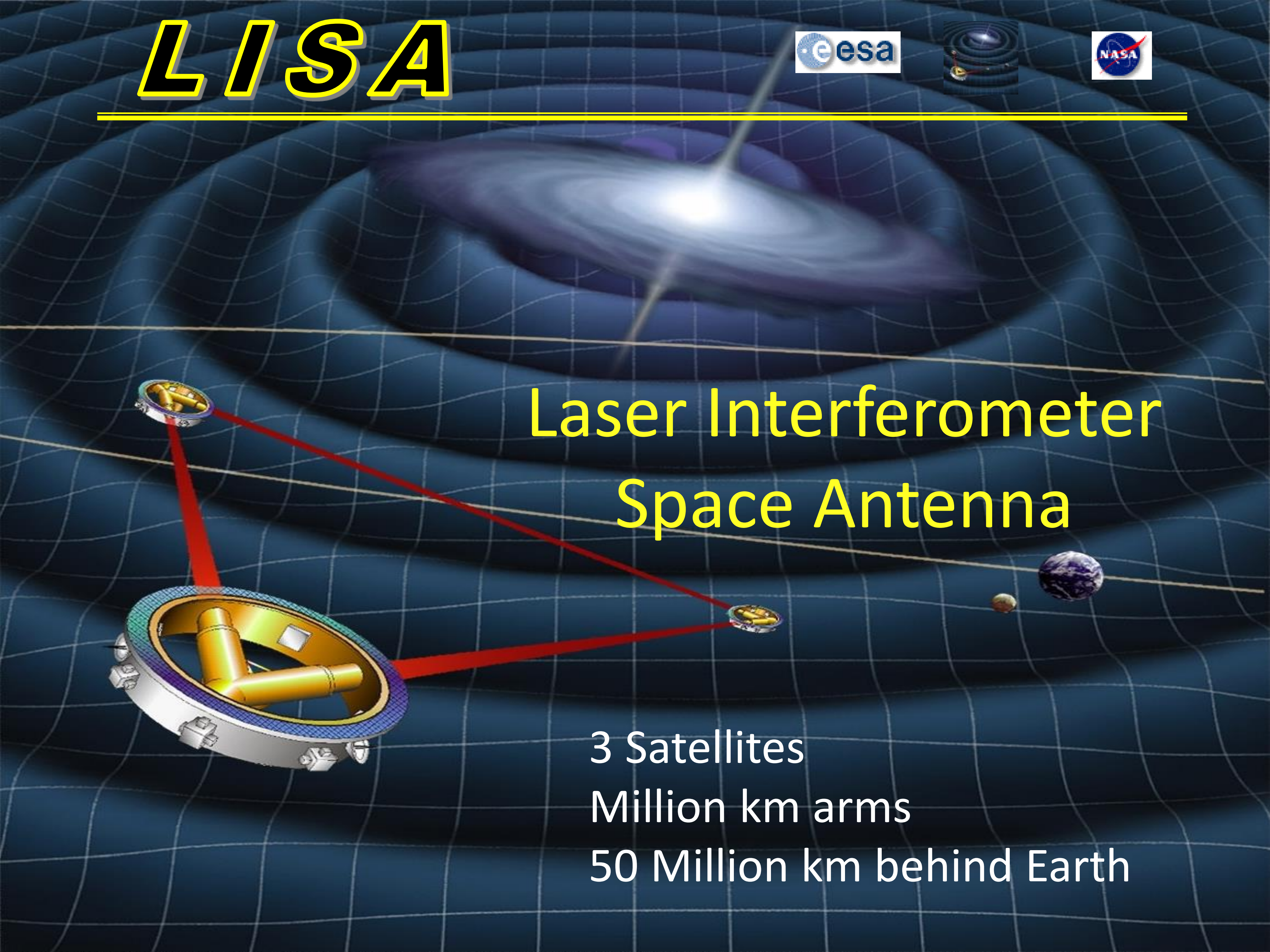
LISA and the Gravitational Universe

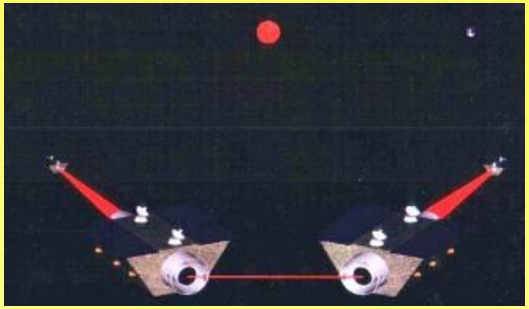
Karsten Danzmann

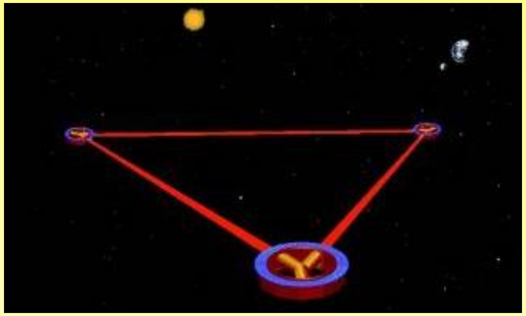
AEI Hannover

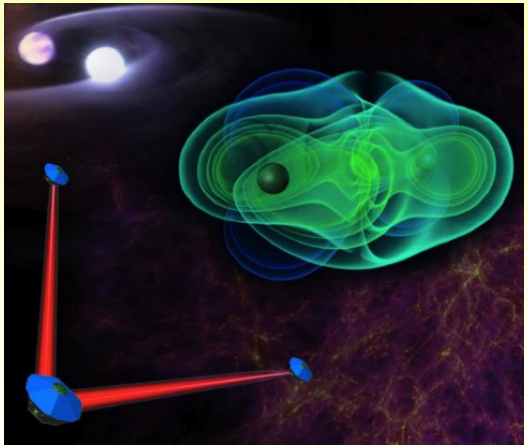

LISA
Laser Interferometer
Space Antenna
3 Satellites
Million km arms
50 Million km behind Earth

LISA: A Mature Concept

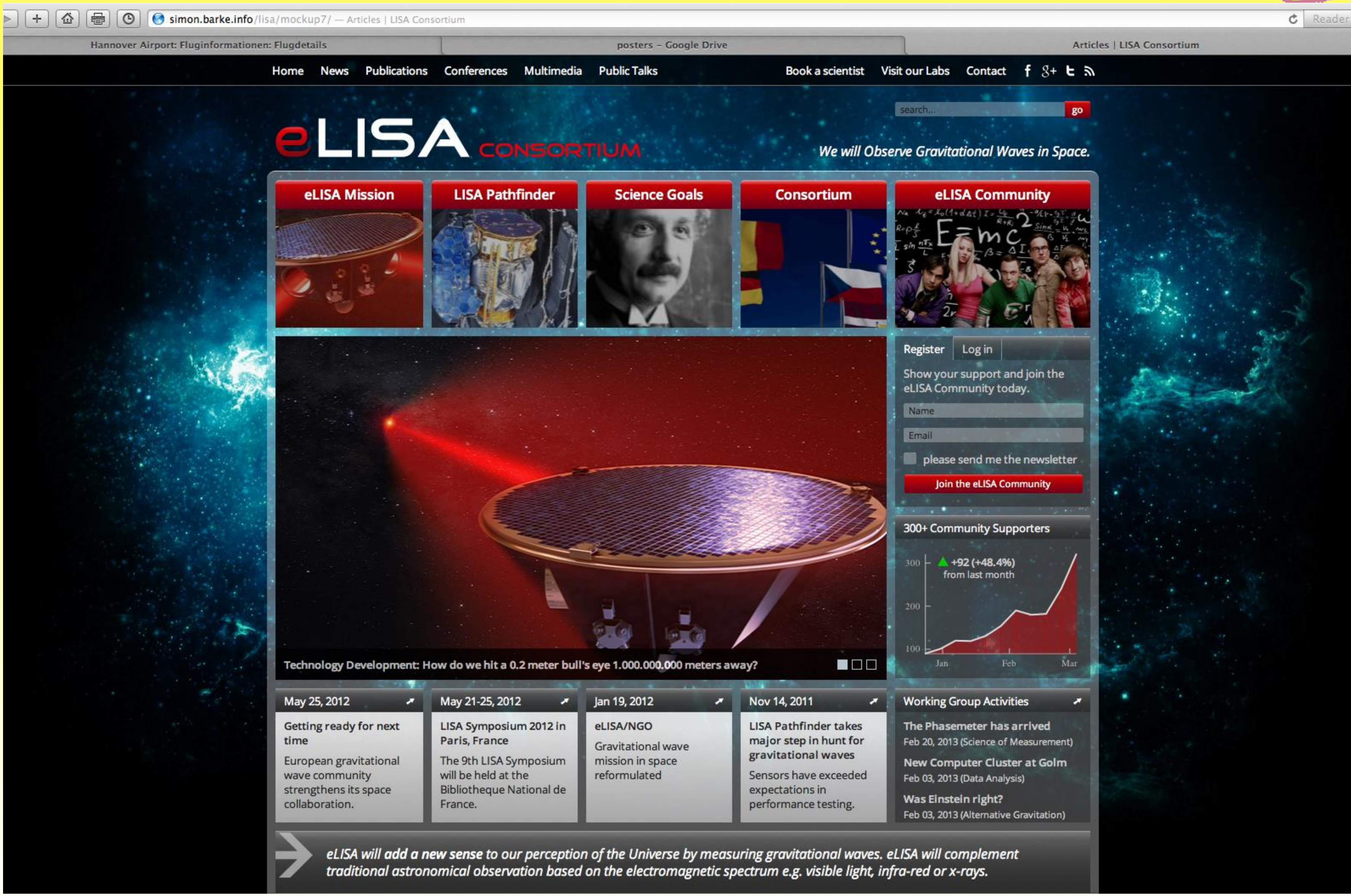
- M3 proposal for 4 S/C ESA/NASA collaborative mission in 1993
- LISA selected as ESA Cornerstone in 1995
- 3 S/C NASA/ESA LISA appears in 1997
- Joint Mission Formulation study until 2011
- Reformulation since 2012 as ESA-led eLISA (evolving LISA) mission concept







Website elisascience.org



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

Stories by keywords

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

This article elsewhere

Blogs linking to this article

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."

