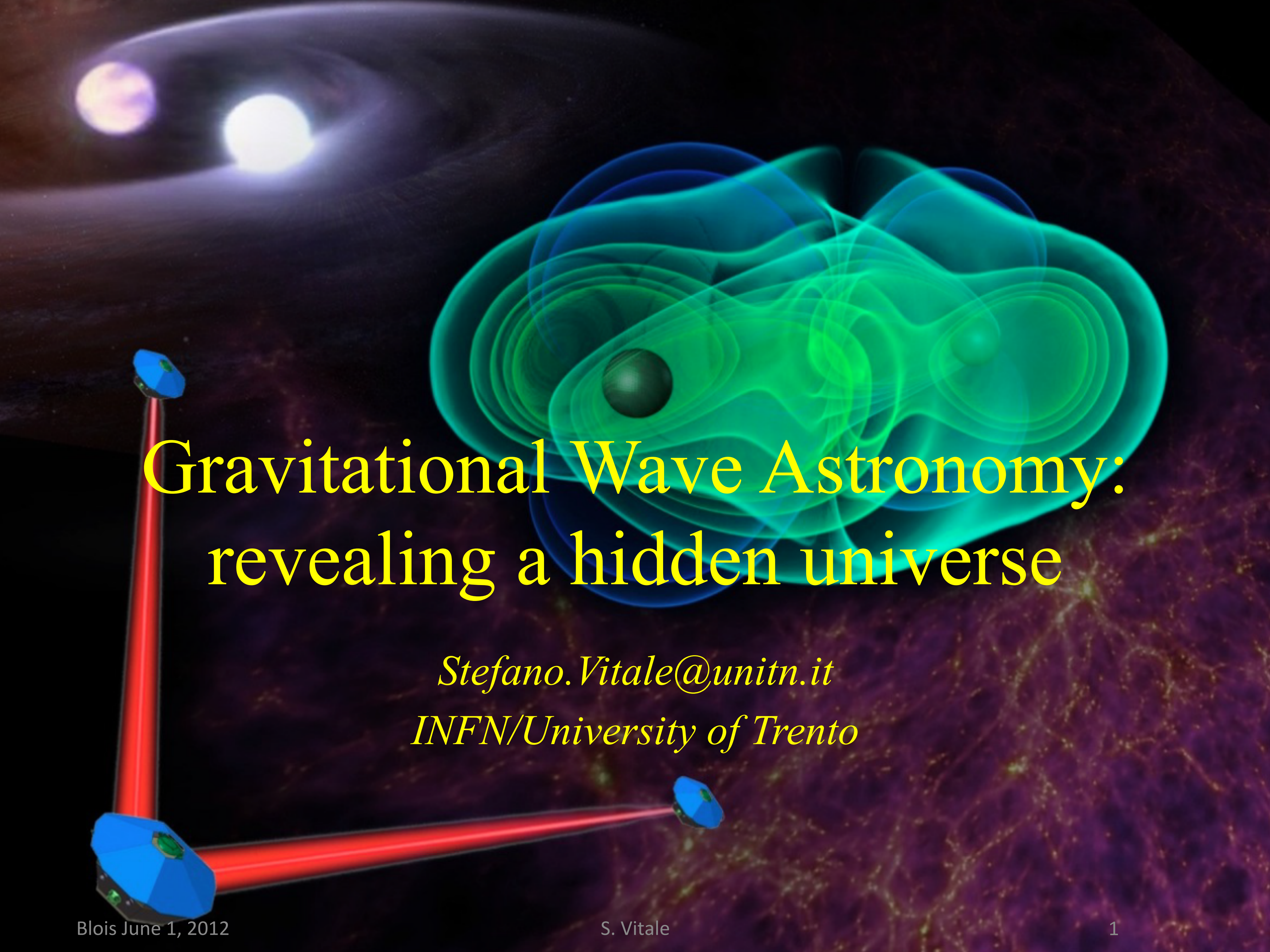

Gravitational Wave Astronomy: revealing a hidden universe

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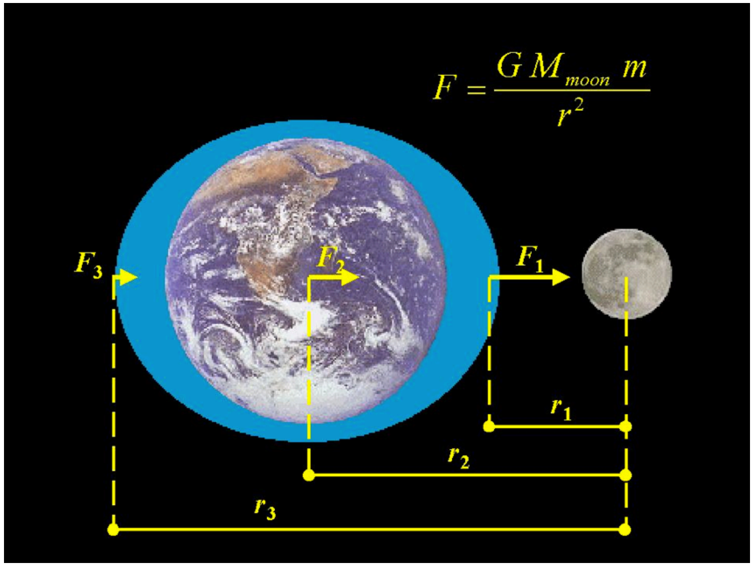
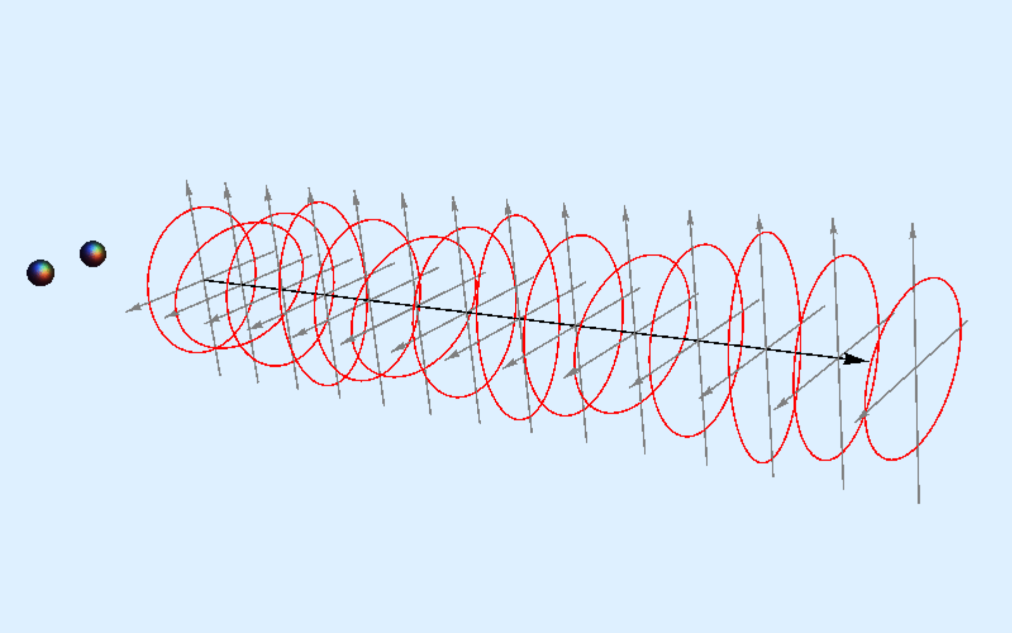
Gravitational Waves (GW)

- In free falling laboratories the only measurable effect of gravitation are tides, i.e. relative acceleration of particles separated in space



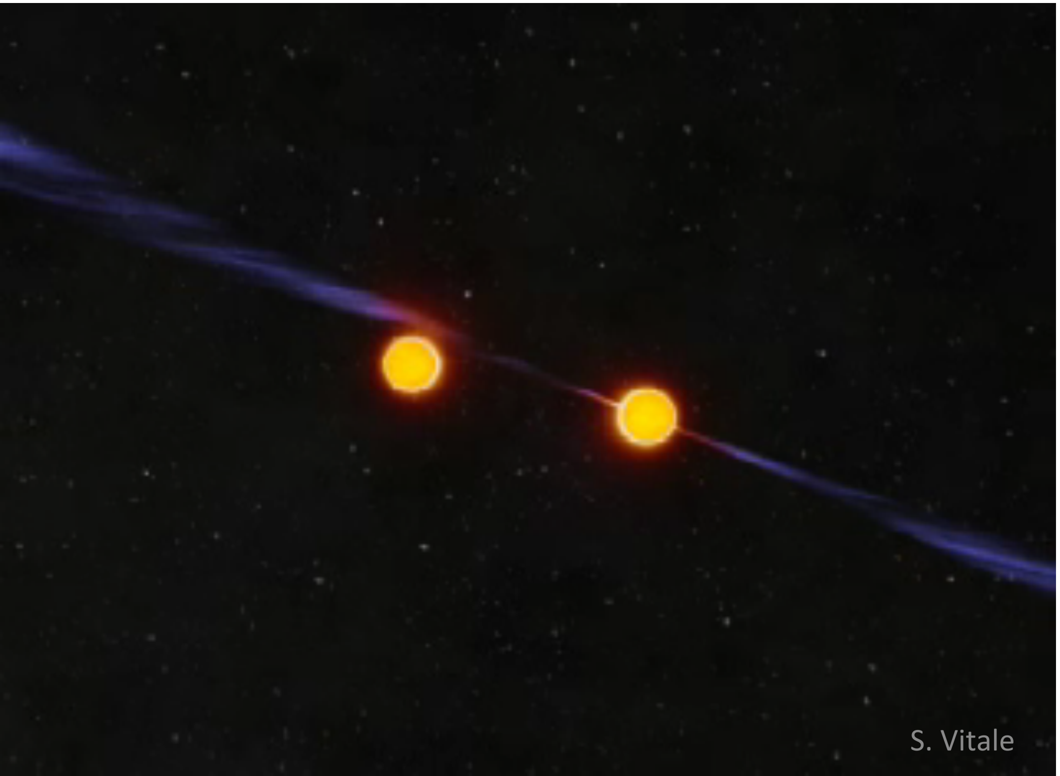
- Relativity requires that perturbations in the gravitational field can only travel at the speed of light

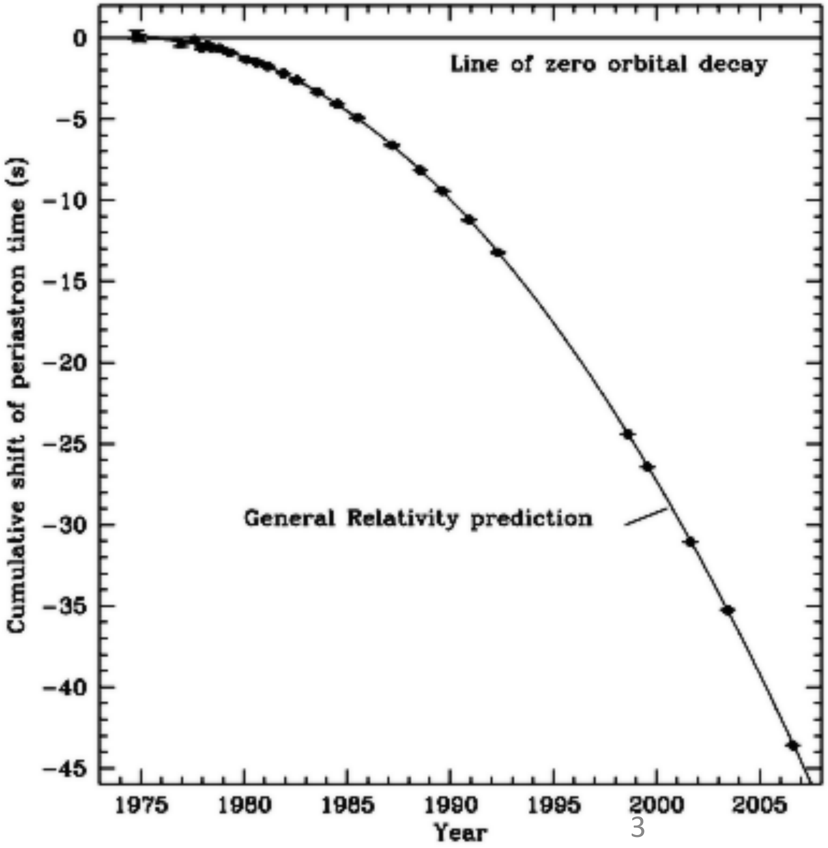
- GW: waves of tidal accelerations traveling at the speed of light (Einstein 1916)



Gravitational Waves

- Caused by acceleration of mass and energy:
  - Binary systems, collapses, primordial fluctuations
- Detected for the first time from energy loss of binary systems (PSR 1913+16)





Detecting Gravitational Waves

- Waves give particles "tidal" accelerations
- Particles send laser beams to each other.
- Acceleration of source modulates frequency of light by Doppler effect
- Tides are proportional to arm-length L: wide is good
- Signal h ∝ $\Delta L/L$

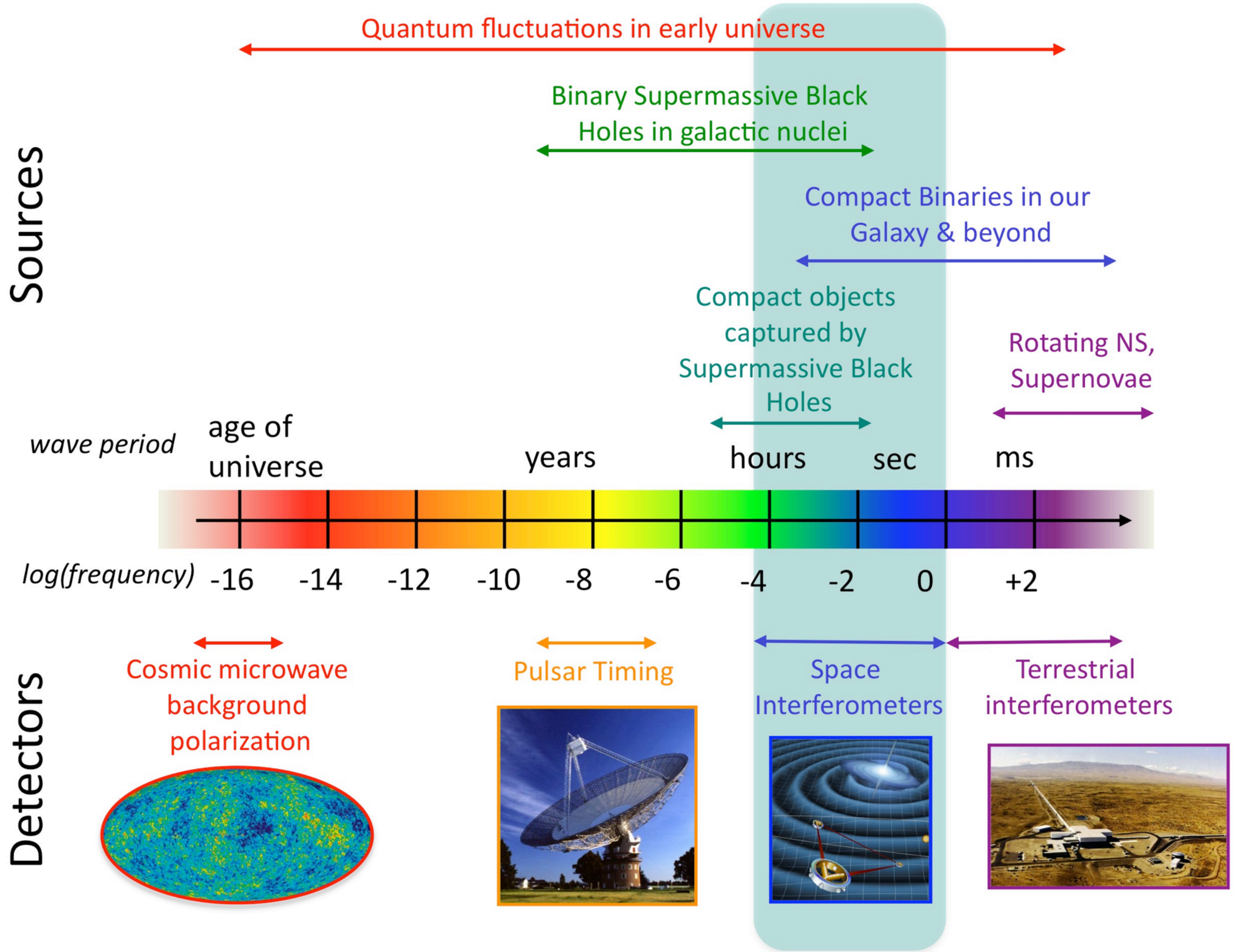
Gravitational Waves

- Coupling of GWs to matter is very different from EM.
- Very weak, $h << \varphi/c^2 = GM/rc^2 \rightarrow \delta L/L \sim h \sim 10^{-21}$ to 10^{-24}.
- Weakness ⇒ negligible scatter, absorption: perfect messengers! Waves penetrate:
  - any matter
  - black holes from the event horizon
  - early universe from singularity
- Waveforms record the motion of distant matter and give distance to source.
- Have huge energy flux; luminosity scale is $c^5/G \sim 3.6 \times 10^{59}$ erg/s.
- Black hole mergers are more luminous than the EM emission during same time of rest of the universe put together!

Like *listening* to the universe

- GWs have many analogies to sound: waves of spacetime
- Detectors are our "microphones"
  - 1D response, not an image. Converts to sound: you can listen to GWs
  - Record the waves coherently, tracking phase and amplitude
  - Nearly omni-directional, but linearly polarized
- GW astronomy adds the audio dimension to our ability to monitor the dynamical universe.

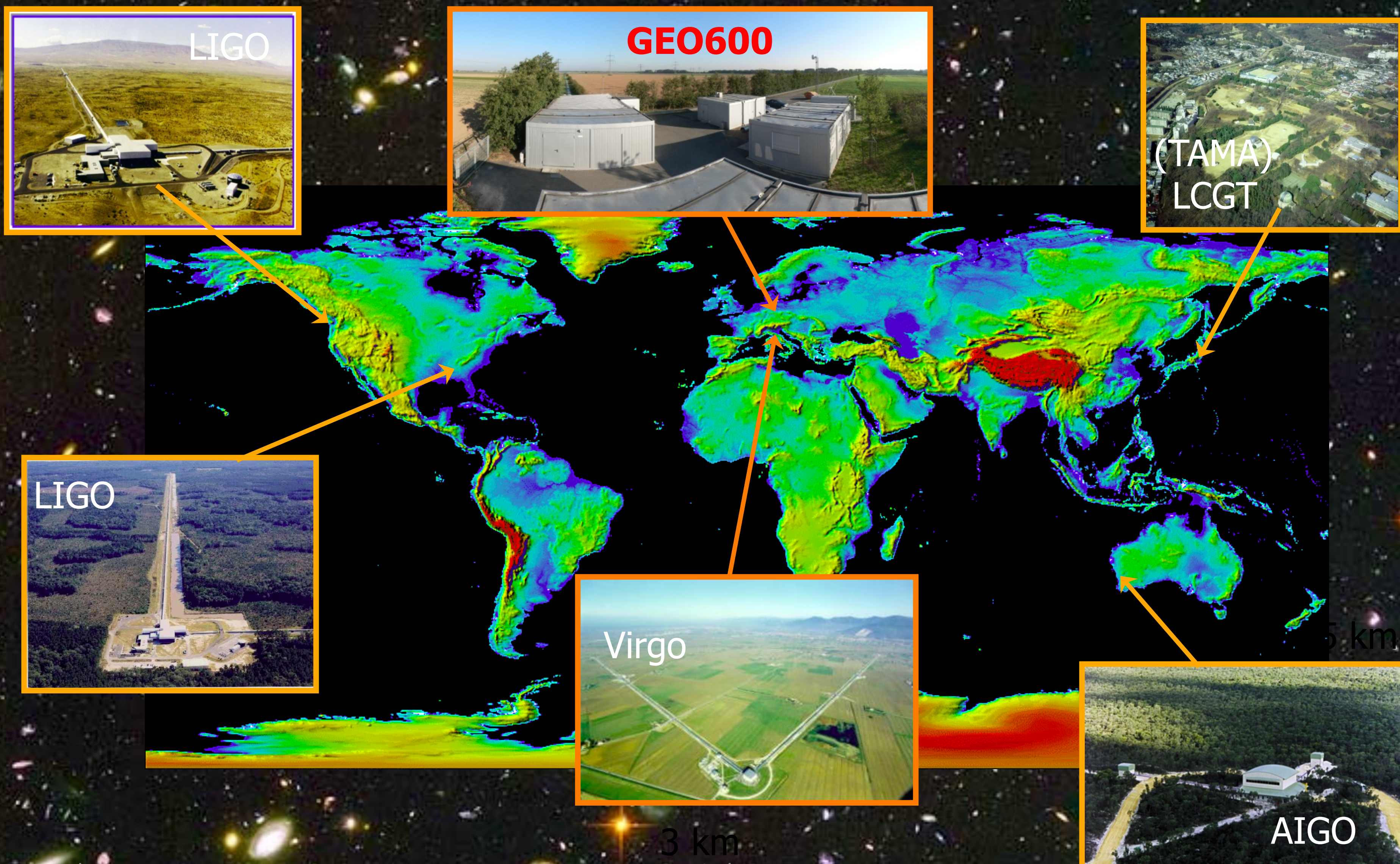
The Gravitational Wave Spectrum



GW observatories

- LIGO, VIRGO likely to make first detections 2015-17.
  - Primary sources: neutron star and stellar black hole binaries, ~tens/yr.
  - Limited: low SNR (< 20), stellar-mass sources, f > 10 Hz.
- Pulsar timing could open nHz band before 2020.
  - Signal confusion, limited information: 3 cycles/10 yr.
- GW detection in space opens the richest GW band: mHz.
  - High SNR (~10^3), thousands of resolvable signals.
  - Astronomy's focus is moving toward space-interferometer capabilities:
    - Massive galactic black holes, key also to galaxy evolution.
    - Transient astronomy: major ground-based facilities coming.
    - The high-redshift universe: astronomy's next frontier.

