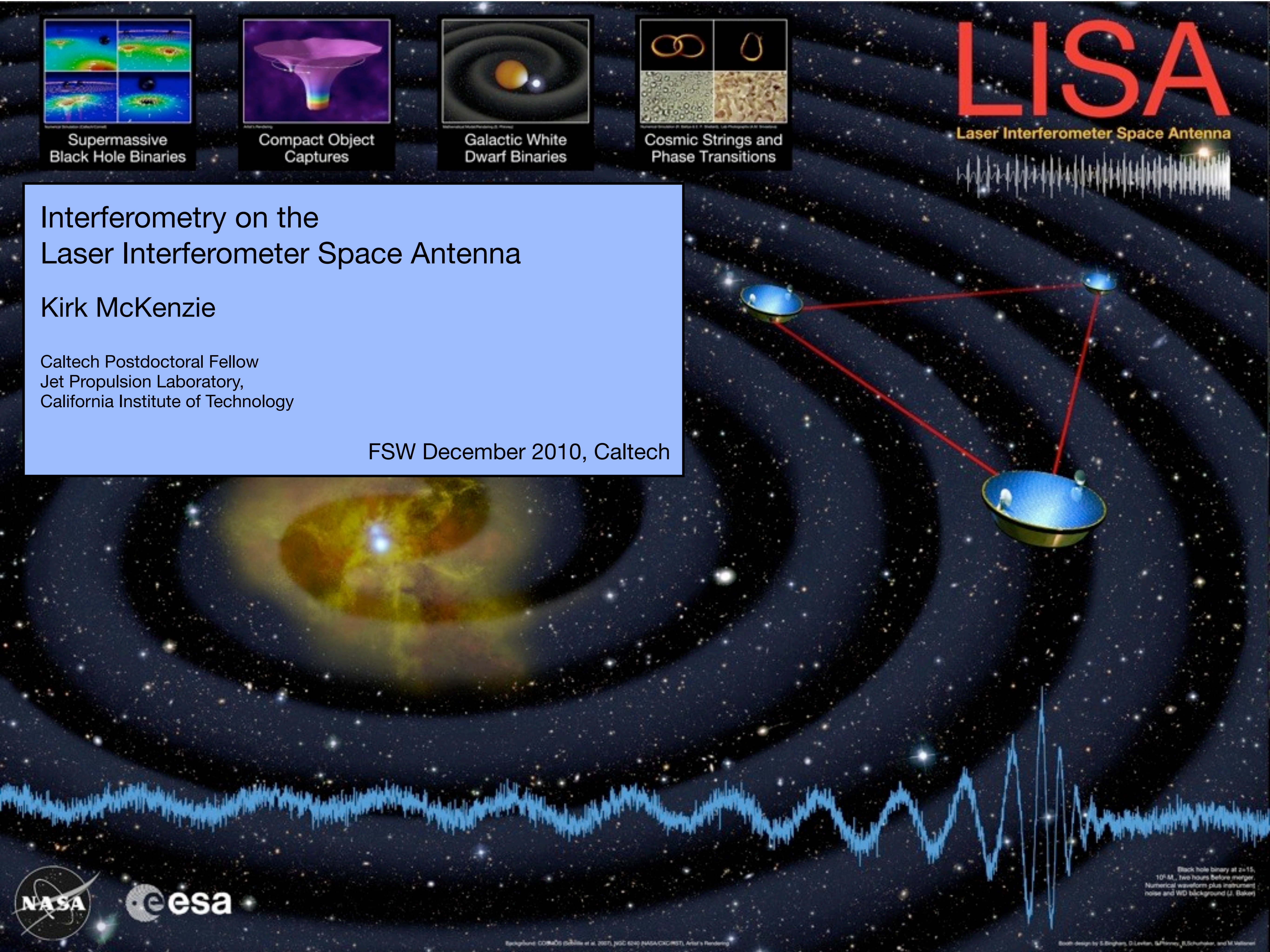
Interferometry on the Laser Interferometer Space Antenna

Kirk McKenzie

Caltech Postdoctoral Fellow
Jet Propulsion Laboratory,
California Institute of Technology

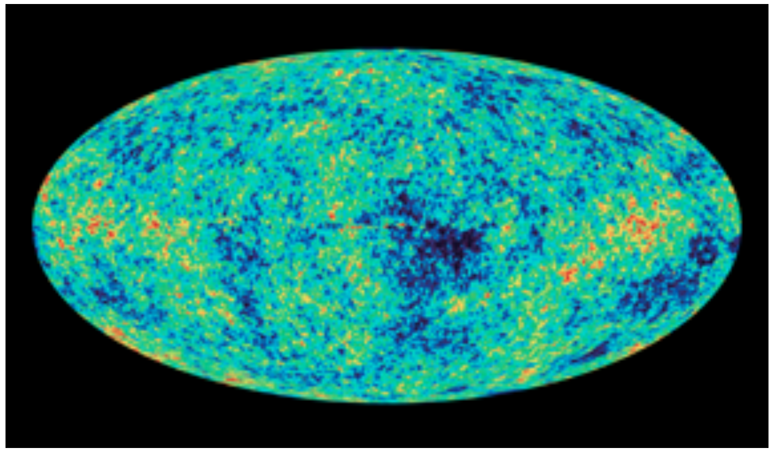
FSW December 2010, Caltech



Central region of Milky Way

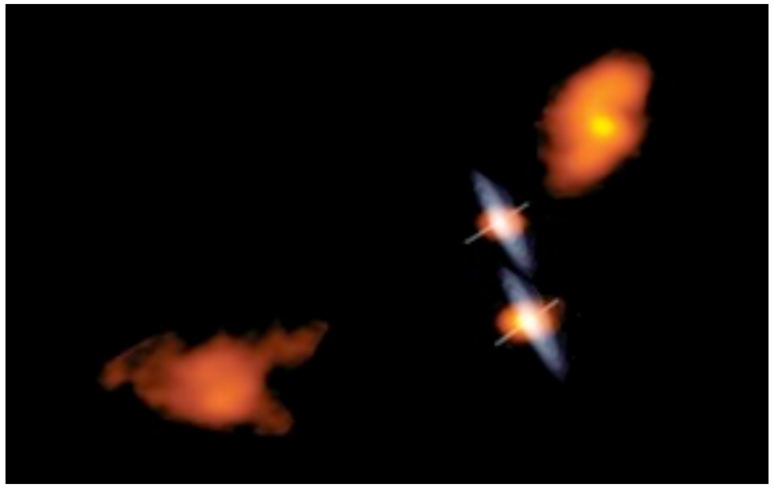
Hubble, Spitzer, and Chandra composite

Cosmic Microwave Background



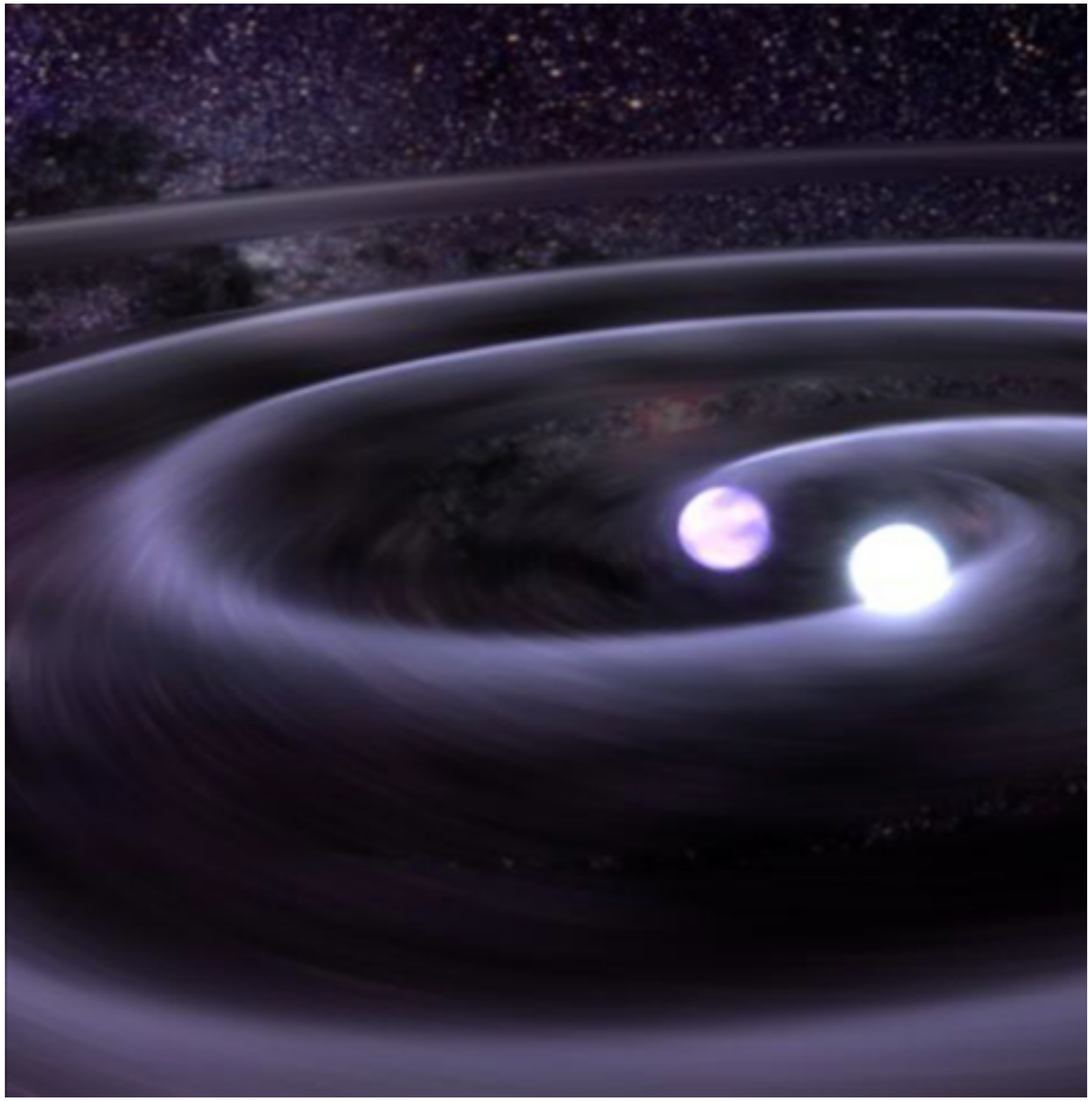
WMAP

Supermassive
binary black holes



NRAO/AUI, Greg Taylor, U of New Mexico

White dwarf binary, J0806 + 15

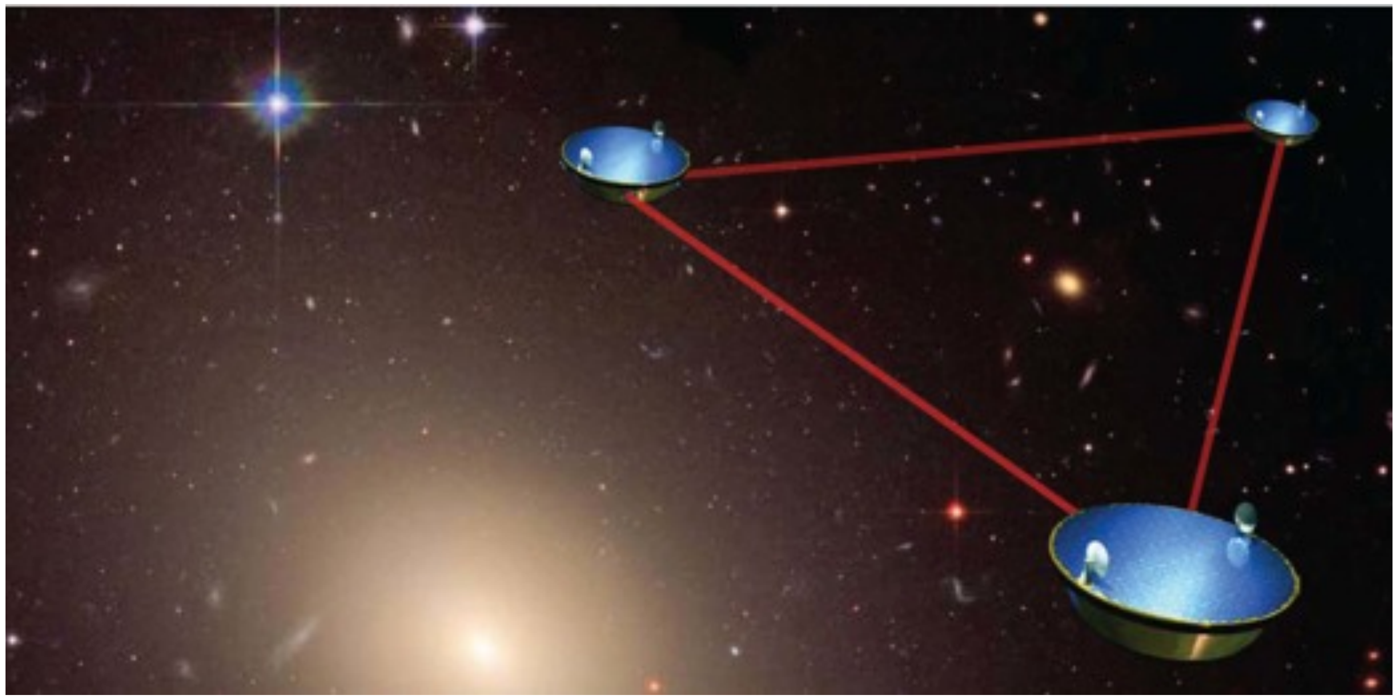


NASA/Tod Strohmayer (GSFC)/Dana Berry (Chandra X-Ray Observatory)

Gravitational waves - a new way to sense the universe.

New technologies, new observatories

Laser Interferometer Gravitational-wave Observatory



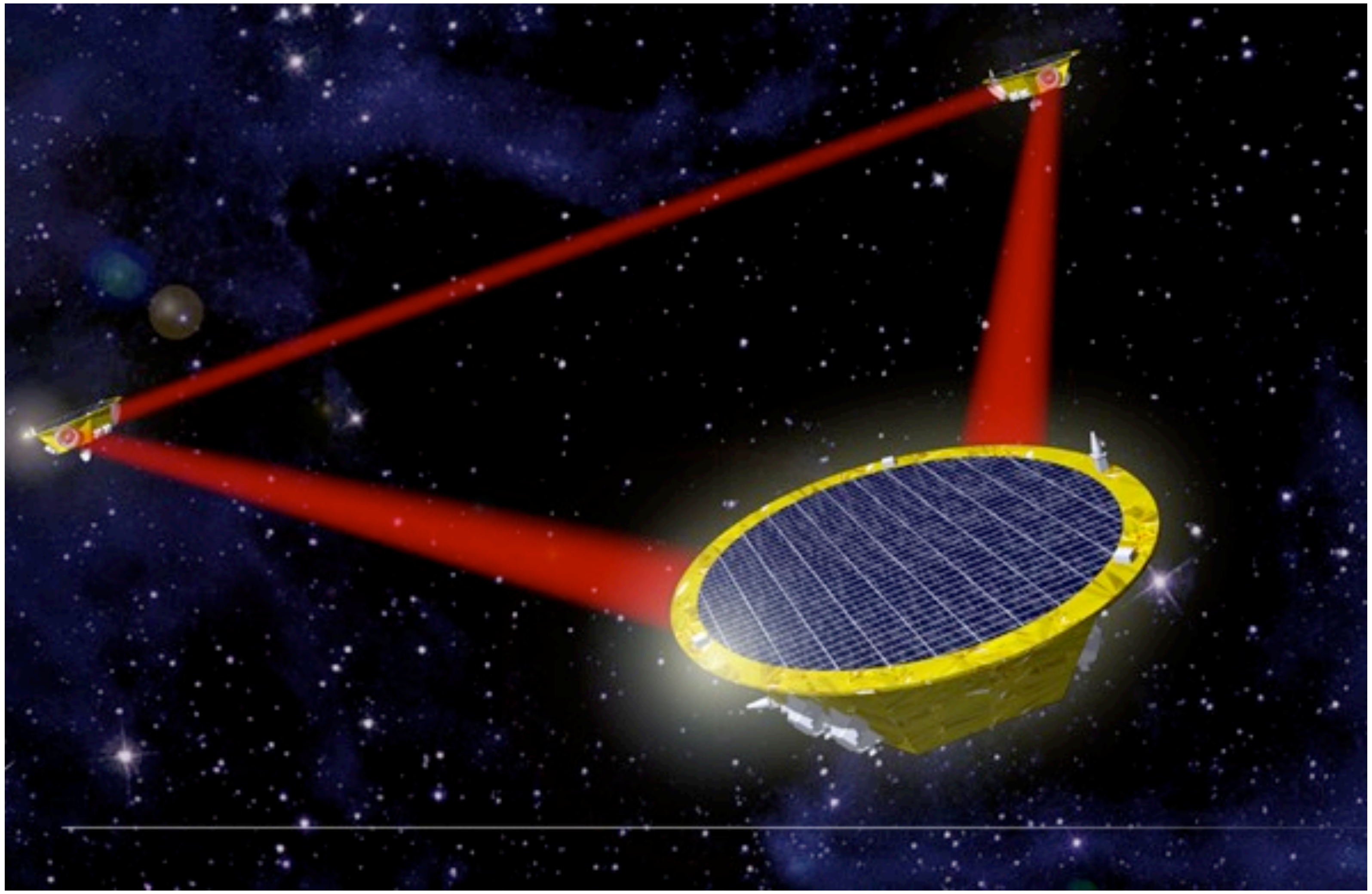
Laser Interferometer Space Antenna

- The Laser Interferometer Space Antenna - (LISA)

- NASA - ESA observatory

- 3 spacecraft,
  Heliocentric orbit

- 2025 Launch



EADS Astrium

Overview

- Sources
- Detectors
- LISA overview
- Laser and clock frequency noise
- LISA Pathfinder

Overview

- Sources
- Detectors
- LISA overview

- Laser and clock frequency noise
- LISA Pathfinder

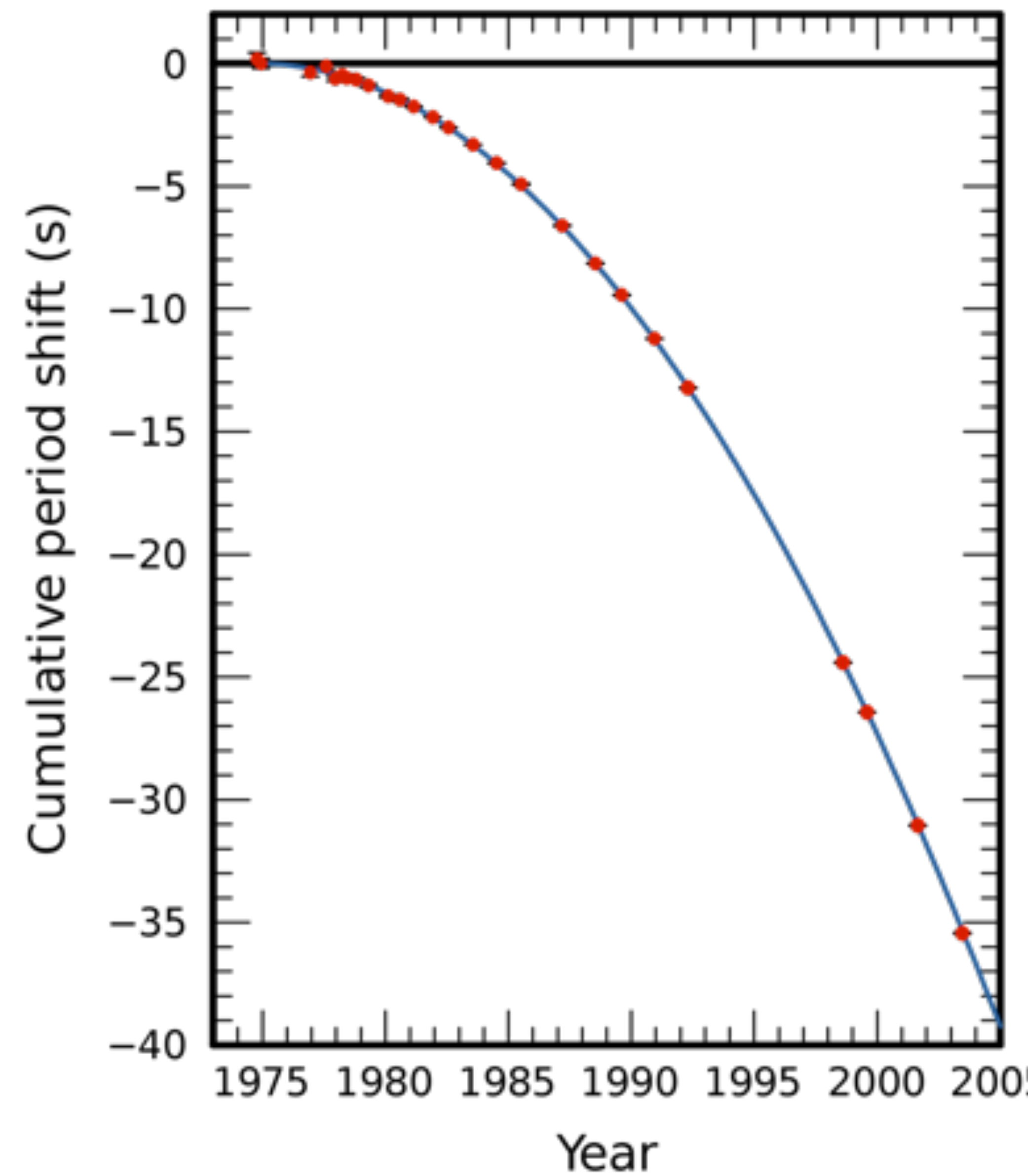
Gravitational waves

- Oscillations of space-time
  -Generated by accelerating masses
  -Interact weakly with matter

- Astronomy & Physics
  - High energy relativity
  - Galaxy formation
  - Early universe cosmology
  - Dark energy
  - ?

- No direct detection of GW yet!

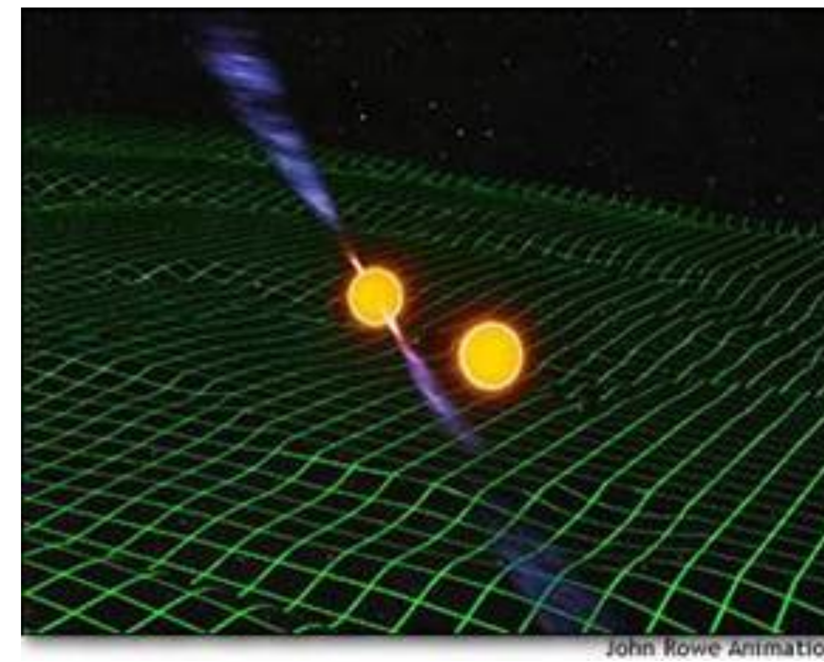
  - Indirect evidence for GW
  - Hulse and Taylor, pulsar timing



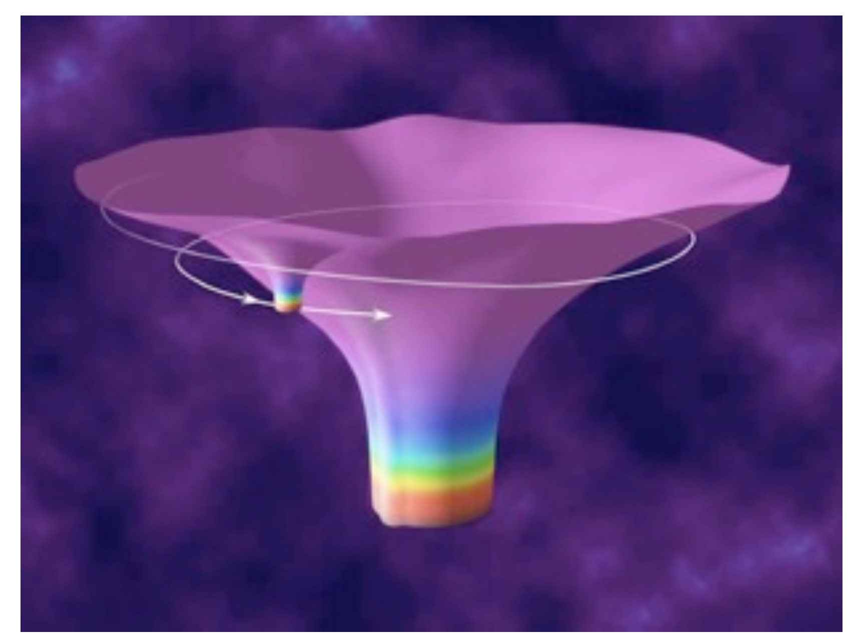
Orbital decay of B1913+16. Red dots are observations; blue line is prediction of general relativity.

Sources: *predictable*

- **Galactic compact binary mergers:**
  - Black hole
  - Neutron star
  - White dwarf



- **Extreme mass-ratio inspirals:**
  - Compact objects falling into galactic BH
  - Precision test of general relativity, "no hair" theorem

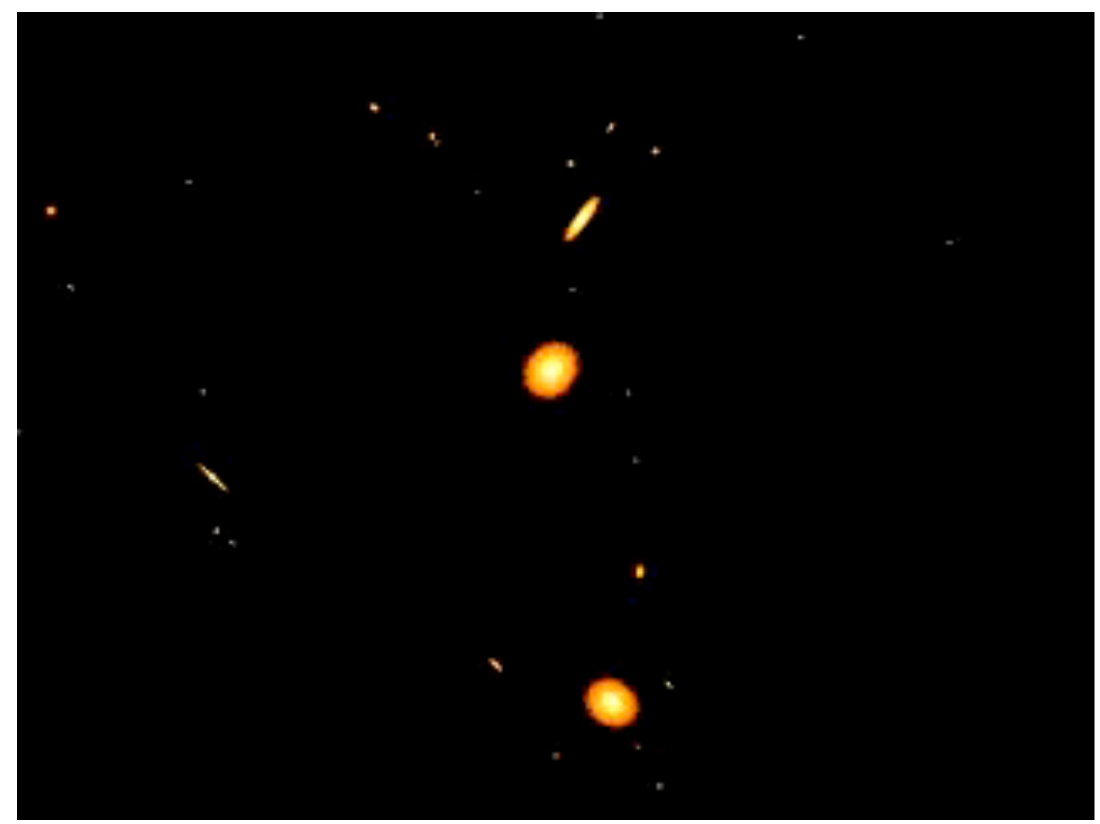


Sources: *powerful*

- Massive BH - Massive BH binaries:
  - Galatic BH merge when galaxies collide
  - 10^4- 10^7 solar masses
  - 10^{49} Watts
  - High energy relativity
  - SNR > 100

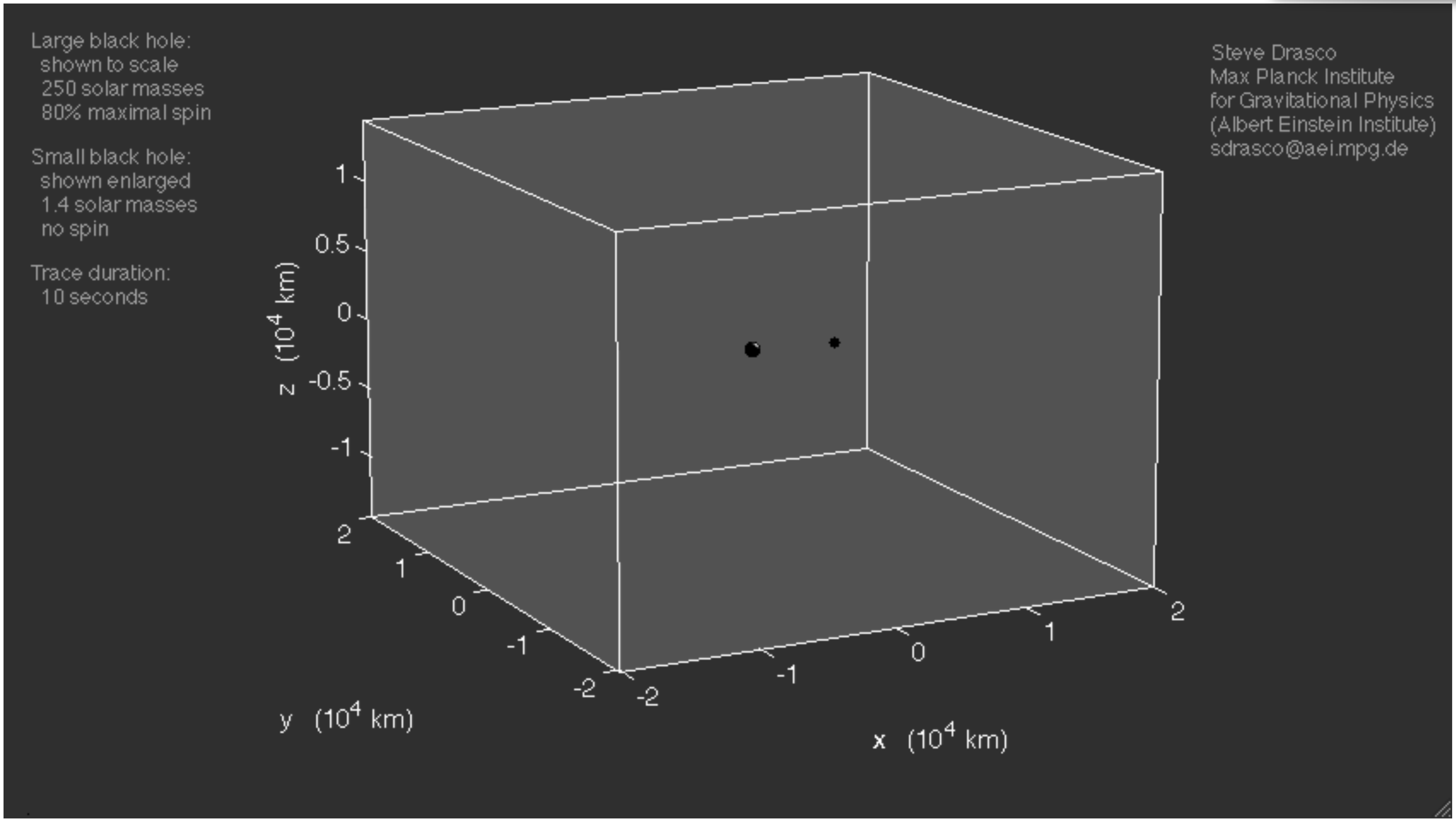
  - Back to protogalaxies, z = 15-20
  - Galaxy formation
  - One signal per week

NGC 2623: Galaxy Merger from Hubble
NASA, ESA and A. Evans (Stony Brook) et al.



