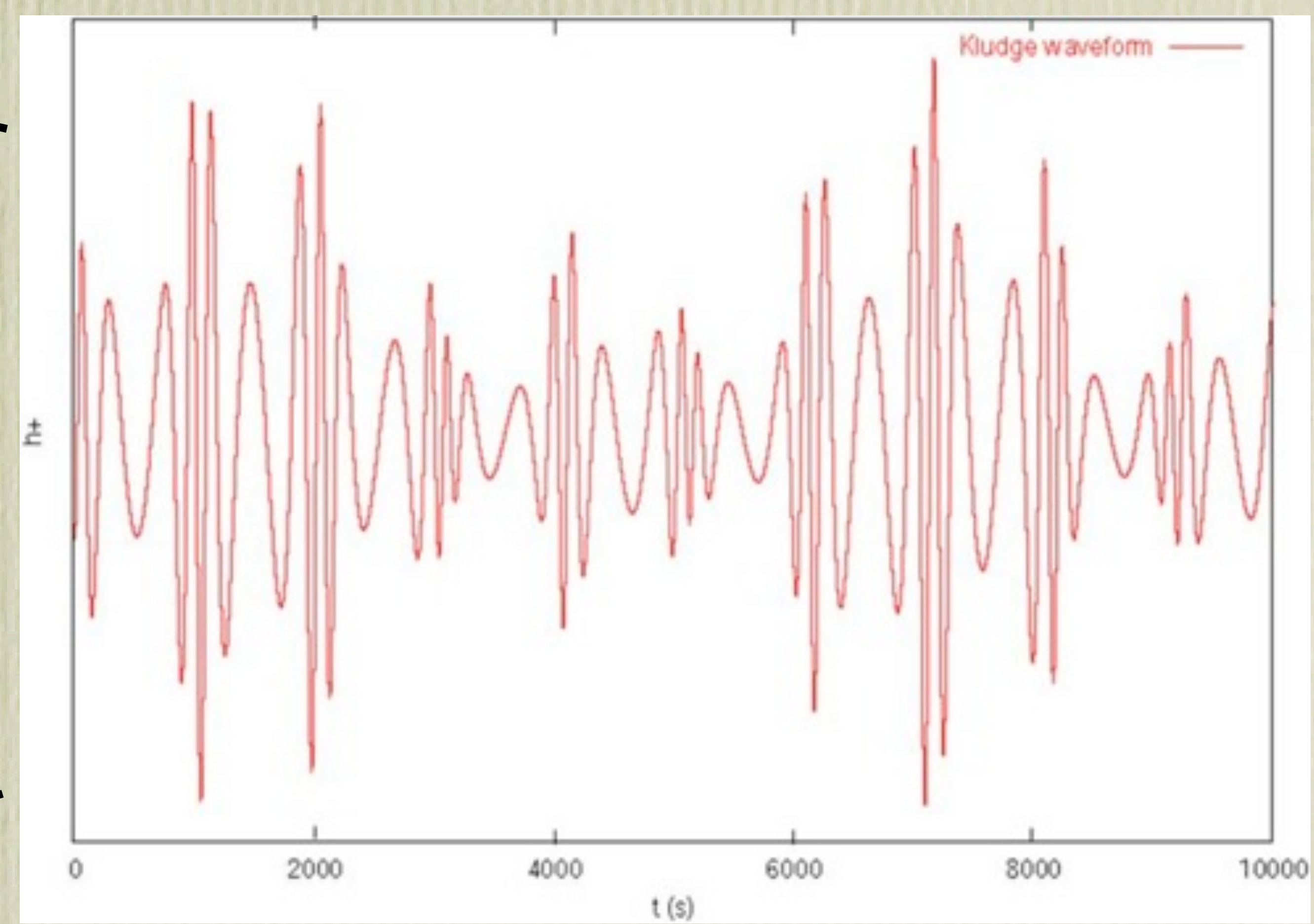
Prospects for detection of extreme-mass-ratio inspirals

Jonathan Gair (IoA, Cambridge)

Capra Meeting, Dublin, July 15th 2013



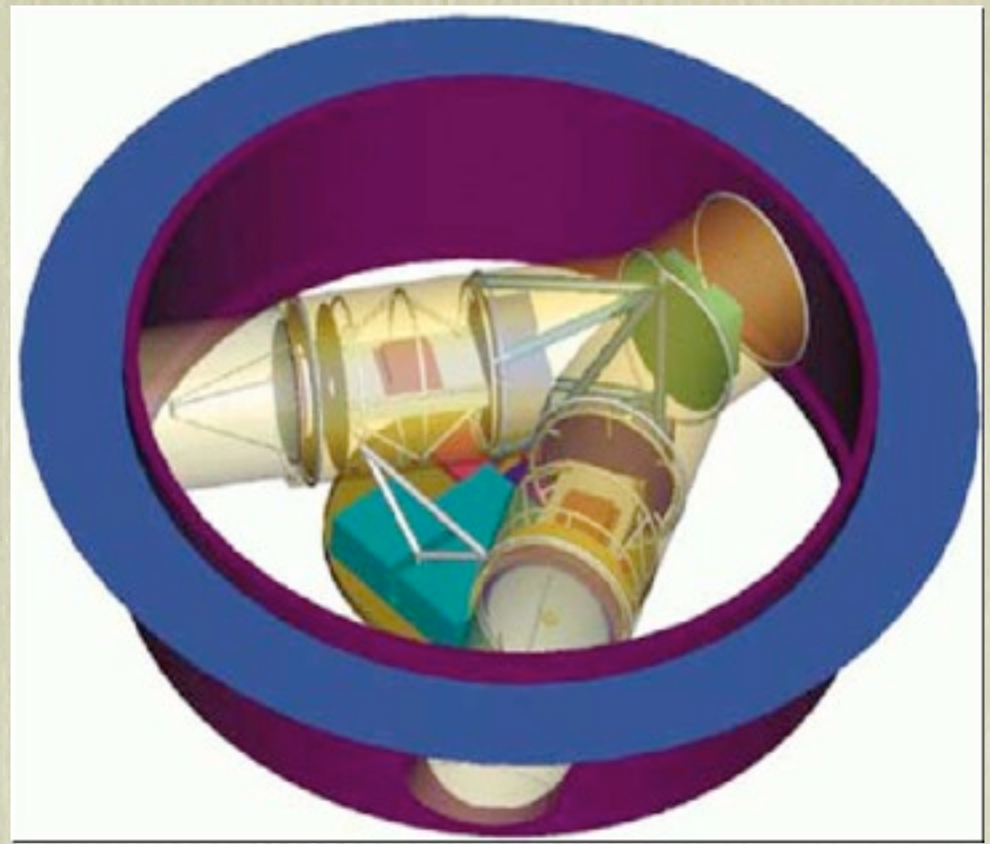
Talk Outline

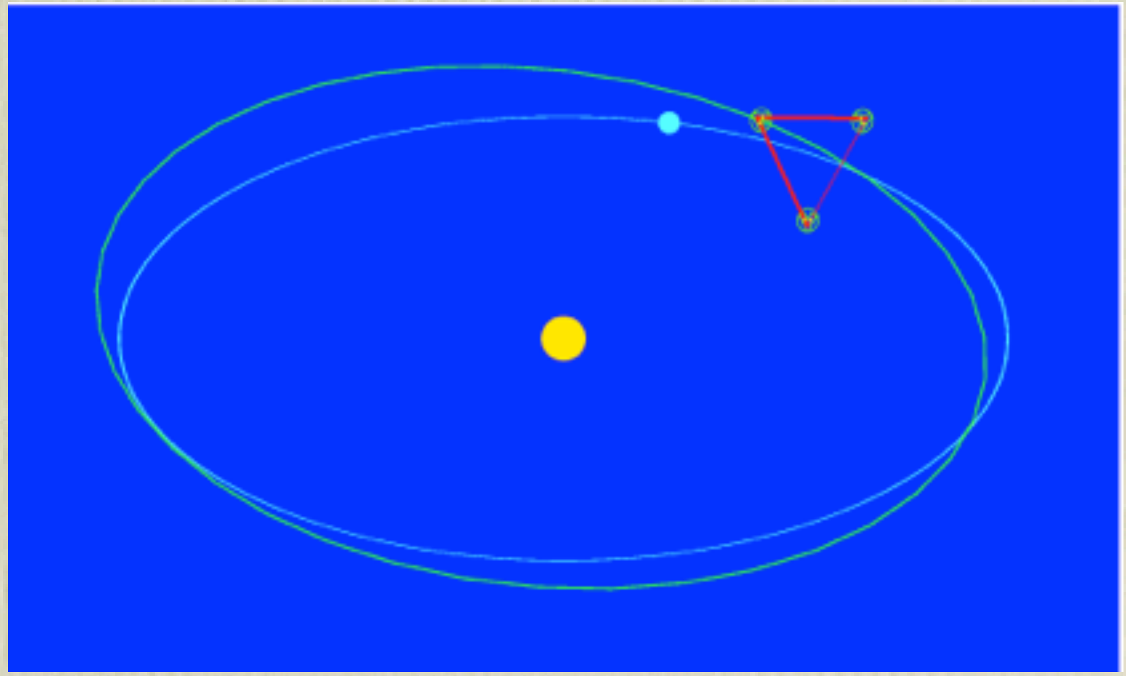
- Three ingredients required for EMRI detection
  - A milihertz gravitational wave detector
    - LISA/eLISA rescope exercise. L1 selection.
    - L2/L3 science theme selection.
  - A sufficient astrophysical event rate
    - EMRI signal to noise ratios.
    - Event rates for eLISA. Likely parameter distributions.
  - Ability to detect EMRIs in the detector output
    - Detection algorithms.
    - Mock LISA Data Challenges.
- Science with EMRI observations.

Ingredient I: a detector!

LISA

- Constellation of 3 spacecraft on a heliocentric Earth-trailing orbit.
- Spacecraft are 5 million km apart and linked by lasers, two along each arm.
- Constellation rotates as it orbits – provides some sky position information.
- Joint NASA/ESA mission.
- Sensitive to gravitational waves with frequencies $10^{-4} - 1\text{Hz}$
- Possible LISA sources include white-dwarf binaries, SMBH mergers, stochastic background, cosmic strings etc. and EMRIs.





NASA funding crisis

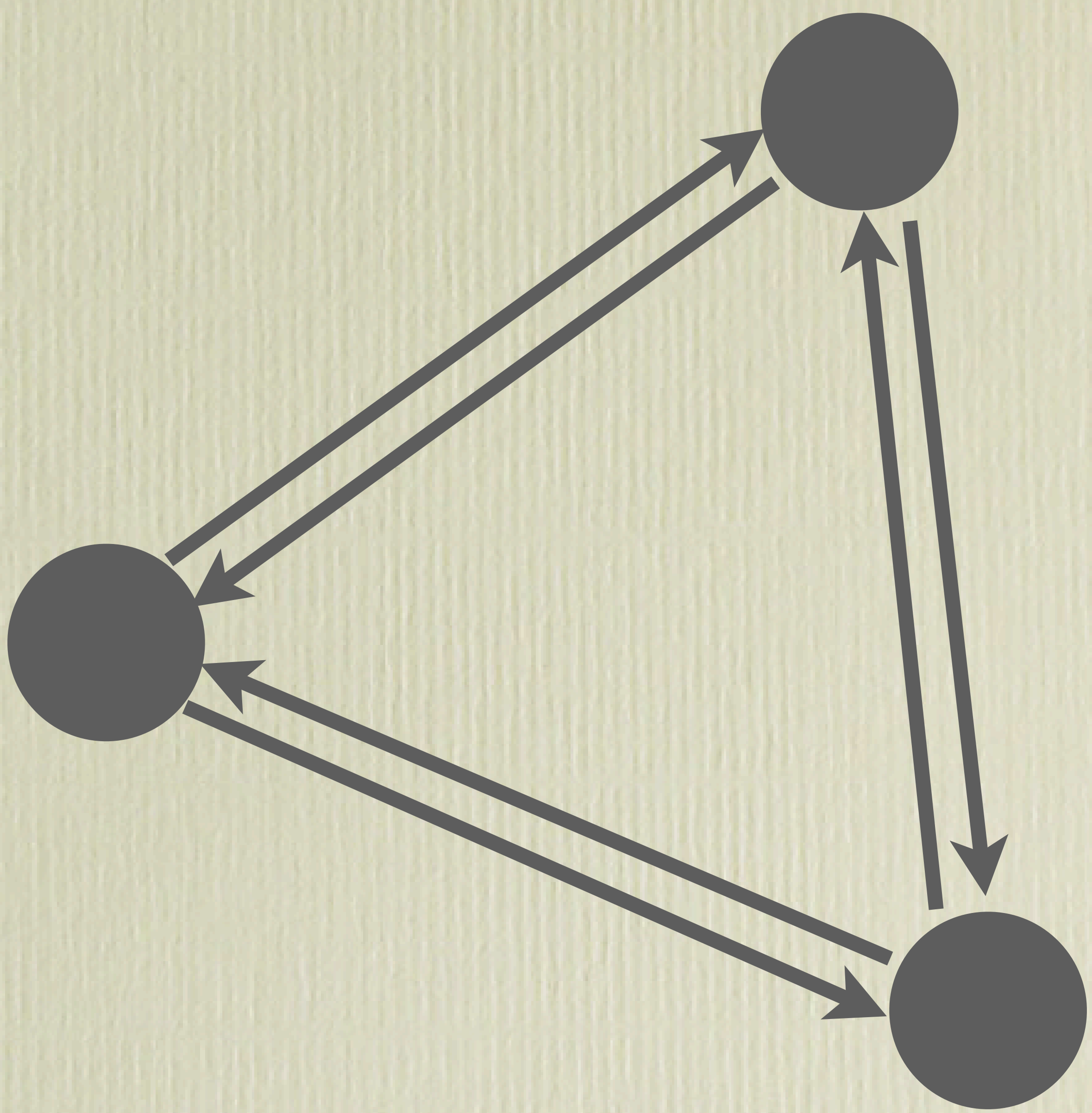
- In April 2011, due to funding shortages and cost overruns of JWST, NASA announced that it would no longer be able to contribute to the joint L-class mission with ESA scheduled for the end of this decade (~2018).
- Three missions in competition for this slot
  - **LISA** - space-based gravitational wave observatory.
  - **IXO** - X-ray mission (formerly Zeus and Constellation X).
  - **Laplace** - planetary mission to Jupiter; two probes, one that would visit Europa and one Ganymede.
- ESA's response was to withdraw from its commitment to a joint mission, and pursue ESA-only mission concepts for each project.

ESA L1 Competition

- Goal: fly a large space observatory by 2022.
- Budget: 850 million Euros + contributions from nation agencies.
- Gravitational mission concept given the working title **New Gravitational Observatory (NGO)**.
- Classic LISA design would have cost ~1.3 billion Euros. Needed to propose a new design within the tighter budget cap.
- Various components to a mission where costs can be reduced
  - **Launcher** - use (several) Soyuz, rather than an Ariane.
  - **Propellant** - closer orbit, shorter mission lifetime.
  - **Spacecraft/Payload** - reduce size and weight of the satellites.

