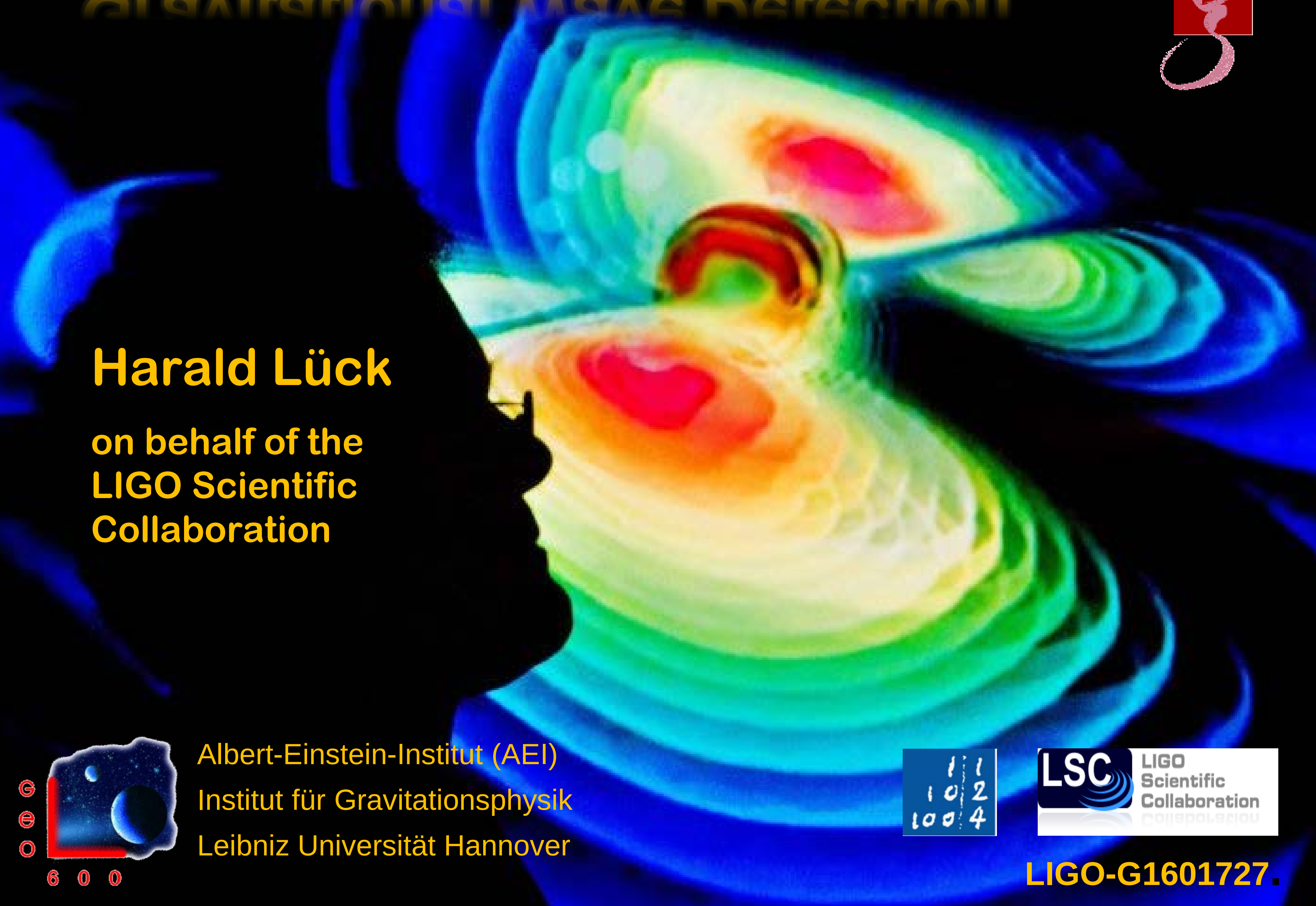
Gravitational Wave Detection



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on behalf of the
LIGO Scientific
Collaboration

Albert-Einstein-Institut (AEI)
Institut für Gravitationsphysik
Leibniz Universität Hannover

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Press conference
Feb. 11th 2016
Washington D.C.

We have detected

GRAVITATIONAL WAVES !

We did it !

Selected for a Viewpoint in *Physics*
PHYSICAL REVIEW LETTERS

Who is *WE*? → paper has 1004 authors

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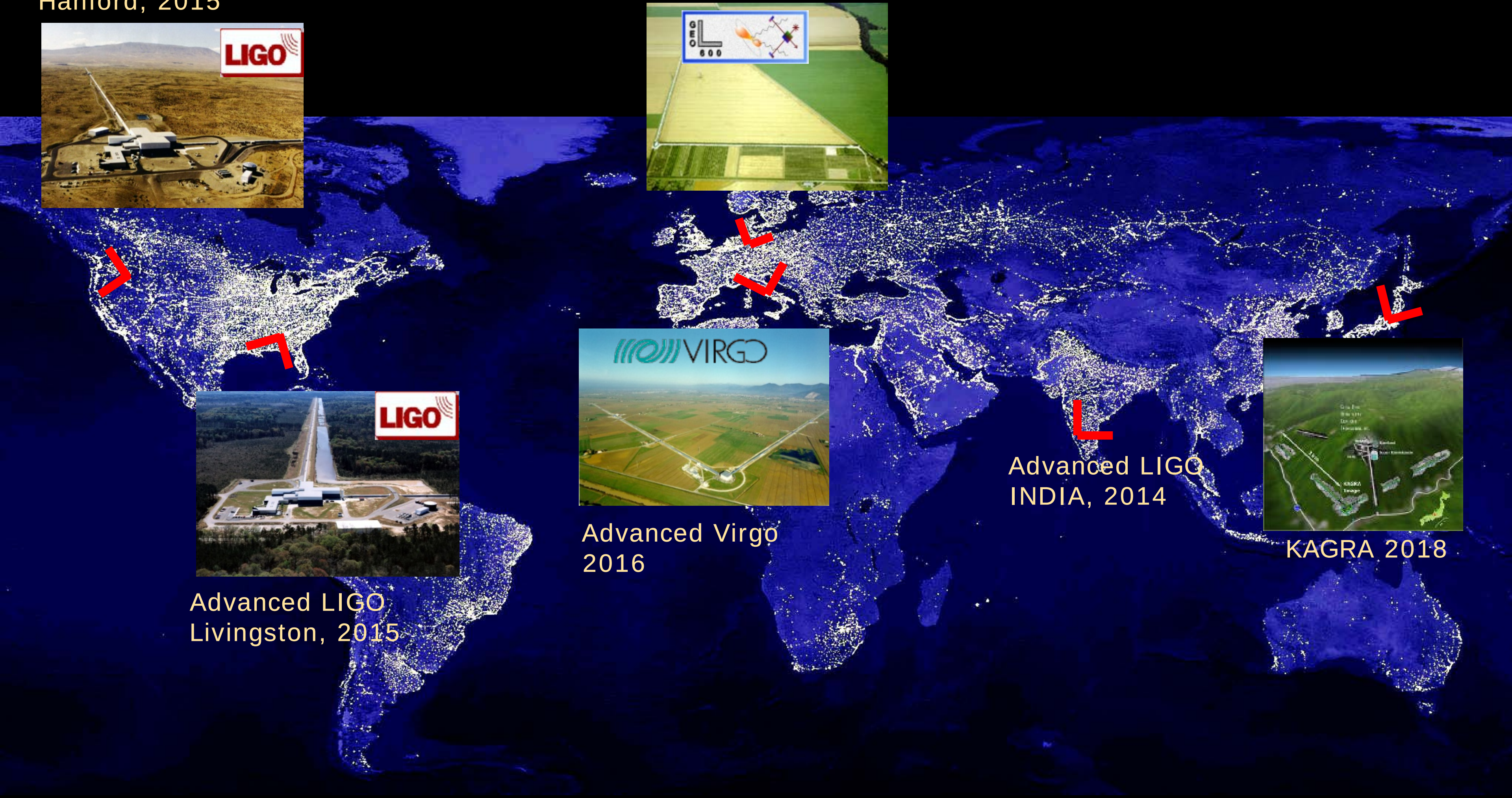
L.-W. Wei,[52] M. Weinert,[8] A. J. Weinstein,[1] R. Weiss,[10] T. Welborn,[6] L. Wen,[50] P. Weßels,[8] M. West,[35] T. Westphal,[8]
K. Wette,[8] J. T. Whelan,[112,8] D. J. White,[86] B. F. Whiting,[5] K. Wiesner,[8] R. D. Williams,[1] A. R. Williamson,[91]
J. L. Willis,[133] B. Willke,[17,8] M. H. Wimmer,[8,17] W. Winkler,[8] C. C. Wipf,[1] A. G. Wiseman,[16] H. Wittel,[8,17] G. Woan,[36]
J. Worden,[37] J. L. Wright,[36] G. Wu,[6] J. Yablon,[82] W. Yam,[10] H. Yamamoto,[1] C. C. Yancey,[62] M. J. Yap,[20] H. Yu,[10]
M. Yvert,[7] A. Zadrożny,[110] L. Zangrando,[42] M. Zanolin,[97] J.-P. Zendri,[42] M. Zevin,[82] F. Zhang,[10] L. Zhang,[1] M. Zhang,[119]
Y. Zhang,[112] C. Zhao,[50] M. Zhou,[82] Z. Zhou,[82] X. J. Zhu,[50] M. E. Zucker,[1,10] S. E. Zuraw,[101] and J. Zweizig[1]

Phys. Rev. Lett. 116, 061102

The advanced GW Network



Advanced LIGO
Hanford, 2015

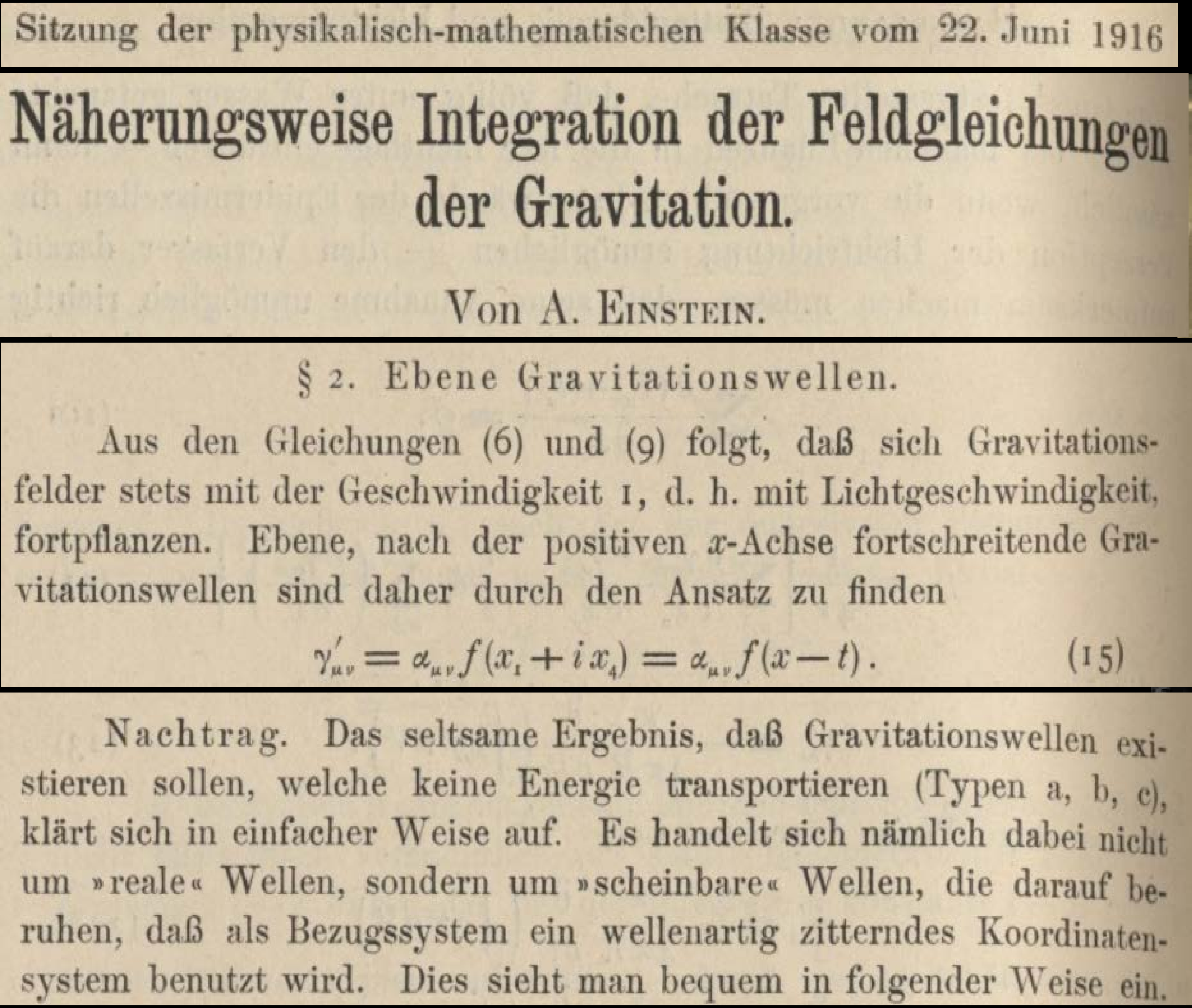
GEO600, 2011

Advanced LIGO
Livingston, 2015

Advanced Virgo
2016

Advanced LIGO
INDIA, 2014

KAGRA 2018



Sitzung der physikalisch-mathematischen Klasse vom 22. Juni 1916

Näherungsweise Integration der Feldgleichungen der Gravitation.

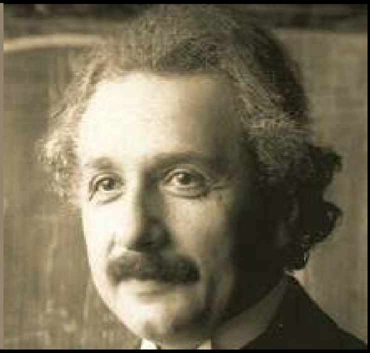
Von A. Einstein.

§ 2. Ebene Gravitationswellen.

