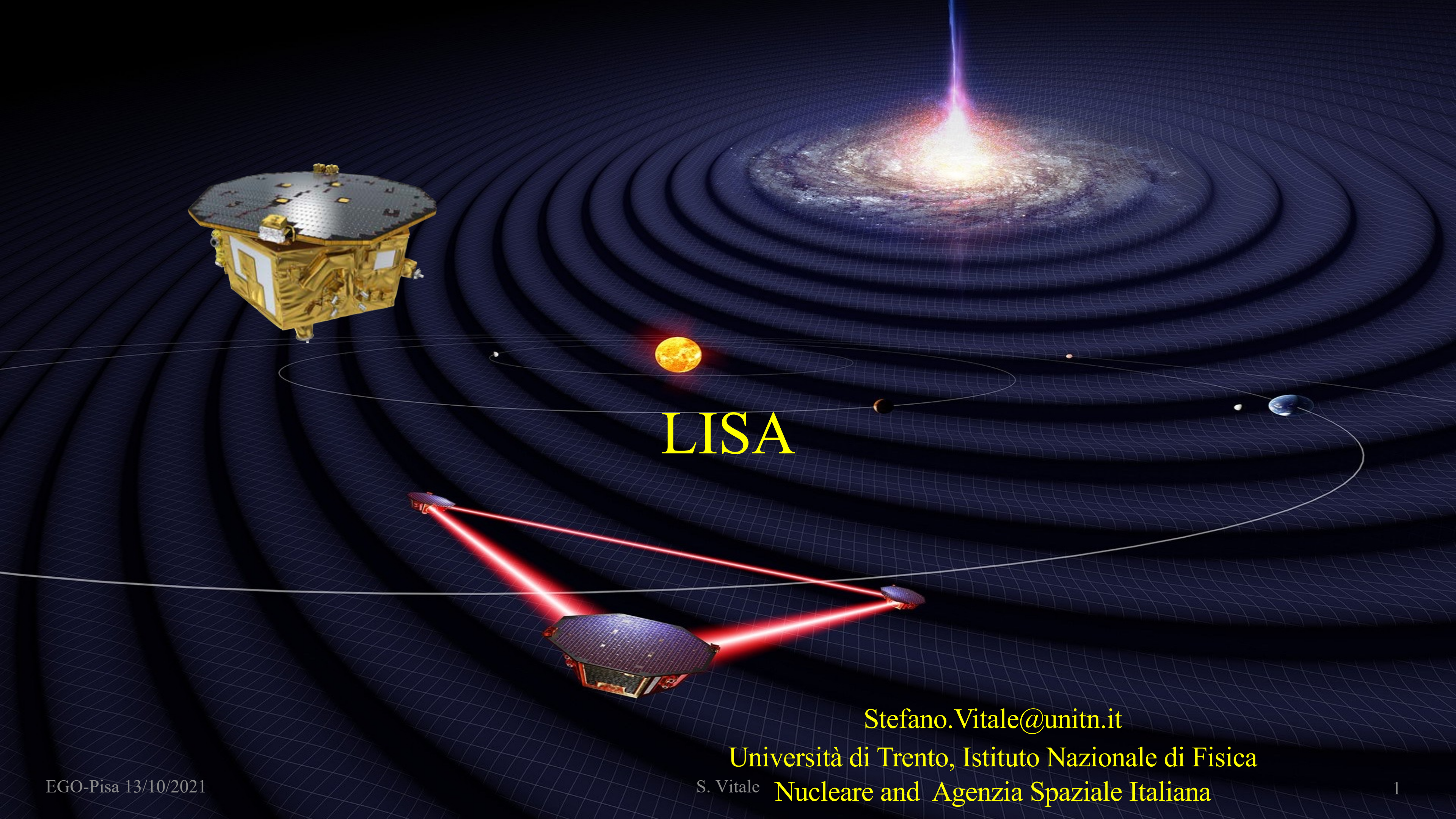
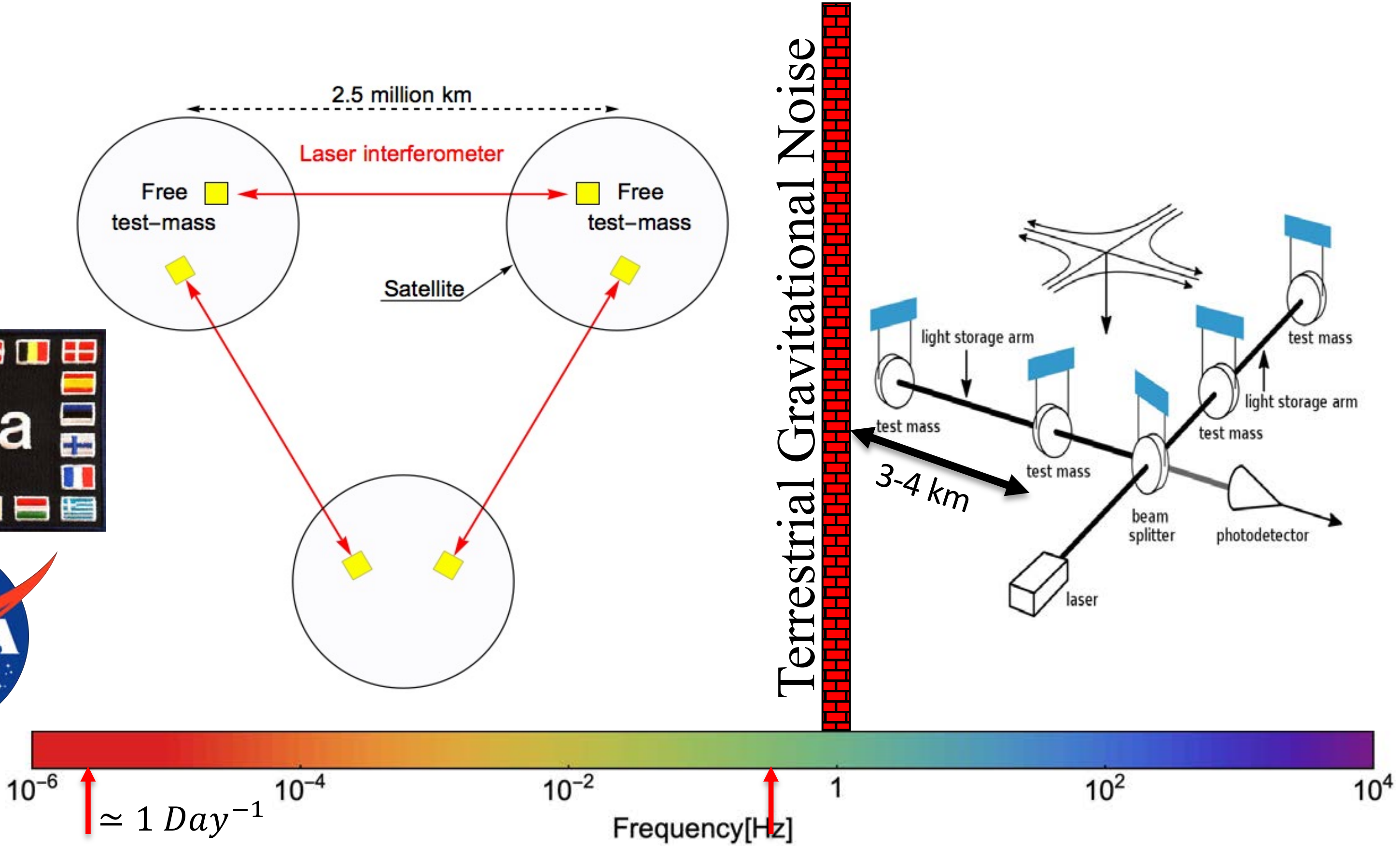


LISA

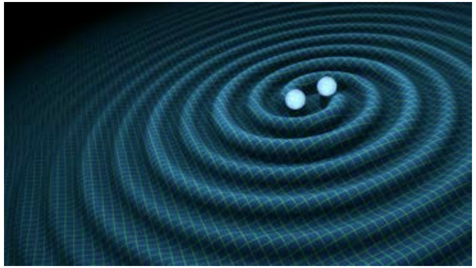
Stefano.Vitale@unitn.it

Università di Trento, Istituto Nazionale di Fisica Nucleare and Agenzia Spaziale Italiana

LISA: the quest for low-frequency GW



Low frequency GW astronomy



- Binaries are nearly Keplerian, frequency of wave twice frequency of revolution

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

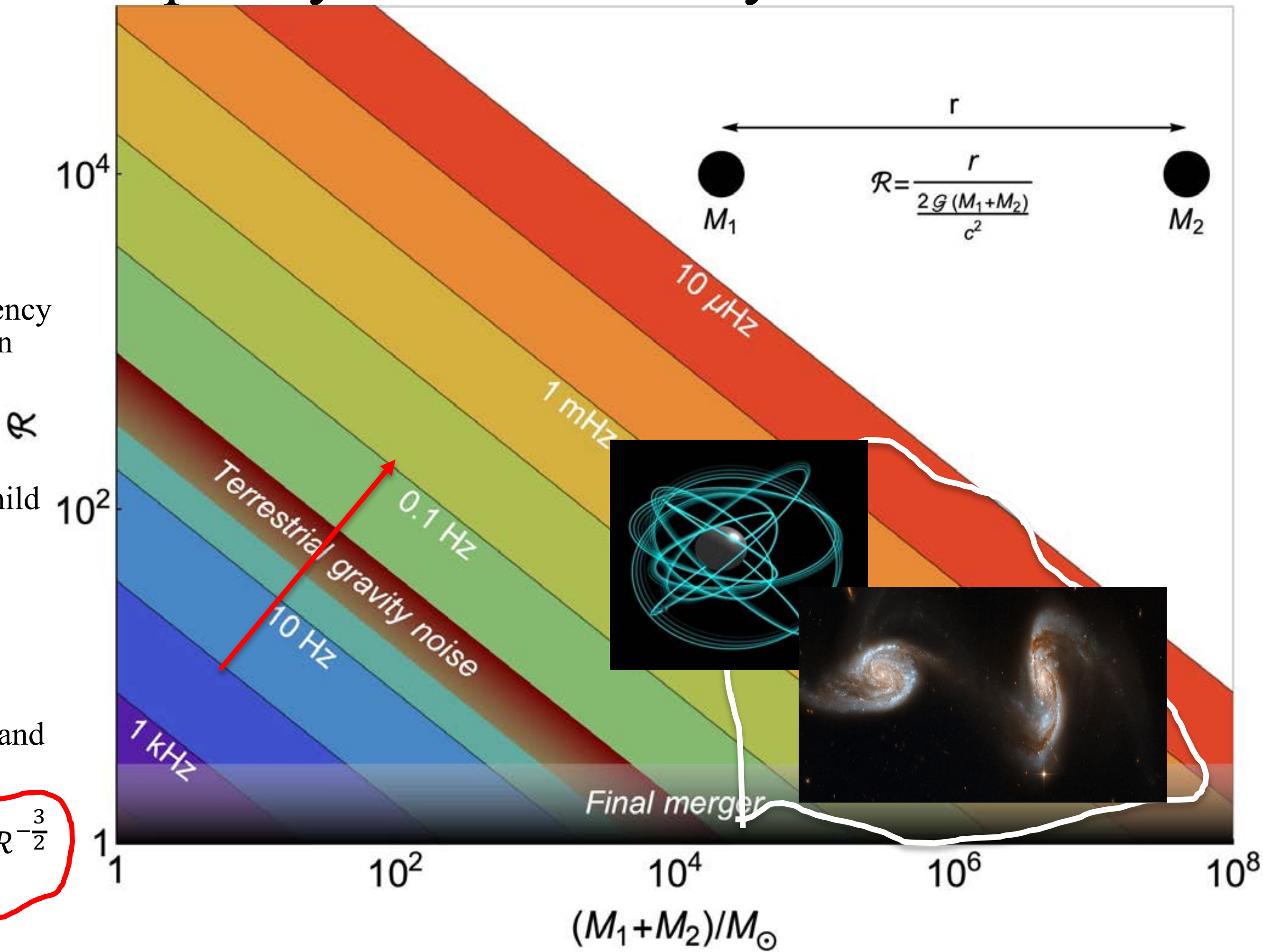
- Separation normalized to Schwarzschild radii:

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

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

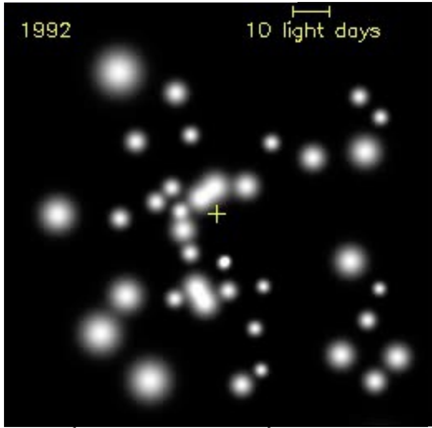
- Frequency decreases with both mass and $\mathcal{R}$

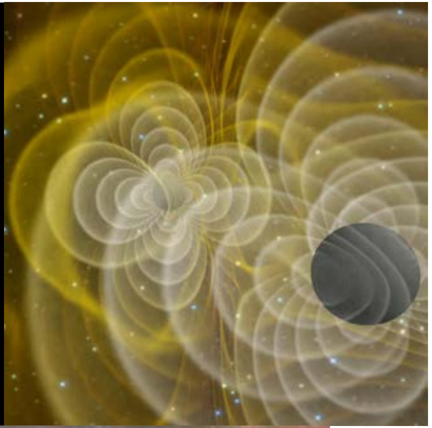
$$f_{GW} = \frac{c}{\pi\sqrt{2}\, R_\odot} \left(\frac{M_1 + M_2}{M_\odot}\right)^{-1} \mathcal{R}^{-\frac{3}{2}}$$

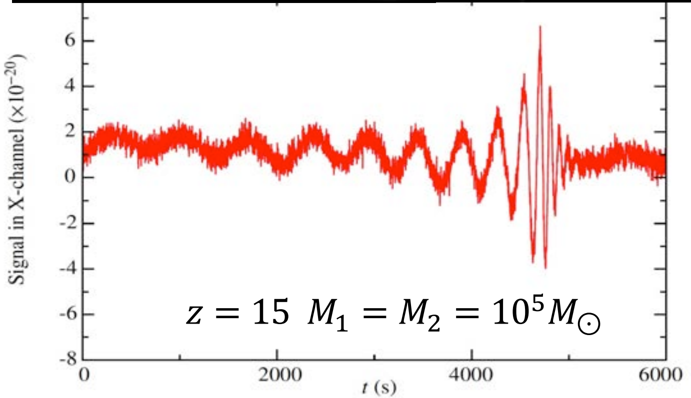


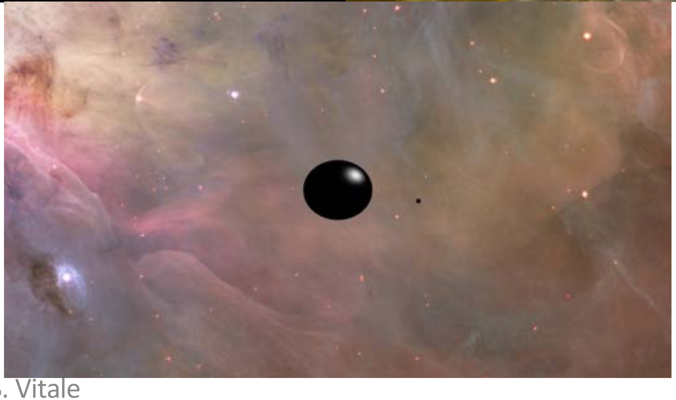
Supermassive BH mergers: the brightest sources

- Wave amplitude scales with $M_1 \times M_2$: detectable “everywhere” in the universe

