The Status of LISA

Karsten Danzmann

AEI Hannover

Twenty Years after the First LISA Symposium at RAL 1996

Twenty Years after the First LISA Symposium at RAL 1996

- **LISA is in better shape than ever!**
  - **LIGO**
  - **LISA Pathfinder**
  - **GOAT**
  - **Mid-Decadal**
  - **NASA**
  - **3-arm LISA is back**
- **Growing pressure to accelerate LISA schedule**
- **ESA reacts**


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We have detected Gravitational Waves!

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_{\odot}$ and $29^{+4}_{-4} M_{\odot}$, and the final black hole mass is $62^{+4}_{-4} M_{\odot}$, with $3.0^{+0.5}_{-0.5} M_{\odot} c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

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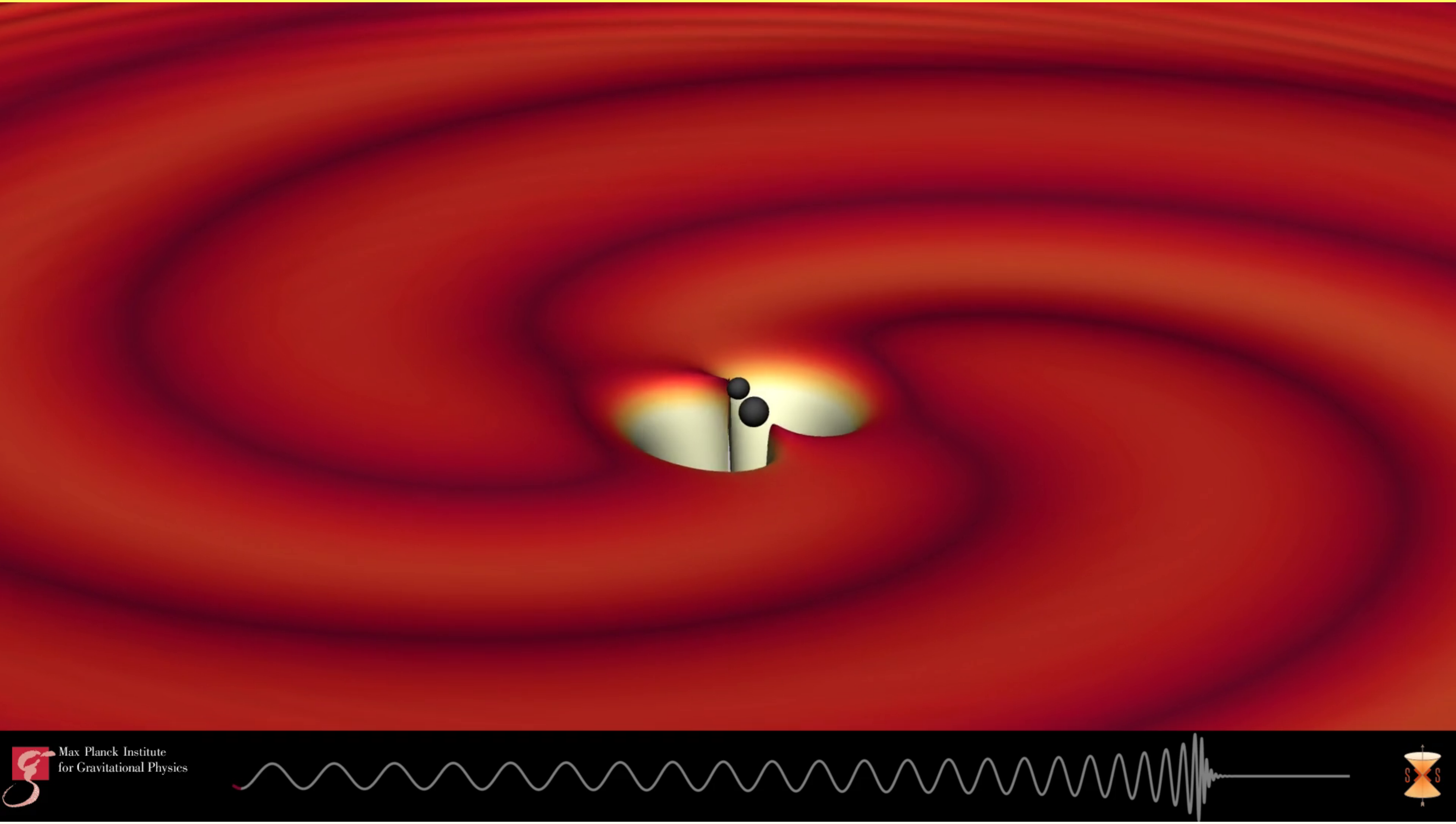
Gravitational Waves from Merging Black Holes on September 14th, 2015



The Christmas Present: 26.12.2015

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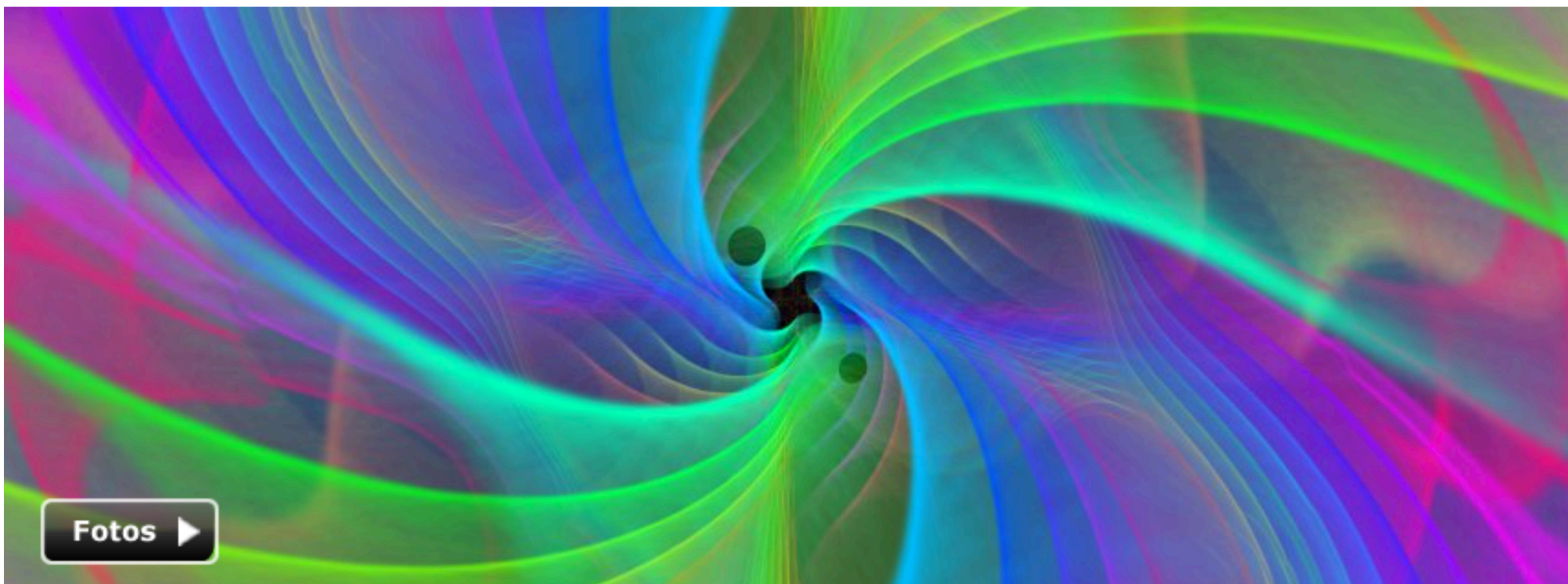
Astrophysik: Gravitationswellen zum zweiten Mal nachgewiesen

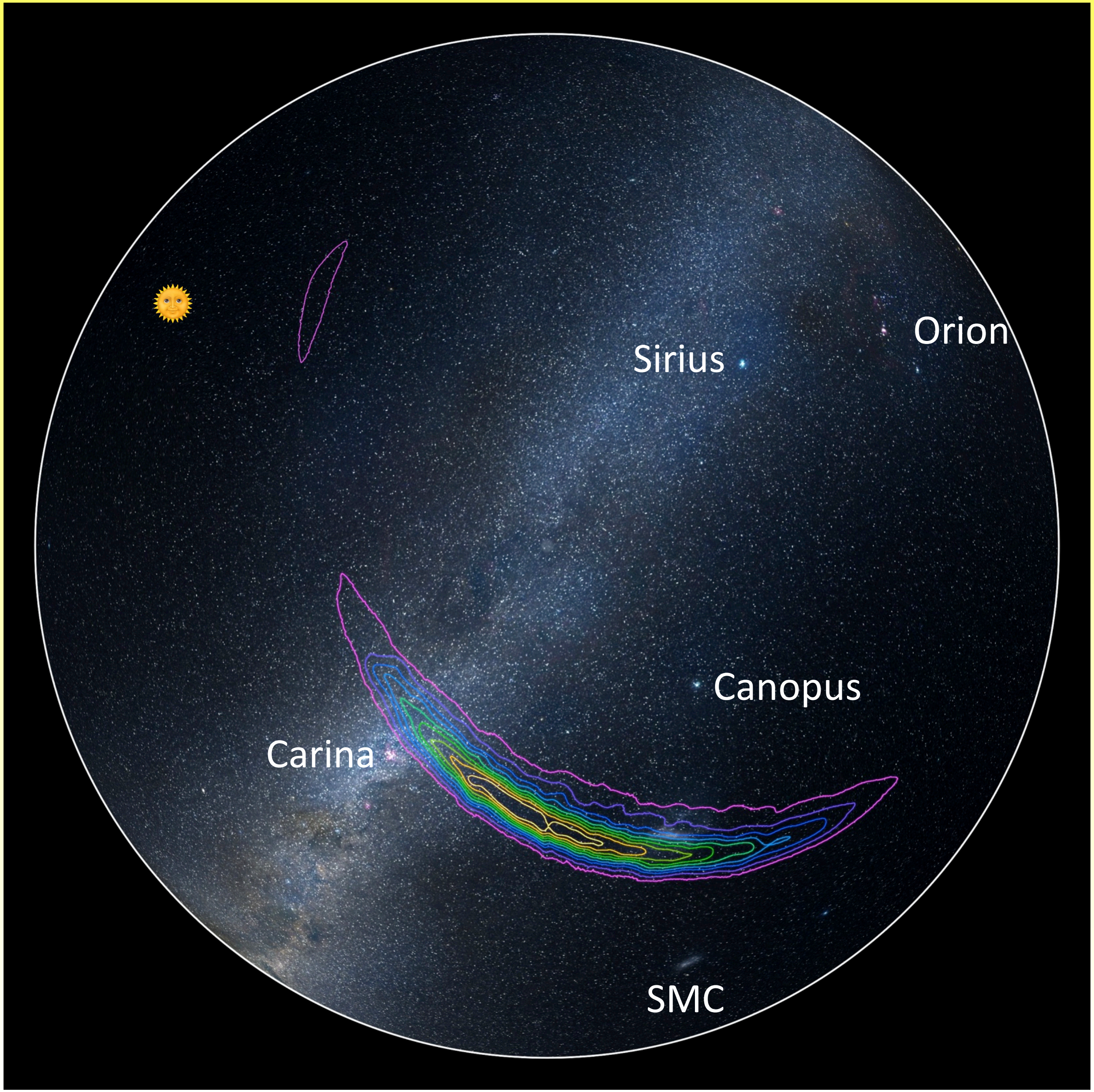
Von Johann Grolle, Boston



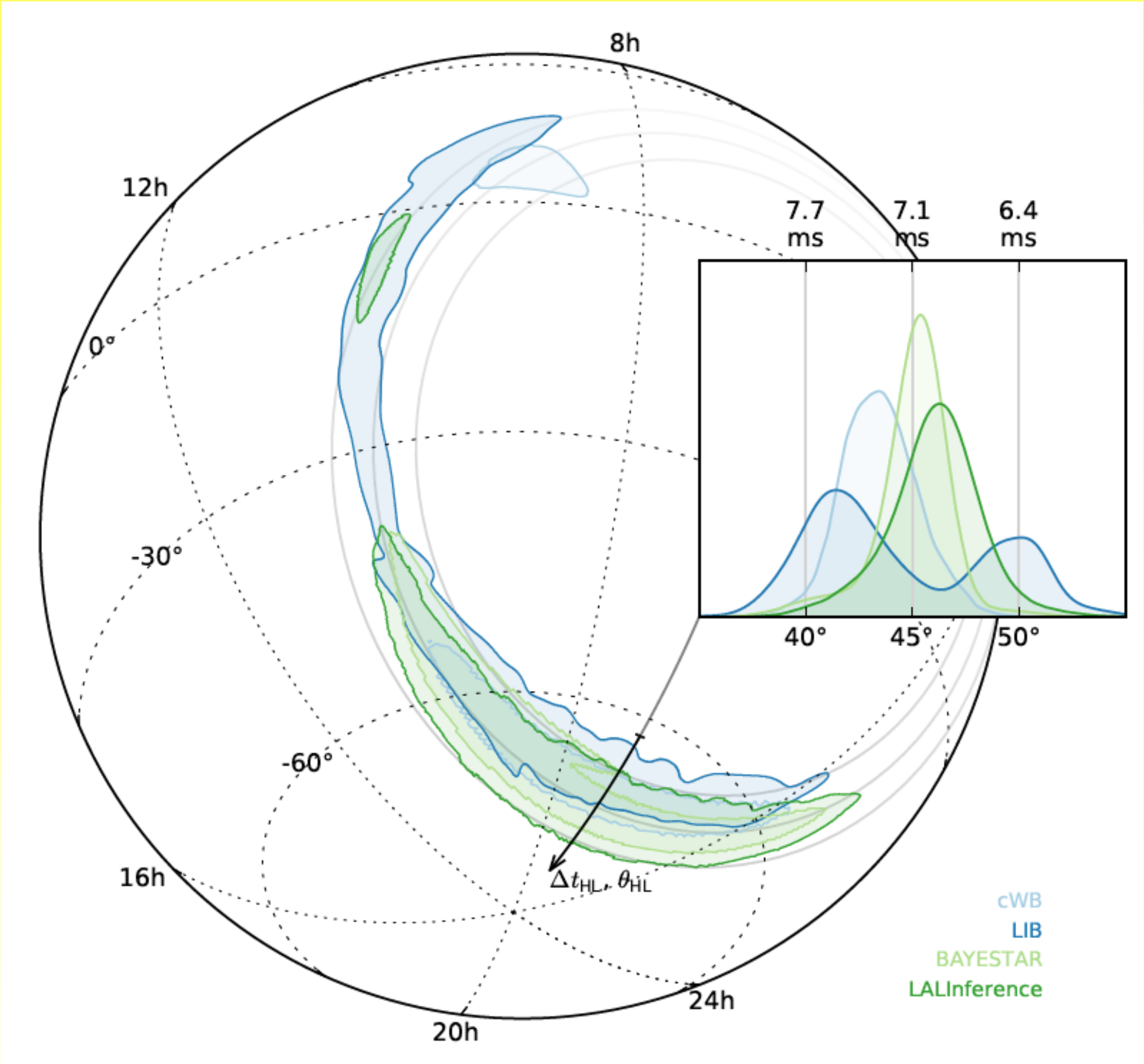
S. Ossokine/ A. Buonanno (Max-Planck-Institut)/ W. Benger (AHM)

Physiker jubeln: Drei Monate nach der sensationellen ersten Messung haben Detektoren in den USA zum

Where did the Signal come from?

