Prospects for observing extreme-mass-ratio inspirals with LISA

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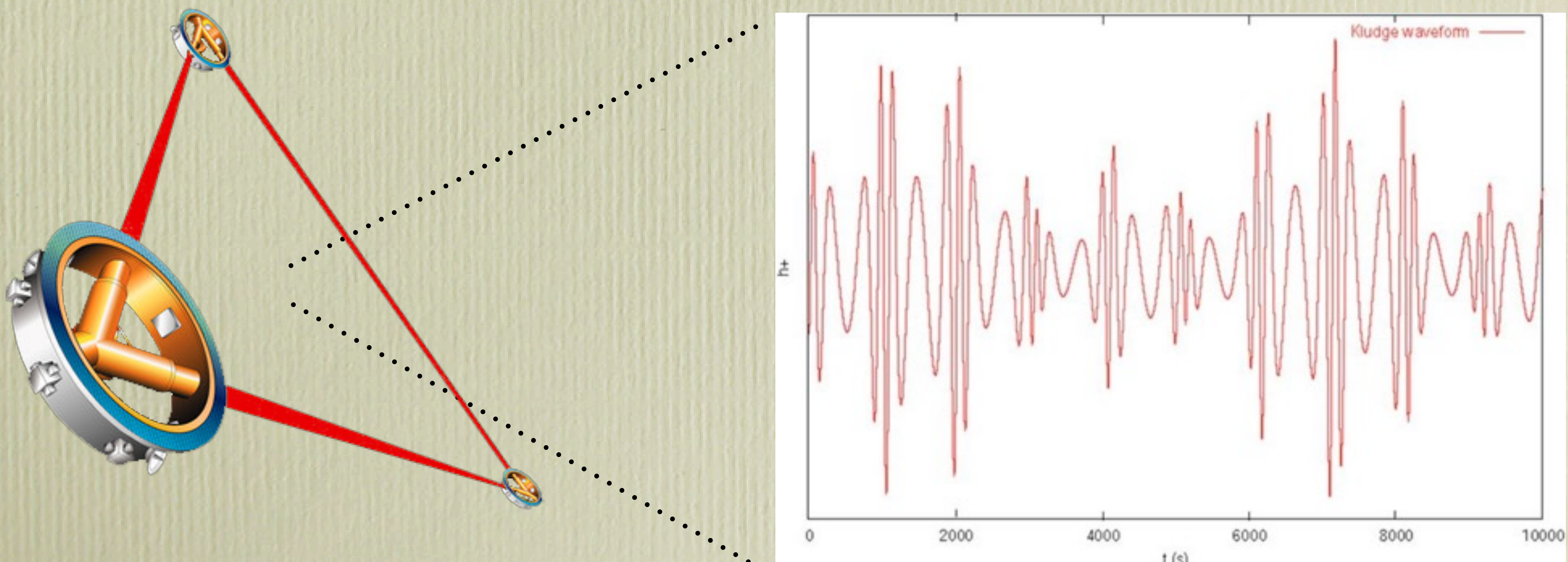
Capra Meeting, Chapel Hill, June 19th 2017



Talk outline

- Current status of LISA
- Estimation of rates of EMRI events observed by LISA
- Implications for science using LISA EMRIs
  - astrophysics
  - fundamental physics
  - cosmology
- Waveform requirements for LISA data analysis.

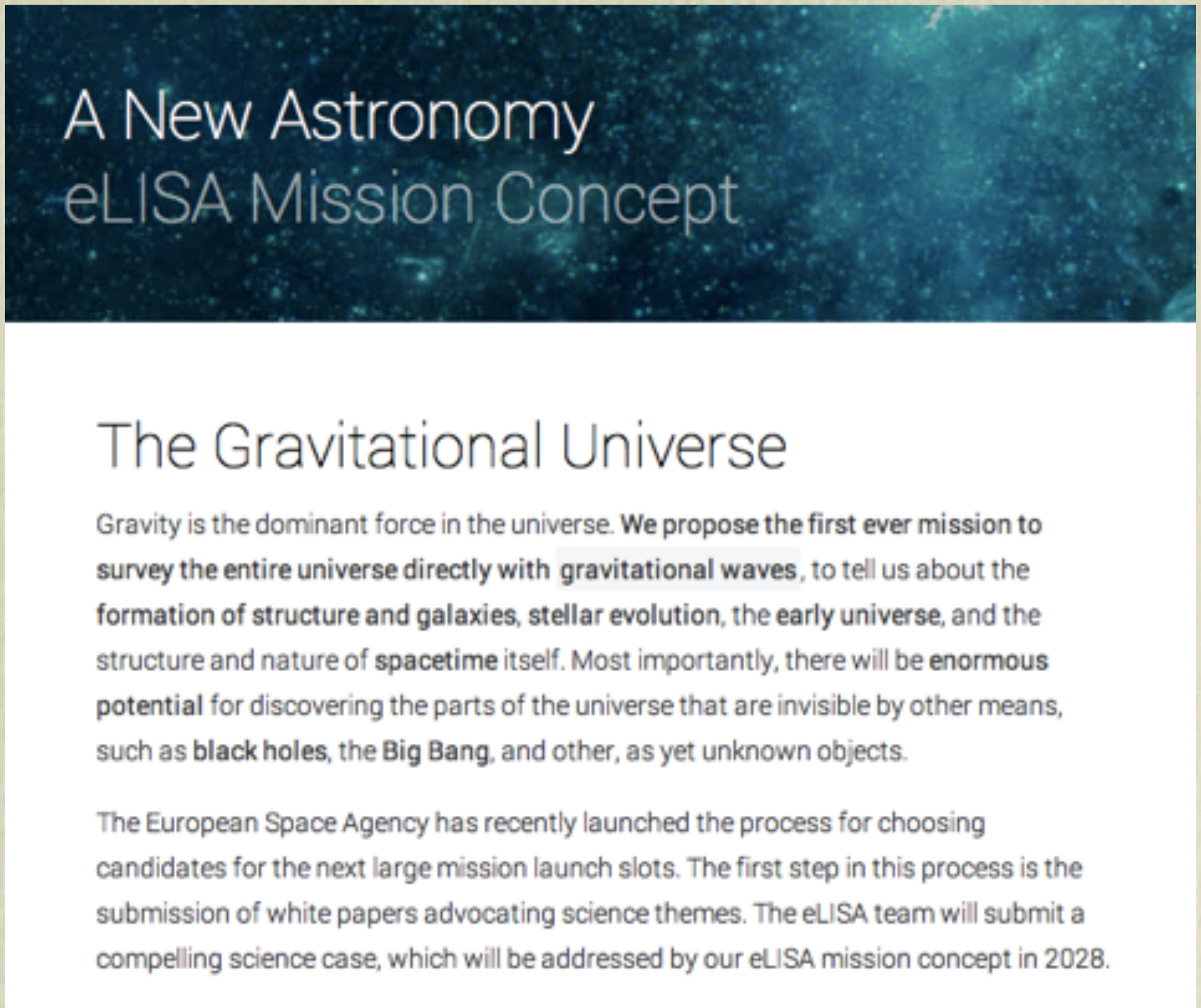
Acknowledgements

- Many of these results have been produced in collaboration with
  - Pau Amaro-Seoane
  - Stanislav Babak
  - Enrico Barausse
  - Emanuele Berti
  - Christopher Berry
  - Alberto Sesana
  - Carlos Sopuerta
- See arXiv:1703.09722 for details of the calculations on expectations for EMRI detections with LISA.
- See arXiv:1702.00786 for the LISA proposal submitted to ESA.

Status of LISA

LISA - Current Status

- LISA originally a joint ESA/ NASA project.
- NASA funding shortfall prompted their withdrawal in 2011.
- ESA only mission, NGO, not selected for L1 in 2011.
- ESA selected "The Gravitational Universe" as the science theme to be addressed by the L3 mission, to launch in 2034.
- *The Gravitational Universe* proposed gravitational wave detection from space.



A New Astronomy
eLISA Mission Concept

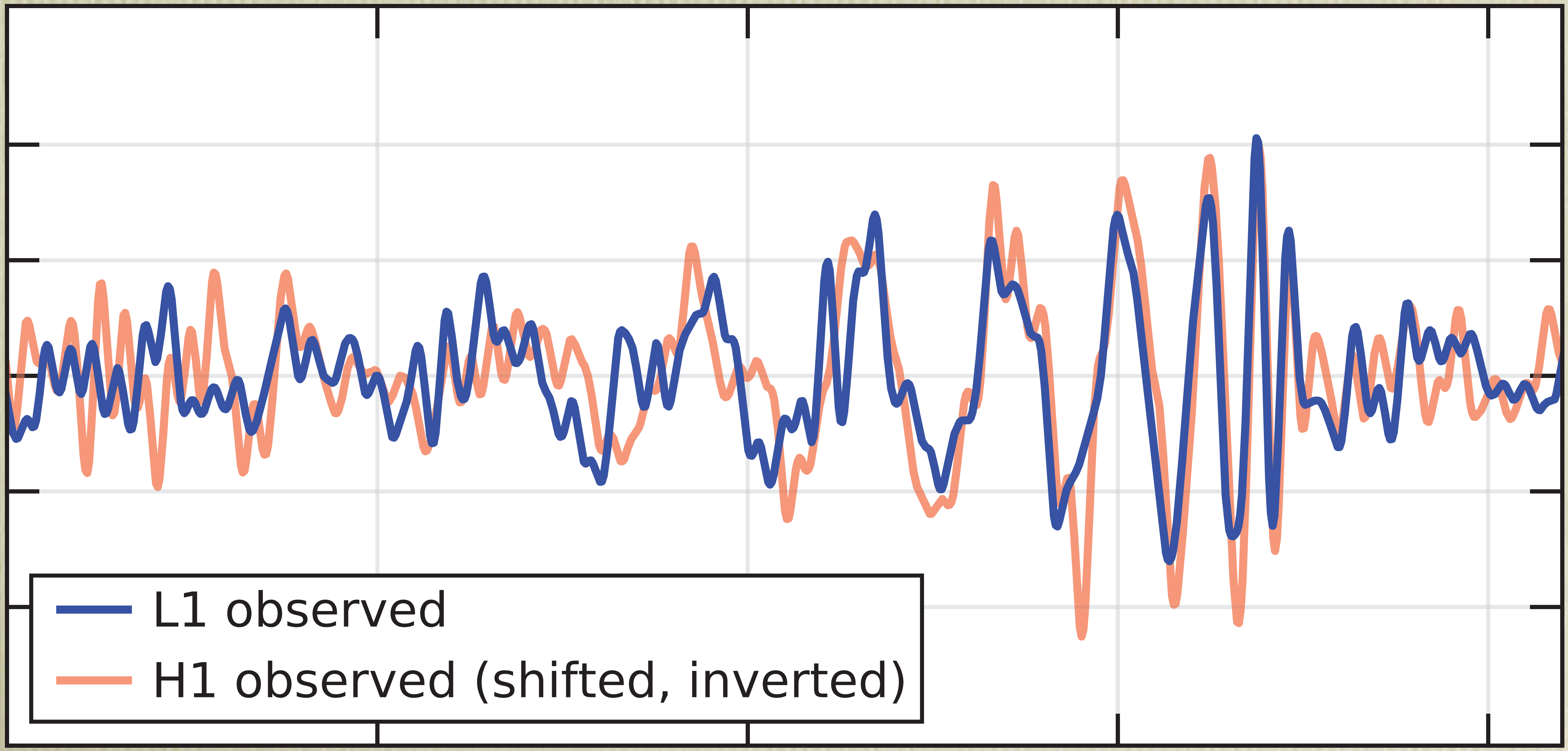
The Gravitational Universe

Gravity is the dominant force in the universe. **We propose the first ever mission to survey the entire universe directly with gravitational waves**, to tell us about the **formation of structure and galaxies, stellar evolution**, the **early universe**, and the structure and nature of **spacetime** itself. Most importantly, there will be **enormous potential** for discovering the parts of the universe that are invisible by other means, such as **black holes**, the **Big Bang**, and other, as yet unknown objects.

The European Space Agency has recently launched the process for choosing candidates for the next large mission launch slots. The first step in this process is the submission of white papers advocating science themes. The eLISA team will submit a compelling science case, which will be addressed by our eLISA mission concept in 2028.

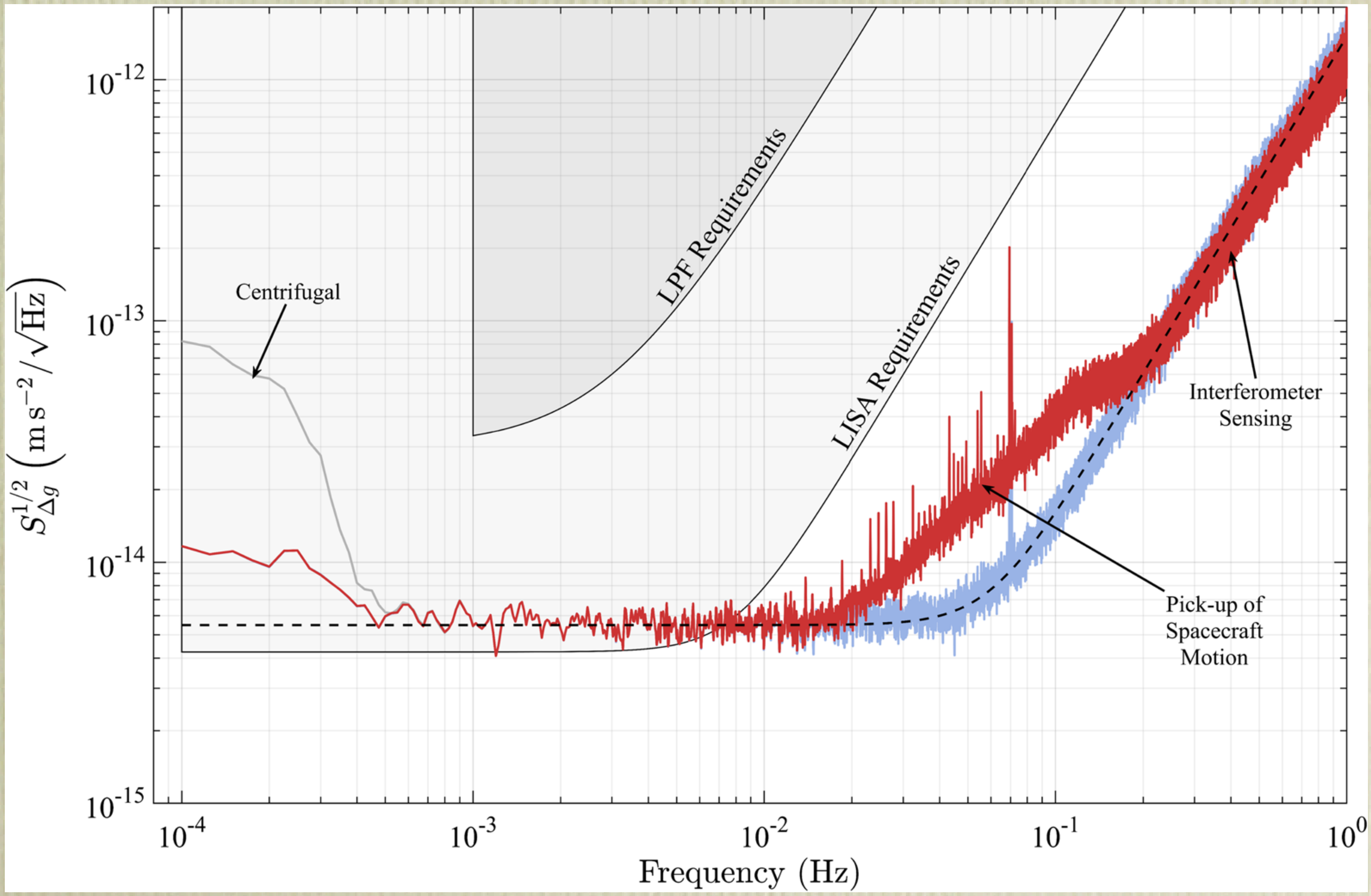
LISA - Current Status

- 2016 was a good year for gravitational waves!
- On February 11th, the LSC announced the first direct detection of gravitational waves by manmade detectors, a binary black hole system GW150914.



