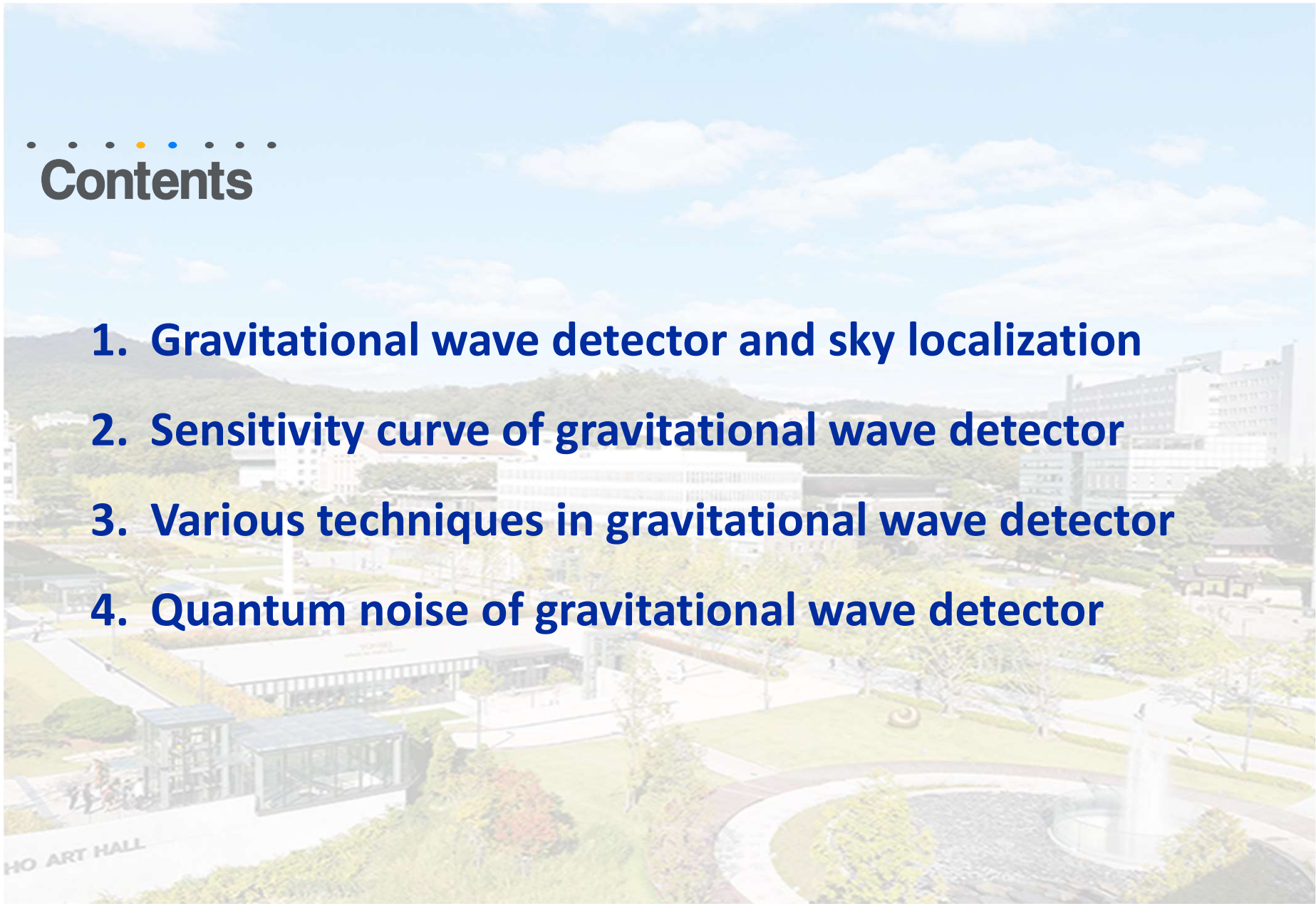
Ground Base Laser Interferometer Gravitational Wave Detector

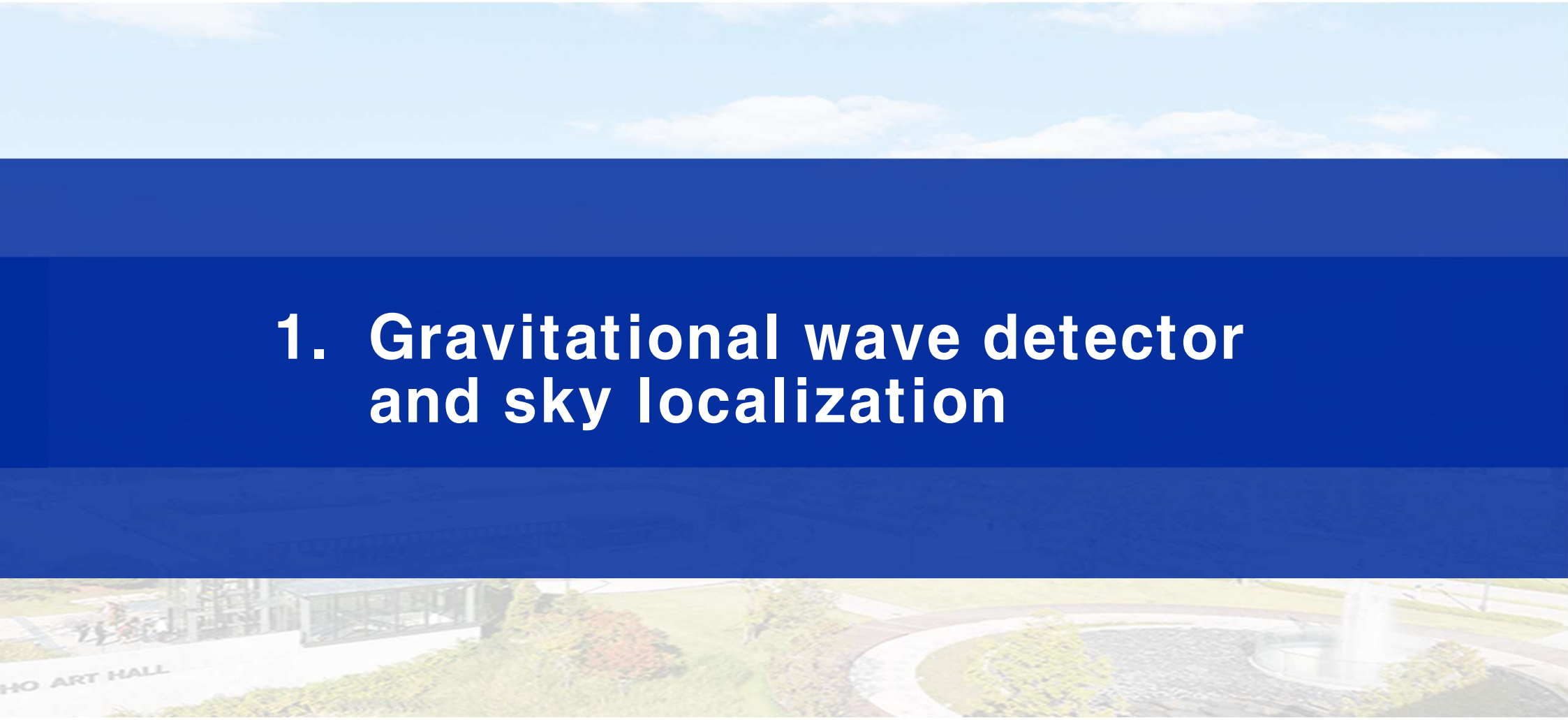
Department of Astronomy
June Gyu Park

연세대학교
YONSEI UNIVERSITY



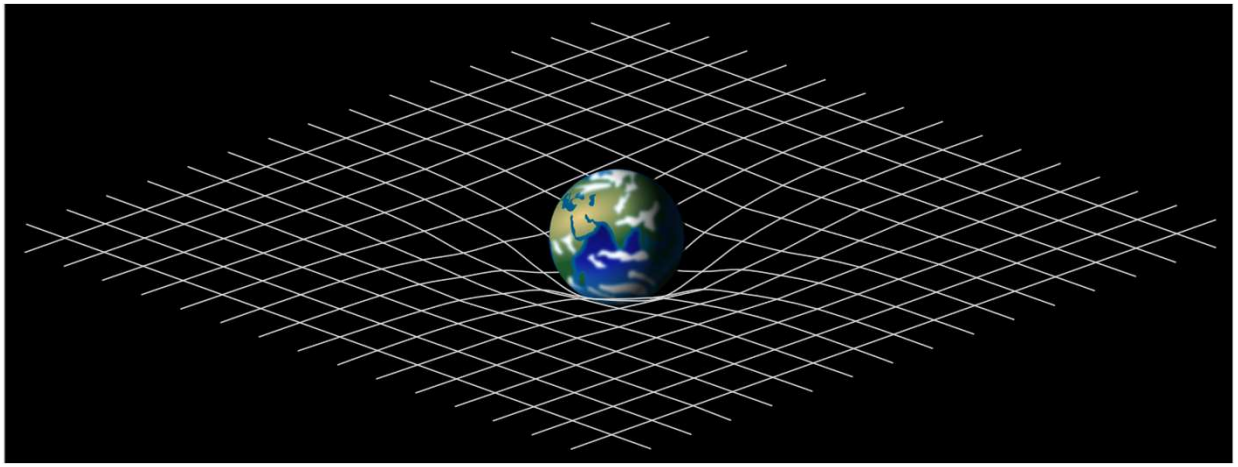
Contents

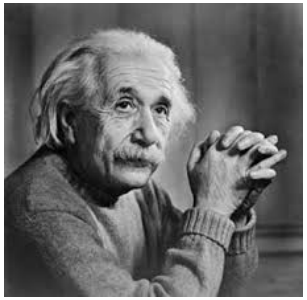
1. Gravitational wave detector and sky localization
2. Sensitivity curve of gravitational wave detector
3. Various techniques in gravitational wave detector
4. Quantum noise of gravitational wave detector



1. Gravitational wave detector and sky localization

Gravity and general relativity





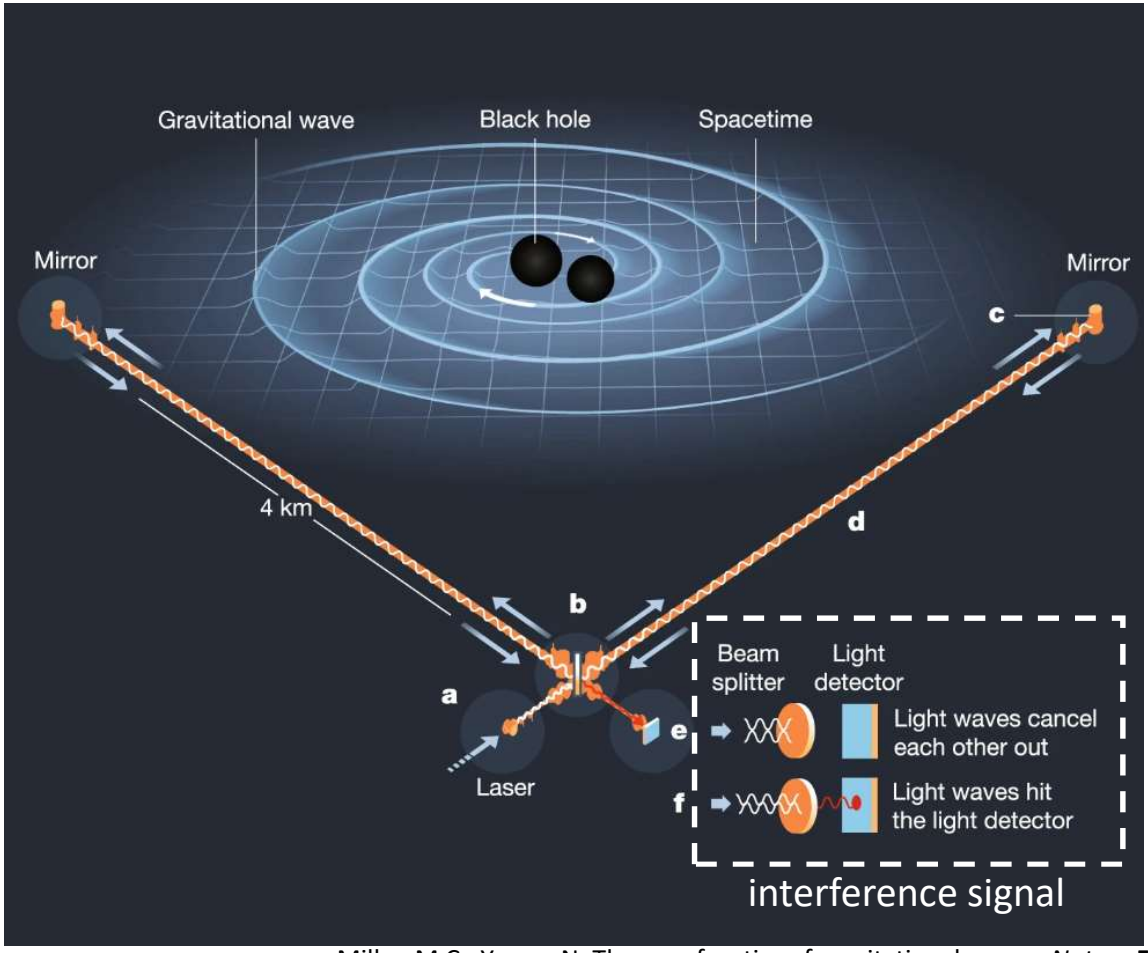
$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \kappa T_{\mu\nu}$$