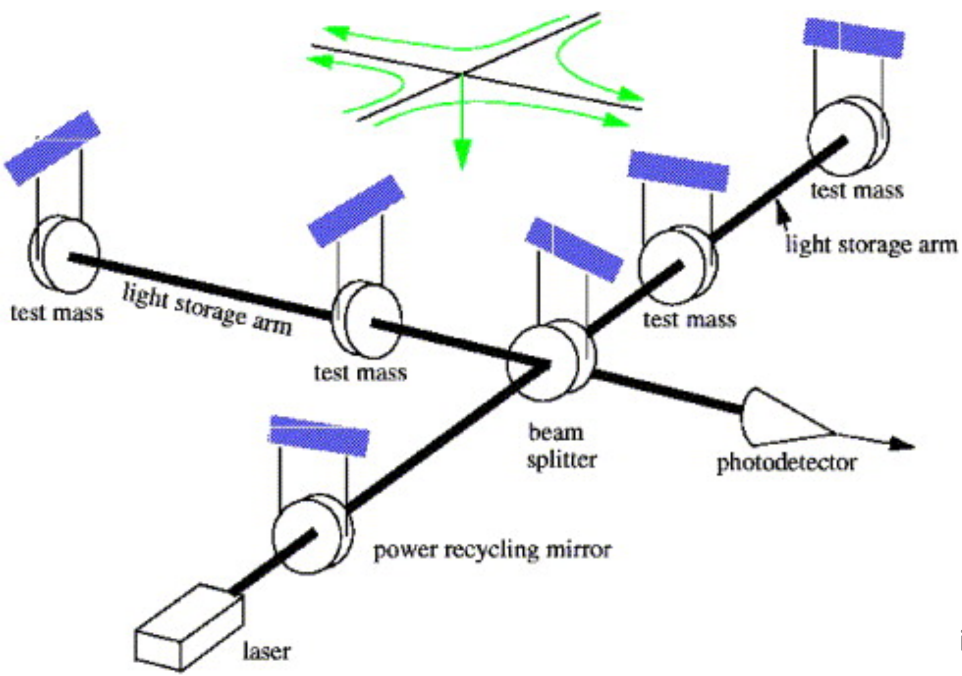
Ground Based Laser Interferometric Gravitational Wave Detector Network: A single observatory

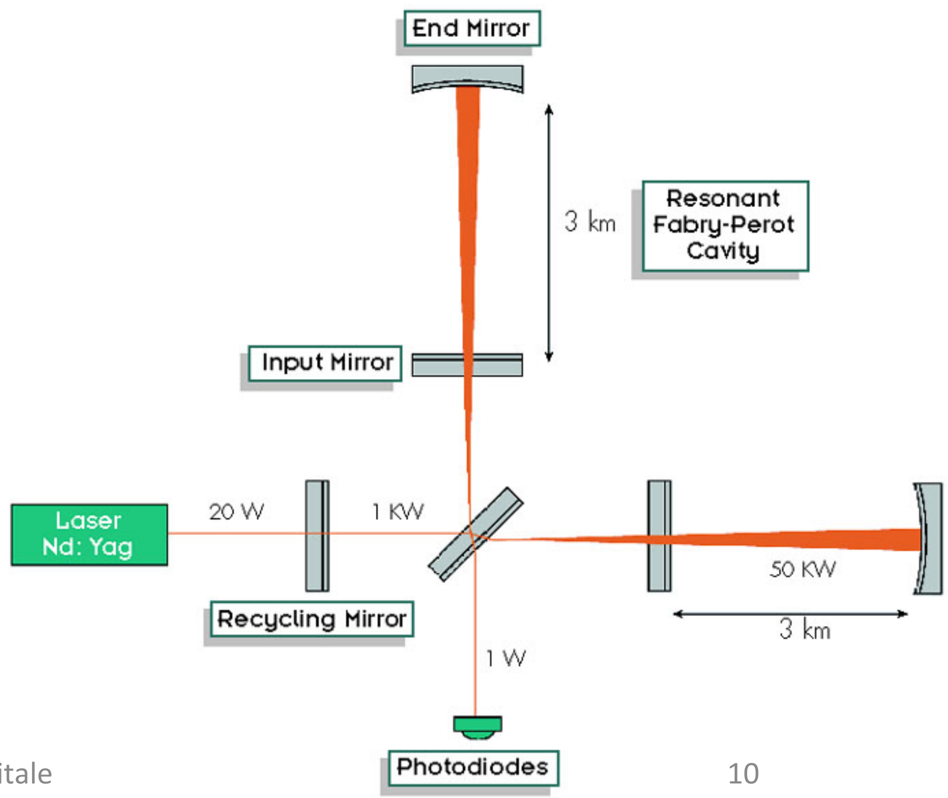


Source: A. Lazzarini, modified

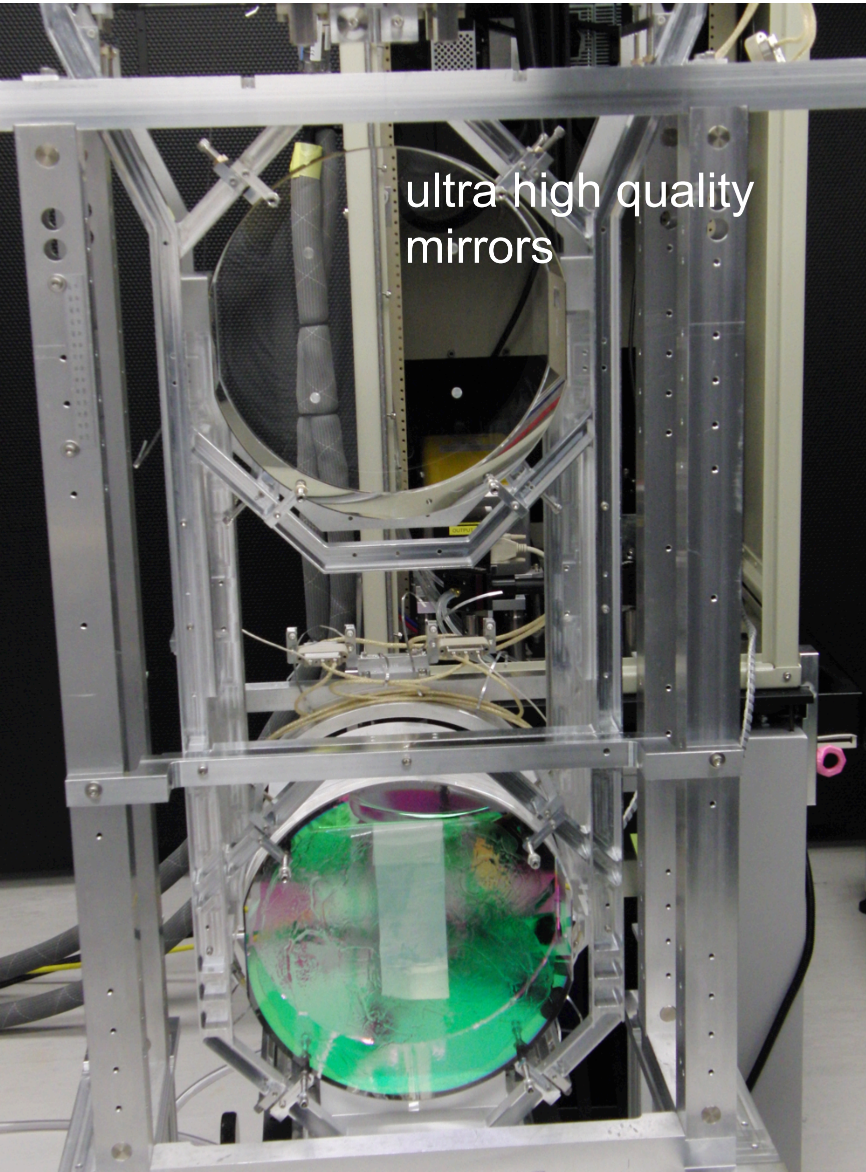
Ground-based detectors

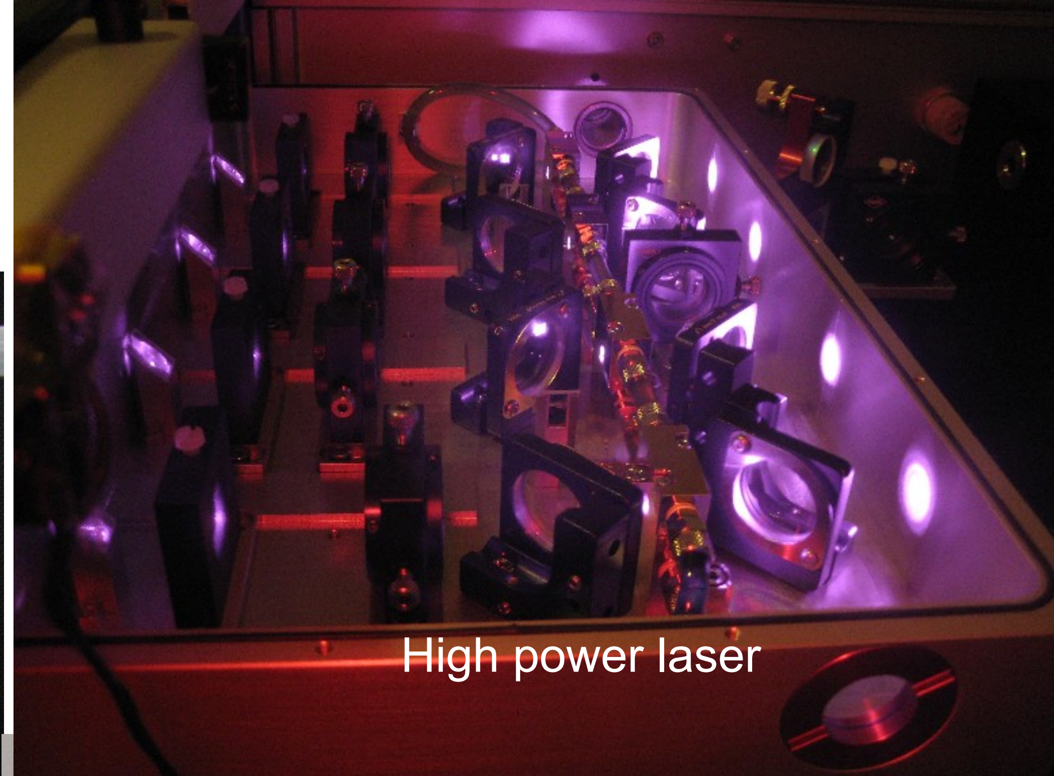
- The basic scheme: a two equal arm laser interferometer .
- Test-masses are suspended mirrors.
- Large circulating power (10-50 kW).





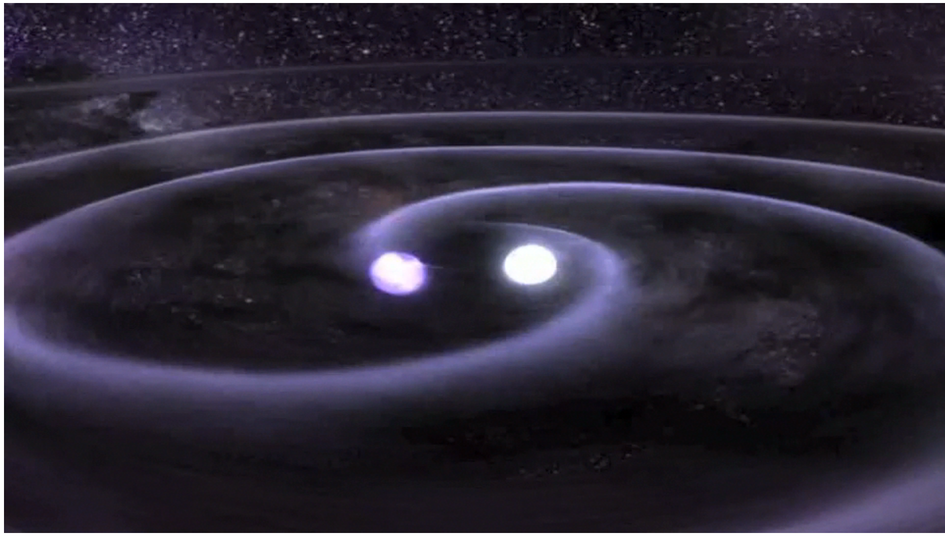
Interferometer technology





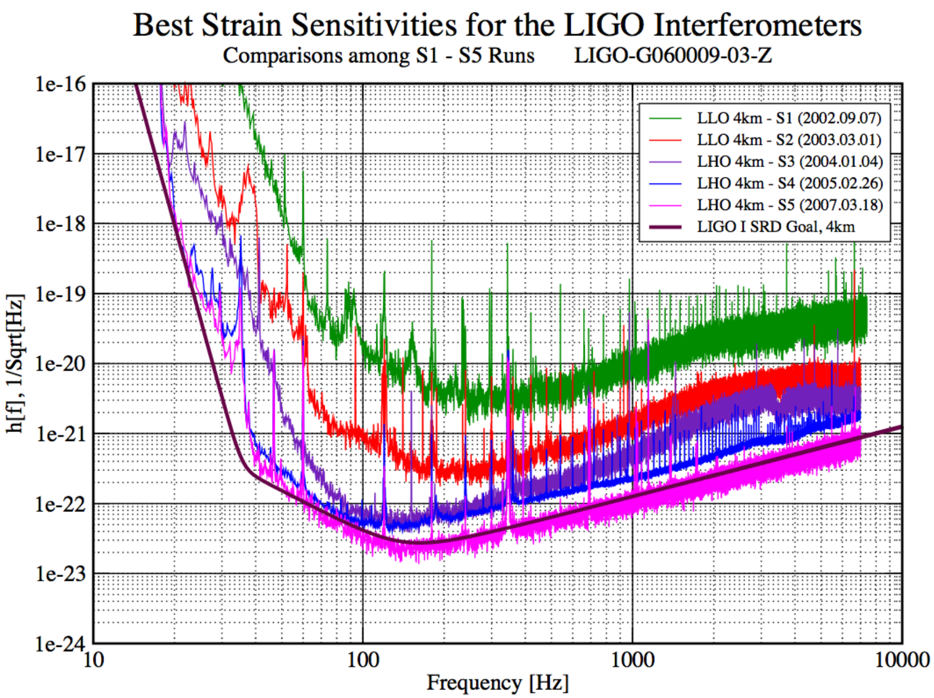
Science with ground based detectors

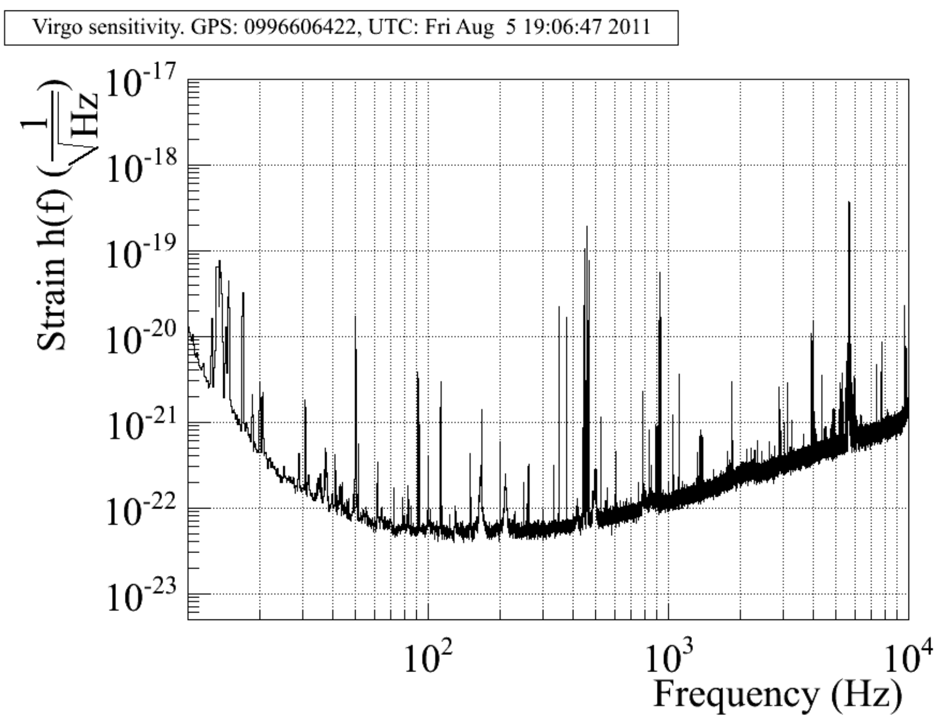
- Main sources at frequency >10 Hz
  - Neutron-Star Binary coalescences
  - Stellar Black-Hole Binaries coalescences
  - Non-spherical pulsars
  - Stochastic bakground



Current best sensitivites

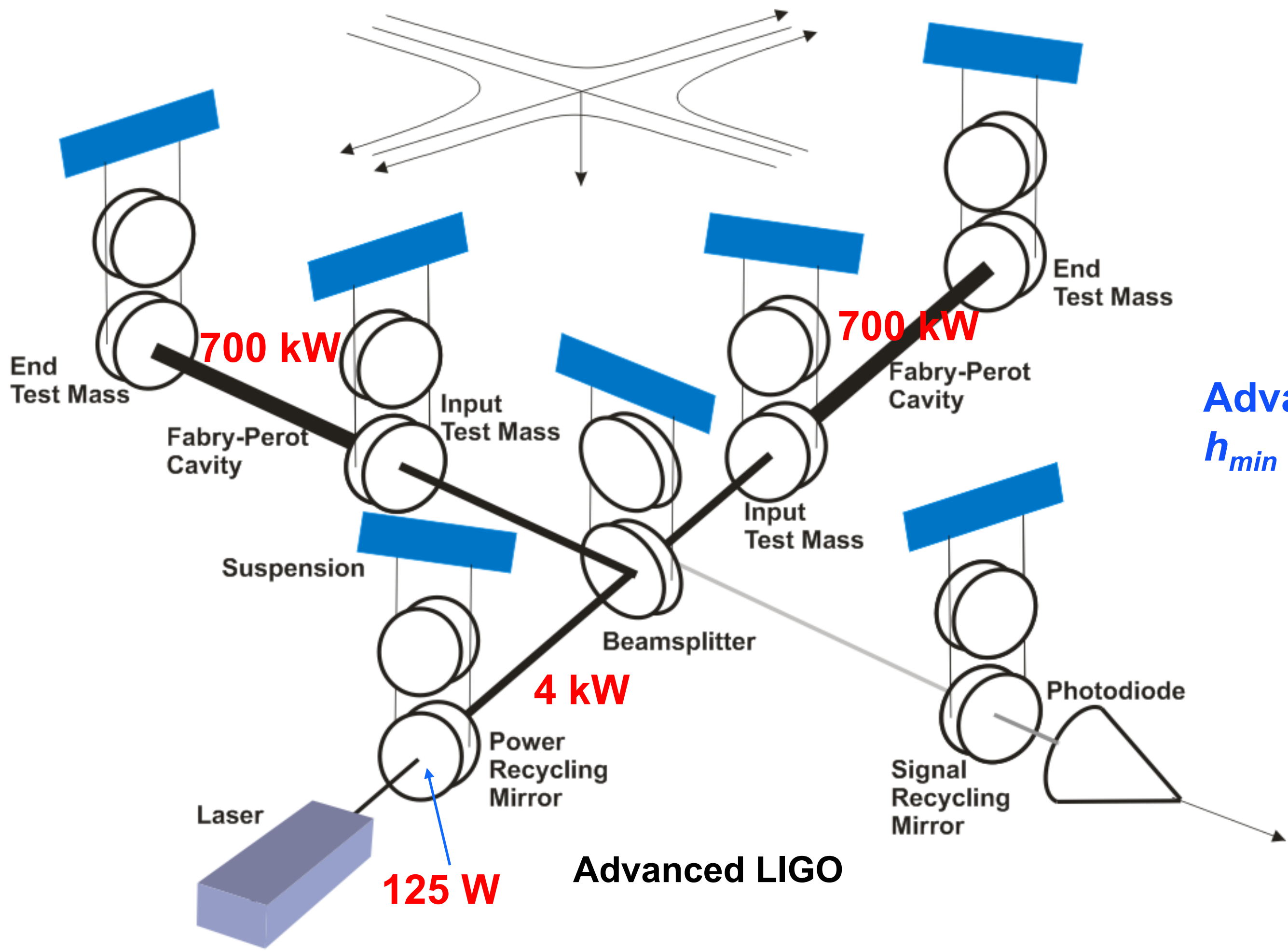
- First generation detectors (LIGO/Virgo) have reached design sensitivities)
- Power spectral density in h $\sqrt{PSD_h} < 10^{-22}/\sqrt{Hz}$ @ 100 Hz
- No detection yet but many significan upper limits
- Operation terminated: second generation detectors funded and under construction





LIGO

Advanced LIGO



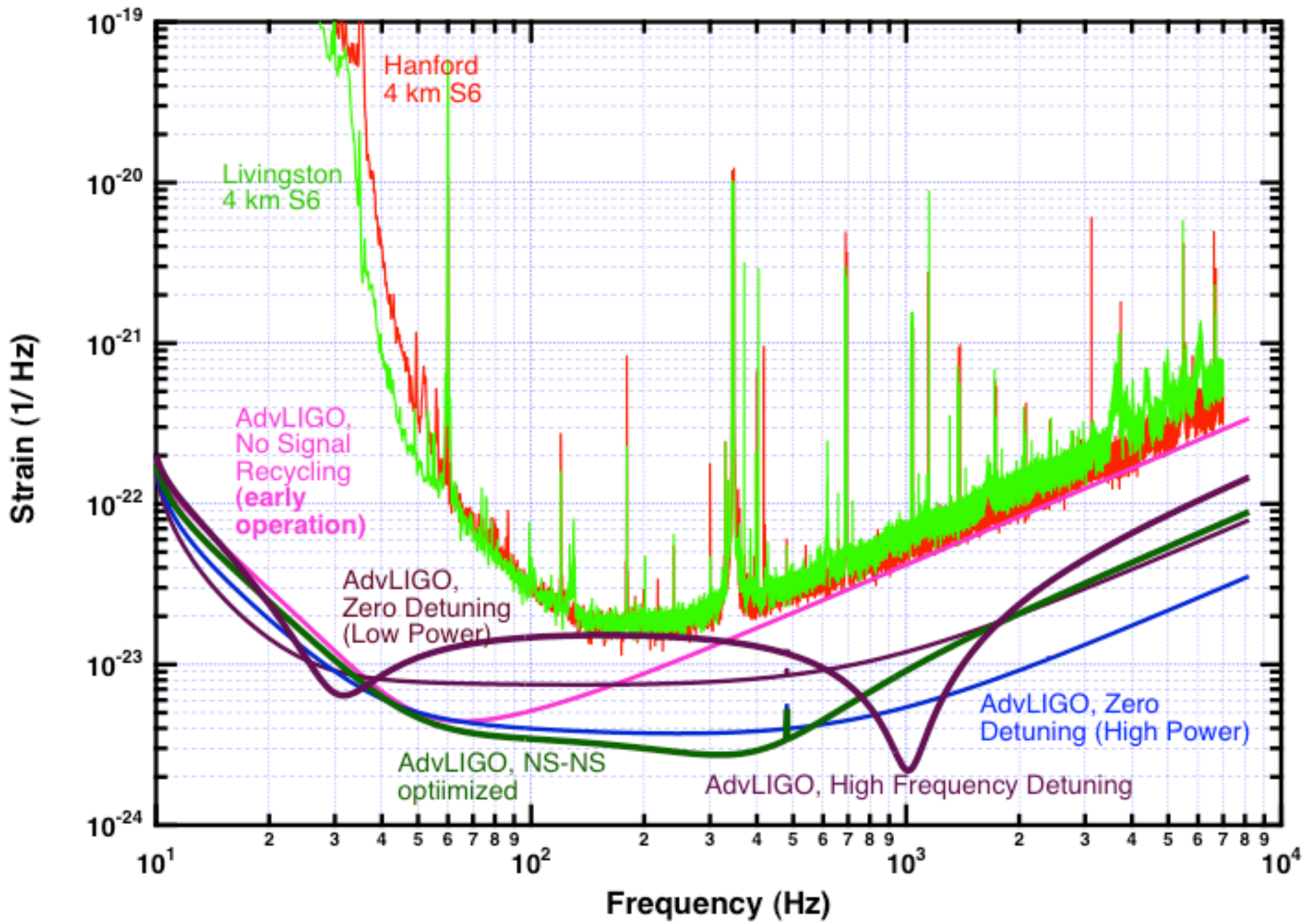
Advanced LIGO

h_{min} ~ 3 x 10^{-23} √Hz

Second generation detectors

- Advanced LIGO (at LIGO sites, US)
- Advanced Virgo (at Virgo site Italy)
- ‘かぐら’. Kagra (at Kamioka site in Japan)

advanced LIGO



Binary coalescences. From 1° to 2° generation

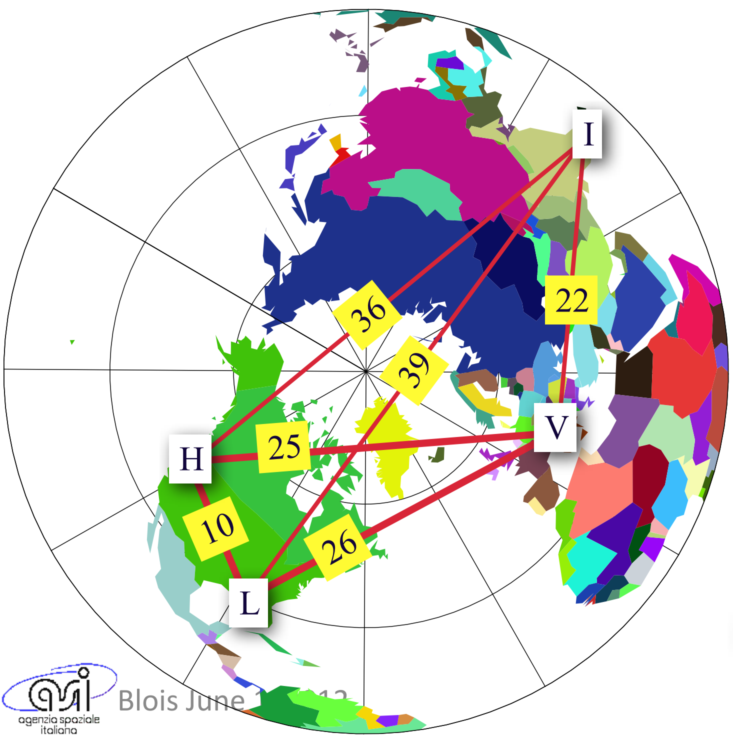
- This is the most likely signal. Target signal to noise ratio SNR>8

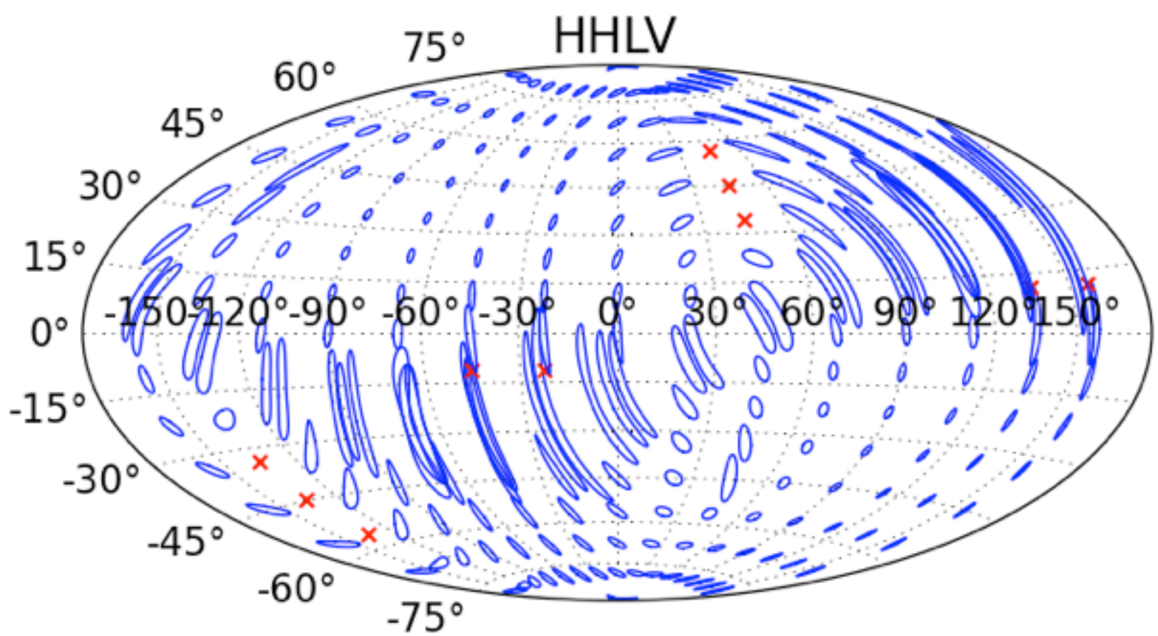
TABLE V: Detection rates for compact binary coalescence sources.

