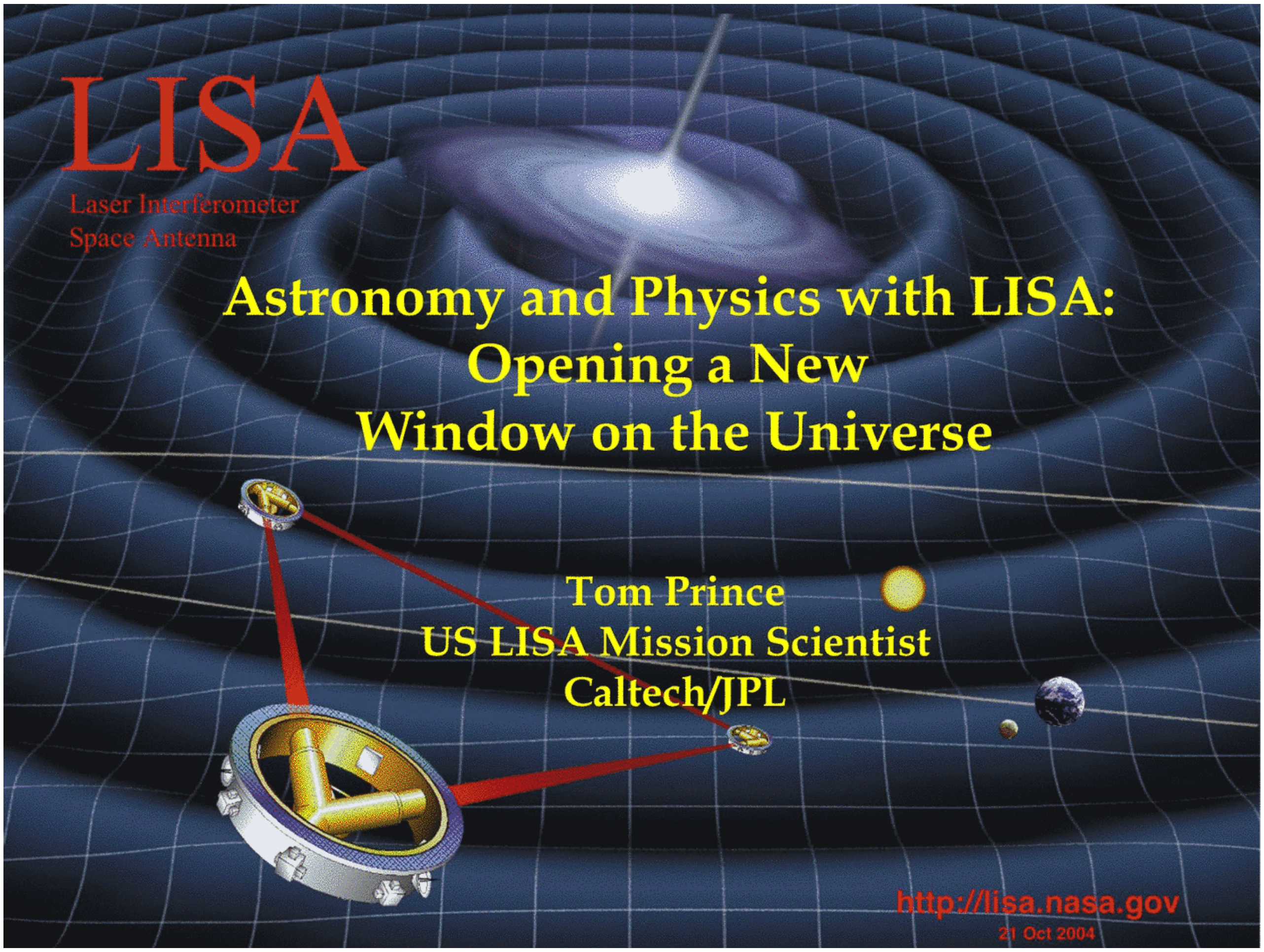


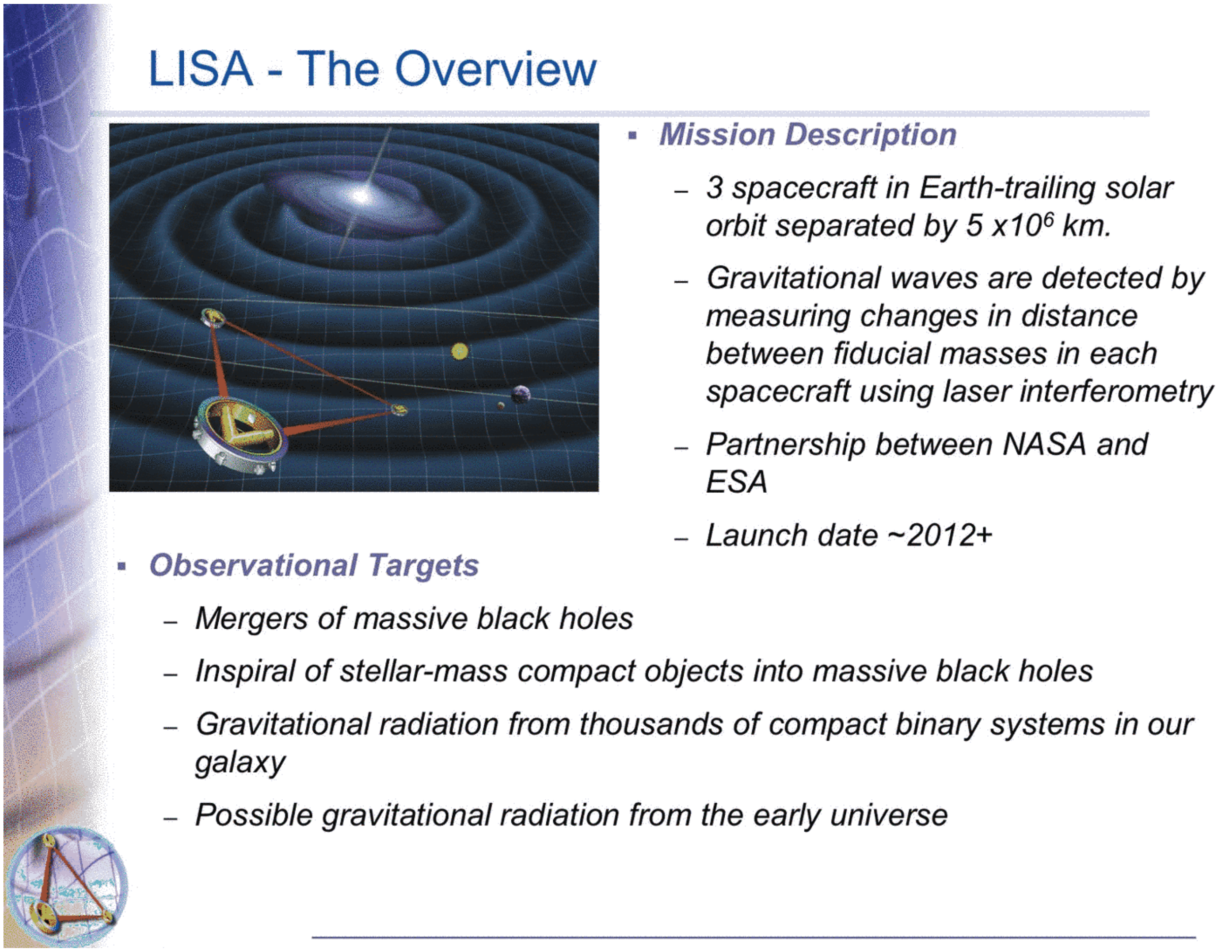
LISA

Laser Interferometer
Space Antenna

Astronomy and Physics with LISA: Opening a New Window on the Universe

Tom Prince
US LISA Mission Scientist
Caltech/JPL

http://lisa.nasa.gov
21 Oct 2004

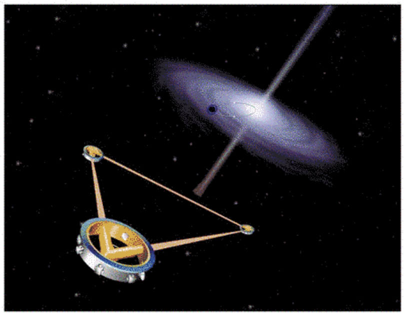


LISA - The Overview

- *Mission Description*
  - *3 spacecraft in Earth-trailing solar orbit separated by 5 x10^6 km.*
  - *Gravitational waves are detected by measuring changes in distance between fiducial masses in each spacecraft using laser interferometry*
  - *Partnership between NASA and ESA*
  - *Launch date ~2012+*
- *Observational Targets*
  - *Mergers of massive black holes*
  - *Inspiral of stellar-mass compact objects into massive black holes*
  - *Gravitational radiation from thousands of compact binary systems in our galaxy*
  - *Possible gravitational radiation from the early universe*

