LISA

Gravitational Wave Astronomy, Relativity Tests, and Massive Black Holes

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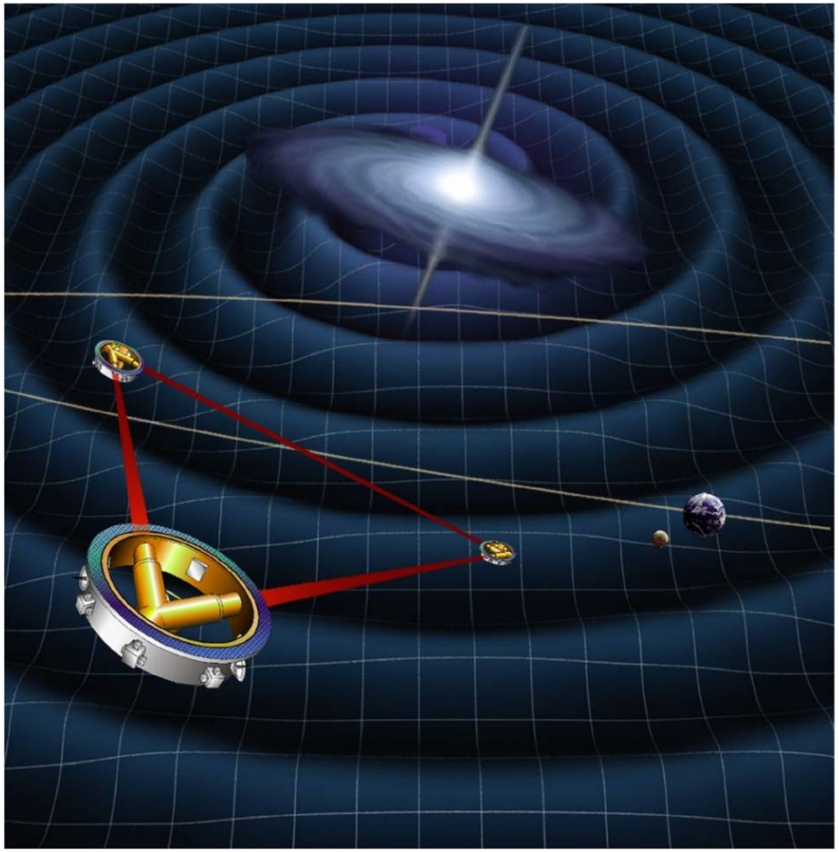
APC *12 May, 2011*

LISA Overview

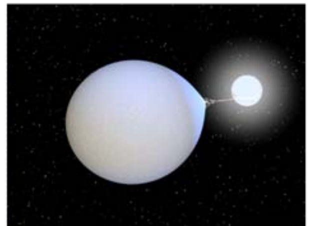


- *The Laser Interferometer Space Antenna (LISA) is a joint ESA-NASA project to design, build and operate a space-based gravitational wave detector.*
- *The 5 million kilometer long detector will consist of three spacecraft orbiting the Sun in a triangular formation.*
- *Space-time strains induced by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

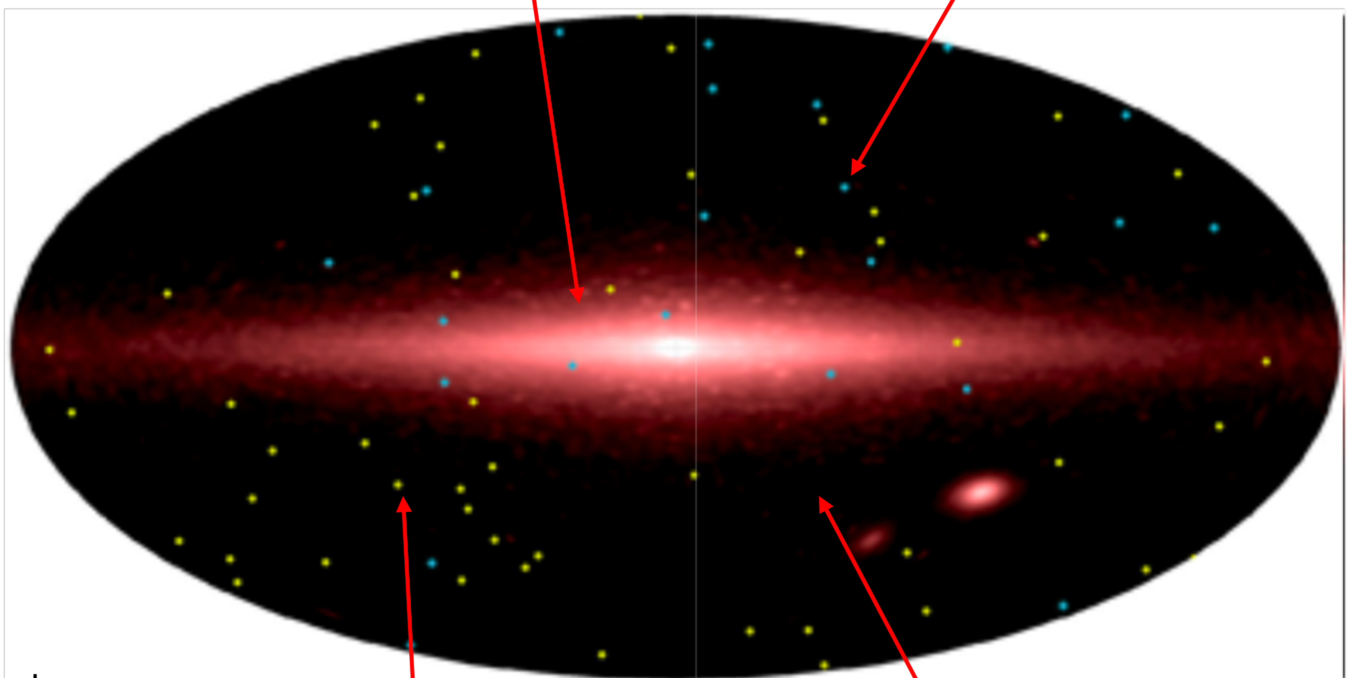
The LISA Sky

Ultra-compact binaries
- ~1 $M_\odot$
- Galactic and extragalactic
- 1000's - 20,000
- Confusion foreground

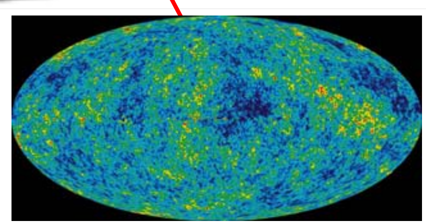


QuickTime™ and a
FF (Uncompressed) decompres
are needed to see this picture

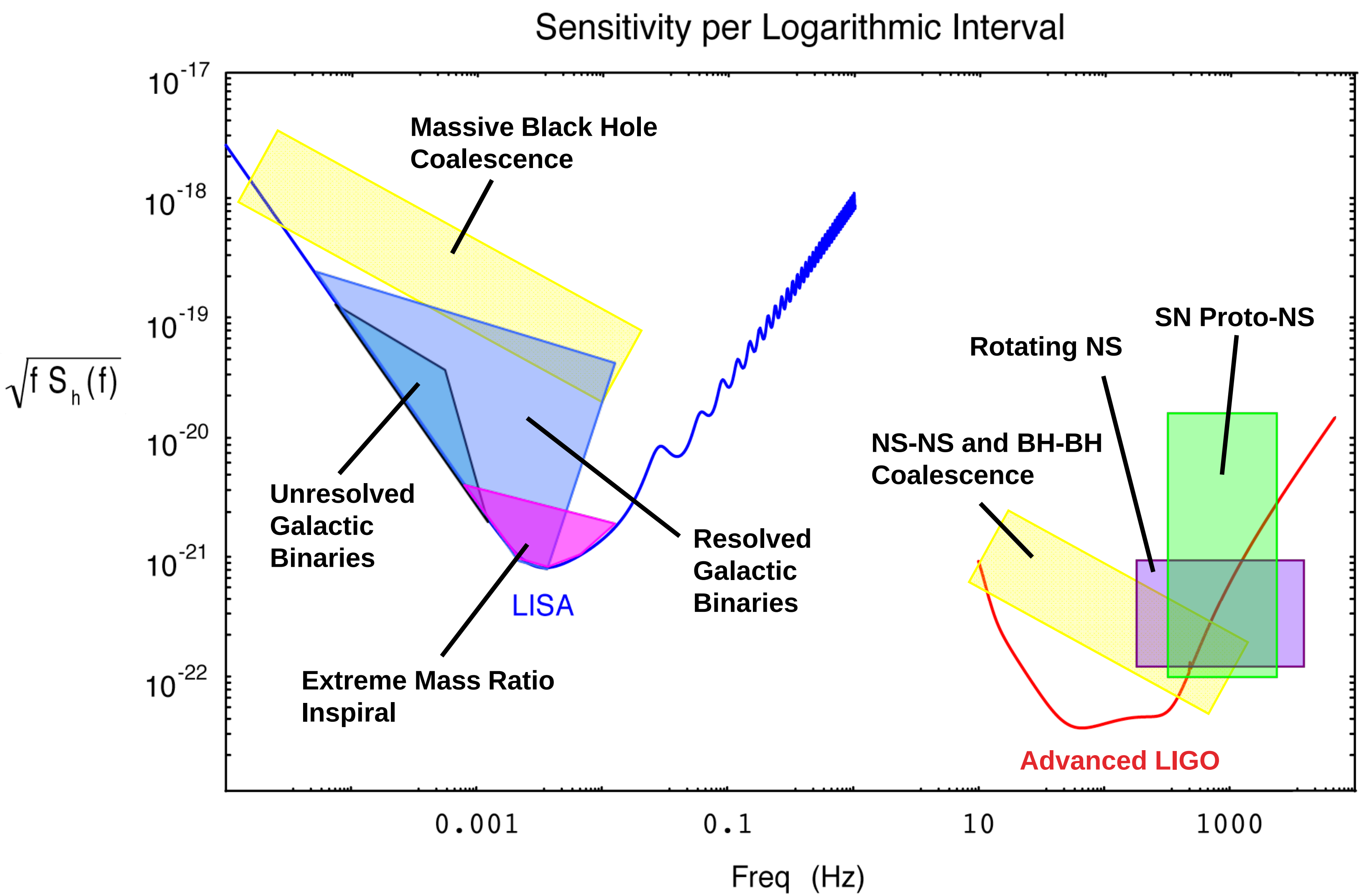
Extreme mass-ratio inspirals
- ~10/ 10^6 $M_\odot$
- $z < 1$
- 10's - 100 per year



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



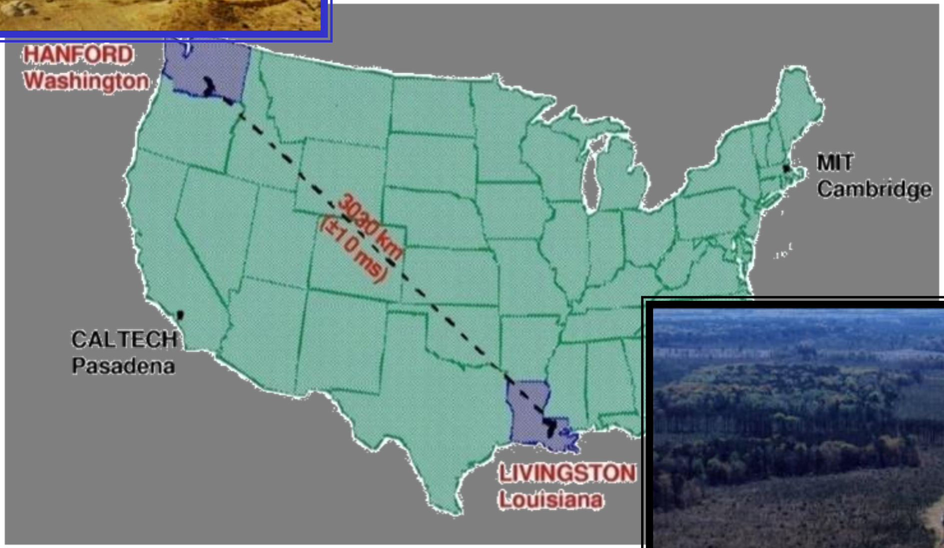
Cosmological back-grounds, bursts and unforeseen sources



