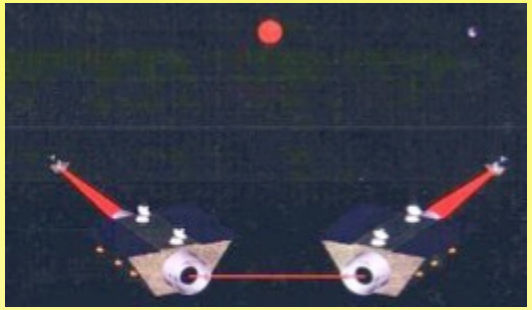
Gravitational Wave Detection from Space: eLISA and LISA Pathfinder

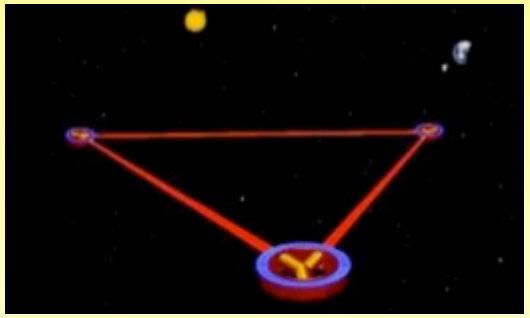
Budapest, 12 November 2013

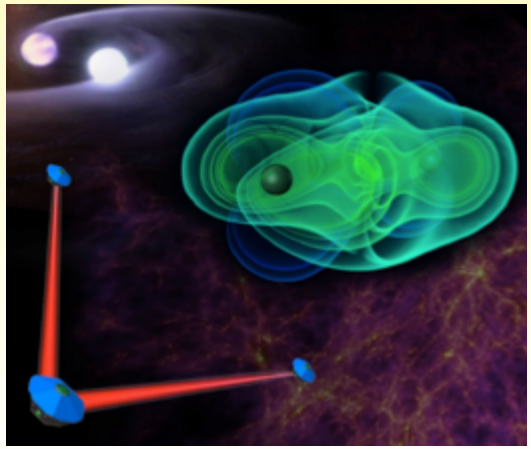
Karsten Danzmann

eLISA: A Mature Concept

- M3 proposal for 4 S/C ESA/NASA collaborative mission in 1993
- LISA selected as ESA Cornerstone in 1995
- 3 S/C NASA/ESA LISA appears in 1997
- Joint Mission Formulation study until 2011
- Reformulation in 2012 as ESA-only NGO mission concept with 1 Mio km arms



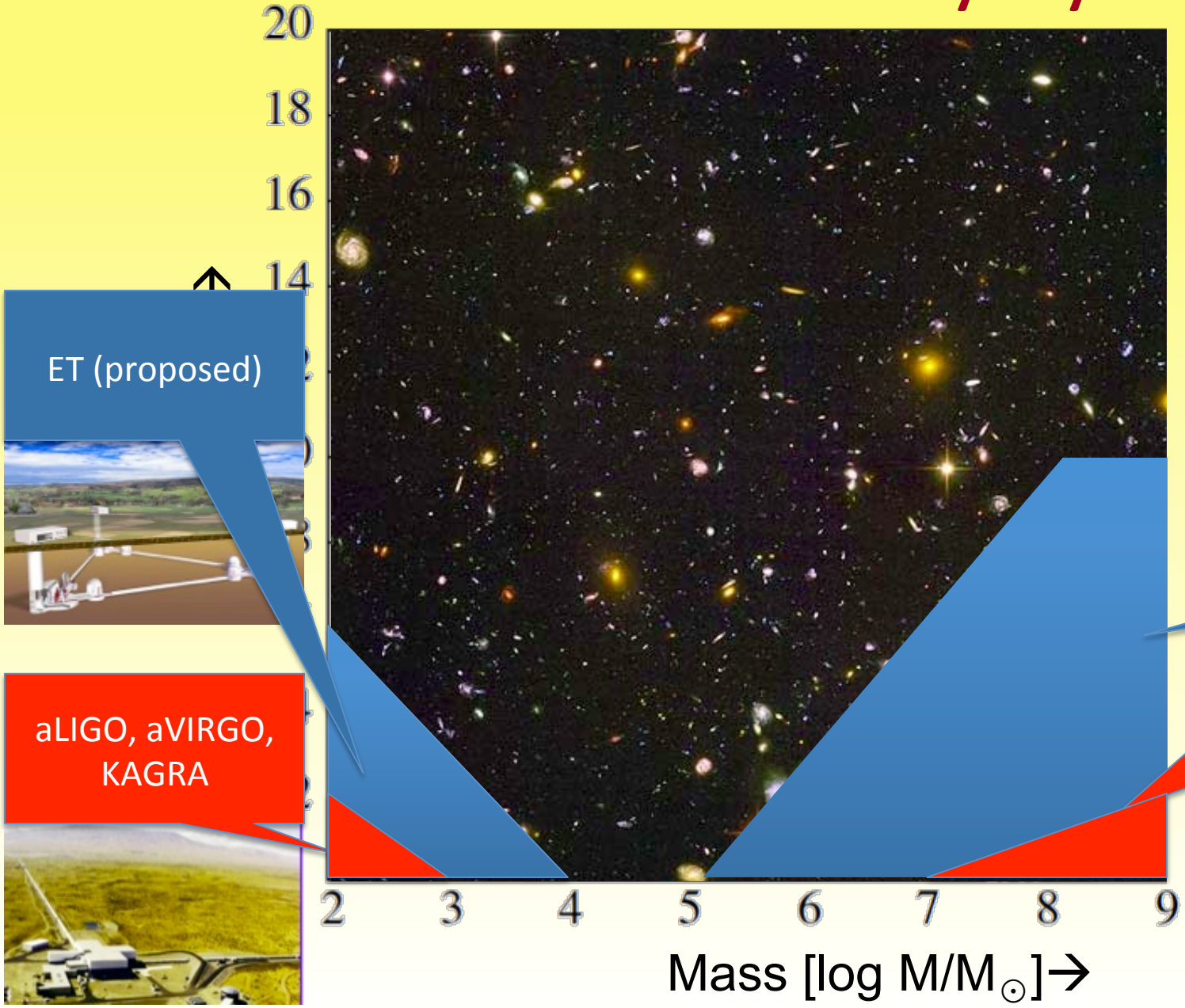




Science around 2030

- Observatories
  - Ground
    - LHC, LSST, (EELT, TMT, GMT), SKA, ALMA, EHT
  - Space
    - JWST, EUCLID, Gaia, WFIRST, eROSITA, GRAVITY
  - Ground-based GW observatories
    - aLIGO, aVIRGO, KAGRA, ET
- Big science questions
  - Cosmic structure formation and Black Hole growth
  - Physics beyond Higgs, supersymmetry, extra dimensions, Phase transitions on TeV scale, cosmic strings, Dark Matter
  - Physics of Dark Energy, gravitation, new fields

Black Hole Astronomy by 2028



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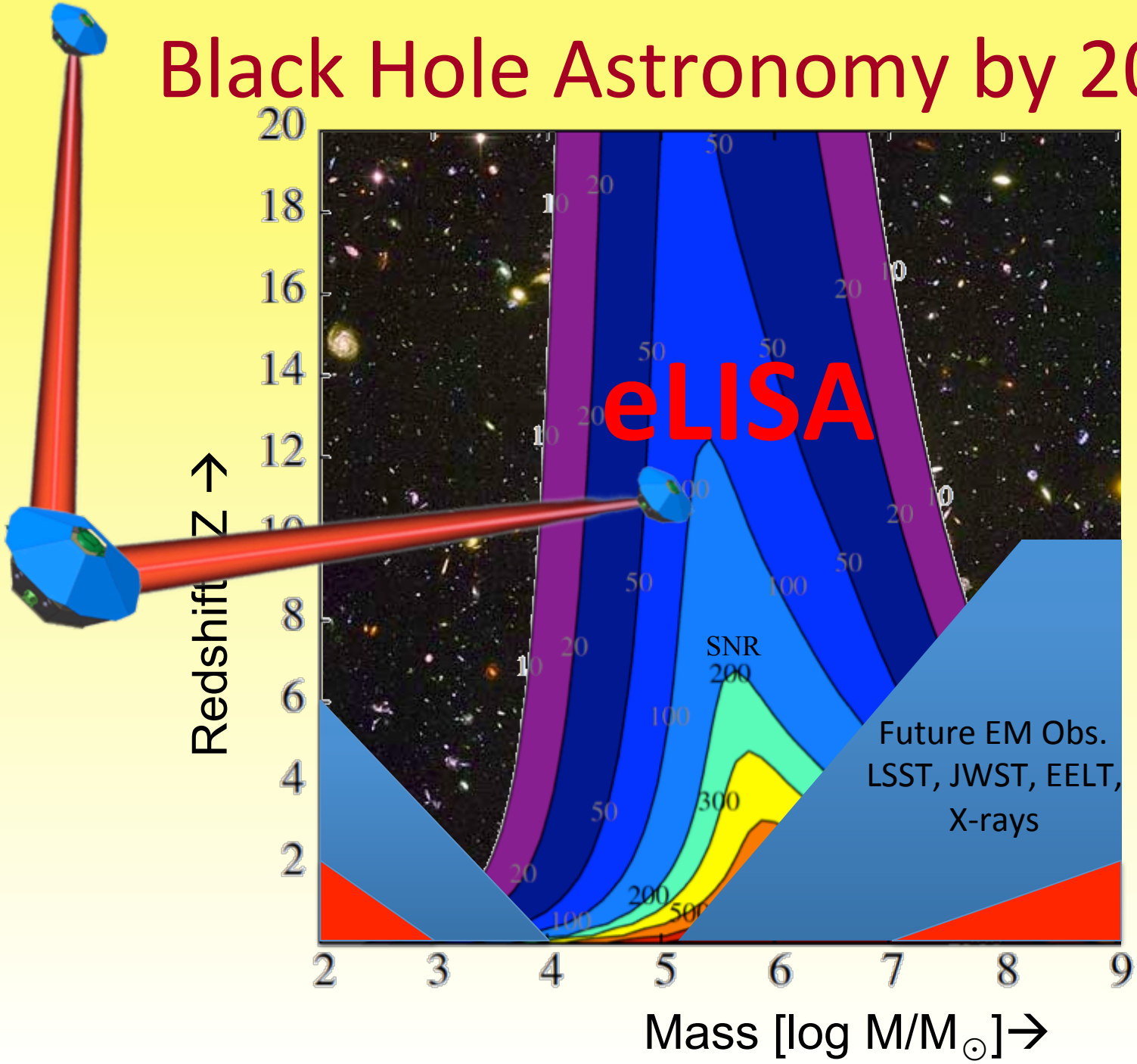

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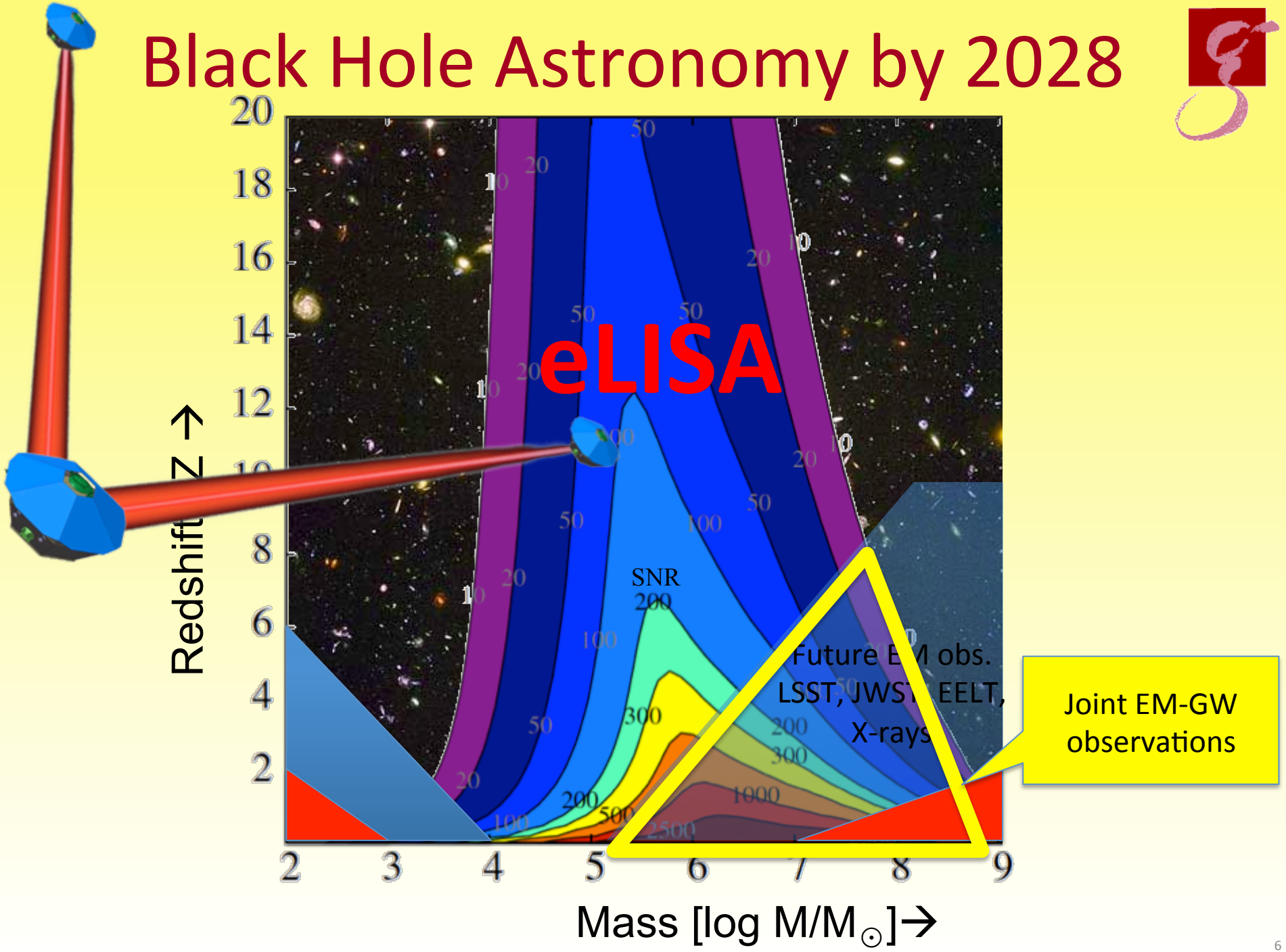
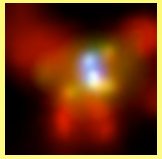