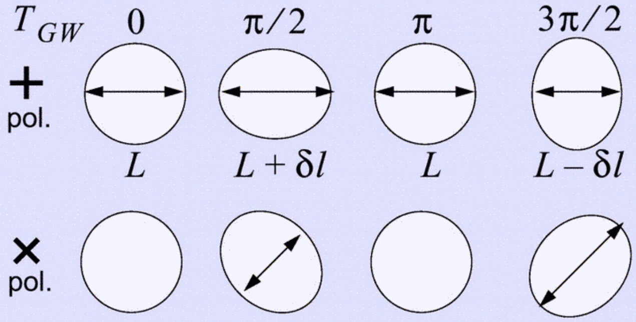
This Talk:

- Characteristics of gravitational waves and gravitational wave sources
- LISA mission concept
- LISA science capabilities
- LISA status

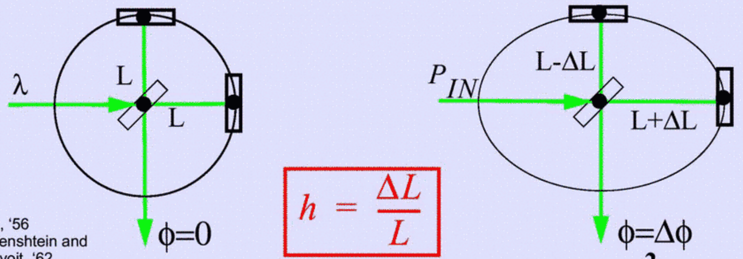


Gravitational Waves

❑ **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

(N. Mavalvala)

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

- Use Newtonian/quadrupole approximation to Einstein Field Equations:

$$h = \frac{\Delta L}{L} \sim \left(\frac{G}{c^4}\right)\frac{\ddot{Q}}{r}$$

[$\ddot{Q}$ is the second time derivative of the source mass quadrupole]

$$h \sim \frac{1}{c^2}\,\frac{4G(E_{kin}^{non-sphere}/c^2)}{r} \sim \frac{4GM_{equiv}}{rc^2}$$

- *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

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

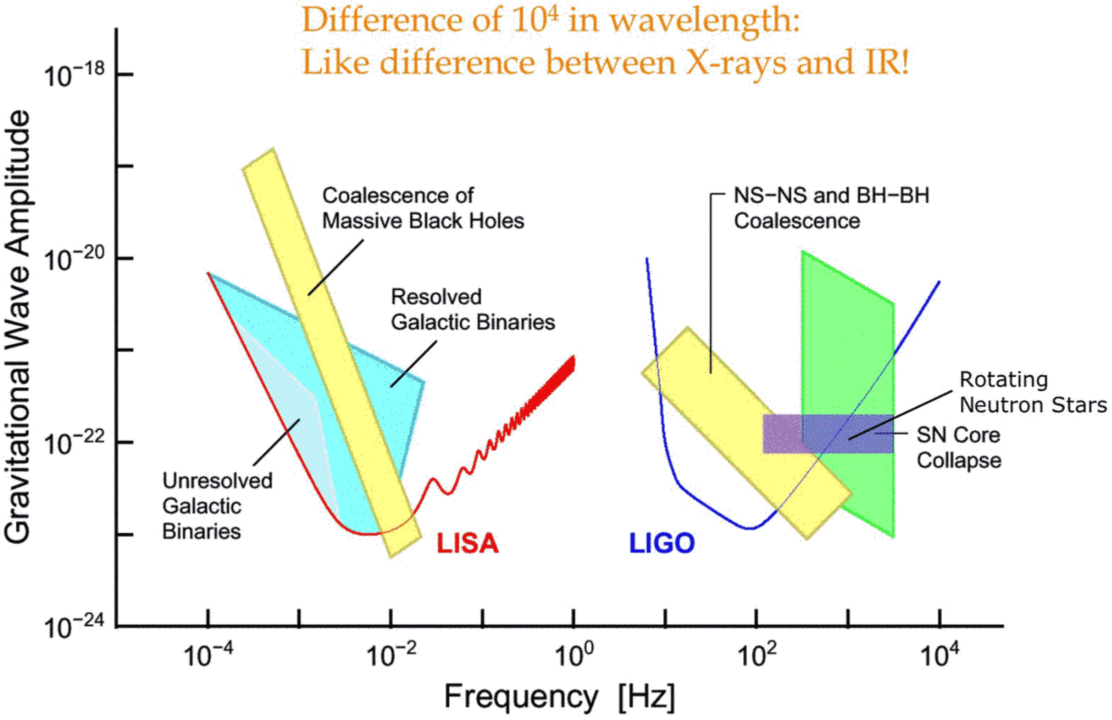
(Compare to typical 10^{-21} to 10^{-23} sensitivity of LISA)

Ground-based Gravitational Wave Detectors

- LIGO, VIRGO, GEO, TAMA … ca. 2003
  - 4000m, 3000m, 2000m, 600m, 300m interferometers built to detect gravitational waves from compact objects

Complementarity of Space- & Ground-Based Detectors

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



This Talk:

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- ➢LISA mission concept
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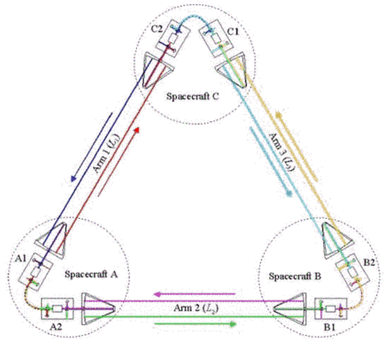
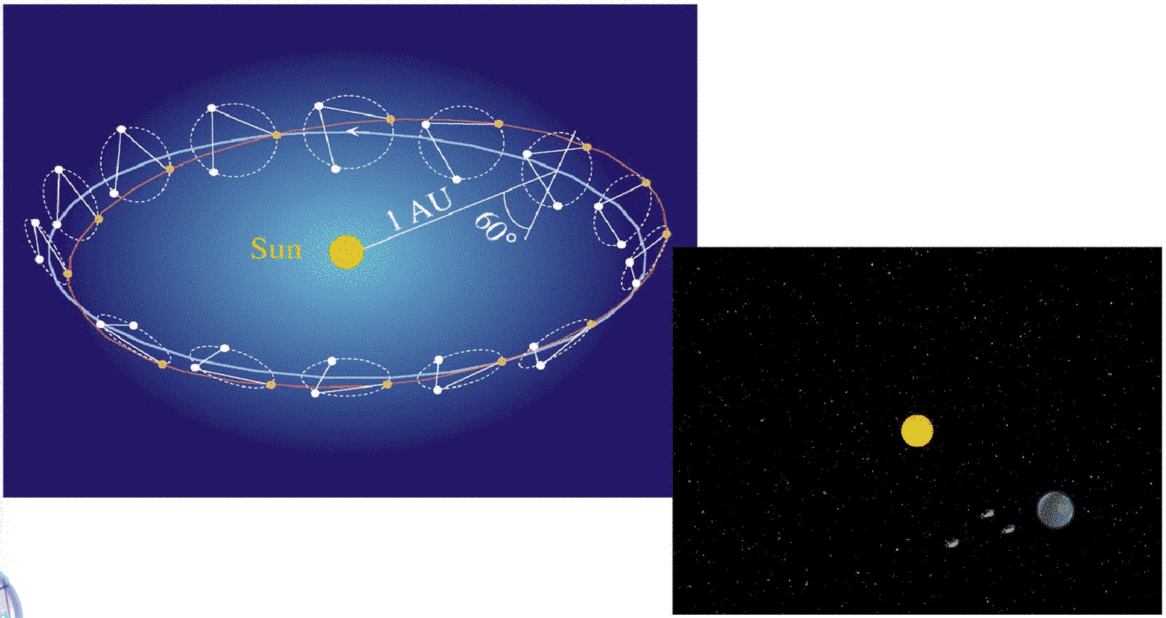


Orbits

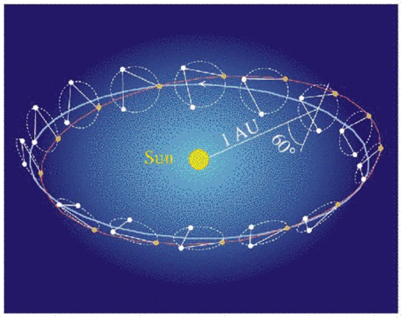
- *Three spacecraft in triangular formation; separated by 5 million km*
- *Spacecraft have constant solar illumination*
- *Formation trails Earth by 20°; approximately constant arm-lengths*



1 AU = 1.5x10^8 km

Determining Source Directions

- Directions (to about 1 degree) : 2 methods: AM & FM
- FM: Frequency modulation due to LISA orbital doppler shifts
  - Analagous to pulsar timing over 1 year to get positions
  - FM gives best resolution for f > 1 mHz
- AM: Amplitude modulation due to change in orientation of array with respect to source over the LISA orbit
  - AM gives best resolution for f < 1 mHz
- Summary: LISA will have degree level angular resolution for many sources (sub-degree resolution for strong, high-frequency sources)
  - See e.g. Cutler (98), Cutler and Vecchio (98), Moore and Hellings (00), also Hughes (02)



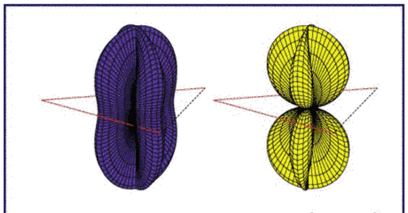


Figure 3. The magnitudes of the detector response functions $F^+(\hat{\Omega}, f)$ and $F^\times(\hat{\Omega}, f)$ in the low frequency limit.

