Beyond Einstein: From the Big Bang to Black Holes

Laser Interferometer Space Antenna

"Listening to the Universe with Gravitational Waves"

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AAPT Workshop

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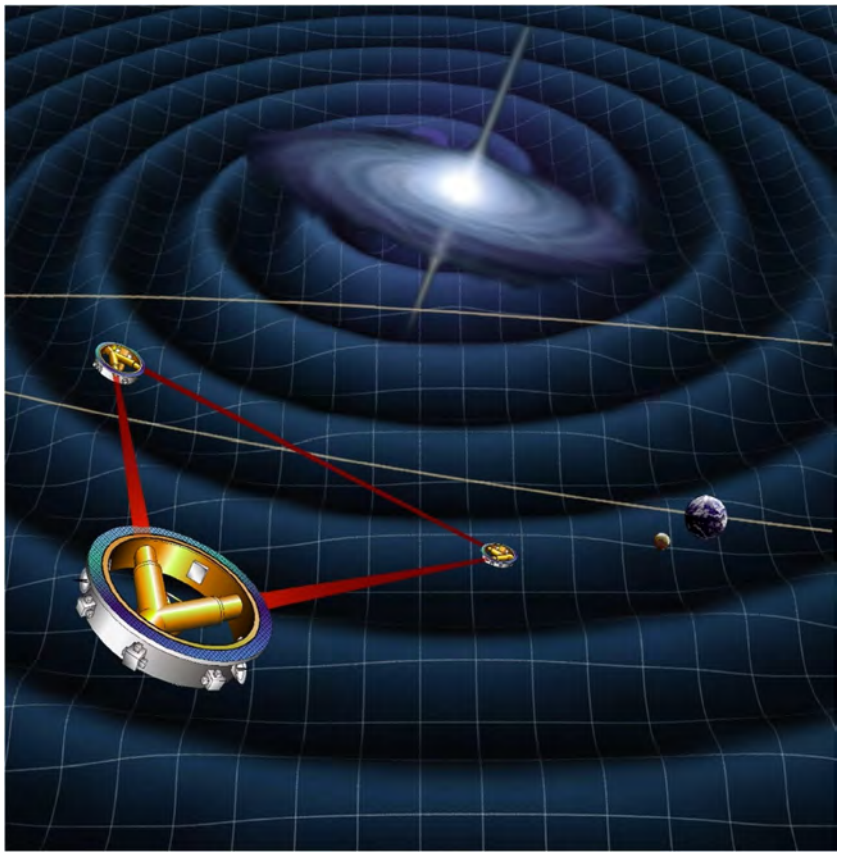
Outline

- LISA Overview
  - What is LISA?
- Gravitational Waves
  - What are they?
- LISA Science
  - What can we learn?
- LISA Mission Factoids
- LISA Outreach
  - What you can do
- Eöt-Wash LISA Experiment
  - What we're doing here

