eLISA – opening a window on the gravitational Universe

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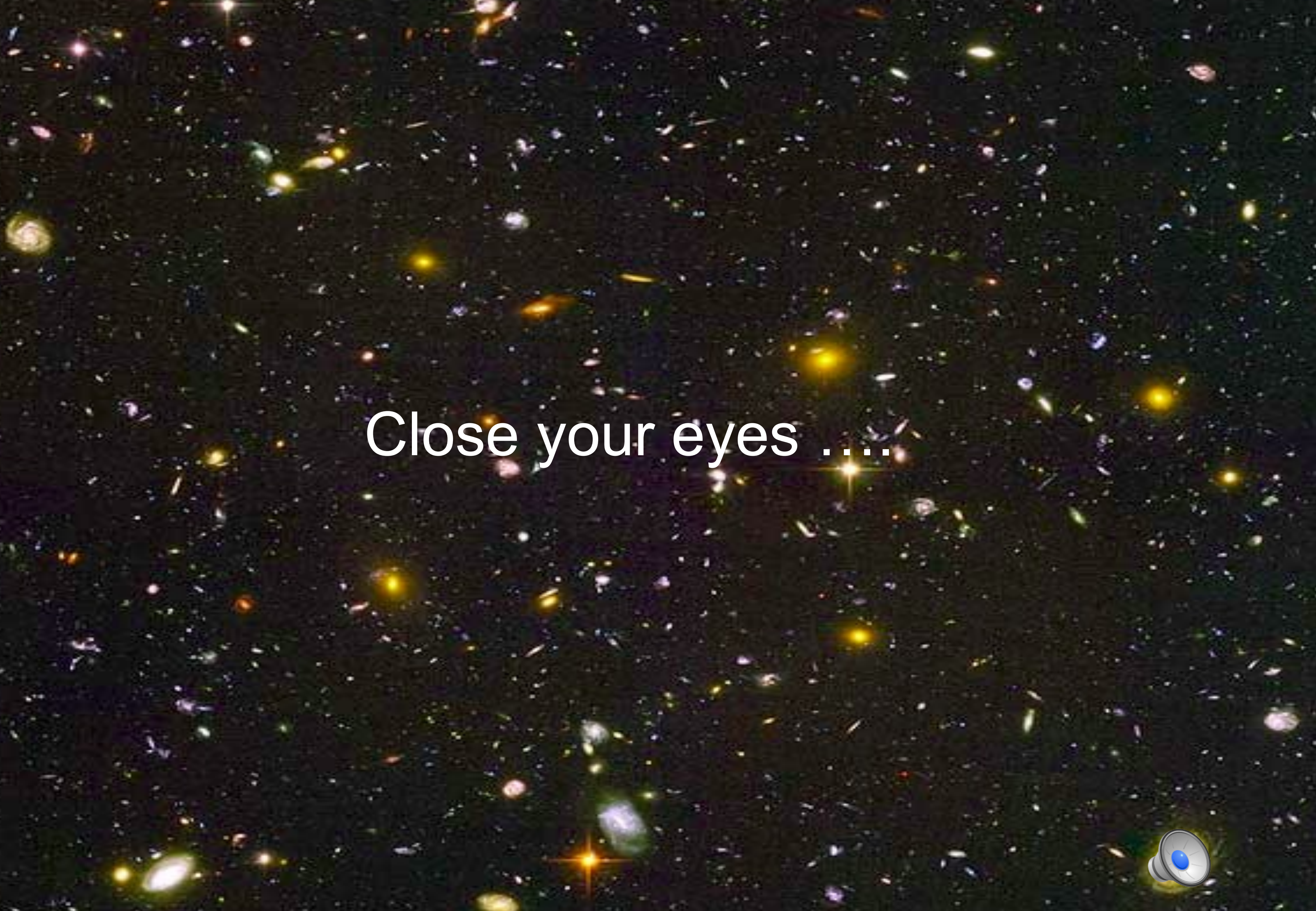
for the eLISA Science Team and community

Q2C6 Conference, Nice
17th October 2013



Close your eyes …..

The gravitational Universe

- You have just experienced a perfectly realistic example of the rich and detailed gravitational information that eLISA is designed to capture

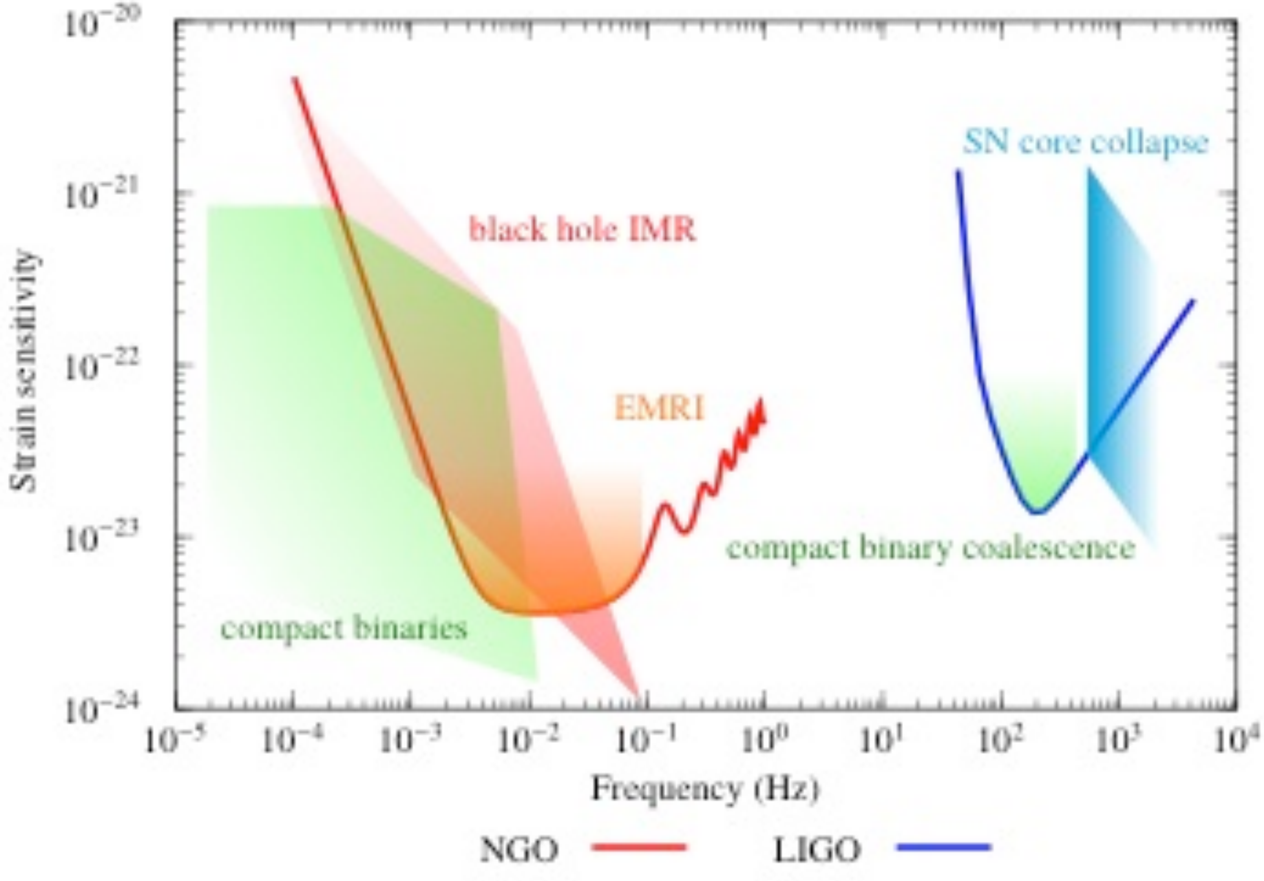
- Accelerating masses produce tidal force waves – gravitational waves – and detecting them will let us listen to the Universe
- Waveforms directly encode the bulk motion of distant matter
- There is no obscuration for GW observations; waves penetrate:
  - any matter
  - black holes from the event horizon
  - the early Universe from singularity
- Observing the Universe through gravity gives clean observations

- With eLISA we are proposing to observe the entire Universe through the medium of gravitational waves

Correcting misconceptions …..

Space and ground-based GW observatories

- Are fully complementary: sensitive in different parts of the frequency domain and target detection of sources of completely different type
- **The strength of the eLISA science case is completely independent of detections – or their absence – by ground-based experiments**



Gravitational Waves are a current hot topic …

- Clearly not "Scientific European" ….!
- Spaceborne GW detection by interferometry is fully studied and relevant technology well developed
- eLISA is very much alive and in good shape, with LISA Pathfinder on-track for success in 2015
- **eLISA is a mature mission and selection as L2 is the goal !**

Science objectives of eLISA

- 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
  -
- 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
- Explore stellar populations and dynamics in galactic nuclei
  - Characterise 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

Science objectives of eLISA

- 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

- 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 to 10^{-1} Hz band
  - Search for gravitational wave bursts from cosmic string cusps and kinks

Sources targeted

- Massive Black Holes
  - 10^4 to 10^8 $M_\odot$
  - Including pre-re-ionisation Black Hole mergers at $z \geq 20$, if they exist
- Extreme Mass Ratio Inspirals, EMRIs
  - 1 to $10 M_\odot$ into $10^4 - 5 \times 10^6$ $M_\odot$
  - a powerful probe of strong-field GR
- Ultra-Compact Binaries in our Galaxy
- Stochastic Signals
- Science goals span a broad range of topics in astrophysics, cosmology & fundamental physics

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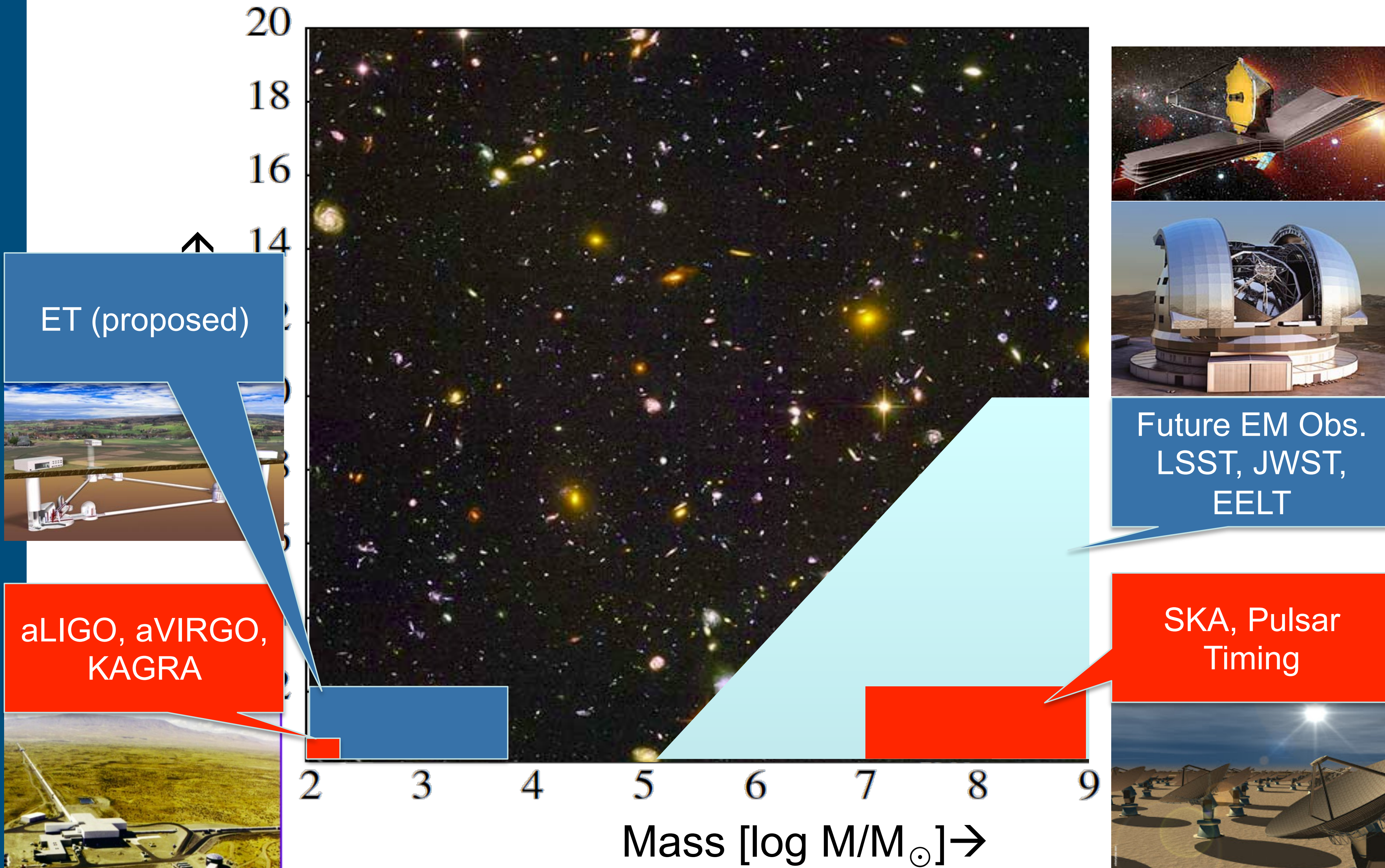
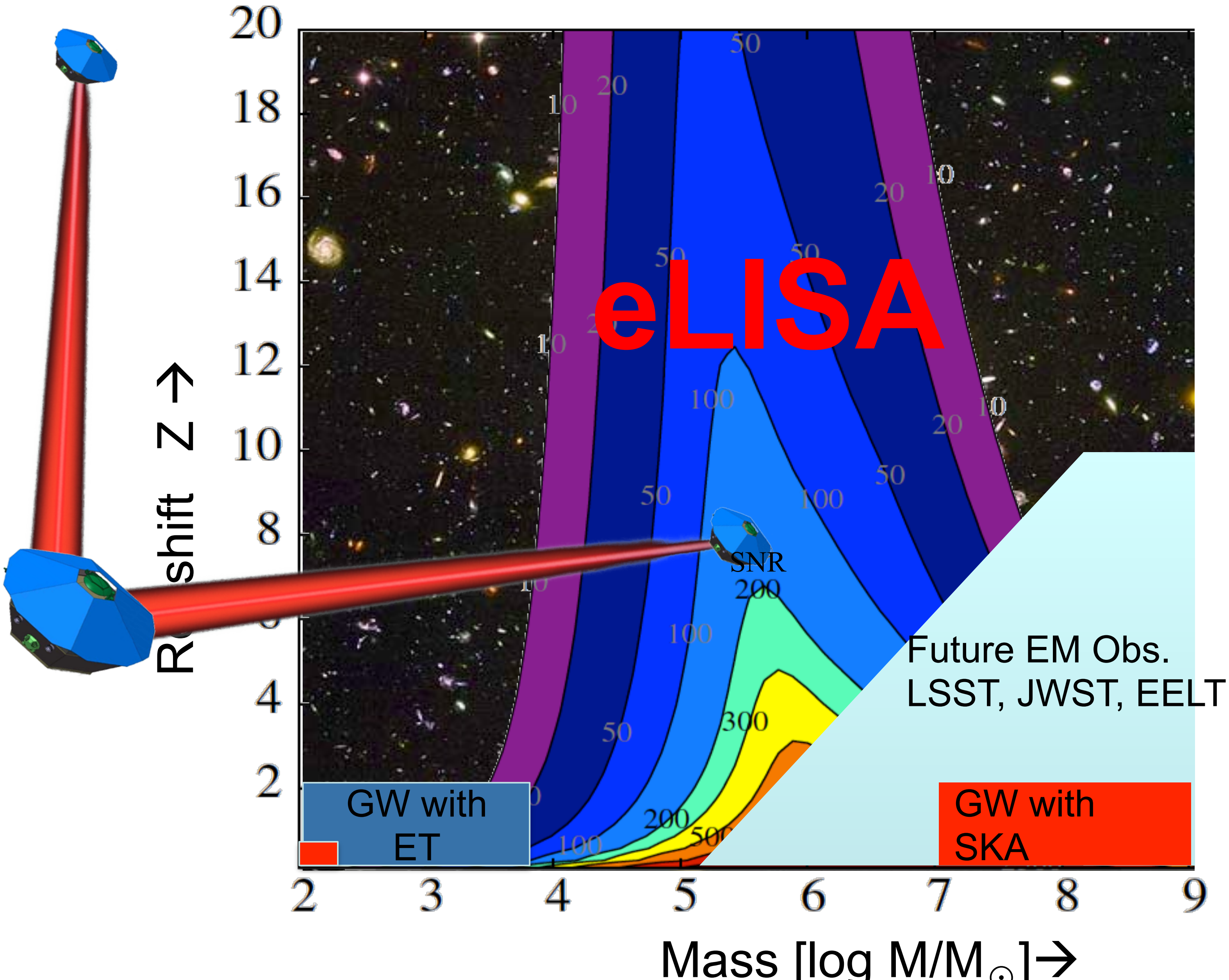
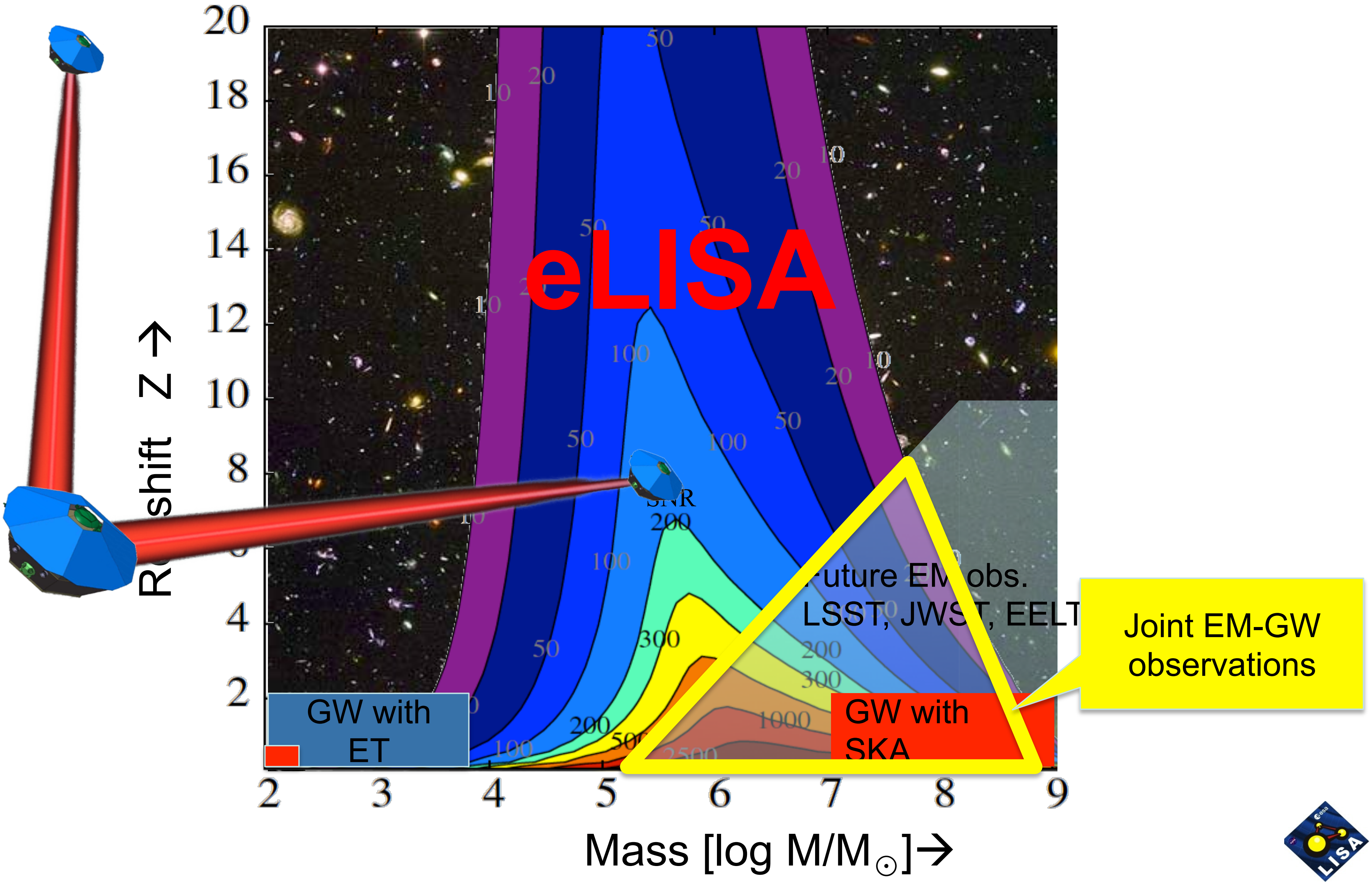
Black Hole Astronomy by 2028