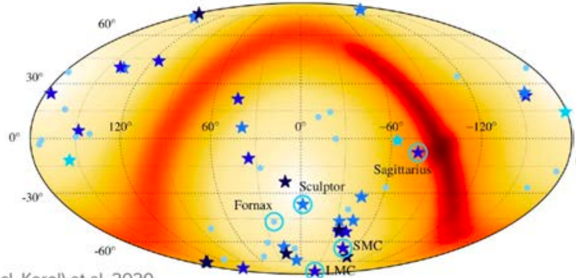






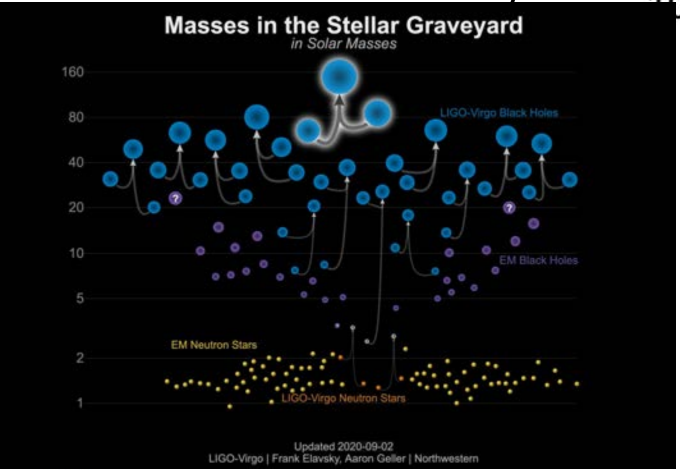


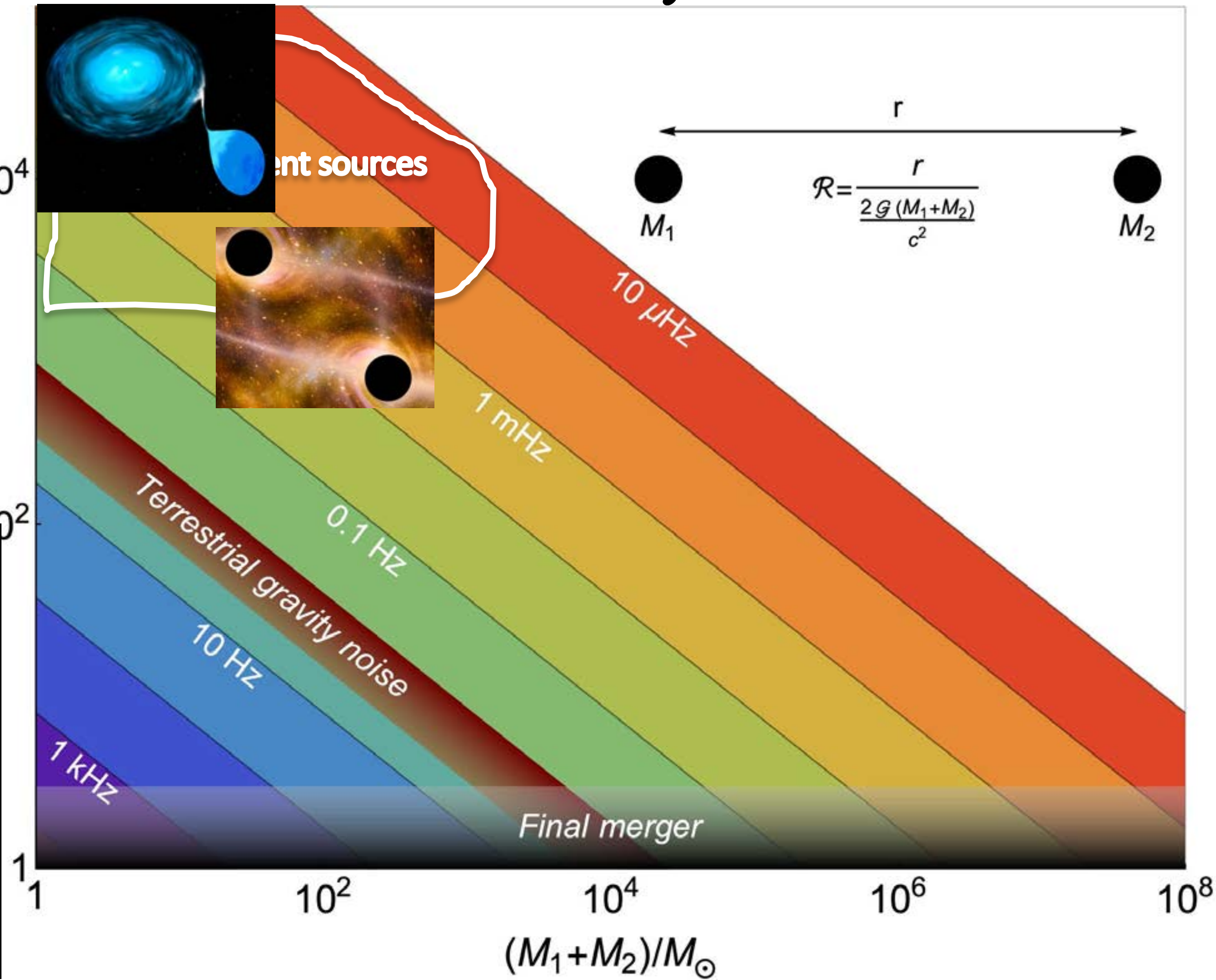
Non-transient GW astronomy



Roebber (incl. Korol) et al. 2020

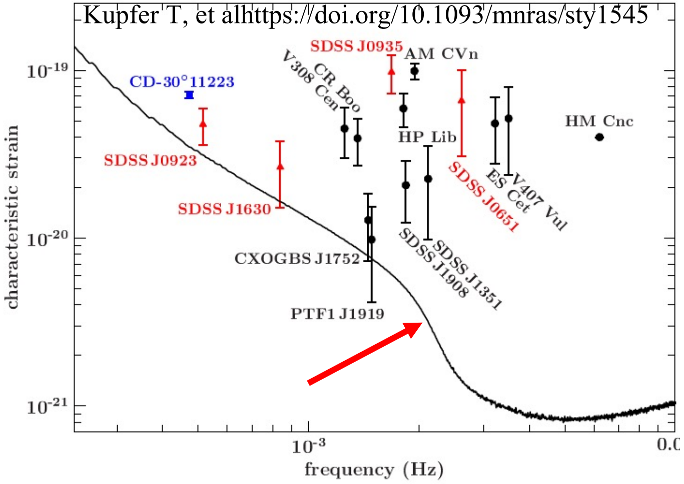
- GW-binary astronomy of local group
- BH multi-band astronomy



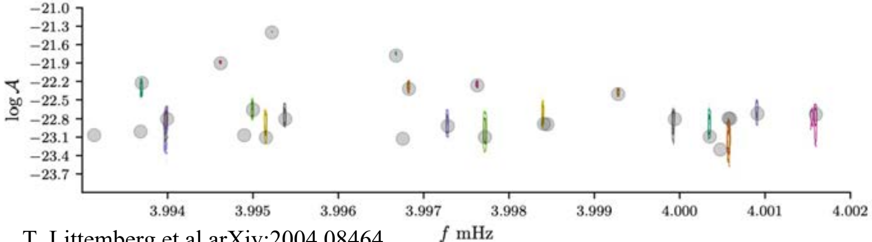


The high $\mathcal{R}$ end: the GW Milky Way

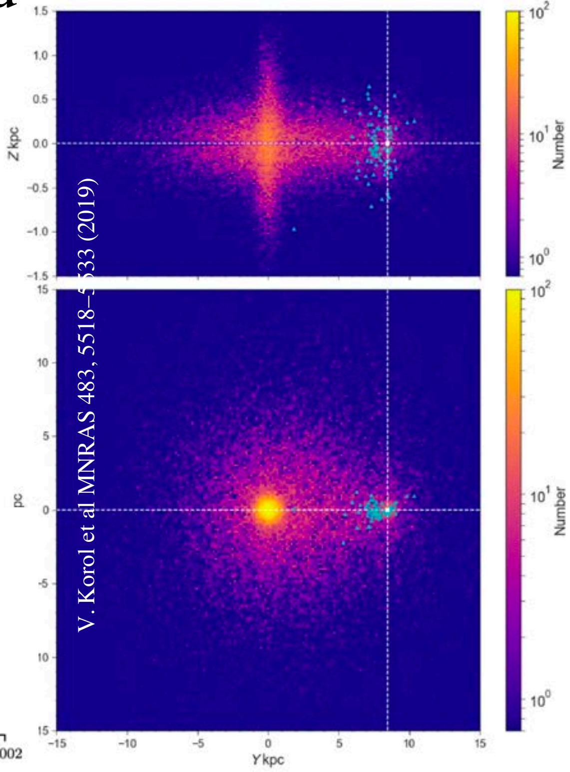
- Tens of thousand of discernible sources
- Plus a stochastic foreground



Kupfer T, et al https://doi.org/10.1093/mnras/sty1545

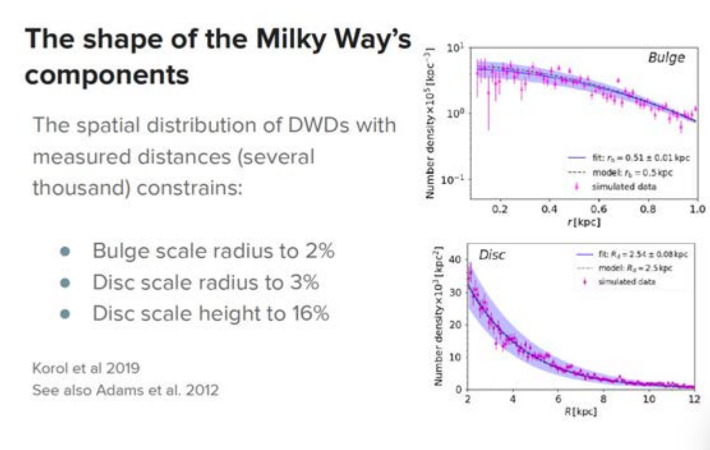


T. Littemberg et al arXiv:2004.08464



V. Korol et al MNRAS 483, 5518–5533 (2019)

Expectations

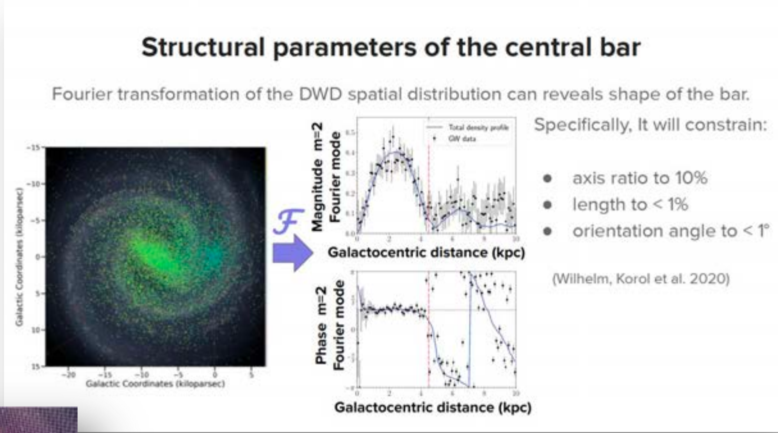


The shape of the Milky Way's components

The spatial distribution of DWDs with measured distances (several thousand) constrains:

- Bulge scale radius to 2%
- Disc scale radius to 3%
- Disc scale height to 16%

Korol et al 2019
See also Adams et al. 2012



Structural parameters of the central bar

Fourier transformation of the DWD spatial distribution can reveals shape of the bar.

Specifically, It will constrain:

- axis ratio to 10%
- length to < 1%
- orientation angle to < 1°

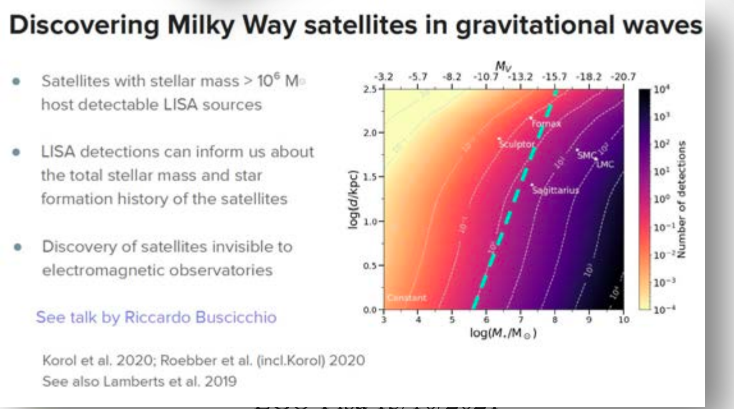
(Wilhelm, Korol et al. 2020)

The detection of circumbinary exoplanets

Camilla DANIELSKI

LISA XIII - Sep 3 2020

Valeriya Korol

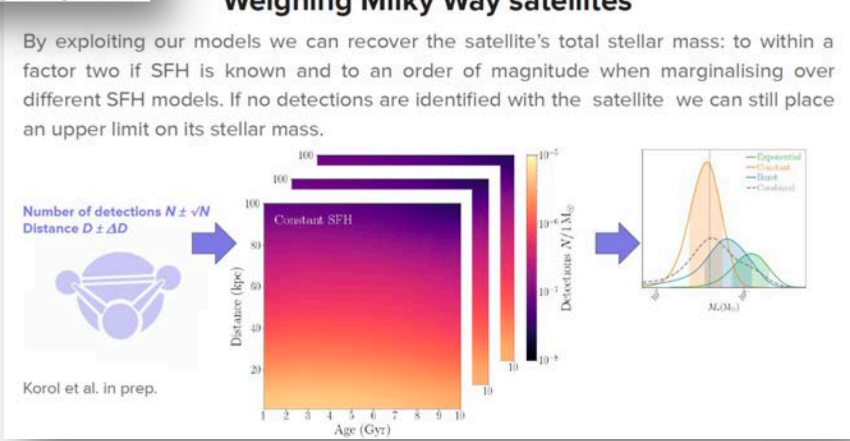


Discovering Milky Way satellites in gravitational waves

- Satellites with stellar mass > 10^6 M⊙ host detectable LISA sources
- LISA detections can inform us about the total stellar mass and star formation history of the satellites
- Discovery of satellites invisible to electromagnetic observatories

See talk by Riccardo Buscicchio

Korol et al. 2020; Roebber et al. (incl.Korol) 2020
See also Lamberts et al. 2019

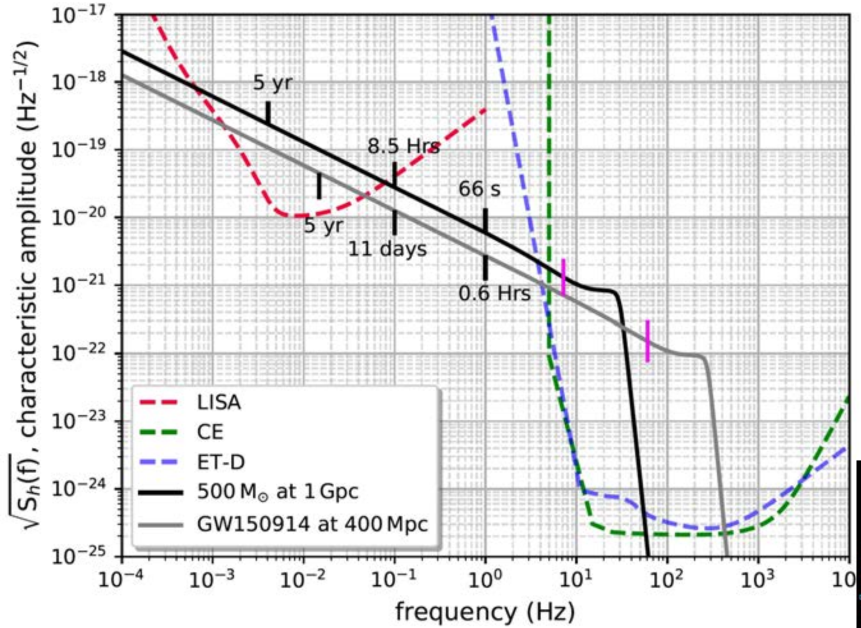


Weighing Milky Way satellites

By exploiting our models we can recover the satellite's total stellar mass: to within a factor two if SFH is known and to an order of magnitude when marginalising over different SFH models. If no detections are identified with the satellite we can still place an upper limit on its stellar mass.

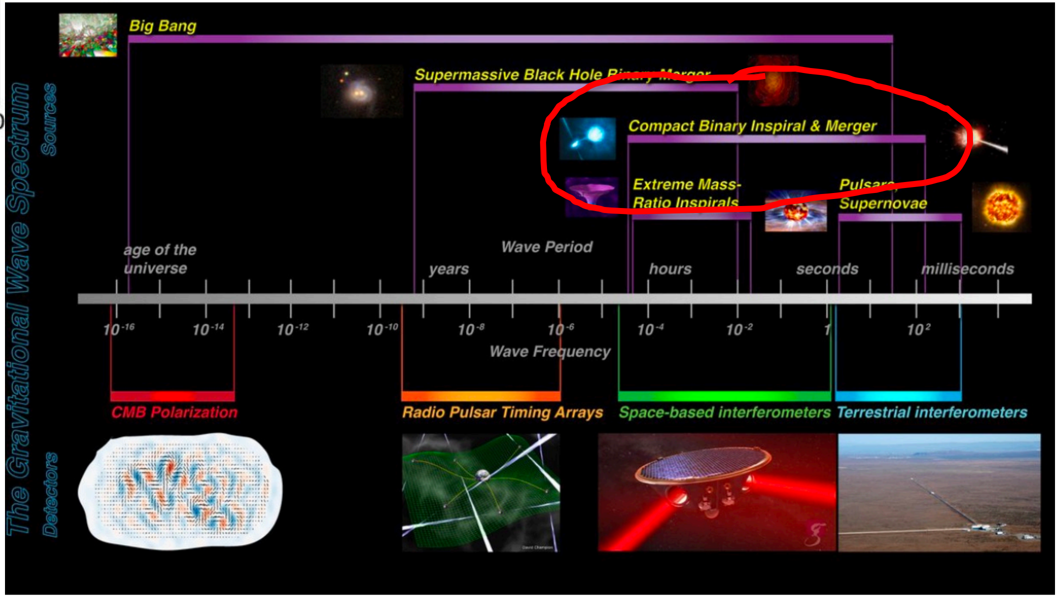
Korol et al. in prep.

Multi-band GW astronomy and fundamental physics



Joint observation greatly improves measurement of deviation from GR

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

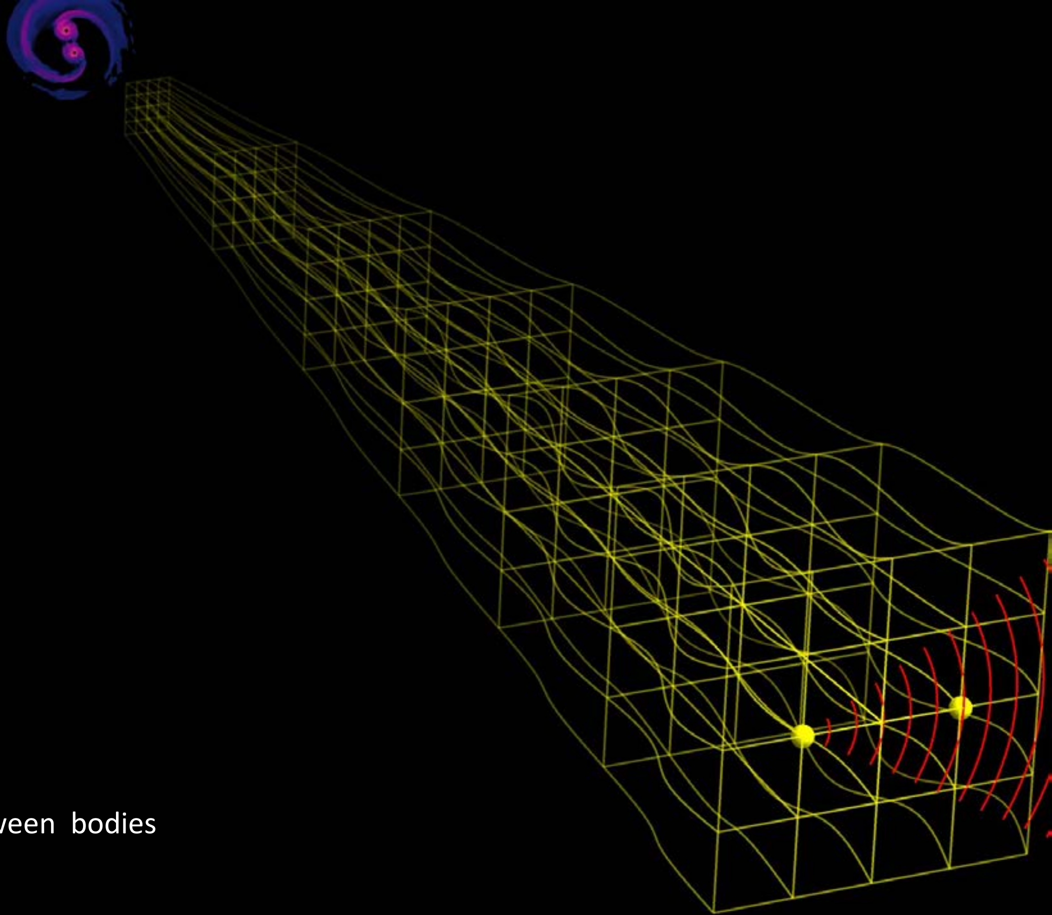


(credit: K. Jani)