eLISA for Astrophysics, Cosmology, and Fundamental Physics



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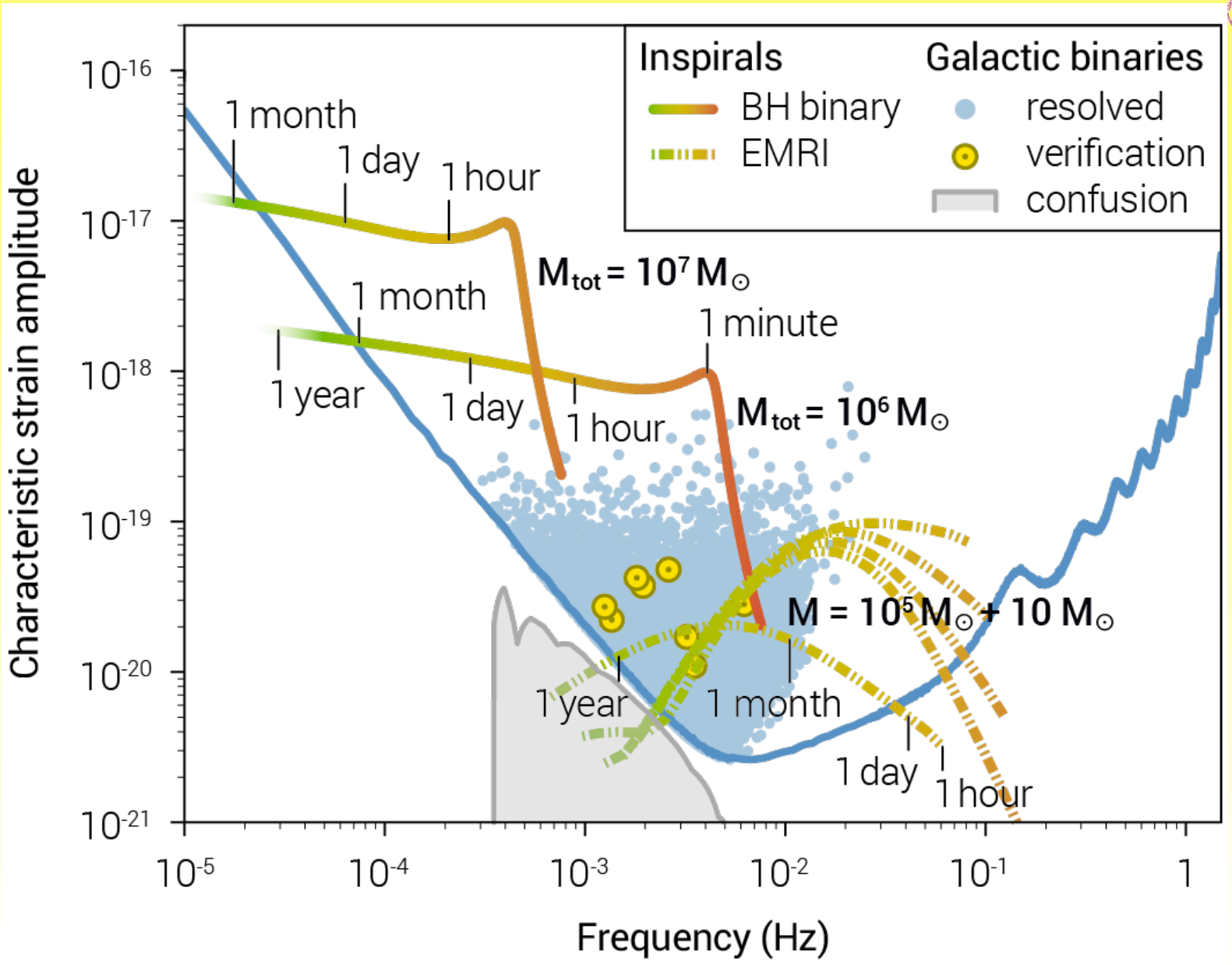
Sensitivity and Black Hole Science

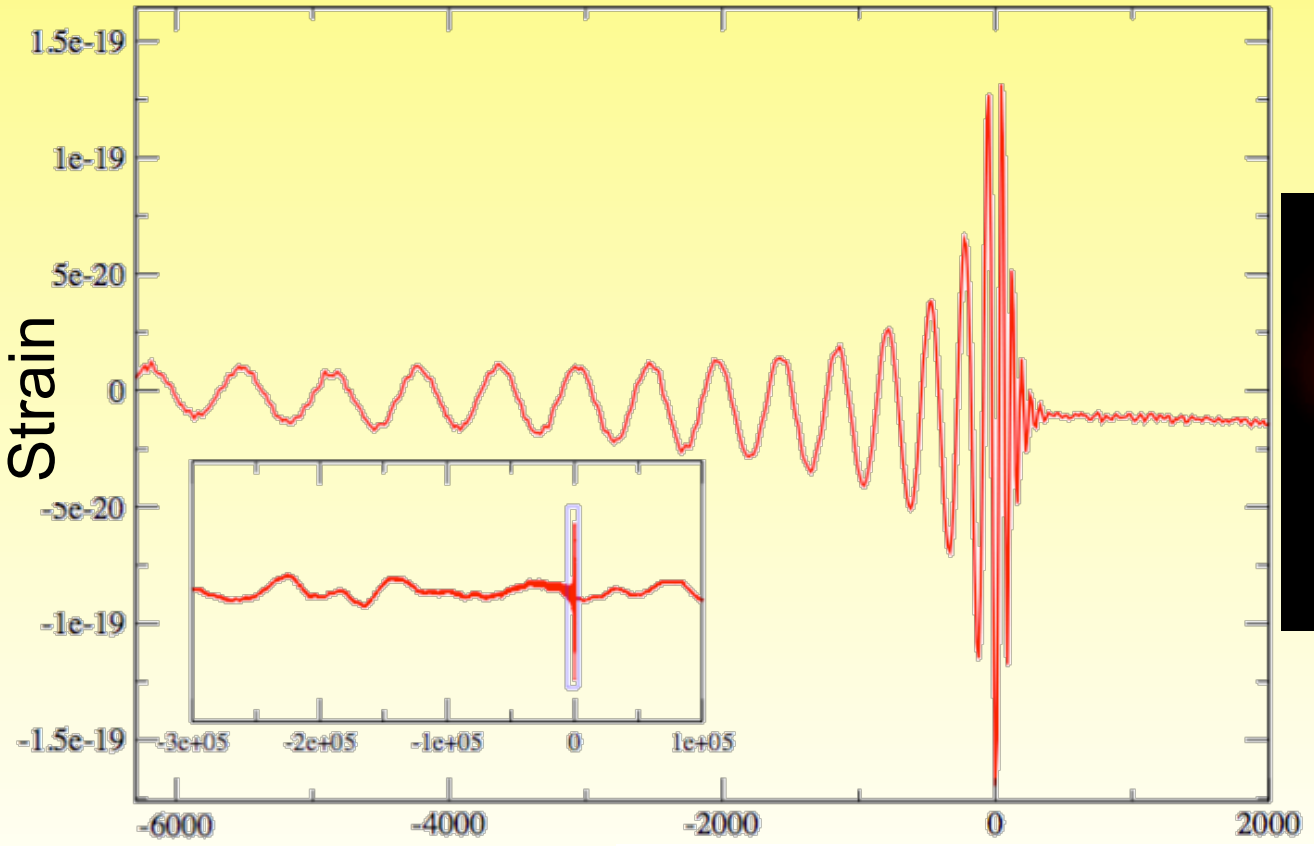


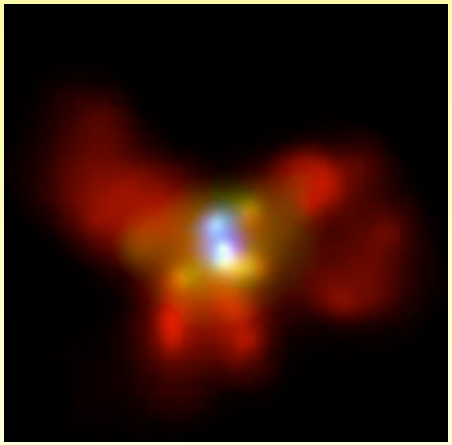
Black Hole Merger Signals far above Noise!

- Simulated eLISA data stream

  $10^5\ M_\odot$ BH binary merger at z=7,

  including instrumental noise (SNR~100)

