LIGO – детектор гравітаційних хвиль

Популярно про Нобелівську премію з фізики 2017 року

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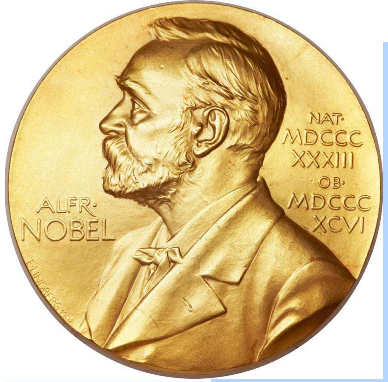
Вступ до спеціальності “Прикладна фізика”

Кафедра прикладної фізики та кафедра фізики енергетичних систем Фізико-технічного інституту Національного технічного університету України “Київський політехнічний інститут імені Ігоря Сікорського”

20 жовтня 2017 р.



Нобелівська премія з фізики 2017

“ за вирішальний внесок у детектор LIGO
та спостереження гравітаційних хвиль ”

Райнер Вайс
Rainer Weiss
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Massachusetts Institute of
Technology (MIT),
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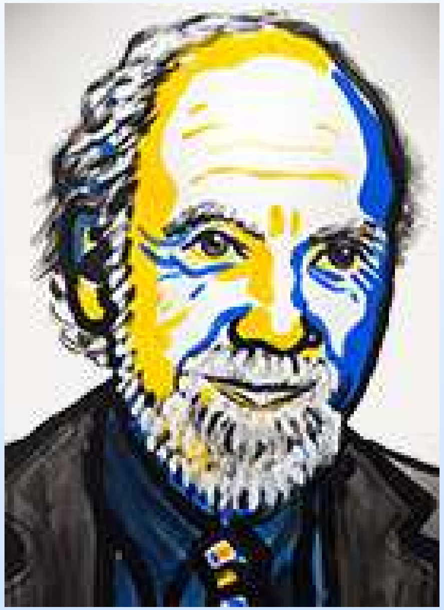

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LIGO

L ASER

I NTERFEROMETER

G RAVITATIONAL-WAVE

O BSERVATORY

Gravitational Waves as Signals from the Universe

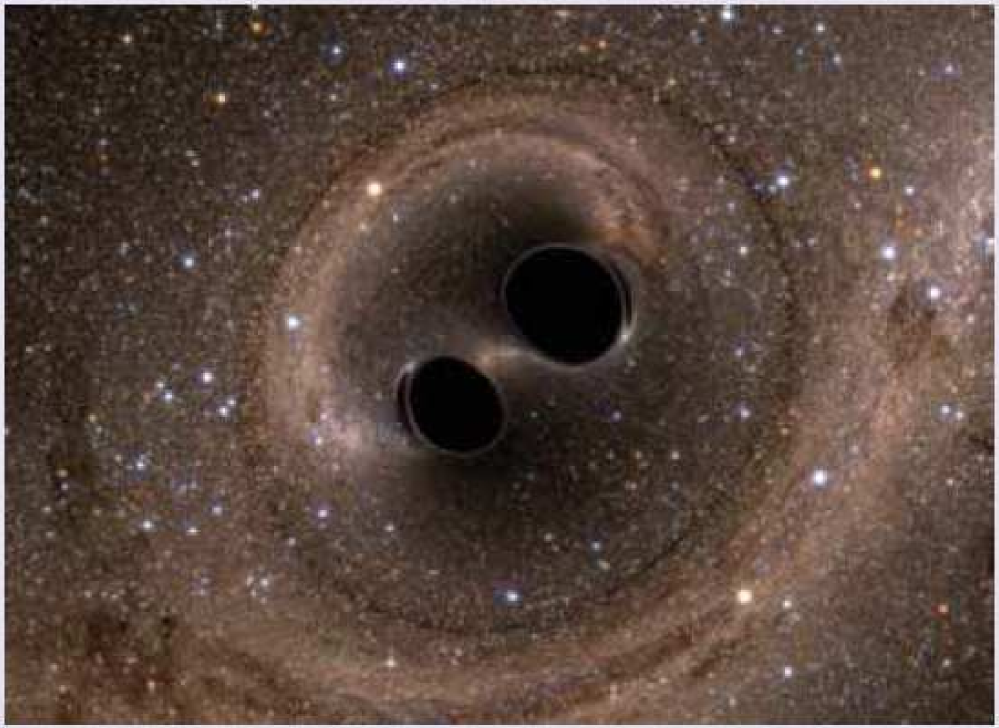


Figure 1: Numerical simulation of two merging black holes. Credit: SXS

Gravitational waves are 'ripples' in the fabric of spacetime caused by accelerating masses such as colliding black holes, exploding stars, and even the birth of the universe itself. Albert Einstein predicted the existence of gravitational waves in 1916, derived from his General Theory of Relativity. Einstein's mathematics showed that massive accelerating objects would disrupt spacetime in such a way that waves of distorted space would radiate from the source. These ripples travel at the speed of light through the universe, carrying information about their origins, as well as clues to the nature of gravity itself. Two black holes in mutual orbit will revolve around each other emitting gravitational waves and losing orbital energy as illustrated in Figure 1. Over time, the energy loss causes the stars to move closer together and orbit around each other faster and faster until they eventually merge together, or coalesce. This type of merger has never before been directly observed, and it is the type of event that emitted the gravitational waves detected by LIGO on September 14, 2015.

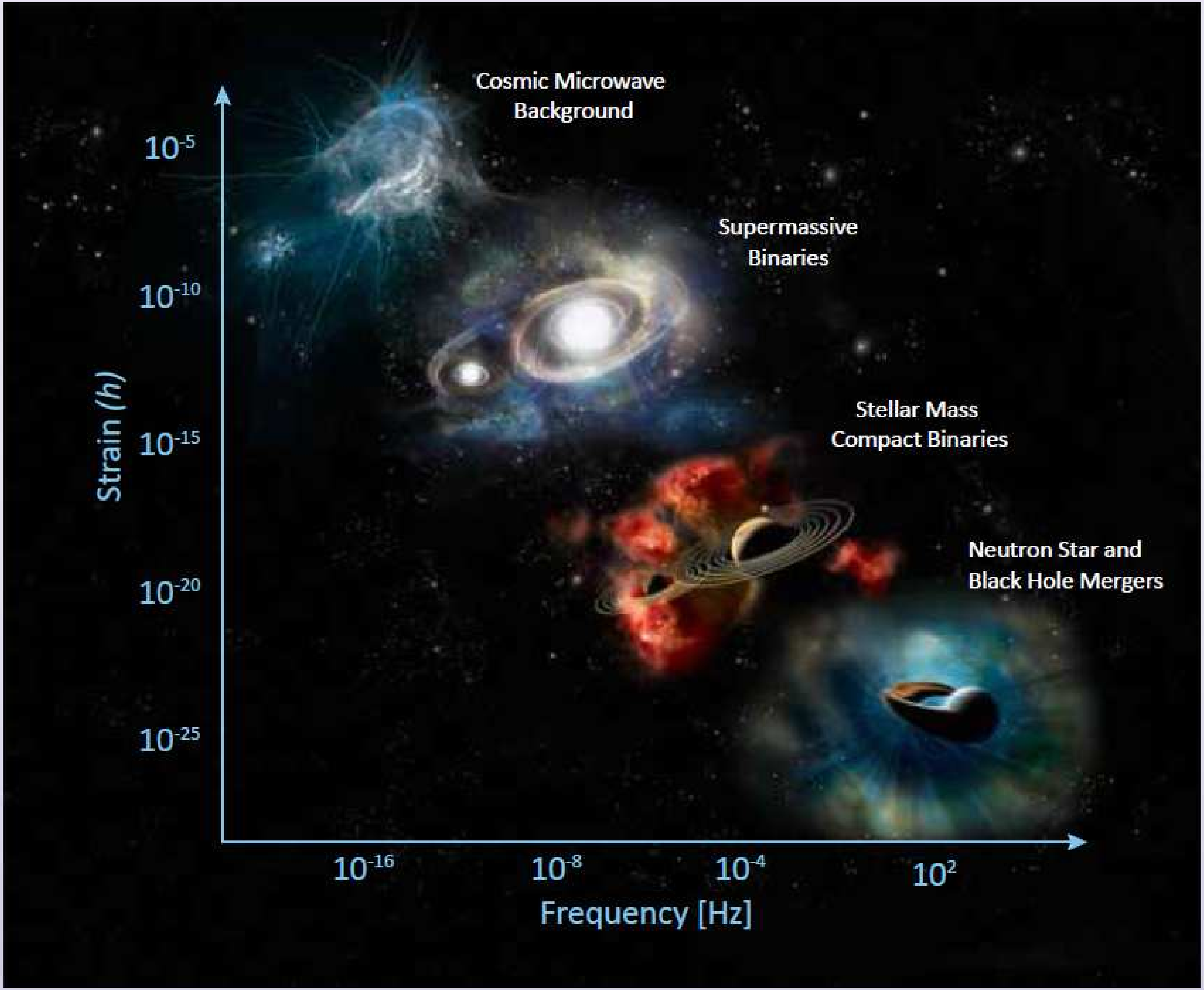
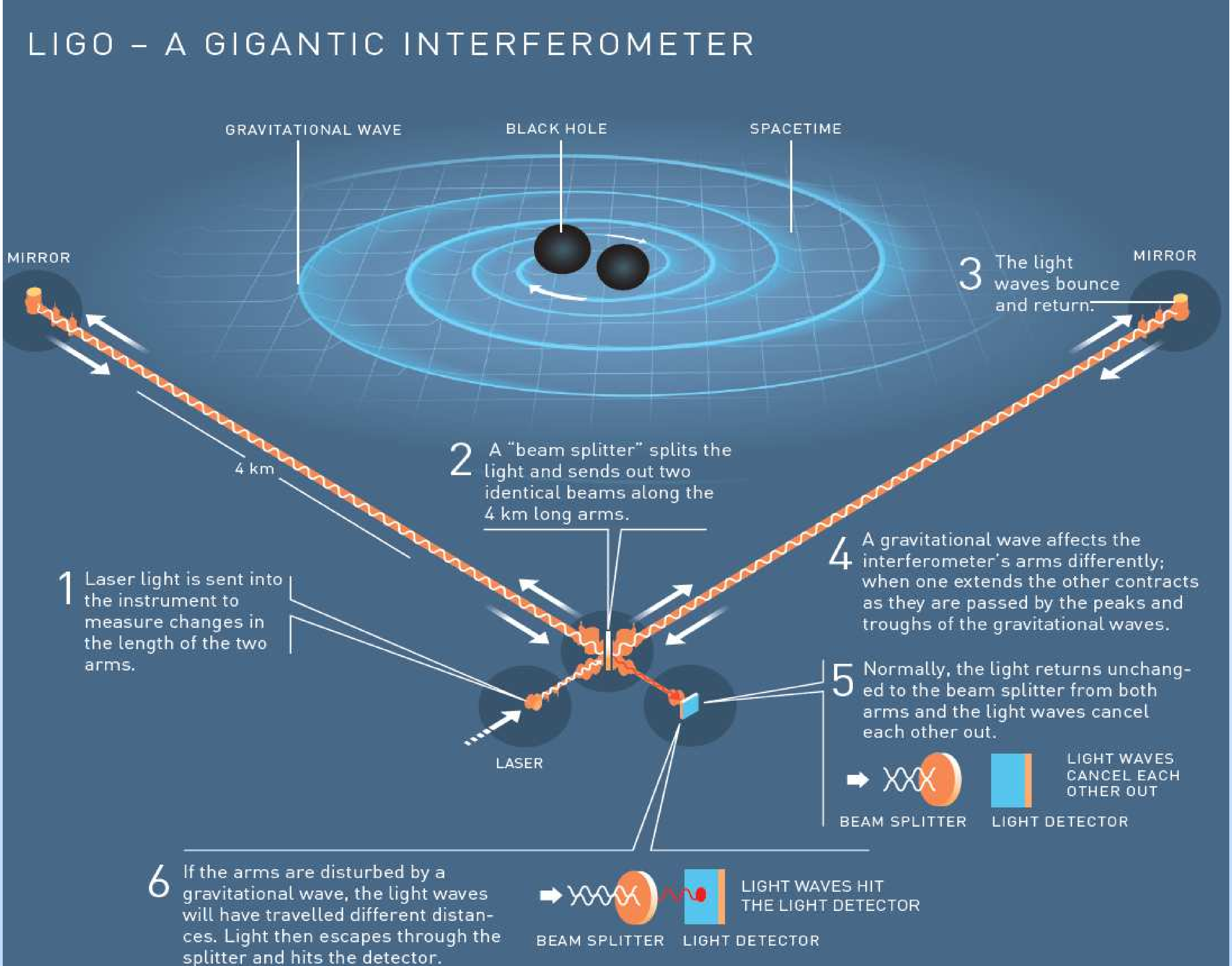


