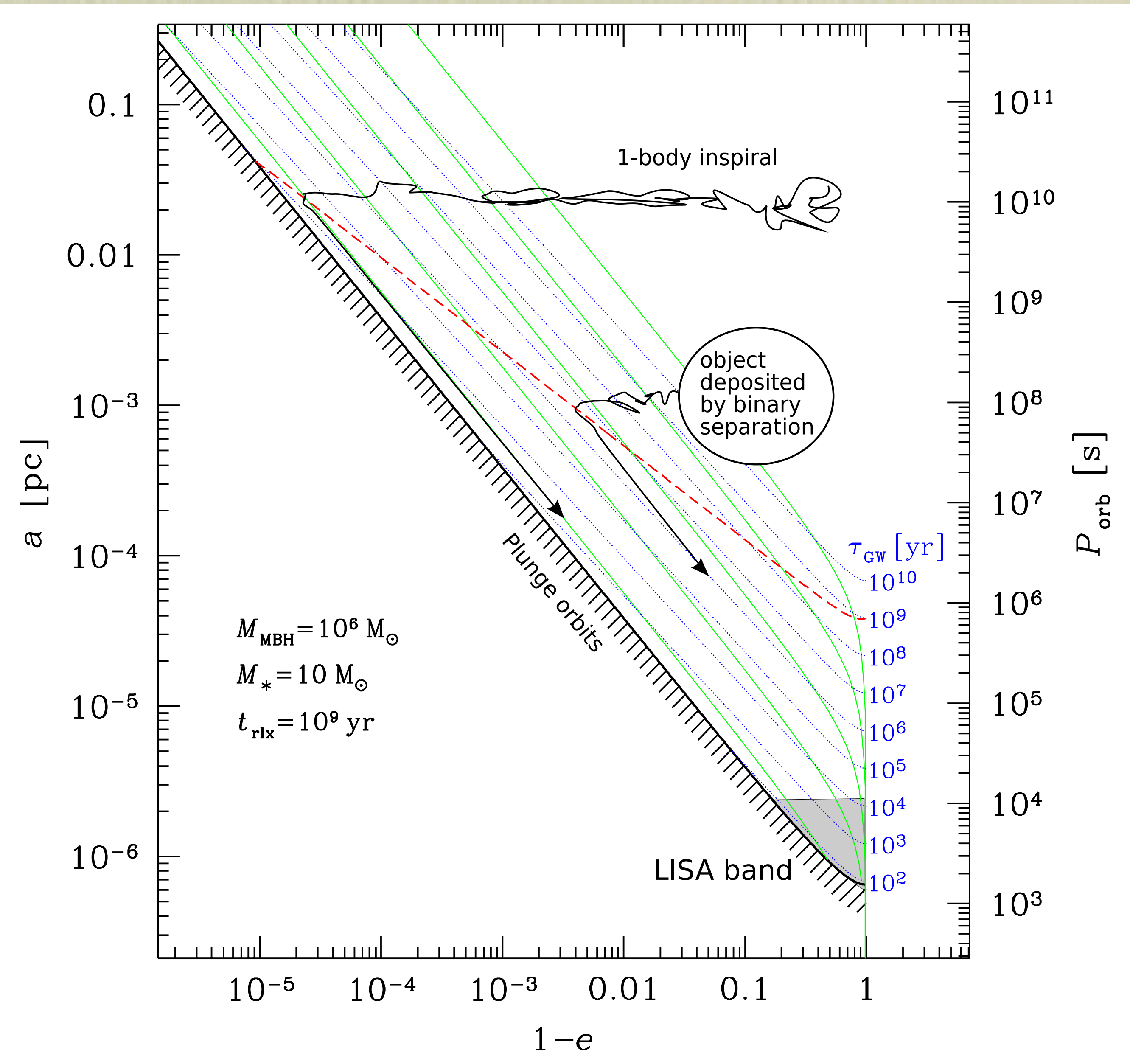
- Consider three scenarios for cusp regrowth
  - fiducial, t ~ 6 Gyr
  - optimistic, t ~ 2 Gyr
  - pessimistic, t ~ 10 Gyr
- Here t is the cusp regrowth time for a $10^6 M_\odot$ black hole following an equal-mass merger.

$$t_{\rm cusp} \approx 6 M_6^{1.19} q^{0.35} {\rm Gyr}$$

EMRIs - Event Rates

- To estimate EMRI event rates need several ingredients

- **Compact object properties**
  - **Mass**: consider only black holes. Assume $m = 10M_\odot$ (usual assumption) or, given GW150914, $m = 30M_\odot$.
  - **Eccentricity distribution:** assume capture through diffusion. Eccentricities mostly moderate at plunge.
  - **Inclination distribution**: random at capture, but prograde EMRIs preferentially inspiral.

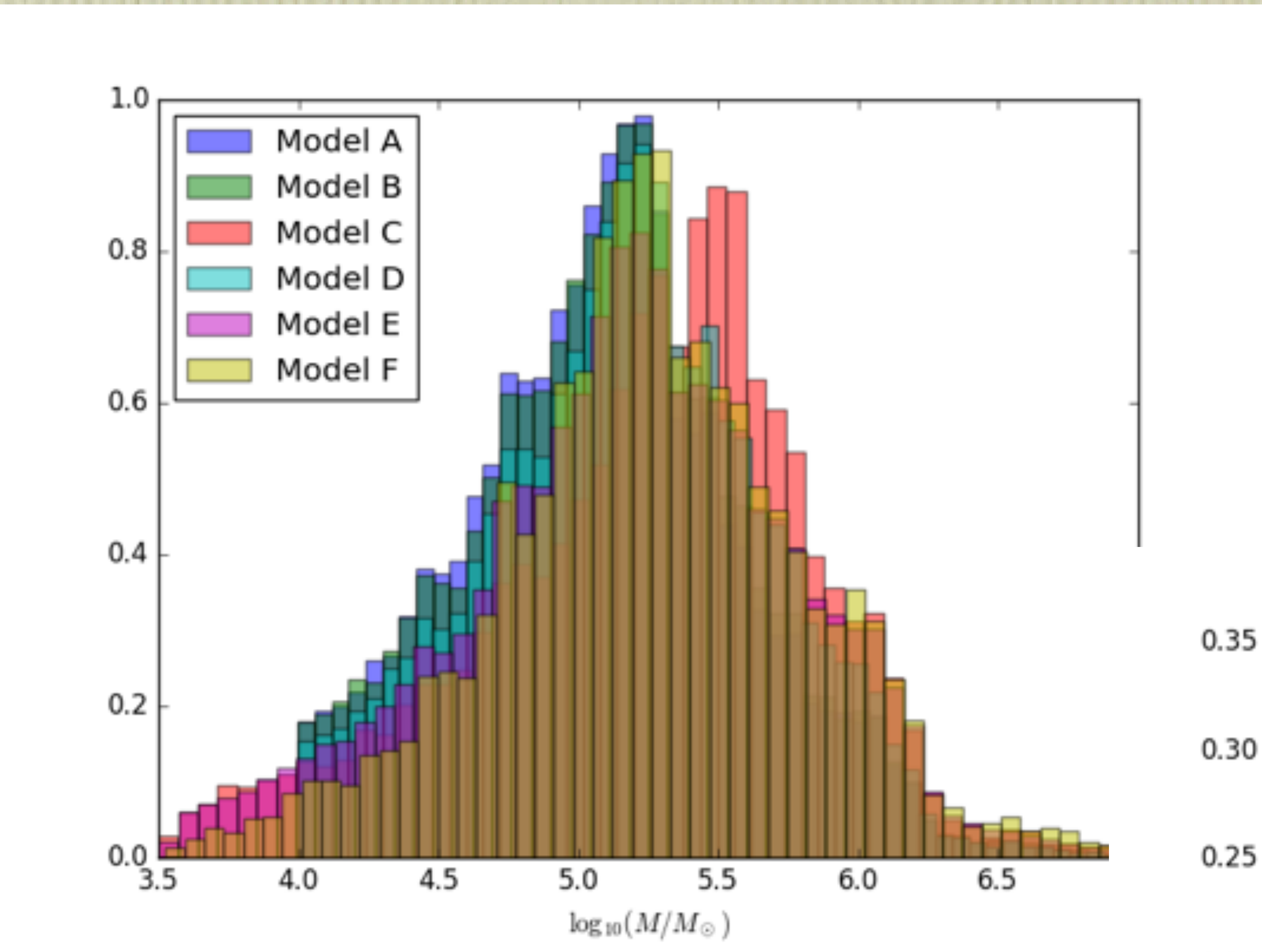


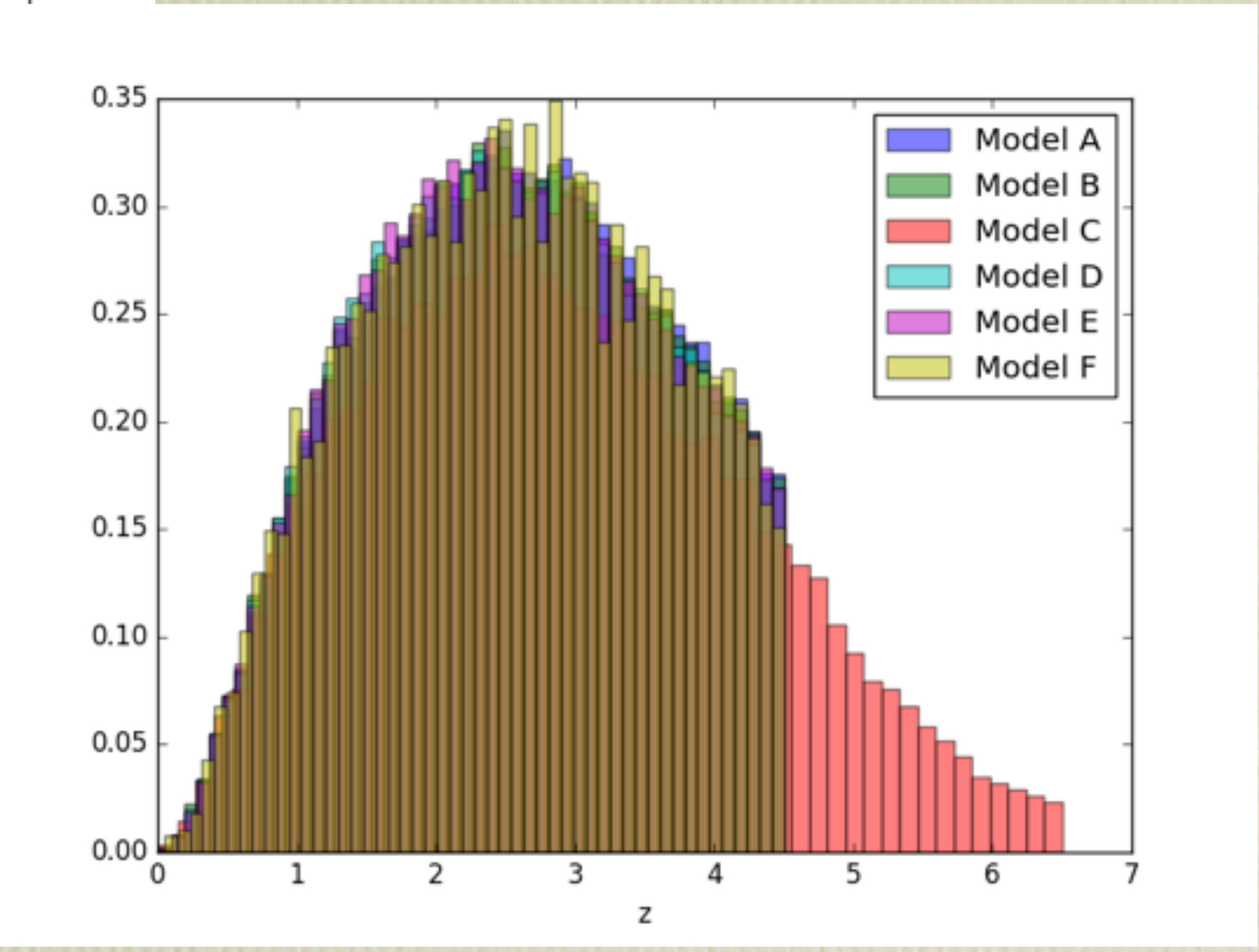
Amaro-Seoane et al. (2007)

Model summary

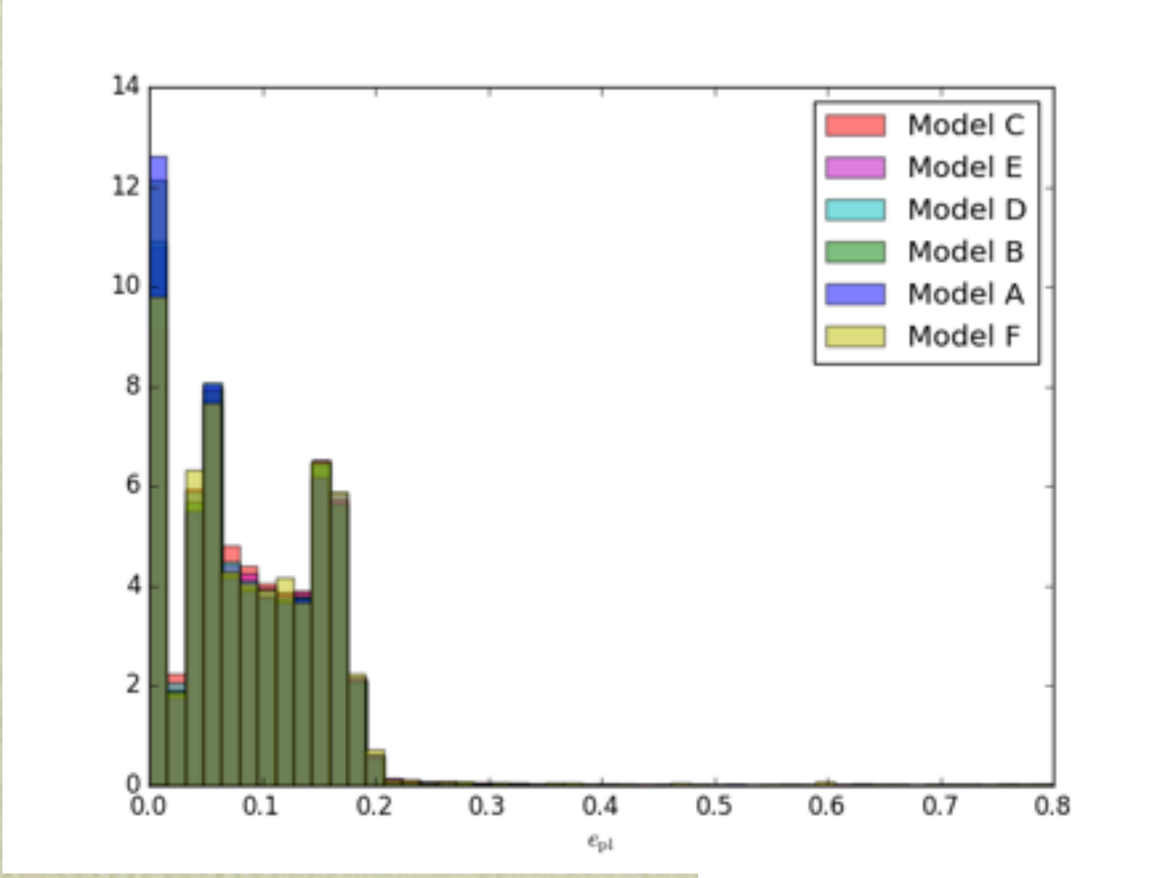
- Summary of models
  - **Model A**: consistent popIII MBH population, pessimistic cusp re-growth (10 Gyr), $m = 10M_{\odot}$.
  - **Model B**: consistent popIII MBH population, reference cusp re-growth (6 Gyr), $m = 10M_{\odot}$.
  - **Model C**: consistent popIII MBH population, reference cusp re-growth (6 Gyr), $m = 30M_{\odot}$.
  - **Model D**: consistent popIII MBH population, optimistic cusp re-growth (2 Gyr), $m = 10M_{\odot}$.
  - **Model E**: consistent popIII MBH population, no cusp destruction, $m = 10M_{\odot}$.
  - **Model F**: conservative MBH population, no cusp destruction, $m = 10M_{\odot}$.

