Overview of LISA Science

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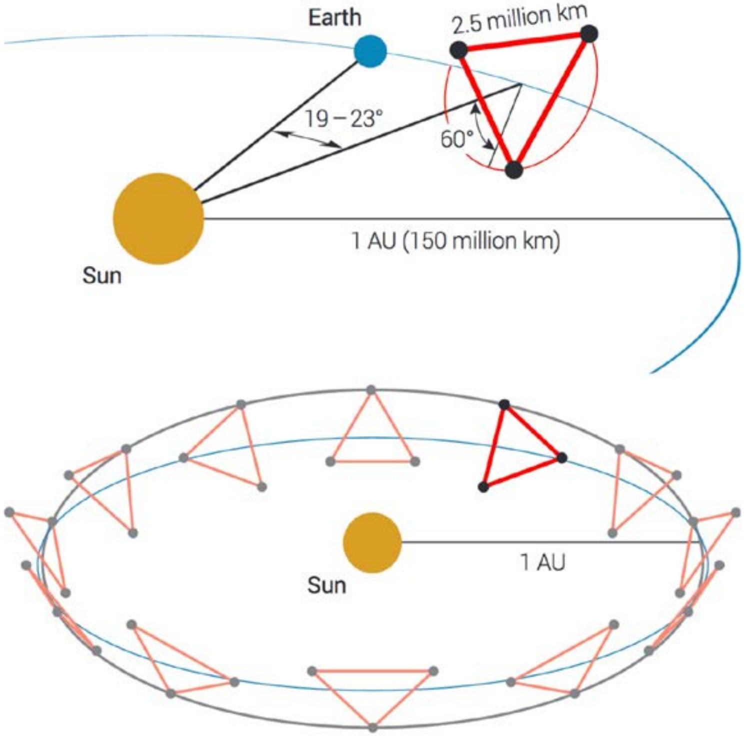
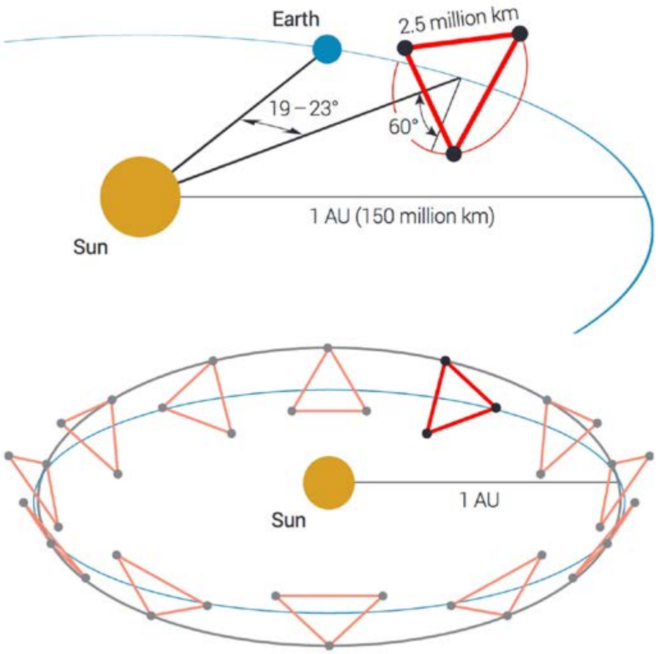
Jet Propulsion Laboratory, California Institute of Technology



Overview of LISA Science

LISA:



➢ESA/NASA (80%/20%) mission

➢is 3 drag-free satellites, separated by 2.5×10^6 km, and trailing the Earth by ~20 deg

➢will detect GWs in ~10^{-4}--10^{-1} Hz band; main sources are:

✓Compact binaries in Milky Way, especially WD-WD binaries

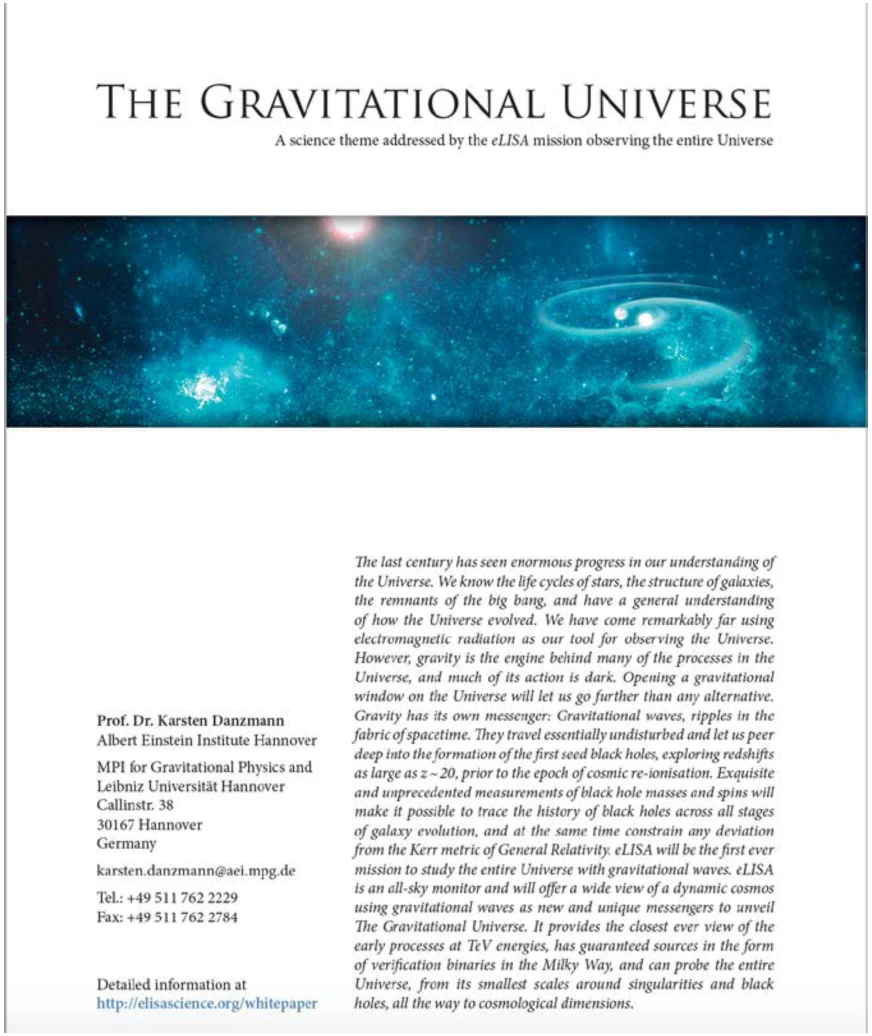
✓Mergers of ~10^4- 10^7 M_{sun} BHs in galactic nuclei at z > 20

