LISA Science Requirements

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Abstract

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The LIST WG1 website, at which reports can be found, is
`http://www.tapir.caltech.edu/listwg1/`

1 Outline

- Sensitivity curves for Pre-Ph A LISA §3, and relatives §4.
- Science case, signal predictions, and resulting requirements on LISA for sources:
  1. Known verification binaries §6.1
  2. Galactic binaries §7.1
  3. Merging supermassive black holes §9.1
  4. Intermediate Mass/Seed supermassive black holes §9.2
  5. Gravitational captures from nuclear star clusters §10.1
  6. Extragalactic backgrounds and bursts §11.1
- Requirements and goals for LISA project.

1.1 Nomenclature

In this document, we give the following meanings to words:

- Requirements: Minimum performance necessary to justify the mission *from the point of view of a particular category of sources.* Above the required levels, new science would be returned and the category could be used as a justification for the mission; below this level it could not.

  The LIST must prioritize the categories of sources, and decide on the minimum set of categories which must return science to justify building LISA. The global minimum of the performance requirements for this minimum set of fields will become the LISA project performance requirements. Agencies should cost the mission to meet these requirements.

- Goals: Performance level beyond the minimum which gives a substantial return of new science for a category of sources.

  The LIST should select the set of source categories to be used to define the global goal of LISA, and the minimum of the performance goals for this set will become the LISA project goals. The mission should be designed to reach these levels, and should meet them if cost and other performance tradeoffs permit.

(warning: use in different bureaucracies may require translations!)

Not addressed: conditions for mission cancellation.

2 The real science goal

Discover the unexpected/unpredicted. Moral lesson from the history of astronomy: when new observational windows are opened, the strongest/most interesting sources are never anticipated beforehand.

Performance goal: widest possible bandwidth in frequency and best possible sensitivity, to maximize discovery volume.

Performance requirement: incalculable.

3 Methods to calculate sensitivities

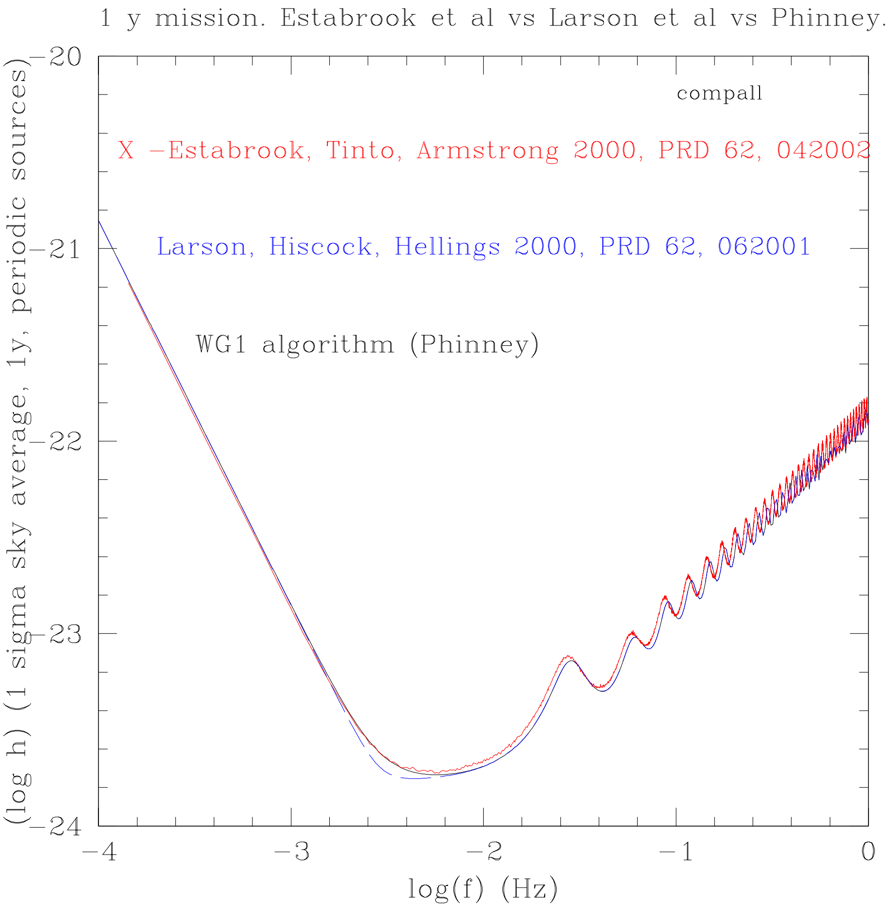
The default LISA mission has been defined as in the July 1998 Pre-Phase A report (MPQ 233):

- Acceleration noise: (white) 3×10^{-15}m s^{-2}Hz^{-1} for each proof mass.
- Arm length: 5×10^{6}km
- Laser power: 1W
- Laser wavelength: 1.06μm
- Optics efficiency: 0.3
- Telescope diameter: 30cm

The low frequency sensitivity is determined by the acceleration noise and the arm length.

The high frequency sensitivity is determined by optical path noise, — assumed white, with amplitude (including pointing noise, master clock noise, uncancelled laser phase noise etc.) *two times* the photon shot noise.