Aus den Gleichungen (6) und (9) folgt, daß sich Gravitationsfelder stets mit der Geschwindigkeit 1, d. h. mit Lichtgeschwindigkeit, fortpflanzen. Ebene, nach der positiven x-Achse fortschreitende Gravitationswellen sind daher durch den Ansatz zu finden

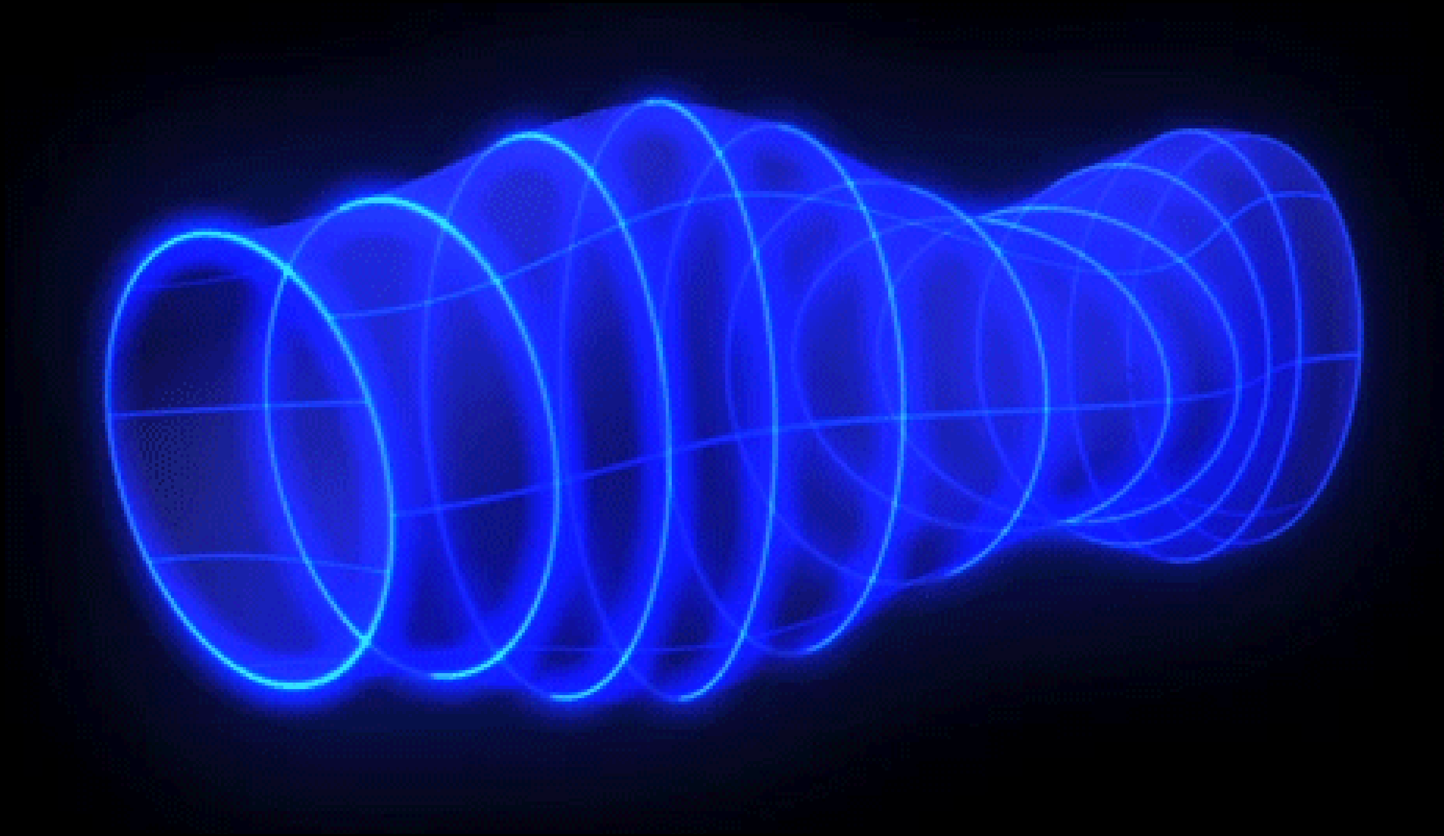
$$\gamma'_{\mu\nu} = \alpha_{\mu\nu} f(x_1 + i x_4) = \alpha_{\mu\nu} f(x - t) . \tag{15}$$

Nachtrag. Das seltsame Ergebnis, daß Gravitationswellen existieren sollen, welche keine Energie transportieren (Typen a, b, c), klärt sich in einfacher Weise auf. Es handelt sich nämlich dabei nicht um »reale« Wellen, sondern um »scheinbare« Wellen, die darauf beruhen, daß als Bezugssystem ein wellenartig zitterndes Koordinatensystem benutzt wird. Dies sieht man bequem in folgender Weise ein.



Propagating Gravitational Waves

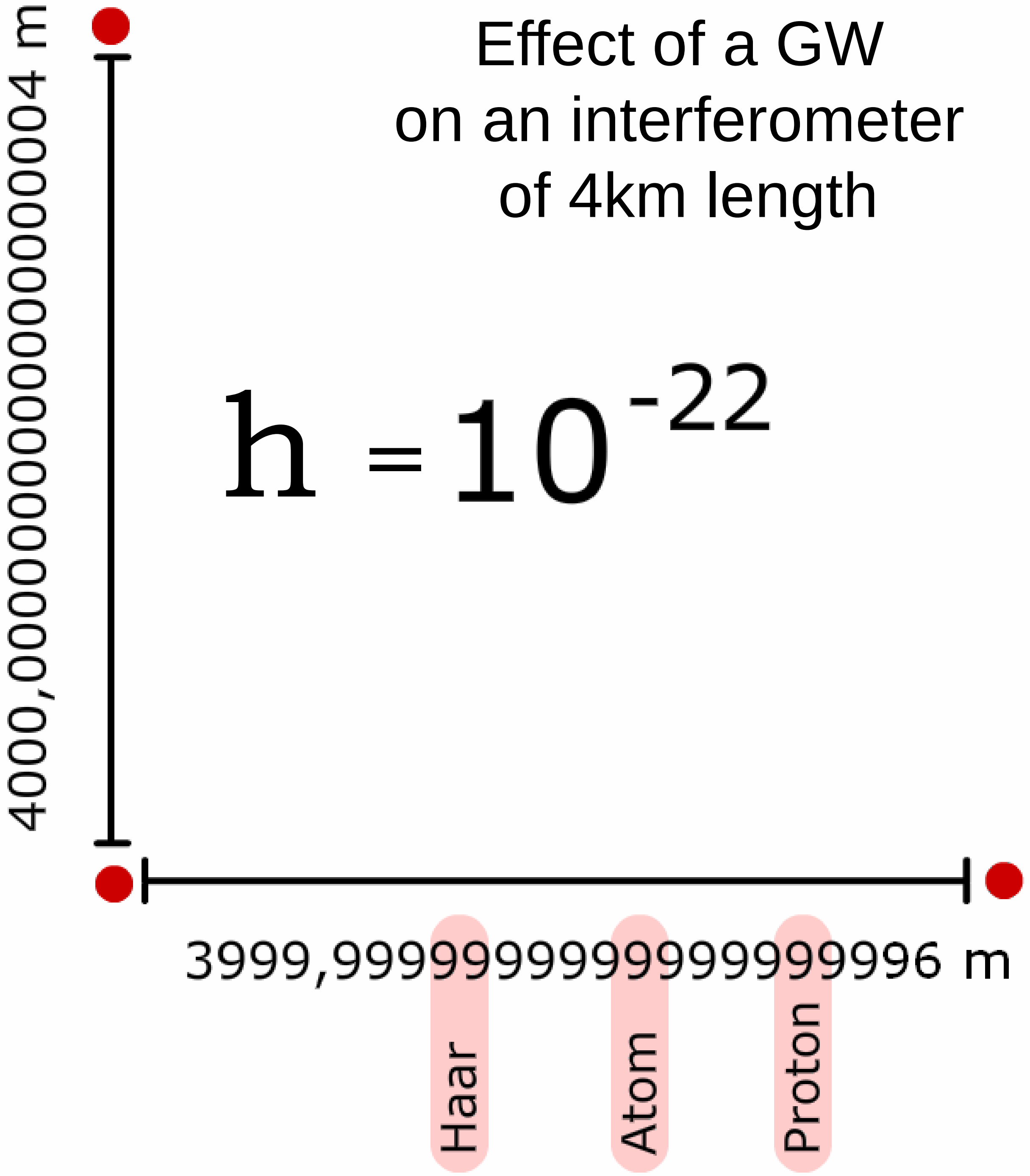
- Transversal waves in space-time travelling @ speed of light



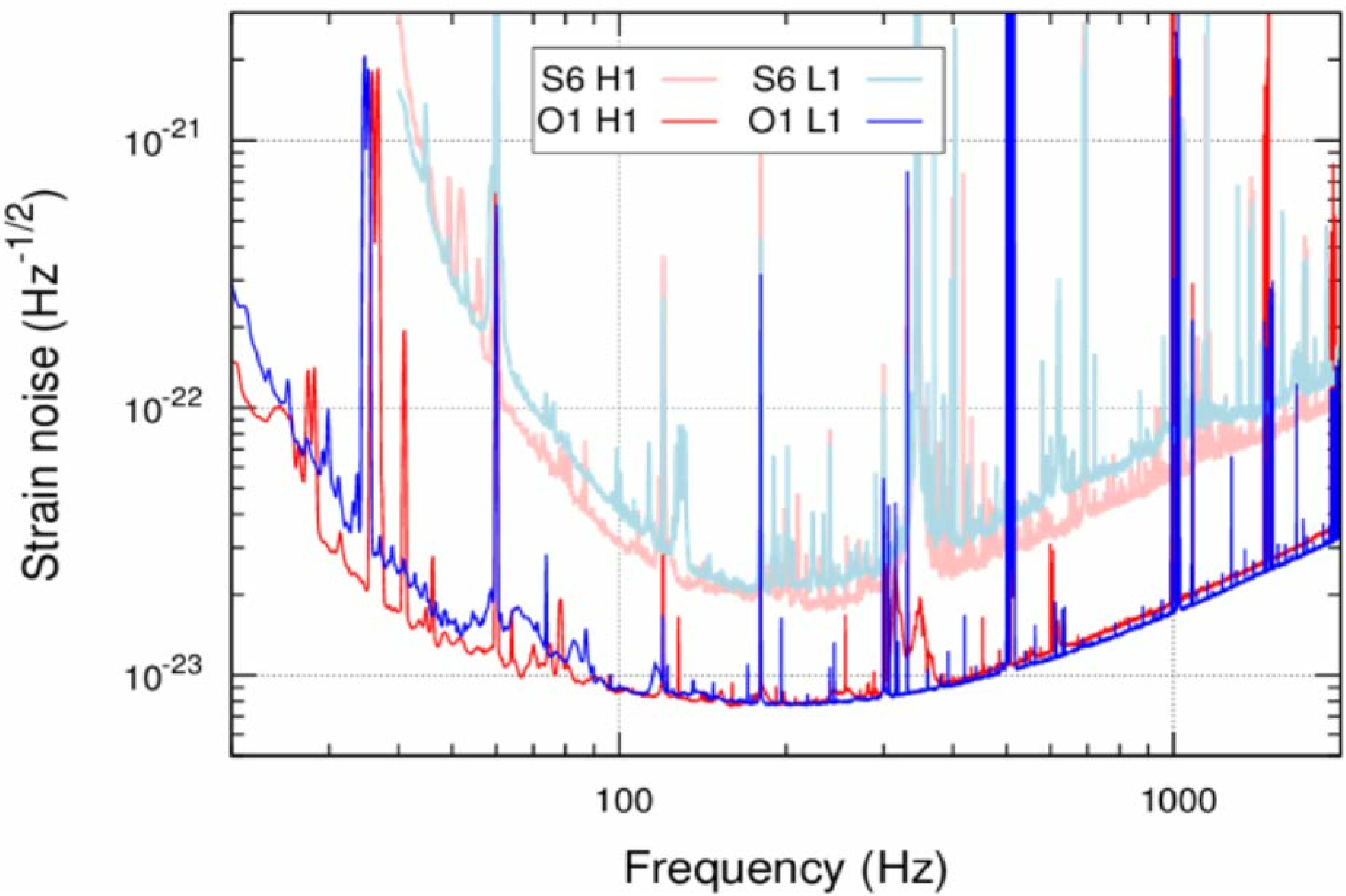
Credit: ESA–C.Carreau

Effect of a GW on an interferometer of 4km length

$$h = 10^{-22}$$



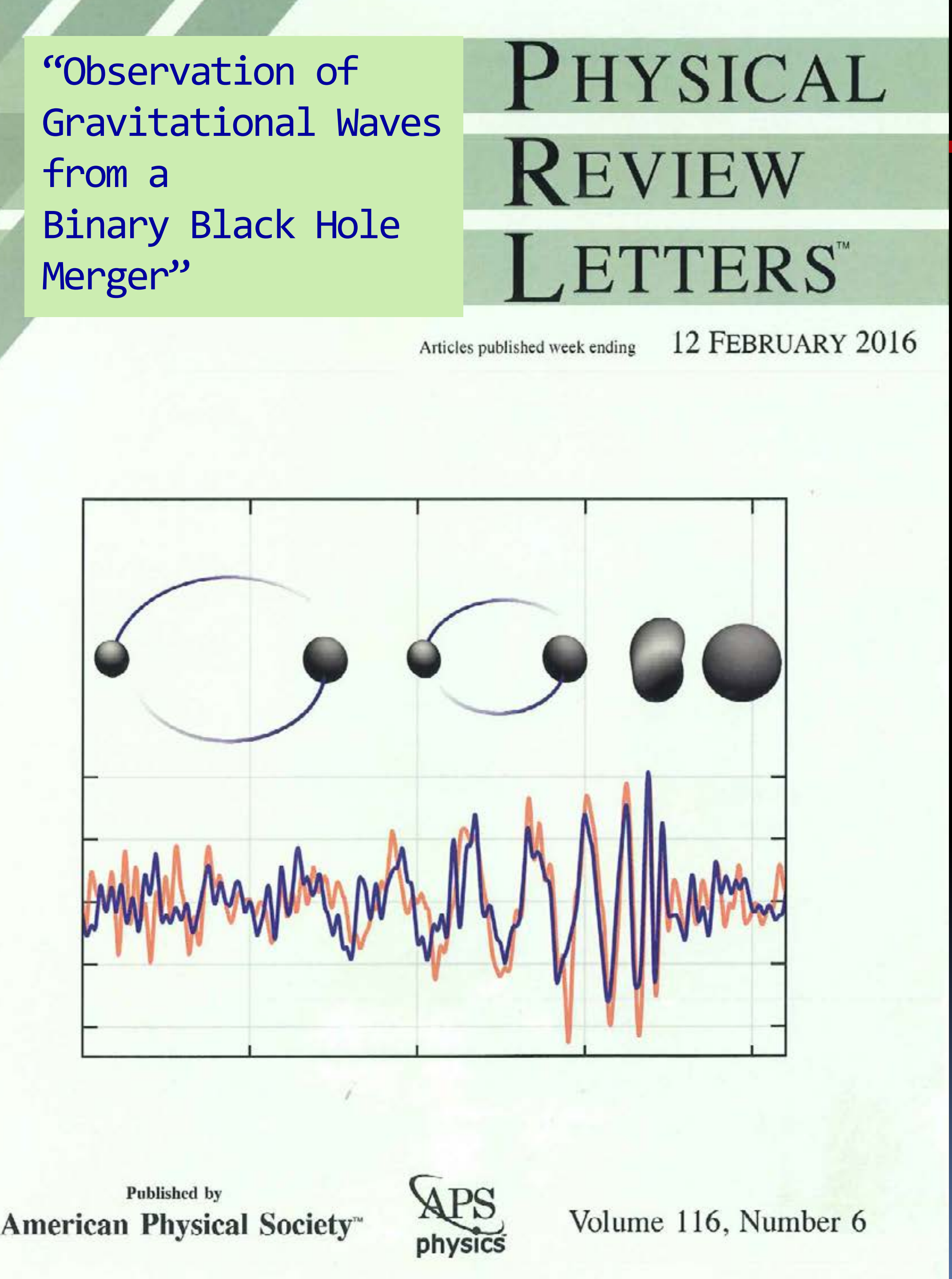
Sensitivity improvement eLIGO <-> aLIGO



THE Detection

GW150914

“Observation of Gravitational Waves from a Binary Black Hole Merger”