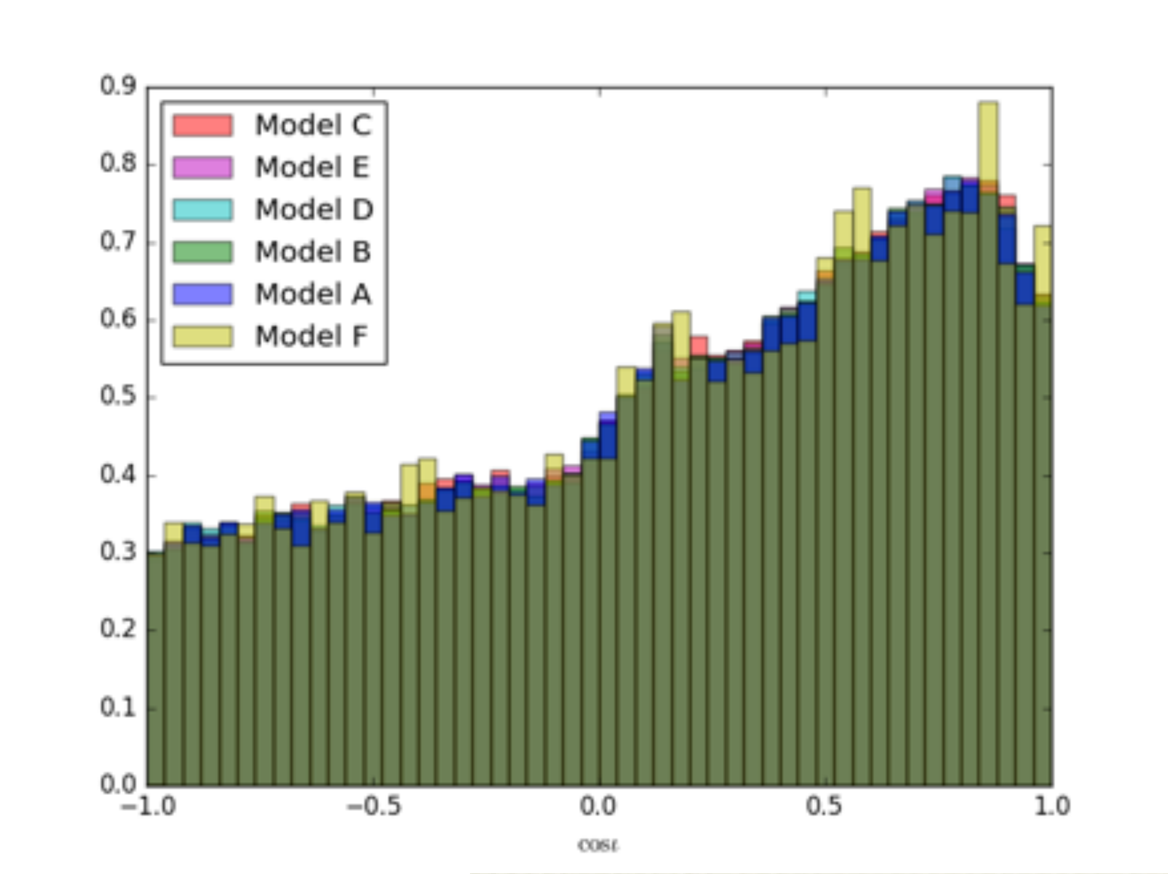
Intrinsic Population

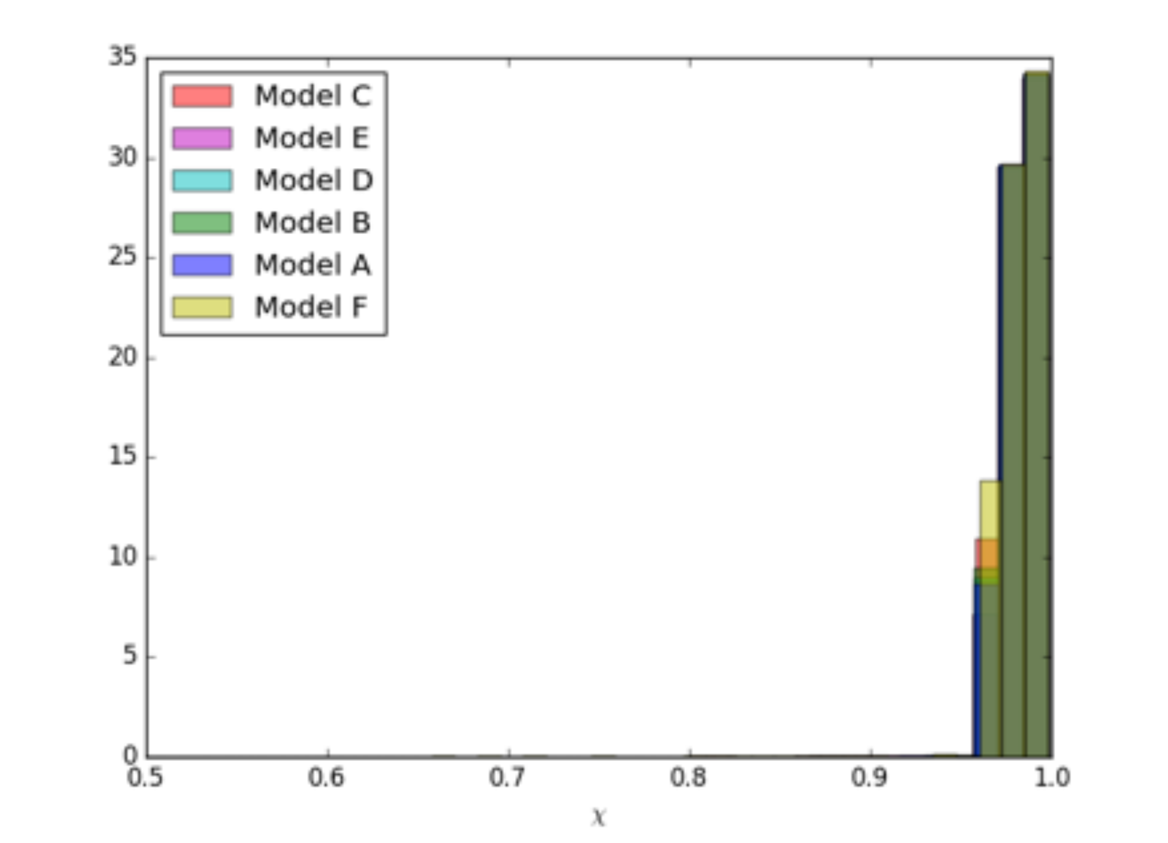




Intrinsic Population

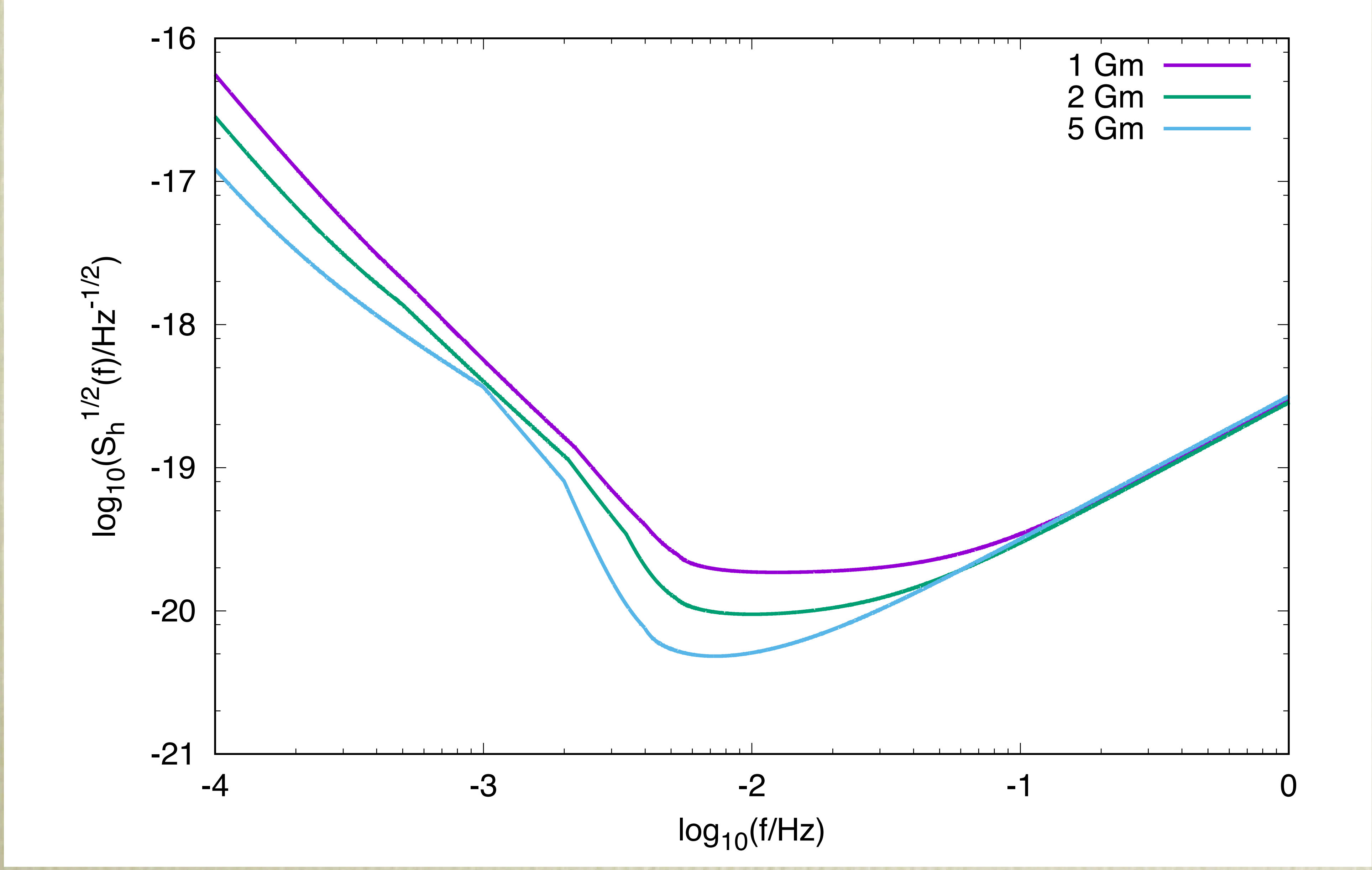






EMRIs - Event Rates

- Final ingredient is detectability criterion. Assume need SNR > 20 for detection. Compute SNR using analytic kludge waveform model (Barack & Cutler 2004).
- Consider three different LISA configurations.