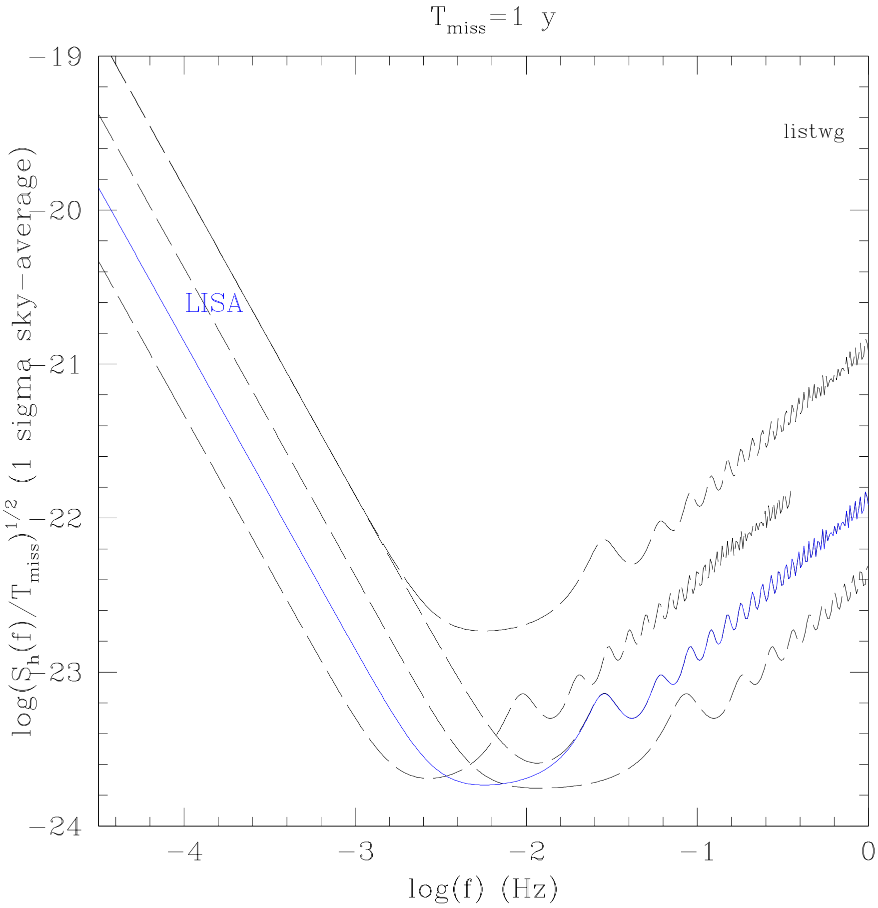
LISA sensitivity to a source depends on the source's position on the sky and (for sources with lifetimes $\ll$ 1 year), the date. We show always sensitivity curves *averaged over the sky*. Computed from instrument strain noise divided by sky-average gw transfer function (single polarisation, Michelson combination).



4 Mission sensitivities

Some toy missions, shown to guide tradeoff discussions:

- LISA (5×10^6km arms, Pre-Ph A specs, white acceleration noise)
- shortlisa (LISA specs, but 1/3x arm length)
- longlisa (LISA specs, but 3x arm length)
- badacclisa (LISA specs, but acceleration noise 10x LISA = 3×10^{-14}m s^{-2}Hz$^{-1/2}$
- badlisa (LISA specs, but 10x LISA acceleration noise, 10x LISA path/shot noise: e.g. 0.01W laser or 10cm diameter mirrors or $\epsilon = 0.03$ or bad ultra-stable oscillator)



5 Choice of plots 1

In all plots shown here, height of source above sensitivity curve is (log base 10) of S/N with which source will be detected with optimal signal processing (i.e. a perfect template, when there are no confusing sources or backgrounds).

Note that this is NOT true of many plots in the 1998 Pre-Phase A Report.

For (almost) periodic sources such as galactic binary stars, achieve this by plotting (inclination-averaged) $\log(h)$ amplitude of sources, and indicating LISA sensitivity by $\log(S_h(f)/T_{\rm miss})^{1/2}$, where S_h is the strain noise spectrum (Hz^{-1}) divided by the sky-average transfer function, and $T_{\rm miss}$ is the mission lifetime (in seconds). We show curves for $T_{\rm miss} = 1$ & 5 years.

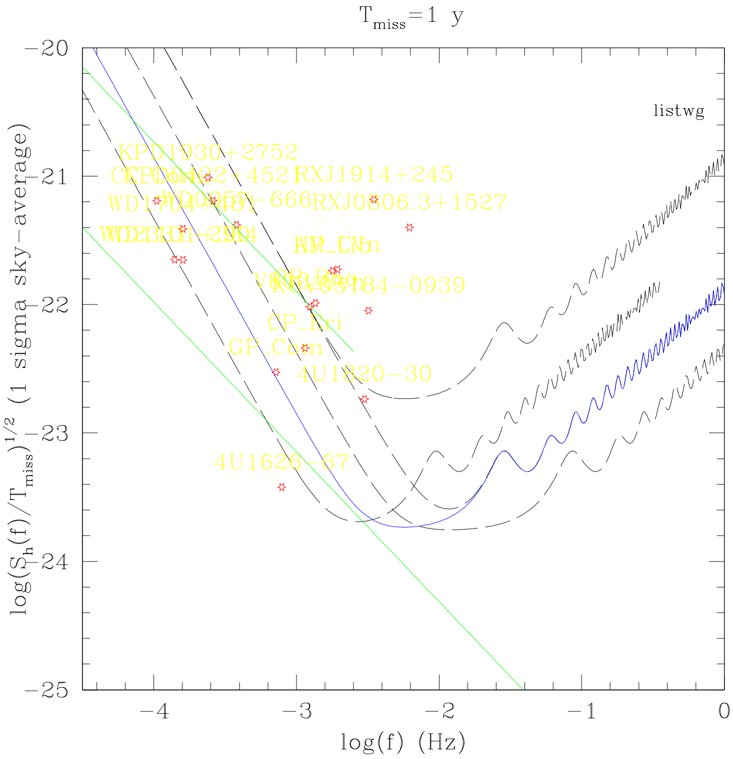
Note: high frequency sources will be spread over many $(1/T_{\rm miss})$ frequency bins by LISA's orbital Doppler, and by their intrinsic $\dot{f}$'s. We plot at central frequency, and assume these are fit with perfect templates. But fitting the additional parameters will require higher S/N for detection.

