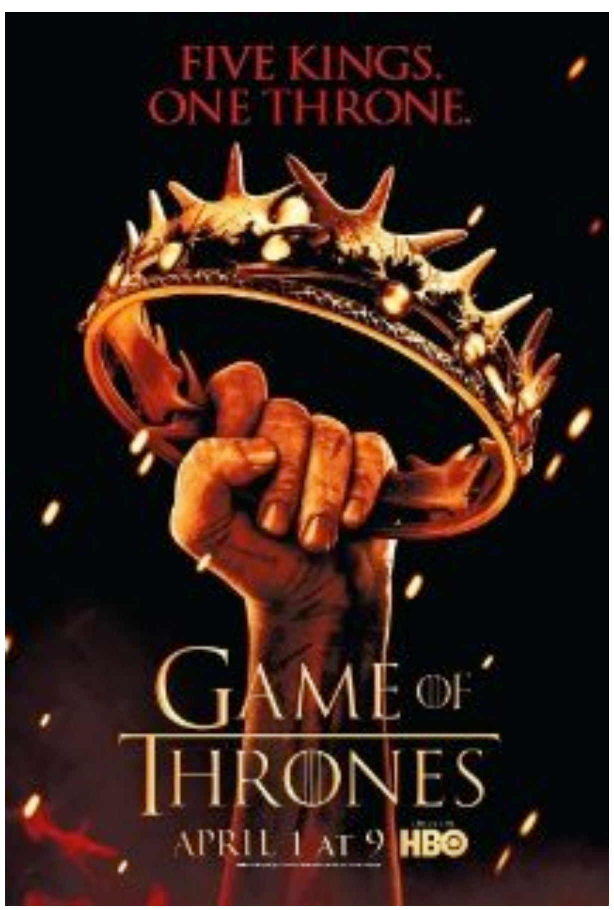
A Game of Thrones:
The science of LISA's would-be successors



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IAP GReCO Seminar
October 1, 2012

Five kings?

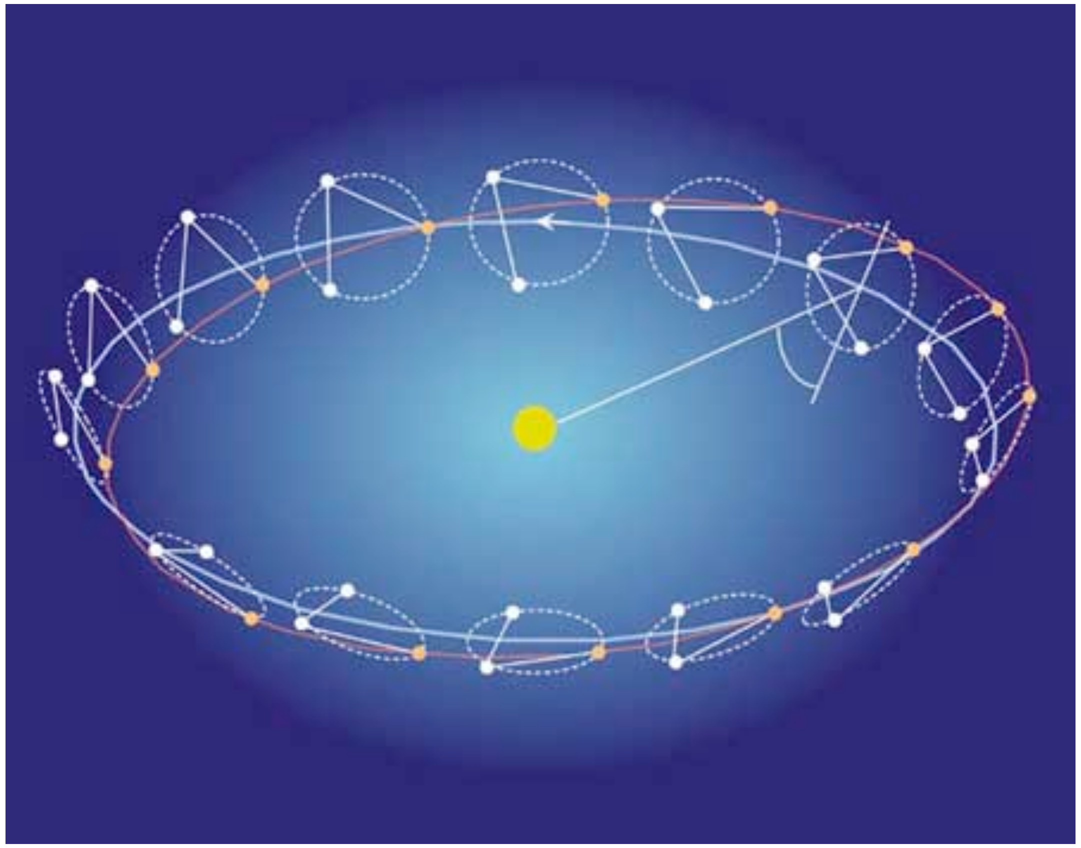
Science Performance	SGO-High	SGO-Mid	LAGRANGE/ McKenzie	OMEGA Option 1	OMEGA Option 2
Massive Black Hole Binaries					
Total detected	108–220	41–52	37–45	21–32	21–32
Detected at $z \geq 10$	3–57	1–4	1–5	1–6	1–6
Both mass errors ≤ 1%	67–171	18–42	8–25	11–26	11–26
One spin error ≤ 1%	49–130	11–27	3–11	7–18	7–18
Both spin errors ≤ 1%	1–17	<1	0	<1	<1
Distance error ≤ 3%	81–108	12–22	2–6	10–17	10–17
Sky location ≤ 1 deg^2	71–112	14–21	2–4	15–18	15–18
Sky location ≤ 0.1 deg^2	22–51	4–8	≤1	5–8	5–8
Total EMRIs detected†	800	35	20	15	15
WD binaries detected (resolved)	4×10^4	7×10^3	5×10^3	5×10^3	5×10^3
WD binaries with 3-D location	8×10^3	8×10^2	5×10^2	1.5×10^2	1.5×10^2
Stochastic Background Sensititvity (rel. to LISA)	1.0	0.2	0.15*	0.25	0.25
Top Team X Risk	Moderate‡	Low	Moderate	Moderate	High
Top Team X + Core Team Risk	Moderate‡	Low	High	High	High
Team X Cost Estimate (FY12$)	2.1B	1.9B	1.6B	1.4B	1.2B

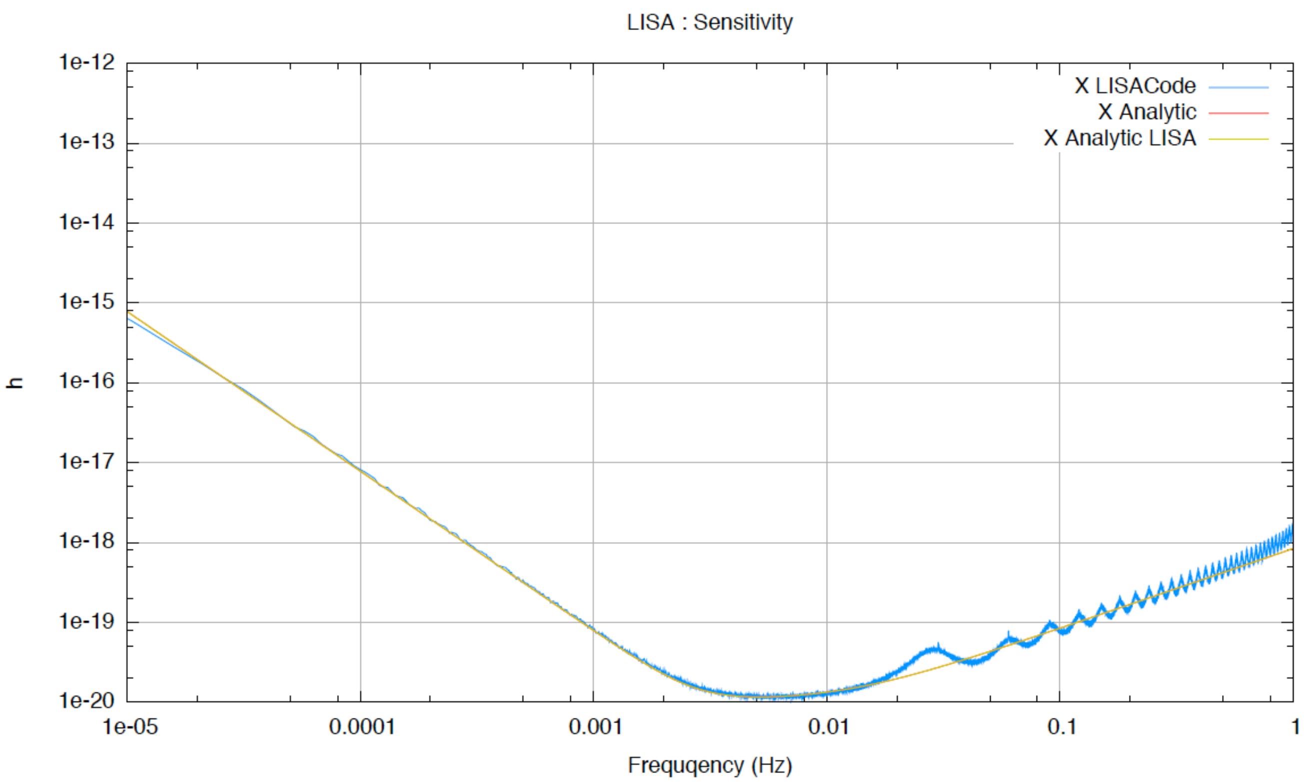
Outline

- The kingdom: space-based gravitational wave astronomy
  - The queen: LISA (Laser Interferometer Space Antenna)
  - Expected sources and science
  - Science assessment, particularly parameter estimation
  - Impact of spin precession, higher harmonics, merger-ringdown
- Winter is coming: Budget cuts! Dissolved partnership!
- The kingsmoot: Comparing cost, risk, science capabilities of the various detector redesigns
  - European L1 choice: eLISA-NGO
  - NASA study of various design choices, e.g. SGO Mid, LAGRANGE, OMEGA

Space-based gravitational wave detection

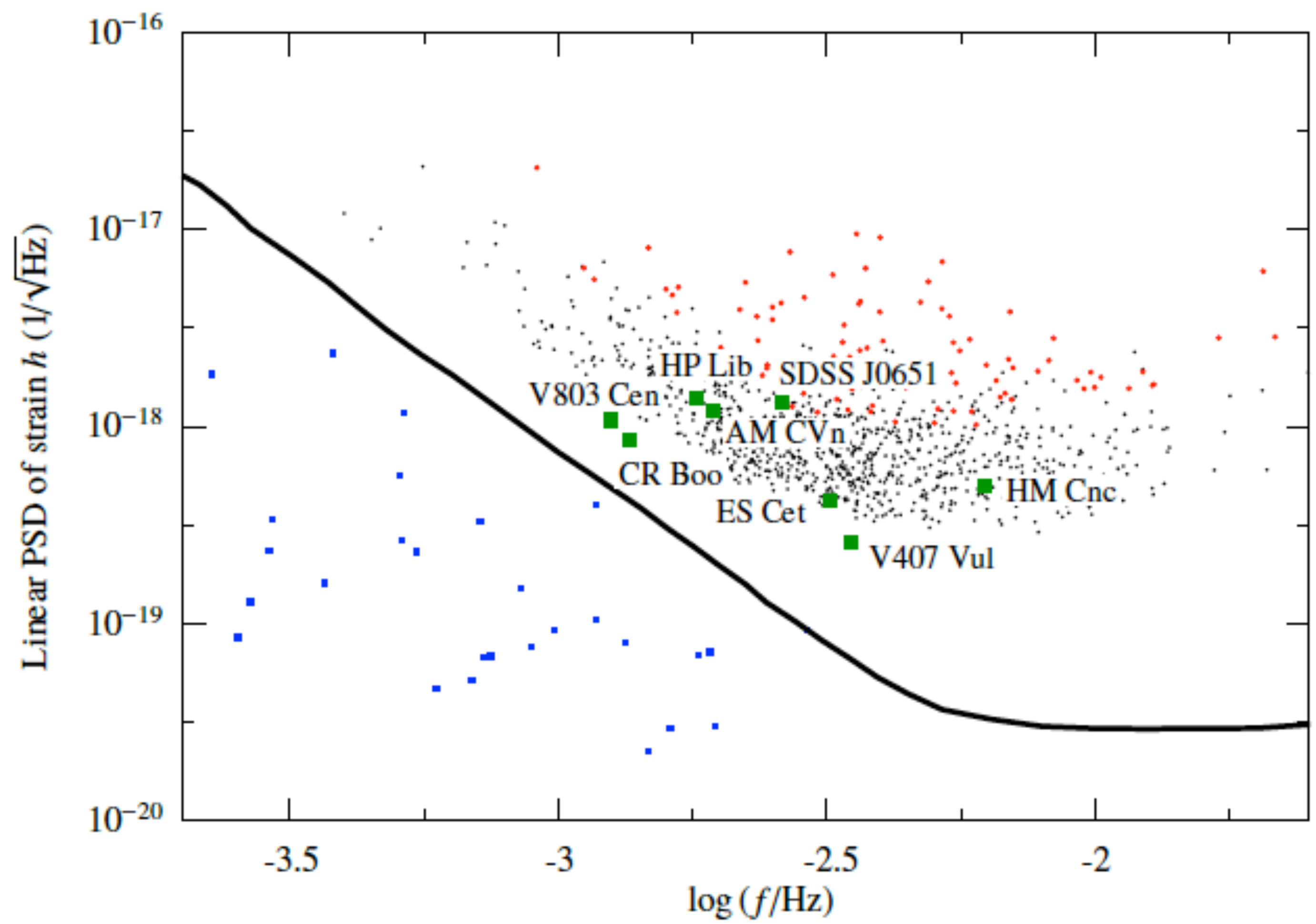
- Gravitational waves (GWs) below ~1 Hz cannot be detected by ground-based detectors (LIGO, Virgo, ET)
  - Seismic noise limit!
- Canonical space-based GW detector design (a.k.a. the "queen"): LISA
  - Six laser links => two (three) interferometer channels





Sources and science: Galactic compact binaries

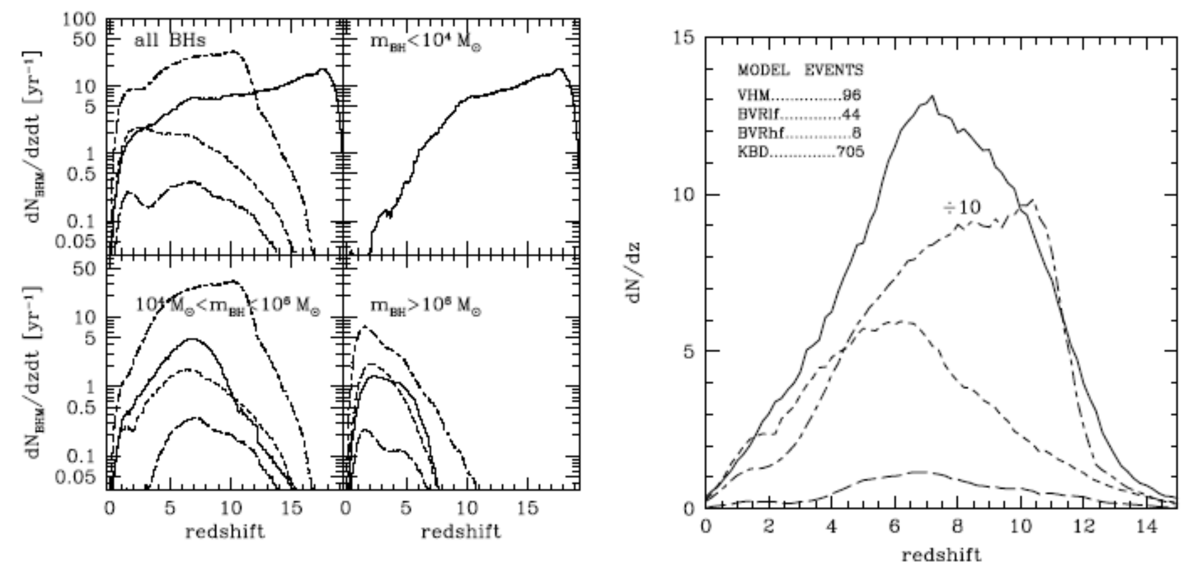
- Composed of WD, NS, stellar-mass BH (50 known so far)
  - Verification binaries
- Thousands detected individually, millions make up foreground.
  - Determine merger rates, constrain binary formation/ evolution. Important for studying, e.g., type Ia supernova scenarios.
  - Measure frequency/phase evolution => study tides/mass transfer.
  - Map the Galaxy.



