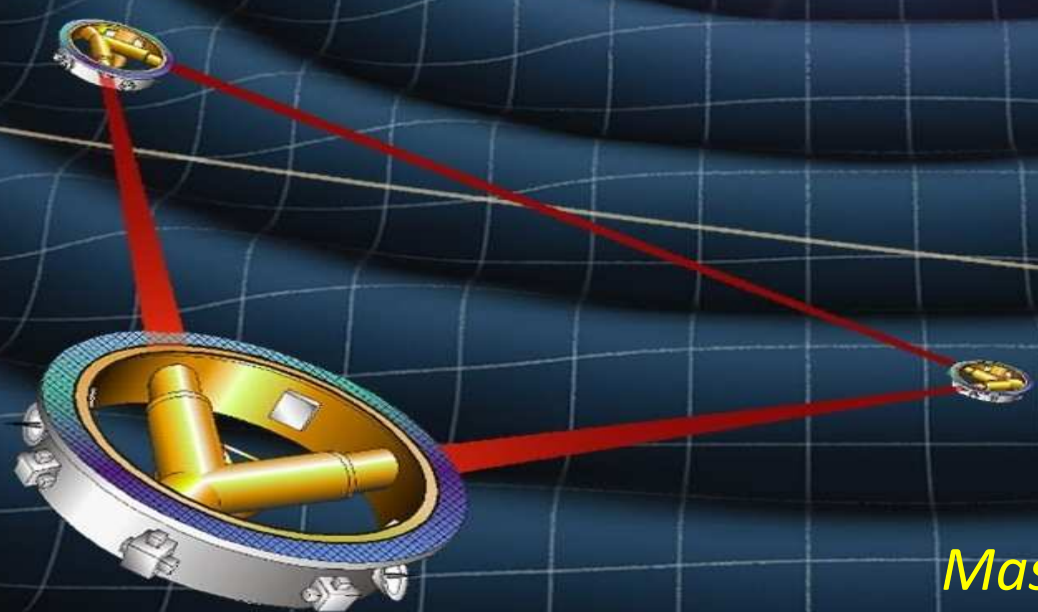
LISA Pathfinder and LISA



Massimo Bassan
Dip. Fisica Università and INFN
Roma Tor Vergata

I have good news and bad news…

First the good news:

LISA Pathfinder is flying, operational and working better than expected

Good news and bad news

and now the bad news…

….I cannot tell you the good news

From: Paul McNamara
Subject: **[Lpf] Embargo on flight data and results**
Date: 22 February 2016 06:42:51 CET
To: lpf@aei.mpg.de

Dear All,

Now that we have flight data available, may I remind you that ALL data and results are embargoed until we release the first
papers. This also includes the commissioning data, which is essentially our first science data.

As a team, we need to be careful on how we distribute results. Before any results are to be used, please request permission
the collaboration (Science team).

This will be discussed further on Thursday at the Science Team meeting.

Thank you for your understanding,

good news and bad news

HOWEVER:

Good news are coming soon…

On June 7th, 12:00 CET

Release of first results:

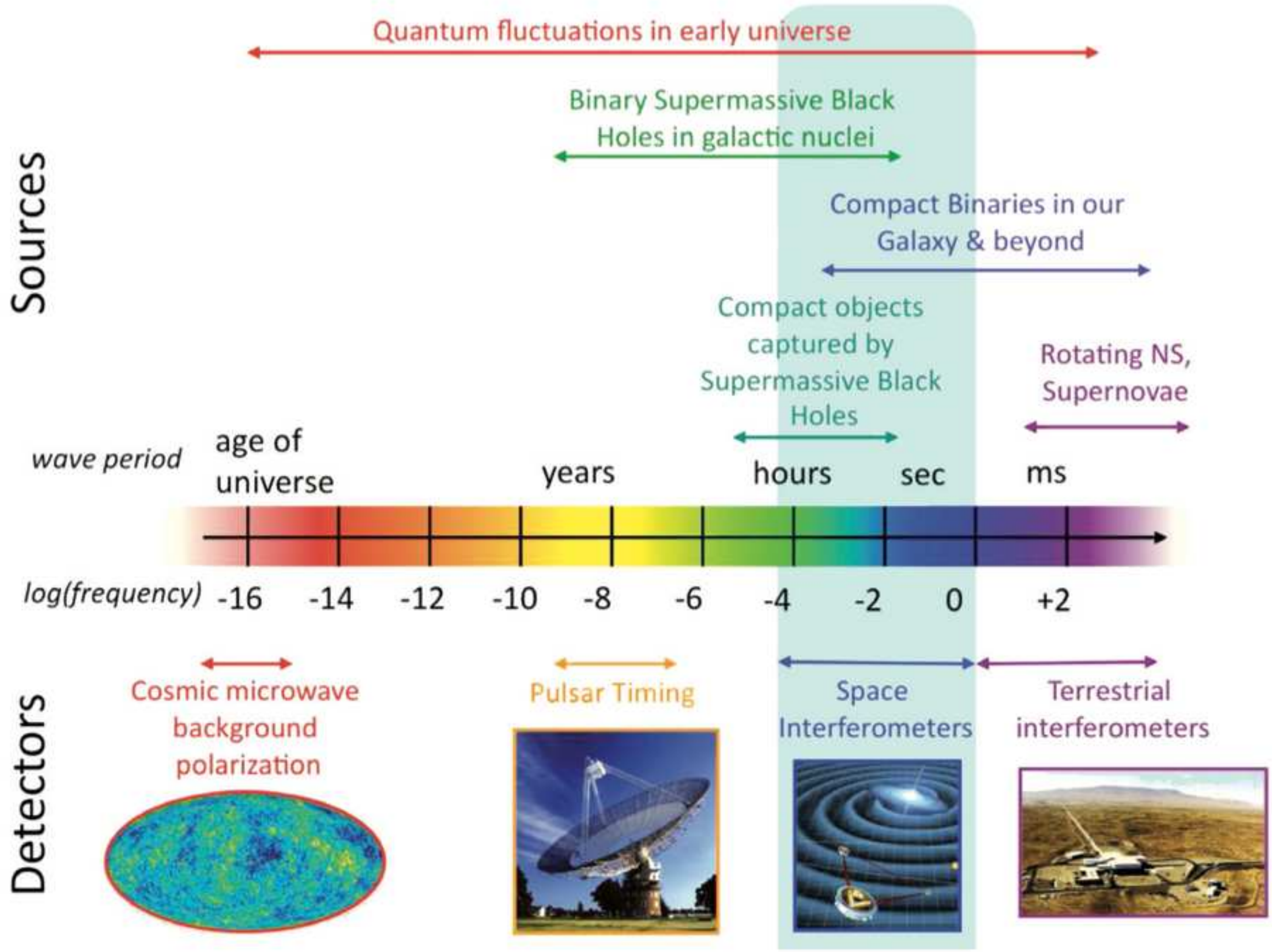
- Press conference

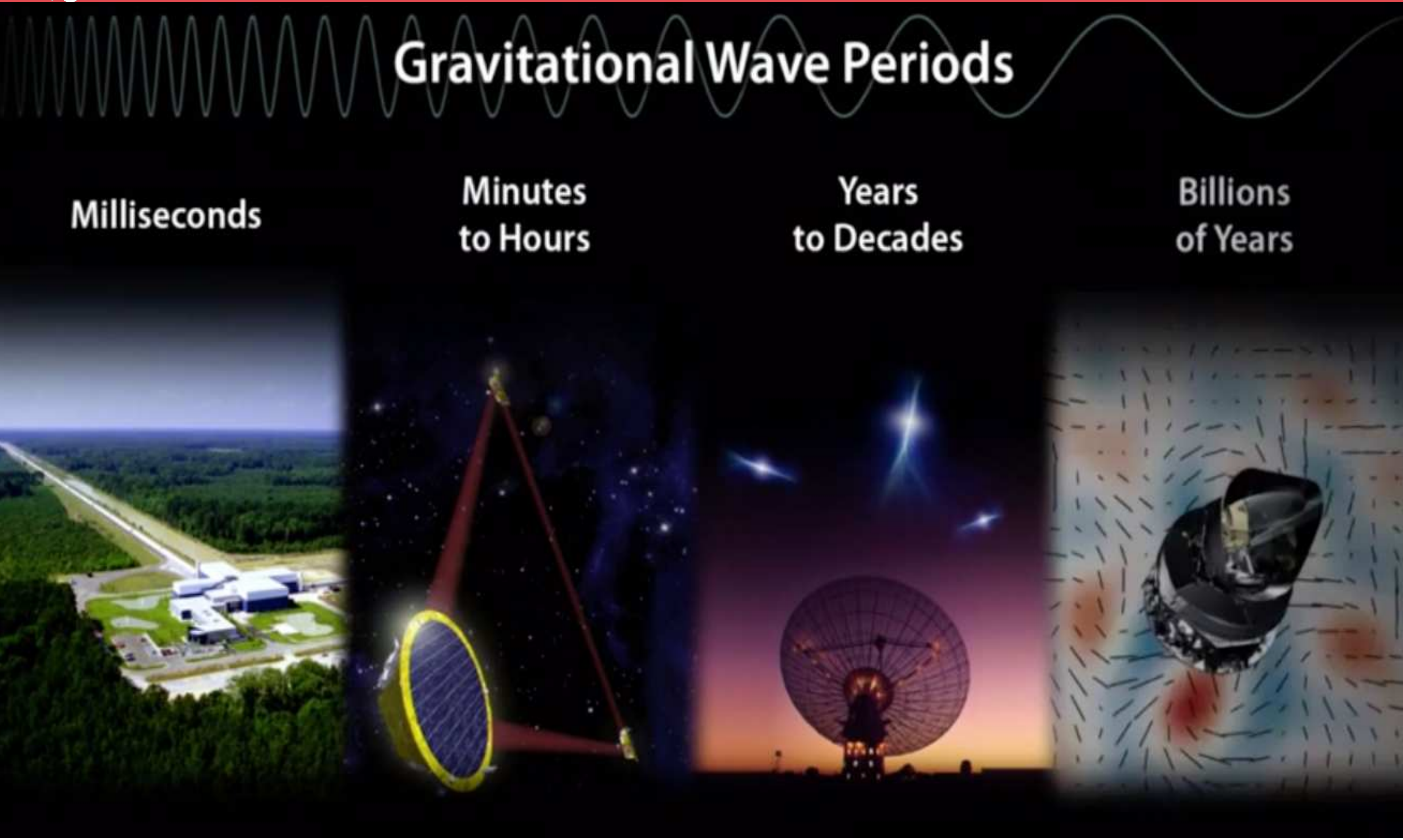
- Paper (10 pages) on Phys Rev. Lett.

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: Announcement of first direct observation of g.w.
- March 1st: LISA Pathfinder begins science operation
- June 8th : LPF first results
- ....?

The Gravitational Wave Spectrum



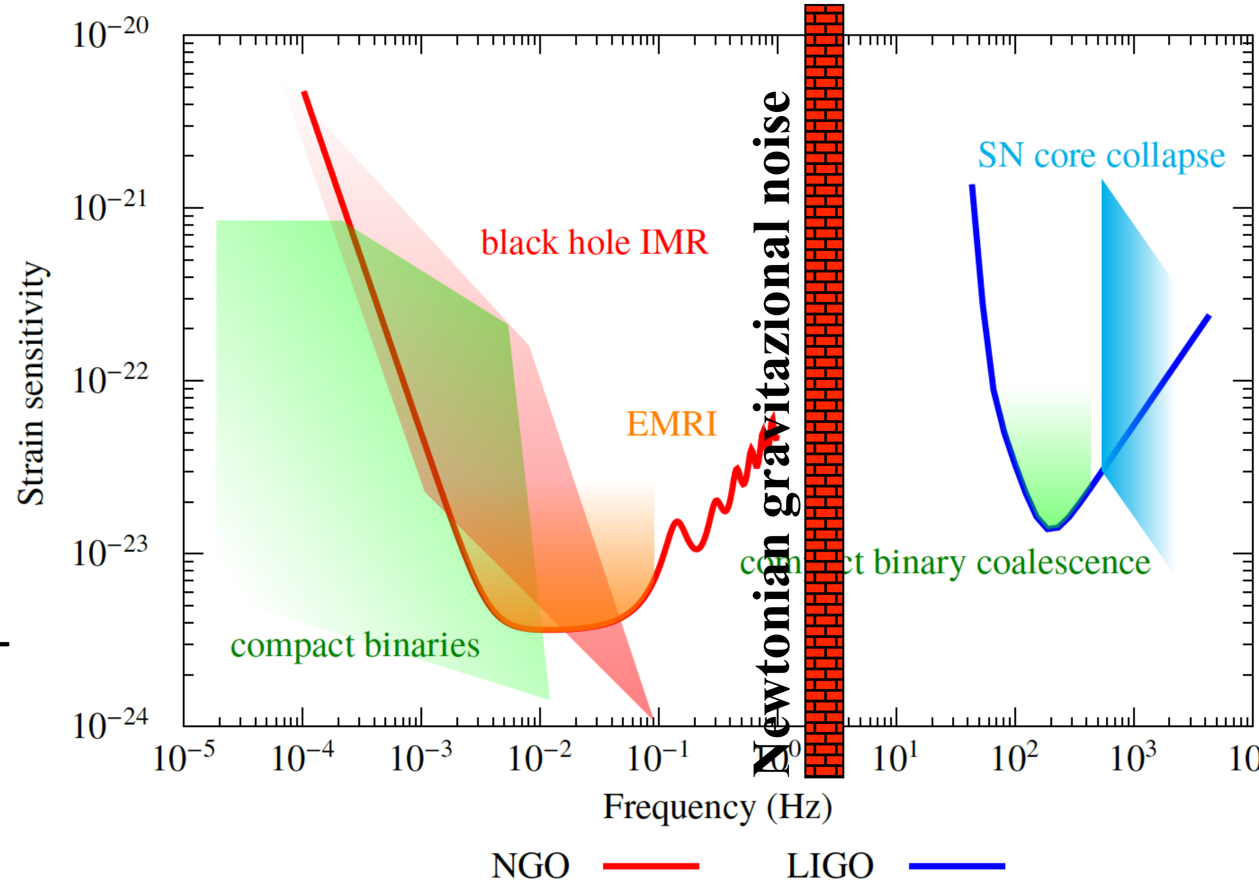


Gravitational Wave Periods
Milliseconds
Minutes
to Hours
Years
to Decades
Billions
of Years

The sensitivity of eLISA and its science

- 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

Binary Star in our Galaxy (WD, NS)

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

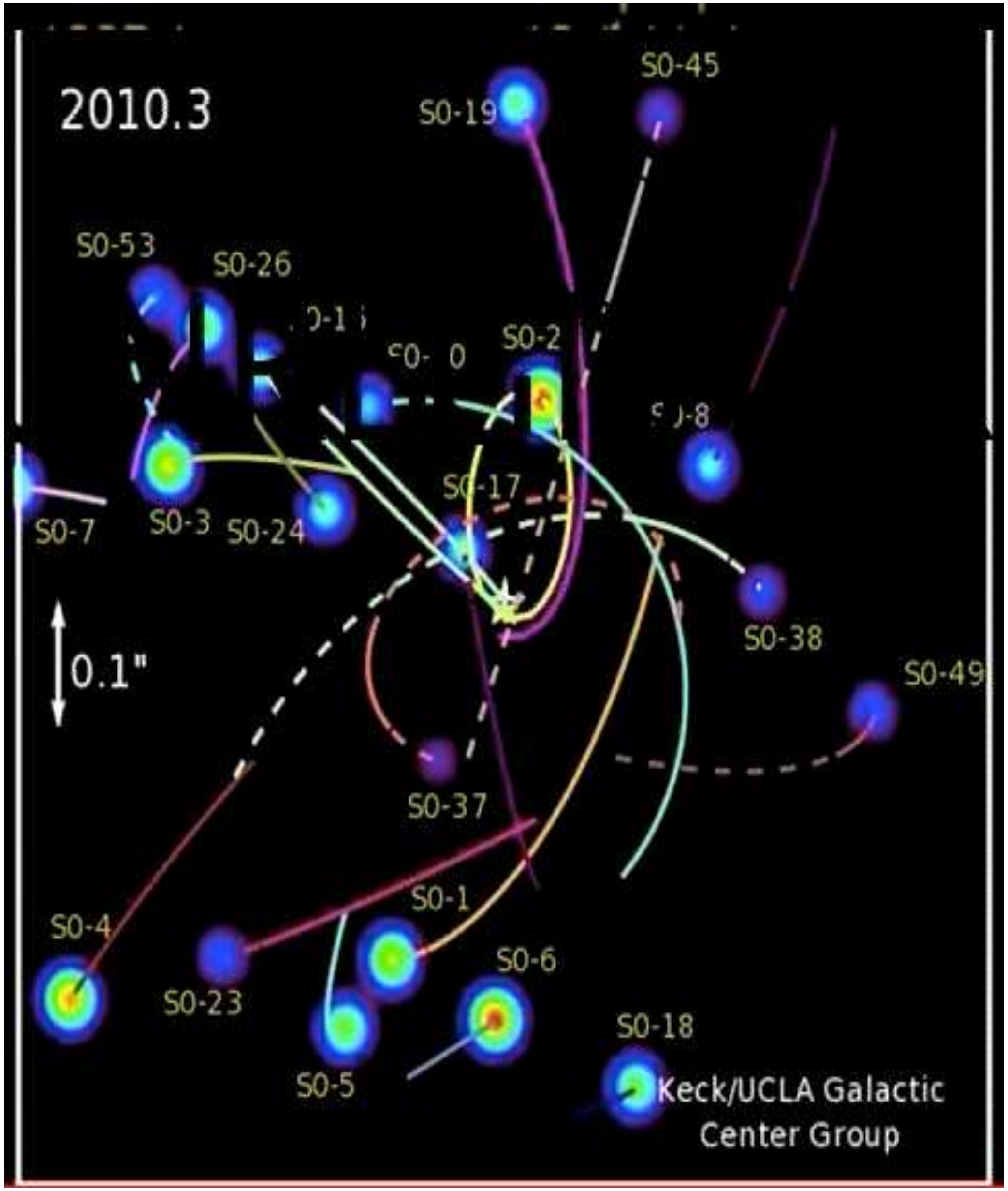
Of some of them we know everything (masses, distance, period...): they're out and waiting for being observed