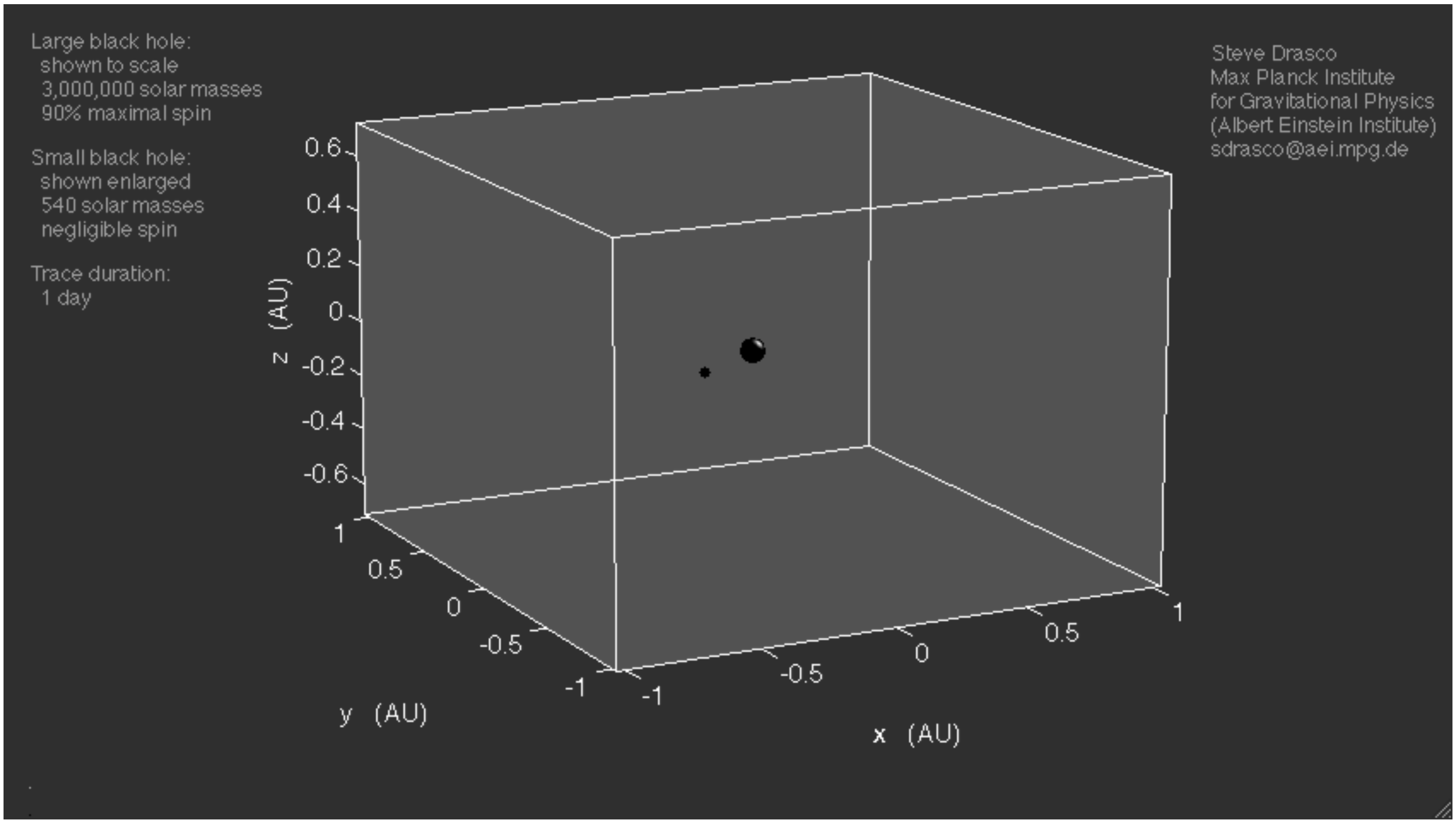
31 minutes = 10seconds

Compact Binary



Credit: Steve Drasco

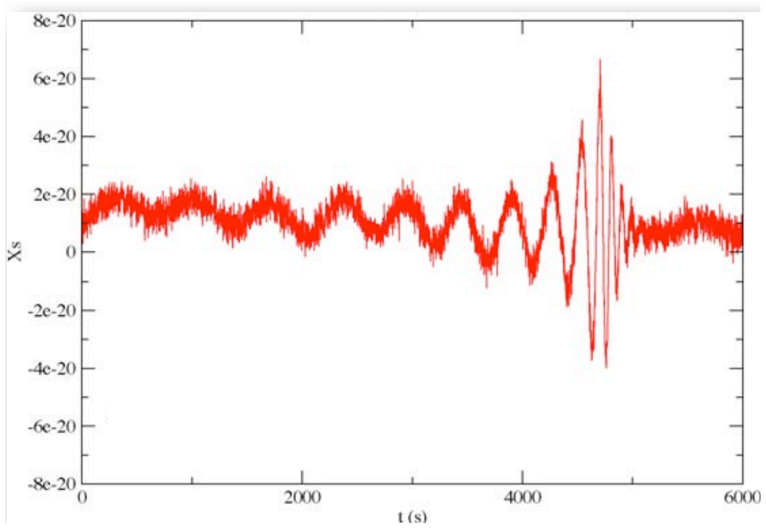
Extreme mass ratio inspiral



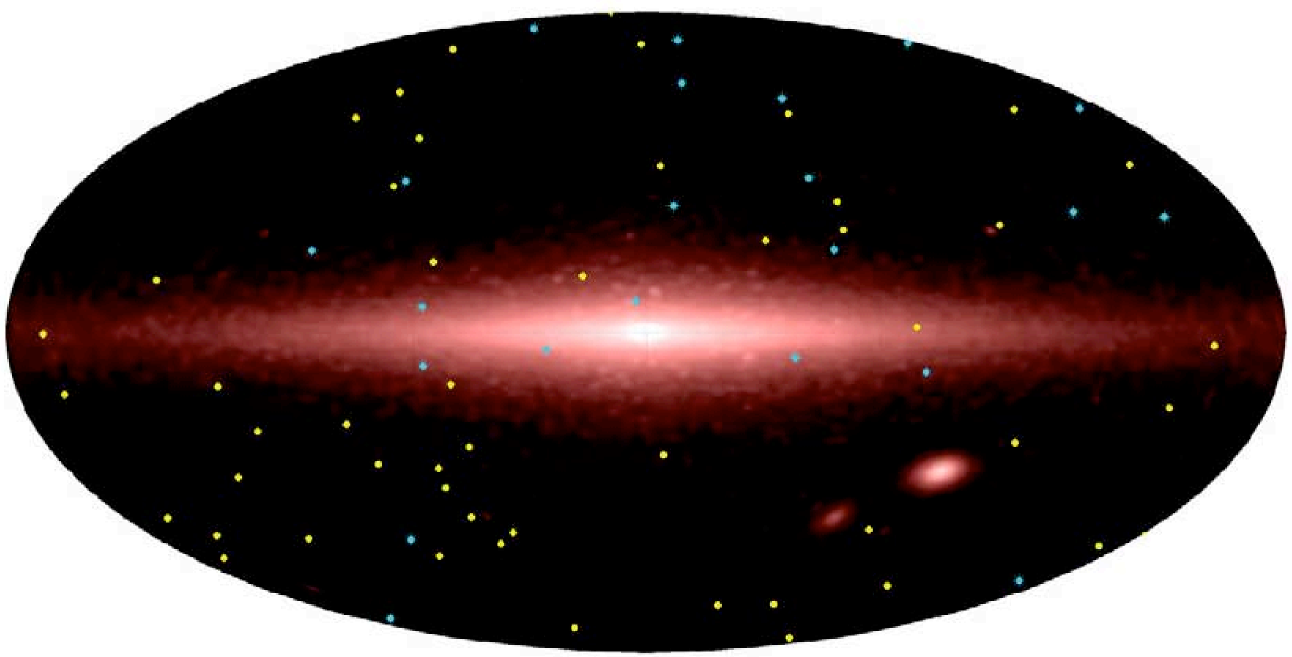
Credit: Steve Drasco

LISA's view

- LISA signal is a time series



Simulated signal for the merger of a massive black hole binary at z = 15



Simulation of a gravitational wave sky as seen by LISA

- Compact binaries in Milky Way & Magellanic clouds (red)

- Massive BH binaries & EMRI's in distant galaxies (blue and yellow)

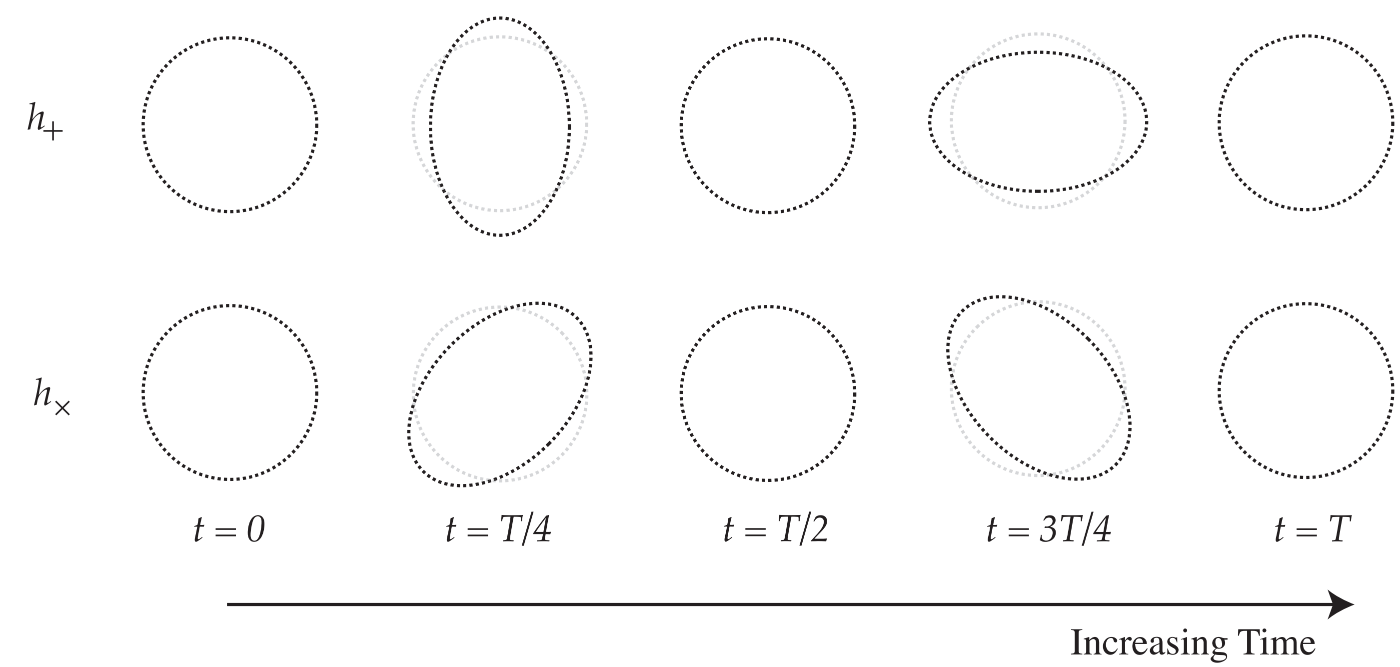
Overview

- Sources
- Detectors
- LISA overview

- Laser and clock frequency noise
- LISA Pathfinder

Direct detection: *measure changing length*

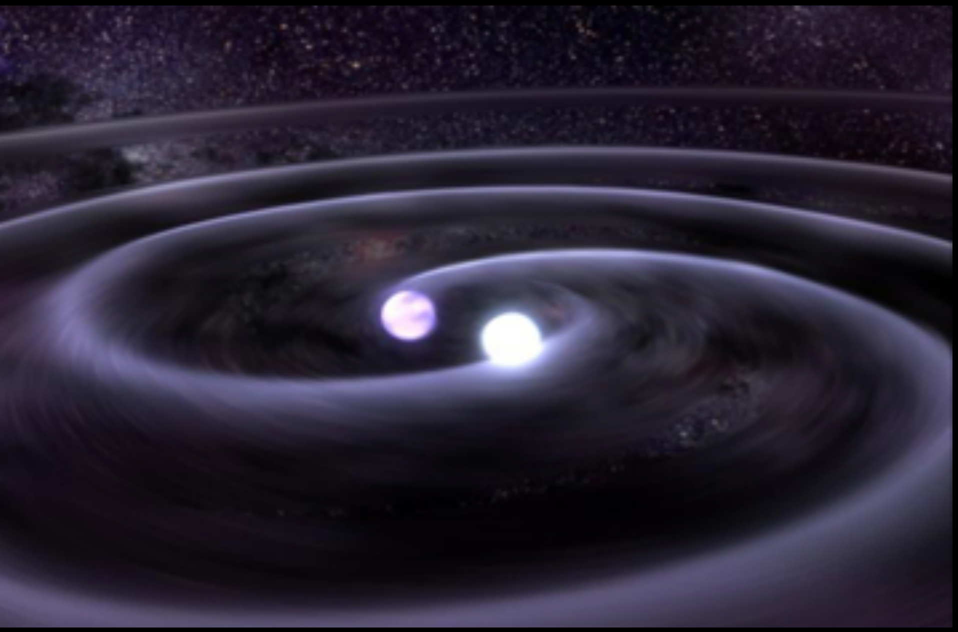
- Measure changing distance between freely falling masses

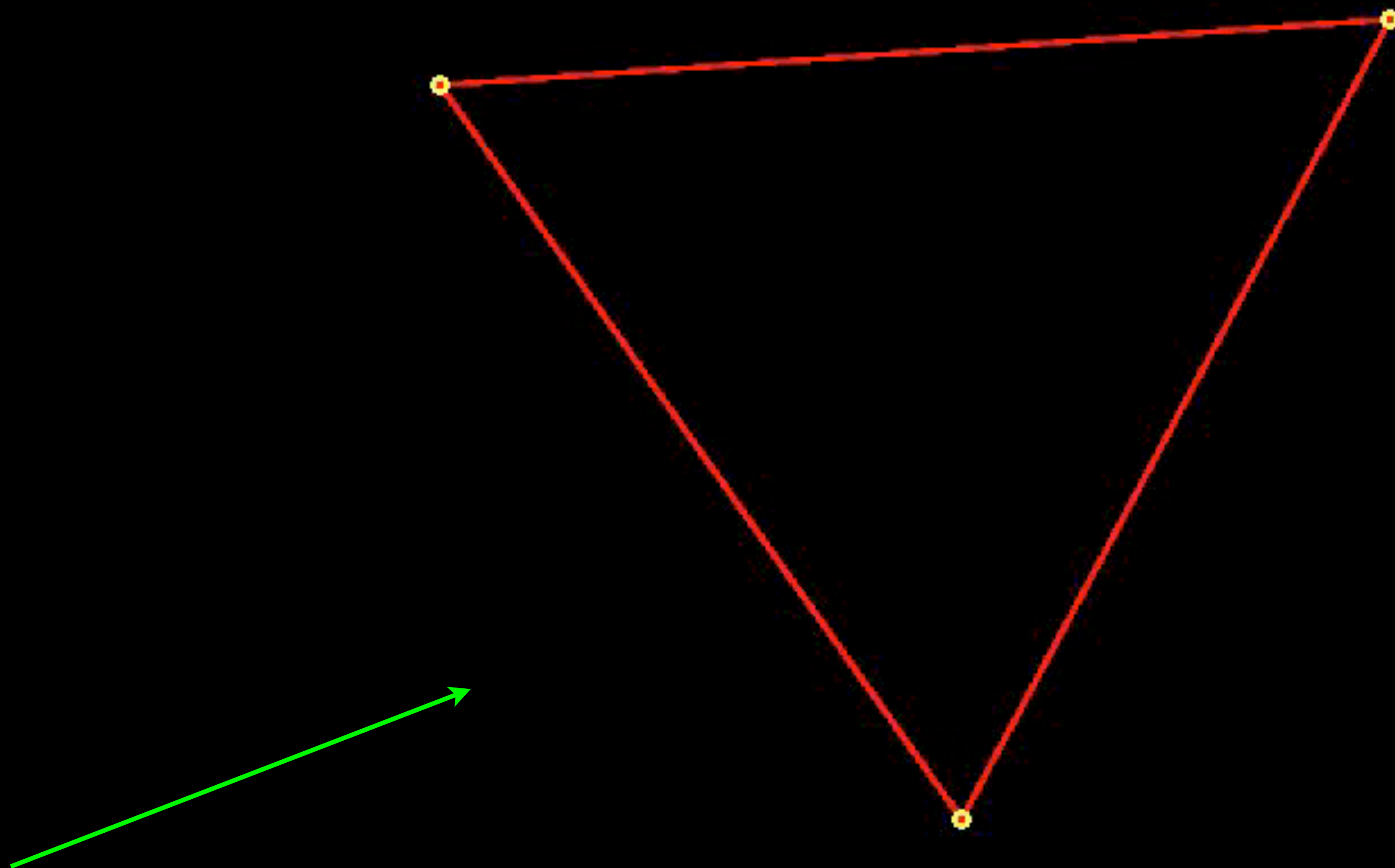


- Gravitational wave amplitude characterized by strain:

$$h = \frac{\Delta L}{L},$$

Source



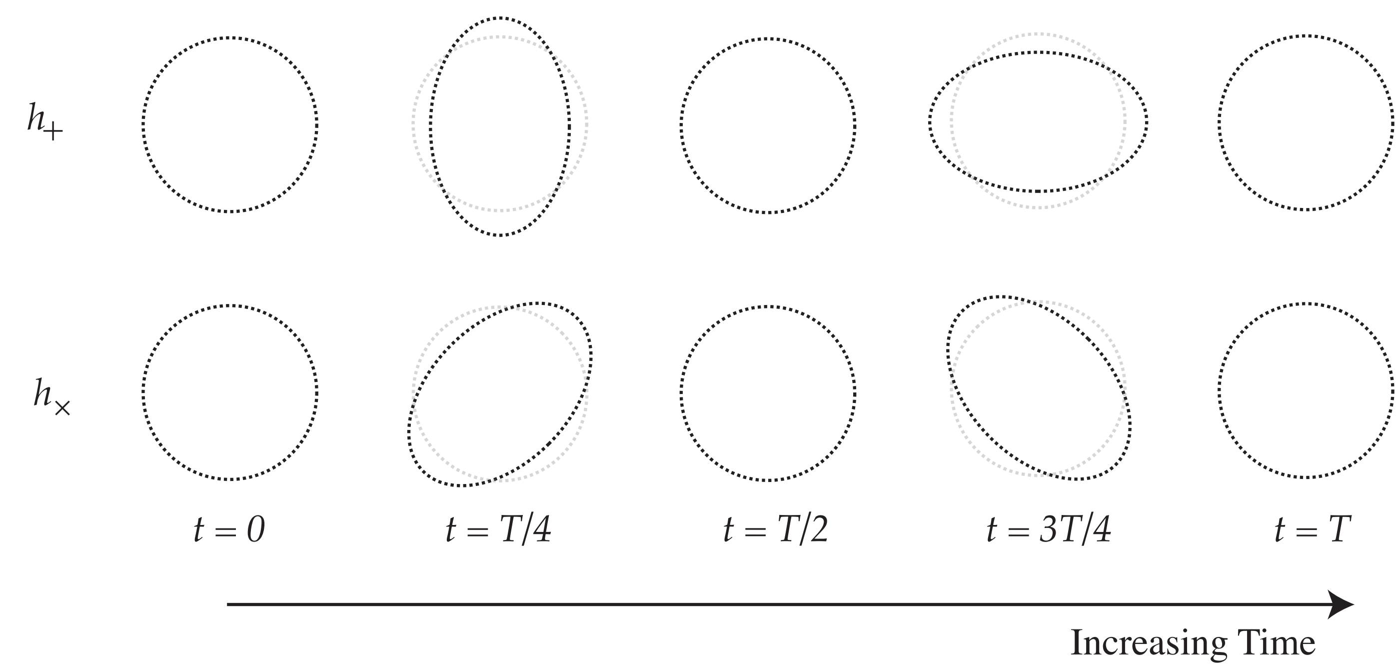


LISA

Source amplitude exaggerated by ~10^{20} times

Direct detection: *measure changing length*

- Measure changing distance between freely falling masses



- Gravitational wave amplitude characterized by strain:

$$h = \frac{\Delta L}{L},$$

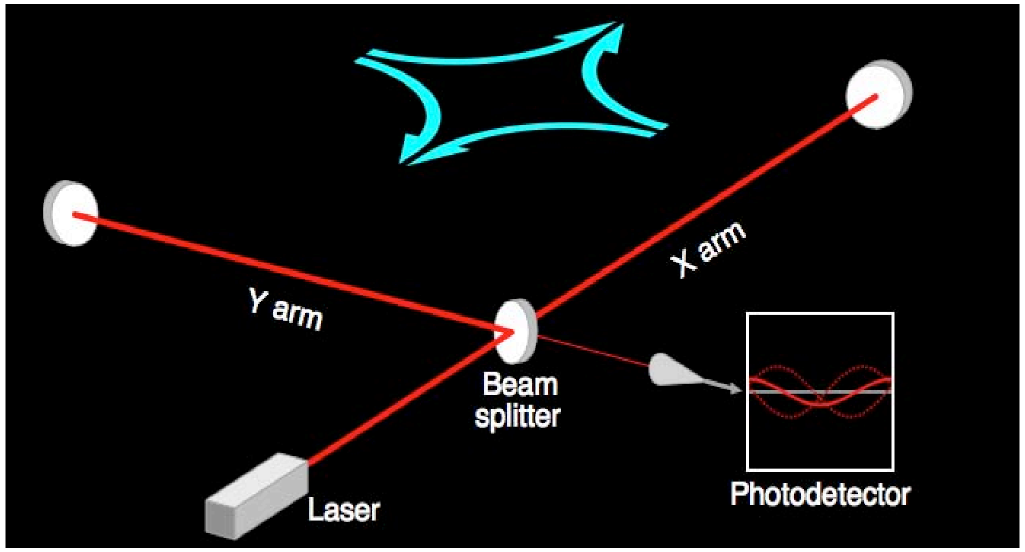
- Two ways to improve detector sensitivity -
  1) Improve measurement precision,
  2) Increase Length

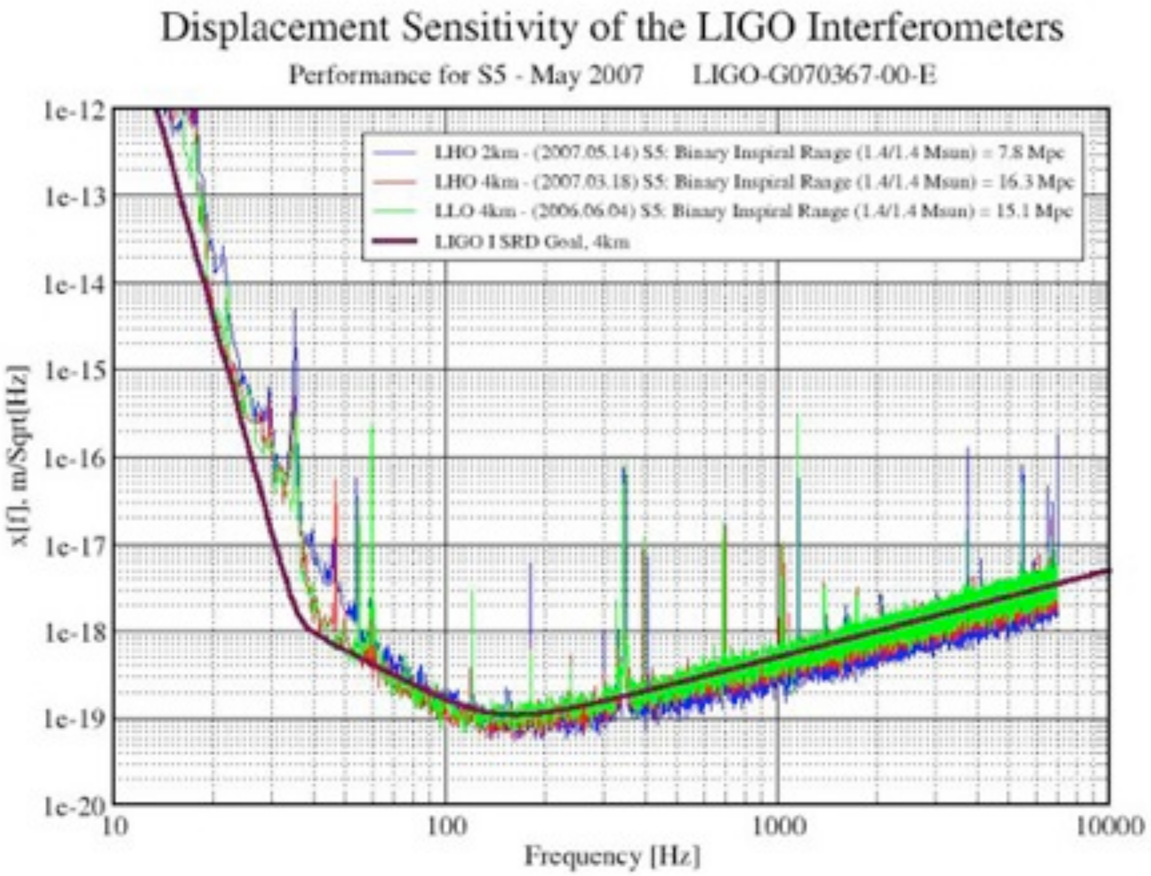
Ground-based detectors

Ground-based detectors

- Michelson Interferometers,
  - Kilometer scale,
  - Incredible precision.
    10^{-19} m/rtHz @ 100Hz
  - Seismic and newtonian gravity noise limit detectors to > 10Hz
  - Shot noise