✓Inspirals of compact stars (BHs, NSs, WDs) into massive BHs

? Stochastic GWs generated by electro-weak phase transition

? Bursts from cusps on cosmic (super-)strings

Recommended recent references



THE GRAVITATIONAL UNIVERSE

A science theme addressed by the *eLISA* mission observing the entire Universe

The last century has seen enormous progress in our understanding of the Universe. We know the life cycles of stars, the structure of galaxies, the remnants of the big bang, and have a general understanding of how the Universe evolved. We have come remarkably far using electromagnetic radiation as our tool for observing the Universe. However, gravity is the engine behind many of the processes in the Universe, and much of its action is dark. Opening a gravitational window on the Universe will let us go further than any alternative. Gravity has its own messenger: Gravitational waves, ripples in the fabric of spacetime. They travel essentially undisturbed and let us peer deep into the formation of the first seed black holes, exploring redshifts as large as $z \sim 20$*, prior to the epoch of cosmic re-ionisation. Exquisite and unprecedented measurements of black hole masses and spins will make it possible to trace the history of black holes across all stages of galaxy evolution, and at the same time constrain any deviation from the Kerr metric of General Relativity. eLISA will be the first ever mission to study the entire Universe with gravitational waves. eLISA is an all-sky monitor and will offer a wide view of a dynamic cosmos using gravitational waves as new and unique messengers to unveil The Gravitational Universe. It provides the closest ever view of the early processes at TeV energies, has guaranteed sources in the form of verification binaries in the Milky Way, and can probe the entire Universe, from its smallest scales around singularities and black holes, all the way to cosmological dimensions.*

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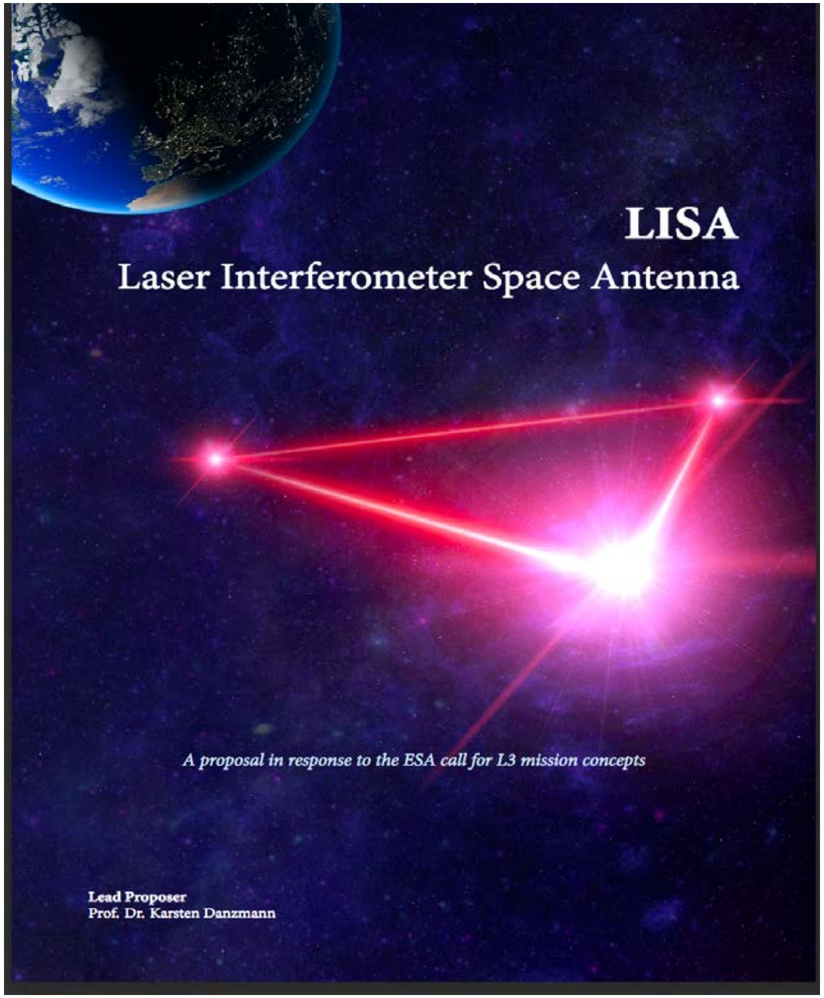
Detailed information at
http://elisascience.org/whitepaper



LISA

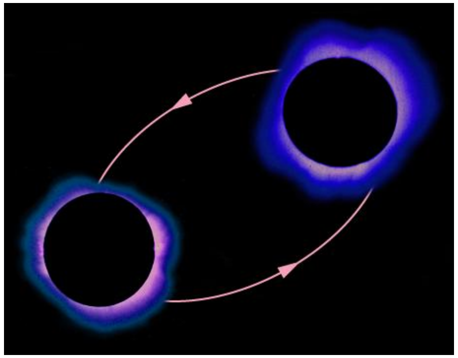
Laser Interferometer Space Antenna

A proposal in response to the ESA call for L3 mission concepts

Lead Proposer
Prof. Dr. Karsten Danzmann

--Most of the figs in this talk were taken from one of these.

Binaries as GW sources



(using quadrupole approximation for simplicity)

