Multi Messenger Astronomy with a Laser Interferometer Gravitational Wave Observatory

Department of astronomy

June Gyu Park

YONSEI UNIVERSITY

중력파 여름학교 2026

Introduction

June Gyu Park

Laser optics
Laser interferometer
Science hall 623

Sogang University PhD (Physics)

Korea basics science institute (KBSI)
Korea research institute of standards and science (KRISS)
Korea astronomy and space science institute (KASI)

Gravitational wave detector

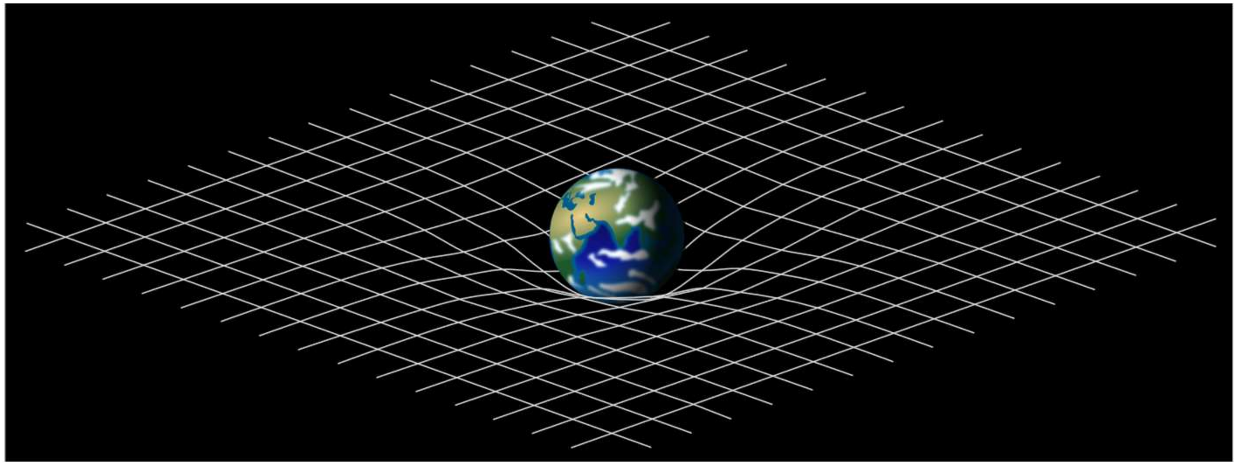
LVK collaboration	KAGRA
VIRGO	Einstein telescope

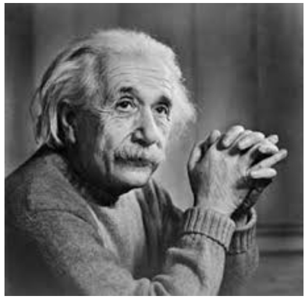
Local Sensor and detector design

Space optics metrology

KRISS	KASI

Gravity and General Relativity





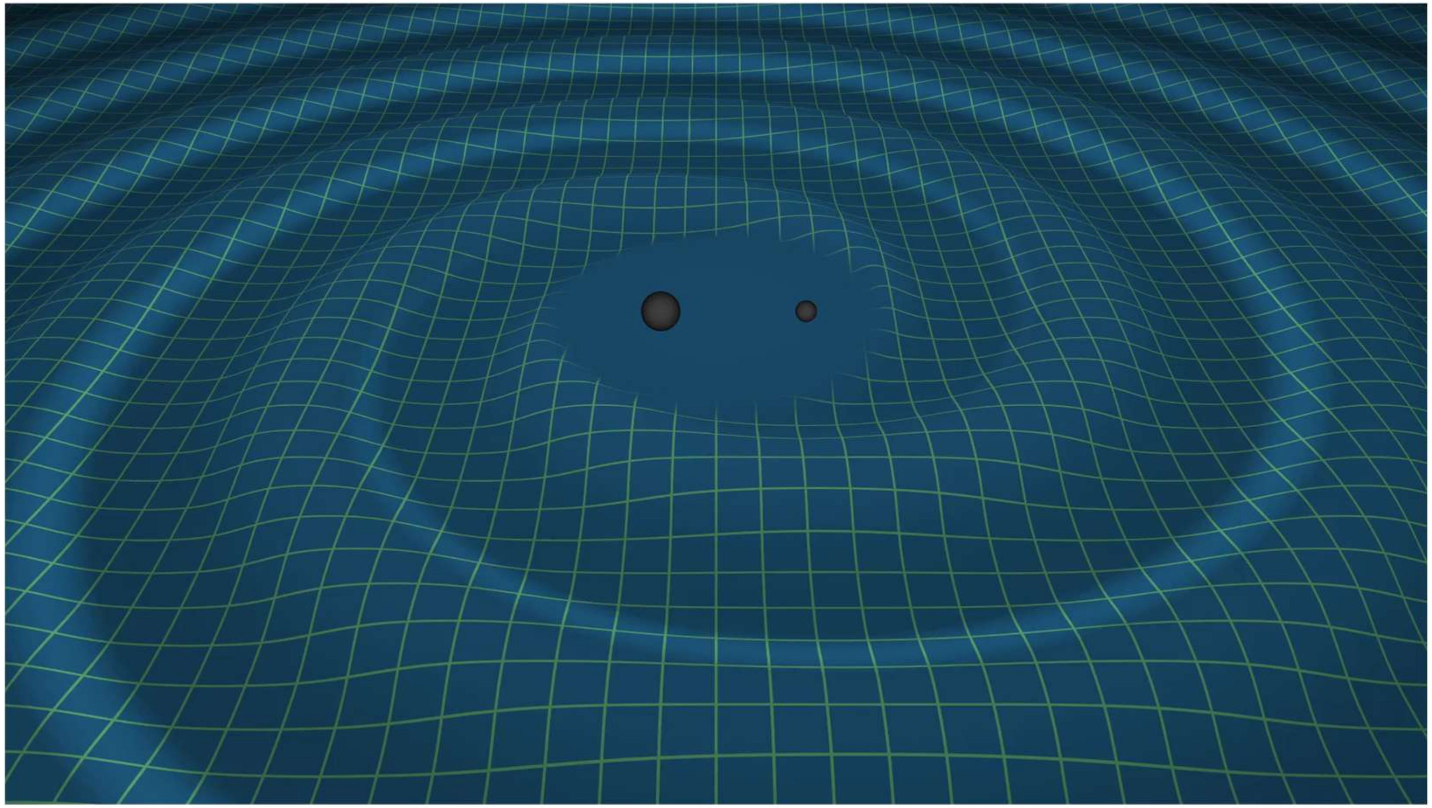
$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \kappa T_{\mu\nu}$$

Local space time curvature

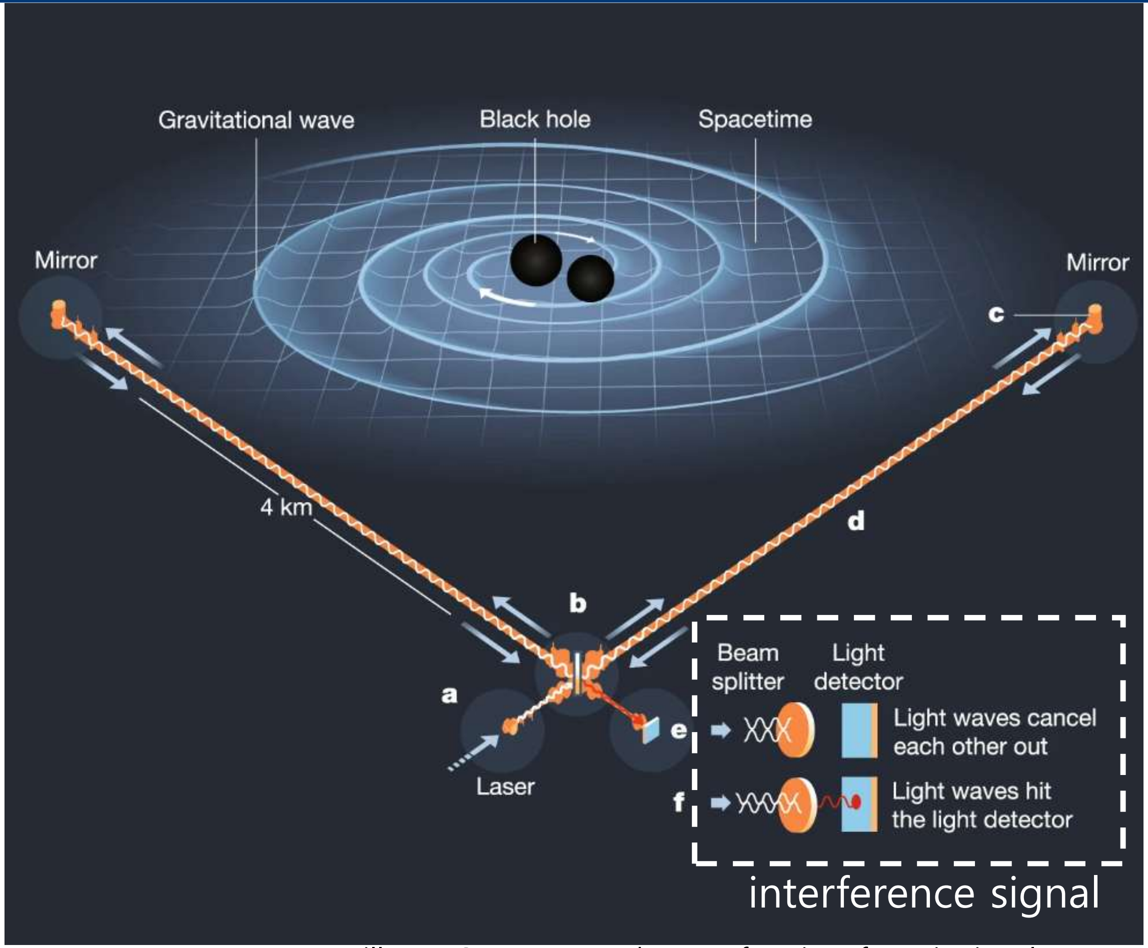
Local energy, momentum stress

Mass of object

Gravitational Wave



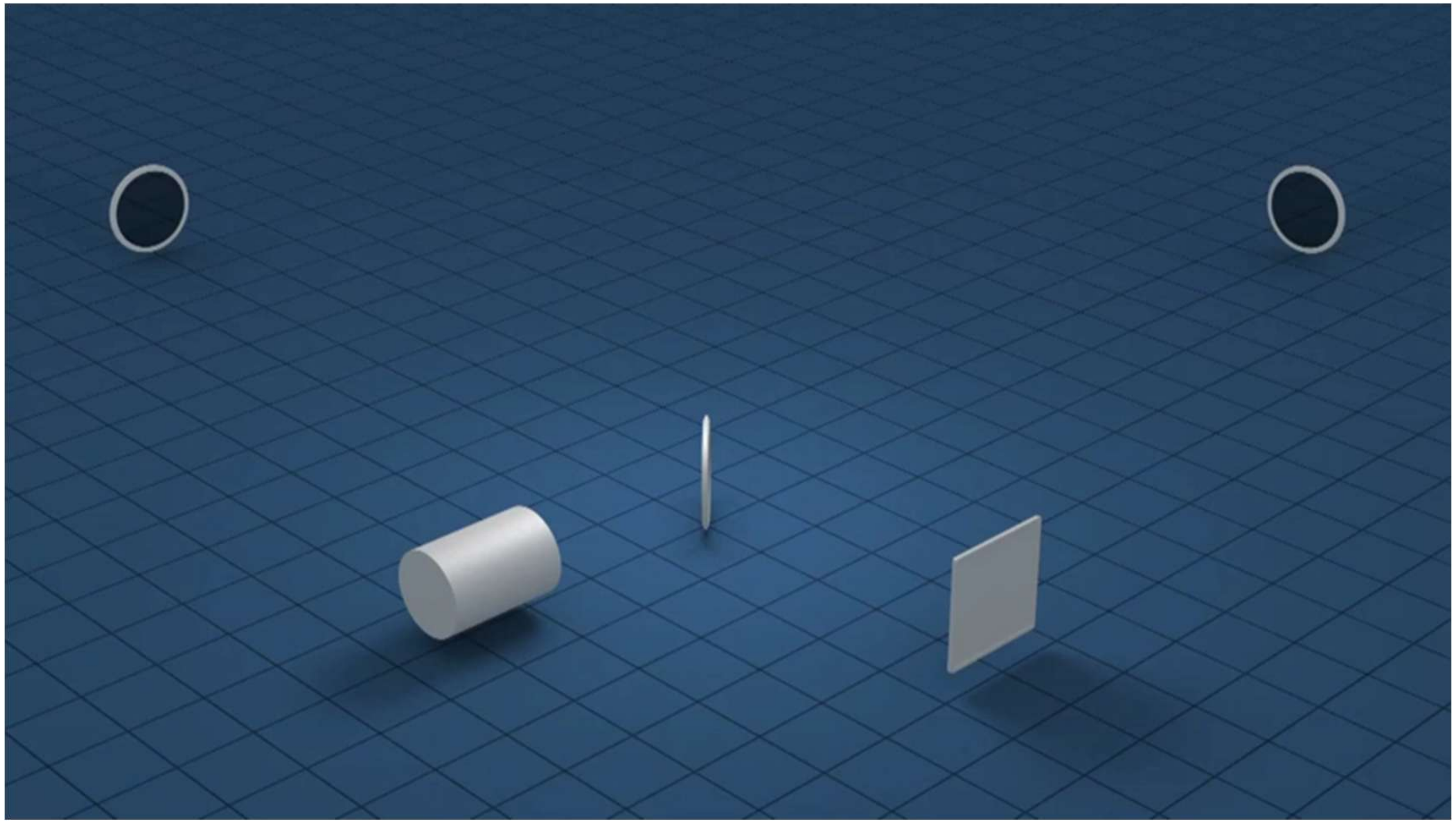
Gravitational Wave Detector



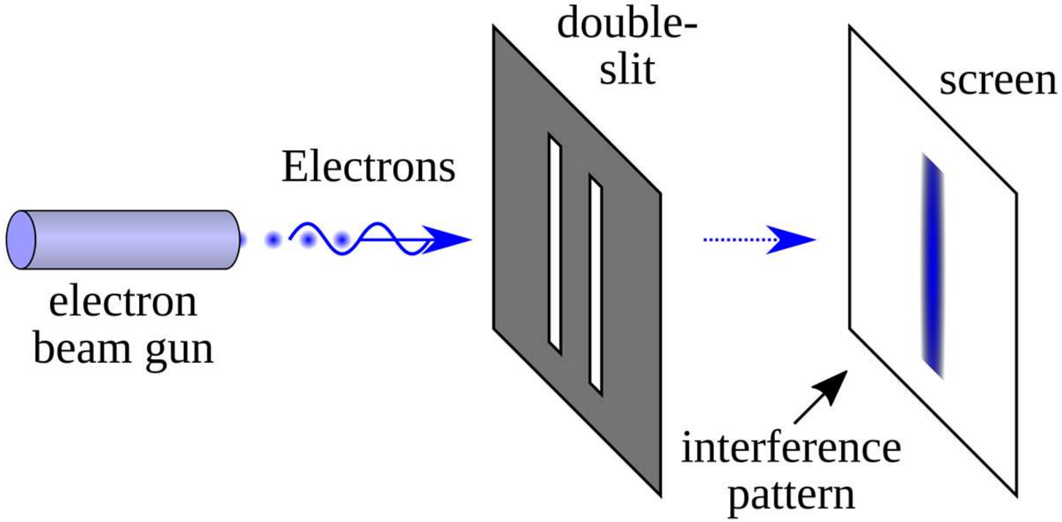
- Ground scale Michelson interferometer
- 4 km vacuum tunnel arm
- Over 1000 km interaction length

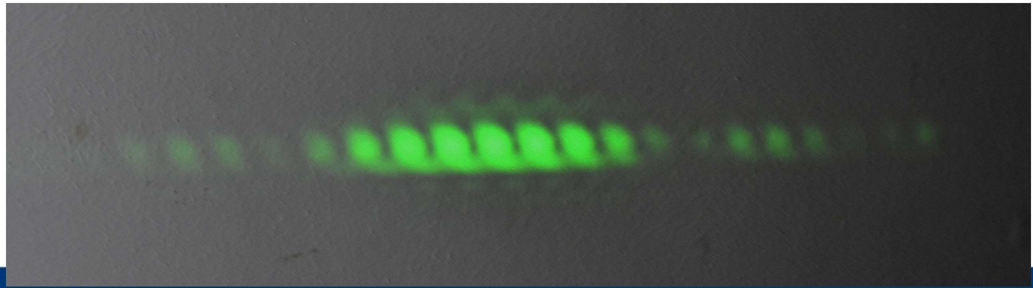
Miller, M.C., Yunes, N. The new frontier of gravitational waves. *Nature* **568,** 469–476 (2019)

Michelson Interferometer

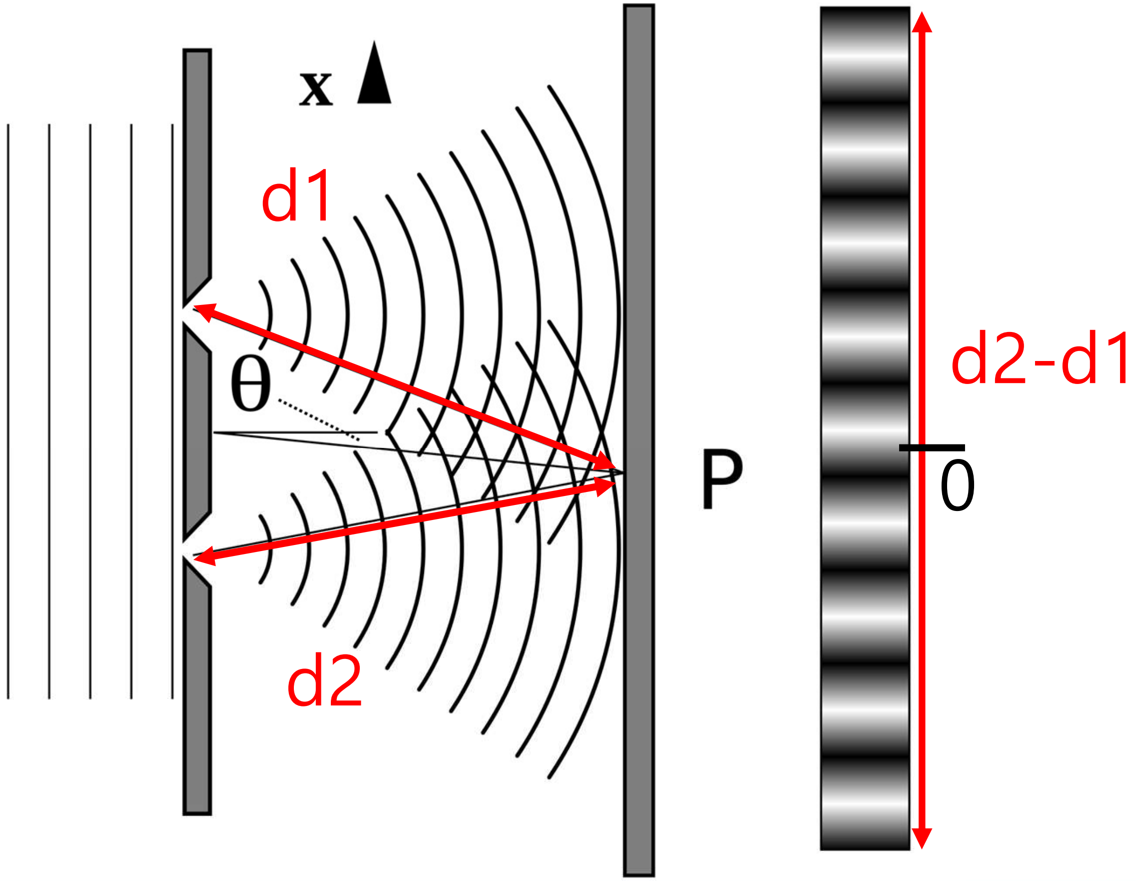


Double Slit Experiment

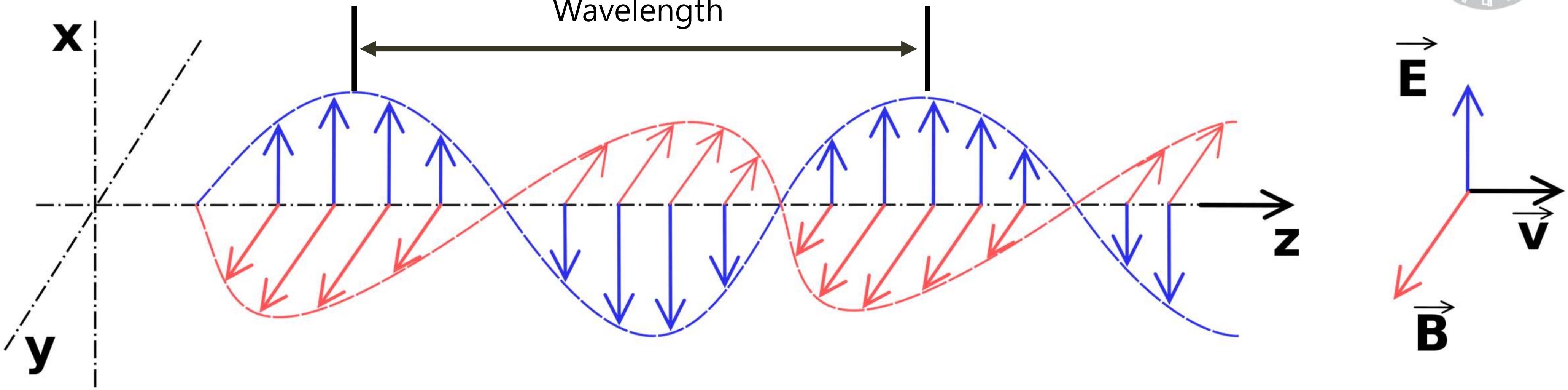




Interference

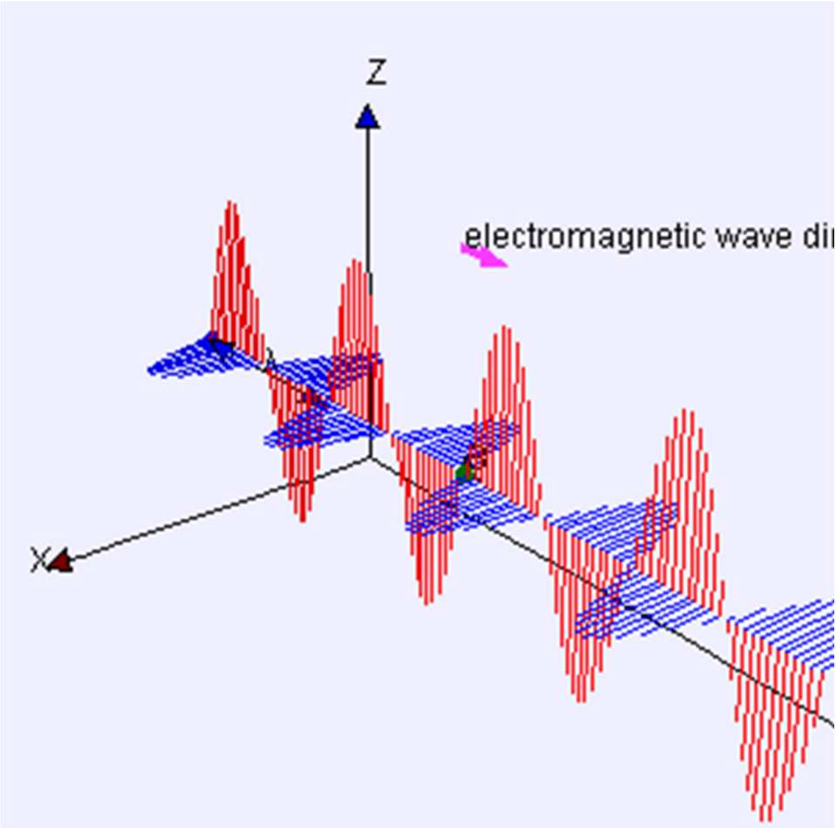


Light(Electromagnetic Wave)

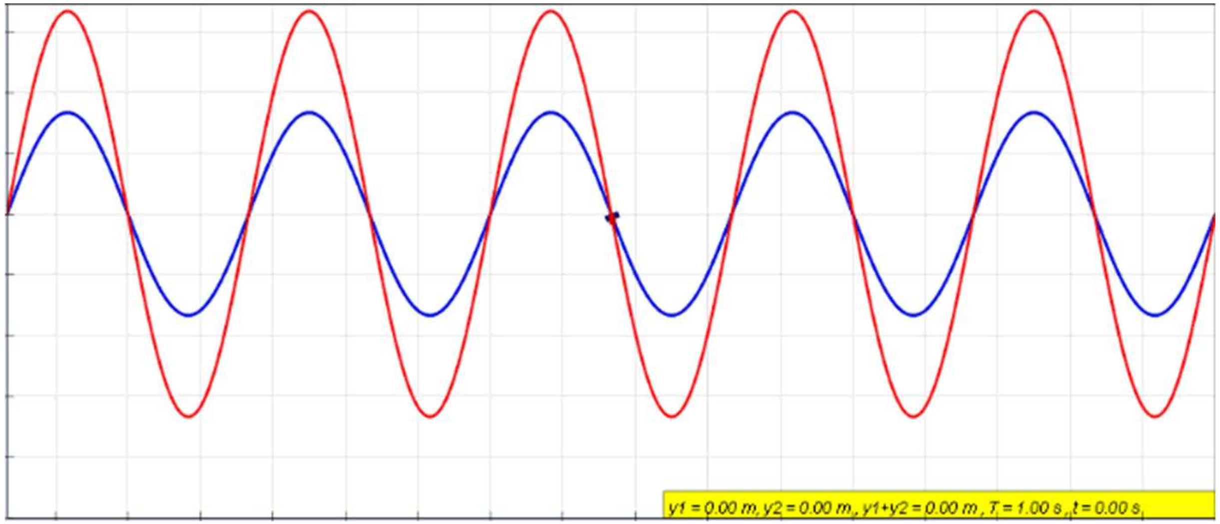


$$\left|\vec{E}\right| \propto Intensity\ of\ Light$$

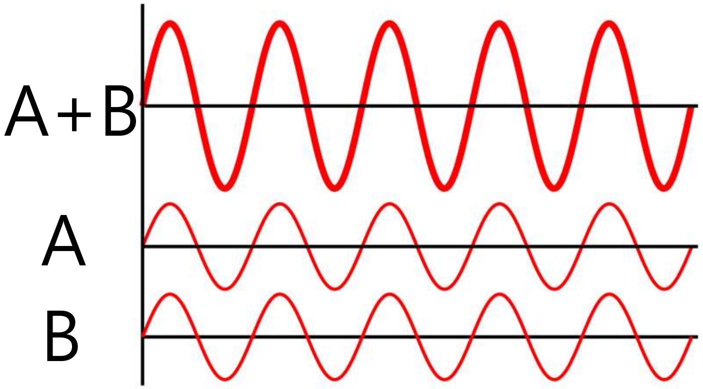
Light(Electromagnetic Wave)

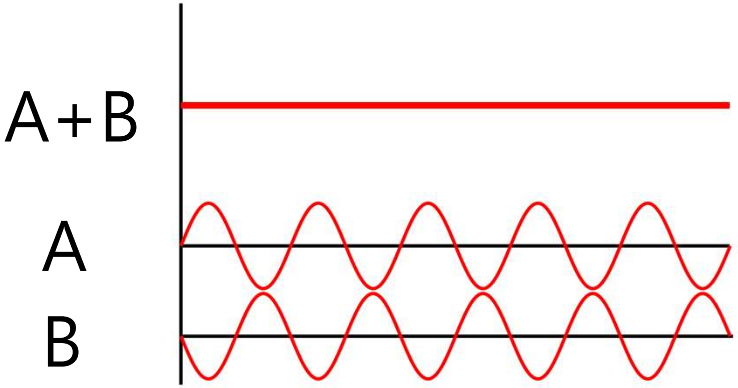


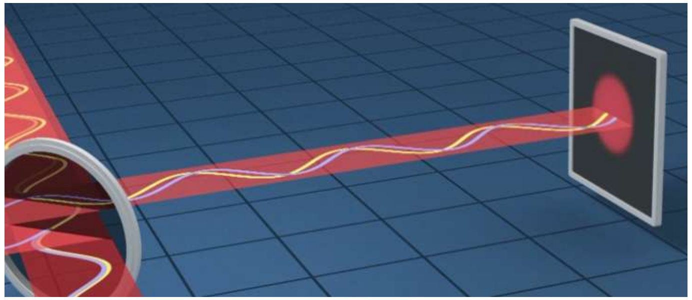
Interference

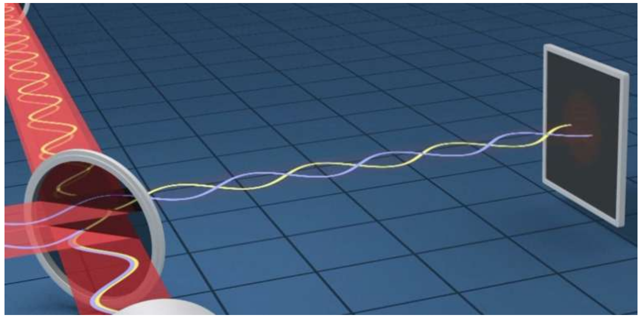


Interference





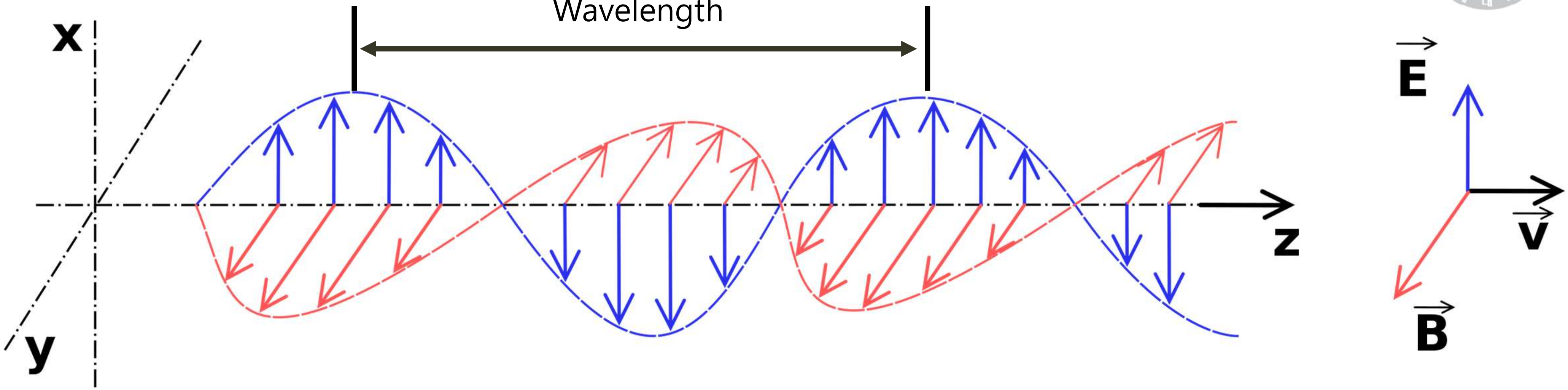




Constructive

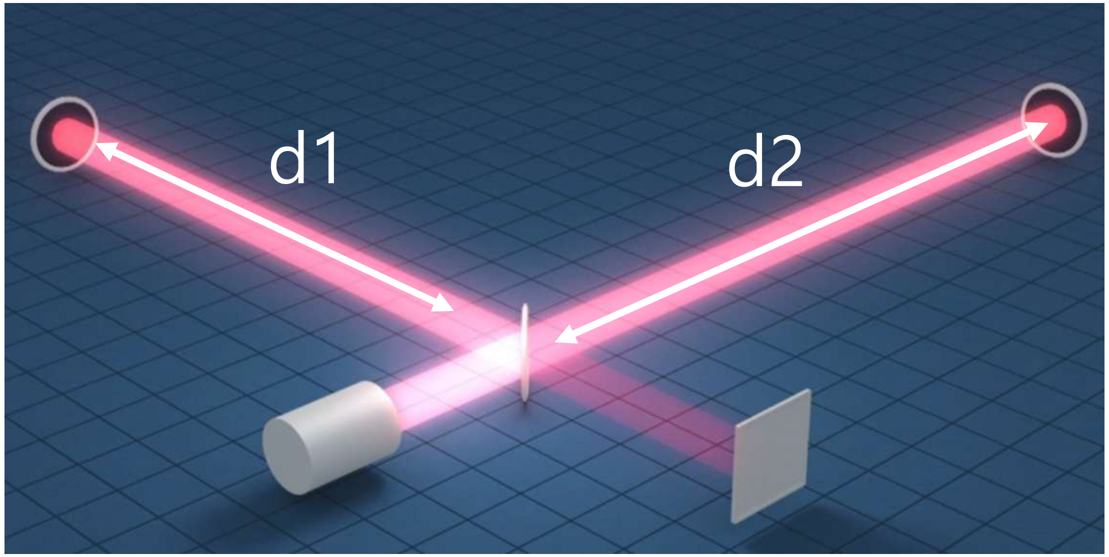
Destructive

Light(Electromagnetic Wave)



$$\vec{\mathrm{E}} = E_0 \cos(kx - \omega t + \varphi)$$

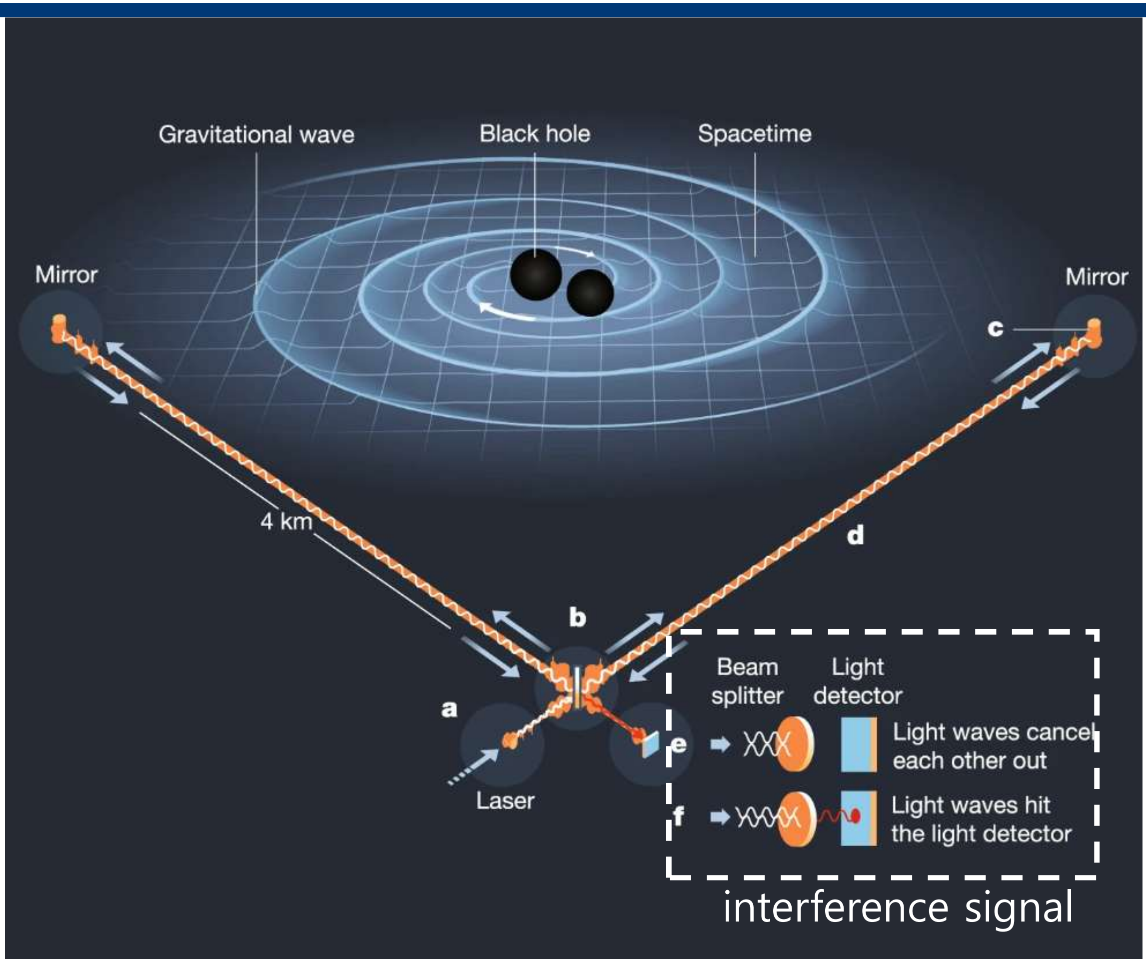
Interference Signal



$\vec{E} = E_0 \cos(kx - \omega t + \varphi)$ $\varphi \propto d1 - d2$ (in some condition)

$k = \frac{2\pi}{\lambda}$ λ : $0.1\mu m \sim 10\mu m$
wavelength

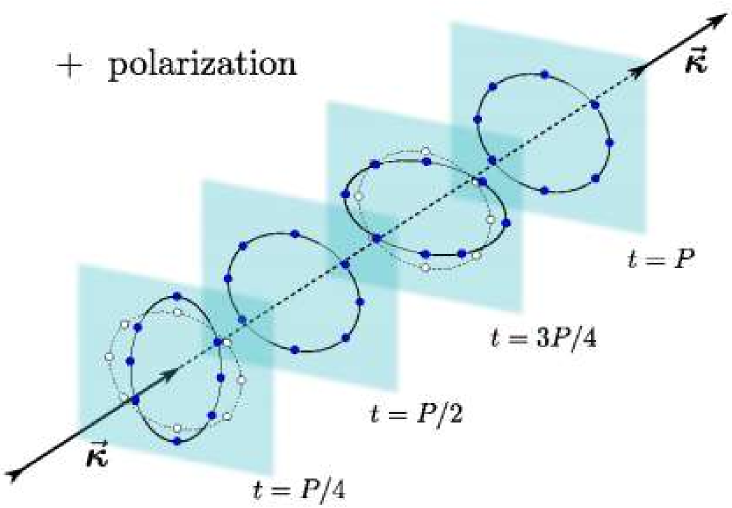
Gravitational Wave Detector



- Ground scale Michelson interferometer
- 4 km vacuum tunnel arm
- Over 1000 km interaction length

