Astrophysics & Gravitational Physics with the LISA Mission

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Workshop on Robotic Science from the Moon

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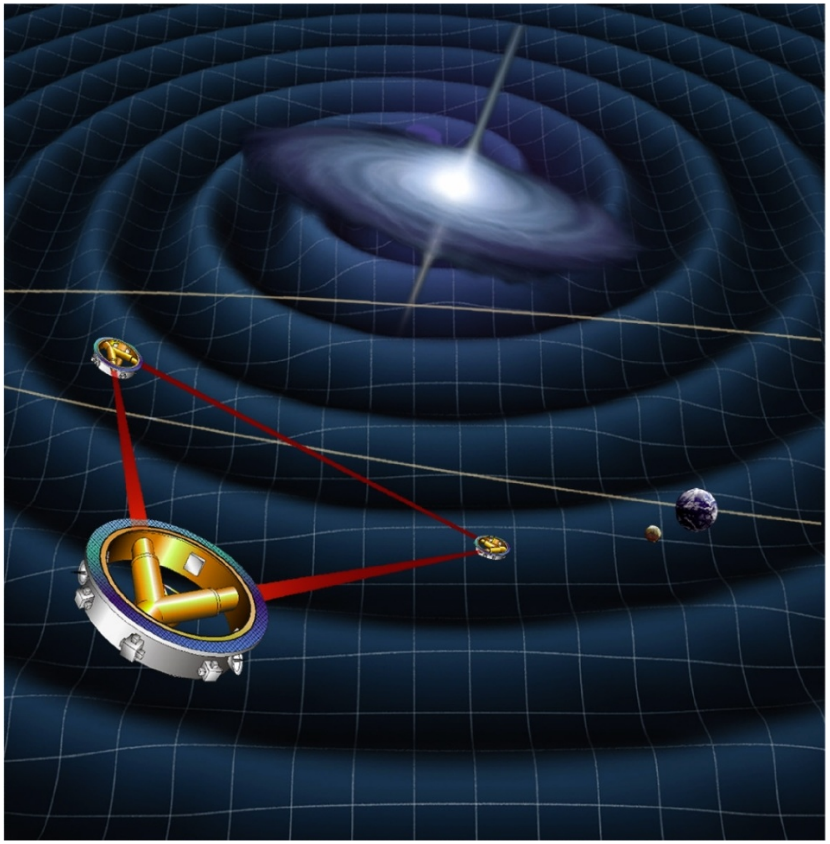
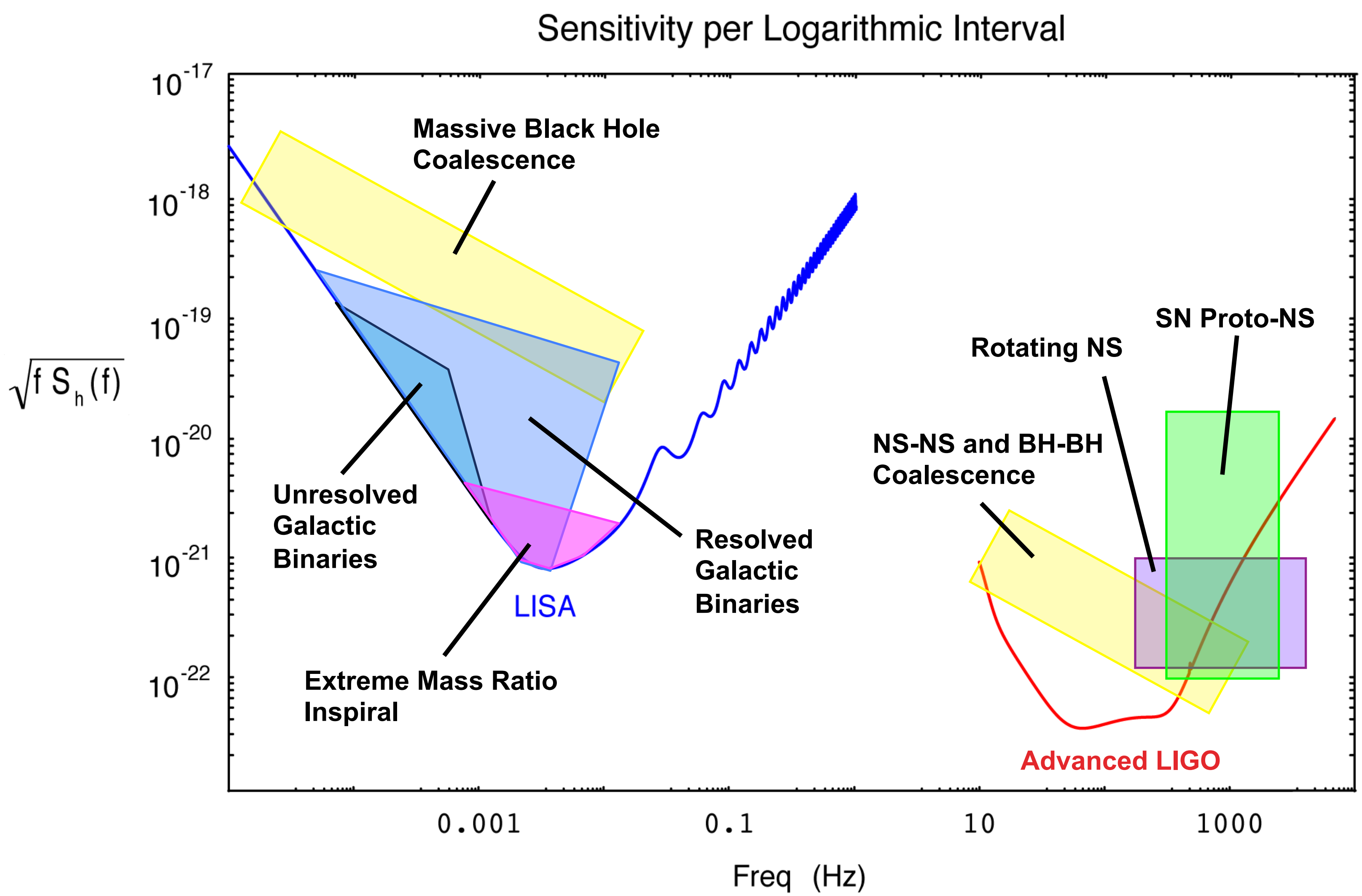
LISA Overview