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APS physics

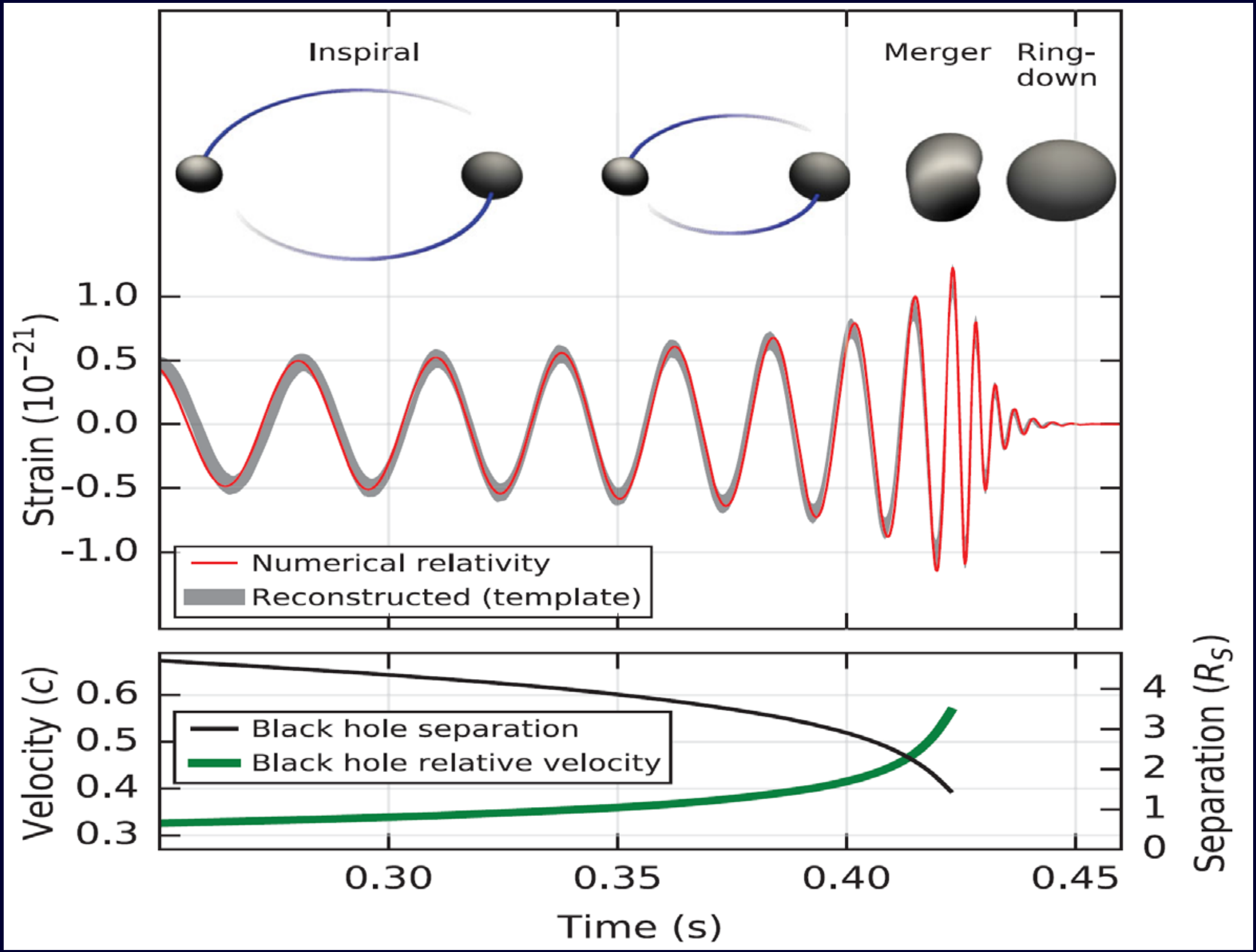
Volume 116, Number 6

14. September 2015
09:50:45 UTC
= 11:50:45 CEST

Detection of a transient signal in **both** advanced LIGO detectors

GW150914

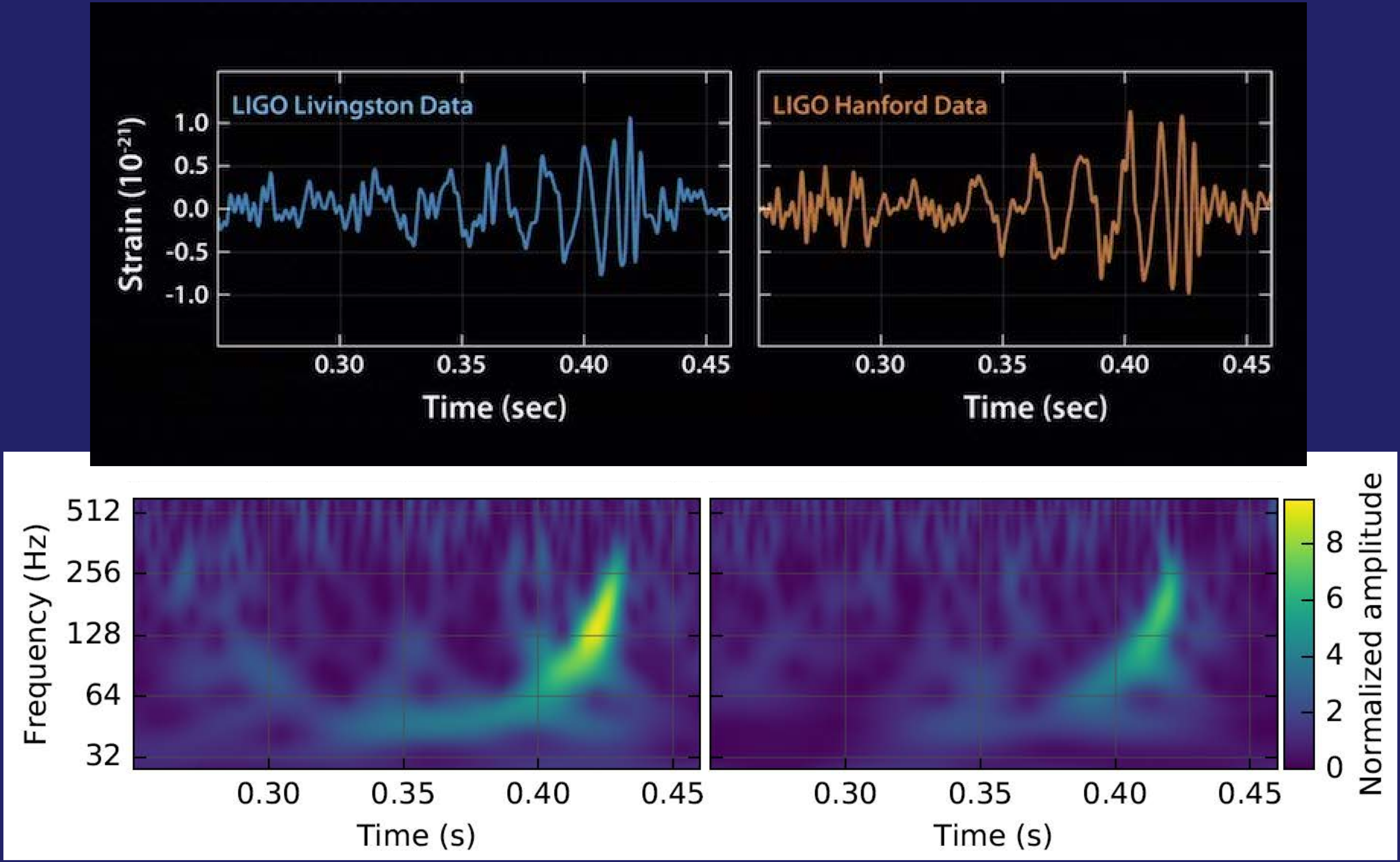
Phys. Rev. Lett. 116, 061102



GW150914

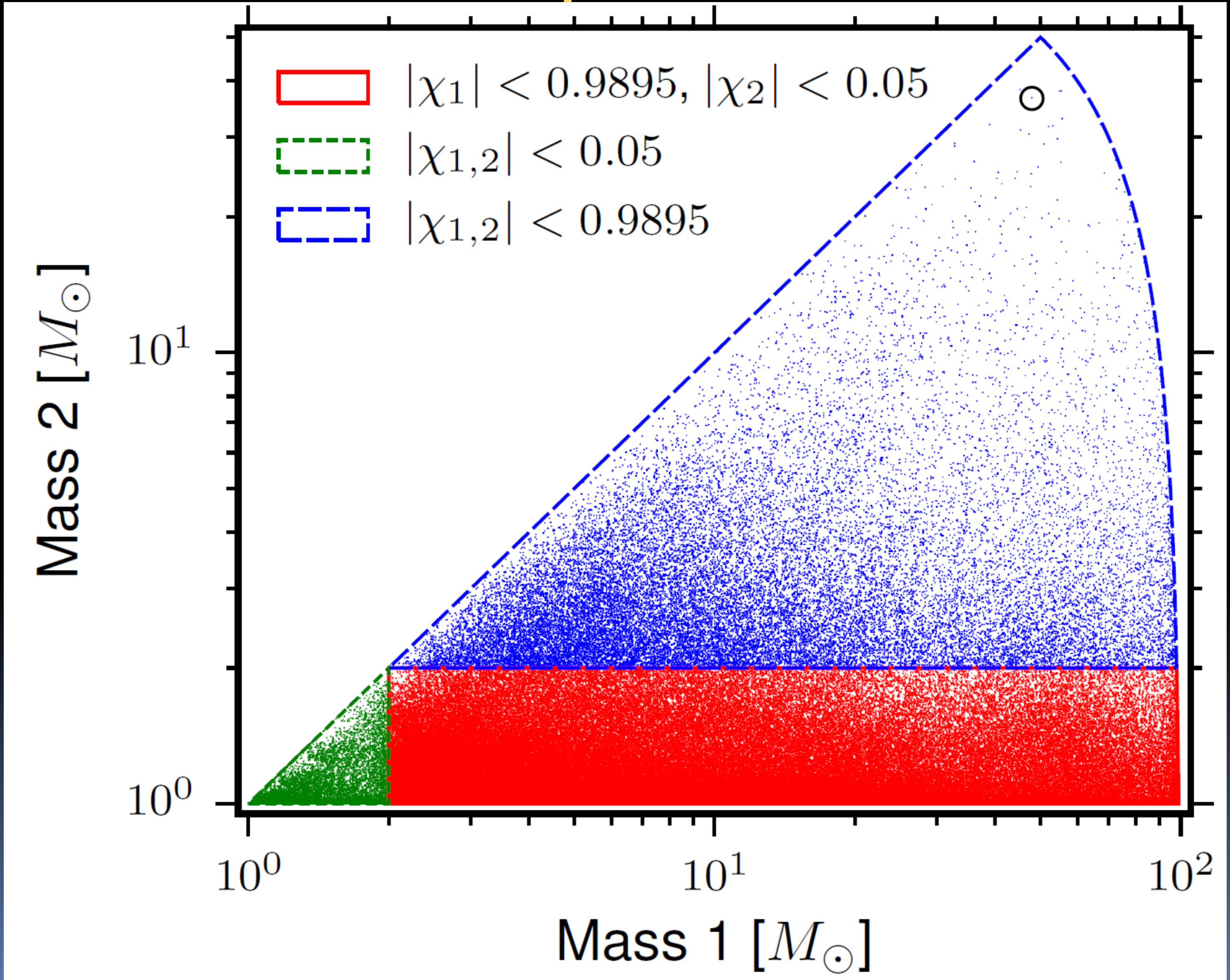
GW150914 = Binary BH

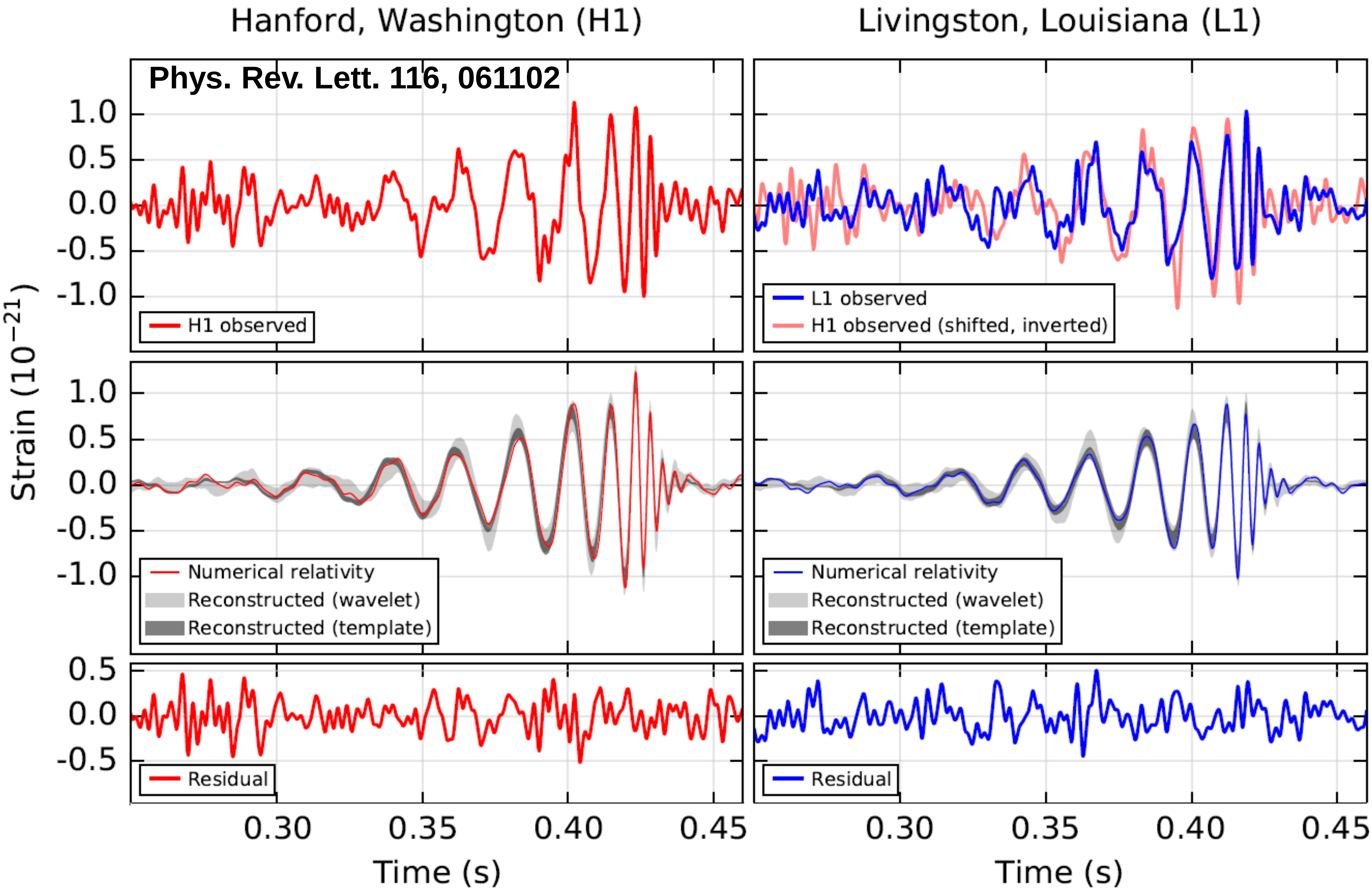
Phys. Rev. Lett. 116, 061102



Large template bank to determine parameters

Phys. Rev. Lett. 116, 061102





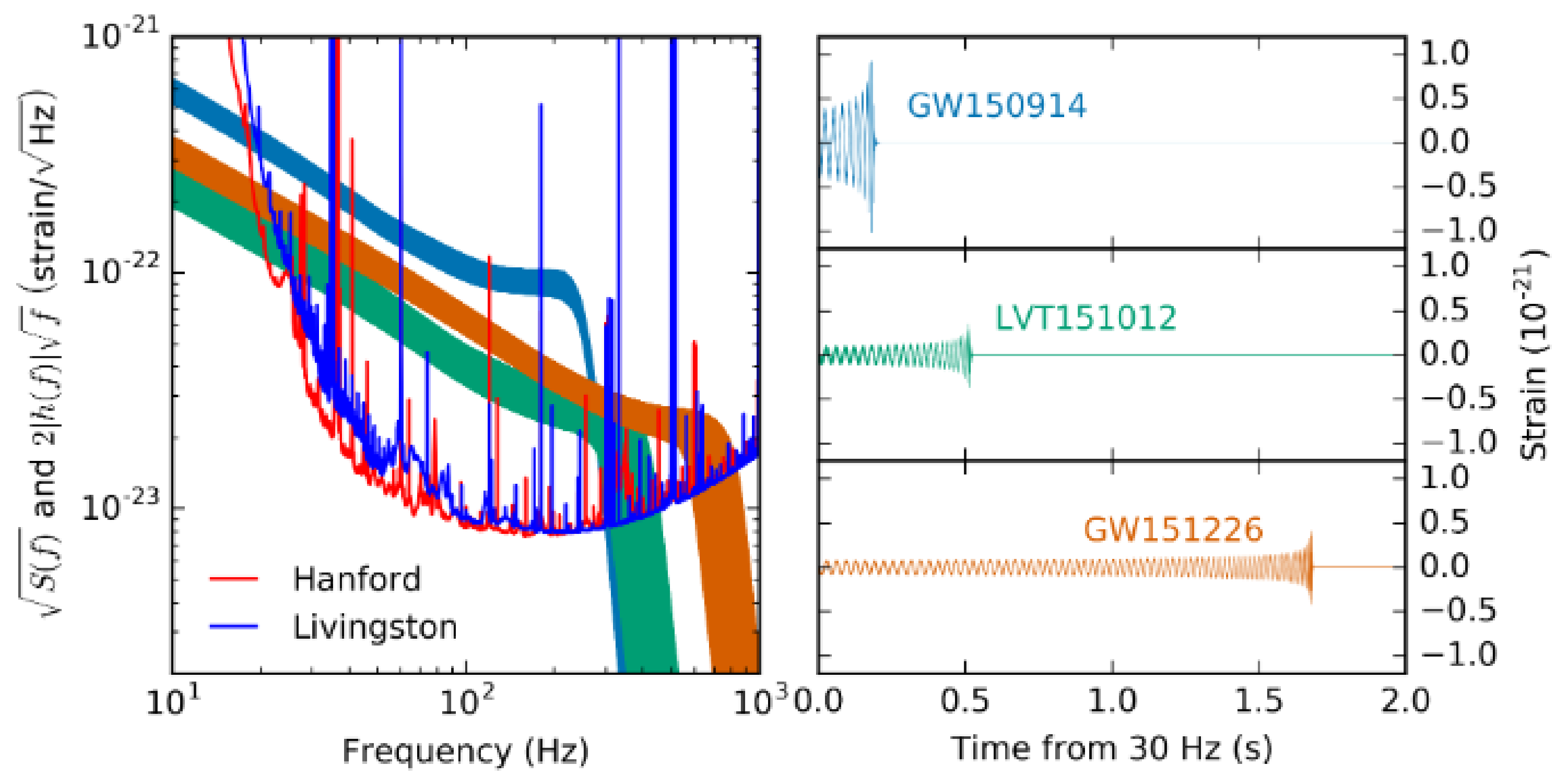
Two black holes with 29 and 36 solar masses

The most powerful event ever “seen”