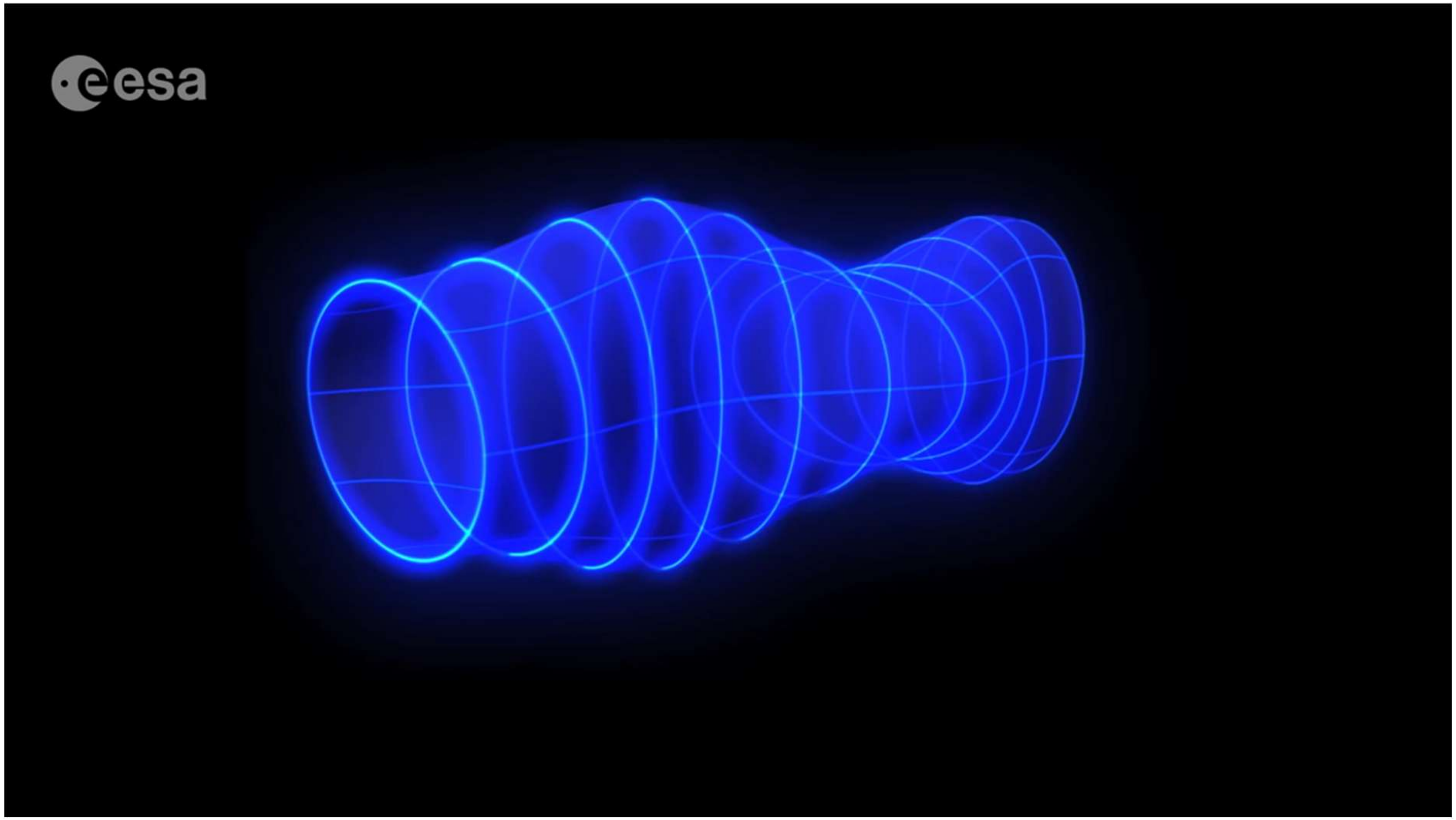
Build most sensitive system
using most simple arrangement

Gravitational Wave

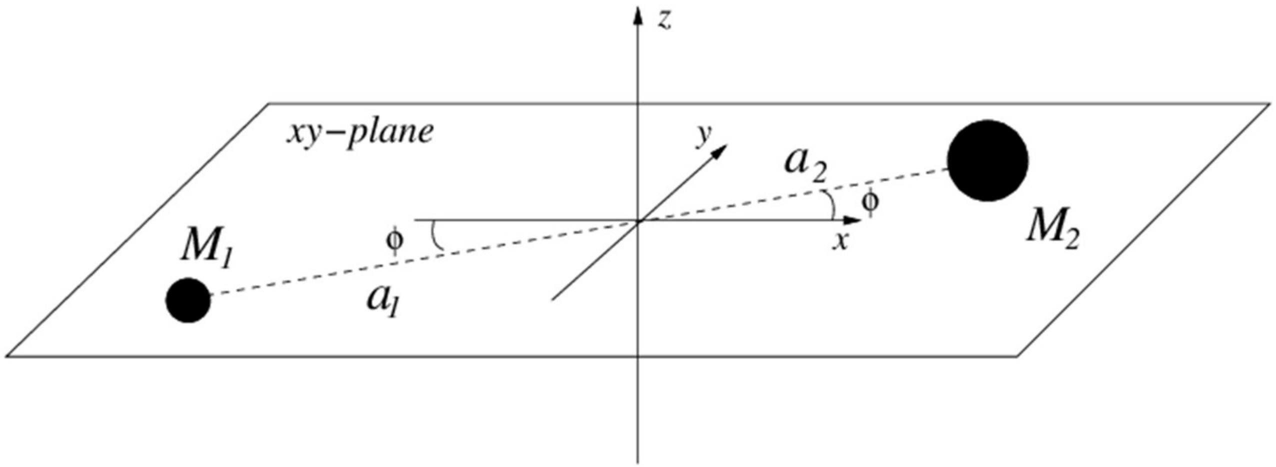


MPA Lectures on Gravitational Waves in Cosmology
Azadeh Maleknejad
Max-Planck-Institute for Astrophysics

Gravitational Wave



Compact Binary System



Andersson, Nils & Kokkotas, Kostas. (2004). Gravitational-wave astronomy: the high-frequency window.

$$h = \frac{2G}{c^4}\frac{1}{r}\frac{\partial^2 Q}{\partial t^2}$$

Amplitude of gravitational wave

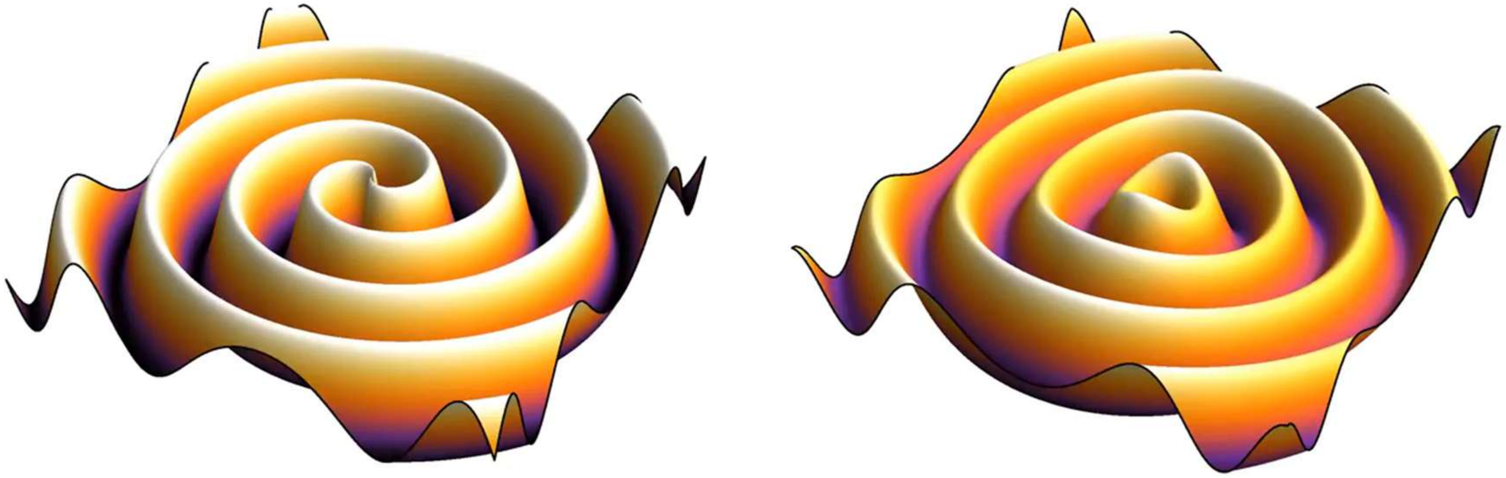
Mass dipole : Center of mass

Conserved

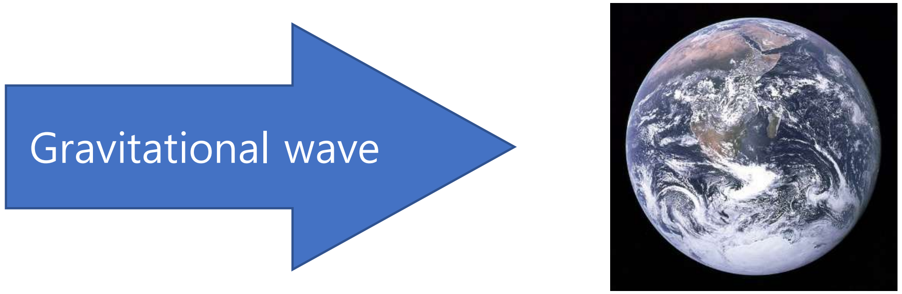
First derivative is momentum

Conserved

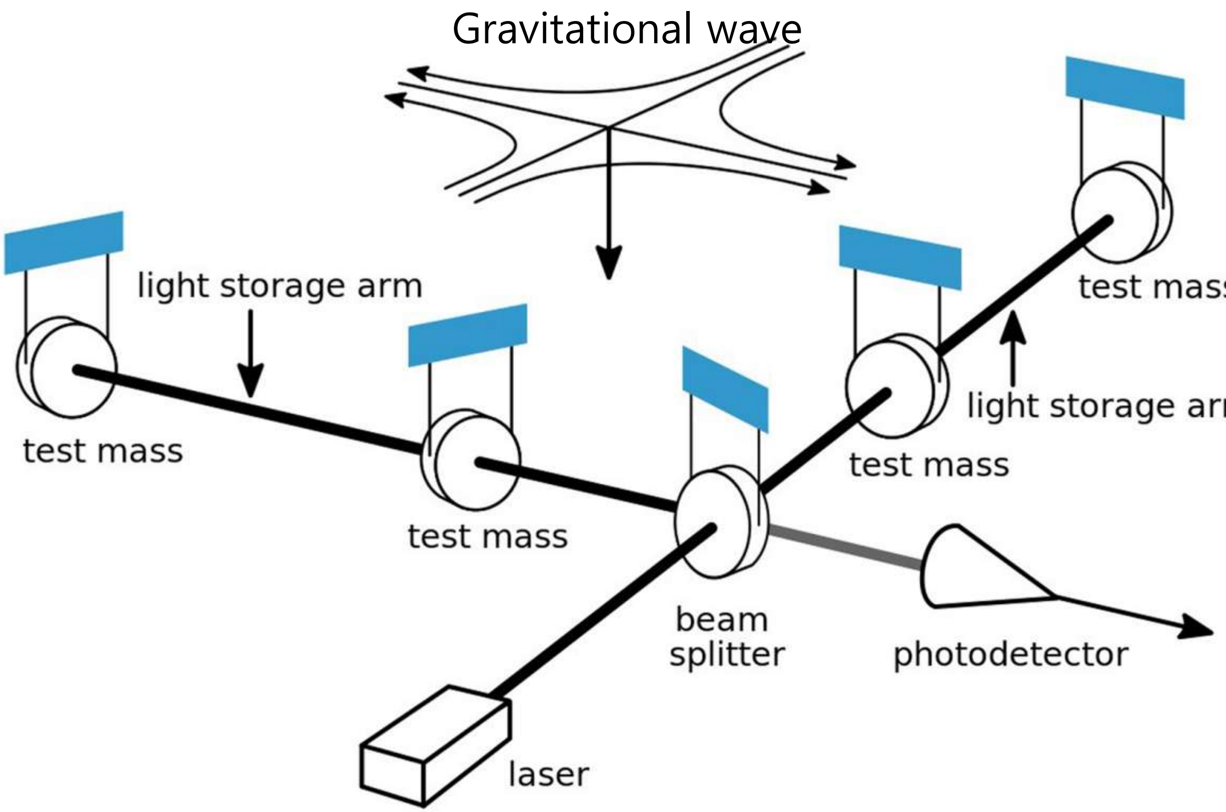
Gravitational Wave Quadrupole Radiation



Effect of Gravitational Wave

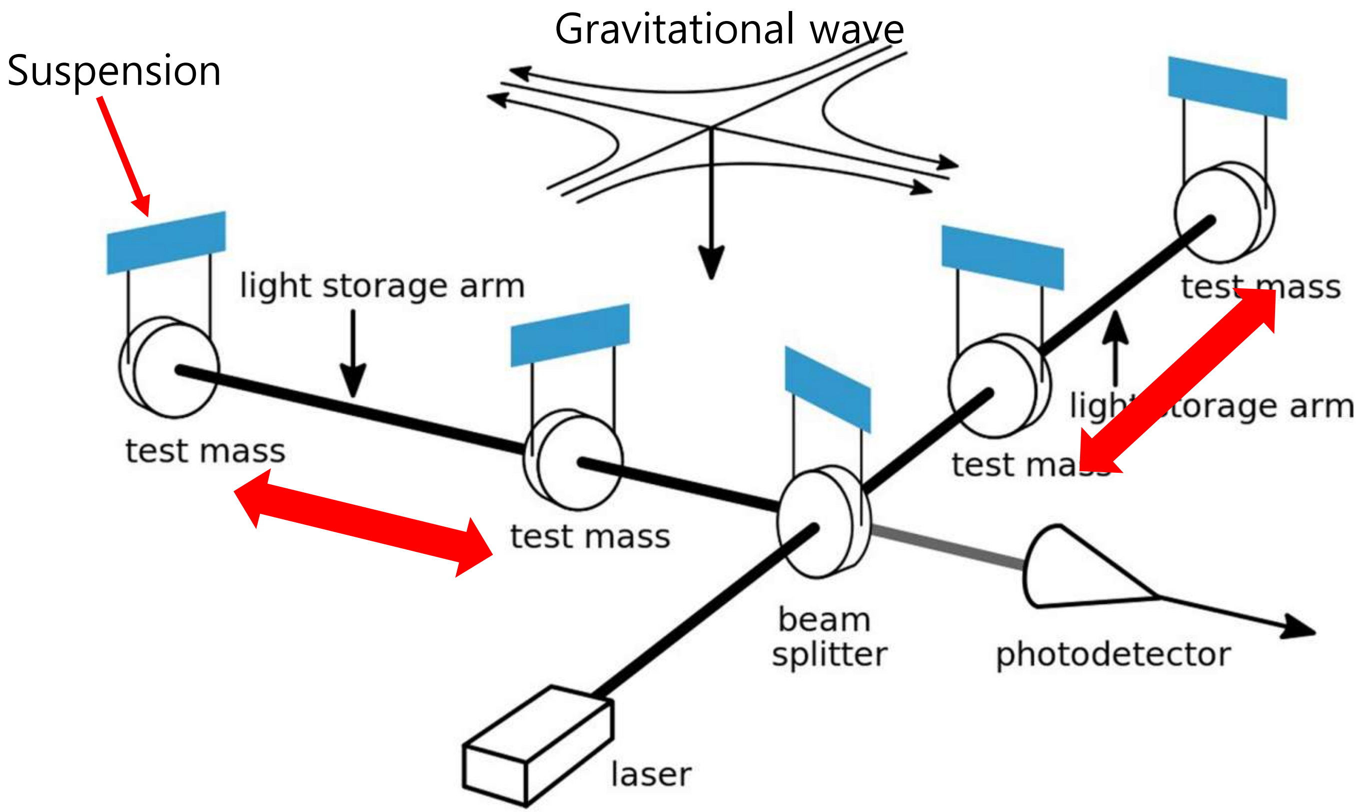


Gravitational wave and GW detector



https://www.ligo.caltech.edu/

Gravitational wave and GW detector



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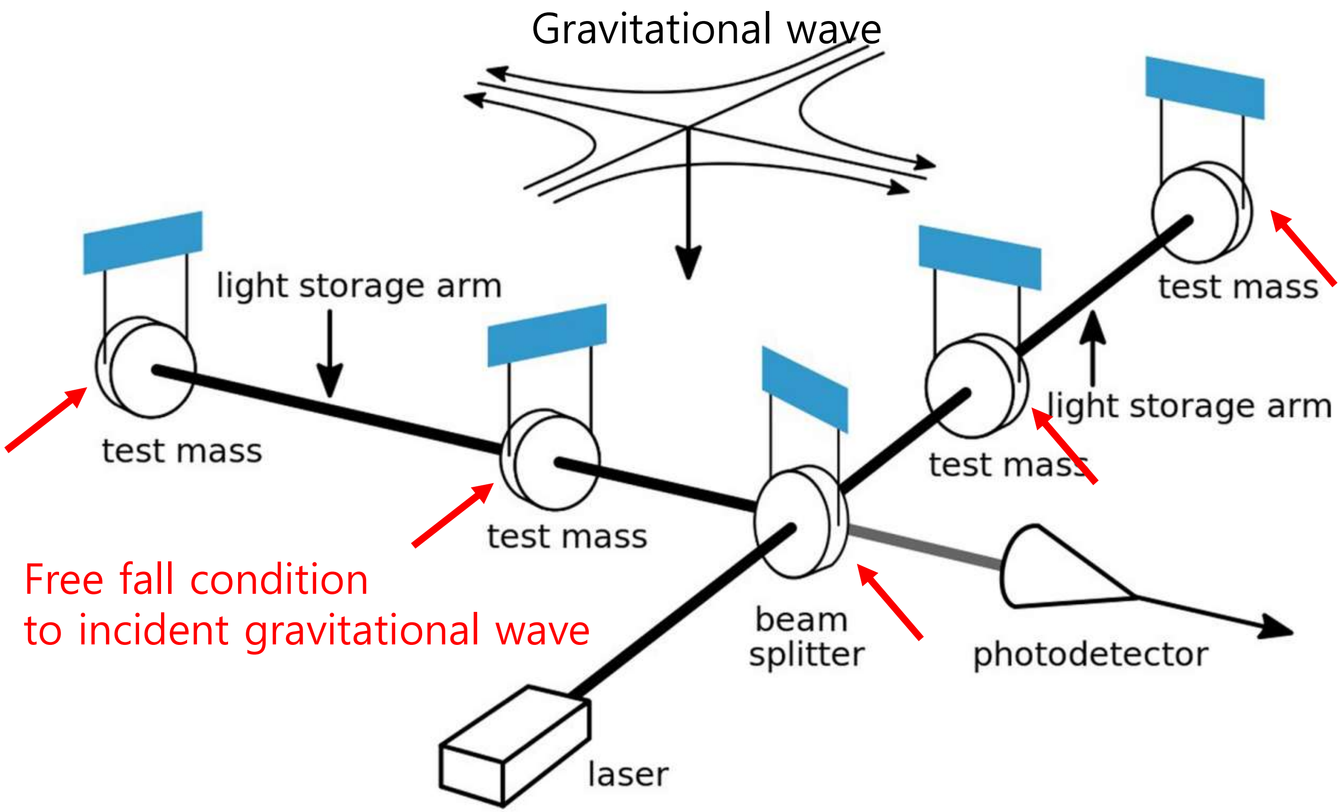
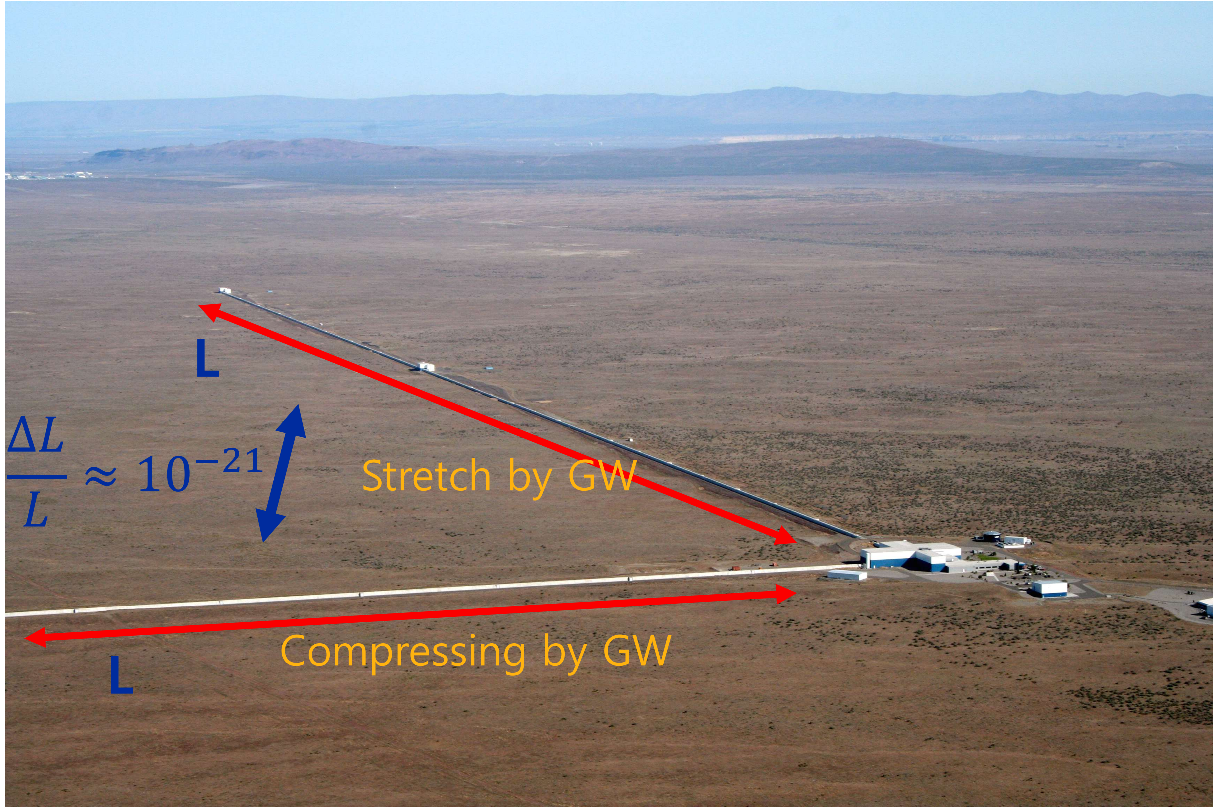
Gravitational wave and GW detector



