LISA Pathfinder and eLISA

Massimo Bassan
Dip. Fisica Università and INFN
Roma Tor Vergata

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for the LISA Pathfinder Team

Outline

PHYSICAL
REVIEW
LETTERS

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Articles published week ending 10 JUNE 2016

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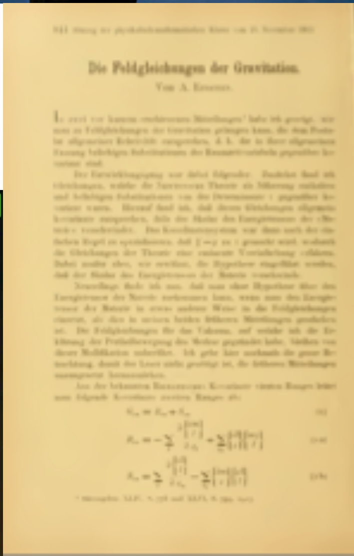
APS physics

Volume 116, Number 23

- You all know what gravitational waves are...
- A milliHertz detector...why ?
- A space-borne detector...how ?
- Challenges and solutions
- LISA Pathfinder: a laboratory in space.
- LPF first results

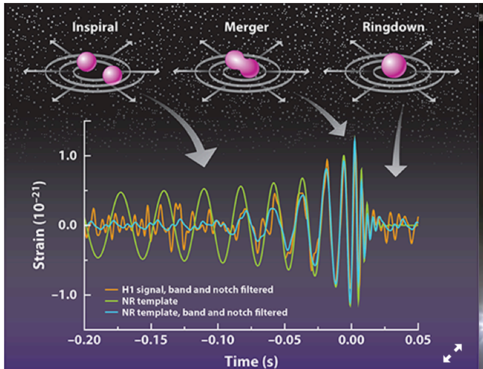
What a year for g.w. physics !

- Sept 18th: Advanced Ligo begins O1 run (discovery on the 14th.....)
- 水曜日, 10月 7th, T. Kajita, PI of Kagra, wins the Nobel prize
- Nov 29th: One century of General Relativity
- Dec 3rd: Launch of LISA Pathfinder
- Feb 14th: First direct observation of g.w.
- June 7th : LPF results
- ....?

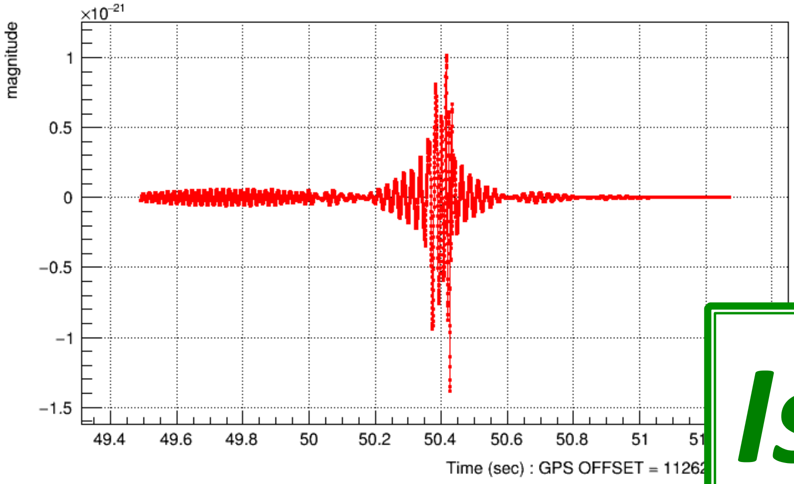


Die Feldgleichungen der Gravitation.

Von A. Einstein.

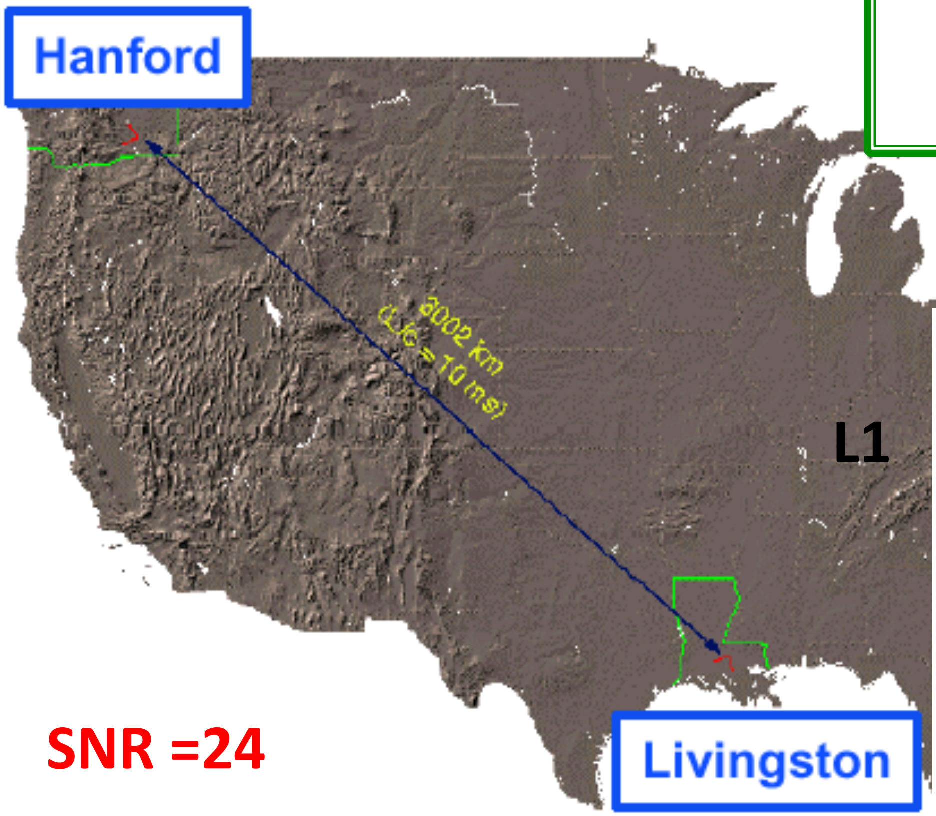


GW15 0914

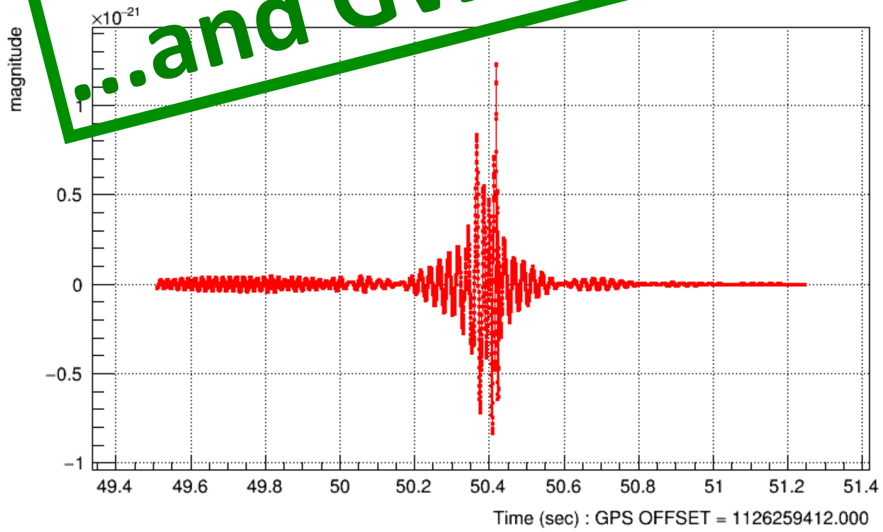


Is there life after GW150914 ?

...and GW151226 ?



SNR =24



Finally, we have detected GWs.

But the best is yet to come!

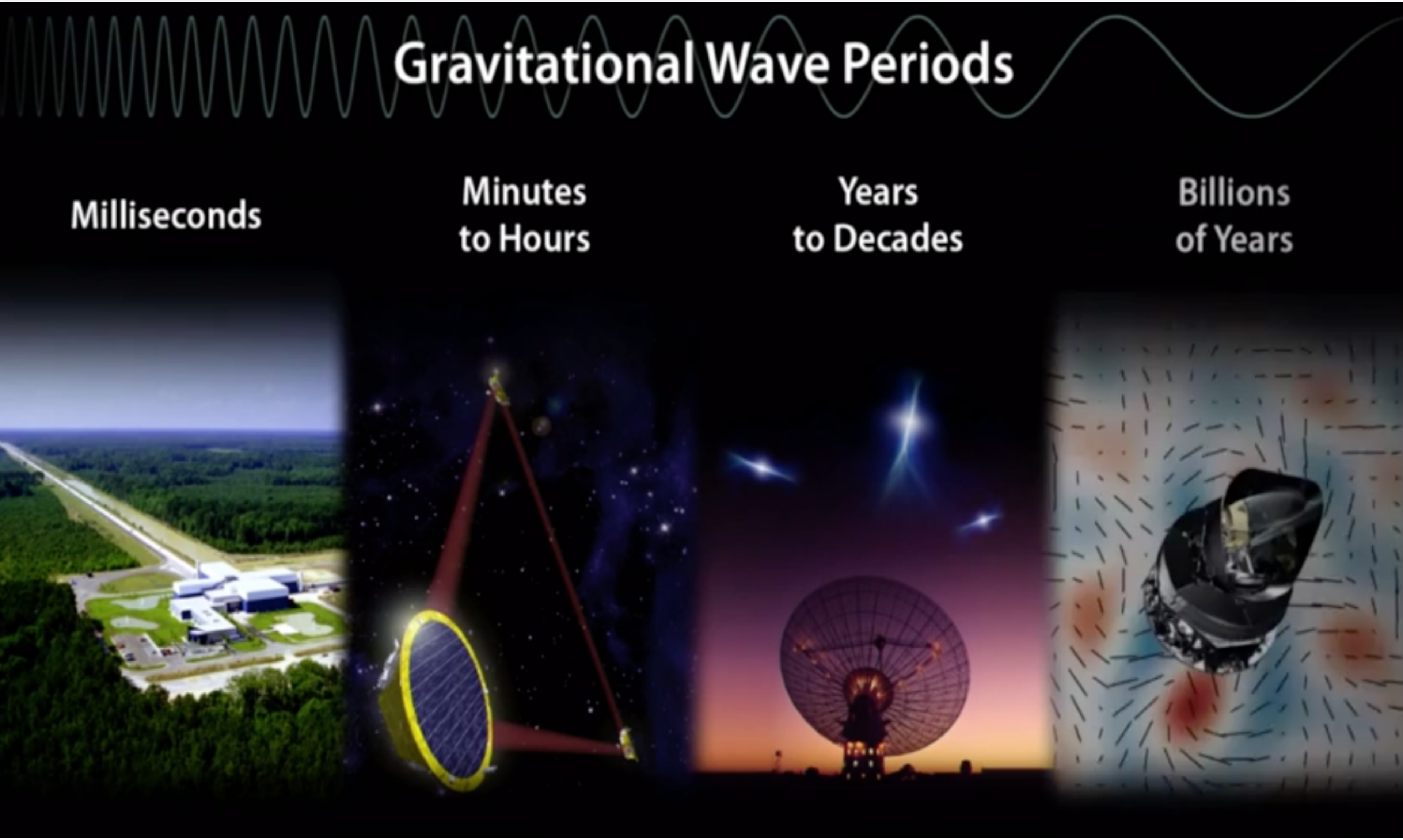
"Recording a GW for the first time has never been a big motivation for LIGO [and Virgo].
The motivation has always been
to open a new window on the Universe,
to see the warped side of the Universe,
an aspect never seen before:
objects and phenomena
made entirely or partially of warped spacetime"

Kip Thorne

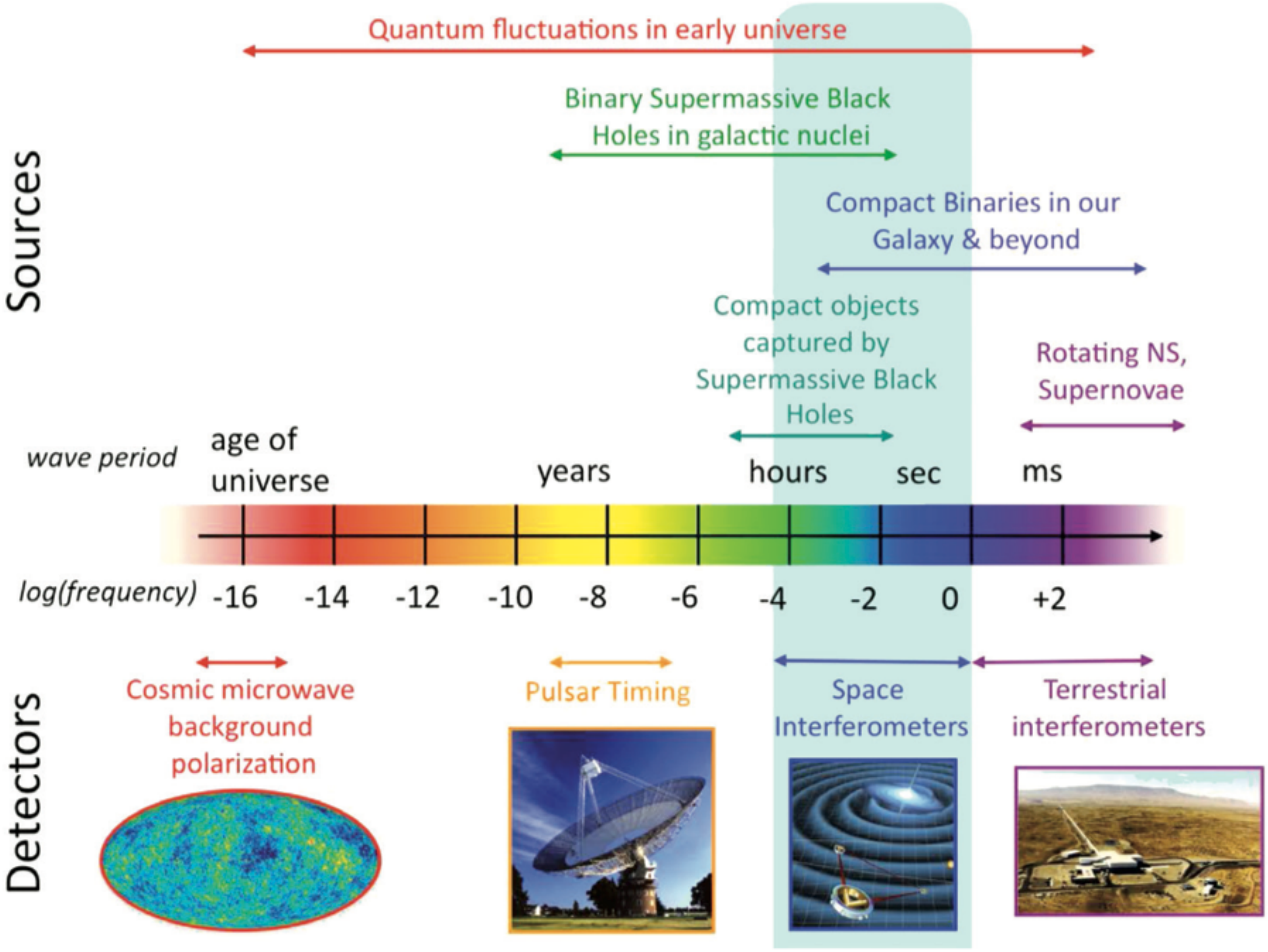
Suddenly, the realm of physics has expanded:
we are able to study strongly gravitating object and phenomena,
of which - up to now - we only had indirect evidence or knowledge.

credit: L.Gualtieri

Each frequency has its tool:



The Gravitational Wave Spectrum



Sources

Quantum fluctuations in early universe

Binary Supermassive Black Holes in galactic nuclei

Compact Binaries in our Galaxy & beyond

Compact objects captured by Supermassive Black Holes

Rotating NS, Supernovae

wave period: age of universe, years, hours, sec, ms

log(frequency): -16, -14, -12, -10, -8, -6, -4, -2, 0, +2

Detectors

Cosmic microwave background polarization

Pulsar Timing

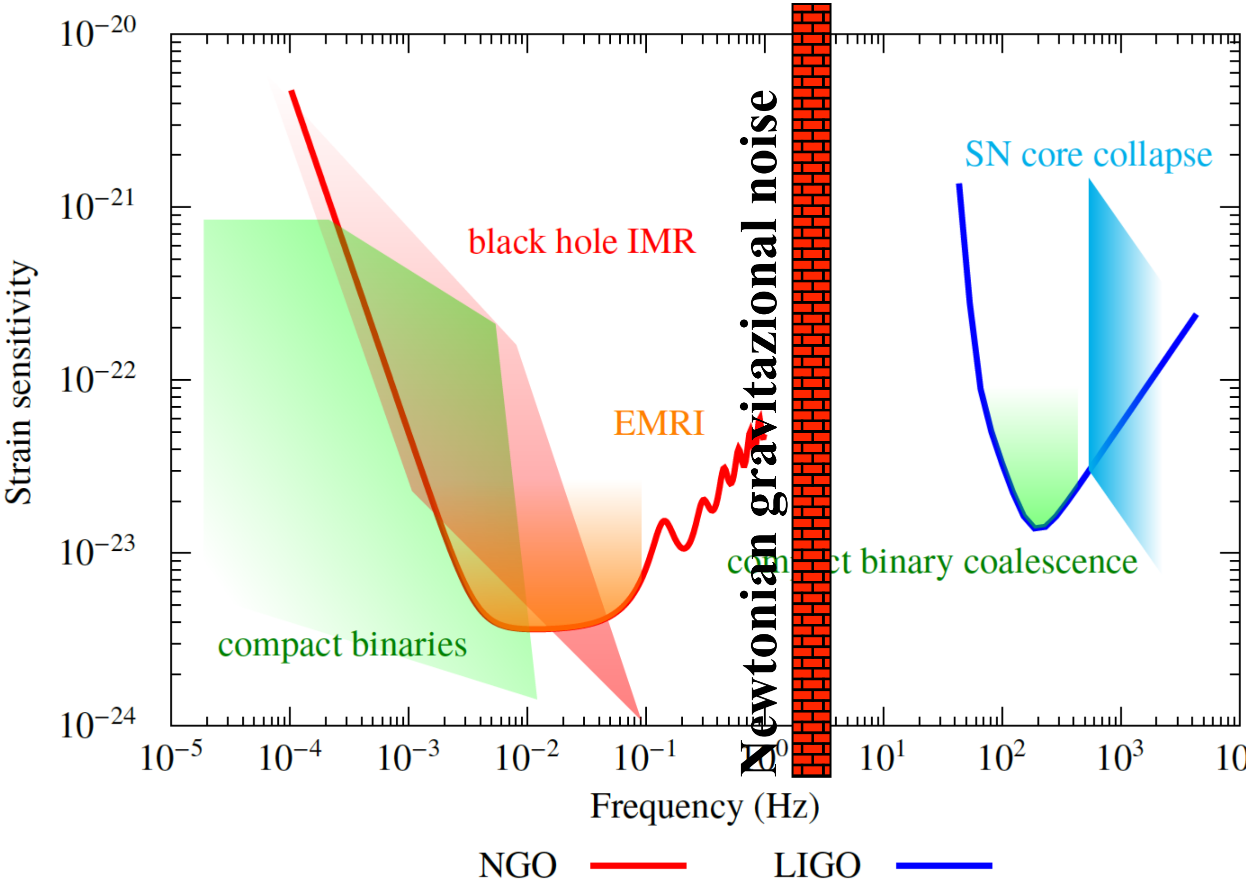
Space Interferometers

Terrestrial interferometers

Low freq. gw antenna in space: Why ?

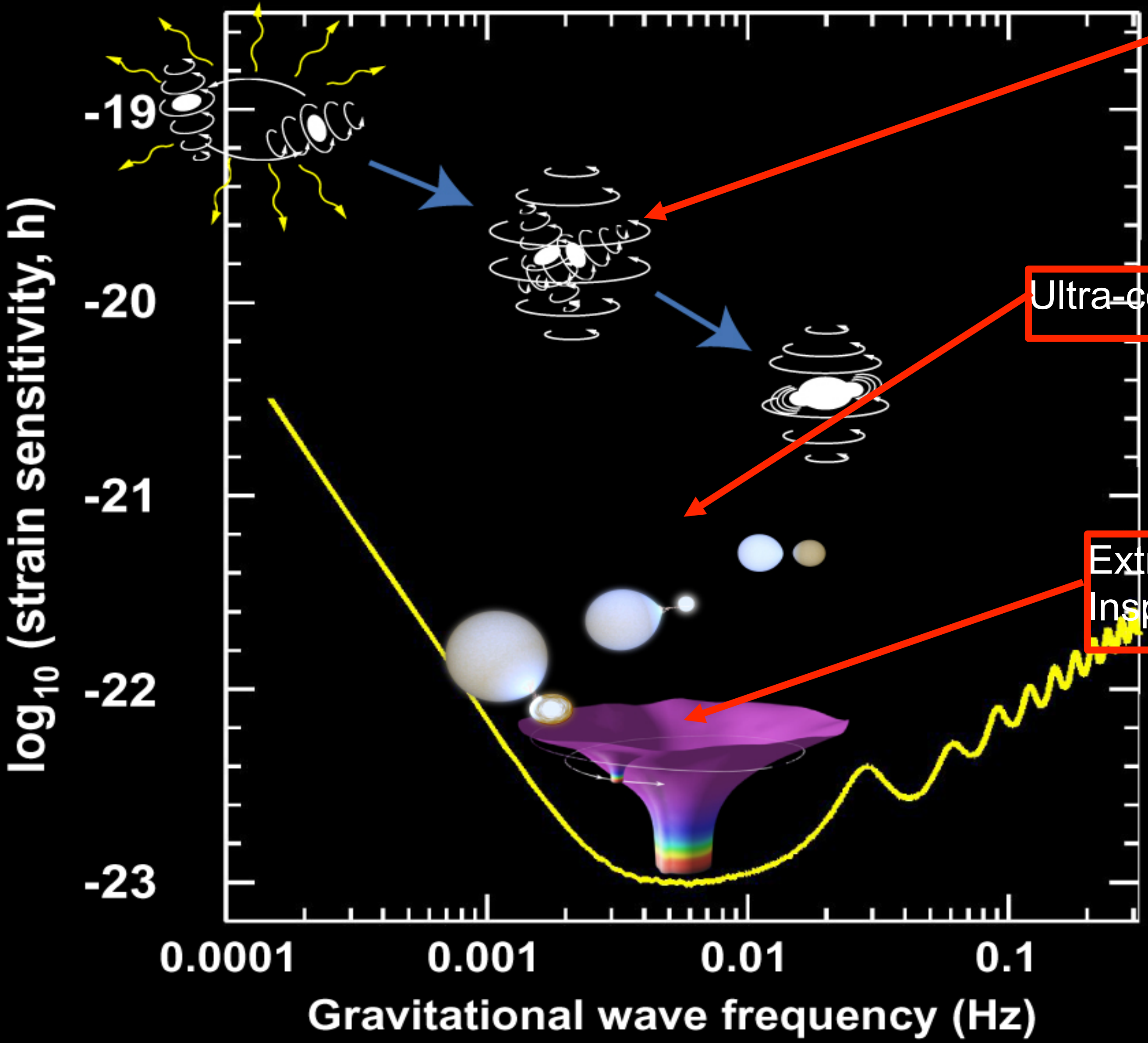
- Low frequency is where the most intense sources emit, and where the SNR is very high.

- eLISA will be a signal-dominated detector !



eLISA is sensitive at low frequencies (0.1 mHz – 1Hz) where ground based detectors cannot operate, due to Earth grav. noise

The rich g.w. sky in the mHz region



Massive Black Hole Binary (BHB) inspiral and merger

Ultra-compact binaries

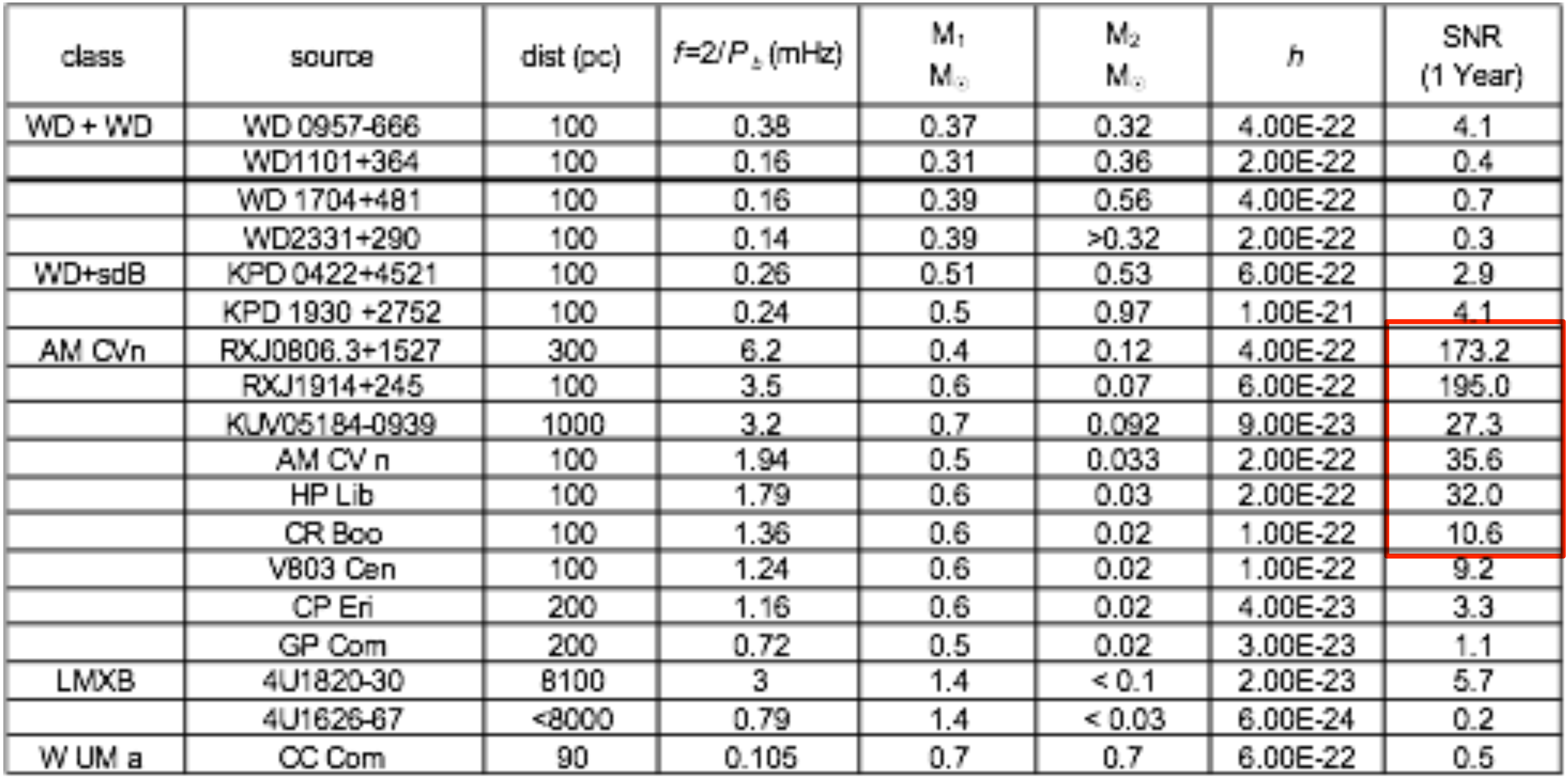
Extreme Mass Ratio Inspiral (EMRI)

Binary Star in our Galaxy (WD, NS)

Very bright signal (Signal >100 times larger than noise)

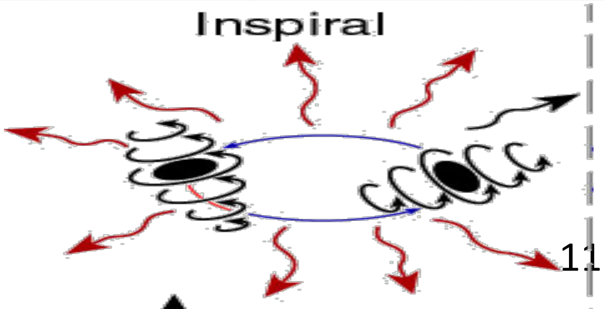
Of some of them we know everything (masses, distance, period...): they're out and waiting for being observed