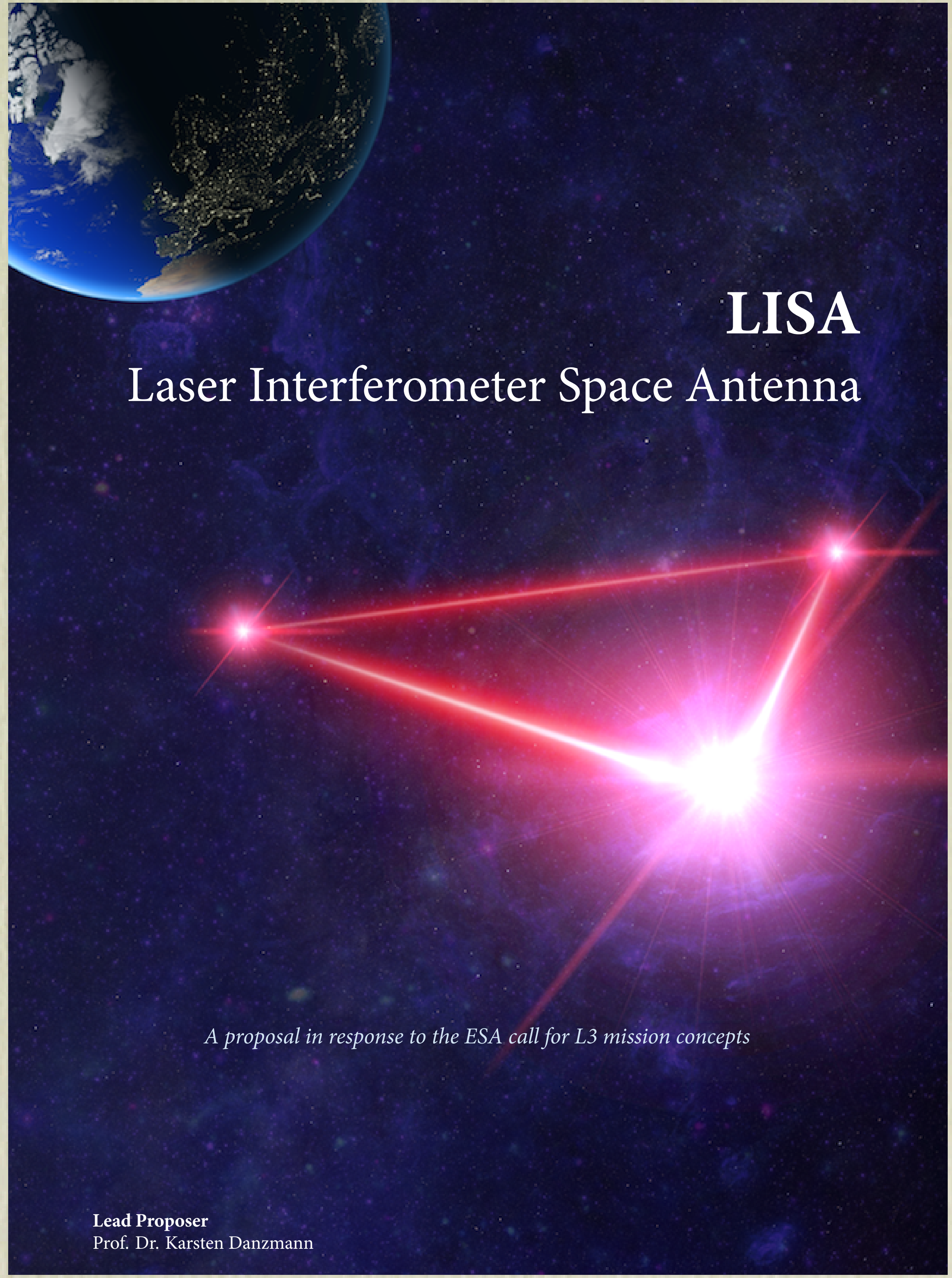
LISA - Current Status

- 2016 was a good year for gravitational waves!
- In June, the first results from LISA Pathfinder were announced, showing performance exceeding LISA requirements.



LISA - Current Status

- These results provided momentum behind gravitational waves which prompted ESA to issue a call for mission proposals in October 2016.
- Call closed mid-January 2017.
- The eLISA Consortium submitted a proposal for "LISA", which was the only serious proposal and has now been accepted.
- NASA involved again, now as a junior partner, contributing ~ $350M.



LISA - Current Status

- Proposal structured around eight **Science Objectives** for the mission, each of which had several associated **Science Investigations** that would realise those objectives. Some of the Science Investigations imposed **Observational Requirements** with associated **Mission Requirements** for LISA performance.
- The first four Science Objectives were:
  - **SO1: Study the formation and evolution of compact binary stars in the Milky Way Galaxy**
  - **SO2: Trace the origin, growth and merger history of massive black holes across cosmic ages**
  - **SO3: Probe the dynamics of dense nuclear clusters using EMRIs**
  - **SO4: Understand the astrophysics of stellar origin black holes**

LISA - Current Status

- The other four Science Objectives were:
  - **SO5: Explore the fundamental nature of gravity and black holes**
  - **SO6: Probe the rate of expansion of the Universe**
  - **SO7: Understand stochastic GW backgrounds and their implications for the early Universe and TeV-scale particle physics**
  - **SO8: Search for GW bursts and unforeseen sources**

LISA - Current Status

- EMRIs/IMRIs appear in **SO2**, **SO3**, **SO5** and **SO6**, in the Science Investigations
  - **SI2.4 Test the existence of Intermediate Mass Black Hole Binaries (IMBHBs)** (sets MR2.4b);

OR2.4.b: Have the ability to detect unequal mass MBHBs of total intrinsic mass $10^4 - 10^6\,M_\odot$ at $z < 3$ with the lightest black hole (the IMBH) in the intermediate mass range (between 10^2 and $10^4\,M_\odot$) [11], measuring the component masses to a precision of 10%, which requires a total accumulated SNR of at least 20.

LISA - Current Status

- EMRIs/IMRIs appear in **SO2**, **SO3**, **SO5** and **SO6**, in the Science Investigations
  - **SI3.1 Study the immediate environment of Milky Way like MBHs at low redshift**;

OR3.1: Have the ability to detect EMRIs around MBHs with masses of a few times $10^5\ M_\odot$ out to redshift $z = 4$ (for maximally spinning MBHs, and EMRIs on prograde orbits) with the SNR ≥ 20. This enables an estimate of the redshifted, observer frame masses with the accuracy $\delta M/M < 10^{-4}$ for the MBH and $\delta m/m < 10^{-3}$ for the SOBH. Estimate the spin of the MBH with an accuracy of 1 part in 10^3, the eccentricity and inclination of the orbit to one part in 10^3.

LISA - Current Status

- EMRIs/IMRIs appear in **SO2**, **SO3**, **SO5** and **SO6**, in the Science Investigations
  - **SI5.2 Use EMRIs to explore the multipolar structure of MBHs**;

OR5.2: Have the ability to detect 'Golden' EMRIs (those are systems from OR3.1 with SNR > 50, spin > 0.9, and in a prograde orbit) and estimate the mass of the SOBH with an accuracy higher than 1 part in 10^4, the mass of the central MBH with an accuracy of 1 part in 10^5, the spin with an absolute error of 10^{-4}, and the deviation from the Kerr quadrupole moment with an absolute error of better than 10^{-3}.

  - **SI5.4 Test the propagation properties of GWs**;
  - **SI5.5 Test the presence of massive fields around massive black holes with masses > 10^3 $M_\odot$**

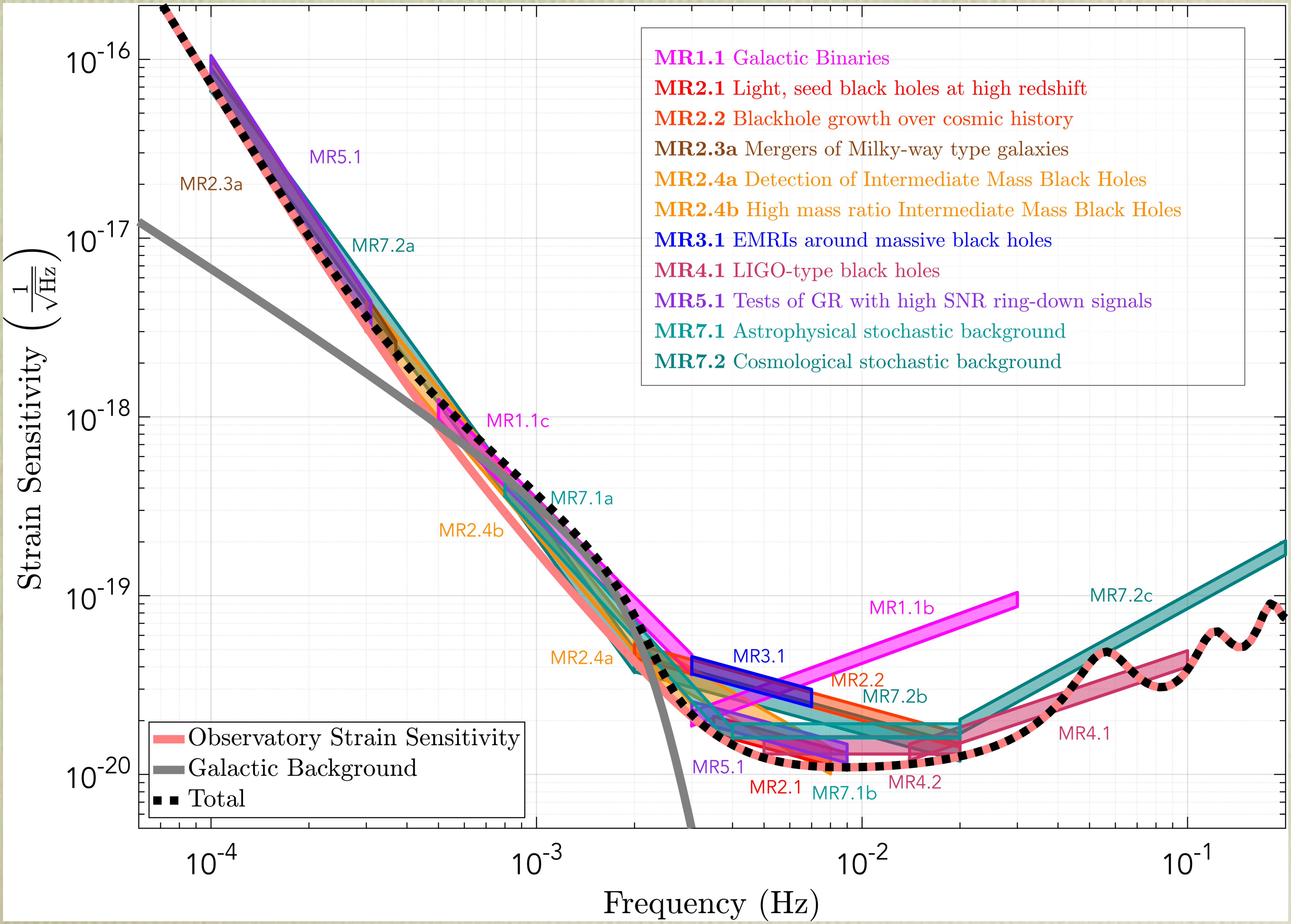
LISA - Current Status

- EMRIs/IMRIs appear in **SO2**, **SO3**, **SO5** and **SO6**, in the Science Investigations
  - **SI6.1: Measure the dimensionless Hubble parameter by means of GW observations only.**

