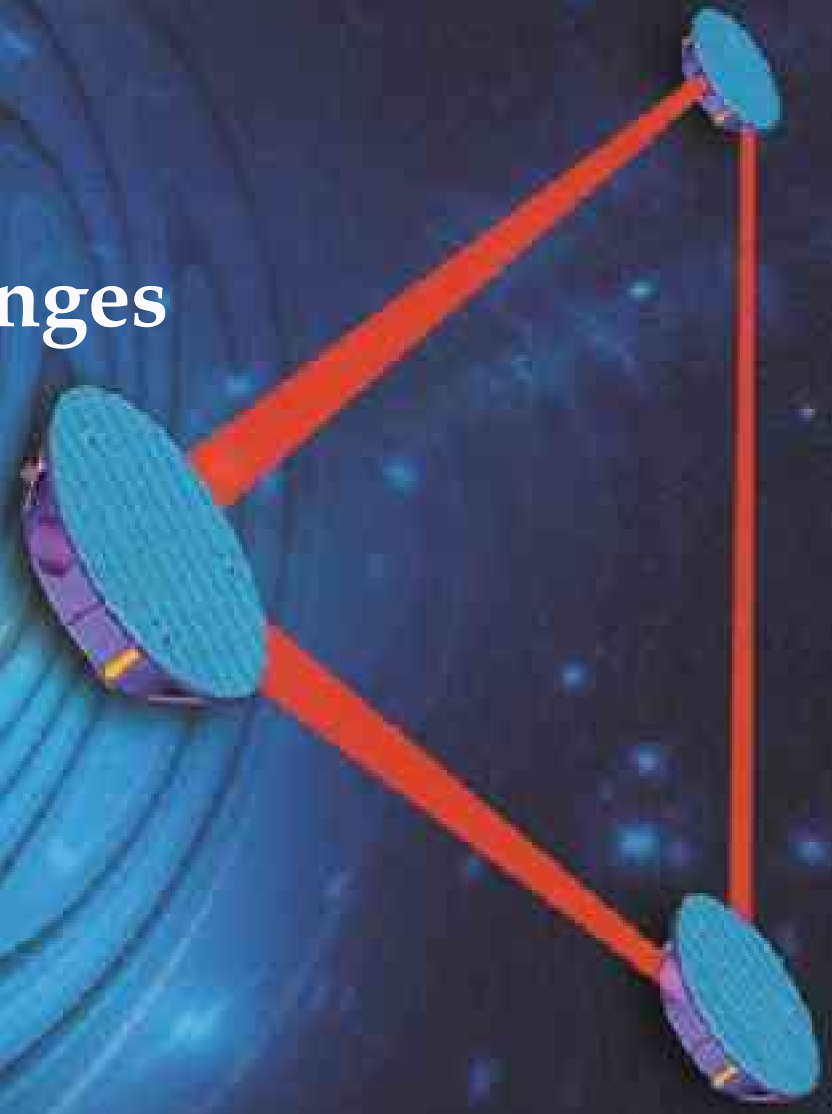
LISA

Laser Interferometer
Space Antenna

Data Analysis Challenges For LISA



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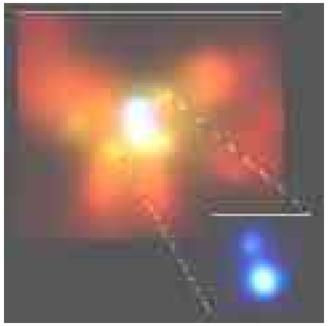
Caltech/JPL