IFO	Source[a]	$\dot{N}_{\mathrm{low}}$ yr^{-1}	$\dot{N}_{\mathrm{re}}$ yr^{-1}	$\dot{N}_{\mathrm{high}}$ yr^{-1}	$\dot{N}_{\mathrm{max}}$ yr^{-1}
	NS-NS	2×10^{-4}	0.02	0.2	0.6
	NS-BH	7×10^{-5}	0.004	0.1	
Initial	BH-BH	2×10^{-4}	0.007	0.5	
	IMRI into IMBH			$< 0.001^{b}$	0.01^{c}
	IMBH-IMBH			$10^{-4\,d}$	$10^{-3\,e}$
	NS-NS	0.4	40	400	1000
	NS-BH	0.2	10	300	
Advanced	BH-BH	0.4	20	1000	
	IMRI into IMBH			10^{b}	300^{c}
	IMBH-IMBH			0.1^{d}	1^{e}

Advanced network

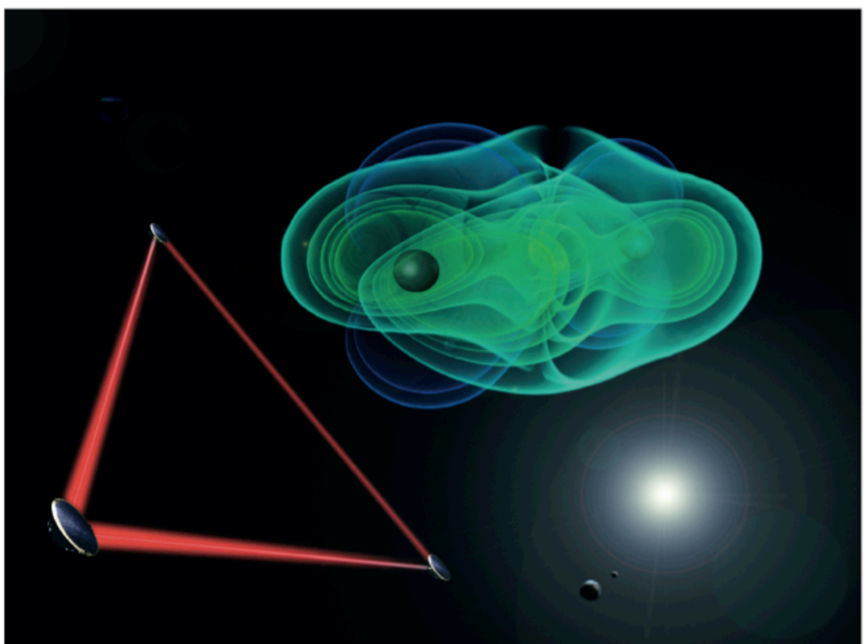
- Operational at design sensitivity ≈ 2017
- Network locates source in the sky
- Gravitational Astronomy will begin (population studies, test of merger dynamics etc.)
- 3° generation under study (Eistein Telescope, Kagra)



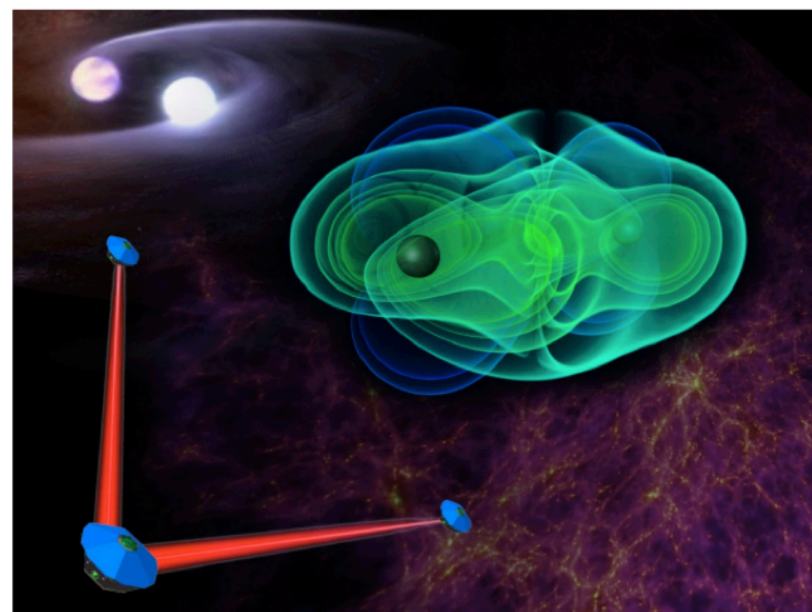


Space-borne observatories

- Two main designs
  - LISA three-arm interferometer studied by ESA and NASA up to formulation level (>10 years)
  - eLISA (NGO) two-arm interferometer. Studied by ESA as an ESA lead mission (simplification of LISA, studied one year)

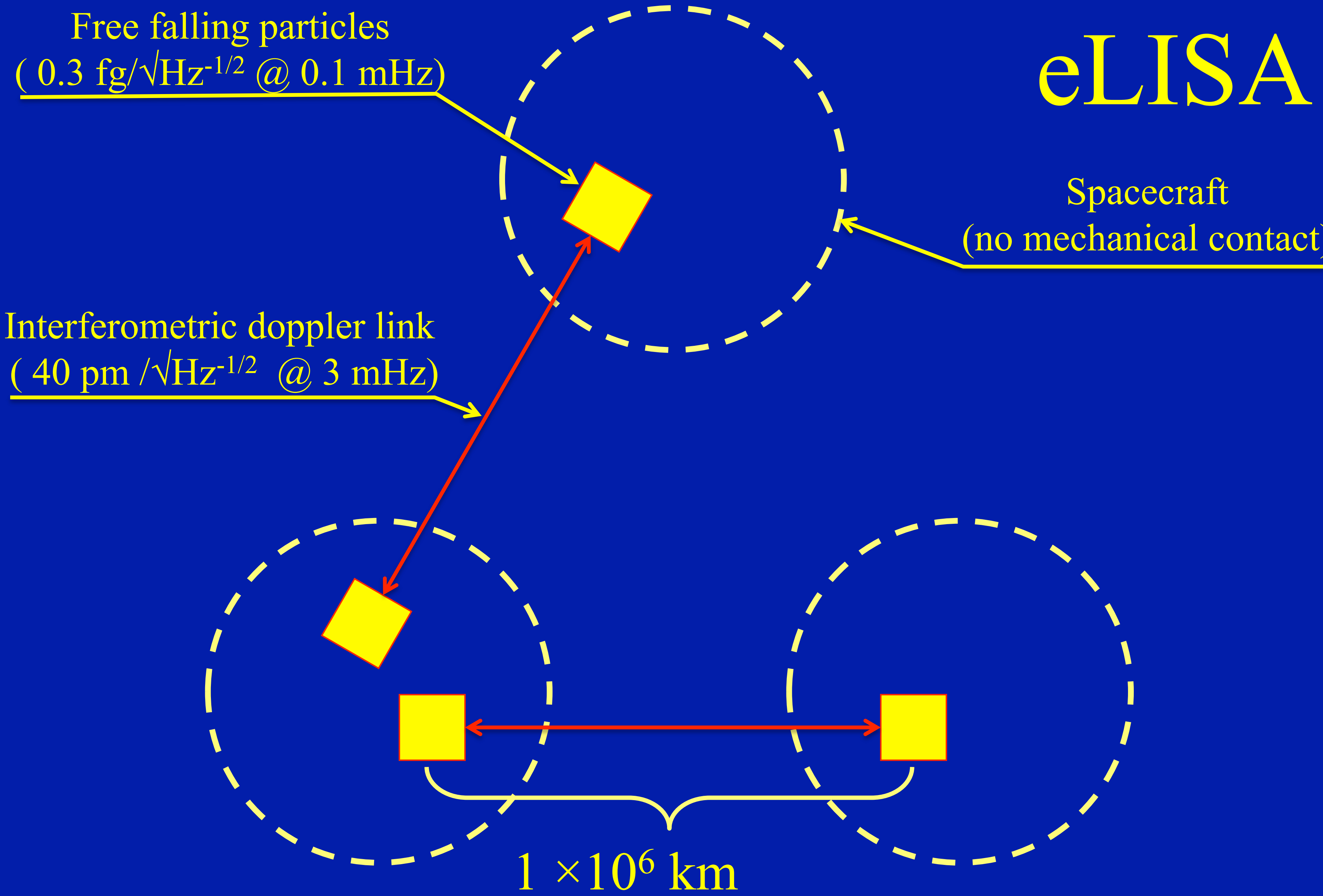


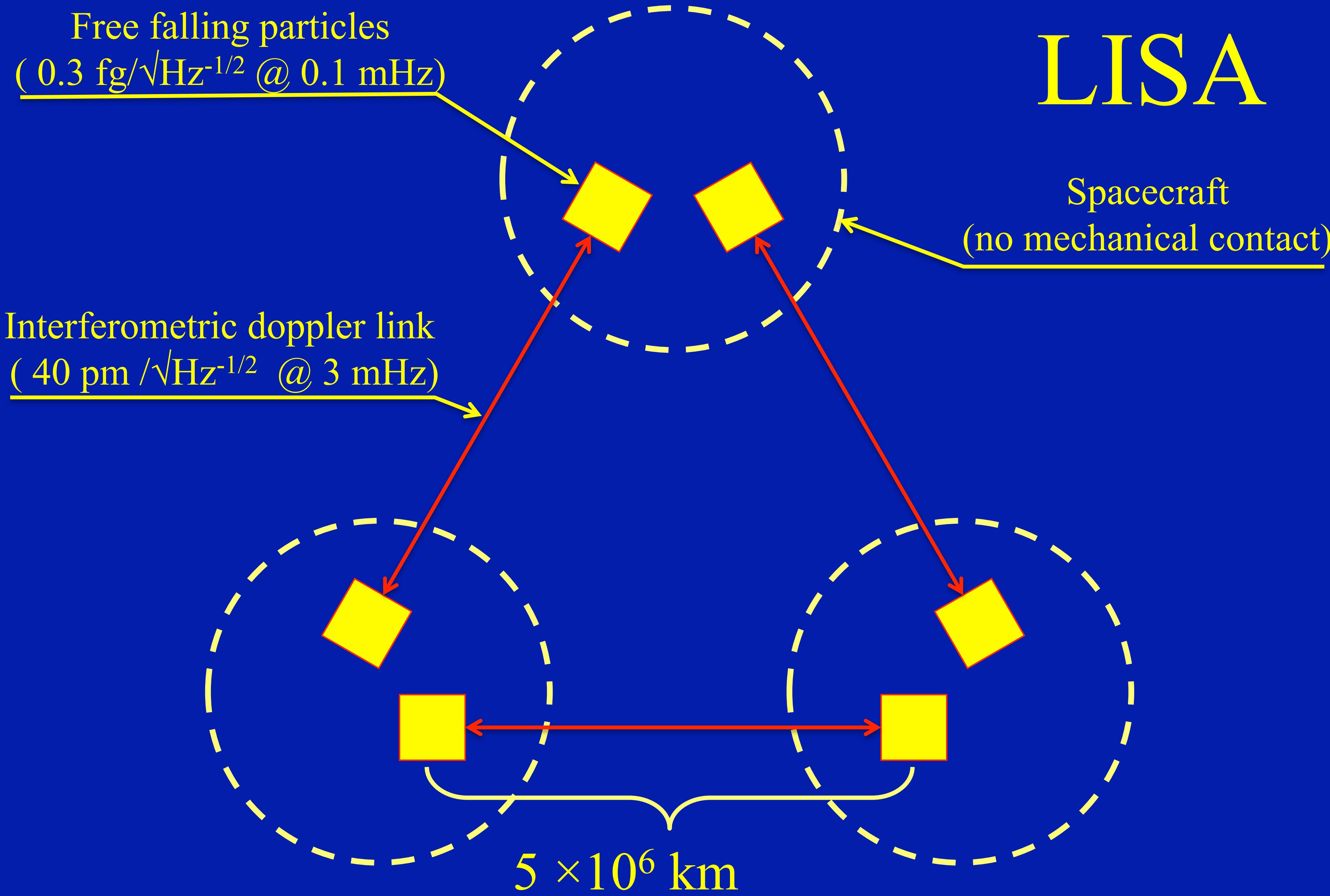
Assessment Study Report



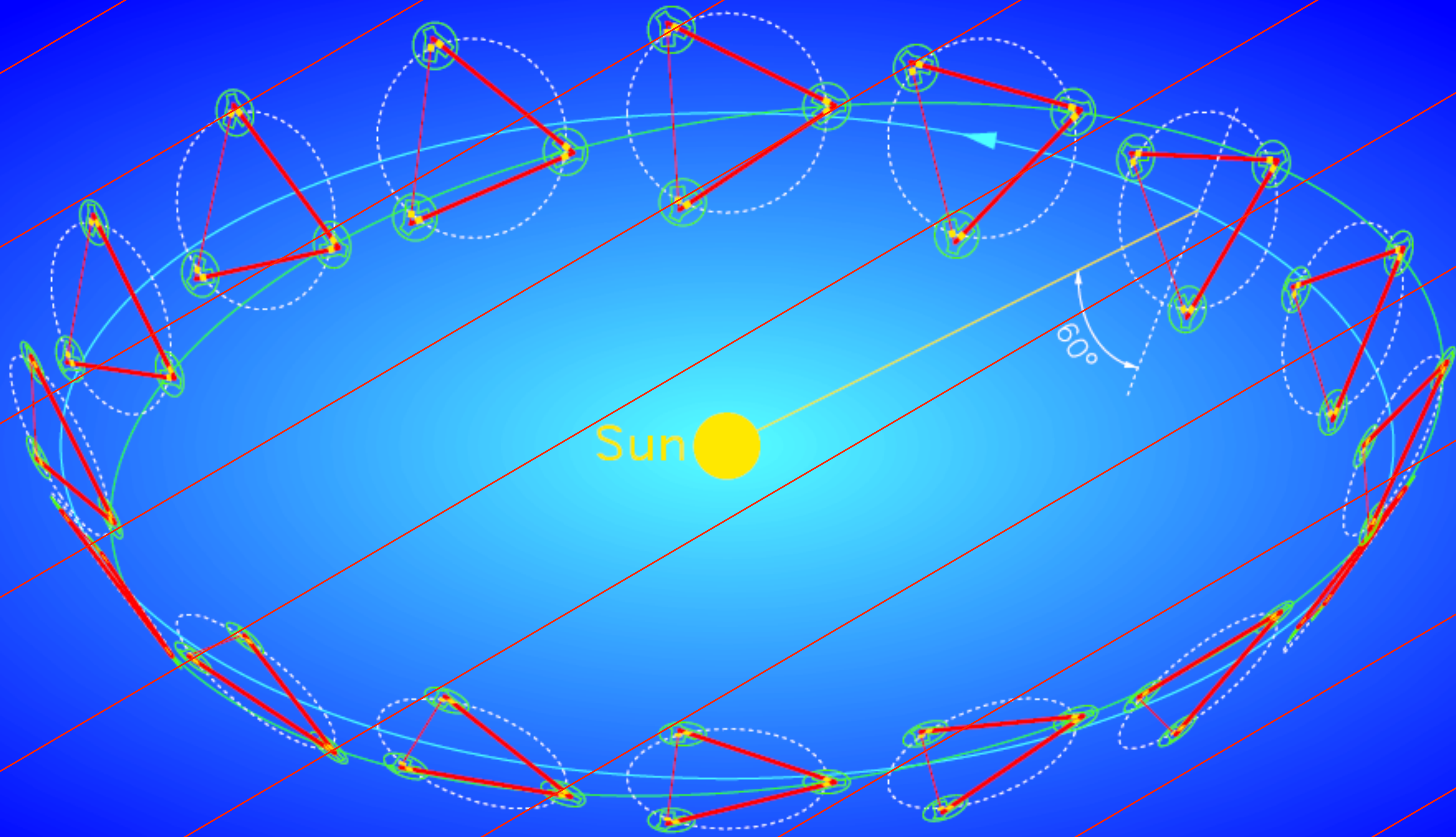
Assessment Study Report

eLISA


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

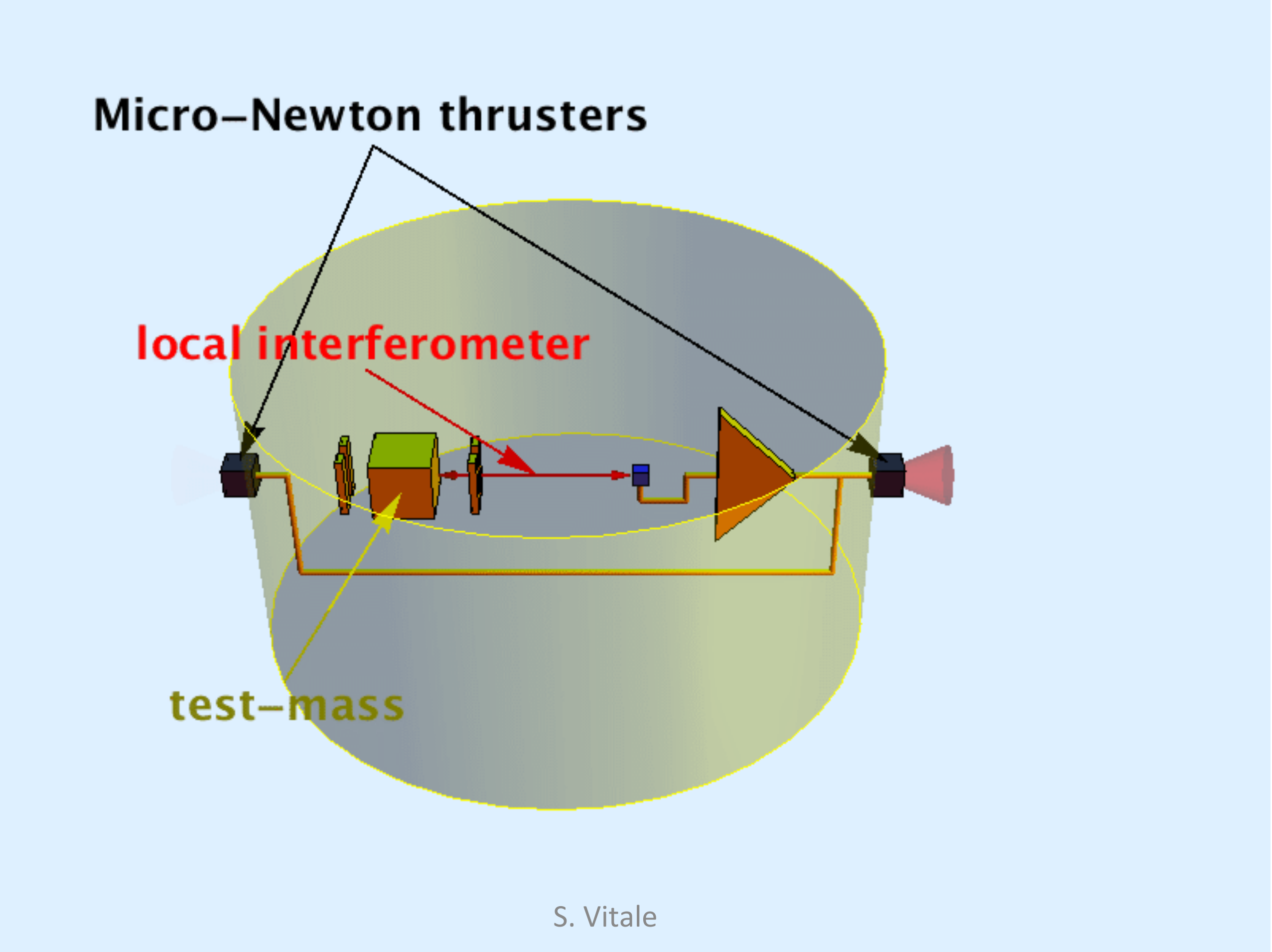

LISA
Free falling particles
(0.3 fg/√Hz-1/2 @ 0.1 mHz)
Spacecraft
(no mechanical contact)
Interferometric doppler link
(40 pm /√Hz-1/2 @ 3 mHz)
5 ×10⁶ km

Three independent heliocentric orbits: detector rotates within GW and gives source location

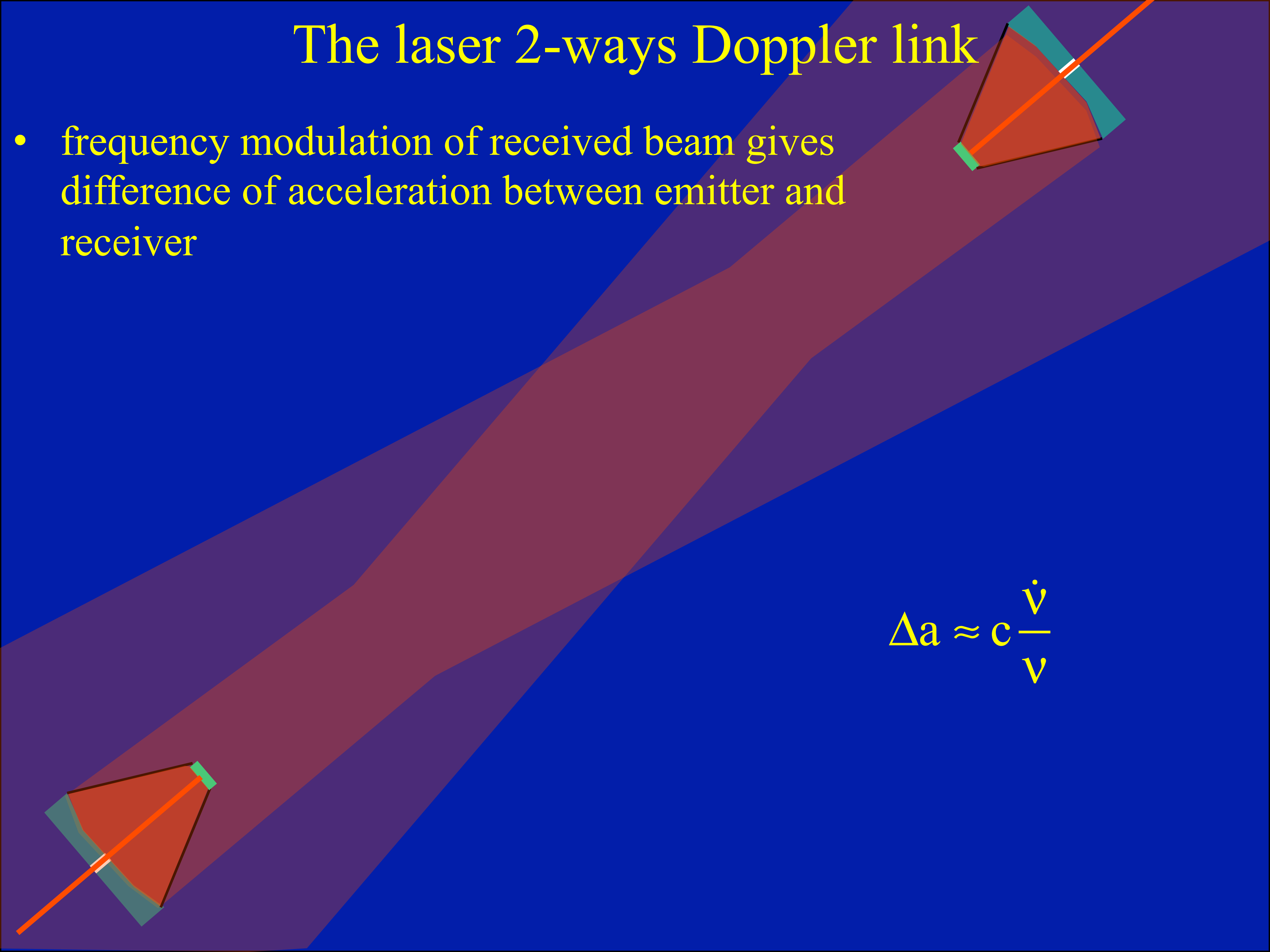


Non contacting spacecraft and no force on test-mass

- Position of spacecraft relative to test-mass is measured by local interferometer
- Spacecraft is kept centered on test-mass by acting on micro-Newton thrusters.