Signals from binary inspiral



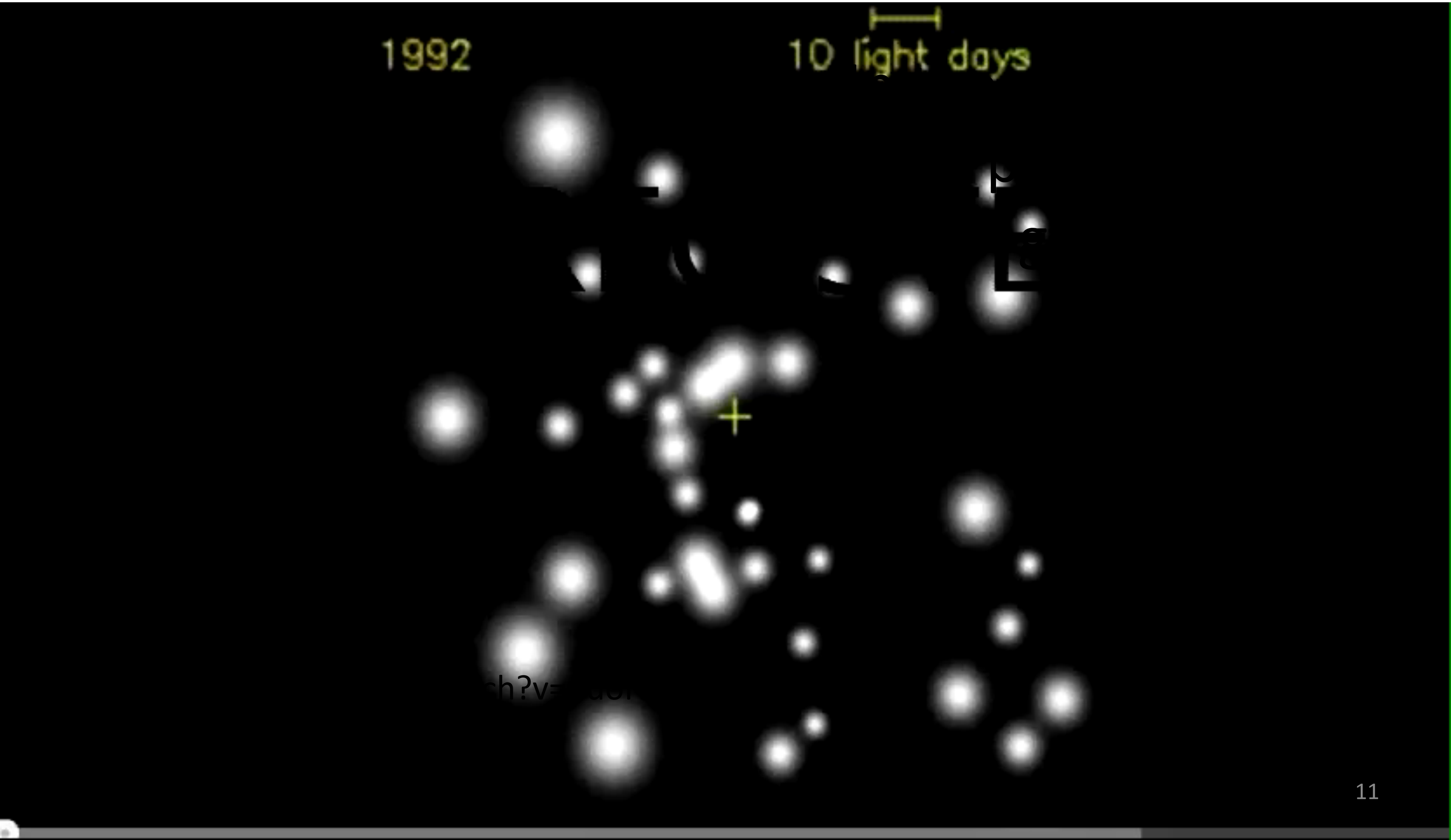
class	source	dist (pc)	$f=2/P_b$ (mHz)	M_1 $M_\odot$	M_2 $M_\odot$	h	SNR (1 Year)
WD + WD	WD 0957-666	100	0.38	0.37	0.32	4.00E-22	4.1
	WD1101+364	100	0.16	0.31	0.36	2.00E-22	0.4
	WD 1704+481	100	0.16	0.39	0.56	4.00E-22	0.7
	WD2331+290	100	0.14	0.39	>0.32	2.00E-22	0.3
WD+sdB	KPD 0422+4521	100	0.26	0.51	0.53	6.00E-22	2.9
	KPD 1930 +2752	100	0.24	0.5	0.97	1.00E-21	4.1
AM CVn	RXJ0806.3+1527	300	6.2	0.4	0.12	4.00E-22	173.2
	RXJ1914+245	100	3.5	0.6	0.07	6.00E-22	195.0
	KUV05184-0939	1000	3.2	0.7	0.092	9.00E-23	27.3
	AM CV n	100	1.94	0.5	0.033	2.00E-22	35.6
	HP Lib	100	1.79	0.6	0.03	2.00E-22	32.0
	CR Boo	100	1.36	0.6	0.02	1.00E-22	10.6
	V803 Cen	100	1.24	0.6	0.02	1.00E-22	9.2
	CP Eri	200	1.16	0.6	0.02	4.00E-23	3.3
	GP Com	200	0.72	0.5	0.02	3.00E-23	1.1
LMXB	4U1820-30	8100	3	1.4	< 0.1	2.00E-23	5.7
	4U1626-67	<8000	0.79	1.4	< 0.03	6.00E-24	0.2
W UM a	CC Com	90	0.105	0.7	0.7	6.00E-22	0.5

We call them “verification binaries”



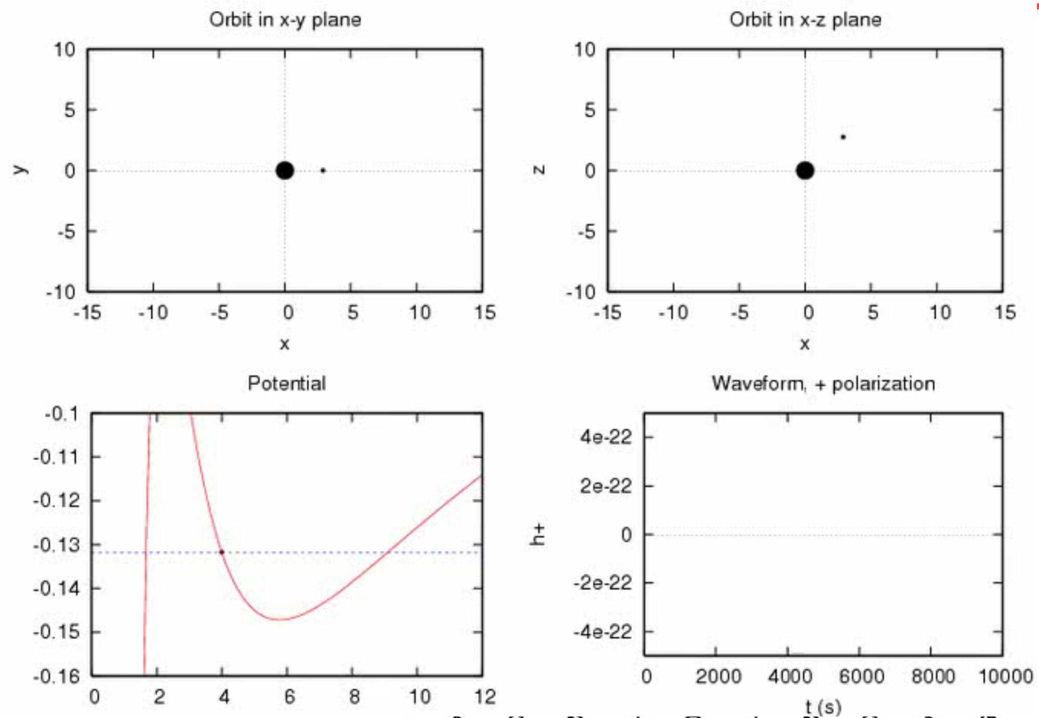
Supermassive Black Holes

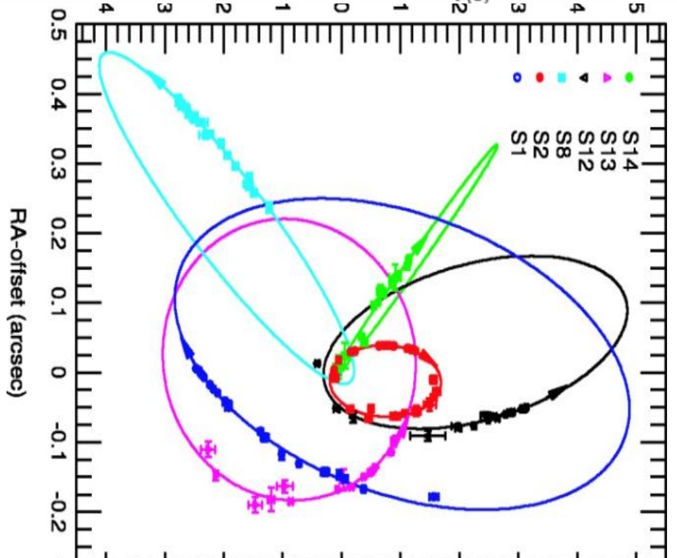
In the center of our (and probably any) galaxy



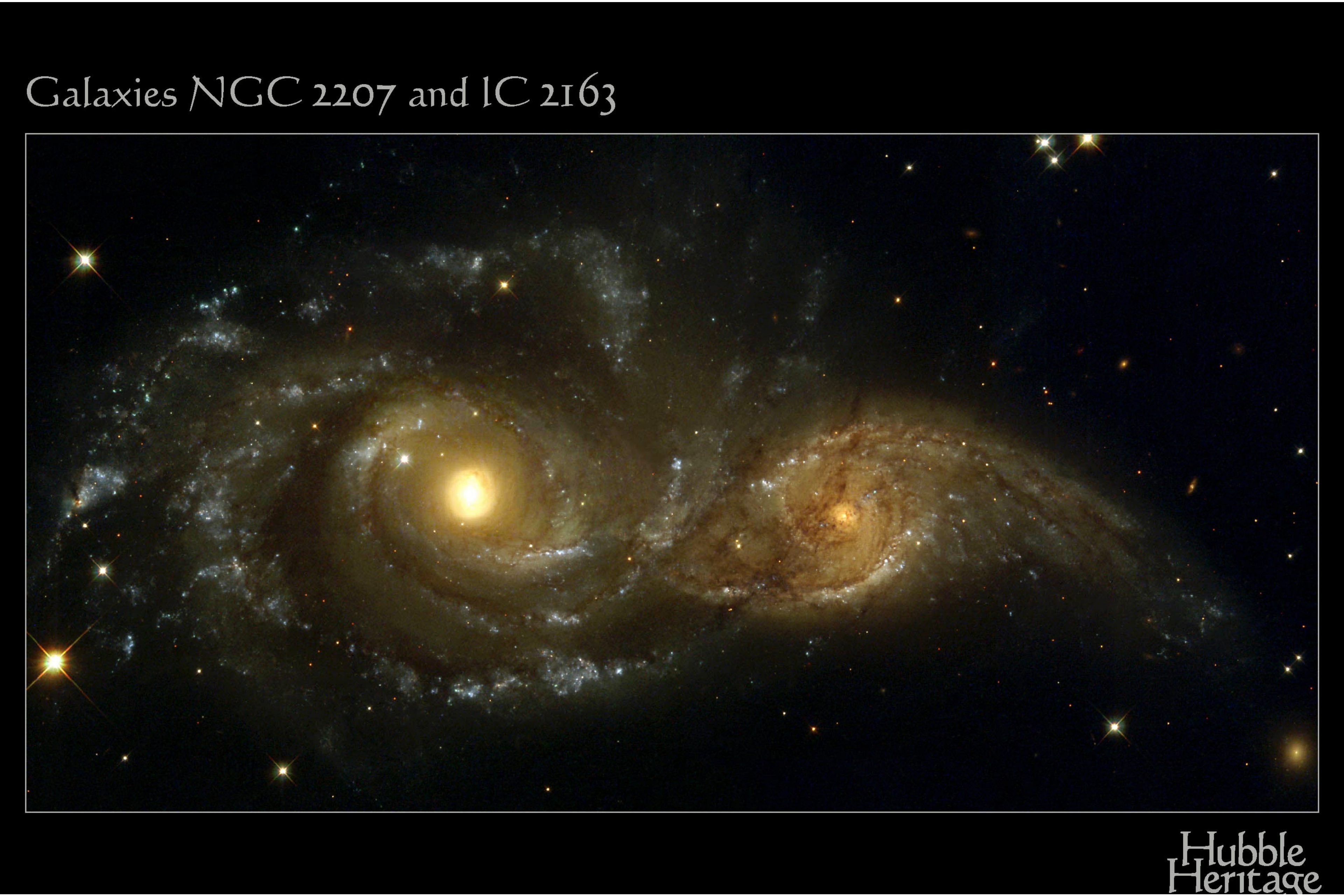
Extreme Mass-Ratio Inspirals: EMRIs

- Stellar-mass BH capture by a massive BH: dozens per year to z~0.7.
- 10^5 orbits very close to horizon. GRACE/GOCE for massive BHs.
  - Prove horizon exists.
  - Test the no-hair theorem to 1
  - Masses of holes to 0.1%
  - Spin of central BH to 0.001.
- Probes environment of central black hole
  - mass and spin spectrum of stellar mass black holes
  - density and mechanism of formation



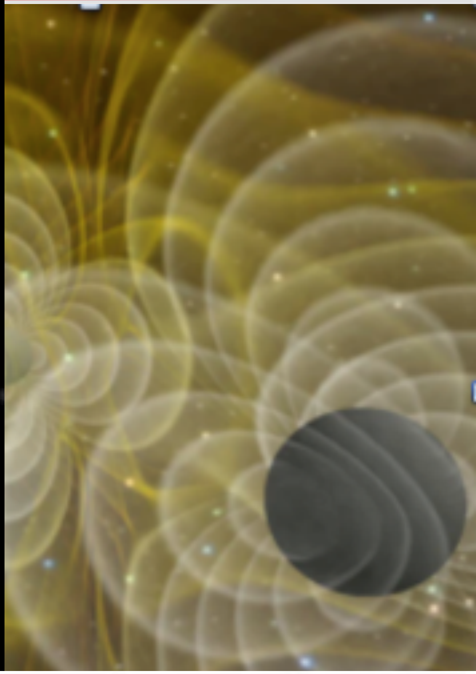


Binaries from galaxy collisions



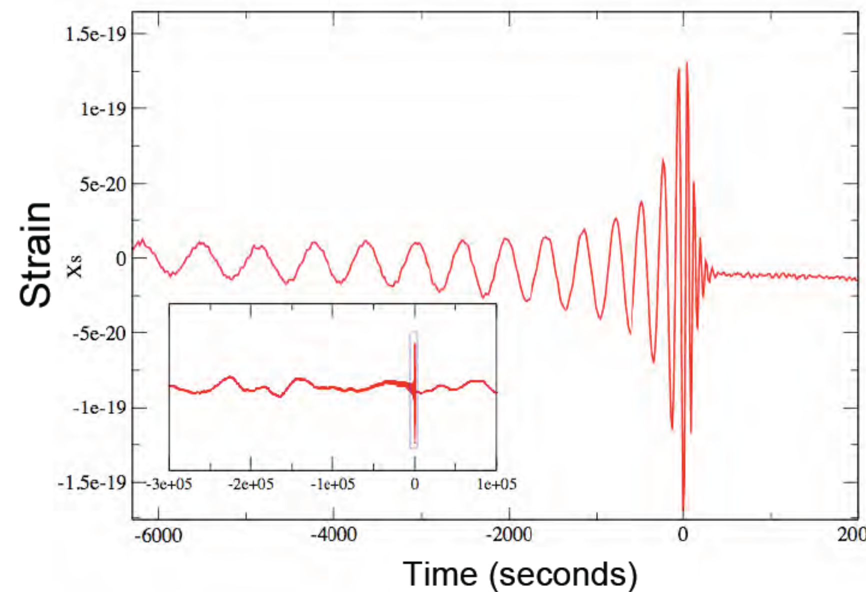
Galaxies NGC 2207 and IC 2163

ers



www.youtube.com/watch?v=PrIk6dKcdoU

Simulated signal for LISA ($10^5 M_\odot$, $z > 5$), no signal processing



Low freq. gw antenna in space: HOW?

LISA Basics:

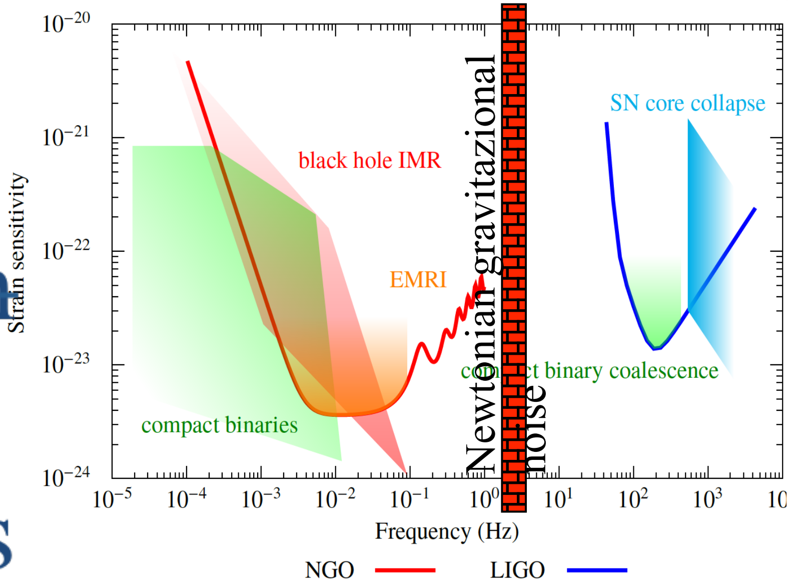
~~1 Redundant configuration~~

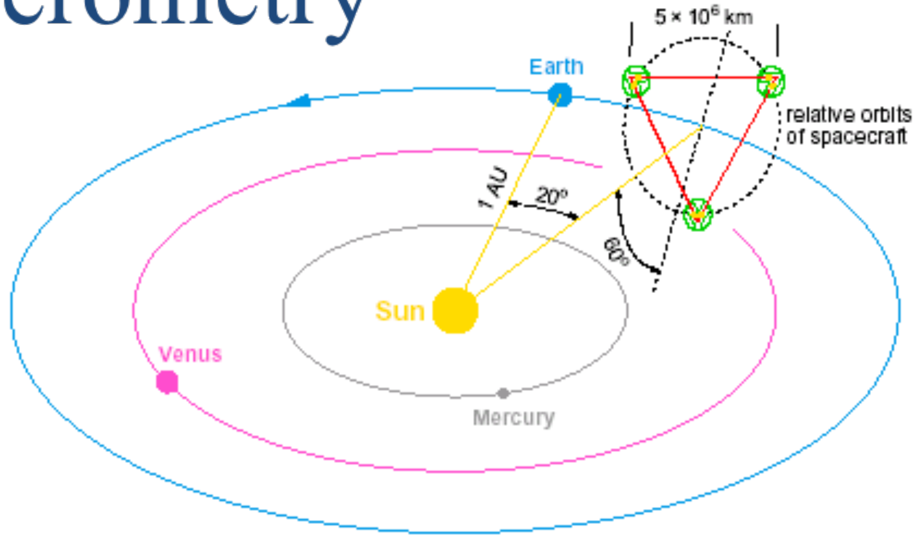
2 Smart Orbits

3 Transponders vs. mirrors

4 Time Delay Interferometry

5 Drag free motion



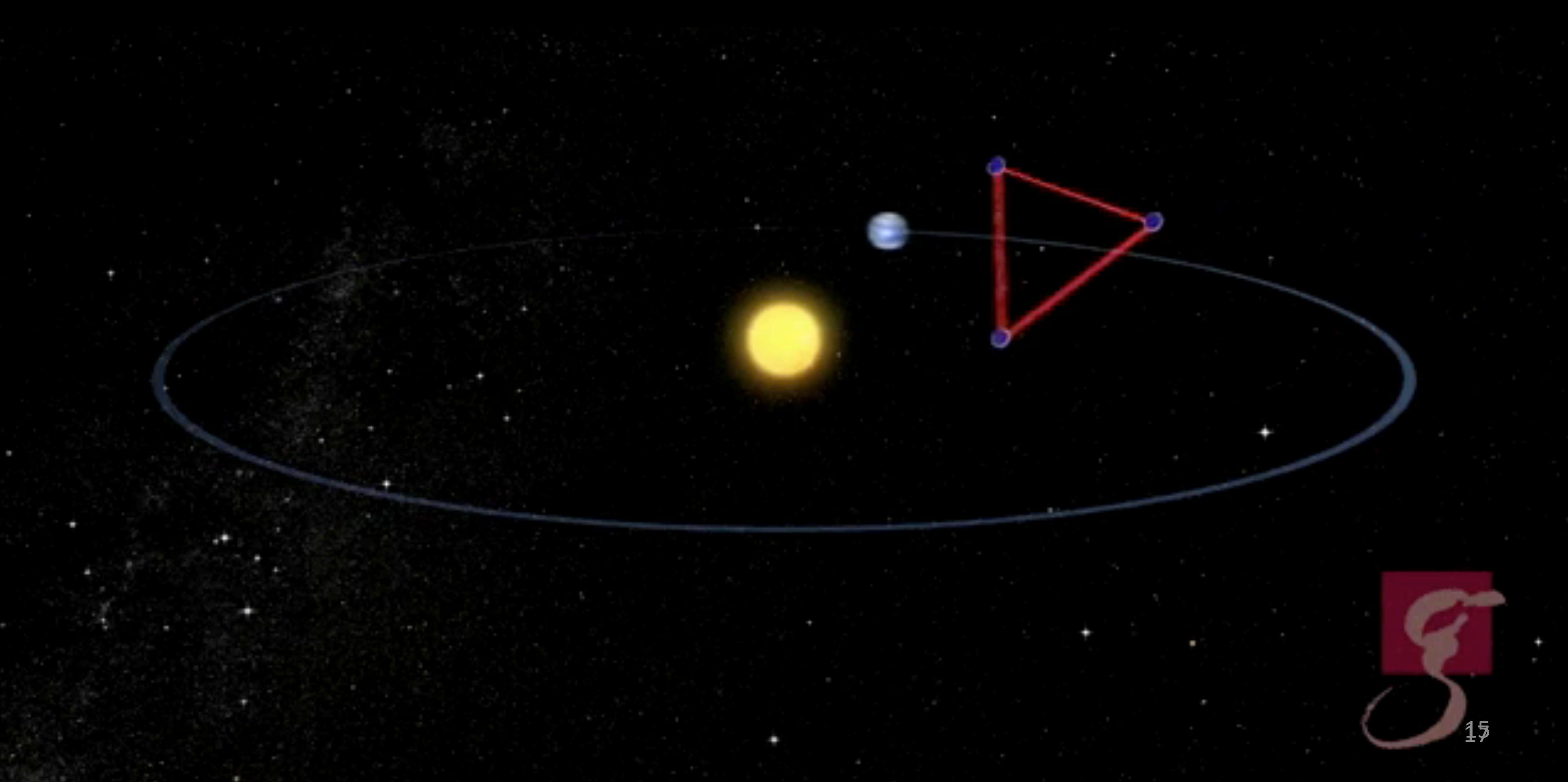


LISA Basic 2 -the smart orbits

3 inclined orbits trailing the Earth; almost rigid triangle configuration.

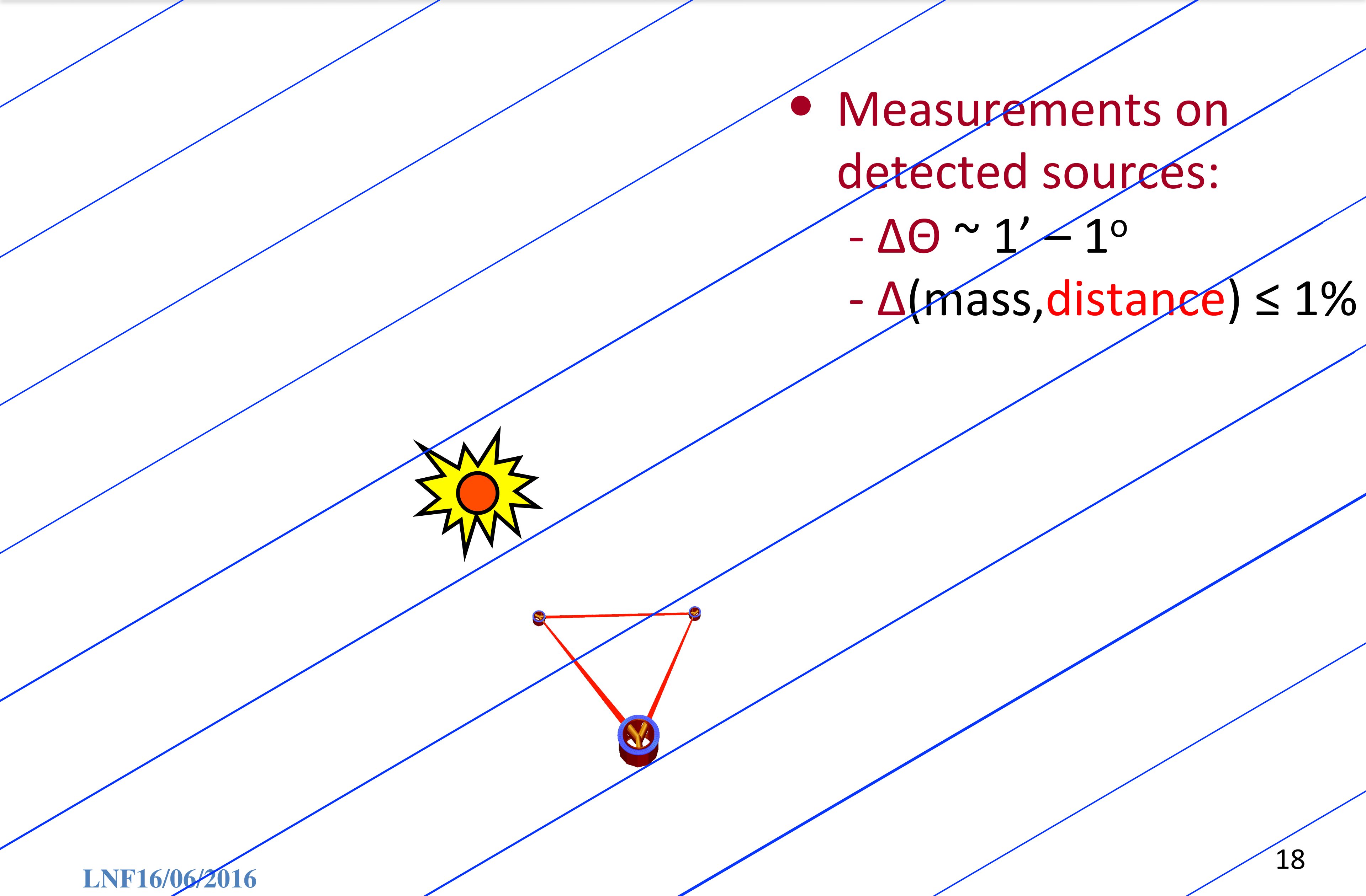
CM at constant distance from Earth.

Constant view of Sun (no thermal effects)

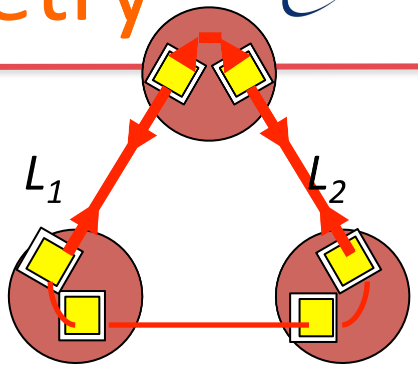


Angular Resolution with LISA

- Measurements on detected sources:
  - ΔΘ ~ 1' – 1°
  - Δ(mass,distance) ≤ 1%

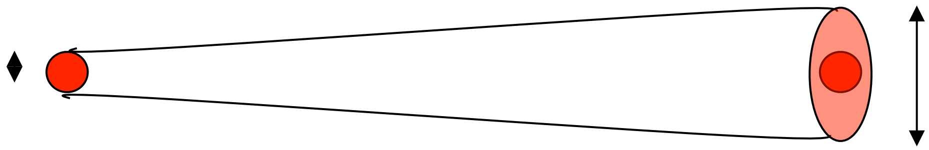


LISA Basic 3 - Interferometry



3 ~ million km arms: 33 sec 2-way light time
(1st interferometry null at 30 mHz)

Laser divergence:



Telescope
D ~ 30 cm

YAG 1.06 μm

Arriving Beam
~20 km

SEND
1 W

RECEIVE
~200 pW (< 100 pW final)

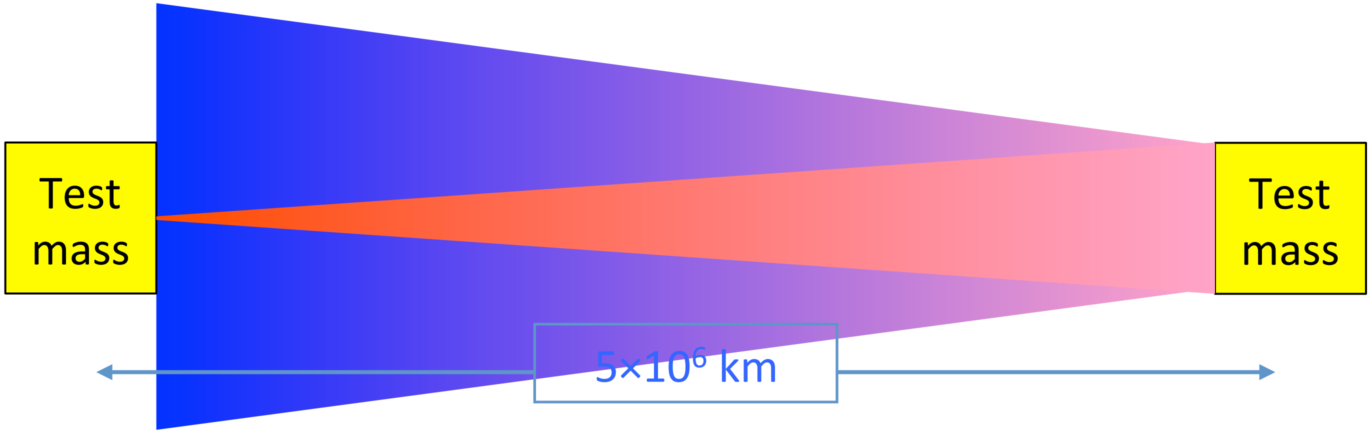
Shot Noise:

$$S_{\delta L}^{1/2} = \sqrt{\frac{\hbar c}{2\pi}\frac{\lambda}{P_{received}}} = \sqrt{\frac{\hbar c}{4\pi}\frac{\lambda}{P_{sent}\eta}\frac{\lambda^2 L^2}{D^4}} \approx 10\ \mathrm{pm/Hz}^{1/2}$$