GW150914

- Before: two BHs (29 $M_\odot$ + 36 $M_\odot$ = 65 $M_\odot$)
- After: One BH (62 $M_\odot$)
- Within 0.2 sec 2 $M_\odot$ were radiated off in GWs $= 4 \times 10^{30}$ kg ($E=M c^2$)
- 3.5×10^{56} erg / s $= 3.5 \times 10^{49}$ W
- 50x as much as all stars in the universe together

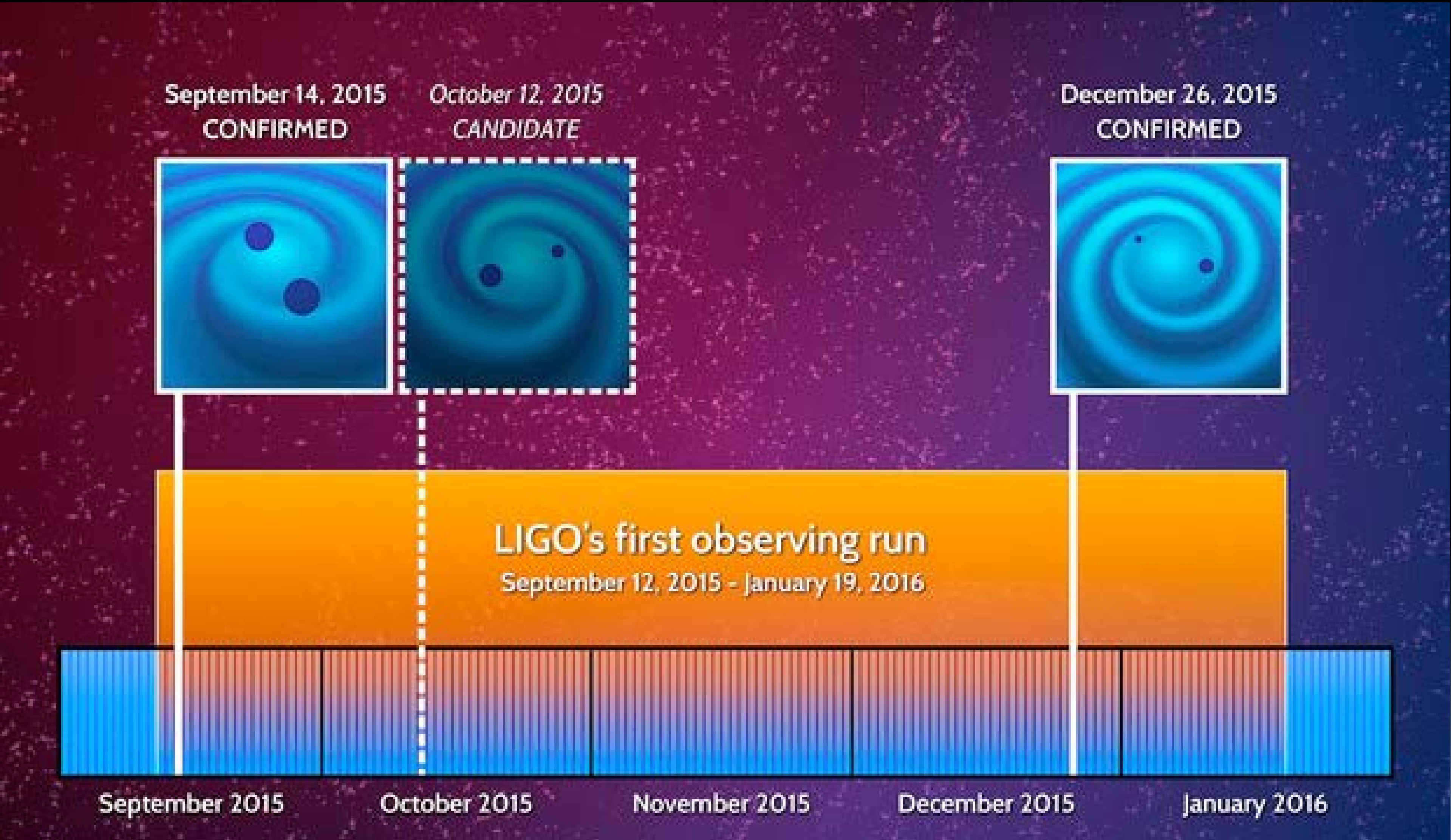
There were more Signals in O1



arXiv:1606.04856 and acc. by Phys. Rev. X;

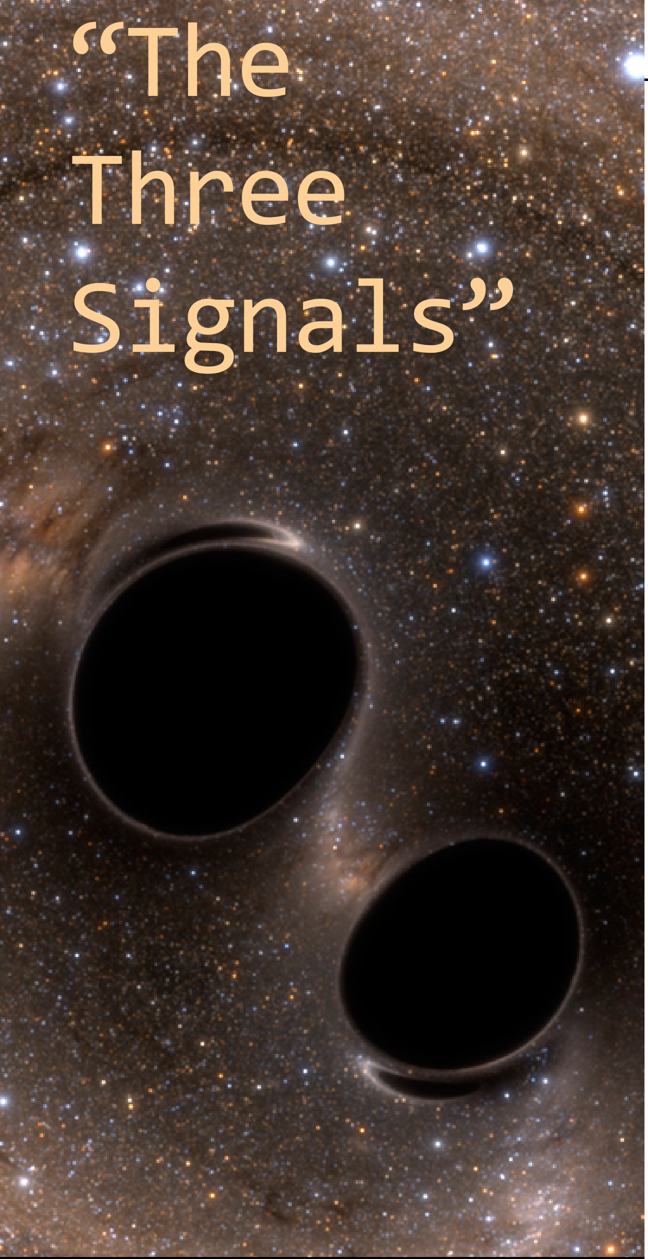
Binary Black Hole Mergers in the first
Advanced LIGO Observing Run

Discovery Timeline O1

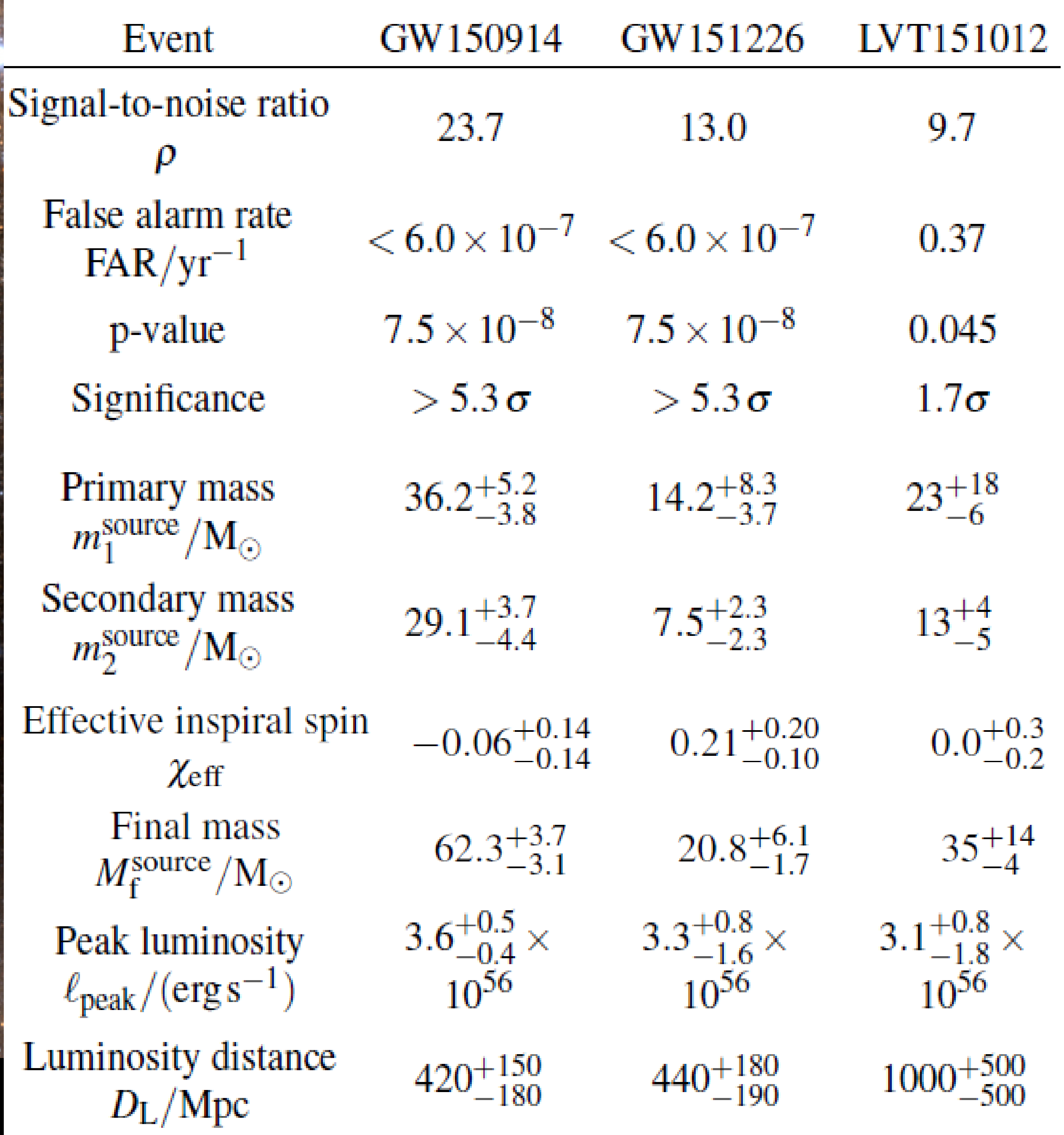


Courtesy Caltech/MIT/LIGO Laboratory

“The Three Signals”



