Instrumental challenges in space-based gravitational wave detectors LISA

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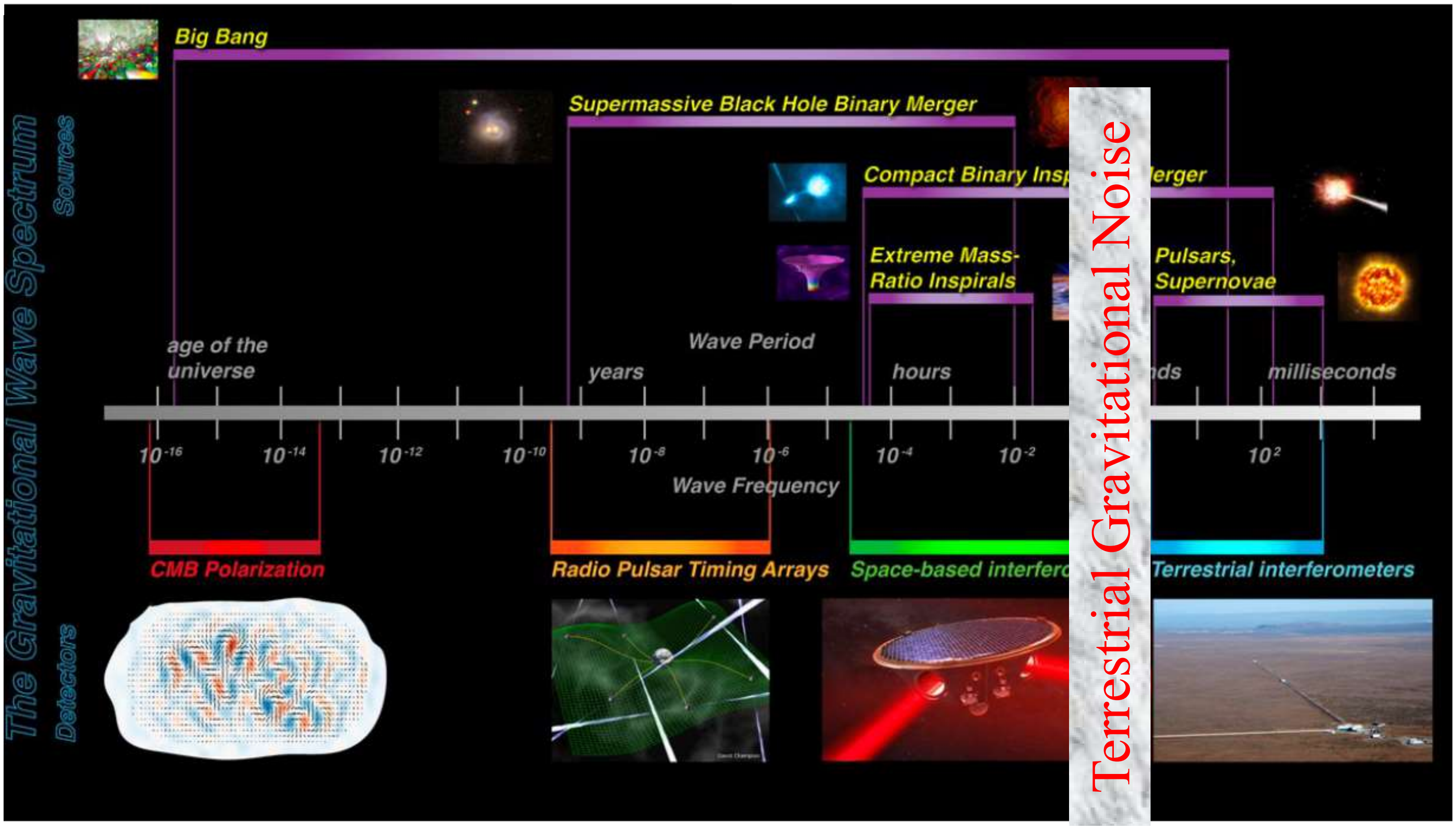
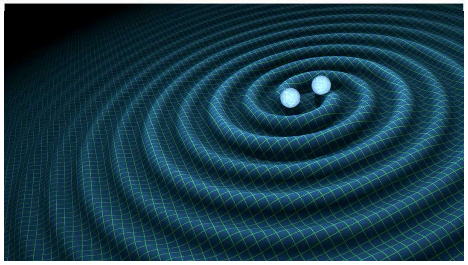
Second European Physical Society Conference on Gravitation: measuring gravity
5-7 July 2021

Gravitational Wave Astronomy



(credit: K. Jani)

Low frequency GW astronomy



- Binaries are nearly Keplerian,

$$f_{GW} = \frac{1}{\pi}\sqrt{\frac{\mathcal{G}(M_1 + M_2)}{r^3}}$$

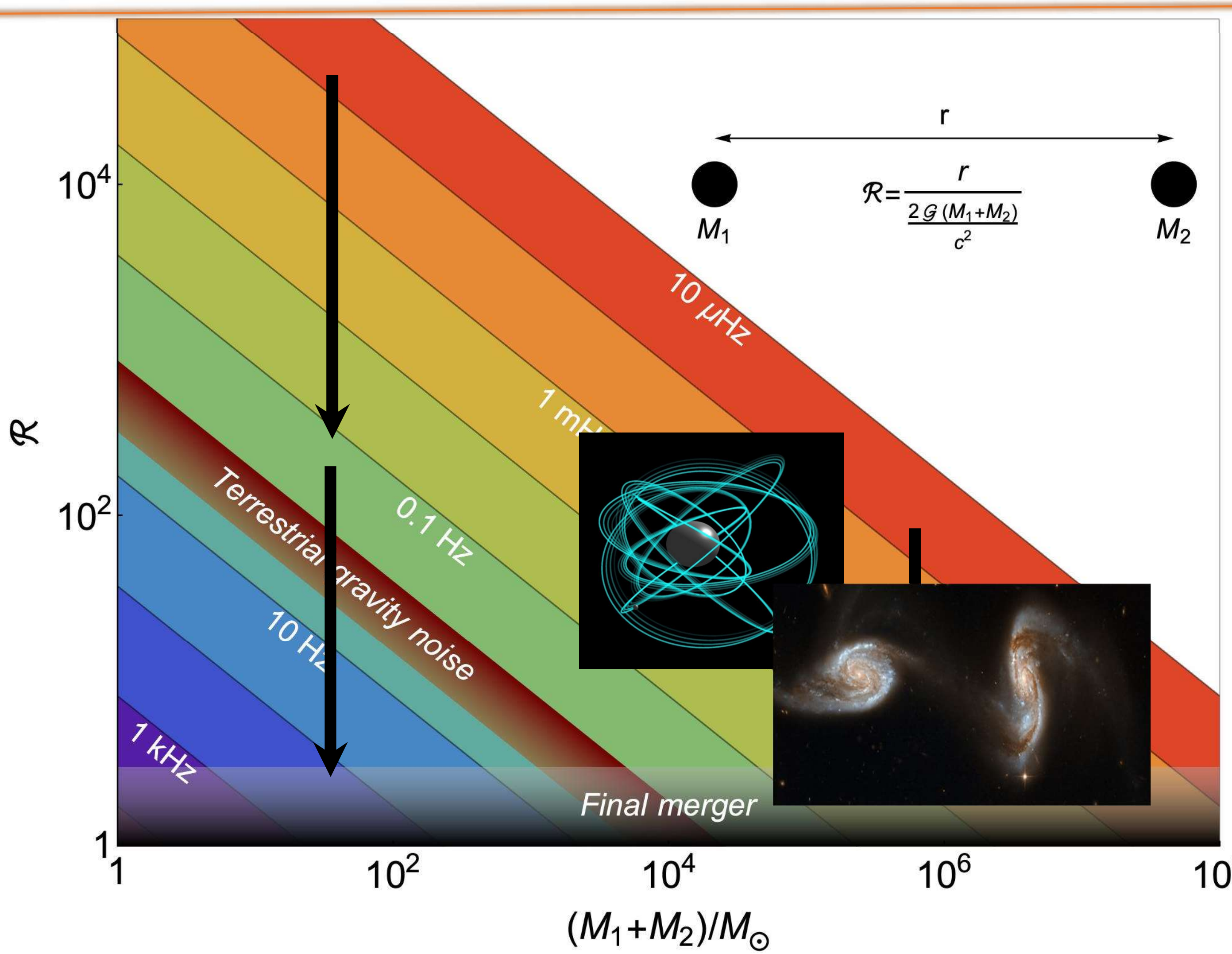
- Separation normalized to Schwarzschild radii:

$$\mathcal{R} = \frac{r}{\left(\frac{2\mathcal{G}(M_1 + M_2)}{c^2}\right)}$$

- Frequency decreases with both mass and $\mathcal{R}$

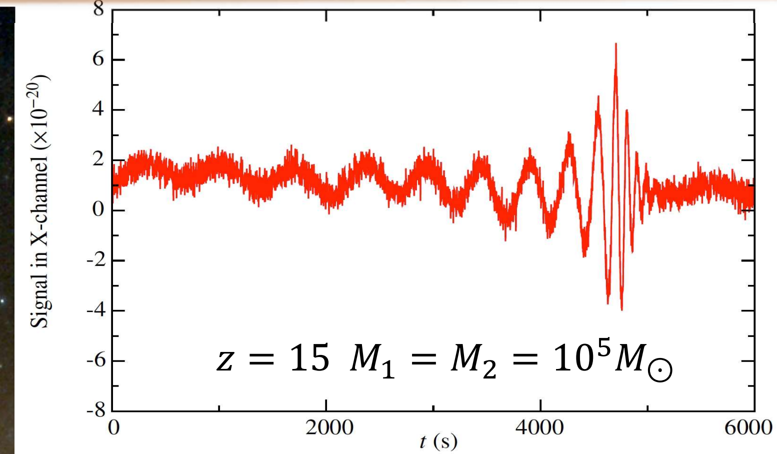
$$f_{GW} = \frac{c}{\pi\sqrt{2}\, R_{\odot}} \left(\frac{M_1 + M_2}{M_{\odot}}\right)^{-1} \mathcal{R}^{-\frac{3}{2}}$$

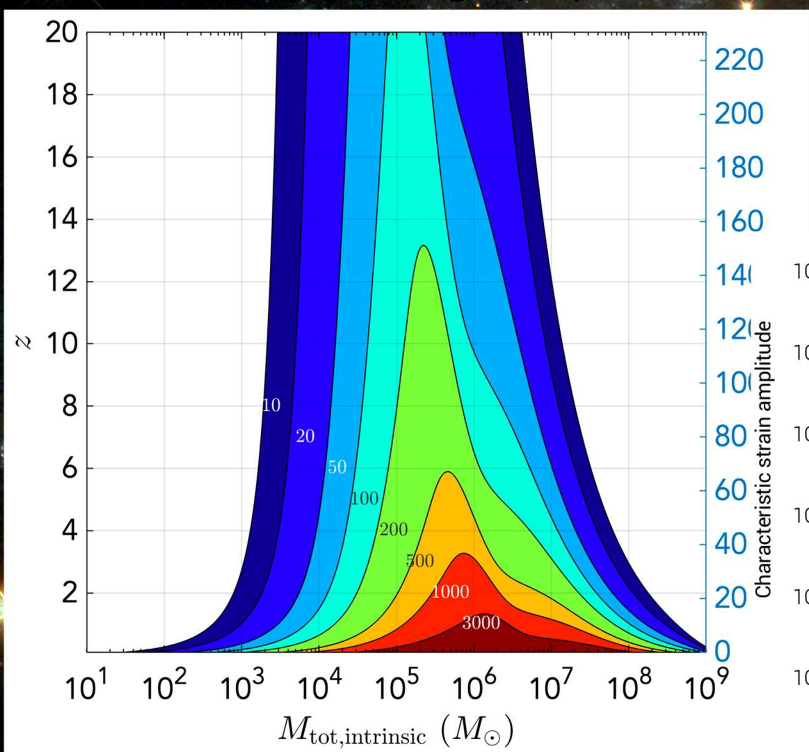
$(\mathcal{R} \to 1 \simeq \text{final merger max } f_{GW})$