6 LISA sensitivity to known binary stars

6.1 Science/engineering case for known binary stars

- Instrument *verification* sources:
- Galactic binaries of known period, position, masses and (to a factor ~ 2) distances.
- Distinguishes LISA from other gravitational wave experiments.
- Highest priority: gives confidence in verification and detection of all other sources.
- Tests of weak field relativity.

class	source	dist pc	$f = 2/P_b$ mHz	M_1 $M_\odot$	M_2 $M_\odot$	τ_{mrg} 10^8y	h
WD+WD	WD 0957-666	100	0.38	0.37	0.32	2	4×10^{-22}
	WD 1101+364	100	0.16	0.31	0.36	20	2×10^{-22}
	WD 1704+481	100	0.16	0.39	0.56	13	4×10^{-22}
	WD 2331+290	100	0.14	0.39	> 0.32	< 30	$> 2 \times 10^{-22}$
WD+sdB	KPD 0422+4521	100	0.26	0.51	0.53	3	6×10^{-22}
	KPD 1930+2752	100	0.24	0.5	0.97	2	1×10^{-21}
AM CVn	RXJ0806.3+1527	300	6.2	0.4	0.12	–	4×10^{-22}
	RXJ1914+245	100	3.5?	0.6	0.07	–	6×10^{-22}
	KUV05184-0939	1000	3.2	0.7	0.092	–	9×10^{-23}
	AM CVn	100	1.94	0.5	0.033	–	2×10^{-22}
	HP Lib	100	1.79	0.6	0.03	–	2×10^{-22}
	CR Boo	100	1.36	0.6	0.02	–	1×10^{-22}
	V803 Cen	100	1.24	0.6	0.02	–	1×10^{-22}
	CP Eri	200	1.16	0.6	0.02	–	4×10^{-23}
	GP Com	200	0.72	0.5	0.02	–	3×10^{-23}
LMXB	4U1820-30	8100	3.0	1.4	< 0.1	–	2×10^{-23}
	4U1626-67	3-8000	0.79	1.4	< 0.03	–	6×10^{-24}
W UMa	CC Com	90	0.105	0.7	0.7	–	6×10^{-22}



Red stars: known verification binary stars (labelled by source name). Distances and therefore h typically uncertain by ×2. Lower green line: extragalactic binary noise. Upper green line: galactic binary noise, ending at point where sources can no longer be separated (Shannon's Theorem).

6.2 Known verification sources: requirements and goals

- requirement: SNR 10 for at least 3 verification sources (to localise to within degrees, and ensure low probability of masquerading by other galactic sources).

  Note: Mission funding of ground-based efforts to find more and stronger verification sources and improve distance determinations, could save money by relaxing requirements!

  At $f = 10^{-2}$Hz, no constraint (no calibrators known at this frequency).

  At $f = 10^{-3}$Hz, must keep LISA noise $< 1/2$ Galactic background. Translates to 4x Pre-Ph A strain limit for any mission duration. Increasing armlength would reduce acceleration noise requirement for these sources. Decreasing it by more than a factor of 5 makes the Pre-Ph A acceleration noise goal become a requirement.

- goal: LISA data stream should be complete enough to enable synthesis of Sagnac channel as well as Michelson channels. Difference in instrument response to gravitational waves between the channels provides additional check on level of instrument noise and reality of signals.

7 LISA sensitivity to Galactic binary stars

$N \sim 10^4 (T_{\rm miss}/2{\rm y})$ binaries distinguishable above confusion frequency $f_{\rm conf} \sim 0.003(T_{\rm miss}/2{\rm y})^{-3/11}$ (i.e. orbital periods $< 700{\rm s}(T_{\rm miss}/2{\rm y})^{3/11}$).

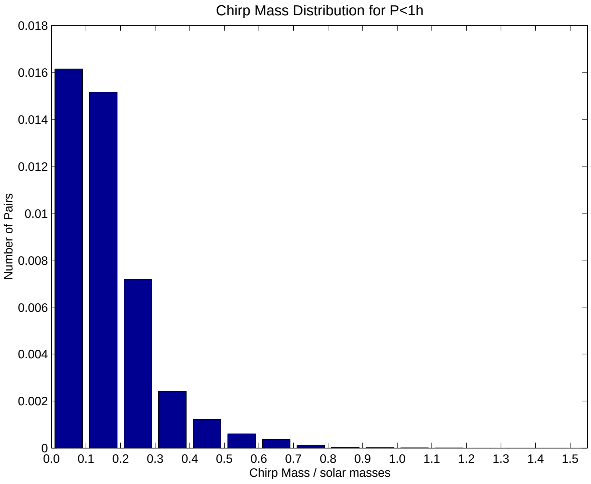
Require $T_{\rm miss} > 2{\rm y}$ to measure $\dot{f}$ (to avoid degeneracy with sky position). $\sim 2000(T_{\rm miss}/2{\rm y})^{16/11}$ sources with $f > 0.006(T_{\rm miss}/2{\rm y})^{-6/11}$ have measureable $\dot{f}$, and hence chirp mass, date of merger, and distance (in cm).

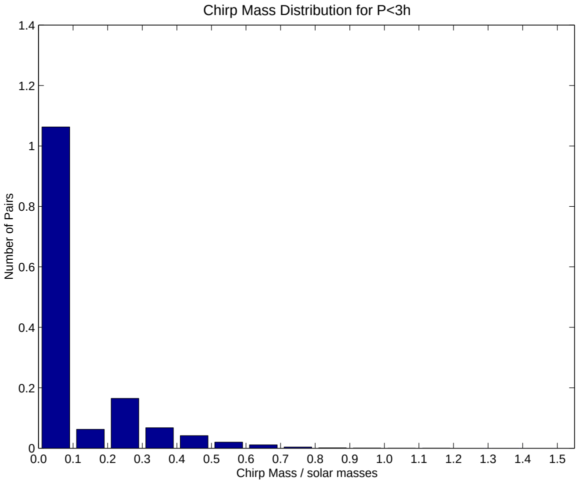
$\sim 10^2$ helium white dwarfs tight enough to have $\dot{f}$ and non-gravitational $\ddot{f}$ determined by tidal synchronisation. Similar population with $\dot{f} < 0$ in stable mass transfer (young AM CVn).

7.1 Science case for galactic binaries

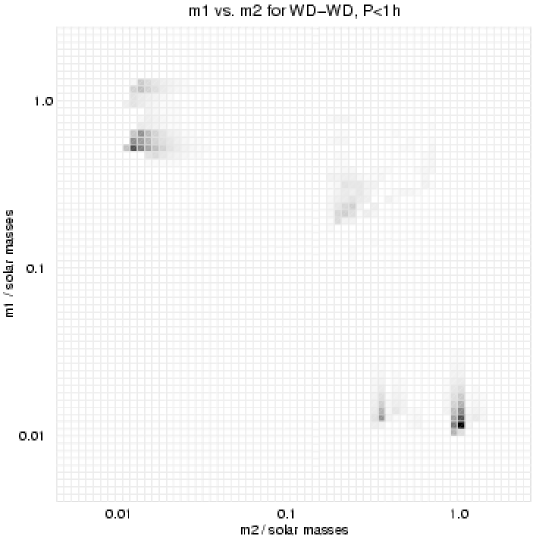
Astronomy of exotic (past or present) interacting binary stars.