Local space time curvature

Local energy, momentum stress

Mass of object

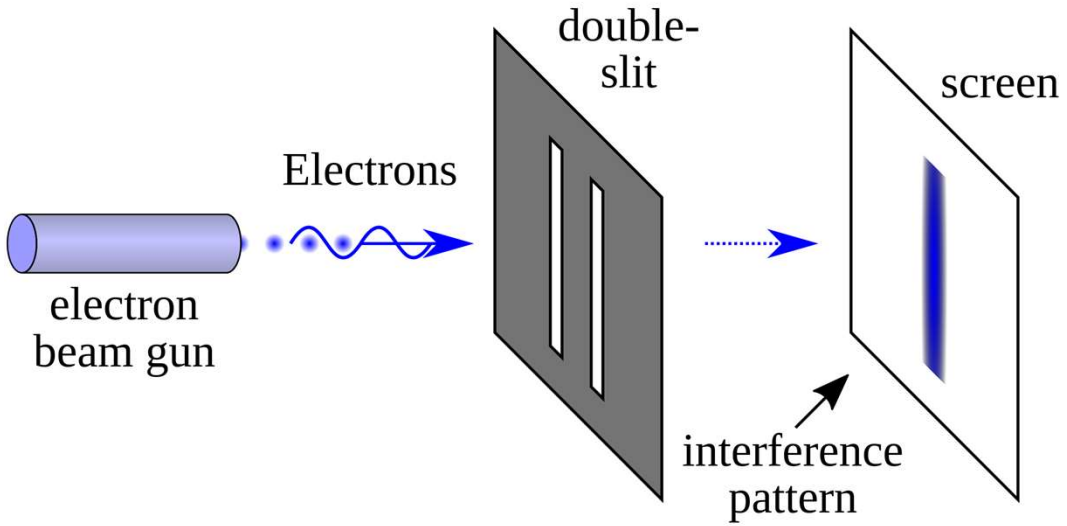
Gravitational wave detector

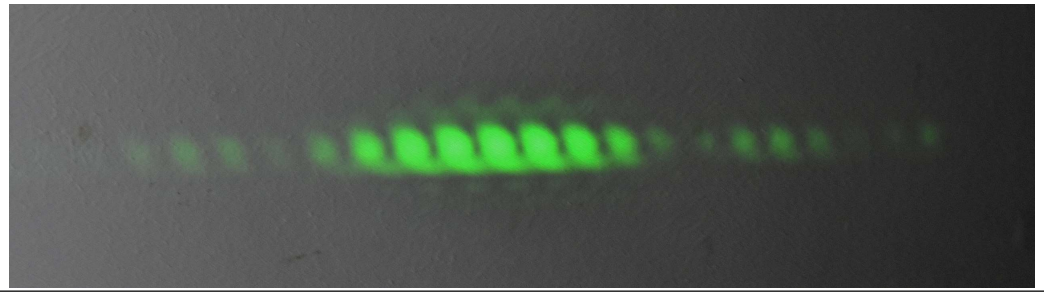


- Ground scale Michelson interferometer
- 4 km vacuum tunnel arm
- Over 1000 km interaction length

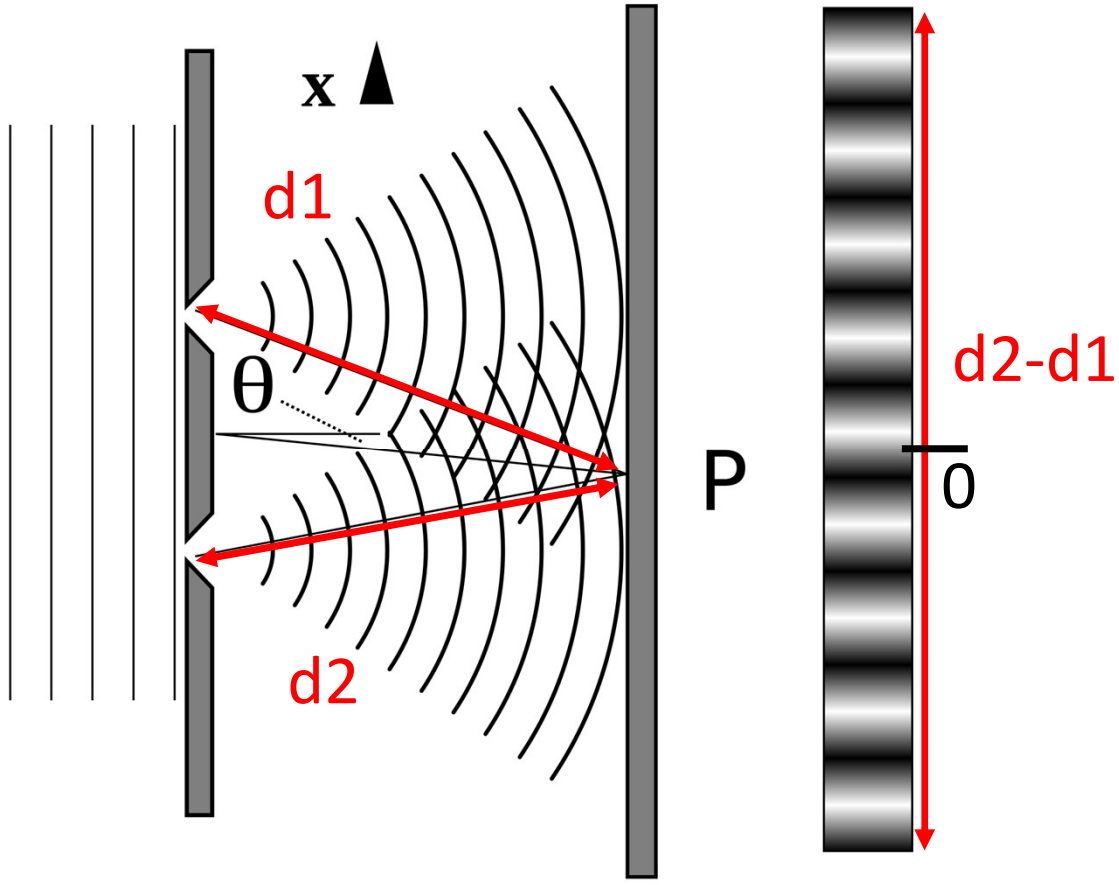
Miller, M.C., Yunes, N. The new frontier of gravitational waves. *Nature* **568,** 469–476 (2019)

Double slit experiment

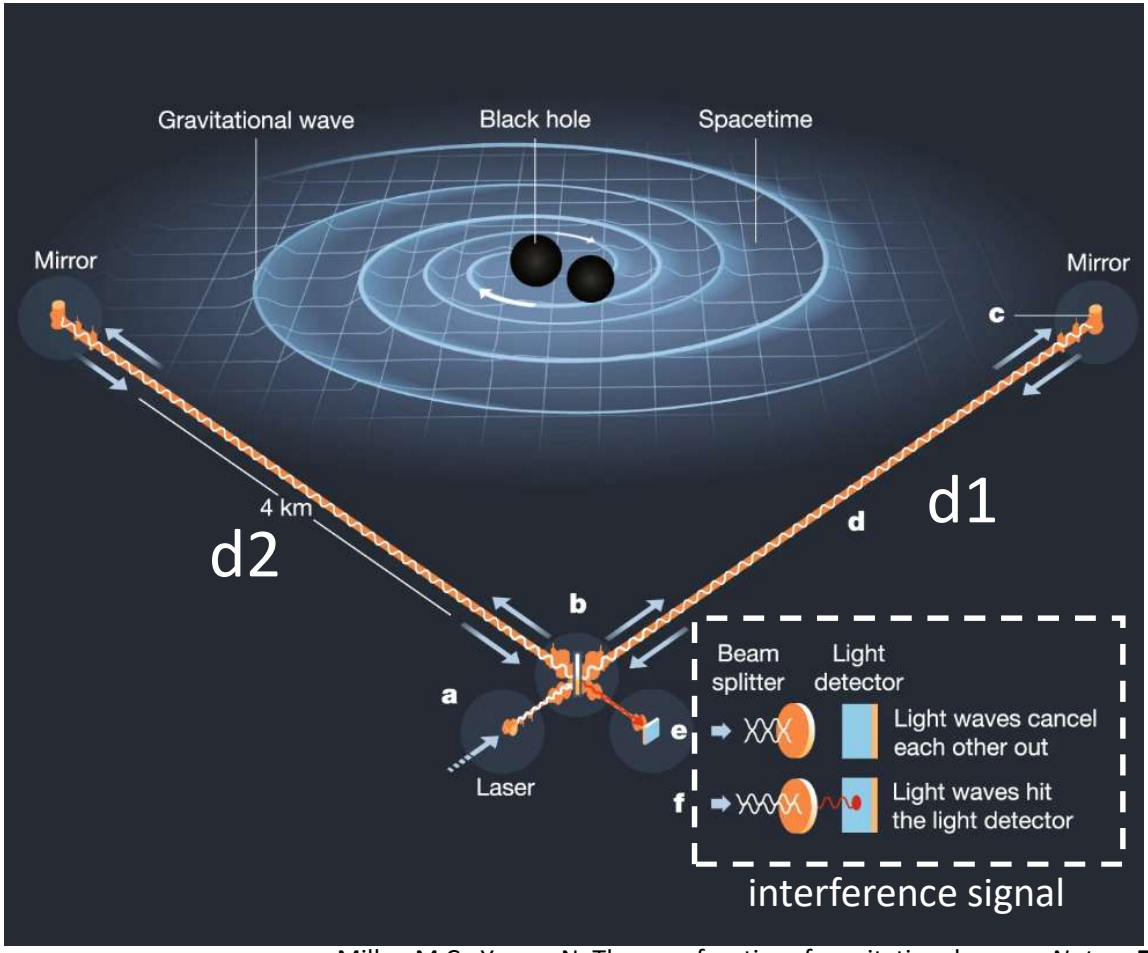




Interference



Gravitational wave detector



- Ground scale Michelson interferometer
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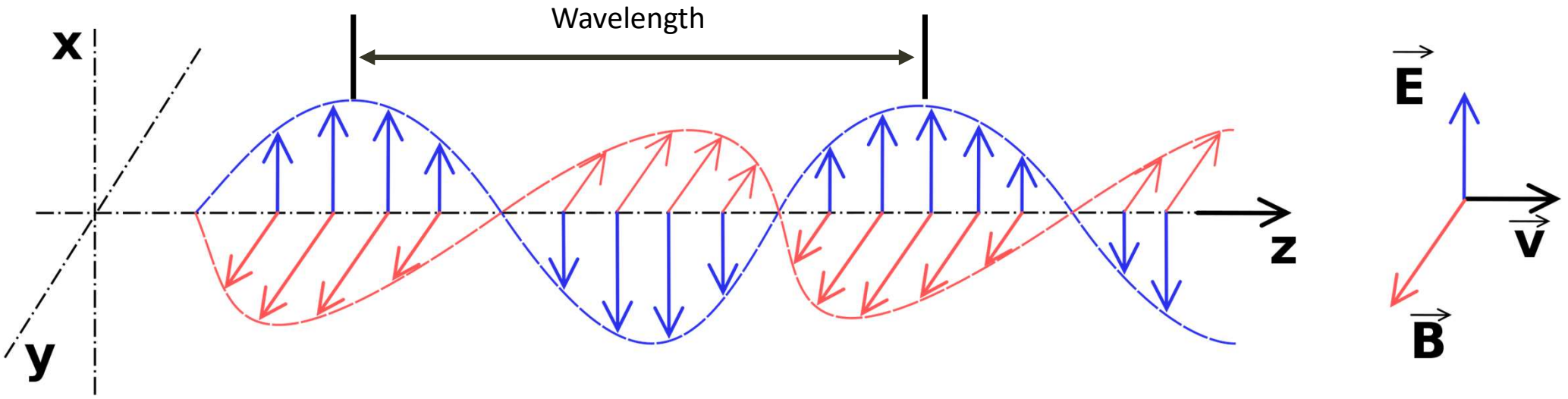
- Over 1000 km interaction length