- Advanced detectors 2015
  - 10 times more sensitive
  - 1 detection per week





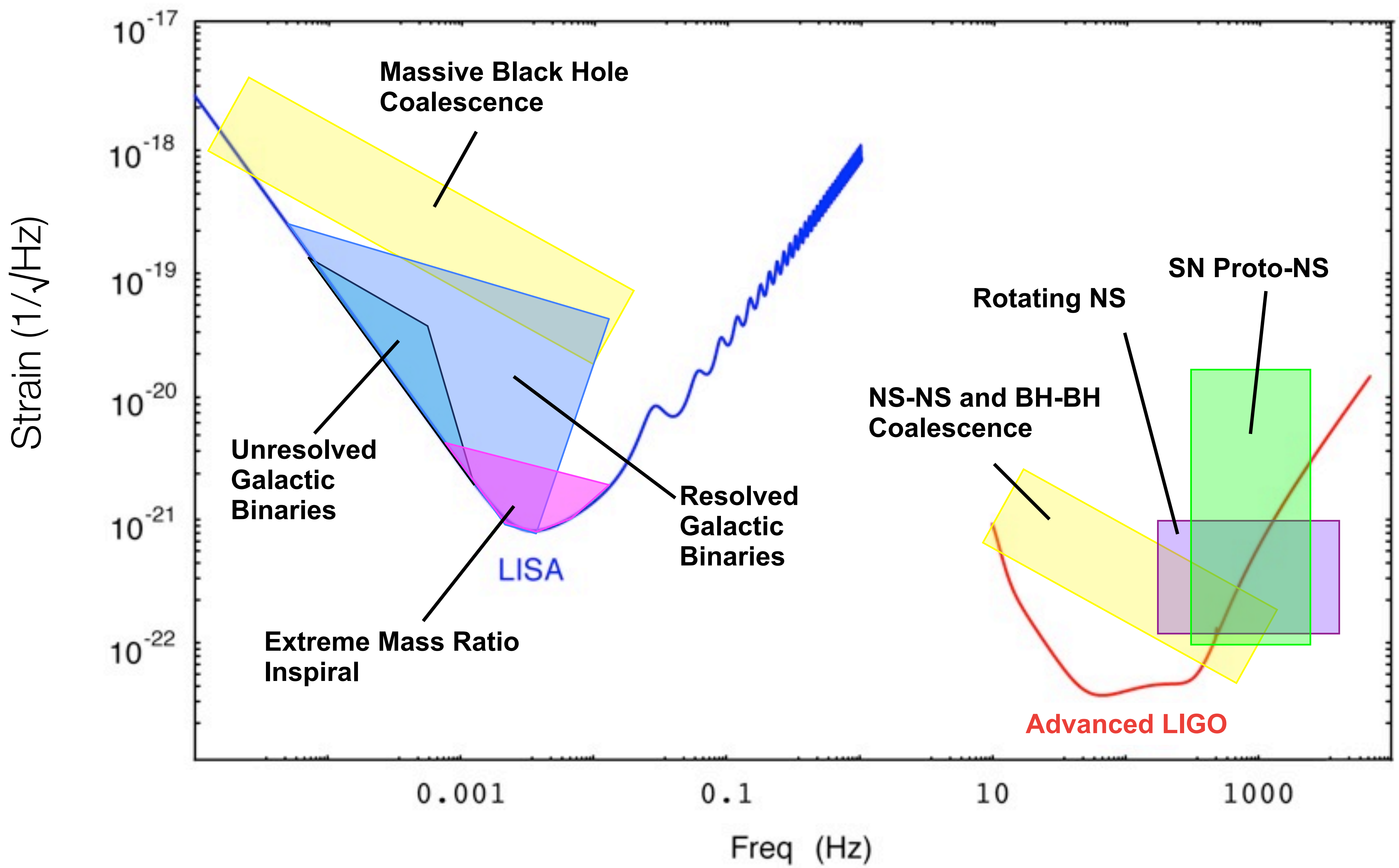
Going to space:
largest signals, long arm lengths, quiet

- **Largest sources are below 10mHz**
  - Earth is too noisy below 10Hz,
  - LISA's drag-free system gives good displacement noise performance

- **Signal scales linearly with arm length**
  - Space has "free" vacuum, can make arm lengths very long
  - LISA's arm lengths (5×10^9m) optimized for 3mHz

- **Noise scales inversely with laser power** - quantum noise
  - Both ground- and space-detectors limited by laser power

Ground and space: complimentary detectors



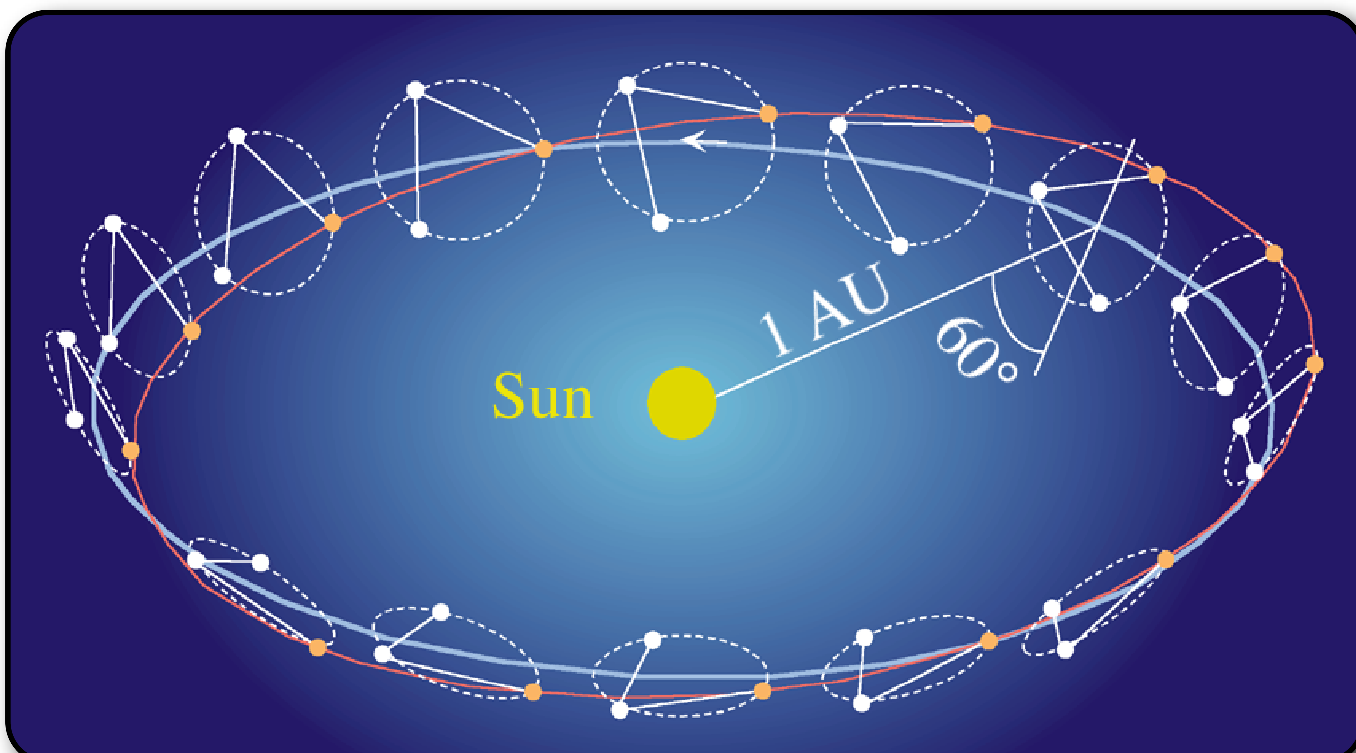
Overview

- Sources
- Detectors
- LISA overview
- Laser and clock frequency noise
- LISA Pathfinder

LISA Constellation

- LISA has 3 arms and thus can measure both GW polarizations.

- Orbits chosen to passively maintain spacecraft formation.



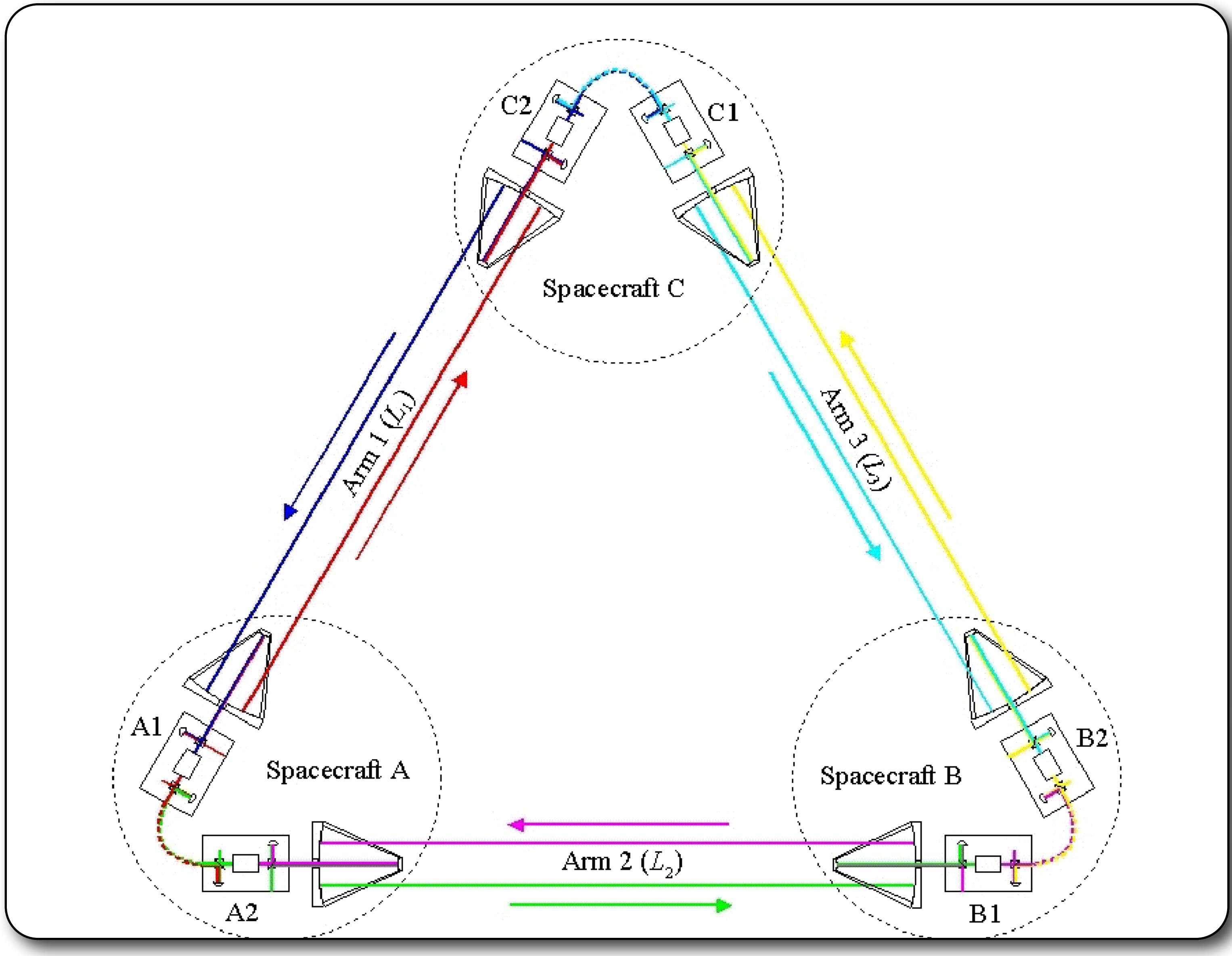
Directional sensitivity through motion of constellation.

- Amplitude modulation from detector rotation.
- Frequency modulation through Doppler shifts.
- ~tens of arcminutes direction depending on source frequency and SNR

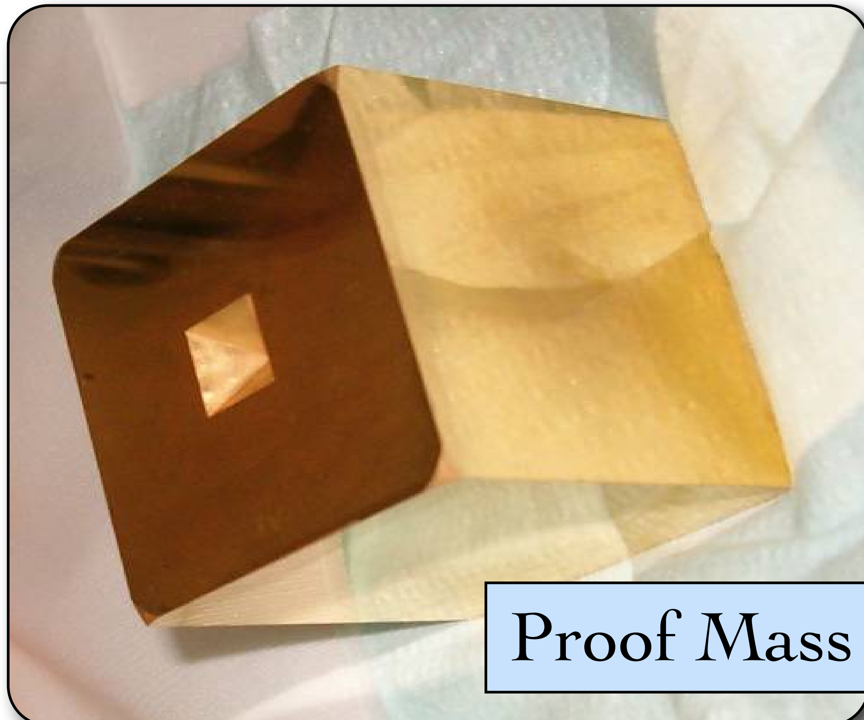
- Constant solar illumination provides a benign thermal environment.

LISA: Six one-way inter-spacecraft measurements

- 2 proof masses per S/C
  one for each sensitive direction
  Drag free operation
- 2 lasers per S/C
- 6 one-way inter-spacecraft phase measurements
- Local phase measurements
- All phase measurements sent to ground
  - Combined in post-processing



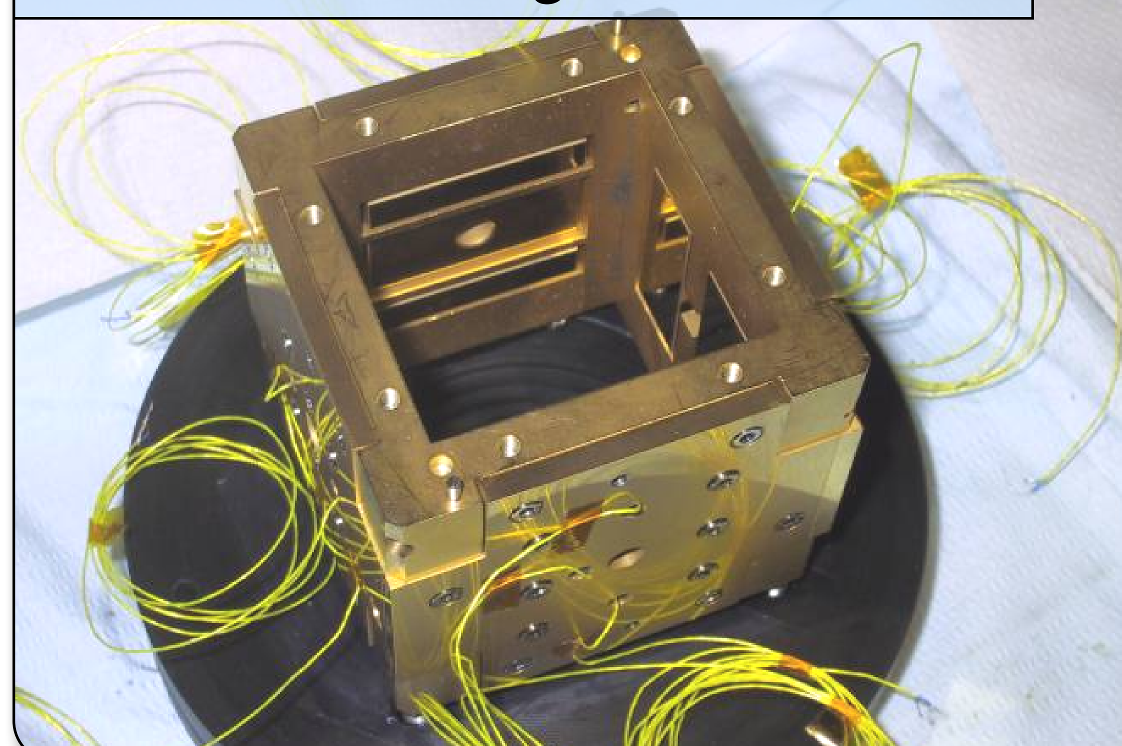
Gravitational Reference Sensor



Proof Mass

- LISA acceleration noise:
  - $\sim 10^{-15}$ m/s^2/$\sqrt{\text{Hz}}$ @ 1 mHz
- 40 mm Gold-Platinum cubical proof mass.
- Proof mass sits inside electrode housing. No mechanical contact.

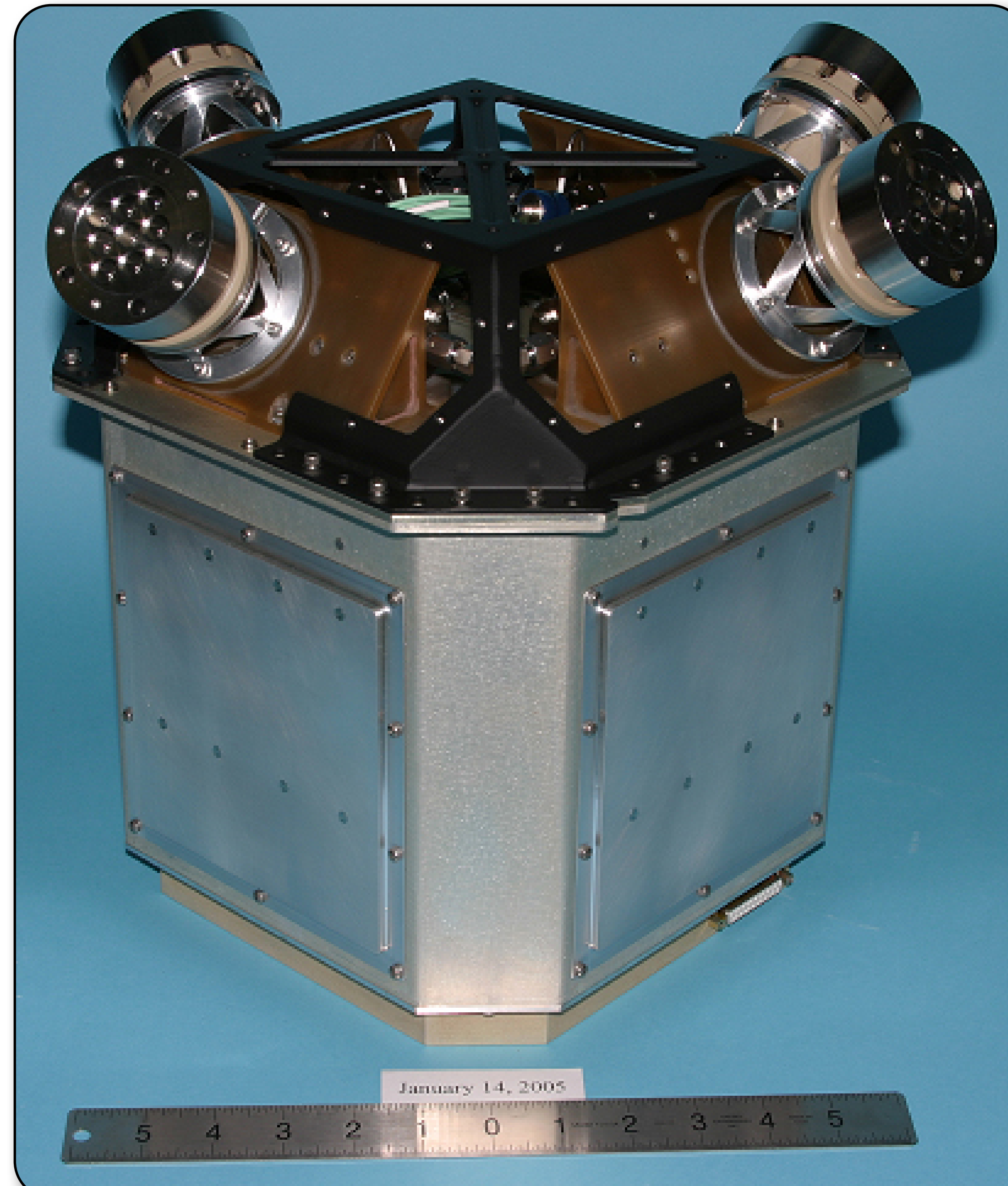
Electrode housing and electrodes



- Capacitive sensors and actuators monitor and feedback proof mass position and orientation.
- Optical fibers provide UV light to discharge the PM.

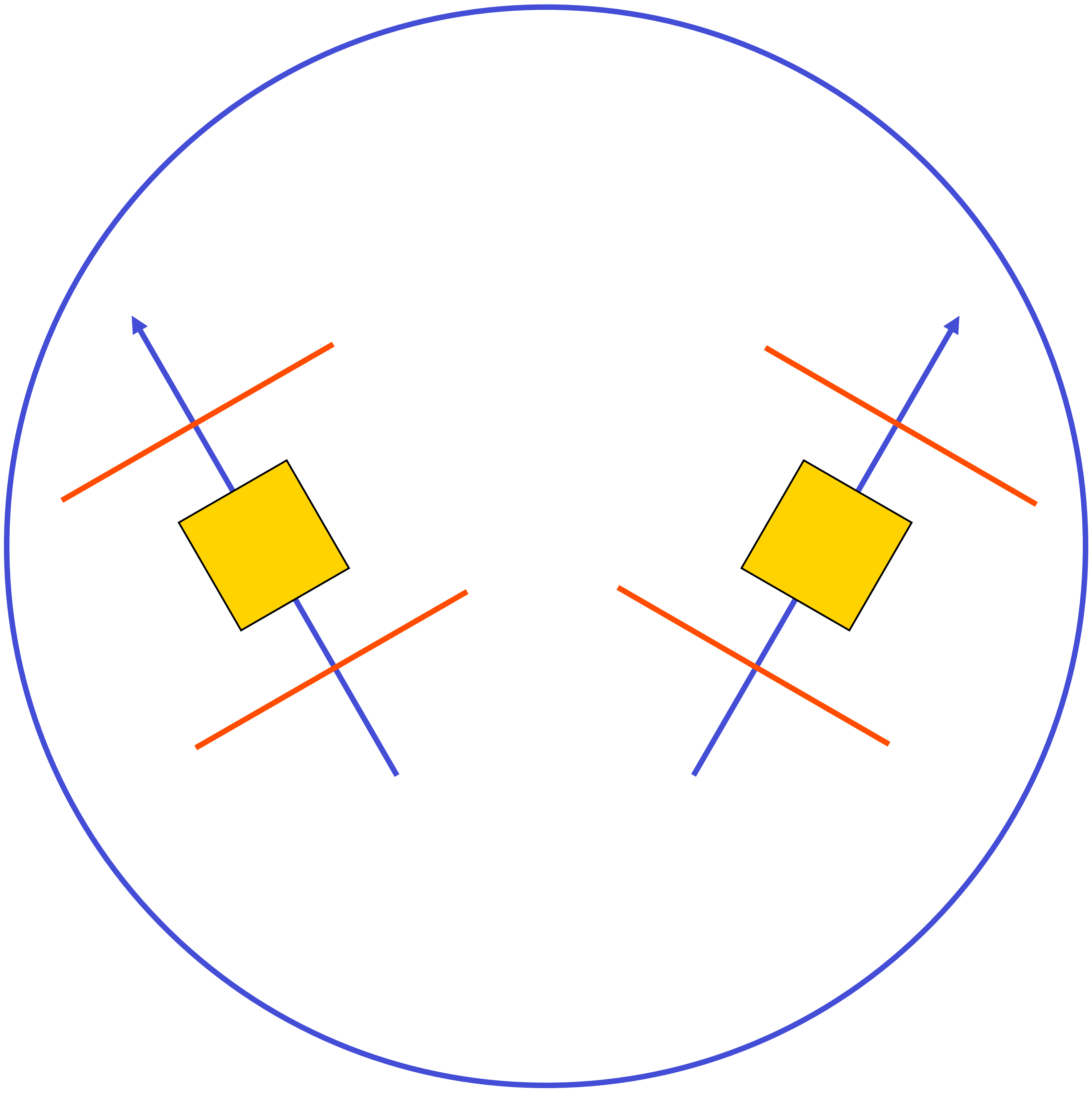
Micro-Newton Thrusters

- Thrusters allow the spacecraft to track proof mass motion in the sensitive direction.
  - Push back against the solar wind.
  - Maintain spacecraft orientation.
- Micro-Newton thrusters for LTP based on Field Emission Electric Propulsion (FEEP)
- NASA-JPL are developing colloid micro-Newton thrusters.

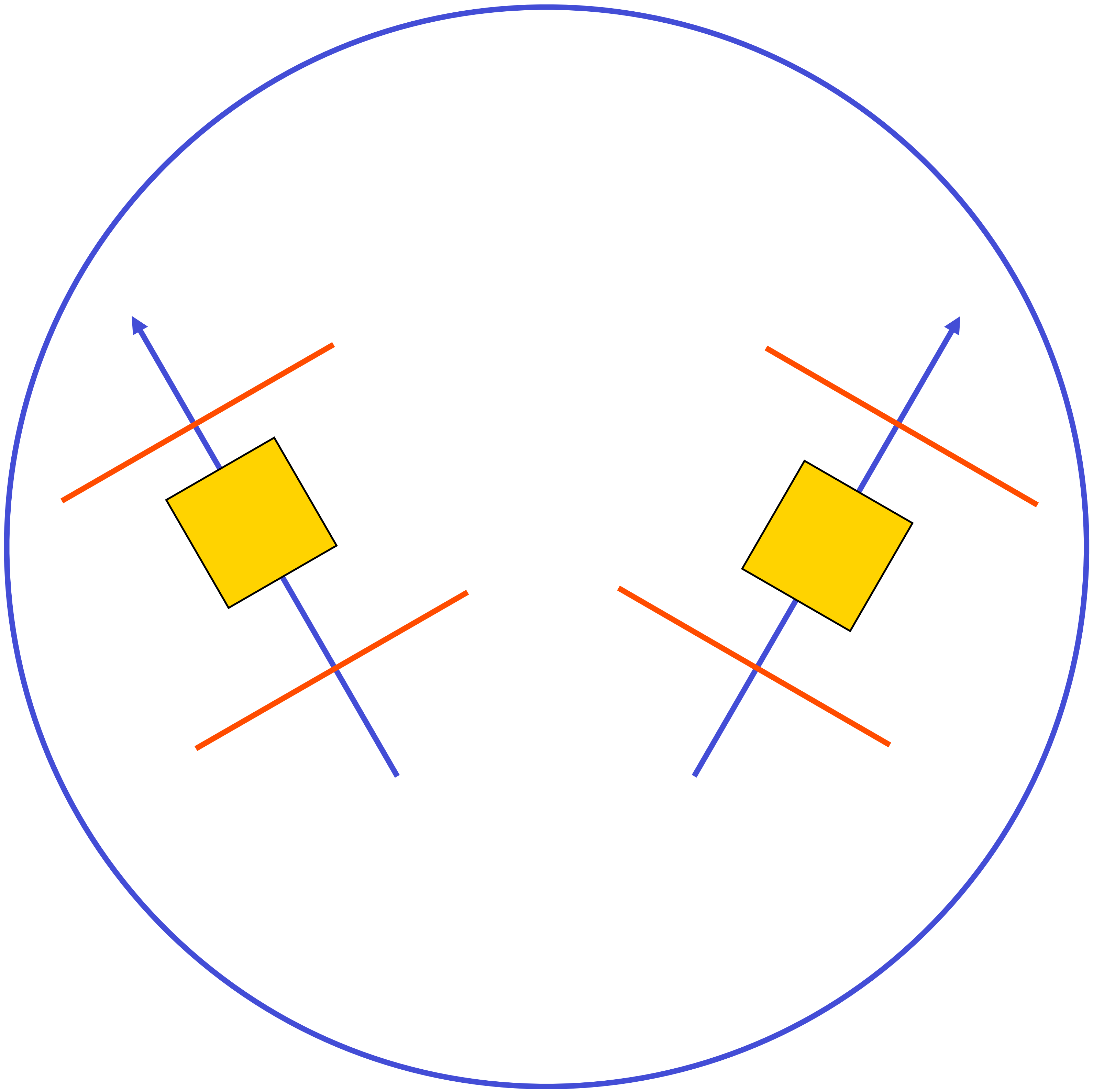


Colloid micro-Newton Thruster

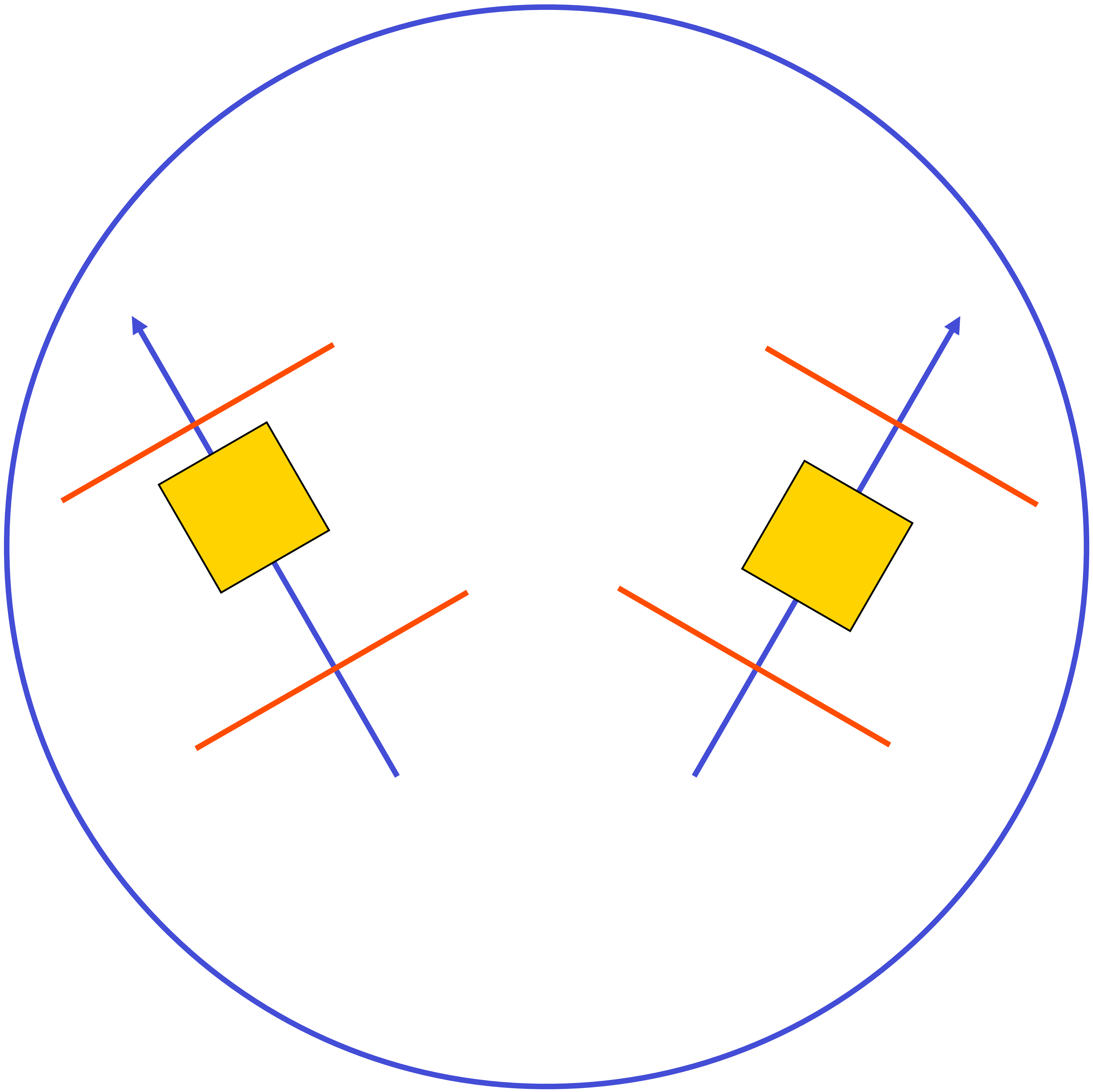
LISA control: spacecraft follows 2 masses at once



