LISA

LISA: The Science and the Instrument

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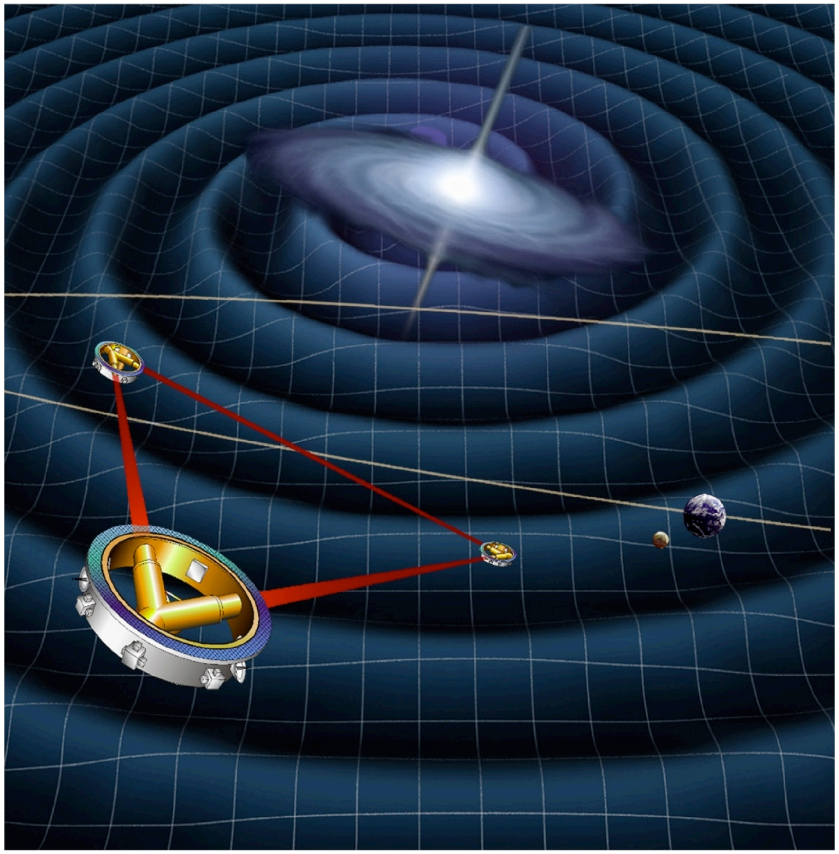
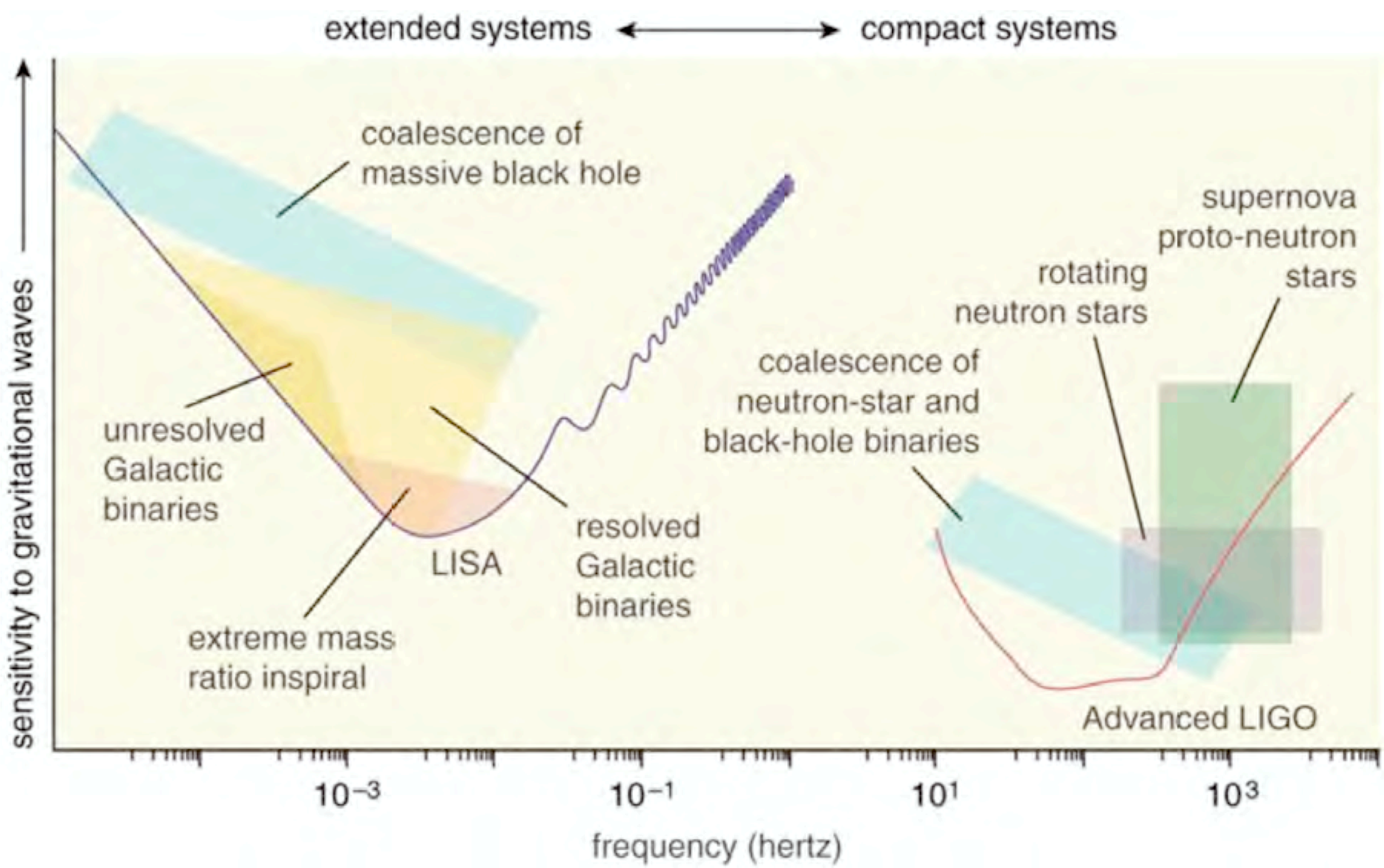
LISA Overview



- ***The Laser Interferometer Space Antenna (LISA) is a joint ESA-NASA project to design, build and operate a space-based gravitational wave detector.***
- ***The 5 million kilometer long detector will consist of three spacecraft orbiting the Sun in a triangular formation.***
- ***Space-time strains induced by gravitational waves are detected by measuring changes in the separation of fiducial masses with laser interferometry.***

- LISA is expected to detect signals from merging massive black holes, compact stellar objects spiraling into supermassive black holes in galactic nuclei, thousands of close binaries of compact objects in the Milky Way and possibly backgrounds of cosmological origin.

LIGO and LISA

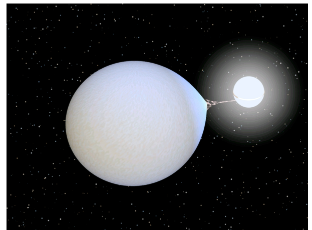


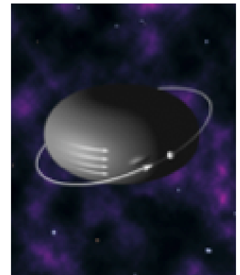
Gravitational Waves: A new way to study the Universe

- ***Signals direct from the most extreme conditions throughout the Universe***
  - *Radiation from the primary objects, not secondary processes*
  - *Source dynamics are directly encoded in the waveforms.*
- ***High precision measurements with simple interpretations***
  - *High signal-to-noise enables precision measurements of mass, spin, and distance*
  - *Systems are simple, have few parameters, and are well described by General Relativity*
- ***Most powerful events in the Universe***
  - *Any pair of merging black holes - of any size - produce more energy than all the stars in the Universe.*
- ***Many phenomena not observable in any other way***
  - *Phenomena are too obscured or too far away or simply electromagnetically dark*
  - *Gravity shapes the Universe. What better to map the Universe with!*

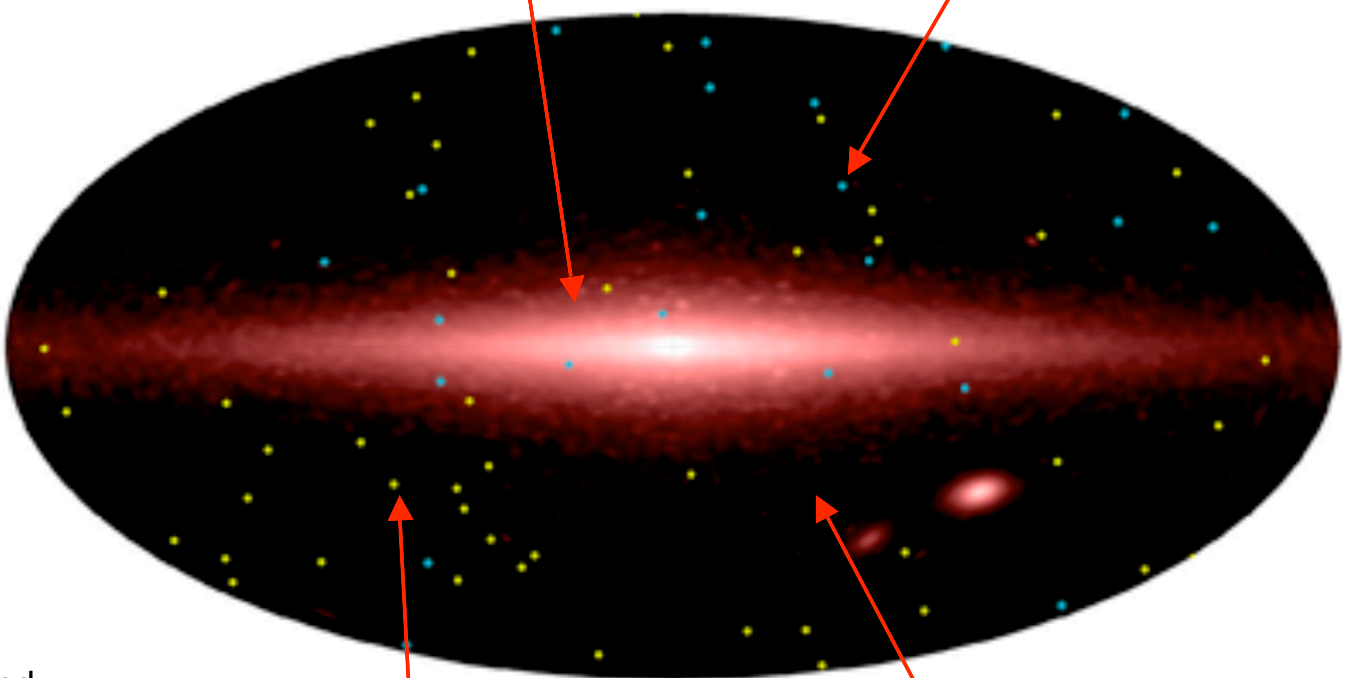
The LISA Sky

Ultra-compact binaries
- *~1* $M_\odot$
- Galactic and extragalactic
- 1000's - 10,000
- Confusion foreground

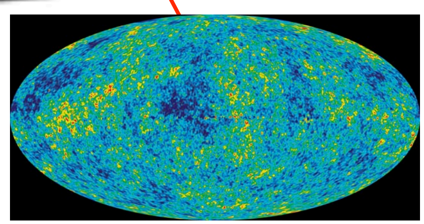




Extreme mass-ratio inspirals
- *~10/* $10^6\ M_\odot$
- $z < 1$
- 10's - 100 per year