Extended Systems ↔ Compact Systems

LIGO: Two Sites, Three Ifos

One interferometer with 4 km Arms, one with 2 km Arms



One interferometer with 4 km Arms

VIRGO: The French-Italian Project
3 km armlength near Pisa

The GEO600 Project

- German-British collaboration, location Hannover / Germany
- Michelson Interferometer with power- and signal-recycling (folded 600m long arms, no armcavities)

MPQ

U Birmingham
U Mallorca

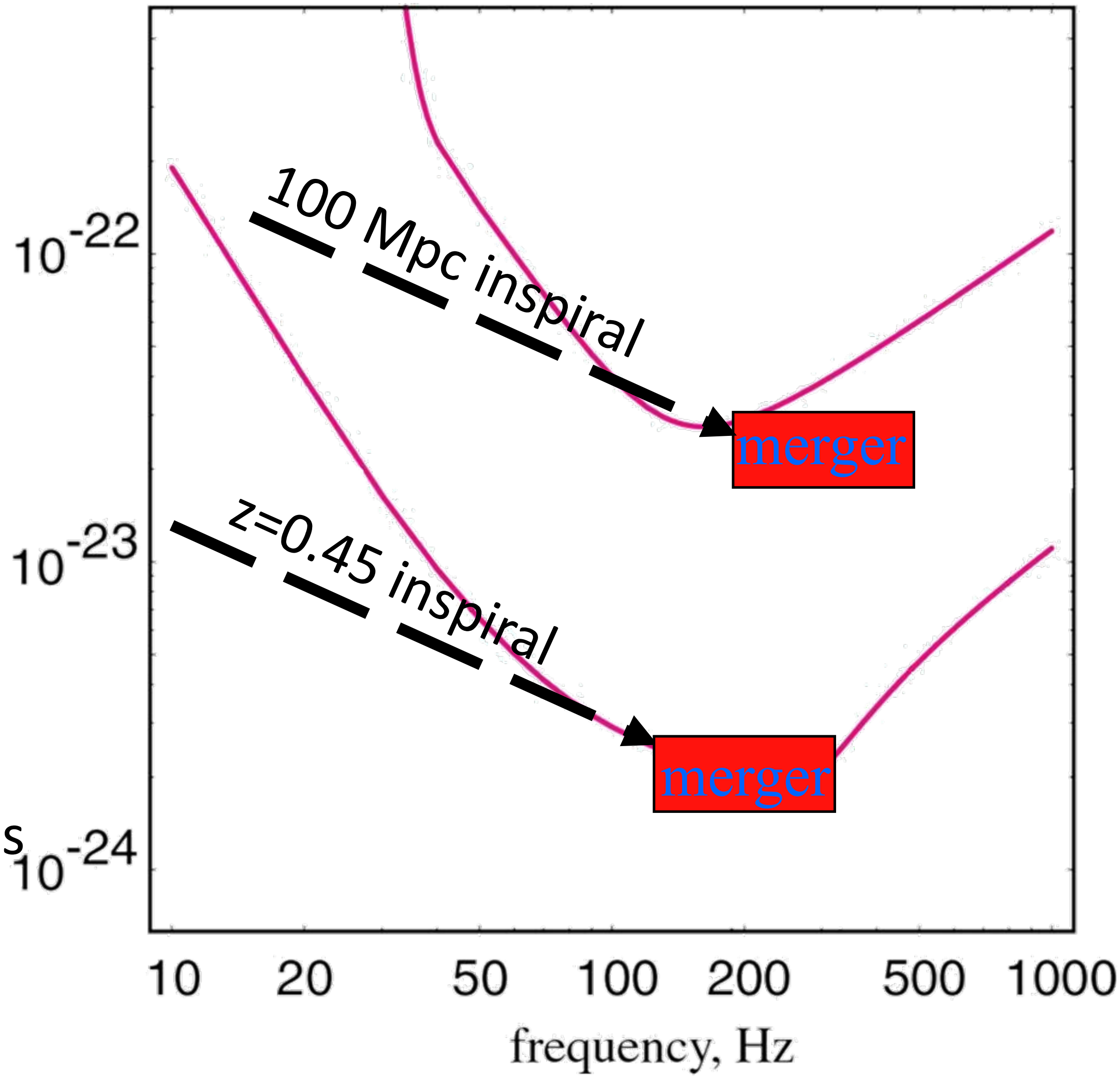
CARDIFF UNIVERSITY

IGR
Glasgow

Advanced LIGO and AdVirgo

- *$10\ M_{sun}$ - $10\ M_{sun}$ BH - BH binaries*
- *Event rates*
  - *Based on population synthesis [Kalogera's summary of literature]*

- Initial IFO event rates
  - Range: 100 Mpc
  - 1 / 600yrs to **~3/yr**
- Advanced IFO event rates
  - Range: z = 0.45
  - **1 / mo to ~30/day**



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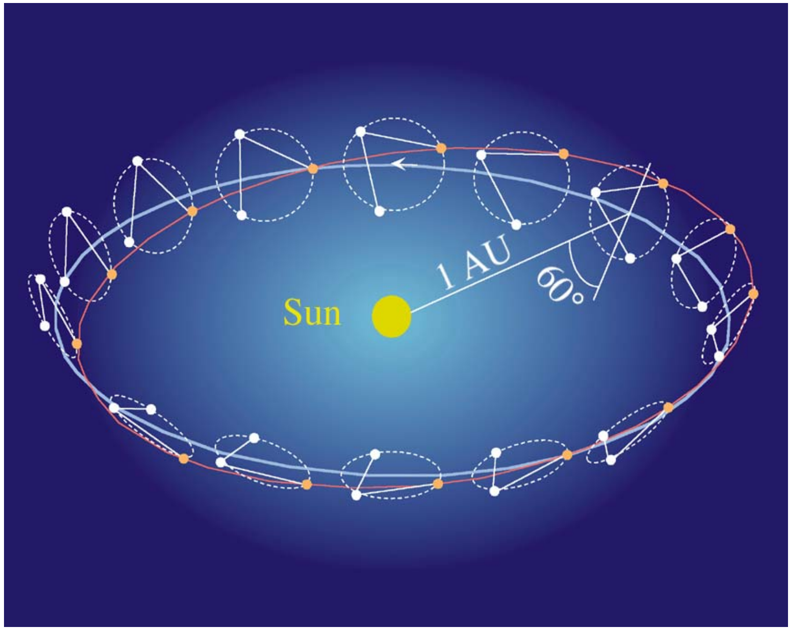
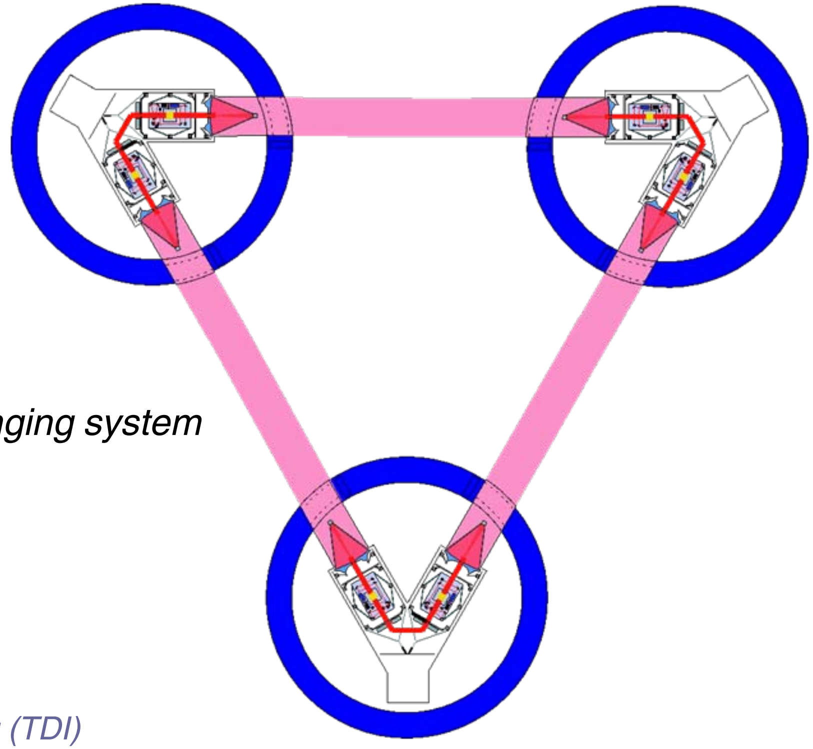
What the science instrumentation does