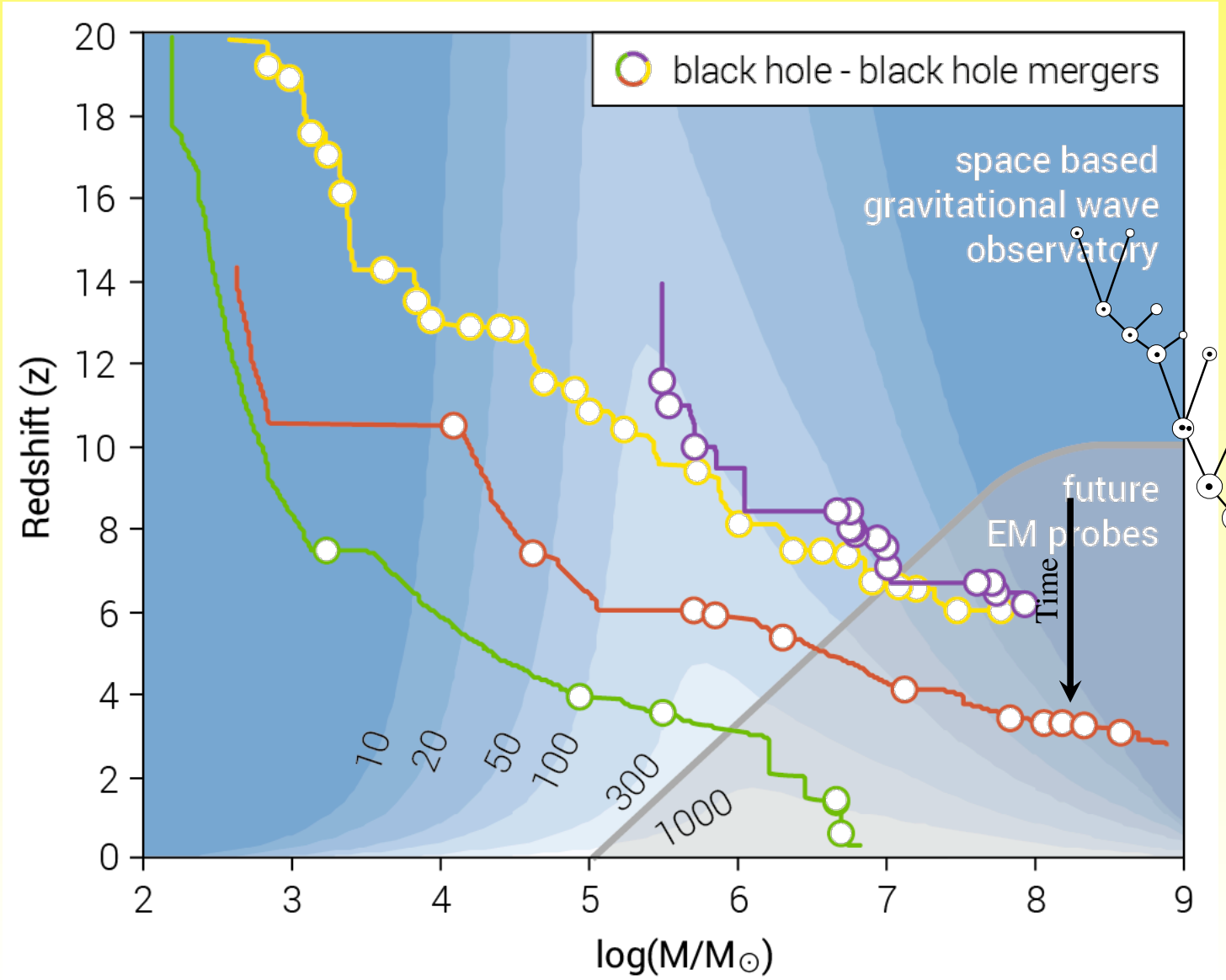




NGC 6240

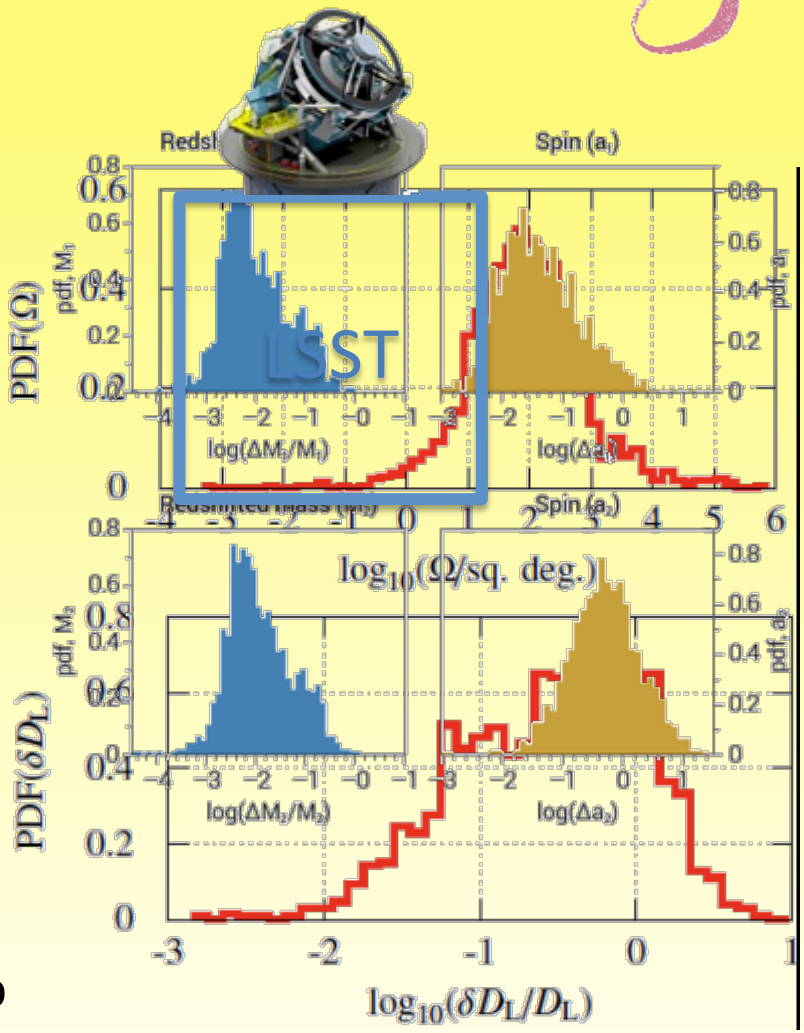
Baker et al. 2006

All Binary Black Holes cross eLISA band: Trace Galaxy Mergers



eLISA Black Hole Physics at high SNR

- BBH rest mass 10^4 – 10^7
- Out to redshift z >> 10
  - if they exist
- 10 – 100 events per year
- Redshifted mass to 0.1%-1%
- Absolute spin to 0.01-0.1
- Luminosity distance 1 – 50 %
- Sky location 1° - 10 °



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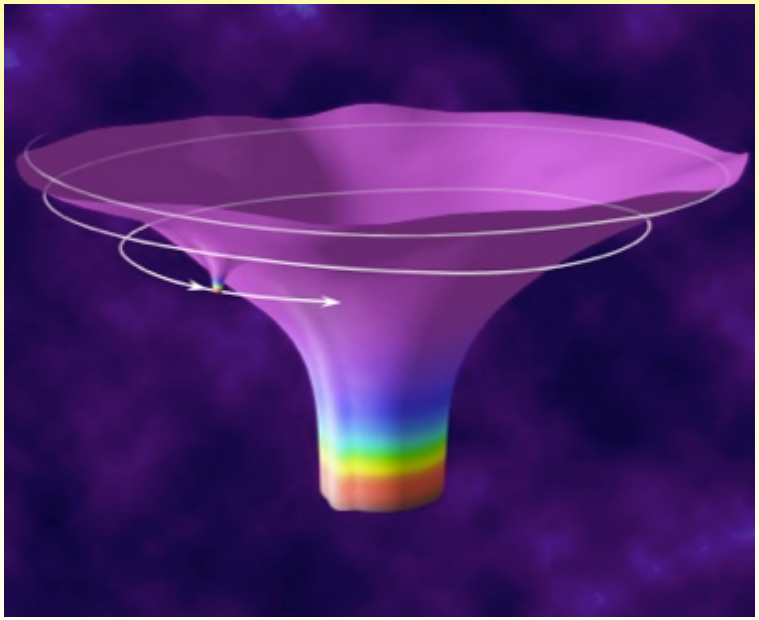
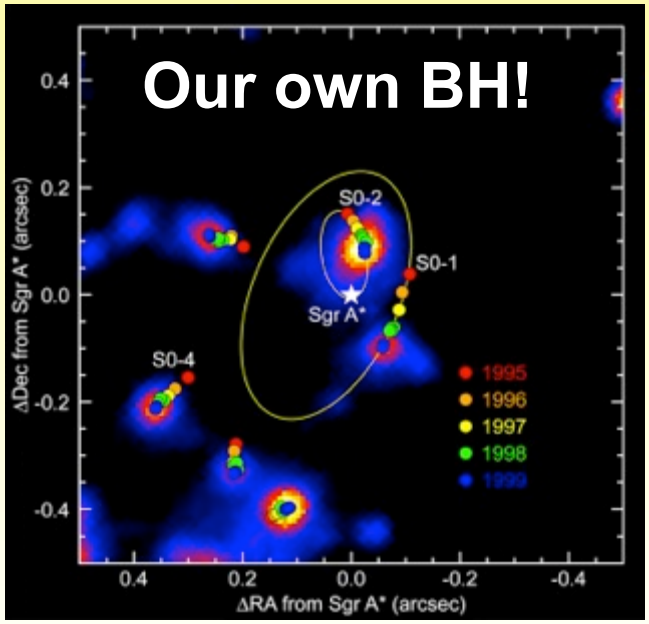
At the Edge of a Black Hole

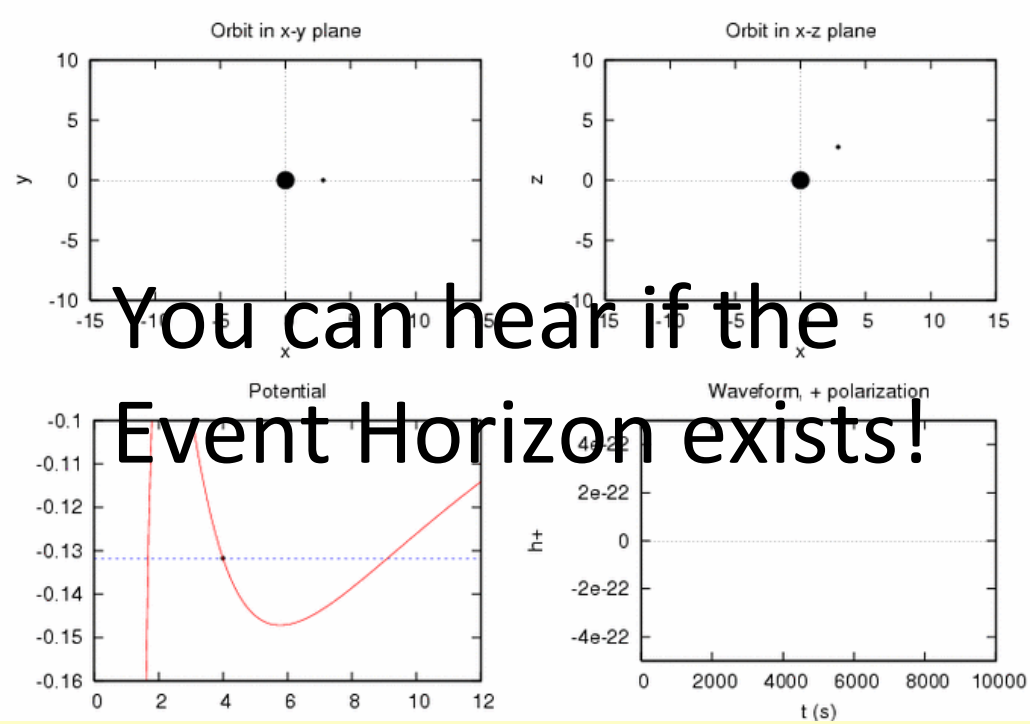
- Capture by Massive Black Holes
  - Compact objects inspiral into massive black hole (MBH),
  - GWs map space-time geometry with superb precision
  - Allows investigation of tiny deviations from General Relativity including the “no hair” theorem



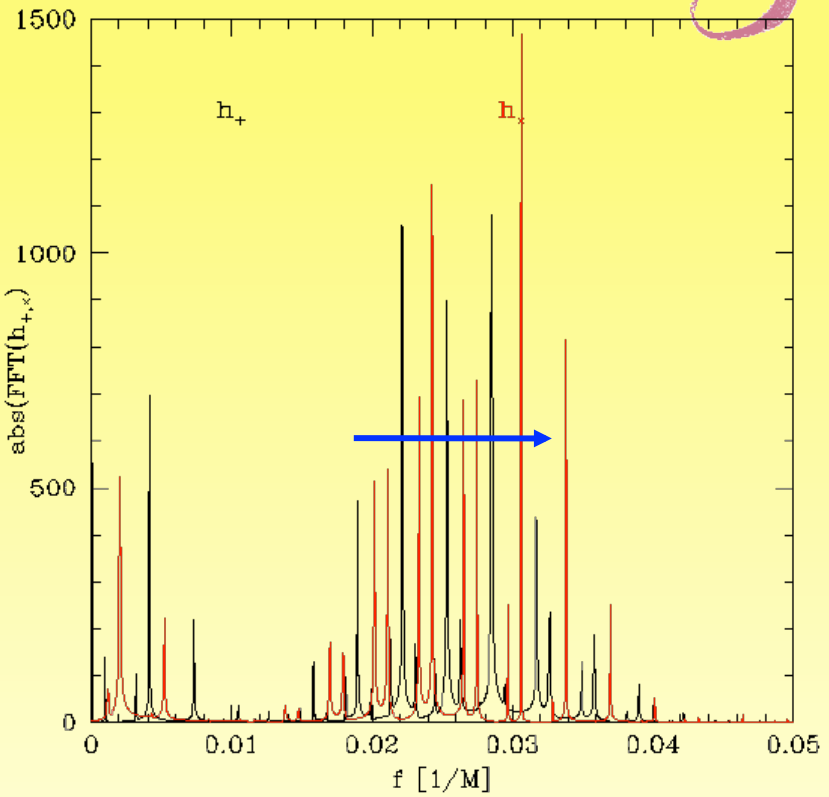


Ghez et al. 1998 ApJ 509, 678, Eckart et al. 2002 MNRAS 331, 917

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.