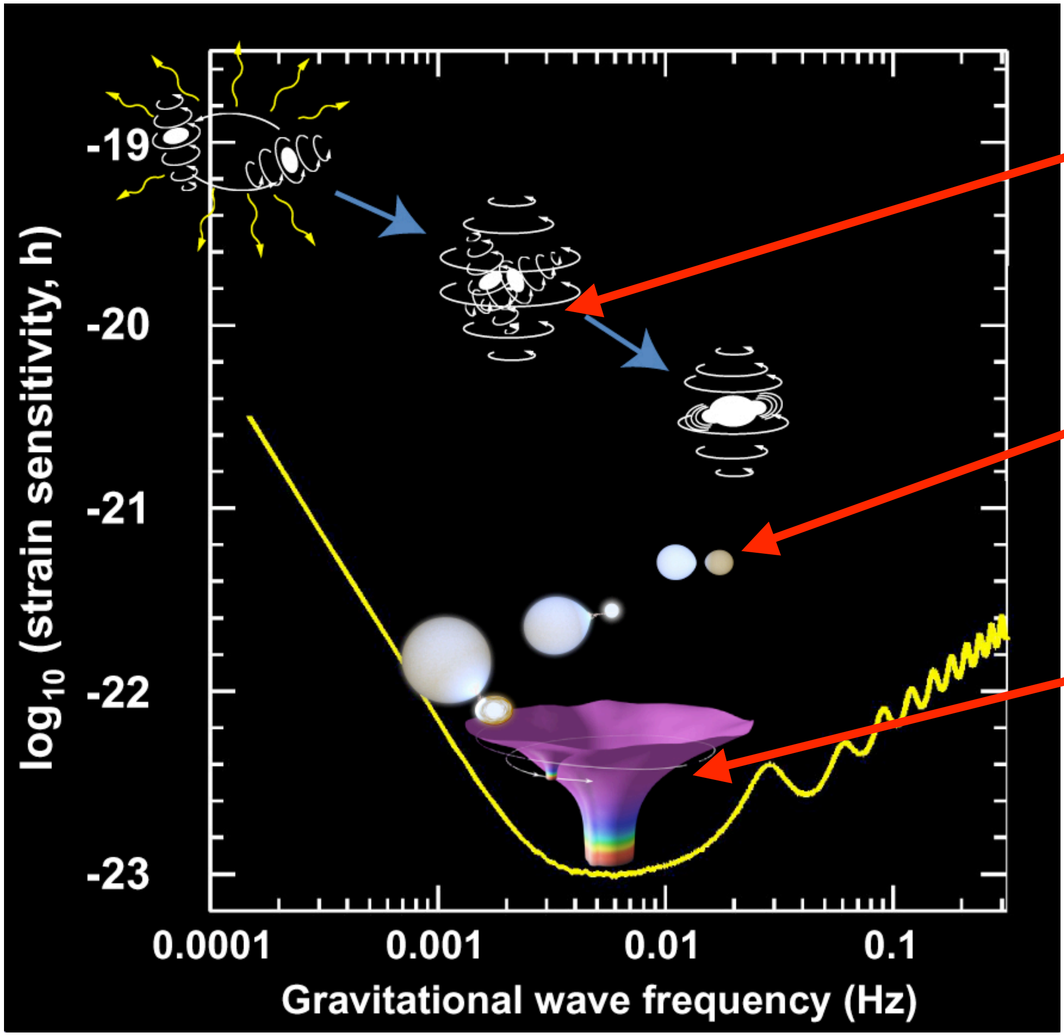


Massive and intermediate-mass black hole binaries
- 10^2 - $10^7\ M_\odot$
- $z < 20$
- 10's to 100 per year



Cosmological back-grounds, bursts and unforeseen sources

Sources and Science Objectives



Formation and growth of massive black holes

Dynamical strong-field gravity

Evolution of ultra-compact binaries in the Galaxy

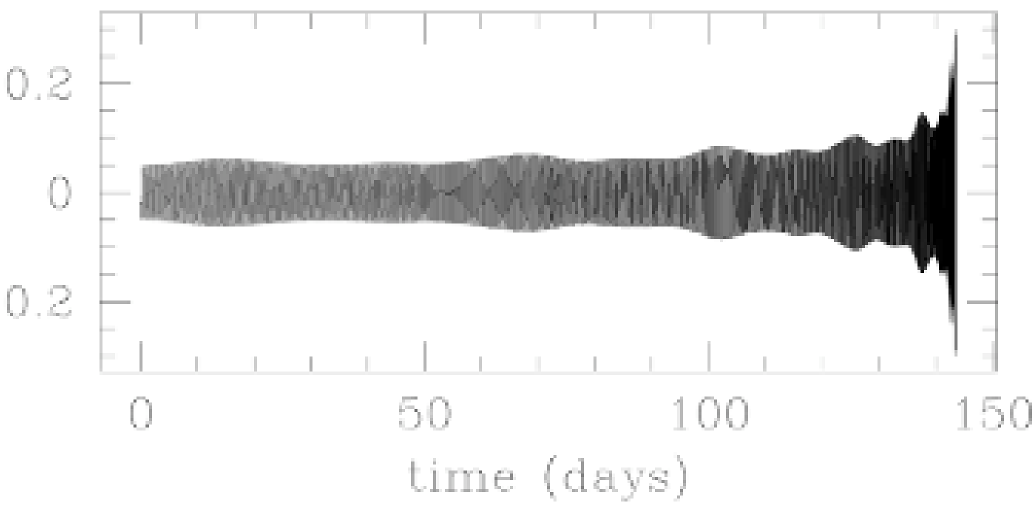
Precision tests of General Relativity

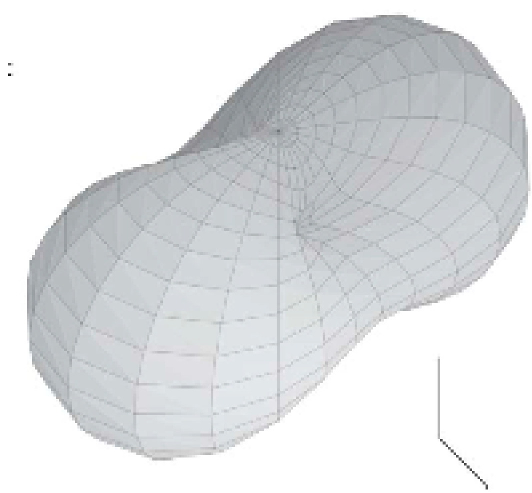
Dynamics of stars in galactic nuclei

New physics: cosmic backgrounds and superstring bursts

What do we measure?

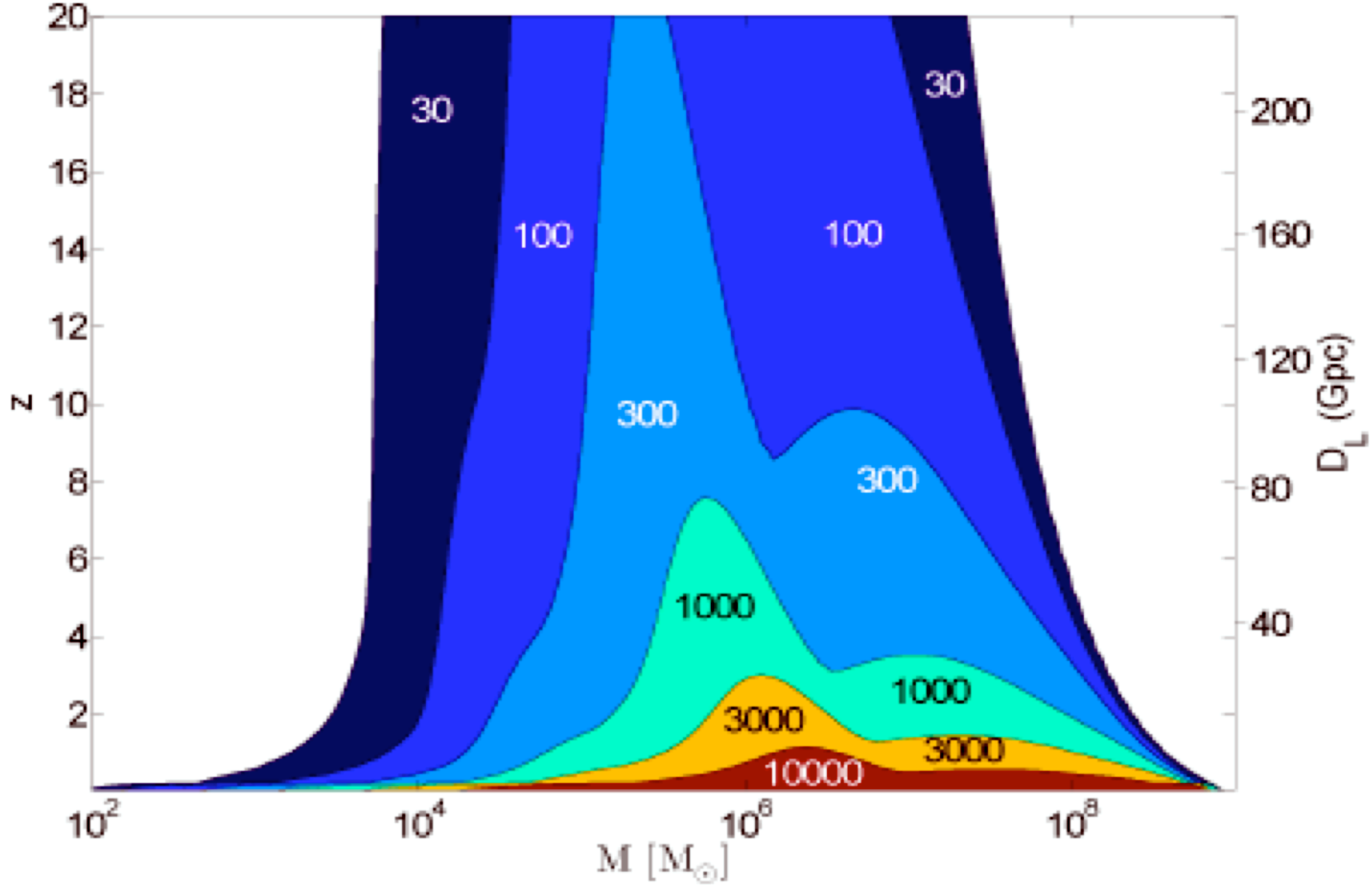
$$h_+ = \frac{[G(1+z)\mathcal{M}/c^2]^{5/3}\,[\pi f(t)/c]^{2/3}}{D_L}\mathcal{F}(\text{“angles”})\cos[\Phi(t)]$$





- ***Observe waveforms from months to years***
  - *–10’s to 100’s of thousands of cycles*
  - *–SNRs from 10 to more than 1,000s*
- ***Waveform depends on 17 parameters***
  - *–Intrinsic parameters of the source*
  - *–Extrinsic parameters of the observer*
- ***Detection vs parameter estimation … an important distinction***