LISA Overview

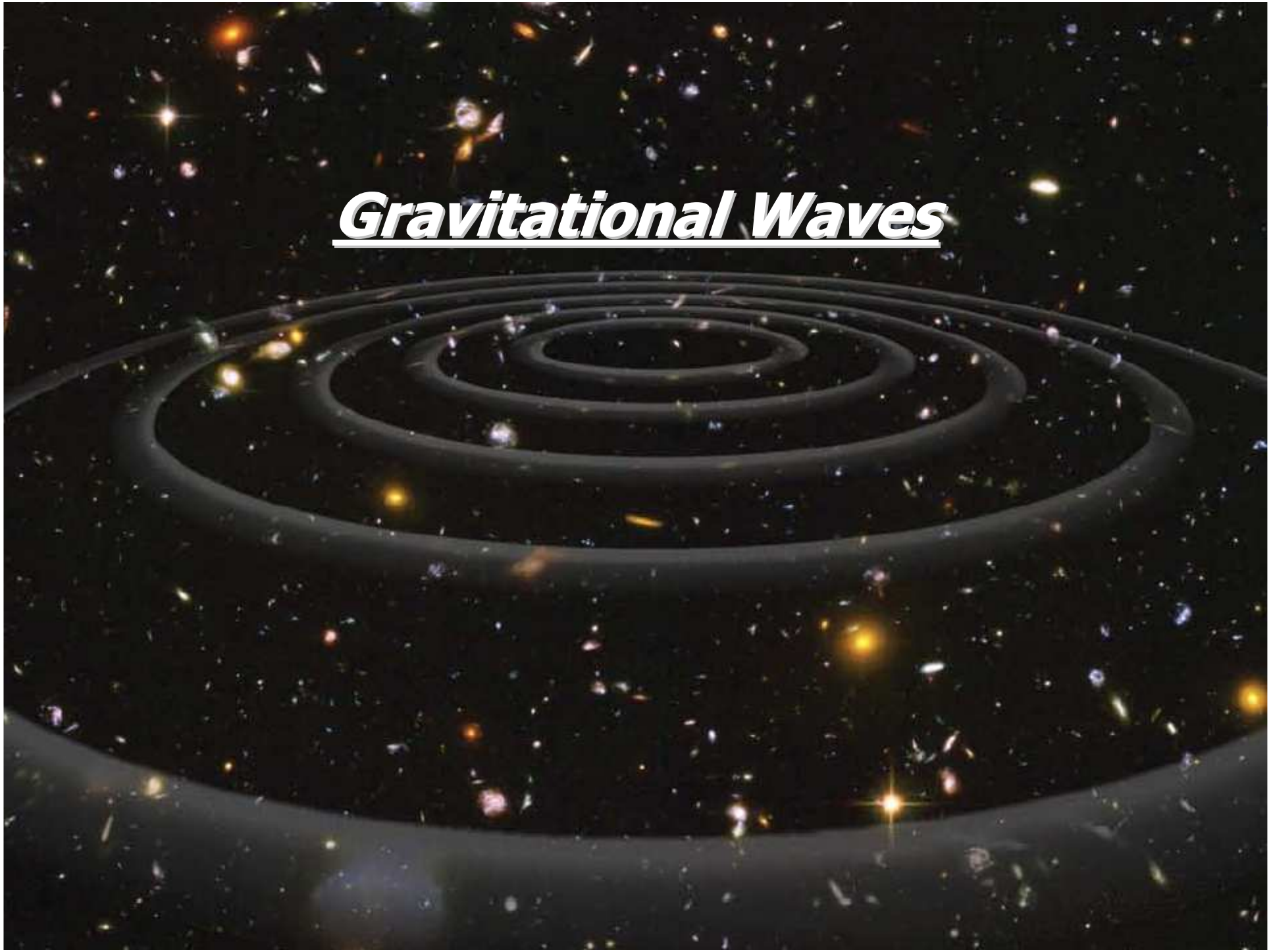
LISA Overview

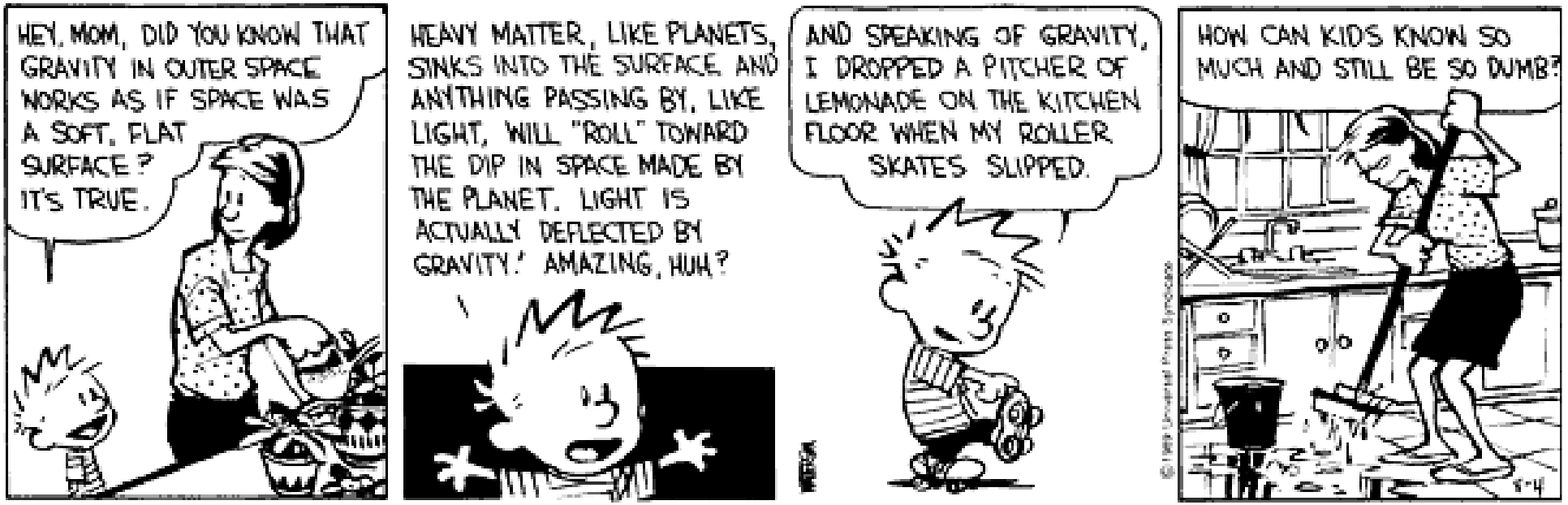


- LISA is a joint NASA / European Space Agency (ESA) project
- 3 sciencecraft 5 million kilometers apart in triangular formation
- Constellation orbits the Sun in Earth orbit—lagging by 50 million kilometers.
- Small proof masses gravitate freely within each spacecraft
  - Laser beams bounce off proof masses to determine arm lengths
  - Basically a Michelson interferometer

- LISA is expected to detect signals from merging supermassive 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.

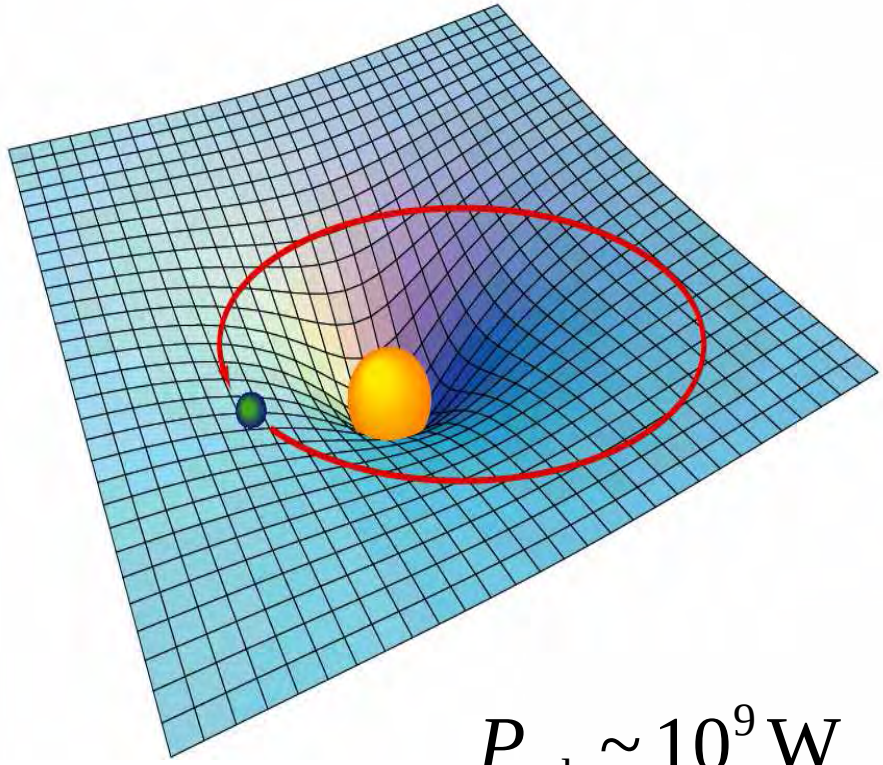
Gravitational Waves



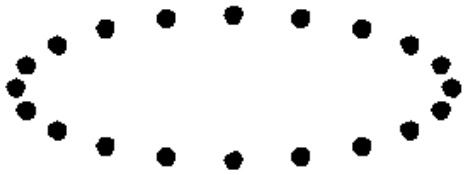

HEY, MOM, DID YOU KNOW THAT GRAVITY IN OUTER SPACE WORKS AS IF SPACE WAS A SOFT, FLAT SURFACE? IT'S TRUE.
HEAVY MATTER, LIKE PLANETS, SINKS INTO THE SURFACE AND ANYTHING PASSING BY, LIKE LIGHT, WILL "ROLL" TOWARD THE DIP IN SPACE MADE BY THE PLANET. LIGHT IS ACTUALLY DEFLECTED BY GRAVITY! AMAZING, HUH?
AND SPEAKING OF GRAVITY, I DROPPED A PITCHER OF LEMONADE ON THE KITCHEN FLOOR WHEN MY ROLLER SKATES SLIPPED.
HOW CAN KIDS KNOW SO MUCH AND STILL BE SO DUMB?

Gravitational Waves

- Einstein (and Calvin) described gravity as a curvature of spacetime.
- Gravitational waves are "ripples in the fabric of spacetime"
  - Akin to water waves
  - they propagate gravitational signals (just like light propagates electromagnetic signals)
- Gravitational waves produce a strain in spacetime:



$$P_{\text{rad}} \sim 10^{9}\,\text{W}$$



$$h = \frac{\Delta L}{L} \sim 10^{-21}$$

Wave is traveling "into the page"

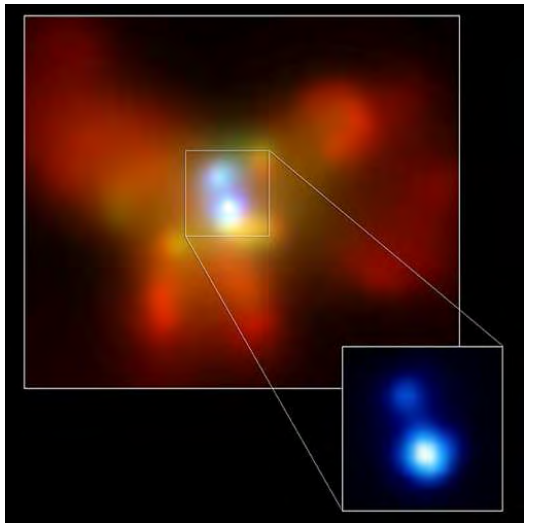
Where do they come from?