- **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*



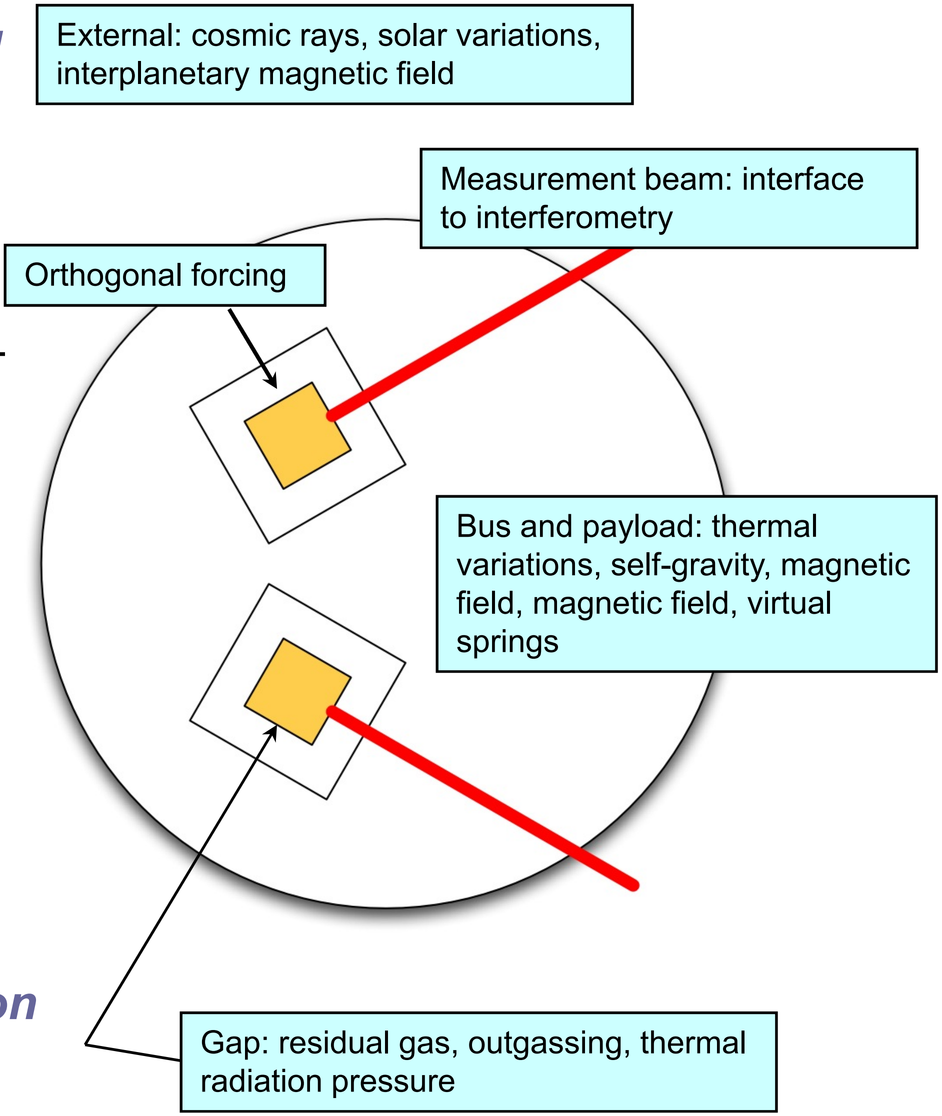
How the science instrumentation works



- **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

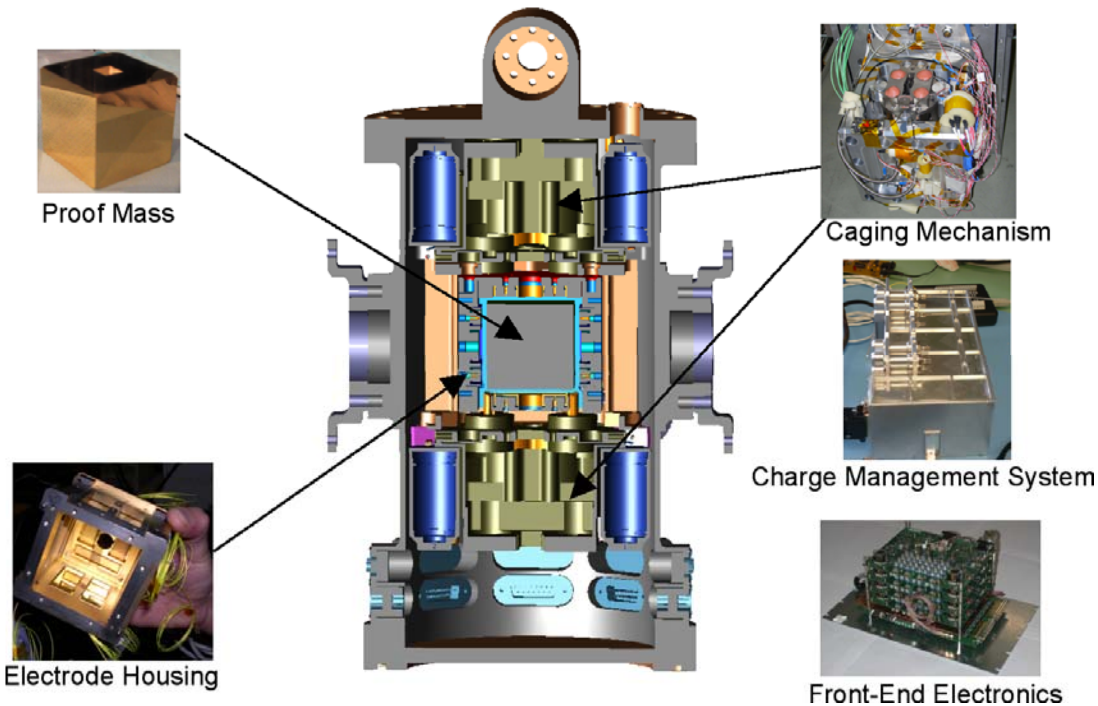
Disturbance Reduction - what it does

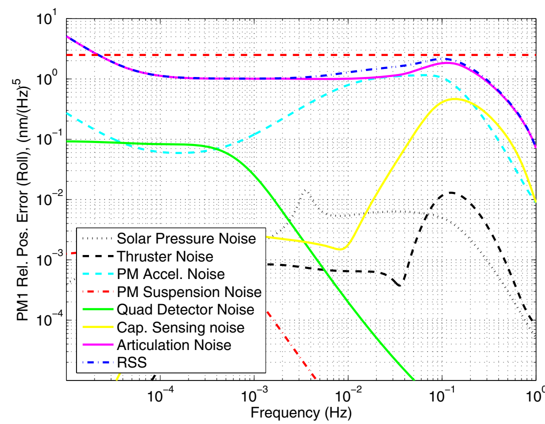
- ***Proof mass is the free-falling mirror***
- ***Housing***
  - *Sensing for drag-free and charge control*
  - *Forcing in orthogonal degrees-of-freedom*
- ***Active discharging***
- ***Quiet environment***
  - *Vacuum enclosure*
  - *Thermal isolation*
  - *Low magnetic field from payload and bus*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

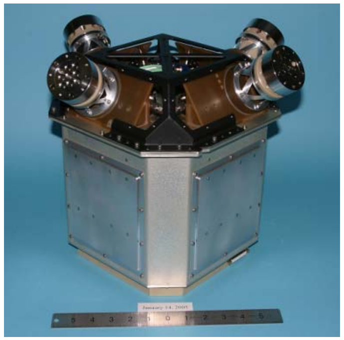


Disturbance Reduction - what it takes

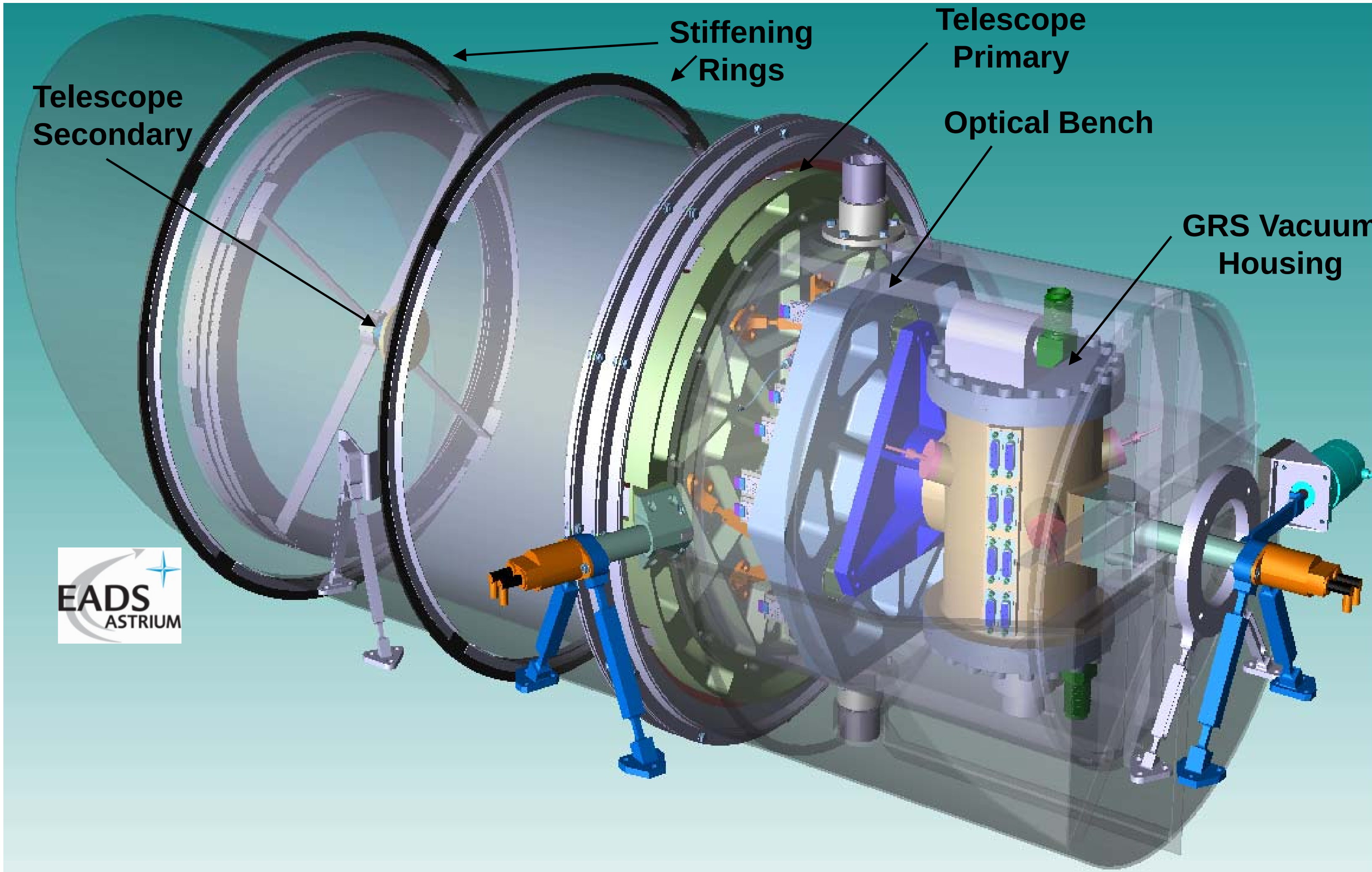
- **Gravitational Reference Sensor**
  - *Proof mass - 44 mm cube, Au:Pt*
  - *Reference housing with capacitive sensing and electrostatic forcing*
  - *Charge control with UV light*
  - *Caging, vacuum system*
- **“Drag-free” control laws**
  - *3 x 19 Degrees of freedom*
  - *Acquisition*
- **Micronewton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





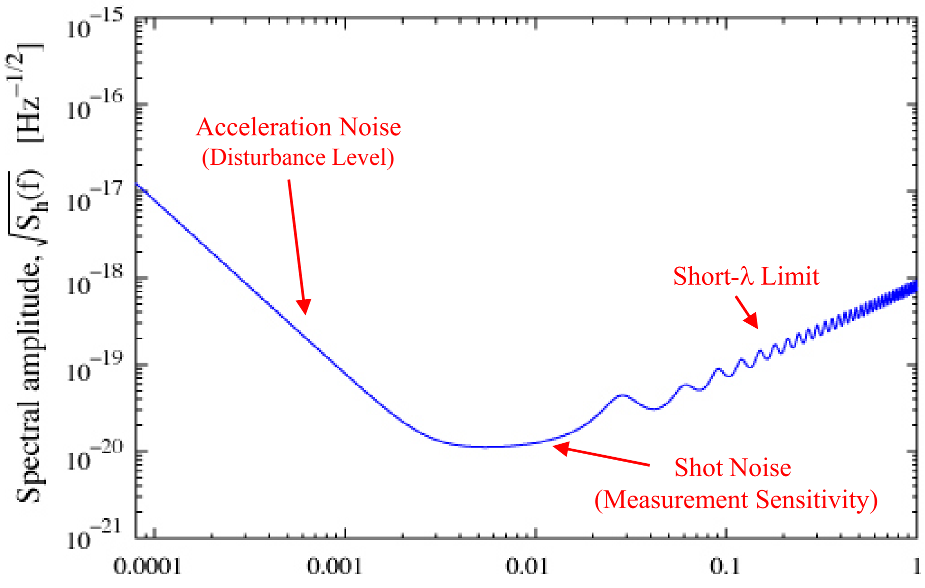


Payload: Optical Assembly



LISA Sensitivity

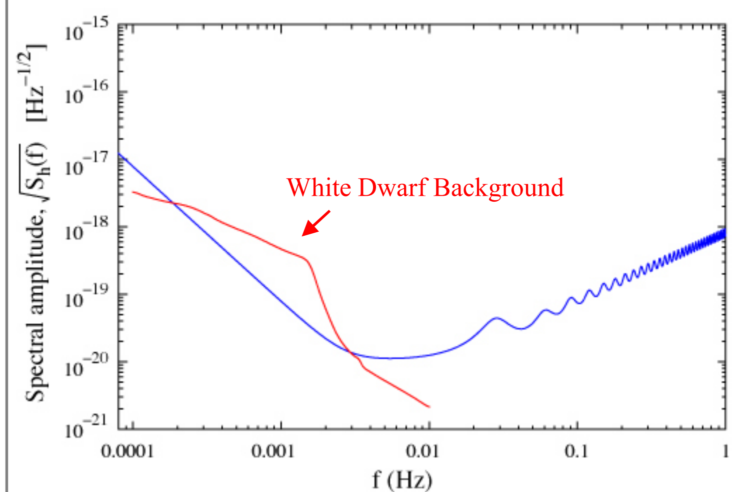
2-arm “Michelson” sensitivity $\left(h * \sqrt{T_{obs}}\right)$