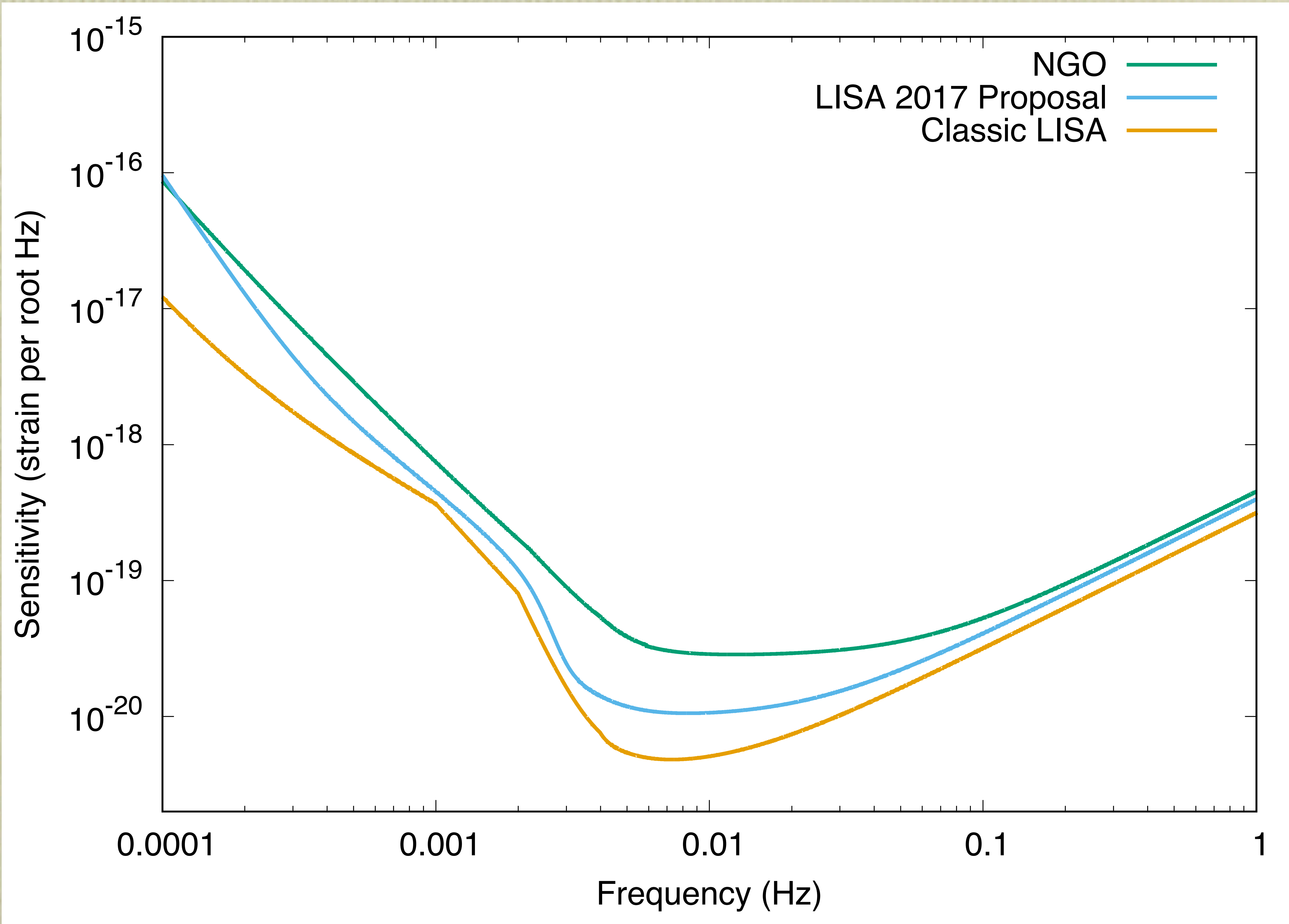
OR6.1b Have the ability to localize EMRIs with an MBH mass of $5 \times 10^5\,M_\odot$ and an SOBH of $10\,M_\odot$ at $z = 1.5$ to better than $1\,\mathrm{deg}^2$.

- OR2.4b and OR3.1 set unique mission requirements. All others are enabled by these mission requirements or mission requirements from other science investigations.

LISA - Current Status



LISA - Current Status



LISA - Current Status

- Mission requirements met by a LISA-like detector with the following characteristics
  - 3 satellites in an Earth-trailing heliocentric orbit, 50-65 Mkm from the Earth; satellites 2.5 Mkm apart;
  - 6 laser links (2 per arm) - allows construction of two independent data streams;
  - 4 year nominal mission lifetime, but consumables and orbital stability should permit 10 years of operation;
  - 30cm diameter telescopes, 2W laser power;
  - gravitational reference sensor performance equal to that achieved in LISA Pathfinder.
- This is the new LISA baseline design, but will be optimised during the phase A design study which will begin soon.

Estimating EMRI event rates

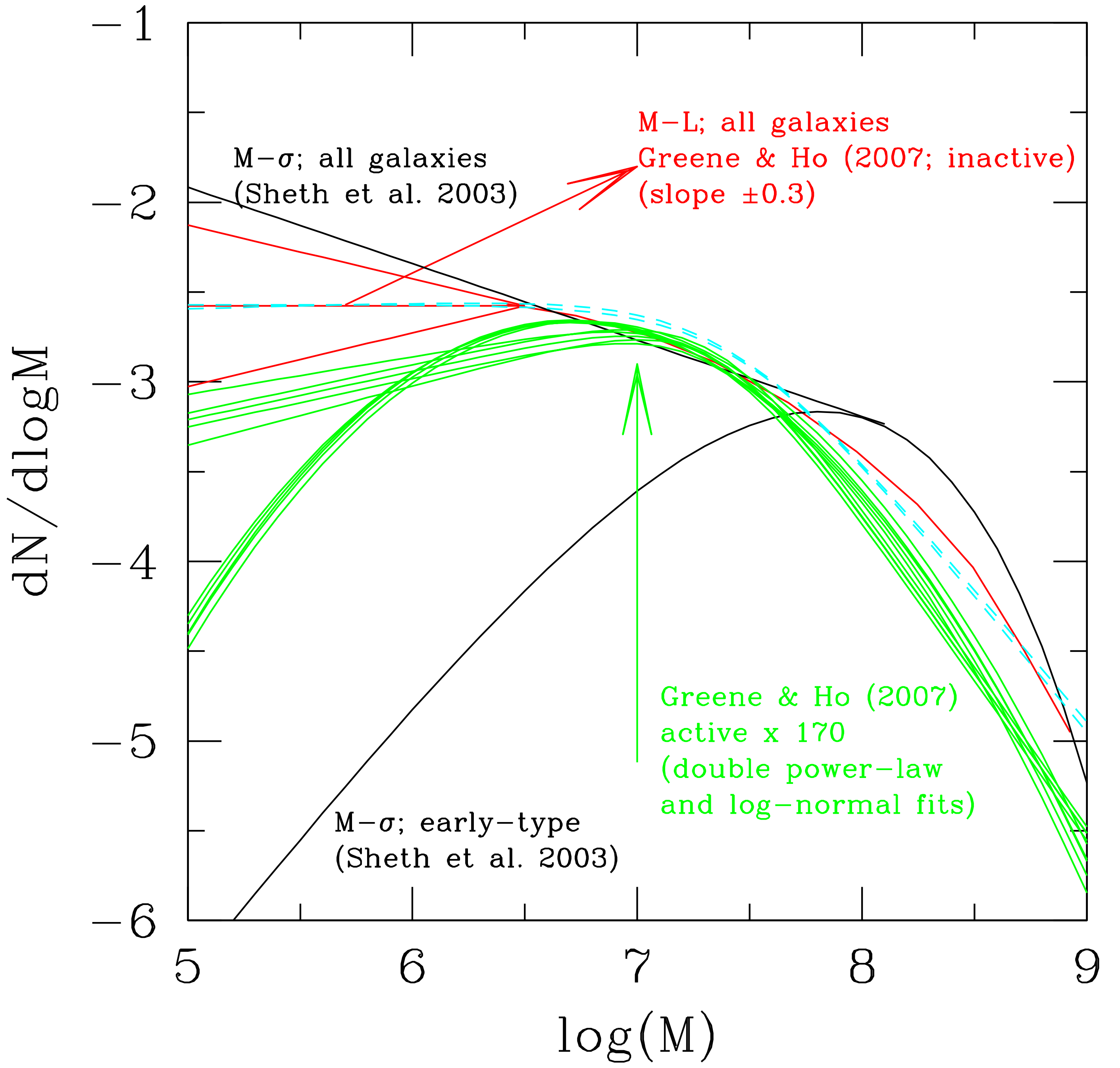
EMRIs - Event Rates

- To estimate EMRI event rates need several ingredients

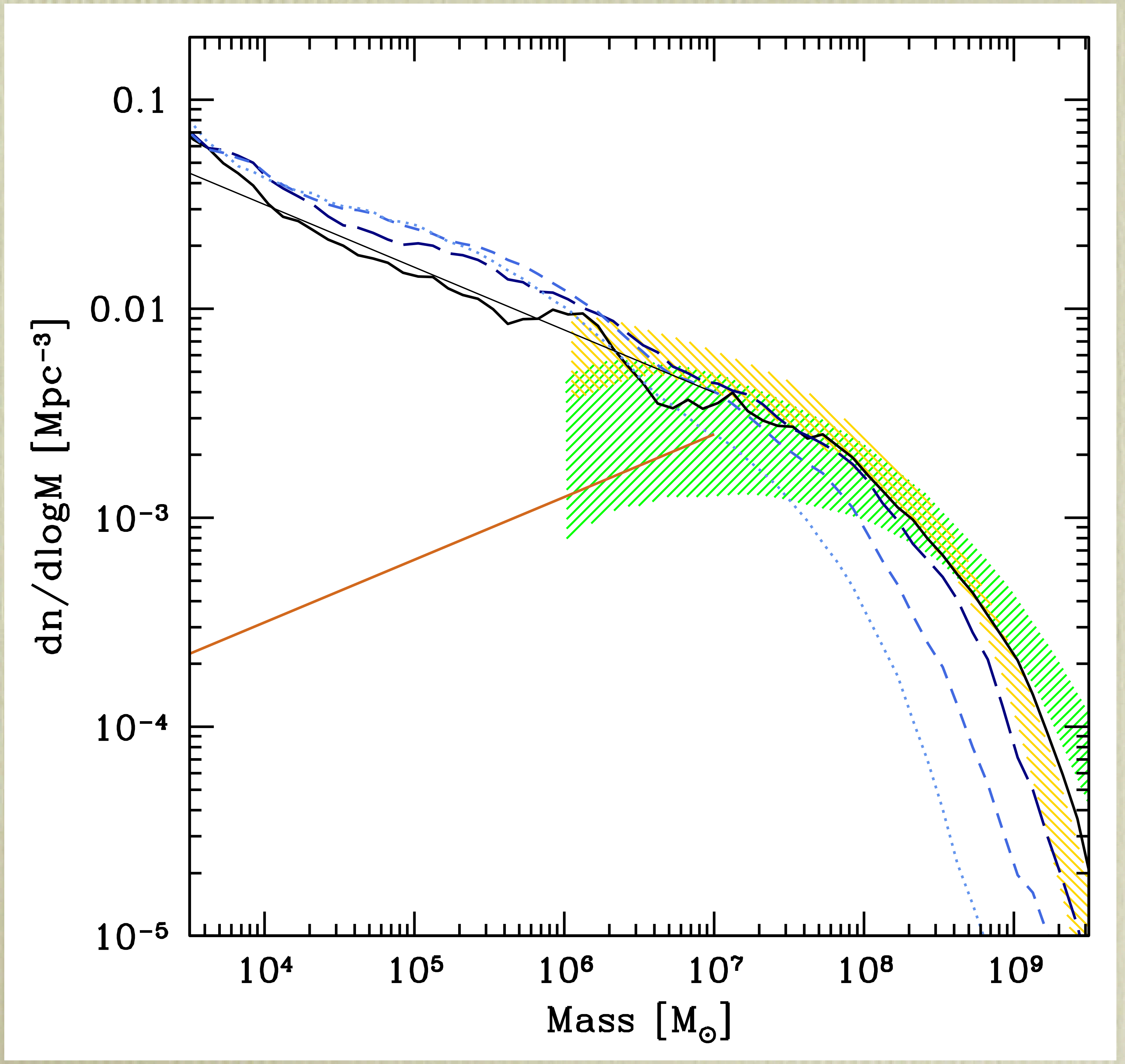
- **Mass function of black holes**: for $10^4 M_\odot \lesssim M \lesssim 10^7 M_\odot$ the BH mass function is not well constrained observationally.
- Traditionally have assumed a flat distribution

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

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



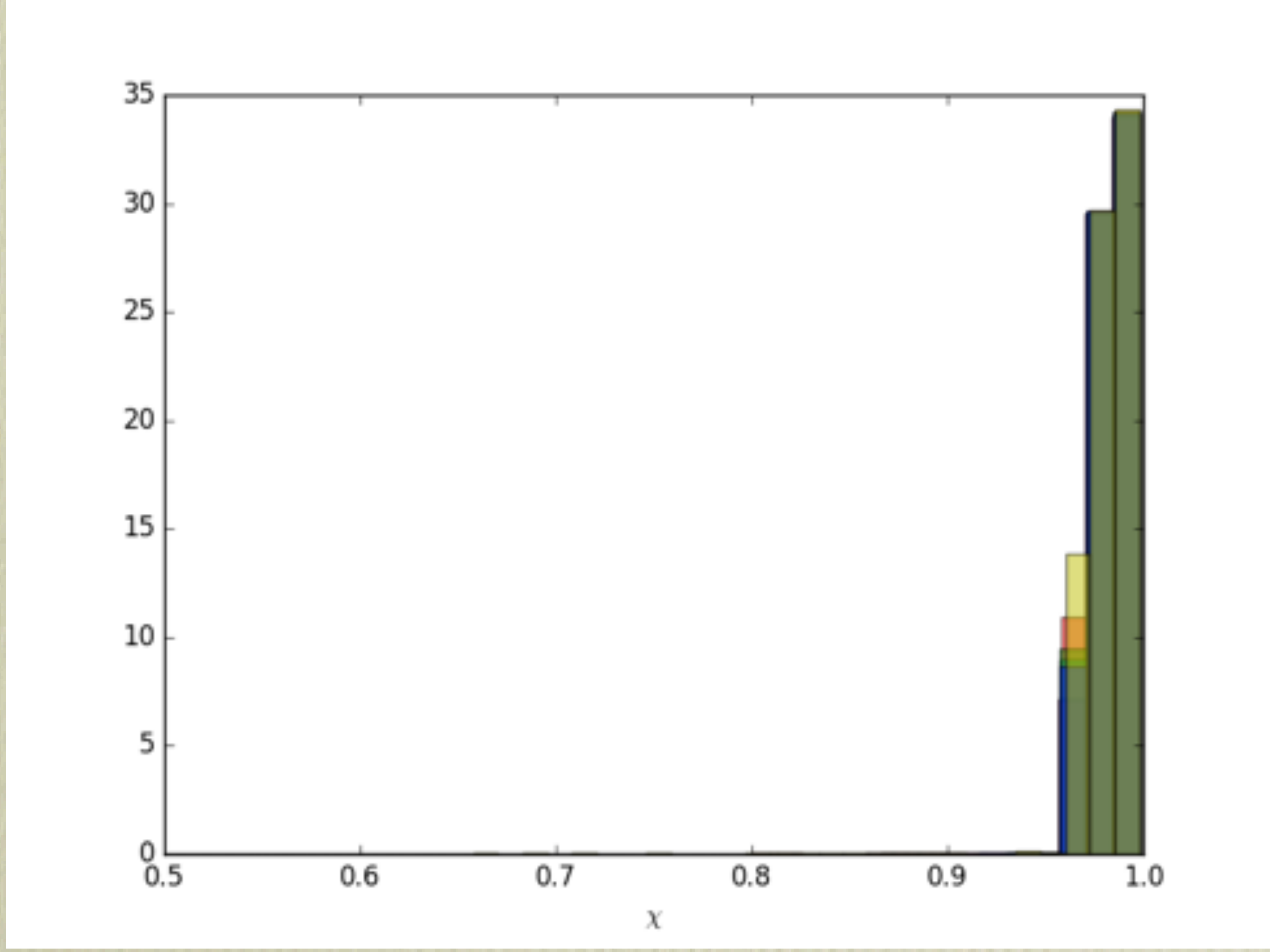
EMRIs - Event Rates



- Consider two cases
  - a numerically simulated population, evolved consistently from pop III seeds: slope ~ -0.3 (Barausse12)
  - a pessimistic analytic model: slope = 0.3 (Gair10)

EMRIs - Event Rates

- **Spin distribution of black holes**: no observational constraints. Self-consistent model predicts high spins for all MBHs. Given uncertainties, consider three spin distributions:
  - **a98**: self-consistent model;
  - **a0**: all black holes have spin a = 0;
  - **aflat**: flat distribution in range [0, 0.98].



