Experimental Methods
Lecture 1

September 21st, 2020

A course on (some) basic principles of physical measurements

- The main goal of the course is the study of the theoretical and practical measurability of physical quantities in the presence of noise.
- The course will discuss design and optimization methods for physical measurements, the methods for signal extraction and the limitations imposed by intrinsic and unavoidable sources of noise, like thermodynamical fluctuations, counting statistics and quantum limits.
- These methods will be applied to examples of experiments in advanced physics.
- The course should enable the student to design an experiment, at least at concept level, and, based on few fundamental laws, to quantitatively predict its potential sensitivity.

Lecture timetable

- Monday/Wednesday/Thursday 8:30-10:30 by zoom. Link is the same as the one we used today
- We only need 5 hour/week. So some weeks we are going to have just two lectures
- We will use this to get some flexibility.
- I will update you on the specific plan for the following 2-3 weeks
- I will record the lectures and post the video.
- Soon after each lecture, I'm going to post, on the course website, a .pdf version of the slides presented during the lecture.

Source books

- Signals and systems
- "Signals, systems, and transforms" . Charles L. Phillips, John M. Paar, Eve A.Riskin. V-621.3822 PHI
- Noise and stochastic processes
- Probability, random variables, and stochastic processes / Athanasios Papoulis, 4. ed Boston, Mass. [etc.] : McGraw-Hill, c2002.
- Numerical signals and noise processes
- Discrete-time signal processing / Alan V. Oppenheim, Ronald W. Schafer.2nd ed. Prentice-Hall, c1999. ISBN: 0130834432
- Kramers-Kronig relations, fluctuation dissipation theorem and thermal noise
- Statistical physics / by L.D. Landau and E.M. Lifshitz ; Pergamon, 1980-1991. CDD: 530.13 1119

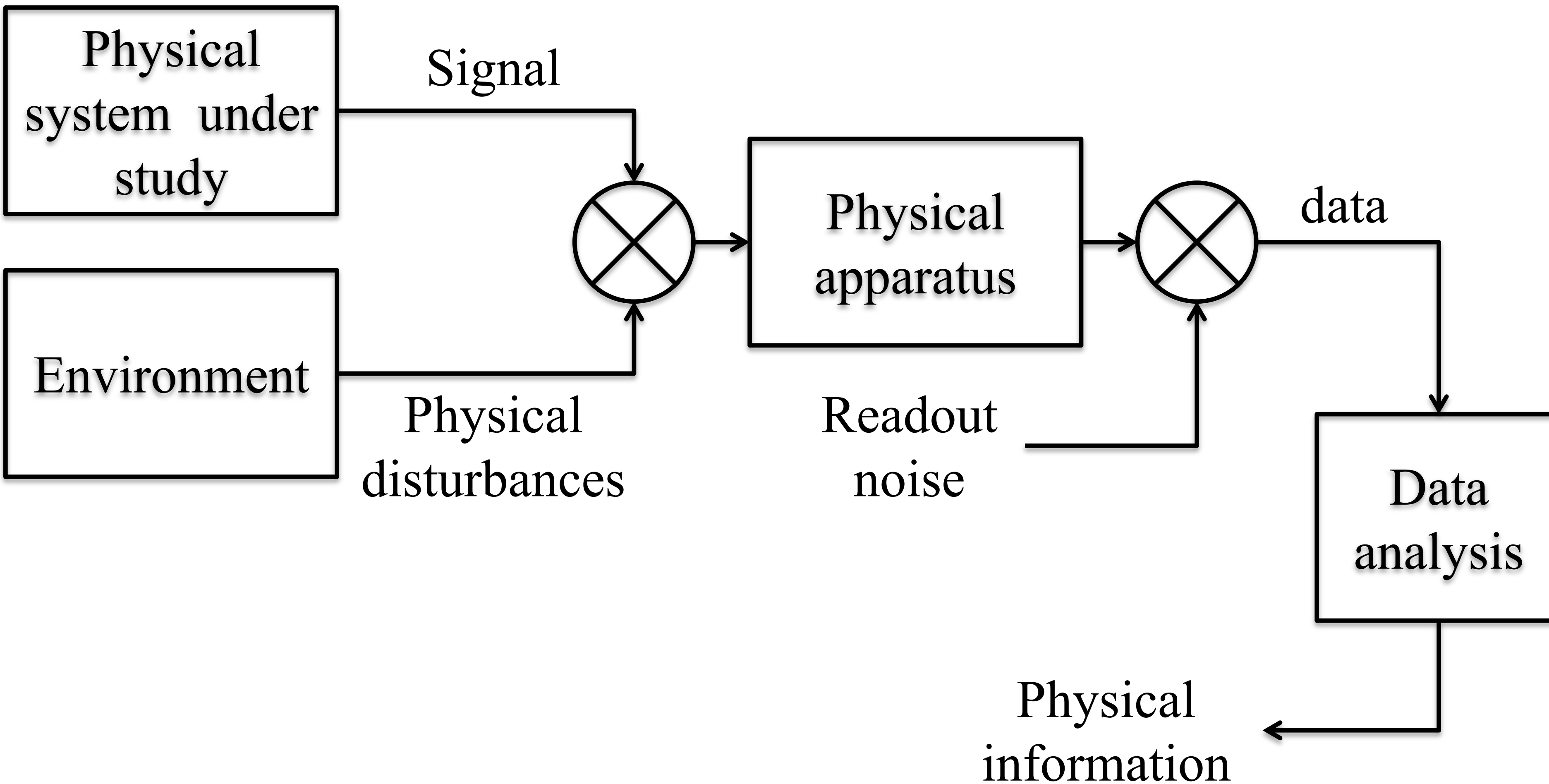
High level mathematical manipulation

- I massively use Mathematica™ in my research work and for teaching
- I speak a little Matlab™
- I don't speak Python (yet)
- I strongly recommend to young colleagues to learn one of these languages of high-level mathematical programming, possibly also including a symbolic manipulation capability
- It would certainly help with following this lecture course

Exam

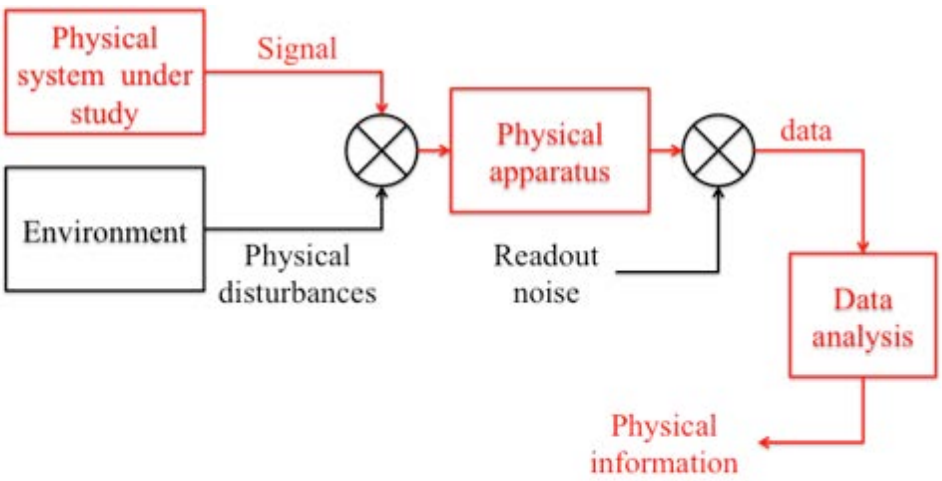
- Final exam consists of a written test.
- Homework will be proposed periodically all along the lecture course

My personal concept for a physical experiment



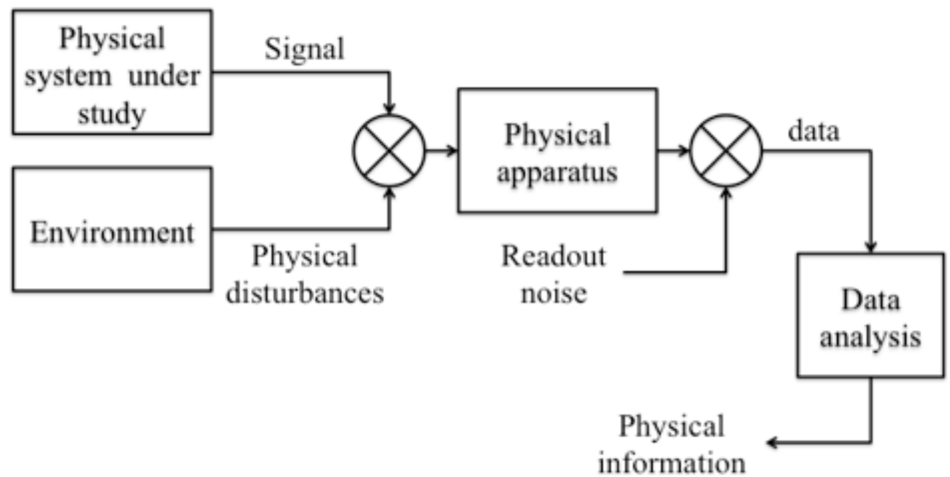
The noiseless chain

- The physical system is modeled by a few measurable quantities and their mathematical relations.
- The signal is a measurable quantity, function of some other measurable parameter(s), for instance time.
- The physical apparatus eventually transforms the signal into a set of recorded data on some memory support.
- The data analysis performs a set of mathematical operations on the data, in order to extract some of the physical parameters of the system under study.