0.1 mHz *1 Hz*

frequency

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

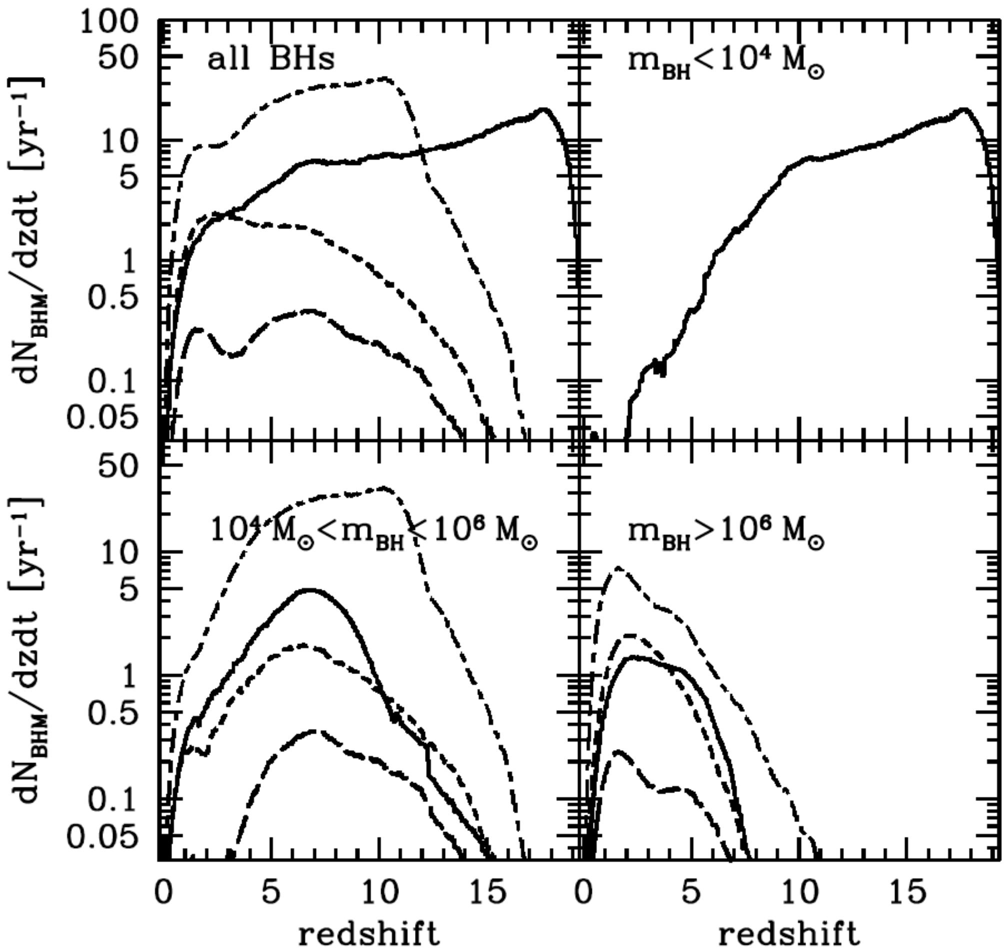


(Includes gravitational wave transfer function averaged over sky position and polarization). Source sensitivities plotted as *h×Sqrt[Tobs])*.

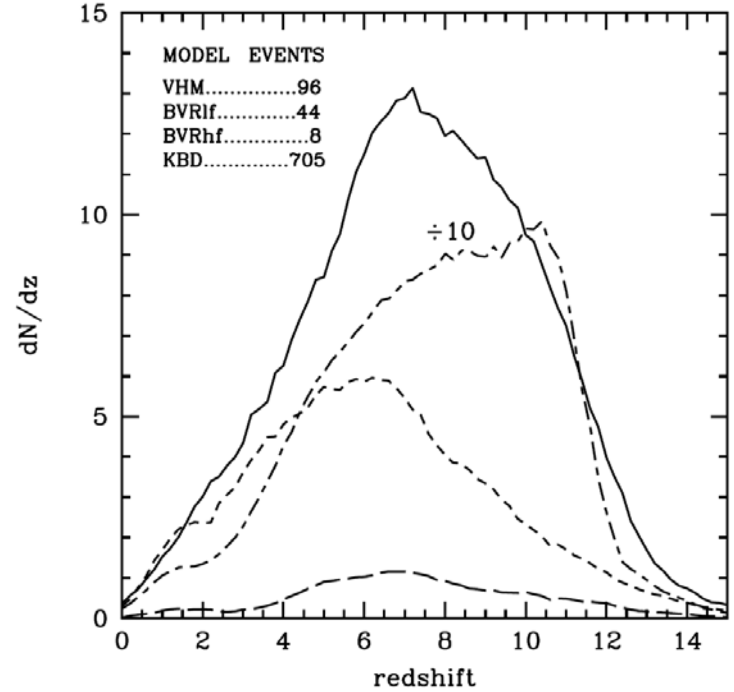
Trace the merger history of MBHs and their host galaxies

- ***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 Rates



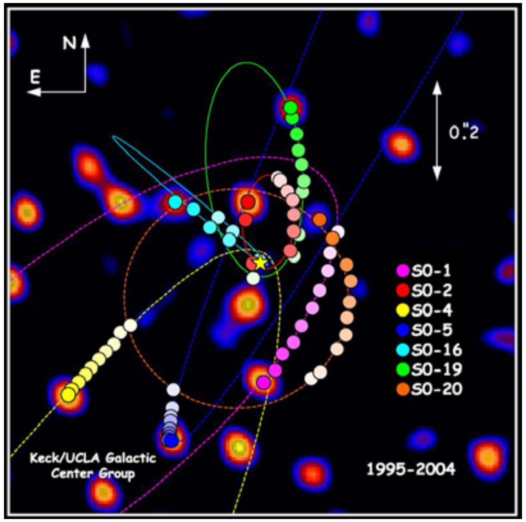
Sesana, Volonteri & Haardt 2007

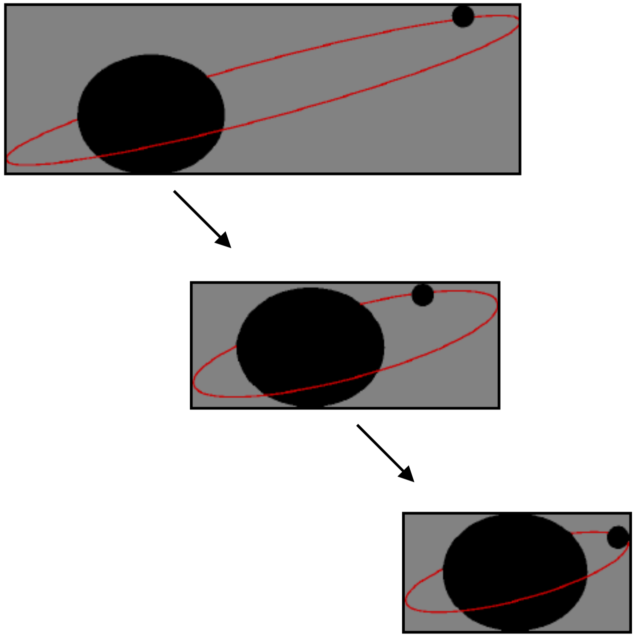


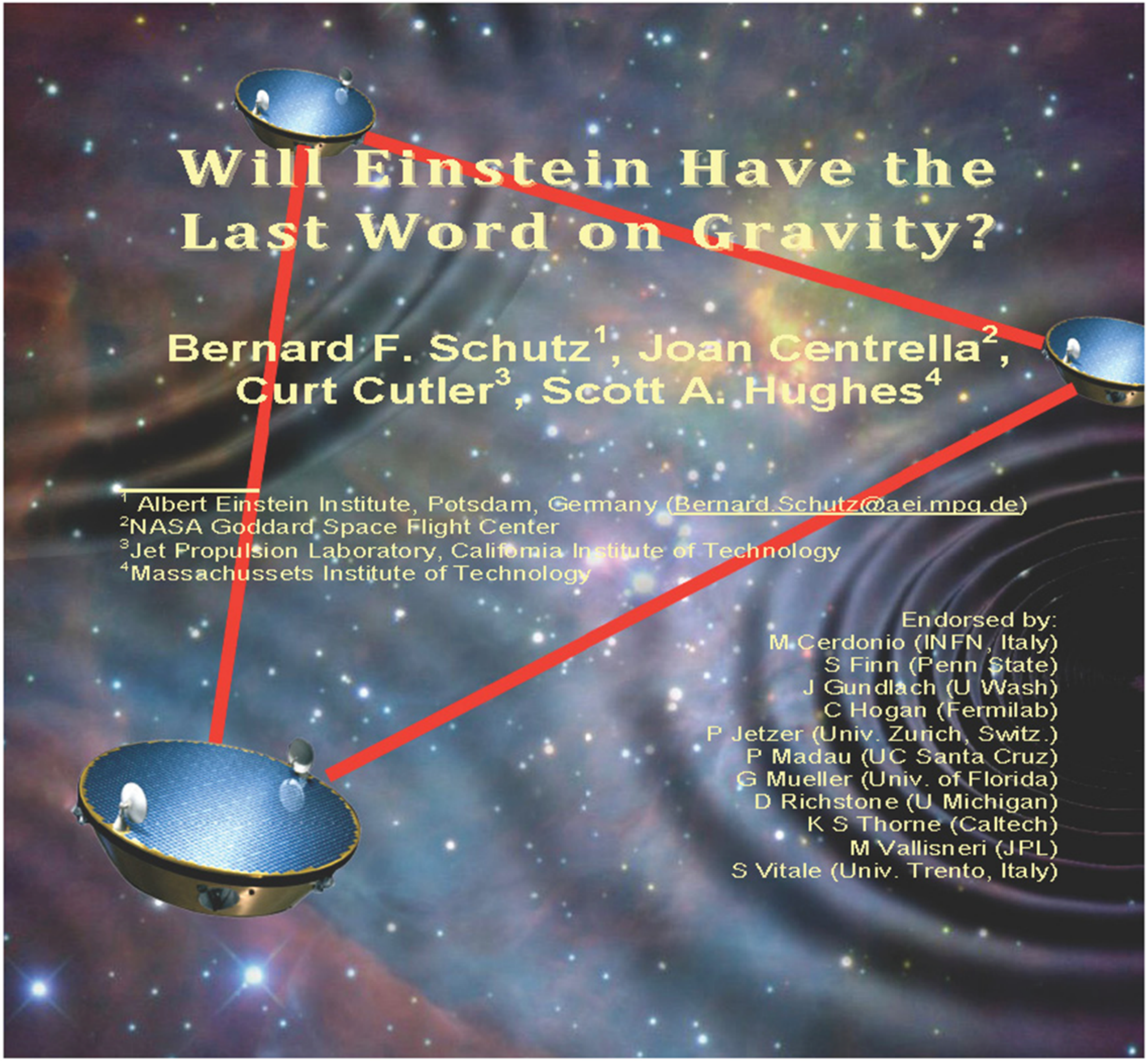
Solid line is VHM model (150 $M_\odot$ seeds from Pop III stars). Short-long dashed is KBD model ($10^{4-5}\ M_\odot$ seeds from cool clouds). Short dashed is BVRlf model (grav. collapse in clouds, low feedback). Long dashed is BVRhf model (grav. collapse in clouds, high feedback). Totals are for 3 yr mission.