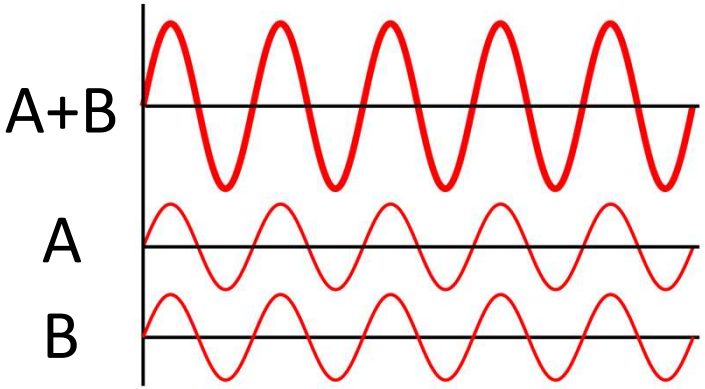
Miller, M.C., Yunes, N. The new frontier of gravitational waves. *Nature* **568,** 469–476 (2019)

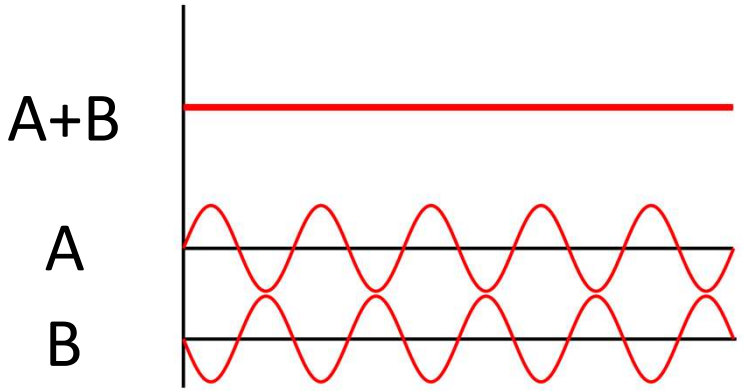
Light(Electromagnetic wave)

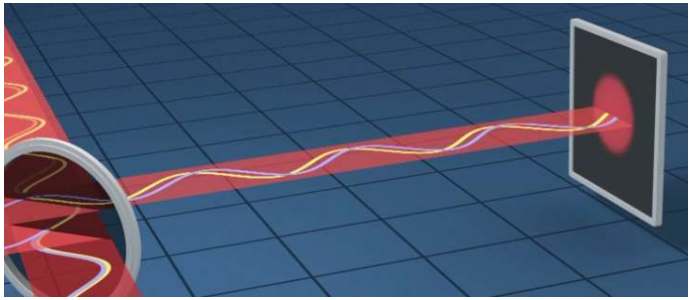


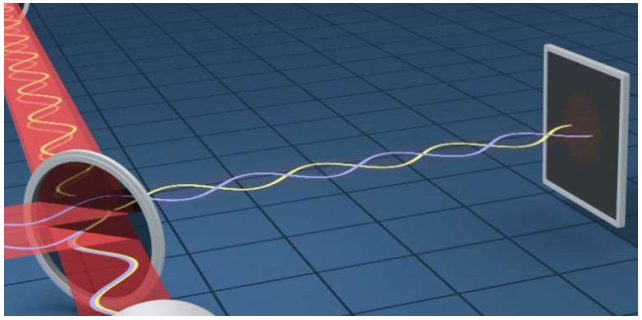
$$\left|\vec{E}\right| \propto Intensity\ of\ Light$$

Interference





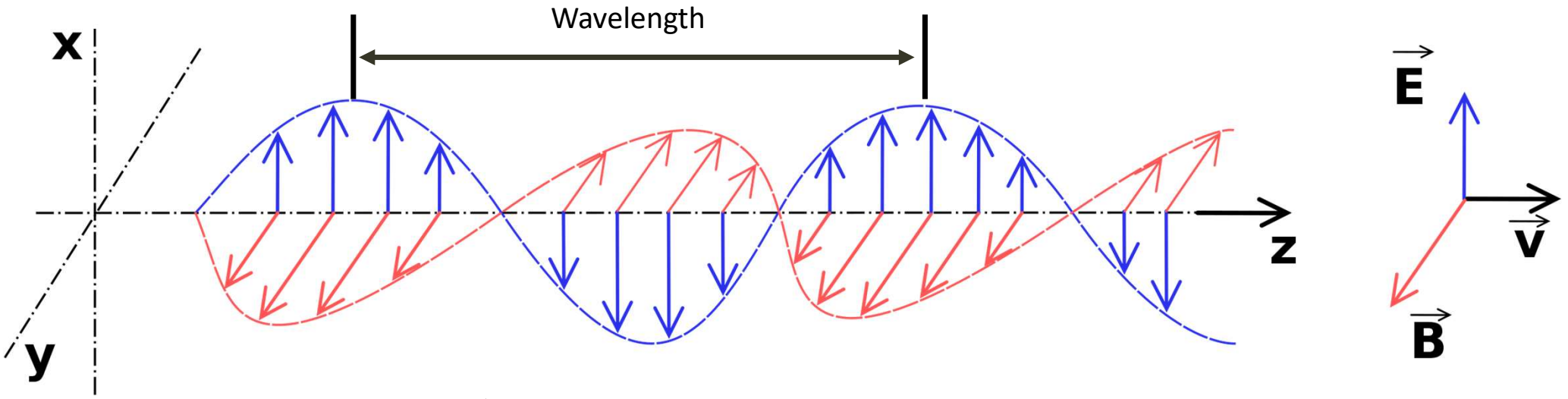




Constructive

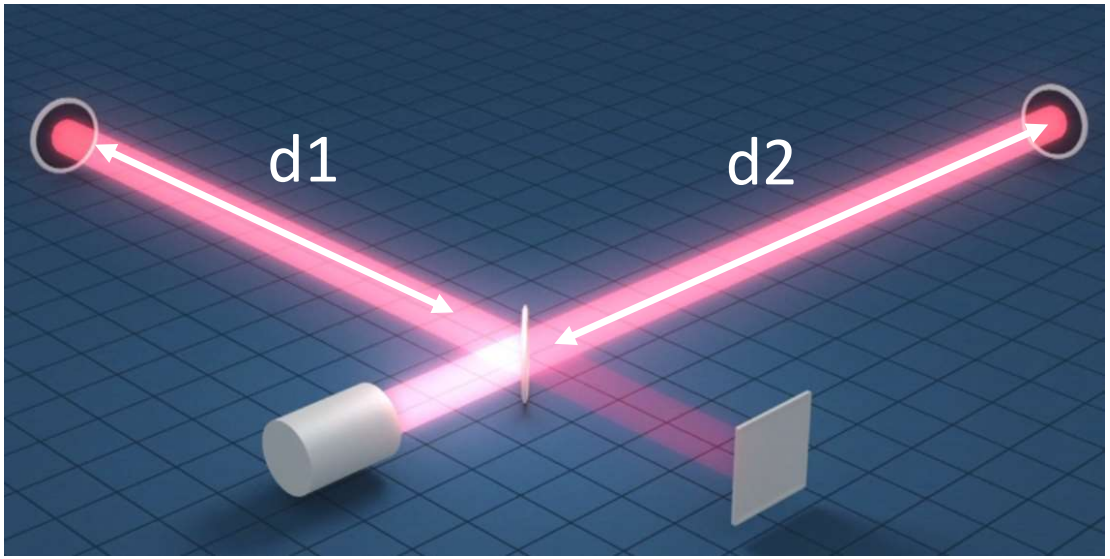
Destructive

Light(Electromagnetic wave)



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

Interference signal

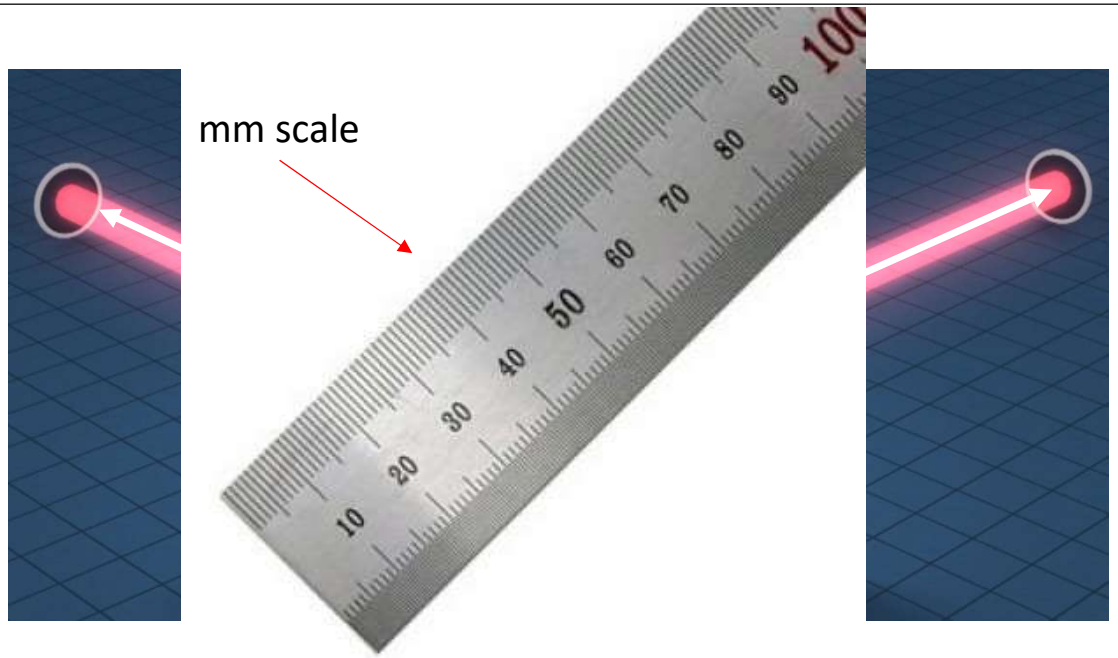


$$\vec{\mathrm{E}} = E_0 \cos(kx - \omega t + \varphi)$$

$\varphi \propto d1 - d2$ (in some condition)

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

Interference signal



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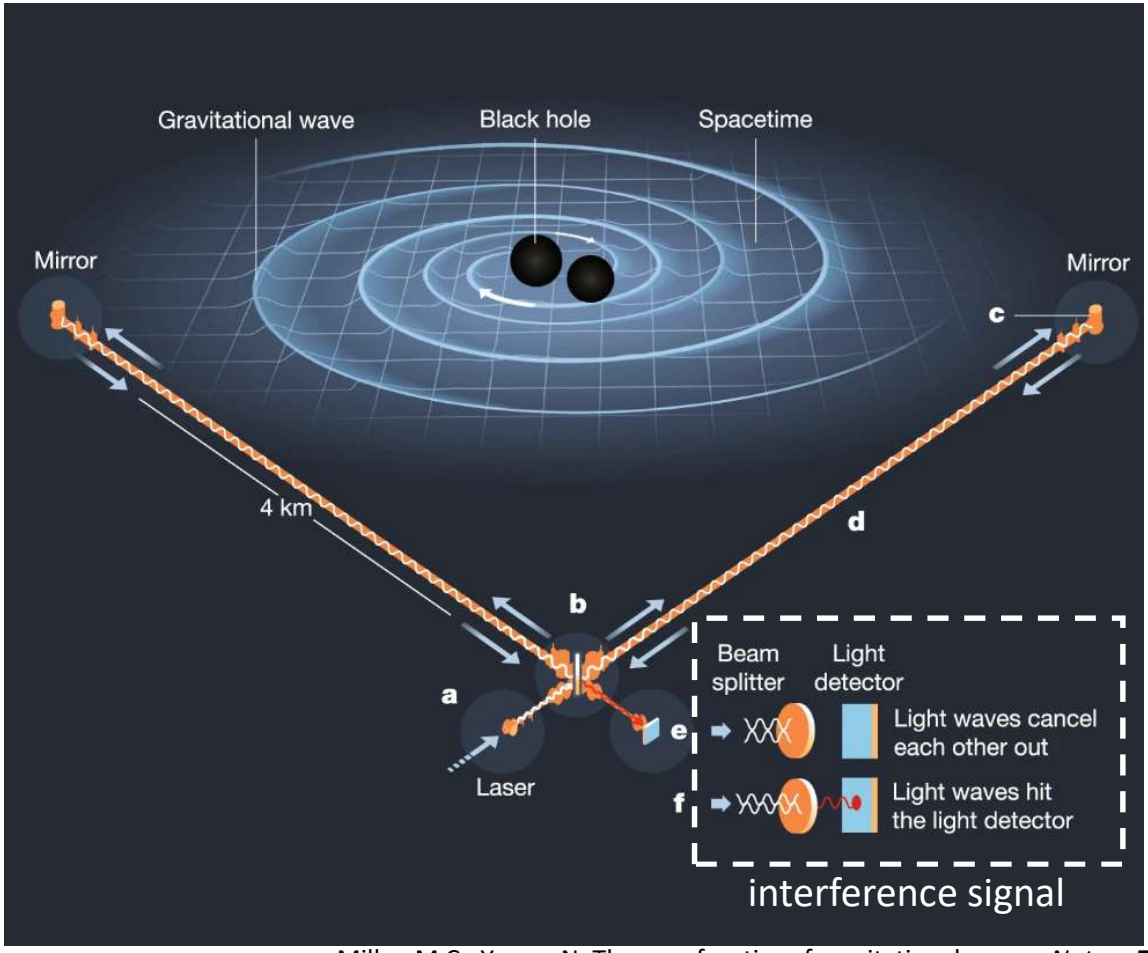
$\varphi \propto d1 - d2$ (in some condition)