Figure 3: Gravitational Wave Spectrum. This figure plots the predicted strain (h, y-axis) vs. the frequency of expected gravitational waves in Hz (x-axis) for different types of cosmic objects. Credit: SSU E/PO/Aurore Simonnet


LIGO – A GIGANTIC INTERFEROMETER
GRAVITATIONAL WAVE
BLACK HOLE
SPACETIME
MIRROR
MIRROR
3 The light waves bounce and return.
4 km
2 A "beam splitter" splits the light and sends out two identical beams along the 4 km long arms.
1 Laser light is sent into the instrument to measure changes in the length of the two arms.
4 A gravitational wave affects the interferometer's arms differently; when one extends the other contracts as they are passed by the peaks and troughs of the gravitational waves.
5 Normally, the light returns unchanged to the beam splitter from both arms and the light waves cancel each other out.
LASER
LIGHT WAVES CANCEL EACH OTHER OUT
BEAM SPLITTER
LIGHT DETECTOR
6 If the arms are disturbed by a gravitational wave, the light waves will have travelled different distances. Light then escapes through the splitter and hits the detector.
LIGHT WAVES HIT THE LIGHT DETECTOR
BEAM SPLITTER
LIGHT DETECTOR

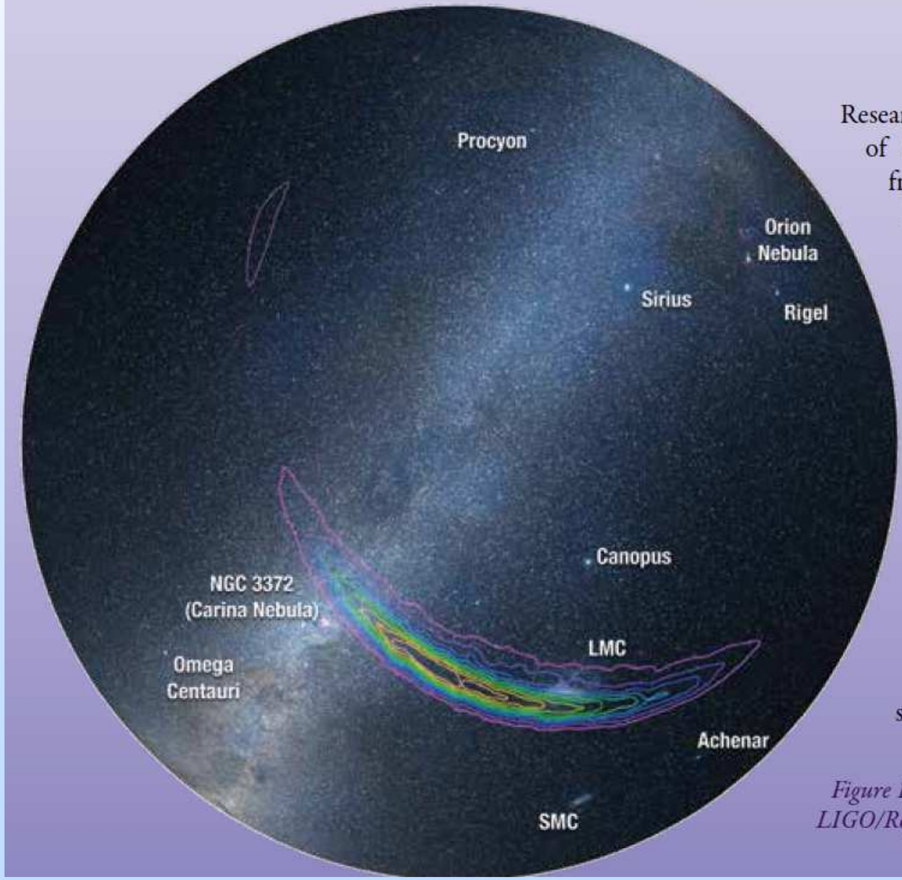


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Figure 13:
LIGO/Roy V

Table 1 – Important Parameters for GW150914		
Time detected	September 14, 2015 09:50:45 UTC	
Mass (in units of Solar Mass)	Black Hole 1	36^{+5}_{-4}
	Black Hole 2	29 ± 4
	Final Mass	62 ± 4
GW Energy	$3.0 \pm 0.5\ M_{\odot} c^2$	
Distance	410^{+160}_{-180} Mpc $\sim 1.34 \times 10^9$ light years	
Redshift	$0.09^{+0.03}_{-0.04}$	
Observing band	35-350 Hz	
Peak strain h	1.0×10^{-21}	

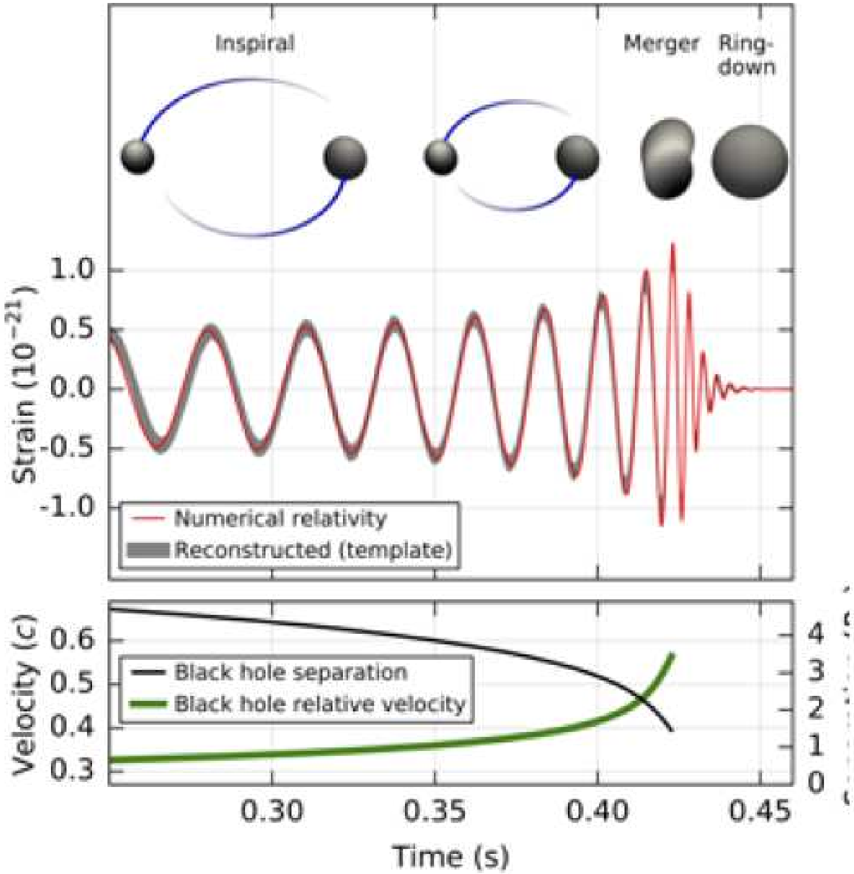


Figure 1: GW150914 models. Credit: LIGO

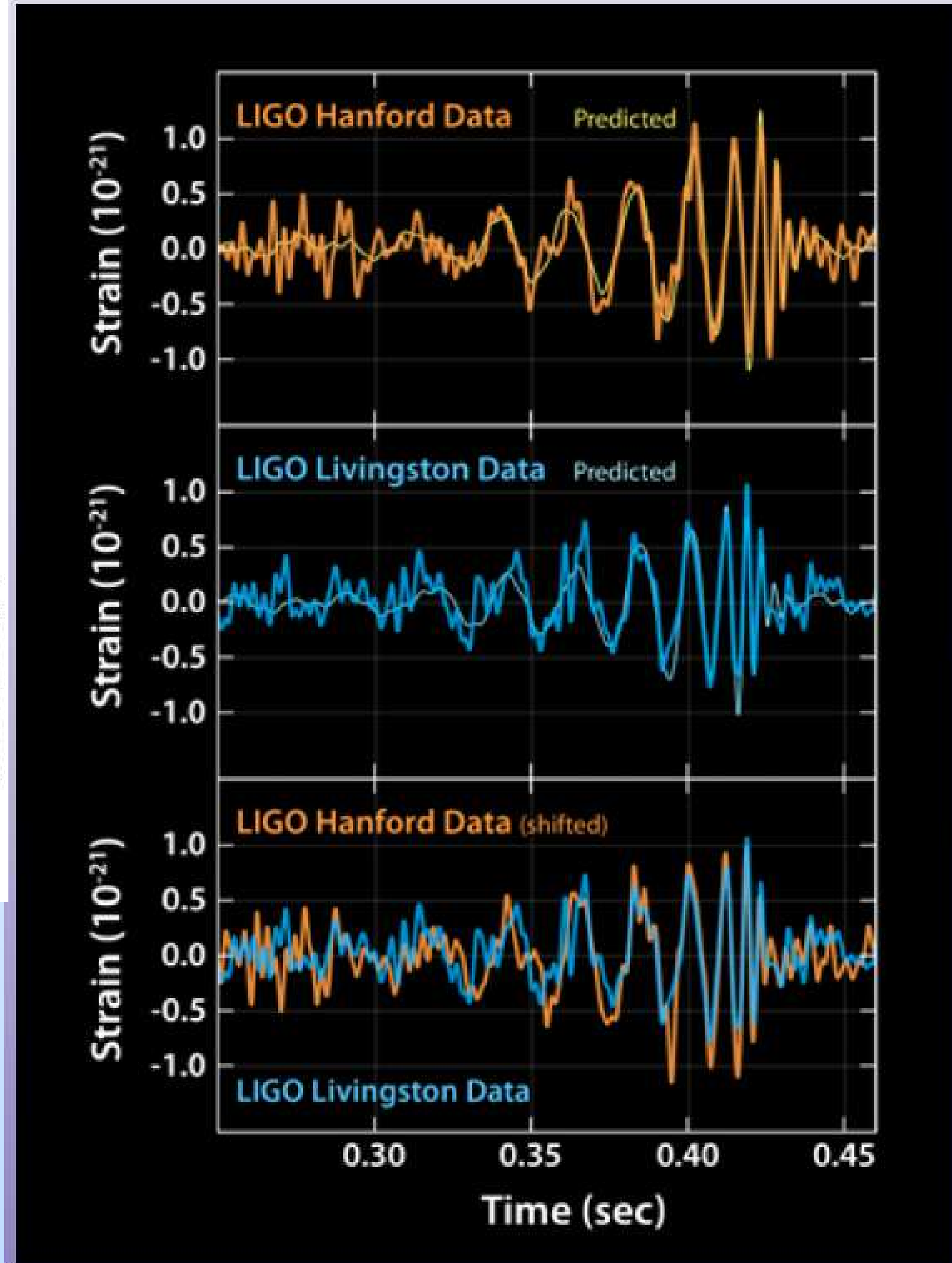
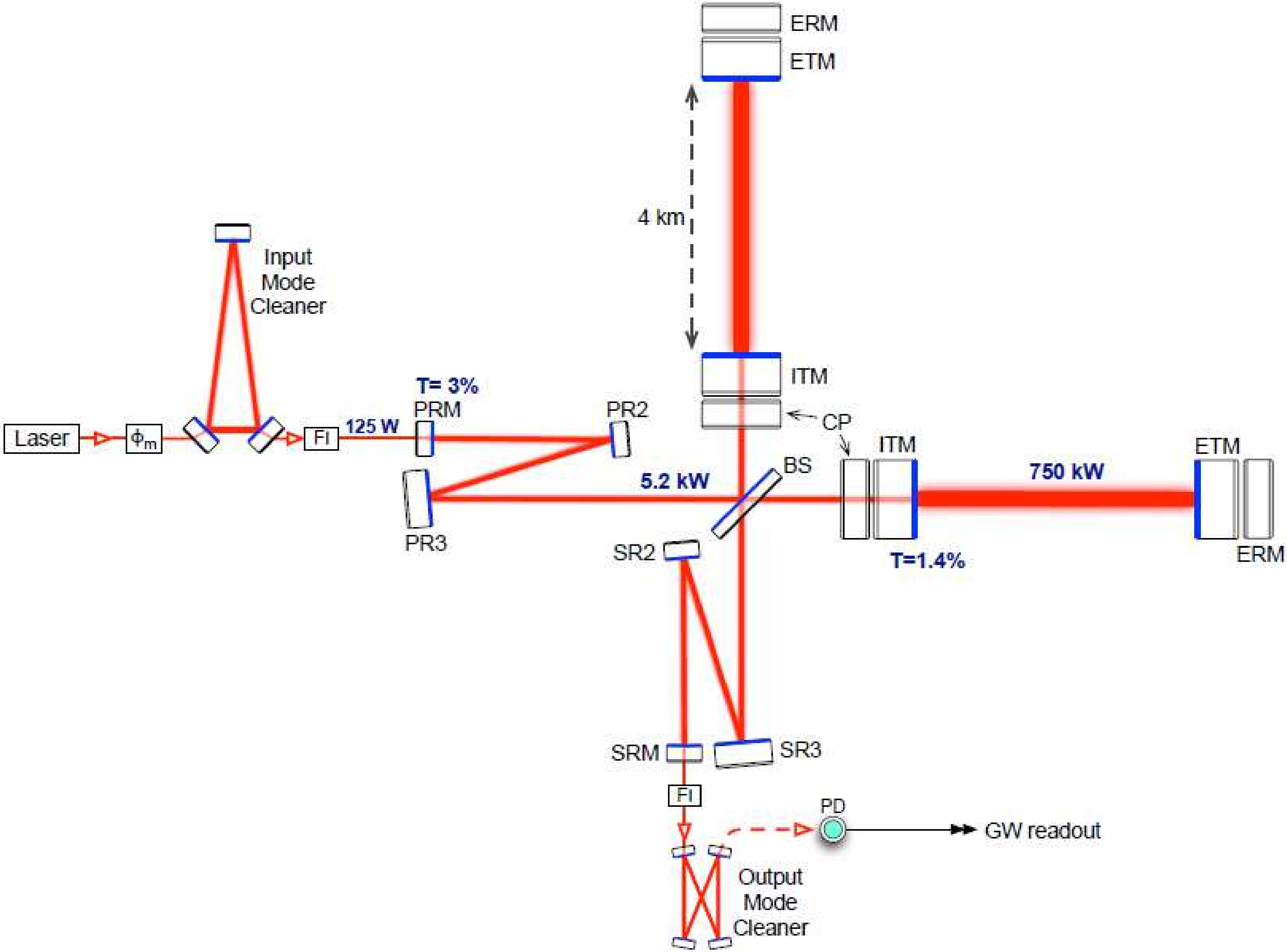