Capture of Compact Objects by Massive Black Holes

- ***Observations of our own Galactic Center indicate that nuclei of normal galaxies are complex and interesting***
  - *Young massive stars orbiting 4 x 10^6 $M_\odot$ BH*
  - *Other (dark) objects should also be orbiting*
    - *Neutron stars*
    - *Stellar-mass BHs*
    - *White dwarf stars?*
- ***LISA can detect captures out to Gpc distances***
  - *Estimate that 10’s to 100’s of stellar-mass BH captures will be seen over course of LISA mission*
    - *Unique information on masses and spins of massive BHs in centers of normal galaxies*
    - *Unique information on compact object populations in galactic nuclei*






Will Einstein Have the Last Word on Gravity?
Bernard F. Schutz[1], Joan Centrella[2], Curt Cutler[3], Scott A. Hughes[4]
[1] Albert Einstein Institute, Potsdam, Germany (Bernard.Schutz@aei.mpg.de)
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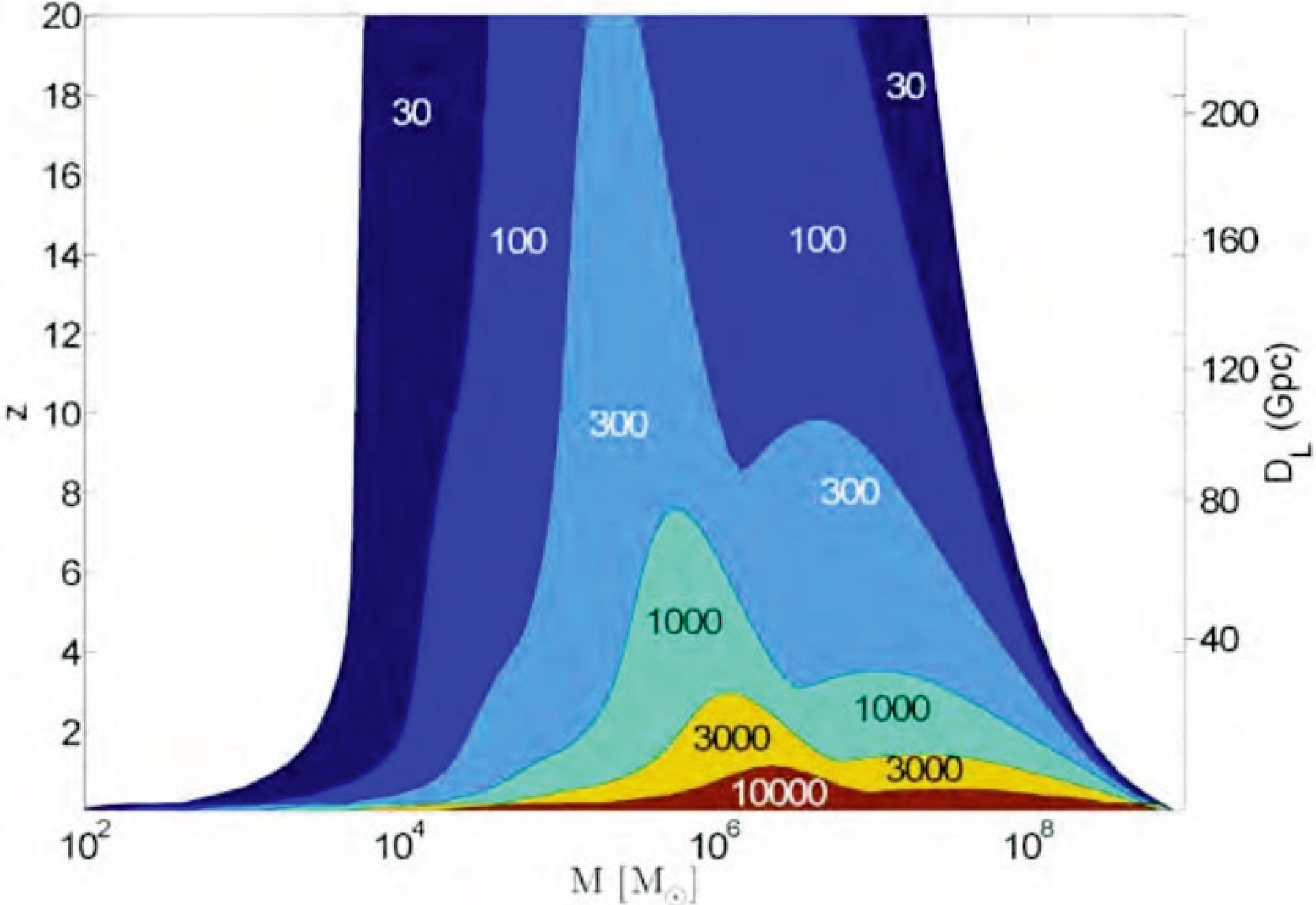
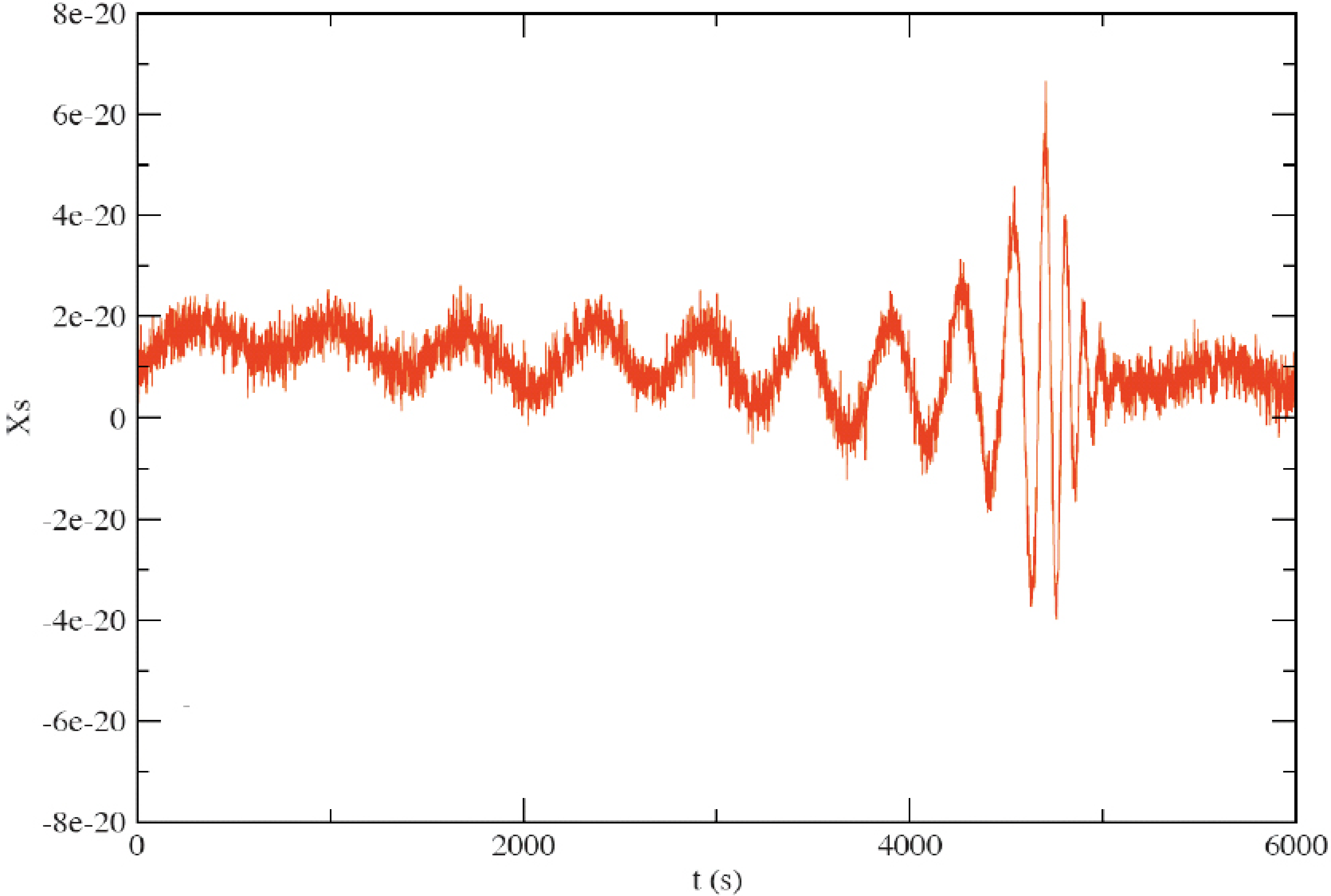
J Gundlach (U Wash)
C Hogan (Fermilab)
P Jetzer (Univ. Zurich, Switz.)
P Madau (UC Santa Cruz)
G Mueller (Univ. of Florida)
D Richstone (U Michigan)
K S Thorne (Caltech)
M Vallisneri (JPL)
S Vitale (Univ. Trento, Italy)