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

Gravitational wave detector

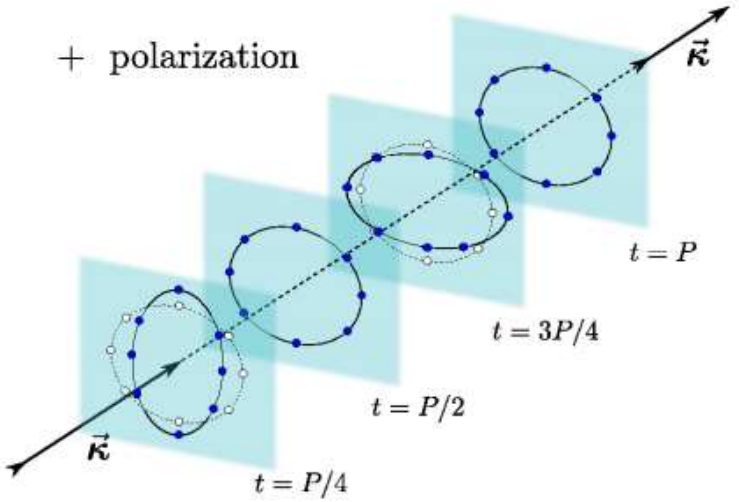


- Ground scale Michelson interferometer
- 4 km vacuum tunnel arm
- Over 1000 km interaction length

Build most sensitive system using most simple arrangement

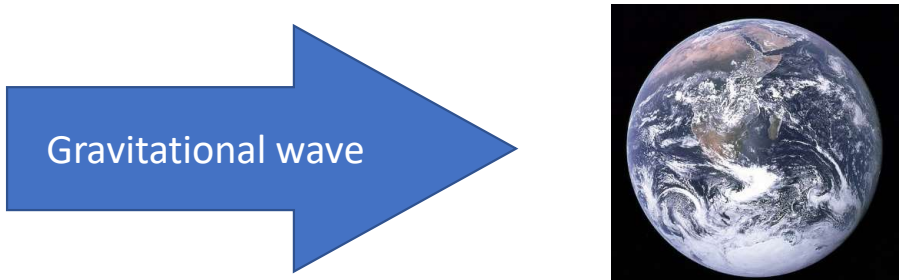
Miller, M.C., Yunes, N. The new frontier of gravitational waves. *Nature* **568,** 469–476 (2019)

Gravitational wave

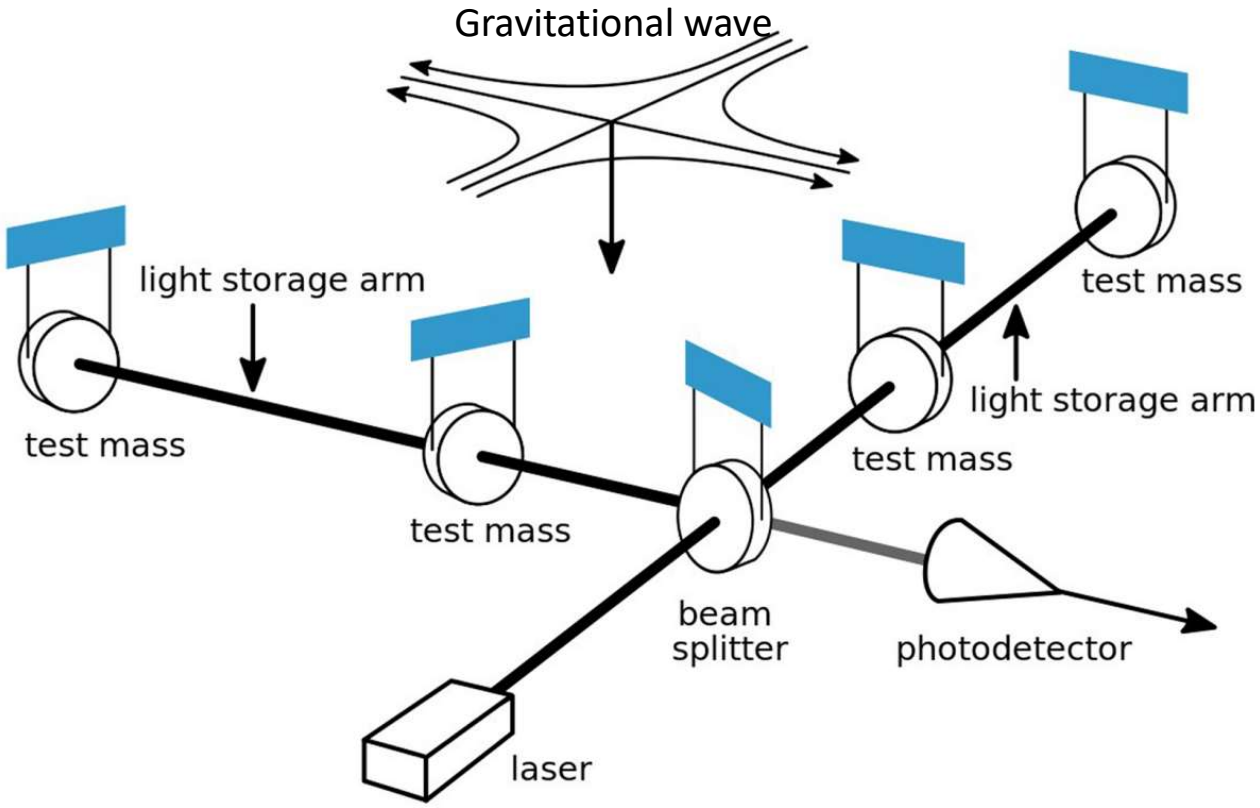


MPA Lectures on Gravitational Waves in Cosmology
Azadeh Maleknejad
Max-Planck-Institute for Astrophysics