- ***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.***

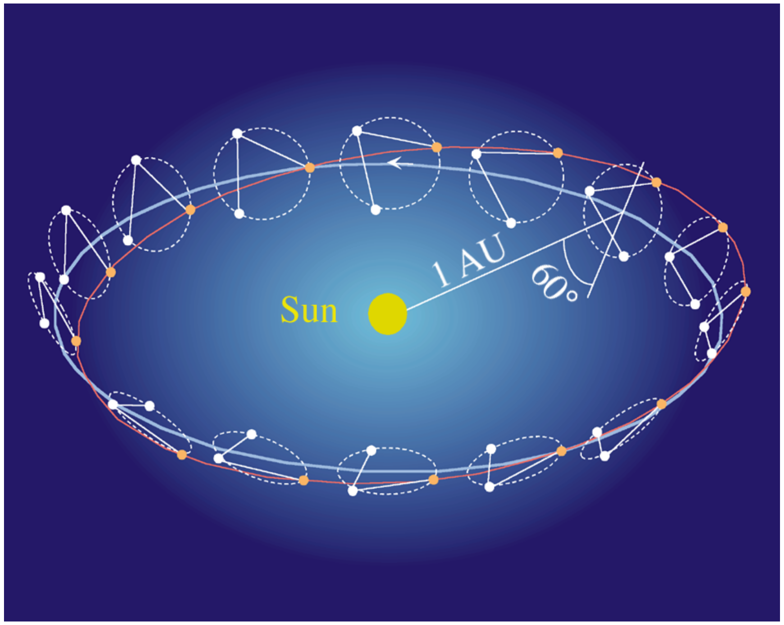
- LISA is expected to detect signals from merging massive black holes, compact stellar objects spiraling into supermassive black holes in galactic nuclei, thousands of close binaries of compact objects in the Milky Way and possibly backgrounds of cosmological origin.



Extended Systems ⟷ Compact Systems

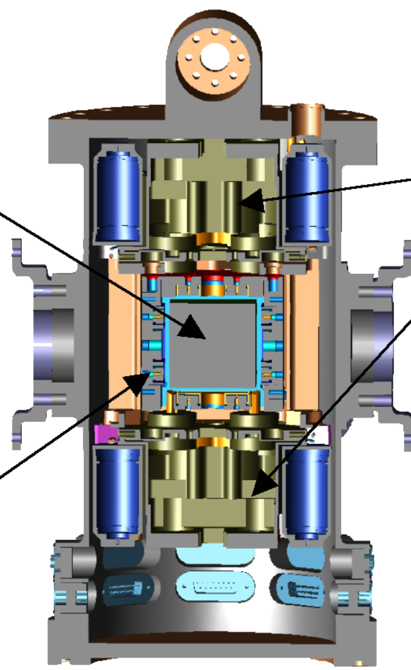
What the science instrumentation does

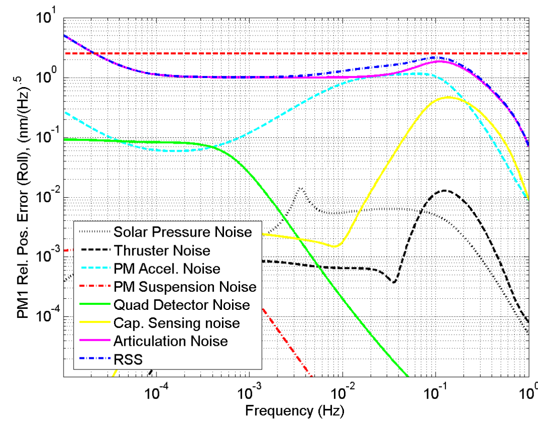
- **Measure changes in relative separation between proof masses**
  - Continuous laser ranging between free-falling proof masses
  - Interferometric readout (μcycles/√Hz over gigameters with 1μ light)
  - Performance characterized by displacement noise
- **Reduce disturbances**
  - Benign environment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

