Gravitationswellen: Ein neues Fenster zur Erforschung des Universums (von LISA Pathfinder zu LISA)

ETH – EMERITENSTAMM
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Gravitational Waves

2 December 1915:
Einstein completes General Relativity
(A. Einstein,
Sitz. Ber. Preuss. Akad. Wiss. Berlin,

- December 1915, 844-847)

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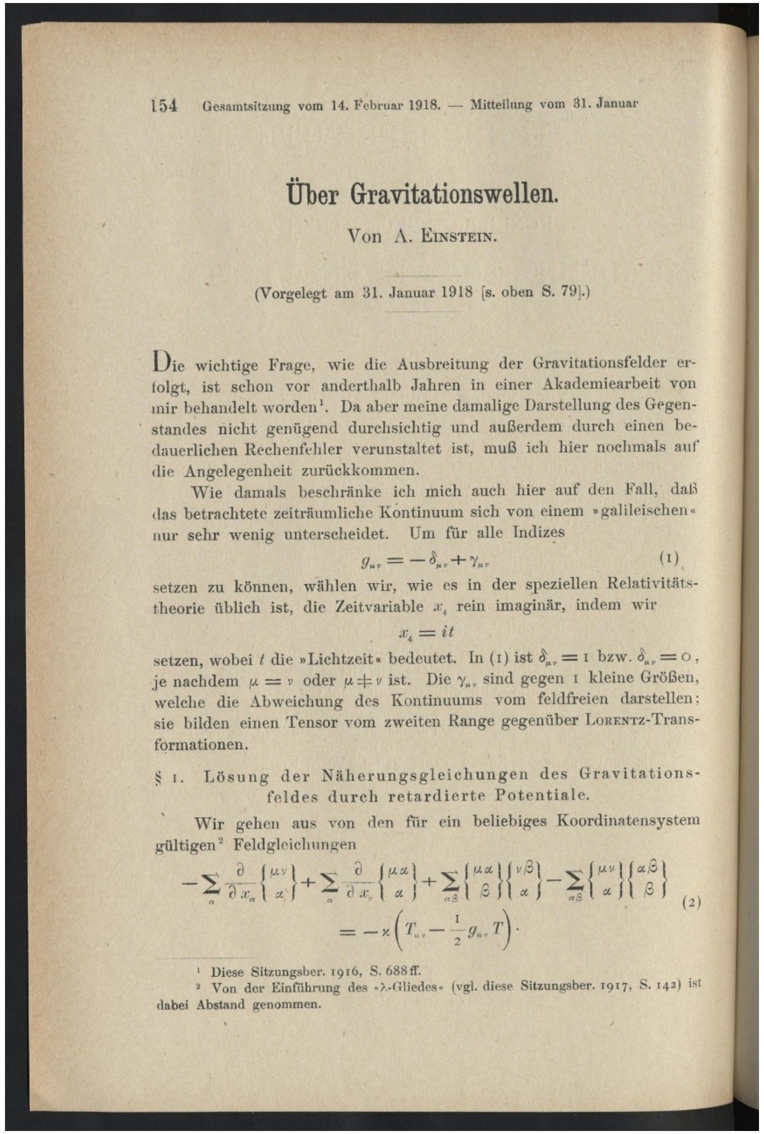

154 Gesamtsitzung vom 14. Februar 1918. — Mitteilung vom 31. Januar

Über Gravitationswellen.

Von A. Einstein.

(Vorgelegt am 31. Januar 1918 [s. oben S. 79].)

Die wichtige Frage, wie die Ausbreitung der Gravitationsfelder erfolgt, ist schon vor anderthalb Jahren in einer Akademiearbeit von mir behandelt worden[1]. Da aber meine damalige Darstellung des Gegenstandes nicht genügend durchsichtig und außerdem durch einen bedauerlichen Rechenfehler verunstaltet ist, muß ich hier nochmals auf die Angelegenheit zurückkommen.

Wie damals beschränke ich mich auch hier auf den Fall, daß das betrachtete zeiträumliche Kontinuum sich von einem »galileischen« nur sehr wenig unterscheidet. Um für alle Indizes

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \qquad (1)$$

setzen zu können, wählen wir, wie es in der speziellen Relativitätstheorie üblich ist, die Zeitvariable x_4 rein imaginär, indem wir

$$x_4 = it$$

setzen, wobei t die »Lichtzeit« bedeutet. In (1) ist $\delta_{\mu\nu} = 1$ bzw. $\delta_{\mu\nu} = 0$, je nachdem $\mu = \nu$ oder $\mu \neq \nu$ ist. Die $\gamma_{\mu\nu}$ sind gegen 1 kleine Größen, welche die Abweichung des Kontinuums vom feldfreien darstellen; sie bilden einen Tensor vom zweiten Range gegenüber Lorentz-Transformationen.

§ 1. Lösung der Näherungsgleichungen des Gravitationsfeldes durch retardierte Potentiale.

Wir gehen aus von den für ein beliebiges Koordinatensystem gültigen[2] Feldgleichungen

$$-\sum_{\alpha} \frac{\partial}{\partial x_\alpha} \begin{Bmatrix} \mu\nu \\ \alpha \end{Bmatrix} + \sum_{\alpha} \frac{\partial}{\partial x_\nu} \begin{Bmatrix} \mu\alpha \\ \alpha \end{Bmatrix} + \sum_{\alpha\beta} \begin{Bmatrix} \mu\alpha \\ \beta \end{Bmatrix} \begin{Bmatrix} \nu\beta \\ \alpha \end{Bmatrix} - \sum_{\alpha\beta} \begin{Bmatrix} \mu\nu \\ \alpha \end{Bmatrix} \begin{Bmatrix} \alpha\beta \\ \beta \end{Bmatrix} = -\varkappa \left(T_{\mu\nu} - \frac{1}{2} g_{\mu\nu} T \right). \qquad (2)$$

[1] Diese Sitzungsber. 1916, S. 688 ff.
[2] Von der Einführung des »λ-Gliedes« (vgl. diese Sitzungsber. 1917, S. 142) ist dabei Abstand genommen.