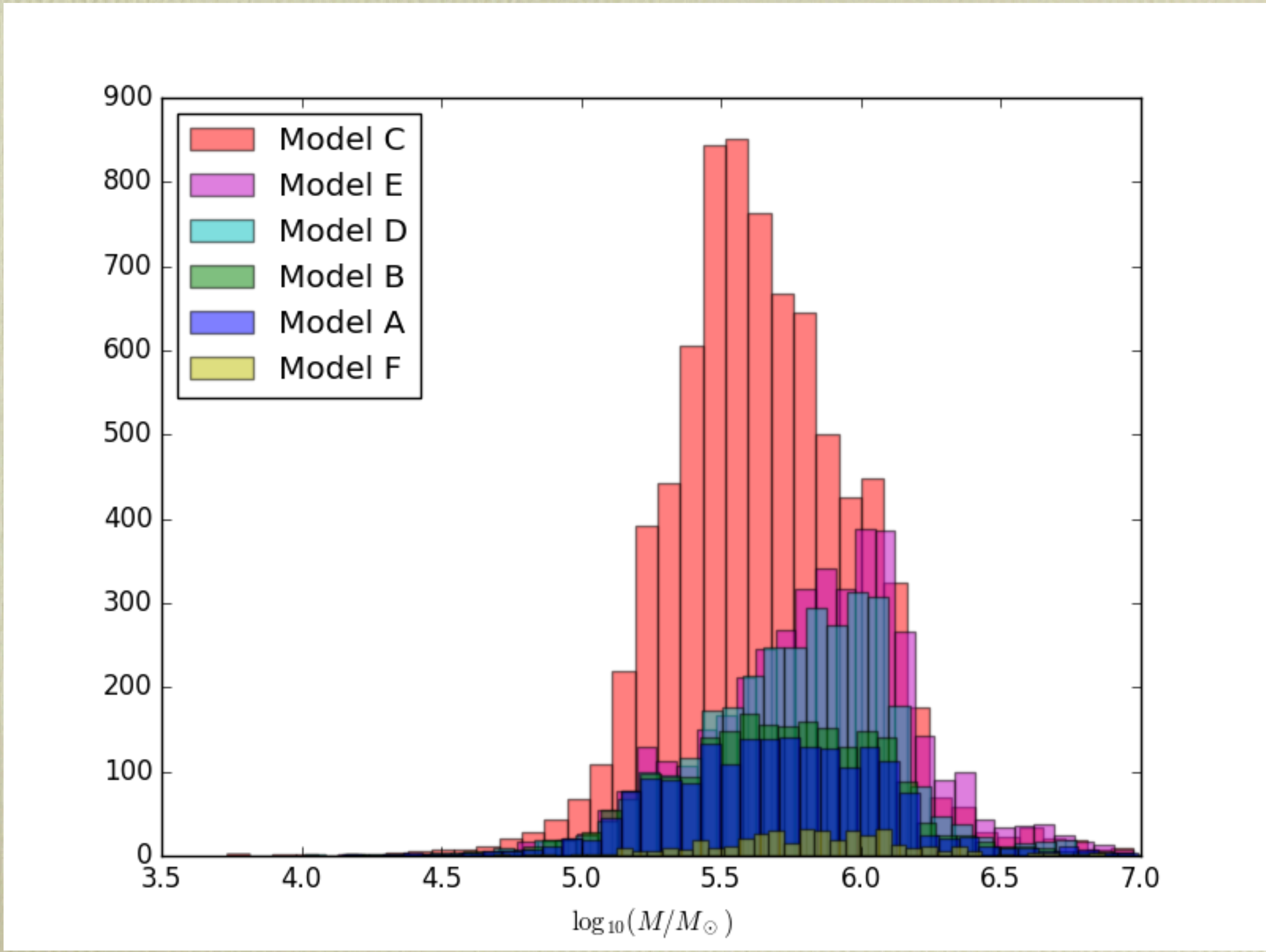


EMRIs - Event Rates

- 1 Gm, 4-link configuration could see O(1) to O(1000) events, depending on model and uncertain astrophysical rate. Uncertainty from model is a factor of ~20. Remaining factor ~50 from rate.
- Gain relative to 1 Gm, 4-link configuration shown in Table below.

	1 Gm		2 Gm		5 Gm	
	4-link	6-link	4-link	6-link	4-link	6-link
Model A	1	2.6	6.2	14	28	44
Model B	1	2.7	6.1	14	26	41
Model C	1	2.1	3.5	5.2	7.0	8.4
Model D	1	2.5	5.4	11	21	32
Model E	1	2.5	5.3	11	19	28
Model F	1	2.6	5.6	12	21	31

Observed Population - 1 Gm



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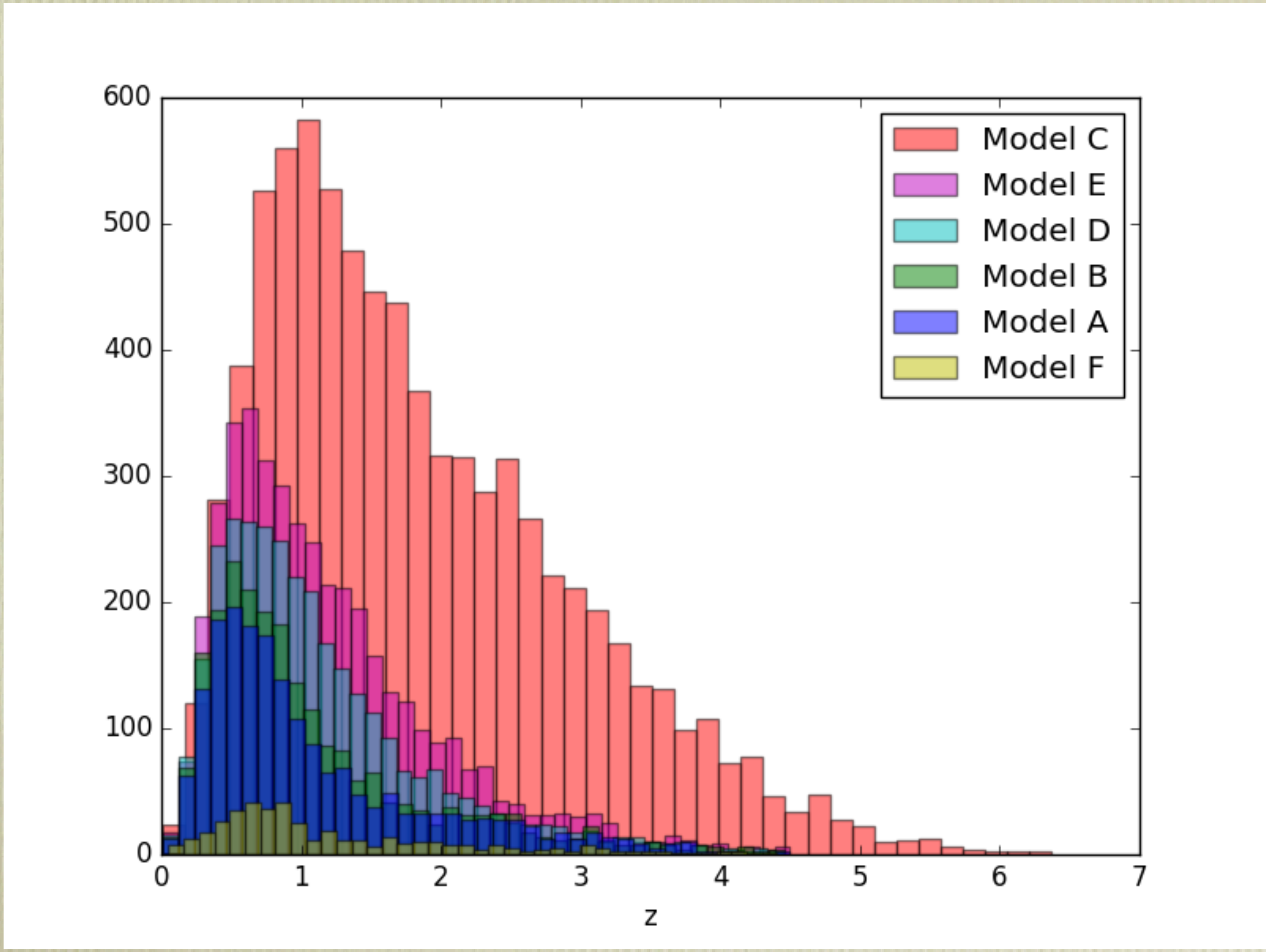

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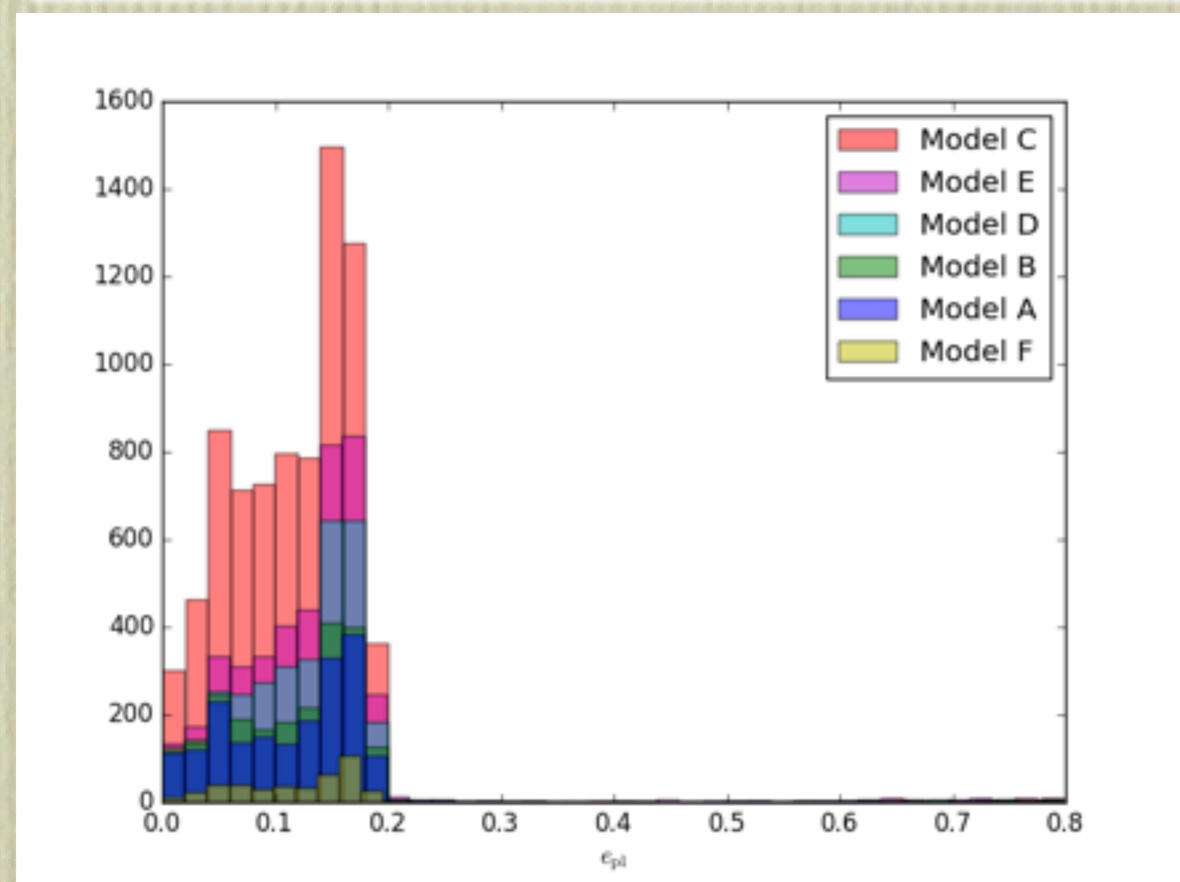
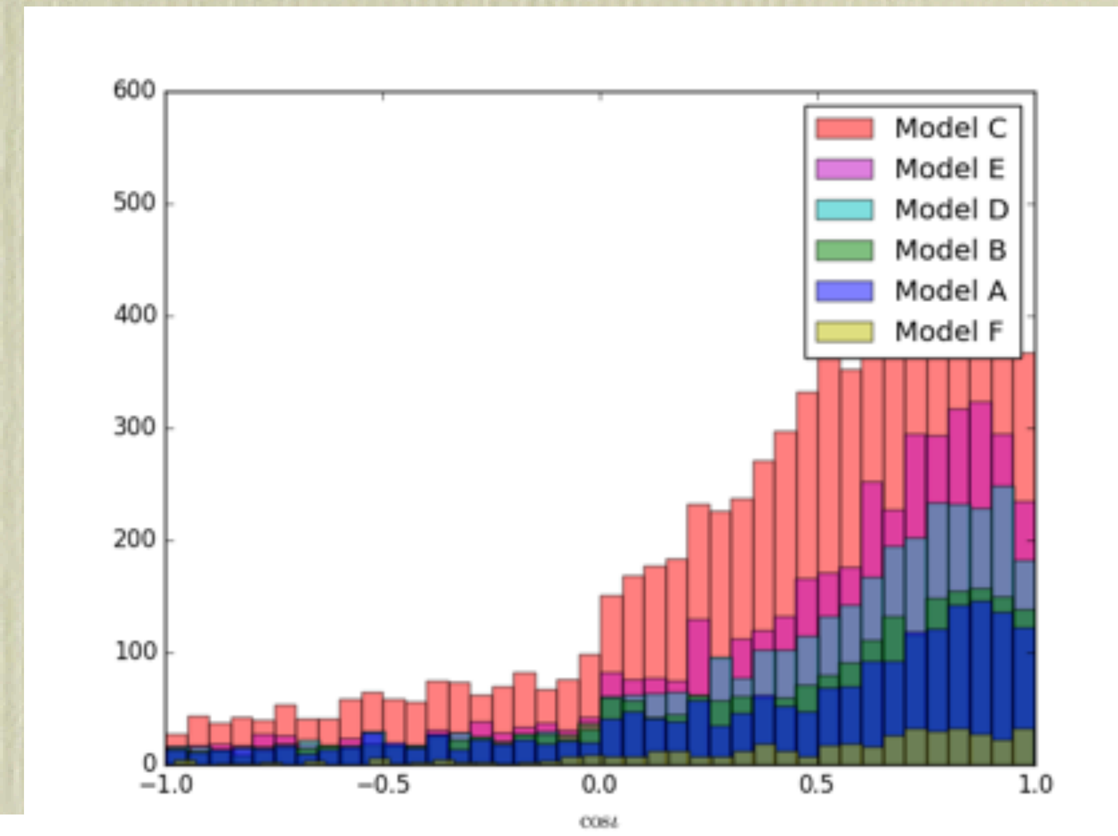
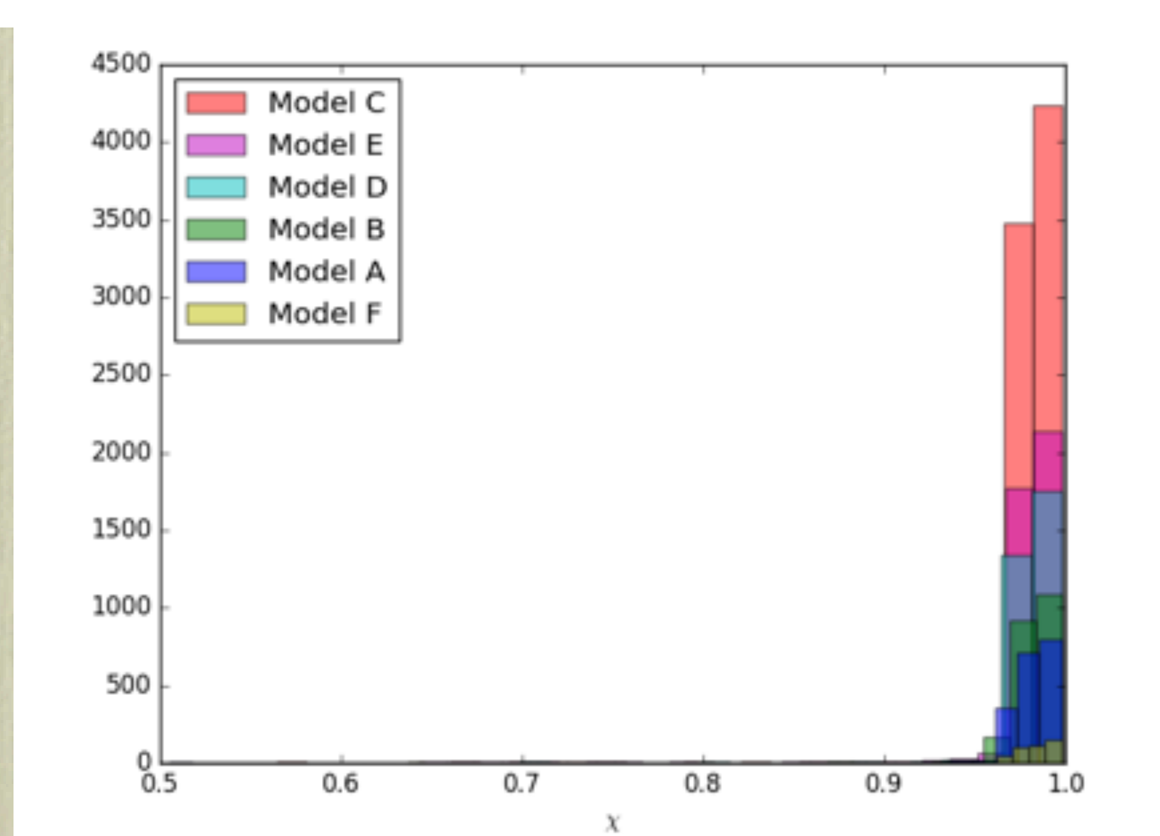
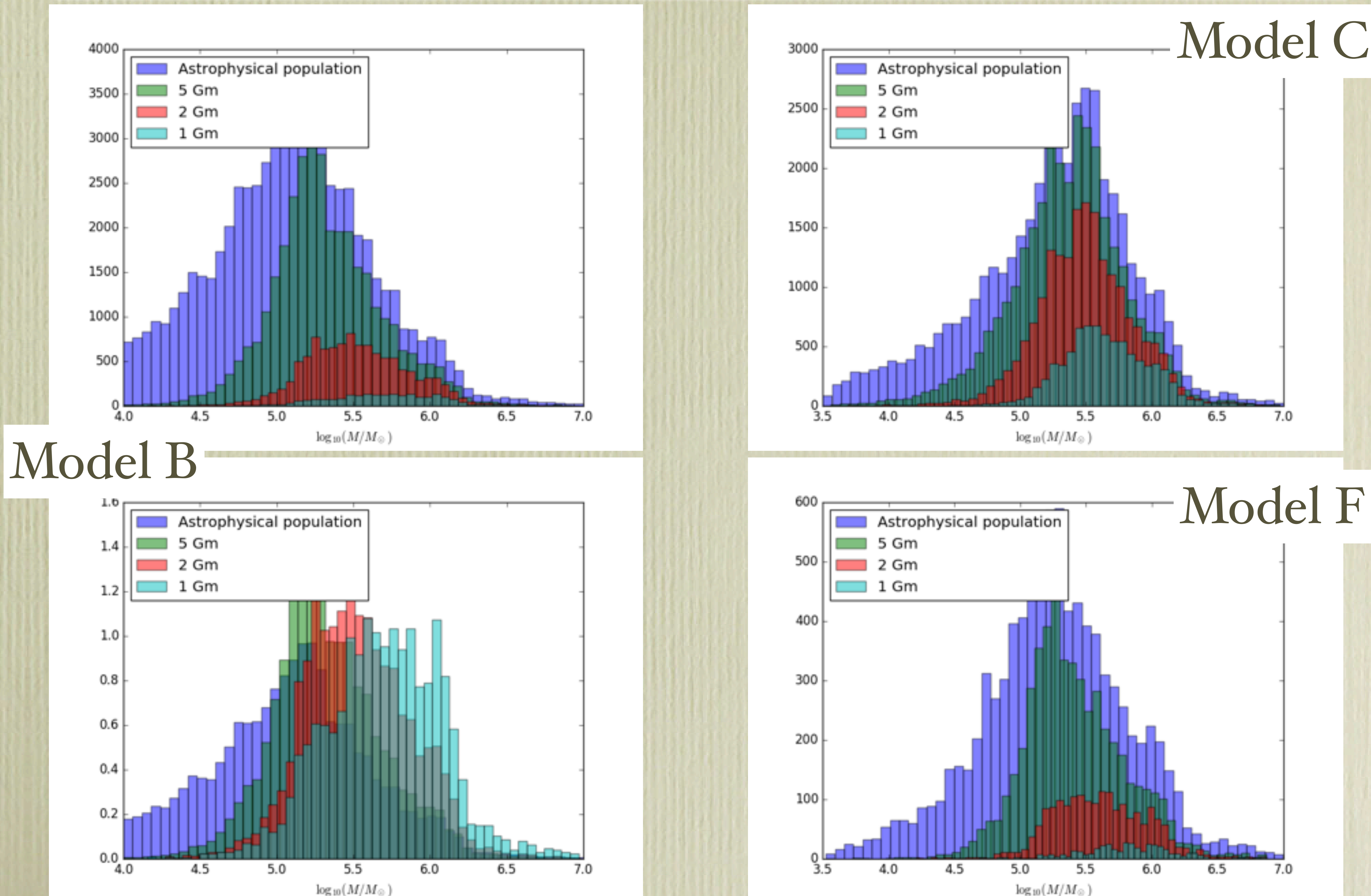