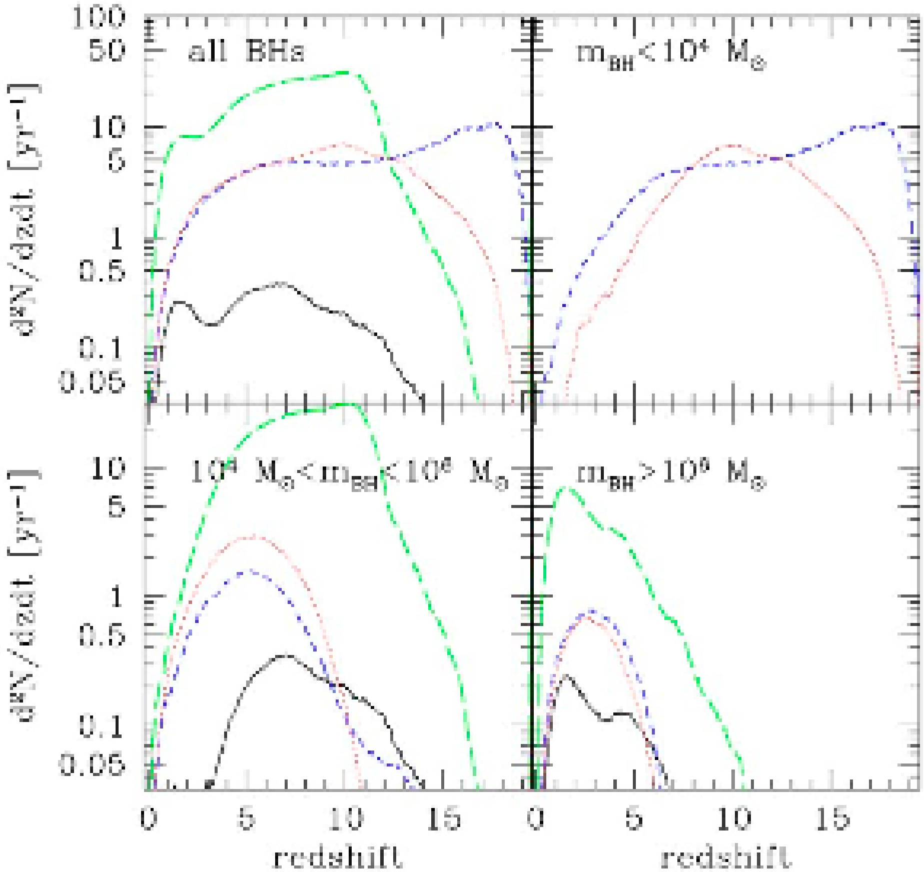
Detection with LISA



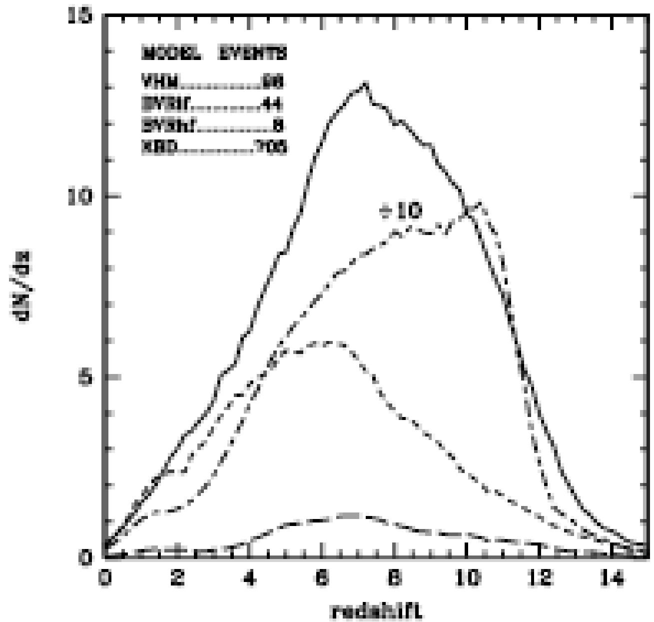
Understanding the Formation and Growth of MBHs

- ***Massive black holes grew from one of two kinds of seeds***
  - *Large stellar mass black holes (~100 $M_\odot$) left over from the first stars (Pop III) at z>20*
  - *~10^{4-5} $M_\odot$ black holes formed directly by the collapse of supermassive star clusters or gas clouds z~15*
- ***Massive black holes must grow at least fast enough to form ~10^9 $M_\odot$ quasars at z~6.4 (~1 Gyr after the Big Bang).***
  - *Accretion*
  - *Mergers*
  - *The gravitational rocket*
- ***LISA will detect ~10^4 $M_\odot$ black holes merging at z=30 with SNR=10.***
- ***LISA will observe 300 $M_\odot$ black holes merging with ~10^4 $M_\odot$ black holes at z=10 with a luminosity distance uncertainty of >35%, redshifted masses <1%, spins <0.2.***

Merger Rates



Sesana et al 2004 ApJ, 611, 623

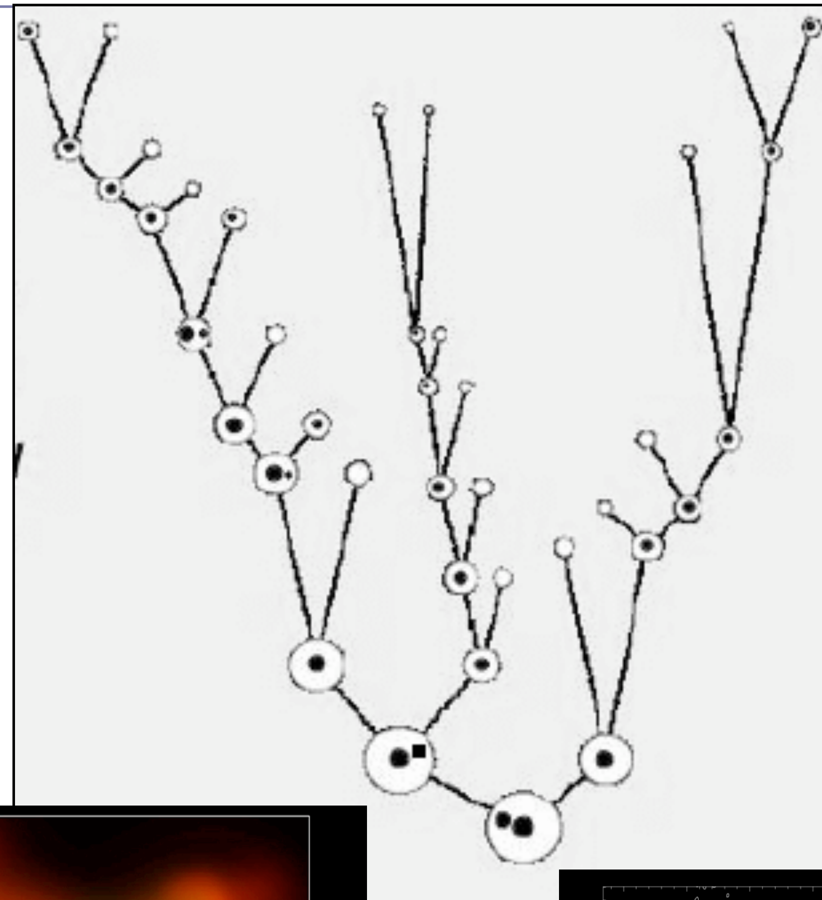


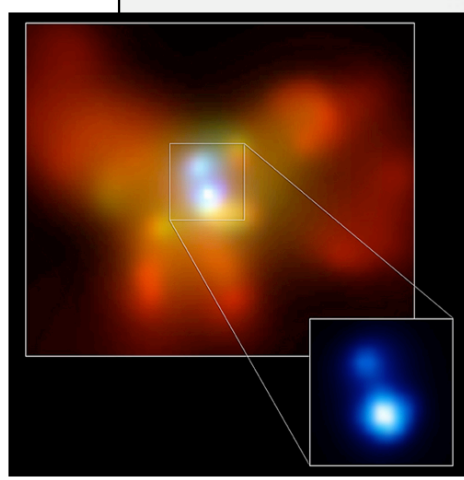
Trace the merger history of MBHs and their host galaxies

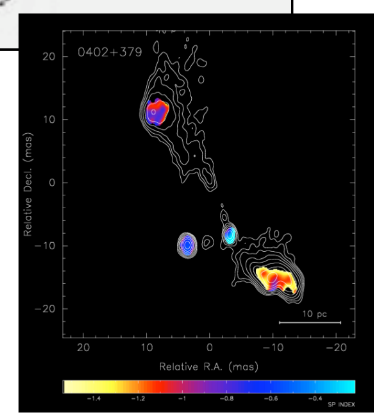
- ***The standard model of hierarchical structure growth calls for***
  - *Formation of small dark matter haloes*
  - *Formation of proto-galaxies within those haloes*
  - *Progressive mergers to form modern galaxies*
- ***Coevolution of galaxies and massive black holes***
  - *Scaling relations between MBH masses and galaxy properties (e.g. bulge mass/luminosity, velocity dispersion) over >3 decades suggest that MBHs grow in conjunction with their host galaxies.*
- ***LISA will observe a wide range of merger events between z=10 and the present:***
  - *At z=10, events with total masses ranging from ~10^4 to 10^6 $M_\odot$, with luminosity distance uncertainties <35%, mass uncertainties <1%, spin uncertainties <0.2*
  - *At z=1, events with total masses ranging from ~10^5 to 10^7 $M_\odot$, with luminosity distance uncertainties <0.4%, mass uncertainties <1%, spin uncertainties <0.01*
  - *Mass ratios can range from 1000 to 1.*

Merger Trees

- ***LISA will produce a source catalog with the 17 parameters, and their uncertainties.***
- ***Accretion will spin up MBHs to near maximal values***
- ***Mergers will randomize spins and leave relatively low average spins.***
- ***The gravitational rocket should preferentially affect lower mass haloes and near equal mass mergers.***
- ***MBHs (~10^4 $M_\odot$) formed in globular clusters may also merge with central MBHs, revealing other galactic dynamics***