Laser transponding: outgoing light phase locked to incoming beam

Goal: keep all optical path errors within 40 $\mathrm{pm/Hz}^{1/2}$

LISA Basic 3: the laser transponding scheme



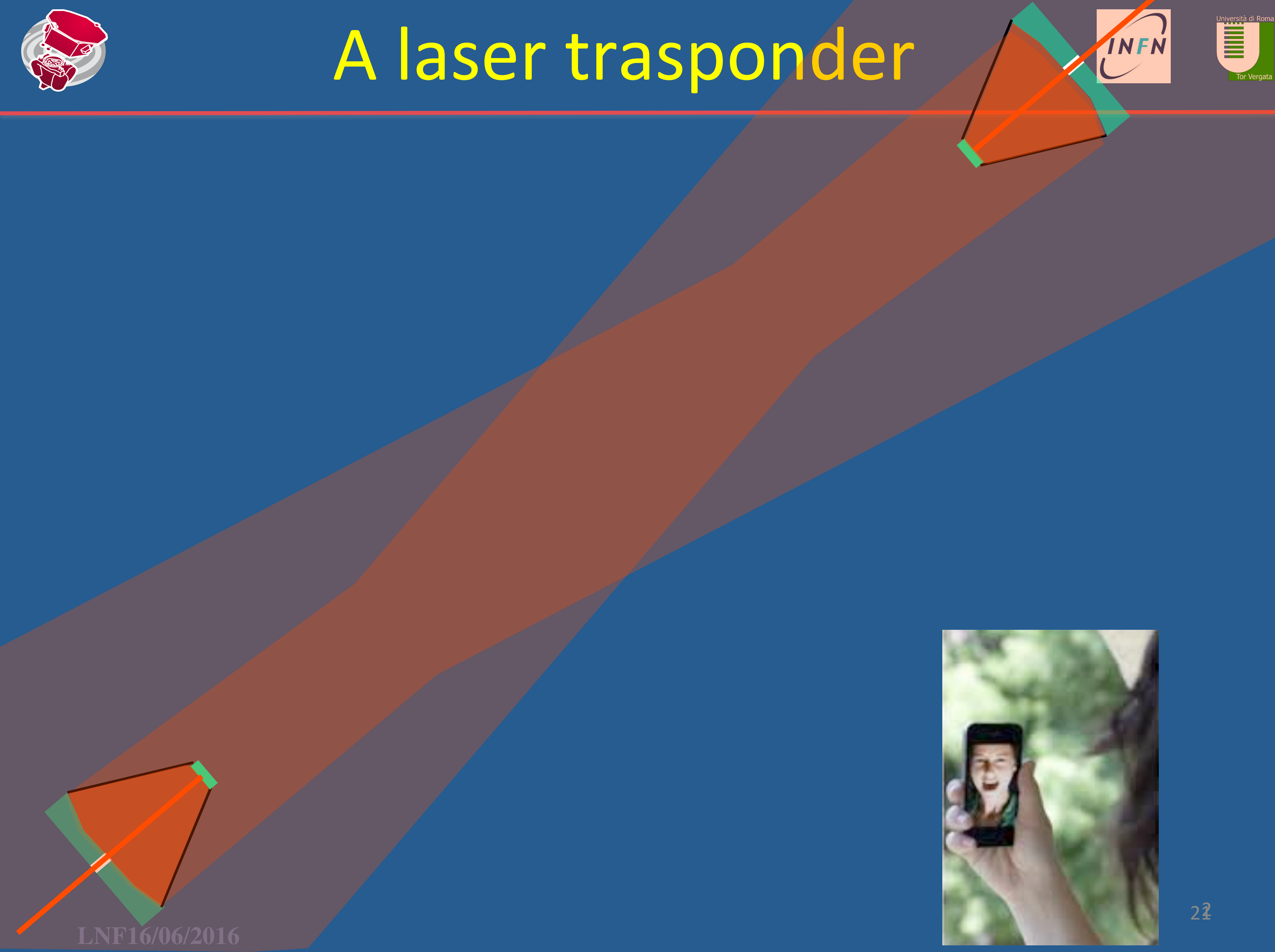
Test mass

Test mass

5×10^6 km

Power loss due to beam divergence makes interferometry by reflection impossible

A laser trasponder

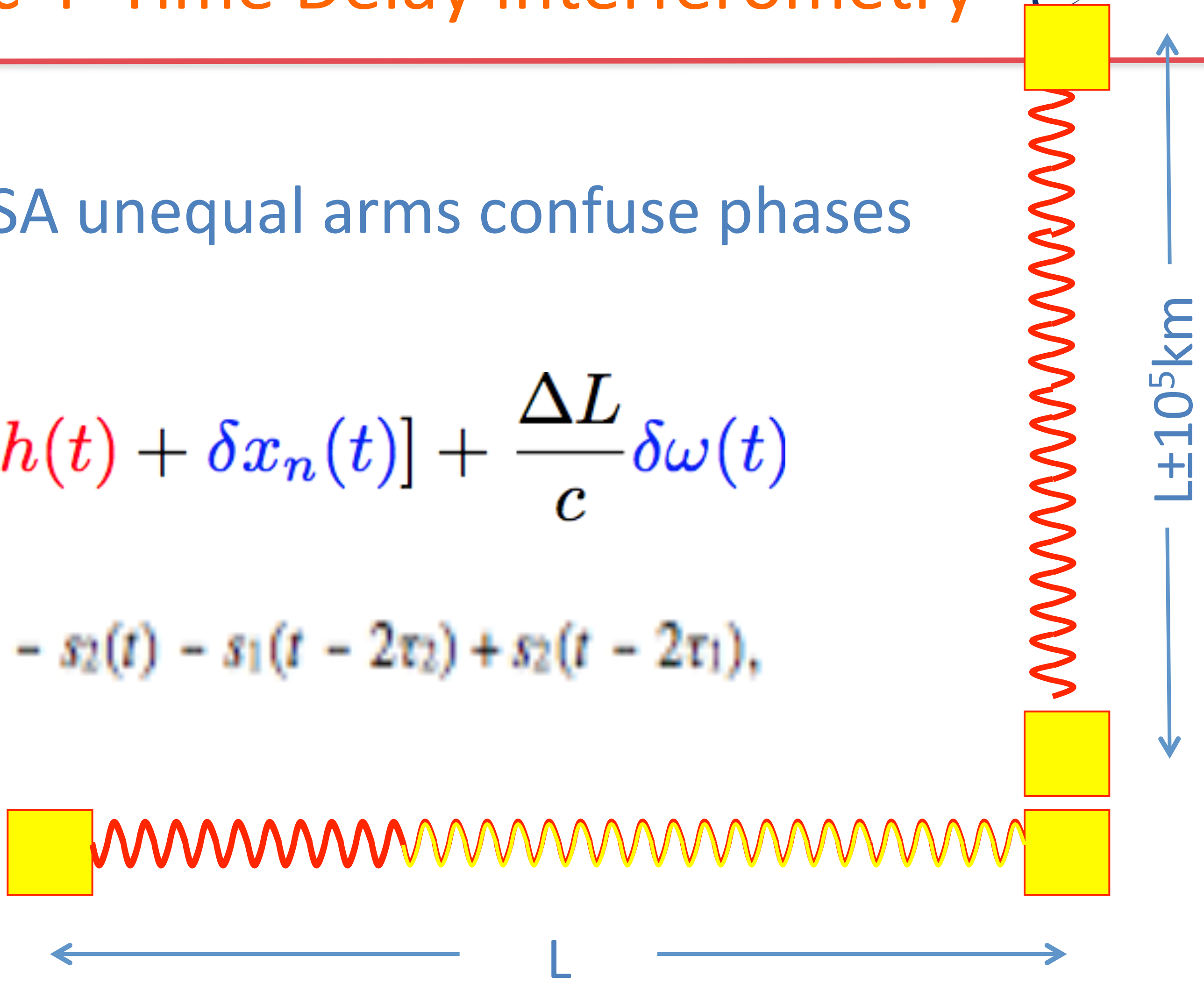


LISA basic 4 Time Delay Interferometry

$\phi(t) = \frac{\omega}{c} X(t)$ LISA unequal arms confuse phases

$$\delta\phi(t) = \frac{\omega}{c}[Lh(t) + \delta x_n(t)] + \frac{\Delta L}{c}\delta\omega(t)$$

$$X(t) = s_1(t) - s_2(t) - s_1(t - 2\tau_2) + s_2(t - 2\tau_1),$$

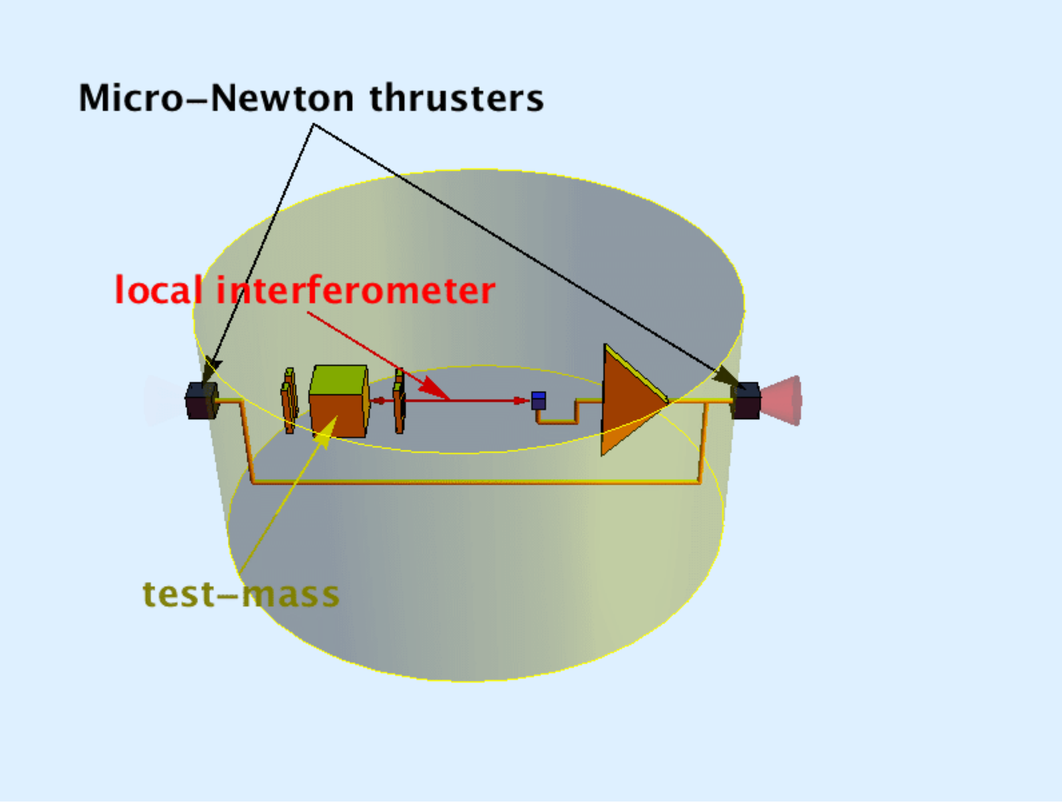


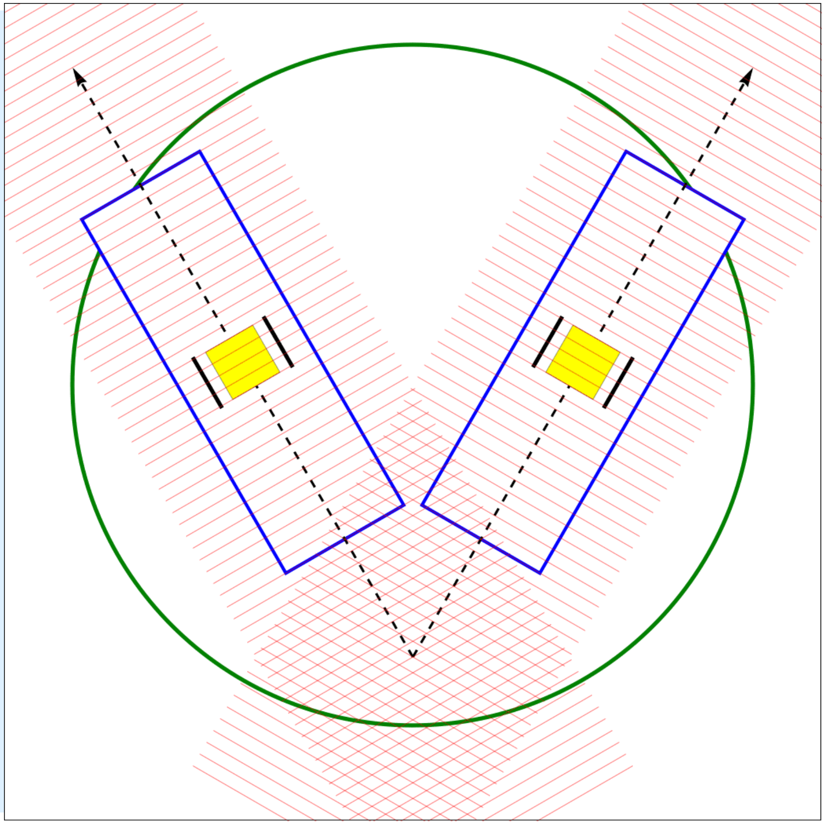
Need to(offline) recombine light emitted at equal times

LISA Basic 5: Drag-free

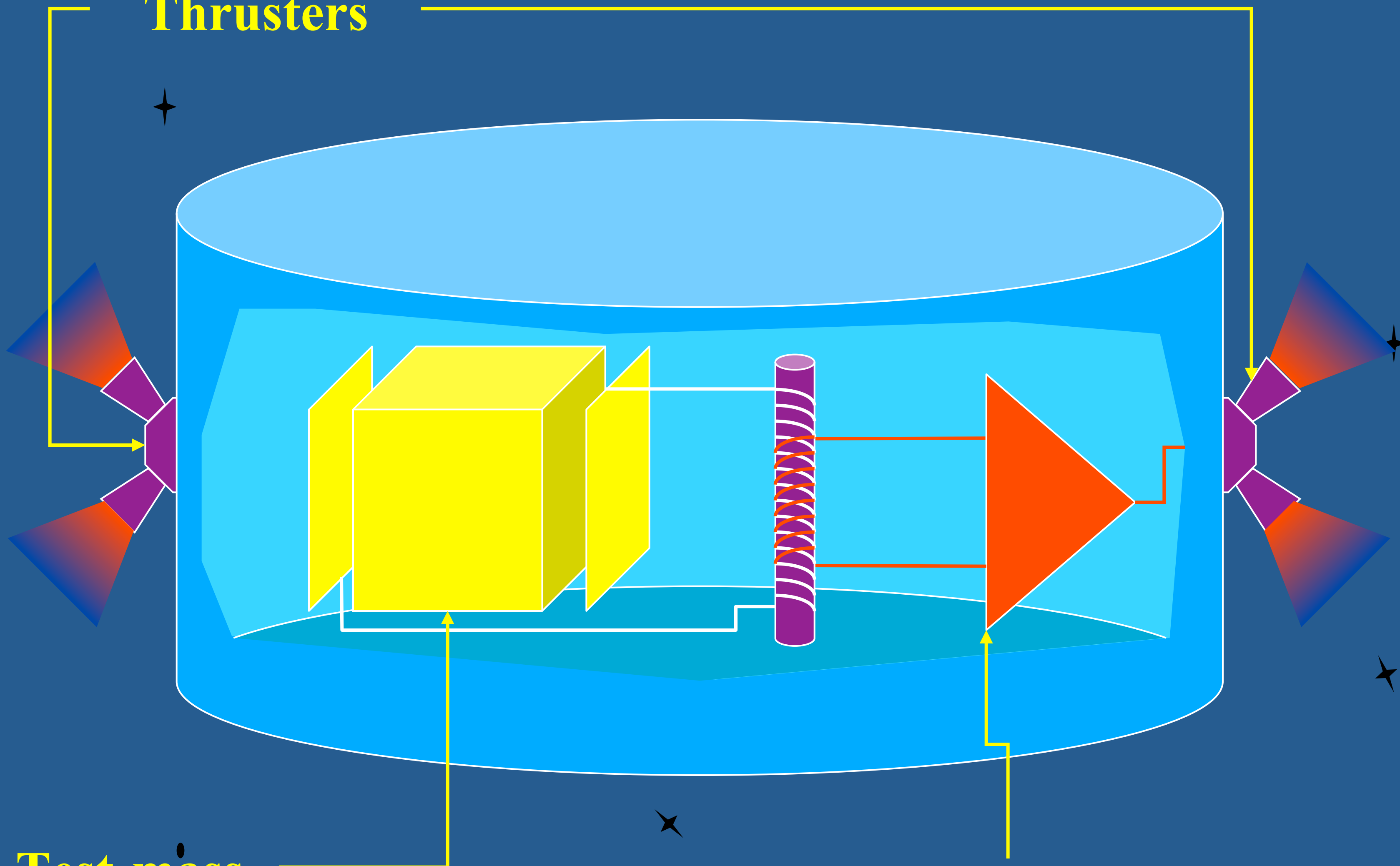
Avoid any contact between S/C and Test Mass

- The local Ifo measures the S/C position w.r.t. the Test Mass.
- Along the Doppler link direction, the S/C is re-centered on the TM using microthrusters.





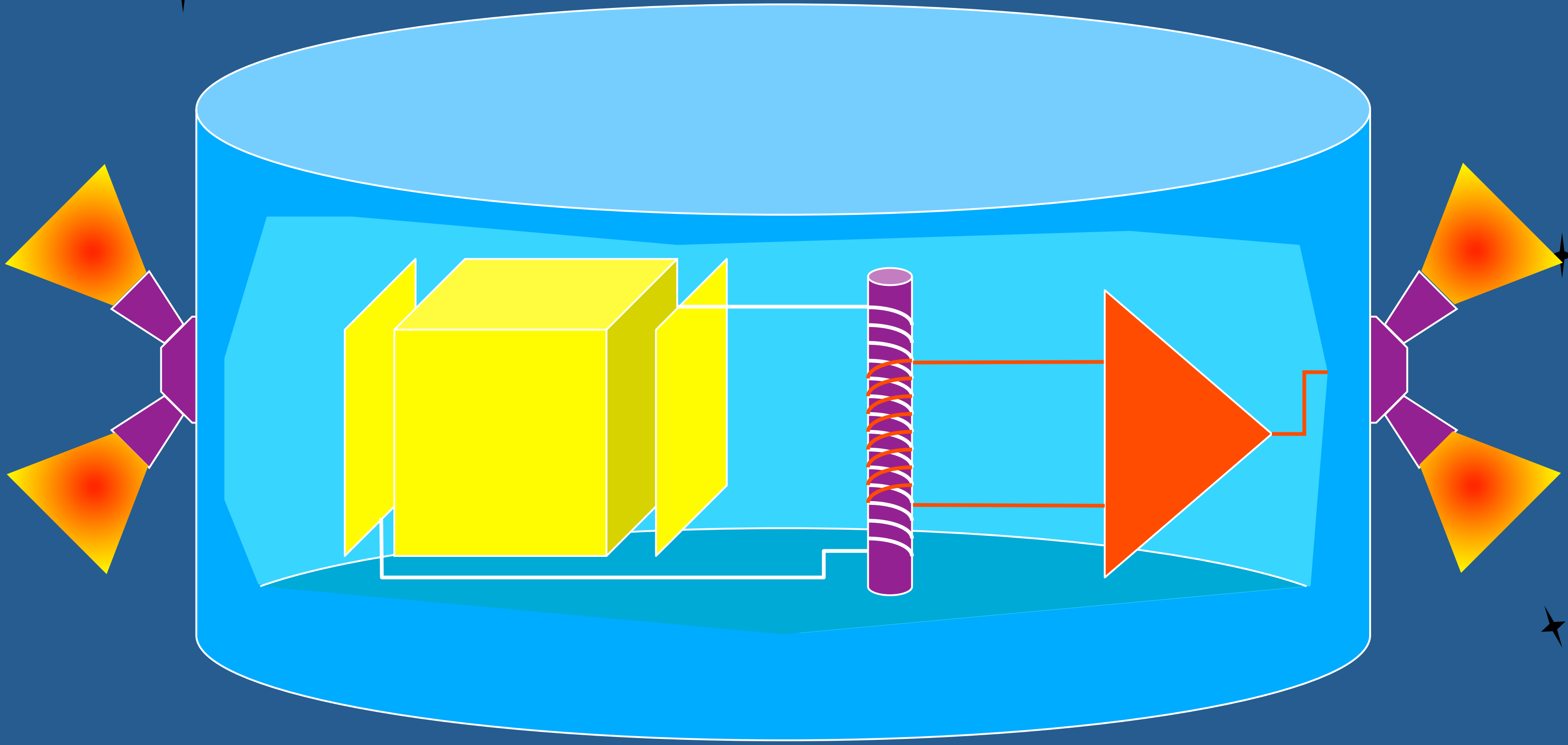
LISA BASIC 5: DRAG-FREE CONTROL LOOP



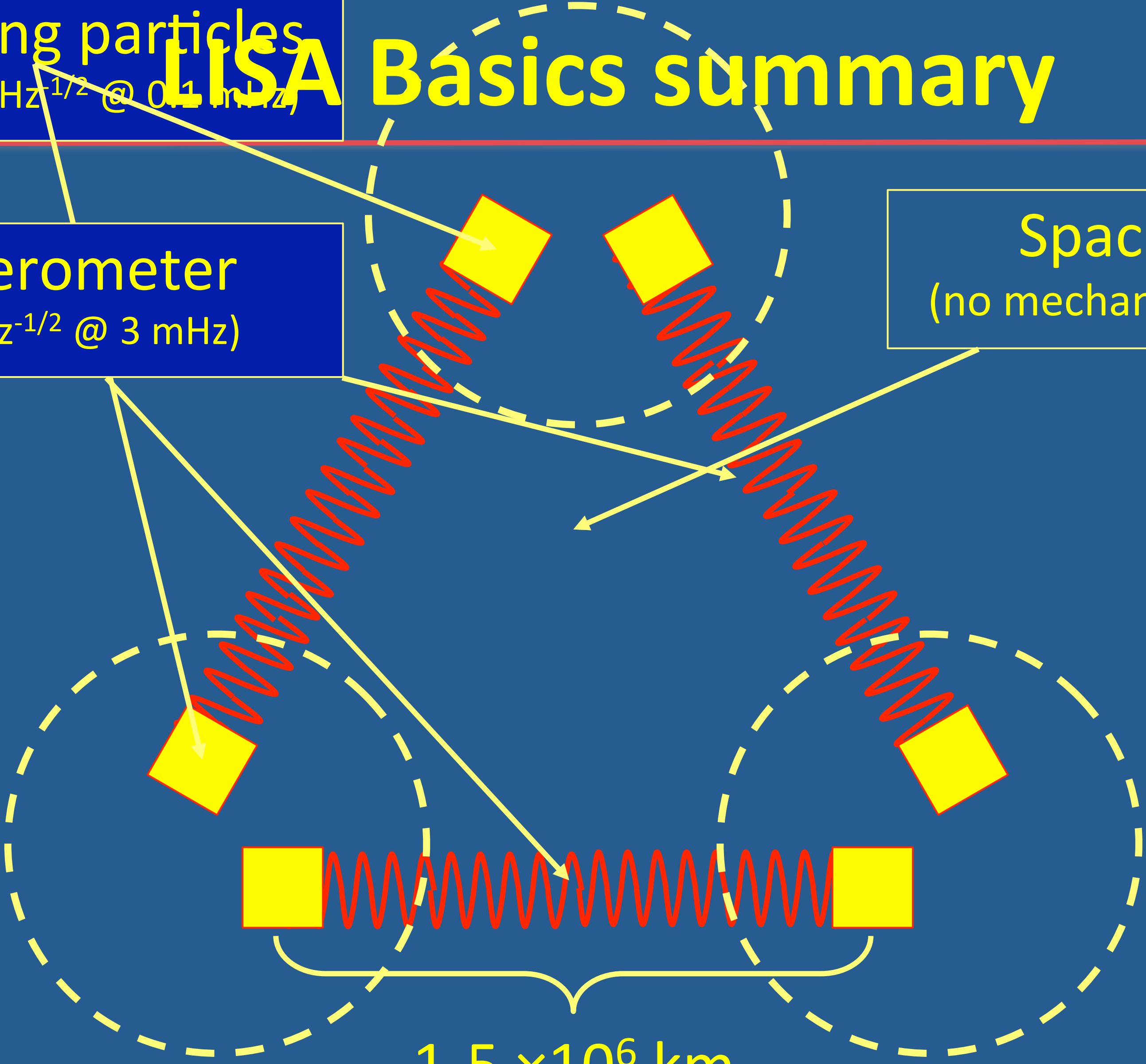
Thrusters

Test-mass

Capacitive motion sensor



LISA Basics summary



Free falling particles
(3 10^{-15} ms^{-2} $Hz^{-1/2}$ @ 0.1 mHz)

Interferometer
(40 pm $Hz^{-1/2}$ @ 3 mHz)

Spacecraft
(no mechanical contact)

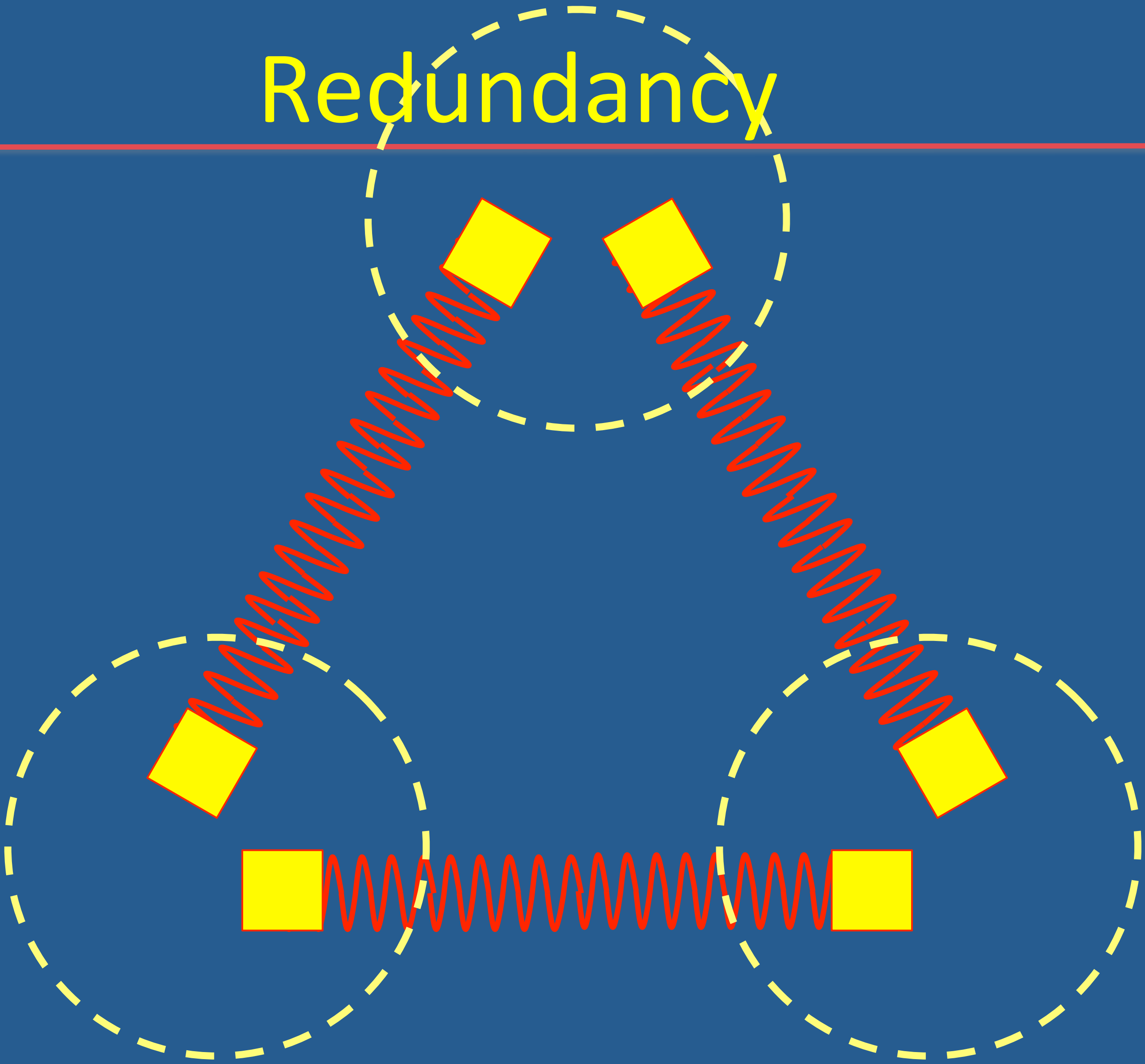
1-5 $\times 10^6$ km

GW at
0.03 mHz – 0.1 Hz

Strain sensitivity

$$h \approx 10^{-20} / \sqrt{\mathrm{Hz}} \quad @ \ 10^{-3}\,\mathrm{Hz}$$

Redundancy



Noise sources for LISA:

Interferometry measures changes in light phase: $\phi(t) = \frac{\omega}{c} X(t)$

$$\delta\phi(t) = \frac{\omega}{c}[L\underset{\uparrow}{h(t)} + \delta \underset{\uparrow}{x_n(t)}] + \frac{\Delta L}{c}\delta\underset{\uparrow}{\omega(t)}$$

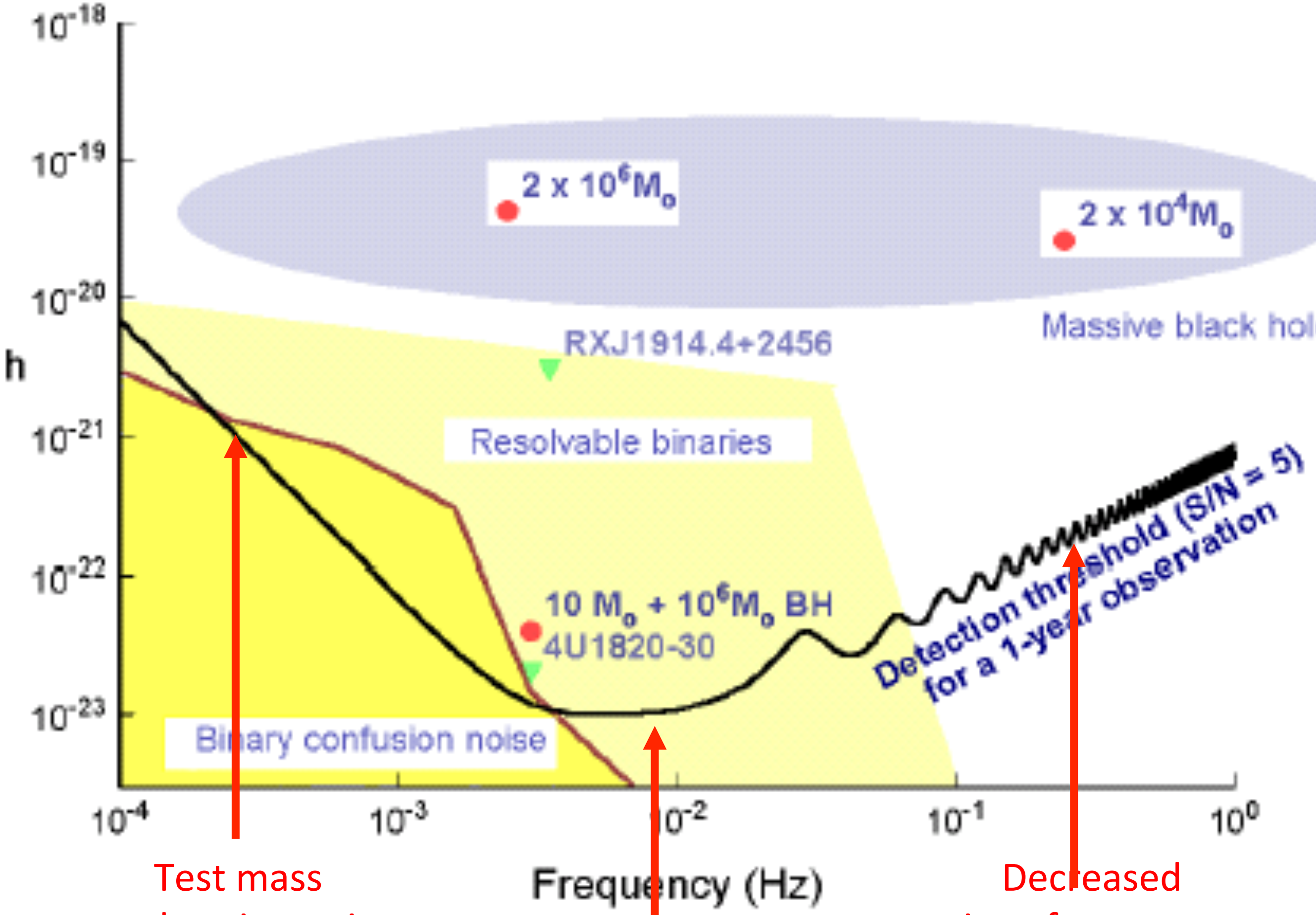
gw displ. noise freq. noise

- Shot noise (20 pW); SNR does not depend on L
- Antenna TF cuts off at high f
- Displacement noise from residual forces:
  - gravity gradients
  - charging (cosmic rays)
  - residual gas
  - thermal fluctuations
  - .....

$$\delta x_n = \frac{F_n}{M\omega^2}$$

- Confusion foreground of galactic binaries gw !