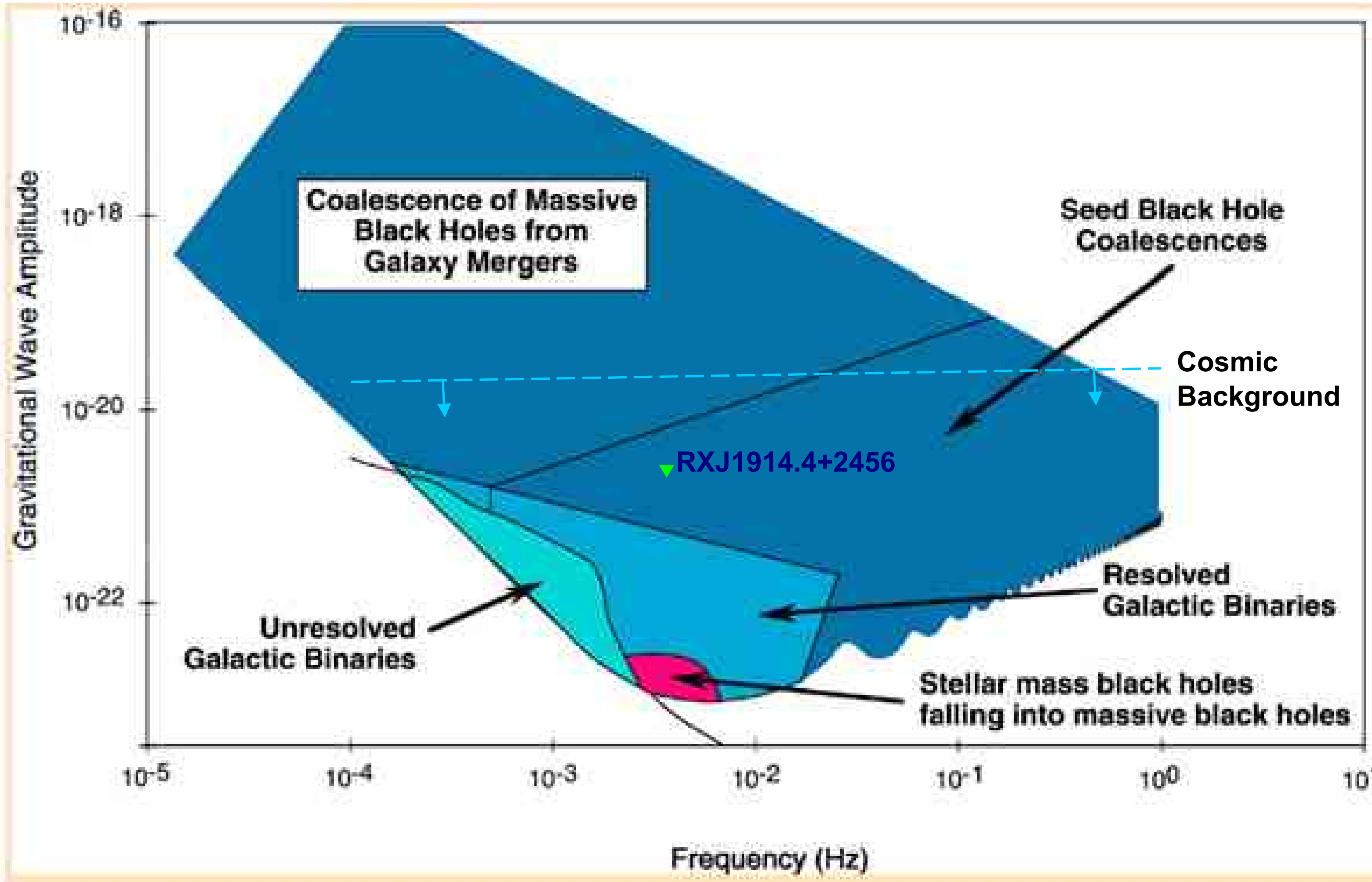
http://lisa.nasa.gov
15 July 2004

This Talk

- Concentrate on technical challenges that are unique or particularly challenging for LISA
  - Large range of additional challenges - not covered here (see good summary by Bernard Schutz to the LIST, Dec 2003)
- Topics of this talk:
  - Data analysis: overview
  - What makes LISA data analysis different?
  - Sampling of technical challenges

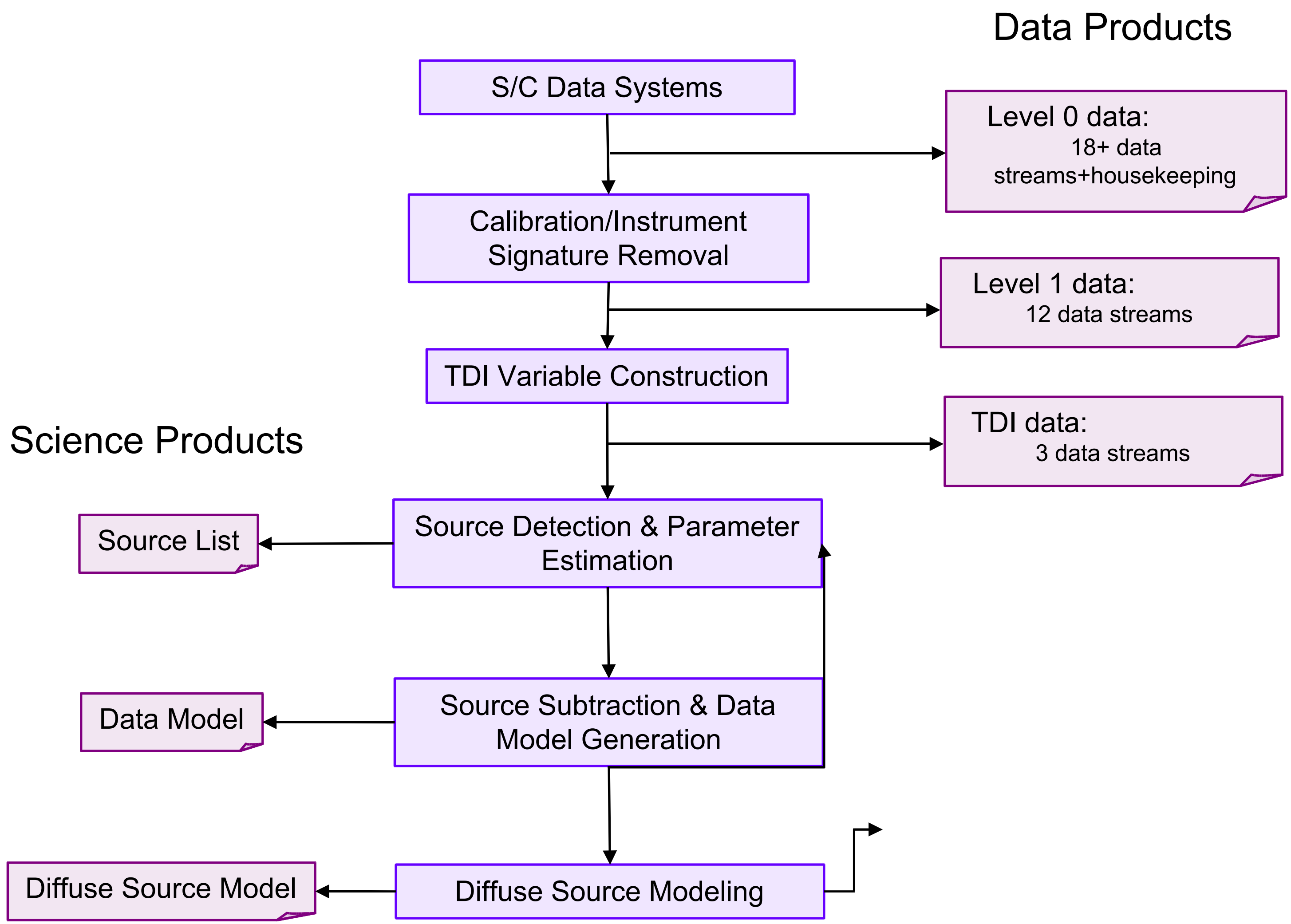


Schematic Landscape for LISA Data Analysis



LISA: Rich landscape of sources in time, frequency, and (3D) spatial domains

LISA Data Flow



What makes LISA data analysis different?

- Source dominated signal processing
- Large numbers of floating point operations per byte of data
- (Complex quasi-periodic waveforms)

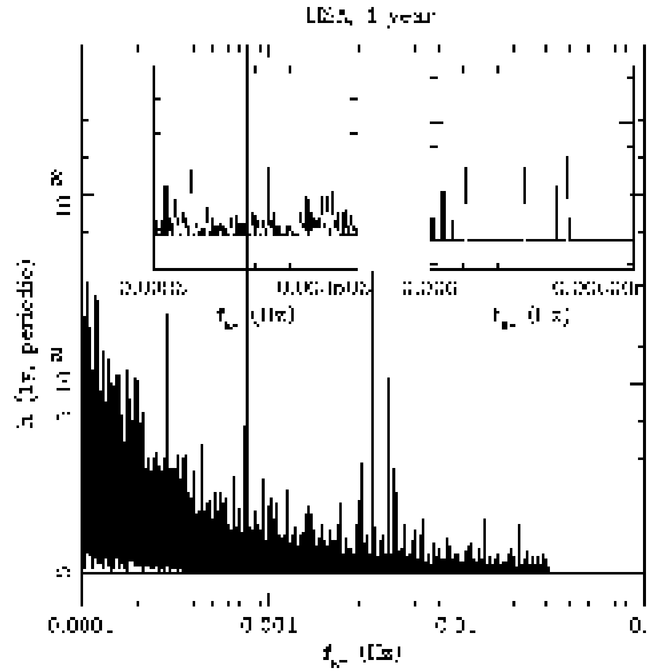
What makes LISA data analysis different?
(1) Source-dominated signal processing

