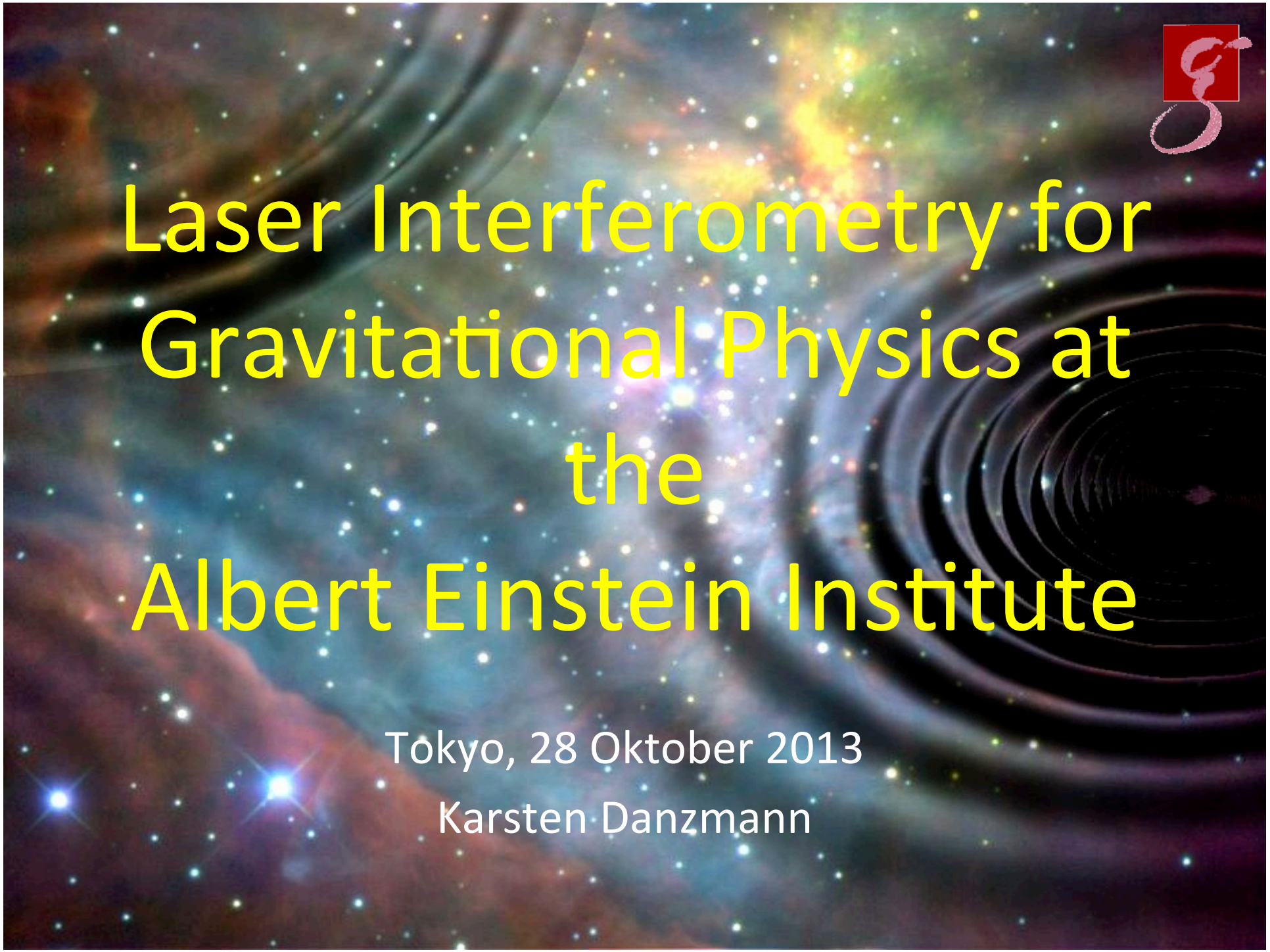
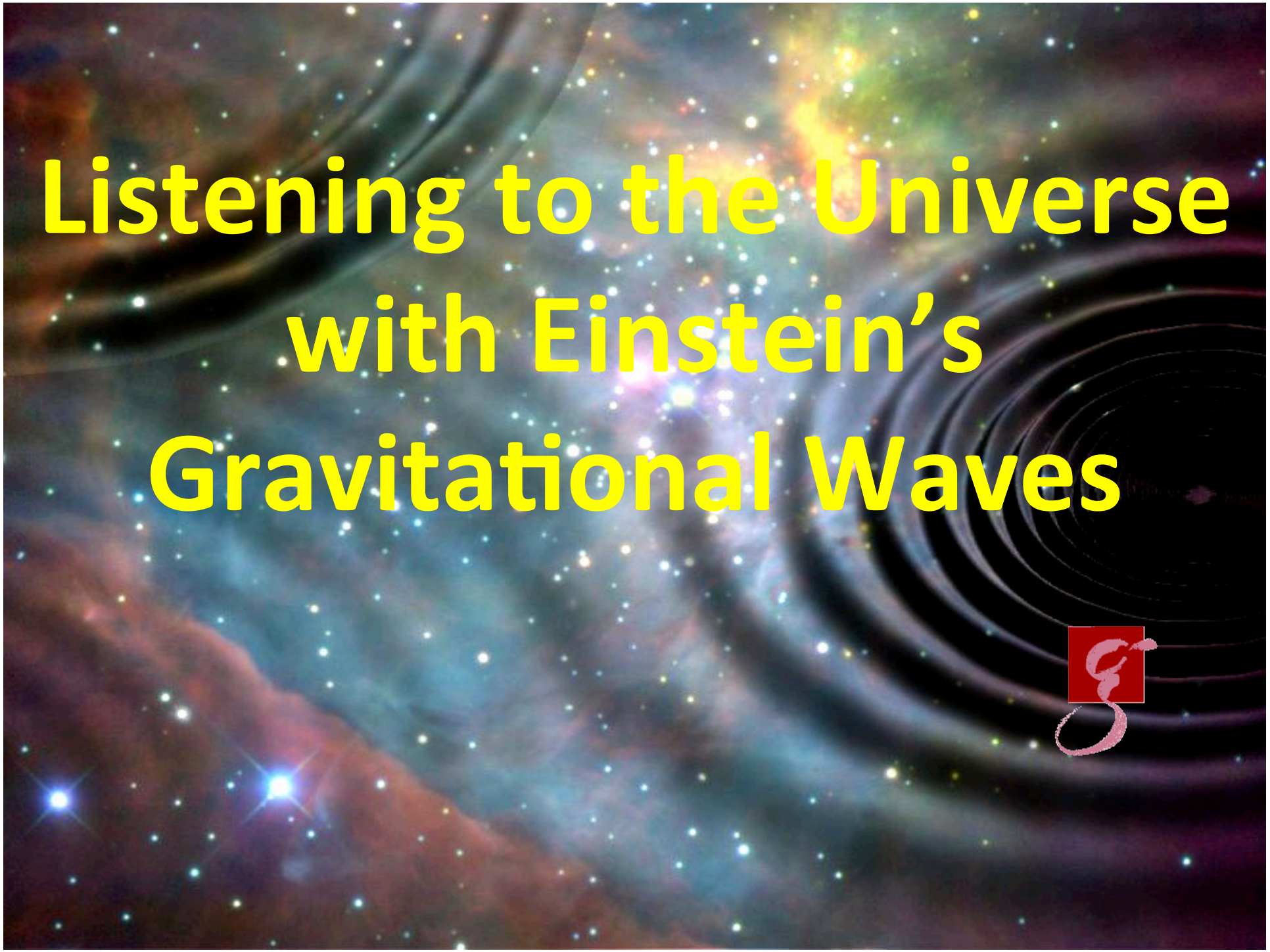
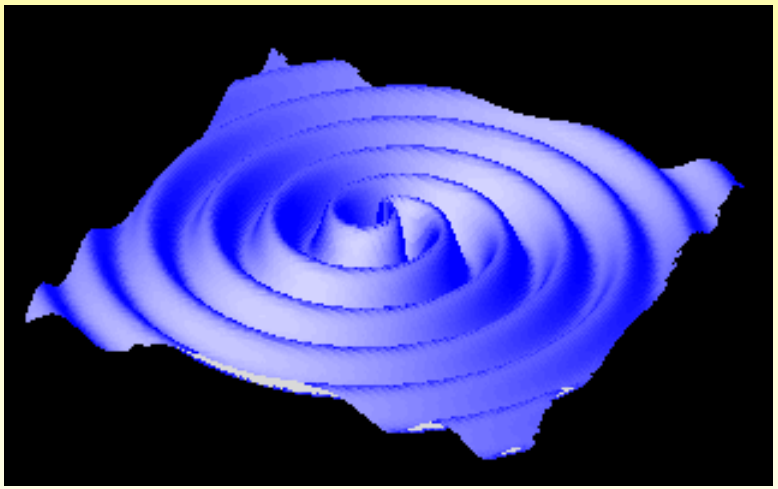

Laser Interferometry for Gravitational Physics at the Albert Einstein Institute
Tokyo, 28 Oktober 2013
Karsten Danzmann


Listening to the Universe
with Einstein's
Gravitational Waves

Gravitational Waves

– Distortions of Space and Time that propagate at the speed of light!



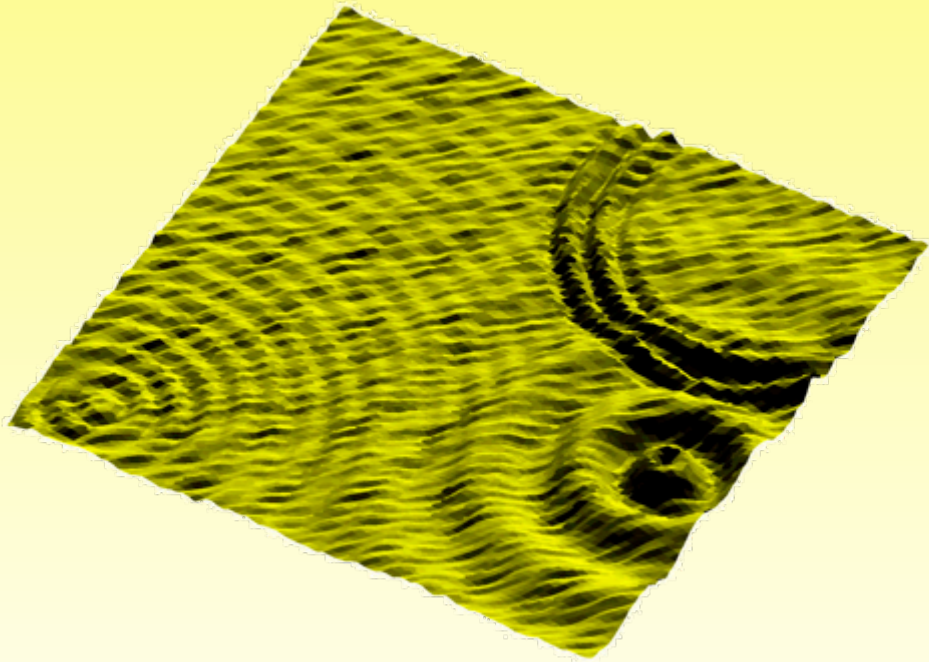
Gravitational Waves

- Predicted by Einstein more than 90 years ago
- No direct detection yet
- Indirect proof of existence

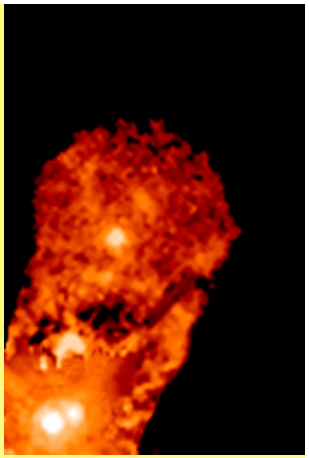
  via energy loss of

  Binary Pulsar PSR1913+16

  (Hulse-Taylor)

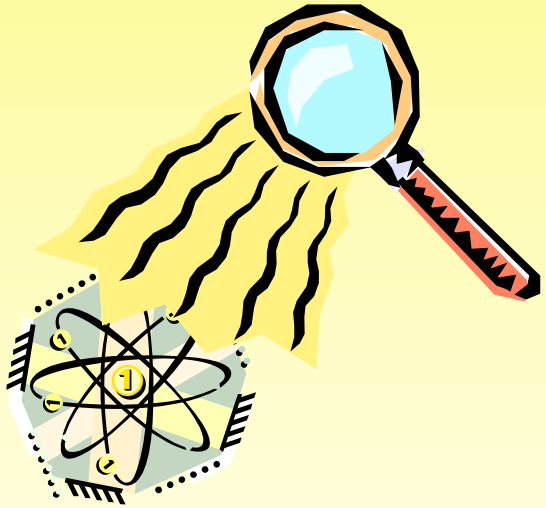


The Effect is small!



- Supernova in local group of galaxies

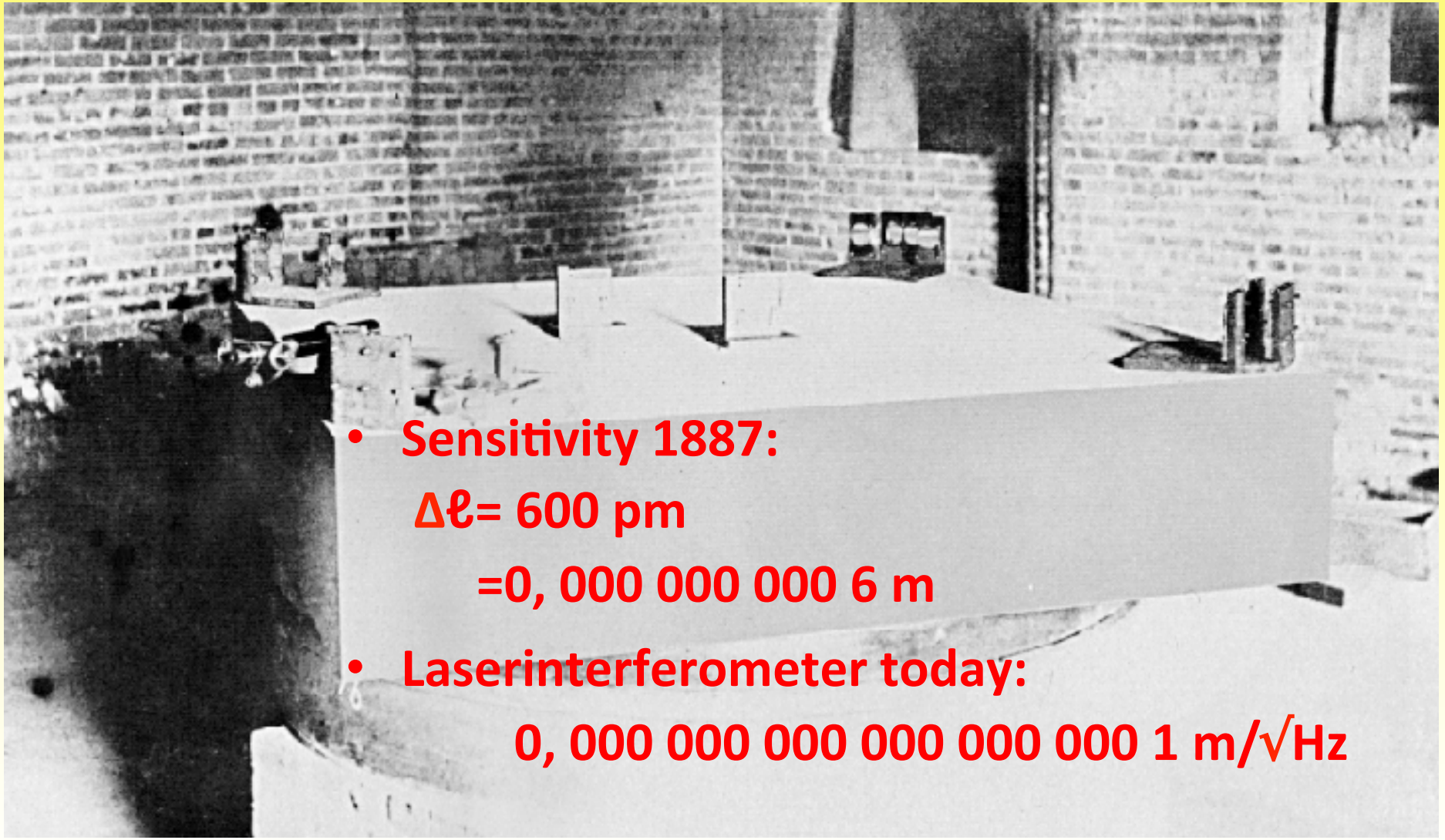
  $\Rightarrow$ Squeezing of space by 10^{-21}



$\Rightarrow$ 1 km baseline changes by 1/1000 of a Proton diameter (10^{-18} m = 1 Attometer)!

$\Rightarrow$ For a few milliseconds!

Original Interferometer of Michelson and Morley 1887



- **Sensitivity 1887:**

  Δℓ= 600 pm

  =0, 000 000 000 6 m

- **Laserinterferometer today:**

  0, 000 000 000 000 000 000 1 m/√Hz

GEO600

- German-British collaboration, location Hannover / Germany
- Michelson Interferometer with power and signal recycling

Leibniz Universität Hannover

quest

U Birmingham
U Mallorca

CARDIFF UNIVERSITY

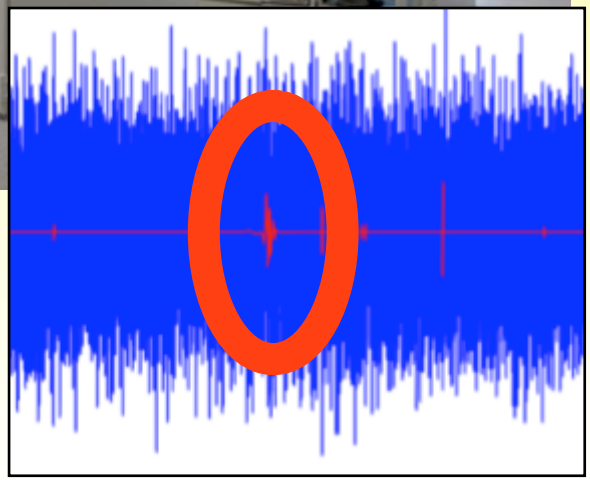
IGR
Glasgow

World-Wide Laser Interferometric Gravitational Wave Detector Network

3 km

Source: A. Lazzarini, modified

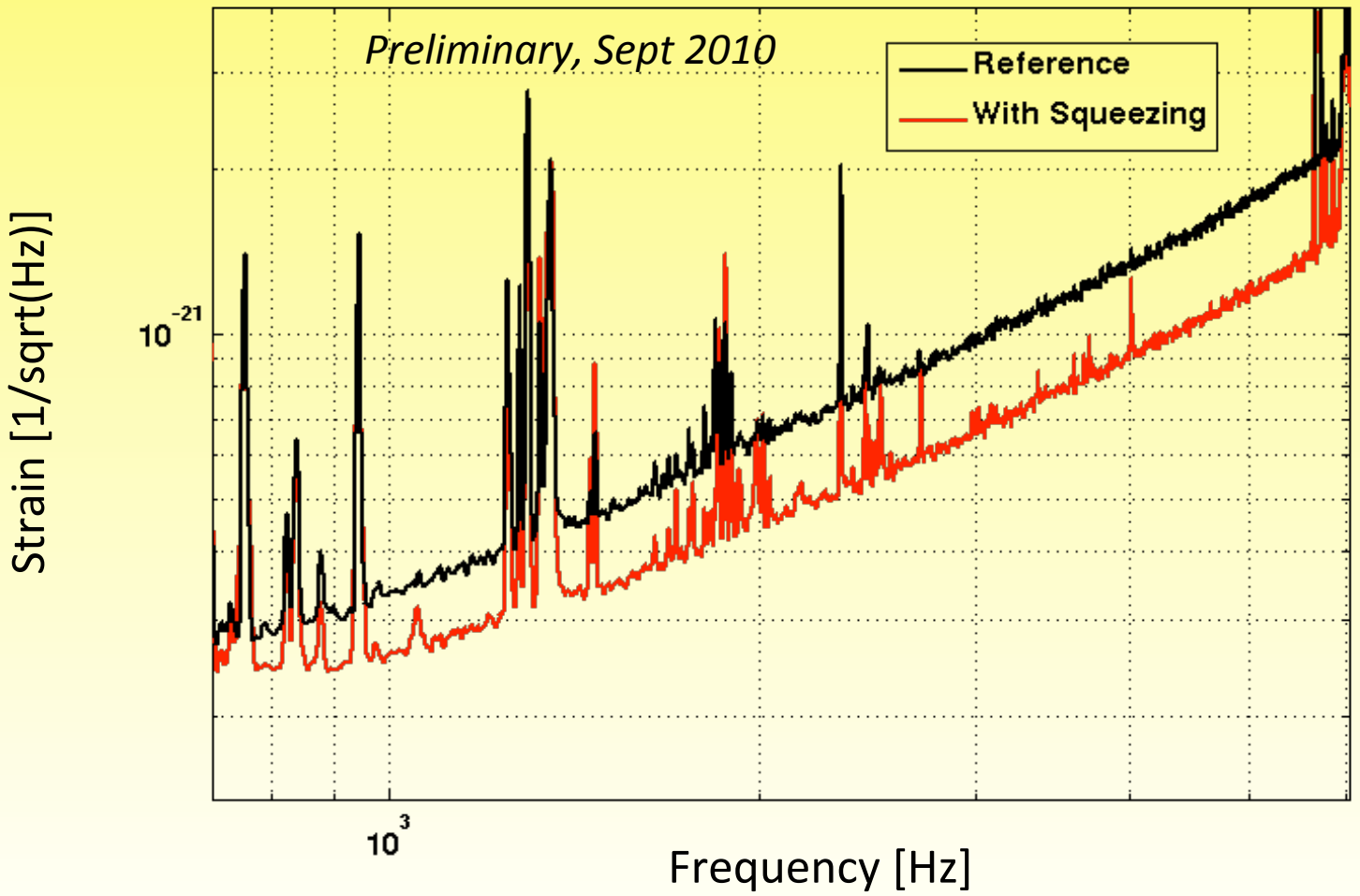
Largest Dedicated Computer Cluster in the World for GW Data Analysis at AEI




GEO600: The First Gravitational Wave Detector using Squeezed Light!

Squeezing result so far: 3.4dB

3-times increase in observable volume!

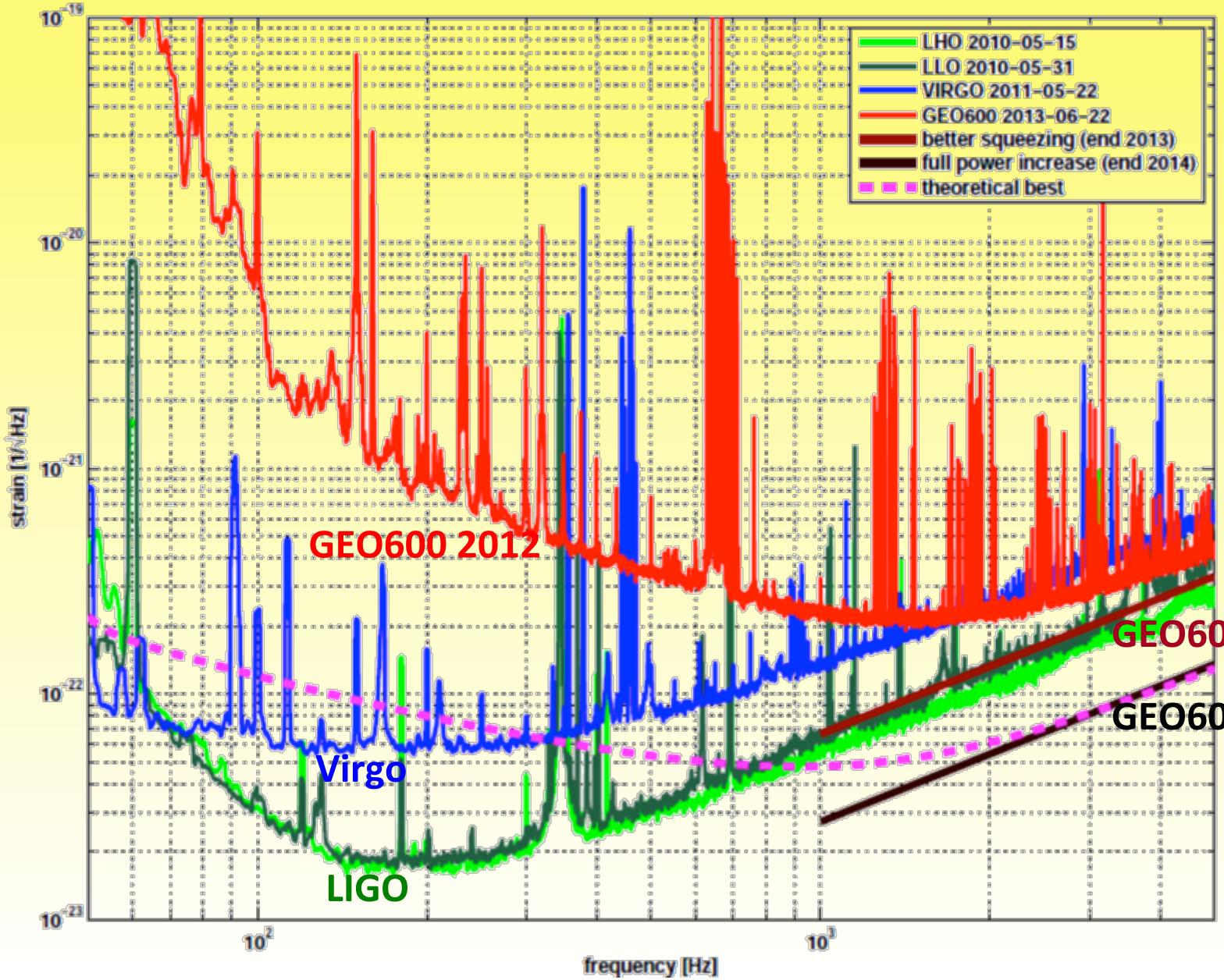


Astrowatch for GEO600 until 2016

- **LIGO and Virgo** offline for upgrading
- Back online 2016, design sensitivity 2019

- **GEO600** taking data 24/7 while others are down
- Occasional interruptions for commissioning and upgrades
- Will continue data taking until Advanced LIGO and Advanced Virgo are more sensitive in maybe 2017/8
- Then upgrade GEO600 beyond GEO-HF

GEO600, Virgo, LIGO Sensitivities



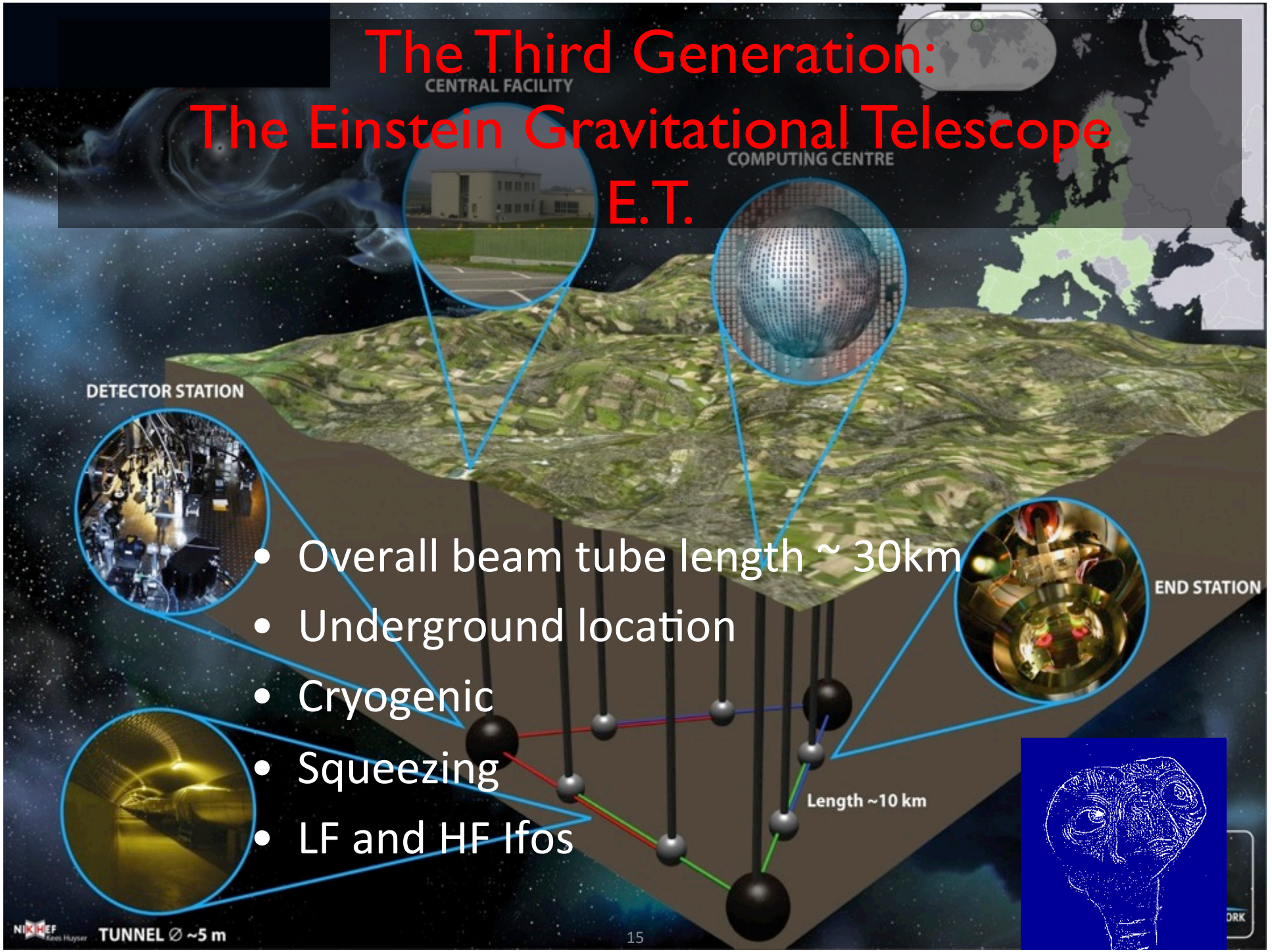
AEI Laser Systems for Advanced LIGO

- High power lasers delivered to LIGO Livingston and LIGO Hanford
  - Third system in storage for LIGO India
  - 165 W output power
  - more than 99% in fundamental Gaussian mode

Installed Pre-Stabilized High Power Laser in the Laser Area Enclosure of the LIGO Livingston Gravitational Wave Observatory

The LIGO Livingston Gravitational Wave Observatory

The Third Generation: The Einstein Gravitational Telescope E.T.



