Gravitational Waves: We can hear the Universe!

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We have detected Gravitational Waves!

Observation of Gravitational Waves from a Binary Black Hole Merger

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(LIGO Scientific Collaboration and Virgo Collaboration)
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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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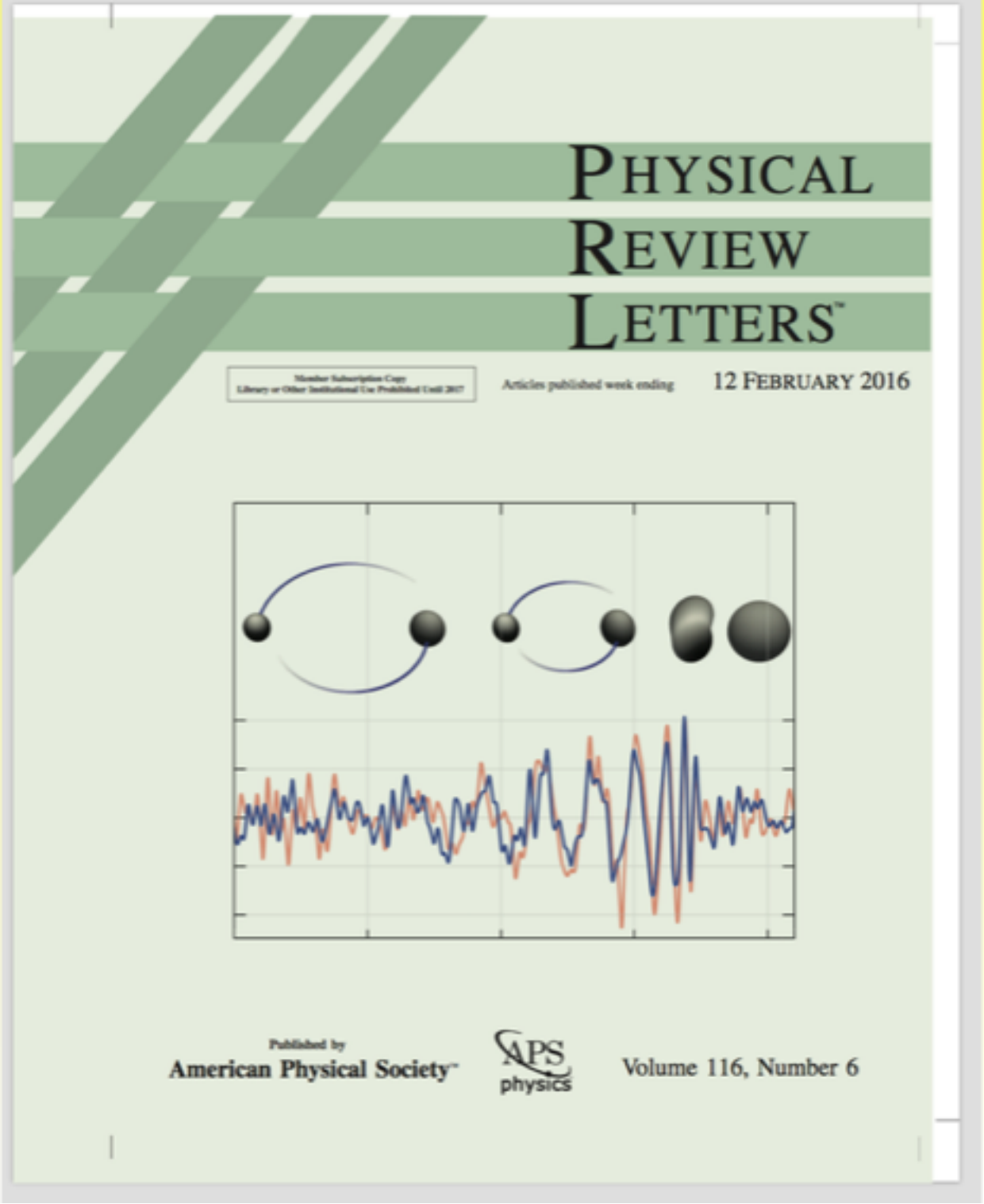
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Thrane,[114] S. Tiwari,[12] V. Tiwari,[91] K. V. Tokmakov,[107] C. Tomlinson,[86] M. Tonelli,[18,19] C. V. Torres,[83,*] C. I. Torrie,[1] D. Töyrä,[46] F. Travasso,[33,34] G. Traylor,[6] D. Trifirò,[22] M. C. Tringali,[89,90] L. Trozzo,[140,19] M. Tse,[10] M. Turconi,[54] D. Tuyenbayev,[83] D. Ugolini,[139] C. S. Unnikrishnan,[99] A. L. Urban,[16] S. A. Usman,[91] H. Vahlbruch,[17] G. Vajente,[1] G. Valdes,[83] M. Vallisneri,[76] N. van Bakel,[53] M. van Beuzekom,[5] J. F. J. van den Brand,[61,5] C. Van Den Broeck,[53] D. C. Vander-Hyde,[36,23] L. van der Schaaf,[5] J. V. van Heijningen,[5] A. A. van Veggel,[37] M. Vardaro,[41,42] S. Vass,[1] M. Vasúth,[39] R. Vaulin,[10] A. Vecchio,[46] G. Vedovato,[43] J. Veitch,[46] P. J. Veitch,[104] K. Venkateswara,[141] D. Verkindt,[7] F. Vetrano,[67,18] A. Viceré,[67,18] S. Vinciguerra,[46] D. J. Vine,[52] J.-Y. Vinet,[54] S. Vitale,[10] T. Vo,[36] H. Vocca,[32,33] C. Vorvick,[38] D. Voss,[51] W. D. Vousden,[46] S. P. Vyatchanin,[50] A. R. 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Zhang,[129] Y. Zhang,[102] C. Zhao,[52] M. Zhou,[82] Z. Zhou,[82] X. J. Zhu,[52] M. E. Zucker,[1,10] S. E. Zuraw,[103] and J. Zweizig[1]

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"For the greatest benefit to mankind"
Alfred Nobel

2017 NOBEL PRIZE IN PHYSICS

Rainer Weiss
Barry C. Barish
Kip S. Thorne

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Rainer Weiss

Prize share: 1/2

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Barry C. Barish

Prize share: 1/4

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Kip S. Thorne

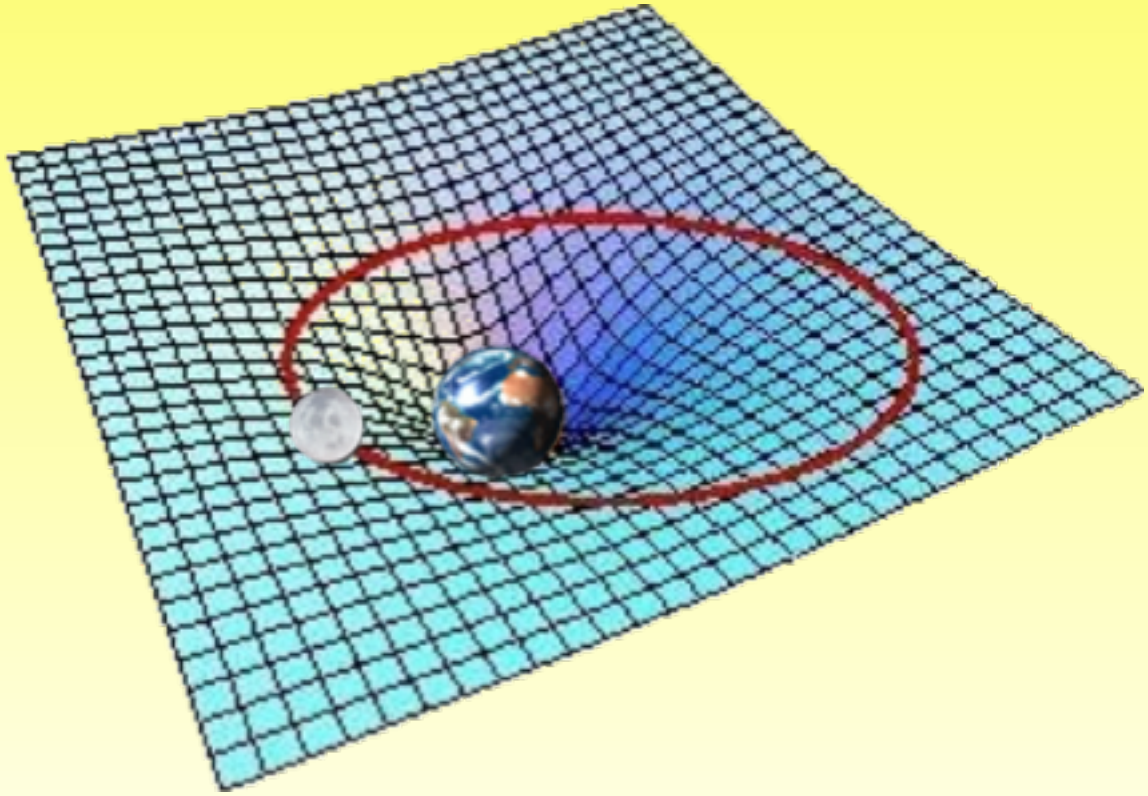
Prize share: 1/4

The Nobel Prize in Physics 2017 was divided, one half awarded to Rainer Weiss, the other half jointly to Barry C. Barish and Kip S. Thorne *"for decisive contributions to the LIGO detector and the observation of gravitational waves"*.