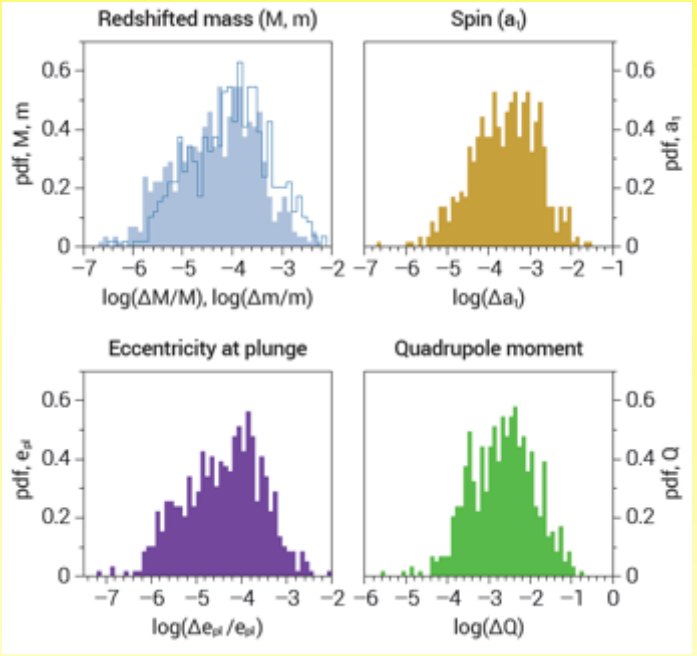
a=6M, e=0.2, i=80

⇒ Like a Geodesy satellite mapping Geopotential!

⇒ GRACE for Black Holes!

Extreme Mass Ratio Inspirals

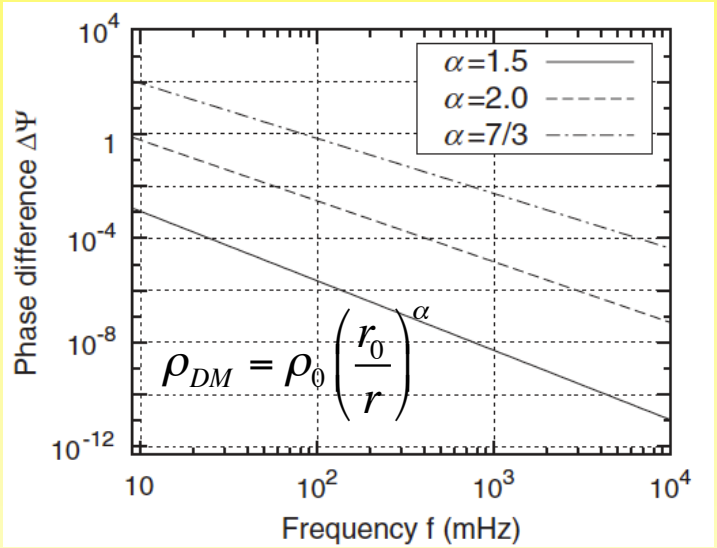
- SNR 20 up to z ≈ 0.7 for 10^5-10^6 $M_\odot$
- Dozens of events per year
- Mass, spin to 0.1% – 0.01 %
- Quadrupole moment to < 0.001 $M_\odot{}^3G^2/c^4$



- Do Black Holes have hair?
  - New objects in General Relativity
    - Boson Stars, Gravastars, non-Kerr solutions (e.g. Manko-Novikov)
  - Deviations from General Relativity
    - Chern-Simons, Scalar-Tensor, light scalar fields (axions) and black hole bomb instabilities
- Each has specific GW fingerprint!

eLISA as Dark Matter Probe

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



PRL 110, 221101 (2013) PHYSICAL REVIEW LETTERS week ending 31 MAY 2013

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

Kazunari Eda,* Yousuke Itoh, and Sachiko Kuroyanagi
Research center for the early universe, School of Science, University of Tokyo, Tokyo 113-0033, Japan

Joseph Silk
Institut d' Astrophysique, UMR 7095, CNRS, Université Pierre et Marie Curie Paris VI, 98 bis Boulevard Arago, Paris 75014, France

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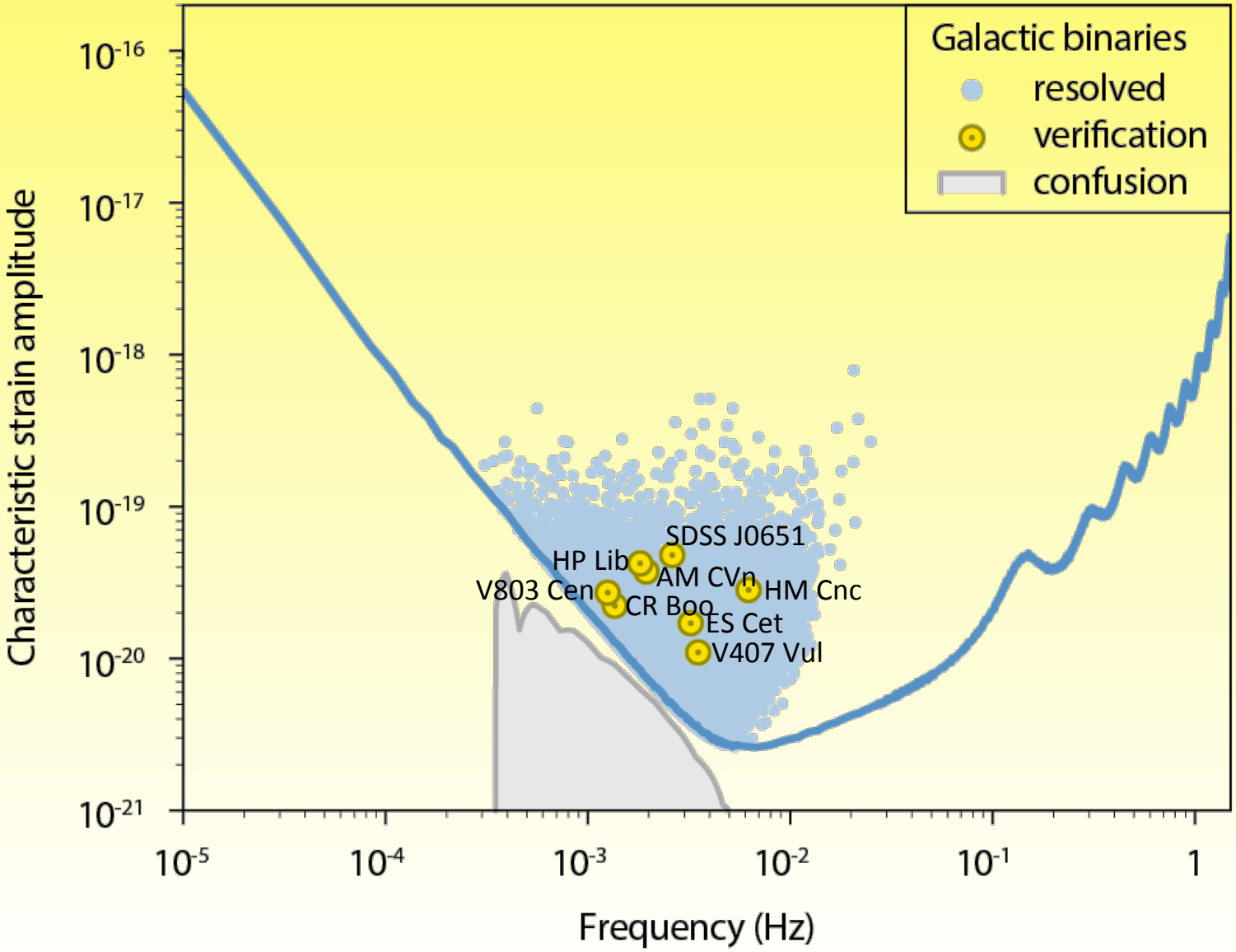
eLISA: 30 Million White Dwarf Binaries!

- Several Thousand resolvable in 2 yr
- Discriminate between BH, NS, and WD binaries
- Synergy between eLISA and GAIA:
  - eLISA polarisation measurement gives *inclination* of orbital plane
  - eLISA gives accurate *distances* to and *masses* of WD/WD binaries whose orbits show effects of gravitational radiation reaction

eLISA has guaranteed Sources: Known Verification Binaries



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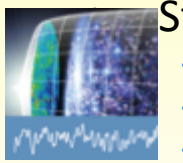

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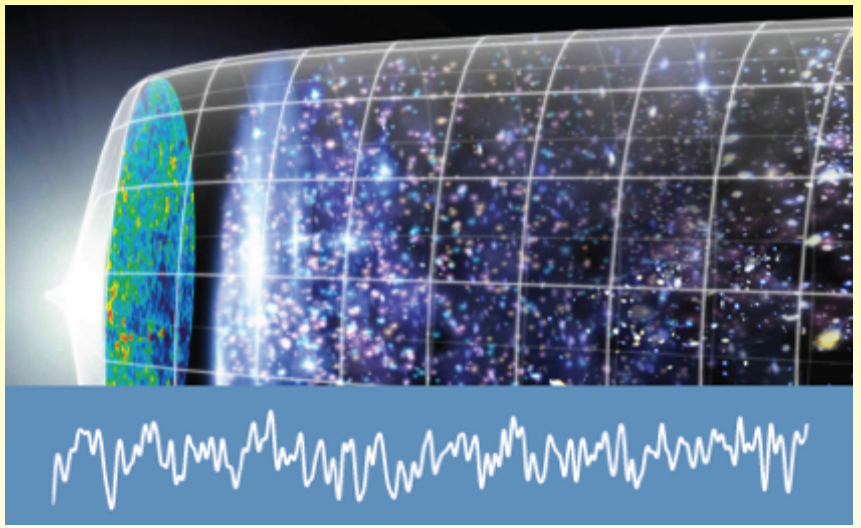
STOCHASTIC GW BACKGROUND

- Wavelength of primordial Gravitational Waves set by horizon scale at time of emission (with temperature T_*):

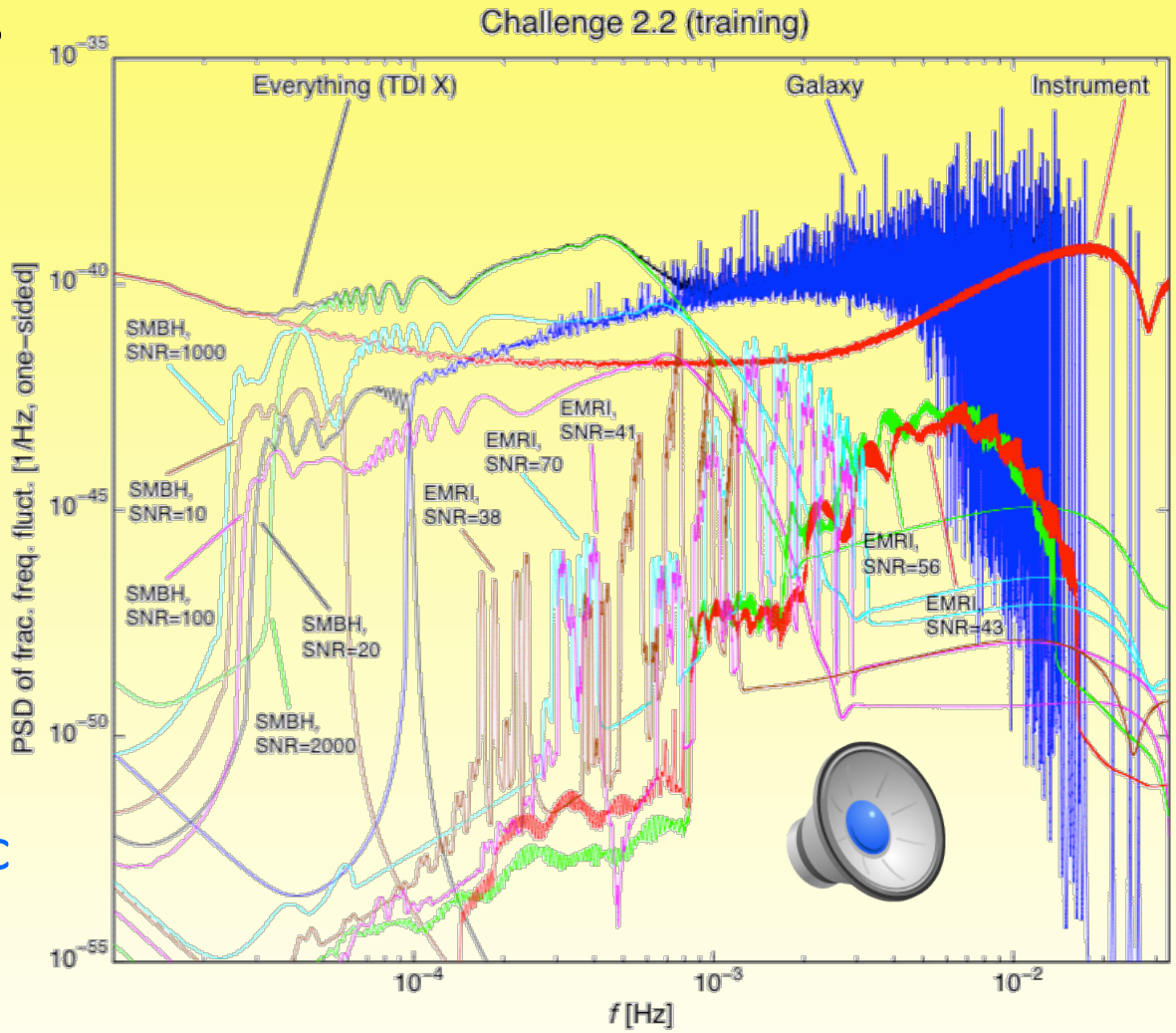
$$f_0 \approx 10^{-4}\,\mathrm{Hz}\sqrt{H_*(t)\times\frac{1\,\mathrm{mm}}{c}} \approx 10^{-4}\,\mathrm{Hz}\,\frac{kT_*}{1\,\mathrm{TeV}}$$

- eLISA band
  - 0.1-100 mHz ⟹ 1-1000 TeV (beyond LHC)
  - 1 mm scale @ TeV
  - 3×10^{-18} - 3×10^{-10} s after the Big Bang
- eLISA sensitive to LHC physics and beyond
  - Higgs self-couplings and potential
  - Supersymmetry
  - Extra dimensions
  - Strings
  - Dark Energy density ≈ $(0.1\ \mathrm{mm})^{-4}$
    - Signature in eLISA band?