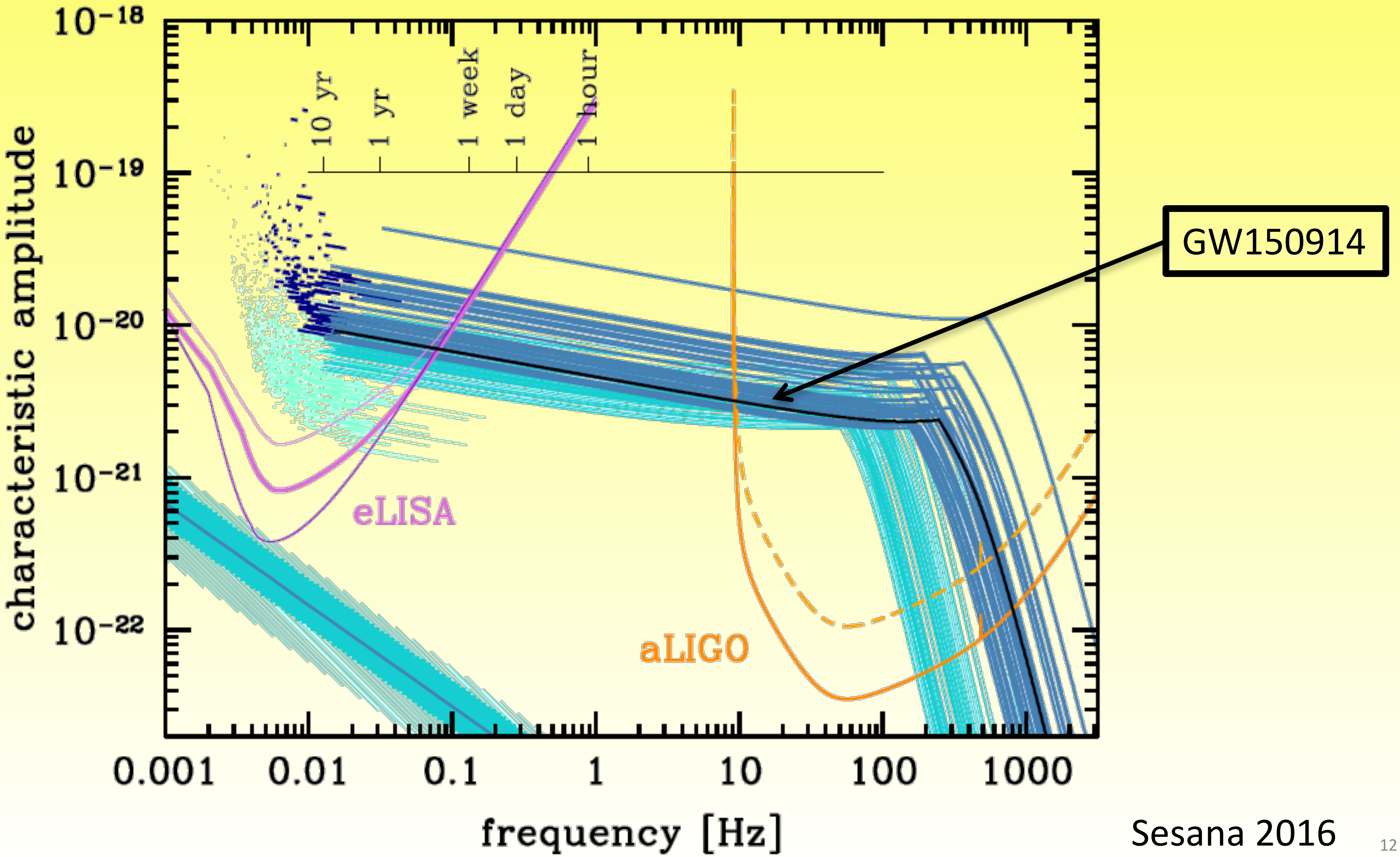


Localisation to 600 Square Degrees



LISA: LIGO Event Predicted 10 Years in Advance!

- Accurate to seconds and within 0.1 square-degree!



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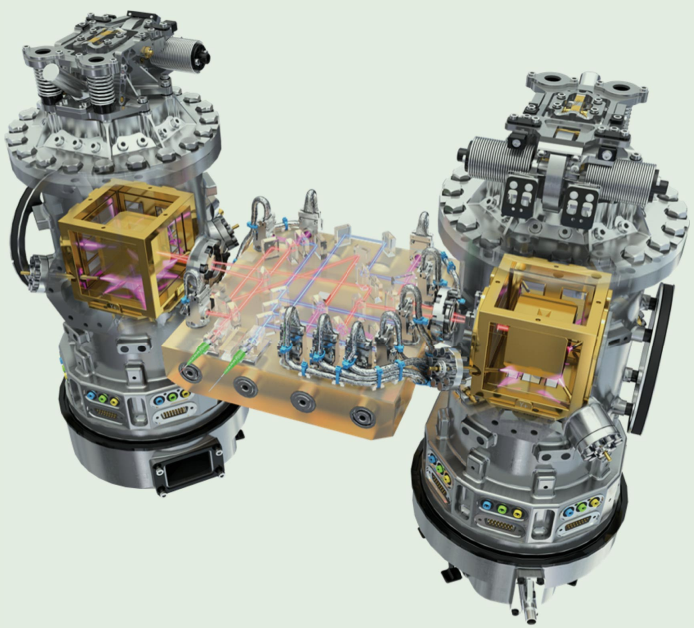

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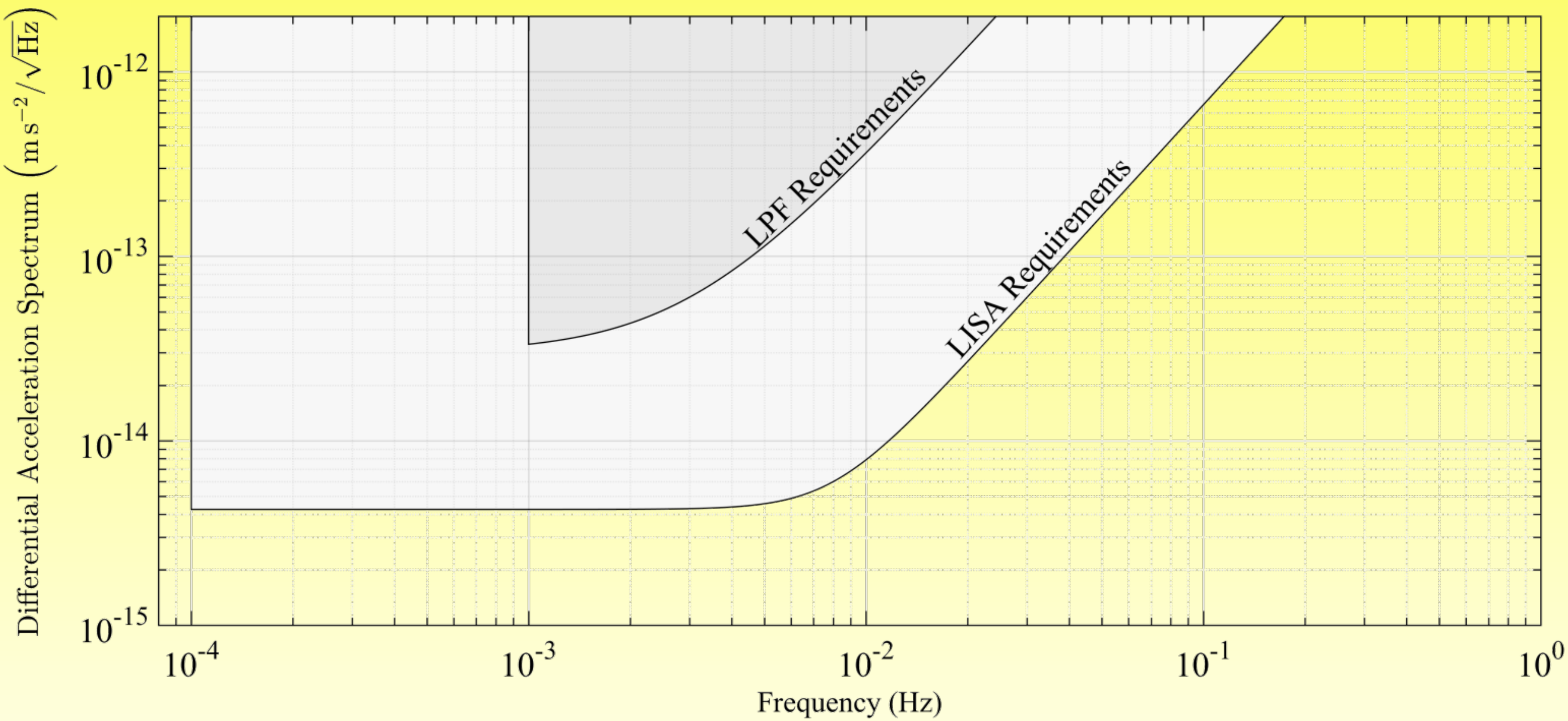
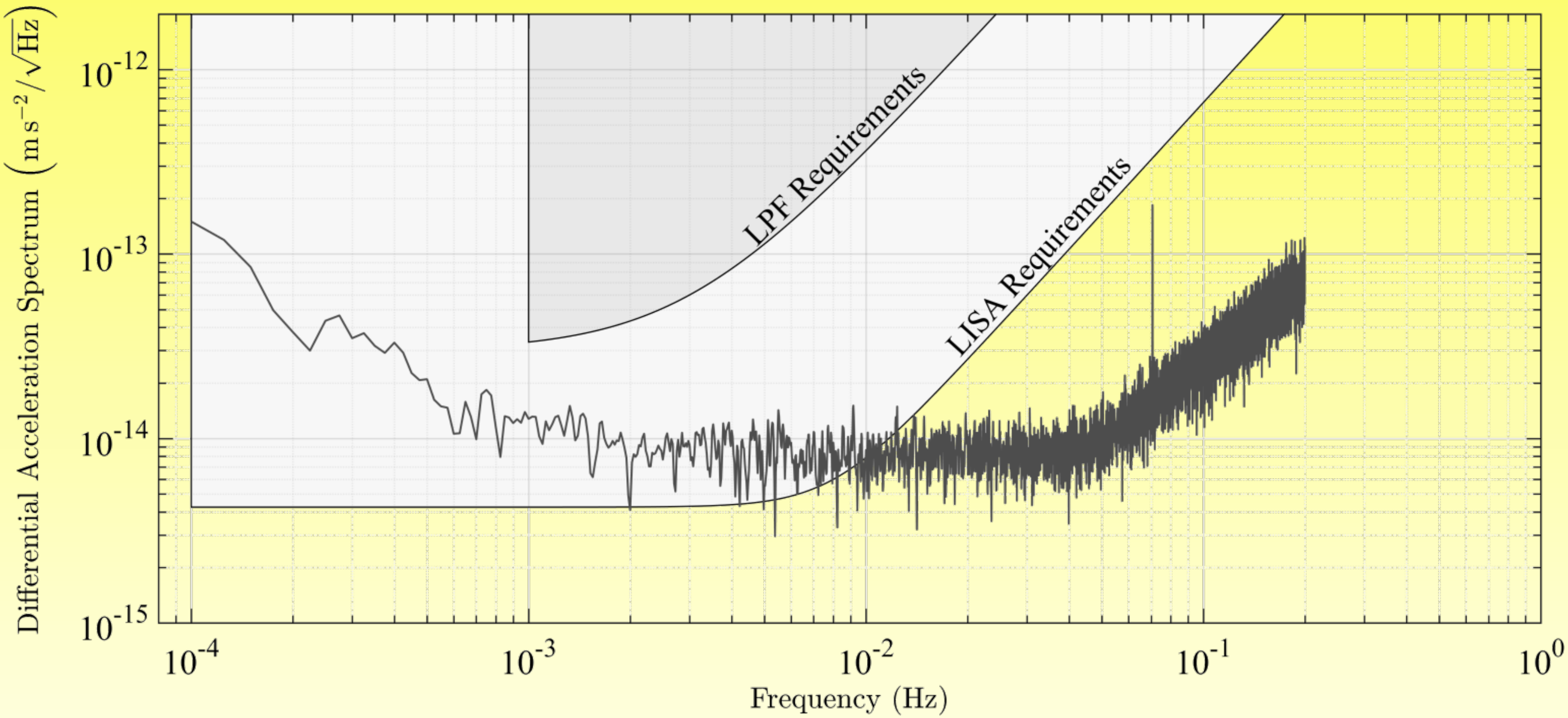
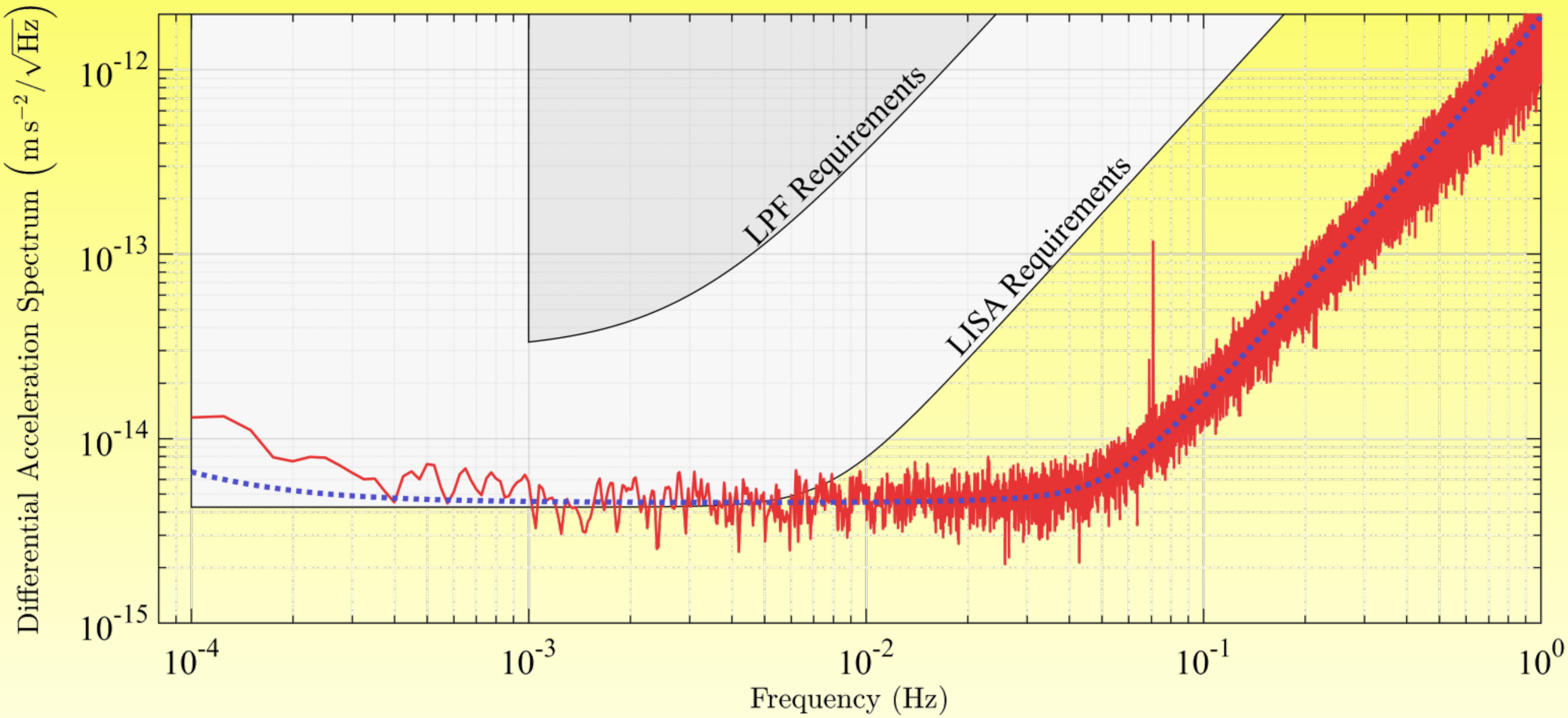
LISA and LPF Requirements