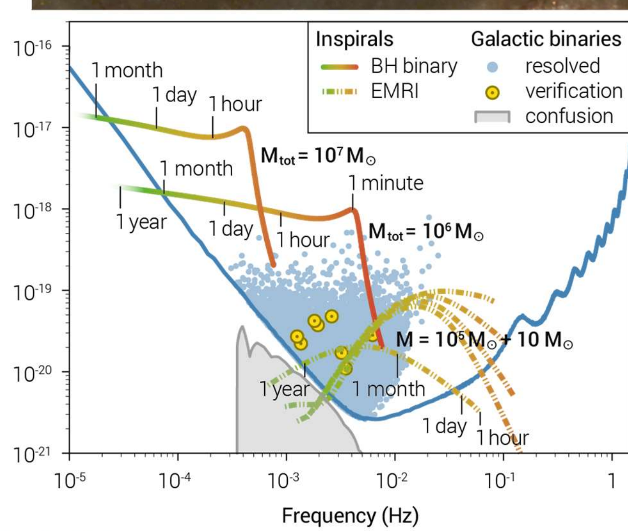


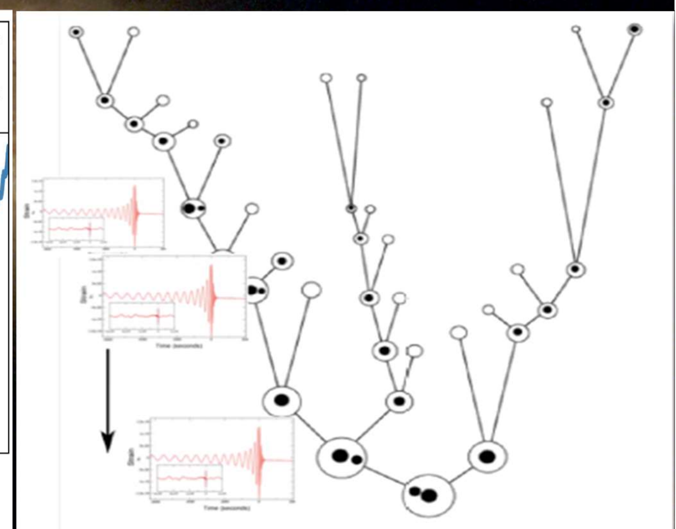
Supermassive BH mergers: the brightest sources

the universe
frequency crosses LISA band :
co stratigraphy



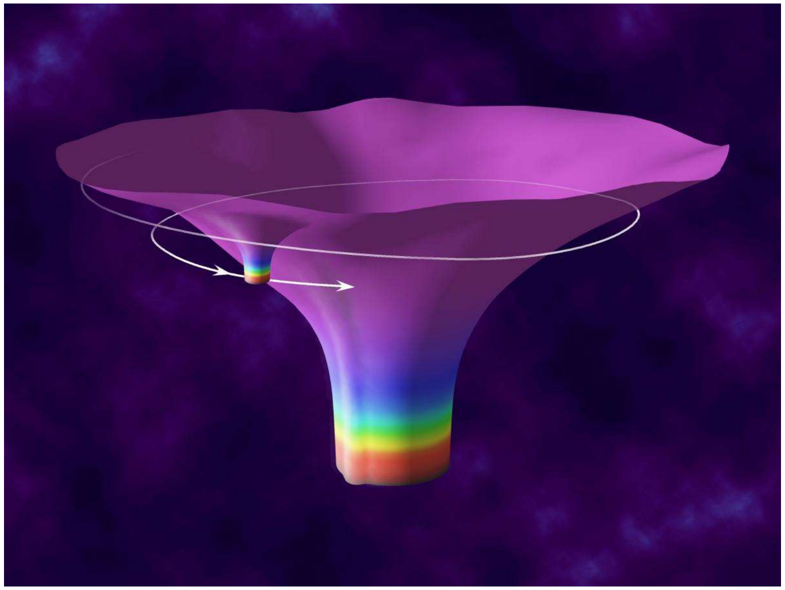


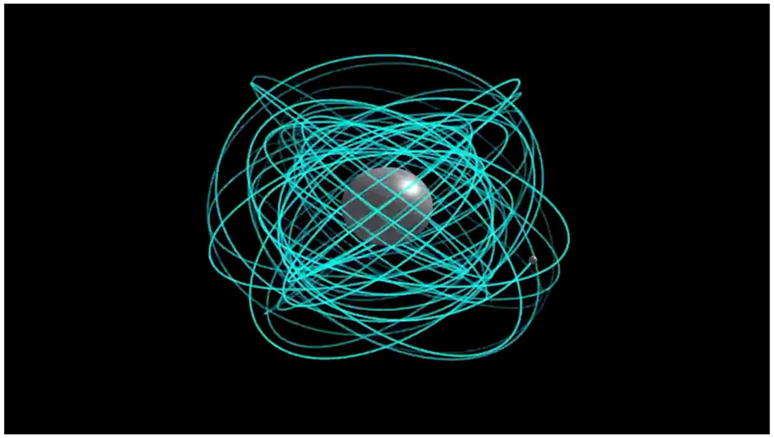




LISA: EMRIs (Extreme Mass Ratio Inspirals)

UNIVERSITÀ DI TRENTO INFN LISA CONSORTIUM





Uniqueness of LISA

Inspiral of stellar –mass compact object into massive black hole

MBH mass $10^4 < M/M_{Solar} < 10^7$

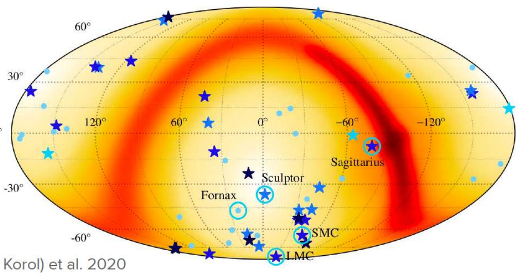
Up to 10^4-10^5 cycles in band

If the compact object is a white dwarf, possible electromagnetic counterpart

Test
the properties of the space time around massive dark objects
the presence of horizons
the no hair theorem
the presence of dark matter which causes a different phase evolution

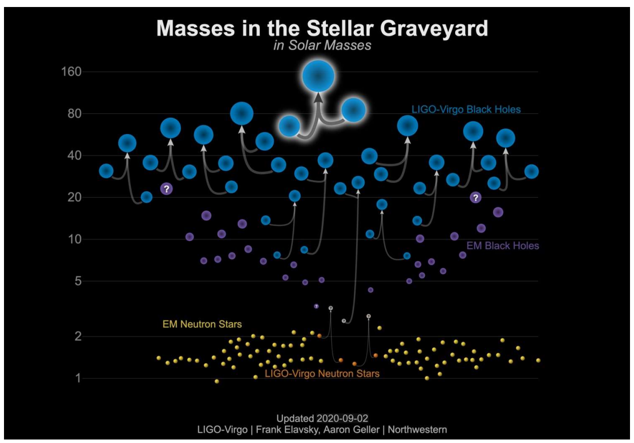
extreme mass ratios in a regime where self-force is important

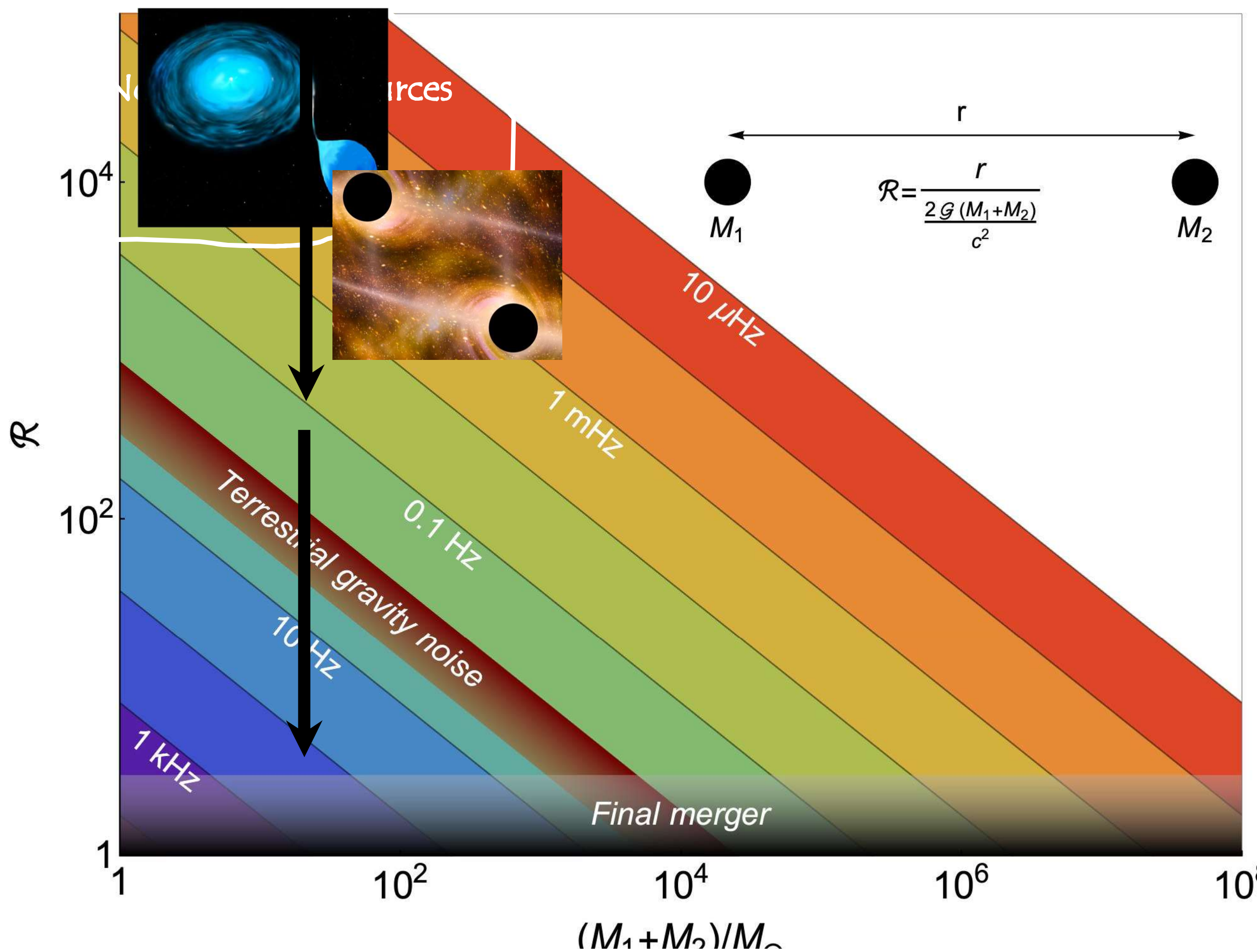
Non-transient GW astronomy



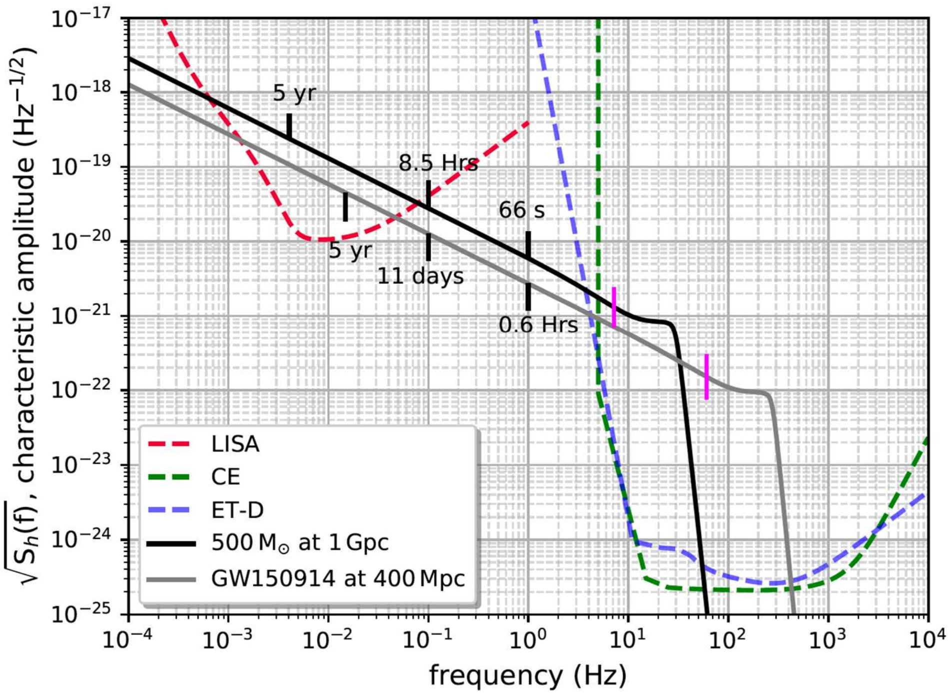
Roebber (incl. Korol) et al. 2020

- GW-binary astronomy of local group
- BH multi-band astronomy





Multi-band GW astronomy and fundamental physics



Joint observation with LISA greatly improves measurement of deviation from GR

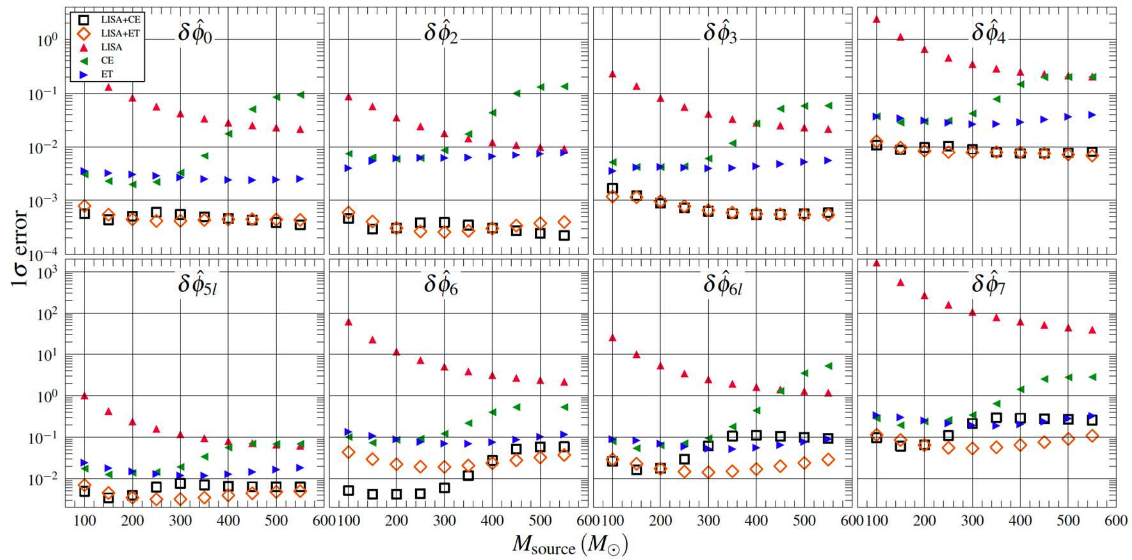


FIG. 3. Top panel shows bounds on deformation parameters at 0PN to 2PN, as a function of total mass in source frame. Bottom panel shows the same but for deformation parameters at 2.5PN to 3.5PN. All the systems have mass-ratio $q = 2$, dimensionless component spins $\chi_1 = 0.2$ and $\chi_2 = 0.1$, and luminosity distance $D_L = 1$ Gpc.