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!

After 15 years of joint LISA development in March 2011…

Published online 22 March 2011 | *Nature* **471**, 421 (2011) | doi:10.1038/471421a

News

Europe makes do without NASA

US budget crisis forces European Space Agency to abandon plans for joint mission.

Eugenie Samuel Reich

The European Space Agency (ESA) is pushing ahead without NASA support for its next big science mission, as the ongoing US budget crunch and competing priorities impose serious constraints on the US space agency (see *Nature* **471,** 278; 2011). ESA last week told leaders of three large, or 'L-class', missions that are competing for funding to revise their proposals by leaving out the substantial US contribution that had previously been assumed.

"The decision was made very reluctantly," says David Southwood, director of science and robotic exploration at ESA. "NASA could not meet our timetable to launch."

Stories by keywords

- European Space Agency
- L-Class missions
- LISA
- IXO
- ESJM-Laplace

This article elsewhere

Blogs linking to this article

- Telescope will track space junk
  22 April 2011
- China hopes research centre can quell food-safety fears
  22 April 2011

Related stories

- US Mars mission takes pole position
  08 March 2011
- ESA on countdown to flagship mission selection

LISA Redefinition Study for L1

- Redesign for ESA-only mission

- Cost-cap for ESA cost at 850 M€ plus member state contributions around 200 M€

  - Build on LISA Pathfinder hardware
  - Shorter arms, smaller telescopes, simpler orbits, less mass
  - Can use cheaper launcher

→Mission Concept called NGO (eLISA)

→eLISA: evolving LISA
→NGO: specific incarnation of eLISA for ESA L1 selection!