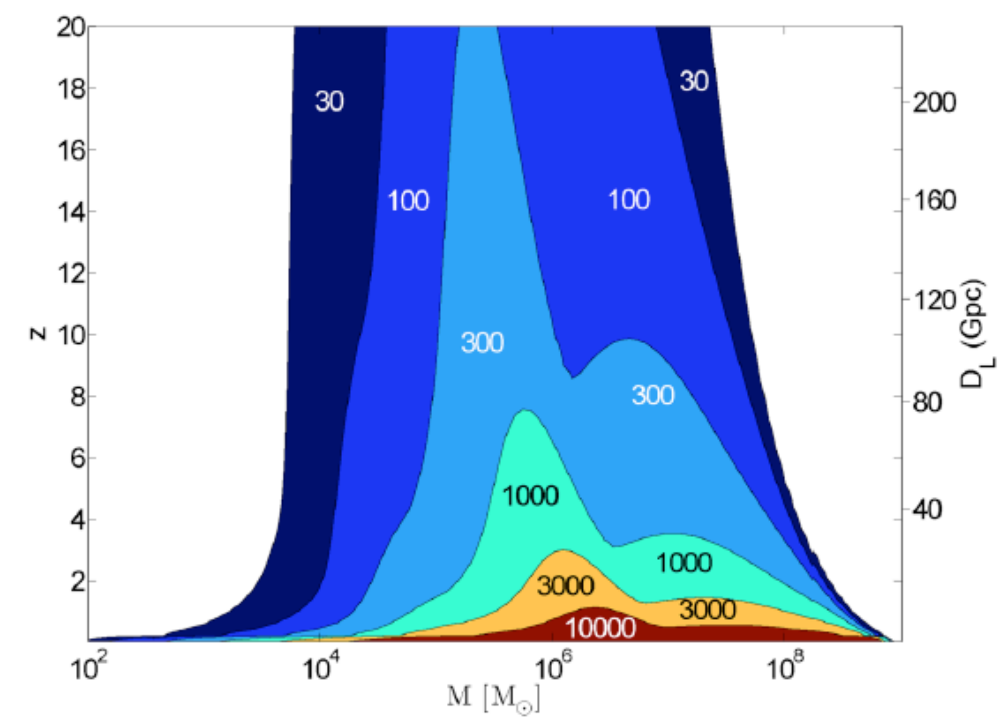
Amaro-Seoane et al. 2012a

Sources and science: MBH binaries

- It is believed that nearly every galaxy hosts a massive black hole (MBH) at its center.
- Massive black hole binaries formed when galaxies merge!
- MBHBs are one of the most promising sources for space-based detectors.
  - Event rates expected to be good.
  - Can be seen with high SNR and to large redshift.



Sesana, Volonteri, and Haardt 2007



Baker et al. 2007

Sources and science: MBH binaries

- Seeds?
  - "Small" (100-1000 $M_\odot$): collapse of Pop III stars
  - "Large" (10^3-$10^5 M_\odot$): direct collapse of gas cloud
- Spin evolution?
  - "Efficient": spin up and (partial) alignment
  - "Chaotic": smaller spins, not aligned
- GWs can tell us about the merger history (and accretion history) of MBHs.
  - Distinguish between LC, LE, SC, SE models.
  - Track mergers of host galaxies.
- Also: cosmology (standard siren with EM counterpart), test GR in strong-field regime.

Sources and science: EMRIs

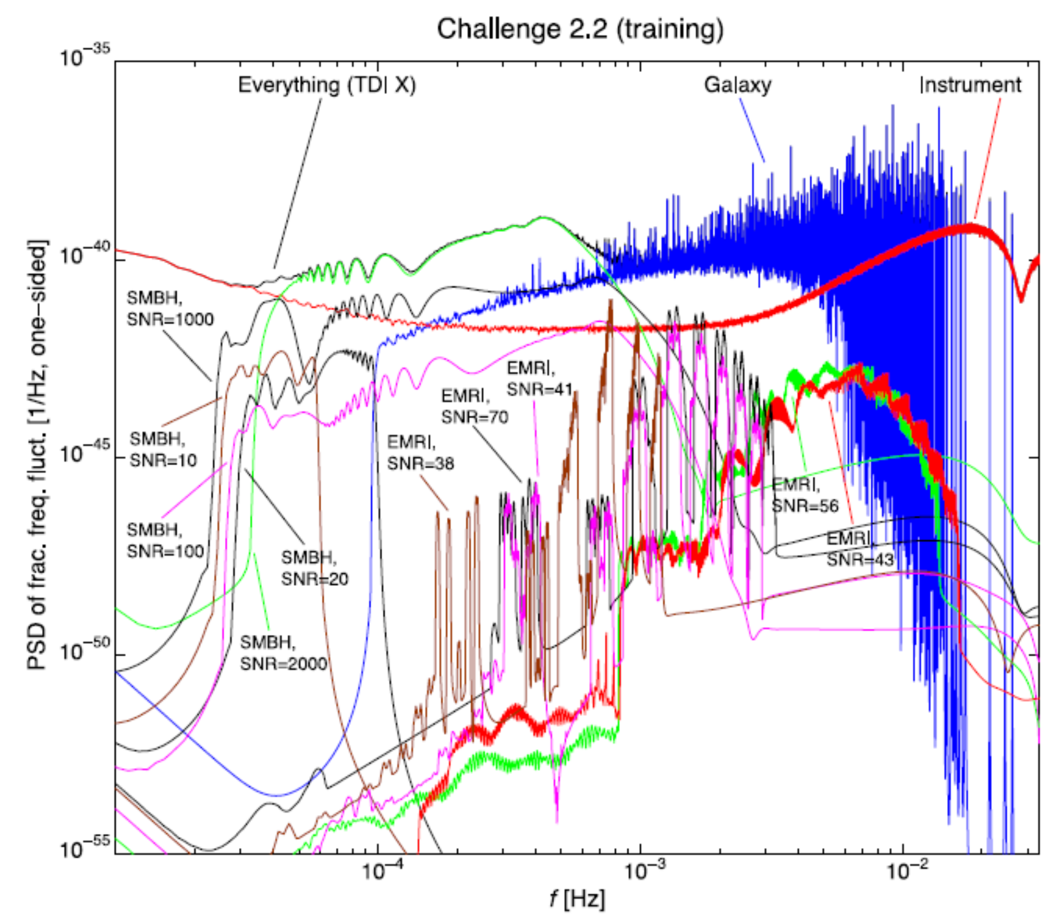
- Extreme mass ratio inspiral: stellar-mass compact objects inspiraling into massive BHs (mass ratio ~ 10^5)
- Formation mechanisms:
  - Two-body scattering
  - Tidal disruption of binaries (=> hypervelocity stars)
  - Star formation in accretion disks
  - Rates very uncertain!!
- Hundreds of thousands of orbits => information-rich signal
  - But can be hard to detect.
- Can tell us about populations near MBHs, constrain MBH/stellar-mass BH mass functions.
- Can test Kerr metric/GR.

Science assessment tools

- Basic metrics: horizon distance, number of detected sources
- More advanced: parameter estimation (estimation)
- While a larger horizon/more sources generally translates to better PE (higher SNR), PE can depend on many other qualities of a detector:
  - Number of laser links/interferometry channels
  - Shape of sensitivity curve
  - Detector size
  - Sweep of antenna pattern
- MBHBs are particularly sensitive to these features.

Parameter estimation (estimation)

- In all, a MBHB is characterized by ~~17~~ 15 parameters: masses (2), spin magnitudes (2) and angles (4), distance (1), sky position (2), orbit orientation (~~3~~ 2), ~~eccentricity (1)~~, reference time (1), reference phase (1). How well can a detector measure these parameters?
  - Fisher matrix: $\Gamma_{ab} = \left(\frac{\partial h}{\partial \theta^a} \middle| \frac{\partial h}{\partial \theta^b} \right)$
  - Inner product: $(a|b) = 4 \text{ Re} \int_0^\infty df \frac{\tilde{a}^*(f)\tilde{b}(f)}{S_n(f)}$
  - Covariance matrix: $\Sigma^{ab} = (\Gamma^{-1}_{\text{tot}})^{ab}$
- This is not actual data analysis (e.g., Mock LISA Data Challenges).
- Fisher matrix not always valid!
  - For low SNR, posterior may be non-Gaussian or multimodal. More detailed analysis needed.



Arnaud et al. 2007

Parameter estimation (estimation)

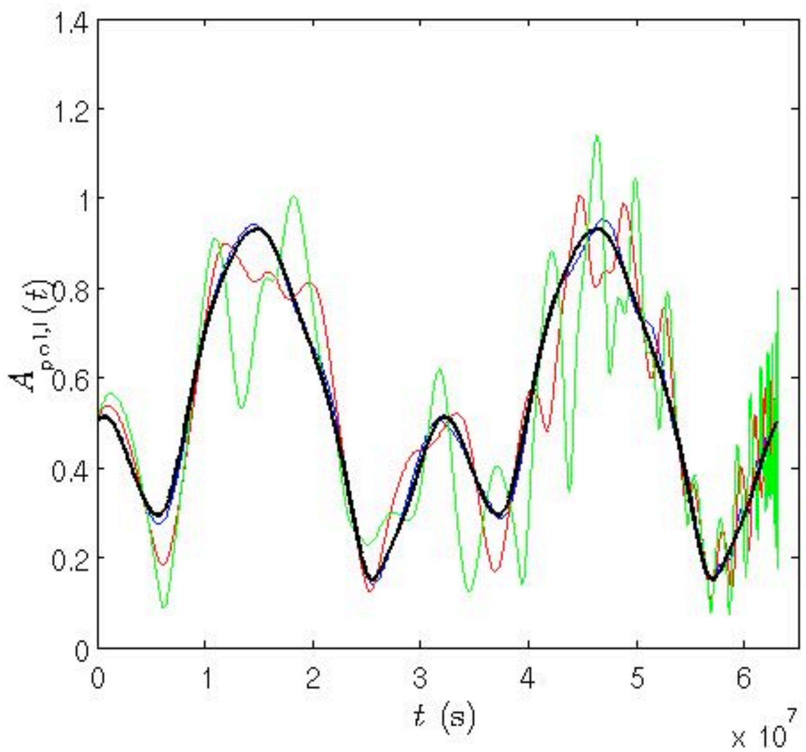
- Procedure:
  - Choose sources.
    - Pick mass and redshift; randomize the rest. OR:
    - Use catalogs based on MBH formation/growth scenarios: Large or Small black hole seeds, Chaotic or Efficient accretion
  - Define waveform model.
    - Spin precession?
    - Higher harmonics?
    - Inspiral only or include merger/ringdown?
  - Choose a detector (response function and noise model).
  - Calculate Fisher!

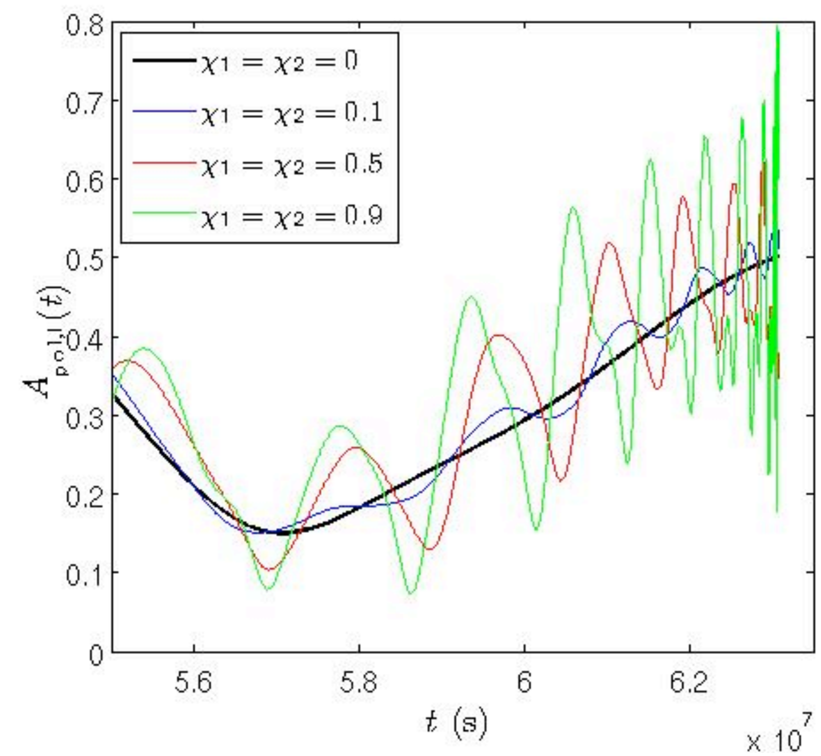
Spin precession

- Spins precess:

$$\dot{\mathbf{S}}_1 = \frac{1}{r^3}\left[\left(2+\frac{3}{2}\frac{m_2}{m_1}\right)\mu\sqrt{Mr}\hat{\mathbf{L}}\right]\times\mathbf{S}_1 + \frac{1}{r^3}\left[\frac{1}{2}\mathbf{S}_2 - \frac{3}{2}(\mathbf{S}_2\cdot\hat{\mathbf{L}})\hat{\mathbf{L}}\right]\times\mathbf{S}_1$$
$$= \mathbf{\Omega}_L\times\mathbf{S}_1 + \mathbf{\Omega}_{S_2}\times\mathbf{S}_1$$

- So does the orbital plane: $\mathbf{J} = \mathbf{L} + \mathbf{S}_1 + \mathbf{S}_2 = \mathrm{const.}$
- Inclusion of precession allows measurement of spin magnitude (0.001-0.01)
- Amplitude and phase modulations break degeneracies and improve parameter errors

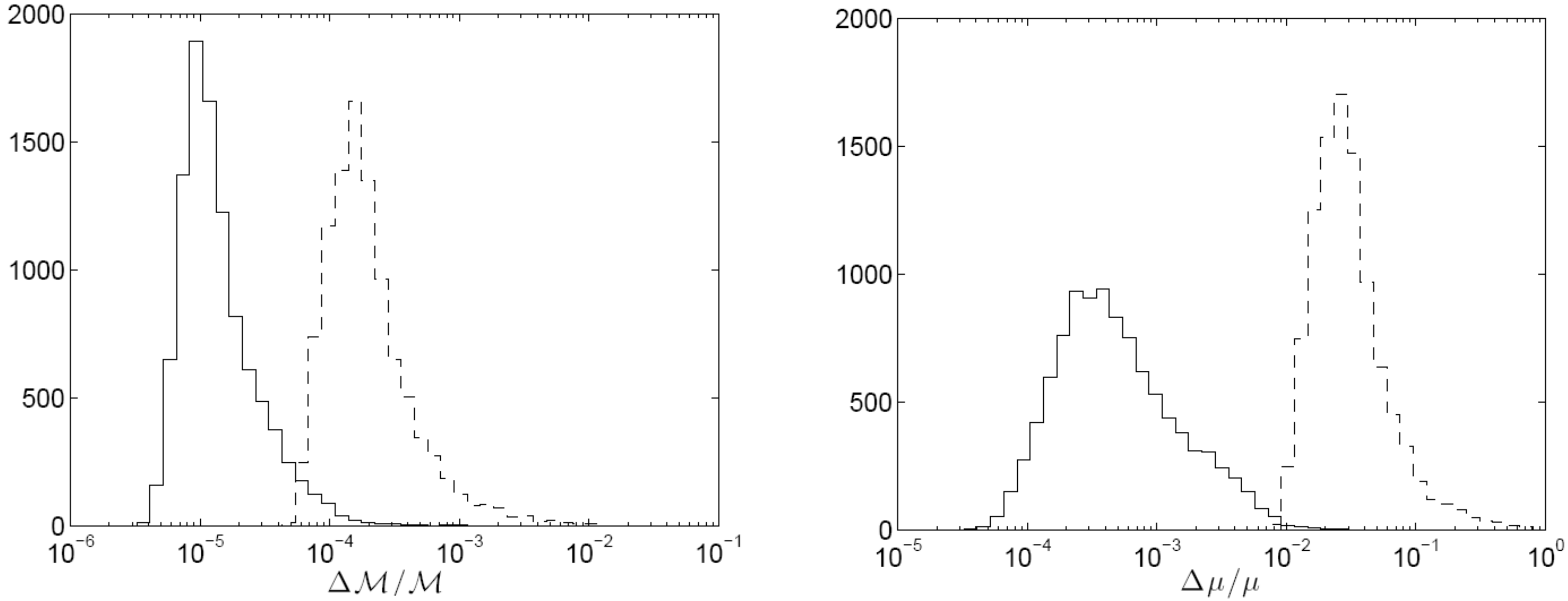




Lang and Hughes 2006

Improvement in mass measurement

$$m_1 = 10^6 M_\odot, m_2 = 3 \times 10^5 M_\odot, z = 1$$

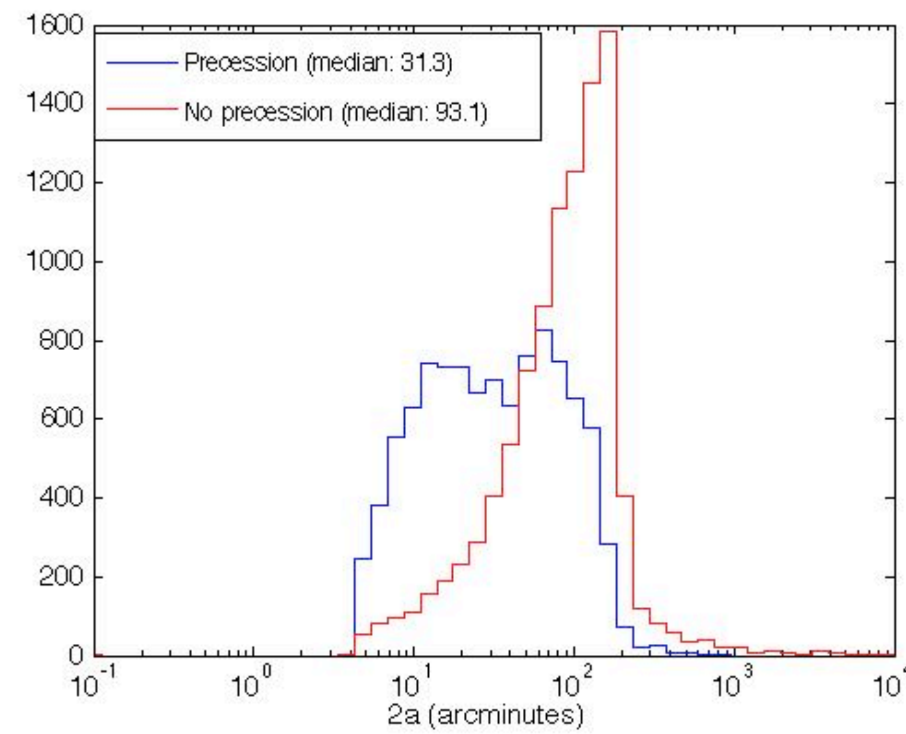


- Masses come from precisely measuring phase. Precession breaks degeneracies between masses and spins in higher post-Newtonian phase terms (Lang and Hughes 2006).