S. Datta et al arXiv:2006.12137v1 [gr-qc] 22 Jun 2020

Detecting gravitational waves in space with LISA

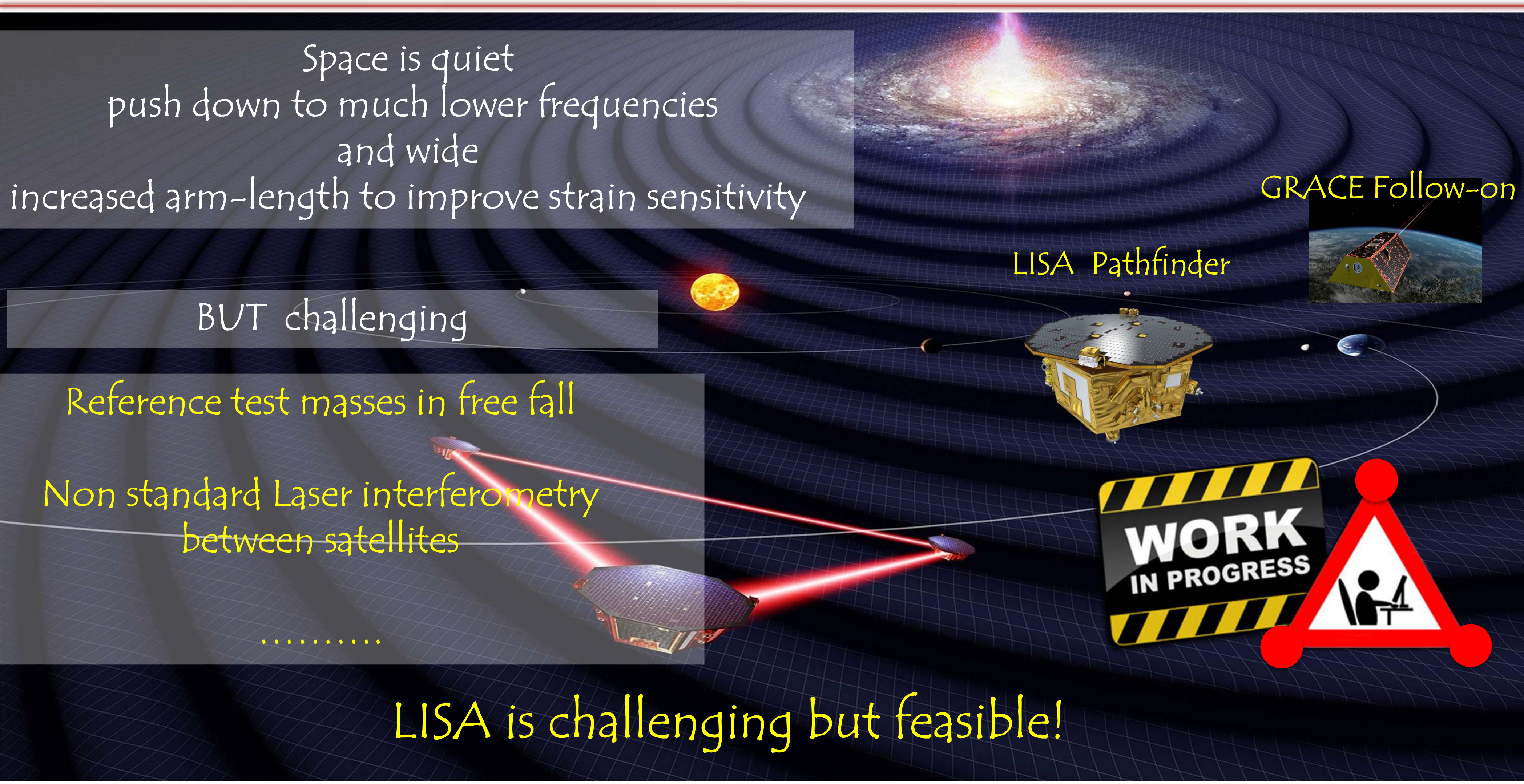
Space is quiet
push down to much lower frequencies
and wide
increased arm-length to improve strain sensitivity

BUT challenging

Reference test masses in free fall

Non standard Laser interferometry
between satellites

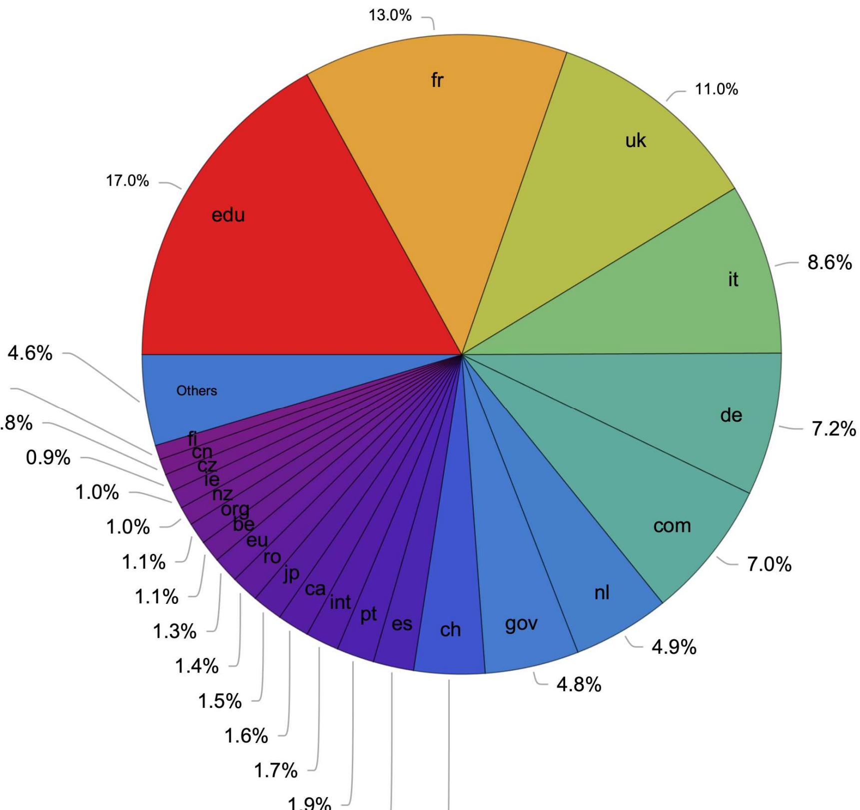
....



LISA is challenging but feasible!

The International Collaboration

- The LISA Consortium (1437 members)



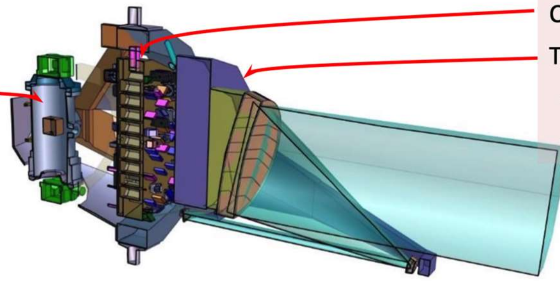
MOSA: moving optical sub-assembly

Gravitational reference system

GRS head

\+ electronics

\+ UV light source



Optical metrology system

Optical bench

Telescope esa

\+ phasemeter

\+ laser esa

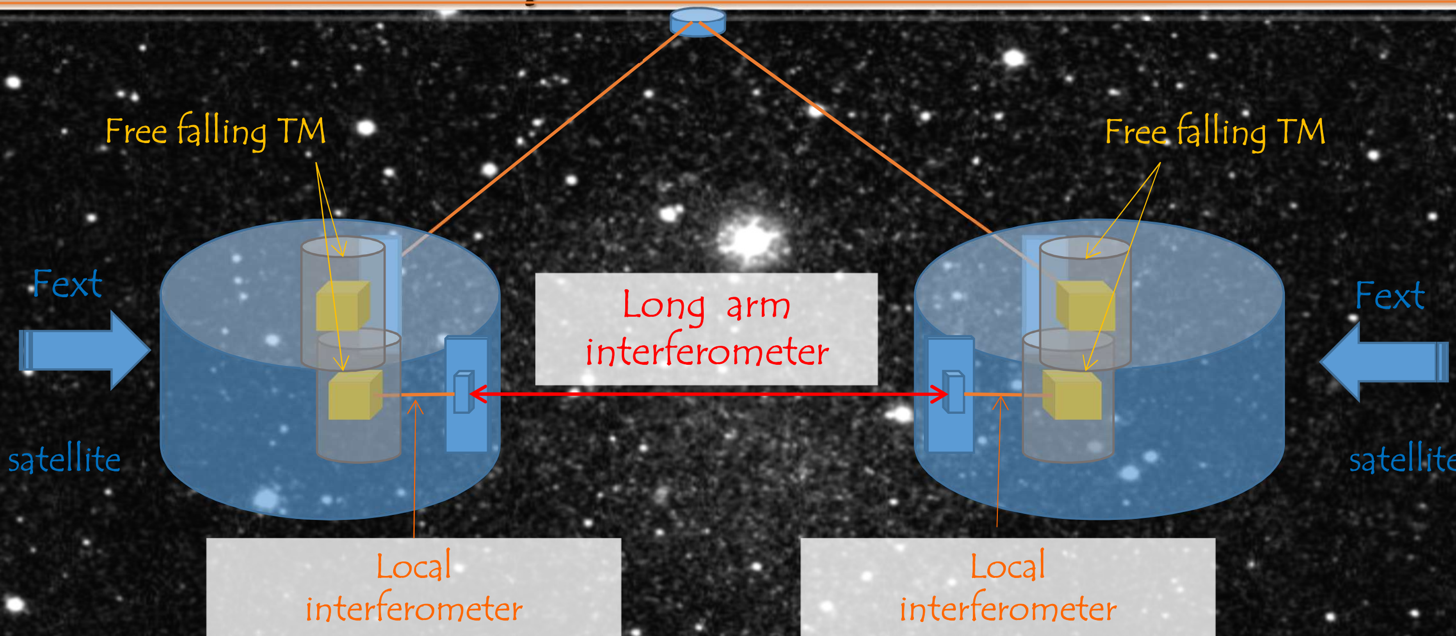
\+ consortium lead

\+ integration and testing

\+ diagnostics/data

\+

LISA basic «link» concept



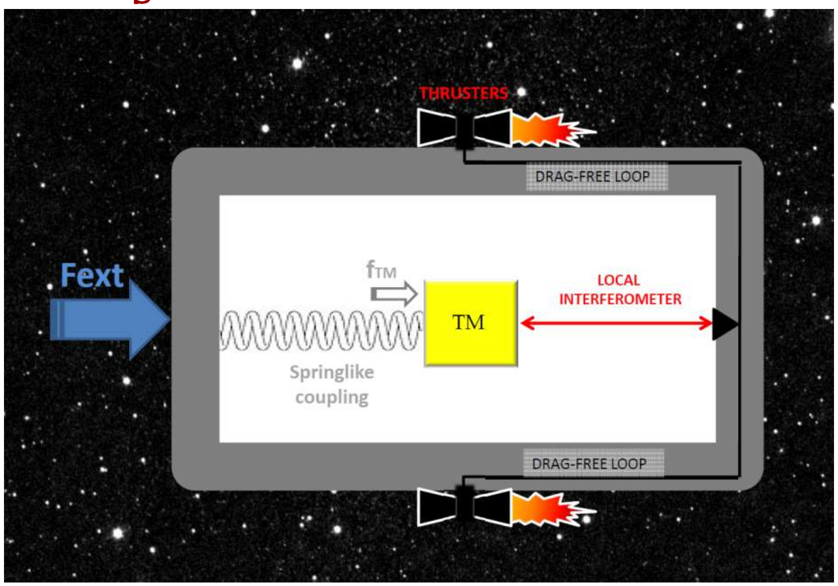
$$\frac{\dot{\nu}_{rec} - \dot{\nu}_{emi}}{\nu} = \frac{\dot{h}_{rec}(t) - \dot{h}_{rec}(t - L/c)}{2} + \frac{a_{Sat\ rec}(t) - a_{Sat\ em}(t - L/c)}{c}$$

$$a_{Sat} - a_{Sat-} = a_{TM} + \ddot{n}_{local\ int}$$

TM residual acceleration
Relative to the local inertial frame

"Drag free" strategy for keeping the TM in "free fall"

The position of the spacecraft relative to the TM is measured by local interferometer and this signal drives micro-Newton thrusters in order to keep spacecraft centered on TM