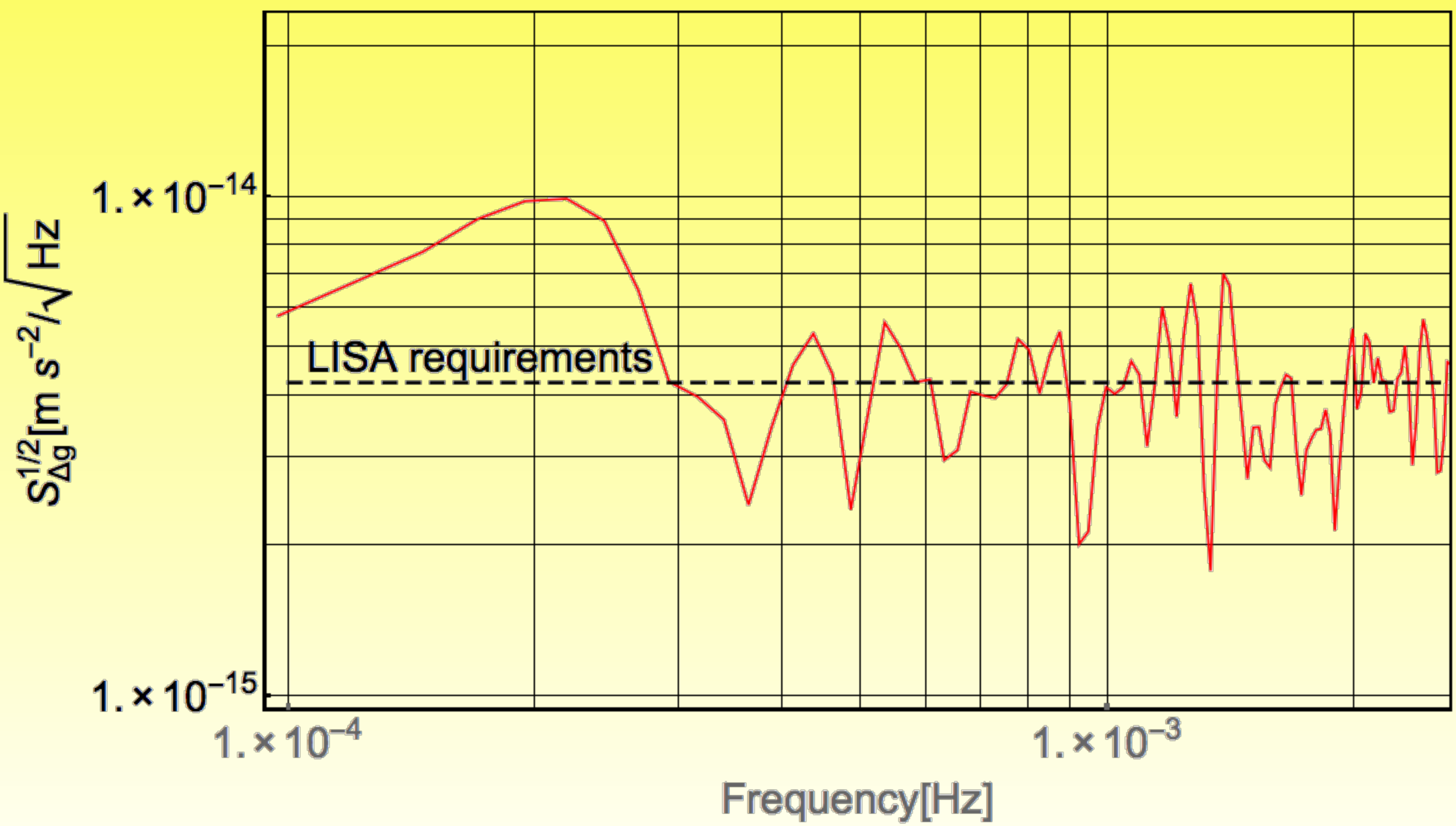
First Day of Operations: March 1, 2016



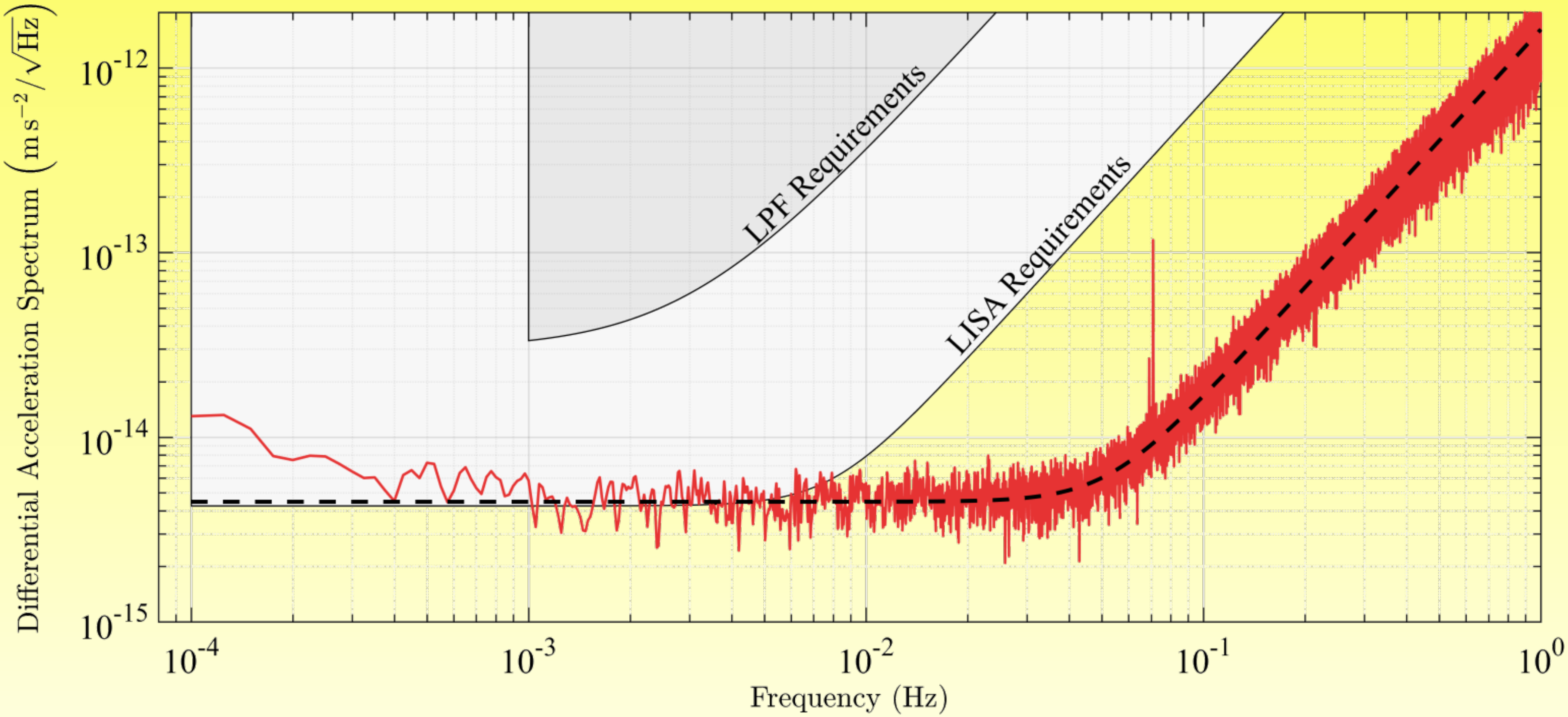
May 16, 2016, System Optimized
Investigations Ongoing



June 16, 2016: Still getting better!

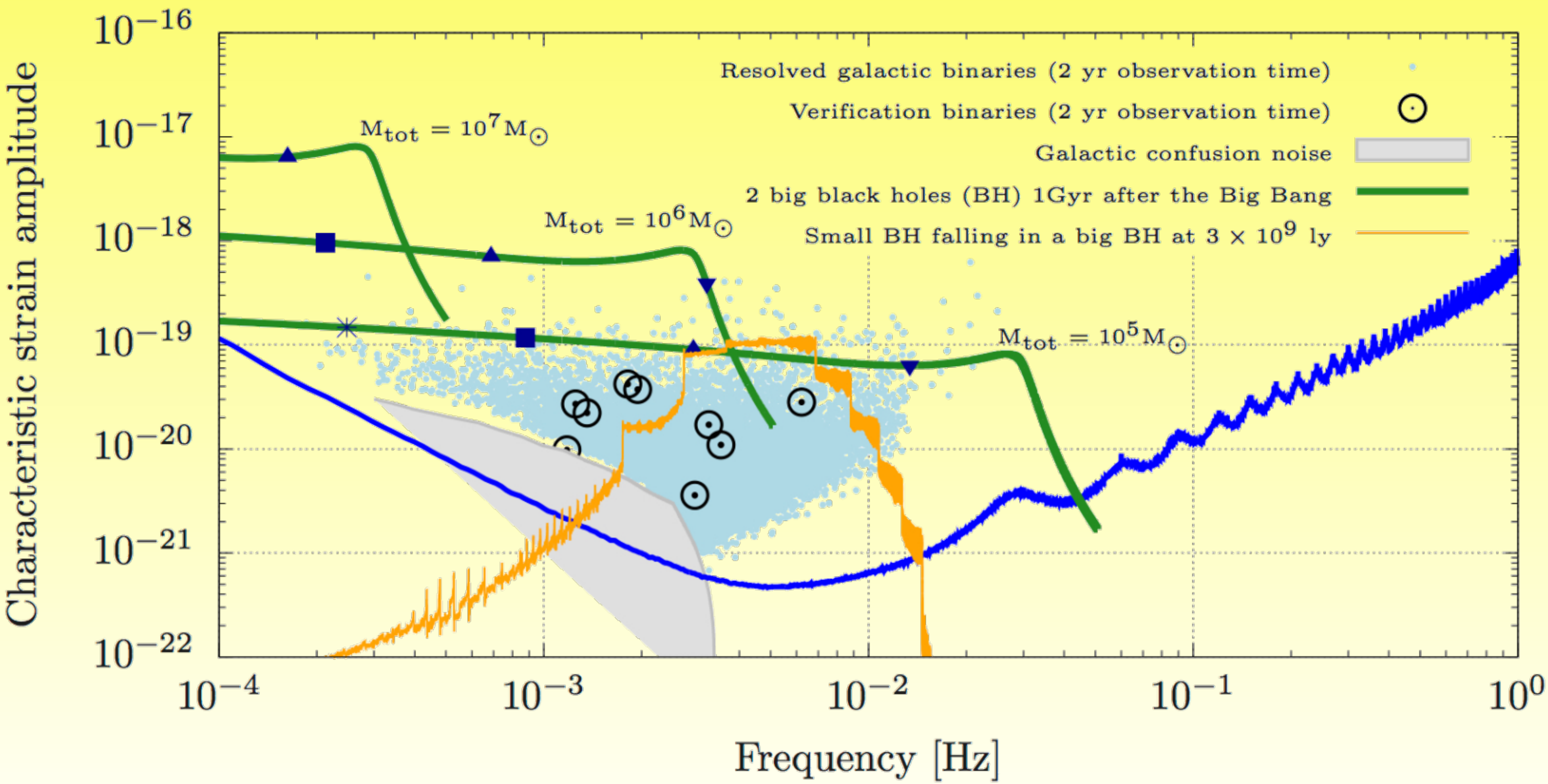


LISA Works!