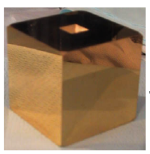


Disturbance Reduction - what it takes

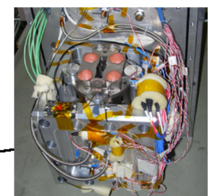
- ***Gravitational Reference Sensor***
  - *Proof mass - 44 mm cube, Au:Pt*
  - *Reference housing with capacitive sensing and electrostatic forcing*
  - *Charge control with UV light*
  - *Caging, vacuum system*
- ***"Drag-free" control laws***
  - *3 x 19 Degrees of freedom*
  - *Acquisition*
- ***Micronewton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



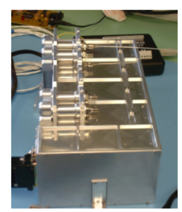




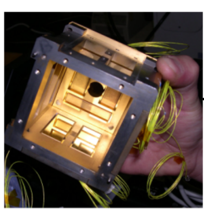
Proof Mass



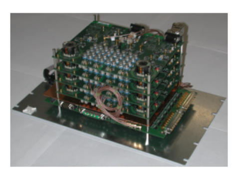
Caging Mechanism



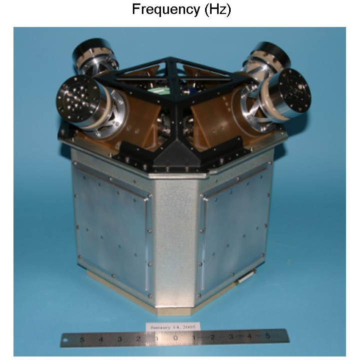
Charge Management System



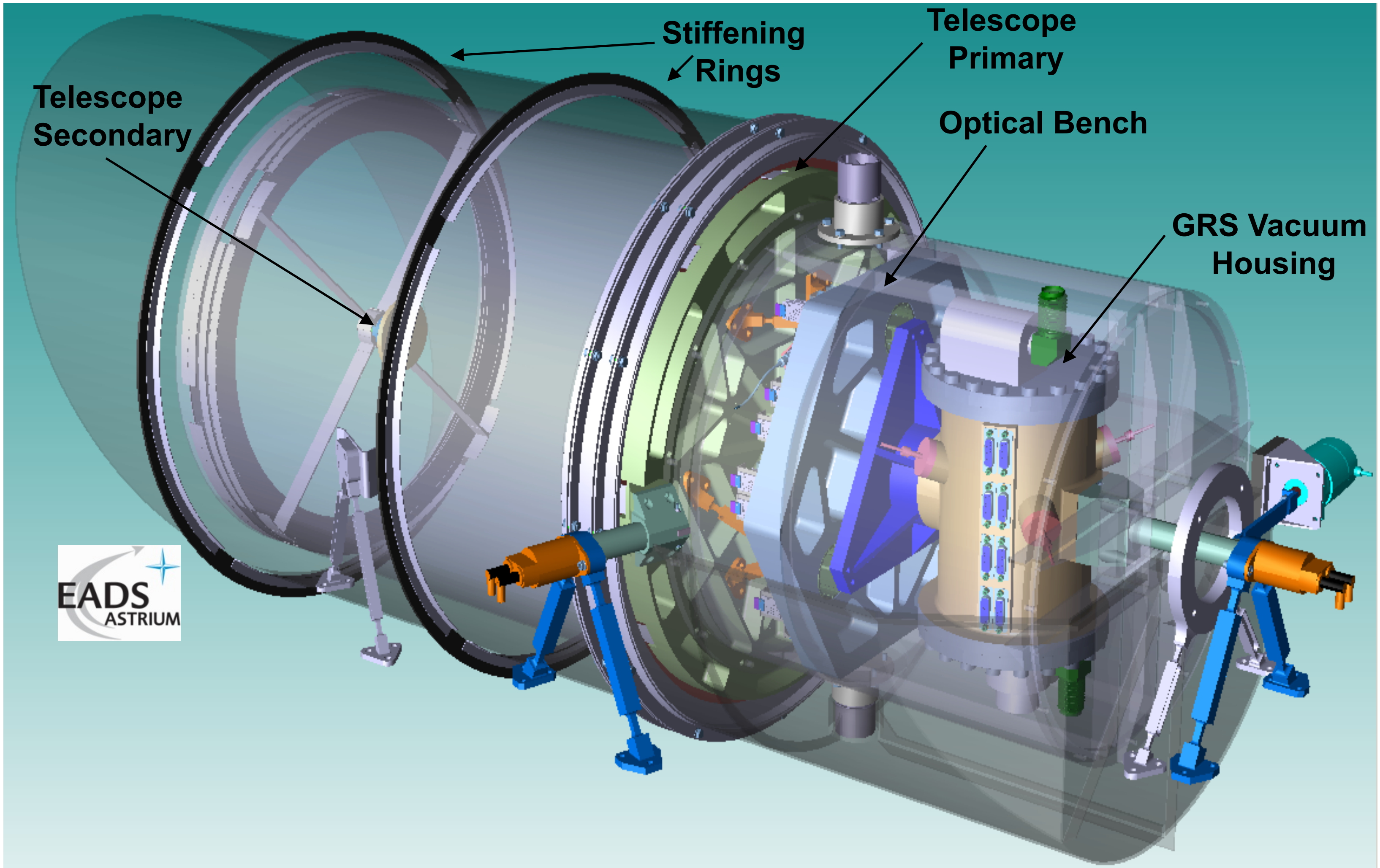
Electrode Housing



Front-End Electronics

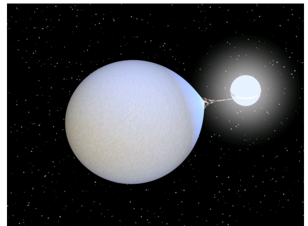


Payload: Optical Assembly



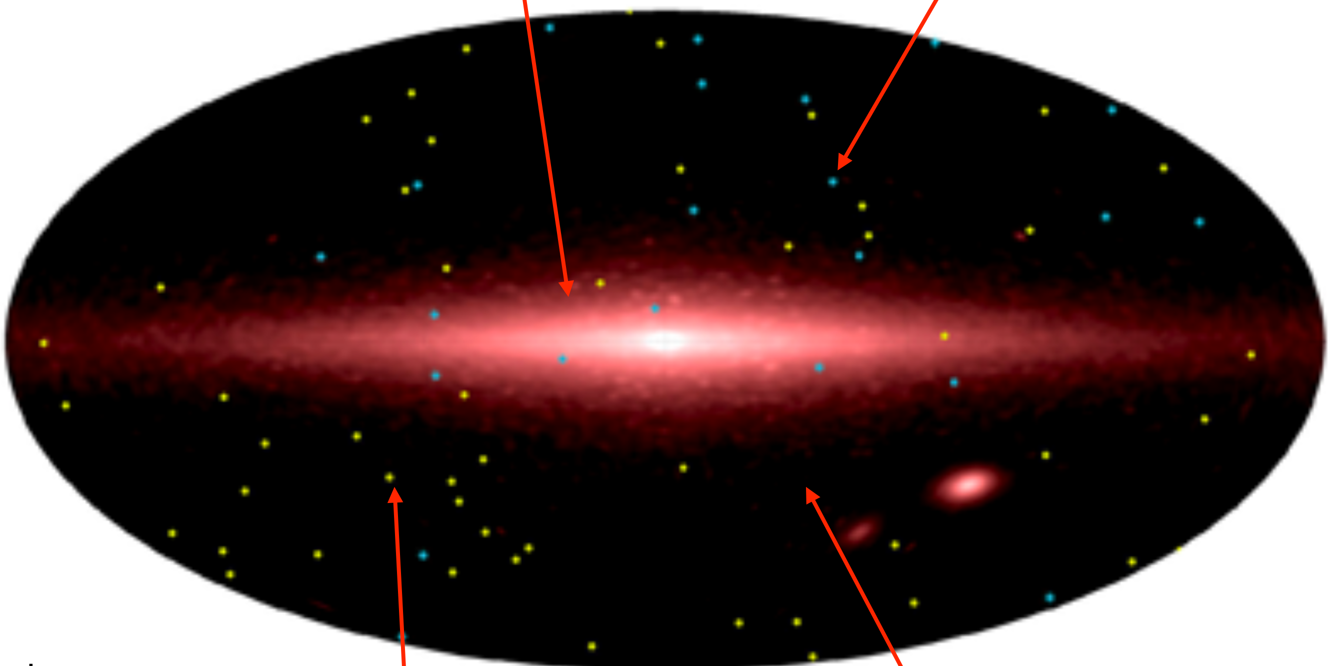
The LISA Sky

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

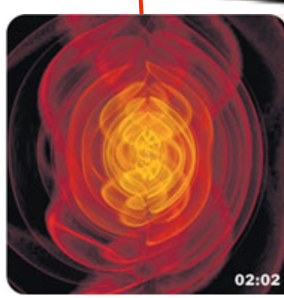


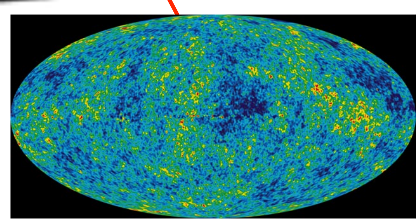
QuickTime™ and a
FF (Uncompressed) decompres
are needed to see this picture