⇨ Source-dominated signal processing

- >10,000 individual sources
  - Mostly ultra-compact binaries
- Large signal-to-noise ratio of some sources
  - Massive Black Hole Mergers: (SNR > 100-1000)

Important corollary: *Parameter estimation* more important than *detection*

- Science exploitation of strong sources
- Detection of weak sources impossible without careful parameter estimation of strong sources
- Many parameters to fit (up to 17); non-diagonal covariance



(galactic binary background, from Phinney)

- Large number of flops per byte
- (Complex quasi-periodic waveforms)

What makes LISA data analysis different?
(2) Large numbers of flops per byte

- Source-dominated signal processing

⇨ Large numbers of floating point operations per byte of data

- Bytes: [3 time series x 10 Hz x 4 byte/sample x 5 years]
  ~ 20 GB
- Flops (extreme case): [10 Teraflops x 5 years]
  ~2×10^{21} flop

⇒ as much as 10^{11} operations/Byte

- (Complex quasi-periodic waveforms)

Notes:

Why so large? Large number of source parameters leads to huge number of possible encodings of signals in data

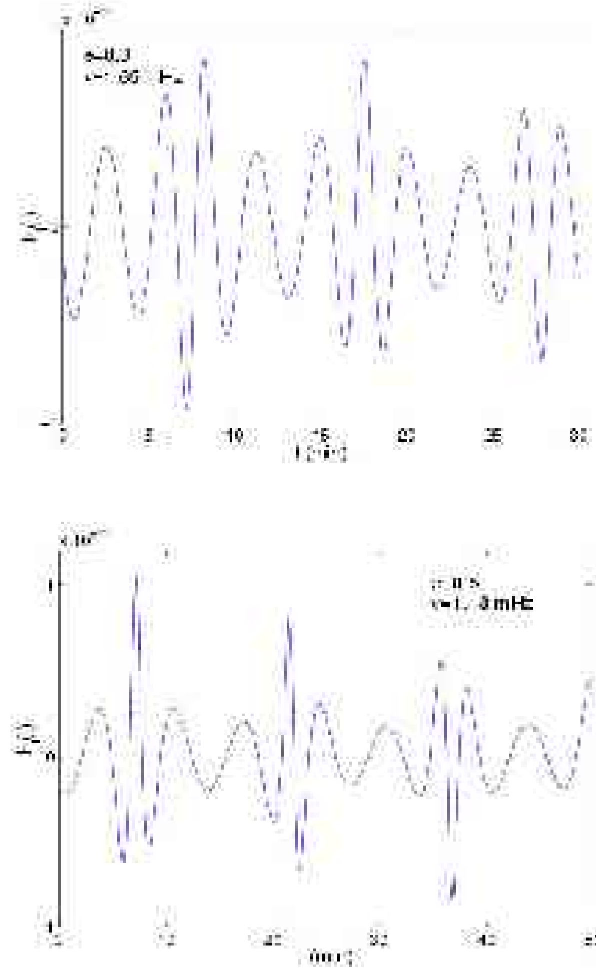
Many sources will require only modest processing

What makes LISA data analysis different?
(3) Complex quasi-periodic waveforms

- Source-dominated signal processing
- Large numbers of floating point operations per byte of data

⇨(Complex quasi-periodic waveforms)

- Complex inspiral waveforms (e.g. extreme mass ratio inspiral)
  - Modulation due to coupling with eccentricity of orbit and spin of black hole
- Time-variable instrument response due to LISA orbital motion
  - Amplitude and phase modulation
  - Significant number of “sky-patches” (particularly at high frequencies, ~ 1000 @ 10 mHz)



(from Barack & Cutler, ‘03)

Sampling of Data Analysis Challenges

7 Theory/Computation Challenges for LISA

[As identified by the LISA International Science Team – March, 2002]

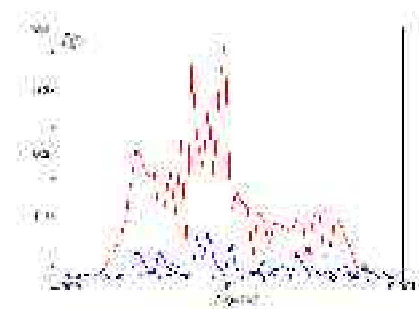
1) Understanding the formation and evolution of nuclear star clusters around supermassive black holes
2) Predicting of waveforms of compact objects spiraling into supermassive black holes
3) Development of methods for separating thousands of simultaneous wavetrains of diverse sources from a single time series
4) Understanding the fate of merging supermassive black holes in galactic mergers
5) Computing the emission from merging massive black holes
6) Predicting theoretically the stochastic primordial background spectra due to inflation, phase transitions, brane worlds and other sources involving new physics
7) Understanding the astrophysics of tides and mass transfer in short-period white dwarf binaries

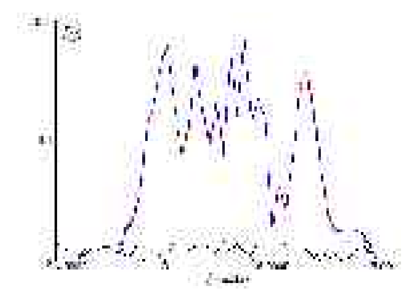
Challenge: Source Subtraction (ala LIST Challenges '02)

Challenge: "Development of methods for separating thousands of simultaneous wavetrains of diverse sorts from one or more time series."

- "Includes both abstract statistical theory and concrete algorithms designed around particular families of waveforms of likely interest in the LISA band."
- "Also includes techniques for estimating spectra of residual confusion backgrounds of unfitted sources, in the context of the specific LISA mission architecture."