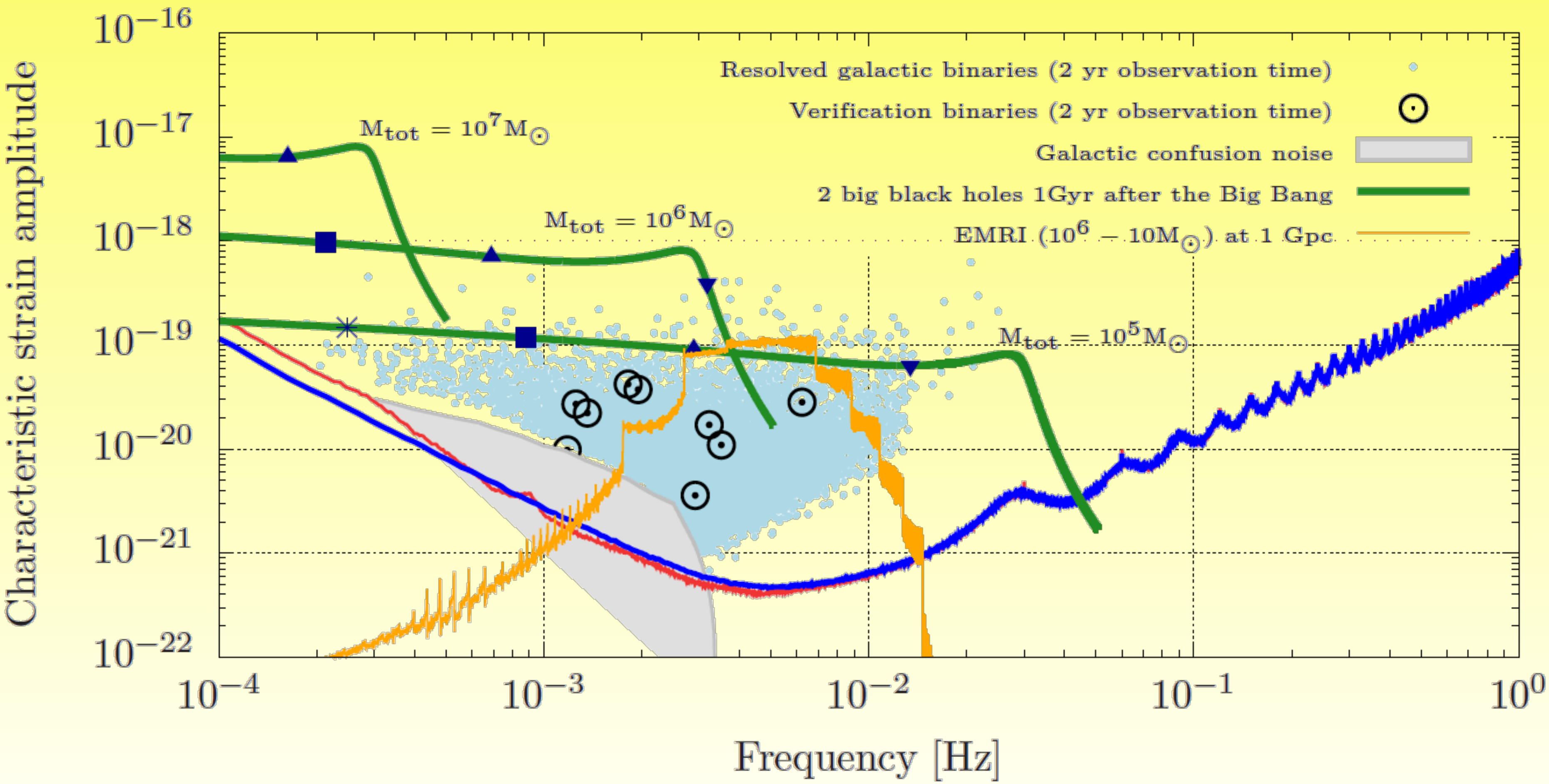
LPF Requirements
LISA Requirements
Differential Acceleration Spectrum $\left(\mathrm{m\,s^{-2}}/\sqrt{\mathrm{Hz}}\right)$
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
Frequency (Hz)

Original LISA Requirements



A. Petiteau 2016

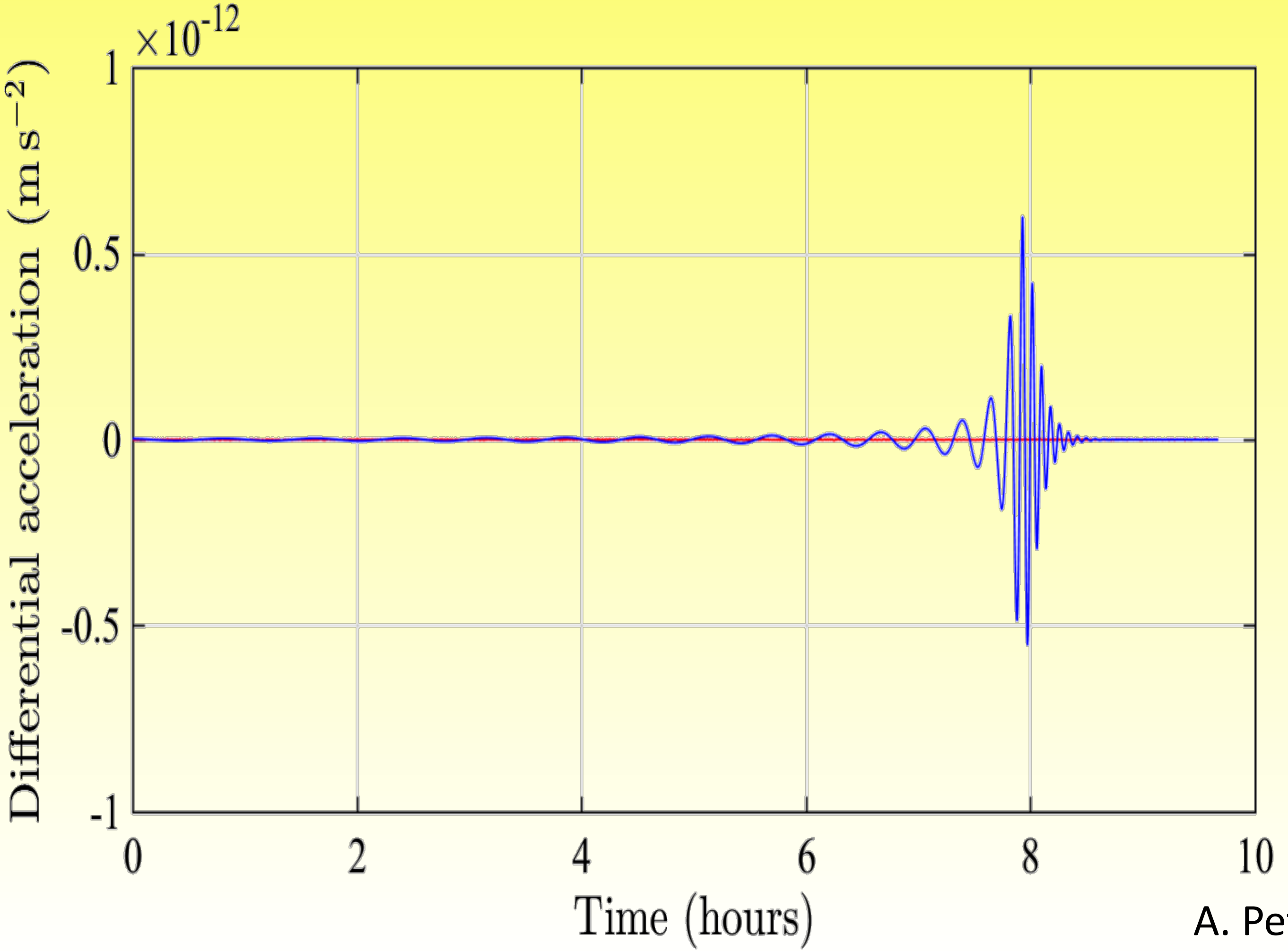
LISA Sensitivity with current Pathfinder Performance



A. Petiteau 2016

Black Hole Mergers far above Noise

- $10^5 M_\odot$ BH binary merger at z=5
- In Red: Pathfinder instrumental noise



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Black Hole Merger far above Noise

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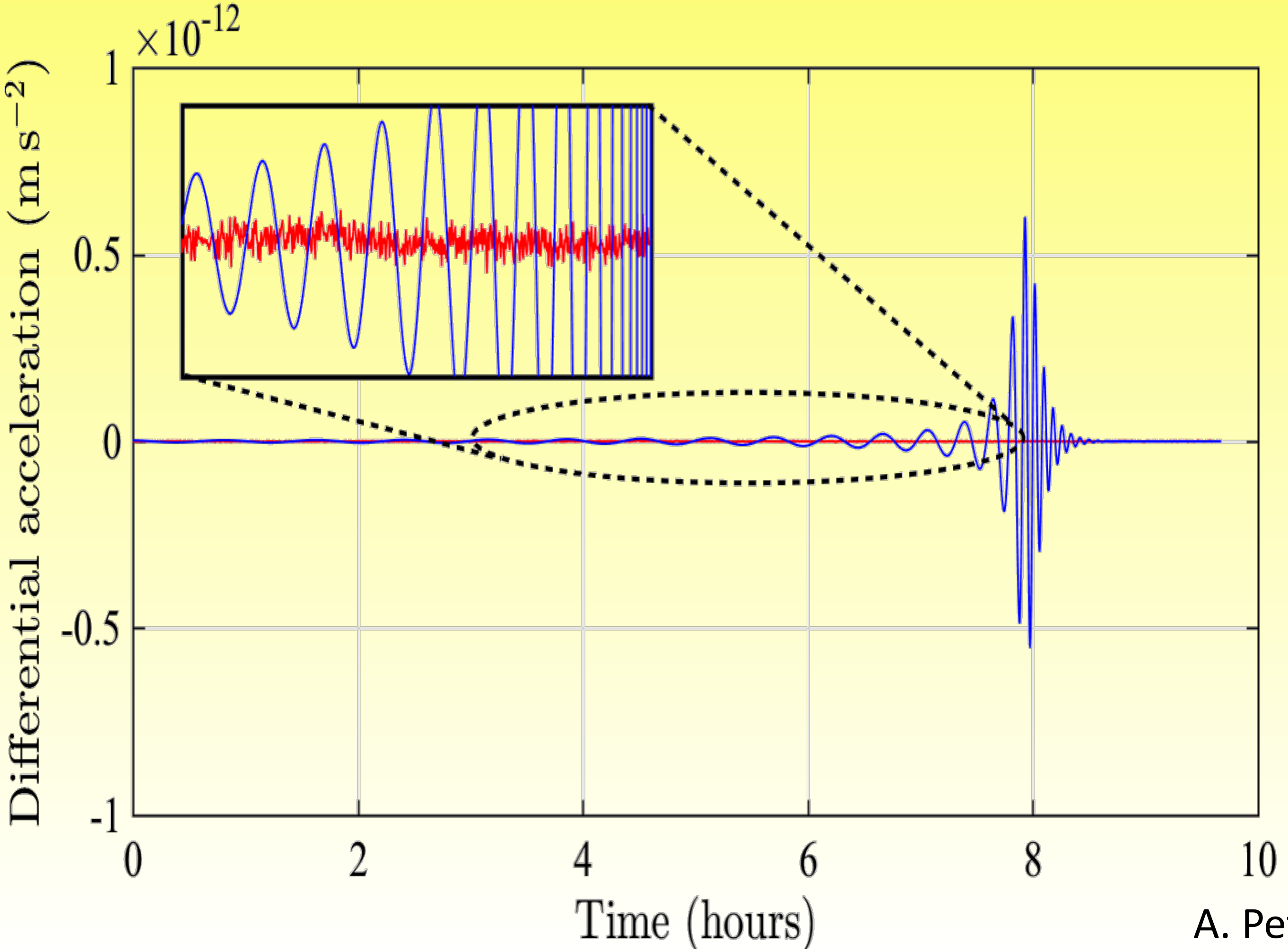

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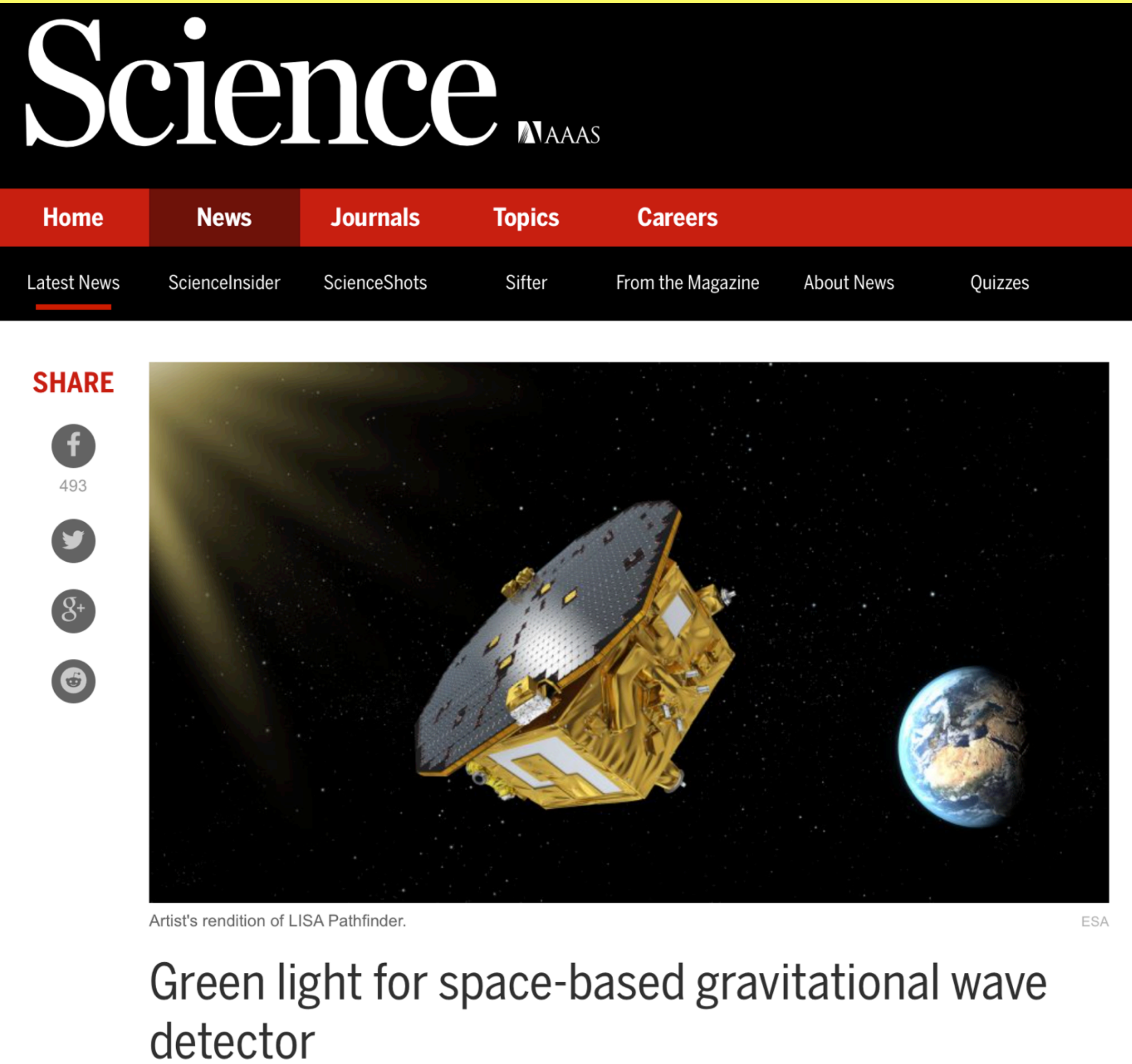

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10 JUNE 2016
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Volume 116, Number 23

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 28 March 2016!
- Technology roadmap clear by early 2016!