- 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€

  - Drop one arm!

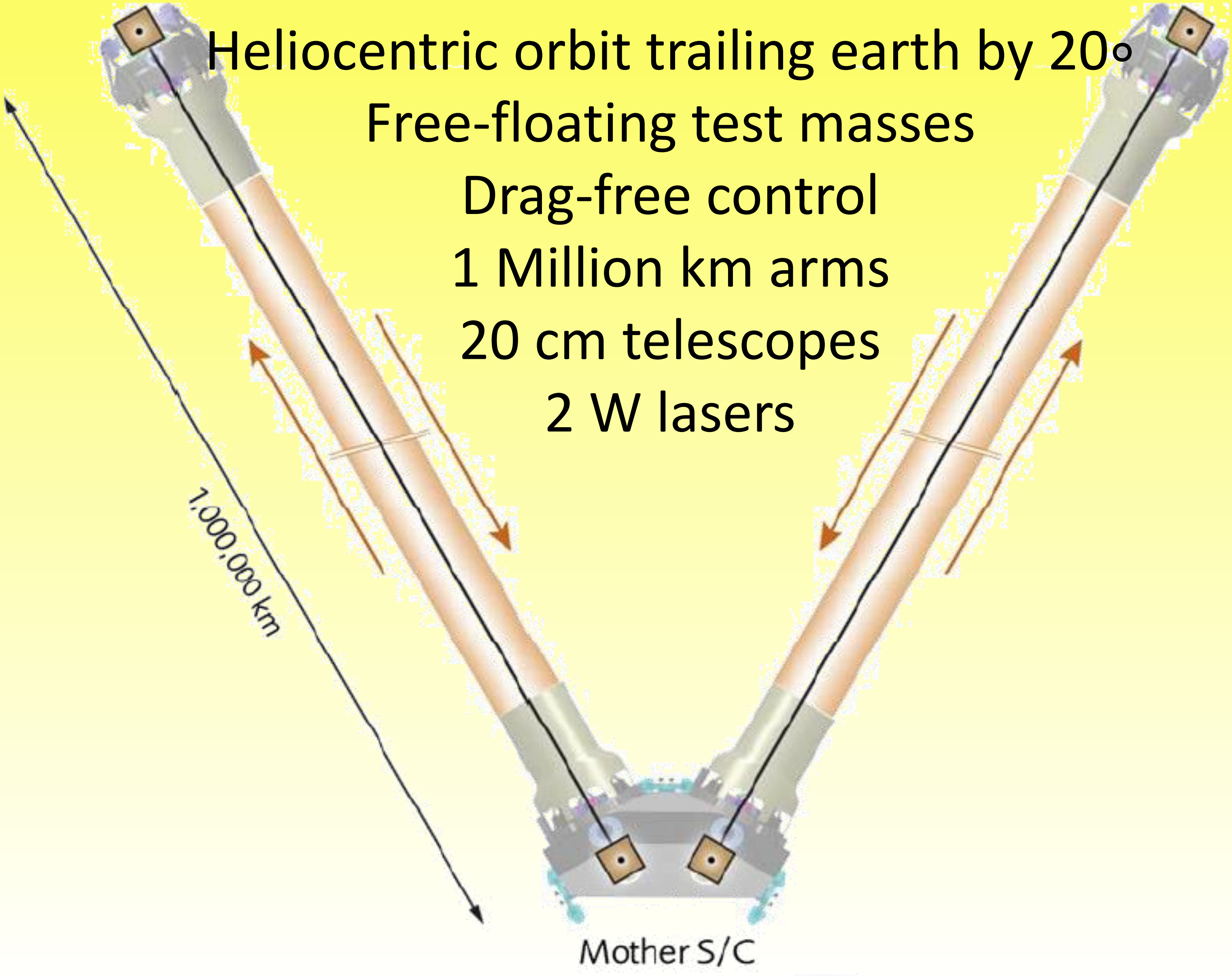
  - Build on LISA Pathfinder hardware
  - Shorter arms, smaller telescopes, simpler orbits, less mass
  - Can use cheaper launcher

→Mission Concept called NGO (eLISA)

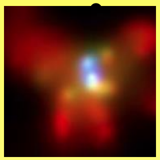
→eLISA: evolving LISA
→NGO: specific incarnation of eLISA for ESA L1 selection!

NGO Layout for eLISA

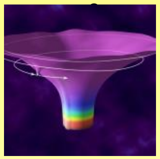
Heliocentric orbit trailing earth by 20∘
Free-floating test masses
Drag-free control
1 Million km arms
20 cm telescopes
2 W lasers



eLISA for Astrophysics, Cosmology, and Fundamental Physics

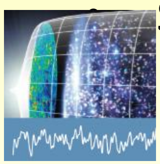


Massive Black Holes (10^4 to 10^8 $M_\odot$)
- When did the first Black Holes appear in pre-galactic halos and what is their mass and spin?
- How did Black Holes form, assemble and evolve from cosmic dawn to present time, due to accretion and mergers?
- What role did Black Holes play in re-ionisation, galaxy evolution and structure formation?
- What is the precise luminosity distance to loud standard siren black hole binaries?
- What is the distance – redshift relation and the evolution history of the universe?
- Does the Graviton have mass?



Extreme Mass Ratio Inspirals, EMRIs (1 to 10 $M_\odot$ into 10^4 to 5×10^6 $M_\odot$)
- How is the stellar dynamics in dense galactic nuclei?
- How does dynamical relaxation and mass segregation work in dense galactic nuclei?
- What is the occupation fraction of black holes in low-mass galaxies?
- How large are deviations from Kerr Metric, and what new physics causes them?
- Are there horizonless objects like boson stars or gravastars?
- Are alternatives to GR viable, like Chern-Simons or scalar tensor theories or braneworld scenarios?

Ultra-Compact Binaries in Milky Way
- What is the explosion mechanism of type Ia supernovae?
- What is the formation and merger rate of compact binaries?
- What is the endpoint of stellar evolution?

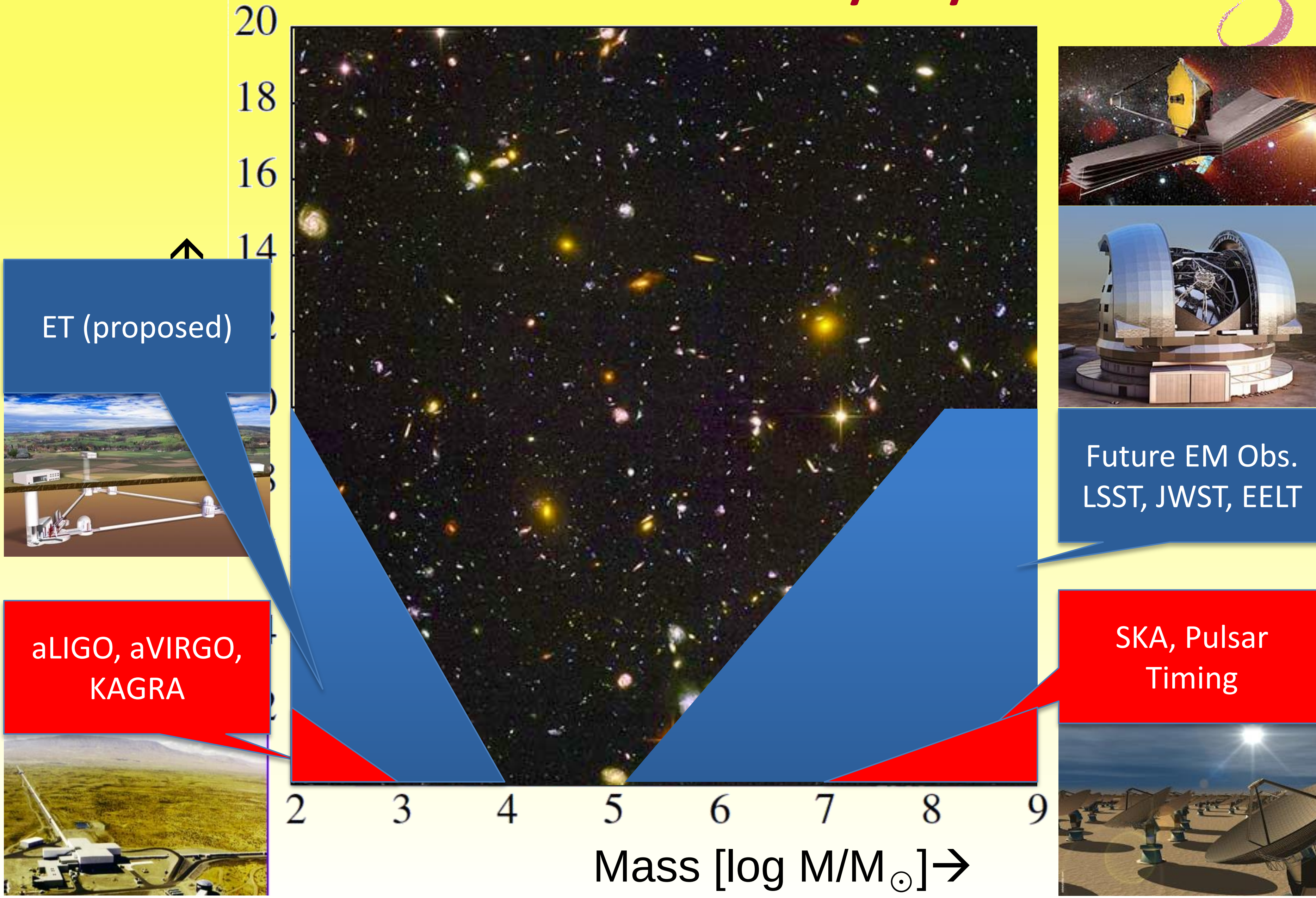


Stochastic Signals
- Directly probe Planck scale epoch at 1 TeV to 1000 TeV before decoupling of microwave background
- Were there phase transitions and of which order?
- Probe Higgs field self coupling and potential, and search for supersymmetry.
- Are there warped sub-millimetre extra-dimensions?
-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