LISA Sensitivity Curve



Test mass
acceleration noise

Photon shot noise

Decreased
interferometer
response

Sensitivity curve for 1 year integration and S/N=5

A bit of history

- Concept first proposed in 1985 (Bender et al)
- 3 s/c configuration stable since 1998 till 2011....then:
- 2011 - NASA pulls out of LISA .

  ESA studies a “rescoping” to try and accomplish a similar mission with half the budget.

  => 9 months of frantic redesigning and the new project (NGO- eLISA) is presented to ESA

- 2012: ESA selects “large” missions: – first (L1, launch 2020) is Juice; second (L2, 2028) is Athena
- Nov 2013: “The gravitational Universe” is the theme of mission L3 – launch 2034.... we have a date !
- Cap cost for ESA: 850 M€ (+200 from member states)

ESA 3rd large class mission

THE GRAVITATIONAL UNIVERSE

A science theme addressed by the *eLISA* mission observing the entire Universe

Prof. Dr. Karsten Danzmann
Albert Einstein Institute Hannover

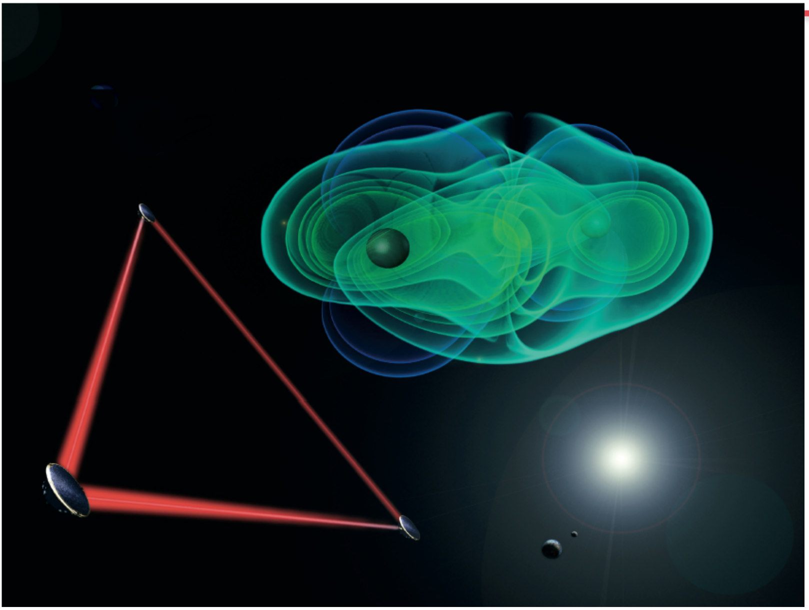
MPI for Gravitational Physics and
Leibniz Universität Hannover
Callinstr. 38
30167 Hannover
Germany

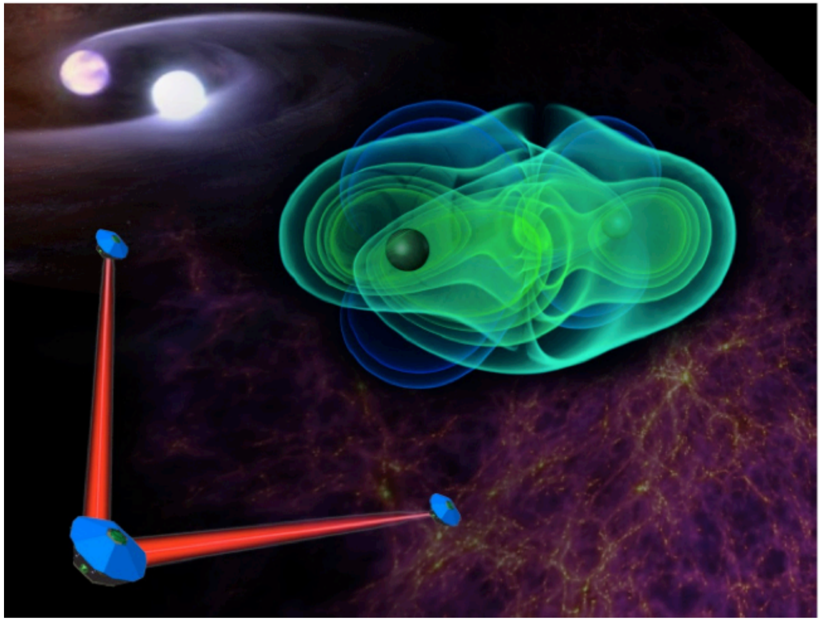
karsten.danzmann@aei.mpg.de

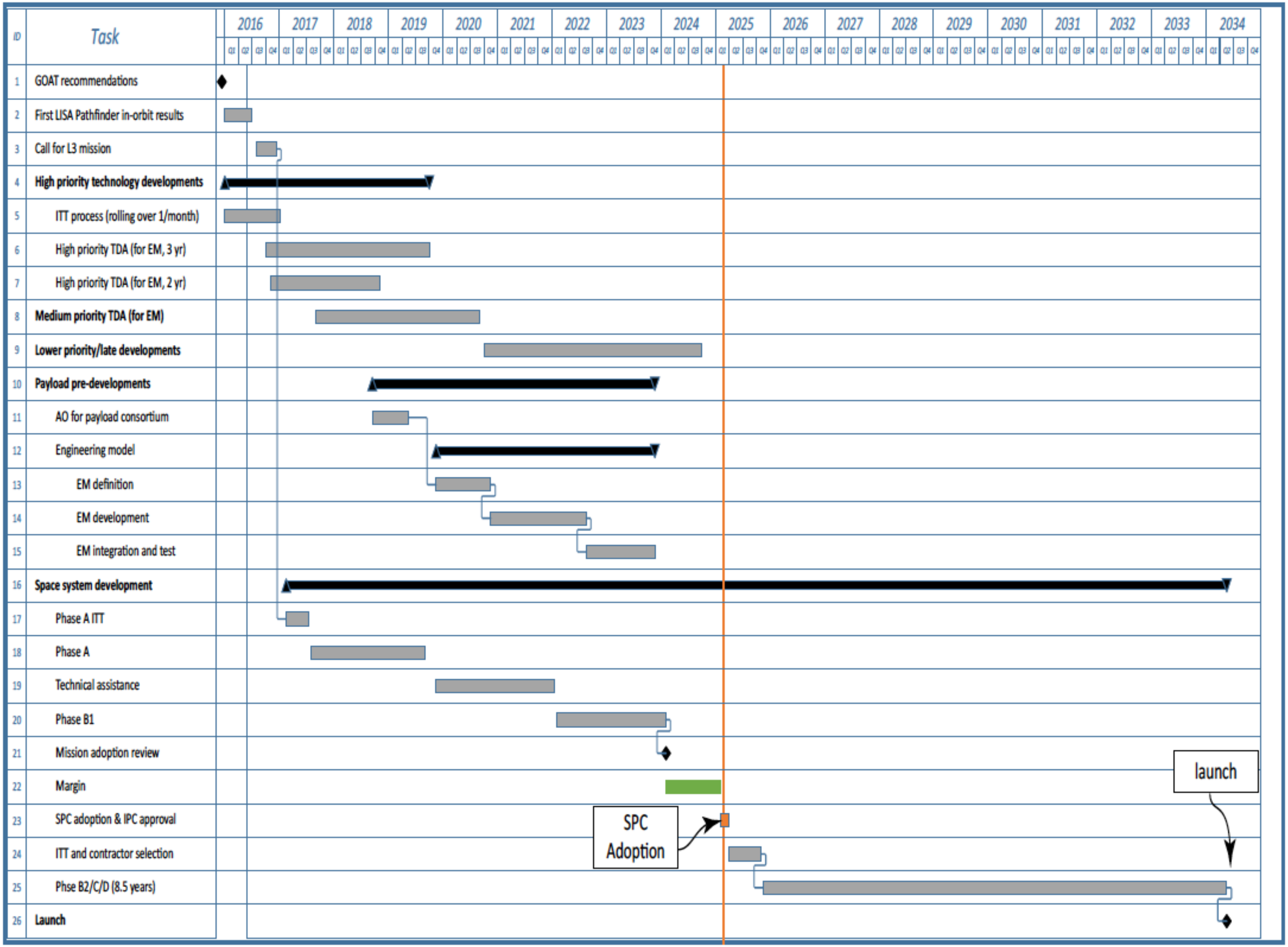
Tel.: +49 511 762 2229
Fax: +49 511 762 2784

Detailed information at
http://elisascience.org/whitepaper

The last century has seen enormous progress in our understanding of the Universe. We know the life cycles of stars, the structure of galaxies, the remnants of the big bang, and have a general understanding of how the Universe evolved. We have come remarkably far using electromagnetic radiation as our tool for observing the Universe. However, gravity is the engine behind many of the processes in the Universe, and much of its action is dark. Opening a gravitational window on the Universe will let us go further than any alternative. Gravity has its own messenger: Gravitational waves, ripples in the fabric of spacetime. They travel essentially undisturbed and let us peer deep into the formation of the first seed black holes, exploring redshifts as large as z ~ 20, prior to the epoch of cosmic re-ionisation. Exquisite and unprecedented measurements of black hole masses and spins will make it possible to trace the history of black holes across all stages of galaxy evolution, and at the same time constrain any deviation from the Kerr metric of General Relativity. eLISA will be the first ever mission to study the entire Universe with gravitational waves. eLISA is an all-sky monitor and will offer a wide view of a dynamic cosmos using gravitational waves as new and unique messengers to unveil The Gravitational Universe. It provides the closest ever view of the early processes at TeV energies, has guaranteed sources in the form of verification binaries in the Milky Way, and can probe the entire Universe, from its smallest scales around singularities and black holes, all the way to cosmological dimensions.



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Q1
Q2
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Q4
1 GOAT recommendations
2 First LISA Pathfinder in-orbit results
3 Call for L3 mission
4 High priority technology developments
5 ITT process (rolling over 1/month)
6 High priority TDA (for EM, 3 yr)
7 High priority TDA (for EM, 2 yr)
8 Medium priority TDA (for EM)
9 Lower priority/late developments
10 Payload pre-developments
11 AO for payload consortium
12 Engineering model
13 EM definition
14 EM development
15 EM integration and test
16 Space system development
17 Phase A ITT
18 Phase A
19 Technical assistance
20 Phase B1
21 Mission adoption review
22 Margin
23 SPC adoption & IPC approval
24 ITT and contractor selection
25 Phse B2/C/D (8.5 years)
26 Launch
SPC Adoption
launch

How is eLISA different (and cheaper) wrt LISA

- Chop arm length from 5 to 1 Gm.
  - Allows to simplify the payload:
    - reduce telescope diam. from 40 cm to 20 cm
    - Reduce laser power from 2 W to 1.4 W
    - S/C formation is more stable and does not need realigning mechanisms.

- 2 interferometer arms rather than 3
- Save 2 instruments out of 6, reducing by 30% complexity and mass.

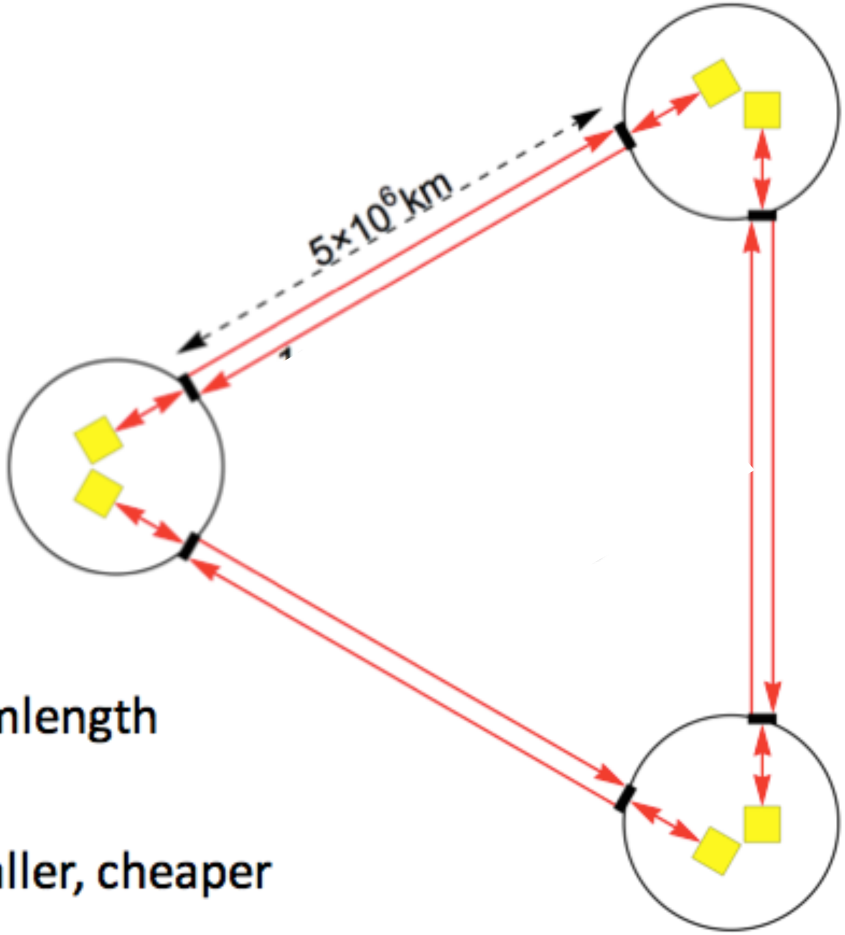
- Operations reduced from 5+5 to 4+2 years
- Allows a “slow drift away” orbit with little Δv
- Reduces the volume of consumables (e.g. μthruster propellent) allowing us to use cold gas thrusters.

From LISA to eLISA / NGO

- Single link IFO noise

  < 10 pm/$\sqrt{\text{Hz}}$ @1 mHz
- Single TM stray acceleration

  < 3 fm/(s$^2\sqrt{\text{Hz}}$) @ 0.1 mHz
- 3 non-contacting ("drag-free") satellites



- *3 arms* → *2 arms*
- *5 Mo km* → *1 Mo km*

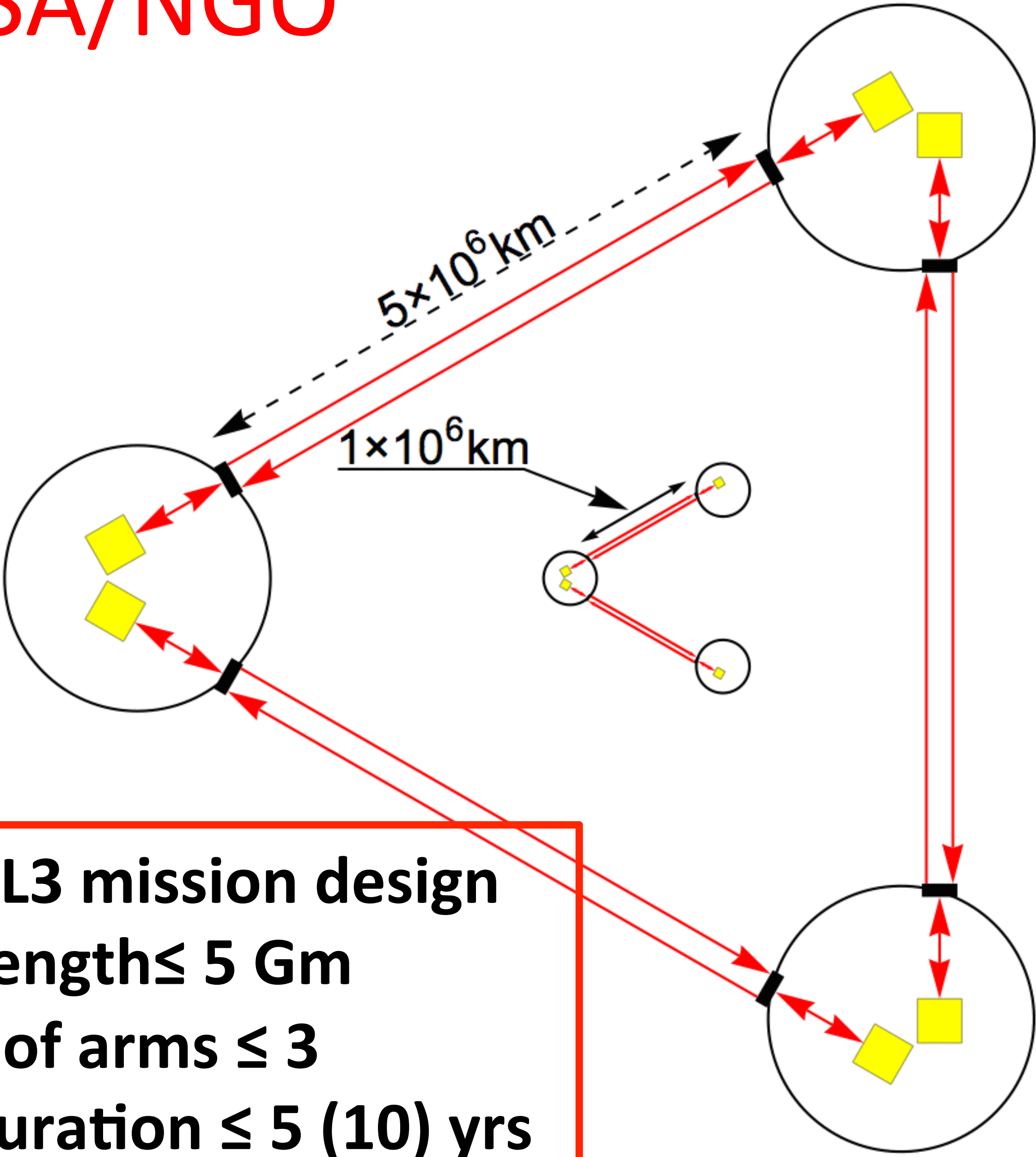
- eLISA design parameter space: 2-3 arms, armlength

- Spectaculare science in reach even with smaller, cheaper NGO design
- 3rd arm gives 2nd and 3rd IFO combinations

→ instantaneous polarization, redundancy / debugging

eLISA/NGO

- *2 arms 1 Gm*
- 10 pm/√Hz single-link interferometry @1 mHz
- Forces (per unit mass) on test-masses < 3 fm/(s²√Hz) @ 0.1 mHz
- 3 non-contacting (“drag-free”) satellites



Parameter space for L3 mission design

- **1 Gm ≤ arm-length≤ 5 Gm**
- **2 ≤ Number of arms ≤ 3**
- **2 (6)yrs ≤ Mission duration ≤ 5 (10) yrs**

https://www.elisascience.org/

Can we trust the free fall on LISA ?

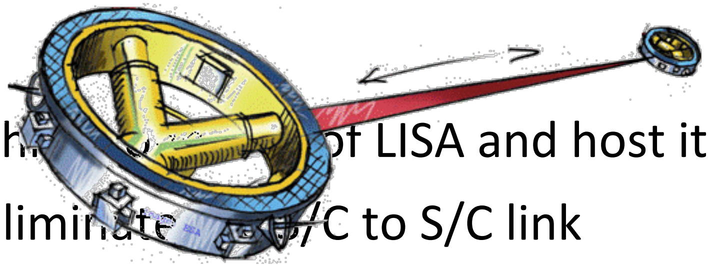
- Can we align an interferometer in space ?

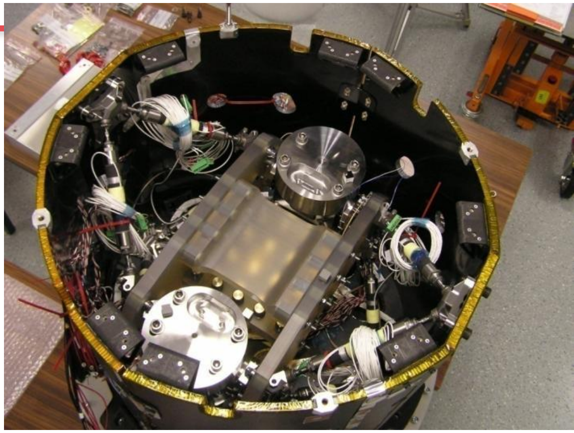
- How good is the free fall we can achieve ?

- How relevant are the spurious forces acting on the Test Mass ?

1. Dedicated technology mission: LISA Pathfinder
2. Extensive test on ground with Torsion Pendulums

The concept of LISA Pathfinder

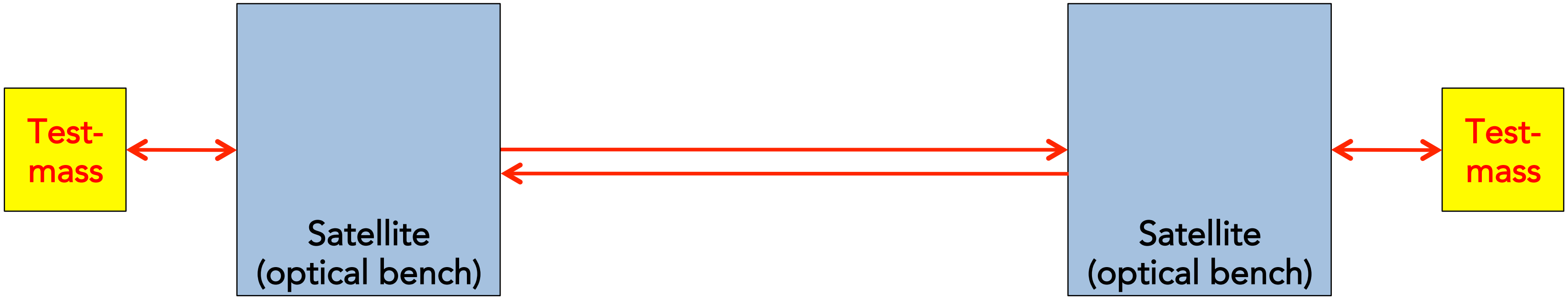


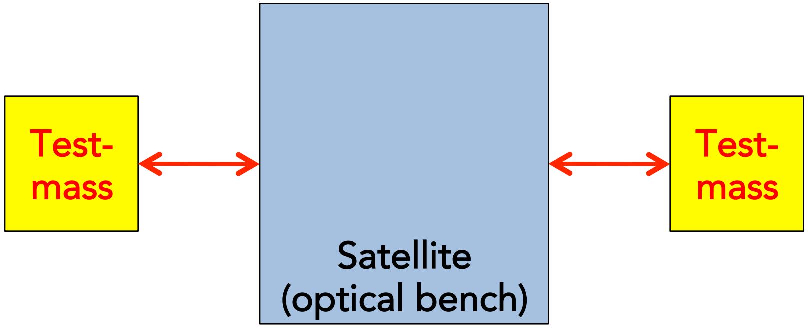


Sh[illegible] of LISA and host it aboard one S/C

Eliminate [illegible] S/C to S/C link

keep the local measurement between Test Masses and S/C

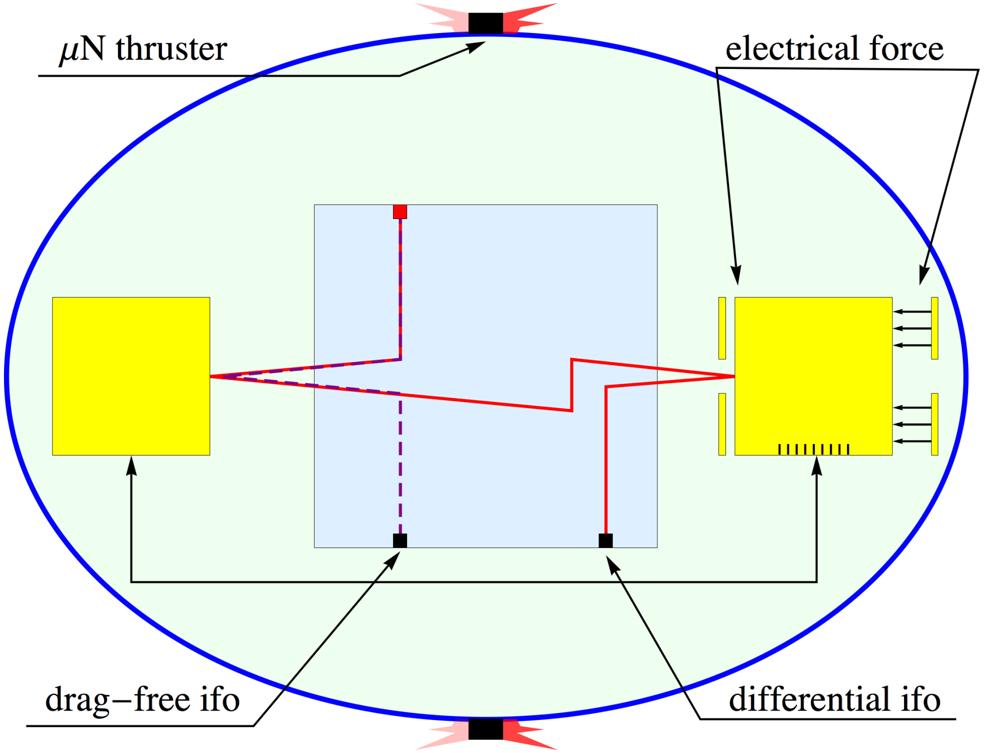




LISA Pathfinder concept (2)

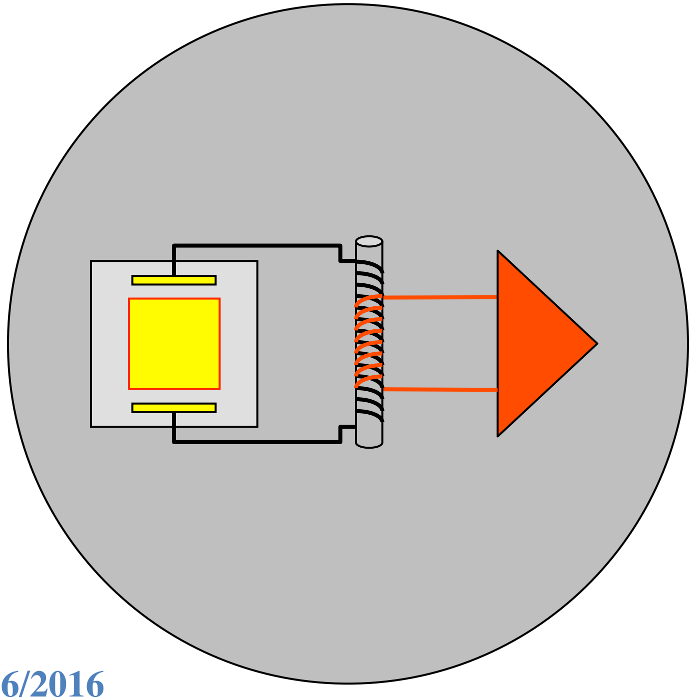
Test of 95% of noise does not need milion km separation

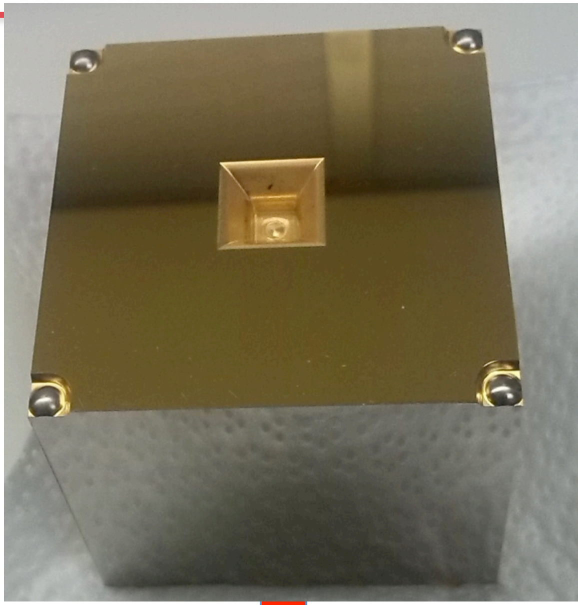
- »Requires free-falling test-masses inside a single spacecraft
- »LPF 2 TMs, 2 Ifos, Satellite chases one test-mass
- »Second test-mass forced to follow the first at very low frequency by electrostatics (different from LISA)



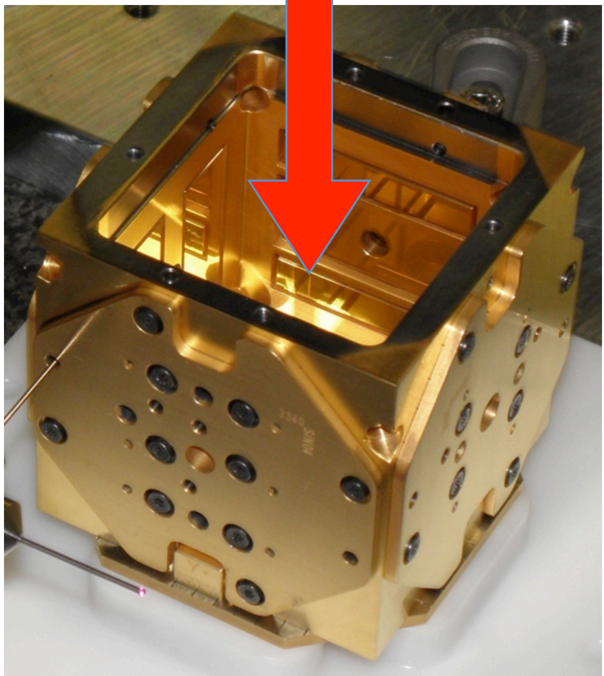
The Gravitational Reference Sensor

- Drag-free along sensitive direction
- Other test-mass degrees of freedom controlled via electrostatic forces
- 3-4 mm clearance between test-mass and electrodes





test-mass



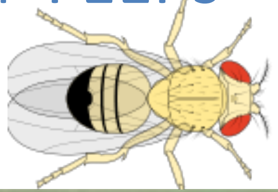
electrode housing

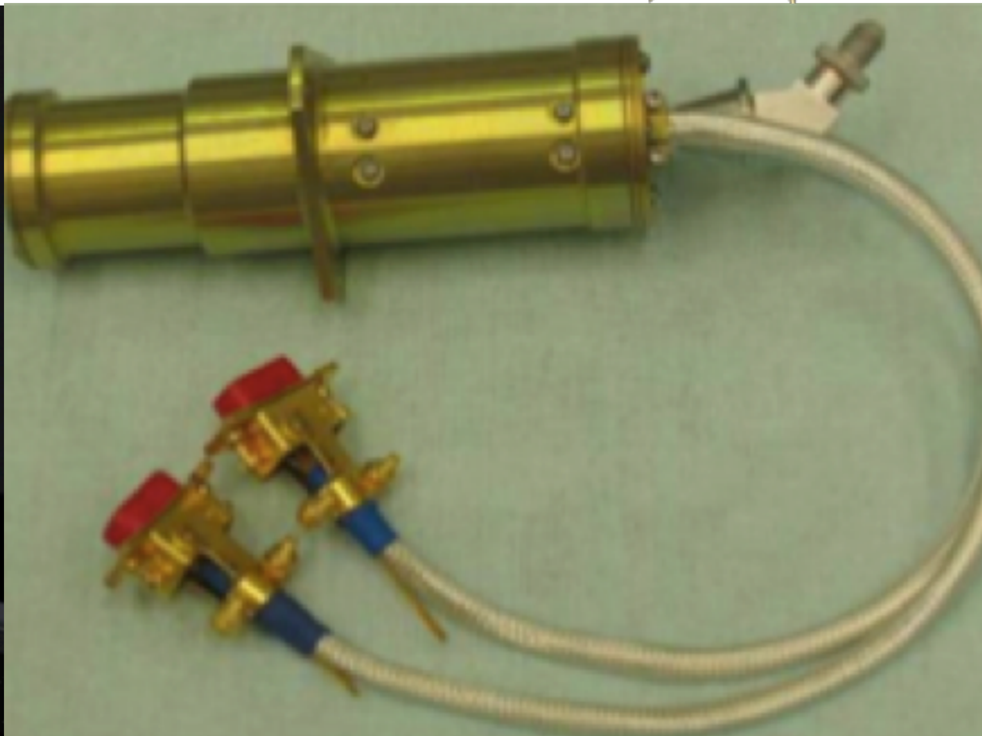
Microthrusters

The S/C is continuosly recentered on the Test Mass by microthrusters.