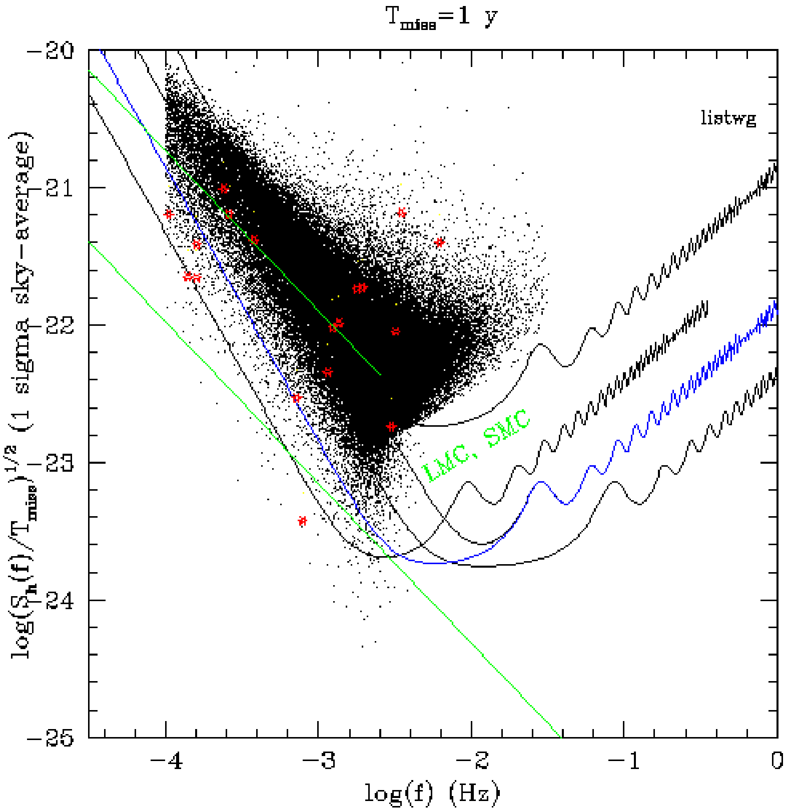
- Binary star map of Galaxy & beyond w/inclinations, orientations: star formation clues?
- Discovery space for exotic binaries hard/impossible to find electromagnetically.
- Identification/study of white dwarf tides/mergers: SN Ia, AIC (accretion induced collapse to NS), rare novae connection?
- Probe strong interior magnetic fields of WD (rotating quadrupoles).
- Galactic background at $3 \times 10^{-5}{\rm Hz} < f < 3 \times 10^{-4}{\rm Hz}$ gives binary star formation history of the galaxy.
- Chirp mass distribution, $\dot{f} < 0$ distribution give tests of binary star evolution theories, especially crucial but poorly understood angular momentum transfer before, during and after common-envelope evolution.





(Alison Farmer)





7.2 Galactic binaries: requirements and goals

- requirement: SNR 20 for 50% of resolvable binaries. Minimum mission lifetime 2 years to separate $\dot{f}$ and sky position. Noise less than Galactic background around 10^{-3}Hz.

  At $f = 10^{-2}$Hz, translates to 3x Pre-Ph A strain limit for 2 year mission, 5x Pre-Ph A strain limit for 5 year mission.

  At $f = 10^{-3}$Hz, translates to 4x Pre-Ph A strain limit for any mission duration.

- goal: SNR 20 for all resolvable binaries. Mission lifetime 5 years to get $\dot{f}$ for all.

  At $f = 10^{-2}$Hz, translates to 2x Pre-Ph A strain limit for 5 year mission.

  Measure Galactic background down to 10^{-4}Hz (binaries as old as the Galaxy):

At $f = 10^{-4}$Hz, translates to Pre-Ph A strain limit for 5 year mission. Also need synthesis of Sagnac channel to provide calibration of the instrument noise at low frequencies.

Optimum baseline for the distinguishable binaries would be 2×10^6km (1/2-1/3 of standard Pre-Ph A arm). However this choice would prevent measuring the Galactic background at 10^{-4}Hz, which requires Pre-Ph A strain limit at 10^{-4}Hz.

8 Choice of plots 2

Remaining sources sweep in frequency, or are broad band (e.g. backgrounds, bursts). To keep the height of source above sensitivity curve = (log base 10) of S/N with which source will be detected with optimal signal processing, *must change our plotting of instrumental sensitivity curve.*

Recall that for matched filtering, averaged over source inclinations and sky positions,

$$(S/N)^2 = \int_0^\infty \frac{df}{f} \frac{h_c^2(f)}{\langle f S_h(f) \rangle} \,. \tag{1}$$

So plot LISA sensitivity as $\langle f S_h(f) \rangle^{1/2}$, and sources as

$$h_c(f) \times \max(1, \sqrt{\Delta f / f}) = \frac{\sqrt{2}}{\pi D_M(z)} \sqrt{\frac{dE}{df}[(1+z)f]} \times \max(1, \sqrt{\Delta f / f}) \,, \tag{2}$$

where $D_M = D_L/(1+z)$ is the proper-motion distance, and S_h is the strain noise spectrum (Hz^{-1}) divided by the sky-average transfer function. Note: $h_c \simeq \sqrt{N} h$, where h is the instantaneous gravitational wave amplitude and N the number of wave cycles accumulated (within an octave of f). If source bandwidth/sweep $\Delta f \ll f$ (e.g. late stages of gravitational capture near isco), we multiply h_c by $\sqrt{\Delta f / f}$ to reproduce graphically the expression (1) for $(S/N)^2$.

Note that $\langle f S_h(f) \rangle^{1/2}$ does *not depend on the mission duration.*

Plots assume perfect templates. Sources should be moved down if not perfect.