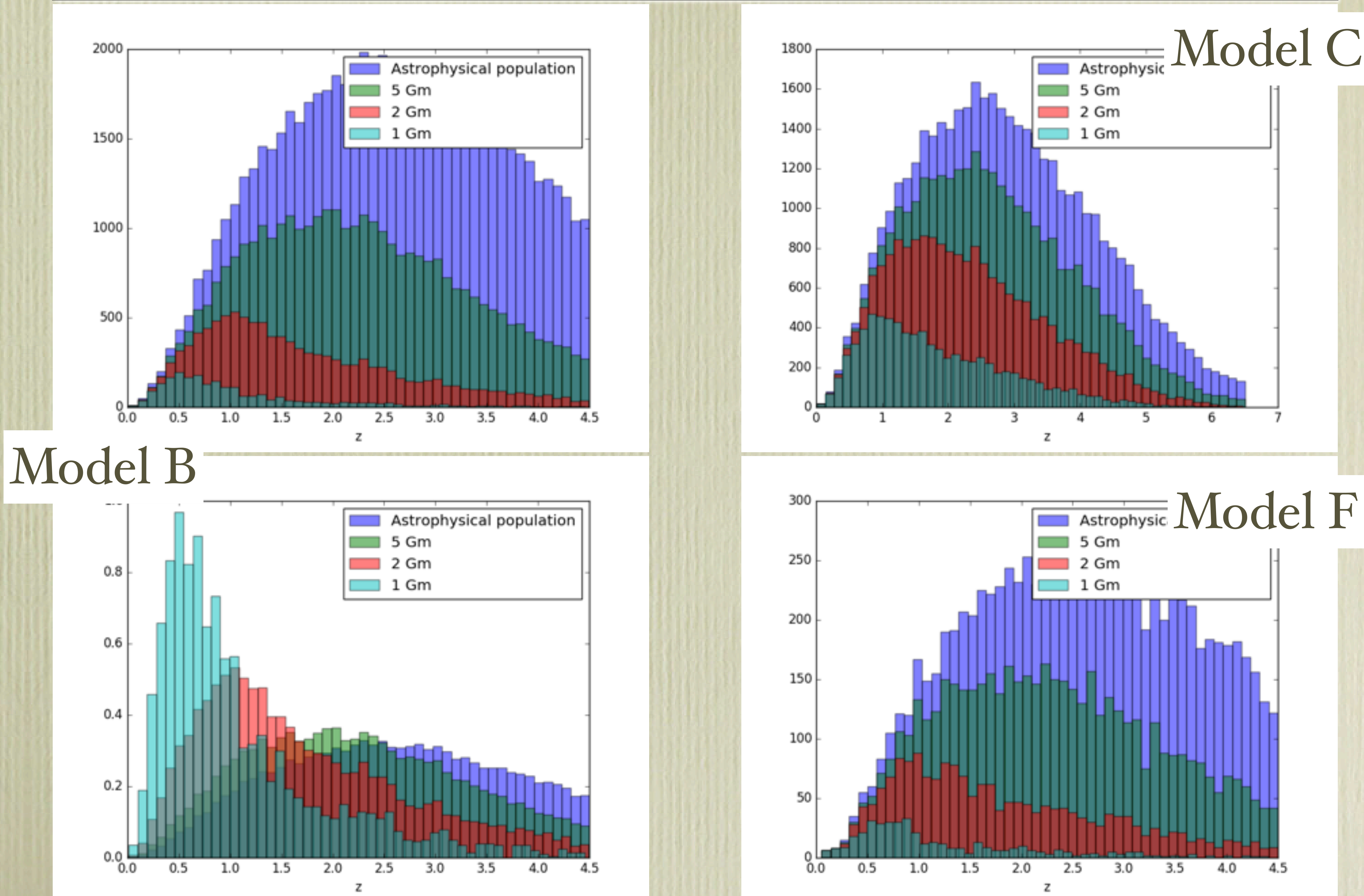




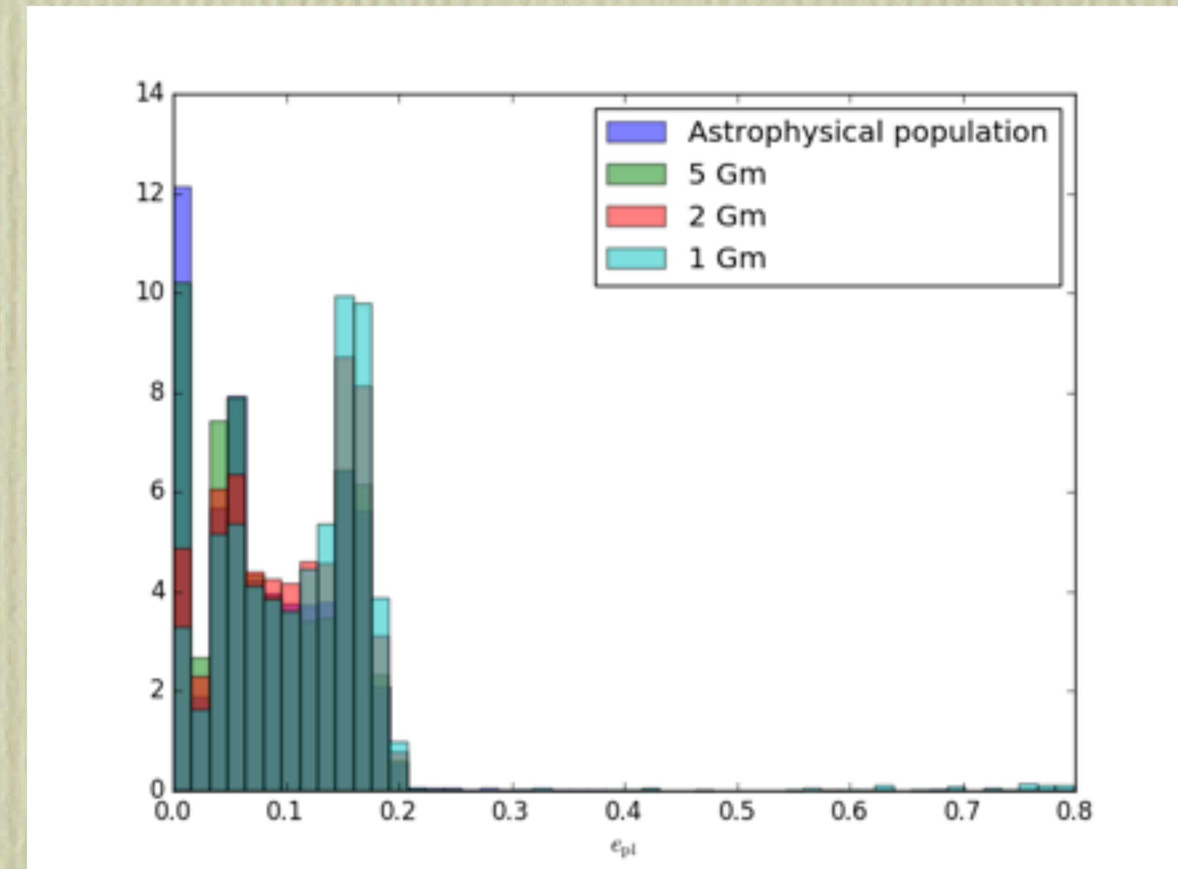
Observed Population - MBH mass

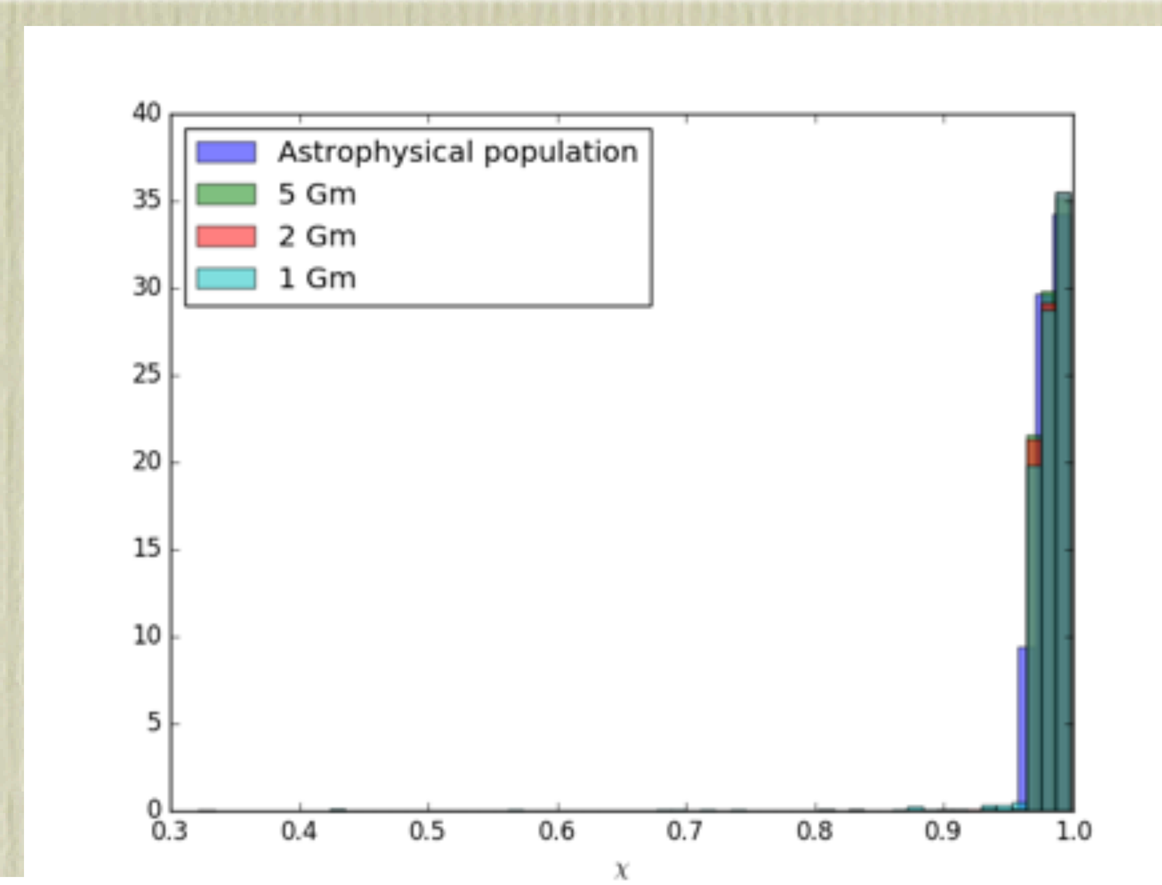


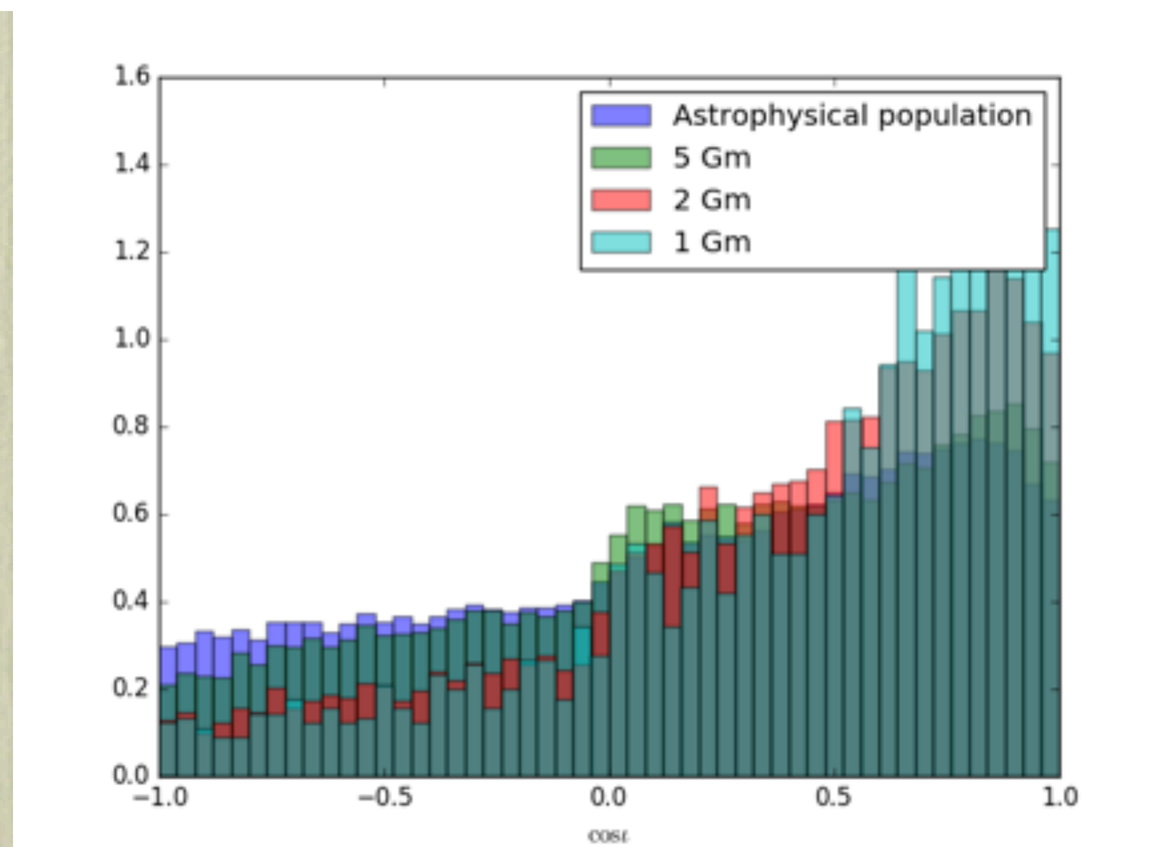
Observed Population - redshift



Observed Population - model B







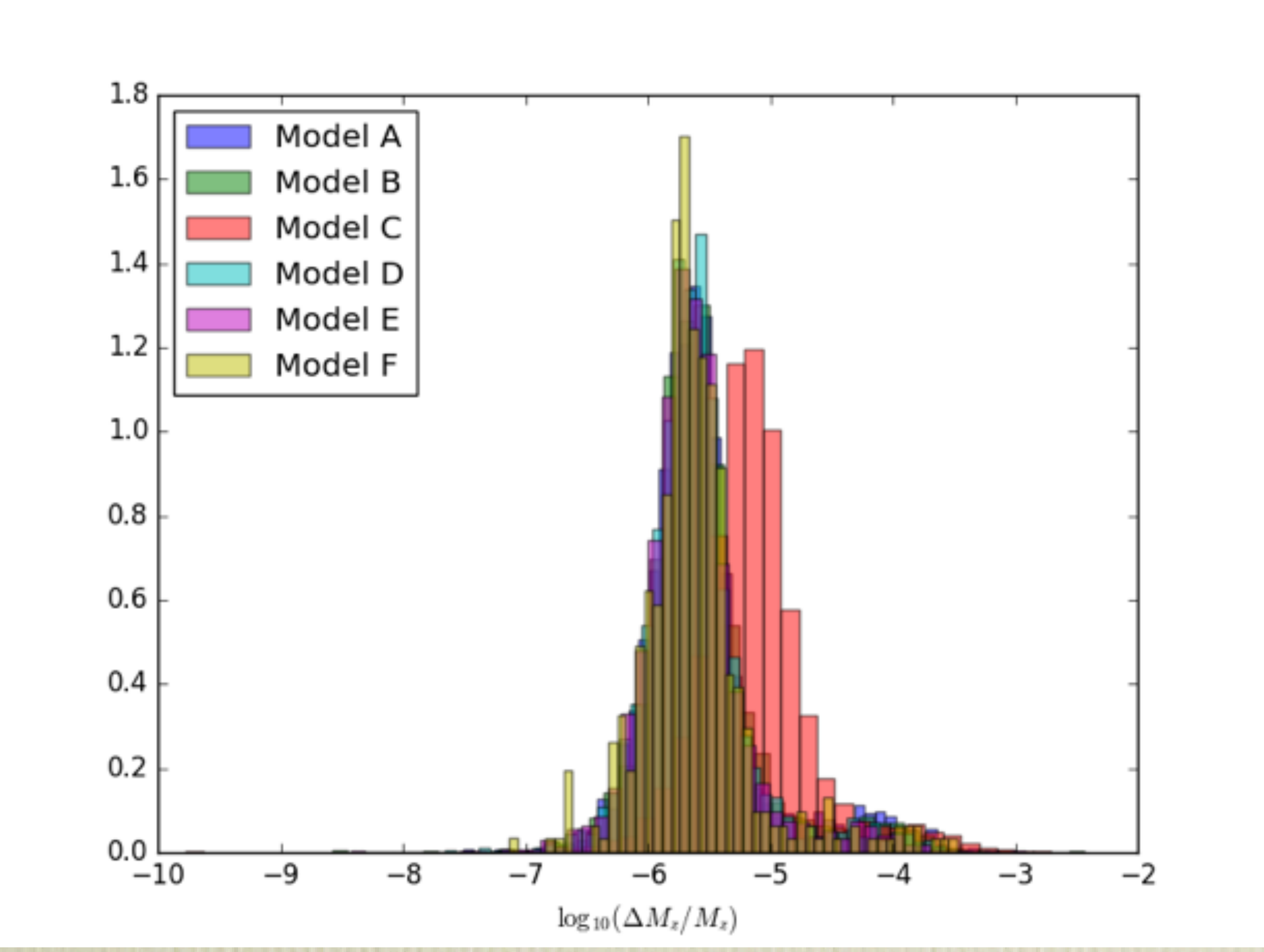
EMRI Science - Astrophysics

- EMRI observations probe quiescent black holes at low to moderate redshift, which are hard to observe electromagnetically.