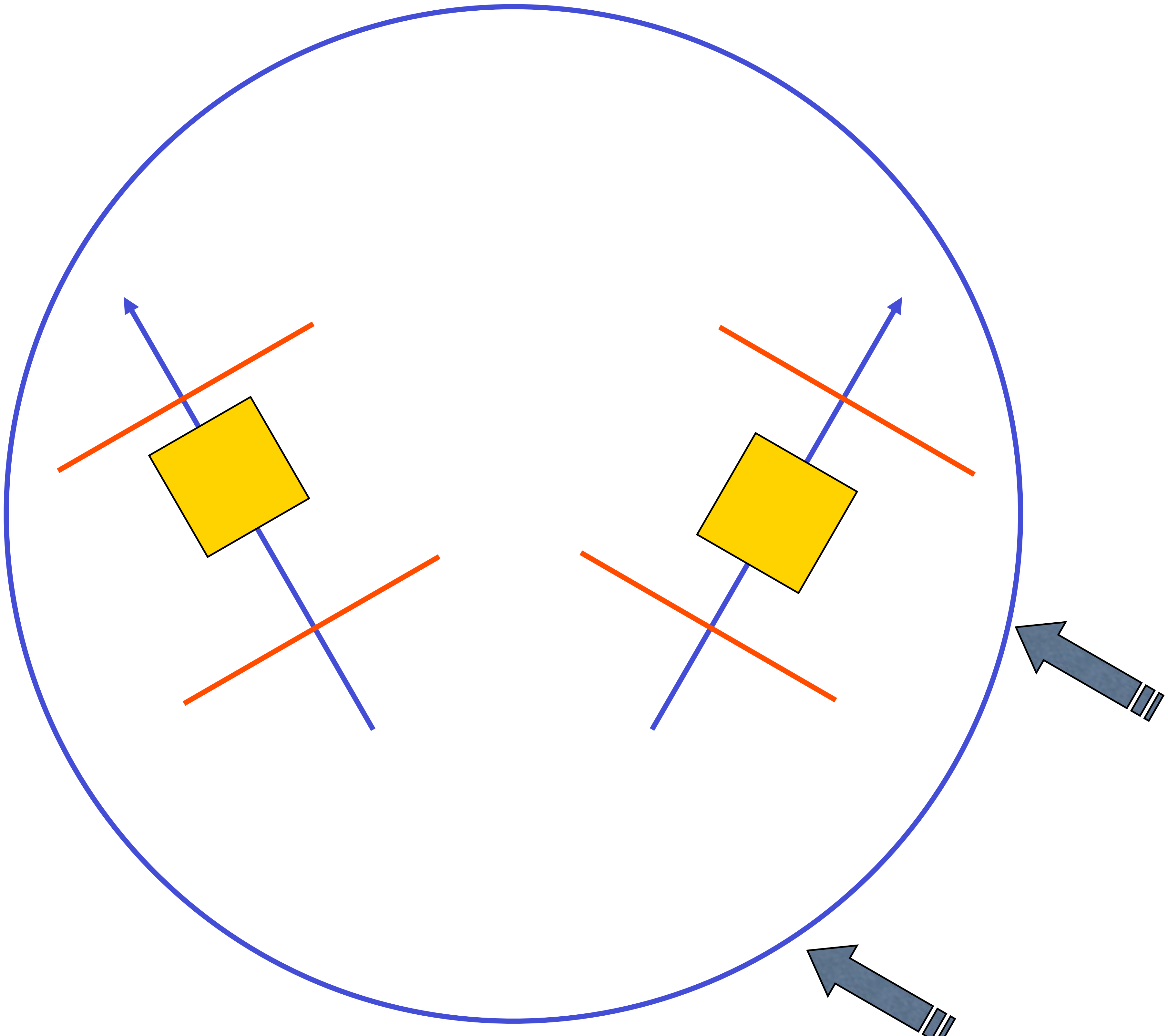
LISA control: spacecraft follows 2 masses at once



LISA control: spacecraft follows 2 masses at once

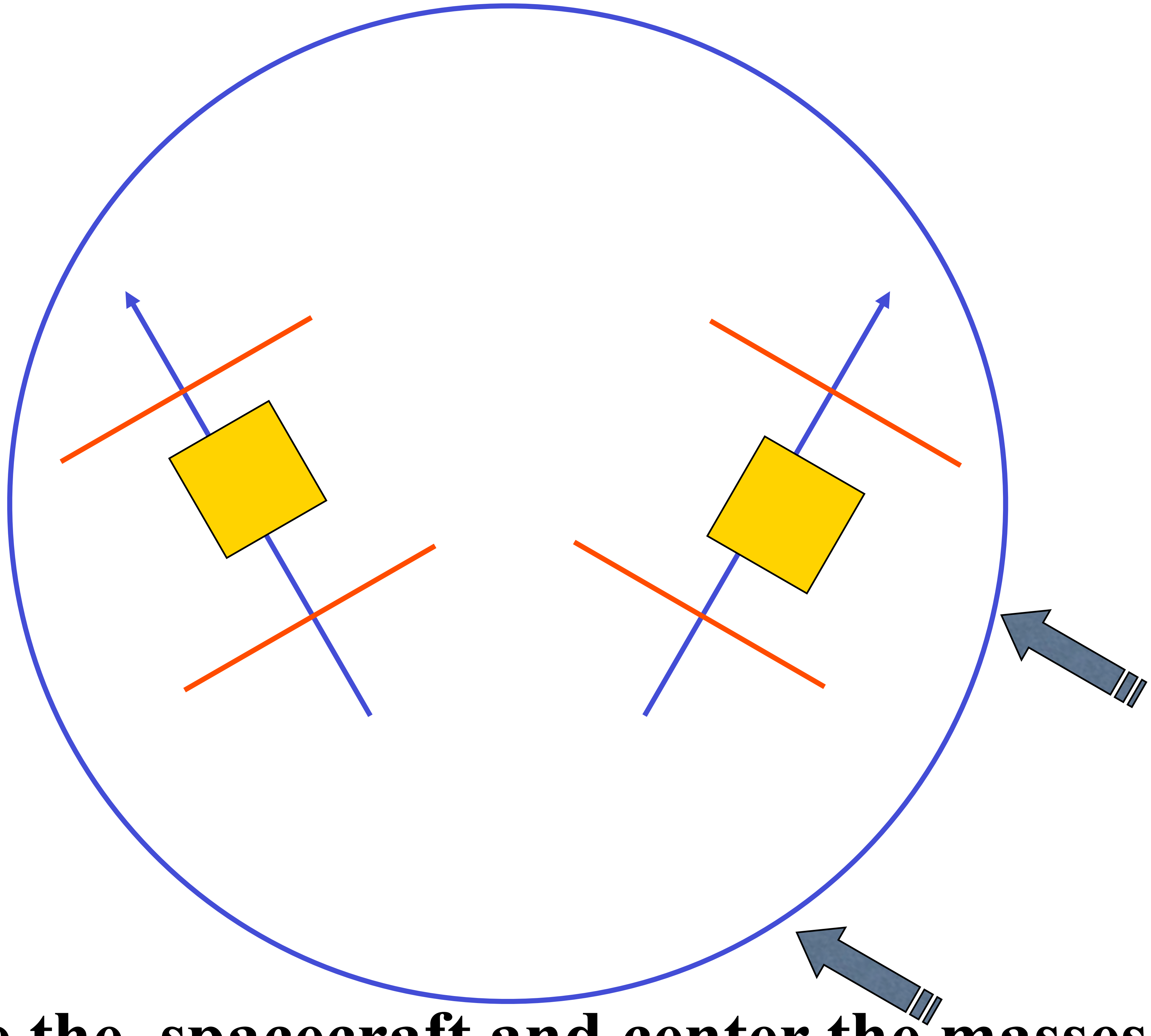


LISA control: spacecraft follows 2 masses at once



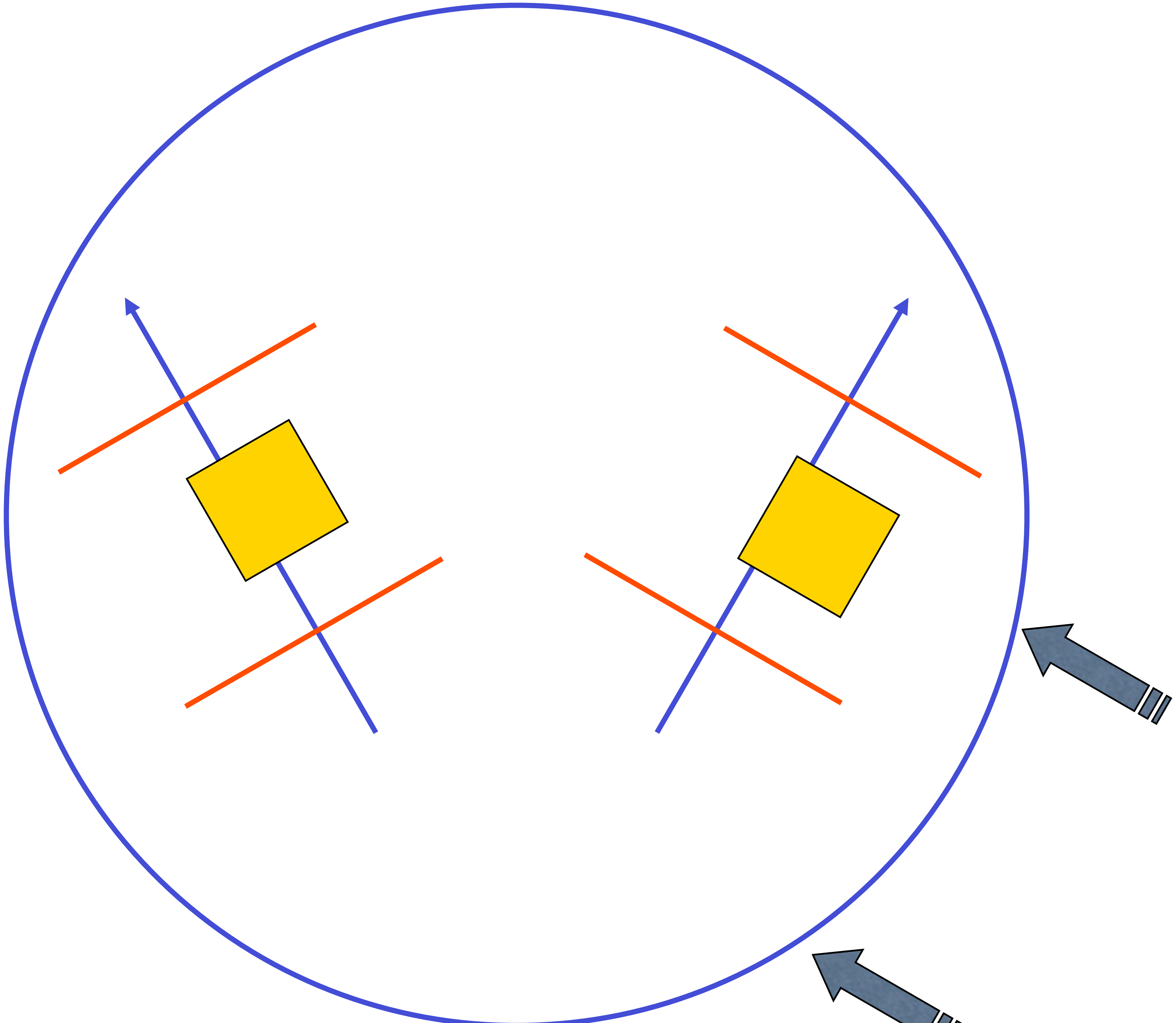
1: Move the spacecraft and center the masses along laser beams

LISA control: spacecraft follows 2 masses at once



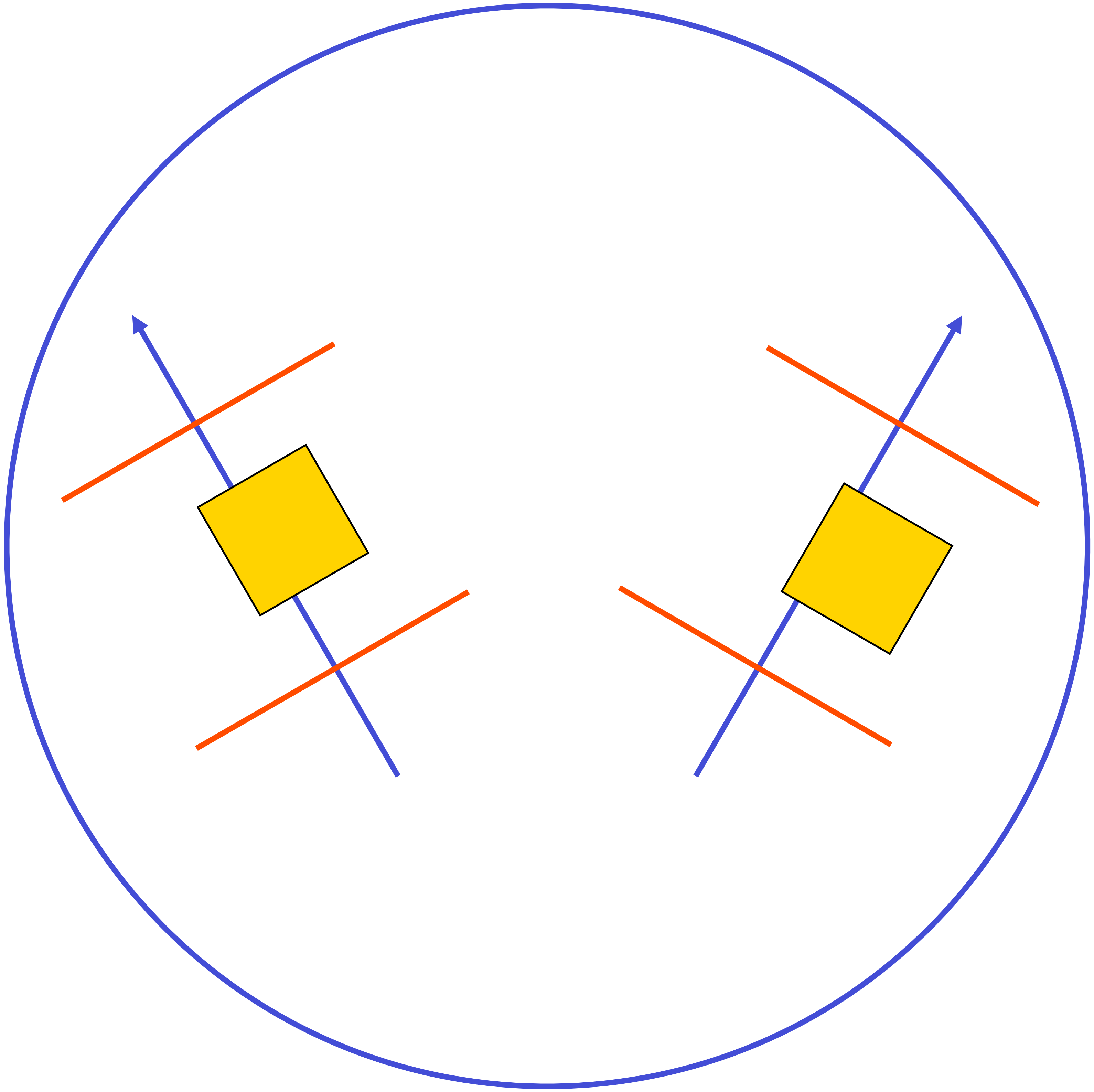
1: Move the spacecraft and center the masses along laser beams

LISA control: spacecraft follows 2 masses at once



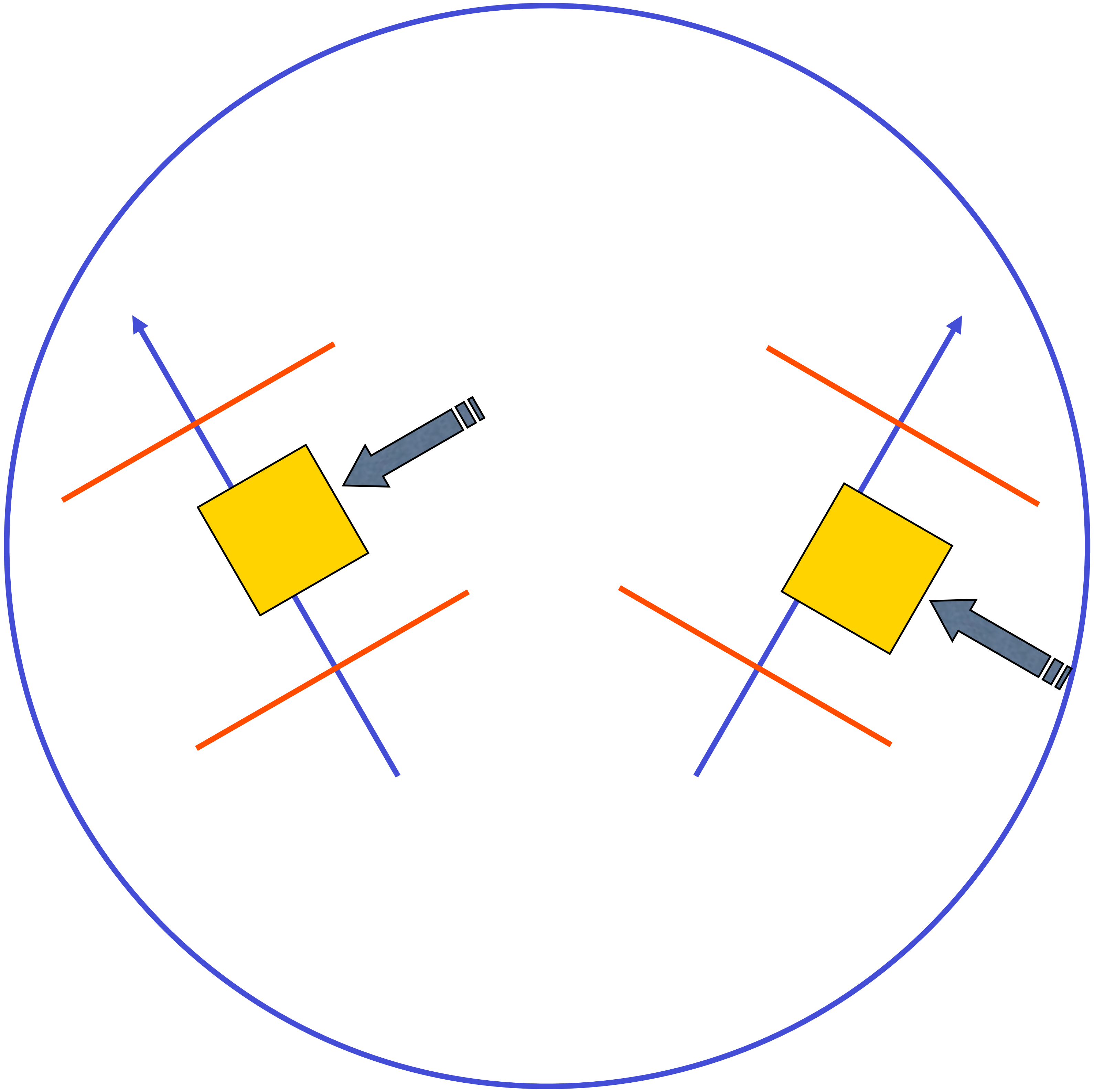
1: Move the spacecraft and center the masses along laser beams

LISA control: spacecraft follows 2 masses at once



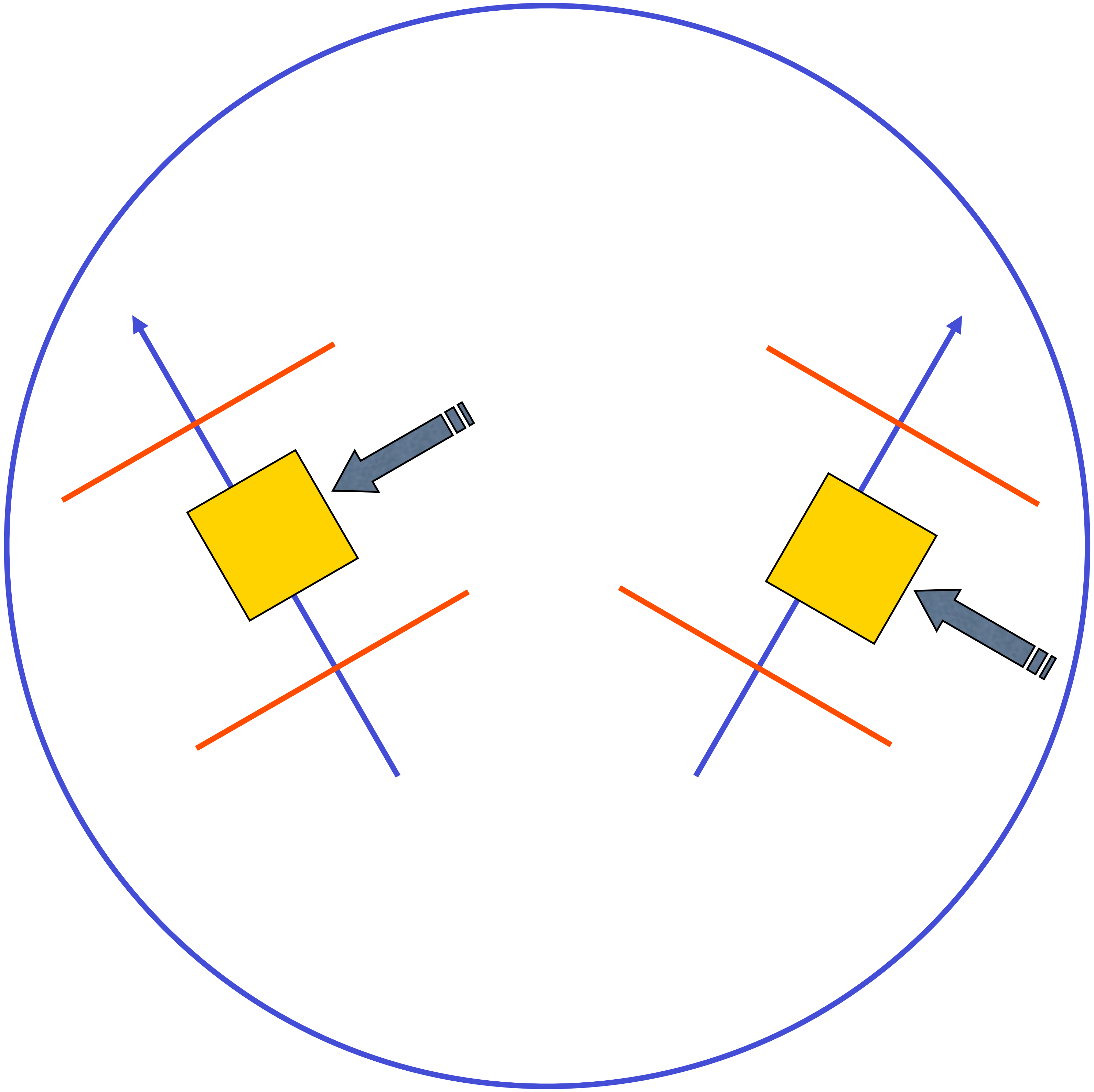
1: Move the spacecraft and center the masses along laser beams

LISA control: spacecraft follows 2 masses at once



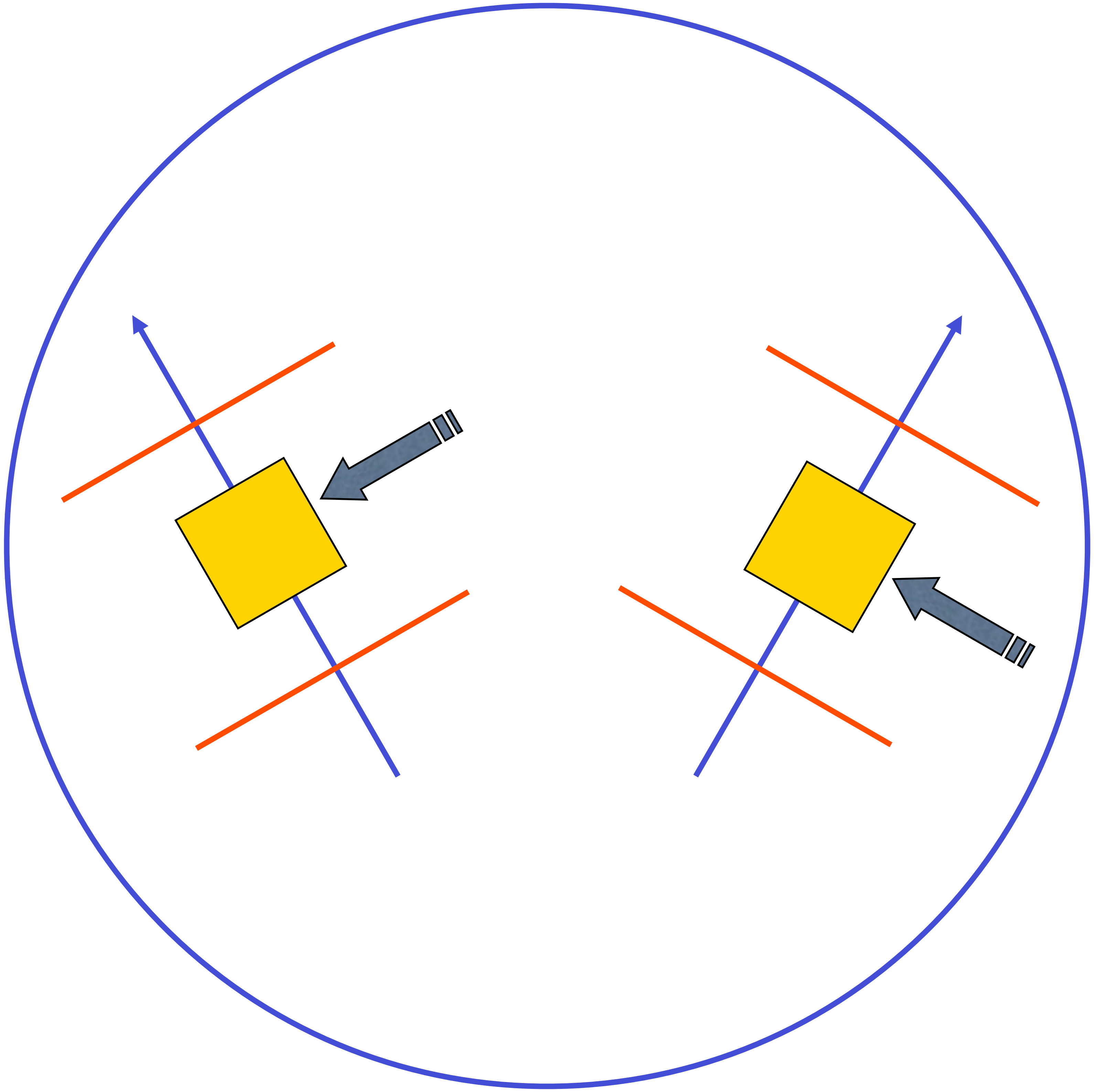
2: Re-center the masses at 90° from the laser beam