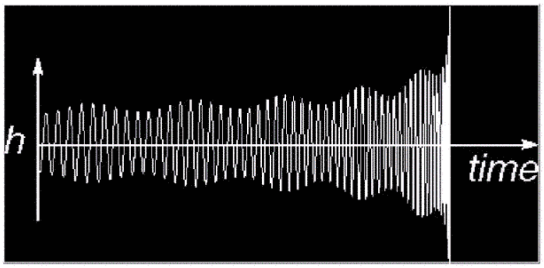
(Cornish and Larson, '01)

Determining Source Distances

- Distances(to about 1%)
- Binary systems with orbital evolution (df/dt)
  - "Chirping" sources
  - Determine the luminosity distance to the system by comparing amplitude, *h*, and period derivative, *df/dt*, of the gravitational wave emission
  - Quadrupole approximation:

$$h \propto \frac{M_{Chirp}^{5/3}}{D_L} f^{2/3}$$

$$\dot{f} \propto M_{Chirp}^{5/3} f^{11/3}$$



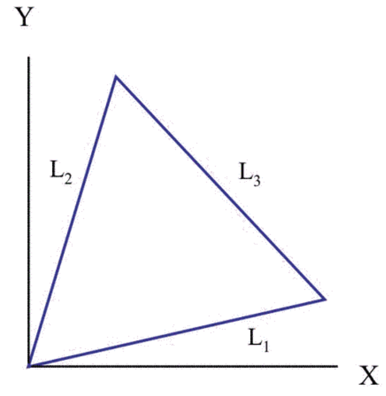
- Luminosity distance (D_L) can be estimated directly from the detected waveform
- See e.g. work by Hughes, Vecchio for quantitative estimates

Determining Polarization

- LISA has 3 arms and thus can measure both polarizations

$$\frac{\delta(L_3 - L_1)}{L} = \frac{\sqrt{3}}{4}\left(H_{XX} - H_{YY}\right) = \frac{\sqrt{3}}{2} h_+$$

$$\frac{\delta(2L_2 - L_3 - L_1)}{L} = \frac{\sqrt{3}}{4}\left(H_{XY} - H_{YX}\right) = \frac{\sqrt{3}}{2} h_\times$$

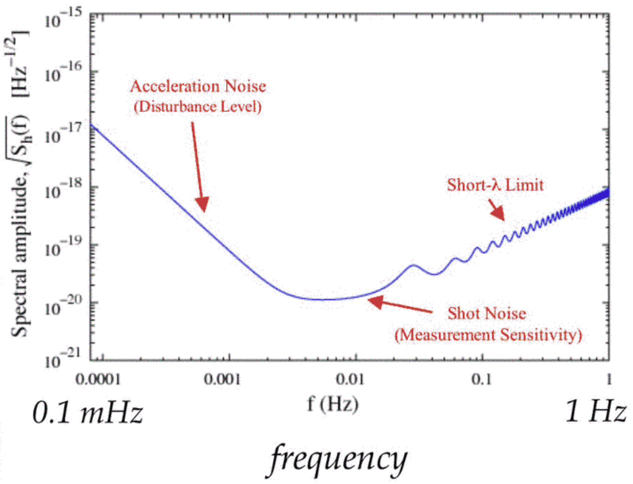


(notation from Cutler,Phinney)

- Gram-Schmidt orthogonalization of combinations that eliminate laser frequency noise yield polarization modes
  - Paper by Prince et al. (2002)
    - gr-qc/0209039

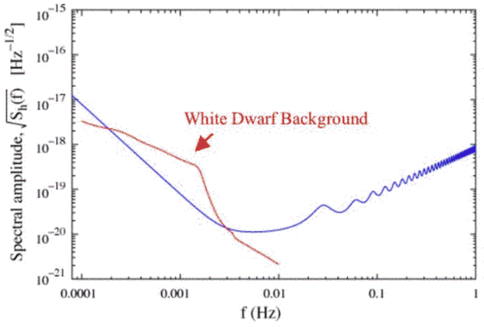
LISA Sensitivity

2-arm “Michelson” sensitivity $\left(h * \sqrt{T_{obs}}\right)$

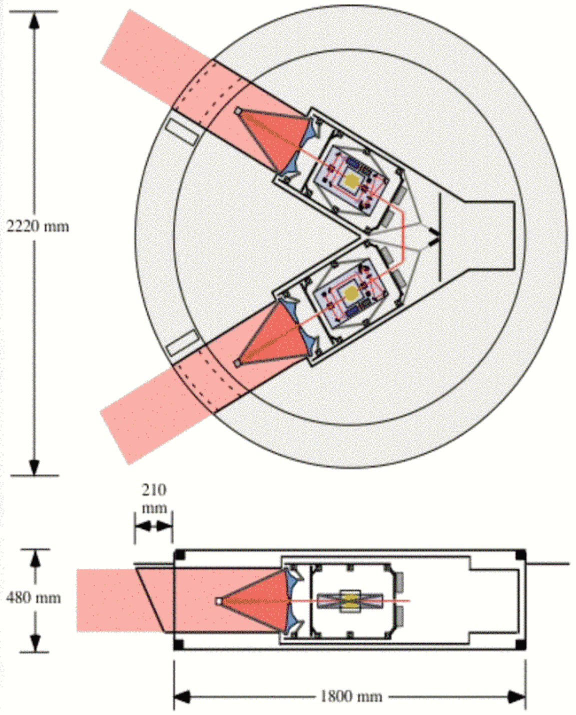


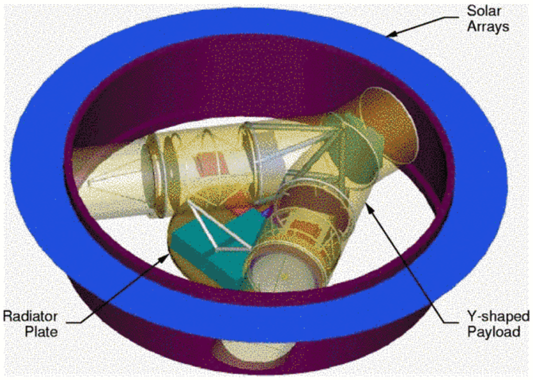
(Includes gravitational wave transfer function averaged over sky position and polarization). Source sensitivities plotted as *h×Sqrt(Tobs)*.

2-arm “Michelson” sensitivity +
White Dwarf binary background



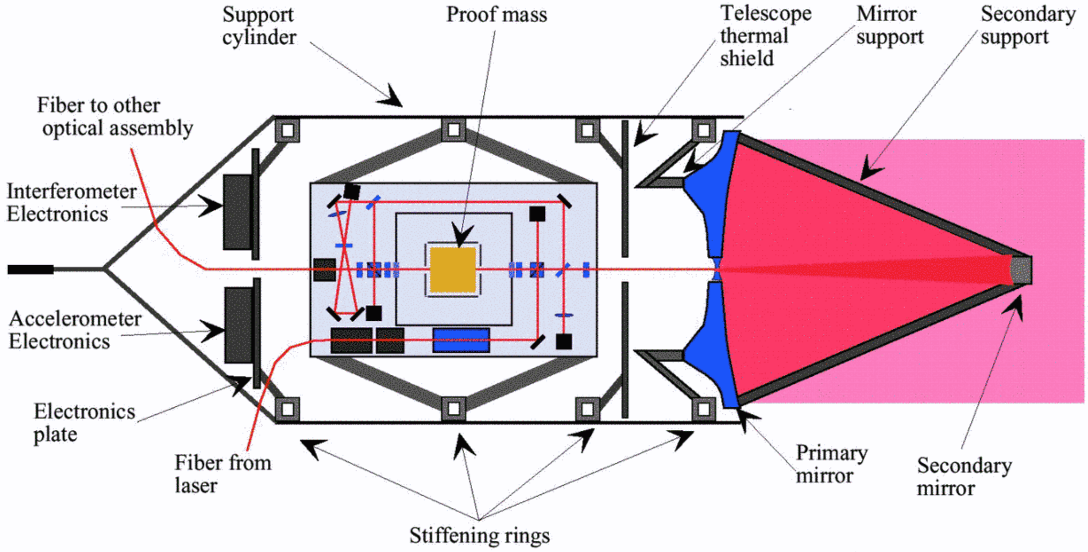
Spacecraft



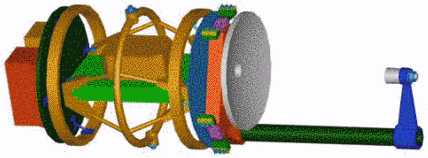


- ***Two optical assemblies***
  - *Proof mass and sensors*
  - *30 cm telescope*
  - *Interferometry: 20 pm/√Hz*
  - *1 W, 1.06 μ Nd:YAG lasers*
- ***Drag-free control***
  - *Positioning to 10 nm/√Hz*
  - *Attitude to 3 nrad/√Hz*