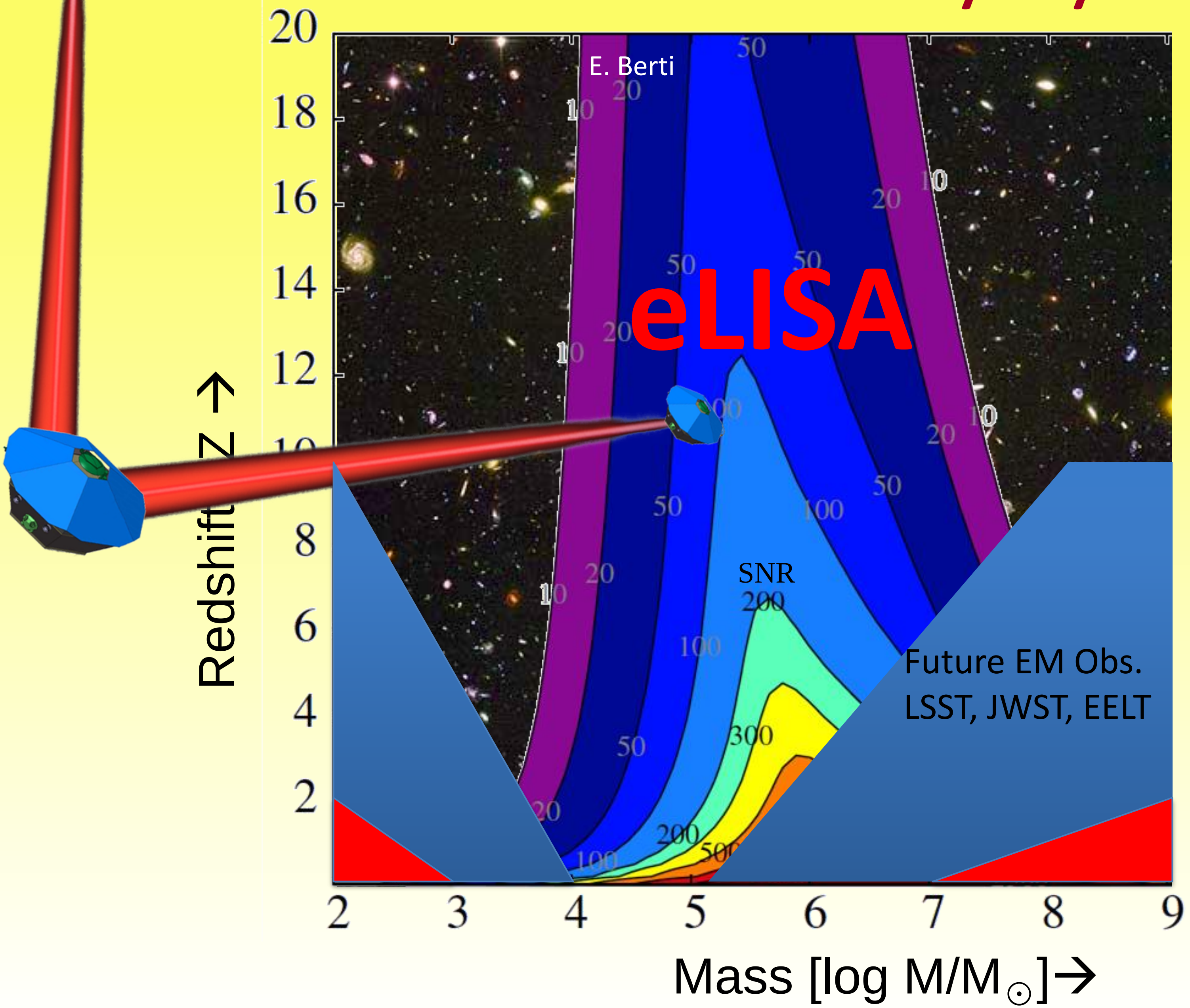
???

The Unknown !