General Relativity

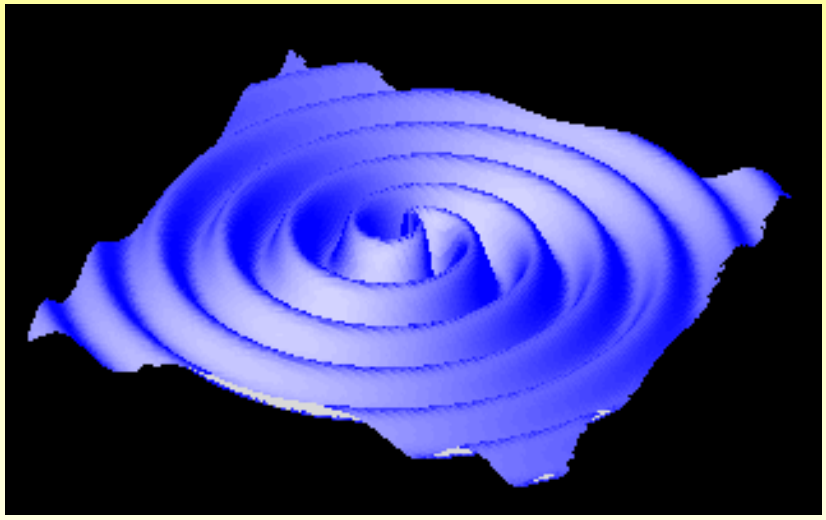
Einstein's Theory of Gravitation, 1915

„Matter curves
space,
and
curved space
tells matter
how to move."

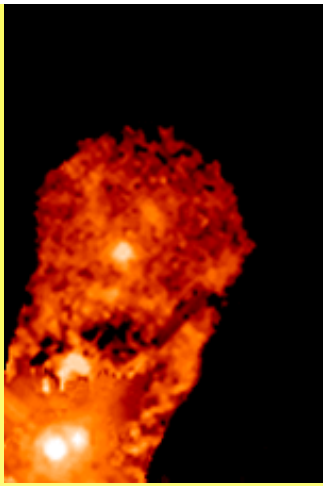


What are Gravitational Waves?

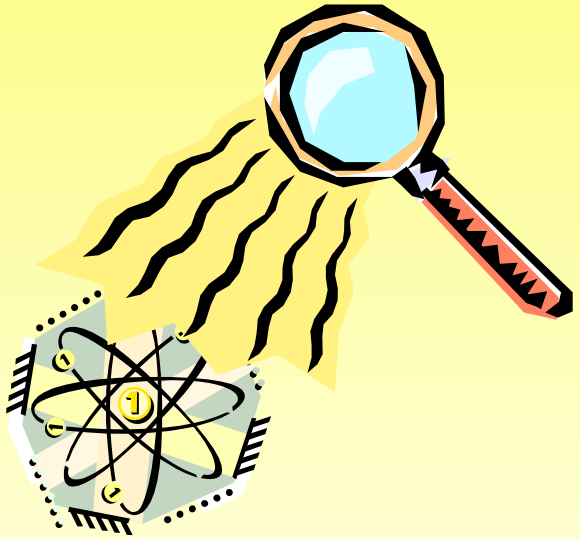
– Distortions of space and time moving at the speed of light



The Effect is Small!



- Supernova in local group of galaxies
  $\Rightarrow$ squeezes space by 10^{-21}



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

$\Rightarrow$ For a few milliseconds!