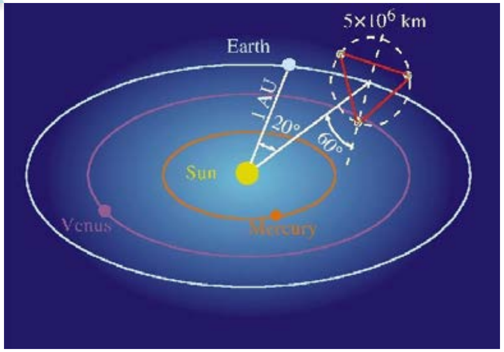
$$I^{ij} = \sum_A M_A r_A^i r_A^j$$

D

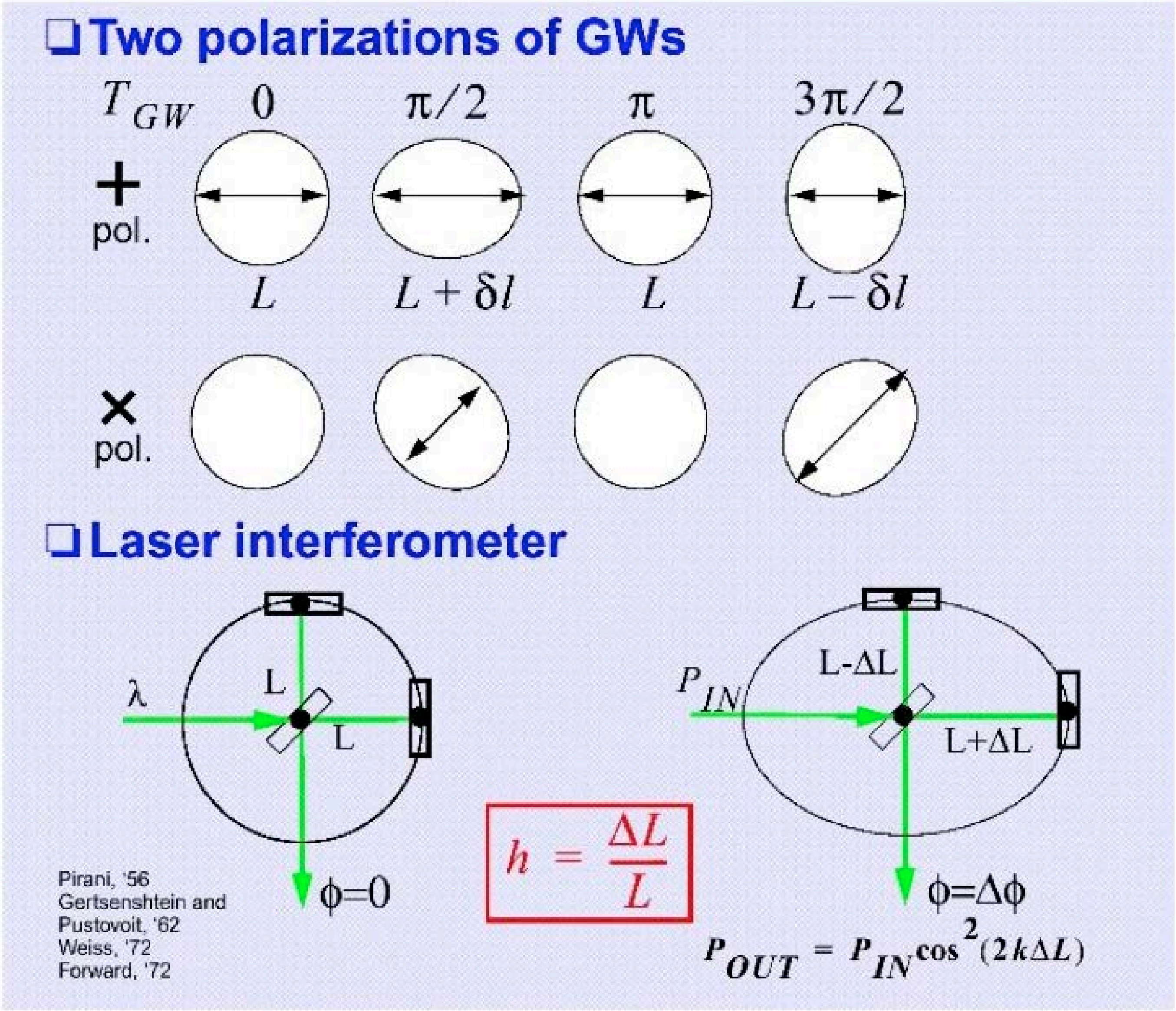
$$h_{ij} = \frac{1}{D} P_{TT} \frac{d^2}{dt^2} I_{ij}(t-D)$$

$$h(t) \sim D^{-1}\mu\, r^2\Omega^2 \sim D^{-1}\frac{M_1 M_2}{M^{1/3}} f^{2/3}$$ x F(angles)

$$\frac{df}{dt} = \frac{96}{5}\pi^{8/3}\frac{M_1 M_2}{M^{1/3}} f^{11/3}$$ + higher order terms