Cold gas thrusters (heritage of GAIA) have replaced FEEPs

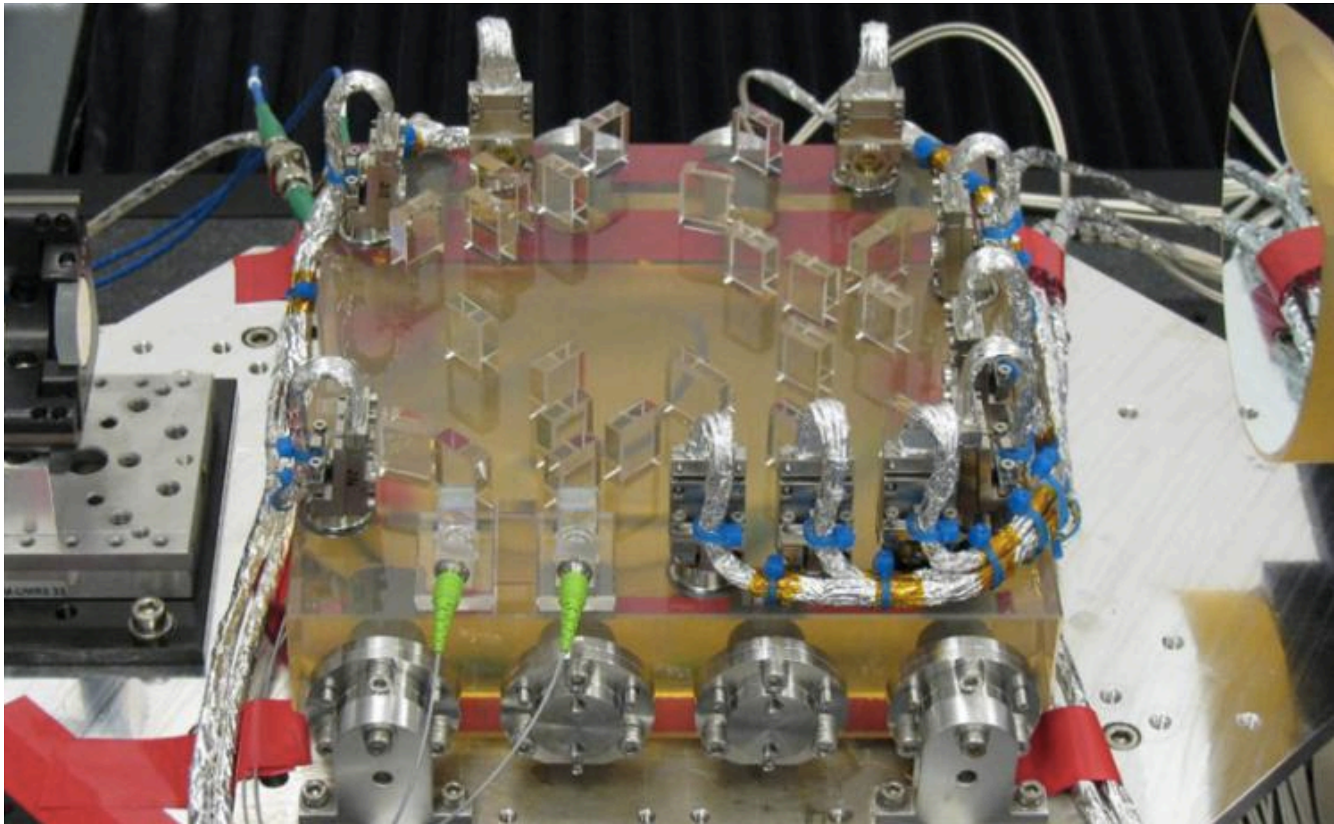
They can deliver thrust w/ resolution of 0.1 μN



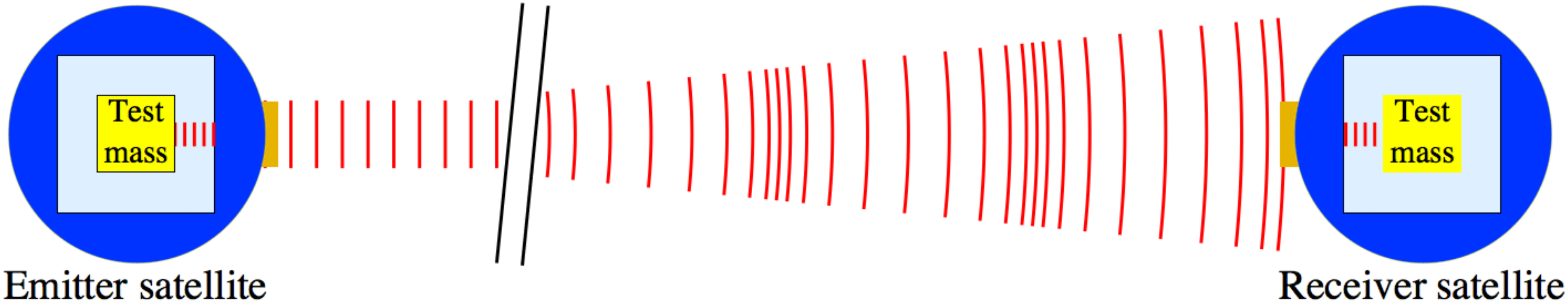


The optical bench

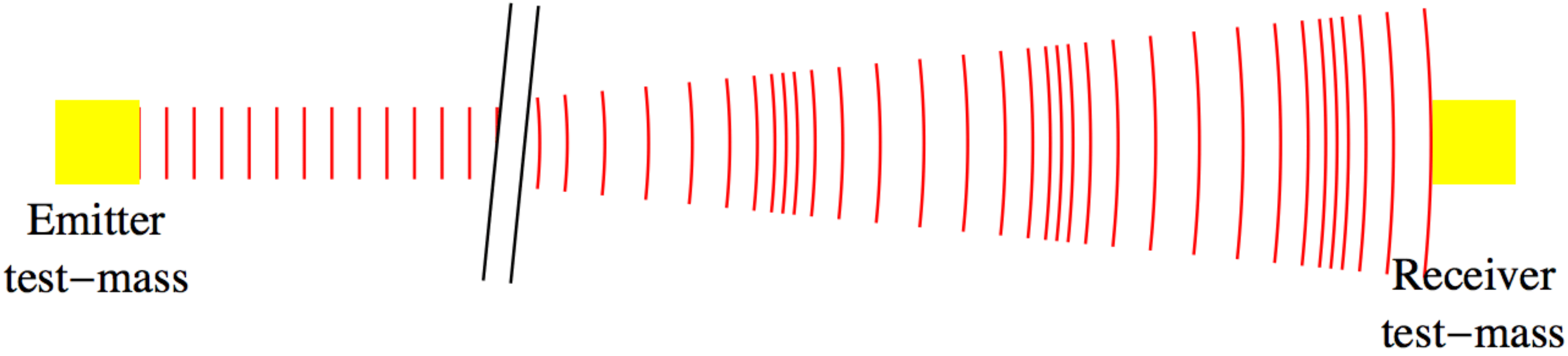
- Monolithic assembly, via silica bonding (hydroxide-catalyst) of mirrors and beam splitters
- Carries all interferometry: both local (in LPF) and between S/Cs (in eLISA).



The eLISA link: a time delayed differential accelerometer

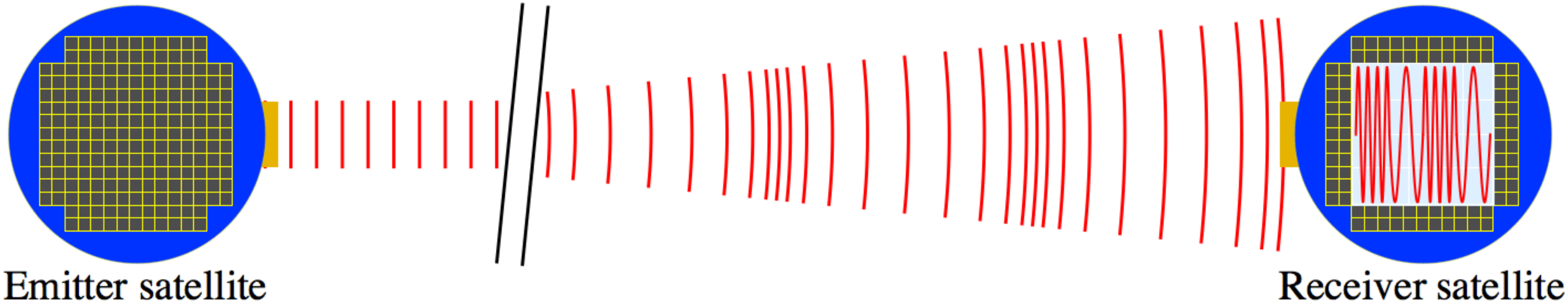


» Inertial reference test-masses are used to correct for satellite acceleration



» Equivalent to directly tracking test-masses

The LISA link



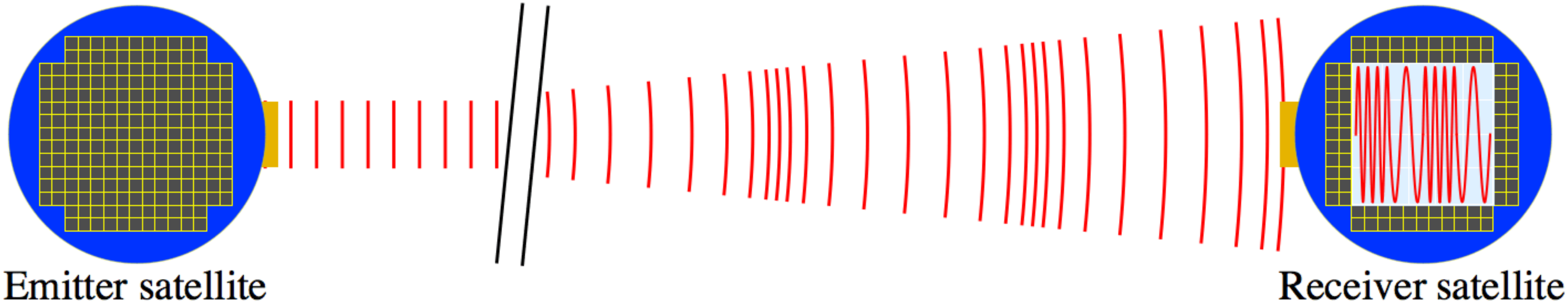
- GW curvature modulates the frequency of the received beam

$$\frac{d\nu_{\mathrm{rec.}}}{dt_r} - \frac{d\nu_{\mathrm{em.}}}{dt_e} = -\frac{c^2}{2\pi}\int_{\mathrm{beam}} k^\sigma u^\nu R^\rho_{\ \nu\sigma 0} k_\rho \, d\lambda = \nu_o \left\{\dot{h}_{\mathrm{receiver}}(t) - \dot{h}_{\mathrm{emitter}}(t - L/c)\right\}$$

PHYSICAL REVIEW D **88,** 082003 (2013)

Space-borne gravitational-wave detectors as time-delayed differential dynamometers

The eLISA link: a time delayed differential accelerometer



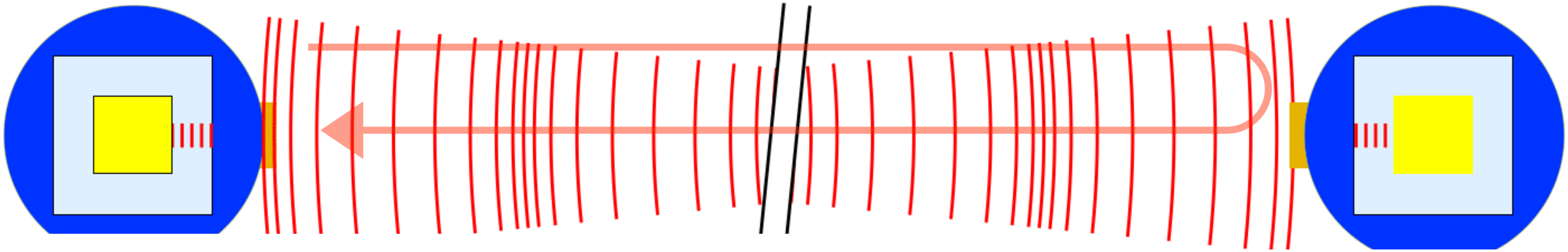
- Accelerations of satellites, *relative to their local inertial frame,* modulate frequency as curvature does.

$$\left(c/\nu_o\right)\left(\dot{v}_{\text{receiver}} - \dot{v}_{\text{emitter}}\right) = c\left\{\dot{h}_{\text{receiver}}\left(t\right) - \dot{h}_{\text{emitter}}\left(t - L/c\right)\right\} +$$
$$+ a_{\text{receiver}}\left(t\right) - a_{\text{emitter}}\left(t - L/c\right)$$

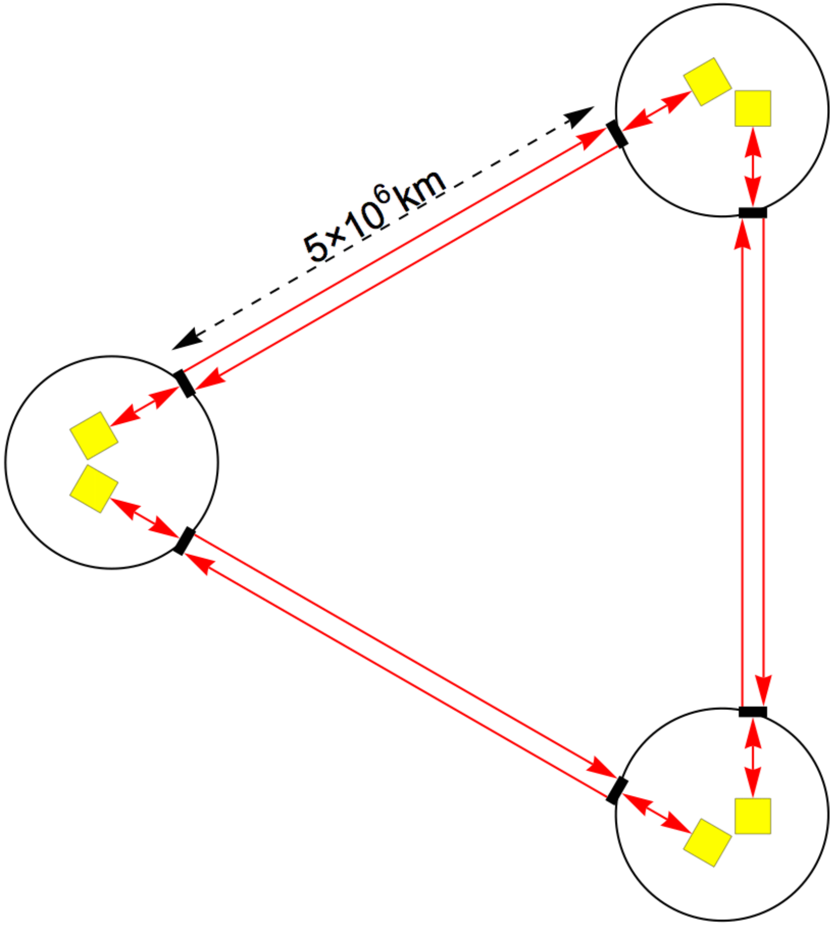
PHYSICAL REVIEW D **88,** 082003 (2013)

Space-borne gravitational-wave detectors as time-delayed differential dynamometers

The detector arm (eLISA)



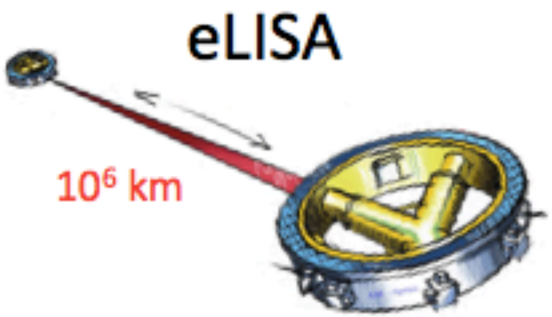
- Two counter-propagating, phase-locked links
- LISA: 3 arms 5 Mo km
- 10 pm/√Hz single-link interferometry @1 mHz
- Forces (per unit mass) on test-masses < 3 fm/(s^2√Hz) @ 0.1 mHz
- 3 non-contacting ("drag-free") satellites



G.W. measurement as diff. accelerometry

Physical observable: tidal acceleration between 2 distant test masses

Measurement technique: time varying Doppler shift in light exchanged between TM



$S_h^{1/2} \approx 10^{-18}\ /\ \mathrm{Hz}^{1/2}$ (1 mHz)

$$\frac{\dot\nu_r - \dot\nu_e}{\nu} = \overbrace{\frac{\left[\dot h(t) - \dot h(t - L/c)\right]}{2}}^{\text{Gravitational wave tidal acceleration}} + \underbrace{\frac{g_r(t) - g_e(t - L/c)}{c}}_{\text{Differential force per unit mass}}$$

IFO doppler signal

$S_{\Delta f/f}^{1/2} \approx 10^{-21}\ /\ \mathrm{Hz}^{1/2}$ (1 mHz)

$S_{\Delta g}^{1/2} \approx 5\ \mathrm{fm/s}^2/\mathrm{Hz}^{1/2}$ (1 mHz)

The LPF Experiment

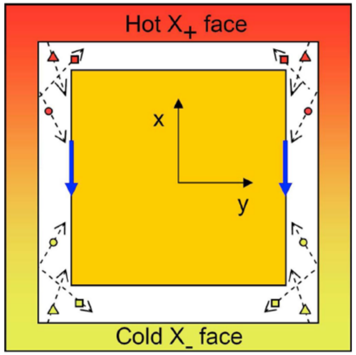
- An experimental, self-consistent verification of the physical model for geodesic motion.
- A repeat of ground campaign at higher accuracy, with real bulk and free floating TM's on orbit
- Composed by a sequence of investigations dedicated to:
  - Quantitatively assess the dominating components of the residual acceleration noise
  - Assess their parametric dependence on measurement conditions and compare with predictions
  - Measure critical physical parameters and compare with models
  - Return an upper limit on non-modeled parasitic forces for eLISA or LISA

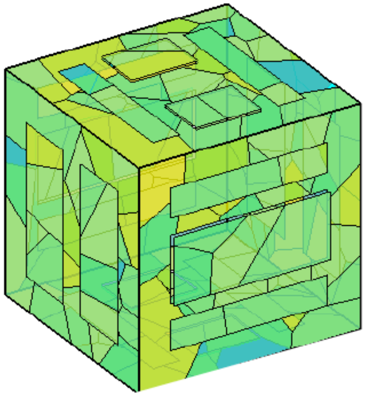
The great conspiracy against free-fall

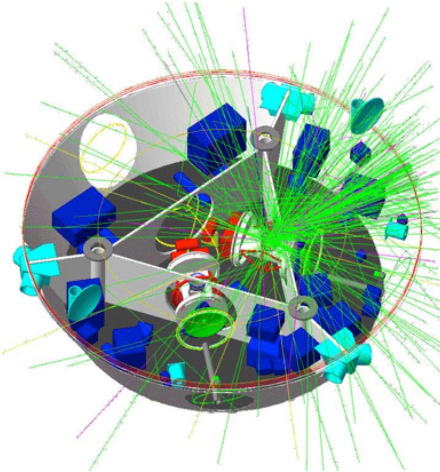
- Many subtle physical effects apply unwanted forces to test-bodies
  - Impact with the few molecules that still surround the bodies in high vacuum
  - Spontaneous electric fields generated by surrounding bodies
  - Fluctuating electrical charge from cosmic rays
  - Changing gravitation generated by thermal deformation of satellite
  - Impact with wandering photons
  - Fluctuations of the interplanetary magnetic field

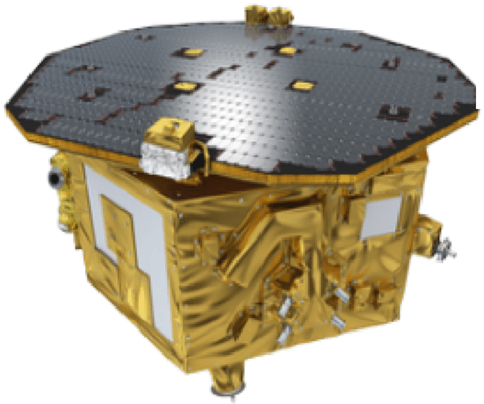
…………

PHYSICAL REVIEW D 76, 102003 (2007)







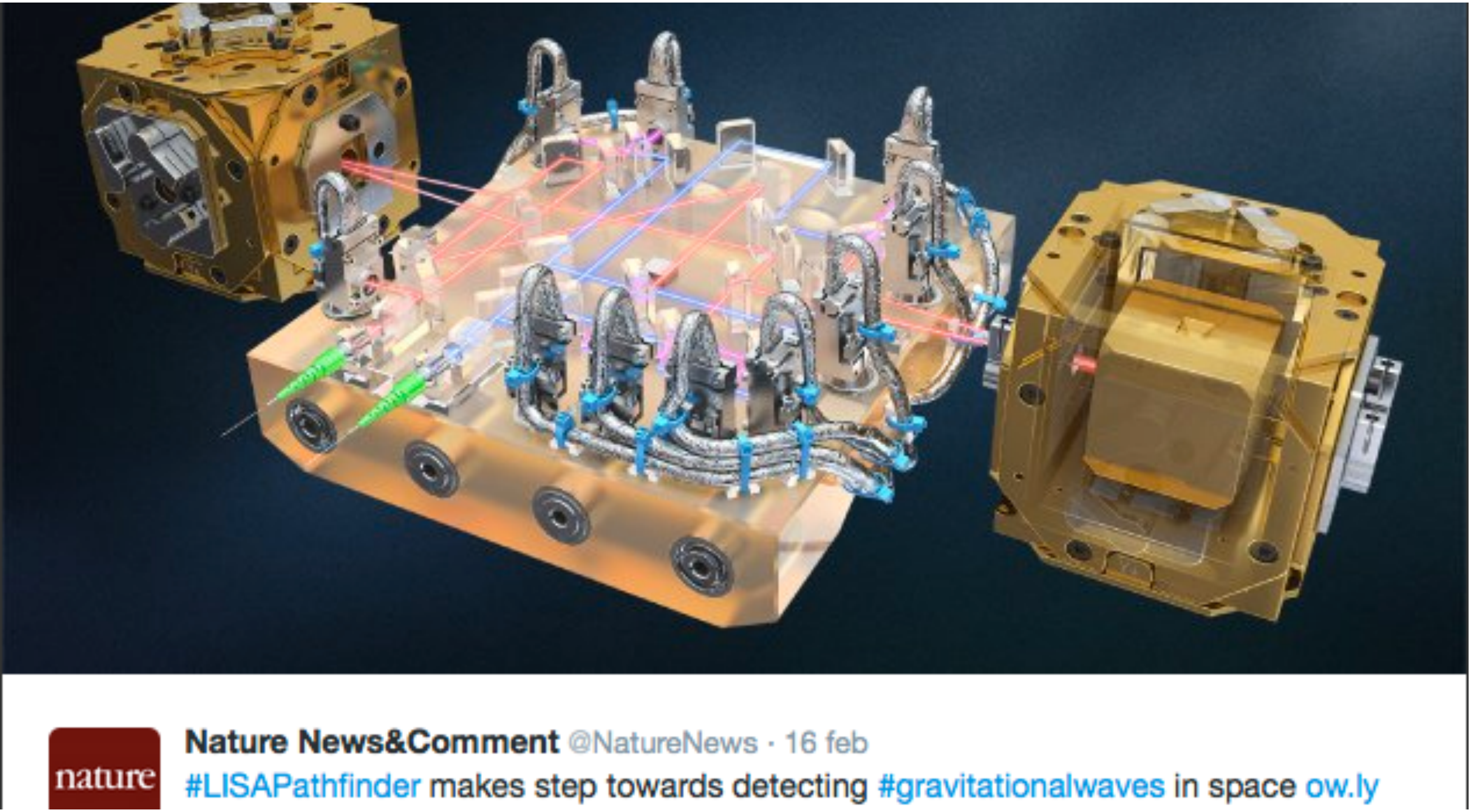


A great first year-phyisics lab

Some of the spurious residual forces that can spoil free fall:

- Non inertial frames and fictitious force
- Electrostatics – forces in capacitors
- Cosmic ray charging
- Thermal conduction
- Magnetic susceptibility
- Gravitational gradients
- Radiation pressure
- . . . .

