NGO
New Gravitational-wave Observatory
(also nicknamed ELISA)

Stefano.Vitale@unitn.it
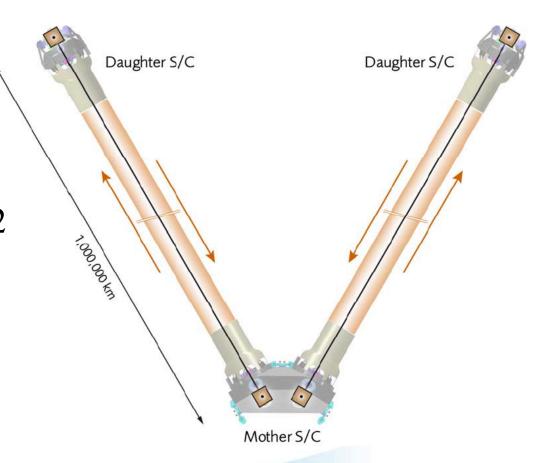
On the behalf of the NGO Science Working Team

NGO

- A space-borne laser interferometer GW astrophysical observatory
- Studied by ESA as a candidate for the selection of a Large mission in 2012

An astrophysical observatory

- **Survey compact stellar-mass binaries and study the structure of the Galaxy**
  - Elucidate the formation and evolution of Galactic stellar-mass compact binaries and thus constrain the outcome of the common envelope phase and the progenitors of (type Ia) supernovae.
  - Determine the spatial distribution of stellar mass binaries in the Milky Way
  - Improve our understanding of white dwarfs, their masses, and their interactions in binaries, and enable combined gravitational and electromagnetic observations

- **Trace the formation, growth and merger history of massive black holes.**
  - Trace the formation, growth and merger history of massive black holes with masses $10^5\,M_\odot - 10^7\,M_\odot$ during the epoch of growth of quasi-stellar objects and widespread star formation ($0 < z < 5$) through their coalescence in galactic halos.
  - Capture the signal of coalescing massive black hole binaries with masses $2\times10^4\,M_\odot - 10^5\,M_\odot$ in the range of $5 < z < 10$ when the universe is less than 1 Gyr old.

- **Explore stellar populations and dynamics in galactic nuclei**
  - Characterize the immediate environment of massive black holes in $z < 0.7$ galactic nuclei from extreme mass ratio capture signals.
  - Discovery of intermediate-mass black holes from their captures by massive black holes.

- **Confront General Relativity with observations**
  - Detect gravitational waves directly and measure their properties precisely
  - Test whether the central massive objects in galactic nuclei are consistent with the Kerr black holes of General Relativity.
  - Perform precision tests of dynamical strong-field gravity.

- **Probe new physics and cosmology with gravitational waves**
  - Measure the spectrum of cosmological backgrounds, or set upper limits on them in the 10^{-4} Hz $- 10^{-1}$ Hz band.
  - Search for gravitational wave bursts from cosmic string cusps and kinks.
  - Cosmography with standard sirens

The approach

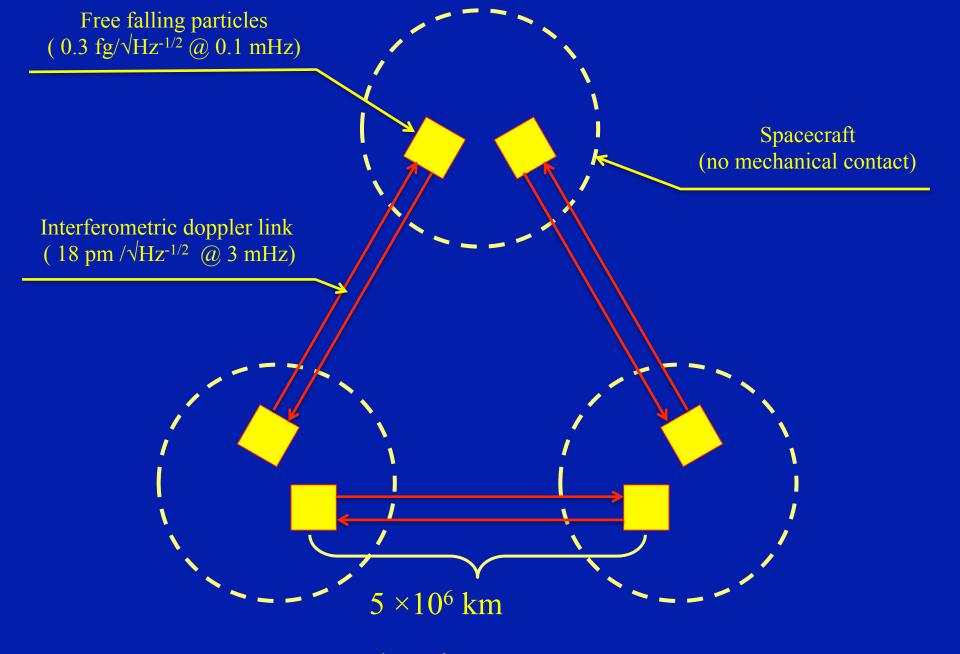**Cosmic Vision 2015-2025**   Science Pr
European

LISA

Next steps for LISA

The space-borne gravitational wave detector LISA has been studied in great detail over the last decade as a collaborative mission between ESA and NASA.

As announced by ESA in March 2011, due to a modified international cooperation scenario, it is now necessary to study a European-only mission that offers a significant reduction of the cost while maintaining its core science objectives.

Whilst maximizing the use of results of the LISA studies performed so far and the heritage from LISA Pathfinder, a number of significant changes to the payload, the spacecraft and the mission architecture have to be made to enable the mission to fit the new budget profile.

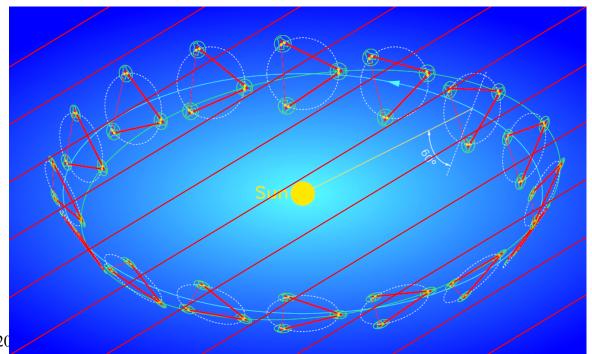- the starting point are LISA with her 6-year long formulation study, and LISA Pathfinder.

Free falling particles
(0.3 fg/$\sqrt{Hz^{-1/2}}$ @ 0.1 mHz)

Spacecraft
(no mechanical contact)

Interferometric doppler link
(18 pm /$\sqrt{Hz^{-1/2}}$ @ 3 mHz)

5×10^6 km

LISA basic concepts

LISA basic concept. 1 Orbits

- Formation rotates within waves (pointing capability)
- Constant solar panels illumination
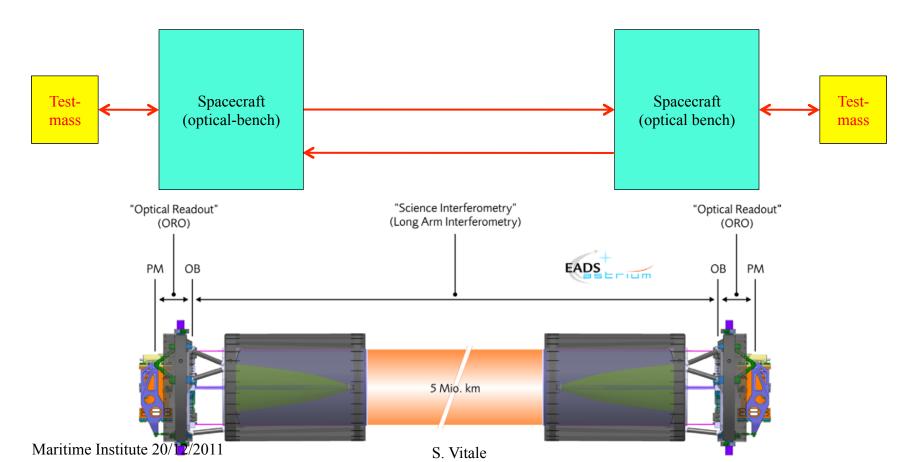- All laser links within common spacecraft (SC)-formation plane