World-Wide Laser Interferometric Gravitational Wave Detector Network

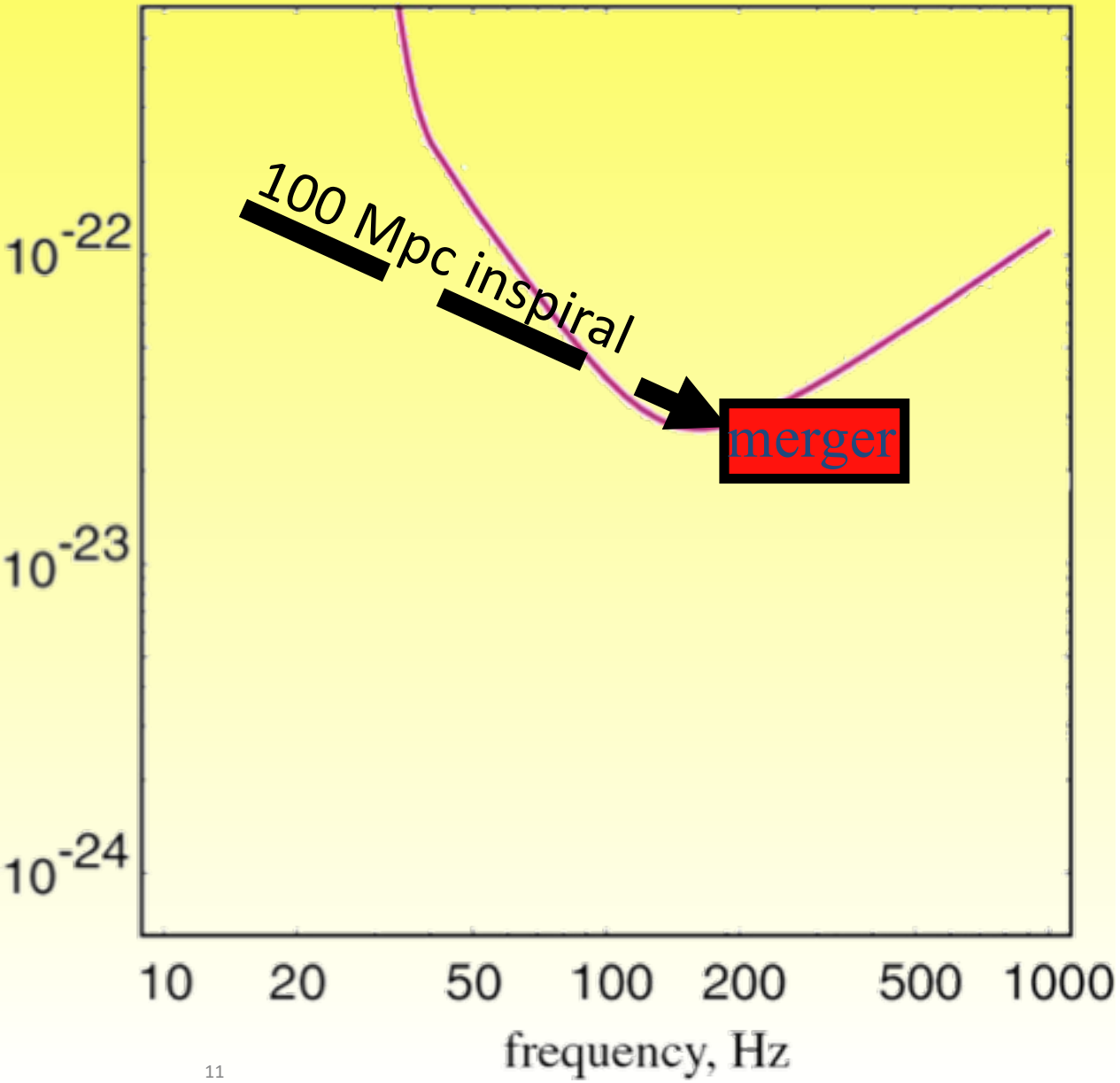
3 km

m

Source: A. Lazzarini, modified

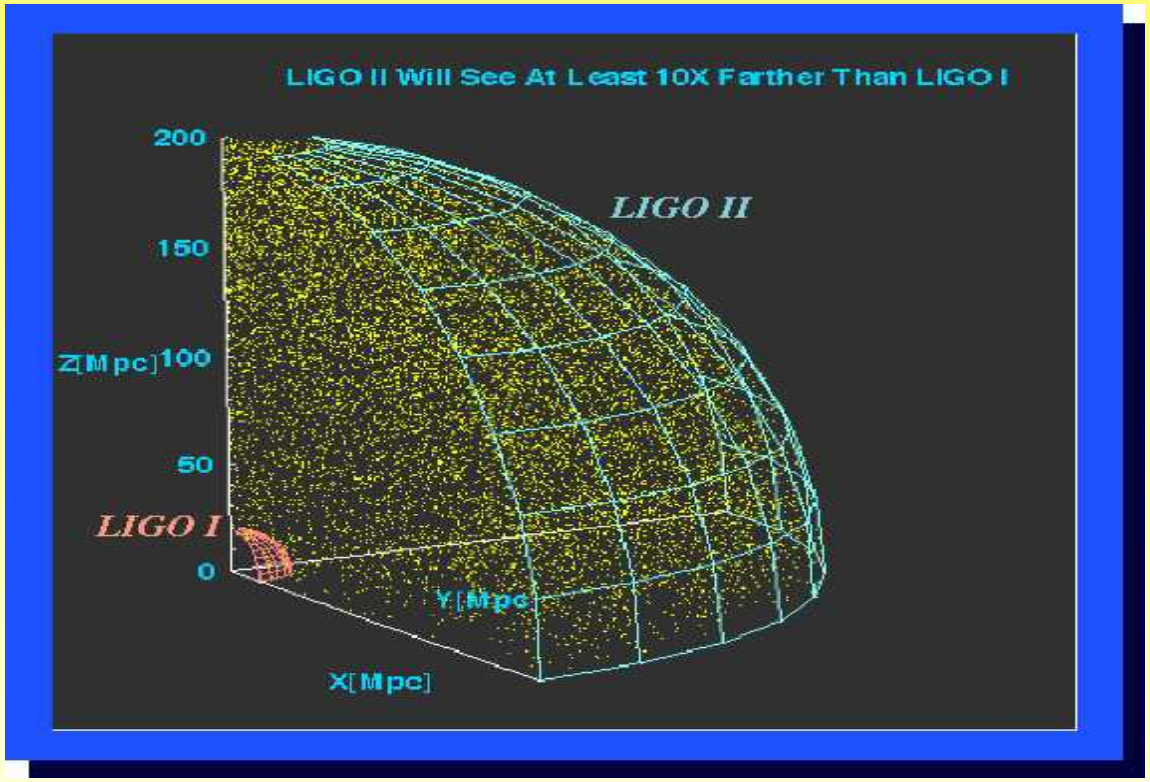
Sensitivity until 2011

- 10 M_{sun} - 10 M_{sun} BH - BH binaries
- Event rates
  - Based on population synthesis [Kalogera's summary of literature]
- Initial IFO event rates
  - Range: 100 Mpc
  - 1 / 600yrs to ~3/yr



After 5 Years of Upgrading: Advanced LIGO

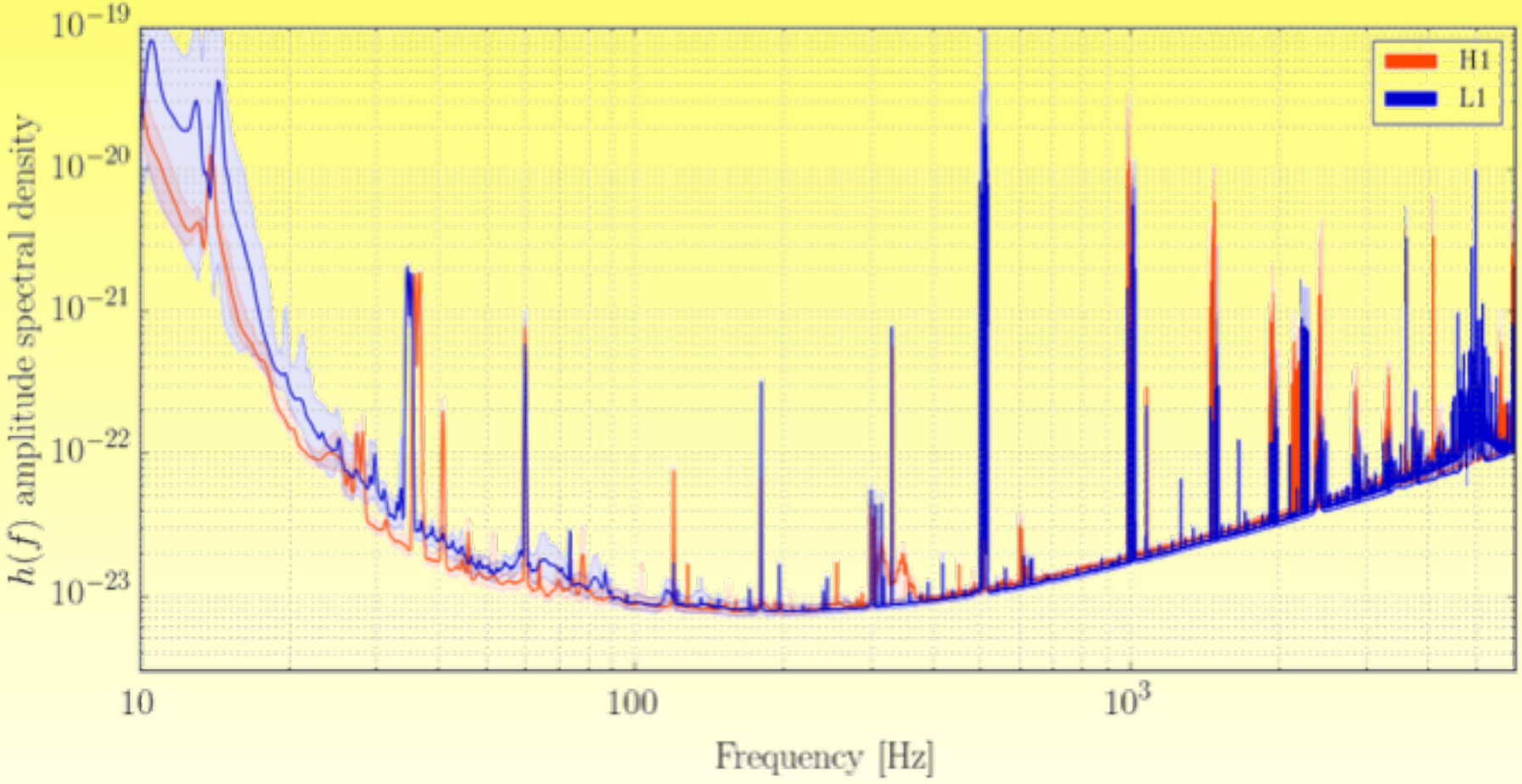
- Observable volume several thousand LIGO!
- Installation 2011-15
- GEO contributions:
- Mirror suspensions
- New optics
- 200 W laser



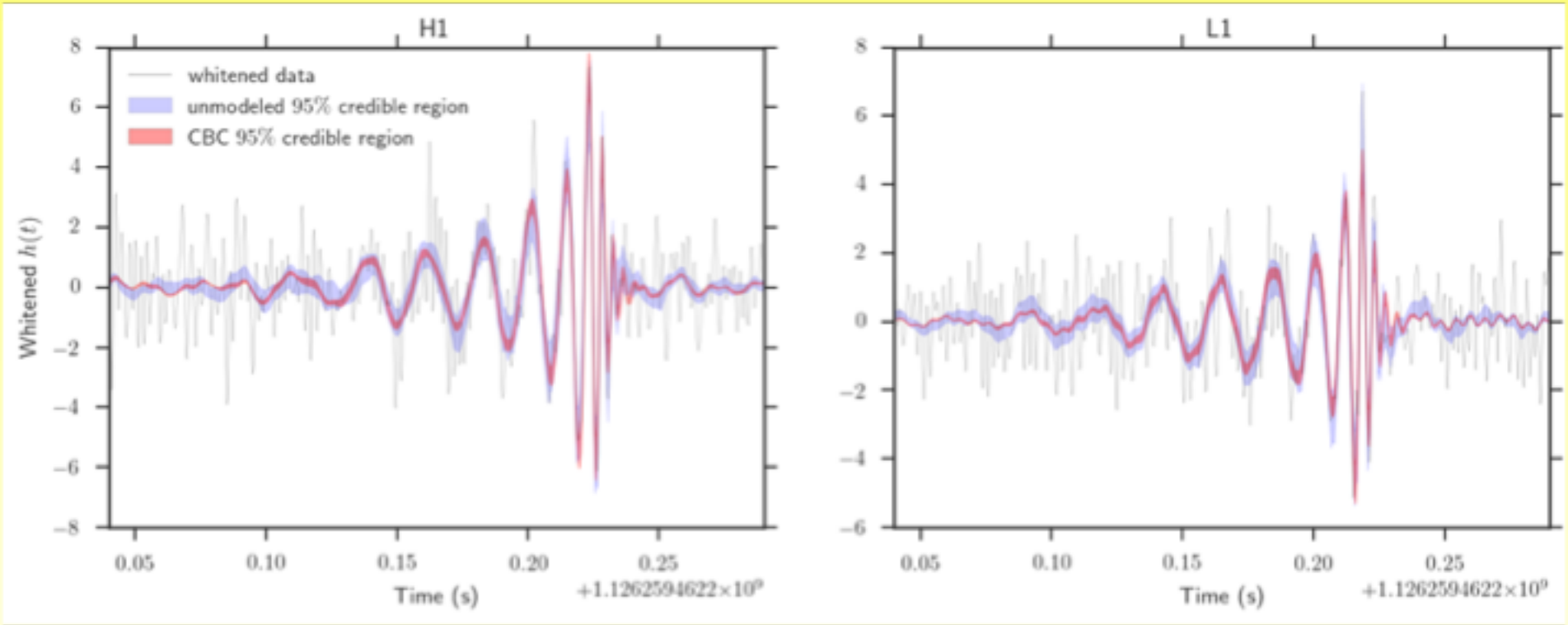
- Signal Recycling – Resonant Sideband Extraction