Gravitational Waves



❑ Two polarizations of GWs

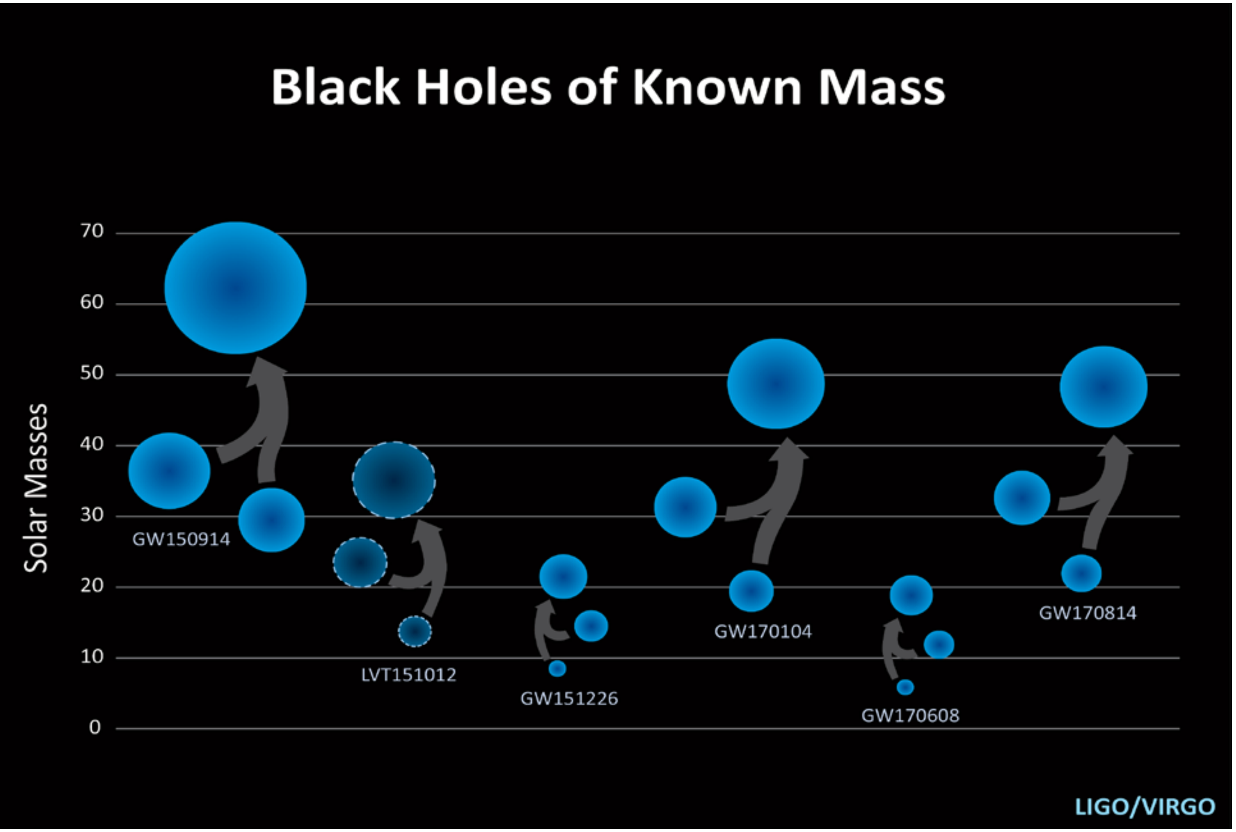
❑ Laser interferometer

$$h = \frac{\Delta L}{L}$$

$$P_{OUT} = P_{IN} \cos^2(2k\Delta L)$$

Pirani, '56
Gertsenshtein and Pustovoit, '62
Weiss, '72
Forward, '72

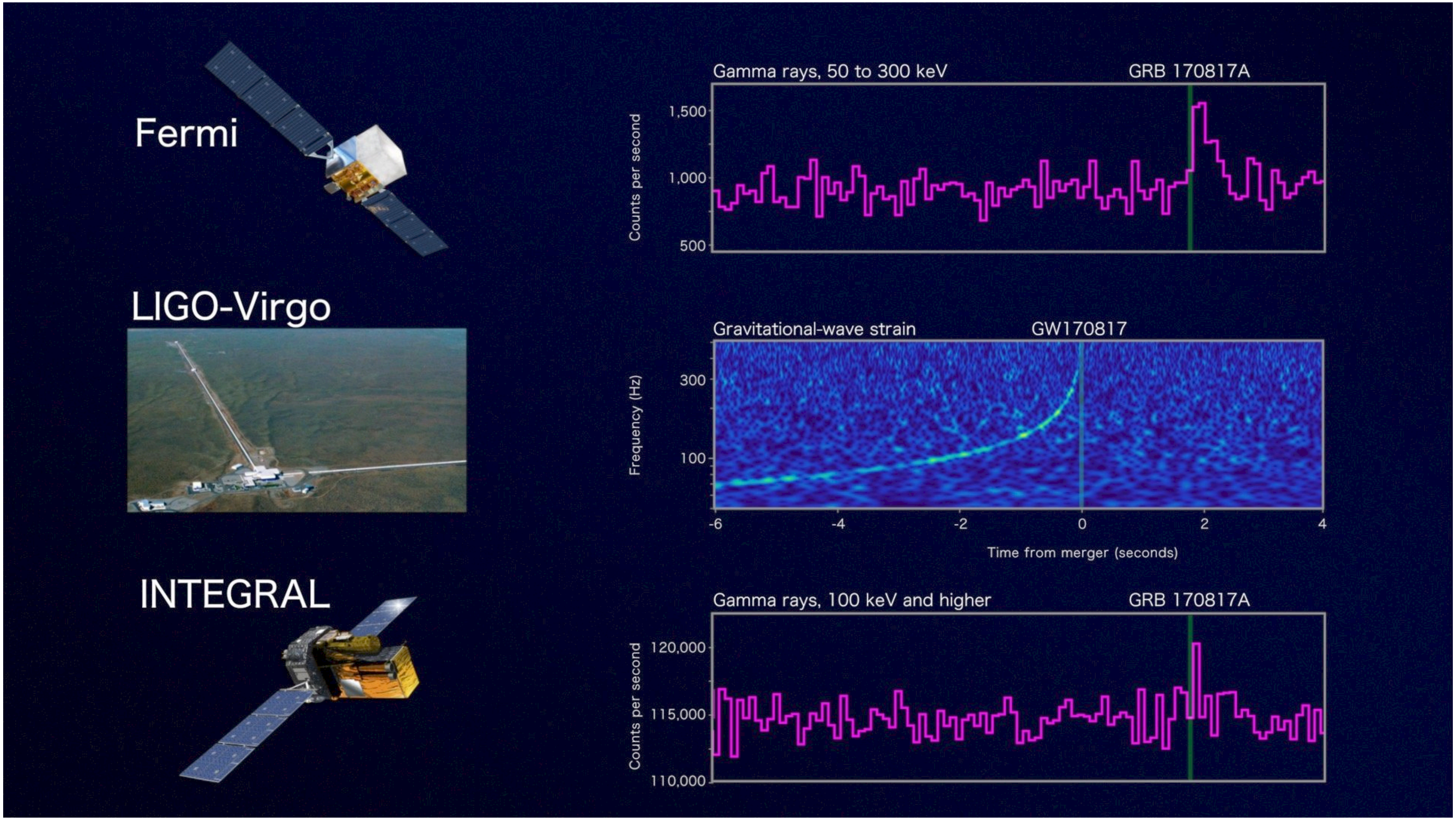
LIGO Hanford &
LIGO Livingston



LIGO/Virgo BH-BH
merger detections
(as of Nov 15, 2017)

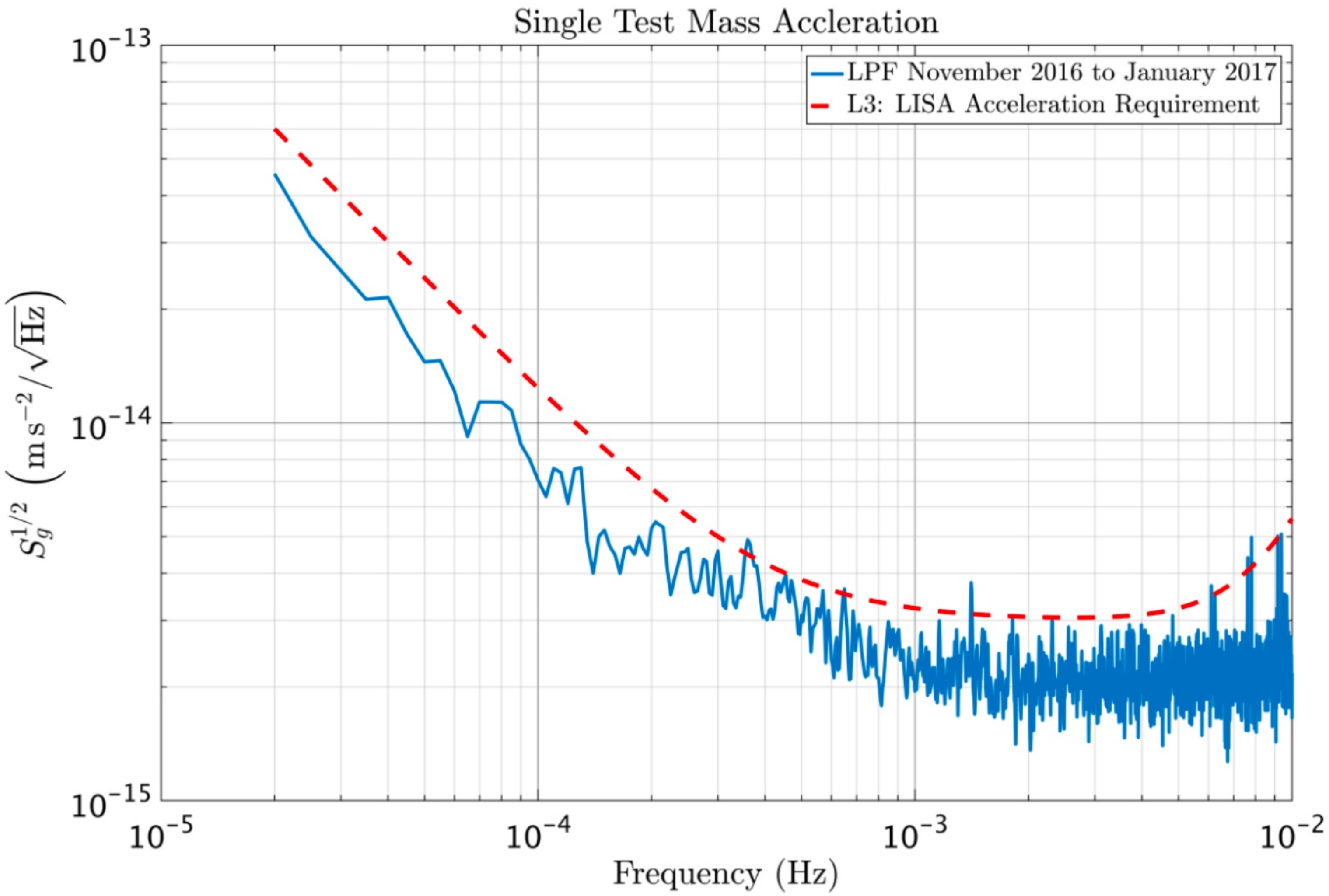
Credit: LSC/LIGO/Caltech/Sonoma State (Aurore Simonnet)