LISA control: spacecraft follows 2 masses at once



2: Re-center the masses at 90° from the laser beam

LISA control: spacecraft follows 2 masses at once

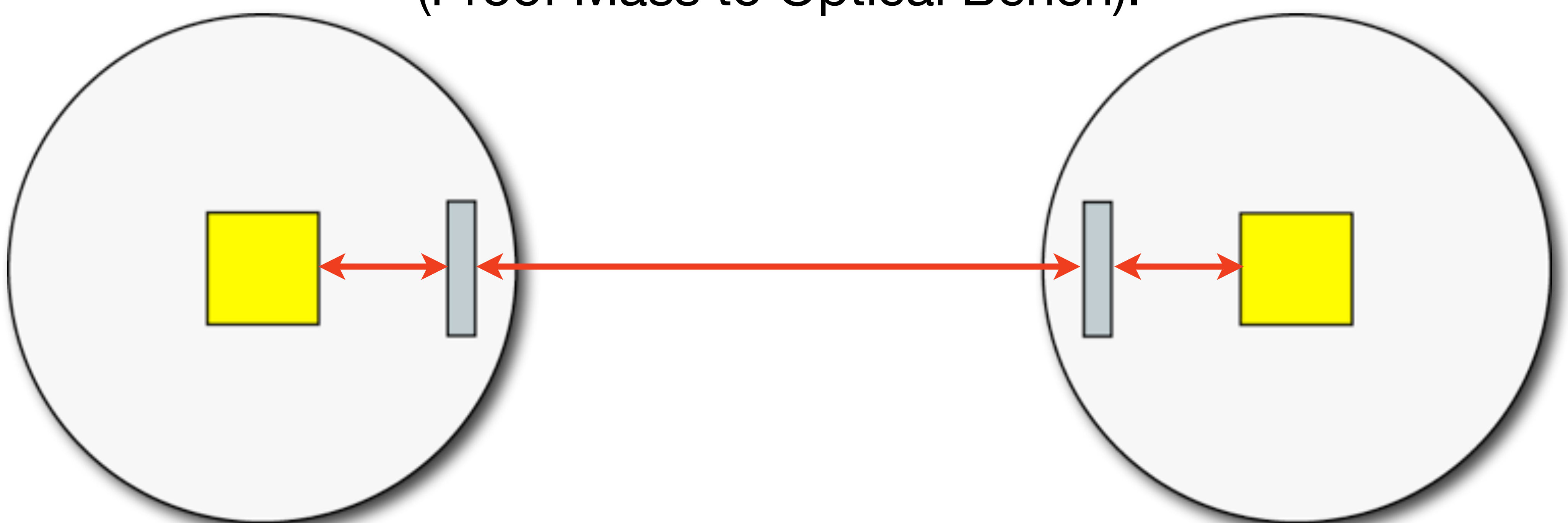


2: Re-center the masses at 90° from the laser beam

LISA Interferometry

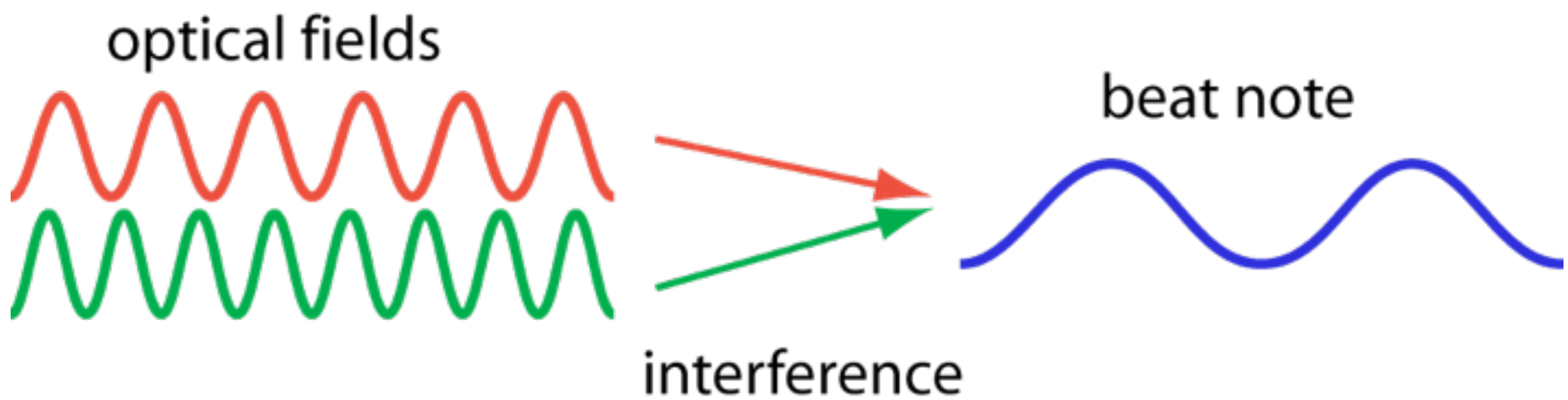
Two-step approach to measuring proof mass separation.

1. Local interferometry
(Proof Mass to Optical Bench).



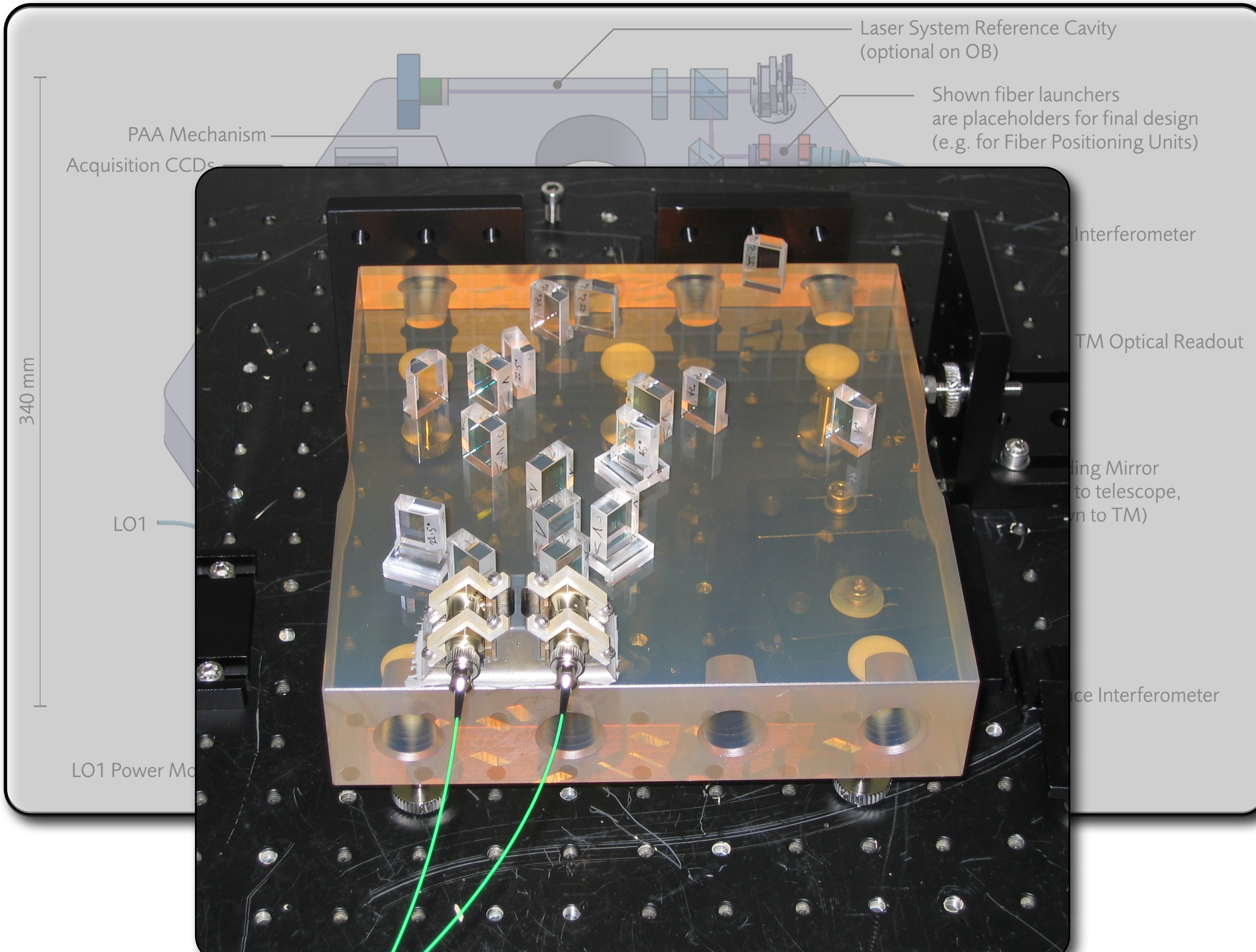
2. Inter-Spacecraft interferometry
(Optical Bench to Optical Bench).

Heterodyne Interferometry



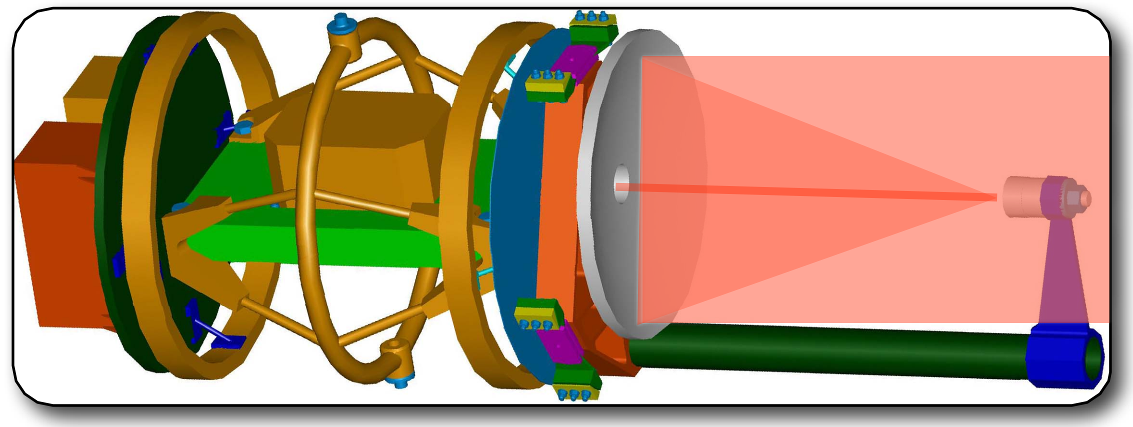
- One wavelength shift in one optical field produces a one wavelength shift in the beat note.
- No "lock" point. Full fringe readout with large dynamic range.
- LISA beat note ranges from 2 MHz -20 MHz due to doppler shift from spacecraft motion.
- The science signal appears as a milliHertz phase modulation on a megahertz beat signal.

Local Interferometry



Inter-spacecraft Interferometry

- 40 cm telescope
- ~1 Watt transmitted.
- ~10^{-10} Watts received.



  - shot noise of received power is dominant noise source at high frequencies ~10 pm/√Hz.
- Pointing fluctuations must be kept to below ~10 nrad/√Hz
- Arm length changes by ±1.5% over a year.

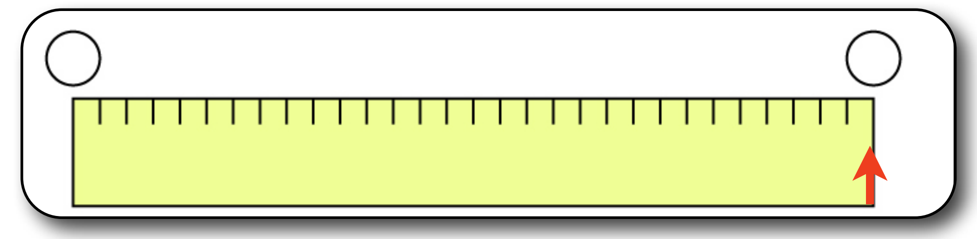
Overview

- Sources
- Detectors
- LISA overviews
- Laser and clock frequency noise
- LISA Pathfinder

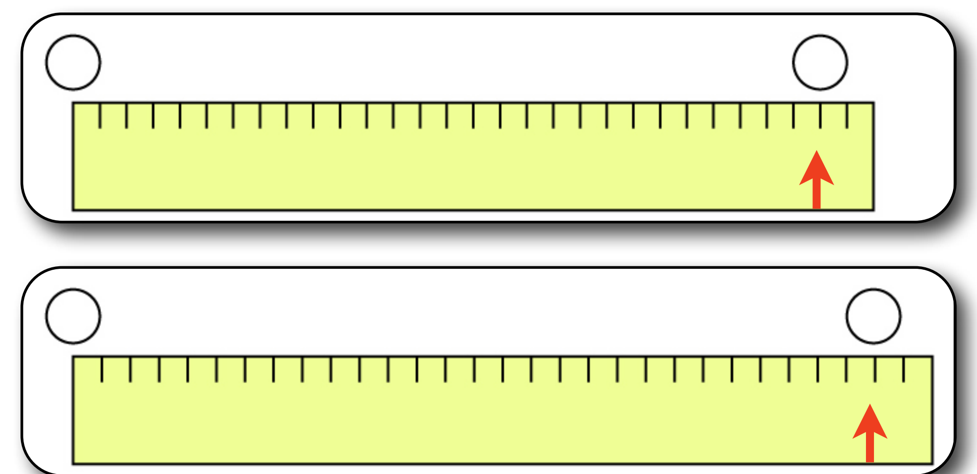
LISA needs frequency stabilized lasers

Spacecraft separation measured by laser "ruler".

Laser's wavelength is analogous to ruler's tick marks



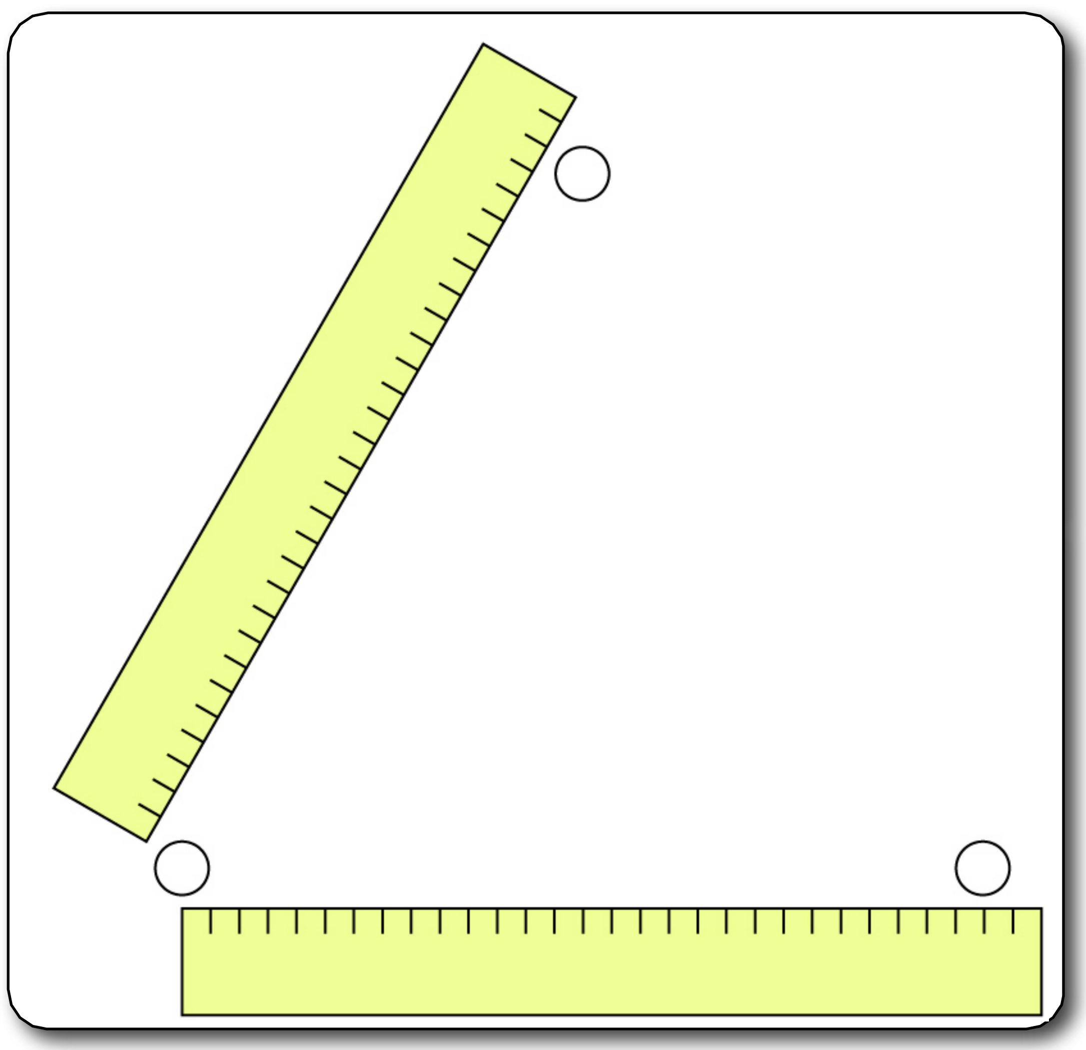
Changes in spacecraft separation are indistinguishable from changes in wavelength.



$$\boxed{\frac{\delta L}{L} = \frac{\delta \nu}{\nu}}$$

(one armed interferometer)

Common mode rejection in a Michelson Interferometer



Difference between two equal length arms is immune to (common) ruler length changes.

$$\boxed{\frac{\delta L}{\Delta L} = \frac{\delta \nu}{\nu}}$$

(Michelson interferometer)

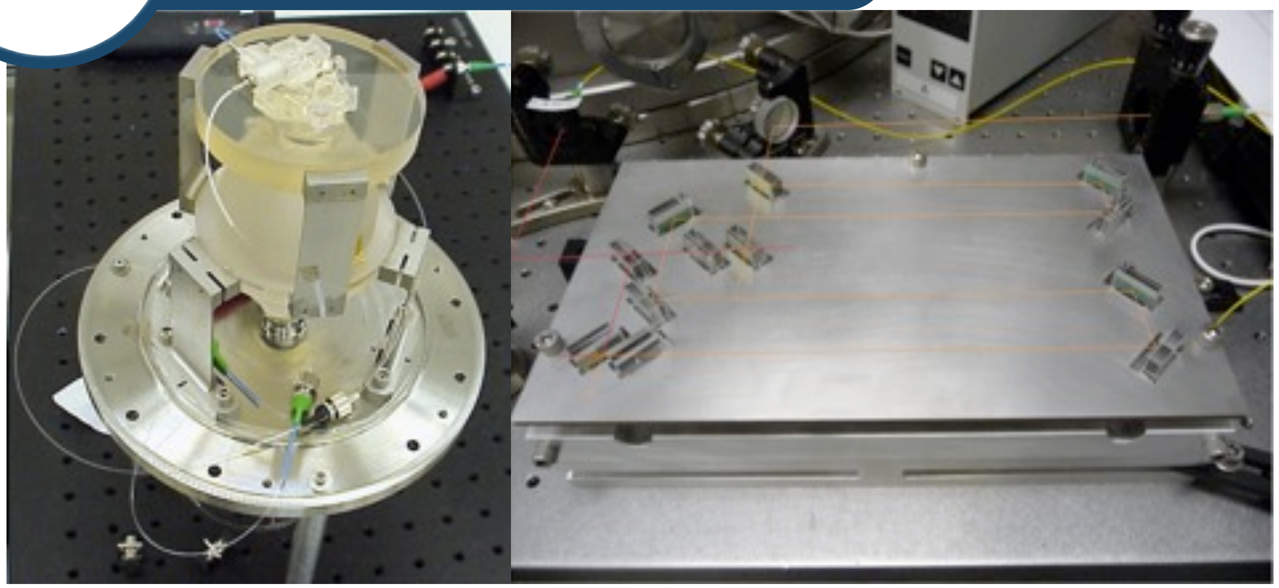
In LISA $\Delta L \approx 50{,}000$ km

1 pm/$\sqrt{}$Hz $\Rightarrow \delta\nu/\nu < 10^{-20}$ /$\sqrt{}$Hz

Best laser: $\delta\nu/\nu \sim 10^{-8}/\sqrt{}$Hz (@ 3 mHz)

3 (maybe 2) steps to reduce frequency noise

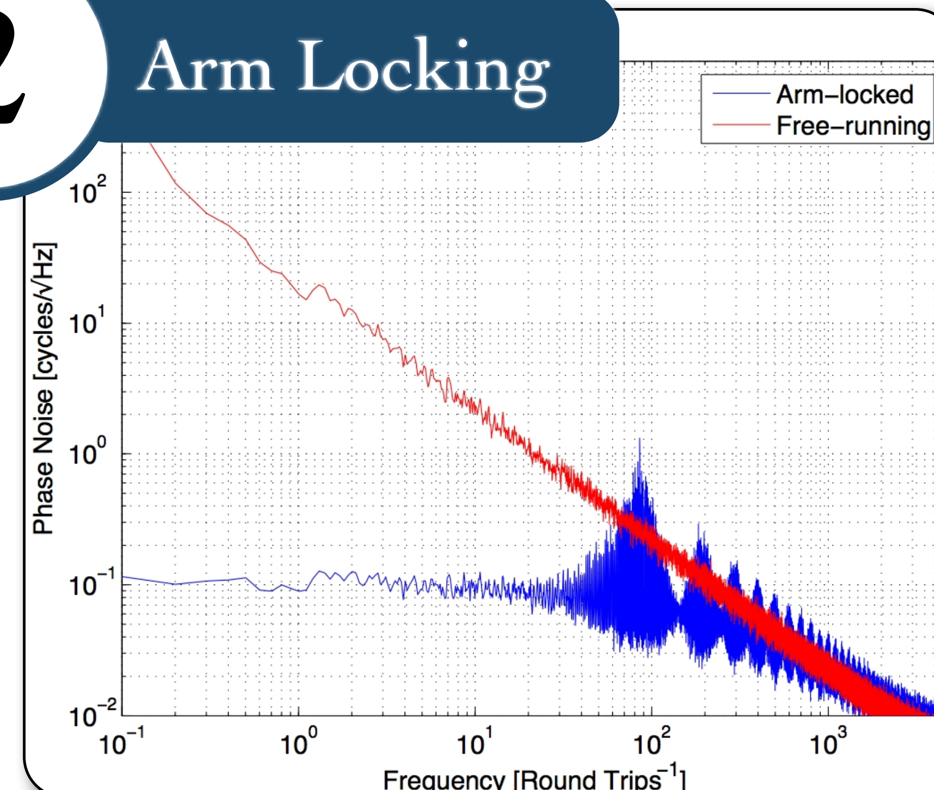
1 Pre-Stabilization



LISA lab

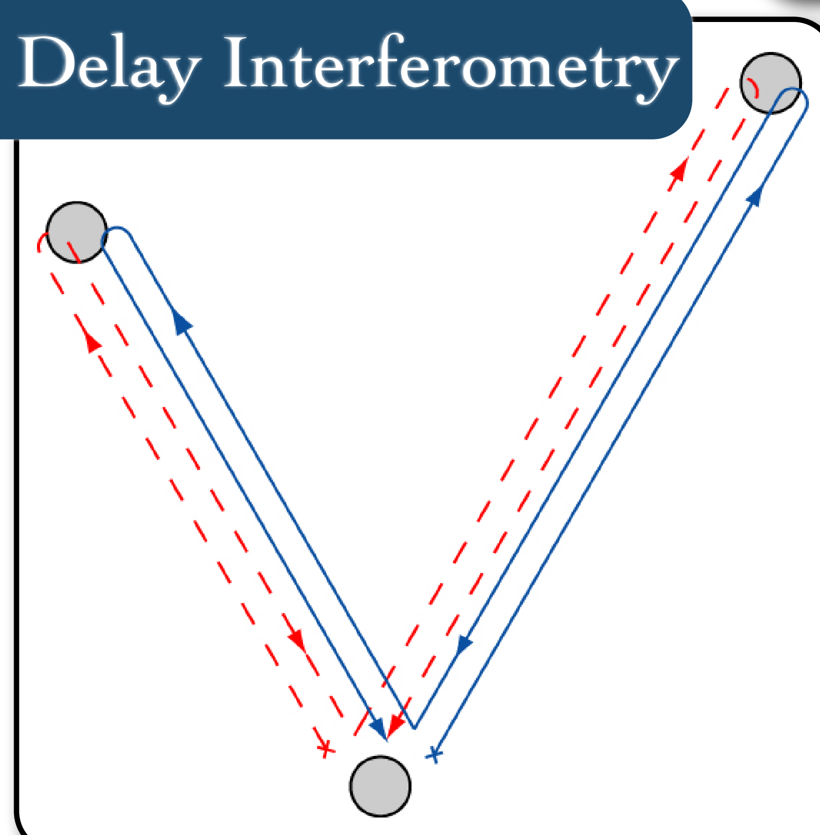
GRACE optical Cavity
Folkner et al 2010

2 Arm Locking



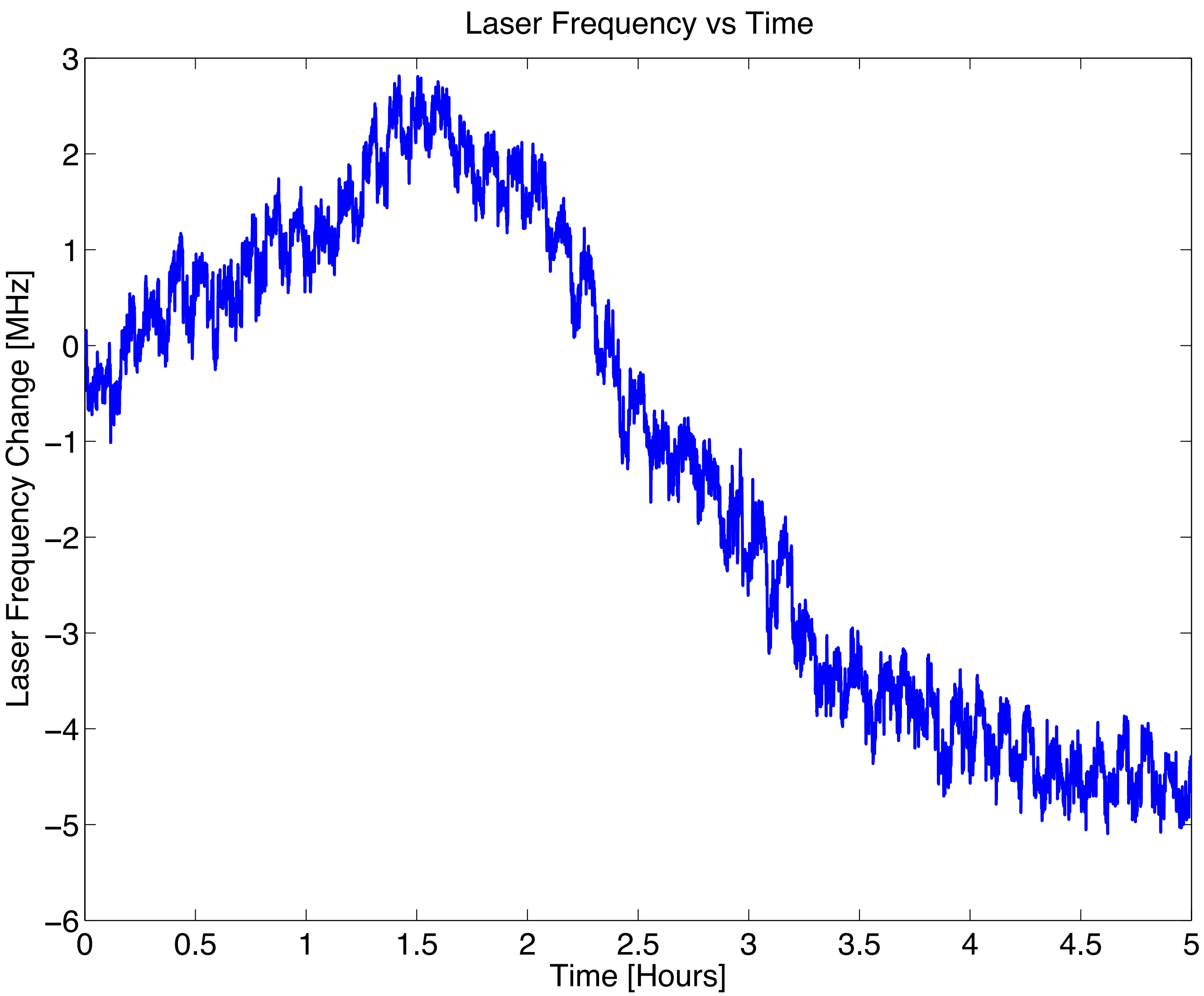
K. McKenzie, R. Spero, and D. Shaddock,
Phys. Rev. D **80** (2009)