The ESA–L3 Gravitational Wave Mission

Gravitational Observatory Advisory Team

Final Report

28 March 2016

GOAT Final 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!

Meeting with delegations on the way ahead for the L3 mission

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

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

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**	

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

esa

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

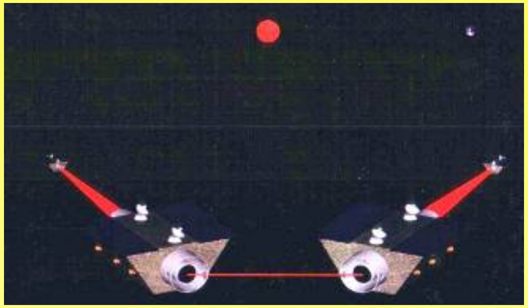
Therefore, need to communicate and coordinate with Funding Agencies on payload activities

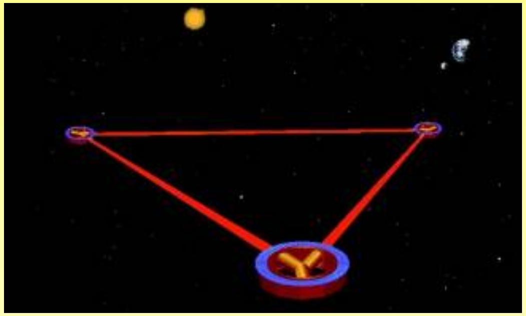
- Although payload consortium should be in place at the beginning of Phase A, early declaration of interest of Delegations for the provision of payload and science ground segment elements will help.
- Currently, ESA/CTP activities are limited to “high likelihood” ESA-provided elements

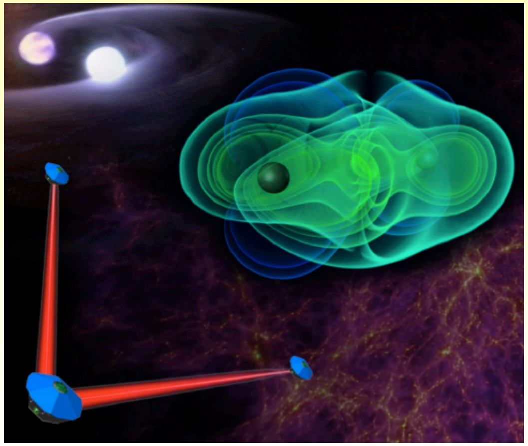
Assuming smooth progress, TRL > 5-6 for critical element/subsystem level could be reached by ~ 2019-2020

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







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

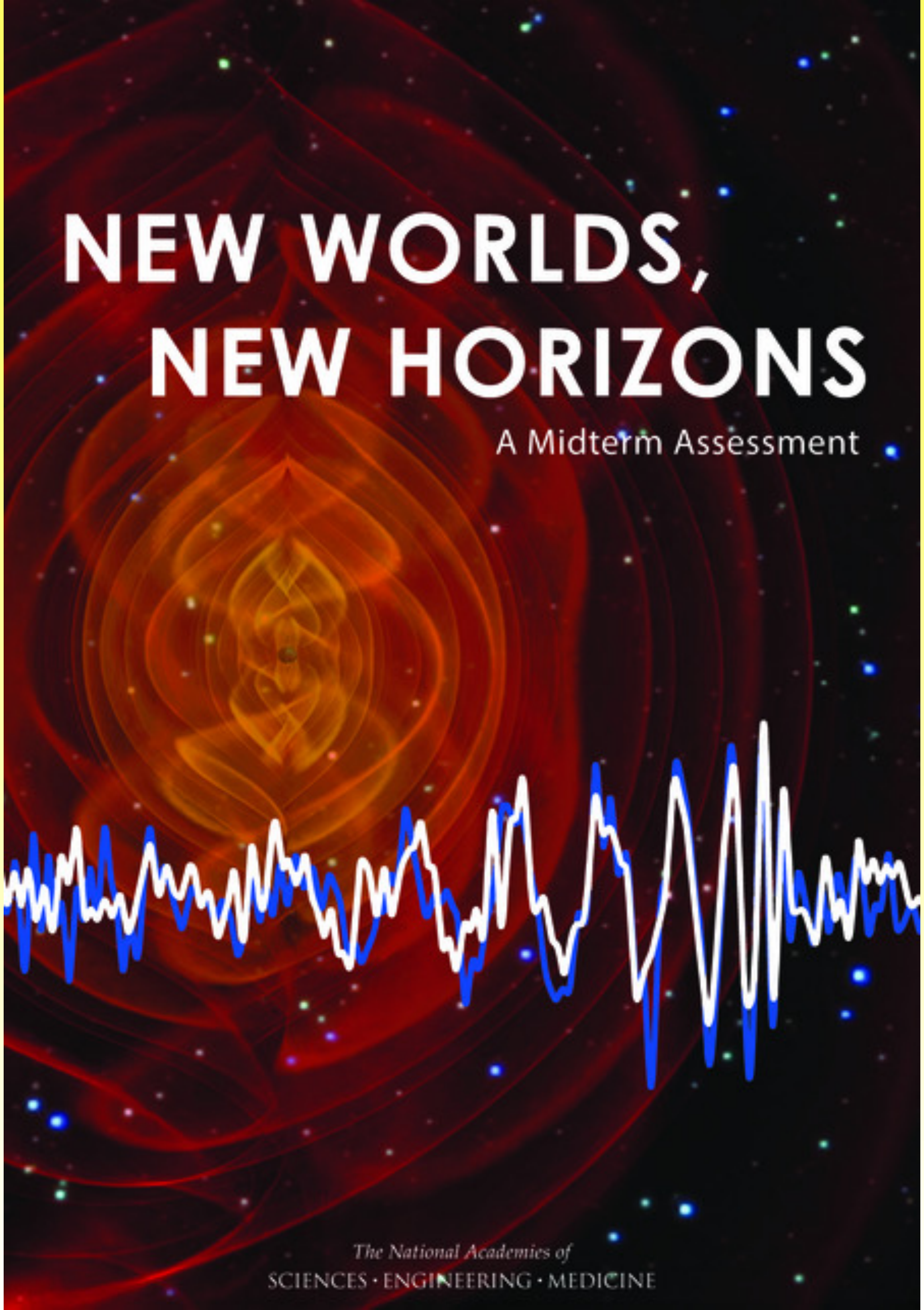
- Cost-cap for ESA cost at 850 M€ plus member state contributions around 200 M€

  - ➢ 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!


NEW WORLDS,
NEW HORIZONS
A Midterm Assessment
The National Academies of
SCIENCES · ENGINEERING · MEDICINE

Mid-Decadal Report

New Worlds, New Horizons: A Midterm Assessment

Committee on the Review of Progress Toward the Decadal Survey Vision in New Worlds, New Horizons in Astronomy and Astrophysics

Space Studies Board

Board of Physics and Astronomy

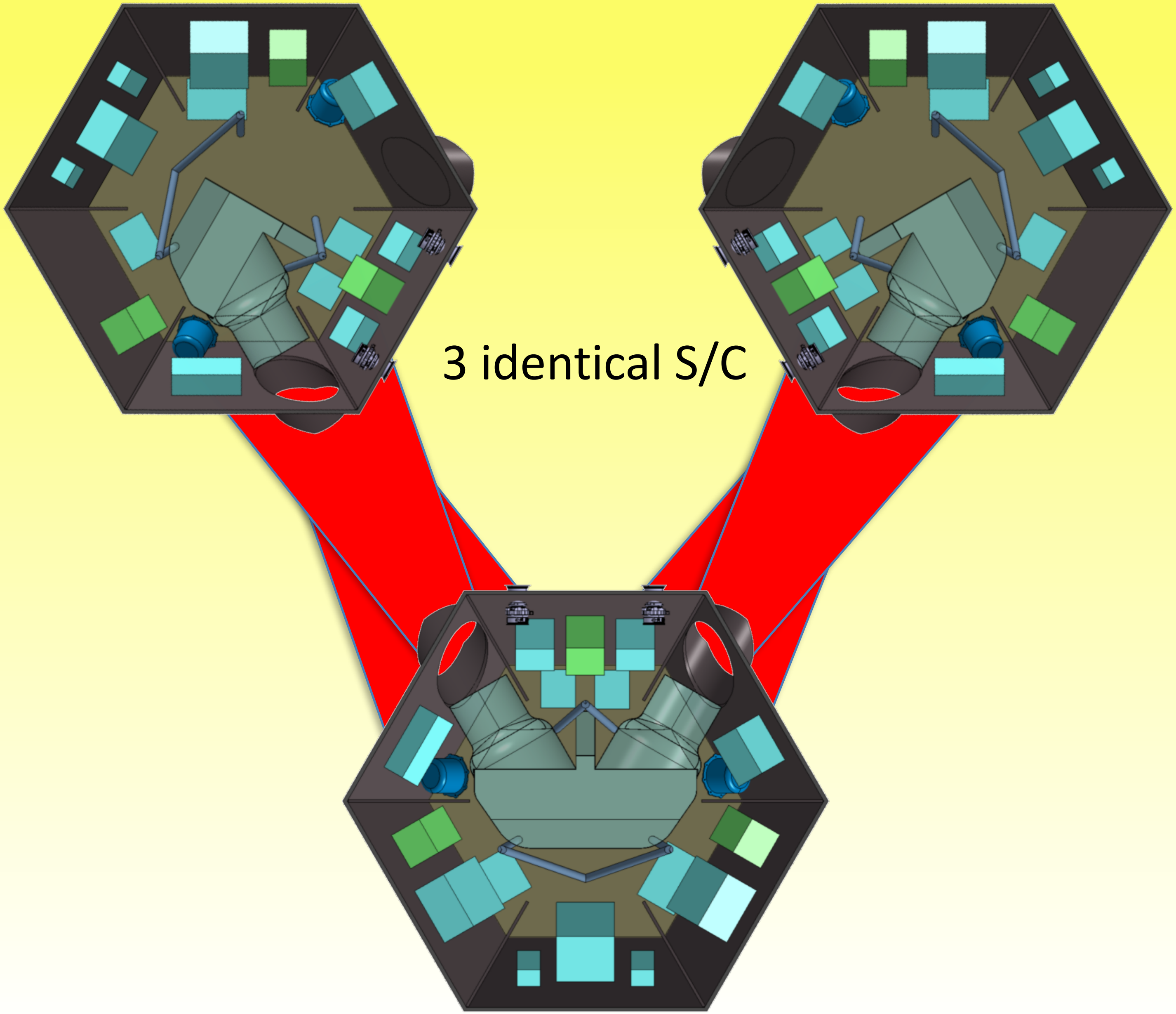
Division on Engineering and Physical Sciences

http://www.nap.edu/catalog/23560/new-worlds-new-horizons-a-midterm-assessment

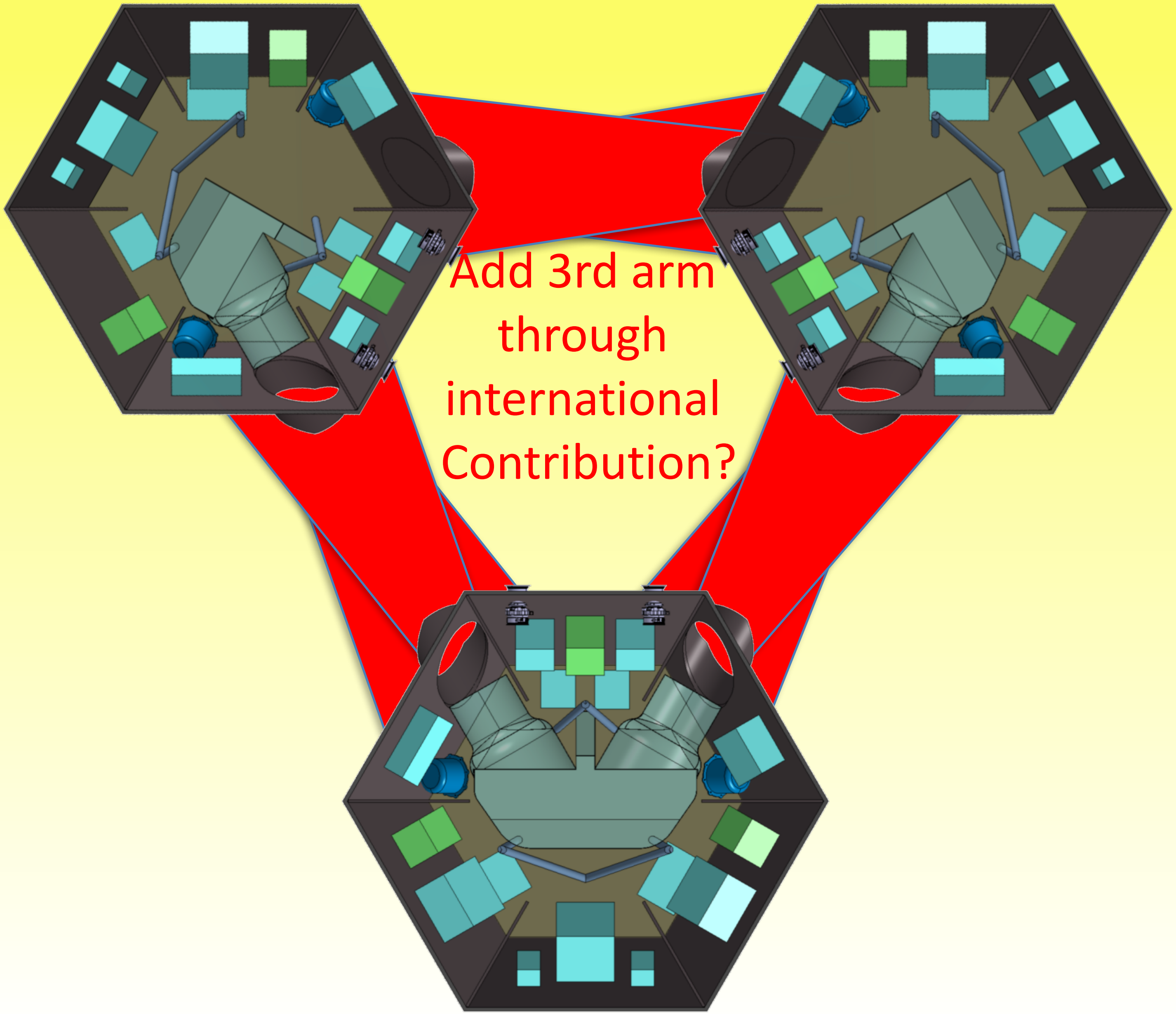
Major Recommendations about LISA:

- RECOMMENDATION 4-4:
  - NASA should restore support this decade for gravitational wave research that enables the U.S. community to be a strong technical and scientific partner in the European Space Agency (ESA)-led L3 mission, consistent with the Laser Interferometer Space Antenna's high priority in the 2010 report New Worlds, New Horizons in Astronomy and Astrophysics (NWNH).
- One goal of U.S. participation should be the restoration of the full scientific capability of the mission as envisioned by NWNH.