- Gravity is a weak force ("spacetime is stiff")
  - Need large masses to produce measurable gravitational waves

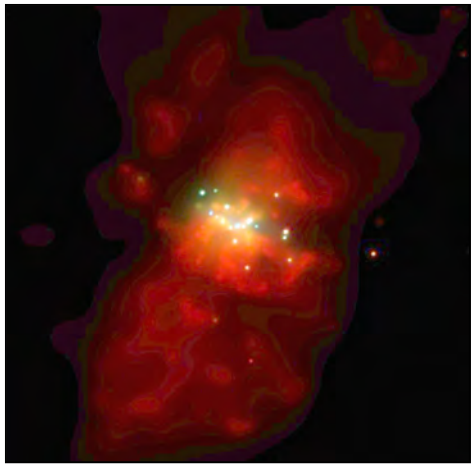
  → Compact massive objects
- Aspherical sources (due to the conservation of momentum)—quadrupolar

  ➡ Binary systems, ***containing***

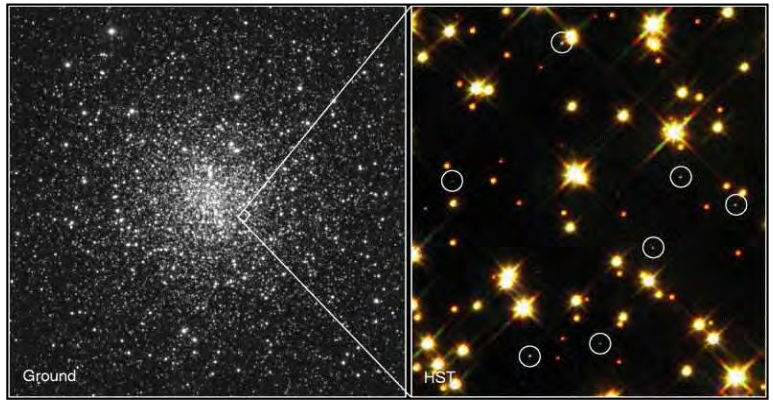
  white dwarfs, neutron stars, black holes



Binary black holes in NGC 6240

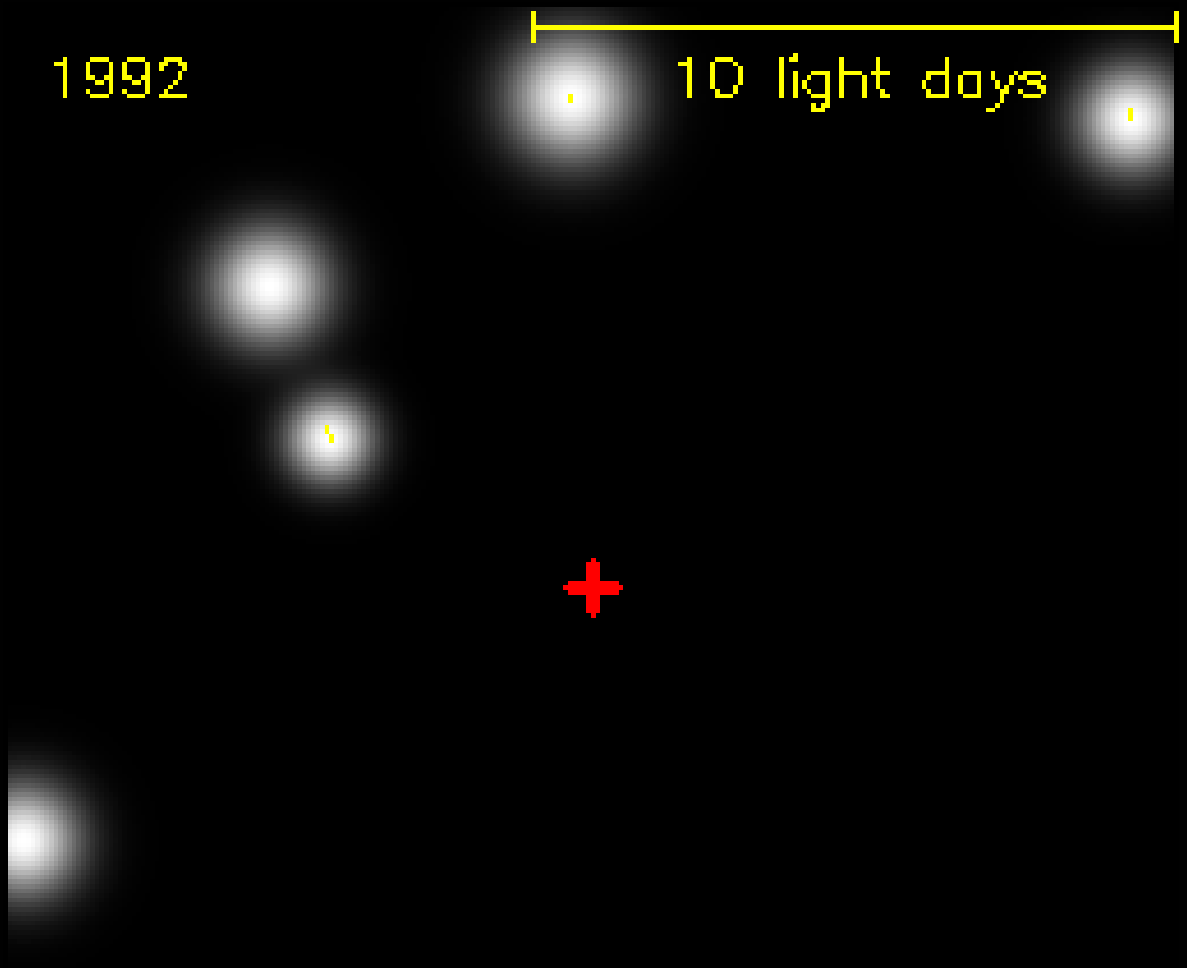


Star forming galaxy NGC 253



White dwarfs in M4

View of the Center of Our Galaxy



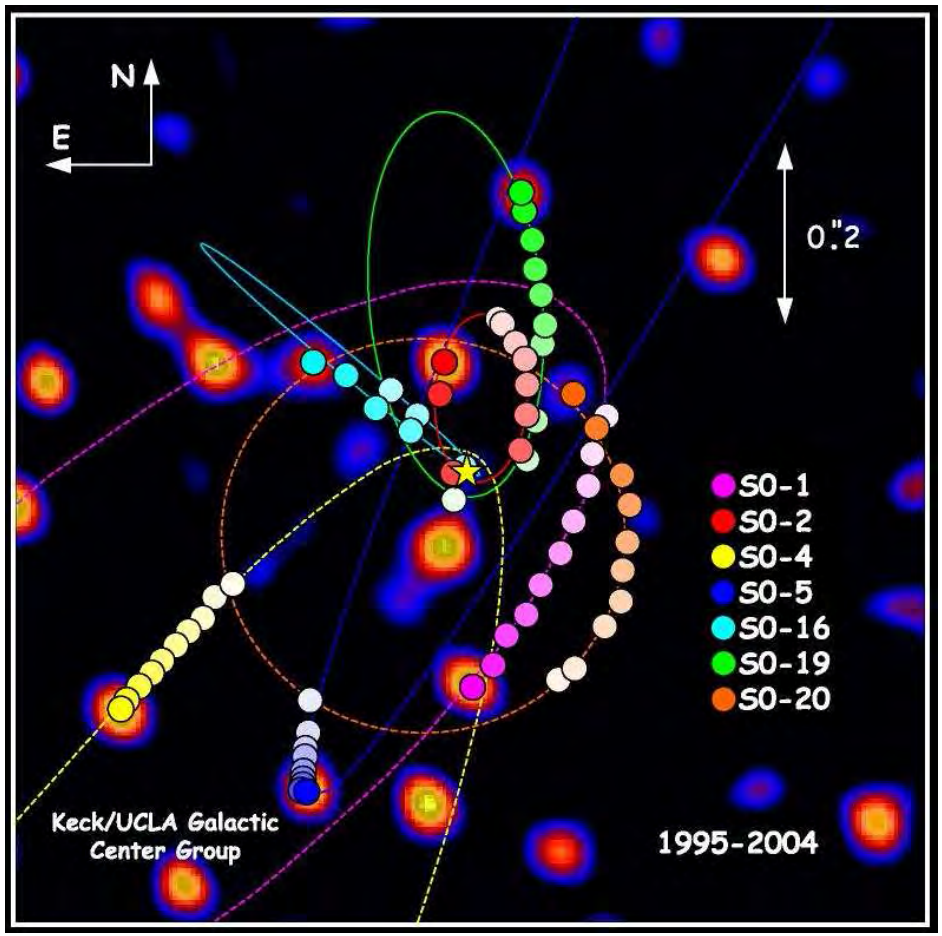
Courtesy of A. Ghez et al, UCLA

Center of Milky Way: Sag A*

- Orbits of stars a few light-days from the center of our galaxy.