The real chain

- The detector is also sensitive to other "signals", the physical disturbances, generated by the "environment". The environment also includes some non-modeled features of the apparatus. These disturbance signals are in principle indistinguishable from the true signal.
- No apparatus is perfect. The random fluctuations of its internal degrees of freedom will corrupt the data. (Readout noise)
- Exploiting the differences between signal and noise, data analysis must retrieve the information on the apparatus with minimum loss.



The (extended) program of the course

Physical signals. Analog, digital, continuous, and discrete signals. Time and frequency. Signal information. Uncertainty relations. Quantization. Sampling.

Physical systems and models. inputs and outputs. Linearity. Time invariance and memory. Stability. Small signals linearization of physical systems. Impulse response and transfer function. Causality and dispersion relations. Two-ports. Electromechanical conversion. Feedback. Linearization of response by feedback. Mixers.

Noise. Continuous and discrete stochastic processes. Random walk. Normal and Poisson processes. Stationary processes. Spectral density. Noise in linear systems. Non linear systems. Mixing. Noise measurements.

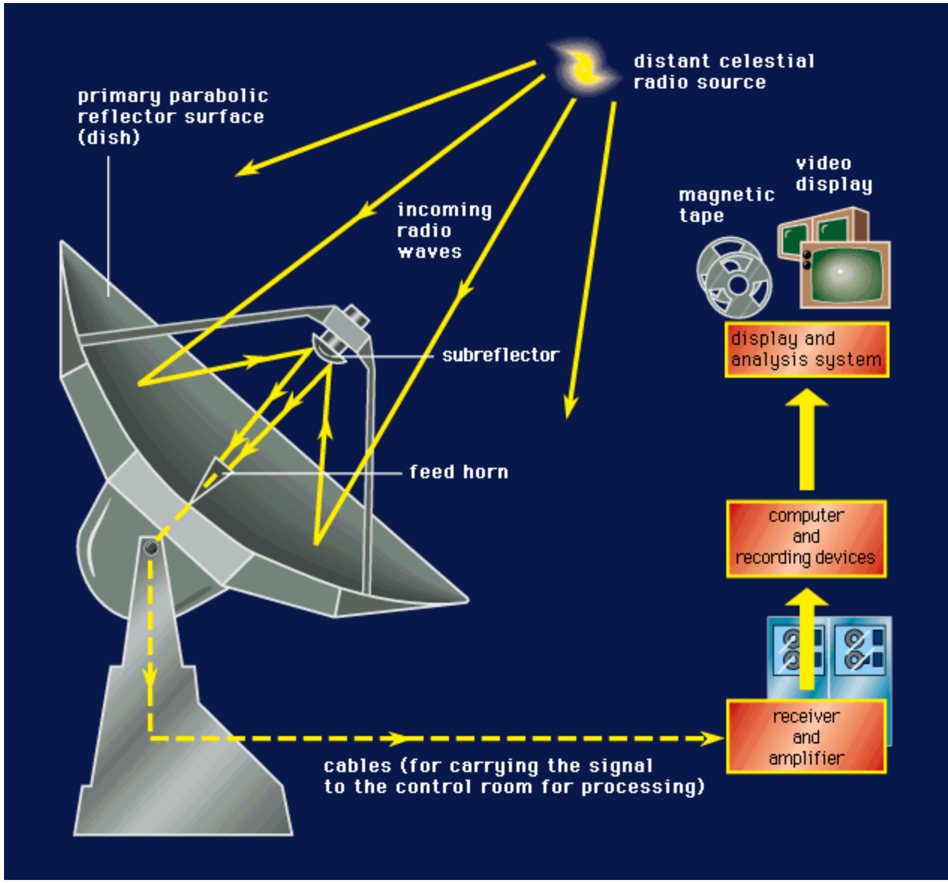
Noise in physical systems. Shot noise in laser systems, interferometers, and electronic devices. Thermal noise. Fluctuation-dissipation theorem. 1/f noise and logarithmic relaxation. Two ports and amplifiers. Series and parallel generators. Noise temperature. Back action. Parametric devices. Back-action evasion and Heisemberg principle. Examples. Sampling noise. Superconducting, microwave and lasers electronics. Electromechanical conversion. Quantum limited devices. Macroscopic quantum tunneling.

Signal detection. Optimum filtering. Signal to noise ratio. Measurements limits. Minimum detectable energy. Synchronous detection. Pulse detection. Random signals and spectral measurements. Standard quantum limit. Squeezed states.

Applications.

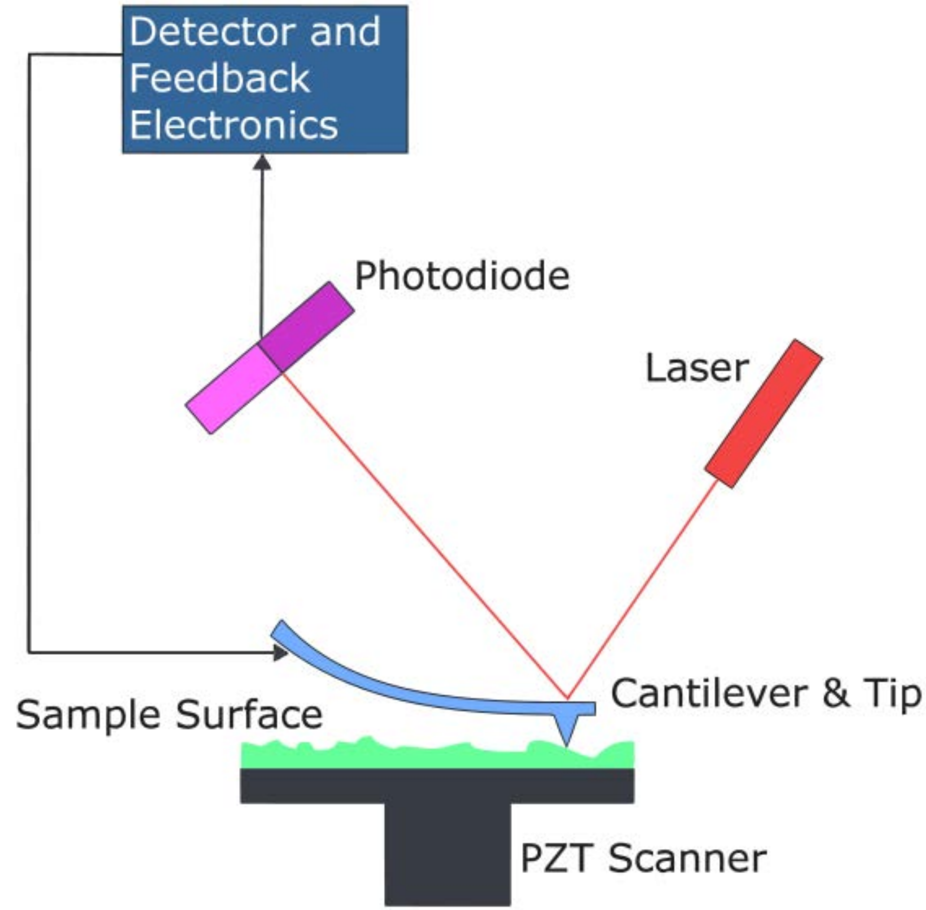
Some examples

- Radio astronomy:
  - Physical system: astrophysical bodies
  - Signal: radio-wave electrical field as a function of time
  - Apparatus: radio-telescope, front-end electronics, d/a converter. Data repository
  - Physical disturbances: stray electromagnetic field from environment hitting the antenna
  - Readout noise: noise in amplifiers etc.