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

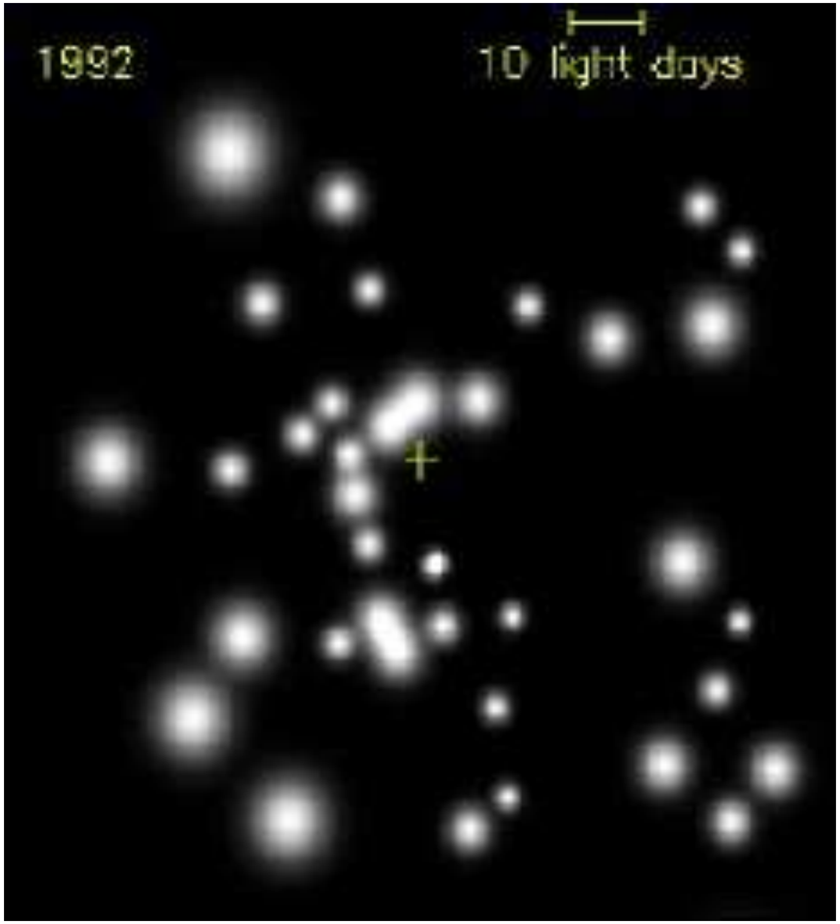
We call them "verification binaries"

Supermassive Black Holes



In the center of our (and probably any) galaxy

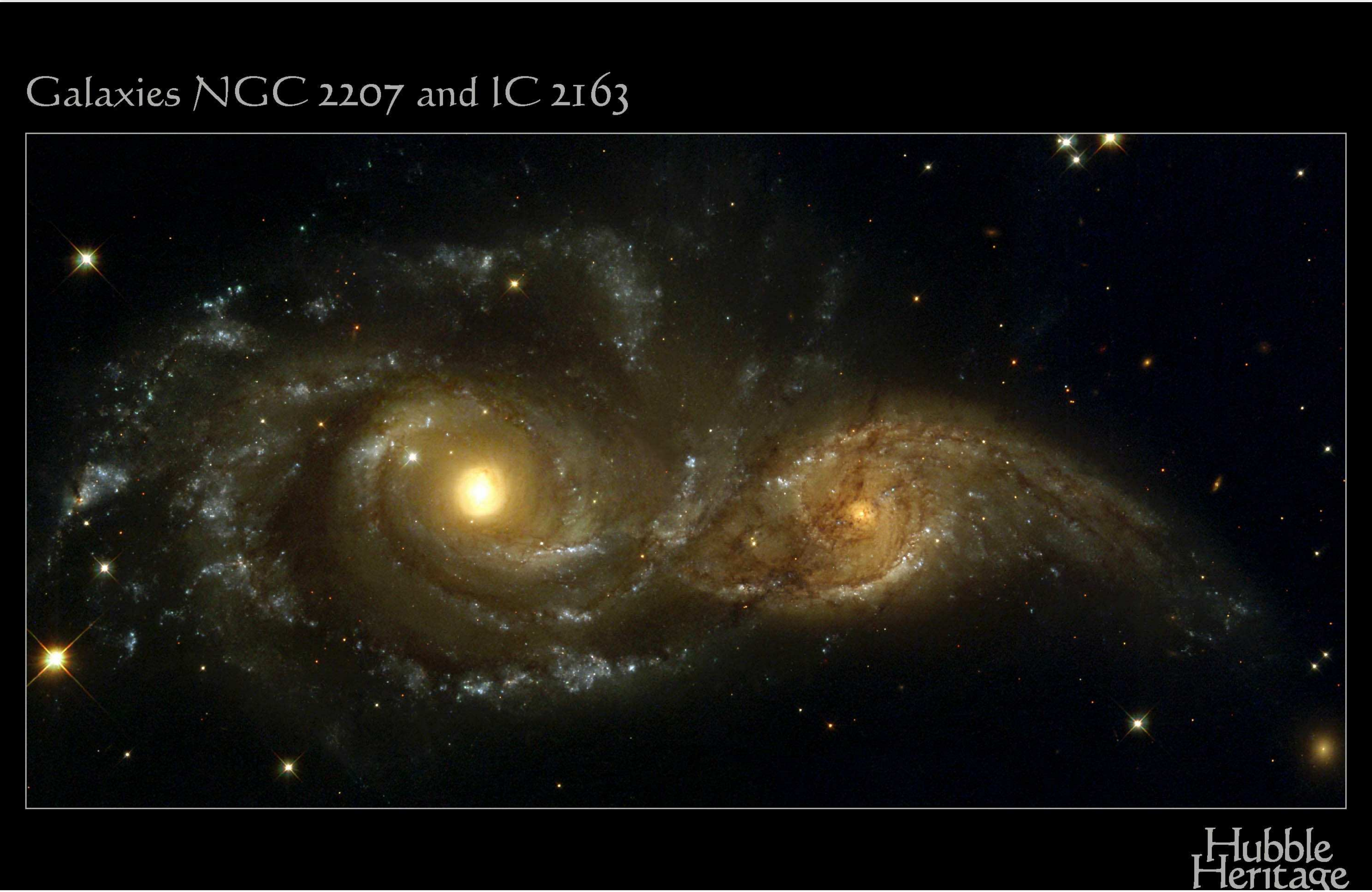
Super Massive Black Holes (SMBH)

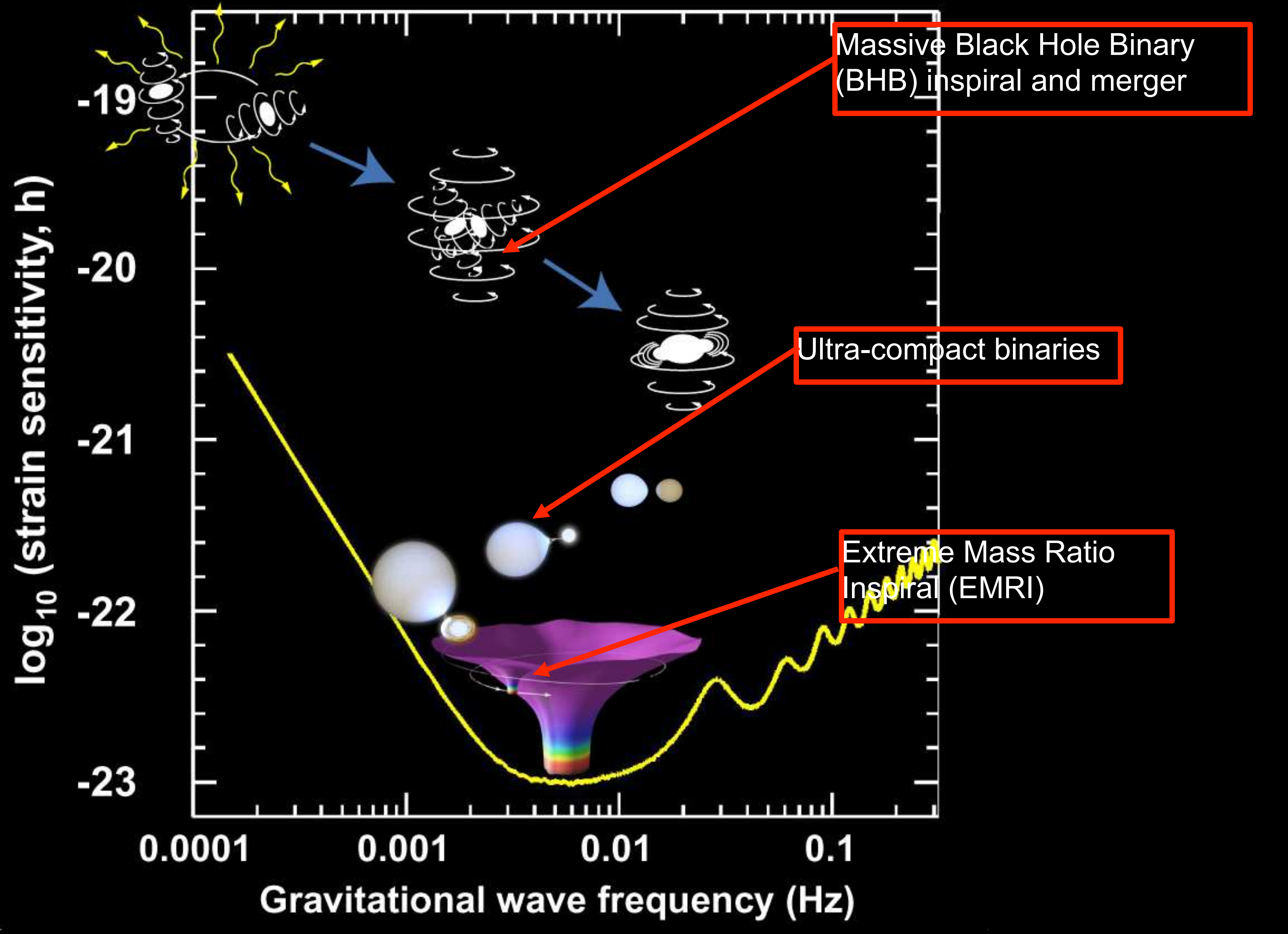


In the center of our (and probably any) galaxy

https://www.youtube.com/watch?v=duoHtJpo4GY
https://www.youtube.com/watch?v=r3qSr5HmGkI

Binaries from galaxy collisions





Massive Black Hole Binary (BHB) inspiral and merger
Ultra-compact binaries
Extreme Mass Ratio Inspiral (EMRI)
-19
-20
-21
-22
-23
$\log_{10}$ (strain sensitivity, h)
0.0001
0.001
0.01
0.1
Gravitational wave frequency (Hz)

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

Gravitational wave tidal acceleration

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

$$\frac{\dot{\nu}_r - \dot{\nu}_e}{\nu} = \frac{\left[\dot{h}(t) - \dot{h}(t - L/c)\right]}{2} + \frac{g_r(t) - g_e(t - L/c)}{c}$$

IFO doppler signal

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

Differential force per unit mass

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

(e)LISA Basic:

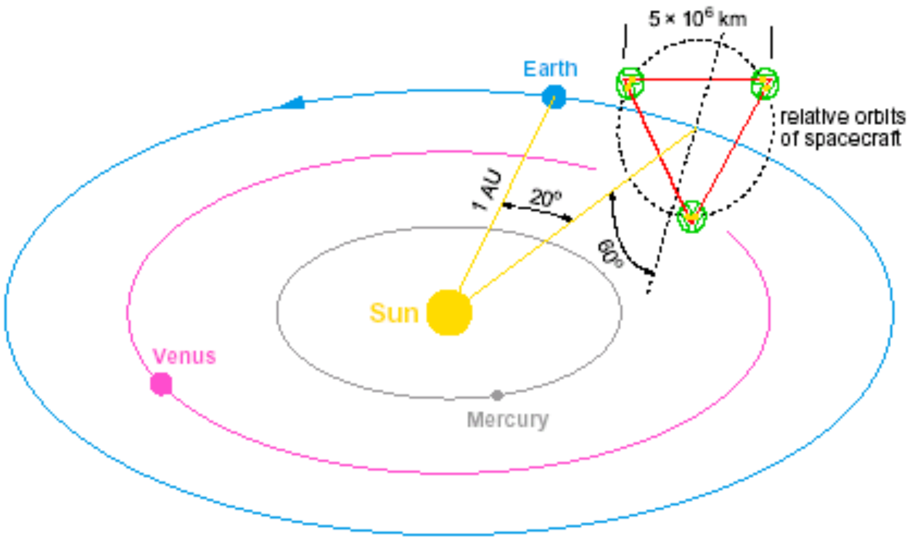
~~1 Redundant configuration~~

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.