- Insert these orbits into Kepler's laws to determine the mass of the central object:

$$M = 3.5 \times 10^6 \text{ Msun}$$

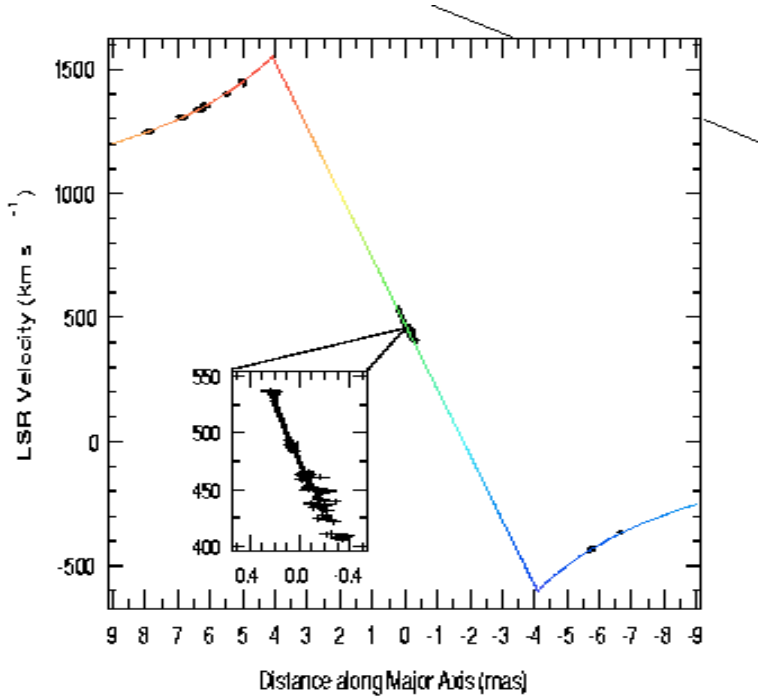


Center of NGC4259 (M106)

- Water maser observed in core of Seyfert galaxy, can use to observe orbiting gas.

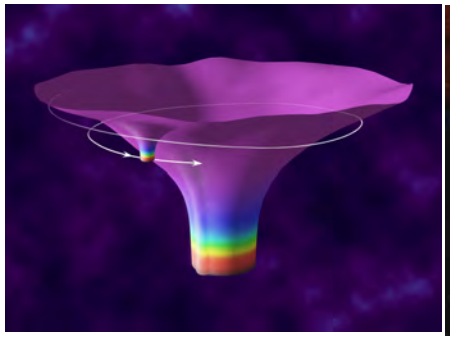
- Apply Kepler's law to the observed gas motion and determine the mass of the central object:

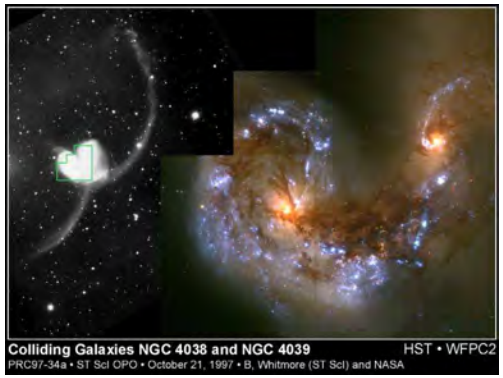
$$M = 3.9 \times 10^7 \text{ Msun}$$

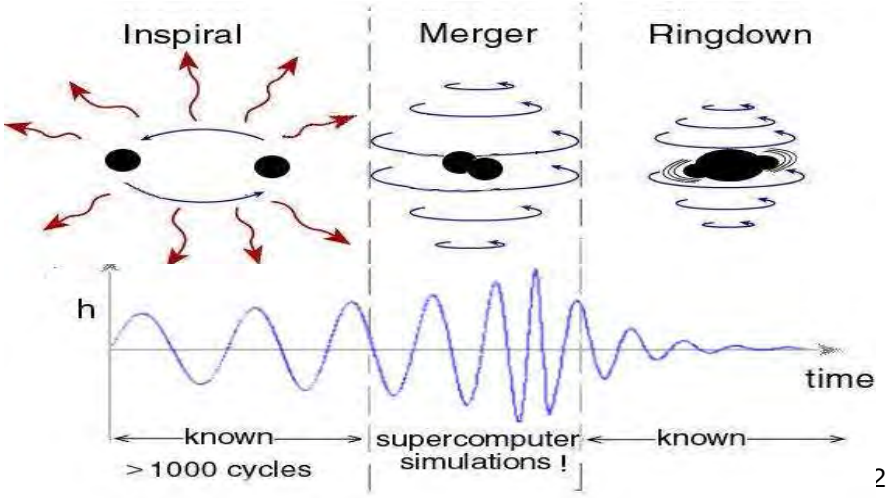


What can we learn?

- Was Einstein right?
  - Precision tests of general relativity in strong gravitational fields
- Galactic and stellar astronomy
  - Thousands of compact binaries throughout the galaxy
- Astrophysics
  - Direct observation of massive black holes over the history of galaxy formation
- Precision Cosmology
  - Gravitational waveforms yield absolute distances (no standard candles included)
  - given a cosmology (i.e., electromagnetically measuring redshift to sources) this determines the **Dark Energy** content of the Universe throughout time