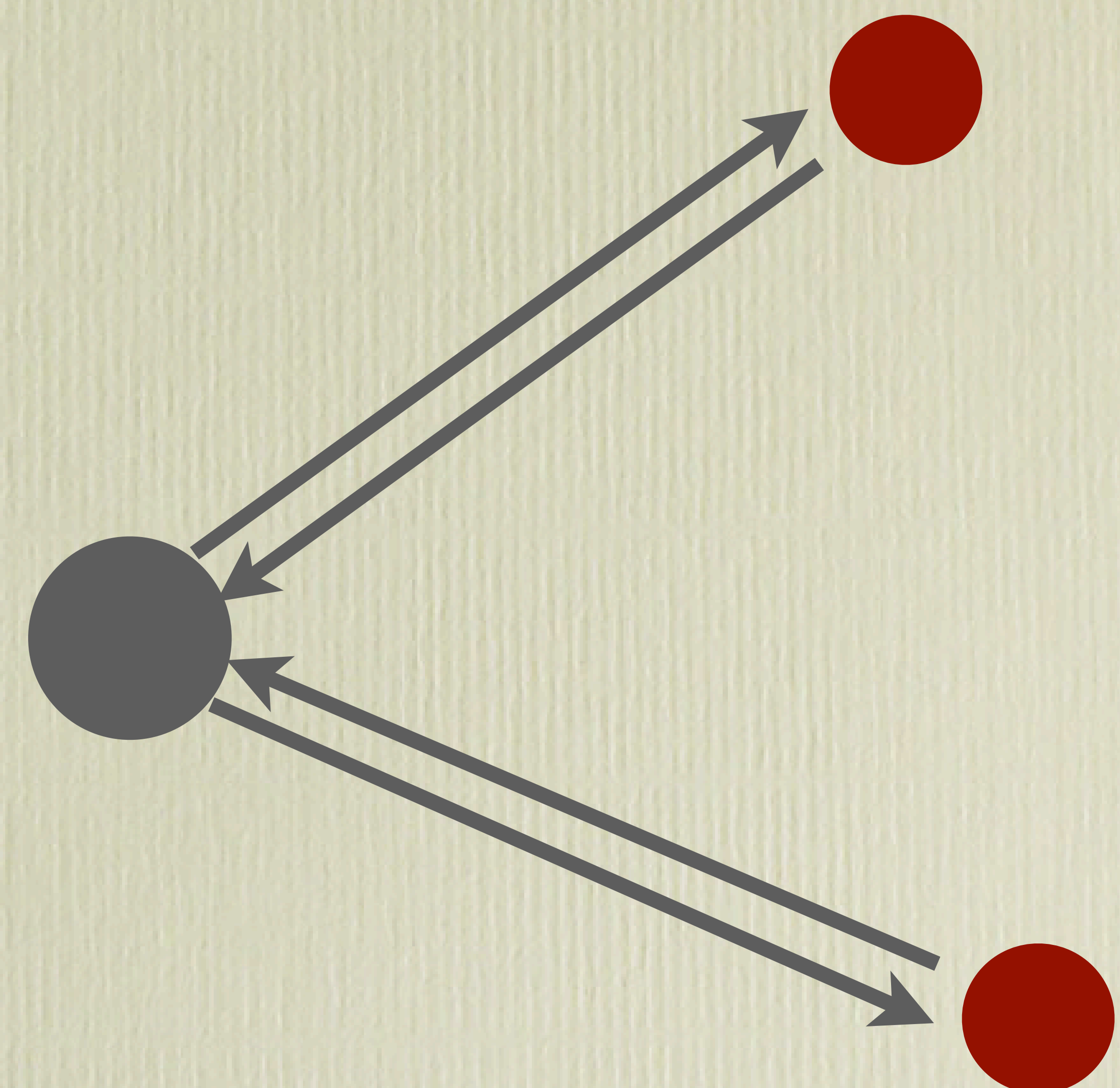
4-link versus 6-link

- Baseline LISA proposal called for **three** identical spacecraft, linked with **six** laser links, **two** along each arm. Response equivalent to **two** independent right-angle Michelson interferometers.



4-link versus 6-link

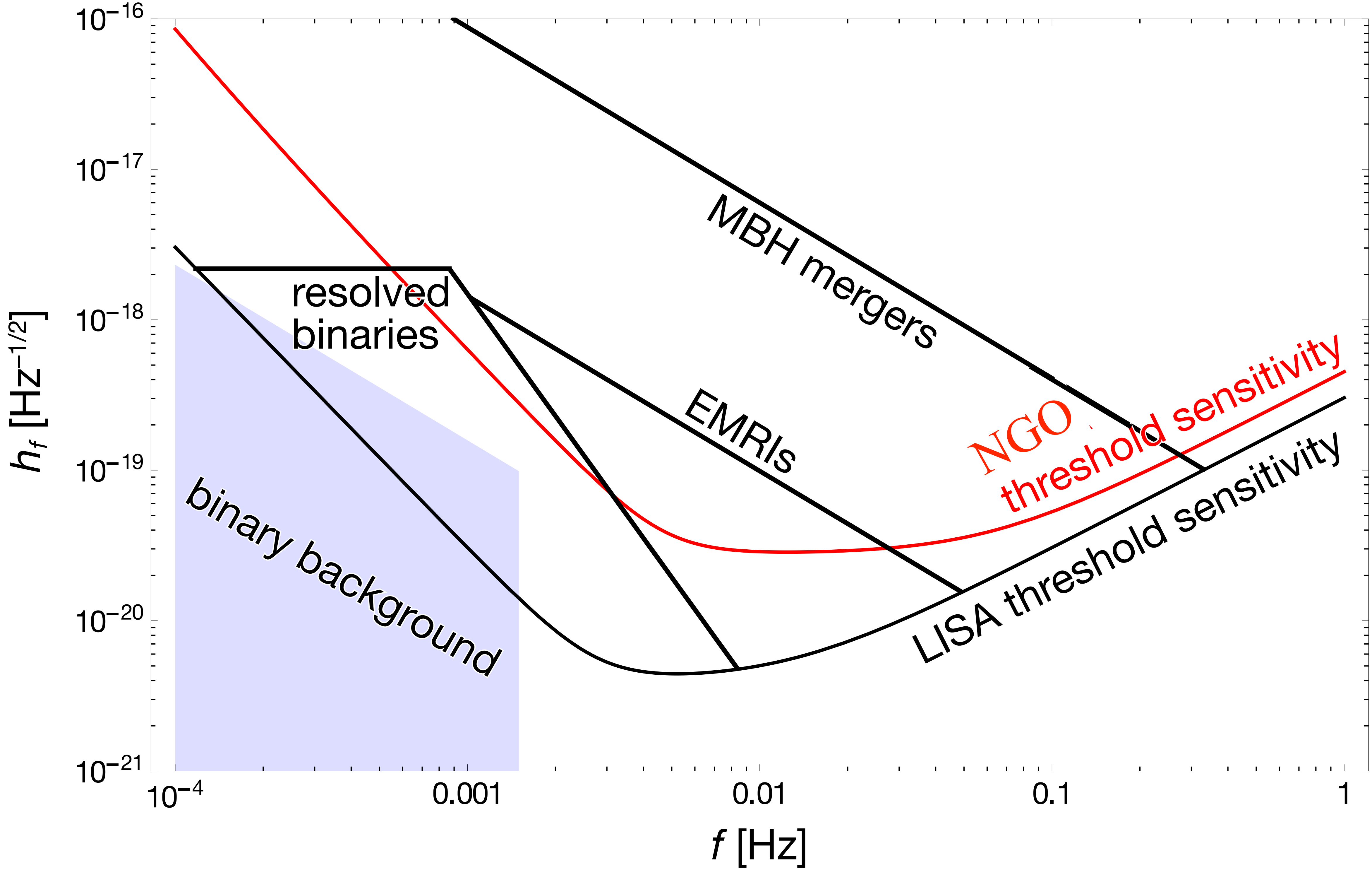
- Baseline LISA proposal called for **three** identical spacecraft, linked with **six** laser links, **two** along each arm. Response equivalent to **two** independent right-angle Michelson interferometers.
- Also consider a **mother-daughter** configuration, with only **four** laser links and equivalent response to **one** Michelson.
- Possible launch configuration: two Soyuz launchers - one with mother, one with daughters.



NGO Design

- The NGO concept submitted for the L1 competition had several differences to classic LISA
  - **4-links**: baseline for NGO was the mother-daughter configuration versus 6-link/2-interferometer LISA.
  - **1 million km armlength**: versus 5 million km for LISA.
  - **Acceleration noise performance** of 3 fm s^{-2} $Hz^{-1/2}$, comparable to LISA Pathfinder, factor of ~5 worse than LISA.
  - **20cm telescopes** compared to 40cm for LISA.
  - **9º Earth trailing "drift-away" orbit**: allow orbit to drift saves fuel. LISA would have been 20º and not drifting.
  - **2 year nominal mission lifetime** versus five years for LISA. Partially determined by orbit and arm length.

NGO Sensitivity Curve



L1 Launch Decision

- ESA's SPC committee met on April 4th-6th 2012 to make decision for the L1 mission. Outcome was disappointing.

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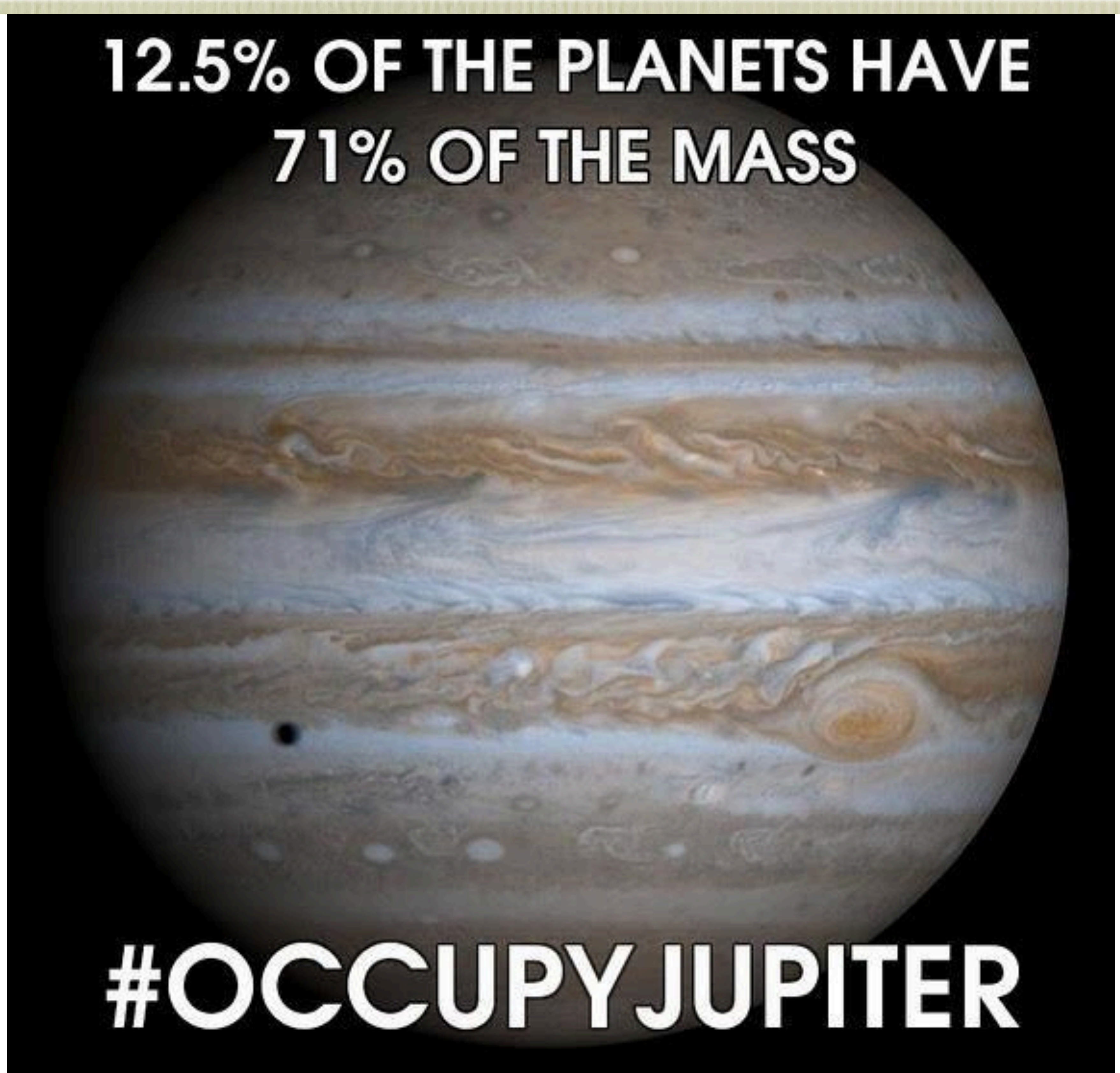
- The SPC "unanimously recognized" the "high scientific value" of NGO.
- The SPC "recognized" the "science value" of Athena.
- The SPC recommended the selection of JUICE.
- NGO was the unanimous winner in the categories of scientific value, strategic value for Europe and strategic value for science. Lost out due to uncertainties over technology, timescale and cost.
- Political motivations were probably also a factor.....