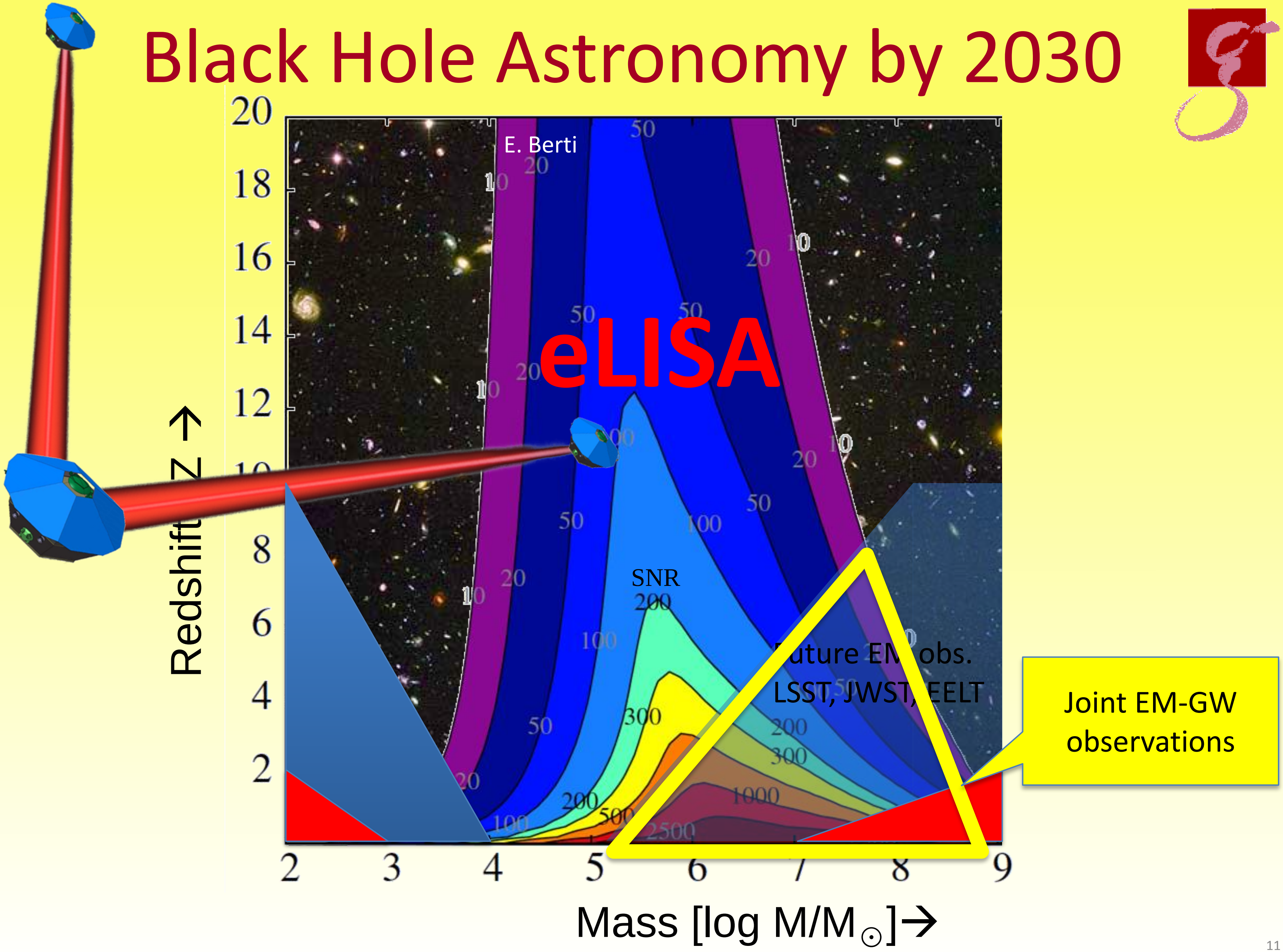
Black Hole Astronomy by 2030



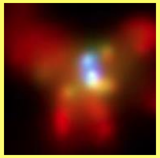
Black Hole Astronomy by 2030



Black Hole Astronomy by 2030



eLISA for Astrophysics, Cosmology, and Fundamental Physics



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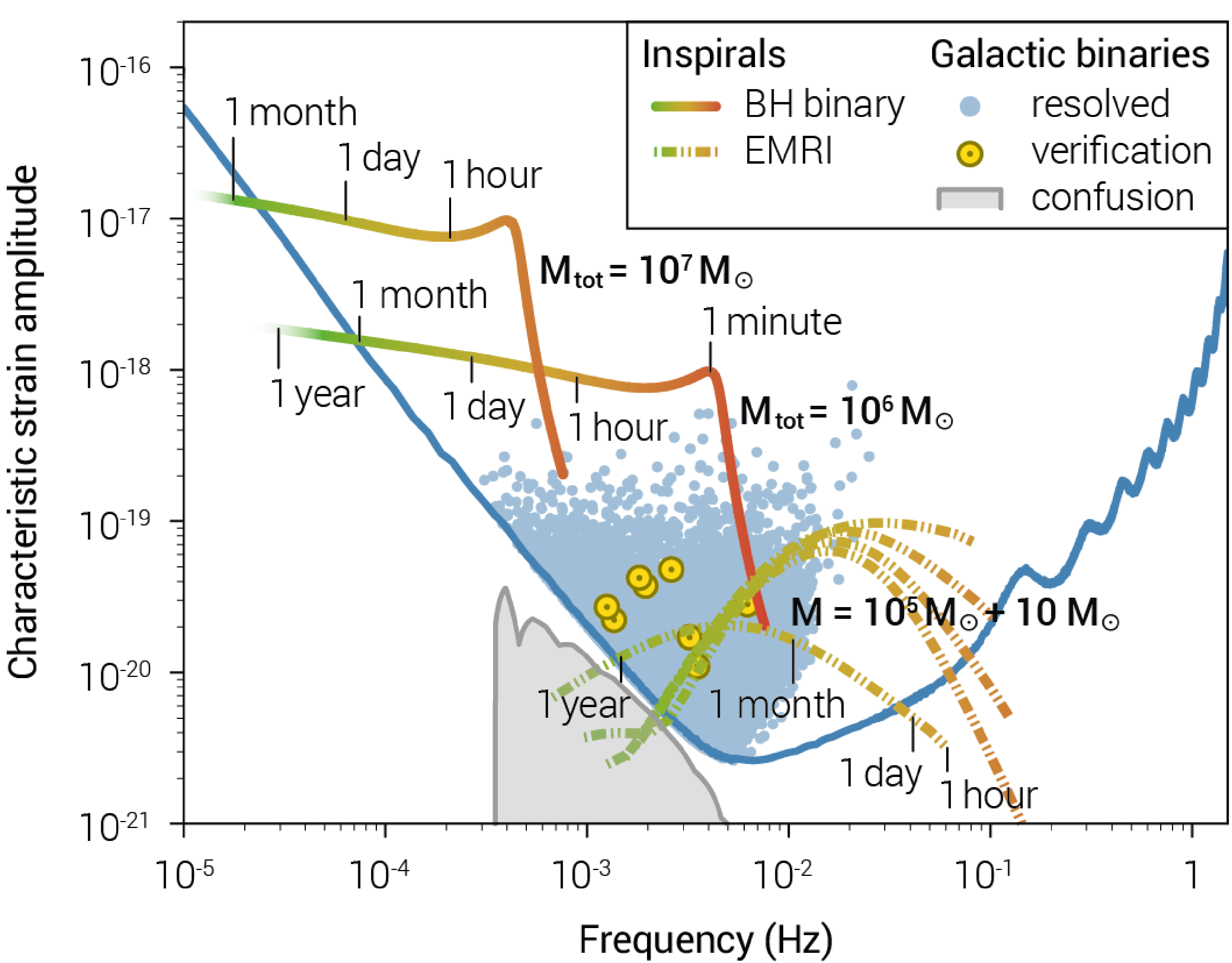
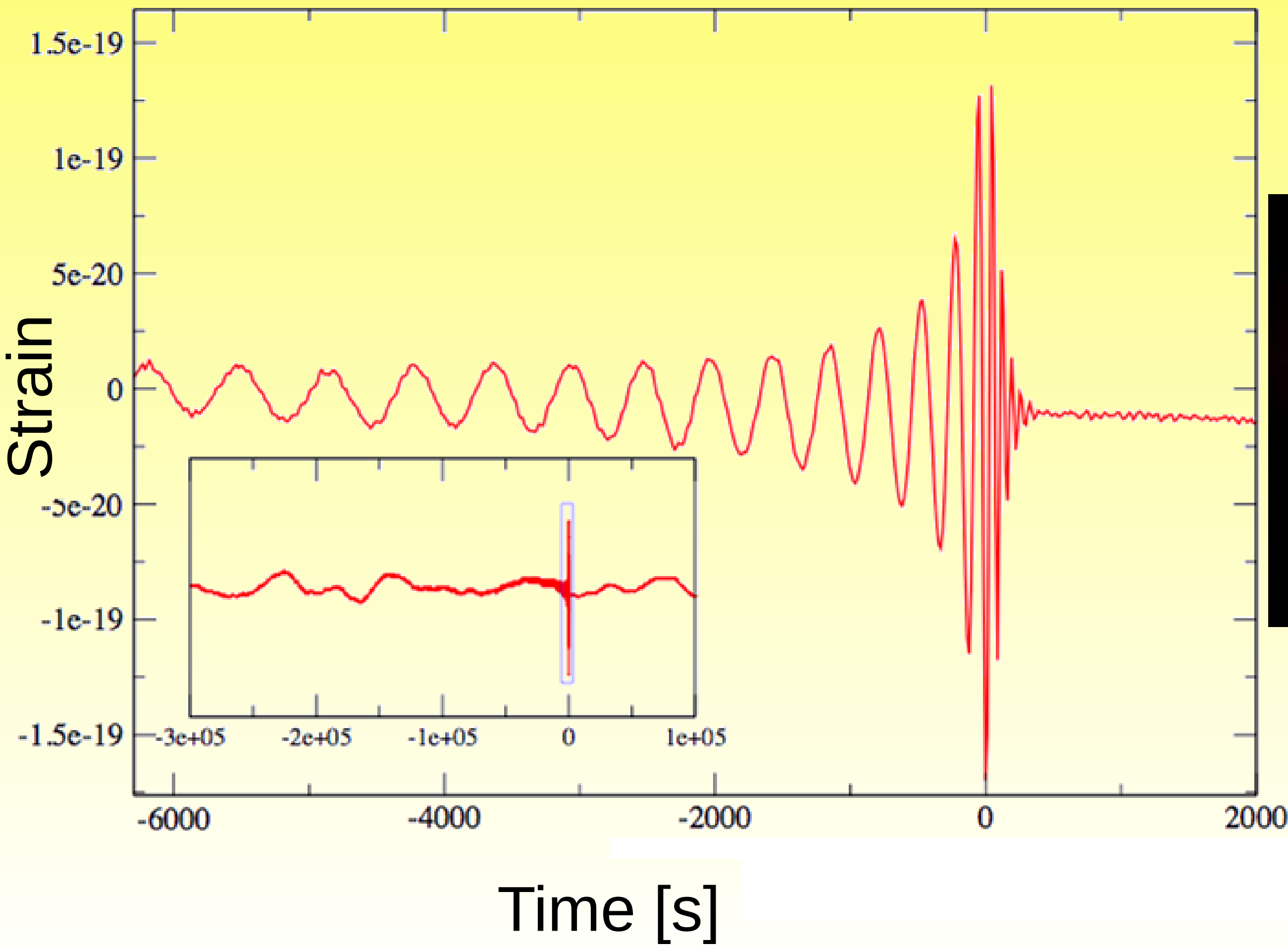
- The Unknown !

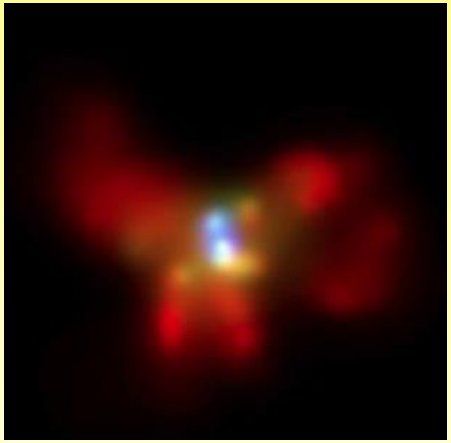
Sensitivity and Black Hole Science



Black Hole Merger Signals far above Noise!

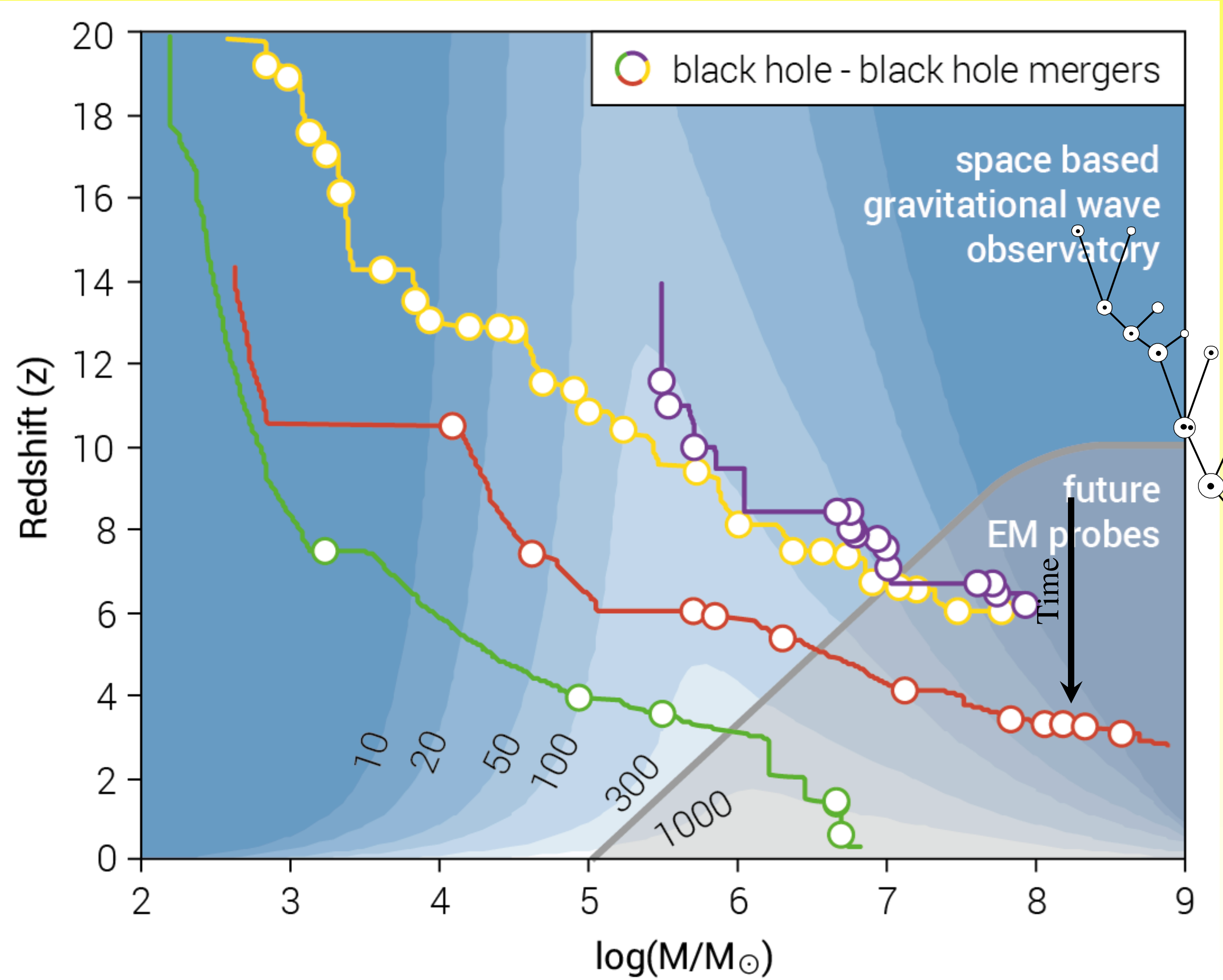
- Simulated eLISA data stream
  $10^5 M_\odot$ BH binary merger at z=7,
  including instrumental noise (SNR~100)