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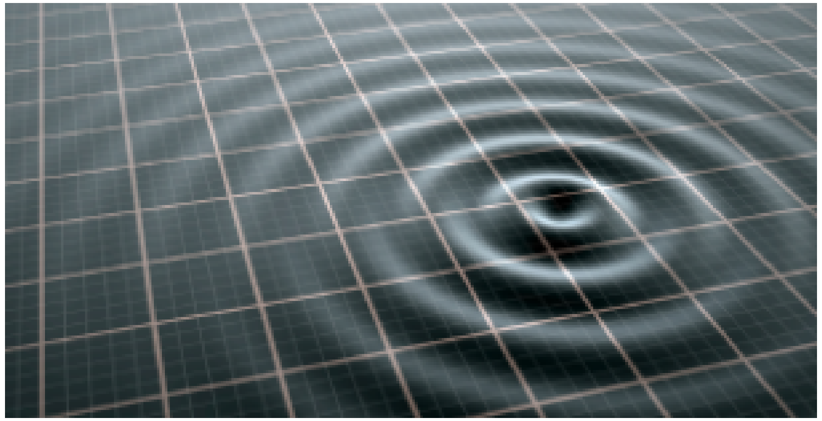
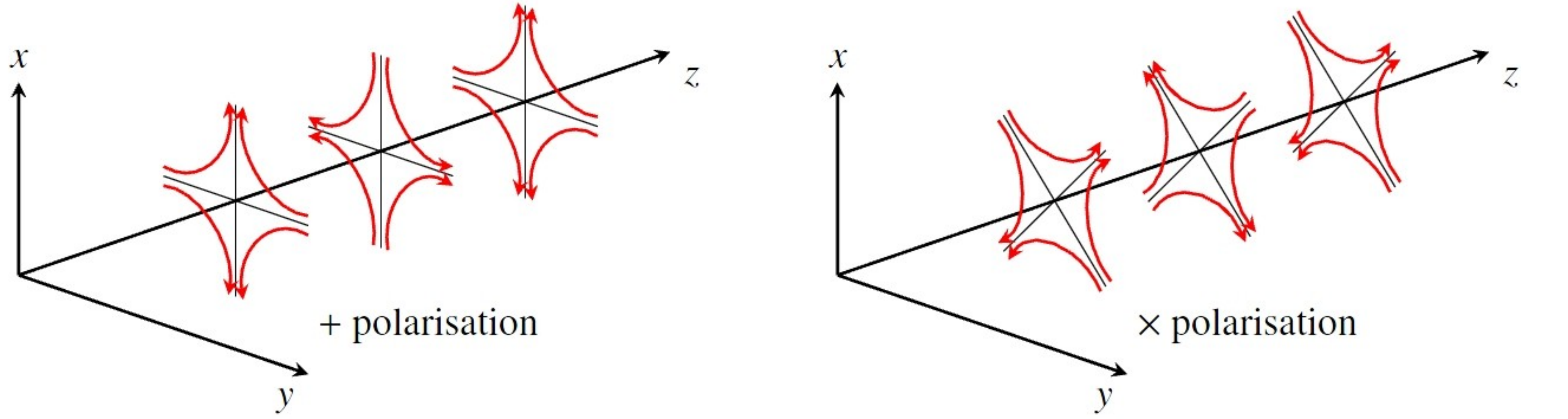


$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \qquad |h_{\mu\nu}| \ll 1$$

$$G\left[g_{\mu\nu}\right] = \Box h_{\mu\nu} = 0 \qquad \Box = \nabla^2 - \frac{1}{c^2}\partial_t^2$$

Understanding Gravitational Waves

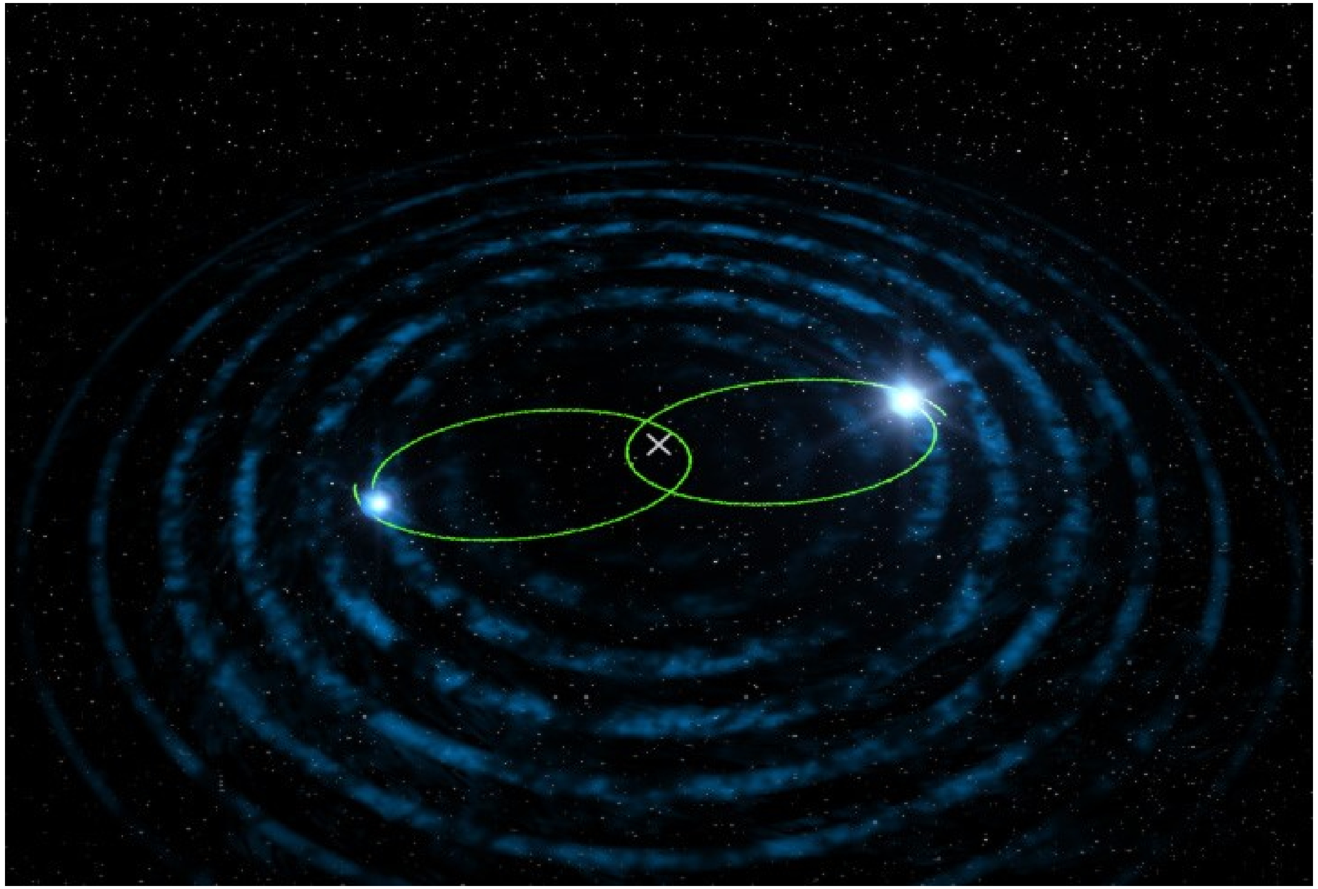
- Strong analogies with EM radiation
  - Two transverse polarisations
  - Move at the speed of light, follow geometrical optics
  - Same behaviour with gravitational lensing, cosmological redshift