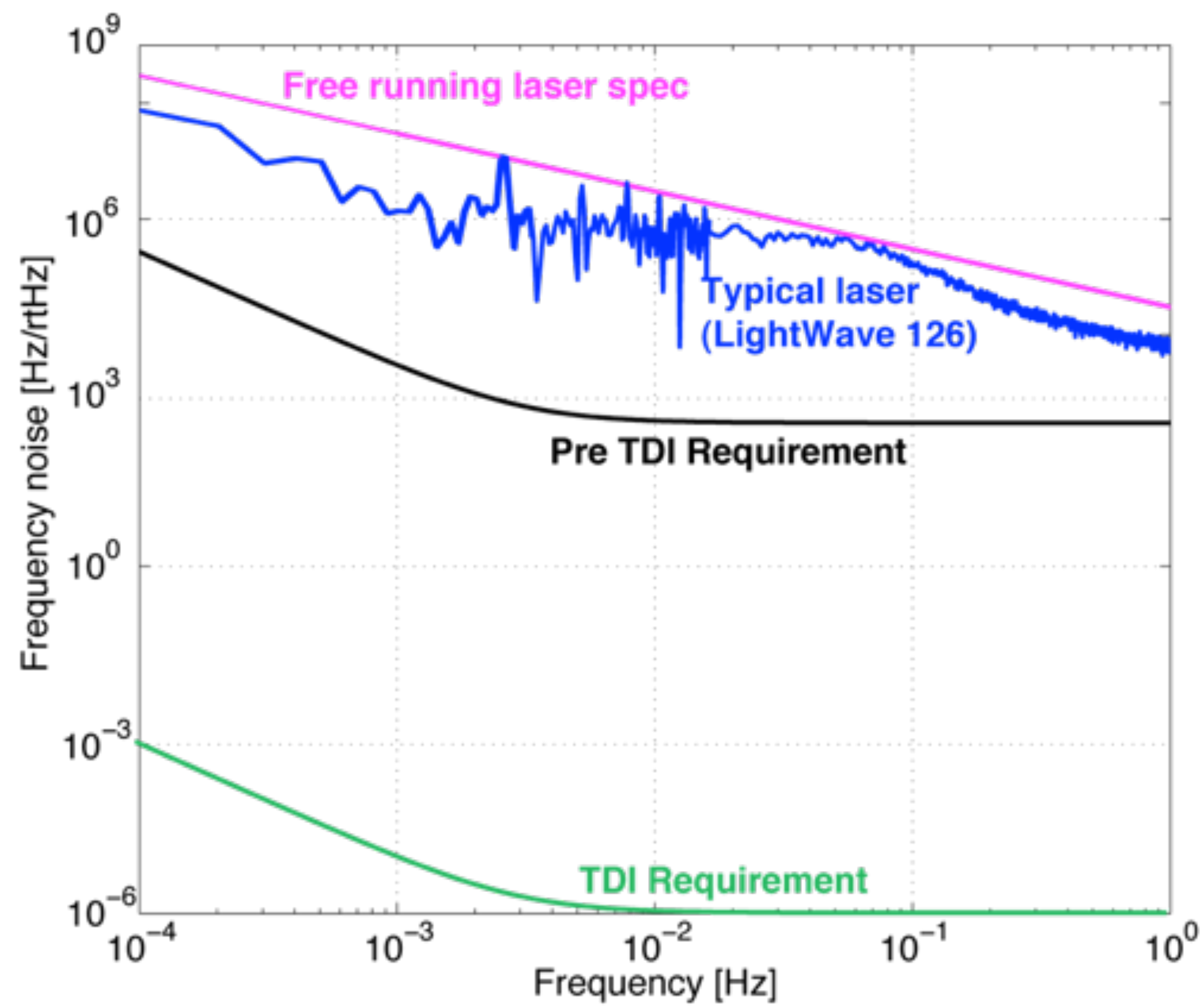
3 Time Delay Interferometry



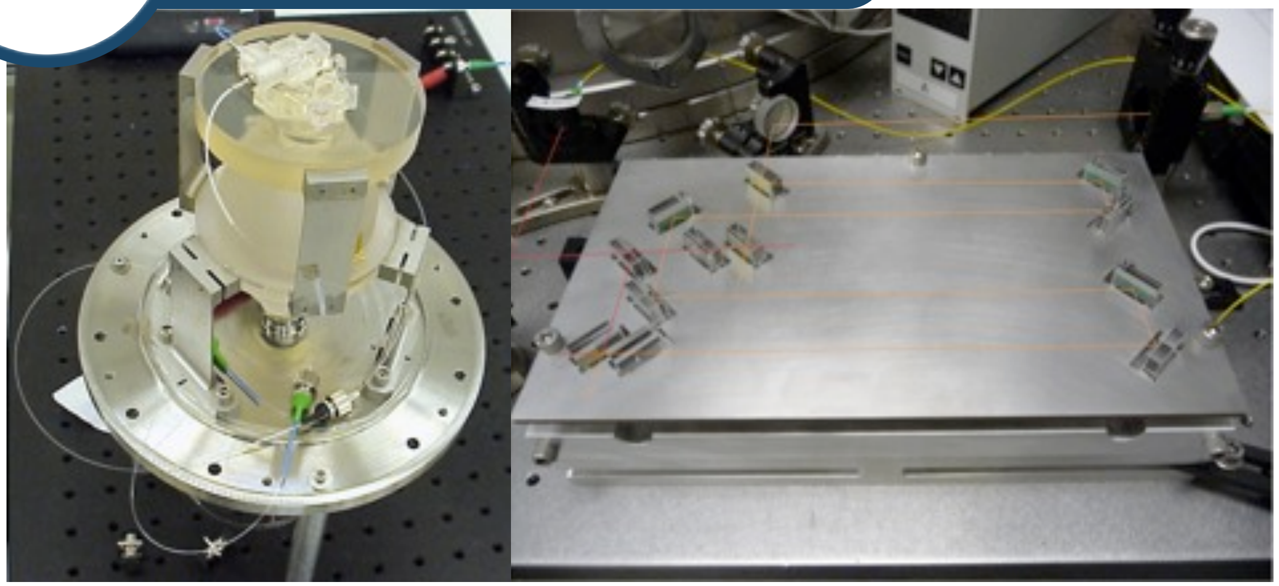
J. W. Armstrong, F. B. Estabrook
and M. Tinto
ApJ **524** 814 (1999)

Free running laser frequency noise





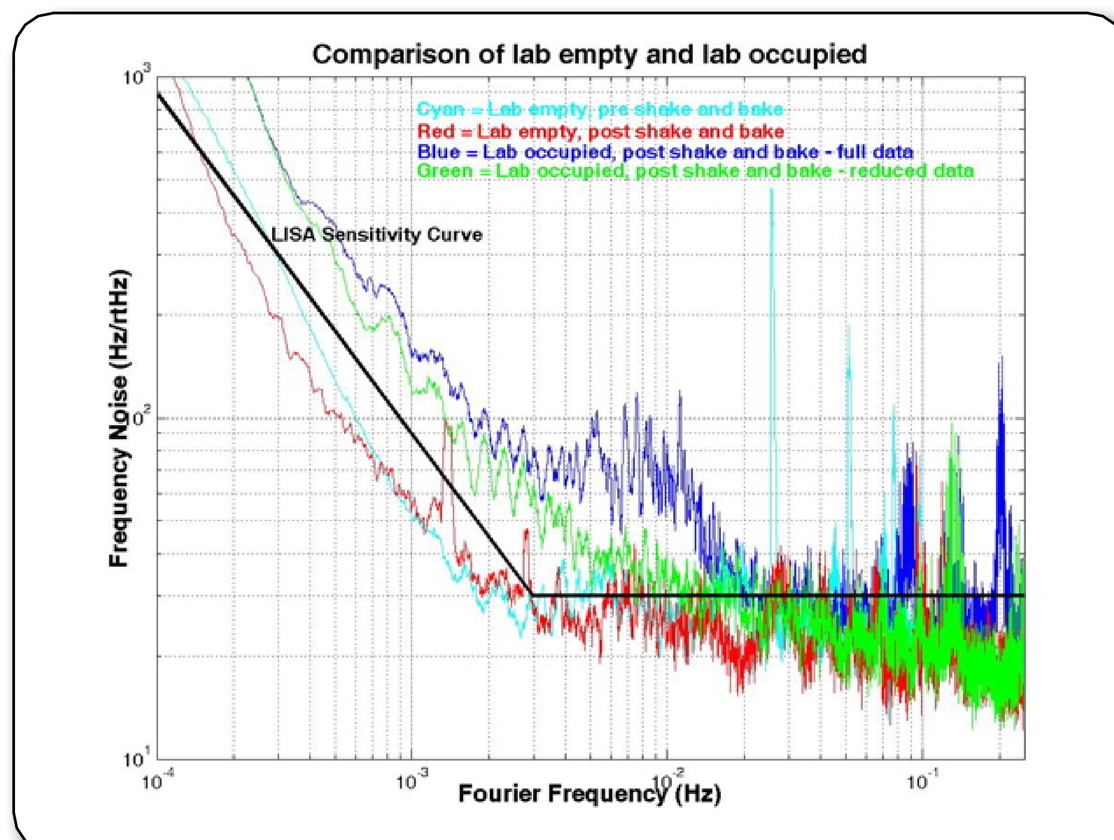
1 Pre-Stabilization



JPL LISA lab

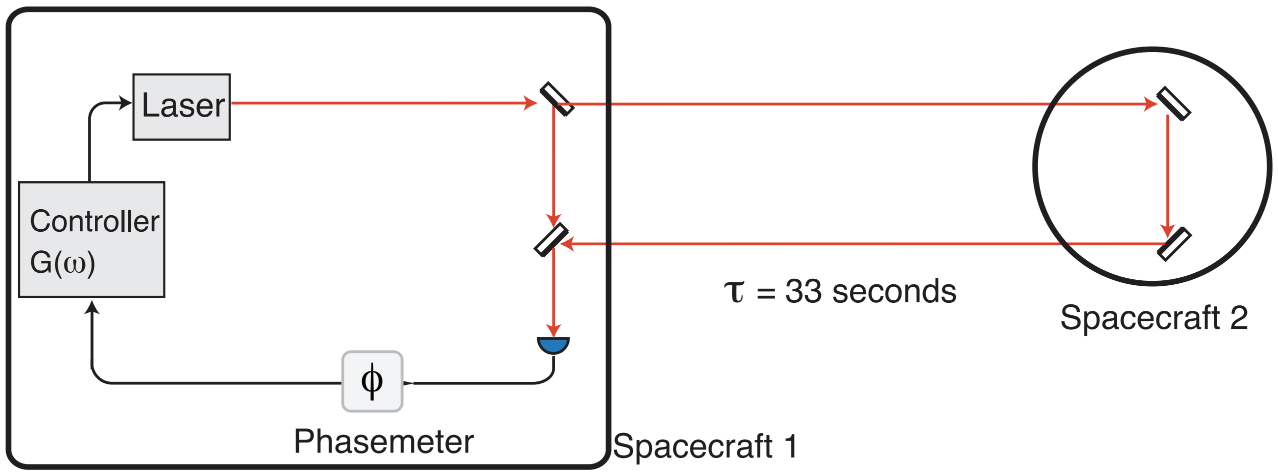
- Ultra-low expansion glass (ULE) optical cavity housed inside layers passive thermal shields.
- Temperature stability of ~10 μK/√Hz.

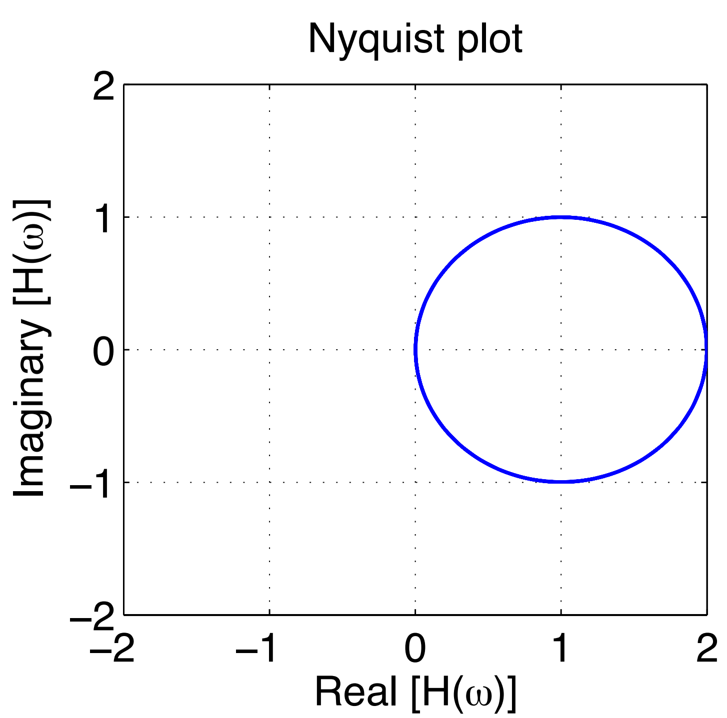
- Frequency noise measured by locking two lasers to two independent cavities.
- Target frequency stability of ~30 Hz/√Hz has been demonstrated by Mueller, McNamara, Thorpe and Camp

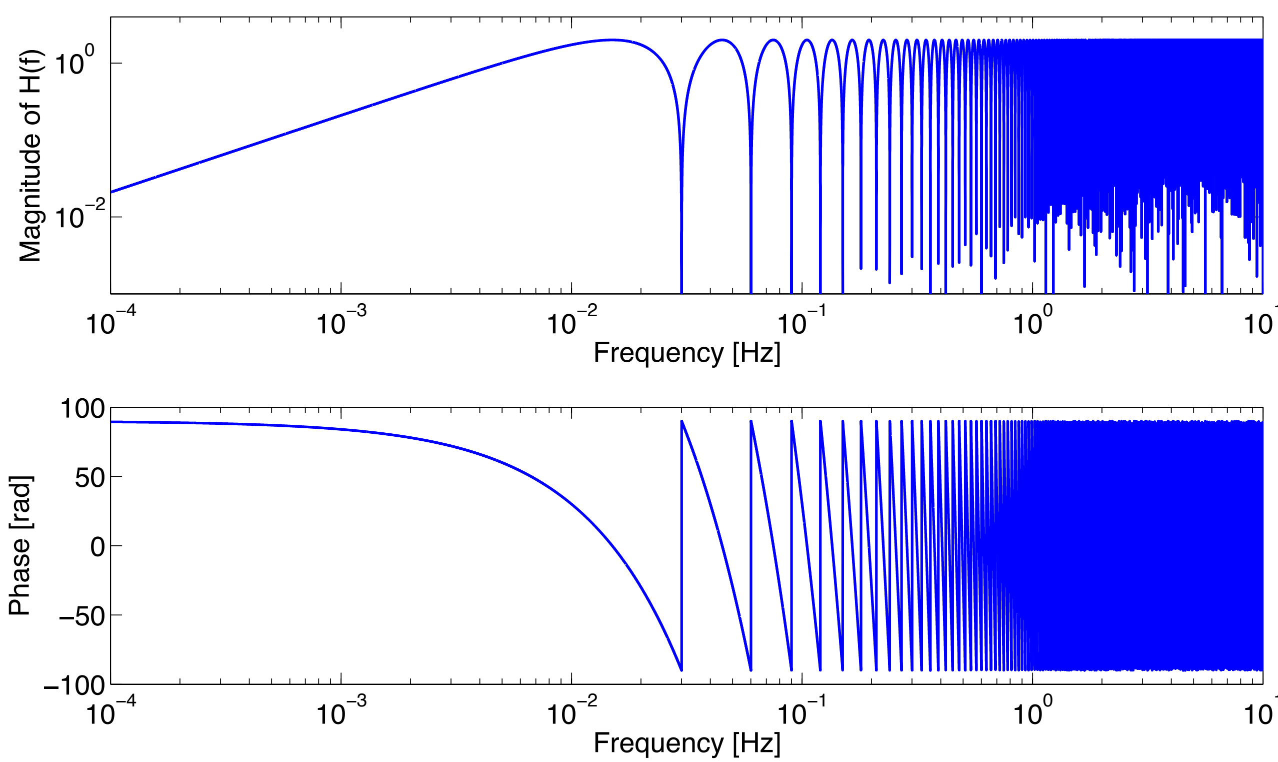


2 Arm Locking

- Sensor: LISA arm $H(\omega) = (1 - e^{-i\omega\tau})$
- *n* unity gain points at $f_{\text{null}} = \frac{n}{\tau}$
- Sensor phase at null = -90 degrees







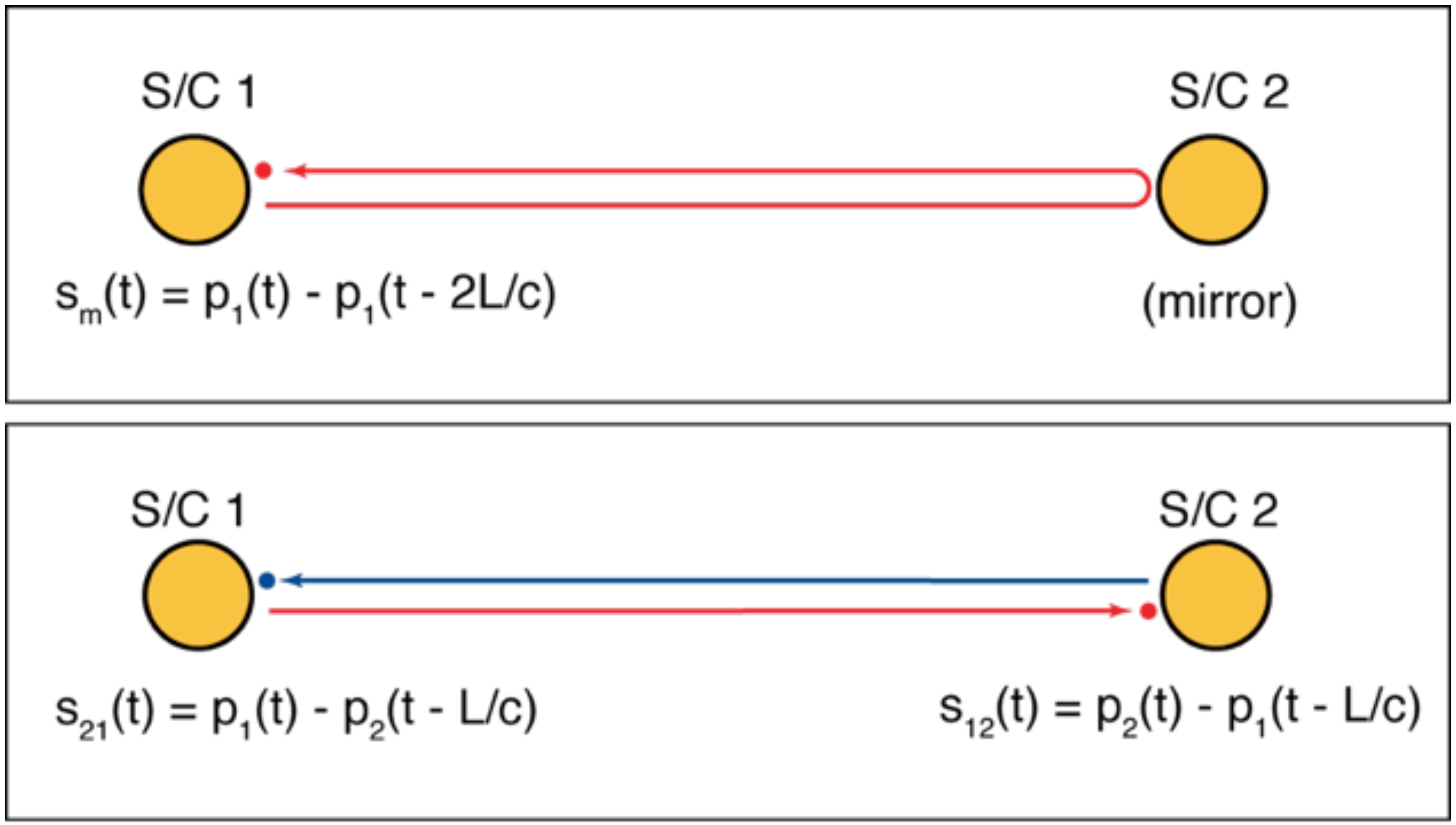
3 Time Delay Interferometry

- TDI combines phase measurements with appropriate delays to synthesize interferometers that are insensitive to laser frequency noise.

- TDI cancels laser frequency noise due to:
  - Unequal arm lengths
  - Independent clocks,
  But, *retains GW signal*

- TDI also corrects for clock frequency fluctuations
  - Clock noise is transferred between spacecraft by phase modulation of the laser light

Synthesizing a round-trip measurement



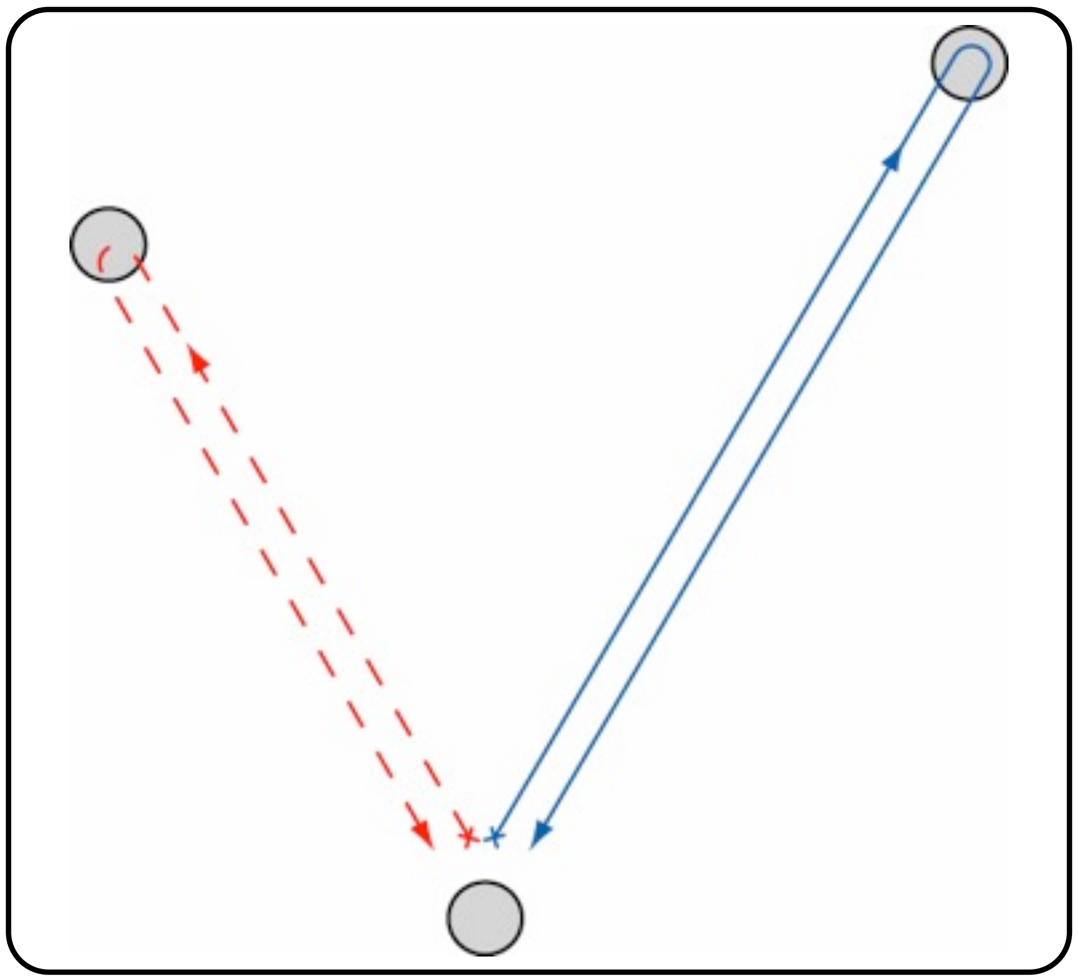
- Measurement is (prompt)–(delayed)
- s(t) phase of interference
  p(t) laser phase

$$s_m(t) = s_{21}(t) + s_{12}(t - L/c)$$

- Measurements combined using knowledge of delays

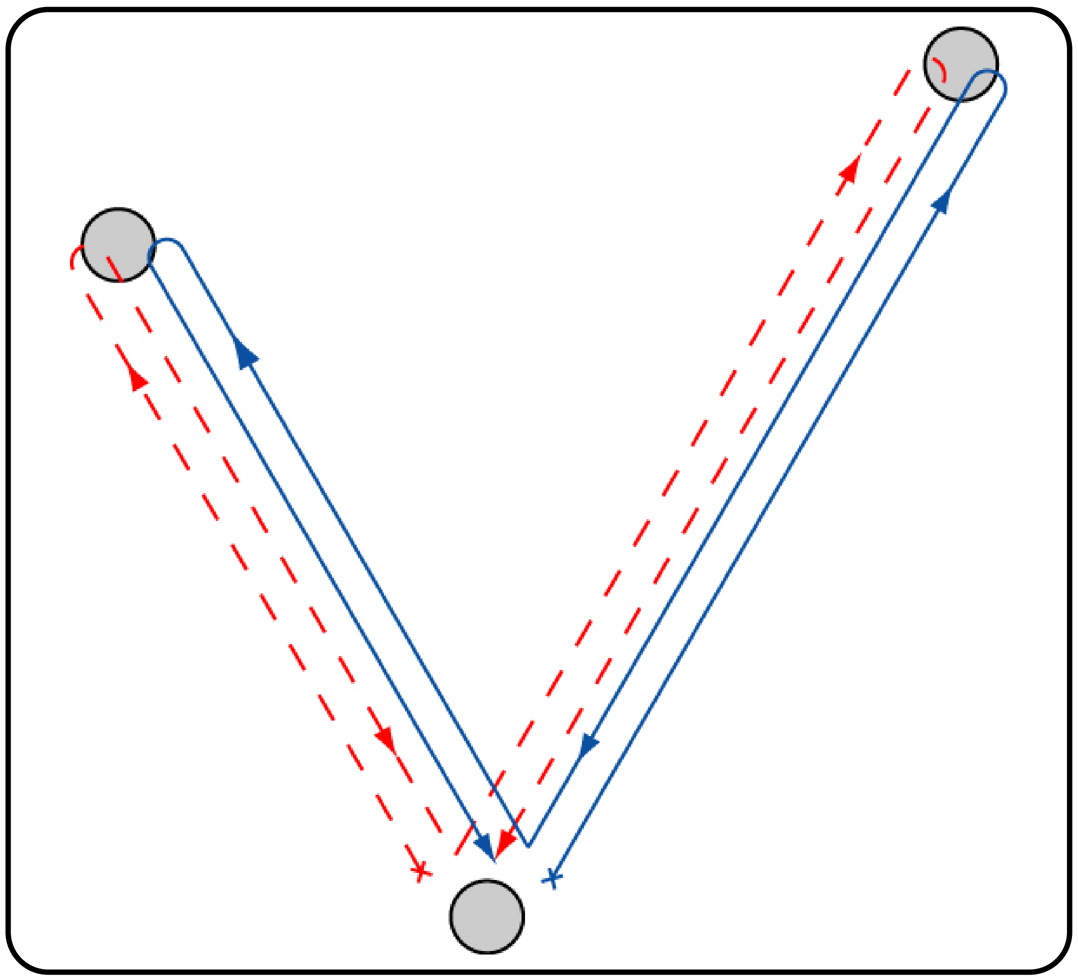
Michelson Interferometer

- TDI "synthesizes" interferometric configurations with equal arm lengths.