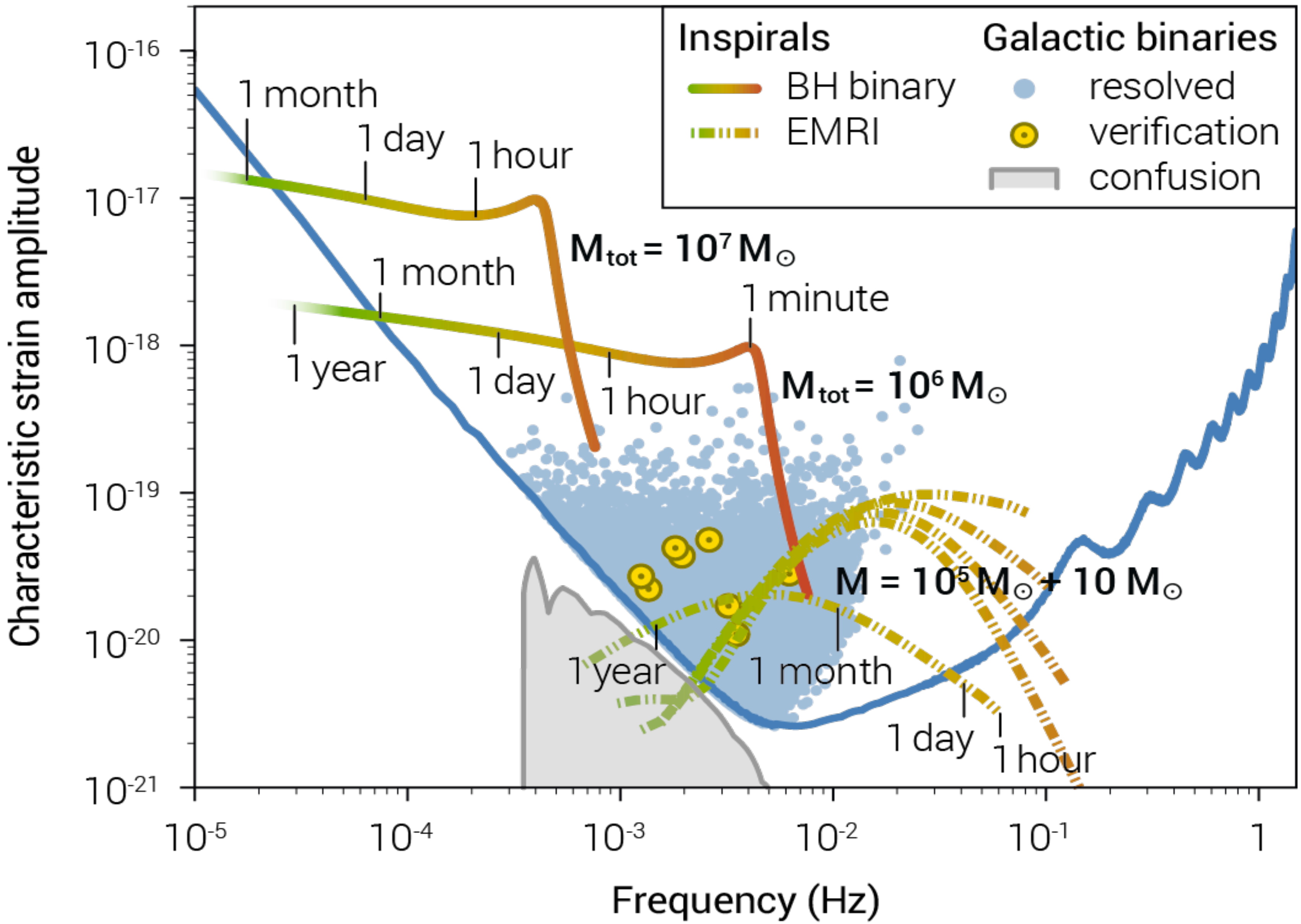
Black Hole Astronomy by 2028



Black Hole Astronomy by 2028

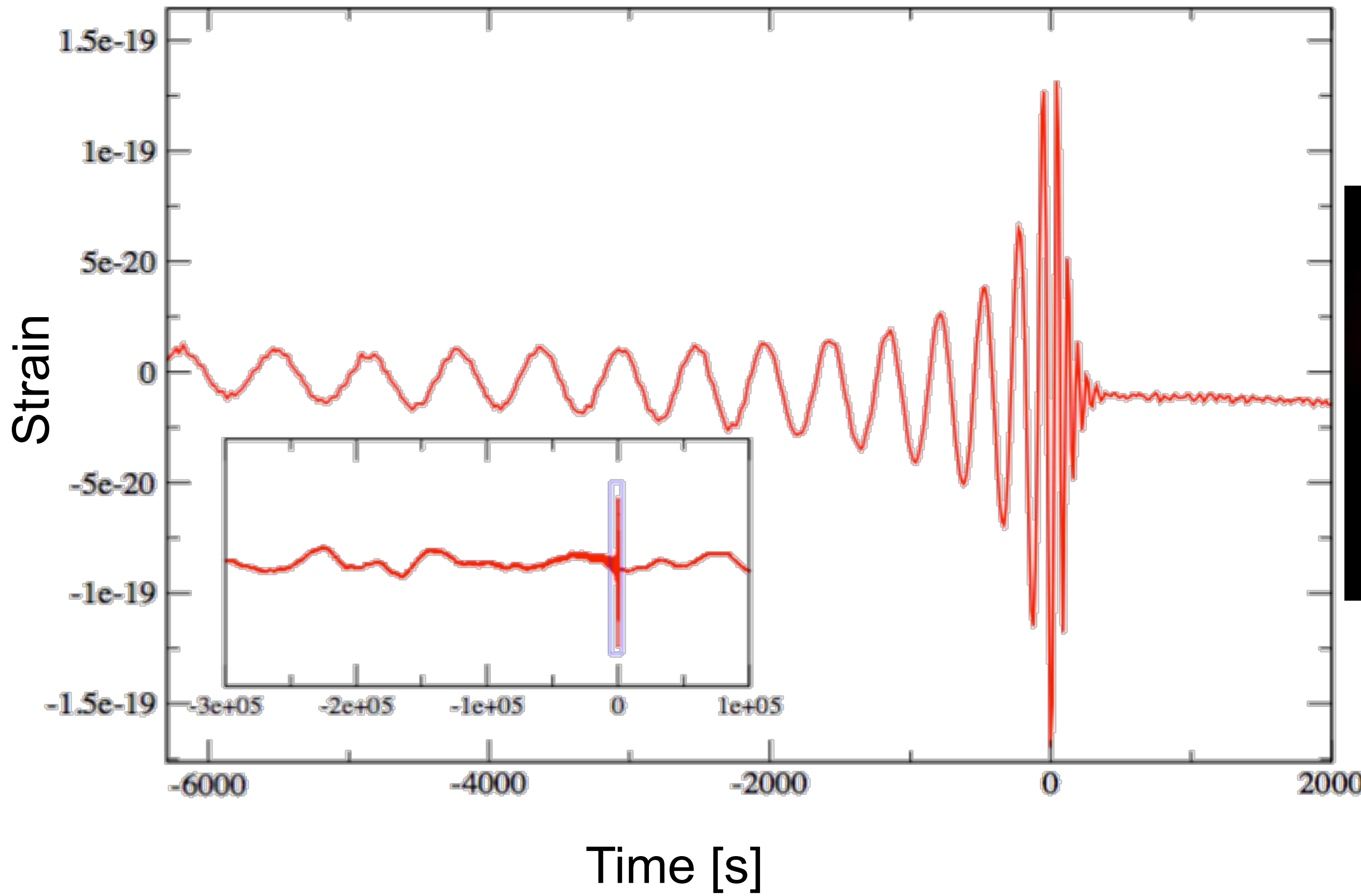


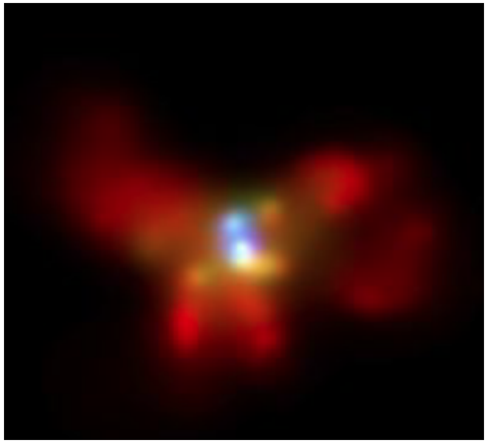
Sensitivity and Black Hole science



BH Merger Signals far above noise!

- Simulated eLISA data stream,
  - $10^5 M_\odot$ BH binary merger at z = 5, including instrumental noise (SNR~100)

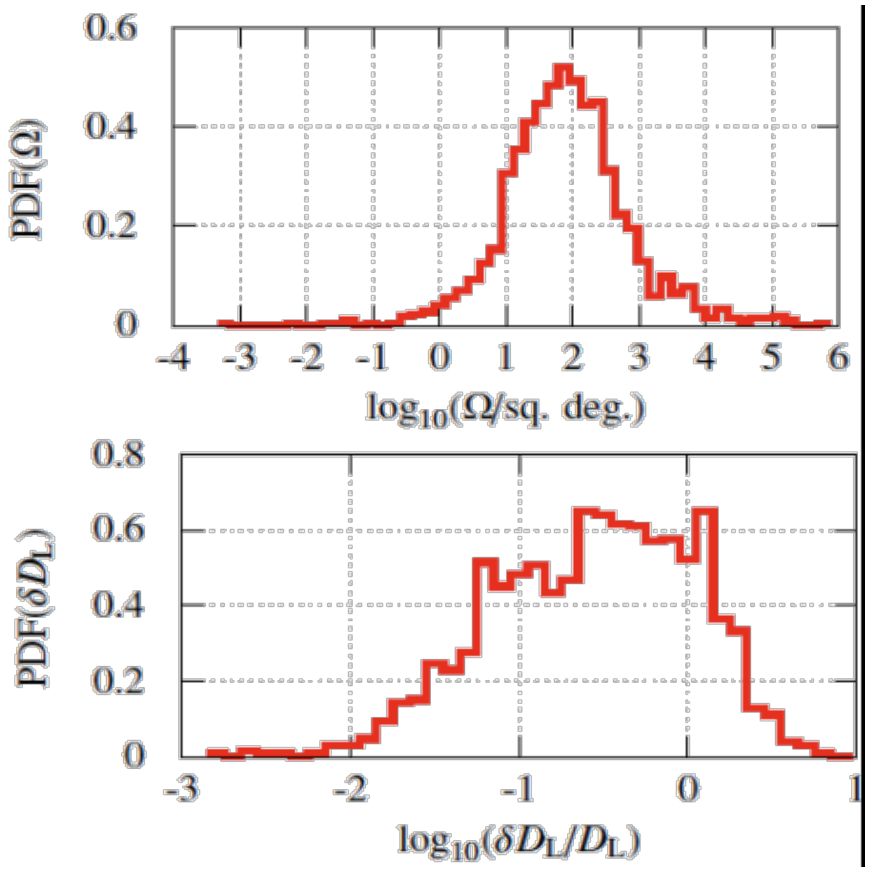




NGC 6240

eLISA Black Hole physics at high SNR

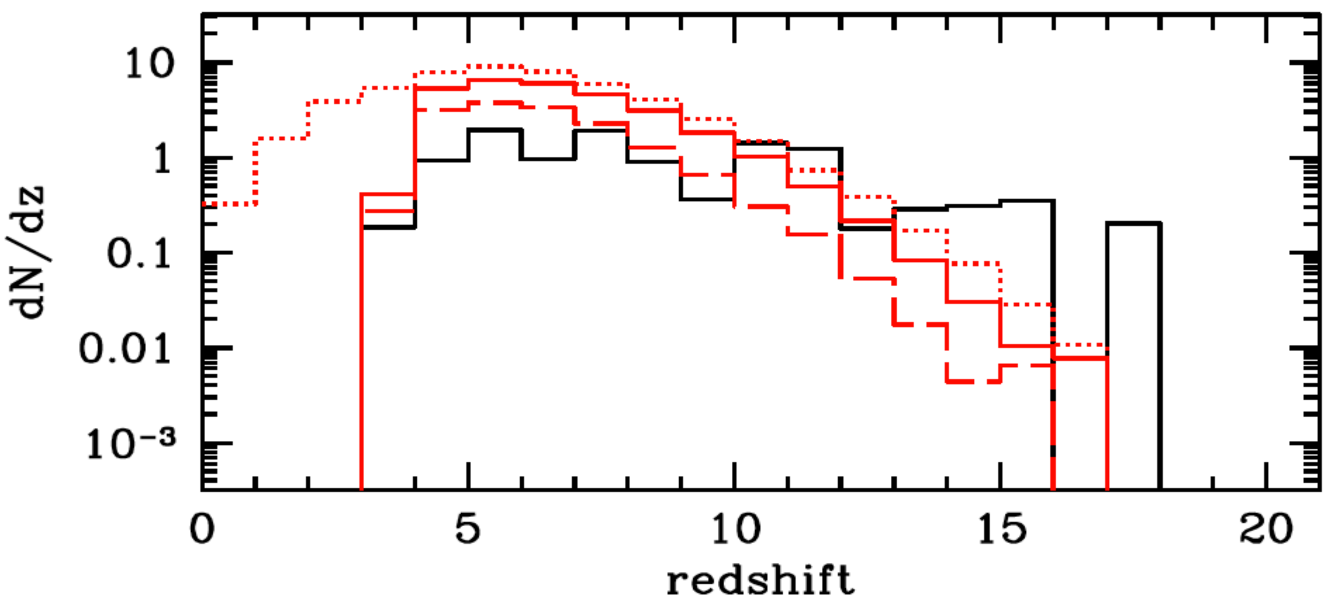
- BBH rest mass $10^4 – 10^7$
- Detection out to redshift $z >> 10$
- 10 – 100 events per year
- Redshifted mass to 0.1%-1%
  - No other astrophysical tool has the capability of reaching a comparable accuracy
- Absolute spin to 0.01-0.1
- Luminosity distance 1 – 50 %
- Sky location in the range 10 to 1000 square degrees