9 LISA sensitivity to merging black holes $m/M > 0.01$

9.1 Science case for merging supermassive black holes

- Precision tests of dynamical nonlinear gravity through comparison with precise numerical simulation of Einstein's equations. Cosmic censorship in horizon merger, ringdown. [ground-based detectors will do this with substantially lower precision with stellar mass BHs, however].
- Determine precision masses, spins for supermassive black holes in galactic nuclei (PN inspiral).
- Determine precision distances to supermassive black holes, get redshifts (if cosmography well-determined). Or if electromagnetic signal gives redshift, determine cosmography.
- Determine combination of merger history of galaxies and protogalactic lumps with nuclear stellar/gas dynamics (black hole binaries vs triples vs clusters, ejection of nuclear stars).

9.2 Science case for merging intermediate mass/seed black holes

- Probe $z = 7 - 30$ 'dark ages', epoch of supermassive black hole formation.

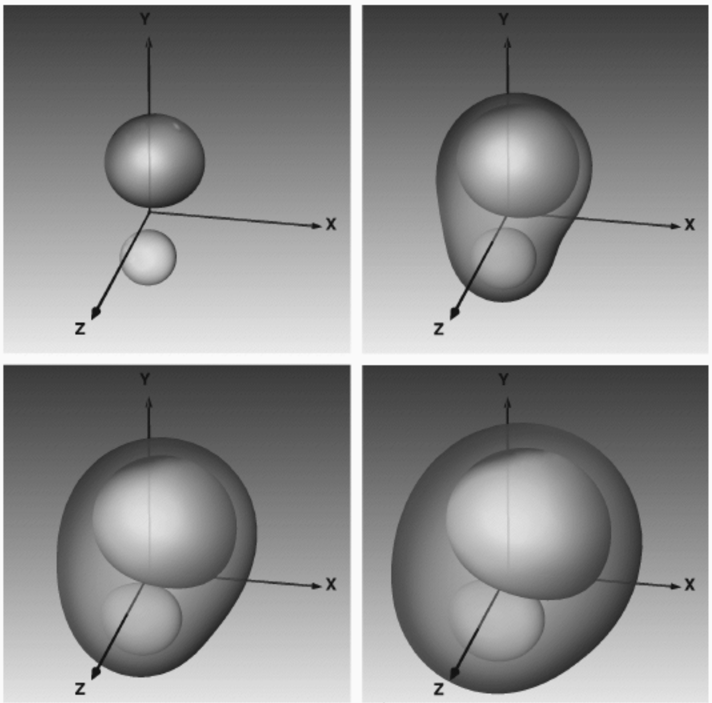
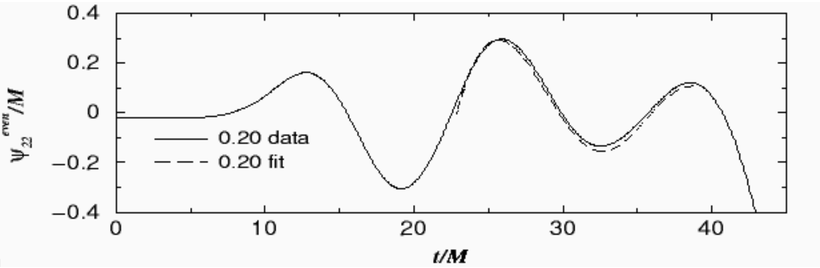


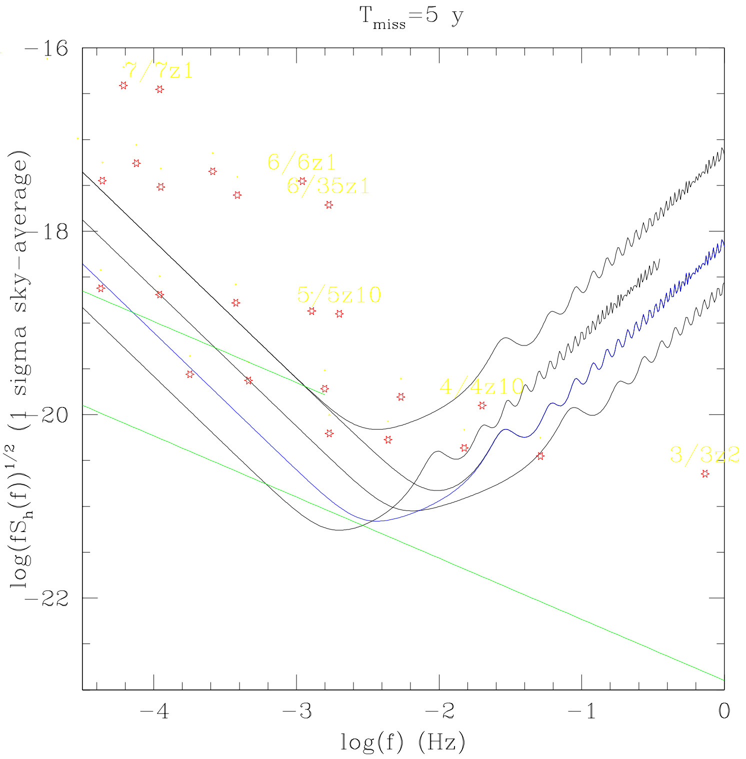
FIG. 6. The merger of the AH. Shown are marginally trapped surfaces at times $2.5M$, $3.7M$, $5.0M$, and $6.2M$. The apparent horizon is the outermost of these surfaces.

Perturbation theory on final merged hole: Quasinormal 'ring down' mode gravitational wave have period and Q

$$\begin{aligned} f_{qn}(m=l=2) &\simeq (0.07/M)(1-0.63(1-a/M)^{0.3}) \\ Q_{qn}(m=l=2) &\simeq 2(1-a/M)^{-9/20} \ . \end{aligned}$$

Compute $a/M = J/M^2$ from $J = L+J_1+J_2-$gws -small here. Compare numerical gw waveform to predicted frequency f_{qn}. Works! Could do observationally also, using waveform of inspiral to get L, J_1, J_2. Check area theorem, check that measured gw losses make up mass and angular momentum deficits. Several significant figure precision possible. Room for new physics.