...but GWs *are* different...

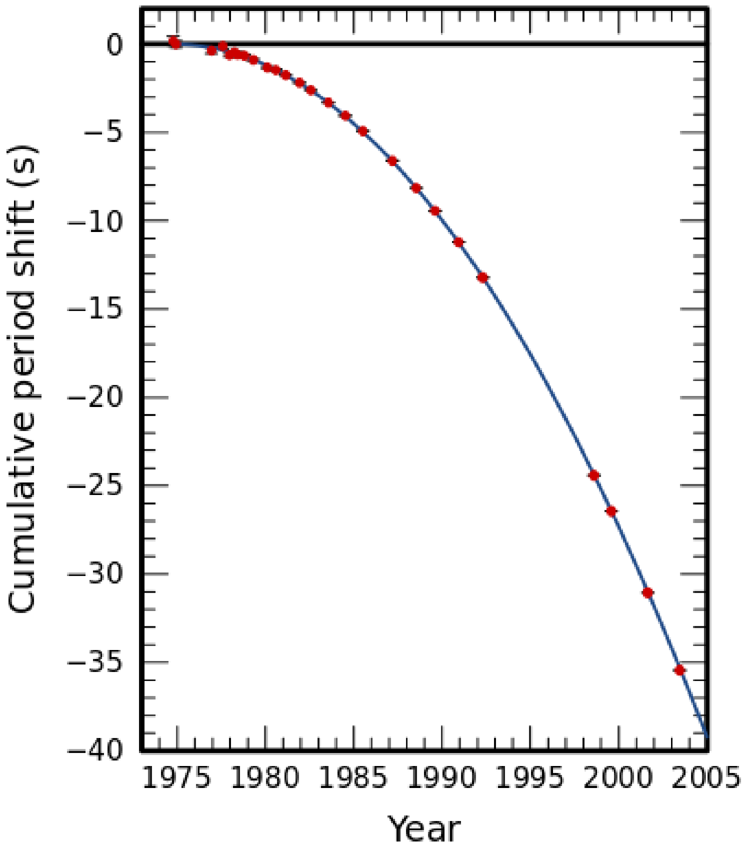
- Coupling of GW to matter is very different from EM
- Very weak
  - $h \approx \delta L / L \approx 10^{-21} \ldots 10^{-24}$
  - $h \approx 1 / r$
- Weakness
  - negligible scatter, absorption
  - perfect messengers!
- Huge energy flux
  - luminosity scale is $(c^5/G) \approx 3.6 \cdot 10^{59}$ erg/s