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



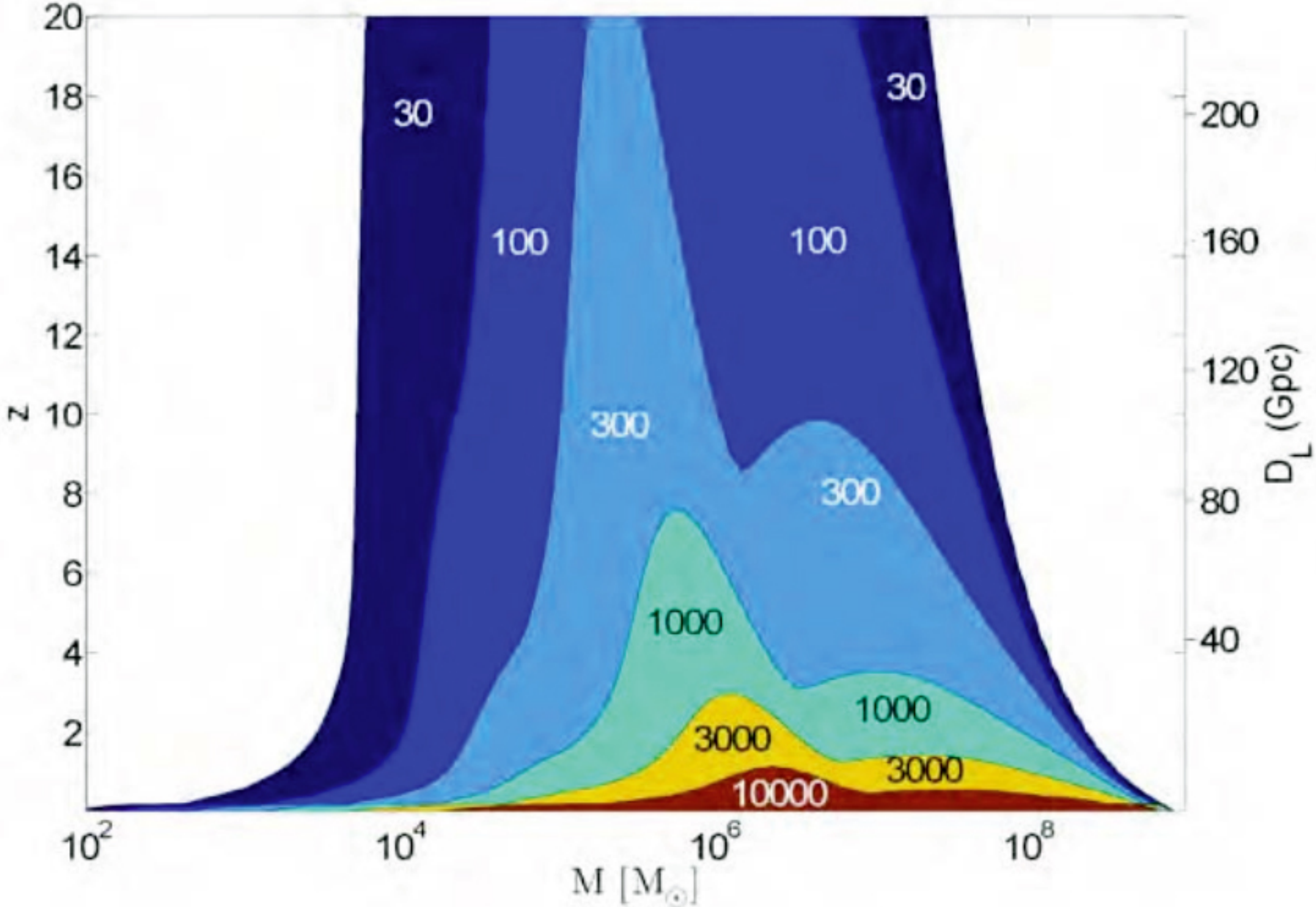


Cosmological back-grounds, bursts