Payload

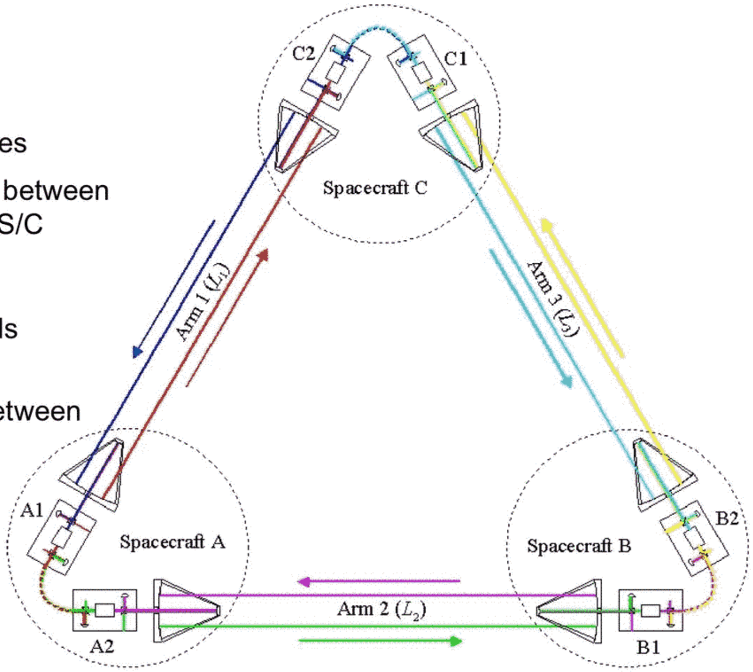


(Acceleration Noise ~ 3 x 10^{-15} (m/s^2)/Hz$^{-1/2}$)



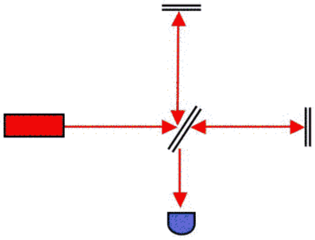
LISA Interferometry

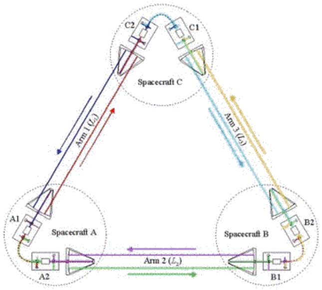
- Components
  - 1 W lasers
  - 30 cm telescopes
  - Drag-free proof masses
  - Optical fiber coupling between assemblies on same S/C
- Measurements
  - 6 laser Doppler signals between S/C
  - 6 reference beams between S/C assemblies



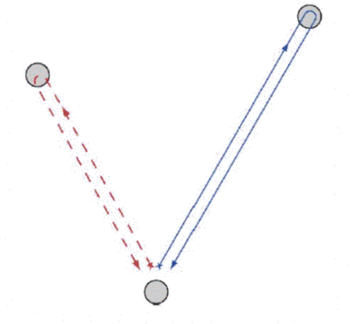
LISA Interferometry

- “LISA is essentially a Michelson Interferometer in Space”
- However
  - No beam splitter
  - No end mirrors
  - Arm lengths are not equal (as much as 10,000 km difference)
  - Arm lengths change continuously (1 m/s)
  - Light travel time ~17 seconds
  - Constellation is rotating and translating in space



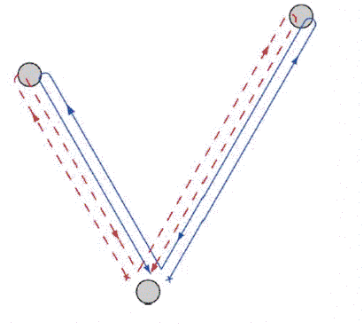


Time Delay Interferometry (TDI)



Unequal-arm Michelson interferometer

•Output corrupted by laser frequency noise



Equal-arm (Sagnac) interferometer (TDI combination X)

•Output immune to laser frequency noise

- Intrinsic phase noise of laser must be canceled by a factor of up to 10^9 in amplitude
- Because the arm lengths are not equal, the laser phase noise will not cancel as it does in an equal-arm Michelson
- Solution: record beat signal of each received laser beam relative to an onboard reference. Delay recorded signals relative to each other and subtract in proper (TDI) combinations.

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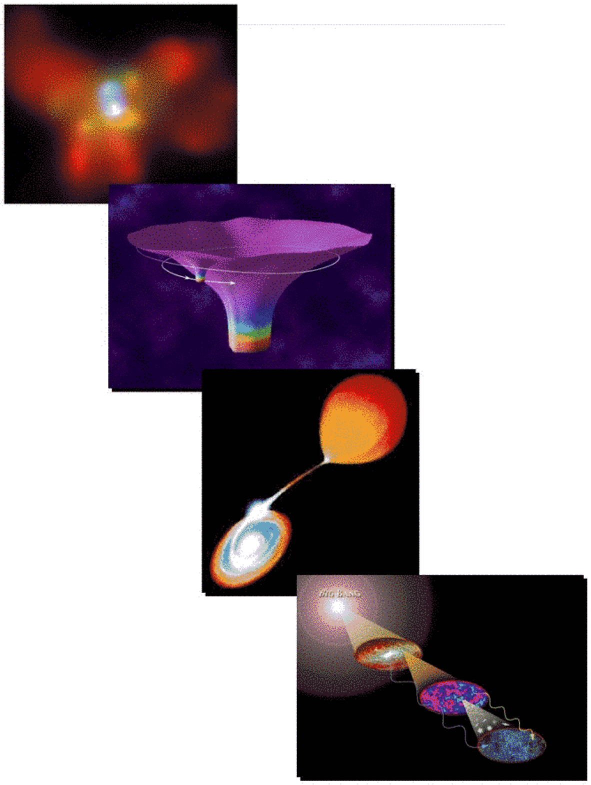


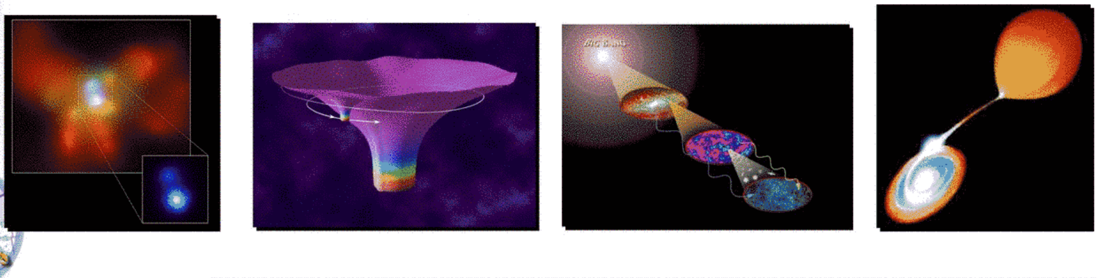
LISA Science Goals & Sources

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



LISA Science: Massive Black Holes

- Two primary classes of BH studies
  - Massive Black Hole Mergers
    - Merger of 2 massive BHs following galaxy merger
    - Merger of Intermediate Mass BH (IMBH) with SuperMassive BH (SMBH)
  - Extreme Mass Ratio Inspirals (EMRI)
    - Capture of stellar-mass compact object by Massive BH (e.g. 10 $M_\odot$x10^6 $M_\odot$)
- Mergers: Key Issues for detection
  - MBH mass spectrum (IMBH and SMBH)
  - Galaxy merger rates
- Capture events: Key Issues for detection
  - Rate of capture events involving massive black holes in galactic nuclei
  - LISA detection of extreme mass ratio inspiral

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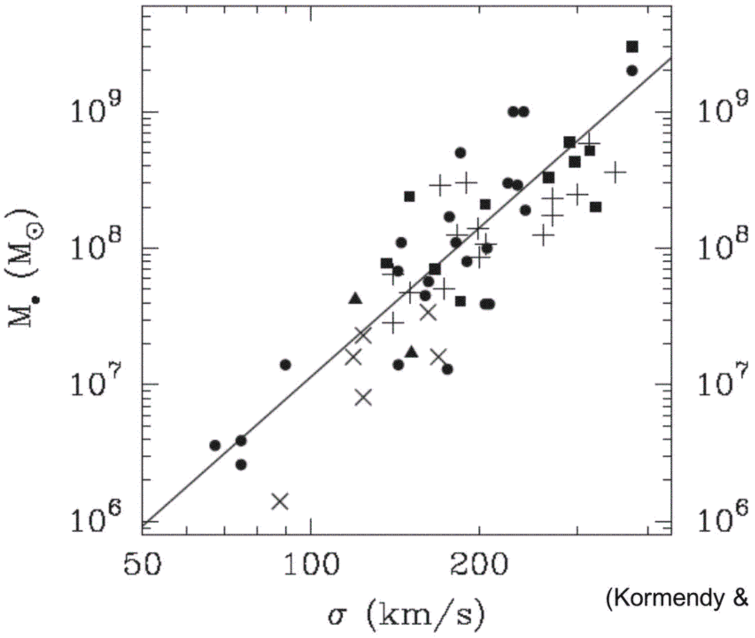
1) Massive Black Hole Mergers

Are Massive Black Holes Common in Galactic Nuclei?