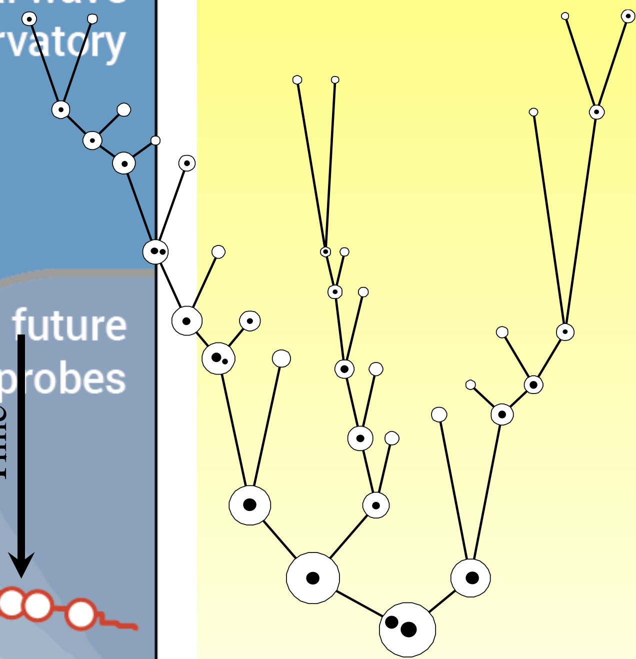



NGC 6240

Baker et al. 2006

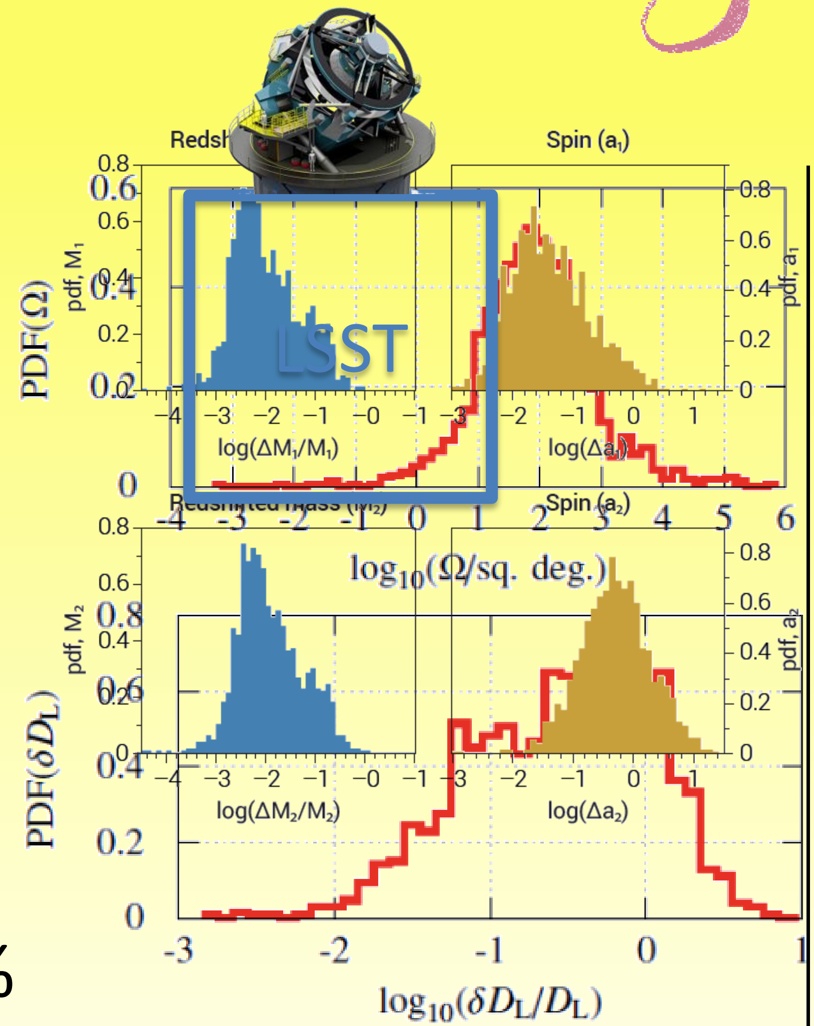
All Binary Black Holes cross eLISA band: Trace Galaxy Mergers





eLISA Black Hole Physics at high SNR

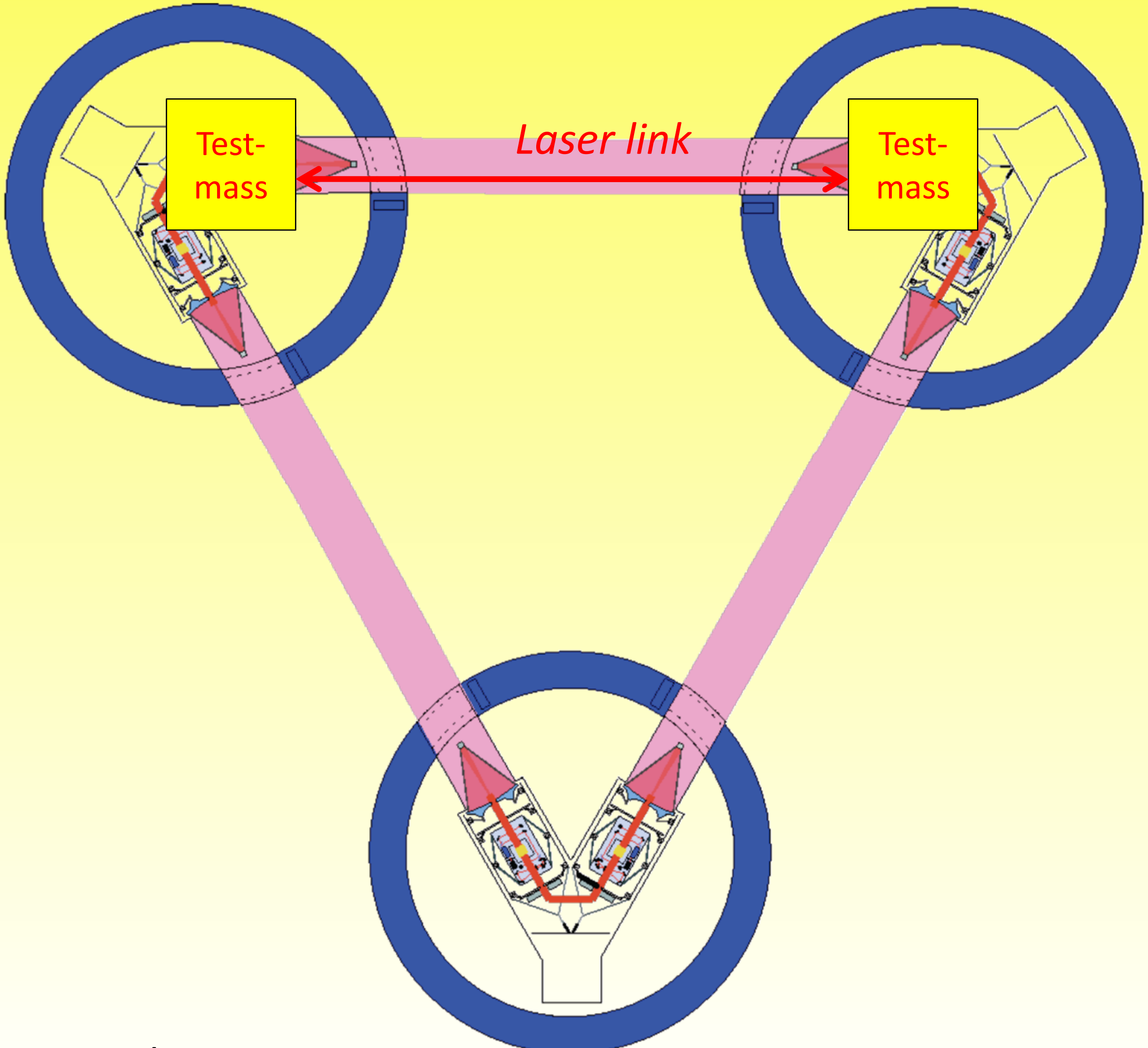
- BBH rest mass $10^4 - 10^7$
- Out to redshift $z >> 10$
  - if they exist
- 10s – 100s events per year
- Redshifted mass to 0.1%-1%
- Absolute spin to 0.01-0.1
- Luminosity distance 1 – 50 %
- Sky location 1° - 10 °



LISA Pathfinder

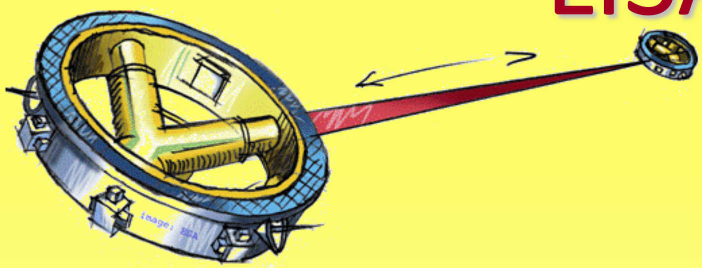
- Testing LISA technology in space!