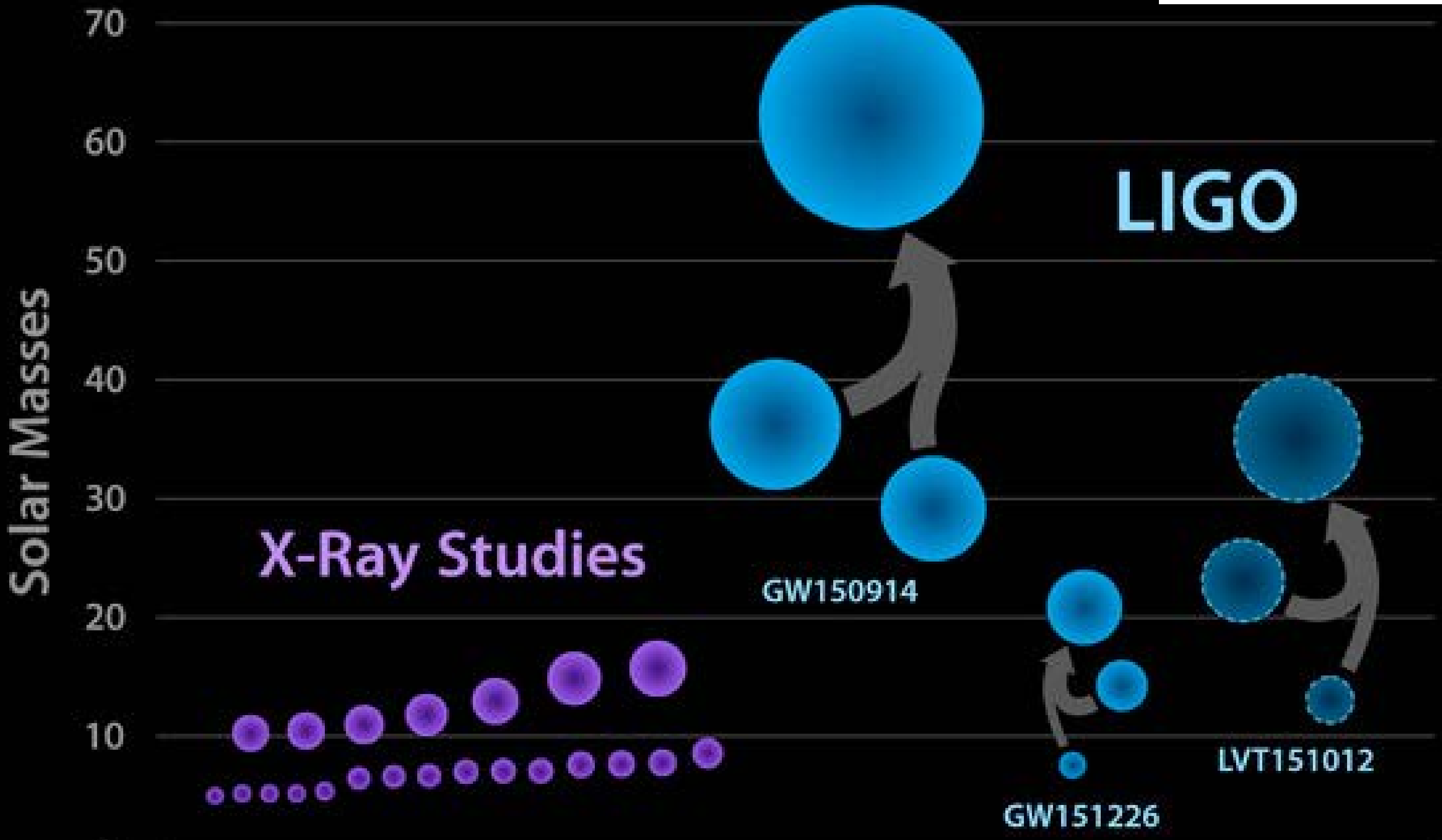
journals.aps.org/prl/abstract/10.1103/PhysRevLett.116.241103, arxiv.org/abs/1606.04856 (accepted to PRX)



Event	GW150914	GW151226	LVT151012
Signal-to-noise ratio ρ	23.7	13.0	9.7
False alarm rate $\mathrm{FAR/yr^{-1}}$	$< 6.0 \times 10^{-7}$	$< 6.0 \times 10^{-7}$	0.37
p-value	7.5×10^{-8}	7.5×10^{-8}	0.045
Significance	$> 5.3\,\sigma$	$> 5.3\,\sigma$	1.7σ
Primary mass $m_1^{\mathrm{source}}/\mathrm{M}_\odot$	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	23^{+18}_{-6}
Secondary mass $m_2^{\mathrm{source}}/\mathrm{M}_\odot$	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	13^{+4}_{-5}
Effective inspiral spin χ_{eff}	$-0.06^{+0.14}_{-0.14}$	$0.21^{+0.20}_{-0.10}$	$0.0^{+0.3}_{-0.2}$
Final mass $M_{\mathrm{f}}^{\mathrm{source}}/\mathrm{M}_\odot$	$62.3^{+3.7}_{-3.1}$	$20.8^{+6.1}_{-1.7}$	35^{+14}_{-4}
Peak luminosity $\ell_{\mathrm{peak}}/(\mathrm{erg\,s^{-1}})$	$3.6^{+0.5}_{-0.4} \times 10^{56}$	$3.3^{+0.8}_{-1.6} \times 10^{56}$	$3.1^{+0.8}_{-1.8} \times 10^{56}$
Luminosity distance $D_{\mathrm{L}}/\mathrm{Mpc}$	420^{+150}_{-180}	440^{+180}_{-190}	1000^{+500}_{-500}

arXiv:1606.04856

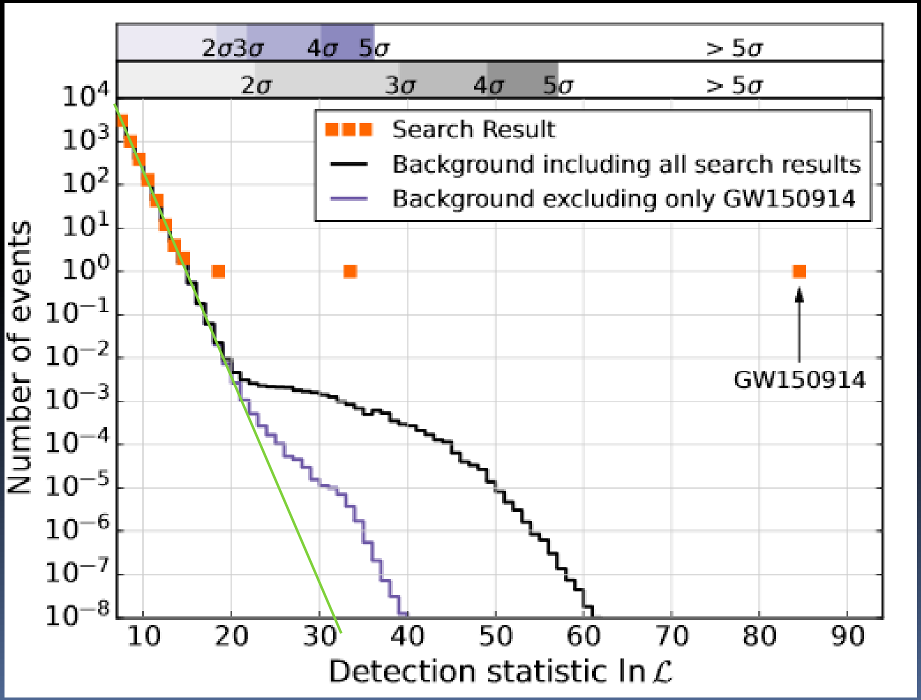
Know Stellar-Mass Black Holes - August 2016

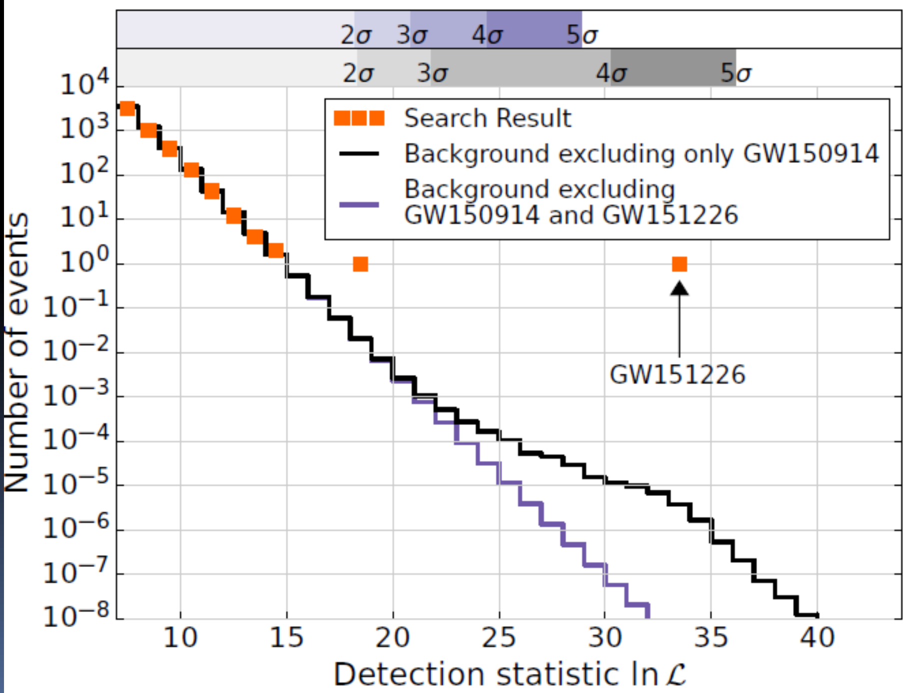


Statistics GW150914 & GW151226

- False alarm rate > 1.6 My
- Significance > 5.3 σ
- False Alarm Probability = 7.5x 10^{-8}

Ca. 48 d coincident time (after cleaning, vetoeing and min. lock duration filter) With 0.1 s time shift background analysis → 1.6My equiv. data





arXiv:1606.04856

Sky Localisation

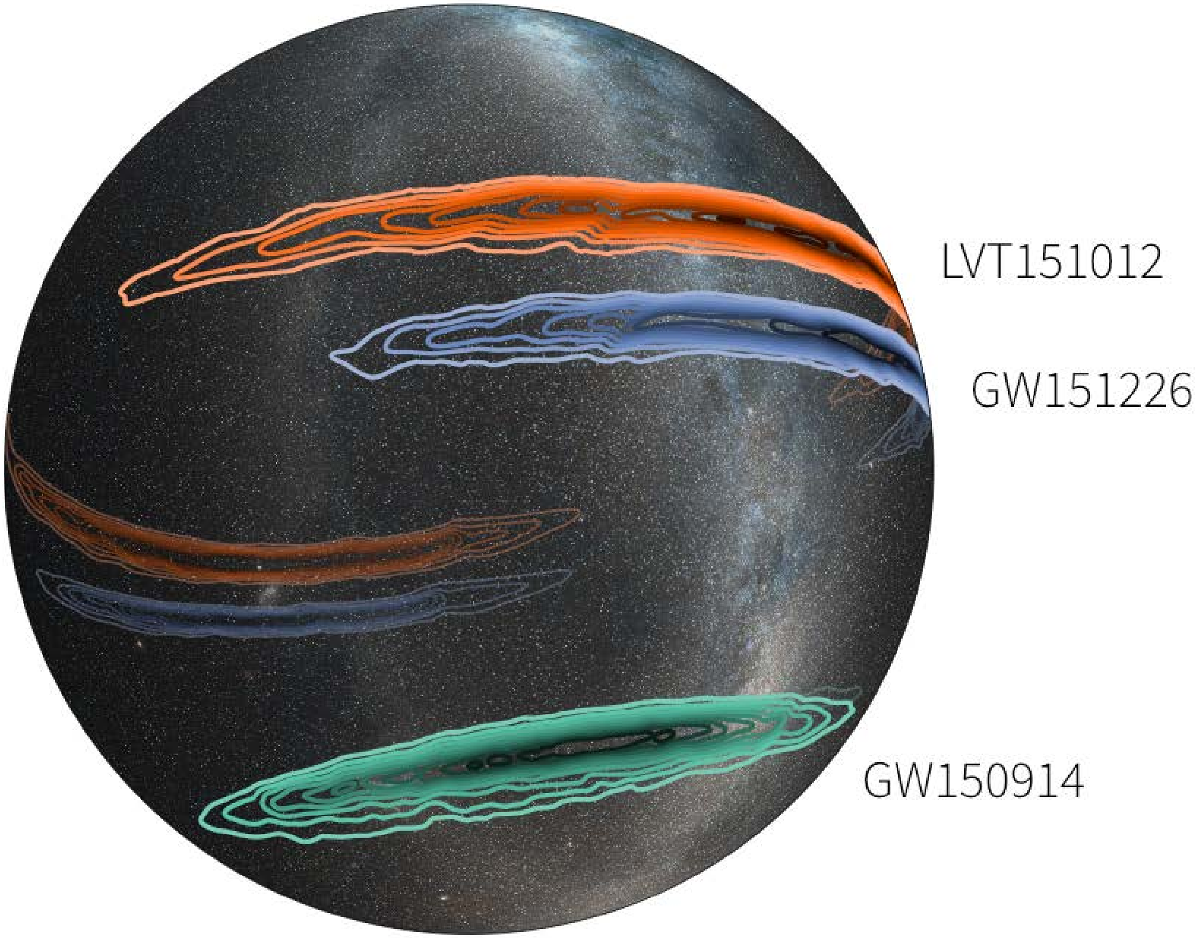
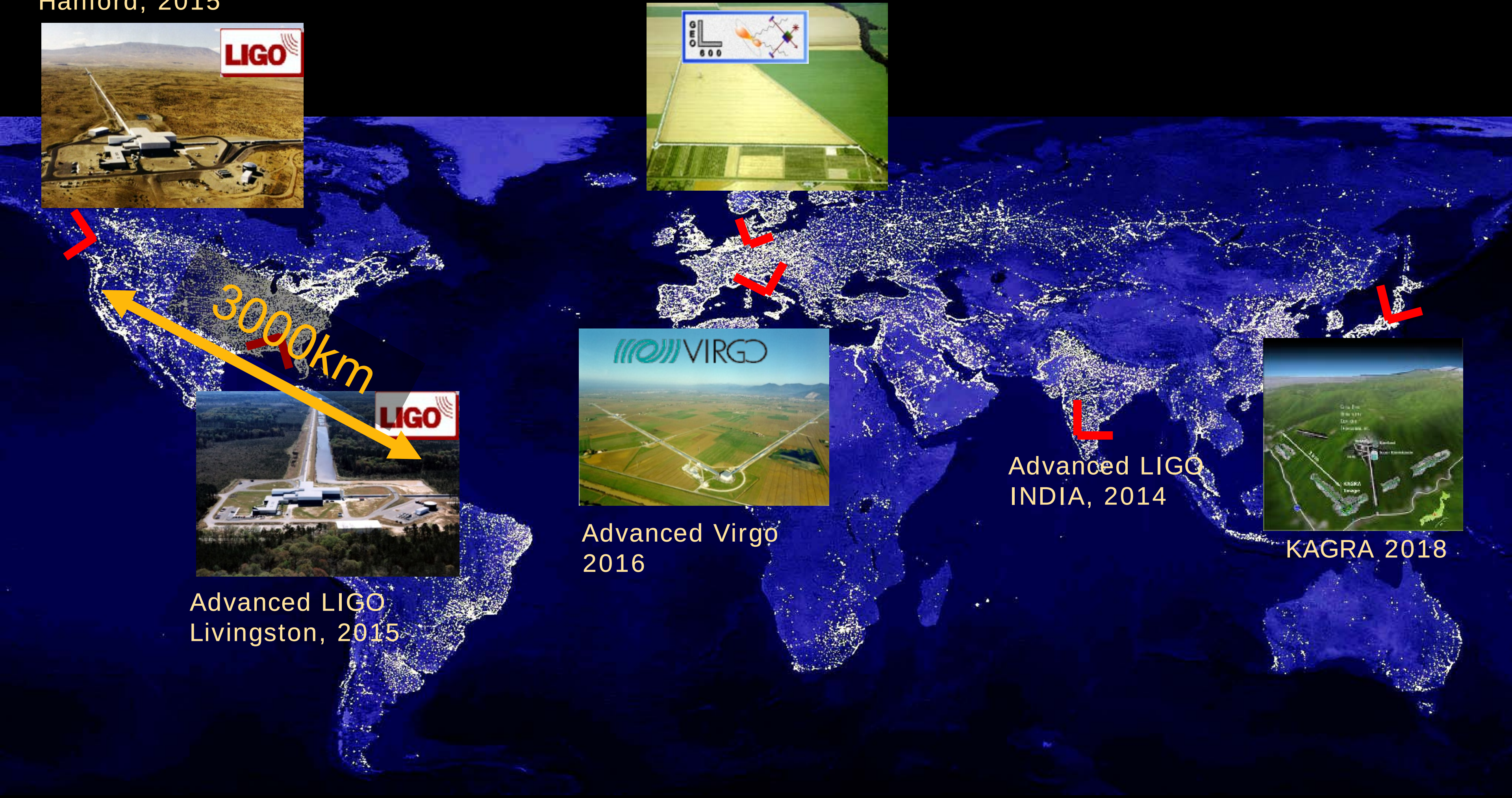