Effect of gravitational wave

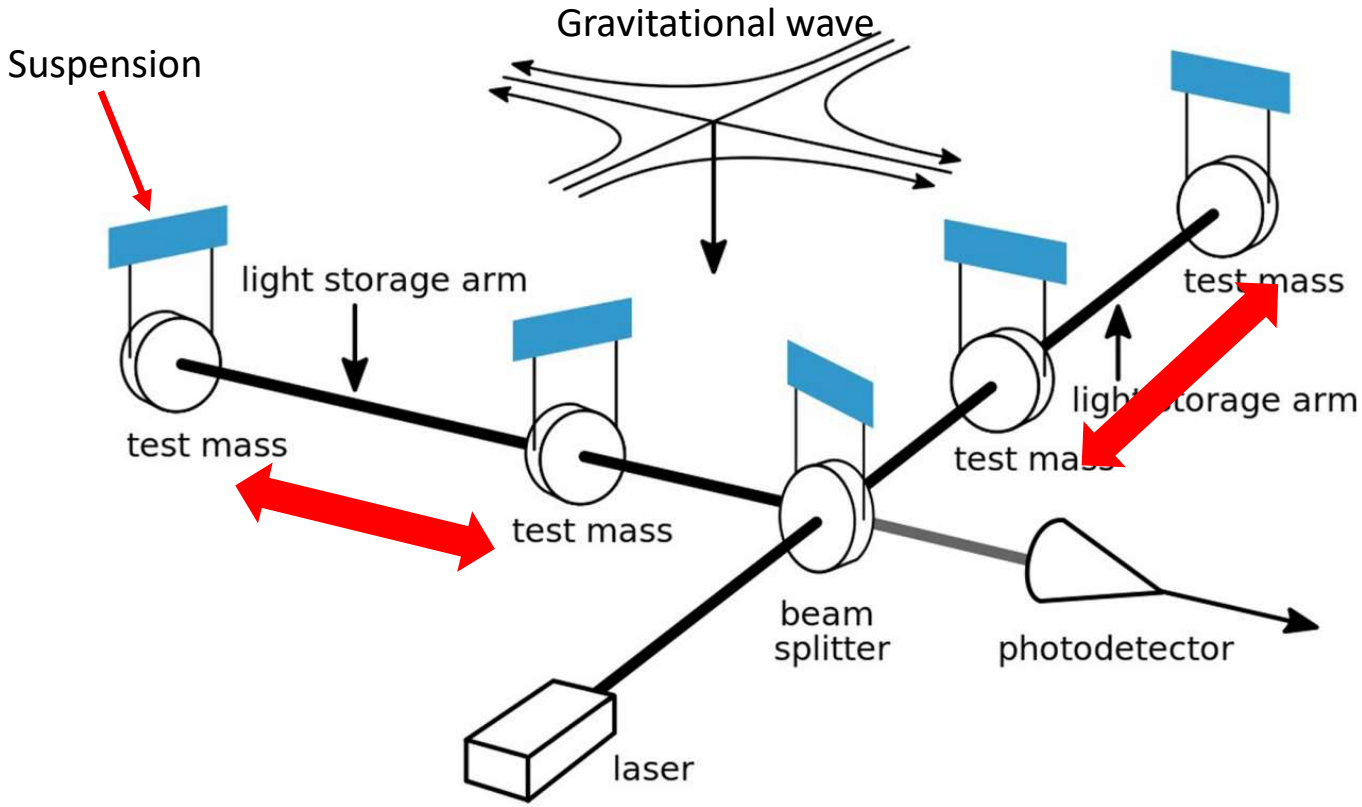


Gravitational wave and GW detector



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

Gravitational wave and GW detector



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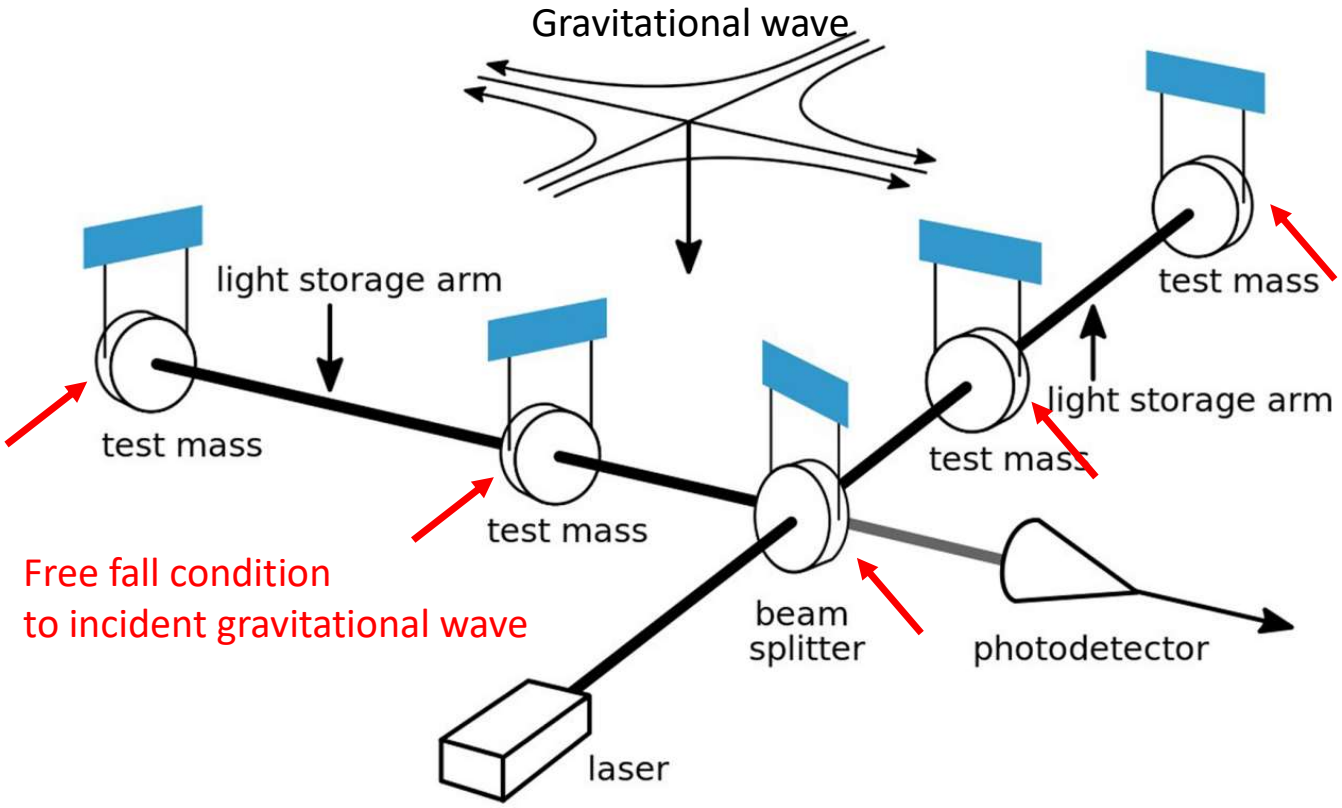
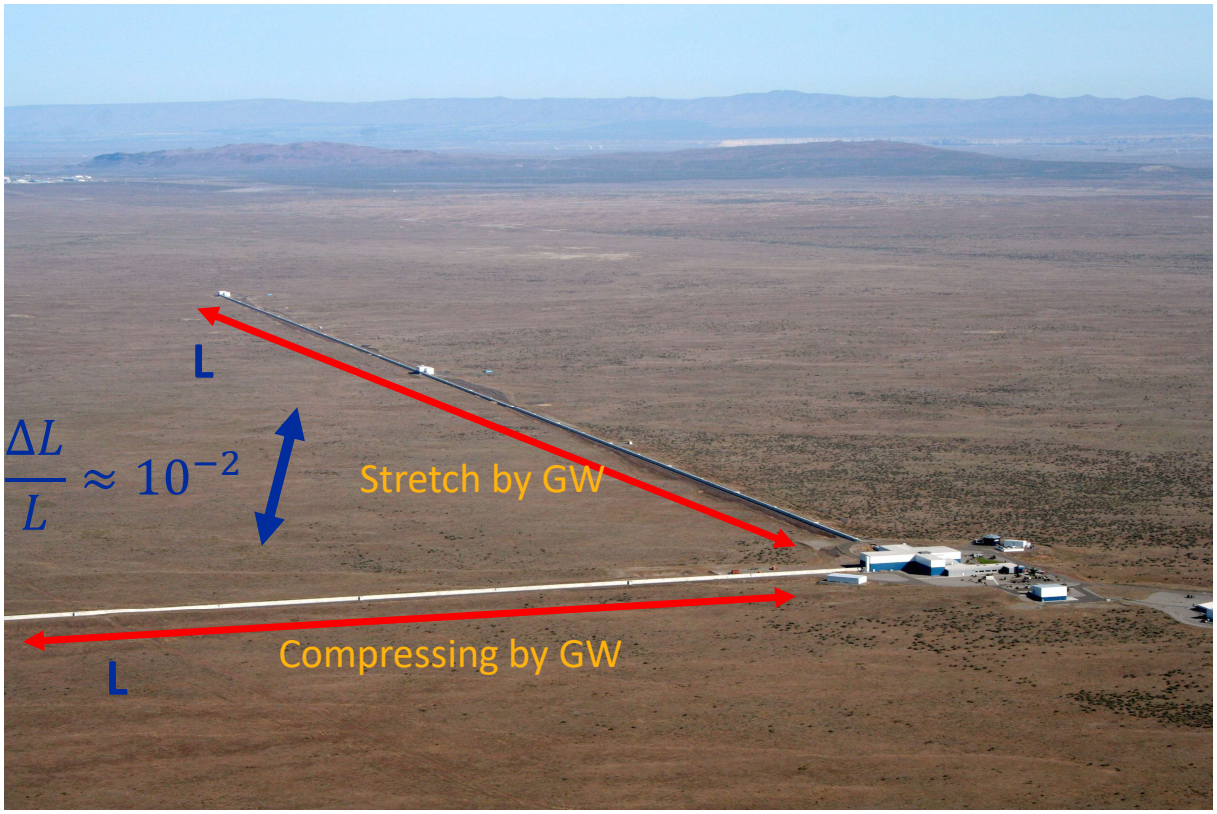
Gravitational wave and GW detector