L1 Launch Decision



What next? - eLISA consortium

- After 9th LISA Symposium in Paris, a new eLISA consortium was formed
  - "During the 9th international LISA Symposium, held May 21 – 25 in Paris, the international LISA* community analyzed the new situation after ESA's decision to choose JUICE for Europe's next large space science mission. As the eLISA** mission, despite not being selected, was reported to have been unanimously ranked first by ESA's scientific review committee in terms of scientific interest, strategic value for science and strategic value for the projects in Europe, the community is in good spirits: this is the first time that any space agency committee has ranked a gravitational wave observatory as the agency's highest scientific priority. In order to prepare a strongest possible bid for the next launch opportunity the community has decided to continue its collaboration as the self-funded and independent eLISA consortium."

eLISA Consortium

- eLISA Consortium had first meeting October 22nd-23rd 2012 in Paris. Seven working groups were established
  - **Science of measurement** - convenors: G Heinzel, H Halloin, W Weber.
  - **Data analysis** - S Babak, M Hewitson, M Hueller, E Porter.
  - **Astrophysical black holes** - A Sesana.
  - **Extreme-mass-ratio inspirals** - C Sopuerta, P Amaro-Seoane
  - **Ultracompact binaries** - G Nelemans.
  - **Cosmology** - C Caprini.
  - **Tests of fundamental laws** - J Gair, P Grandclement.
- Similar structure now being established in US. Plan to have European meetings every ~6 months plus more frequent working group meetings/telecons. Sign up at http://www.elisascience.org
- Join the LISA community on Facebook, Google+ and Twitter.

eLISA Consortium

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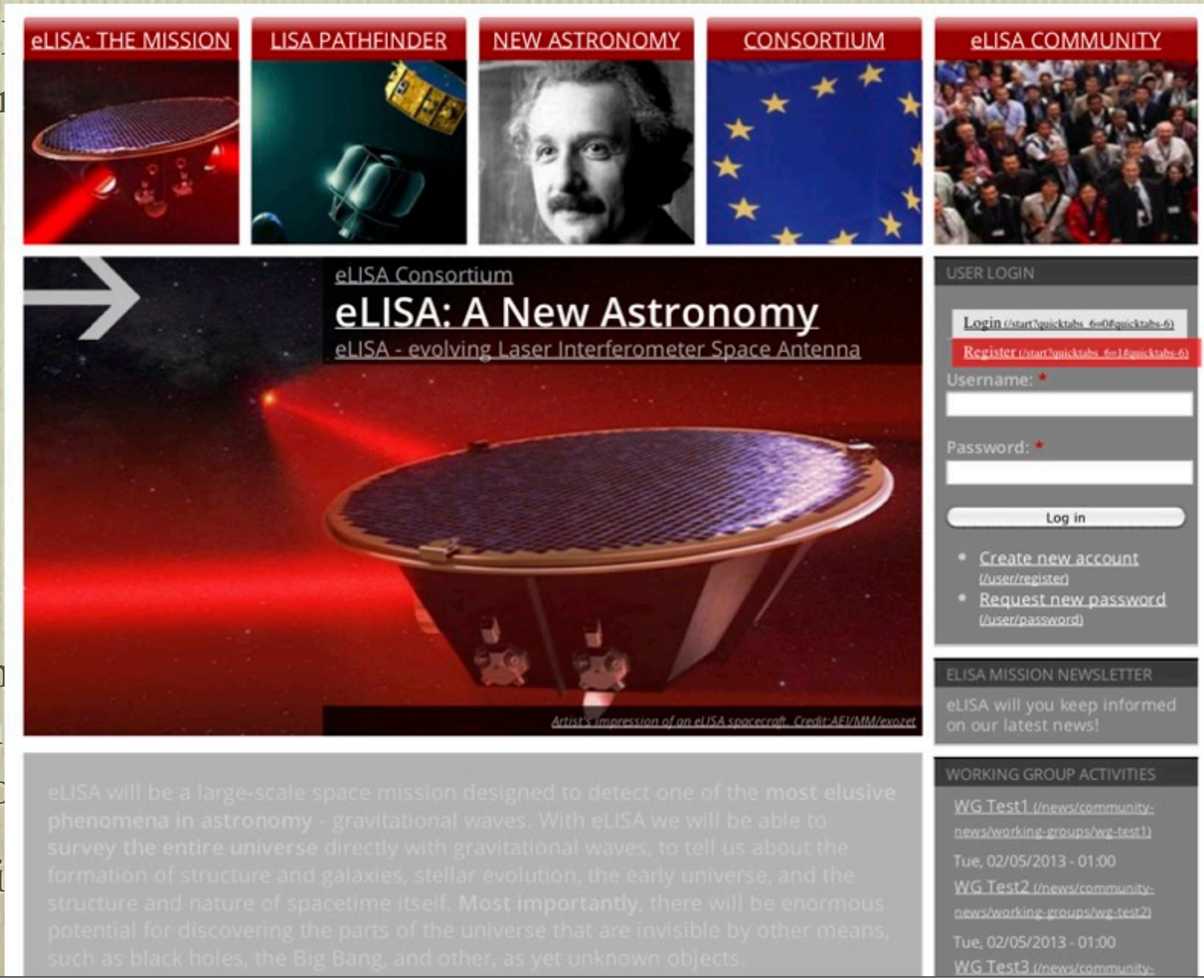
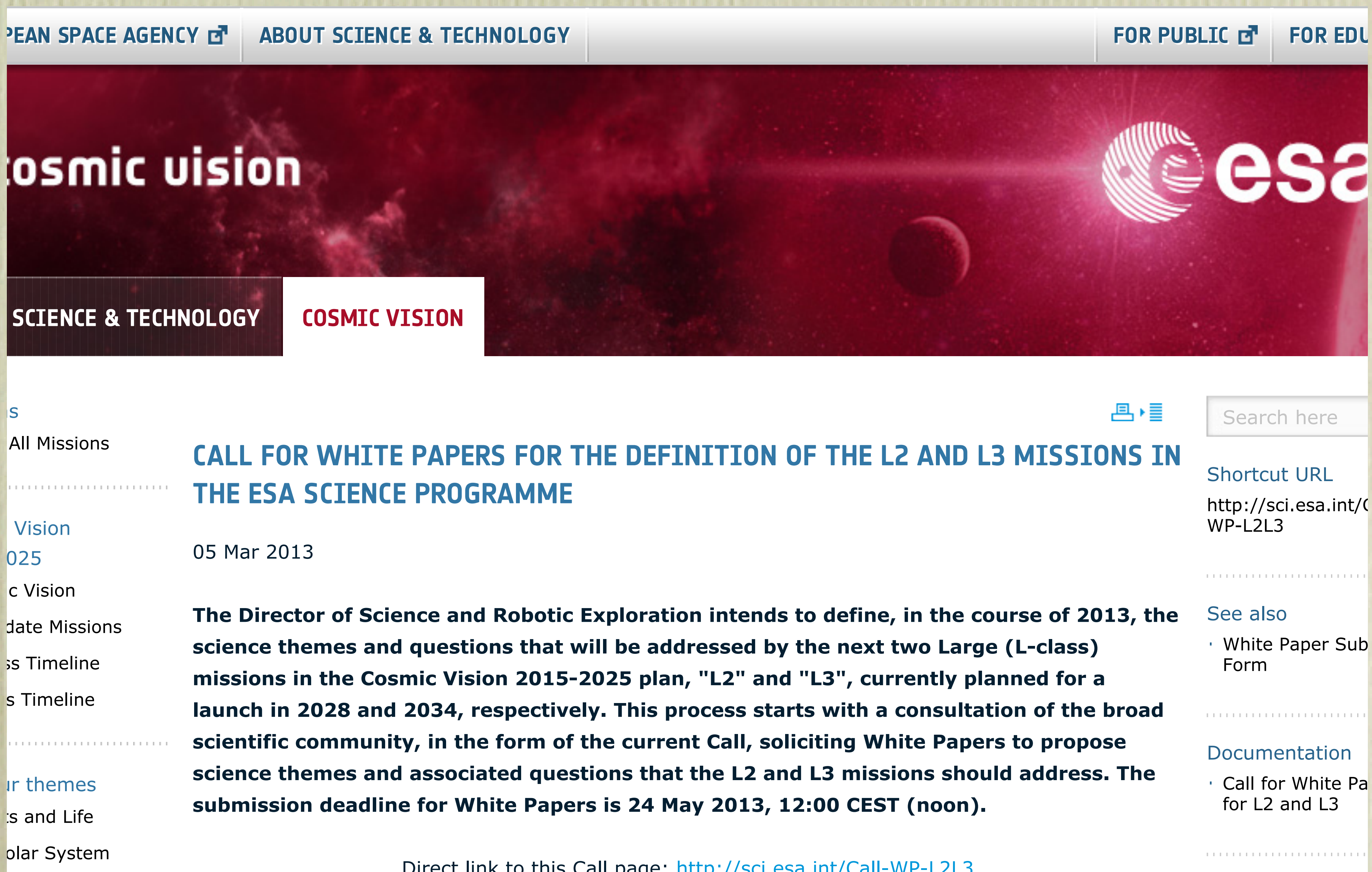


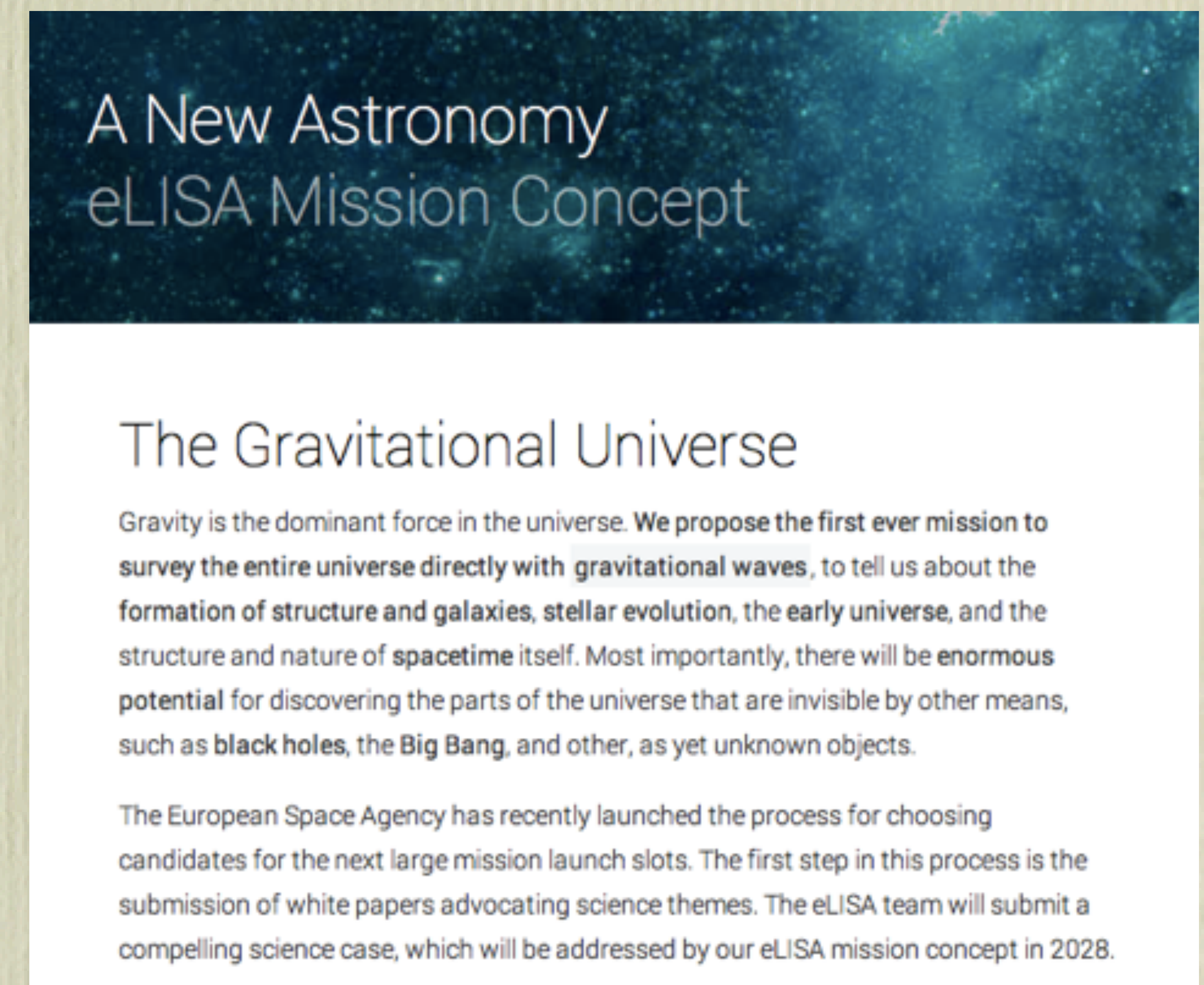
L2/L3 Theme Selection

- In March 2013, ESA issued a call for the definition of science themes to be addressed by the next two Large mission opportunities - L2 (2028) and L3 (2034).



L2/L3 Theme Selection

- We submitted “The Gravitational Universe” as a theme, using NGO as the associated straw-man mission concept. 79 authors, 81 contributors and 1062 scientific supporters, plus 2791 eLISA friends.
- Main science areas
  - **Astrophysical black holes** - growth of galaxies and black holes, stellar populations.
  - **Ultra-compact binaries in the Milky Way**
  - **The laws of nature** - high precision tests of GR, cosmology on the TeV scale.
- Primary source types were compact galactic binaries, supermassive BH binaries and EMRIs.



L2/L3 Theme Selection

- L2/L3 selection set-up in a way that suits eLISA
  - First selection is on basis of science only.
  - Budget has increased (to 1G Euro plus member state contributions). Using NGO as "strawman mission", which has official cost within this budget.
  - There will be a call next year for mission concepts that address the L2/L3 science themes.
  - Selected mission designs will undergo a detailed 1 year feasibility study and costing. L2 selection in second half of 2015.
- All groups invited to make presentations at a meeting in Paris on September $3^{rd}/4^{th}$ 2013.
- Committee makes recommendation to ESA director. Final decision in November.

L2/L3 Selection - Competitors

- Thirty white papers were submitted for consideration.
  - Lunar science
  - Venus science
  - Asteroid science
  - Mars sample return
  - Science at Saturn
  - Science at the icy giants
  - Planetary science IR observatory
  - Solar system debris disk
  - In-situ investigations of the local interstellar medium
  - Fundamental processes in solar science
  - The hypertelescope project

L2/L3 Selection - Competitors

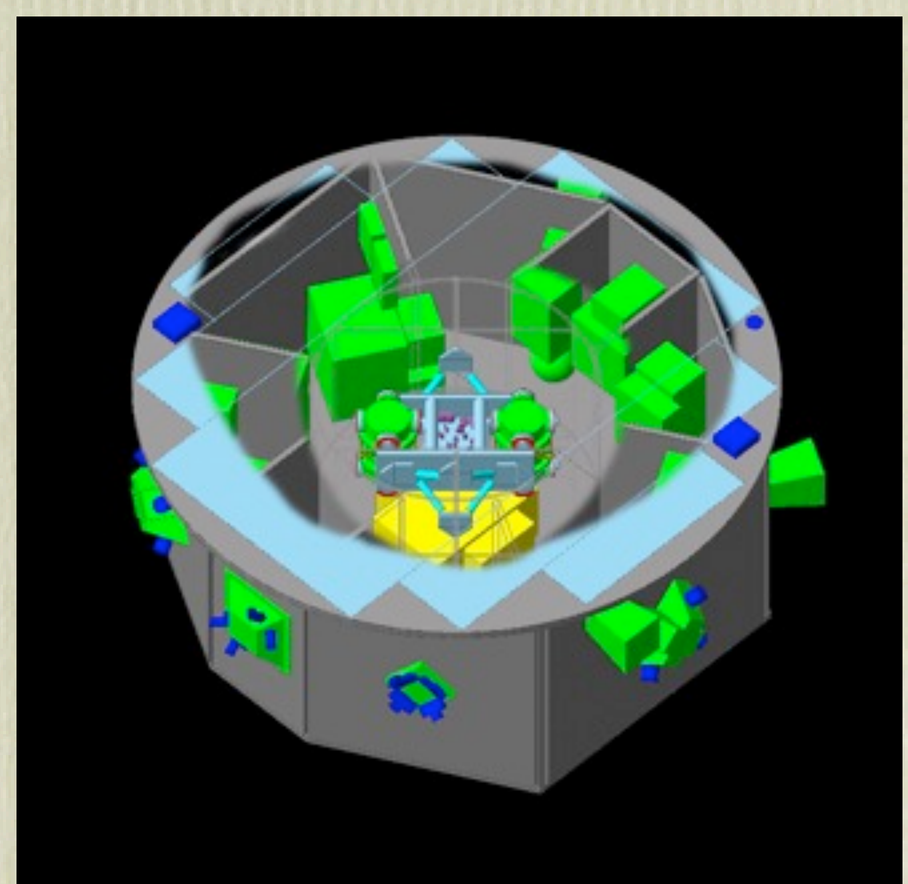
- Thirty white papers were submitted for consideration.
  - Astrometry
  - Microwave and FIR polarimetric spectro-imaging of the sky
  - High spatial resolution FIR observations
  - NIR galaxy formation surveys
  - Ultraviolet and visible observatories
  - Low-frequency radio emission and the dark ages
  - Gamma ray bursts: light from the cosmic frontier.
  - Habitable worlds beyond the solar system
  - The hot and energetic Universe
  - **The Gravitational Universe**

M3 Selection

- M3 selection will have some bearing on L2/L3 mission choice.
- At present there are four M3 mission candidates
  - **LOFT** - the Large Observatory for X-ray Timing: X-ray observatory with both a wide field monitor and large area detector.
  - **ECHO** - Exoplanet CHaracterisation Observatory: mission to investigate exoplanetary atmospheres.
  - **MarcoPolo-R** - near-Earth asteroid sample return mission.
  - **STE-QUEST** - SpaceTime Explorer and Quantum Equivalence principle Space Test: fly an atomic clock and compare to clocks on ground.
- SSAC recommendation for down-selection to 1 mission will be "before end 2013". Outcome may already be known.