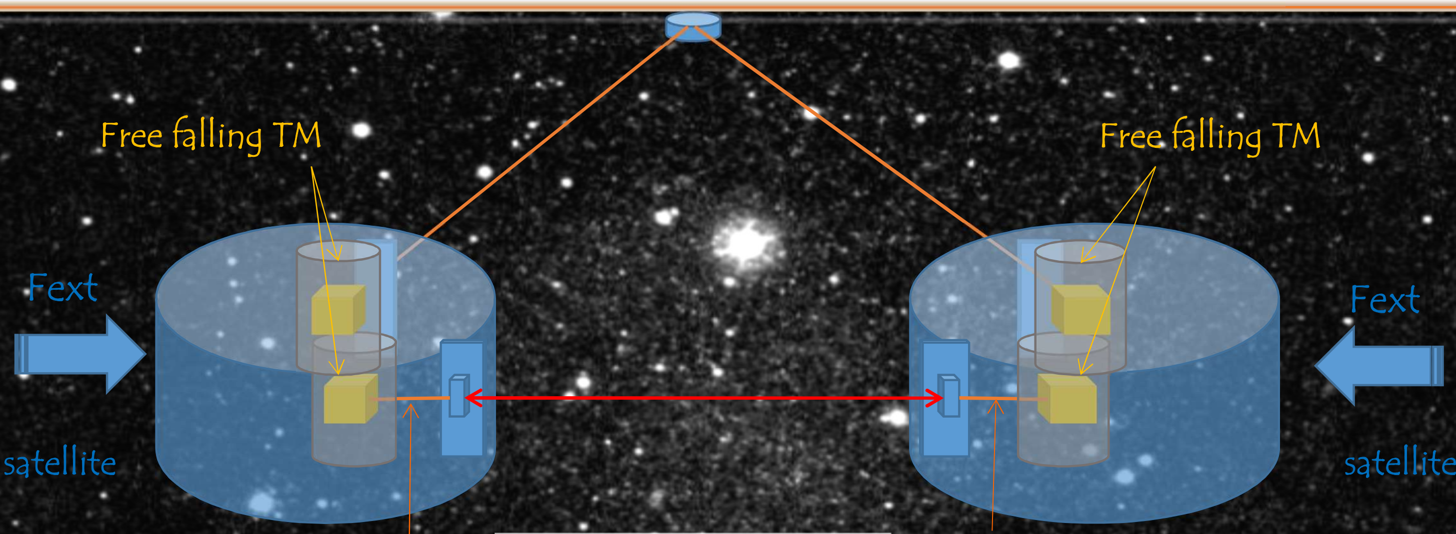
TM residual acceleration
Relative to the local inertial frame

$$a_{TM} = \underbrace{\frac{f_{TM}}{m}}_{\text{Stray forces}} - \underbrace{\omega_p^2 \delta x_n}_{\text{Residual TM jitter}}$$

$$a_{TMr} - a_{TMe} = \left(\frac{f_{TMr}}{m} - \frac{f_{TMe}}{m} \right) + \omega_e^2 \delta x_{ne} - \omega_r^2 \delta x_{nr}$$

Differential acceleration arising from parasitic forces in direct competition with gravitational wave signal

LISA link: combination of 3 interferometric measurements



Local Interferometer 1

$$\frac{\Delta\dot{\nu}_{local,1}}{\nu_o} = \frac{a_{TM1} - a_{SC1}}{c}$$

Long arm interferometer

$$\frac{\Delta\dot{\nu}_{SC\leftrightarrow SC}}{\nu_o} = \frac{a_{SC2} - a_{SC1}}{c} + \frac{\Delta\dot{\nu}_{GW}}{\nu_o}$$

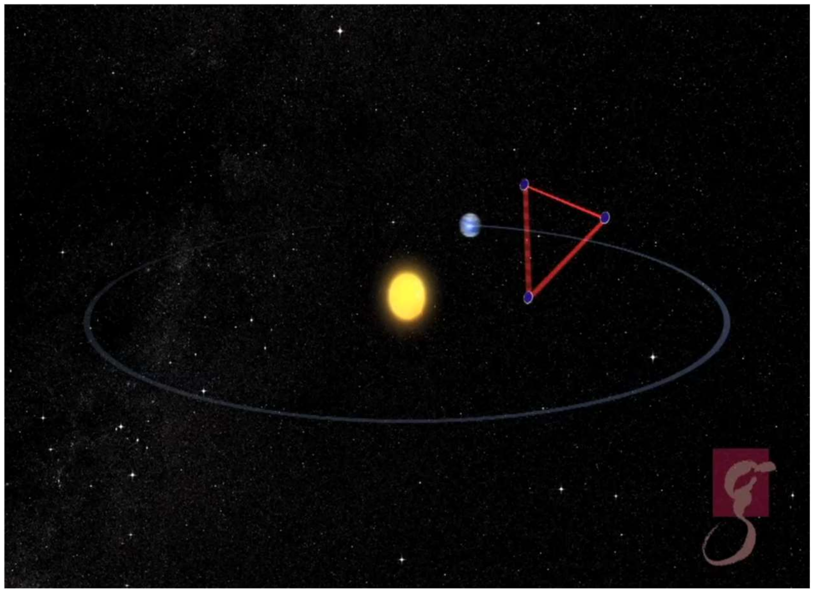
Local Interferometer 2

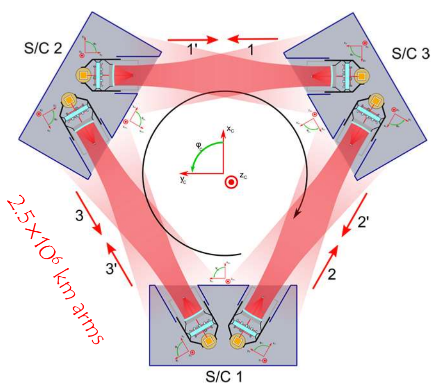
$$\frac{\Delta\dot{\nu}_{local,2}}{\nu_o} = \frac{a_{TM2} - a_{SC2}}{c}$$

$$\frac{\Delta\dot{\nu}_{local,2}}{\nu_o} + \frac{\Delta\dot{\nu}_{SC\leftrightarrow SC}}{\nu_o} - \frac{\Delta\dot{\nu}_{local,1}}{\nu_o} = \frac{a_{TM2} - a_{SC2} + a_{SC2} - a_{SC1} + a_{SC1} - a_{TM1}}{c} + \Delta\dot{\nu}_{GW} =$$

$$= \frac{a_{TM2} - a_{TM1}}{c} + \Delta\dot{\nu}_{GW}$$

LISA fundamental challenging features





LISA CONFIGURATION

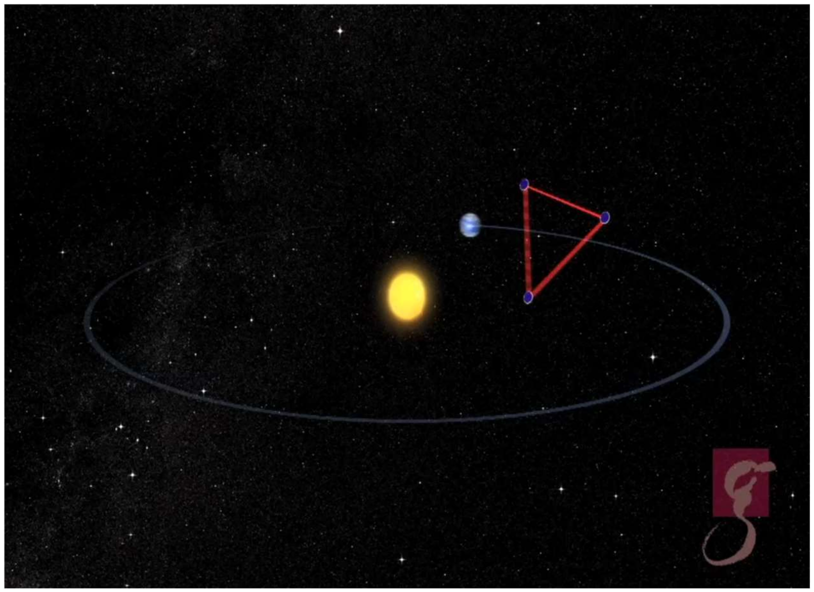
- 3 identical spacecraft
- 3 arms of 2.5 Million km
- LISA constellation quasi rigid, quasi equilateral rotating configuration: 1 AU , 20-degree trailing Earth orbit

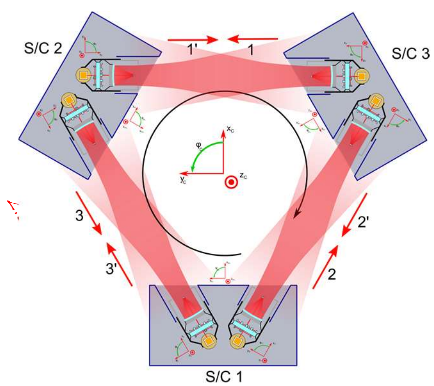
LISA IMPLEMENTATION

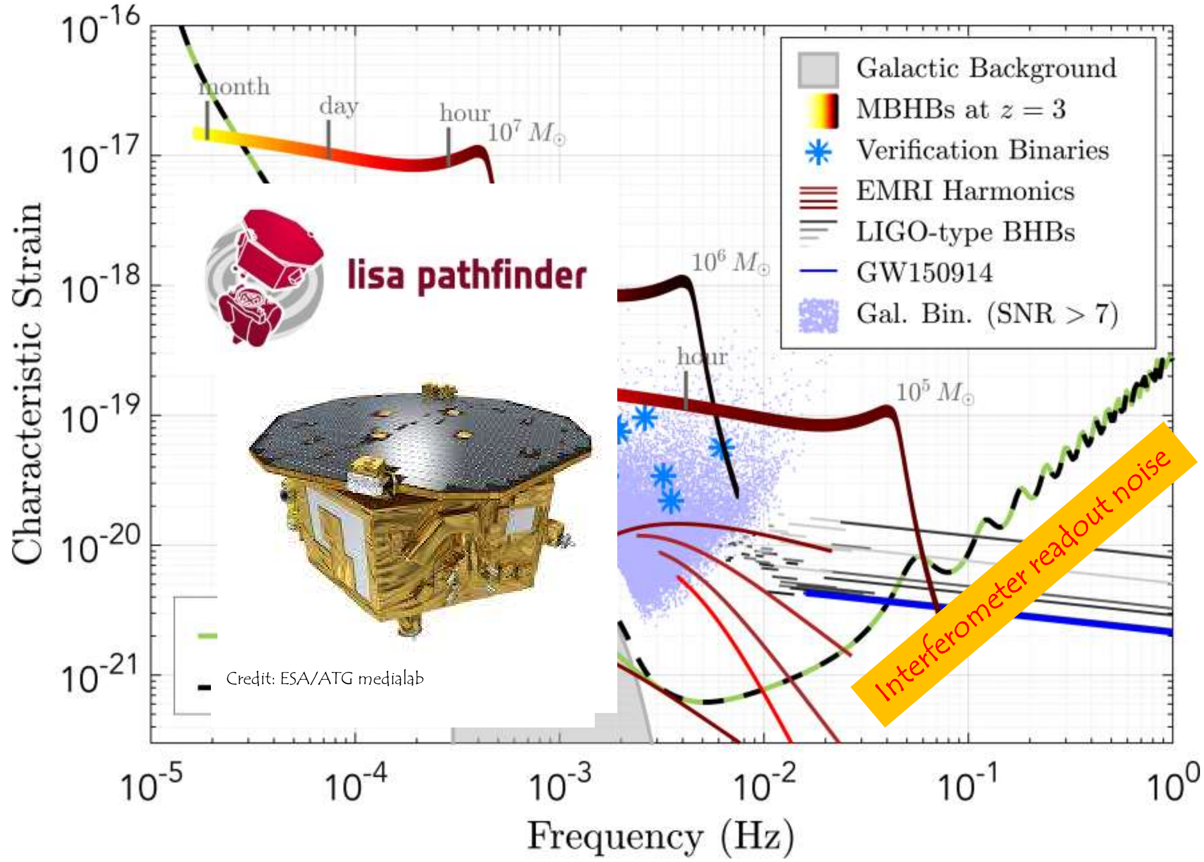
30 cm telescopes, 2W lasers, 100 pW at receiver, 1064 nm:

- Inter satellite heterodyne laser interferometry in transponder mode
  10 pm/√Hz,
- Time Delay Interferometry to suppress laser frequency noise
- Test masses in sub-femto-g free fall
  3 fm/s²/√Hz