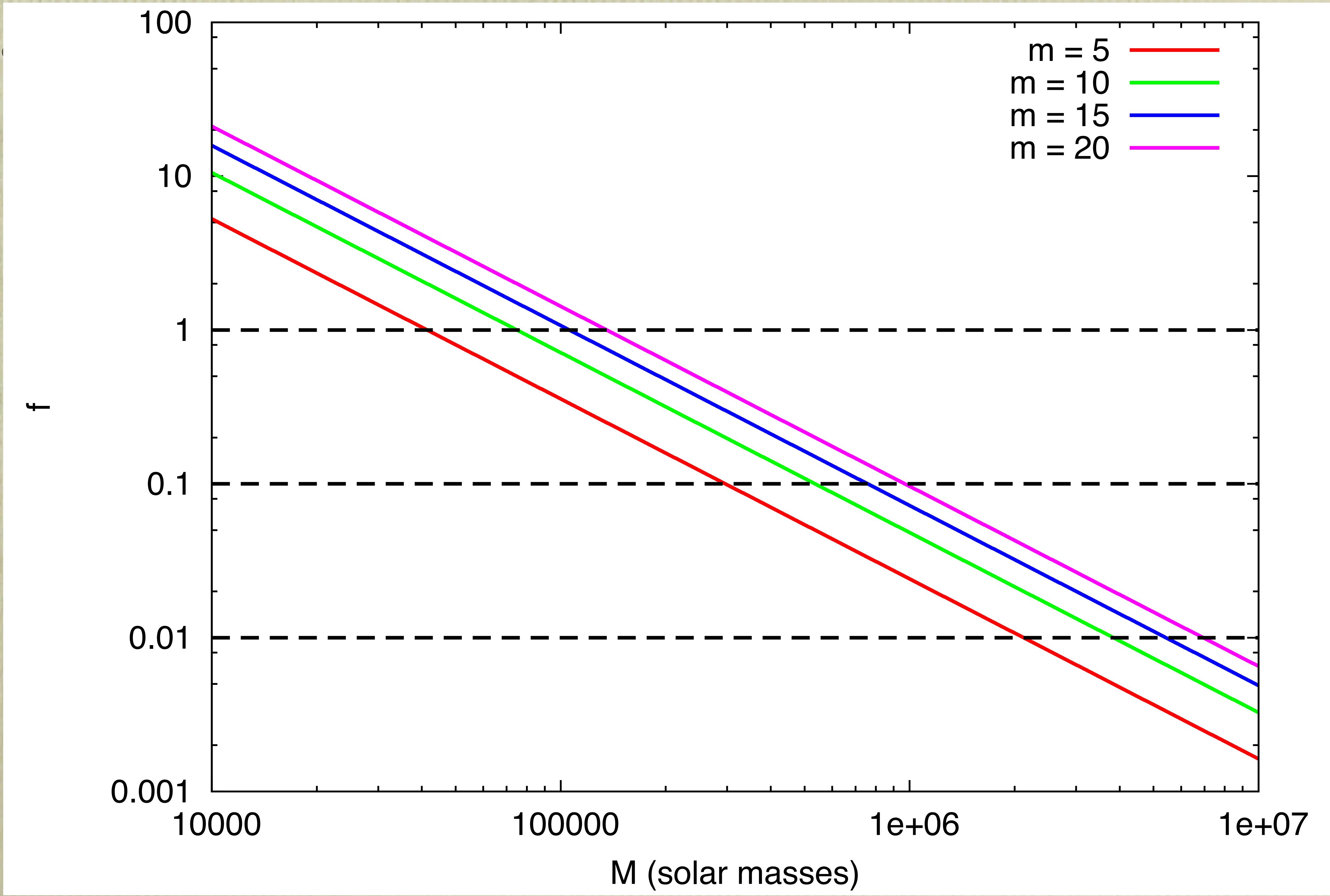
EMRIs - Event Rates

- 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)

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

  - **But** cannot have such a high rate over whole cosmic history or light massive black holes grow too much!

EMRIs - Event Rates



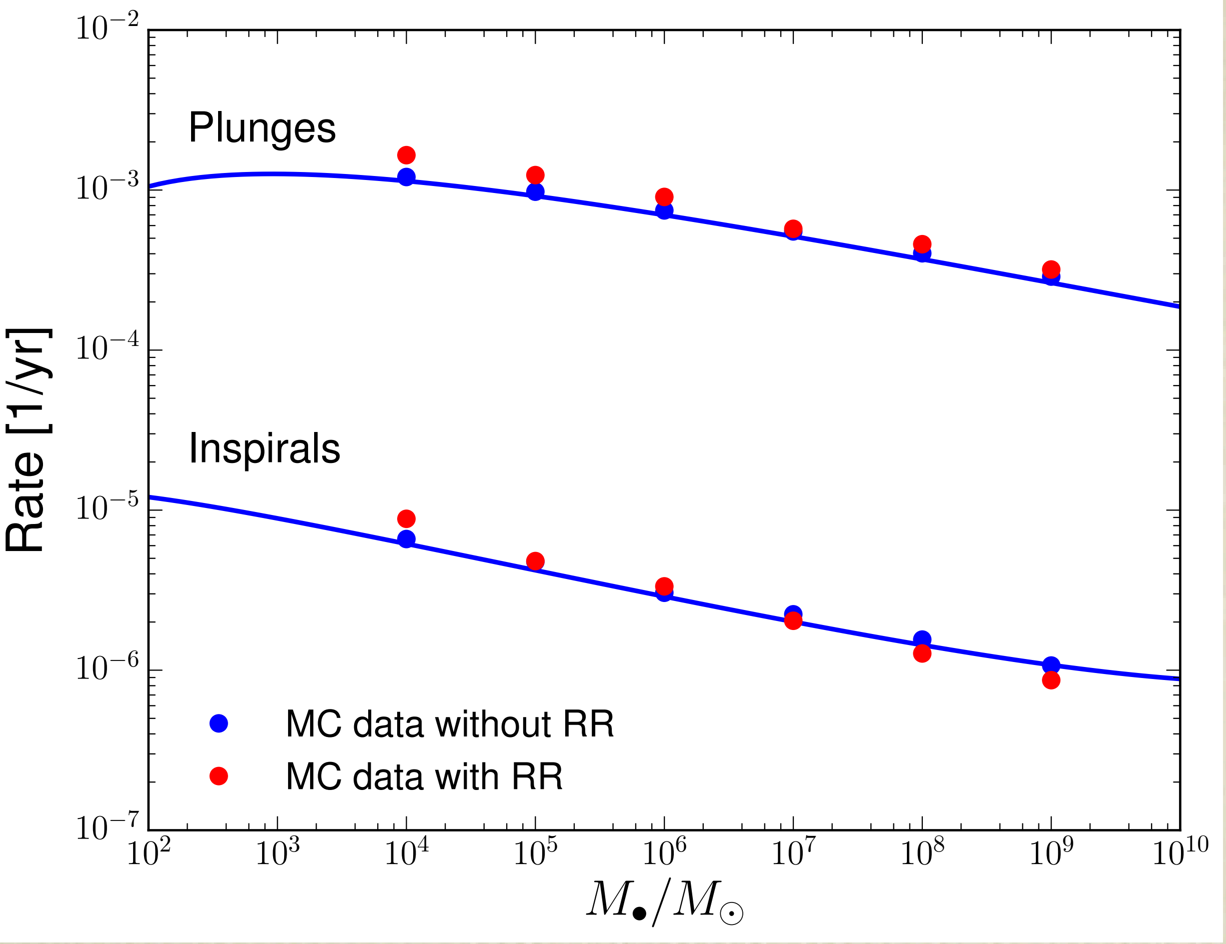
EMRIs - Event Rates

- The problem is made even worse by the fact there are typically 10-100 **direct plunges** for every successful **inspiral.**

TABLE 3
THE PLUNGE AND INSPIRAL RATES IN MILKY WAY-LIKE CUSP MODELS

$M_\star$ [1]	Processes[2]	T_c [3]	Noise[4]	Plunge[5]	Inspiral[5]
1	No RR	—	—	730	3.1
1	GW1	SQ	W	16000	0.0
1	GW1	SQ	E	860	3.3
1	GW1	SQ	G	880	2.3
1	GW1	M	W	930	0.0
1	GW1	M	E	840	3.2
1	GW1	M	G	840	3.2
10	No RR	—	—	610	2.8
10	GW1	SQ	W	6060	0.0
10	GW1	SQ	E	760	1.9
10	GW1	SQ	G	690	2.4
10	GW1	M	W	800	0.0
10	GW1	M	E	730	2.0
10	GW1	M	G	730	2.5
10	GW2	M	G	730	1.2
10	GW3	M	G	740	1.1

[1] Stellar mass in $M_\odot$.
[2] GW approximations: GW1 Gair et al. (2006), GW2 Peters (1964), GW3 Hopman & Alexander (2006a)
[3] Coherence time: M = Mass prec., SQ = Self-quenching.
[4] Noise model: W = White, E = Exponential, G = Gaussian.
[5] Event rates in units of 10^{-6} yr^{-1}.

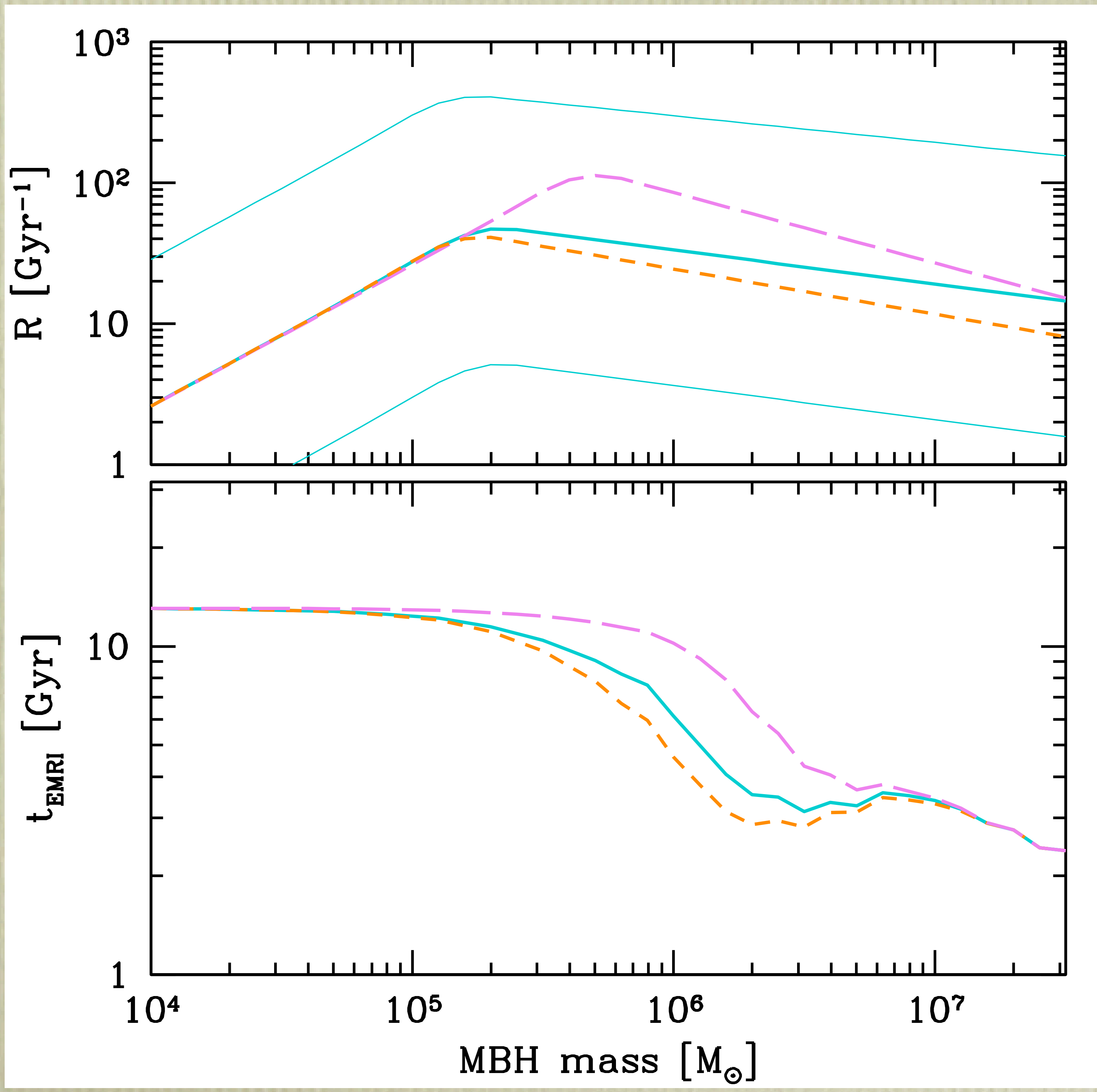


Bar-Or & Alexander (2015)

EMRIs - Event Rates

- Additionally, stellar cusps around massive black holes do not contain enough COs to support such high inspiral rates - the loss cone is depleted by EMRIs much faster than it is refilled by relaxation.
- Therefore we reduce the reference EMRI rate so that
  - an MBH acquires no more than 1/e of its mass from EMR inspirals plus direct plunges;
  - an MBH consumes no more than the number of COs expected in its radius of influence within a relaxation time.
- Need to assume certain ratio of plunges to inspirals. Use Np=0, 10, 100.
- Black hole spin/inclination influence capture cross-section - enhanced rate for spinning black holes and prograde EMRIs (Amaro-Seoane et al. 2013).
- Host galaxy mergers also disrupt stellar cusps - massive black hole is not available as EMRI host until cusp has regrown.