Image credit: LIGO (Leo Singer) /Milky Way image (Axel Mellinger)

The advanced GW Network



Advanced LIGO
Hanford, 2015

GEO600, 2011

Advanced Virgo
2016

Advanced LIGO
INDIA, 2014

KAGRA 2018

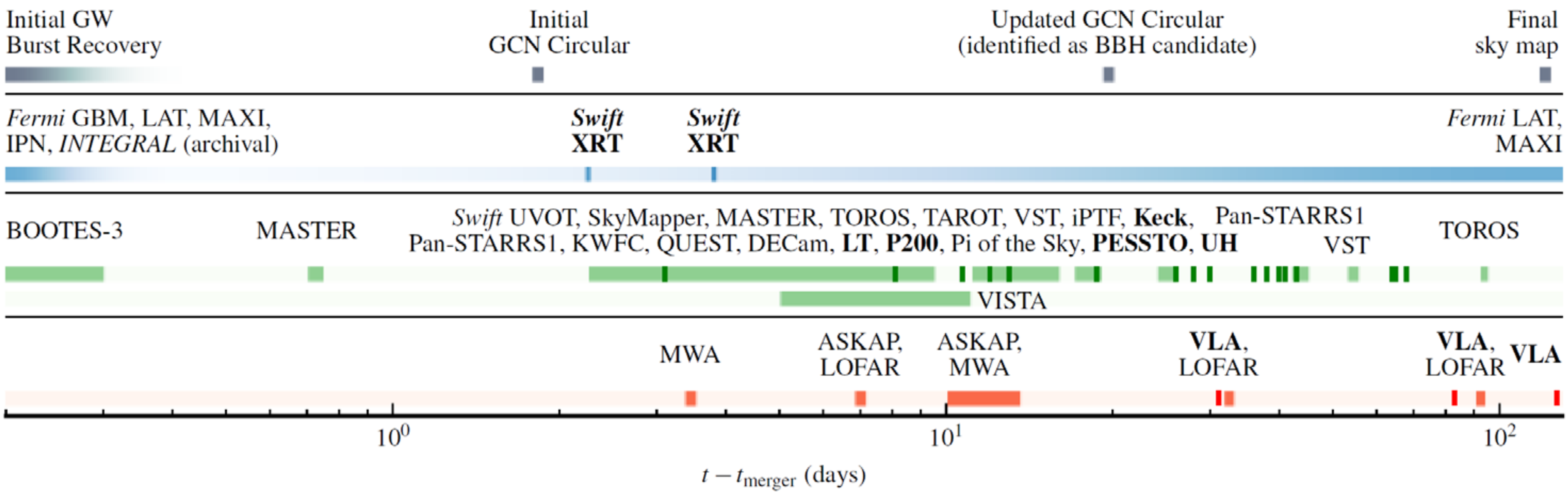
Advanced LIGO
Livingston, 2015

How far away was GW150914?

- 1.3 billion light years away
- The merger happened 1.3 Gy ago
- How do we know?
- Time evolution → mass of the objects
- mass + time evolution → GW amplitude @ origin
- $h(r) = h_o / r$
- $h@earth = h_{observed}$ → distance

EM Follow-up observations

THE ASTROPHYSICAL JOURNAL LETTERS, 826:L13, 2016 JULY 20



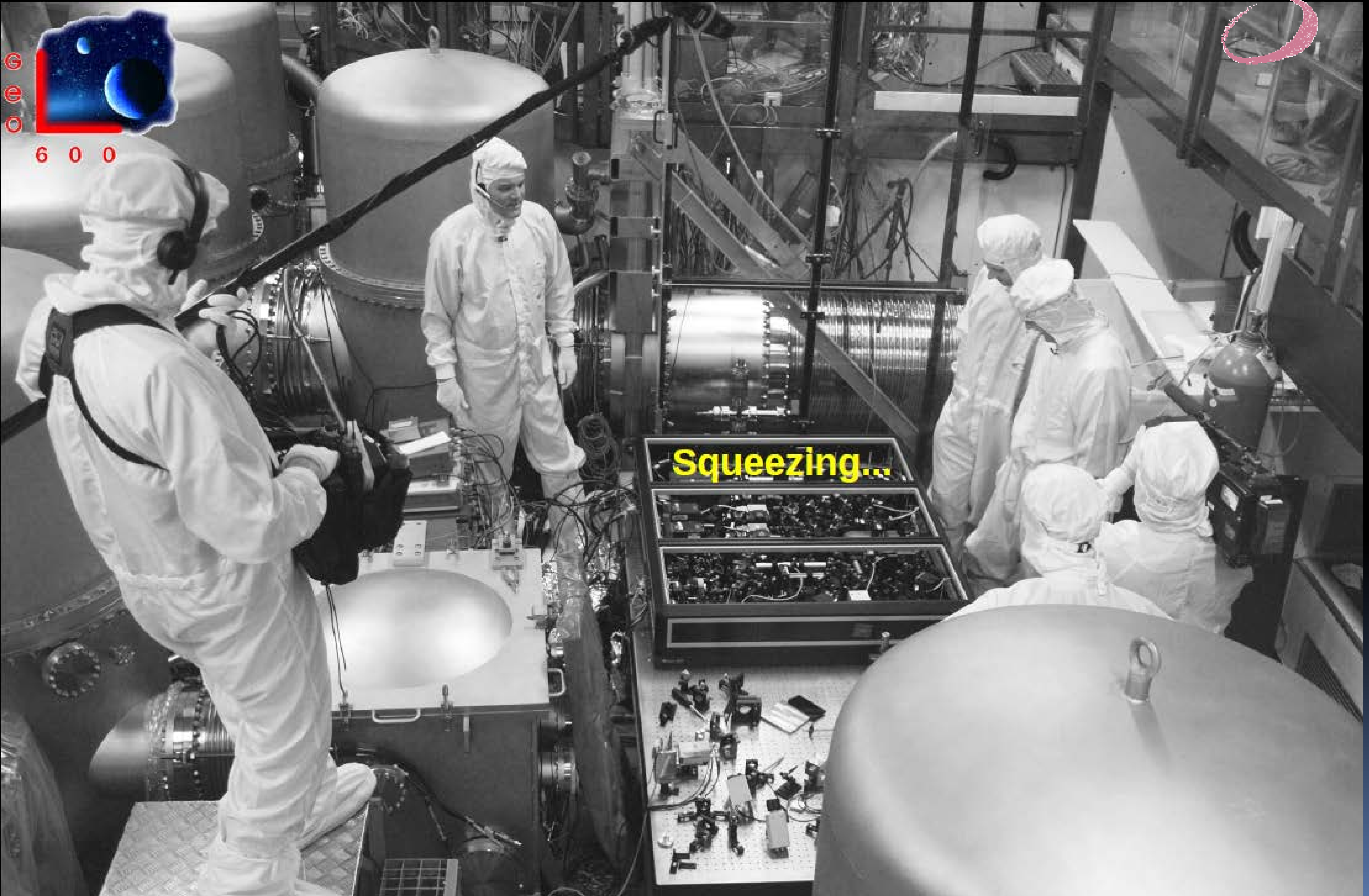
Preliminary estimates of the time, significance, and sky location of the event were shared with 63 (80 now) teams of observers covering radio, optical, near-infrared, X-ray, and gamma-ray wavelengths with ground- and space-based facilities

Alerts if FAR> < 1/month

Upgrades → advanced generation

Upgrade	Parameter	Improvement
More laser power	Up to 200 W 800 kW in cavity	Shot noise
Larger Optics	~ 40 kg	Less thermal noise
Better optics	< 0.25 ppm/cm < 0.3 nm rms	Less thermal lensing Less scattered light
Signal Recycling / RSE		Chose bandwidth independent from cavity buildup Tune centre frequency
Better suspensions (mainly LIGO)	Seismic isol. Glas fibres	Low frequency sensitivity Lower suspension thermal noise
Essentially all subsystems • Input optics • Output Mode Cleaner • Electronics • Auxiliary optics • Thermal compensation • Electrostatic Actuators		Less technical noise Minor improvements O1 → O2 (~50% Vol)

More to come



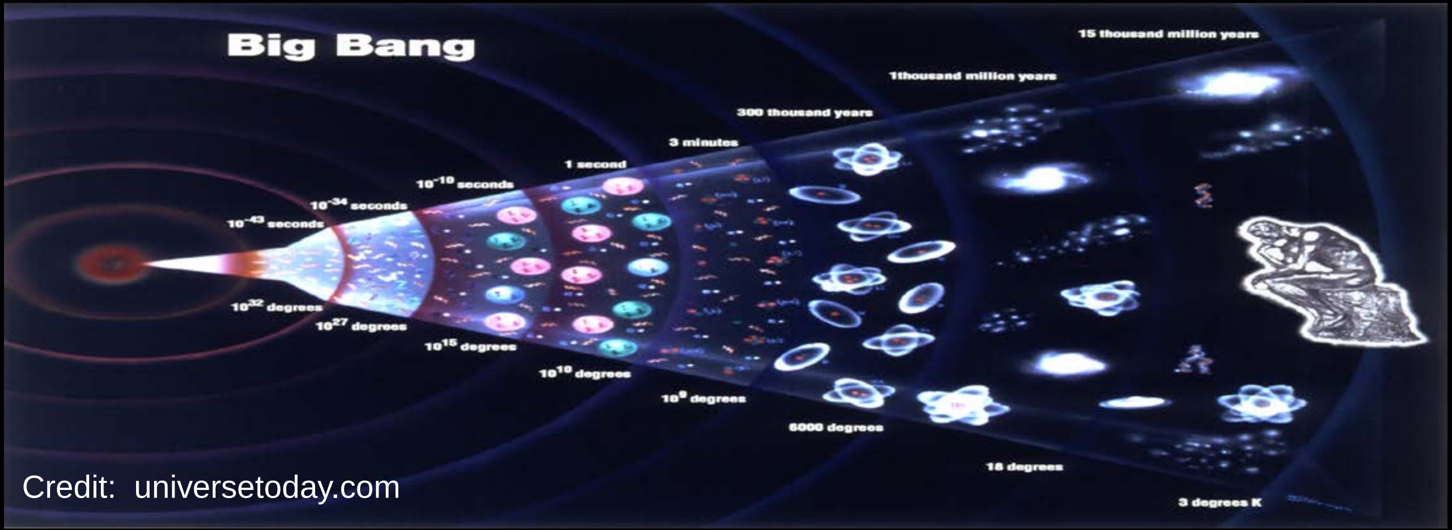
Detection is just the first step

The goal is

Gravitational Wave **Astronomy**

→ routinely observing regions and times which are inaccessible by other messengers