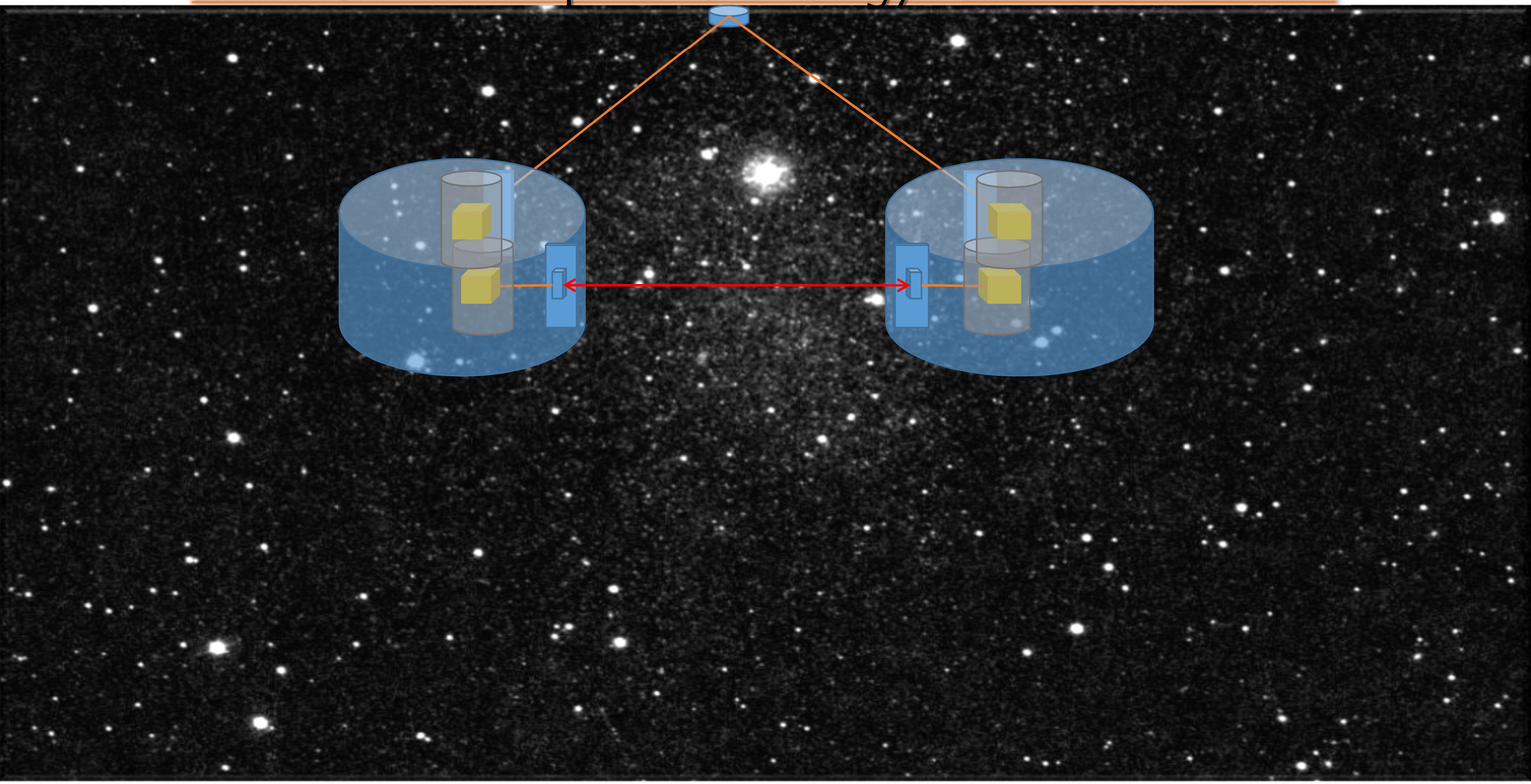
LISA fundamental challenging features







LISA Pathfinder Concept and Strategy



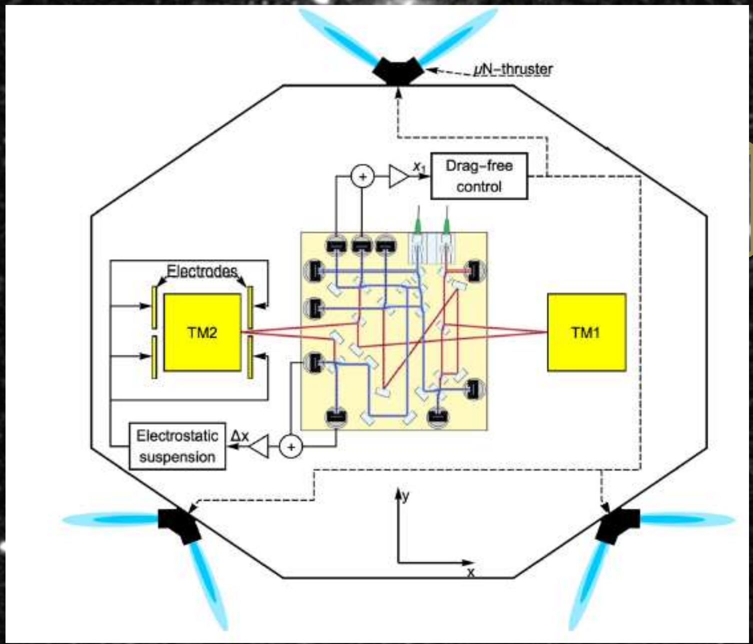
LISA Pathfinder Concept and Strategy

- Most of disturbances are local and can be tested within one satellite!

With performances exceeding the expectations

Tested the differential acceleration noise from stray forces acting on 2 LISA TM

Demonstrated the local interferometric measurement of TM acceleration



THE LEGACY of LISA PF

Key technologies for LISA

Stray forces noise model

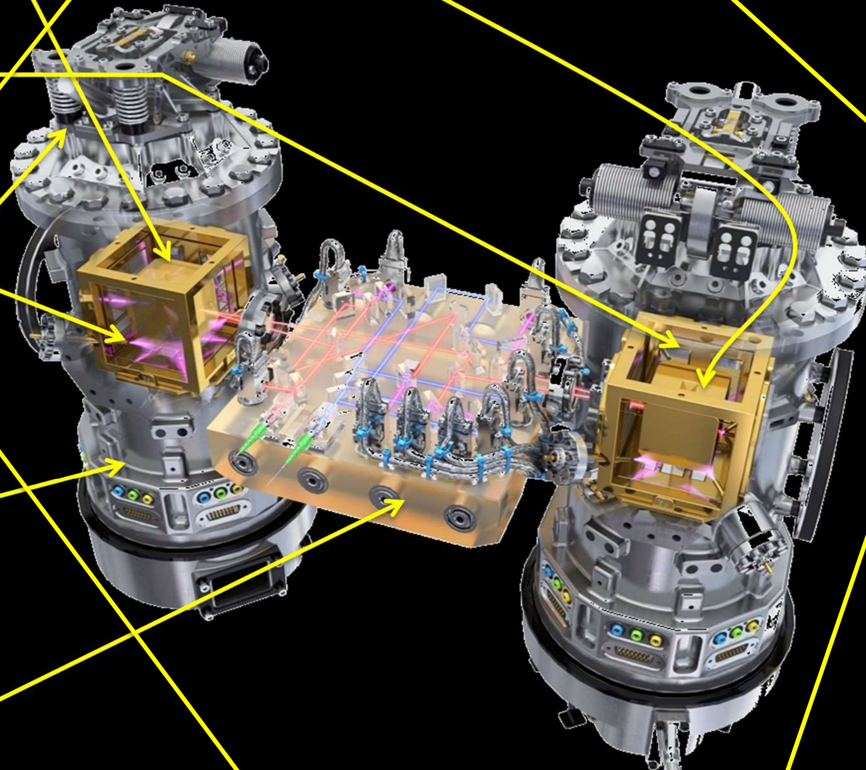
Environmental parameter control and stability feasibility

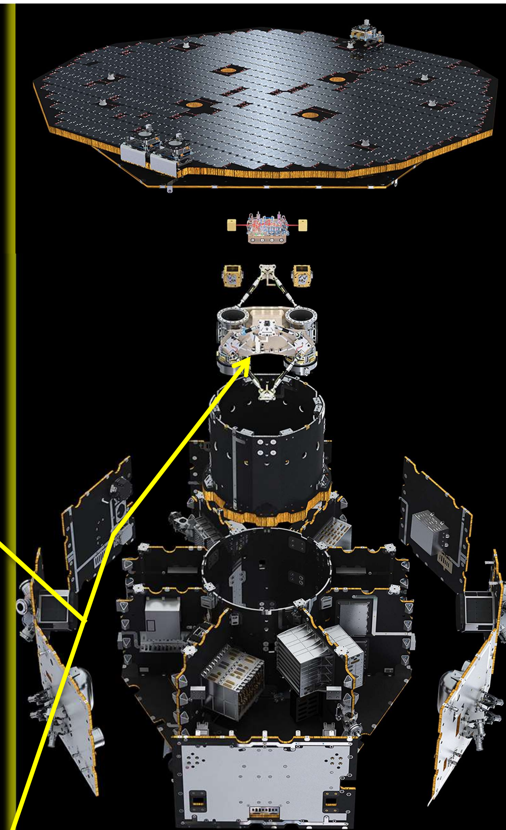
Strategies of calibration, measurements, mitigations, subtraction of stray effects

Integration and on ground testing experience

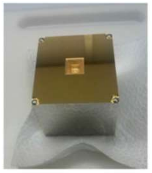
The LTP

- 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

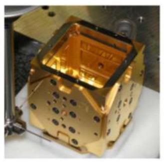




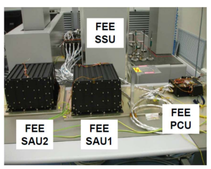
Gravitational Reference Sensor



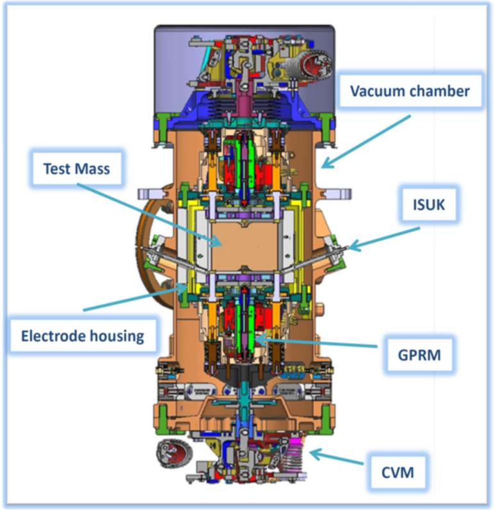
Test Mass (FM)



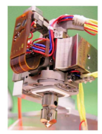
Electrode Housing (FM)



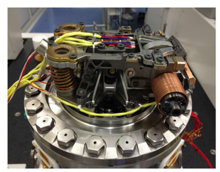
Front End Electronic (FM)



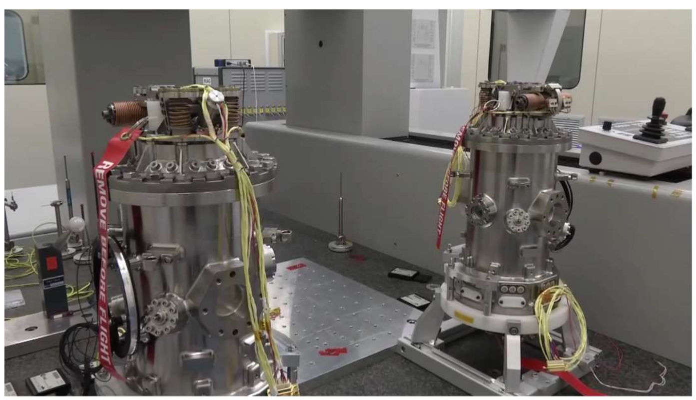
UV Lamp Unit and ISUK (FM)



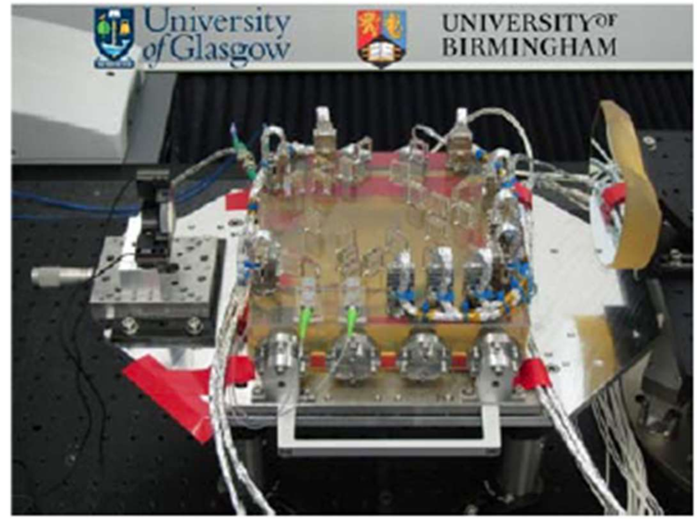
Grabbing, Position and Release Mechanism (FM)



Caging and Venting Mechanism (FM)