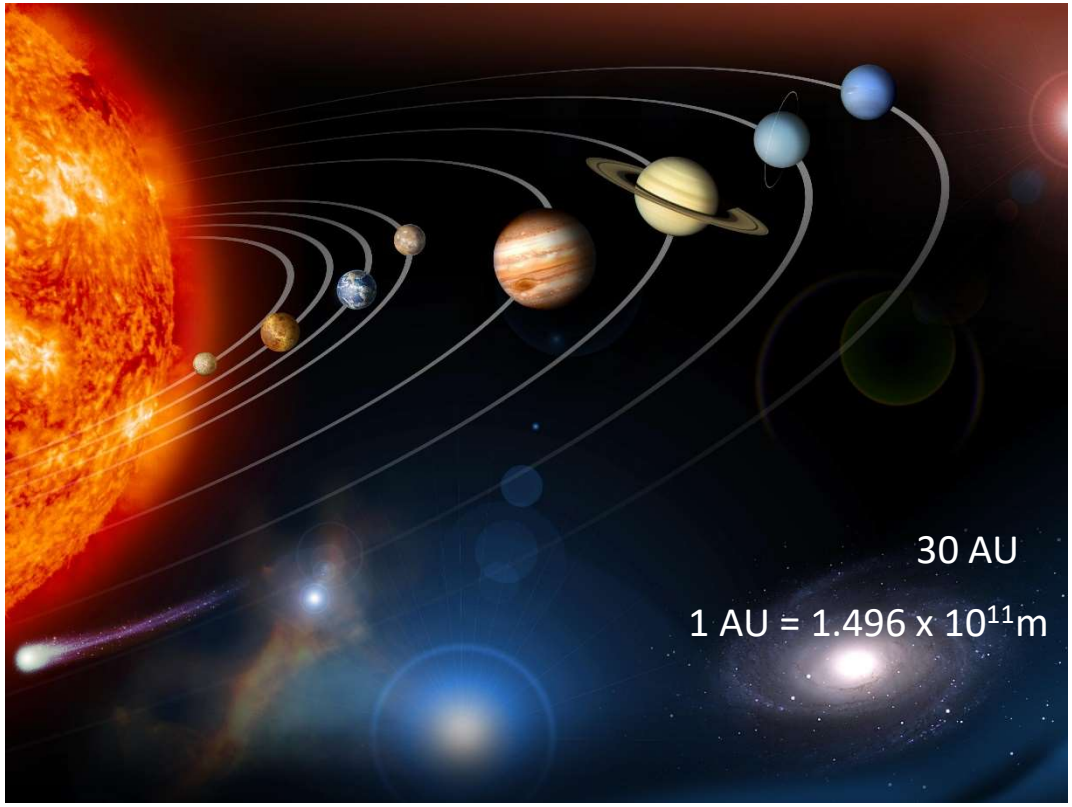
Strain sensitivity

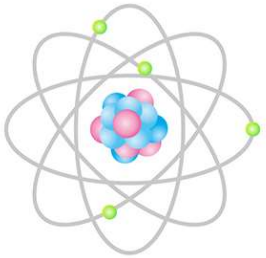


Minimum sensitivity

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

Strain due to gravitational wave



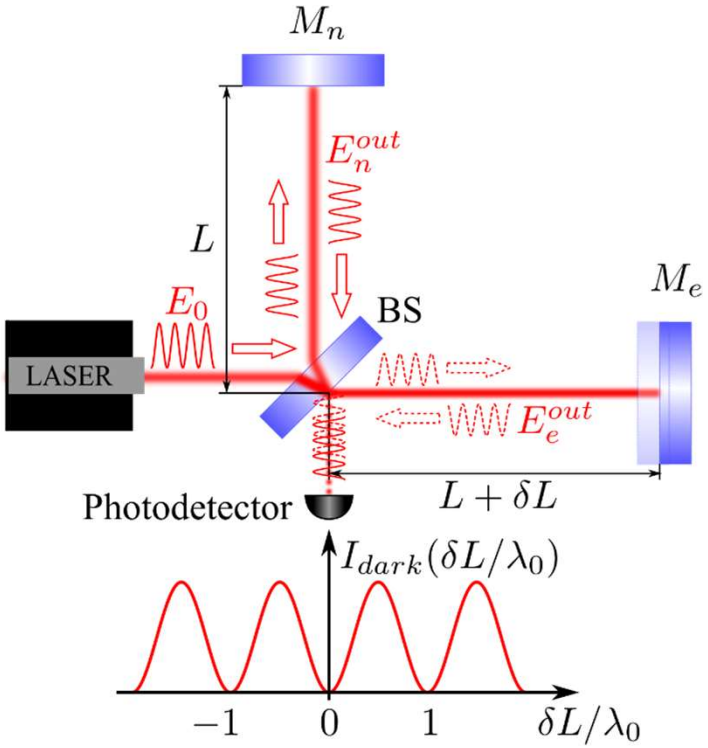


Size of atom = 1 x 10^{-10} m

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

Detect existence of a single atom

Sensitivity of michelson interferometer

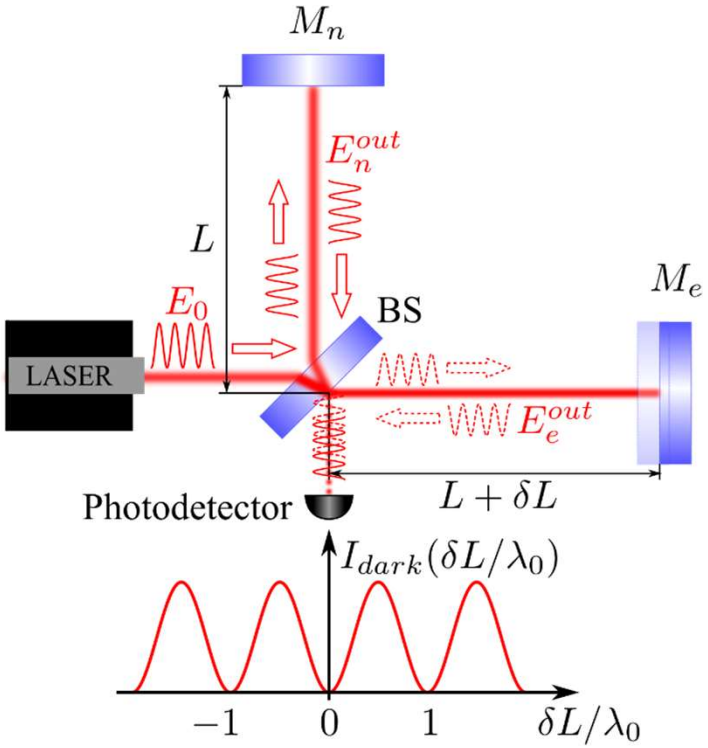


When L = 1 m

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

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

Sensitivity of michelson interferometer



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

When L = 1 m

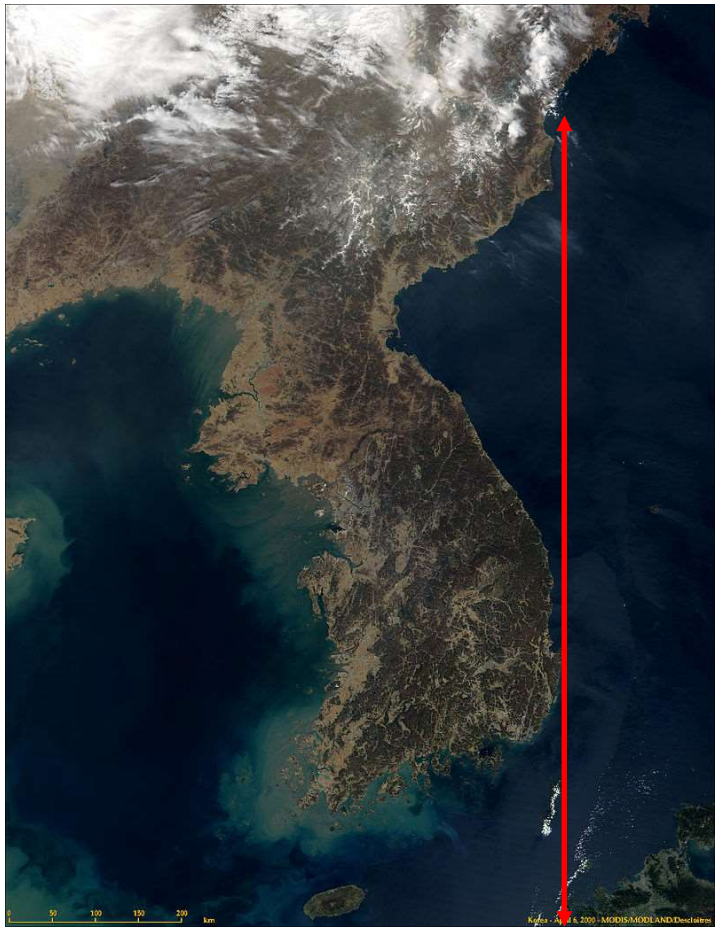
$$\frac{\Delta L}{L} \approx 10^{-16}$$

IF L = 1000 km

$$\frac{\Delta L}{L} \approx 10^{-2}$$

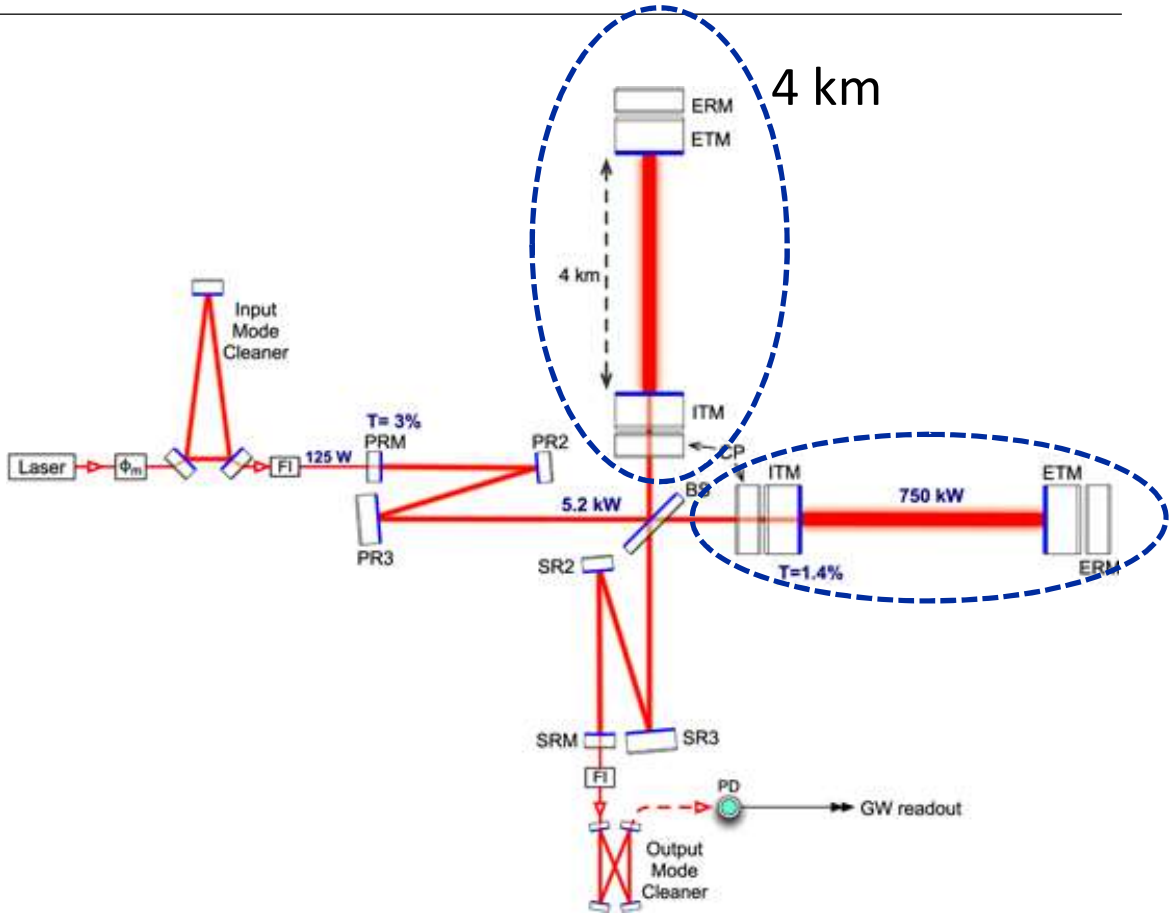
오 1000 km 간섭계를 만들면 되겠다!