Localization of MBHBs

- GW detectors generally “all-sky” instruments.
- Sky position determined by:
  - Multiple polarizations
  - Detector motion
  - And now, spin precession!
- Degree of improvement not as impressive, but much more critical!

$$m_1 = 10^6 M_\odot, m_2 = 3 \times 10^5 M_\odot, z = 1$$



Lang, Hughes, and Cornish 2011

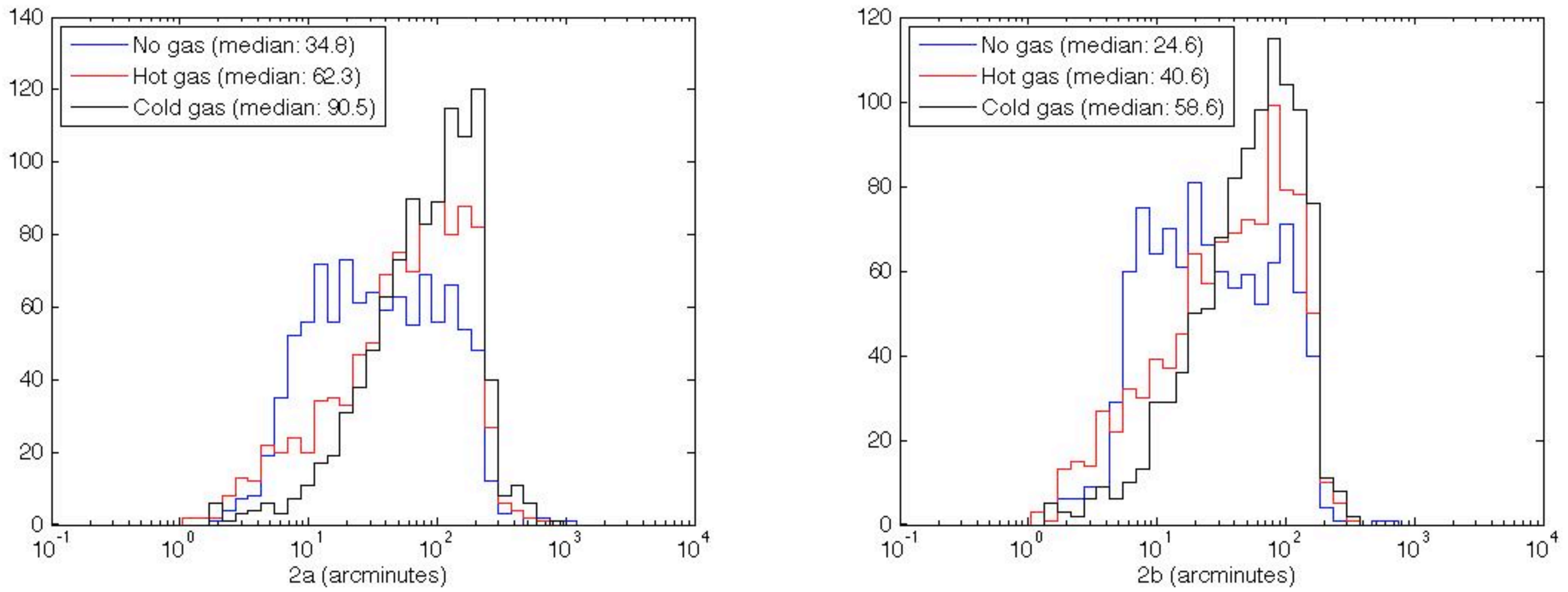
Higher harmonics

- Another way to break degeneracies is to use higher harmonics beyond the quadrupole.
- As an example, let's consider systems partially aligned by gas accretion (e.g., LE, SE catalogs).
  - Hot gas: 30 deg. alignment
  - Cold gas: 10 deg. alignment
- Alignment restricts precession.

$$
\begin{aligned}
h_+(t) &= 2\frac{\mathcal{M}^{5/3}(\pi f)^{2/3}}{D_L}\Bigg[(1+c_i^2)\cos 2\Phi_{\rm orb} \\
&+ x^{1/2}\frac{s_i}{8}\frac{\Delta m}{M}\Bigg[(5+c_i^2)\cos\Phi_{\rm orb} \\
&- 9(1+c_i^2)\cos 3\Phi_{\rm orb}\Bigg] \\
&+ x\Bigg[-\frac{1}{6}\Bigg(19+9c_i^2-2c_i^4 \\
&- \eta\Big(19-11c_i^2-6c_i^4\Big)\Bigg)\cos 2\Phi_{\rm orb} \\
&+ \frac{4}{3}\Big(s_i^2(1+c_i^2)(1-3\eta)\Big)\cos 4\Phi_{\rm orb}\Bigg]\Bigg]
\end{aligned}
$$

Effect of partial alignment

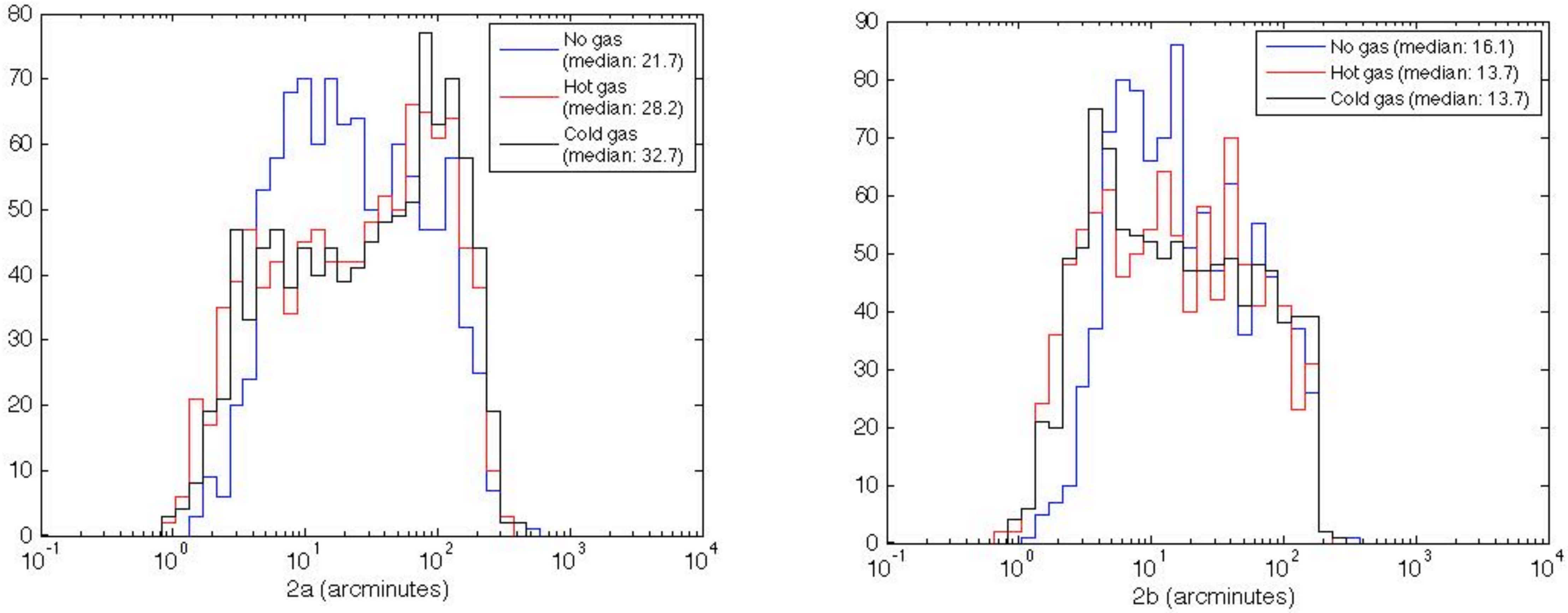
$$m_1 = 10^6 M_\odot, m_2 = 3 \times 10^5 M_\odot, z = 1$$



Lang, Hughes, and Cornish 2011

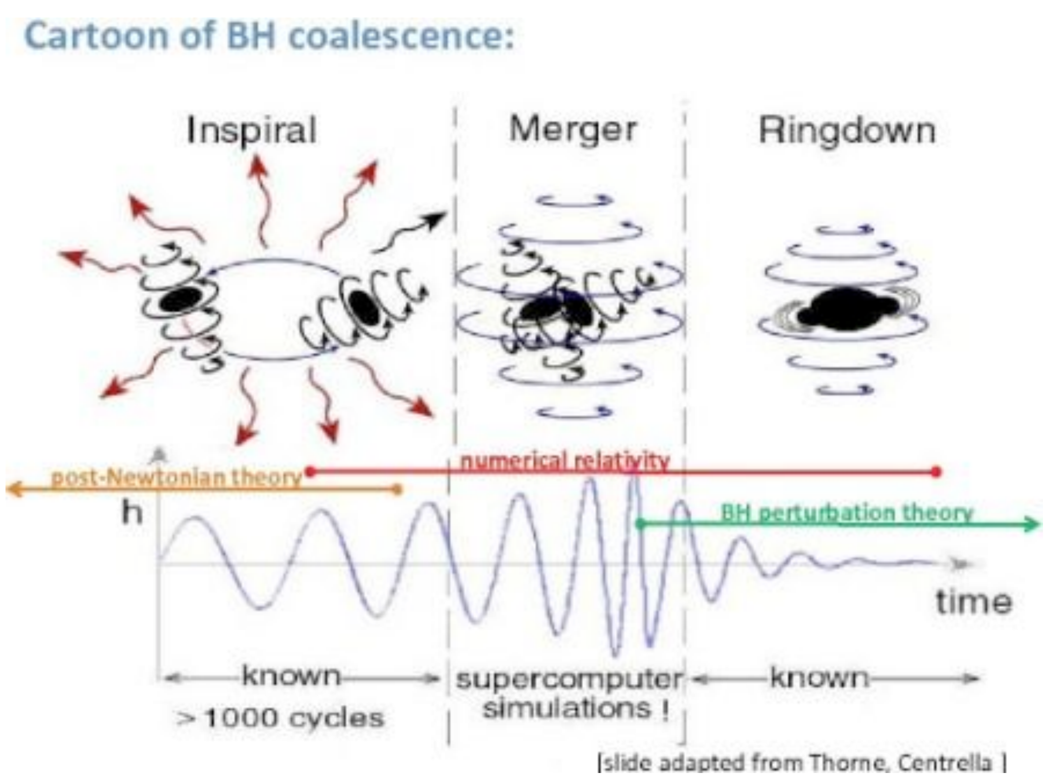
Higher harmonics to the rescue!

$$m_1 = 10^6 M_\odot, m_2 = 3 \times 10^5 M_\odot, z = 1$$



Lang, Hughes, and Cornish 2011

Merger-ringdown signal

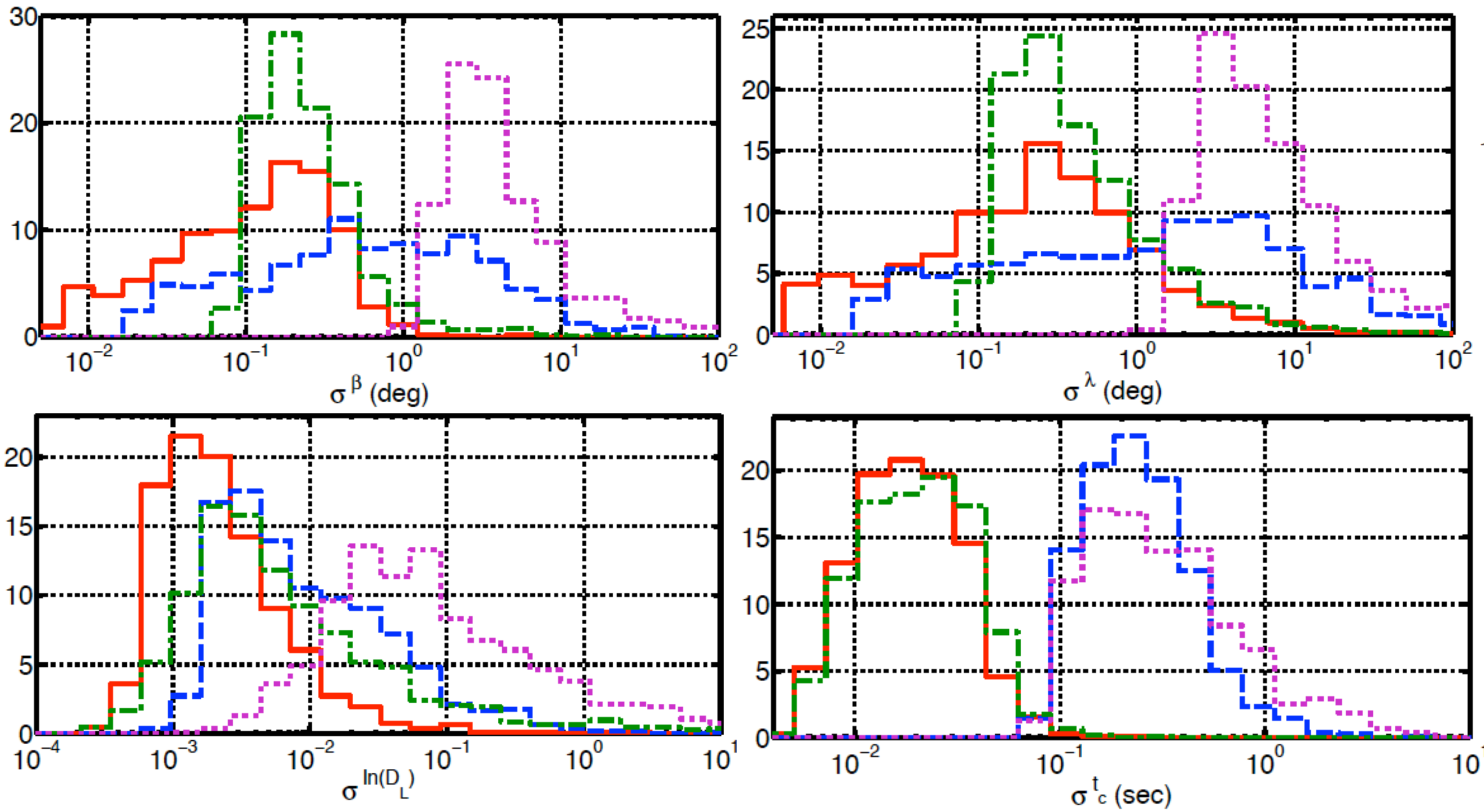


Favata (from Thorne)