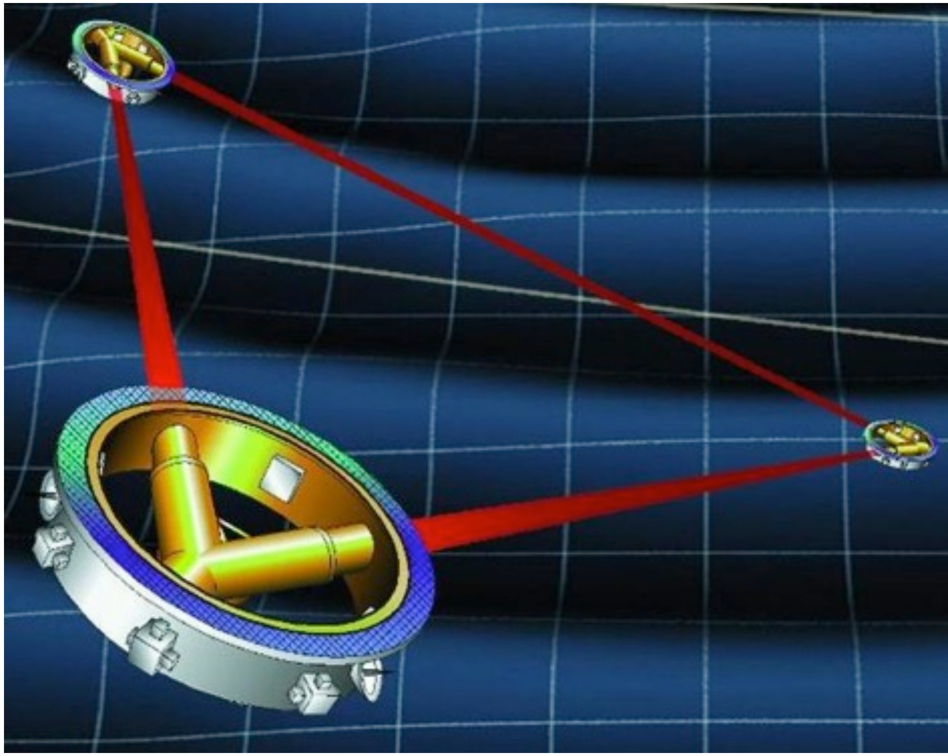
Some examples

- Atomic force microscopy:
  - Physical system: sample surface
  - Signal: atomic force between surface and tip as a function of position
  - Apparatus: Cantilever & tip, force actuator, laser position readout, front-end electronics, d/a converter. Data repository
  - Physical disturbances: stray forces on tip
  - Readout noise: noise in laser amplifiers etc.



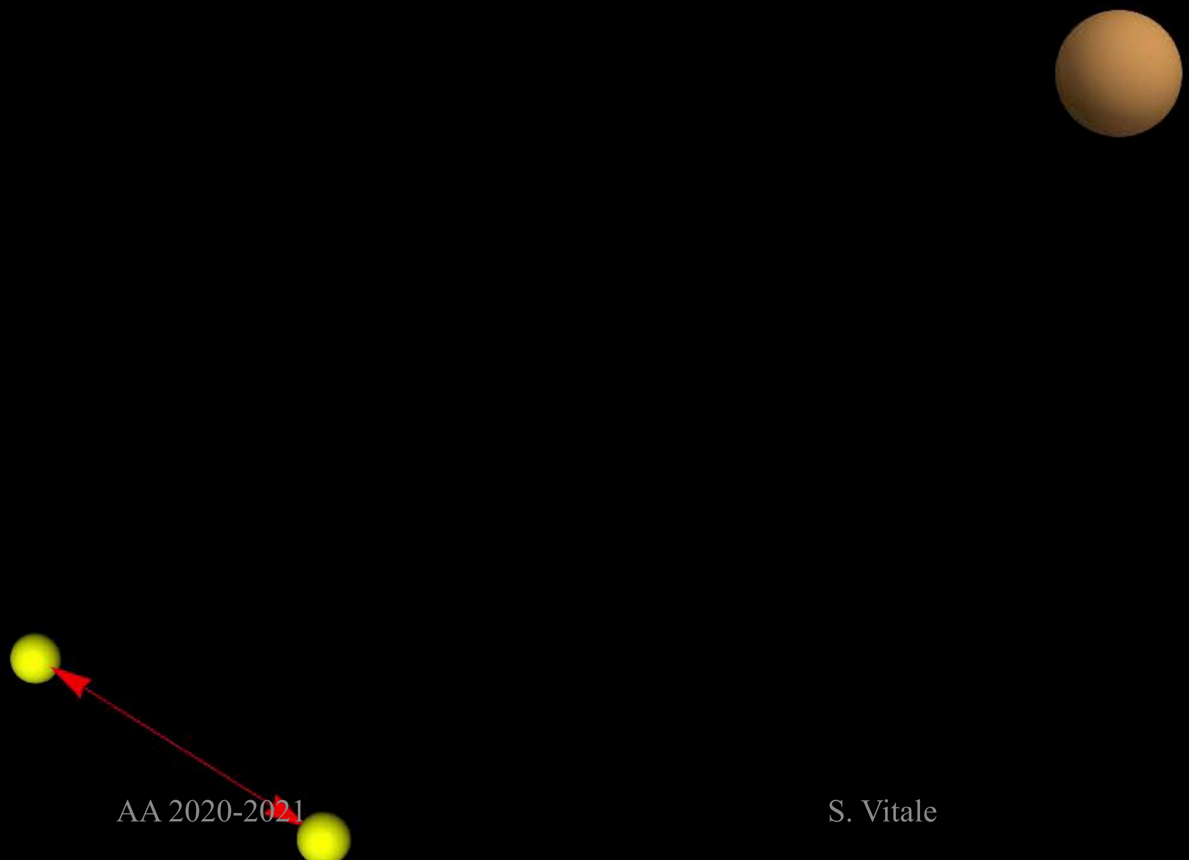
Some examples

- My favored example: Gravitational wave astronomy (see next slides for details)
  - Physical system: astrophysical bodies: binary black-holes, galactic binaries, big-bang
  - Signal: gravitational wave
  - Apparatus: gravitational wave detector
  - Physical disturbances: stray forces on test-masses
  - Readout noise: laser noise, electronic noise.