Evidence: Hulse – Taylor Binary Pulsar discovered in 1974

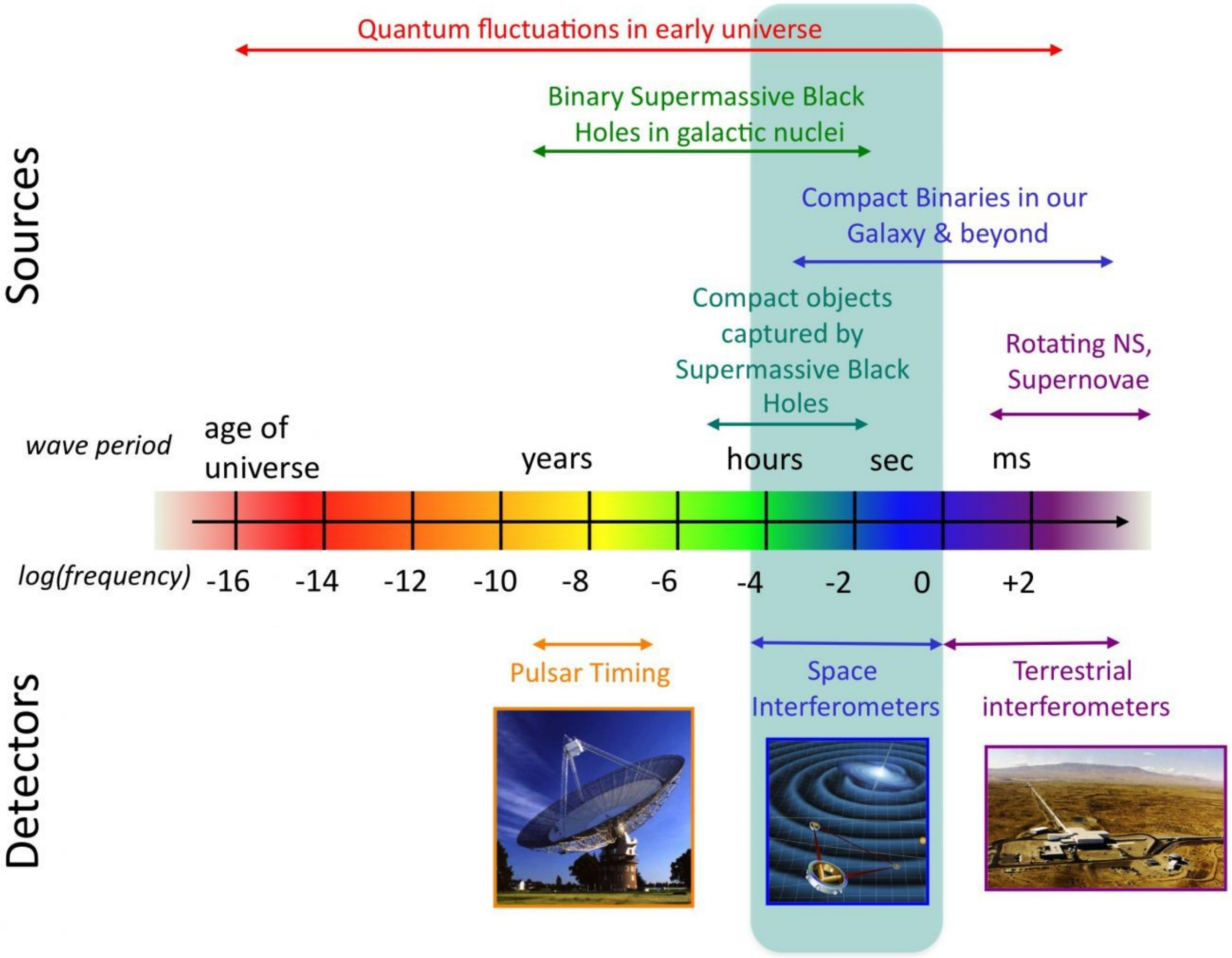


Evidence: Hulse – Taylor Binary Pulsar discovered in 1974

- Orbital decay of PSR 1913 + 16 binary pulsar systems
  - from data points represent the cumulative shift of periastron time measured whereas the parabola curve shows the same quantity predicted by the General Relativity.
- Mass of both pulsars of about 1.4 solar masses.
- Orbital period: 7.75 hours.



Gravitational Wave Spectrum - Detectors



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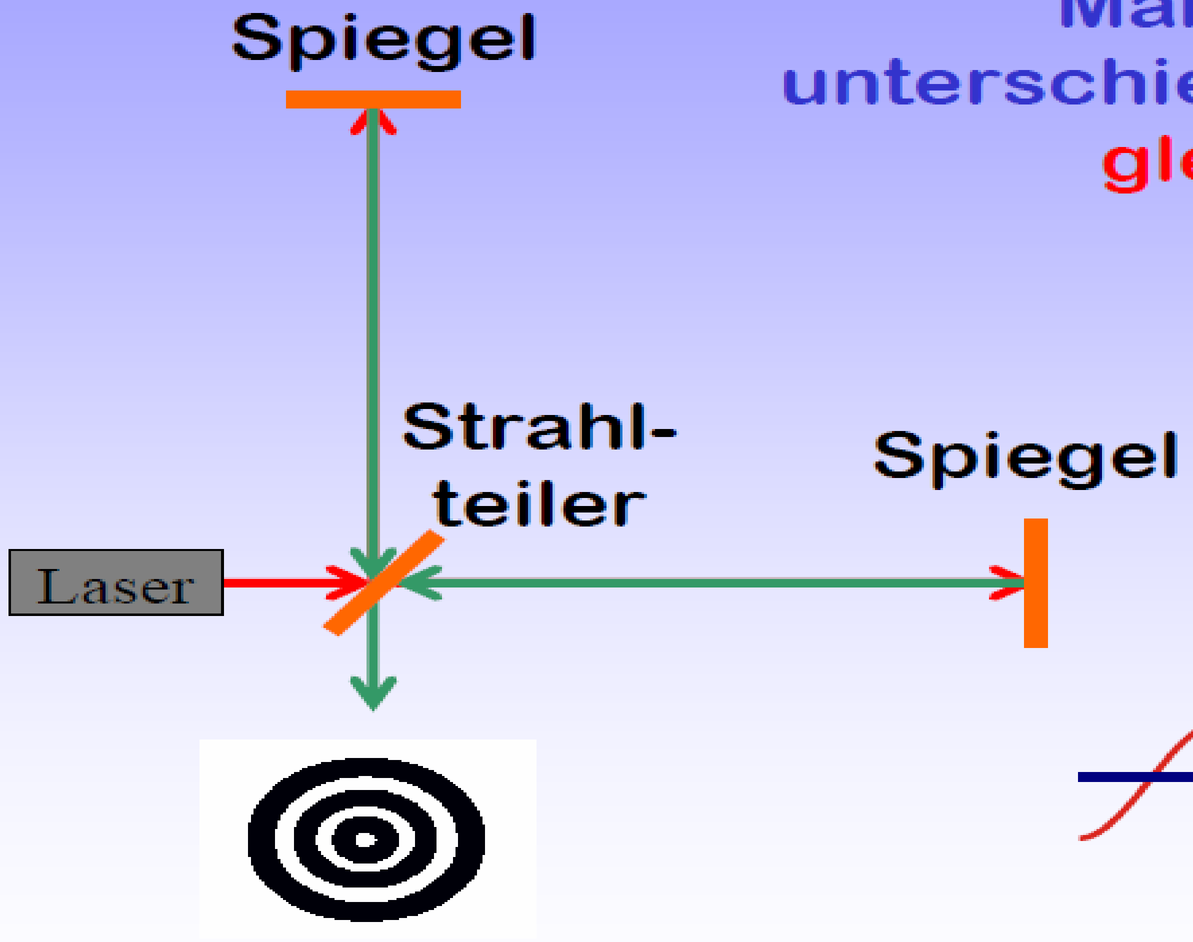
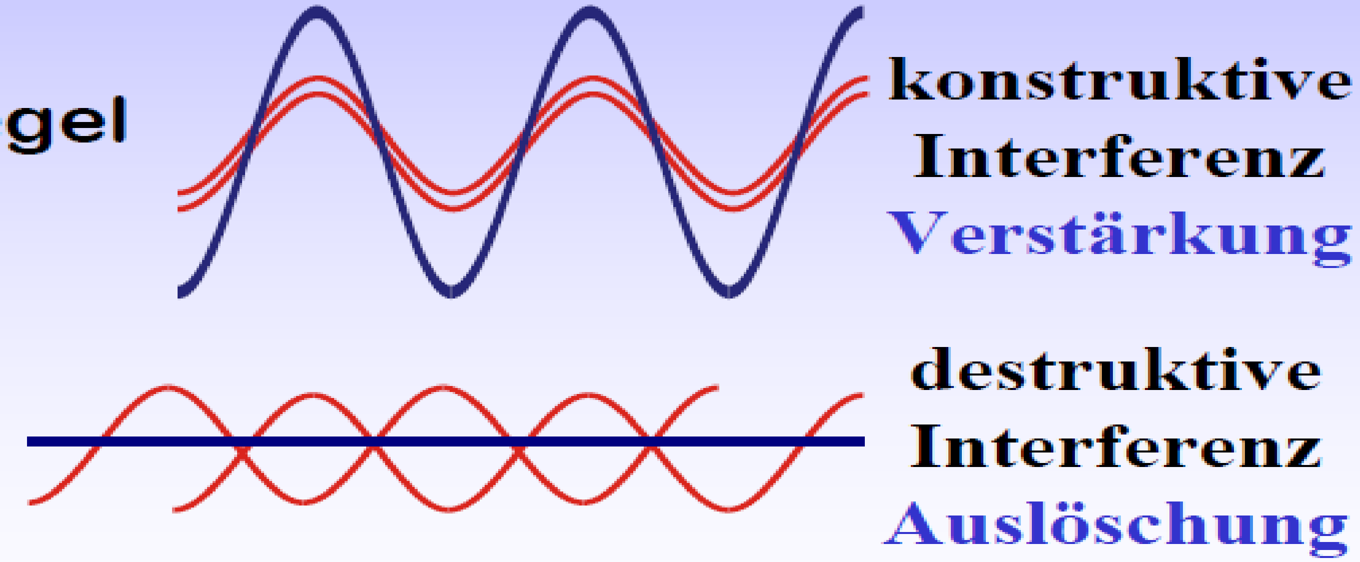
Michelson-Interferometer