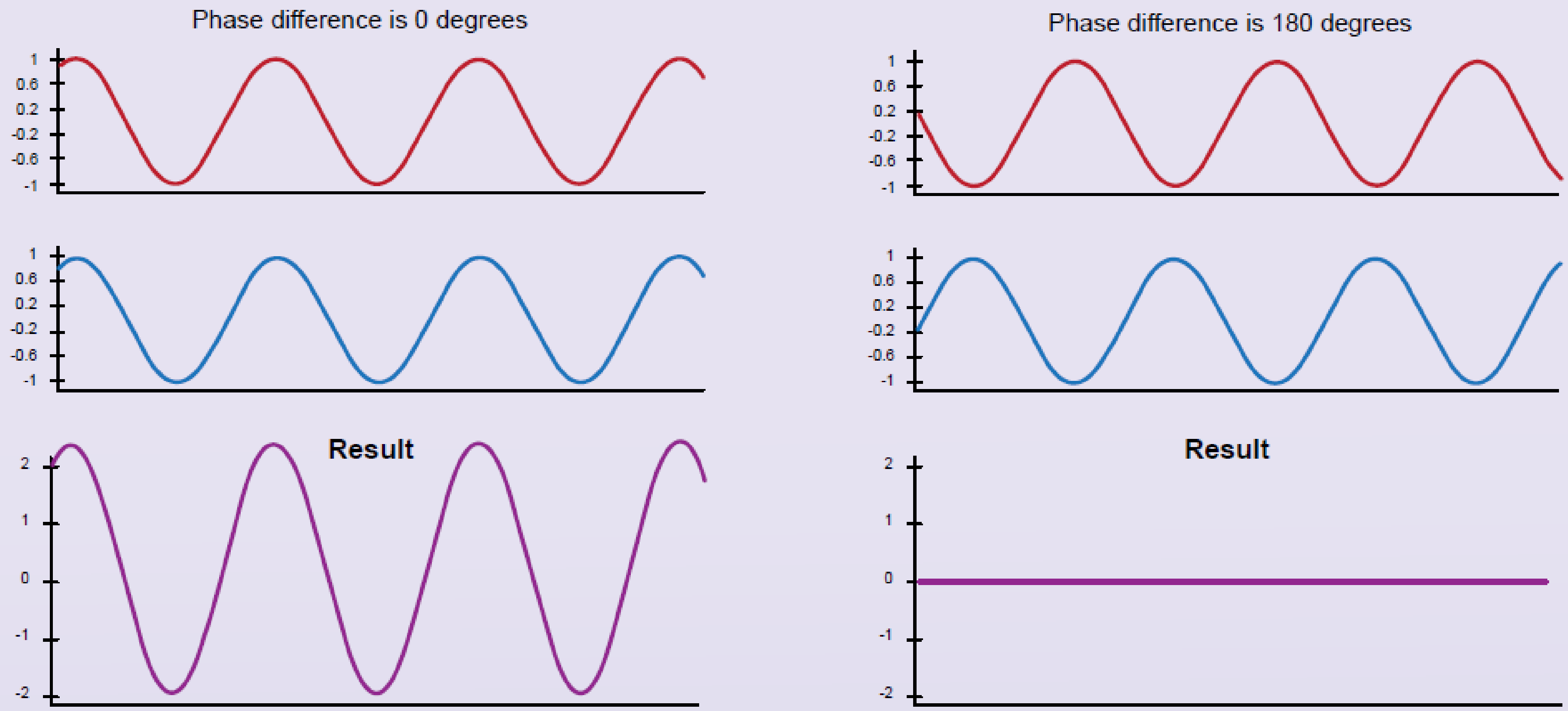
Figure 12: Data and Best-fit Models for LIGO's Direct Detection of Gravitational Waves. Credit: LIGO

LIGO (Laser Interferometer Gravitational-wave Observatory) is the world's largest gravitational wave observatory. LIGO consists of two laser interferometers located thousands of kilometers apart, one in Livingston, Louisiana and the other in Hanford, Washington. LIGO uses the physical properties of light and of space itself to detect gravitational waves. It was funded by the US National Science Foundation, and it is managed by Caltech and MIT. Hundreds of scientists in the LIGO Scientific Collaboration, in many countries, contribute to the astrophysical and instrument science of LIGO. There are also other gravitational wave observatories in the world, including Virgo in Italy and GEO 600 in Germany.

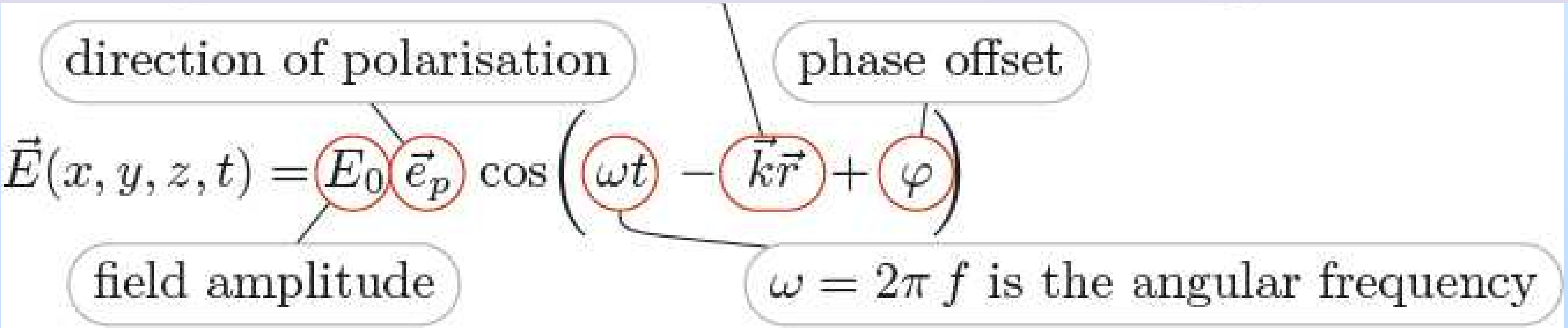
Figure 9 LIGO Hanford and LIGO Livingston.
Credit: Caltech/MIT/LIGO