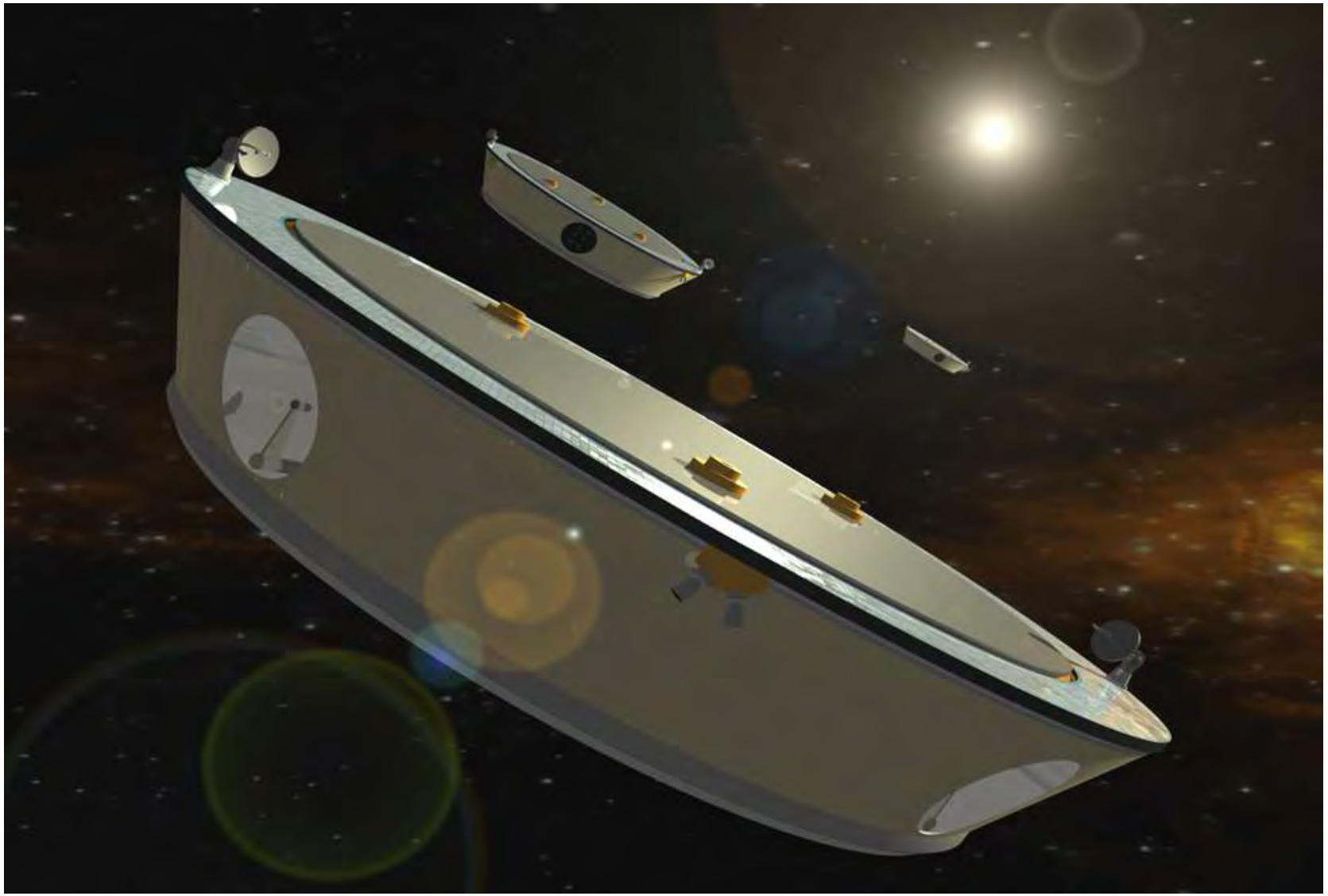






LISA Factoids

Beyond Einstein: From the Big Bang to Black Holes



LISA Factoids

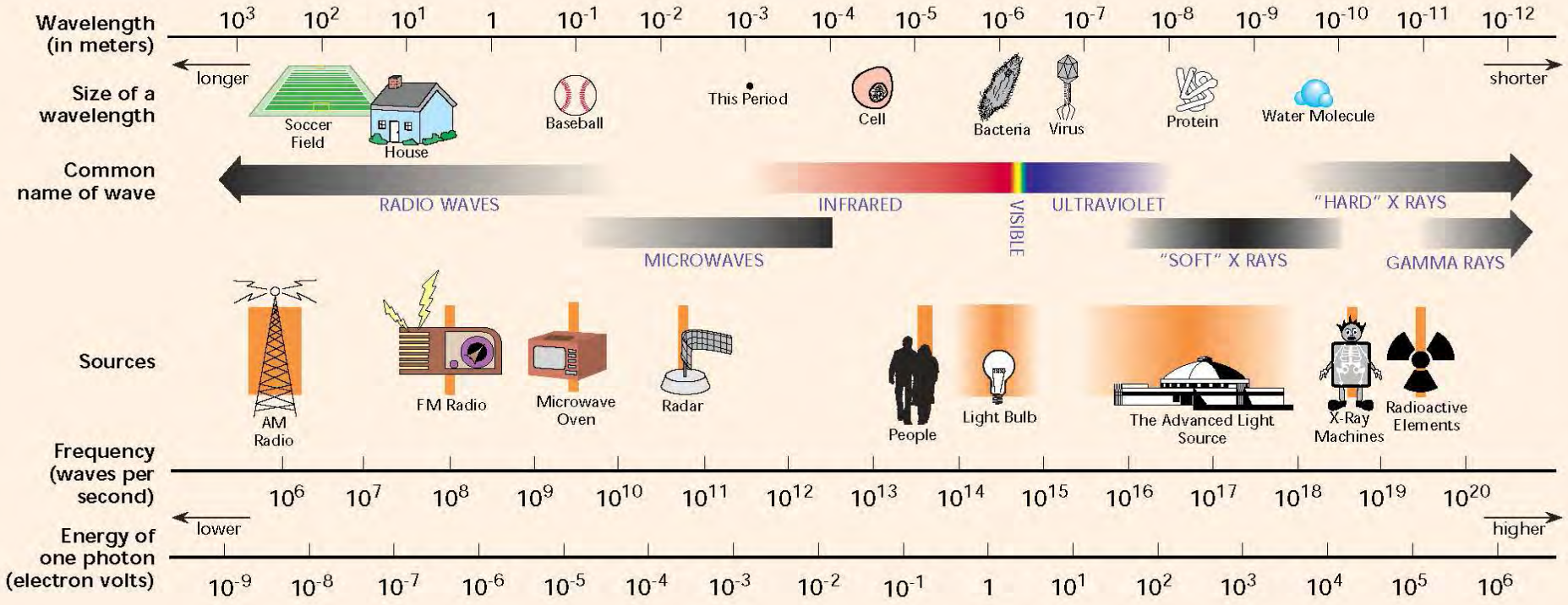
- L = 5 million km
- h = $\Delta L/L \sim 10^{-21}$

} LISA's positional precision: ΔL = 20 pm

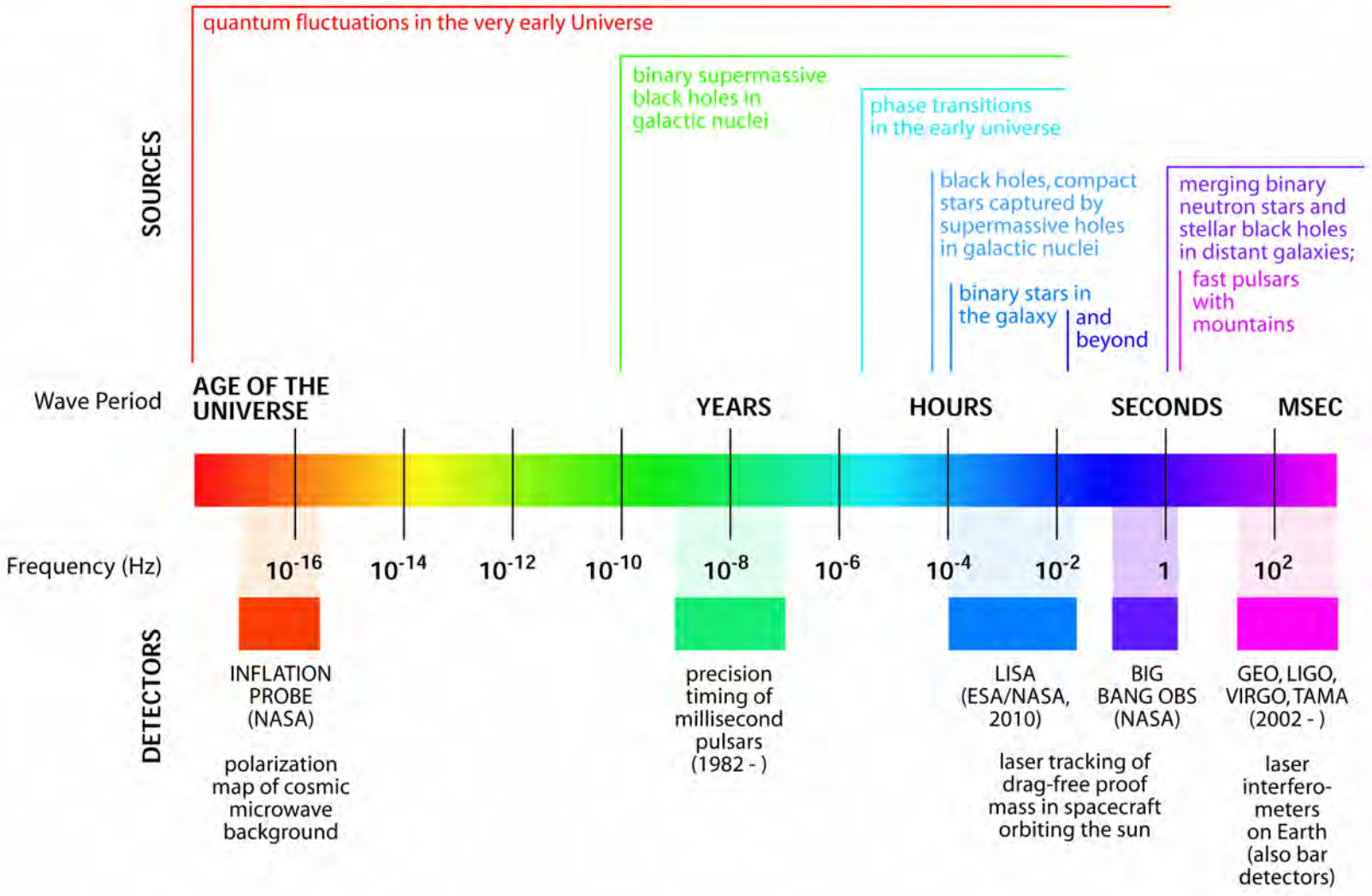
  - Like measuring the distance between the Earth & Alpha Centauri with *better* than the precision of human hair!