BH Mass vrs Bulge Velocity Dispersion

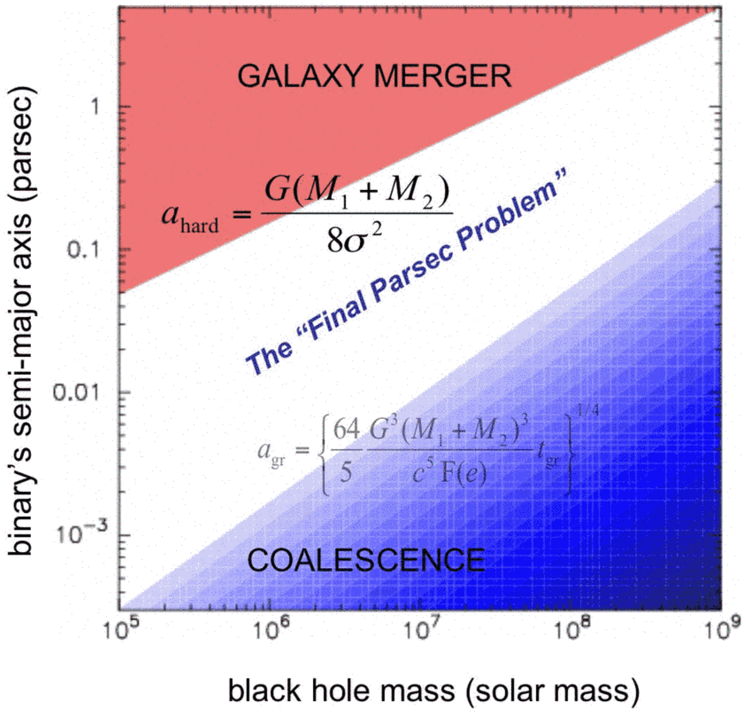


(Kormendy & Gebhardt, 01)

(New result from Greene and Ho, 2004: sample of 19 AGN with BH masses between 10^5 and 10^6 $M_\odot$)

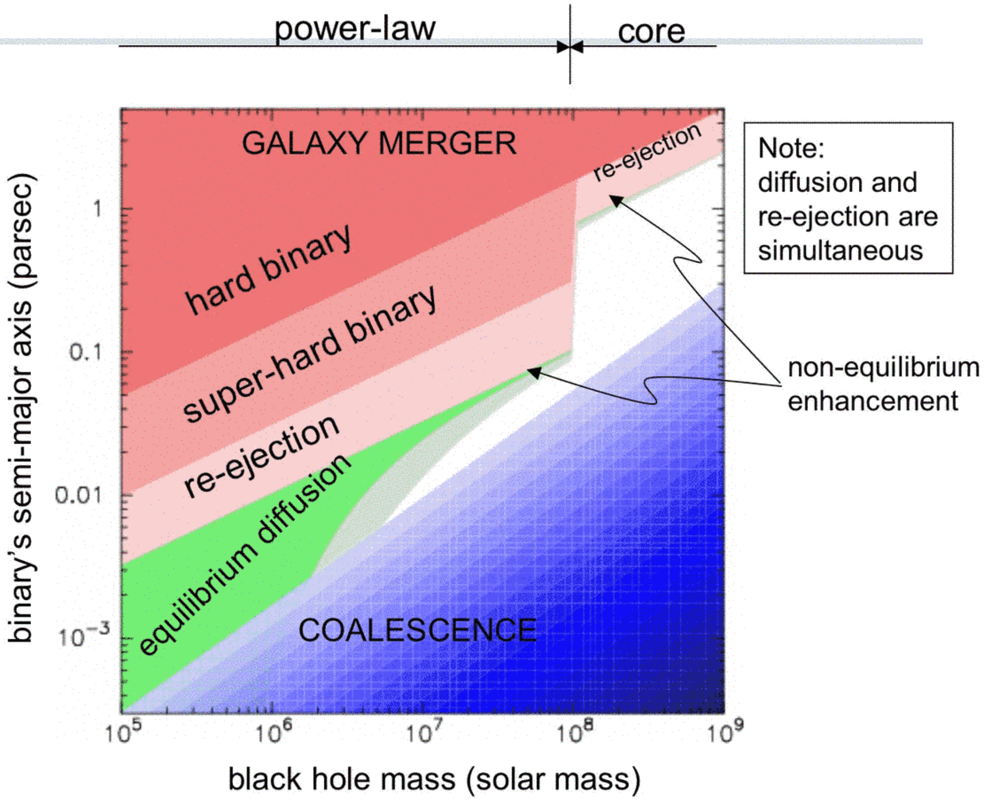
But do they merge?

Do Massive BH Binaries Merge?



(Adapted from Milosavljevic, '02)

The "Last Parsec Problem"



Note:
diffusion and
re-ejection are
simultaneous

(Adapted from Milosavljevic, '02)

Rate Estimates for Massive Black Hole Mergers

- Use hierarchical merger trees
- Rate estimates depend on several factors
  - In particular space density of MBHs with $M_{BH}<10^6 M_\odot$
  - Depends on assumptions of formation of MBHs in lower mass structures at high-z
- Some recent estimates
  - Sesana et al. (2004): about 1 per month
  - Menou (2003): few to hundreds per year depending on assumptions
  - Haehnelt (2003): 0.1 to 100 per year depending on assumptions

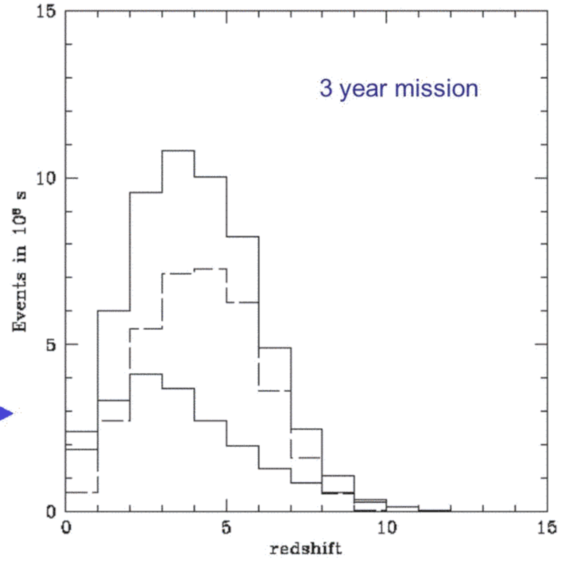
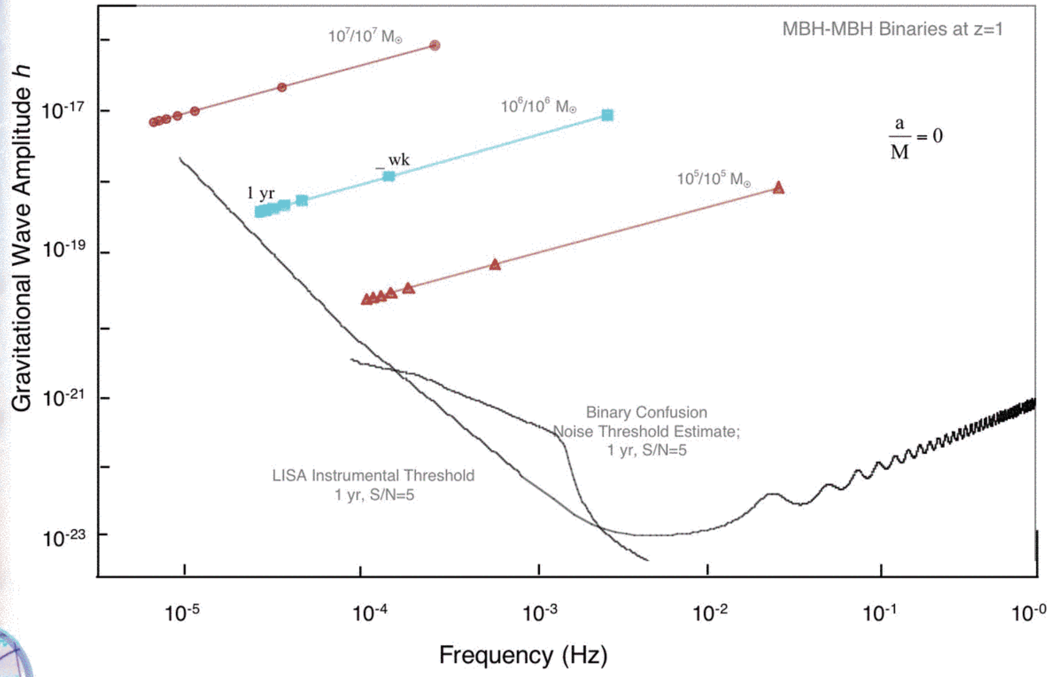


FIG. 8.— Number of events per unit redshift interval resolved by *LISA* with $S/N > 5$ in 10^8 secs. *Thick-solid histogram:* total number of events in 10^8 secs. *Solid histogram:* number of stationary events. These events are of much longer duration compared to the mission lifetime. *Dashed histogram:* number of bursts in 10^8 secs. These events are of short duration compared to the mission lifetime.