- Significant research required
  - "Cocktail Party Problem" (for LISA more like a rock concert!)
- Recent results
  - E.g Cornish and Larson ('03), Krolak and Tinto ('03)
- Issues
  - Theoretical limits of source subtraction
  - Practical algorithms for subtraction
  - Parameter estimation
- Areas for further work
  - Detection of low-SNR signals in presence of high SNR source (SMBH mergers)
  - Backgrounds of variable-frequency (e.g. EMRIs)

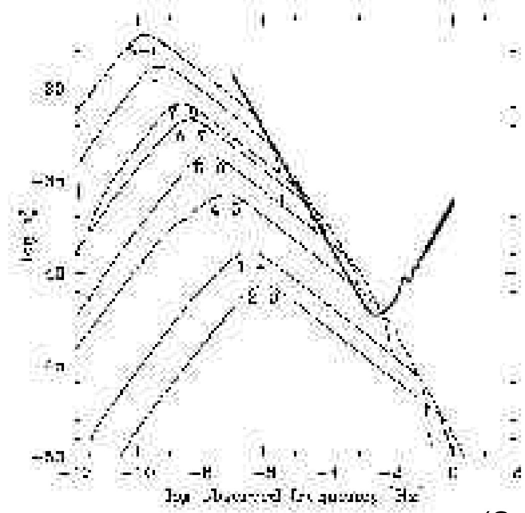




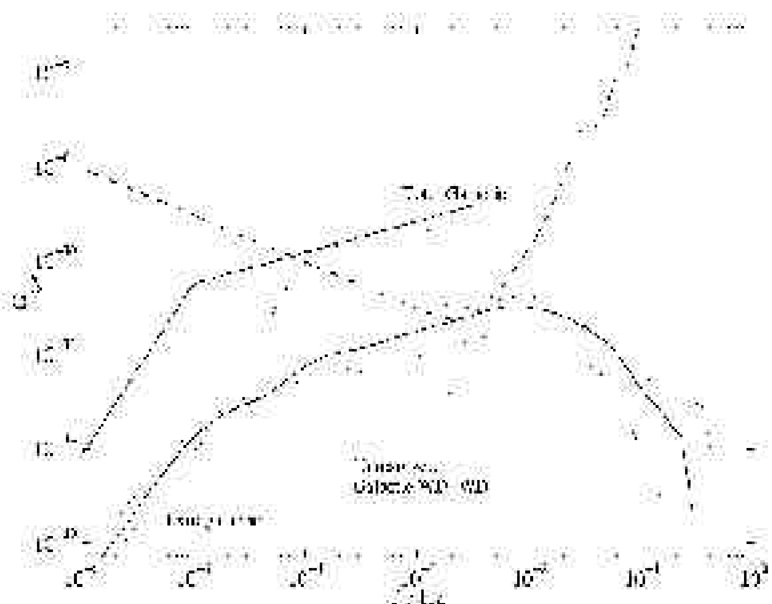
[from Cornish and Larson, '03]

Data Analysis/Astrophysics Challenge
Determination of self-confusion noise

- Confusion noise backgrounds
  - Galactic WD-WD
  - Extragalactic WD-WD
  - SMBH mergers
  - Extreme Mass Ratio Inspirals
- Key question: impact of unresolvable background for study of discrete sources?
- Some results to date
  - WD-WD (see e.g. Nelemans, 2000 & 2001; also Farmer & Phinney, 2004)
  - SMBH mergers (Sesana et al. 2004)
- Further work needed
  - EMRIs (variable frequency, potentially high numbers)



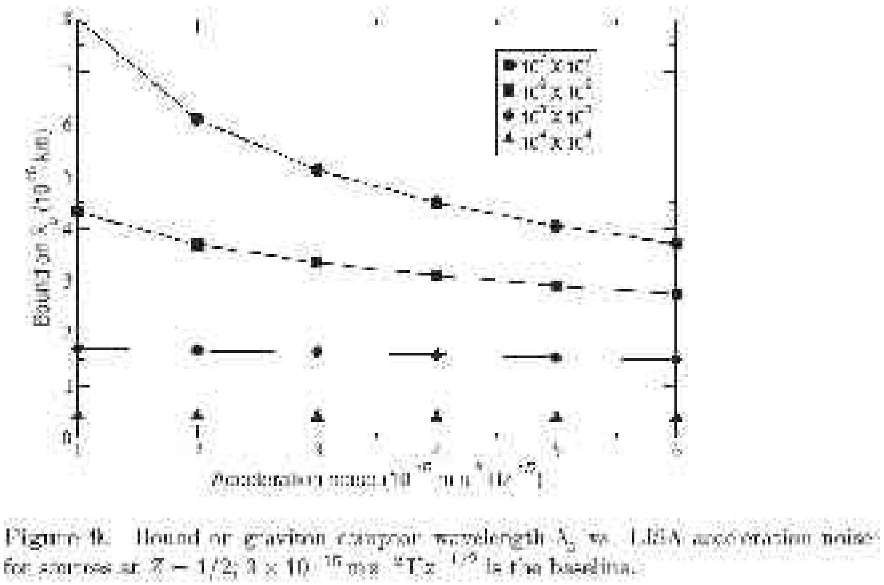
(Sesana at al.)



(Farmer and Phinney)

Challenge: Quantitative Tests of Physical Theory

- Issues
  - How to quantitatively realize the LISA potential for testing GR and other physical theories
- Recent results
  - Will & Yunes (2004)
    - GR parameter tests
  - Collins and Hughes (2004)
    - Metric tests (Testing “no hair”)
- Areas for further work
  - Quantitative tests of GR
    - “Not clear how to quantify the accuracy of the test of GR”, Bernard Schutz (this symposium)
  - Setting quantitative limits on Cosmic Gravitational Wave Background (CGWB) using e.g. symmetrized-Sagnac mode in presence of other diffuse backgrounds



(bounds on graviton mass using LISA, from Wills and Yunes, 2004)

Challenges at the Instrument/Data Analysis Interface

- Time-Delay Interferometry
  - Significant results since last LISA Symposium (e.g. 2nd gen TDI)
- Noise characterization
  - What happens when we move away from “ideal” noise models?
  - Example: measurement of noise covariance from LISA data itself (e.g. Sylvestre and Tinto, 2003)
- Many other issues
  - Windowing (data gaps and spectral leakage issues)
  - Efficient calculation of LISA response functions with orbital modulation
  - Simulation
  - …

Status and Future Directions?