EMRIs - Event Rates



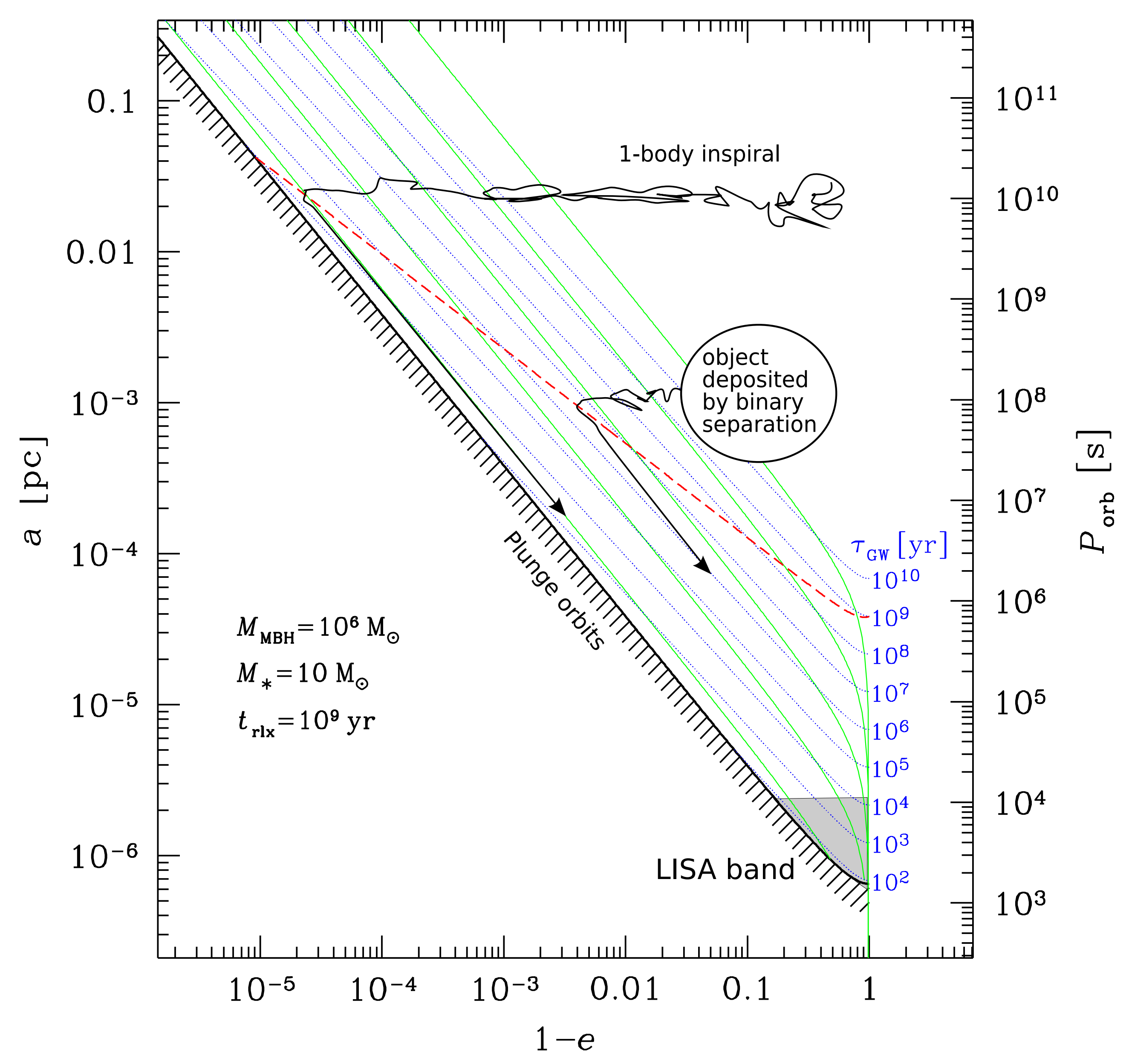
- Consider three scenarios for cusp regrowth
  - fiducial, t ~ 6 Gyr (Gultekin09)
  - optimistic, t ~ 2 Gyr (GrahamScott13)
  - pessimistic, t ~ 10 Gyr (KormendyHo13)
- Here t is the cusp regrowth time for a $10^6 M_\odot$ black hole following an equal-mass merger.

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

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)

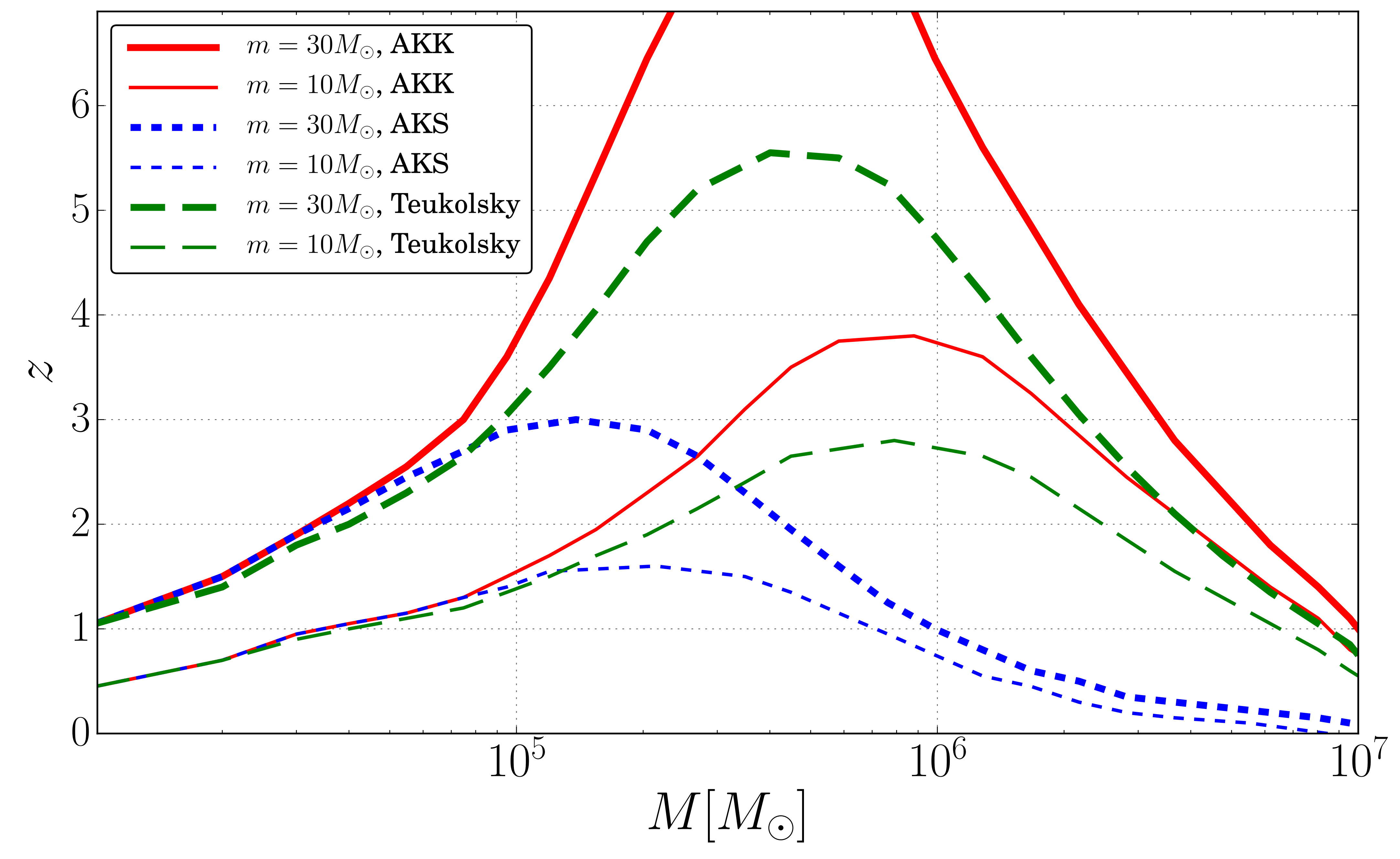
Model summary

- Twelve models in total. Model 1 is the fiducial reference model.

Model	Mass function	MBH spin	Cusp erosion	M–σ relation	N_{p}	CO mass $[M_\odot]$
M1	Barausse12	a98	yes	Gultekin09	10	10
M2	Barausse12	a98	yes	KormendyHo13	10	10
M3	Barausse12	a98	yes	GrahamScott13	10	10
M4	Barausse12	a98	yes	Gultekin09	10	30
M5	Gair10	a98	no	Gultekin09	10	10
M6	Barausse12	a98	no	Gultekin09	10	10
M7	Barausse12	a98	yes	Gultekin09	0	10
M8	Barausse12	a98	yes	Gultekin09	100	10
M9	Barausse12	aflat	yes	Gultekin09	10	10
M10	Barausse12	a0	yes	Gultekin09	10	10
M11	Gair10	a0	no	Gultekin09	100	10
M12	Barausse12	a98	no	Gultekin09	0	10

EMRIs - Event Rates

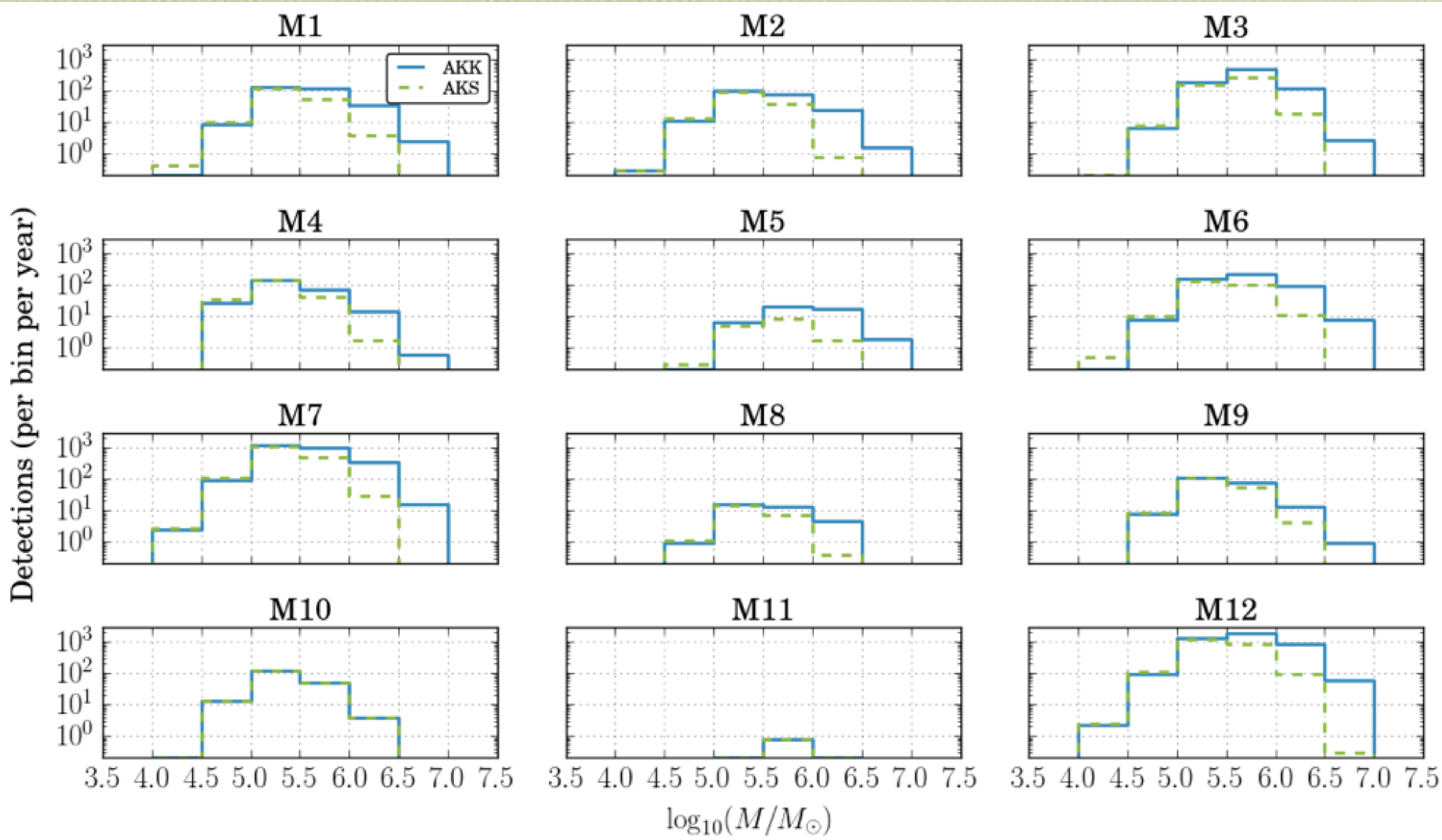
- Final ingredient is detectability criterion. Assume need SNR > 20 for detection. Compute SNR using analytic kludge waveform model (Barack & Cutler 2004), either cut off at the Kerr ISCO (AKK) or the Schwarzschild ISCO (AKS).