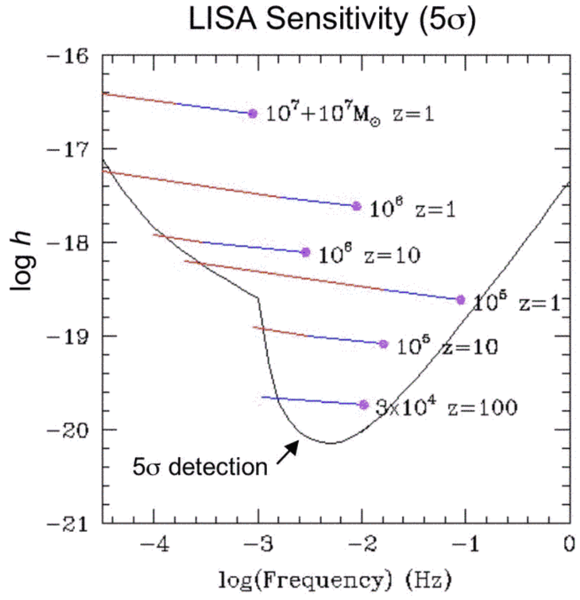
[Sesana et al, astro-ph/0401543]

Can LISA Detect Massive Black Holes Mergers?



LISA Capabilities for Intermediate-Mass BHs

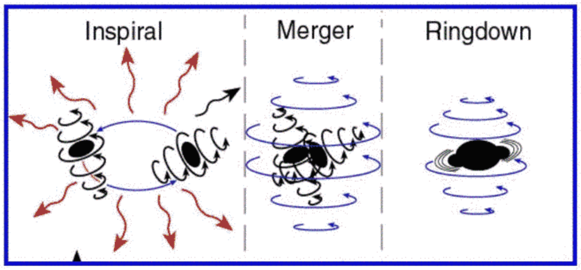
- How did the $>10^6 M_\odot$ black holes we see today arise?
  - What were the masses of the "seed" black holes?
- Do black holes exist in significant numbers in the mass range: $10^2 M_\odot < M_{BH} < 10^6 M_\odot$?
- LISA capabilities
  - Maximum frequency scales roughly inverse to mass
  - ⇒ Intermediate-mass BH mergers at high redshift can be in optimal LISA sensitivity band


LISA Sensitivity (5σ)

(From Phinney)

Summary: Massive Black Hole (MBH) Mergers

- Science Measurements
  - Comparison of merger, and ringdown waveforms with predictions of numerical General Relativity
  - Number of mergers vs distance
  - Mass distribution of MBHs in merger events (masses to ~10^{-4} accuracy)
  - Spin of MBHs
- MBH Mergers
  - Fundamental Physics
    - Precision tests of dynamical non-linear gravity
  - Astrophysics
    - What fraction of galactic merger events result in an MBH merger?
    - When were the earliest MBH mergers?
    - How do MBHs form and evolve? Seed BHs?



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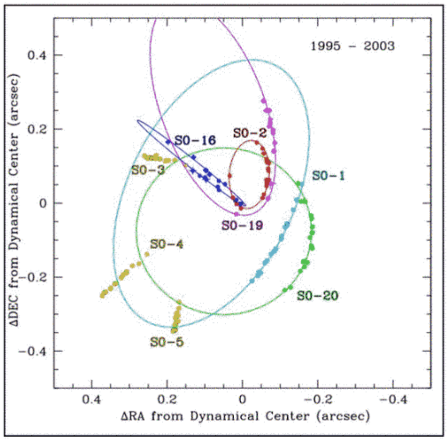
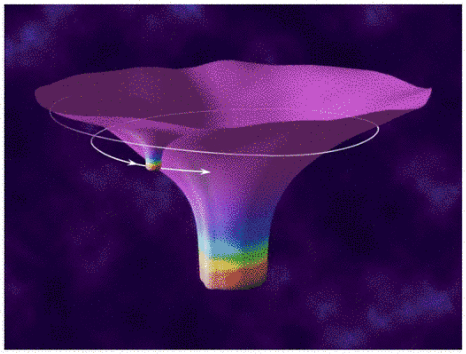
2) Extreme Mass Ratio Inspirals (Gravitational Capture Events)



Extreme Mass Ratio Inspiral: Key Issues

- What is the rate of compact object capture by MBH in galactic nuclei?
- How does the orbit of a compact object evolve as it spirals into a massive BH?
- What are the GW waveforms?
- Can the complex GW waveforms be detected by LISA?
- Can other backgrounds be subtracted (e.g. binary white dwarf systems)?
- How do we test GR with the ~10^5 orbits that occur during inspiral?



Typical EMRI event: 10 $M_\odot$ BH captured by 10^6 $M_\odot$ BH

Significant progress on many of these issues during the last year

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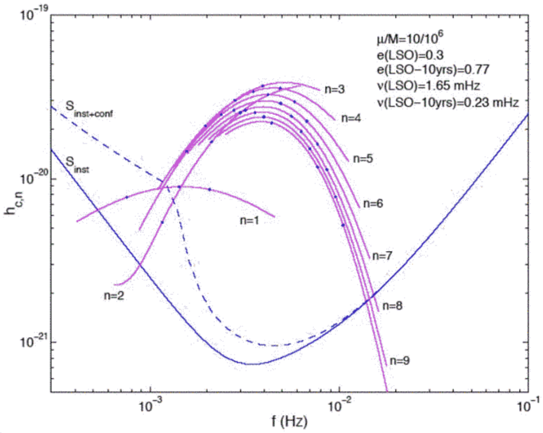
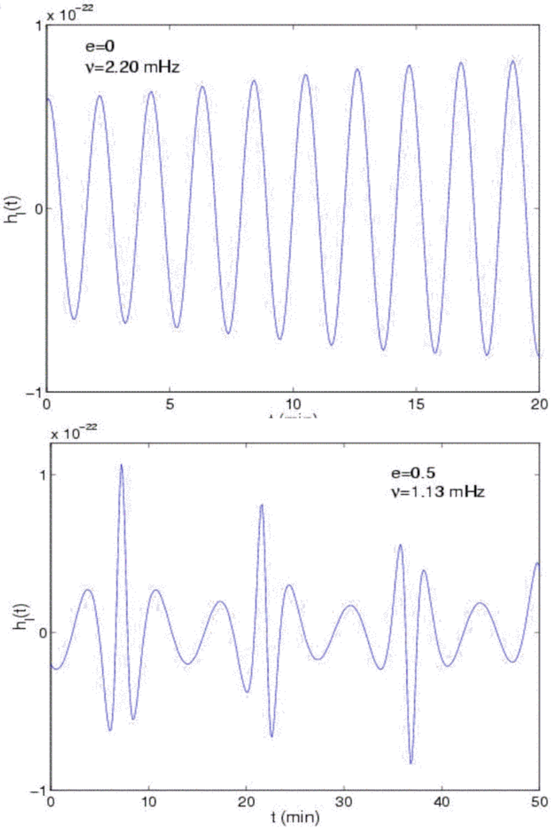
Estimating Waveforms

Temporal and harmonic content of approximate waveforms





[Barack and Cutler, 2003]

Extreme Mass Ratio Inspiral Detection Estimates

- Takes into account
  - MBH space density estimates
  - Monte Carlo results on capture rates scaled to range of galaxies
  - Approximate waveforms
  - Subtraction of binary background
  - Computational limits in number of templates
    - Assumes multi-Teraflop computer
    - 3 week coherent segments
- Results
  - LISA sensitivity degraded by about x2 with respect to optimal => reduction of x10 in detection rates
  - Largest rate from stellar-mass BHs captured by ~10^6 Msol MBHs
  - Predict hundreds of inspirals over LISA lifetime

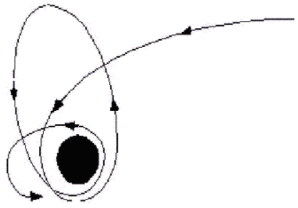
Estimated Total Number of Detected Events

$M_\bullet$	m	LISA	
		Optimistic	Pessimistic
300 000	0.6	8	0.7
300 000	10	739	89
300 000	100	1*	1*
1 000 000	0.6	94	9
1 000 000	10	1000*	800
1 000 000	100	1*	1*
3 000 000	0.6	67	2
3 000 000	10	1700*	134
3 000 000	100	2*	1*

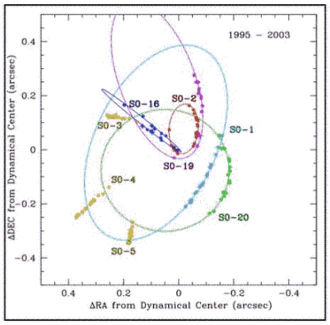
Optimistic: 5 years/3 arms/ideal subtraction
Pessimistic: 3 years/2 arms/gClean subtraction

[Phinney et al., 2003]