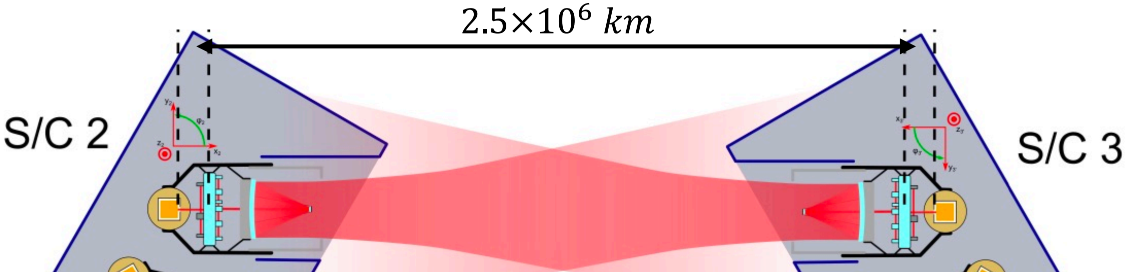
Detecting gravitational wave in space

- Waves of space-time curvature that propagate at speed of light
- Doppler tracking of free orbiting bodies modulated at period of gravitational wave

$$\frac{\Delta\dot{\nu}}{\nu_o} \simeq c\underbrace{R^{x}{}_{0\,x\,0}}_{\text{Curvature tensor}}\left.L\right\}\text{Separation between bodies}$$

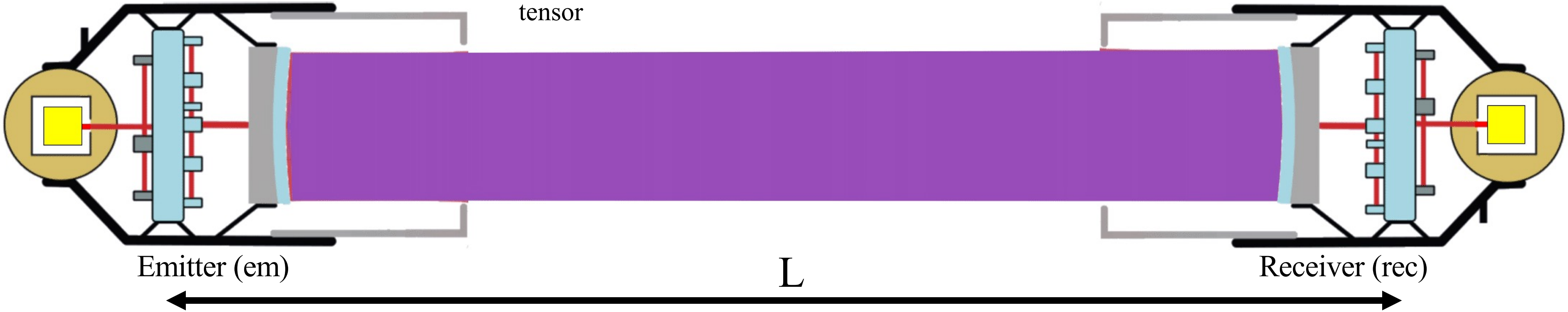


LISA



The LISA link

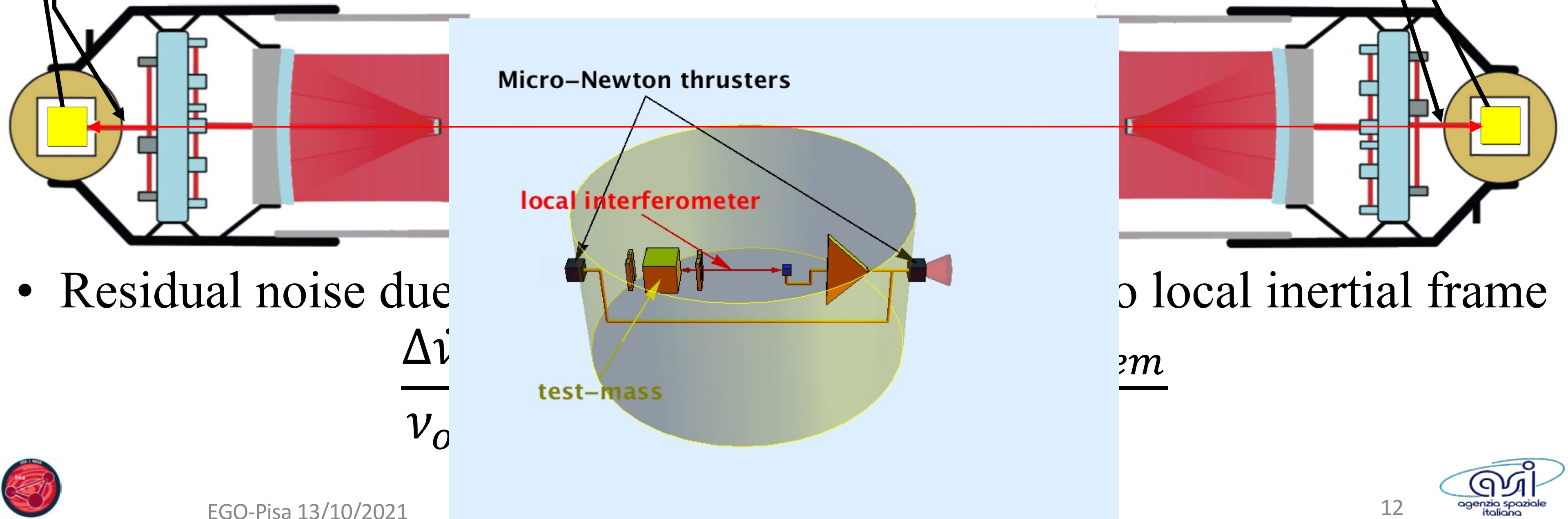
- Propagating throughout GW curvature, beam accumulates a time modulated frequency shift $\frac{\Delta\dot{\nu}}{\nu_o} \simeq \underbrace{cR^{x}{}_{0\,x\,0}}_{\text{Curvature tensor}} \left. L \right\}$ Size of detector



- Acceleration of spacecraft via standard Doppler effect also shifts frequency and mimics GW $\frac{\Delta\dot{\nu}}{\nu_o} = cR^{x}{}_{0\,x\,0}L + \frac{a_{rec}-a_{em}}{c}$
- Spacecraft (S/C) accelerate too much because of solar radiation pressure

Coping with S/C acceleration

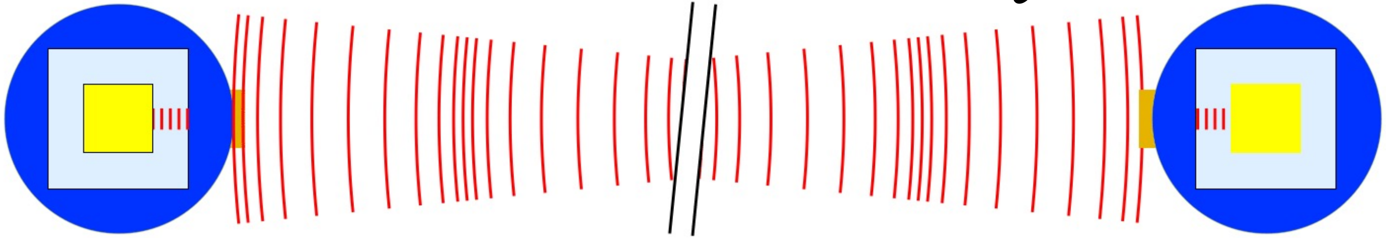
- Free-floating test-masses (TM) are carried inside S/C
- No contact between TM and S/C, “drag-free” along the beam
- Measure S/C-to-TM acceleration and correct signal for Doppler



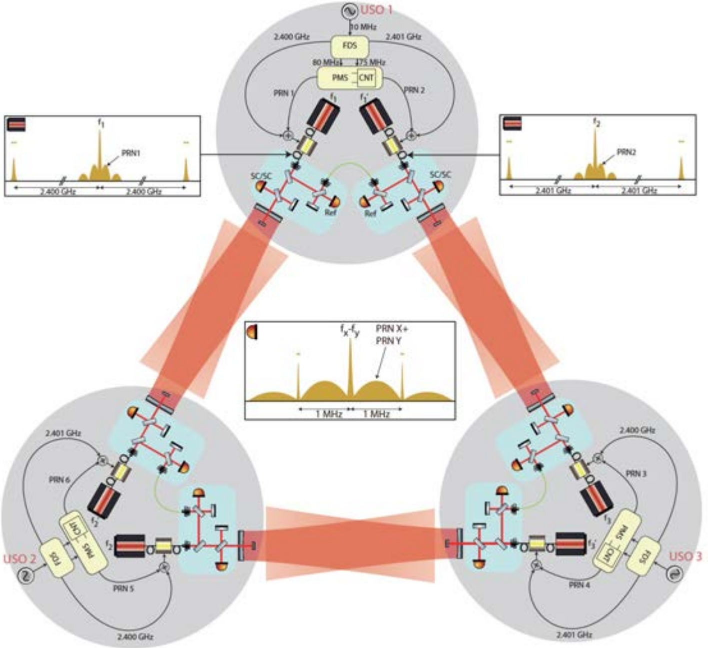
- Residual noise due o local inertial frame

$\frac{\Delta\nu}{\nu_o}$ em

LISA interferometry

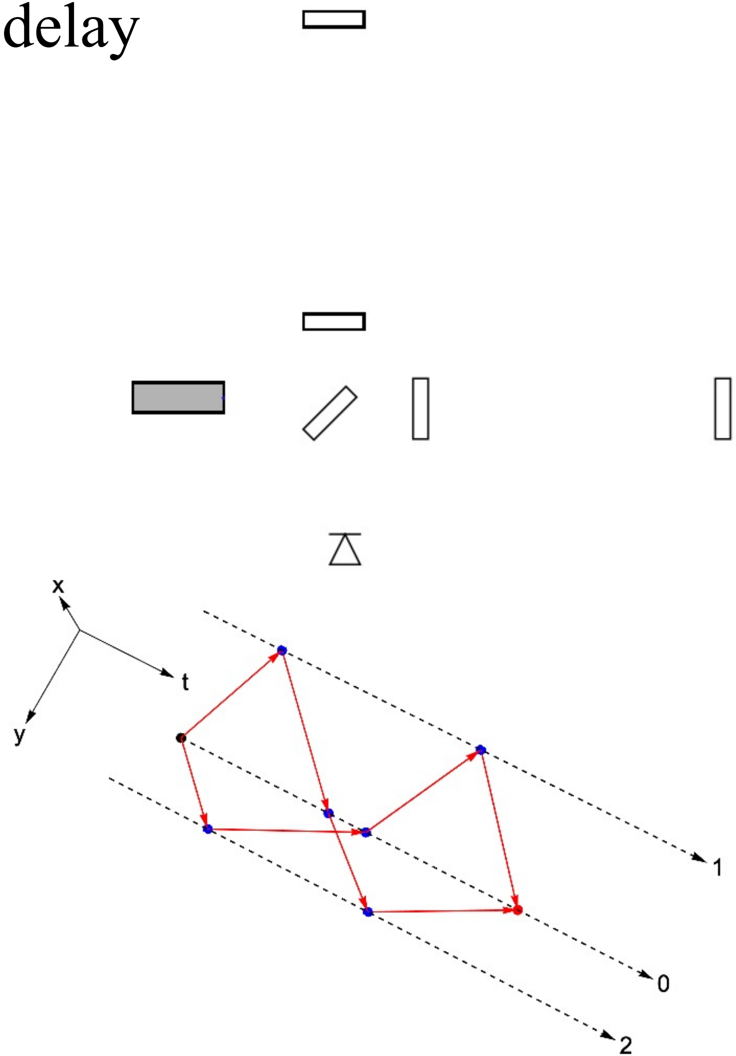


- The LISA arm: two counter-propagating links.
- LISA 3 arms: 6 single-link frequency signals, 100 pW interferometry, $\simeq 10\ pm/\sqrt{Hz}$ equivalent test-mass displacement.
- To beat laser noise, data processing requires knowledge of light travel time within 3 ns/1 m. Done with internal “laser GPS”



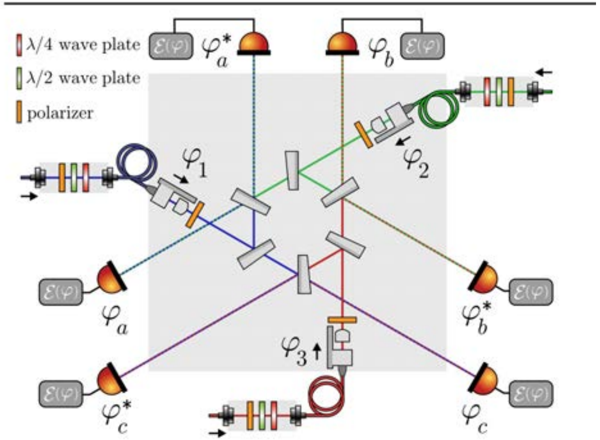
Laser frequency noise & time delay interferometry

- Best stabilized laser frequency noise off scale:
  - Required $\lesssim 1\ \mu Hz/\sqrt{Hz}$
  - Available $\lesssim 1\ kHz/\sqrt{Hz}$
- Ground based interferometers beat noise comparing beams emitted at same time (equal arms)
- LISA: arms are unequal ($\Delta \mathrm{L} \simeq 10^5 km$) and time varying over the year.
- Combine single-link signals to mimic light beams that have traveled equal lengths



Requires high accuracy measurement of phase

- Demonstrated in lab by many teams
- For instance



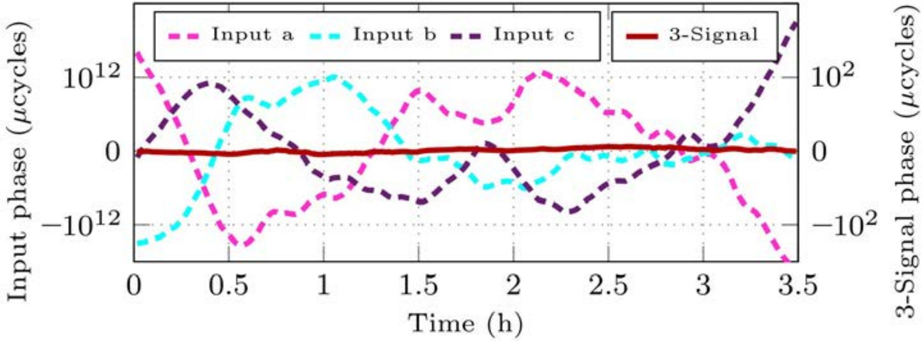
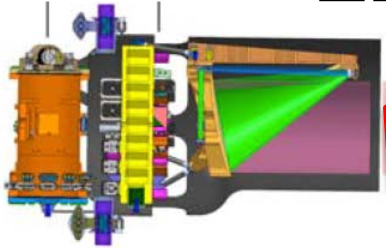


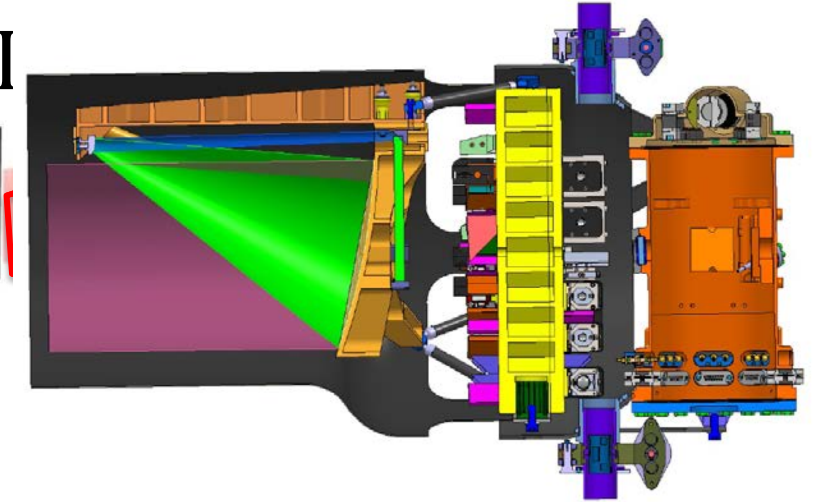
FIG. 4. Time series of input phase fluctuations and resulting three-signal combination, illustrating the high dynamic range essential for TDI.