LISA basic concept 2. The Doppler link

- A Doppler test-mass (TM) to TM relative speedometer $\Delta\nu/\nu \approx \Delta v/c$
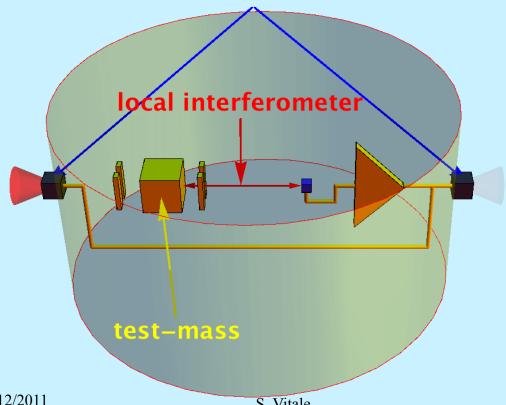
- Real Link is split in three: two TM-SC two-way links, two one-way SC-SC links

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LISA basic concept. 3 Drag-free

- Position of spacecraft relative to test-mass is measured by local interferometer
- Along each link direction, spacecraft is kept centered on test-mass by acting on micro-Newton thrusters.
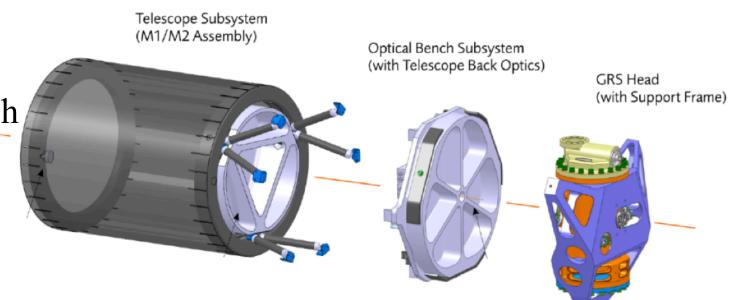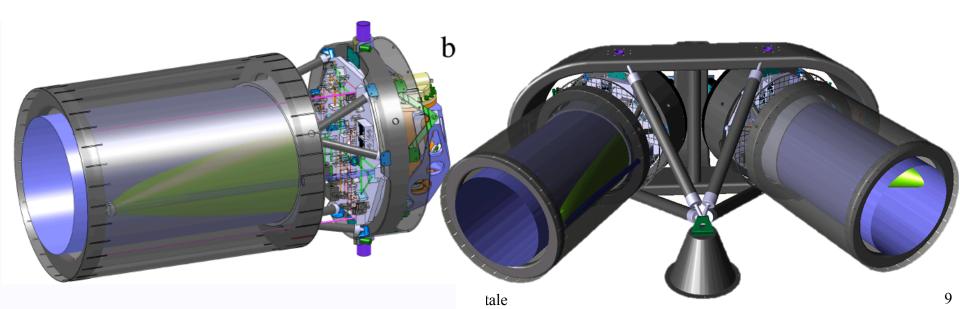
LISA Instrument main elements

- Telescope
- Optical Bench
- GRS
- 2 per SC

Telescope Subsystem
(M1/M2 Assembly)

Optical Bench Subsystem
(with Telescope Back Optics)

GRS Head
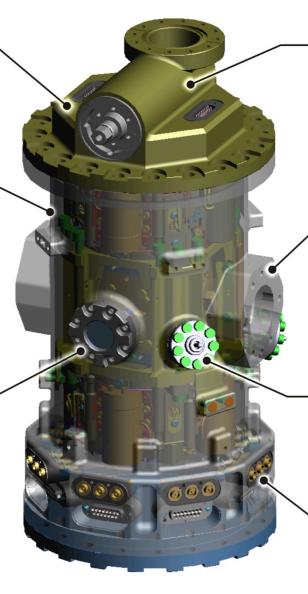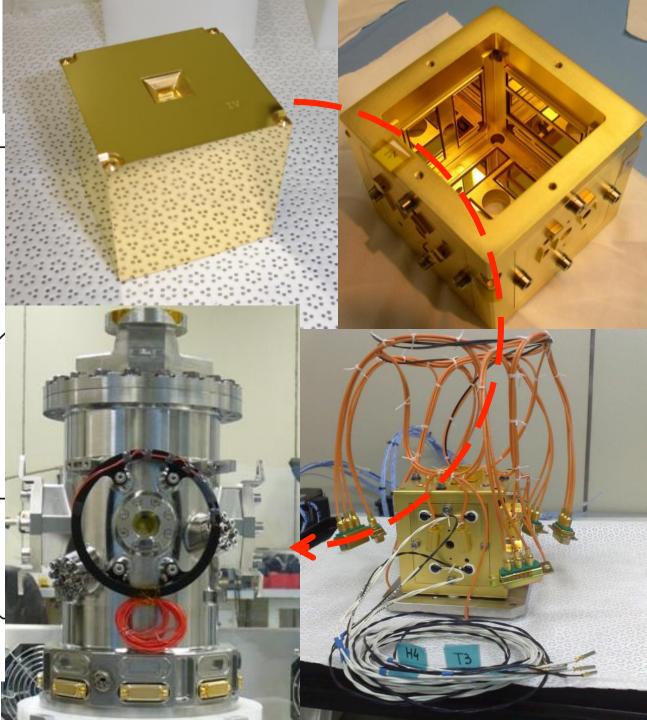(with Support Frame)

b
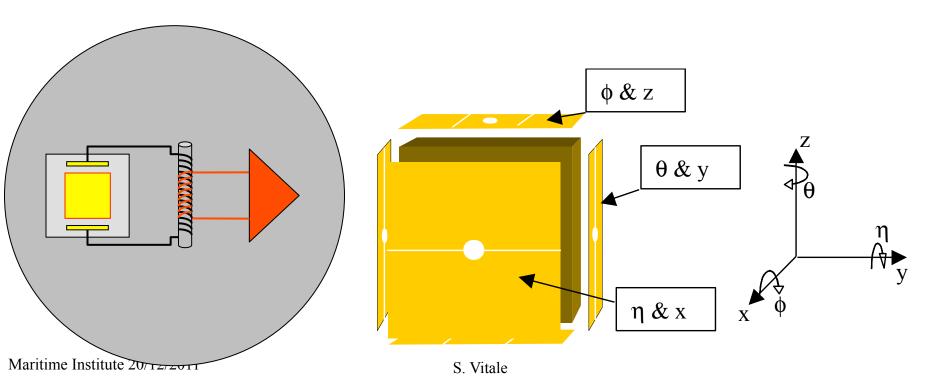
Gravity Reference Sensor (GRS)

- Provides electrostatic sensing along all degrees of freedom (dof) for initial acquisition and for normal operation of non interferometric dof.

- Provides TM actuation for non-drag-free dof.

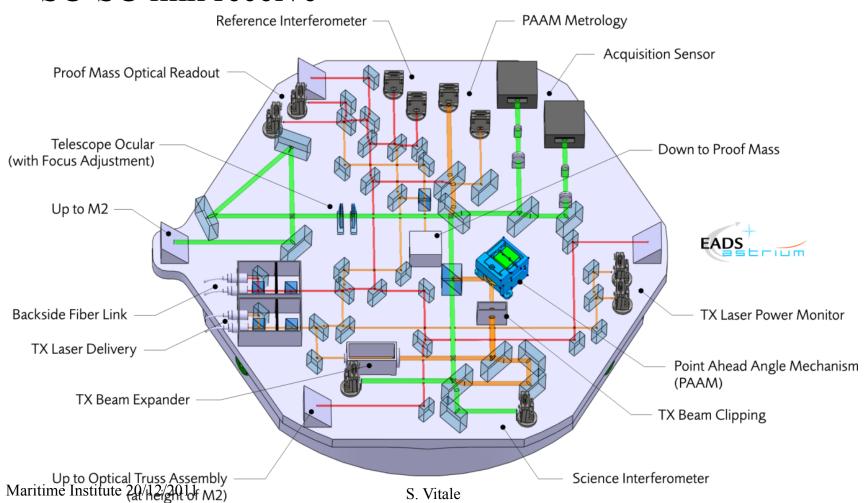φ & z

θ & y

η & x

GRS

Optical bench

- Local TM-SC metrology
- SC-SC link send
- SC-SC link receive

Reference Interferometer

PAAM Metrology

Acquisition Sensor

Proof Mass Optical Readout

Telescope Ocular
(with Focus Adjustment)

Down to Proof Mass

Up to M2

Backside Fiber Link

TX Laser Delivery

TX Beam Expander

TX Laser Power Monitor

Point Ahead Angle Mechanism
(PAAM)