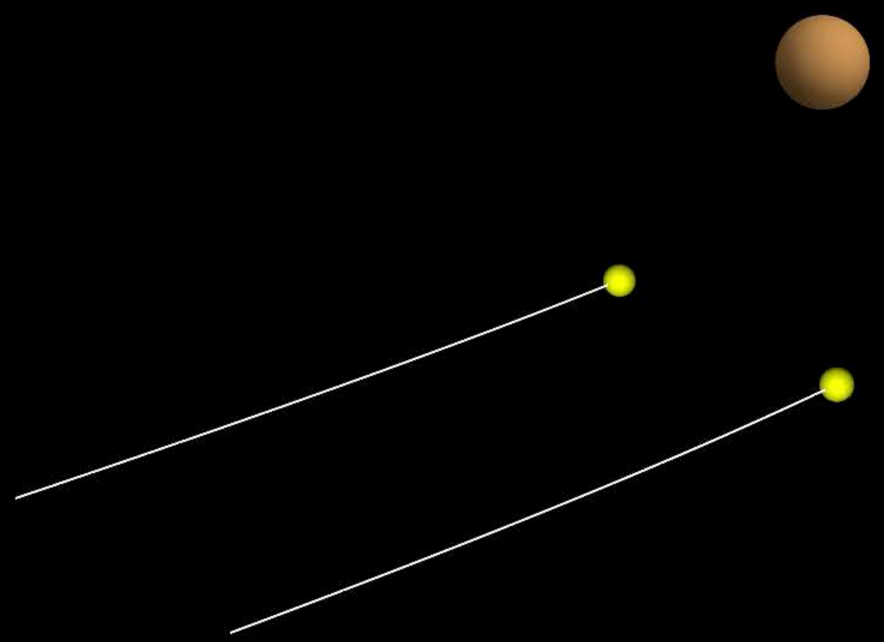
Gravitation as curvature

- Matter energy curve space-time trajectories of *free-falling* test-masses



Curvature and acceleration of test-masses

- Curvature: free falling particles see each other accelerating



Curvature and acceleration of test-masses

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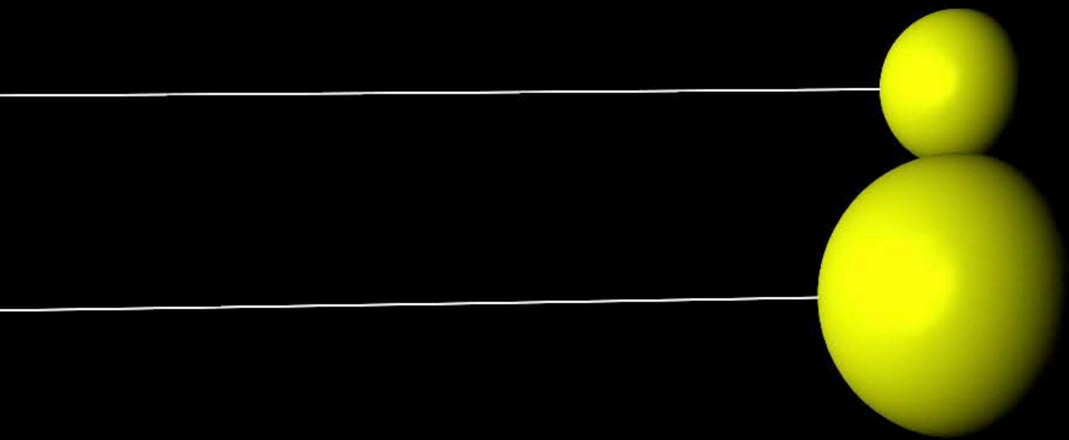
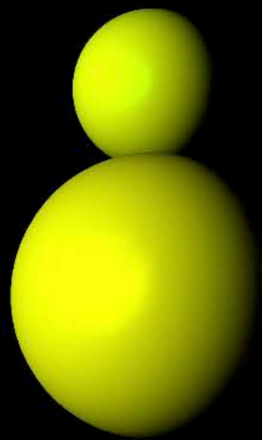


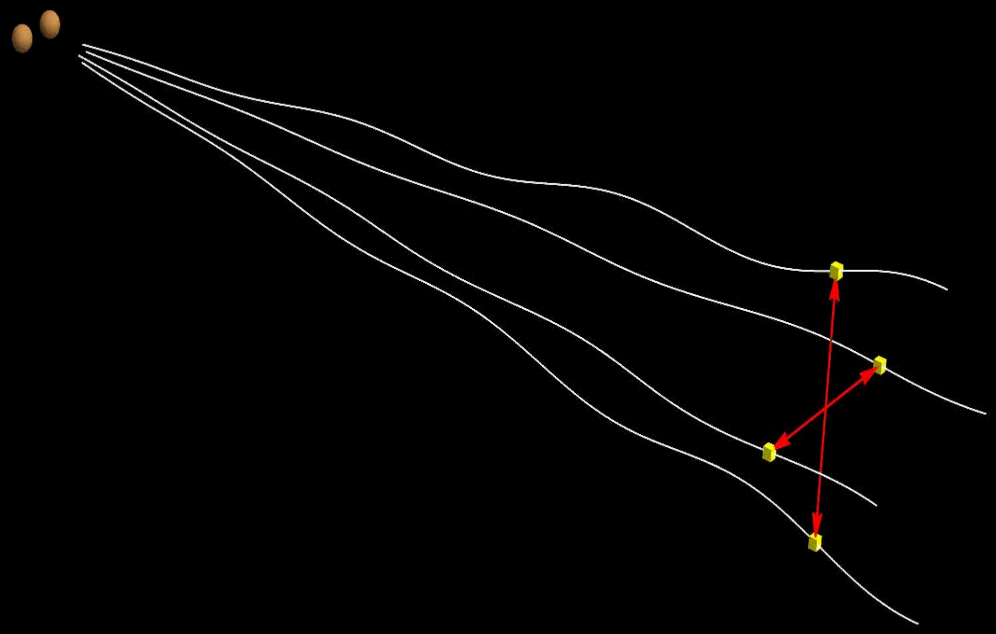
Curvature and acceleration of test-masses

- Acceleration only detectable effect of curvature if source is invisible

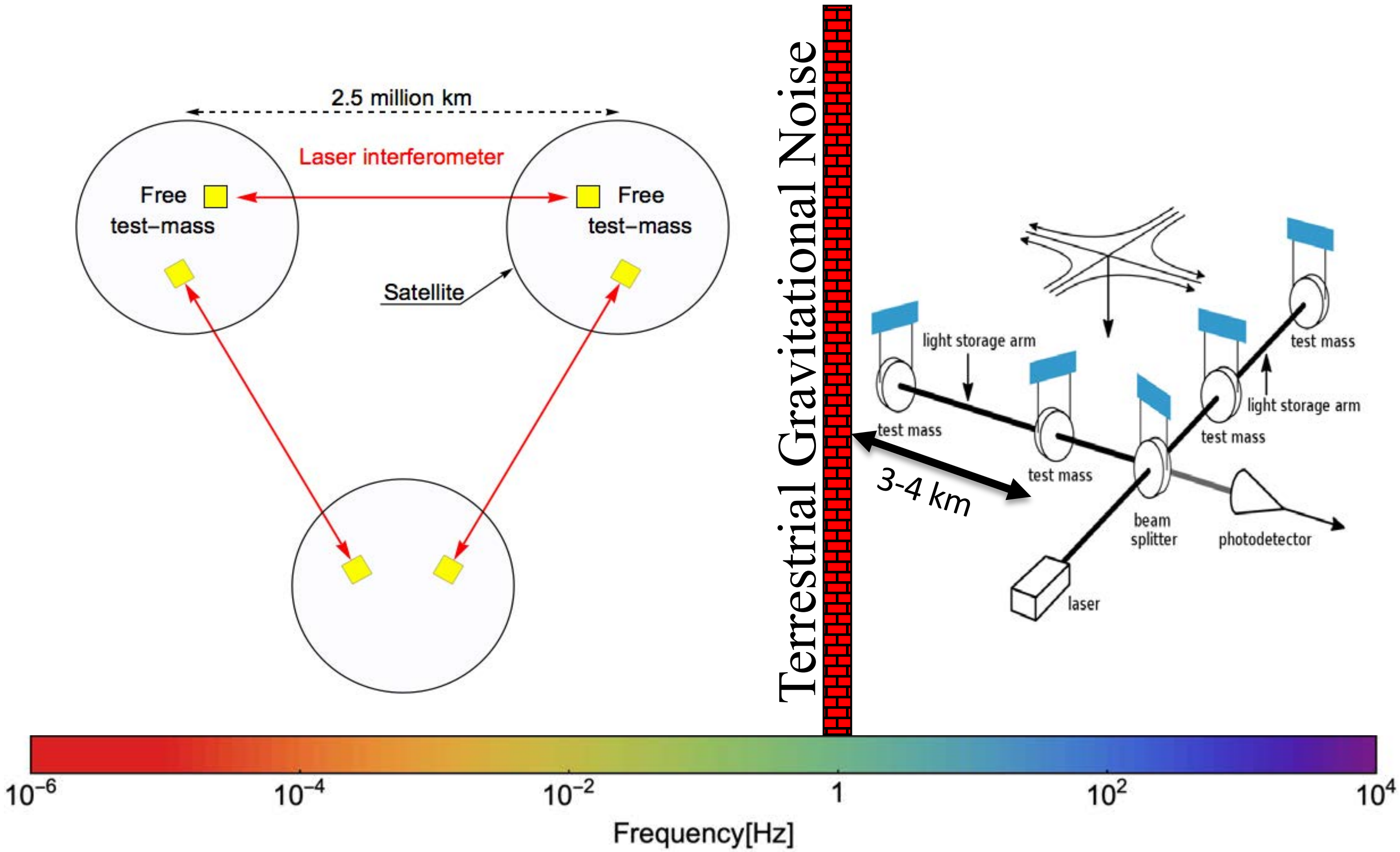


Gravitational waves

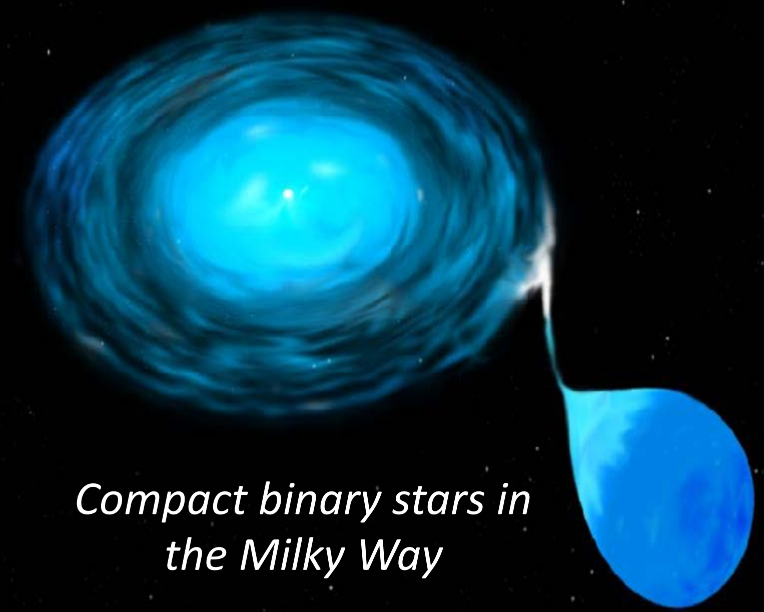
- Waves of curvature due to acceleration of matter-energy
- Can be detected form relative acceleration of free falling test-masses