- Noteworthy progress since last LISA symposium
  - Source subtraction
  - Waveforms (EMRI)
  - Parameter estimations
  - Time-Delay Interferometry

Important for sensitivity, science requirements and objectives

- Priorities for additional work?
  - Parameter estimation
    - All TDI variables, large fraction of LISA orbit, different types of sources esp. high-frequency
  - CGWB quantification and limits
  - Quantitative tests of relativity
  - Continued work on waveforms

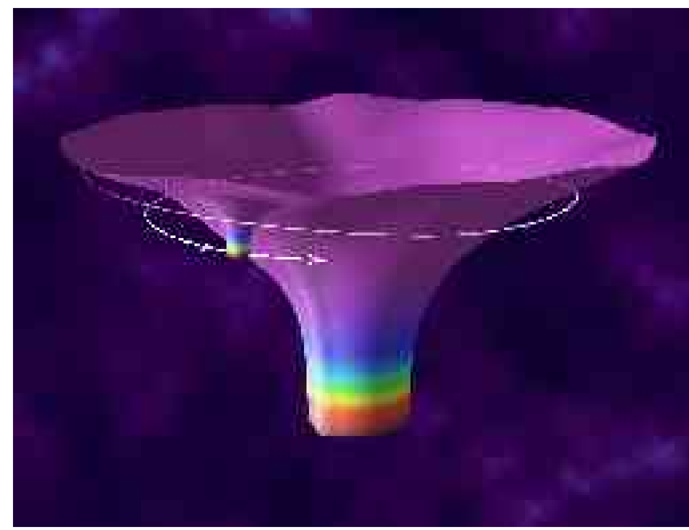
Important for further refinement of sensitivity, science requirements and objectives

Backup Slides

Extreme Mass Ratio Inspiral:
A Critical Issue (Challenges #1&2)

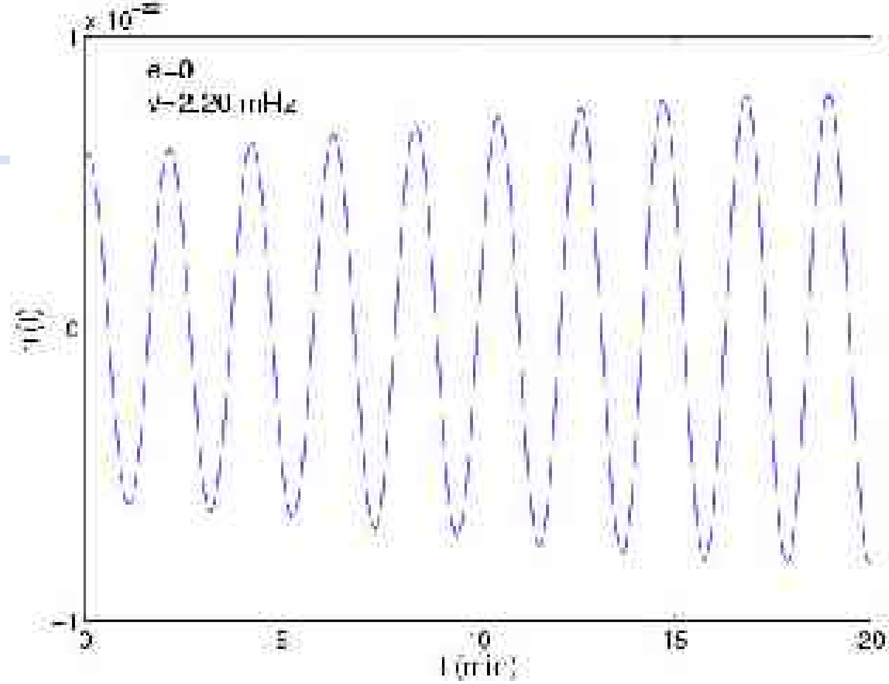
1. Predicting of waveforms from compact objects spiralling into supermassive black holes ($m/M < 10^{-4}$ limit)
   - First, approximate waveforms (1-2 yr timescale)
   - Then develop radiation reaction formalism to give exact waveforms (8 yr timescale)

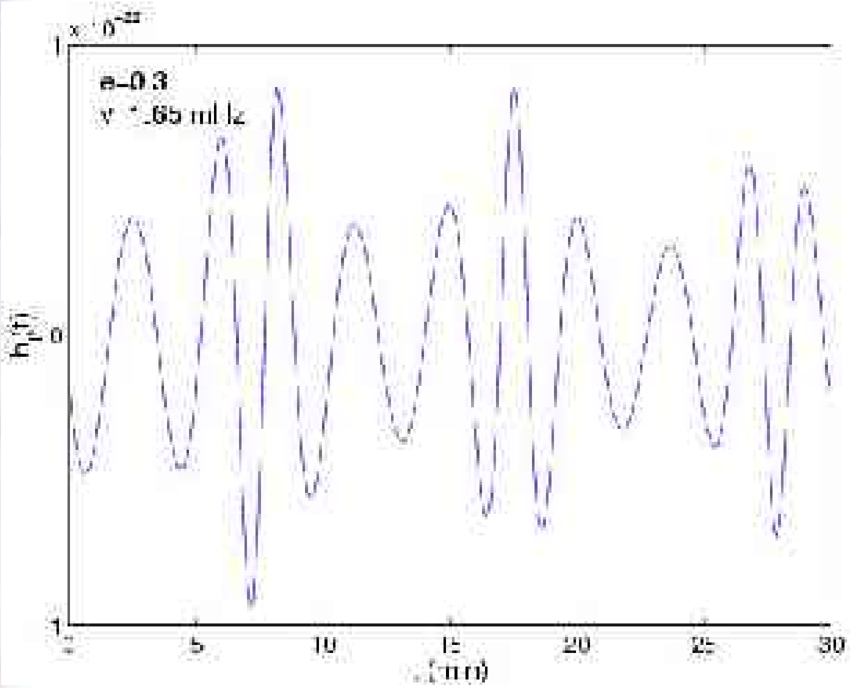
- How does the orbit of a compact object evolve as it spirals into a massive BH?
- What is its GW emission?
- How do we test GR with the 10^4 orbits that occur during inspiral?