The laser 2-ways Doppler link

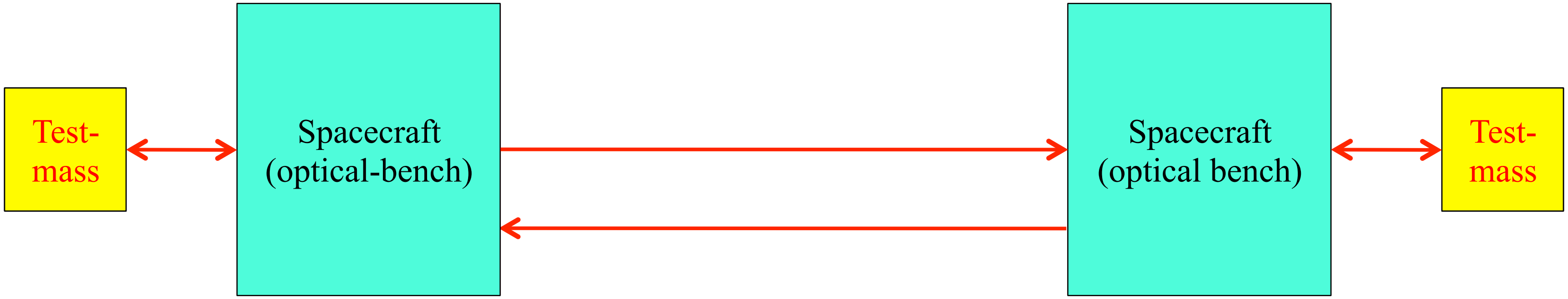


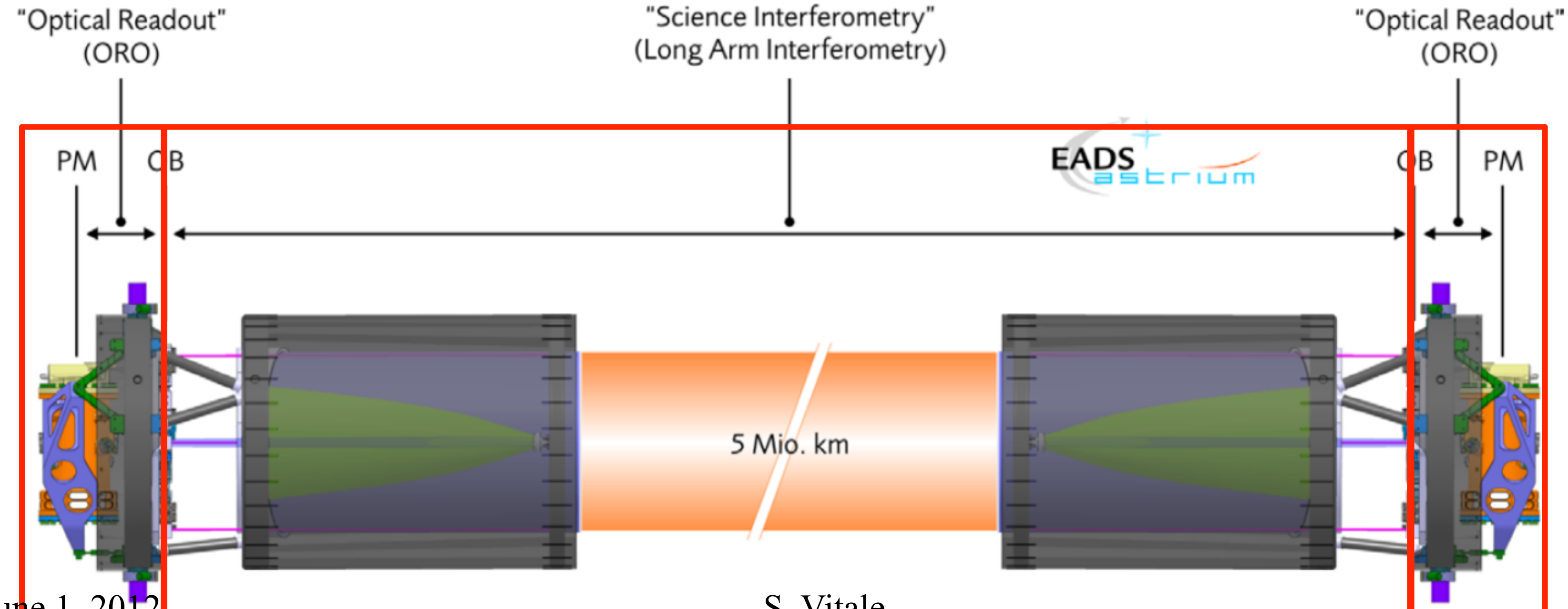
- frequency modulation of received beam gives difference of acceleration between emitter and receiver

$$\Delta a \approx c \frac{\dot{\nu}}{\nu}$$

The link is split in three

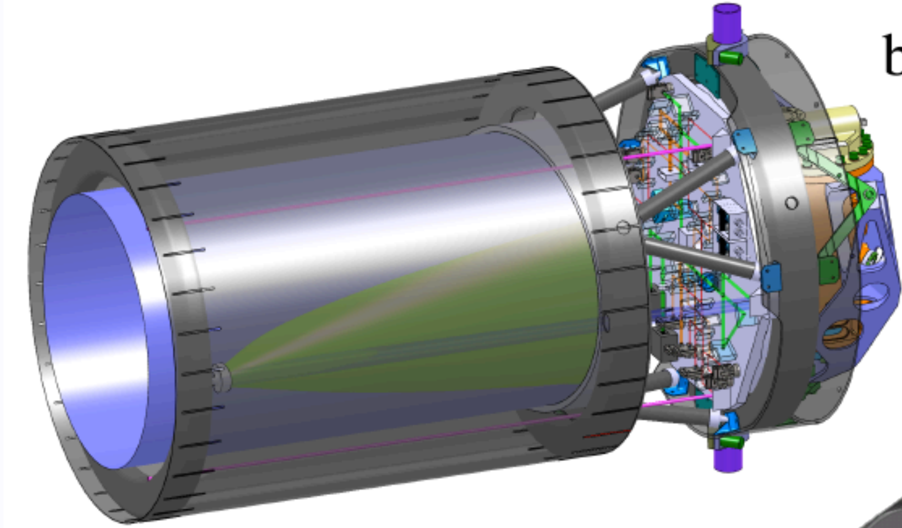
- 2×test-mass-to-spacecraft measurements
- 2×spacecraft-to-spacecraft one-way links

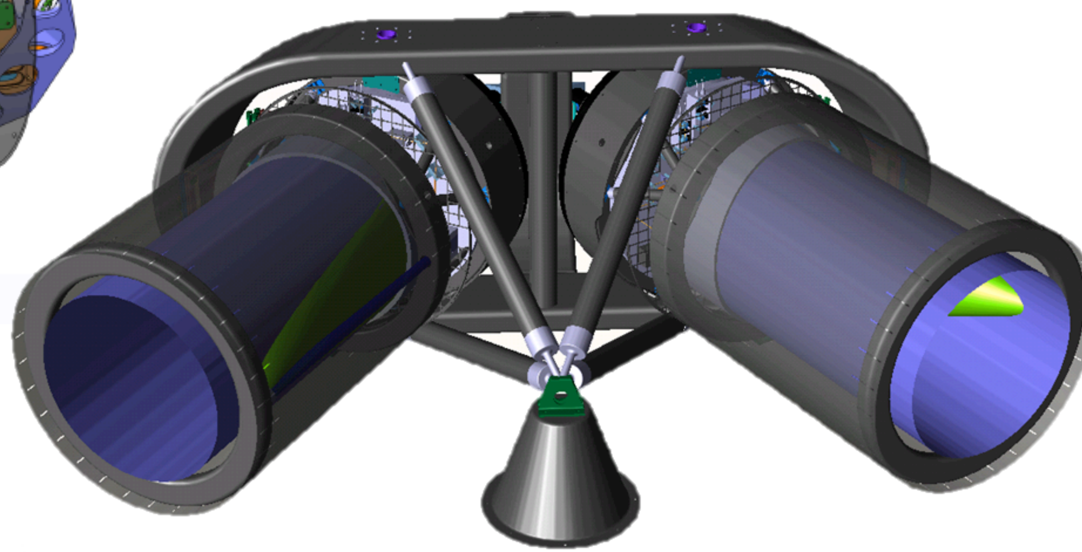


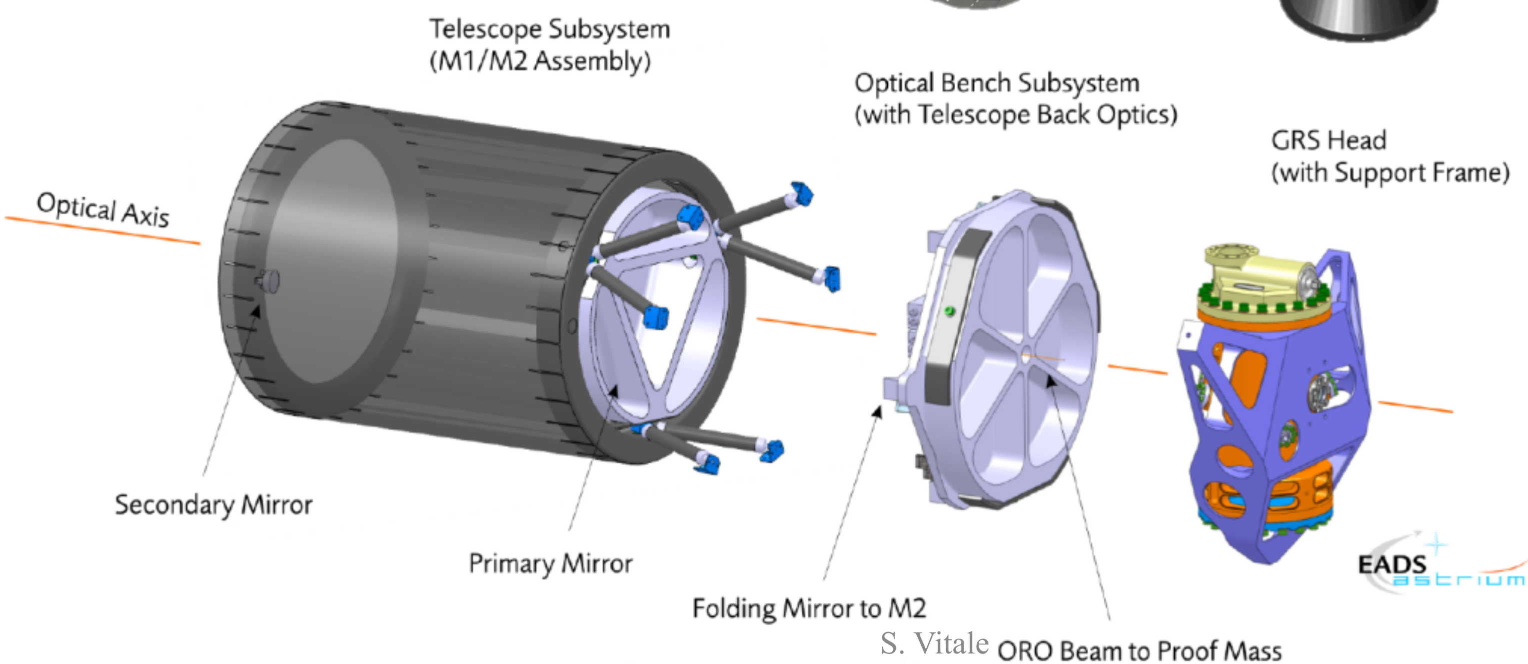


LISA Instrument

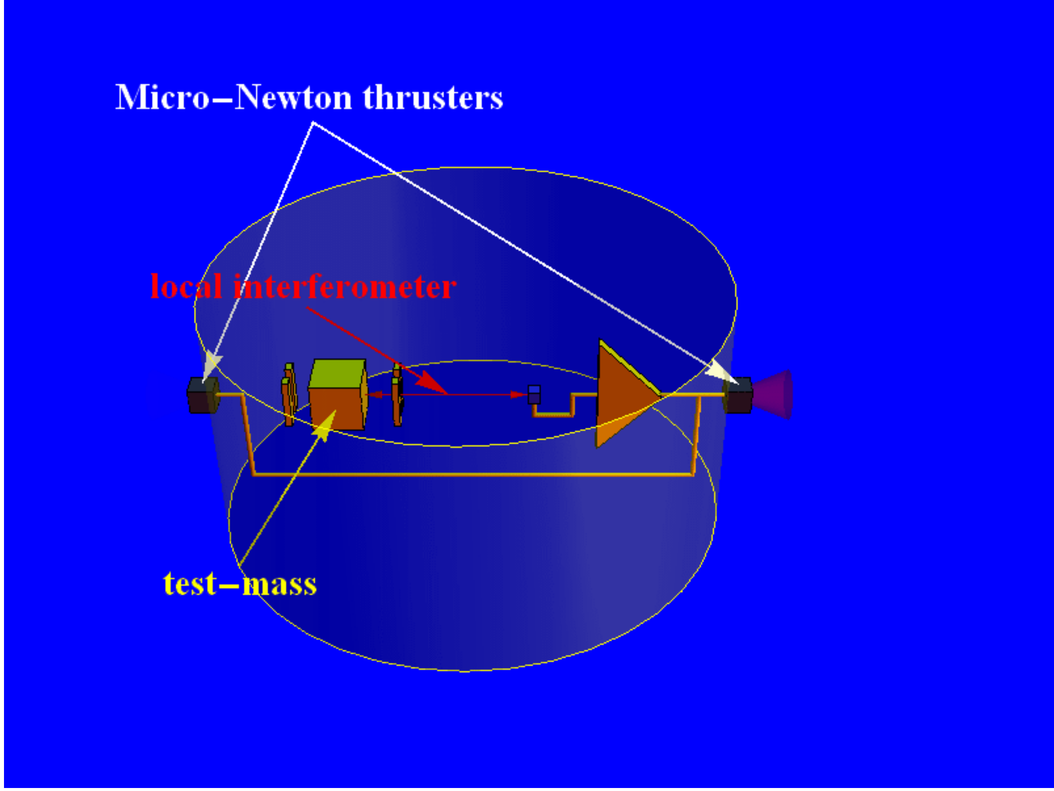
b

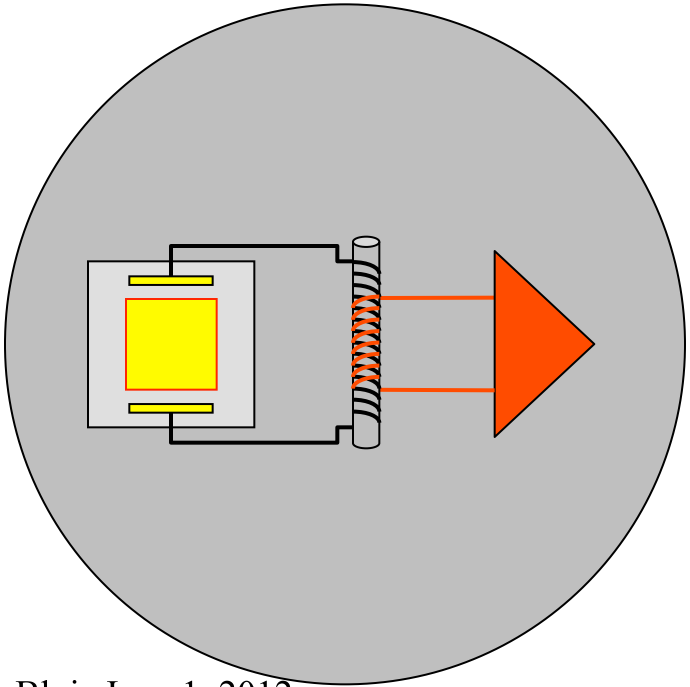


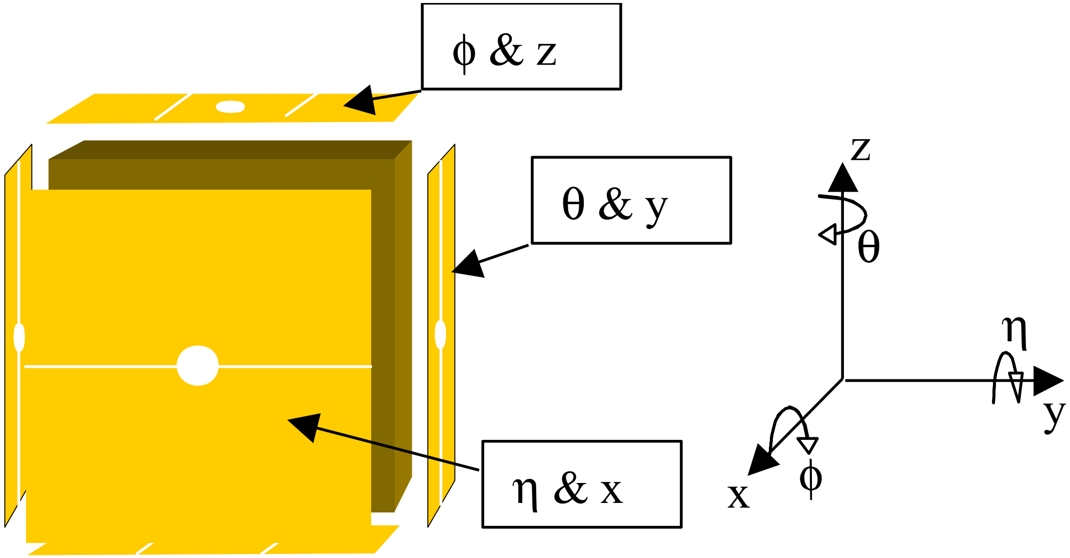




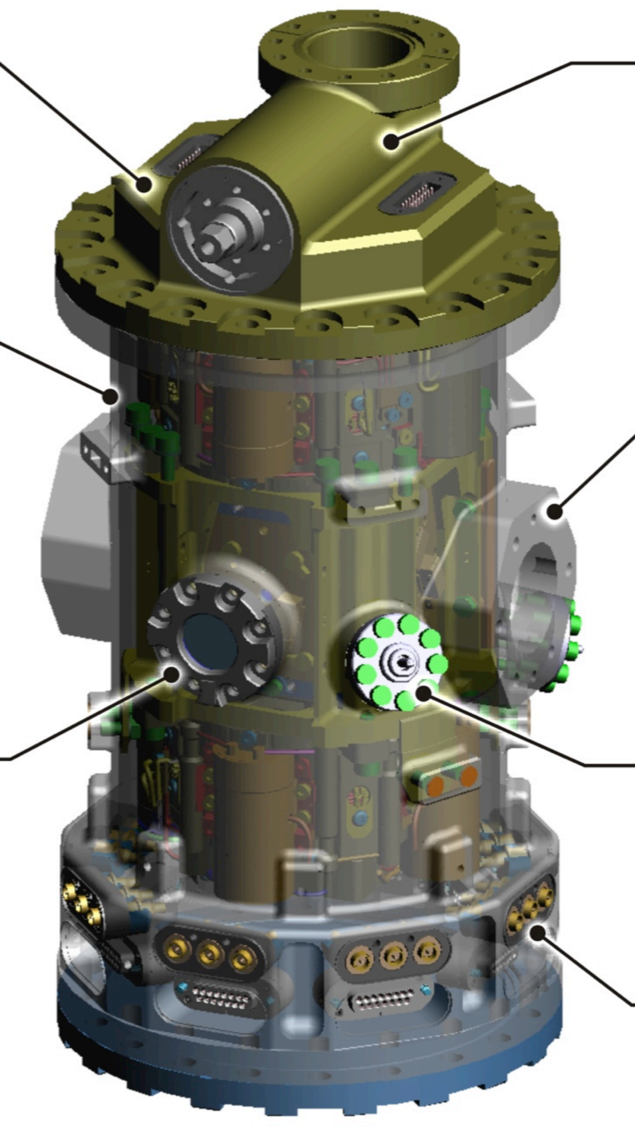
- Drag-free along sensitive direction
- Test-mass control along the remaining ones

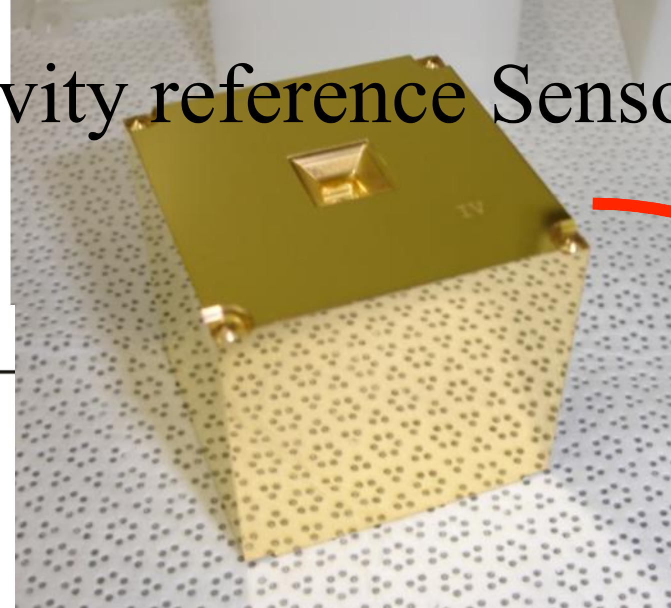


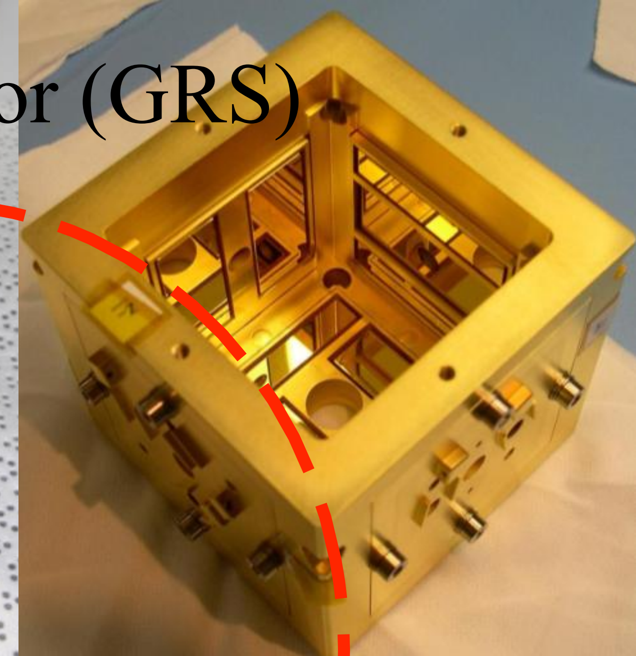


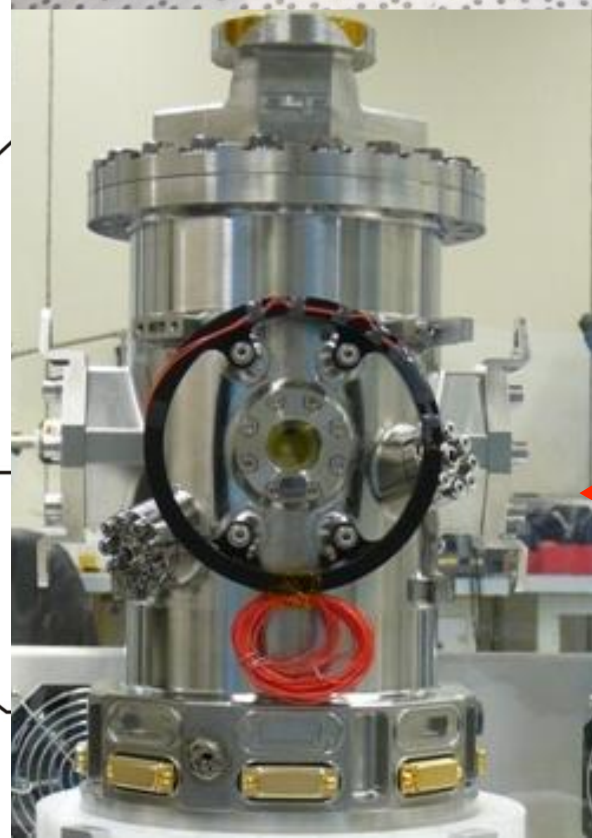


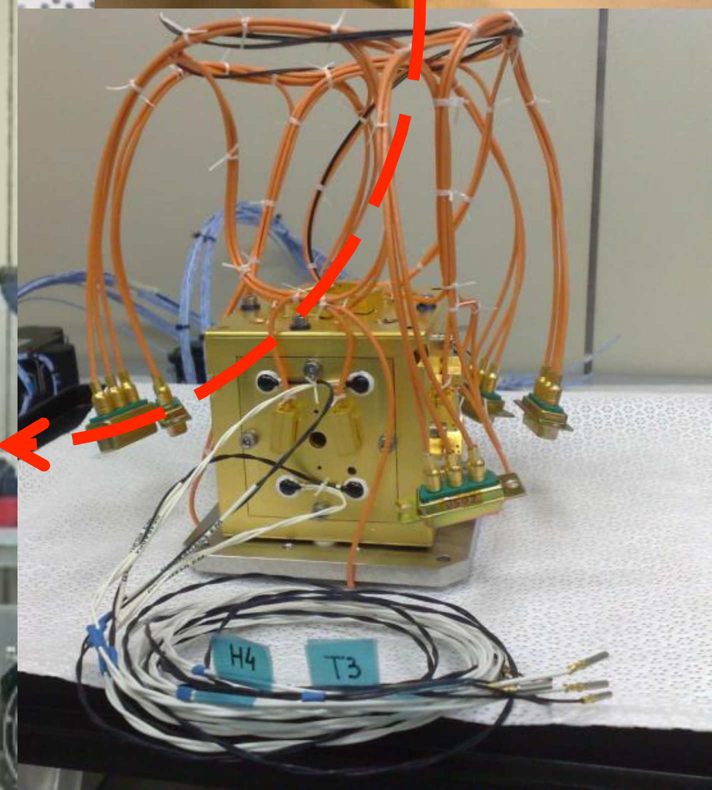
The Gravity reference Sensor (GRS)