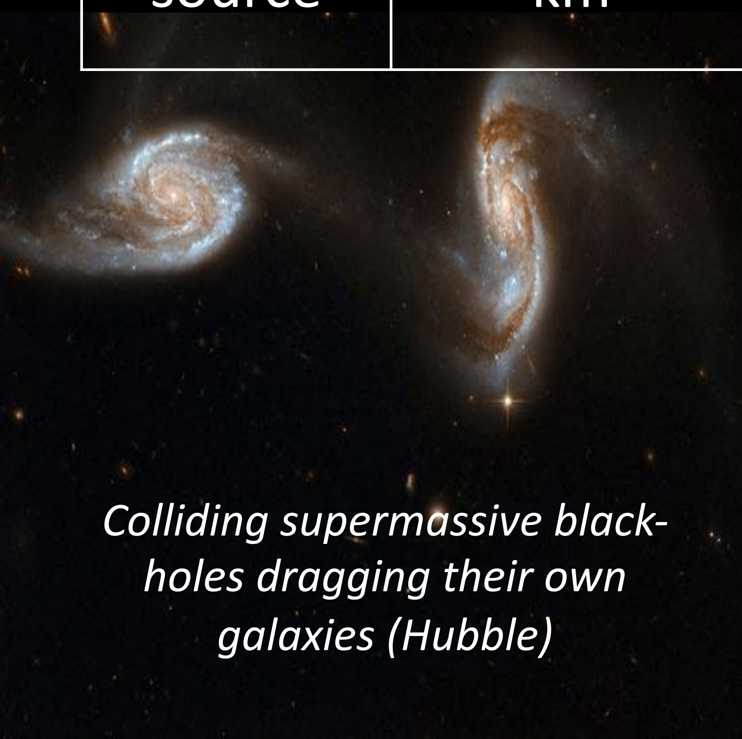
LISA: the quest for low-frequency GW



	LIGO	LISA
Size	km	Million km
Wave period	0.001-0.1 seconds	minutes to hours
Mass of sources	~ 1-10 Sun	up to 1-10 Million Sun
Size of the source	~ 100-1000 km	1-10 Million km



Compact binary stars in the Milky Way

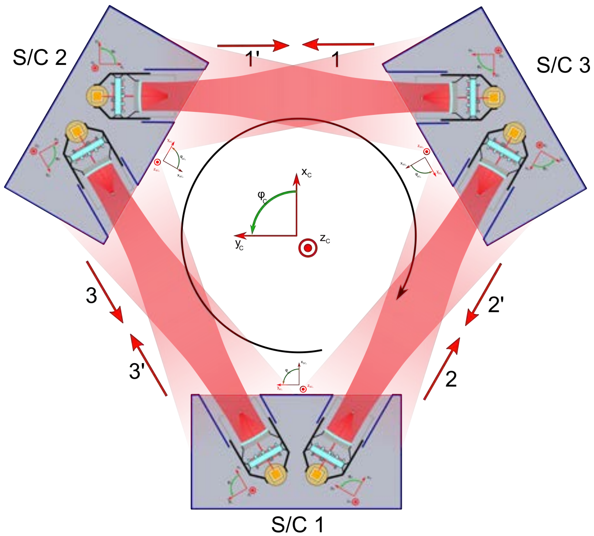


Colliding supermassive black-holes dragging their own galaxies (Hubble)

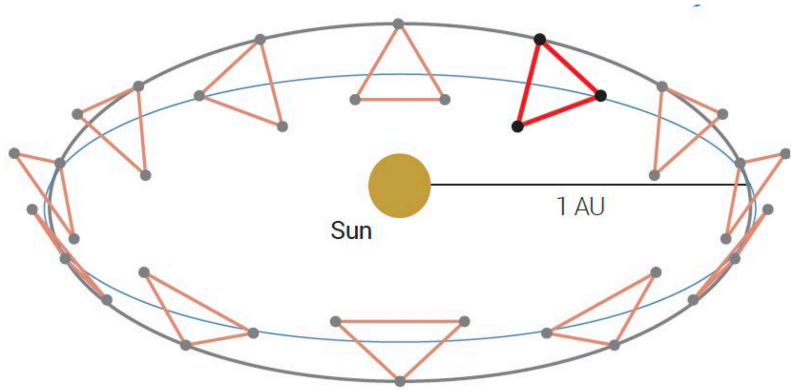
Supermassive black-hole swallowing a small one

LIGO black-hole years before final merger

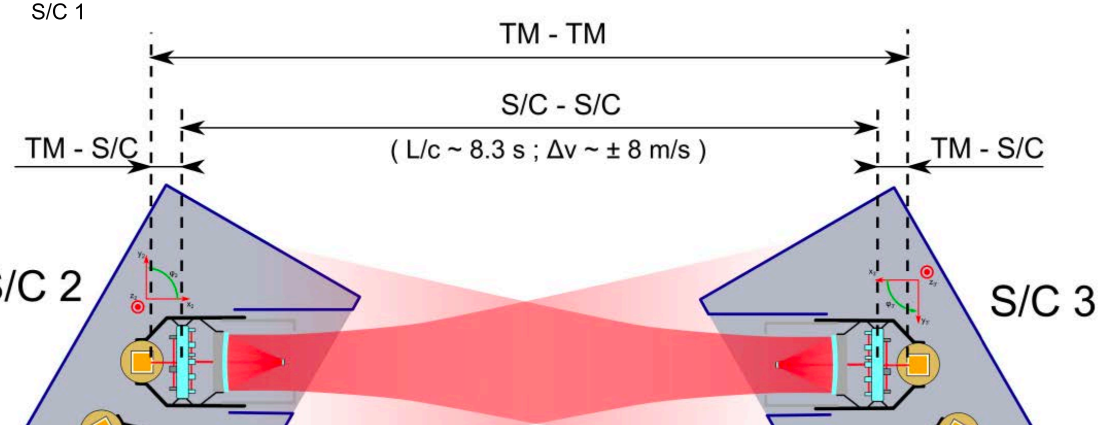
LISA



S/C 2
S/C 3
S/C 1
1'
1
2
2'
3
3'



Sun
1 AU



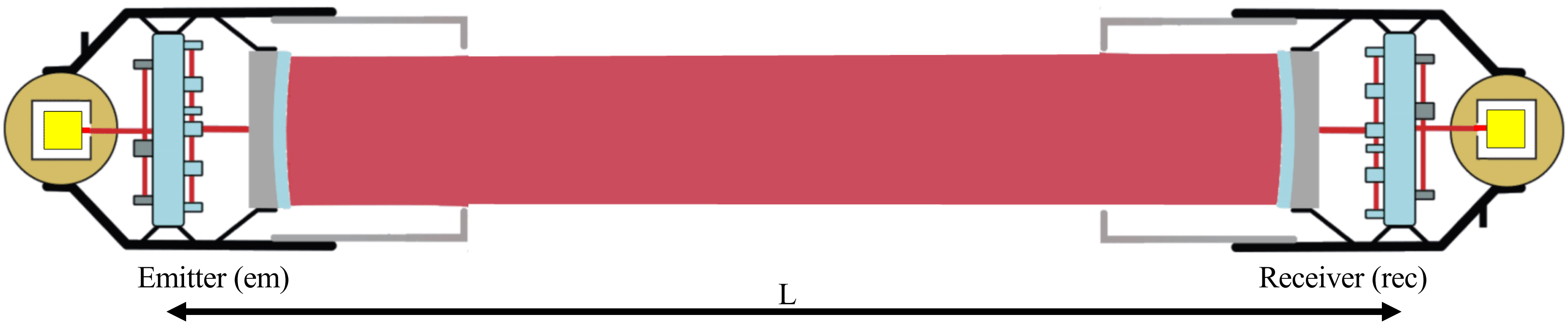
TM - TM
S/C - S/C
(L/c ~ 8.3 s ; Δv ~ ± 8 m/s)
TM - S/C
TM - S/C
S/C 2
S/C 3