Free fall condition
to incident gravitational wave

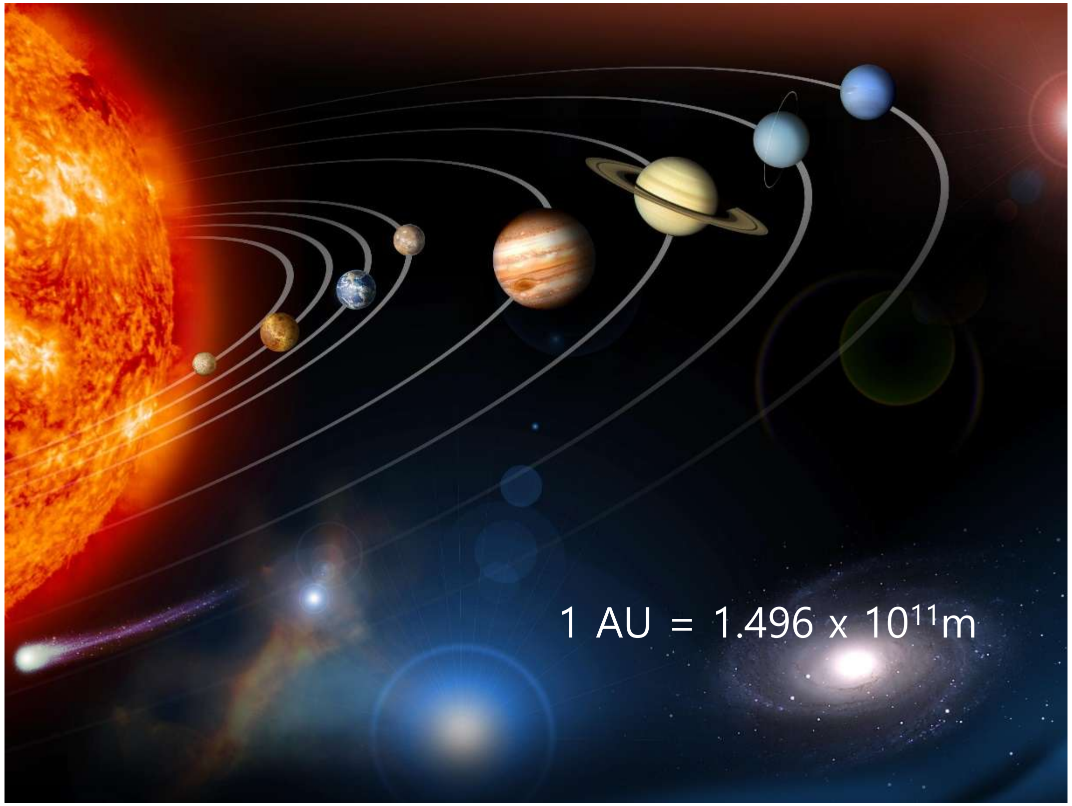
Strain sensitivity

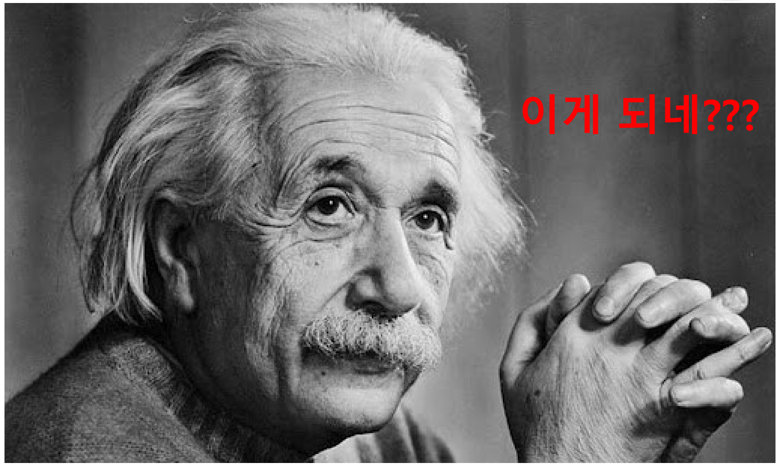


Minimum sensitivity

$$\frac{\Delta L}{L} \approx 10^{-21}$$

Strain due to gravitational wave

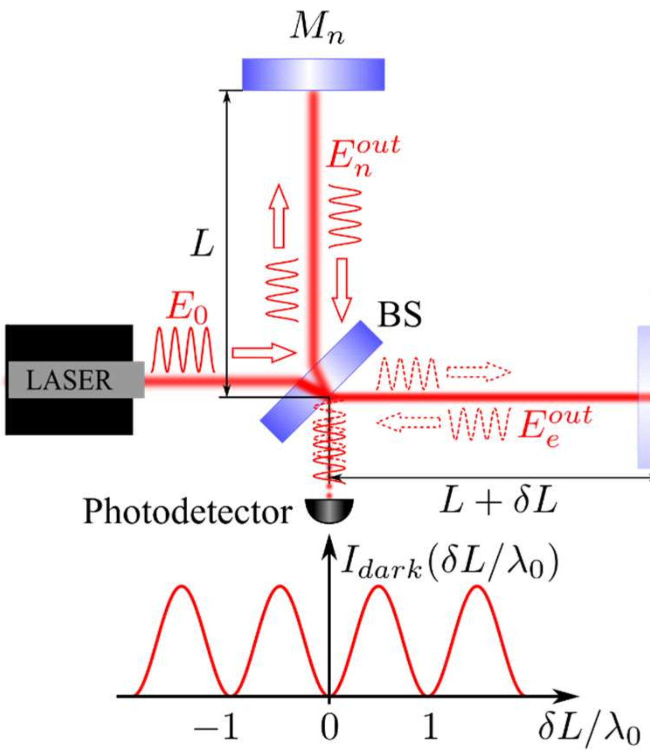




$$\frac{\Delta L}{L} \approx 10^{-21}$$

Detect existence of a single atom

Sensitivity of michelson interferometer

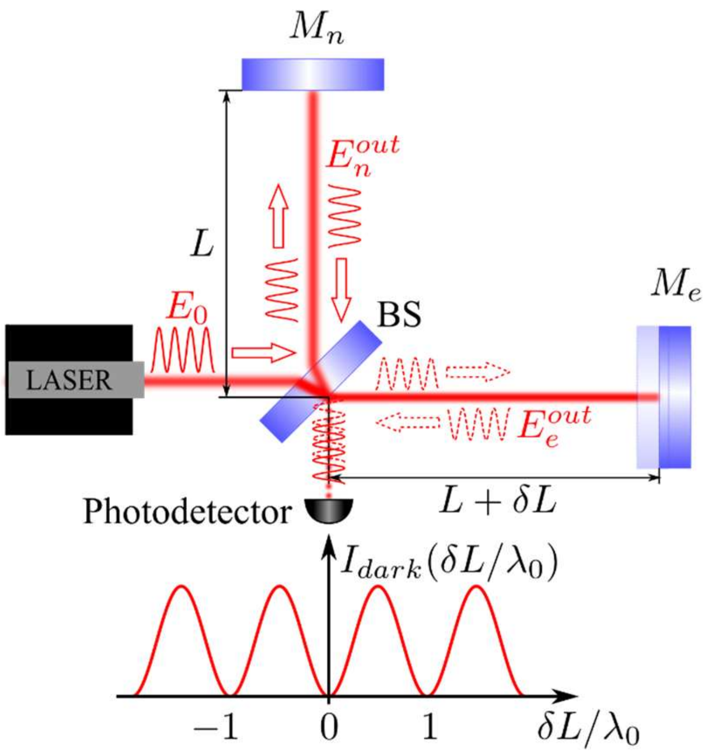


Danilishin, Stefan L. et al. Living Rev.Rel. 15 (2012) 5
arXiv:1203.1706

When L = 1 m

$$\frac{\Delta L}{L} \approx 10^{-16}$$

Sensitivity of michelson interferometer



Danilishin, Stefan L. et al. Living Rev.Rel. 15 (2012) 5
arXiv:1203.1706

When L = 1 m

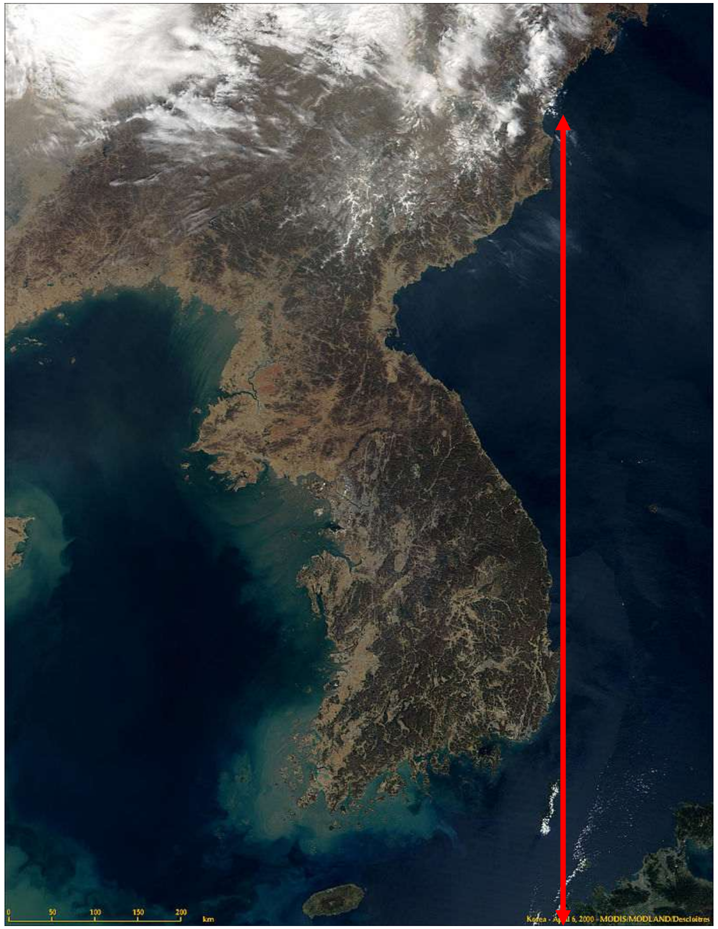
$$\frac{\Delta L}{L} \approx 10^{-1}$$

IF L = 1000 km

$$\frac{\Delta L}{L} \approx 10^{-21}$$

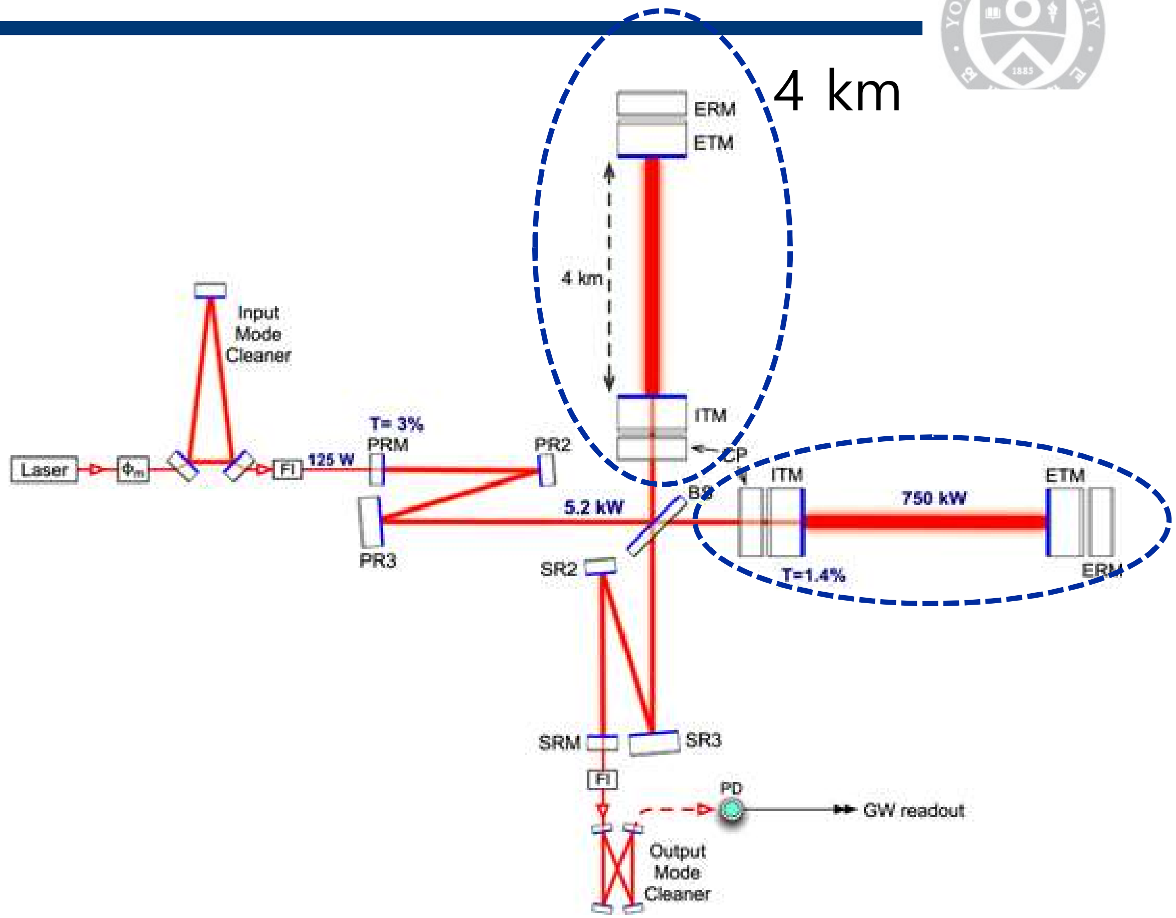
오 1000 km 간섭계를 만들면 되겠다

1000 km Interferometer



~1100km

LIGO Interferometer

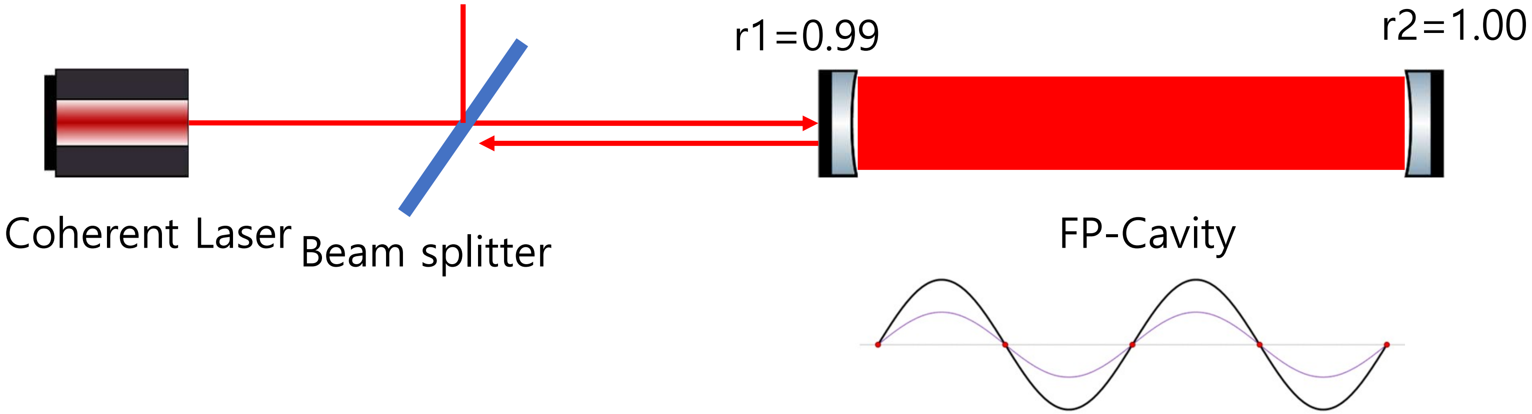


LIGO interferometer / Livingston

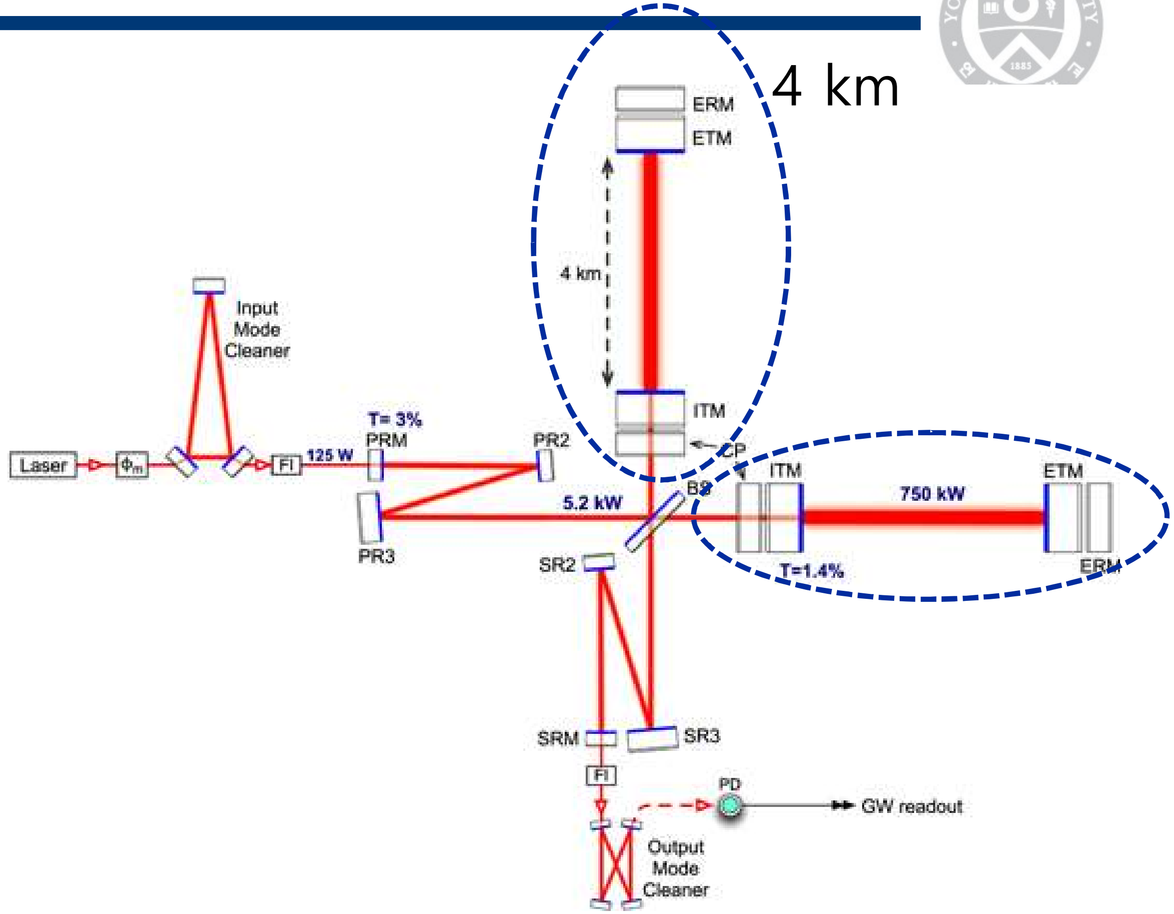
Fabry-Perot Cavity

Number of round trip > 250

4 km x 250 ~ 1000 km



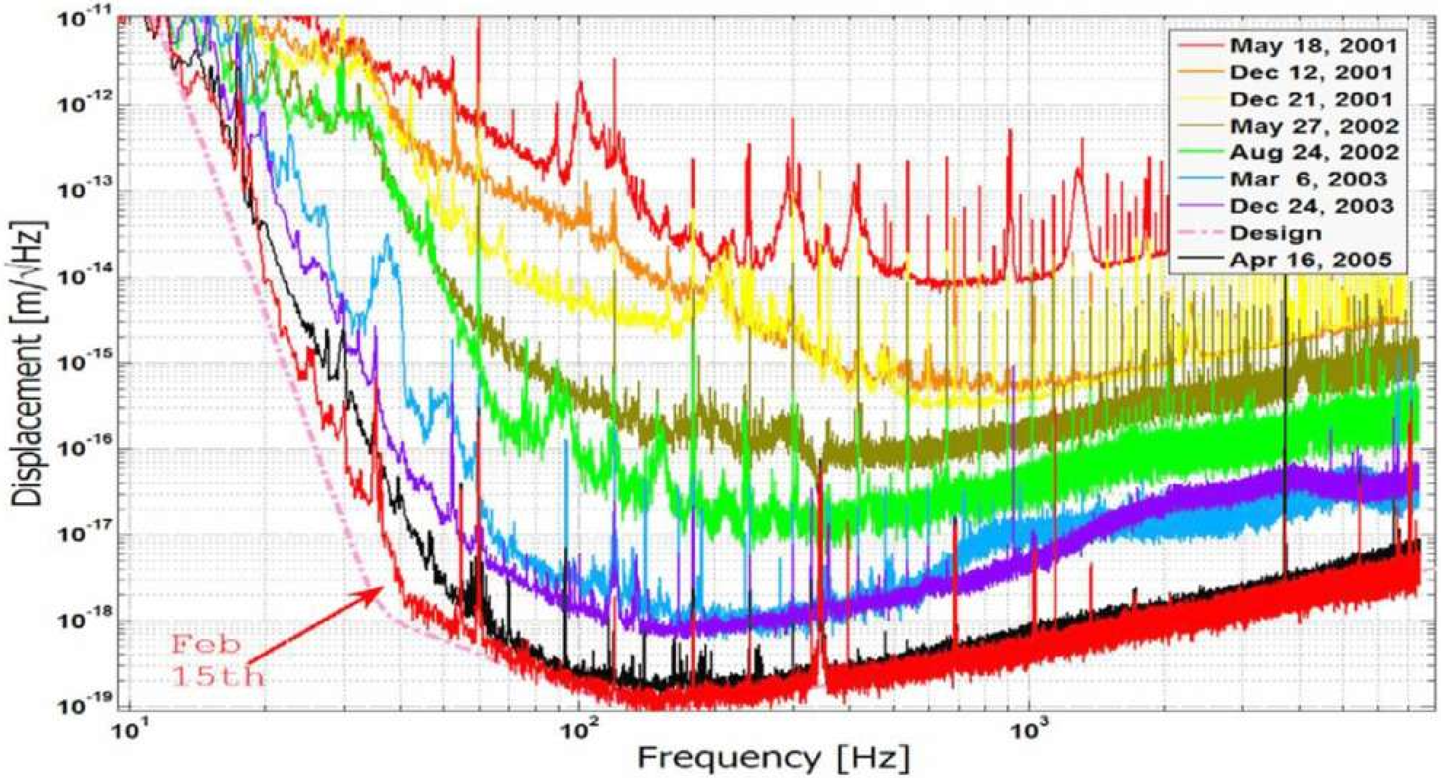
LIGO Interferometer



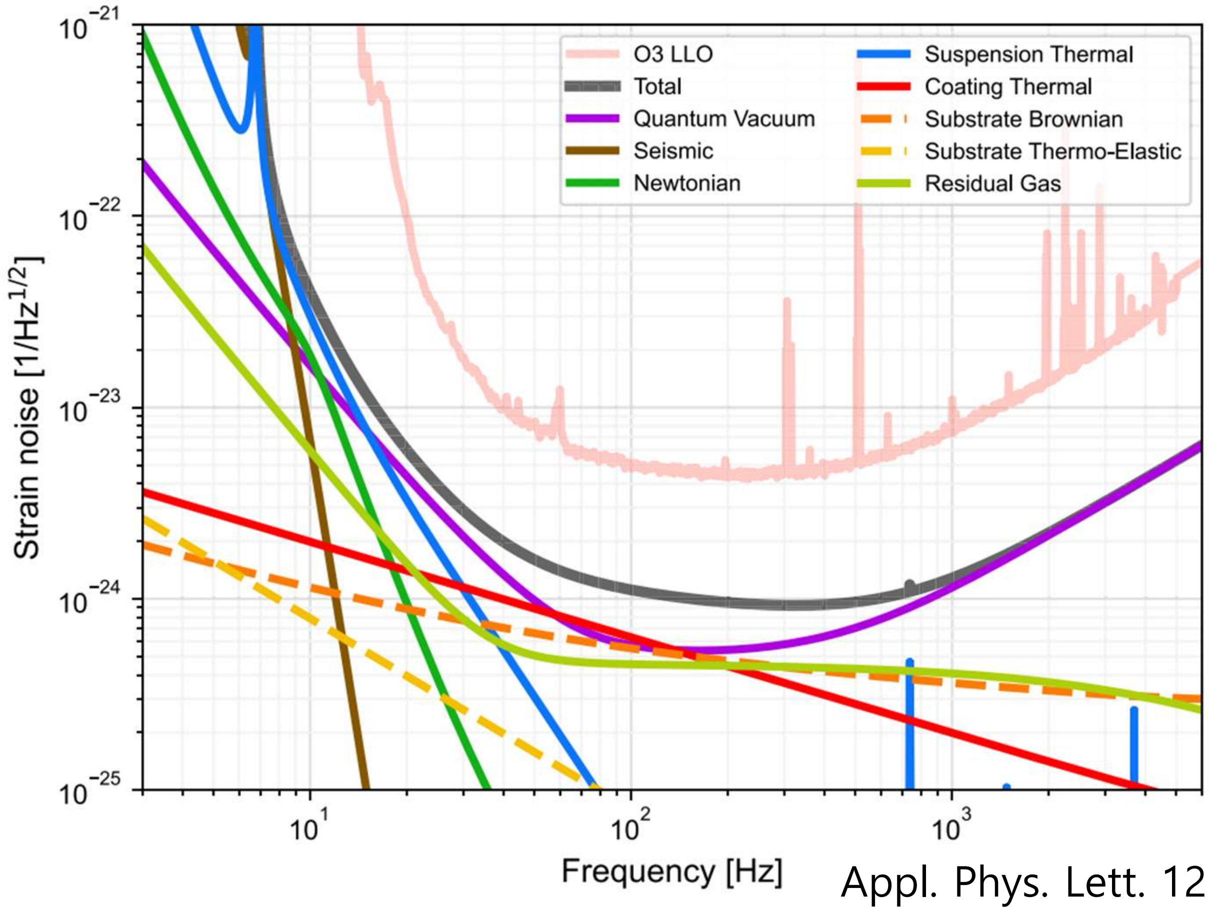
LIGO interferometer / Livingston

4 km Interferometer

Sensitivity During Science Run

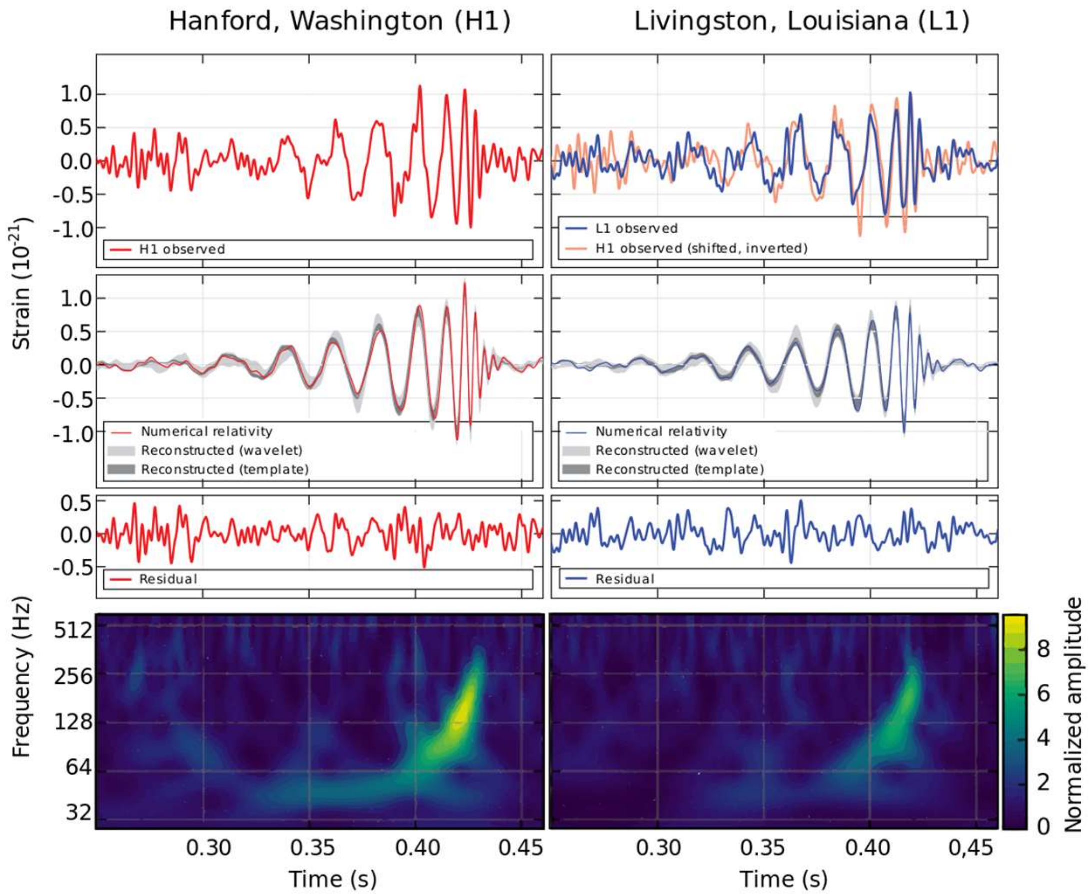


LIGO Sensitivity

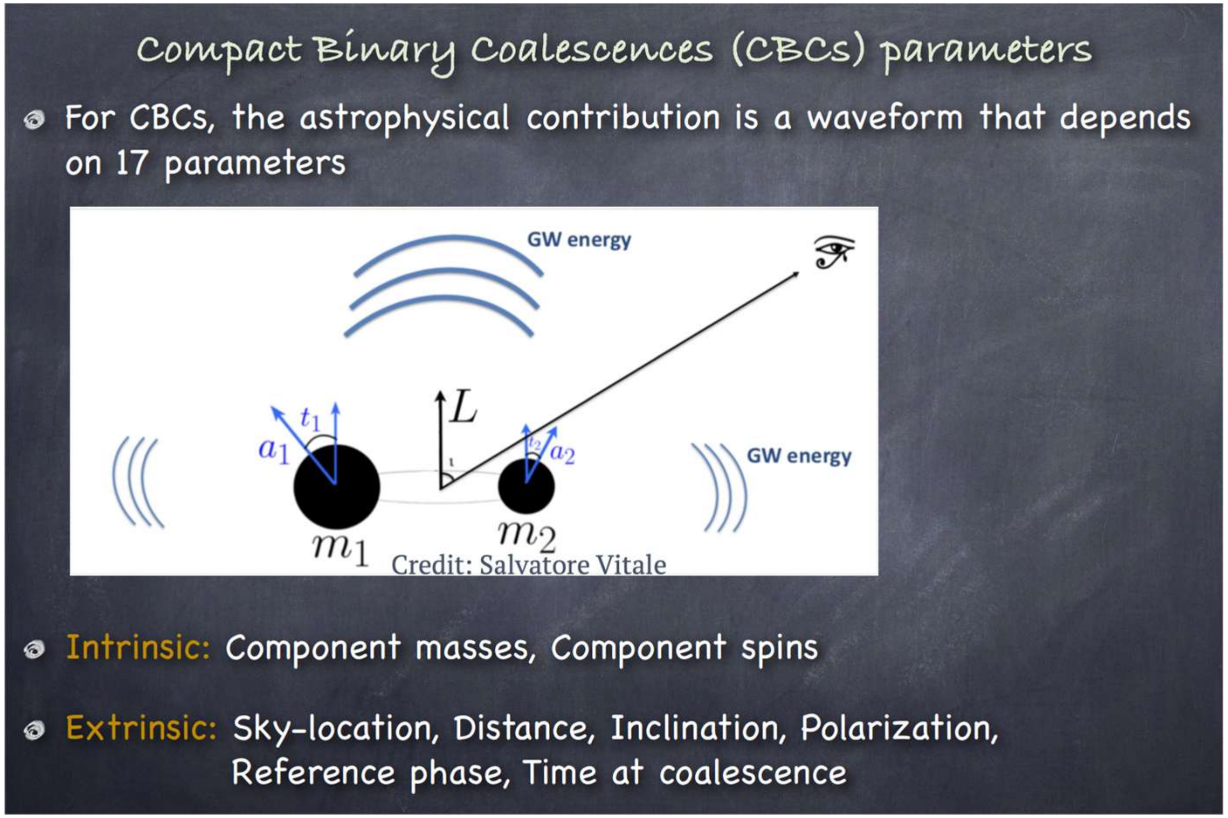


Appl. Phys. Lett. 122, 110502 (2023)

First Detection of Gravitational Wave



Parameter Estimation

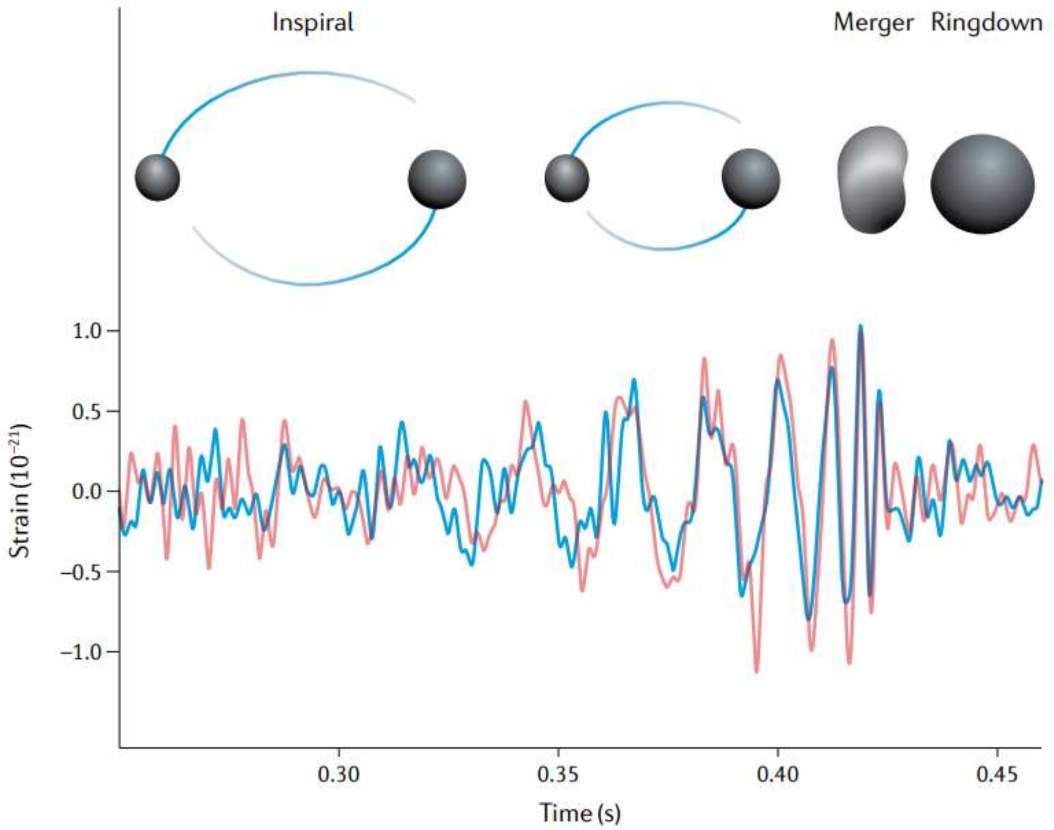


Shu-Wei Yeh (NTHU)

Black Hole

- High mass
- High density(point source)
- No hair

Inspiral-Merger-Ringdown

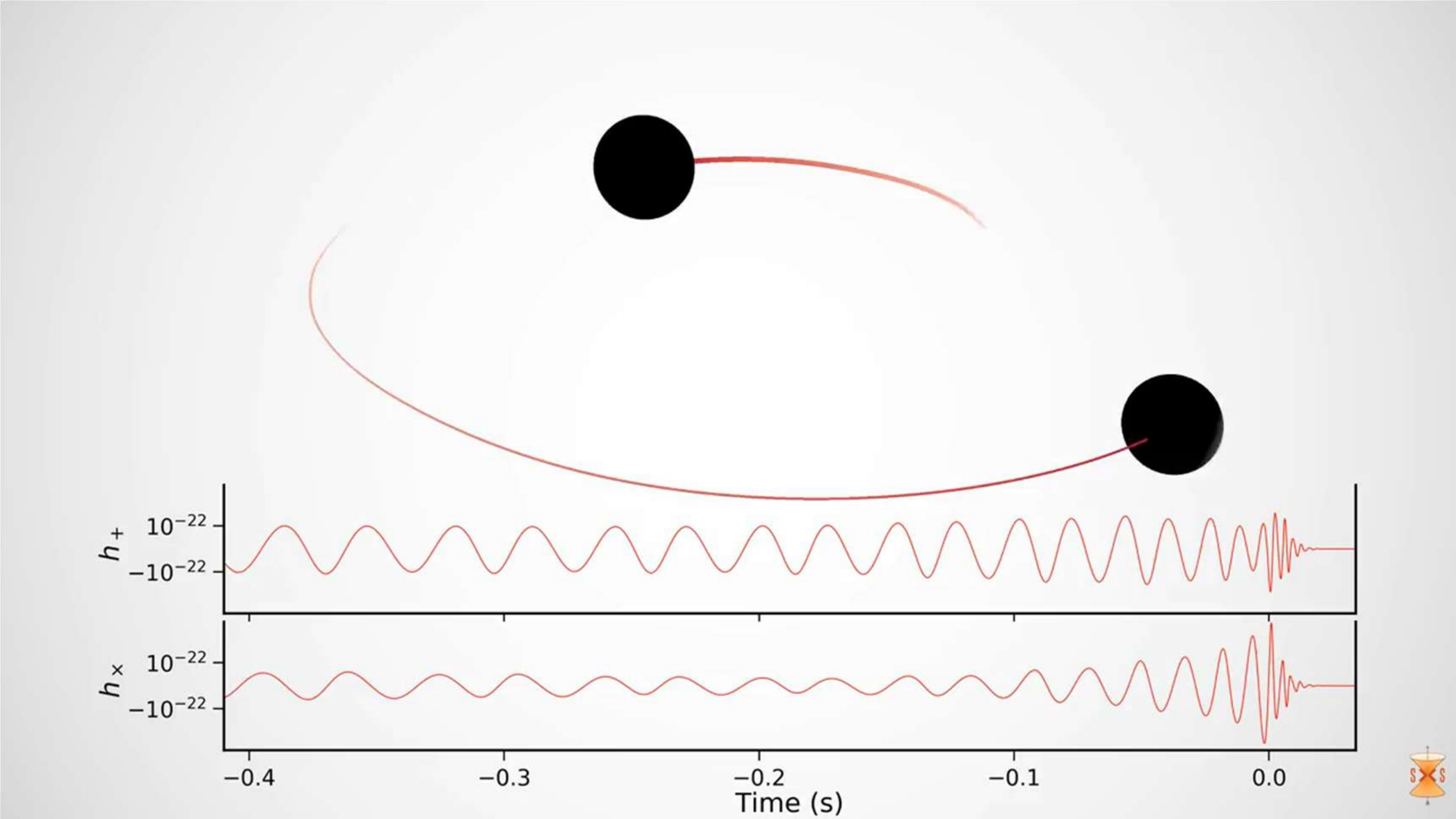


Nature Reviews Physics **volume 3**, pages344–366 (2021)

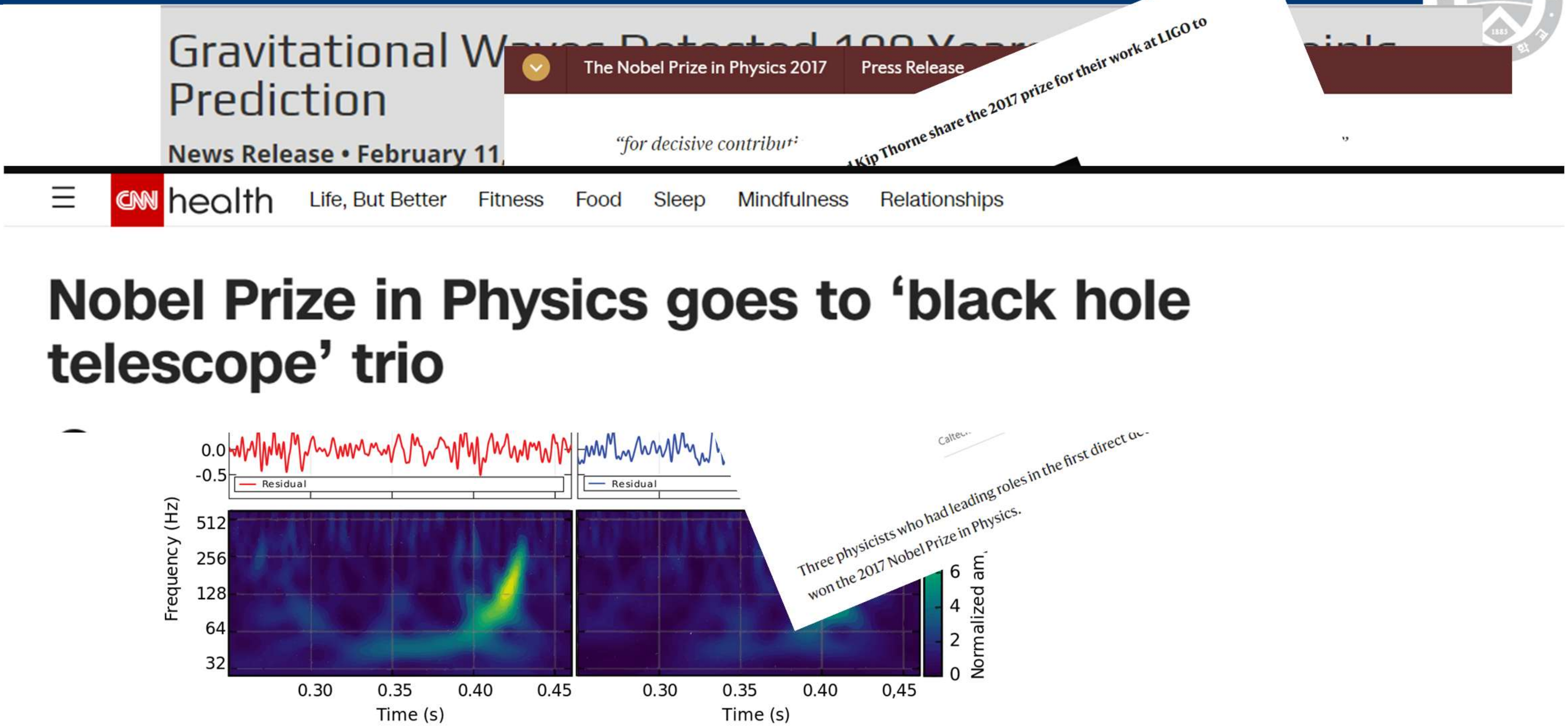
GW170104

+ pol

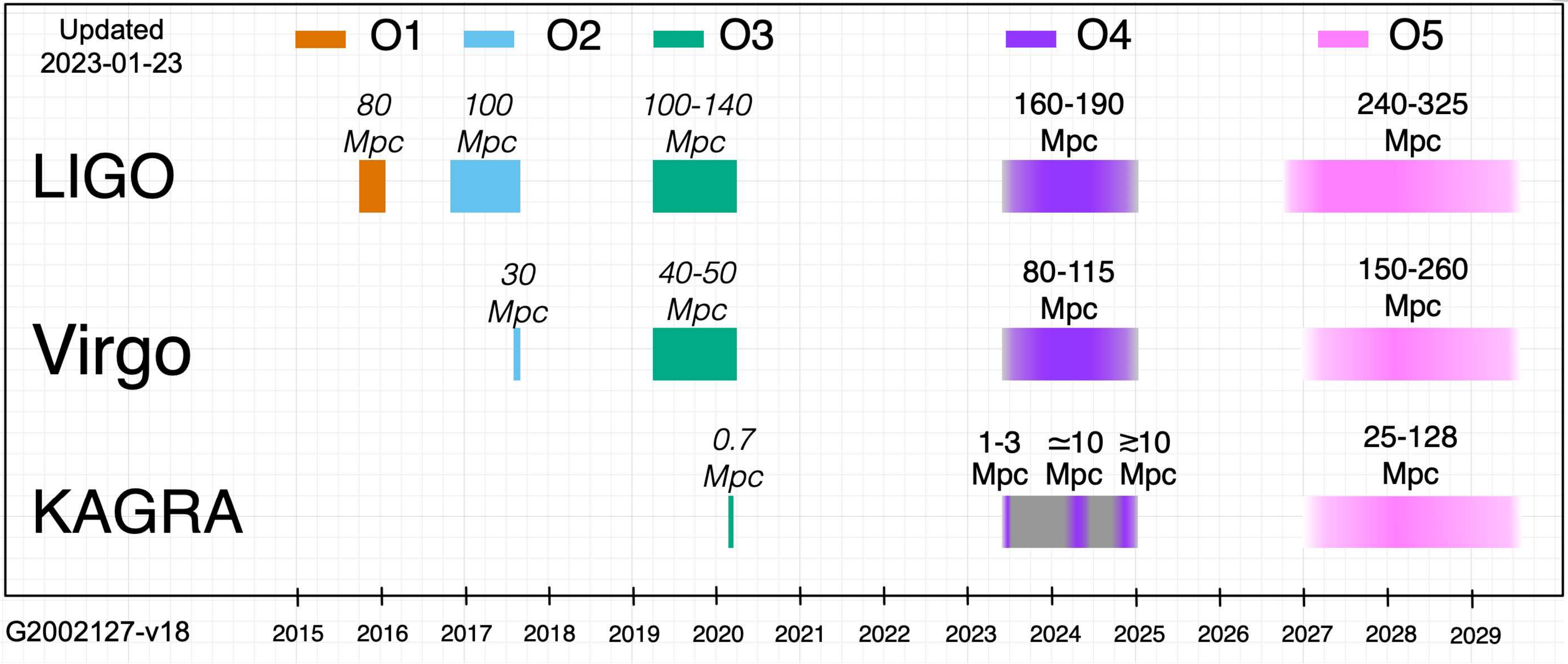
x pol



First Detection of Gravitational Wave

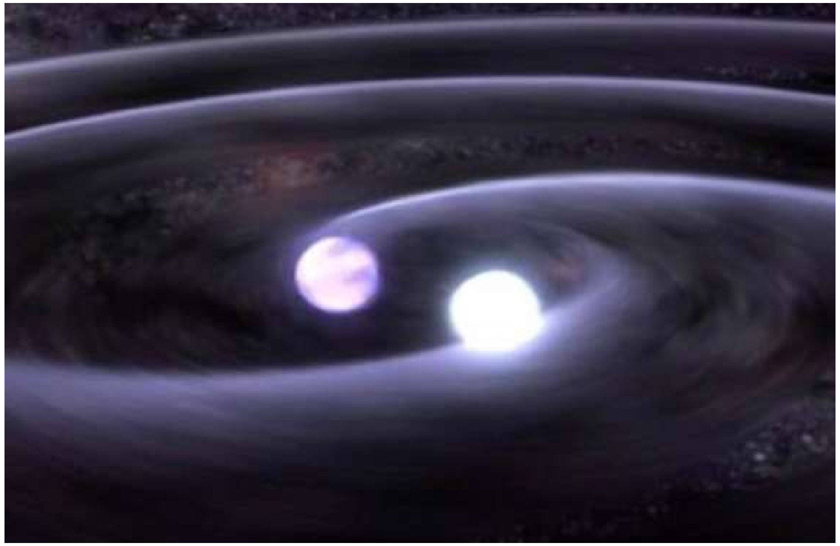


LVK Observation Plan



BNS Range

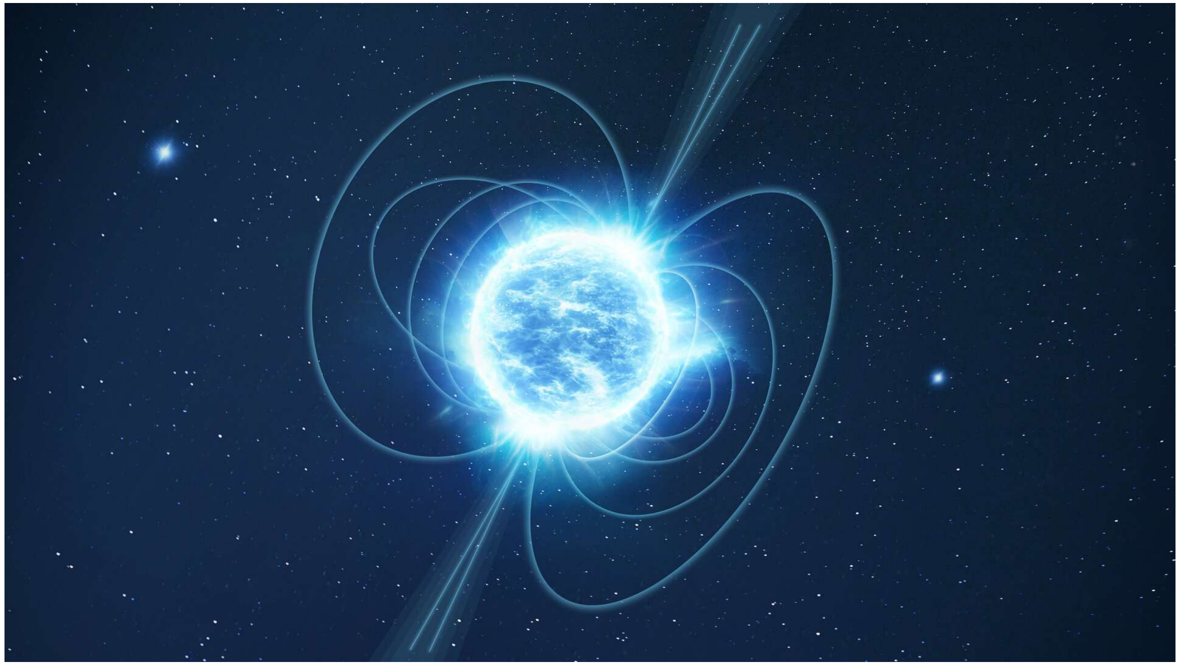
- Binary-neutron-star range
- Common benchmark of sensitivity
- Made up of two 1.4 solar mass neutron stars
- Signal-to-noise ratio of 8



https://svs.gsfc.nasa.gov/10543

Maximum distance at which an event can be detected

Neutron Star

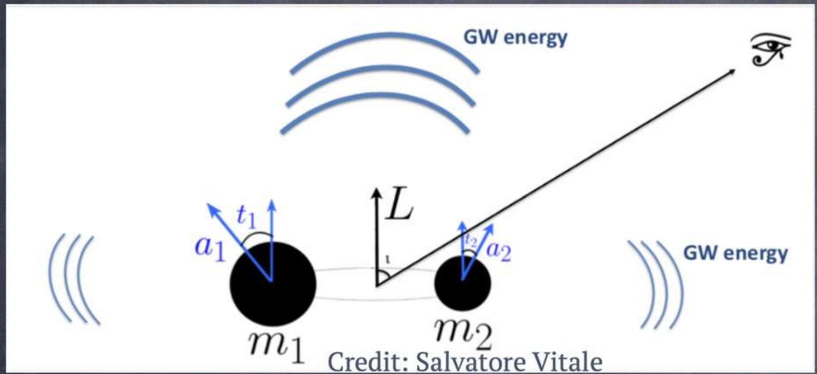


Why binary neutron star?

Parameter Estimation

Compact Binary Coalescences (CBCs) parameters

- For CBCs, the astrophysical contribution is a waveform that depends on 17 parameters



- Intrinsic: Component masses, Component spins
- Extrinsic: Sky-location, Distance, Inclination, Polarization, Reference phase, Time at coalescence

Shu-Wei Yeh (NTHU)

Black Hole

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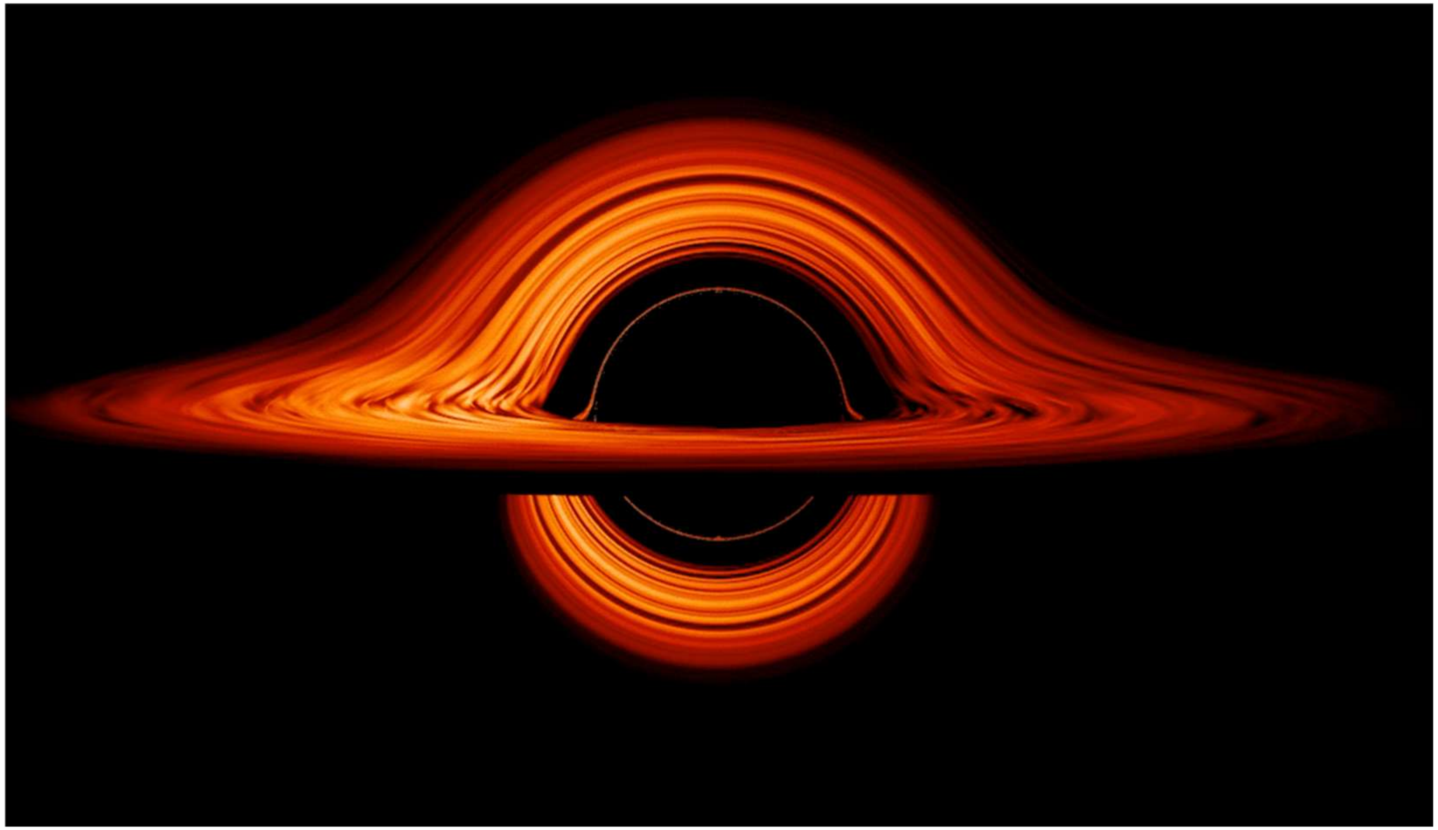
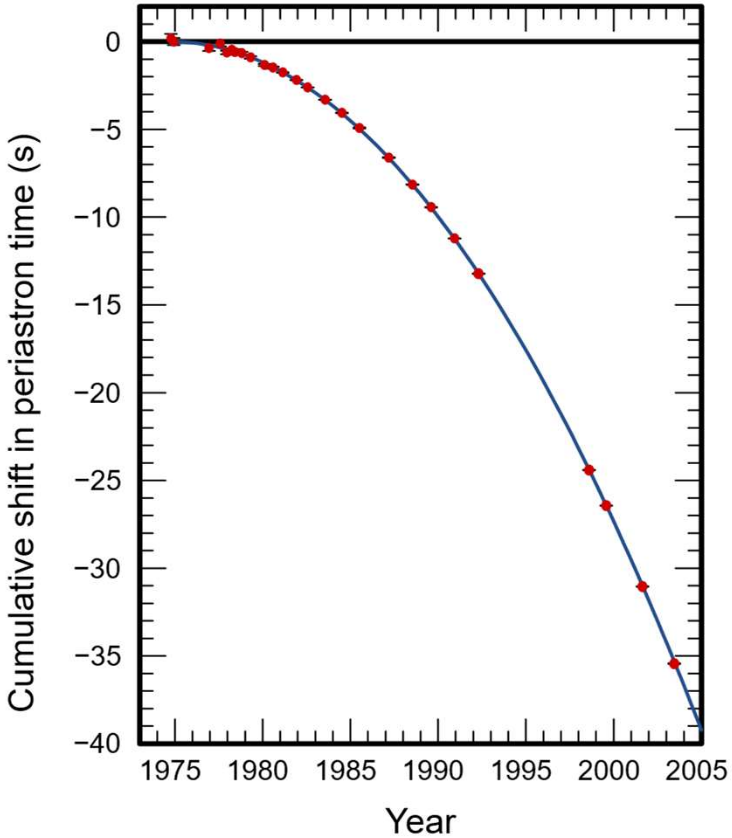
- High density(point source)
- No hair