- EMRI observations will provide very precise parameter measurements for every observed event.

$$\frac{\Delta M_z}{M_z}, \quad \frac{\Delta \mu_z}{\mu_z},$$

$$\Delta\chi, \quad \Delta e_{\rm pl}$$

$$\sim 10^{-6} - 10^{-4}$$



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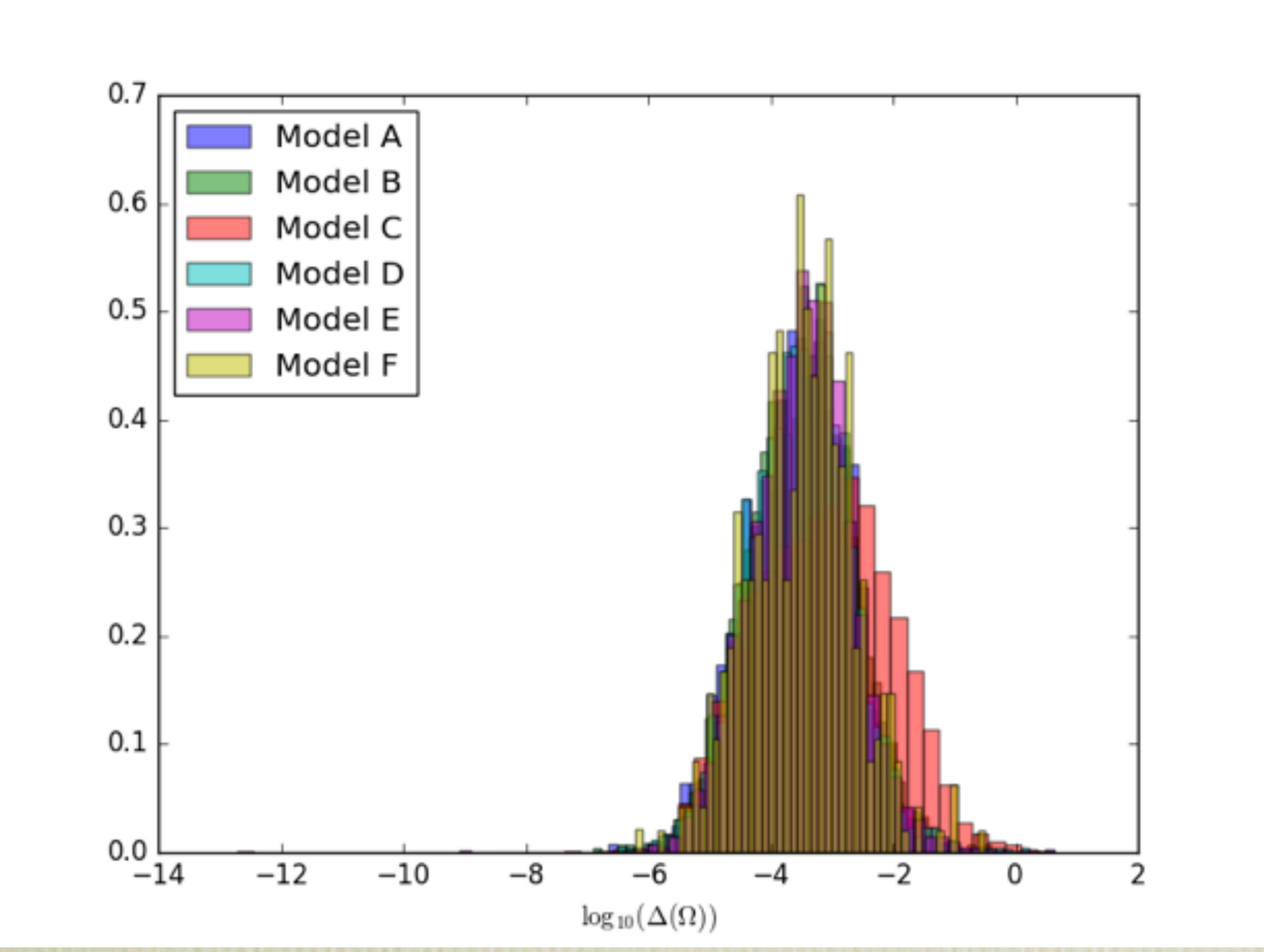
$$\Delta\Omega \sim 10^{-5} - 10^{-3}$$