The LISA link

- Laser beam propagates through GW curvature
- Beam frequency ν shifts along propagation

$$\frac{\Delta\nu}{\nu_o}=\frac{1}{2}\left(h(t_{em})-h(t_{rec})\right)$$

Metric tensor perturbation



- Shift is also modulated in time: time derivative directly proportional to curvature

$$\frac{\Delta\dot{\nu}}{\nu_o}=\frac{1}{2}\left(\dot{h}(t_{em})-\dot{h}(t_{rec})\right)\simeq\frac{1}{2}\ddot{h}\frac{L}{c}$$

Riemann tensor

Spacecraft acceleration and Doppler effect

- Standard Doppler effect in flat space-time also shifts frequency and mimics GW
- Time varying shift caused by acceleration along beam of emitter and receiver relative to inertial frame

$$\frac{\Delta\dot{\nu}}{\nu_o} = \frac{1}{2}\ddot{h}\frac{L}{c} + \frac{a_{rec} - a_{em}}{\mathrm{c}}$$

- Spacecraft (S/C) accelerate too much because of solar radiation pressure

Coping with S/C acceleration

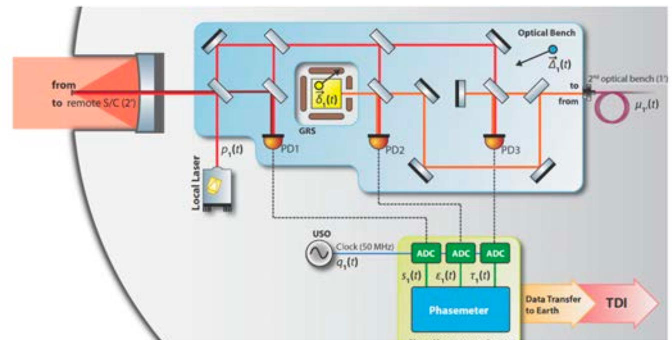
- Free-floating test-masses (TM) are carried inside S/C
- No contact between TM and S/C, "drag-free" along the beam
- Measure S/C-to-TM acceleration and correct signal for Doppler

- Residual noise due to acceleration of *TM* relative to local inertial frame

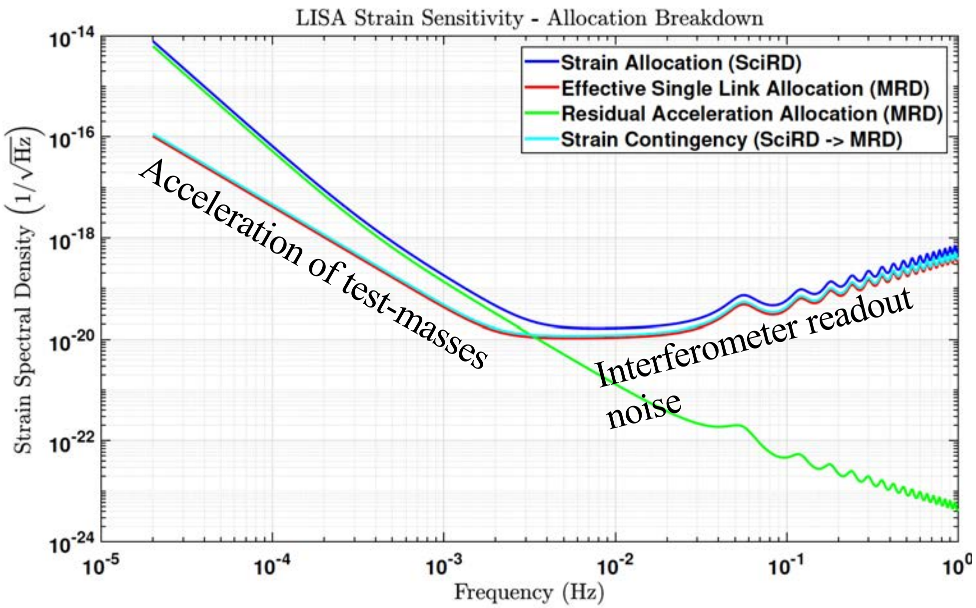
$$\frac{\Delta\dot{\nu}}{\nu_o} = \frac{1}{2}\ddot{h}\frac{L}{c} + \frac{a_{TM,rec} - a_{TM,em}}{\mathrm{c}}$$