Event rates for MBH mergers

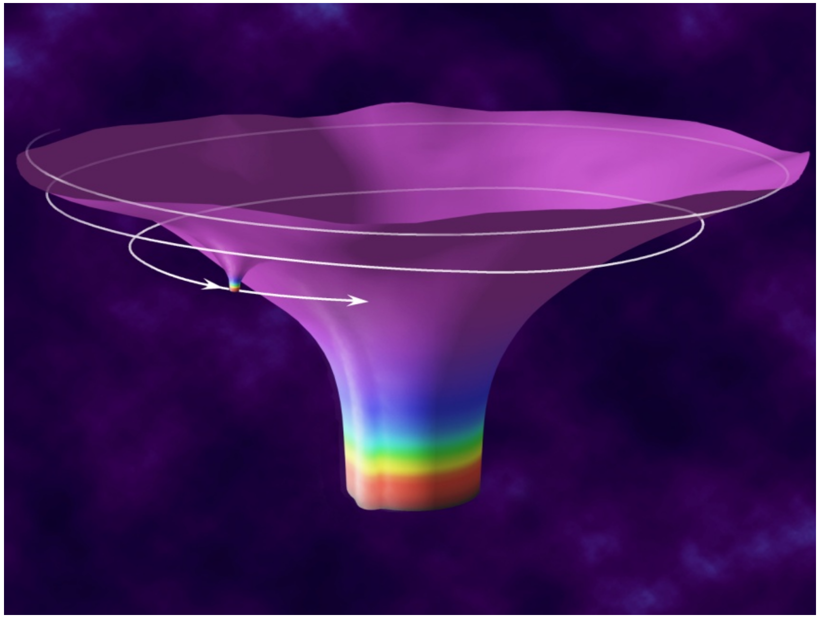
- 10 – 100 events/year from semi-analytic merger tree models
  - Account for hierarchical clustering of dark matter halos
  - Do not trace baryon physics along cosmic history
- Recently, full hydrodynamic simulations of structure formation show importance of cold gas flow to feed BH growth

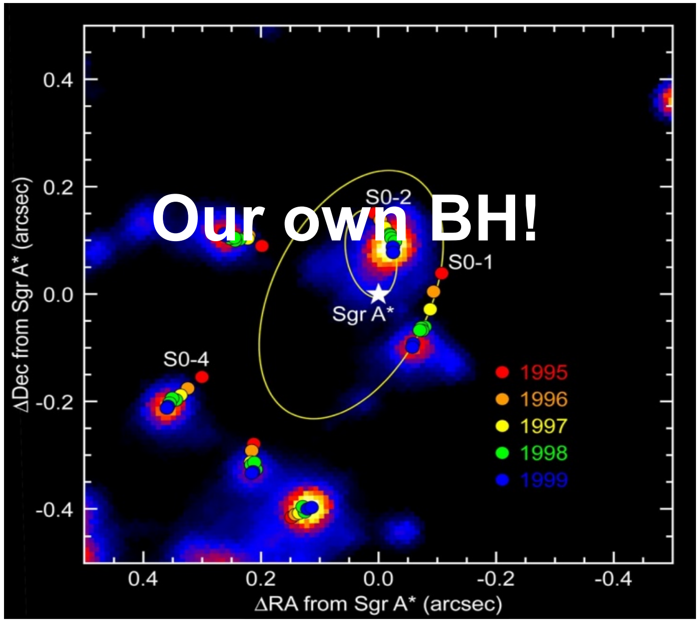
→ Merger rates largely unaffected!



At the edge of a Black Hole

- Capture by Massive Black Holes
  - Compact objects inspiral into massive black hole (MBH)
  - GWs map space-time geometry with superb precision
  - Allows investigation of tiny deviations from General Relativity including the “no hair” theorem

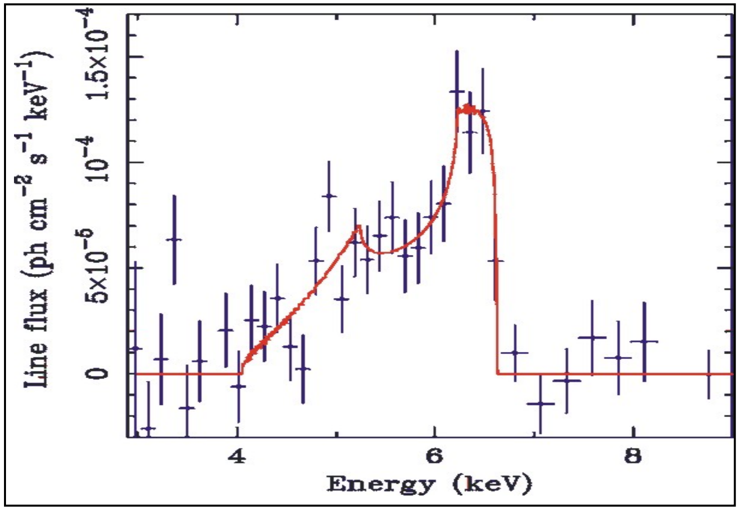




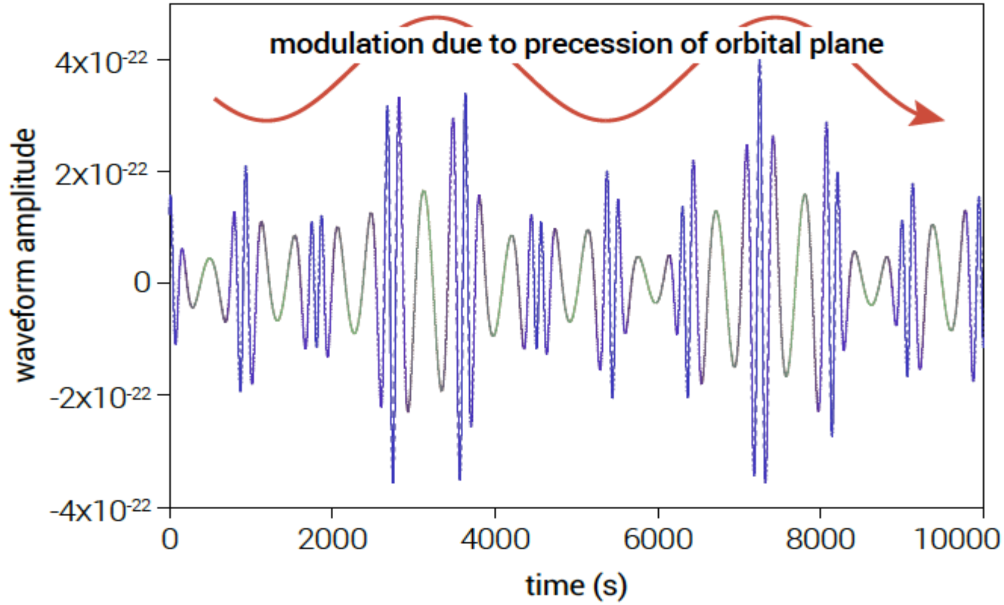
Ghez et al. 1998 ApJ 509, 678, Eckart et al. 2002 MNRAS 331, 917

What happens at the edge of a Black Hole ?

- X-Ray Spectroscopy
  - Iron lines near the event horizon of a black hole
  - Line exhibits a strong redshift probing the inner accretion region around black holes

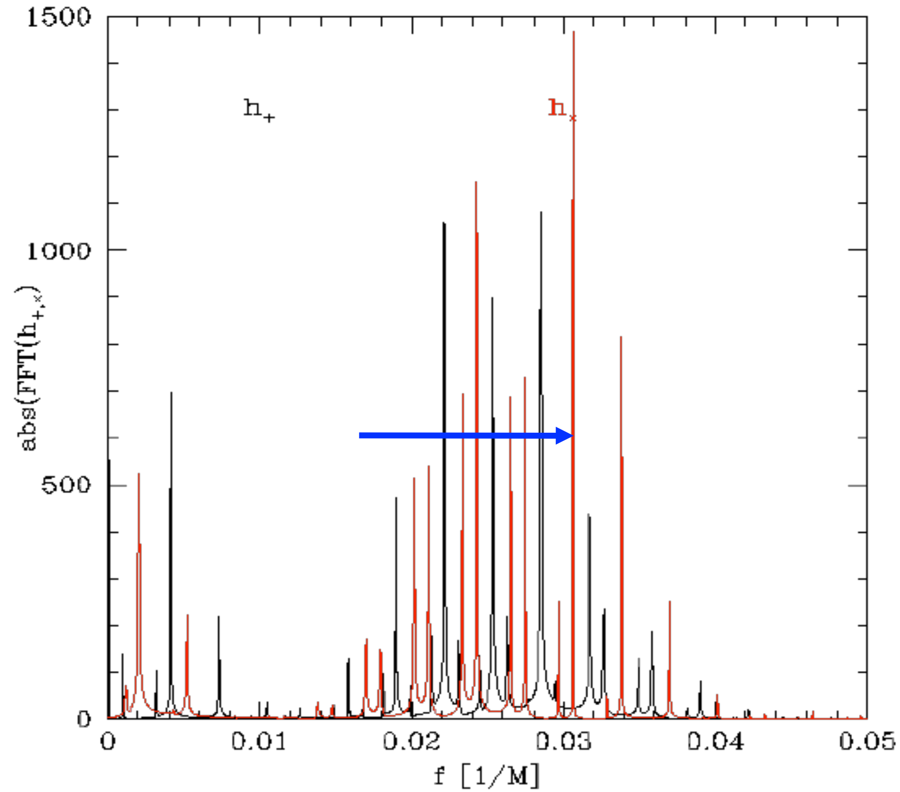


- Gravitational Waves
  - Gravitational radiation is the only radiation directly emitted by a Black Hole itself



Extreme Mass Ratio Inspiral (EMRI)

You can hear if the Event Horizon exists!

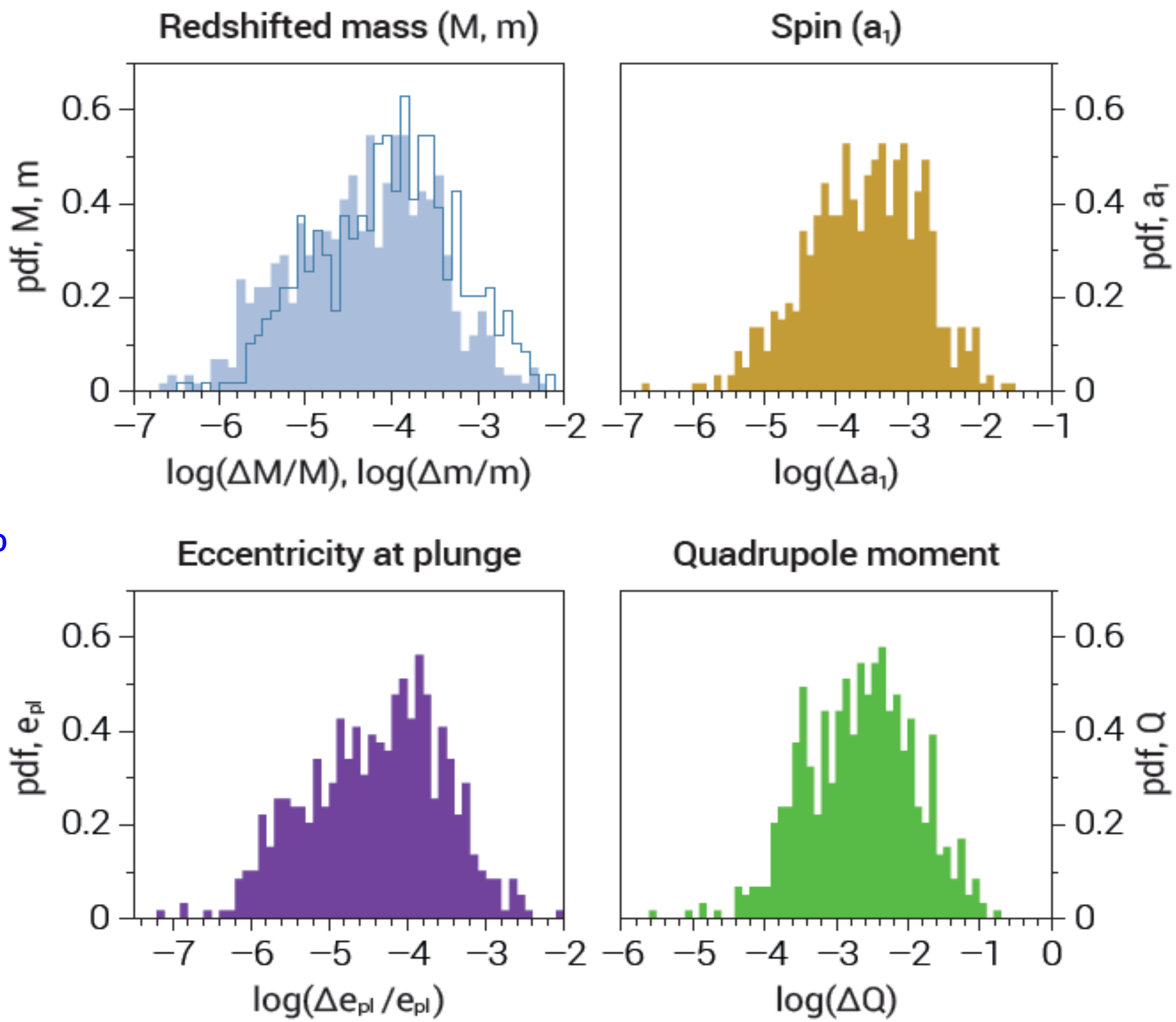


- Frequencies sweep and shift during inspiral, mapping space-time outside the horizon
  - ⇒ Like a Geodesy satellite mapping Geopotential!
  - ⇒ GRACE for Black Holes!

a = 6M, e = 0.2, i = 80

Extreme Mass Ratio Inspirals

- Tens of events per year
- SNR 20 up to $z \approx 0.7$ for 10^5-10^6 $M_\odot$
- Extraordinarily high precision measurements
  - Mass, spin to 0.1% – 0.01%
  - Quadrupole moment to $< 0.001\ M_\odot^3 G^2/c^4$
- Allows stringent tests of BH "no-hair" nature, or potentially discovery of new phenomena



Ultra-compact stellar-mass binaries

- Several thousand systems are expected to be detected individually in a 2 yr mission, with their parameters determined to high precision

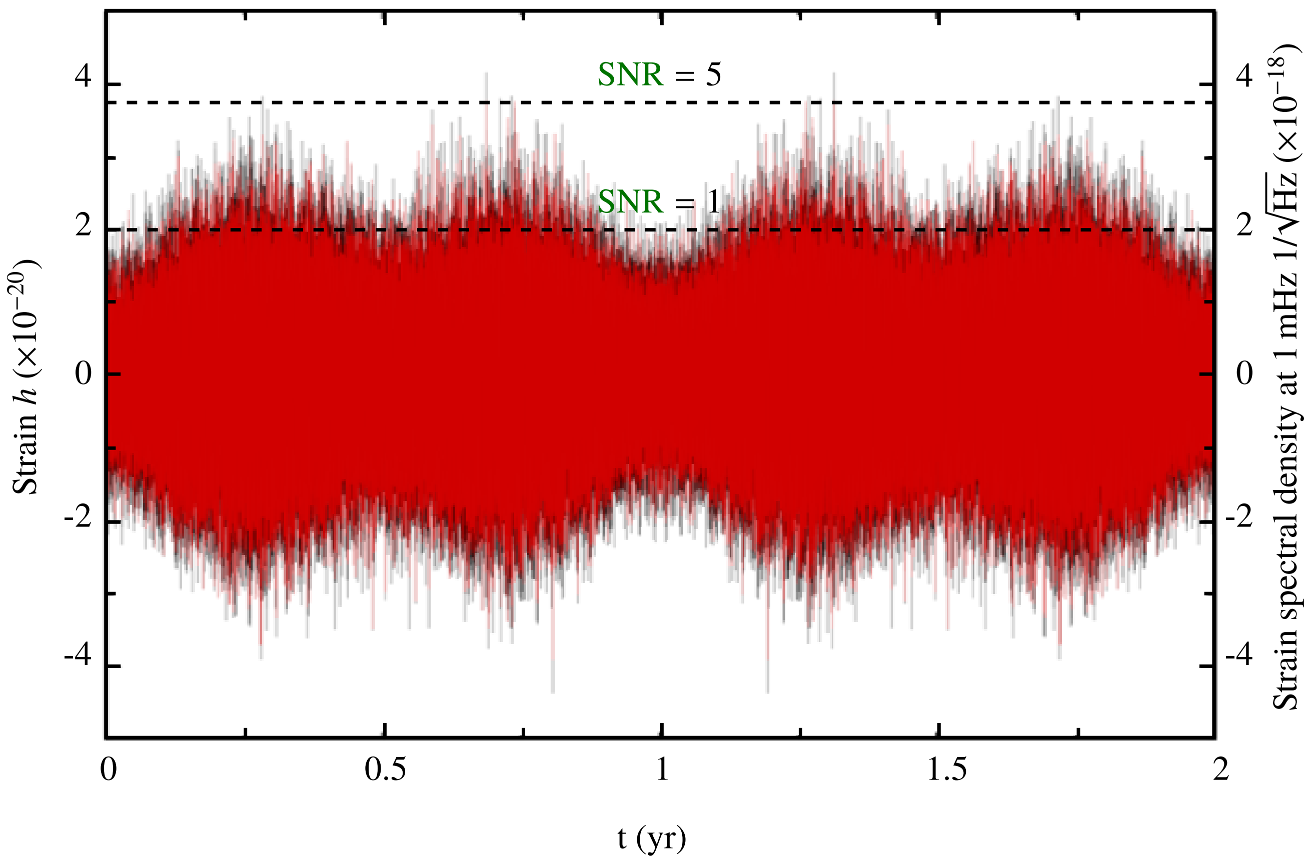
- Many of the binaries are close (within a few kpc) resulting in high signal-to-noise detection ratios of >50 and allowing detailed study of the sources