First detection of NS-NS merger: 8/17/2017



Credit: NASA's Goddard Space Flight Center

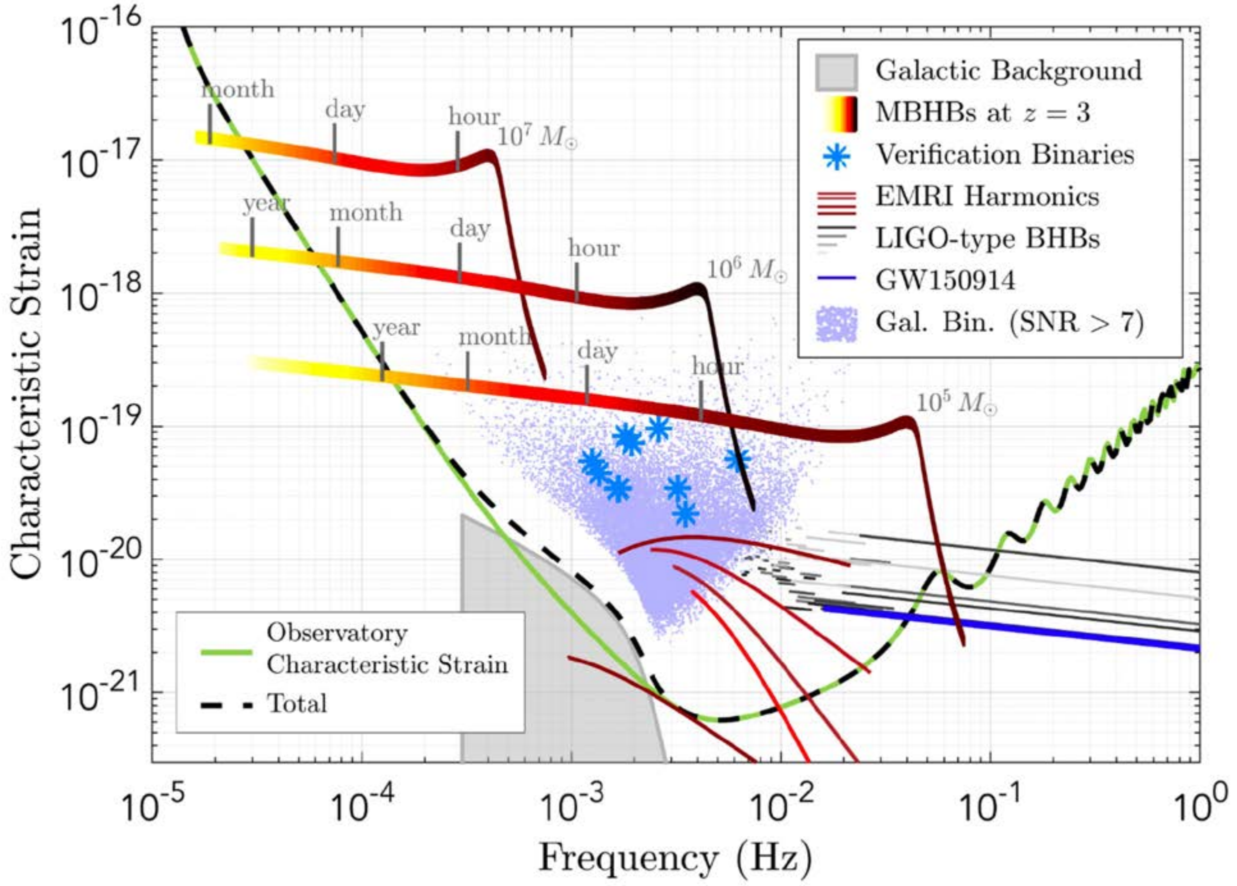
Acceleration noise measured by LISA Pathfinder, compared to LISA requirement



LIGO/Virgo vs. LISA: similarities and differences

- LISA’s freq band is factor ~ 10^4 lower, so will see (mostly) different kinds of objects.
- LISA’s sources will typically be “in-band” for months or longer, and thousands will be “on” simultaneously.

- LISA’s “bread-and-butter” sources will likely be binaries.
- Probably most of the astronomy we will learn from LISA will be obtained by combining LISA observations with electromagnetic ones.