EMRIs - Event Rates

Model	EMRI rate [yr^{-1}] Total	Detected (AKK)	Detected (AKS)
M1	1600	294	189
M2	1400	220	146
M3	2770	809	440
M4	520 (620)	260	221
M5	140	47	15
M6	2080	479	261
M7	15800	2712	1765
M8	180	35	24
M9	1530	217	177
M10	1520	188	188
M11	13	1	1
M12	20000	4219	2279

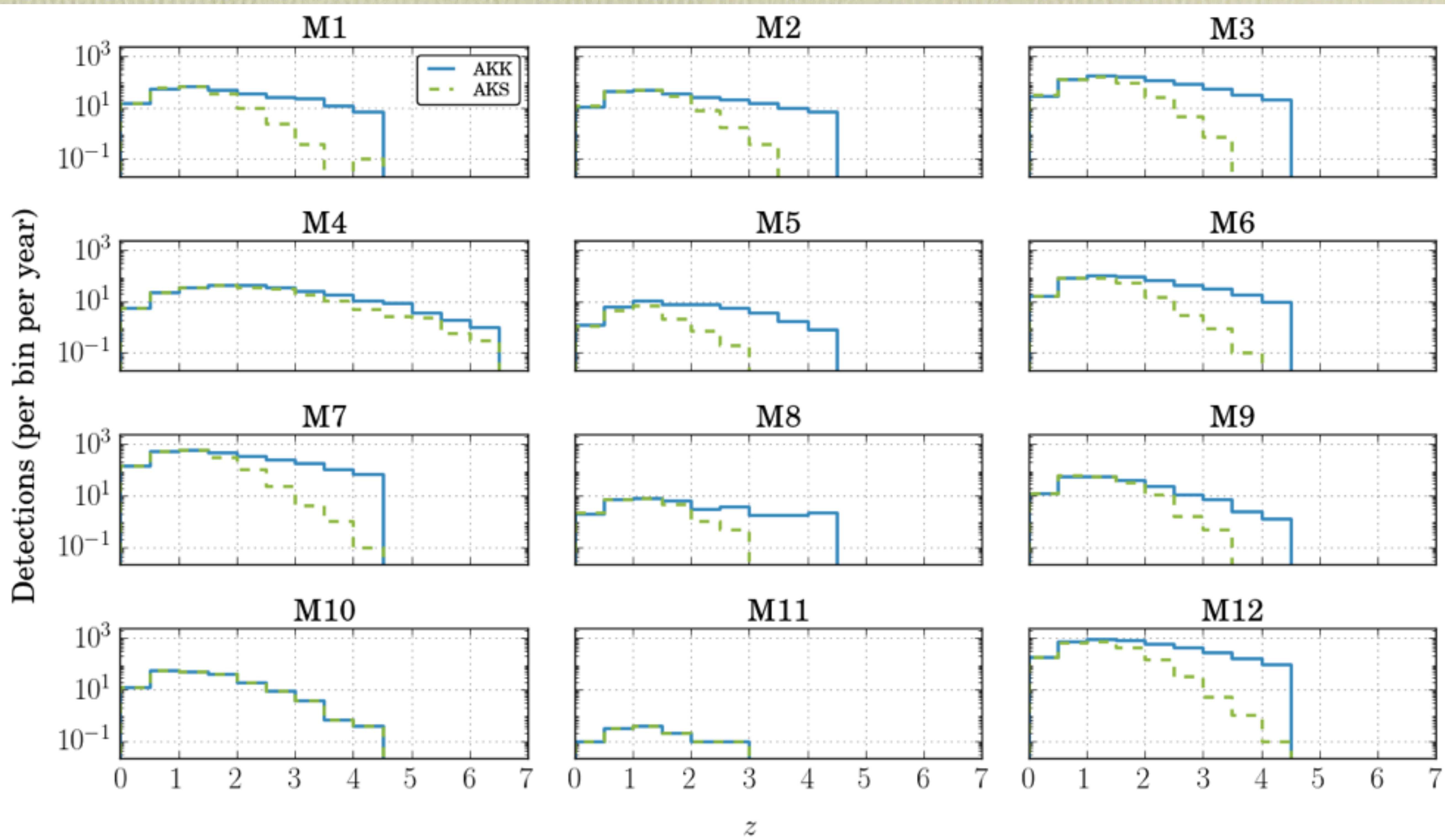
Observed Population



Observed Population

Model	Number of events in mass range				Total
	$M_{10} < 5$	$5 < M_{10} < 5.5$	$5.5 < M_{10} < 6$	$6 < M_{10}$	
M1	20 (0)	260 (60)	230 (100)	80 (60)	590 (230)
M2	20 (0)	210 (50)	160 (70)	50 (40)	440 (160)
M3	10 (0)	360 (90)	1000 (470)	240 (180)	1620 (750)
M4	50 (10)	300 (150)	140 (100)	30 (30)	520 (280)
M5	0 (0)	10 (0)	40 (20)	40 (30)	90 (50)
M6	20 (0)	300 (80)	430 (200)	200 (150)	960 (440)
M7	190 (40)	2390 (600)	2110 (930)	730 (510)	5420 (2090)
M8	0 (0)	30 (10)	30 (10)	10 (10)	70 (30)
M9	20 (0)	230 (60)	160 (70)	30 (20)	430 (160)
M10	30 (10)	240 (70)	100 (40)	10 (10)	370 (130)
M11	0 (0)	0 (0)	1 (0)	0 (0)	1 (0)
M12	190 (40)	2700 (680)	3710 (1690)	1830 (1380)	8440 (3790)

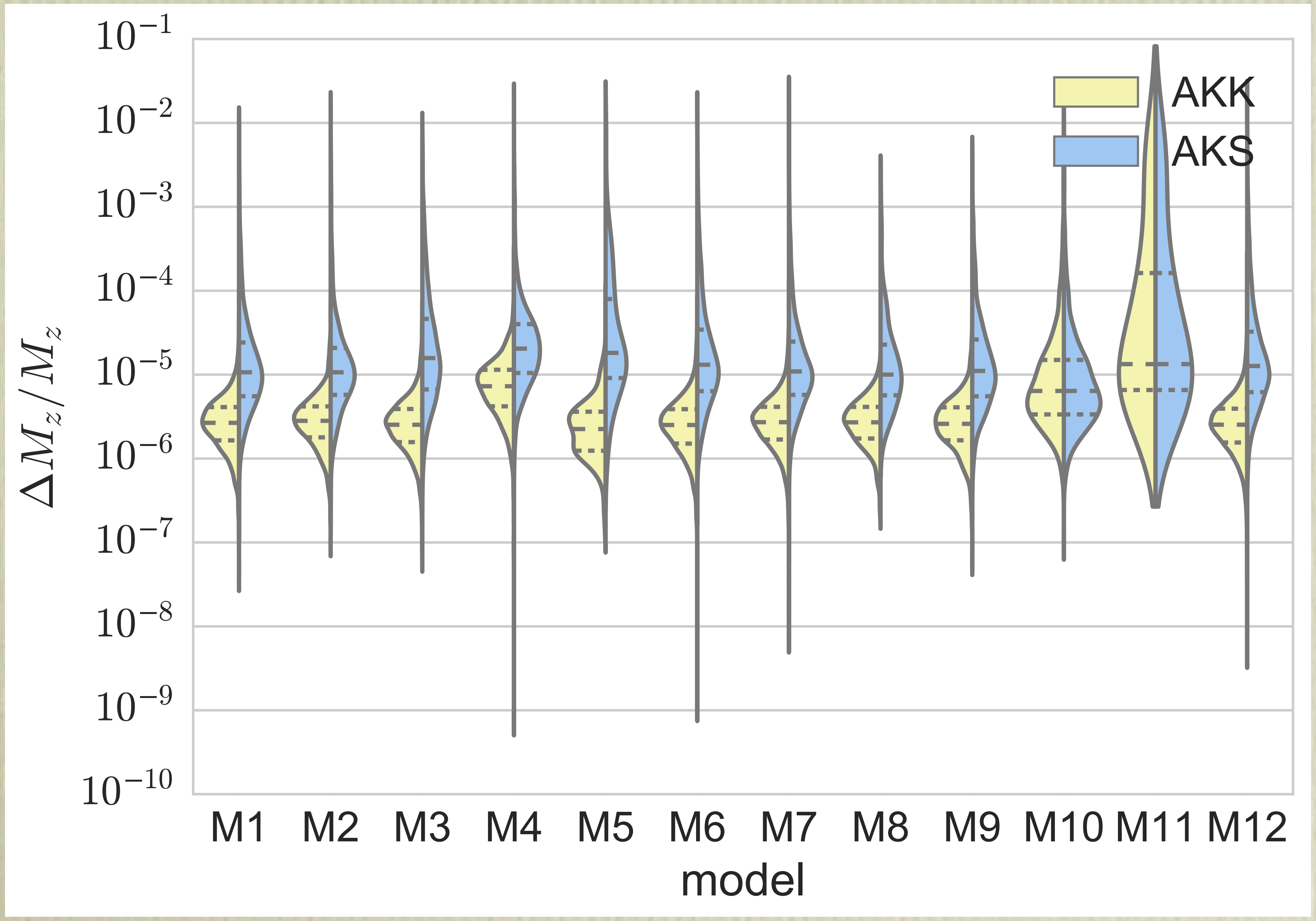
Observed Population



Science using EMRI detections

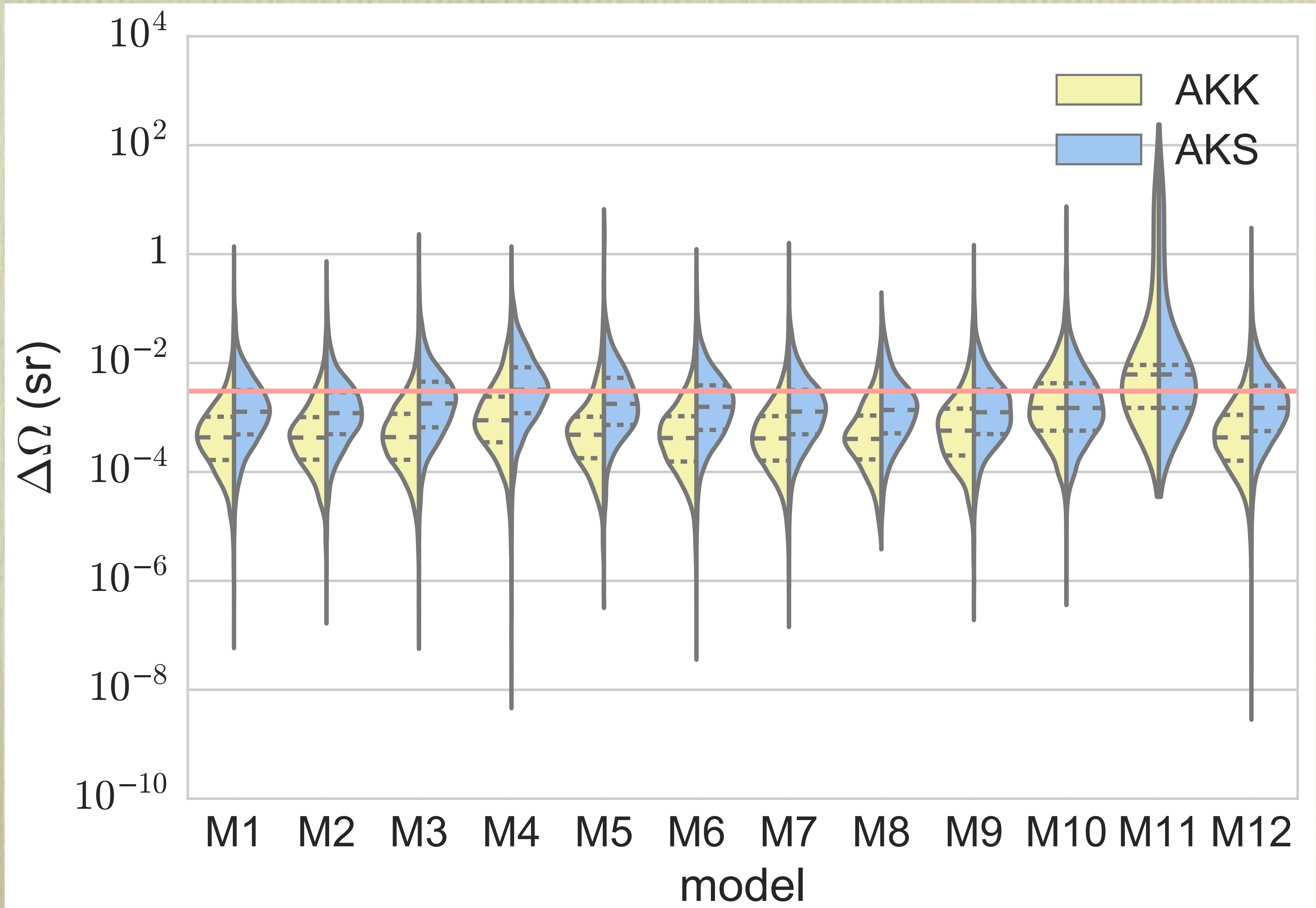
EMRI Science - Astrophysics

- 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. Typical errors ~10^{-6}–10^{-4} for intrinsic parameters.



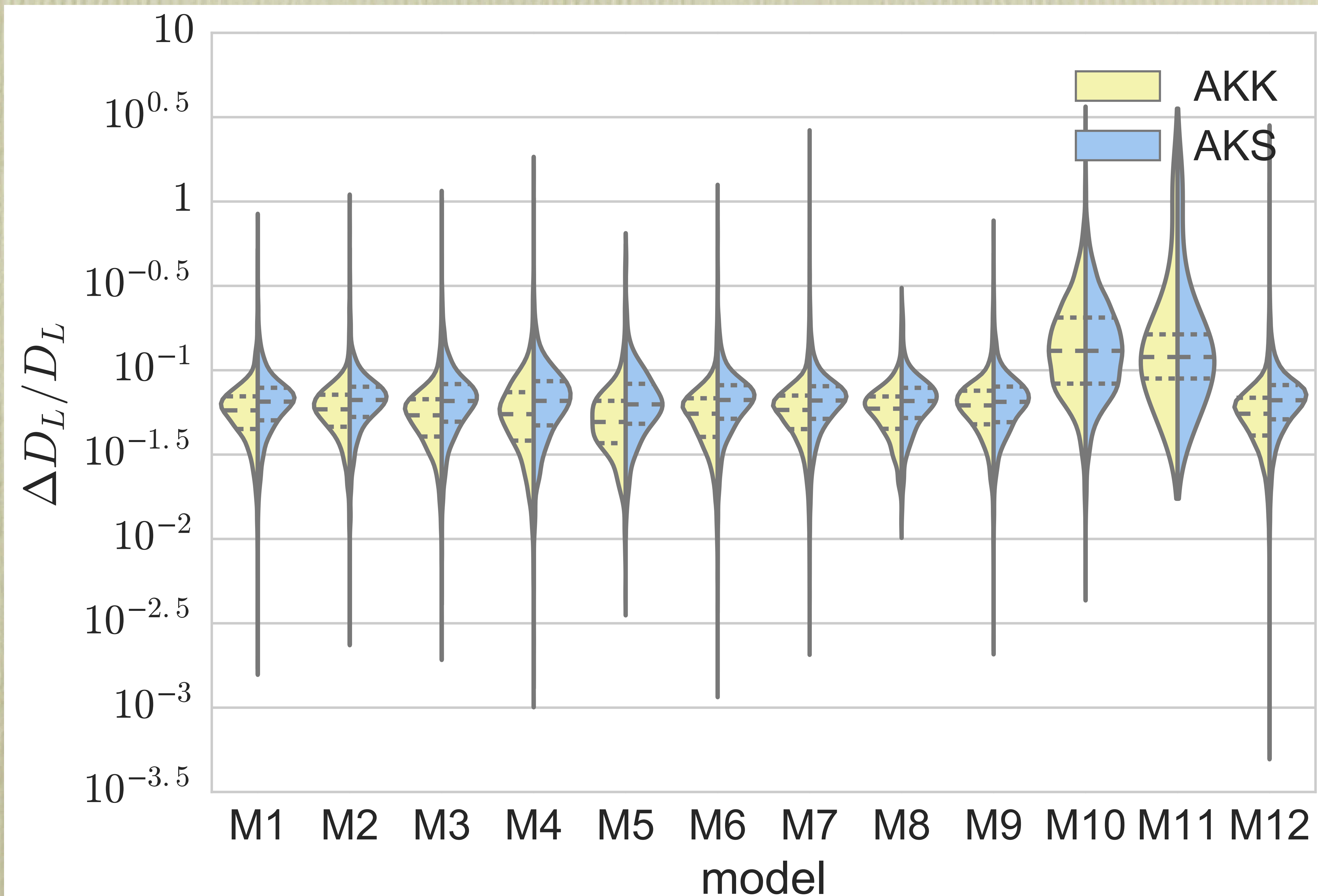
EMRI Science - Astrophysics

- Typical sky localisation precisions are a few square degrees, or ~10^{-5}–10^{-3} steradians.