- LISA's acceleration precision: 3 x 10^{-15} m/s^2 (recall $g \approx 9.8$ m/s^2)
  - An object starting from rest accelerating at a rate of 3 fm/s^2 reaches a speed of 1 nm/s after a year, and a dazzling 0.1 m/s = 4 in/s after one million years!
  - The ambient ground acceleration is on the order of nm/s^2, so ground motion limits acceleration sensitivity → go to space
- LISA has known verification sources in our galaxy
- Signal-to-noise ratio of many sources will be in the 1000's or greater
- An abundance of sources (~10,000s) observable for many years
- LISA's arm length determines the frequency of gravitational radiation:

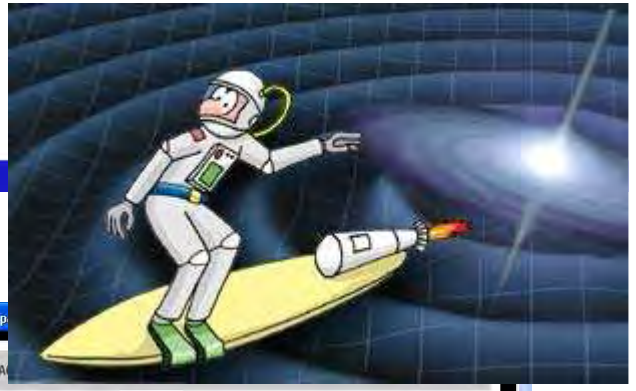
THE ELECTROMAGNETIC SPECTRUM



THE GRAVITATIONAL WAVE SPECTRUM



Outreach

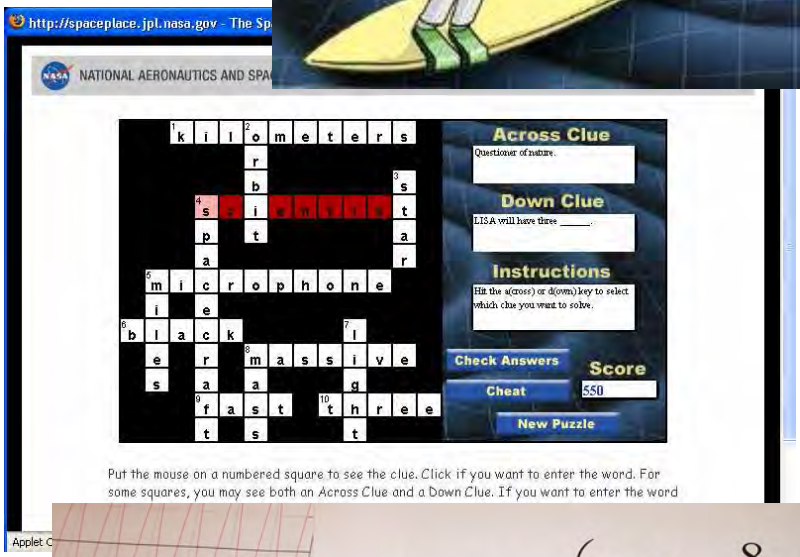


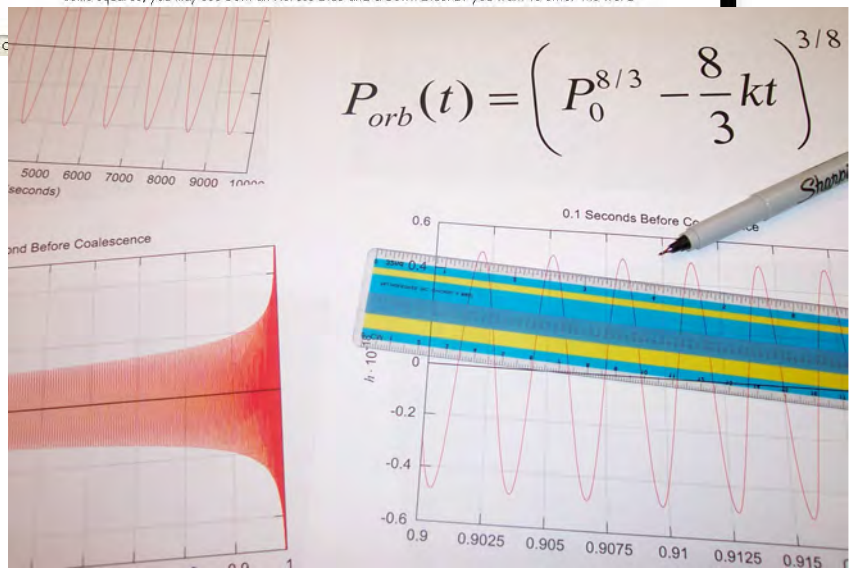
Resources:

- http://www.einstein-online.info
  - Einstein's relativity
- http://lisa.nasa.gov
  - General information on LISA, gravitational waves
- http://www.lisascience.org
  - Public Collaboration Portal
- http://spaceplace.nasa.gov
  - Geared for elementary/middle school
  - Has articles, games, and cartoon interviews
  - Crossword puzzle
- http://cgwp.gravity.psu.edu/outreach/
  - Activities, articles, audio, and more!