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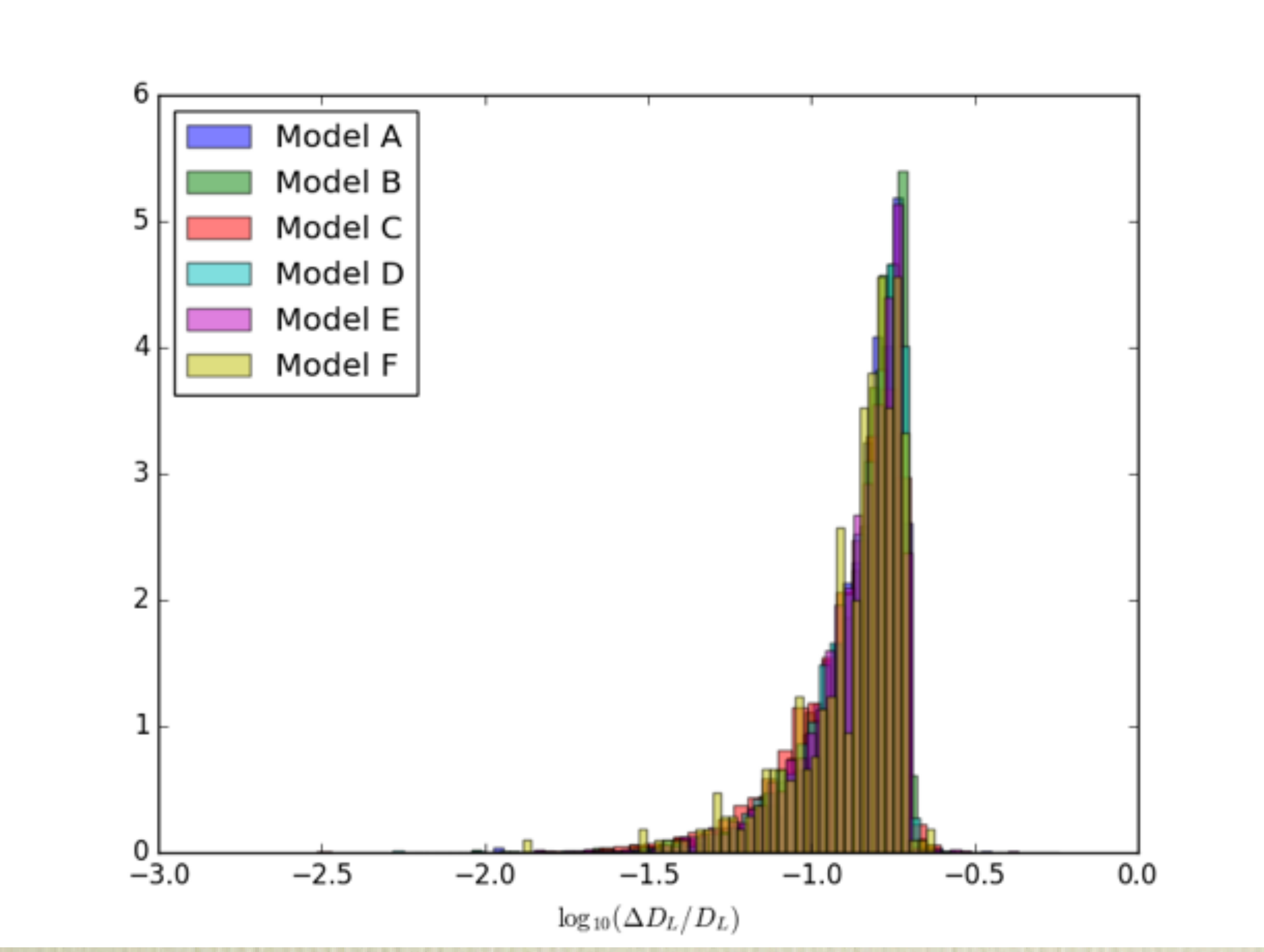
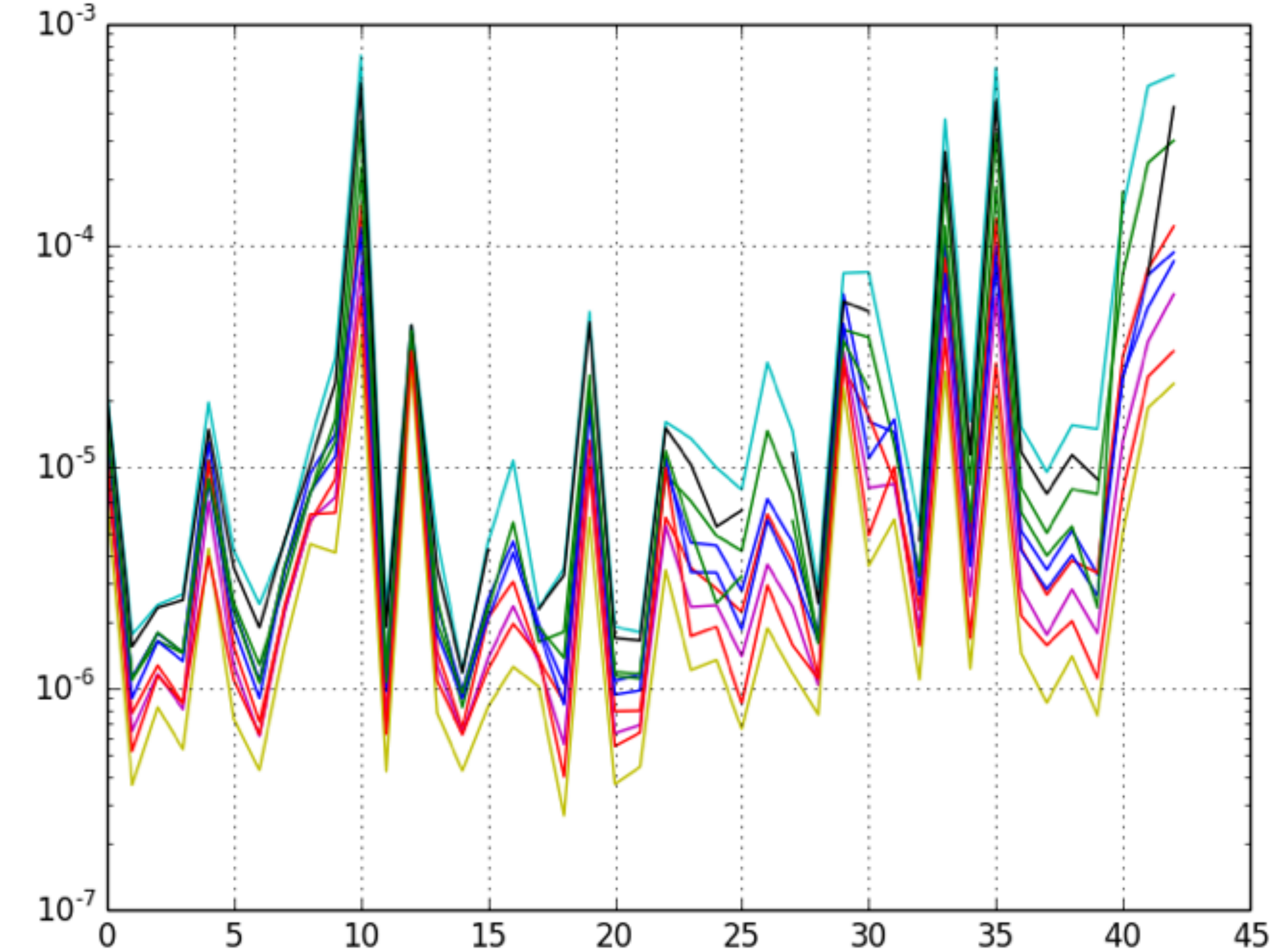
$$\frac{\Delta D_L}{D_L} \sim 0.05 - 0.2$$



EMRIs - Parameter Estimation

- Very weak dependence on mission configuration, at fixed S/N.



Precision on compact object mass versus event ID.
Each coloured line is a different LISA configuration.

Raw

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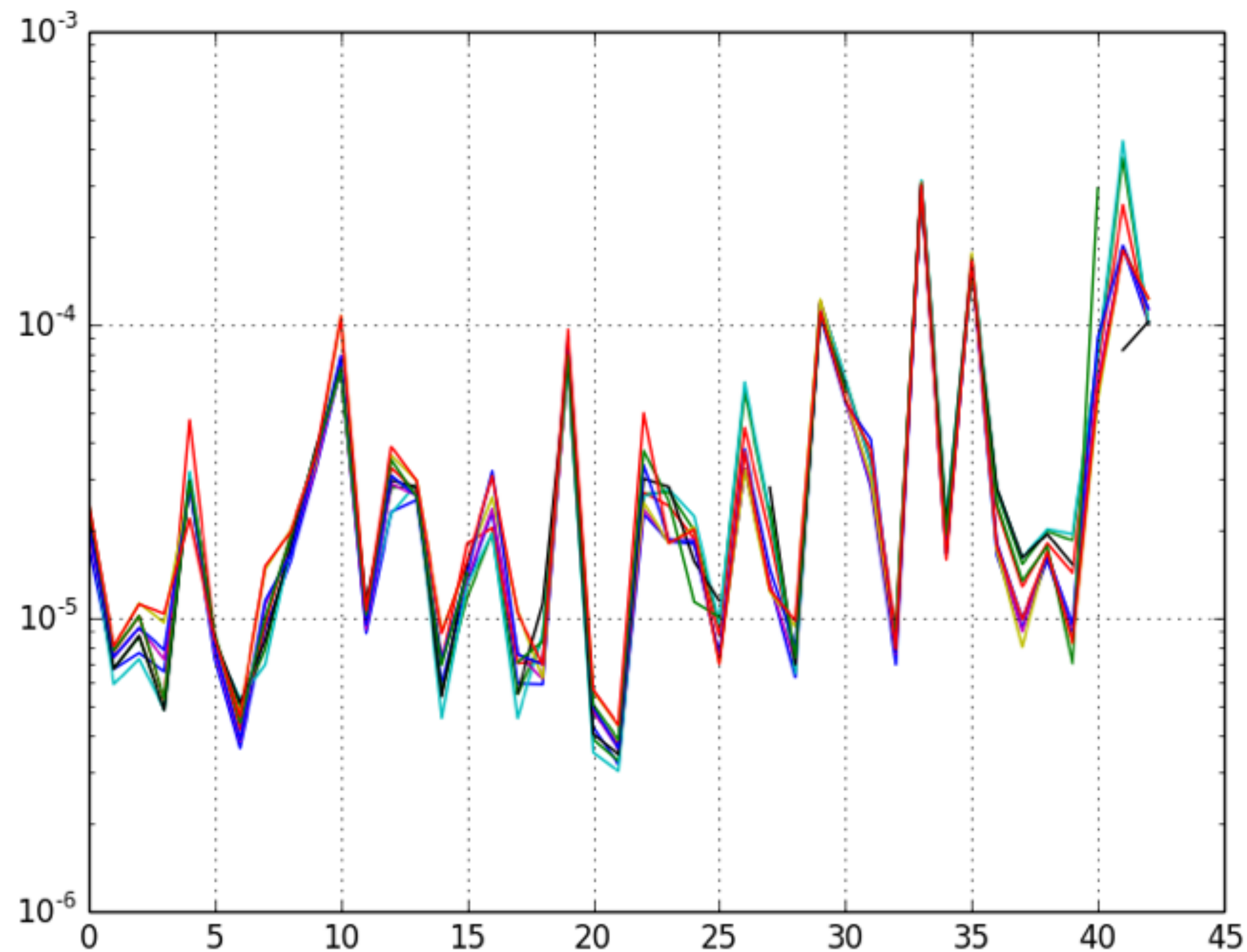


Precision on compact object mass versus event ID.
Each coloured line is a different LISA configuration.

Fixed S/N=20

EMRI Science - Astrophysics

- Can use set of observed EMRI events to probe the properties of black holes in the LISA range.
- Model BH mass function as a power law

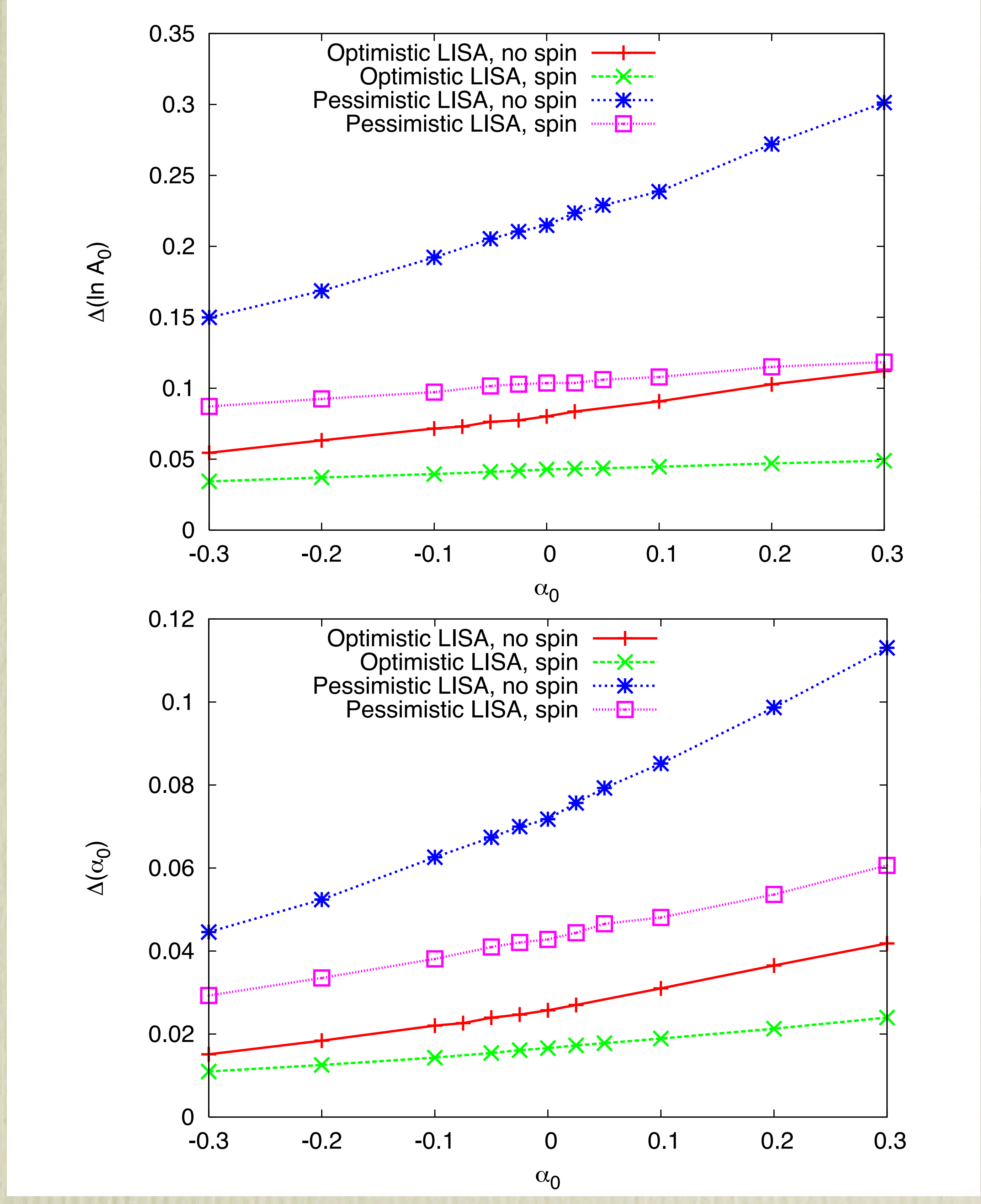
$$\frac{\mathrm{d}n}{\mathrm{d}\ln M} = AM^{\alpha}$$