1000 km interferometer



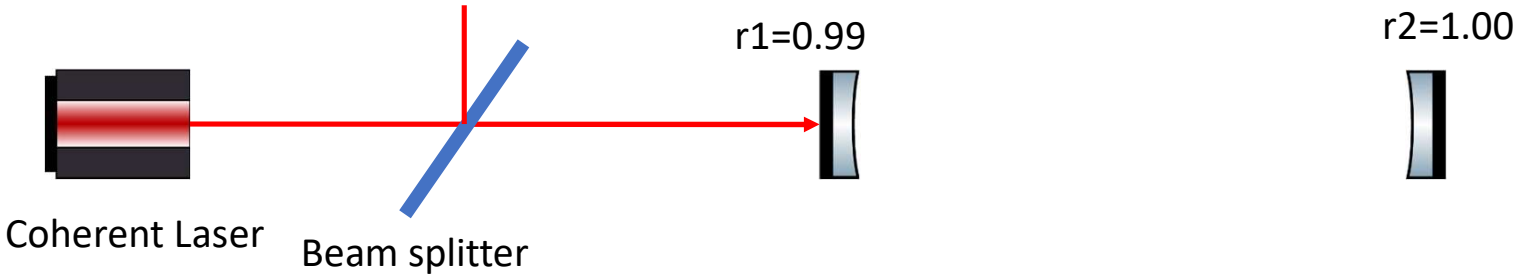
~1100km

LIGO interferometer

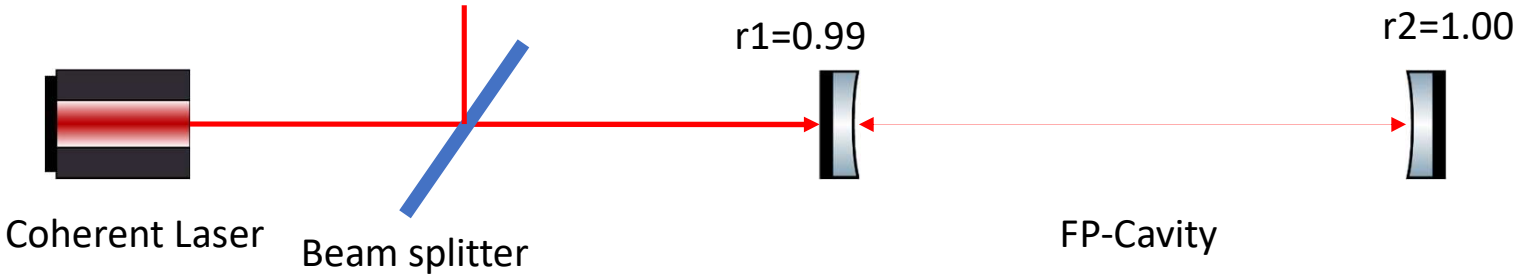


LIGO interferometer / Livingston

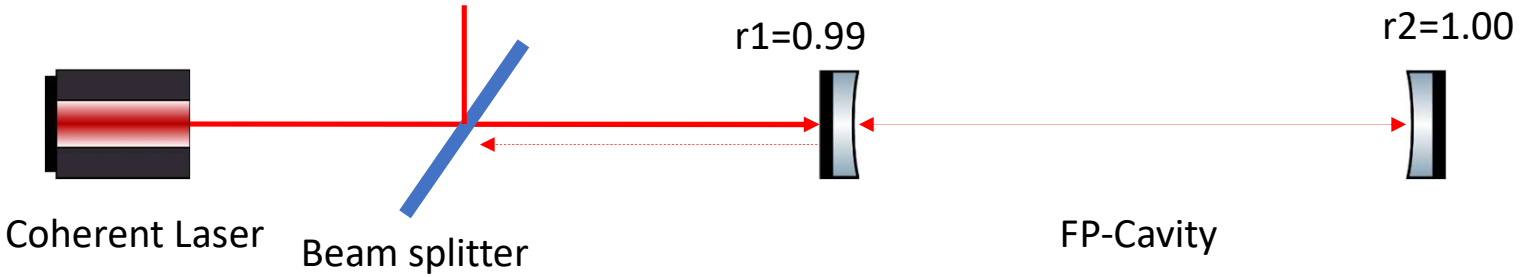
Fabry-perot cavity



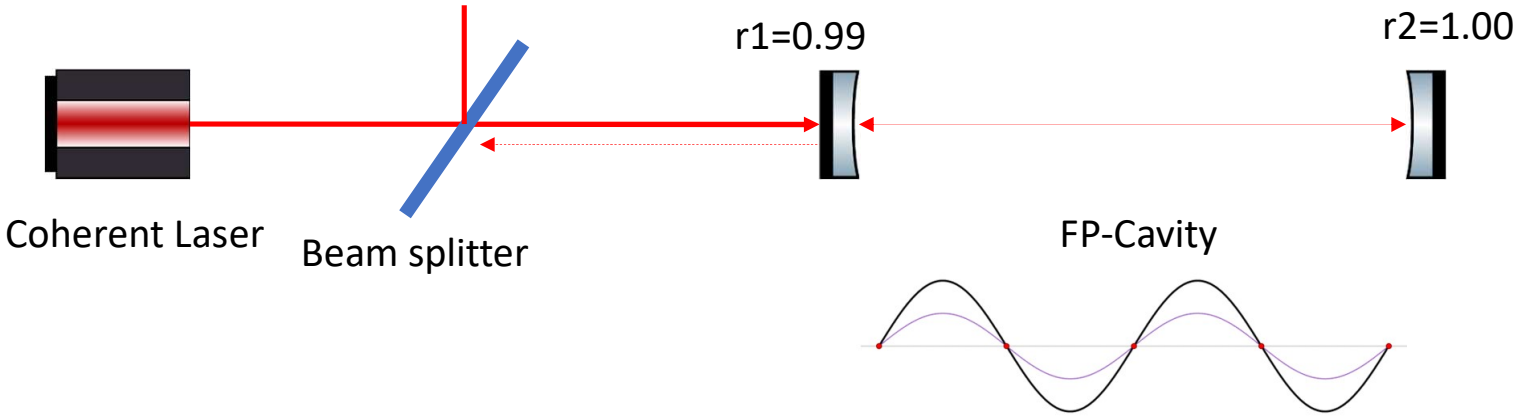
Fabry-perot cavity



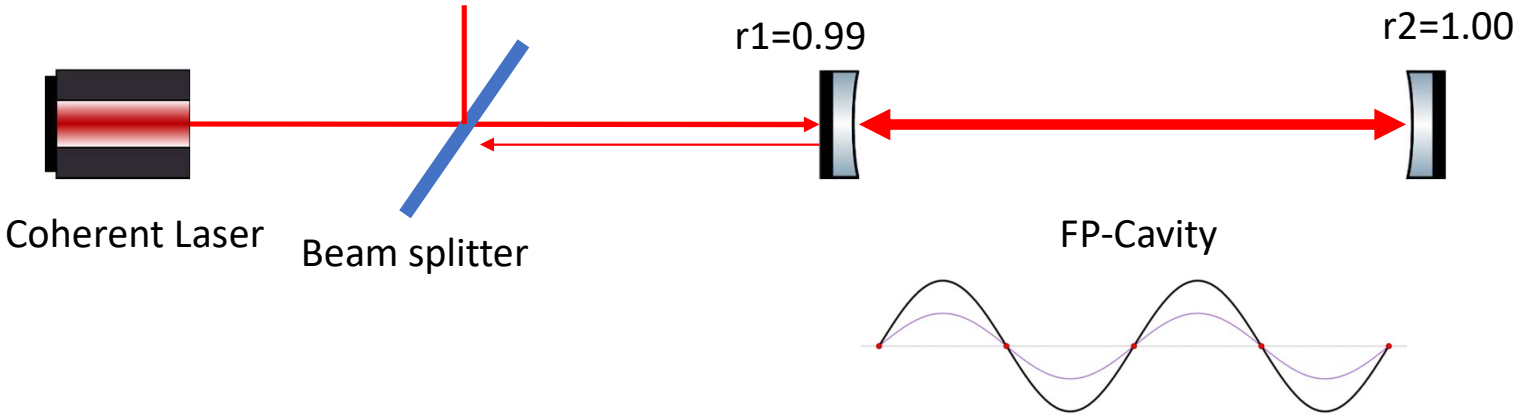
Fabry-perot cavity



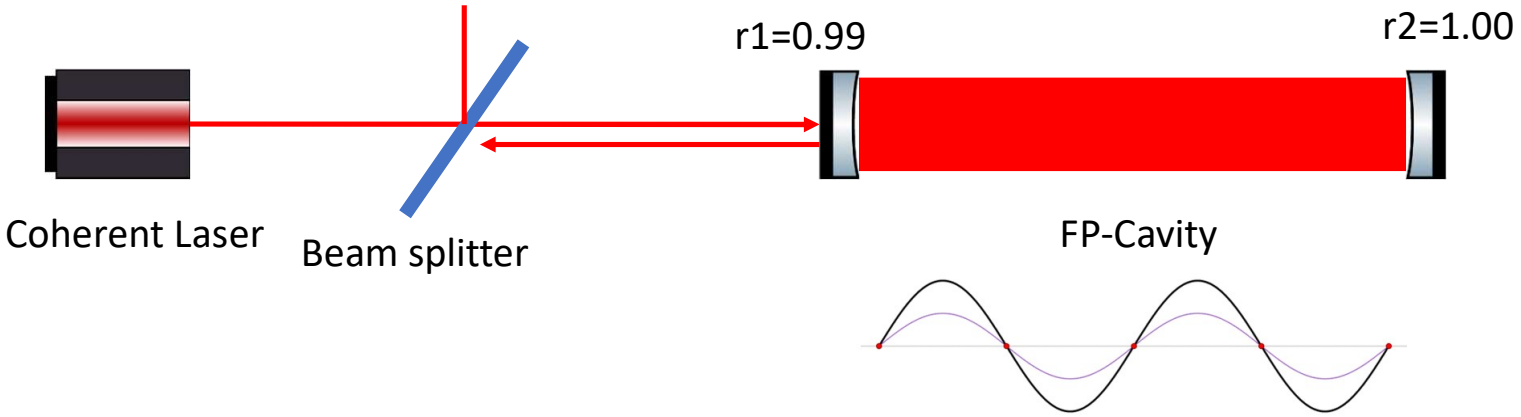
Fabry-perot cavity



Fabry-perot cavity

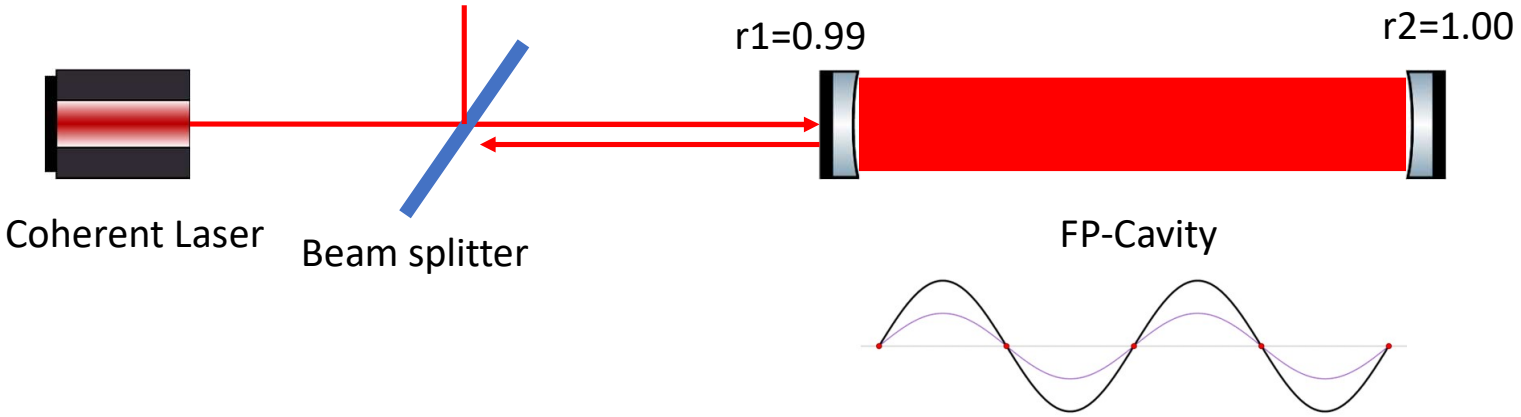


Fabry-perot cavity



Fabry-perot cavity

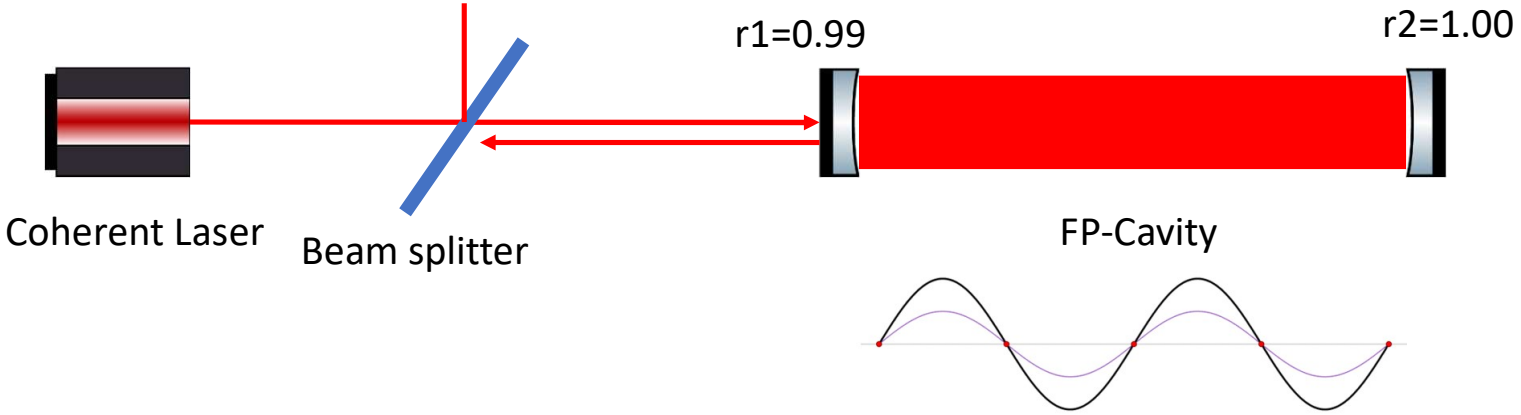
Number of round trip > 250



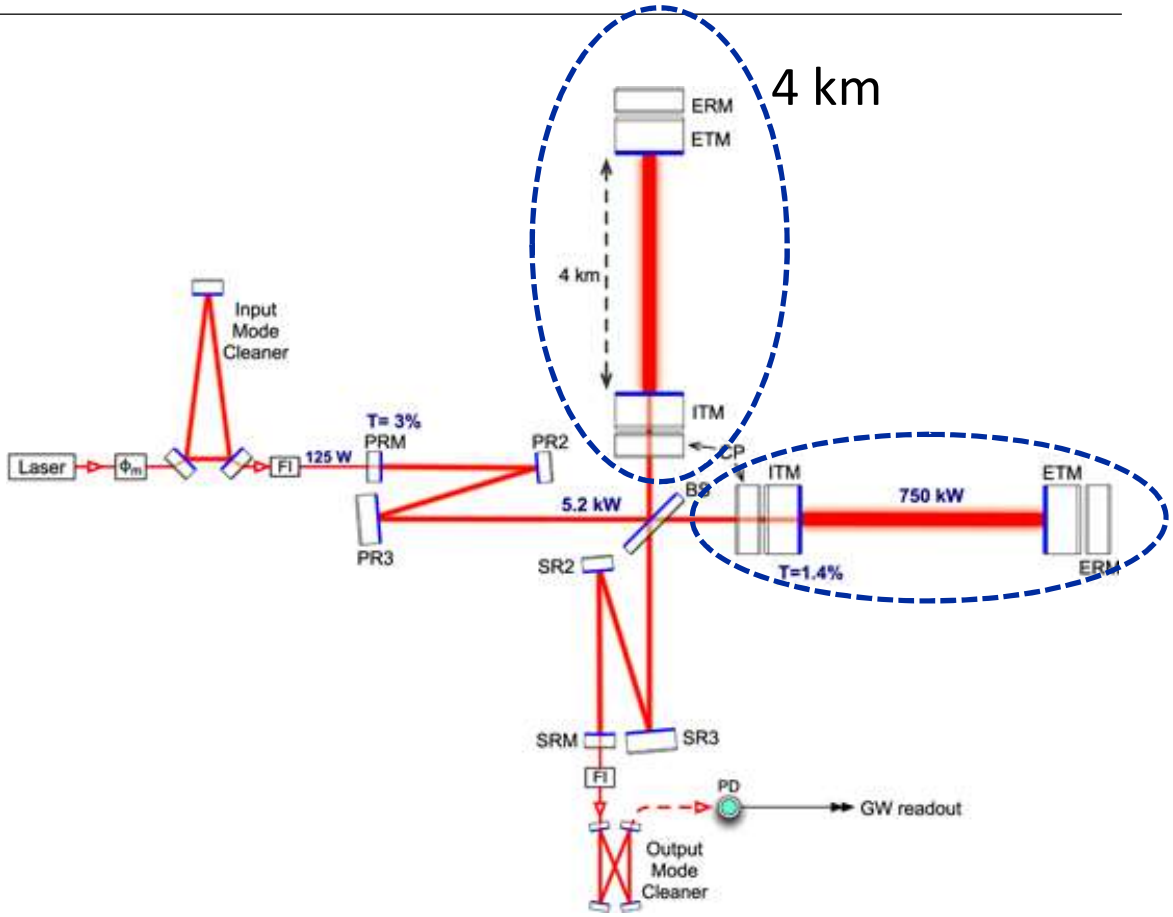