- For many hundreds, the frequency and phase evolution can be studied, enabling the study of the physics of tides and mass transfer in unprecedented detail
  - The extreme conditions of short orbital periods, strong gravitational fields and high mass-transfer rates are unique in astrophysics

- eLISA observations can determine distances and inclinations
  - including distances to binaries close to the Galactic centre, a complementary population to that to be observed by Gaia

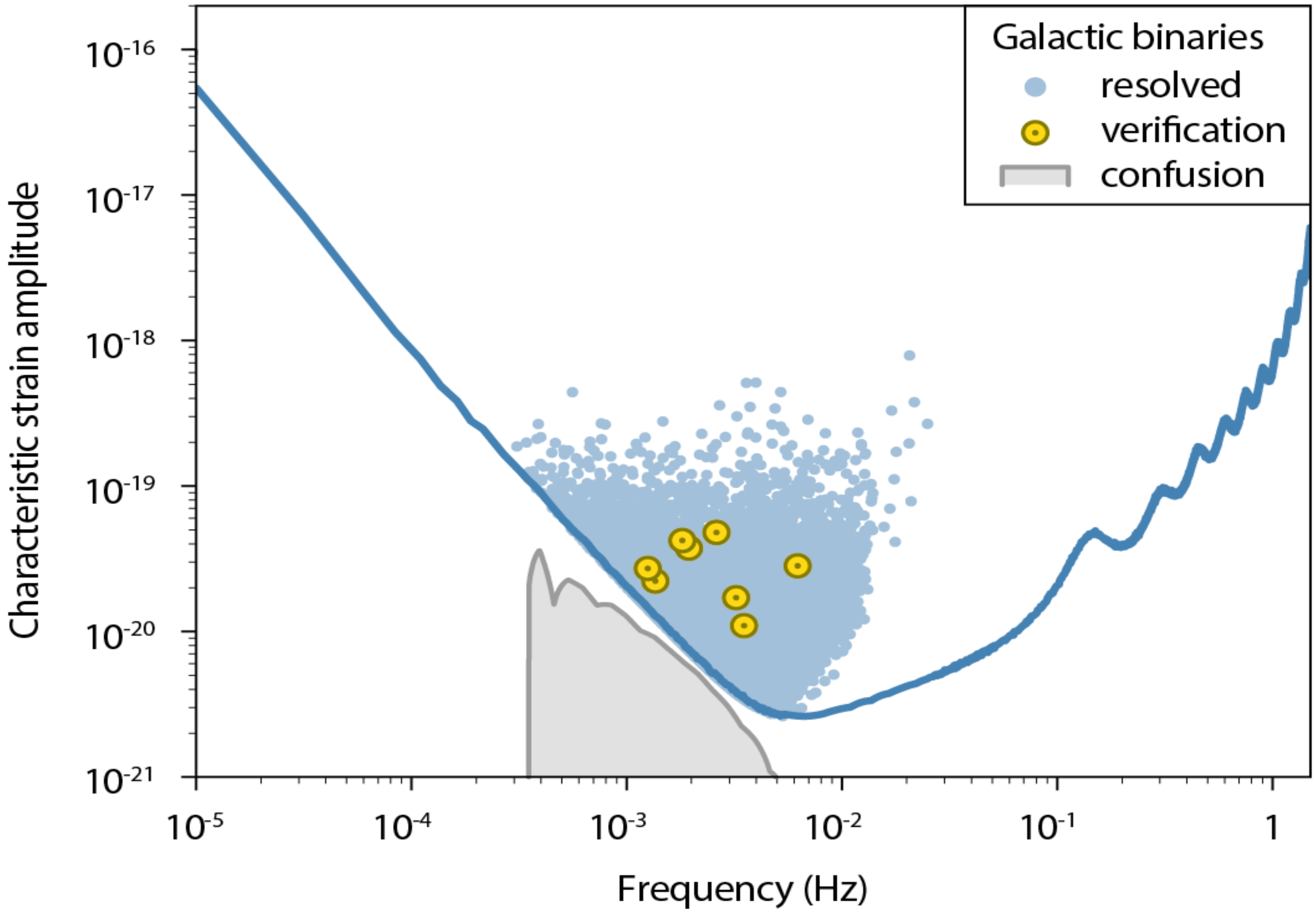
Ultra-compact stellar-mass binaries

- Millions more will form a foreground unresolved signal
- The level and shape of the foreground will constrain the relative contributions of thin disk, thick disk and halo populations and their properties



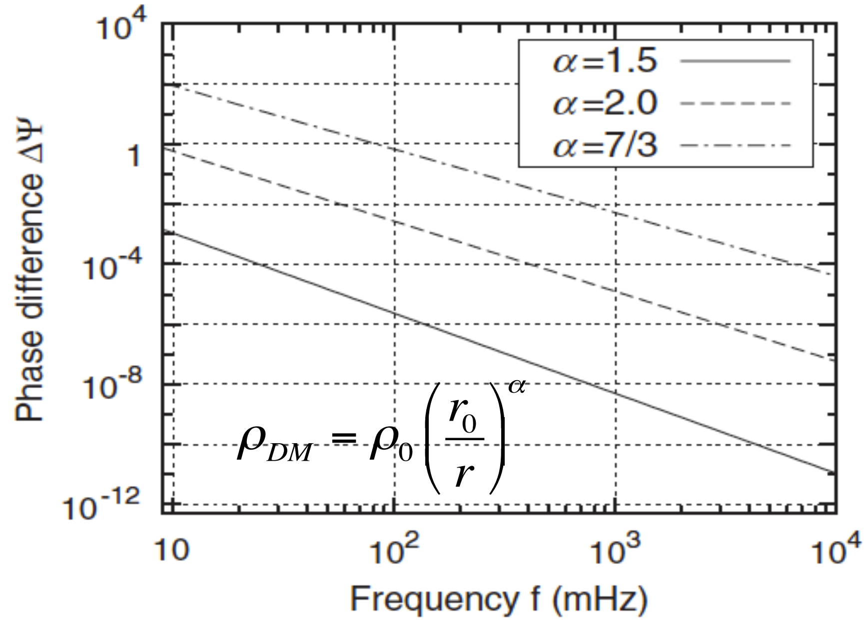
Ultra-compact stellar-mass binaries

- Eight currently known binaries will be detected – and will act as verification signals
  - Ground-based observations make it very likely that many more will be known before eLISA launches



eLISA as Dark Matter Probe

- Dark Matter spike around BH changes inspiral GW phase
- Sensitive even to non-interacting Dark Matter



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New Probe of Dark-Matter Properties: Gravitational Waves from an Intermediate-Mass Black Hole Embedded in a Dark-Matter Minispike

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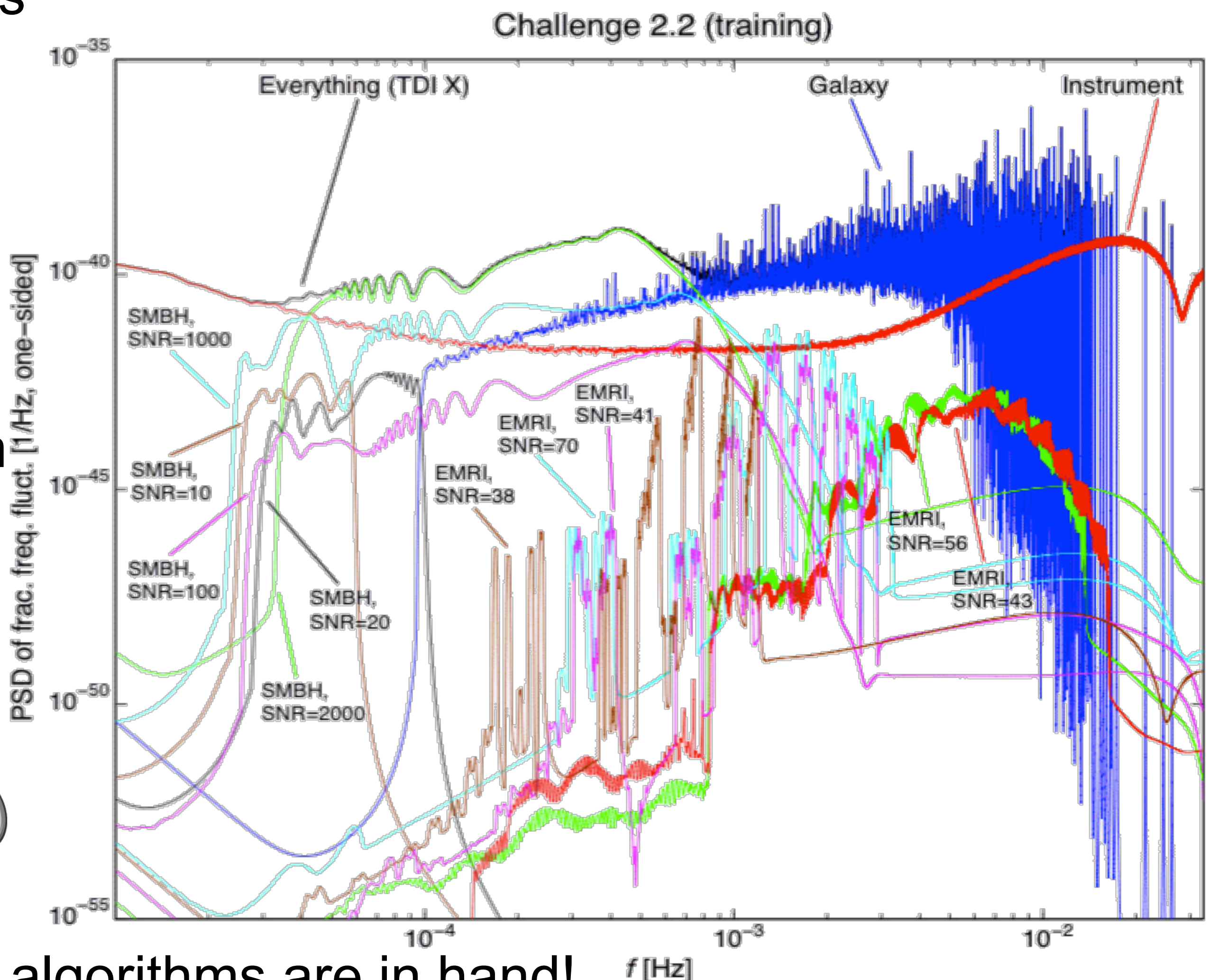
LISA Mock Data Challenge

- Practicing data analysis on synthetic data
- Blind international challenge
- Full eLISA data stream
  - Instrumental noise
  - 4 MBH events
  - 5 EMRI events
  - 26.1 million Galactic binaries



- Effective data analysis algorithms are in hand!

Some history

- How do you construct a spaceborne detector?
  - Simple! Just fly a ground-based interferometer on a big spacecraft
  - *This was in fact a suggestion made in the early-to-mid 1970s when a NASA study talked about using an orbiting machine to extrude aluminium beams to construct a km-scale cross-shaped frame*
- These early thoughts quickly developed with the realisation that the “mirrors” in the interferometer could be mounted on separate drag-free spacecraft, avoiding the need for huge structures
  - *This development also paved the way to the much longer armlengths that are now planned for eLISA*
- By the end of the 1970s the basic measurement ideas that we see today in eLISA were largely established
- The early 1980s saw the identification of convenient orbits for the spacecraft and also some refinement of the measurement techniques to allow compensation of laser phase noise

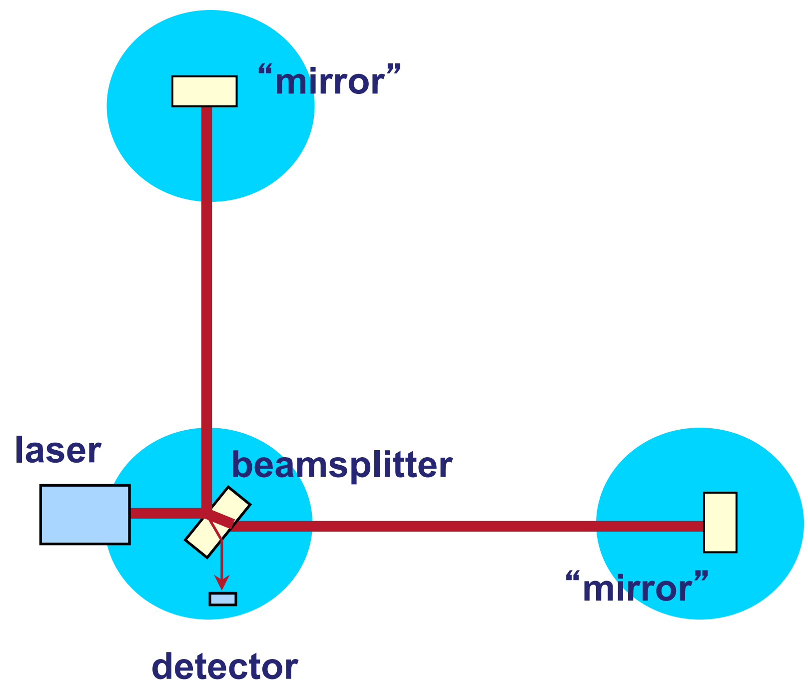
LISA / NGO / eLISA

- Originated over 1970-85: conceptual thinking by Bender, Faller, Hall and Hils
- Until 2012 a collaborative ESA / NASA mission called LISA
- Cluster of 3 S/C in heliocentric orbit at 1 AU
- Equilateral triangle with 1 (eLISA) to 5 (LISA) Million km armlength
- Cluster trailing the Earth by 20°
- S/C contain lasers and free-flying test masses
- Measurement band: 0.05 to 100 mHz
- 2+ (eLISA) to 5+ (LISA) years operational lifetime
- Reformulated as NGO in 2012 as a European-only mission
- Reproposed as eLISA for L2

Detection principle

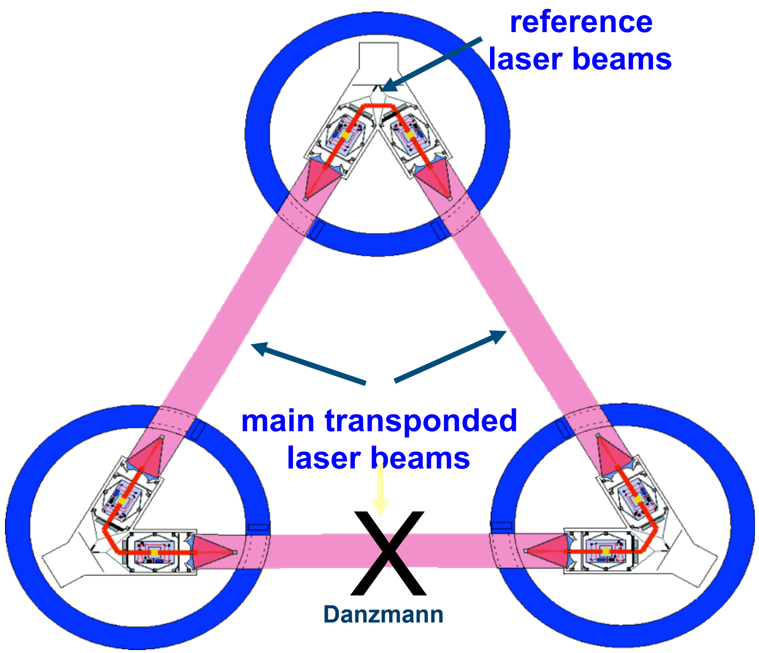
- As for the ground-based systems, a Michelson interferometer is used to measure the relative lengths of arms formed between "free" test masses
  - But now the test masses are shielded by drag-free spacecraft

- For good low frequency response we want very long arm lengths
  - Diffraction then means that little laser power is intercepted by a distant spacecraft – even if reasonably large telescopes are used to transmit and receive the light
  - Laser transponders used, rather than mirrors