TX Beam Clipping

Up to Optical Truss Assembly
(at height of M2)

Science Interferometer
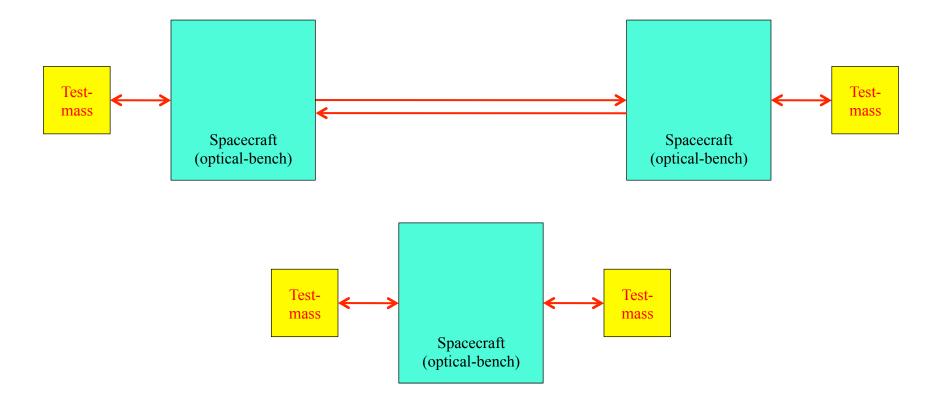
EADS astrium

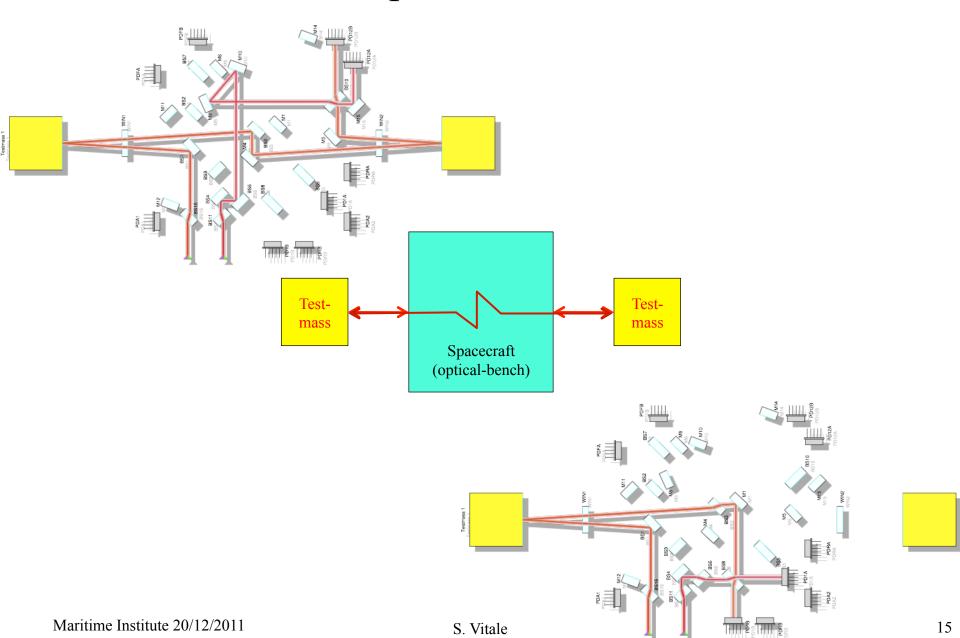# LISA Pathfinder Heritage

S. Vitale

The Concept of LISA Pathfinder

- Drop the 5 Million kilometer spacecraft↔spacecraft measurement
- Maintain both spacecraft↔test-mass local measurements

The Concept of LISA Pathfinder

Test-mass

Spacecraft
(optical-bench)

Test-mass

Q2: What will LPF test exactly?

- The end-to-end performance of a reduced version of one LISA arm. Specifically:
  - The suppression of parasitic relative acceleration of two test-masses at 3×10^{-14} ms^{-2}√Hz. (a factor 7 in amplitude from LISA) above 10^{-3}Hz (a factor 10 in frequency from LISA)
  - The interferometric ranging of two free-falling test-masses at 10pm/√Hz (same as LISA).

- The entire spacecraft to test-mass local measurement, including drag-free and controls, with hardware designed for LISA.
- The detailed physical model of the disturbances, to allow for final verification of the parts of LISA design under test.

Note: LISA Pathfinder results are not needed as an input to the design of LISA. Pathfinder is a verification step within the LISA development.

LISA Pathfinder Design and Development Approach

- Design is for LISA.
- Relaxation of performance requirements is only allowed to make testing conditions achievable. It cannot affect design.
- Implications:
  - When one subsystem item reaches a given level of readiness for LISA Pathfinder (CDR, Pre-launch Review etc.,) it reaches the same level of readiness for LISA too.
  - All the development risks up to that stage are consequently retired also for LISA
  - Risk of unforeseen system level problems (estimated to be low) is finally retired by the flight.

LISA Design Items Verified on Pathfinder (in black)

– **Free flying test mass subject to very low parasitic forces:**
  - Drag free control of spacecraft (non-contacting spacecraft)
  - Low noise microthruster to implement drag-free
  - Large gaps, heavy masses with caging mechanism
  - High stability electrical actuation on cross degrees of freedom
  - Non contacting discharging of test-masses
  - Thermomechanical stability of S/C
  - Gravitational field cancellation

– **Precision interferometric, *local* ranging of test-mass and spacecraft:**
  - pm resolution ranging, sub-mrad alignments
  - High stability monolithic optical assemblies

– **Precision spacecraft to spacecraft ranging:**
  - High stability telescopes
  - High accuracy phase-meter
  - High accuracy frequency stabilization
  - Constellation acquisition
  - Precision attitude control of S/C

LPF expected performance

- Interferometry tested end-to end in thermal vacuum chamber with entire SC on, and solar radiation simulator

- Performance of interferometers better then requirements: better than 5 pm/√Hz and 0.3 nrad/√Hz at at 10 mHz
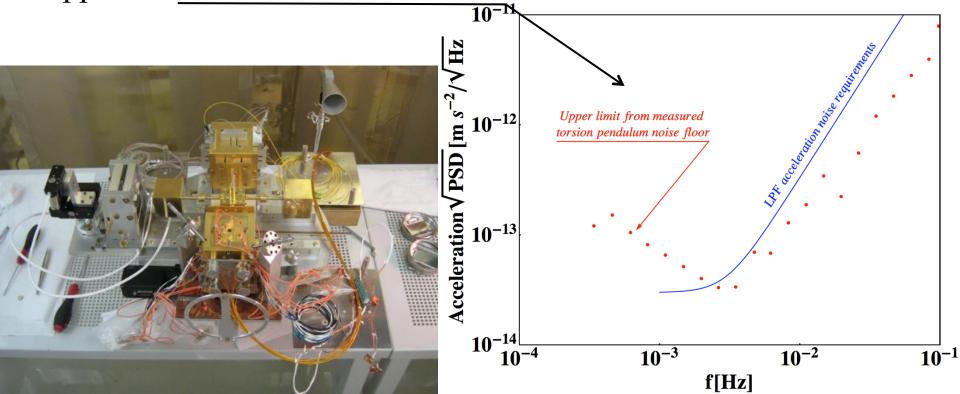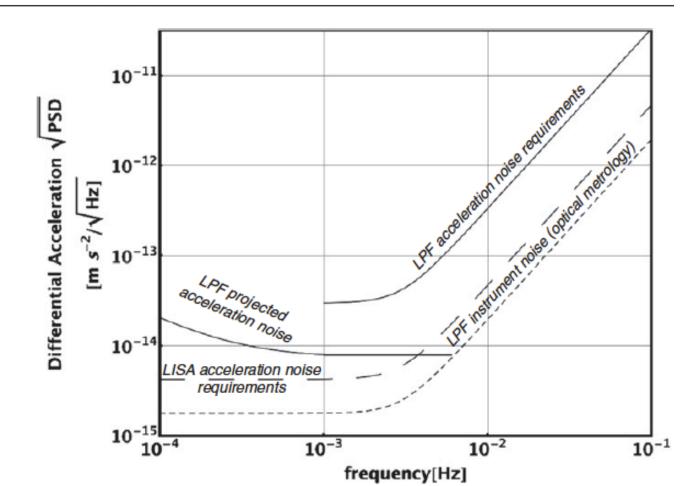
Torsion pendulum test of GRS performance