- Three distinct phases:
  - Adiabatic inspiral
  - Strong merger
  - Quasi-normal ringdown
- Merger can only be calculated by integrating Einstein's equations numerically: numerical relativity
  - Breakthroughs in 2005-6

Impact of MR signal on parameter estimation

- First studied by McWilliams et al. (2010)
  - Included MR and higher harmonics, but no spin or orbital motion.
- Found that including MR signal improves errors, by ~ half an order of magnitude (less for mass, more for reference time)



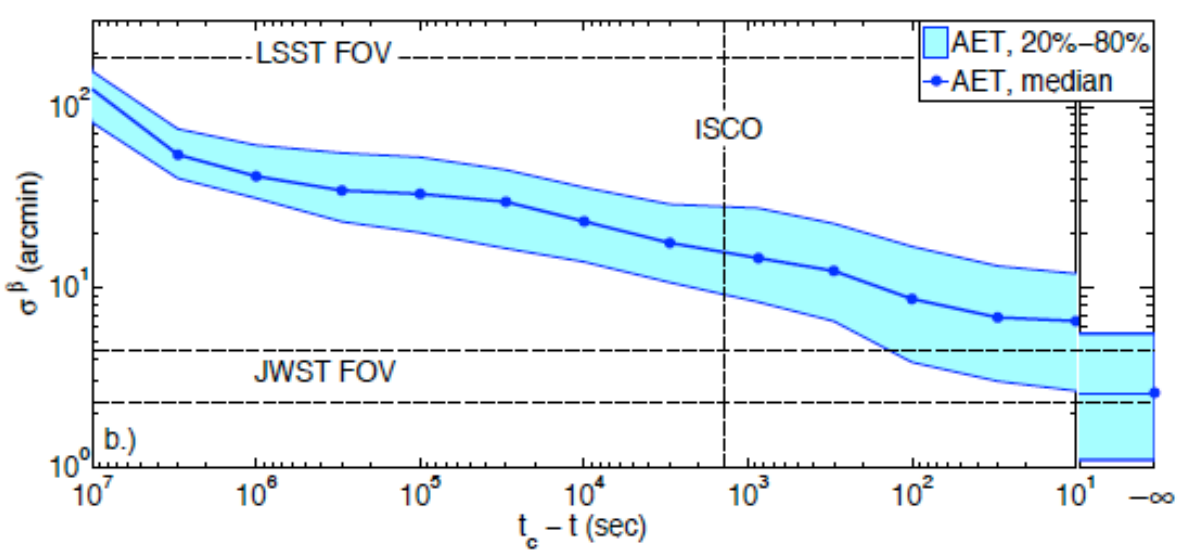
$M = 1.33 \times 10^6 M_\odot,\ q = 1$

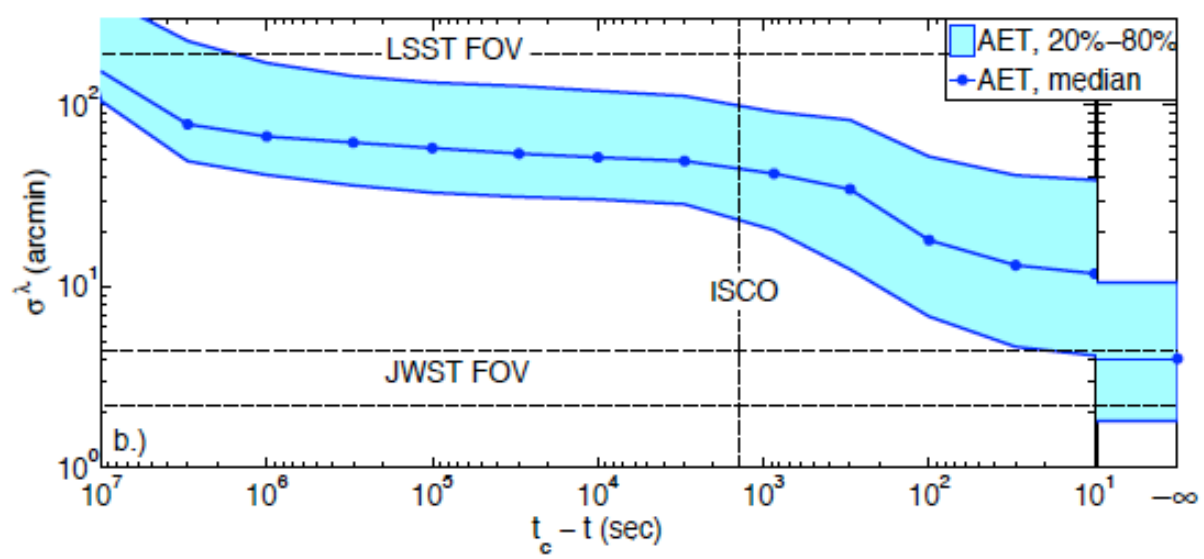
$z = 1$

Blue: I only
Red: IMR

Sky localization with merger-ringdown

- Now include detector motion and examine time evolution of localization capability.
- Well inside LSST FOV (10 sq. deg.) months before merger
    - Advance localization of source for EM followup
- Possibly within JWST FOV (2.2 arcmin x 4.4 arcmin) with complete signal
- MR improvement due to interaction with non-trivial high frequency response





$$M_o = 2 \times 10^6 \ \mathrm{M}_{\odot} \ \text{at} \ z = 1$$

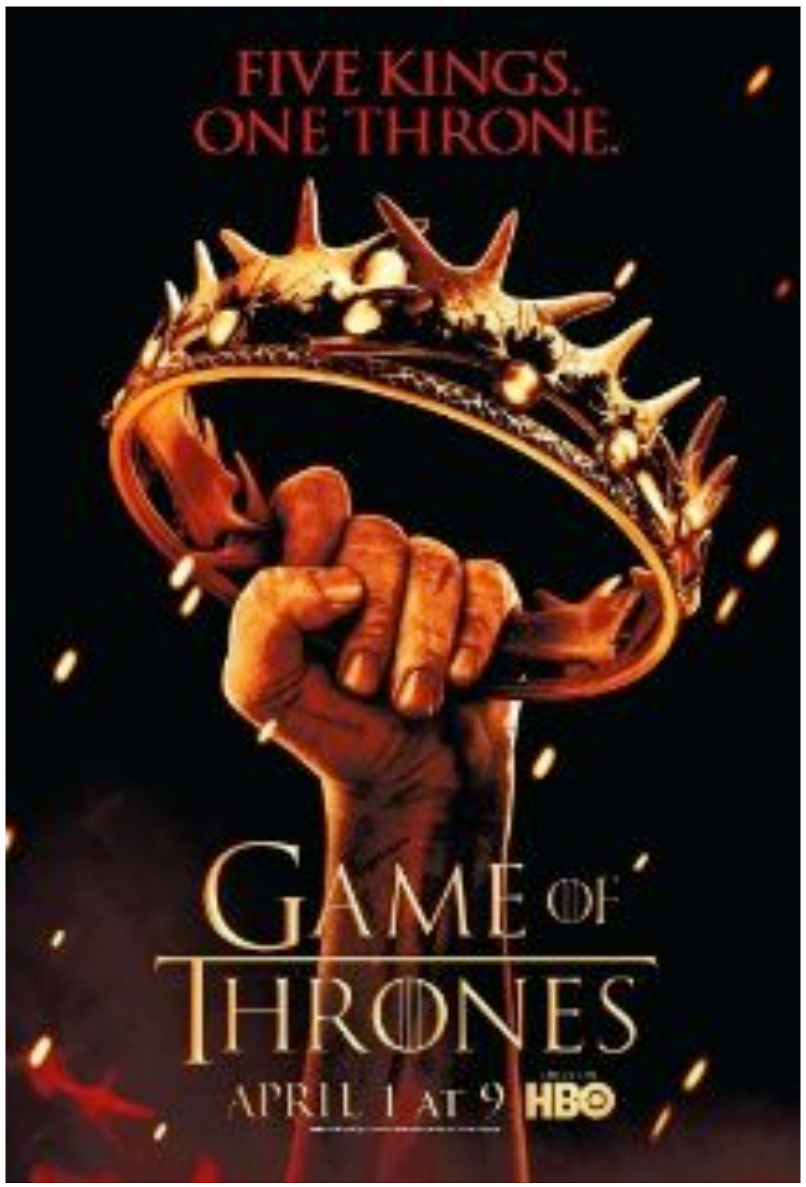
$$q = 1$$

McWilliams, Lang, Baker, and Thorpe 2011

A kingdom in mourning

- LISA was designed to be a joint NASA-ESA mission.
  - Excellent science case!
  - High priority in the 2010 Decadal Survey
  - LISA Pathfinder (a technology testing mission) scheduled to fly in 2014
- NASA budget woes (esp. JWST) caused dissolving of partnership in spring 2011. Now what?

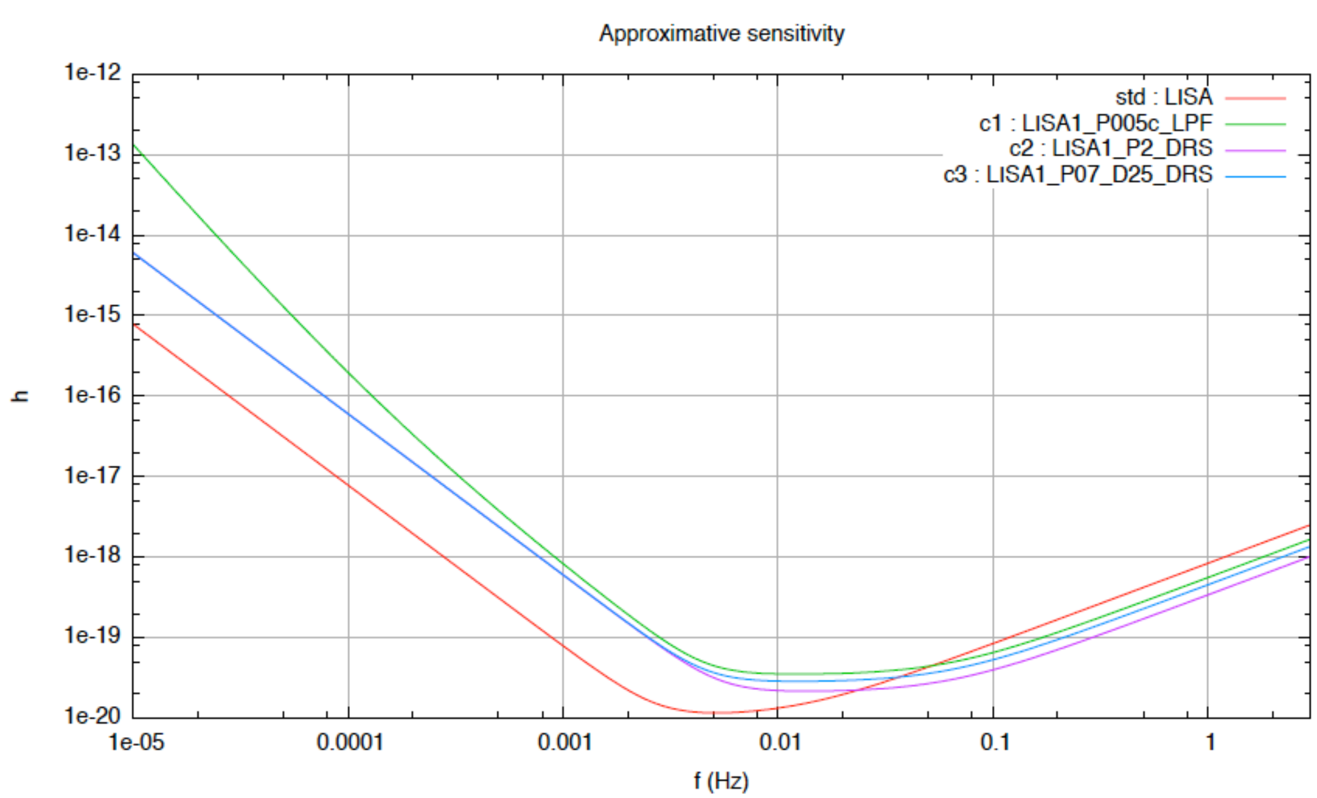
The game of thrones

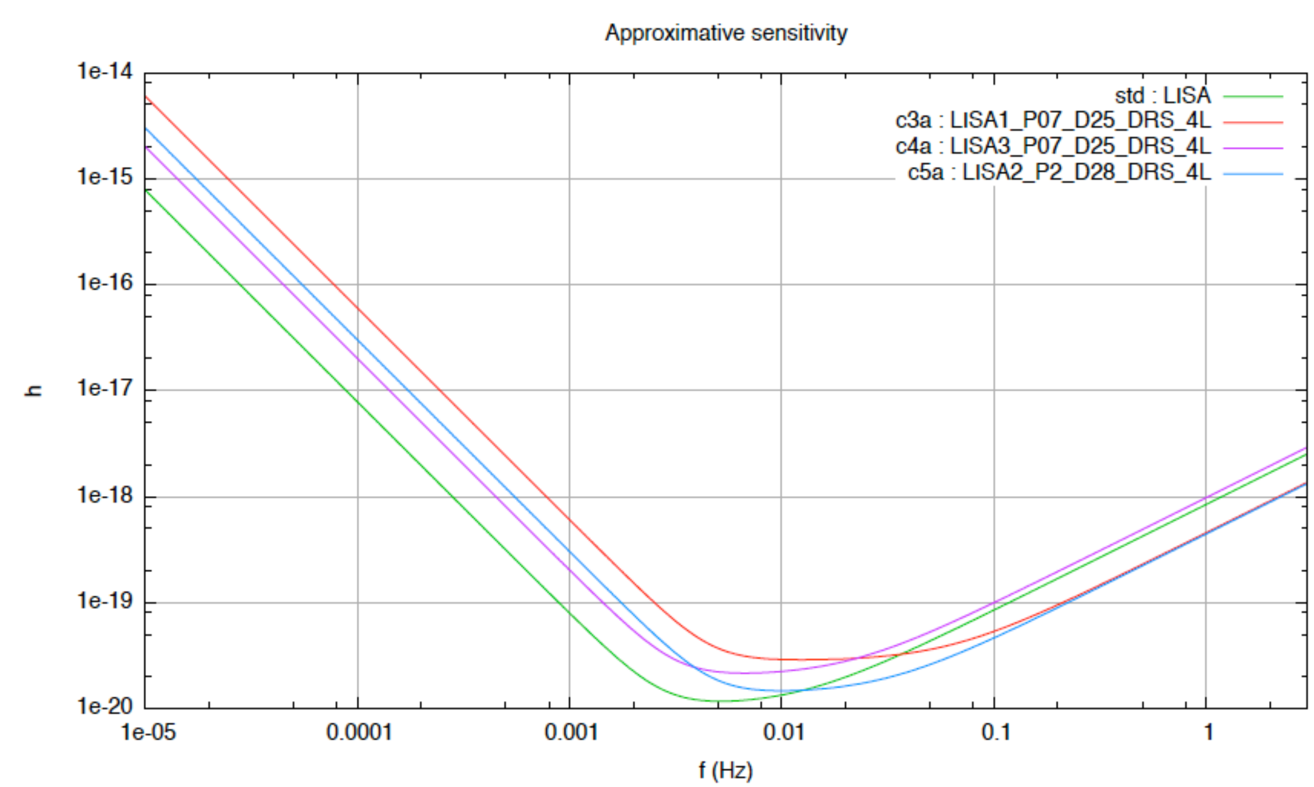


- The queen is dead. But space-based gravitational-wave astronomy is not dead!
- ESA, NASA are continuing separate efforts to develop the "new LISA."
  - ESA: Quick turnaround for L1 Cosmic Vision proposal (due late 2011)
    - Up to 7 concepts, narrowed to 1
  - NASA: More leisurely study of multiple concepts
    - 17 RFI respondents, 3 in engineering studies, no final choice (but recommendations)