One LISA Arm:
Few Million kms – two test masses

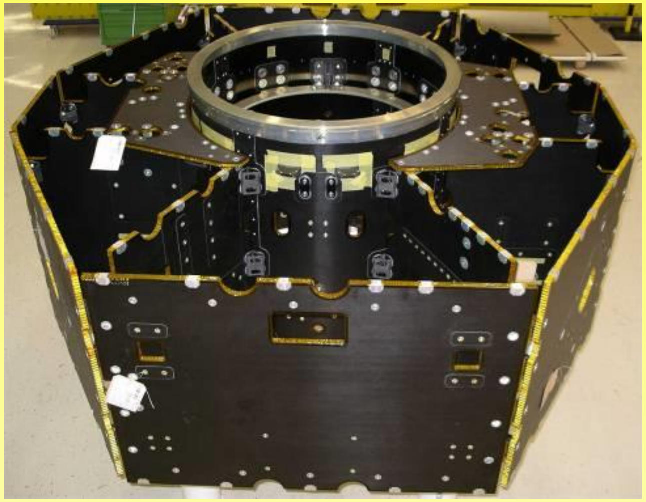


Courtesy: Stefano Vitale

LISA Pathfinder



- Take one LISA arm
- Squeeze it into ONE satellite



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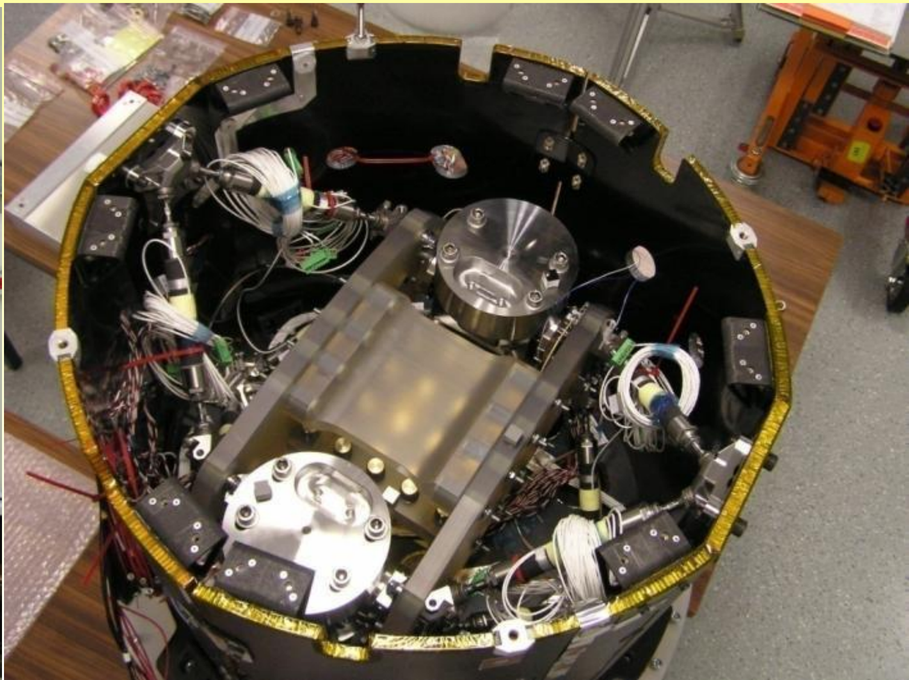
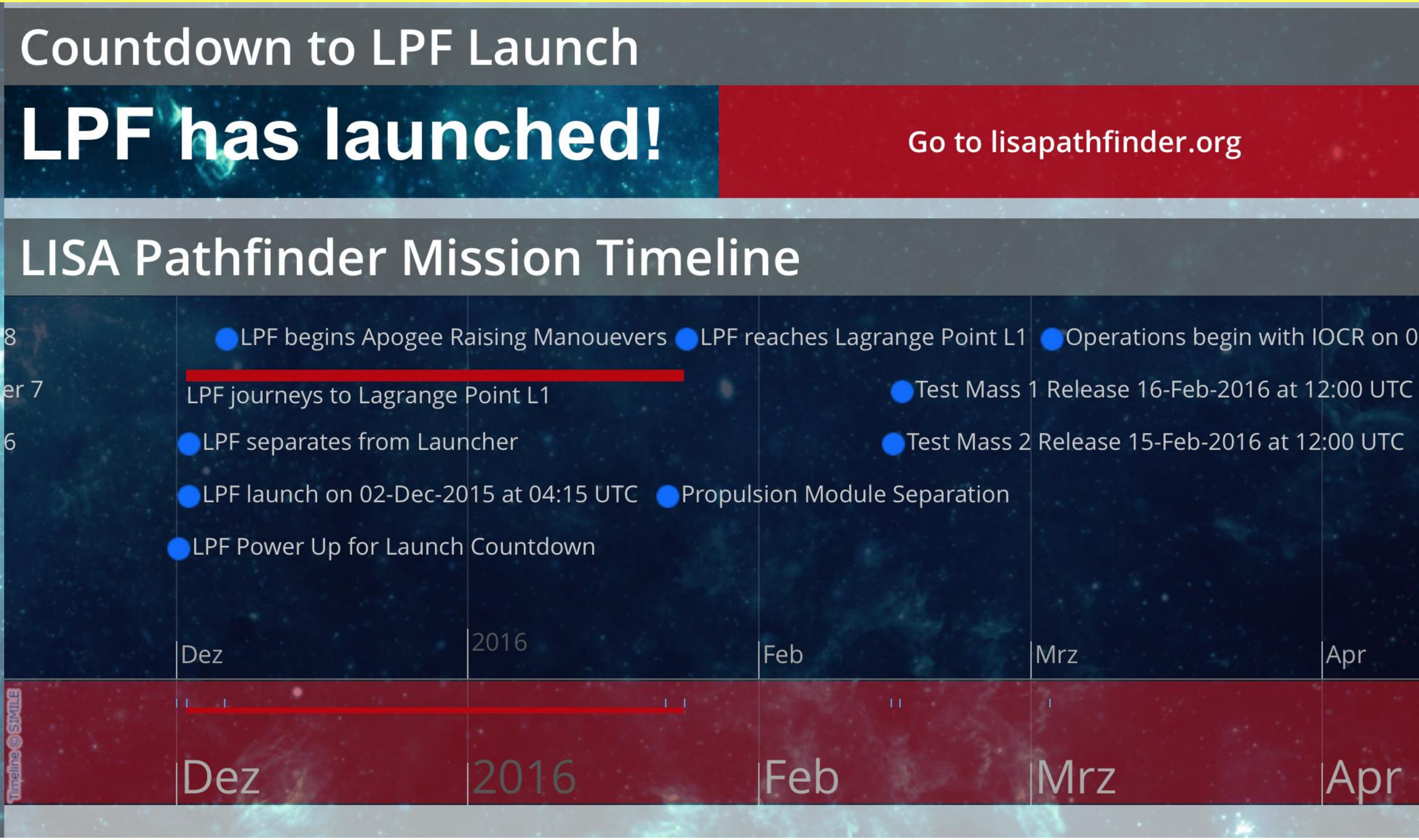


Spacecraft is completed!

100 Years since GR Publication: Dec. 2, 2015



LISA Pathfinder Launch

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 - Athena
- Launch of L3 in 2034 - LISA

Technology Team for L3: The GOAT: Gravitational Observatory Advisory Team

- Appointed in 2014
- 10 European members, 4 US members, 1 observer from Japan
- Interim Report published in fall 2015
- Final Report after Pathfinder flies!
- Technology roadmap clear by early 2016!