- GRS flight hardware replica tested. Ok for LISA/NGO for:
  - Thermal effects
  - Charge patches noise
  - Actuation noise
  - Molecular impacts
- Upper limit to unforeseen disturbances noise

Expected LPF performance close to LISA/ NGO requirements

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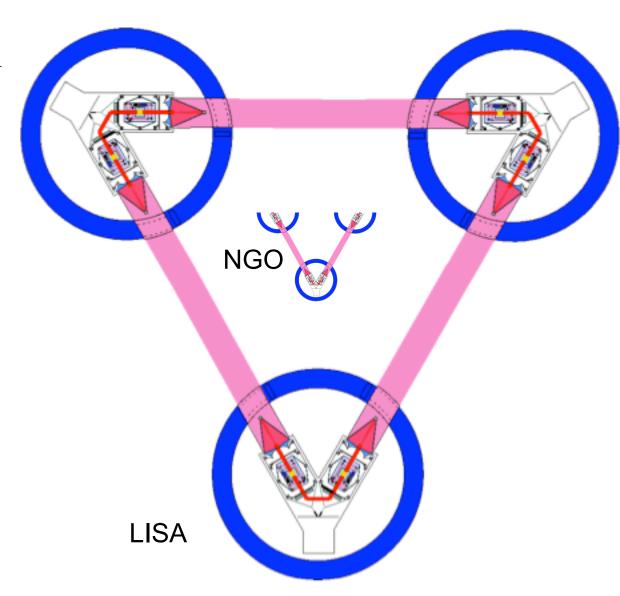
NGO

- Key features:
- Suppression of one arm
- Squeezing of size to 1 Mio Km
- Shortening of duration

NGO

LISA

Technical simplifications

- Reduction of the Arm Length from 5 to 1 Mio. km
  - Enables significant simplification of the Payload
    - Telescope Diameter reduced from 40 cm to 20 cm
    - Laser Power reduced from 2 W to 1.4 W
    - Point-Ahead Angle Mechanism not required
- Realization of only 2 interferometer arms
  - Saves hardware for the 3rd arm
- Duration of Science Operations reduced from 5+5 to 4+2 years
  - Enables a stable "Slow Drift Away" orbit with minimal Δv
  - Reduces consumable like propellant for micro-thruster allowing for cold gas
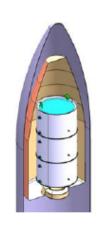
Cost reduction measures
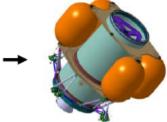
- Dual Soyuz launch scenario
  - Selected on the basis of current ESA cost estimates
  - Instead of single Ariane
- Propulsion modules inherited from LPF
  - Maximum heritage
  - Minimal design changes avoid re-qualification
- Removal of Ancillary Metrology Functions not required anymore to meet performance requirements
  - no PAAM Metrology
  - no Optical Truss
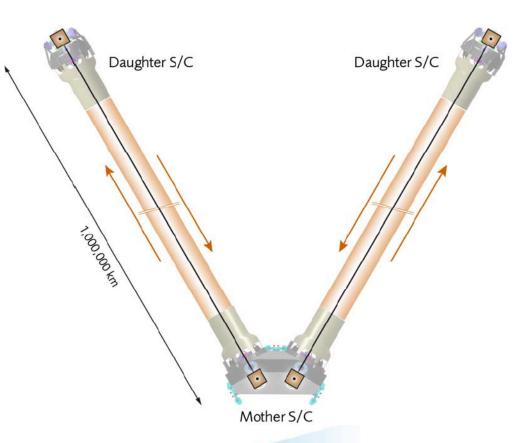- Minimal payload height

Mother/Daughter configuration

- Hardware for the 3rd arm is saved in Daughters. This reduces the Daughter's
  - Dry mass
  - Propellant mass
  - Wet launch mass
  - Payload AIVT effort

Orbit

- Many considered, Halo, Lagrange points, Earth centered….
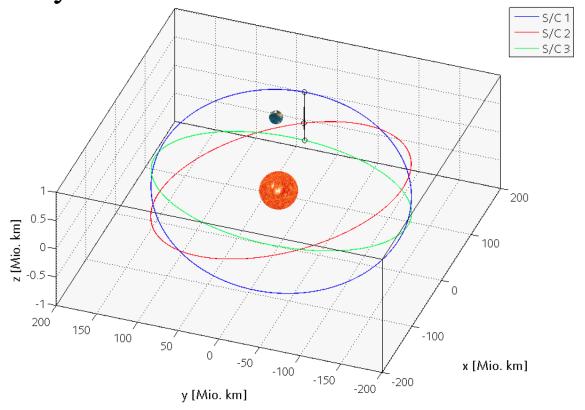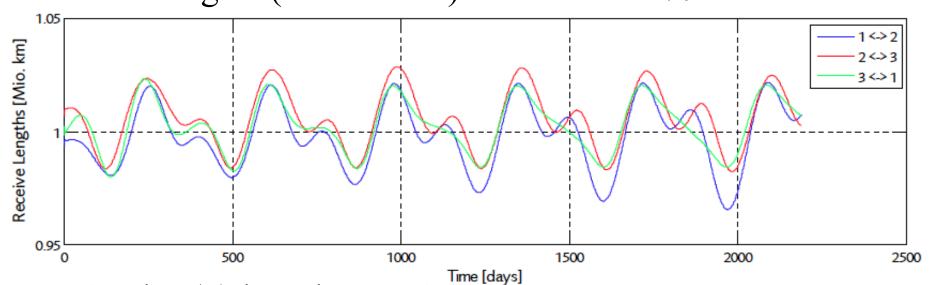- Baseline: slow drift away orbit starting at 10°, reaching 22° after 6 years

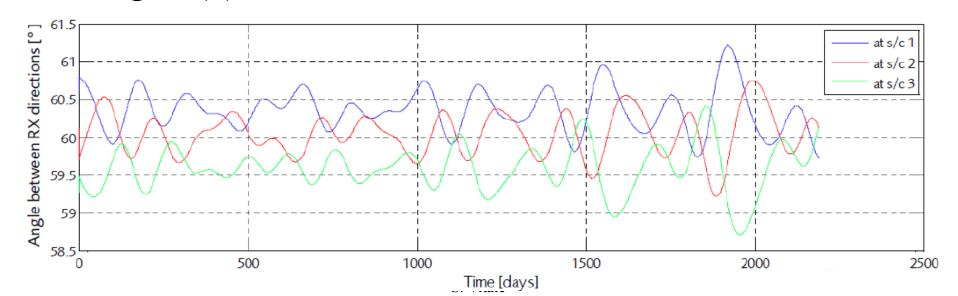**Figure 20:** *Earth-trailing heliocentric orbits of the 3 individual spacecraft (note the exaggerated scale on the z axis)*

Arm-length and angles

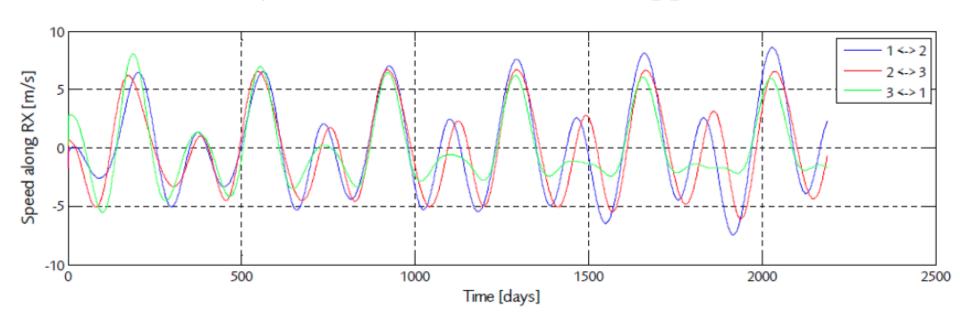- Arm-lengths (1-2 and 2-3) stable at 2-3 %

- Angles (2) less then 0.9°

SC-SC velocity and distance to earth

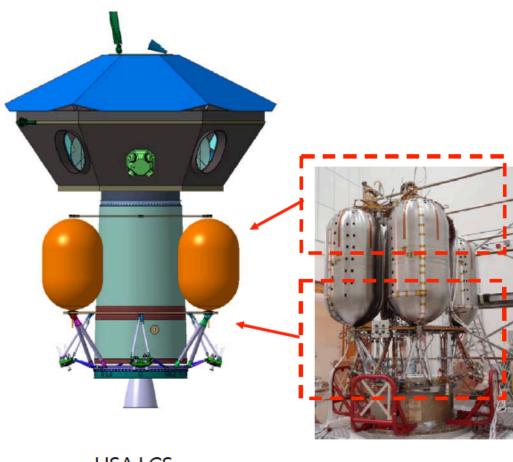- Max velocity < 10 Km/s (<10 MHz Doppler shift