LISA / eLISA interferometry – simplest concept

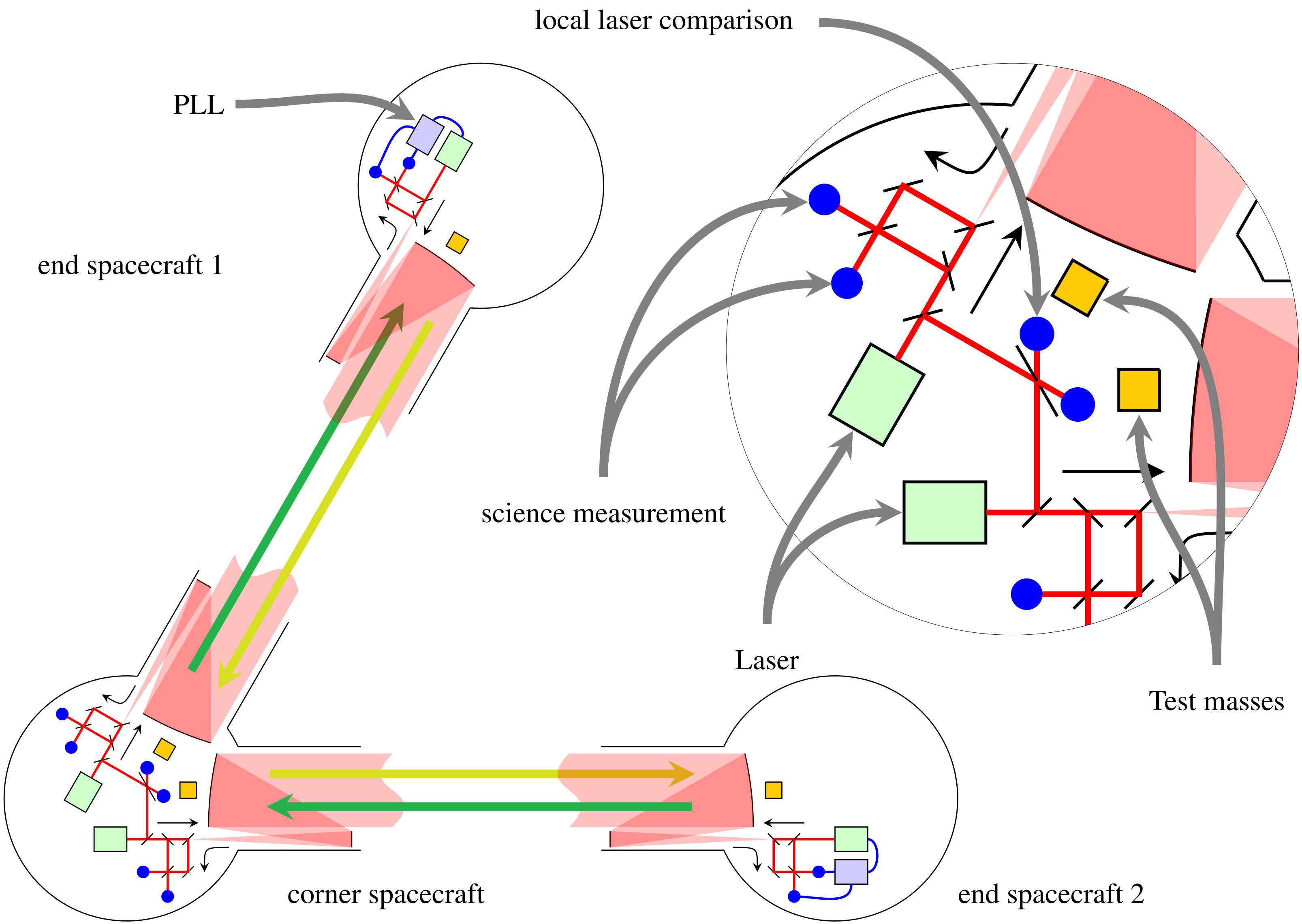
- In full 3-arm system, each S/C carries 2 lasers, 2 telescopes, 2 test masses
- Laser beams probe inter-spacecraft distance and also intra-spacecraft position of each free-flying test mass
  - Overall measurement strategy is designed to make the long armlength measurement insensitive to S/C motion
- 6 main beat signals plus 6 reference beat signals formed
  - Reference beam beat signals can be used to phase-lock lasers in same S/C
  - Laser noise from sum of main beat signals
  - Gravitational wave signal from difference
- Effectively a Michelson interferometer with a 3rd arm in the full LISA design; descoped to 2 arms for eLISA



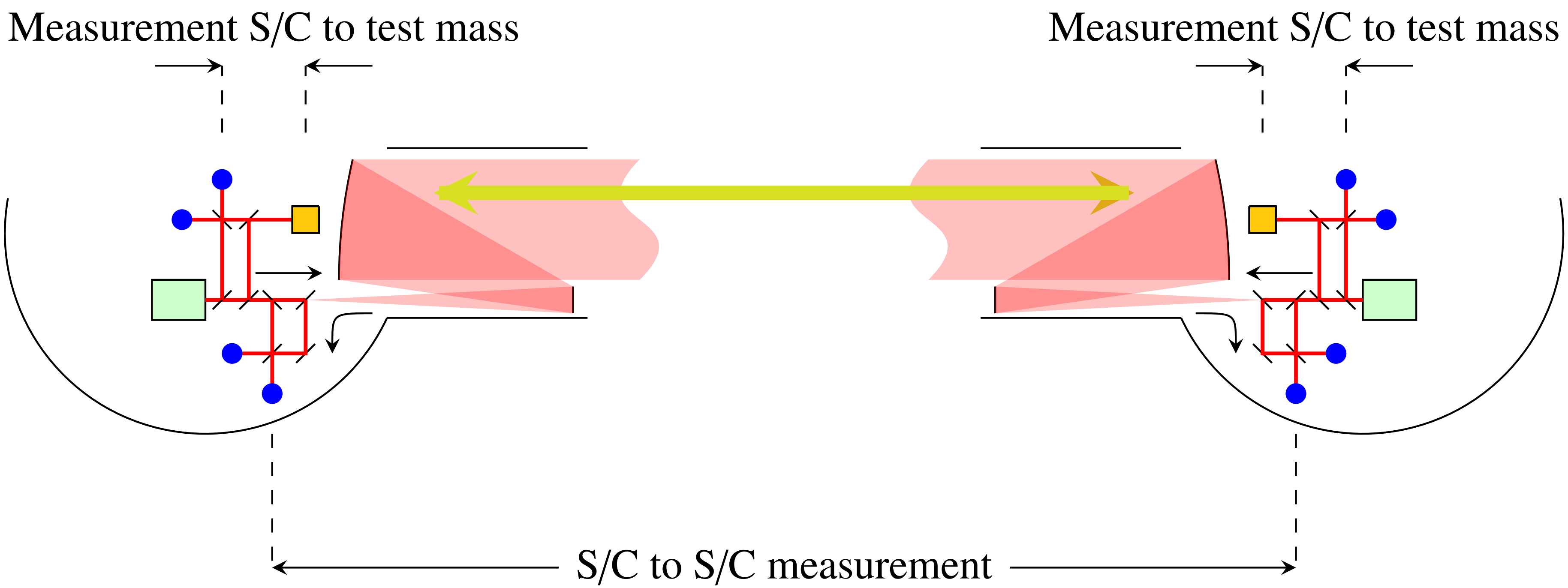
Armlength slowly changing as orbits evolve

Fringe rate of a few MHz makes interferometer self-calibrating based on laser wavelength

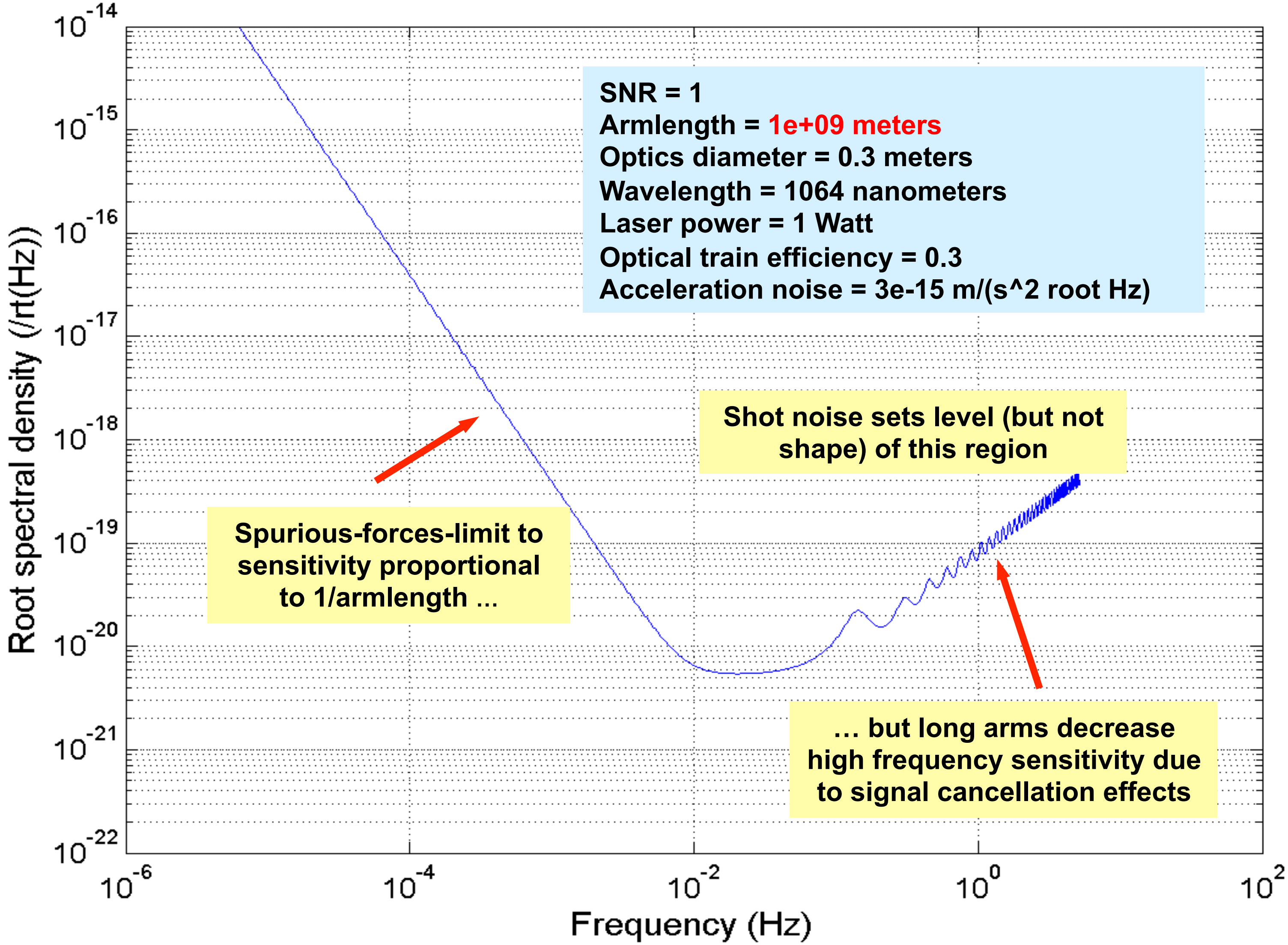
Measurement overview



Split measurement approach



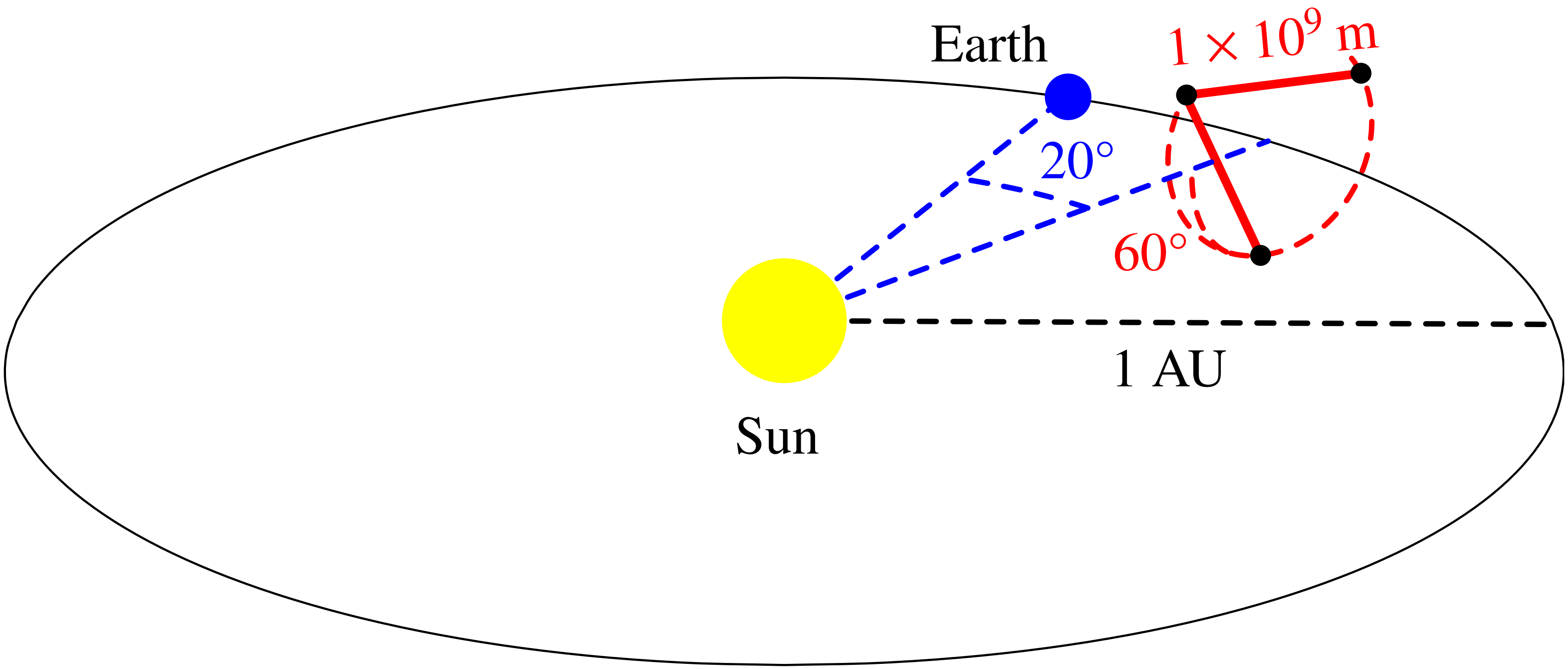
Typical sensitivity curve



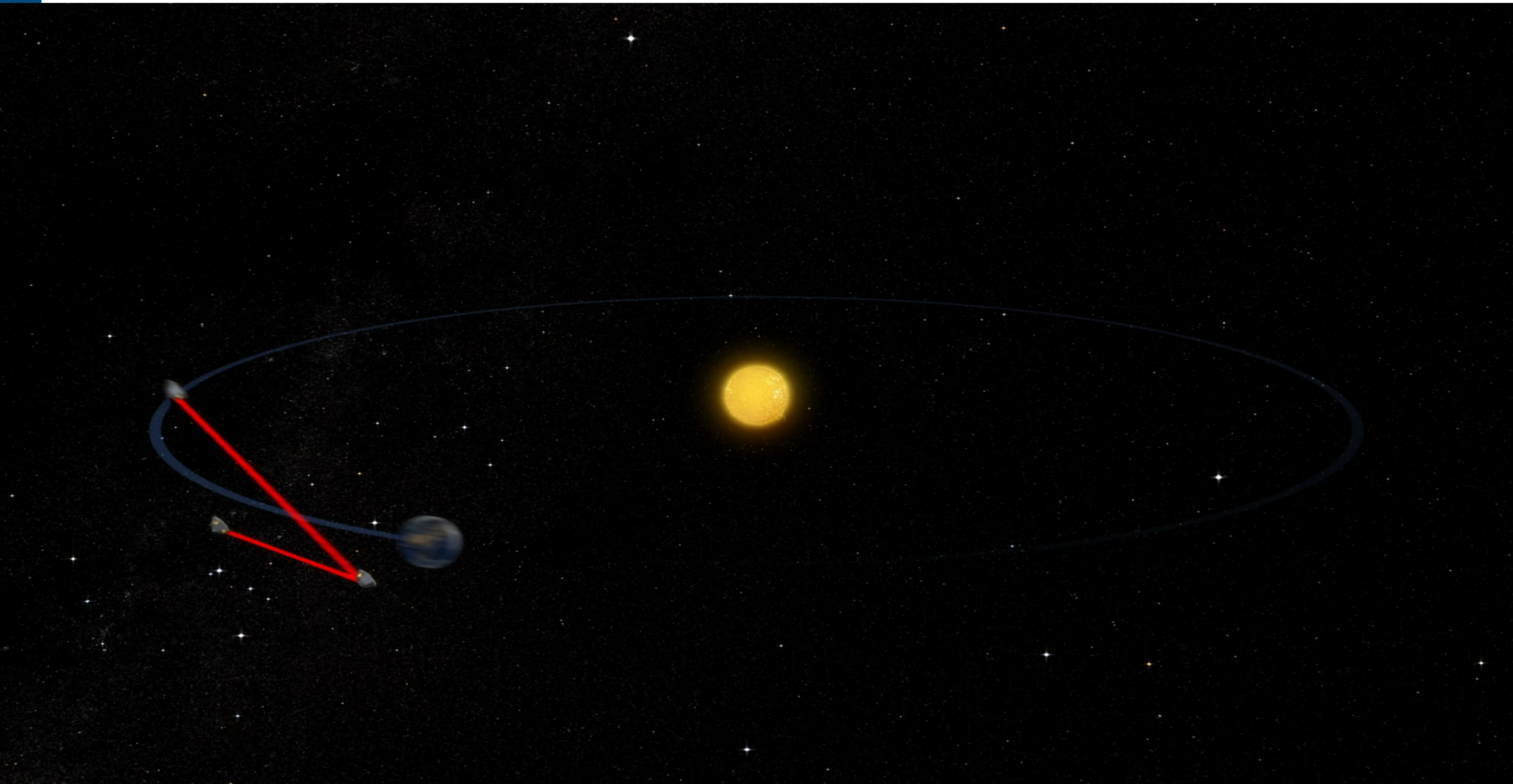
eLISA design details

- Armlength 1 Million km, 2 arms
- Identical Mother/Daughter S/C, based on LISA Pathfinder
- 3 spacecraft in a V-configuration, nominal angle 60°, max Doppler <10m/s
- Minimize out-of-plane pointing variation to drop point-ahead-actuator on Optical Bench
- Heliocentric slow drift-away orbit, Earth-leading or trailing, starting 10°, 60° inclination wrt ecliptic, range to Earth not exceeding 50 Mkm after 4 years and 65 Mkm after 6 years;
- Launch to (sub-)GTO, separation from LV, escape and transfer to final orbit by jetisonable propulsion module
- Two Soyuz-FRG (or shared Ariane V launch)
- Mission lifetime: baseline 2 years + 2 + 2
- Downlink capability from each S/C, one-axis HGA + LGAs