Summary: Extreme Mass Ratio Inspiral



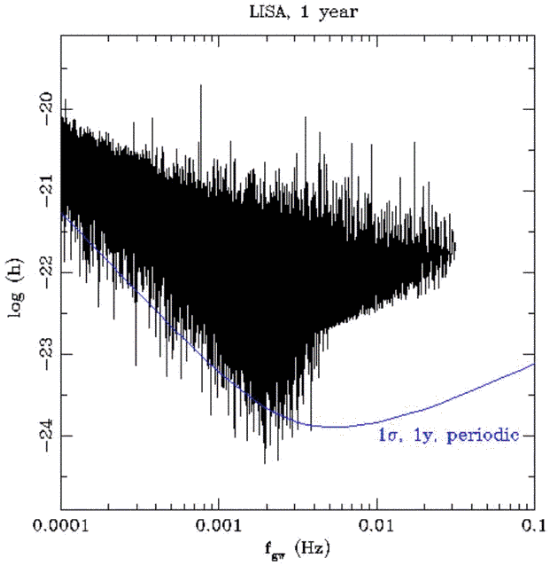
- LISA signals expected to come primarily from low-mass (~10 $M_\odot$) BH inspiral into massive (~10^6 $M_\odot$) BH
- Potential to "map" spacetime of MBH as compact object spirals in (e.g. ~10^5 orbits available for mapping)
- Study properties of nuclear BHs and their associated star clusters
  - Masses, spins, distances, population of nuclear star clusters
- Recent progress in estimating detection rates
  - Several per month 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 suggest significant rate of compact object capture (February 2004 news article on disruption event - RX J1242.6-1119A; Komossa et al., 2004)

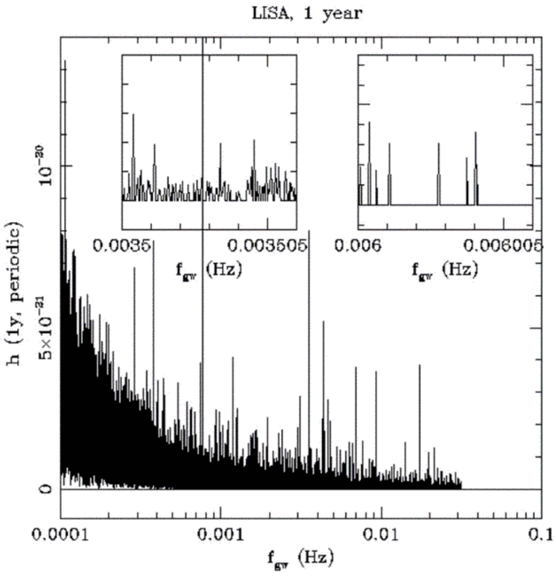


3) Ultra-Compact Binaries in the Galaxy

Galactic Binary Sources and Background

- LISA will observe distinguishable signals from ~10^4 binary star systems in the Galaxy + a background from an even larger population of unresolved sources

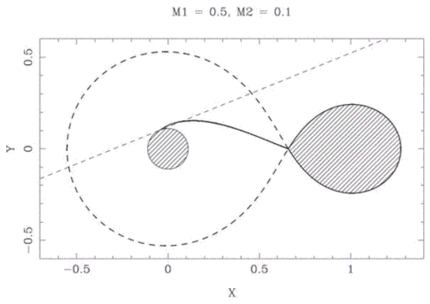




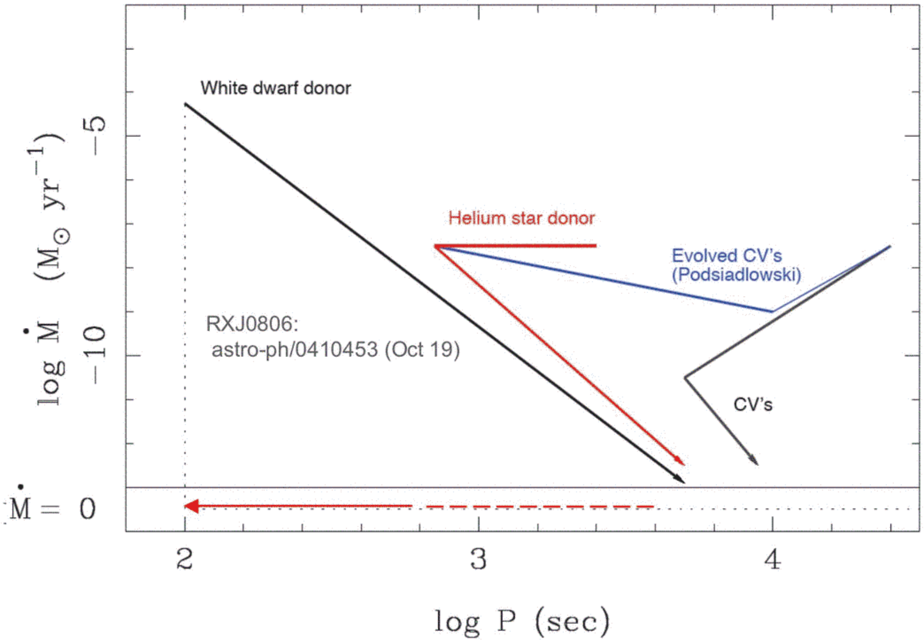
Monte-Carlo simulation of the gravitational-wave signals from galactic binaries with periods less than 1 hour. The right-hand plot has a linear scale for the signal amplidude; insets show expanded (in frequency) views of narrow-band regions near 3 mHz and 6 mHz. (Phinney)

Formation Scenarios for ultra-compact binaries

- Observationally seen as LMXBs or AM CVn systems
- Evolution through common envelope phase(s), but progenitors and evolutionary paths still uncertain
- Several possible progenitors/scenarios
  - White dwarf secondary + (wd,ns,or bh)
  - Semi-degenerate He star + (wd, ns, or bh)
  - CVs with evolved donors
- Systems observed via mass transfer
  - White dwarf primary (AM CVn systems)
  - NS or BH primary (ultra-compact X-ray binary)



Mass-transfer Binaries



LISA will detect binaries with and w/o mass transfer

(From Nelemans, '03)

Estimate of systems observable with LISA

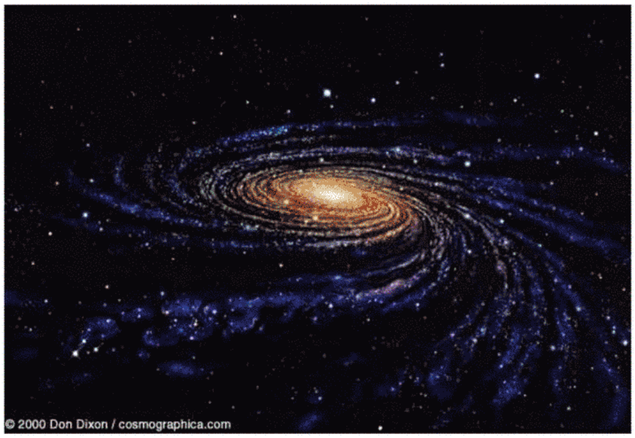
- Estimate from Nelemans et al

Change	Mass Xfer?	Resolved	Frequency
(wd,wd)	No	12163	560
AM CVn	Yes	10117	49
Compact XRB	Yes	37	0
(ns,wd)	No	21	3
(ns,ns)	No	1	0
(bh,wd)	No	1	0
(bh,ns)	No	0	0

( ) = detached

Summary: Ultra-compact Binary Studies with LISA

- LISA will observe over 10,000 individual compact binaries
  - Explore evolutionary pathways in considerable detail
  - Large sample of both detached systems & Roche-lobe filling
- LISA will observe a frequency derivative (fdot) for the few thousand highest frequency binaries
  - Get chirp masses and distances (plus period, inclination, etc.)
  - 3D obscuration-free map of galaxy (LISA will see all such sources)
  - New types of sources, e.g.
    - WDs with strong internal magetic fields
    - WDs with tidal excitation and dissipation