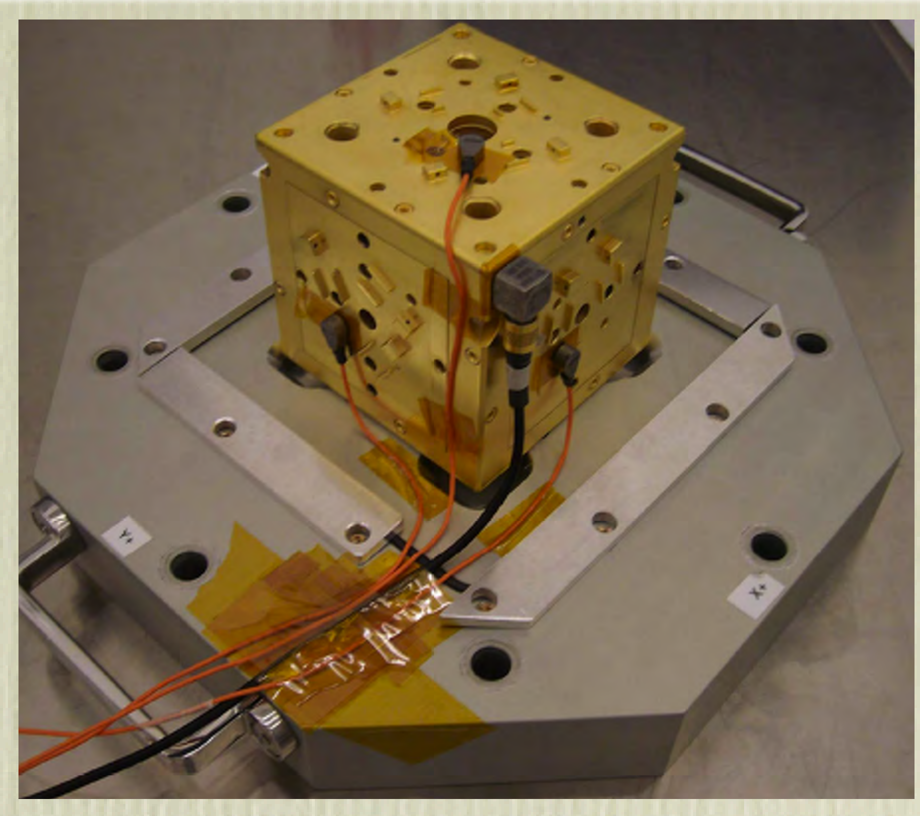
LISA Pathfinder

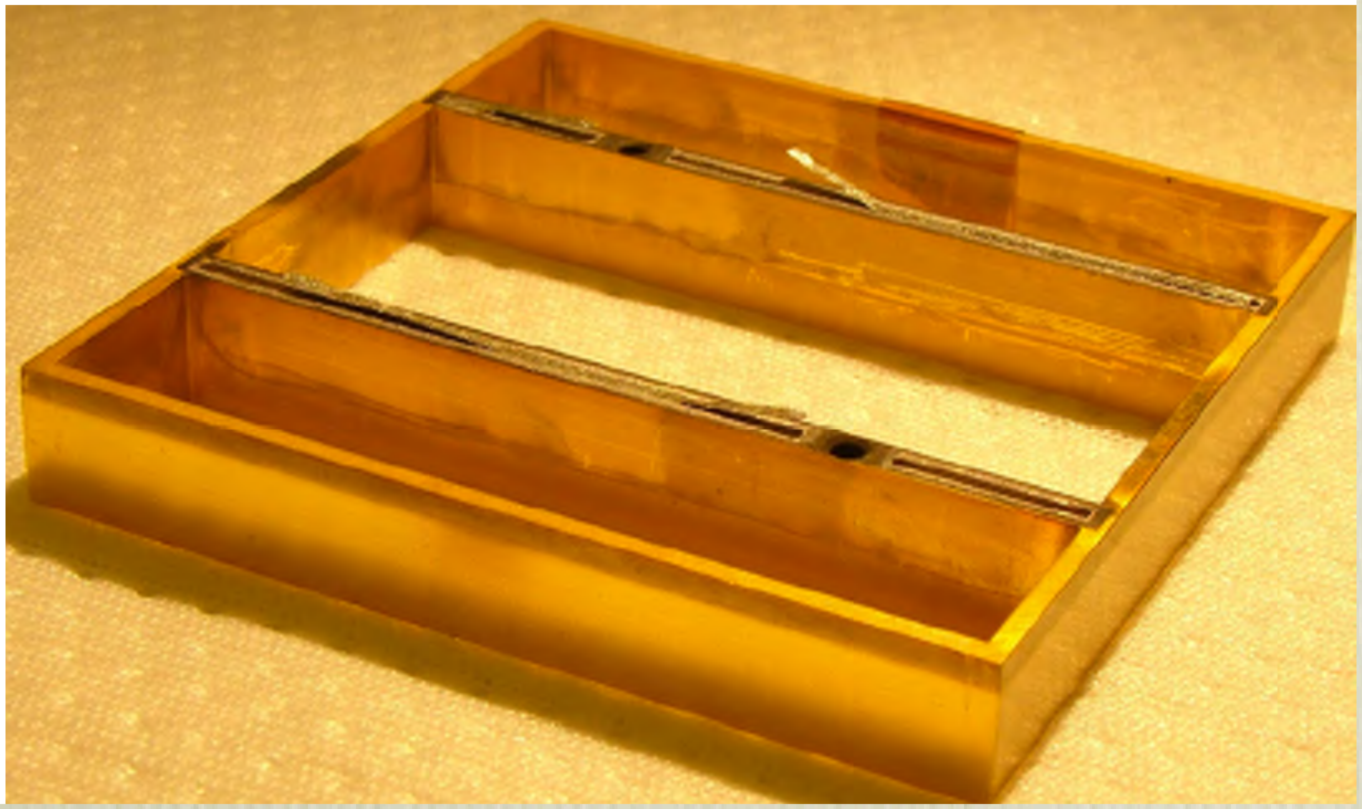
- Final selection will be crucially dependent on a successful LISA Pathfinder completion and launch.
- LISA Pathfinder is a technology demonstration mission to show required acceleration noise target can be met.
- Single LISA arm, shrunk down to 30cm to fit in a single spacecraft.
- After many delays, only one critical issue remains - brazing of electrode housing.



LISA Pathfinder

- When electrode housing underwent vibration testing, a brazed joint failed.
- Almost resolved, but has delayed LISA Pathfinder launch by a further 6 months. Launch date is now first half of 2015.





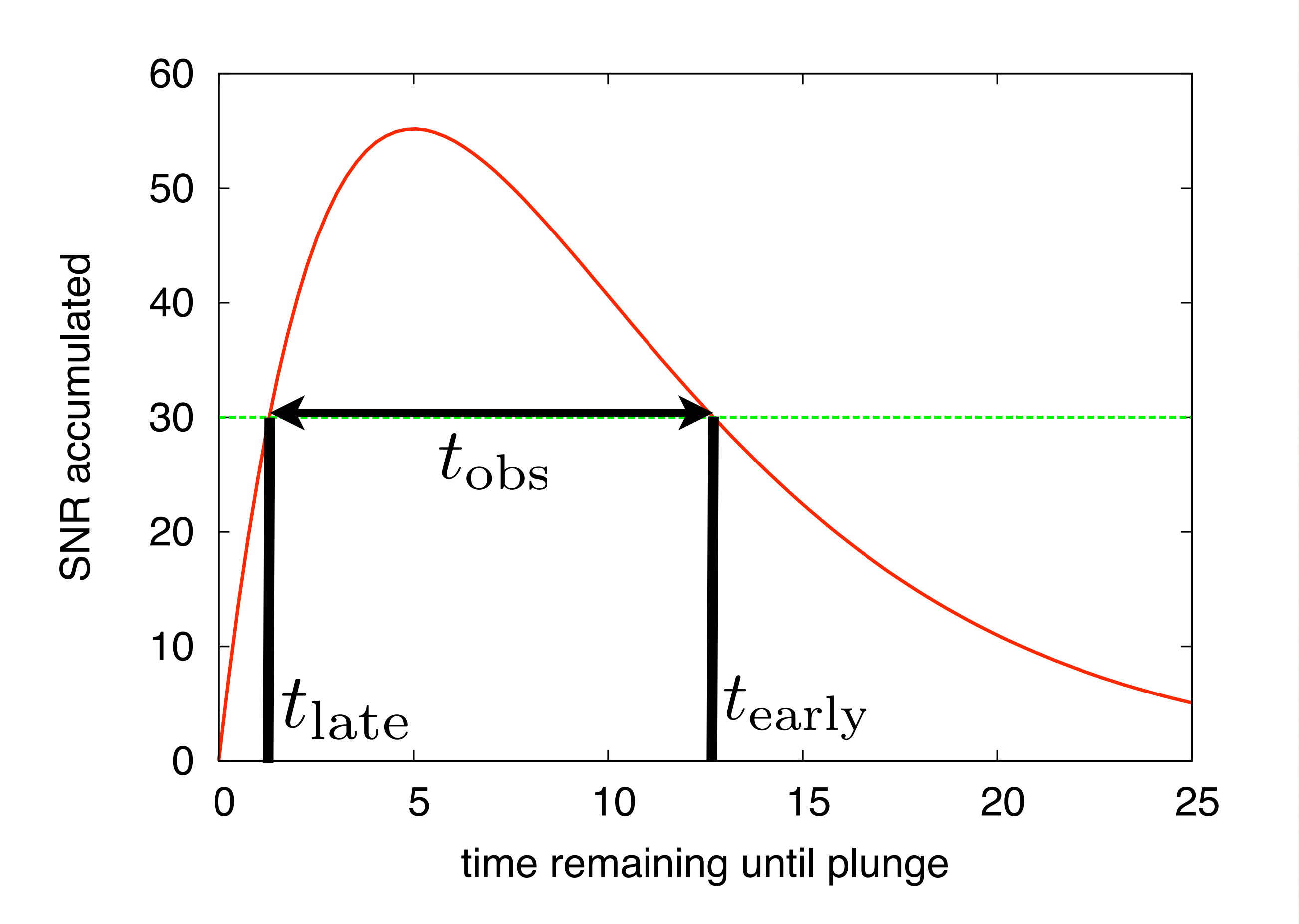
International Participation

- If selected, eLISA will invite international partners to contribute as junior partners.
  - **China**
    - Space science is seen as a high priority by the Chinese government.
    - Actively researching their own space based detector concept: ALIA. See eLISA participation as an opportunity to gain experience.
    - Have offered $200 million contribution.
  - **US**
    - LISA was the third priority in the decadal survey. eLISA participation seen as an economical route to meet that commitment
    - Could contribute $350 million ("Explorer" class budget).
- International contributions could allow third arm to be recovered - significant impact on science.

Ingredient II: event rates

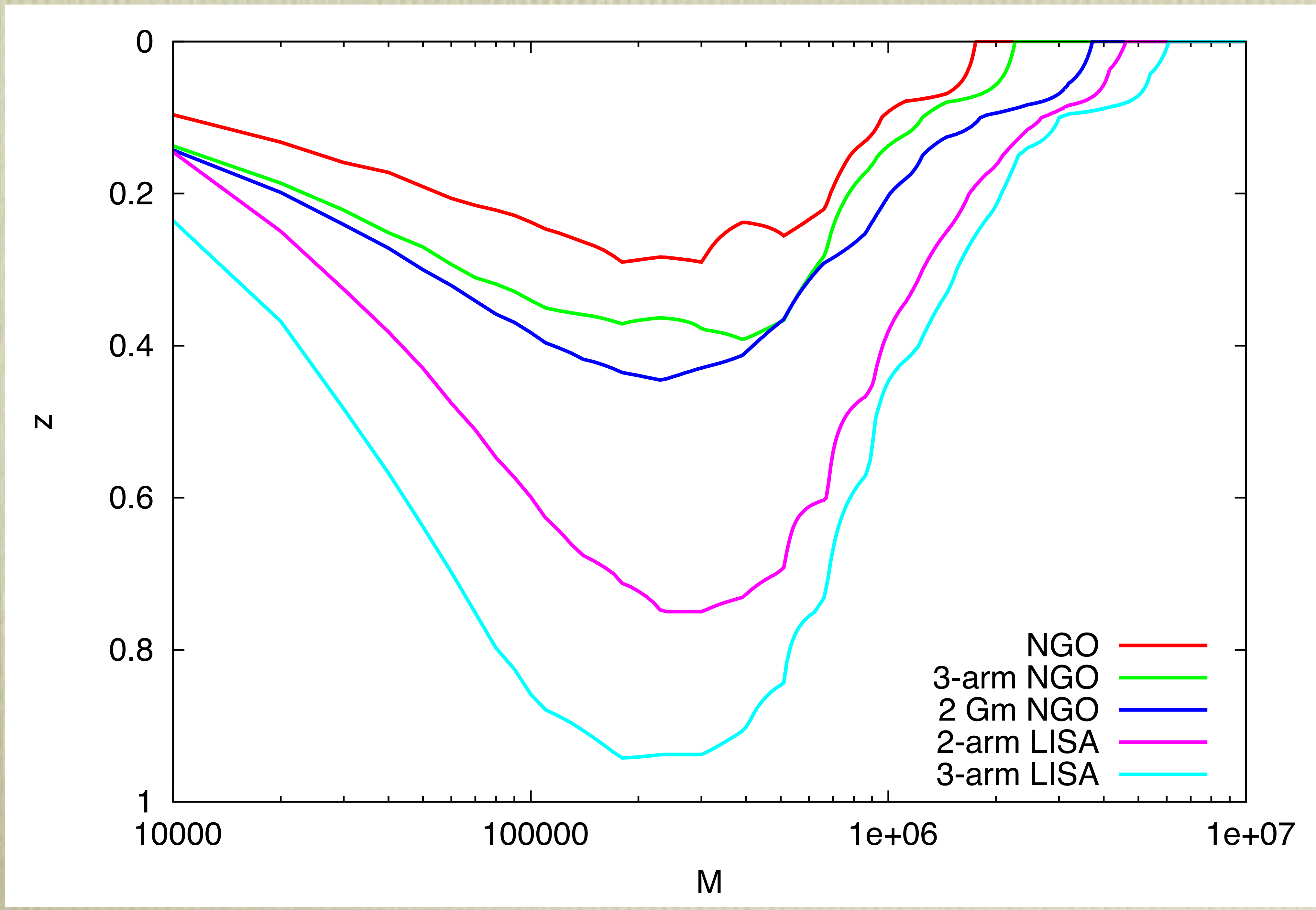
EMRIs - SNRs

- Characterise EMRI detectability in terms of the **observable lifetime**, t_{obs} - the length of time during which LISA could start taking data and an event be observed with sufficient SNR.
- Rate of observed events is then t_{obs}/T, where T is the average time between plunges.
- Compute observable lifetimes for EMRIs in the (e)LISA configurations using circular, equatorial Teukolsky fluxes. Take SNR detection threshold of 20.