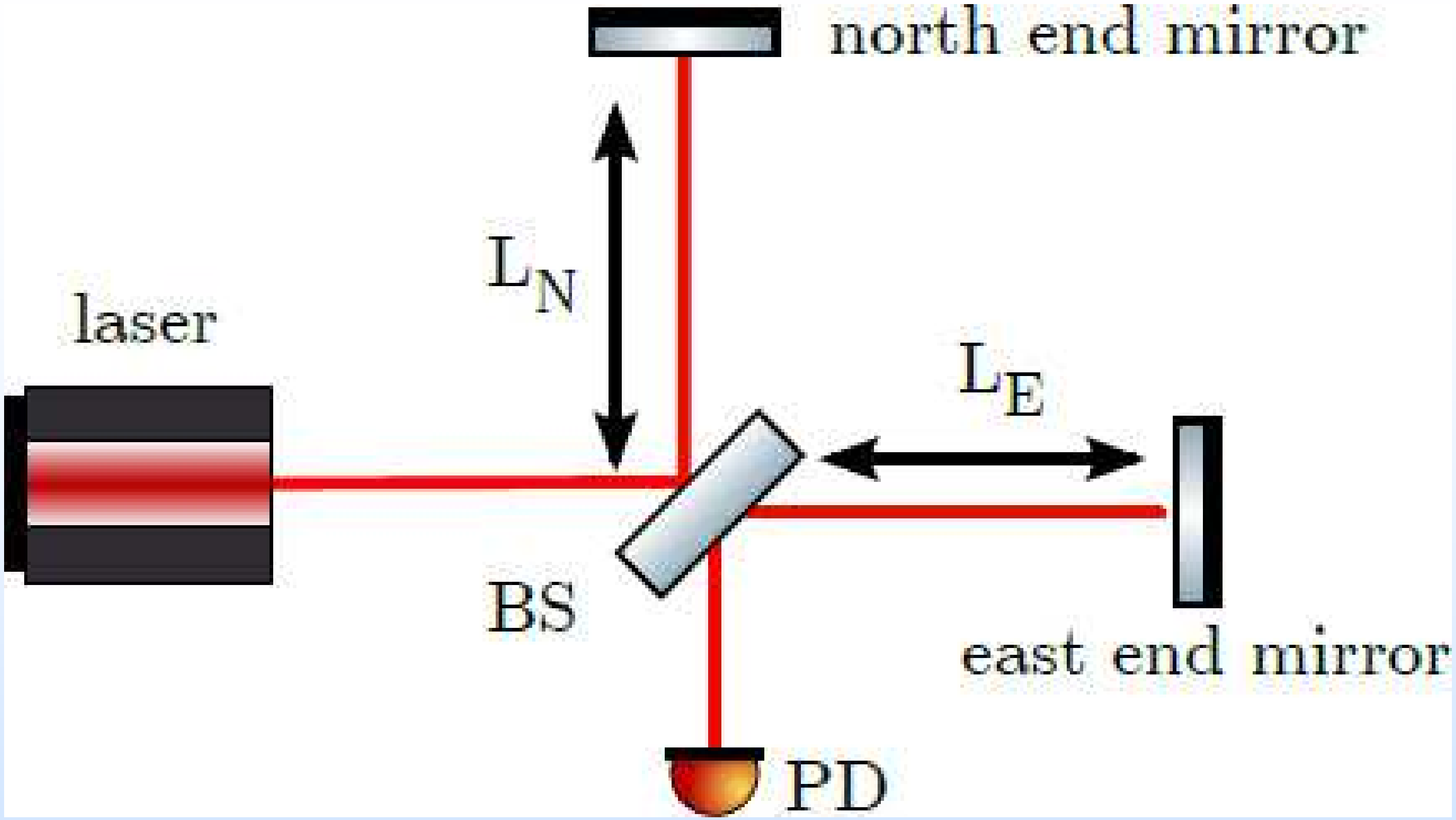


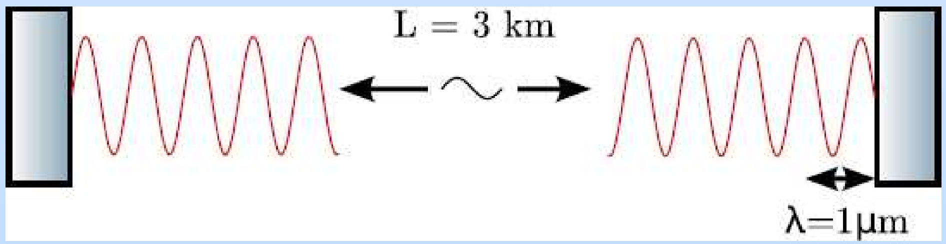
Загальна схема LIGO

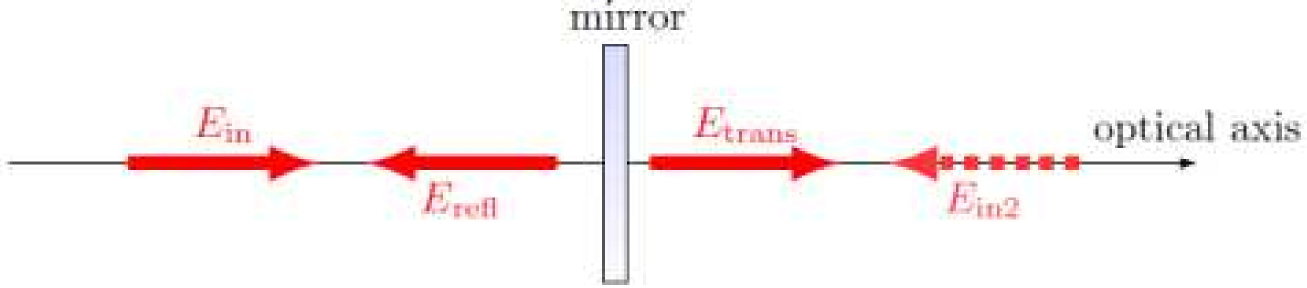


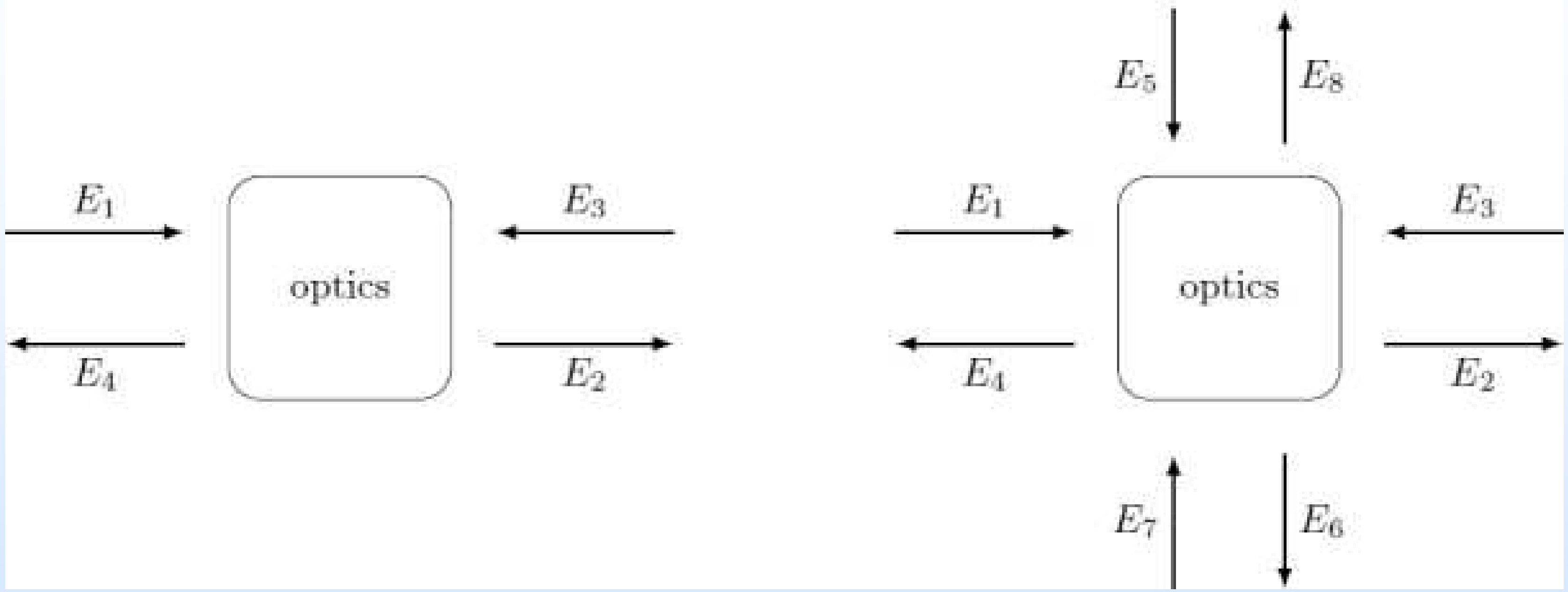
Figures 11a and 11b: Illustration of the interference pattern produced by two waves that are a) in phase and b) 180 degrees out of phase. Credit: SSU E/PO Aurore Simonnet