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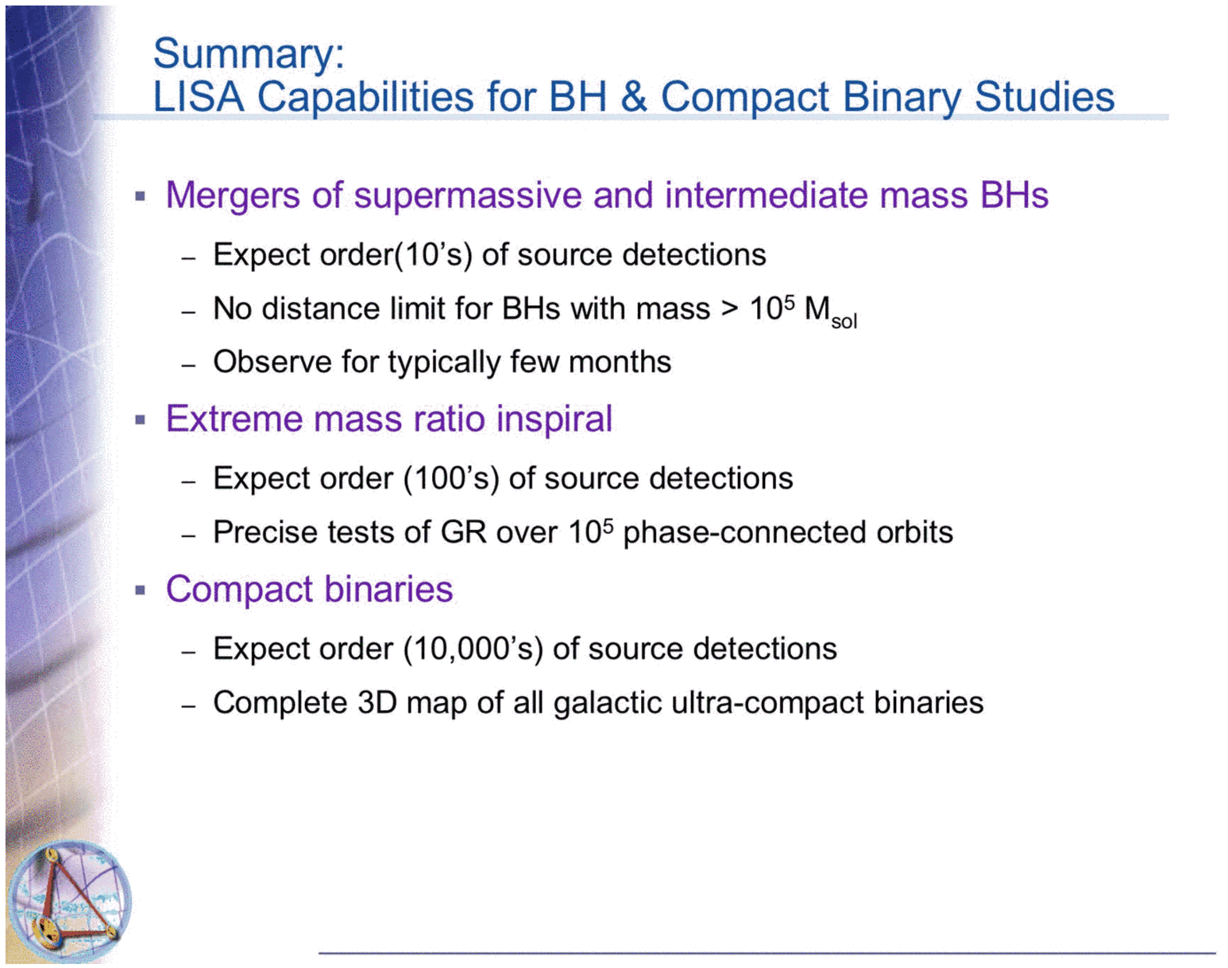
LISA will allow construction of
a complete 3-D map of the close binary
systems in the galaxy

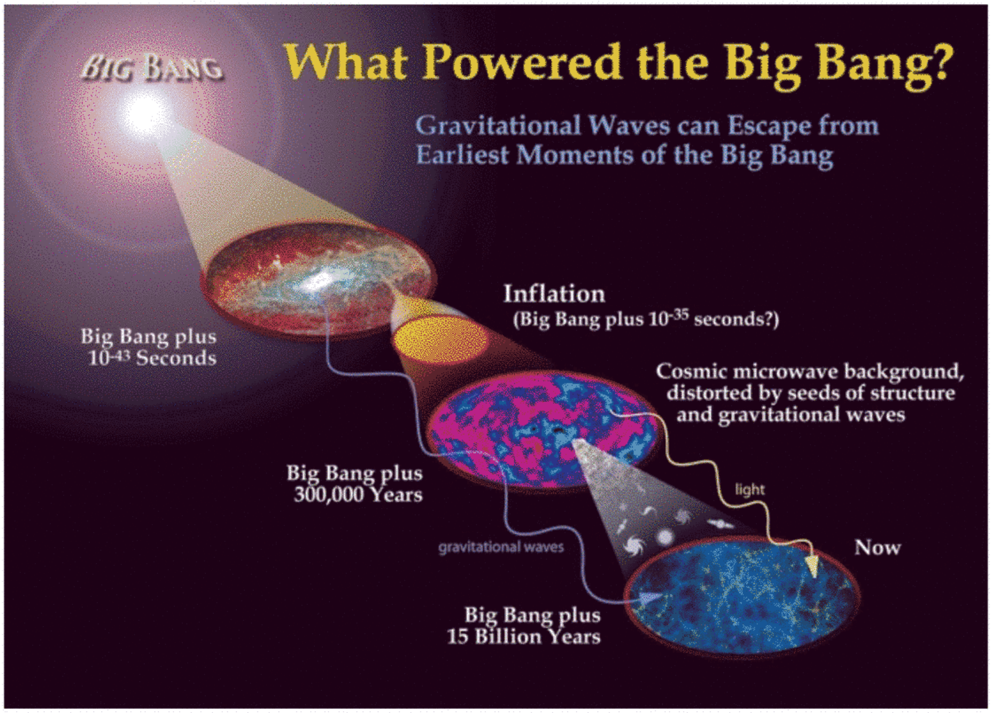


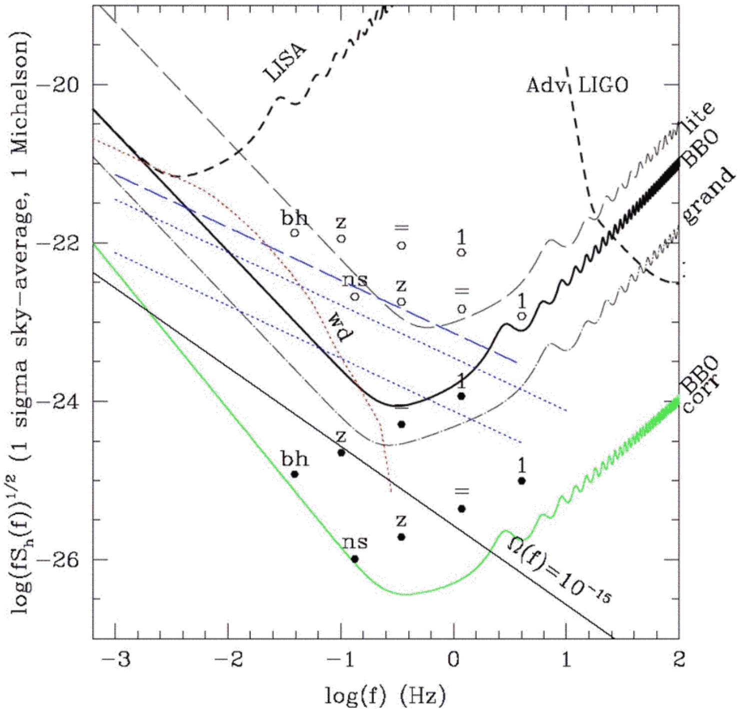
Summary:
LISA Capabilities for BH & Compact Binary Studies

- Mergers of supermassive and intermediate mass BHs
  - Expect order(10's) of source detections
  - No distance limit for BHs with mass > 10^5 M_{sol}
  - Observe for typically few months
- Extreme mass ratio inspiral
  - Expect order (100's) of source detections
  - Precise tests of GR over 10^5 phase-connected orbits
- Compact binaries
  - Expect order (10,000's) of source detections
  - Complete 3D map of all galactic ultra-compact binaries

4) GW from the Early Universe

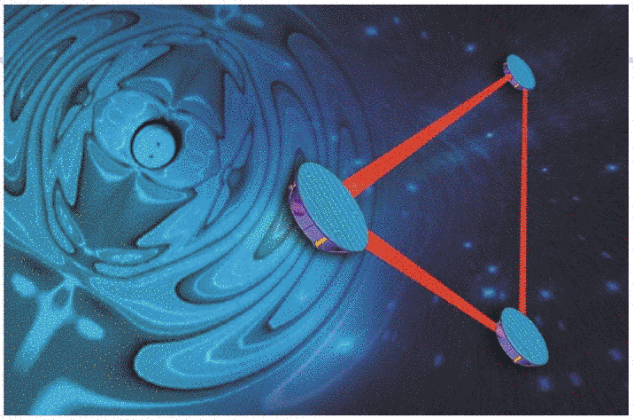
Gravitational Waves and the Big Bang





Gravitational Waves from the Early Universe

- Universe became transparent to gravitational waves at very early times (~ 10^{-35} sec after the big bang)
  - Gravitational waves provide our only chance to directly observe the Universe at its earliest times
  - The cosmic microwave background (CMB) probes much later times (400,000 years after the big bang), although inflationary GW may have left a polarization imprint on the CMB
  - LISA will probe GW length and energy scales at least 15 orders of magnitude shorter and more energetic than the scales probed by CMB
  - Possibilities for relic gravitational wave emission: Non-standard inflation, phase transitions, cosmic strings?
- LISA sensitivity: $\Omega_{GW} \sim 10^{-11} - 10^{-10}$ (Vecchio, 2001)
  - Compare to "slow-roll" prediction in range $\Omega_{GW} \sim 10^{-16} - 10^{-15}$



LISA: Opening a New Window on the Universe

- LISA Status Summary:
- Ranked by the science community as a very high-priority mission in both US and Europe
- Started Formulation (Phase A) on October 1 as part of the "Beyond Einstein" program
- Technology development validation flight on ESA Smart-II spacecraft in 2008
- LISA currently planning for 2012+ launch