Event Horizon



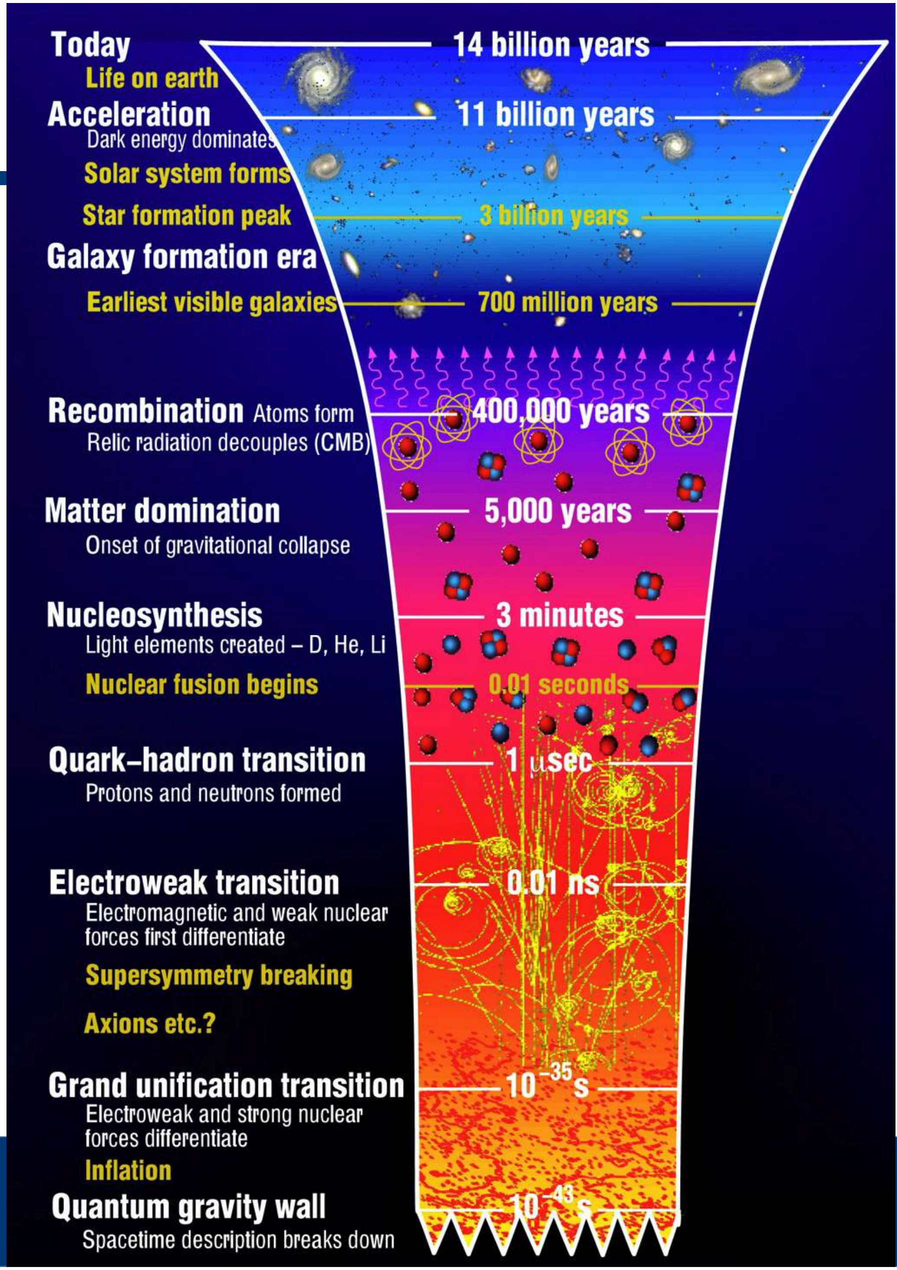
Test of General Relativity

Hulse-Taylor Pulsar

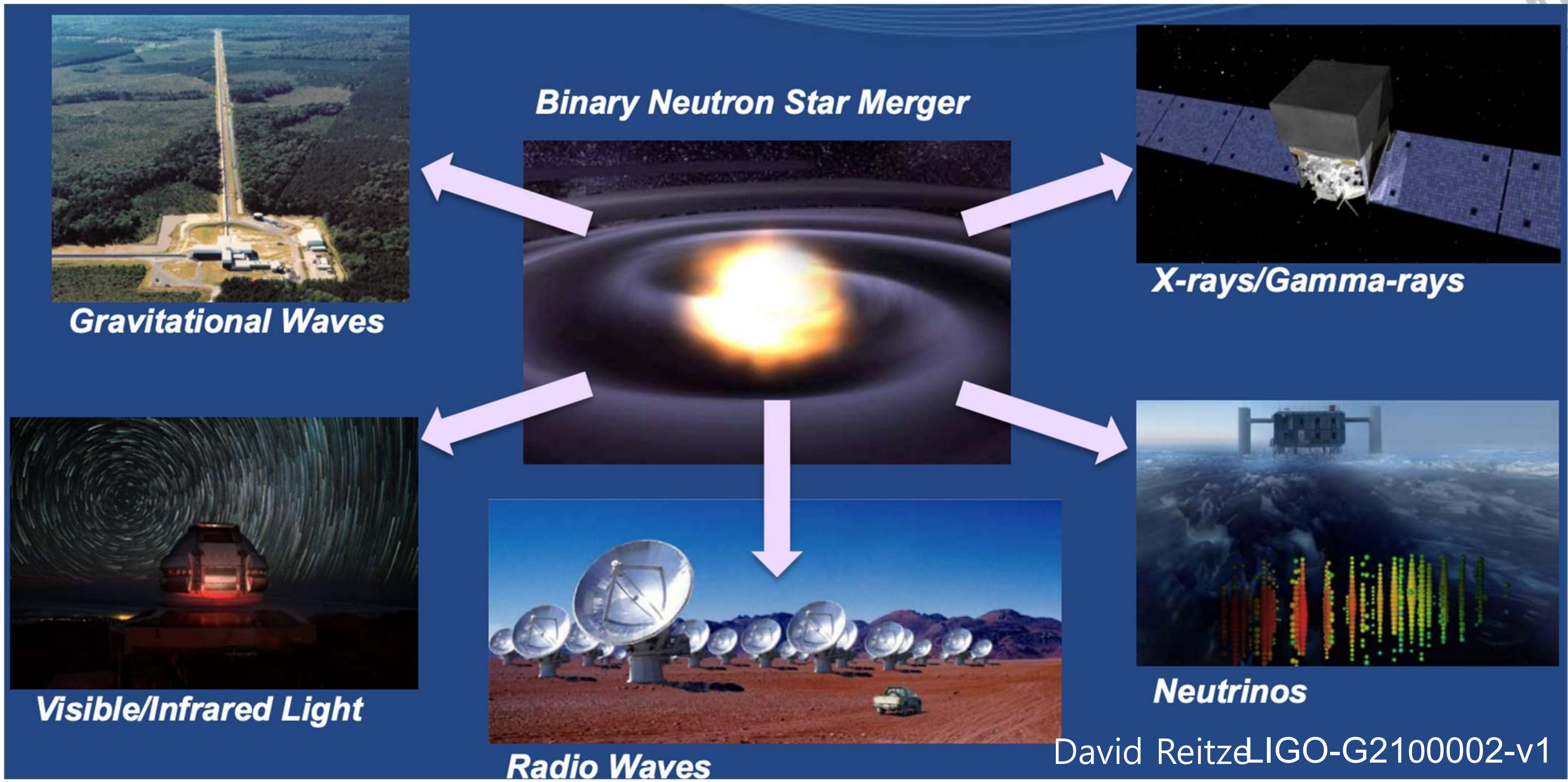


Bigbang Timeline

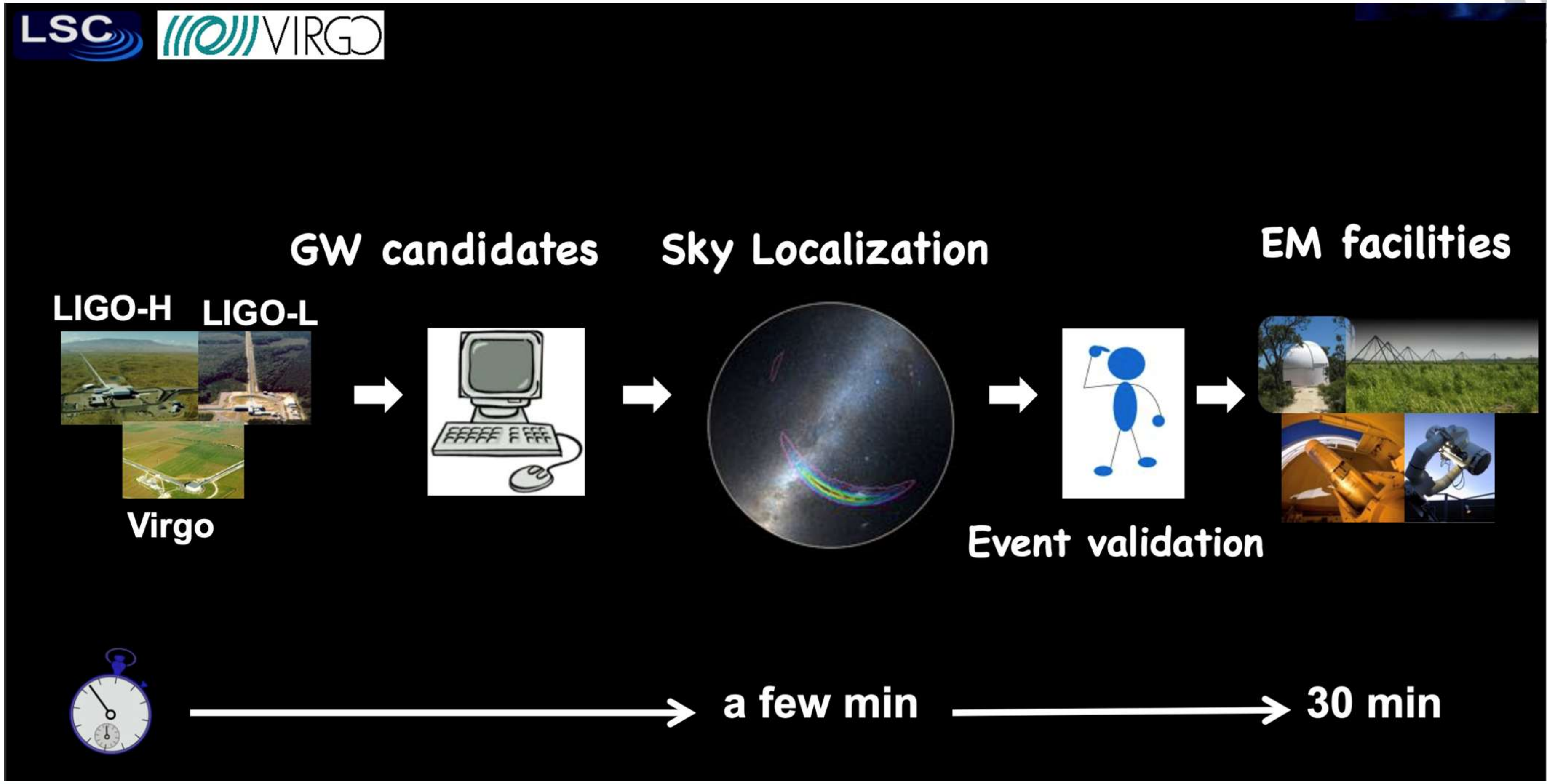
Group → / Period ↓	1	2		3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																		2 He
2	3 Li	4 Be												5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg												13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca		21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr		39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	*	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	**	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
			*	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb		
			**	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No		



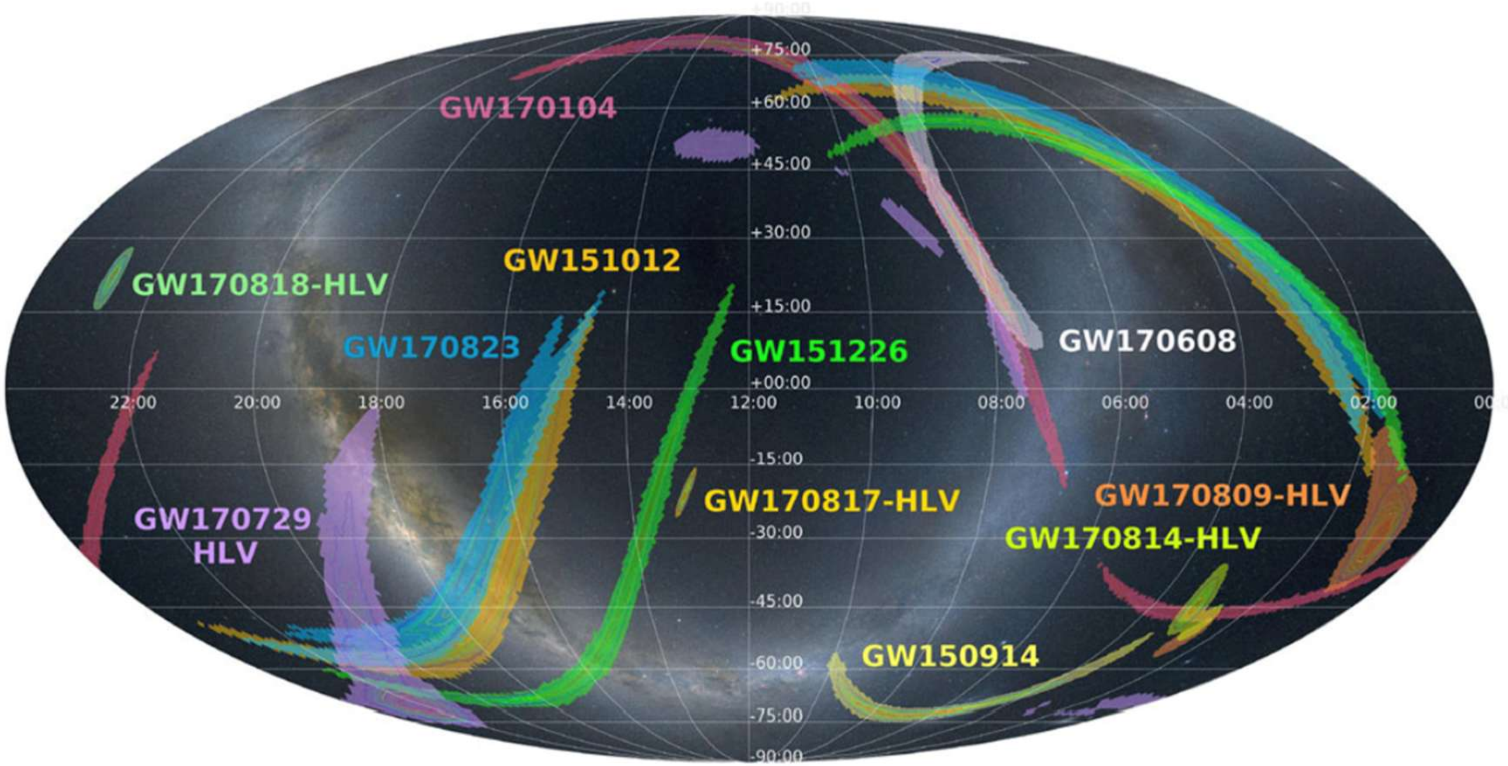
Multi-messenger Astronomy with Gravitational Waves

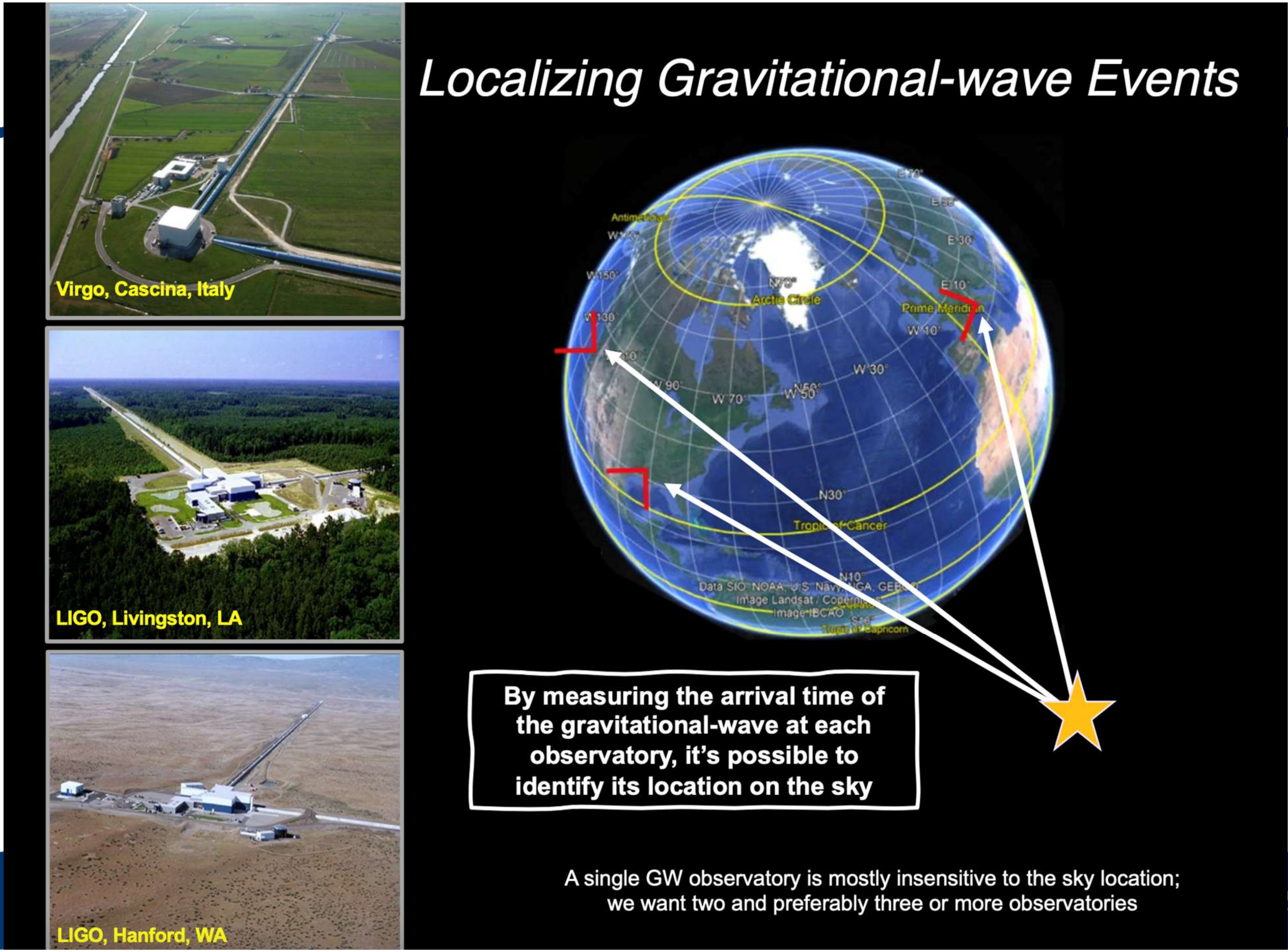


GW Alert Procedure



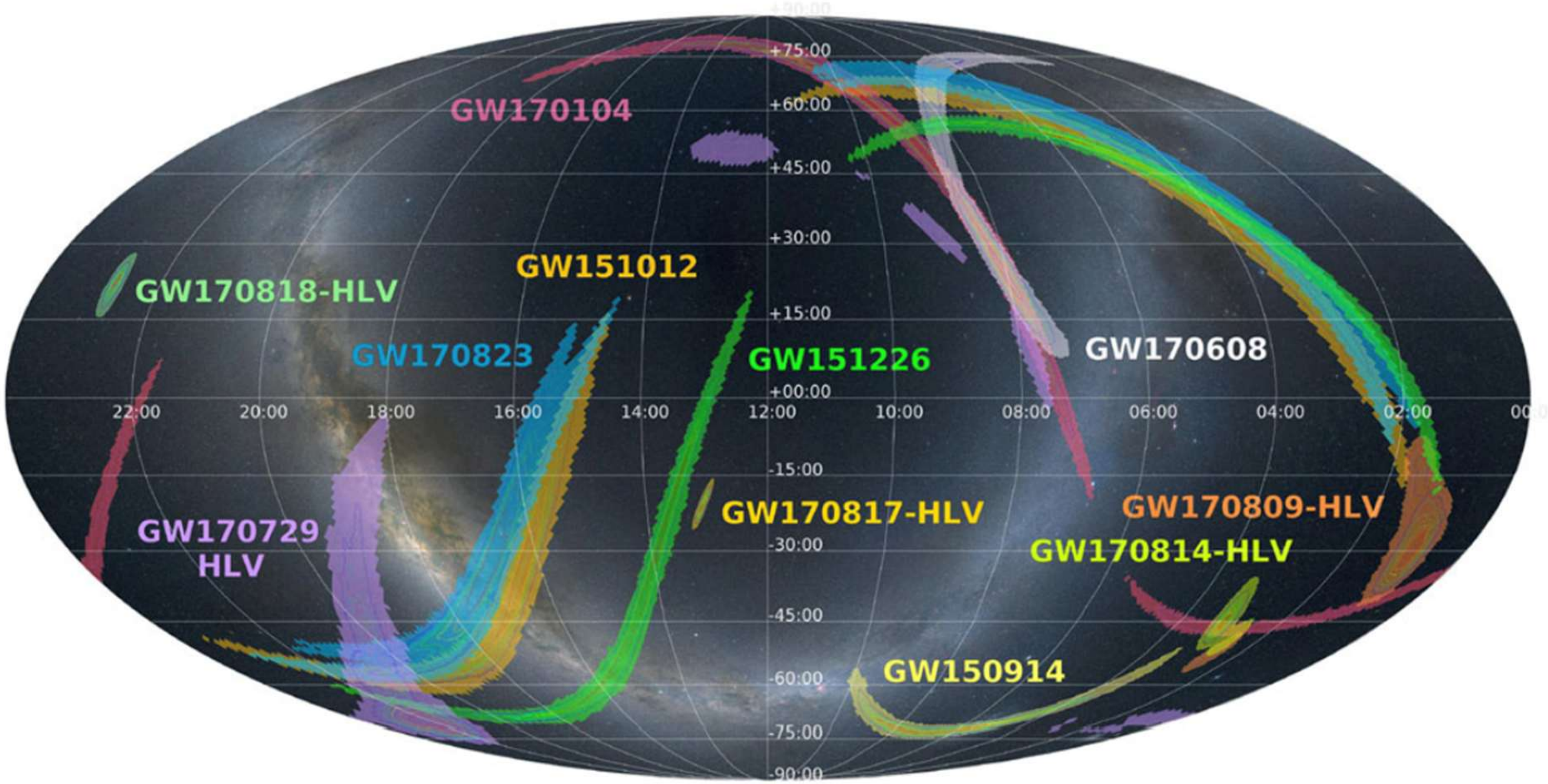
Sky Localization



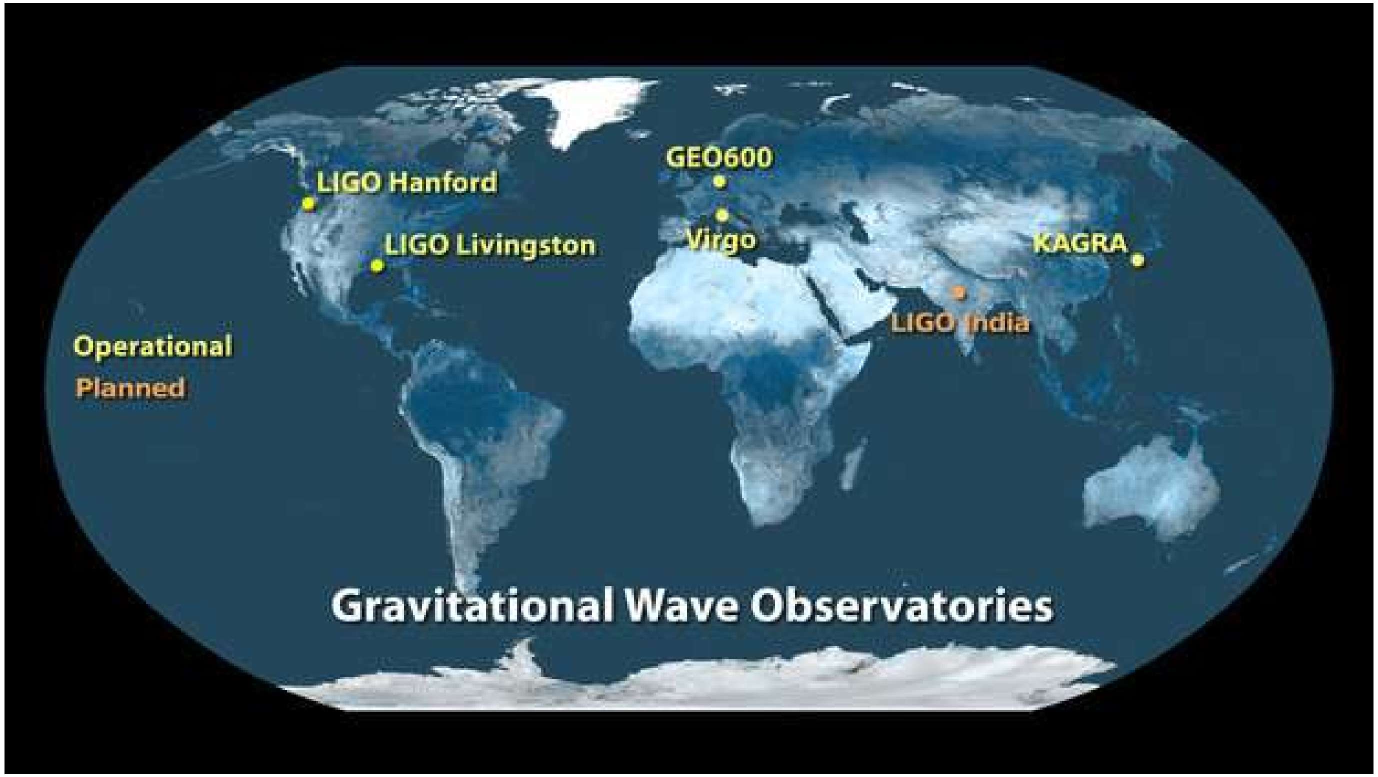


Yokohama GRB 201
Marci Branchesi

Sky Localization



Gravitational Wave Observatories

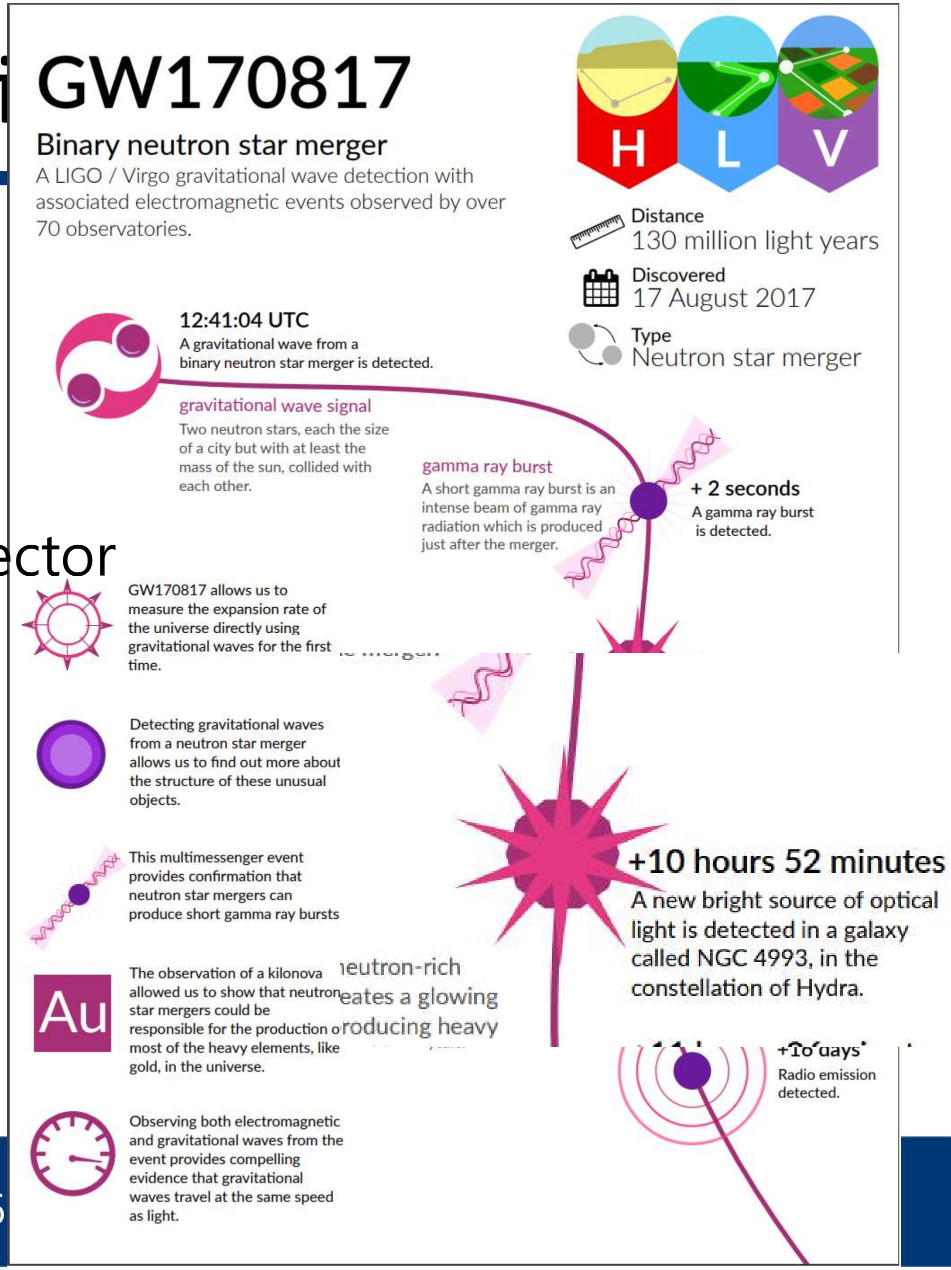


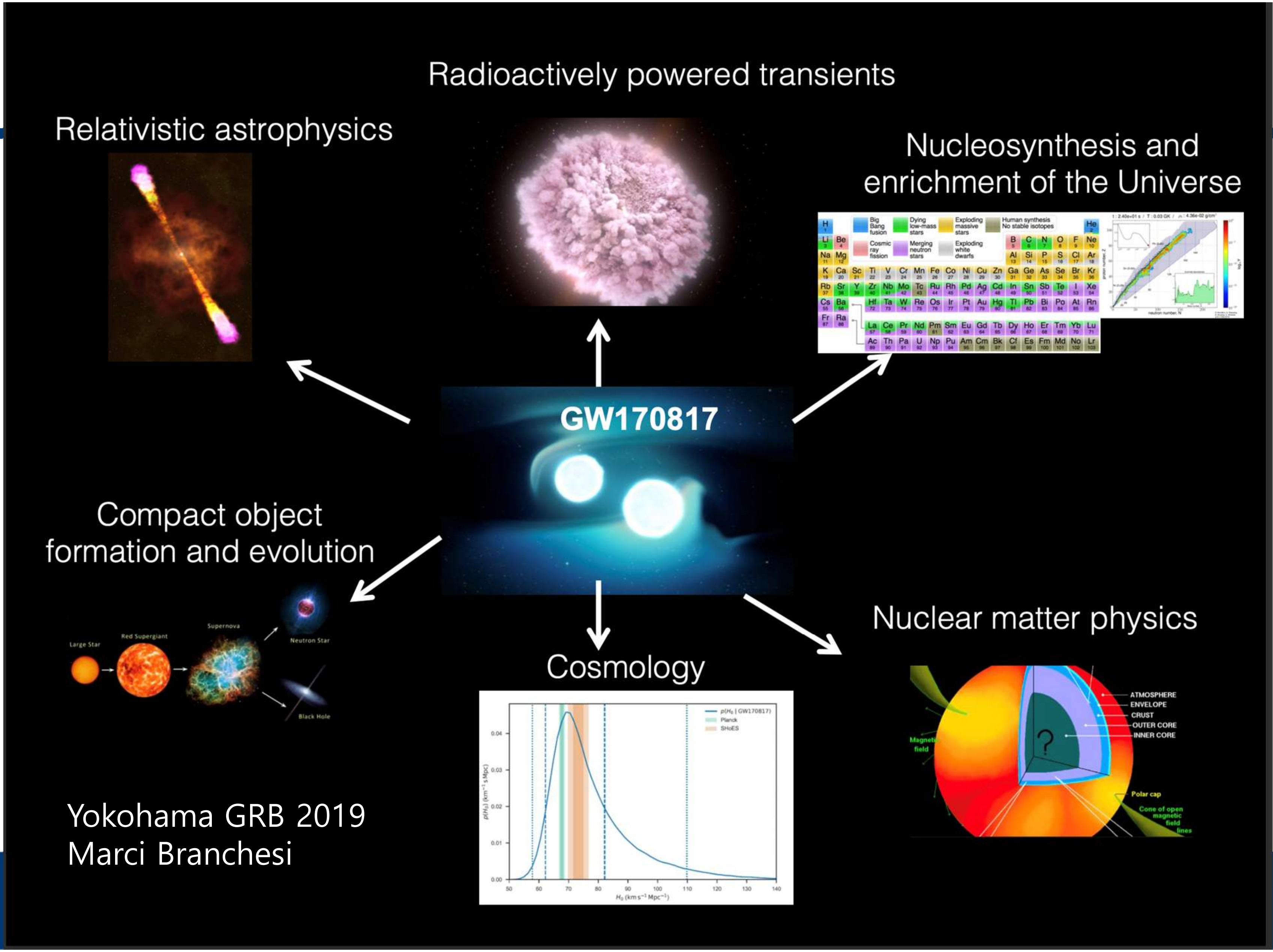
First Multi-Messenger Detecti

Binary neutron star merger

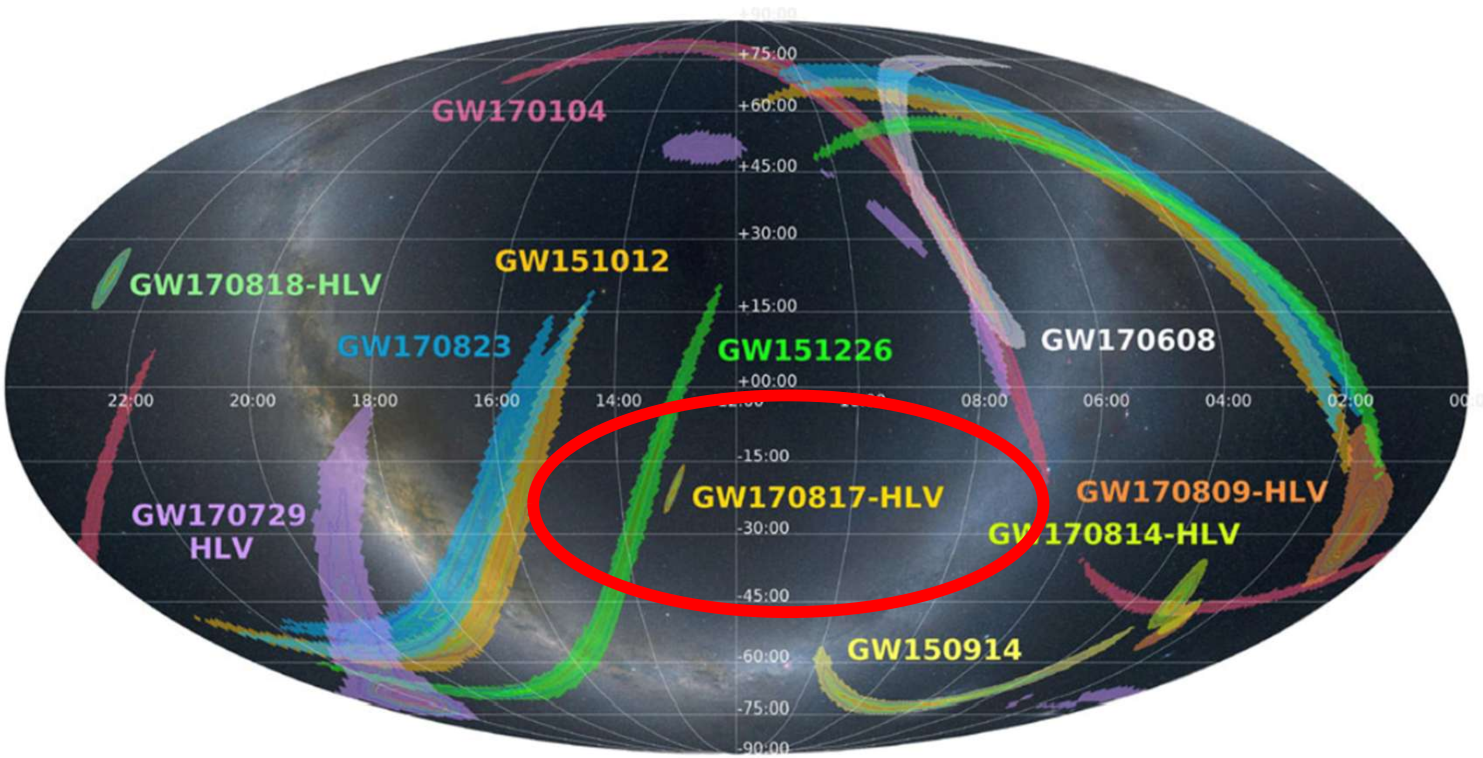
Gamma ray burst detection with Fermi-detector

Kilonova detection using telescope

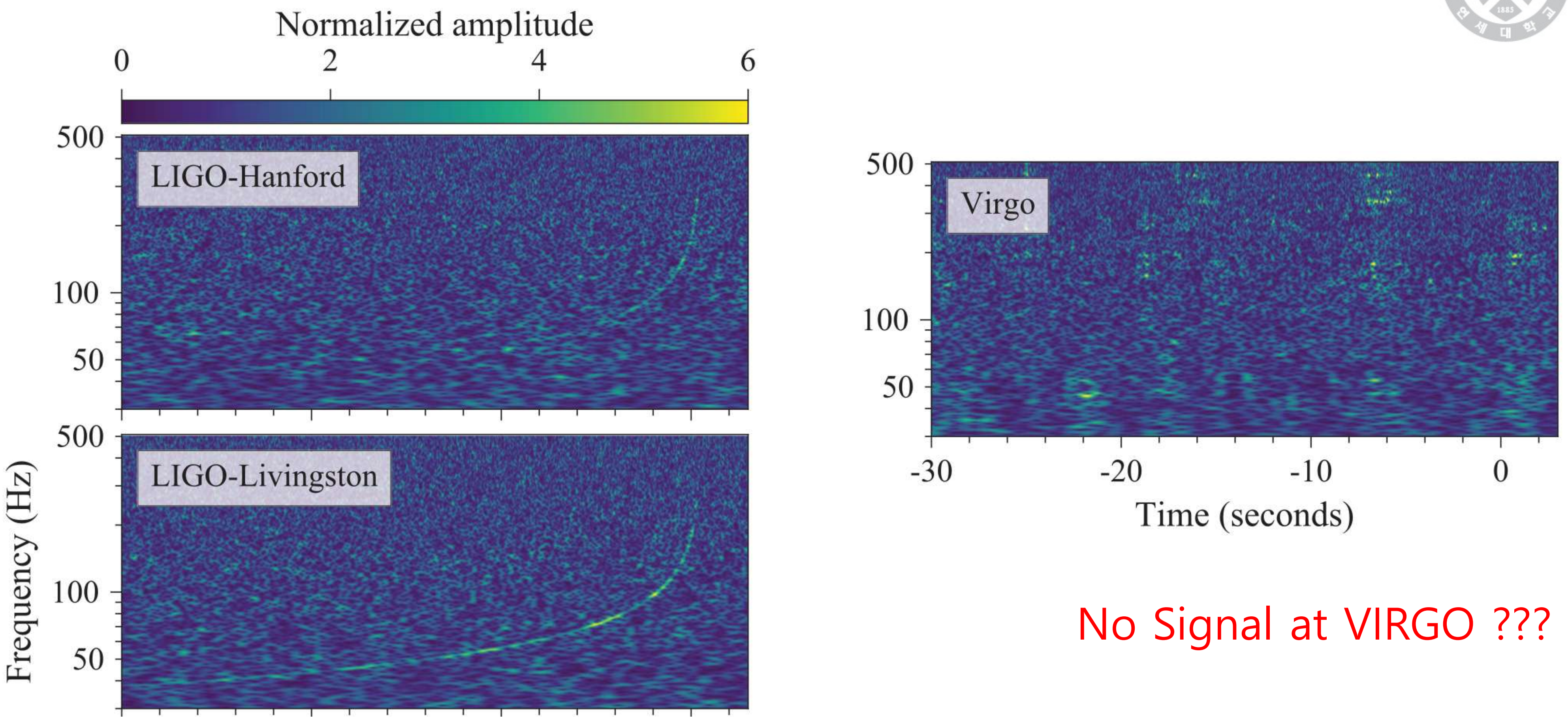



Radioactively powered transients
Relativistic astrophysics
Nucleosynthesis and enrichment of the Universe
GW170817
Compact object formation and evolution
Large Star
Red Supergiant
Supernova
Neutron Star
Black Hole
Cosmology
Nuclear matter physics
ATMOSPHERE
ENVELOPE
CRUST
OUTER CORE
INNER CORE
Polar cap
Yokohama GRB 2019
Marci Branchesi

Sky Localization

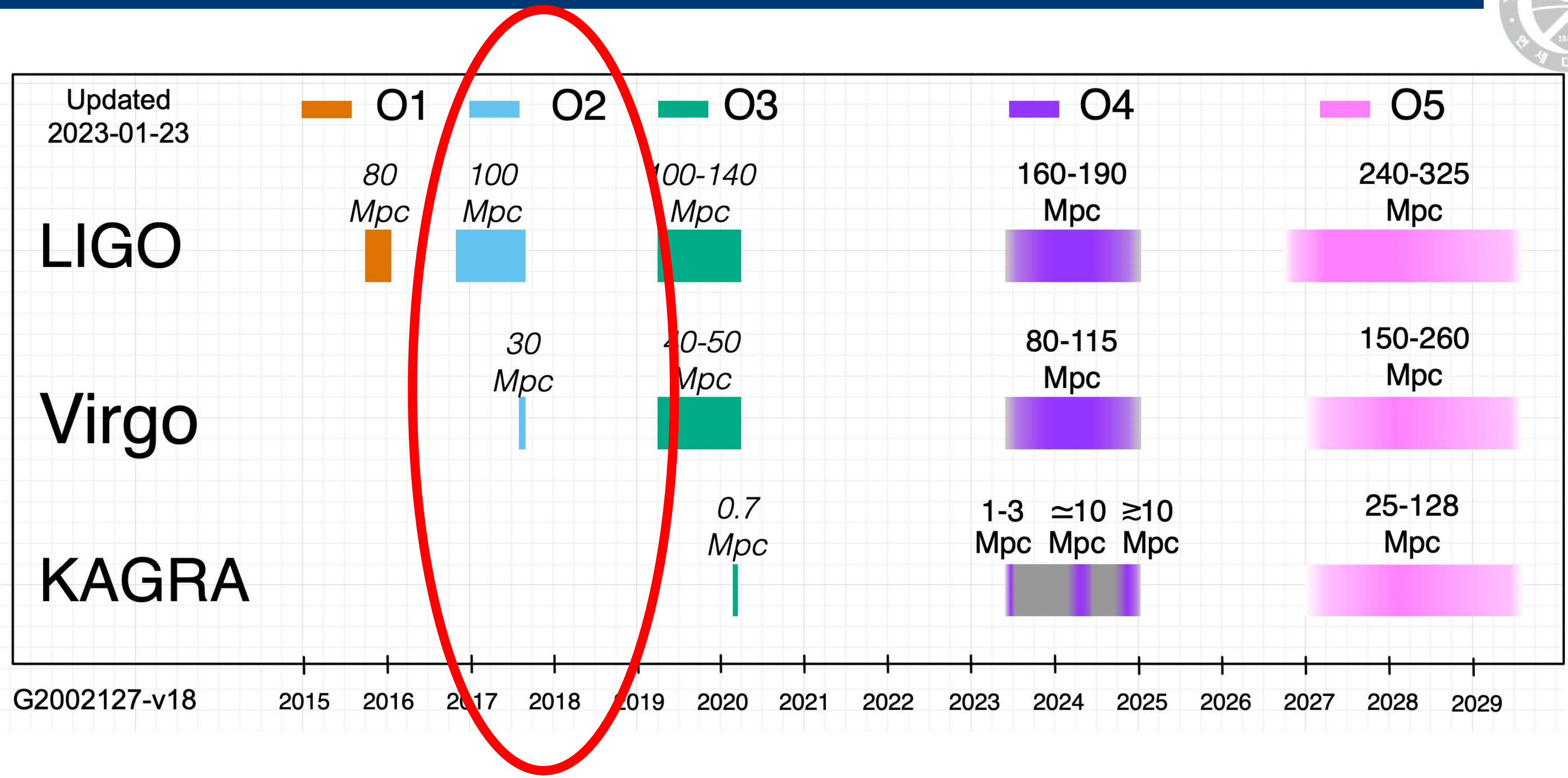


GW170817



No Signal at VIRGO ???