north end mirror
L_N
laser
L_E
BS
east end mirror
PD

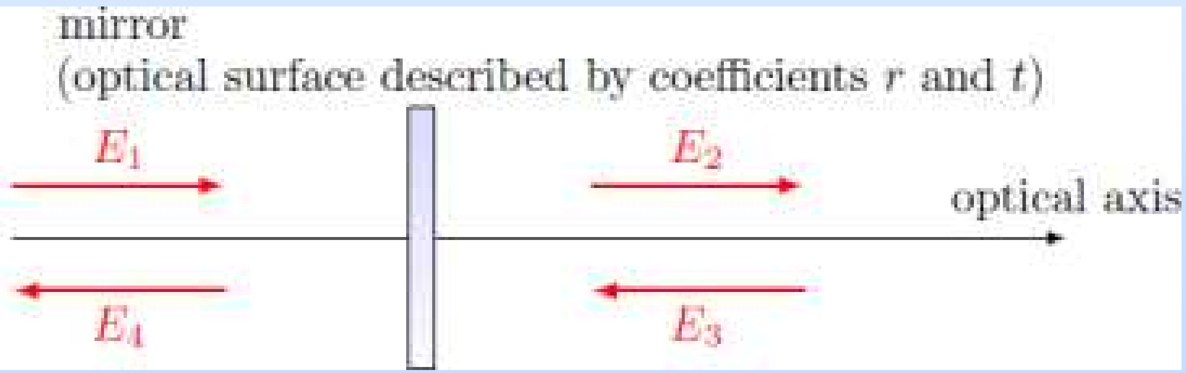

L = 3 km
λ=1μm

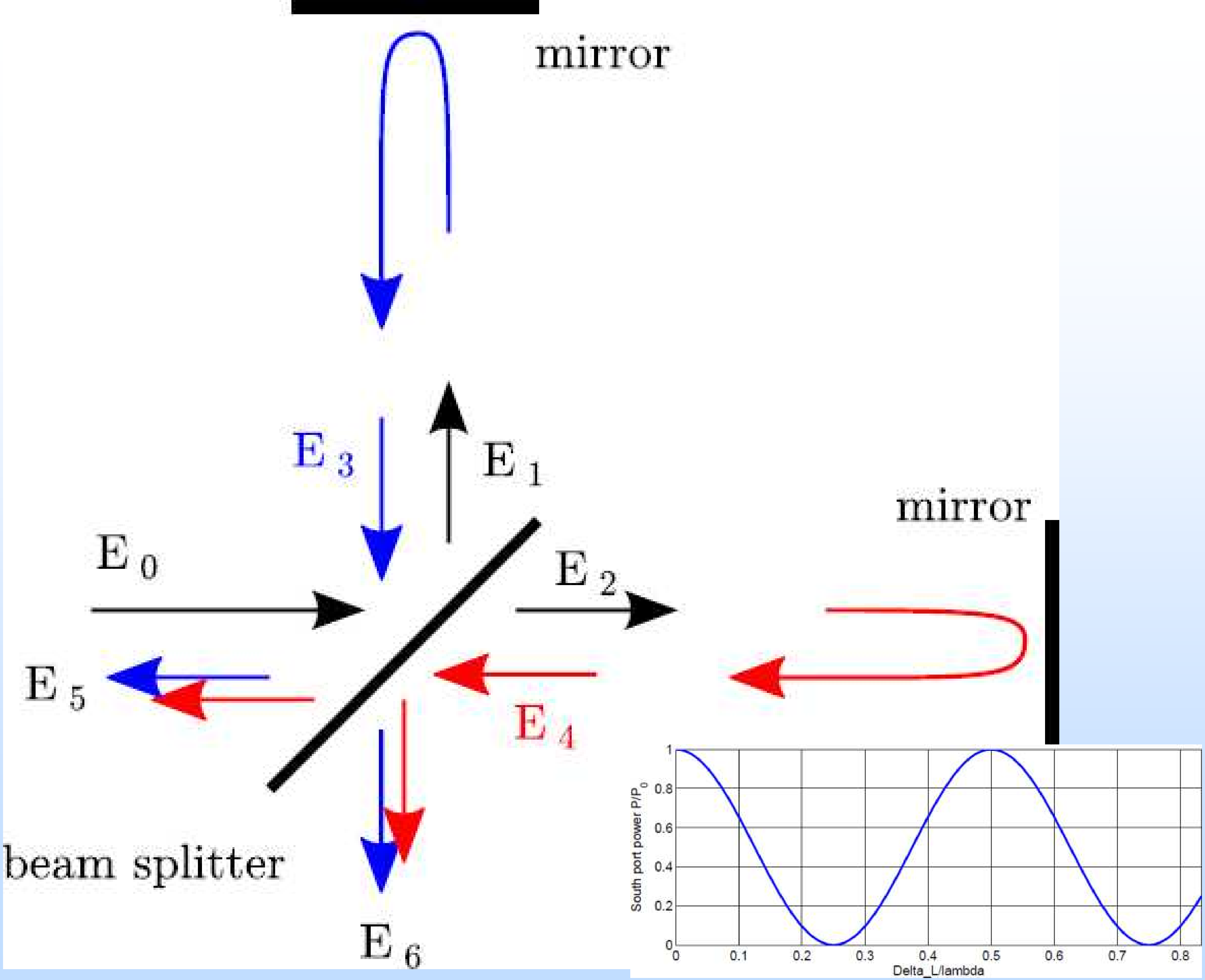




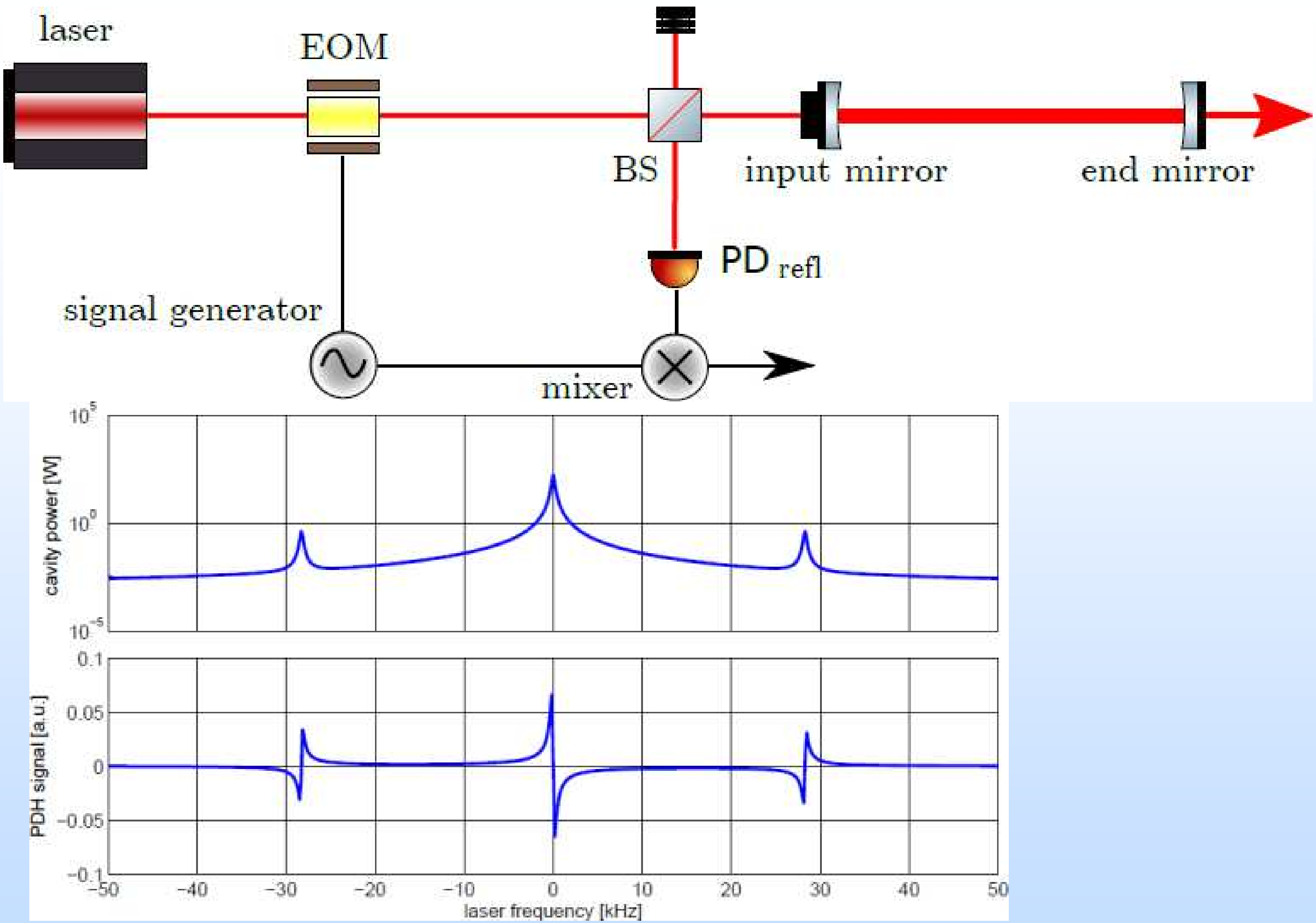
$$E_2 = r E_3 + \mathrm{i}\, t E_1$$

$$E_4 = r E_1 + \mathrm{i}\, t E_3$$

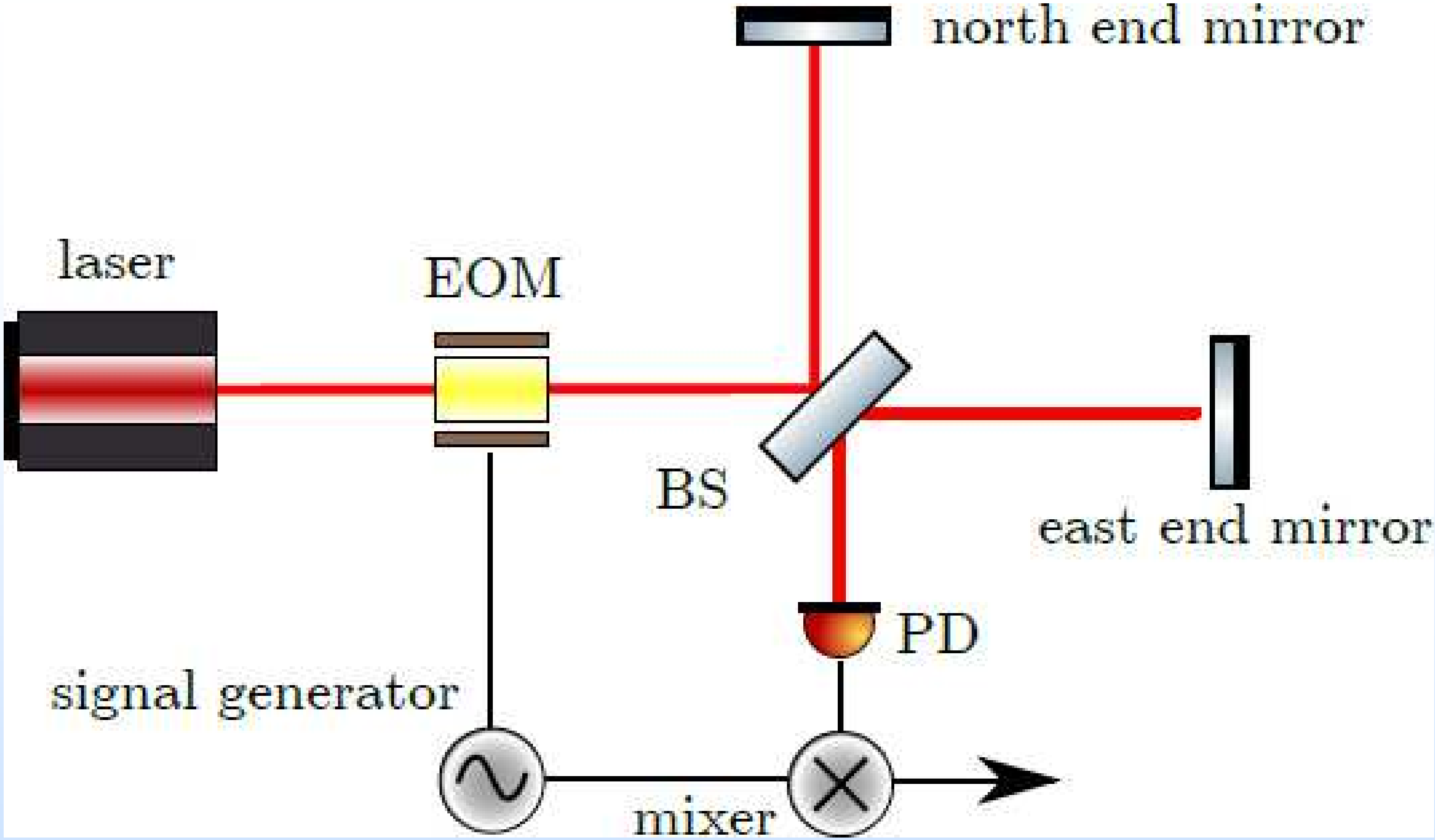




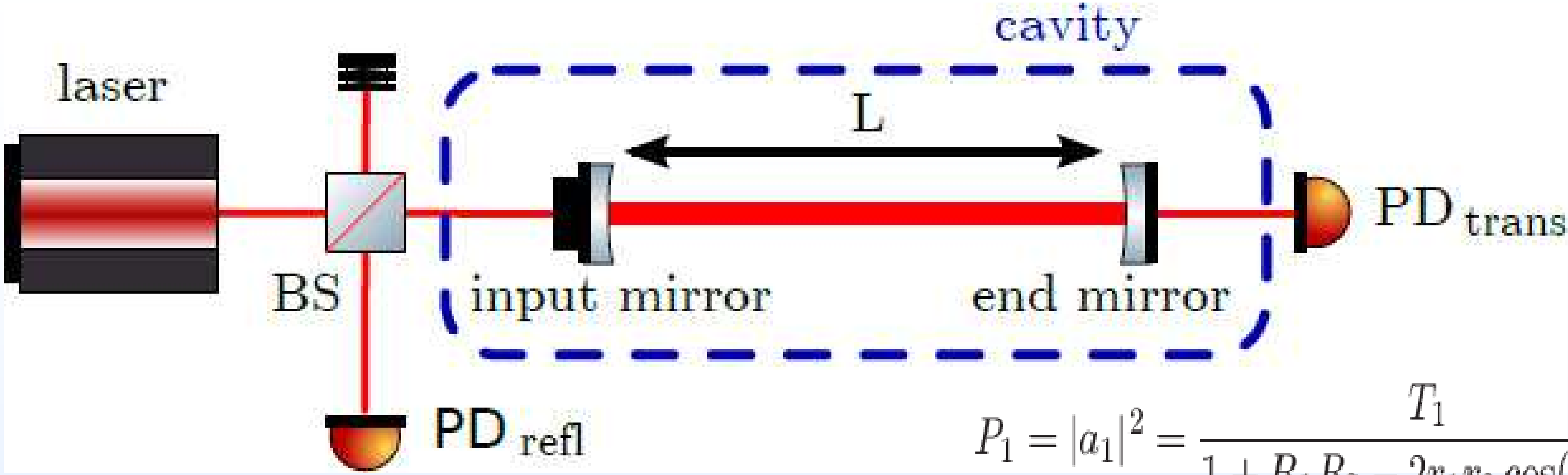
$$S = E_S E_S^* = P_0 \cos^2(k\Delta L) = P_0 \cos^2(2\pi\Delta L/\lambda).$$



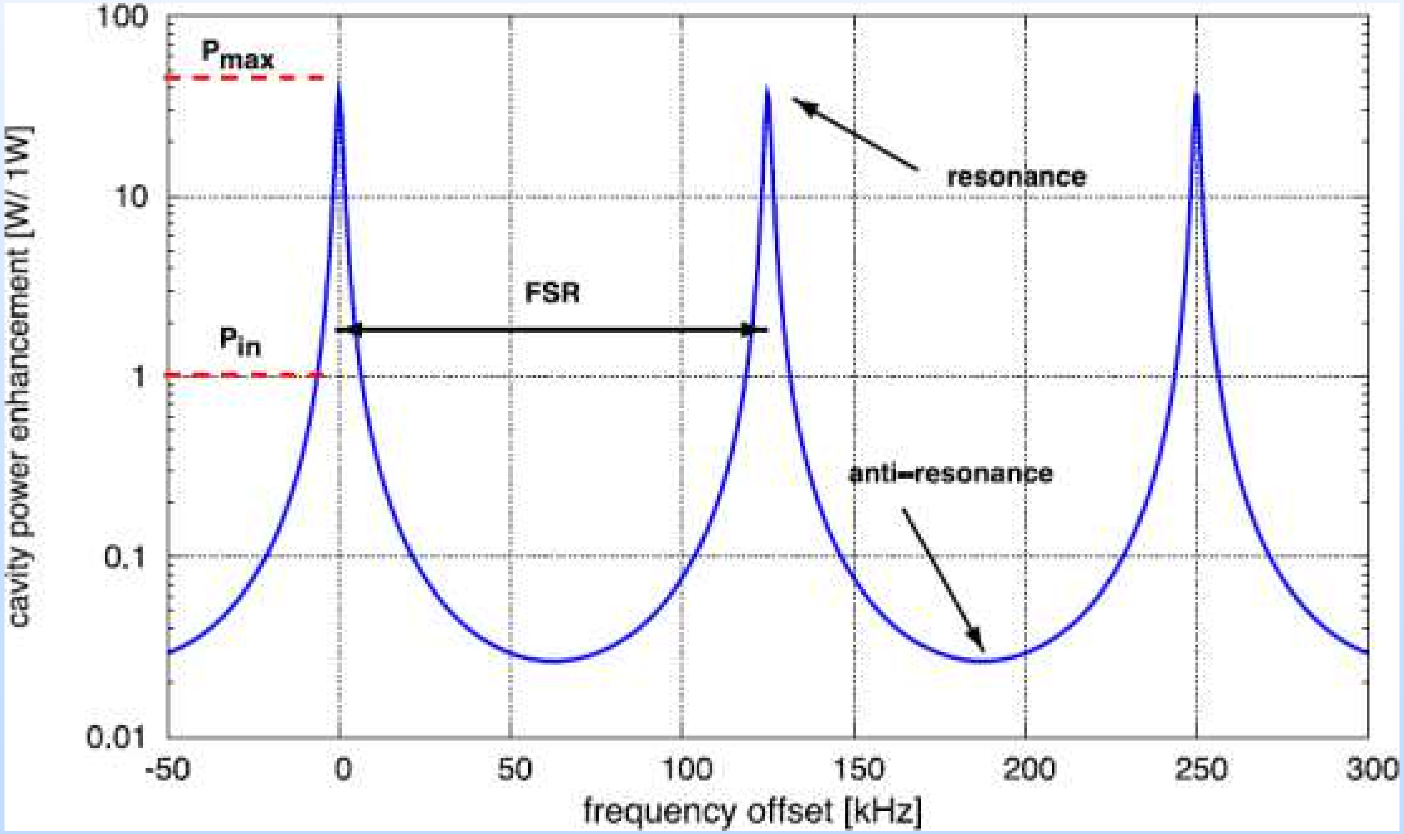
This figure shows an example of a Pound-Drever-Hall (PDH) signal of a two-mirror cavity

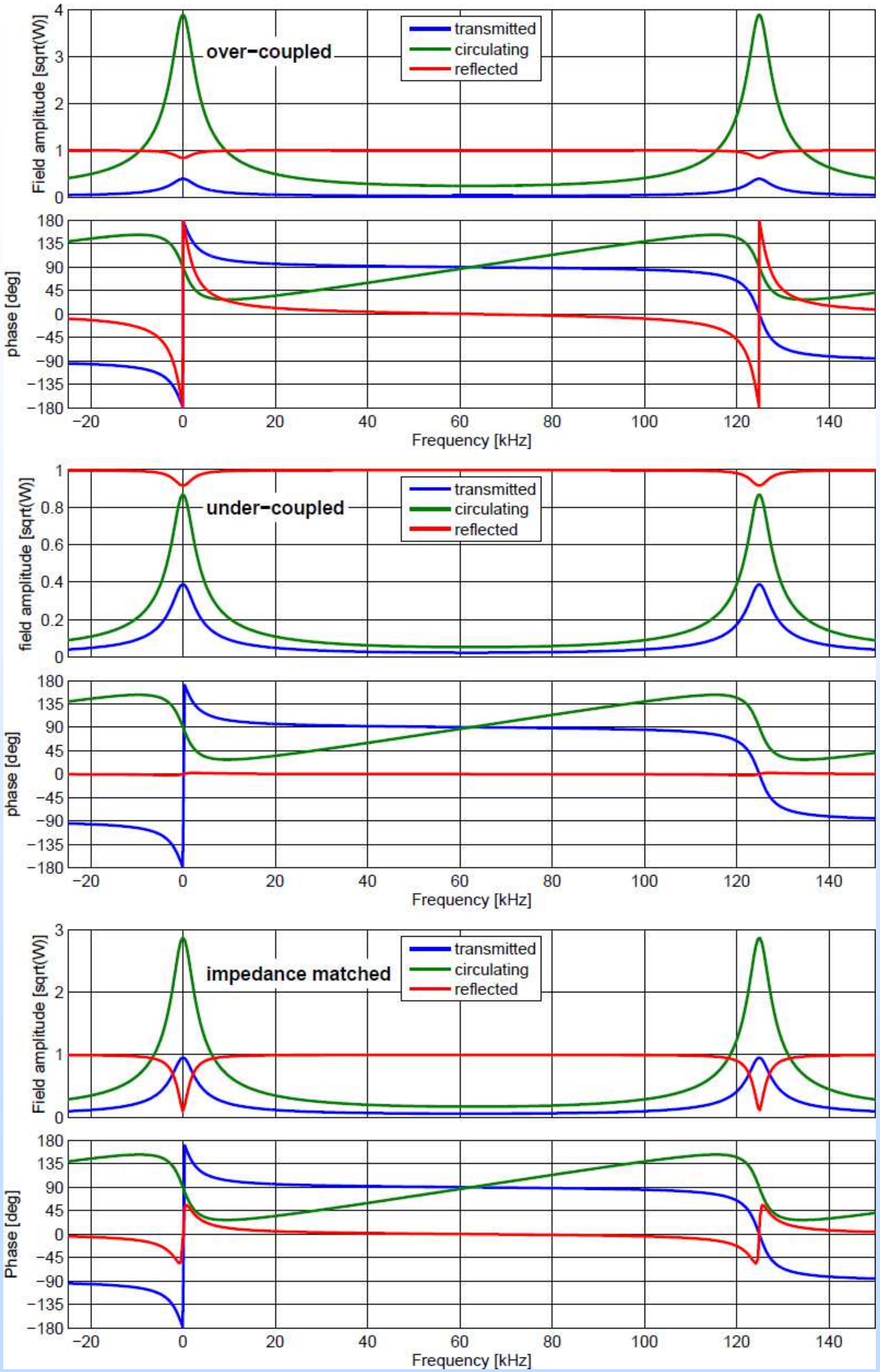


frontal or *Schnupp modulation*



$$P_1 = |a_1|^2 = \frac{T_1}{1 + R_1 R_2 - 2 r_1 r_2 \cos(2kL)},$$





when $T_1 < T_2$ the cavity is called *undercoupled*
when $T_1 = T_2$ the cavity is called *impedance matched*
when $T_1 > T_2$ the cavity is called *overcoupled*