Type into Google:

"gravity outreach"



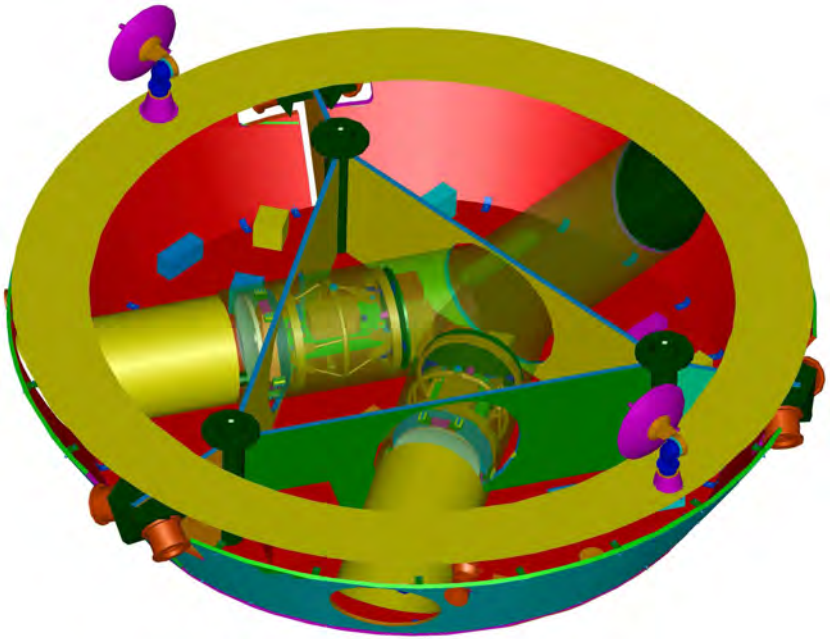


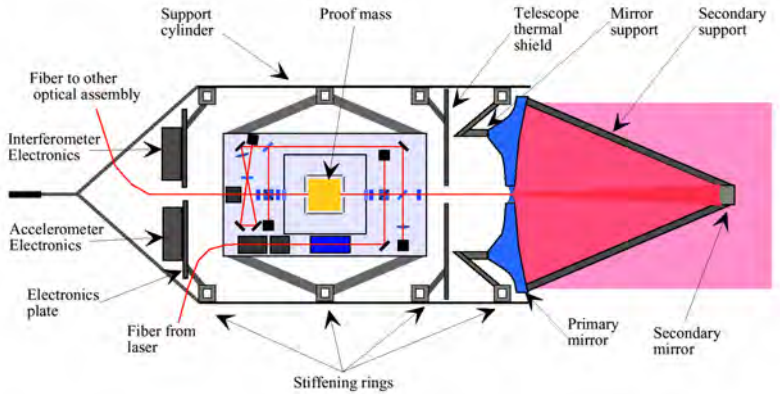
LISA = the next frontier in astronomy

- Precision tests of gravity, especially in the strong field
  - Extreme mass ratio inspiral events
- Determine stellar population statistics of our galaxy
  - White dwarf, neutron star, and stellar mass black hole binaries
- Observe the most violent events in the Universe
  - Supermassive black hole coalescences
- Observe the merger history of black holes throughout time
  - Probe galactic and proto-galactic evolution
  - Determine absolute distances thereby the Dark Energy content
- Discovery space: grand unification, cosmic superstrings, ???

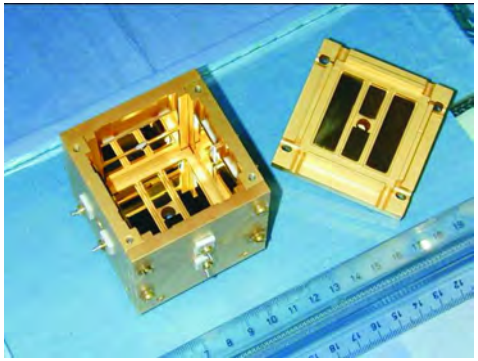
Whereas electromagnetic radiation allows us to *see* the Universe, gravitational waves allow us to *listen* to the Universe