Advanced LIGO in September 2015

Factor-10 better than Initial LIGO
Factor 3 missing till design goal



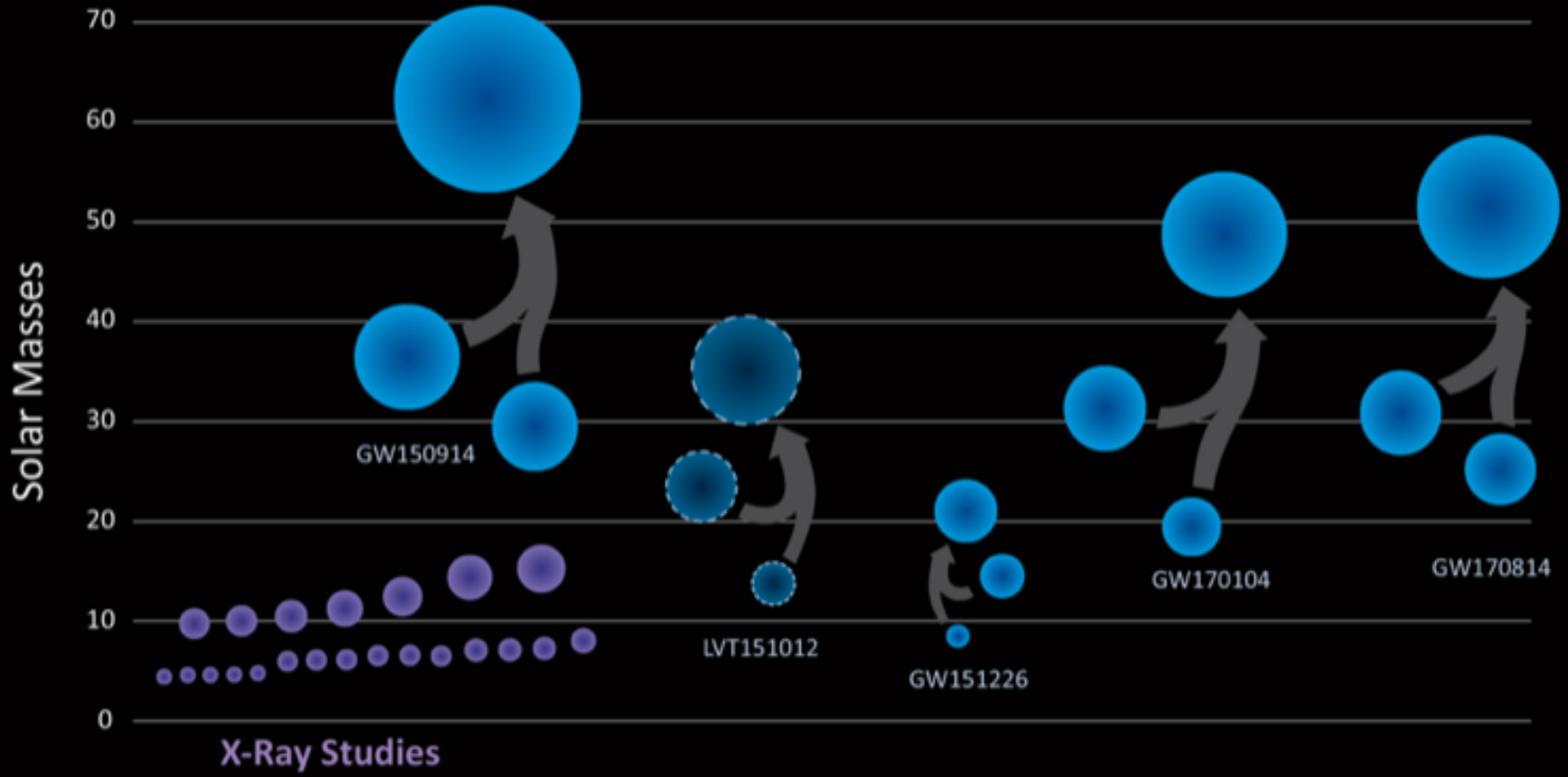
We are listening to Black Holes!



The Source:
Two Merging Black Holes

Quantity	Value	Upper/Lower error estimate	Unit
Primary black hole mass	**36**	+5 -4	M sun
Secondary black hole mass	**29**	+4 -4	M sun
Final black hole mass	**62**	+4 -4	M sun
Final black hole spin	**0.67**	+0.05 -0.07	
Luminosity distance	**410**	+160 -180	Mpc
Source redshift, *z*	**0.09**	+0.03 -0.04	
Energy radiated	**3**	+0.5 -0.5	M sun

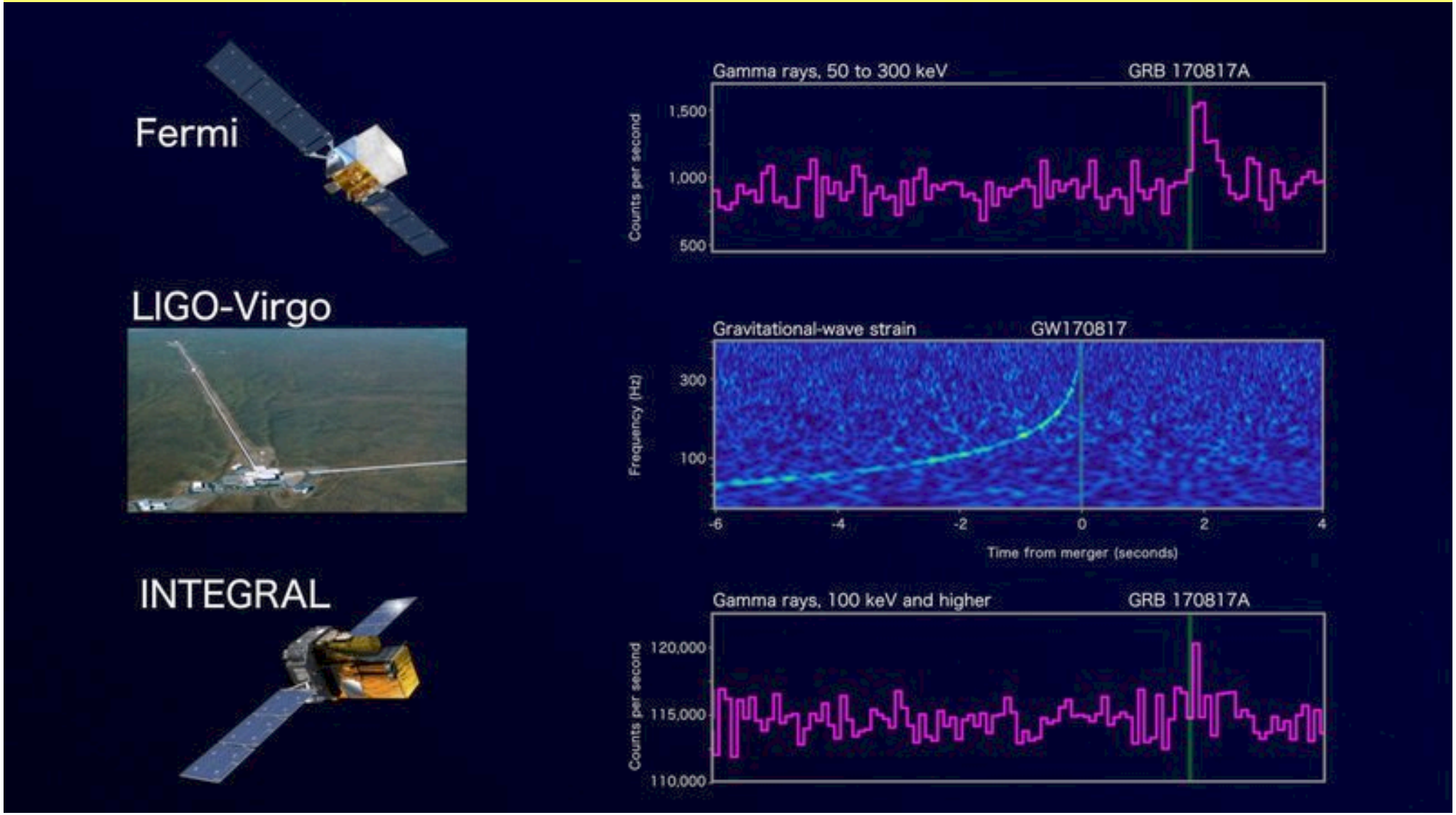
Black Hole Mergers every Month!