- Distance to Earth 30→65 Mio Km in 6 Years

Launch configuration

- LISA Composite Spacecraft (LCS) consists of Sciencecraft mounted on Propulsion Module

- Propulsion Module derived from LPF by shortening tanks and cone only
  - LPF tanks too large to launch at minimum 70% fill, smaller existing Eurostar family tanks used
  - Identical for Mother and Daughter

- Facetted array permits upper layer inside Soyuz fairing
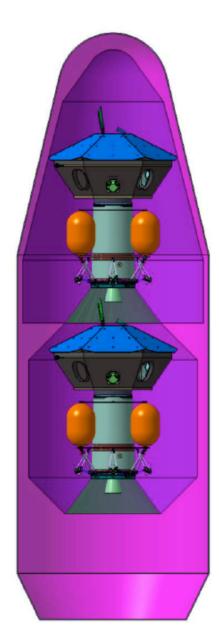
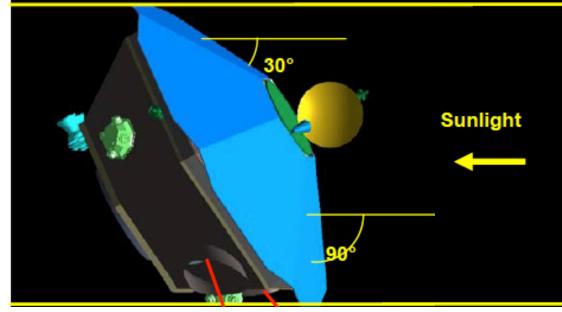

LISA LCS

LPF PM

Launch configuration

- Daughter and Mother launch look identical
- Mother has useful spare capacity in excess of 1000kg (shared launch)
- Ariane launch also possible, cost less solid
- Budgets. Worst case: RIT power and cold gas mass
- Wet mass
  - Mother 1650 kg
  - Daughter 1583 Kg (each)
- Dry mass (20% margin)
  - Mother 1003 kg
  - Daughter 849 kg
- Payload mass
  - Mother 282 kg
  - Daughter 155 kg
- Power (20% margin)
  - Mother 863 W
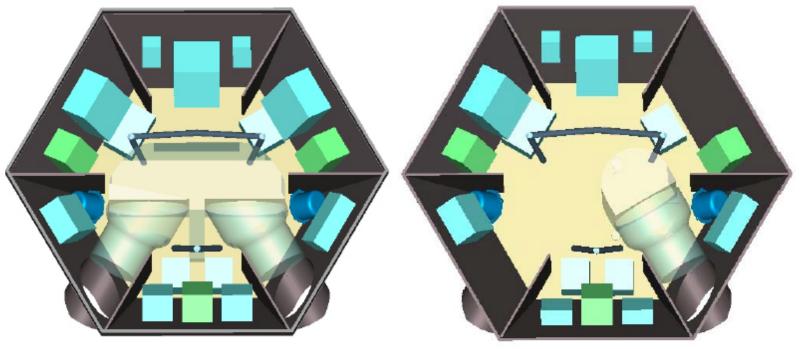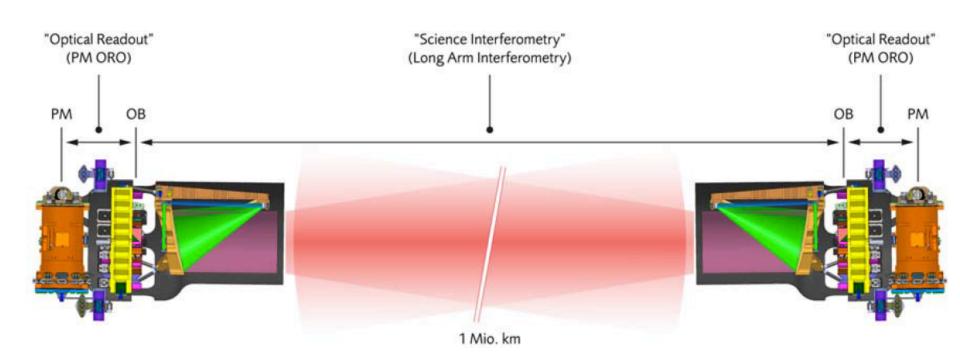 - Daughter 755 W

Spacecraft

30°

Sunlight

90°

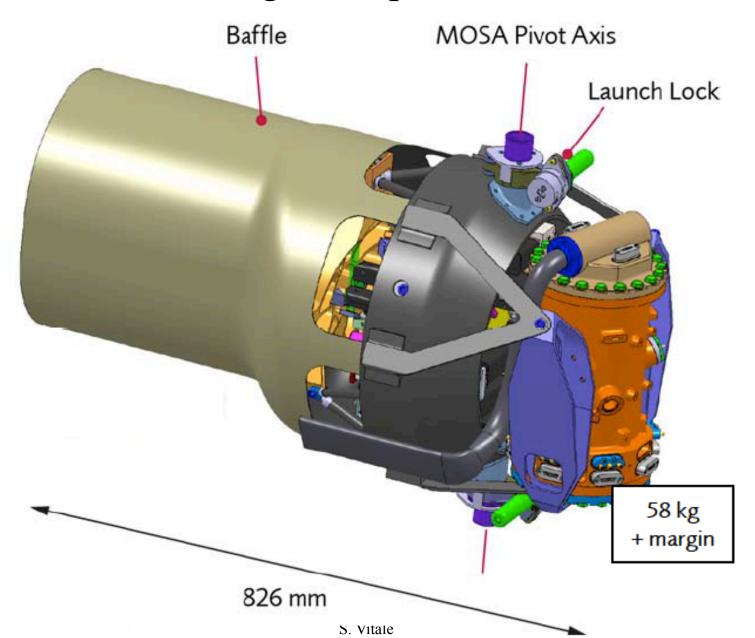**Figure 7**: Mother (left) and Daughter (right) payload bays

Metrology

- Link configuration similar to LISA
- GRS identical to LPF
- Metrology simplified by decreased telescope diameter, removal of point ahead mechanism, optical truss
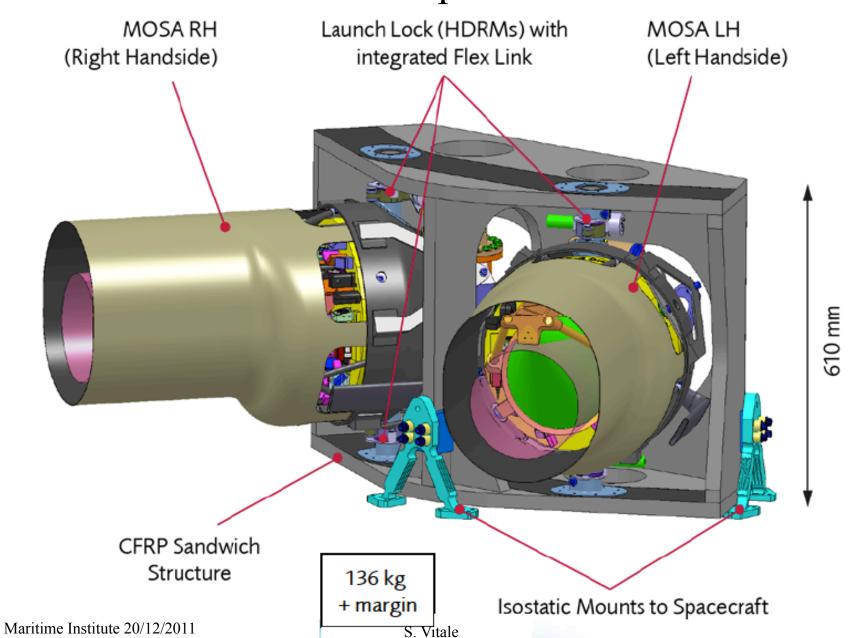
Daughter Spacecraft