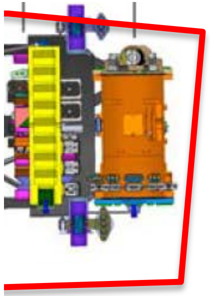
$10^8 - 10^{11}$ dynamic range

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

LI

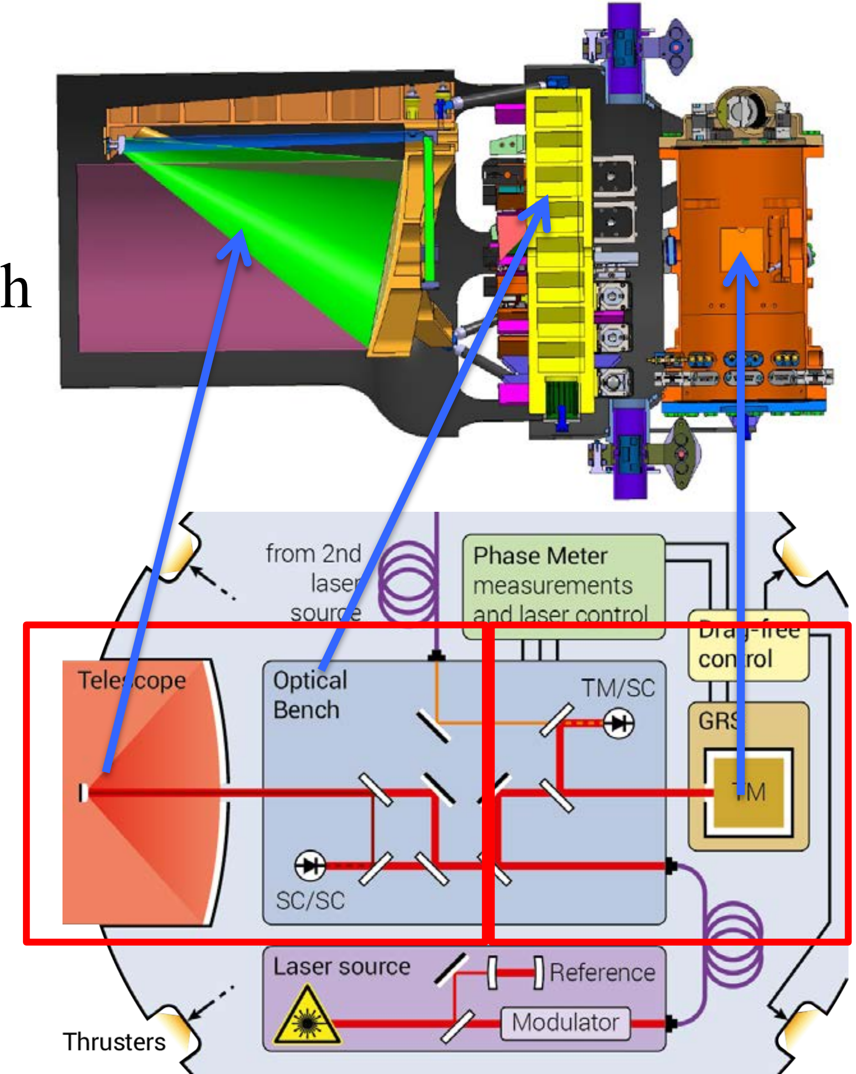


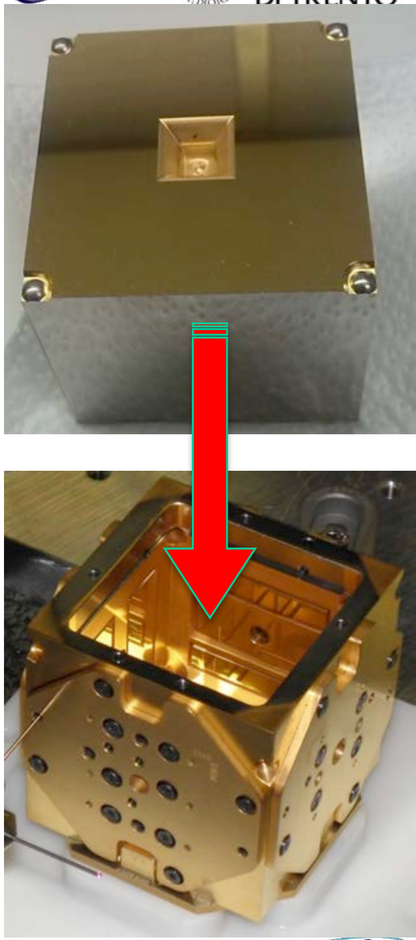




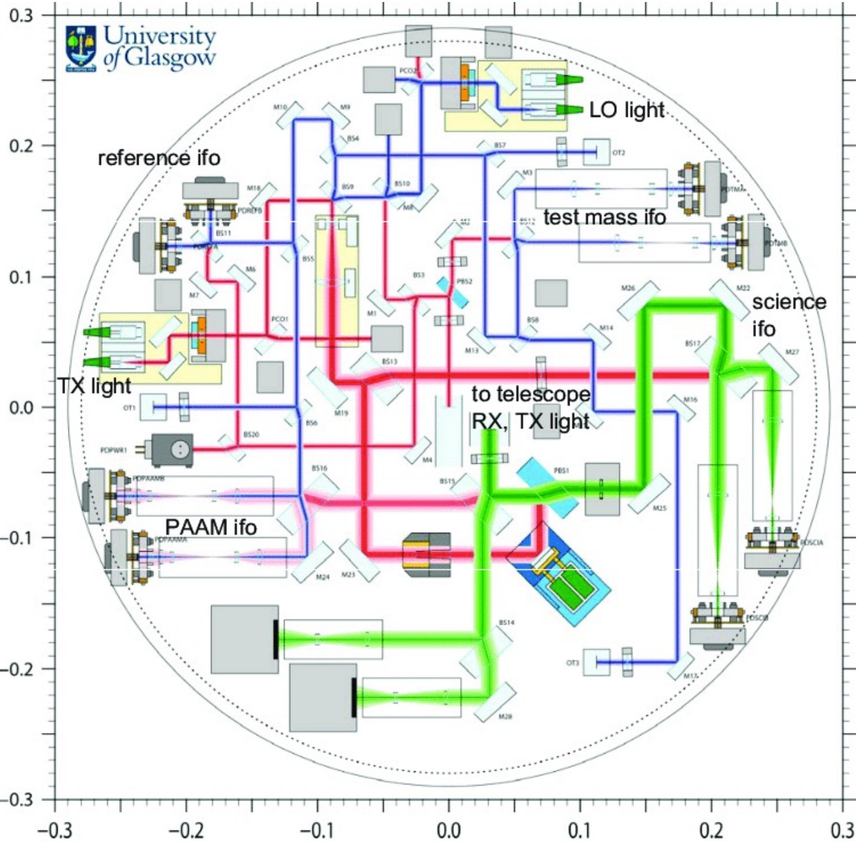
LISA link Instrument

- The Gravitational Reference Sensor with the test-mass
- The Optical Bench with:
  - Local interferometer
  - Spacecraft to spacecraft interferometer, including telescope





The optical bench



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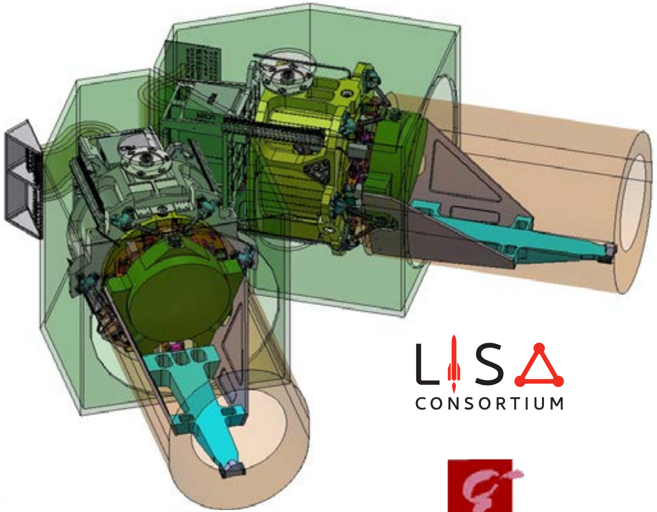
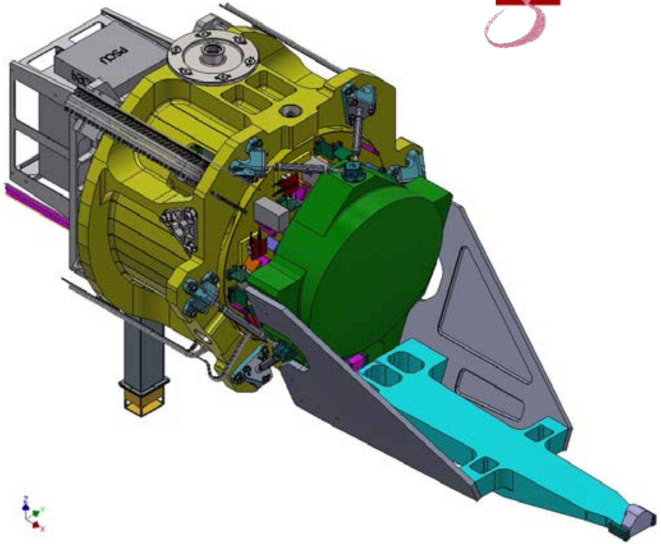
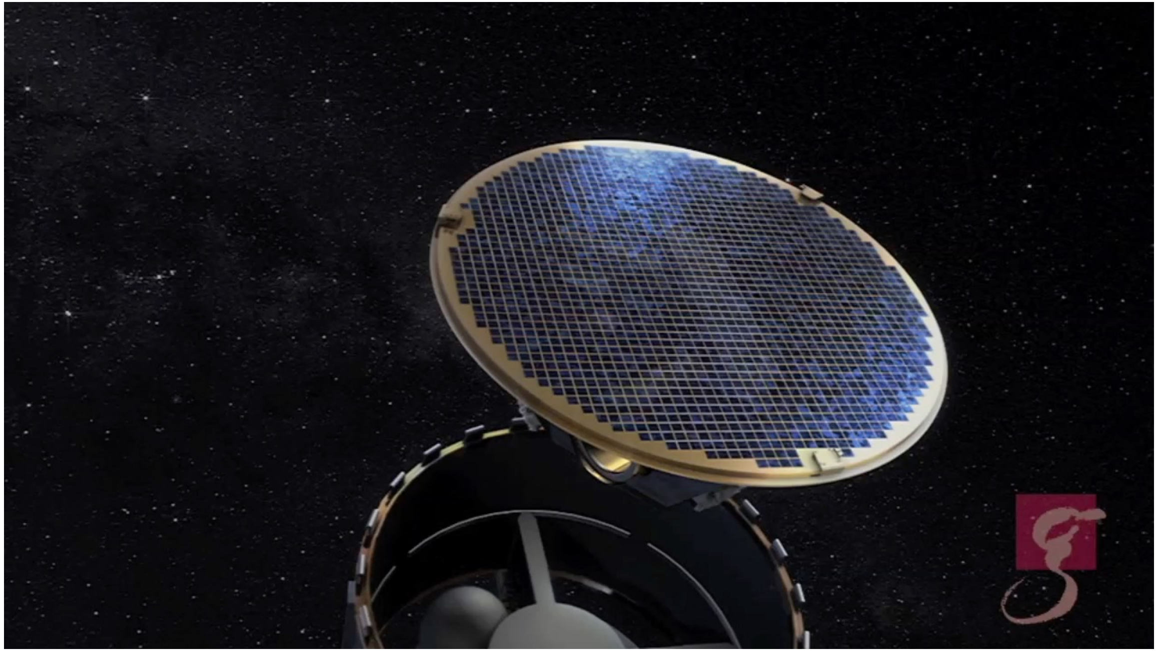
The full complement



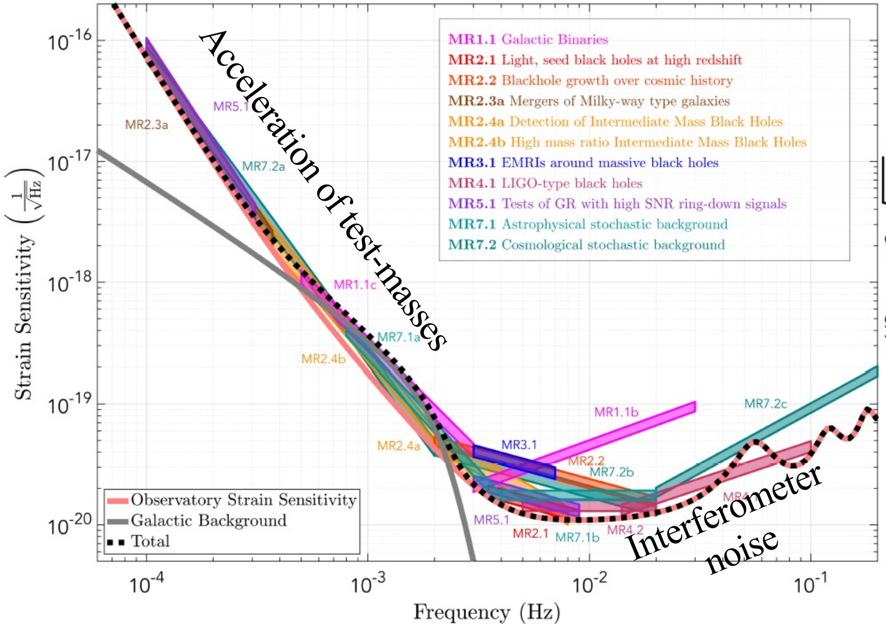
LISA CONSORTIUM

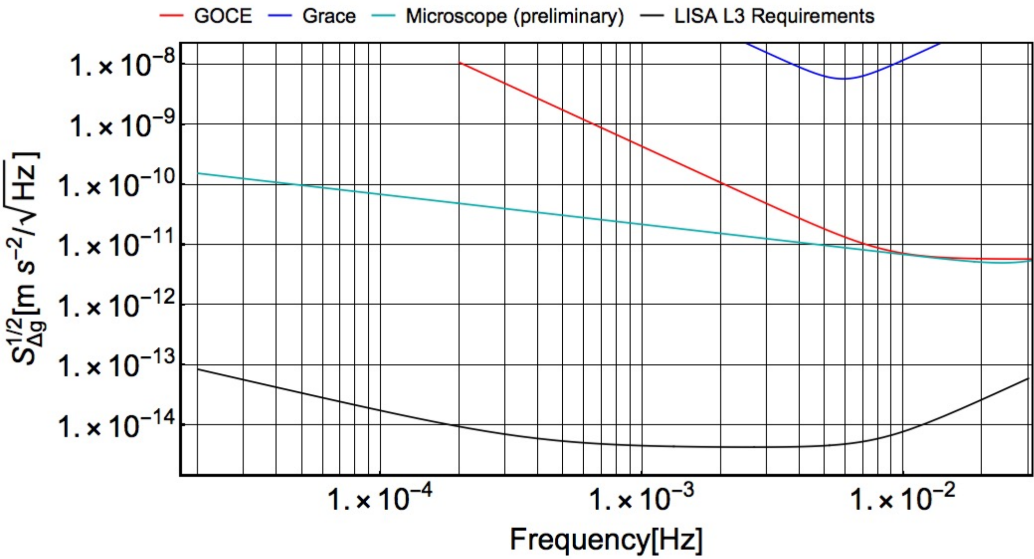




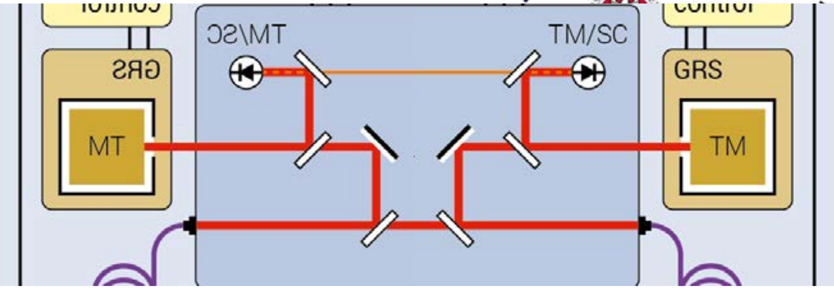
Acceleration noise and LISA science

- LISA sensitivity limited at low frequency by acceleration of test-masses
- LISA is a low frequency instrument: much of SNR for most interesting sources accumulated $\lesssim$ 10 mHz
- Acceleration noise $\leq femto\ g/\sqrt{Hz}$
- Cannot be demonstrated on ground or in LEO