Man muß man die beiden unterschiedlich veränderten Strecken **gleichzeitig** betrachten

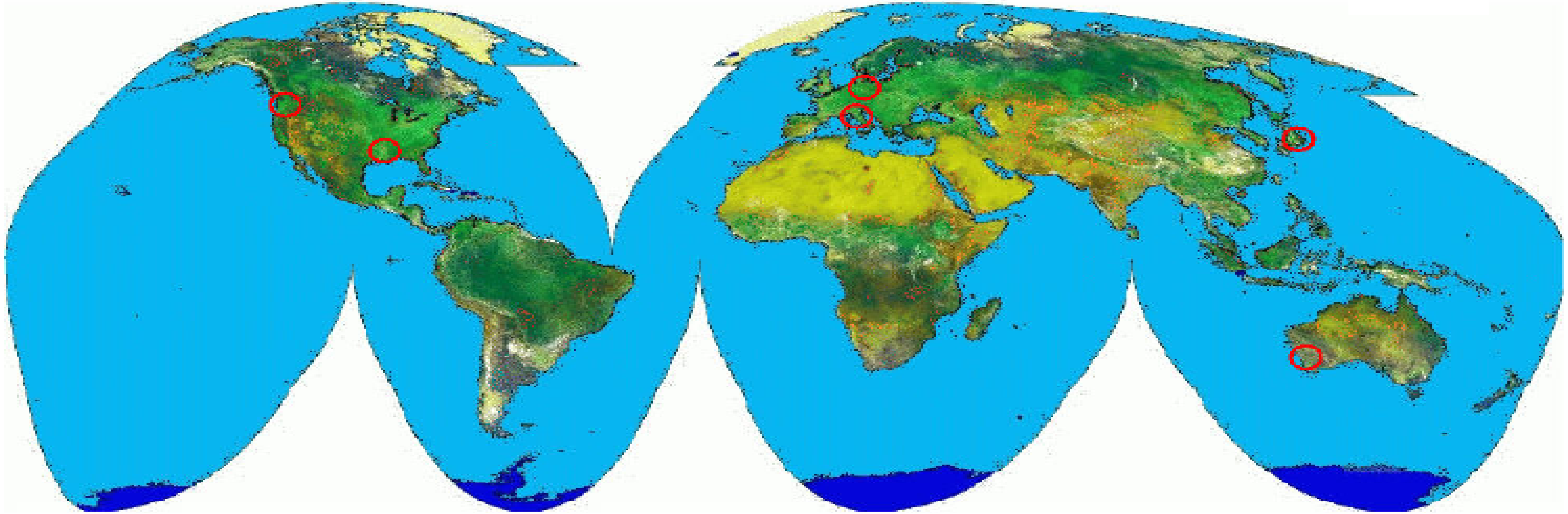




Eine weltweites Netz von GW-Detektoren

LIGO | VIRGO | GEO 600 | TAMA

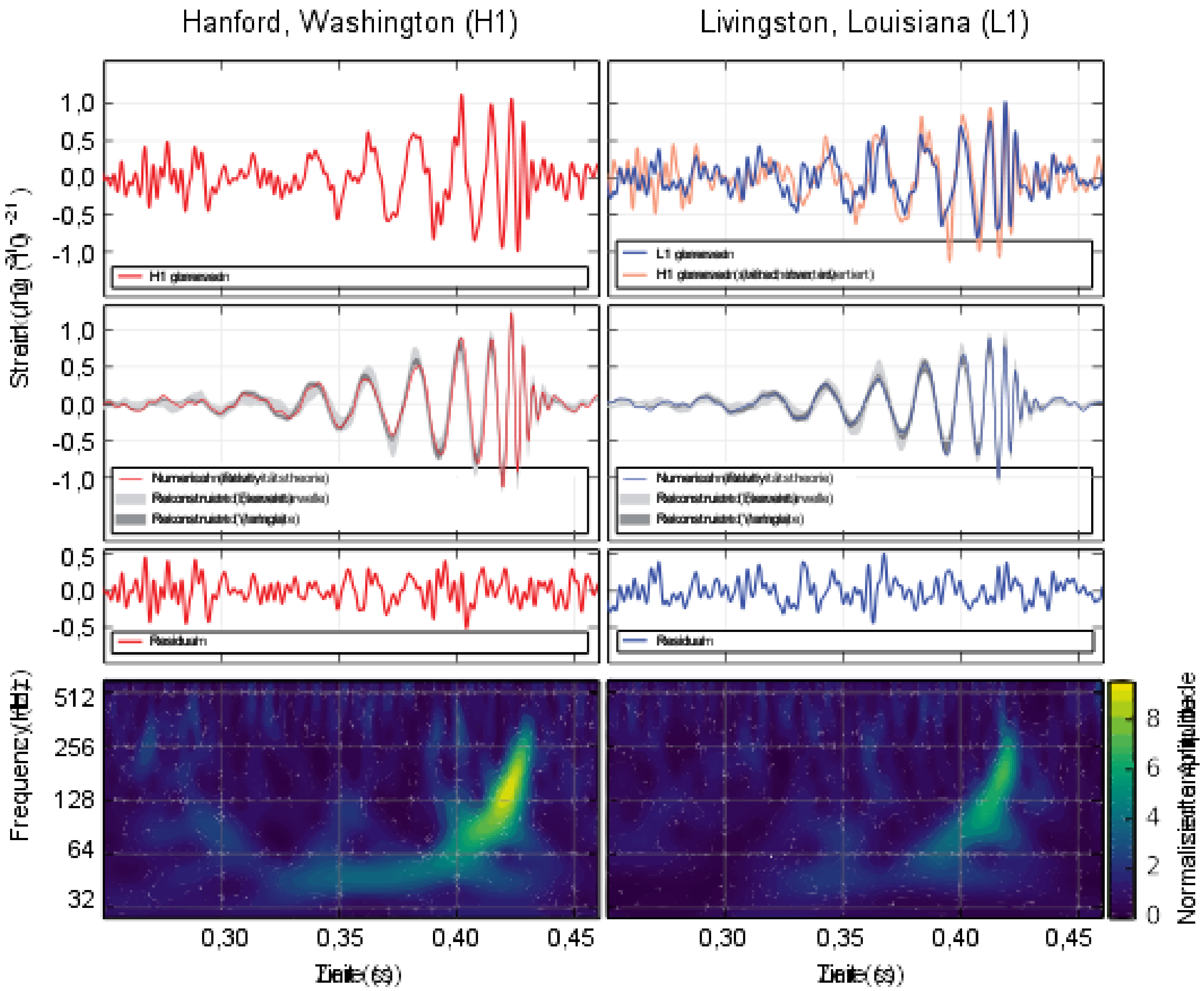
2 × 4 km | 3 km | 600 m | 300 m