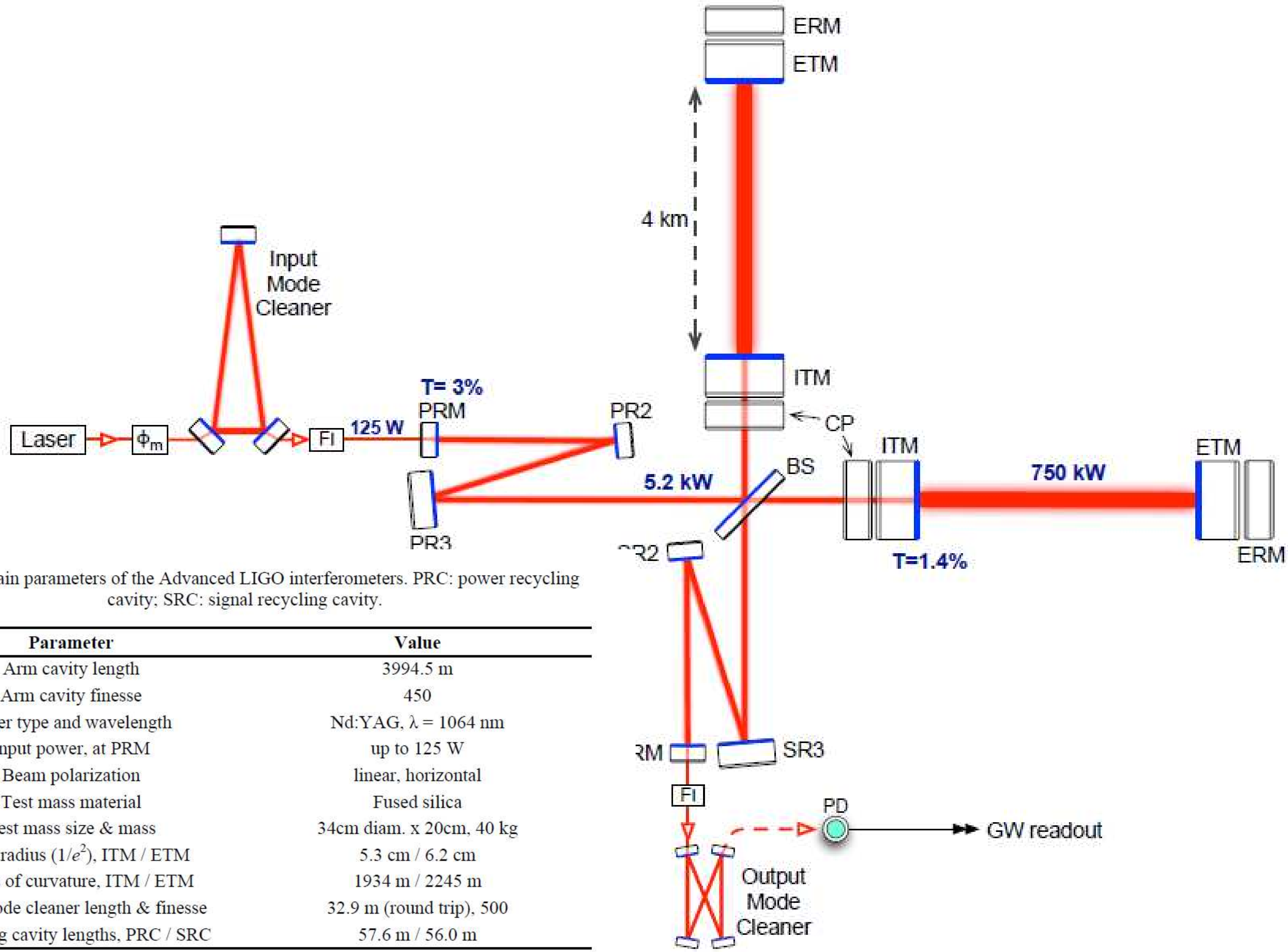


Table 1. Main parameters of the Advanced LIGO interferometers. PRC: power recycling cavity; SRC: signal recycling cavity.

Parameter	Value
Arm cavity length	3994.5 m
Arm cavity finesse	450
Laser type and wavelength	Nd:YAG, $\lambda = 1064$ nm
Input power, at PRM	up to 125 W
Beam polarization	linear, horizontal
Test mass material	Fused silica
Test mass size & mass	34cm diam. x 20cm, 40 kg
Beam radius ($1/e^2$), ITM / ETM	5.3 cm / 6.2 cm
Radius of curvature, ITM / ETM	1934 m / 2245 m
Input mode cleaner length & finesse	32.9 m (round trip), 500
Recycling cavity lengths, PRC / SRC	57.6 m / 56.0 m

Загальна схема LIGO

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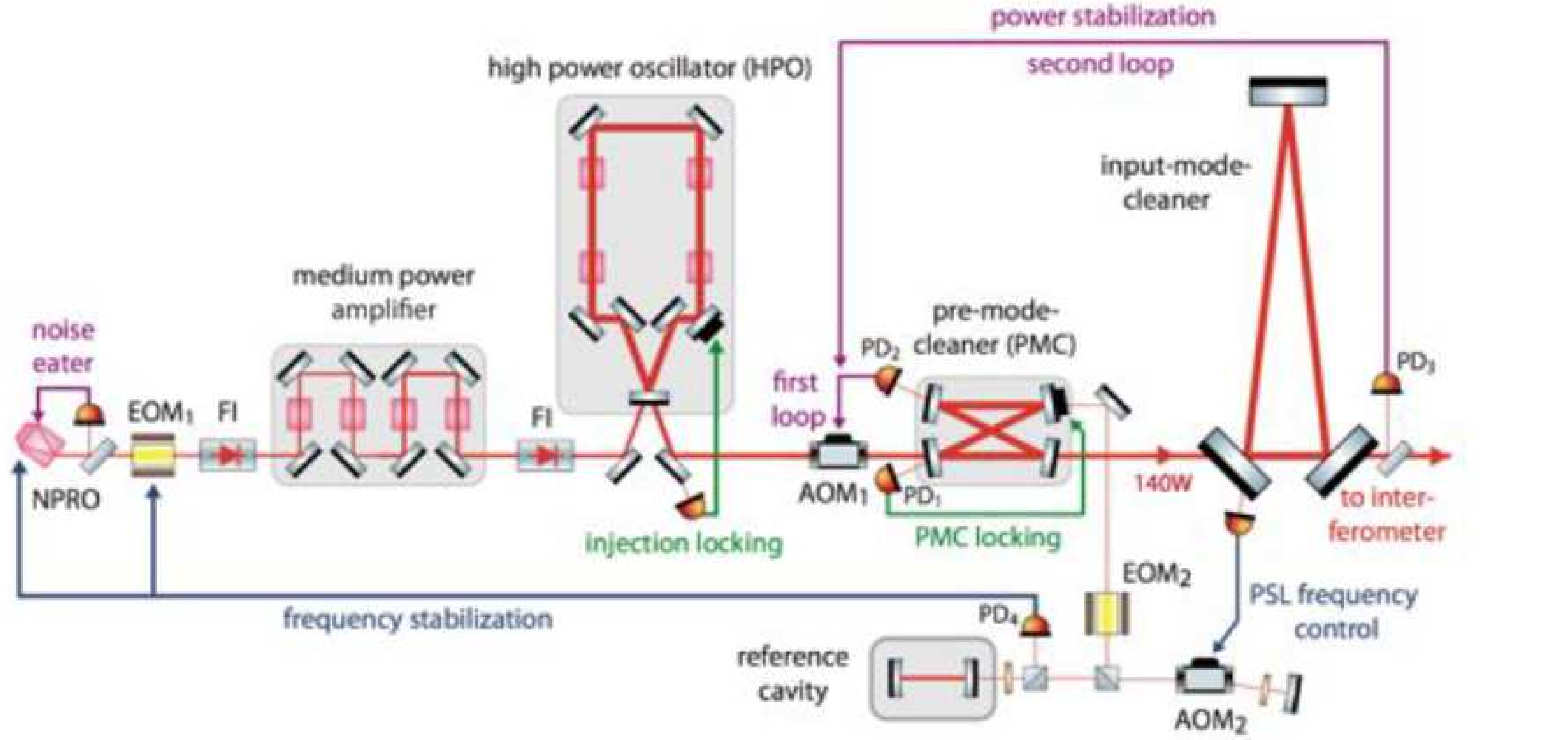
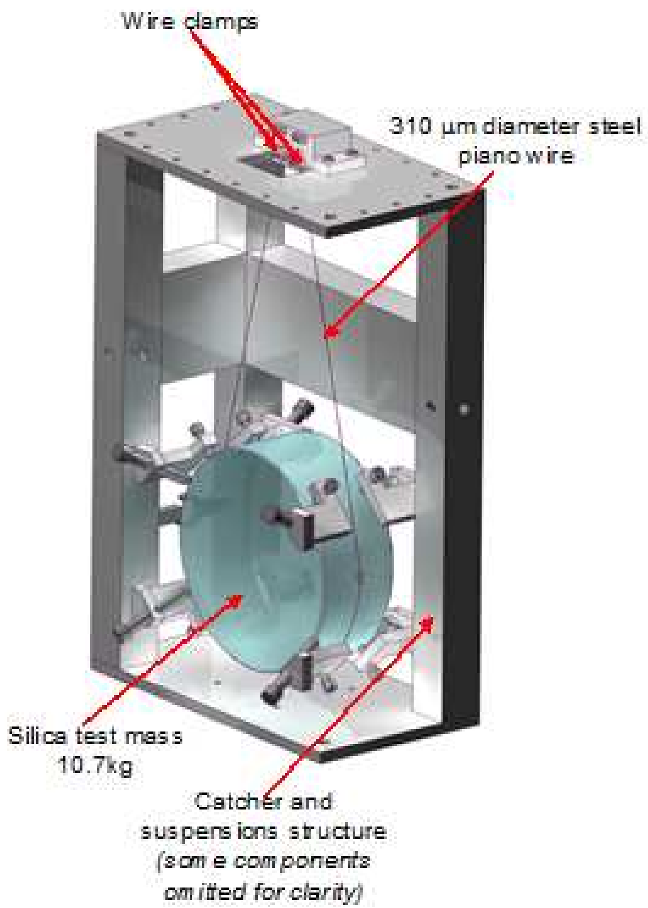