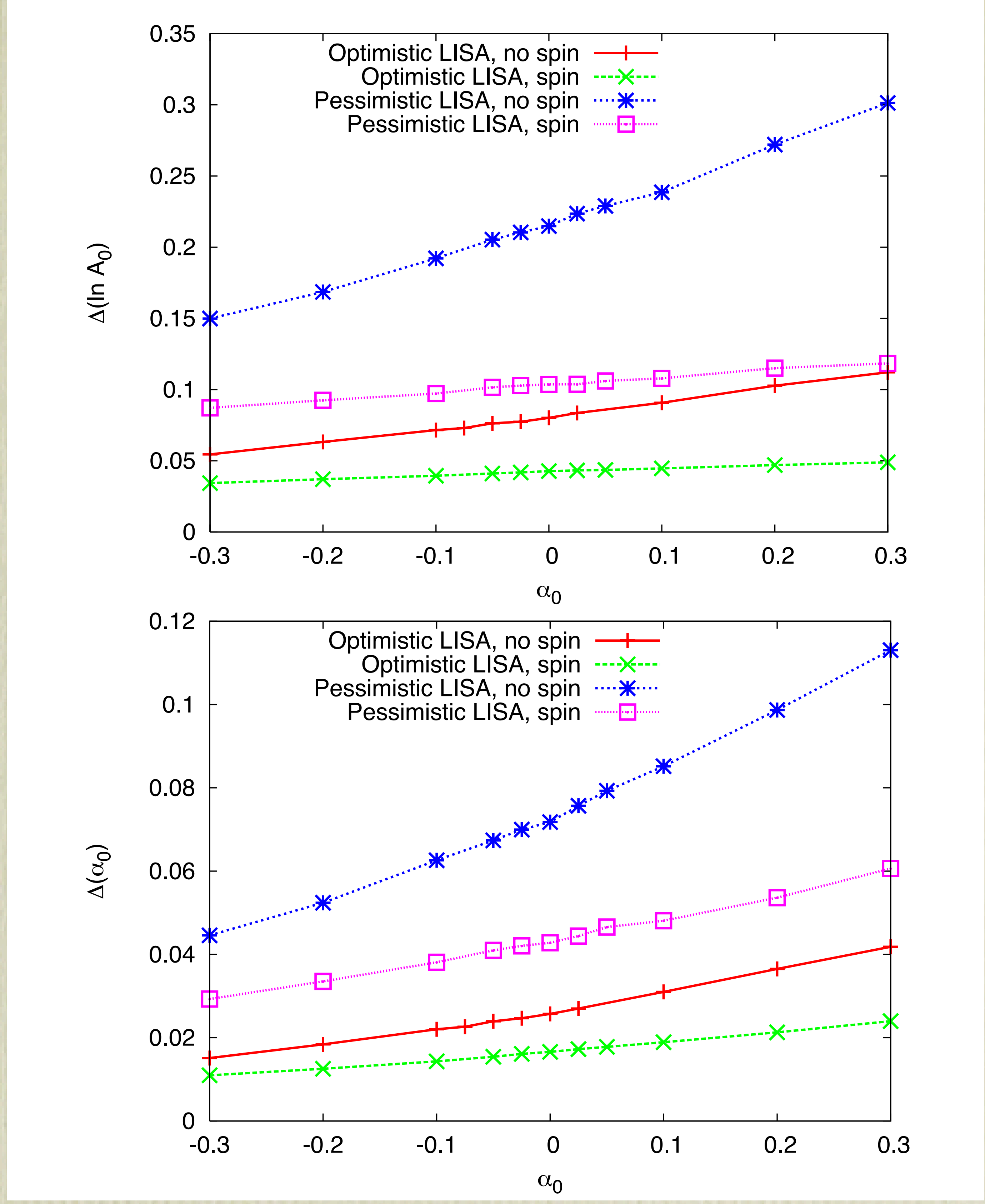
EMRI Science - Astrophysics

- Luminosity distance measured to a few percent.