NGO Layout for eLISA

Heliocentric orbit trailing earth by 20°

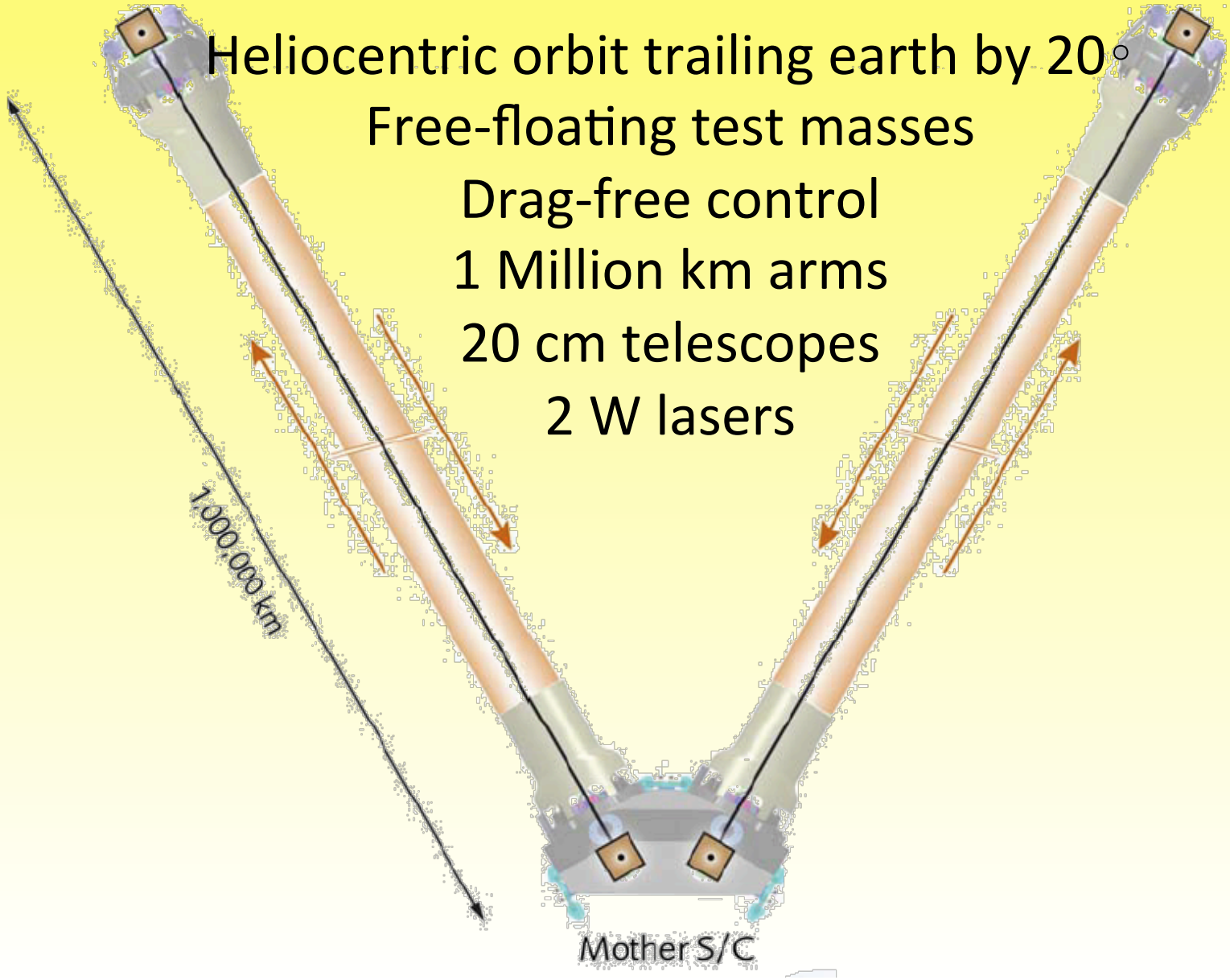
Free-floating test masses

Drag-free control

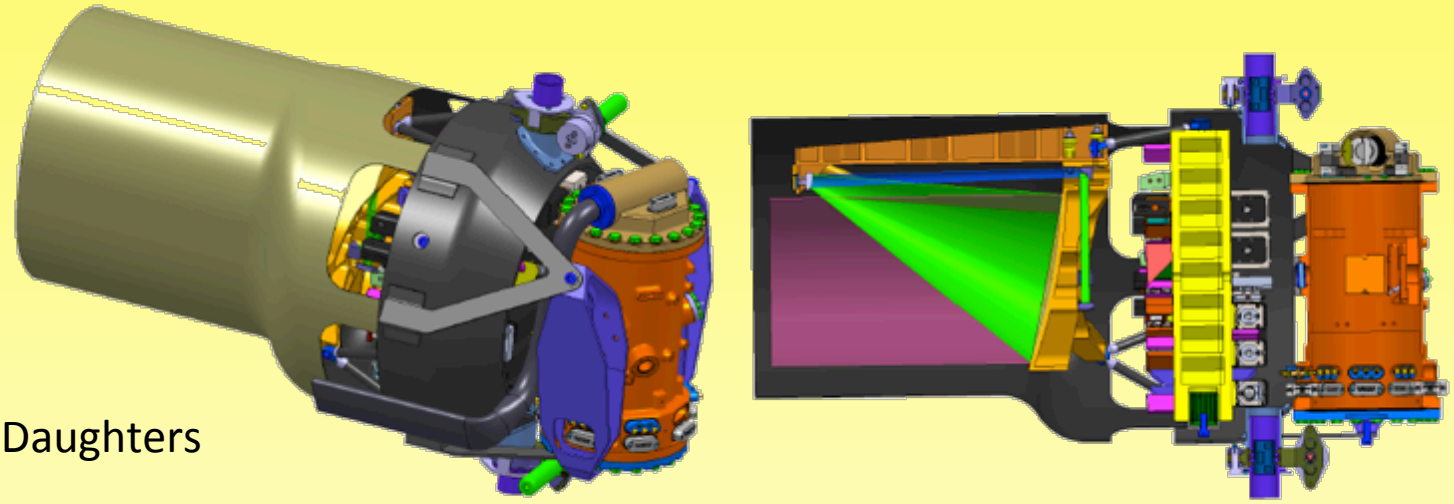
1 Million km arms

20 cm telescopes

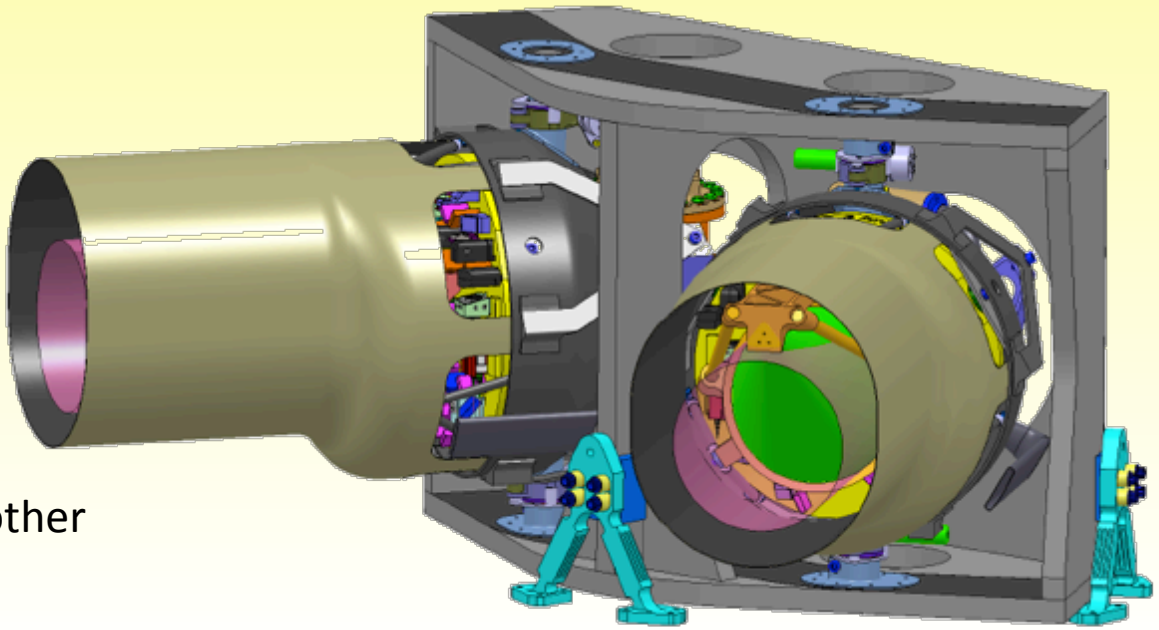
2 W lasers



Optical Assembly



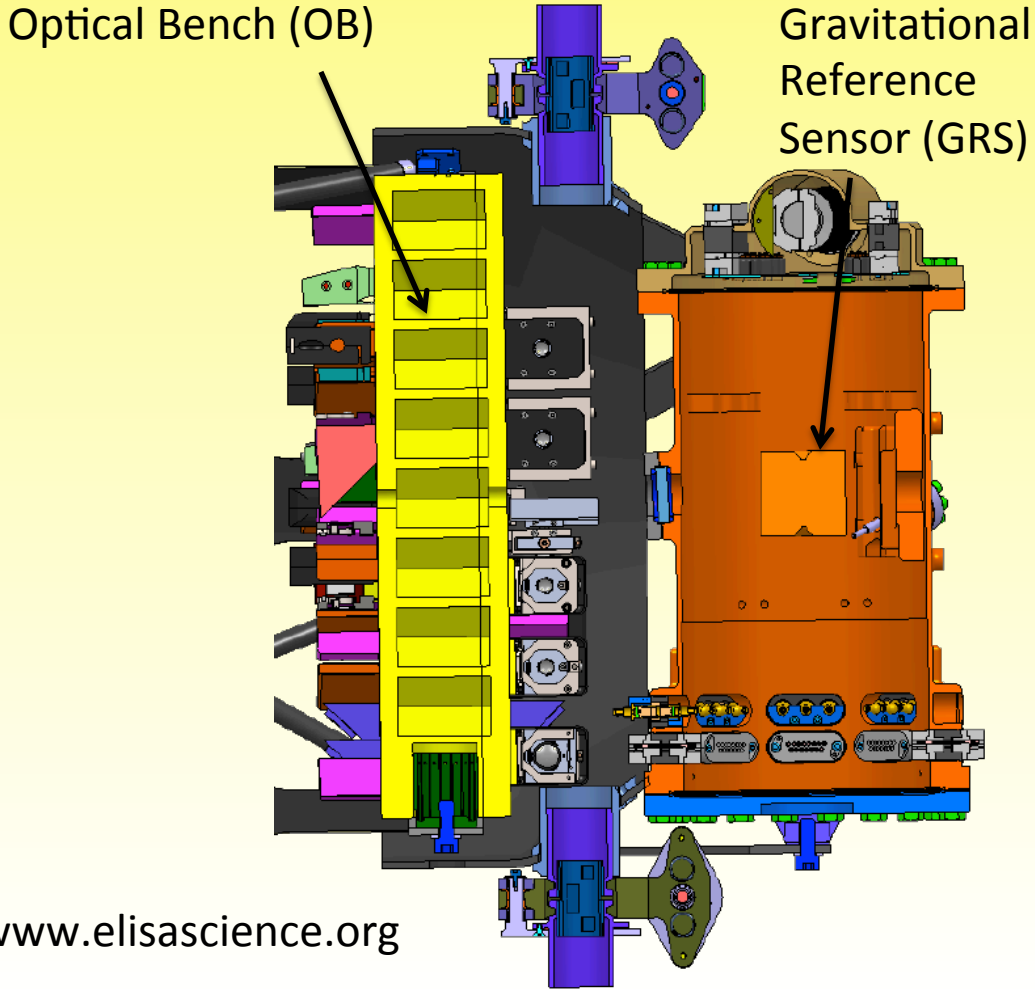
Daughters

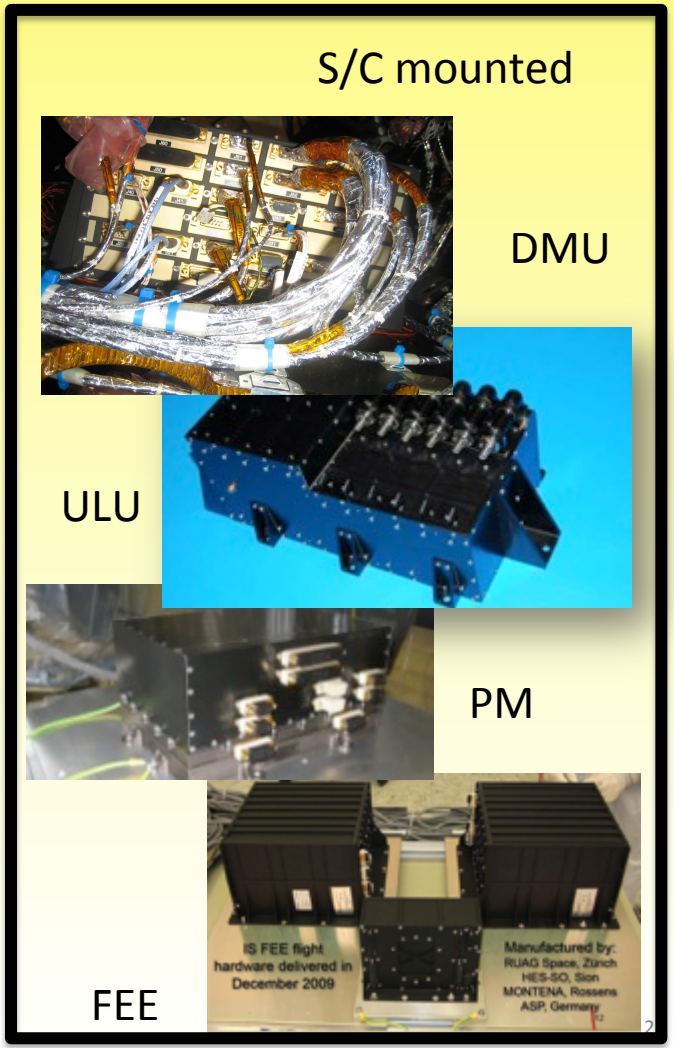


Mother

The Science Instrument

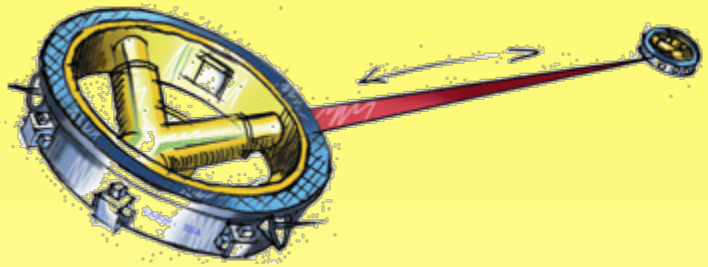
- Provided by eLISA Consortium (D, F, I, UK, ES, CH, DK, NL)
- Also providing LISA Pathfinder Instrument



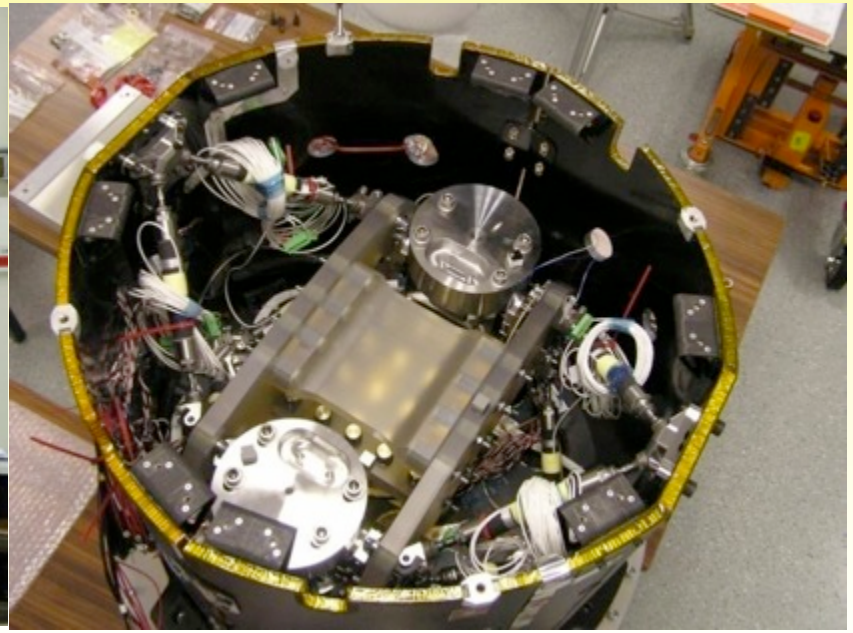


www.elisascience.org

LISA Pathfinder



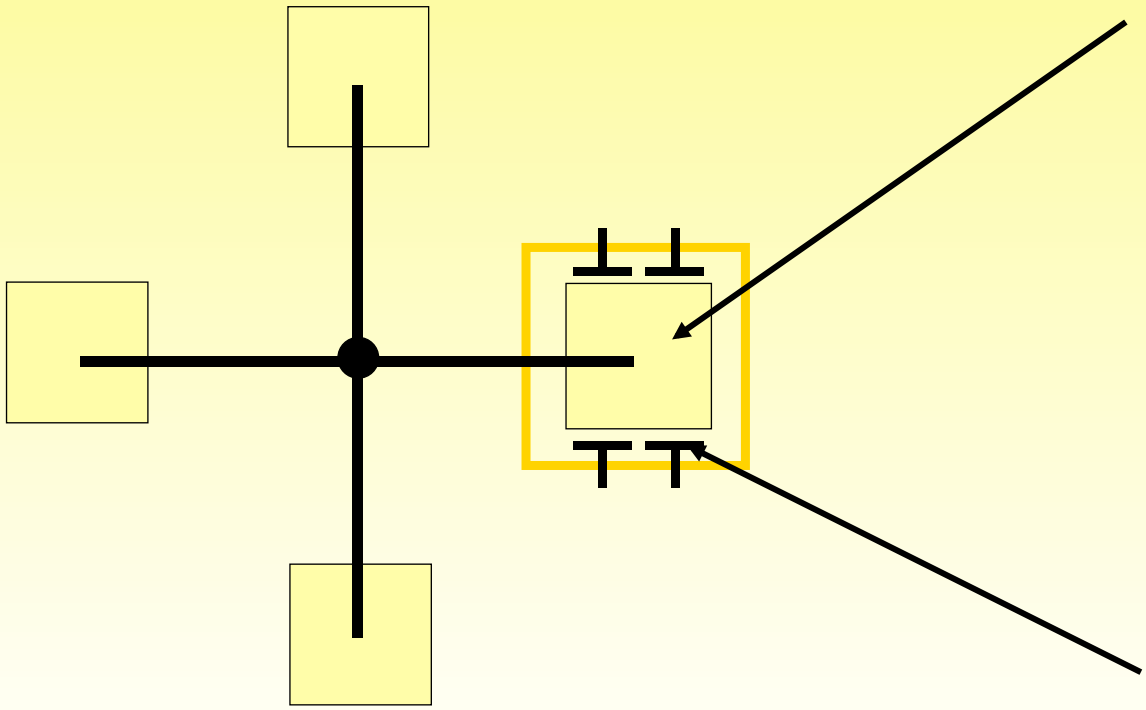
- Take one eLISA link
- Hardware designed for LISA
- Squeeze it into one spacecraft

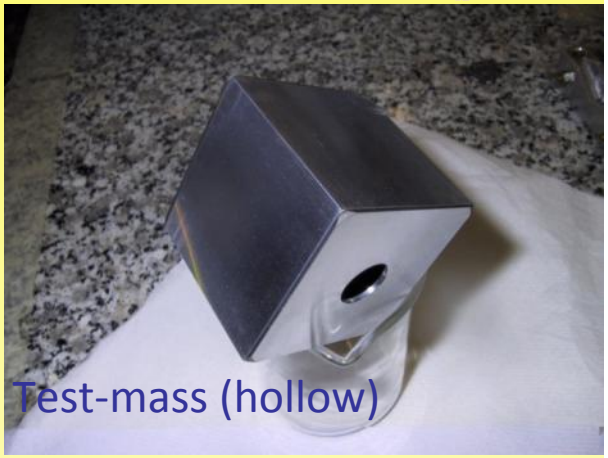


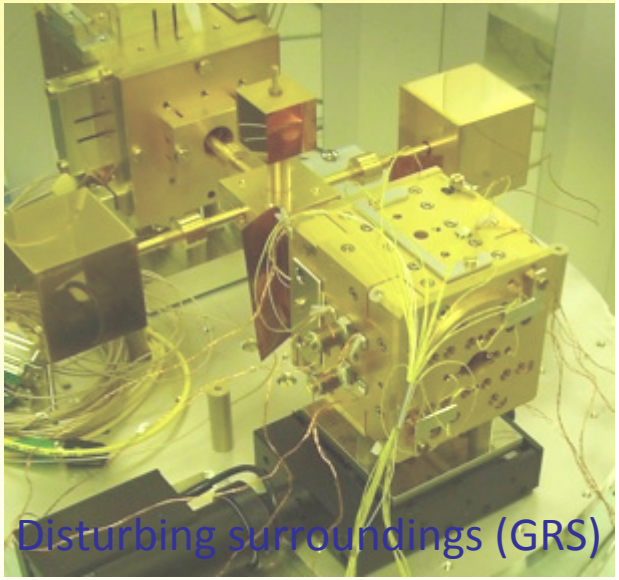
LISA Pathfinder

- Launch date has now been stable at July 2015!