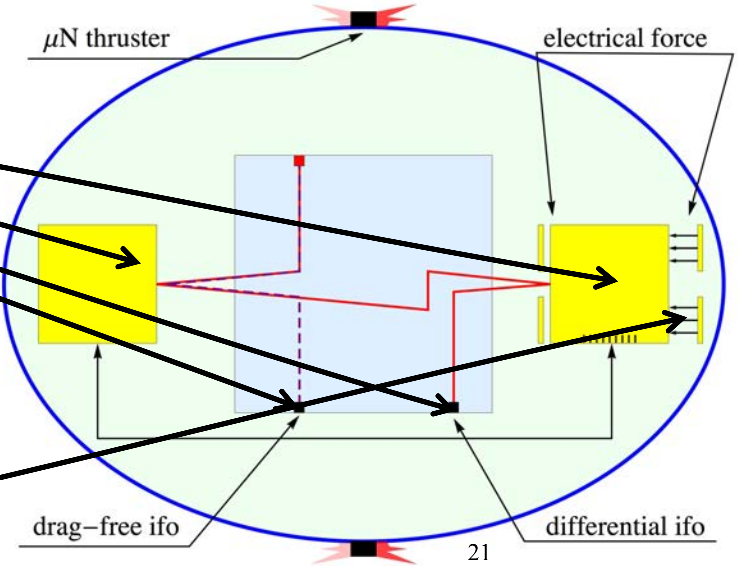




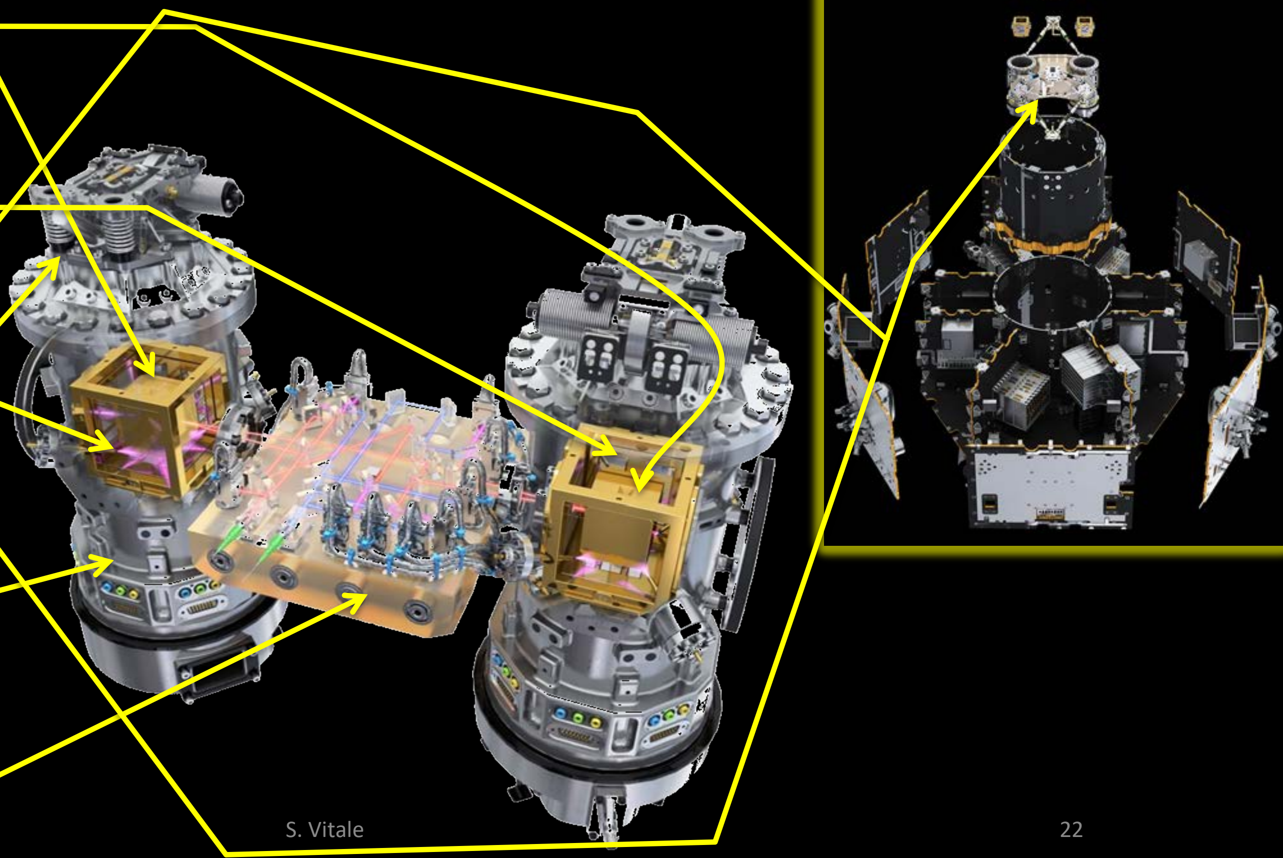
LISA Pathfinder



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

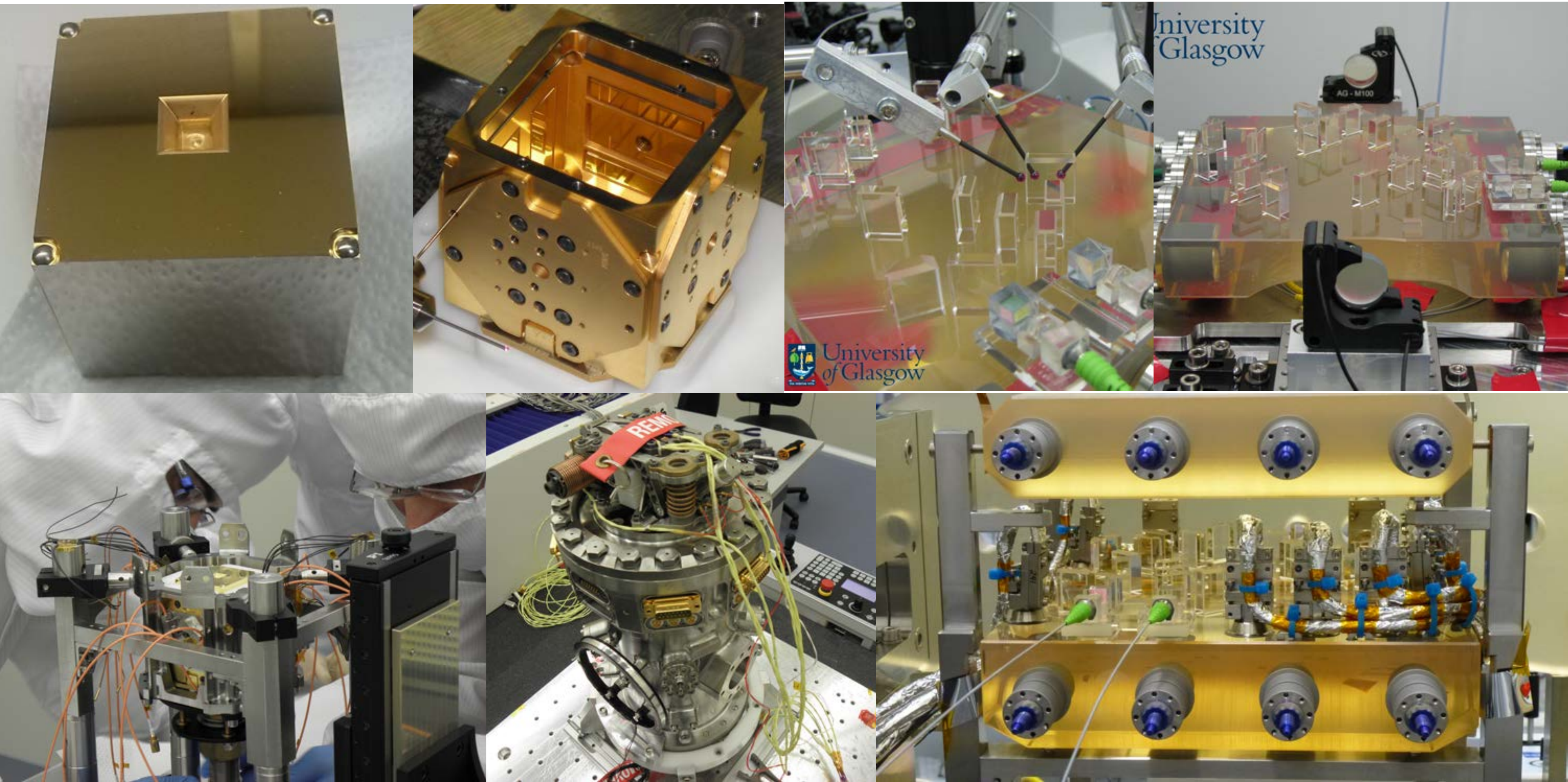


The LTP

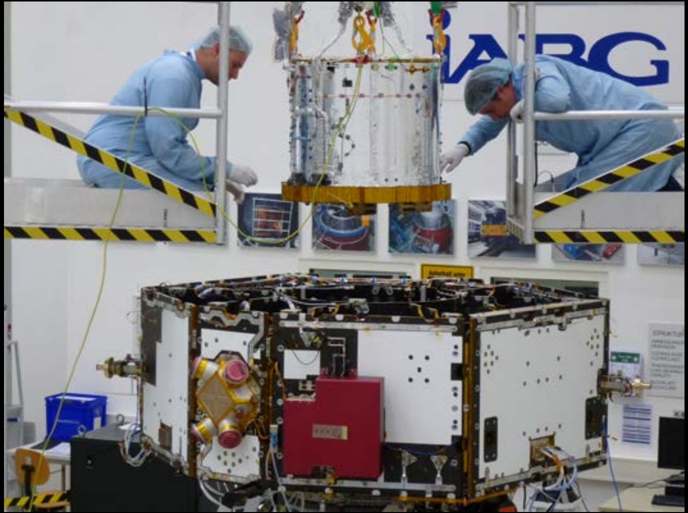


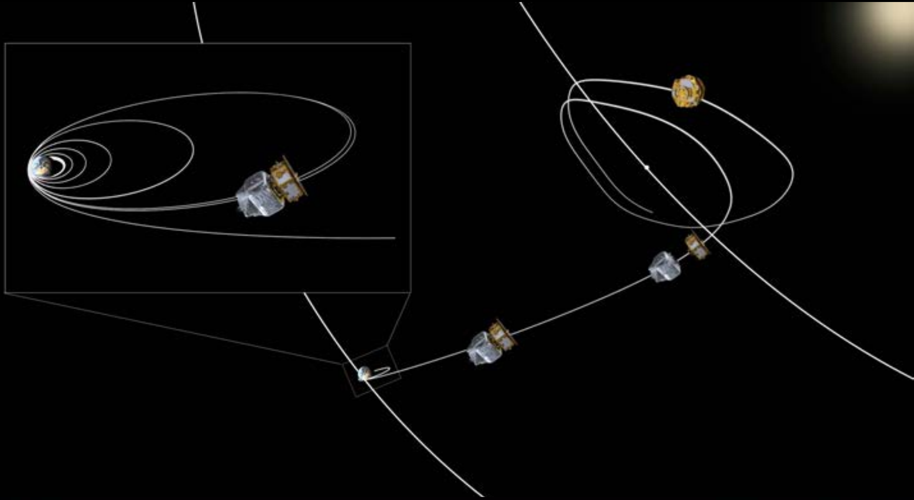
- Test masses gold-platinum, highly non-magnetic, very dense
- Electrode housing: electrodes are used to exert very weak electrostatic force
- UV light, neutralize the charging due to cosmic rays
- Caging mechanism: holds the test-masses and avoid them damaging the satellite at launch
- Vacuum enclosure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

The real H/W



Instrument integration

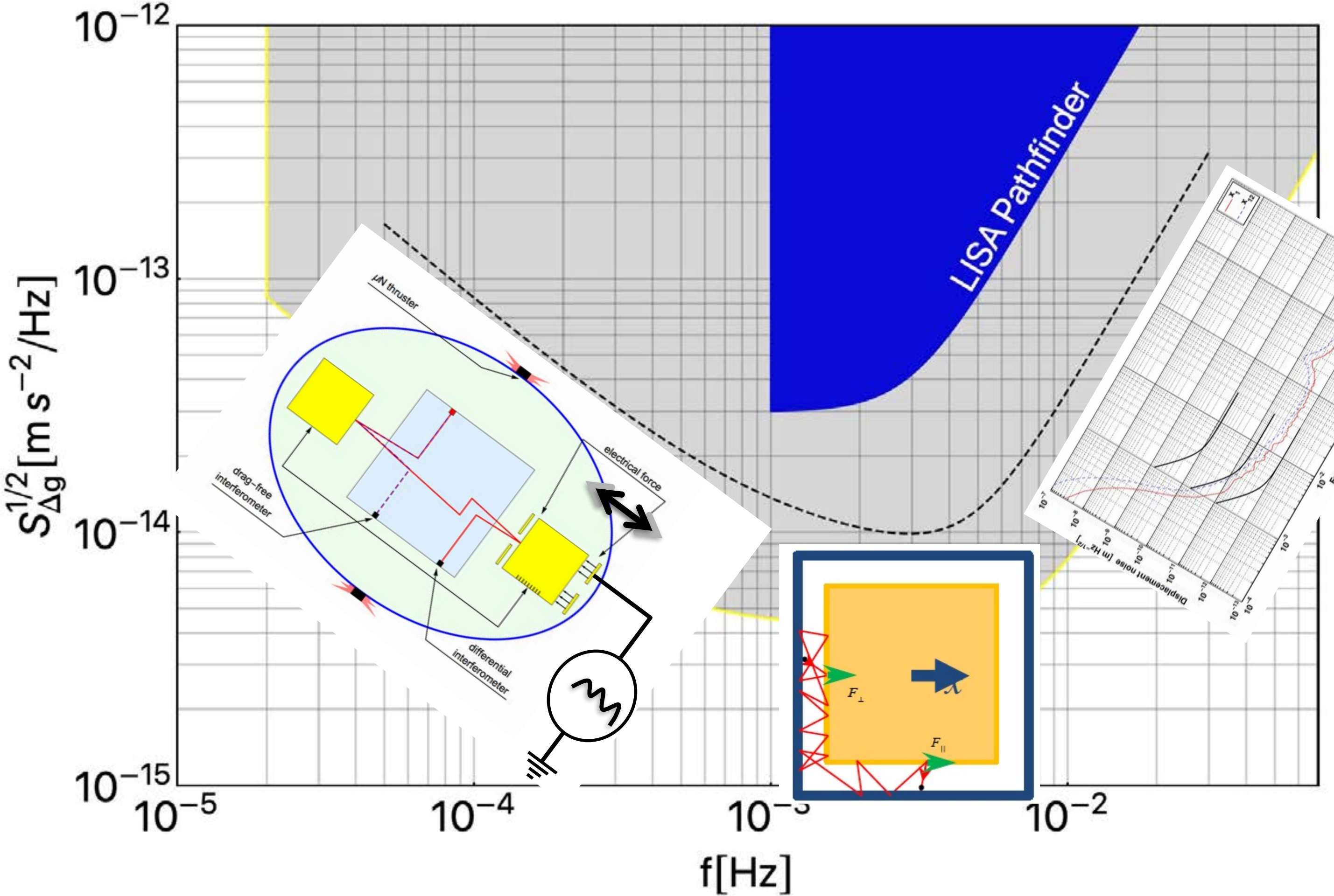




From instrument integration to orbit

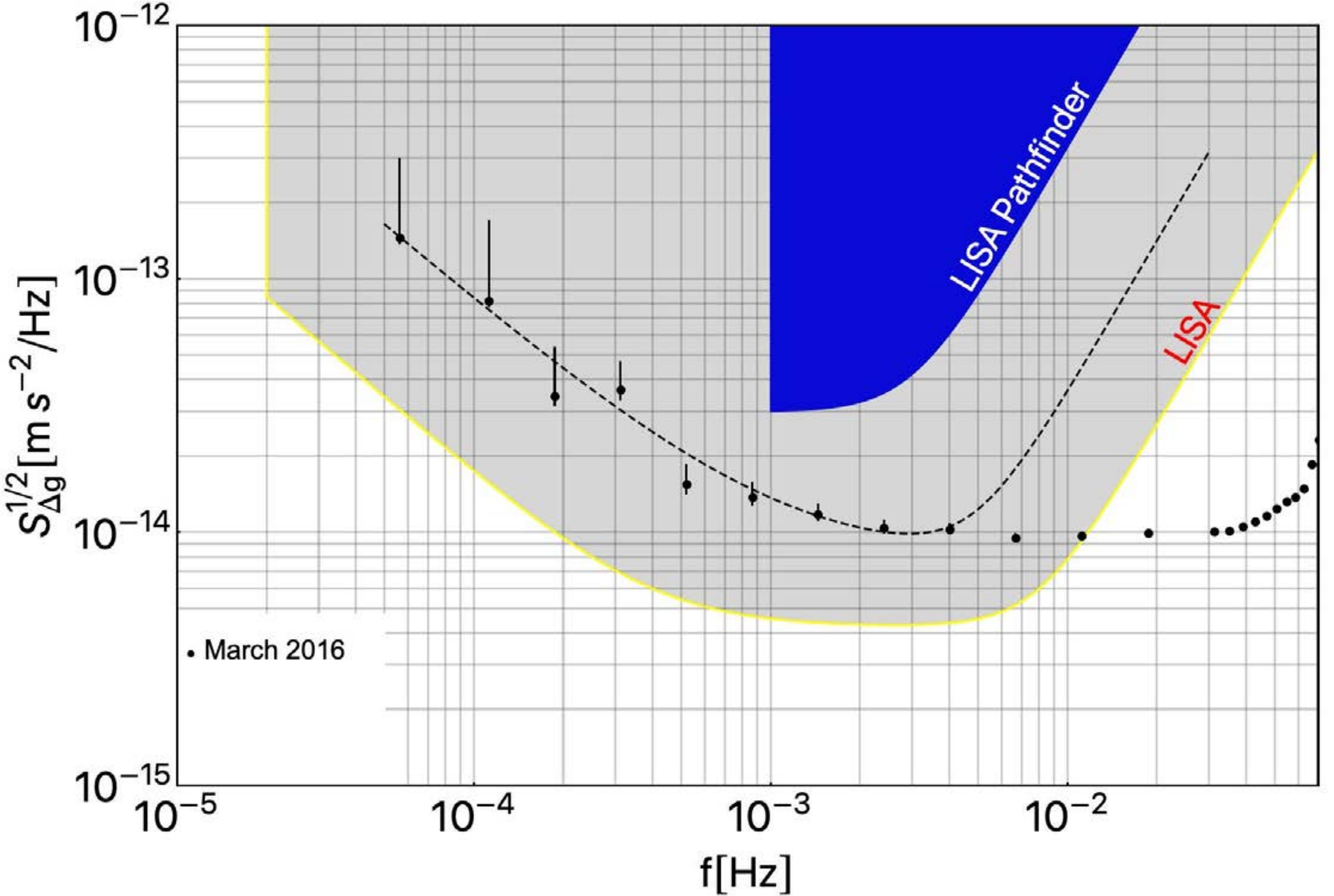
Requirements and expected performance

- Electrostatic actuation noise:
  - For a given voltage source noise, the larger the needed force you set, the larger the force noise.
  - Required force set by accuracy of gravitational balance
- Brownian noise from residual gas:
  - The larger the pressure surrounding the test-mass the larger the noise
- Interferometer readout noise: $\simeq 10\ pm/\sqrt{Hz}$ as for LISA

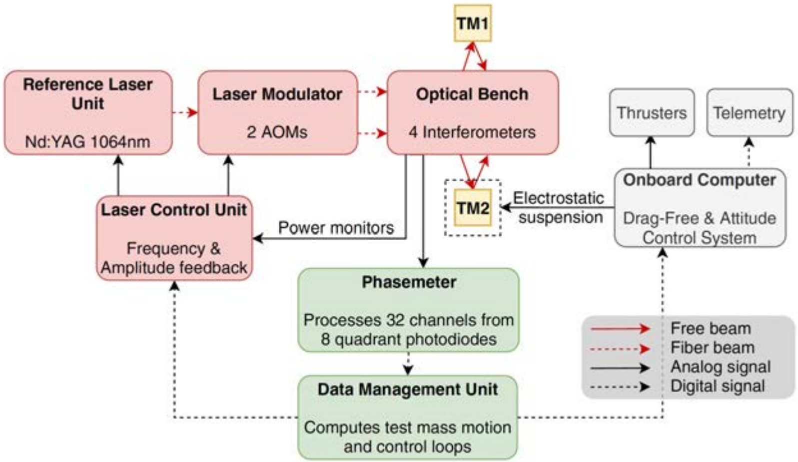


First day of operations: March 1st 2016

- Close to prediction
- Except for interferometer noise at 35 fm/√Hz instead of 10 pm/√Hz we could show on ground!