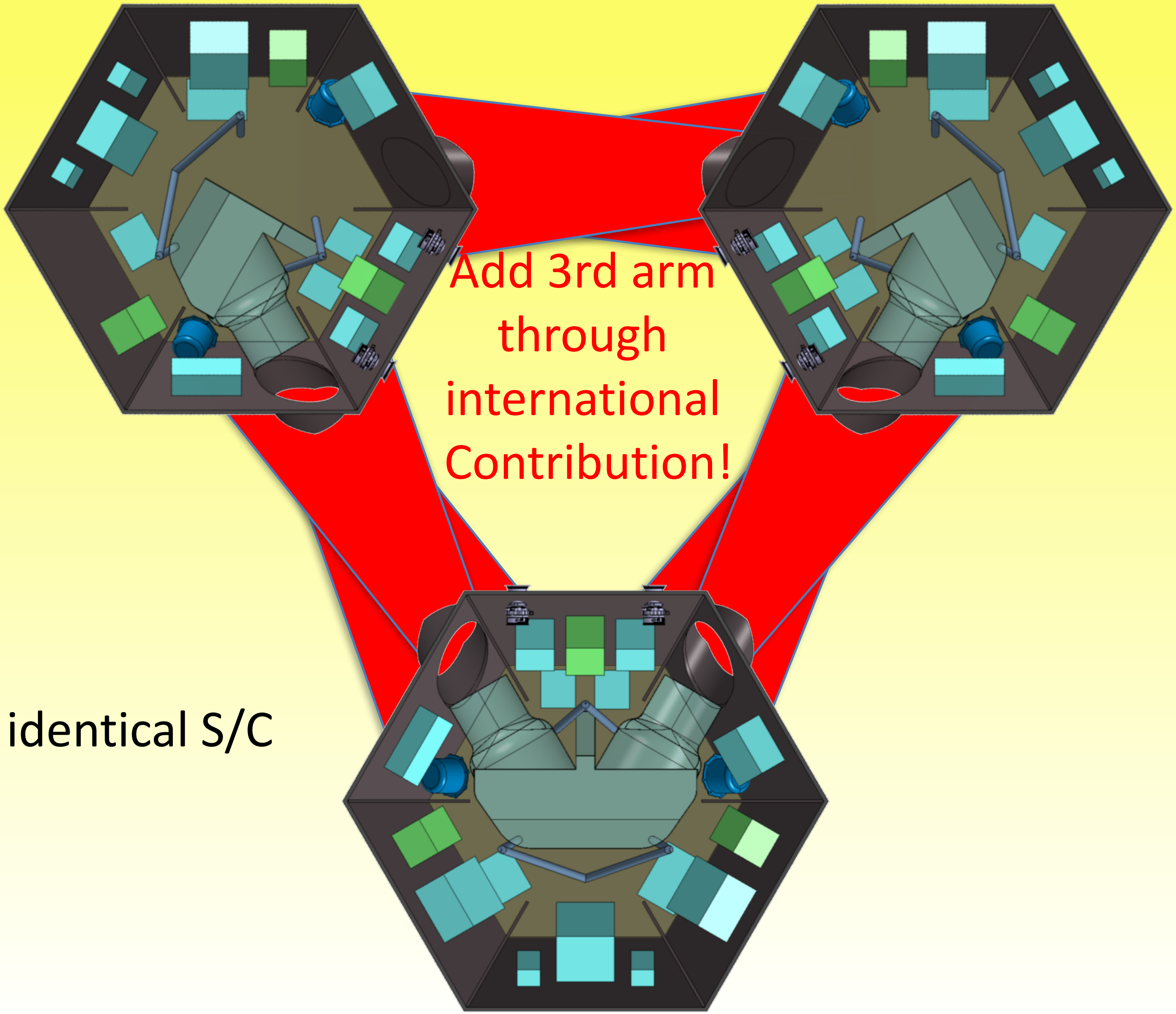
eLISA Lay-Out



eLISA Lay-Out

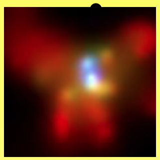


We got the third arm back!

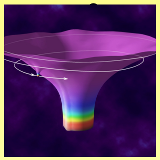


3 identical S/C

eLISA for Astrophysics, Cosmology, and Fundamental Physics

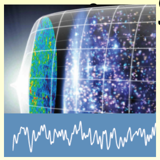


- Massive Black Holes (10^4 to 10^8 $M_\odot$)
  - When did the first Black Holes appear in pre-galactic halos and what is their mass and spin?
  - How did Black Holes form, assemble and evolve from cosmic dawn to present time, due to accretion and mergers?
  - What role did Black Holes play in re-ionisation, 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 x 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?

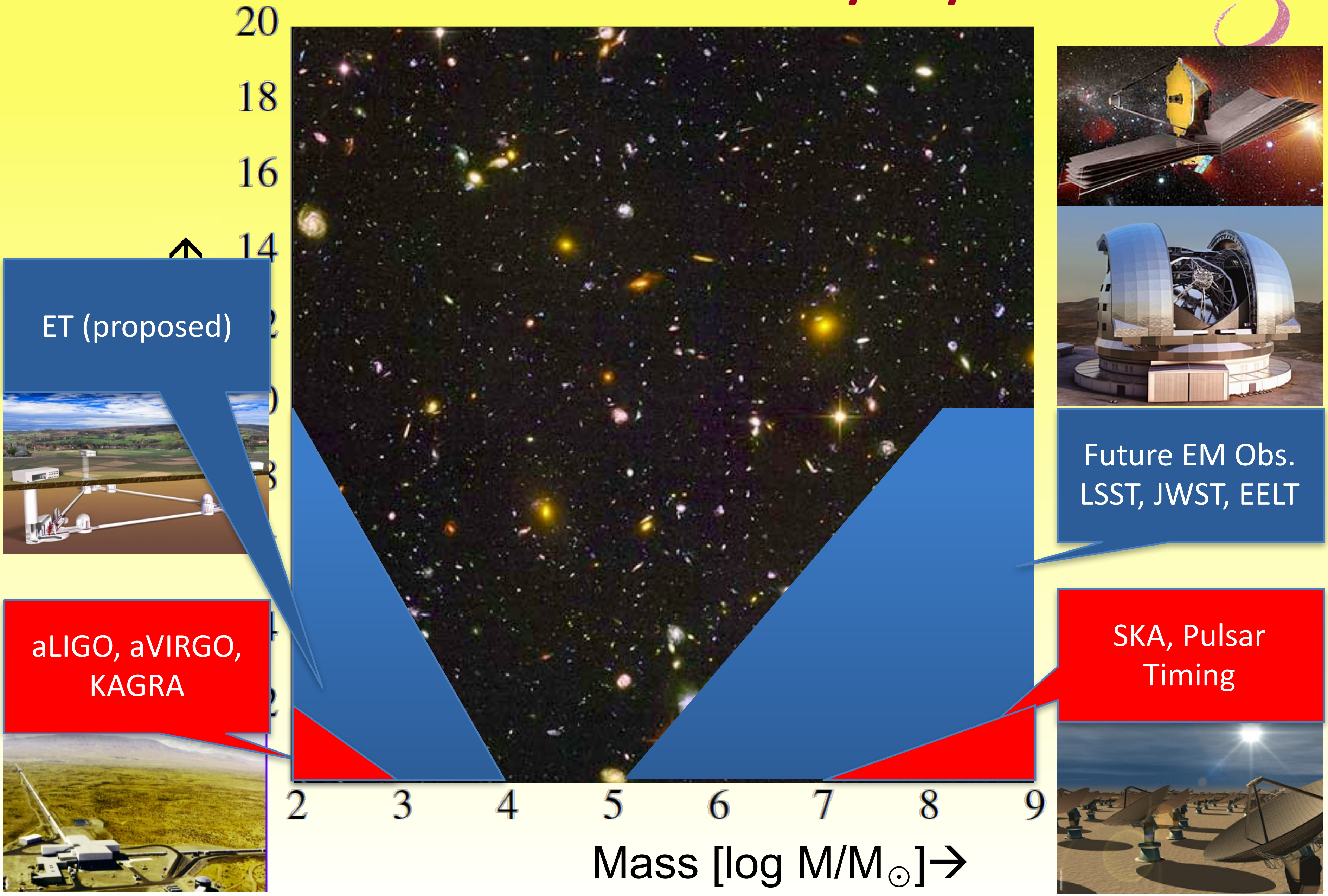
- Ultra-Compact Binaries in Milky Way
  - What is the explosion mechanism of type Ia supernovae?
  - What is the formation and merger rate of compact binaries?
  - What is the endpoint of stellar evolution?



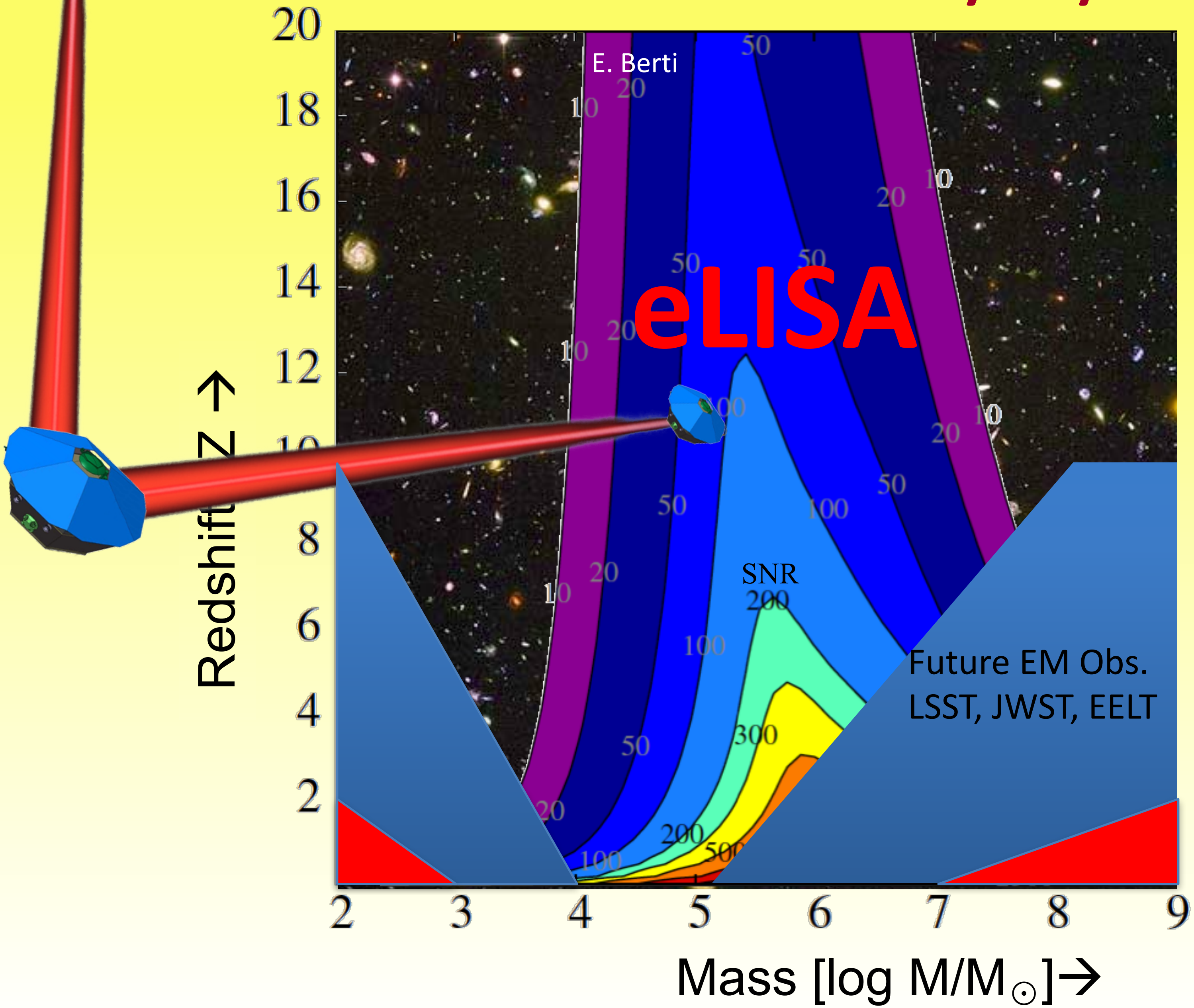
- Stochastic Signals
  - Directly probe Planck scale epoch at 1 TeV to 1000 TeV before decoupling of microwave background
  - Were there phase transitions and of which order?
  - Probe Higgs field self coupling and potential, and search for supersymmetry.
  - Are there warped sub-millimetre extra-dimensions?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

??? The Unknown !