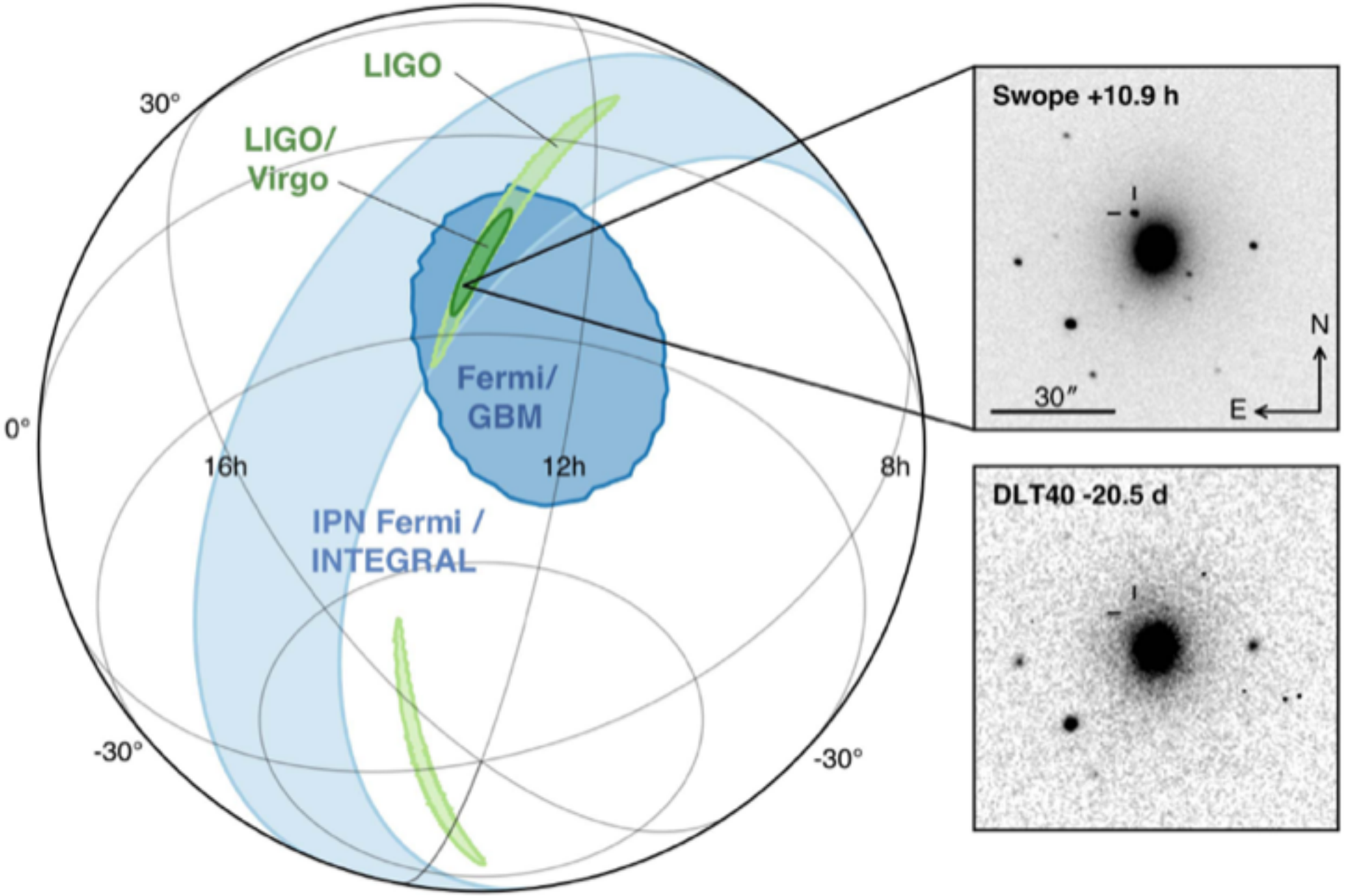
Credit: LIGO/Caltech/Sonoma State (Aurore Simonnet)

LIGO/VIRGO

August 17th, 2017: Neutron Star Merger plus Gamma Ray Burst



Optical Counterpart



The Astrophysical Journal Letters, 848:L12 (59pp), 2017 October 20

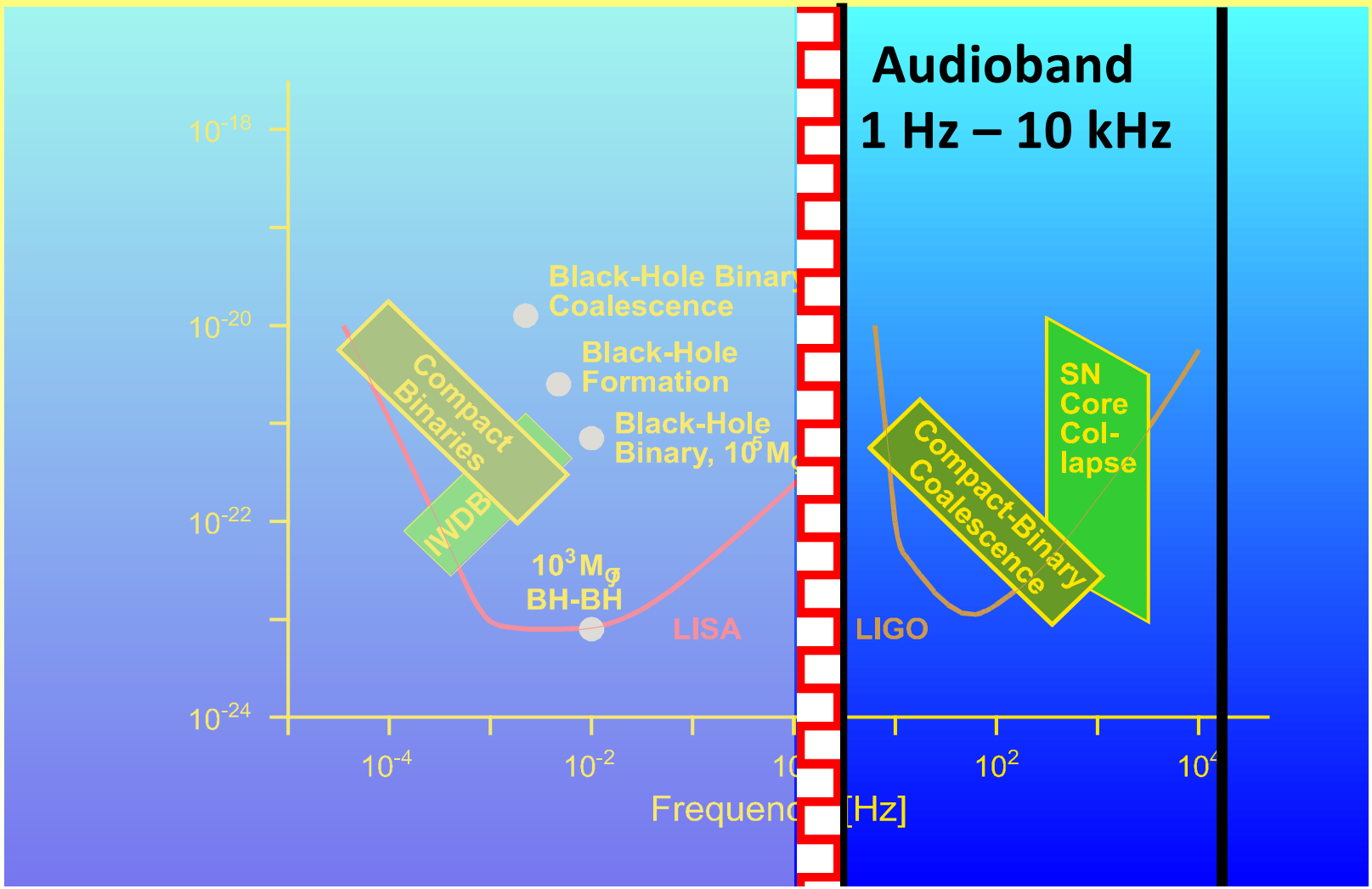
Where is all the Gold coming from?

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

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

Sources of Gravitational Waves

- Ground-based detectors: Audioband



LISA:

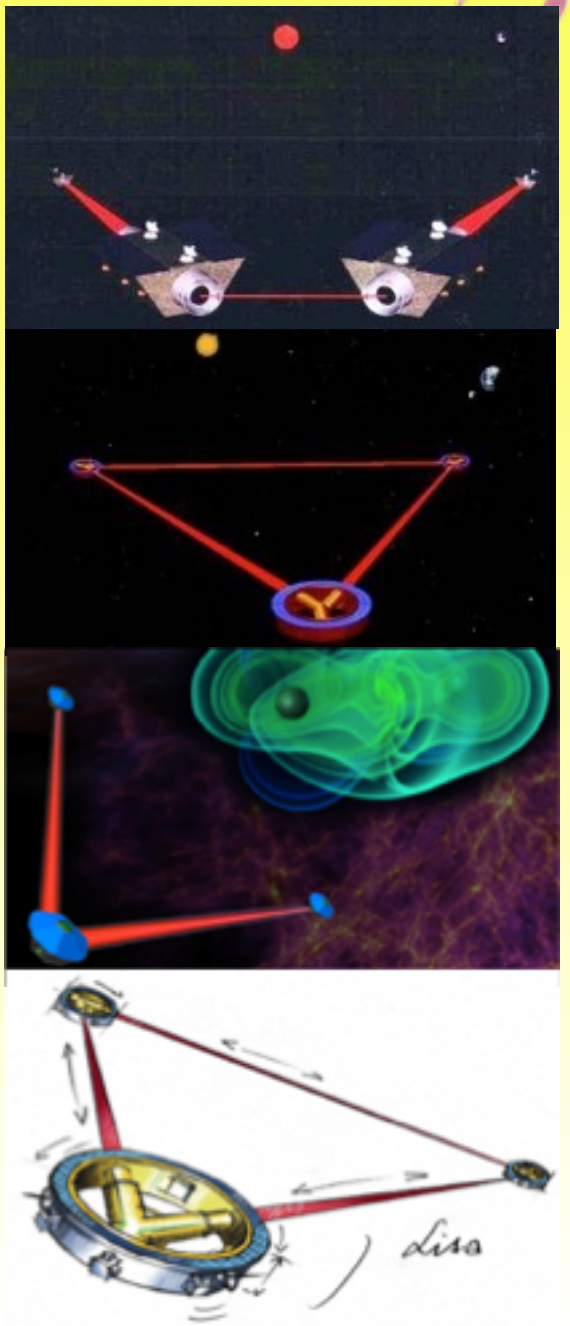
Opens the low-frequency gravitational universe !