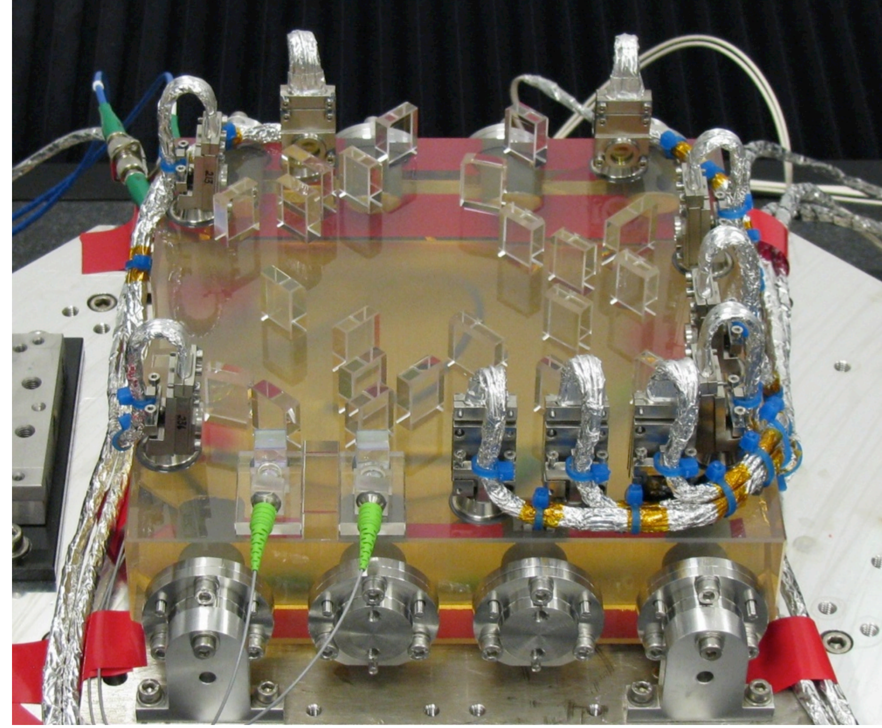


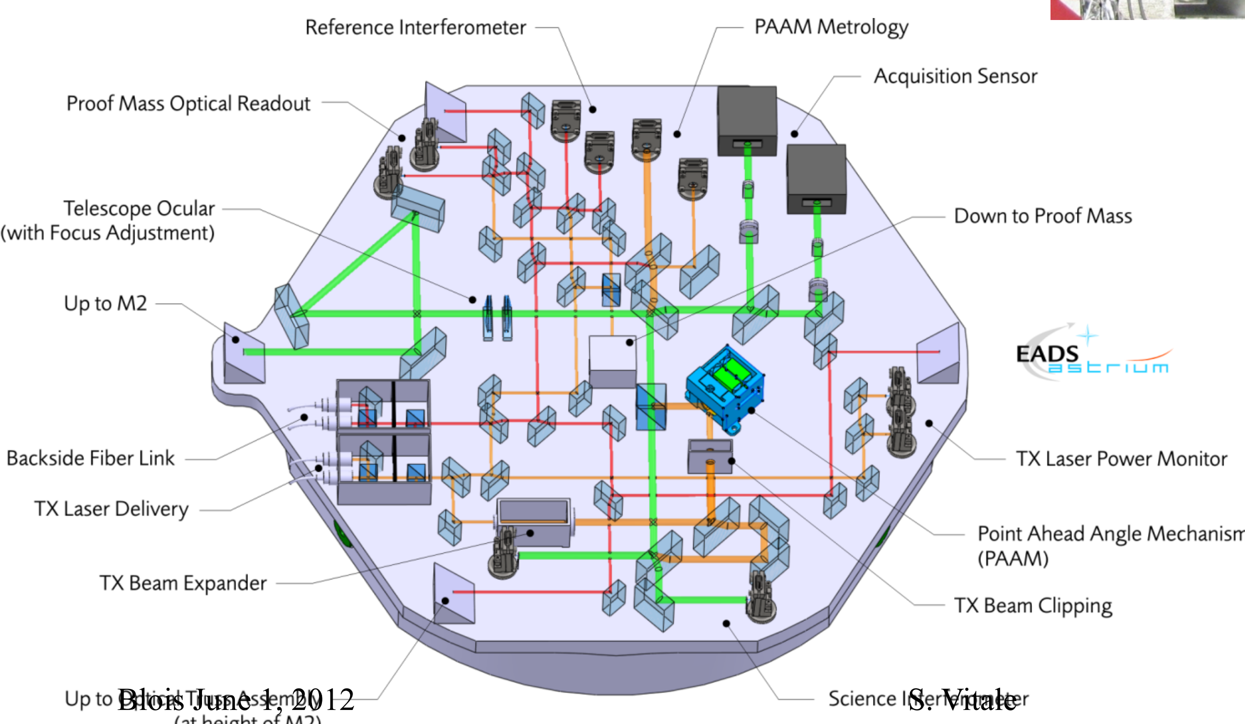




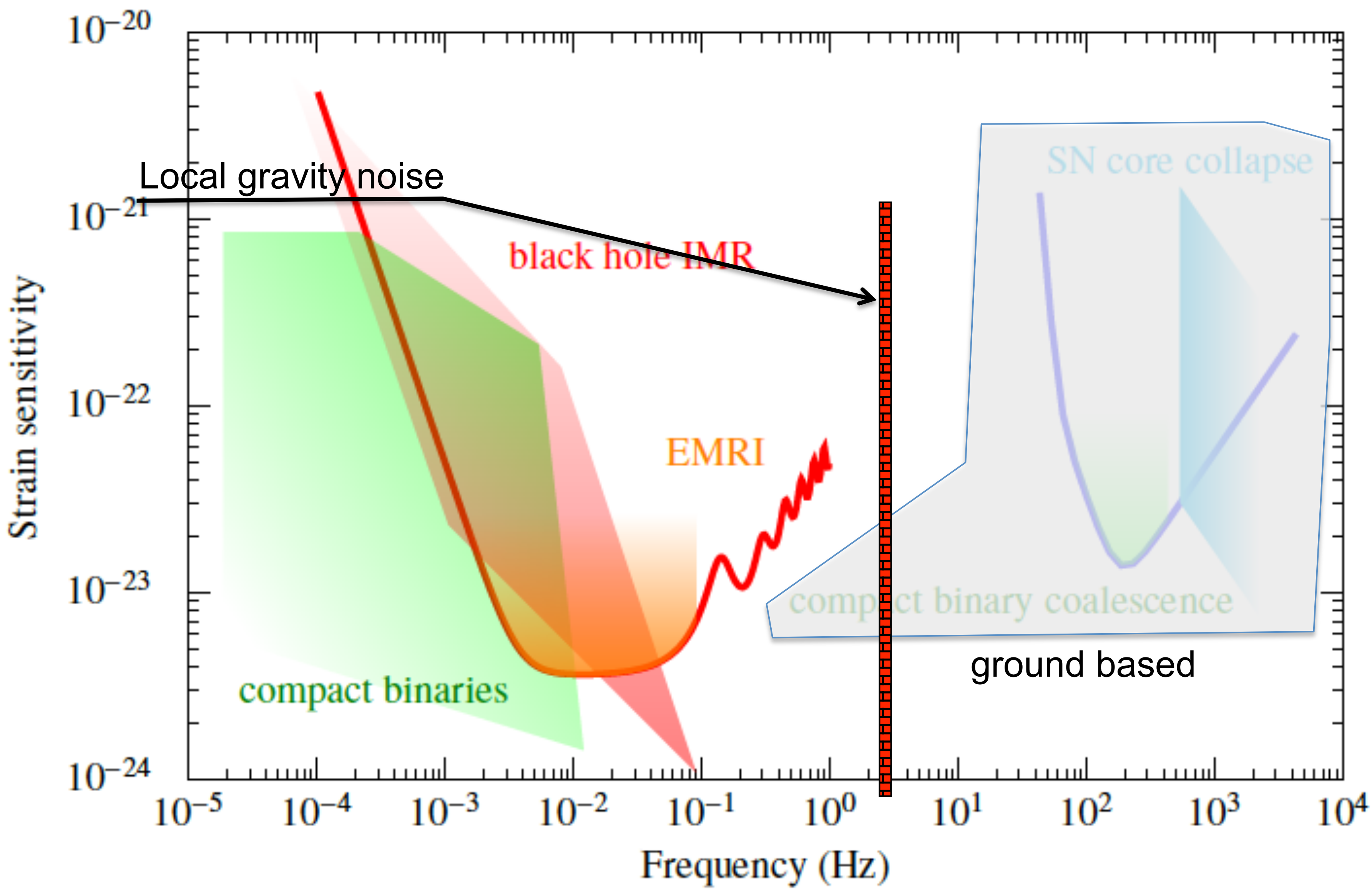
The optical bench

- Carries all needed interferometry
- Monolithic ultra high stable structure obtained by silica bonding





Science with space-borne GW detector

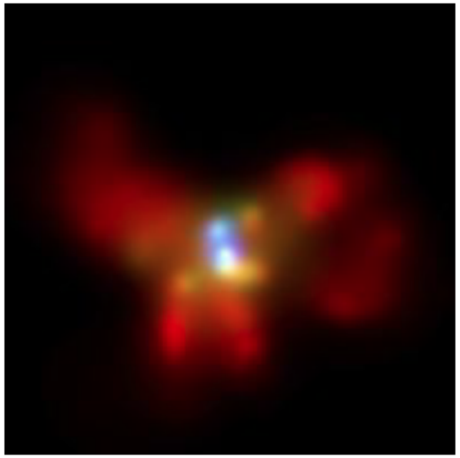


eLISA revolutionary science

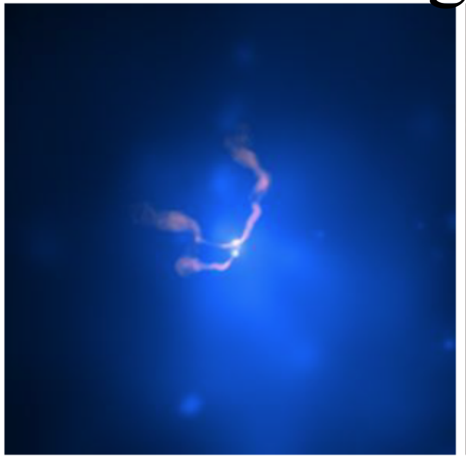
- **Massive BHs (10^5--10^7 M_o)**
  - Measurement of mass at z = 1 to ±0.1%, spin a/M to ±0.01.
  - Mass function, central cluster of black holes in ordinary galaxies to z = 0.5.
- **Evolution of the Cosmic Web at high redshift**
  - Observation of objects before re-ionisation: BH mergers at z >> 10.
  - Testing models of how massive BHs formed and evolved from seeds.
- **Compact WD binaries in the Galaxy**
  - Catalogue ~2000 new white-dwarf binary systems in the Galaxy.
  - Precise masses & distances for dozens of systems + all short-period NS-BHs.
- **Fundamental physics and testing GR**
  - Ultra-strong GR: Prove horizon exists; test no-hair theorem, cosmic censorship; search for scalar gravitational fields, other GR breakdowns.
  - Fundamental physics: look for cosmic GW background, test the order of the electroweak phase transition, search for cosmic strings.

Super-massive black-hole mergers

Arp 299

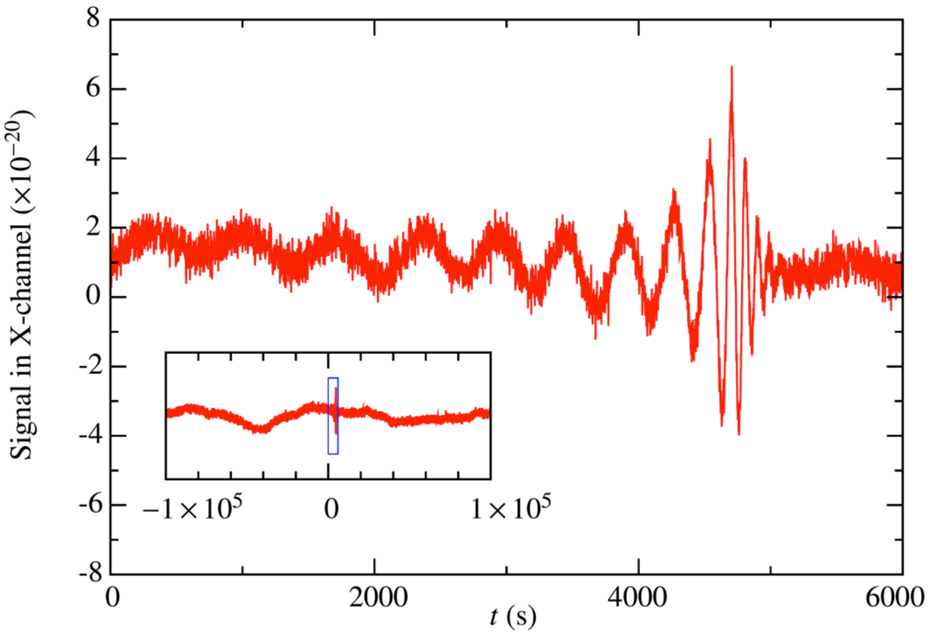


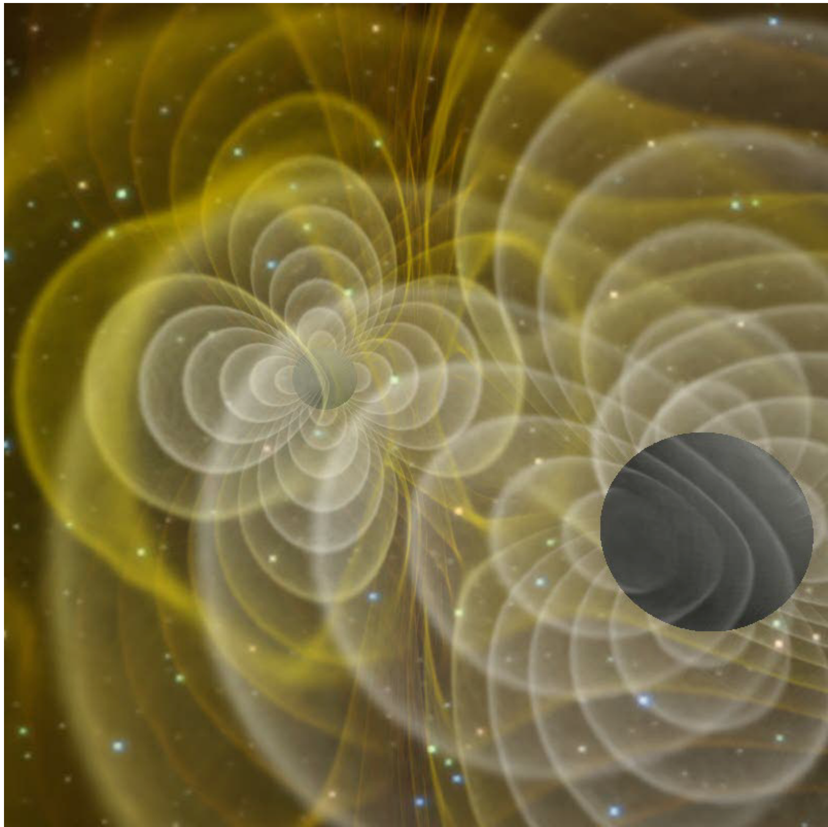
NGC6240



Abell 400

NGC 3393

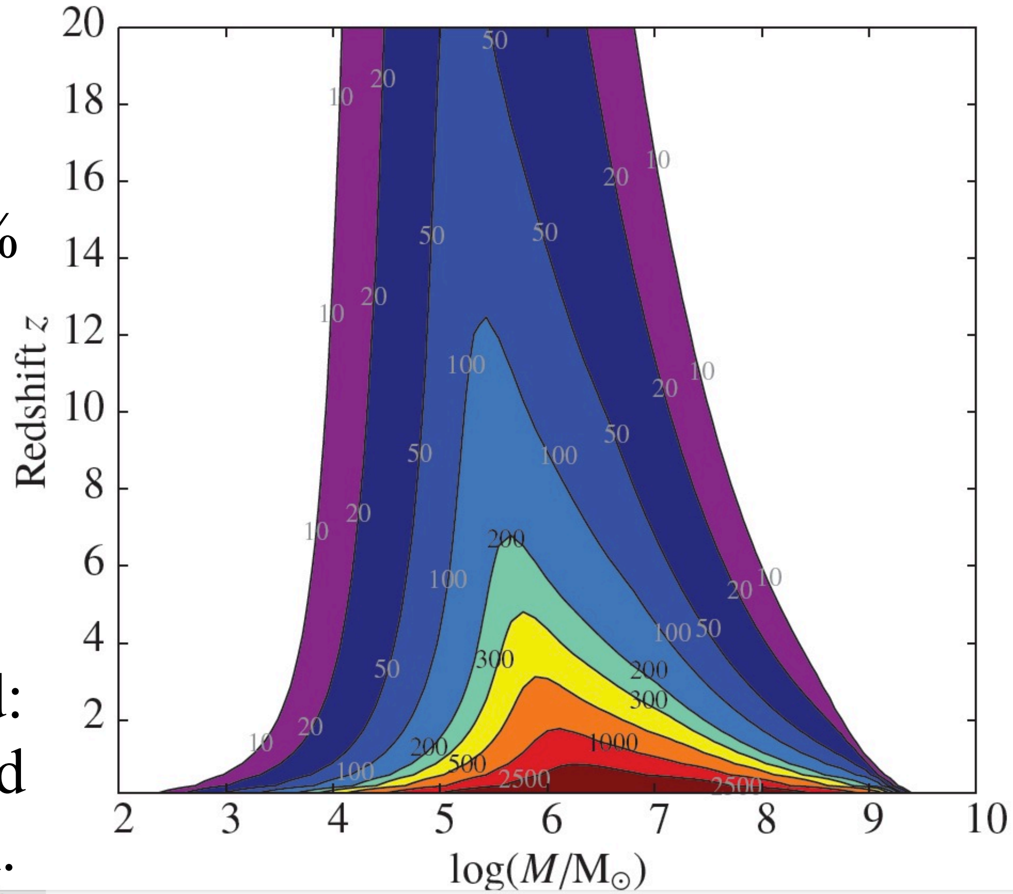




- High SNR to $z \approx 15$

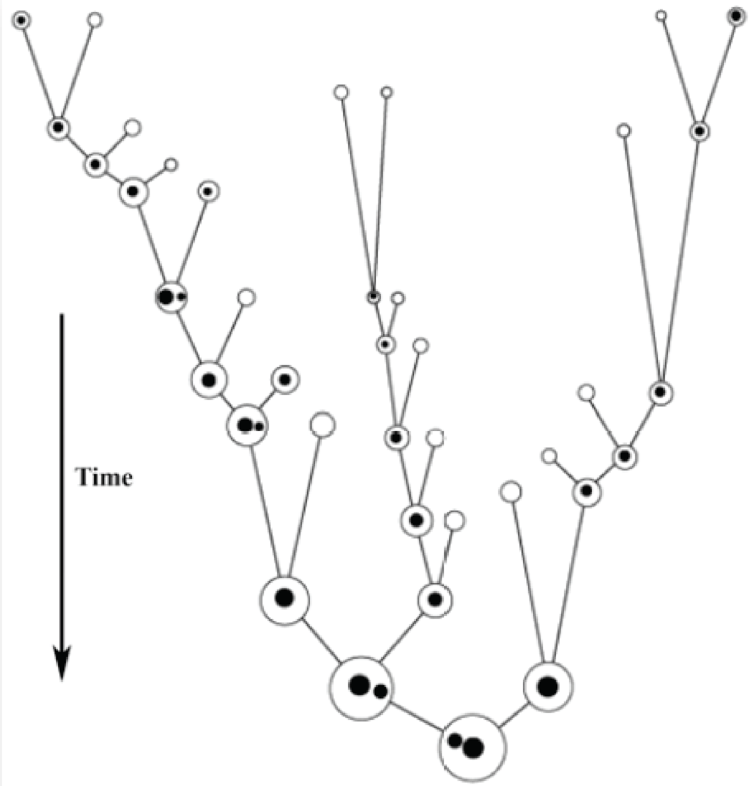
Observing the entire universe

- ELISA will detect ALL the mergers in the universe in its frequency band, even out to z=15 and beyond if they are happening.
- BBH rest mass $10^4 - 10^7$
- Luminosity distance 1 – 50 %
- Sky location 3° - 10 °
- Masses to ±0.5%
- Spin magnitudes to ±0.01.
- Spin alignments
- No complex modeling needed: these data are directly encoded in phase of inspiral waveform.



How did SMBHs form and grow? Are BH BH?

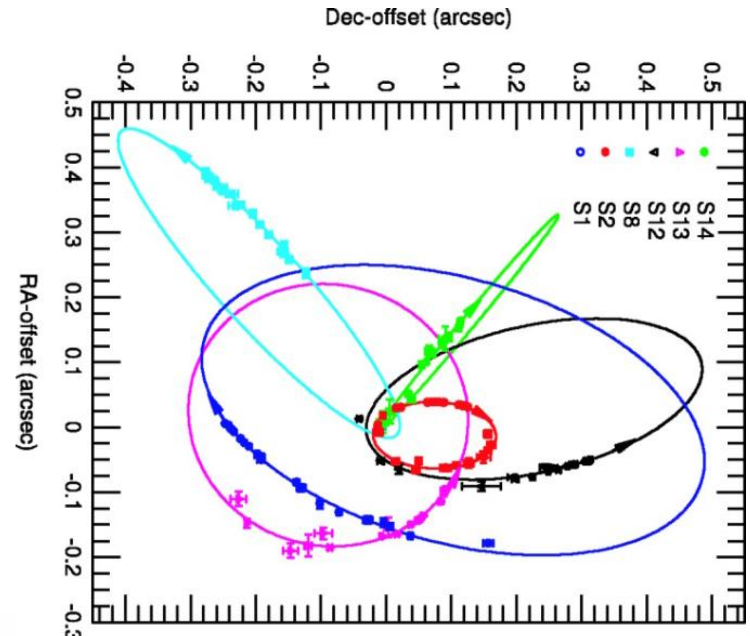
- eLISA should detect 10-200 BH-BH binary mergers in 2 years.
- enough mergers to discriminate among different seed models (early or late), accretion models, metallicities.
- Test GR in strong gravity at the edge of a black hole.
  - Compare merger in detail with numerical simulations in GR (and other theories).
  - Look for violations of cosmic censorship: still a conjecture in GR!
  - Look for evidence of other gravitational degrees of freedom; test energy and angular momentum balance (before and after).

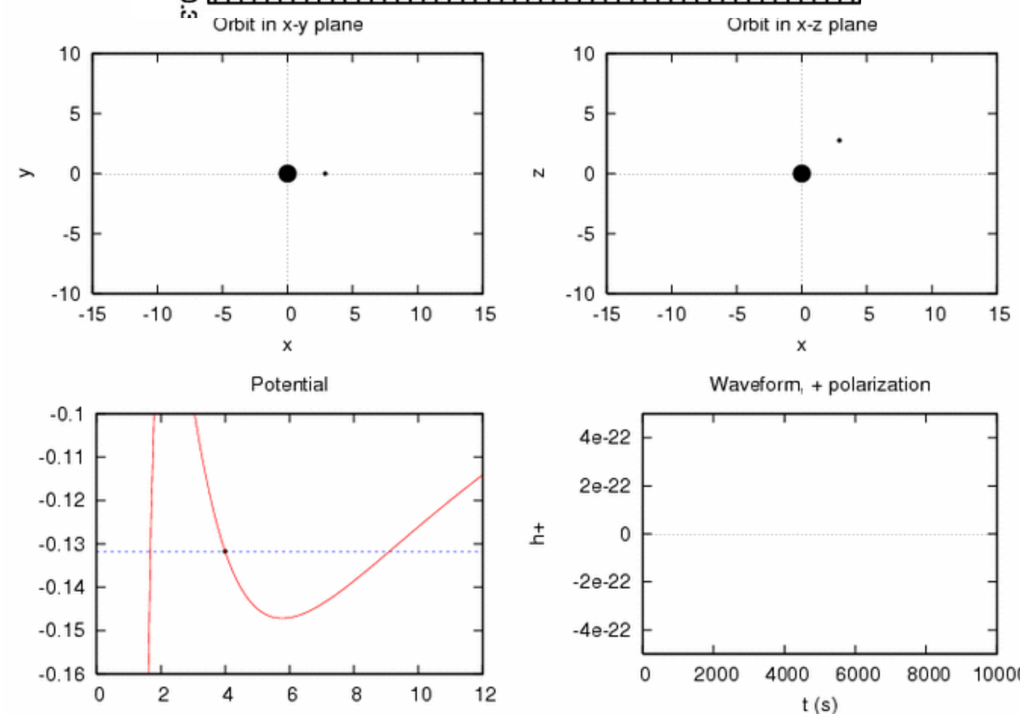


M. Volonteri: "Most if not all massive black holes are in the LISA band at some point in their cosmic evolution."

Extreme Mass-Ratio Inspirals: EMRIs

- Stellar-mass BH capture by a massive BH: dozens per year to z~0.7.
- We have measured the mass of the GC BH using a few stars and with at most 1 orbit each, still far from horizon.
- Imagine the accuracy when we have 10^5 orbits very close to horizon! GRACE/GOCE for massive BHs.
  - Prove horizon exists.
  - Test the no-hair theorem to 1%.
  - Measure masses of holes to 0.1%, spin of central BH to 0.001.
  - Population studies of central and cluster BHs.
  - Find IMBHs: captures of 10^3 M_o BHs.