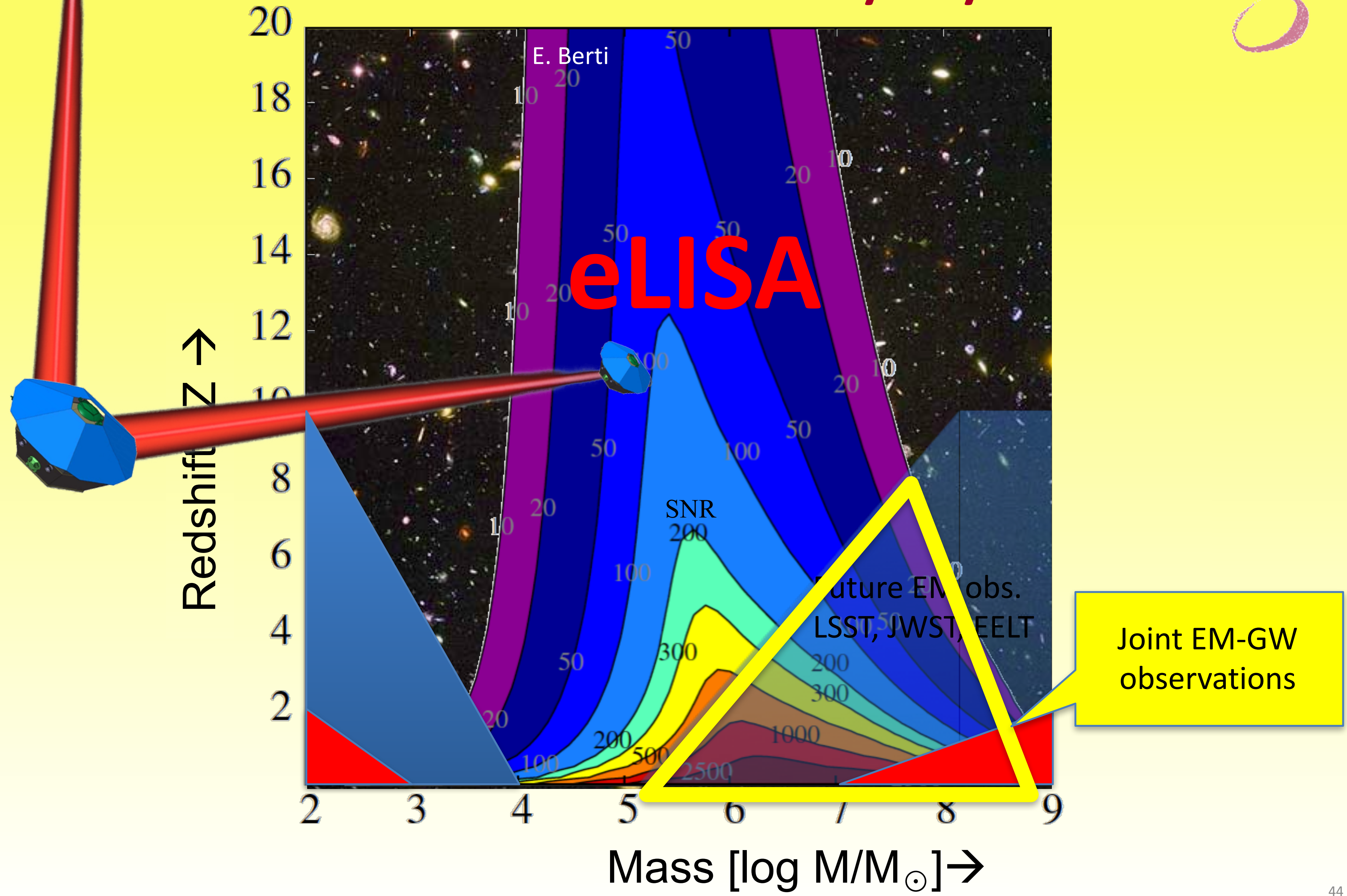
Black Hole Astronomy by 2030



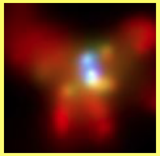
Black Hole Astronomy by 2030



Black Hole Astronomy by 2030



eLISA for Astrophysics, Cosmology, and Fundamental Physics



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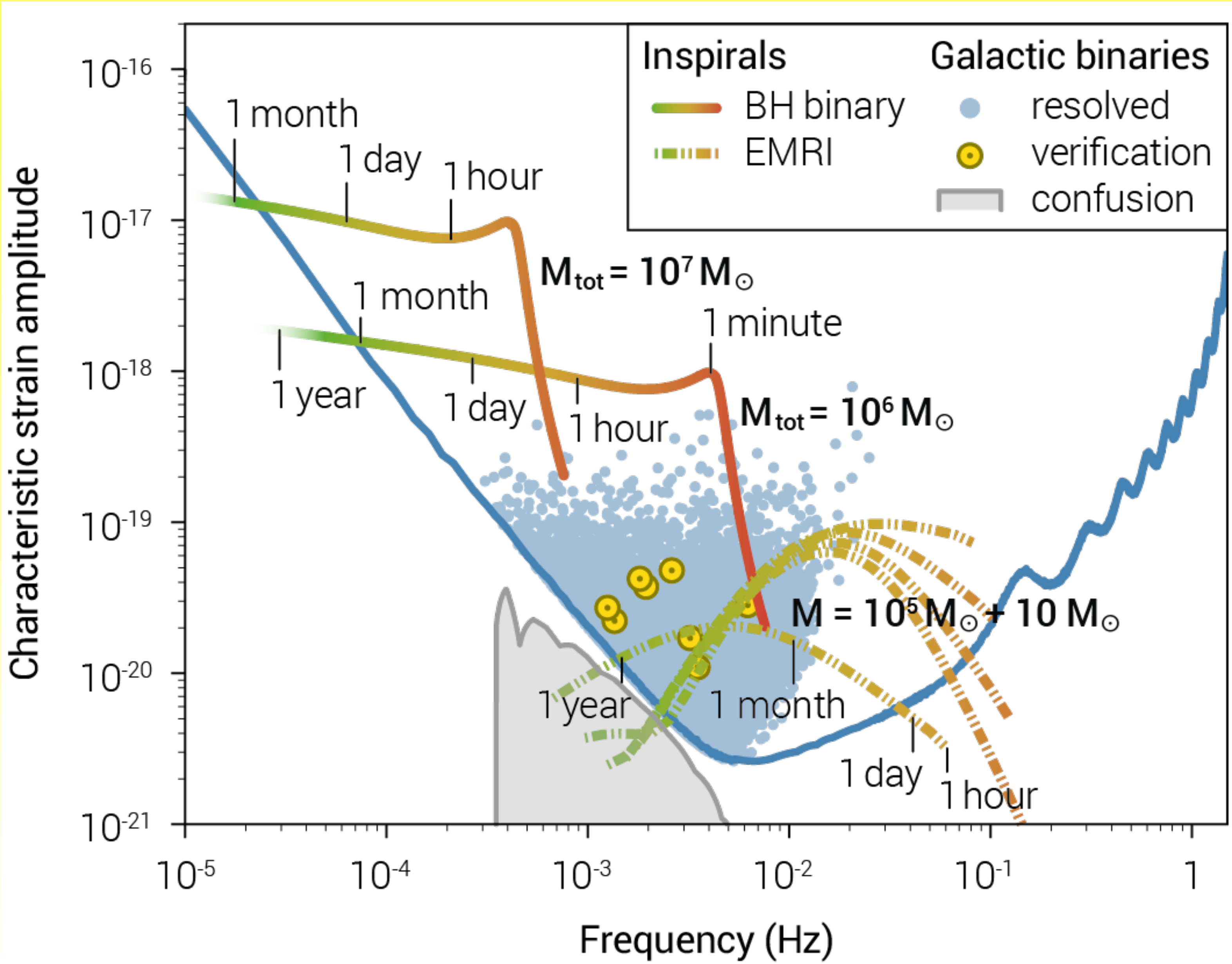
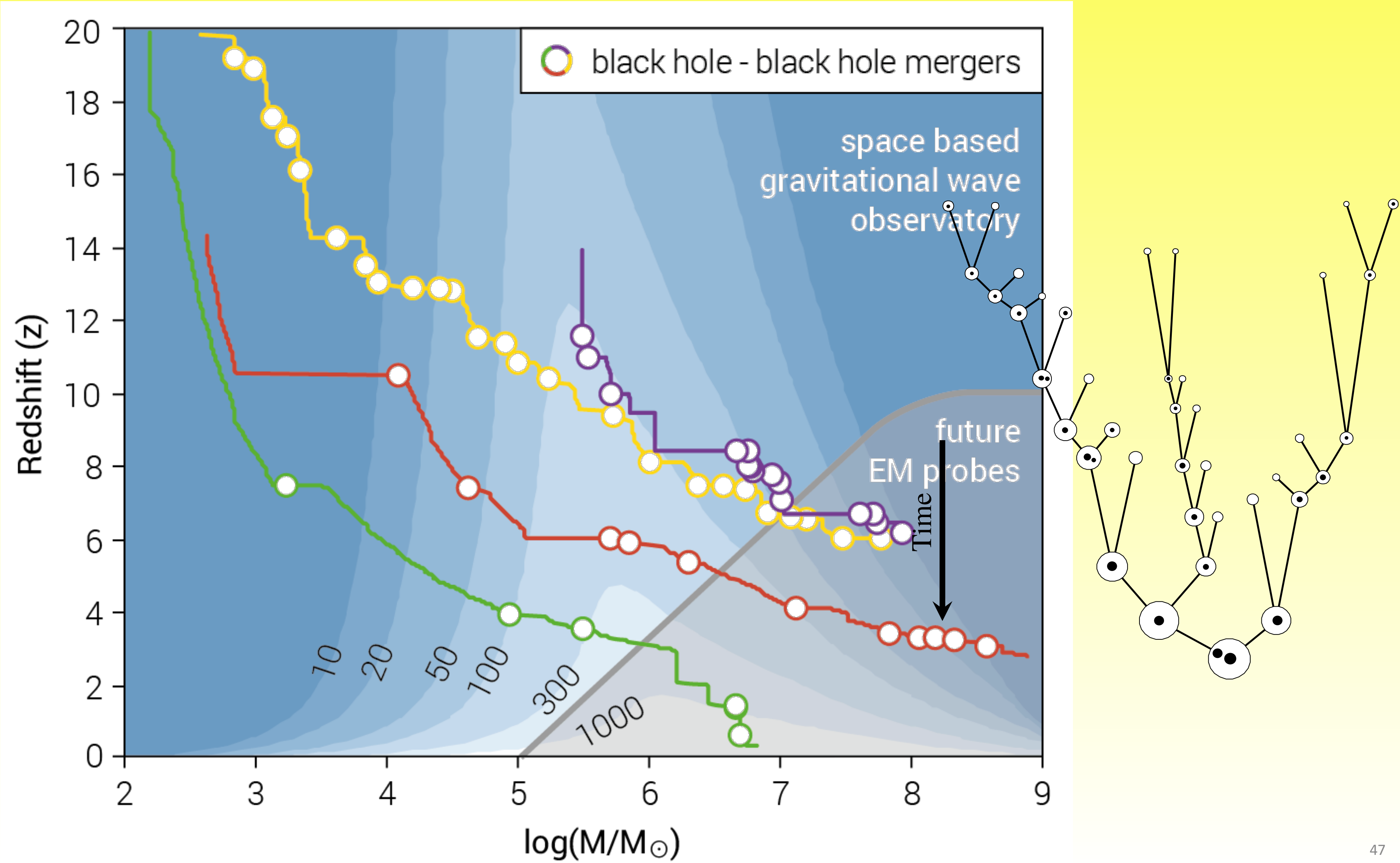
- The Unknown !

Sensitivity and Black Hole Science

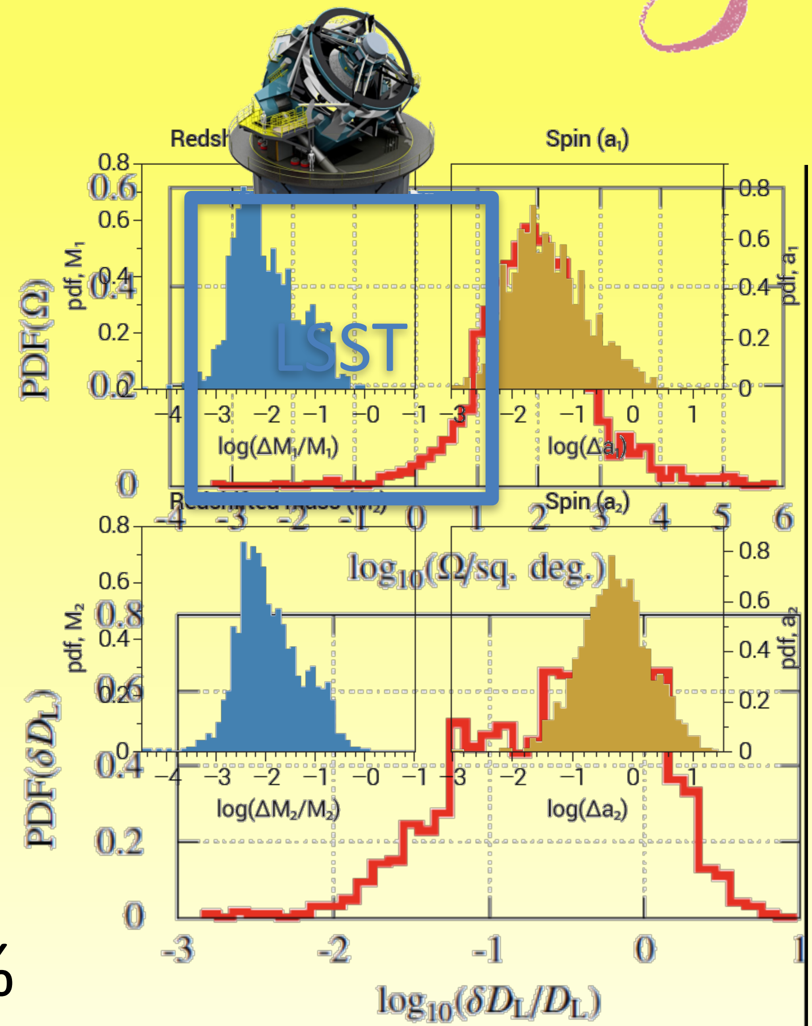


All Binary Black Holes cross eLISA band: Trace Galaxy Mergers



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 °



Science Gain from 3 Arms

- More Sources

- x 3 Extreme Mass Ratio Inspirals
- x 2 Galactic Binaries
- x 10 Low Mass Seed Black Holes