2 TM and 2 Interferometers



Nature News&Comment @NatureNews · 16 feb

#LISAPathfinder makes step towards detecting #gravitationalwaves in space ow.ly

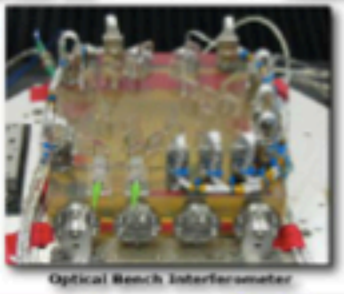
LPF Interferometer metrology

$< 9\ \mathrm{pm/Hz}^{1/2}$

- First high-precision interferometer coupled to free-falling TM in space
- Demonstration of eLISA local position measurement
- Zerodur optical bench with 4 heterodyne interferometers

Reference Laser Unit

Phasemeter



Optical Bench Interferometer

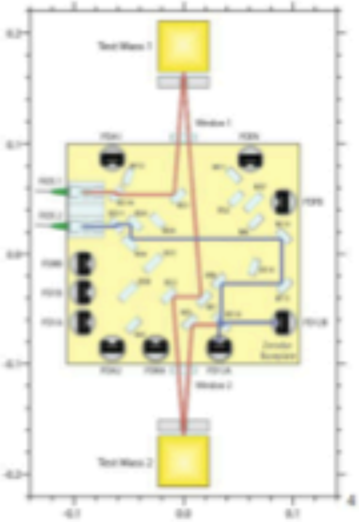
Laser Modulator

Data Management Unit

o_{12} $(x_2 - x_1)$

TM - TM

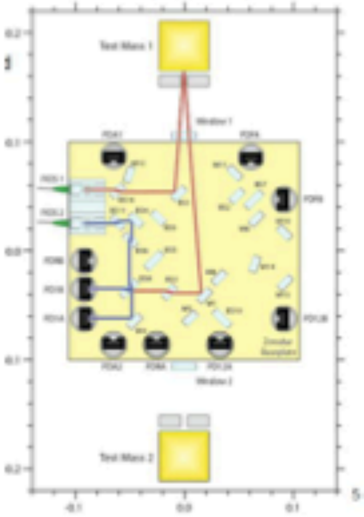
$+\phi_1, \eta_1$



o_1 $(x_1 - x_{SC})$

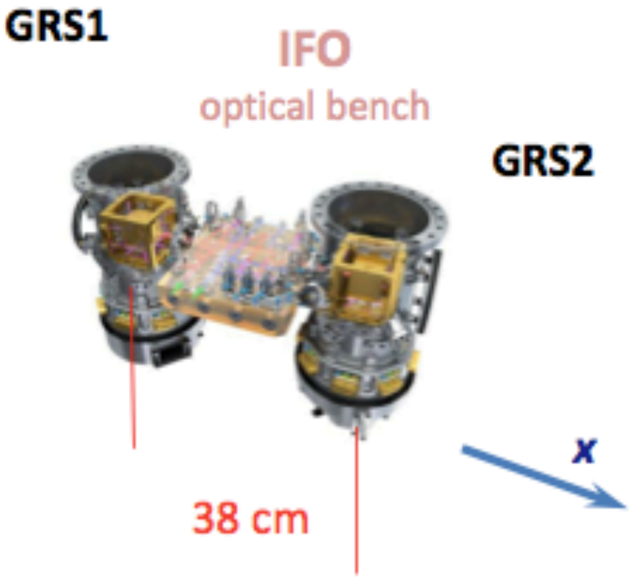
TM - SC

$+\Delta\phi, \Delta\eta$



+ frequency and phase stabilization IFO

The LPF differential accelerometer



1 spacecraft

drag-free control

2 test masses

→ 38 cm separation along x science axis

→ 1TM drag-free reference

→ 2nd TM electrostatically forced

Each TM inside gravitational reference sensor (GRS)

→ 6 DOF capacitive position sensor + actuator

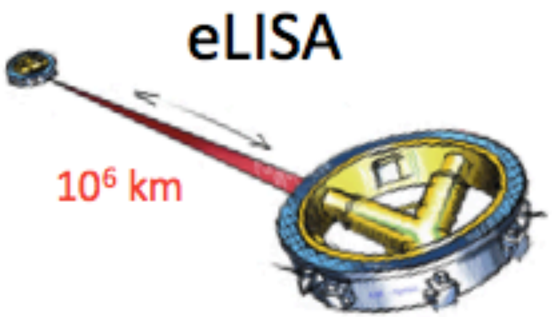
Interferometer to measure relative TM acceleration

LPF tests force noise and local IFO measurement for eLISA

G.W. measurement as diff. accelerometry

Physical observable: tidal acceleration between 2 distant test masses

Measurement technique: time varying Doppler shift in light exchanged between TM



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IFO doppler signal

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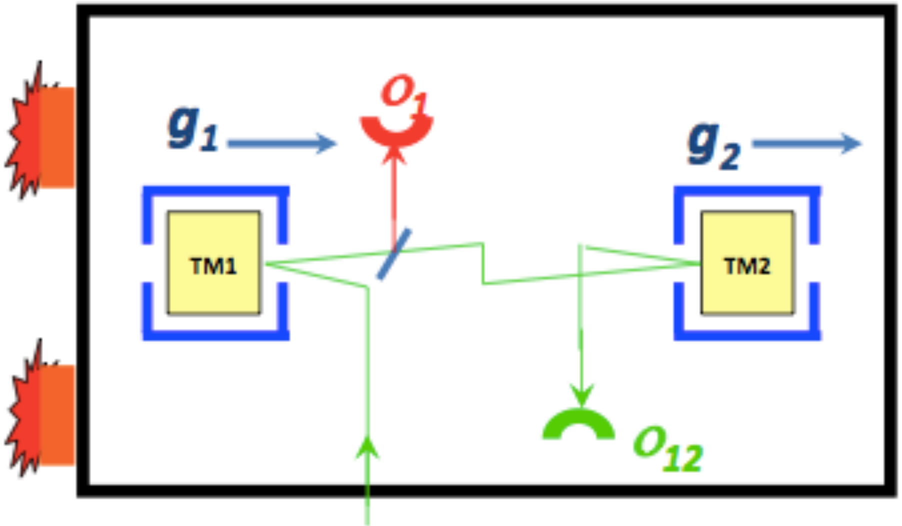
Differential force per unit mass

$S_{\Delta g}^{1/2} \approx 5\ \mathrm{fm/s}^2/\mathrm{Hz}^{1/2}$ (1 mHz)

LISA Pathfinder as a diff. accelerometer



Readouts:	o_1 (TM –SC) o_{12} (TM – TM)
Actuators:	thrusters electrostatic TM2

Drag-free:	thrust SC to follow TM1	(null IFO **o1**, 1 Hz BW)
Electrostatic suspension:	force TM2 to follow TM1	(null IFO **o12**, 1 mHz BW)

$$\Delta g \equiv \frac{F_2}{m} - \frac{F_1}{m} = g_2 - g_1$$

«gravitational observable»
differential force per unit mass

LISA Pathfinder as a diff. accelerometer

Newton's Eqns:

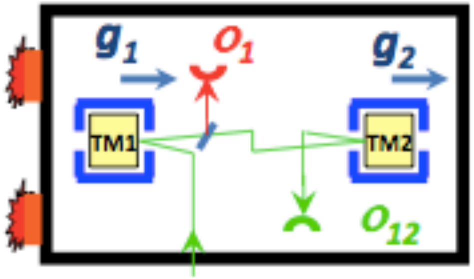
$$m\ddot{x}_1 = F_1 - m\,\omega_{1p}^2(x_1 - x_{SC})$$

$$m\ddot{x}_2 = F_2 - m\,\omega_{2p}^2(x_2 - x_{SC}) + F_{ES}$$

IFO Readouts :

$$o_{12} = x_2 - x_1$$

$$o_1 = x_1 - x_{SC}$$



$$\Delta g \equiv \frac{F_2}{m} - \frac{F_1}{m} = g_2 - g_1$$

Δg estimator:

IFO Acceleration

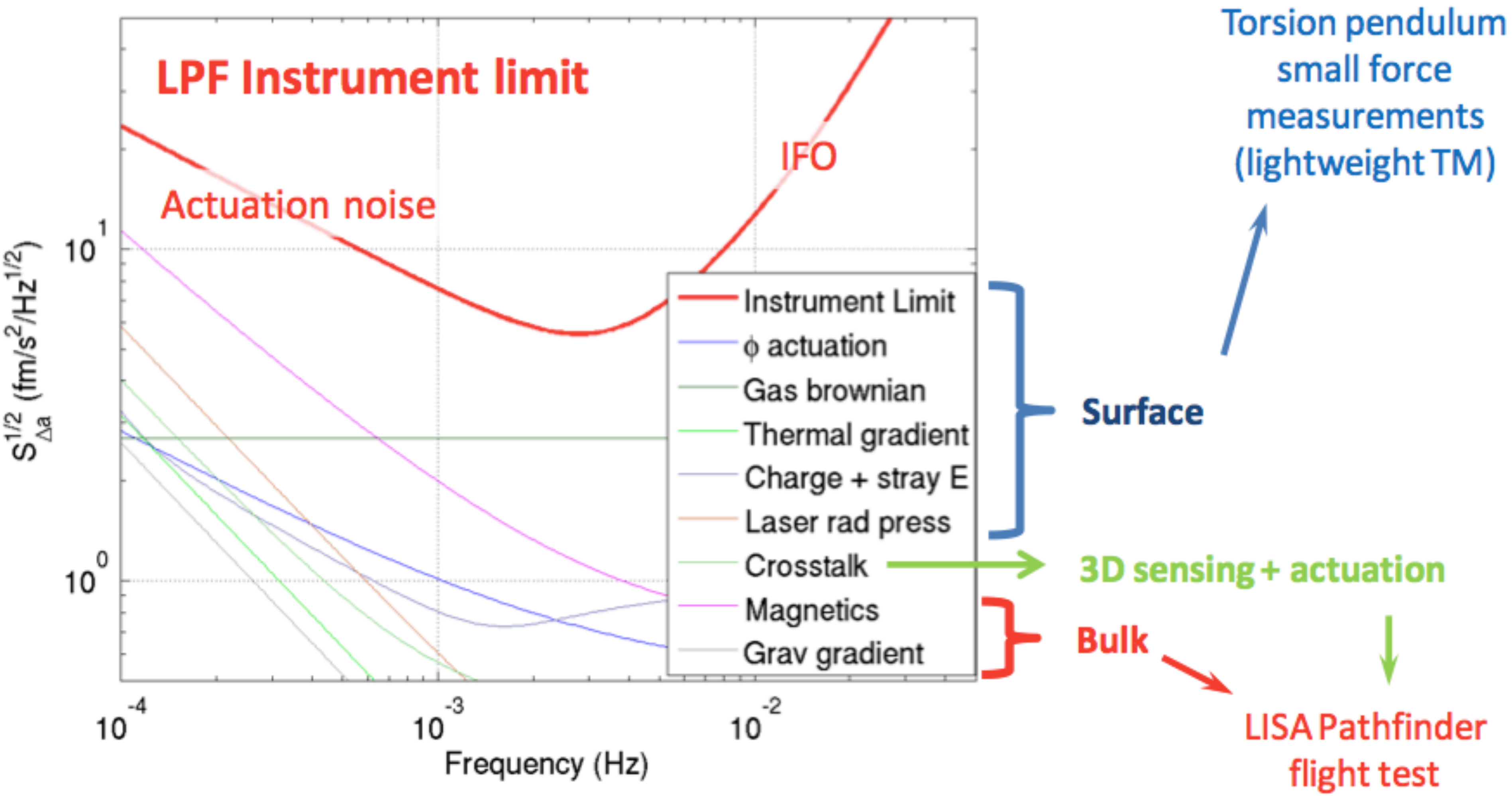
$$\Delta\hat{g} \equiv \ddot{o}_{12} - \frac{F_{ES}}{m} + (\omega_{2p}^2 - \omega_{1p}^2)o_1 + \omega_{2p}^2 o_{12} = \Delta g + \text{IFO noise}$$

Commanded control forces

Elastic coupling

- Produce differential acceleration time series
- Spacecraft coupling term (stiffness) subtracted (also for LISA)

LPF performance and TM acceleration noise sources for eLISA



Torsion pendulum small force measurements (lightweight TM)

Surface

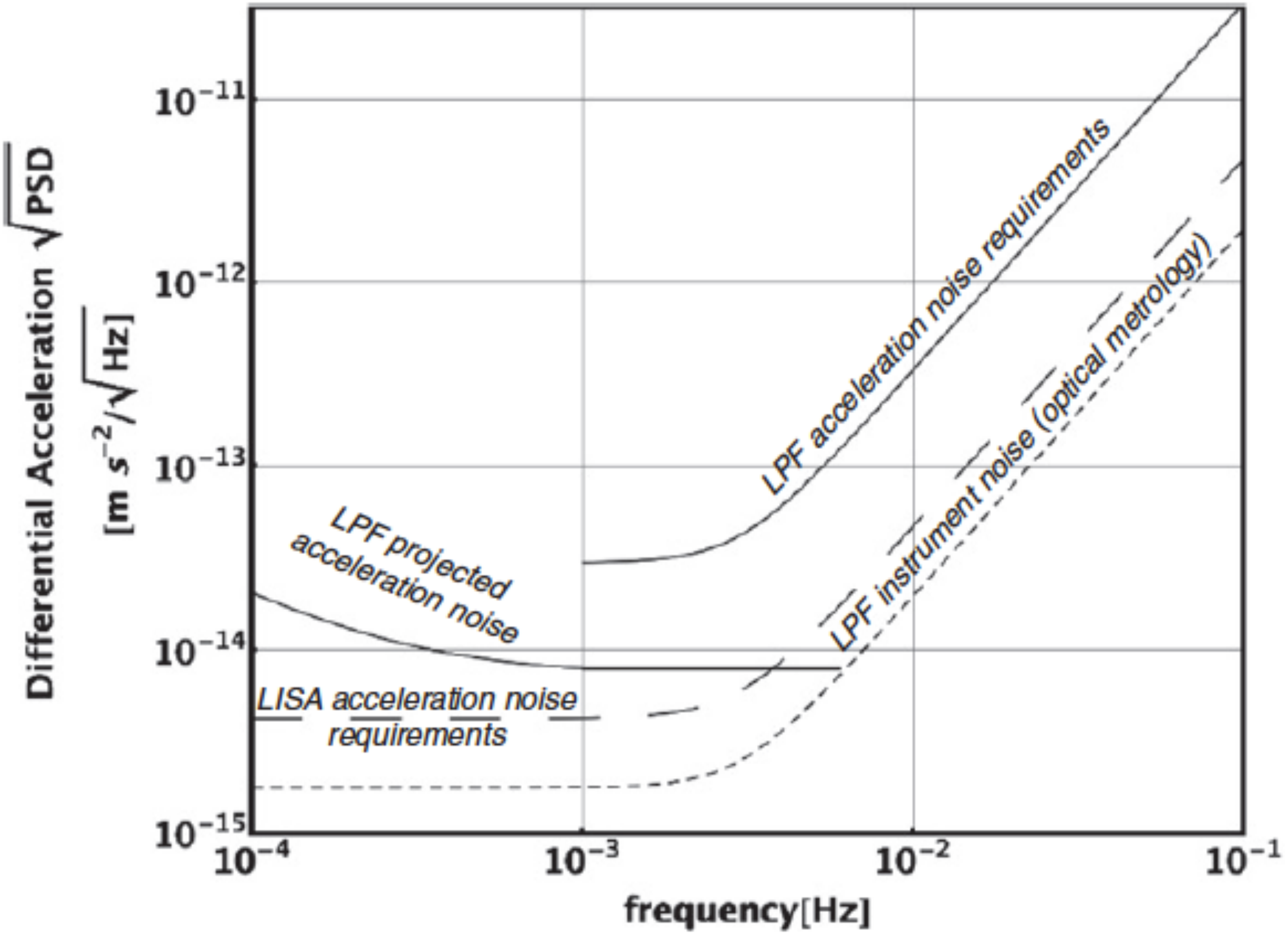
3D sensing + actuation

Bulk

LISA Pathfinder flight test

Expected performances of LISA Pathfinder are close to eLISA specs

Class. Quantum Grav. **28** (2011) 094002



LISA Pathfinder as a test bench for LISA

Design element for eLISA verifiable by LPF

- Free falling TM, very low level of unwanted accelerations.
  - drag-free controls
  - microthusters
  - inertial sensors with heavy masses, large gaps and caging mechanism
  - very stable electrostatic actuation
  - Charge control of the TM charge, no contact.
  - High thermomechanic stability of the S/C
  - Gravitational field cancelation
- High precision interferometric measurement of the TM – S/C motion
  - displacement measurement down to pm and rotation down to 100 nrad
  - high stability, high precision, low noise optical systems

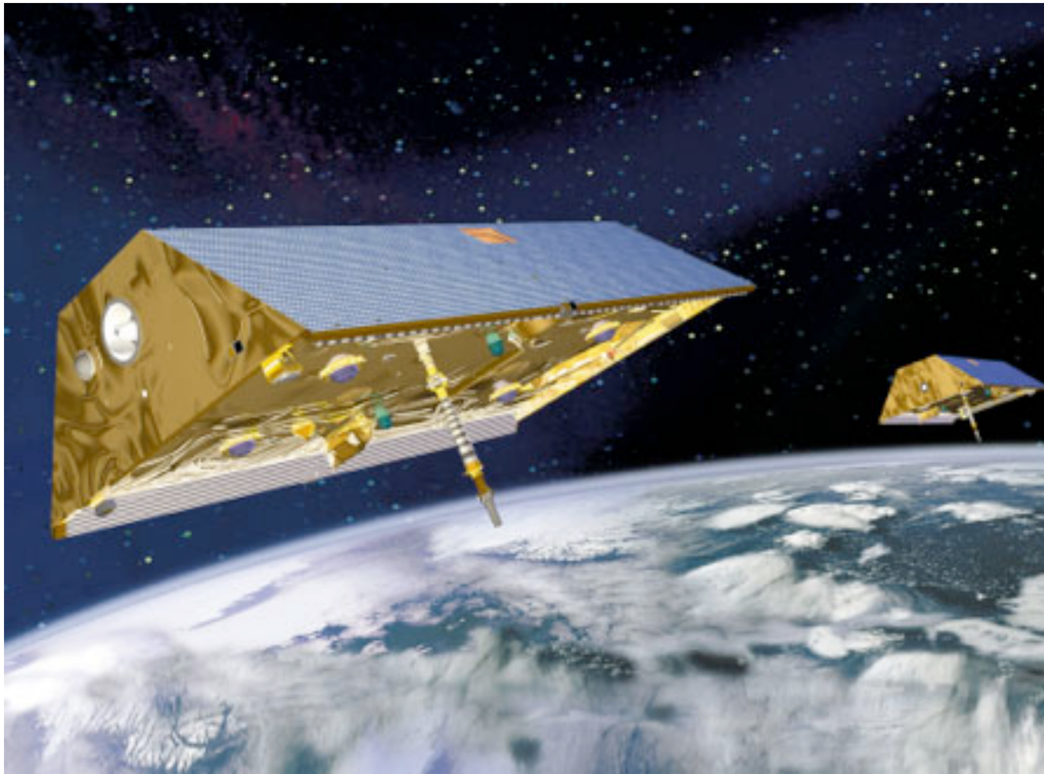
» Will instead need ranging of S/Cs milions of km apart

- high stability telescopes
- Fhigh accuacy phase meters
- frequency stabilization of lasers
- constellation formation and keeping
- High precision S/C attitude control

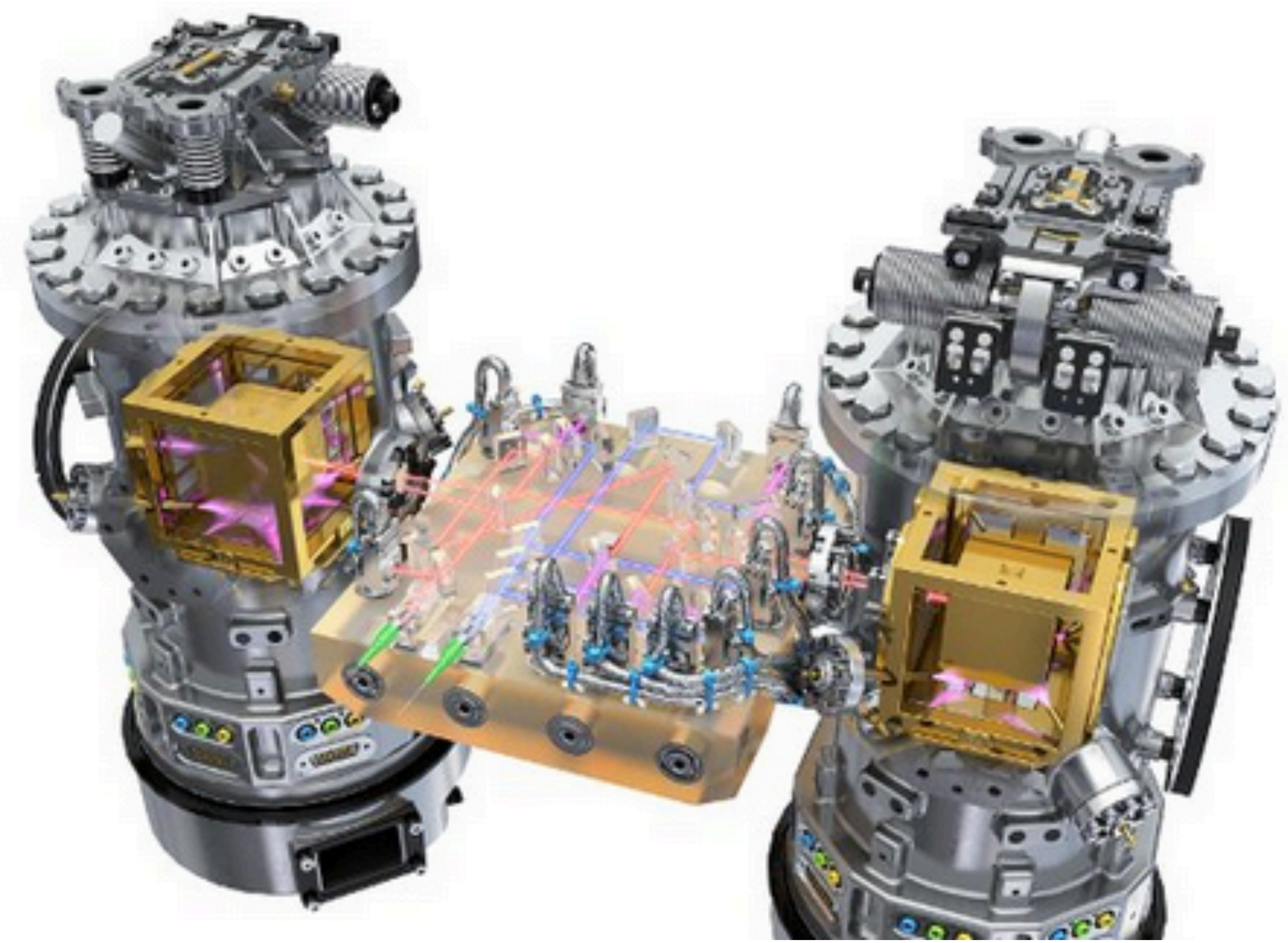
GRACE Follow On

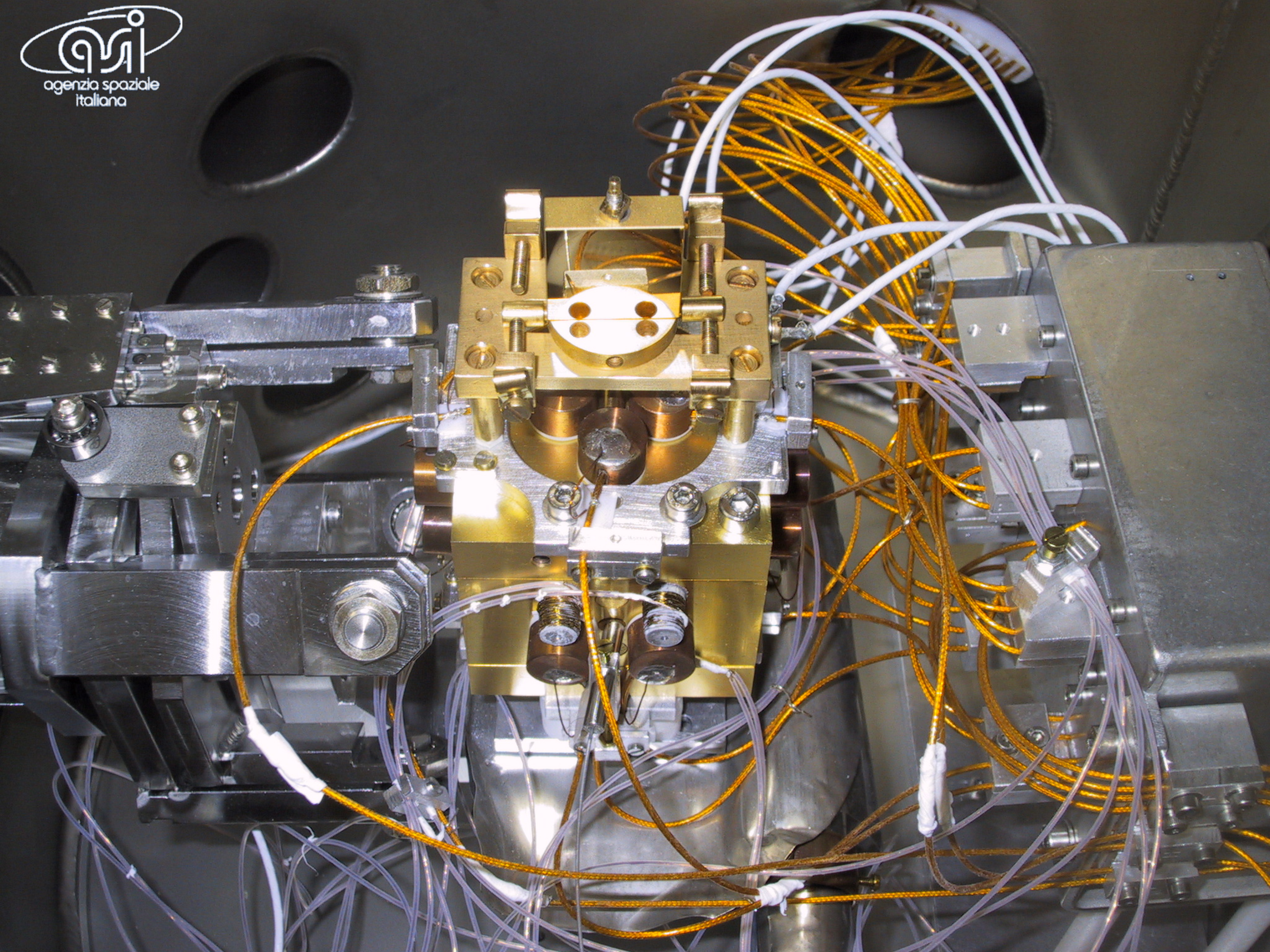
GRACE: 2 S/C in Low Earth orbit, connected by a microwave link: very successfull geodesy mission

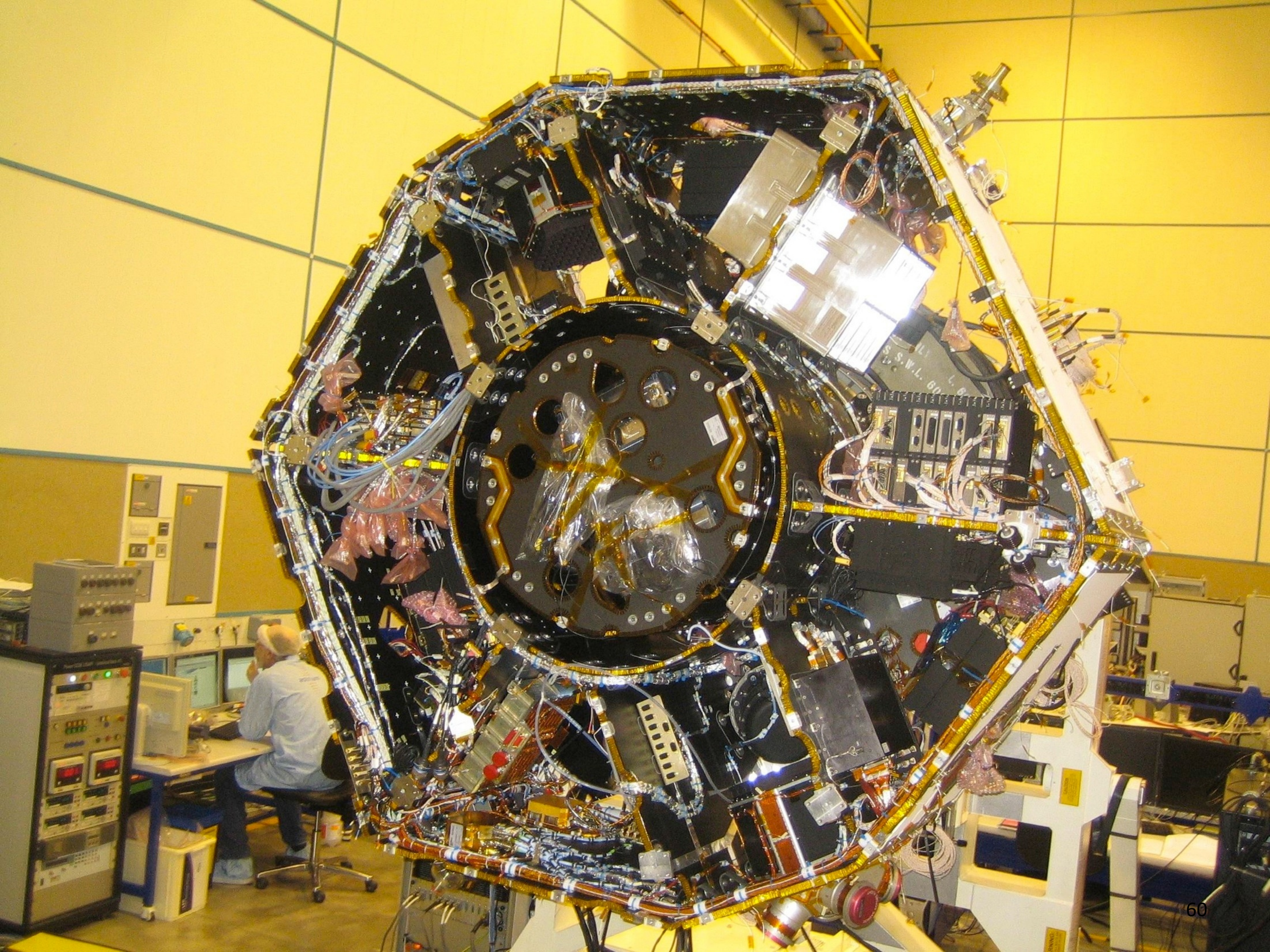
In 2017, the new mission will have an optical link: A test of S/C to S/C interferometry