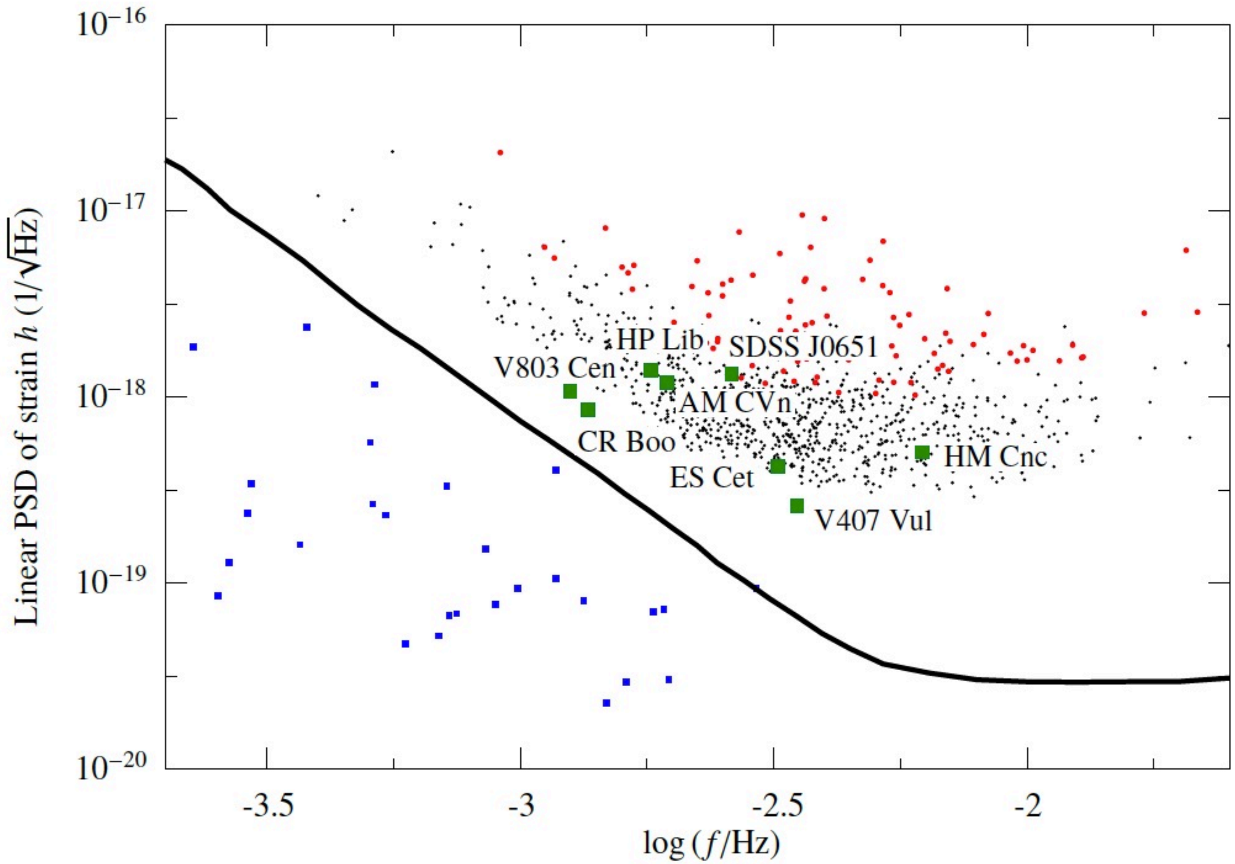




Compact binaries

- e-LISA will make major contributions to the study of binary evolution and the endpoint of stellar evolution.
    1. The mission has guaranteed (known) sources: verification binaries

Known binaries and strongest 1000 simulated binaries

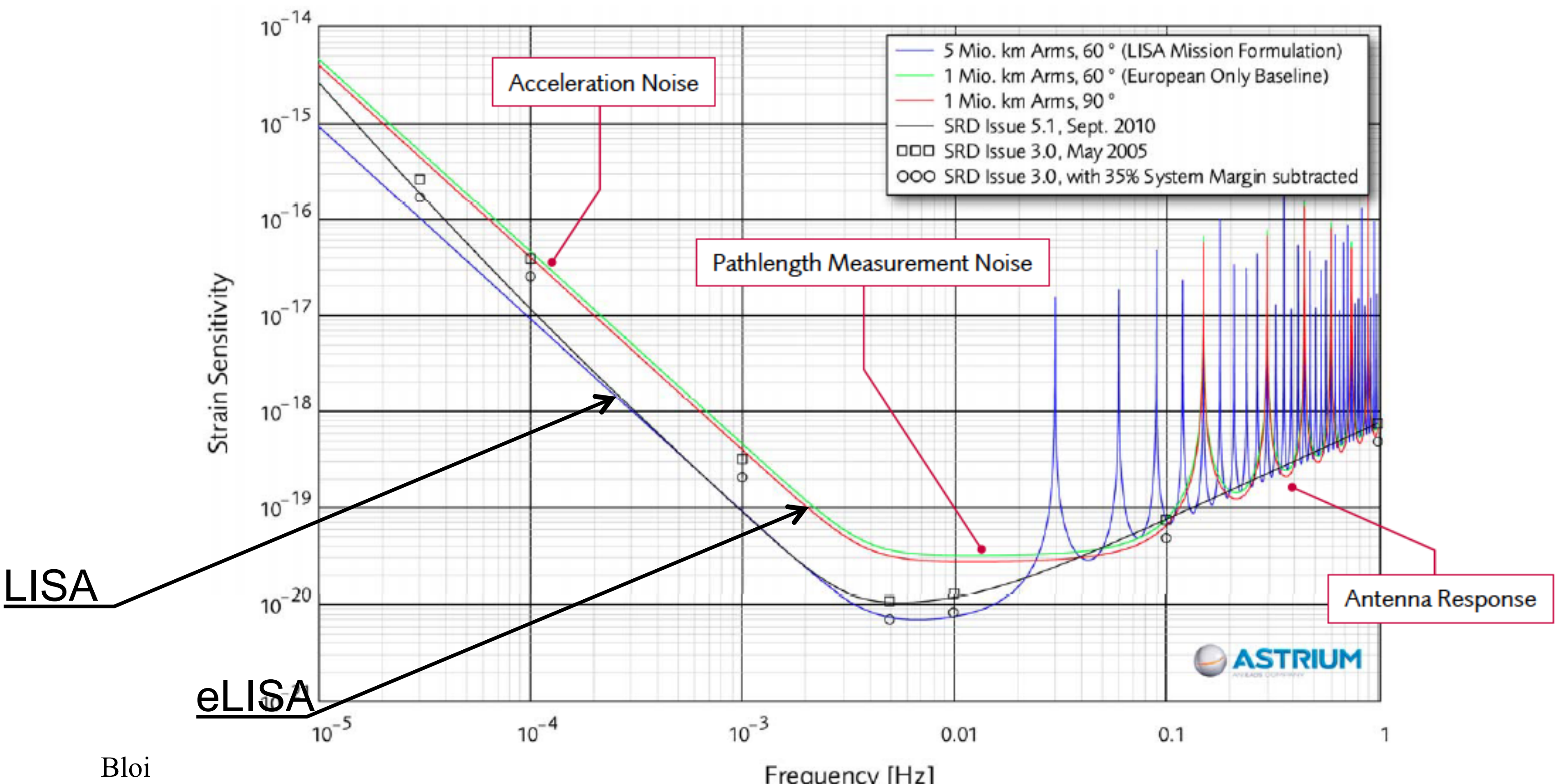


Compact binary astrophysics

- Synergy with GAIA, upcoming large-area surveys, radio pulsar binary surveys
- eLISA supplies unique new information:
  - Orbital inclination (helps determine masses)
  - Accurate distance (for known masses, or for chirping systems)
  - Discovery of distant/obscured/faint binaries.
- These observations address key astrophysics issues, e.g.:
  - Binary evolution, common envelope evolution
  - Precursors of Type Ia supernovae in the Galaxy
  - Population studies of Galaxy, tracers of star formation
  - Interacting binaries, mass transfer, tides
  - Population studies of NS-NS, NS-BH, BH-BH binaries

LISA: reaching even further

- LISA: better low frequency sensitivity (5 million km)
- Third arm:
  - polarisation of short-lived events.
  - Instrument noise in-situ calibration



eLISA→LISA (gross picture)

- Galactic binaries:
  - resolvable binaries 3000→10000
  - verification binaries 8→20
  - sky location 10°→1°
  - With electromagnetic counterpart: distance to 10% location to 0.1 °
  - Spectral properties of galactic foreground
- BH binaries
  - number 20-200 → 50-5000
  - z 15→20
  - Location ≈1°
  - Distance: see *Cosmology*
- EMRI
  - number 10→50
  - SNR 20→30
- Detection of stochastic background
  - Detection based on noise modeling → *detection in Sagnac Mode*

LISA gives absolute distances

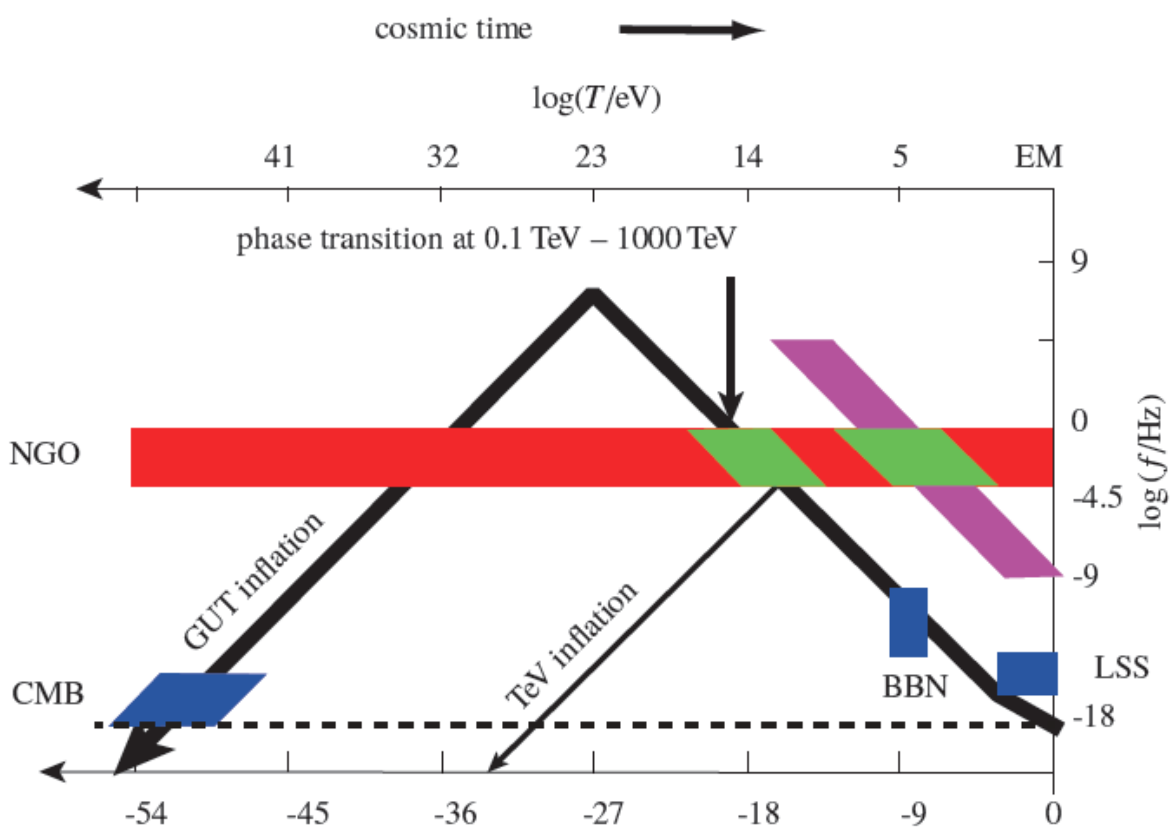
- GW are standard sirens: absolute luminosity distances to chirping binary systems can be derived *directly* from:

$$D_L = \text{Luminosity Distance} \propto \underbrace{c\,\text{Period}\,\frac{\text{dPeriod}}{\text{dt}}}_{\propto \text{Absolute amplitude}} \frac{1}{\text{Amplitude}}$$

- Distances D_L given in light-seconds: no calibration needed
- Accuracy better than 5% at z=3, limited by micro-lensing
- Requires approximate location of source to de-correlate source and antenna patterns.
- Third LISA arm gives all also for short lived events like coalescences and provides accurate and independent measurements of H_0 and equation of state parameter w.
- Using EMRIs, LISA can determine H_0 to ±0.4%, i.e. ±0.3 km s^{-1} Mpc^{-1} in 3 months.
- Using massive mergers out to z = 3 and fit to EM observation gives w to 2-4 %

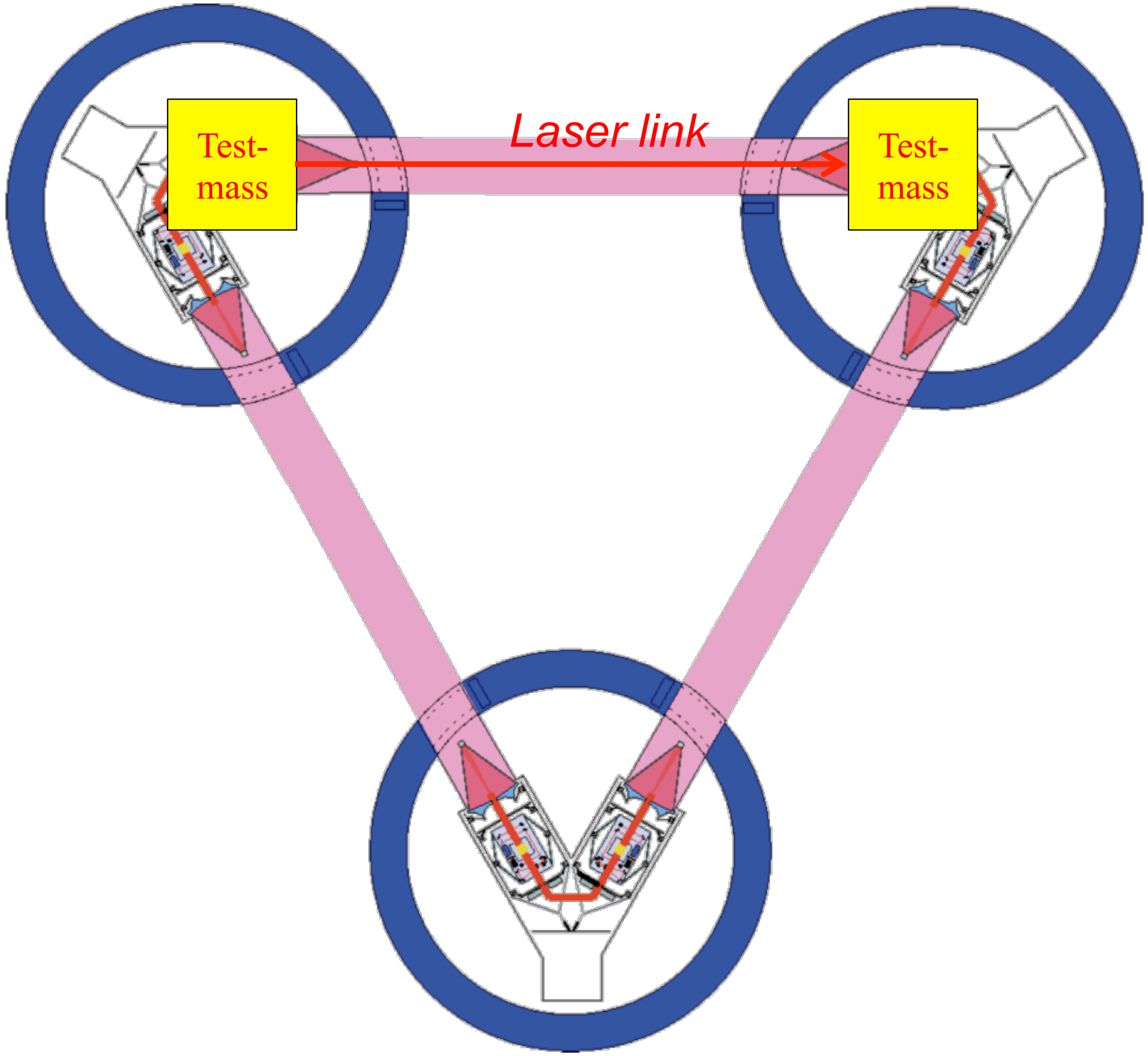
GW from 10^{-18} to 10^{-10} s after Big Bang

- Relic stochastic background of GW predicted in various scenarios, cosmic strings, phase transition.
- Waves in the eLISA/LISA band originates from phenomena between 10^{-18} to 10^{-10} s after big bang, i.e. 0.1-1000 TeV scale
- LISA can turn-off sensitivity to GW (Sagnac interferometer mode) and calibrate background instrument noise



Status of hardware development:LISA Pathfinder

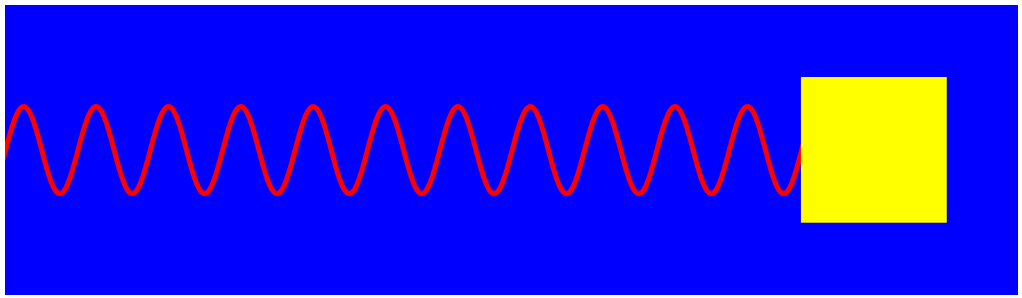
- ESA's demonstrator of measurement scheme
- A verification of eLISA/LISA flight hardware
- Launch in 2014



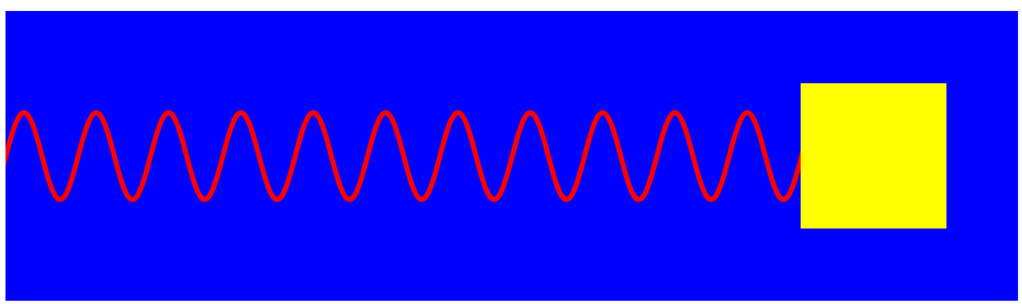
The Basic Element of one LISA Arm:
the Test-mass to Test-mass Doppler Link

Noise in the Doppler Link: 1 force noise

- Tidal acceleration due to GW cause modulate frequency of received beam



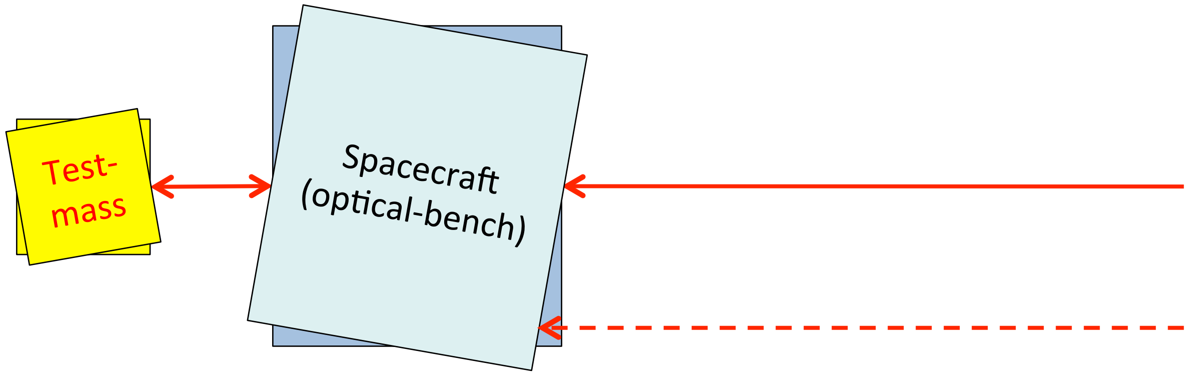
- True forces accelerates test-mass relative to inertial frame. Accelerated observer will detect frequency modulation even in the absence of waves: a local source of disturbance



- *Force noise* 100% of noise <1 mHz. Can be tested in 0-g only

Noise in the Doppler link: reference frame and interferometer noise

- *Reference frame noise*: misaligned measurements causes link to pick-up large motion of spacecraft relative to test-masses.
- A local source of disturbance: 30% of noise >10 mHz. Can be tested in 0-g only



- Interferometer *readout noise* (testable in 1 g) results from:
  – local contributions (65% of noise>10 mHz): electronics, photodiodes etc..
  – non-local contribution : laser frequency noise. Suppressed by differentiating two arms *à la* Michelson. (5 % of noise >10 mHz, after suppression)

Noise in the Doppler link: 3. Readout noise

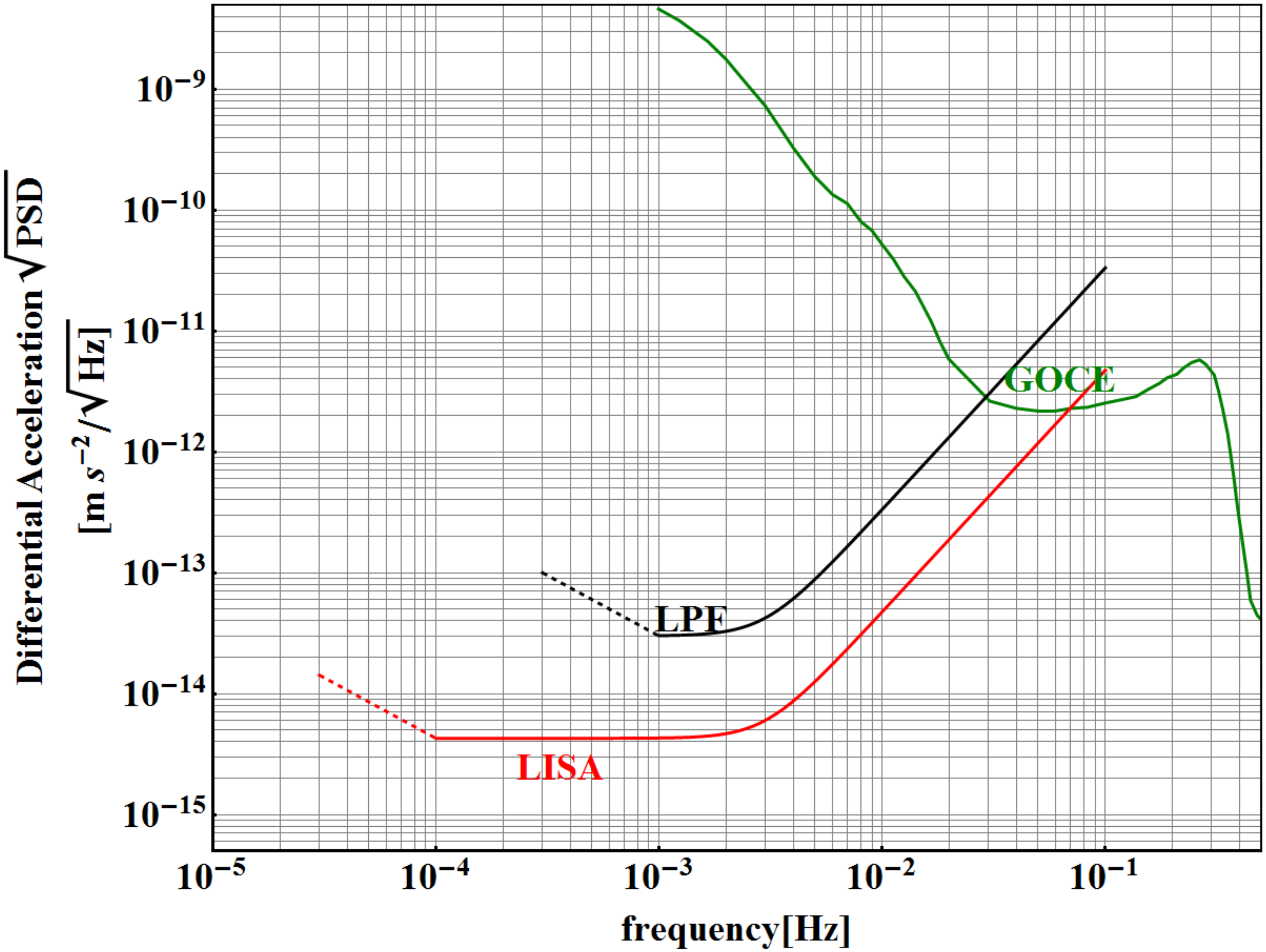
- Interferometer *readout noise* results from:
  - local (spacecraft level) contributions:
    - electronics, photodiodes etc..
    - 65% of noise>10 mHz
  - non-local contribution (constellation level):
    - laser frequency noise, indistinguishable from frequency modulation
    - Suppressed by differentiating two arms *à la* Michelson.
    - (5 % of noise >10 mHz, after suppression)
- All of interferometer noise is testable in 1 g