LVK Observation Plan



LIGO-VIRGO Joint Observation

VIRGO JOINS LIGO FOR THE O2 DATA-TAKING PERIOD

Warning: Use of undefined constant multiple - assumed 'multiple' (this will throw

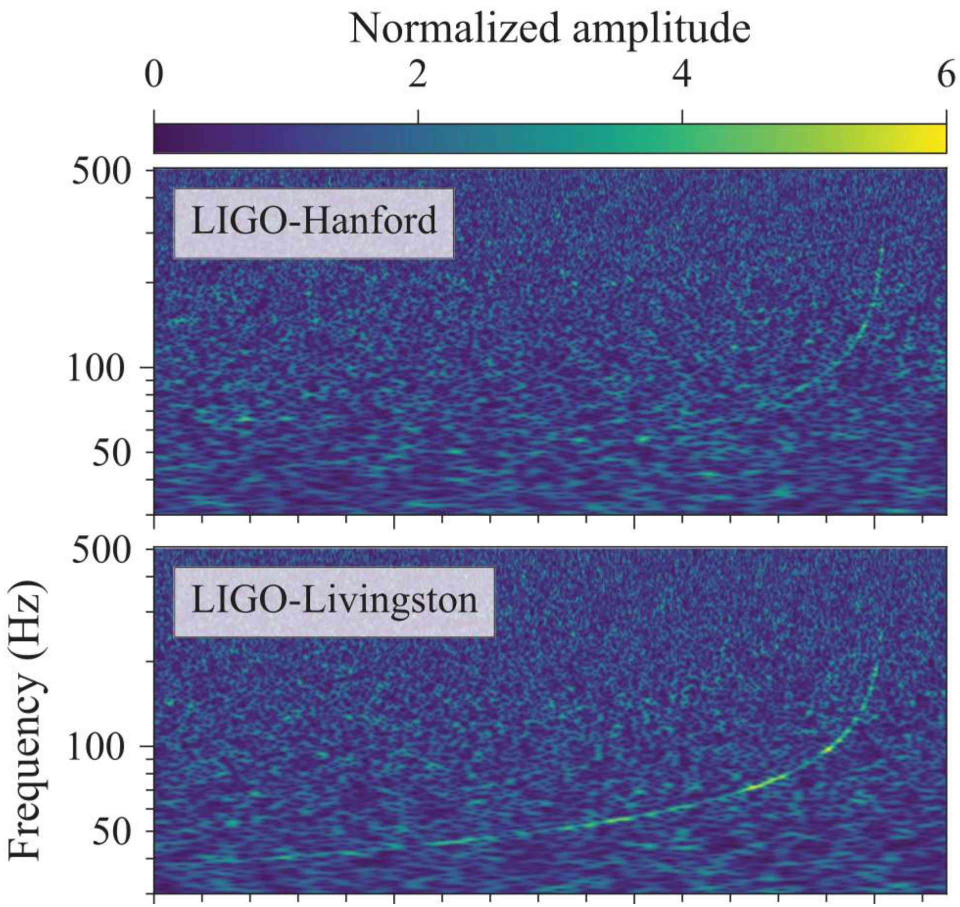
content/themes/

By Massimiliano Razzano August 1, 2017 News, Press Releases

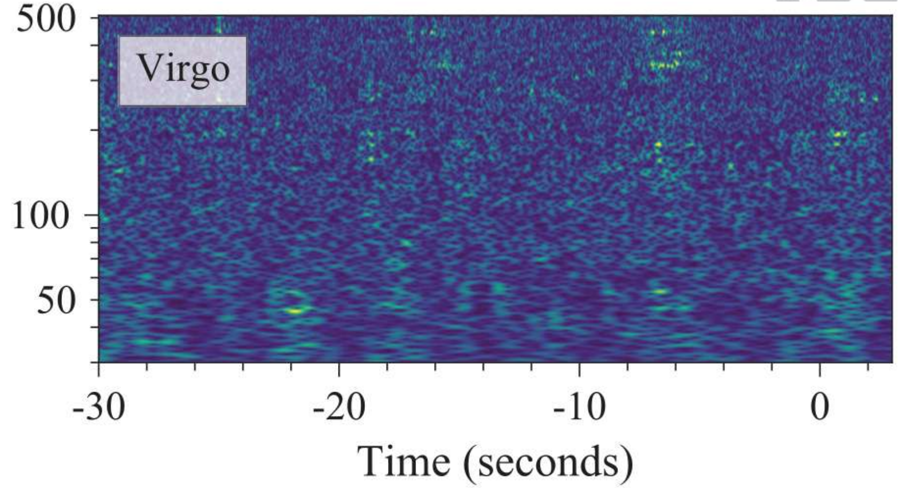
VIRGO joins LIGO for the “Observation Run 2” (O2) data-taking period

Today, Tuesday August 1st 2017, the VIRGO detector based in Europe has officially joined “Observation Run 2” (O2) a
based twin LIGO detectors.

GW170817

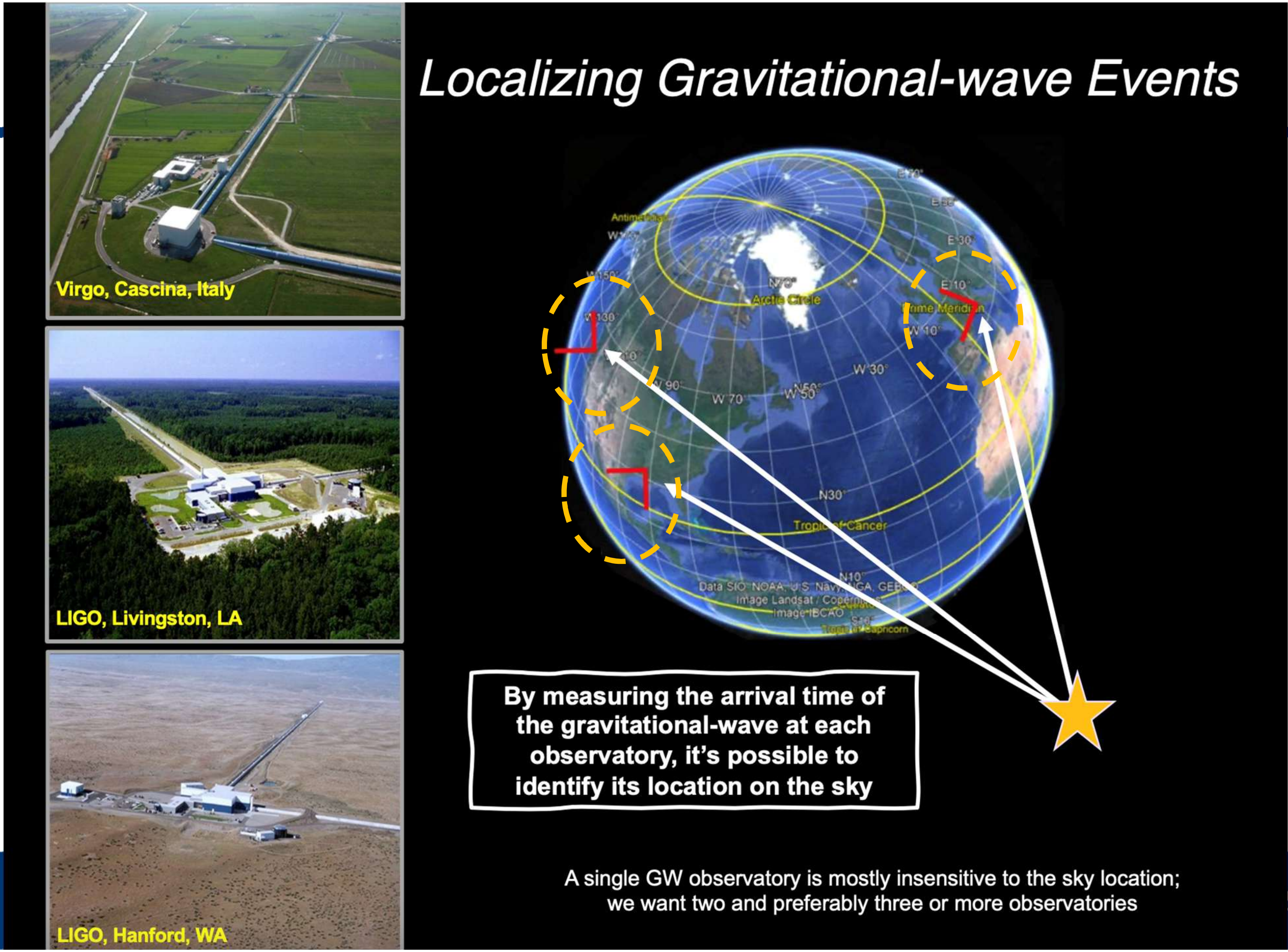


Normalized amplitude
0
2
4
6
500
LIGO-Hanford
100
50
500
LIGO-Livingston
100
50
Frequency (Hz)



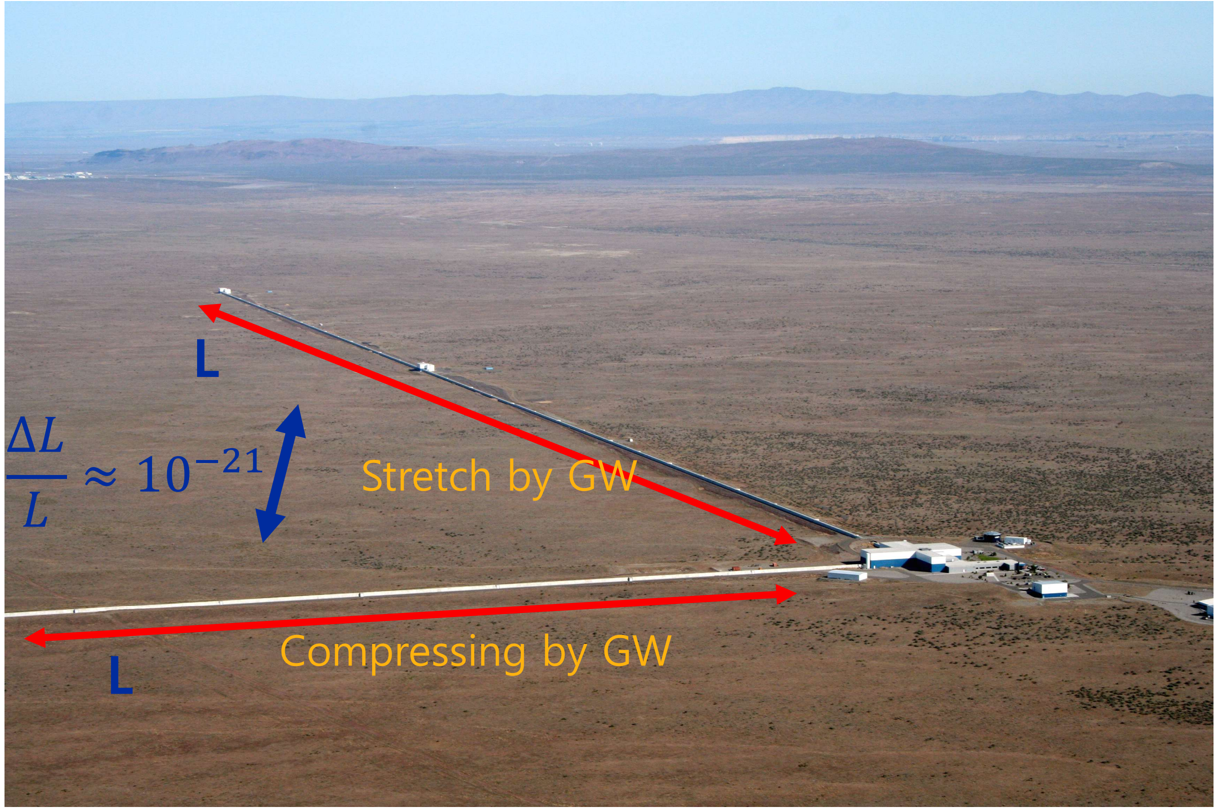
500
Virgo
100
50
-30
-20
-10
0
Time (seconds)

VIRGO



Yokohama GRB 201
Marci Branchesi

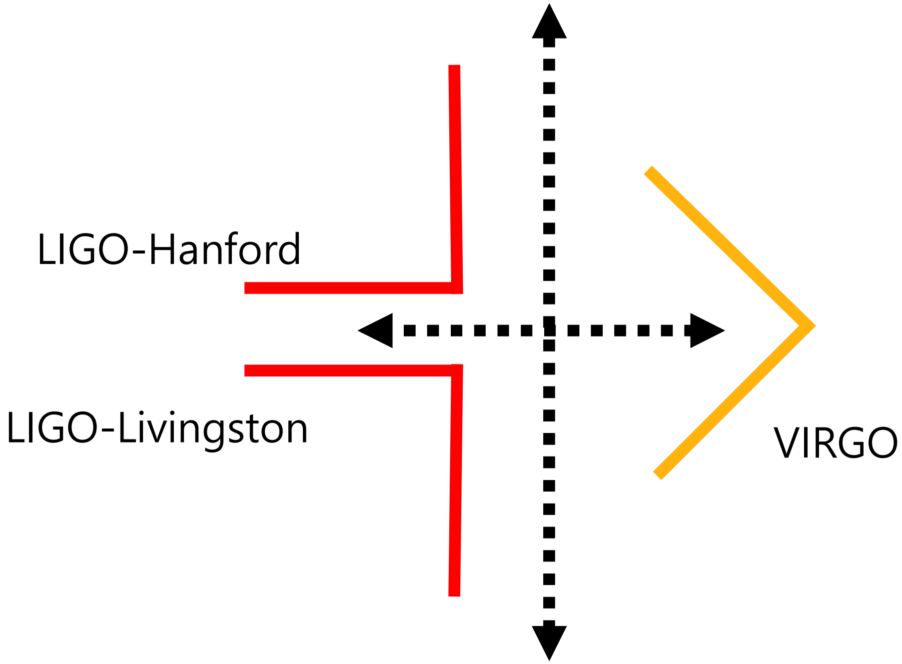
Strain Sensitivity



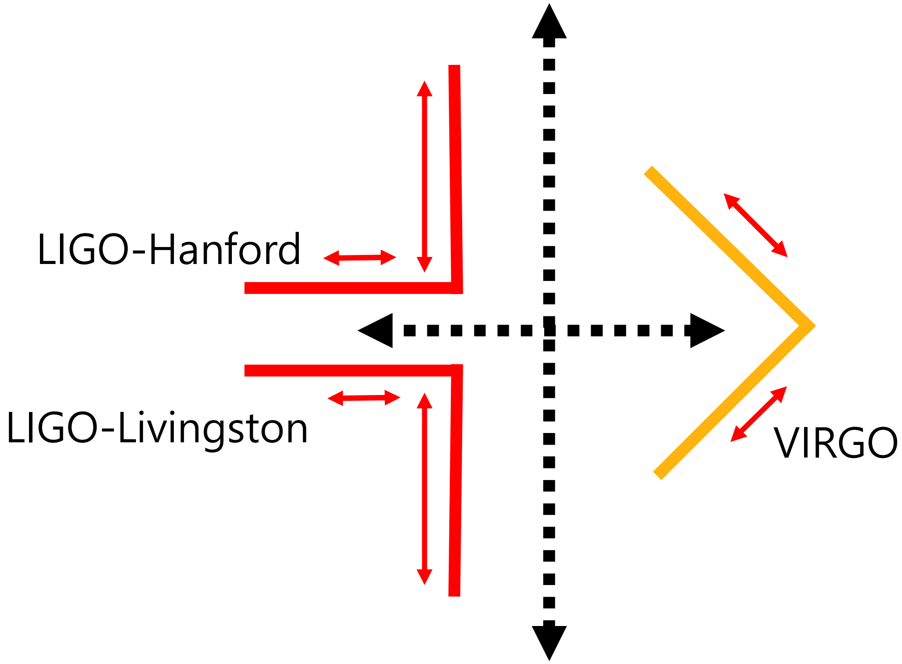
Minimum sensitivity

$$\frac{\Delta L}{L} \approx 10^{-21}$$

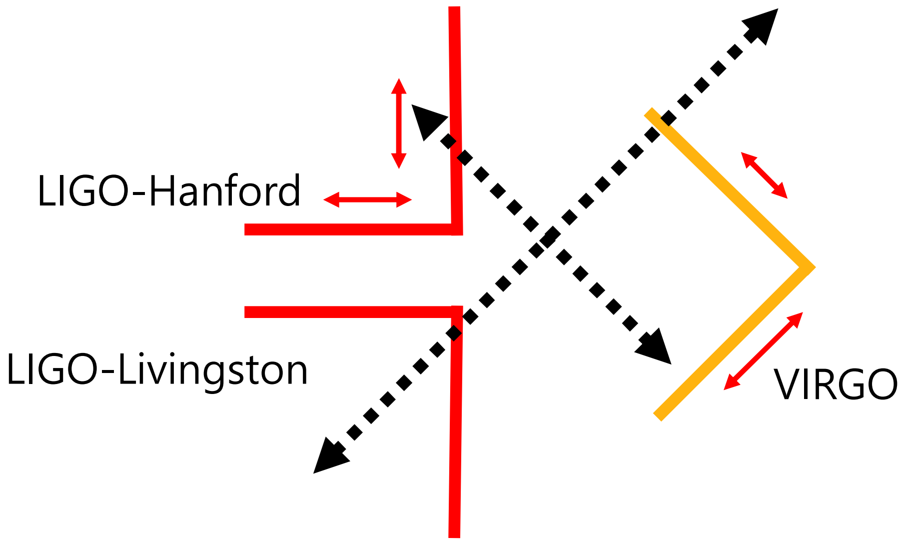
Polarization of Gravitational Wave



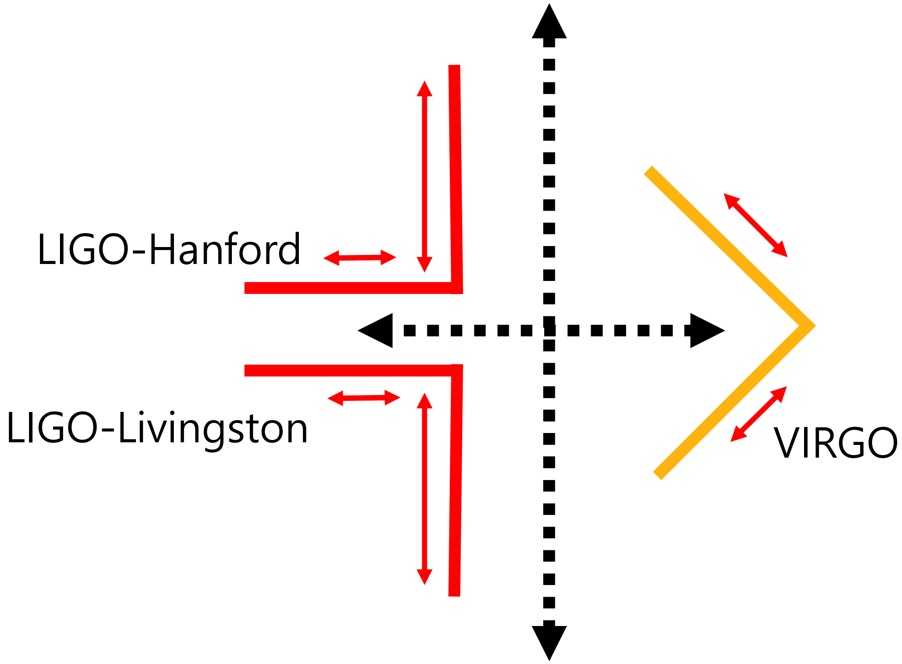
Polarization of Gravitational Wave

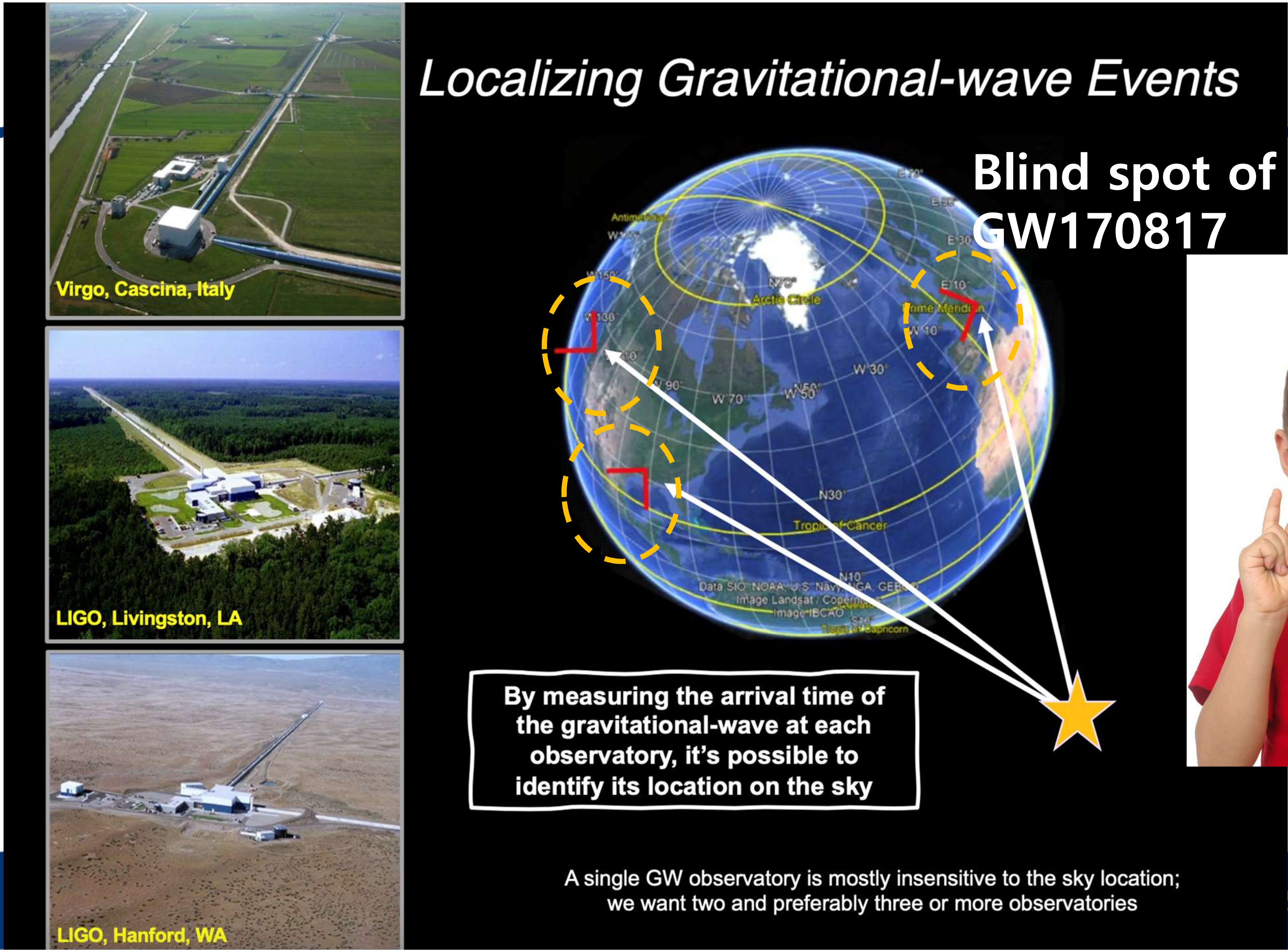


Polarization of Gravitational Wave



Polarization of Gravitational Wave

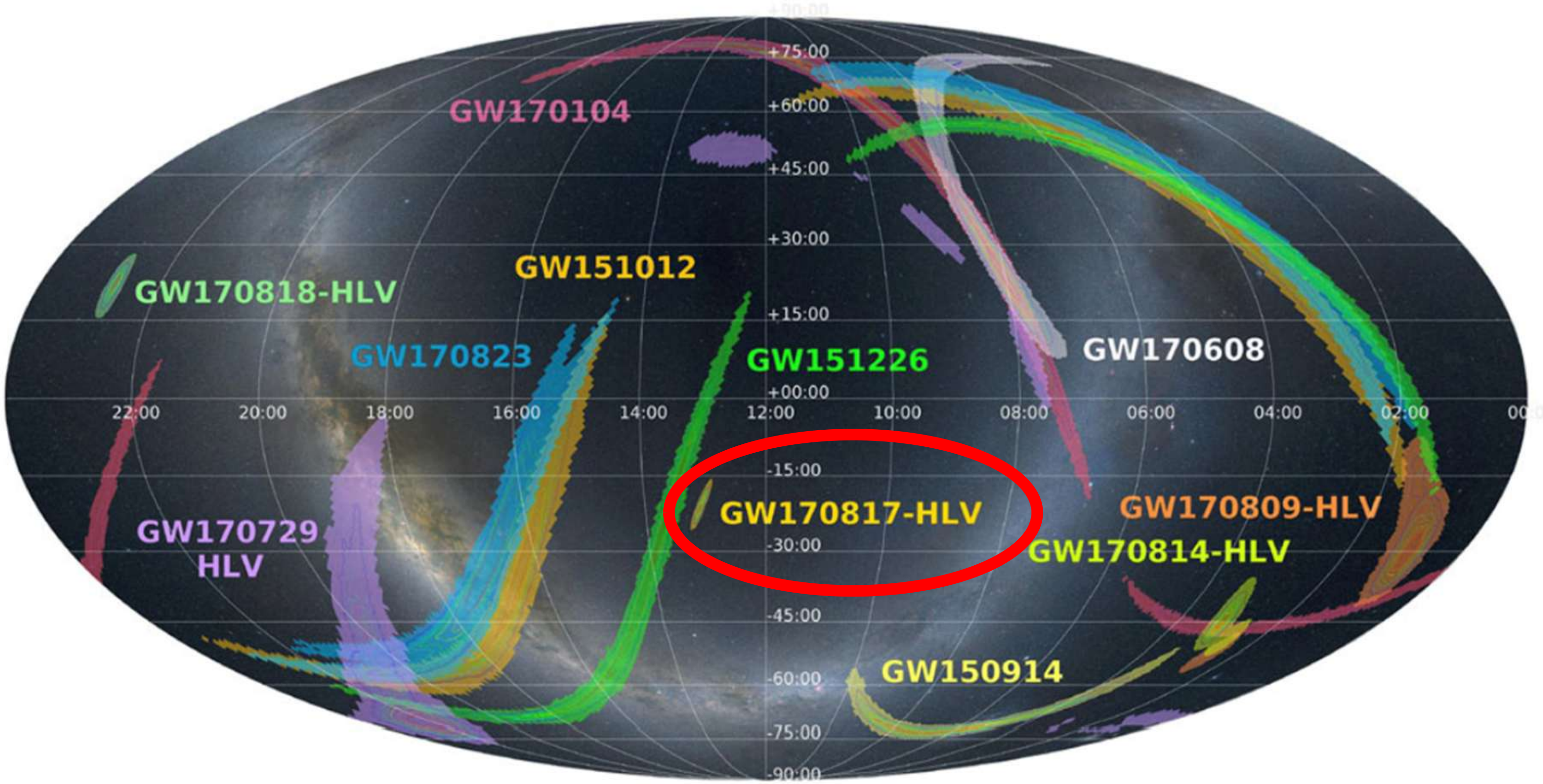




Blind spot of GW170817

Yokohama GRB 201
Marci Branchesi

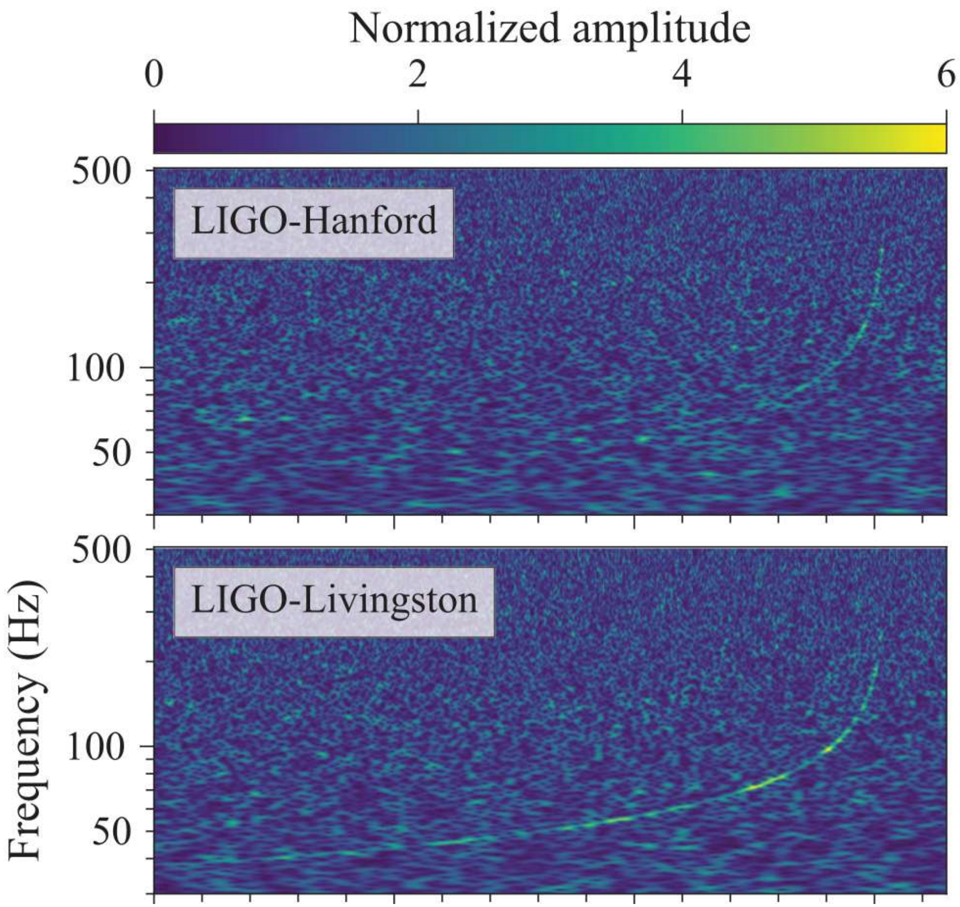
Sky localization

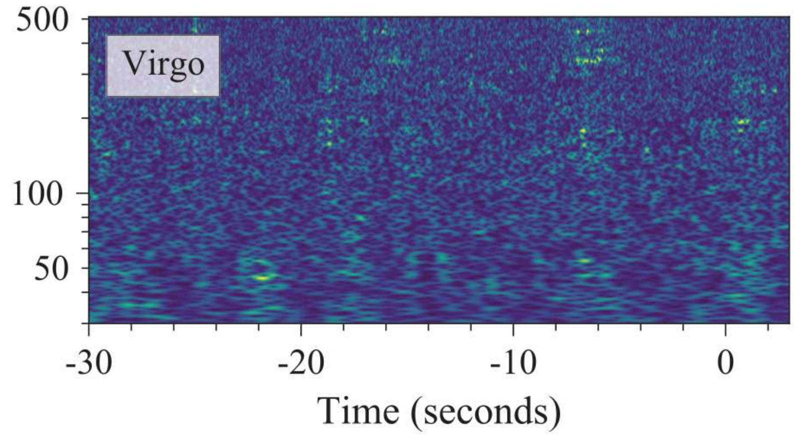


GW170817

SSS17a
August 17, 2017
August 21, 2017
Swope & Magellan Telescopes

GW170817

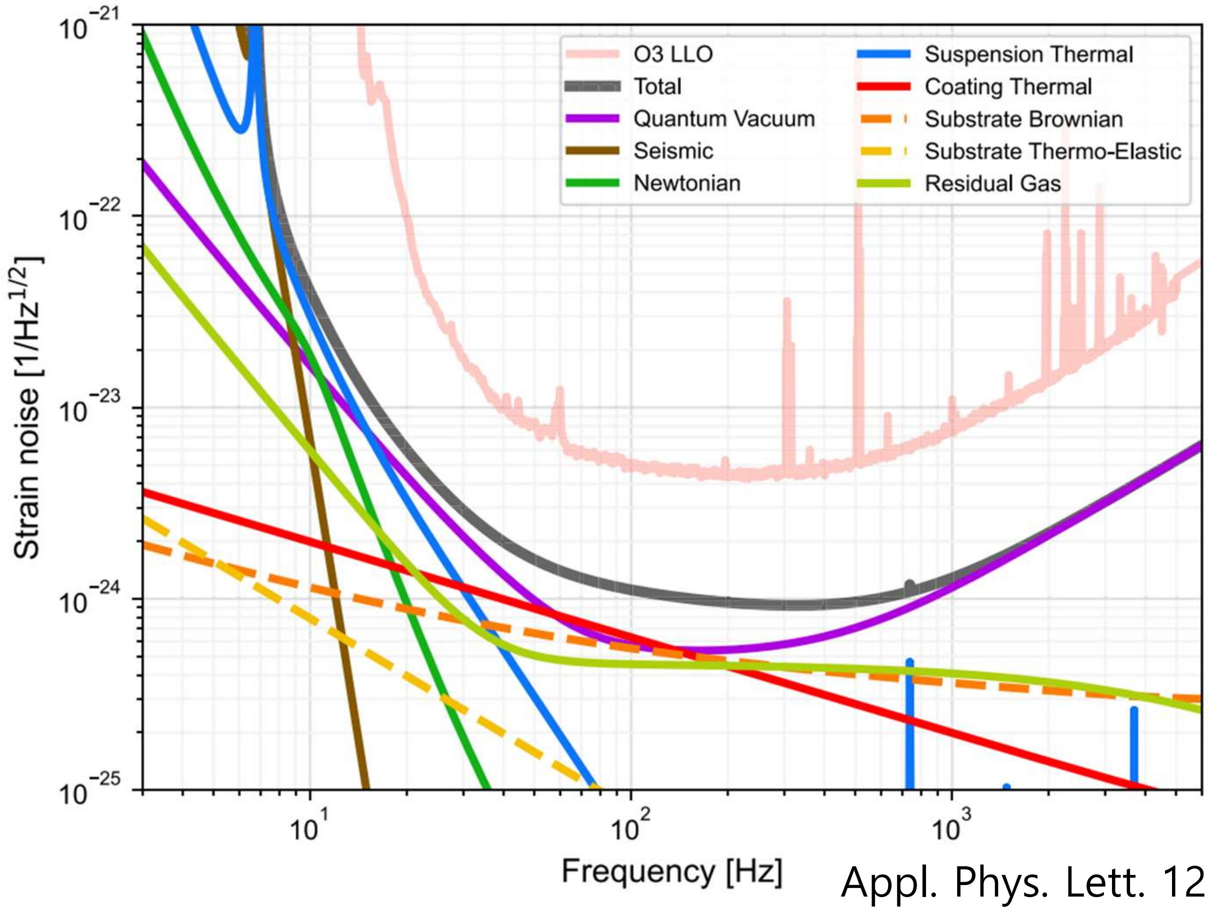

Normalized amplitude
0
2
4
6
500
LIGO-Hanford
100
50
500
LIGO-Livingston
100
50
Frequency (Hz)


500
Virgo
100
50
-30
-20
-10
0
Time (seconds)


VIRGO

2. Sensitivity Curve of Gravitational Wave Detector

LIGO Sensitivity



Appl. Phys. Lett. 122, 110502 (2023)

Spectral density

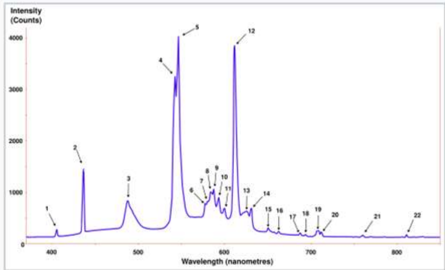
19 languages

Article Talk   Read Edit View history Tools

From Wikipedia, the free encyclopedia

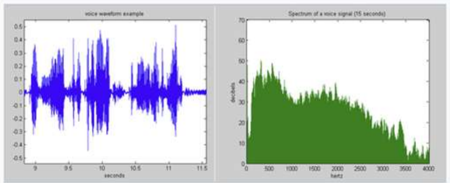
This article is about signal processing and relation of spectra to time-series. For further applications in the physical sciences, see Spectrum (physical sciences).
"Spectral power density" redirects here; not to be confused with Spectral power.

This article **may be too technical for most readers to understand**. Please help improve it to make it understandable to non-experts, without removing the technical details. *(June 2024) (Learn how and when to remove this message)*



The spectral density of a fluorescent light as a function of optical wavelength shows peaks at atomic transitions, indicated by the numbered arrows.