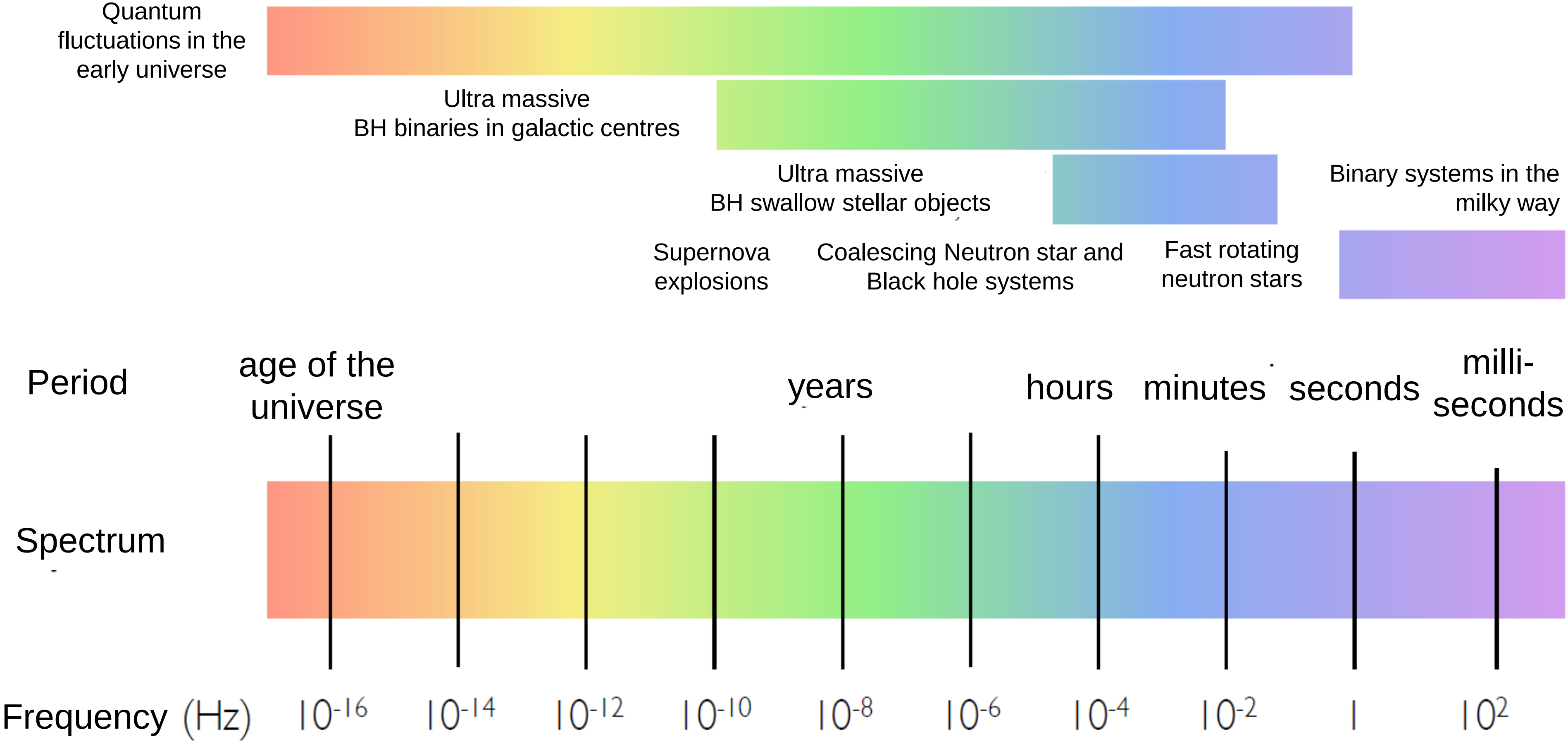
→ add info by combining GW & other messengers



Credit: universetoday.com

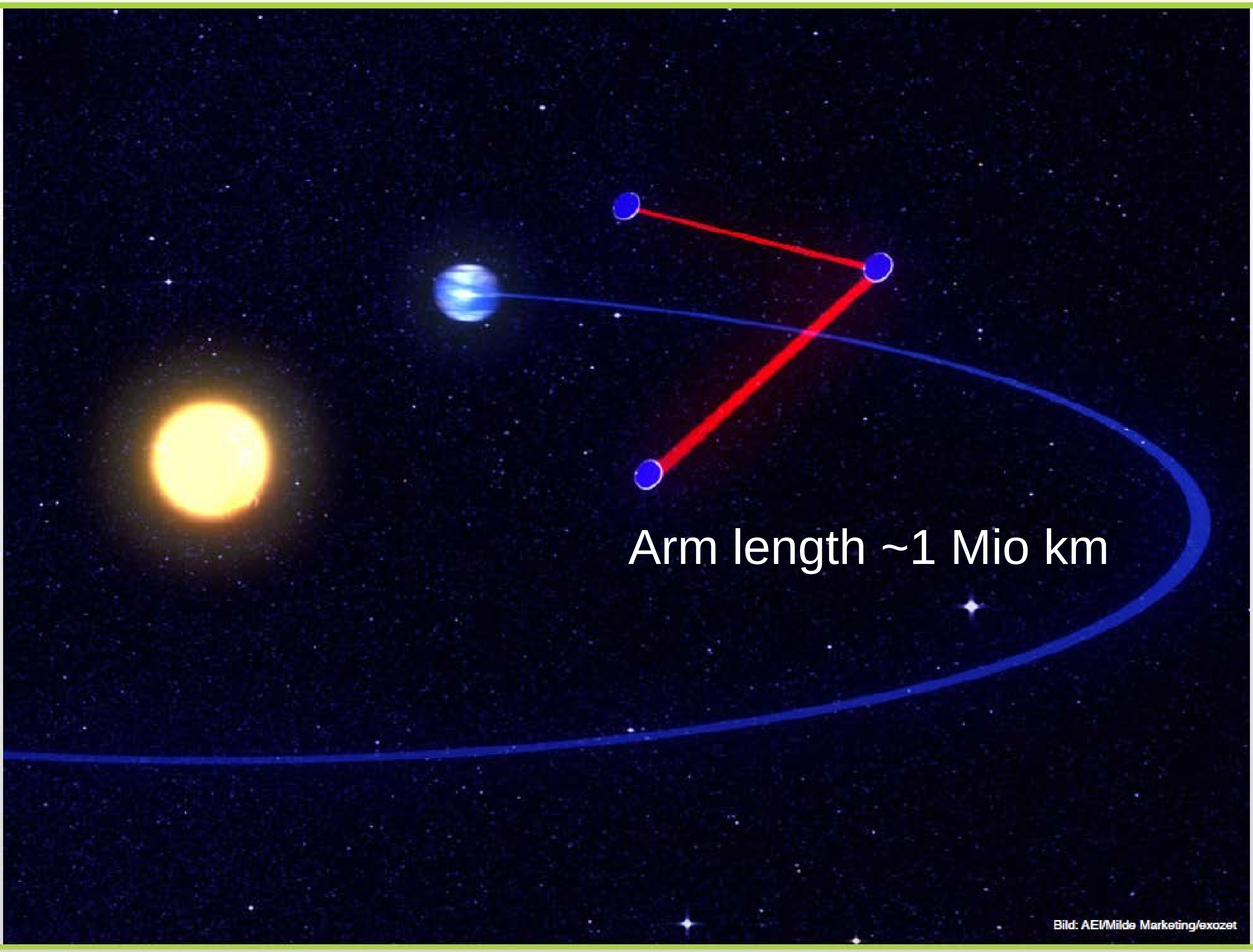
GW Spectrum

Sources



Detectors

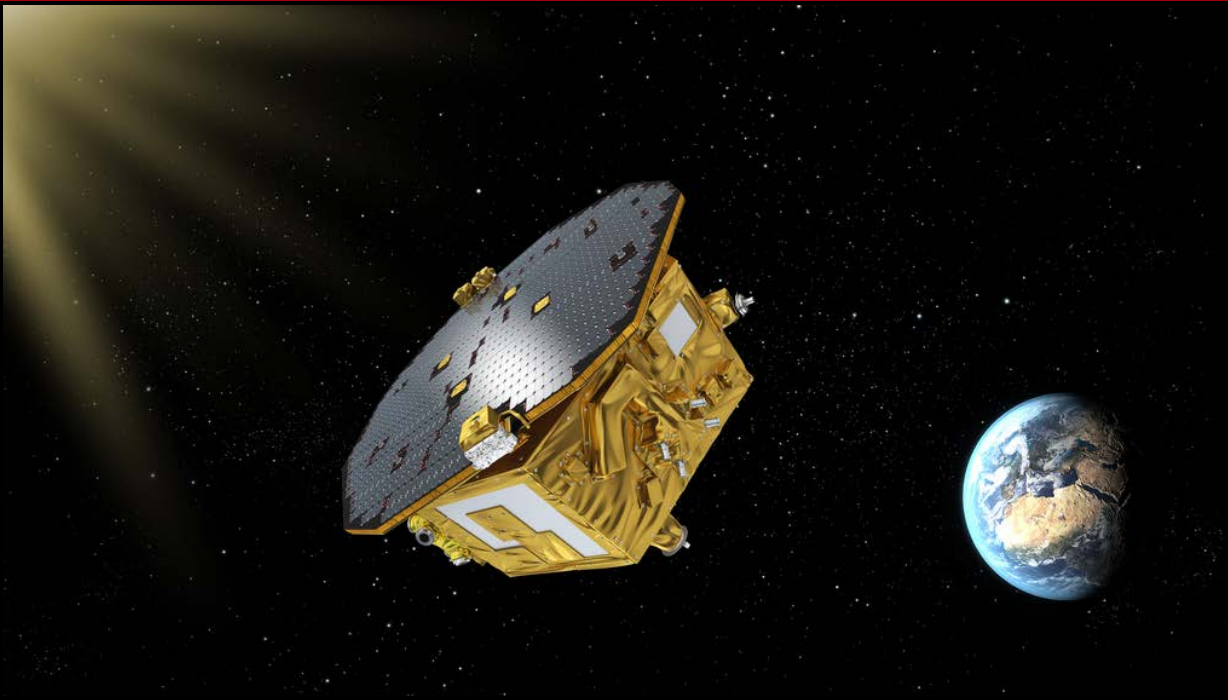
eLISA



Arm length ~1 Mio km

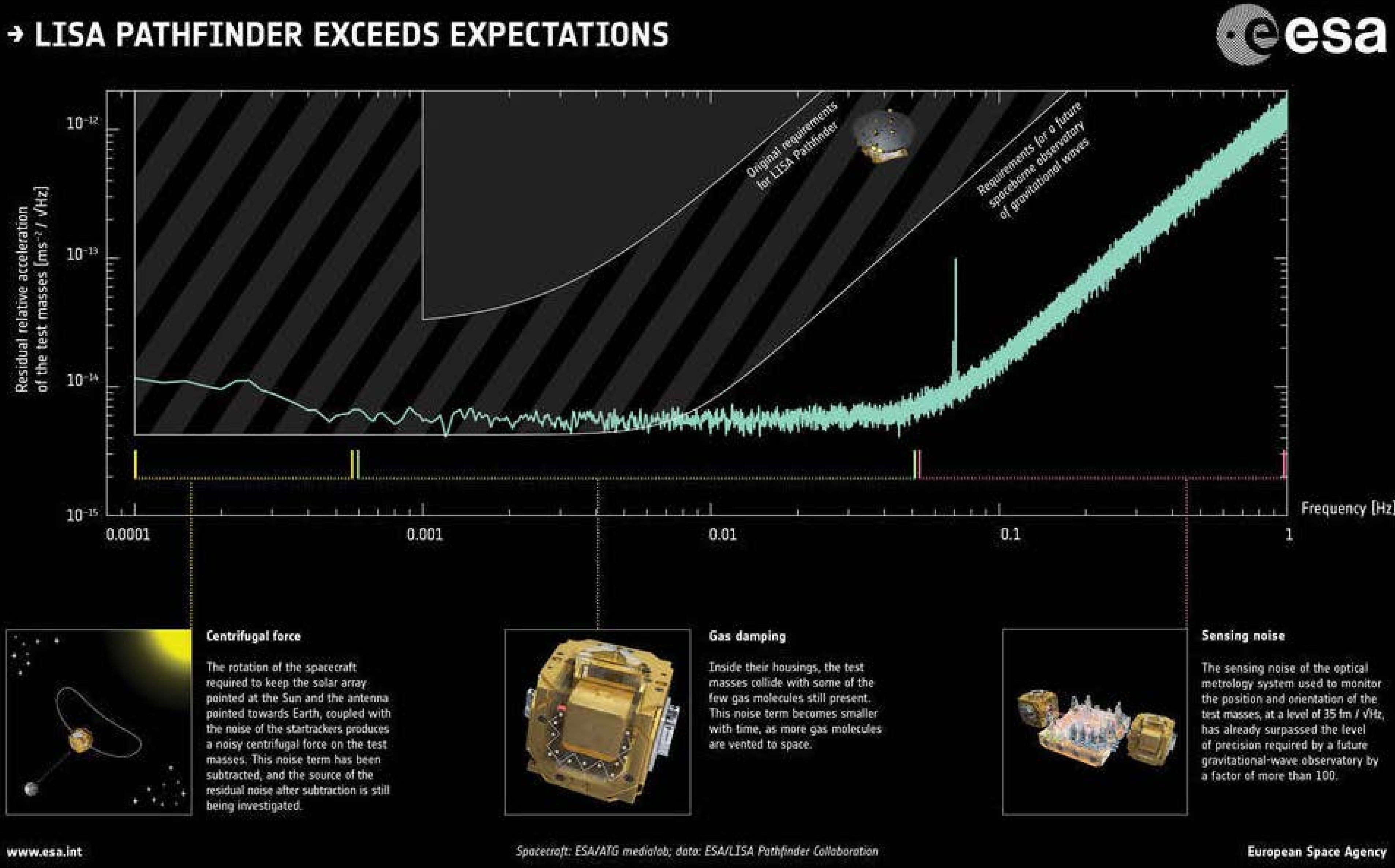
Bild: AEI/Milde Marketing/exozet

LISA and LISA Pathfinder



LISA Pathfinder results exceed expectations by orders of magnitude

LISA und LISA Pathfinder



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.