The aim of LISA Pathfinder

- A test of the entire local measurement
  - Force noise
  - Reference frame noise
  - Local interferometer noise
- Deliverable: the physical model for test-mass geodesic motion
  - Show forces and reference frame effects are within requirements for (e-)LISA, quantitatively understood and physically modeled.
- A verification step in the development of e-LISA/LISA using same hardware/processes:
  - GRS
  - Micro-thrusters
  - Monolithic, silica-bonded optical bench
  - Master laser
  - Disturbance reduction system, including gravitational control and free test-mass technique (DFACS)

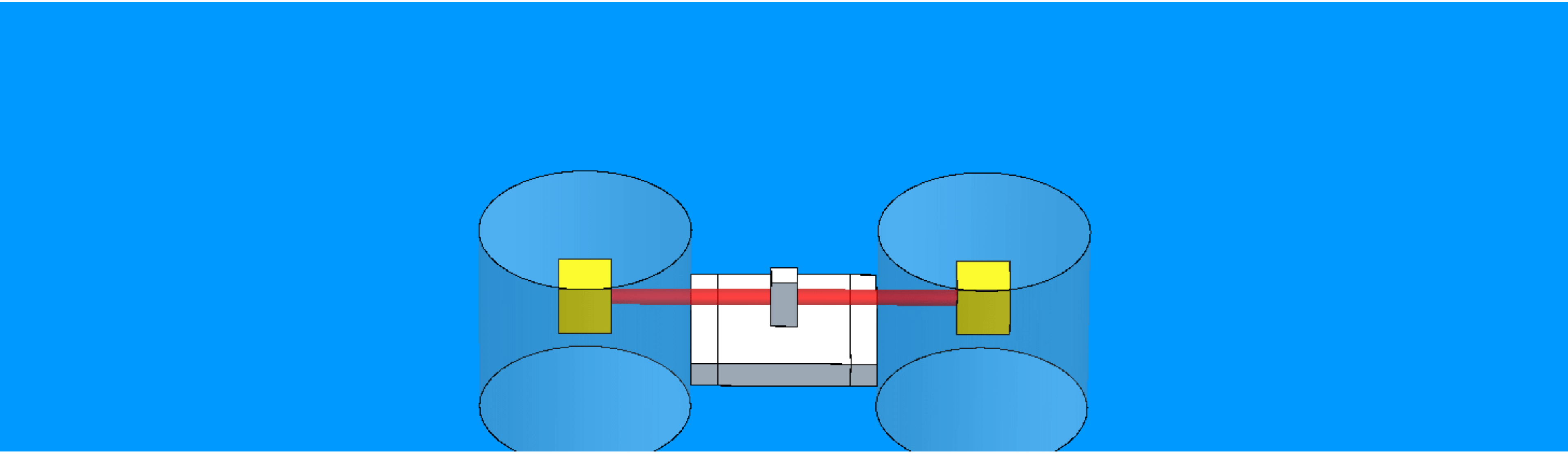
LISA and LPF requirements (differential acceleration)

- Requirements are relaxed for the test conditions not for the hardware design



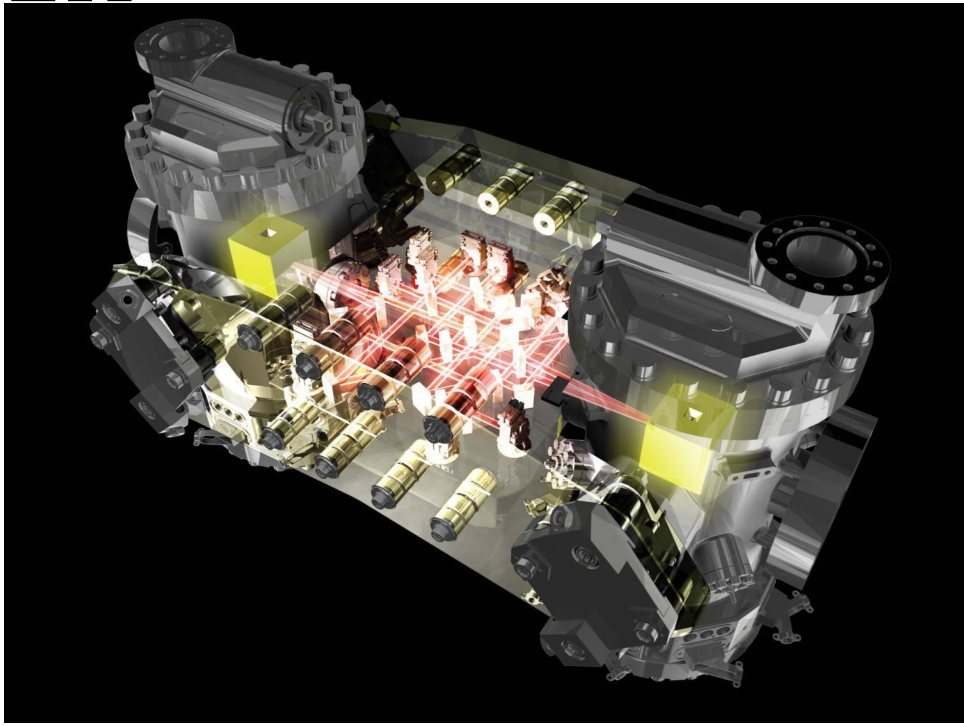
LISA Pathfinder concept

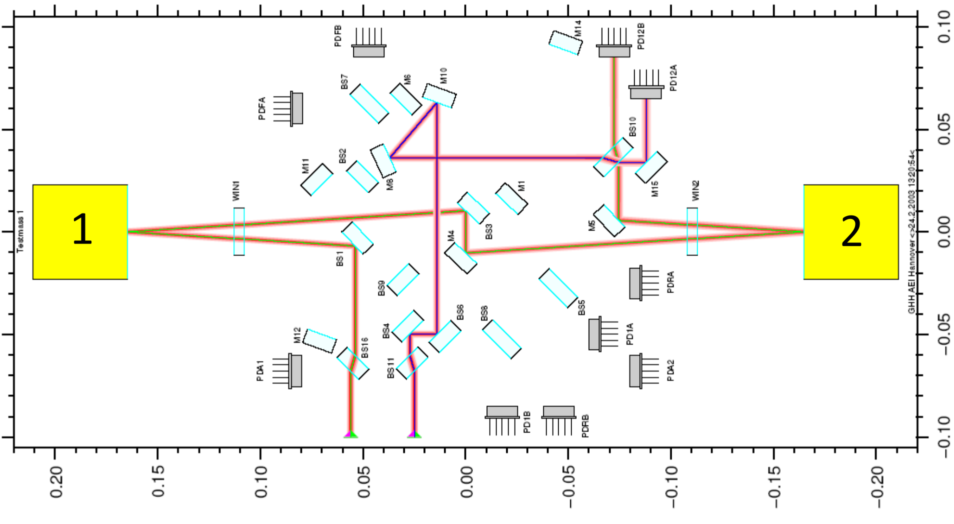
- Take away the long-arm interferometer
- Substitute the long-arm laser beam reference, with a second (quasi-)free test-mass
- One (e-)LISA arm squeezed into one spacecraft

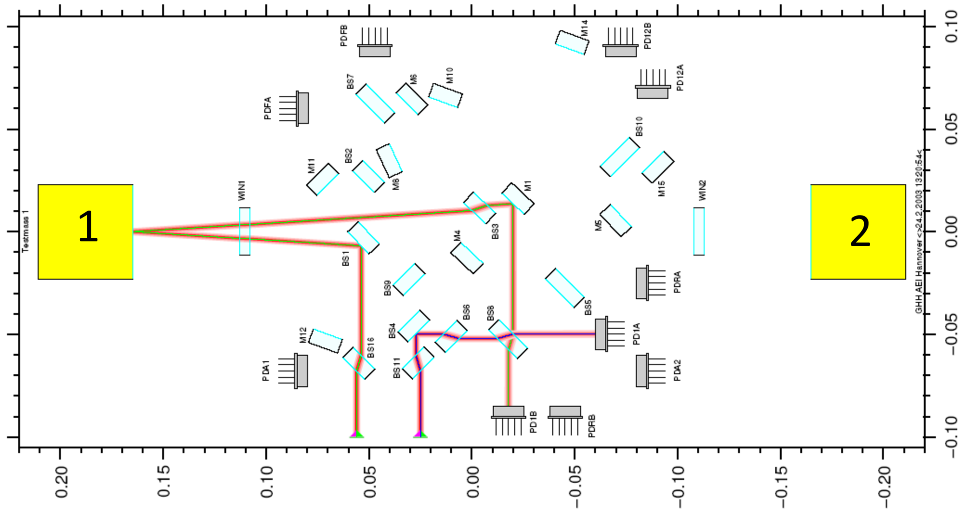


The LTP

- Two local interferometers on a high stability optical bench
- Two Au-PT test-masses enclosed in their GRS

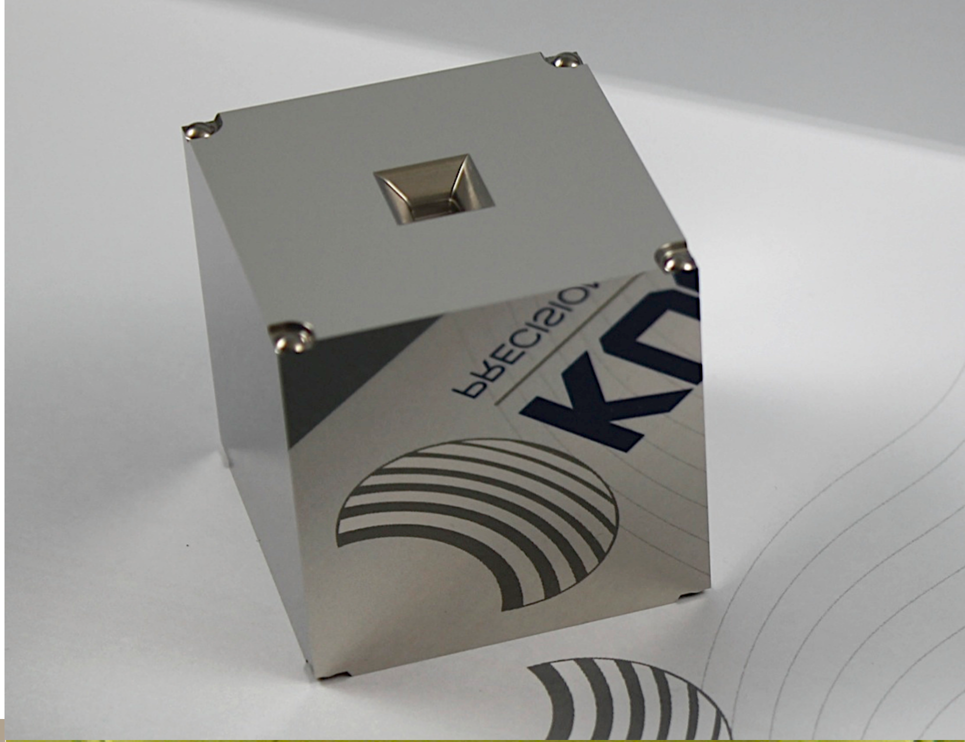


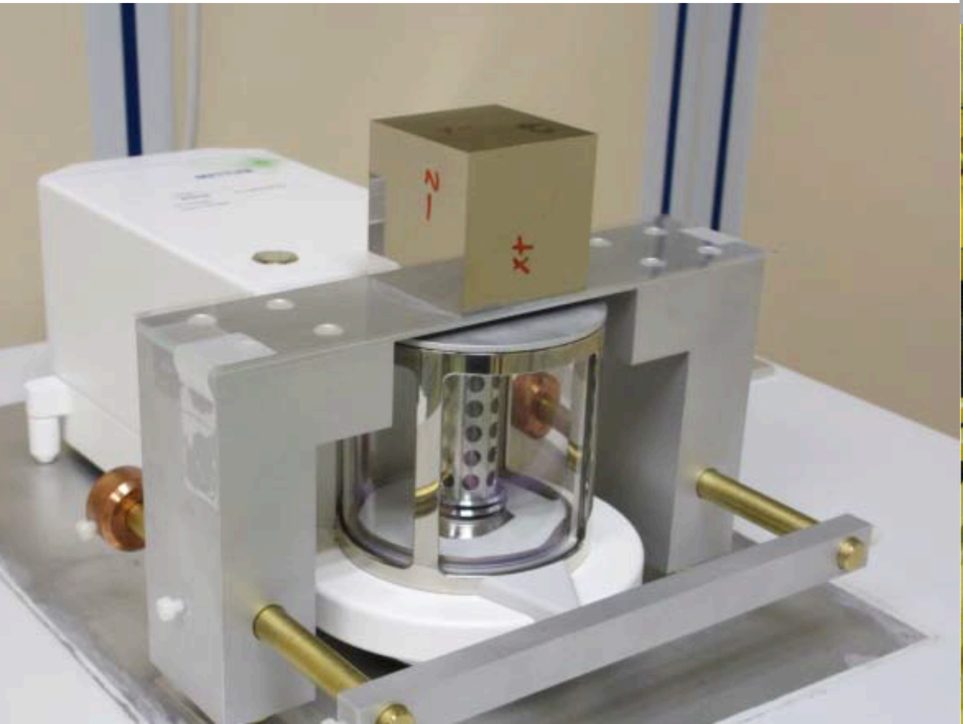




The GRS: test-mass

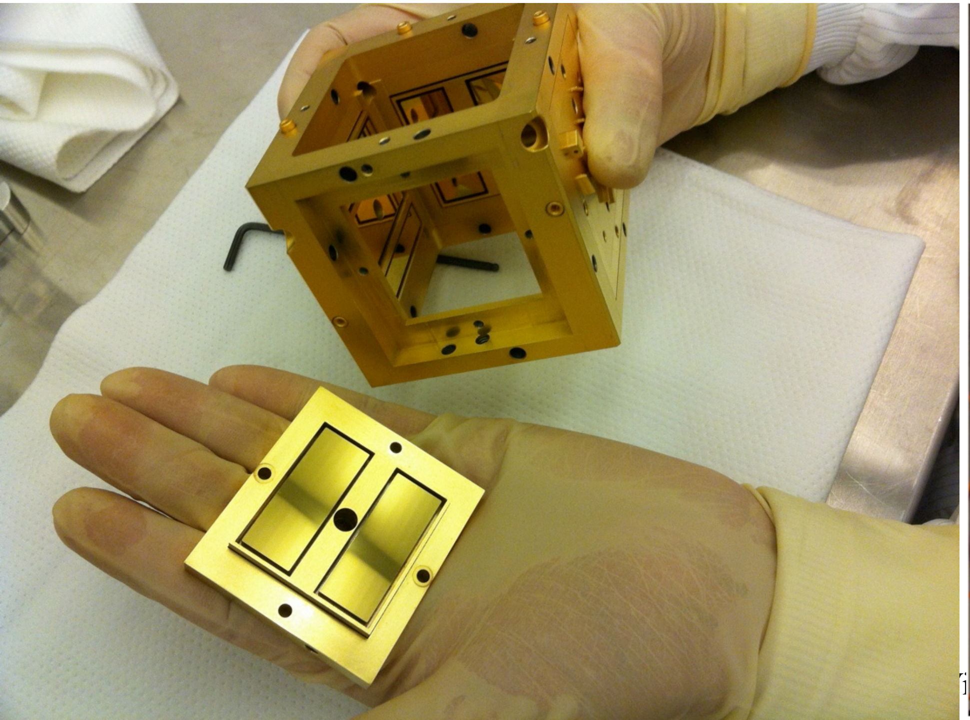
- Flight test-masses
- Very high density homogeneity (<<1μm pores)
- CoG at geometrical center within ±2 μm
- Magnetic susceptibility at $\chi = -(2.3 \pm 0.2) \times 10^{-5}$
- Magnetic moment < 4 nAm^2

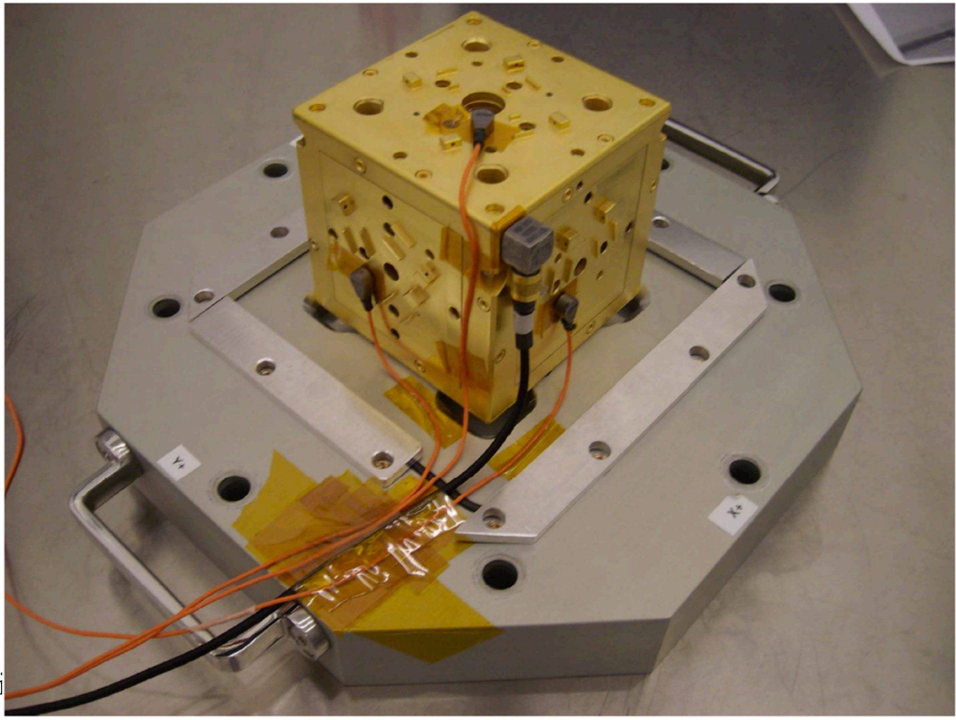




The GRS

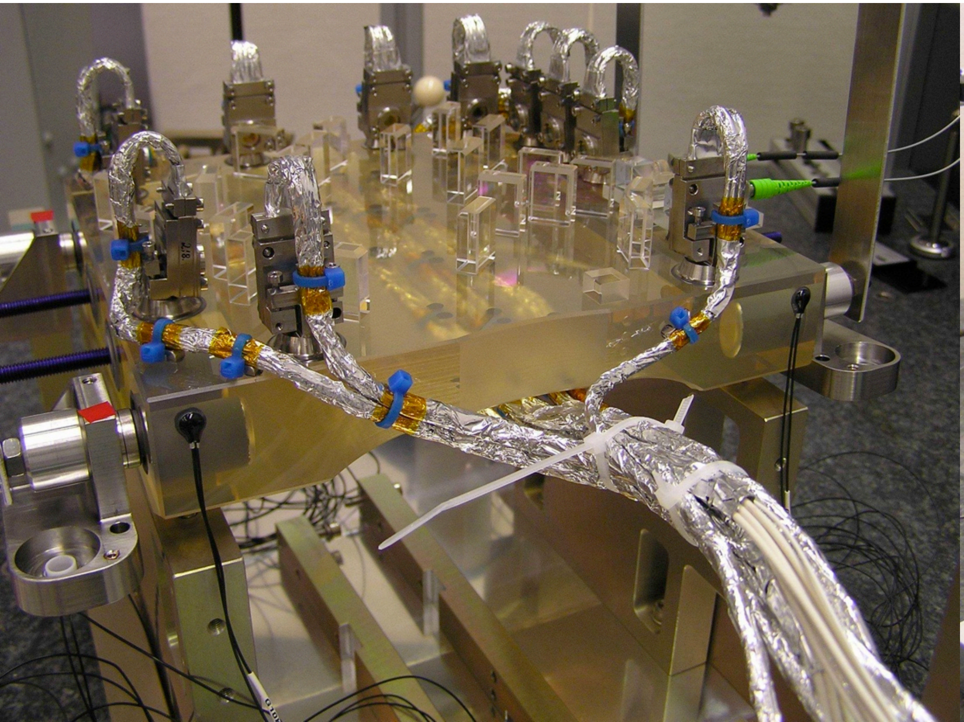
- GRS electrode housing FM1
- Under final acceptance