The magic interferometer



TM1

Reference Laser Unit

Nd:YAG 1064nm

Laser Modulator

2 AOMs

Optical Bench

4 Interferometers

Thrusters

Telemetry

TM2

Electrostatic suspension

Onboard Computer

Drag-Free & Attitude Control System

Laser Control Unit

Frequency & Amplitude feedback

Power monitors

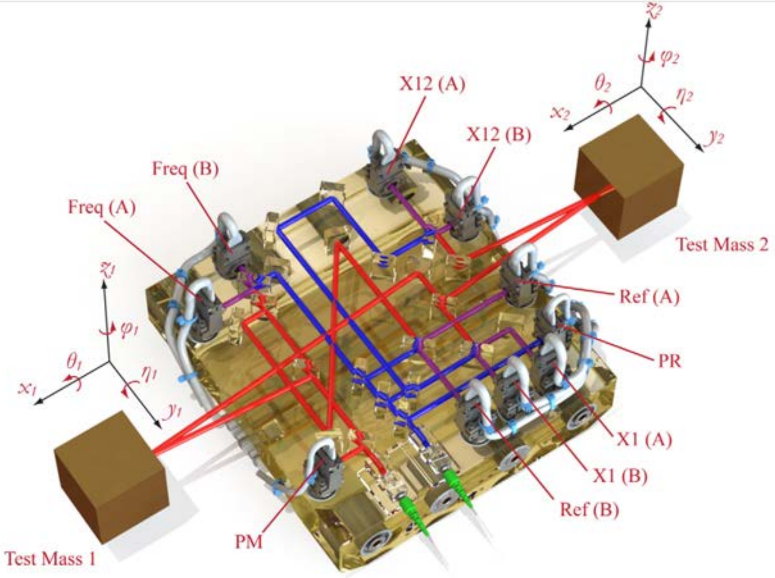
Phasemeter

Processes 32 channels from 8 quadrant photodiodes

Free beam
Fiber beam
Analog signal
Digital signal

Data Management Unit

Computes test mass motion and control loops



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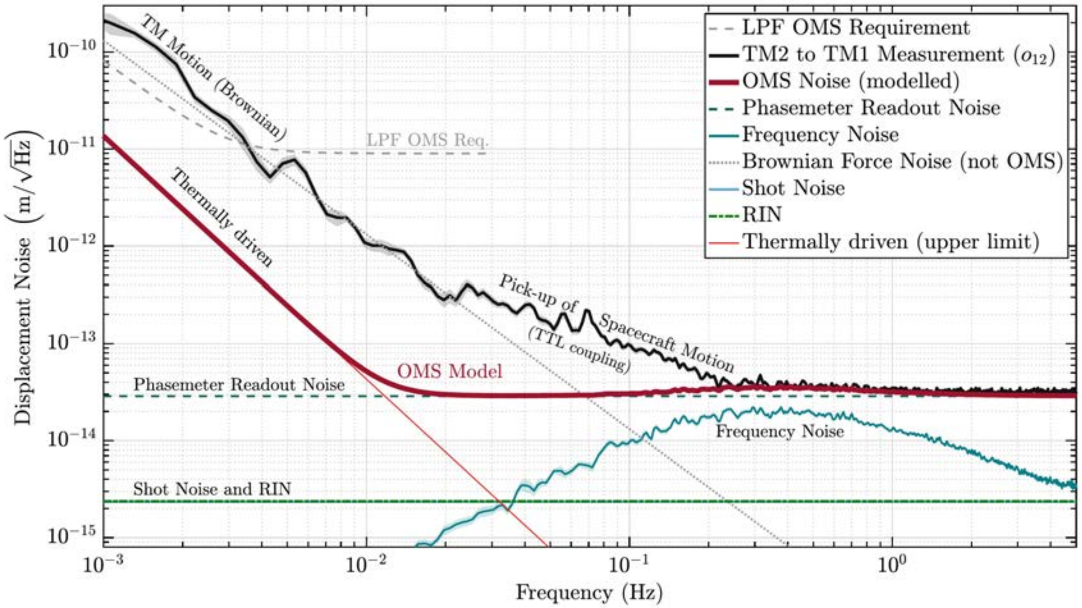
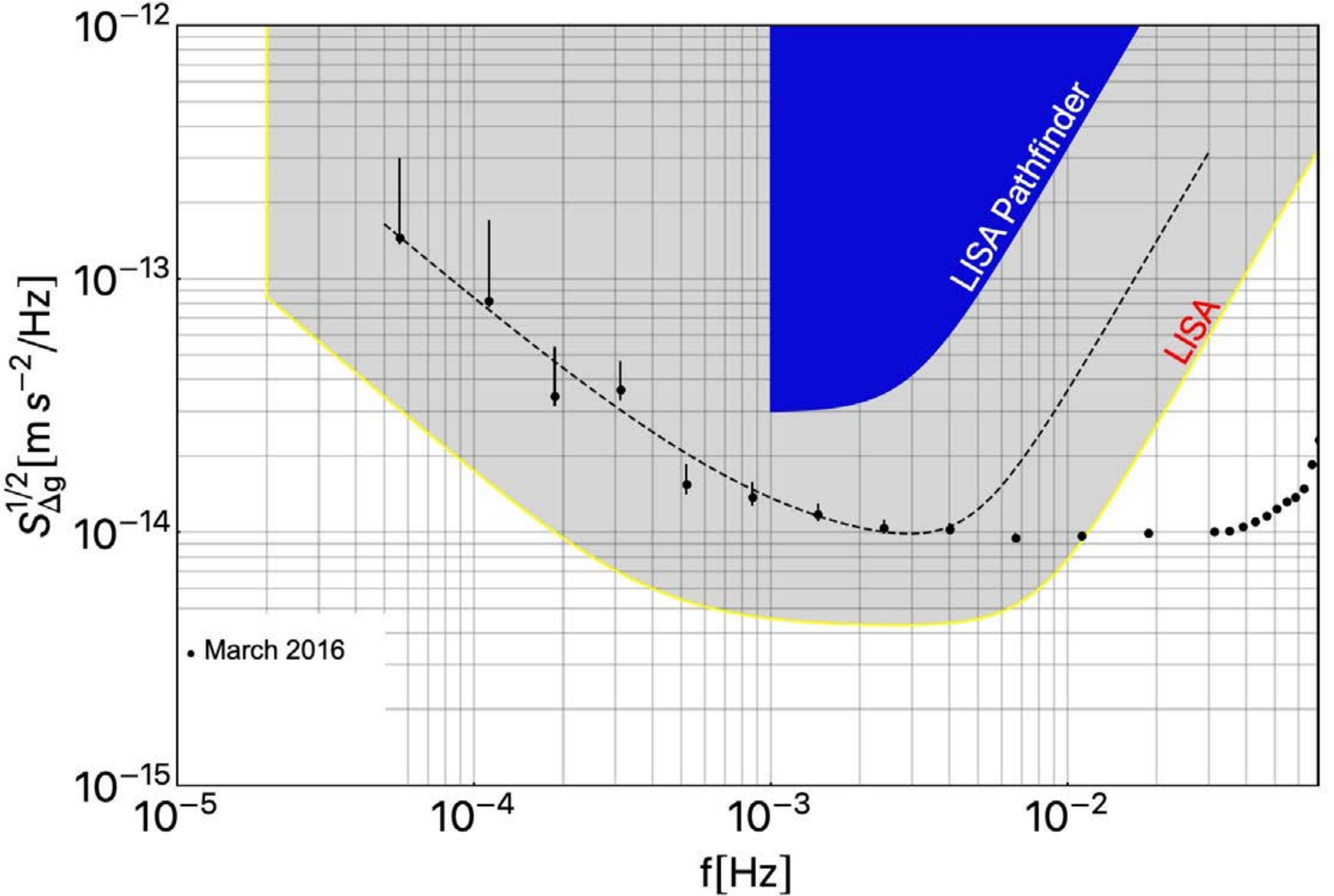
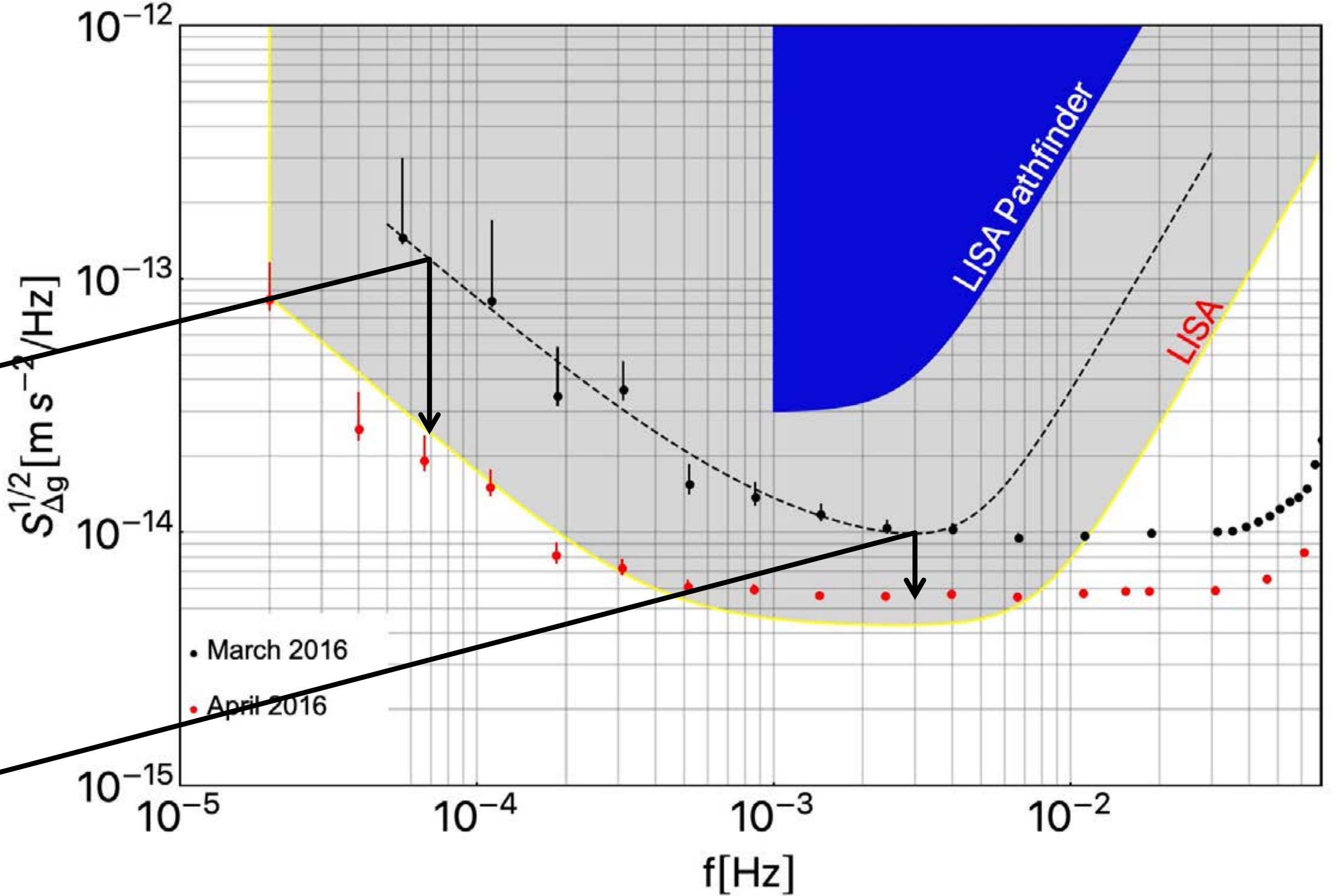


First day of operations: March 1st 2016

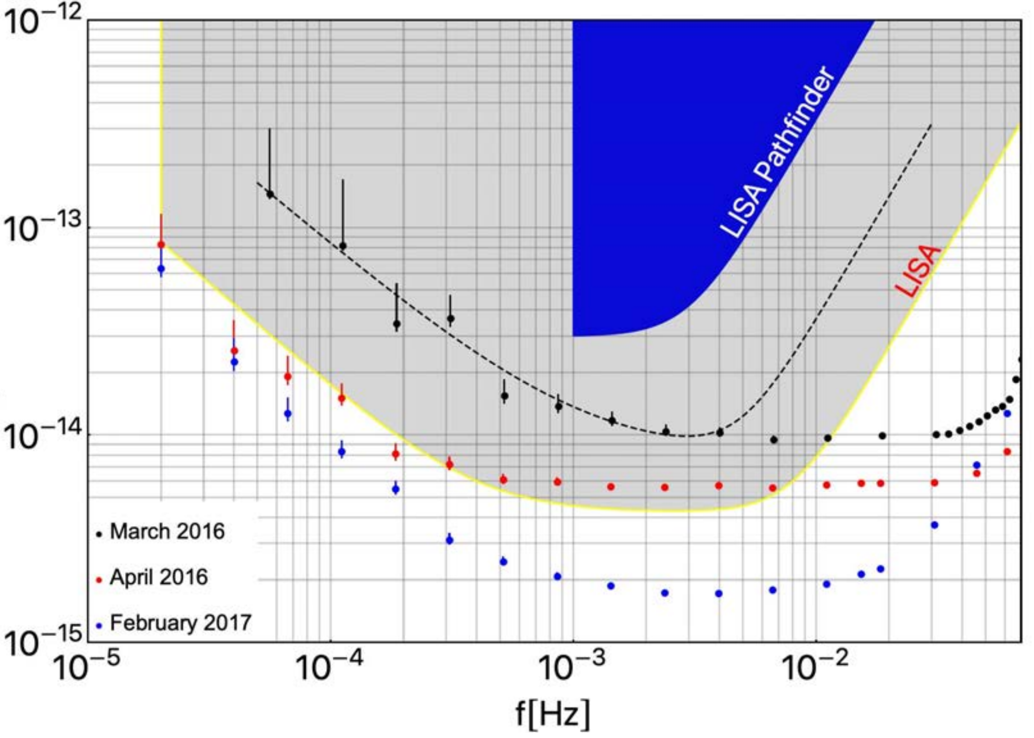


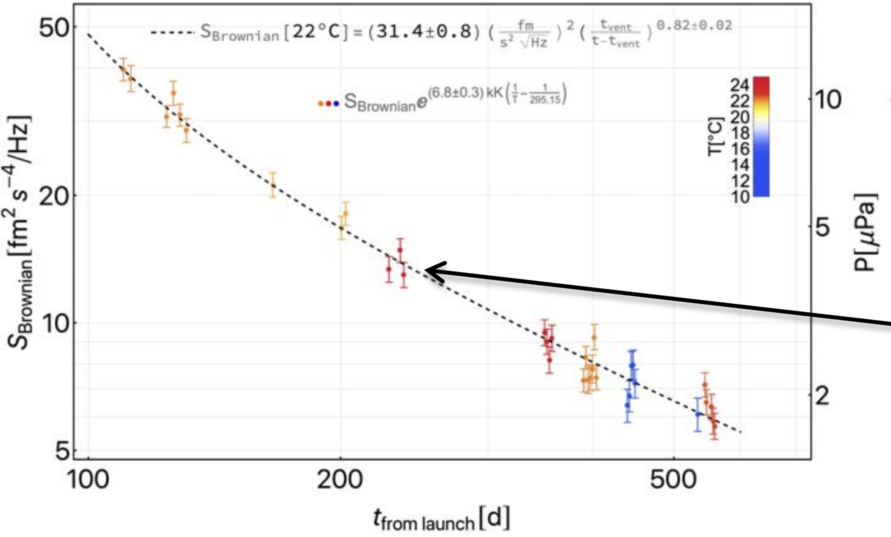
Improving performance

- Gravitation suppression: predicted worst case $\pm 65\, pg$. Actual $2\, pg$!
- Brownian noise decreases with pressure as the system is vented to outer space



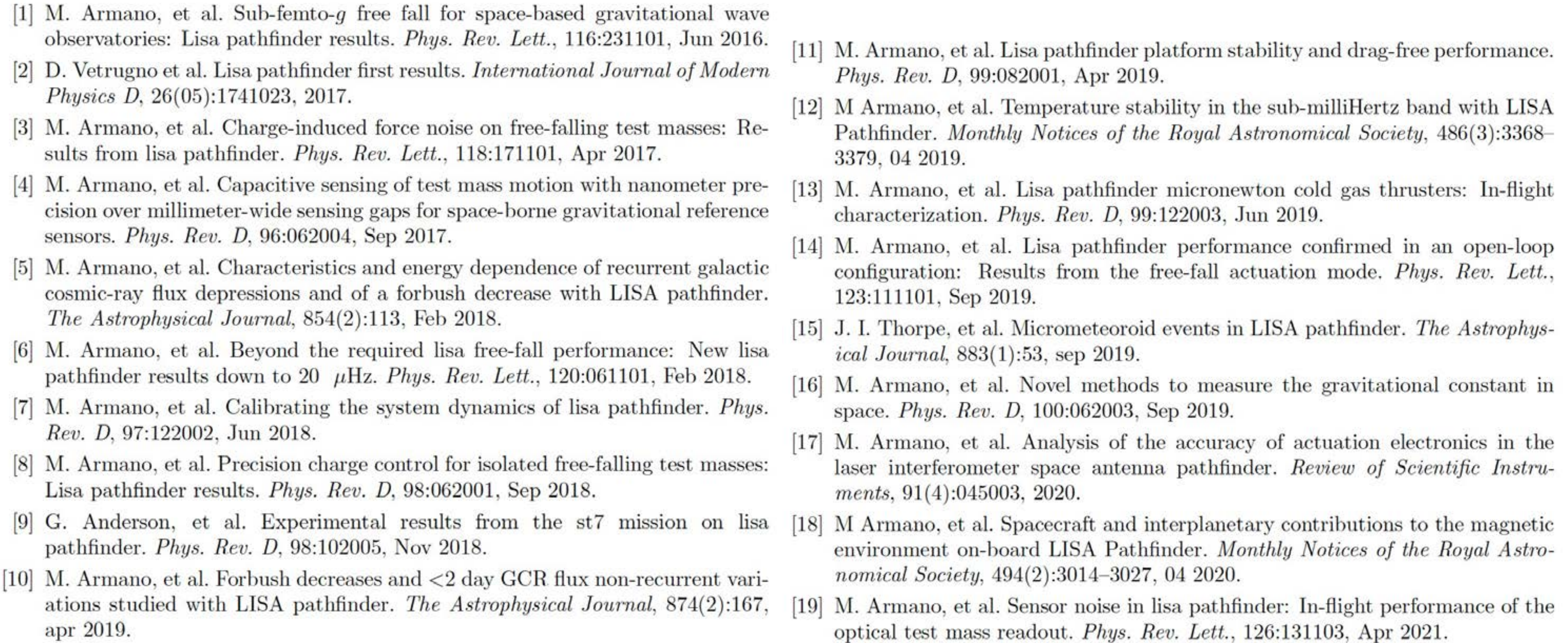
LISA requirements met with some margin





Brownian noise (pressure) vs time throughout the mission

Consolidating the noise model: LPF full menu of experiments



[1] M. Armano, et al. Sub-femto-*g* free fall for space-based gravitational wave observatories: Lisa pathfinder results. *Phys. Rev. Lett.*, 116:231101, Jun 2016.

[2] D. Vetrugno et al. Lisa pathfinder first results. *International Journal of Modern Physics D*, 26(05):1741023, 2017.

[3] M. Armano, et al. Charge-induced force noise on free-falling test masses: Results from lisa pathfinder. *Phys. Rev. Lett.*, 118:171101, Apr 2017.

[4] M. Armano, et al. Capacitive sensing of test mass motion with nanometer precision over millimeter-wide sensing gaps for space-borne gravitational reference sensors. *Phys. Rev. D*, 96:062004, Sep 2017.

[5] M. Armano, et al. Characteristics and energy dependence of recurrent galactic cosmic-ray flux depressions and of a forbush decrease with LISA pathfinder. *The Astrophysical Journal*, 854(2):113, Feb 2018.

[6] M. Armano, et al. Beyond the required lisa free-fall performance: New lisa pathfinder results down to 20 μHz. *Phys. Rev. Lett.*, 120:061101, Feb 2018.

[7] M. Armano, et al. Calibrating the system dynamics of lisa pathfinder. *Phys. Rev. D*, 97:122002, Jun 2018.

[8] M. Armano, et al. Precision charge control for isolated free-falling test masses: Lisa pathfinder results. *Phys. Rev. D*, 98:062001, Sep 2018.

[9] G. Anderson, et al. Experimental results from the st7 mission on lisa pathfinder. *Phys. Rev. D*, 98:102005, Nov 2018.

[10] M. Armano, et al. Forbush decreases and <2 day GCR flux non-recurrent variations studied with LISA pathfinder. *The Astrophysical Journal*, 874(2):167, apr 2019.