European designs

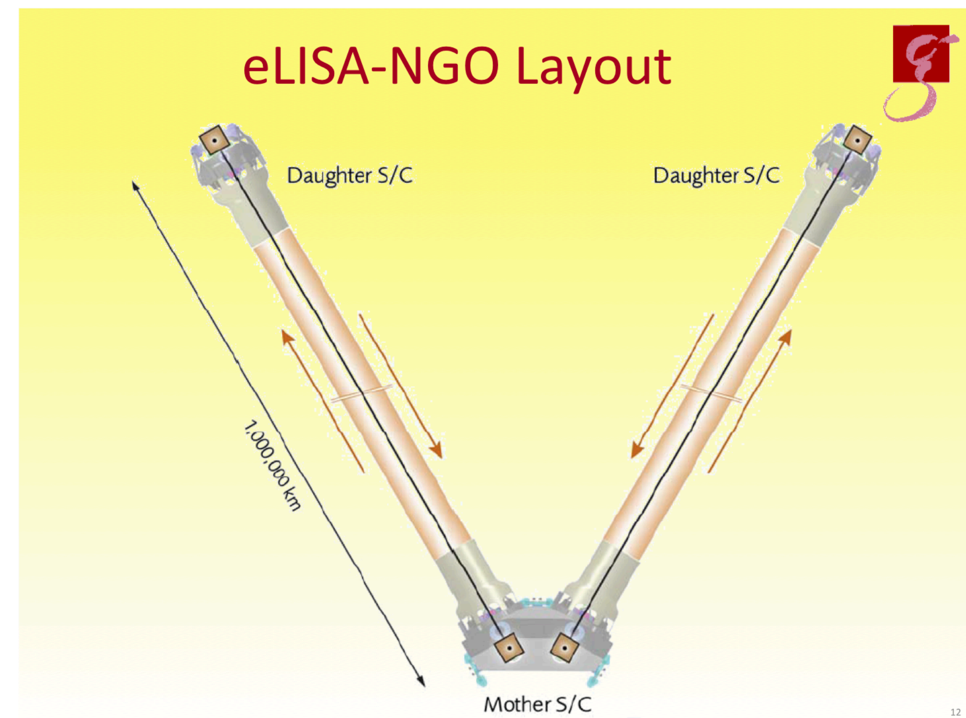
- Underwent many iterations: C1-C7
  - All LISA variants, differences in arm length, telescope, laser power
  - Final decision driven by budget, available launch vehicles
  - Question: Can the desired design do science?
    - Science Performance Task Force (including U.S. contingent)

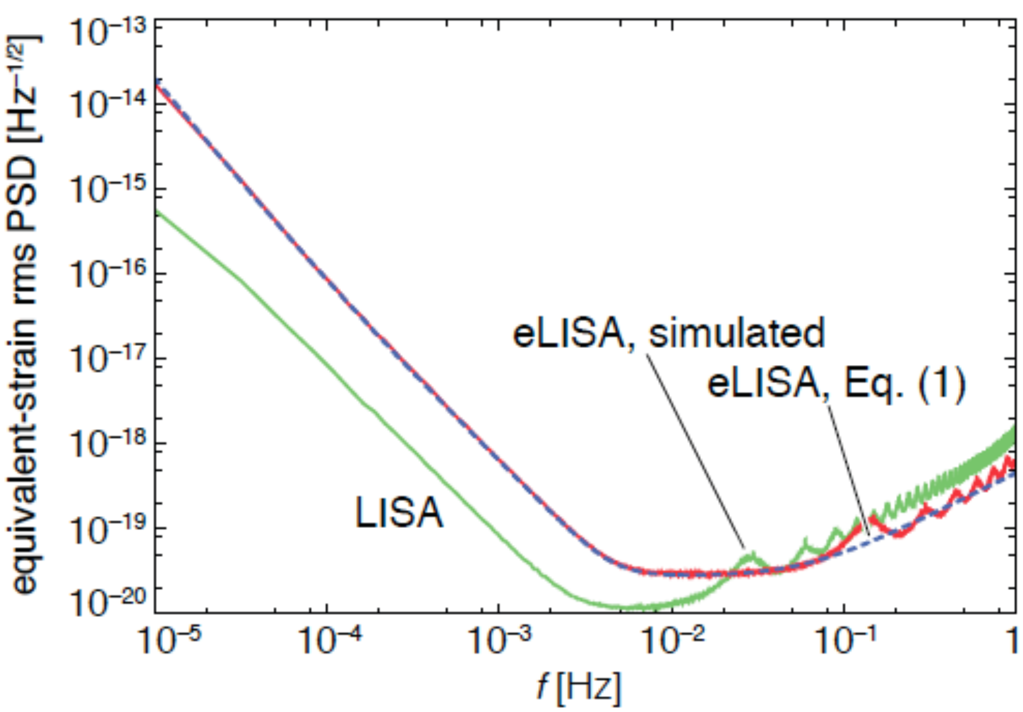




NGO: New Gravitational-wave Observatory

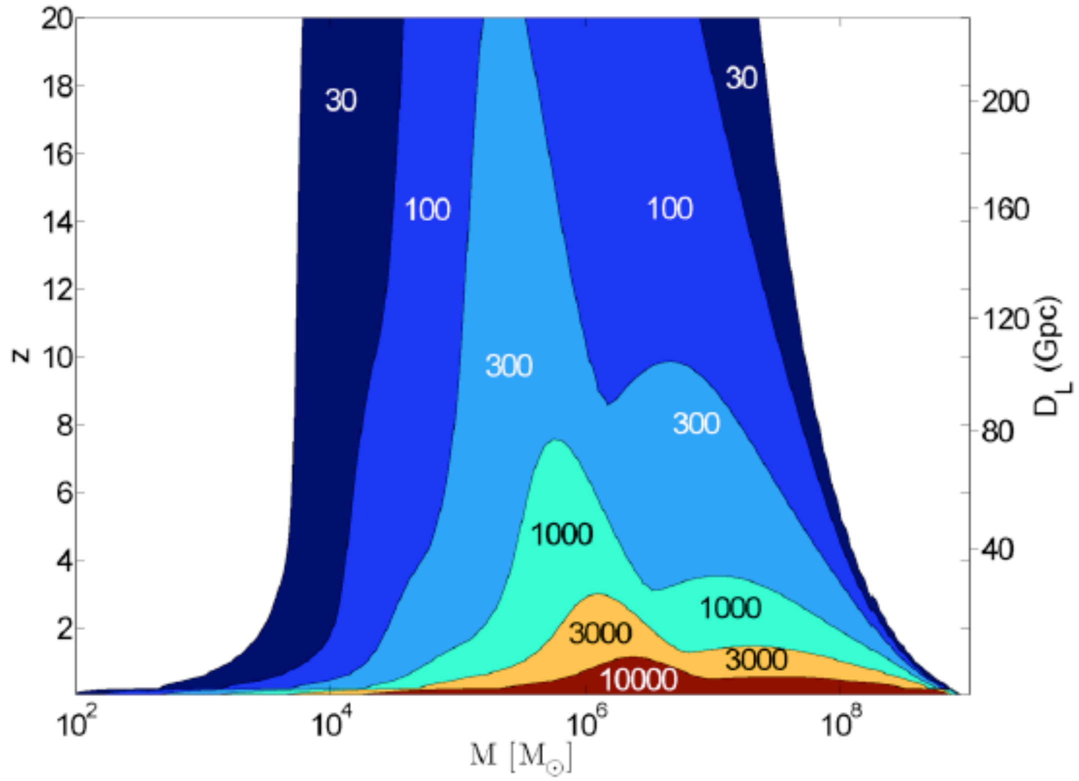
- Also known as eLISA (evolved LISA): elisa-ngo.org
- Changes from LISA:
  - Shorter lifetime (2 yr)
  - Shorter arms (1 Gm)
  - Four links (mother-daughter configuration)
    - One signal channel!



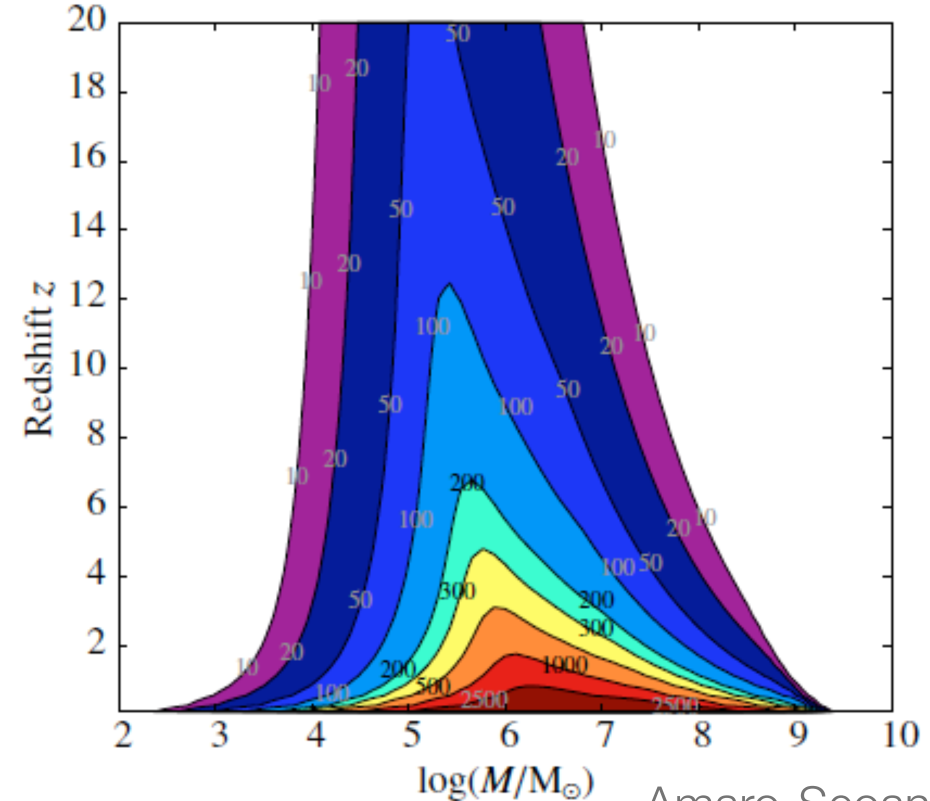


Amaro-Seoane et al. 2012b

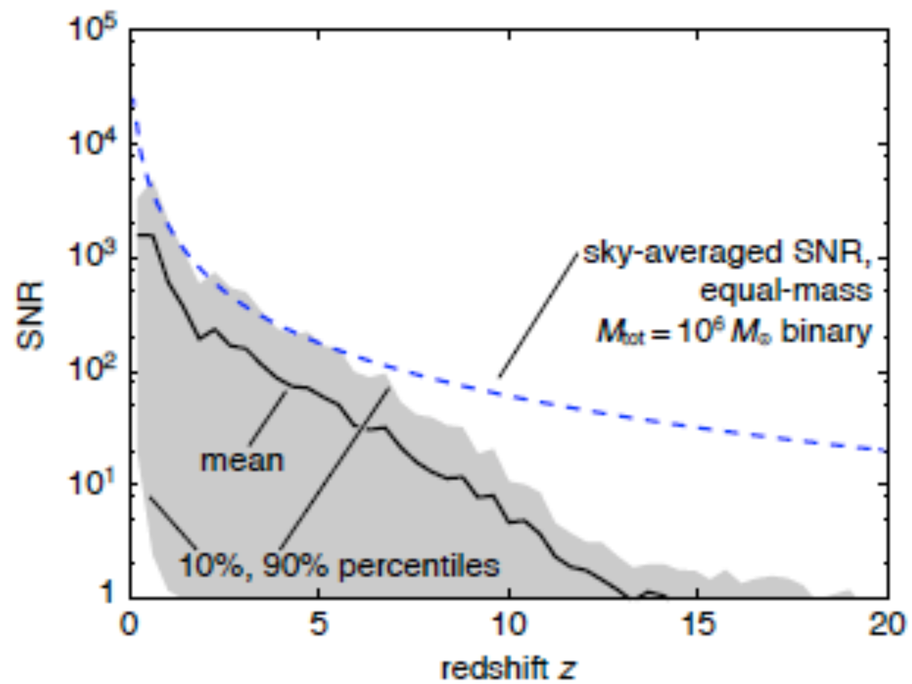
NGO MBHB detections



Baker et al. 2007



Amaro-Seoane et al. 2012a



Amaro-Seoane et al. 2012b

NGO parameter estimation

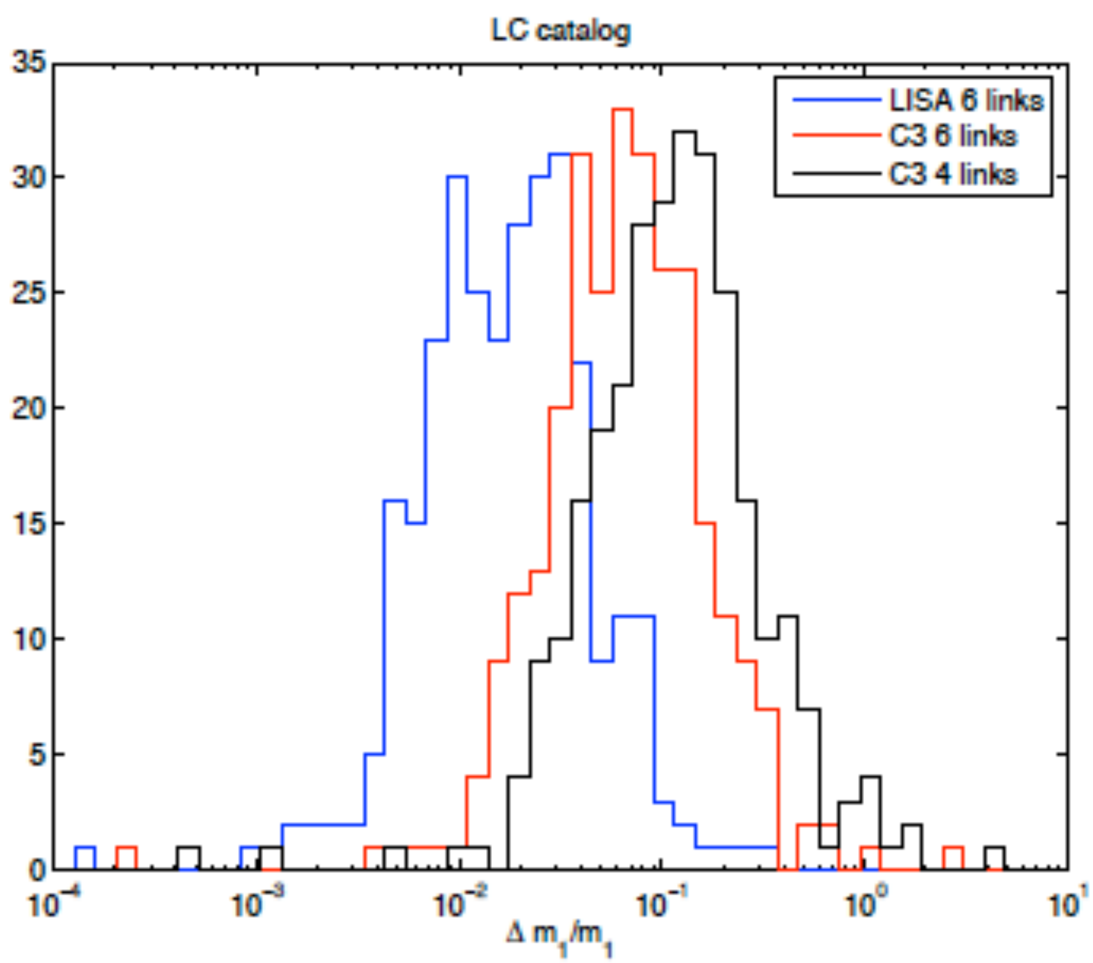
- NGO measures only one polarization at a time: need to include as many other features (precession, higher harmonics, MR) as possible.