The ESA–L3 Gravitational Wave Mission

Gravitational Observatory Advisory Team

Intermediate Report

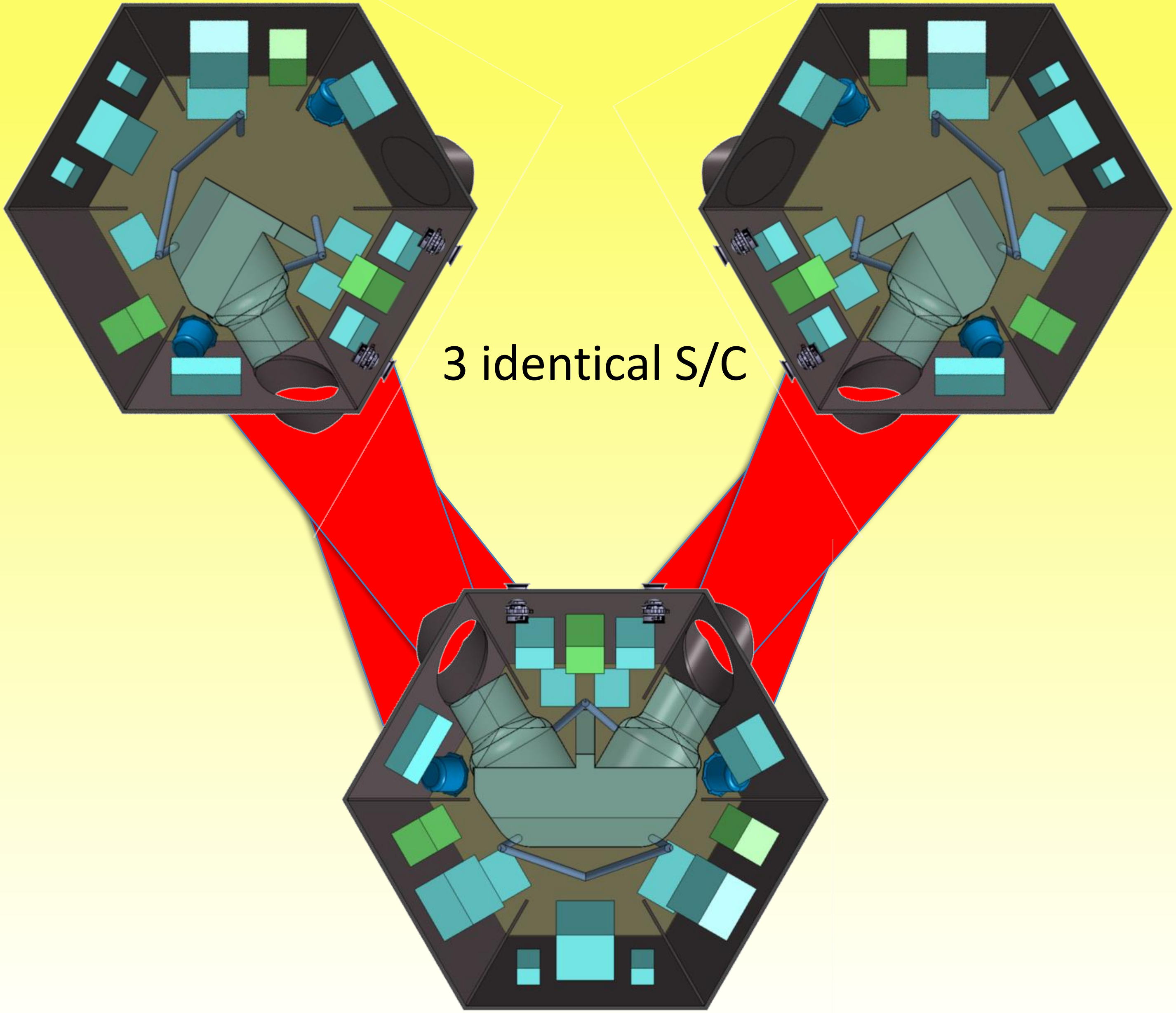
15 June 2015

GOAT Intermediate Report

- Main Results:
  - There is no practical alternative to LISA-like laser interferometry for L3
  - After successful Pathfinder flight technology work to start end of 2016 on 4 key areas:
    - optical architecture
    - telescope,
    - laser,
    - optical bench

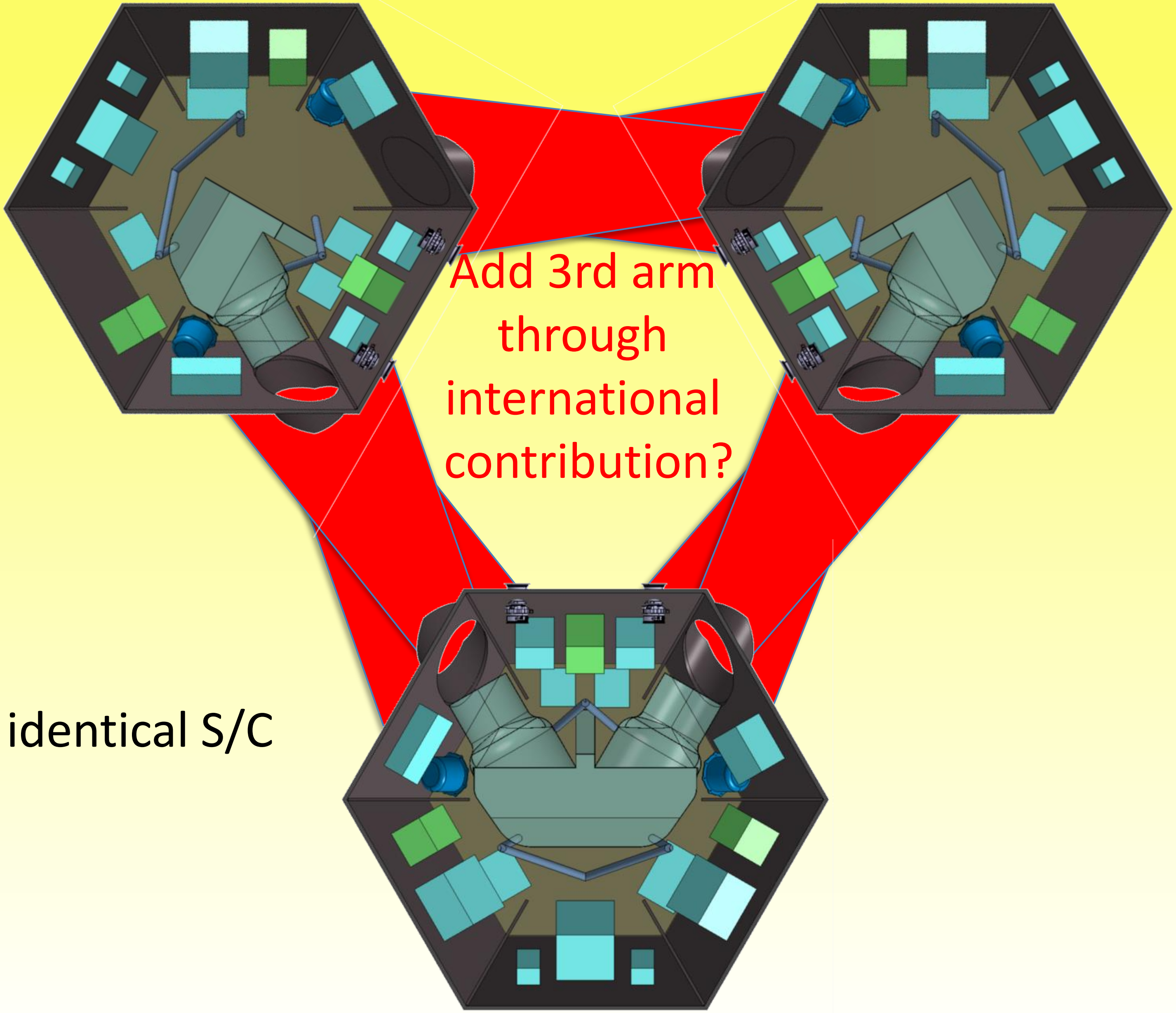
  - Call for mission concepts in 2016
  - Mission concept selection in 2017
  - Launch well before 2034 technically possible!

eLISA Lay-Out



3 identical S/C

eLISA Lay-Out



3 identical S/C

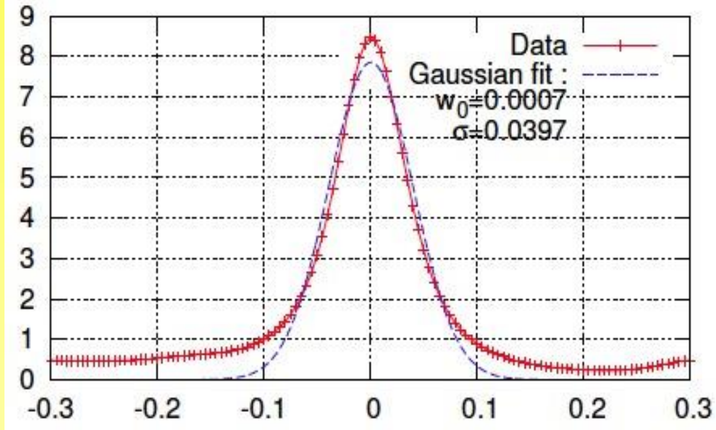
Cosmology with standard sirens

- With luminosity distances, LISA gives accurate and independent measurements of H_0 and w.

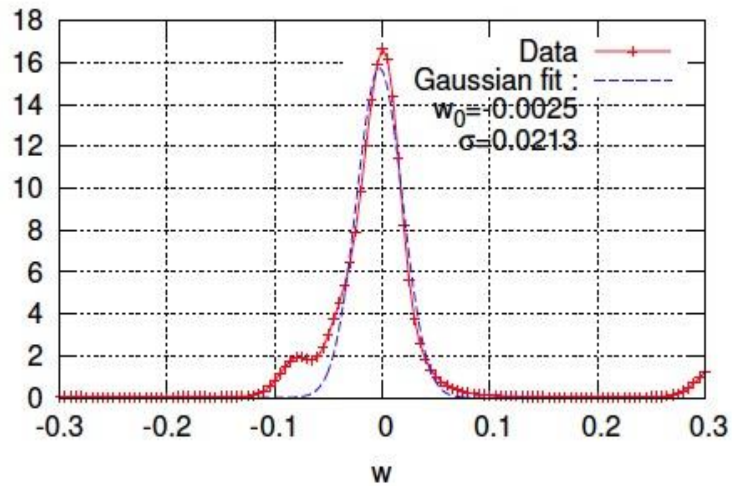
- Using EMRIs, *without* identifications, LISA can determine H_0 to ±0.4% = ±0.3 km s^{-1} Mpc^{-1} after just 20 EMRI detections: ~3 months LISA data. (MacLeod & Hogan, PRD, 2008; SDSS) Today (WMAP) ±1.2 km s^{-1} Mpc^{-1}.

- Using massive mergers out to z = 3, again with *no* identifications, LISA can (in 3 years) determine dark energy equation of state parameter w to ±2-4%. (Petiteau et al, ApJ, 2011; Millennium). Compare EUCLID ±2%.

No identifications



With identifications



International Contributions for L3

- Must not be mission critical
  - Flight equivalent must exist in Europe
- Must bring real cost savings
  - Needs clean interfaces
  - Minimize shadow engineering required in ESA and Member States
  - Low friction losses required
- We want third arm back
  - Has implications both at ESA and Member States
- We need a creative mix of contributions

International Contributions

- What is noble work and what is not?
- Easily identifiable S/C building blocks:
  - Launcher
  - Propulsion modules
  - Thrusters
  - Pieces like: Solar arrays, power supplies, batteries, structures, mechanisms, star trackers, TTC, antennas
- Easily identifiable Payload items:
  - Telescopes
  - Lasers, Modulators, reference cavities
  - CCDs, Diodes, Pre-Amps
  - Proof masses
  - Actuators
  - Electronics, USO

Strawman Mission Scenario

- L1 NGO as baseline
  - Cost envelope in 2013 e.c. is (1000 M€ from ESA plus 200 - 400 M€ from MSs) = 1200 - 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 performance enhancement !
- → We want third arm and longer mission lifetime!

What is the instrument on eLISA?