[11] M. Armano, et al. Lisa pathfinder platform stability and drag-free performance. *Phys. Rev. D*, 99:082001, Apr 2019.

[12] M Armano, et al. Temperature stability in the sub-milliHertz band with LISA Pathfinder. *Monthly Notices of the Royal Astronomical Society*, 486(3):3368–3379, 04 2019.

[13] M. Armano, et al. Lisa pathfinder micronewton cold gas thrusters: In-flight characterization. *Phys. Rev. D*, 99:122003, Jun 2019.

[14] M. Armano, et al. Lisa pathfinder performance confirmed in an open-loop configuration: Results from the free-fall actuation mode. *Phys. Rev. Lett.*, 123:111101, Sep 2019.

[15] J. I. Thorpe, et al. Micrometeoroid events in LISA pathfinder. *The Astrophysical Journal*, 883(1):53, sep 2019.

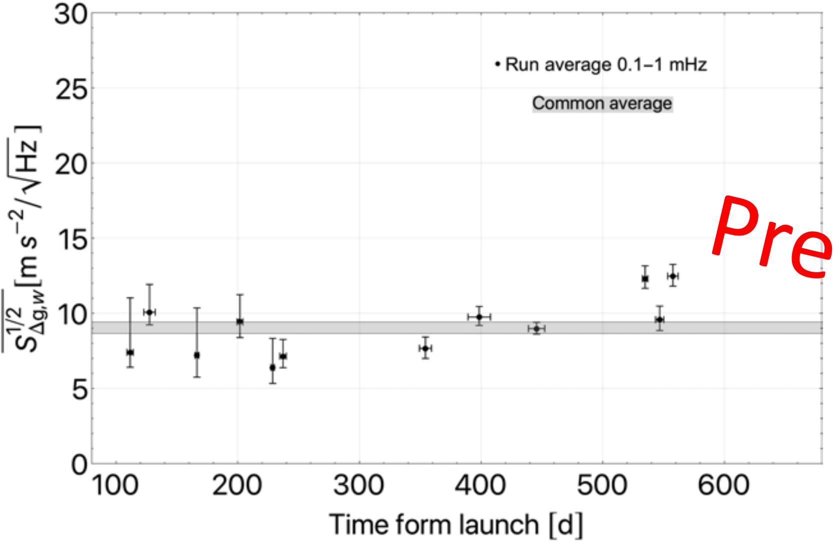
[16] M. Armano, et al. Novel methods to measure the gravitational constant in space. *Phys. Rev. D*, 100:062003, Sep 2019.

[17] M. Armano, et al. Analysis of the accuracy of actuation electronics in the laser interferometer space antenna pathfinder. *Review of Scientific Instruments*, 91(4):045003, 2020.

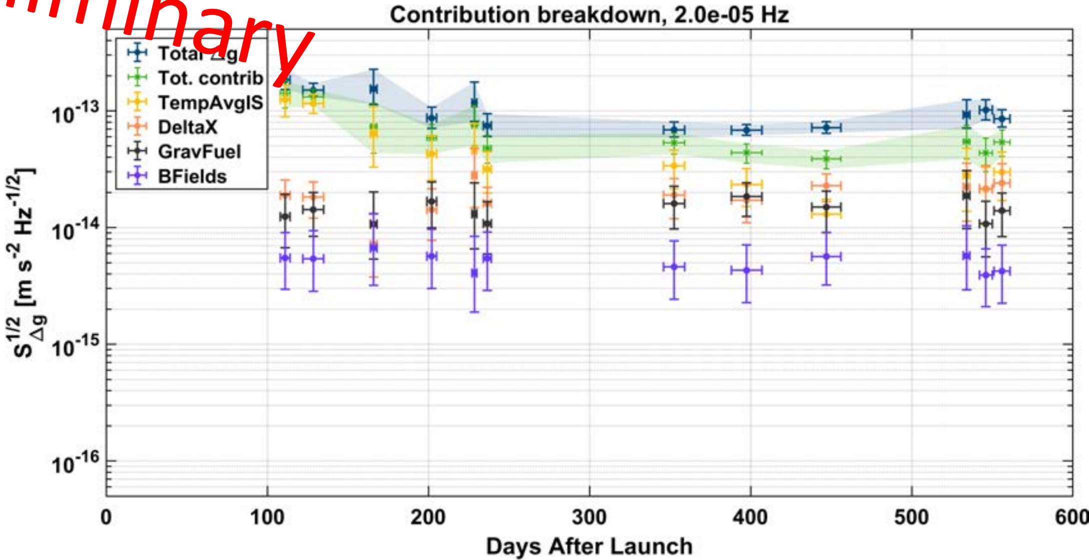
[18] M Armano, et al. Spacecraft and interplanetary contributions to the magnetic environment on-board LISA Pathfinder. *Monthly Notices of the Royal Astronomical Society*, 494(2):3014–3027, 04 2020.

[19] M. Armano, et al. Sensor noise in lisa pathfinder: In-flight performance of the optical test mass readout. *Phys. Rev. Lett.*, 126:131103, Apr 2021.

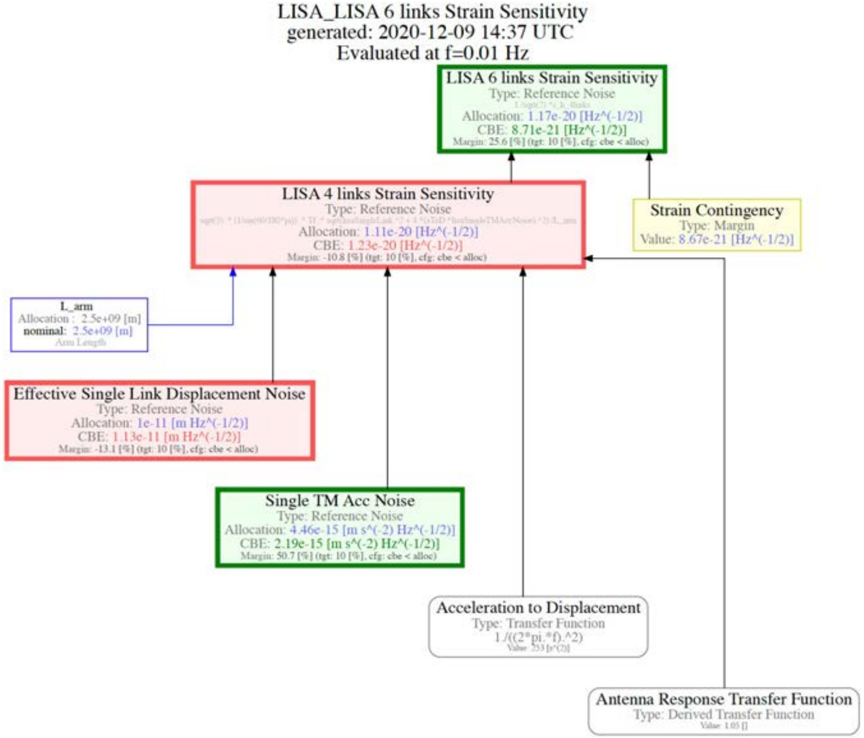
Understanding the (remarkably stable) residual noise



Preliminary



Transferring knowledge to LISA Performance



LISA_LISA 6 links Strain Sensitivity
generated: 2020-12-09 14:37 UTC
Evaluated at f=0.01 Hz

LISA 6 links Strain Sensitivity
Type: Reference Noise
Allocation: 1.17e-20 [Hz^(-1/2)]
CBE: 8.71e-21 [Hz^(-1/2)]
Margin: 25.6 [%] (tgt: 10 [%], cfg: cbe < alloc)

LISA 4 links Strain Sensitivity
Type: Reference Noise
Allocation: 1.11e-20 [Hz^(-1/2)]
CBE: 1.23e-20 [Hz^(-1/2)]
Margin: -10.8 [%] (tgt: 10 [%], cfg: cbe < alloc)

Strain Contingency
Type: Margin
Value: 8.67e-21 [Hz^(-1/2)]

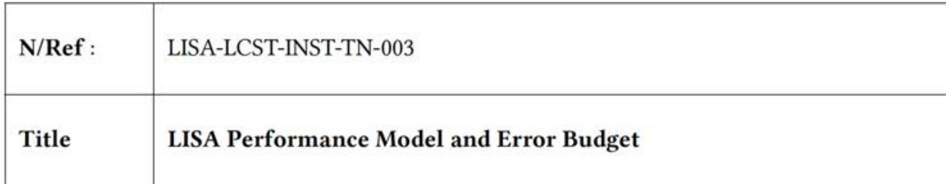
L_arm
Allocation : 2.5e+09 [m]
nominal: 2.5e+09 [m]
Arm Length

Effective Single Link Displacement Noise
Type: Reference Noise
Allocation: 1e-11 [m Hz^(-1/2)]
CBE: 1.13e-11 [m Hz^(-1/2)]
Margin: -13.1 [%] (tgt: 10 [%], cfg: cbe < alloc)

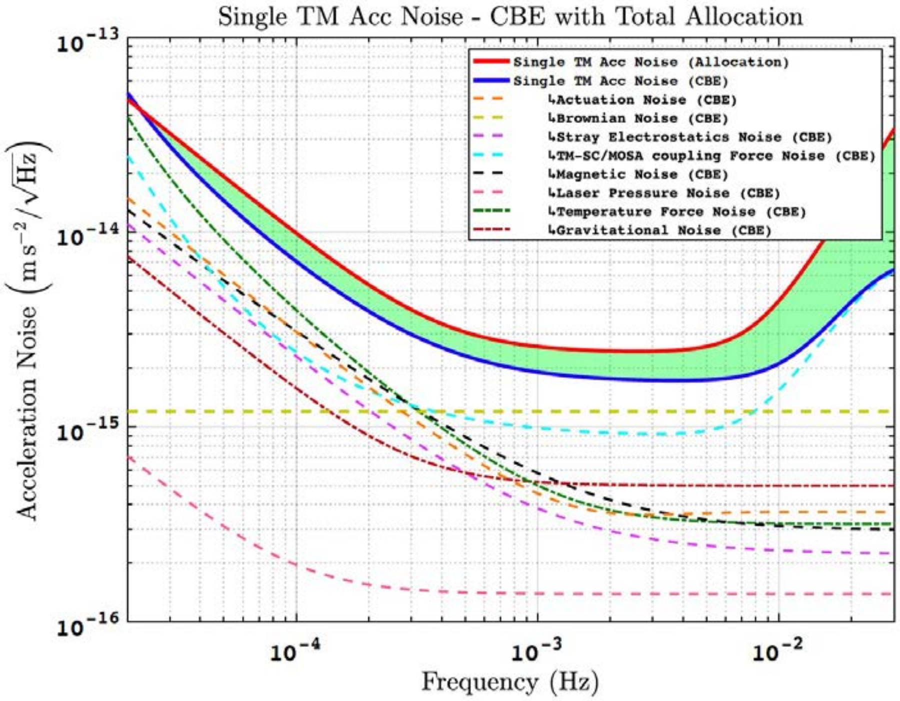
Single TM Acc Noise
Type: Reference Noise
Allocation: 4.46e-15 [m s^(-2) Hz^(-1/2)]
CBE: 2.19e-15 [m s^(-2) Hz^(-1/2)]
Margin: 50.7 [%] (tgt: 10 [%], cfg: cbe < alloc)

Acceleration to Displacement
Type: Transfer Function
1./((2*pi.*f).^2)
Value: 253 [s^(2)]

Antenna Response Transfer Function
Type: Derived Transfer Function
Value: 1.05 []



N/Ref :	LISA-LCST-INST-TN-003
Title	**LISA Performance Model and Error Budget**



Single TM Acc Noise - CBE with Total Allocation

LISA marching ahead

Timeline

October 2013:	Selection of "The Gravitational Universe" as science theme for the 3rd ESA flagship mission (L3)
October 2016:	Call for mission proposals for L3
June 2017:	Selection of LISA as L3 with an anticipated 2034 launch date
May 2018:	Phase A Kick-Off
2018-2021:	**Mission Phase A**
Oct '20-Oct '21:	**Mission Phase A Extension**
<end 2021:	Formulation Review (end Phase A)
>2021:	Mission Phase B1
<2024:	Mission Adoption
>Adoption:	Mission Implementation (Phase B2/C/D)
<2034:	Launch
>Launch:	6.5 years operations (+6 years potential extension)

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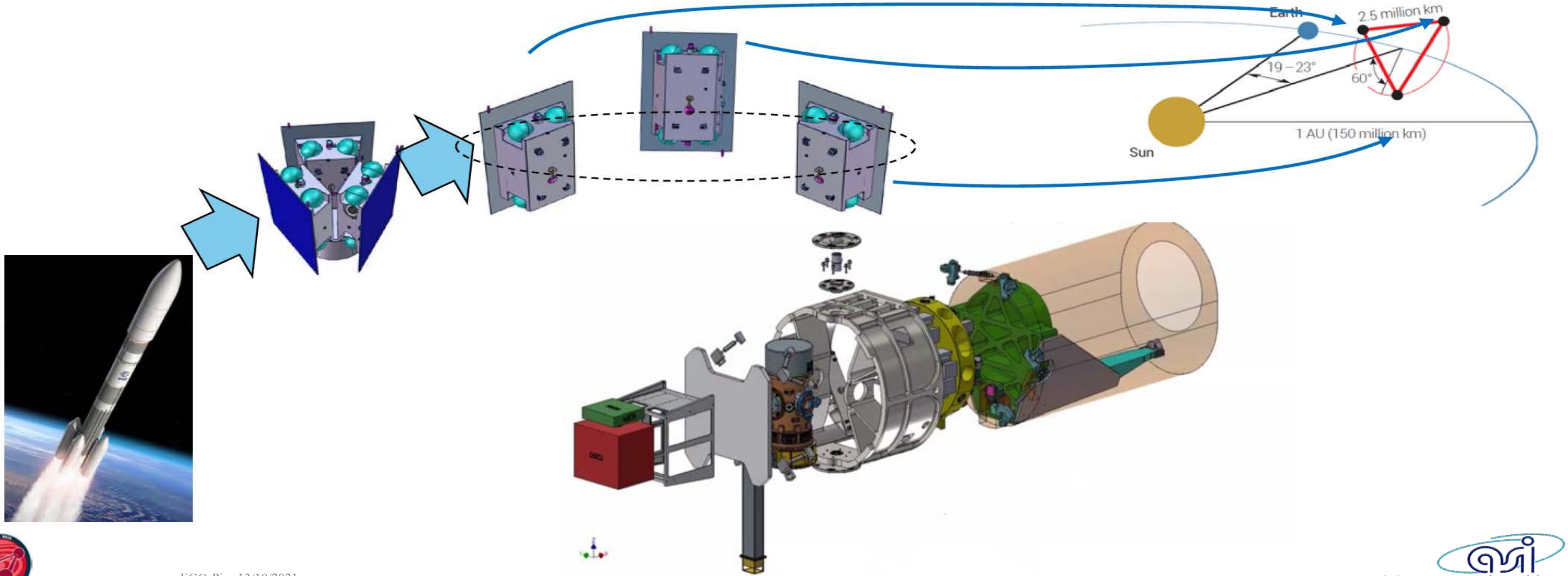
Martin Gehler, Oliver Jennrich, Nora Luetzgendorf | ESTEC | 21/08/2020 | Slide 4

European Space Agency

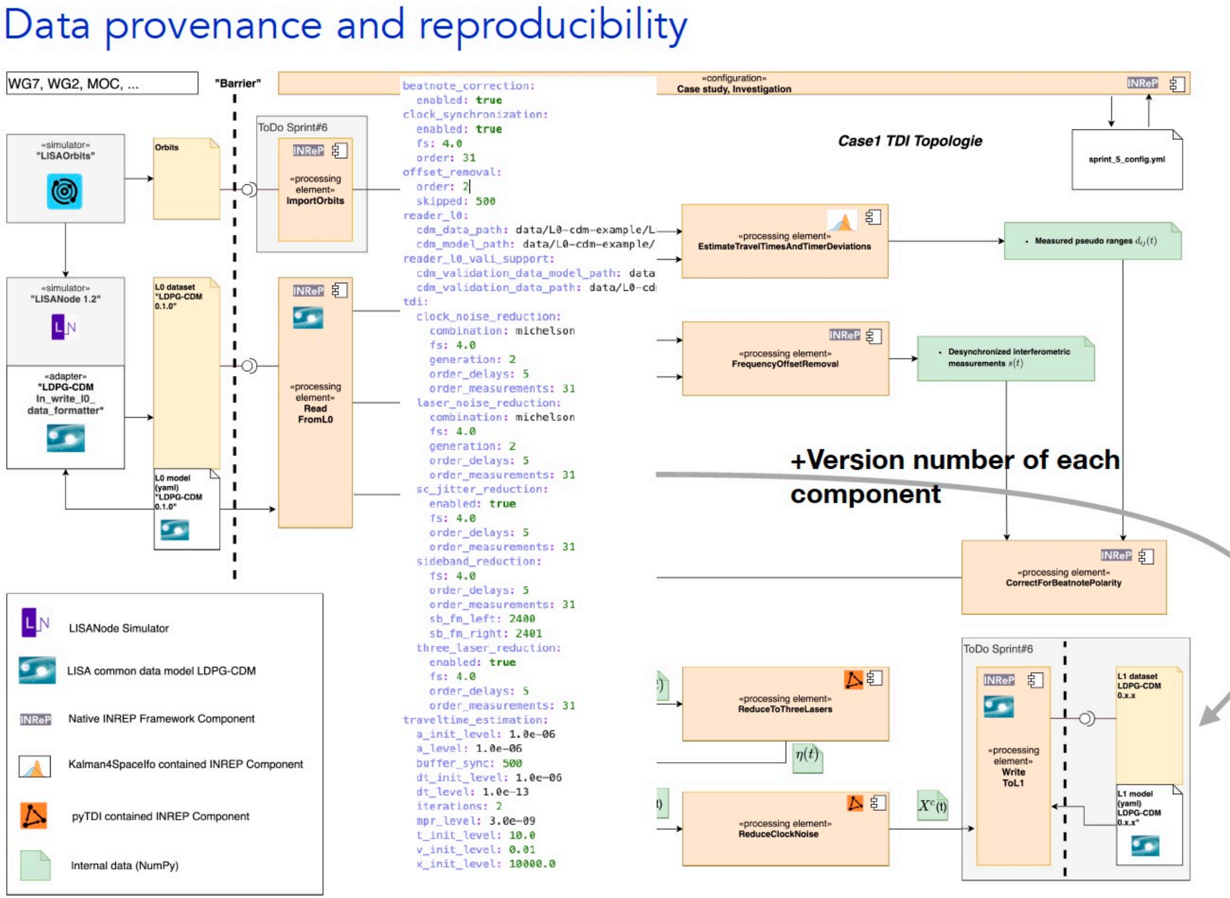
Ongoing while we speak

LISA currently in phase A→B1

- Phase-A study competitive: cannot show much!
- A rather stable concept, working out the details