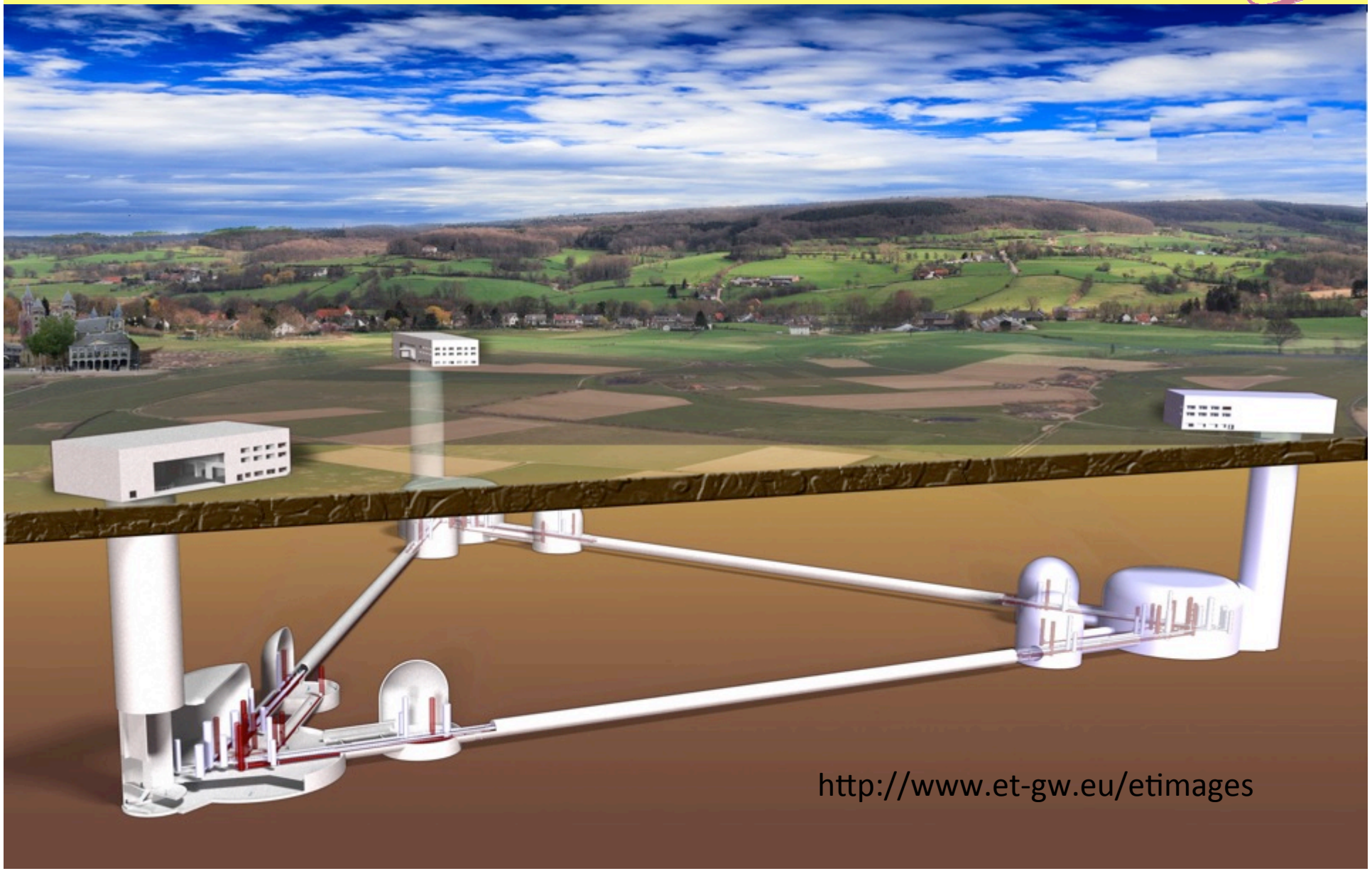
- Overall beam tube length ~ 30km
- Underground location
- Cryogenic
- Squeezing
- LF and HF Ifos

Conceptual Design Study in European Union FP7 Program

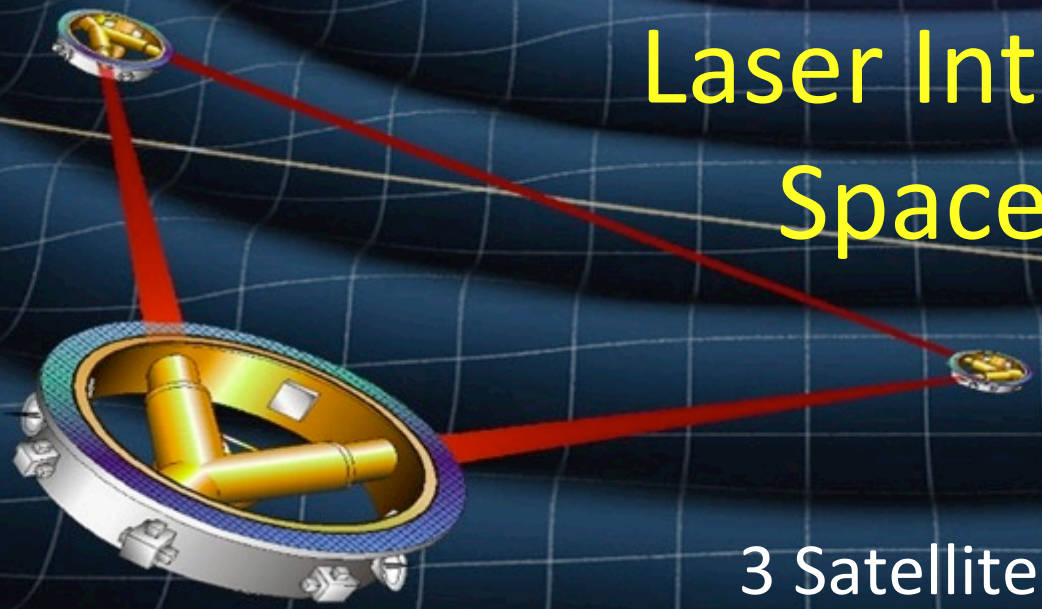
- AEI Co-PI
- Kick-Off May 2008
- Final Presentation
  May 20, 2011 in Cascina

SEVENTH FRAMEWORK PROGRAMME

Artistic/Schematic views



LISA

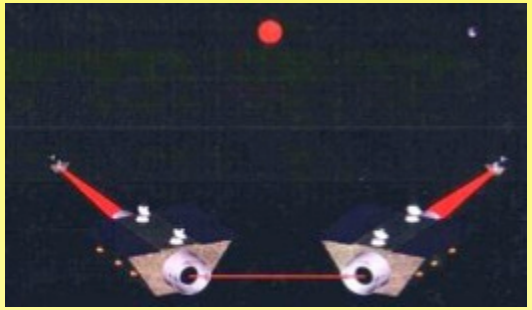


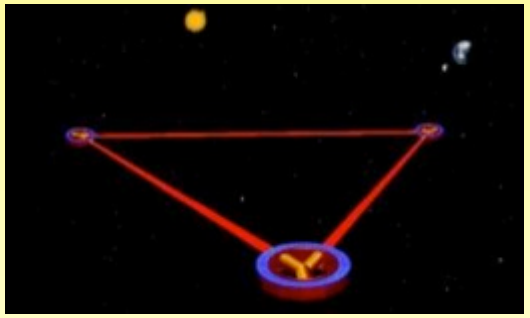
Laser Interferometer Space Antenna

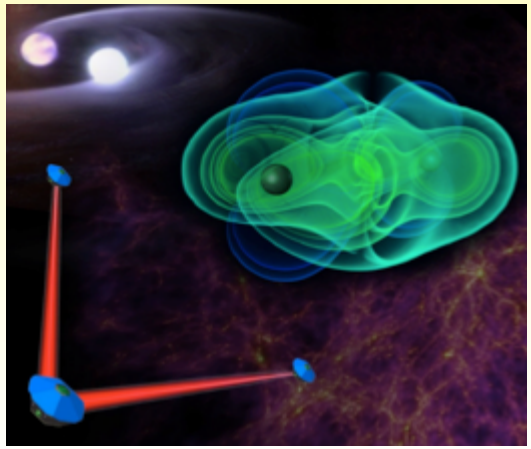
3 Satellites
Million km arms
50 Million km behind Earth

eLISA: A Mature Concept

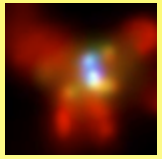
- M3 proposal for 4 S/C ESA/NASA collaborative mission in 1993
- LISA selected as ESA Cornerstone in 1995
- 3 S/C NASA/ESA LISA appears in 1997
- Joint Mission Formulation study until 2011
- Reformulation in 2012 as ESA-only NGO mission concept with 1 Mio km arms







eLISA for Astrophysics, Cosmology, and Fundamental Physics



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Ultra-Compact Binaries in Milky Way

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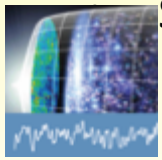

Stochastic Signals

- Directly probe Planck scale epoch at 1 TeV to 1000 TeV before decoupling of microwave background
- Were there phase transitions and of which order?
- Probe Higgs field self coupling and potential, and search for supersymmetry.
- Are there warped sub-millimetre extra-dimensions?
- Can we see braneworld scenarios with reheating temperatures in the TeV range?
- Do topological defects like Cosmic Strings exist?

??? The Unknown !

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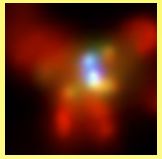

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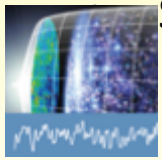

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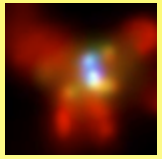

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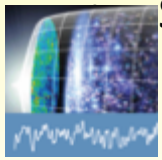

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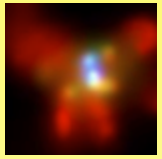

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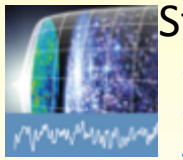

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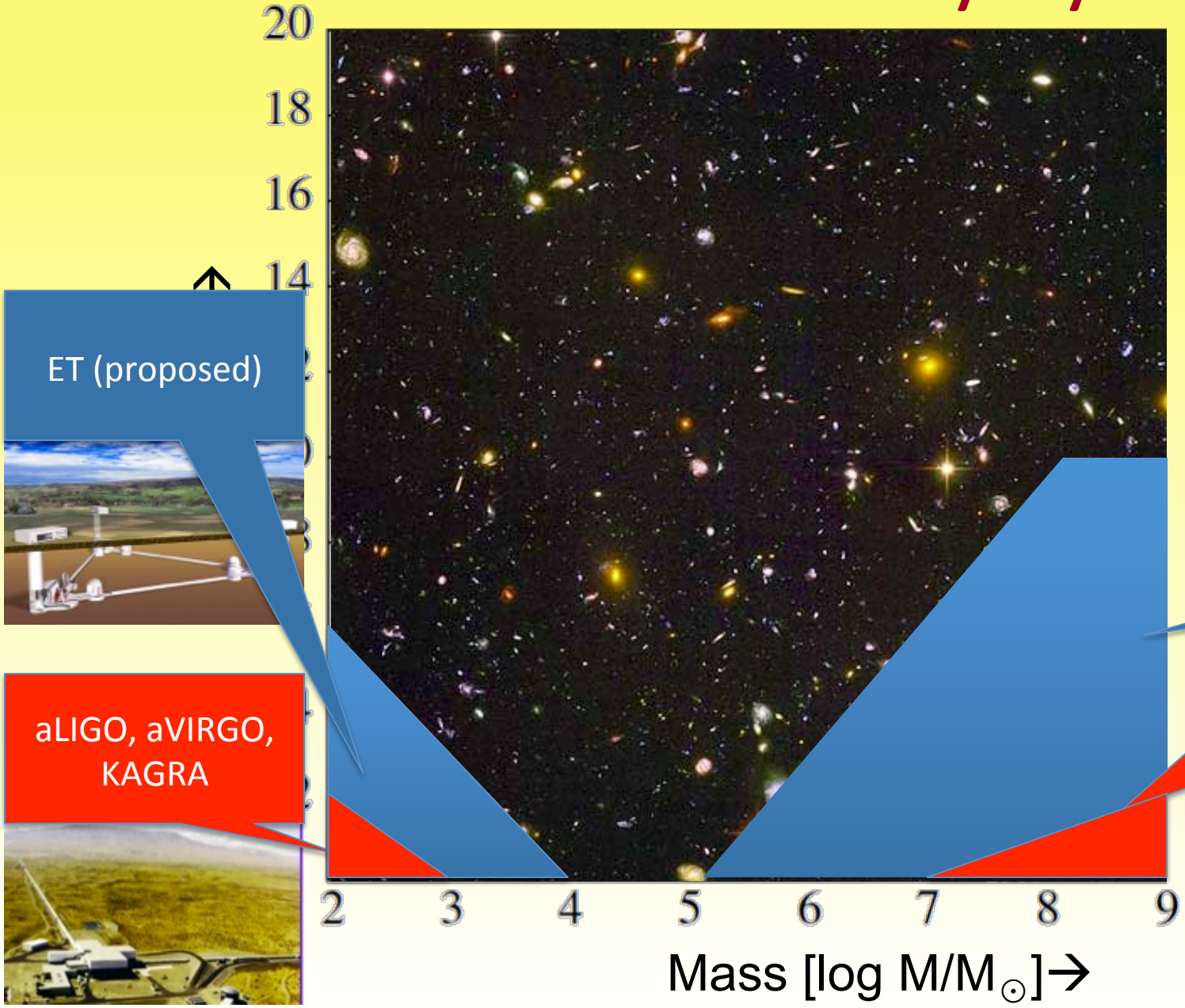
??? The Unknown !

Science in the 2020s

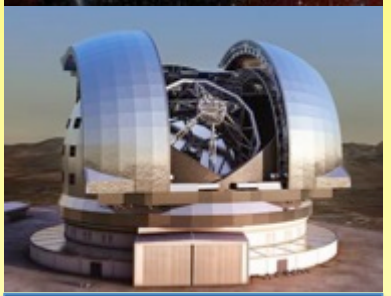
- Observatories
  - Ground
    - LHC, LSST, (EELT, TMT, GMT), SKA, ALMA, EHT
  - Space
    - JWST, EUCLID, Gaia, WFIRST, eROSITA, GRAVITY
  - Ground-based GW observatories
    - aLIGO, aVIRGO, KAGRA, ET
- Big science questions
  - Cosmic structure formation and Black Hole growth
  - Physics beyond Higgs,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

Black Hole Astronomy by 2028



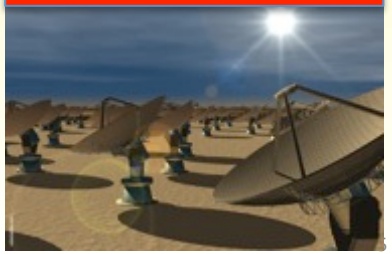
ET (proposed)

aLIGO, aVIRGO, KAGRA



Future EM Obs. LSST, JWST, EELT, X-rays

SKA, Pulsar Timing



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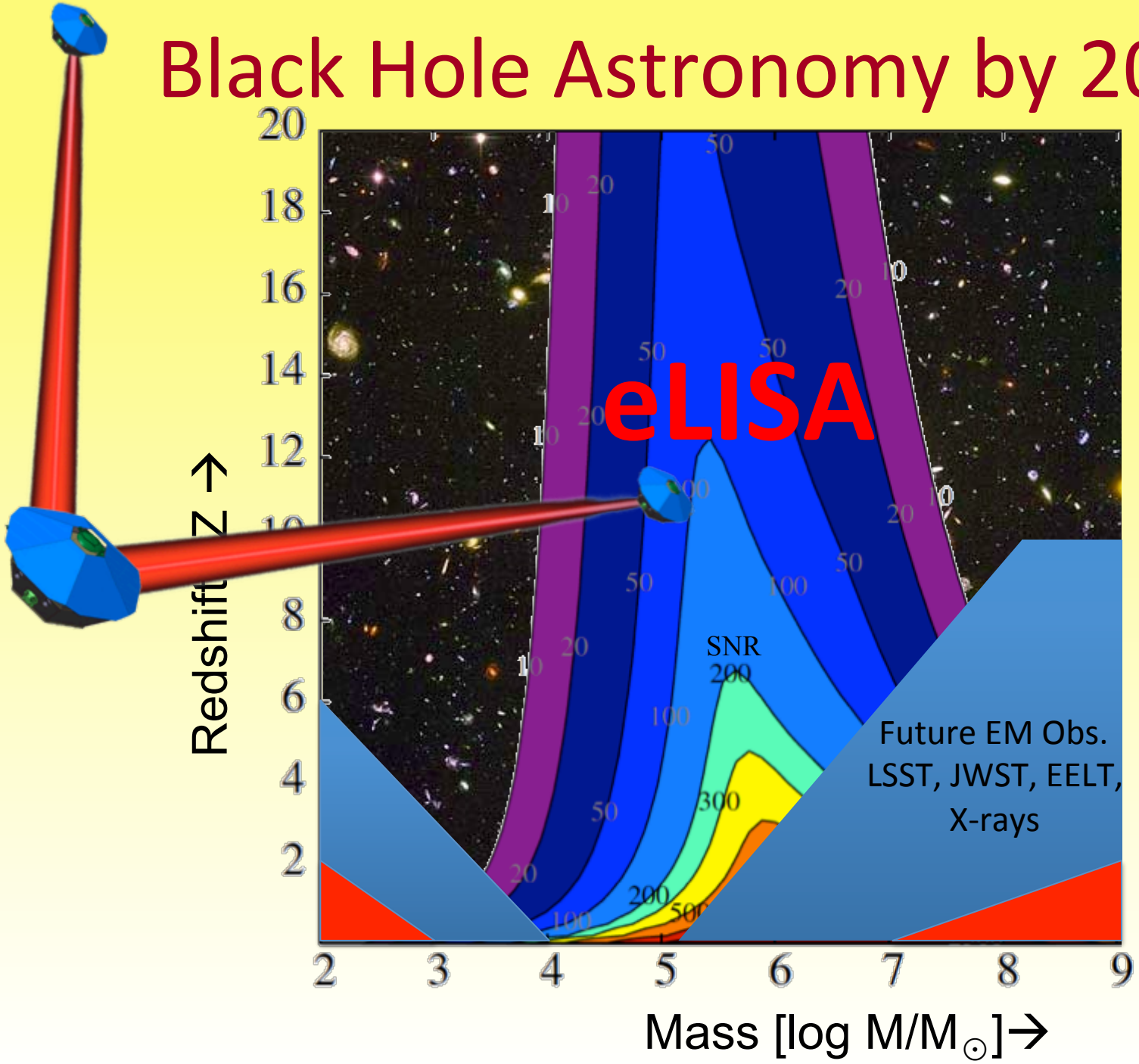

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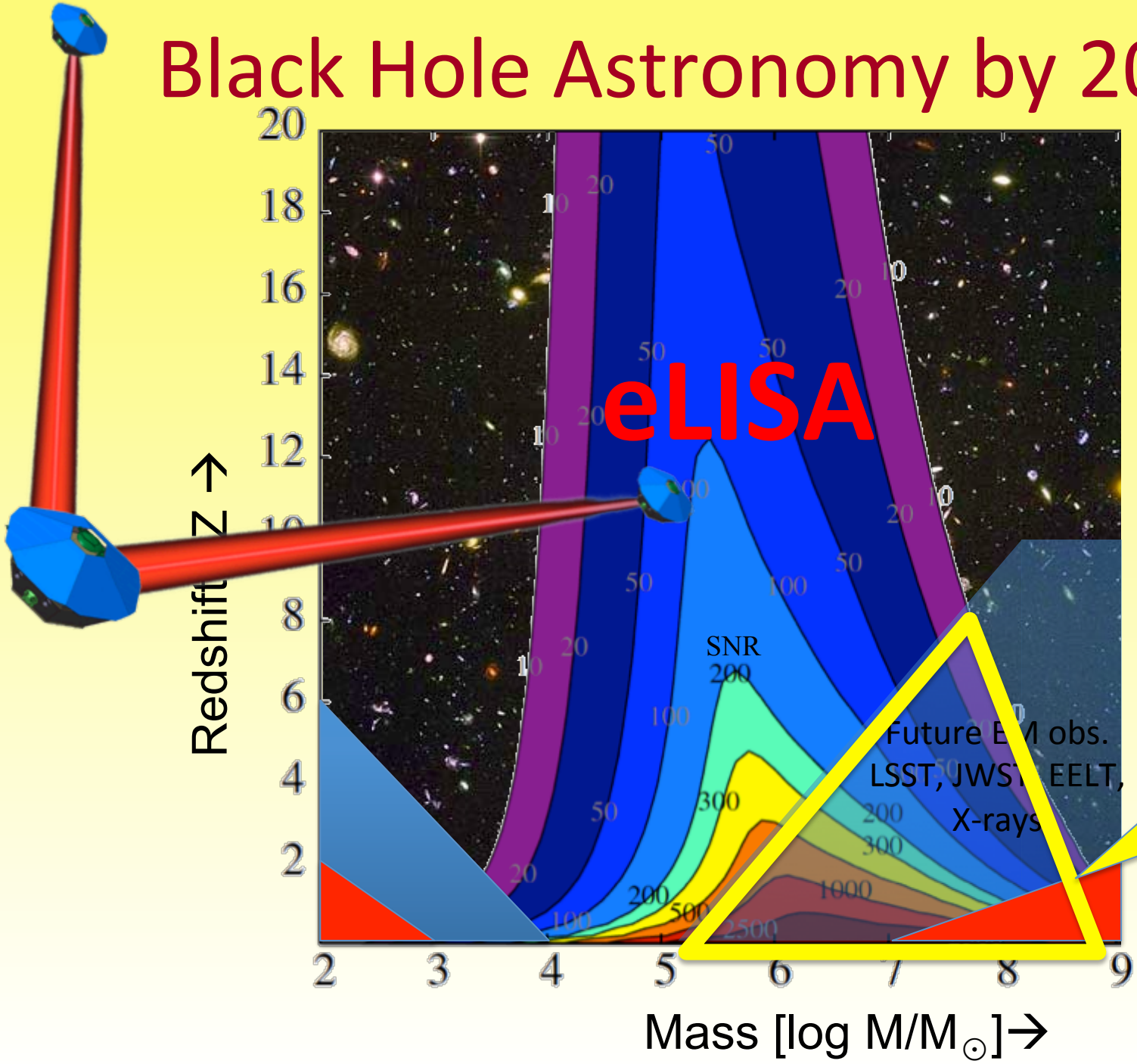

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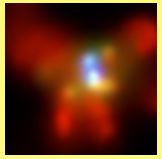

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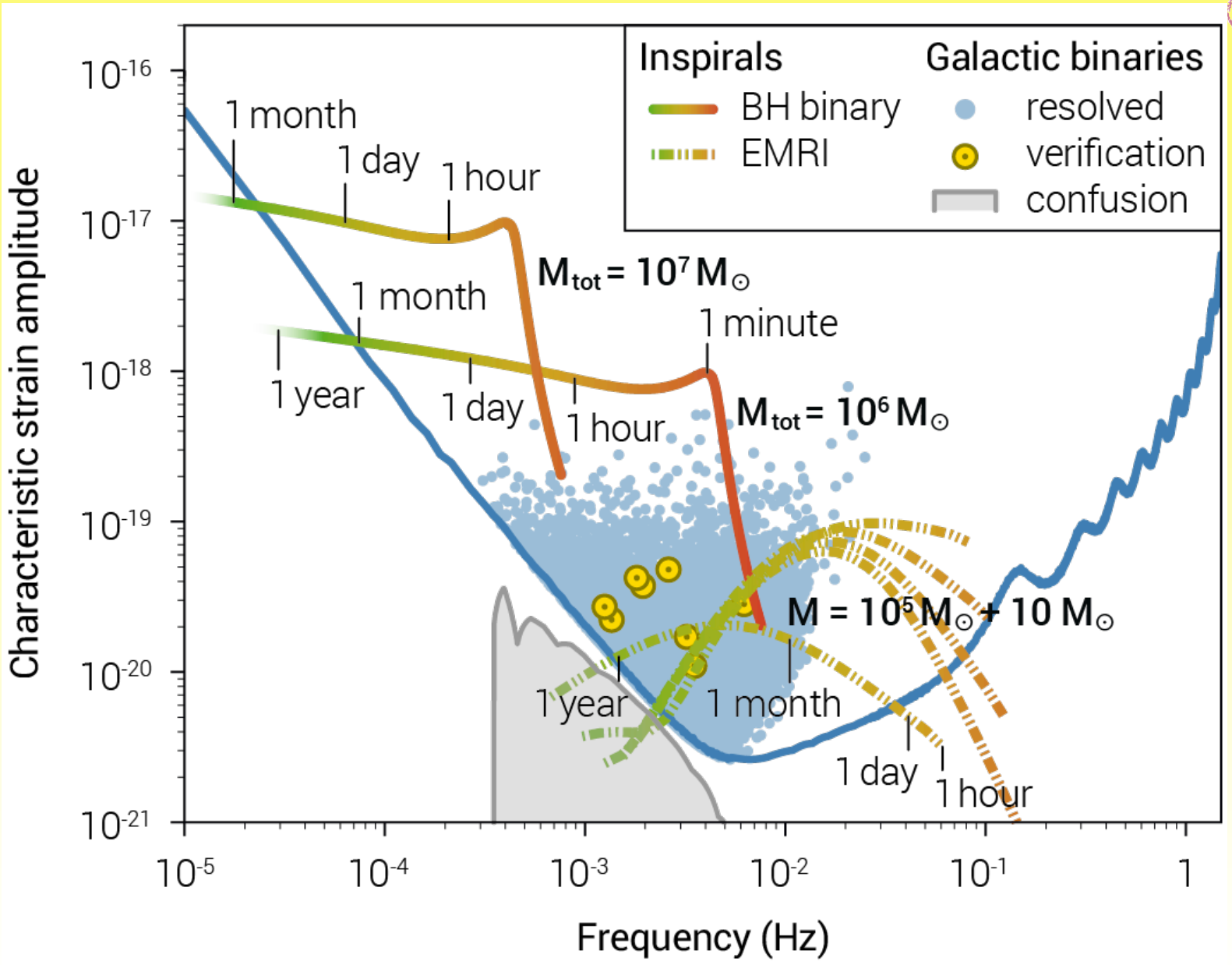
Sensitivity and Black Hole Science

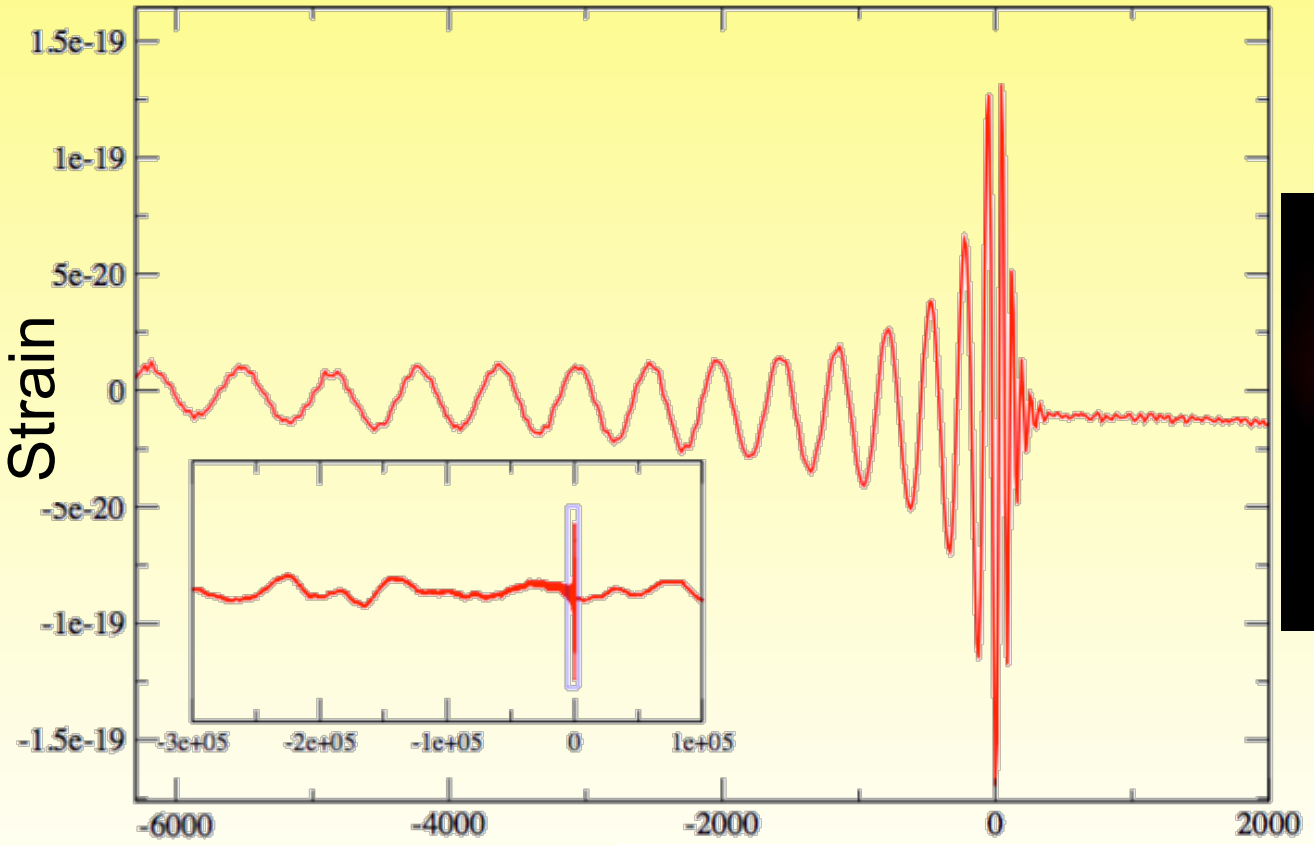


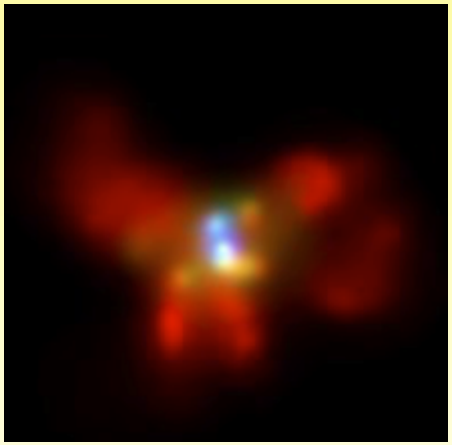
Black Hole Merger Signals far above Noise!