Selected! June 20, 2017! ESA-L3!

3 satellites
2.5 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 ESA/NASA LISA appears in 1997
- Joint ESA-NASA Mission Formulation study 2005-2011
- Reformulation 2012-13 as ESA-led eLISA (evolving LISA)
- Now back to 3-arm LISA with NASA

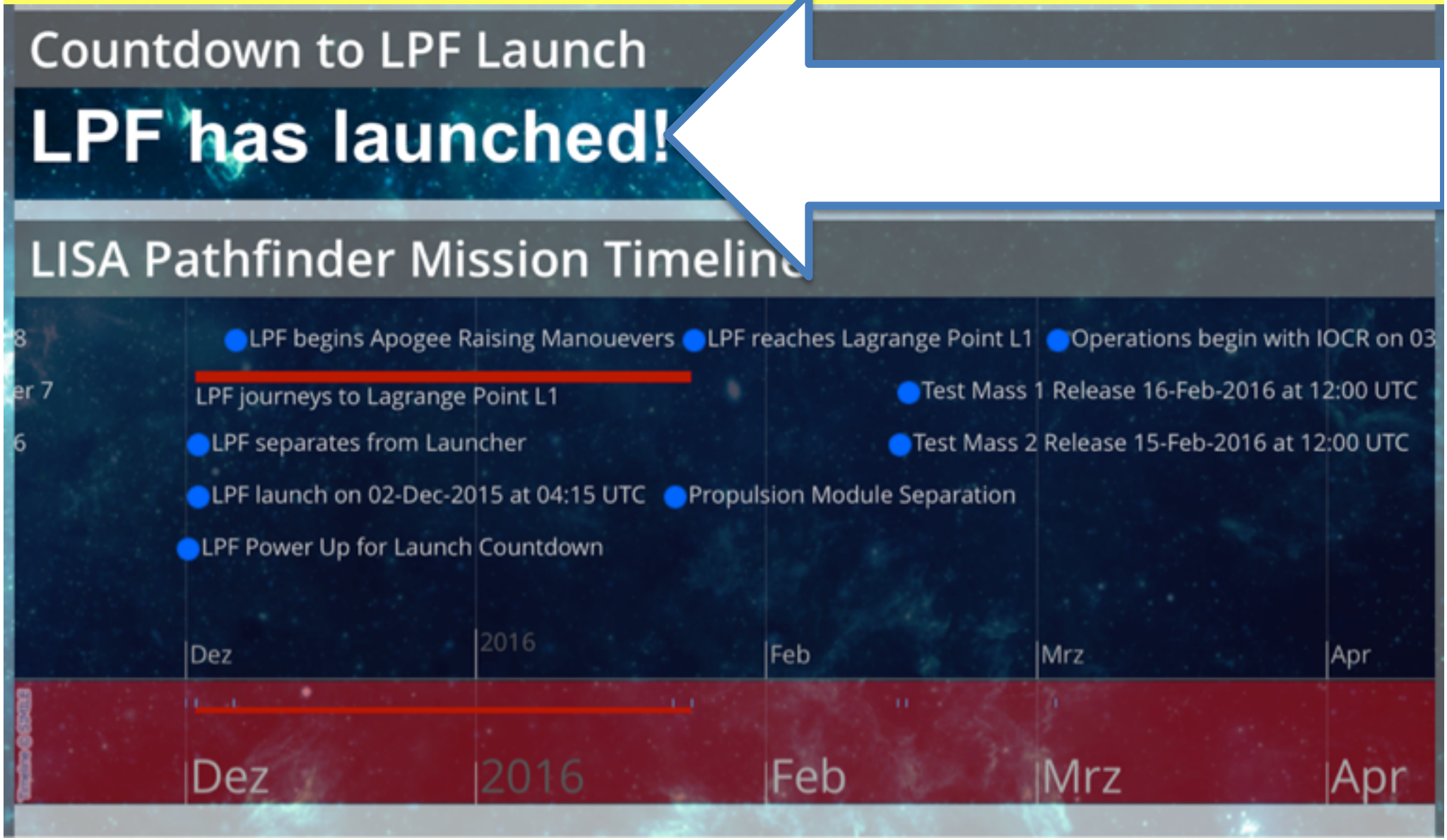


LISA Pathfinder

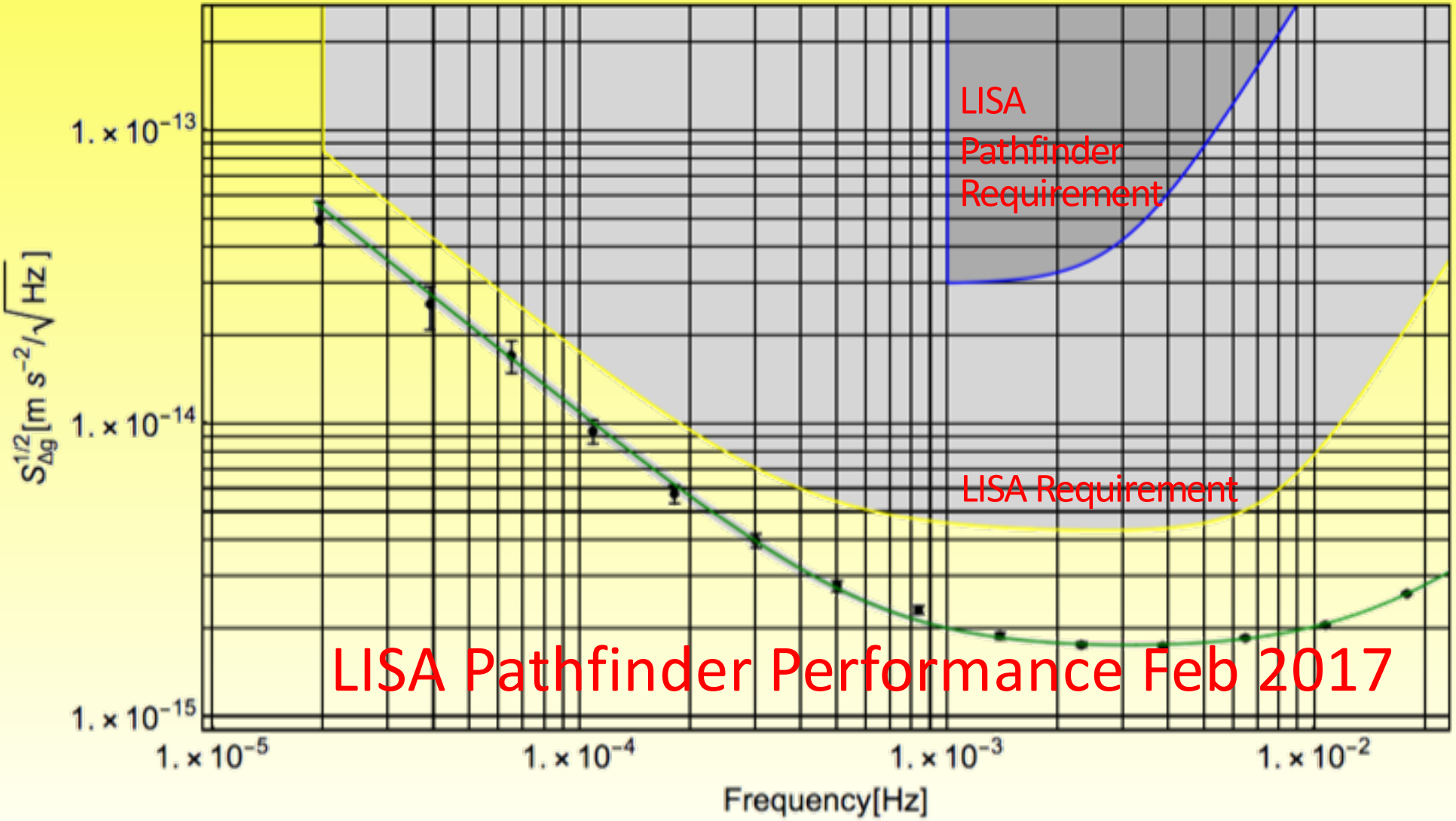
- Testing LISA technology in space!