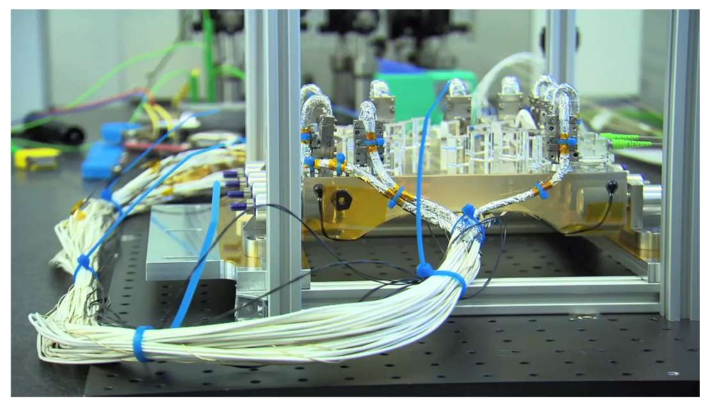


Optical Metrology System

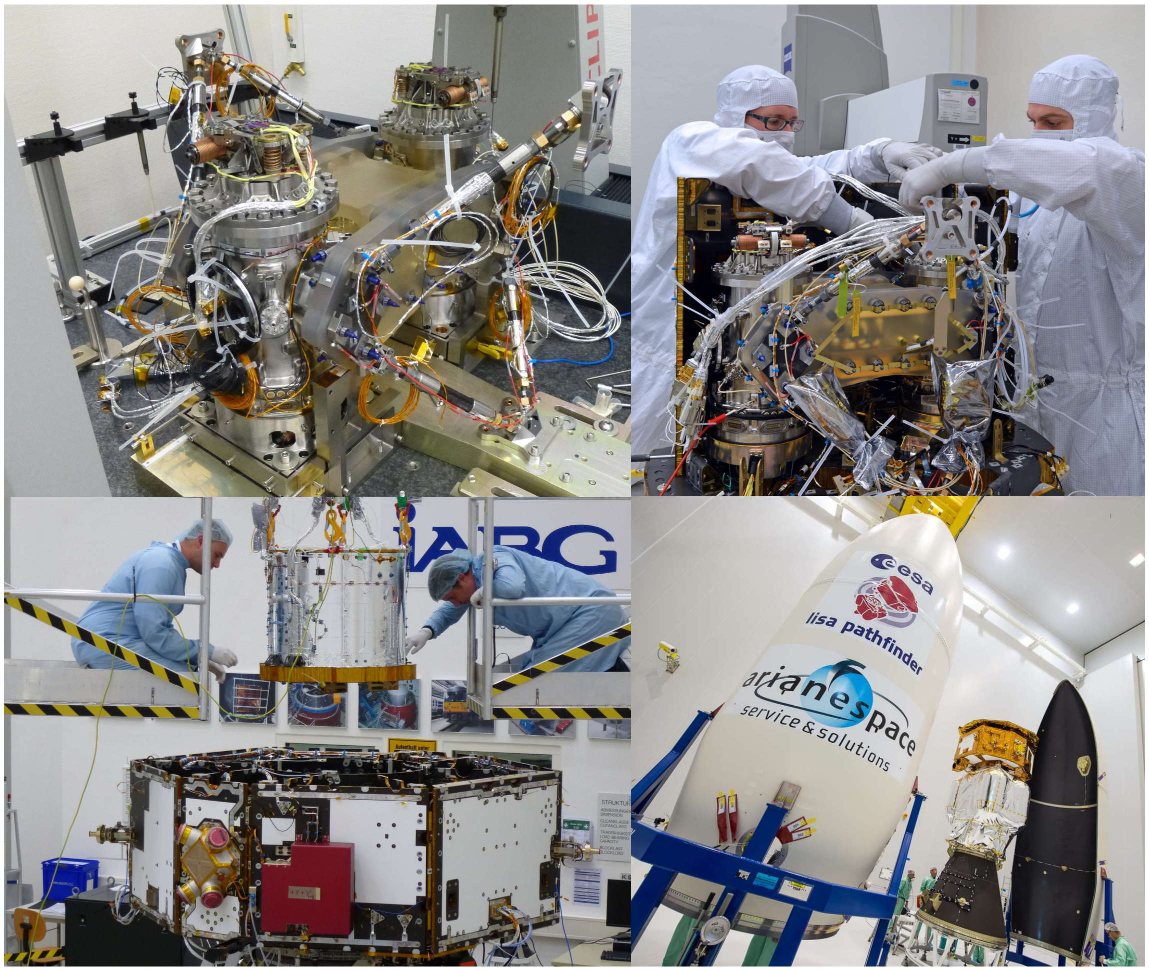


Critical component hydroxy-catalysis bonded to the Zerodur

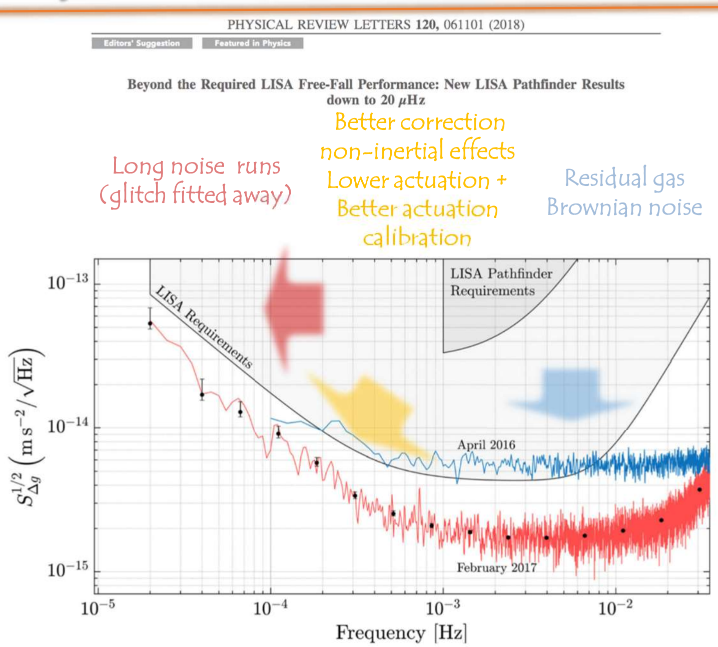
University of Glasgow, ASD, AEI Milde Communicatios



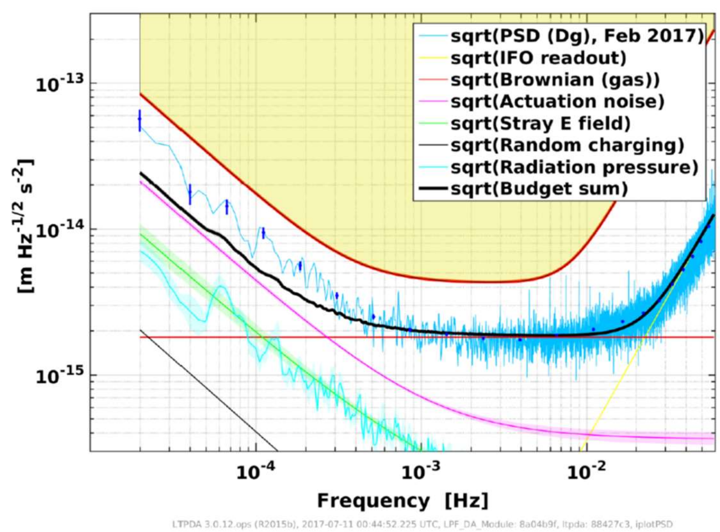
From the instrument integration to orbit



LISA PF: published results in February 2018



LISA Pathfinder Δg noise budget (February 2017)

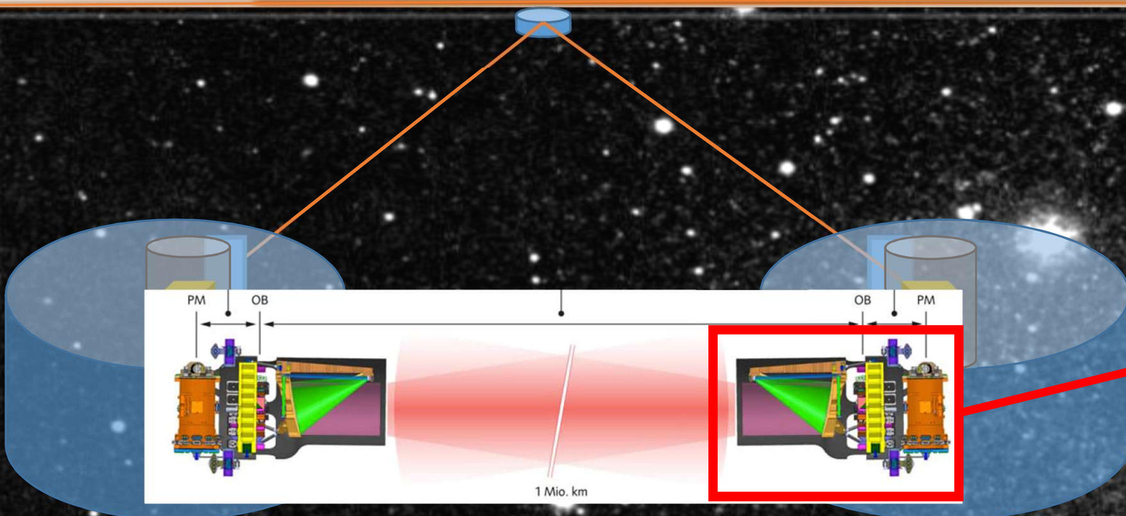


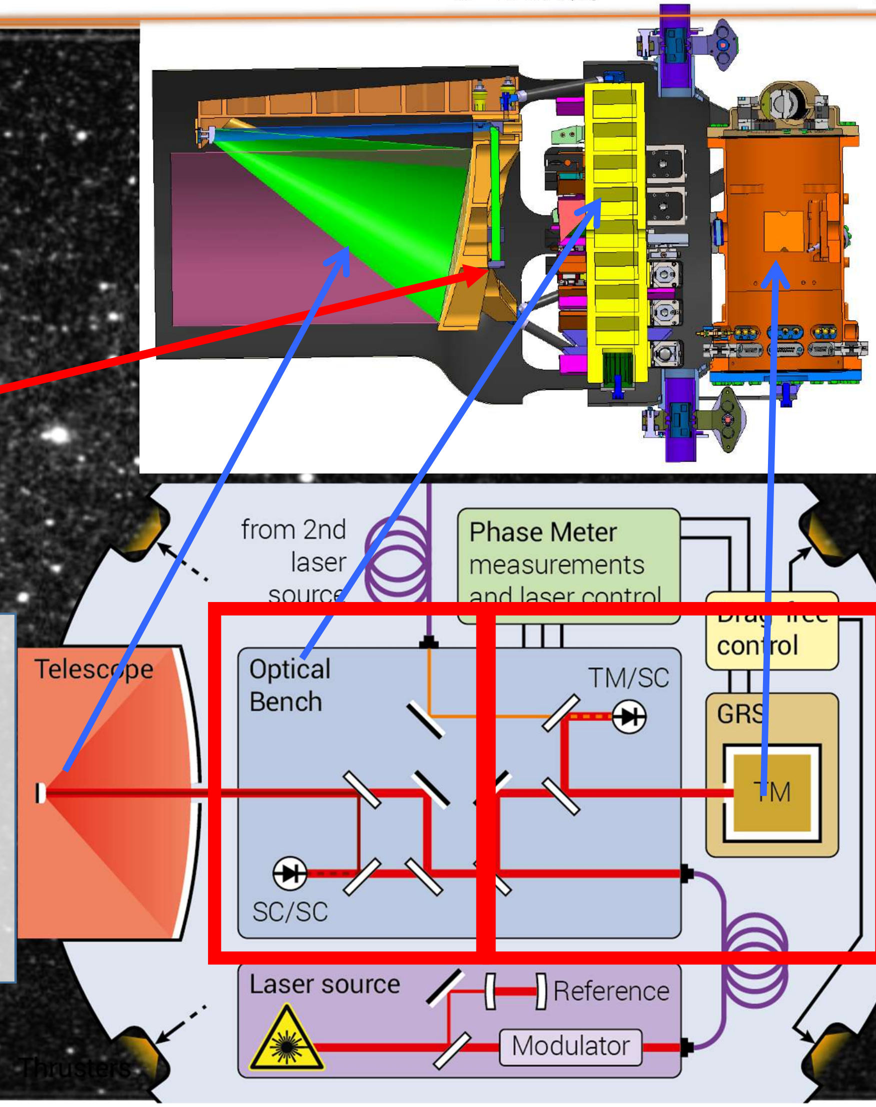
LPF demonstrates LISA free-fall requirement at all frequencies

- Low frequency noise still not fully understood

Need to consolidate LPF result, understand how to reproduce it robustly

LISA instrument





The Gravitational Reference Sensor with the test-mass

The Optical Bench with:

Local interferometer

Spacecraft to spacecraft interferometer

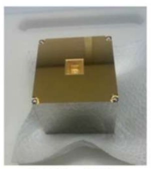
Telescope for the spacecraft to spacecraft interferometer

Free fall: from LISA Pathfinder to LISA

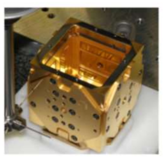
LISA Critical Technologies: GRS

Consolidate/improve performances of some items
and the suppression/verification strategies

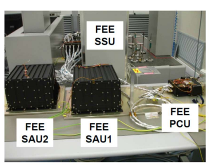
New Test Mass Charge Management
device based on LED UV photoelectron
(→ TRL6 by Adoption, 2024)



Test Mass (FM)

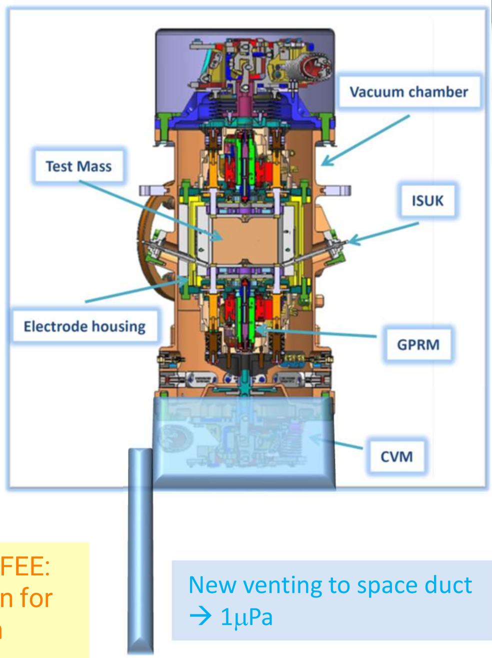


Electrode Housing (FM)

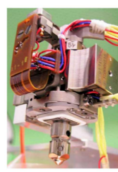


Front End Electronic (FM)

Capacitive sensor FEE:
design optimization for
LISA actuation
electronics.