- Simulated eLISA data stream

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

  including instrumental noise (SNR~100)

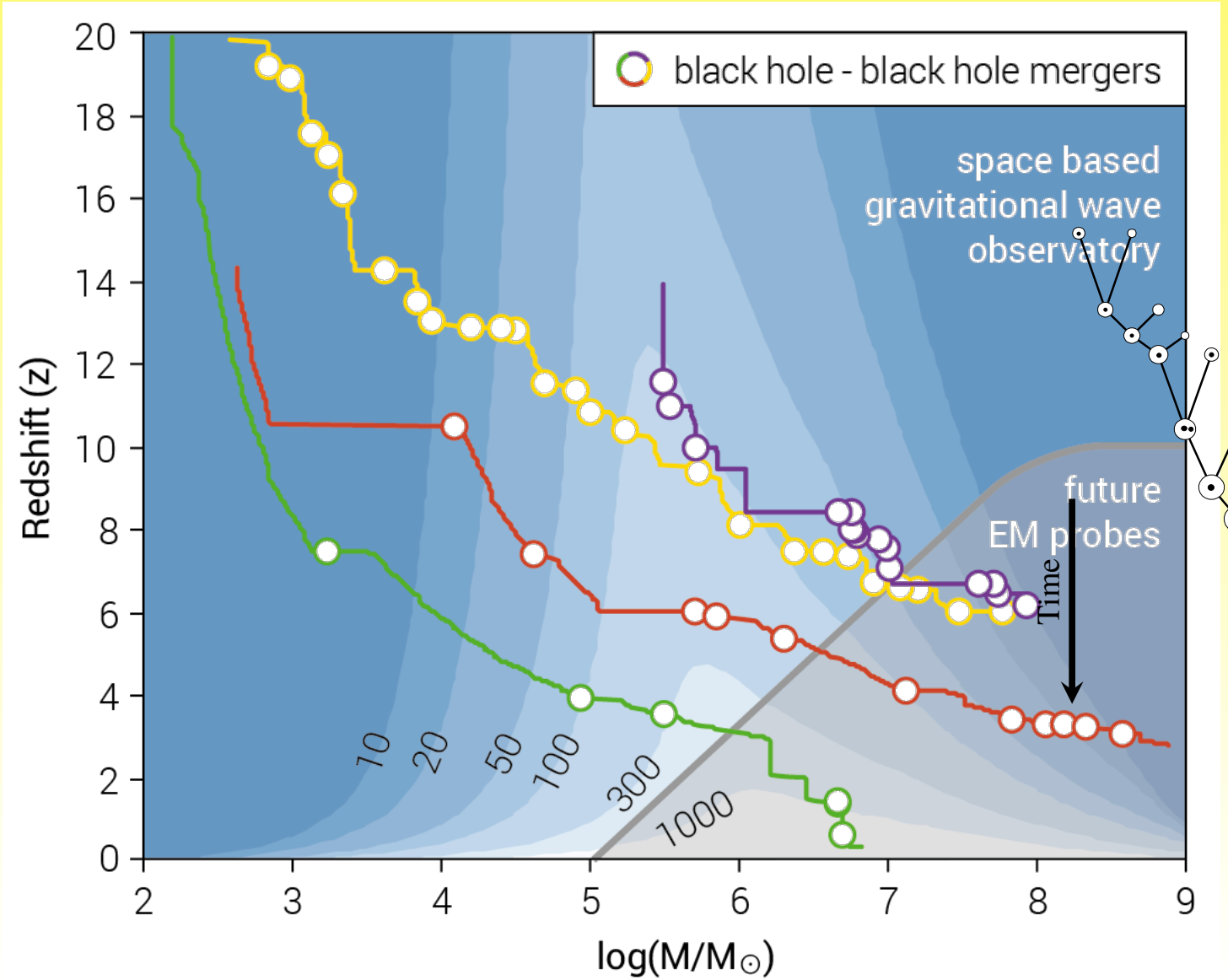


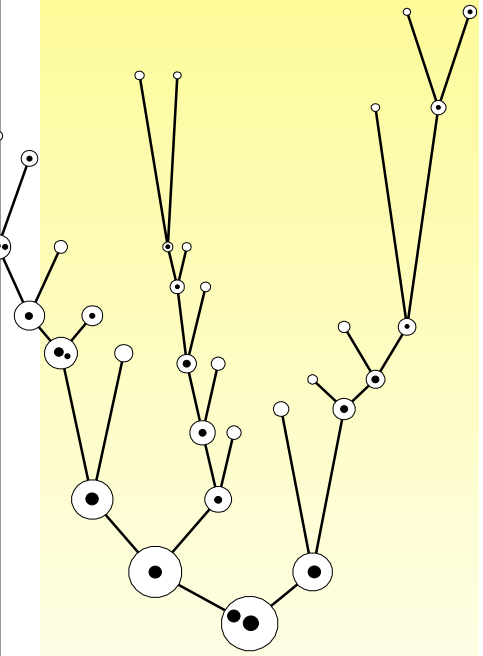


NGC 6240

Baker et al. 2006

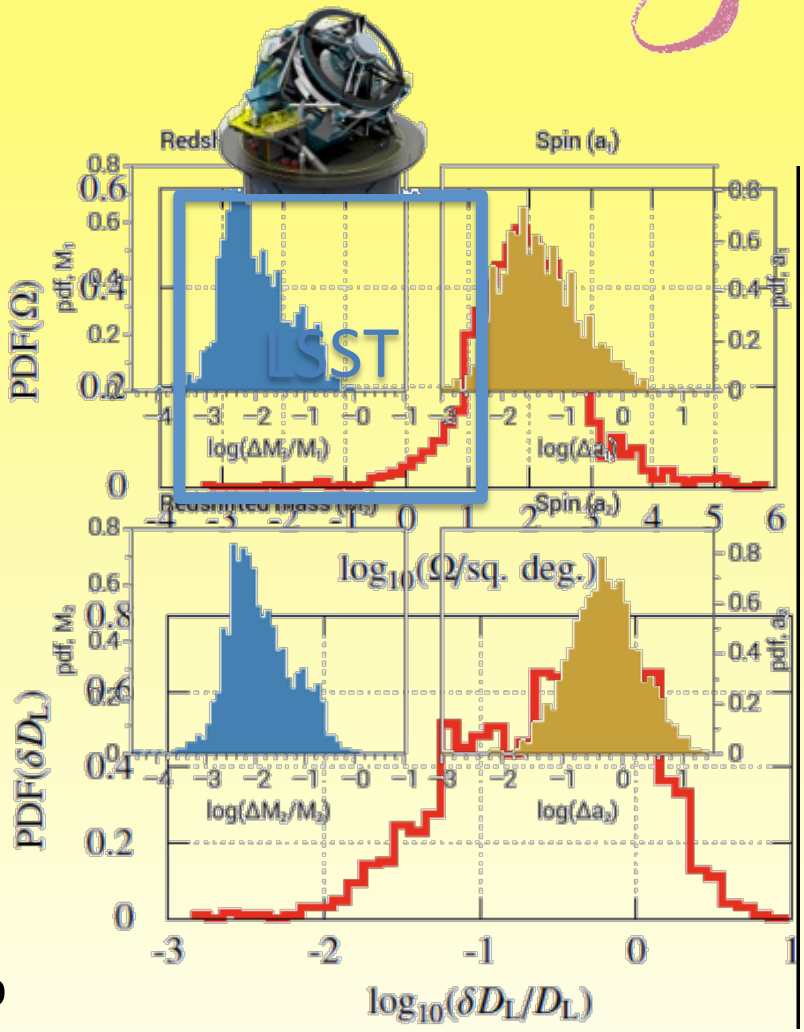
All Binary Black Holes cross eLISA band: Trace Galaxy Mergers





eLISA Black Hole Physics at high SNR

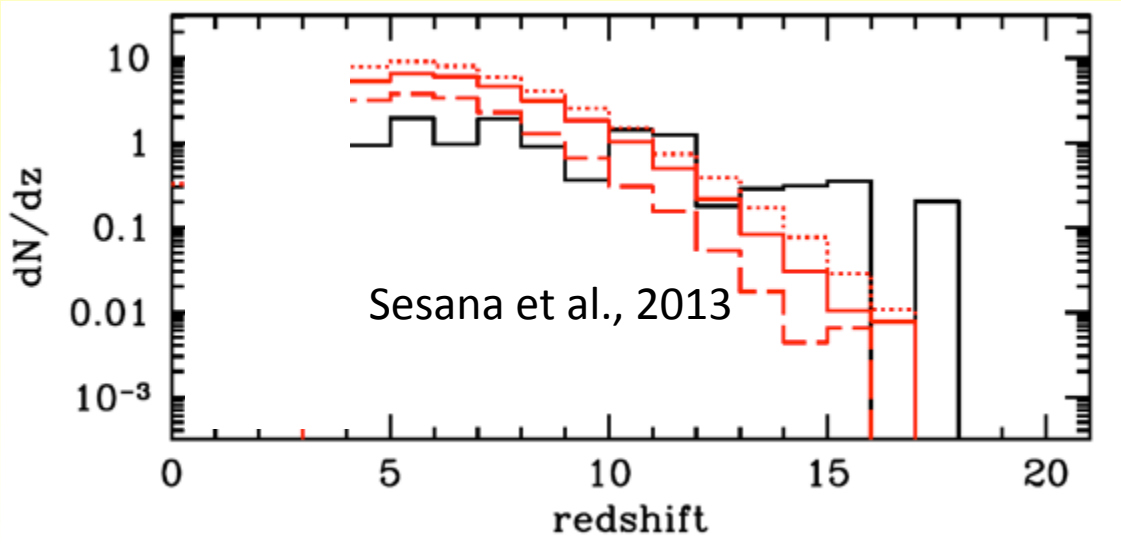
- BBH rest mass 10^4 – 10^7
- Out to redshift z >> 10
  - if they exist
- 10 – 100 events per year
- Redshifted mass to 0.1%-1%
- Absolute spin to 0.01-0.1
- Luminosity distance 1 – 50 %
- Sky location 1° - 10 °



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!



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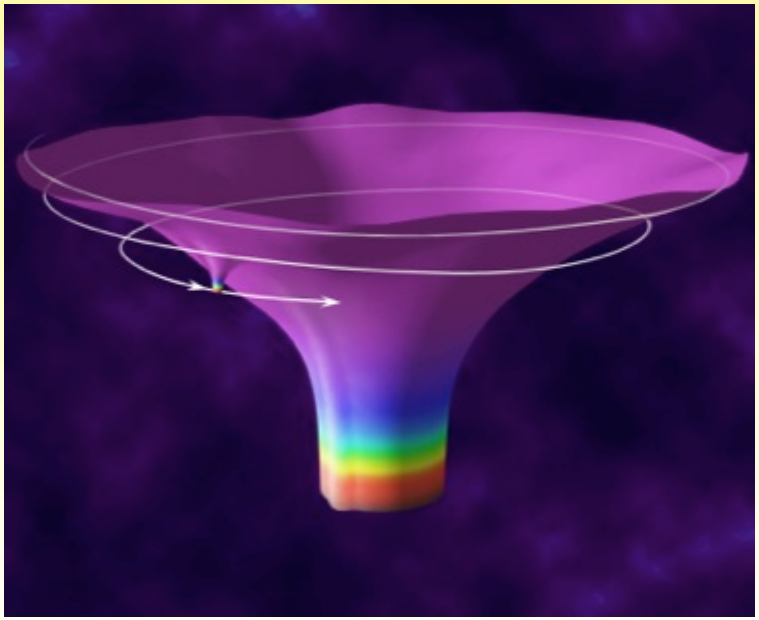
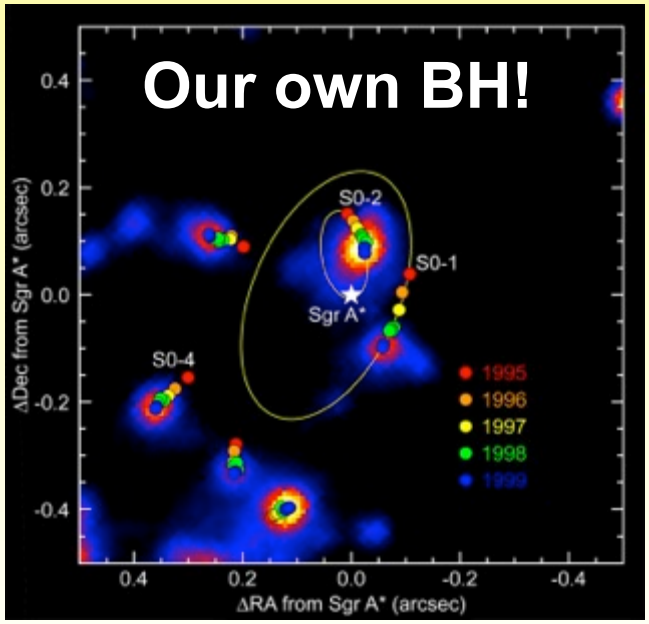
- The Unknown !

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



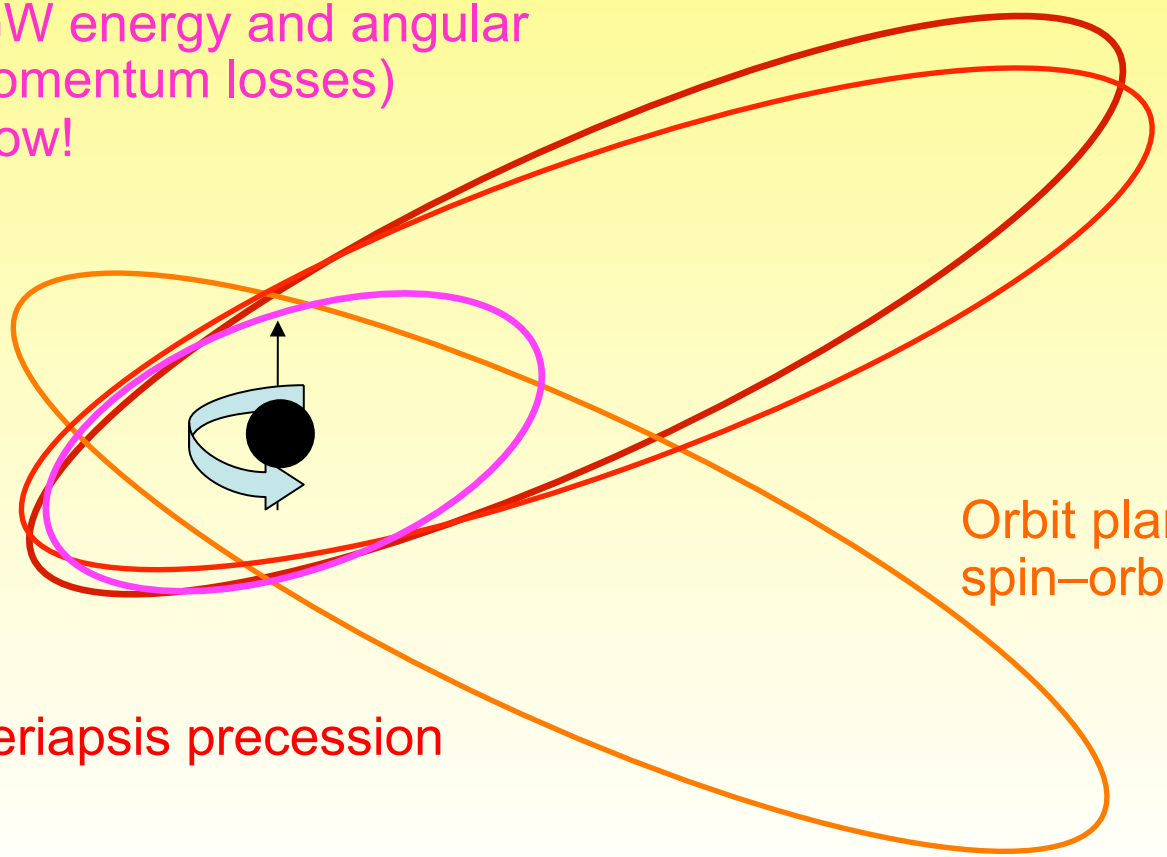


Ghez et al. 1998 ApJ 509, 678, Eckart et al. 2002 MNRAS 331, 917

Orbits and spiral-in of small bodies around spinning Black Holes

(Extreme Mass Ratio Inspirals, EMRIs)

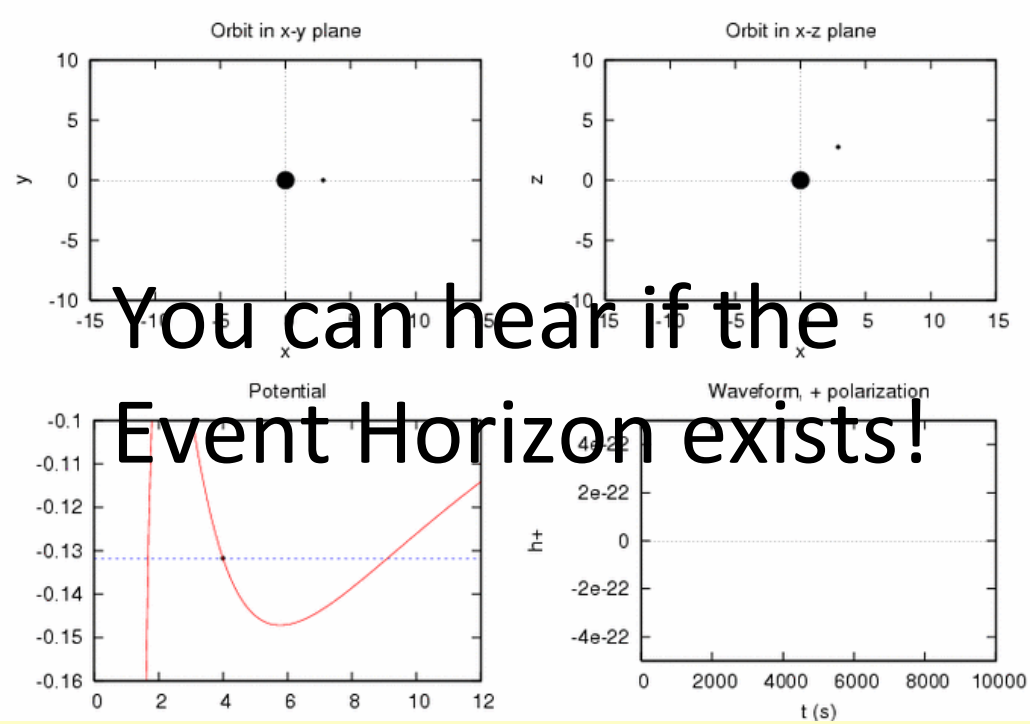
Spiral-in and Circularization
(GW energy and angular momentum losses)
Slow!



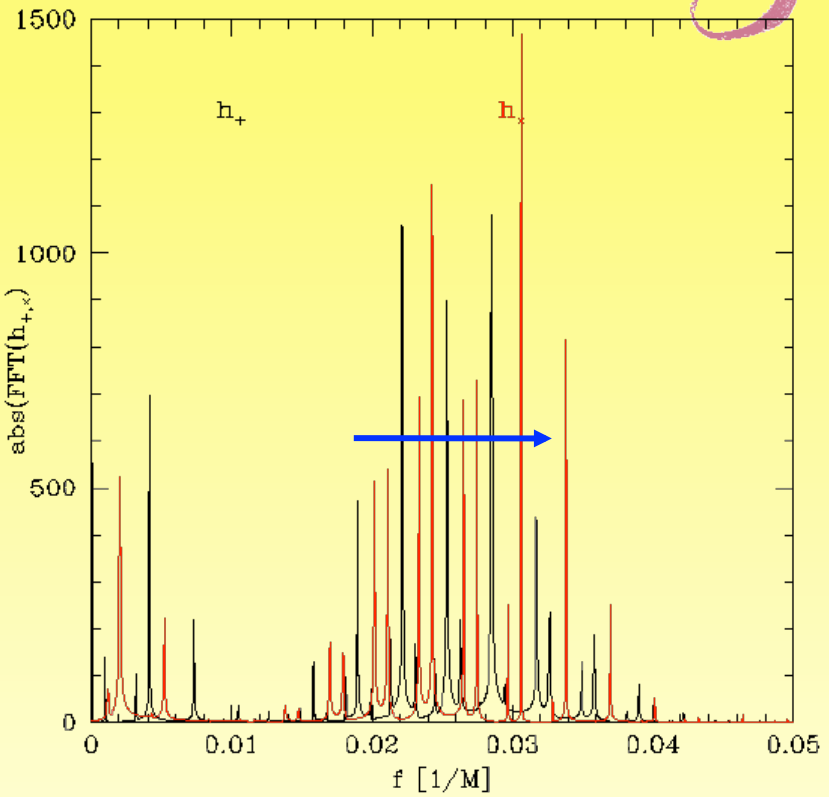
Orbit plane precession
spin–orbit; L-T(Lense-Thirring)

Periapsis precession

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.

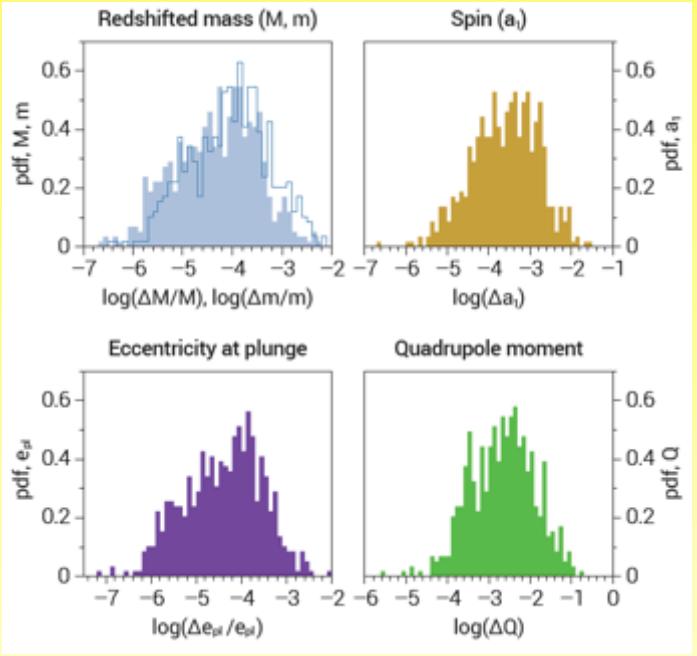
a=6M, e=0.2, i=80

⇒ Like a Geodesy satellite mapping Geopotential!

⇒ GRACE for Black Holes!

Extreme Mass Ratio Inspirals

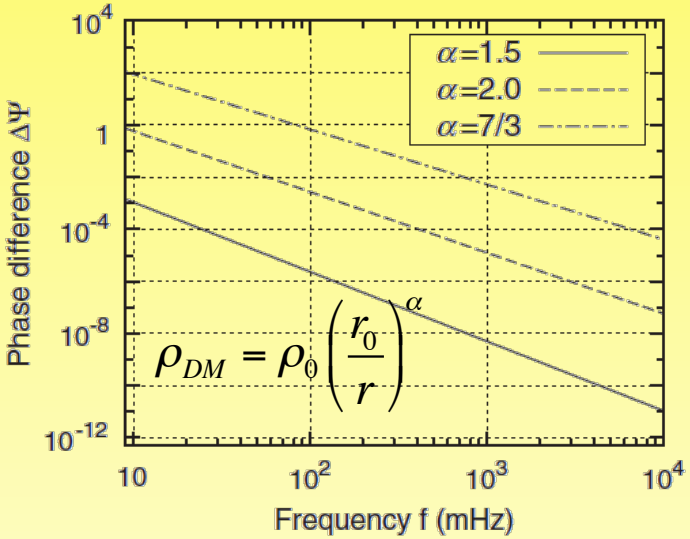
- SNR 20 up to z ≈ 0.7 for 10^5-10^6 $M_\odot$
- Dozens of events per year
- Mass, spin to 0.1% – 0.01 %
- Quadrupole moment to < 0.001 $M_\odot^3 G^2/c^4$



- 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 Dark Matter interacting only gravitationally



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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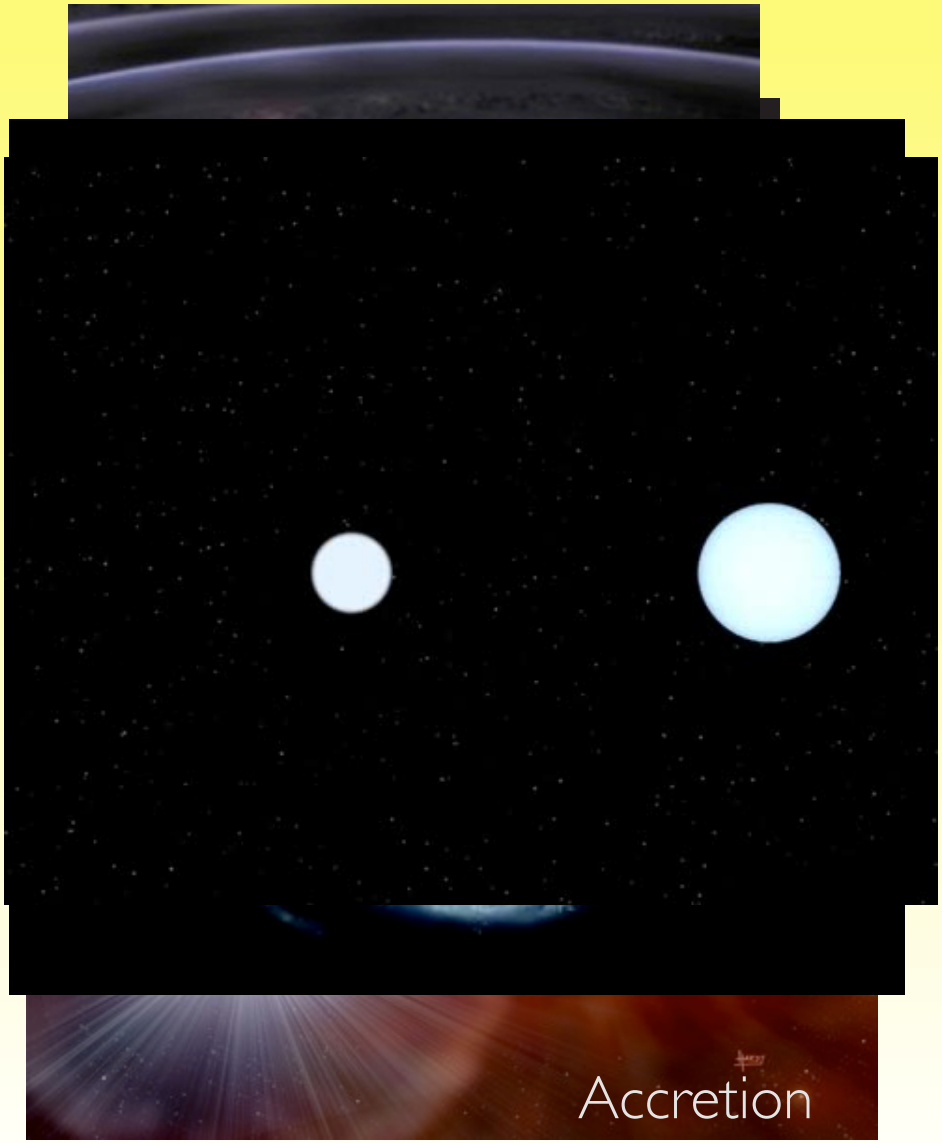
Galactic binaries: relevance