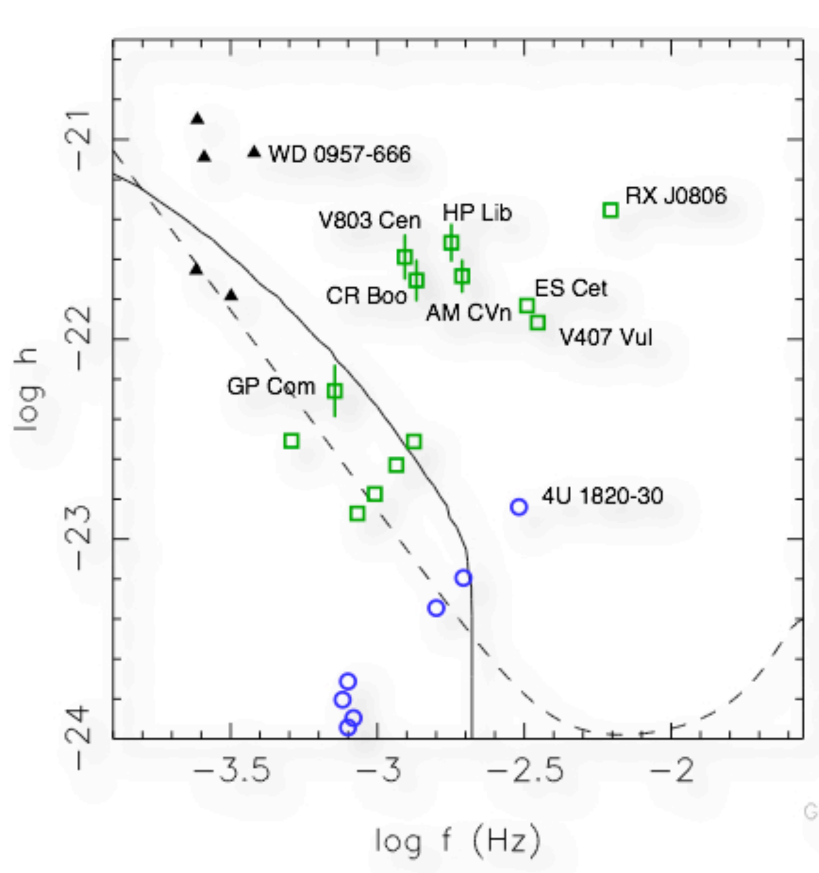


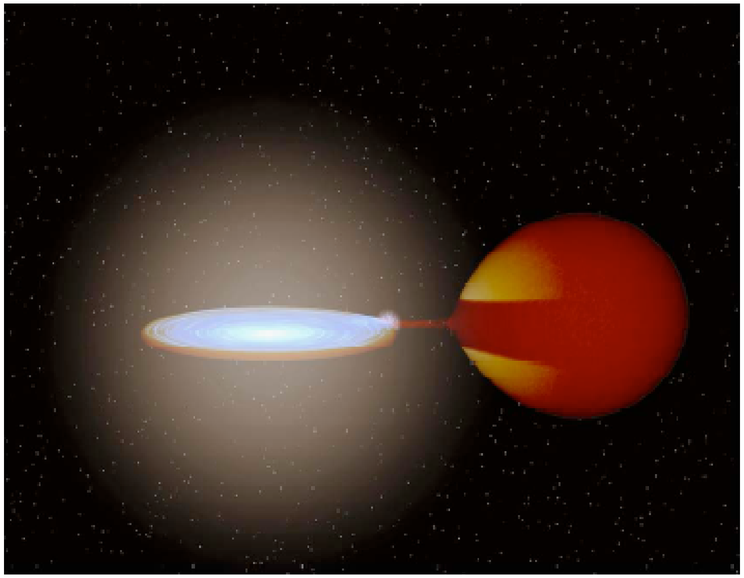
Survey binaries of stellar mass objects

- ***There are an estimated 26 million compact-star binaries in the Milky Way that will radiate appreciable gravitational radiation in the LISA band.***
  - *Mostly WD-WD binaries*
  - *Some NS-NS binaries*
  - *Possibly a few BH-BH binaries*
- ***LISA should separate about 10,000 of them.***
- ***There are currently about 10 known sources that LISA can detect, making them guaranteed gravitational wave sources with optical counterpart. Many more will be known by the time that LISA flies.***
- ***The known sources can be used to verify the***

Science with stellar-mass binaries

- *Study demographics of these endpoints of stellar evolution*
- *Study exotic binary systems, e.g., common envelope, contact binaries*
- *Map the distribution of these stars in the Milky Way*



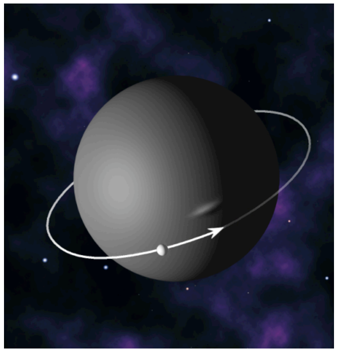


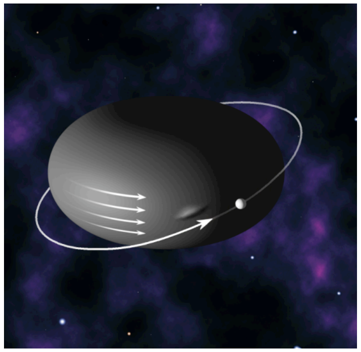
Testing theories of relativity

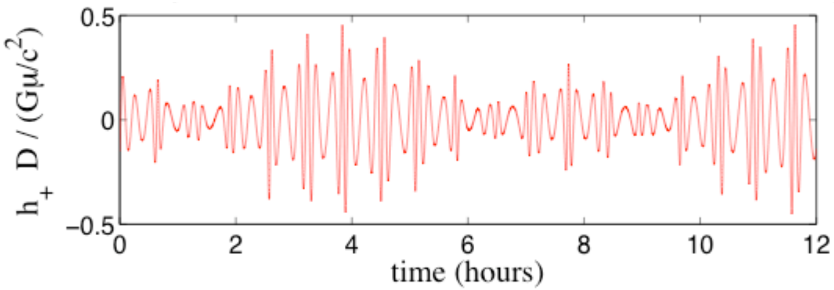
- ***Stellar mass black holes (~10 $M_\odot$) will be gravitationally scattered into highly eccentric orbits about central MBHs (~10^6 $M_\odot$). These "Extreme Mass Ratio Inspirals" (EMRIs) are estimated to occur at the rate of 20-40 per year out to z~1.***
- ***SMBH mergers (~10^6 $M_\odot$) result from the mergers of their host galaxies, and are estimated to occur at the rate of a few per year.***
- ***Observations of compact-star binaries will directly verify the propoeries of gravitational waves four decades of frequency below the LIGO band. The "verification binaries" alone will directly confirm***

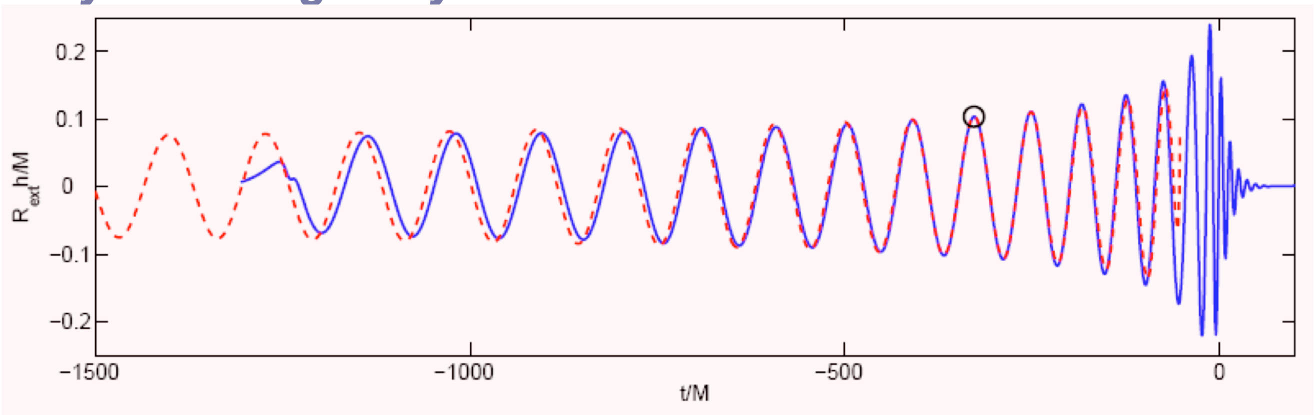
Waveforms

- *"Verification binaries" will directly confirm the properties of gravitational waves four decades below the LIGO band with known sources.*
- *EMRIs have rich waveforms which enable :*
  - *Mapping the spacetime around*
  - *Testing the "No-hair Theorem" of General Relativity to ~1% accuracy*
  - *Measuring the dynamical tide on horizon to ~10%*
- *Testing extreme dynamical gravity with MBH binaries.*







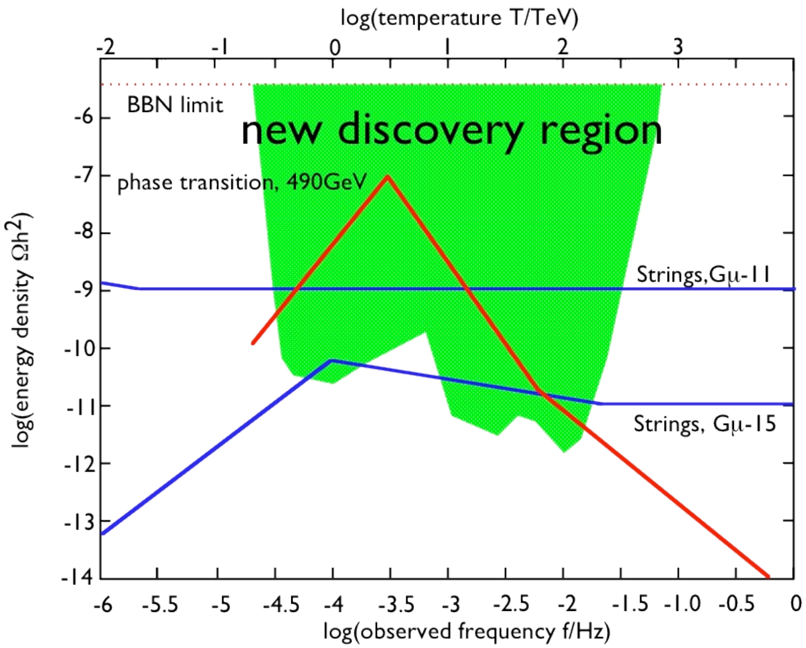


Probing New Physics and Cosmology

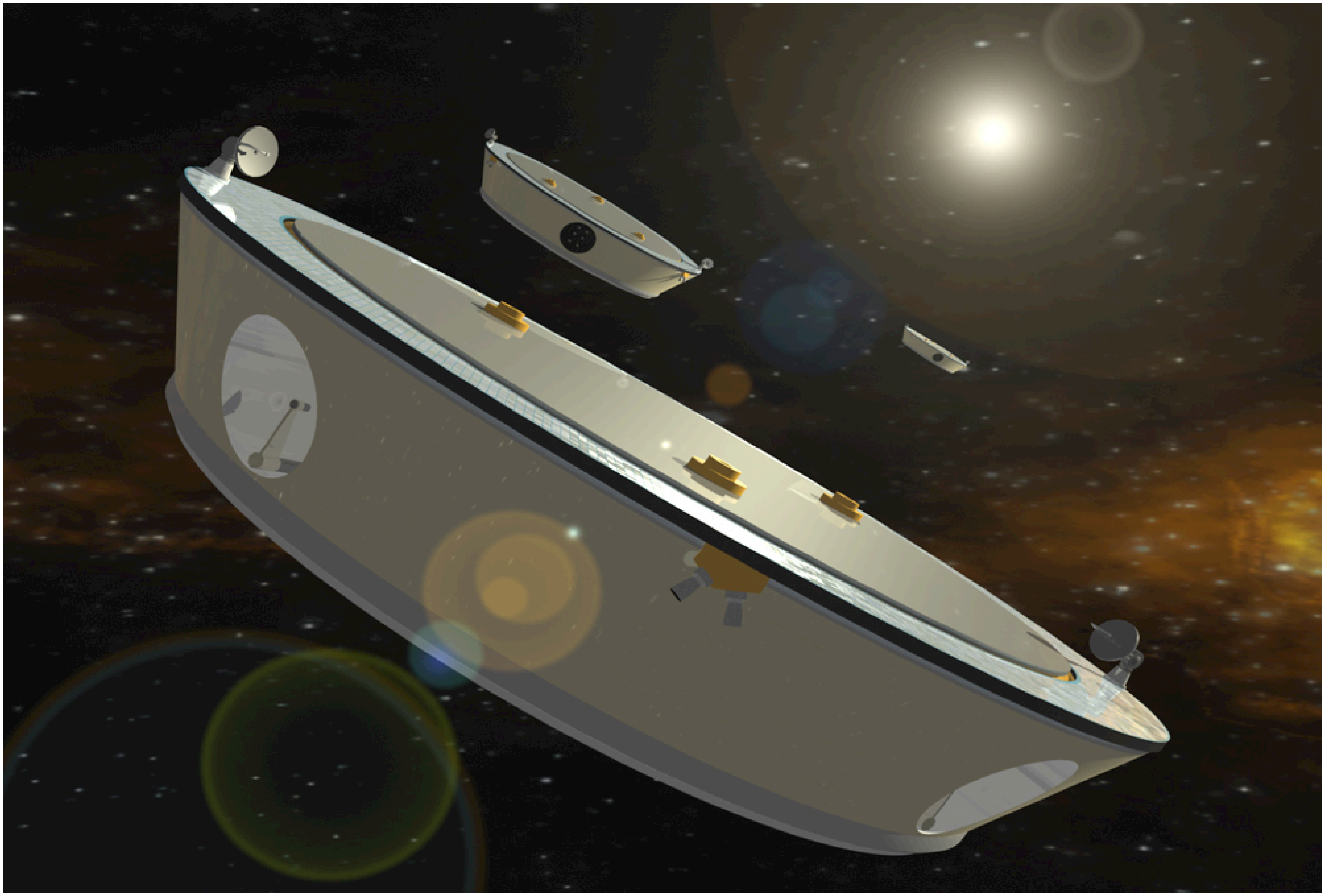
- ***MBH mergers with electromagnetic counterparts***
  - *LISA can predict merger time well in advance*
  - *For the strongest sources, LISA can locate the sources within 10's of arc minutes on the sky and within a few percent in redshift from the inspiral phase*
- ***Possible electromagnetic counterparts***
  - *Pre-merger variability*
  - *Post merger from disturbance of the accretion ring by the lost of mass (Phinney 2007)*
  - *Post merger signal from re-establishing accretion (Phinney and Milosavlejvic 2007)*
- ***Search for cosmological gravitational wave background.***
- ***Search for unexpected sources***