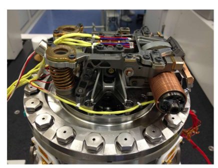


New venting to space duct
→ 1μPa



Grabbing, Position and
Release Mechanism (FM)

Required Test Mass
release velocity
< 15 μm/s



Caging and Venting
Mechanism (FM)

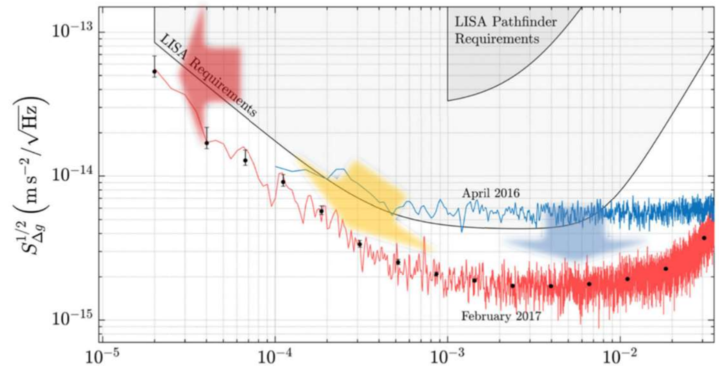
Stray forces noise model

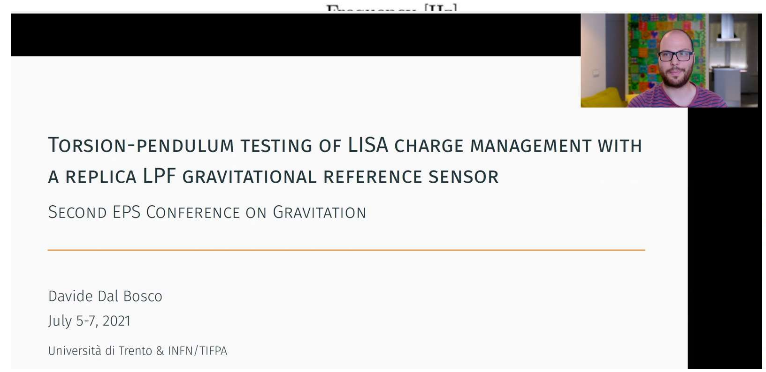
Consolidation and mitigation/suppression strategies

Long noise runs
(glitch fitted away)

Better correction
non-inertial effects
Lower actuation +
Better actuation
calibration

Residual gas
Brownian noise



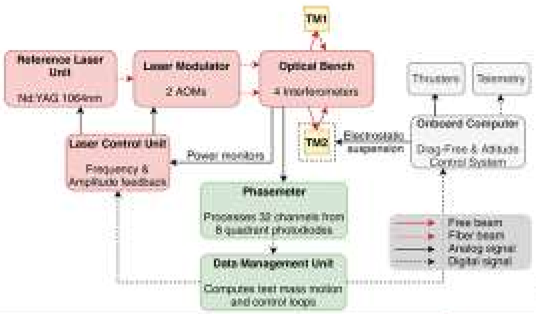


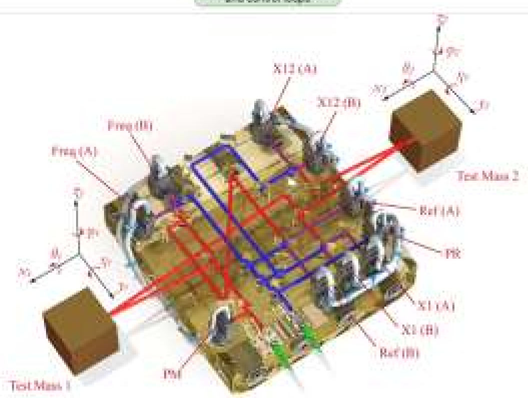
Free fall: from LISA Pathfinder to LISA

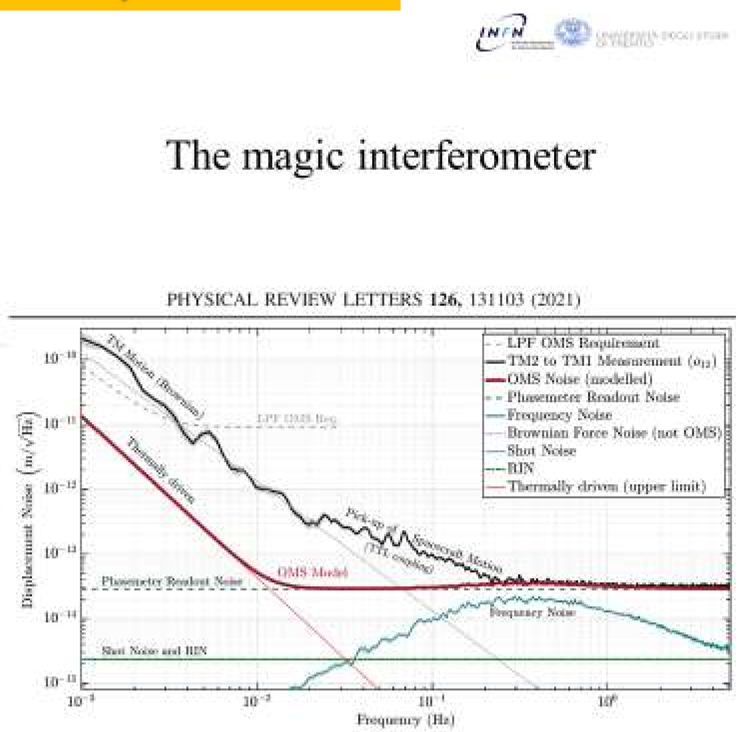
LISA Critical Technologies: Local (Test Mass-Spacecraft) interferometer

Largely understood from LPF, minor differences between LTP and LISA

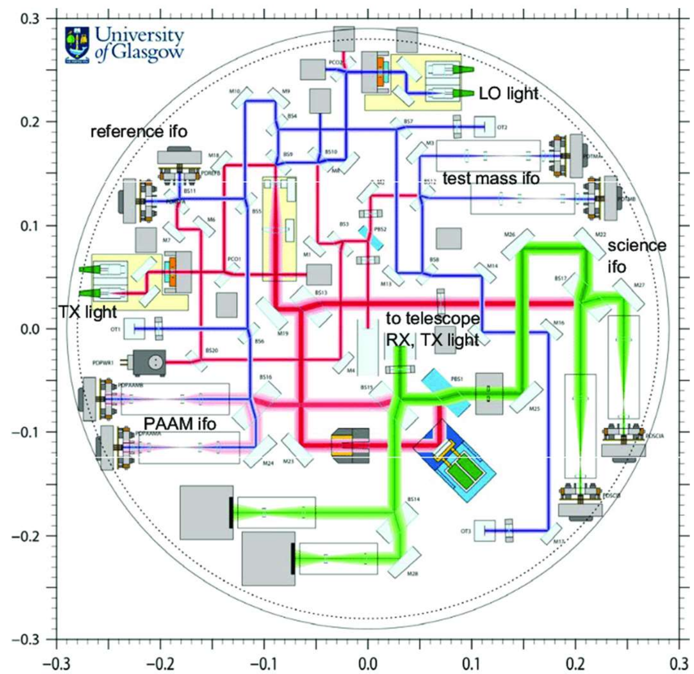
LISA Pathfinder Optical Bench



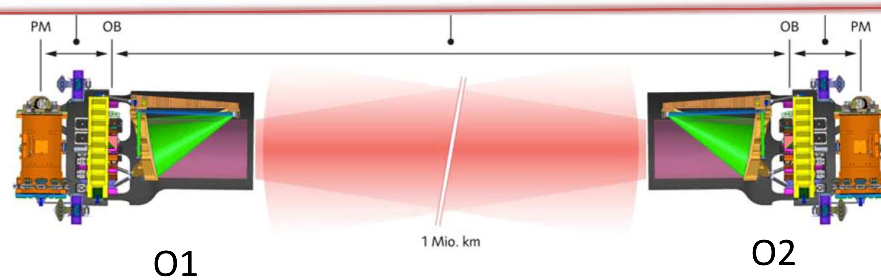




LISA Optical Bench



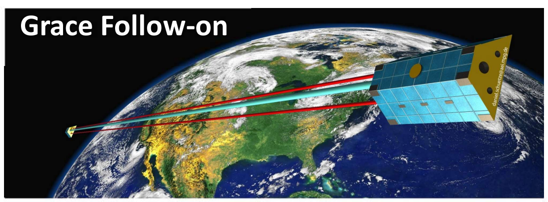
LISA Critical Technologies



LISA Long arm interferometer

Inter-spacecraft laser interferometry:

Laser Ranging Interferometer done in Grace Follow-On (2018)
not the same, but many similarities.



Talk of Malte Misfeldt
On Wed 7thJul 12:00

The first interspacecraft laser ranging interferometer on GRACE Follow-On and conclusions for future gravity missions

But LISA needs to measure pm over millions of km at sub-mHz frequencies.

Beam divergence over 2.5 10^9 m:

→2 W from 30 cm telescope →500 pW received power

weak light phase-lock transponder

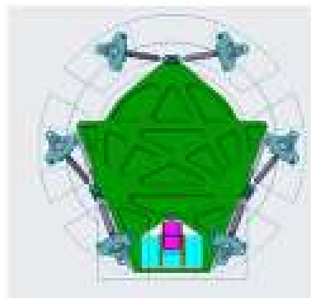
LISA Critical Technologies

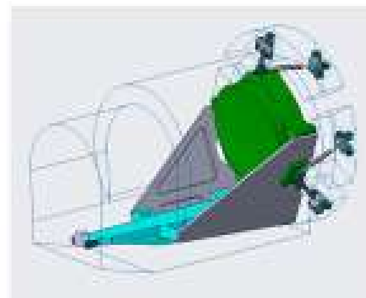
The LISA Telescope (TRL6 by adoption, 2024)

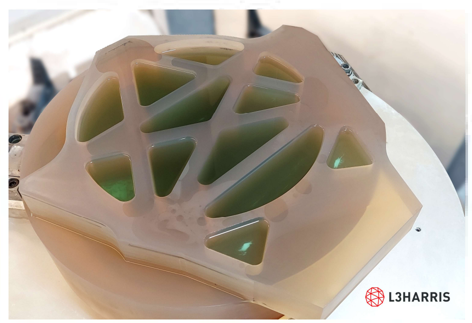
Telescope Functional Description

- Efficiently deliver power on-axis between spacecraft (2.5 million km)
- Simultaneous transmit and receive (TX/RX)
- Afocal beam expander
  - 300 mm dia. large beam
  - 2.24 mm dia. on bench
  - 134X magnification
- **Application is PRECISION LENGTH MEASUREMENT, not image formation**
  - Keep optical pathlength stable to ~ 1 pm/√Hz over the measurement BW
  - Minimize phase noise from coherent transmitter backscattered light
  - Minimize tilt to length (TTL) coupling

All major design reviews completed





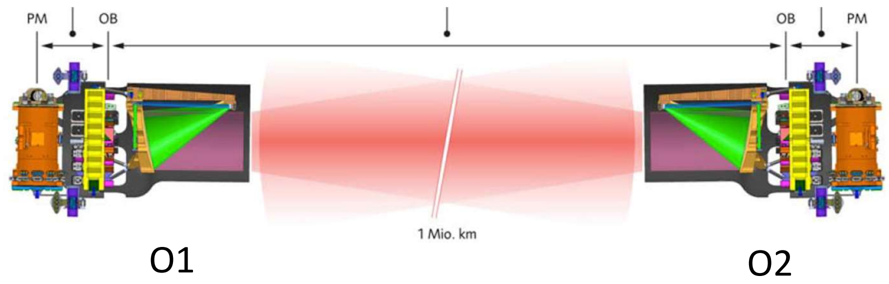


back of the primary mirror mount with light-weighting pockets that has just finished the first round of machining. The material is Zerodur

Thanks to Jeffrey Livas !

LISA Critical Technologies

LISA Long arm interferometer



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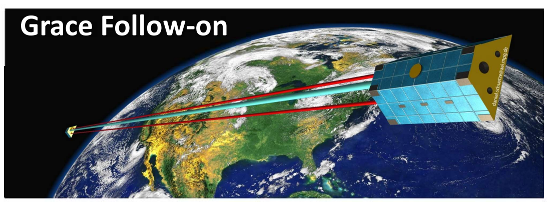


But LISA needs to measure pm over millions of km at sub-mHz frequencies.

Talk of Malte Misfeldt
On Wed 7thJul 12:00

The first interspacecraft laser ranging interferometer on GRACE Follow-On and conclusions for future gravity missions

weak light phase-lock transponder

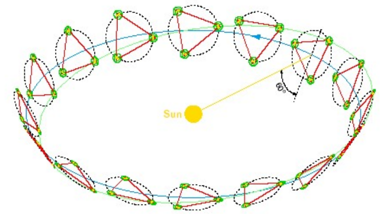
- O1 emits beam with frequency ν_{1E}
- O2 receives, measures phase and sends back phase-coherent copy
- O1 interferes returning beam with local beam,
- measures «beat frequency»: $\Delta\nu$

LISA makes this measurement along 3 arms

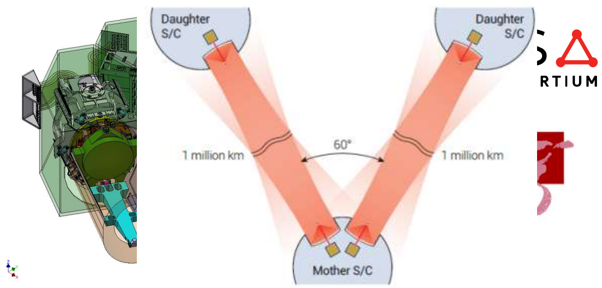
LISA Critical Technologies

LISA constellation rotates «quasi-rigid, quasi-equilateral»

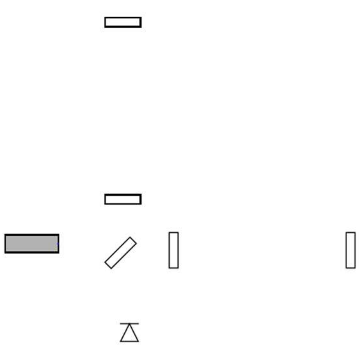
Keplerian dynamics and secular Earth pull produce «breathing»