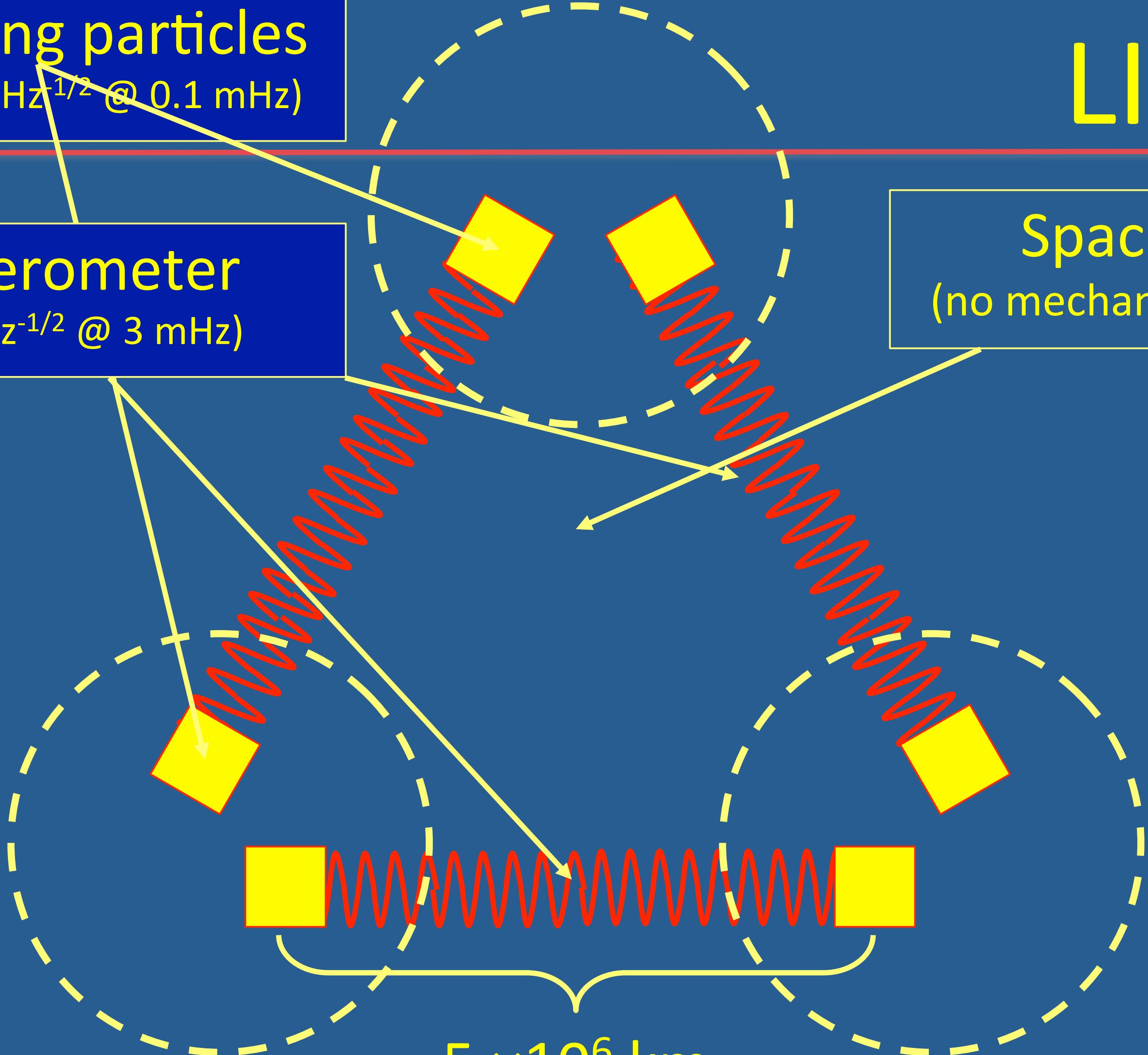
Constant view of Sun (no thermal effects)

LISA

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)

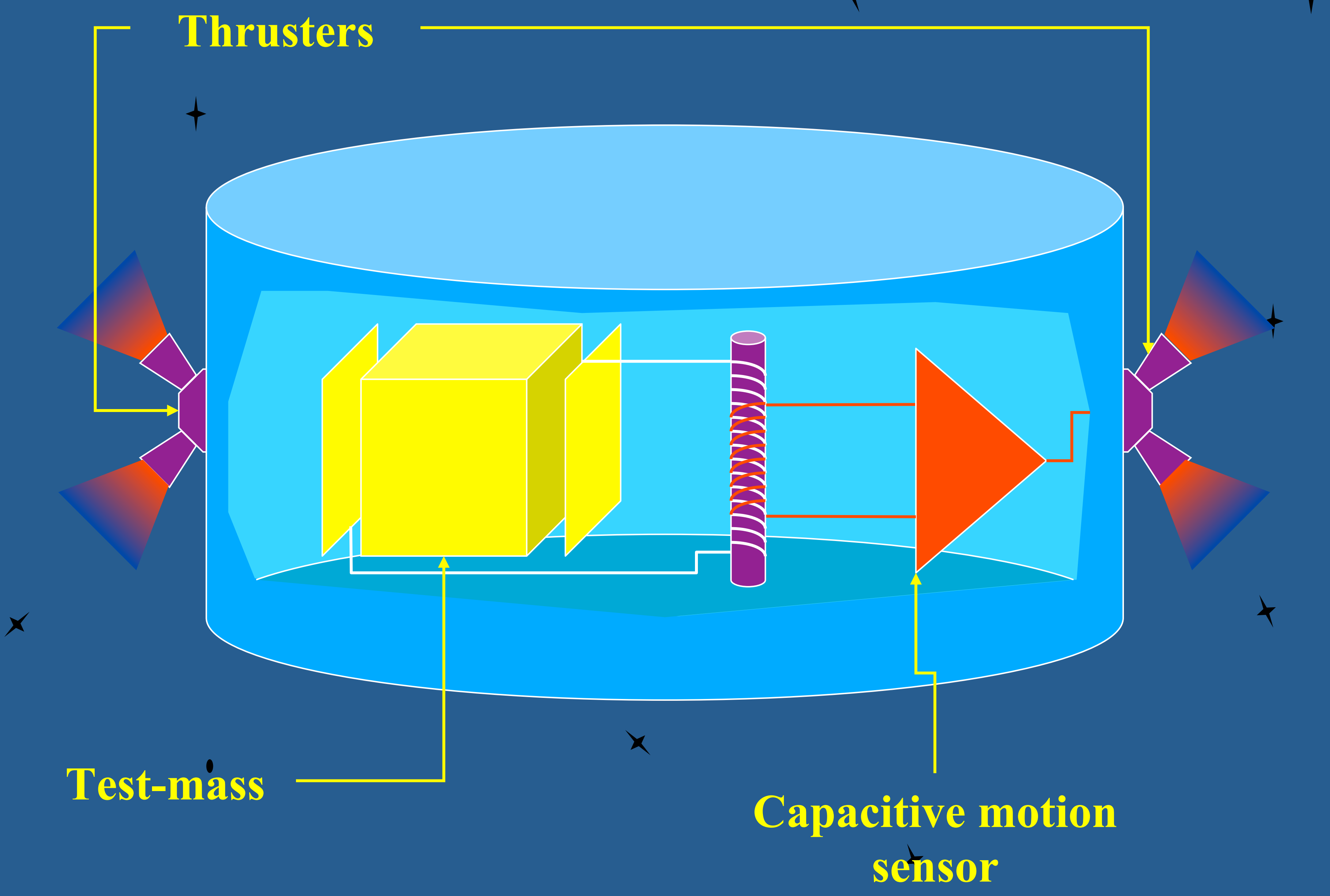


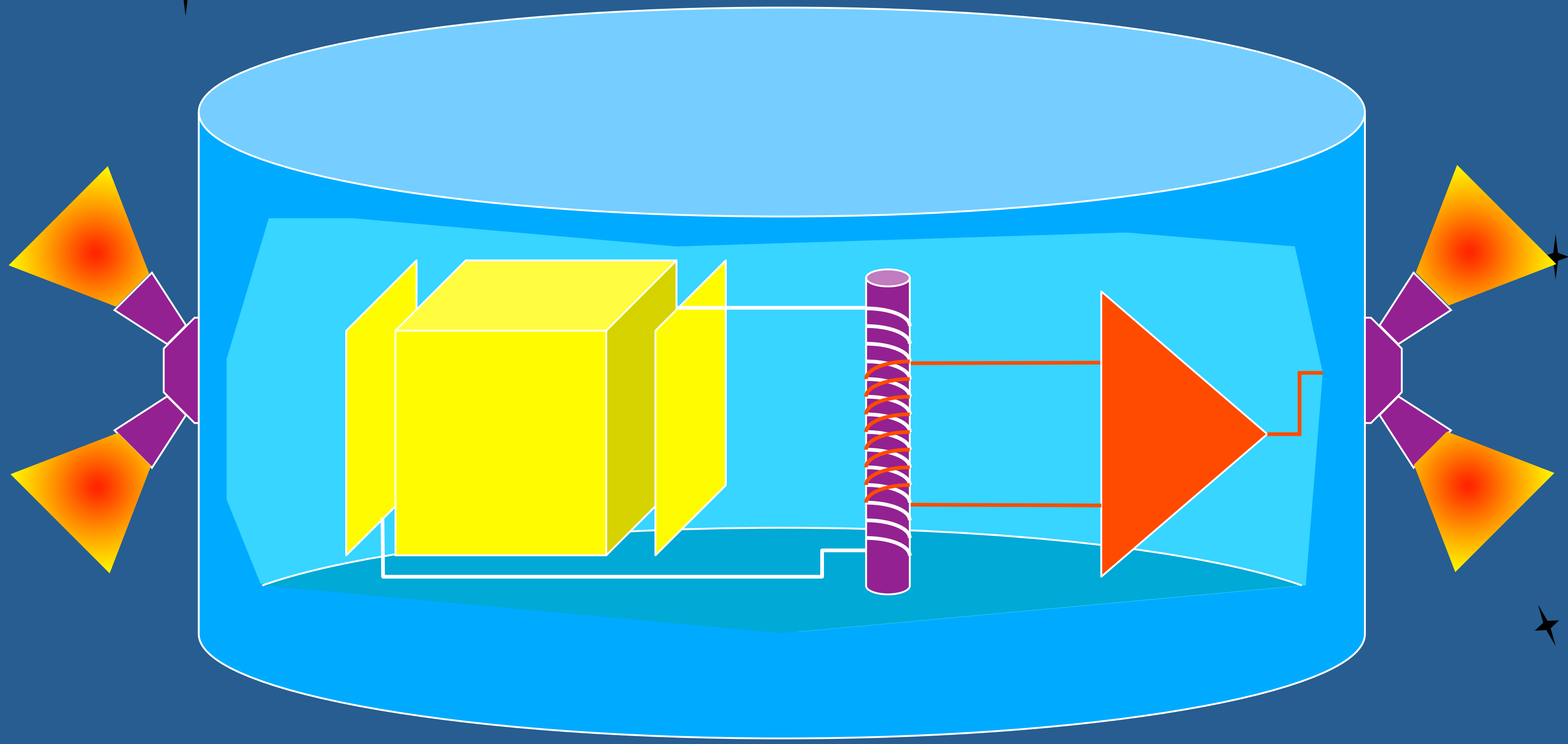
GW at
0.03 mHz – 0.1 Hz

Strain sensitivity

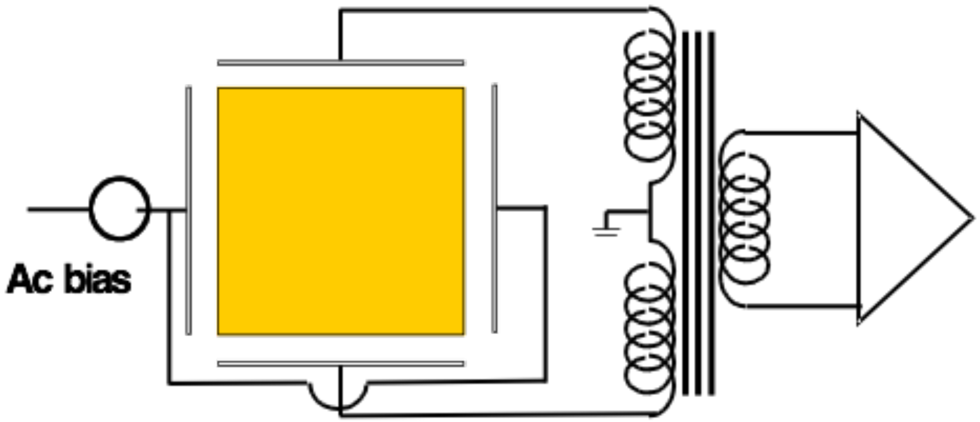
$$h \approx 10^{-20}/\sqrt{Hz} \quad @ \; 10^{-3} Hz$$

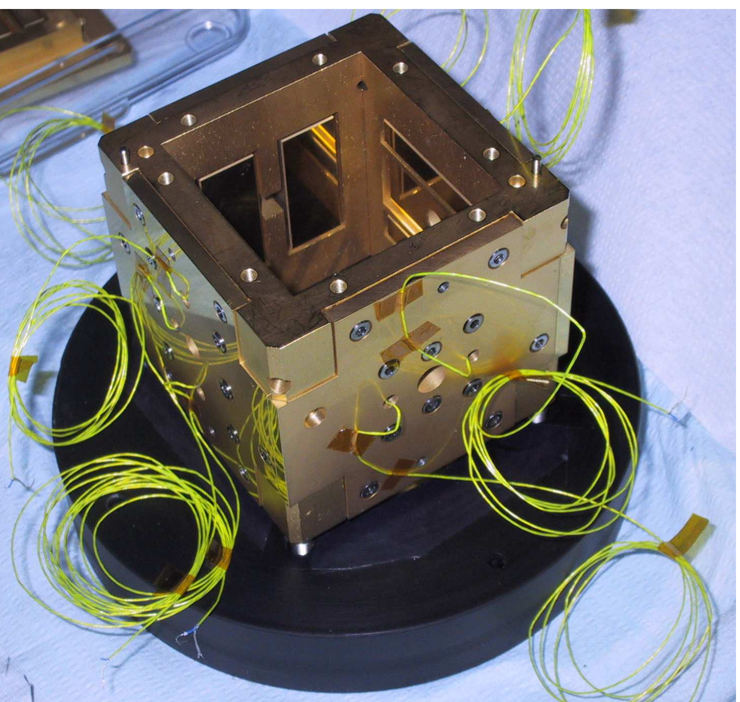
LISA BASIC 5: DRAG-FREE CONTROL LOOP

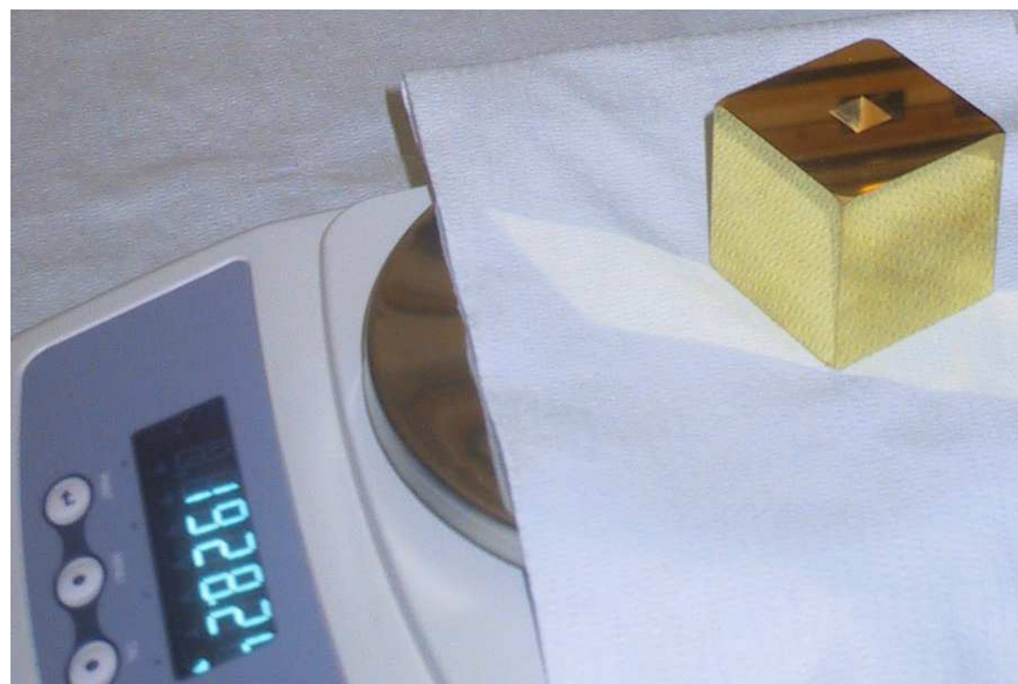




The drag-free key elements: the displacement sensor







The micro-Newton thrusters

- Cold gas developed for Gaia better than requirements
- Now selected as baseline in place of FEEPs

Date 14/09/2012 Ref SRE-PN/18234-12/CGM

From C. Garcia Marirrodriga (SRE-PN) Visa T. Passvogel (SRE-P)

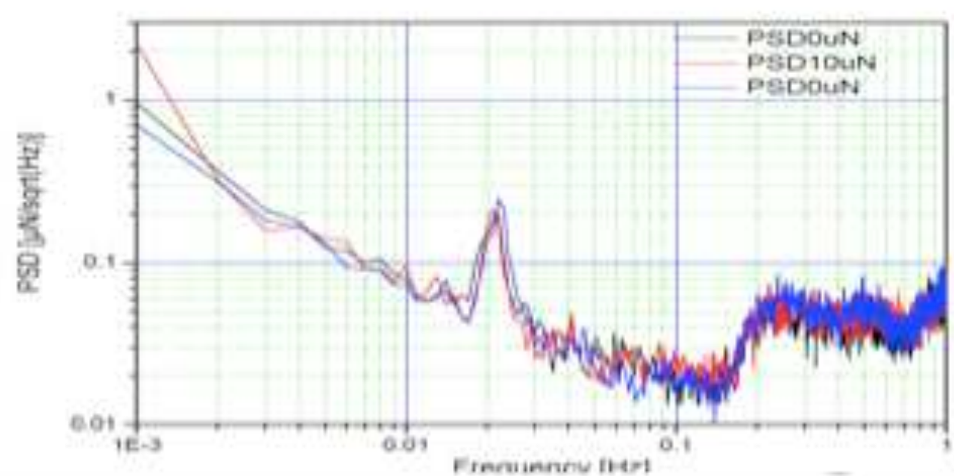
To LISA Pathfinder MPSR Board:
R. Schmidt (DG-I)
W. Veith (TEC-Q)
C. Stavrinidis (TEC-M)
A. Tobias (TEC-S)
M. McCaughrean (SRE-S)
G. Saccoccia (TEC-MP)