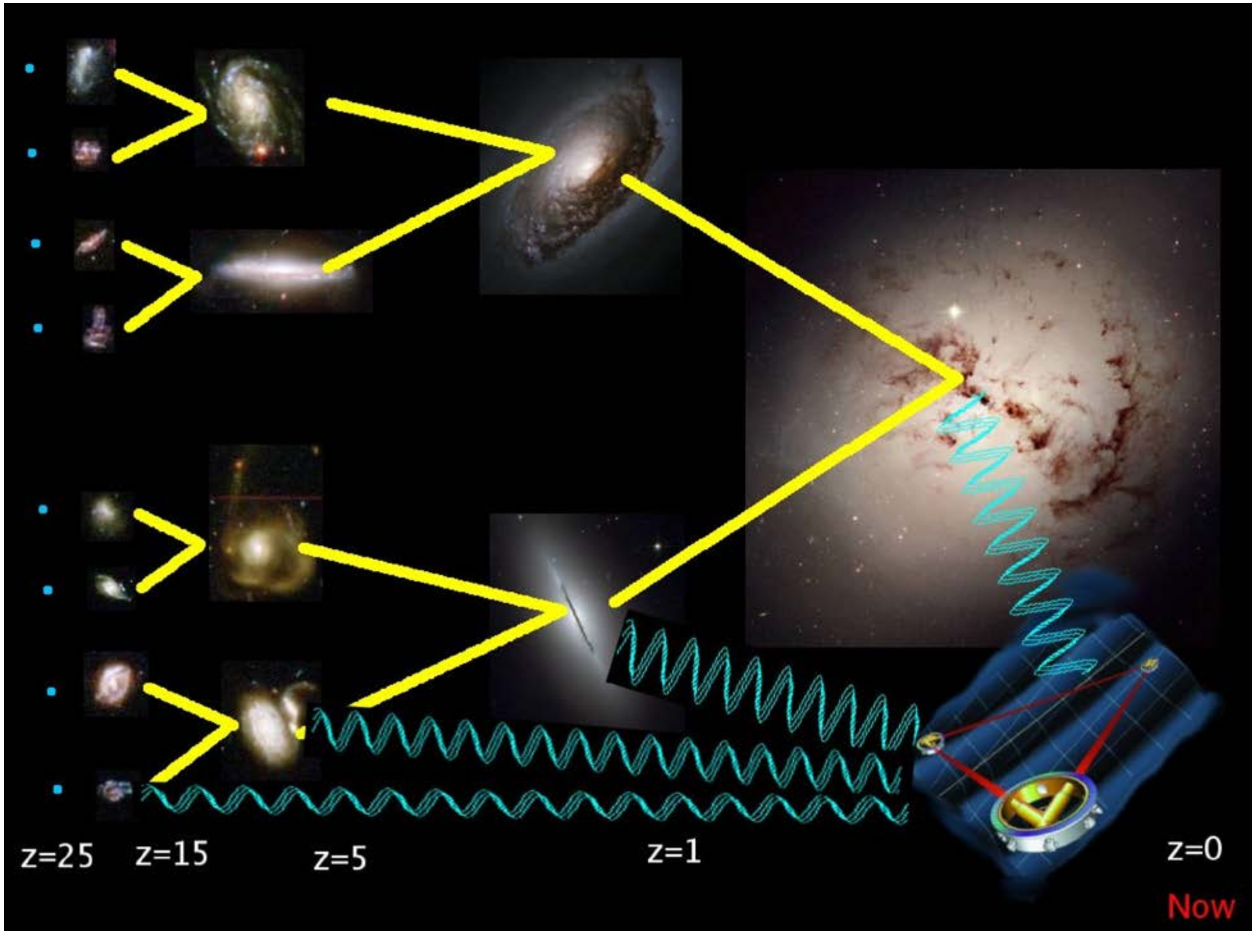
Estim. Source Numbers/Rates

--from "The Gravitational Universe"

- MBH mergers: ~10-100/yr
- Extreme-mass-ratio inspirals: ~5-50/yr
- Galactic Binaries: ~3000 resolvable, and ~3×10^7 in band, but not resolvable

Massive BH mergers

- Basically all large galaxies contain massive BHs in their cores.
- Structure formation in the early universe is bottom-up: small galaxies merge to form larger galaxies, which merge to form even larger galaxies, etc.
- When galaxies merge, dynamical friction brings their two BHs close together, and eventually gravitational radiation reaction leads BHs to merge.



--from “The Gravitational Universe”

MBH mergers: measurement accuracy

-from "The Gravitational Universe"

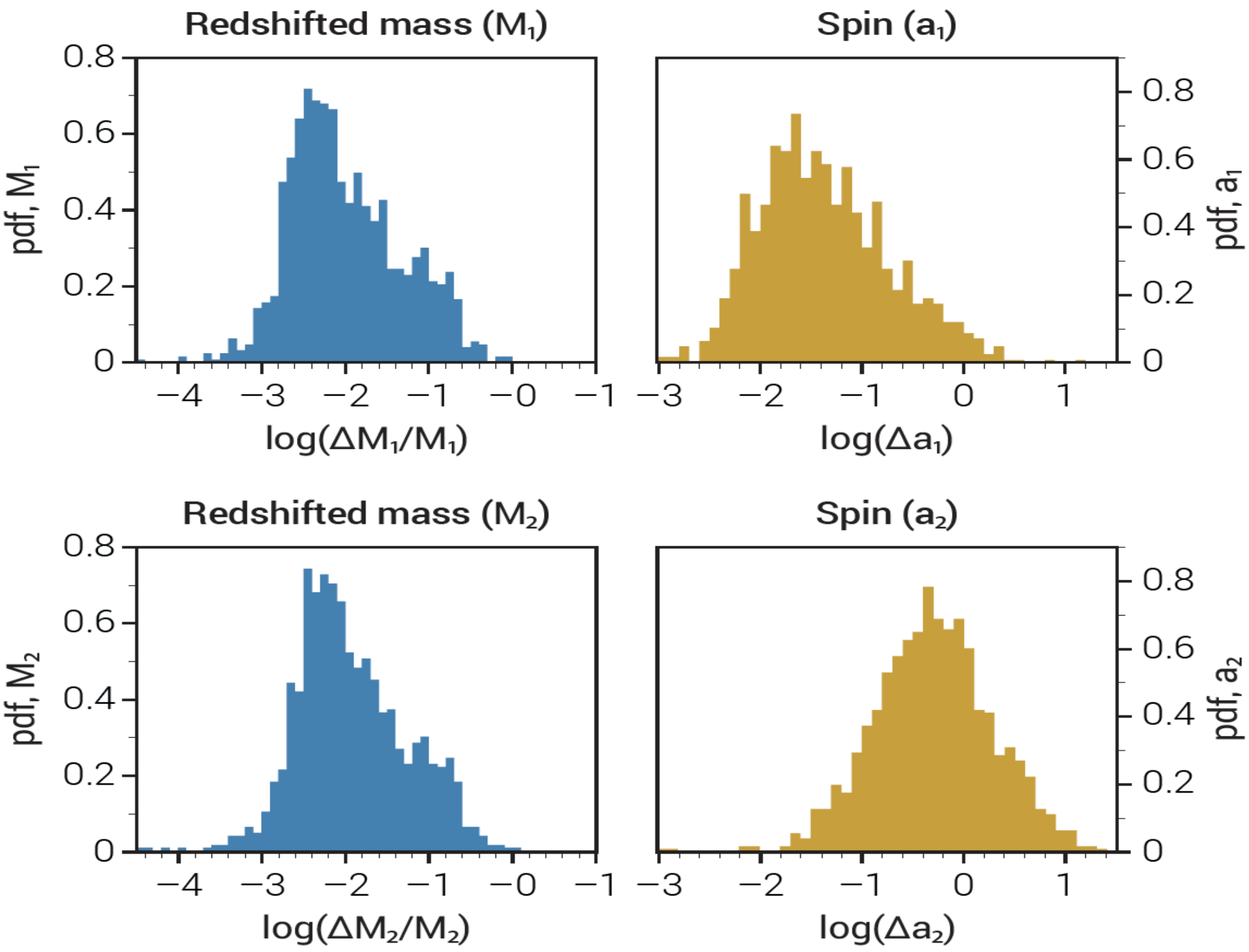


Figure 3: eLISA parameter estimation accuracy for massive black hole binaries – probability density functions. Left panels show errors on the redshifted mass, and right panels on the spins. Top panels refer to the primary black hole, bottom panels to the secondary black hole.

Extreme-mass-ratio inspirals

- Captured main sequence stars are not LISA source, since they are tidally disrupted before they enter the LISA band.