In signal processing, the power spectrum $S_{xx}(f)$ of a continuous time signal $x(t)$ describes the distribution of power into frequency components f composing that signal.[1] According to Fourier analysis, any physical signal can be decomposed into a number of discrete frequencies, or a spectrum of frequencies over a continuous range. The statistical average of any sort of signal (including noise) as analyzed in terms of its frequency content, is called its spectrum.



The voice waveform over time (left) has a broad audio power spectrum (right).

When the energy of the signal is concentrated around a finite time interval, especially if its total energy is finite, one may compute the **energy spectral density**. More commonly used is the **power spectral density** (PSD, or simply **power spectrum**), which applies to signals existing over *all* time, or over a time period large enough (especially in relation to the duration of a measurement) that it could as well have been over an infinite time interval. The PSD then refers to the

In signal processing, the energy of a signal $x(t)$ is given by

$$E \triangleq \int_{-\infty}^{\infty} |x(t)|^2 \ dt.$$

Assuming the total energy is finite (i.e. $x(t)$ is a square-integrable function) allows applying Parseval's theorem (or Plancherel's theorem).[6] That is,

$$\int_{-\infty}^{\infty} |x(t)|^2 \, dt = \int_{-\infty}^{\infty} |\hat{x}(f)|^2 \, df,$$

where

$$\hat{x}(f) = \int_{-\infty}^{\infty} e^{-i2\pi ft} x(t) \ dt,$$

is the Fourier transform of $x(t)$ at frequency f (in Hz).[7] The theorem also holds true in the discrete-time cases. Since the integral on the left-hand side is the energy of the signal, the value of $|\hat{x}(f)|^2 df$ can be interpreted as a density function multiplied by an infinitesimally small frequency interval, describing the energy contained in the signal at frequency f in the frequency interval $f + df$.

Therefore, the **energy spectral density** of $x(t)$ is defined as:[8]

$$\bar{S}_{xx}(f) \triangleq |\hat{x}(f)|^2 \quad \textbf{(Eq.1)}$$

The function $\bar{S}_{xx}(f)$ and the autocorrelation of $x(t)$ form a Fourier transform pair, a result also known as the Wiener–Khinchin theorem (see also Periodogram).

As a physical example of how one might measure the energy spectral density of a signal, suppose $V(t)$ represents the potential (in volts) of an electrical pulse propagating along a transmission line of impedance Z, and suppose the line is terminated with a matched resistor (so that all of the pulse energy is delivered to the resistor and none is reflected back). By Ohm's law, the power delivered to the resistor at time t is equal to $V(t)^2/Z$, so the total energy is found by integrating $V(t)^2/Z$ with respect to time over the duration of the pulse. To find the value of the energy spectral density

Fourier transformation

- Fourier series
  > basis
- Fourier transformation
- Application

Fourier series

$$f(x) = f(x+T)$$ Periodic function

$$\int_a^b |f|^2\,dx$$ Periodic function

$$g_n = \frac{1}{T}\int_{t_0}^{t_0+T} \exp\left(-\frac{2n\pi i x}{T}\right) f(x)\,dx, \quad t_0 \in \mathbb{R}.$$

$$f(x) = \sum_{n=-\infty}^{\infty} g_n \exp\left(\frac{2n\pi i x}{T}\right).$$

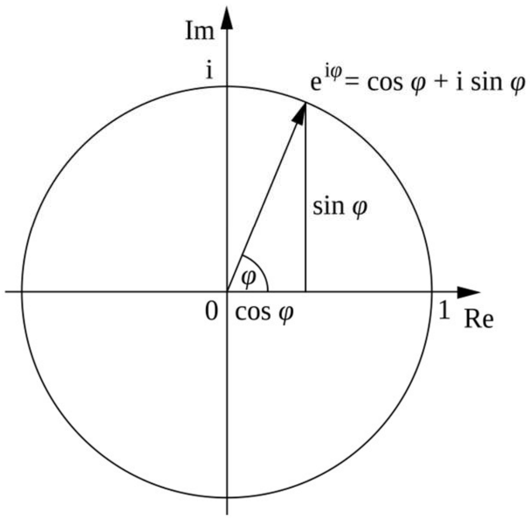
Fourier series

$$f(x) = \sum_{n=-\infty}^{\infty} g_n \exp\left(\frac{2n\pi i x}{T}\right).$$

$f(x) = g_0 \exp(2\pi \mathrm{in}_0 x) + g_1 \exp(2\pi \mathrm{in}_1 x) \ldots$

Fourier Series

$$f(x) = \sum_{n=-\infty}^{\infty} g_n \exp\left(\frac{2n\pi i x}{T}\right).$$



Fourier Transform

$$\hat{f}(\xi) = \int_{-\infty}^{\infty} f(x)\, e^{-2\pi i x \xi}\, dx$$

* We use a caret (^) to denote the Fourier transform.

Transform

$$f(x) = \int_{-\infty}^{\infty} \hat{f}(\xi)\, e^{2\pi i x \xi}\, d\xi$$

Inverse transform

Fourier Transform

Fourier transformation with the angular frequency k

$$\hat{f}(k) = \int_{-\infty}^{+\infty} f(x) e^{-ikx} dx$$

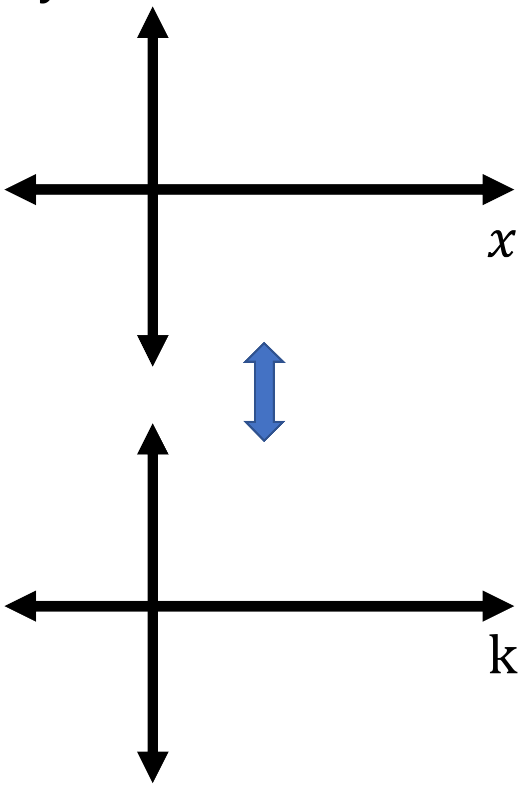
$$f(x) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} f(k) e^{ikx} dk$$

Fourier Transform

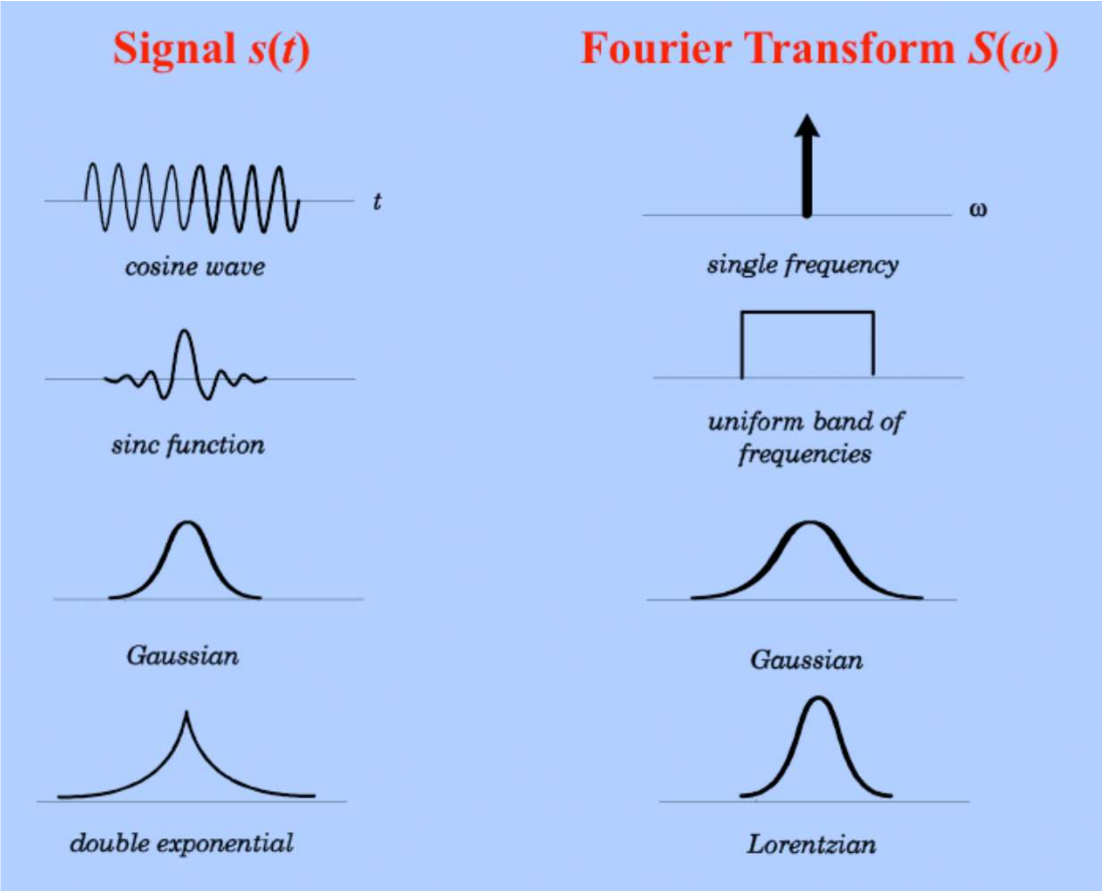
Fourier transformation with the angular frequency k

$$\hat{f}(k) = \int_{-\infty}^{+\infty} f(x) e^{-ikx} dx$$

$$f(x) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} f(k) e^{ikx} dk$$



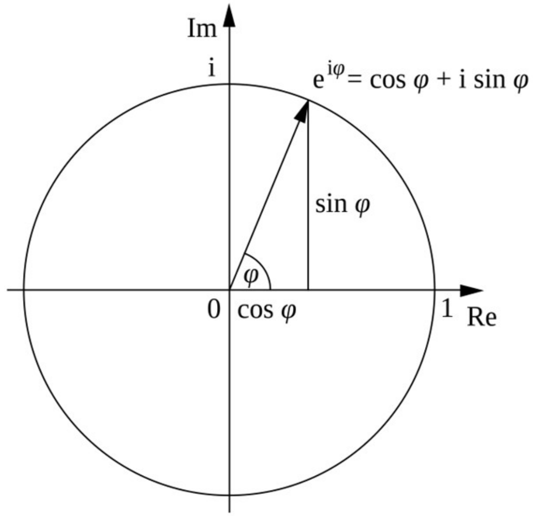
Fourier Transform



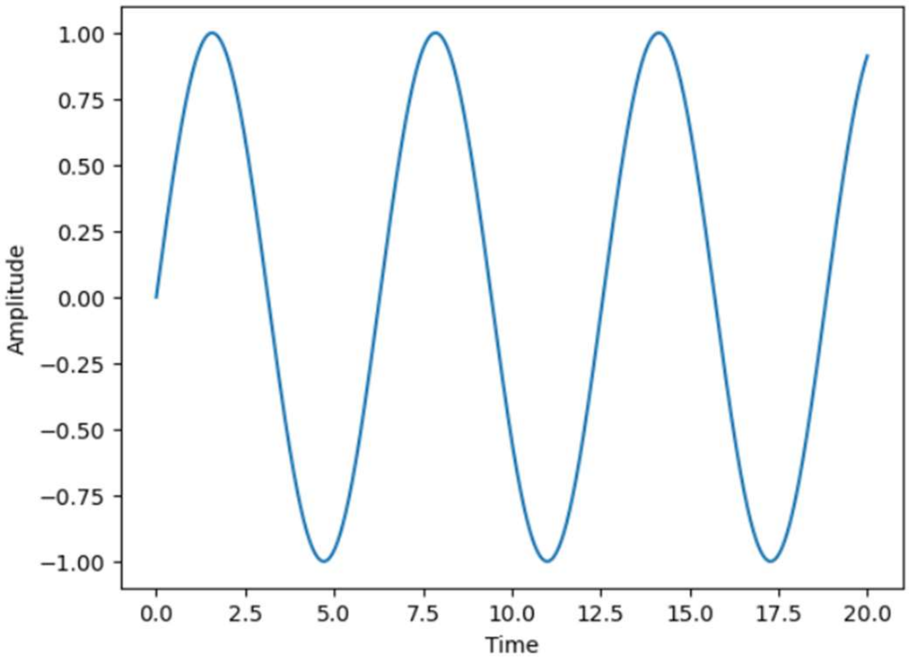
Fourier Expansion

$$\hat{f}(k) = \int_{-\infty}^{+\infty} f(x) e^{-ikx} dx$$

$$f(x) = \sum_{n=-\infty}^{\infty} a_n e^{inx}$$

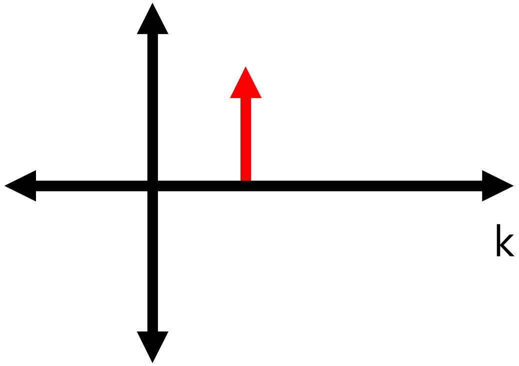


Fourier Expansion

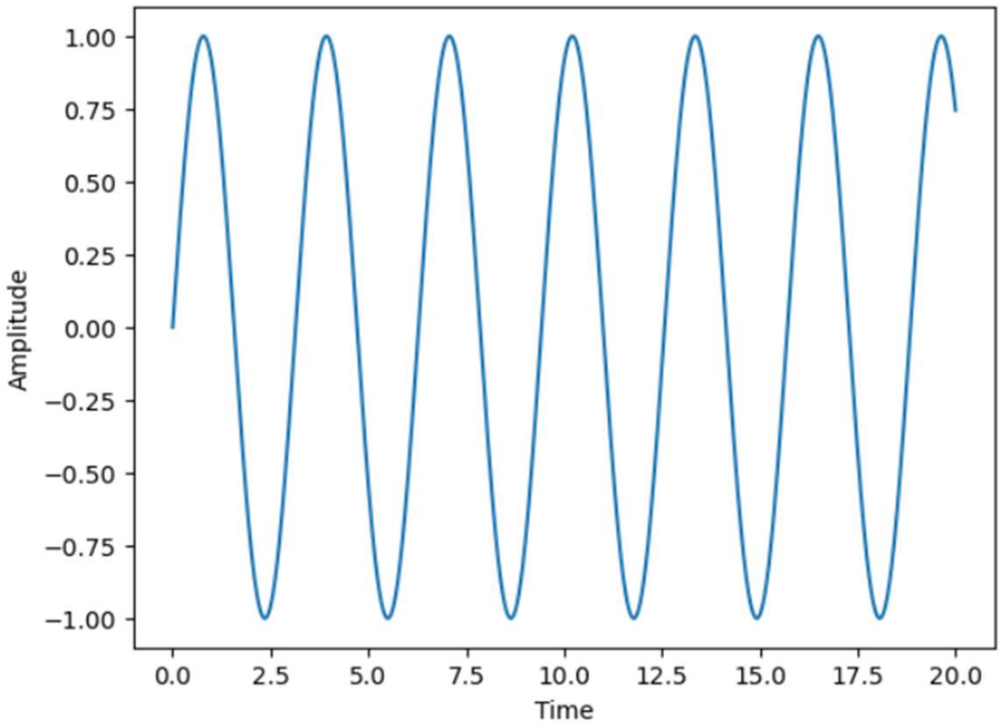


$$f(x) = \sum_{n=-\infty}^{\infty} a_n e^{inx}$$

$$= \mathrm{a}\sin \mathrm{k}x$$

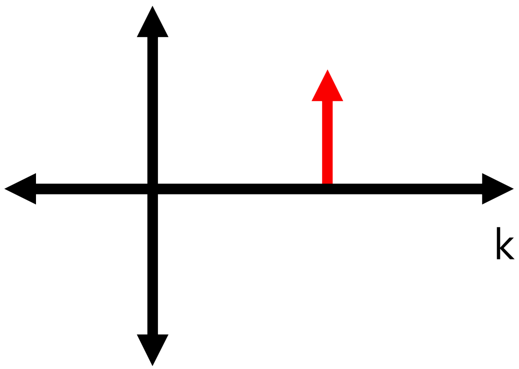


Fourier Expansion

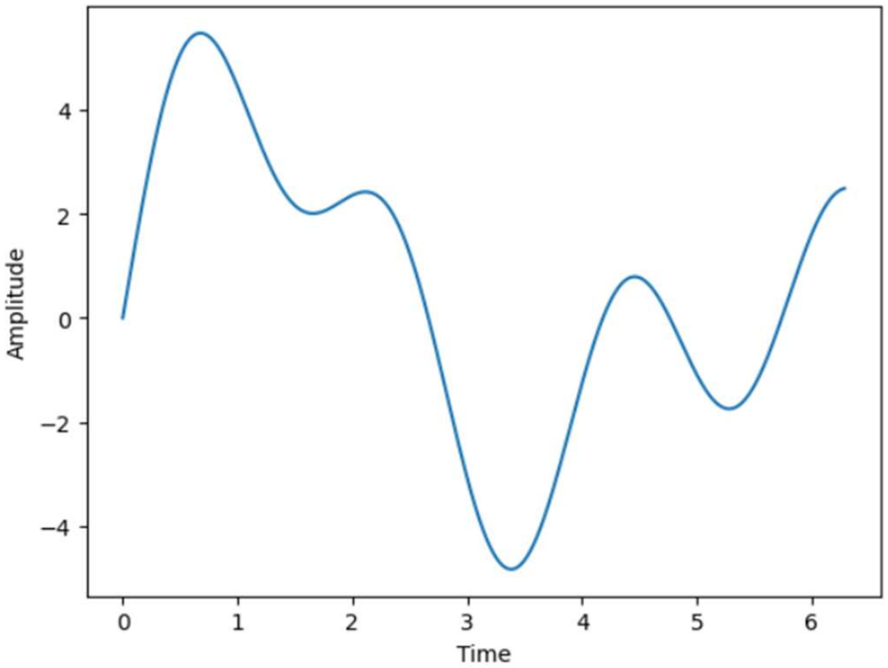


$$f(x) = \sum_{n=-\infty}^{\infty} a_n e^{inx}$$

$$= \mathrm{a}\sin 2\mathrm{k}x$$

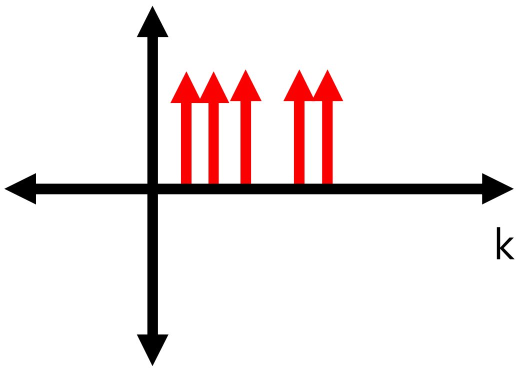


Application of Fourier transformation

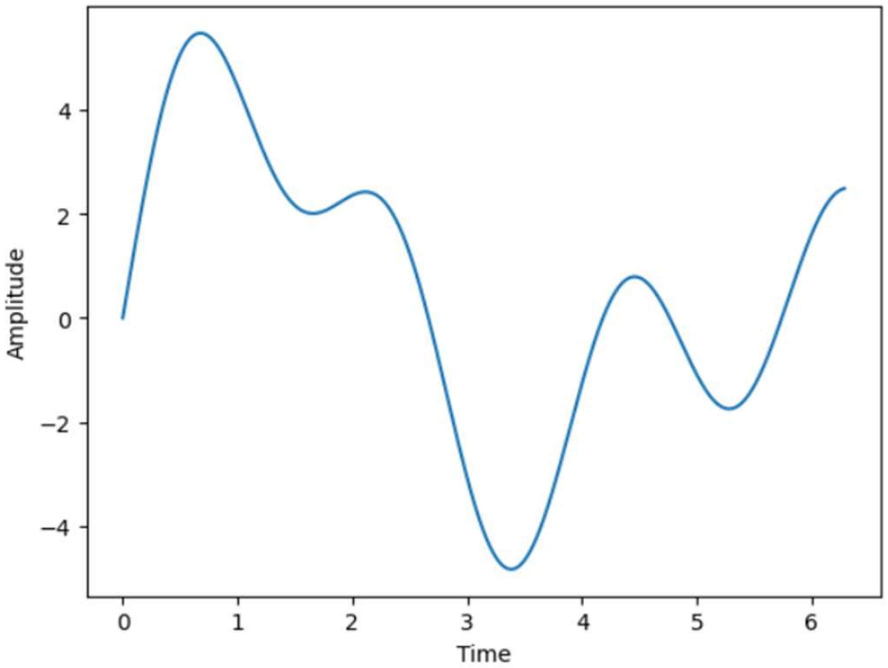


$$f(x) = \sum_{n=-\infty}^{\infty} a_n e^{inx}$$

$$= \mathrm{a}\sin \mathrm{k}x \quad + \mathrm{a}\sin 2\mathrm{k}x$$

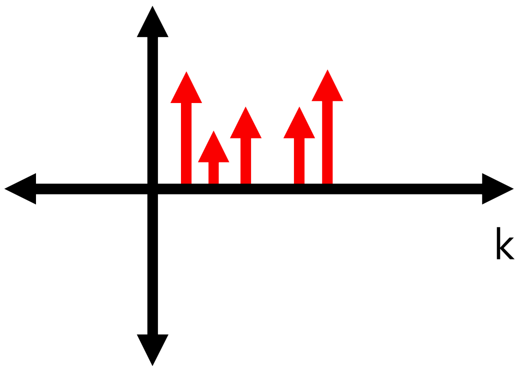


Application of Fourier transformation

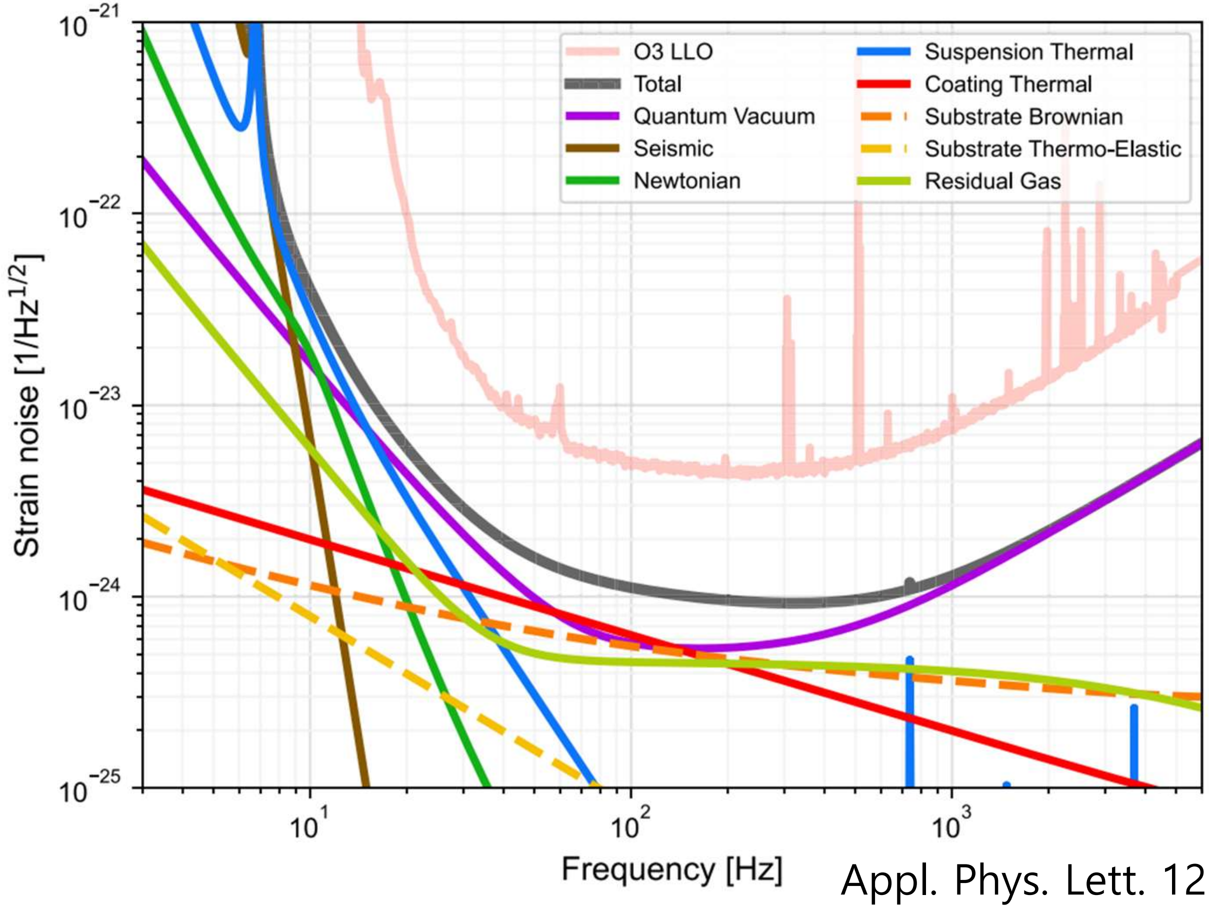


$$f(x) = \sum_{n=-\infty}^{\infty} a_n e^{inx}$$

$$= a\sin kx \quad + a\sin 2kx$$



LIGO Sensitivity



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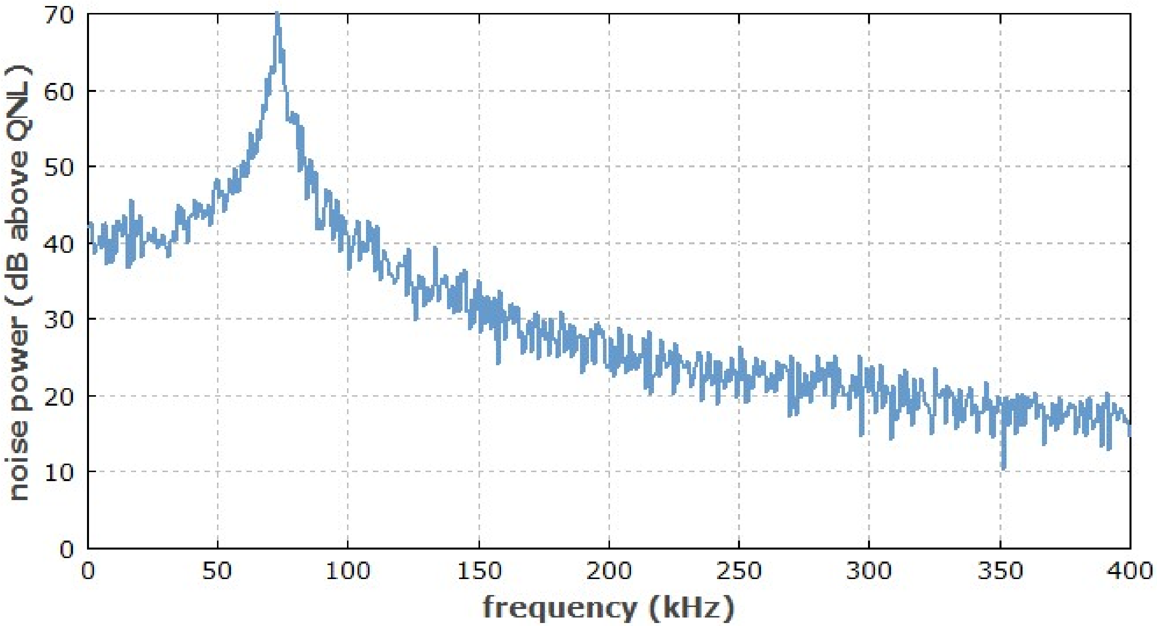
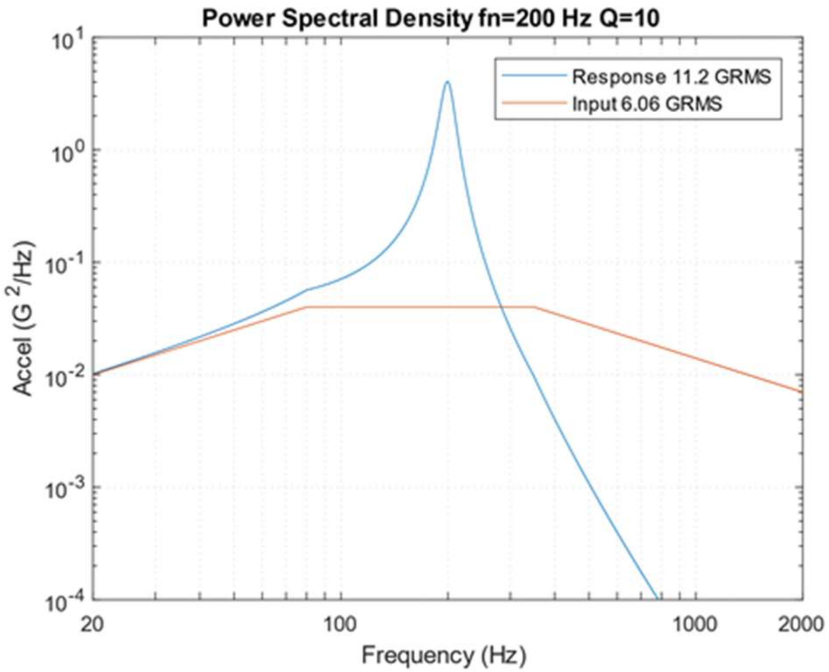
Power Spectral Density



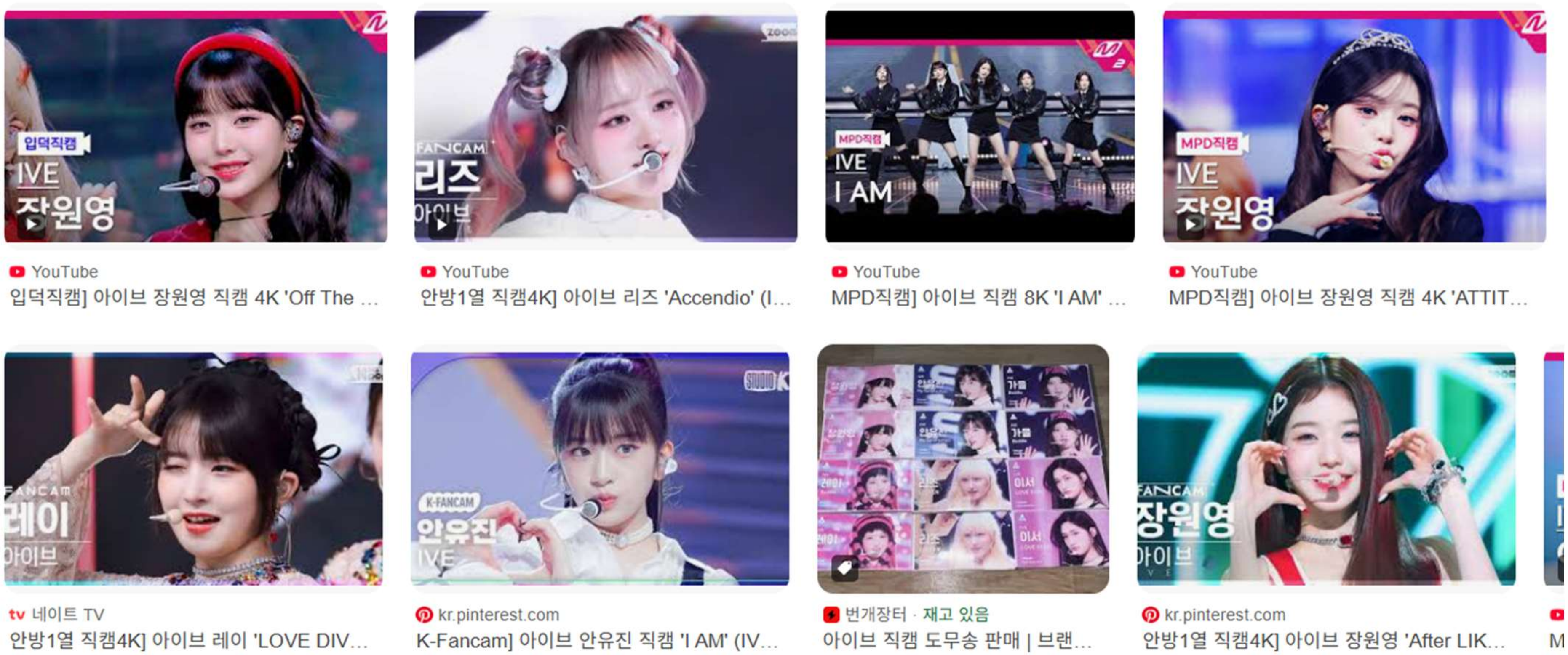
Power Spectral Density



Signal and Noise

Signal : 전달하고 자 하는 것

Noise : 시그널을 제외한 나머지


YouTube
입덕직캠] 아이브 장원영 직캠 4K 'Off The ...
YouTube
안방1열 직캠4K] 아이브 리즈 'Accendio' (I...
YouTube
MPD직캠] 아이브 직캠 8K 'I AM' ...
YouTube
MPD직캠] 아이브 장원영 직캠 4K 'ATTIT...
네이트 TV
안방1열 직캠4K] 아이브 레이 'LOVE DIV...
kr.pinterest.com
K-Fancam] 아이브 안유진 직캠 'I AM' (IV...
번개장터 · 재고 있음
아이브 직캠 도무송 판매 | 브랜...
kr.pinterest.com
안방1열 직캠4K] 아이브 장원영 'After LIK...

아이돌 직캠?

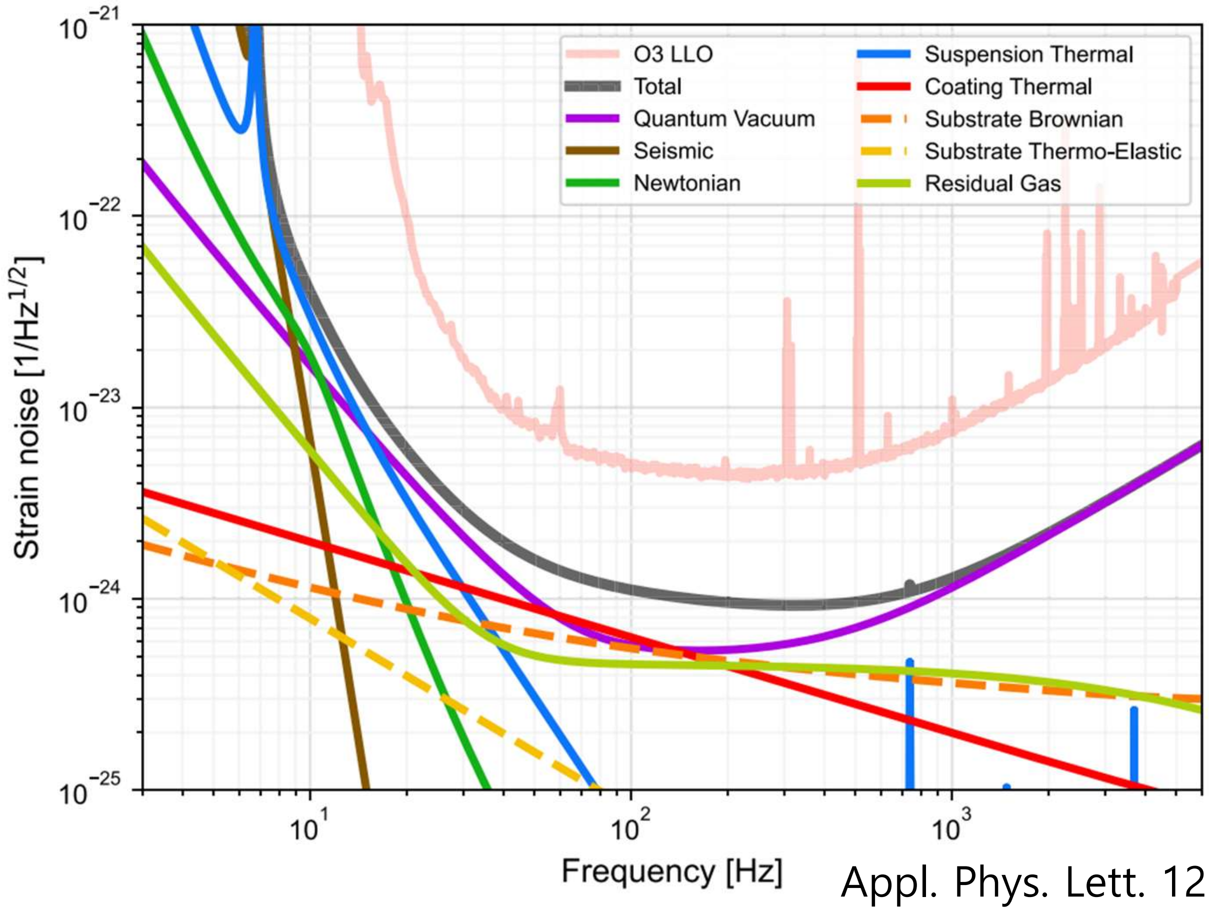
왜??