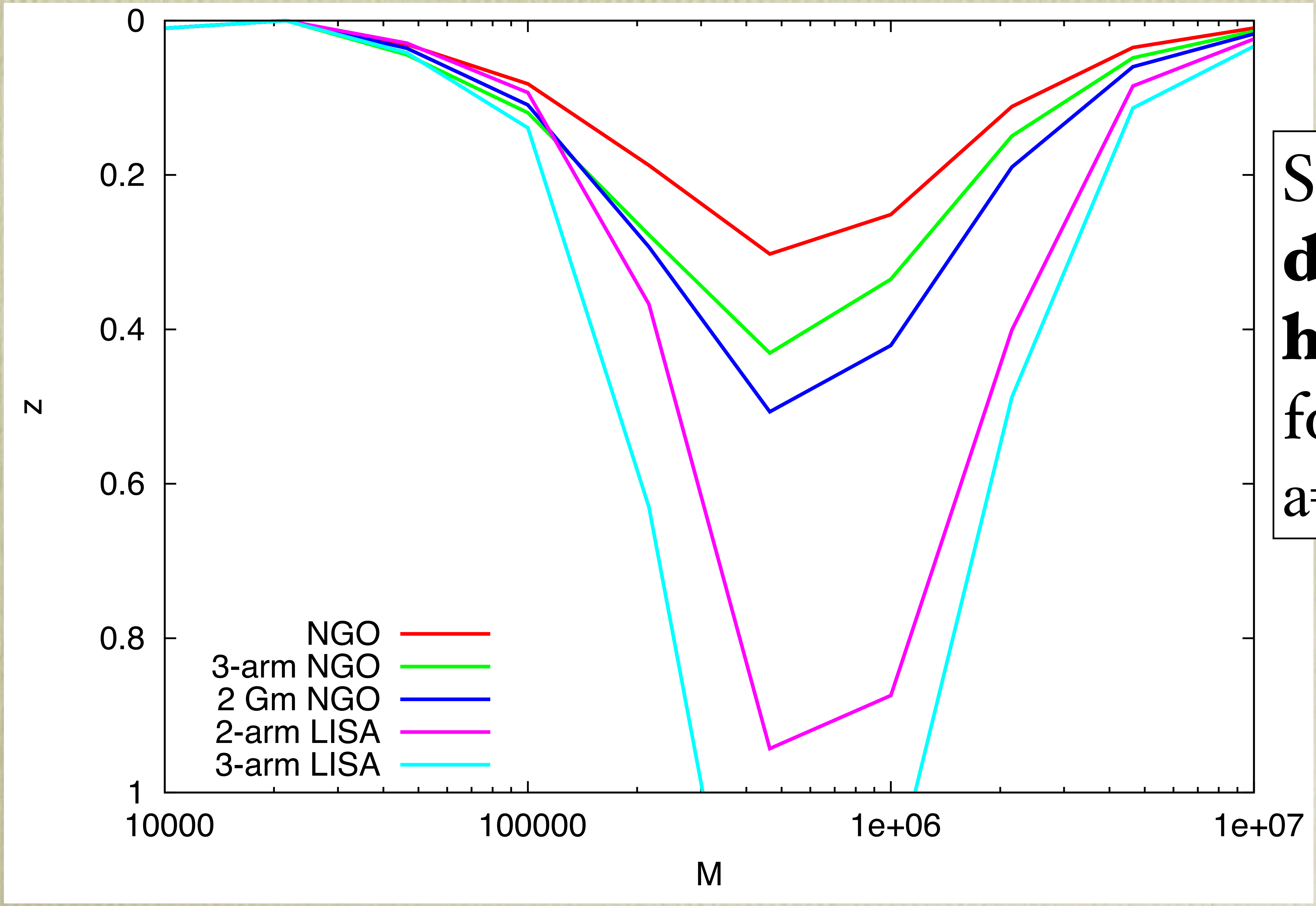
EMRIs - SNRs

- Contours of constant observable lifetime of 1 year, assuming all black holes are non-spinning and compact object mass m=10.



EMRIs - SNRs

- Compute SNRs using analytic kludge waveforms to include eccentricity and as a cross-check.



Showing **detection horizon** for e_p=0.25, a=0

EMRIs - Event Rates

- Estimate number and properties of eLISA events by assuming
  - **Mass function of black holes** is flat in logarithm in the LISA range, $10^4 M_\odot \lesssim M \lesssim 10^7 M_\odot$

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

  - **EMRI rate per galaxy** has a simple power-law scaling with the mass of the central black hole.

$$\rho = 400\mathrm{Gyr}^{-1}\left(\frac{M}{3\times 10^6 M_\odot}\right)^{-0.17}$$

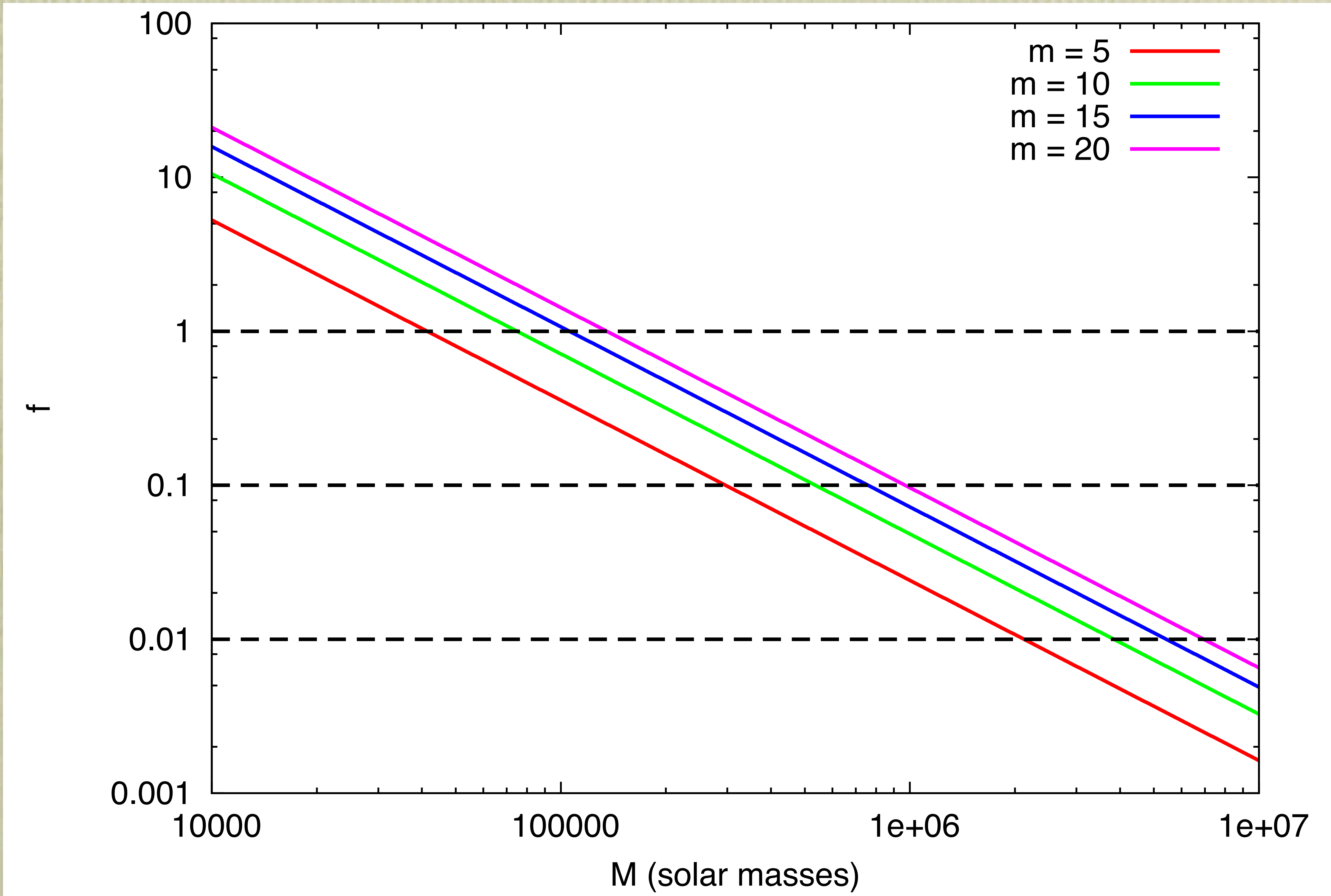
  - **EMRI orbits are circular and equatorial**, so we can use Teukolsky results. Assume all black holes have the same spin, a = 0, 0.5, 0.9.

EMRIs - Event Rates

Configuration	Black hole spin		
	0	0.5	0.9
NGO	45	50	90
3-arm NGO	110	140	190
2Gm NGO	150	165	250
Classic LISA (2-arm)	600	650	750
Classic LISA (3-arm)	1000	1150	1250

EMRIs - Event Rates

- BUT, have constraint on rate from total mass accreted by black holes.



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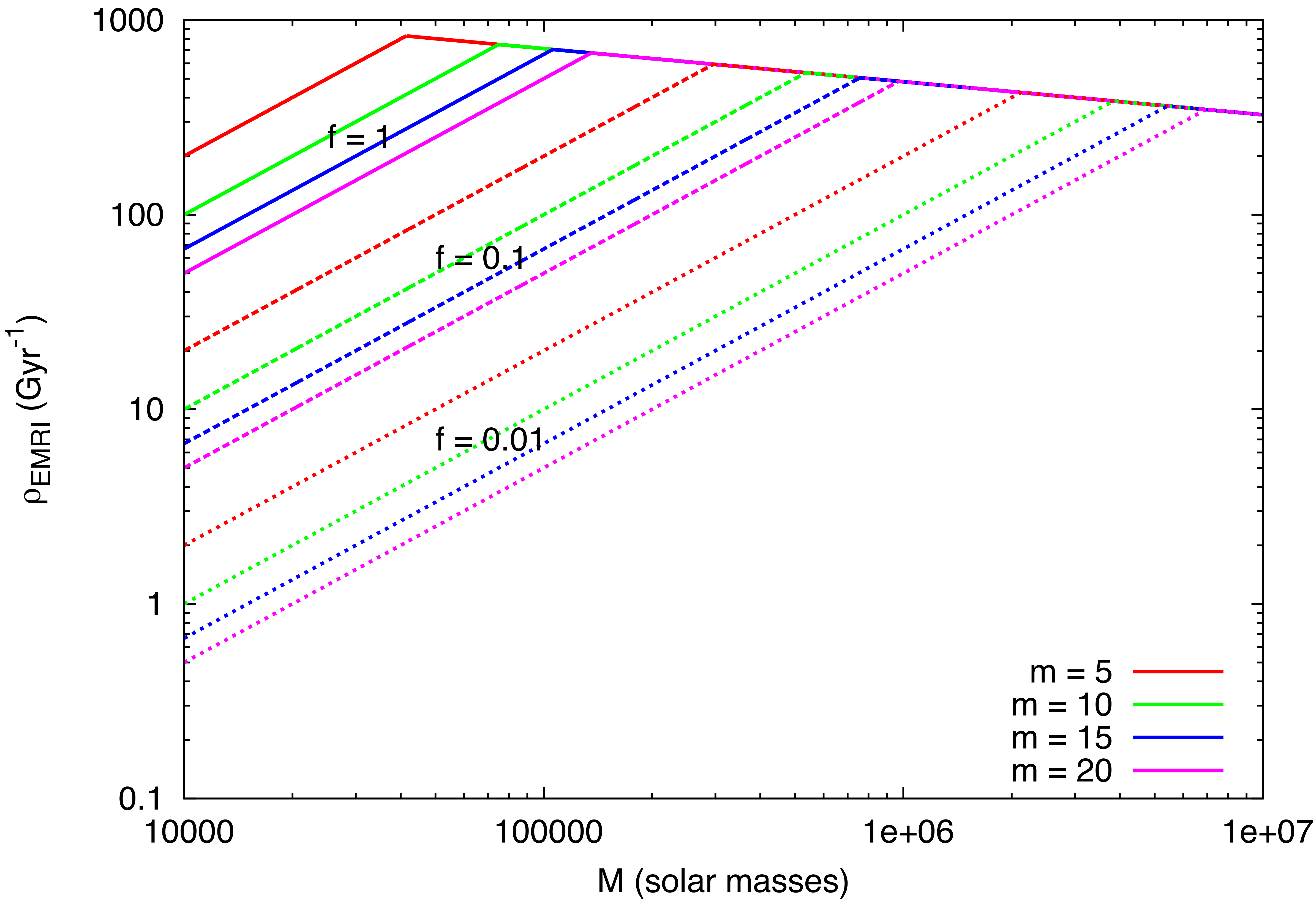


EMRIs - Event Rates

- Assume all massive black holes have spin a=0.9 and detection with NGO.

	f = 0.01			f = 0.1			f = 1		
CO mass	No. events with M >			No. events with M >			No. events with M >		
	10^4	10^5	10^6	10^4	10^5	10^6	10^4	10^5	10^6
5	7	7	4	20	20	5	30	25	5
10	10	10	5	60	60	15	85	75	15
15	15	15	10	90	90	30	160	150	30
20	15	15	10	100	100	40	230	200	40

EMRIs - Event Rates

- Consider dependence on black hole spin, assuming f = 0.1 and detection with NGO.