Tracks (top row to bottom row) for zero spins $10^7/10^7 M_\odot$, $z = 1$ (1d, merger); $10^6/10^6 M_\odot$, $z = 1$ (1mo, 1d, merger); $10^6/3 \times 10^5 M_\odot$, $z = 1$ (1y, 1mo, 1d, merger); $10^5/10^5 M_\odot$, $z = 10$ (1y, 1mo, 1d, 1h, merger); $10^4/10^4 M_\odot$, $z = 10$ (same); $10^3/10^3 M_\odot$, $z = 2$ (same). Endpoints of prograde, equatorial maximal spin are ~ 10 times higher in frequency.

9.3 Merging supermassive black holes: requirements and goals

The least massive reliably known masses of black holes in galactic nuclei are $\sim 10^6 M_\odot$. To determine the sky position of the supermassive black hole, and therefore its true signal amplitude (transferred through position-dependent LISA antenna pattern) requires observing it for at least 2 months (Hughes astro-ph/0108483, and additional plots on the LIST WG1 website). We see that even at z=1, black holes more massive than $10^6 M_\odot$ (i.e. *all* reliably known black holes in galactic nuclei) will not satisfy this requirement, unless the LISA frequency response continues below 3×10^{-5}Hz. The merger rate of these massive black holes is also low and uncertain ($\sim 1\mathrm{y}^{-1}$ with an order of magnitude uncertainty), so a multi-year mission lifetime is necessary to make detection probable.

- requirements: Detect black holes with $3 \times 10^5 M_\odot$ at $S/N = 2$ two months before merger (just adequate to get position and hence inclination, etc.).

  At $f = 10^{-4}$Hz, translates to 5x Pre-Ph A strain limit. Shortening the arm length hurts badly. To ensure reasonable chance of seeing one event requires 3 year mission life.

  Black holes of $> 10^5 M_\odot$ set no significant requirement at high frequencies, since S/N of the merger $\sim 10^3 - 10^4$ for LISA; detection is not an issue. Science output will be limited by the accuracy with which initial parameters can be determined, in turn set by the (low S/N) early stages of inspiral.

- goals: To do precision cosmography, goal should be $S/N > 10$ in first several months of source inspiral. This gives distances to $\sim 4\%$ vs $\sim 30\%$ for S/N of 2 (requirement). At $f = 10^{-4}$Hz, this means Pre-Ph A strain limit for $10^6 M_\odot$ black holes. Also need synthesis of Sagnac channel to provide calibration of the instrument noise at low frequencies.

  Optimum arm length for supermassive black hole mergers would be $> 10^7$km (2-3 times standard Pre-Ph A arm). Mission lifetime > 5 years to ensure events.

- goal: Duration of routine breaks in data should not exceed $\sim 10^3$s, so as to reduce the probability of missing the merger phase of the handful of massive black hole mergers.

9.4 Merging intermediate mass/seed black holes: requirements and goals

- requirement: To detect merging seed ($\sim 10^3 - 10^5 M_\odot$) black holes in the protogalactic fragments ($z = 7 - 30$) predicted in CDM models with no more than one false alarm per year (merger rate is predicted to be $10 - 1000\text{y}^{-1}$) requires 1.5x Pre-Ph A strain limit at 5×10^{-3}Hz.

- goal:Pre-Ph A strain limit. An arm length 1/2 the nominal Pre-Ph A arm would be acceptable.

10 LISA sensitivity to gravitational captures

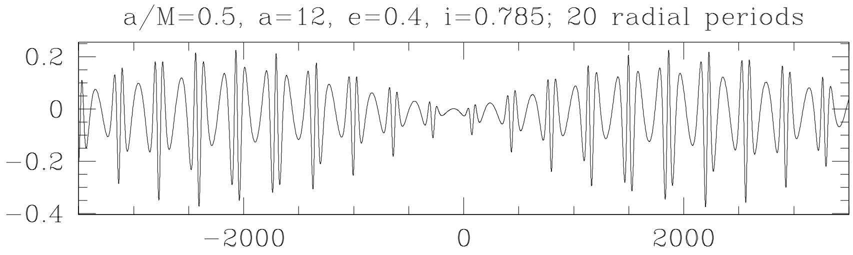
Two crucial issues, not yet fully clarified theoretically, are

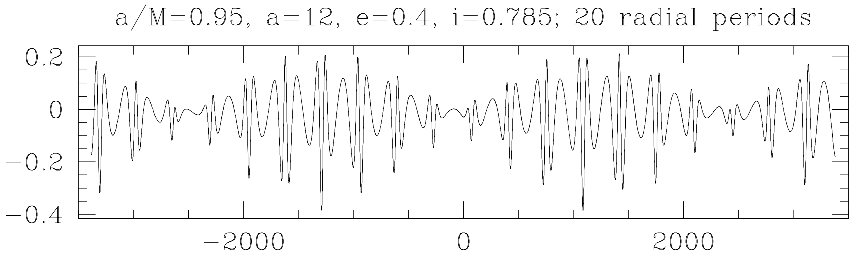
1. Whether it is feasible (given computational and theoretical resources) to perform optimal signal processing on these complicated, many parameter signals, or whether one will have to accept the substantial reduction in detection S/N given by a non-optimal search.
2. A few strong nearby sources imply many distant sources giving a much larger signal to LISA (Olbers' paradox). The overlap of these distant sources with the nearby signal template creates background noise, whose amplitude increases if one is reduced (previous item) to non-optimal signal processing. About 1/3 of the energy comes from 'bursts' at pericenter of highly eccentric orbits, which cannot be fitted and removed.