Signal and Noise

Signal : 내가보고 싶은 멤버

Noise : 내가 보고싶은 멤버 뺀 나머지

LIGO Sensitivity



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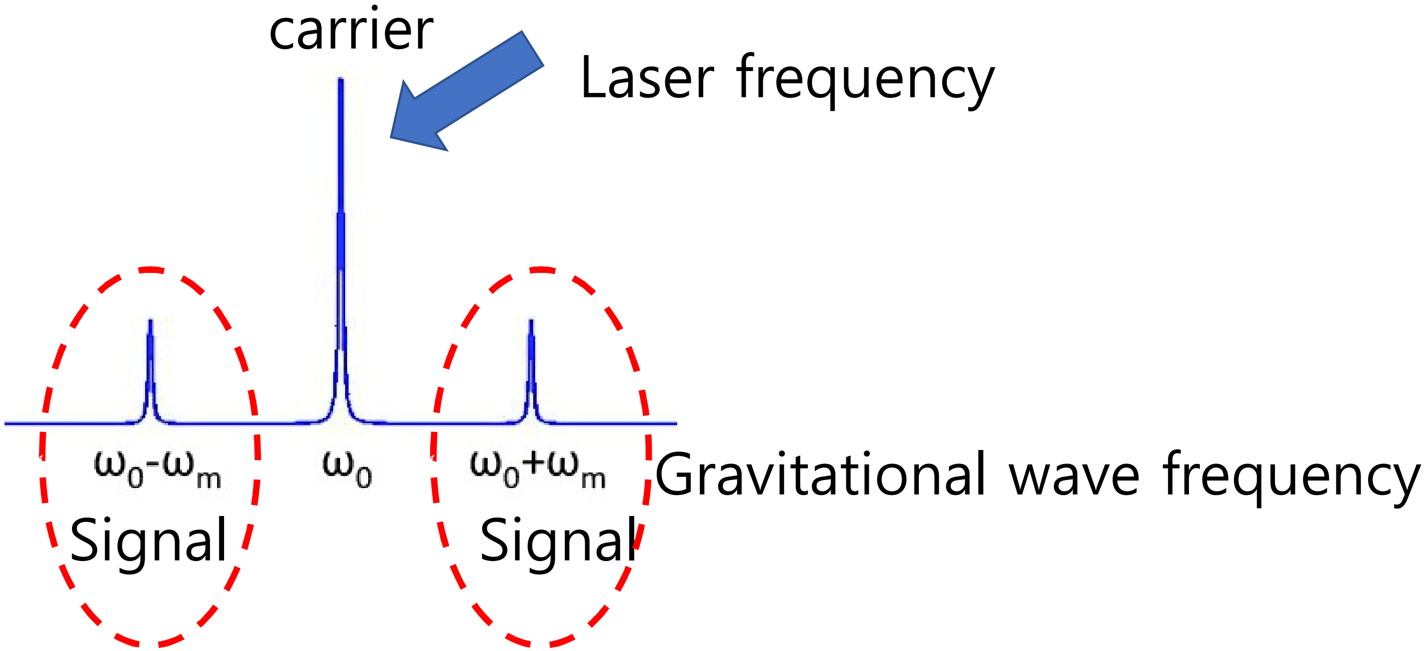
Side Band Figure



Side Band Figure

We can illustrate the creation of sidebands with one trigonometric identity:

$$\cos(A) \cdot \cos(B) \equiv \tfrac{1}{2}\cos(A+B) + \tfrac{1}{2}\cos(A-B)$$

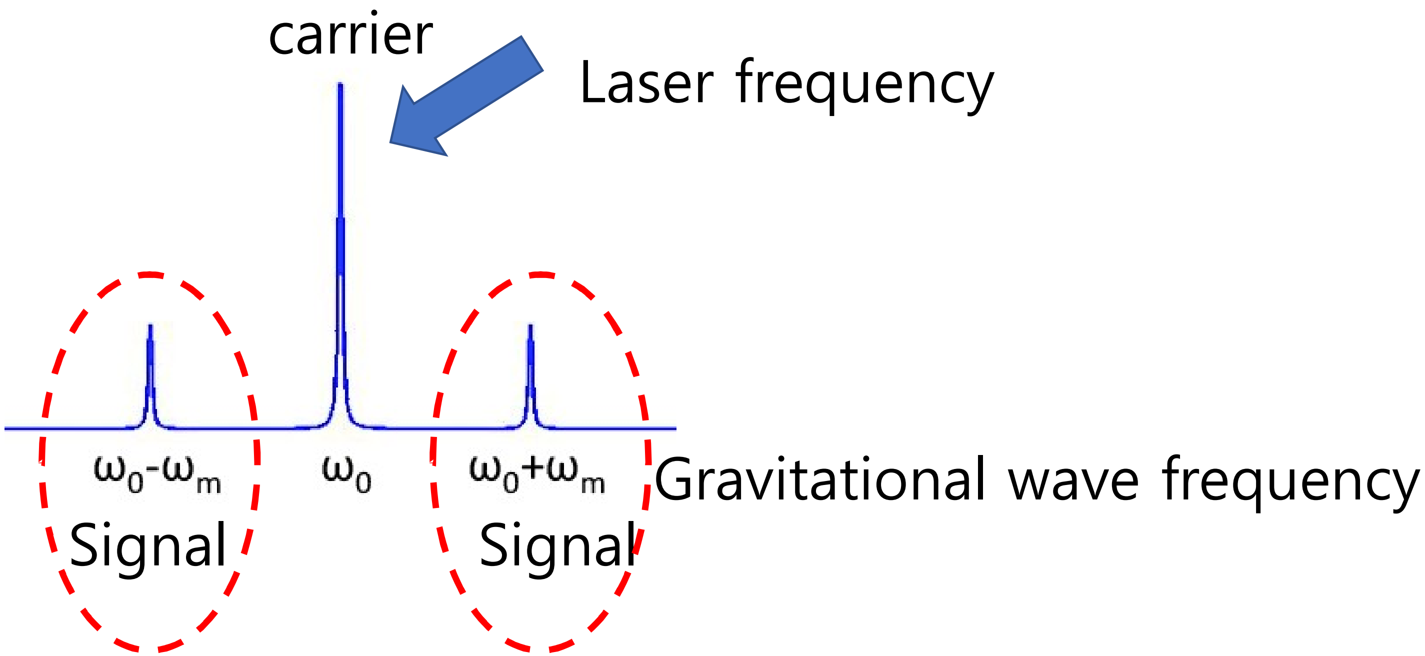
Adding $\cos(A)$ to both sides:

$$\cos(A) \cdot [1 + \cos(B)] = \tfrac{1}{2}\cos(A+B) + \cos(A) + \tfrac{1}{2}\cos(A-B)$$

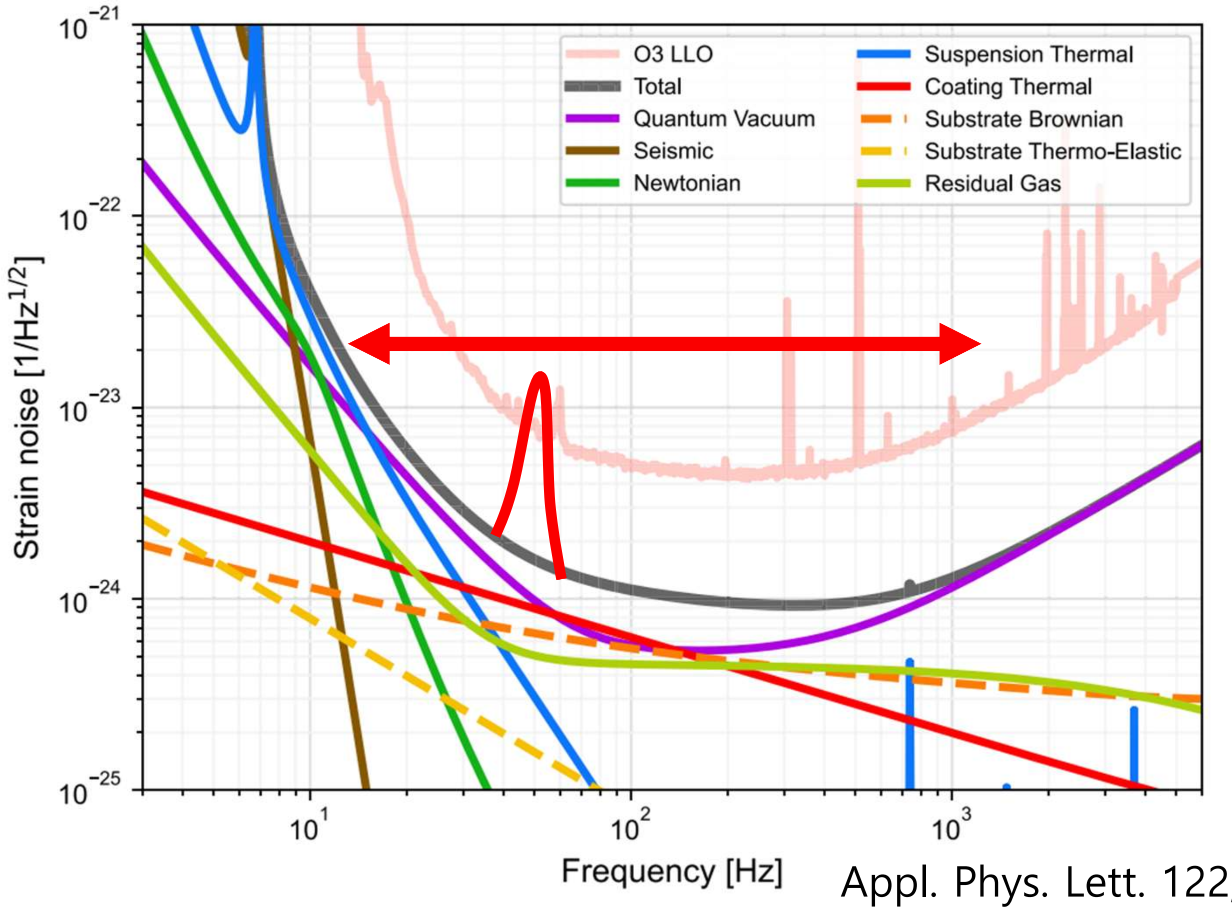
Substituting (for instance) $A \triangleq 1000 \cdot t$ and $B \triangleq 100 \cdot t,$ where t represents time:

$$\underbrace{\cos(1000\,t)}_{\text{carrier wave}} \cdot \underbrace{[1 + \cos(100\,t)]}_{\text{amplitude modulation}} = \underbrace{\tfrac{1}{2}\cos(1100\,t)}_{\text{upper sideband}} + \underbrace{\cos(1000\,t)}_{\text{carrier wave}} + \underbrace{\tfrac{1}{2}\cos(900\,t)}_{\text{lower sideband}}.$$

Side Band Figure



LIGO Sensitivity



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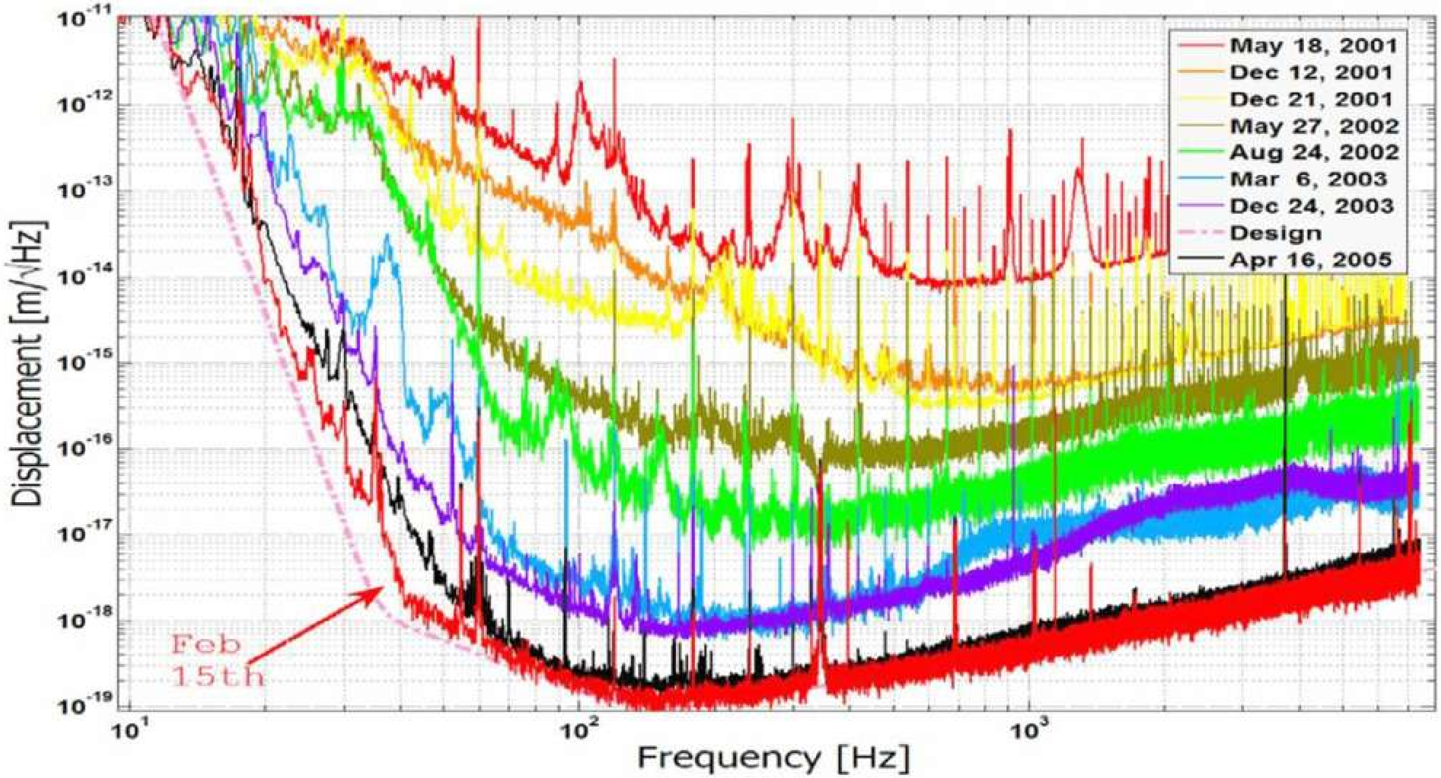
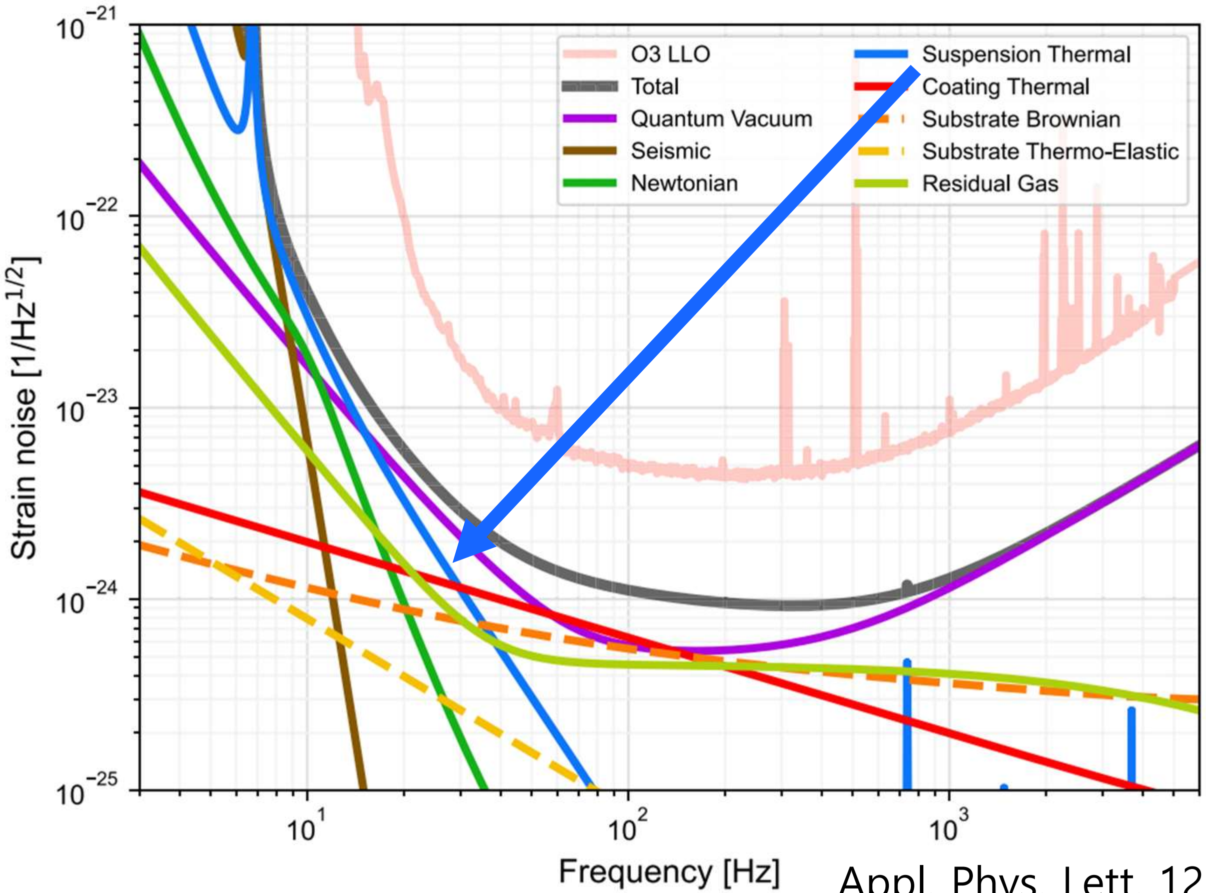
Sensitivity During Engineering Run



LIGO Sensitivity



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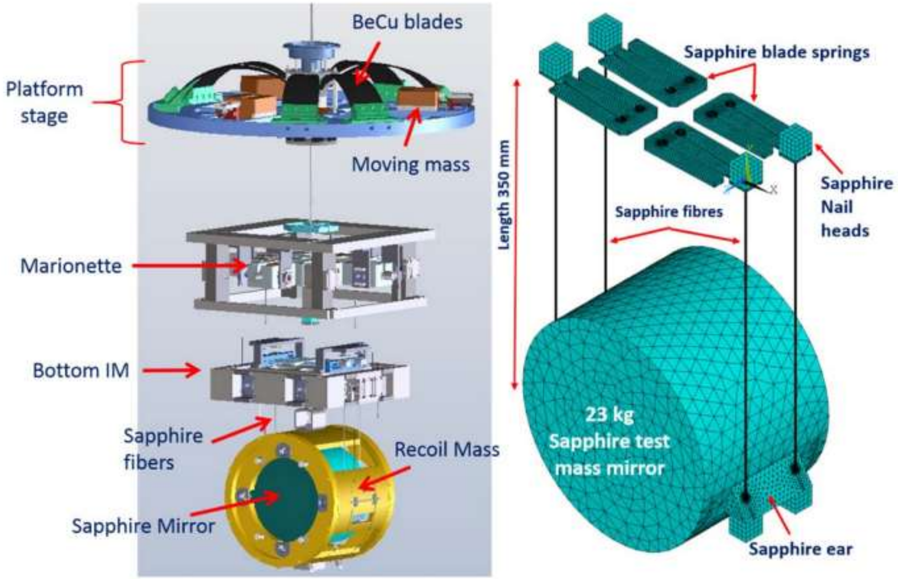
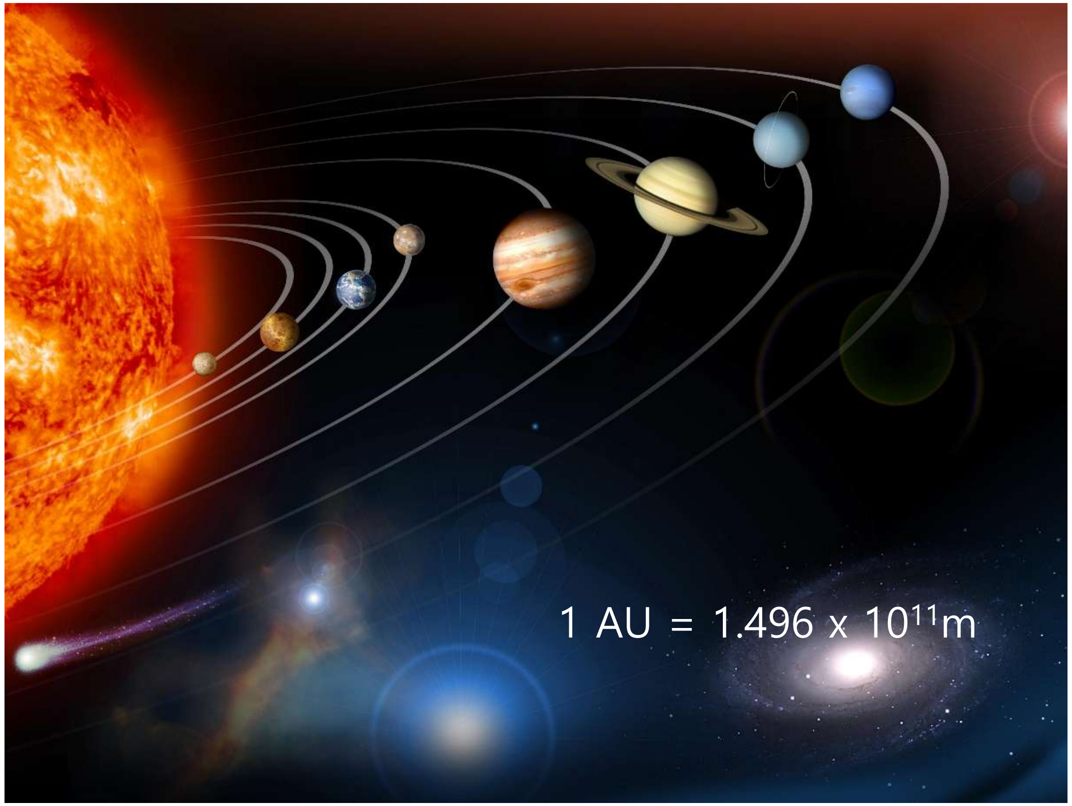
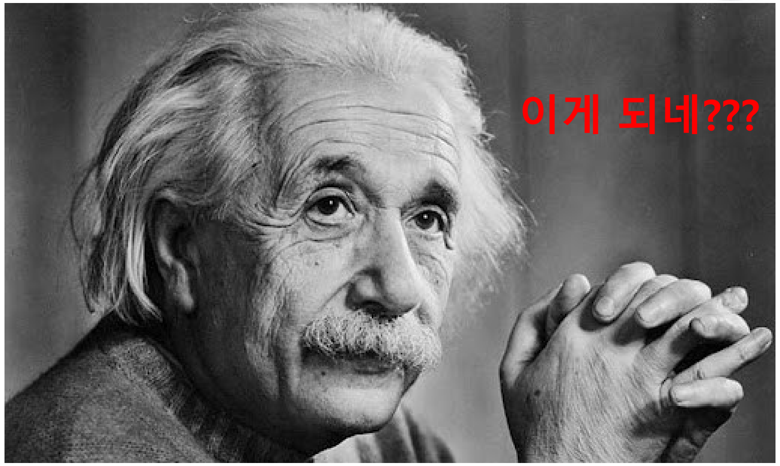
Suspension



BeCu blades
Platform stage
Moving mass
Marionette
Bottom IM
Sapphire fibers
Recoil Mass
Sapphire Mirror
Sapphire blade springs
Length 350 mm
Sapphire Nail heads
Sapphire fibres
23 kg Sapphire test mass mirror
Sapphire ear

Strain Due to Gravitational Wave

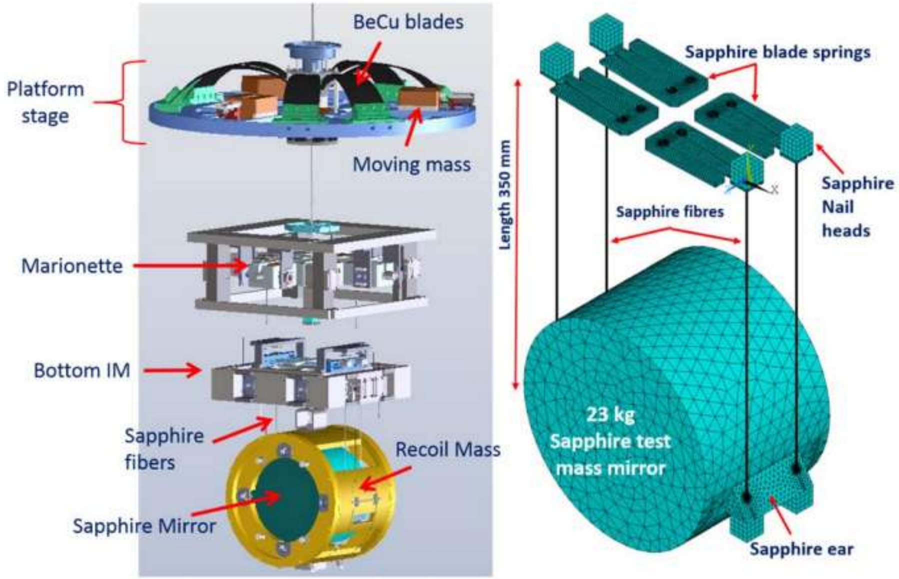


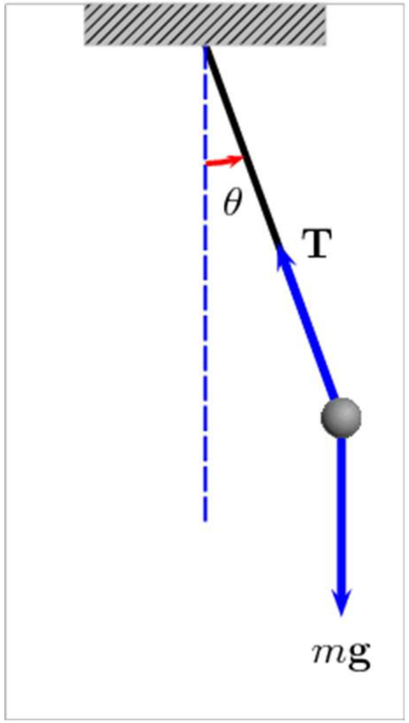


$$\frac{\Delta L}{L} \approx 10^{-21}$$

Detect existence of a single atom

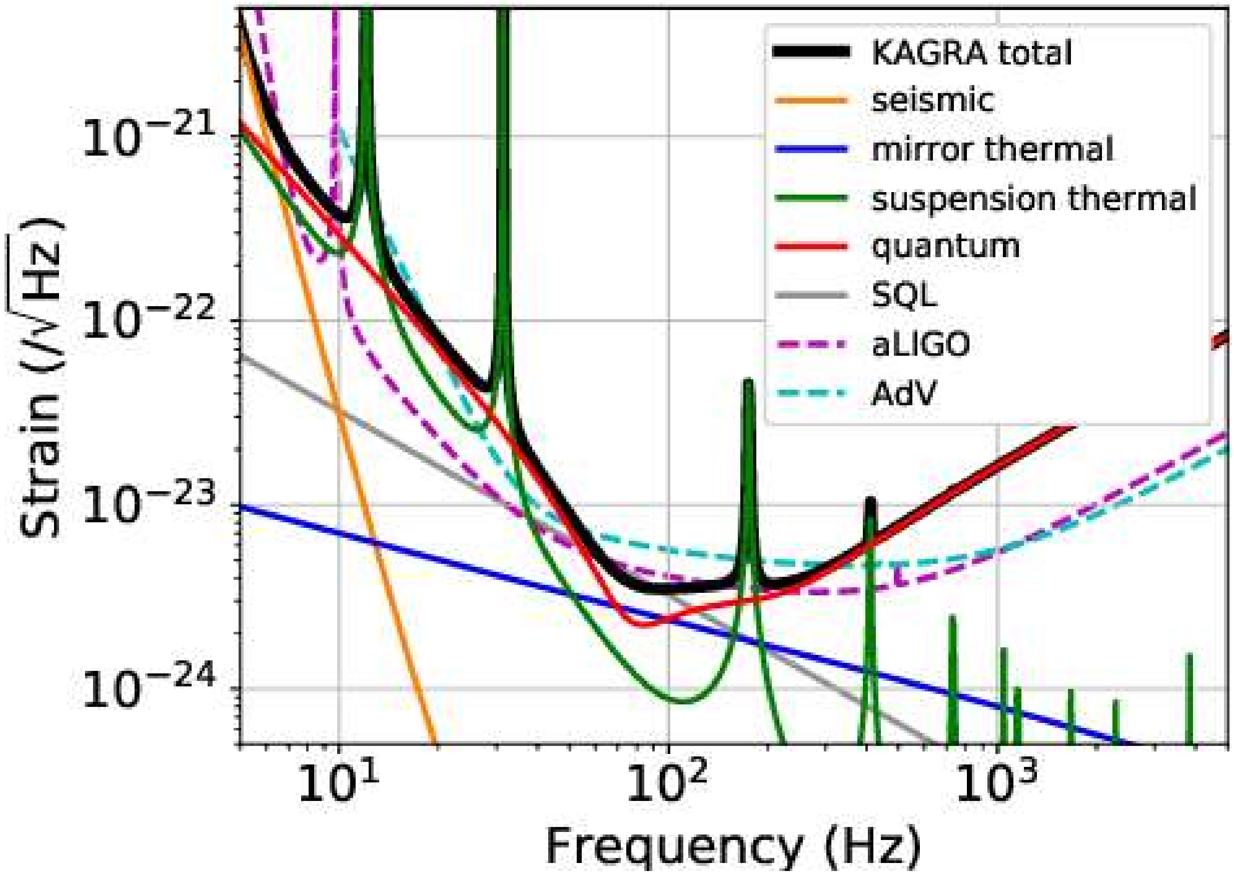
Suspension



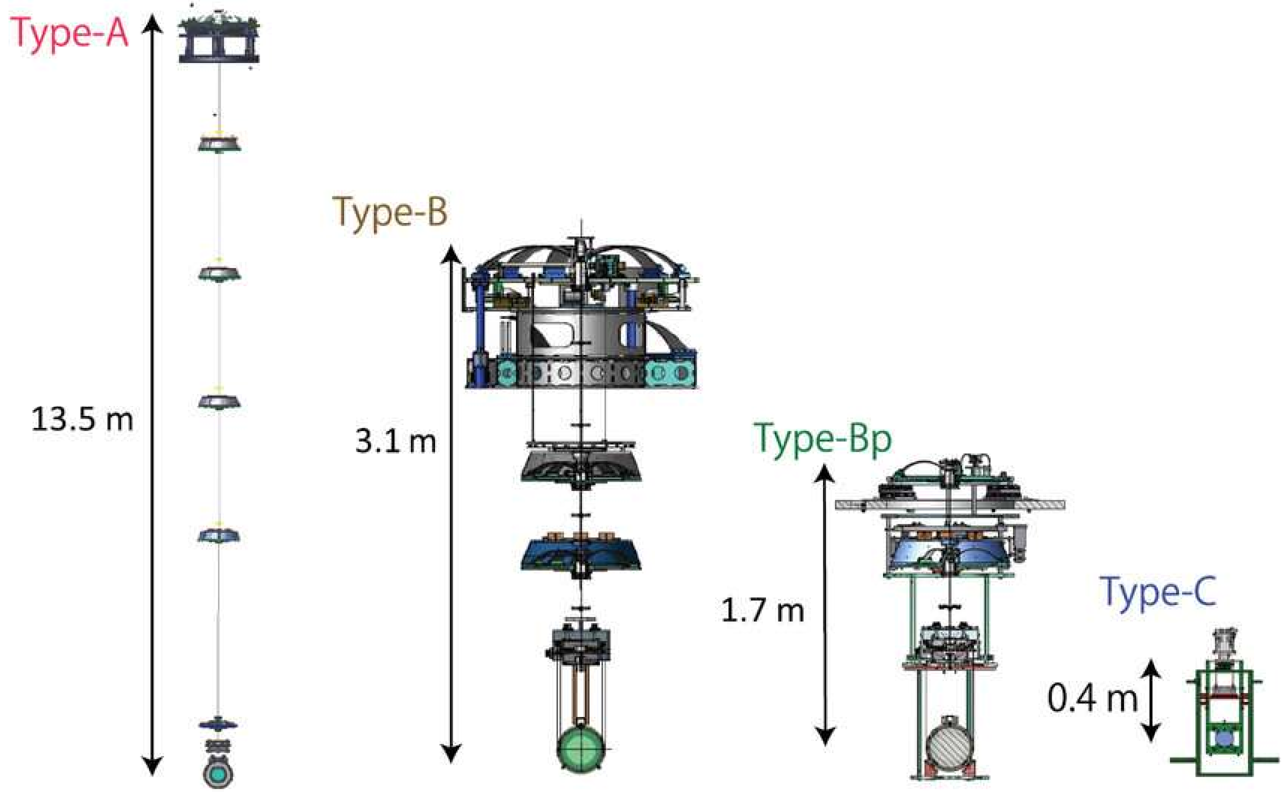


$$T \approx 2\pi\sqrt{\frac{L}{g}}$$

Sensitivity curve of KAGRA

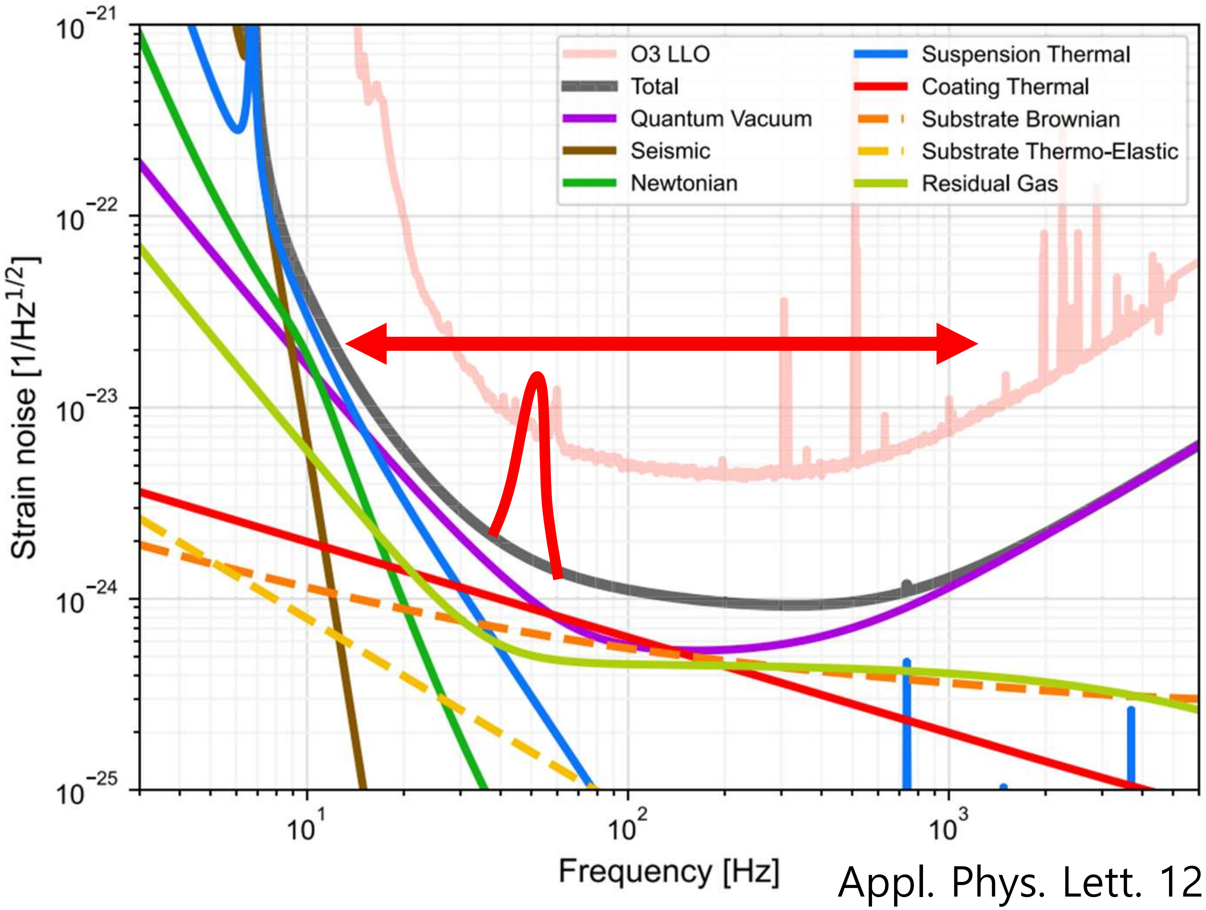


Vibration Isolation



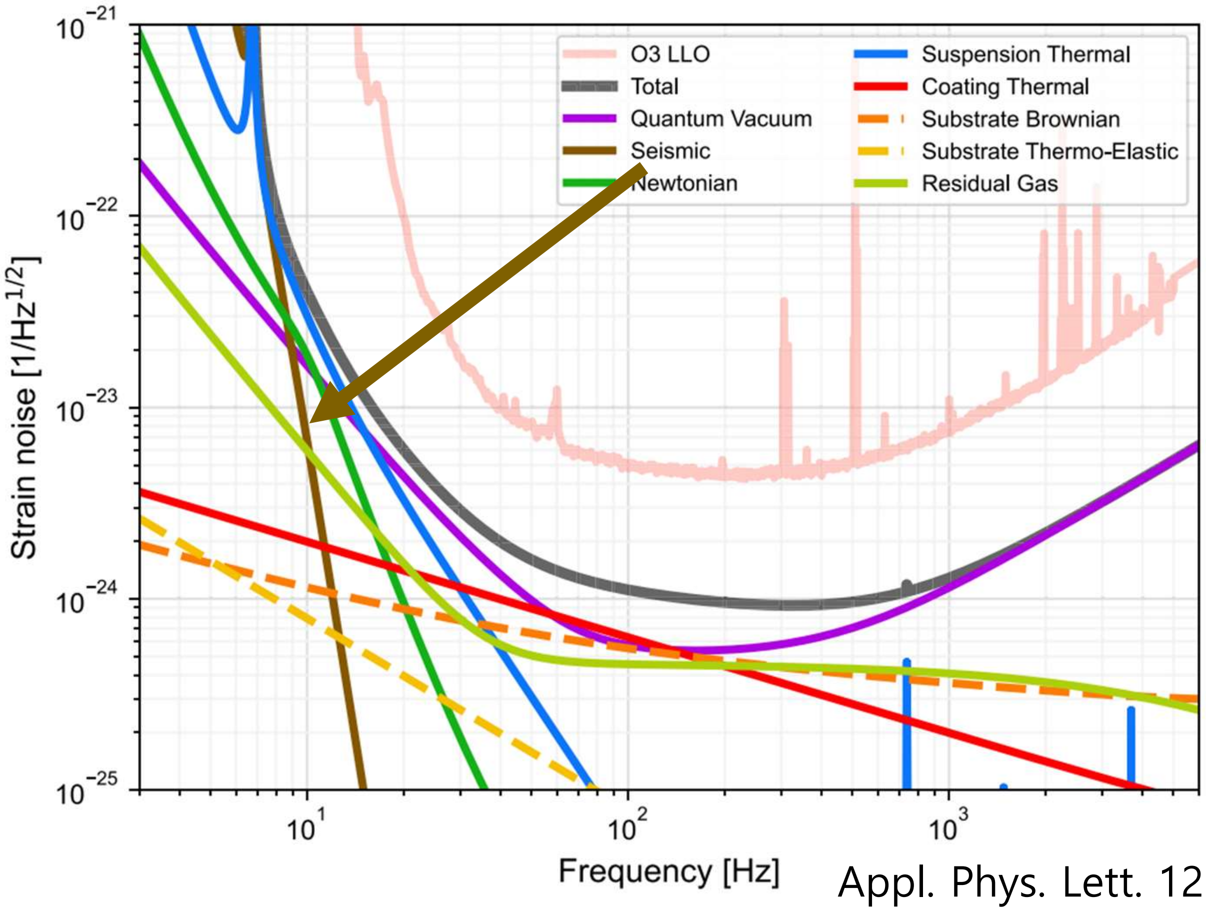
Vibration isolation system with a compact damping system for power recycling mirrors of KAGRA
T.Akuts et al.,

LIGO Sensitivity



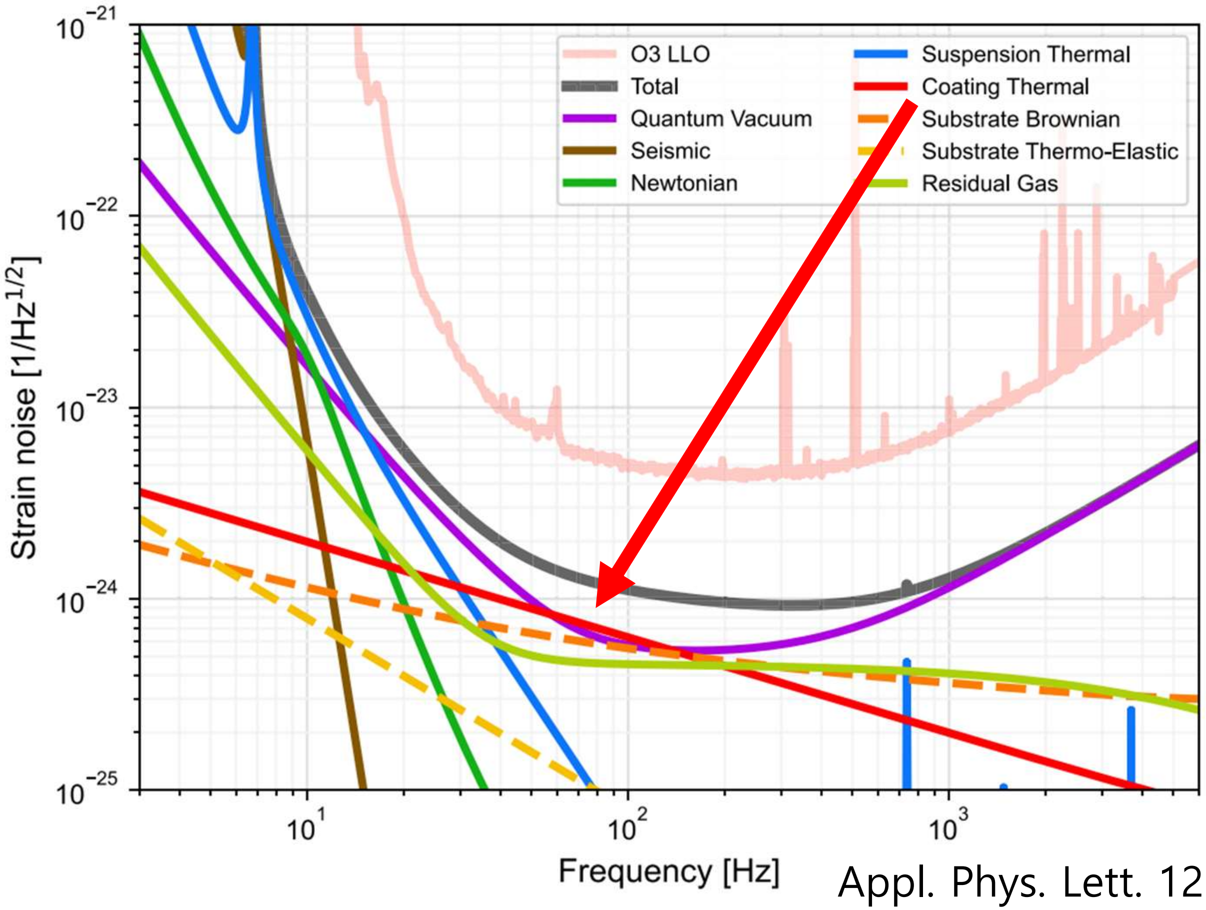
Appl. Phys. Lett. 122, 110502 (2023)