and unforeseen sources

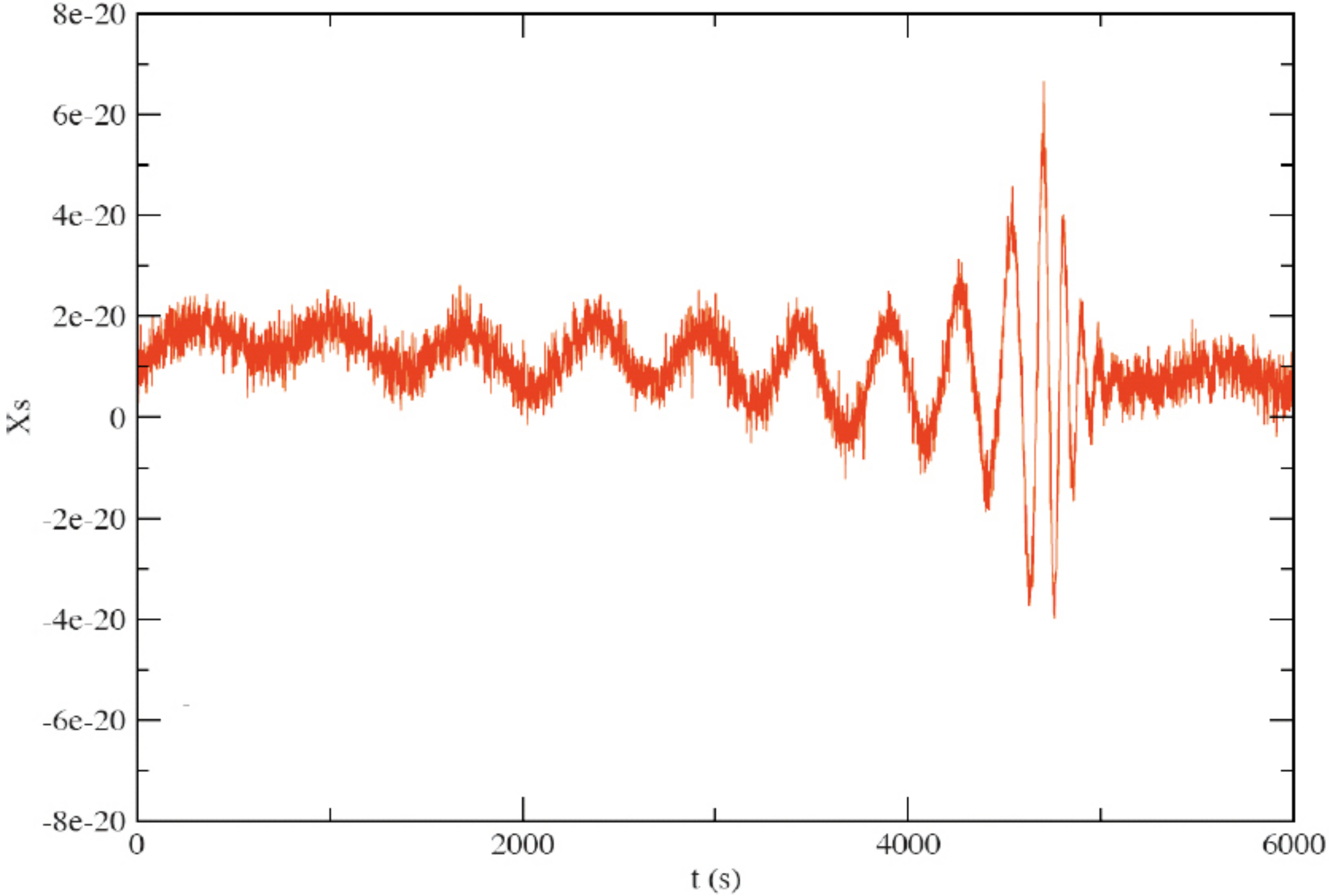
Trace the merger history of MBHs and their host galaxies