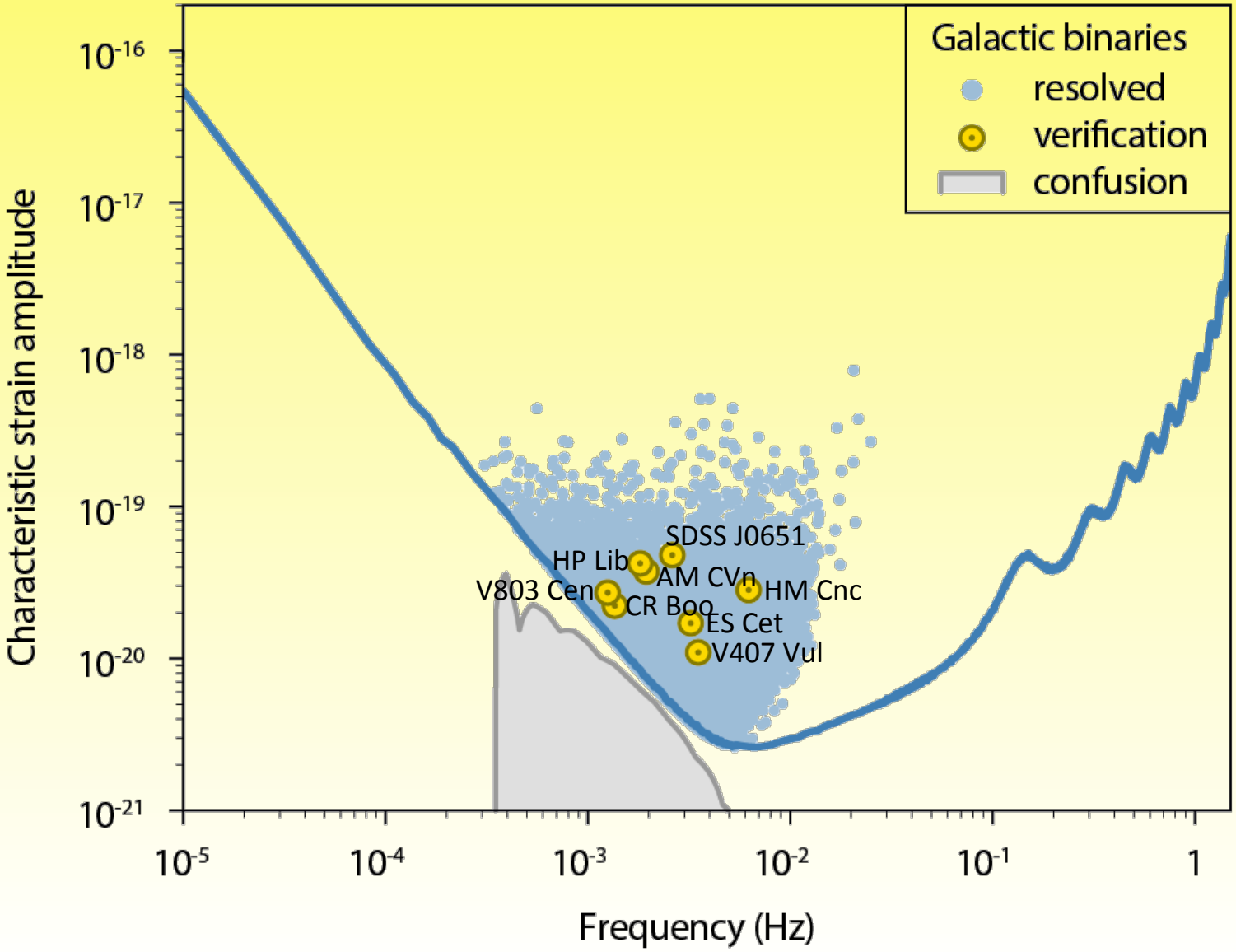
- Probes binary evolution
  - Common envelope
- Type Ia Supernovae
  - Same populations
- Galactic populations/ structure
  - Tracers of star formation
- Binary interactions
  - Mass transfer/tides



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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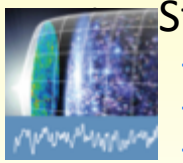

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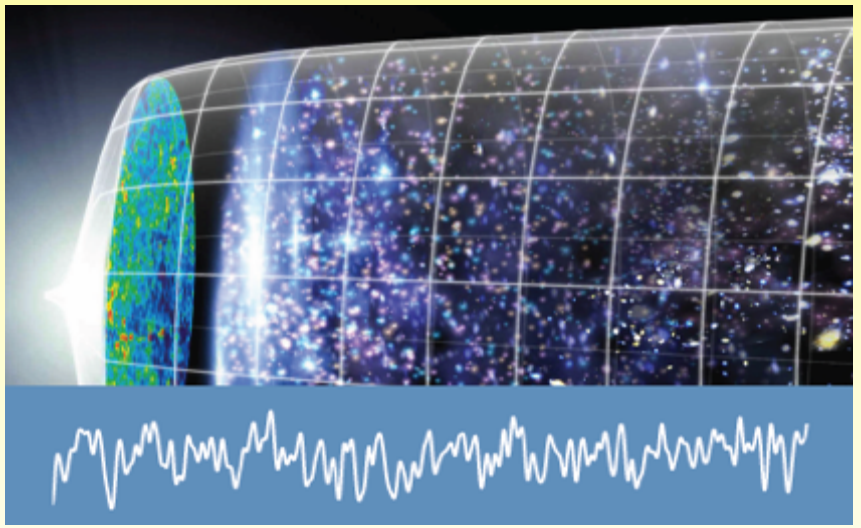
STOCHASTIC GW BACKGROUND

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

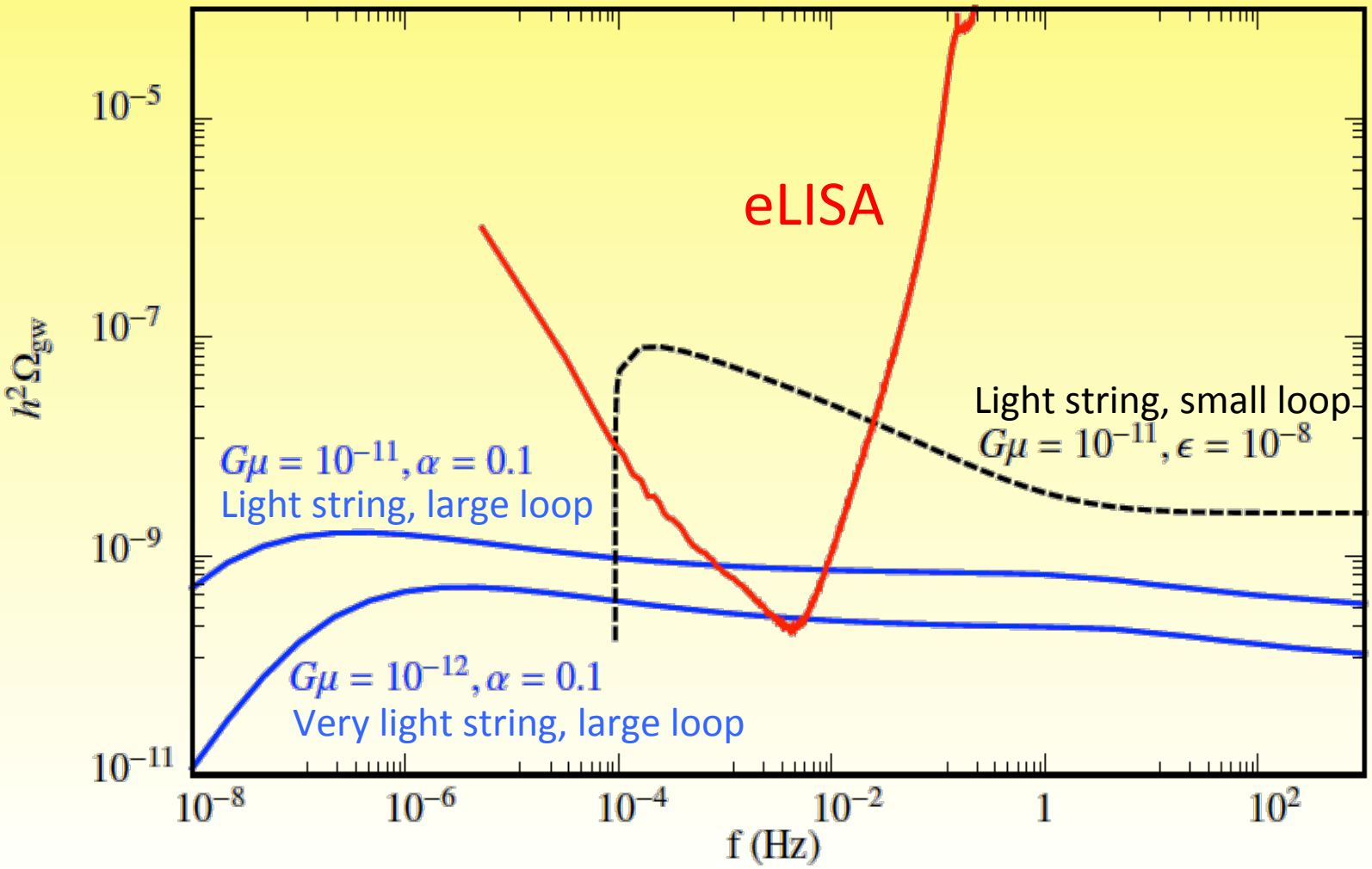
$$f_0 \approx 10^{-4}\,\mathrm{Hz}\sqrt{H_*(t)\times\frac{1\,\mathrm{mm}}{c}} \approx 10^{-4}\,\mathrm{Hz}\,\frac{kT_*}{1\,\mathrm{TeV}}$$

- 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?



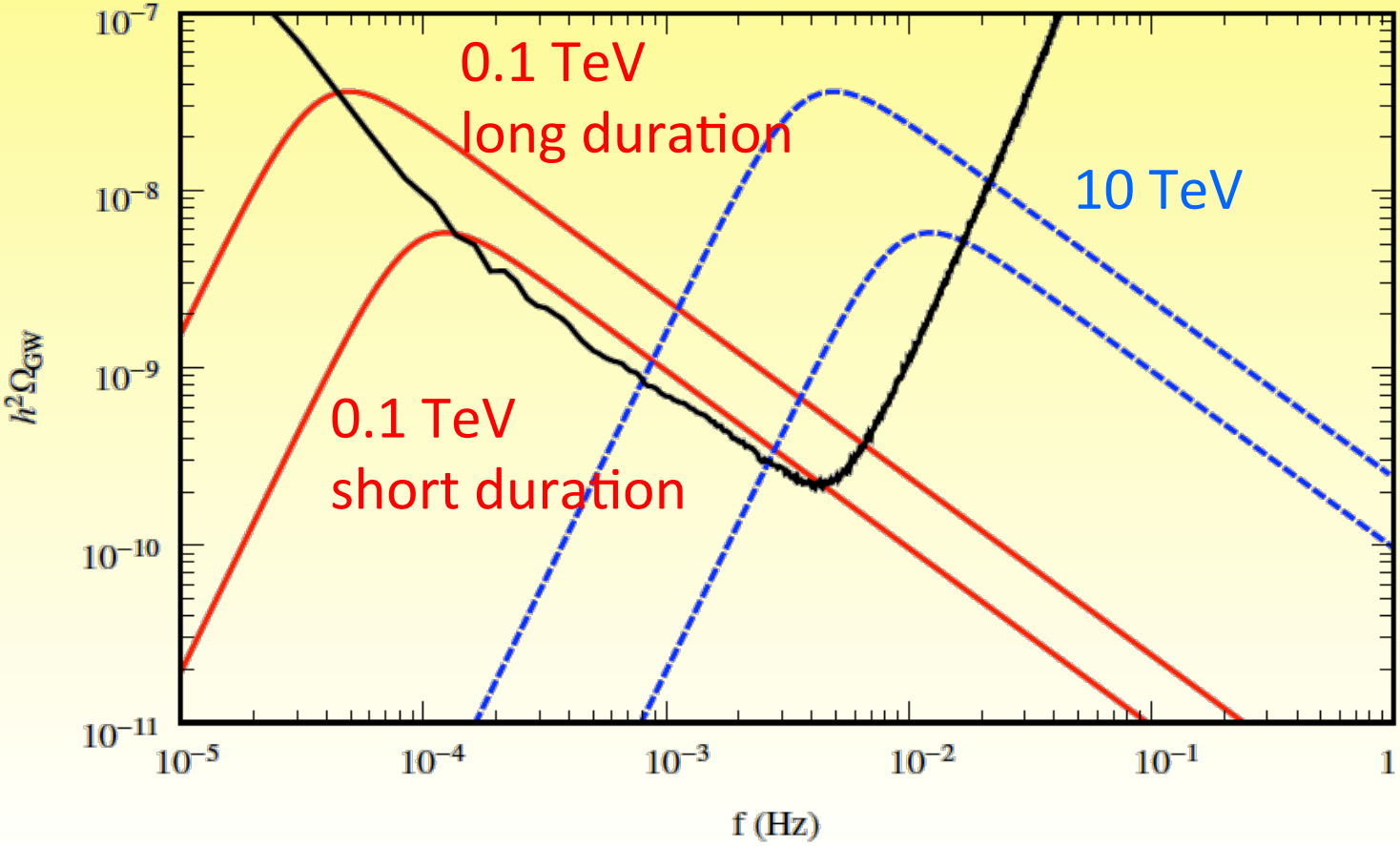
Topological Defects

- Cosmic Strings detectable as background, if they exist
- Cusps visible as time resolved bursts



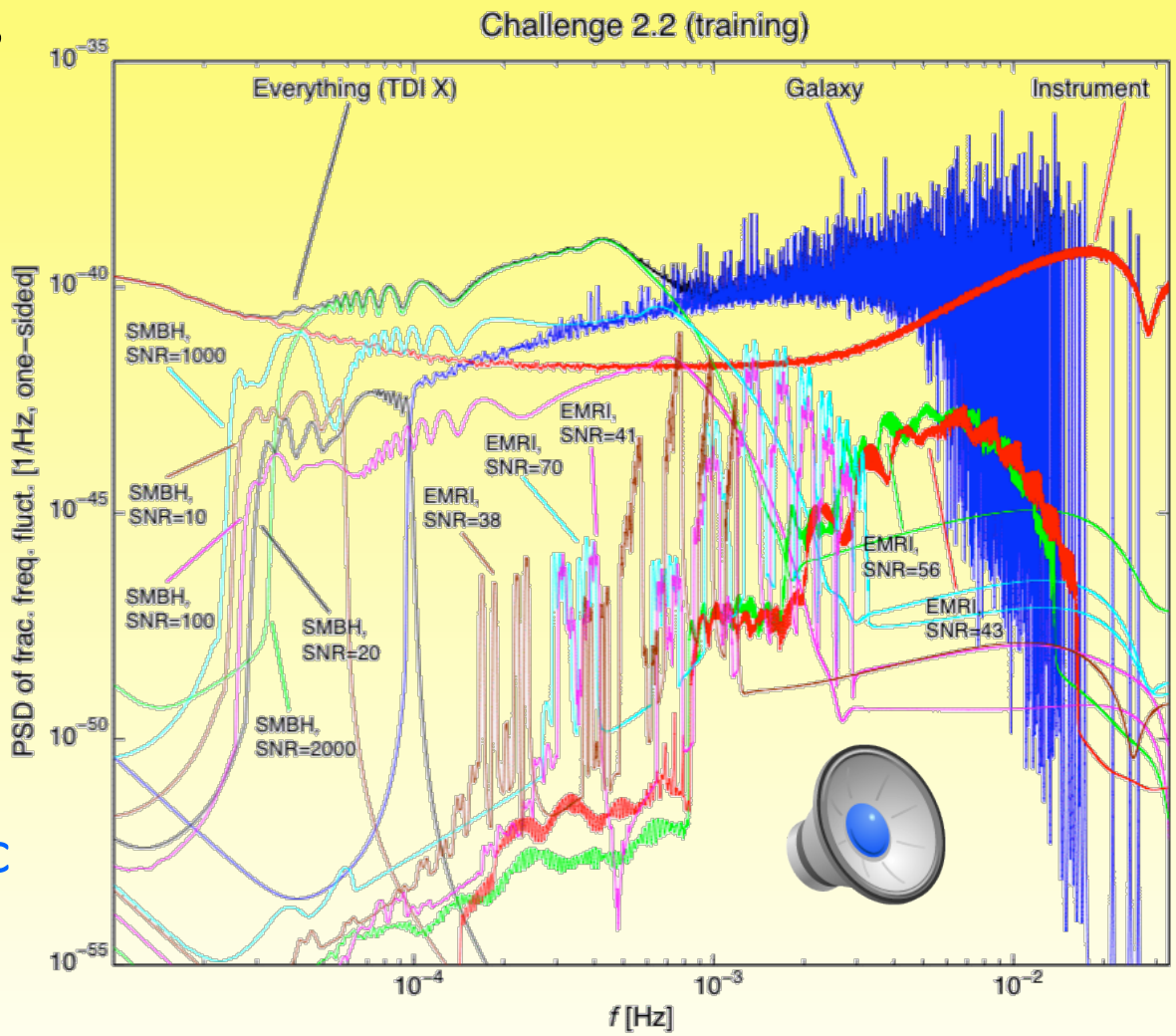
Probing Phase Transitions at the TeV Scale

- First order phase transition well above 1 TeV
- Konstandin et al., 2010: Randall and Sundrum (1999) sub-mm brane model looks like scalar field phase transition



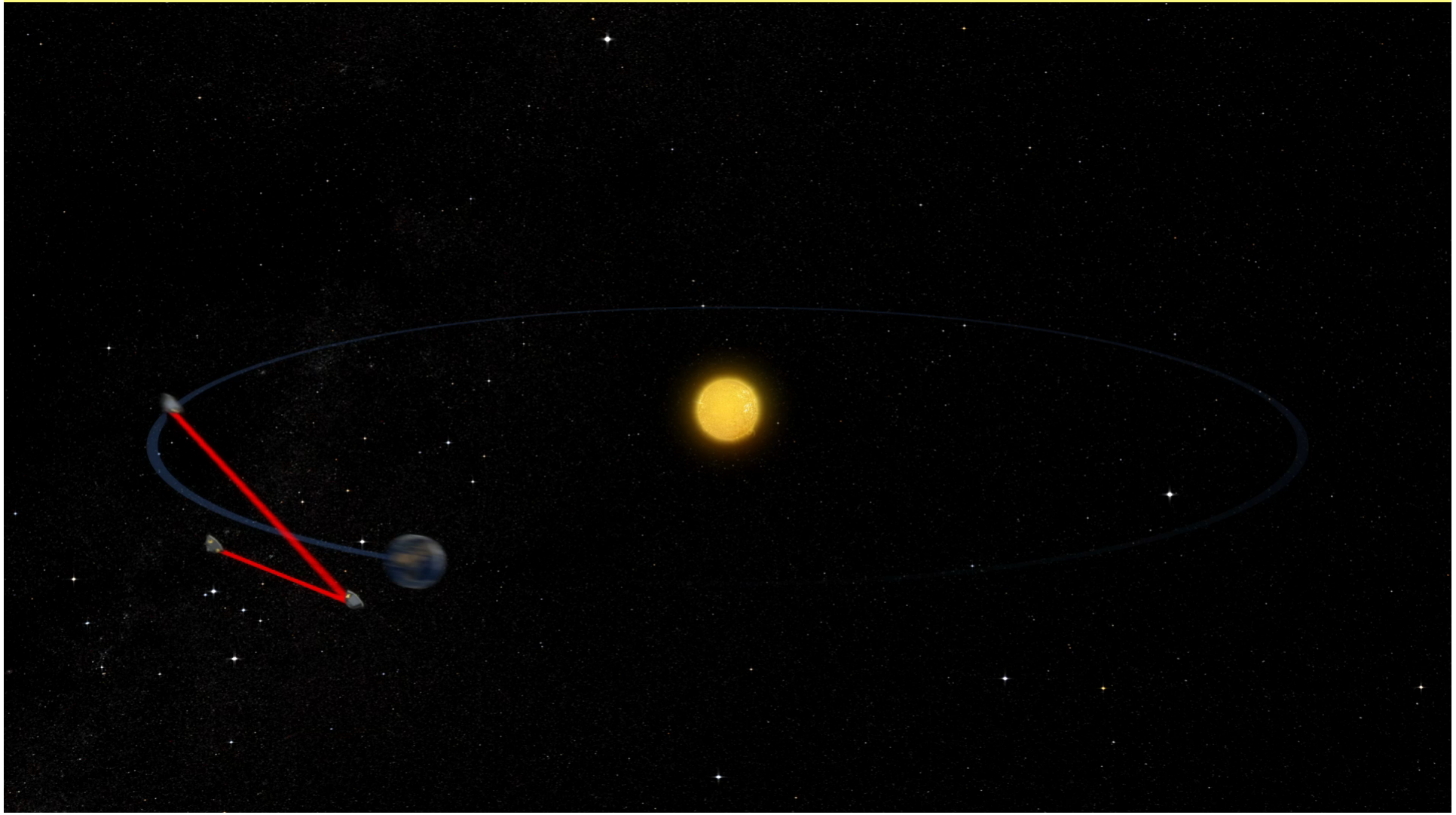
LISA Mock Data Challenge

- 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

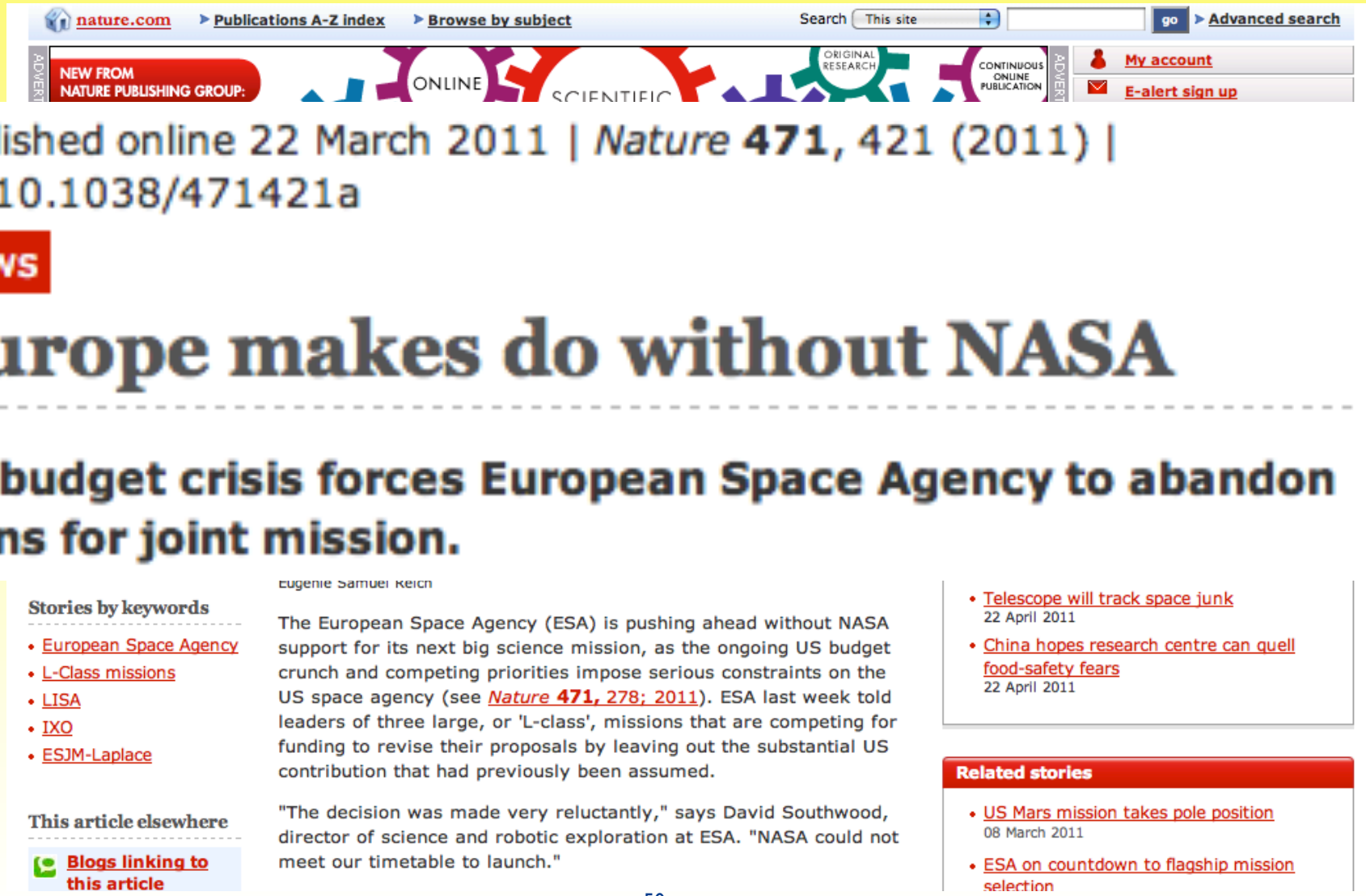


- Effective data analysis algorithms are in hand!

Strawman Mission Concept for eLISA: NGO as proposed for ESA L1 Selection



After 15 years of joint LISA development in March 2011…



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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°