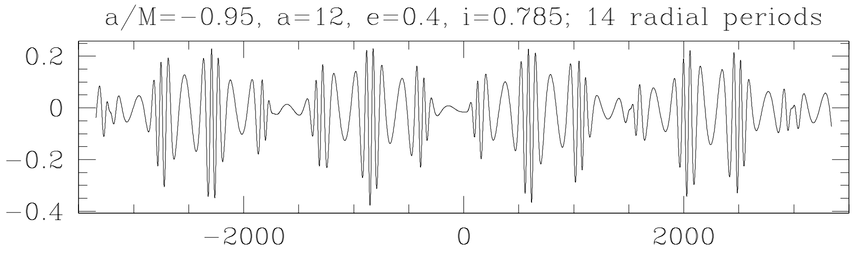
10.1 Science case for gravitational captures

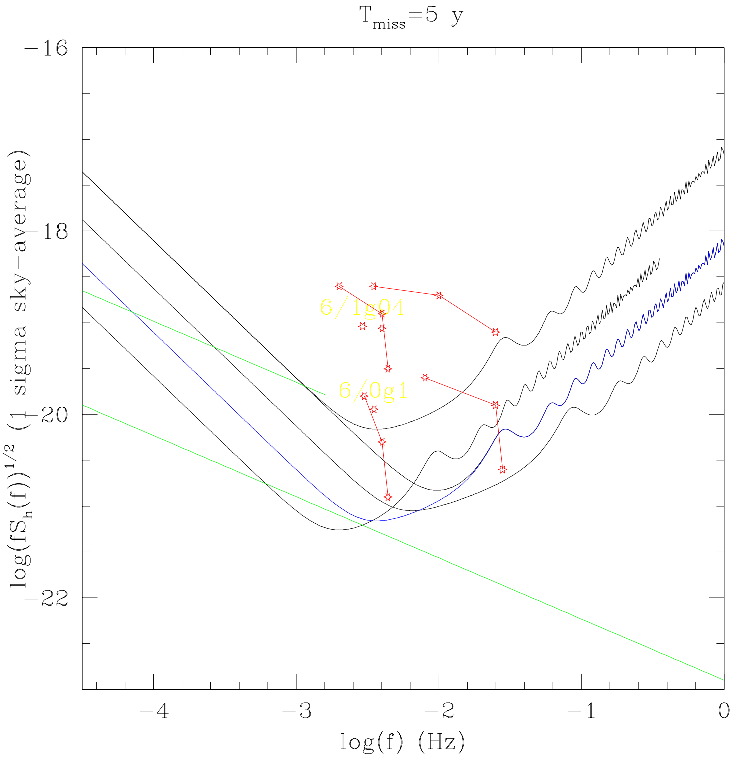
Bothrodesy

- Measure $M = M_0$, $a/M = S_1$ to $< 1\%$.
- Measure higher mass and current multipoles M_2, S_3, etc to sufficient precision to test "no hair theorem" (e.g. Kerr predicts $M_2 = Ma^2$; uniform density slowly rotating Newtonian star, radius R, has $M_2 = (25/8)(R/M)Ma^2$.).
  - No hair satisfied: highest precision probe of strong field nonlinear gravity yet envisaged. [Note: black holes almost certainly have non-Abelian hair, and "no hair theorem" strictly false for fields beyond E&M. QCD hair not detectable -femtometer multipoles! But in some models fields in dark hidden sectors of string theory could make measurable effects on bothrodesy.]
  - No hair not satisfied: discovery of hypothetical new types of massive compact bodies —e.g. soliton stars, naked singularities. Inversion of multipoles gives detailed map of spacetime.
- Measure to high precision the orbiting body's tidal extraction of rotational energy and angular momentum from the black hole (via its $\sim 5 - 10\%$ effect on the rate of inspiral).
- Astrophysical parameters: mass, spin, distance of supermassive bodies, mass, orbital eccentricity, inclination all to better than a few %. Infer population and evolution of supermassive black holes and their surrounding star clusters (mass segregation, IMF, density structure).


a/M=0.5, a=12, e=0.4, i=0.785; 20 radial periods


a/M=0.95, a=12, e=0.4, i=0.785; 20 radial periods


a/M=−0.95, a=12, e=0.4, i=0.785; 14 radial periods



Circular equatorial prograde orbits, $m = 2$ harmonic, as in Finn & Thorne (2000) PRD 62, 124021. Points are at 1 y, 1 mo, 1 day.

Left pair: Schwarzschild. Right pair: a/M=0.998. Upper pair: $10M_\odot/10^6M_\odot$, $z = 0.1$ (0.4 Gpc) —strongest in 1 year with Freitag normal rate. Lower pair: $1M_\odot/10^6M_\odot$, $z = 0.25$ (1 Gpc) —strongest in 1 year with Bender & Hils rate.

10.2 Gravitational captures: requirements and goals

Lower mass nuclear black holes have denser star clusters (observational correlation). Black hole mass function then predicts most of rate will come from $\sim 10^6M_\odot$ black holes ($\sim$ minimum known), unless black hole mass function rises sharply for $M < 10^6M_\odot$. Rate subject to considerable astrophysical uncertainty (e.g. IMF, star formation and merger history of galactic nuclei).

Capture statistics imply $\sim 1/2$ of orbits will be $\sim$ *circular* when in LISA band. Other $\sim 1/2$ will be substantially eccentric —not fully analysed yet. Most S/N comes at $t >$ 1y before plunge, when gravitational wave frequency is approaching confusion limit of galactic binaries.

Must prepare for nonoptimal signal processing loss of S/N for detection, and Olbers' confusion. *Could* be factor of 10 if supermassive objects are black holes of GR, will certainly be > factor of 10 if they aren't.

- requirement: $T_{\text{miss}} > 3$y to avoid galactic white dwarf confusion. Pre-Ph A nominal strain limit at 5×10^{-3}Hz to ensure detection (with nonoptimal processing) at 'conservative' rate estimate.

- goal:4x better than Pre-Ph A strain limit at 5×10^{-3}Hz. Arm length 2.5×10^{6}km (1/2 of Pre-Ph A nominal arm).