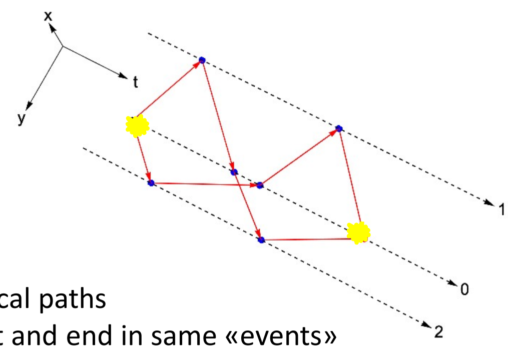
- $\Delta\phi \sim 1°$ → telescope angle must breathe
- $\Delta v \sim$ 10 m/s → Doppler shifts 10 MHz (fringe rates)
- $\Delta L \sim$ 30000 km → unequal arm interferometer laser frequency noise dominant noise without Time Delay Inteferometry (7 orders of magnitude)



Ground based interferometers
beat laser frequency noise comparing
beams emitted at same time (equal arms)



TDI in LISA: combine phase measurements
retarded in time in such a way
that laser frequency noise is killed



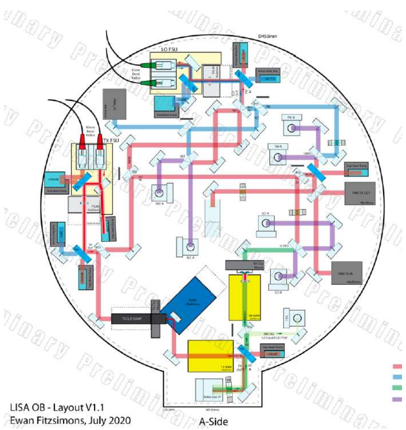
optical paths
start and end in same «events»

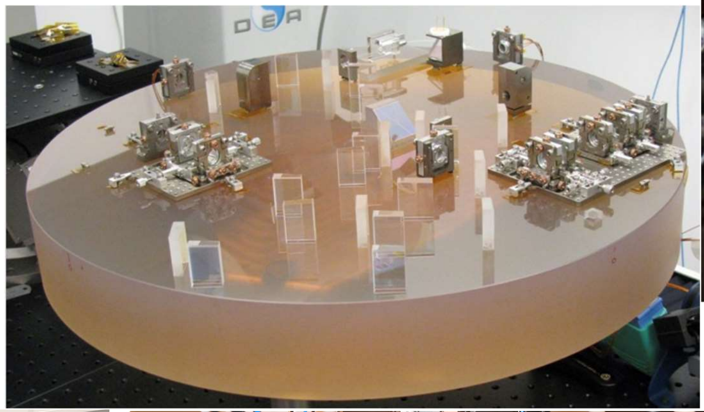
- ➢ Requires knowledge of light travel time within 3 ns/1 m
  → predicted accuracy $1-10\ cm$
- ➢ Requires high accuracy measurement of phase
  → demonstrated by Schwarz et al

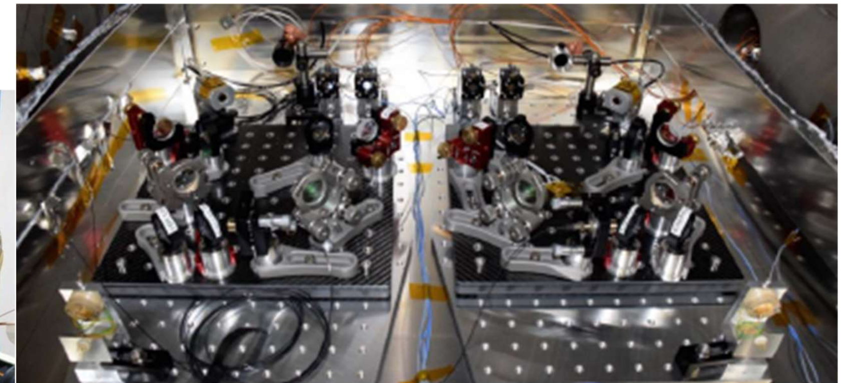
PHYSICAL REVIEW LETTERS **122,** 081104 (2019)

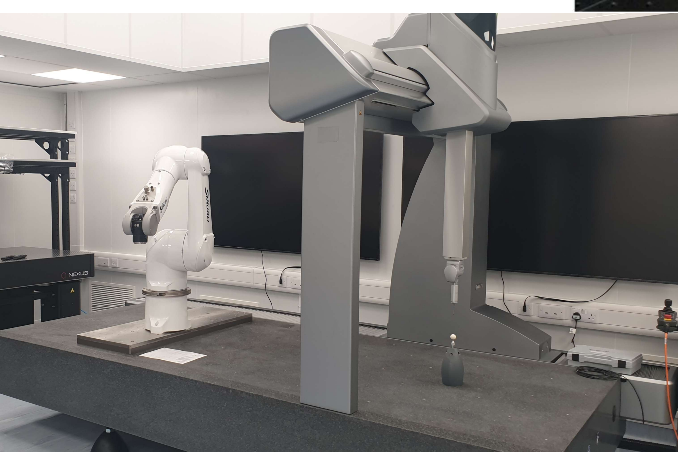
LISA Critical Technologies

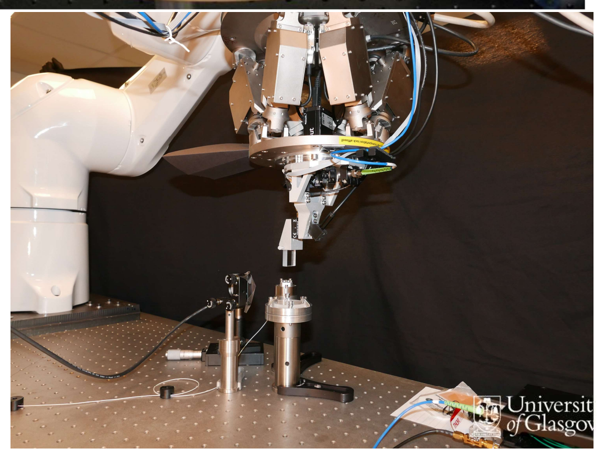
Technology developments: LISA interferometry is challenging but feasible
(TRL 6 by adoption)

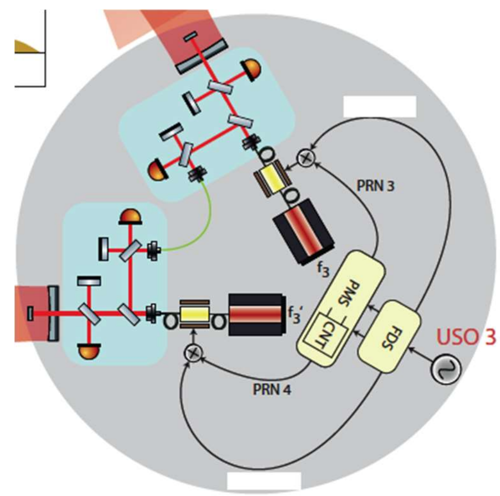




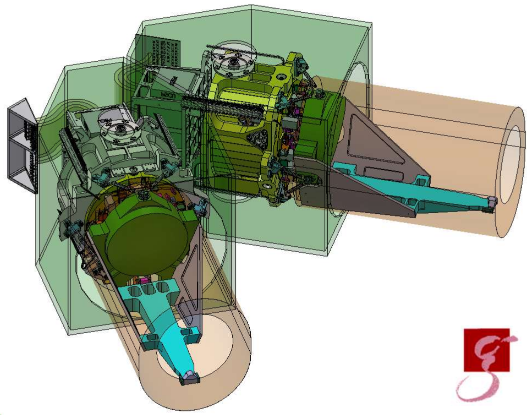


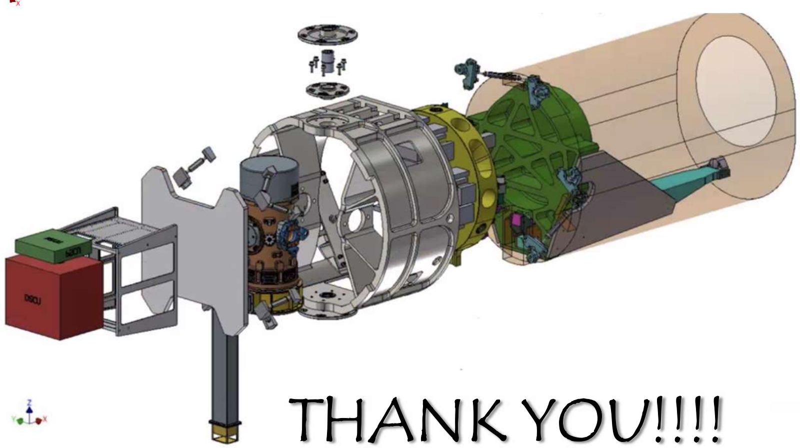






LISA status



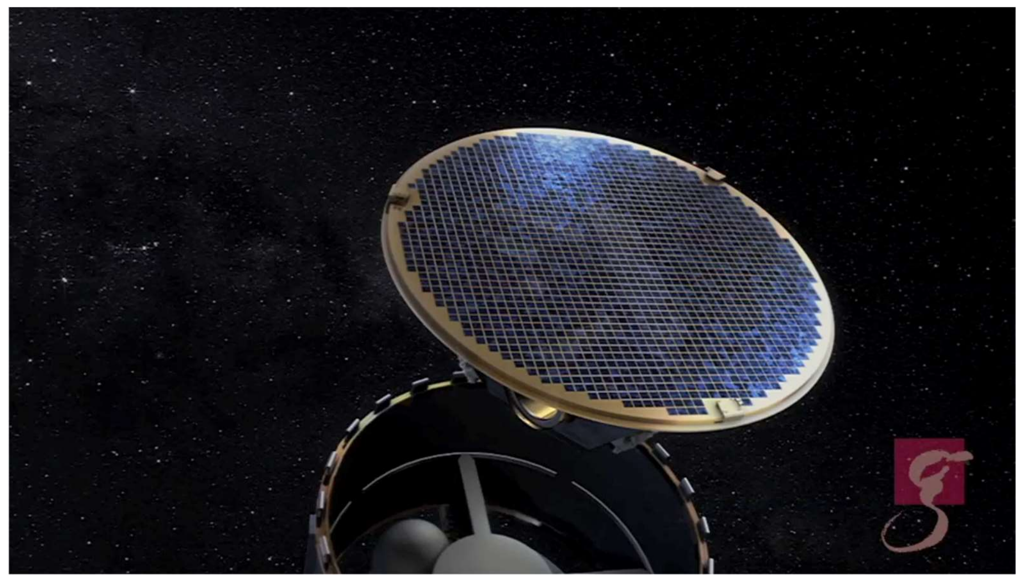


THANK YOU!!!!

NOW: Industrial Phase-A study is competitive: cannot show more! ☹

☺→ Mission adoption 2024

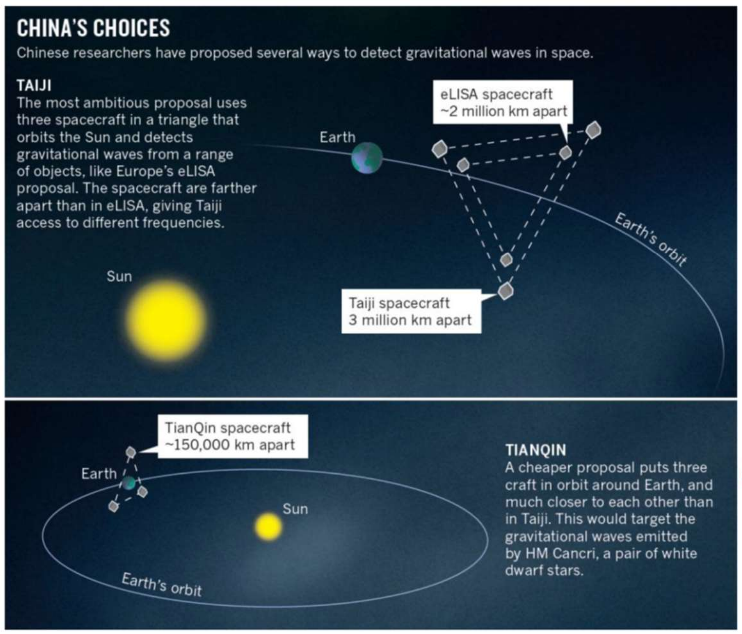
☺→ LISA project team technical work towards launch in 2034



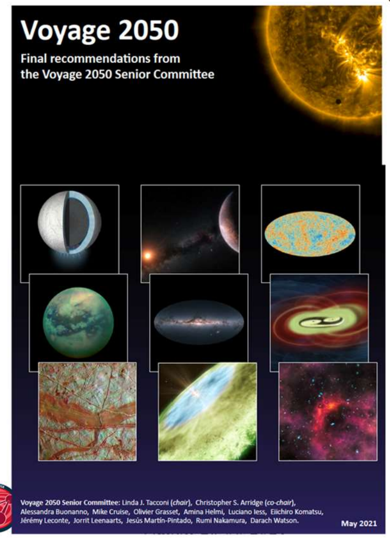
Thanks to the LISA Consortium (https://www.lisamission.org/)

Beyond and besides LISA

At the moment in China : TAIJI e TIANQIN
The case of two cooperating observers is very strong



- Planning for the future



- **New Physical Probes of the Early Universe.** How did the Universe begin? How did the first cosmic structures and black holes form and evolve? These are outstanding questions in fundamental physics and astrophysics, and we now have new astronomical messengers that can address them. Our recommendation is for a Large mission deploying gravitational wave detectors or precision microwave spectrometers to explore the early Universe at large redshifts. This theme follows the breakthrough science from *Planck* and the expected scientific return from *LISA*.