- ***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.*

High SNR observations out to z = 20

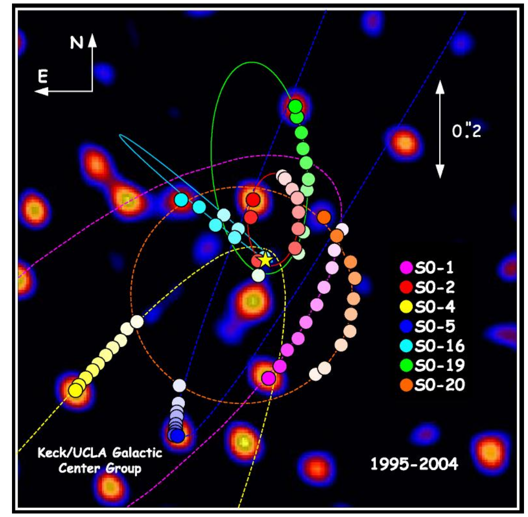


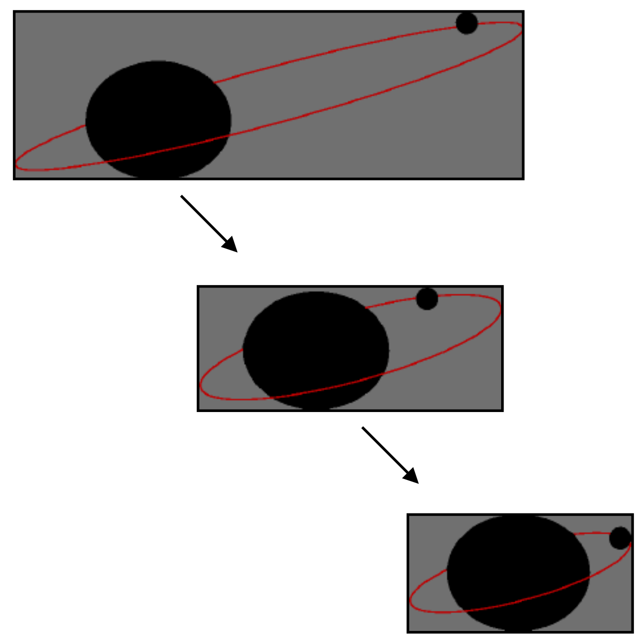
Strong signals even from z = 15



Capture of Compact Objects by Massive Black Holes

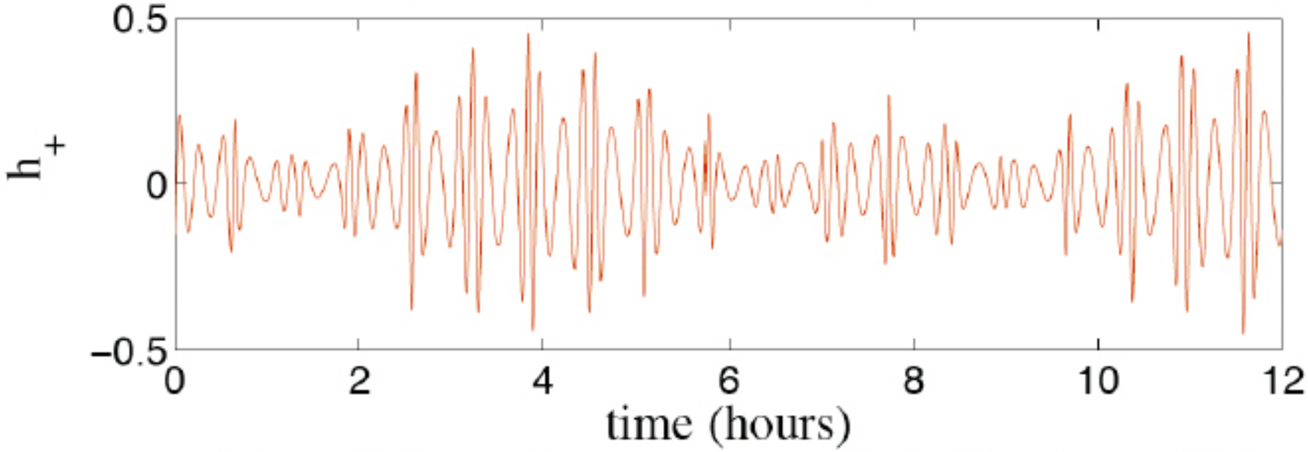
- ***Observations of our own Galactic Center indicate that nuclei of normal galaxies are complex and interesting***
  - *Young massive stars orbiting 4 x $10^6 M_\odot$ BH*
  - *Other (dark) objects should also be orbiting*
    - *Neutron stars*
    - *Stellar-mass BHs*
    - *White dwarf stars?*
- ***LISA 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*