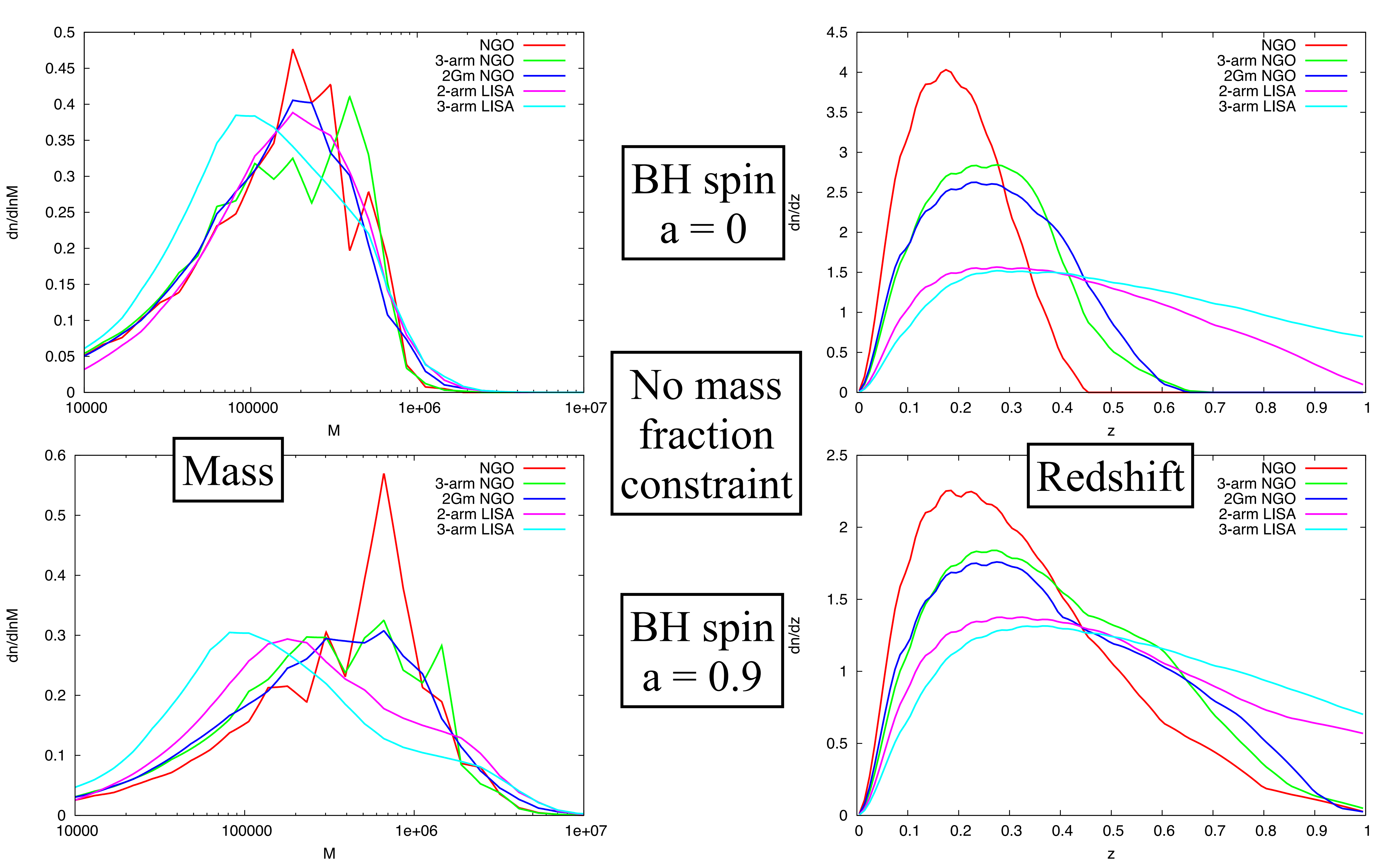
	Black Hole Spin								
	a = 0			a = 0.5			a = 0.9		
CO mass	No. events with M >			No. events with M >			No. events with M >		
	10^4	10^5	10^6	10^4	10^5	10^6	10^4	10^5	10^6
5	5	5	0	10	10	< 1	20	20	5
10	15	15	< 1	20	20	1	60	60	15
15	15	15	< 1	30+1	30	5	90	90	30
20	45	45	1	40+1	40	5	100	100	40

EMRIs - Event Rates

- Consider dependence on detector configuration, assuming f = 0.1 and compact object mass m = 10.

	Black Hole Spin								
	a = 0			a = 0.5			a = 0.9		
Detector	No. events with M >			No. events with M >			No. events with M >		
	10^4	10^5	10^6	10^4	10^5	10^6	10^4	10^5	10^6
NGO	15	15	< 1	20	20	1	60	60	15
3-arm	35+2	35	< 1	60+2	60	3	105+2	105	35
2 Gm	50	45	2	60+2	60	5	140+3	140	45
LISA (2 arm)	210	200	10	250	240	30	360	350	130
LISA (3 arm)	340	300	20	370	340	50	490	460	160

EMRIs - Event Properties



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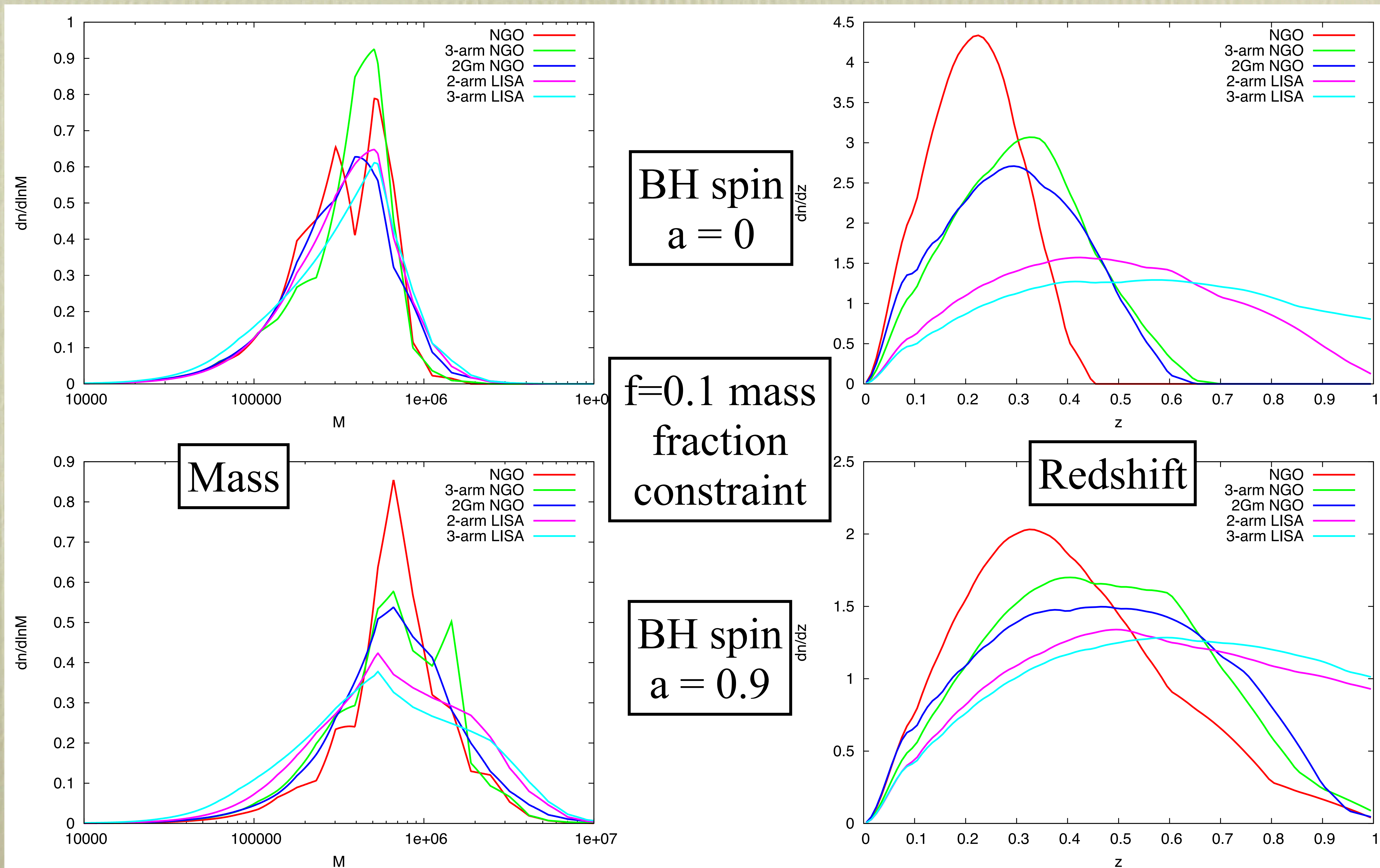


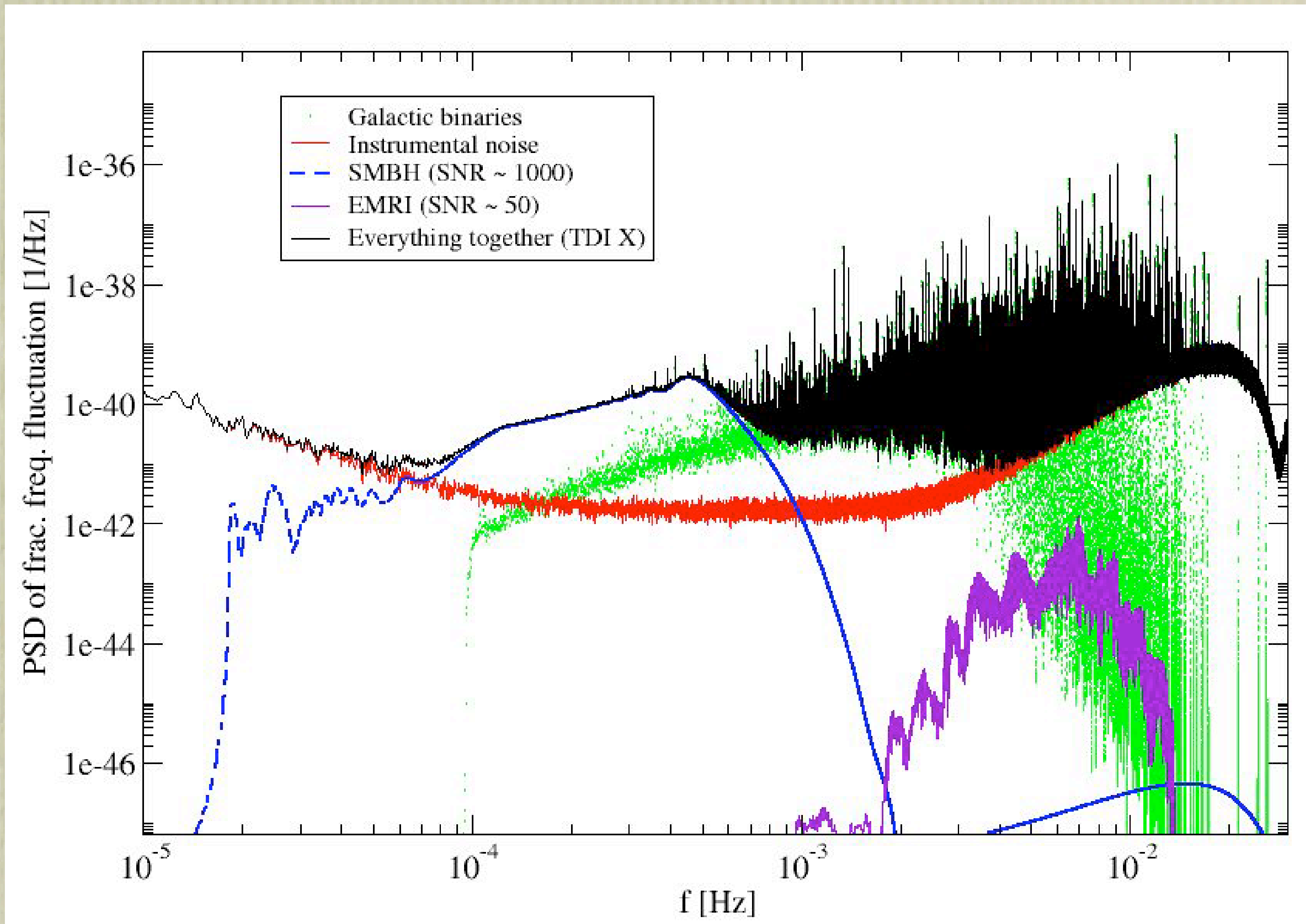
EMRI event rates - uncertainties

- The EMRI rate depends on poorly understood physics
  - **Dynamics of galacto-centric stellar clusters**
    - Rate affected by the efficiency of resonant relaxation, mass segregation, "Schwarzschild" barrier etc.
    - Non-standard processes including triaxiality, binary tidal splitting, tidal stripping of giant stars, disc star formation etc. can boost rates.
    - Steep cusp density profile can be destroyed by mergers. Cores have much lower EMRI rates than cusps.
  - **Massive black hole number density**
    - Only three massive black holes in the eLISA range are known.
    - "Light seed" and "heavy seed" models are both consistent with current observations. Heavy seed models predict fewer black holes in eLISA range and lower galaxy black hole occupation fraction.
- There are at least two orders of magnitude uncertainty in these numbers. eLISA has great potential to constrain this physics!

Ingredient III: detection algorithms

Challenges of eLISA data analysis

- eLISA sources are not isolated in time or frequency:
  - Every compact binary in the galaxy radiates in the eLISA band continuously - expect to resolve ~5000 sources.
  - Typically, there will be a few SMBH merger signals per year, each of which lasts several months and has SNR of hundreds, possibly one thousand.
  - EMRI events last for the full mission lifetime, and there could be 100 of them.



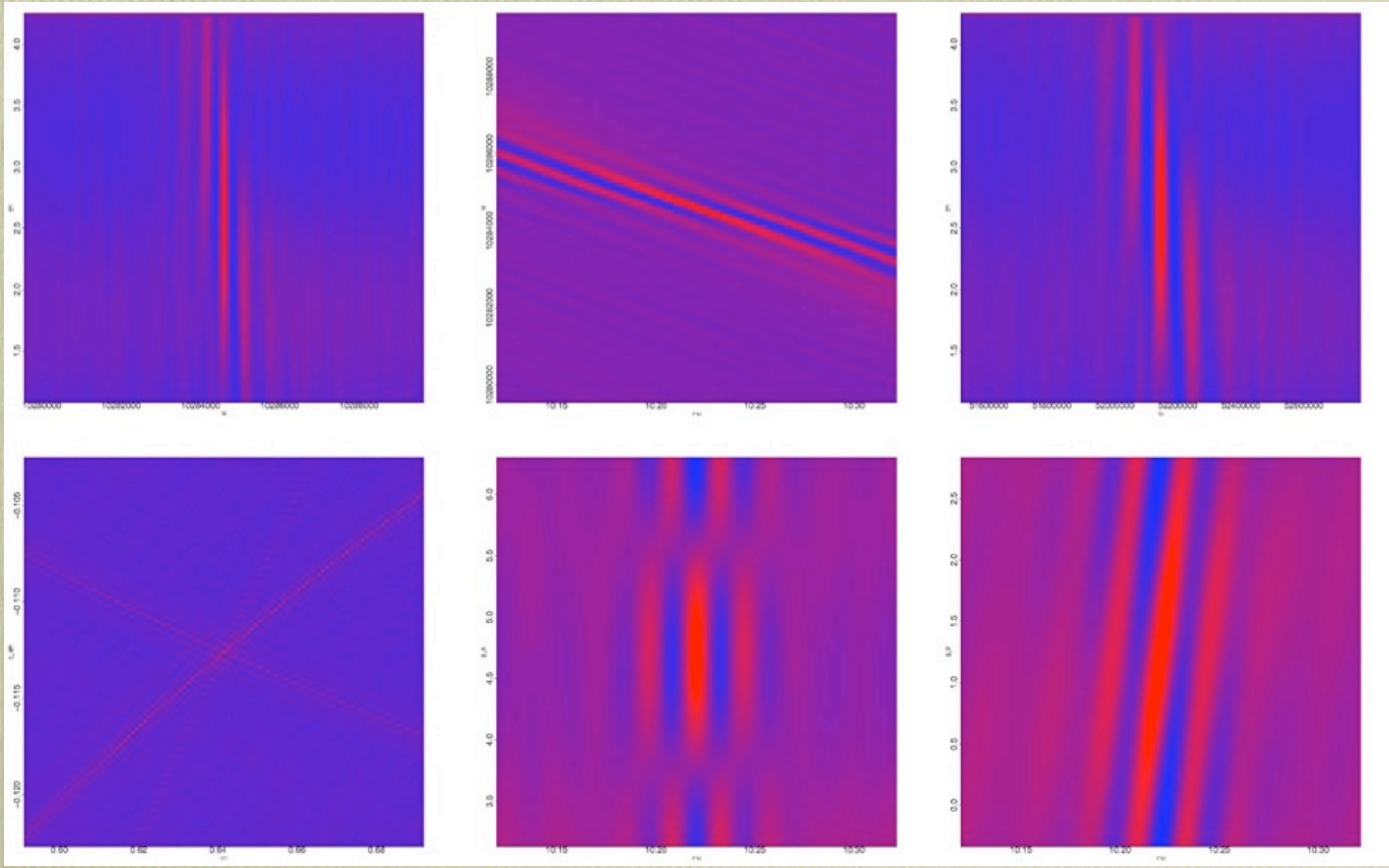
Challenges of EMRI data analysis

- EMRI waveforms depend on 14 different parameters –

$$M, S, m, e, r_p, \iota, \psi_0, \chi_0, \phi_0, \theta_K, \phi_K, \theta_S, \phi_S, D$$

- The gravitational waveform has $\sim 10^5$ cycles during last year of inspiral. Might naïvely estimate $\sim (10^5)^8 = 10^{40}$ templates required. Lots of secondaries in likelihood.