Copy A. Giménez Cañete (D/SRE)
P. McNamara (SRE-SA)
S. Vitale (University of Trento)
E. Bachem (DLR)
B. Sanders (TNO)
LPF Project Team & MPS support

Subject: Decision on the change of Micro-Propulsion System baseline for LISA Pathfinder

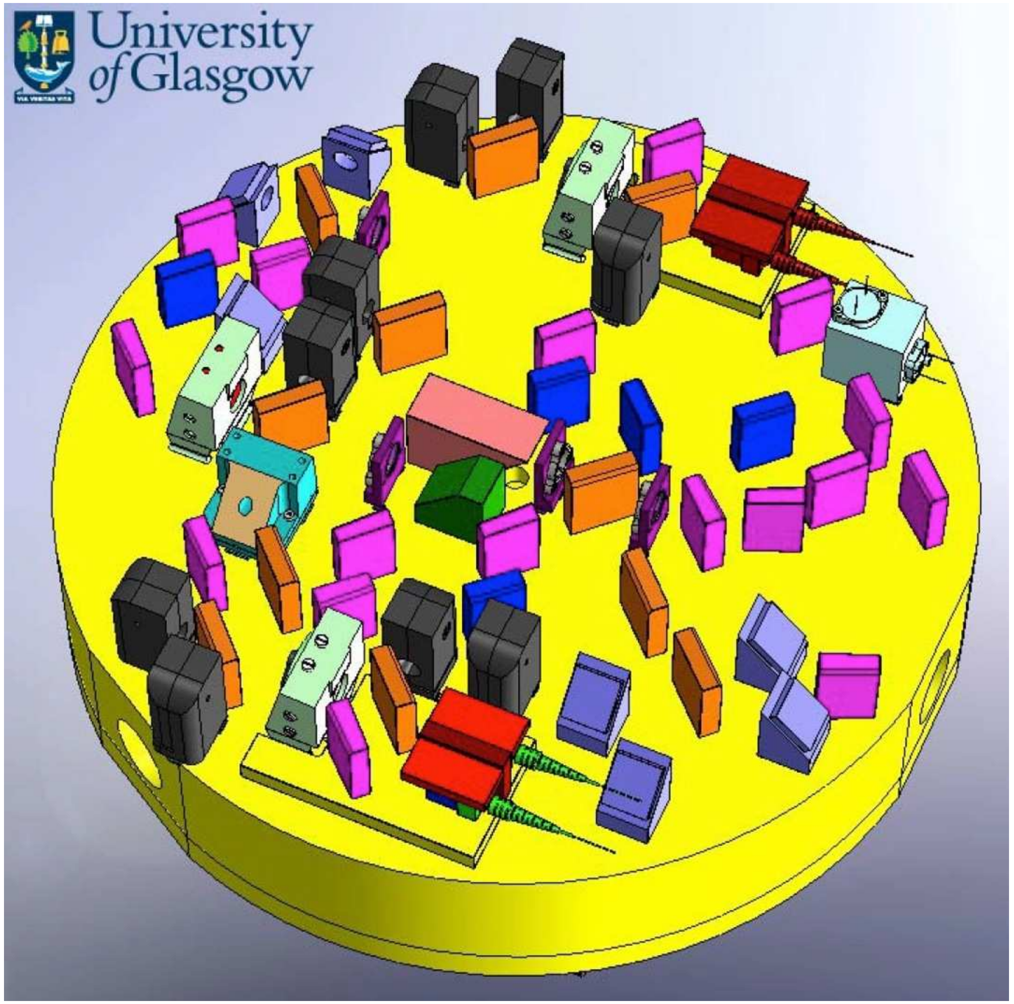
In November 2011 the LISA Pathfinder Micro-Propulsion System Review (MPSR) Board reviewed the status of the Caesium FEEP development tests and of the alternative Cold Gas system. The Board recommended (cf. Board Report DG-IR/2011/109/KL) continuing the testing of the FEEPs on unit and assembly level (TUVT and TAET respectively). In parallel, as a backup, the Board recommended to proceed with and complete the design work for the cold gas system, and to initiate the procurement of the long lead items. The overall status should be presented to the Board not later than April 2012. Such report was released in due time by the LPF Project (cf. SRE-PN/17498-12-GR), including the criteria to reach a decision on the MPS for LPF.

This memorandum summarizes the status reached at the present time, and introduces the LPF Project decision to select the cold gas micro-propulsion system as baseline and to discontinue further development work of the FEEP system within the context of the LISA Pathfinder project.



The optical bench

- Monolithic assembly, via silica bonding
- Carries all interferometry: both local and between S/Cs.



Recent facts

- 2010 - NASA Decadal review: high priority for LISA
- 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 work and the new project (NGO-eLISA) is presented to ESA
- April 2012: First "large" mission– L1 (launch 2020) is Juice; the second – L2: 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)

From LISA to eLISA / NGO

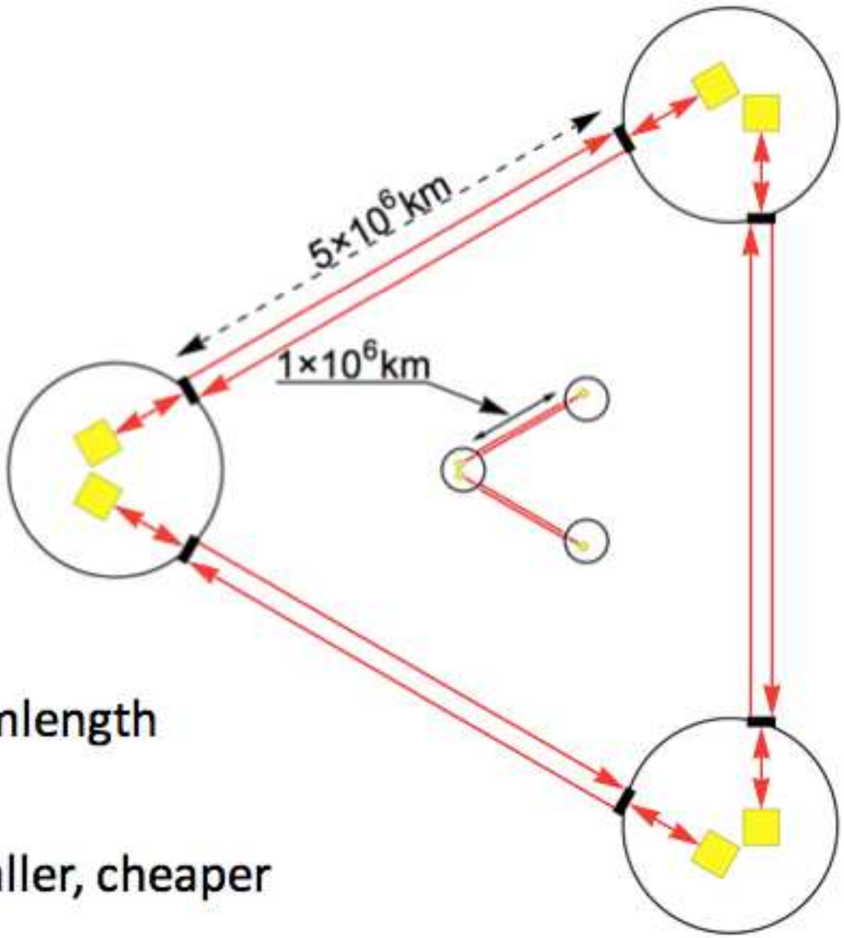
- Single link IFO noise
  < 10 pm/√Hz @1 mHz
- Single TM stray acceleration
  < 3 fm/(s^2√Hz) @ 0.1 mHz
- 3 non-contacting ("drag-free") satellites

- *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



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.

https://www.elisascience.org/

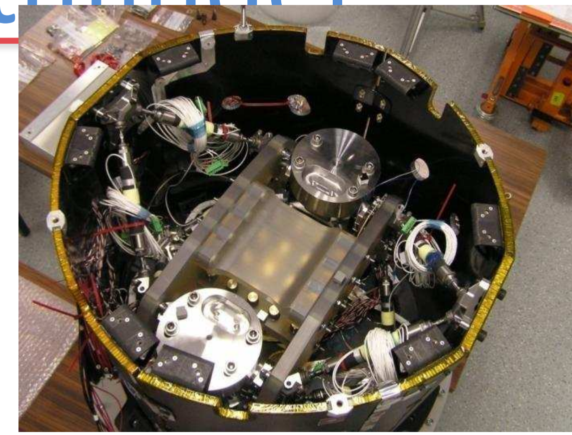
Can we trust to test the free fall on LISA ?

- How good is the free fall we can achieve ?

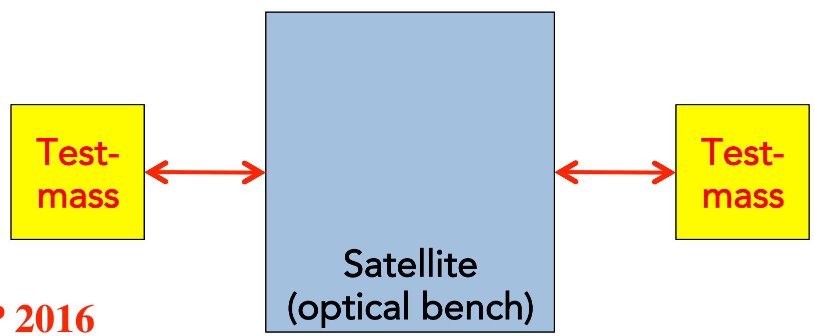
- How relevant are the spurious forces acting on the Test Mass ?

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

The concept of LISA Pathfinder

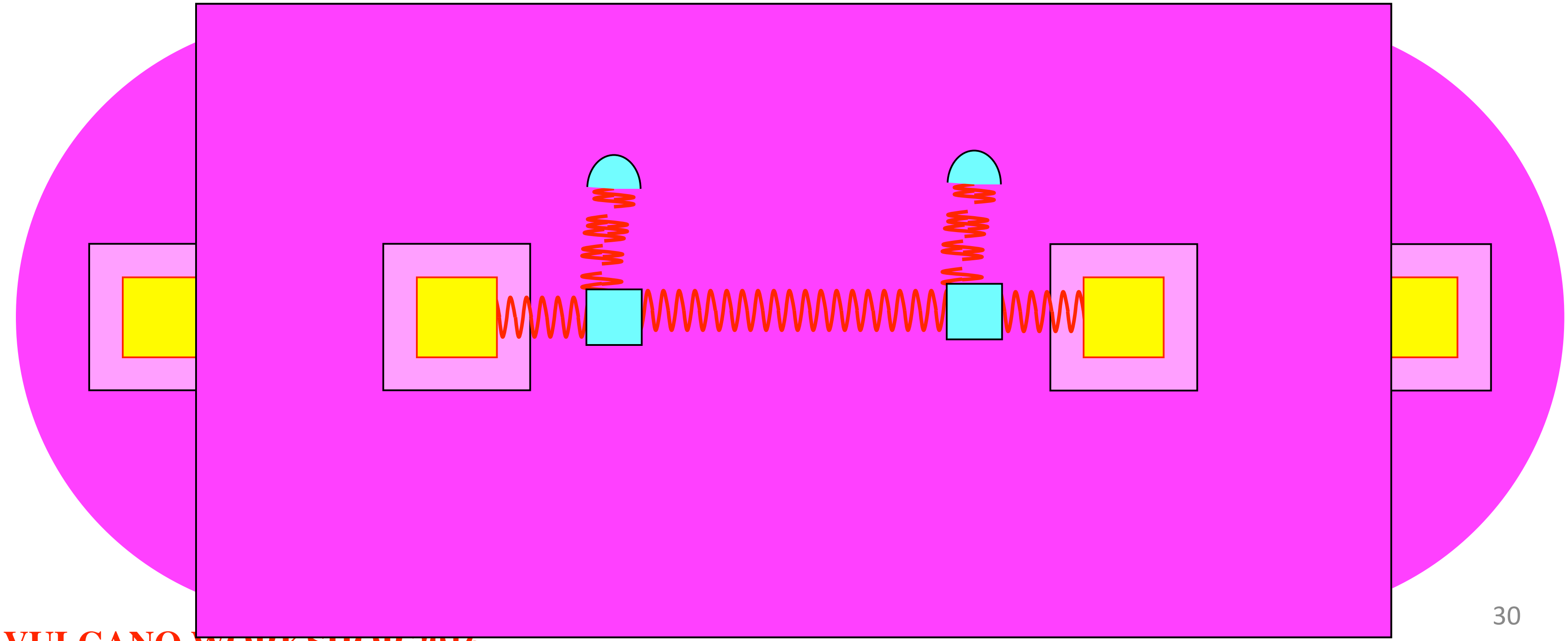


- Sh[illegible] of NGO/LISA and host it aboard one S/C
- Eliminate S/C to S/C link
- keep the local measurement between Test Masses and S/C



validation of the measurement

- One 5-million-kilometer LISA arm squeezed into one S/C
- Demonstrate relative acceleration within a factor ≈10



The LISA Pathfinder 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

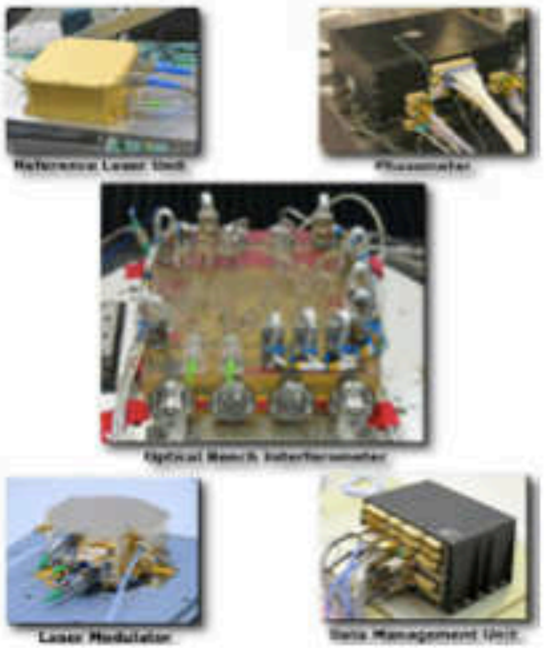
2 Test Masses and 1 optical bench

2 TM and 2 Interferometers

LPF Interferometer metrology

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

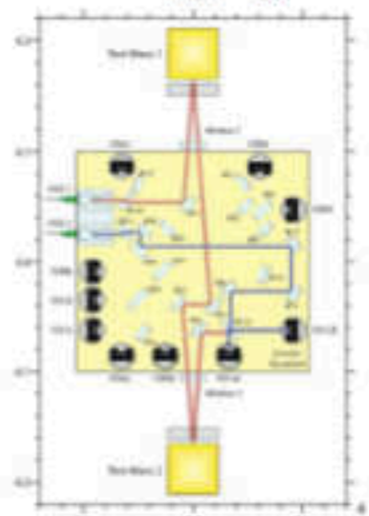
- First high-precision interferometer coupled to free-falling TM in space
- Demonstration of eLISA local position measurement
- Zerodur optical bench with 4 heterodyne interferometers



o_{12} $(x_2 - x_1)$

TM - TM

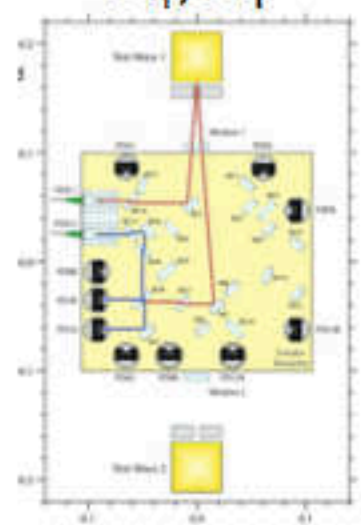
$+\phi_1, \eta_1$



o_1 $(x_1 - x_{SC})$

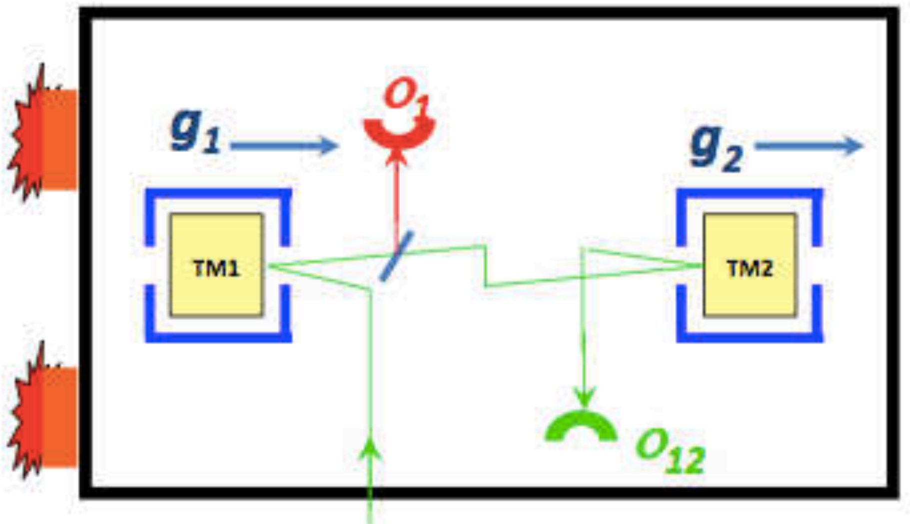
TM - SC

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



+ frequency and phase stabilization IFO

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)