eLISA orbital configuration

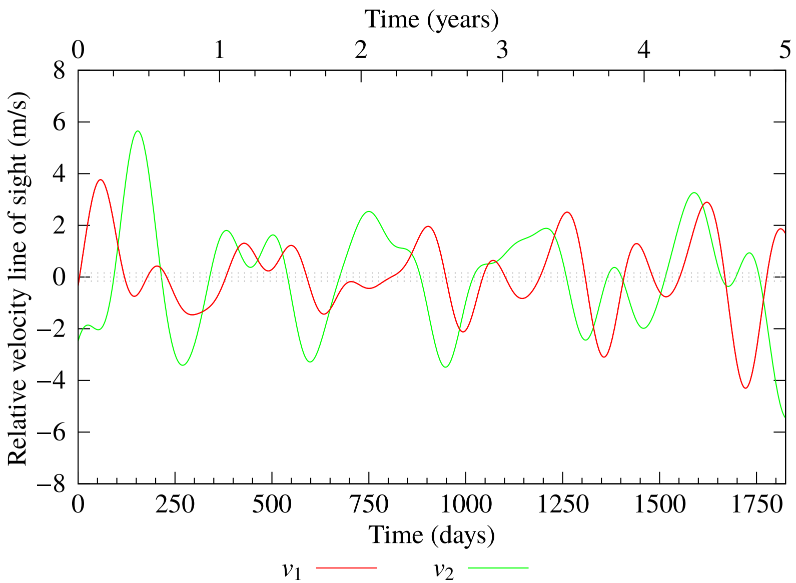


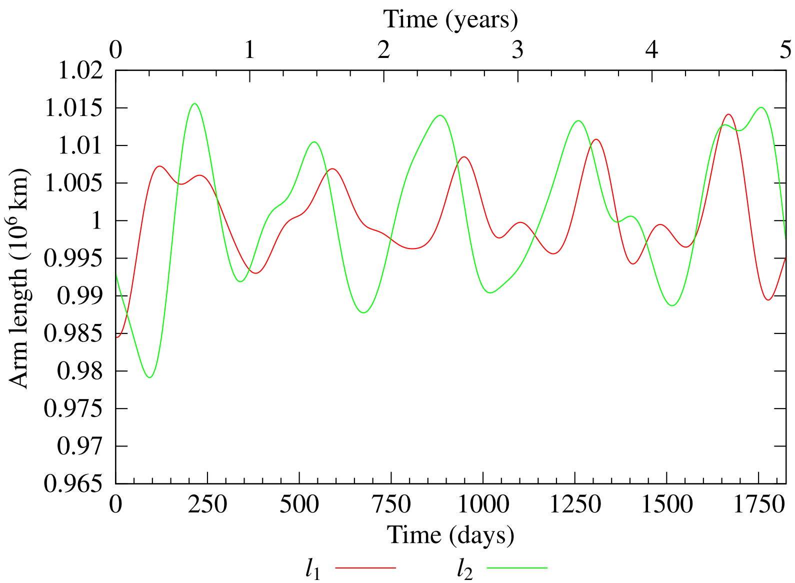
eLISA heliocentric orbit



Orbital evolution

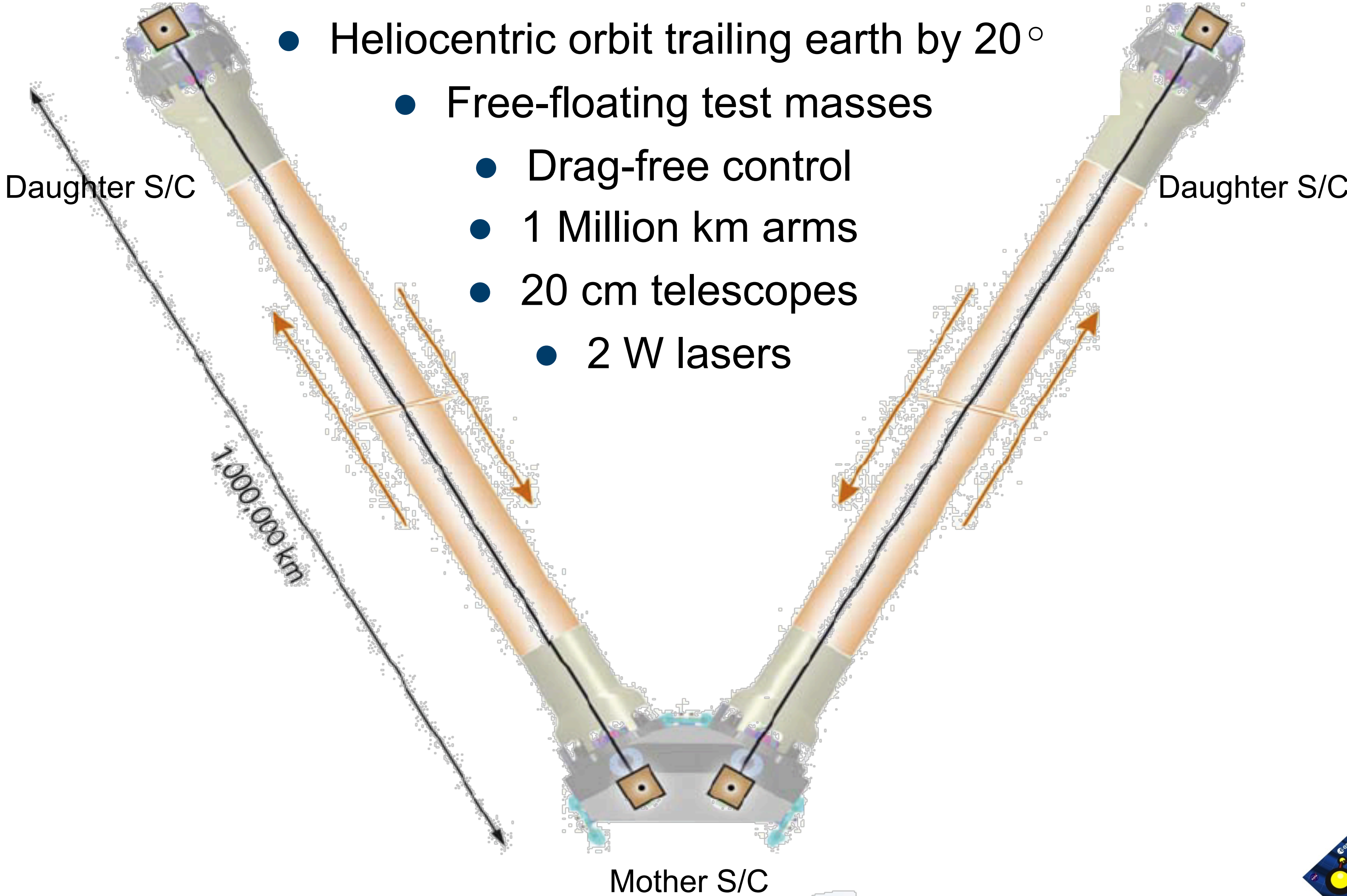
- Designed to
  - keep beat notes within range of precision measurement by the phasemeter
  - maintain acceptable distance of constellation to allow communication



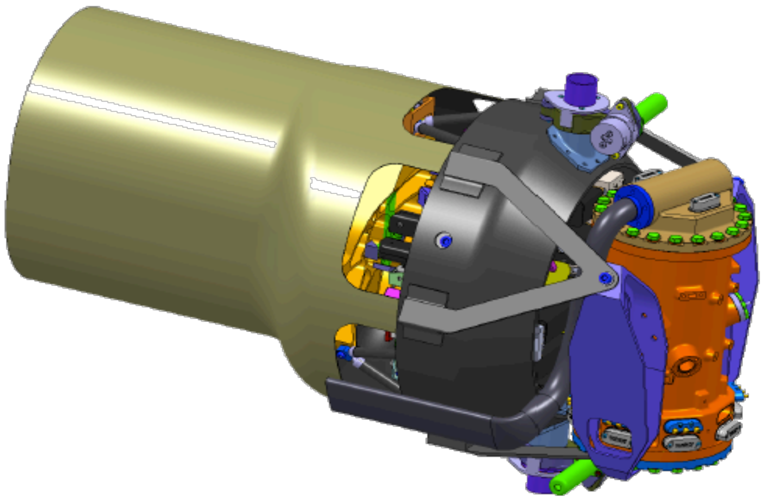


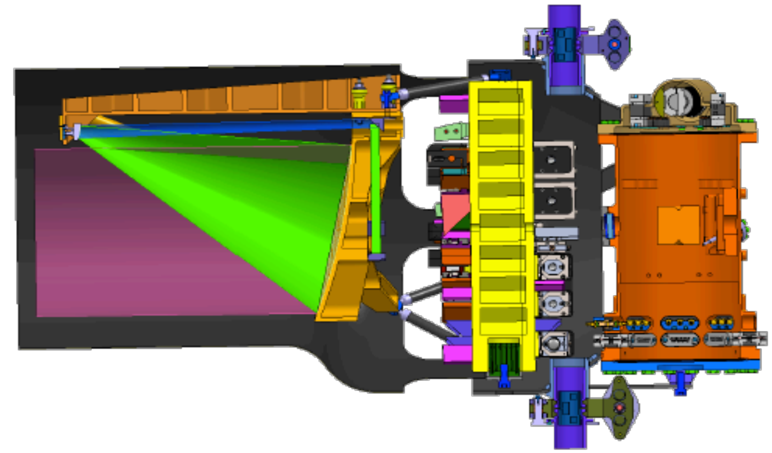
eLISA configuration

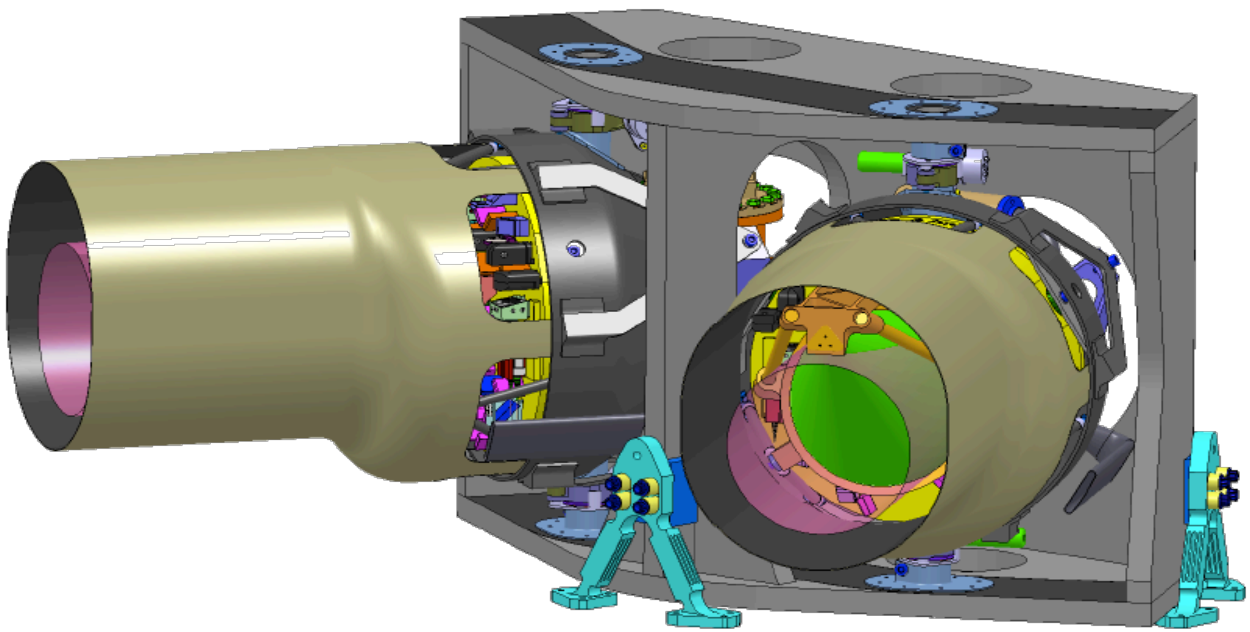
- Heliocentric orbit trailing earth by 20°
- Free-floating test masses
- Drag-free control
- 1 Million km arms
- 20 cm telescopes
- 2 W lasers