- WDs, NSs, and BHs all captured whole. Captures of $\sim 10\ M_{sun}$ probably dominate the detection rate, due to mass segregation in the inner few parsecs, and because they can be seen to greater distance: to $z \geq 1$

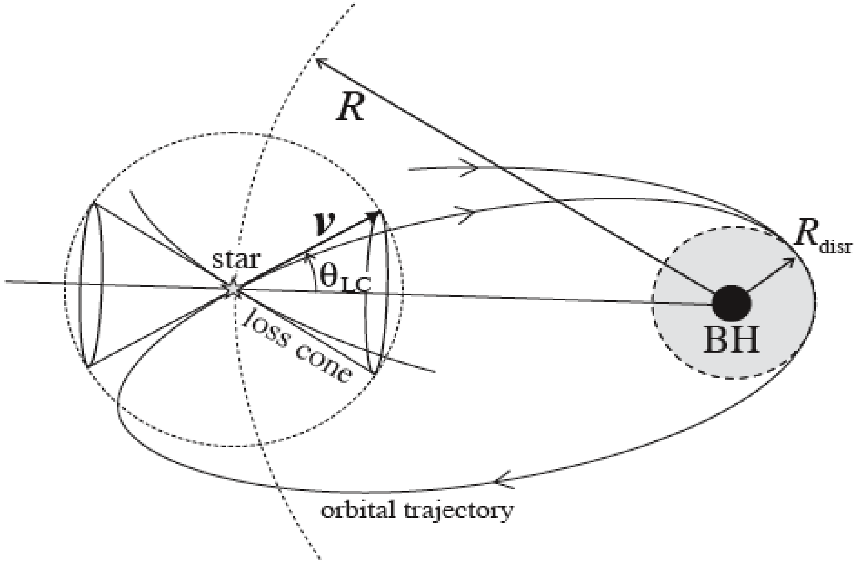


Fig. 3. Diagram of the loss cone. --Freitag&Benz (2002)

EMRI orbits/waveforms

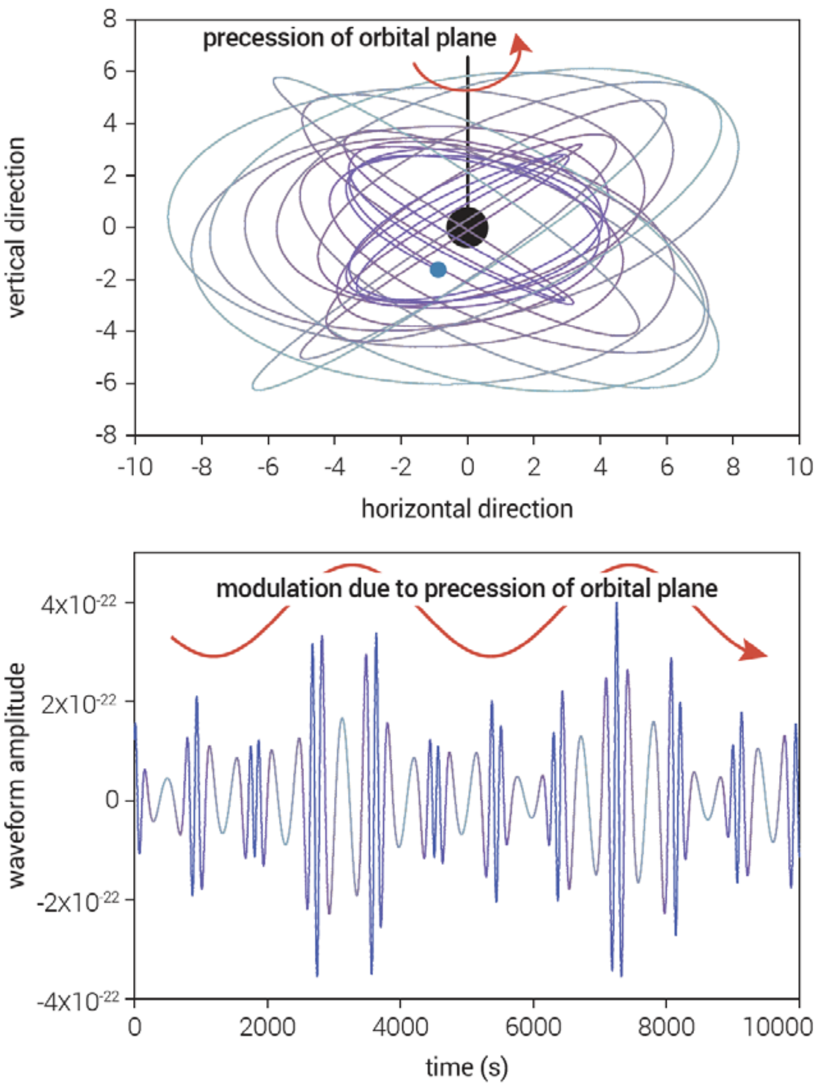


Figure 5: EMRI orbit and signal. In the top panel we see the geometrical shape of the ornate relativistic EMRI orbit. The lower panel shows the corresponding gravitational wave amplitude as a function of time.

EMRI measurement accuracy

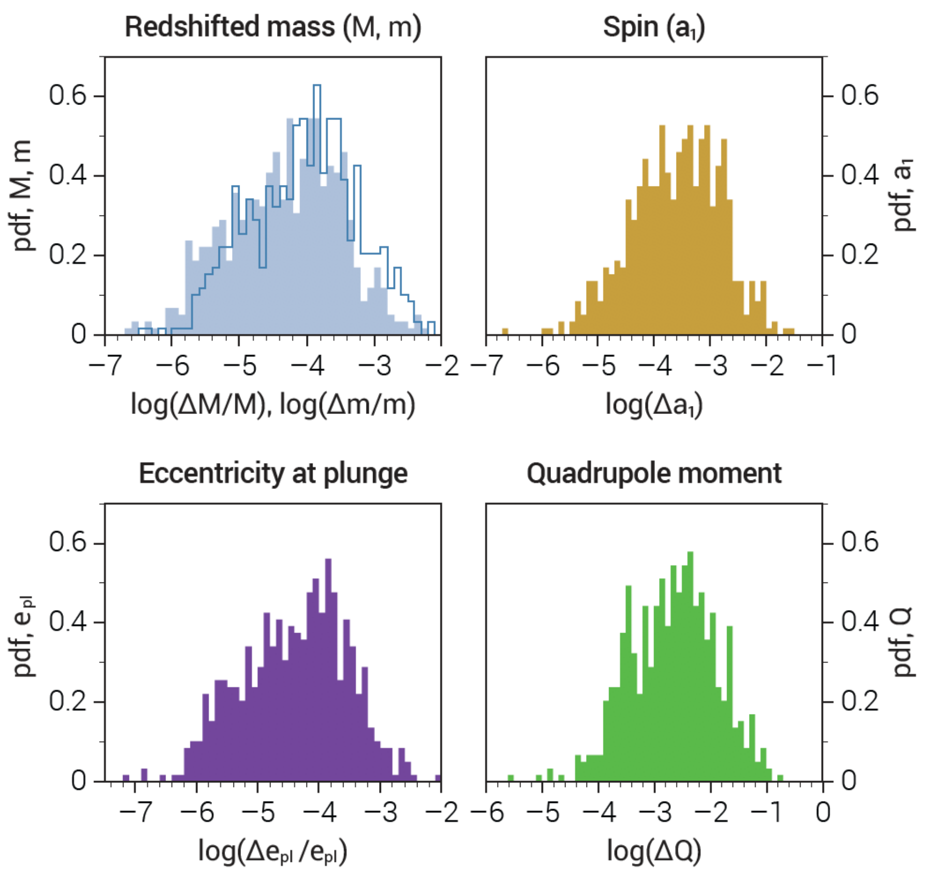


Figure 6: eLISA parameter estimation accuracy for EMRIs. Top left panel: estimation of the redshifted masses (filled: massive black hole; solid line: stellar black hole); top right panel: spin of the massive black hole; bottom left panel: eccentricity at plunge; bottom right panel: minimum measurable deviation of the quadrupole moment of the massive black hole from the Kerr value.