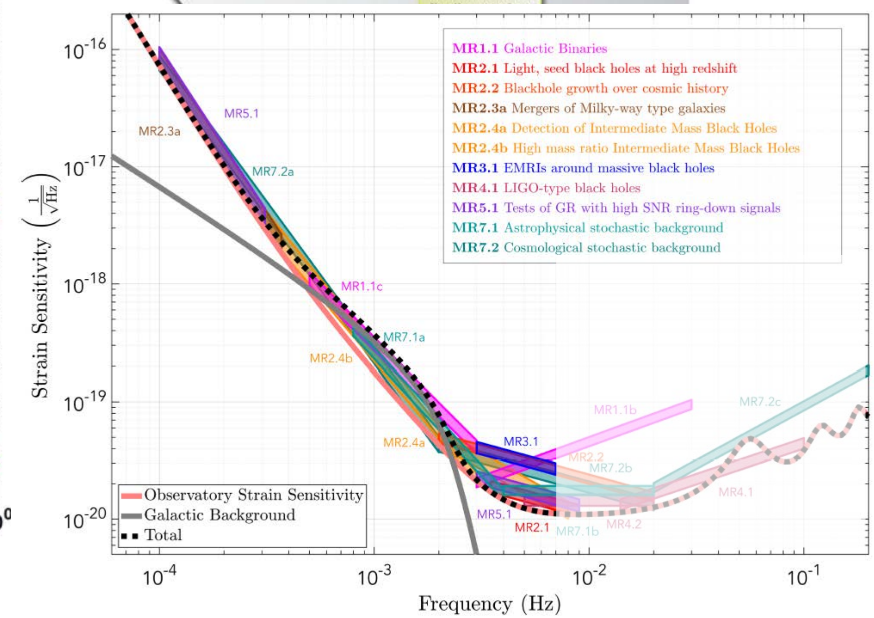
Noise in a LISA link

Class. Quantum Grav. 29 (2012) 205003 M Otto et al

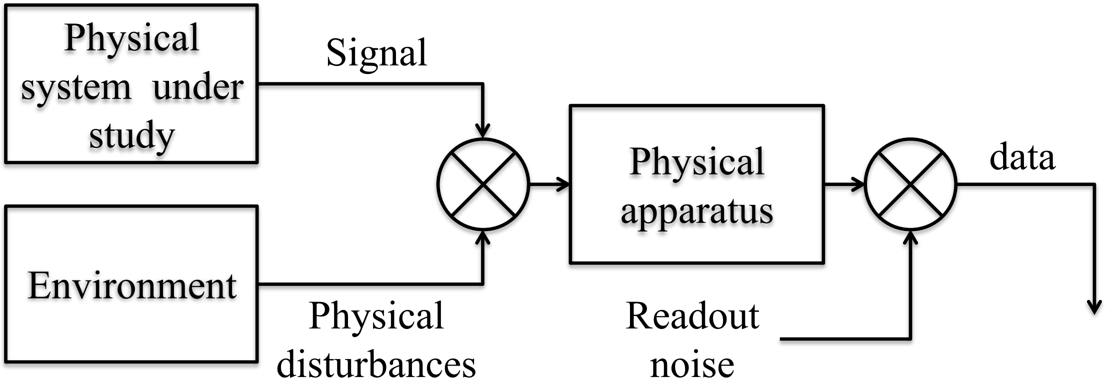


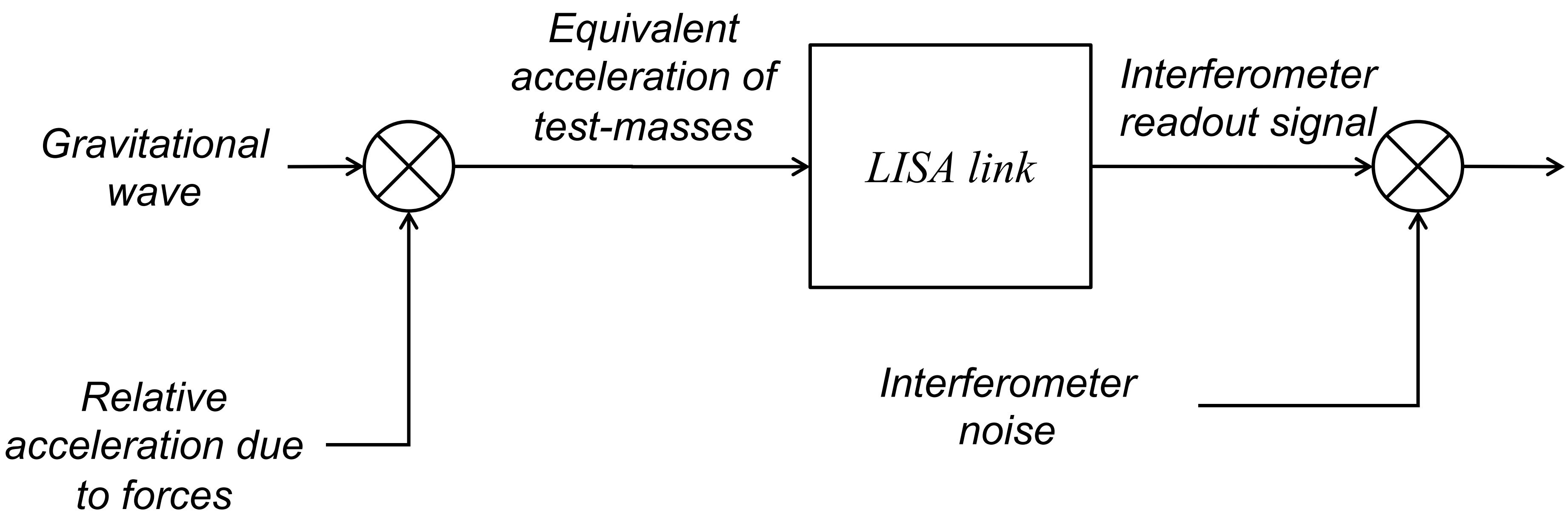
- Frequency measurements are noisy: interferometer readout noise
- Total noise





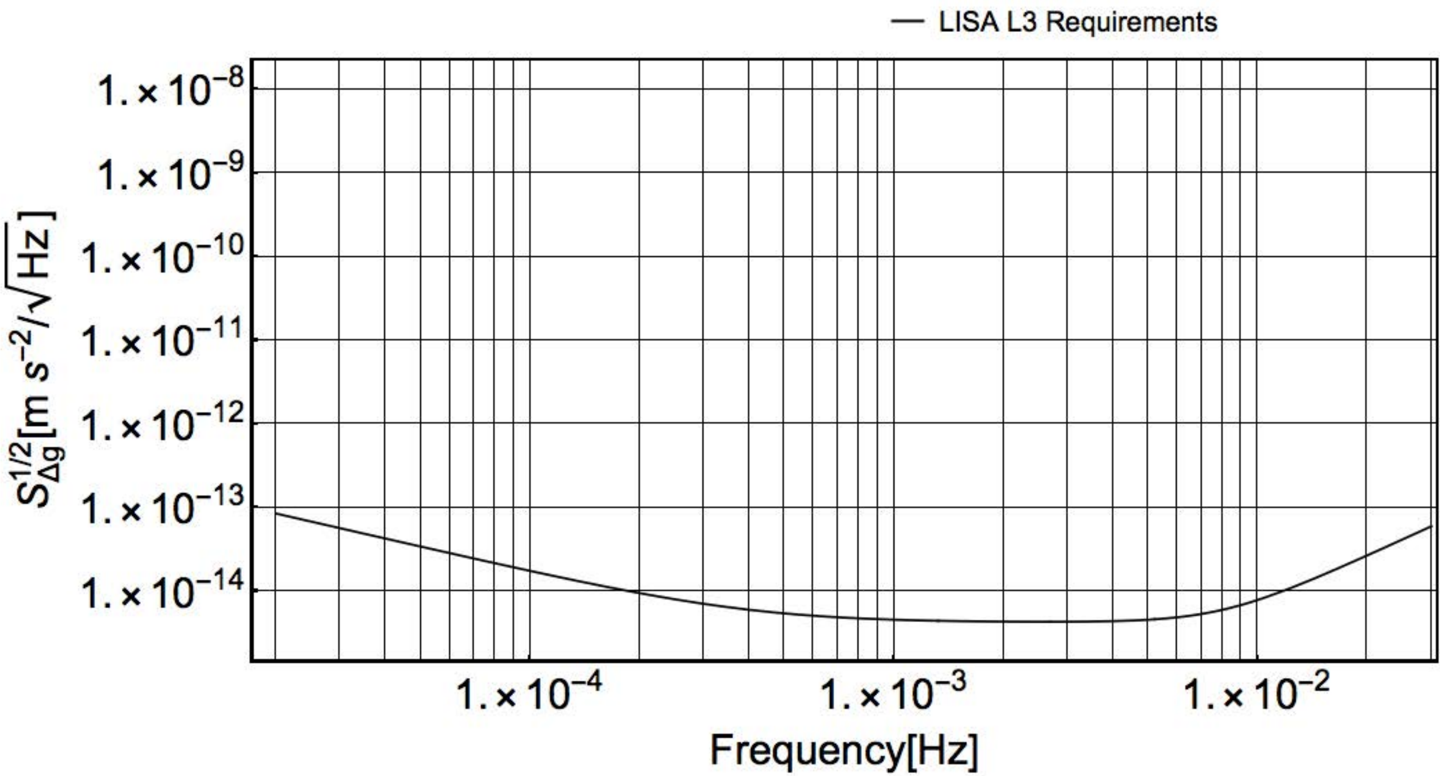
Disturbances in One LISA Arm





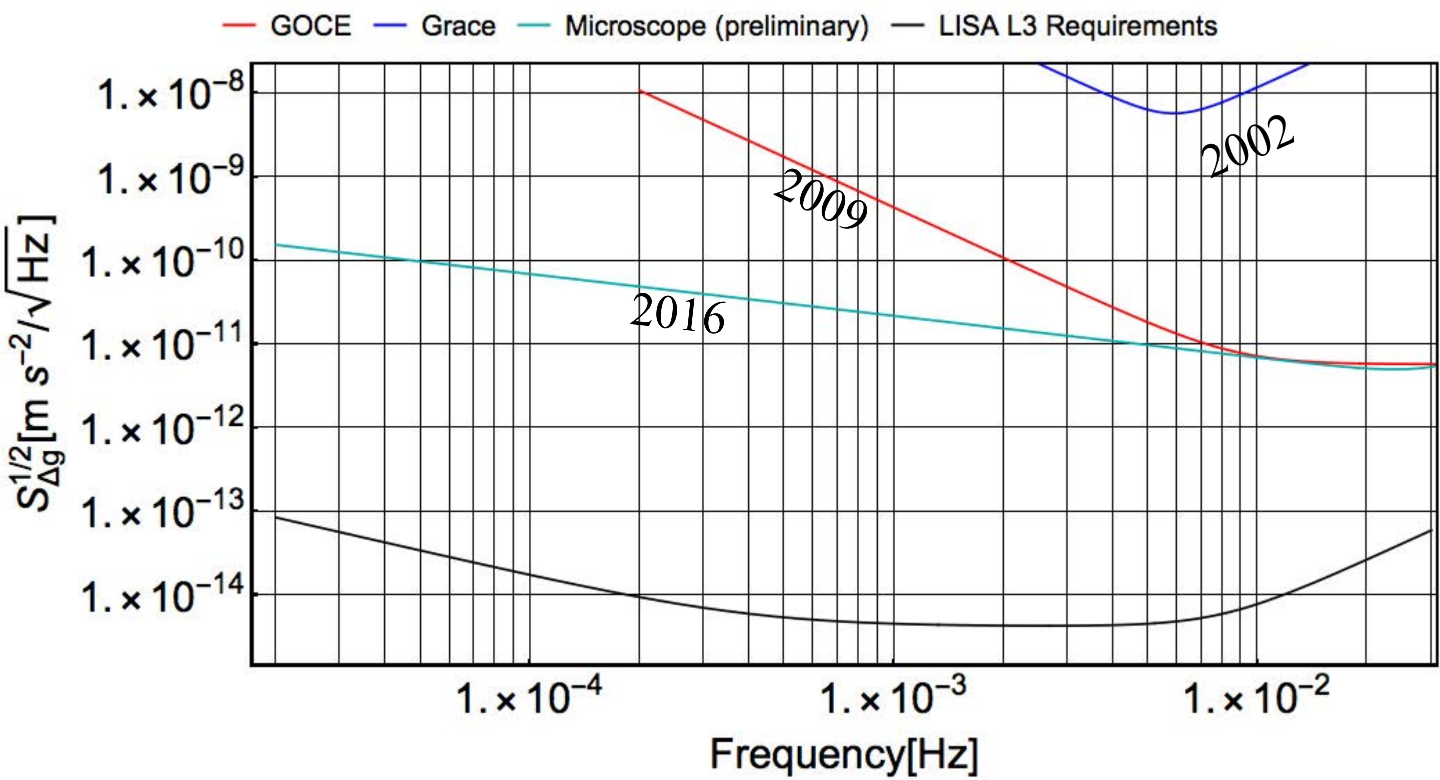
LISA: Sub-femto-g force suppression required