2 Test Masses and 1 optical bench








lisa pathfinder
esa
APCO TECHNOLOGIES
APCO TECHNOLOGIES

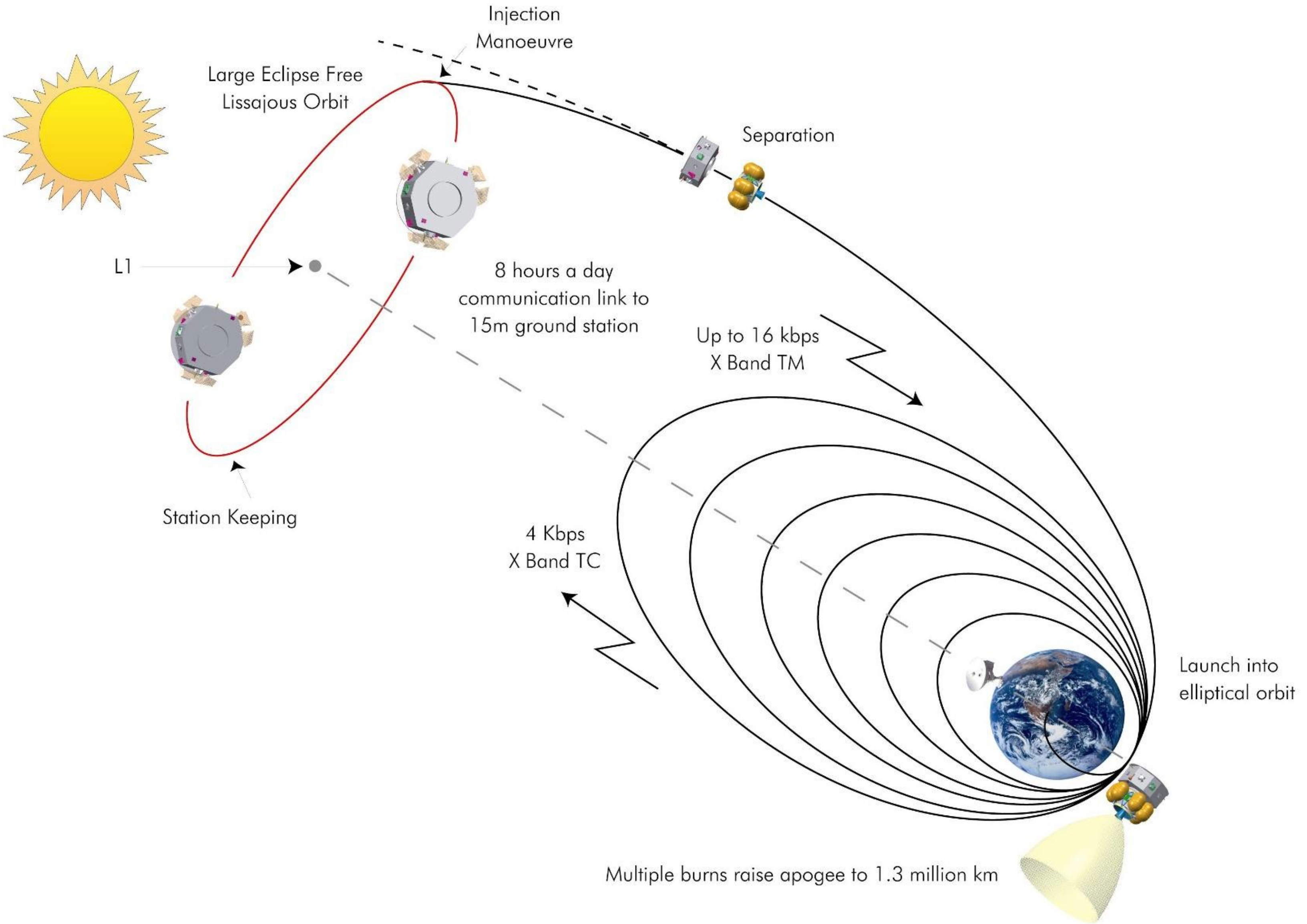

cnes

Two Test Masses along geodesics

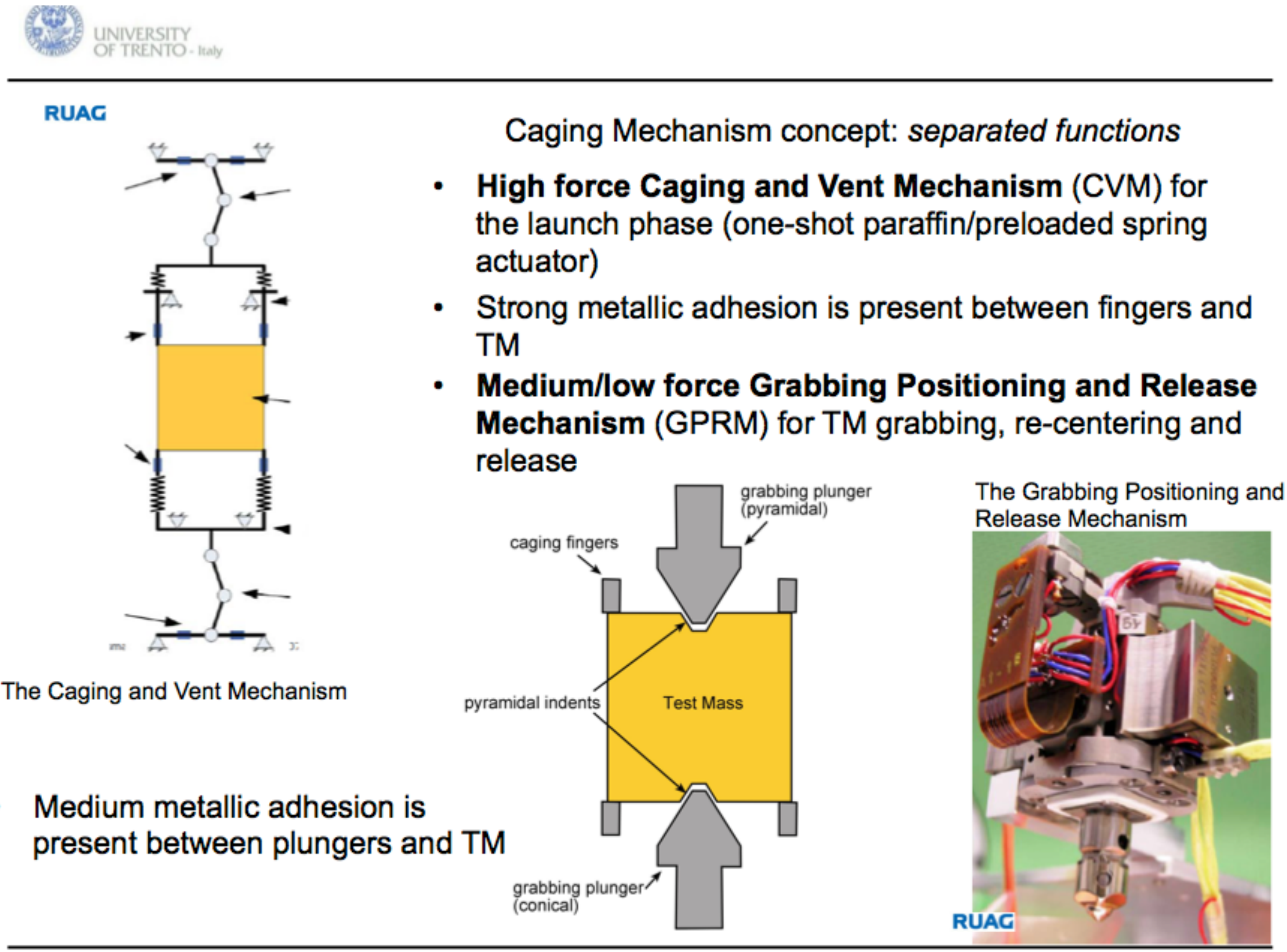
LISA Pathfinder First Results

3/12 2015 Dèpart de Kourou

Long journey to L1



De-caging and TM release



UNIVERSITY OF TRENTO - Italy

RUAG

Caging Mechanism concept: *separated functions*

- **High force Caging and Vent Mechanism** (CVM) for the launch phase (one-shot paraffin/preloaded spring actuator)
- Strong metallic adhesion is present between fingers and TM
- **Medium/low force Grabbing Positioning and Release Mechanism** (GPRM) for TM grabbing, re-centering and release

The Caging and Vent Mechanism

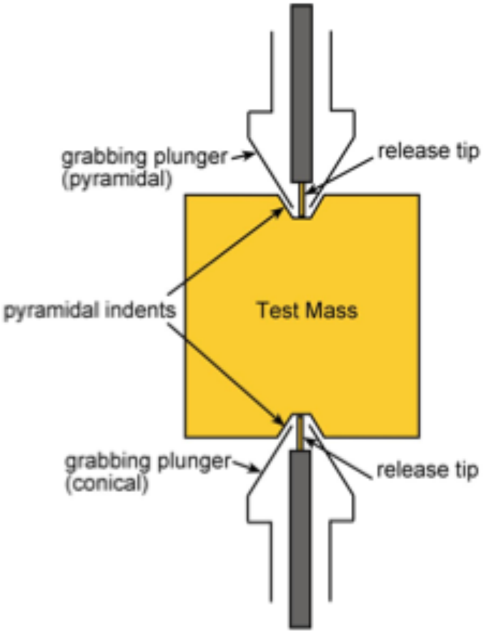
- Medium metallic adhesion is present between plungers and TM

The Grabbing Positioning and Release Mechanism

RUAG

15-16 Feb. Test Masses free !

Further reduction of the contact forces and surface area is needed for the following release phase



- Two opposing tips, minimized contact (ϕ0.8mm, sphere/flat)
- Customized surfaces (Au-based) and mechanisms

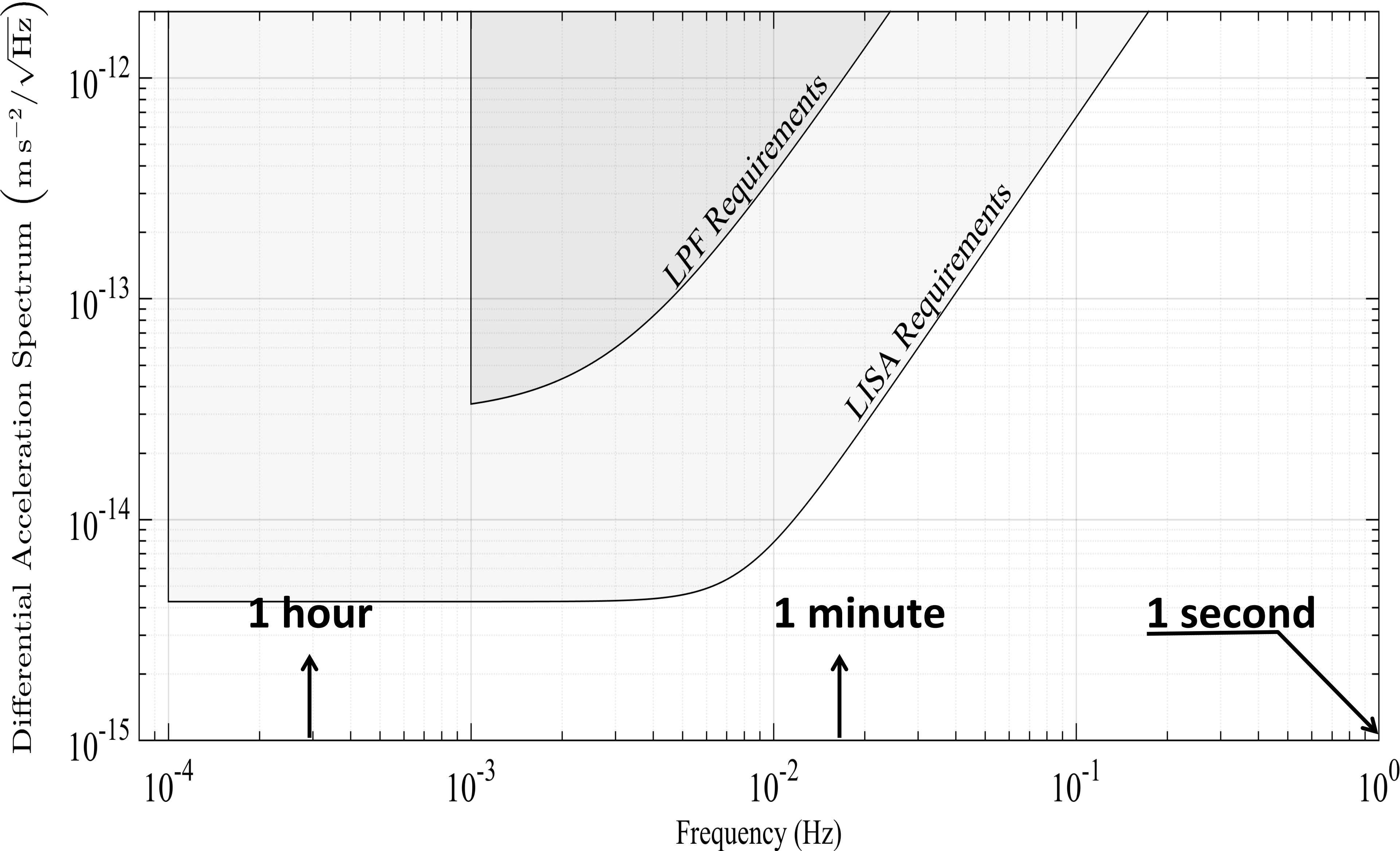
- Low metallic adhesion (mN) is expected, still much larger than the force authority on the TM (μN)
- *Dynamic* release: detachment relies on TM inertia

- Low force/quick piezo mechanism for TM **release to free-falling conditions**

$$v_{max} = 5\frac{\mu m}{s}$$

$$p_{max} = 2kg \cdot 5\frac{\mu m}{s} = 10^{-5}Ns$$

LISA and LISA Pathfinder noise acceleration requirements

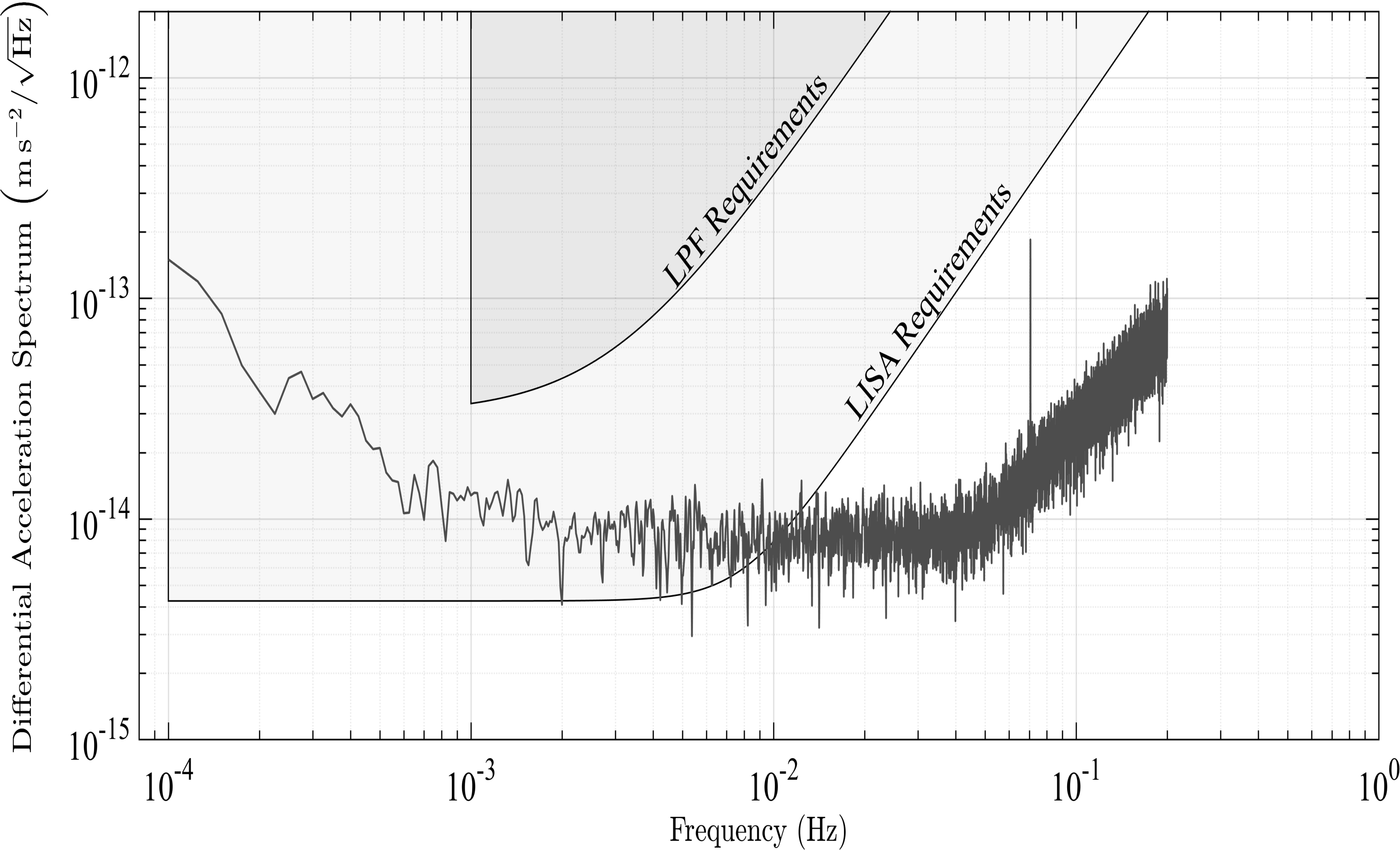


1 hour

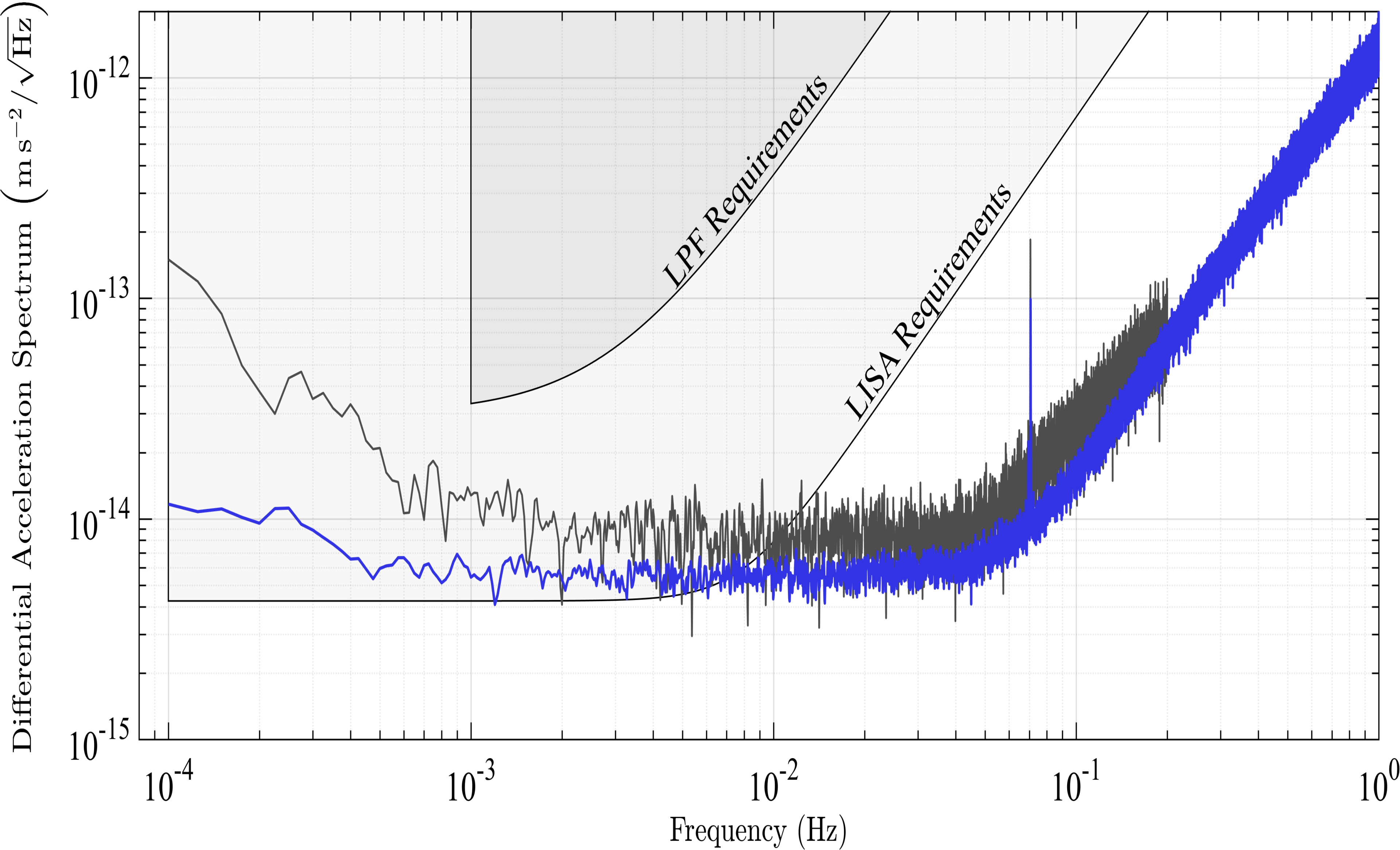
1 minute

1 second

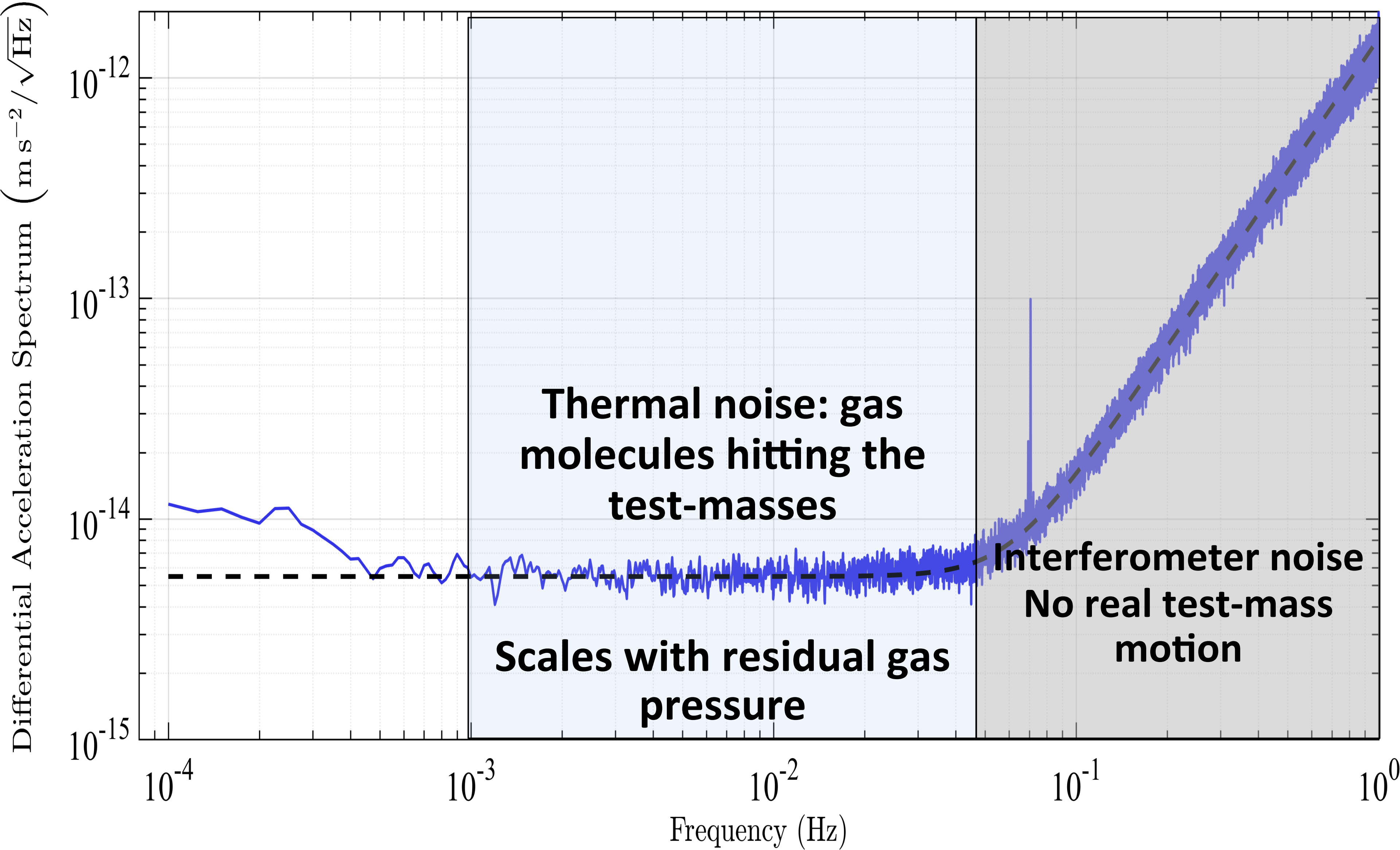
First day of operation. March 1st, 2016



April 8-14, 2016. The results shown in PRL. Reduced due to elapsed time and instrument optimization



The limiting disturbances

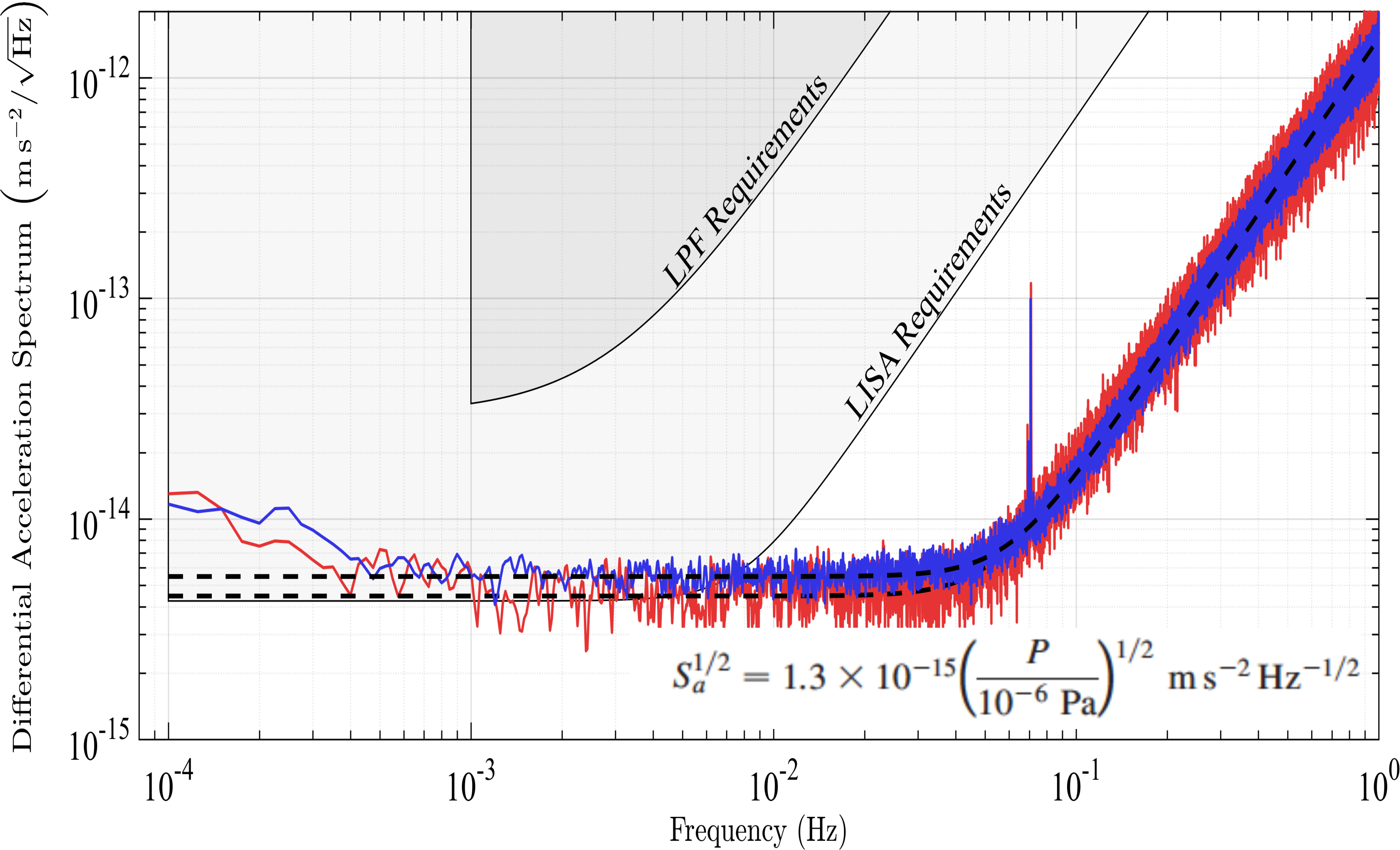


Thermal noise: gas molecules hitting the test-masses

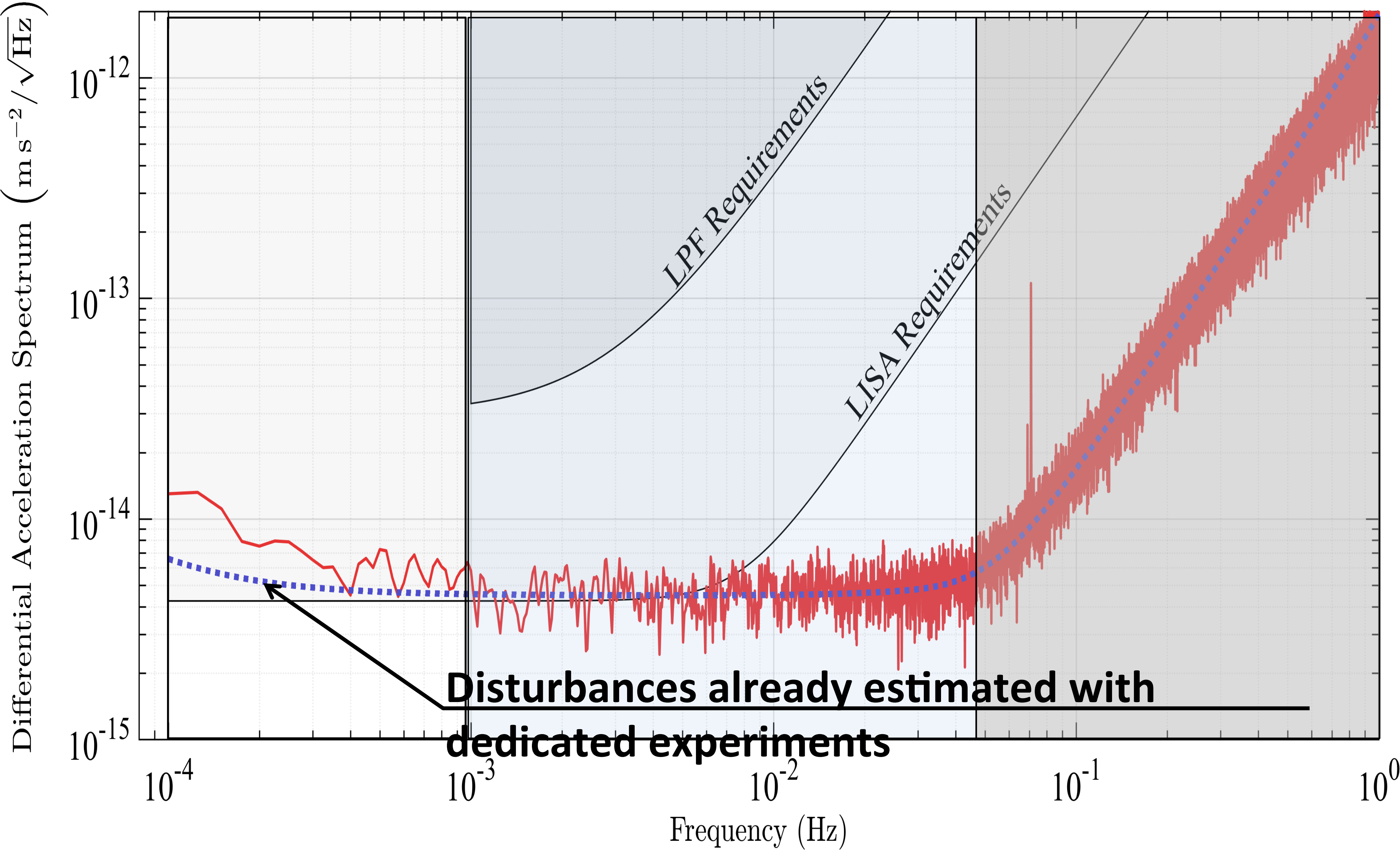
Scales with residual gas pressure

Interferometer noise No real test-mass motion

May 16-18, 2016. Pressure gone further down (System continuously vented to outer space)