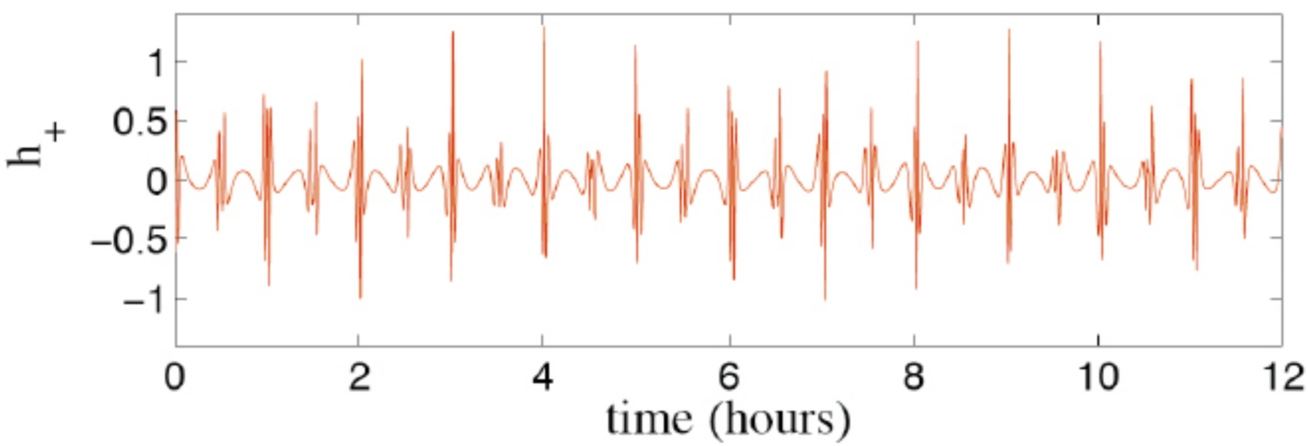


Capture waveform: encoding the geometry

eccentricity = 0.3, semilatus rectum = 12, inclination = 140 degrees



eccentricity = 0.7, semilatus rectum = 6, inclination = 60 degrees

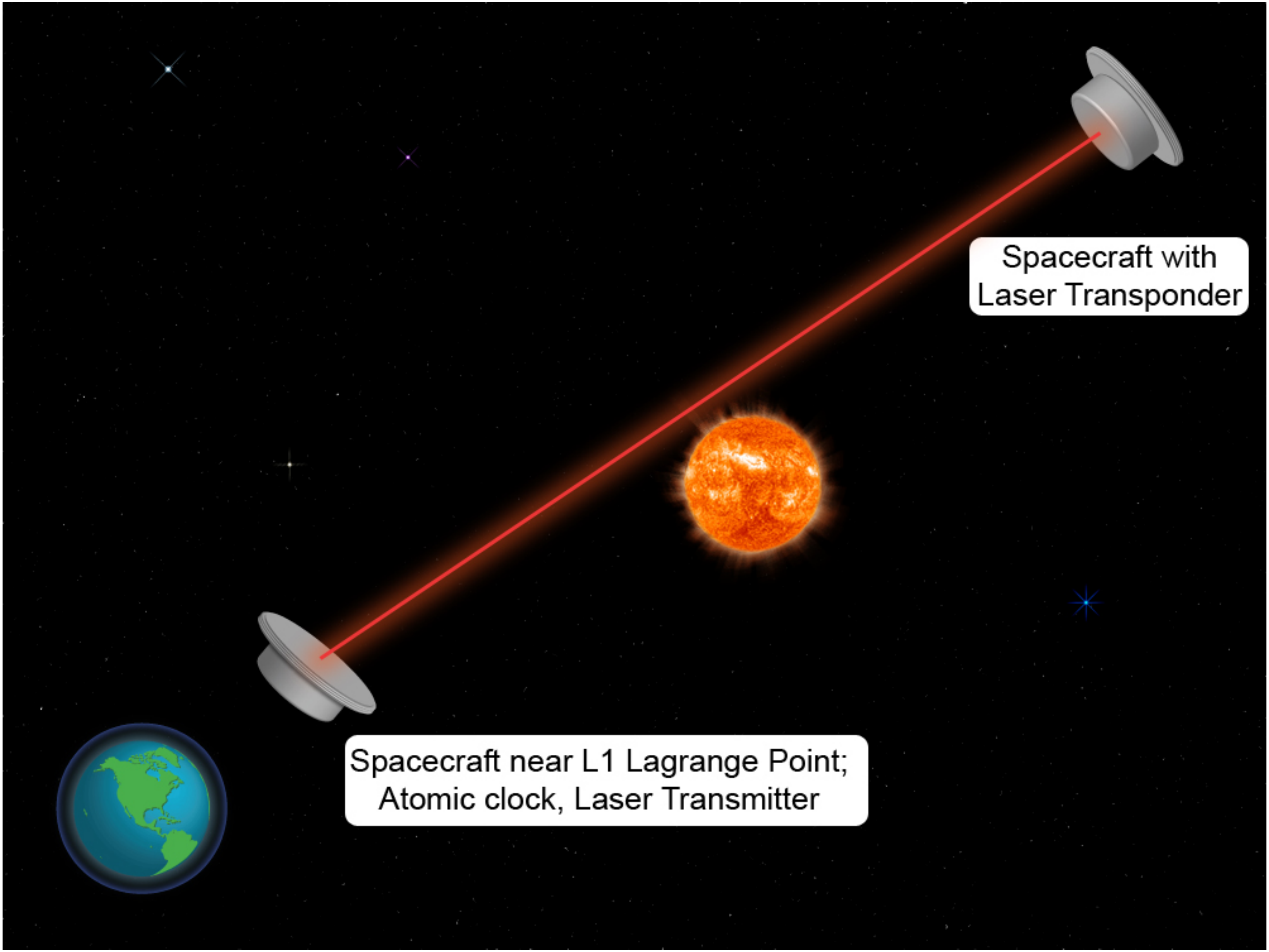


Extreme Mass Ratio Inspirals in the Last Year

- ***About 10^5 cycles of orbital motion***
- ***Greater than 10^4 cycles of precession of perihelion***
- ***Greater than 10^4 cycles of Lense-Thirring precession for expected massive black hole spins***
- ***S/N will be considerably reduced if the actual signal is even slightly different from the theoretical signal, after fitting the necessary roughly 17 parameters***
- ***"Nearly ideal" test of general relativity***

Three Opinions and a Question

- ***Lunar Laser Ranging is the most cost-effective test of General Relativity!***
- ***LISA can give a "nearly ideal" test of both the static and the dynamical predictions of General Relativity!***
- ***If neither shows deviations from the predictions, one of the two other strong candidates for tests in space is improved Shapiro time delay measurements!***
- ***Is the Dynamical Chern-Simons Modified Gravity theory an attractive alternate theory of gravity??? (see e.g. Carlos Sopuerta article in G W Notes, #4, Sept. 7, 2010; pp. 3-48)***


Spacecraft with
Laser Transponder
Spacecraft near L1 Lagrange Point;
Atomic clock, Laser Transmitter