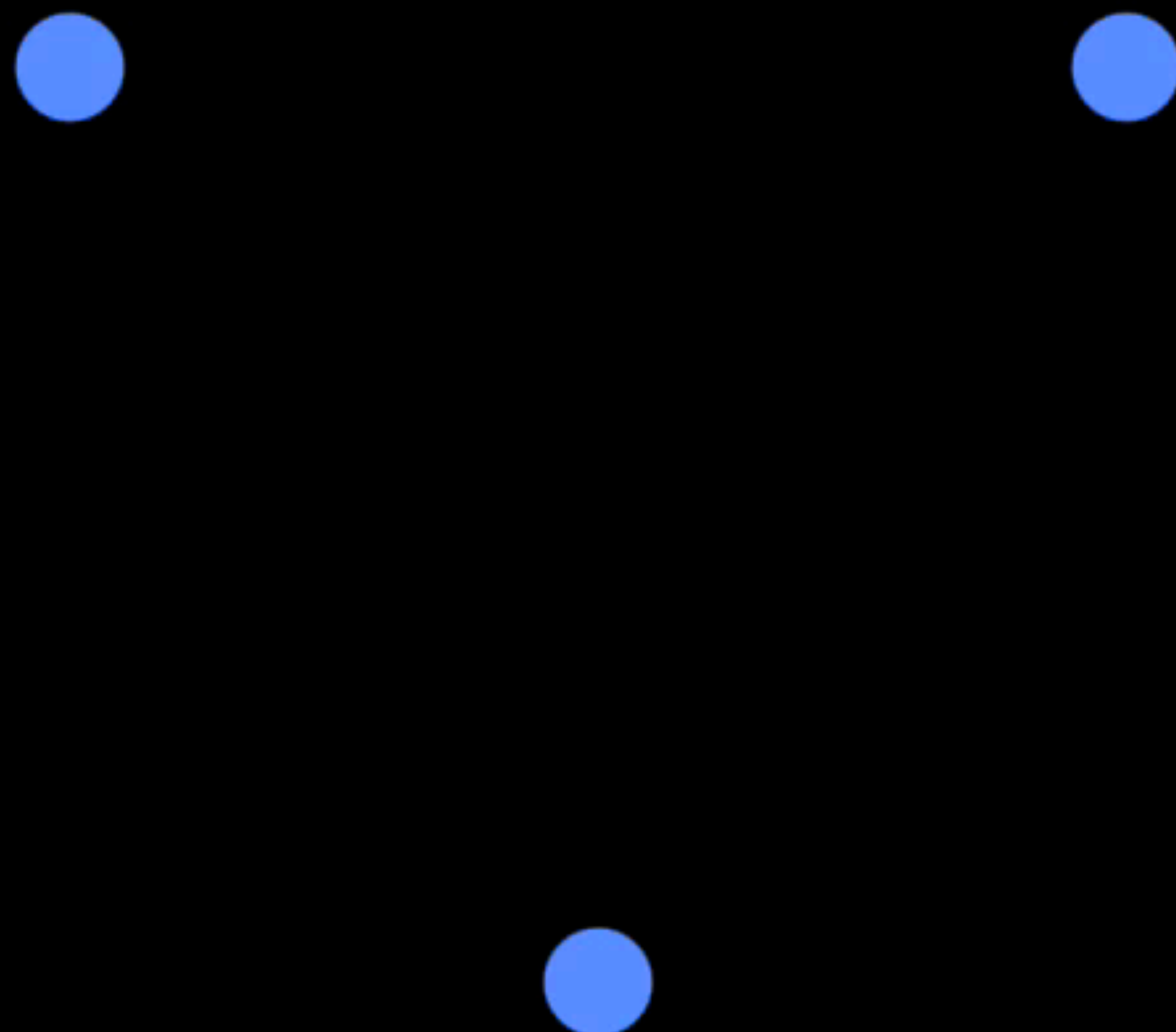
Unequal arm length
Michelson interferometer

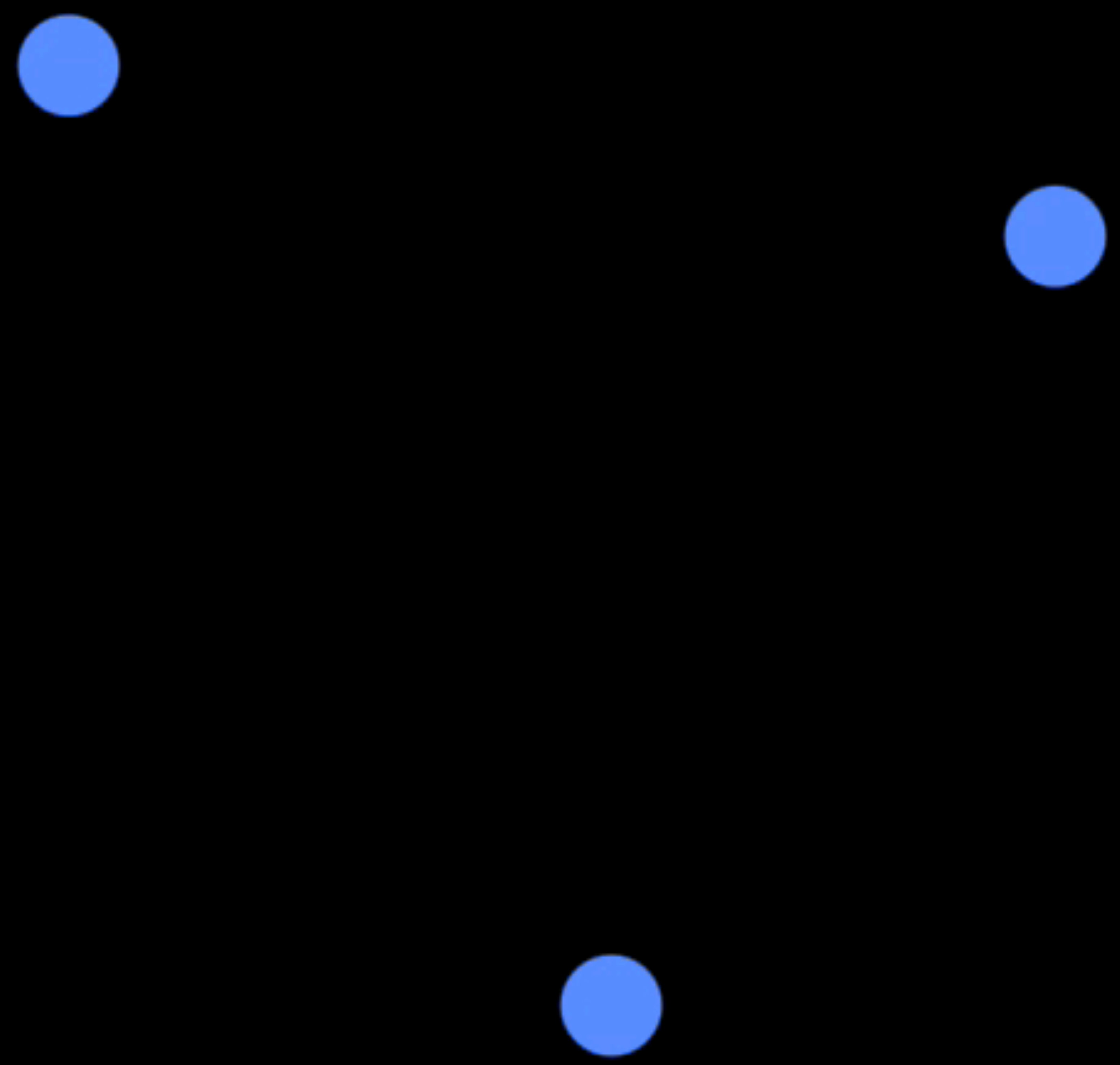
Output corrupted by frequency noise

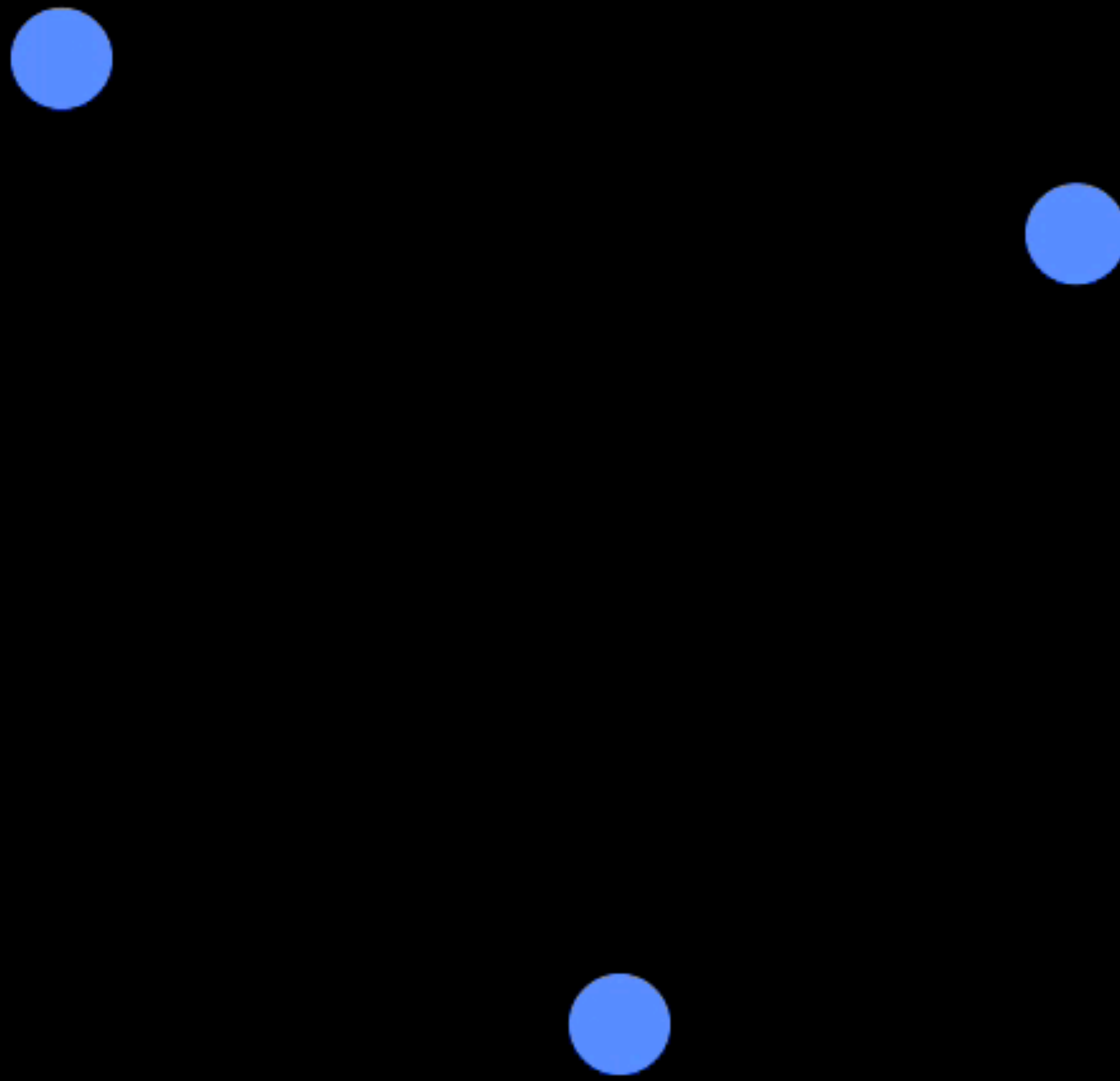


Equal arm length
"Michelson interferometer"

Immune to frequency noise





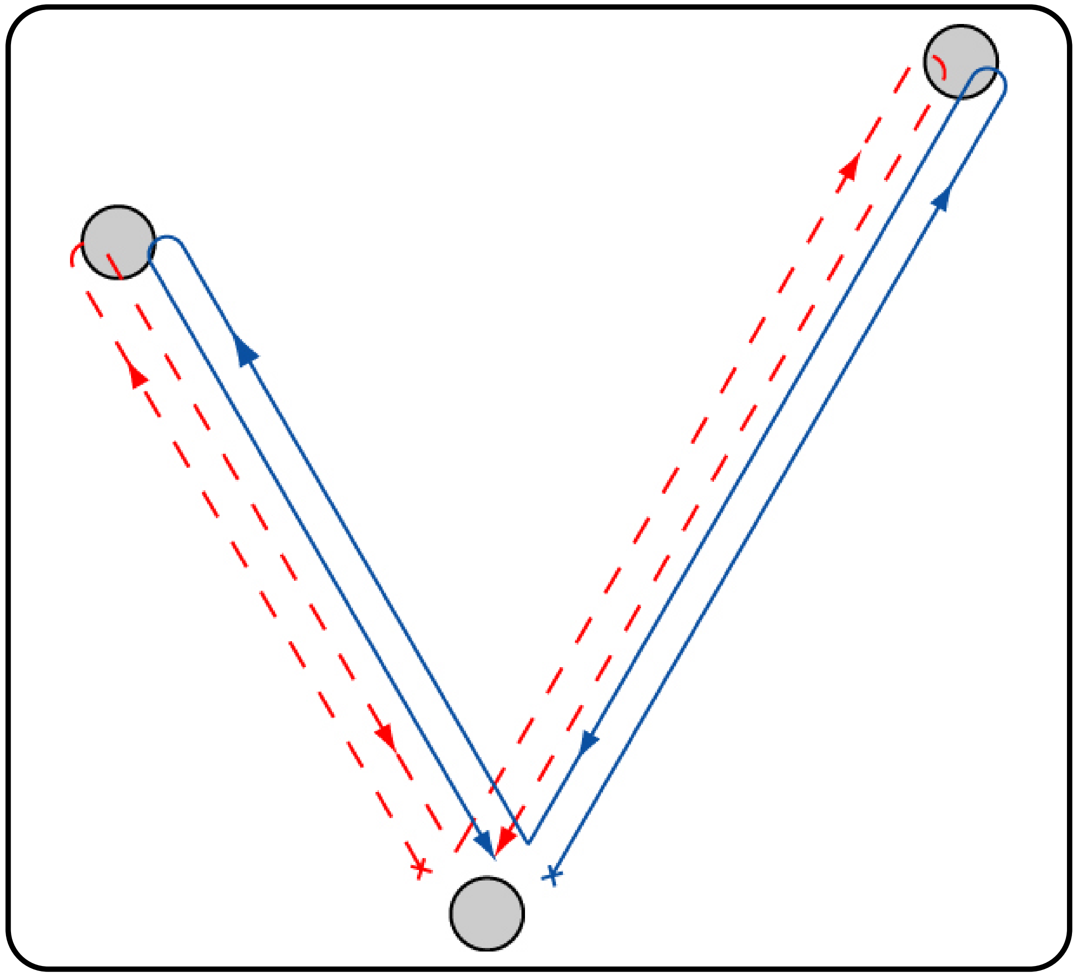


Michelson Interferometer

- TDI “synthesizes” interferometric configurations with equal arm lengths.

- Only one pair of laser beams in each arm.

- TDI combinations formed in post-processing on Earth

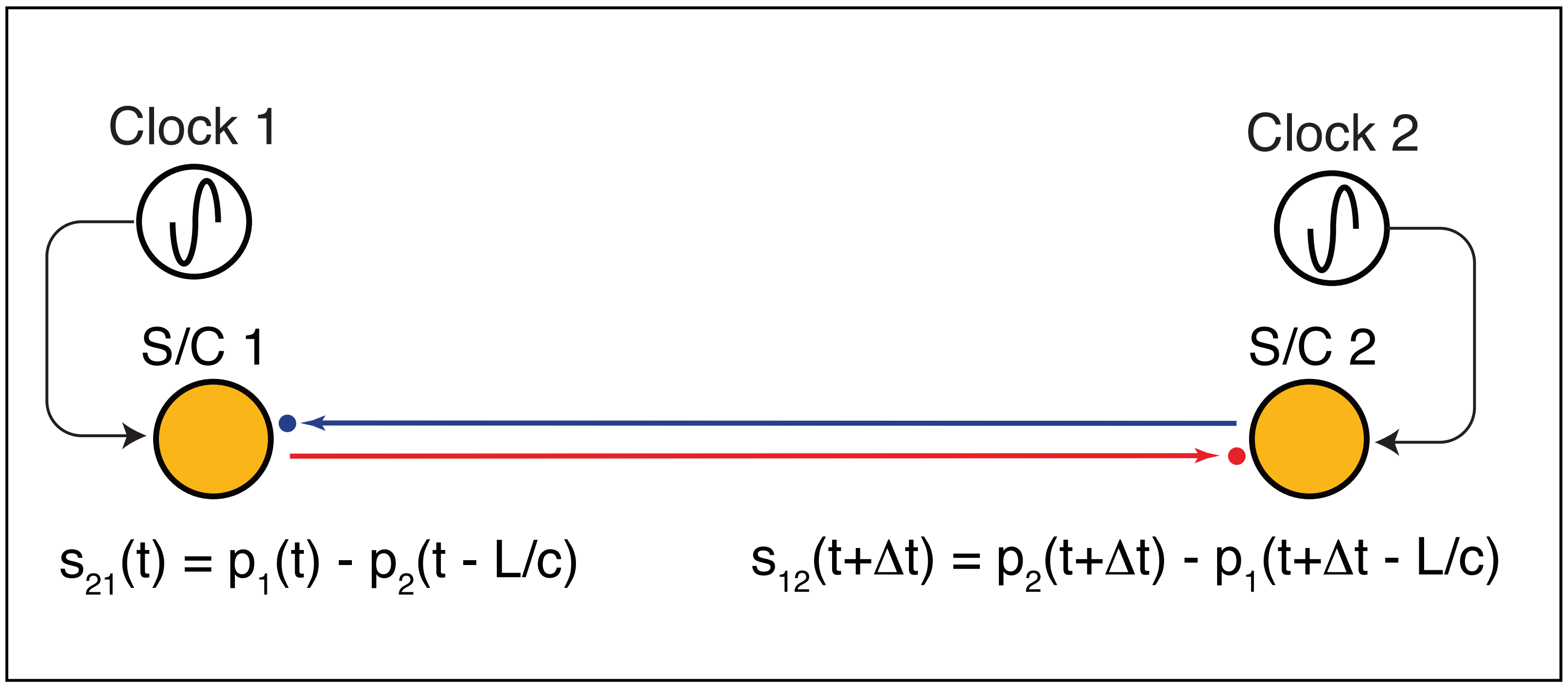


Equal arm length
“Michelson interferometer”

Immune to frequency noise

TDI - corrects for different clock rates

- TDI corrects for independent “clocks”



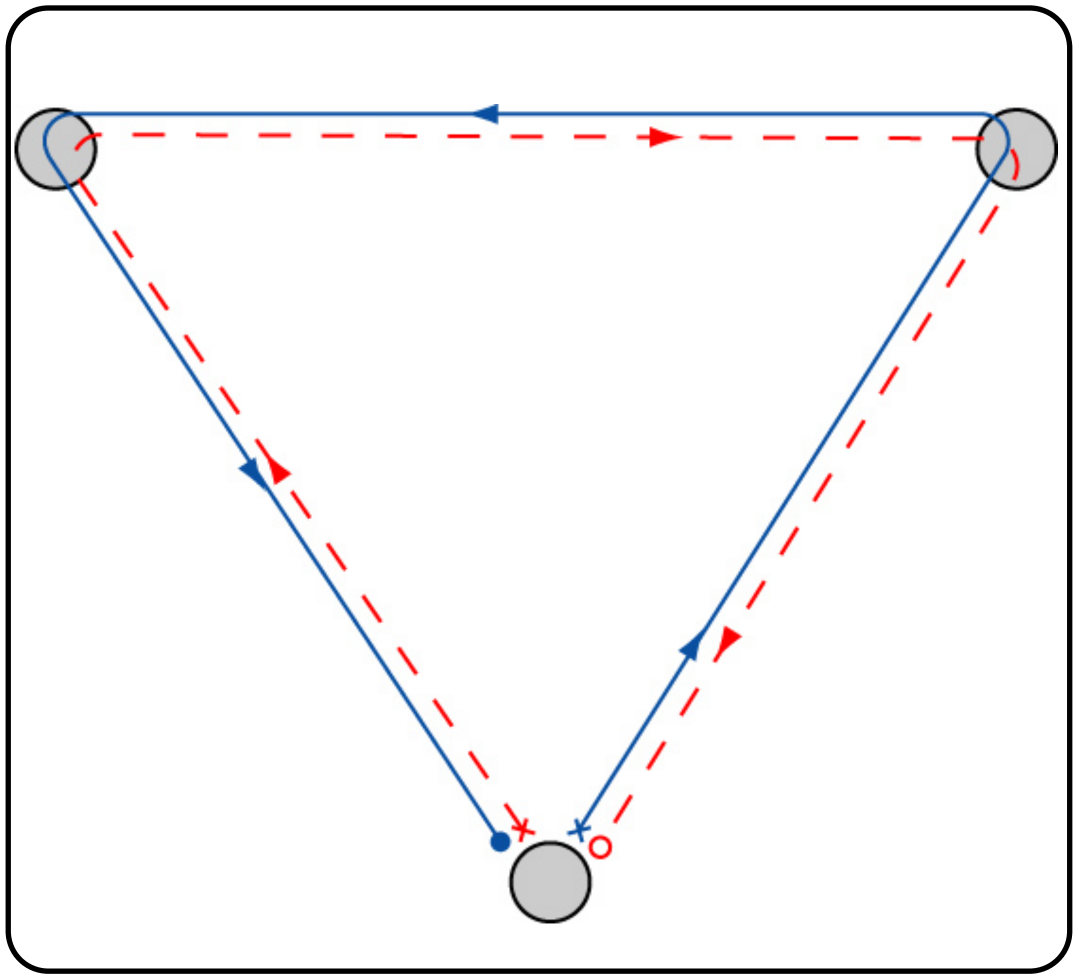
$$s_m(t) = s_{21}(t) + s_{12}(t+\Delta t - L/c - \Delta t)$$

Light travel

Clock difference

Sagnac Interferometer

- Counter-propagating beams traverse the same optical path.



(Equal arm length)
Sagnac interferometer

Immune to frequency noise

Gravitational waves response
similar to Michelson combination

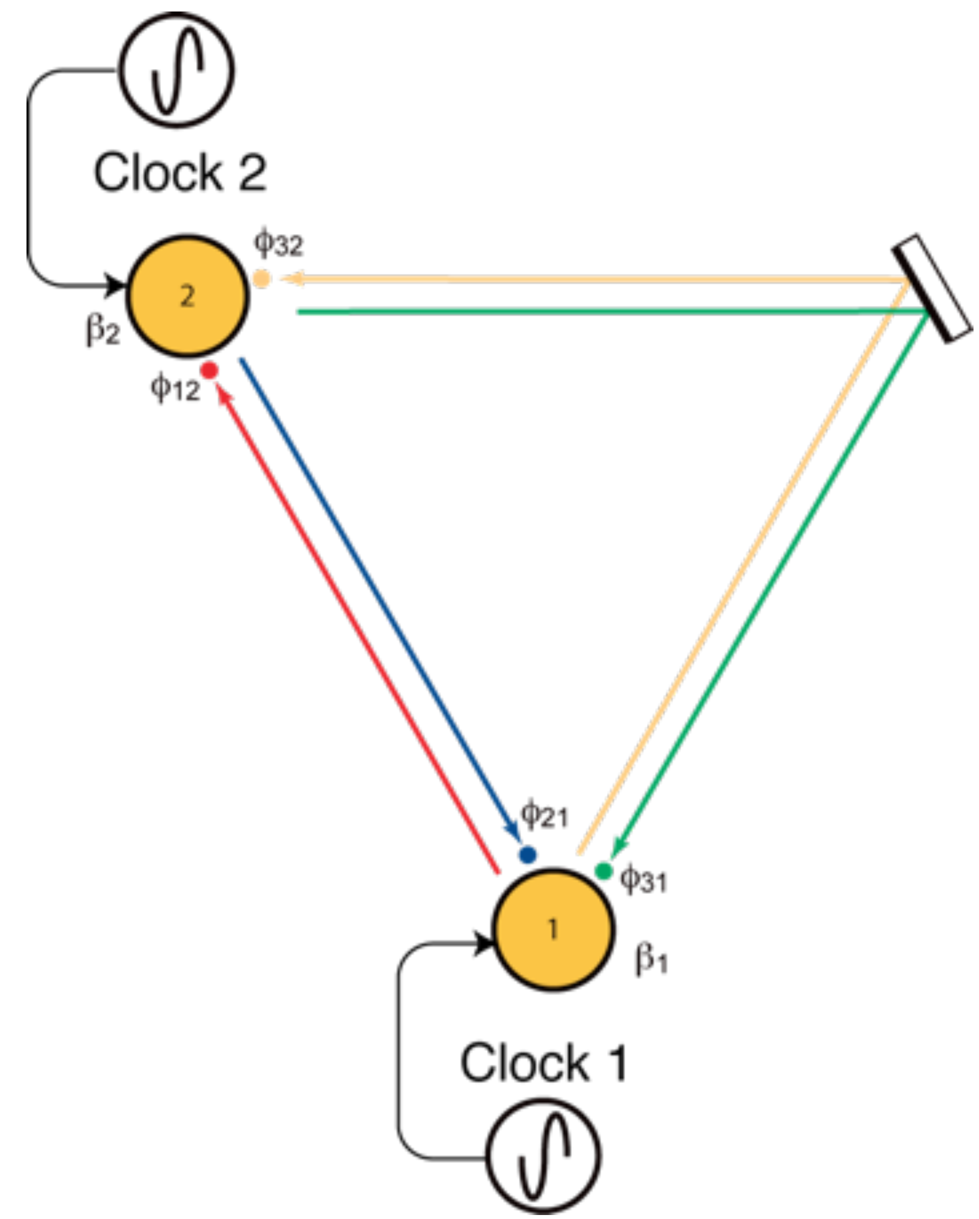
JPL Interferometry Testbed:
Testing TDI in the lab.

- Sagnac Interferometer
  - Immune to path noise between S/C
  - Sensitive to proof mass motion

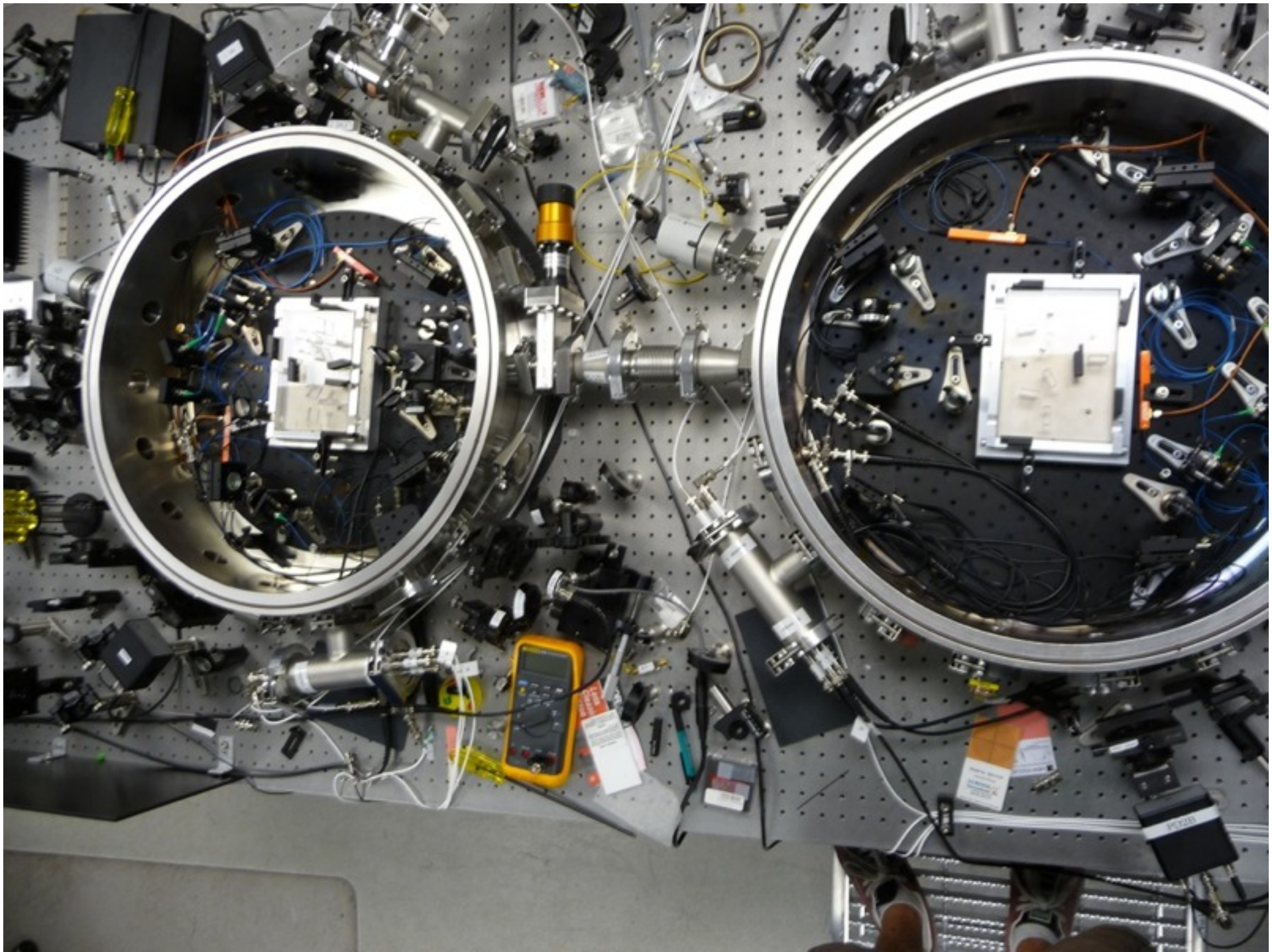
- 2 (rather than 3) independent S/C
  - Each run off own clock

- Wireless
  - Only connection is laser link

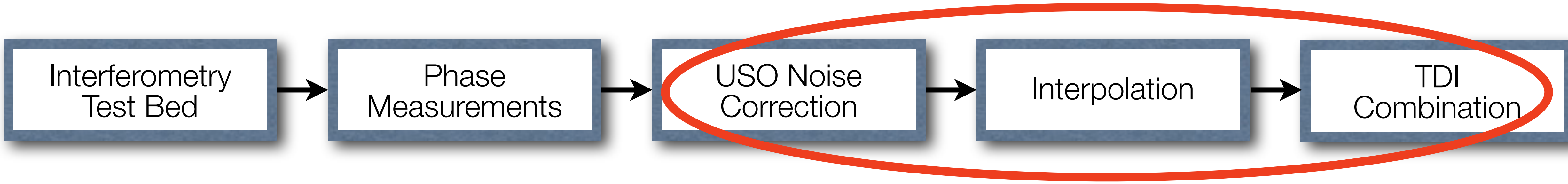
- Same signal processing chain as LISA

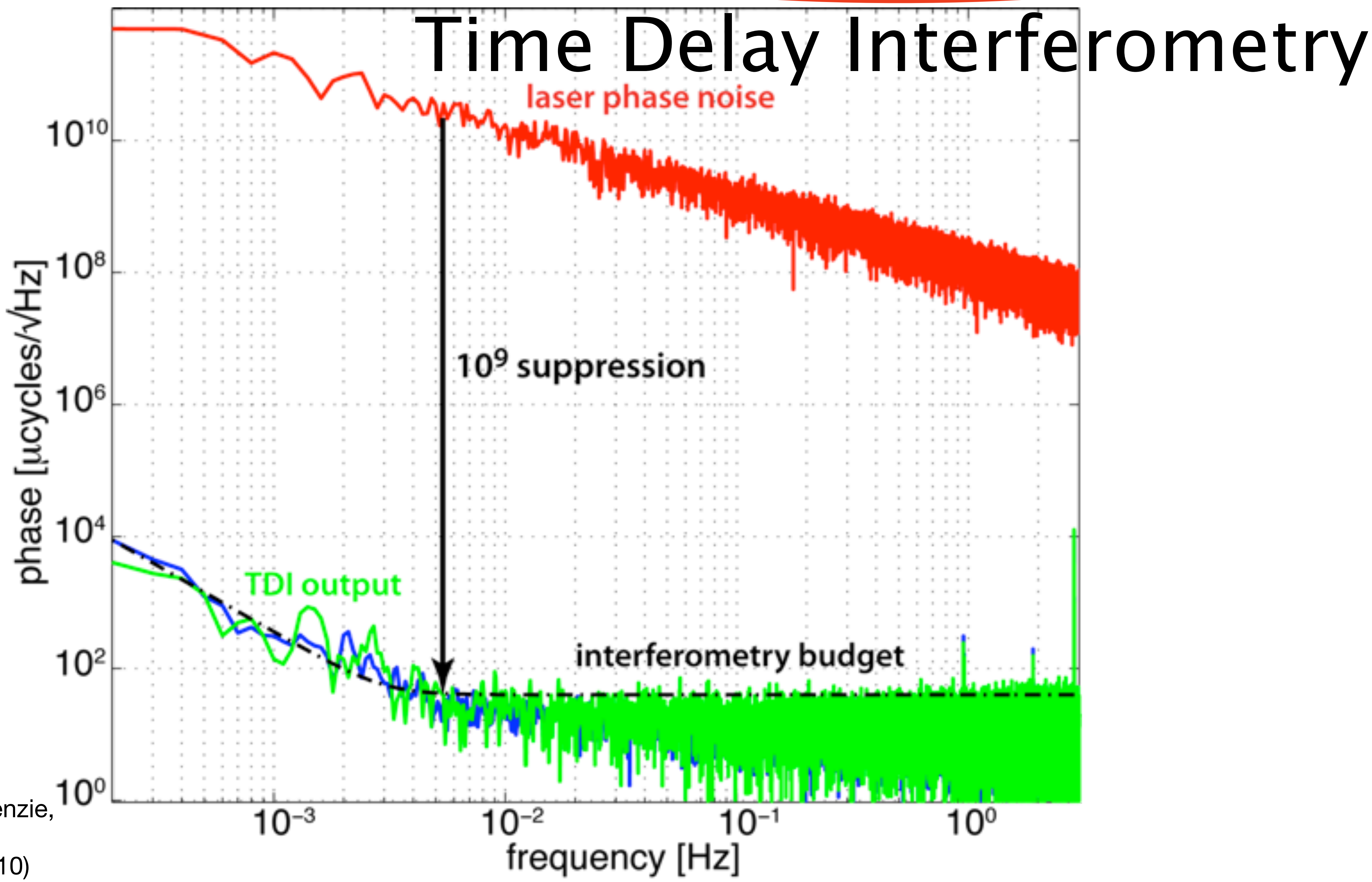


JPL Interferometry Testbed: Testing TDI in the lab.