Including non trivial data reduction

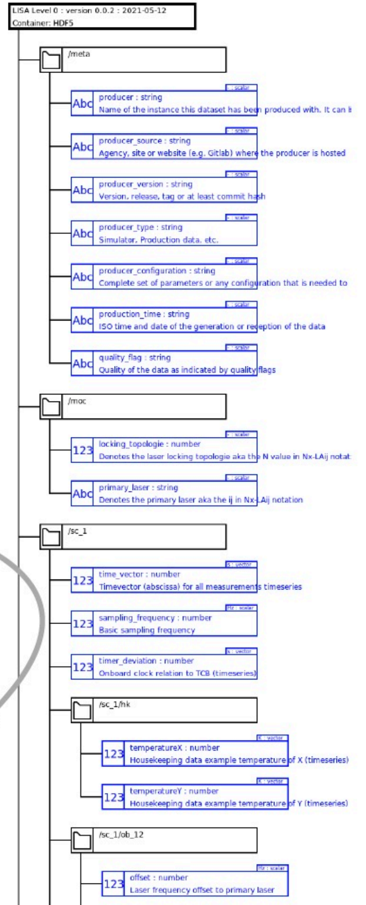


Data provenance and reproducibility

```
beatnote_correction:
  enabled: true
clock_synchronization:
  enabled: true
  fs: 4.0
  order: 31
offset_removal:
  order: 2
  skipped: 500
reader_l0:
  cdm_data_path: data/L0-cdm-example/L
  cdm_model_path: data/L0-cdm-example/
reader_l0_vali_support:
  cdm_validation_data_model_path: data
  cdm_validation_data_path: data/L0-cd
tdi:
  clock_noise_reduction:
    combination: michelson
    fs: 4.0
    generation: 2
    order_delays: 5
    order_measurements: 31
  laser_noise_reduction:
    combination: michelson
    fs: 4.0
    generation: 2
    order_delays: 5
    order_measurements: 31
  sc_jitter_reduction:
    enabled: true
    fs: 4.0
    order_delays: 5
    order_measurements: 31
  sideband_reduction:
    fs: 4.0
    order_delays: 5
    order_measurements: 31
    sb_fm_left: 2400
    sb_fm_right: 2401
  three_laser_reduction:
    enabled: true
    fs: 4.0
    order_delays: 5
    order_measurements: 31
traveltime_estimation:
  a_init_level: 1.0e-06
  a_level: 1.0e-06
  buffer_sync: 500
  dt_init_level: 1.0e-06
  dt_level: 1.0e-13
  iterations: 2
  mpr_level: 3.0e-09
  t_init_level: 10.0
  v_init_level: 0.01
  x_init_level: 10000.0
```

LN	LISANode Simulator
	LISA common data model LDPG-CDM
INReP	Native INREP Framework Component
	Kalman4SpaceIfo contained INREP Component
	pyTDI contained INREP Component
🟩	Internal data (NumPy)

+Version number of each component



LISA Level 0 : version 0.0.2 : 2021-05-12
Container: HDF5

/meta

producer : string
Name of the instance this dataset has been produced with. It can b

producer_source : string
Agency, site or website (e.g. Gitlab) where the producer is hosted

producer_version : string
Version, release, tag or at least commit hash

producer_type : string
Simulator, Production data, etc.

producer_configuration : string
Complete set of parameters or any configuration that is needed to

production_time : string
ISO time and date of the generation or reception of the data

quality_flag : string
Quality of the data as indicated by quality flags

/moc

locking_topologie : number
Denotes the laser locking topologie aka the N value in Nx-LAij notat

primary_laser : string
Denotes the primary laser aka the ij in Nx-LAij notation

/sc_1

time_vector : number
Timevector (abscissa) for all measurements timeseries

sampling_frequency : number
Basic sampling frequency

timer_deviation : number
Onboard clock relation to TCB (timeseries)

/sc_1/hk

temperatureX : number
Housekeeping data example temperature of X (timeseries)

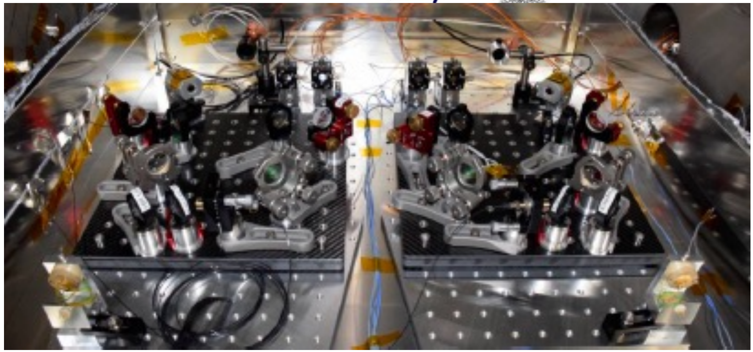
temperatureY : number
Housekeeping data example temperature of Y (timeseries)

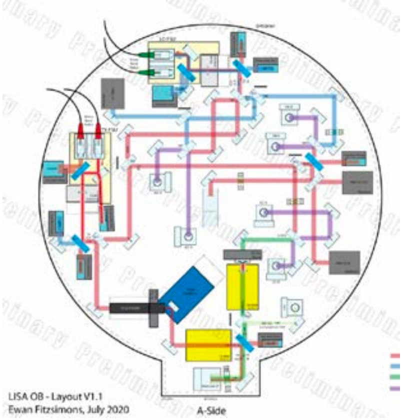
/sc_1/ob_12

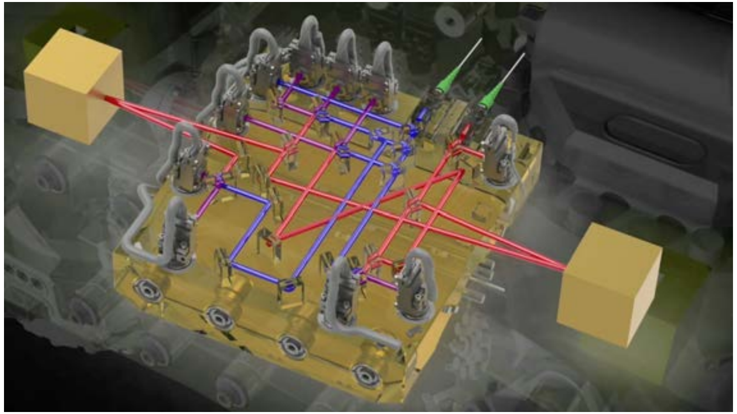
offset : number
Laser frequency offset to primary laser

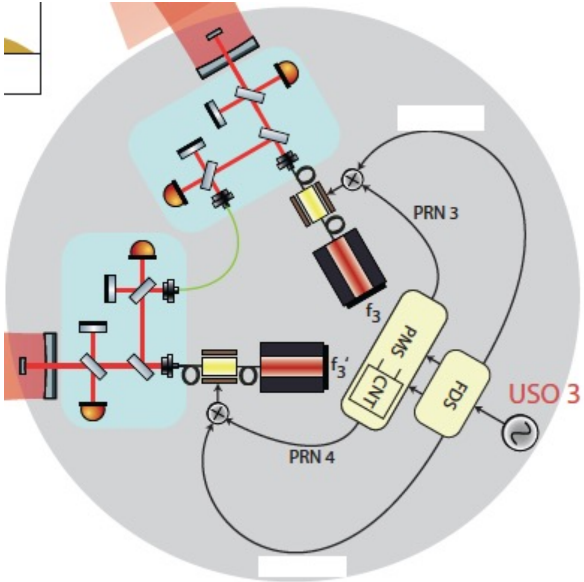
A. Petiteau

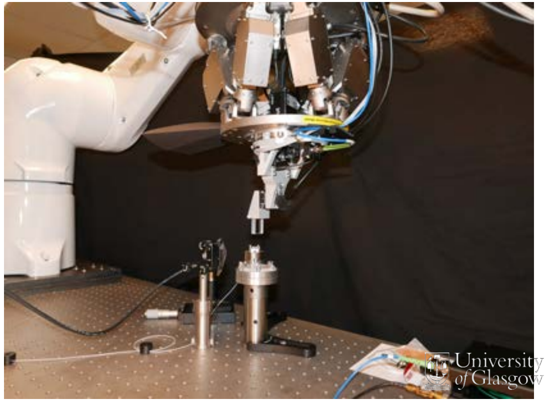
Technology developments (TRL 6 by adoption)



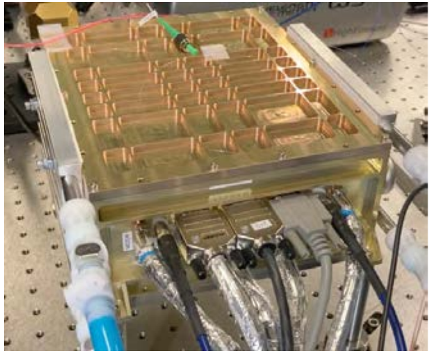








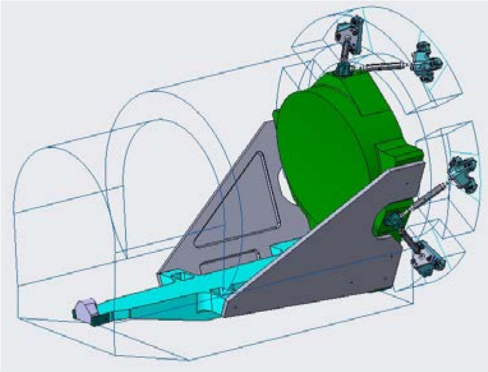
Technology developments (TRL6 by adoption)

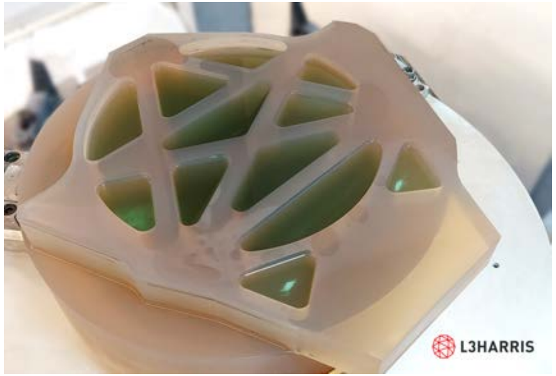


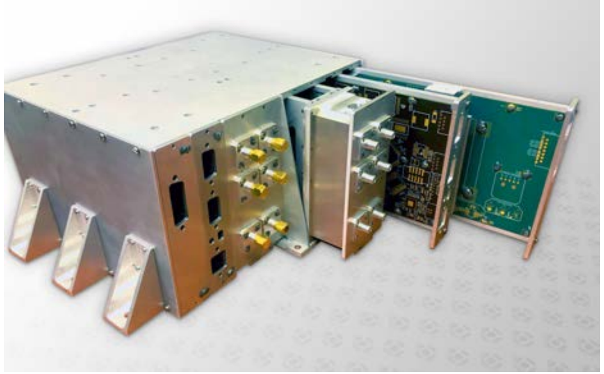
Laser

Telescope

Charge management

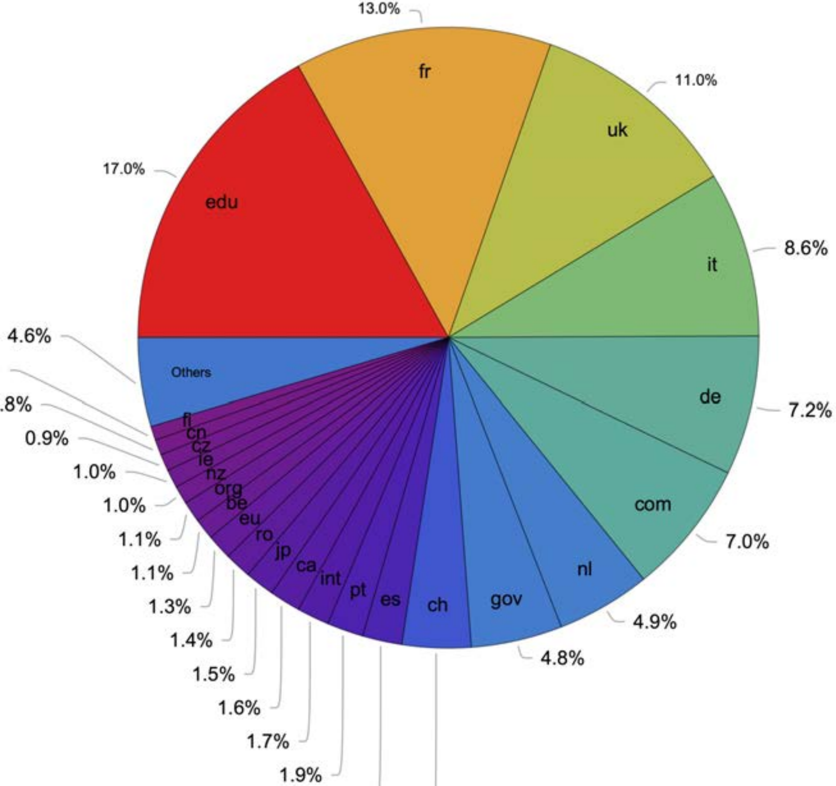


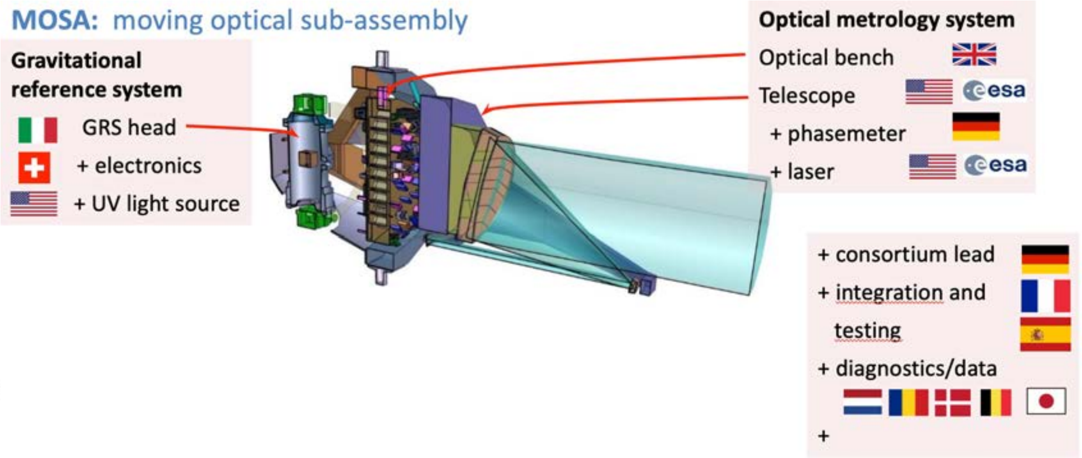




The International Collaboration

- The LISA Consortium (1437 members)





MOSA: moving optical sub-assembly

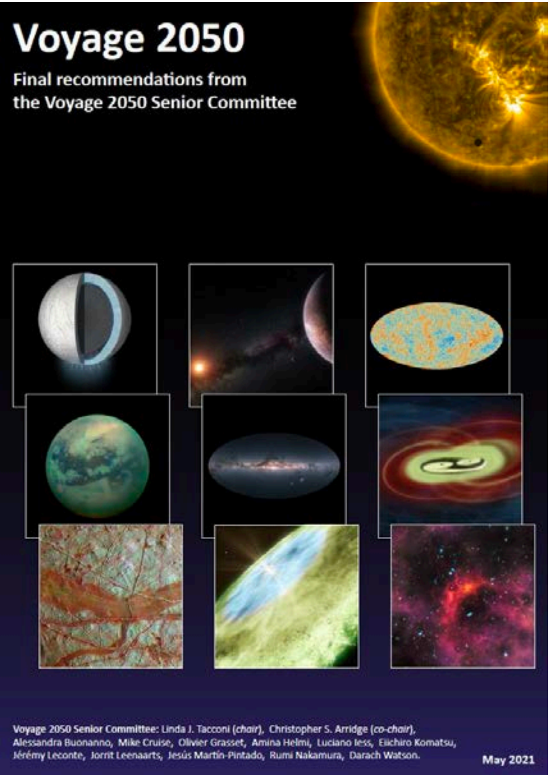
Gravitational reference system
🇮🇹 GRS head
🇨🇭 + electronics
🇺🇸 + UV light source

Optical metrology system
Optical bench 🇬🇧
Telescope 🇺🇸 esa
+ phasemeter 🇩🇪
+ laser 🇺🇸 esa

+ consortium lead 🇩🇪
+ integration and testing 🇫🇷 🇪🇸
+ diagnostics/data
🇳🇱 🇷🇴 🇩🇰 🇧🇪 🇯🇵
+

Beyond LISA

- Planning for the future



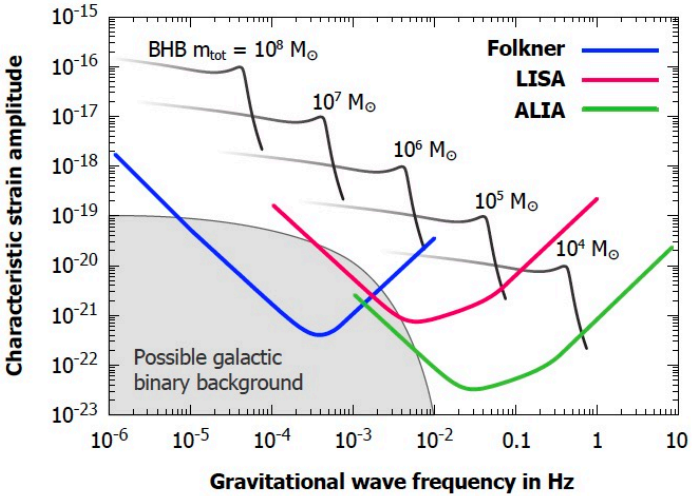
Voyage 2050

Final recommendations from
the Voyage 2050 Senior Committee

Voyage 2050 Senior Committee: Linda J. Tacconi (*chair*), Christopher S. Arridge (*co-chair*), Alessandra Buonanno, Mike Cruise, Olivier Grasset, Amina Helmi, Luciano Iess, Eiichiro Komatsu, Jérémy Leconte, Jorrit Leenaarts, Jesús Martín-Pintado, Rumi Nakamura, Darach Watson.

May 2021

- **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*.



Thank you!