What we're doing here



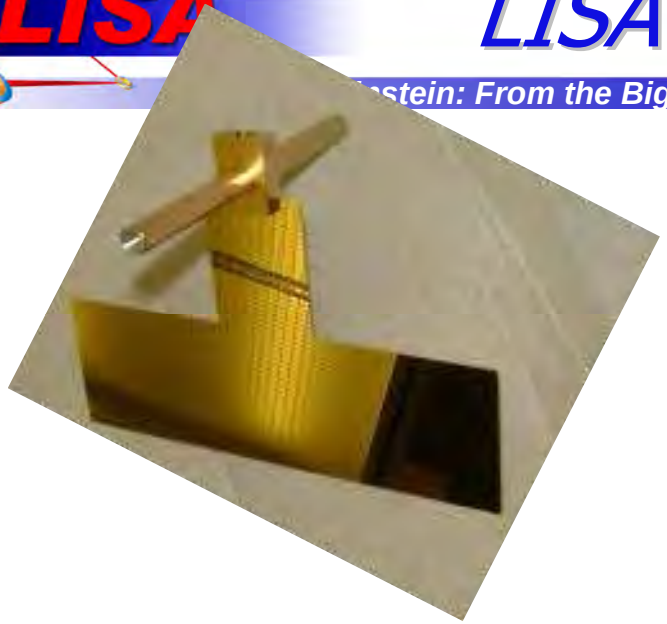


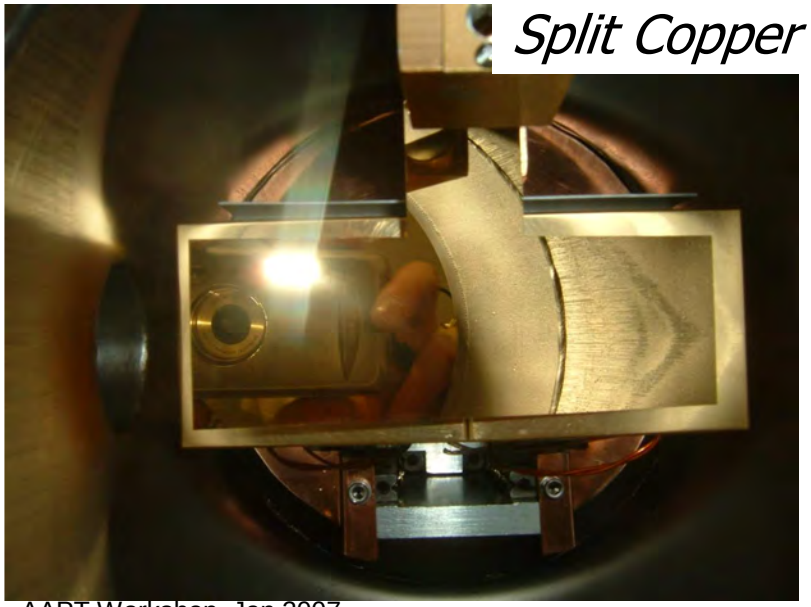
LISA Proof Mass

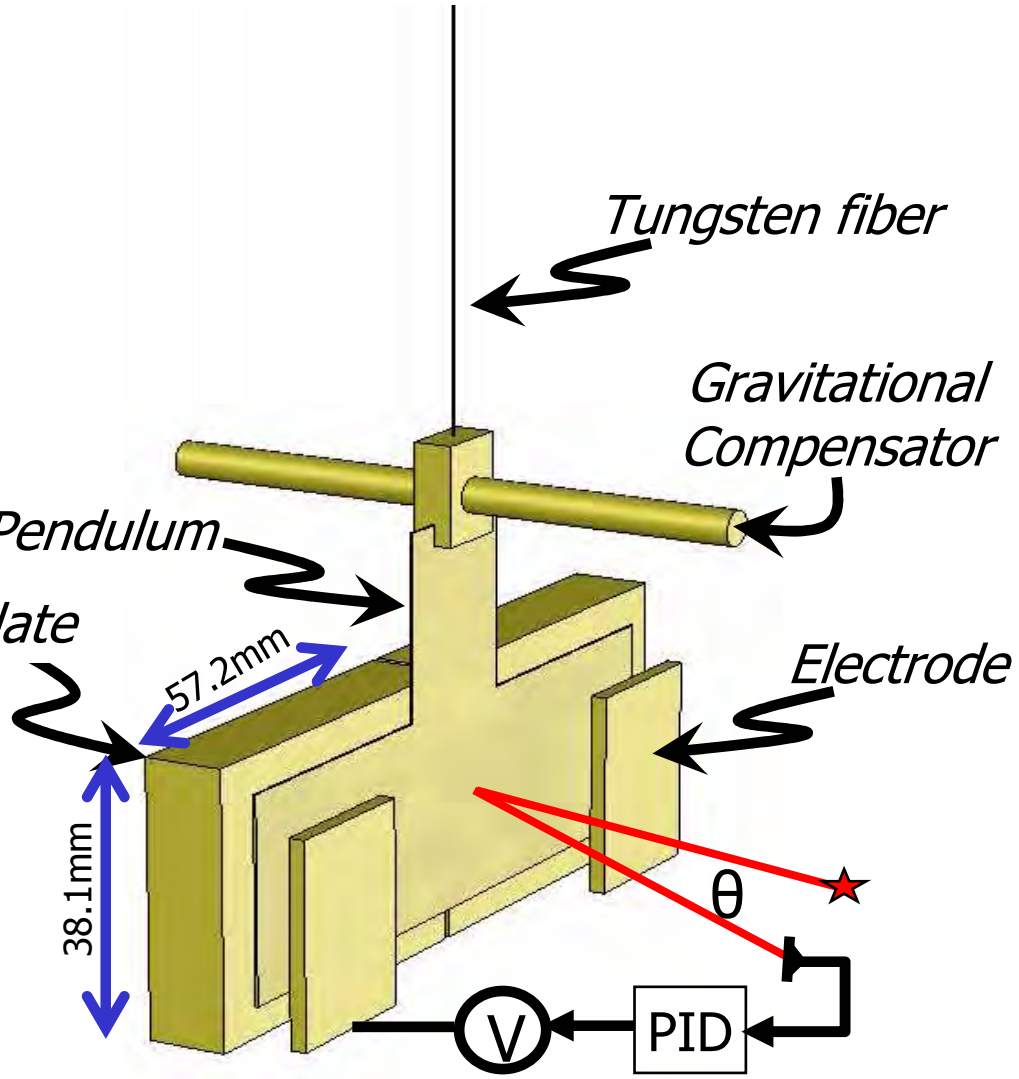


Proof Mass Housing

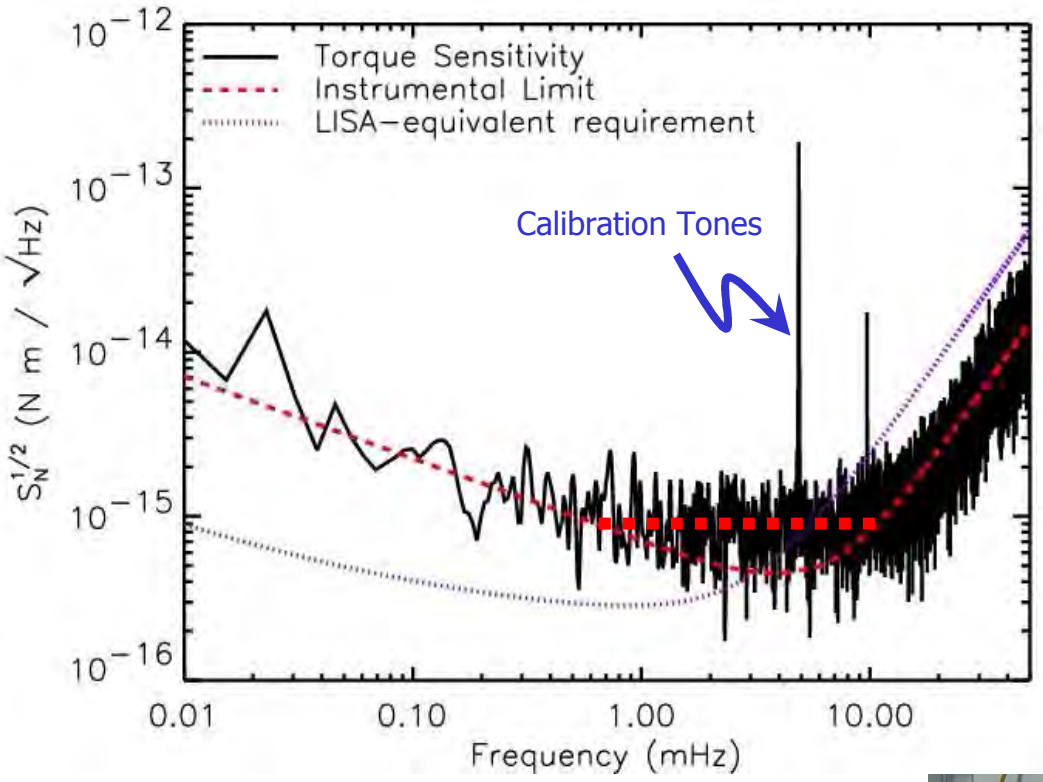
LISA Torsion Pendulum

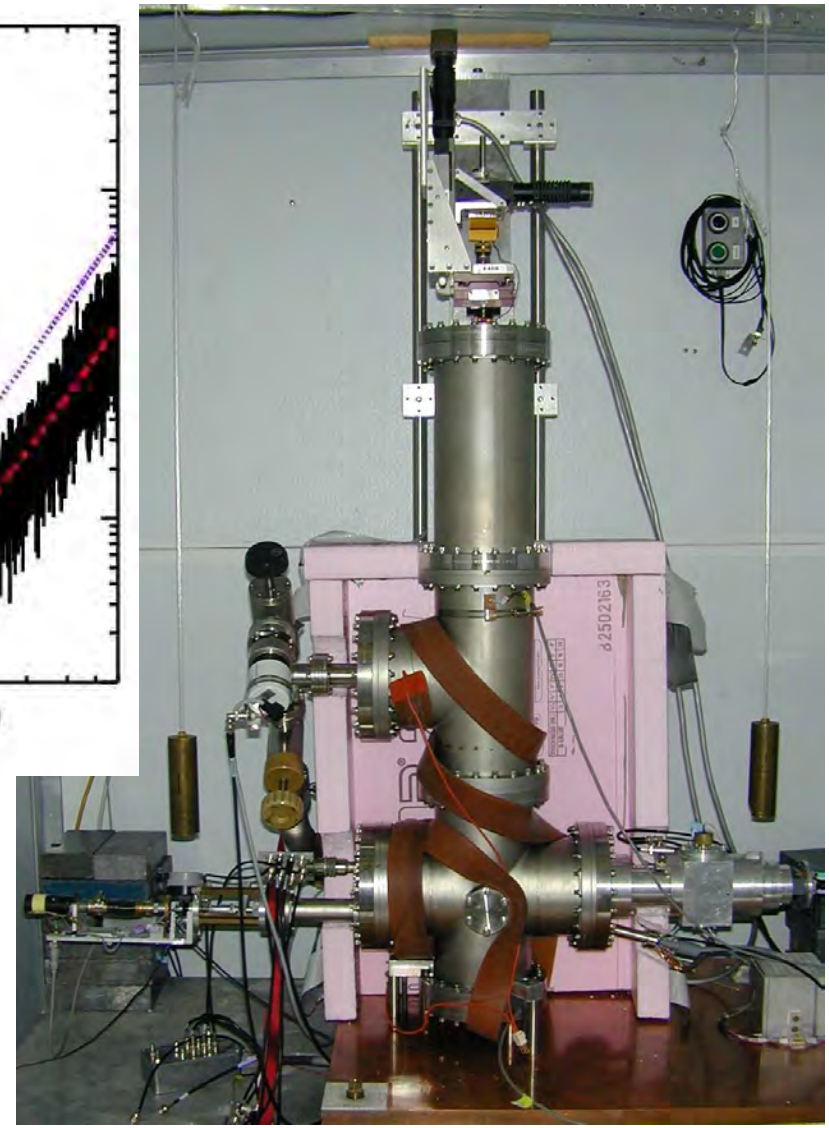






LISA Torsion Pendulum





Most sensitive torsion pendulum. Nearly reaching the required LISA acceleration sensitivity!