- Previous theoretical work gave

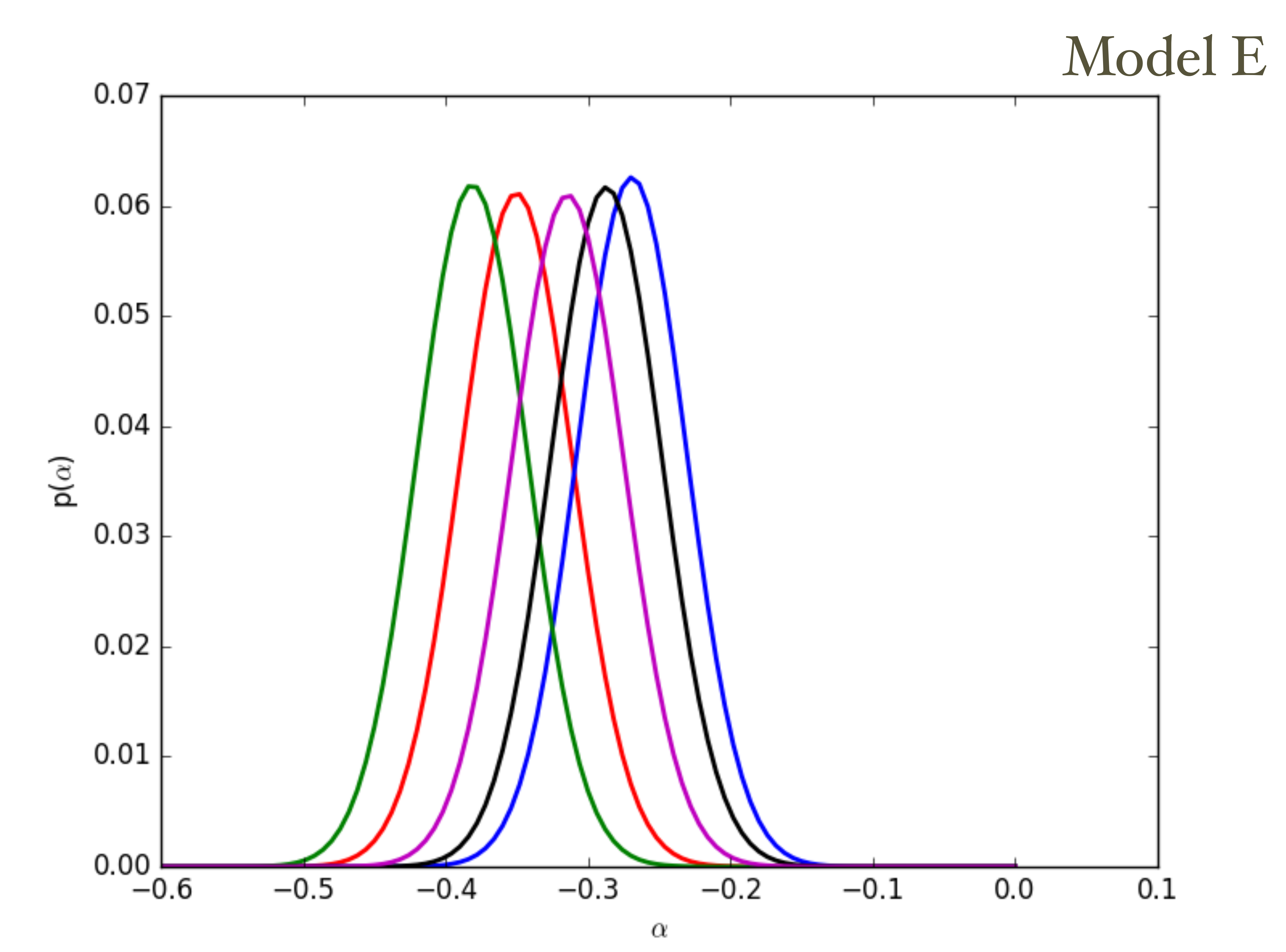
$$\Delta(\ln A) \approx 1.1\sqrt{10/N_{\rm obs}}$$

$$\Delta(\alpha) \approx 0.35\sqrt{10/N_{\rm obs}}$$

- Can repeat this analysis on our modelled EMRI populations.



EMRI Science - BH Mass Function



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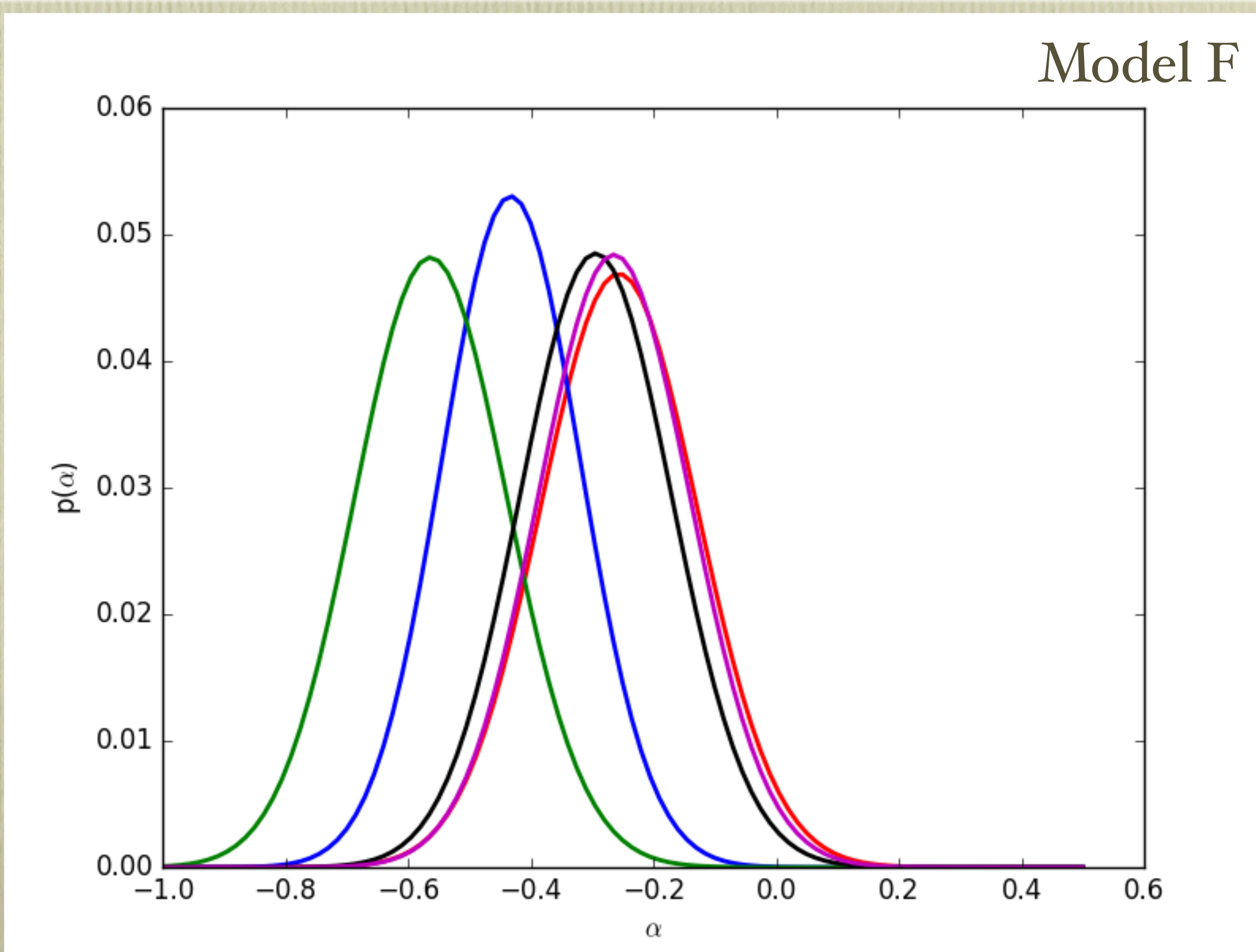

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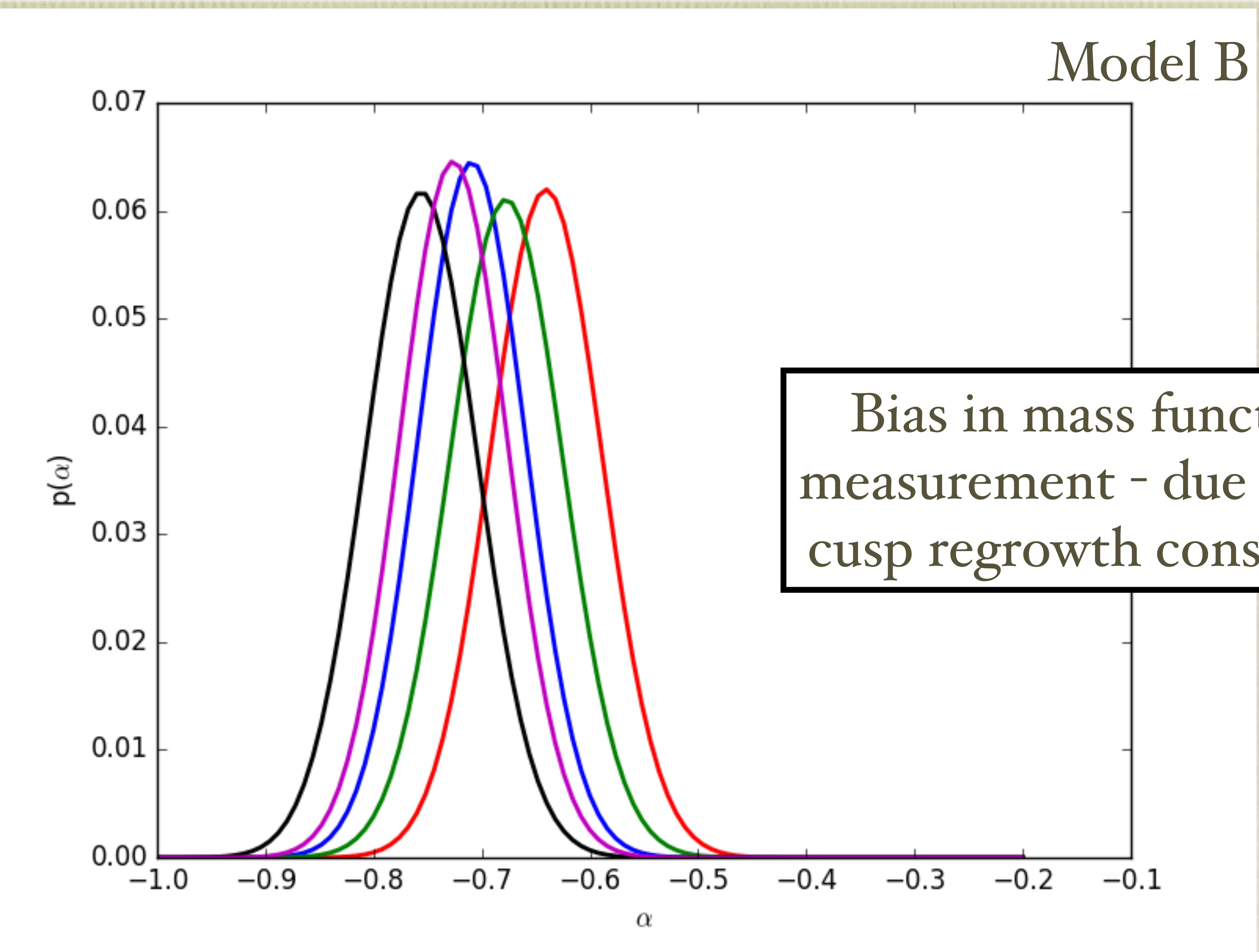
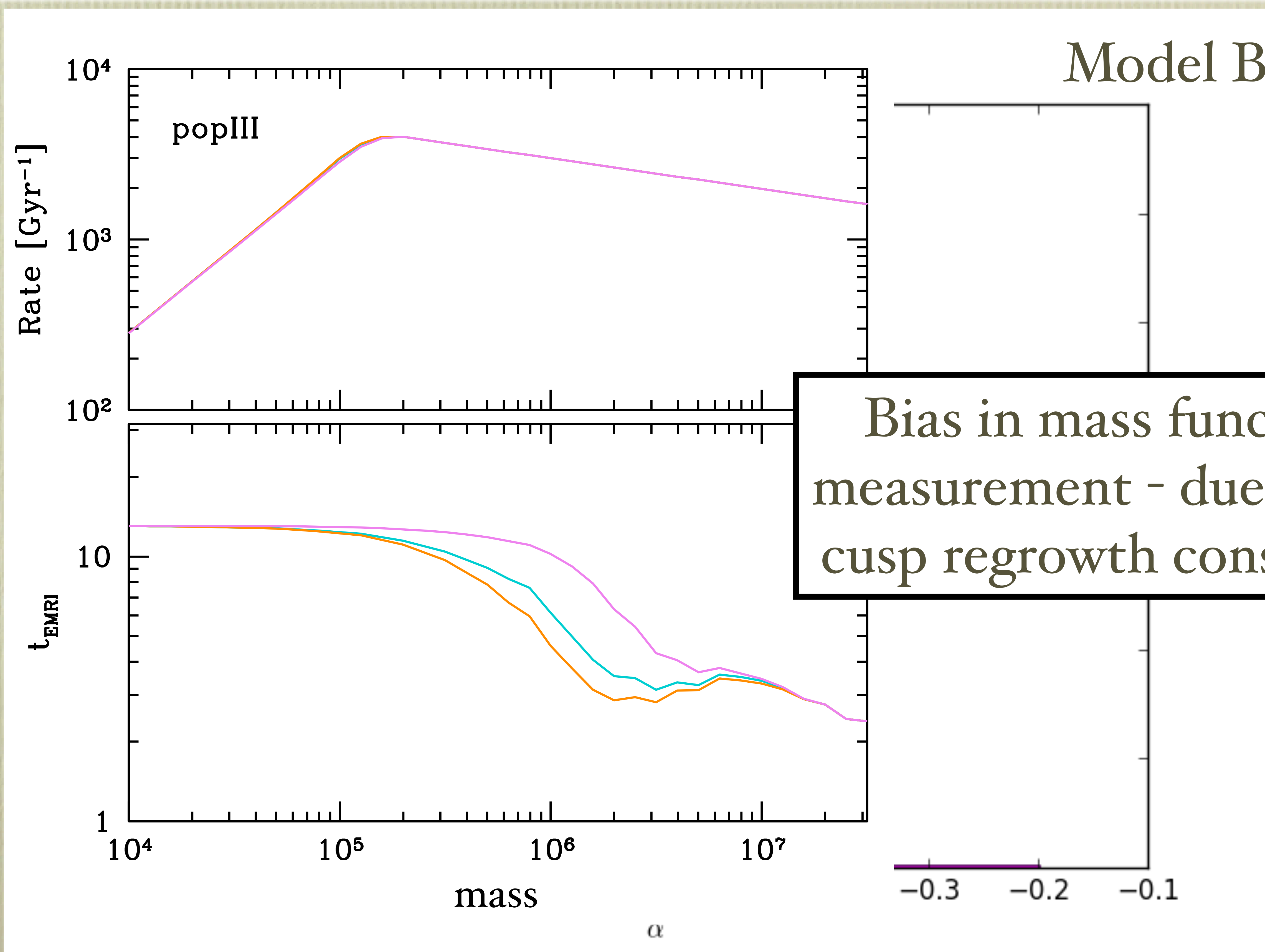