Challenges of EMRI data analysis



Cornish and Crowder, GWDAW (2007)

Challenges of EMRI data analysis

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$$M, S, m, e, r_p, \iota, \psi_0, \chi_0, \phi_0, \theta_K, \phi_K, \theta_S, \phi_S, D$$

- The gravitational waveform has $\sim 10^5$ cycles during last year of inspiral. Might naïvely estimate $\sim (10^5)^8 = 10^{40}$ templates required. Lots of secondaries in likelihood.
- Computationally infeasible to do fully coherent matched filtering or include whole parameter space in MCMC.
- Several alternative algorithms have been investigated, with promising results.
- All analyses so far have assumed that we have a clean data stream and are searching for one EMRI.

The Mock LISA Data Challenges

- Development of LISA data analysis was encouraged through a sequence of Mock LISA Data Challenges (MLDCs).

Round	Sources	Released	Deadline
1	1.1: White dwarf binaries (single, multiple resolvable, multiple confused) 1.2: 2 isolated SMBH mergers	June 2006	Dec 4 2006
2	2.1: Full galaxy 2.2: “Whole enchilada” 1.3: 5 isolated EMRIs	Jan 1 2007	June 15 2007
1B	As round 1, plus EMRIs from Rd. 2	July 2007	Dec 1 2007
3	3.1: Galaxy with chirping binaries 3.2: SMBH mergers with galaxy confusion 3.3: 5 EMRIs in one dataset 3.4: Cosmic string bursts 3.5: Stochastic background	Jan 2008	April 2009
4	“Whole enchilada” - all sources from Rd. 3	Nov 2009	June 2011

MLDC Round 2 Results

- Time-frequency methods were most successful for first EMRI MLDC. No correct source parameter measurements using Bayesian techniques.

Table 3. Recovered SNRs and parameter errors for the EMRI signal in data set 1.3.1. All errors are given as *fractions of the allowed prior range* for the corresponding parameters (0.15 for e_0), except for the errors on ν_0 and D. Not all parameters are shown. For their definitions, see tables 2 and 5 of [4]. The true (optimal) SNR is **130.98**.

	SNR	$\delta\beta$	$\delta\lambda$	$\delta\theta_K$	$\delta\phi_K$	δa	$\delta\mu$	δM	$\frac{\Delta\nu_0}{\nu_0}$	δe_0	$\frac{\Delta D}{D}$
BBGP	74.86	−0.33	−0.0095	−0.13	−0.076	0.28	−0.15	−0.51	0.017	0.21	−1.21
	72.96	−0.32	0.011	−0.15	−0.078	0.27	−0.15	−0.51	0.017	0.21	−1.22
	72.52	−0.28	0.025	−0.063	−0.036	0.41	−0.17	−0.35	−0.009	0.29	−2.15
	72.49	−0.28	0.025	−0.063	−0.034	0.41	−0.17	−0.36	−0.009	0.29	−2.17
	70.59	−0.31	−0.020	−0.36	−0.21	0.44	−0.12	−0.12	−0.03	0.28	−0.91
EtfAG	–	0.016	0.0012	–	–	−0.082	0.10	−0.17	0.0026	0.098	–
MT	74.85	0.15	0.47	−0.069	−0.15	−0.026	0.073	0.18	0.00025	−0.11	−0.71
	76.52	0.084	−0.49	−0.33	−0.10	−0.022	0.046	0.16	0.00026	−0.10	−0.70

MLDC Round 1B Results

- Round 1B was a repeat of round 1/round 2.
- t-f methods again successful.
- One successful MCMC recovery of an EMRI, for the high mass system, before challenge deadline.
- Subsequently, a successful recovery of the parameters of all the sources has been demonstrated.

Table 5. Overlaps and recovered SNRs for TDI observables A, E and combined recovered SNR for data sets 1B.3.1–5.

Group	C_A	SNR_A	C_E	SNR_E	total SNR
1B.3.1 ($\mathrm{SNR_{opt}} = 123.7$)					
BBGP	0.57	51.0	0.58	51.6	72.5
MT	0.998	86.1	0.997	88.3	123.4
1B.3.2 ($\mathrm{SNR_{opt}} = 133.5$)					
BBGP	0.07	6.6	0.18	18.2	17.6
BBGP[a]	0.39	37.6	0.41	39.8	54.7
MT	0.54	49.5	0.54	50.8	70.9
1B.3.3 ($\mathrm{SNR_{opt}} = 81.0$)					
BBGP	−0.06	−4.2	−0.0003	−0.05	−3.0
BBGP[a,c]	−0.2	−11.5	−0.32	−19.0	−21.5
MT	0.38	22.0	0.35	20.9	30.4
1B.3.4 ($\mathrm{SNR_{opt}} = 104.5$)					
BBGP[c]	0.0007	2.1	−0.0002	−0.8	2.1
BBGP[b]	0.16	13.9	0.04	6.7	14.6
1B.3.5 ($\mathrm{SNR_{opt}} = 57.6$)					
BBGP	0.09	3.4	0.1	4.2	5.3

[a] C and SNR after correcting the sign of β, lost on input to the MLDC webform.
[b] C and SNR after correcting phases at $t = 0$, to account for a **BBGP** bug.
[c] The **BBGP** SNRs can be negative because **BBGP** maximized likelihood analytically over amplitude, which makes SNR sign-insensitive (a minus sign corresponds to a change of π in the phase of the dominant harmonic). This degeneracy is broken when all the harmonics are found correctly.

MLDC Round 1B Results

- Round 1B was a repeat of round 1/round 2.
- t-f methods again successful.
- One successful MCMC recovery of an EMRI, for the high mass system, before challenge deadline.
- Subsequently, a successful recovery of the parameters of all the sources has been demonstrated.

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)

MLDC Round 3 Results

- Round 3 EMRIs had mild confusion (5 sources in 1 dataset) and lower SNR. Three sources successfully recovered.

Table 2. Parameter-estimation errors for the EMRIs in MLDC 3.3. M and μ are the masses of the central and inspiraling bodies; ν_0 and e are the initial azimuthal orbital frequency and eccentricity; $|S|$ is the dimensionless central-body spin; $\lambda_{\rm SL}$ is the spin–orbit misalignment angle, and D the luminosity distance. Δspin and Δsky are the geodesic angular distances between the estimated and true spin direction and sky position. SNR$_{\rm true}$ is computed with the LISA Simulator; the SNR for each entry with the simulator used in that search (the LISA Simulator [26] for MTAPCIOA, Synthetic LISA [27] for EtfAG and BabakGair).

Source (SNR$_{\rm true}$)	Group	SNR	$\frac{\Delta M}{M}$ $\times 10^{-3}$	$\frac{\Delta\mu}{\mu}$ $\times 10^{-3}$	$\frac{\Delta\nu_0}{\nu_0}$ $\times 10^{-5}$	Δe_0 $\times 10^{-3}$	$\Delta\|S\|$ $\times 10^{-3}$	$\frac{\Delta\lambda_{\rm SL}}{\lambda_{\rm SL}}$ $\times 10^{-3}$	Δspin (deg)	Δsky (deg)	$\frac{\Delta D}{D}$
EMRI-1	MTAPCIOA	21.794	5.05	3.29	1.61	−5.1	−1.4	−19	23	2.0	0.07
(21.673)	MTAPCIOA	21.804	−0.06	−0.01	−0.08	−0.05	0.02	0.54	3.5	1.0	0.13
EMRI-2	MTAPCIOA	32.387	−3.64	−2.61	−3.09	3.8	0.87	12	11	3.7	3×10^{-3}
(32.935)	BabakGair	22.790	33.1	−19.7	10.1	−33	−7.3	250	47	3.5	−0.25
	BabakGair	22.850	32.7	−20.0	9.94	−32	−7.2	250	58	3.5	−0.24
	BabakGair	22.801	33.5	−19.5	10.5	−33	−7.4	240	40	3.5	−0.25
EMRI-3	MTAPCIOA	19.598	1.62	0.38	−0.10	−0.35	−0.94	−3.0	5.0	3.0	−0.04
(19.507)	BabakGair	21.392	1.77	1.01	1.95	−1.2	−0.68	−2.3	116	4.5	0.13
	BabakGair	21.364	2.26	1.88	2.71	−2.0	−0.69	−2.5	65	6.1	0.14
	BabakGair	21.362	1.51	1.01	2.09	−1.3	−0.50	−1.7	7.6	6.2	0.14
	EtfAG	—	54.0	4.88	−7375	26	17	—	—	32	0.83
EMRI-4 (26.650)	MTAPCIOA	−0.441	−8.77	−10.1	−6.03	−3.7	144	950	99	13	−2.3
EMRI-5 (36.173)	MTAPCIOA	17.480	−3.32	5.00	−1.80	0.22	55	62	43	1.8	−1.3

EMRI data analysis: uncertainties

- EMRI identification was a success story of the MLDC, but the problem is not solved yet.
- Outstanding issues include
  - **Source confusion**: to date, there has been no successful recovery of an EMRI in a data set containing other sources; EMRI self-confusion has only been mild - 5 sources at very different frequencies.
  - **Low-mass EMRIs**: algorithms have been most successful at finding EMRIs in the mass ranges $M \sim 5 \times 10^6 M_\odot$ and $M \sim 1 \times 10^7 M_\odot$, but expect event rate to be dominated by EMRIs with $M \lesssim 1 \times 10^6 M_\odot$.
  - **Model uncertainties**: algorithms have relied on knowledge of the EMRI likelihood surface that has either a) been dependent on only one source in the data; b) specific to approximate waveform model. Need more generic approaches and better waveforms: self-force!
- There are plans to address these concerns in future MLDCs.

Result:
Science

EMRIs - Parameter Estimation

- Precision of EMRI parameter estimation is affected by configuration choice only through SNR. Parameter estimation accuracies for sources observed at a fixed SNR of 30 are very similar.

	Configuration			
Parameter	**NGO**	**3-arm NGO**	**2Gm NGO**	**Classic LISA**
ln(M)	2×10^{-4}	2×10^{-4}	2×10^{-4}	2×10^{-4}
ln(m)	1×10^{-4}	1×10^{-4}	1×10^{-4}	1×10^{-4}
a	3×10^{-4}	3×10^{-4}	3×10^{-4}	3×10^{-4}
Sky Pos.	2^{o}	1^{o}	2^{o}	1^{o}
ln(D)	0.125	0.1	0.125	0.1

EMRI Science - Astrophysics

- The set of observed EMRI events not only provide precise parameter measurements for individual systems, but can tell us about black hole populations at low redshift, about galacto-centric stellar clusters, EMRI formation channels etc.
- E.g., constraints on the BH mass function $\mathrm{d}n/\mathrm{d}\log M = AM^{\alpha}$

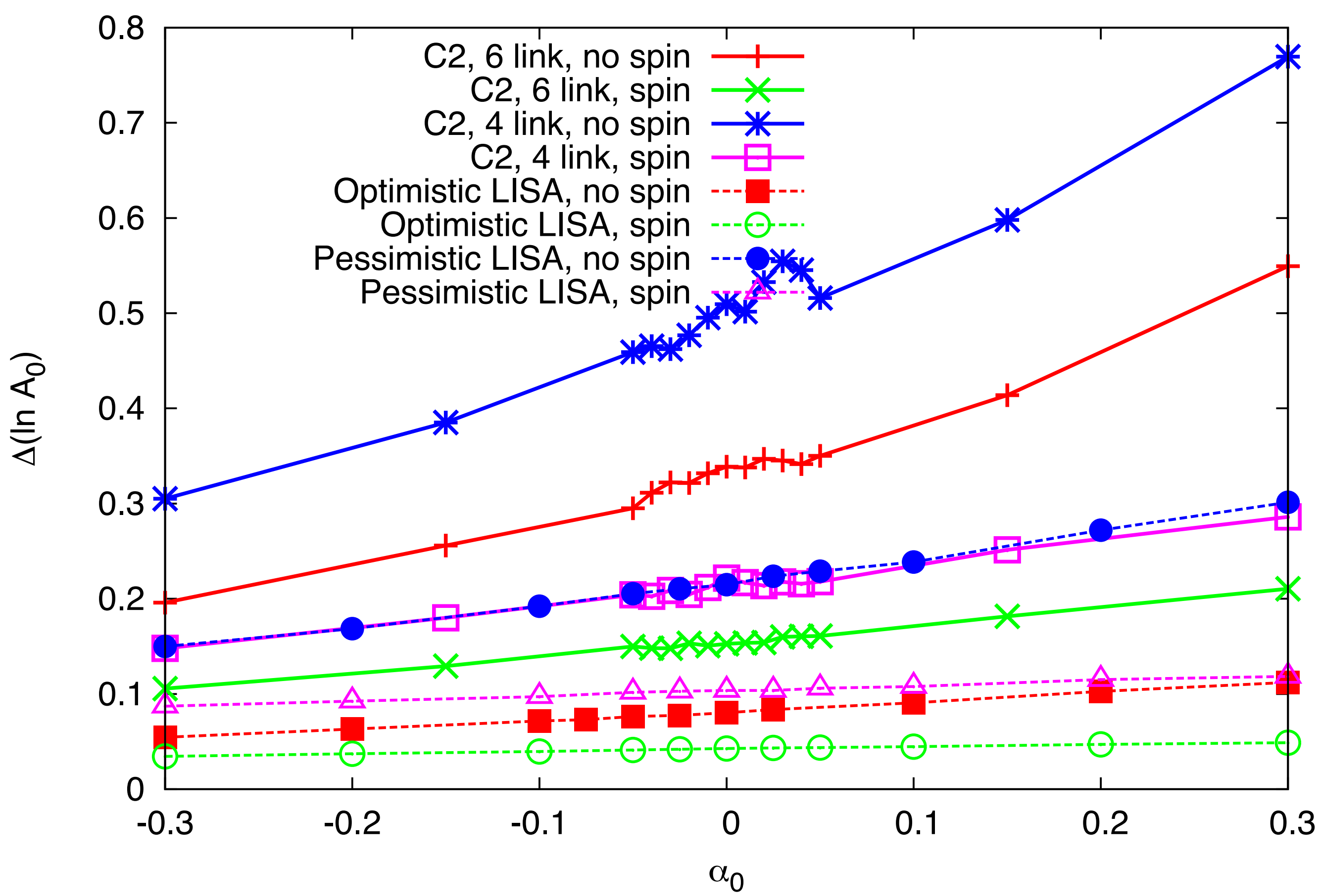
$$\Delta(\ln A_0) \approx 1.1\sqrt{10/N_{\rm obs}} \qquad \Delta(\alpha_0) \approx 0.35\sqrt{10/N_{\rm obs}}$$