11 LISA sensitivity to backgrounds and bursts

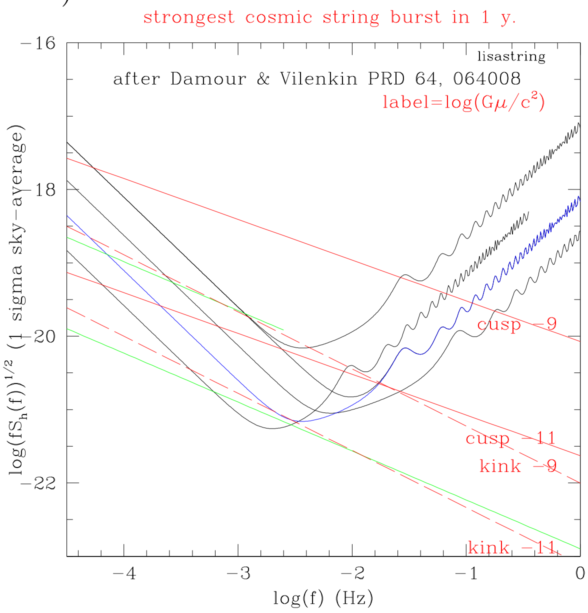
11.1 The science case for extragalactic backgrounds and bursts

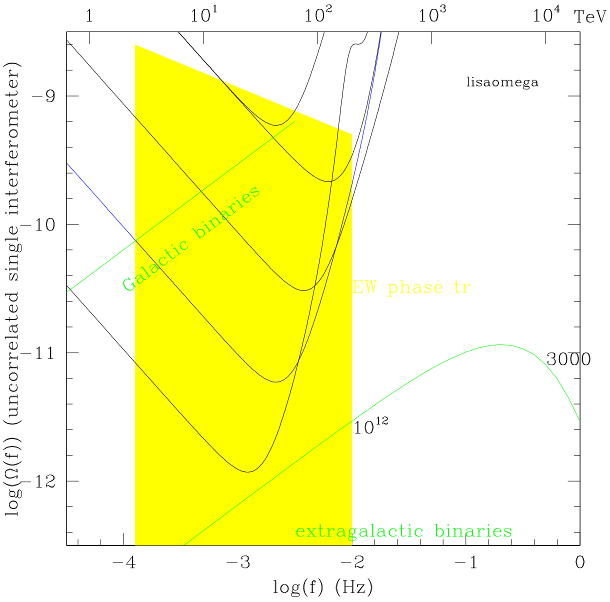
Perhaps the most exciting thing LISA could find. And the most uncertain.

Gravitational waves: unique unobscured view back to Planck time.

Cosmological sources of wave bursts: cosmic string kinks and cusps. Population III VMO collapses, formation of intermediate mass black holes.

Cosmological sources of stochastic backgrounds: electroweak phase transition (optimally placed in frequency), other phase transitions, brane-world dimensionality transition, inflation (slow roll undetectable, but others detectable).





11.2 Backgrounds and bursts: requirements and goals

Unexplored parameter space is huge, and little constrained by theory or observation: limits on backgrounds with arbitary spectra at all frequencies are set by gw energy density not exceed limit set by expansion rate at nucleosynthesis, $\Omega < 3 \times 10^{-6}$.

Situation might be described by saying that LISA will explore 10% of the (logarithmic) parameter space, and something much less sensitive than LISA would instead explore 6%.

An exciting payoff, but so uncertain it does not drive *sensitivity* goals or requirements.

However, if background is of detectable amplitude, *it is crucial that it be possible to unambiguously distinguish it from instrumental noise*, to ensure acceptance of the paradigm-shifting detection.

- Requirement:LISA data stream should be complete enough to enable synthesis of Sagnac channel as well as Michelson channels.

- Requirement: If the Sagnac channel can be synthesised, the non-Gaussian instrumental 'glitch' rate should be less than a few per day, to ensure that instrumental glitches are not confused with gravitational wave bursts at a false alarm rate of more than once per three years. If the Sagnac channel is not enabled, the constraint on the rate of instrumental glitches at $f < 2 \times 10^{-3}$Hz becomes no more than one per mission lifetime.

- Goal:Keep statistics and correlations of high frequency noise, well-understood (e.g. shot noise vs pointing jitter or residual master clock noise), so that it can be estimated and subtracted to enable background searches below the instrument noise (cf. Hogan & Bender 2001 PRD 64, 062002).

12 Summary of LISA requirements and goals

In table, h requirements scaled to Pre-Phase A values at that frequency.

Requirement	10^{-4}Hz	10^{-3}Hz	5×10^{-3}Hz	10^{-2}Hz	Arm	T_{miss}
Verification binaries		4x 5x (5y)	3x (1.5y)		long	1.5y
Galactic binaries		4x 5x (5y)	3x (2y)		short	2y
Cosmic backgrounds	Sagnac channel, < 3 glitch/d					
Gravitational capt		4x	1x	1x	short	3y
Merging supermassive	5x	10x	10x		long	3y
High z BHs		4x	1.5x	1.5x	short	3y

Max expected source freqs: 0.03Hz (2,4,6). ⇒ Min data sampling rate 0.2Hz?

Goal	10^{-4}Hz	10^{-3}Hz	5×10^{-3}Hz	10^{-2}Hz	Arm	T_{miss}
Verification binaries						
Galactic binaries	1x	3x	2x	2x		5y
Cosmic backgrounds	< 1 glitch/d					
Gravitational capt			1/4x	1/4x	short	5y
Merging supermassive	1x$*$				long	> 5y
High z BHs					short	

$*$ (5) White acceleration noise at least down to 3×10^{-5}Hz. (2,3,4,6) sources could exist at > 0.03Hz. ⇒ data sampling rate 1Hz? (1,2,5) have *Sagnac mode* as goal.

12.1 Additional requirements

- Frequency of breaks in data stream requiring fitting for unknown changes in spacecraft positions should not exceed once per week, to avoid loss of information in source fitting. [needs further analysis]

- Duty cycle: If the operational duty cycle is η, T_{miss} in this document should be increased to T_{miss}/η ('time on target').

- Data latency: No more than a week. Data should be transmitted to earth and processed (in preliminary way) with a delay of < 1 week, so that astronomers can be alerted to search for electromagnetic signals from impending merger events.

- Reliability: All 3 spacecraft must work for full mission lifetime. All 6 lasers/gravitational reference sensors must work for at least 1.5 years.

12.2 Data products

- Primary: the six interspacecraft one-way Doppler streams $y_{ij}(t)$ (or equivalent phase streams, $y_{ij}(t) = \text{fringe rate}/\nu_0$, where ν_0 is laser frequency), plus records of the spacecraft positions in solar system barycenter.
- Secondary: public codes for fitting sums of various source types to the data. Catalog of 'official' fitted wave sources.