New Physics and Cosmology

- ***MBH mergers with electromagnetic counterparts***
  - *Measure the Hubble constant*
  - *Map cosmic acceleration to ~1% with absolute distance measurement from GWs and redshift from EM spectroscopy*
- ***Search for cosmological gravitational wave background***
  - *Not likely*
  - *Probe Terascale, electro-weak phase transitions*
- ***Search for a background from decaying cosmic string loops***
- ***Search for burst events from cosmic string cusps***
- ***Search for unexpected sources***

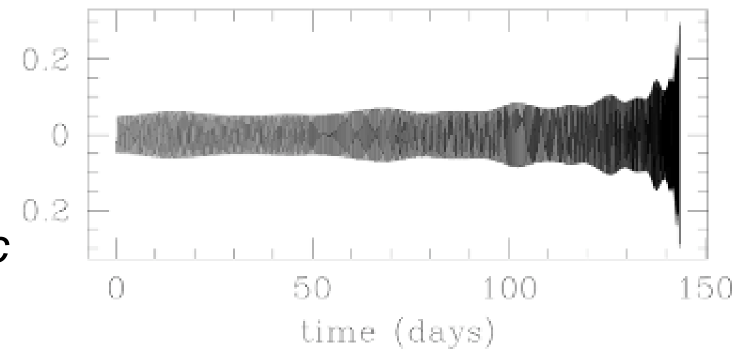


Mission Concept

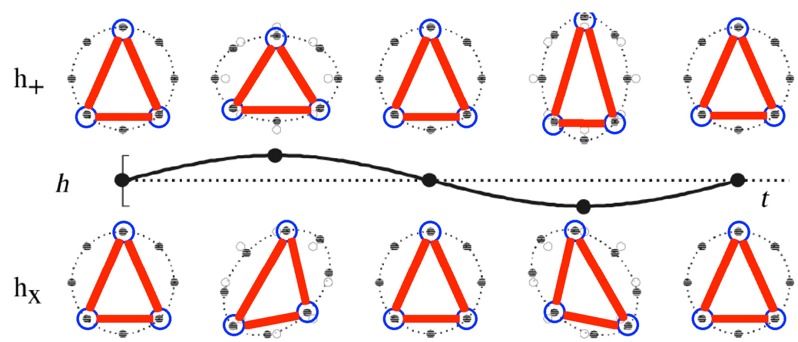


Measurement Concept

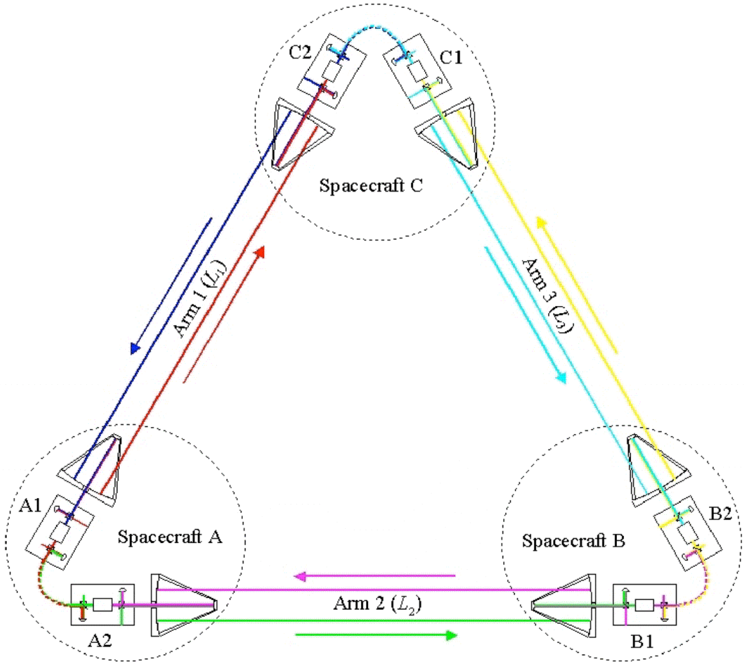
- **What's to be measured**
  - Time-varying strain ($\Delta L/L$) in spacetime as small as $10^{-22}/\sqrt{\text{Hz}}$
  - Variations are periodic or quasi-periodic between $3\text{x}10^{-5}$ and 0.1 Hz, observable for months to years

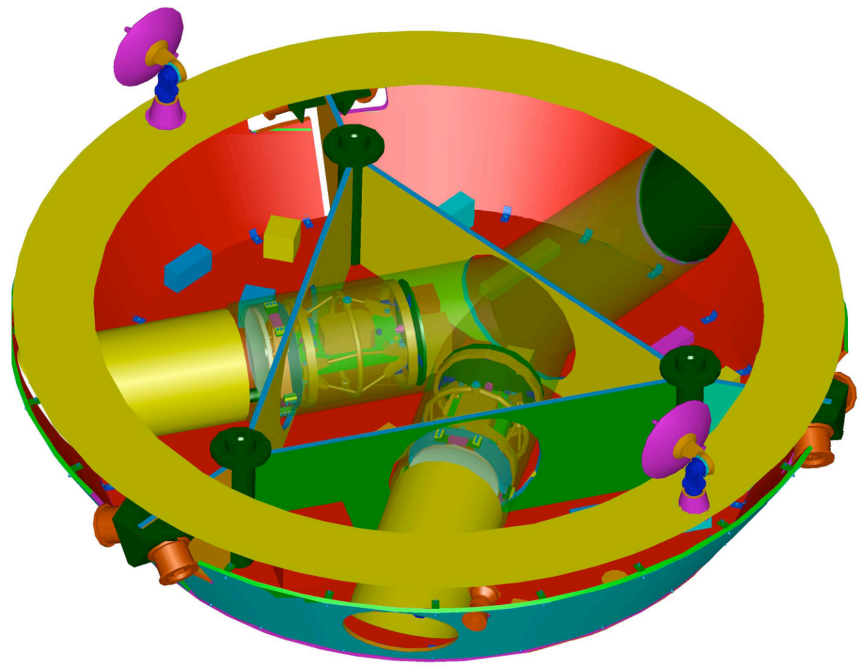


- **Measurement concept**
  - Measure distance changes between free-falling mirrors (Bondi)
    - Proof masses are the mirrors
    - Interferometric measurement of distance changes
  - Desired
    - A long measurement path to make ΔL large
    - A very quiet place to avoid disturbances to the proof masses



Sciencecraft



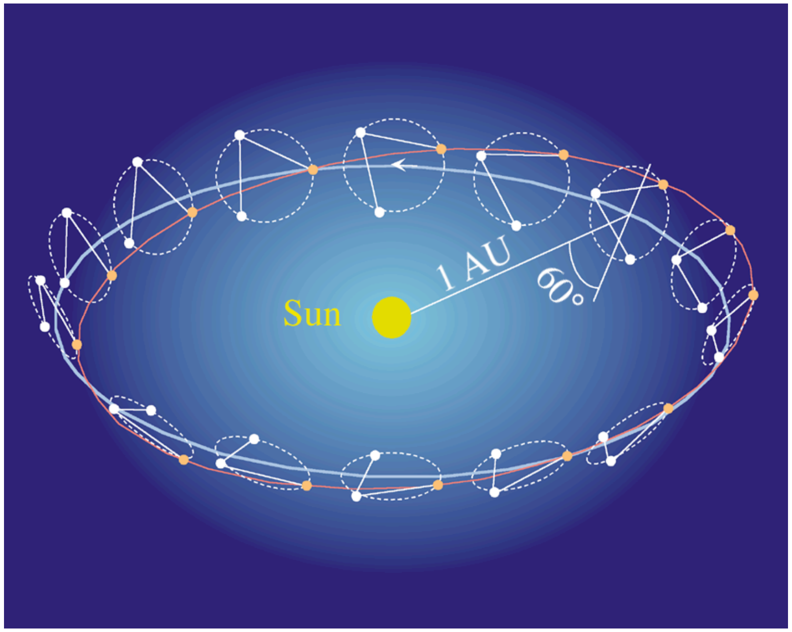


- Three interacting spacecraft make up the “science instrument”
- Multiple combinations of one-way measurements.

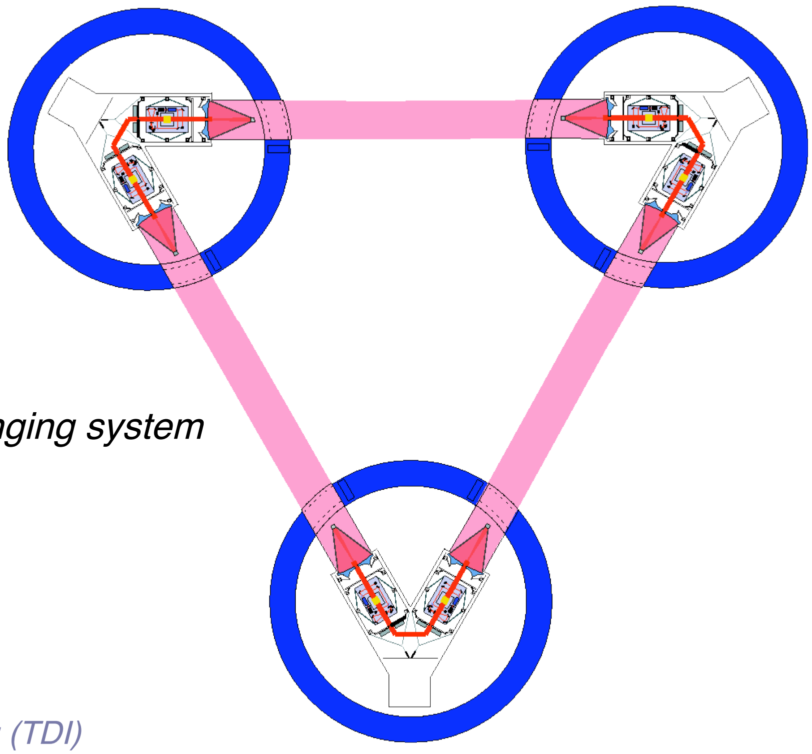
- Drag-free control protects the proof masses from the ambient environment and reduces the disturbances on the proof masses from the spacecraft.