LSC LIGO Scientific Collaboration

AIGO

LIGO (Laser Interferometer Gravitational wave Observatory) Handford (USA).



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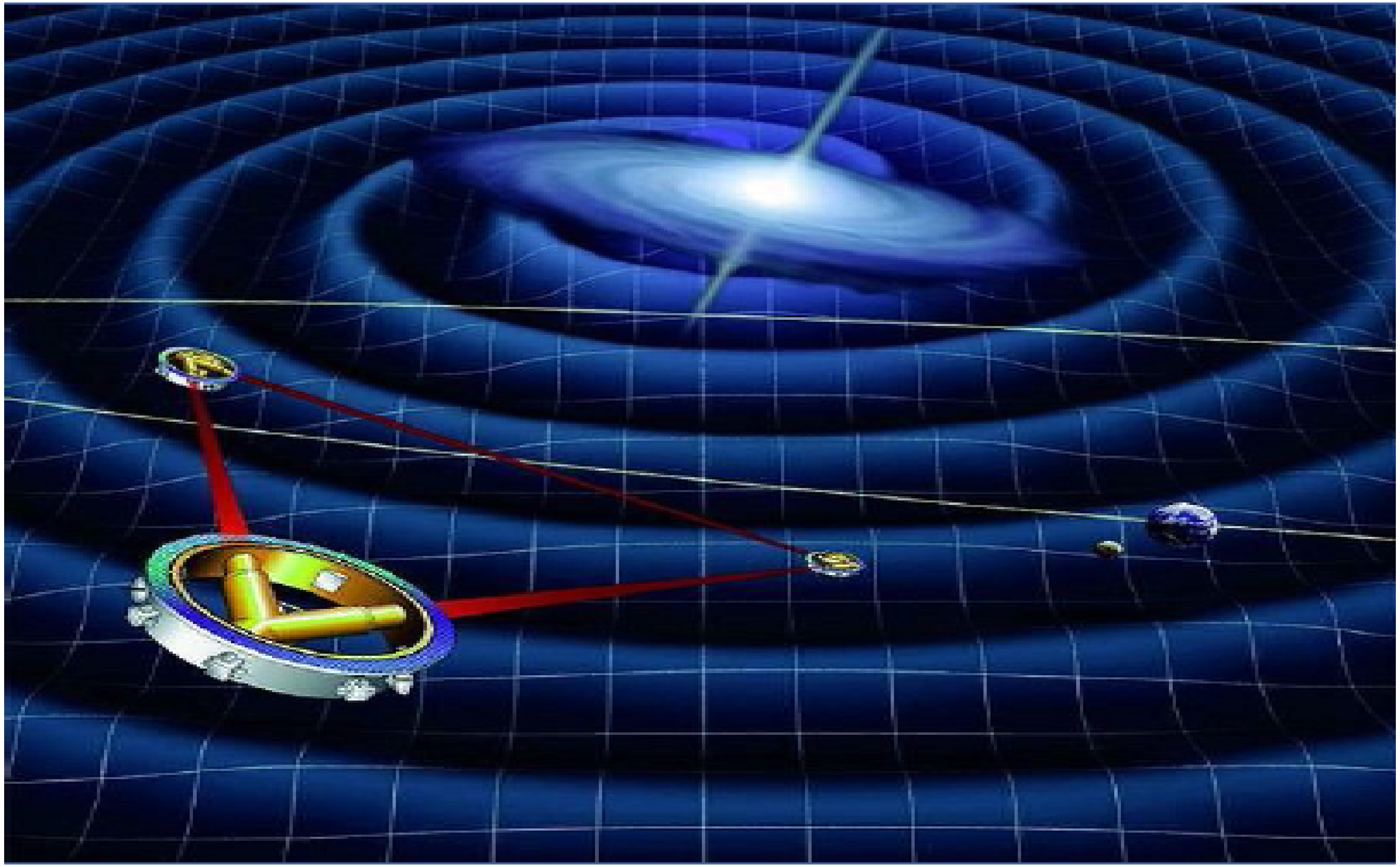

LISA (Laser Interferometer Space Antenna): Satellit zur Detektion von Gravitationswellen.