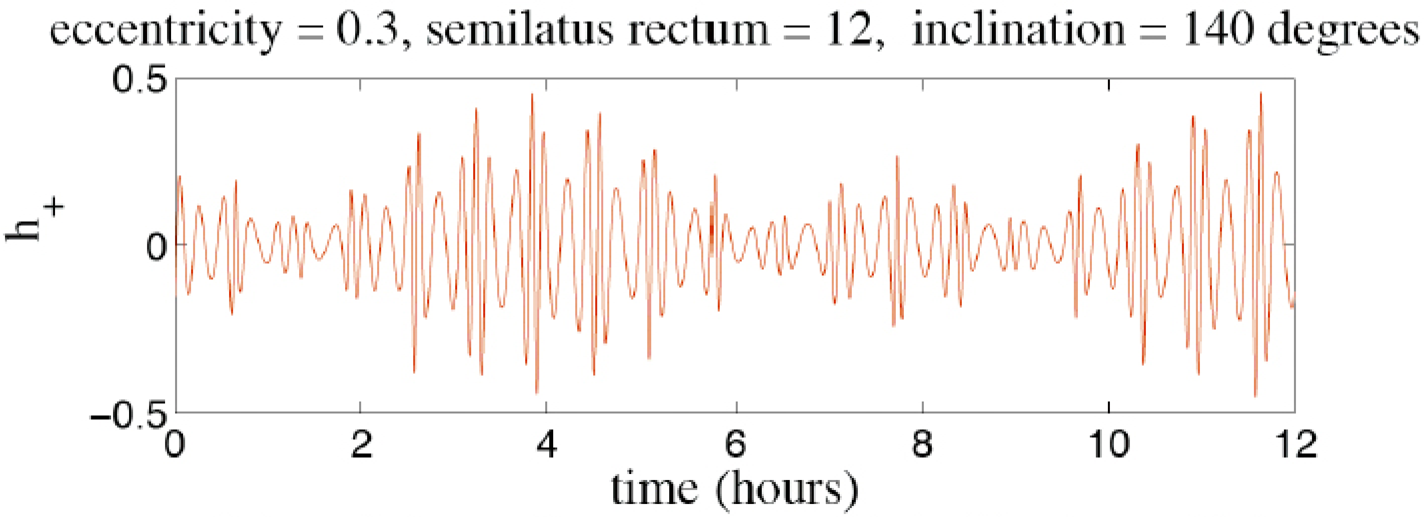
High SNR observations out to z = 20

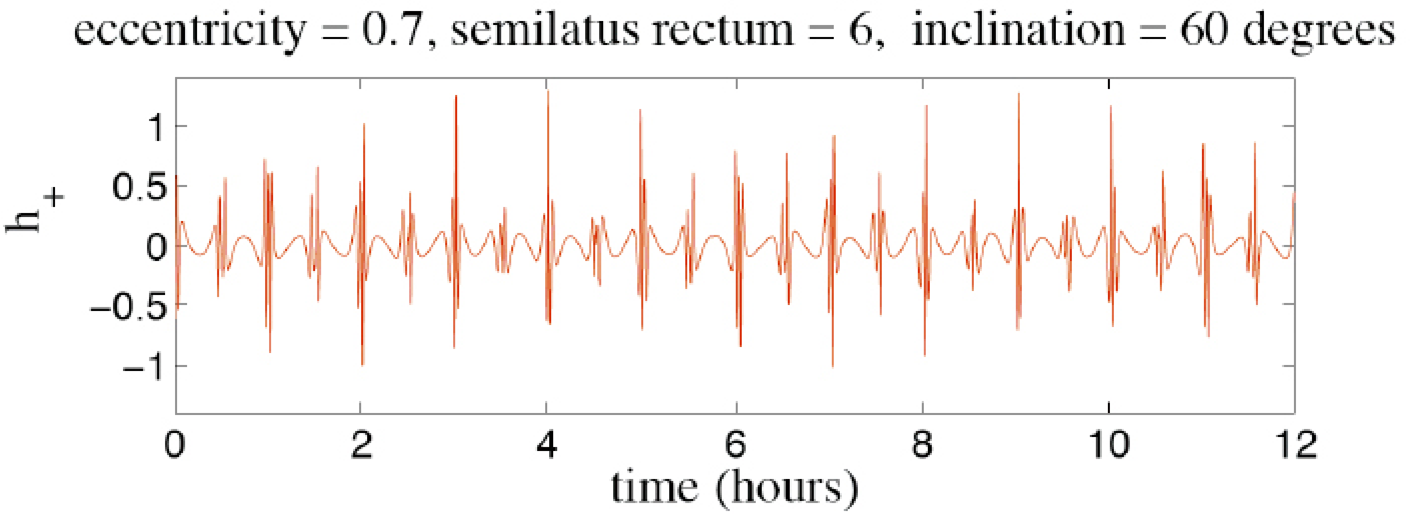


Strong signals even from z = 15

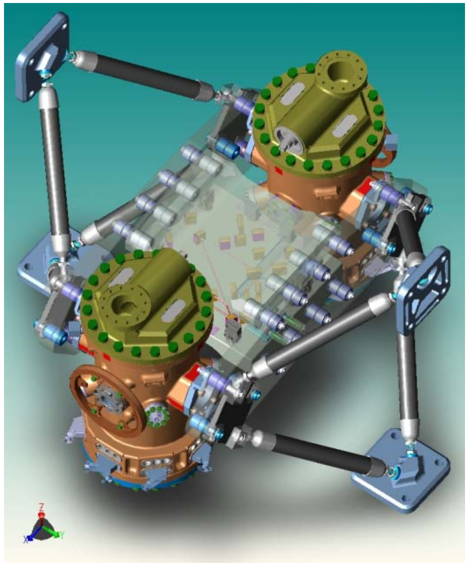


Capture waveform: encoding the geometry

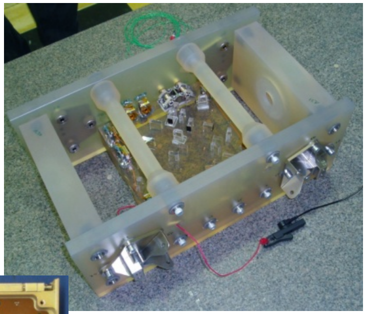


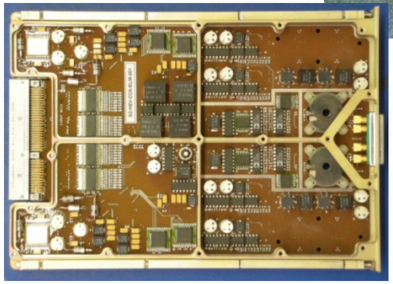


Technology - LISA Pathfinder

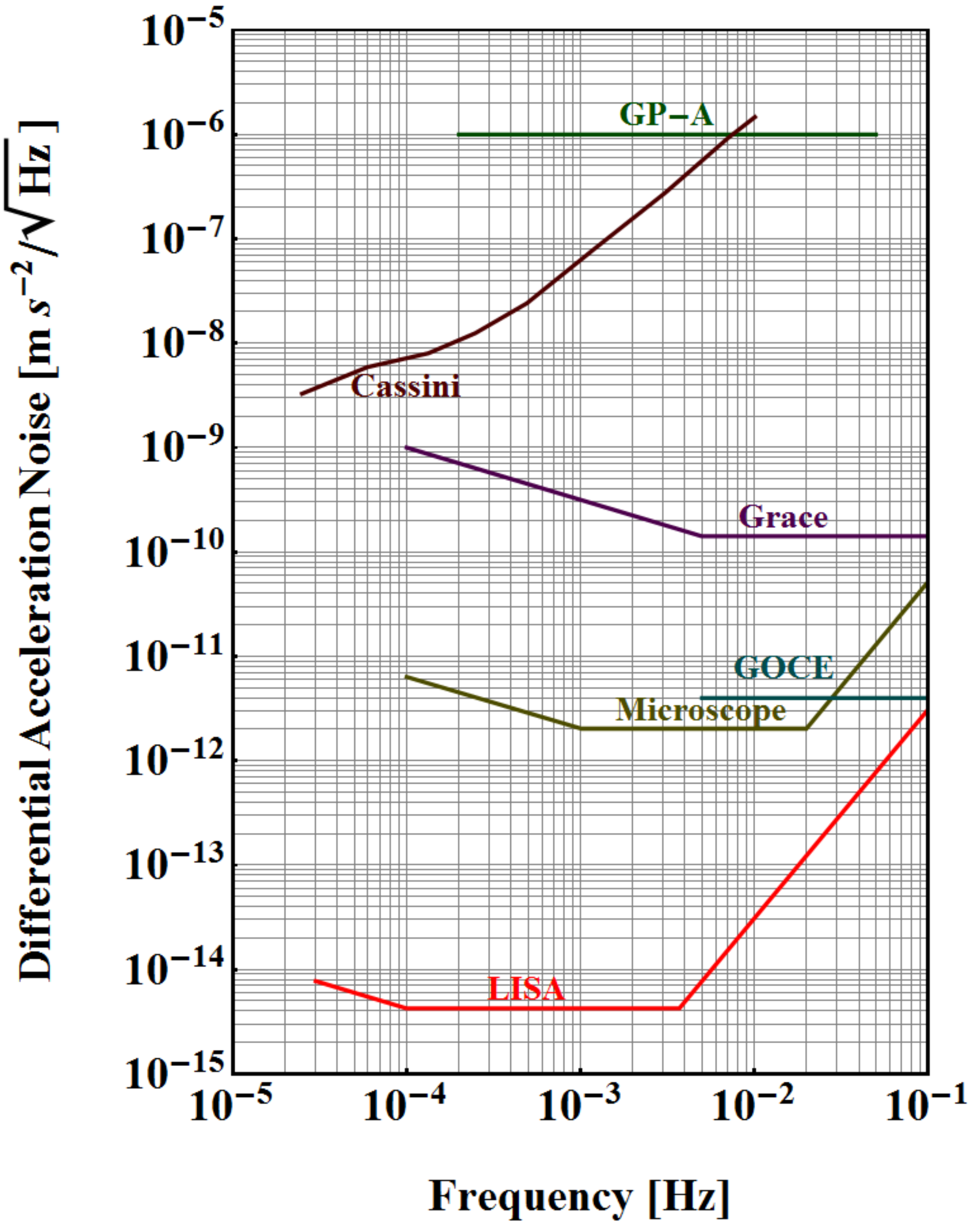


- **Pathfinder status**
  - Pathfinder now in implementation phase.
  - Ground development is complete.
- **GRS**
  - The Pathfinder GRS is the LISA GRS.
  - Demonstrated engineering model performance on torsion pendulum.
  - EM successfully passed thermal-vac and vibration testing.
- **Drag-free control 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]**