What the science instrumentation does

- **Measure changes in relative separation between proof masses**
  - Continuous laser ranging between free-falling proof masses
  - Interferometric readout (μcycles/√ Hz over gigameters with 1μ light)
  - Performance characterized by displacement noise
- **Reduce disturbances**
  - Benign environment
  - Enclosed proof masses
  - Control disturbances from spacecraft
  - Limit relative motion of spacecraft with “drag-free” control
  - Performance characterized by residual acceleration noise



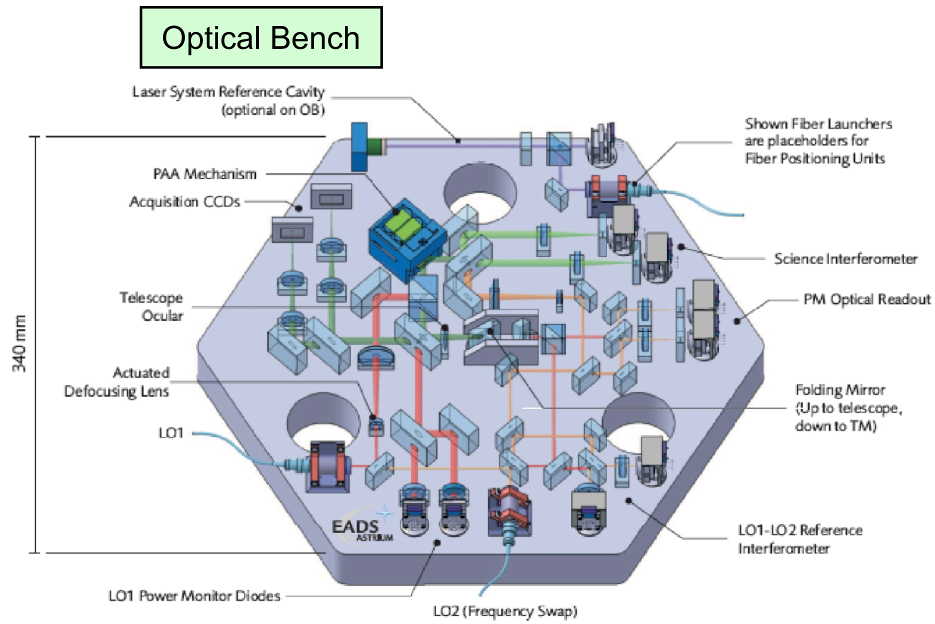
How the science instrumentation works

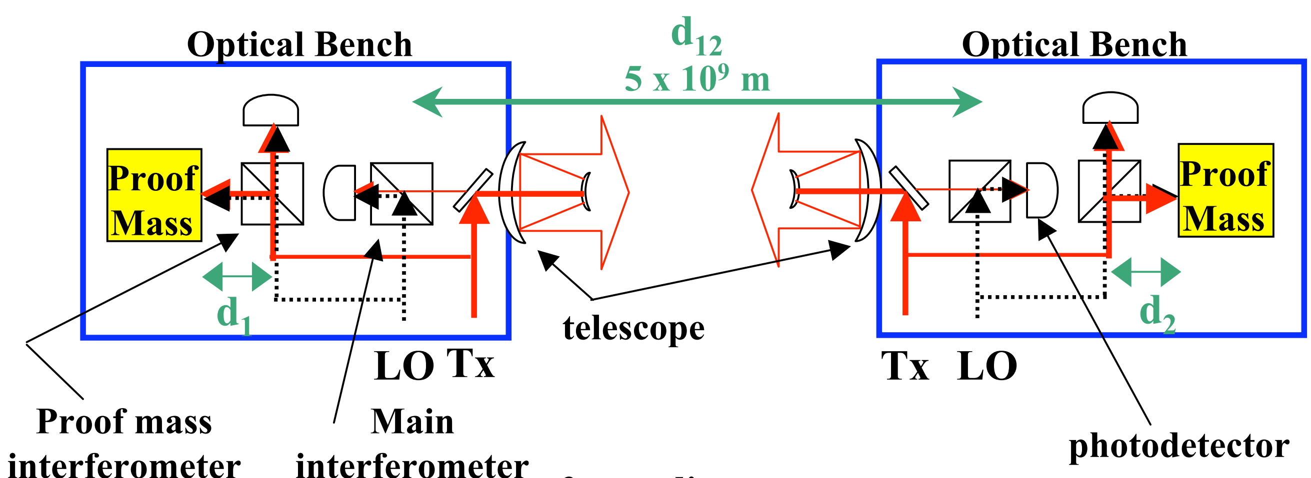


- ***The Constellation is the Instrument***
  - *Orbits passively maintain formation*
  - *"Sciencecraft" houses*
    - *Proof masses*
    - *Interferometry equipment*
- ***Interferometer Measurement System (IMS)***
  - *Active transponder offset phase-locked laser ranging system*
  - *3-part distance measurement*
    - *(2) "short-arms" from proof mass to sciencecraft*
    - *"Long-arms" measure between sciencecraft*
  - *Laser frequency noise correction*
    - *Pre-stabilization, arm-locking, and post-processing (TDI)*
  - *Phasemeter records fringe signal*
- ***Disturbance Reduction System (DRS)***
  - *Free-falling proof masses don't contact the sciencecraft*
  - *Drag-free stationkeeping reduces sciencecraft proof mass relative motion and force gradients*
  - *Design to limit thermal, magnetic, electrostatic, mechanical, self-gravity disturbances*

Interferometry - what it does

- *Laser system*
  - *Transmitter and local oscillator*
  - *Modulation sidebands*
- *Frequency control*
  - *Pre-stabilize*
  - *Doppler shift compensation*
- *Clock noise transfer*
  - *Record and remove in post-processing*
- *Pointing*
- *Optical bench*
  - *Acquisition CCD*
  - *Beam combining/mode matching*
- *Telescope for transmit/receive over long arm*

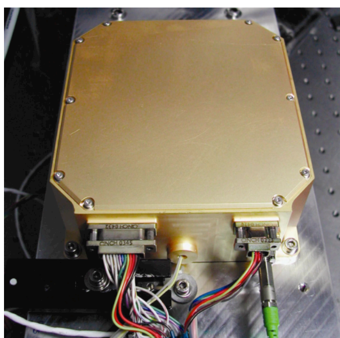
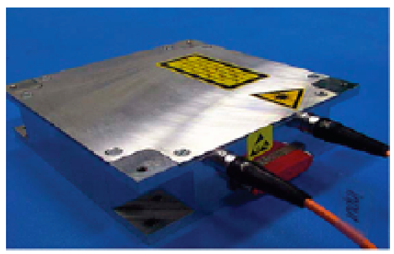
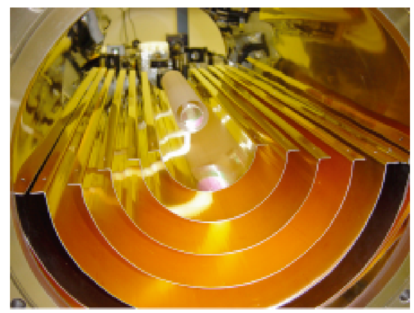
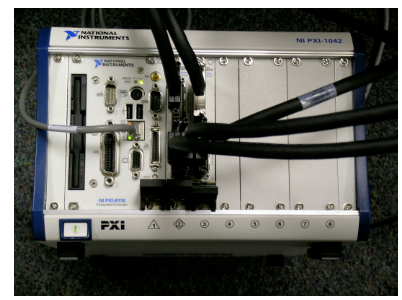
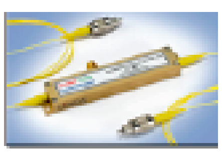
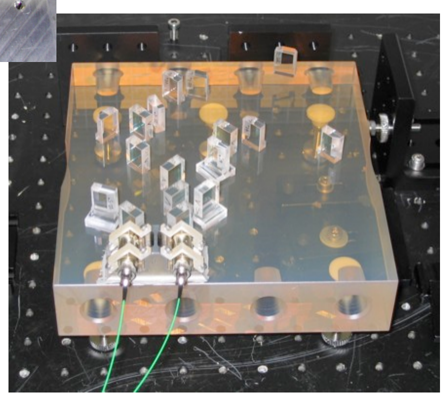
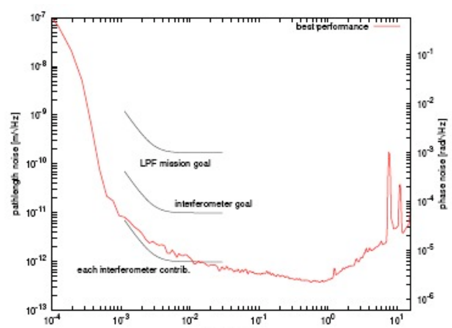


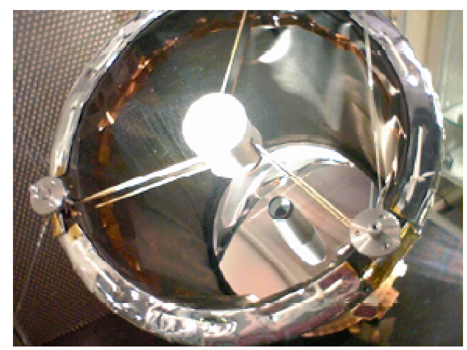


3 part distance measurement:
Short arm (d_1+d_2) + long arm (d_{12}) = d_total

Interferometry - what it takes

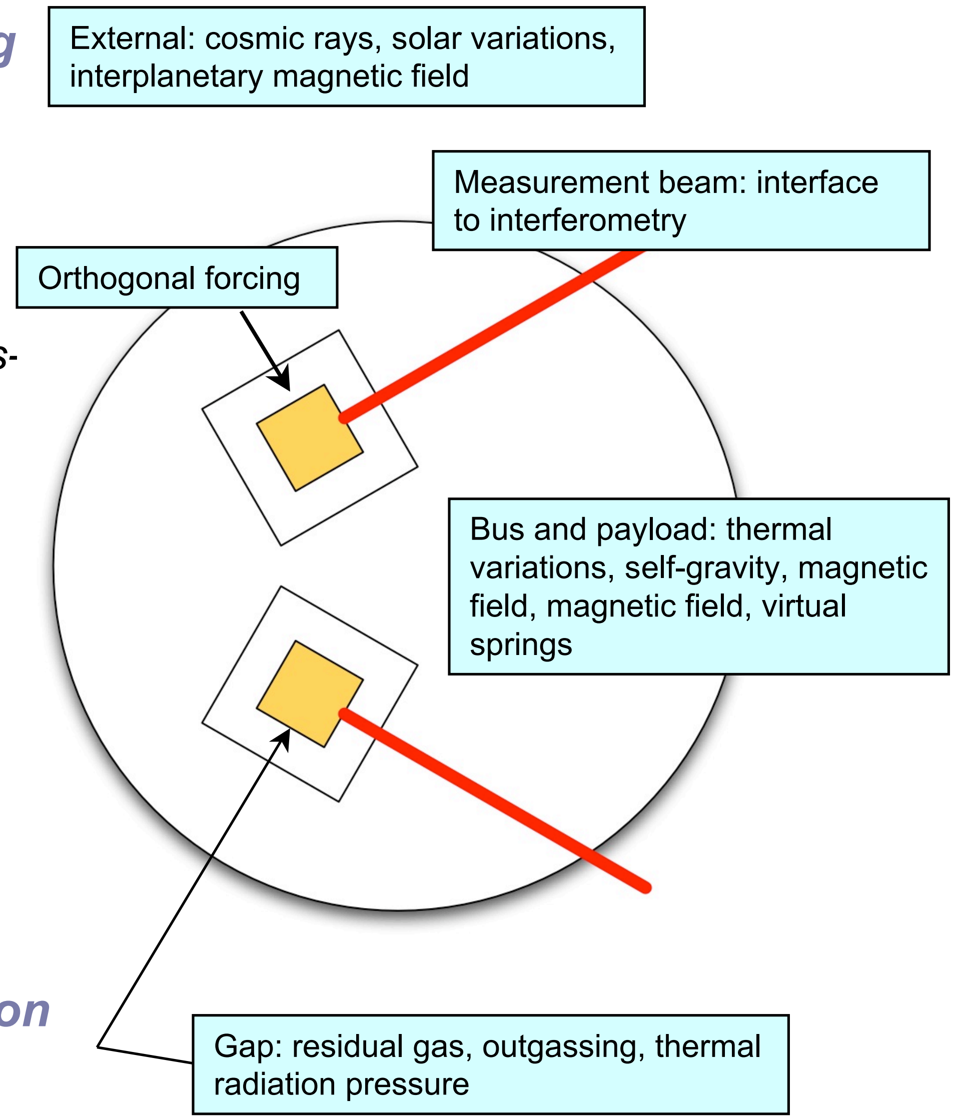
- ***Laser:***
  - *Diode-pumped solid state (Nd:YAG)*
  - *Fiber coupled master-oscillator (25 mW), power-amplifier (1 W) architecture*
  - *Electro-optic phase modulator*
  - *Fully redundant*
- ***Laser frequency control: 3-stage***
  - *Reference cavity*
  - *Arm-locking control loop and actuator*
  - *Post-processing (TDI)*
- ***Optical Bench***
  - *ULE or Zerodur for stability*
  - *Hydroxy-catalysis bonding*
- ***Phasemeter***
  - *Photoreceiver*
  - *1 μcycle/$\sqrt{}$ hz demonstrated*
- ***LTP Short arm***
  - *Performance exceeds requirements*
- ***Telescope***
  - *40 cm, f/1.5 Cassegrain*
  - *λ/30 wavefront error*