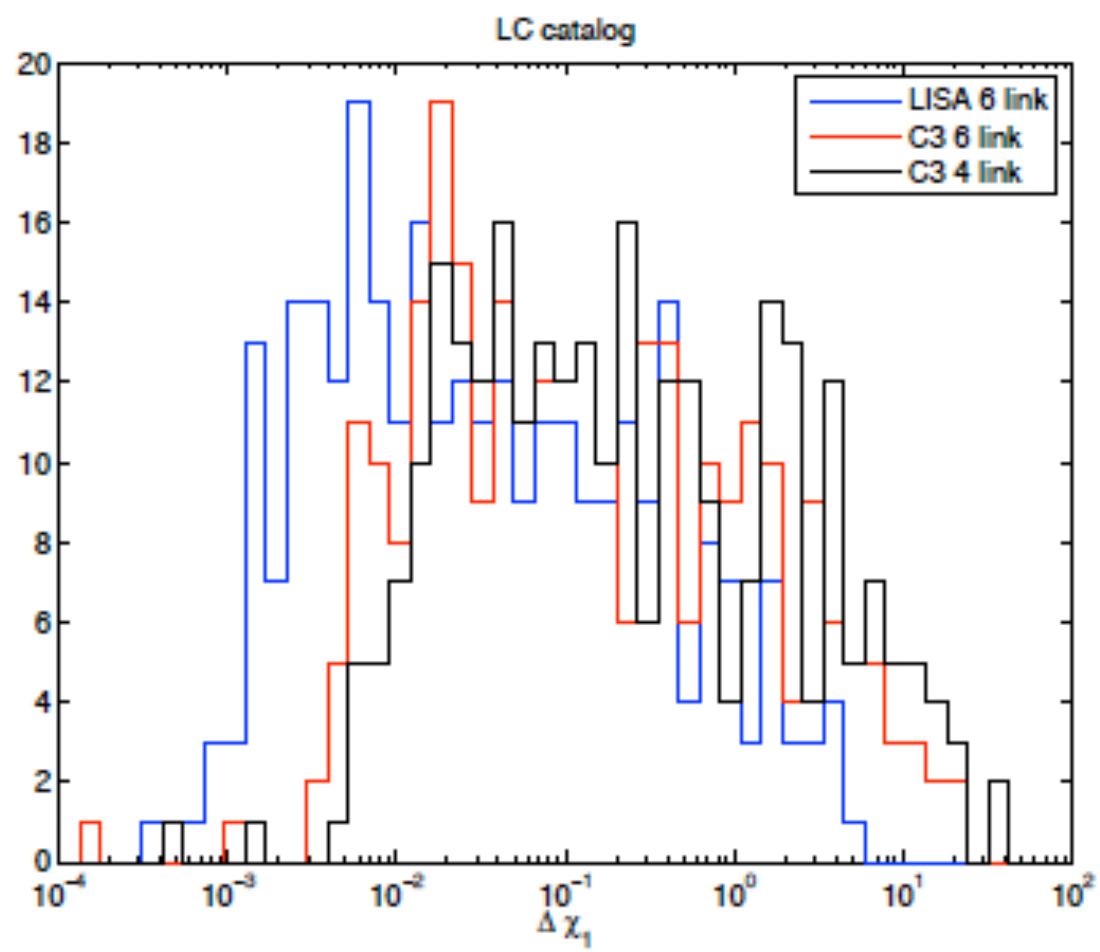
- Original code (Lang, Hughes, Cornish 2011) includes spin precession and higher harmonics in inspiral only.
  - No merger/ringdown! Solution: Calculate two separate Fisher matrices and add.
    - Appropriate tapering keeps overall power correct (“blending” region).

- For now: phenomenological “PhenomC” MR waveforms (Santamaria et al. 2010)
  - Aligned spins, fundamental harmonic

NGO performance without MR signal

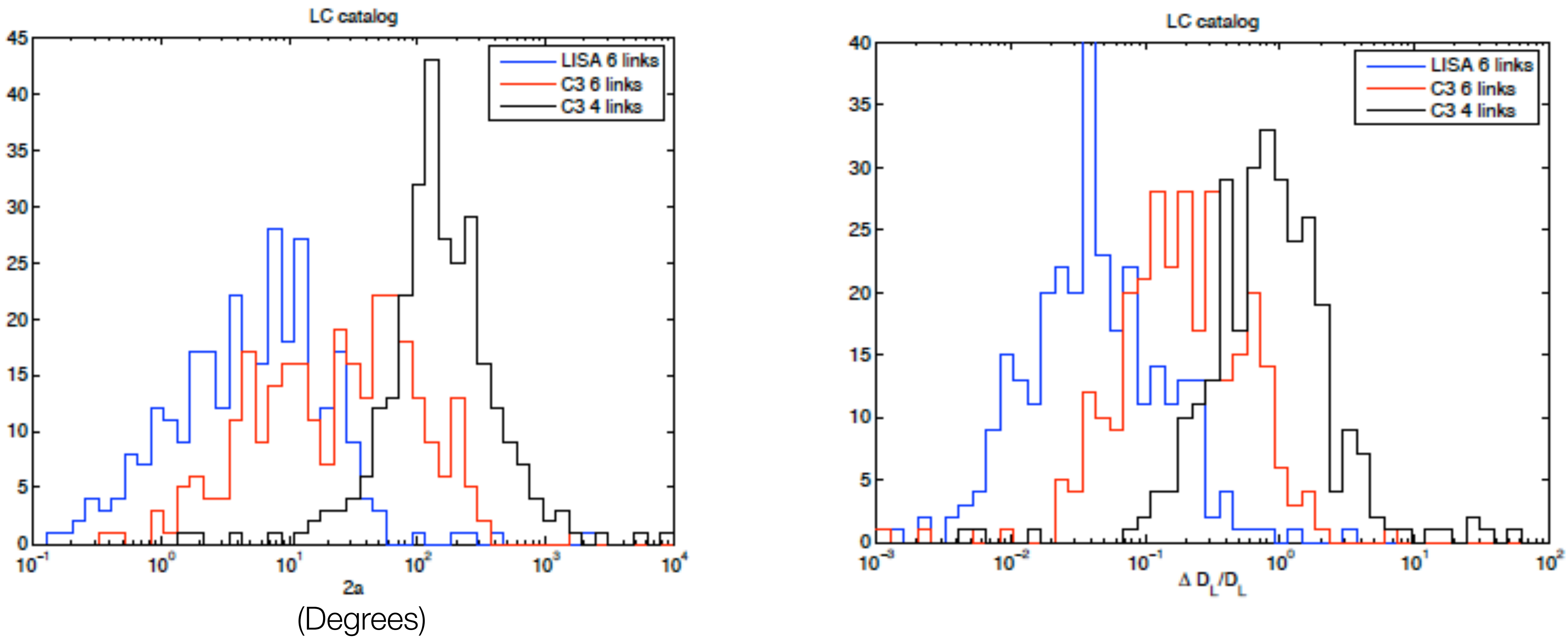
- LC catalog, similar to final NGO configuration (Lang, Cornish, and Berti):





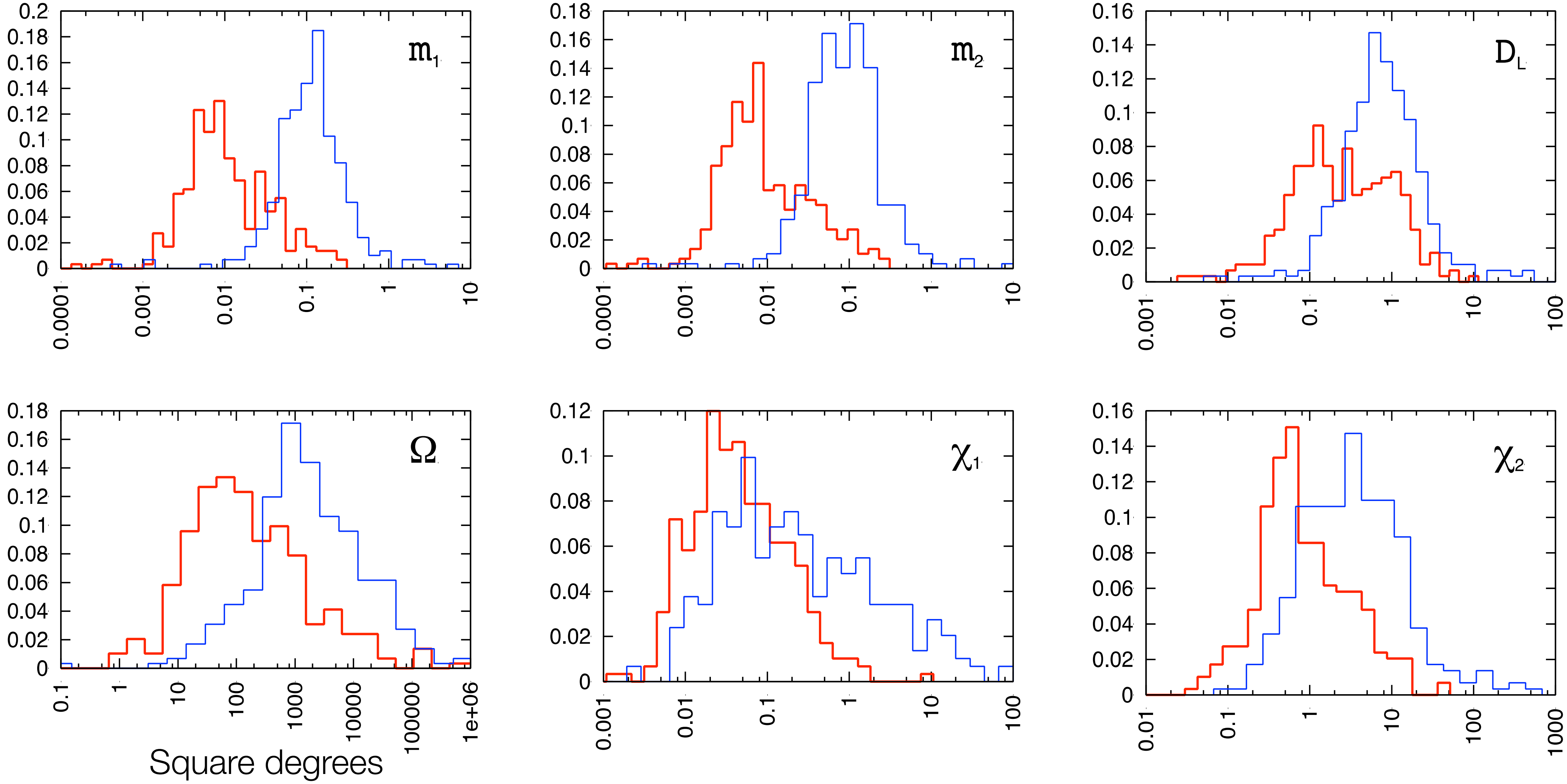
NGO performance without MR signal

- Loss of extra arm more damaging to sky position, distance measurements:



NGO performance including MR signal

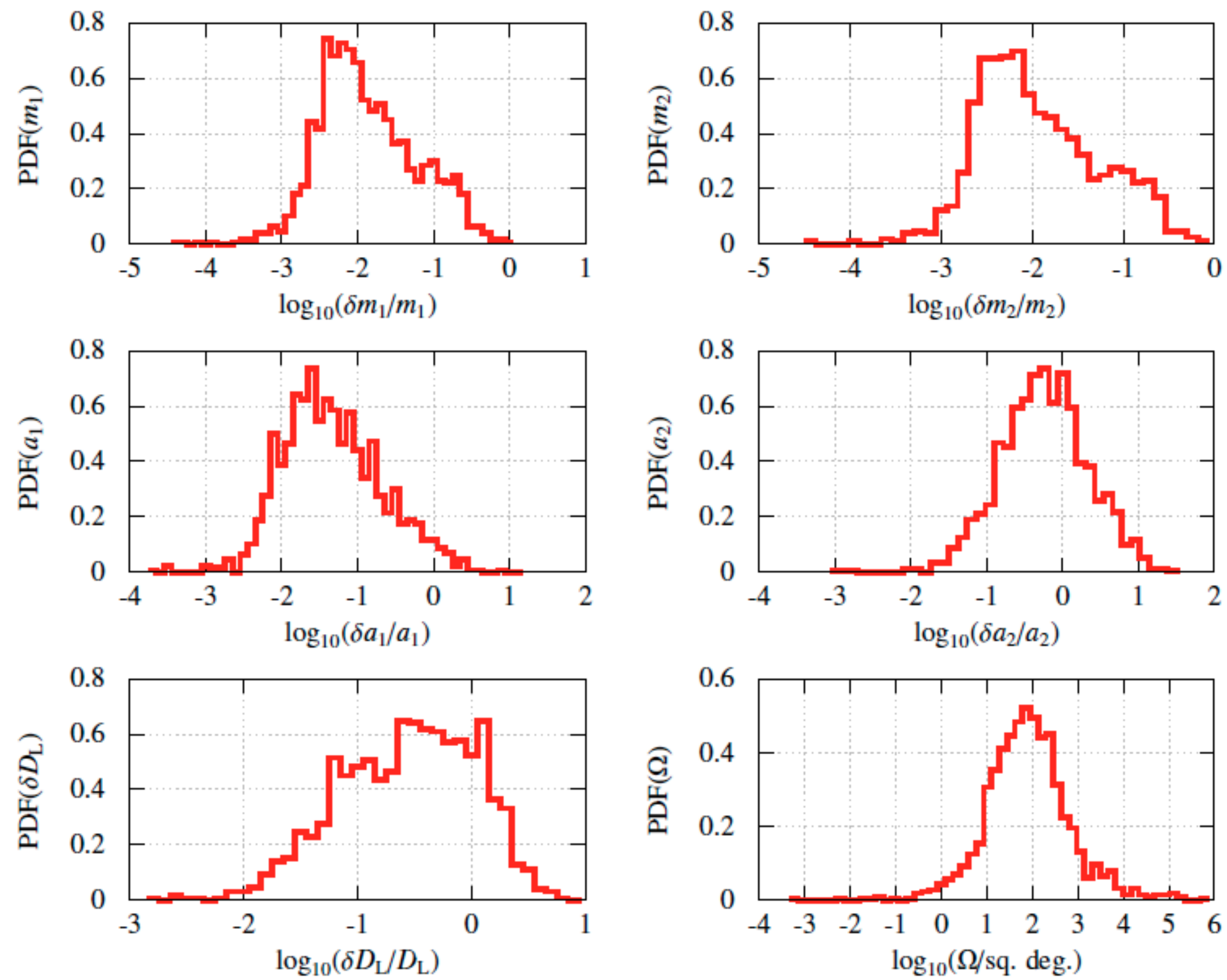
- LC catalog, final NGO configuration (Lang, Cornish, and Berti):



Blue: I only, Red: Complete IMR signal

NGO parameter estimation summary

- Full waveforms, all 4 models:



- It was also shown that NGO can distinguish between the 4 models:

	Without spins				With spins			
	SE	SC	LE	LC	SE	SC	LE	LC
SE	×	0.48	0.99	0.99	×	0.96	0.99	0.99
SC	0.53	×	1.00	1.00	0.13	×	1.00	1.00
LE	0.01	0.01	×	0.79	0.01	0.01	×	0.97
LC	0.02	0.02	0.22	×	0.02	0.02	0.06	×

Figure and table: Amaro-Seoane et al. 2012a

NGO science summary

- GBs: Rates down by ~3, shorter arms/shorter mission limit PE
- EMRIs: Rates down by ~10, PE still fine
- Stochastic background: loss of null channel
- MBHBs: Loss of localization/distance accuracy due to missing arm. Really hurts cosmology application.
- Conclusions: Still very good science with NGO! Many LISA goals are met.
  - Reason: Improvements in waveforms/data analysis. LISA would still do better!
  - NGO suffers in a few key areas.
  - Risk?
- The best we could do.
- Not selected for L1. Try for L2 (~2028 launch).

NASA study

- Physics of the Cosmos (PCOS) program charge to develop new mission concepts--at potentially lower cost--which meet some or all of Astro2010 science objectives

Science Questions	Measurements Addressing the Questions
How do cosmic structures form and evolve?	Tracing galaxy-merger events by detecting and recording the gravitational-wave signatures
How do black holes grow, radiate, and influence their surroundings?	Using gravitational-wave inspiral waveforms to map the gravitational fields of black holes.
What were the first objects to light up the universe, and when did they do it?	Identifying the first generation of star formation through gravitational waves from core-collapse events.
What are the progenitors of Type Ia supernovae and how do they explode?	Detecting and recording the gravitational-wave signatures of massive-star supernovae, of the spindown of binary systems of compact objects, and of the spins of neutron stars.
How do the lives of massive stars end?	
What controls the mass, radius, and spin of compact stellar remnants?	
How did the universe begin?	Detecting and studying very-low-frequency gravitational waves that originated during the inflationary era.
Why is the universe accelerating?	Testing of general relativity—a deviation from general relativity could masquerade as an apparent acceleration—by studying strong-field gravity using gravitational waves in black hole systems, and by conducting space-based experiments that directly test general relativity.

Table 2. Science Questions and Gravitational-Wave Measurements. (Adapted from Astro2010 Panels 2011, box 8.2, p. 385).