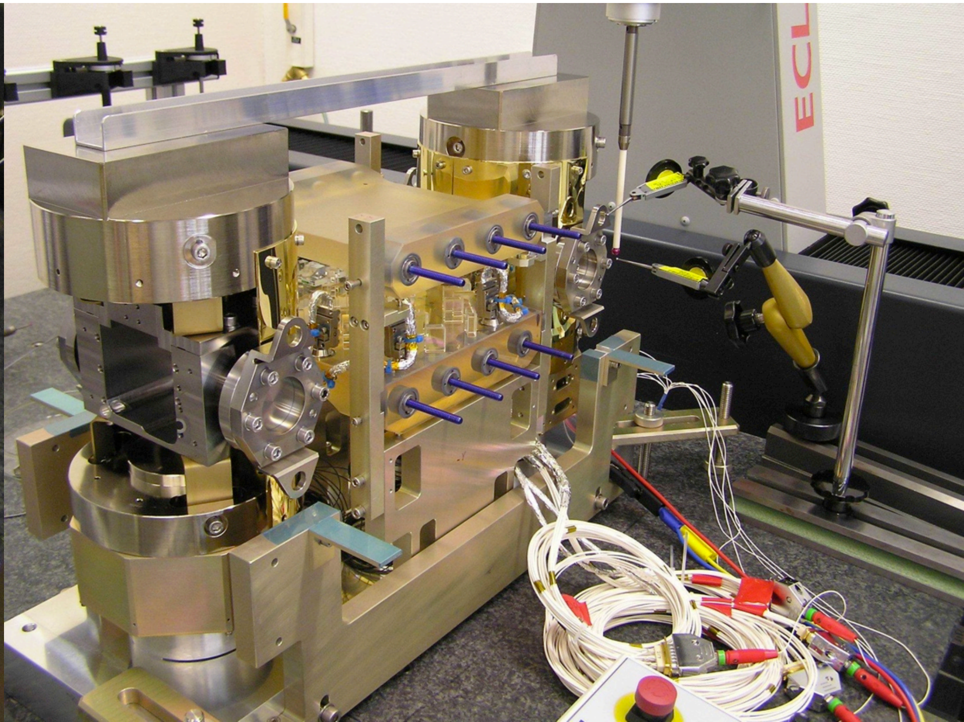


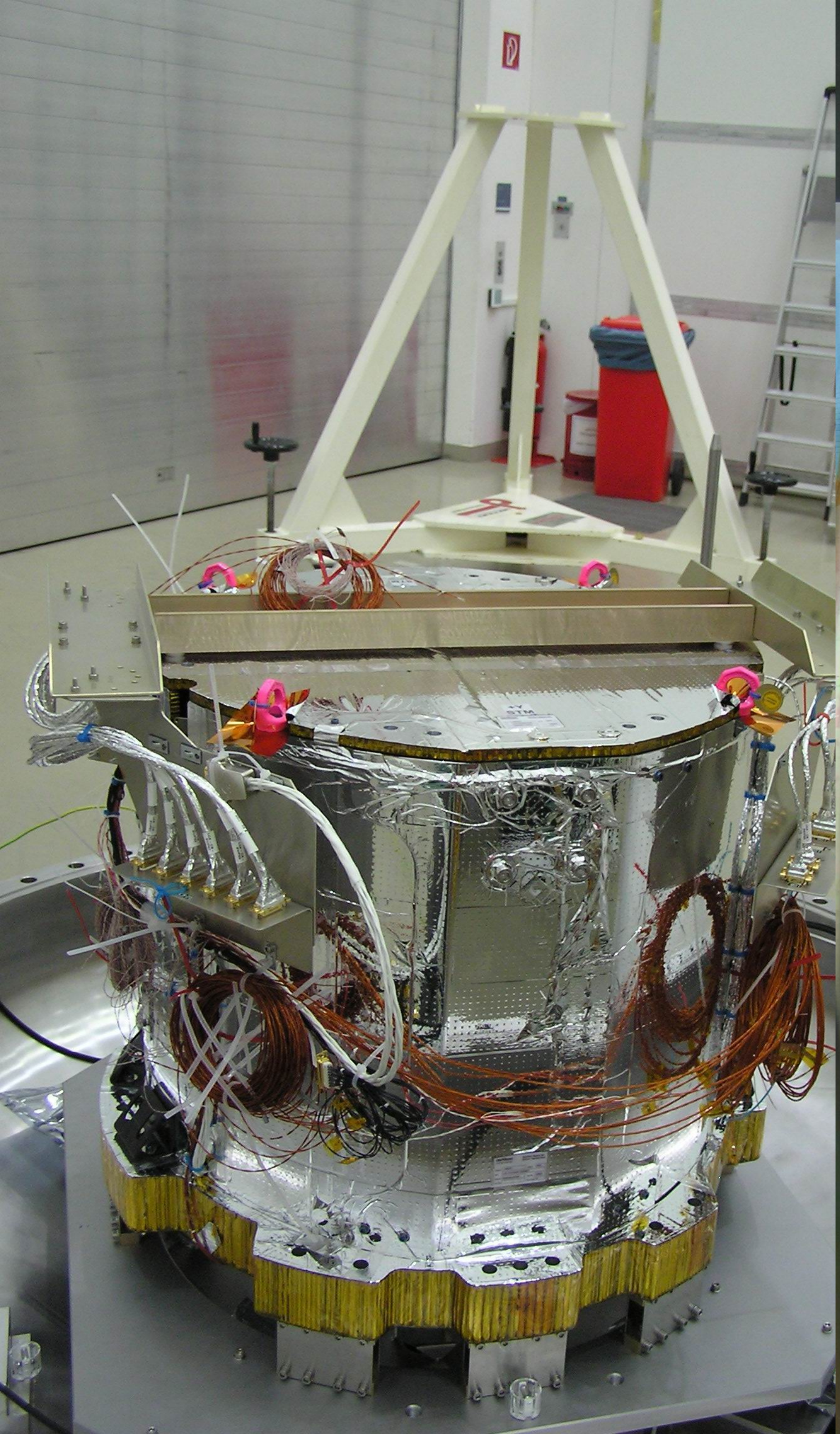


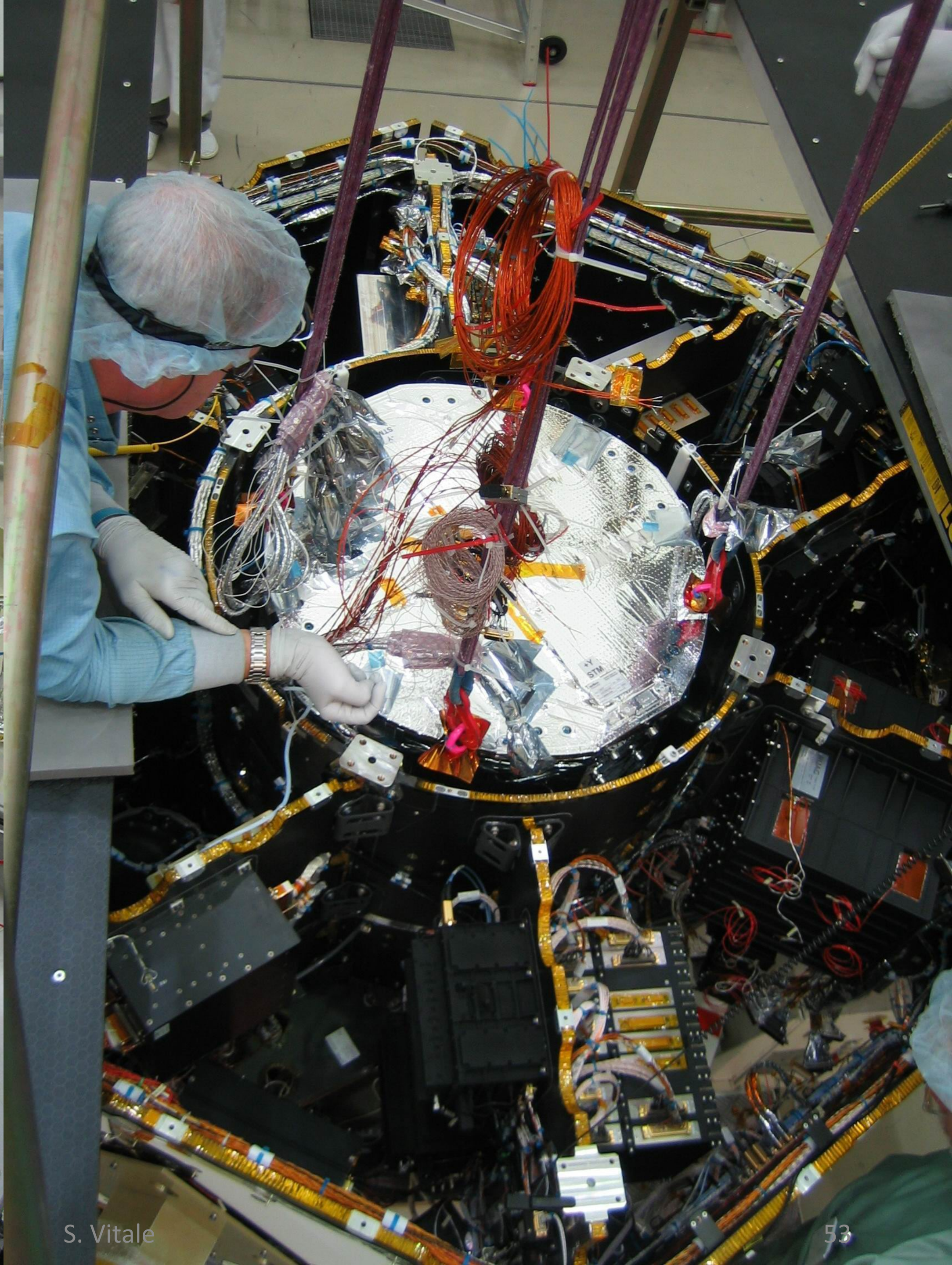
The Optical Bench and Structure

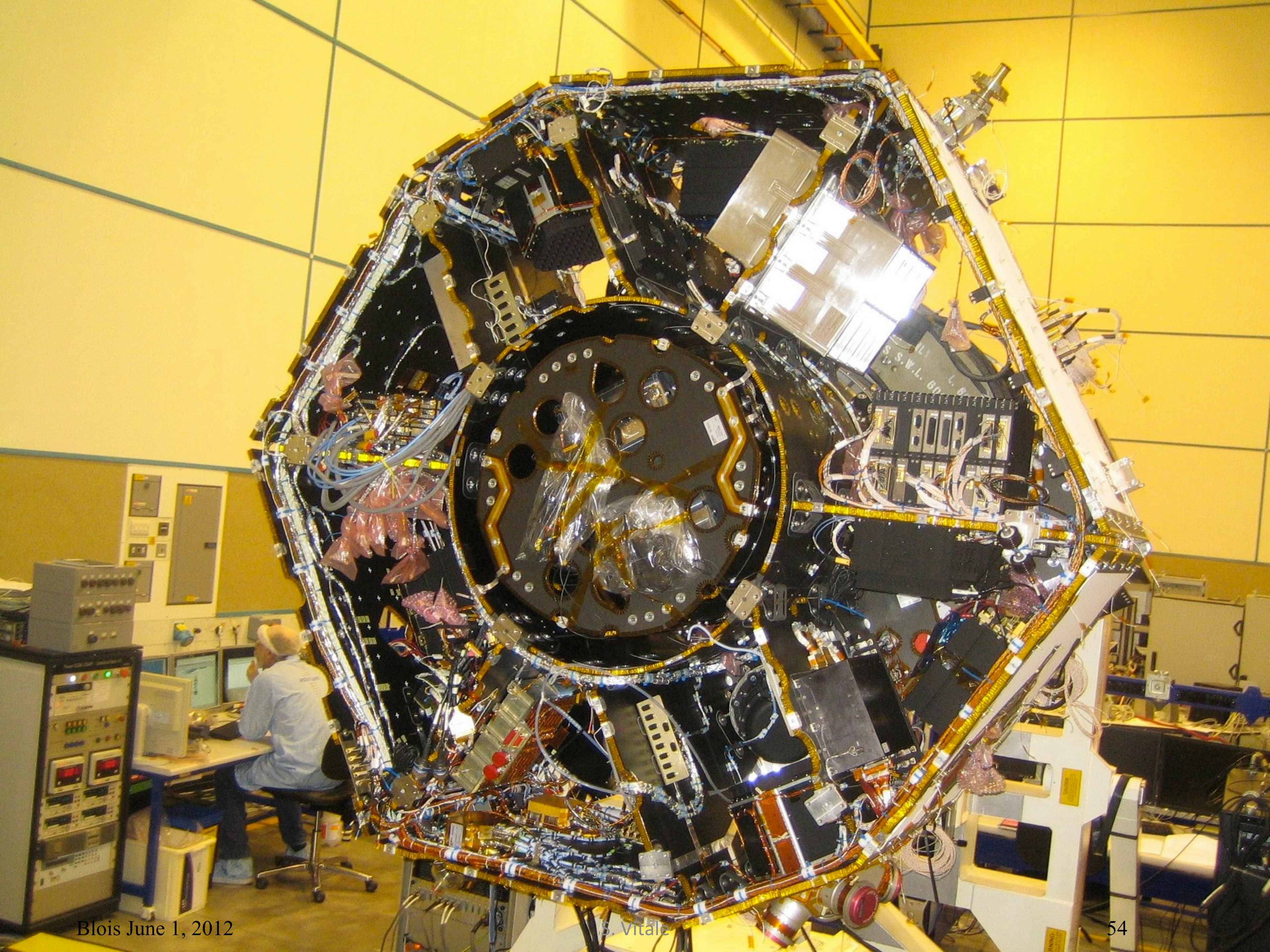
- Optical bench and structure
- Successfully tested end-to-end for optical performance







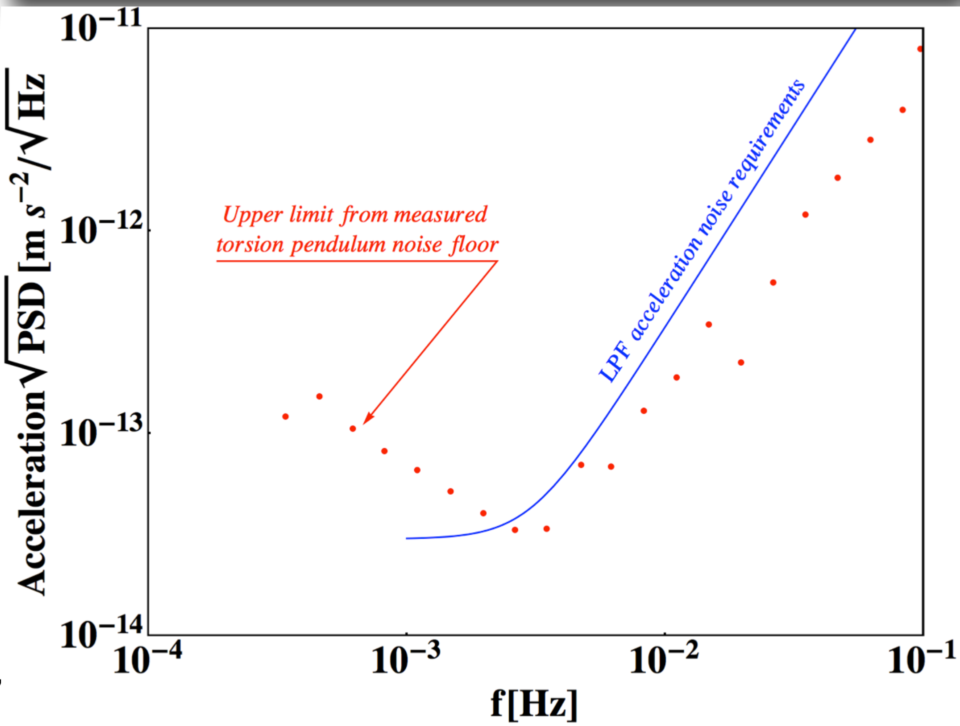




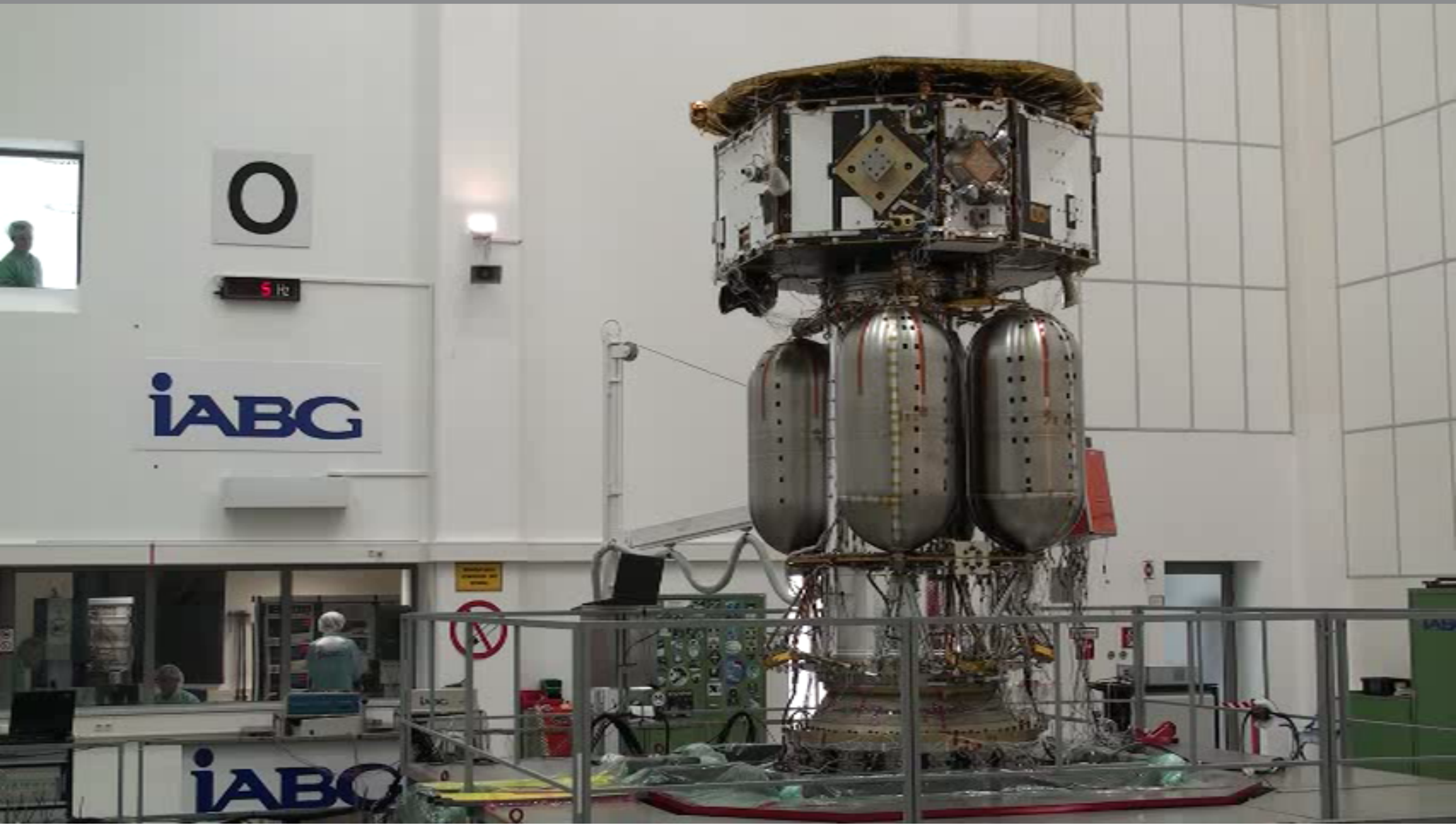

IABG
N

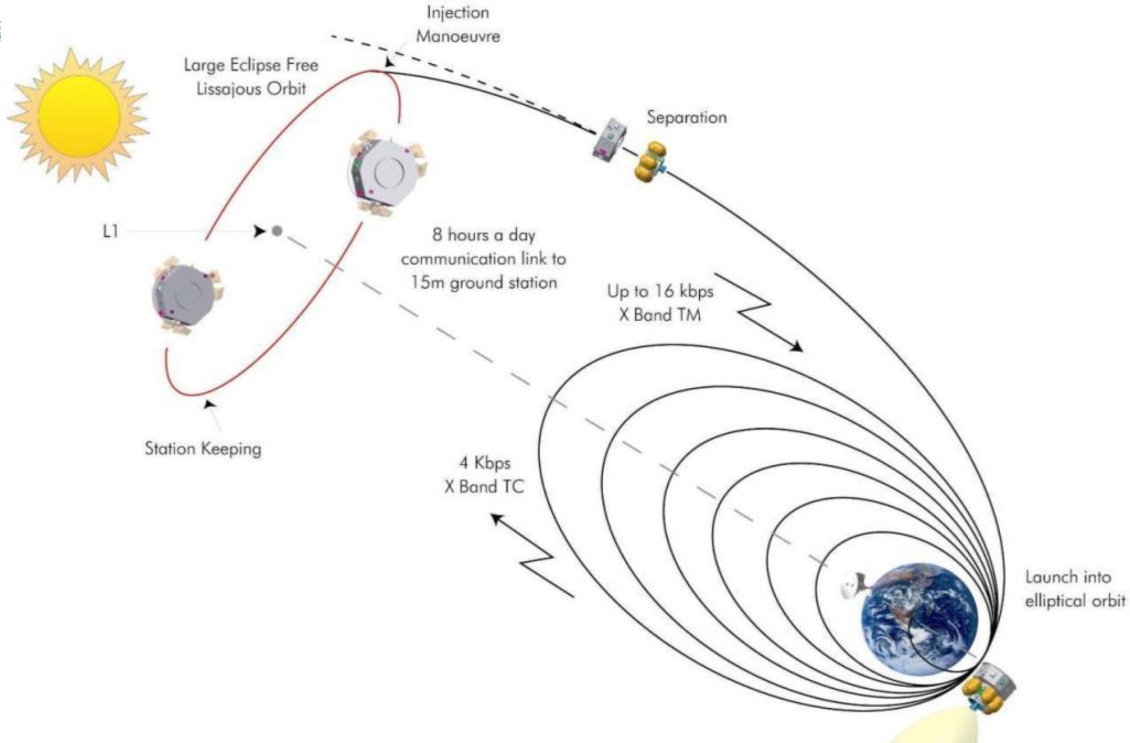
LPF expected performance

- 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
- Upper limit on force noise from dedicated torsion pendulum experiments close to requirements



Sine Vibration Test



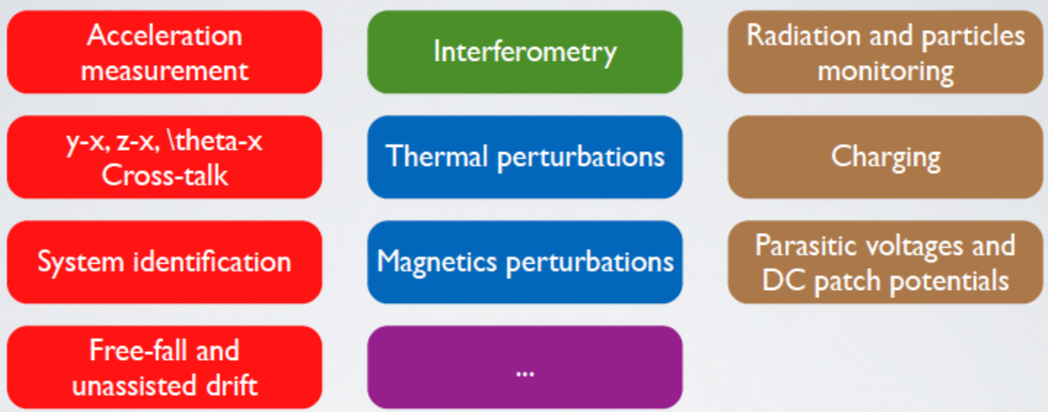

Injection
Manoeuvre
Large Eclipse Free
Lissajous Orbit
Separation
L1
8 hours a day
communication link to
15m ground station
Up to 16 kbps
X Band TM
Station Keeping
4 Kbps
X Band TC
Launch into
elliptical orbit


00:04
esa


arianespace
esa
VEGA

Experiment implementation

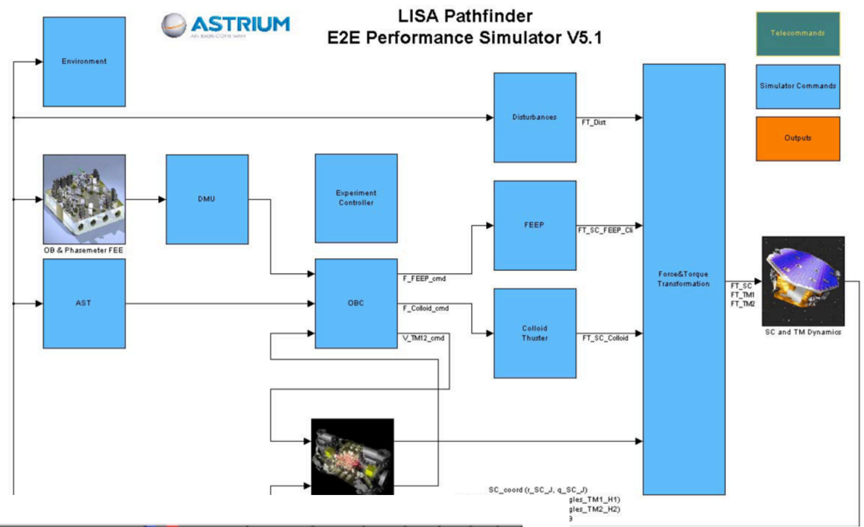
- Method: a sequence of dedicated investigations in a closed packed arrangement
- Preparation:
  - Experiment design and theoretical analysis
  - Experiment simulation on mission simulator
  - Supporting experiments in the laboratory and from flight hardware testing campaign

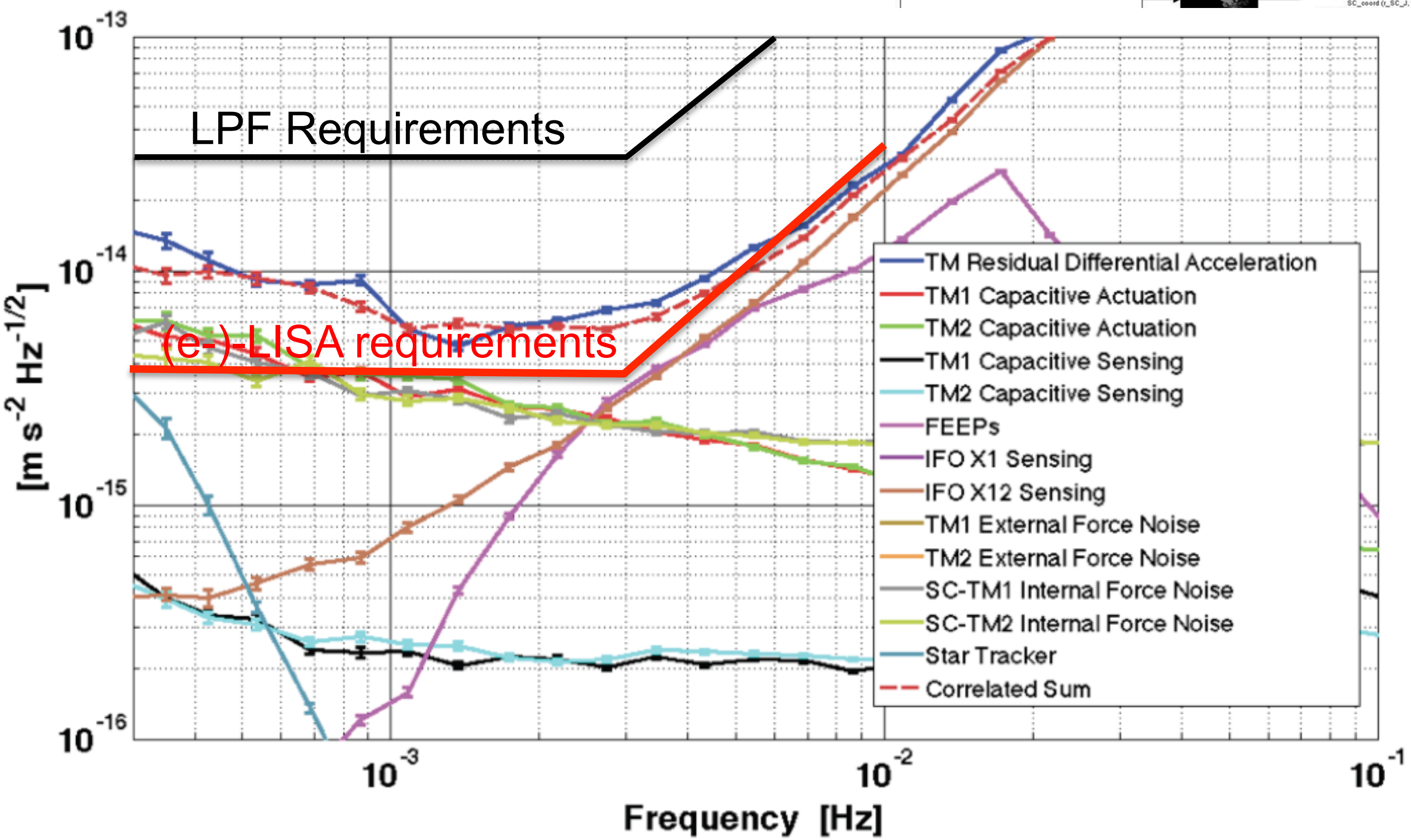


from	to	name	from	to	name
inv00001	inv00999	acceleration	inv05001	inv05999	charging
inv01001	inv01999	system identification	inv06001	inv06999	detailed interferometry
inv02001	inv02999	cross-talk	inv07001	inv07999	thermal
inv03001	inv03999	parabolic flight	inv08001	inv08999	magnetics
inv04001	inv04999	DC potentials	...	...	...

Simulation on end-to-end mission simulator

- Performance expected significantly better than requirements.
- Estimate of major contribution demonstrated to be feasible.





Status of development

- LISA Pathfinder launch in 2014
- LISA studied for more than a decade as a joint NASA-ESA mission.
- With JWST-based NASA crisis, ESA has studied eLISA (NGO) as ESA only mission
- Mission assessed to be feasible within budget for and ESA Large Mission and considered as a candidate for a launch at next slot (L-1)
- ESA´s scientific review committee unanimously ranked it first for:
  - scientific interest
  - strategic value for science
  - strategic value for the project in Europe
- For programatic reasons it was not given the go ahead for this slot
- ESA will pursue technology developments not covered by LISA Pathfinder
- Adoption likely after LISA Pathfinder flight

http://elisa-ngo.org/

http://arxiv.org/abs/1201.3621