- Better Measurements

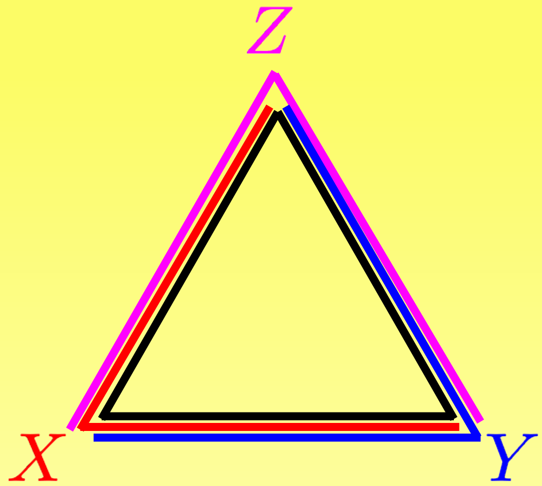
- x 400 Strength of GR tests with Extreme Mass Ratio Inspirals
- x 1.5 Well Localized Galactic Binaries
- x 7 Well Localized Massive Black Hole Mergers
- x 5 Black Hole Systems with Precise Spin Determination

- Wider Discovery Space

- Enable unambiguous detection of stochastic background
- Confident detection and characterization of exotic signals

Source: http://www.cosmos.esa.int/web/goat and N. Cornish

Measurement Benefits of 3 Arms

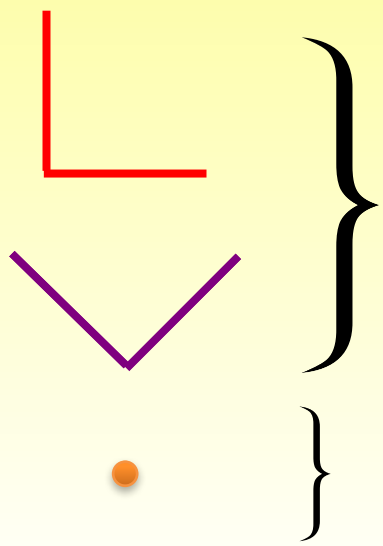


Three interferometers!

$$S_+ = \frac{\sqrt{3}}{2} X \Rightarrow$$

$$S_\times = \frac{1}{2}(X + 2Y) \Rightarrow$$

$$S_\odot = \frac{1}{3}(X + Y + Z) \Rightarrow$$



Instantaneous measurement of both polarization states and increased signal-to-noise

Null channel to monitor average low frequency instrument noise

Source: N. Cornish

Impact on “Known” Sources: Detection Accuracy

Galactic Binaries

with sky location better than 1 square degree x 1.9

with sky location better than 1 square degree
and distance to better than 10% x 1.5

Extreme Mass Ratio Inspirals

Accuracy of all parameters estimates improved by x 1.4

Comparable Mass Black Hole Mergers

with sky location better than 10 square degrees x 5

with distance better than 10% x 3

with sky location better than 10 square degrees
and distance to better than 10% x 7

with both spins better than 10% x 2 to 13

Source: N. Cornish

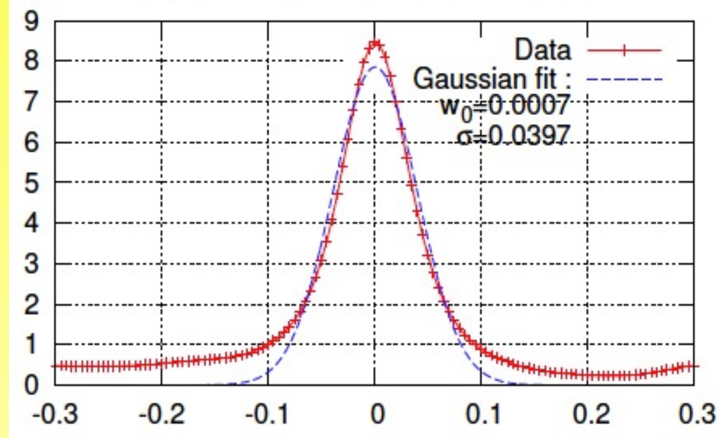
Cosmology with standard sirens

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

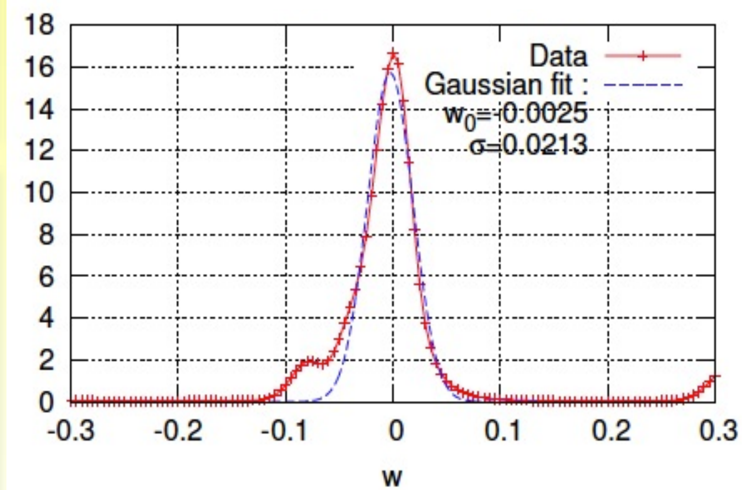
- **Using EMRIs, *without* identifications, LISA can determine H_0 to ±0.4% = ±0.3 km s^{-1} Mpc^{-1} after just 20 EMRI detections: ~3 months LISA data. (MacLeod & Hogan, PRD, 2008; SDSS)**
  Today (WMAP) ±1.2 km s^{-1} Mpc^{-1}.

- **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

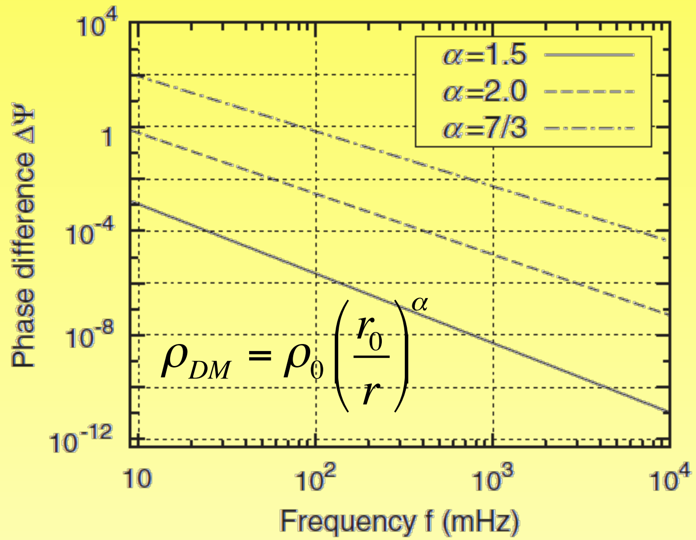


With identifications



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

Technical and Cost Impact of 2→ 3

- Ariane 5 can launch six science units in three identical S/C
- eLISA initially based on Soyuz rockets, required two launches
- Increased recurring engineering costs
  - Adds ≤ 30% for payload
- Decreased non-recurring engineering costs
  - Now all S/C are identical, reduces cost
  - Amount: Difficult to estimate.
    Best guess: Savings similar to cost increase for payload
- Larger propulsion modules for 2nd and 3rd S/C add cost
  - Reduced again by non-recurring engineering costs
- Net effect on cost difficult to estimate.
  - NASA estimates range from 2% to 20%

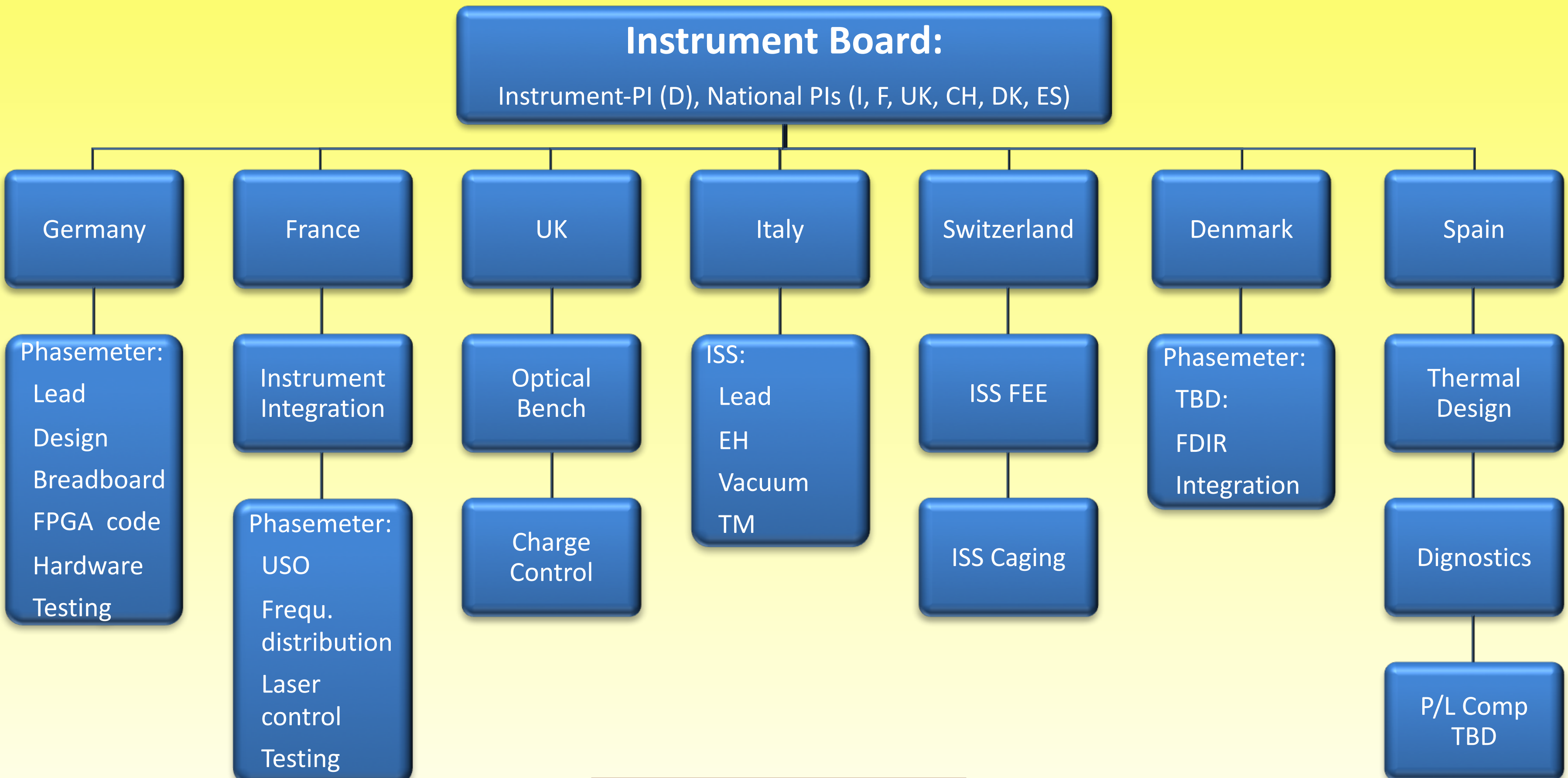
The Gravitational Universe

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)*.

Instrument Consortium



New Members

Potential new Hardware Providers

- Interest from:
  - Belgium
    - Data analysis, mechanics, optics, integration, GSE
  - Netherlands
    - Data analysis, suspensions, electronics
  - Portugal
    - Data analysis, electrooptics
  - Sweden
    - Data processing, laser interferometry
  - Netherlands
    - Mechanisms, electronics
- Very promising:
  - NASA
    - System Engineering, testing, telescopes, lasers, electronics

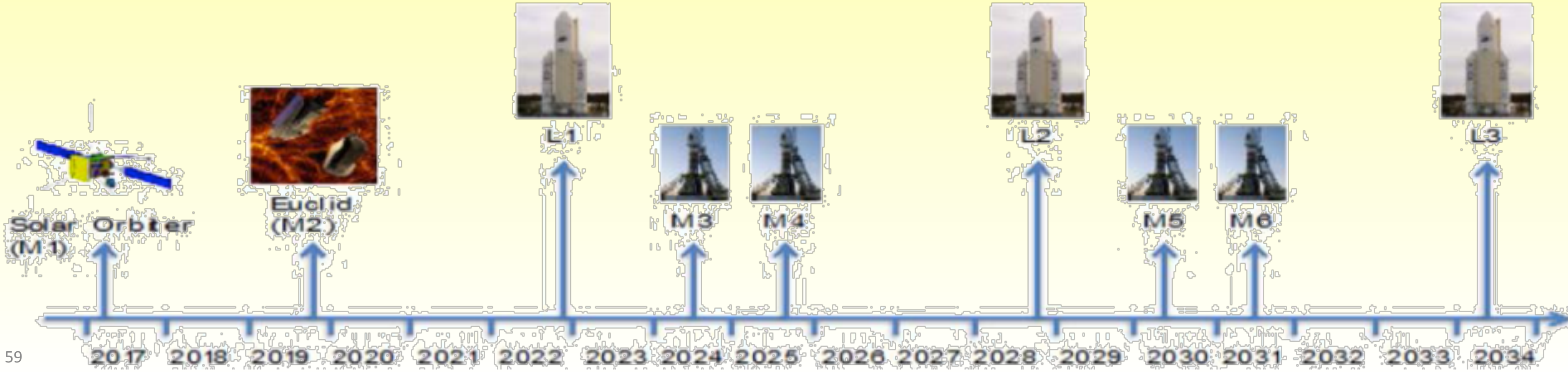
LISA is in good shape!

- LISA Pathfinder a glaring success!

- International partners looking promising
- NASA coming back at several 100 M€ level
- China standing by with increasing interest
- Japan possibly small contribution
- New European Consortium hardware providers for LISA P/L instrument

ESA L2 and L3 Missions

- Call for Mission Concepts fall 2016
- Decision on Implementation 2020
- Launch of L2 in 2028
- Launch of L3 in 2034
- LISA is ready for 2028!



We will hear the Universe and the Big Bang!

The End