Disturbance Reduction - what it does

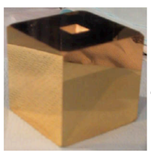
- ***Proof mass is the free-falling mirror***
- ***Housing***
  - *Sensing for drag-free and charge control*
  - *Forcing in orthogonal degrees-of-freedom*
- ***Active discharging***
- ***Quiet environment***
  - *Vacuum enclosure*
  - *Thermal isolation*
  - *Low magnetic field from payload and bus*
  - *Low self-gravity*
- ***Caging***
- ***Sensor for spacecraft position and attitude control***

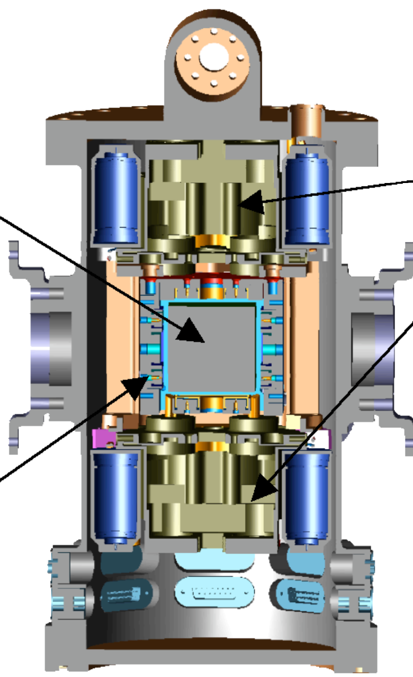


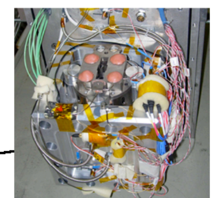
Disturbance Reduction - what it takes

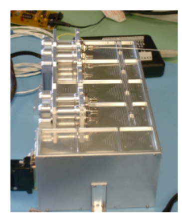
- *Gravitational Reference Sensor*
  - *Proof mass - 44 mm cube, Au:Pt*
  - *Reference housing with capacitive sensing and electrostatic forcing*
  - *Charge control with UV light*
  - *Caging, vacuum system*
- *"Drag-free" control laws*
  - *3 x 19 Degrees of freedom*
  - *Acquisition*

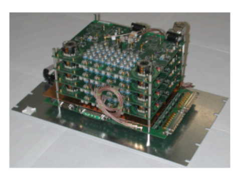
- *Micronewton thrusters*
  - *Electro-spray of nano-droplets or metal ions, neutralizer*
  - *30 μN authority, 0.1μN/√ Hz noise*
- *General design features*
  - *Low self-gravity*
  - *Low magnetism spacecraft*
  - *Passive thermal shielding*

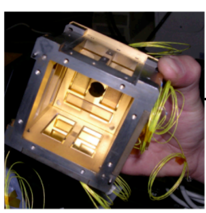

Proof Mass

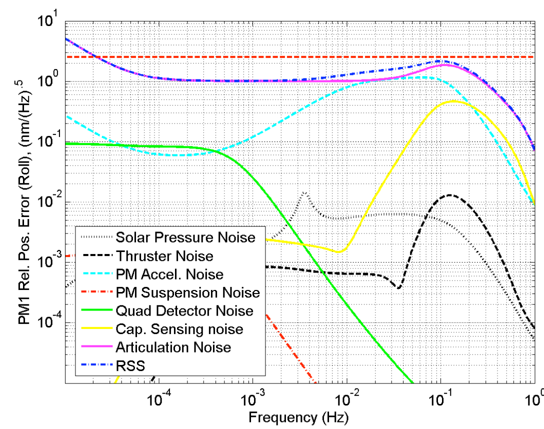


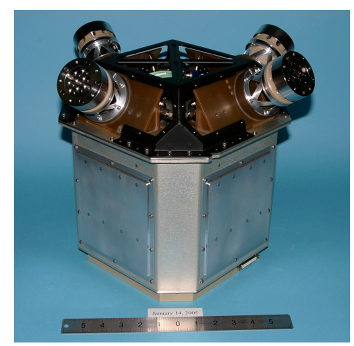

Caging Mechanism


Charge Management System


Front-End Electronics


Electrode Housing





Requirements Flowdown

- **The Instrument Sensitivity Model is a combination of**
  - Displacement noise from the IMS
  - Acceleration noise from the DRS
  - Arm Length ($5x10^6$ km)
- **The arm length also determines the instrument transfer function**
- **The requirements for the DRS and IMS are then suballocated.**

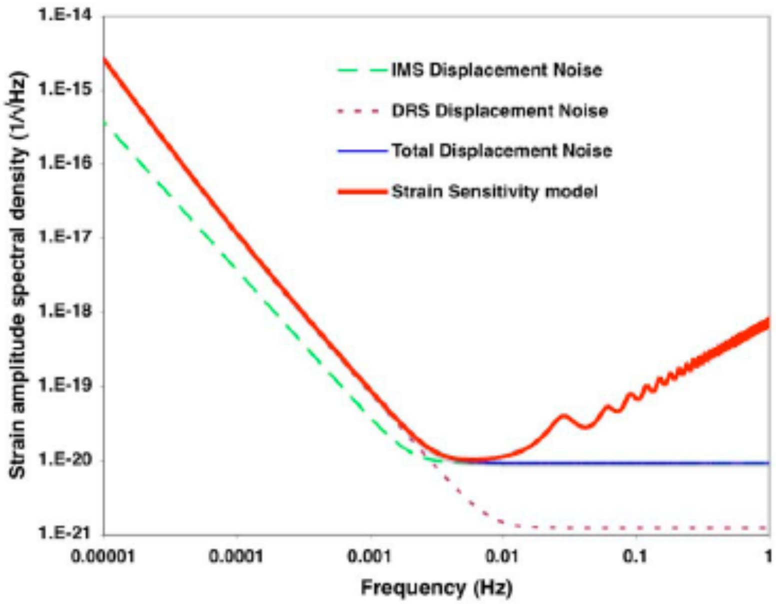


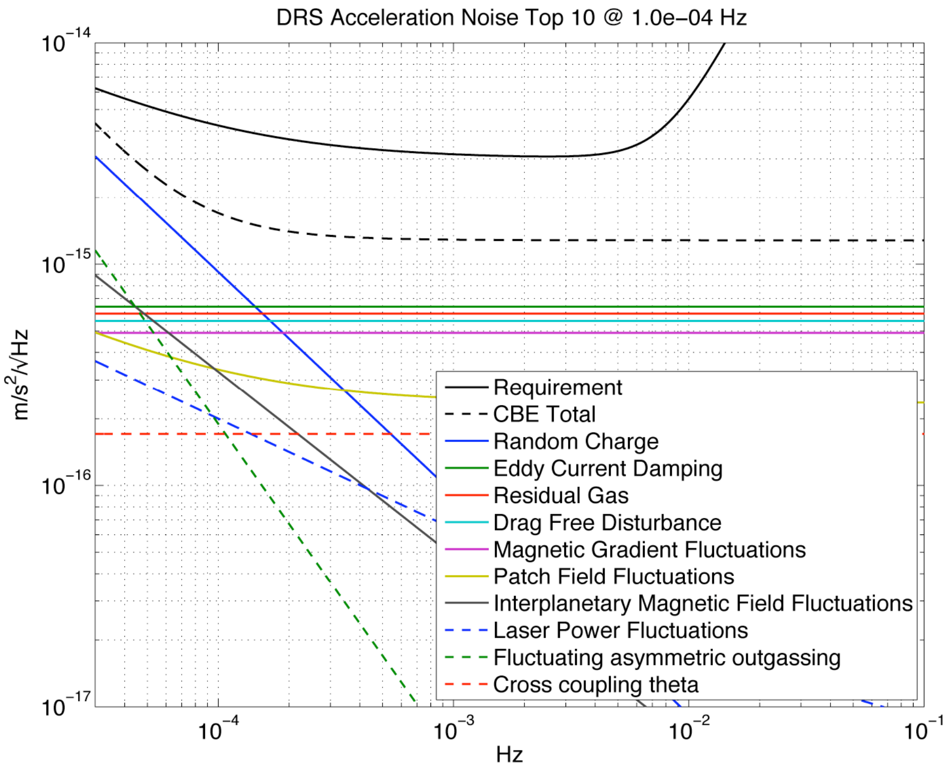
Table 1: Summary of IMS subsystem noise allocations.

	$\times 10^{-12} \frac{m}{\sqrt{Hz}} \sqrt{1+\left(\frac{2\,mHz}{f}\right)^4}$		
Effect	**Total per group**	**Sub -Allocation**	**Comments**
Total Error Budget	**18.0**		
Contingency (35%)	**6.3**		Held by System Engineering
Total available for allocation	**11.7**		RSS of subsystems
Subsystem Allocations			
Shot noise	**7.7**		100 pW received power
Pathlength noise	**7.0**		RSS of sub-allocations
Pointing Errors		5.3	
Telescope pathlength stability		1	
Optical bench pathlength stability		4.5	
Measurement noise	**5.4**		RSS of sub-allocations
Photoreceiver errors		3	
Residual laser frequency noise		2	
Residual clock frequency noise		3	
Phasemeter noise		1	
ADC jitter		1	
Phase reconstruction		1	
straylight		2	

Table 1: Summary of DRS Subsystem allocations

	$\times 10^{-16} \frac{m}{s^2\sqrt{Hz}} \sqrt{1+\left(\frac{f}{8\,mHz}\right)^4} \sqrt{1+\left(\frac{0.1 mHz}{f}\right)}$		
Effect	**Total per group**	**Per group**	**Comments**
Total Acceleration noise	**30.0**		
Contingency (35%)	**10.5**		Held by System Engineering
To be allocated (linear subtract)	**19.5**		RSS of sub-allocations
Disturbance Groups			
Electrostatics		12.0	
Brownian		9.1	
Spacecraft magnetic		7.0	
Spacecraft coupling		6.0	
Spacecraft cross coupling		4.5	
Thermal		4.0	
Interplanetary Magnetic		4.0	
Misc small effects		4.0	