- Cannot be tested on ground $\lesssim$ 0.1 Hz

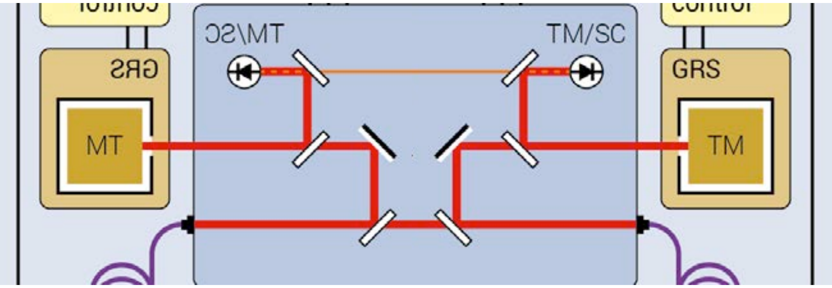


LISA: Sub-femto-g force suppression required

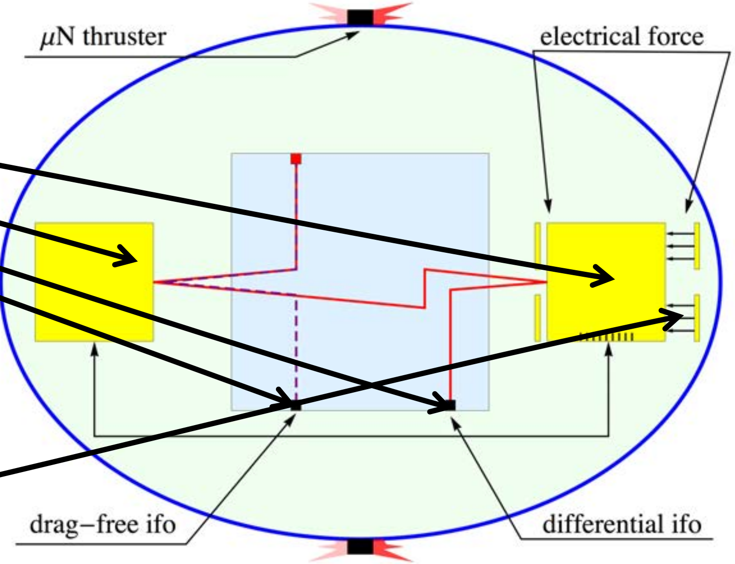
- Cannot be tested on ground $\lesssim$ 0.1 Hz
- Not even in low Earth orbit: orders (>3) of magnitude better than any other space mission



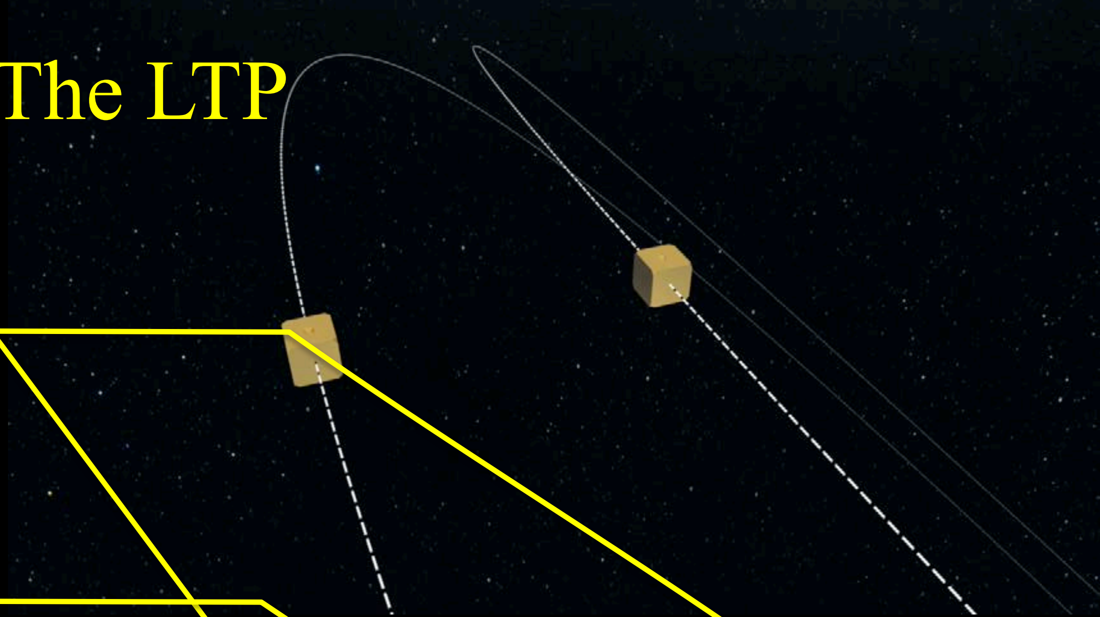
LISA Pathfinder



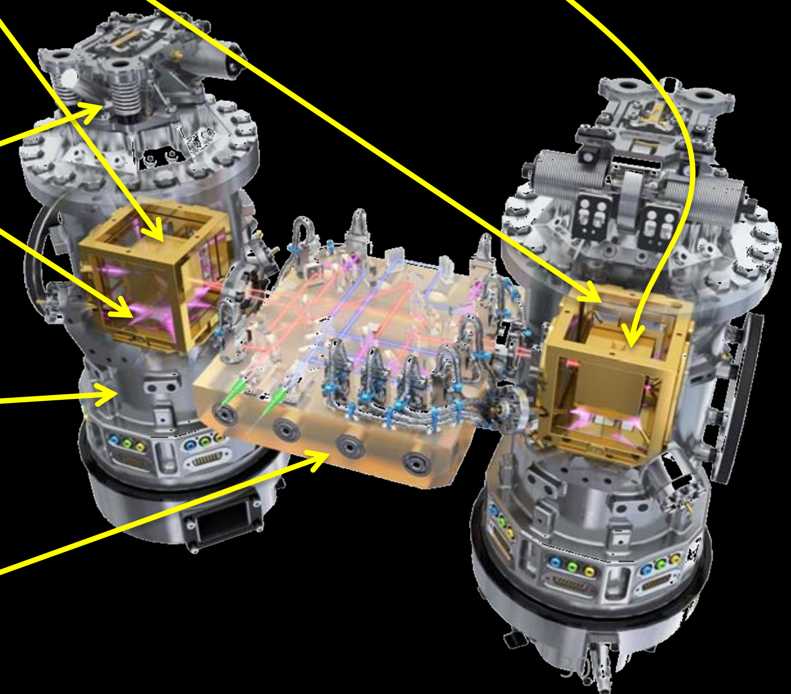
- Force disturbance is local. Test does not require million km size
- One LISA link inside a single spacecraft (no million km arm)
- 2 TMs,
- 2 Interferometers (Ifo)
- Satellite chases one test-mass
- Contrary to LISA, second test-mass forced to follow the first at very low frequency by electrostatics



The LTP



- Test masses gold-platinum, highly non-magnetic, very dense
- Electrode housing: electrodes are used to exert very weak electrostatic force
- UV light, neutralize the charging due to cosmic rays
- Caging mechanism: holds the test-masses and avoid them damaging the satellite at launch
- Vacuum enclosure to handle vacuum on ground
- Ultra high mechanical stability optical bench for the laser interferometer



From instrument integration to beginning of operations 2014-2016

The ultimate performance