Testing Free Flying Test Mass (GRS) on Ground: Torsion Pendulum

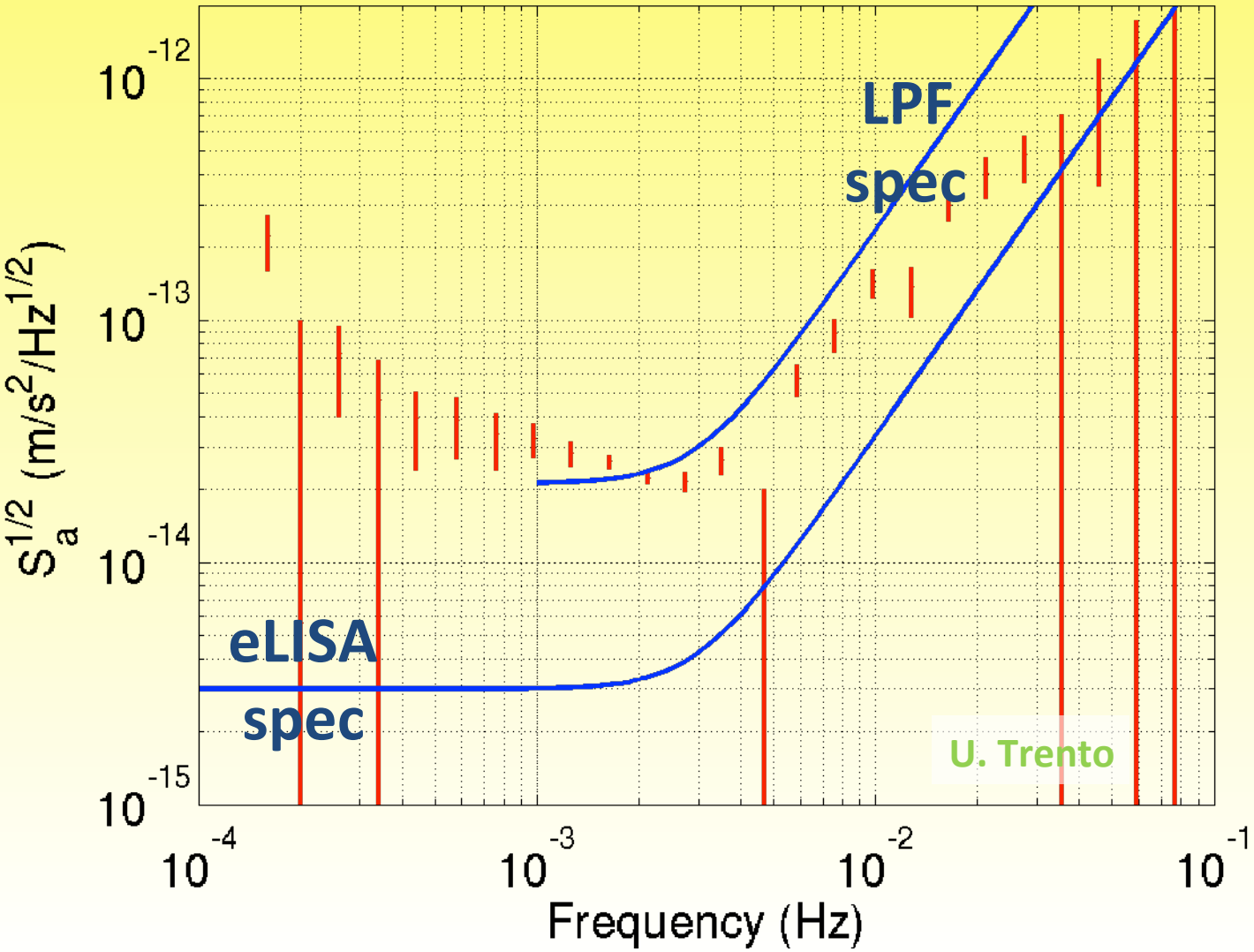




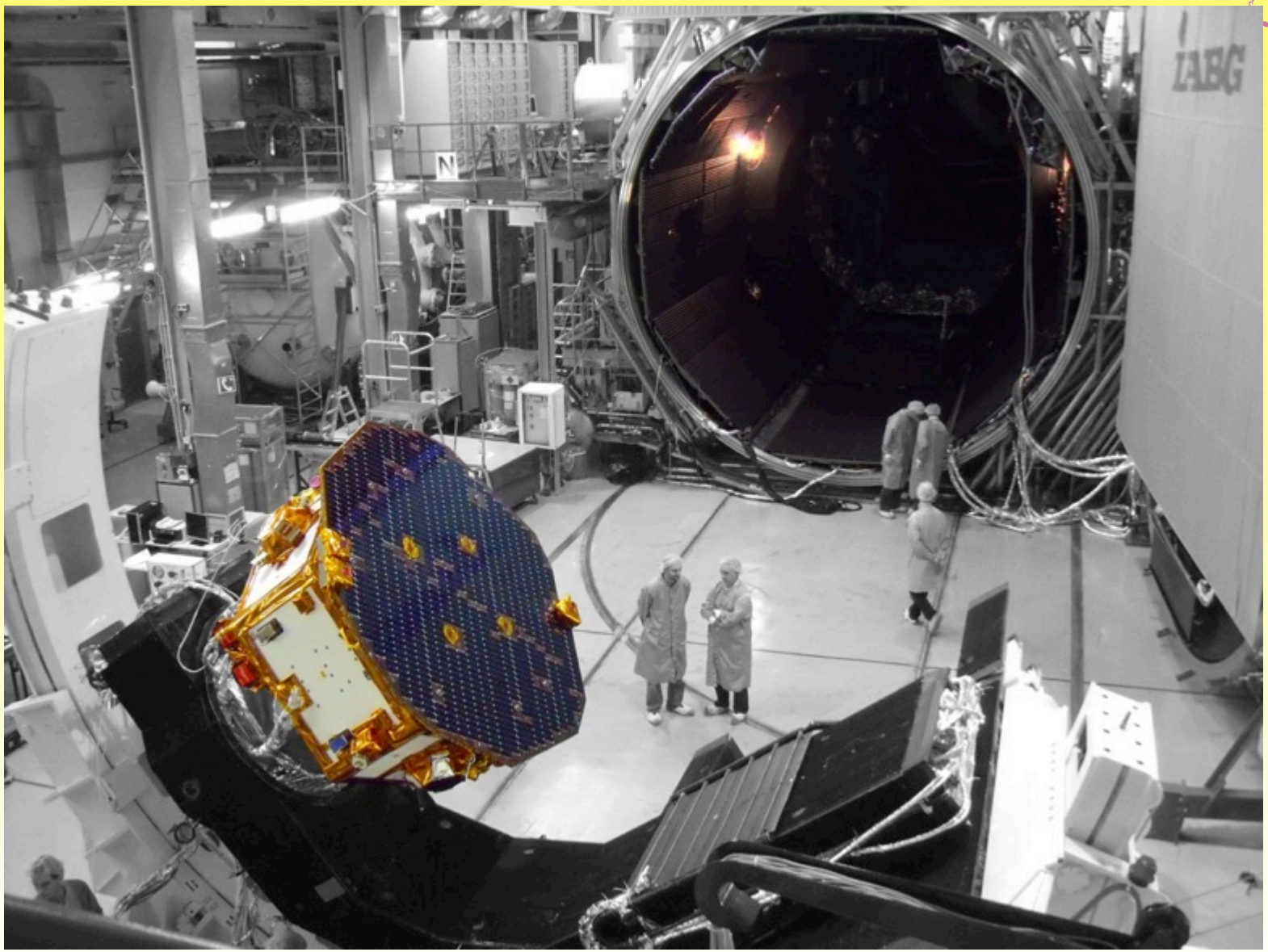


Superb GRS Performance on Ground

- Upper limits from torsion pendulum



Optical Metrology Ground Testing

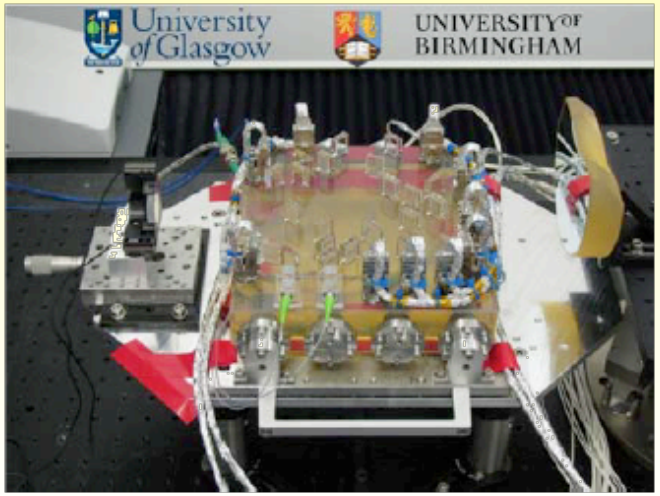


Superb Optical Performance on Ground

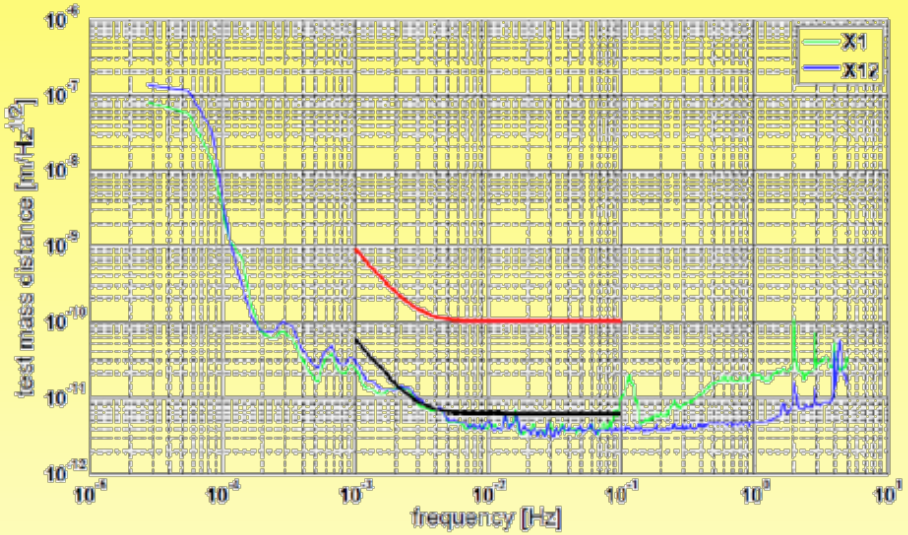
Optical metrology performance at hot/cold confirmed.

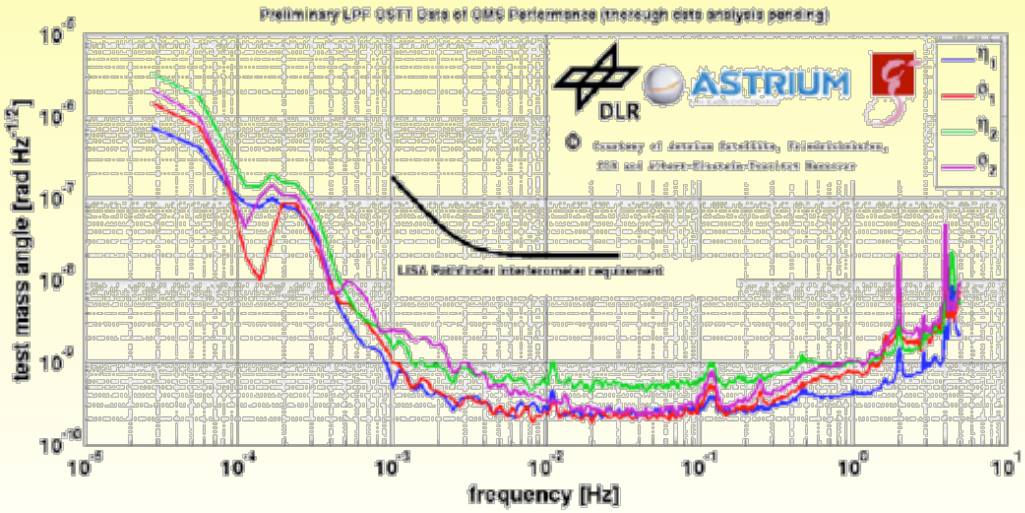
- Test mirror translation noise <6 pm/sqrtHz
- Test mirror rotational noise <1 nrad/sqrtHz

In-orbit performance expected to be better than in test chamber.