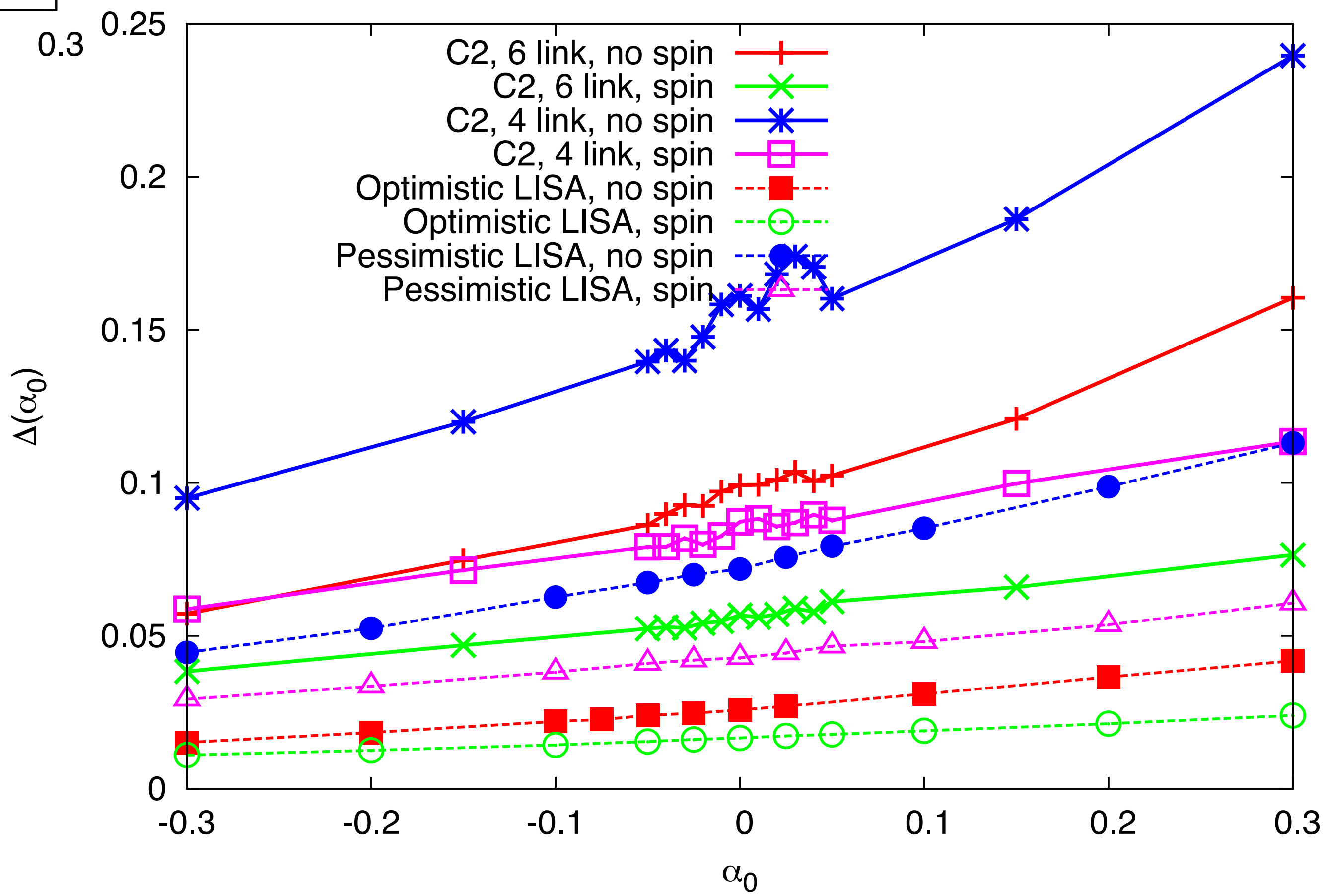
- The precision is improved slightly by addition of third arm

$$\Delta(\ln A_0) \approx 0.7\sqrt{10/N_{\rm obs}} \qquad \Delta(\alpha_0) \approx 0.25\sqrt{10/N_{\rm obs}}$$

- but otherwise there is only a weak dependence on the final detector configuration, for a fixed number of observed EMRIs.
- **A LISA-like GW detector that observes at least 10 EMRI events will be able to place constraints on the black hole mass function that are better than those currently available.**

EMRI Science - Astrophysics

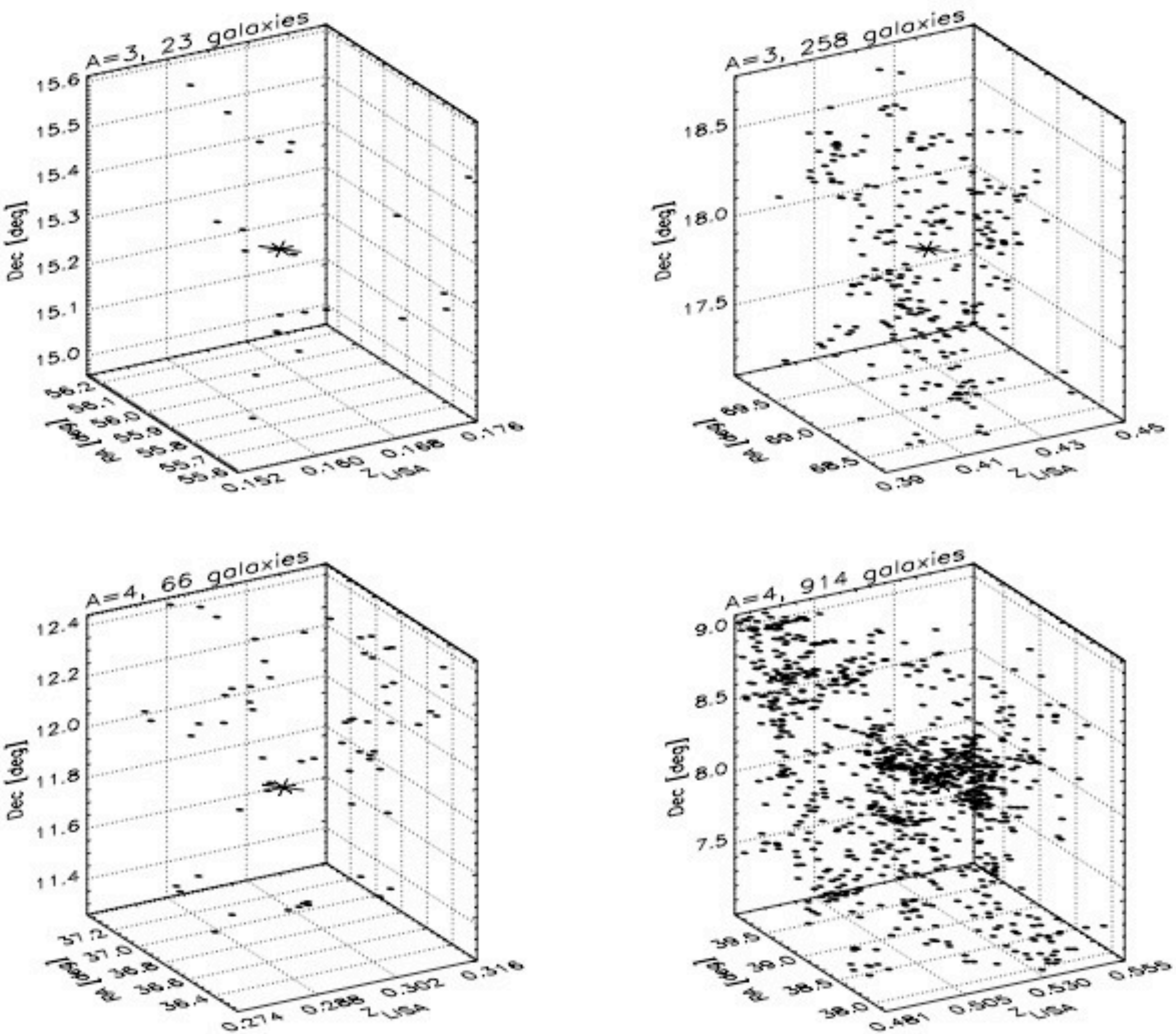




EMRI Science - Cosmology

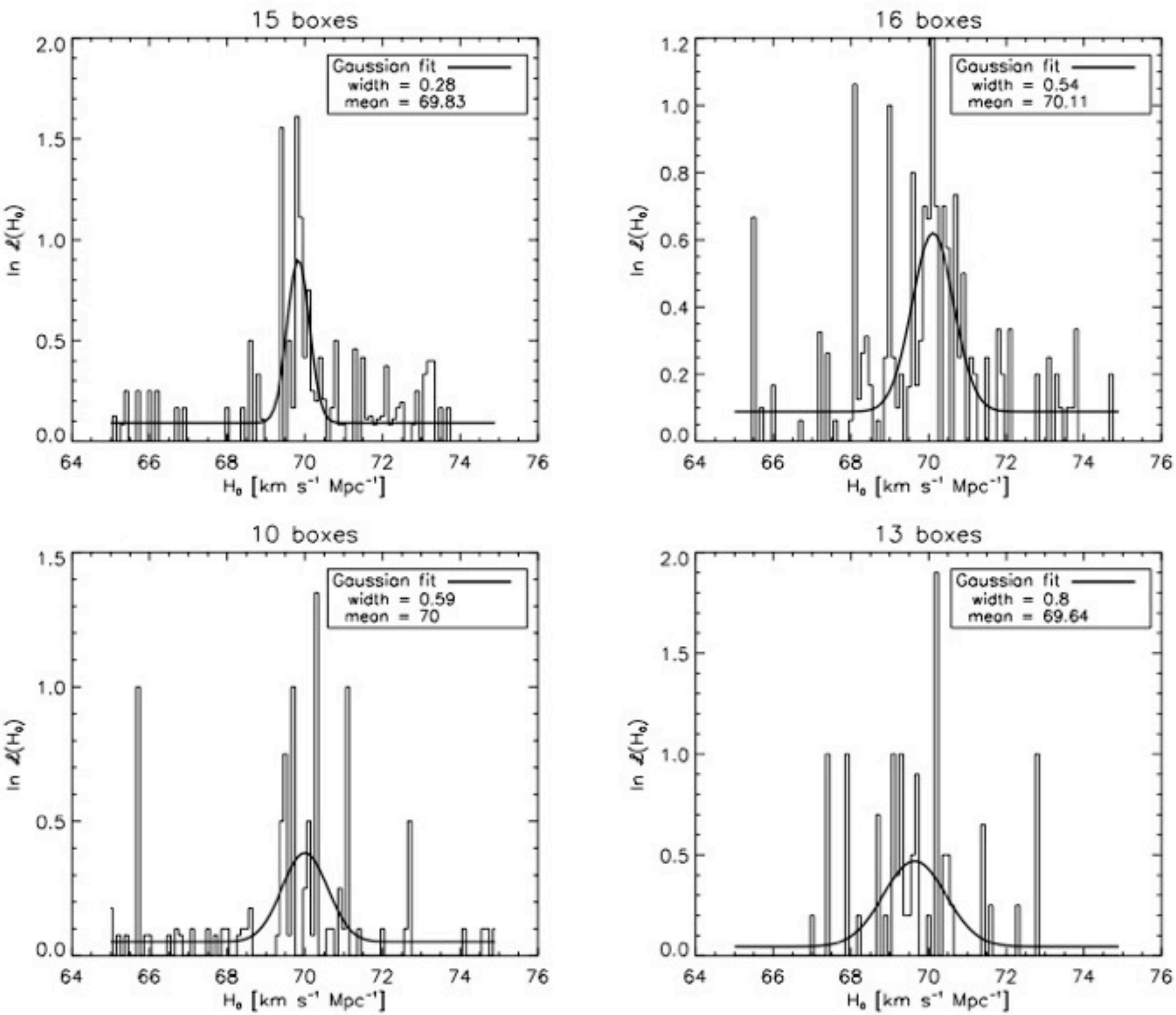
- A single EMRI event with an electromagnetic counterpart (and hence a redshift measurement) will give the Hubble constant to an accuracy of ~3%. N events give an accuracy of ~$3/\sqrt{N}$%.
- Even without a counterpart, can estimate Hubble constant statistically (McLeod & Hogan 08)
  - Let every galaxy 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 ~$3/\sqrt{N}$%.
- 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%.
- 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 LISA-like detector will place constraints on H_0.**

EMRI Science - Fundamental Physics

- Large number of waveform cycles generated in strong field make EMRIs ideal laboratories for fundamental physics
  - Verify 'no-hair' property of massive objects in centres of galaxies and hence test hypothesis that these are Kerr black holes. Hence test assumptions of the uniqueness theorem, i.e., axisymmetry, presence of a horizon, no closed-timelike-curves.
  - Look for signatures of astrophysical perturbations, e.g., accretion discs or other material in the black hole vicinity (Barausse et al., 2007,2008) or massive perturbers (Yunes et al. 2011) etc.
  - Test theory of gravity, e.g., Brans-Dicke, dynamical Chern-Simons modified gravity (Sopuerta & Yunes 2009, Canizares et al. 2012).
- These tests just rely on observing many EMRI waveform cycles. **Any EMRIs detected can be used for fundamental physics tests.**

Summary

- Four main obstacles stand in the way of EMRI detection
  - **A detector** - eLISA is one of the leading competitors for the ESA L2 mission opportunity in 2028.
  - **Astrophysical event rates** - our current best guess is that an eLISA-like detector would see tens of events. Highly uncertain.
  - **Data analysis** - considerable progress was made through the Mock LISA Data Challenges. Confident that EMRIs with signal-to-noise ratio of 20 (perhaps 15) will be detectable.
  - **Source modelling** - where the Capra programme fits in! Essential for scientific interpretation of data, if not detection.
- If detected, extreme-mass-ratio inspirals have great potential for astrophysics, cosmology and fundamental physics.