LIGO Sensitivity



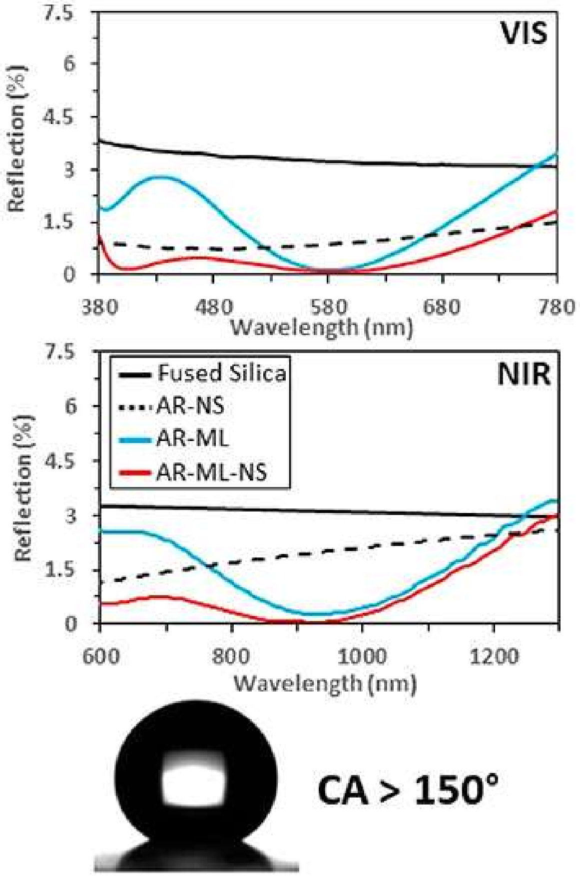
Appl. Phys. Lett. 122, 110502 (2023)

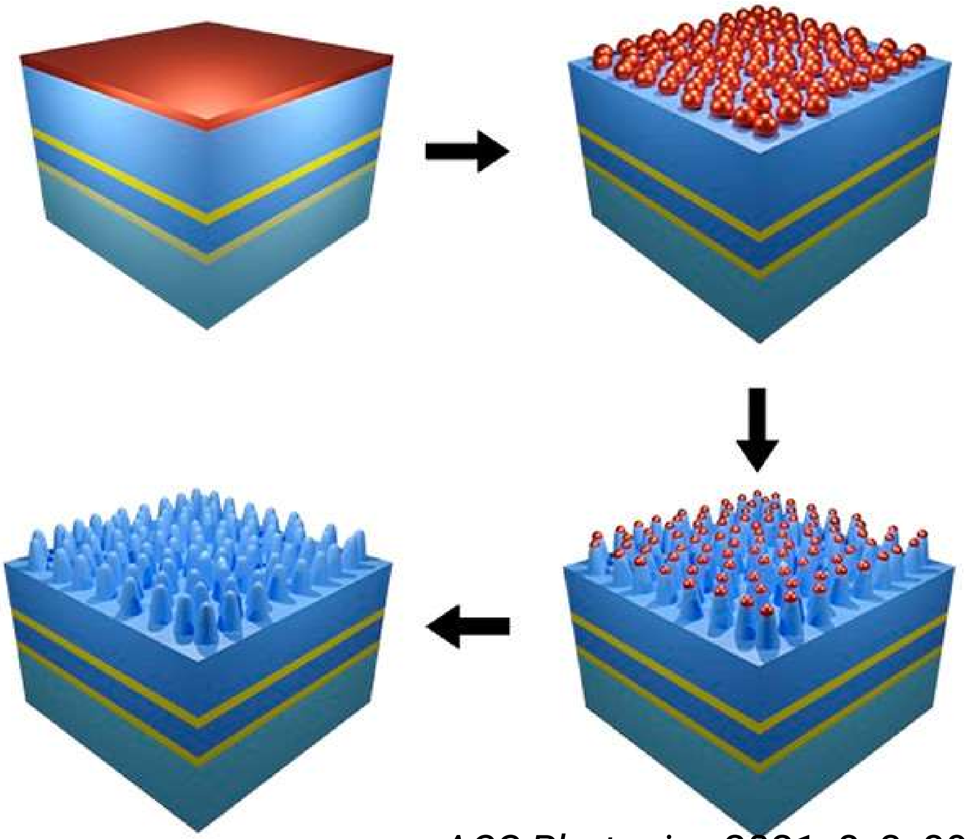
LIGO Sensitivity



Appl. Phys. Lett. 122, 110502 (2023)

Optical Coating





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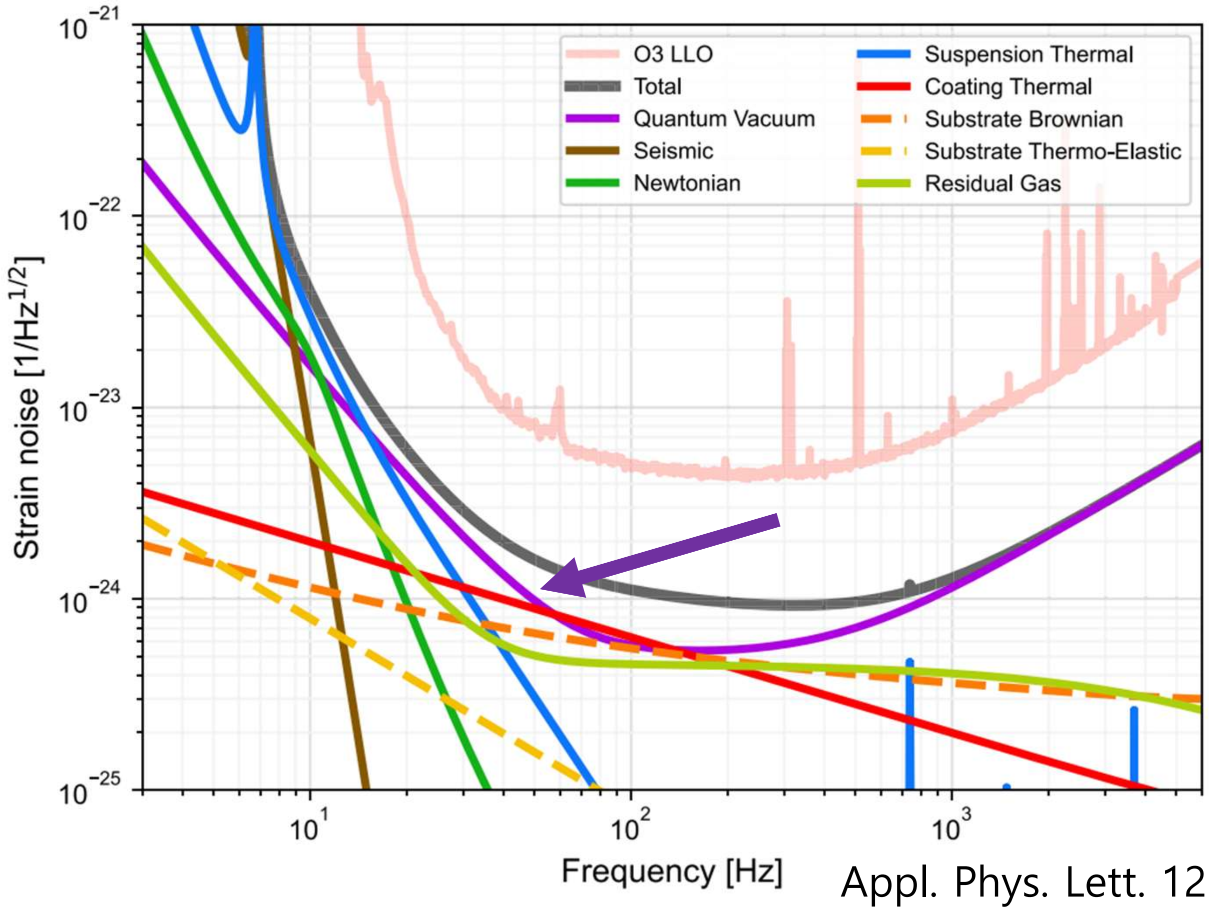
https://doi.org/10.1021/acsphotonics.0c01909

LIGO Sensitivity



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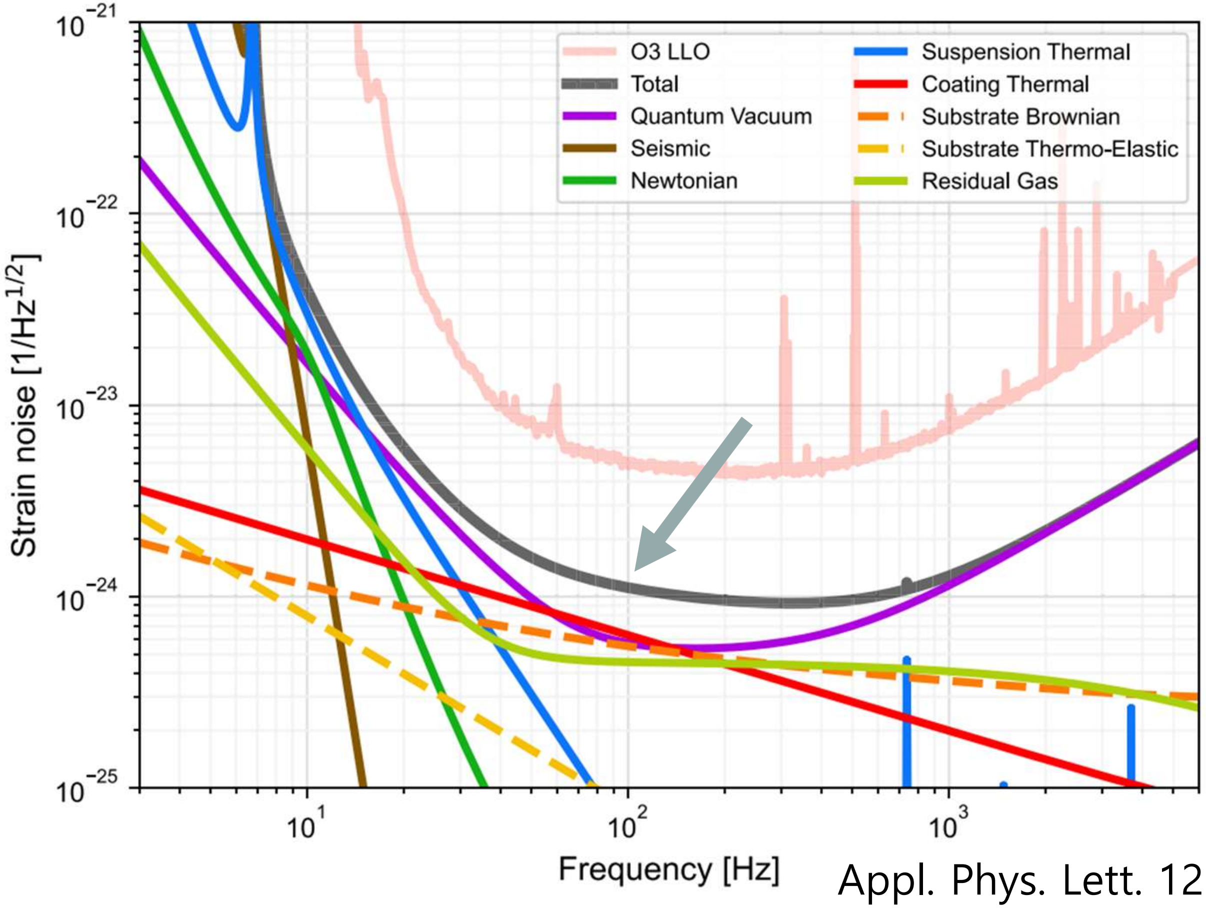
LIGO Sensitivity



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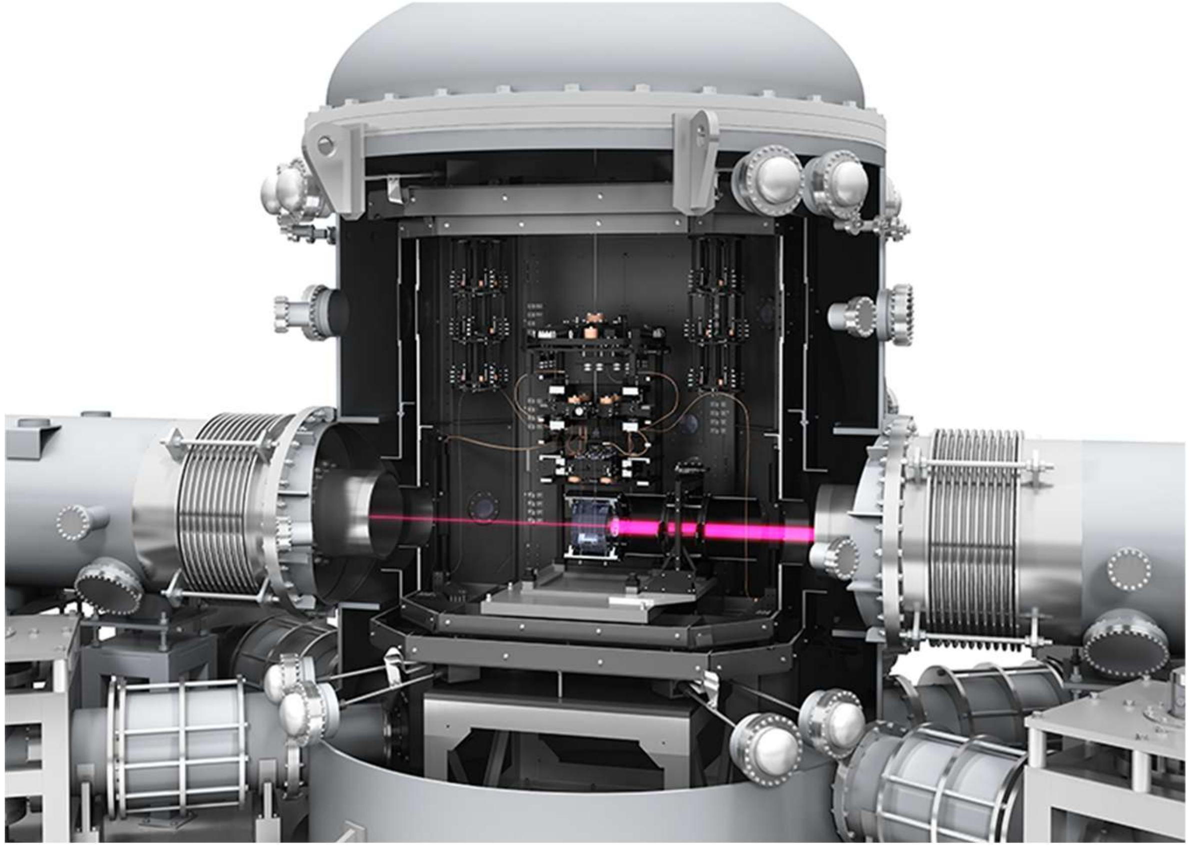
Vacuum Tunnel

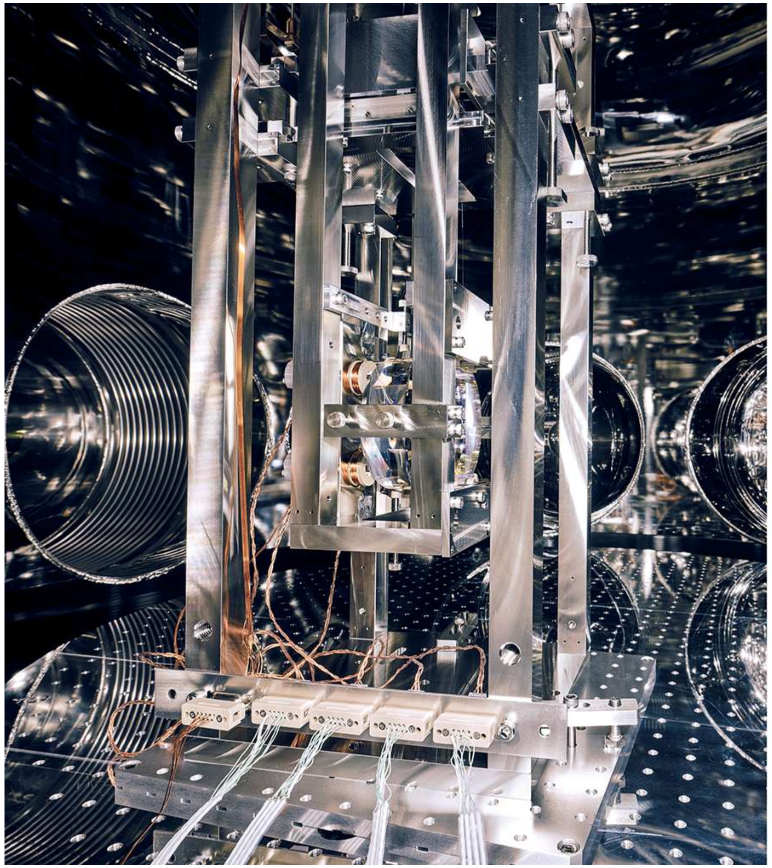
Air turbulence, scattering from air

Test Mass Vacuum Chamber



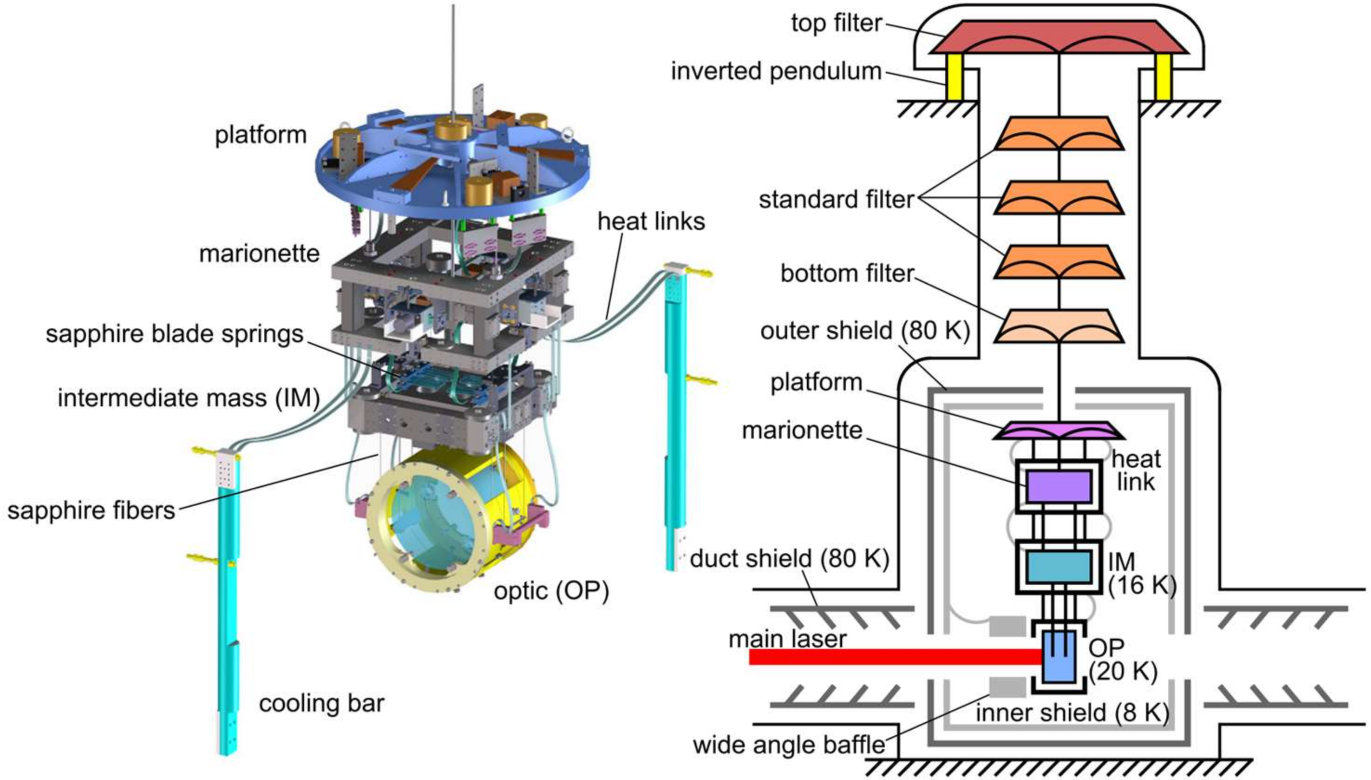
Rey.Hori

KAGRA Vacuum Chamber



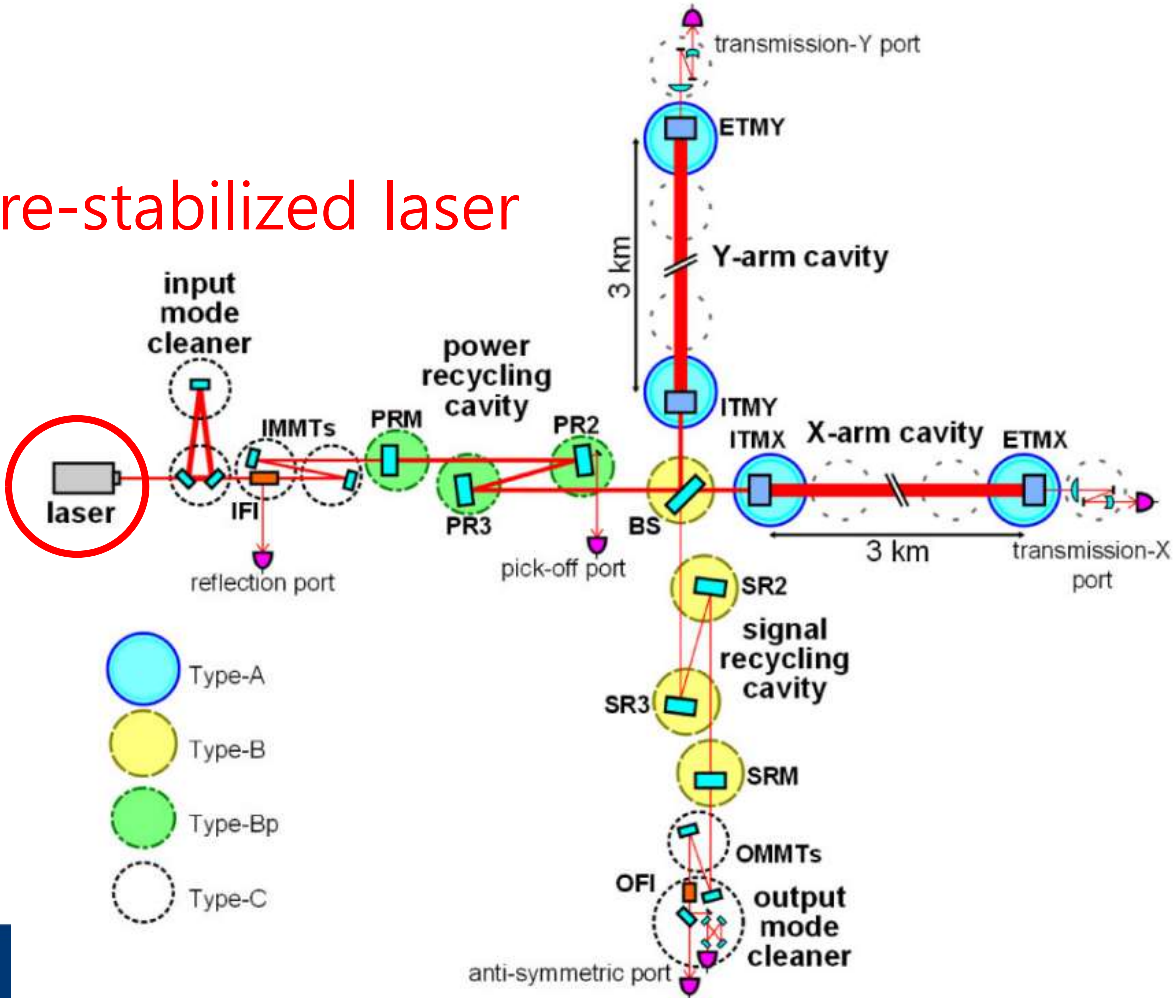
Cryocooler of KAGRA

KAGRA Cryostat



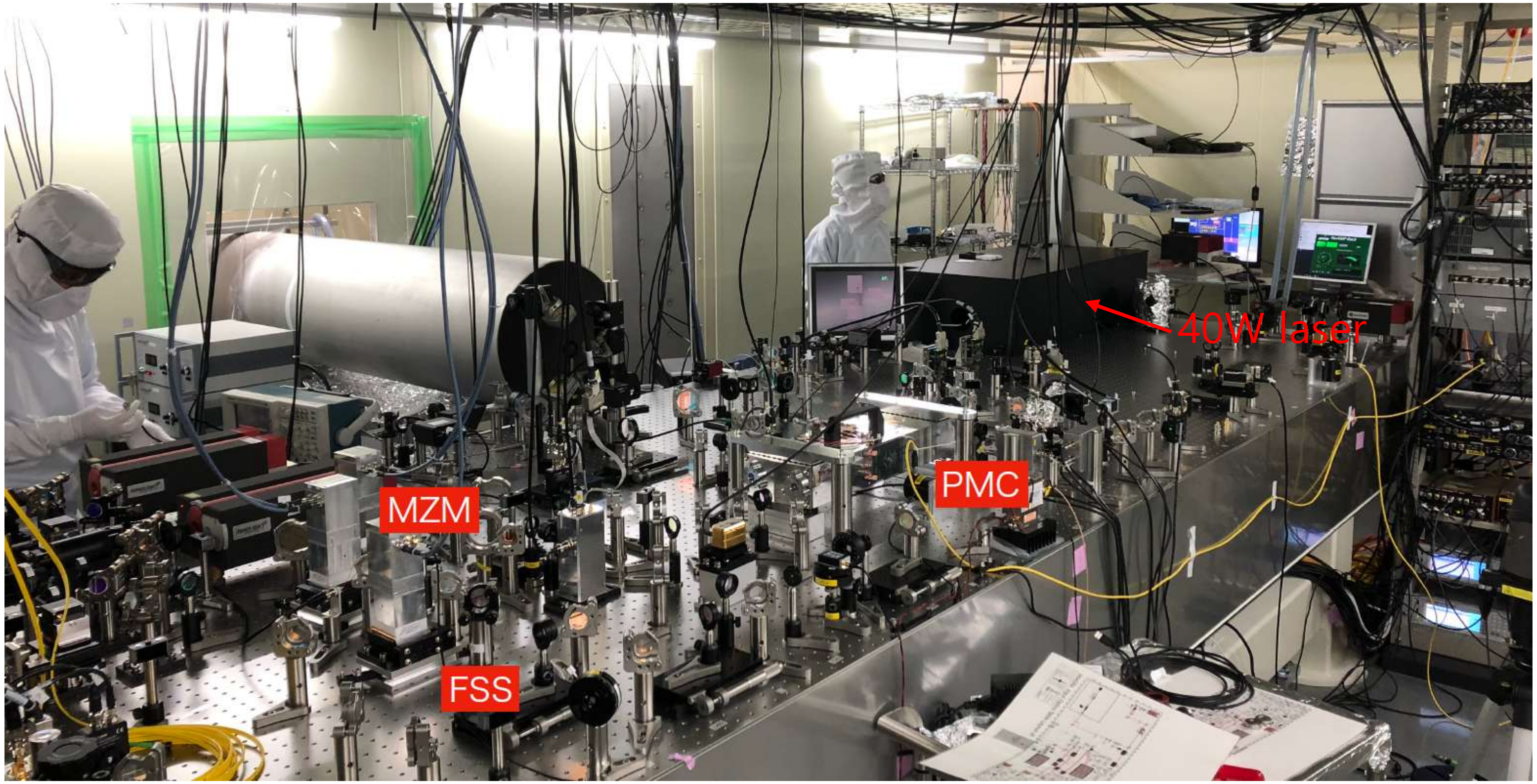
KAGRA Interferometer

Pre-stabilized laser



IOO : Input output optics
MIF : Main interferometer
MIR : Mirror
MMT : Mode matching telescope
OMC : Output mode cleaner

PSL Room of KAGRA



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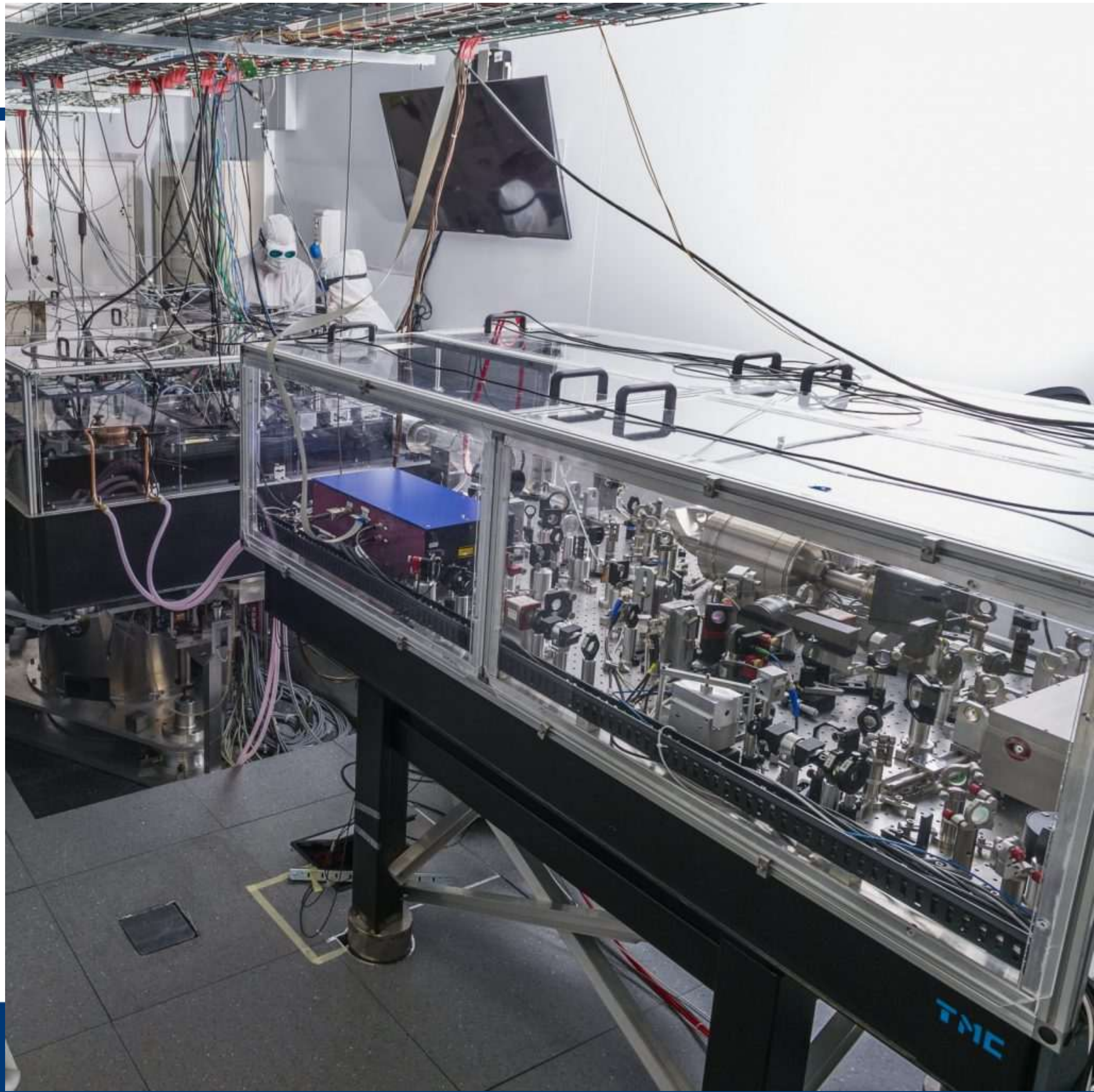
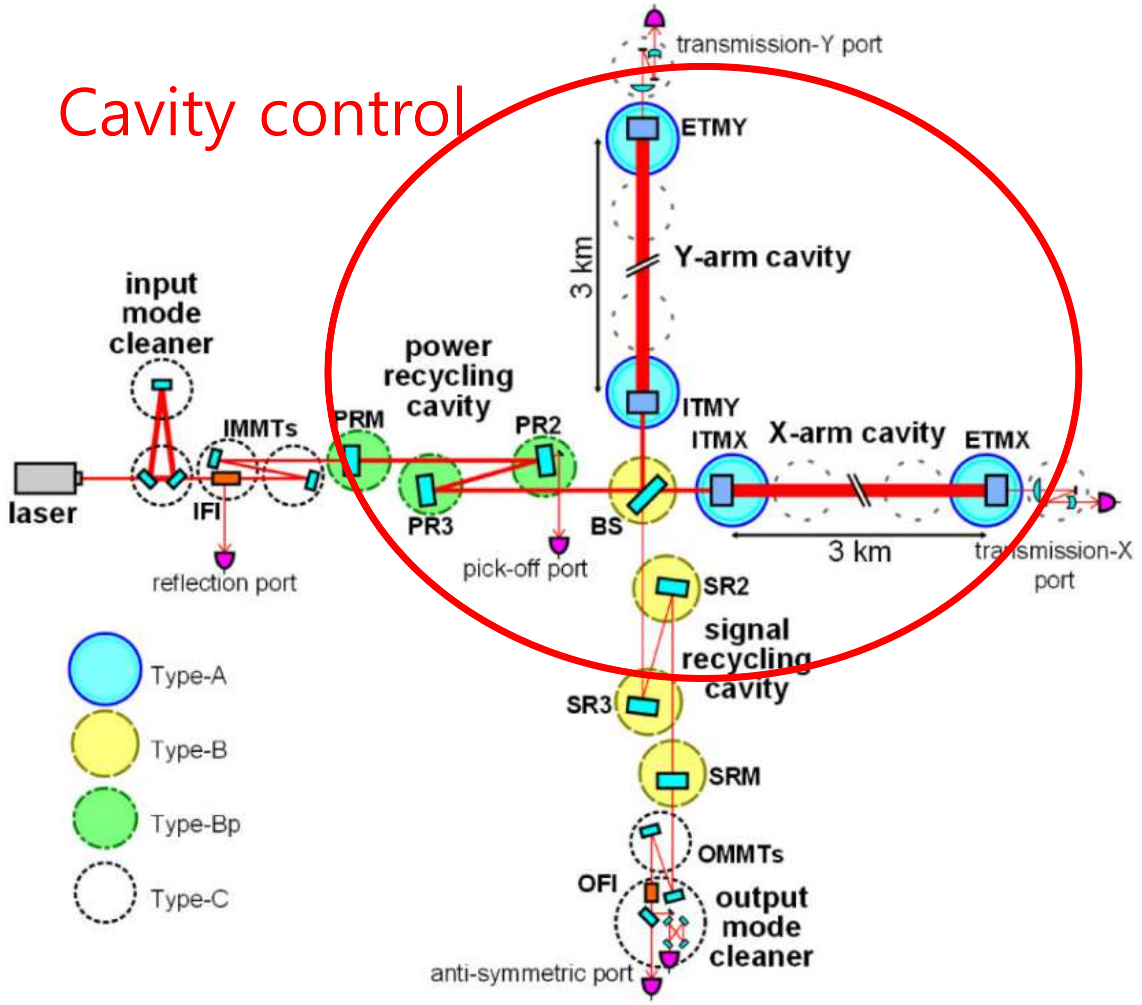

TMC

KAGRA Interferometer



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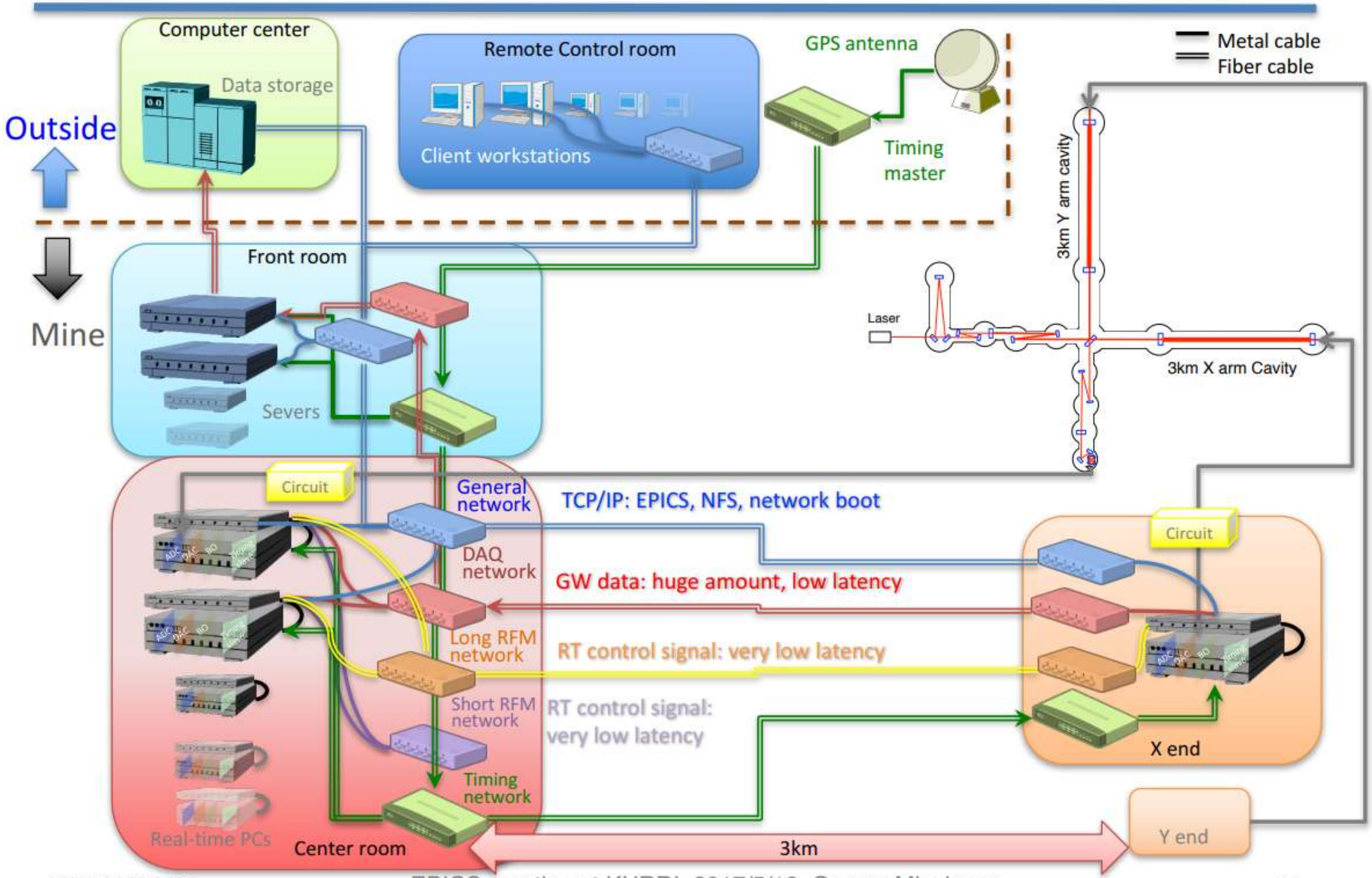
KAGRA control network design



Sensors in KAGRA