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

«gravitational observable»
differential force per unit mass

LISA Pathfinder as a diff. accelerometer

Newton's Eqns:

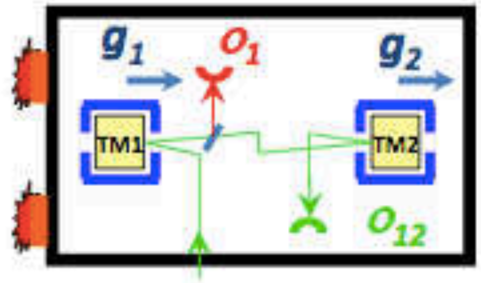
$$m\ddot{x}_1 = F_1 - m\,\omega_{1p}^2 (x_1 - x_{SC})$$

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

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 ↓

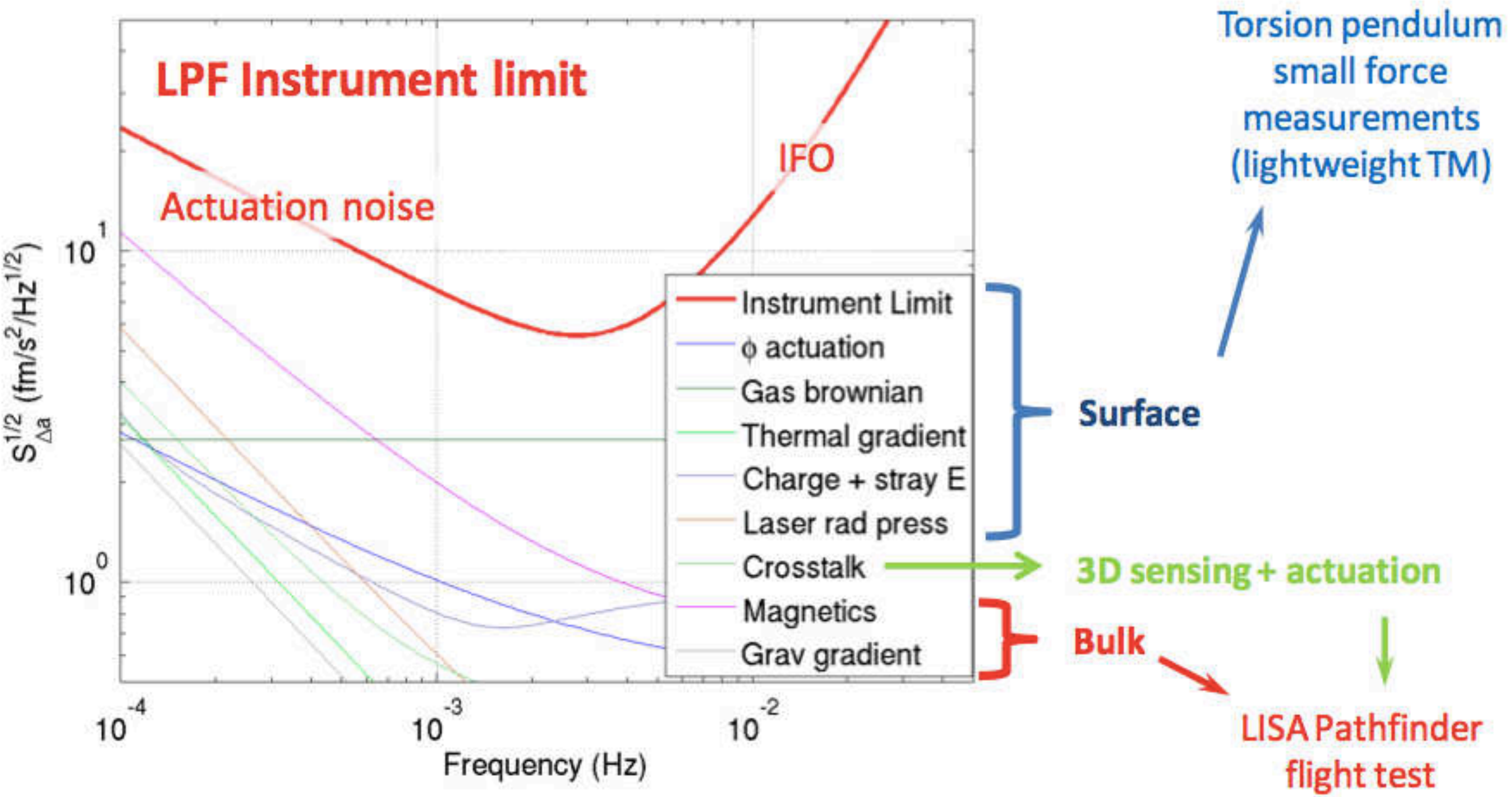
$$\Delta\hat{g} \equiv \ddot{o}_{12} - \frac{F_{ES}}{m} + \left(\omega_{2p}^2 - \omega_{1p}^2\right)o_1 + \omega_{2p}^2 o_{12} = \Delta g + \text{IFO noise}$$

Commanded control forces

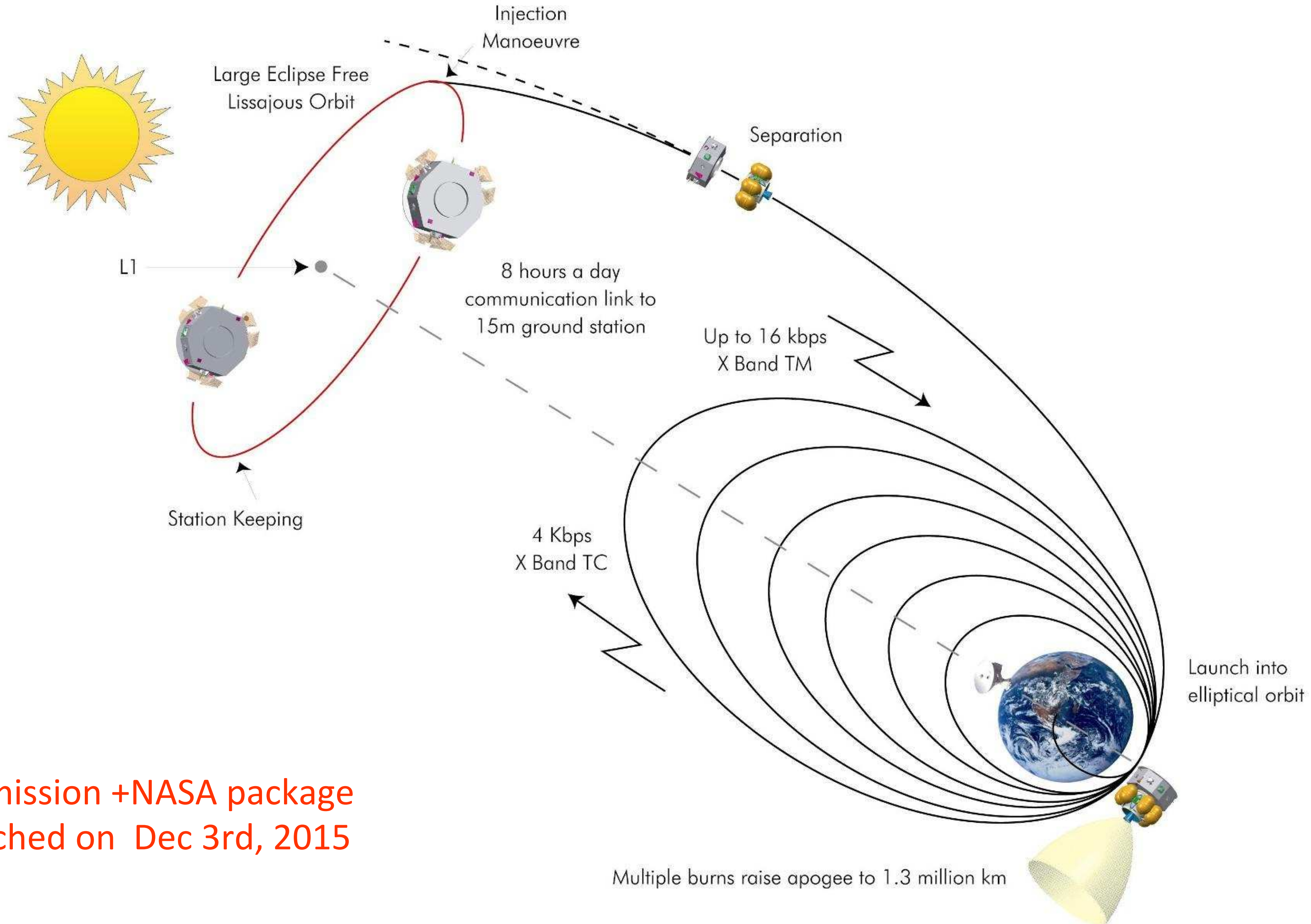
Elastic coupling

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

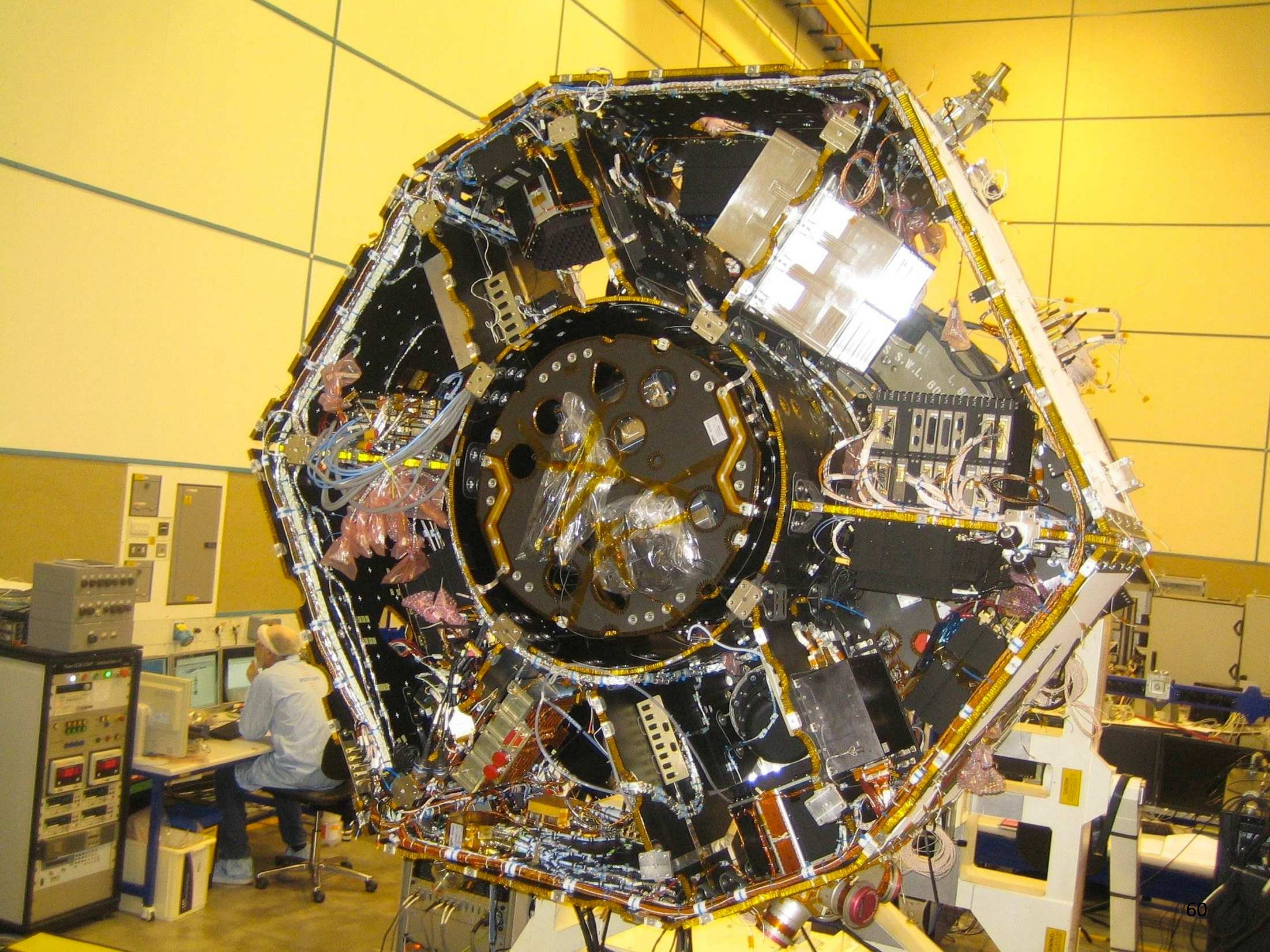
LPF performance and TM acceleration noise sources for eLISA