--from “The Gravitational Universe”

Fundamental signal analysis tool: matched filtering

measured signal = inst. noise + GW

$$s(t) = n(t) + h(t)$$

$$\int_0^T dt\, s(t)h(t) = \int_0^T \underset{\substack{\downarrow \\ \sim T^{1/2}}}{dt\, n(t)h(t)} + \int_0^T \underset{\substack{\downarrow \\ \sim T}}{dt\, h^2(t)}$$

$$SNR \sim \frac{rms\{h\}}{rms\{n\}} N_{cyc}^{1/2}$$

Recall N_cyc ~ 10^5 for EMRIs

Constructing Theoretical Waveforms

We need theoretical waveforms to do matched filtering, but the 2-body problem in GR does not have an analytic solution, so we must use approximation methods:

- Numerical relativity
- Post-Newtonian approximation (expansion in v/c)
- Effective-one-body approximation
- Expansion in the mass-ratio

EMRIs and the mass-ratio expansion

- The mass ratio $m/M \sim 10^{-5}$, so natural to try perturbation theory, with mass-ratio as expansion param.

- At lowest order, $m/M \rightarrow 0$, the small mass just travels on a geodesic of the background black hole. At next order, radiation reaction saps energy from the orbit, and small mass spirals in.

- But: the radiation reaction force diverges at the point particle, and so must be regularized. A prescription for doing

The regularization was given by Wald&Quinn ('97) and Mino, Sasaki, &Tanaka ('97), but developing a practical implementation thru $(m/M)^2$ remains an active research area. Current waveforms are adequate for detecting EMRI signals, but not for extracting maximal information content.

Some of the science yield from LISA observations of compact binaries in our galaxy:

- Census of ultra-compact binaries in Milky Way: white dwarfs, neutron stars and black holes.

- Their distribution in mass, space, and frequency.

- How mass transfer works in white-dwarf binaries --which governs their late-time evolution.

- A few should later be observable by ground-based interferometers, allowing multi-band GW astronomy.

A speculative source: GWs from strongly 1st-order electro-weak phase transition

Colliding bubbles produce GWs with $\lambda \sim H^{-1}$, which then get redshifted. GWs produced by an electro-weak phase transition at $kT_* \sim 100\,Gev$ would be in the LISA band today.

The E-W transition is not strongly 1st order in the standard model, but is in some supersymmetric extensions, with $\Omega_{gw} \leq 4 \times 10^{-11}$ (Apreda et al., hep-ph/0102140)

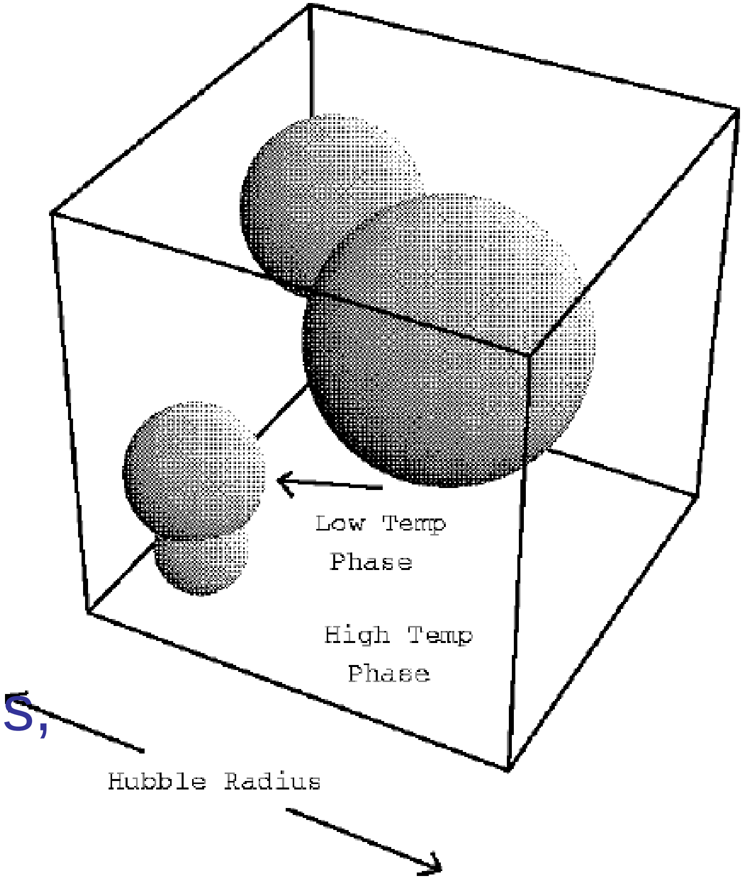


Fig. from B. Allen, gr-qc/9604033

LISA & tests of General Relativity

Bayesian approach requires reasonable alternatives to GR; then one could calculate the relative evidence for each. But I’m not aware of any serious alternatives.

So tests tend to be consistency tests; e.g.,

- given inspiral part of MBH merger signal, can infer masses and spins of MBHs, and hence predict the GW signal from merger and ringdown signal
- for EMRIs, imagine MBH has quadrupole moment different from GR value, and then use measured waveform to bound that difference

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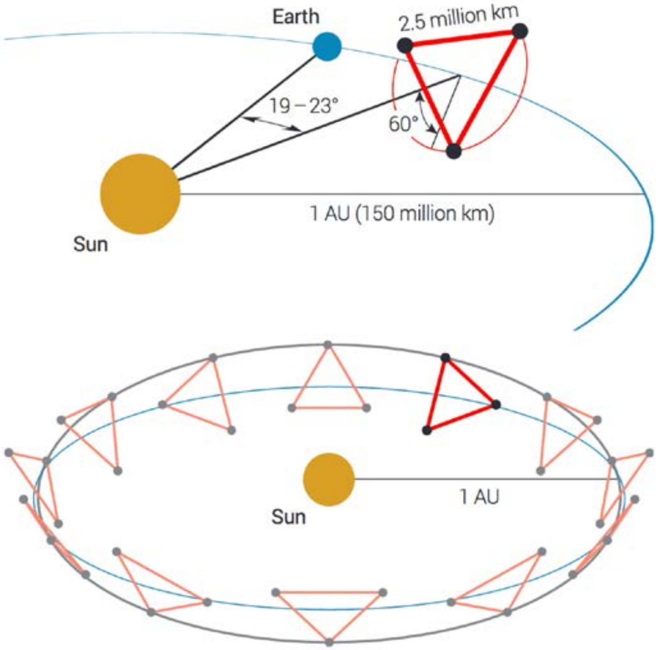

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