Explaining the noise: investigations ongoing

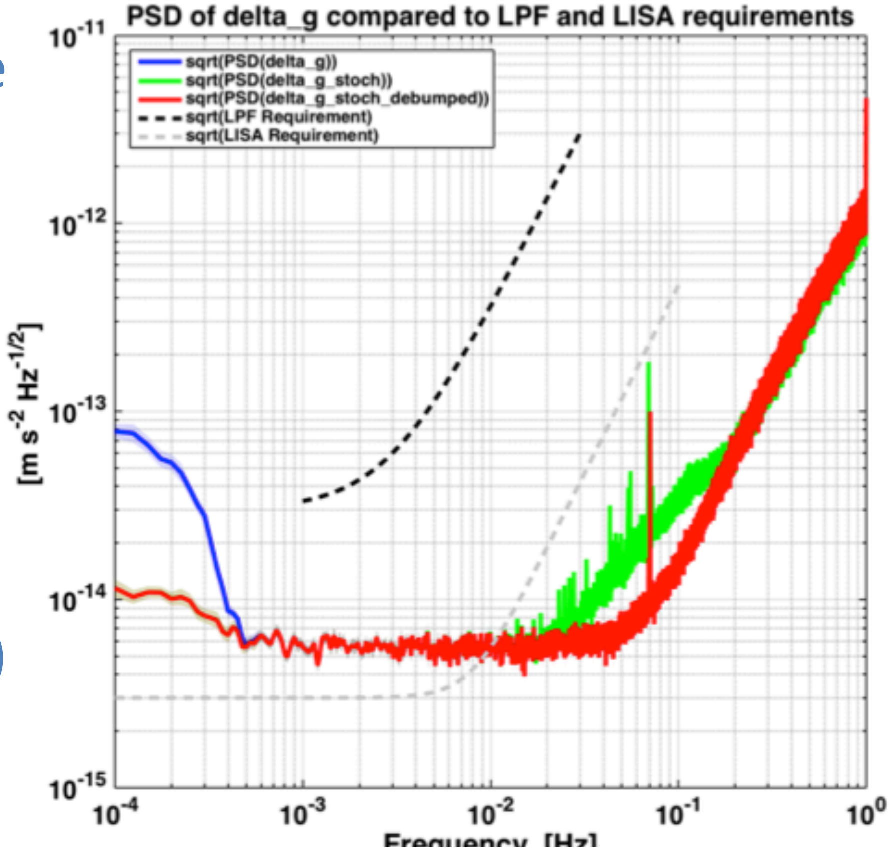


Disturbances already estimated with dedicated experiments

Accelerated frame:

At high f: cross-talk from some angulare DOFs

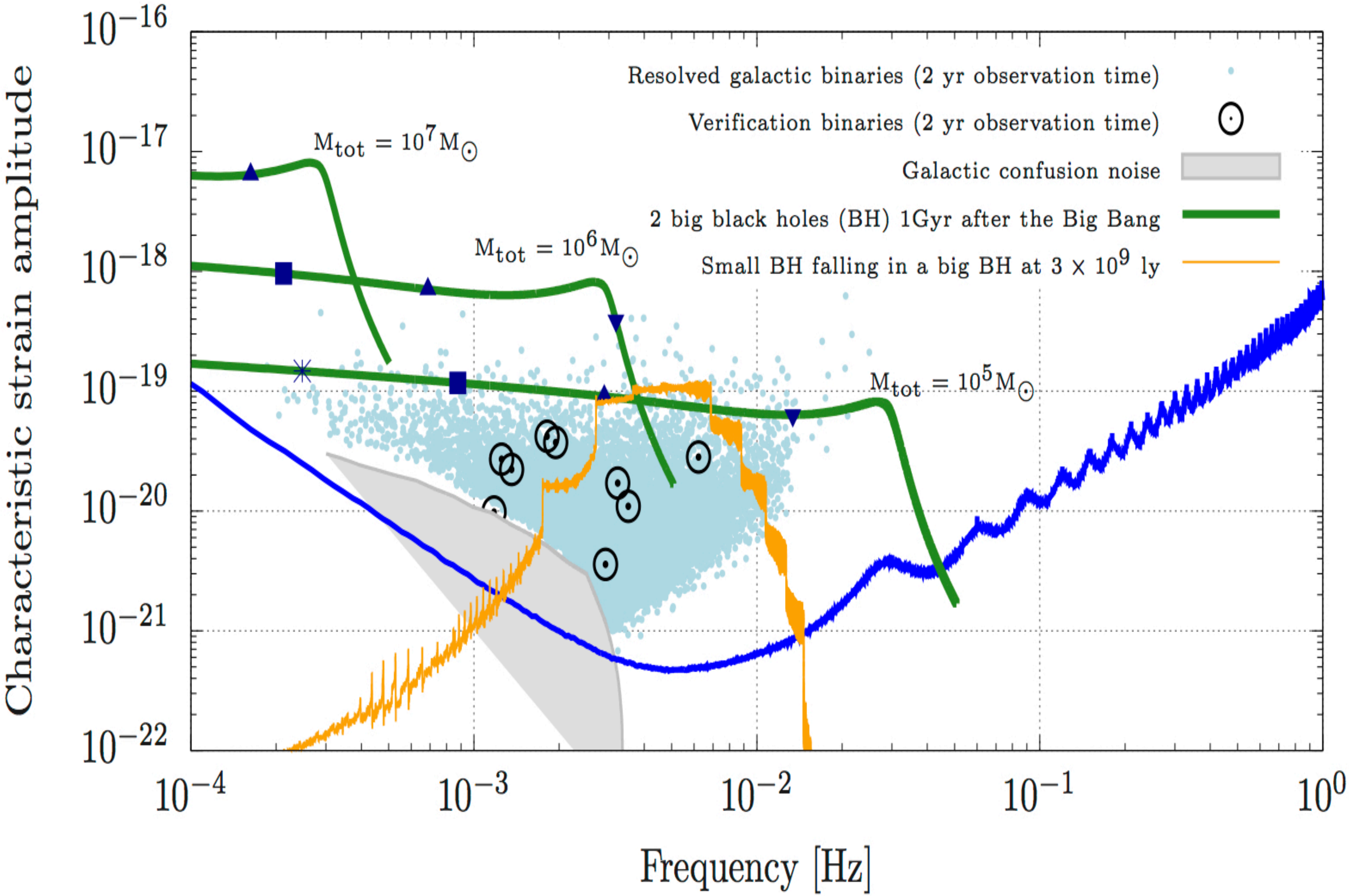
At low f: contribution from attitude rotation of S/C (2^0/day)



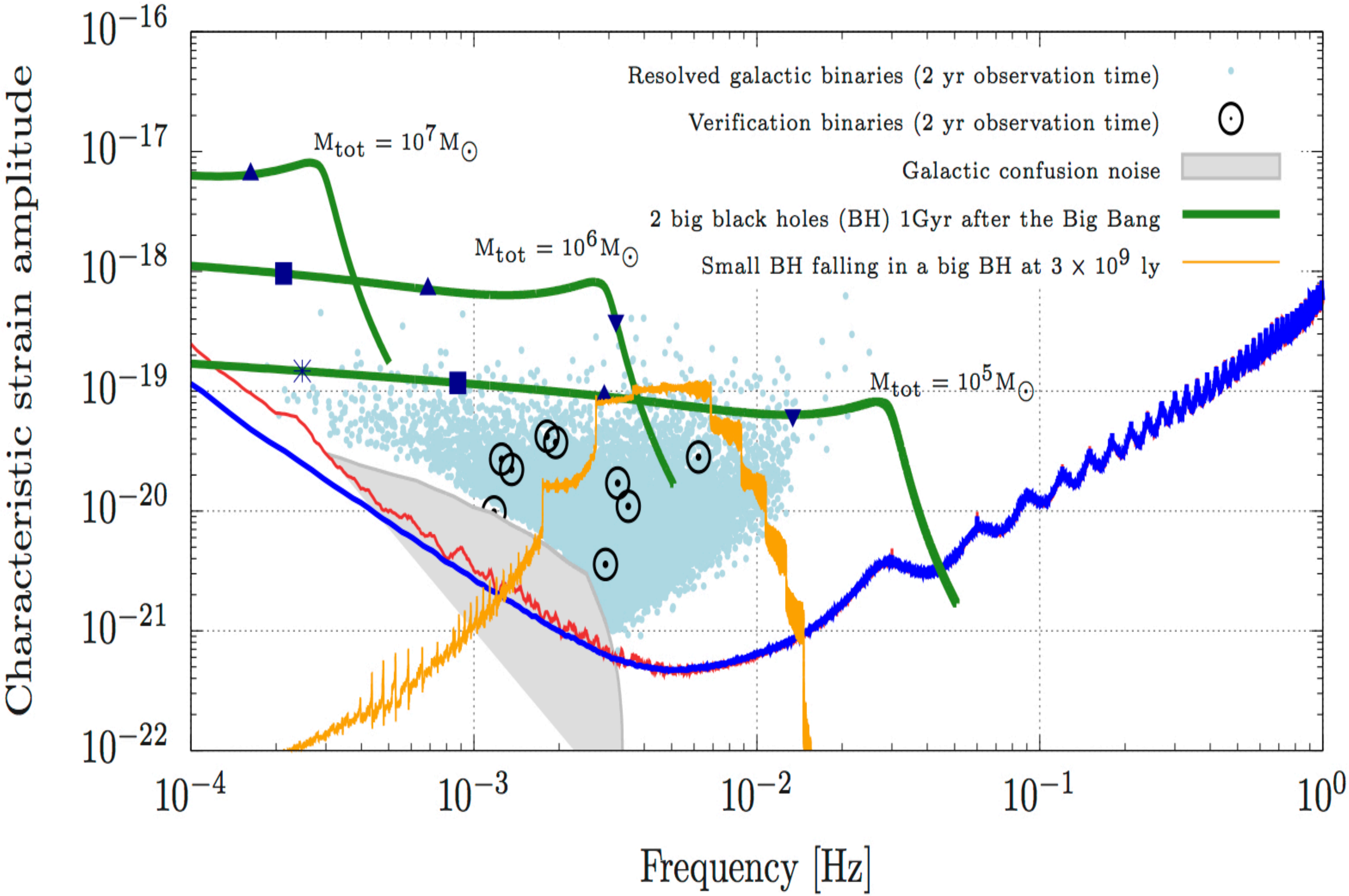
$$\frac{d^2}{dt^2}\left(x_{12}\right)_B+\left[\dot{\vec{\omega}}_{B/J}\times\vec{r}_{T2/T1}+2\vec{\omega}_{B/J}\times\frac{d}{dt}\left(\vec{r}_{T2/T1}\right)_B+\vec{\omega}_{B/J}\times\left(\vec{\omega}_{B/J}\times\vec{r}_{T2/T1}\right)\right]\cdot$$

$$\vec{e}_{B,x}=\frac{F_{cmd,x2}}{m_2}+\Delta g+\omega_{12}^2 x1+\omega_2^2 x12$$

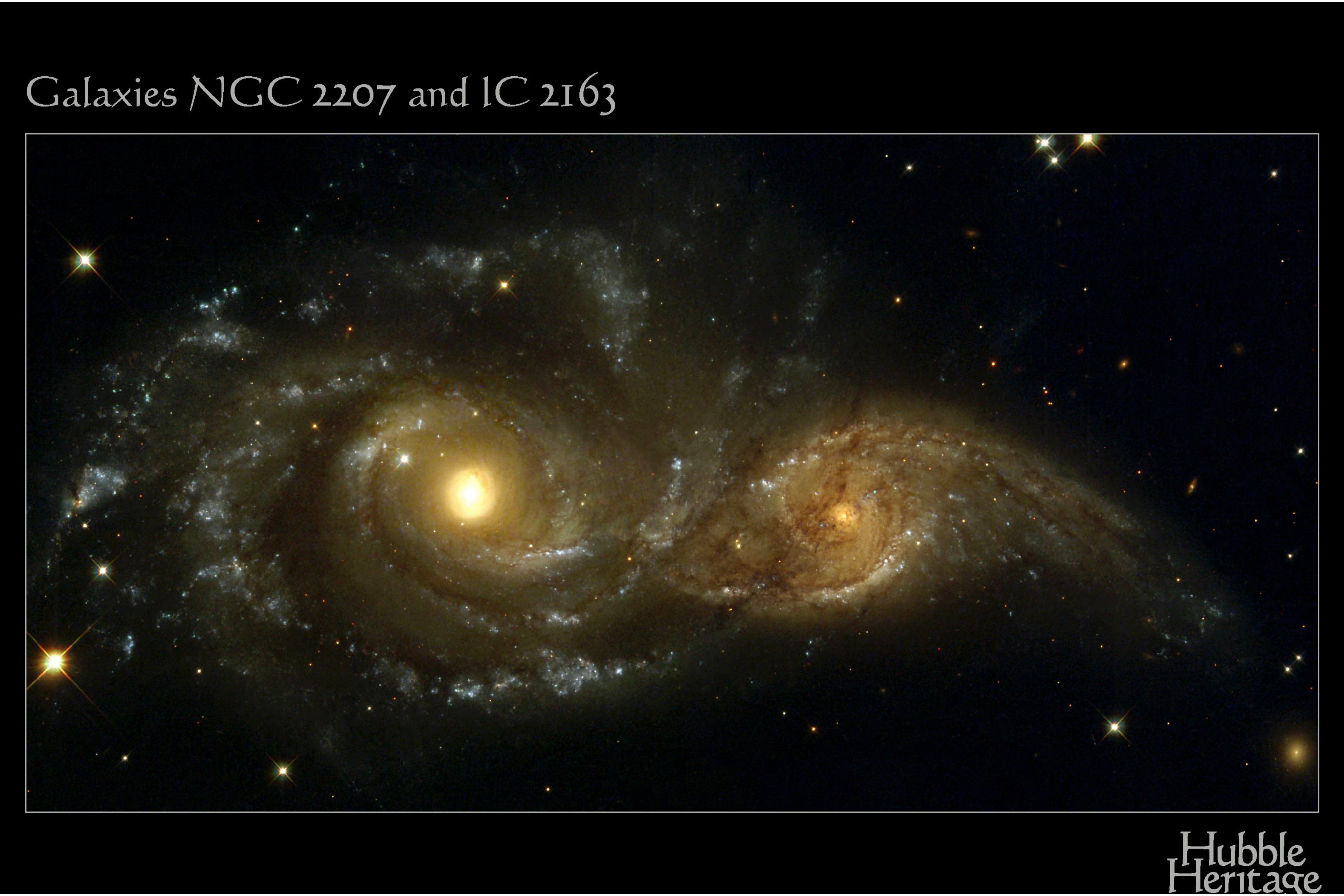
Noise almost entirely modeled: original LISA requirements at hand



With current demonstrated sensitivity most science obtained anyway

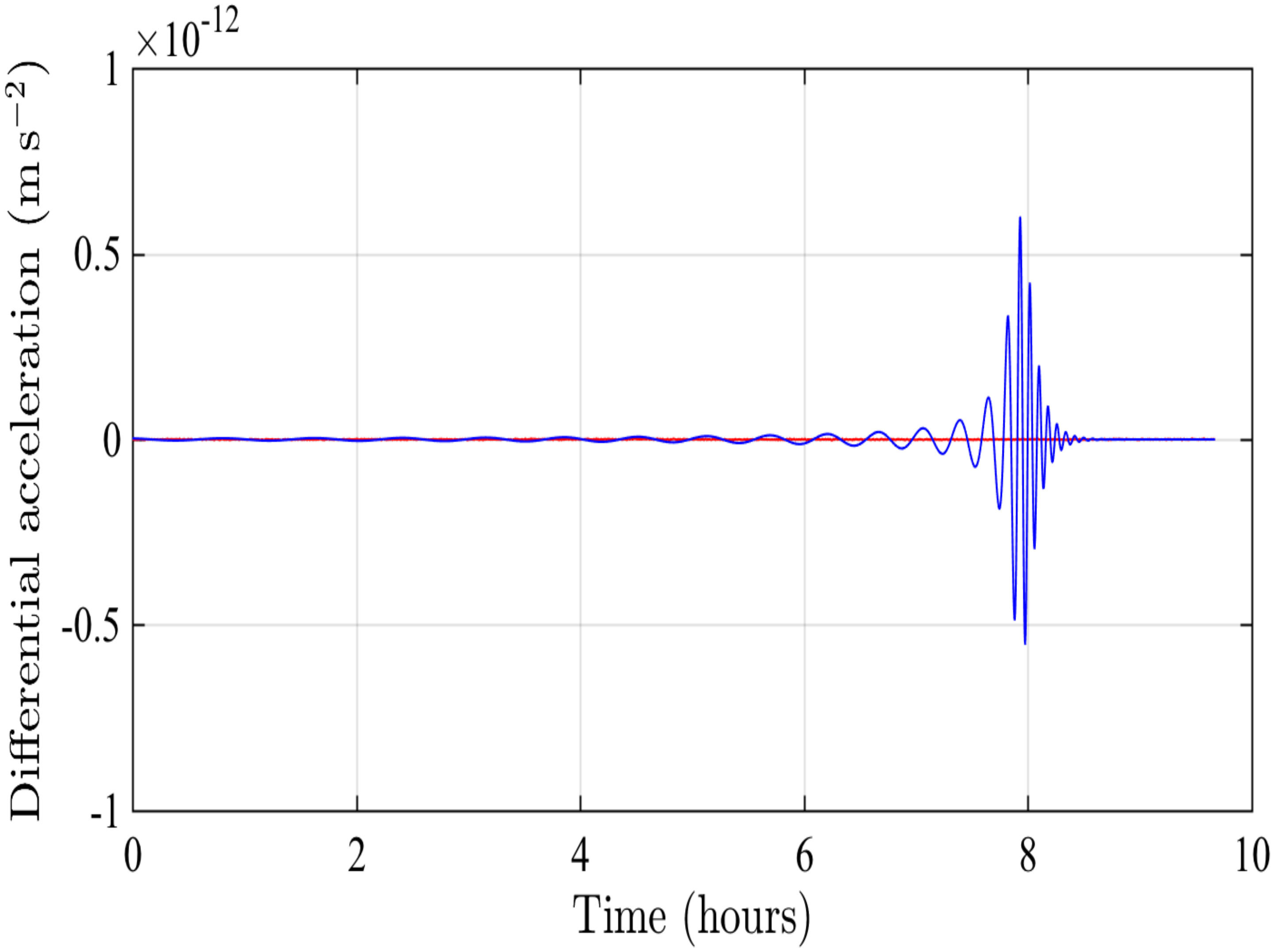


Back to...binaries from galaxy collisions



-- Simulated LISA acceleration signal for merging of two $10^6 M_\odot$ black-holes at 4 Gpc

-- LISA Pathfinder measured acceleration data



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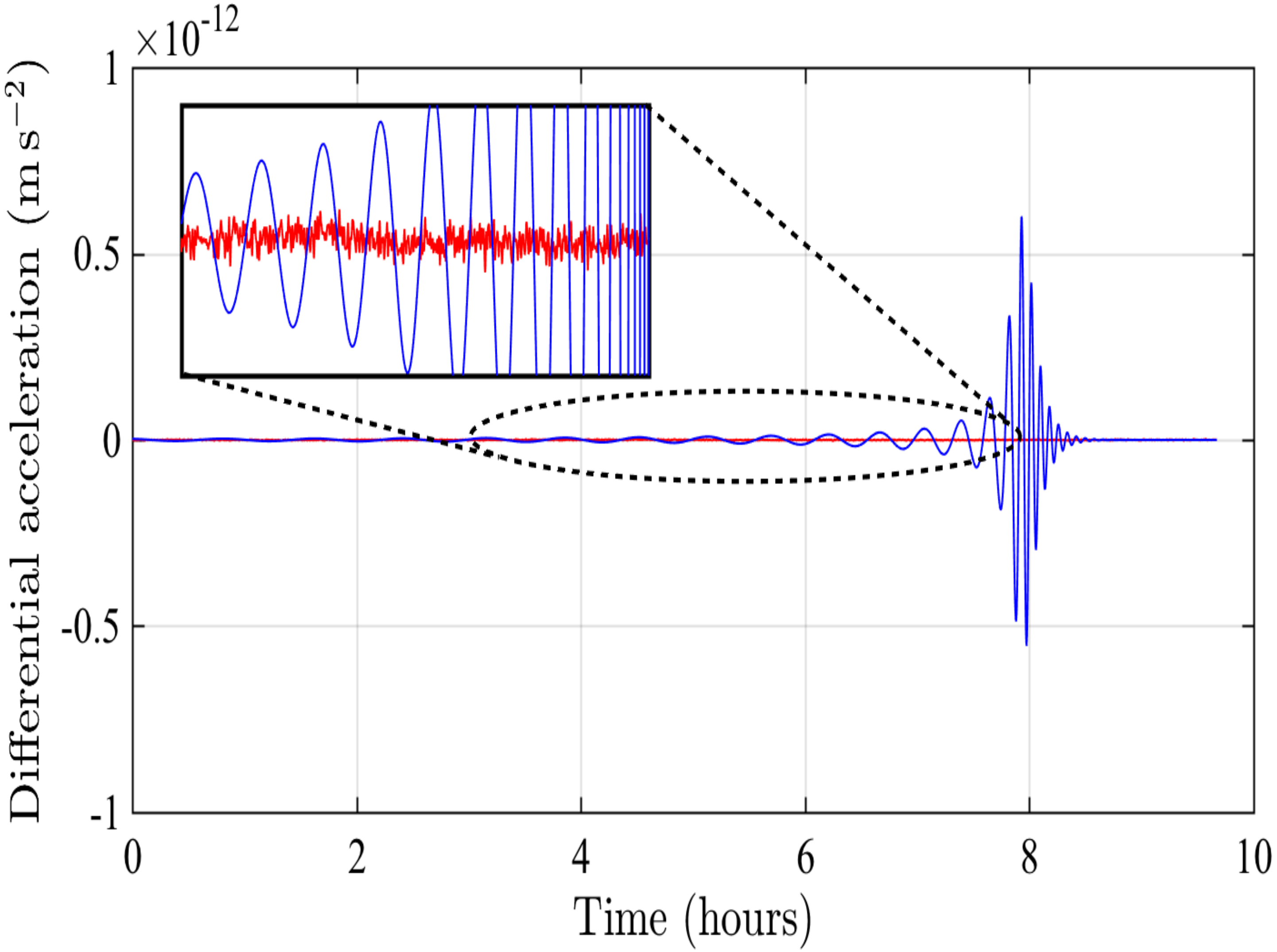
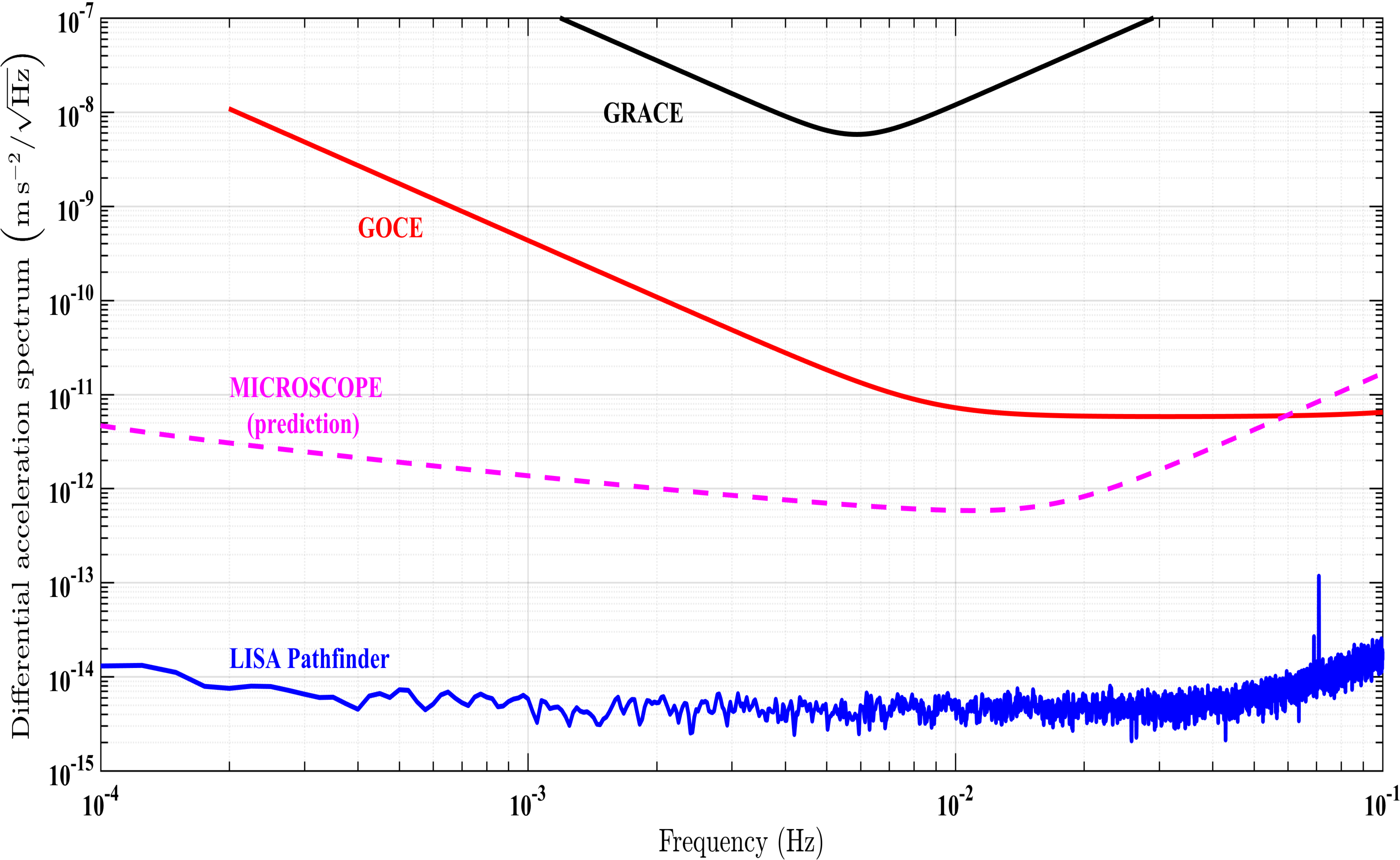
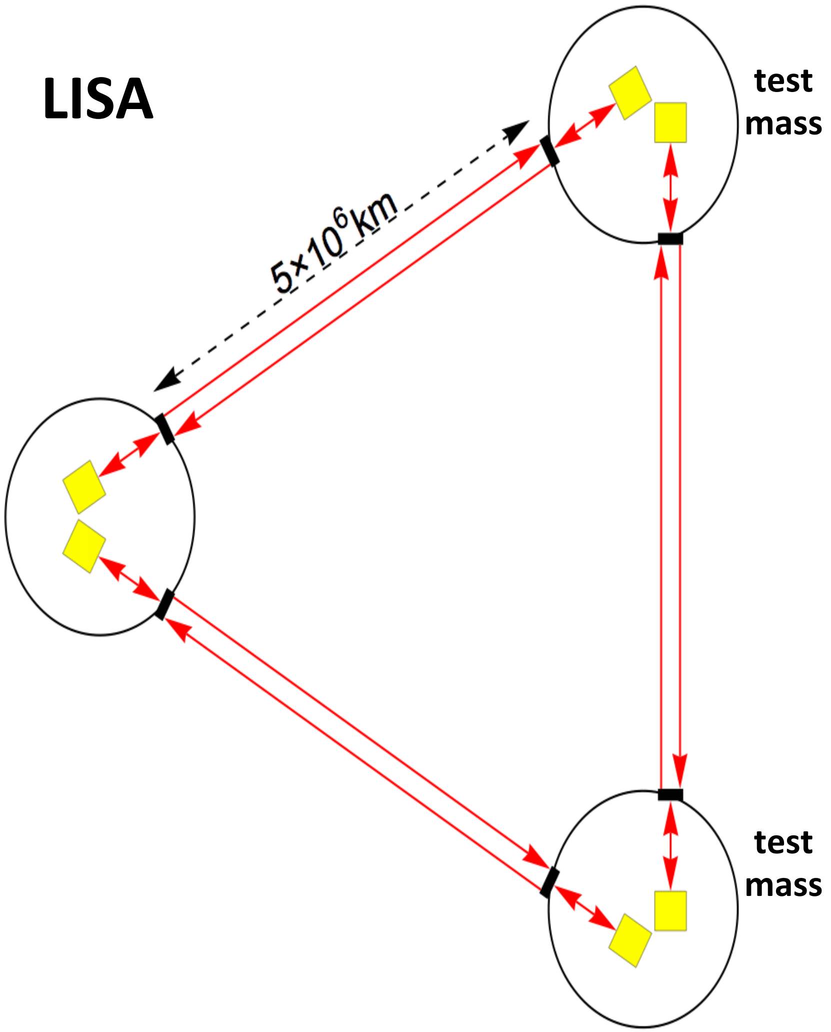


Sub-femto-g differential accelerometry: orders of magnitude improvement in the field of exp. gravitation



A green light for LISA!

We made the acceleration of test-masses due to disturbances much smaller than that expected from gravitational wave signals




That's all Folks!

Thanks to a great team !

OHB
CGS

Max-Planck-Institut
für Gravitationsphysik
(Albert-Einstein-Institut)

INFN
Istituto Nazionale di Fisica Nucleare

University of Glasgow

UNIVERSITÀ DEGLI STUDI DI TRENTO

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

IFR

UNIVERSITY OF BIRMINGHAM

INSTITUT D'ESTUDIS ESPACIALS DE CATALUNYA
IEEC

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A Finmeccanica Company

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SSO
Swiss Space Office

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asi
agenzia spaziale italiana

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Deutsches Zentrum
für Luft- und Raumfahrt

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