Baffle

MOSA Pivot Axis
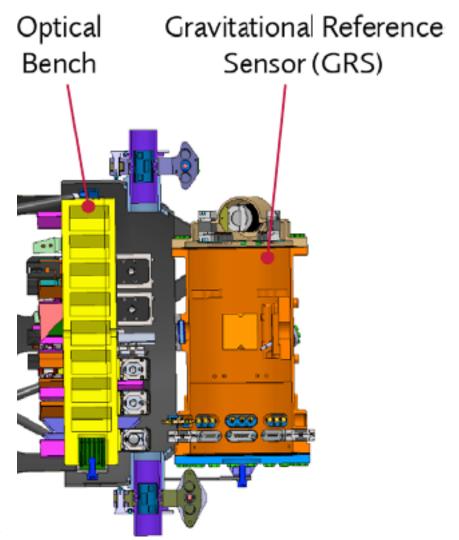
Launch Lock

58 kg
+ margin

826 mm

Mother Spacecraft

MOSA RH
(Right Handside)

Launch Lock (HDRMs) with
integrated Flex Link

MOSA LH
(Left Handside)

610 mm

CFRP Sandwich
Structure

136 kg
+ margin

Isostatic Mounts to Spacecraft

Instrument

- The basic complement
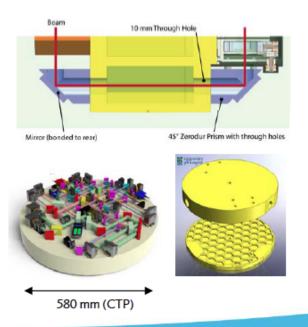
Optical Bench

Gravitational Reference Sensor (GRS)

Payload Architecture
Optical Bench (University of Glasgow)

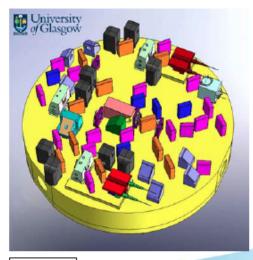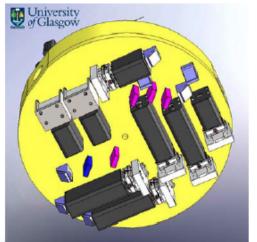- To take full advantage of reduced telescope dimensions, it is essential to also minimize the mechanical envelope of the OB

  - OB diameter drives payload *height* (as in LMF), and thus s/c height

  - Enabled by removal of PAAM, PAAM Metrology & Optical Truss on **double-sided** OB
    - Two sides joint by adhesive bonding (e.g. ultra-stable Astrium precision bonding technology)
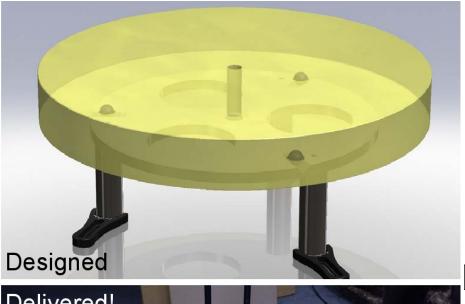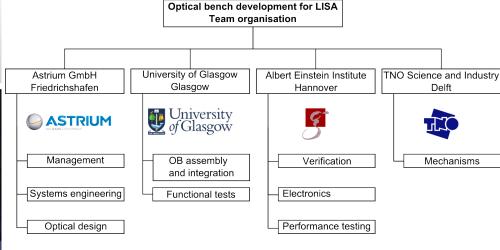   - "Periscopes" for beam transfer

Beam — 10 mm Through Hole
Mirror (bonded to rear) — 45° Zerodur Prism with through holes

580 mm (CTP)

University of Glasgow

15.3 kg + margin

University of Glasgow

350 mm

All the space you need

ASTRIUM
AN EADS COMPANY

Designed

Delivered!

Optical bench development for LISA
Team organisation

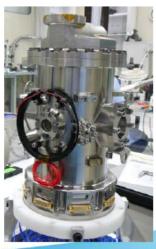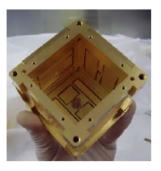| Astrium GmbH Friedrichshafen	University of Glasgow Glasgow	Albert Einstein Institute Hannover	TNO Science and Industry Delft
ASTRIUM AN EADS COMPANY	University of Glasgow		TNO
Management	OB assembly and integration	Verification	Mechanisms
Systems engineering	Functional tests	Electronics	
Optical design		Performance testing	

Payload Architecture
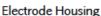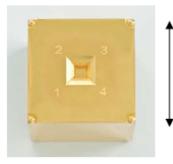## Gravitational Reference Sensor (GRS)

- The Gravitational Reference Sensor provides the inertial reference for the LISA measurement
  - For each MOSA, the inertial reference is established by a "Proof Mass", which is drag-free controlled along the respective measurement direction ("sensitive axis")
  - The GRS sensor heads are actuators and sensors of the DFACS software which is responsible to achieve the drag free condition and to control the telescope pointing

- The architecture of the GRS is directly inherited from the LISA Pathfinder "Inertial Sensor"
  - Minor modifications (apart from lessons learned) have always been anticipated for extrapolation of the LPF results to the specific LISA conditions (e.g. self gravity environment)

Getter Pump Assembly
Vacuum Valve
Vacuum Enclosure
Mechanical Interface Flange
Optical Window for PM ORO
UV Fiber Feedthroughs
Harness Feedthroughs
20 kg + margin

46 mm

Electrode Housing

AuPt Proof Mass

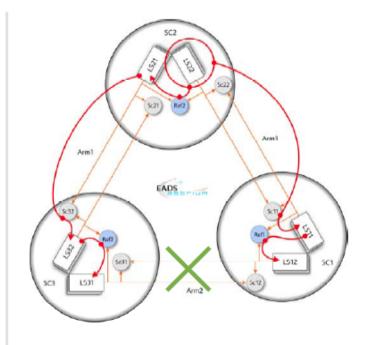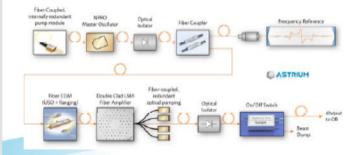All the space you need

S. Vitale

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Payload Architecture
Laser Subsystem

- Each Optical Bench is fed by a High Power Laser Subsystem (1.1W + 30% margin)

  - Provides laser light for TX Beam

  - Internal cold redundancy between a nominal and redundant Laser Head

  - Frequency Reference for in-orbit frequency stabilization

  - LMF architecture remains applicable

- Each Optical Bench requires additionally a "Local Oscillator" for the local interferometry

  - Obtained from the 2nd OB in the Mother via "Backlink Fiber"

  - Generated by a dedicated Low Power Laser Subsystem in the 2 Daughters (~ 50 mW TBC)

    - Copy of Master Oscillator in High Power Laser Subsystems

    - Alternatively can be generated by frequency modulation of High Power laser (cf. LTP)
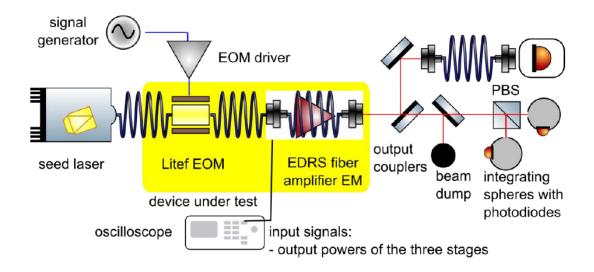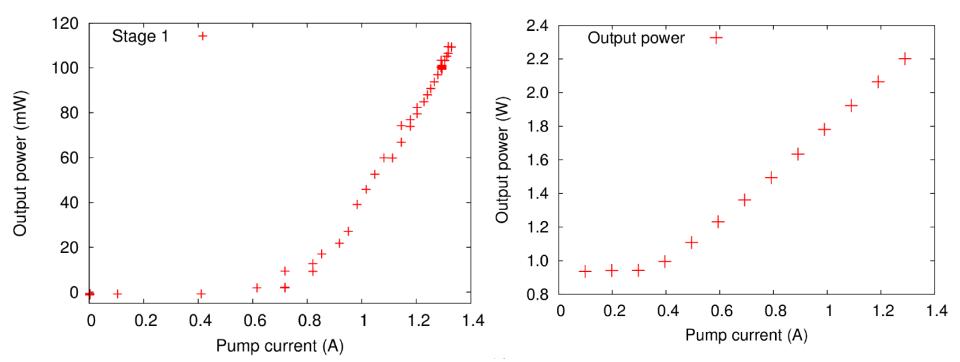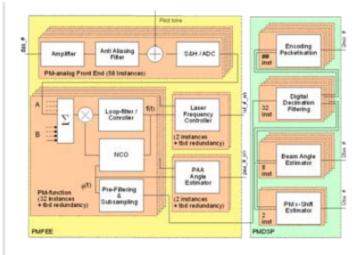
Laser development in ESA