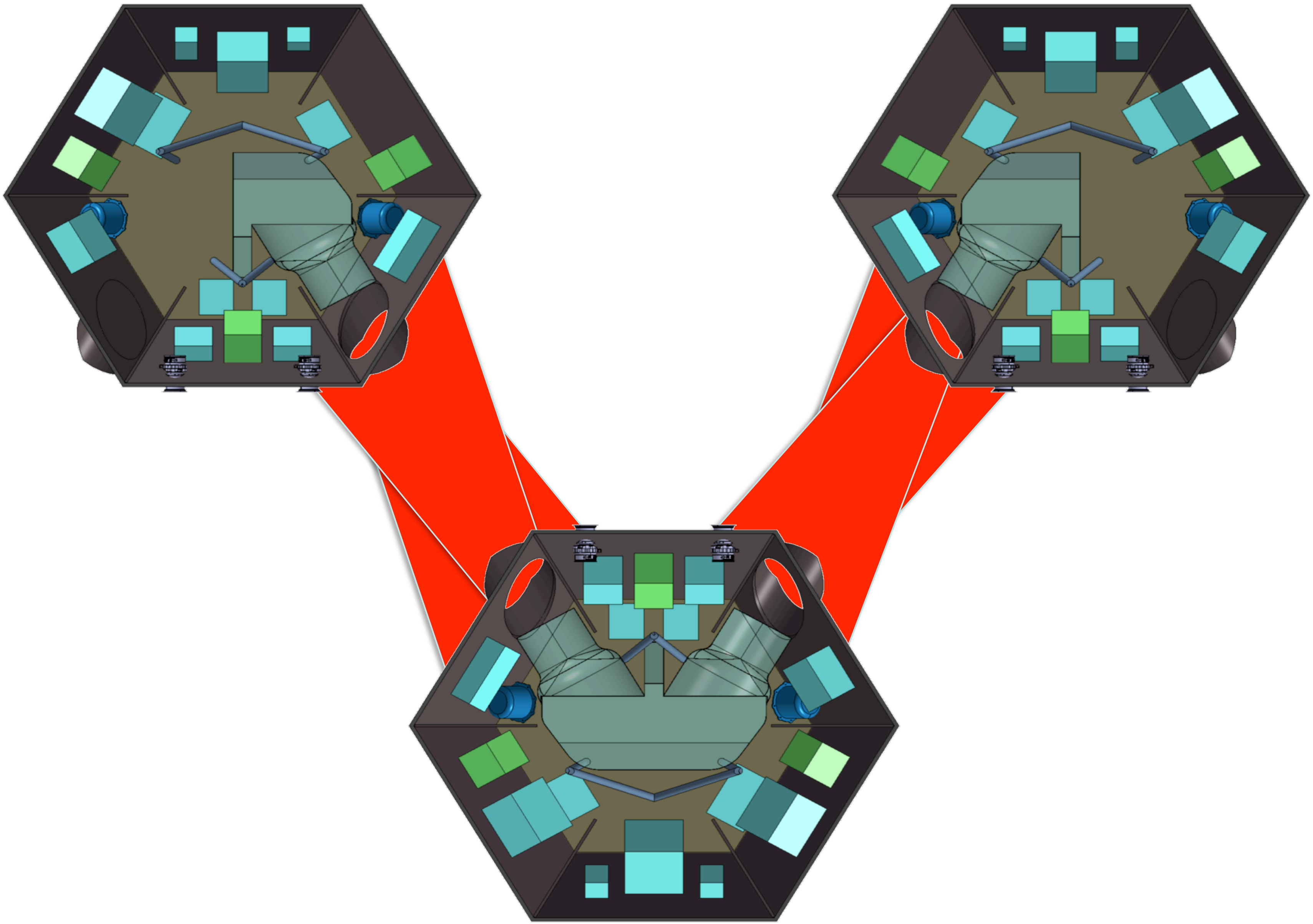
Optical Assembly



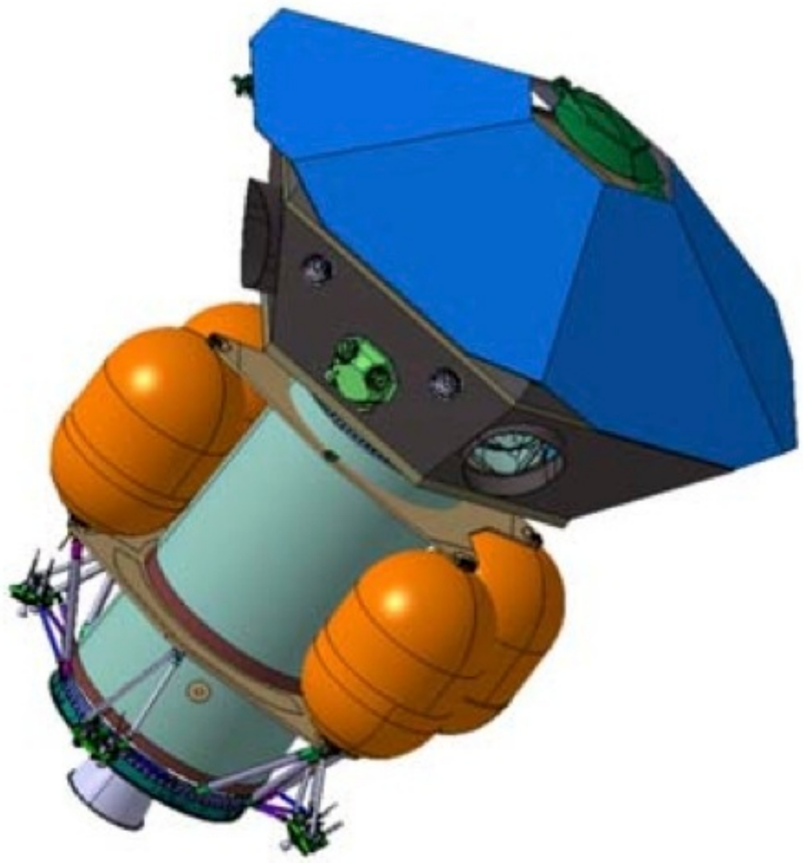




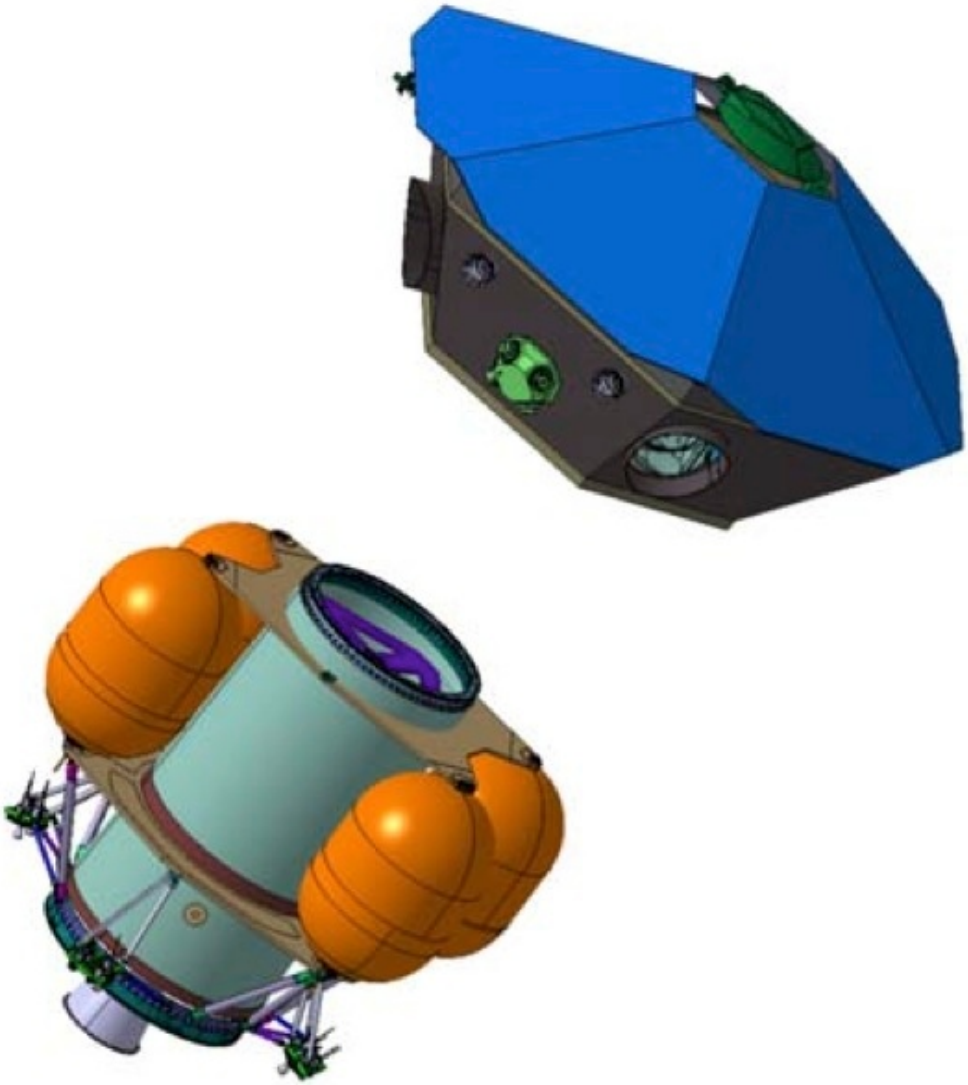
eLISA layout



En-route

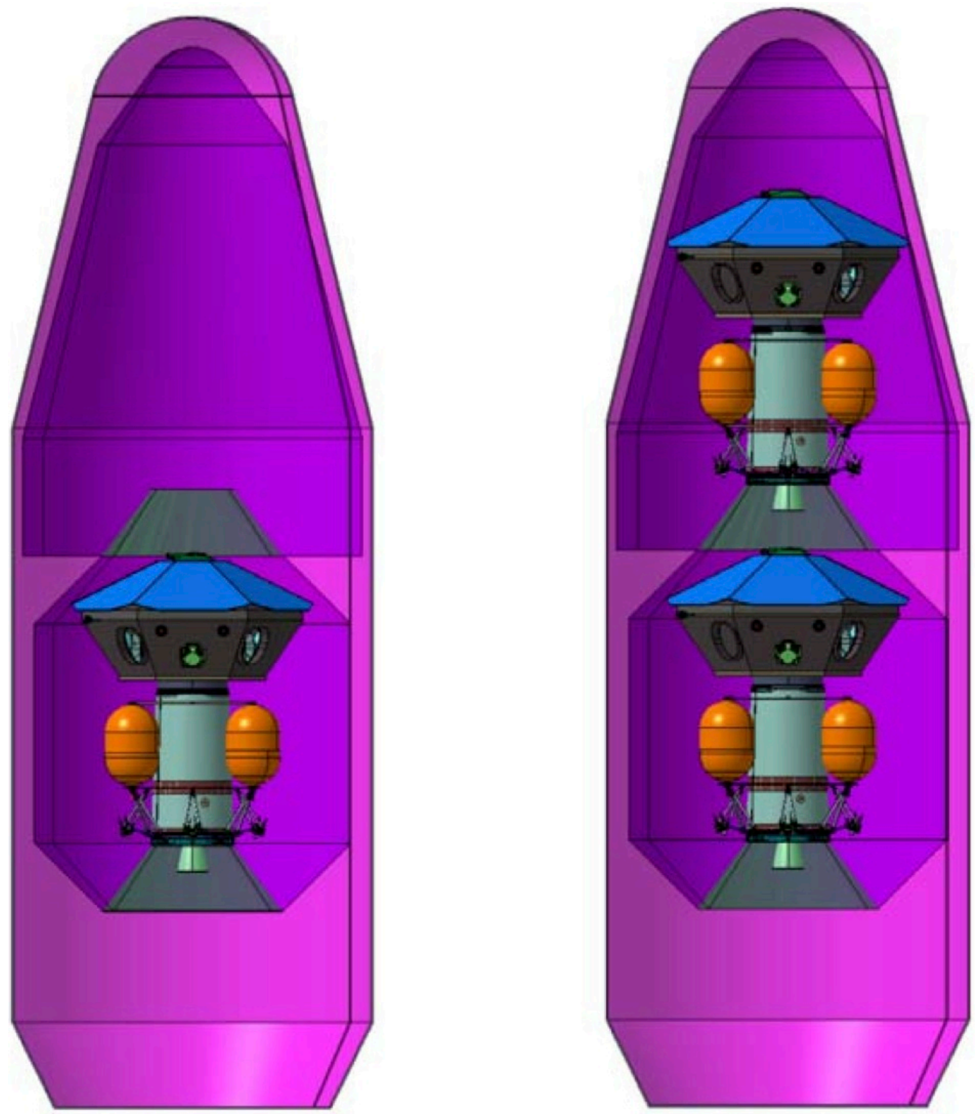


Sciencecraft separates from propulsion module

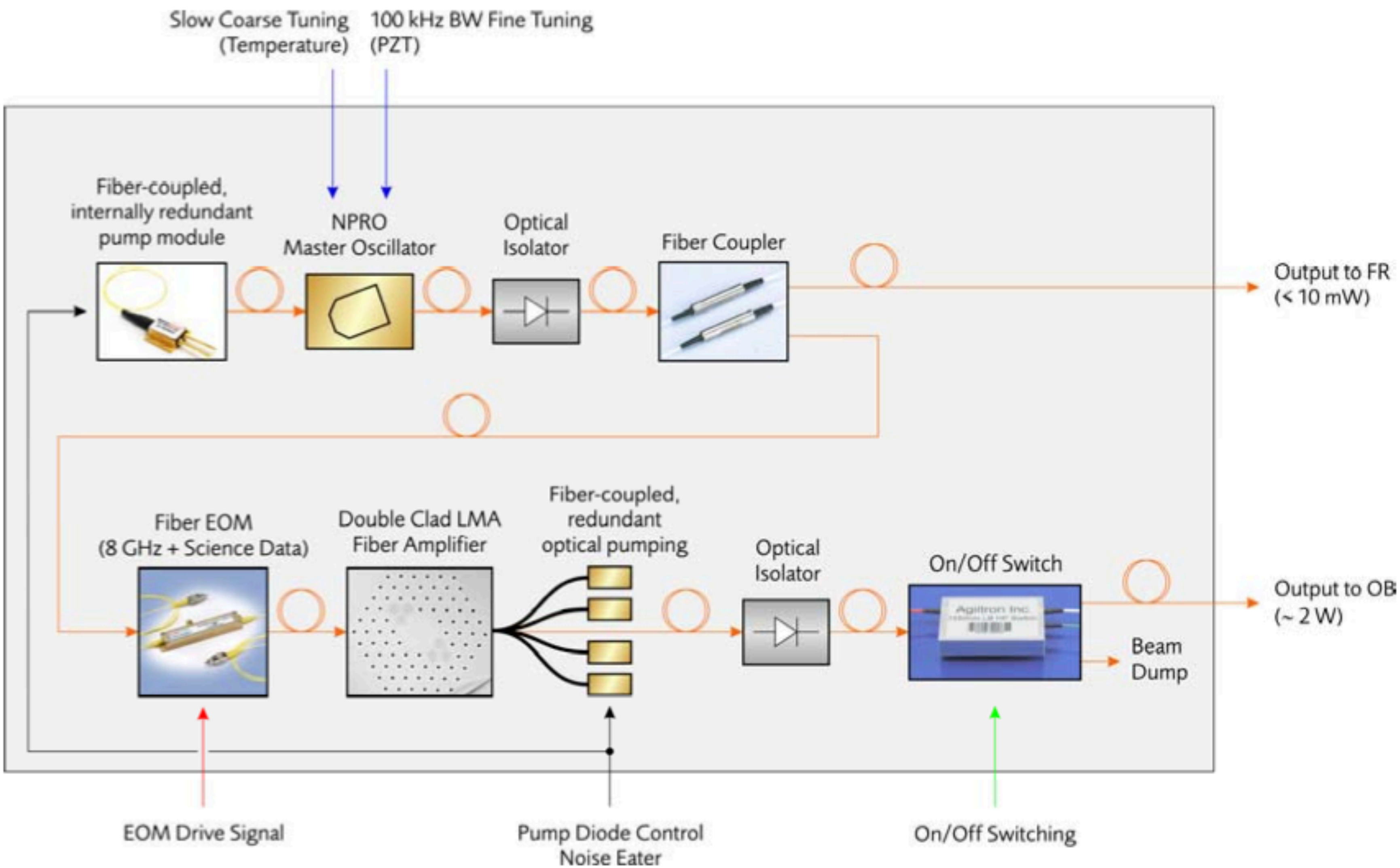


Possible twin Soyuz launch configuration

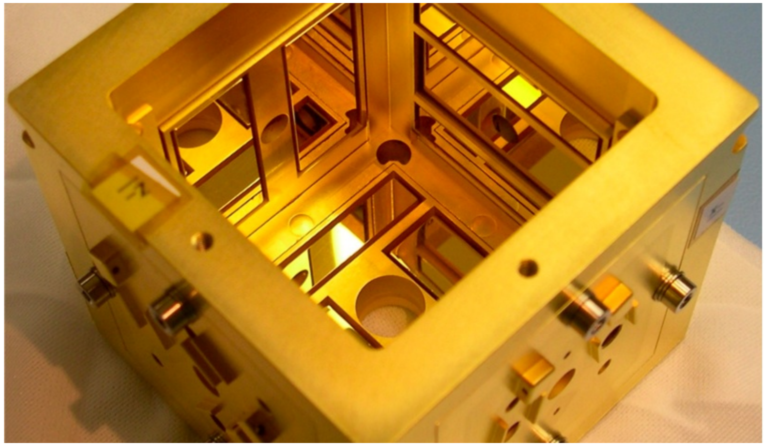
- Other launch options possible

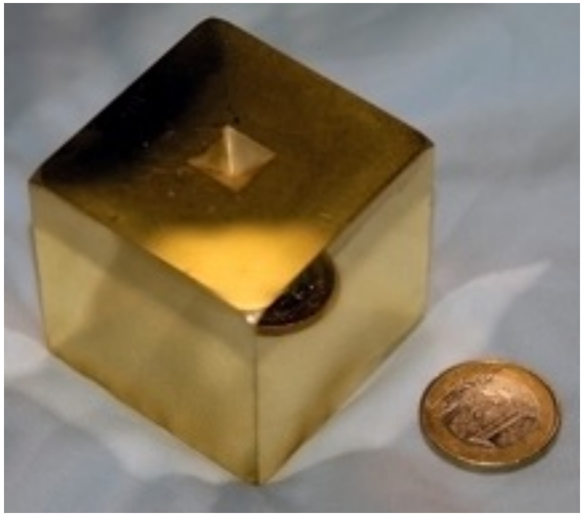


Laser system – proven technology

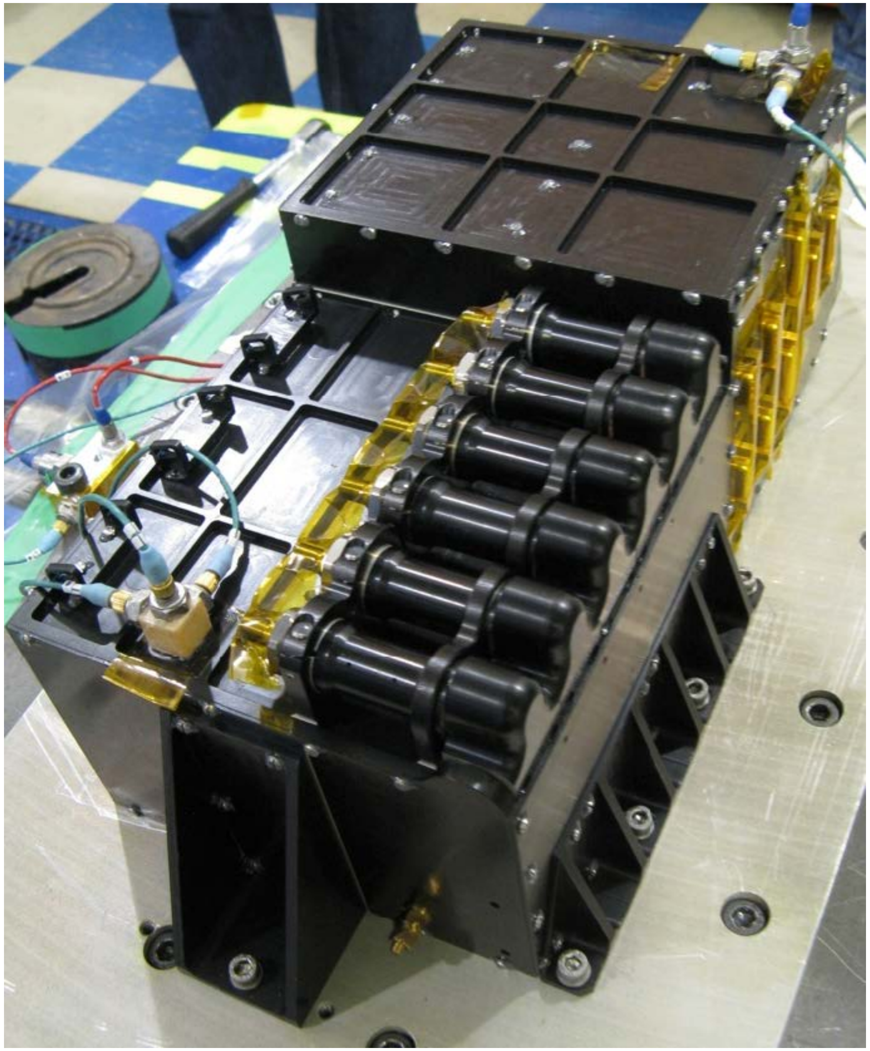


The inertial sensor – proven technology





Charge management – proven technology



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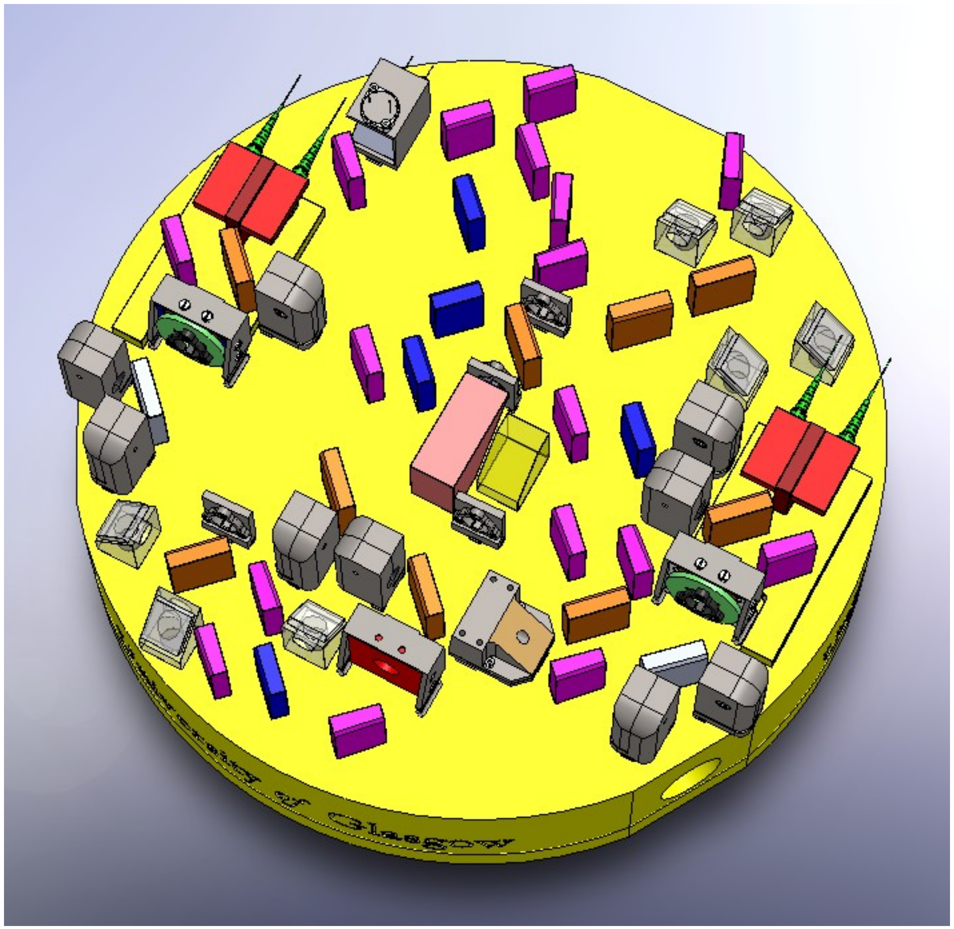
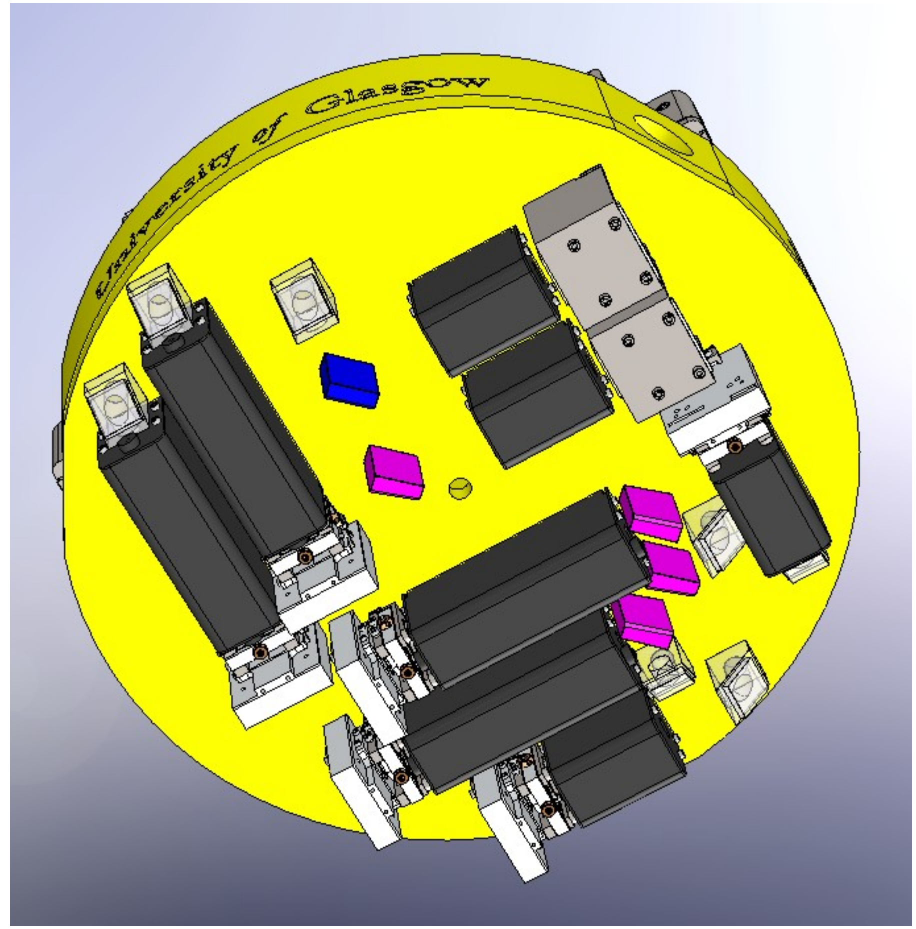
LPF Optical Bench – proven technology

… evolves to the eLISA design

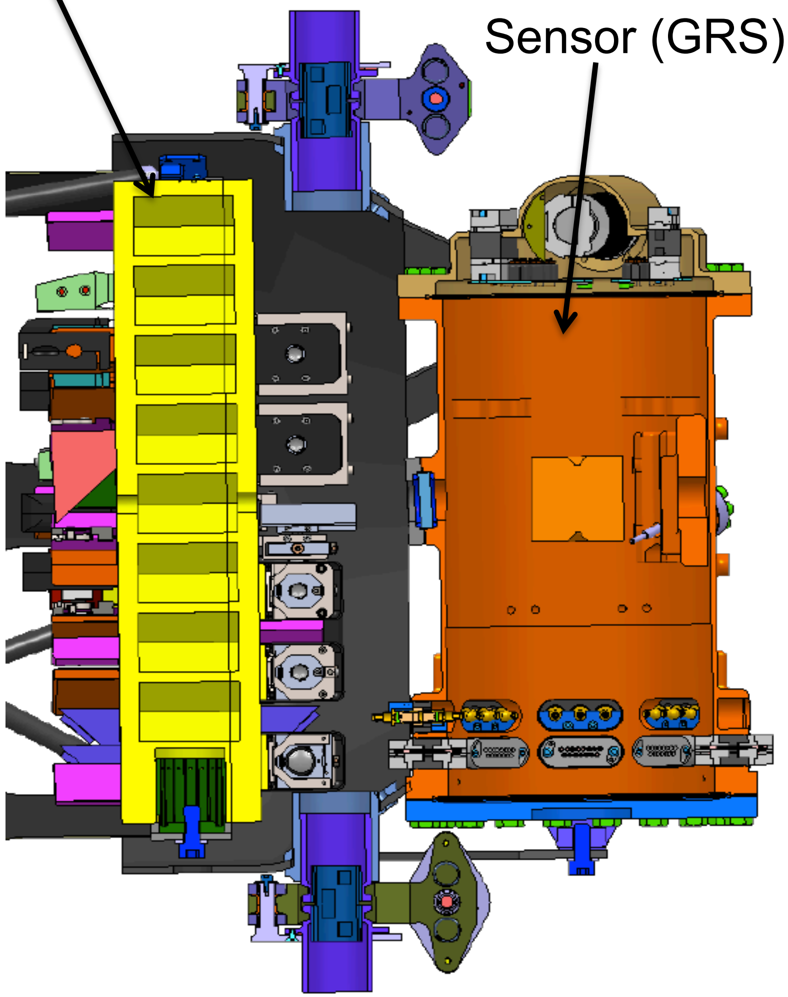
- New two-sided design to minimise size



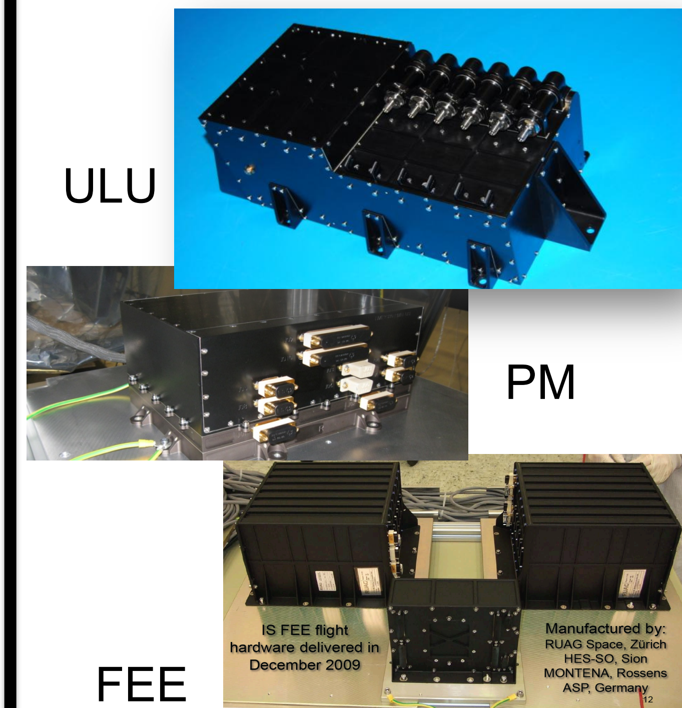


The overall Science Instrument

- 2 on Mother
- 1 each on Daughter



S/C mounted



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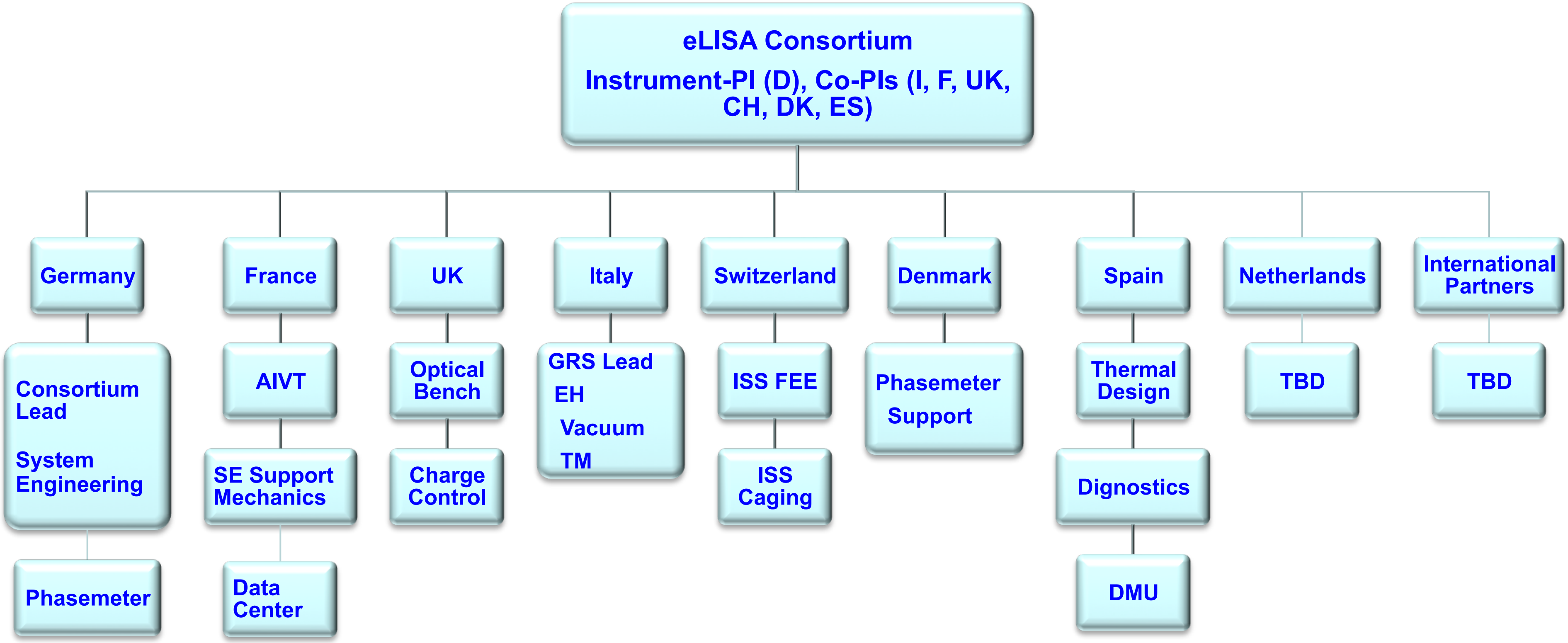
eLISA Consortium provides Science Instrument



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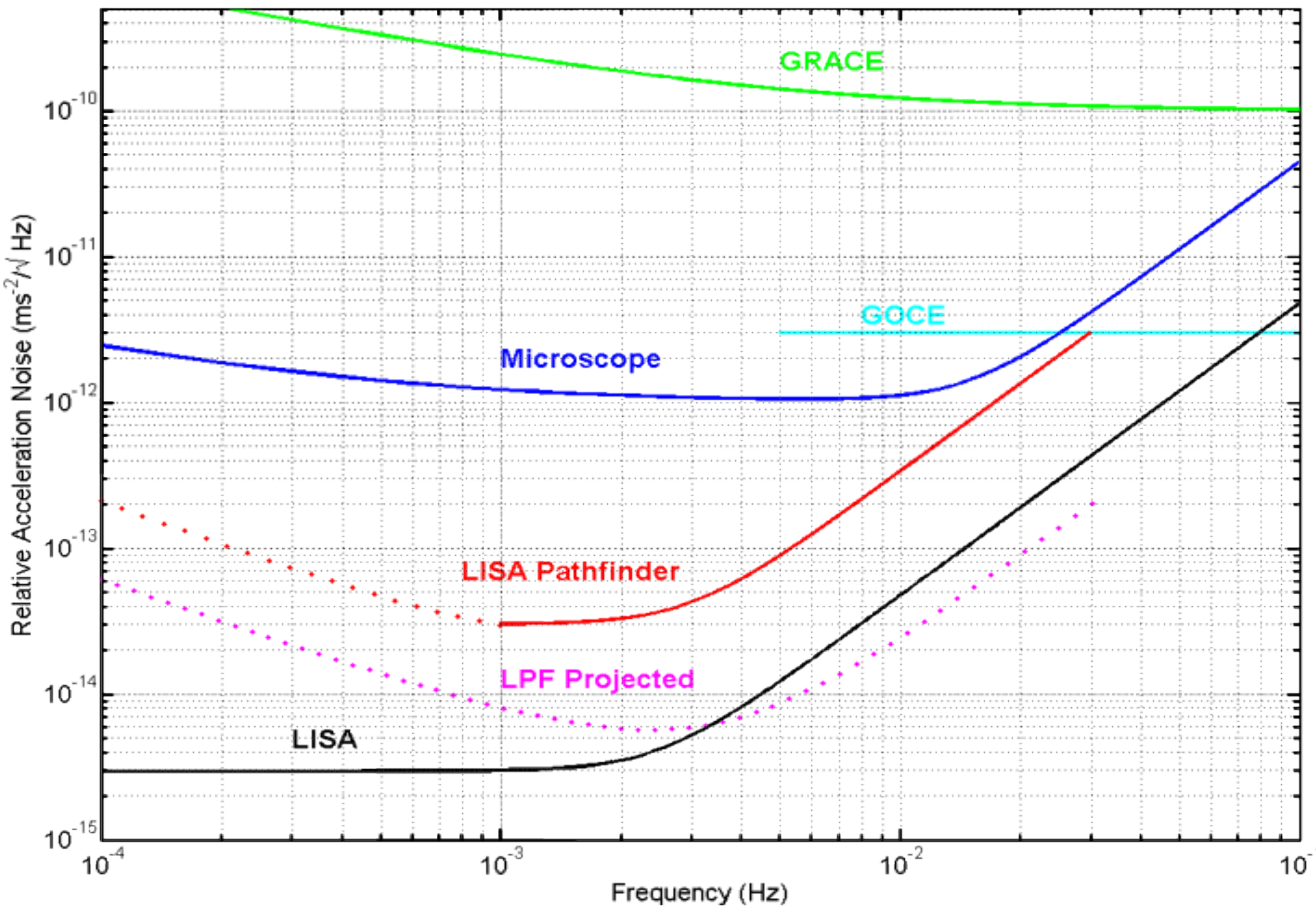
LPF expected Performance



The summary …

- LISA first proposed around 1992
- Over 20 years the general mission approach has been extremely well-studied
- There has been a vast amount of LISA-targeted technology development for LISA Pathfinder and also for specific LISA-style subsystems

- *Roughly 30% of the overall cost of cost of flying a LISA-style gravity wave interferometer has already been expended bringing the field to its high level of technological maturity*

Conclusions

- The scientific case for eLISA is completely compelling
  - and is completely independent of detections – or their absence – by ground-based experiments
- The eLISA concept is optimized and delivers the science
  - no other mission concept is competitive on timescale or cost
- With the developments made for LISA Pathfinder, together with other lab-based demonstrations, the technology required for eLISA is mature
- LISA Pathfinder is firmly on-track for a mid 2015 launch
- Programmatically eLISA is fully compatible with an L2 launch in the late 2020s, a timescale that secures the heritage gained from LISA Pathfinder

With eLISA, Europe stands ready to drive forward the new field of gravitational wave astronomy