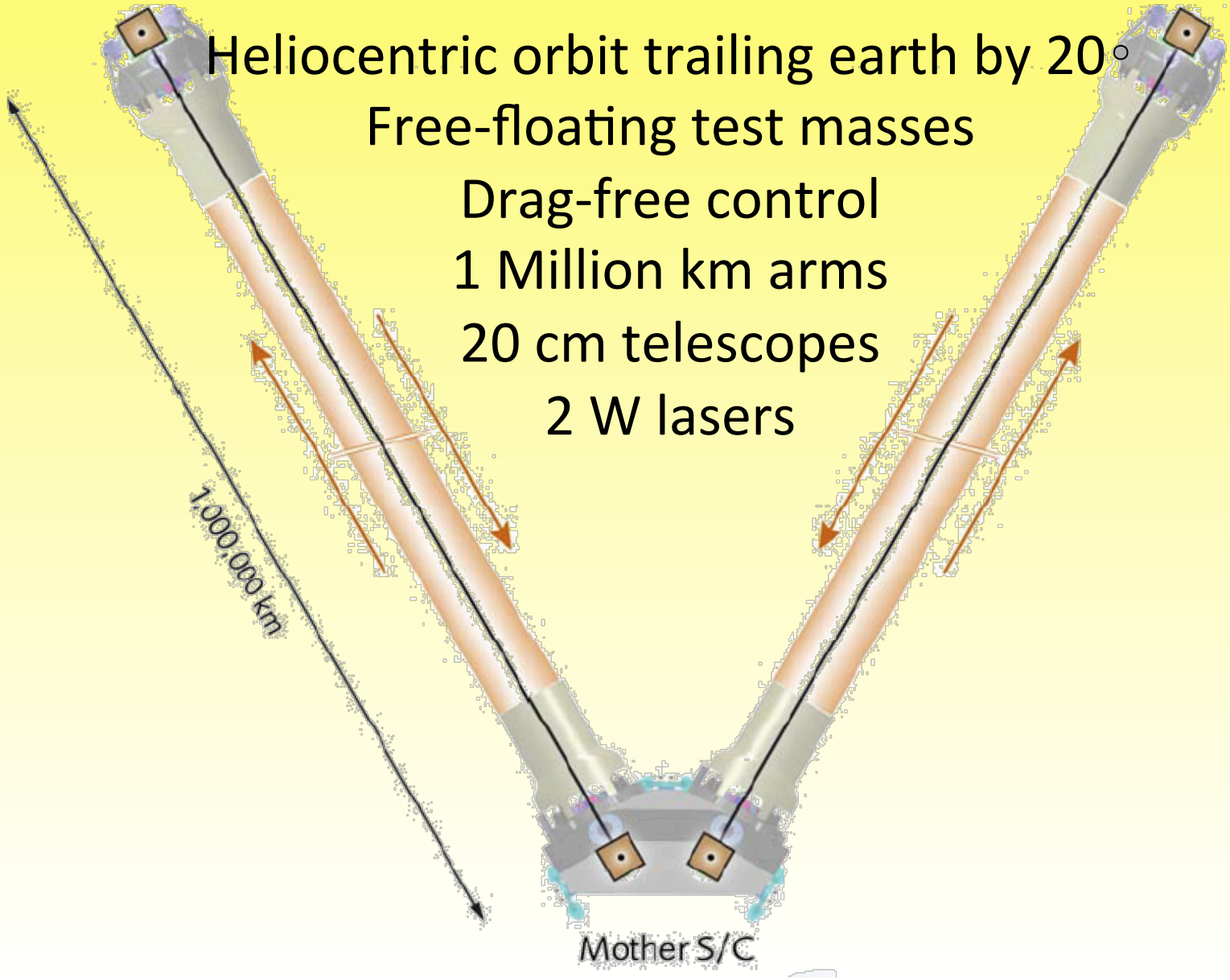
Free-floating test masses

Drag-free control

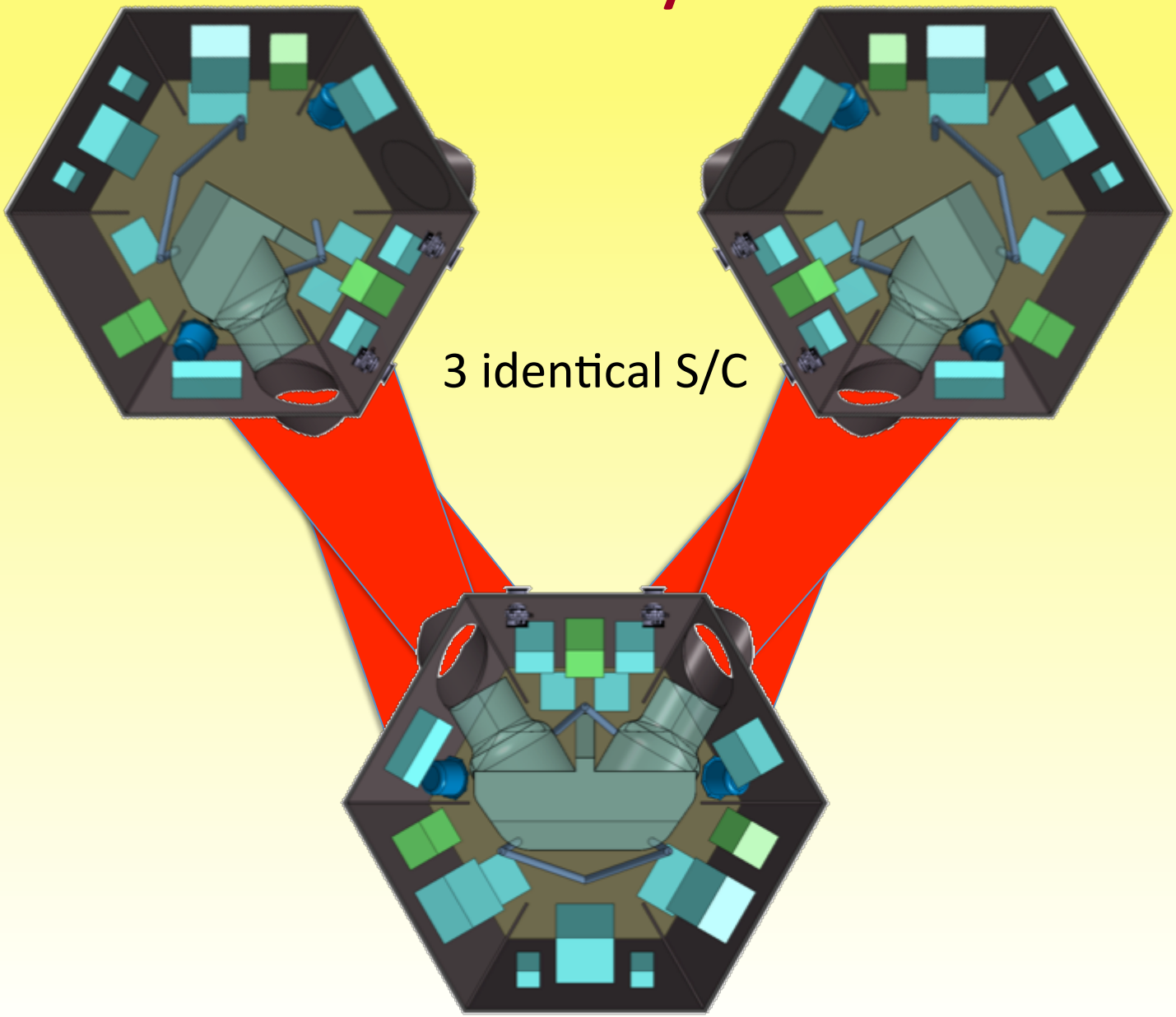
1 Million km arms

20 cm telescopes

2 W lasers



eLISA Lay-Out



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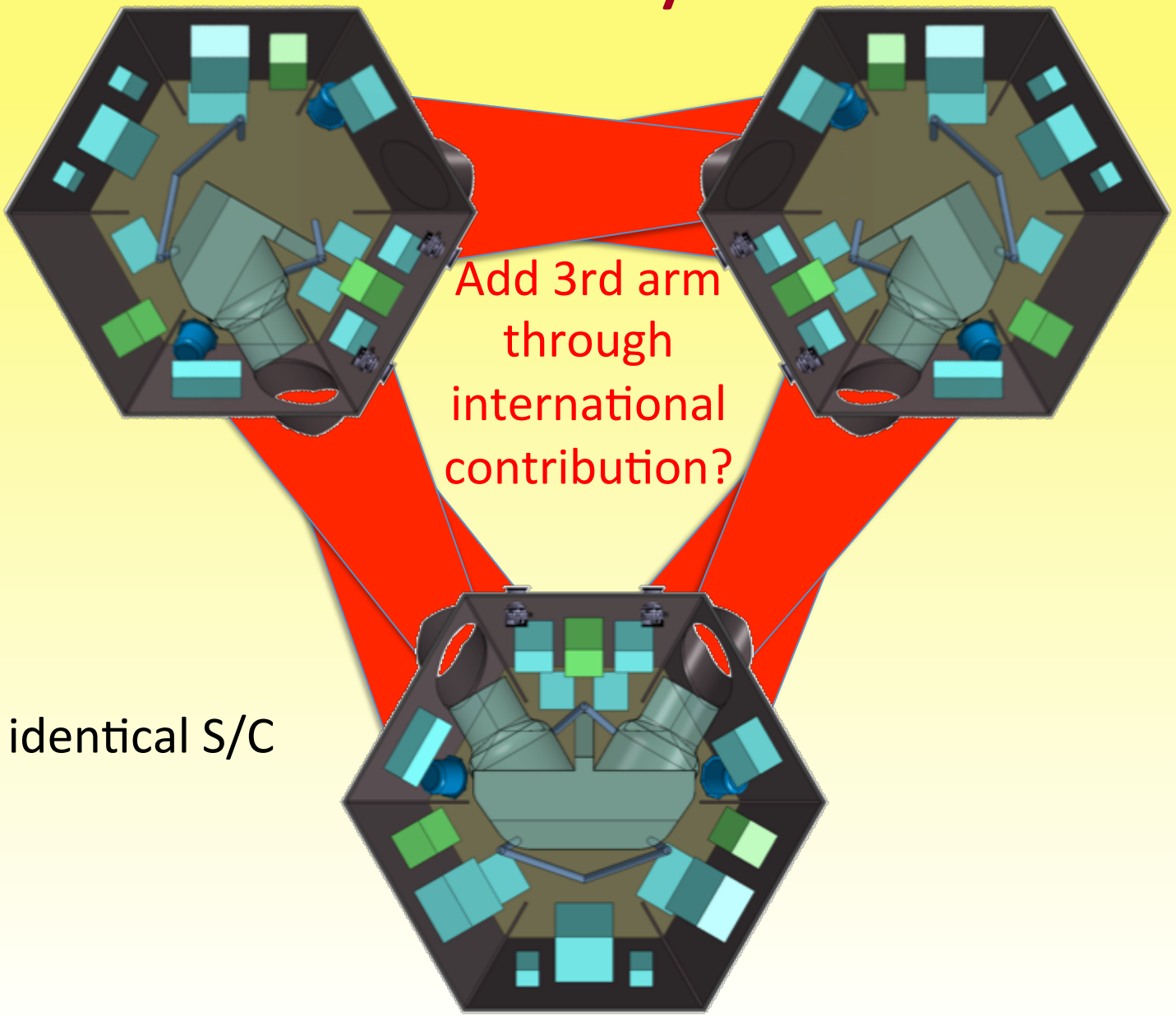
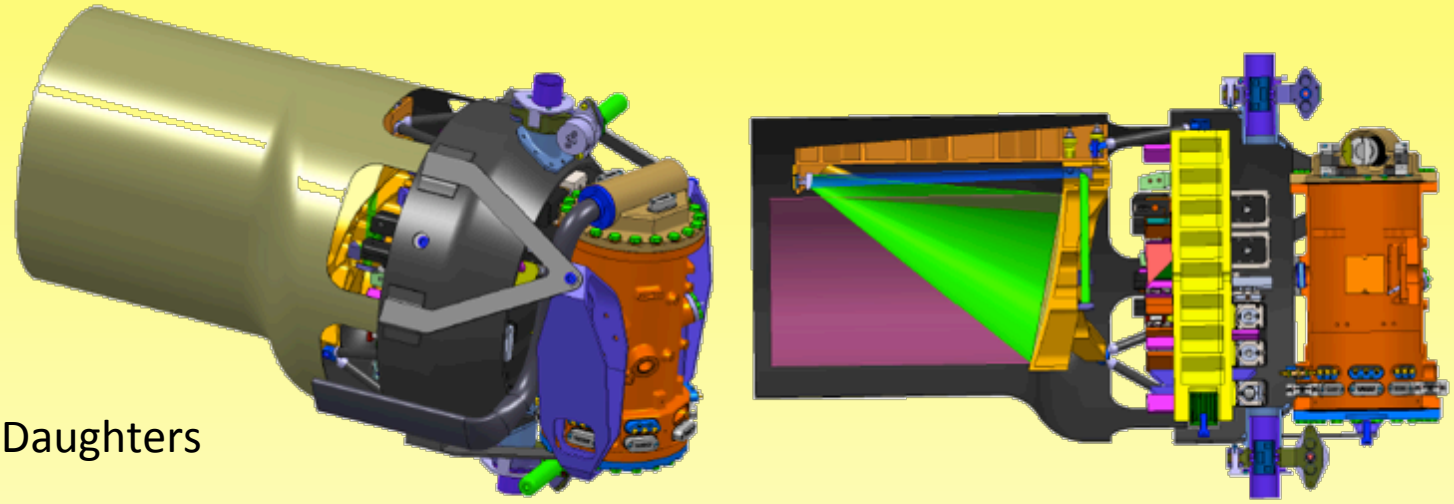
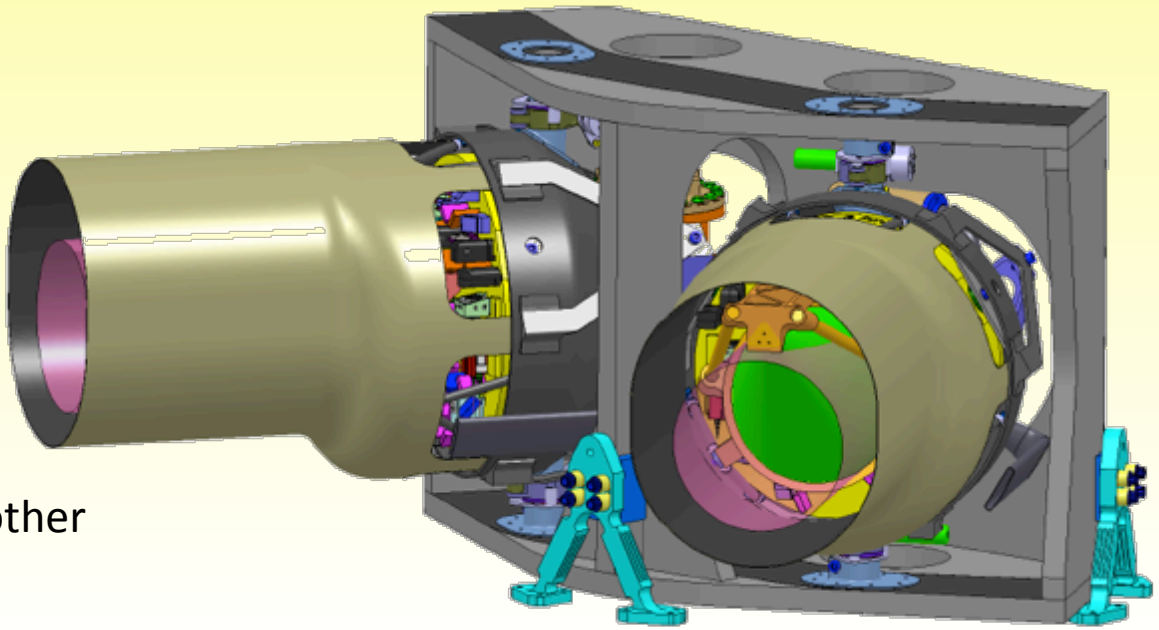


3 identical S/C

Optical Assembly



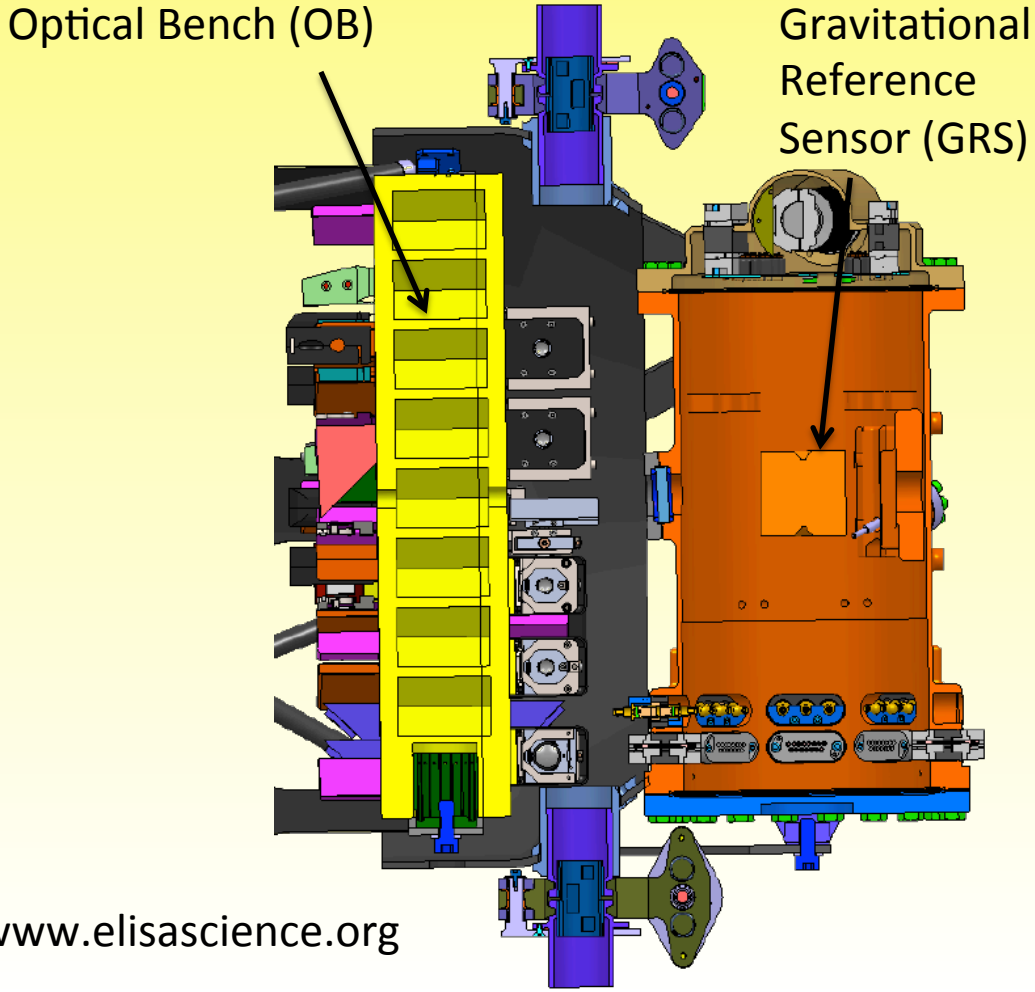
Daughters

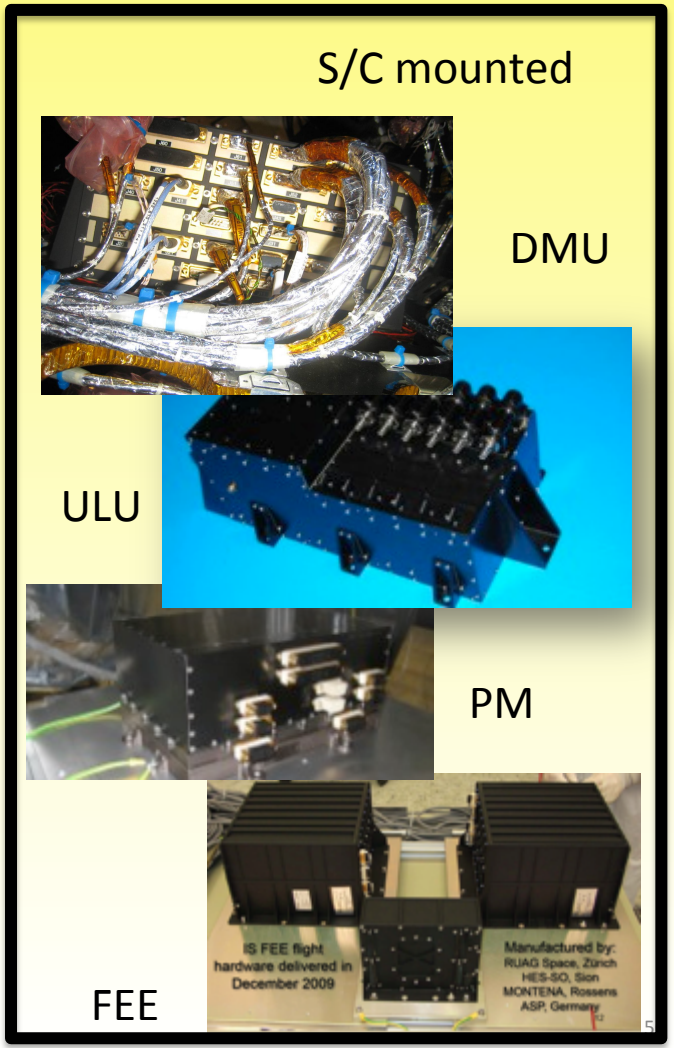


Mother

The Science Instrument

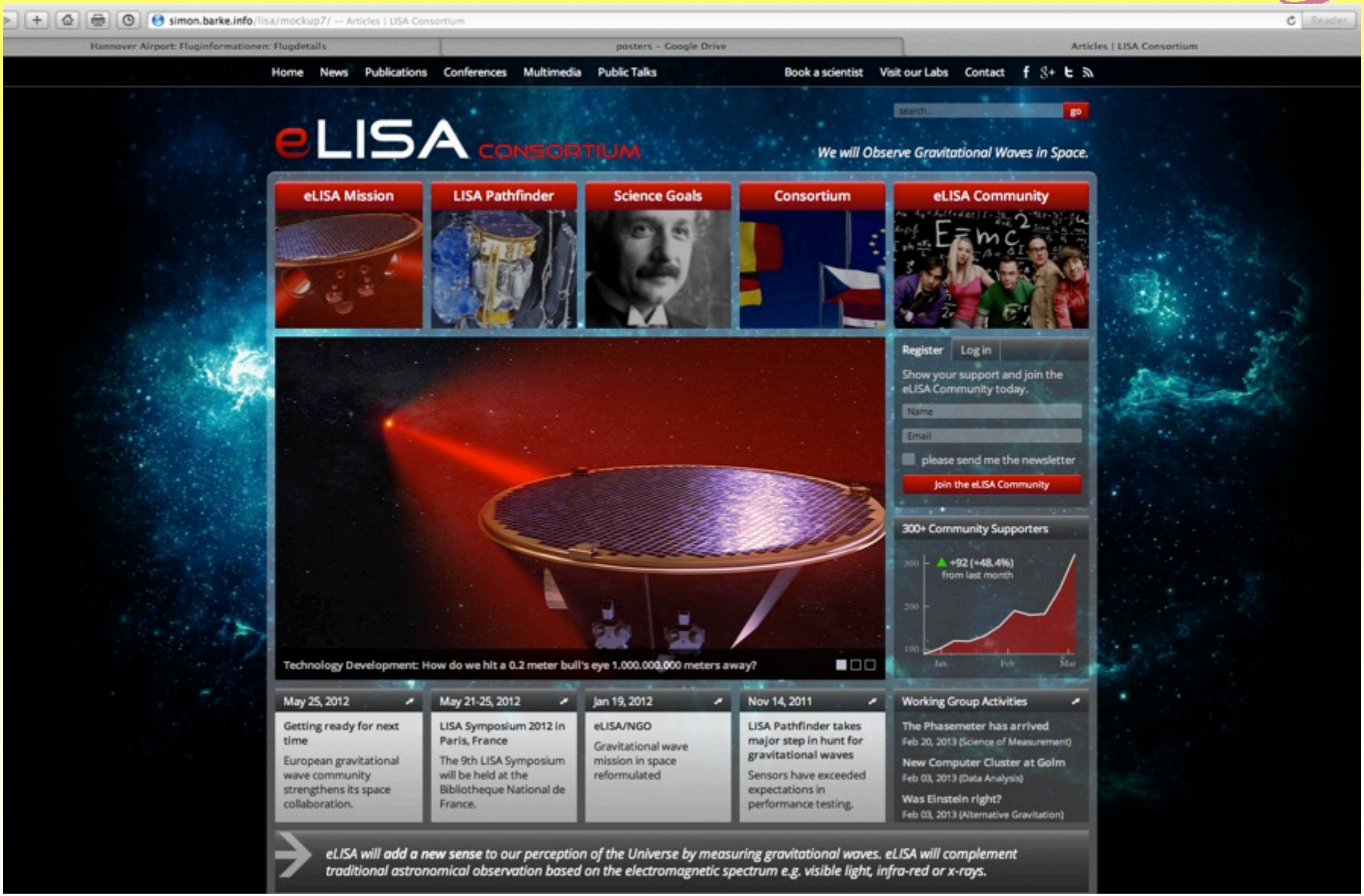
- Provided by eLISA Consortium (D, F, I, UK, ES, CH, DK, NL)
- Also providing LISA Pathfinder Instrument





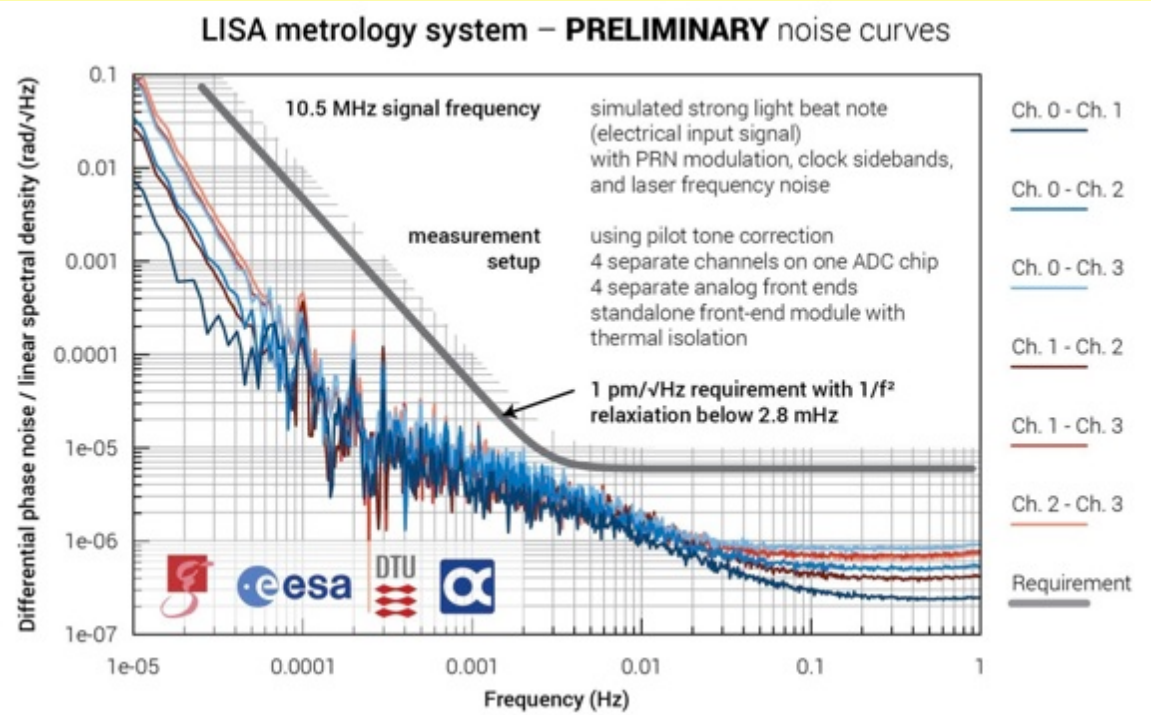
www.elisascience.org

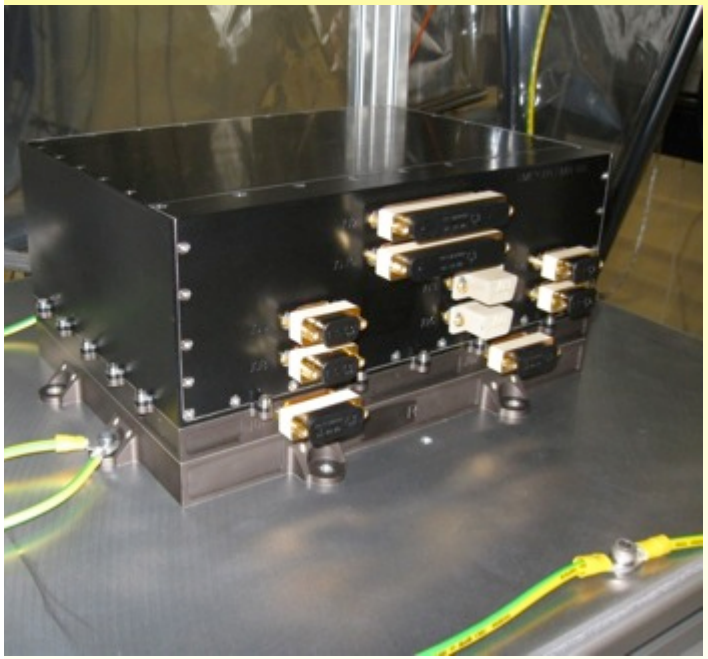
Website elisascience.org



Germany: Phasemeter

- Some heritage from LISA Pathfinder
- ESA-CTP and DLR funding for flight quality hardware
- German/Danish team
- Performance well in spec



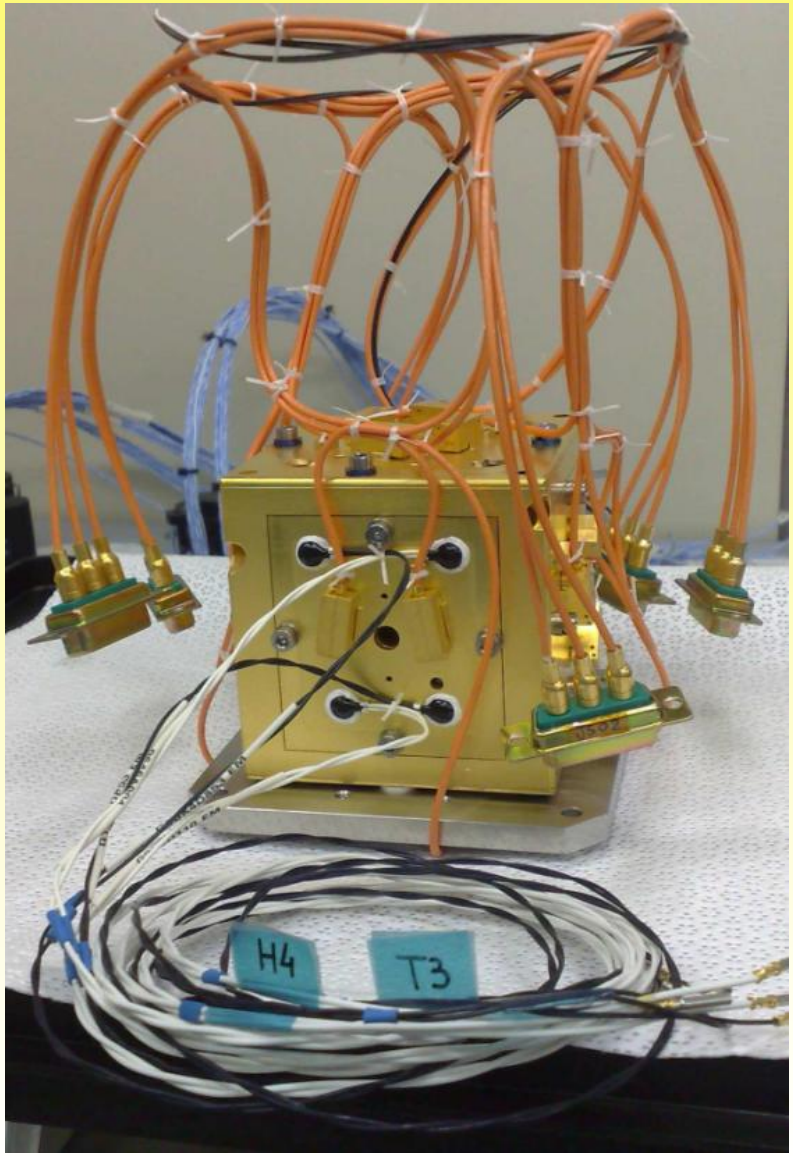


France: Data Center at APC

- Data storage, software provision and support
- Data input from ESA SOC
- Timely provision of Level 2 and 3 data
  - to SOC and NC national data centers

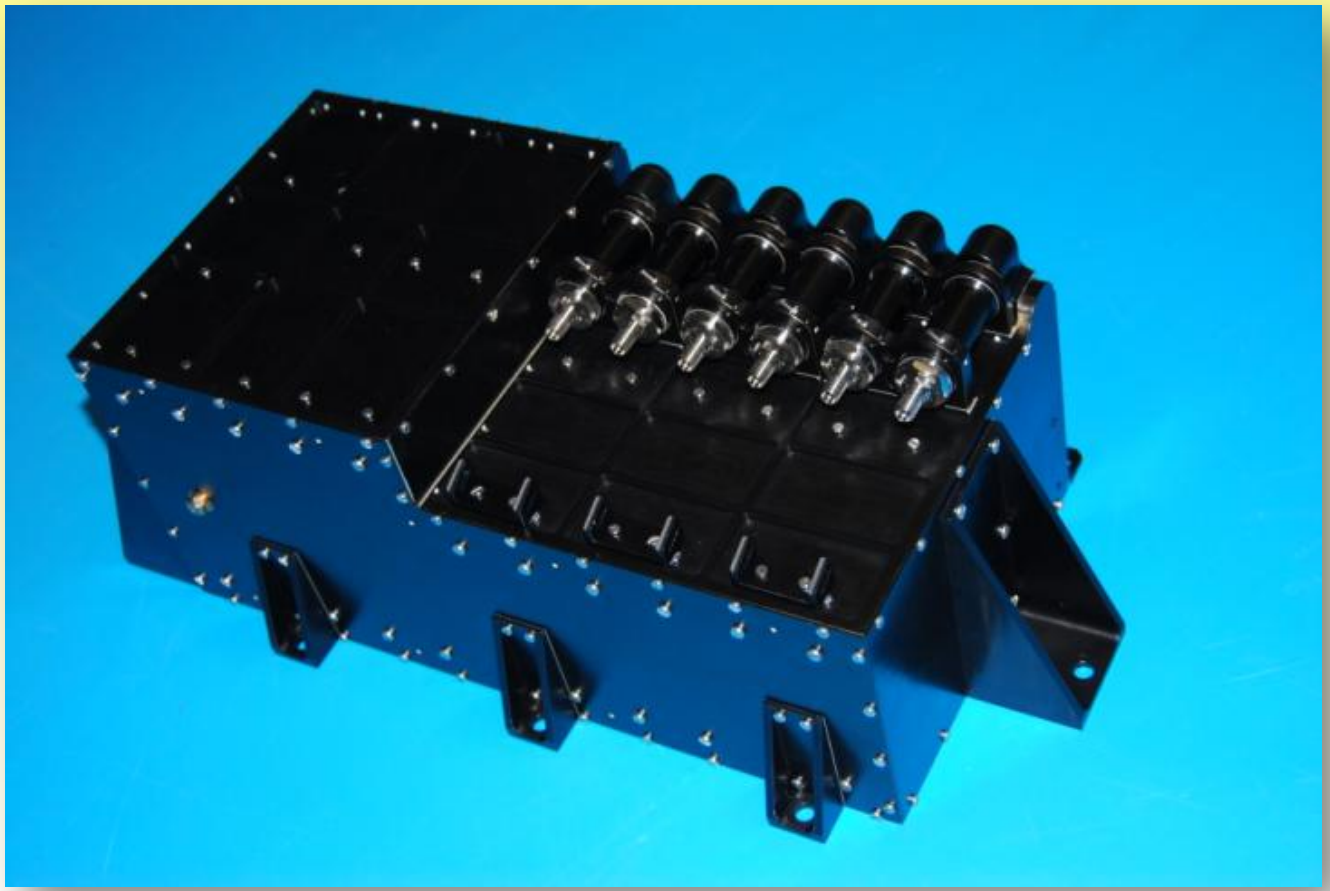
- Already used for Pathfinder
- CNES funds Level 0 study for LISA