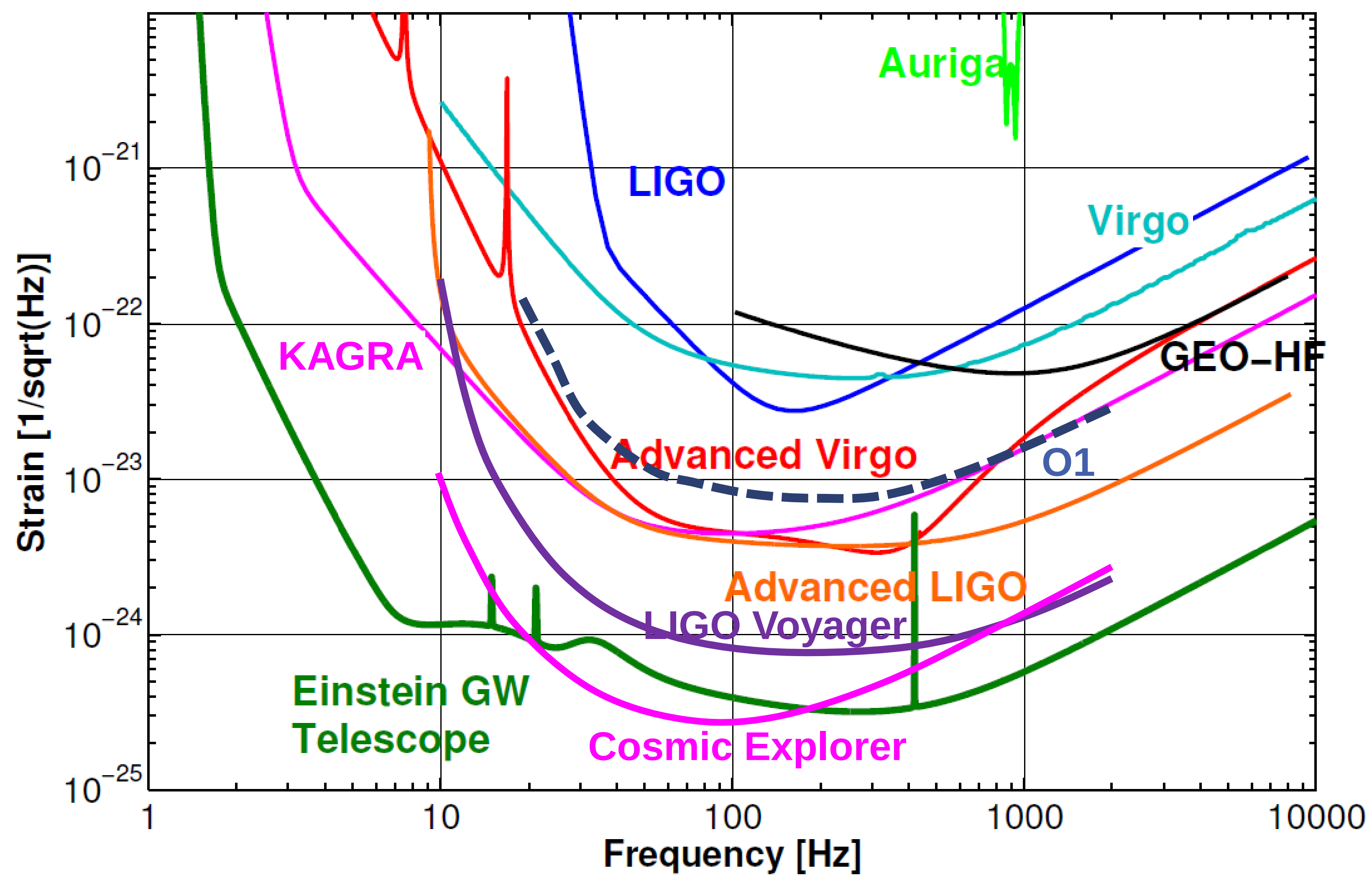
www.esa.int

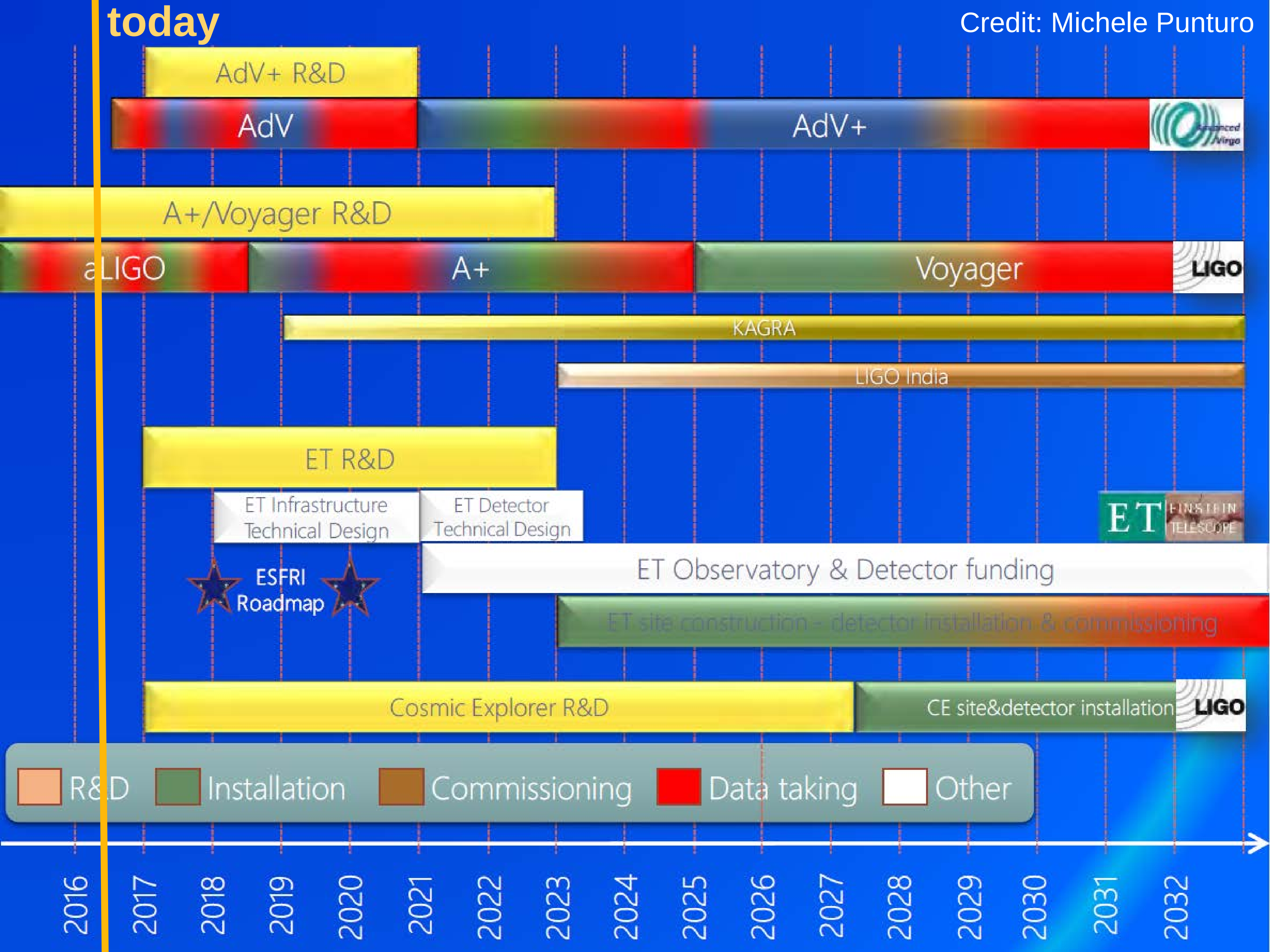
Spacecraft: ESA/ATG medialab; data: ESA/LISA Pathfinder Collaboration

European Space Agency

A long journey…

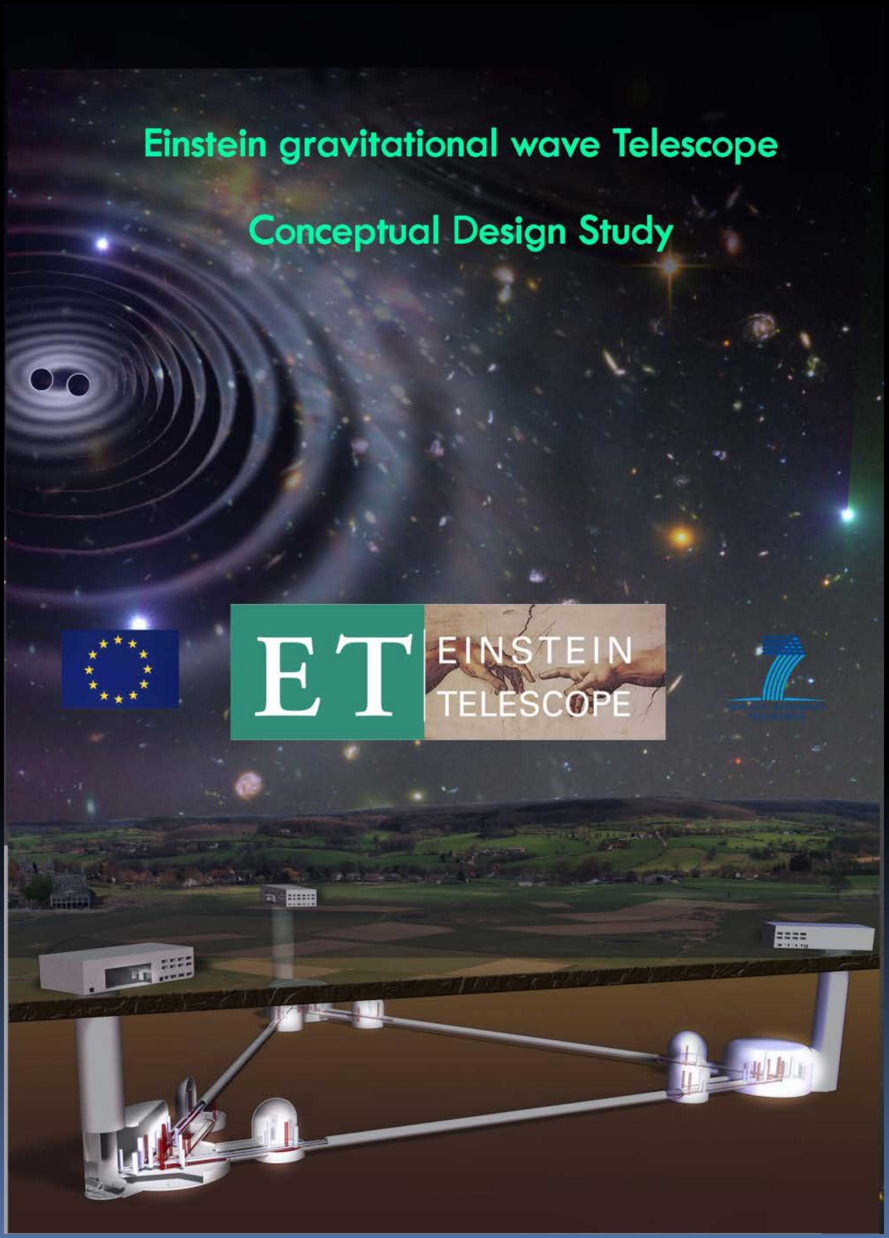
…on the path to routine GW astronomy





Credit: Michele Punturo

3rd Generation Gravitational Wave Observatories



Einstein gravitational wave Telescope

Conceptual Design Study

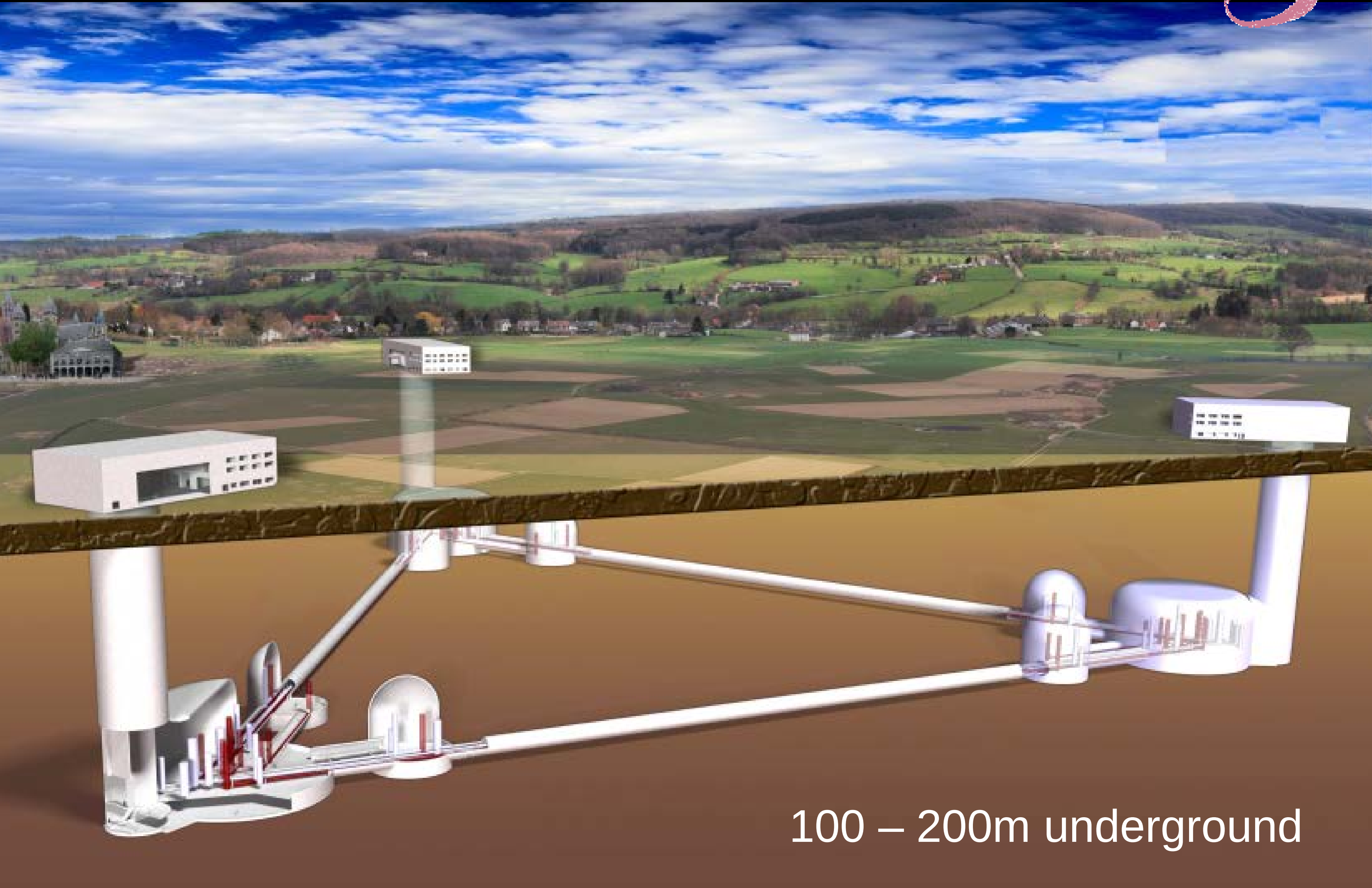
ET EINSTEIN TELESCOPE

Einstein Telescope Conceptual Design Study

- May 2008 – May 2011
- Pan European effort
- Science Team = ca. 250 members

http://www.et-gw.eu/etdsdocument

Einstein Teleskop



100 – 200m underground

Einstein Telescope

4×10^{49} J/s peak power of source, 40 yotta yotta watt.

1×10^{25} meter distance to source, 10 yotta meter.

4×10^{3} meter LIGO arm length, 4 kilometer.

2×10^{0} meter test mass suspension length, 2 meter.

1×10^{-6} meter ground vibration, 1 micrometer.

1×10^{-18} meter arm difference at peak signal, 1 attometer.

Prefix		1000^{m}	10^{n}	Decimal
Name	Symbol			
yotta	Y	1000^{8}	10^{24}	1 000 000 000 000 000 000 000 000
zetta	Z	1000^{7}	10^{21}	1 000 000 000 000 000 000 000
exa	E	1000^{6}	10^{18}	1 000 000 000 000 000 000
peta	P	1000^{5}	10^{15}	1 000 000 000 000 000
tera	T	1000^{4}	10^{12}	1 000 000 000 000
giga	G	1000^{3}	10^{9}	1 000 000 000
mega	M	1000^{2}	10^{6}	1 000 000
kilo	k	1000^{1}	10^{3}	1 000
hecto	h	$1000^{2/3}$	10^{2}	100
deca	da	$1000^{1/3}$	10^{1}	10
		1000^{0}	10^{0}	1
deci	d	$1000^{-1/3}$	10^{-1}	0.1
centi	c	$1000^{-2/3}$	10^{-2}	0.01
milli	m	1000^{-1}	10^{-3}	0.001
micro	μ	1000^{-2}	10^{-6}	0.000 001
nano	n	1000^{-3}	10^{-9}	0.000 000 001
pico	p	1000^{-4}	10^{-12}	0.000 000 000 001
femto	f	1000^{-5}	10^{-15}	0.000 000 000 000 001
atto	a	1000^{-6}	10^{-18}	0.000 000 000 000 000 001
zepto	z	1000^{-7}	10^{-21}	0.000 000 000 000 000 000 001
yocto	y	1000^{-8}	10^{-24}	0.000 000 000 000 000 000 000 001