Лазер та система стабілізації частоти, потужності, напряму пучка

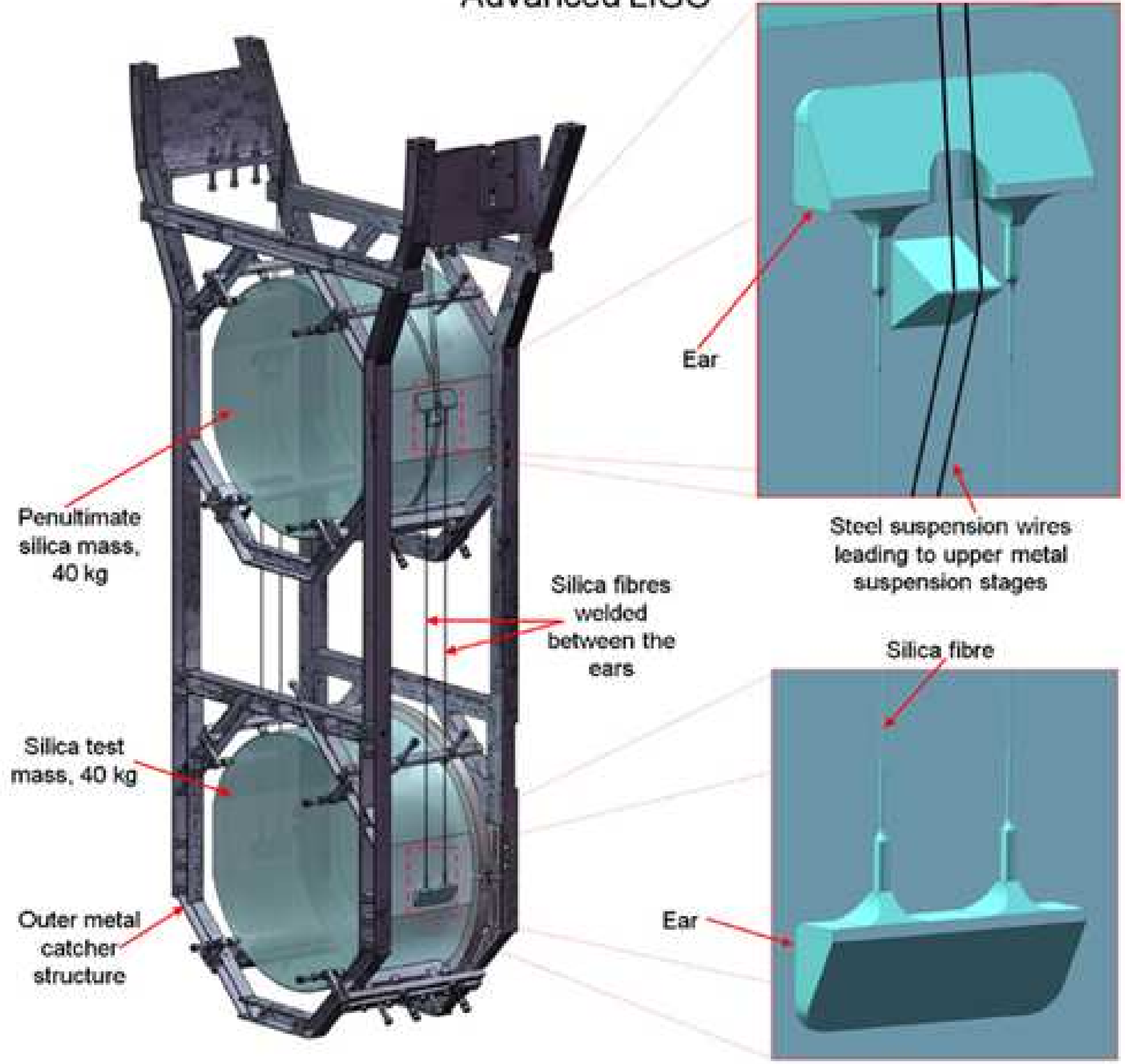
Table 3 Parameters of the core optics. ETM/ITM: end/input test mass; CP: compensation plate; ERM: end reaction mass; BS: beam splitter; PR3/2: power recycling mirror 3/2; SR3/2: signal recycling mirror 3/2; PRM/SRM: power/signal recycling mirror. ROC: radius of curvature; AR: anti-reflection. Transmission values are at 1064 nm, except for those in parentheses, which are for 532 nm.

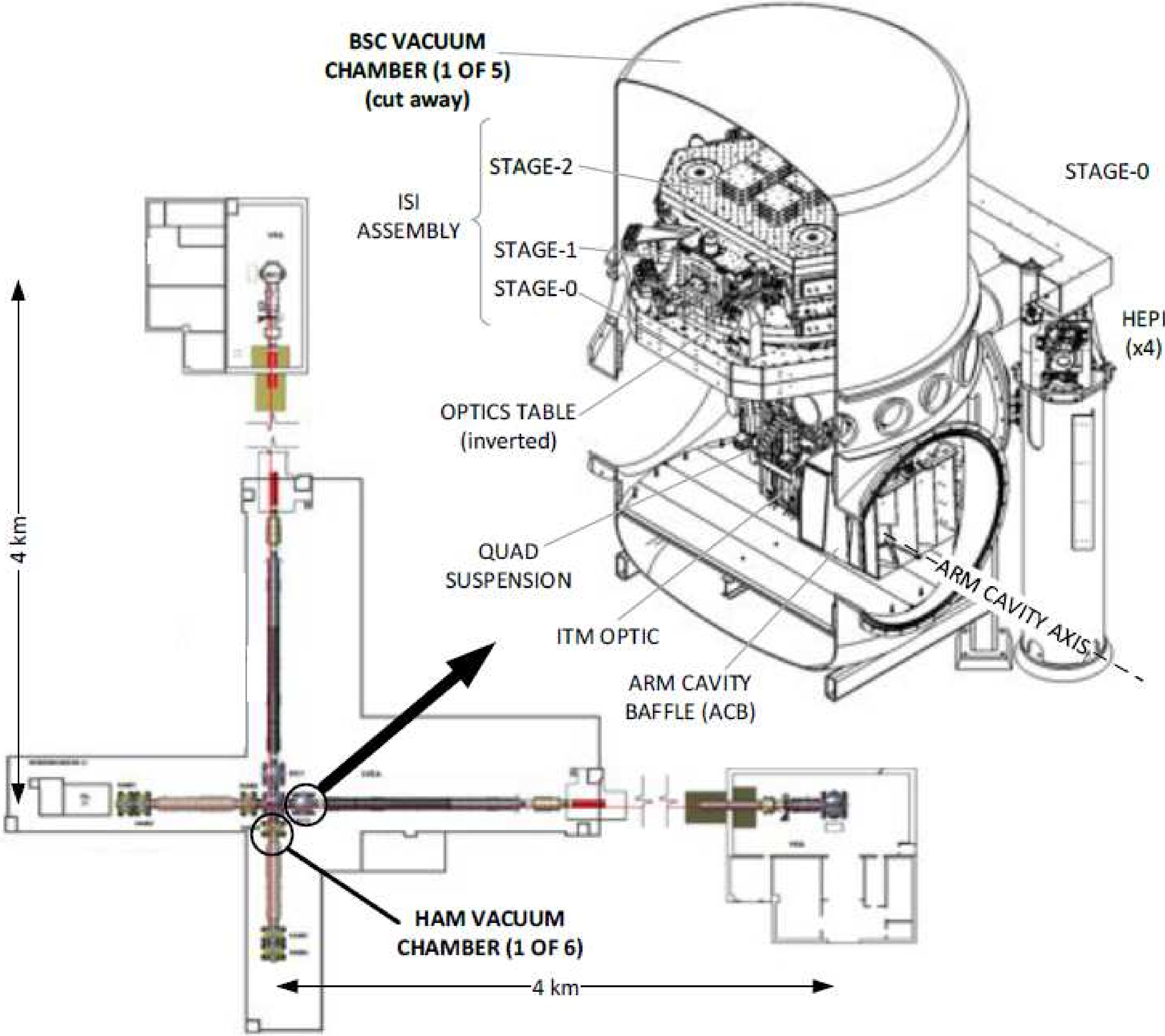
Optic	Dimensions: diam.×thickness	Mass	Transmission	ROC	Beam size ($1/e^2$ radius)
ITM	34×20 cm	40 kg	1.4% (0.5-2%)	1934 m	5.3 cm
ETM	34×20 cm	40 kg	5 ppm (1-4%)	2245 m	6.2 cm
CP	34×10 cm	20 kg	AR< 50 ppm	flat	5.3 cm
ERM	34×13 cm	26 kg	AR< 1000 ppm	flat	6.2 cm
BS	37×6 cm	14 kg	50%	flat	5.3 cm
PR3	26.5×10 cm	12 kg	< 15 ppm	36.0 m	5.4 cm
SR3	26.5×10 cm	12 kg	< 15 ppm	36.0 m	5.4 cm
PR2	15×7.5 cm	2.9 kg	225 ppm (>90%)	-4.56 m	6.2 mm
SR2	15×7.5 cm	2.9 kg	< 15 ppm	-6.43 m	8.2 mm
PRM	15×7.5 cm	2.9 kg	3.0%	-11.0 m	2.2 mm
SRM	15×7.5 cm	2.9 kg	20%	-5.69 m	2.1 mm

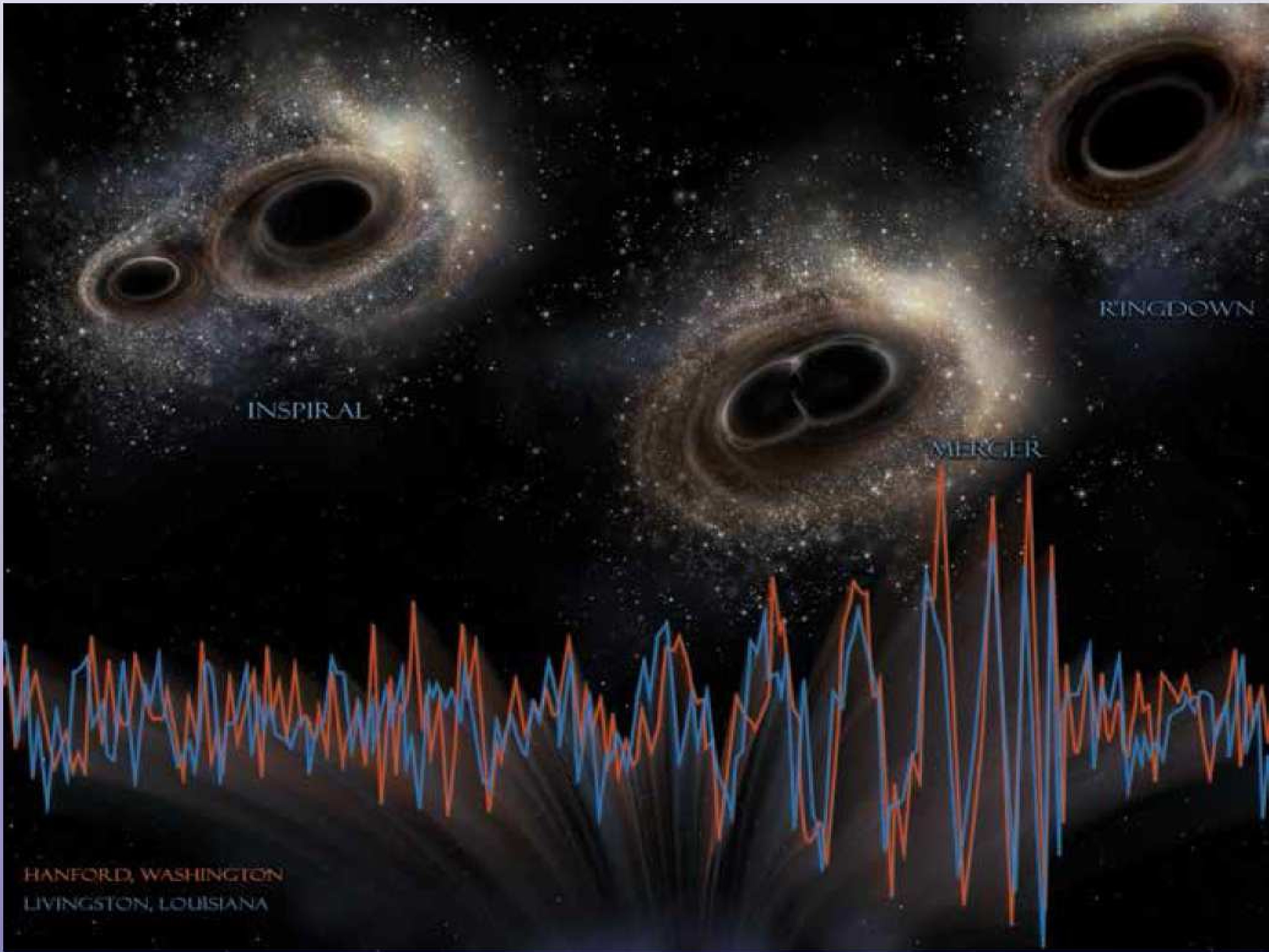
LIGO



Advanced LIGO




BSC VACUUM
CHAMBER (1 OF 5)
(cut away)
ISI
ASSEMBLY
STAGE-2
STAGE-1
STAGE-0
STAGE-0
HEPI
(x4)
OPTICS TABLE
(inverted)
QUAD
SUSPENSION
ITM OPTIC
ARM CAVITY
BAFFLE (ACB)
ARM CAVITY AXIS
4 km
4 km
HAM VACUUM
CHAMBER (1 OF 6)


INSPIRAL
MERGER
RINGDOWN
HANFORD, WASHINGTON
LIVINGSTON, LOUISIANA

Properties of the Binary Black Hole Merger GW150914

B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 18 February 2016; revised manuscript received 18 April 2016; published 14 June 2016)

On September 14, 2015, the Laser Interferometer Gravitational-Wave Observatory (LIGO) detected a gravitational-wave transient (GW150914); we characterize the properties of the source and its parameters. The data around the time of the event were analyzed coherently across the LIGO network using a suite of accurate waveform models that describe gravitational waves from a compact binary system in general relativity. GW150914 was produced by a nearly equal mass binary black hole of masses $36^{+5}_{-4} M_{\odot}$ and $29^{+4}_{-4} M_{\odot}$; for each parameter we report the median value and the range of the 90% credible interval. The dimensionless spin magnitude of the more massive black hole is bound to be < 0.7 (at 90% probability). The luminosity distance to the source is 410^{+160}_{-180} Mpc, corresponding to a redshift $0.09^{+0.03}_{-0.04}$ assuming standard cosmology. The source location is constrained to an annulus section of 610 deg^2, primarily in the southern hemisphere. The binary merges into a black hole of mass $62^{+4}_{-4} M_{\odot}$ and spin $0.67^{+0.05}_{-0.07}$. This black hole is significantly more massive than any other inferred from electromagnetic observations in the stellar-mass regime.