Italy: GRS Lead
LISA Pathfinder Heritage



UK: Charge Management System

- LISA Pathfinder Heritage
  - New developments: UV diodes
  - ESA TRP ongoing

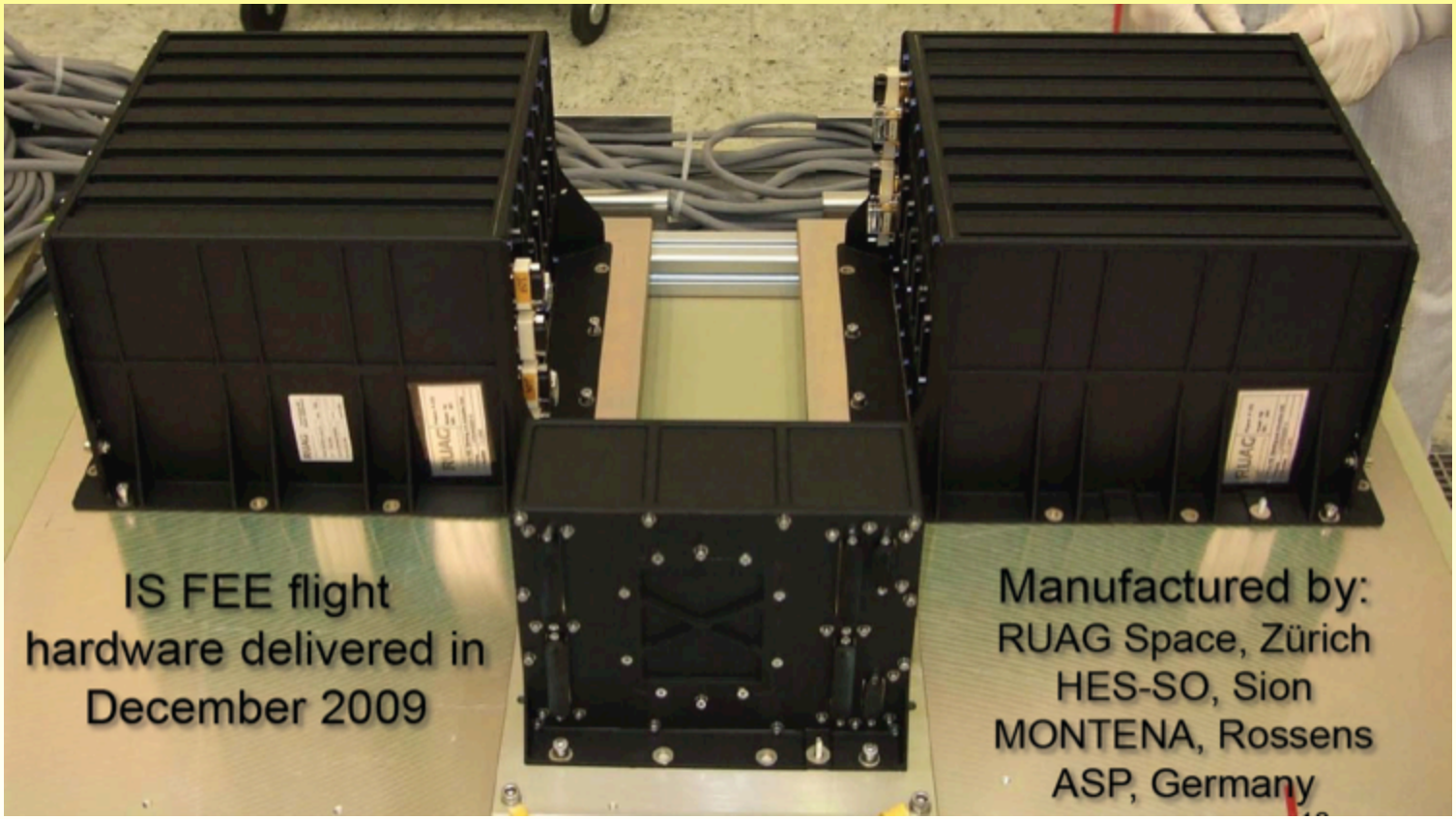


UK: Optical Bench

- LISA Pathfinder Heritage

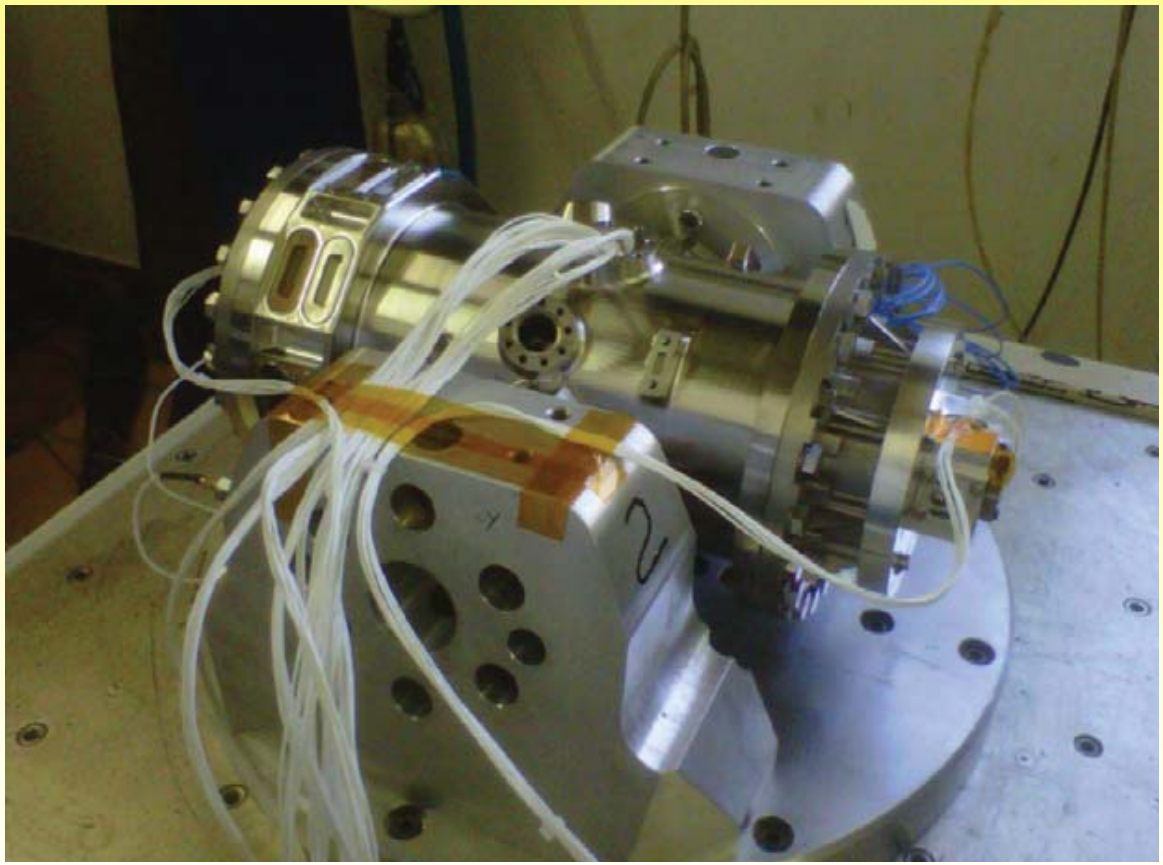
Switzerland: GRS Front-End Electronics

- LISA Pathfinder heritage
  - Needs delta qualification for lower frequencies
  - ESA TRP ongoing



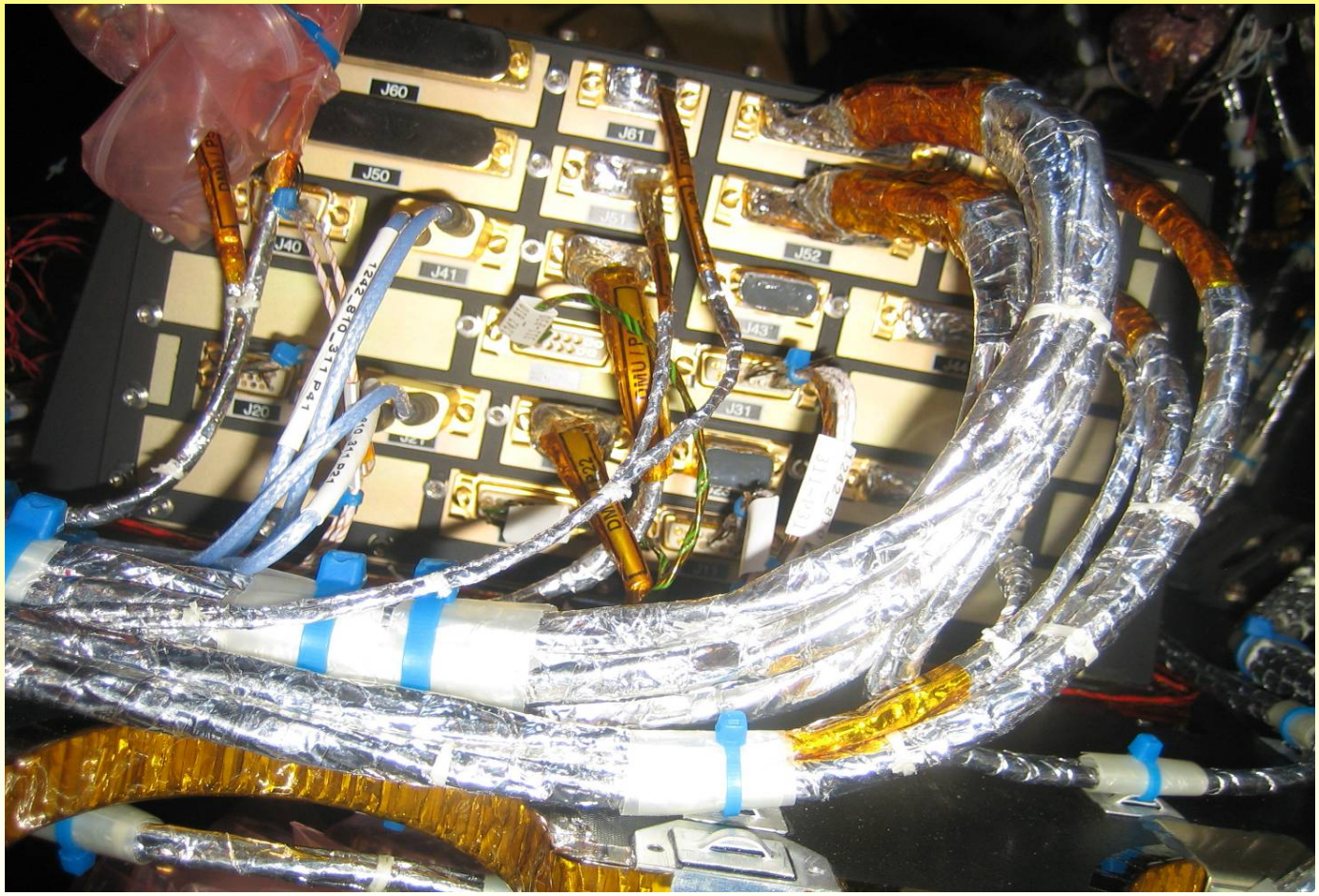
Switzerland: Caging Mechanism

- LISA Pathfinder Heritage
- After successfull LPF flight available as is



Spain: Diagnostic System

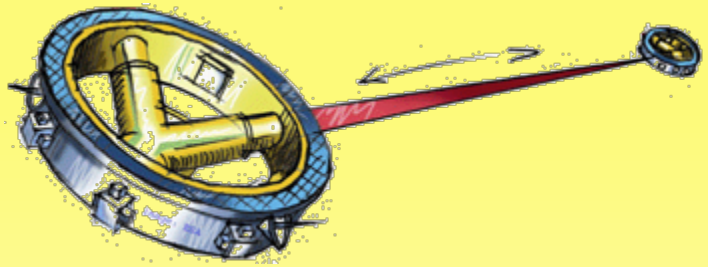
- LISA Pathfinder Heritage
  - Needs more channels for eLISA



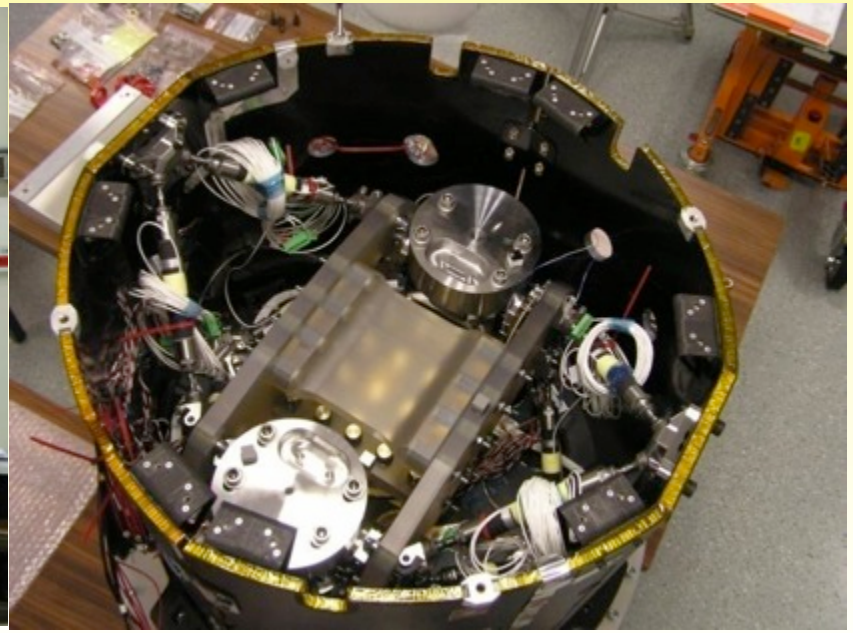
LISA Pathfinder

- Launch date has now been stable at July 2015!

LISA Pathfinder



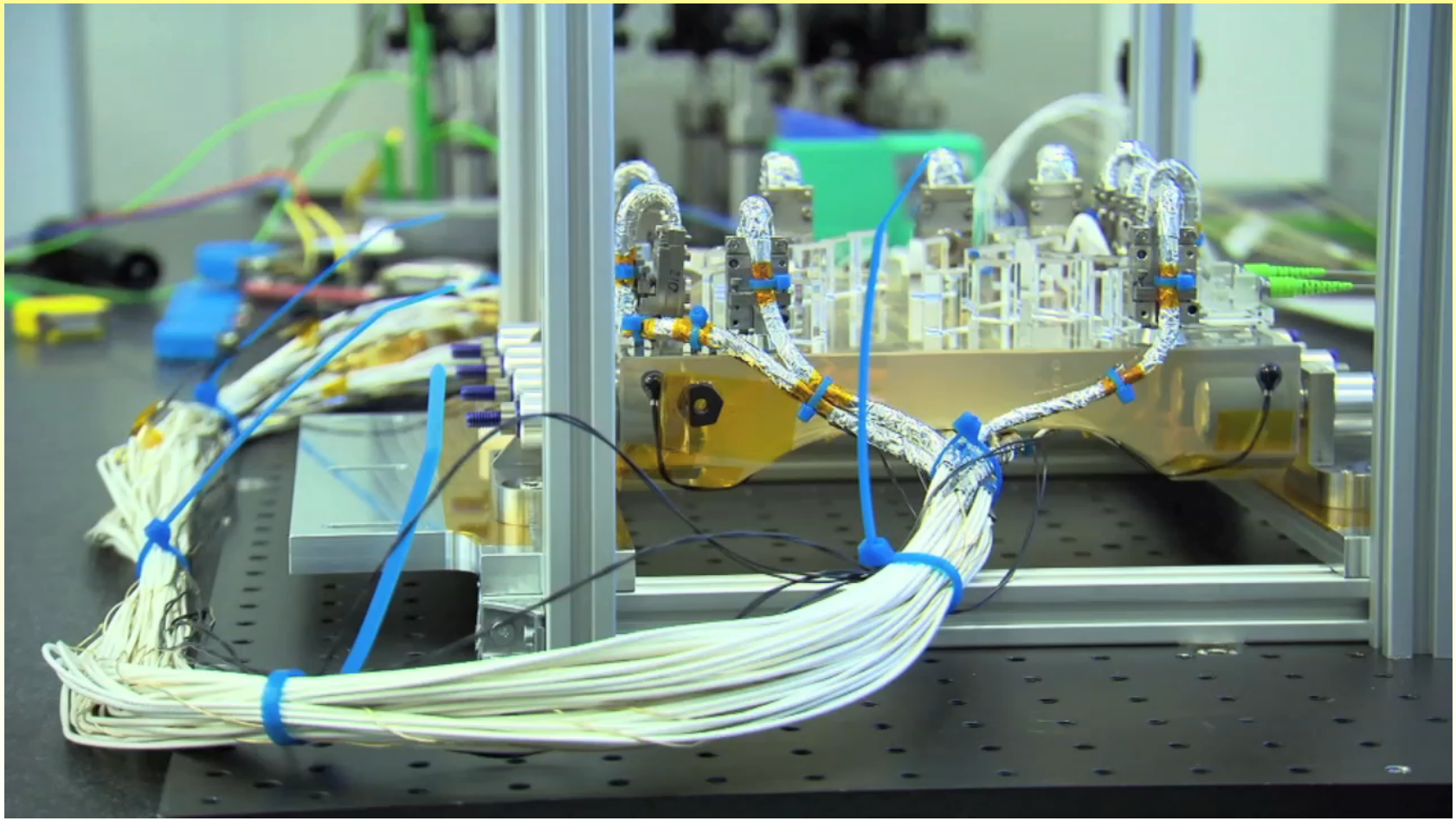
- Take one eLISA link
- Hardware designed for LISA
- Squeeze it into one spacecraft



S/C Ready and Propulsion Module ready and tested

The Optical Bench and Structure

- Successfully tested end-to-end for optical performance
- Delivered for integration in May 2013

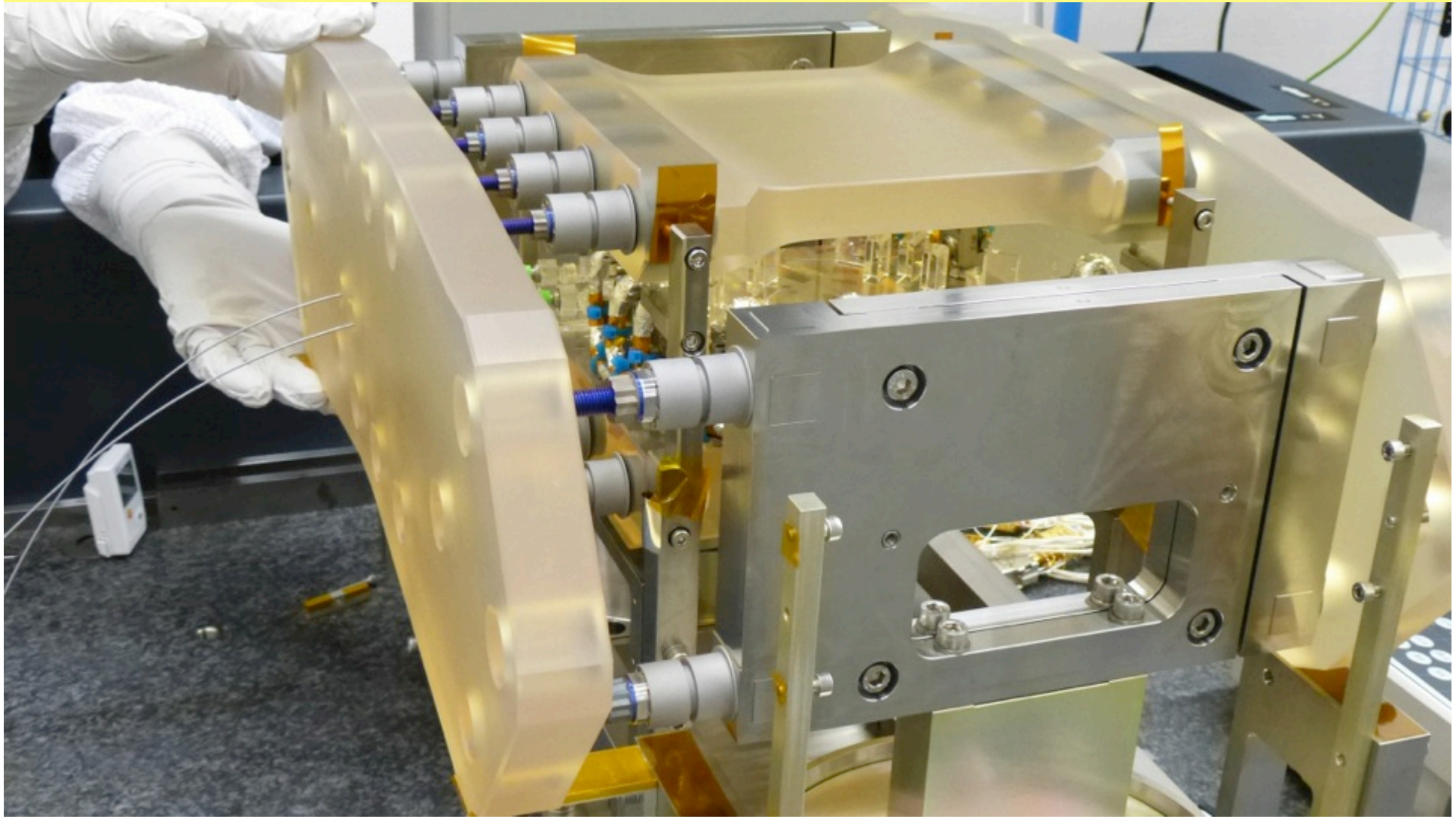


Optical Bench and Structure

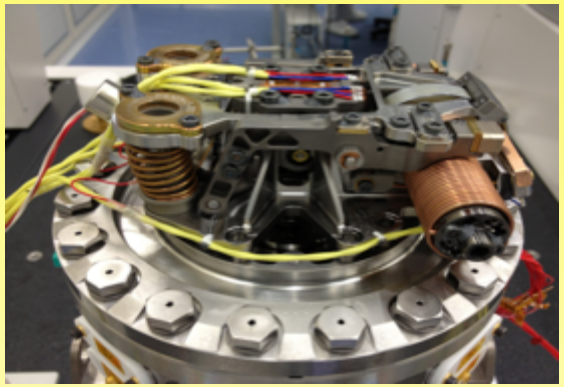
- Delivered in May 2013, currently under integration

Optical Bench and Structure

- Delivered in May 2013, currently under integration

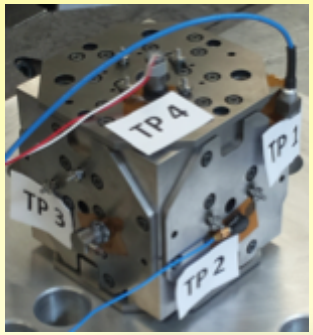


Engineering Problems solved:

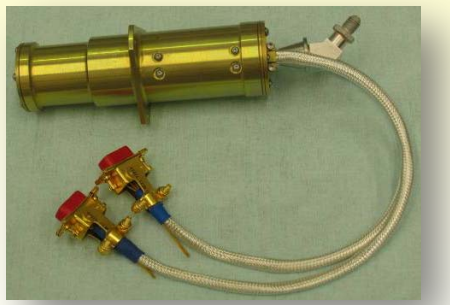


- The motor was wrong on the caging
  - Flight models of new design delivered in April 2013

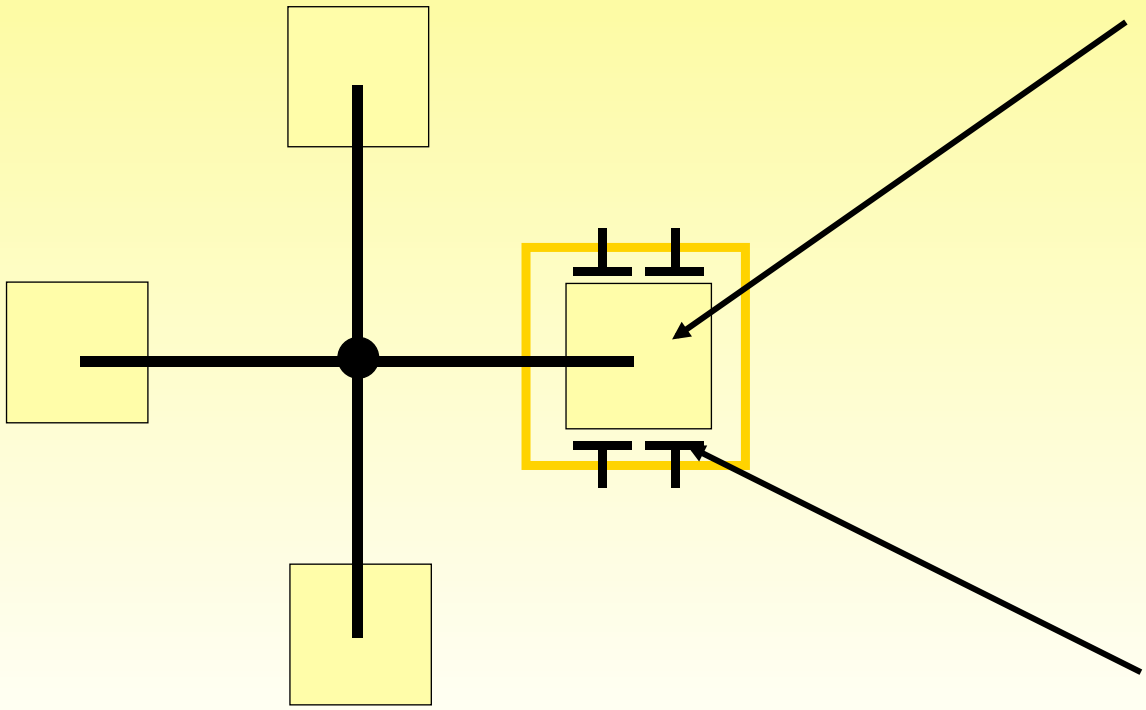
- One soldering was wrong on the electrode housing
  - New assembly technique passed Qualification review on August 28, 2013
    FMs to be delivered October 2013

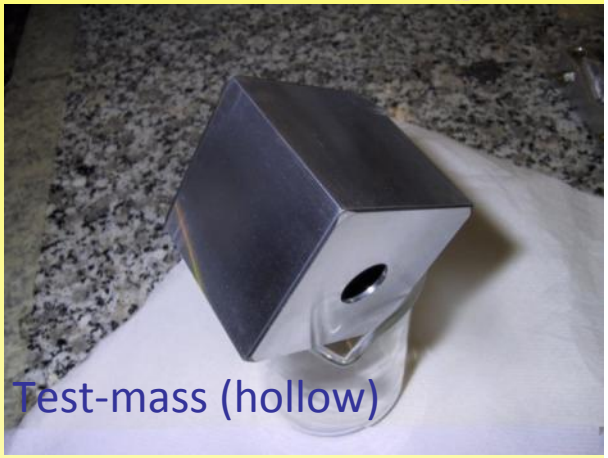


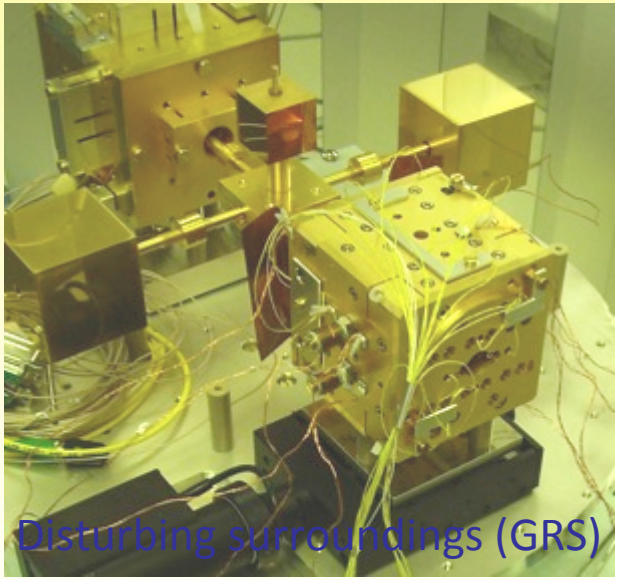
- We needed new µ-Newton thrusters
  - Cold gas thrusters and electronics can be used identical to Gaia,
    to be delivered in September 2014