Payload Architecture
Phase Measurement Subsystem

- The Phase Measurement Subsystem (PMS) is the source of all data used for nominal LISA ground processing with the exception of PM lateral shift (provided from GRS)

  - Measures the **phase** of the beat note of all interferometers (thus providing all lengths and angle measurements determined by interferometry)

  - Provides a consistent **datation** to these measurements

  - Generates the modulation tones for the **USO frequency exchange** modulation and measure the phase difference of the sub-carrier beat notes resulting thereof

  - Transmits and receives timing semaphores as needed to measure **arm delay** and **establish a consistent constellation time** (evaluation in ground processing)

- Additional functions related to the phase measurements are also allocated to the PMS

  - Provide PM and Pointing metrology to the DFACS
  - Perform Laser Frequency Control

- Architecture and functions identical to LMF

  - Reduced number of channels

	LMF	Mother	Daughter
No. of input lines	70	48	24
No. of active channels	46	32	16
Mass (w/o margin)	16 kg	12 kg	8 kg
Power (w/o margin)	49 W	38 W	23 W

All the space you need

Under development under ESA contract
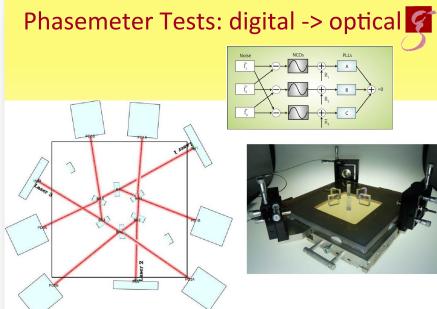
Science Performance
Strain Sensitivity @ 1 Mio. km Arm Length

Science

Science Objectives

Through the detection and observation of gravitational waves
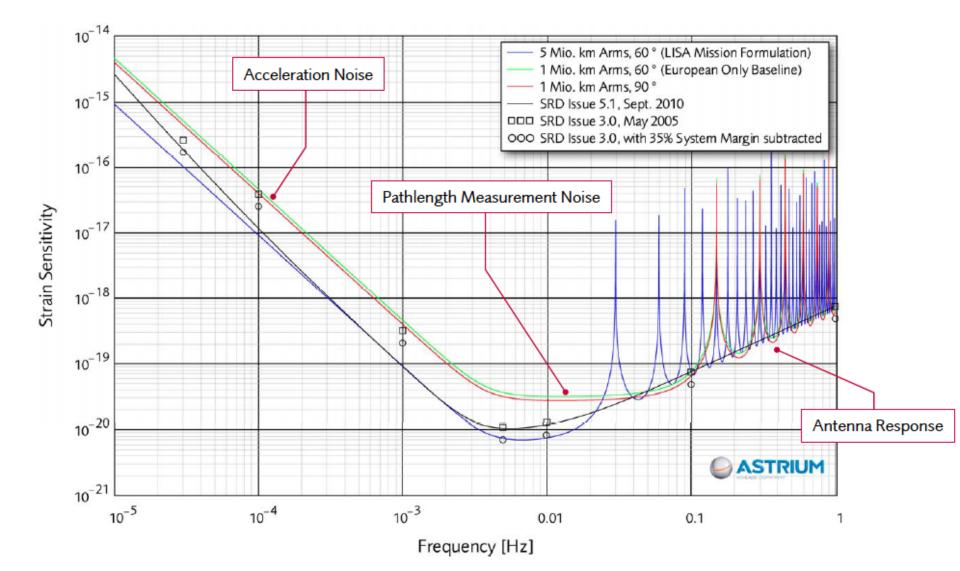- Survey compact stellar-mass binaries and study the structure of the Galaxy
- Trace the formation, growth, and merger history of massive black holes
- Explore stellar populations and dynamics in galactic nuclei
- Confront General Relativity with observations
- Probe new physics and cosmology

Event Rates and Event Numbers

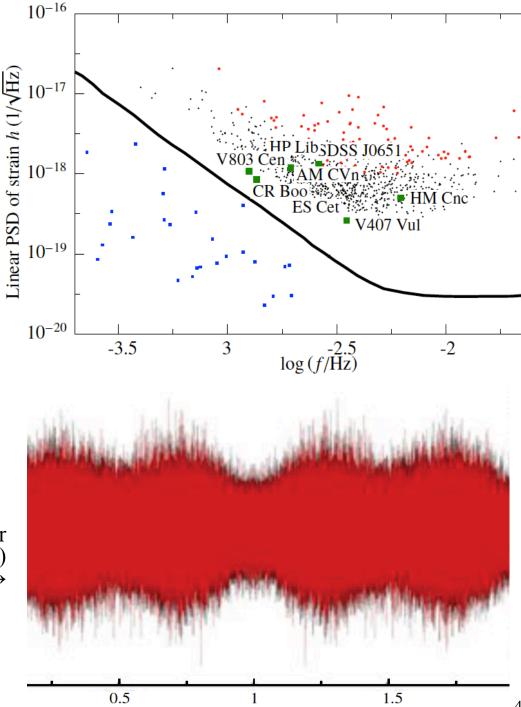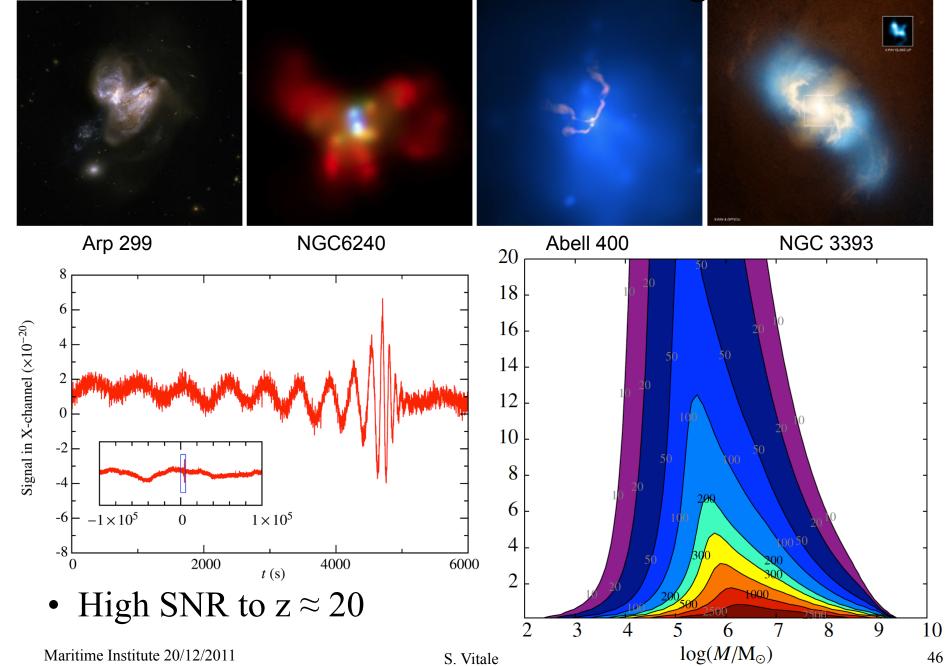|	
Frequency band	1×10^{-4} Hz to 1 Hz, (3×10^{-5} Hz *to* 1 Hz *as a goal*)
Massive black hole mergers	$10 \, \mathrm{yr}^{-1}$ to $100 \, \mathrm{yr}^{-1}$
Extreme mass ratio inspirals	$1 \, \mathrm{yr}^{-1}$ to $10 \, \mathrm{yr}^{-1}$
Galactic Binaries	~ 3000 resolvable out of a total of $\sim 30 \times 10^6$ in the NGO band

Compact binaries

- \> 8 Verification binaries (pending upcoming surveys)

- \>3000 other individually detectable sources (progenitors of supernovae, test of enhanced formation in globular clusters), <3° location, 10° inclination, distances down to 1 %

- Detailed study of high SNR ones give tidal and mass-transfer behavior.