NASA final report

NASA study

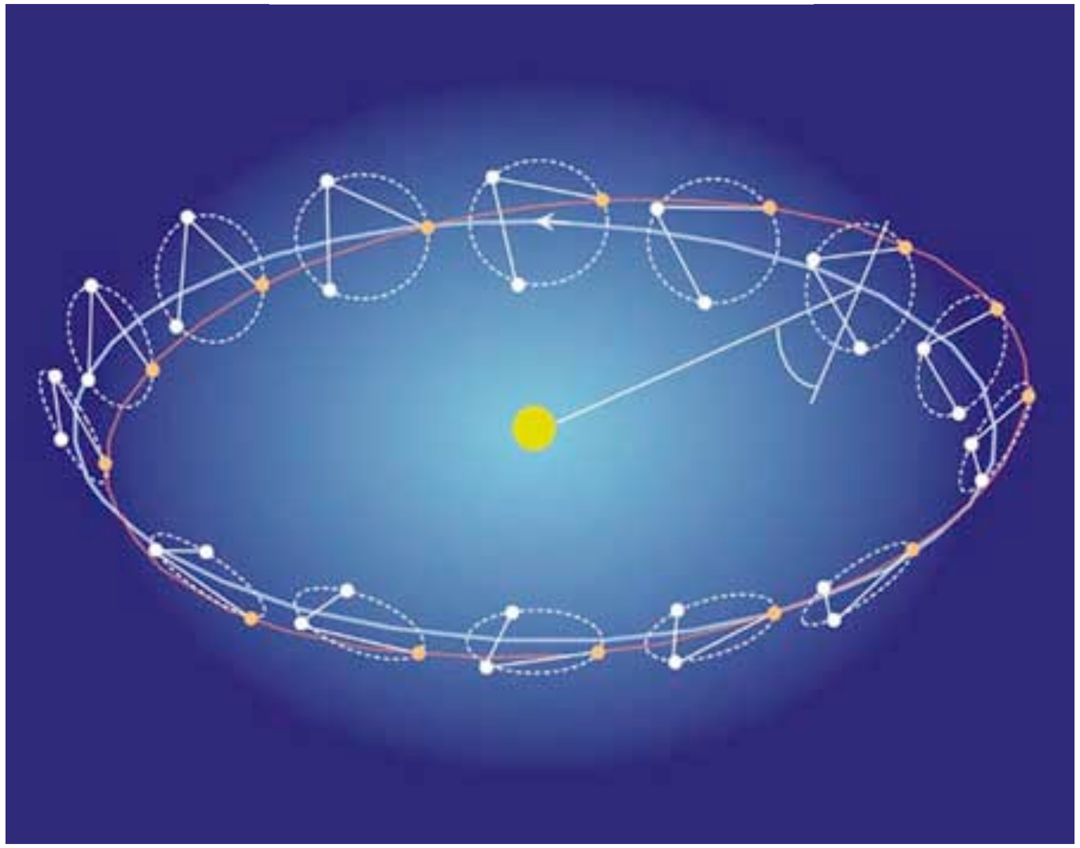
- Study Team:
  - Core Team
  - Community Science Team
  - Science Task Force
- Step 1: NASA-sponsored RFI. White papers due in November (2011).
- Step 2: Workshop held in December.
- Step 3: Study Team selected 3 concepts for JPL Team X design/cost studies in Spring 2012.
- Step 4: Study Team assembles final report, including summaries of RFI responses, Science Task Force assessment, Team X studies--plus overall Study Team conclusions.

- All information at: http://pcos.gsfc.nasa.gov/studies/gravitational-wave-mission.php

What makes a queen

- Key LISA technologies:
  - Drag-free control
  - Heliocentric orbits
  - ~ 1 million km arms (LISA: 5 Gm)

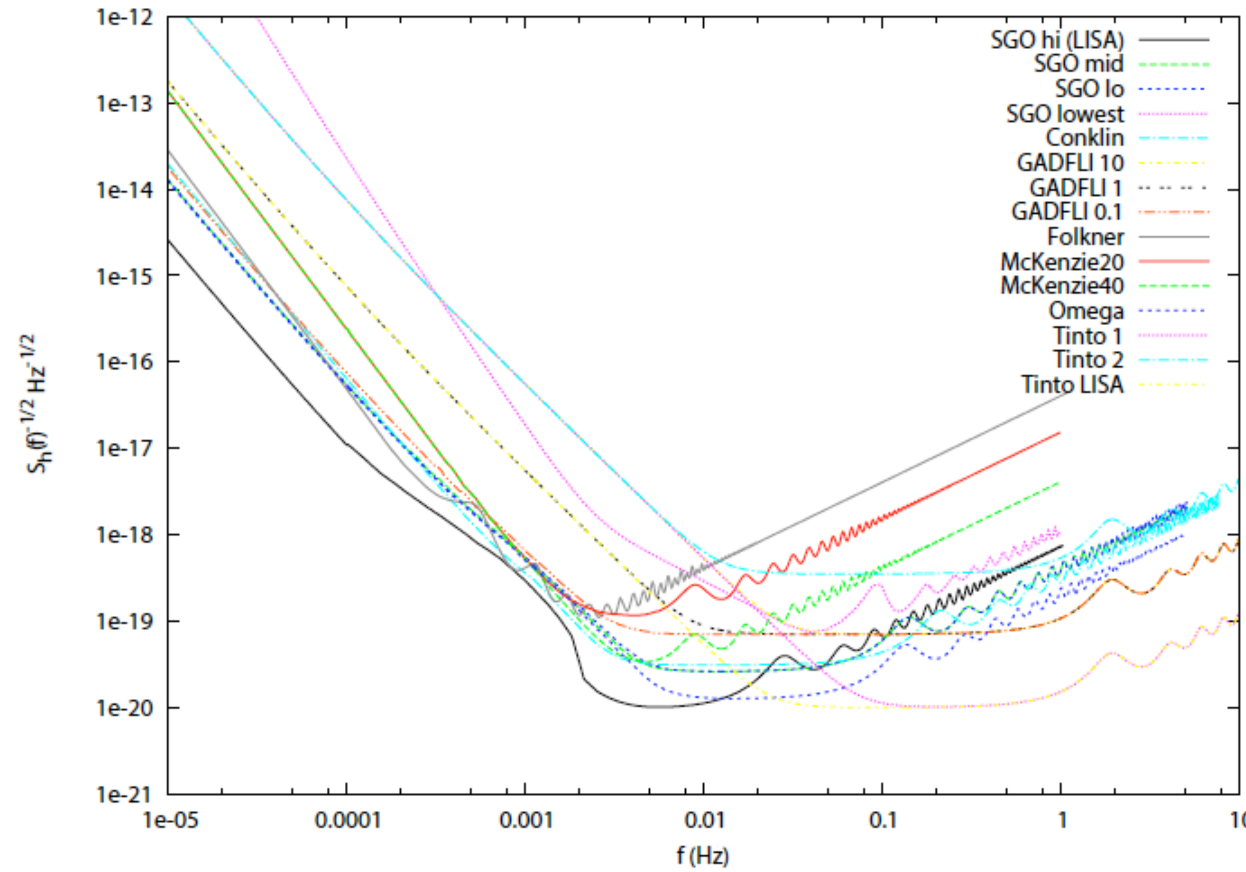
- These sacred cows disappear in some of the RFI responses.

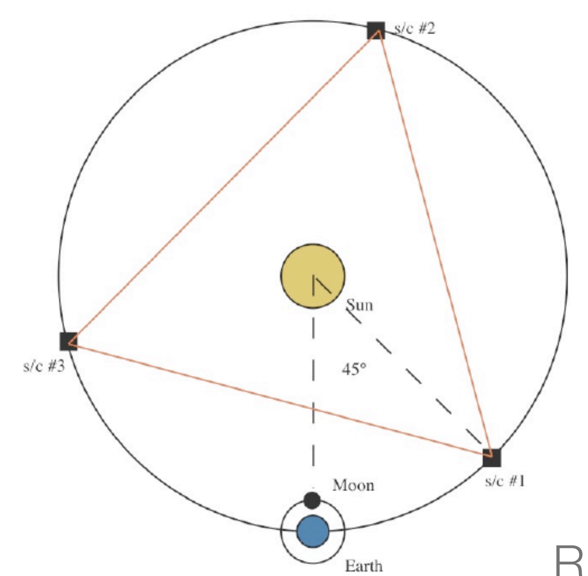


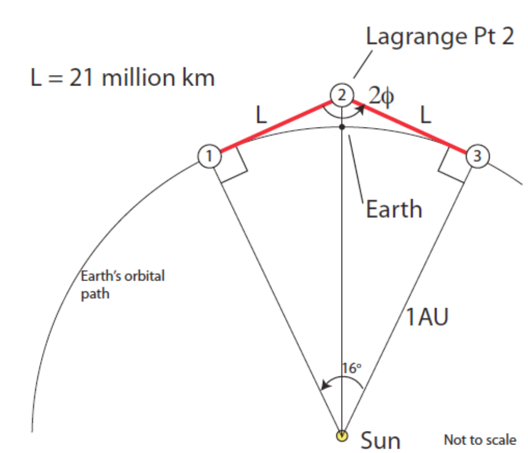
RFI response categories

- 1. LISA-like: But descoped. (5)
  - SGO High = LISA
  - SGO Mid = NGO dimensions, 6 links
  - SGO Low = NGO (4 links), but 4 spacecraft
  - SGO Lowest = Linear design
- 2. Non-drag-free: Measure and remove disturbances. (2)
  - Folkner = 50x arms
  - LAGRANGE = 4x arms, geometric reduction
- 3. Geocentric (4)
  - GADFLI/GEOGRAWI = geostationary, very short arms
  - OMEGA = Earth-Moon plane, 1 Gm arms
- 4. Other (3)
- 5. Instruments and technology: Could be applied to many concepts. (3)

NASA final report



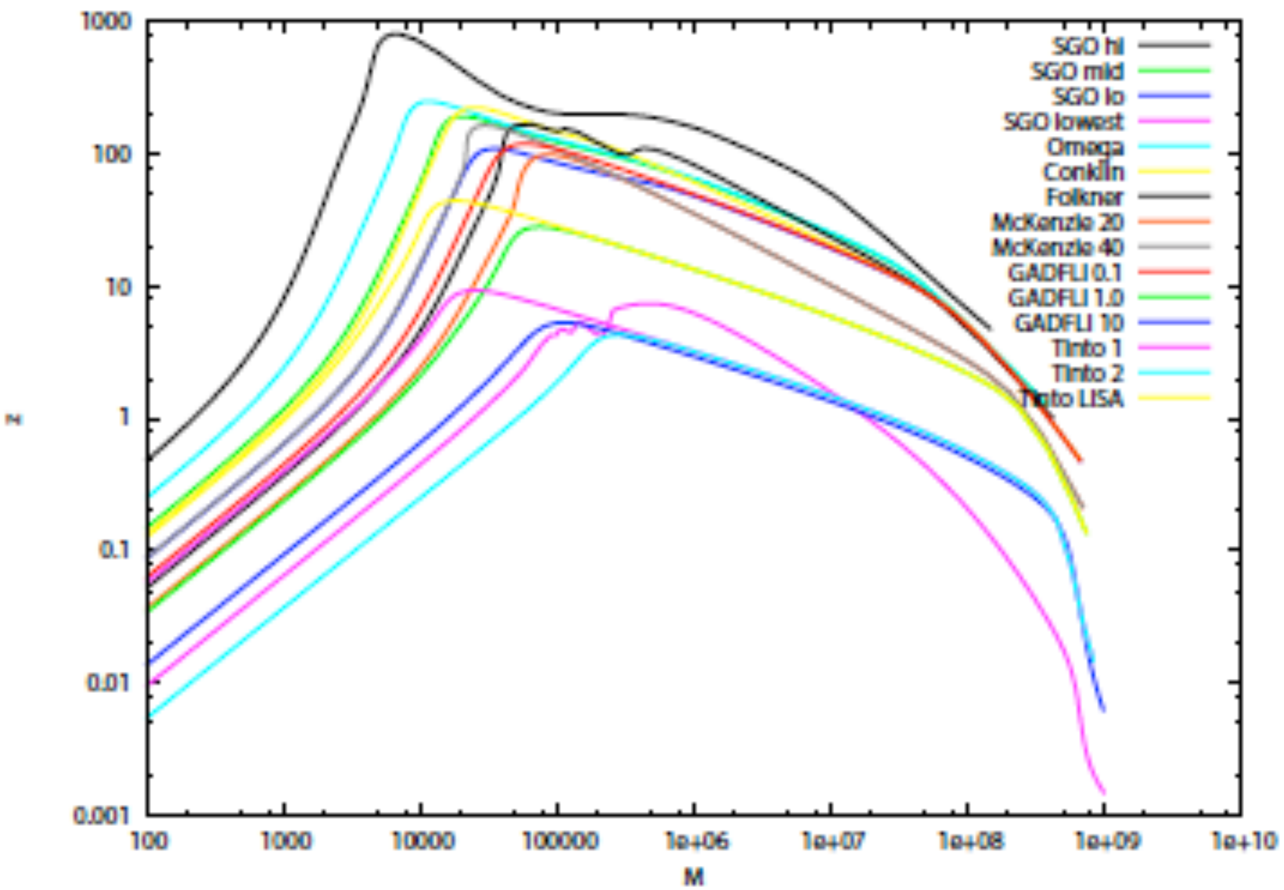




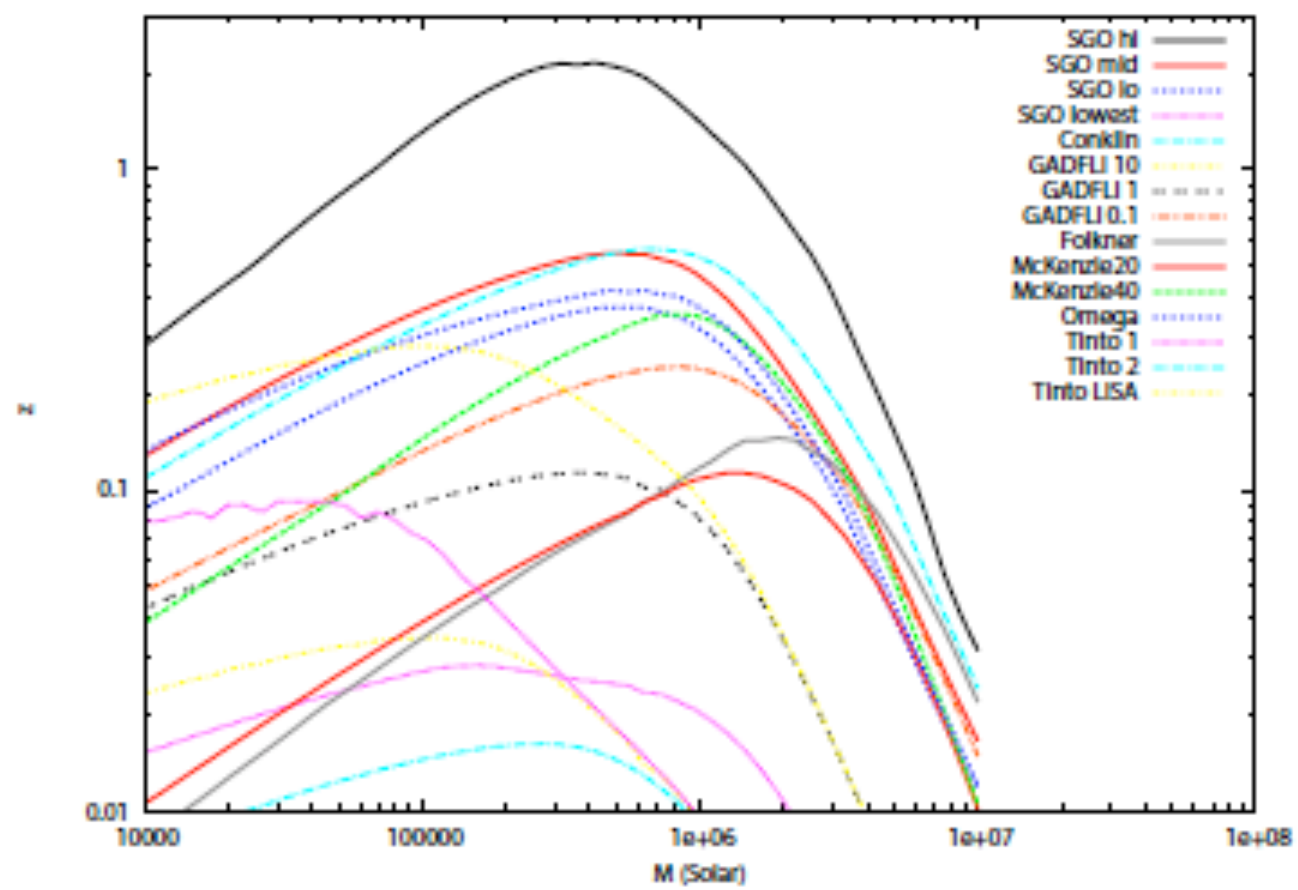
RFI responses

Horizon distances

MBHBs (SNR = 10)



EMRIs (SNR = 15)