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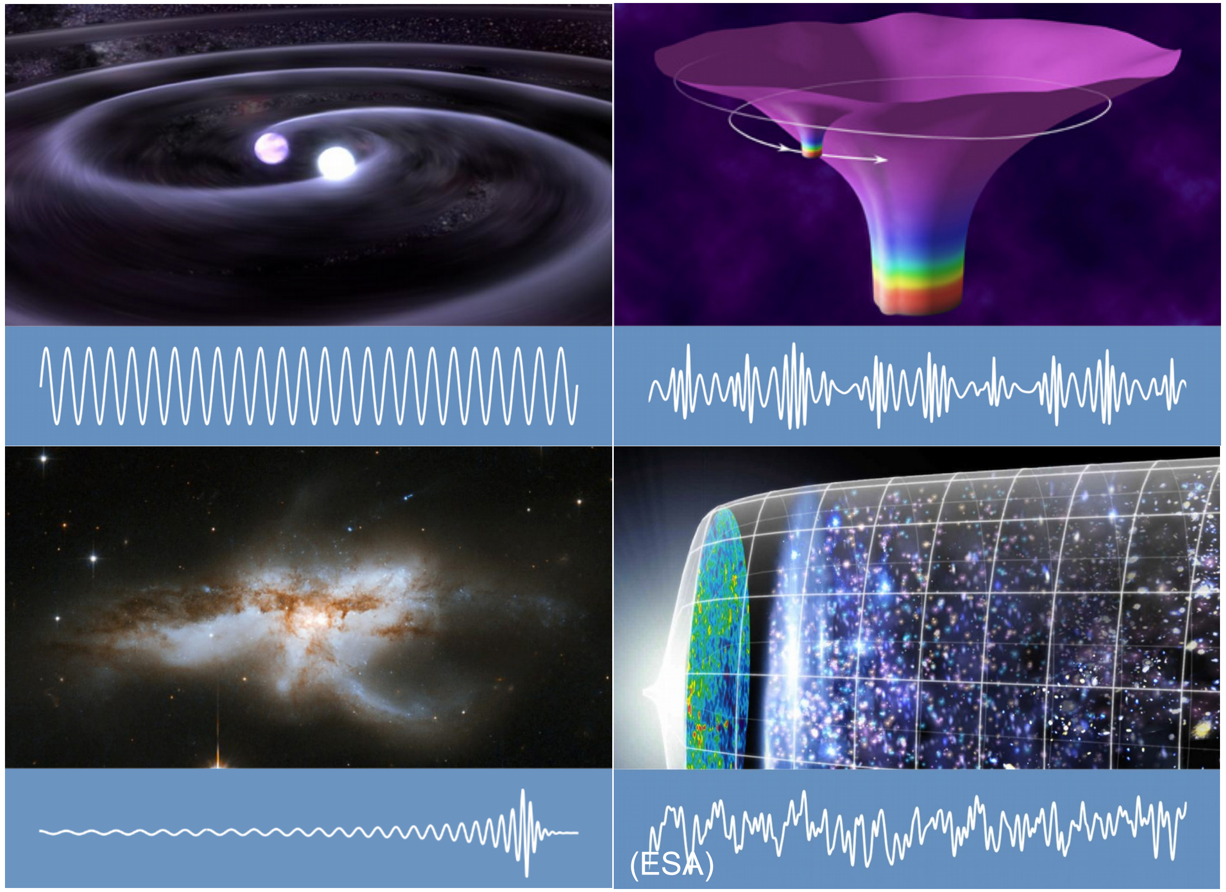
LISA (Laser Interferometer Space Antenna)

- LISA is a mission to detect and observe gravitational waves
  - Gravitational waves are predicted by any "reasonable" theory of gravity
  - Yet not directly detected
  - Gravitational waves are a tool for astronomers, astrophysicists and cosmologists
- LISA will address important questions in fundamental physics, astrophysics and cosmology
  - Precision tests of GR
  - Nature of objects in the centre of galaxies
  - History and evolution of galaxies
  - Structure formation in the Universe