DRS Requirements



- ***Flow-down***
  - *35% contingency*
  - *Allocation*
  - *Sub-allocation*
  - *Roll-up arithmetic (RSS or linear)*
- ***Current best estimate***
  - *Models*
  - *Laboratory anchor points*
  - *LPF testing (presently ground, eventually flight)*

Table 1: Summary of DRS Subsystem allocations

	$\times 10^{-16} \frac{m}{s^2\sqrt{Hz}} \sqrt{1+\left(\frac{f}{8\,mHz}\right)^4} \sqrt{1+\left(\frac{0.1\,mHz}{f}\right)}$		
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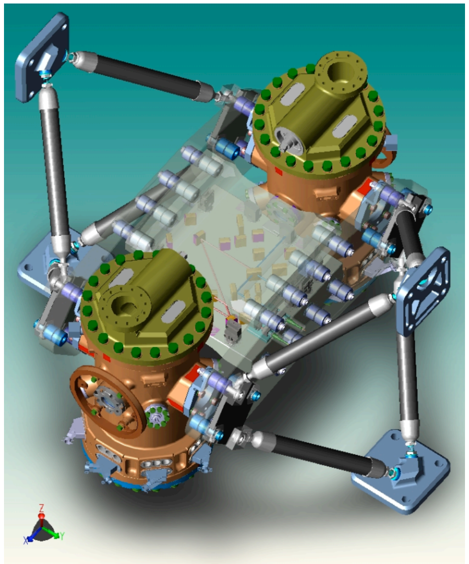
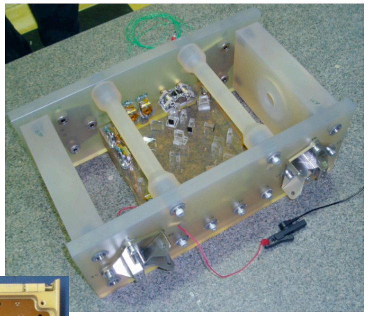
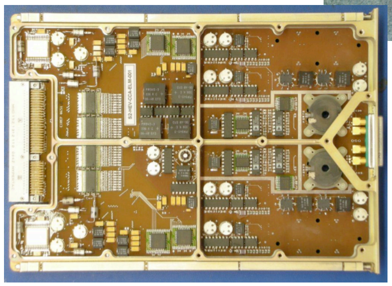
Technology - LISA Pathfinder



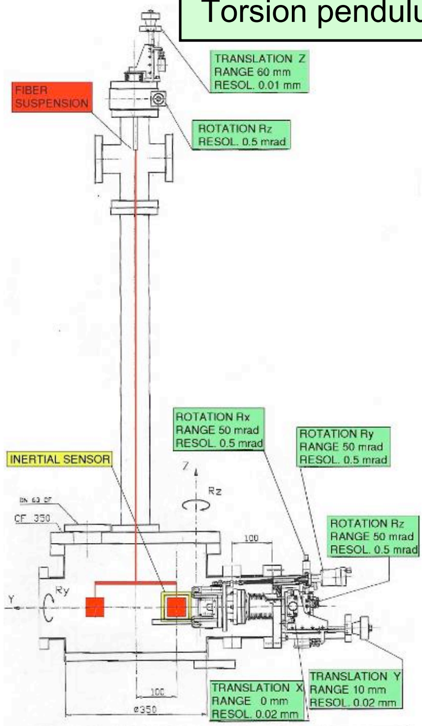
- ***Pathfinder status***
  - *Pathfinder now in implementation phase.*
  - *Ground development is complete.*
- ***GRS***
  - *The Pathfinder GRS is the LISA GRS.*
  - *Demonstrated engineering model performance on torsion pendulum.*
  - *EM successfully passed thermal-vac and vibration testing.*
- ***Drag-free control laws***
  - *Drag-free control similar to LISA configuration will be demonstrated on LPF.*
  - *Better than required performance predicted from full non-linear simulations.*
- ***Laser master oscillator***
  - *Pathfinder flight-qualified laser is LISA Master Oscillator.*
- ***Optical block and opto-mechanical construction***
  - *LTP Bench demonstrates construction materials and techniques.*
  - *Measured performance exceeds requirements.*
- ***[For Thrusters, see Architecture section]***

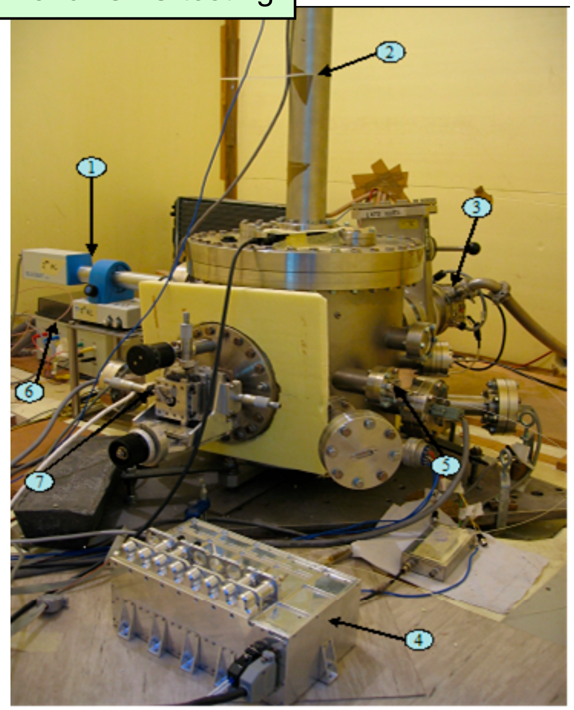




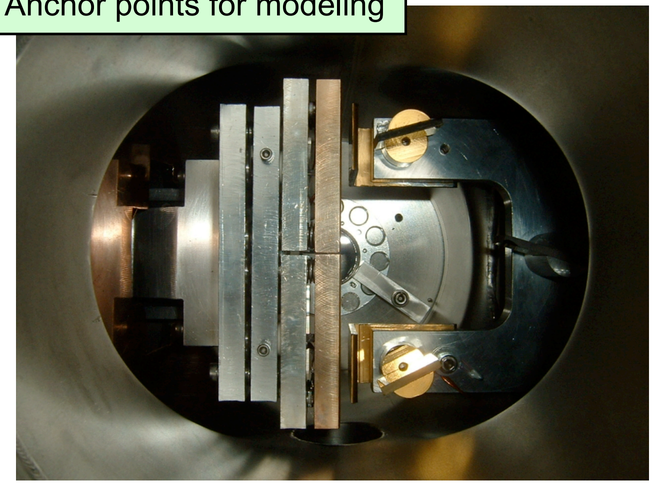
Technology - Ground Development

Torsion pendulums for GRS testing



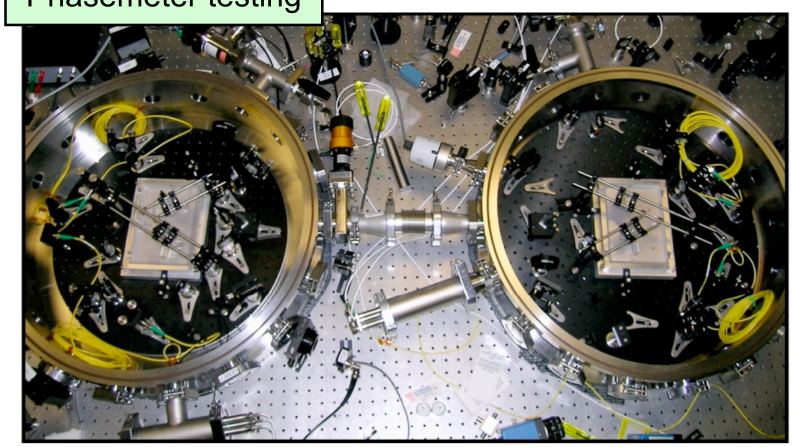


Anchor points for modeling



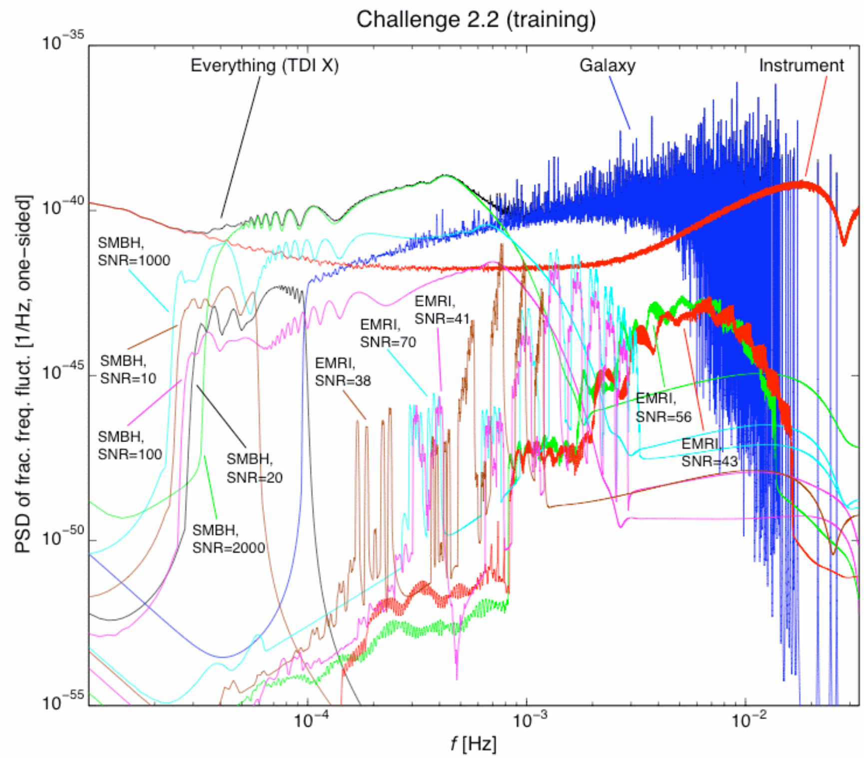
Thruster lifetime testing

Phasemeter testing



Science Operations and Data Analysis

- ***Science operations are straightforward***
  - *Single science mode: observes all the sky, all the sources, all the time*
  - *No pointing of the constellation, no scheduling of detectors or observing slots necessary (or possible)*
  - *Science data volume is small (< 30 Gbyte for 5 year mission)*
- ***Analysis methodology is well-developed***
  - *Time-Delay Interferometry*
    - *High-fidelity simulations*
    - *Laboratory hardware validation*
  - *Algorithms for source detection and parameter estimation*
- ***Data analysis algorithms are being validated with sophisticated high-fidelity simulations***
  - *Planning and implementation underway since 2005*
  - *"Mock LISA Data Challenges provide validation testbed*
  - *Results of round 2 challenge due in June 2007*
    - *All classes of LISA sources + instrumental background (see figure)*



Training data for the ongoing round of data challenges (to be completed in June 2007). The simulated data stream is a high-fidelity representation of the full LISA data set containing instrumental noise plus 4 massive black hole events, 5 EMRI events, and 26.1 million Galactic binaries.

* http://www.tapir.caltech.edu/dowiki/listwg1b:home &

http://astrogravs.nasa.gov/docs/mldc

Summary

- ***LISA will perform a wide range of science***
  - *Formation and growth of massive black holes*
  - *Assembly of galaxies*
  - *Compact-star binaries*
  - *High precision tests of relativity in extreme field limit*
  - *Exploration of cosmology and new physics*
- ***The current mission concept is mature and well-understood***
  - *The science requirements and the associated performance requirements are well understood.*
  - *Architecture is well defined, and extensively analyzed.*
- ***The technology is well advanced.***
  - *LISA Pathfinder has completed ground development and is now in implementation*
  - *Substantial progress has been made on ground-based technology demonstrations*