Testing TDI

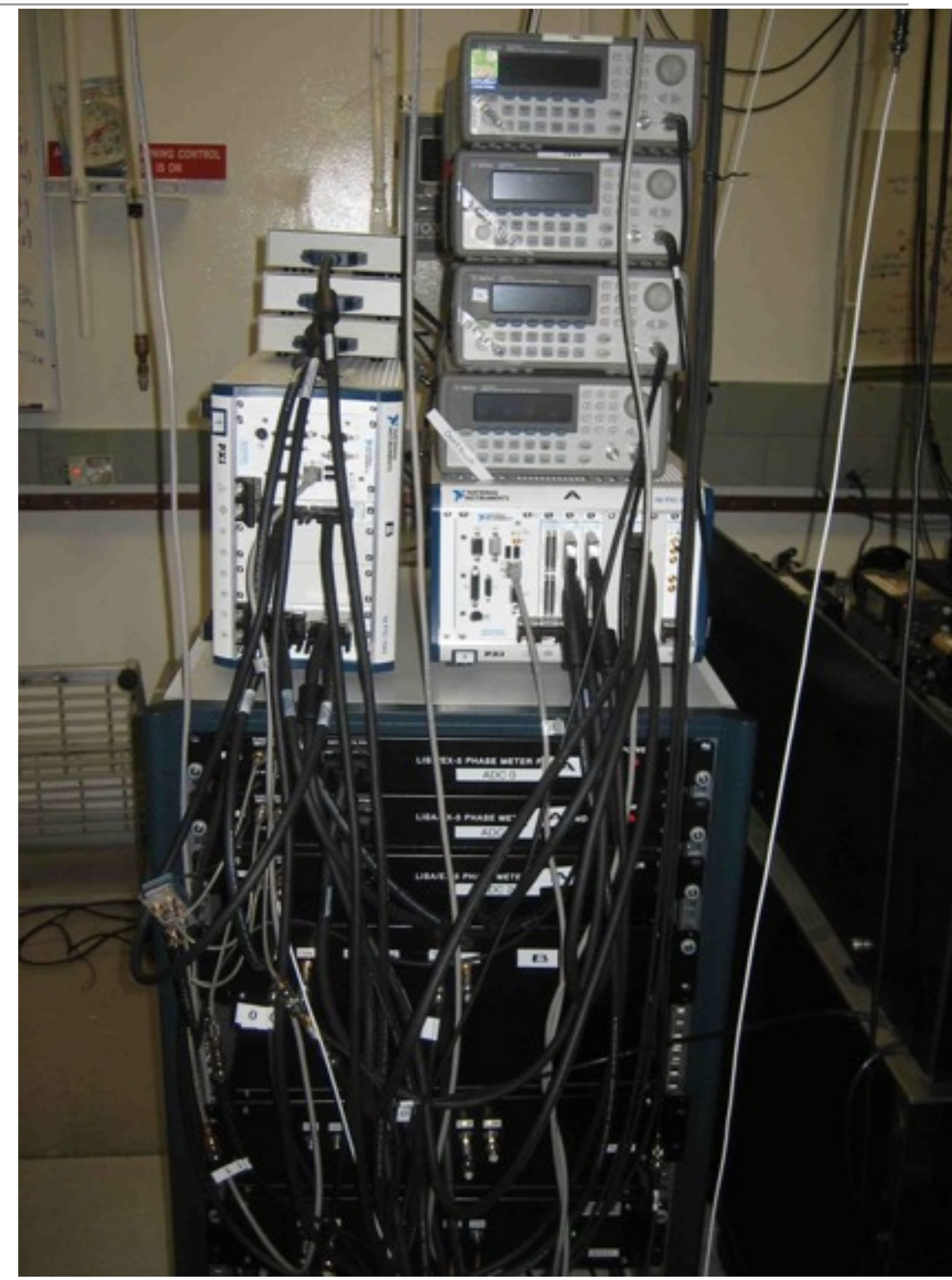




G. de Vine, B. Ware, K. McKenzie, R.E. Spero, W. M. Klipstein and D. A. Shaddock PRL (2010)

JPL Phasemeter

- The phasemeter measures the phases of the photoreceiver signals, comparing them to internal clock (USO) references
- Challenge to measure µcycles in large noises associated with LISA readout
- LISA Phasemeter:
  - JPL is developing the phasemeter for LISA
- The phase measurement system is now at TRL-4, some components at TRL 5-6



JPL Phasemeter

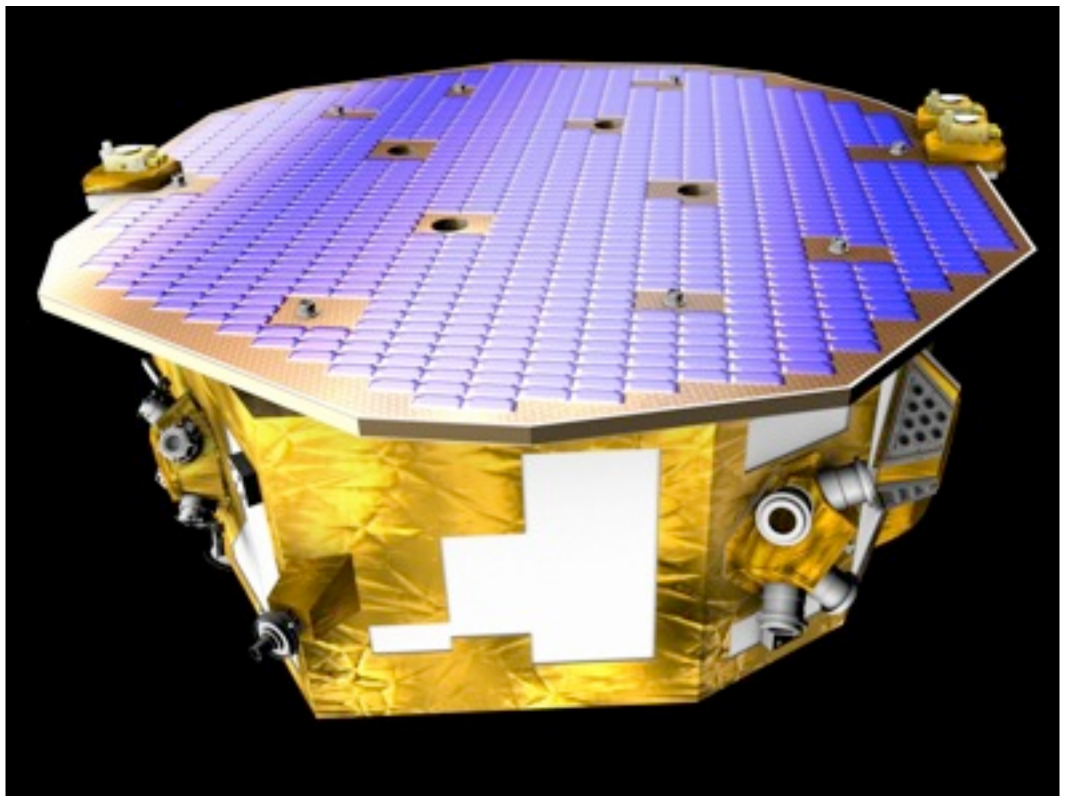
Phasemeter Performance	
Measurement limit	1 μcycle
Linearity	> 1 part in 10^{14}
Aliasing	< 1 μcycle
Amplitude sensitivity	< 0.014 μcycle/%
Quantization noise	< 0.1 μcycle/$\sqrt{\text{Hz}}$
Frequency slew rate	758 kHz/s
Track Doppler	2-18 MHz
Laser phase-locking	<10 μcycle @ 139 pW

Phasemeter Features
Multi-tone tracking
FPGA FFT automatic tone acquisition
Automatic gain control
ADC jitter removal
PRN ranging (2010)
Optical communications (2010)

Overview

- Sources
- Detectors
- LISA overviews
- Laser and clock frequency noise
- LISA Pathfinder

LISA PathFinder

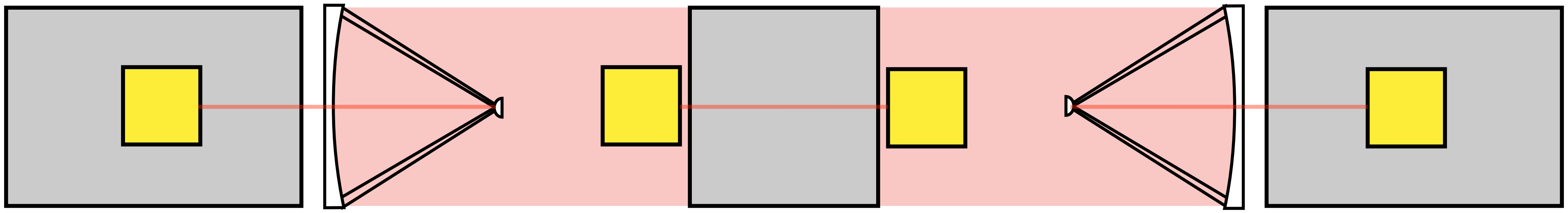


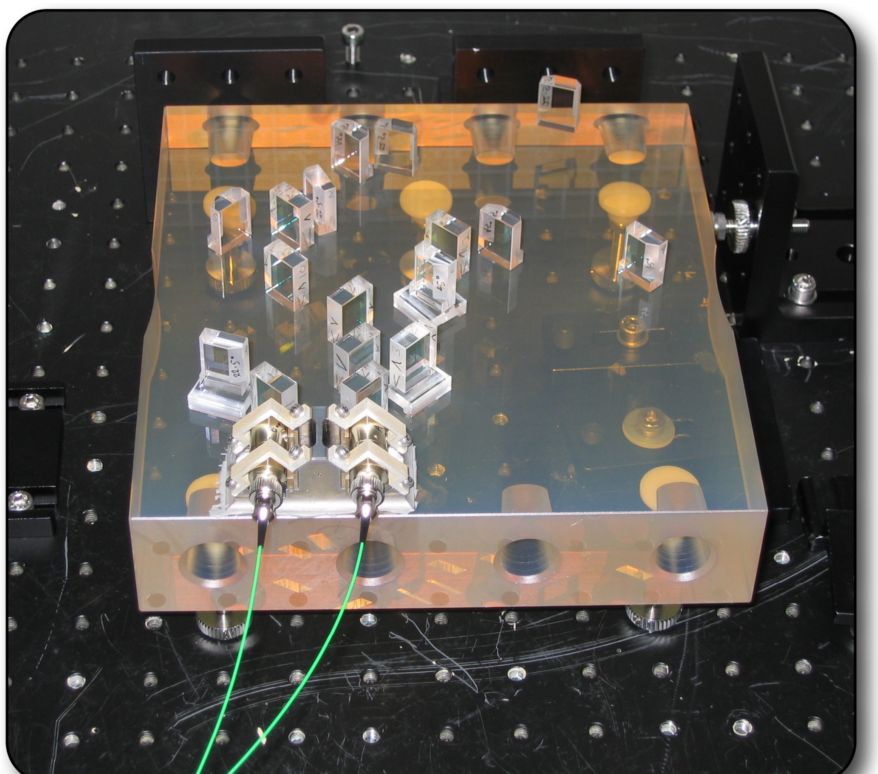
Credit: ESA

- To demonstrate critical LISA technologies in a space environment:
  - Gravitational Reference Sensing
  - Drag-free attitude control
  - Micro-Newton thrusters
  - Interferometry with free-falling mirrors
- LPF is scheduled to launch in 2013.
- 2 months later 6 months science operations begin.
- Vega Launcher

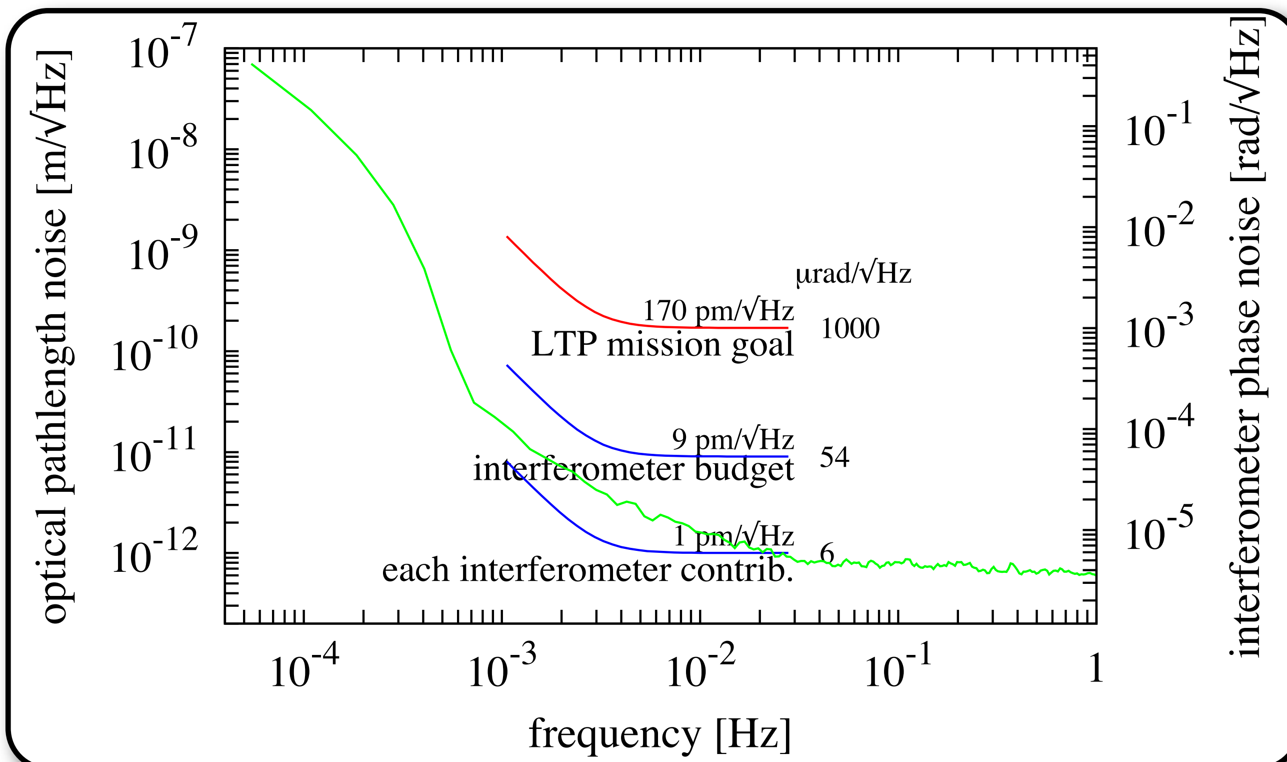
LISA PathFinder

Shrink a LISA arm to fit inside one spacecraft.



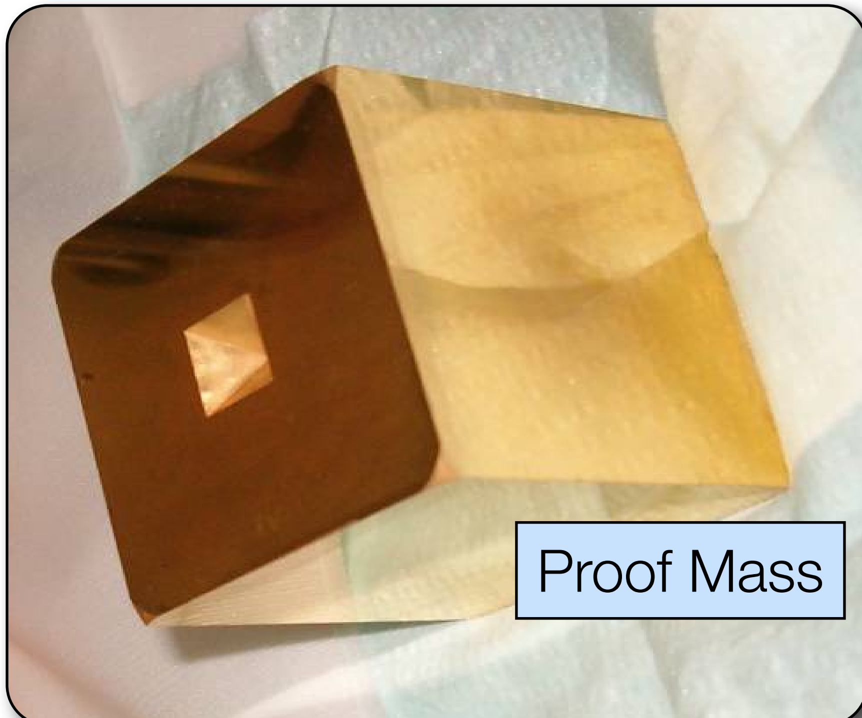


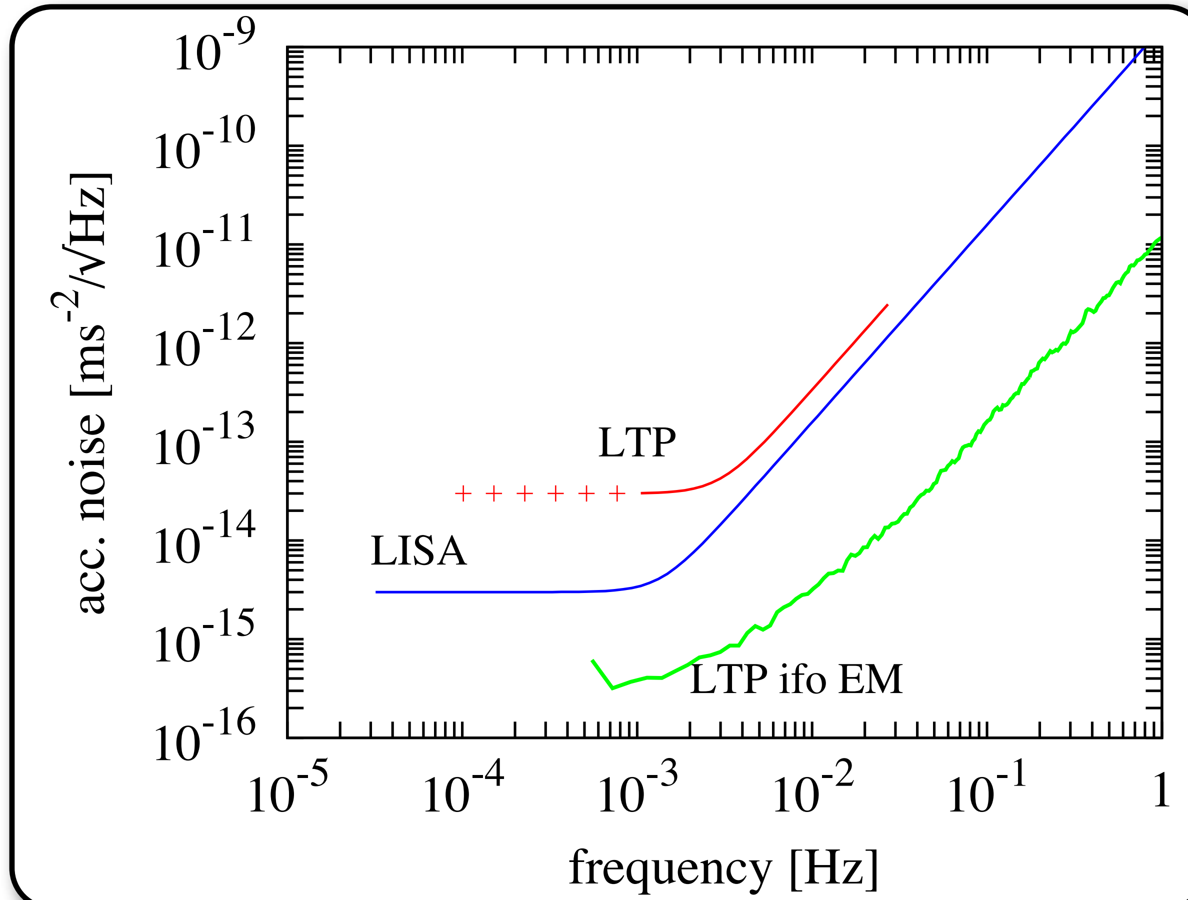
Engineering model of optical bench.

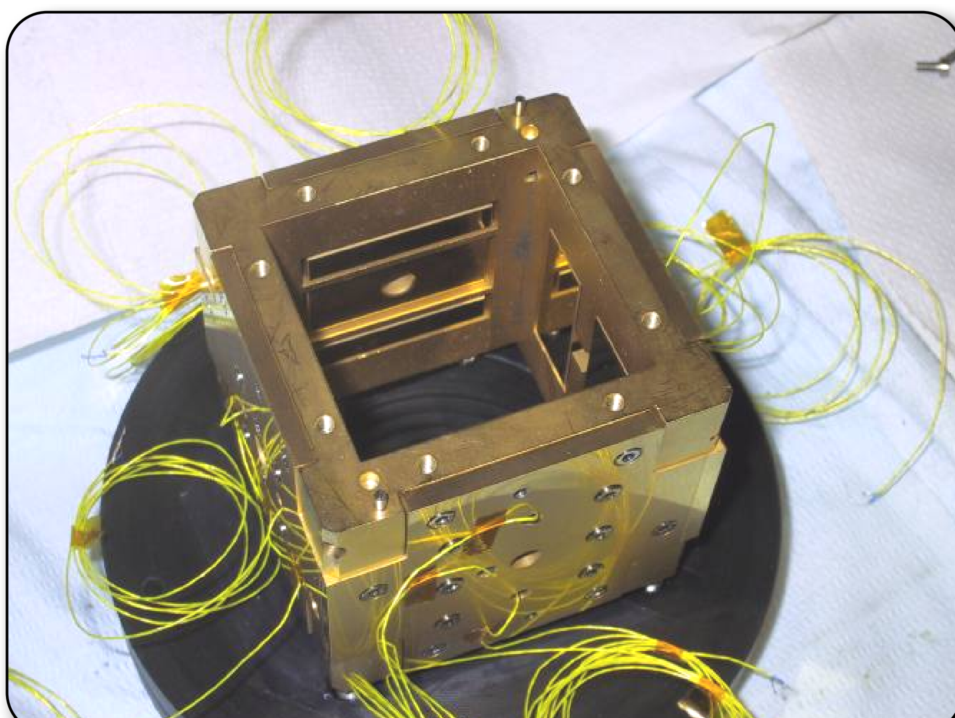


LISA PathFinder Optical path length noise

LISA PathFinder







Electrode housing and electrodes

LISA's future is bright

- Astro2010 decadal committee recommends LISA as one of two large space missions to be implemented this decade (behind WFIRST).

- The report praises LISA as

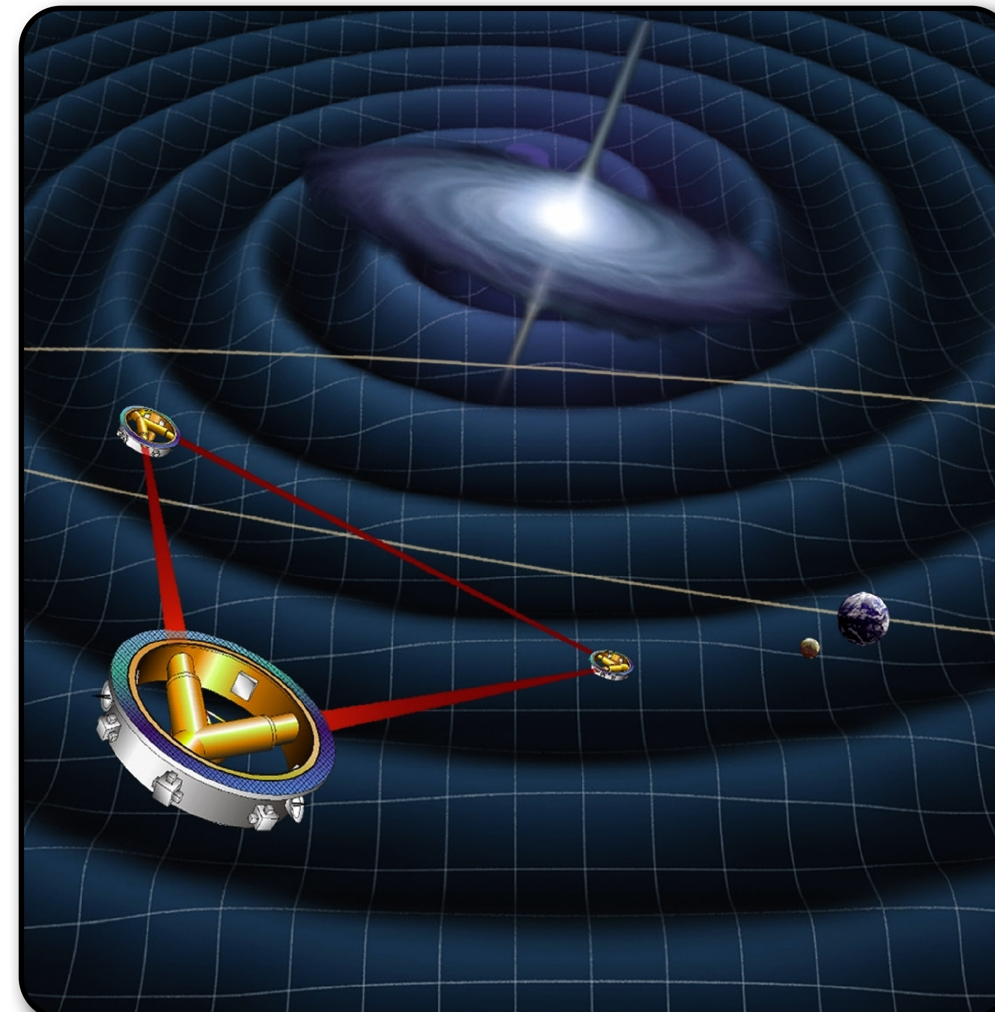
  "*a gravity wave observatory that would open an entirely new window in the universe*",

  whose

  "*recommendation and prioritization reflect its compelling science case and the relative level of technical readiness*"

Summary

- Spectacular, rich science
  - Many sources, high SNR observable throughout the universe.
- Mature design, technology is well advanced
- Eagerly awaiting start of major mission funding.



- ASTRO 2010 Report recommends:
  Start 2016, launch ~2025

- LISA interferometry group at JPL
  Bob Spero, Brent Ware, Daniel Shaddock, Glenn de Vine, Kirk McKenzie and Bill Klipstein

End