Bias in mass function measurement - due to the cusp regrowth constraint

EMRI Science - BH Mass Function



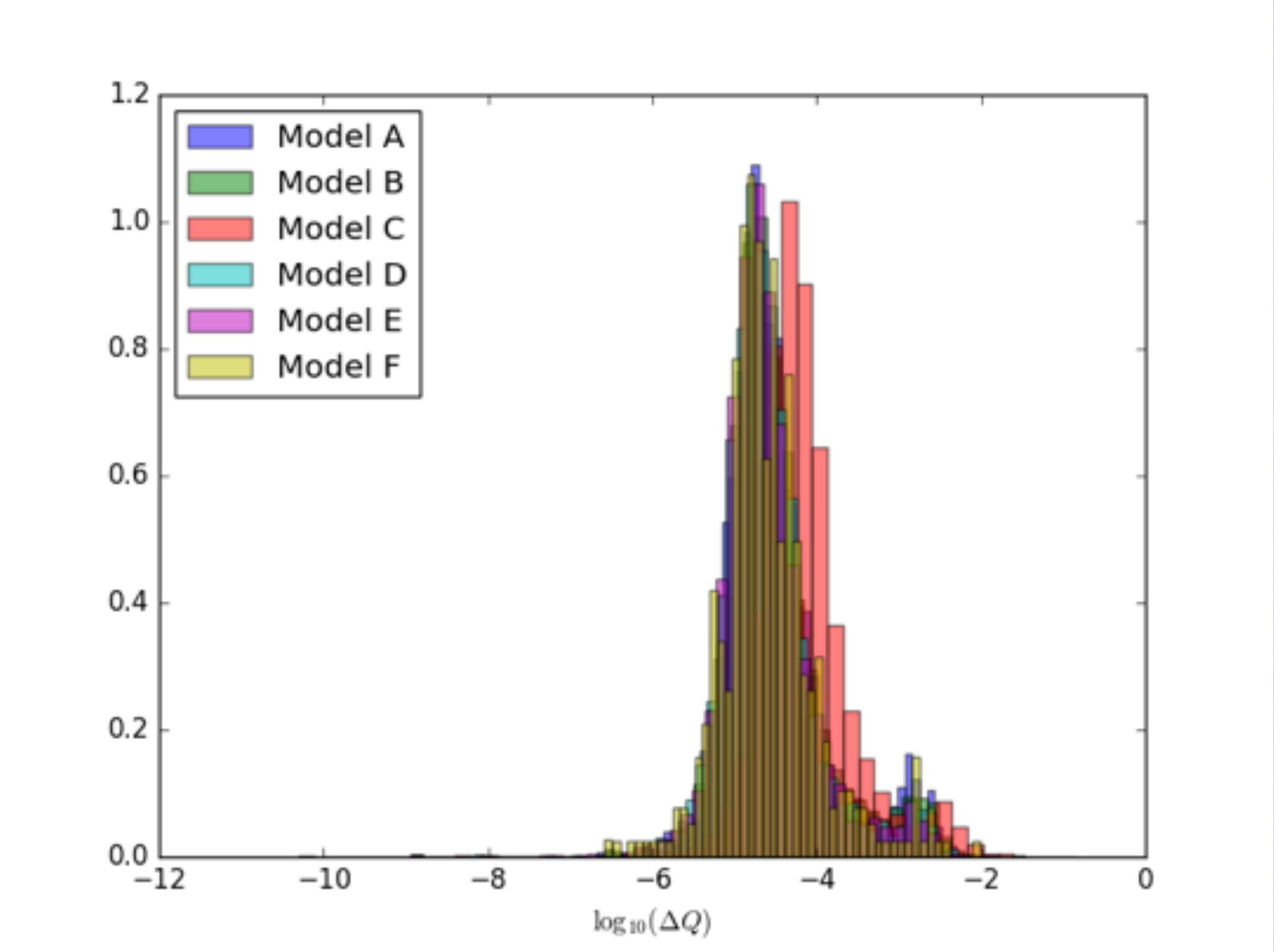
Bias in mass function measurement - due to the cusp regrowth constraint

EMRI Science - Fundamental physics

- EMRIs are exquisite probes of fundamental physics.
- Key LISA science goal is to test the "no-hair theorem"

$$M_l + iS_l = M(ia)^l$$

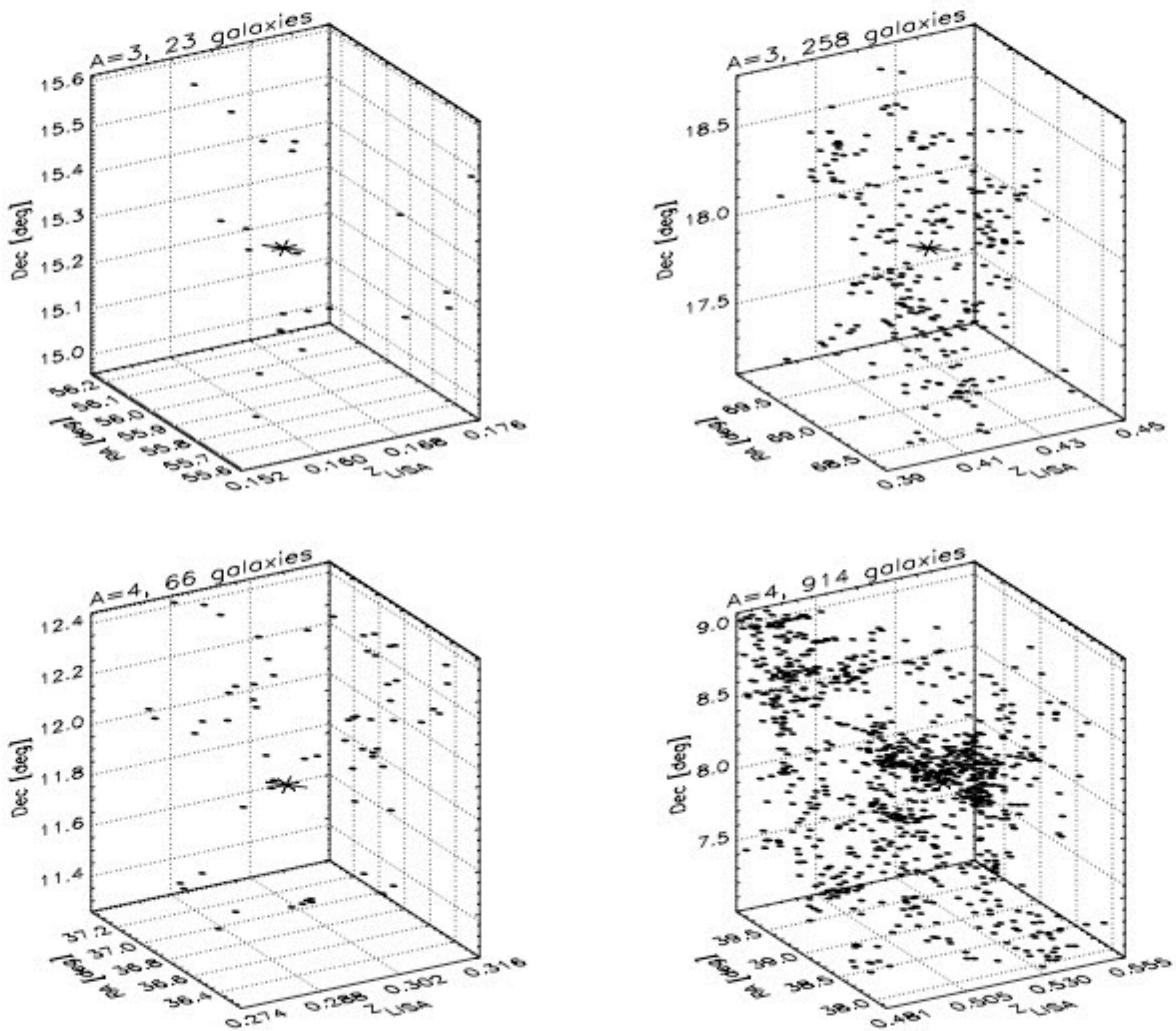
- Can detect deviations in quadrupole moment from no-hair prediction at level of 0.0001.
- These tests just rely on accurate tracking of EMRI phase over many cycles - any LISA configuration can do this to high precision.



EMRI Science - Cosmology

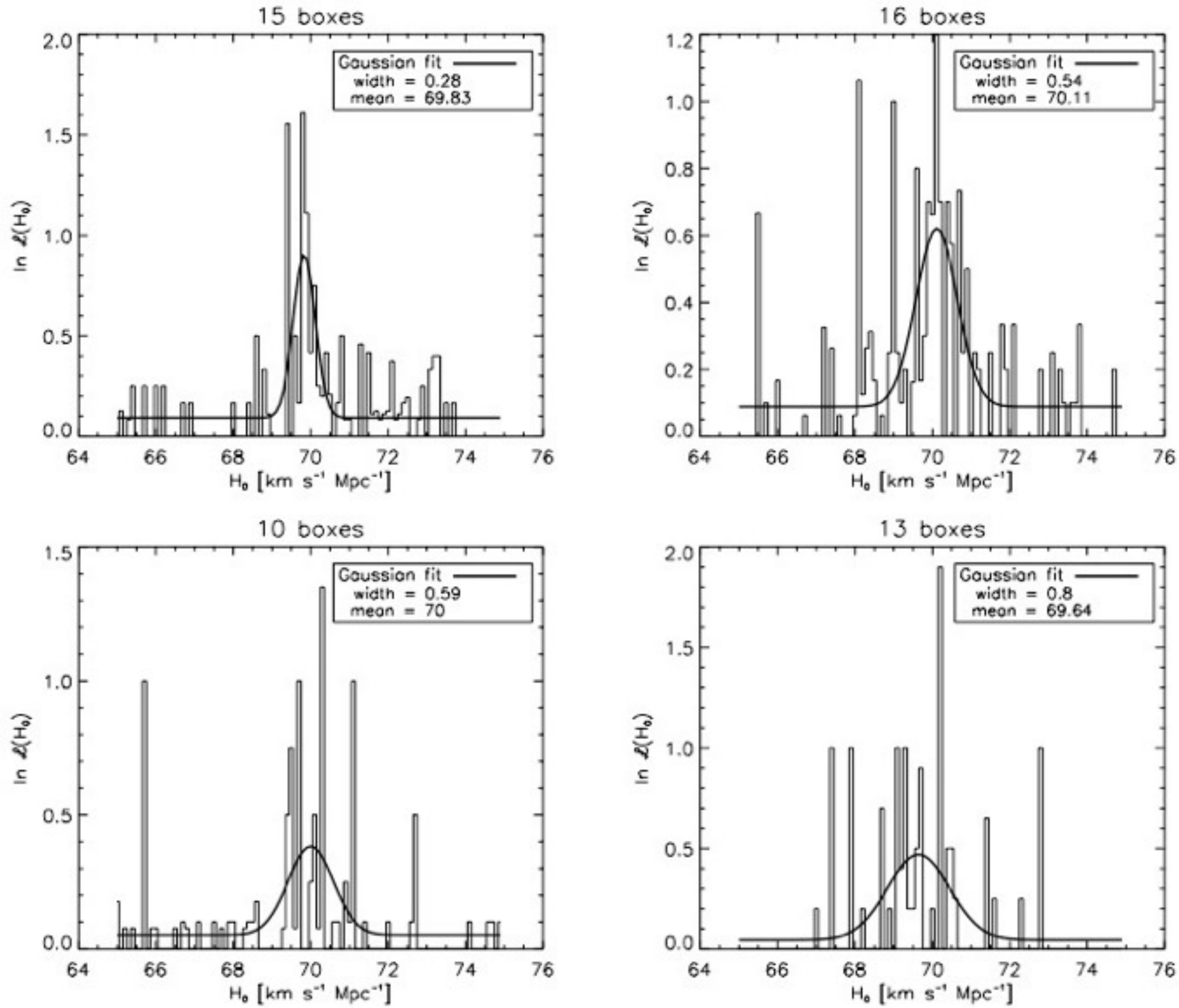
- A single EMRI event with an electromagnetic counterpart (and hence a redshift measurement) will give the Hubble constant to an accuracy of ~3%. N events give an accuracy of $\sim 3/\sqrt{N}\%$.
- Even without a counterpart, can estimate Hubble constant statistically (McLeod & Hogan 08)
  - Let every galaxy in the LISA error box “vote” on the Hubble constant.

EMRI Science - Cosmology



McLeod & Hogan (2008)

EMRI Science - Cosmology



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- Even without a counterpart, can estimate Hubble constant statistically (McLeod & Hogan 08)
  - Let every galaxy in the LISA error box "vote" on the Hubble constant.
  - If ~20 EMRI events are detected at $z < 0.5$, will determine the Hubble constant to ~1%.
- Analysis assumed typical distance uncertainties for Classic LISA. Pessimistically, eLISA could have a factor 2 larger distance error; ~20 events at $z < 0.5$ would provide ~2% Hubble measurement, ~80 events would provide 1% precision
- Any of the LISA configurations should deliver this science.

Summary

- EMRIs are an exciting LISA source and we would expect to see hundreds or thousands of events, for any LISA configuration, and measure the parameters of every event very precisely.
- Irrespective of configuration, EMRIs have fantastic potential for
    - **Astrophysics**: probe quiescent massive black holes, measure black hole mass function;
    - **Fundamental physics**: testing the black hole no-hair theorem;
    - **Cosmology**: determining the Hubble constant.
- Some important open questions need to be addressed
    - re-assess the level of the EMRI confusion background;
    - understand what EMRI observations can tell us about the physical parameters driving theEMRI black hole mass function.