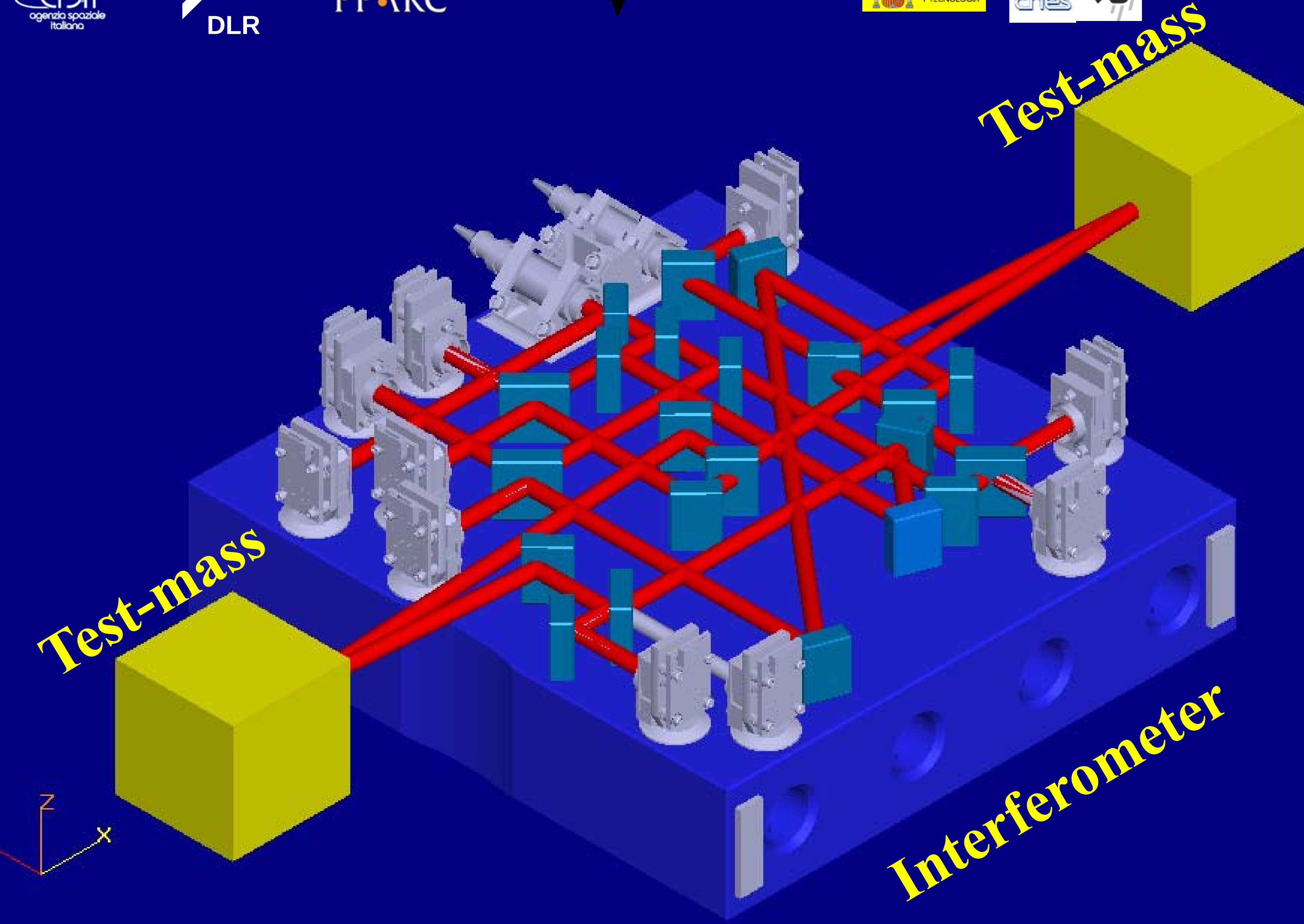


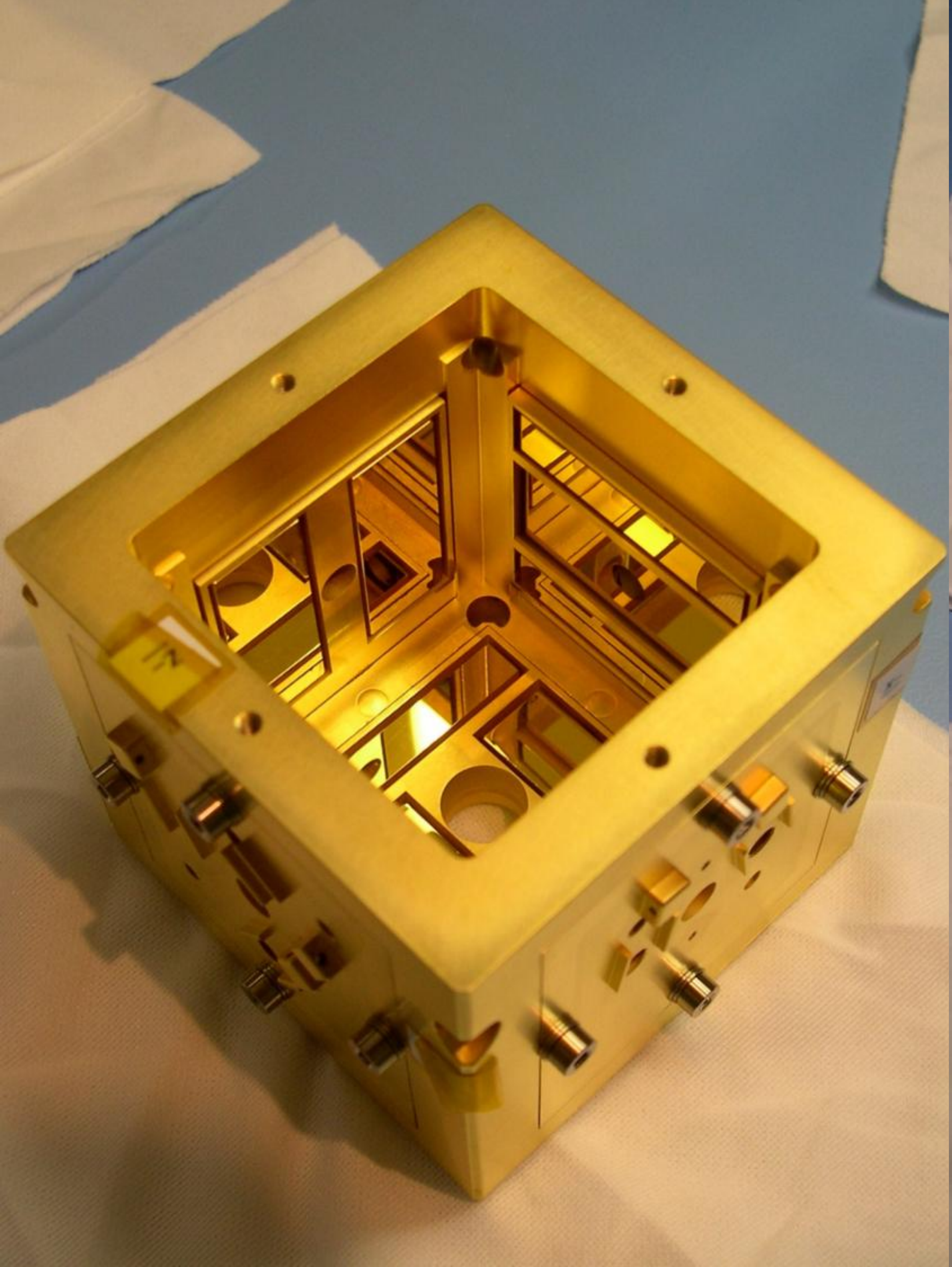


Differential acceleration performance

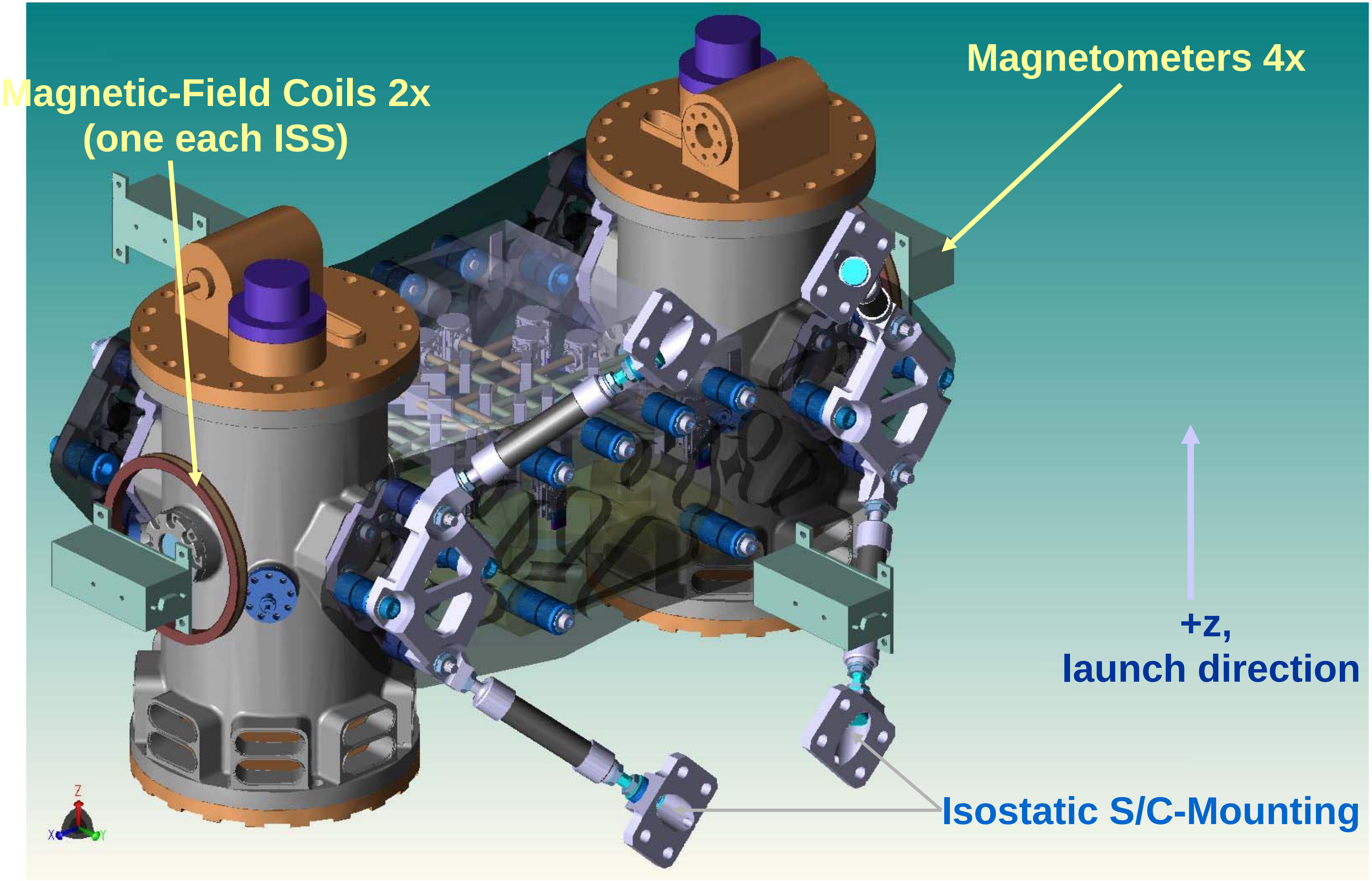


agenzia spaziale italiana DLR The Physics of the Universe PPARC SSO SRON MINISTERIO DE CIENCIA Y TECNOLOGÍA cnes CNRS



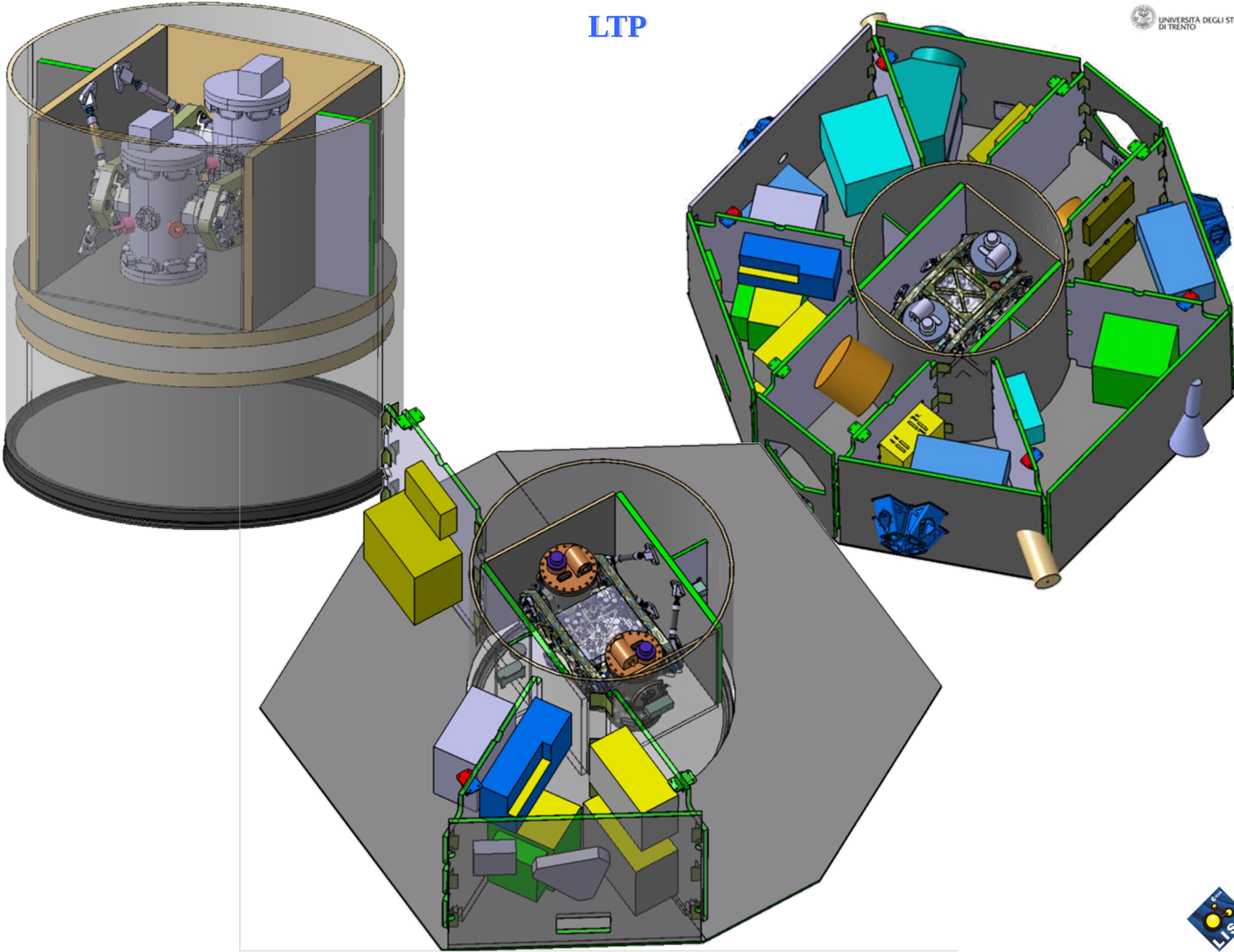



FACE Z TOP B


Magnetic-Field Coils 2x
(one each ISS)
Magnetometers 4x
+z,
launch direction
Isostatic S/C-Mounting