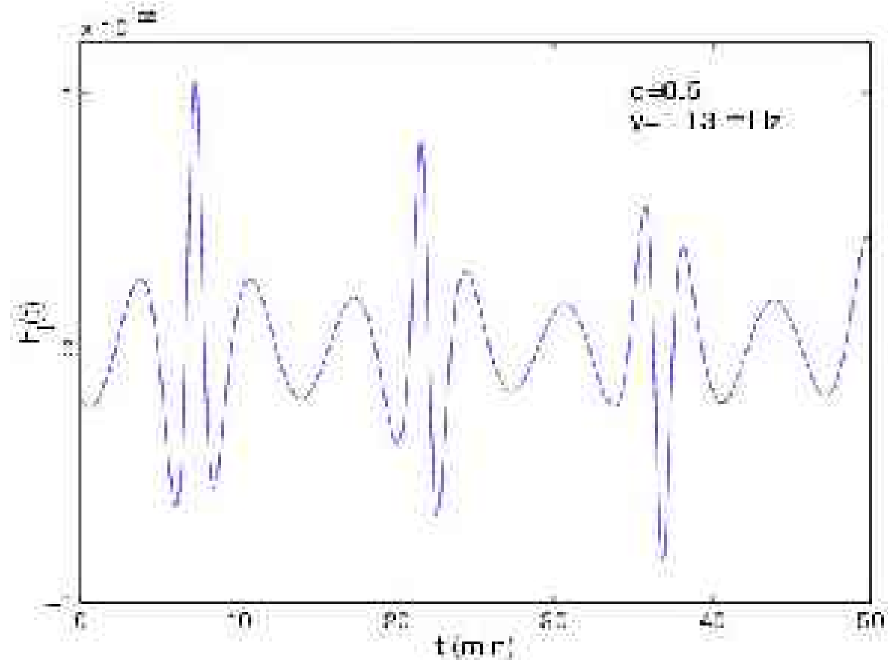


"Analytic Kludge" Waveforms

Short stretches of waveforms, for varying eccentricity.







[Barack and Cutler]

How big might *h* be for a typical LISA source?

- Use Newtonian/quadrupole approximation to Einstein Field Equations:

$$h \sim \frac{\Delta L}{L} \sim \frac{G}{c^4}\frac{\ddot{Q}}{r}$$

[$\ddot{Q}$ is the second time de

$$h \sim \frac{1}{c^2}\frac{4G\left(E_{kin}^{nonsphere}/c^2\right)}{r} \sim \frac{4GM_{equ}}{rc^2}$$

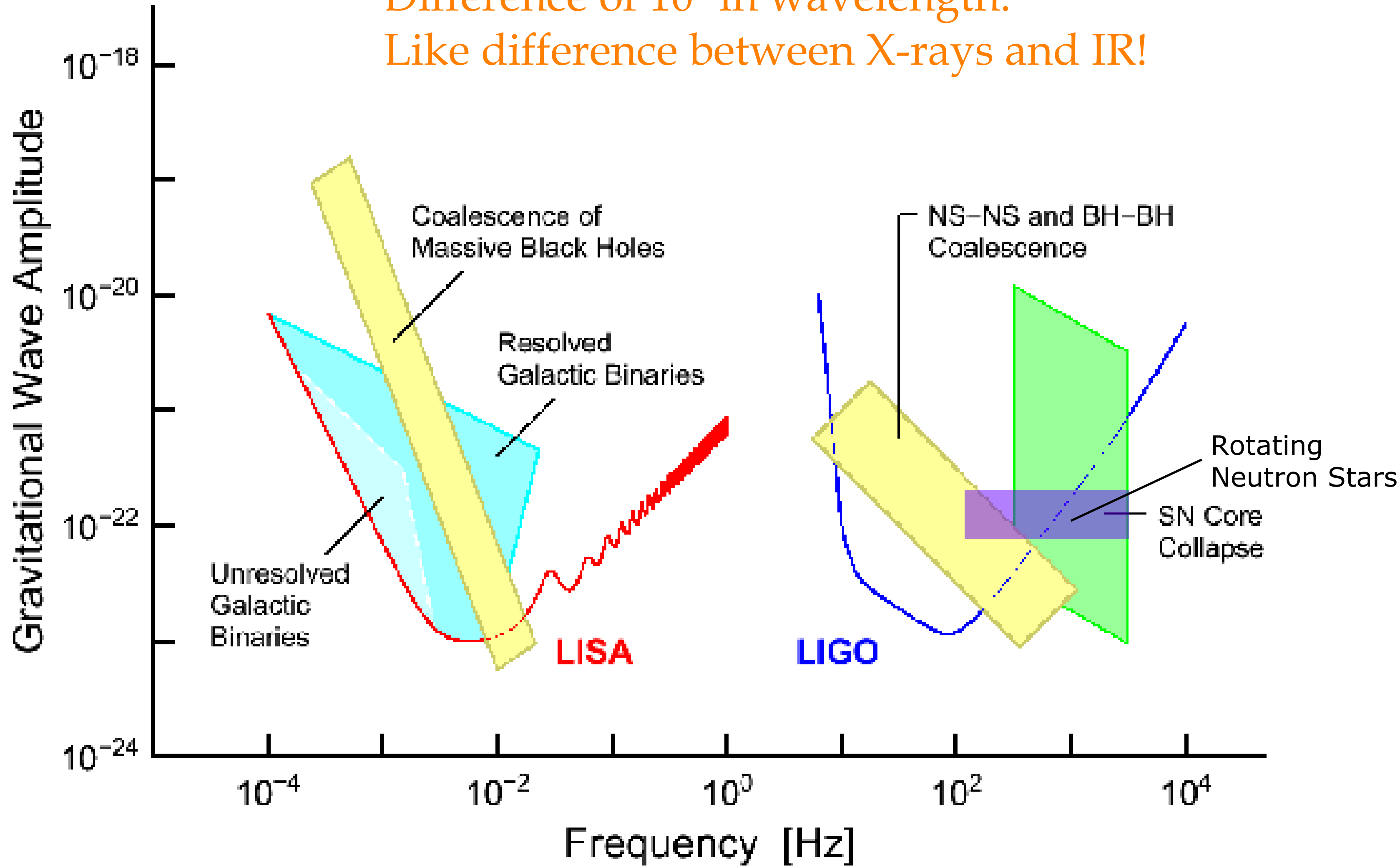
- *That is, h* is about 4 times the dimensionless gravitational potential at Earth produced by the mass-equivalent of the source's non-spherical, internal kinetic energy

⇒ $h \sim 10^{-18}$ for $10^6\ M_\odot$ BH merger at 10 Gpc

(Compare to typical 10^{-21} to 10^{-23} sensitivity of LISA)

Complementarity of Space- & Ground-Based Detectors

Difference of 10^4 in wavelength:
Like difference between X-rays and IR!