Different Sources – Different Signals

Binary White Dwarfs,
Neutron Stars,
Stellar Black Holes

Extreme
Mass-Ratio
In-Spirals



Coalescence of
Massive
Black Holes

Primordial
Gravitational
Waves

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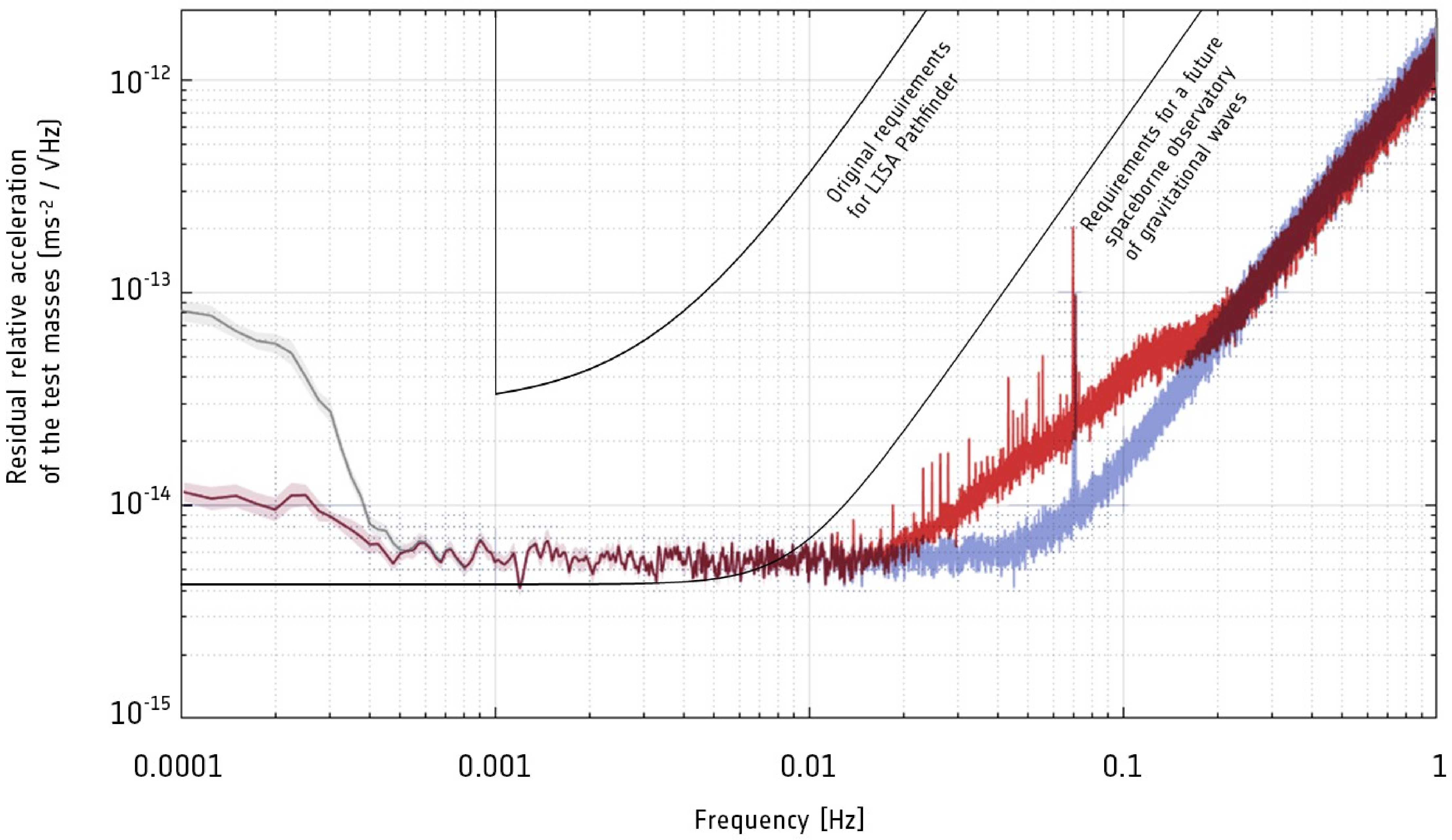
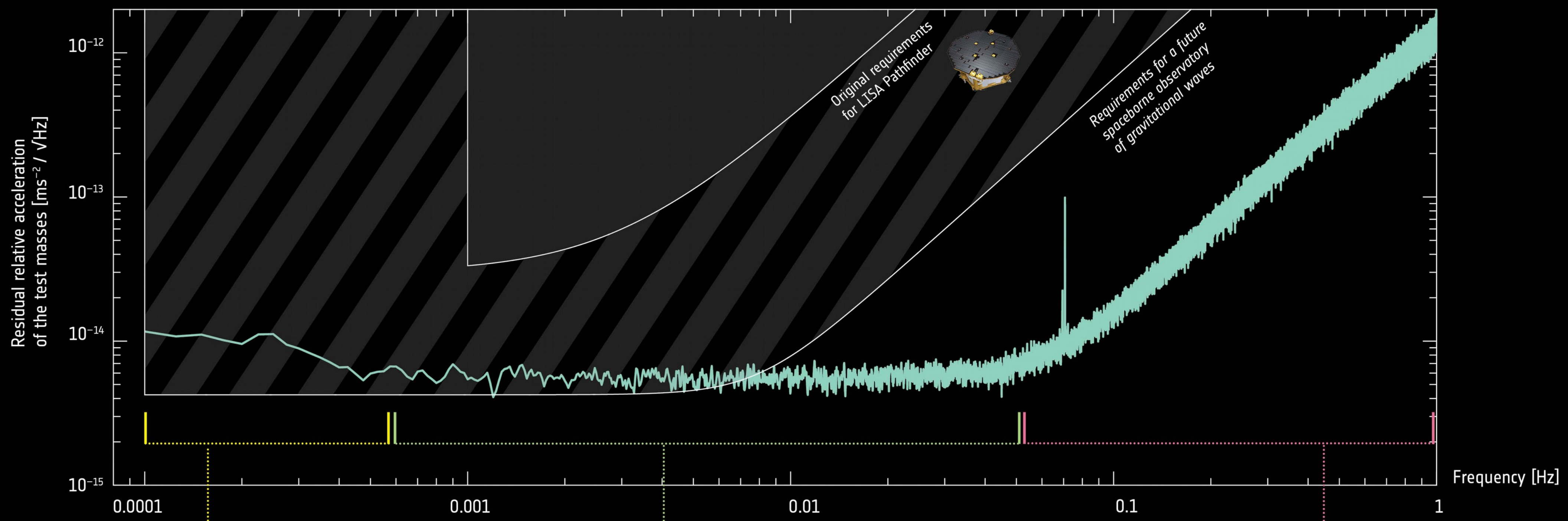
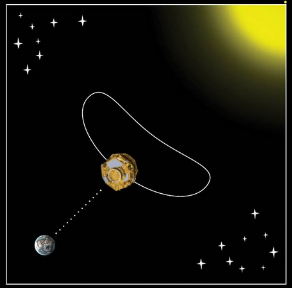
VEGA Rakete in Kourou. Start 3 Dezember 2015



Residual relative acceleration of the test masses [ms-2 / √Hz]
10-12
10-13
10-14
10-15
0.0001
0.001
0.01
0.1
1
Frequency [Hz]
Original requirements for LISA Pathfinder
Requirements for a future spaceborne observatory of gravitational waves

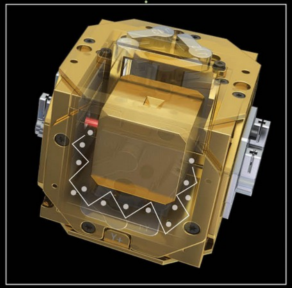
→ LISA PATHFINDER EXCEEDS EXPECTATIONS





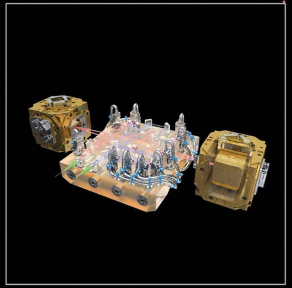
Centrifugal force

The rotation of the spacecraft required to keep the solar array pointed at the Sun and the antenna pointed towards Earth, coupled with the noise of the startrackers produces a noisy centrifugal force on the test masses. This noise term has been subtracted, and the source of the residual noise after subtraction is still being investigated.



Gas damping

Inside their housings, the test masses collide with some of the few gas molecules still present. This noise term becomes smaller with time, as more gas molecules are vented to space.



Sensing noise

The sensing noise of the optical metrology system used to monitor the position and orientation of the test masses, at a level of 35 fm / √Hz, has already surpassed the level of precision required by a future gravitational-wave observatory by a factor of more than 100.

www.esa.int

Spacecraft: ESA/ATG medialab; data: ESA/LISA Pathfinder Collaboration

European Space Agency