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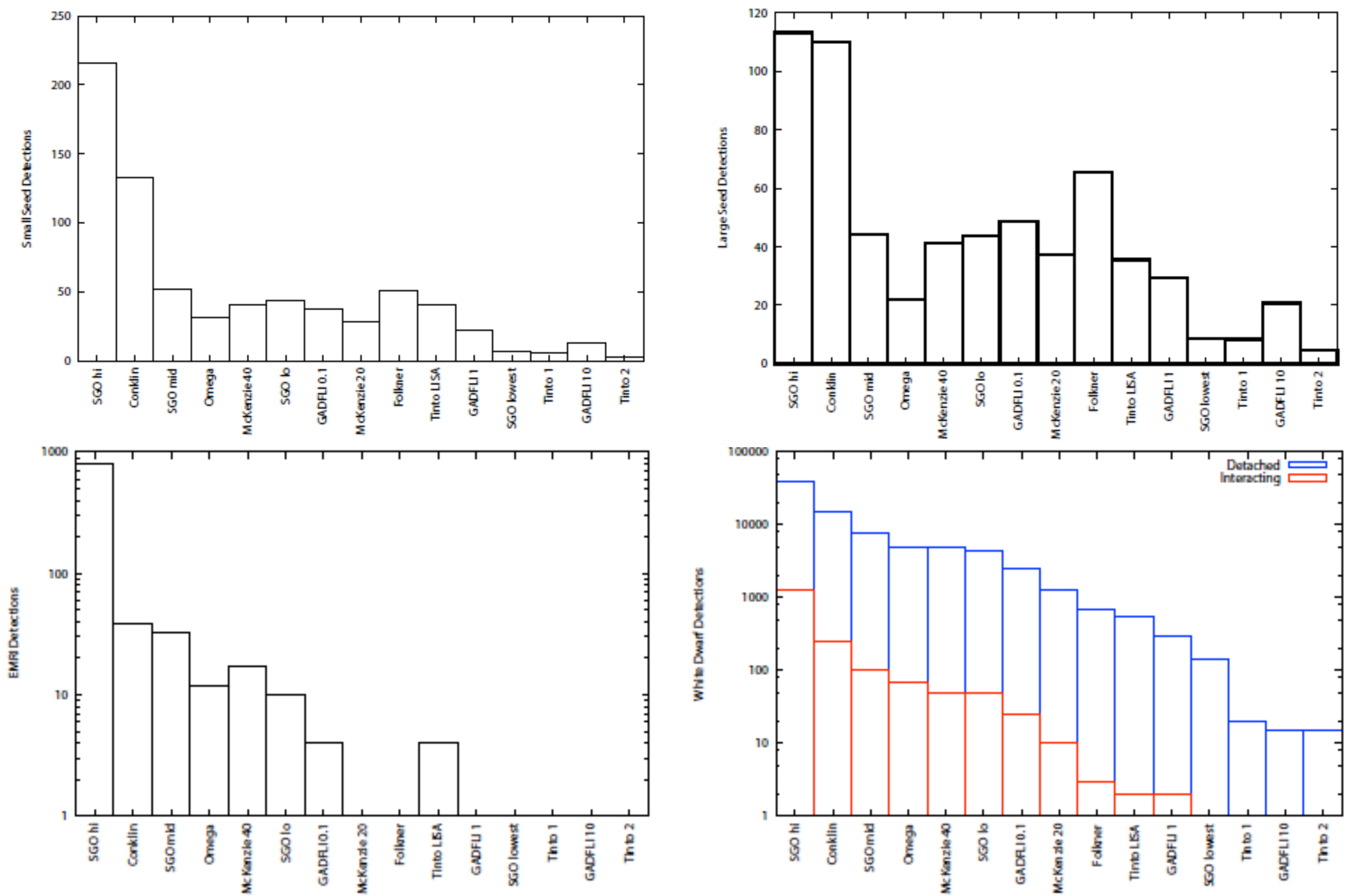
- Some fiducial parameters were chosen.
- EMRI detections really suffer from loss in 2-10 mHz range.
  - Factor of 2 in sensitivity => factor of 10 in number of detections
  - And rates are uncertain!

Source counts



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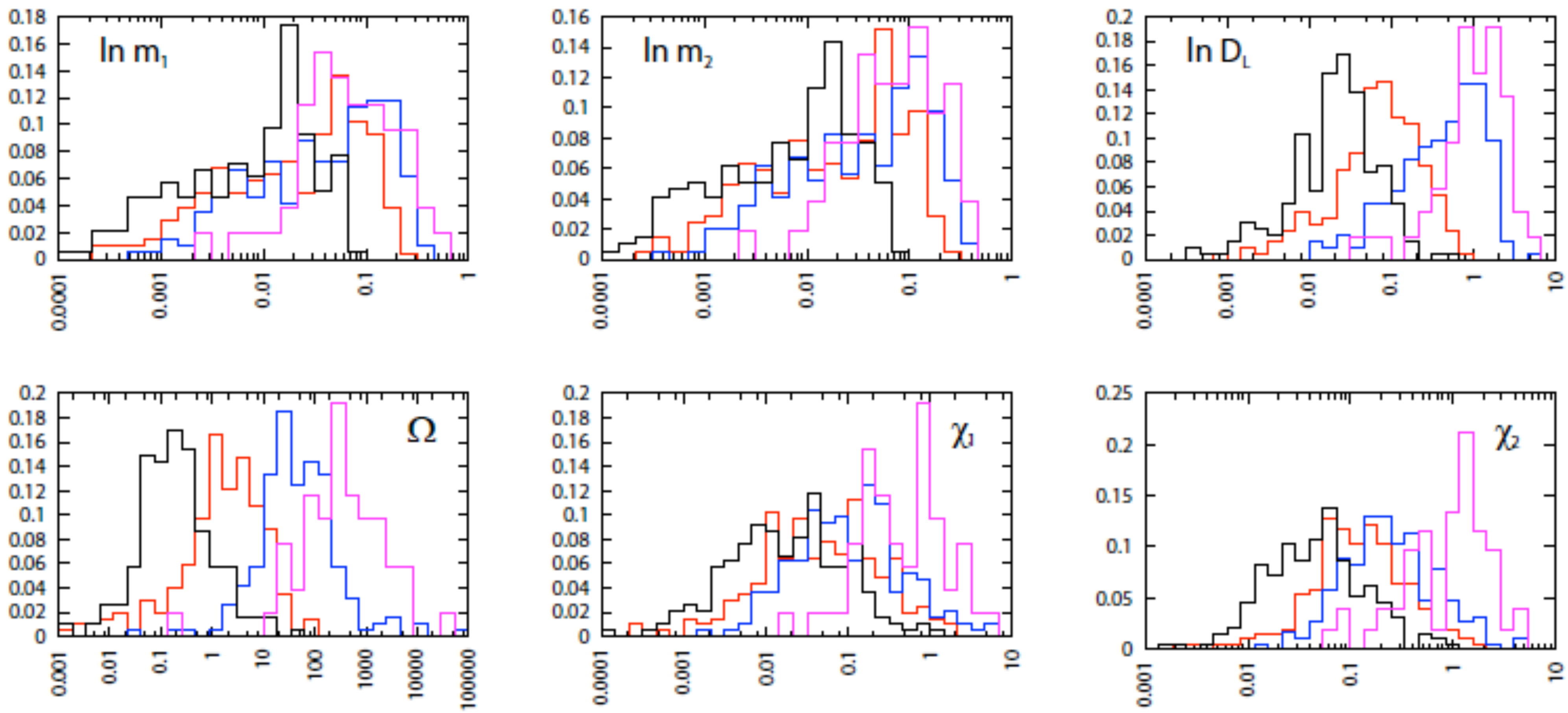
Parameter estimation

- For the four SGO concepts, LE catalog
  - Lose a factor of 3 (localization) for each descope--don’t lose 3 in cost!
  - Still, SGO High/Mid/Low can deliver significant fraction of science goals.



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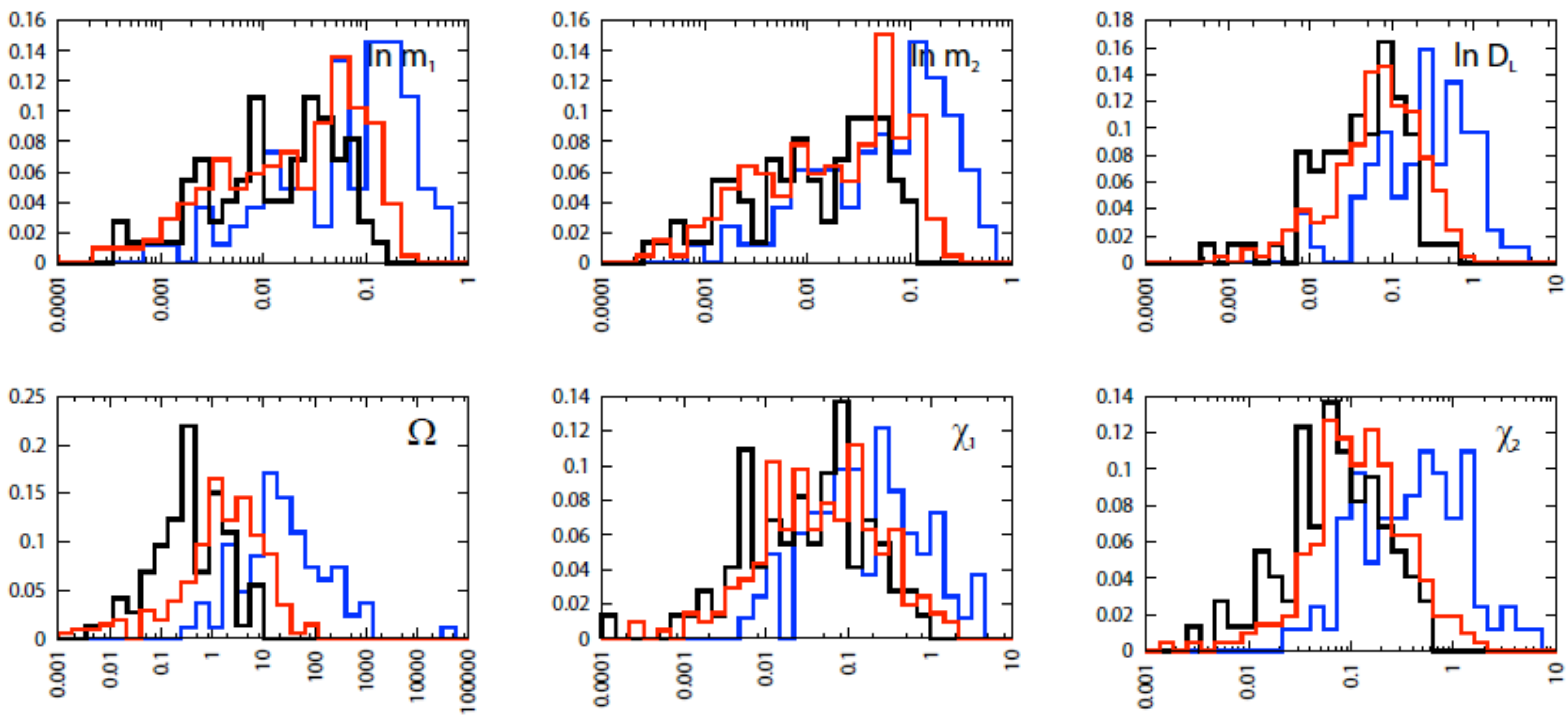
Parameter estimation

- For the Team X studied concepts, LE catalog
  - OMEGA (black) and SGO Mid (red) do about the same, LAGRANGE (blue) suffers from missing arm



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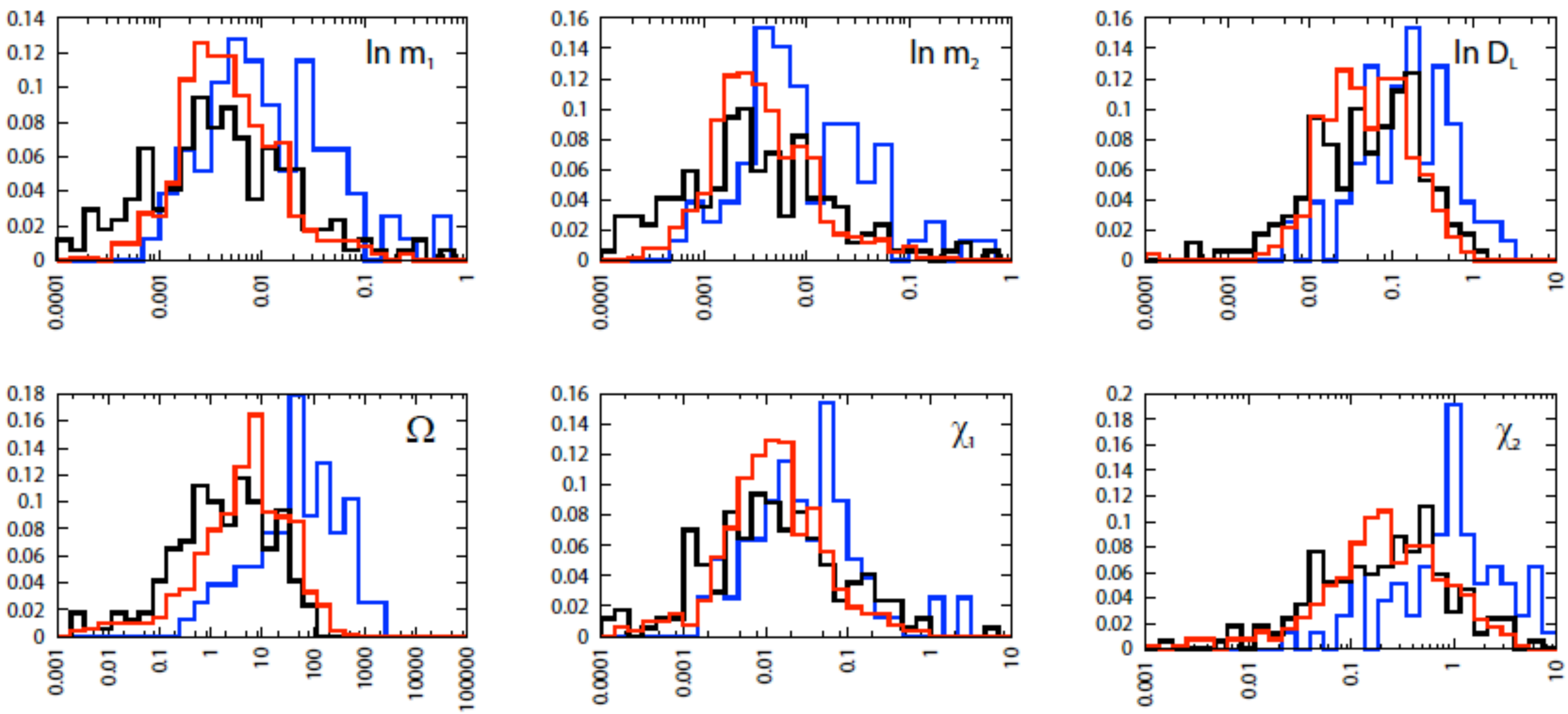
Parameter estimation

- For the Team X studied concepts, SC catalog



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NASA study summary

Science Performance	SGO-High	SGO-Mid	LAGRANGE/ McKenzie	OMEGA Option 1	OMEGA Option 2
Massive Black Hole Binaries					
Total detected	108–220	41–52	37–45	21–32	21–32
Detected at $z \geq 10$	3–57	1–4	1–5	1–6	1–6
Both mass errors ≤ 1%	67–171	18–42	8–25	11–26	11–26
One spin error ≤ 1%	49–130	11–27	3–11	7–18	7–18
Both spin errors ≤ 1%	1–17	<1	0	<1	<1
Distance error ≤ 3%	81–108	12–22	2–6	10–17	10–17
Sky location ≤ 1 deg^2	71–112	14–21	2–4	15–18	15–18
Sky location ≤ 0.1 deg^2	22–51	4–8	≤1	5–8	5–8
Total EMRIs detected†	800	35	20	15	15
WD binaries detected (resolved)	4×10^4	7×10^3	5×10^3	5×10^3	5×10^3
WD binaries with 3-D location	8×10^3	8×10^2	5×10^2	1.5×10^2	1.5×10^2
Stochastic Background Sensititvity (rel. to LISA)	1.0	0.2	0.15*	0.25	0.25
Top Team X Risk	Moderate‡	Low	Moderate	Moderate	High
Top Team X + Core Team Risk	Moderate‡	Low	High	High	High
Team X Cost Estimate (FY12$)	2.1B	1.9B	1.6B	1.4B	1.2B
Mission length (yr)	5	2	2	1	1

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Science findings

- Several mission concepts can achieve basic science goals for MBHBs/GBs (including discerning between merger history models).
- EMRI science is at risk (remember ~ order of magnitude uncertainty in rates).
- Three arms are much better than two.
  - Including null channel for detecting stochastic signals
- More years = more science
  - More sources, chance of finding "better" ones
  - Better PE for EMRIs/GBs
- Waveform/data analysis research has helped make SGO Mid, et al. acceptable. (SGO High/LISA does even better than thought before.)

Overall findings

- Cheaper mission concepts, but not below $1B.
  - No dramatic reductions of cost. Will not produce a probe class mission!
  - Risk ~ 1/cost.
- SGO Mid: decent science, less cost, no extra risk.
  - Still, 10% less cost for 3-20x less science!!
- Eliminating arm: less science, less cost (but not significantly), added risk.
- “Radical” choices (non-drag-free, geocentric): much more risk, cost savings uncertain.
- LISA is still the queen!
  - Can she rise from the ashes and reclaim her rightful throne?