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

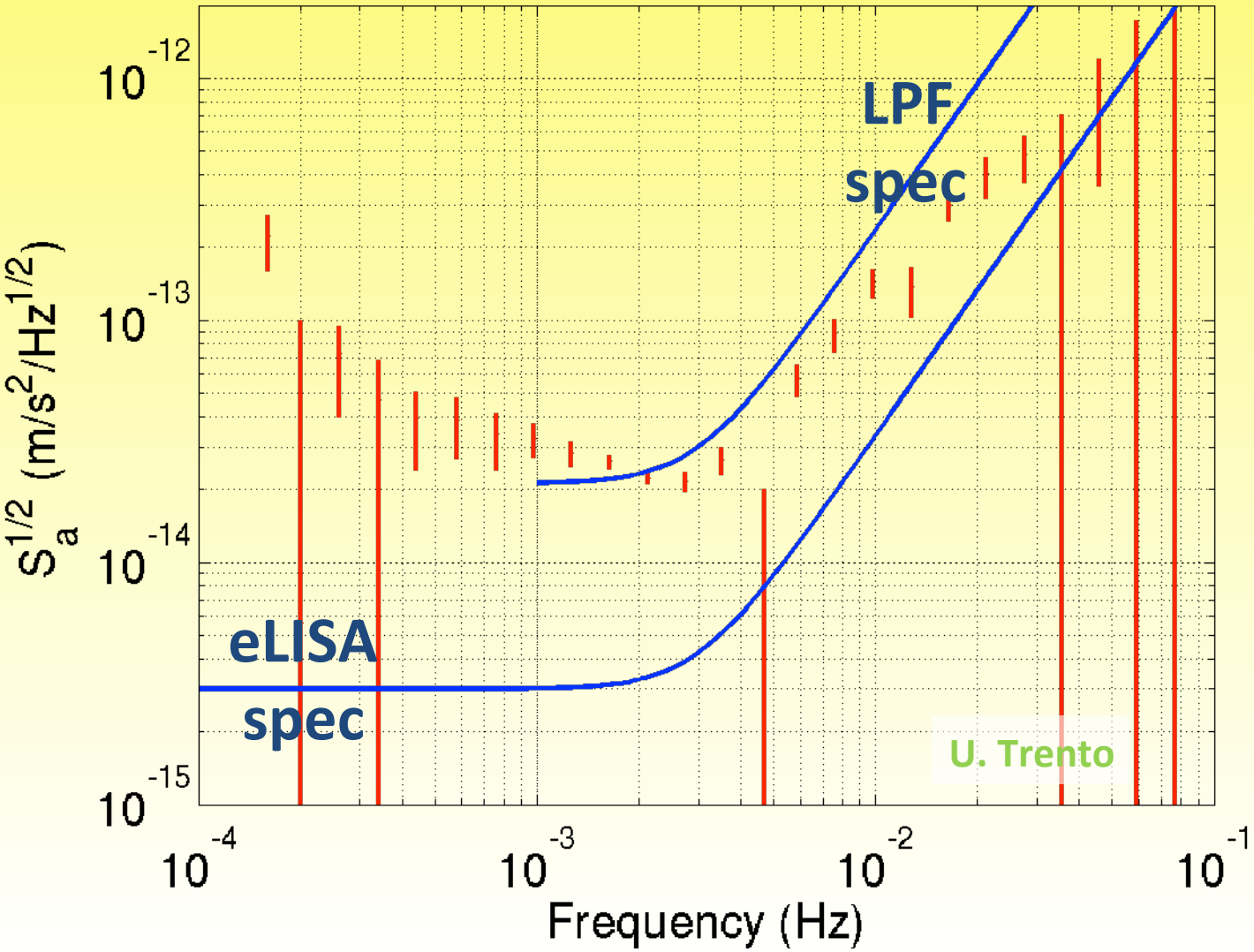




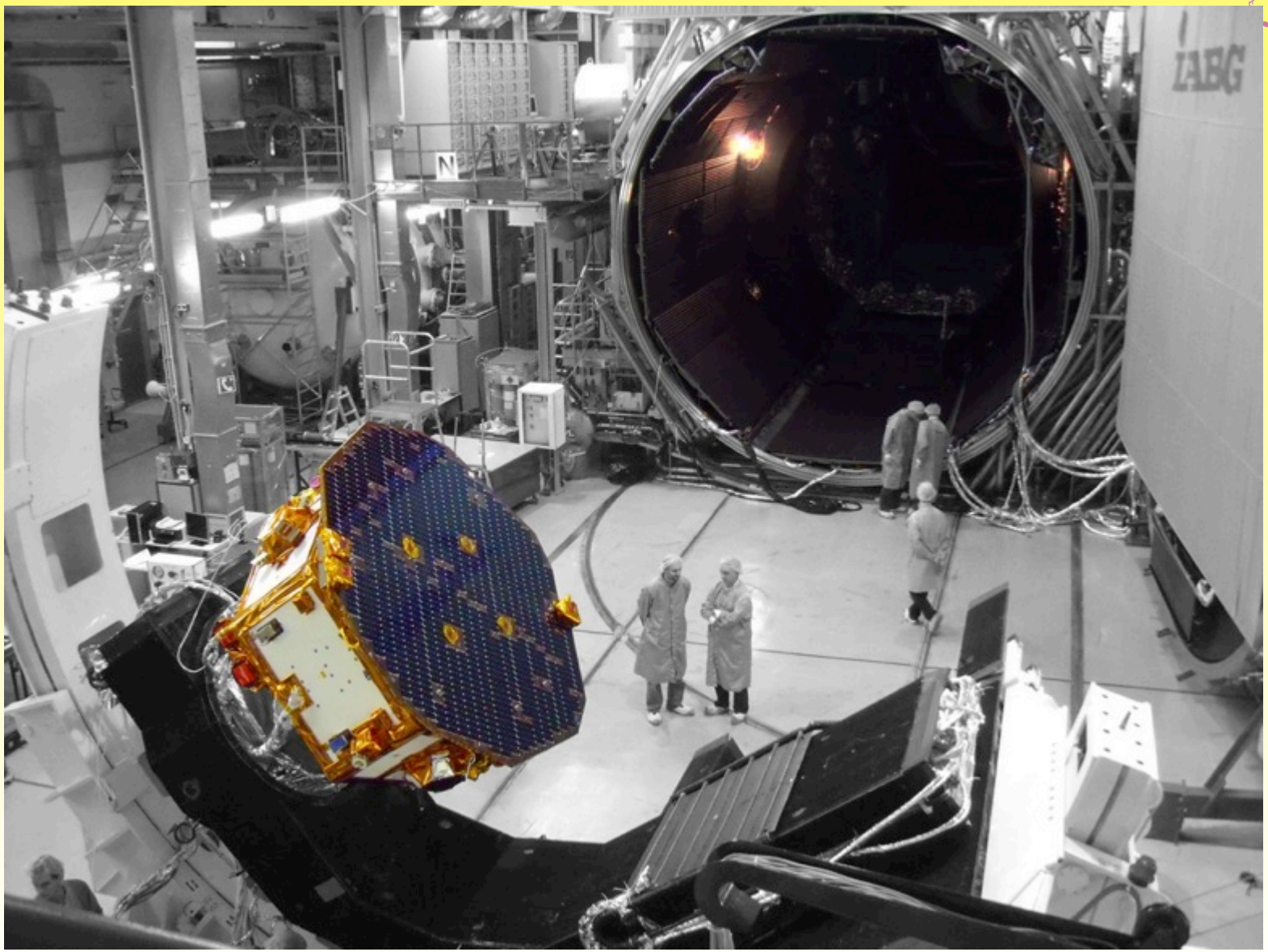


Superb GRS Performance on Ground

- Upper limits from torsion pendulum



Optical Metrology Ground Testing

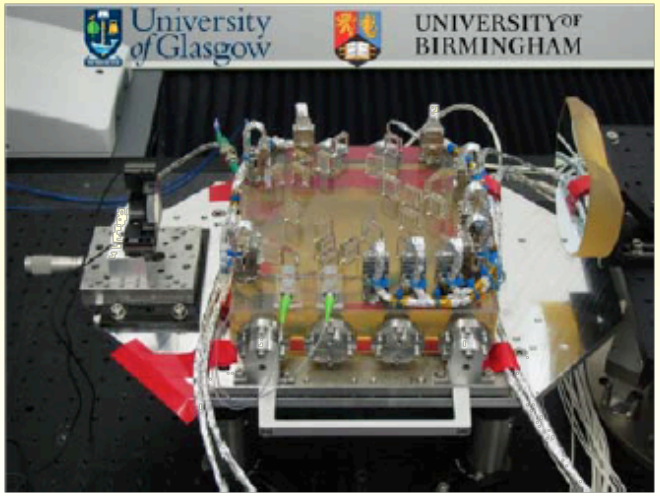


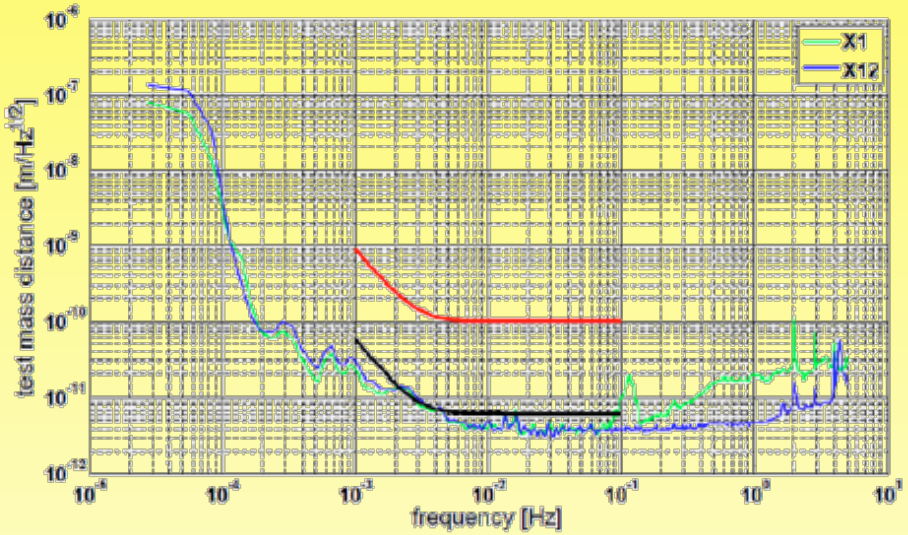
Superb Optical Performance on Ground

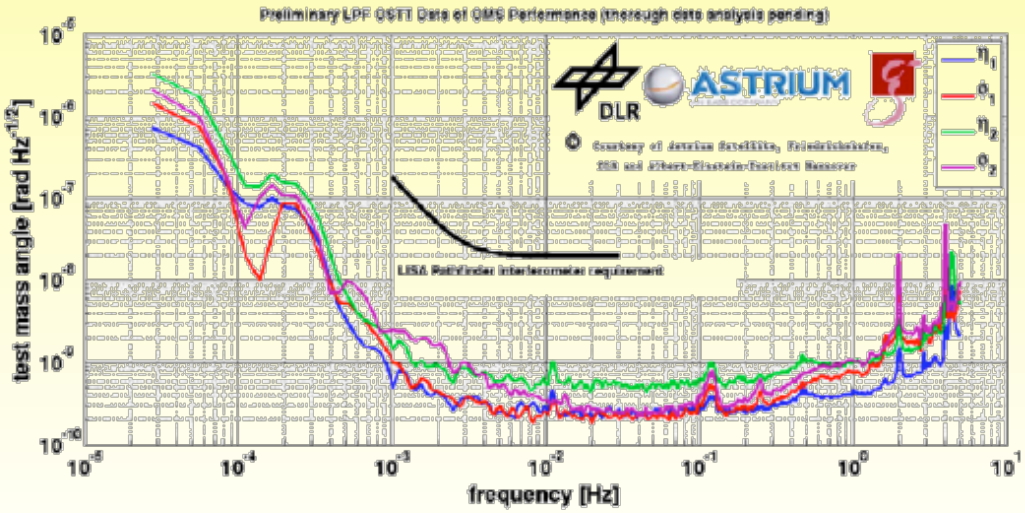
Optical metrology performance at hot/cold confirmed.

- 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.

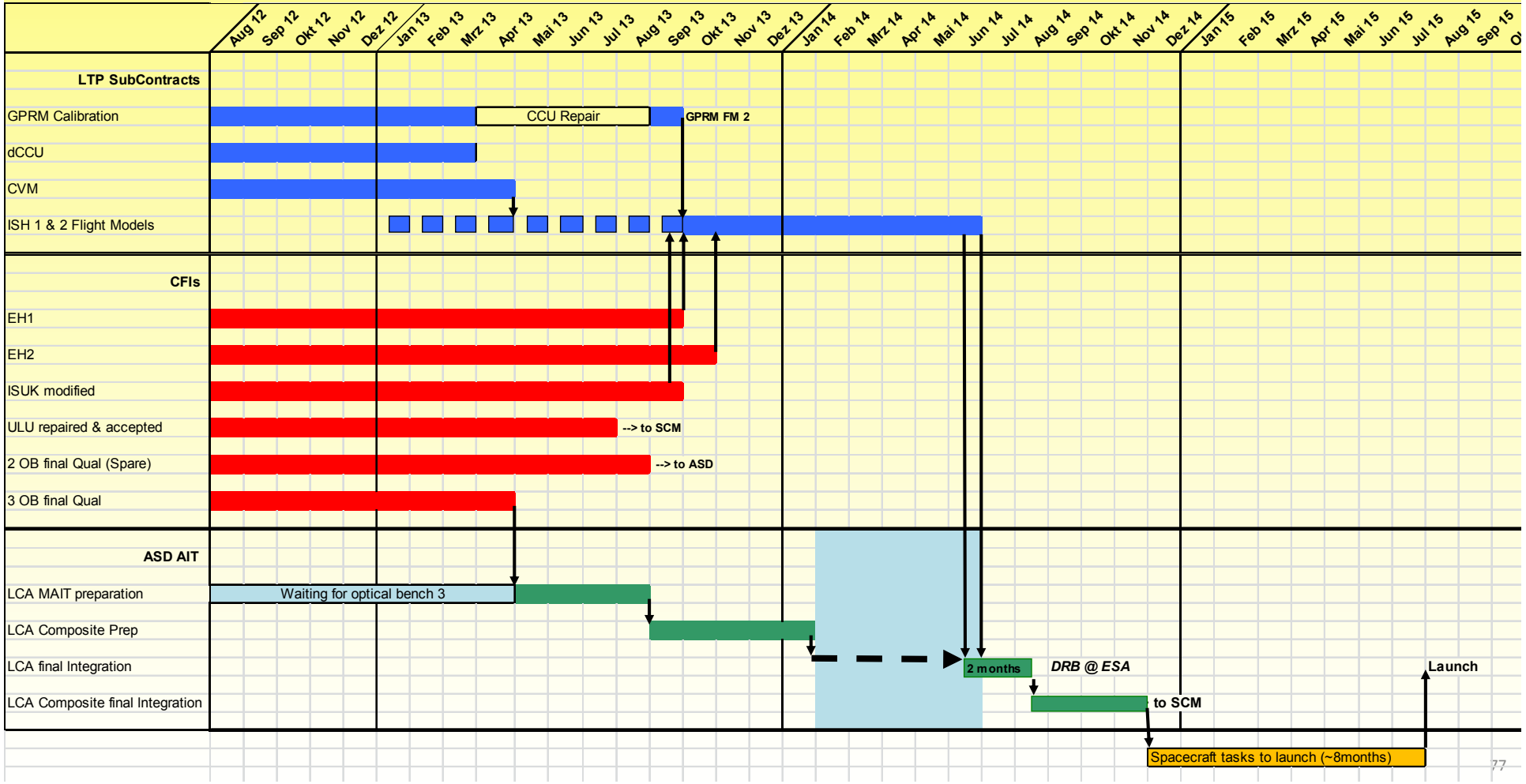


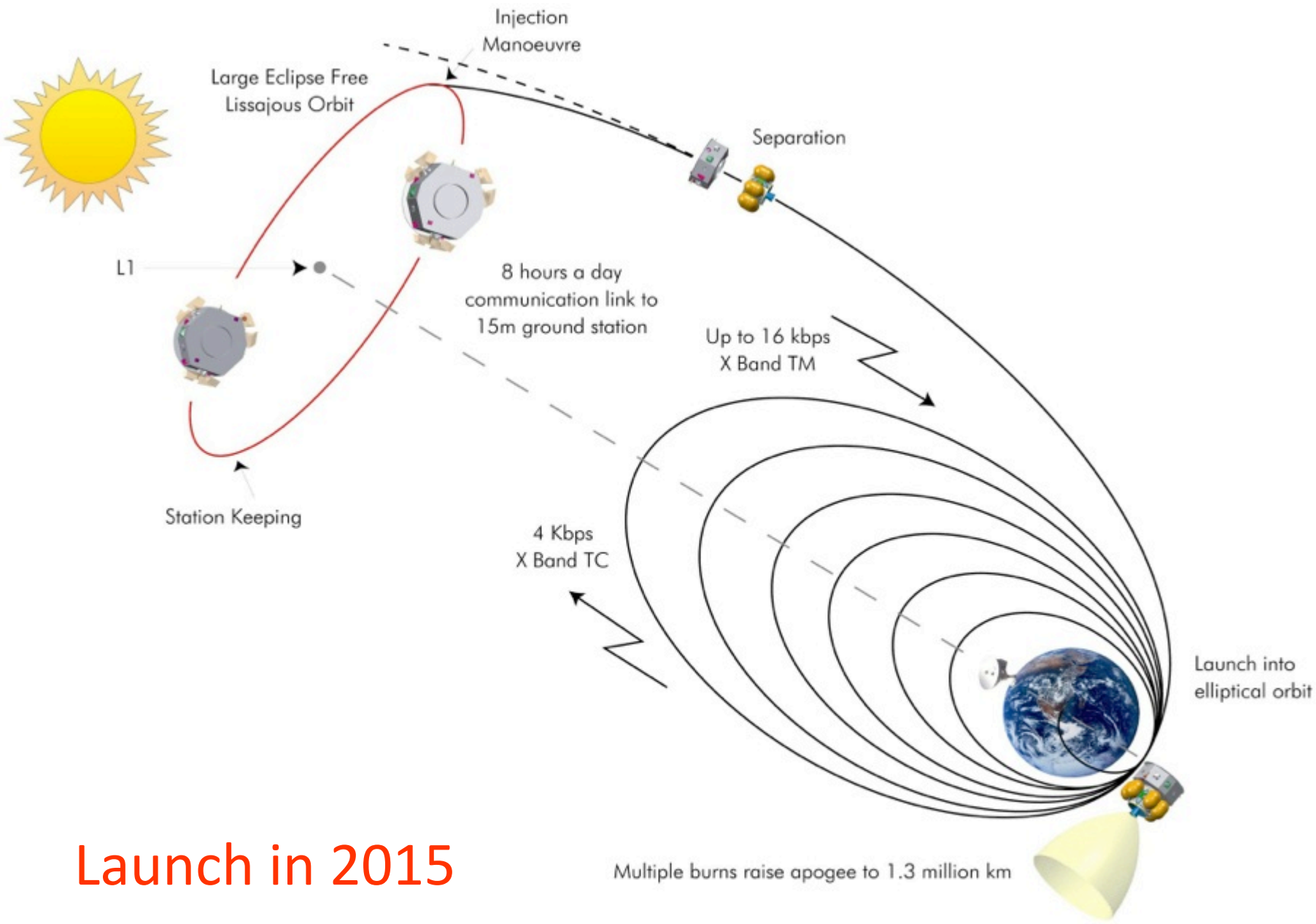




All Payload Hardware delivered and tested by November 2013

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





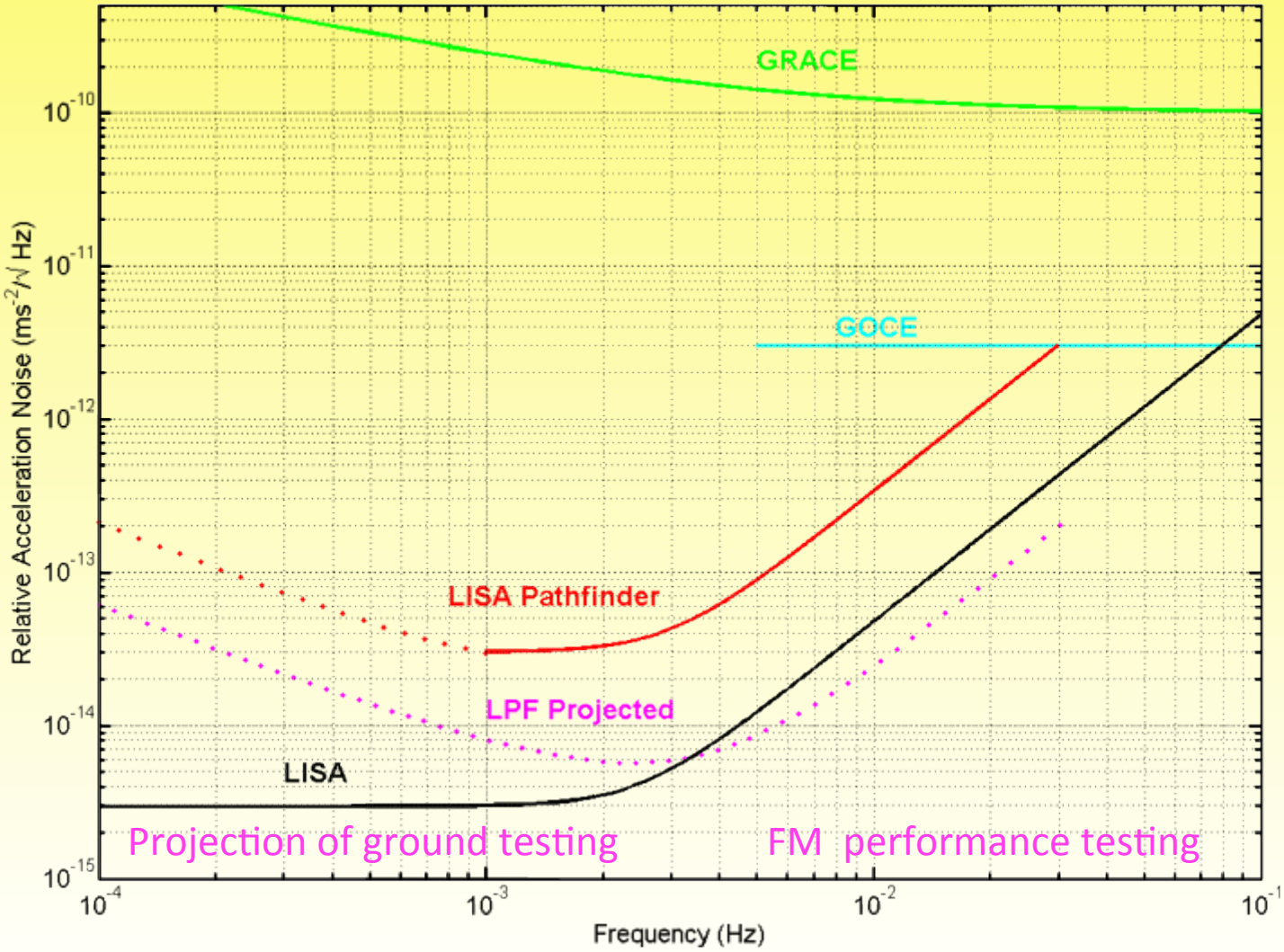
Launch in 2015

Lagrange Point L1

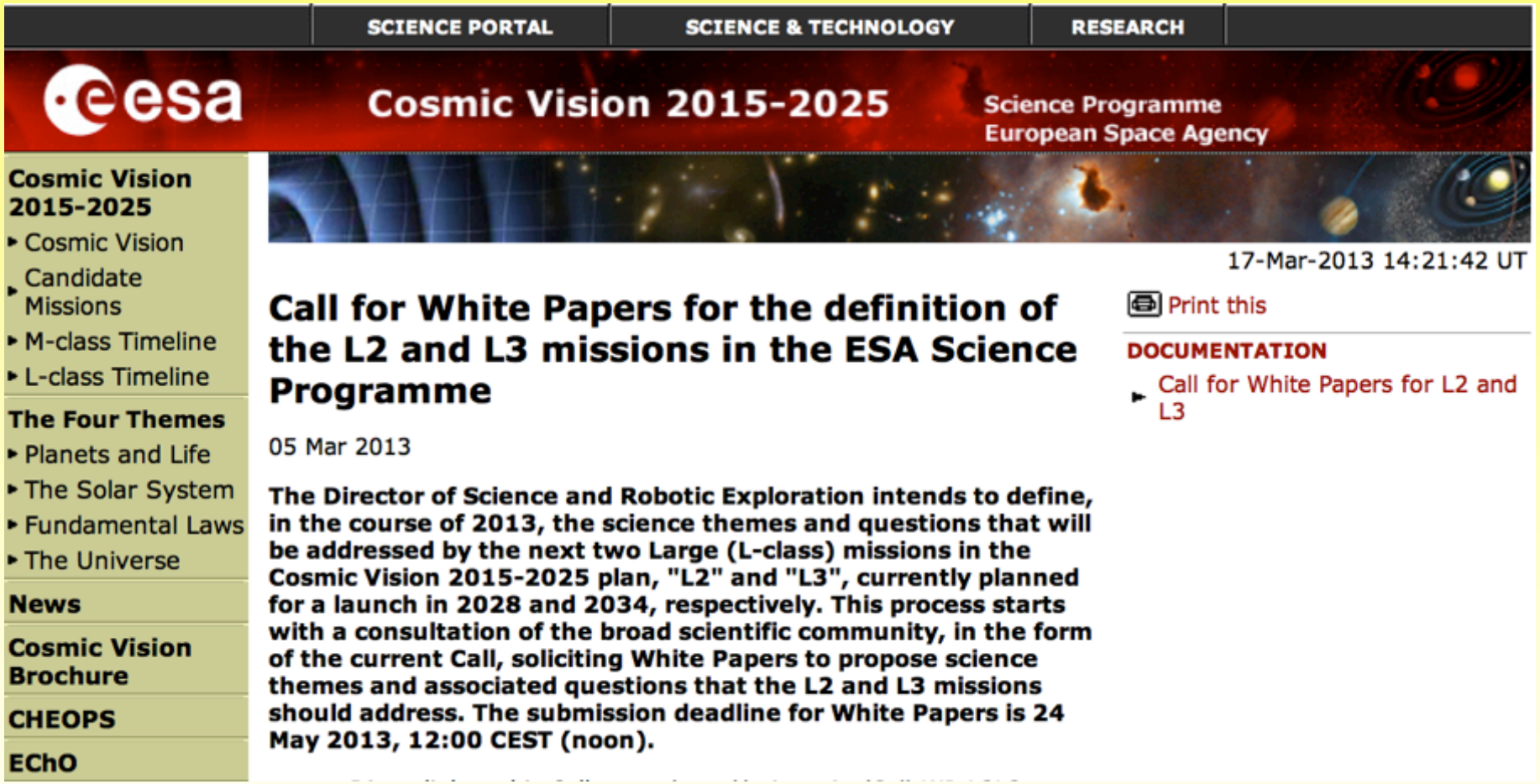
Launch on new Vega

LPF expected Performance

- Comparable to eLISA requirement



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

EChO

17-Mar-2013 14:21:42 UT

Print this

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)*.

Von: Fabio Favata <Fabio.Favata@esa.int>
Betreff: **Invitation to present your White paper to the L2L3 workshop**
Datum: 3. Juli 2013 16:42:19 MESZ
An: Karsten Danzmann <Karsten.Danzmann@aei.mpg.de>

Dear Karsten,

first of all thanks for having submitted a response to the Call for White Papers that we issued for the definition of the science themes for the future "L2" and "L3" Large missions in the ESA Scientific Programme.

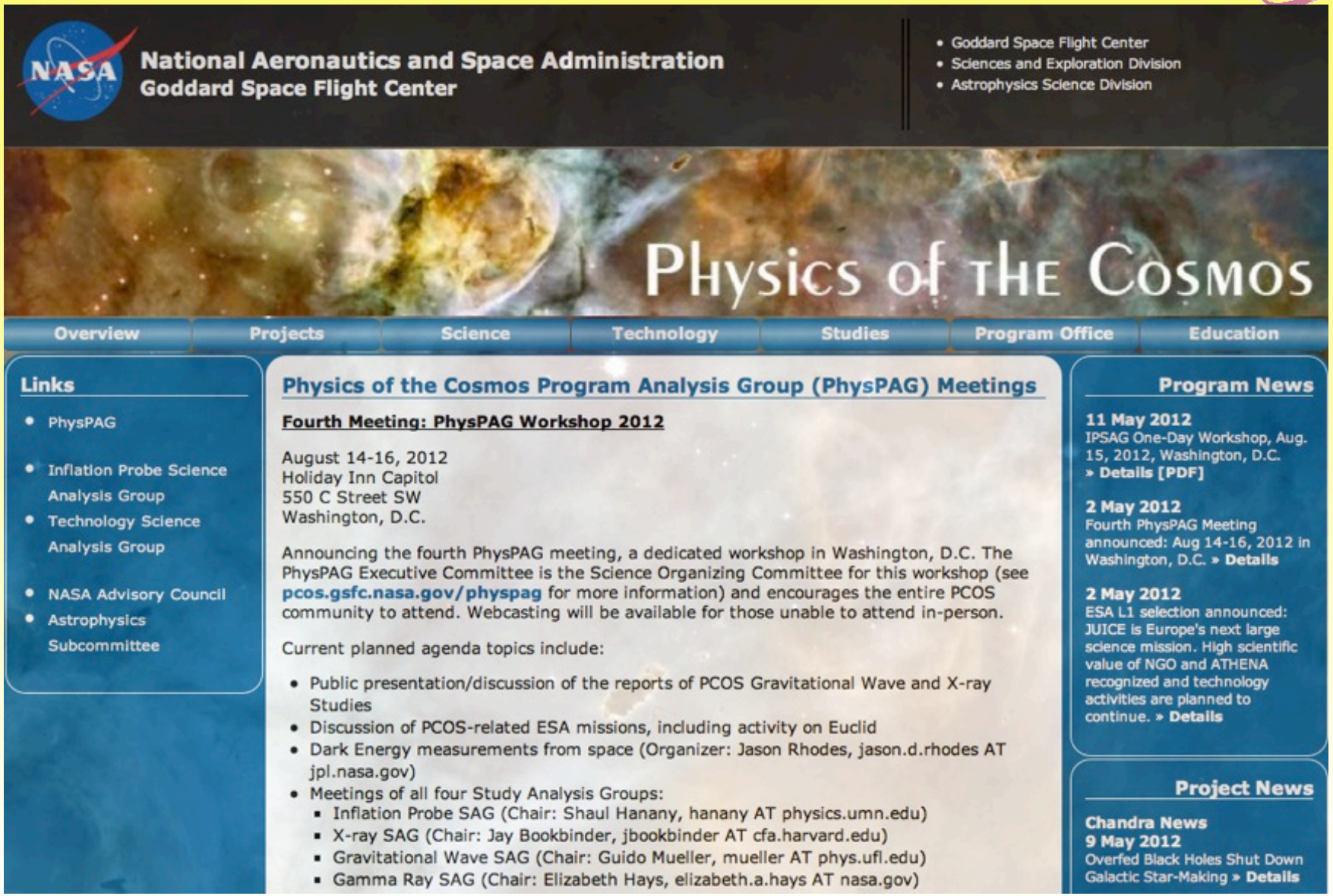
As you know, the Director of Science and Robotic Exploration, Dr. Alvaro Gimenez, has invited a Senior Survey Committee chaired by Dr. Catherine Cesarsky to advise him on the selection of the science themes for L2 and L3. A key step in the selection process is the public presentation of a selected number of White Papers at an open workshop in Paris on September 3 and 4. At this occasion, a number of authors will be invited to present their proposed science theme in front of the Senior Survey Committee and of the broad scientific community.