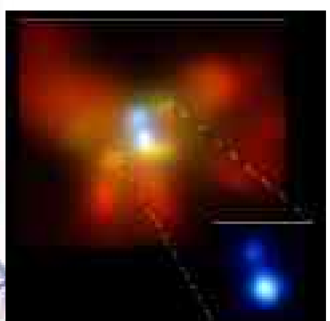
LISA Science Goals & Sources

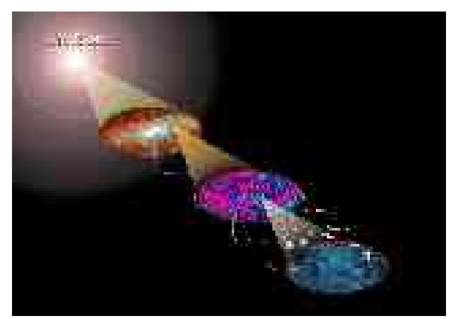
Science Objectives:

- Determine the role of massive black holes in galaxy evolution, including the origin of seed black holes
- Make precision tests of Einstein's Theory of Relativity
- Determine the population of ultra-compact binaries in the Galaxy
- Probe the physics of the early universe

Observational Targets:

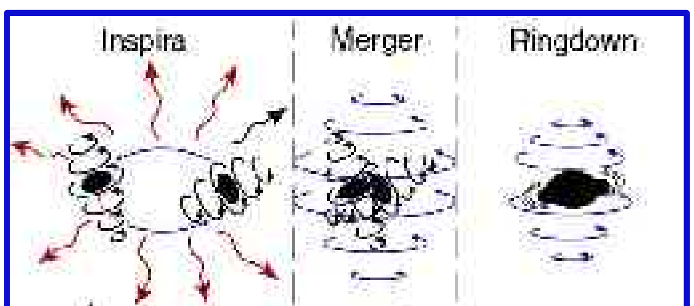
- Merging supermassive black holes
- Merging intermediate-mass/seed black holes
- Gravitational captures by supermassive black holes
- Galactic and verification binaries
- Cosmological backgrounds



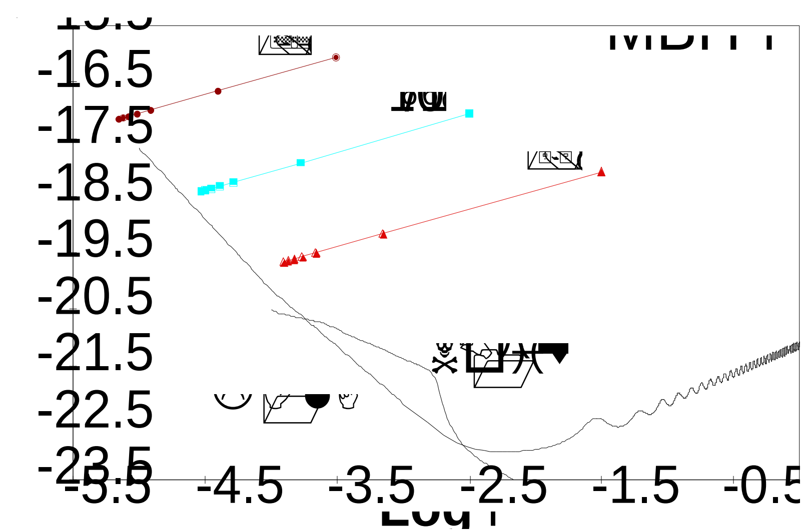


Massive Black Hole (MBH) Mergers

- MBH Mergers are a primary science objective of LISA
  - Fundamental Physics
    - Precision tests of dynamical non-linear gravity
  - Astrophysics
    - What is the role of MBH in galaxy evolution?
    - What fraction of galactic merger events result in an MBH merger?
    - When were the earliest MBH mergers?



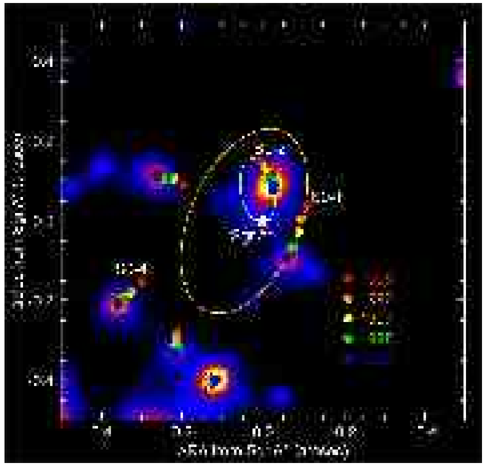
- Science Measurements
  - Comparison of inspiral waveform with prediction of numerical General Relativity
  - Rate of MBH merger vs redshift
  - Mass spectrum of MBHs in merger events
  - Spin of MBHs

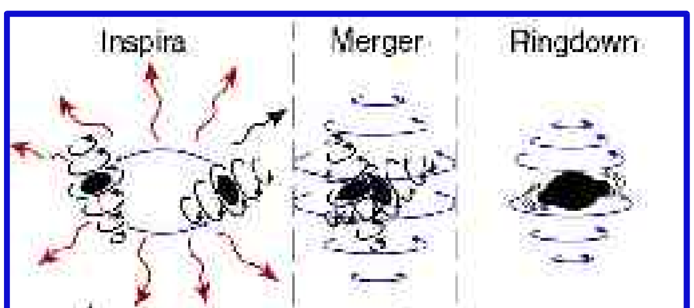


Compact Object Inspiral into a Supermassive BH

- Important Science Objective for LISA
- LISA signals expected to come primarily from low-mass (~10 $M_\odot$) BH inspiral into massive (~10^6 $M_\odot$) BH
- Potential to "map" spacetime of MBH as compact object spirals in (e.g. ~10^4 orbits available for mapping)
  - Distinguish between Kerr and alternate metrics ("no hair")
  - For Kerr, all multipoles parametrized by mass M_{BH} and spin a_{BH}
- Also measure astrophysical parameters
  - Masses, spins, distances, properties of nuclear star clusters
- Recent progress in estimating rates
  - Complications: Loss cones, stellar density, IMF, triaxiality, merger history, black hole mass function, etc.
  - Several per year are potentially detectable by LISA
    - Barack & Cutler, gr-qc/0310125
    - LISA WG1 EMRI Task Group: Barack, Creighton, Cutler, Gaier, Larson, Phinney, Thorne, Vallisneri (December, 2003)
  - Note: Capture and tidal disruption of stars may be common
    - X-ray observations (Komossa) suggest significant rate of compact object capture
    - News article in February 2004 on X-ray detection of disruption!