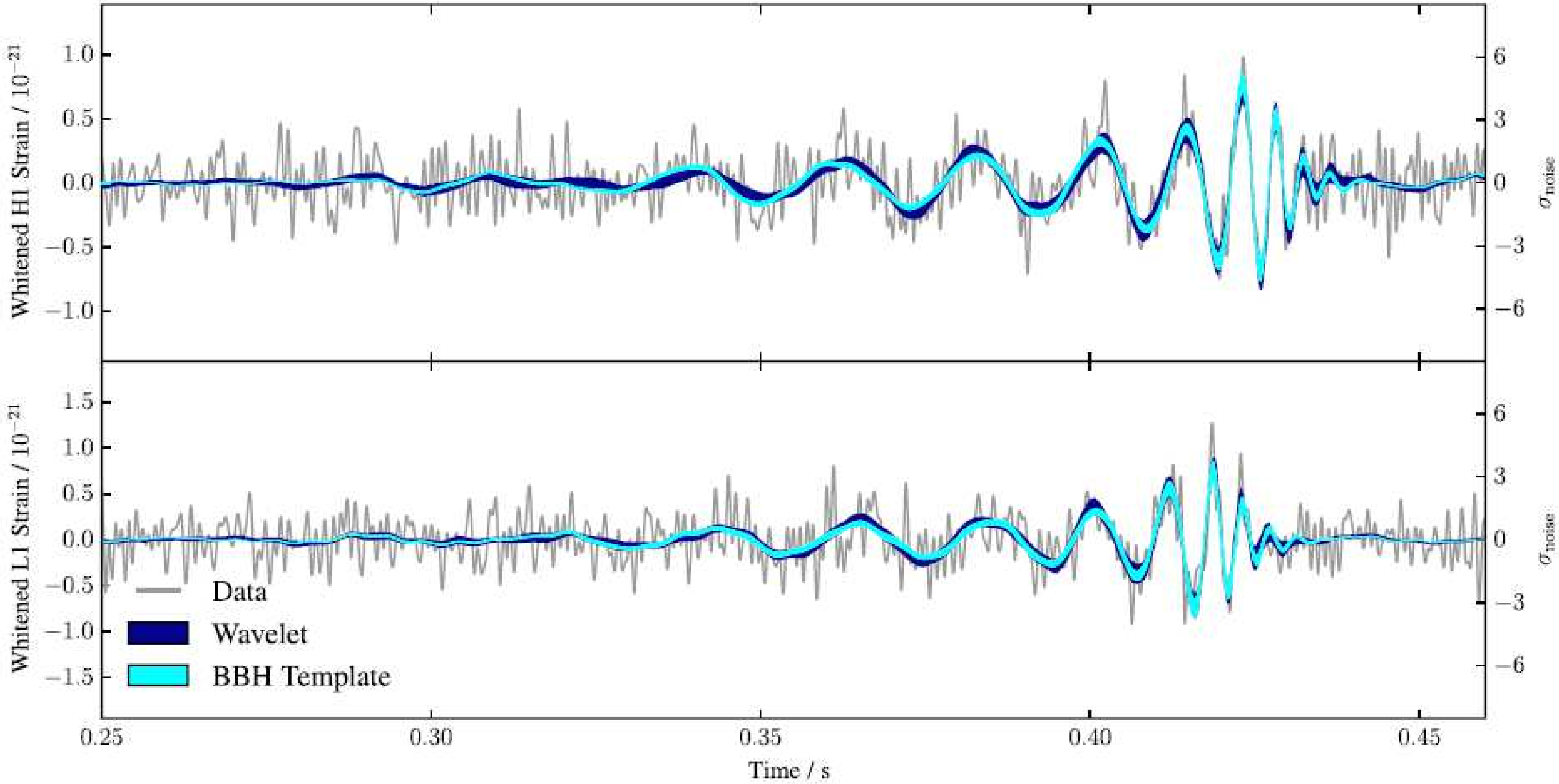


FIG. 6. Time-domain data (sampled at 2048 Hz) and reconstructed waveforms of GW150914, whitened by the noise power spectral

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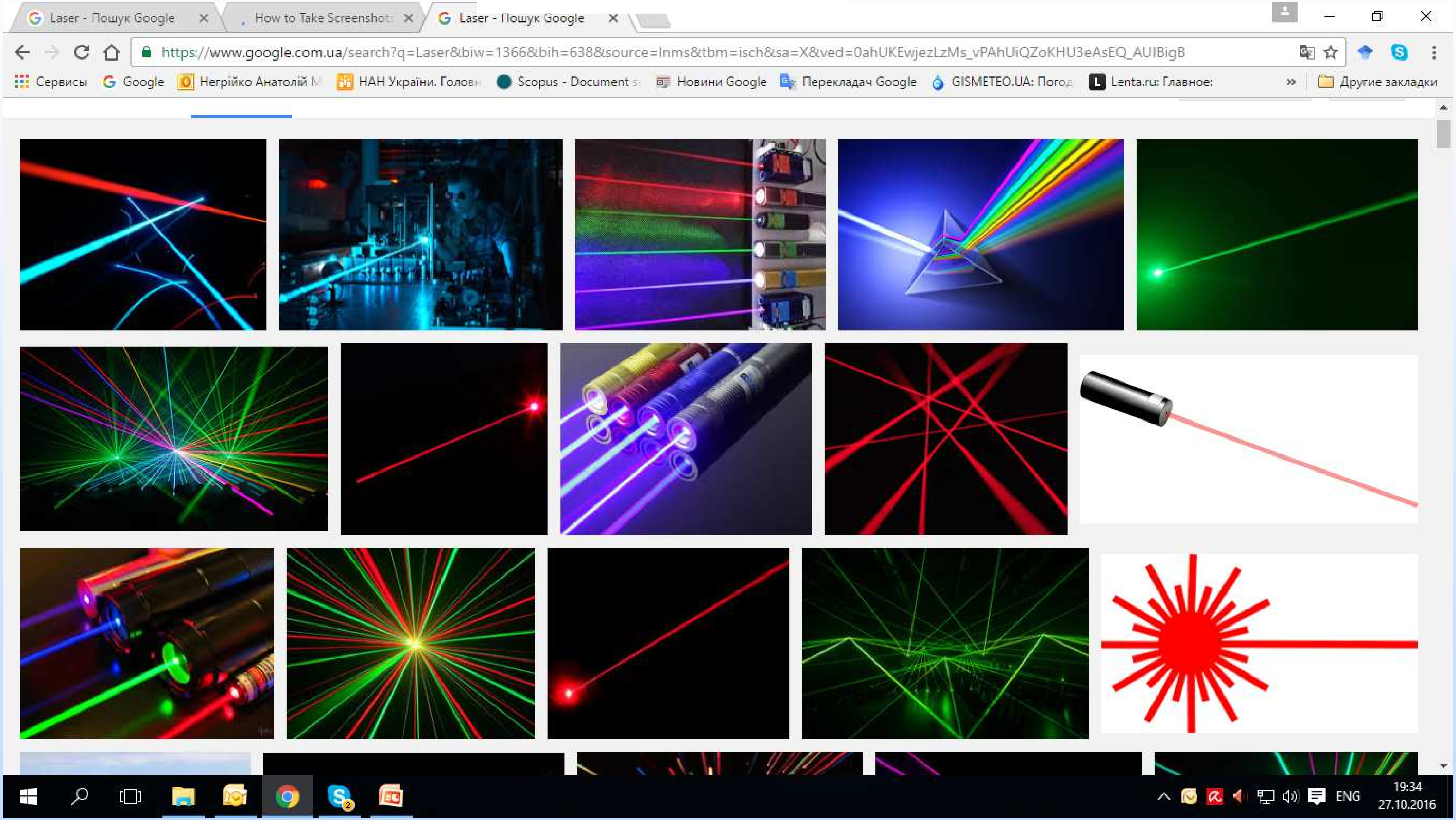

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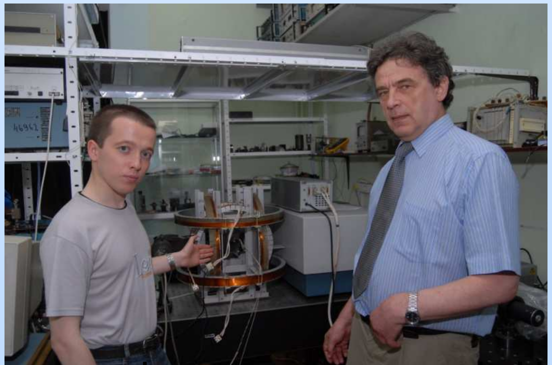

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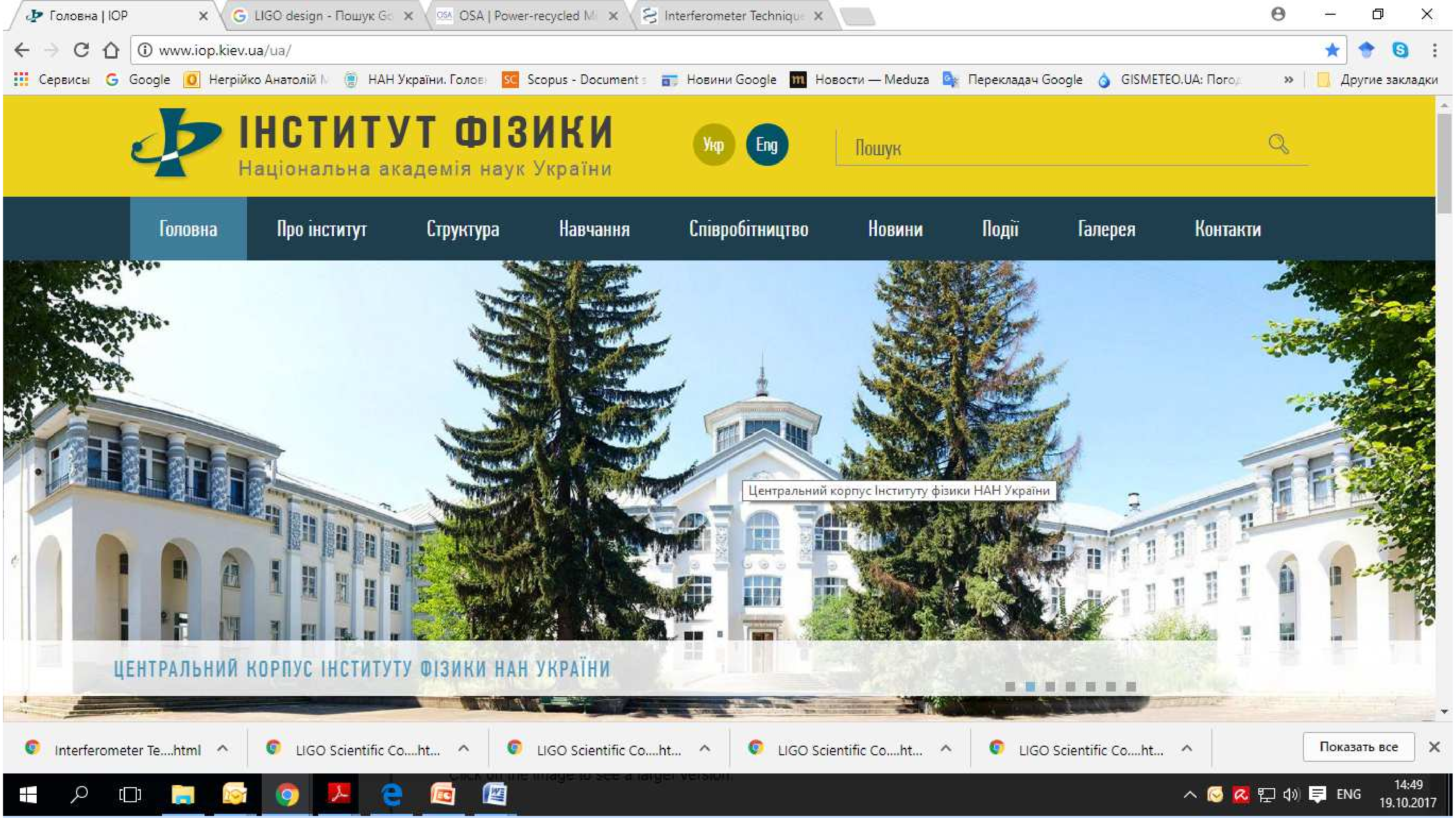

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