On behalf of Dr. Catherine Cesarsky I would like to invite you to present the White Paper "The Gravitational Universe" for which you have been designated as spokesperson. You

Strawman Mission Scenario

- Go with L1 NGO as baseline
  - L2 Cost envelope is (1000 M€ from ESA plus 400 M€ from MSs) = 1400 M€
  - NGO L1 cost assessed by ESA was 1268 M€
    - Affordable as ESA only!
  - plus 250 M€ international contrib. = 1650 M€ total
    - 250 M€ = 330 M$ → M-Class or Probe @ NASA!
- Going to 3 arms possible with no design change
- Use international contributions for cost risk mitigation or performance enhancement !

New NASA Activities



Interest from China

CHINESE ACADEMY OF SCIENCES — MAX-PLANCK-GESELLSCHAFT
SHANGHAI INSTITUTE FOR ADVANCED STUDIES
EXPLORATORY ROUND TABLE CONFERENCES

Prof. Dr. Karsten Danzmann
Max Planck Institute for Gravitational Physics
Callinstr. 38
30167 Hannover

Chairman:

Prof. Gerhard Wegner
Max Planck Institute
for Polymer Research
Ackermannweg 10
55128 Mainz / Germany
Phone: +49-6131-379-131
wegner@mpip-mainz.mpg.de

5. April 2012

Zusammenarbeit mit China
"Exploratory Round Table Conference (ERTC)"

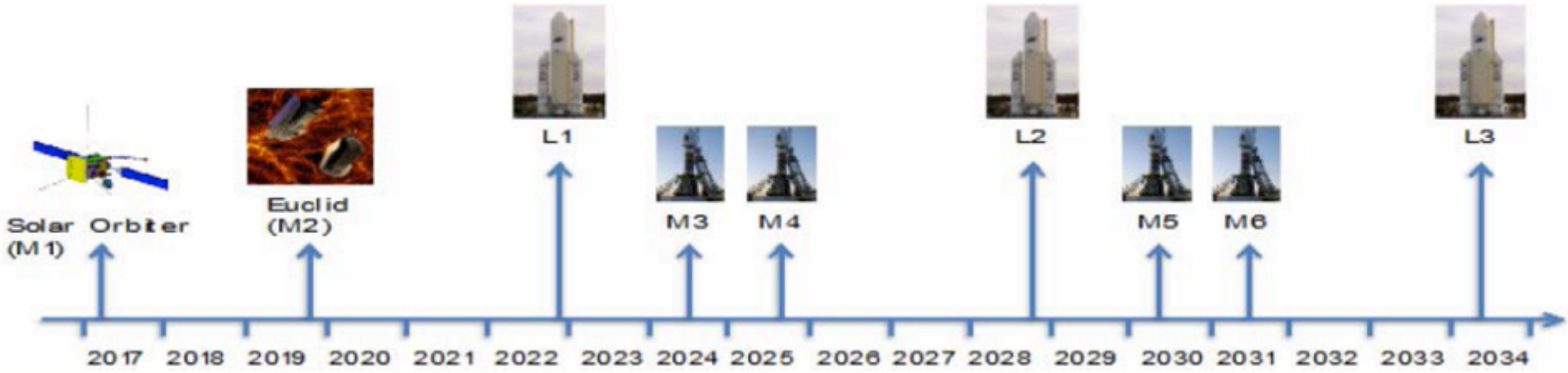
Thema:
Space Science Research/Satellite Based Scientific Exploration,
Shanghai, Anfang November 2012

International plans for space-based detectors

- USA
  - Scenario 1: Junior partner in eLISA (highest priority)
  - Scenario 2: NASA-led mission (SGO)
  - Ongoing technology developments in the US: Telescope, Laser system, Interferometry , Optical Bench technology, GRS, Charge management, torsion pendulum test benches
- China: two options, both in some degree of collaboration with ESA
  - Join eLISA for L2
  - Develop a similar Chinese program if eLISA is selected as L3.
  - Technology: Telescopes, interferometry, GRS and torsion pendulum
- Japan: Decigo-Pathfinder strong candidate for a small mission by Jaxa

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

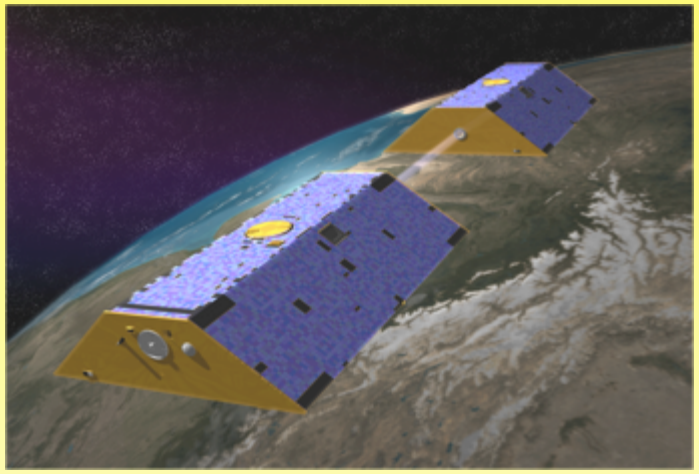
- Launch LISA Pathfinder in 2015
- Coordination of international partners
- If LISA is L2:
  - Build EQM of complete Payload in 2016 – 2020
  - Start industrial implementation in 2020
  - Launch in 2028
- If LISA is L3:
  - Technology development until 2018
  - Payload EQM 2019 – 2023
  - Start industrial implementation 2024
  - Launch 2034

Summary

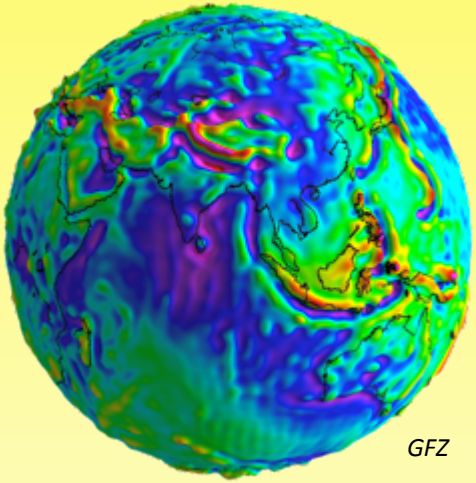
- LISA will
  - Explore the whole Universe through Gravity only
  - Probe assembly of cosmic structure through Black Holes and observe their seeds
  - Investigate General Relativity in Strong Field Regime
  - Explore the Early Universe
  - Have a huge discovery space
- LISA Pathfinder
  - Has all payload 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 !

LISA Technology for Gravity Field Missions

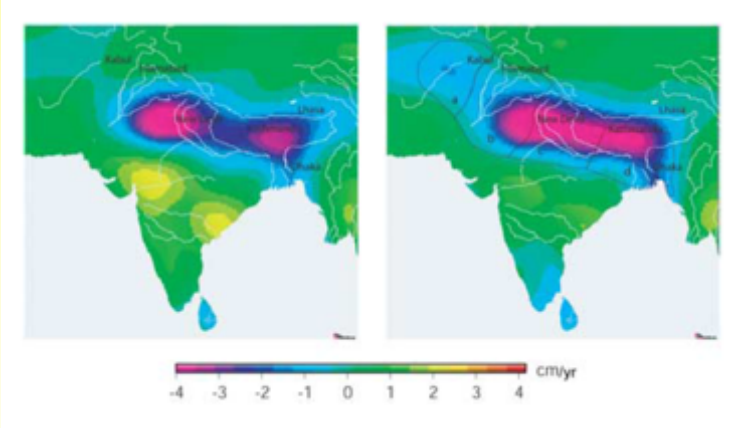
Gravity Recovery and Climate Experiment (GRACE)



GRACE Mission (UTCSR, GFZ, DLR, JPL). *Image credit: NASA*

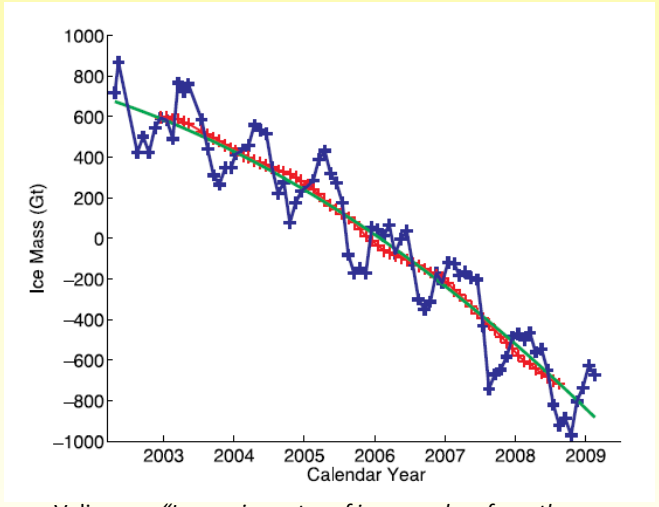


GFZ



Tiwari et al., *"Dwindling groundwater resources in northern India, from satellite gravity observations"*, Geophys. Research Lett. **36**, L18401 (2009).

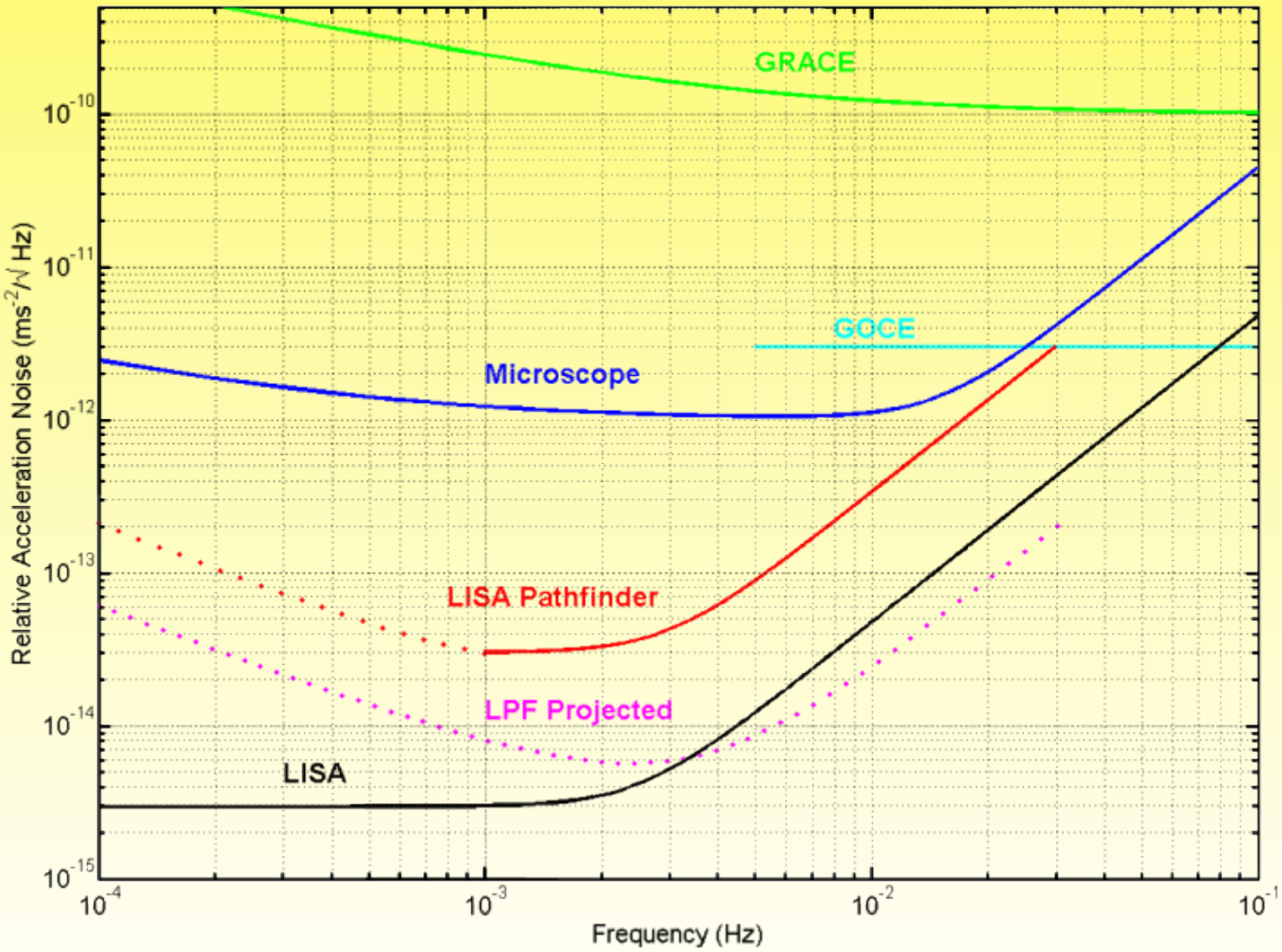
Ground water loss in India



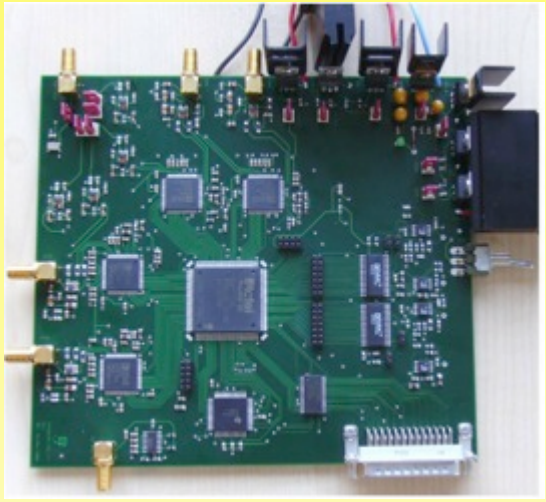
Velicogna, *"Increasing rates of ice mass loss from the Greenland and Antarctic ice sheets revealed by GRACE"* Geophys. Research Lett. **36**, L19503 (2009).

Ice mass loss in Greenland

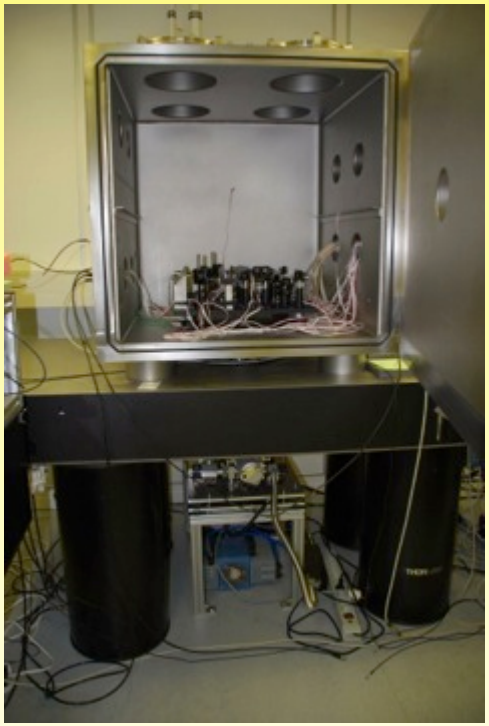
Acceleration Noise Comparison



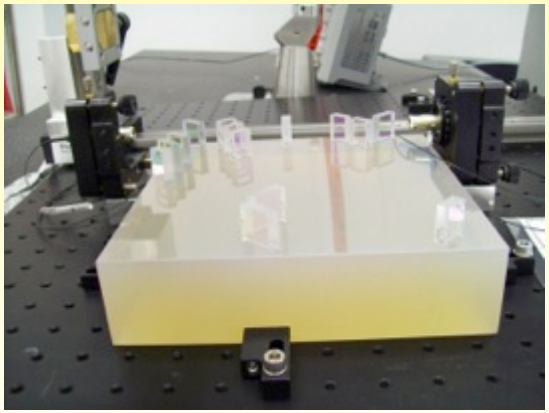
Next Generation Geodesy Mission
Work at AEI



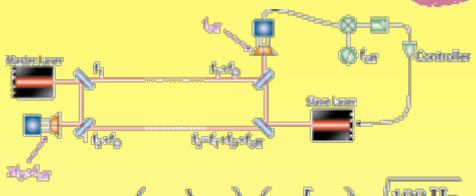
Hardware phasemeter prototype



Interferometer breadboard tests

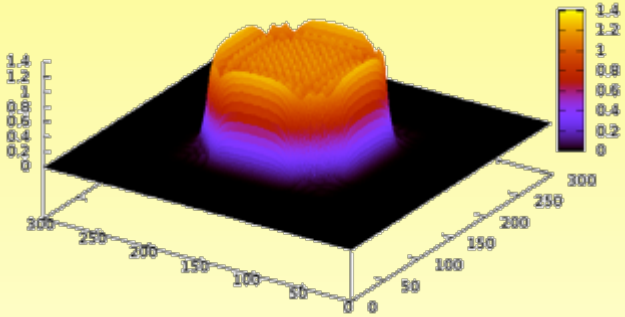


Hydroxy-catalysis bonding

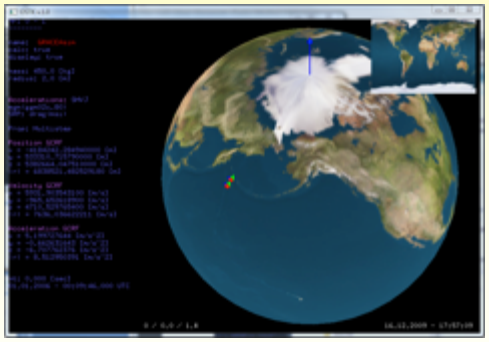


$$\tilde{\delta x}_{\mathrm{fm}}(f) = 355 \times 10^{-12} \left(\frac{\lambda}{1064\,\mathrm{nm}}\right) \left(\frac{L}{100\,\mathrm{km}}\right) \sqrt{\frac{100\,\mathrm{Hz}}{f}}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$$

Interferometer design and analysis



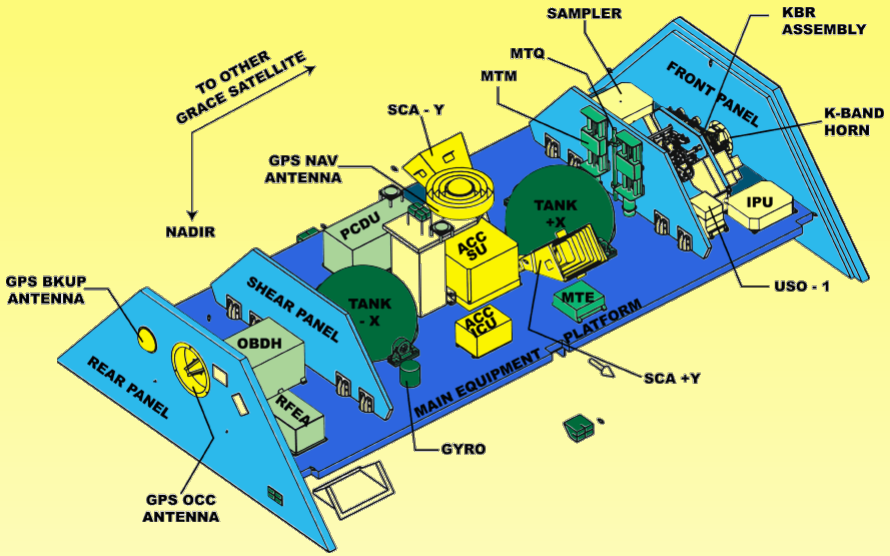
Optical simulations

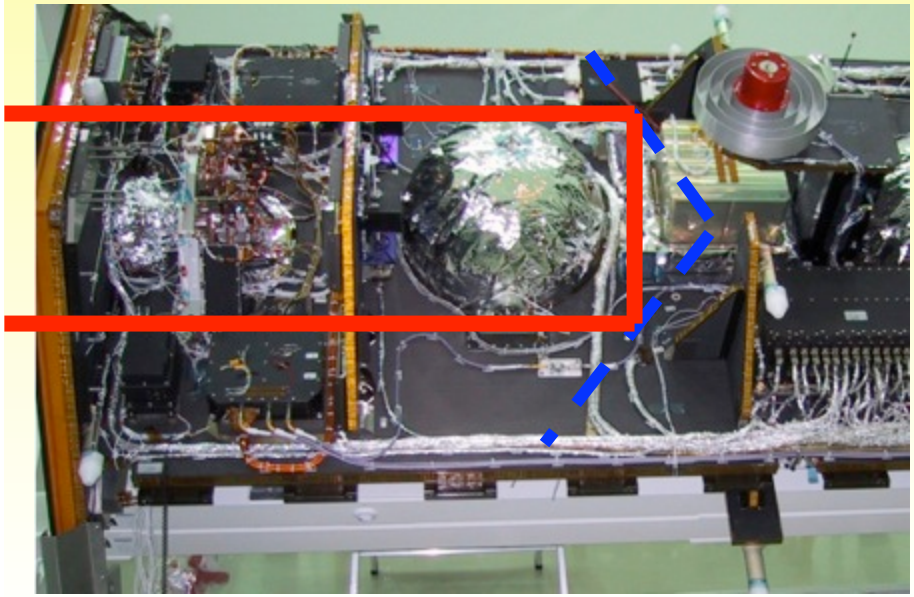


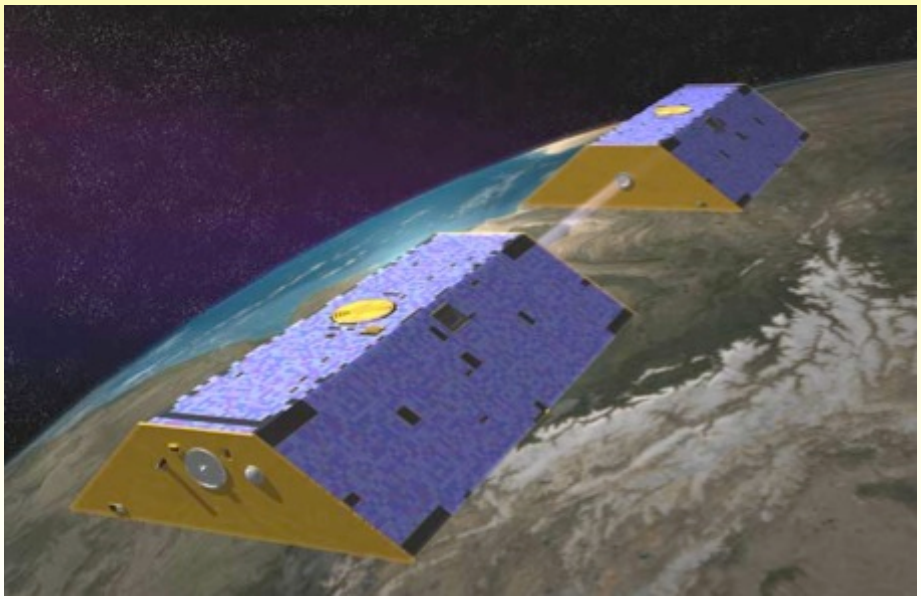
Orbit simulations

GRACE-FO Mission

- Central optical path obstructed
- Go around with virtual cornercube

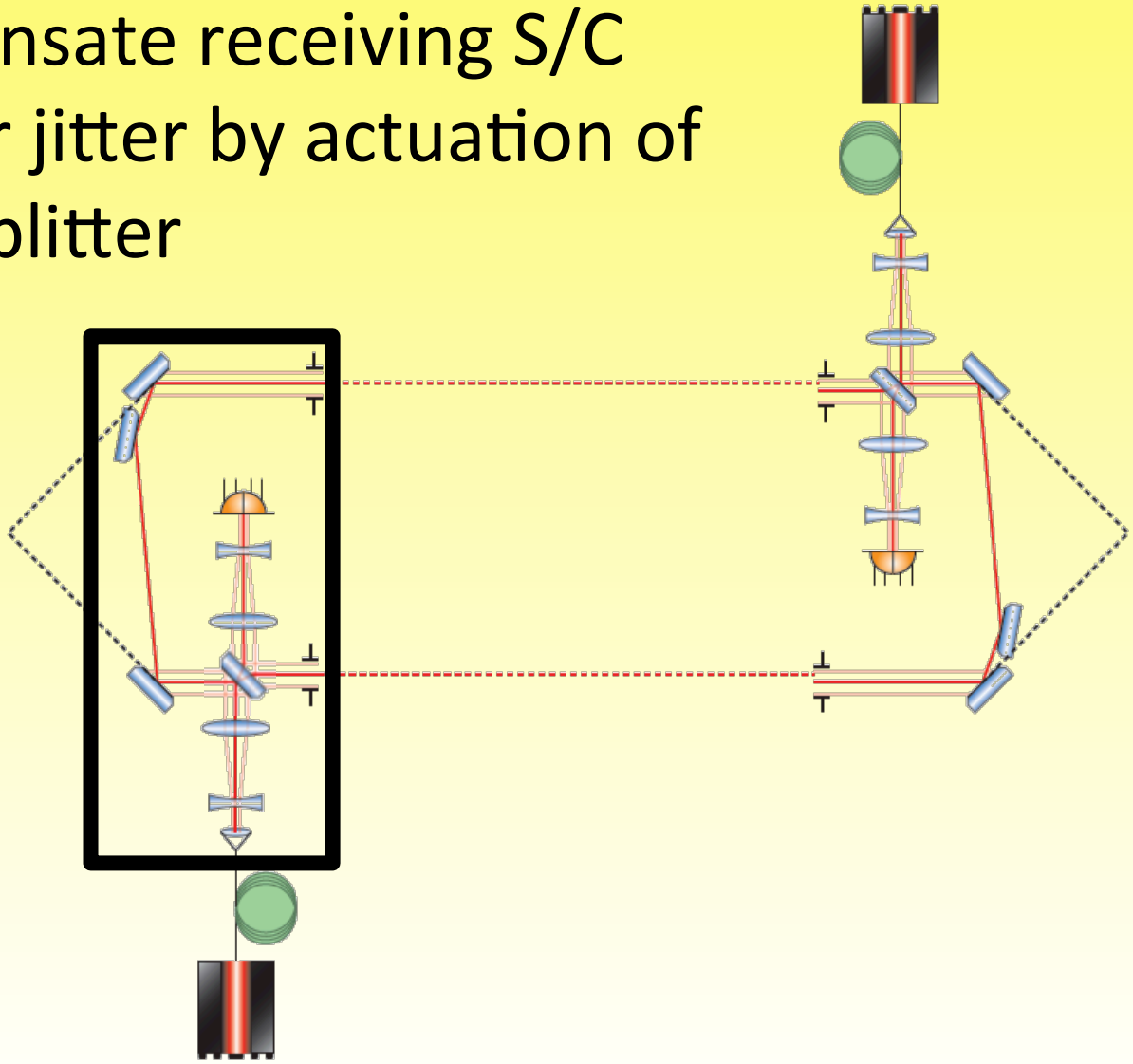






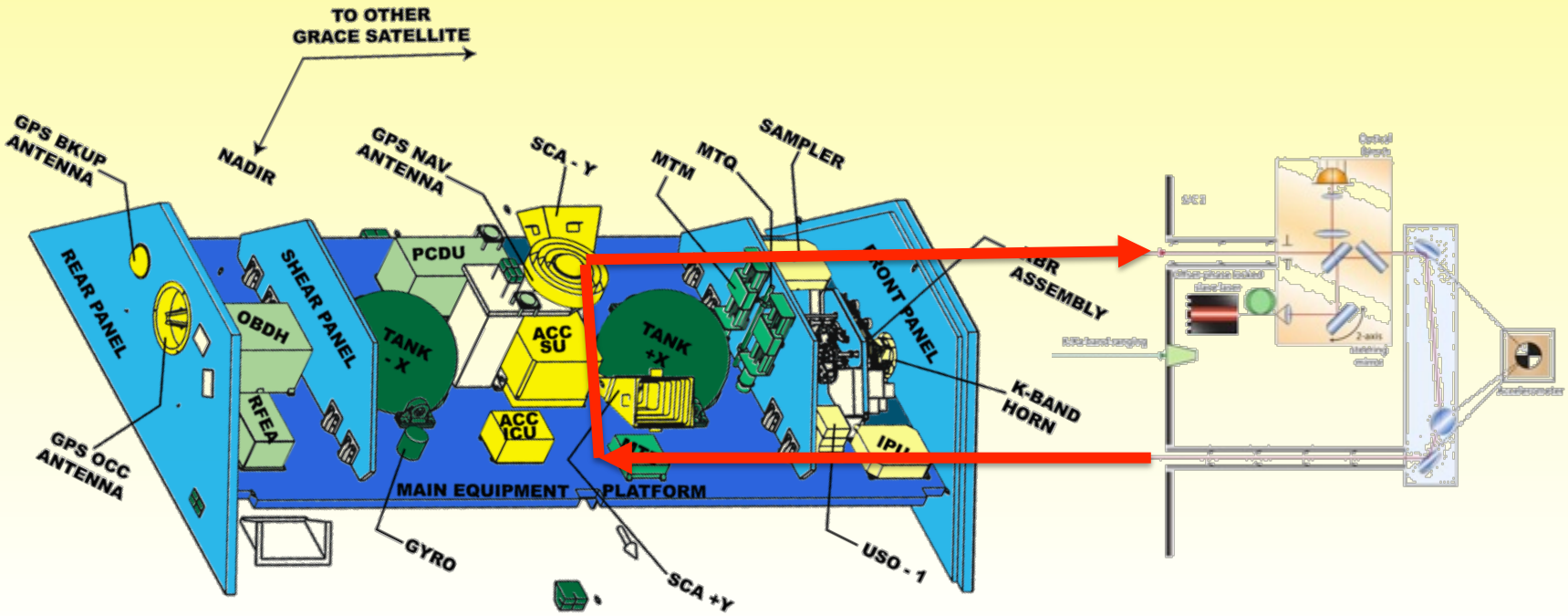
Racetrack Layout

- Compensate receiving S/C angular jitter by actuation of beamsplitter



GRACE Follow-On Mission Approved!

- USA/Germany, approved in Dec 2011, launch in 2017!
- Laser interferometer instrument from Germany
- First-ever intersatellite laser ranging instrument!
- AEI: Design lead / PI for interferometry!



We will hear the Universe and the Big Bang!

- And LISA technology will enable all future generations of gravitional geodesy missions!