- $>10^7$ undistinguishable binaries galactic foreground gives population census and properties

signal in time domain before (black) and after (red) subtracting resolvable sources)
→→→→

Super-massive black-hole mergers

Arp 299   NGC6240   Abell 400   NGC 3393
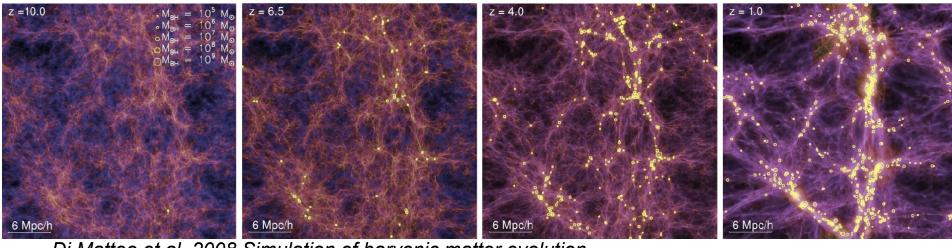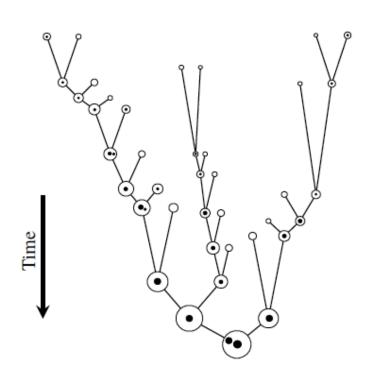
- High SNR to $z \approx 20$

Cosmic stratigraphy

Di Matteo et al. 2008 Simulation of baryonic matter evolution

- During their cosmic evolution black holes transit into the mass interval to which NGO is sensitive.

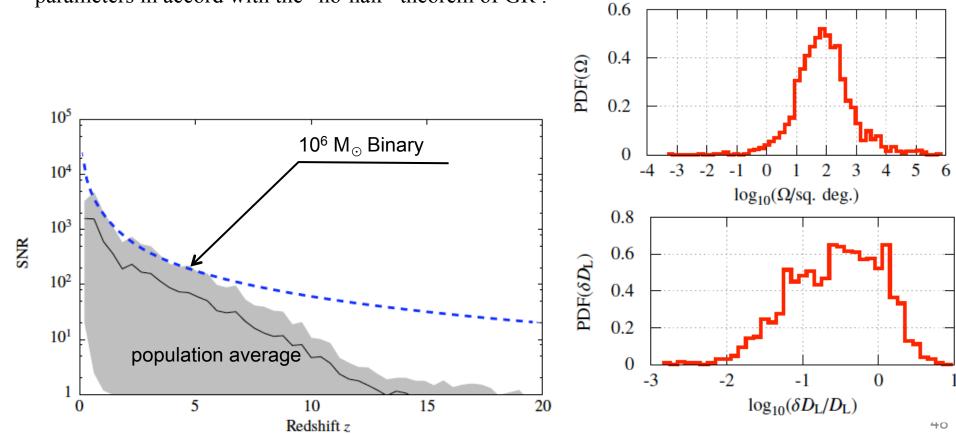- NGO will map galaxies formation and clustering , using black holes as clean tracers.

S. Vitale

BH physics at high SNR

- NGO will be able to detect the gravitational waves emitted by black hole binaries with total mass (in the source rest frame) as small as $10^4 M_\odot$ and up to $10^7 M_\odot$, out to a redshift as remote as z ~ 20 .

- NGO will measure red-shifted mass to an unprecedented accuracy, up to the 0.1 % – 1 % level, whereas absolute errors in the spin determination are expected to be in the range 0.01 to 0.1 dimensionless units.

- Luminosity distance to 1-50 %. Sky location for brightest ≈3° -10°

- Final merger in GR leads to a single ringing Kerr black hole characterized by its mass and spin. Detecting two quasi-normal modes checks whether the final object indeed is described only by two parameters in accord with the "no-hair" theorem of GR .
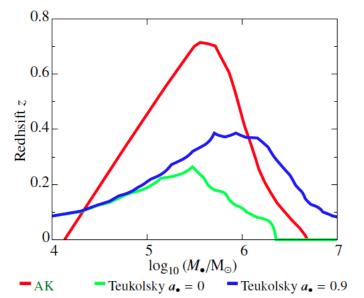

$10^6 M_\odot$ Binary

population average

Extreme Mass Ratio inspiral
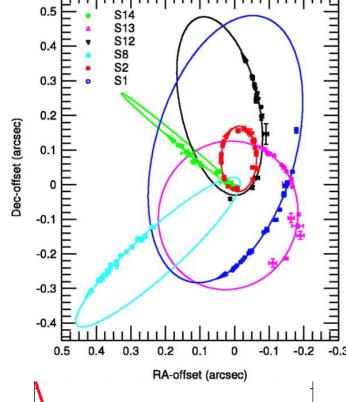
- Stellar mass black-hole into a Massive black-hole

- SNR 20 up to z ≈ 0.7
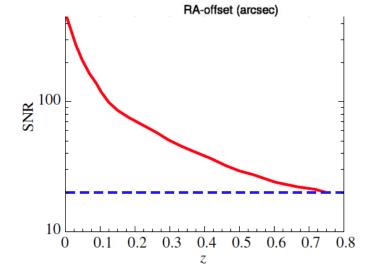
- Rate in 2 years (2< <50)

Waveform model	Teukolsky with black hole spin			Analytic Kludge
	$a_\bullet = 0$	$a_\bullet = 0.5$	$a_\bullet = 0.9$	
Number of events	30	35	55	50

Maritime Institute ☐   ▬ AK   ▬ Teukolsky $a_\bullet = 0$ ▬ Teukolsky $a_\bullet = 0.9$

Extreme Mass Ratio inspiral

- NGO observes ~ 10^5 final cycles of the inspiral of a stellar mass object into a black hole with mass $10^5 M_\odot - 10^6 M_\odot$ up to z ~ 0.7.

- Give precisely the parameters of the central object including mass, spin (0.1-0.01 % accuracy) and quadrupole moment (0.001 $M_\odot{}^3 \mathcal{G}^2/ c^{4)}$.
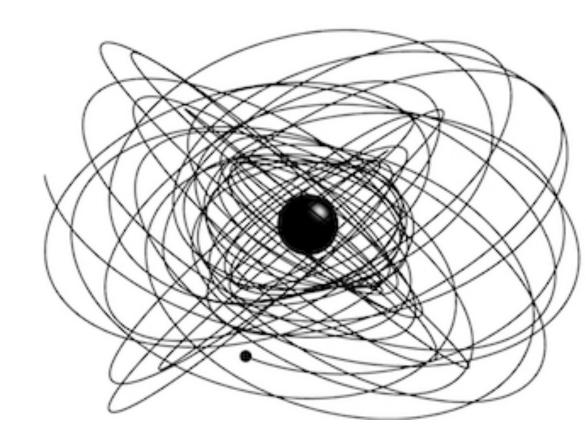
- Allows to check whether it is consistent with a GR Kerr black hole.

Science objectives

- **Survey compact stellar-mass binaries and study the structure of the Galaxy**
  - Elucidate the formation and evolution of Galactic stellar-mass compact binaries and thus constrain the outcome of the common envelope phase and the progenitors of (type Ia) supernovae.
  - Determine the spatial distribution of stellar mass binaries in the Milky Way
  - Improve our understanding of white dwarfs, their masses, and their interactions in binaries, and enable combined gravitational and electromagnetic observations

- **Trace the formation, growth and merger history of massive black holes.**
  - Trace the formation, growth and merger history of massive black holes with masses $10^5 \, M_\odot - 10^7 \, M_\odot$ during the epoch of growth of quasi-stellar objects and widespread star formation ($0 < z < 5$) through their coalescence in galactic halos.
  - Capture the signal of coalescing massive black hole binaries with masses $2 \times 10^4 \, M_\odot - 10^5 \, M_\odot$ in the range of $5 < z < 10$ when the universe is less than 1 Gyr old.

- **Explore stellar populations and dynamics in galactic nuclei**
  - Characterize the immediate environment of massive black holes in $z < 0.7$ galactic nuclei from extreme mass ratio capture signals.
  - Discovery of intermediate-mass black holes from their captures by massive black holes.

- **Confront General Relativity with observations**
  - Detect gravitational waves directly and measure their properties precisely
  - Test whether the central massive objects in galactic nuclei are consistent with the Kerr black holes of General Relativity.
  - Perform precision tests of dynamical strong-field gravity.

- **Probe new physics and cosmology with gravitational waves**
  - Measure the spectrum of cosmological backgrounds, or set upper limits on them in the 10^{-4} Hz $- 10^{-1}$ Hz band.
  - Search for gravitational wave bursts from cosmic string cusps and kinks.
  - Cosmography with standard sirens

NGO Science Working Team

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