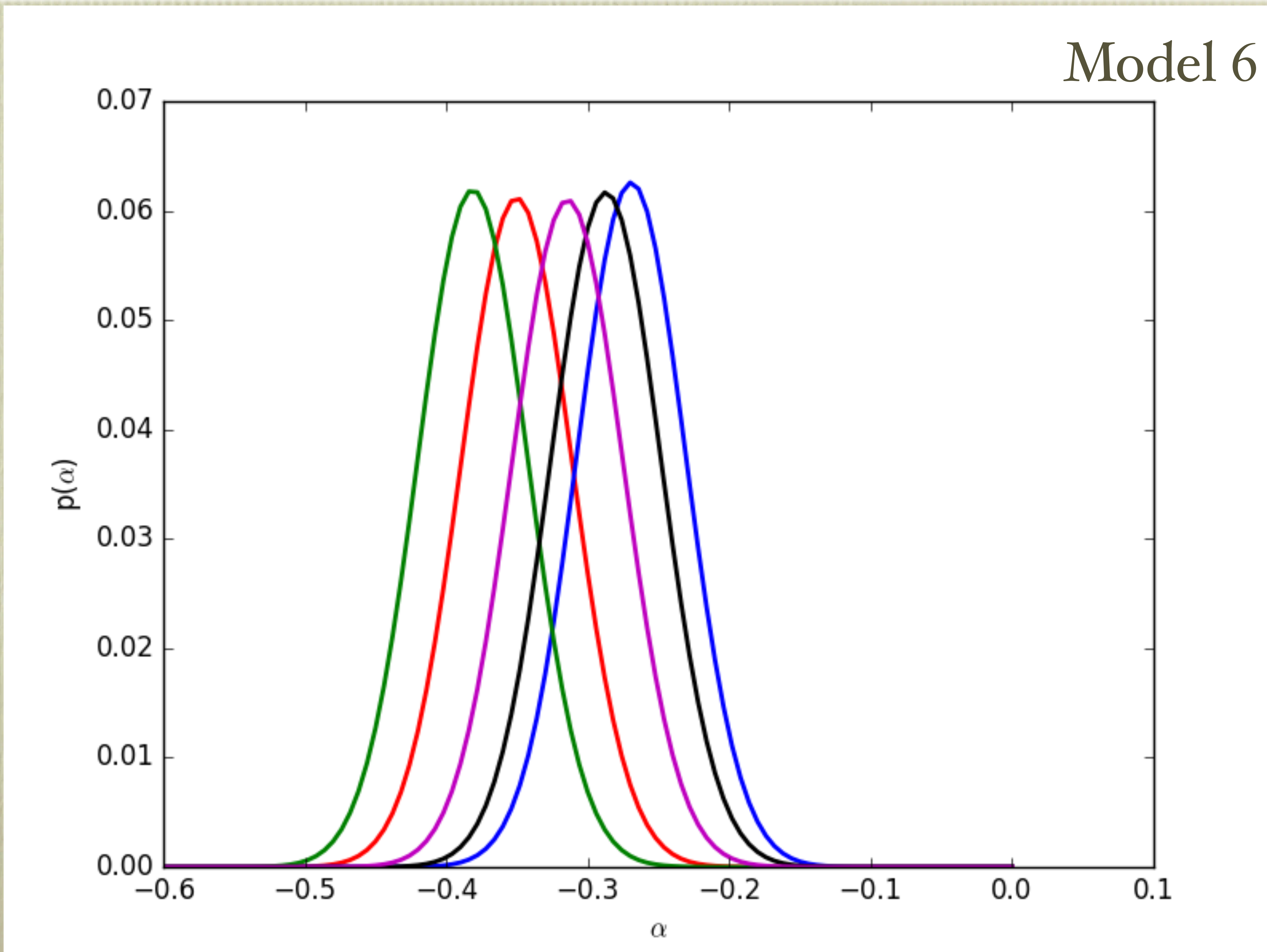


EMRI Science - Astrophysics

- 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

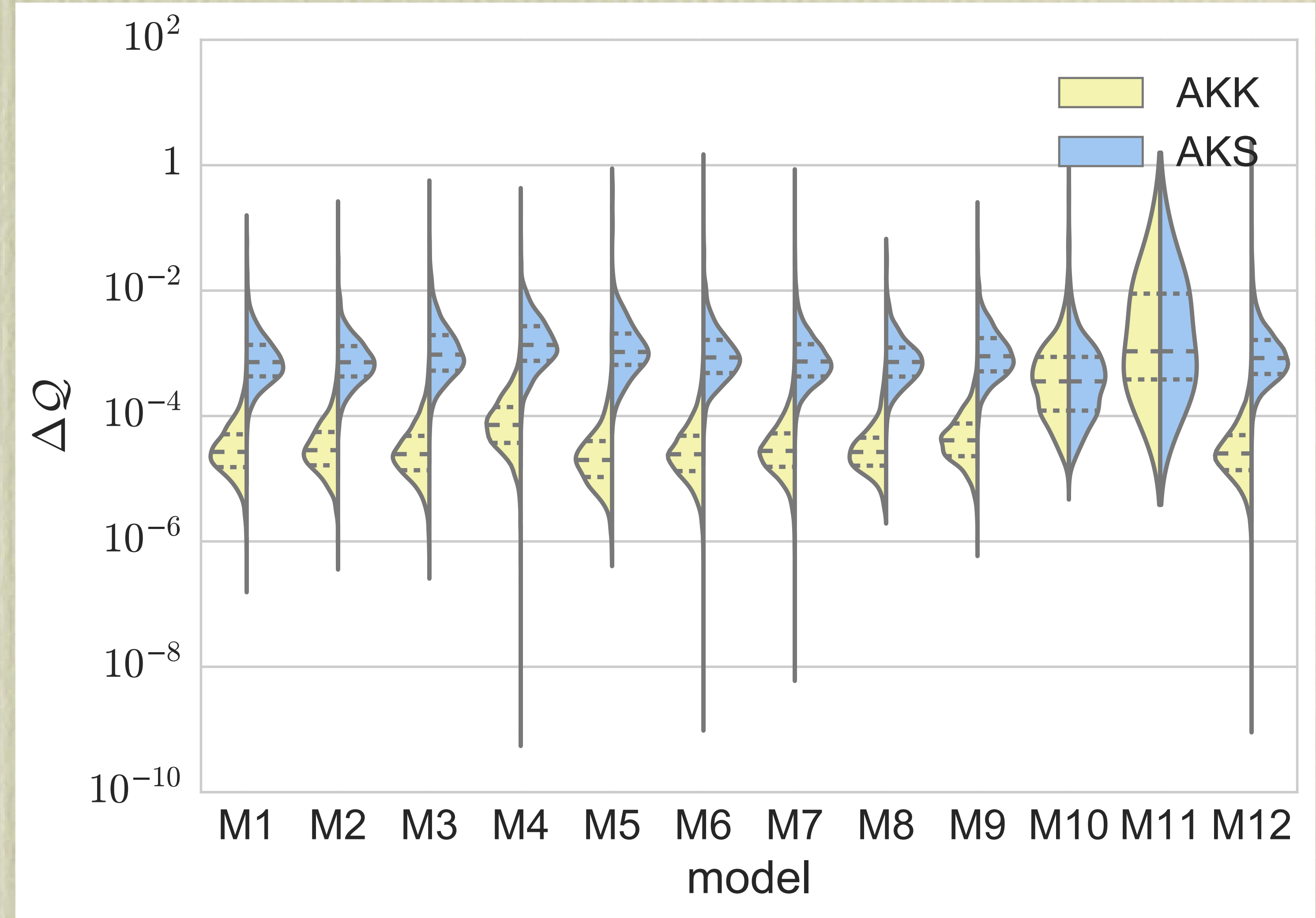


EMRI Science - Fundamental physics

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

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

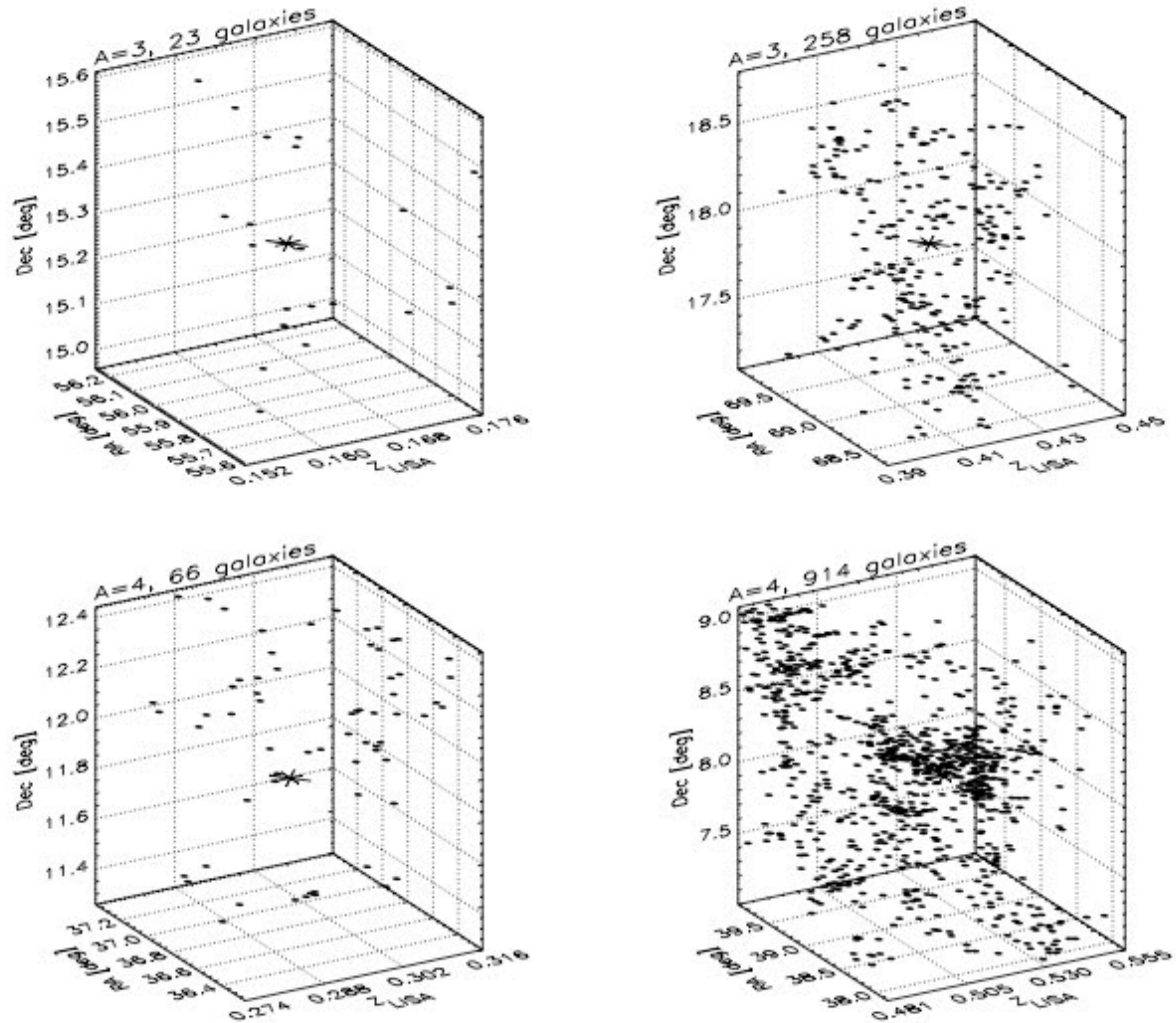
- Can detect deviations in quadrupole moment from no-hair prediction at level of 0.0001.
- These tests just rely on accurate tracking of EMRI phase over many cycles - any LISA configuration can do this to high precision.



EMRI Science - Cosmology

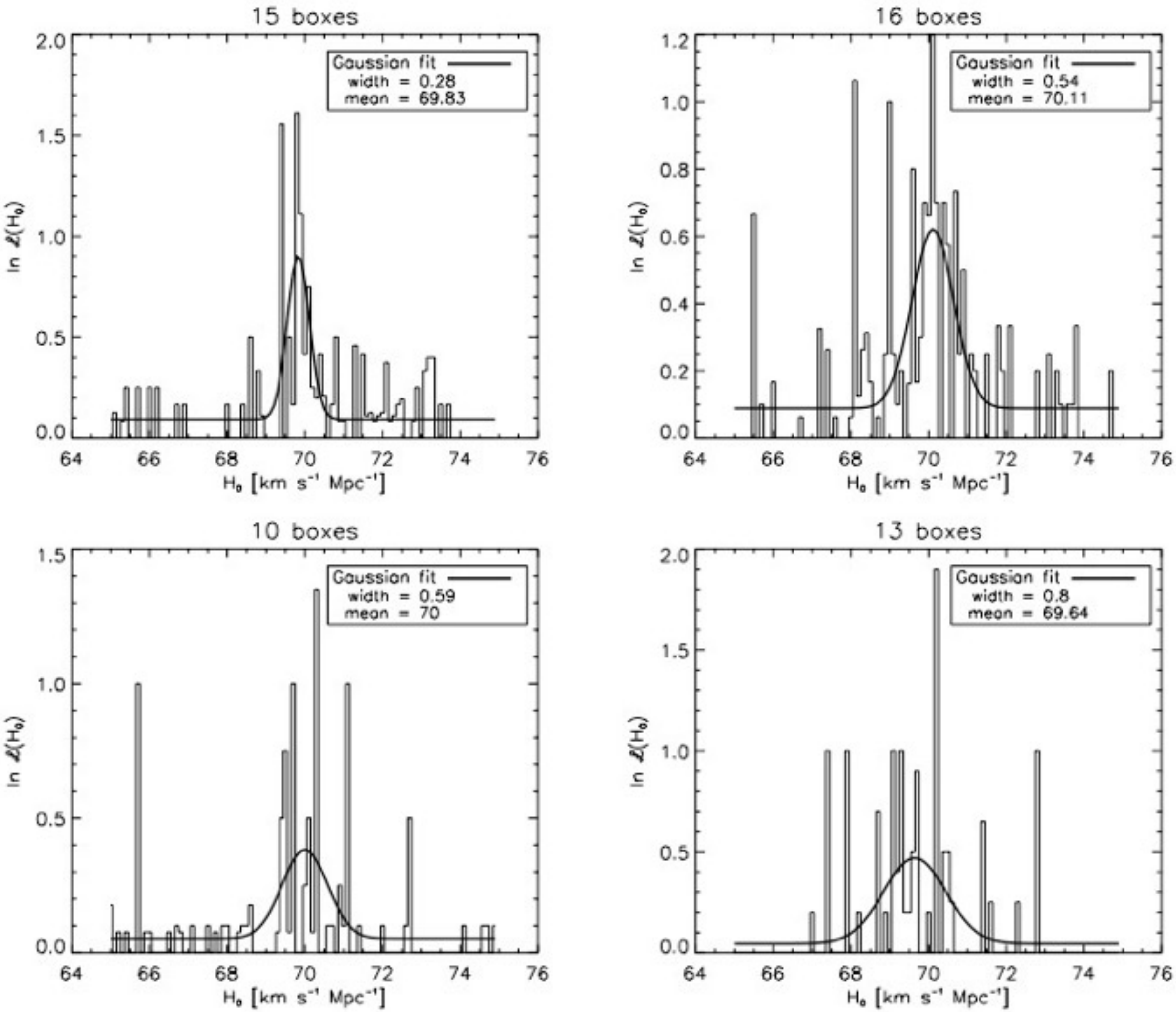
- A single EMRI event with an electromagnetic counterpart (and hence a redshift measurement) will give the Hubble constant to an accuracy of ~3%. N events give an accuracy of $\sim 3/\sqrt{N}\%$.
- Even without a counterpart, can estimate Hubble constant statistically (McLeod & Hogan 08)
  - Let every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

EMRI Science - Cosmology



McLeod & Hogan (2008)

EMRI Science - Cosmology



McLeod & Hogan (2008)

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.
  - If ~20 EMRI events are detected at $z < 0.5$, will determine the Hubble constant to ~1%.

EMRI Science - Cosmology

- Analysis assumed typical distance uncertainties for Classic LISA, but these will be achieved for some events with new configuration.

	Schwarzschild plunge condition		Kerr plunge condition	
Model	$N(z < 0.5)$	$N(z < 0.5;\ \text{small error})$	$N(z < 0.5)$	$N(z < 0.5;\ \text{small error})$
M1	30	5	29	7
M2	23	4	22	4
M3	62	15	60	16
M4	11	4	11	4
M5	2	0	3	1
M6	35	6	35	8
M7	298	48	285	52
M8	4	0	4	1
M9	25	3	25	5
M10	24	0	24	0
M11	0	0	0	0
M12	354	60	354	74

Waveform requirements for LISA data analysis

EMRI Data Analysis

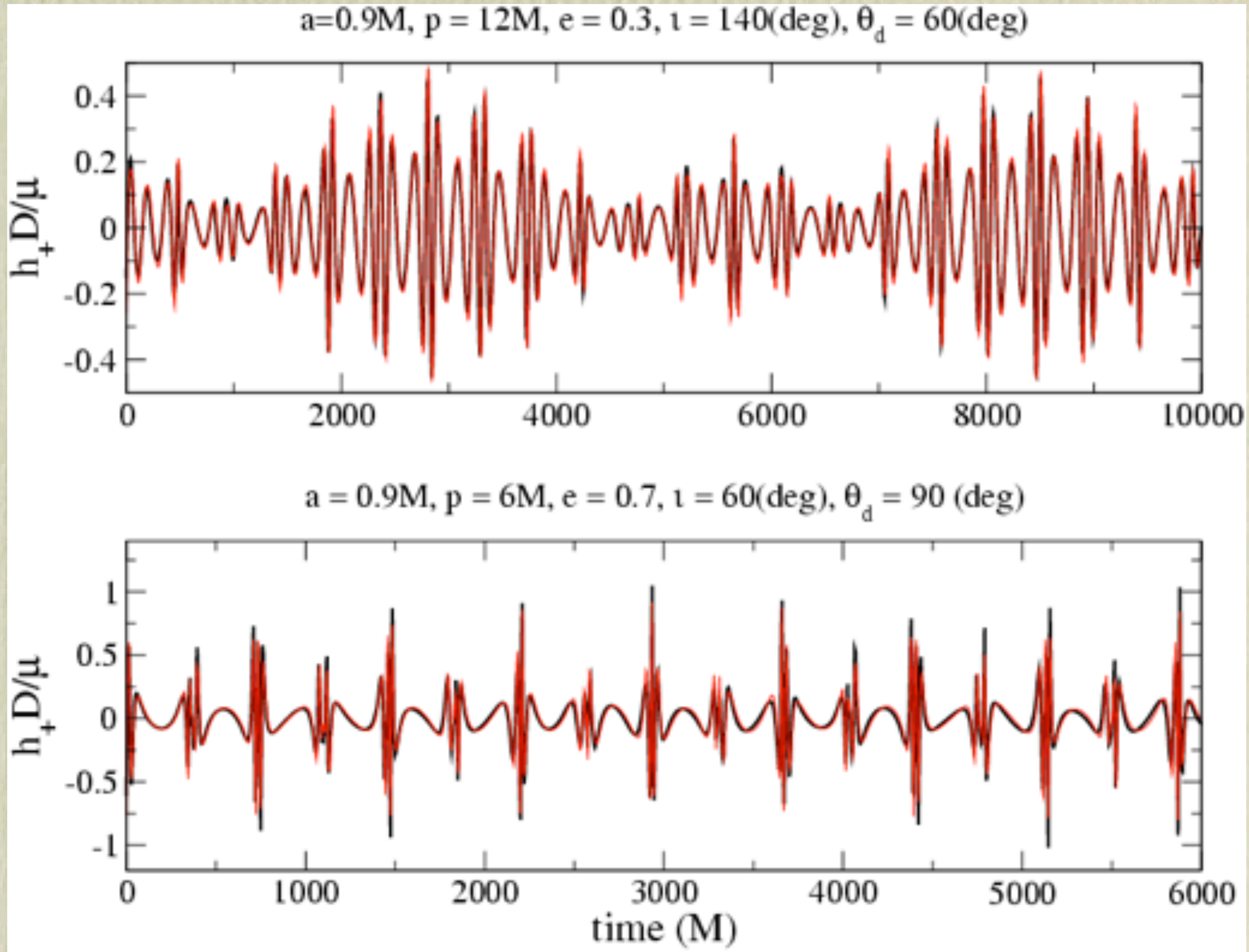
- Our ability to detect EMRIs in simulated LISA data was demonstrated in the Mock LISA Data Challenges, under idealised assumptions.

type[1]	ν (mHz)	$\mu/M_\odot$	$M/M_\odot$	e_0	θ_S	φ_S	λ	a/M^2	SNR
True	0.1920421	10.296	9517952	0.21438	1.018	4.910	0.4394	0.69816	120.5
Found	0.1920437	10.288	9520796	0.21411	1.027	4.932	0.4384	0.69823	118.1
True	0.34227777	9.771	5215577	0.20791	1.211	4.6826	1.4358	0.63796	132.9
Found	0.34227742	9.769	5214091	0.20818	1.172	4.6822	1.4364	0.63804	132.8
True	0.3425731	9.697	5219668	0.19927	0.589	0.710	0.9282	0.53326	79.5
Found	0.3425712	9.694	5216925	0.19979	0.573	0.713	0.9298	0.53337	79.7
True	0.8514396	10.105	955795	0.45058	2.551	0.979	1.6707	0.62514	101.6
Found	0.8514390	10.106	955544	0.45053	2.565	1.012	1.6719	0.62534	96.0
True	0.8321840	9.790	1033413	0.42691	2.680	1.088	2.3196	0.65829	55.3
Found	0.8321846	9.787	1034208	0.42701	2.687	1.053	2.3153	0.65770	55.6
Blind									
True	0.1674472	10.131	10397935	0.25240	2.985	4.894	1.2056	0.65101	52.0
Found	0.1674462	10.111	10375301	0.25419	3.023	4.857	1.2097	0.65148	51.7
True	0.9997627	9.7478	975650	0.360970	1.453	4.95326	0.5110	0.65005	122.9
Found	0.9997626	9.7479	975610	0.360966	1.422	4.95339	0.5113	0.65007	116.0

Babak, JG & Porter (2009)

Kludge Waveforms

- Most algorithms rely on *matched filtering* - need waveforms.
- **But**, have various kludge waveforms (e.g., *analytic kludge*, *numerical kludge*, *augmented analytic kludge* etc. — N. Warburton talk).
- Some missing features, but these can be incorporated. Improved kludges should be able to match EMRI waveforms for O(months) or even O(year).
- Enough for **detection** and **astrophysical parameter estimation** [e.g., to get precision of $O(10^{-2})$ if not $O(10^{-4})$].



Self-force Waveforms

- Accurate waveforms from the self-force programme will be essential for
  - **Calibration of approximations**: kludges include various elements that have been fit to the results of perturbative calculations. These fits can be improved and new features included as perturbation theory calculations are completed.
  - **Validation**: need accurate waveforms to validate approximations prior to LISA data analysis; will also want to compare observed signals to accurately modelled signals (as for GW150914).
  - **Tests of general relativity/the no-hair theorem**: these rely on constraining O(1 cycle) differences from our predictions. Need the model to be at least as accurate as the size of the GR deviation being tested.

Summary

- LISA is starting to happen now and EMRIs are a key element within the scientific objectives.
- Have now properly explored the astrophysical uncertainties for the first time. A range of plausible models all give reasonable numbers of EMRI detections, prediction tens to thousands of observed events.
- We will precisely measure the parameters of every observed event. Therefore, irrespective of the model, EMRIs have fantastic potential
    - **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.
- EMRI data analysis will rely on waveform models. Kludges may be sufficient for detection but self-force models needed for calibration of approximations, validation and for performing precise tests of GR.