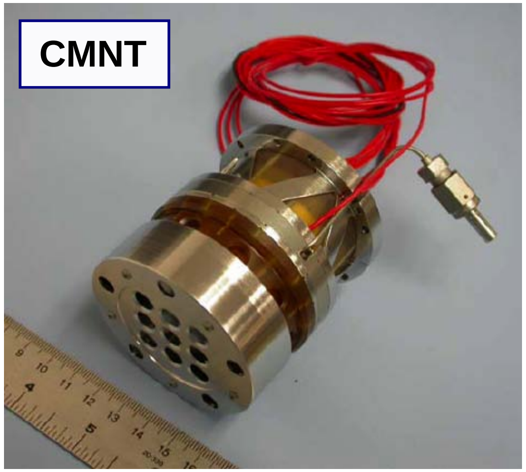
LTP

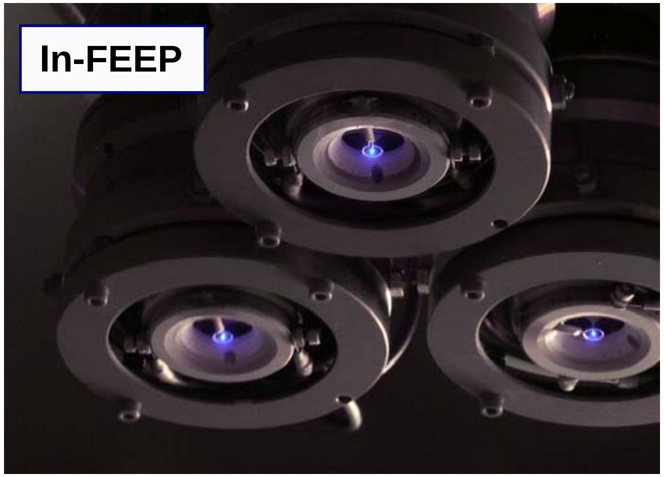
UNIVERSITÀ DEGLI STUDI DI TRENTO



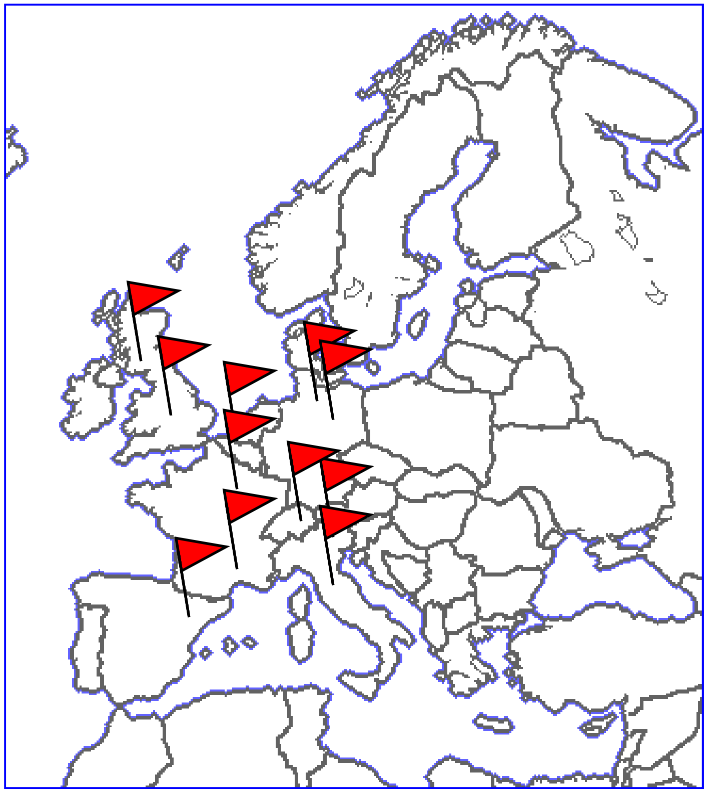
Technologies – μN Thrusters

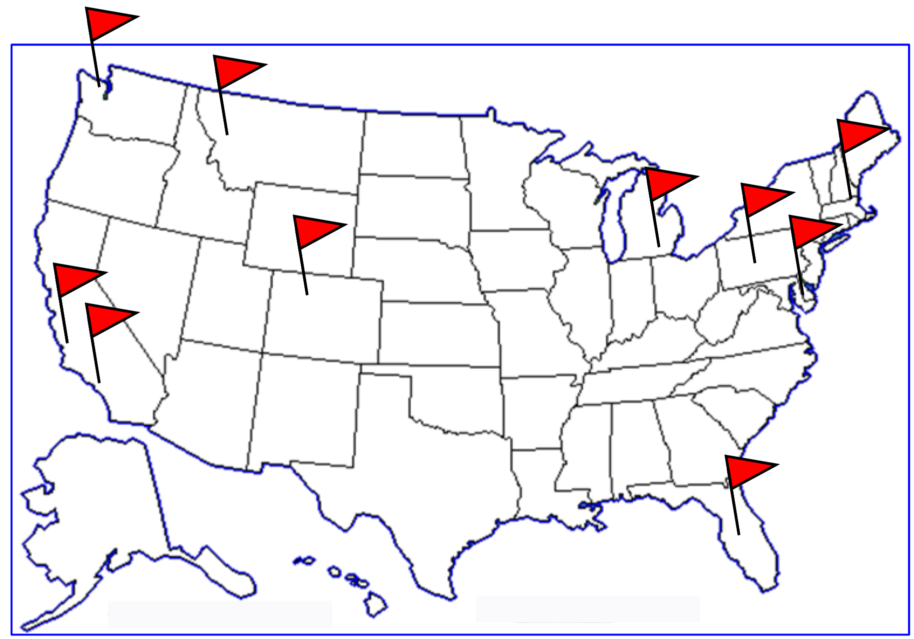
- ***Three different thrusters under development -***
  - Busek Co. Colloid Micro-Newton Thruster (CMNT), ARC Seibersdorf indium needle Field Emission Electric Propulsion (FEEP) and ALTA S.p.A cesium slit FEEP
- ***Engineering models for all three types have met performance requirements***
- ***Lifetime demonstration is the major remaining task***
  - > 50,000 hours of operation with multiple thruster units and 3000-hour class long-duration tests over the past 3 years
  - Full EM-level life tests completed for all 3 Pathfinder candidates up to 3400 hours





LISA International Science Team





THE LOW-FREQUENCY GRAVITATIONAL WAVE SITUATION AFTER LISA

Peter L. Bender
JILA, University of Colorado and NIST

1. The scientific case for early flight of a first space GW mission to observe the signals from massive black hole mergers throughout the universe and from inspirals of stellar mass black holes into galactic center black holes appears to be strong.

2. But, the justification for a second space GW mission will depend strongly on what the first one finds.

3. LISA is expected to tell us a great deal about IMBH formation and growth at early times, and their relationship with galaxy evolution.

4. However, it seems likely that a second mission with sufficient sensitivity and the proper frequency response would provide considerably more detailed information on these subjects.

Possible Main Scientific Objective for a Second GW Mission: Detailed Study of the Formation and Growth of IMBHs

1. A number of scenarios are being investigated for how intermediate mass black holes formed and then grew.

2. Different scenarios could have been responsible for forming the IMBH seeds for SMBHs in quasars at $z = 6$ than for the roughly 10^6 to 10^7 $M_{\odot}$ MBHs in many galaxies today.

3. Although most IMBH growth took place by gas accretion, a significant fraction may have been due to inspiral of stellar mass black holes in high-mass cusps in galactic nuclei.

4. If so, gravitational waves from such inspirals would provide a valuable tracer for the formation and initial growth of IMBHs.

Tentative Design for ALIA

1. 3 spacecraft forming an equilateral triangle, as for LISA.

2. 500,000 km arm lengths.

3. 1 meter diameter send/receive telescopes.

4. 30 W of laser power at 1.064 micron wavelength.

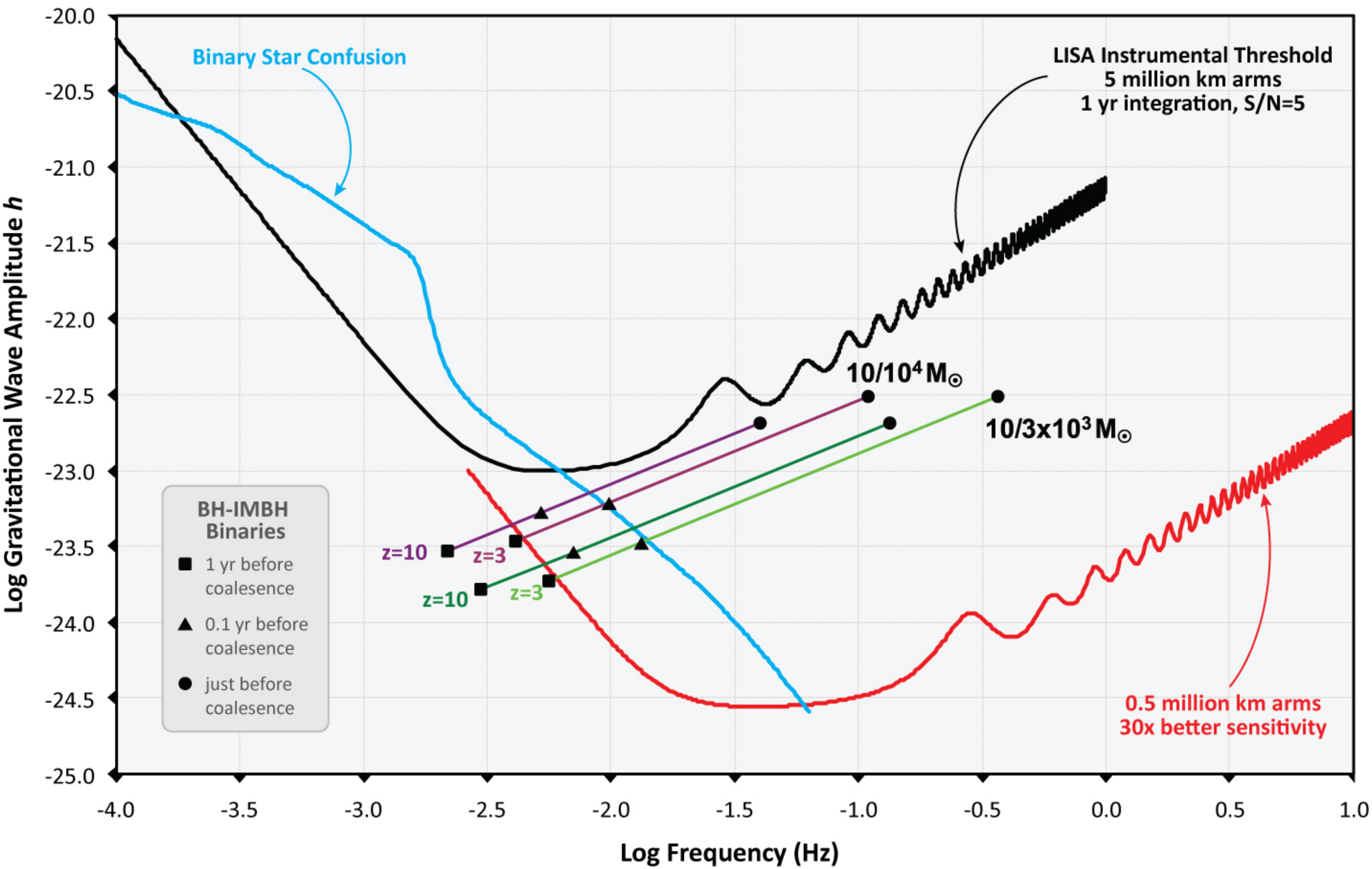
5. $< 3 \times 10^{-16}$ m/s^2/√Hz spurious accelerations of test masses from 3 to 30 millihertz.

6. Beam pointing jitter corrections: < 0.1 nanorad/√Hz.

Reference:

P. L. Bender and M. C. Begelman, in Trends in Space Science and Cosmic Vision 2020, ESA SP-588, Proc. 39th ESLAB Symp., Noordwijk, 19-21 April, 2005.

Strain Amplitudes During Last Year Before BH-IMBH Coalescence



Results from Gair et al. (2009) Approach for $M_2 = 10\ M_\odot$