17 years later!
September 2015:
Spacecraft is completed!

100 Years since GR Publication: Dec. 2, 2015

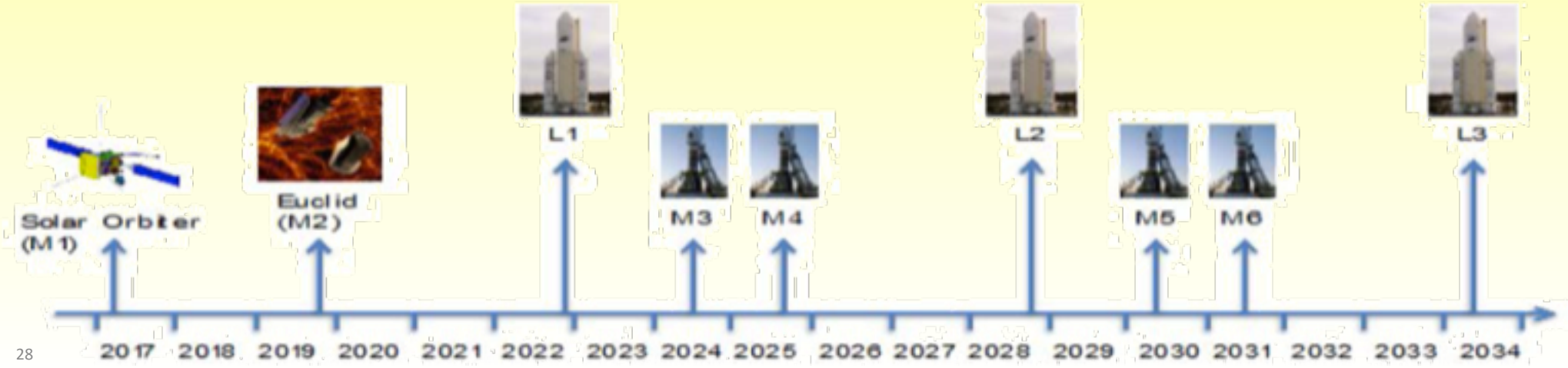


LISA Pathfinder shows: LISA Works!



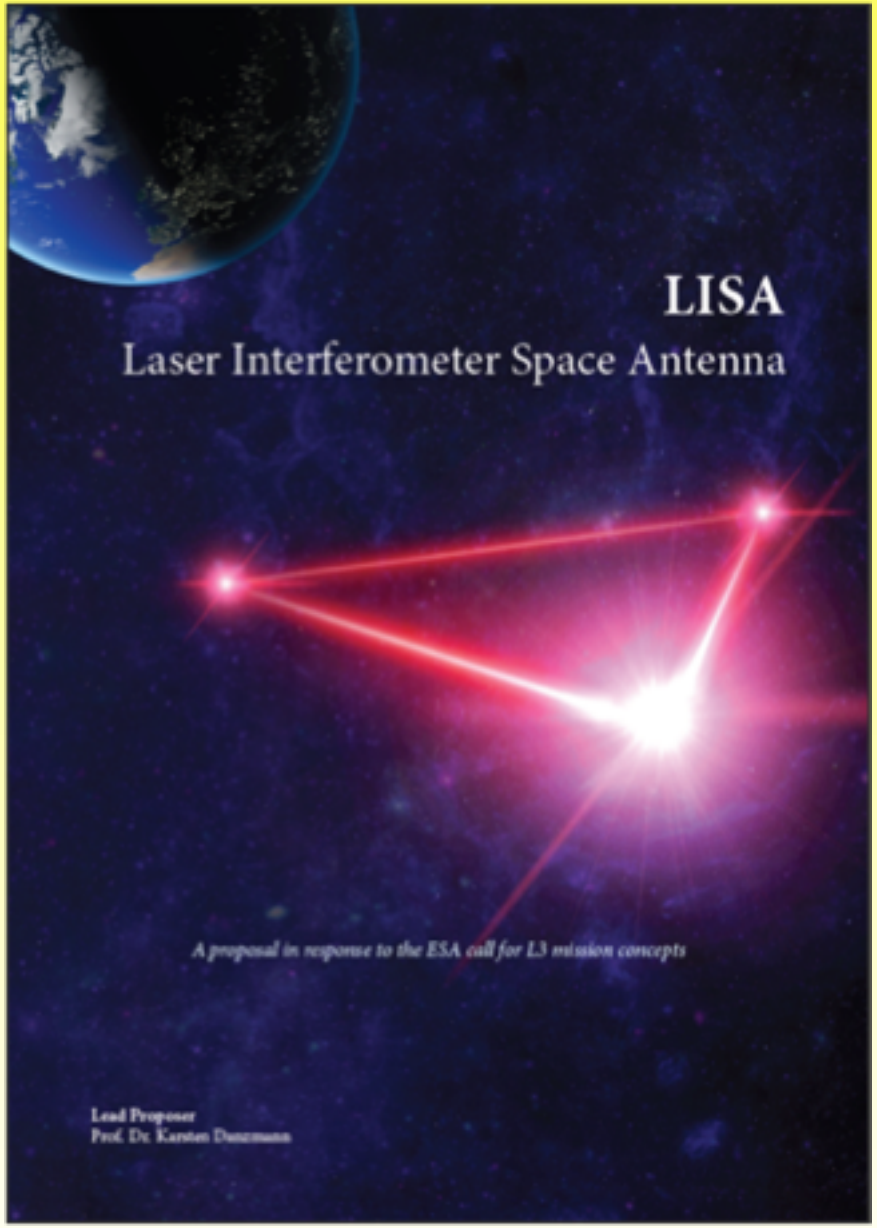
ESA L2 and L3 Missions

- Call for Mission Concepts fall 2016



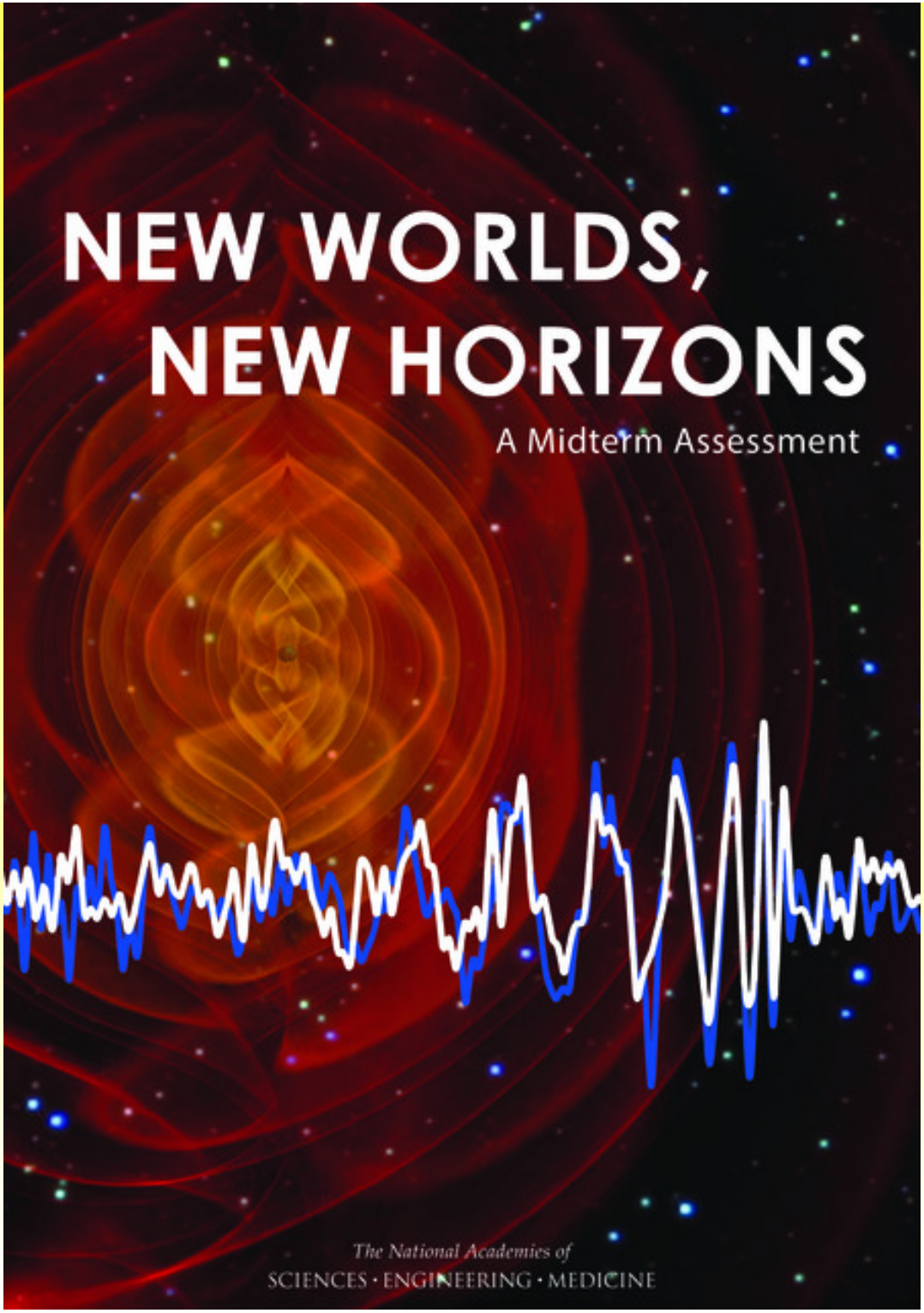
LISA Mission Concept Document

- Submitted on January 13th, 2017
- The LISA Consortium: 12 EU Member States plus the US !