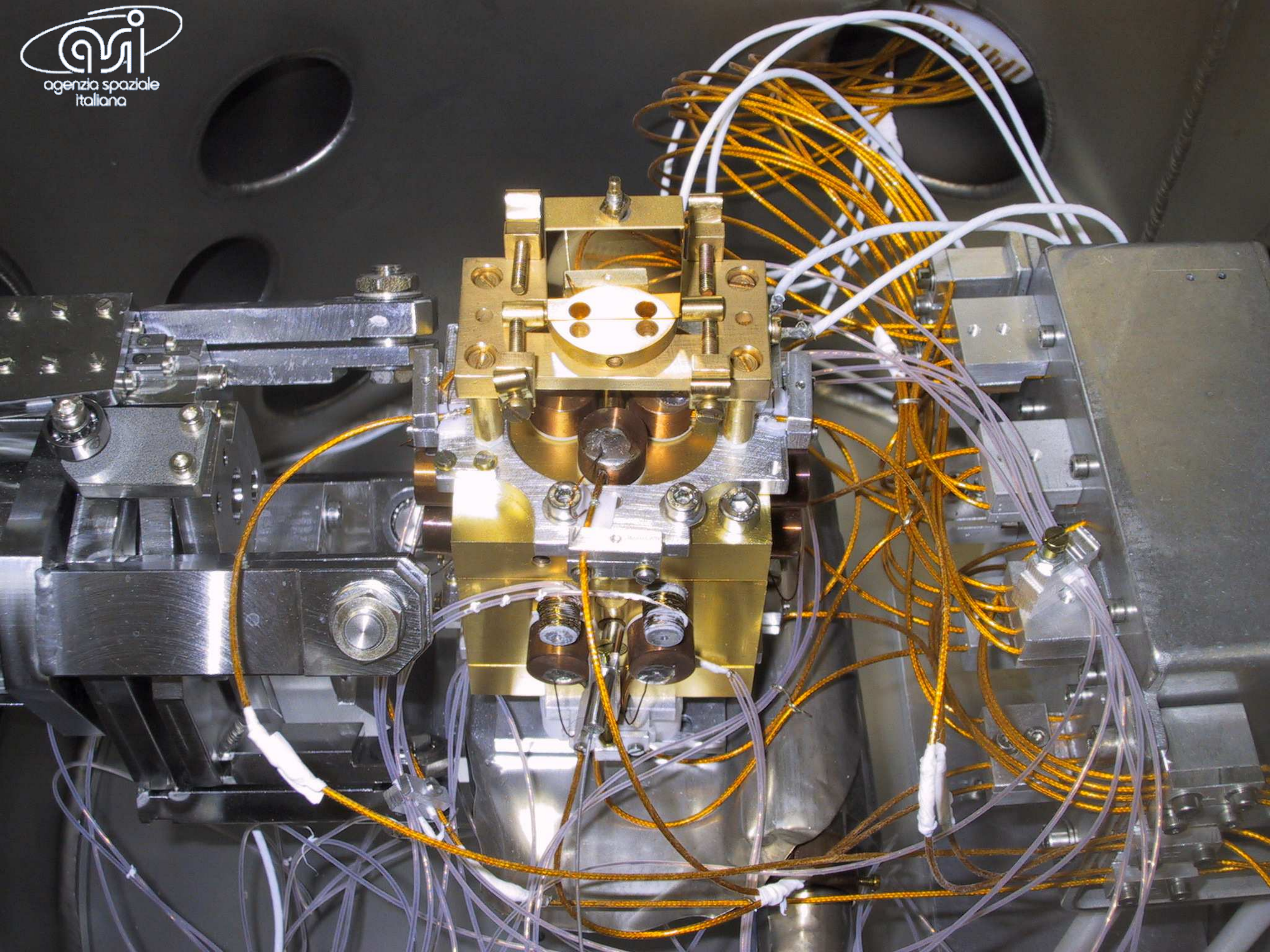
LISA Pathfinder



ESA mission +NASA package
Launched on Dec 3rd, 2015




lisa pathfinder
esa
APCO
TECHNOLOGIES


agenzia spaziale
italiana

Design element for LISA/eLISA that can be verified by LISA Pathfinder

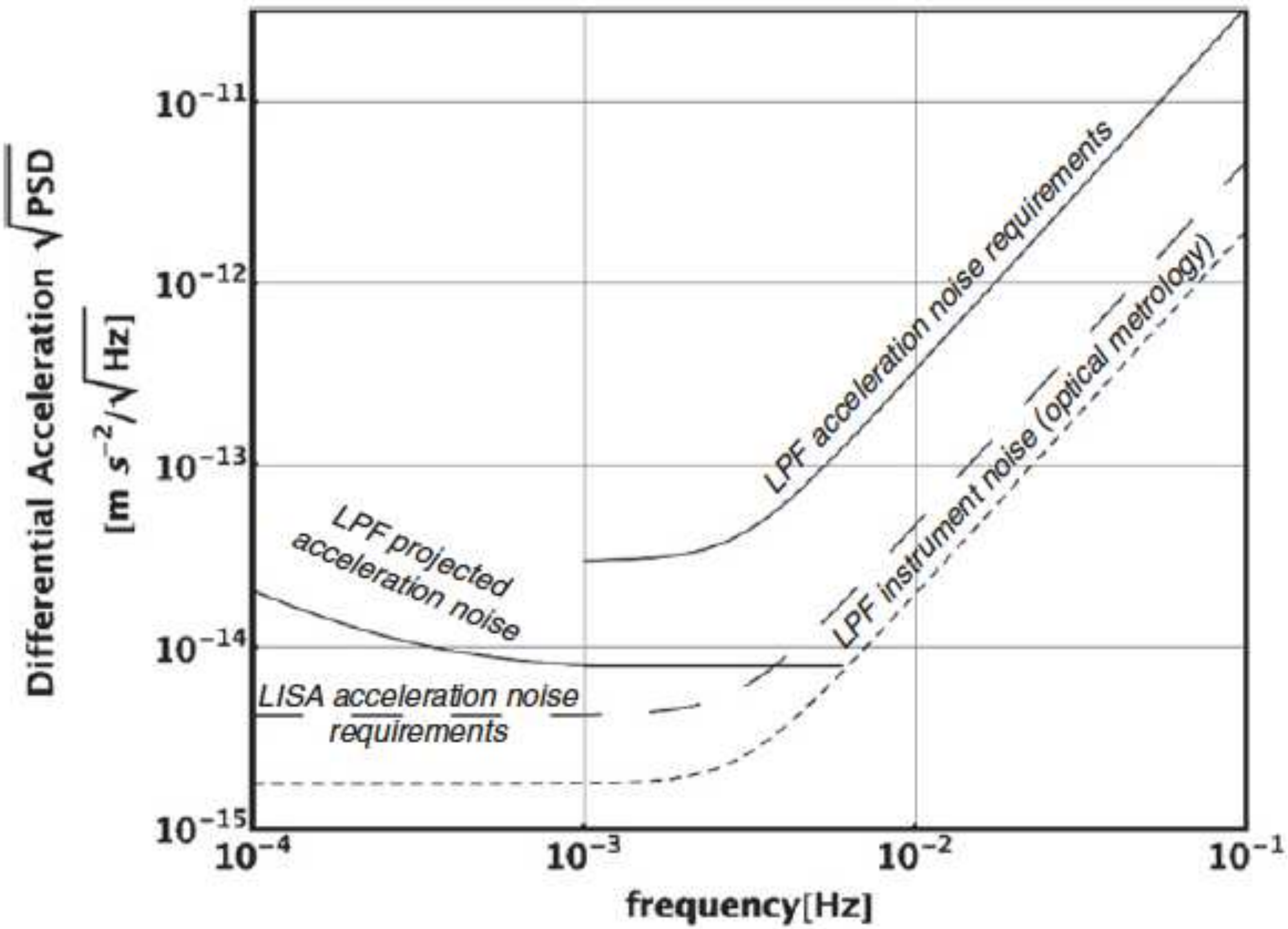
- Free falling TM, very low level of unwanted accelerations.
  - drag-free controls
  - micropropulsori
  - inertial sensors with heavy masses, large gaps and caging mechanism
  - very stable electrostatic actuation
  - Charge control of the TM charge, no contact.
  - Hiigh thermomechanic stability of 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 optical systems

Testabili solo in orbita

- 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

Expected performances of LISA Pathfinder is close to eLISA specs

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



How is it going ?

something does leak:
http://sci.esa.int/lisa-pathfinder/
https://twitter.com/hashtag/lisapathfinder
https://twitter.com/hashtag/GoLPF

Oliver Jennrich @OliverJennrich · 15 mar
Living the fast and dangerous life: shaking things by a micrometer with 10 mHz.
@ESA_LPF #LPF **#LISAPathfinder**
6 12

Stefano Vitale @VitaleTrident
And the charge management system works as predicted.
#GOLPF

From the horse's mouth…

lisa pathfinder

nature

Successful test drive for space-based gravitational-wave detector

Mission paves the way for planned €1-billion space observatory

25 February 2016

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Scientists have long dreamed of launching a constellation of detectors into space to observe gravitational waves — the ripples in space-time predicted by Albert Einstein and observed for the first time earlier this month.

That dream is now a step closer to reality. Researchers working on a €400-million (US$440-million) mission to try out the necessary technology in space for the first time — involving firing lasers between metal cubes in free fall — have told *Nature* that the initial test drive is performing just as well as they had hoped.

Nature Special: Gravitational Waves

"I think we can now say that the principle has worked," says Paul McNamara, project scientist for the LISA Pathfinder mission, which launched last December. "We believe that we now are in a good shape to look to the future and look to the next generation."

"Everything works as we designed it. It's sort of magical, and you rarely see that in your career as an experimentalist," says Stefano Vitale, a physicist at the University of Trento in Italy, and a principal investigator for the Pathfinder mission.

PRECISION LAB IN SPACE

LISA Pathfinder has shown that an intricate experiment consisting of two metal cubes in freefall, isolated from all forces except gravity, can operate in space.

At the heart of Pathfinder are two free-falling metal cubes, shielded from all forces except gravity by their housing.

Any disturbance to the relative motion of the cubes affects

"I think we can now say that the principle has worked" Paul McNamara, LPF project scientist

"Everything works as we designed it. It's sort of magical, and you rarely see that in your career as an experimentalist," Stefano Vitale, principal investigator for the Pathfinder mission.

"Woo-hoo!" Cesar Garcia, LPF Project Manager

http://www.nature.com/news/successful-test-drive-for-space-based-gravitational-wave-detector-1.19452

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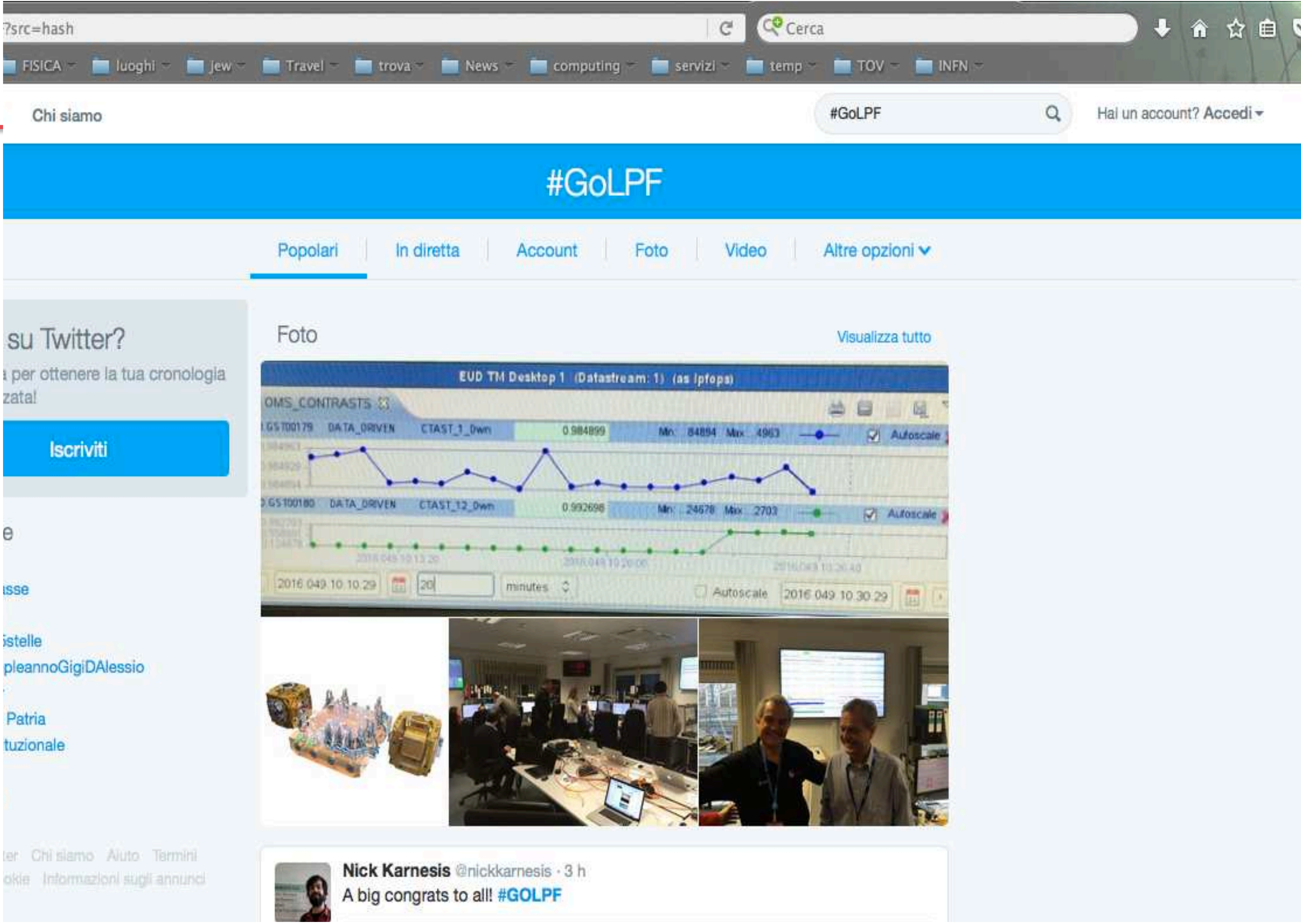
Si librano nello spazio i cubetti lanciati da Lisa Pathfinder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zata!
Iscriviti
Foto
Visualizza tutto
EUD TM Desktop 1 (Datastream: 1) (as lpfops)
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isse
stelle
pleannoGigiDAlessio
Patria
tuzionale
Chi siamo
Aiuto
Termini
Informazioni sugli annunci
Nick Karnesis @nickkarnesis · 3 h
A big congrats to all! #GOLPF

Concluding...


Miquel Nofrarias @miqno · 4 mag Visualizza traduzione
First #LISAPathfinder results are coming. It took more than a decade and hundreds of people to get here!

Stefano Vitale @VitaleTrident
LPF paper submitted! Stay tuned.

#GOLPF

Stay tuned for press conference:

June 7th 12:00 CET !


That's all Folks!

lisa pathfinder

Thanks to a great team !

OHB CGS

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

INFN

University of Glasgow

UNIVERSITÀ DEGLI STUDI DI TRENTO

ETH Eidgenössische Technische Hochschule Zürich Swiss Federal Institute of Technology Zurich

IFR

UNIVERSITY OF BIRMINGHAM

IEEC

CSIC

RUAG Aerospace

KAYSER-THREDE

APC

University of Zurich UZH

NASA

AIRBUS DEFENCE & SPACE

esa ESTEC

ZARM

ThalesAlenia Space

Universitat de Barcelona

Università di Roma Tor Vergata

Selex ES

esa

SRON Netherlands Institute for Space Research

CDTI

SSO Swiss Space Office

UK SPACE AGENCY

asi agenzia spaziale italiana

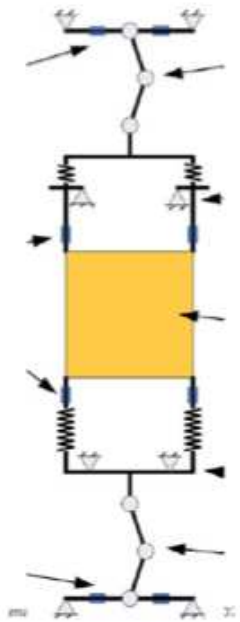
DLR Deutsches Zentrum für Luft- und Raumfahrt

cnes

Caging – decaging – TM release

UNIVERSITY OF TRENTO - Italy

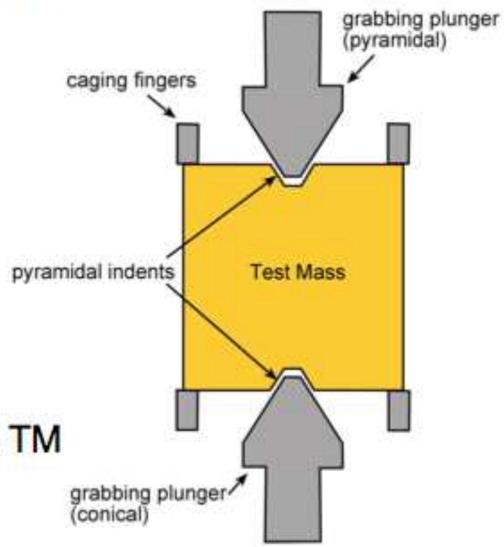
RUAG



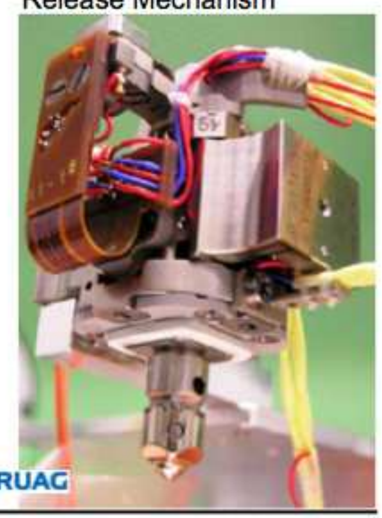
The Caging and Vent Mechanism

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

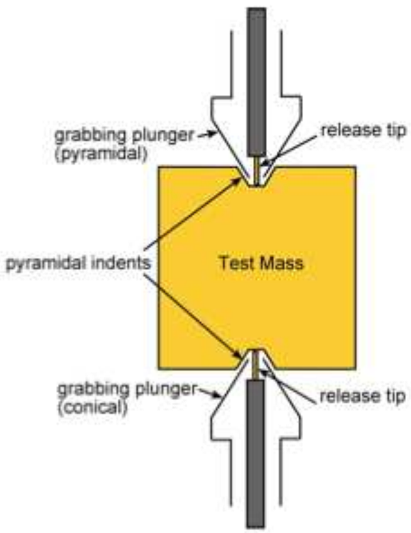


The Grabbing Positioning and Release Mechanism



- Medium metallic adhesion is present between plungers and TM

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

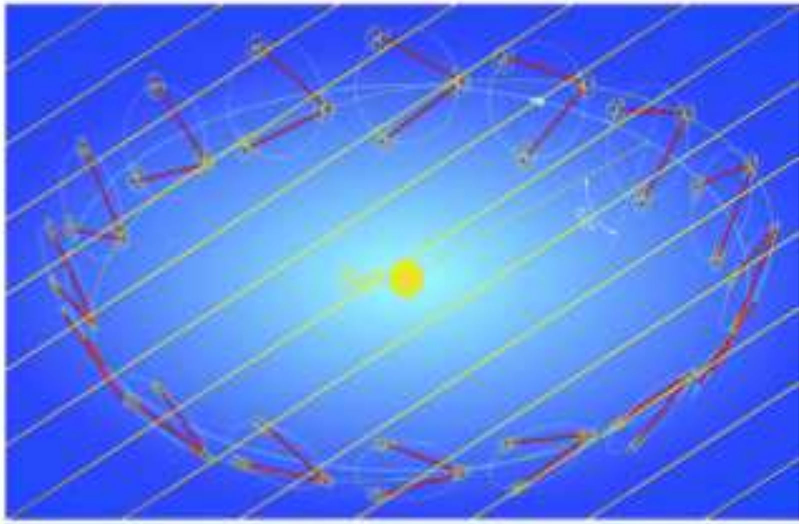
- Low force/quick piezo mechanism for TM **release to free-falling conditions**