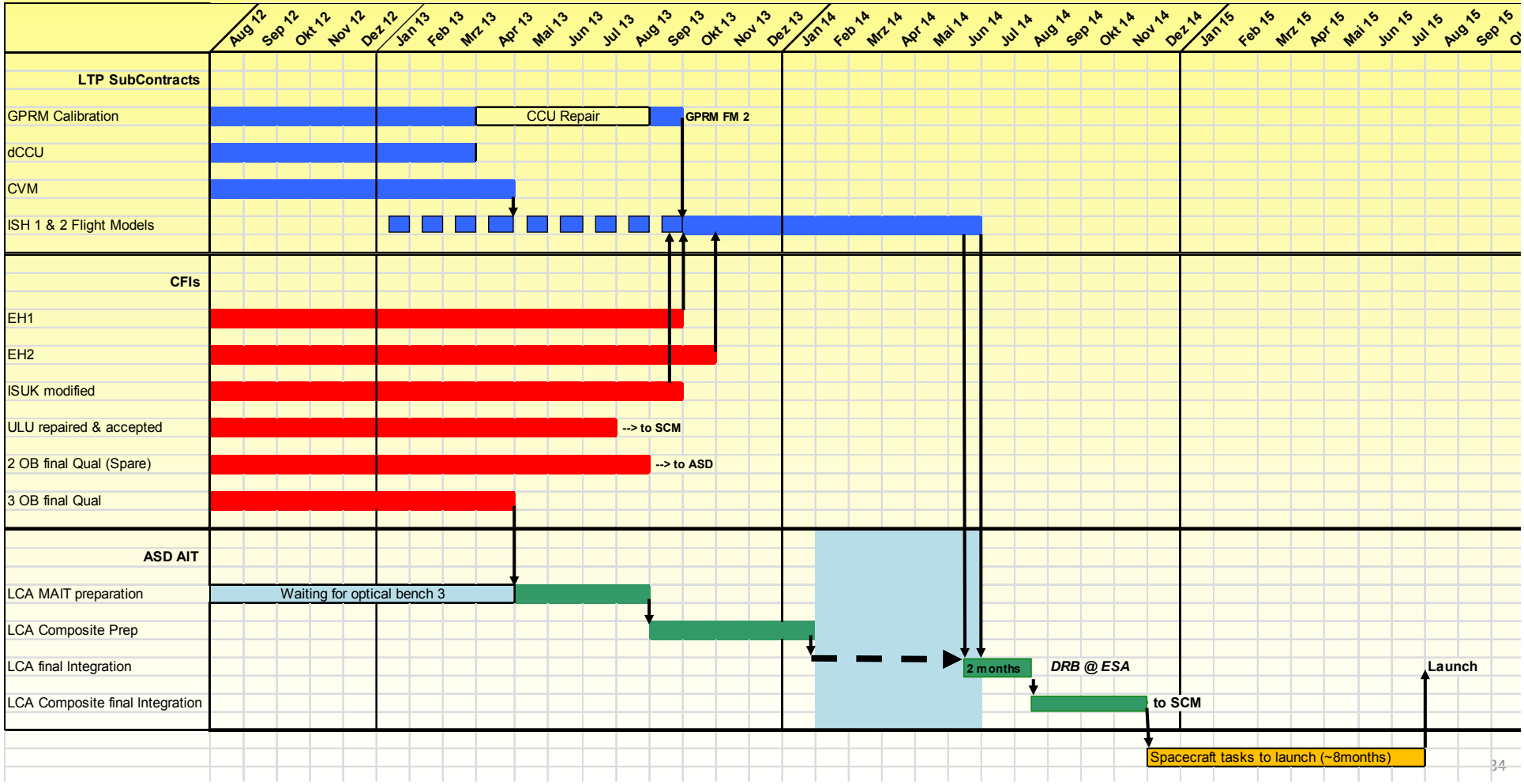
13th Man



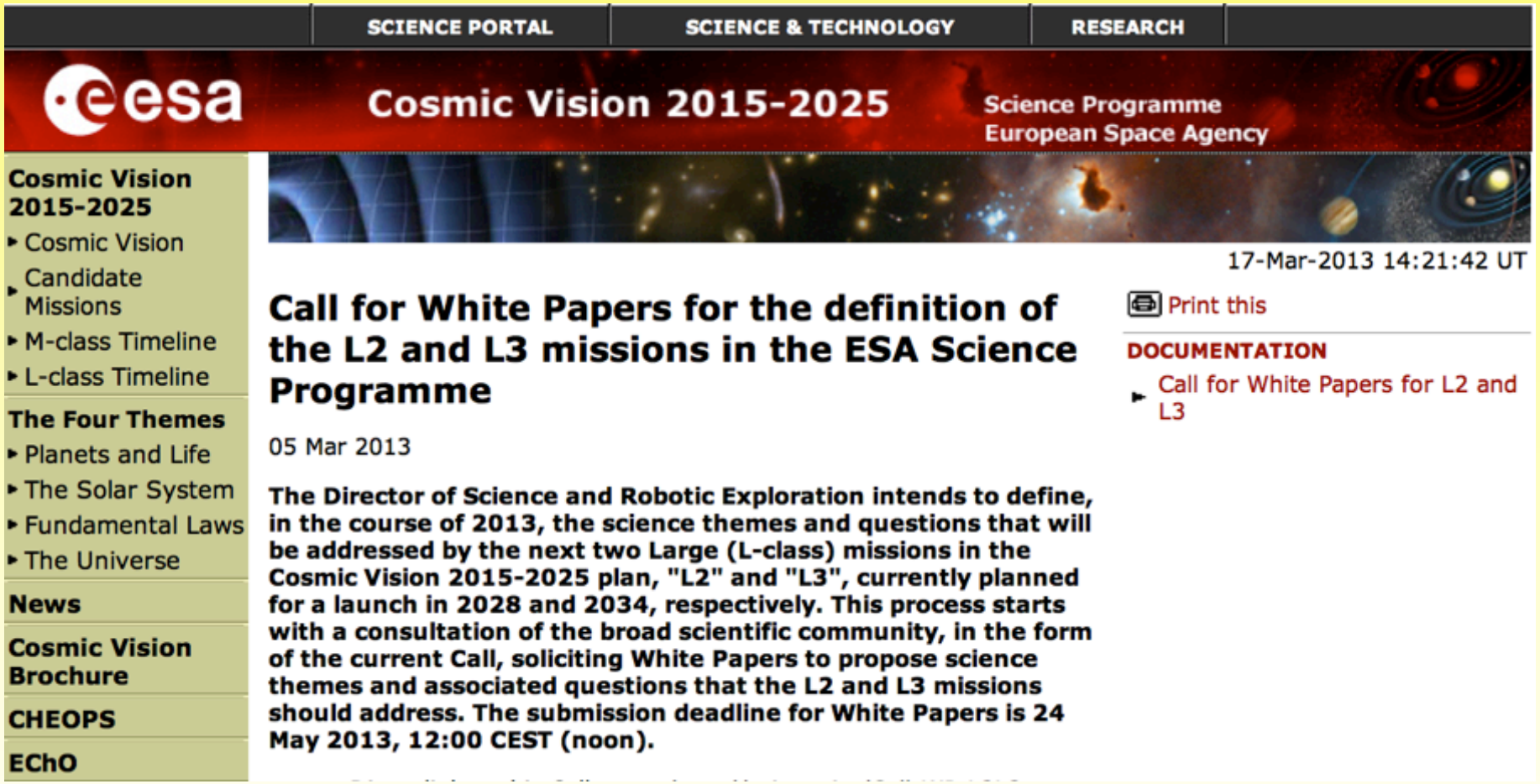


All Payload Hardware delivered and tested by November 2013

- All remaing integration steps successfully practiced
- Launch July 2015 now stable !



New ESA Call for Large Missions



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esa Cosmic Vision 2015-2025 Science Programme European Space Agency

Cosmic Vision 2015-2025
- Cosmic Vision
- Candidate Missions
- M-class Timeline
- L-class Timeline

The Four Themes
- Planets and Life
- The Solar System
- Fundamental Laws
- The Universe

News

Cosmic Vision Brochure

CHEOPS

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DOCUMENTATION
- Call for White Papers for L2 and L3

Call for White Papers for the definition of the L2 and L3 missions in the ESA Science Programme

05 Mar 2013

The Director of Science and Robotic Exploration intends to define, in the course of 2013, the science themes and questions that will be addressed by the next two Large (L-class) missions in the Cosmic Vision 2015-2025 plan, "L2" and "L3", currently planned for a launch in 2028 and 2034, respectively. This process starts with a consultation of the broad scientific community, in the form of the current Call, soliciting White Papers to propose science themes and associated questions that the L2 and L3 missions should address. The submission deadline for White Papers is 24 May 2013, 12:00 CEST (noon).

THE GRAVITATIONAL UNIVERSE

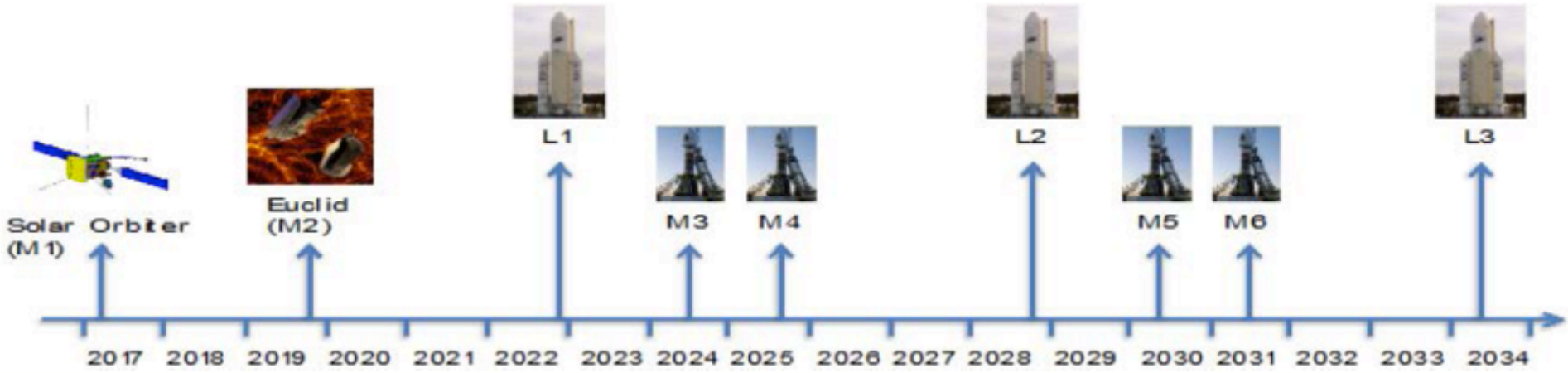
A science theme addressed by the *eLISA* mission observing the entire Universe

Among the, roughly, 1000 scientific supporters of the Gravitational Universe science theme, are

GERARDUS 'T HOOFT *Utrecht University (Netherlands)*, BARRY BARISH *Caltech (United States)*, CLAUDE COHEN-TANNOUDJI *College de France (France)*, NEIL GEHRELS *NASA Goddard Space Flight Center (United States)*, GABRIELA GONZALEZ *LIGO Scientific Collaboration Spokesperson, LSU (United States)*, DOUGLAS GOUGH *Institute of Astronomy, University of Cambridge (United Kingdom)*, STEPHEN HAWKING *University of Cambridge, DAMTP (United Kingdom)*, STEVEN KAHN *Stanford University/SLAC National Accelerator Laboratory (United States)*, MARK KASEVICH *Stanford University, Physics Dept. (United States)*, MICHAEL KRAMER *Max-Planck-Institut fuer Radioastronomie (Germany)*, ABRAHAM LOEB *Harvard University (United States)*, PIERO MADAU *University of California, Santa Cruz (United States)*, LUCIANO MAIANI *Università di Roma La Sapienza (Italy)*, JOHN MATHER *NASA Goddard Space Flight Center (United States)*, DAVID MERRITT *Rochester Institute of Technology (United States)*, VIATCHESLAV MUKHANOV *LMU München (Germany)*, GIORGIO PARISI *Universita di Roma la Sapienza (Italy)*, STUART SHAPIRO *University of Illinois at Urbana-Champaign (United States)*, GEORGE SMOOT *Universite Paris Diderot (France)*, SAUL TEUKOLSKY *Cornell University (United States)*, KIP THORNE *California Institute of Technology (United States)*, GABRIELE VENEZIANO *Collège de (France)* (France), JEAN-YVES VINET *Virgo Collaboration Spokesperson, OCA Nice (France)*, RAINER WEISS *MIT (United States)*, CLIFFORD WILL *University of Florida (United States)*, EDWARD WITTEN *Institute for Advanced Study, Princeton (United States)*, ARNOLD WOLFENDALE *Durham University (United Kingdom)*, and SHING-TUNG YAU *Harvard University (United States)*.

ESA‘s L2 and L3 Missions

- Call for Science Themes 2013
- Selection of Themes in Nov 2013
- LISA Pathfinder launch 2015
- Launch of L2 in 2028
- Launch of L3 in 2034



Roadmap for LISA

- Launch LISA Pathfinder in 2015
- Coordination of international partners
- If LISA is L2:
  - Build EQM of complete Payload in 2016 – 2020
  - Start industrial implementation in 2020
  - Launch in 2028
- If LISA is L3:
  - Technology development until 2019
  - Payload EQM 2020 – 2024
  - Start industrial implementation 2025
  - Launch 2034

Summary

- LISA will
  - Explore the whole Universe through Gravity only
  - Probe assembly of cosmic structure through Black Holes and observe their seeds
  - Investigate General Relativity in Strong Field Regime
  - Explore the Early Universe
  - Have a huge discovery space
- LISA Pathfinder
  - Has all payload hardware tested and delivered next month
  - Will fly in 2015 on a robust schedule
  - Will fly hardware designed for and usable by eLISA
- LISA will be a true Cosmic Vision !