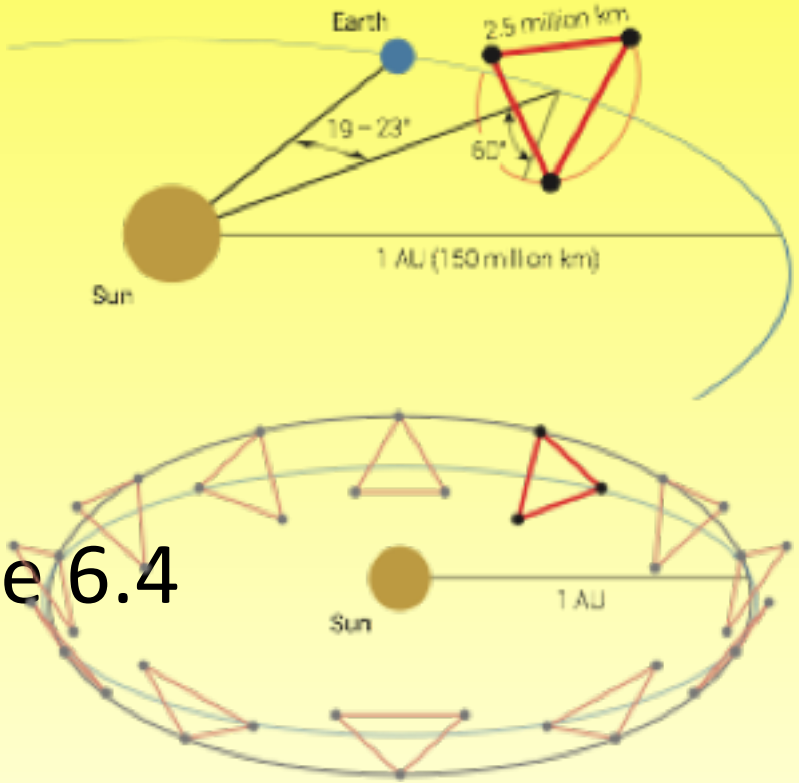
https://www.lisamission.org/proposal/LISA.pdf

NASA is back in LISA!



Mission Profile and Orbit

- Three arms of 2.5 Million km
- 2W lasers
- 30 cm telescopes
- Breathing angles ± 1 deg
- Doppler shifts ± 5 MHz
- Launch on dedicated Ariane 6.4
  - Transfer time ~400 days
  - Direct escape V∞ = 260 m/s
  - Propulsion module and S/C composite



ESA SPC selected LISA as L3 !

cosmic vision

esa

ESA | SCIENCE & TECHNOLOGY | COSMIC VISION

Missions
- Show All Missions

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

Cosmic Vision themes
- The Hot and Energetic Universe
- Planets and Life
- The Solar System
- Fundamental Laws
- The Universe

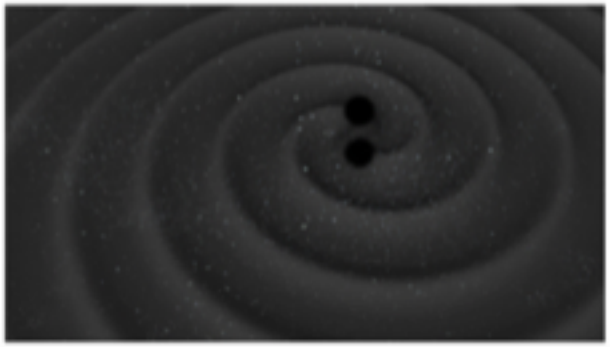
GRAVITATIONAL WAVE MISSION SELECTED, PLANET-HUNTING MISSION MOVES FORWARD

20 June 2017

The LISA trio of satellites to detect gravitational waves from space has been selected as the third large-class mission in ESA's Science programme, while the PLATO exoplanet hunter moves into development.

These important milestones were decided upon during a meeting of ESA's Science Programme Committee today, and ensure the continuation of ESA's Cosmic Vision plan through the next two decades.

The 'gravitational universe' was identified in 2013 as the theme for the third large-class mission, L3, searching for ripples in the fabric of spacetime created by celestial objects with very strong gravity,



Search here

9-Jul-2017 18:39 UT

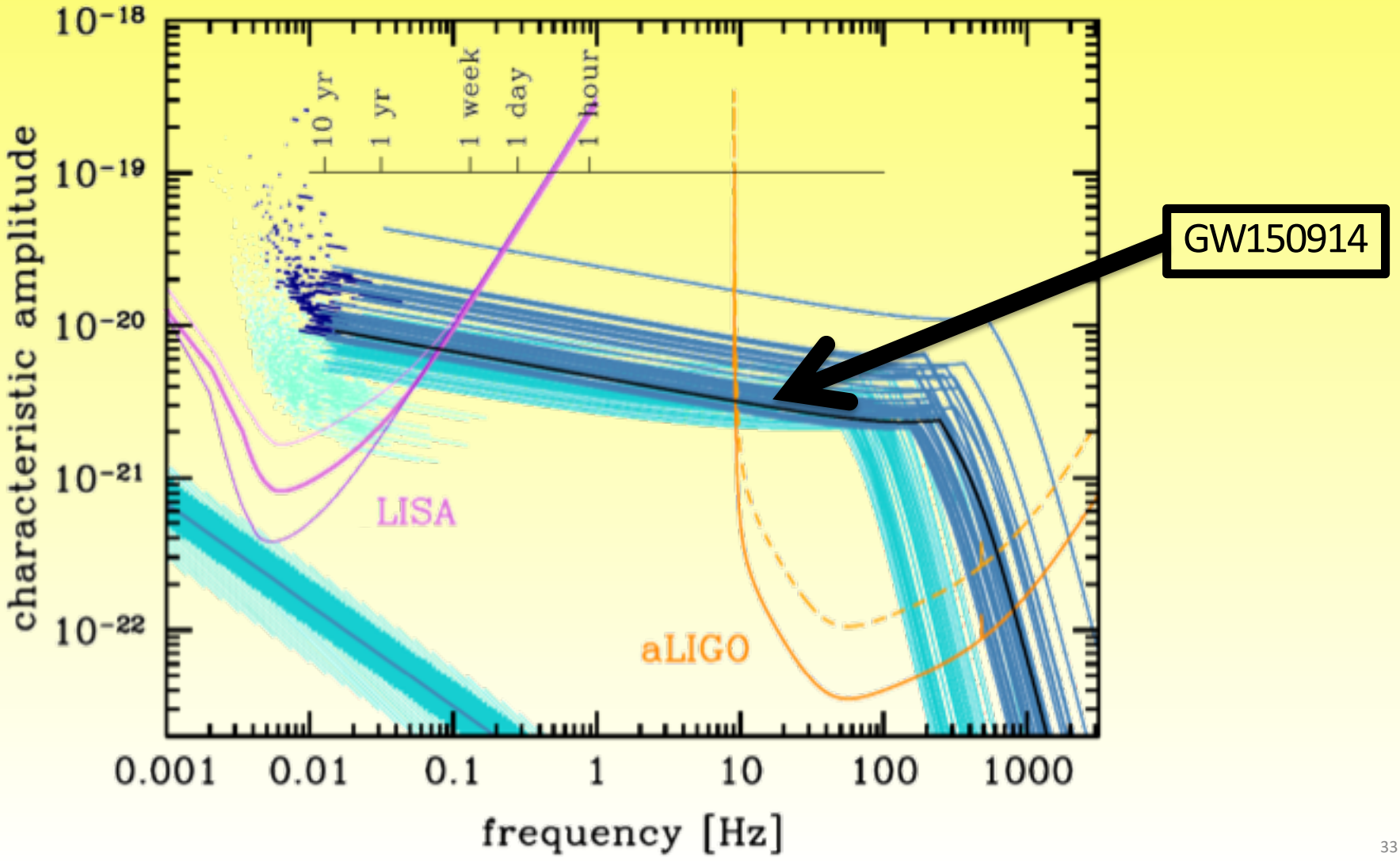
Shortcut URL
http://sci.esa.int/jump.cfm?oid=59243

Images And Videos

- Merging black holes
- Searching for exoplanetary systems

LISA: LIGO Event Predicted 10 Years in Advance!

- Accurate to seconds and within a square-degree!



ESA L2 and L3 Missions

- Call for Mission Concepts fall 2016
- Decision on L3 Adoption 2021
- Launch of L2 in 2028
- Launch of L3 in 2034
- LISA shall be ready for an early launch!