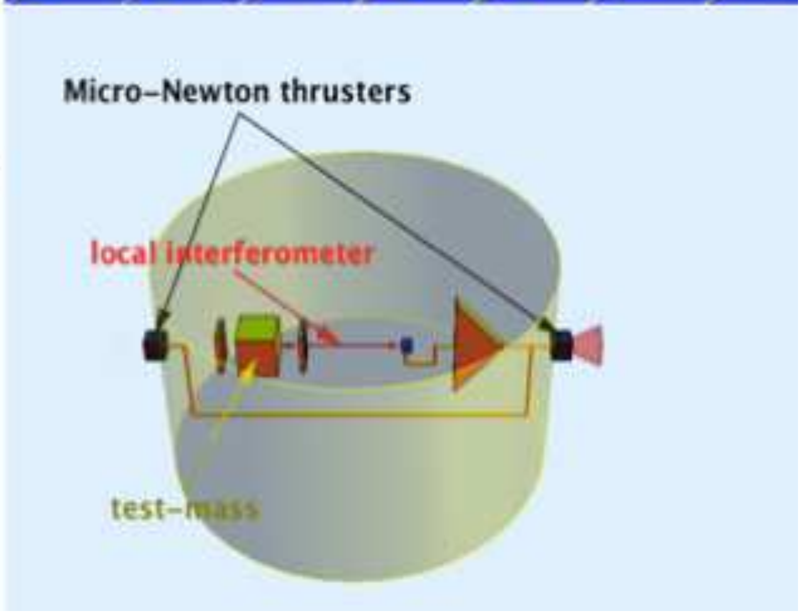
$$v_{max} = 5\frac{\mu m}{s}$$

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

Basic concepts of LISA

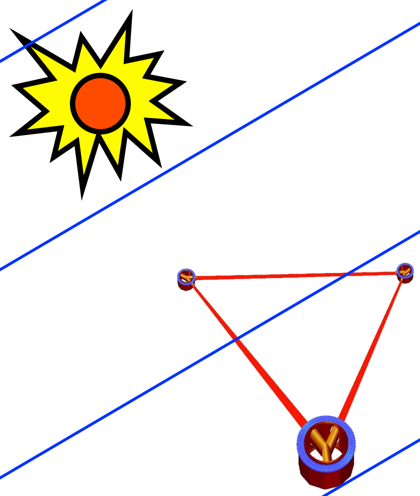
- Orbits:
  - Satellites follow independent heliocentric orbits. No formation keeping needed
  - Constellation rotates within waves and give source location (and distance)
- Non contacting spacecraft
  - Position of spacecraft relative to test-mass is measured by local interferometer
  - Spacecraft is kept centered on test-mass by acting on micro-Newton thrusters.





Angular Resolution with LISA

- Measurements on detected sources:
  - $\Delta\Theta \sim 1' - 1^o$
  - Δ(mass,distance) $\leq$ 1%



Noise sources for LISA: $\phi(t) = \frac{\omega}{c} X(t)$

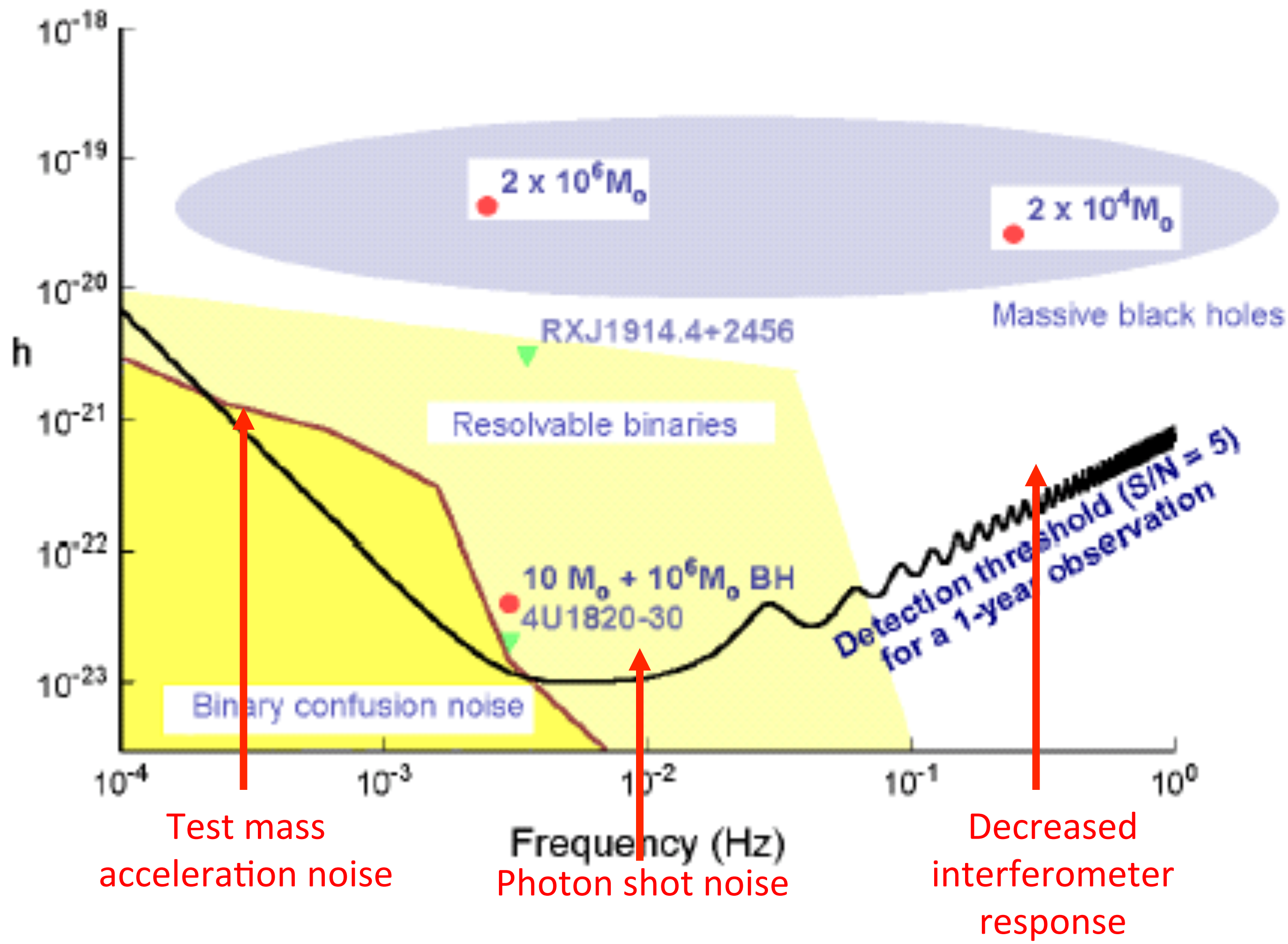
$$\delta\phi(t) = \frac{\omega}{c}[Lh(t) + \delta x_n(t)] + \frac{\Delta L}{c}\delta\omega(t)$$

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
    - .....
- Confusion foreground of galactic binaries gw !

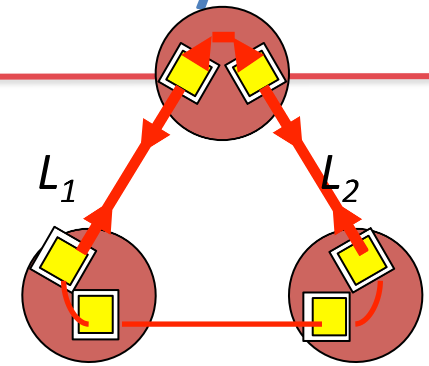
$$\delta x_n = \frac{F_n}{M\omega^2}$$

LISA Sensitivity Curve



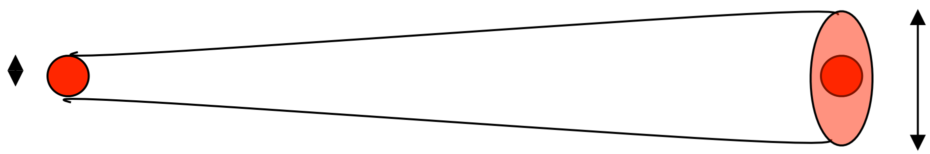
Sensitivity curve for 1 year integration and S/N=5

LISA Basic 3 - Interferometry



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

Laser divergence:



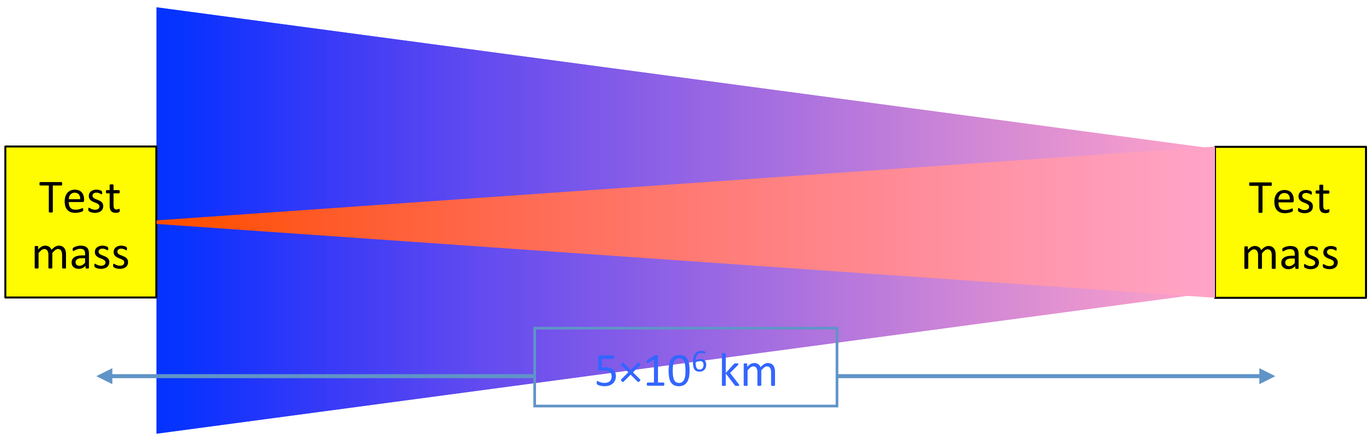
Shot Noise:

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

Laser transponding: outgoing light phase locked to incoming beam

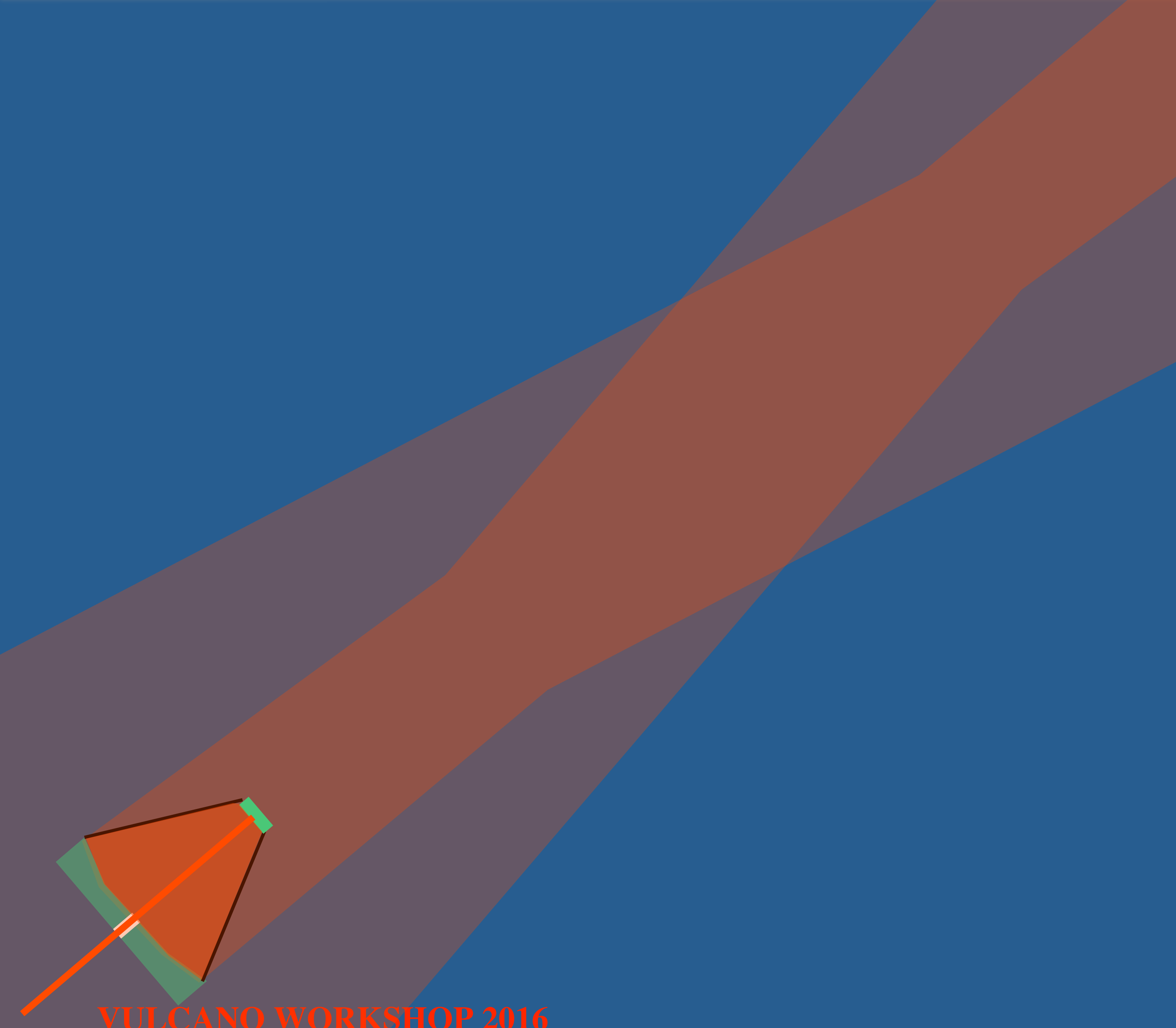
Goal: keep all optical path errors within 40 $\mathrm{pm/Hz^{1/2}}$