Summary: Physics with Massive Black Holes





Capture by Massive Black Holes

By observing 10,000 or more orbits of a compact object as it inspirals into a massive black hole (MBH), LISA can map with superb precision the space-time geometry near the black

Allows tests of many predictions of General Relativity including the “no hair” theorem

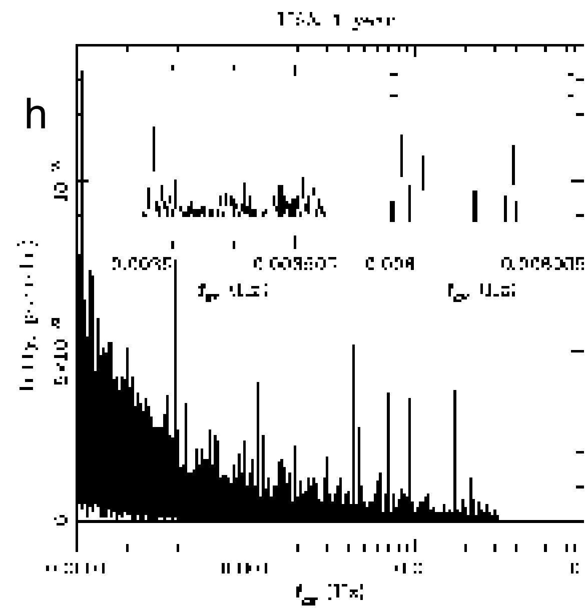
Mergers of Massive Black Holes

Massive black hole binaries produce gravitational waves in all phases of their evolution

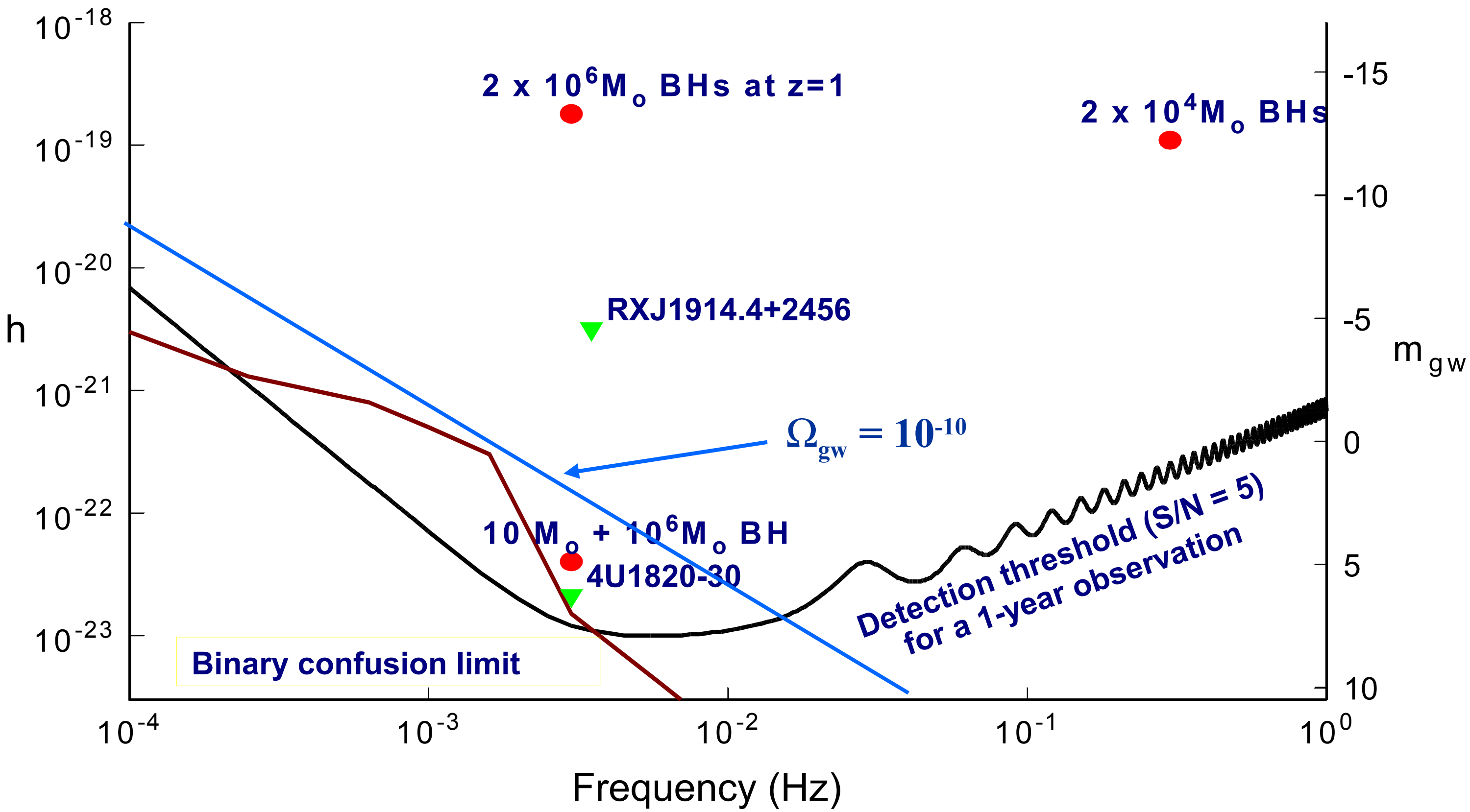
Signal-to-noise of 1000 or more allows LISA to perform precision tests of General Relativity at ultra-high field strengths

Galactic Binaries

- Galactic compact binaries are a "sure source" for LISA
  - Important both for science and for instrument performance verification
- LISA will observe distinguishable signals from ~10^4 binary star systems in the Galaxy + a background from an even larger population (10^8) of unresolved sources
- Below ~3 mHz (~650 second orbital period)
  - More than one binary per frequency bin for a 1 yr observation
  - Confusion noise background
- Above ~3 mHz
  - Resolved sources
  - Chirping sources for f >6 mHz => mass, distance, time to merger
  - Several known binaries (e.g. AM CVn) will be detected
- LISA will allow construction of a complete map of compact galactic binaries in the galaxy
- Studies include structure of WDs, interior magnetic fields, mass transfer in close WD systems, binary star formation history of galaxy



Landscape of LISA Data Analysis



(from Schutz)