- Treat like focal plane instrument for Astronomy mission
- ESA responsible for:
  - Satellite platform, including:
    - Telescope, laser and structure for optical assembly mounting
- Member States fund:
  - Scientific consortium to deliver instrument consisting of:
    - Optical Bench with attached Inertial Sensor and detached Phasemeter, Payload Computer TBD

Meeting with delegations on the way ahead for the L3 mission

Frédéric Safa
Future Missions Office
ESA-HQ, 5 November 2015

L3 schedule aspects

Assuming 8.5 years development (including margins, based on previous studies and programmatic reviews), and launch early 2034, the schedule would be :

- Phase B2/C/D kick-off: ~ mid-2025
- Mission adoption by SPC: Nov 2024
- Phase B1 start (ITT): Q2 2022

Therefore, assuming L3 activities are initiated in 2016, only ~ 6 years (2016-2021) are available for critical technology developments and freezing the mission concept

Gravitation Observatory Advisory Team main conclusions

No credible alternative to Laser Interferometry for L3

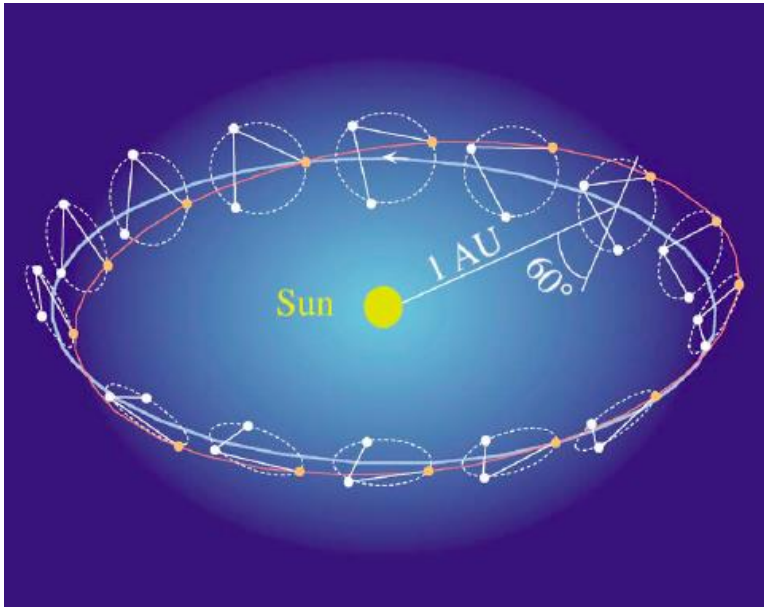
Atom Interferometry (AI) sole identified potential alternative (see GOAT report). Rapidly evolving field, however:

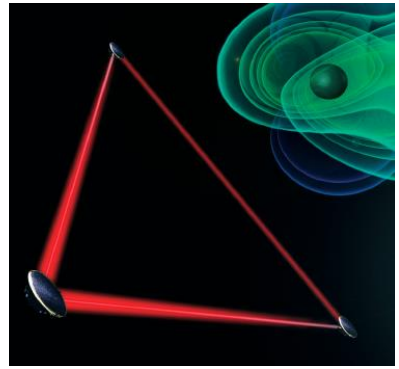
- AI technology maturity far below Laser Interferometry.
- Compatibility with mission adoption by 2024 is at risk
- Furthermore, no transformational technical/hardware simplification in comparison to Laser Interferometry

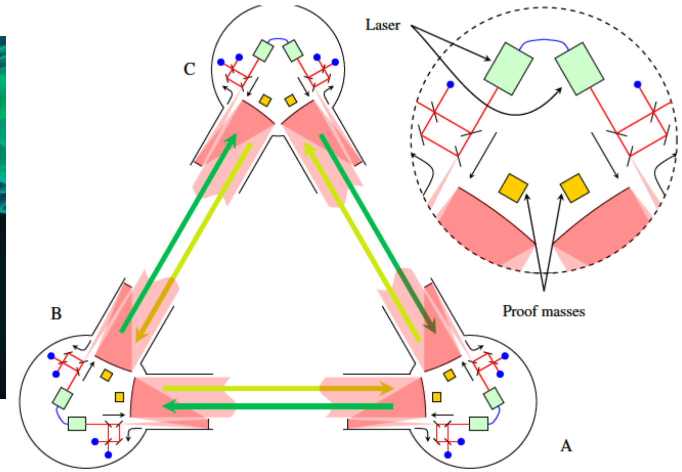
Laser Interferometry concept, building on LISA-PathFinder demonstration and LISA/eLISA studies is confirmed as the sole credible baseline for L3

- Features at least 3 spacecraft and 2 interferometric arms

Recall of LISA/eLISA laser interferometry concepts





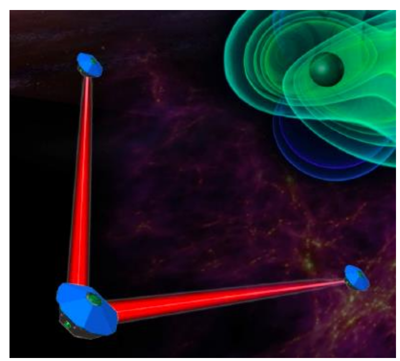


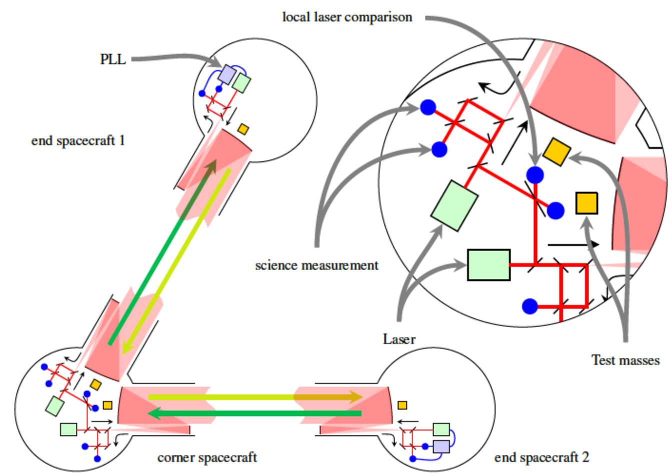
LISA (2010) with 3 arms and 3 identical S/C

Earth trailing constellation of 3 spacecraft in quasi-equilateral configuration, 1 to 5 Mkm distance

Each S/C carries test mass in free fall (drag-free control);

Laser interferometry measurement of the distance between the test masses with picometer accuracy in the frequency range 0.1 mHz -1 Hz





eLISA/NGO (2012) with 2 arms
One mother and two daughter S/C

Two or three interferometric arms for L3?

Parametric analysis performed by GOAT

- by varying: the number of arms (2 or 3), inter-S/C distance; mission duration; and noise level. See GOAT intermediate report.

ESA would baseline the 3-arm configuration for the upcoming study activities –affordability TBC!

- Fully recurring spacecraft development; failure tolerance.
- Some arguments suggested in 2011 for two arms not valid, e.g. lower launch costs with 2 Soyuz launches vs single Ariane 5…the 3 Spacecraft configuration may be compatible with a single Ariane 6.2!
- Note that some of NGO/eLISA simplifications will probably be maintained, even when moving back to 3 arms

No urgent decision needed: short/medium term technology developments are devoted to payload subsystems

ESA approach for the short/medium term: Technology preparation (1/2)

ESA generally concurs with GOAT intermediate report statements on technology readiness.

ESA technology work plan submitted to November SPC/IPC includes in particular development activities on the laser and the telescope assembly. Subject to IPC approval, ESA plans to initiate critical activities in 2016.

Prog.	IPC Appr.	ESA Ref.	Activity Title	Budget 2016 k€	Remarks
CTP	N/A	C216-137FM	Optical Bench Manufacturing Industrialisation Study	400	
CTP	IPC	C216-138FM	Metrology Telescope Design for a Gravitational Wave Observatory Mission	600	Parallel contract
CTP	IPC	C216-138FM-B	Metrology Telescope Design for a Gravitational Wave Observatory Mission	600	Parallel contract
CTP	IPC	C217-045FM	Phase Reference Distribution for Laser Interferometry	1200	
CTP	IPC	C217-046FM	Gravitational Wave Observatory Metrology Laser	3500	Phased activity with intention of two parallel Phase I contracts of 600 k€ and one Phase II contract of 2300 k€
Total – L3-Mission Theme: The Gravitational Universe				**6300**	

Agency

ESA approach for the short/medium term: Technology preparation (2/2)

L3 technology plan will be progressively complemented over the next years.

Therefore, need to communicate and coordinate with Funding Agencies on payload activities

- Although payload consortium should be in place at the beginning of Phase A, early declaration of interest of Delegations for the provision of payload and science ground segment elements will help.
- Currently, ESA/CTP activities are limited to “high likelihood” ESA-provided elements

Assuming smooth progress, TRL > 5-6 for critical element/subsystem level could be reached by ~ 2019-2020

Technically driven LISA Roadmap

• eLISA Science Theme selected as L3 in	2013
• Technology Roadmap work	2013 – 2015
• Continued Mission Concept Study	2014 – 2015
• Successful LISA Pathfinder flight in	2015
– Assessment of technology status	
– Technology ITTs in 2016	
• Selection of Mission Concept in	2017
• Possibly Start EM of complete Payload	2017
• Start of Industrial Definition Study	2018
• Start of Industrial Implementation	2020
• Launch in	2028

LISA is in good shape!

- Advanced LIGO is in operation
- 70 Mpc BNS inspiral range
  - Good enough for signal?

LISA is in good shape!

- Advanced LIGO is in operation
- 70 Mpc BNS inspiral range
- O1 science observing run has started Sept. 21
  - 3 months Oct - Dez 2015
  - LIGO Hanford + Livingston and GEO600 online 24/7

LISA is in good shape!

- Advanced LIGO is in operation
- 70 Mpc BNS inspiral range
  - Good enough for signal?
- O1 science observing run has started Sept. 21
  - 3 months Oct - Dez 2015
  - LIGO Hanford, LIGO Livingston and GEO600 are online 24/7
- The world will be different after the first GW detection!
- LISA will have many friends!

We will hear the Universe and the Big Bang!