LISA Basic 3: the laser transponding scheme



Power loss due to beam divergence makes interferometry by reflection impossible

A laser trasponder

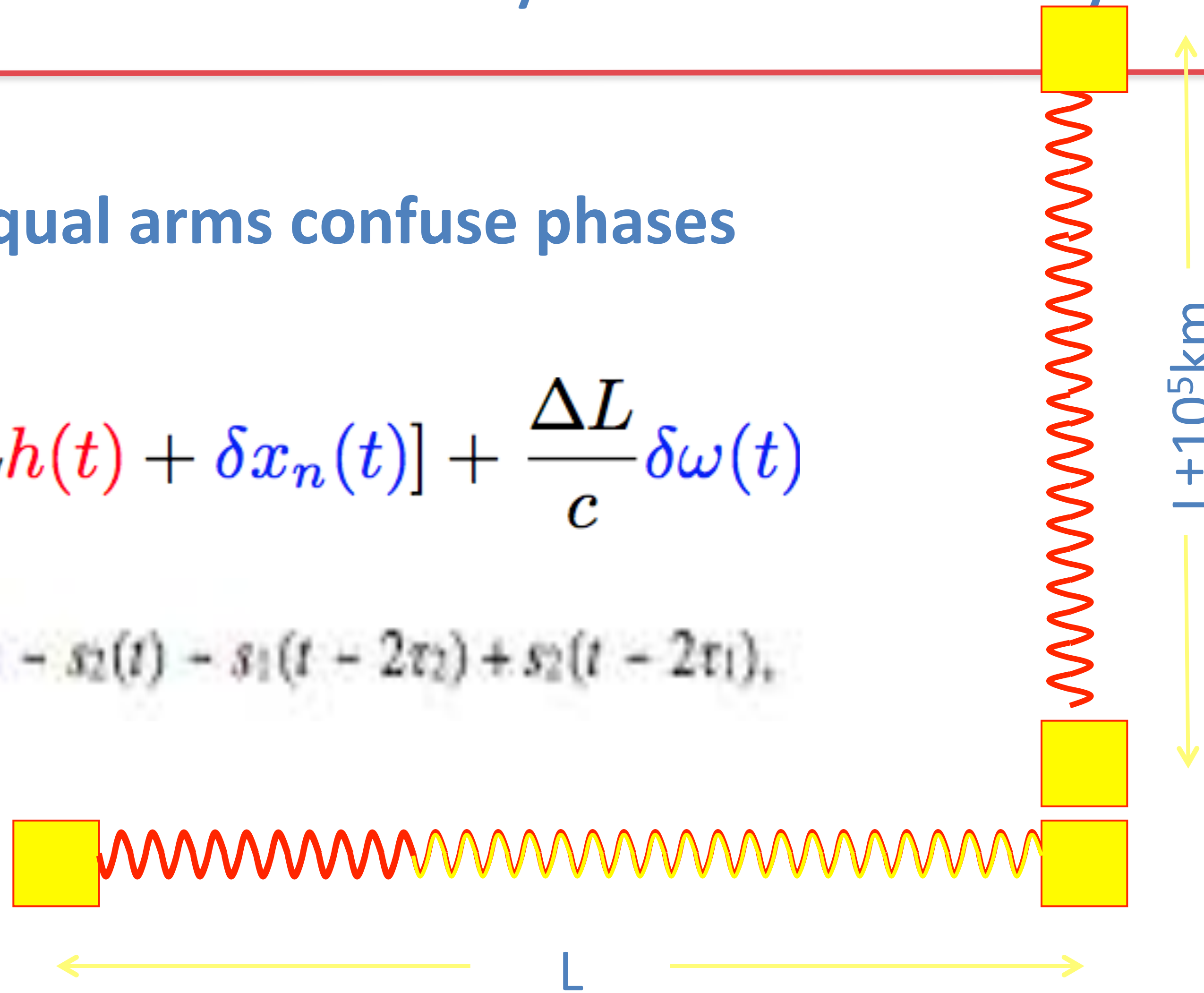


LISA basic 4 Time Delay Interferometry

LISA unequal arms confuse phases

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

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

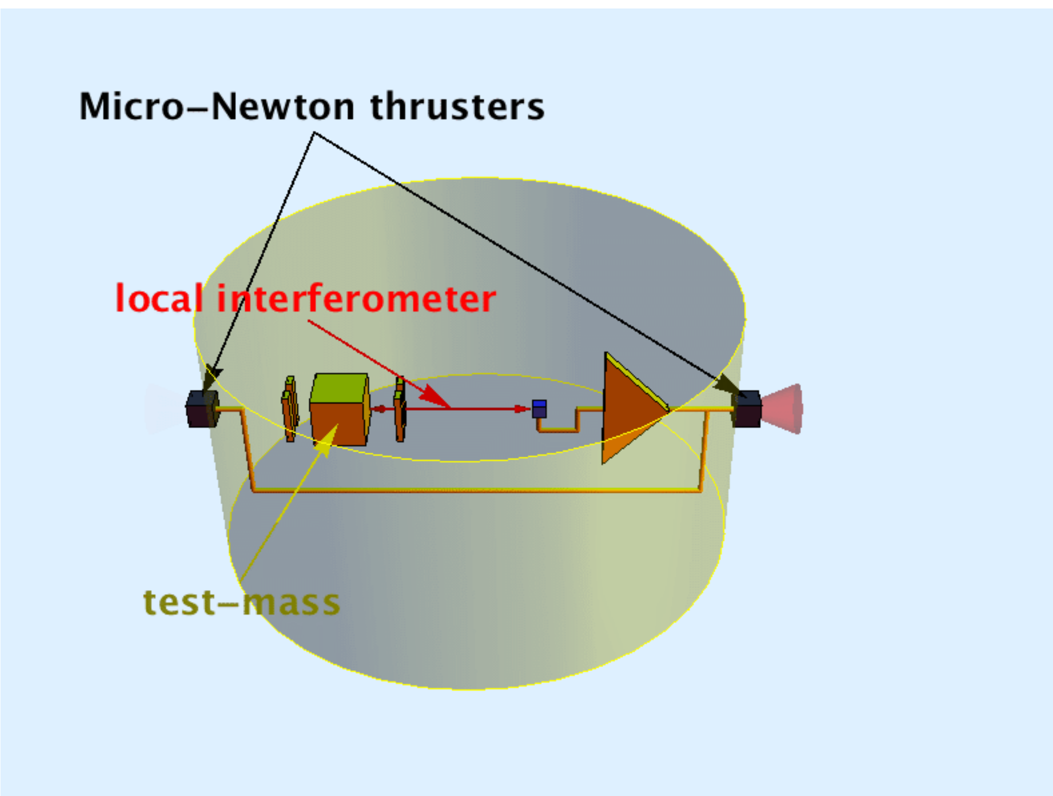


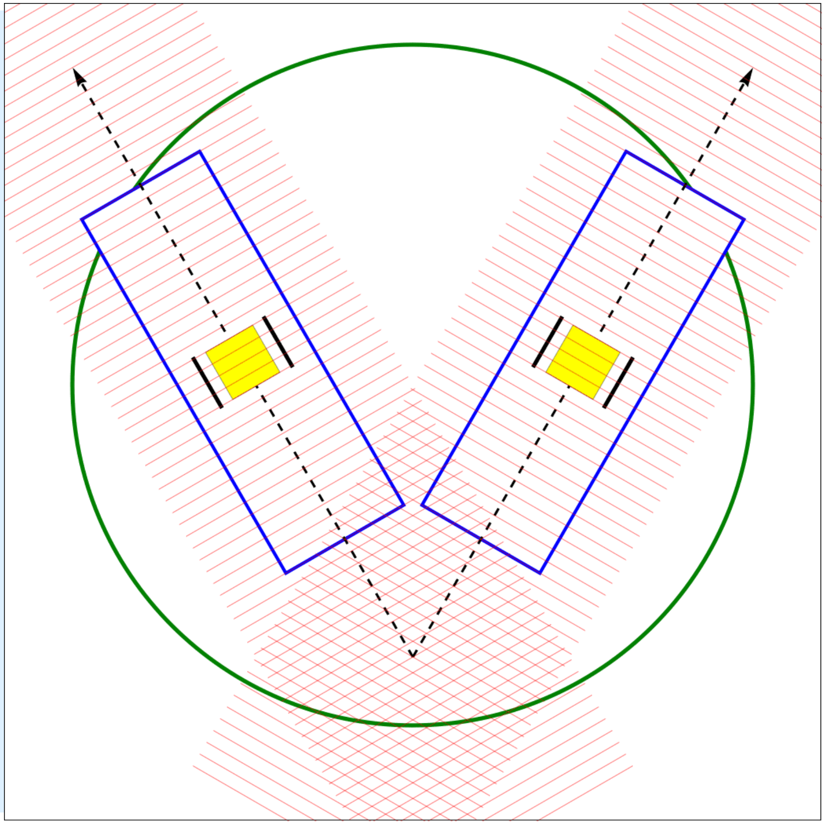
Need to recombine light emitted at equal times

LISA Basic 5: Drag-free

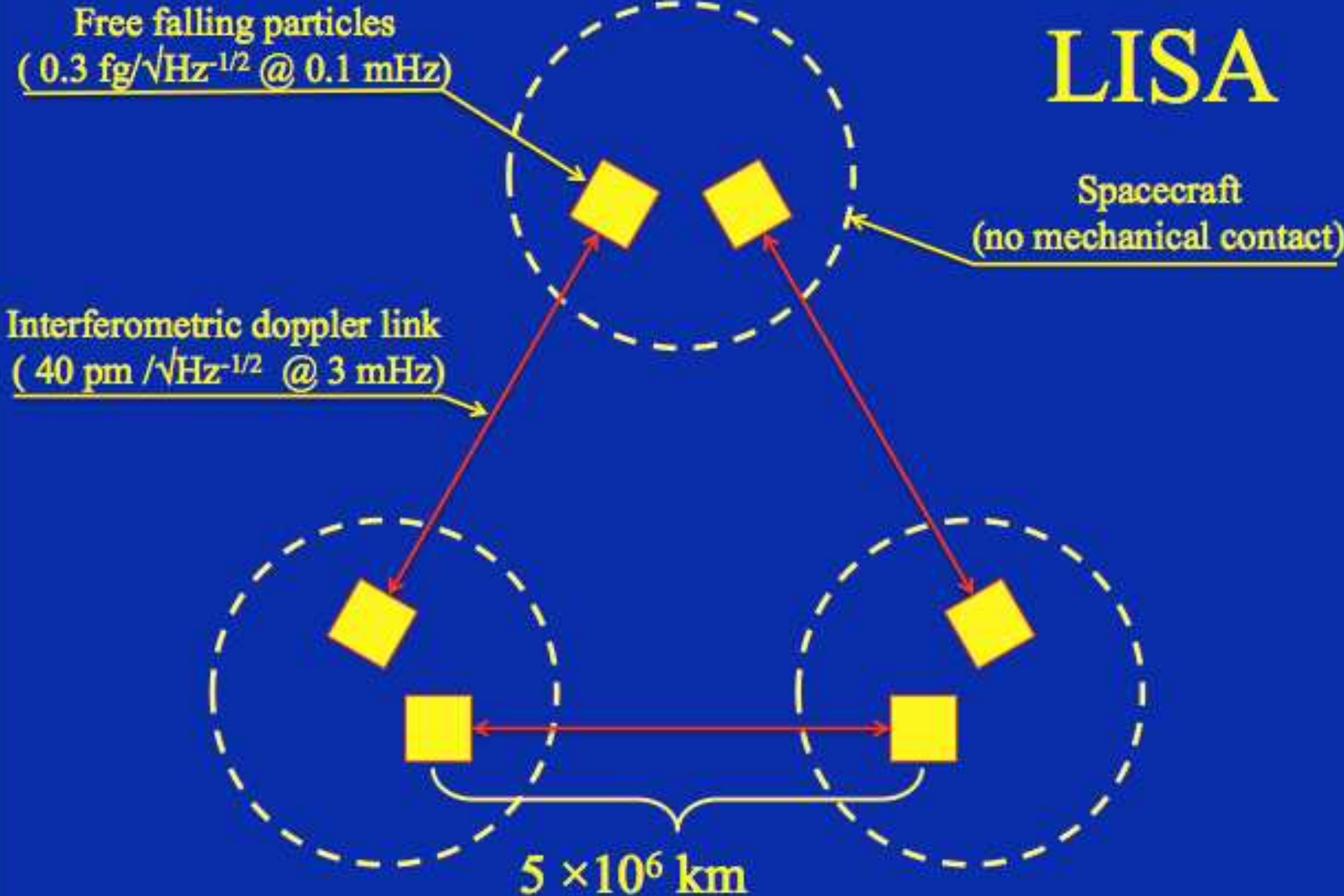
Avoid any contact between S/C and Test Mass

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

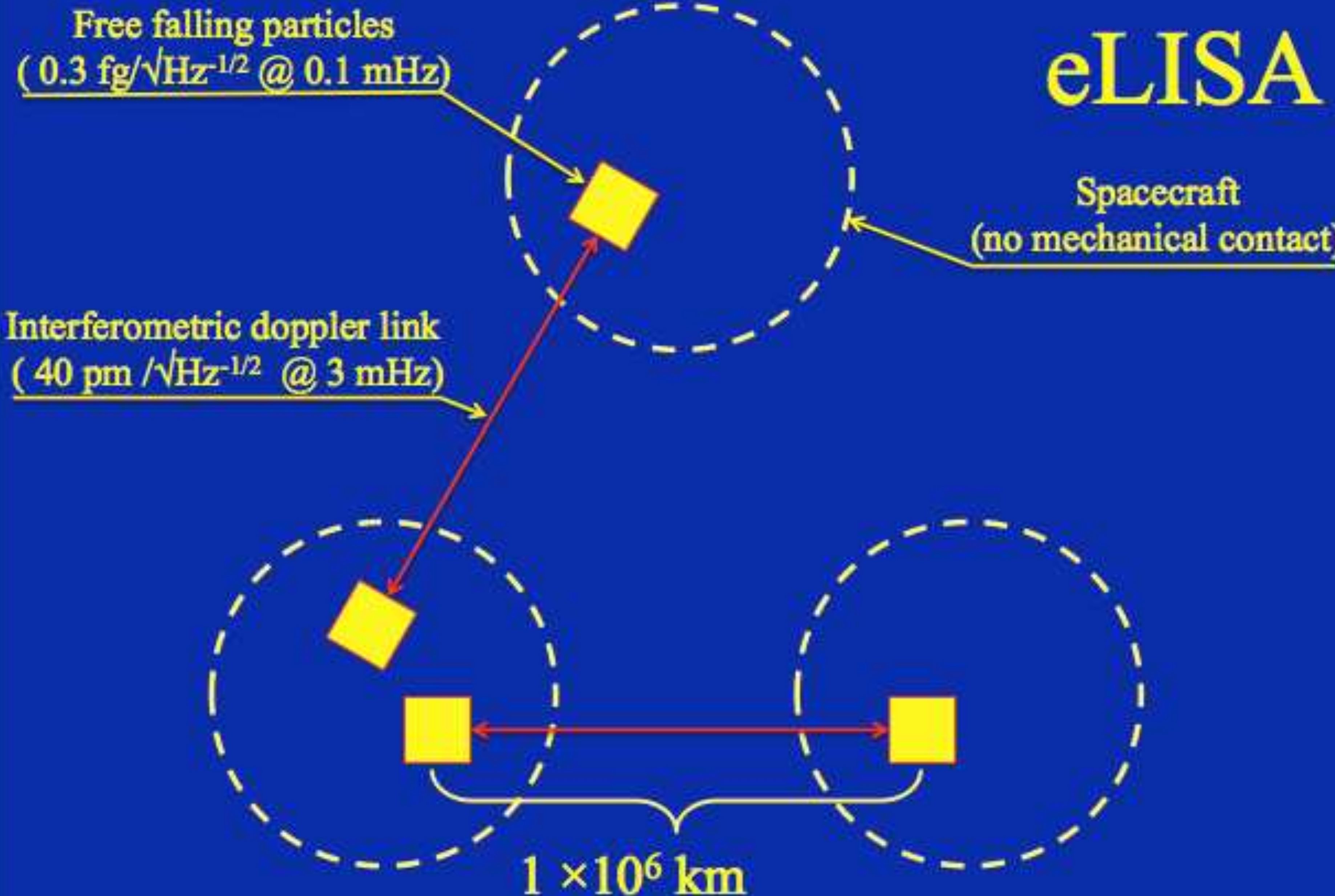




LISA


Free falling particles
(0.3 fg/√Hz-1/2 @ 0.1 mHz)
Spacecraft
(no mechanical contact)
Interferometric doppler link
(40 pm /√Hz-1/2 @ 3 mHz)
5 ×10^6 km

eLISA


Free falling particles
(0.3 fg/√Hz-1/2 @ 0.1 mHz)
Spacecraft
(no mechanical contact)
Interferometric doppler link
(40 pm /√Hz-1/2 @ 3 mHz)
1 ×10^6 km