Fabry-perot cavity

Number of round trip > 250

4 km x 250 ~ 1000 km

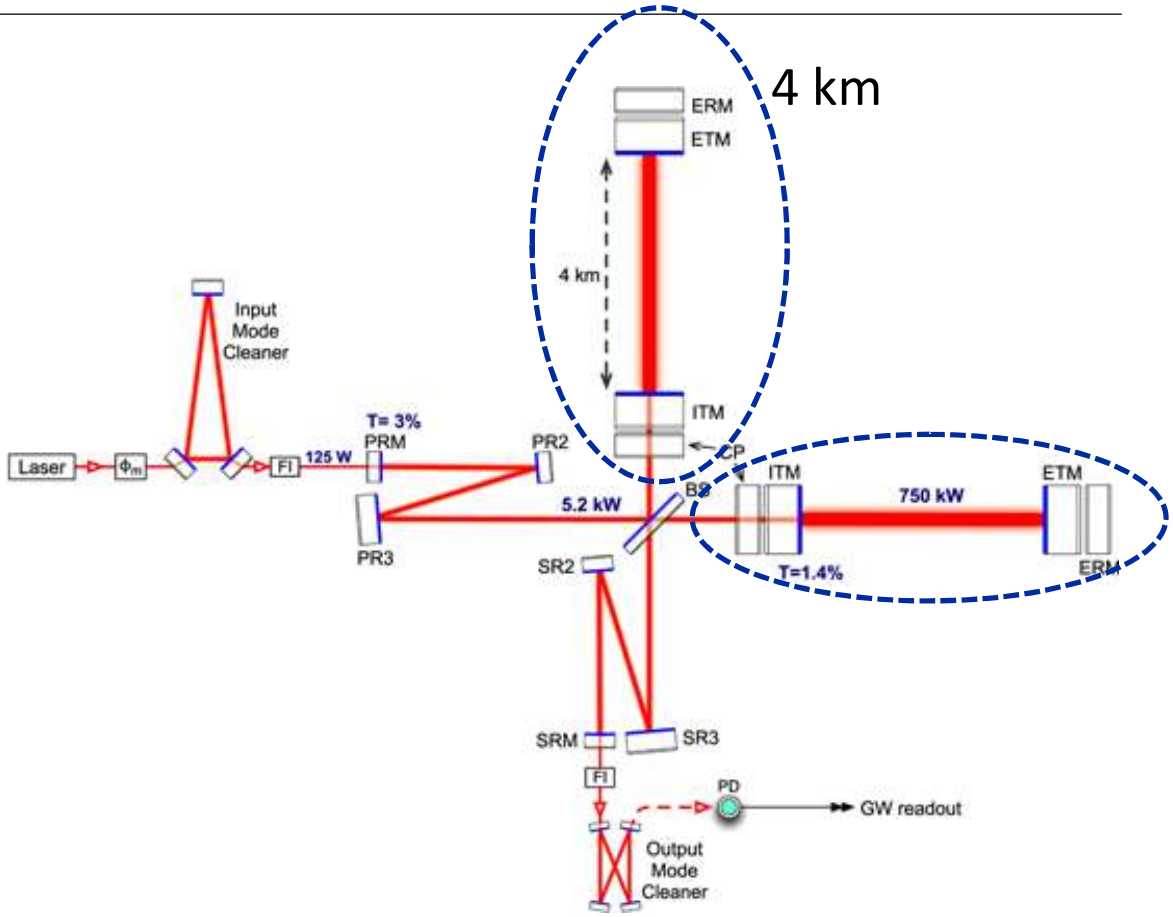


LIGO interferometer



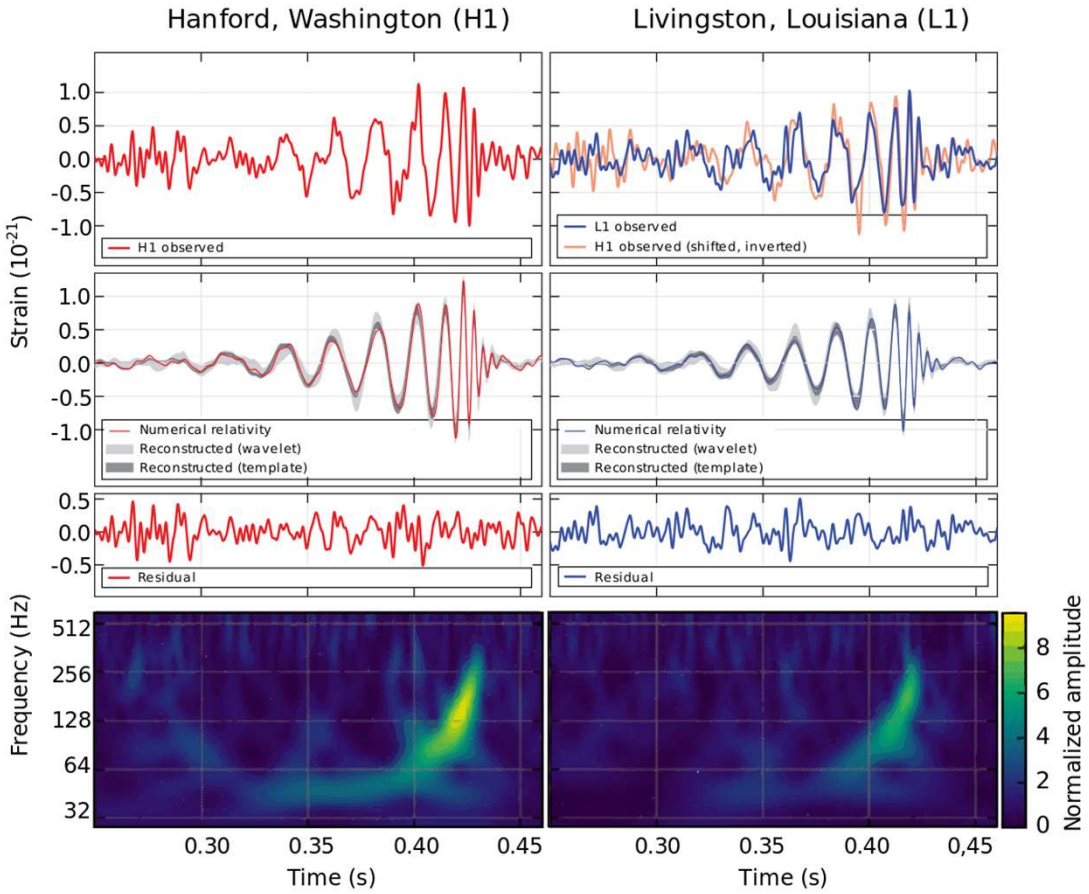
LIGO interferometer / Livingston

LIGO interferometer

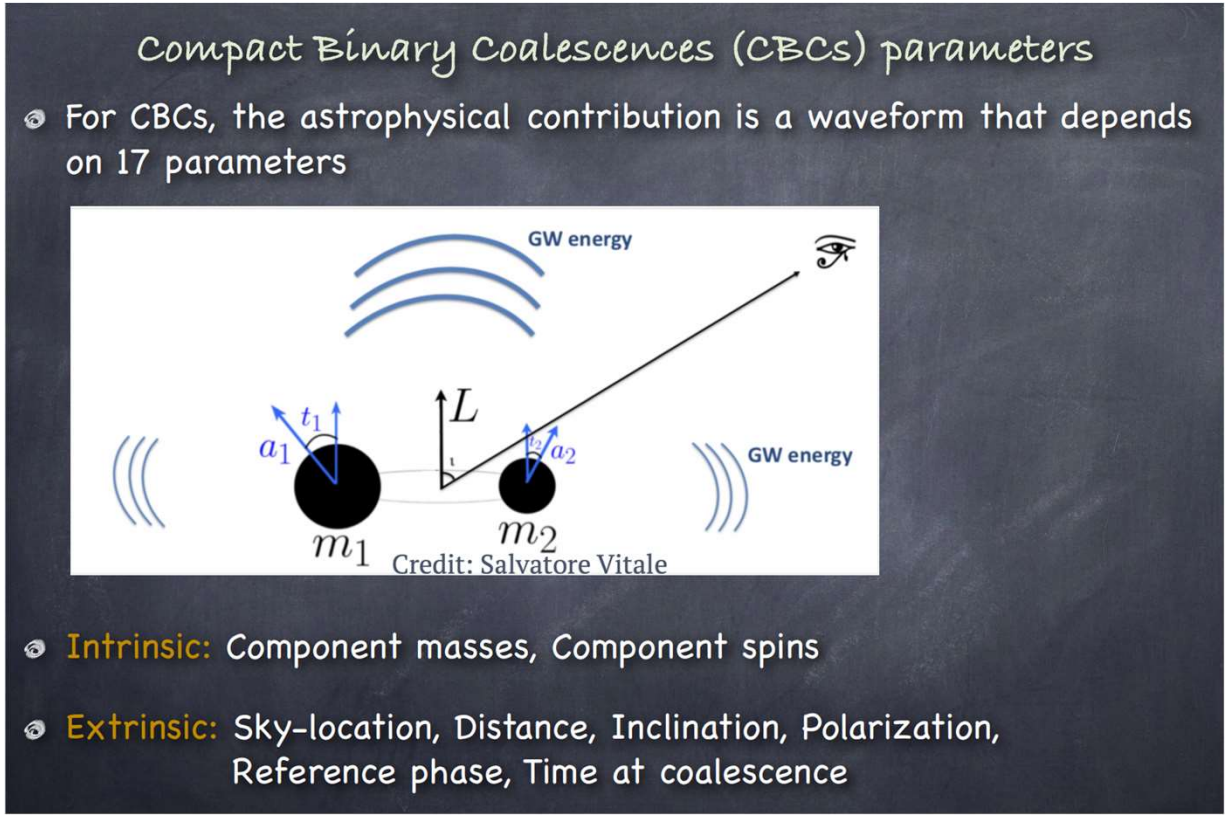


LIGO interferometer / Livingston

First detection of gravitational wave



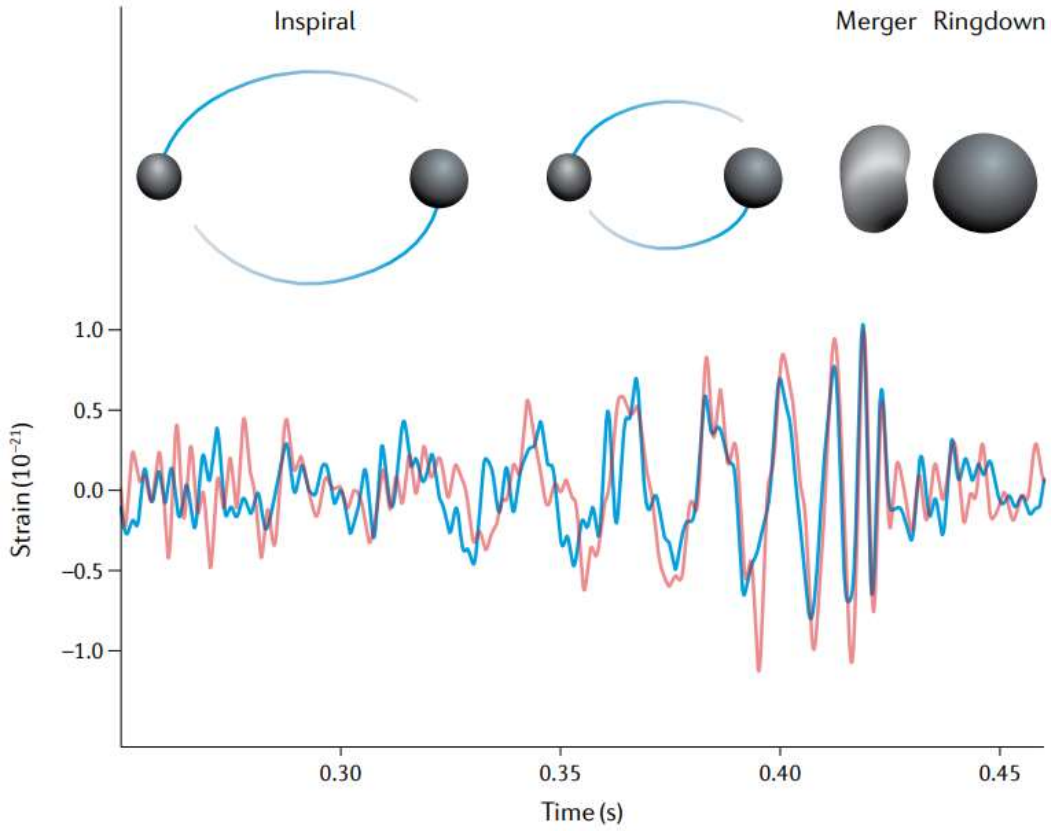
Parameter estimation



Black Hole

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

Inspiral–Merger–Ringdown

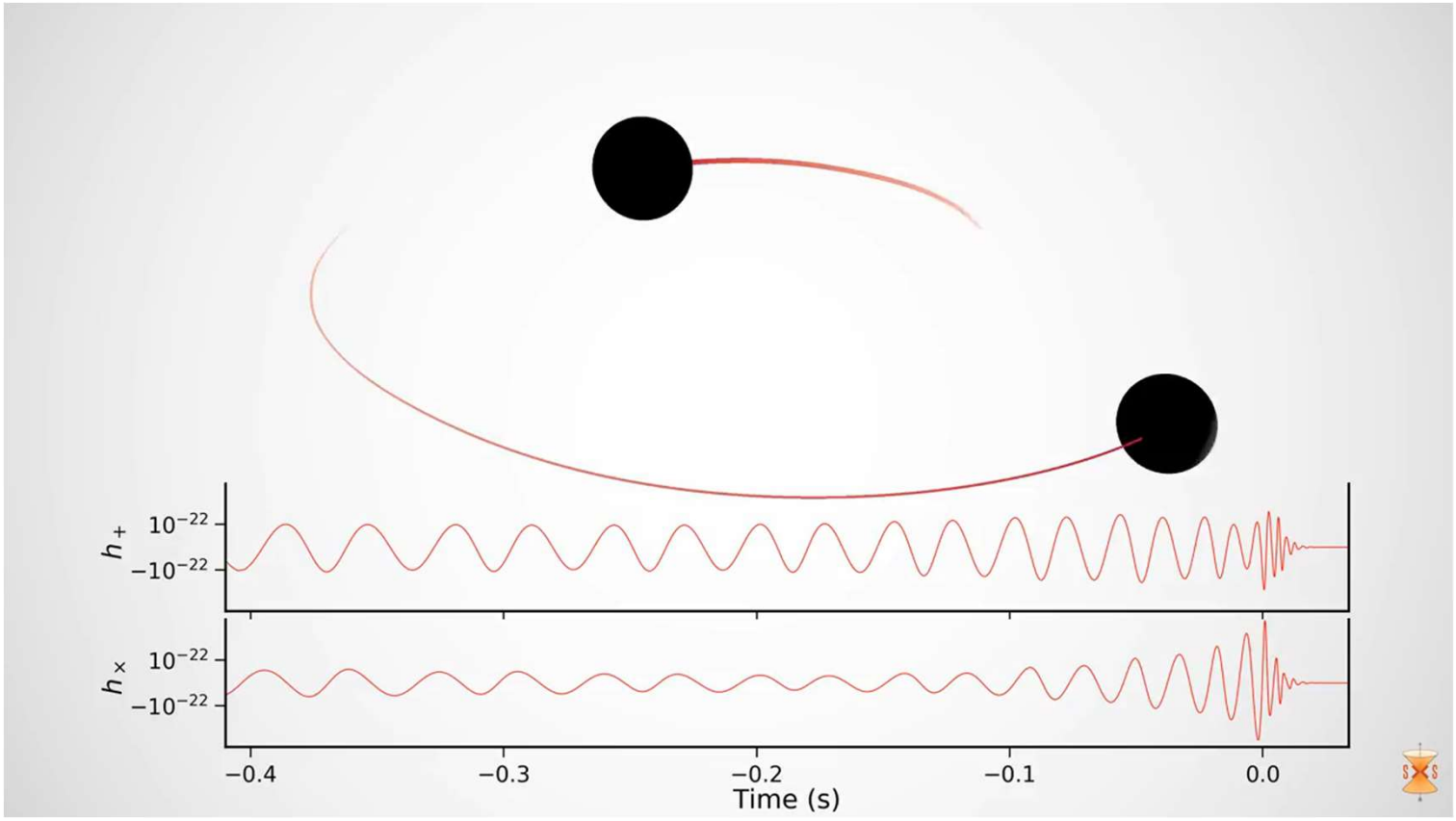


Nature Reviews Physics **volume 3**, pages344–366 (2021)

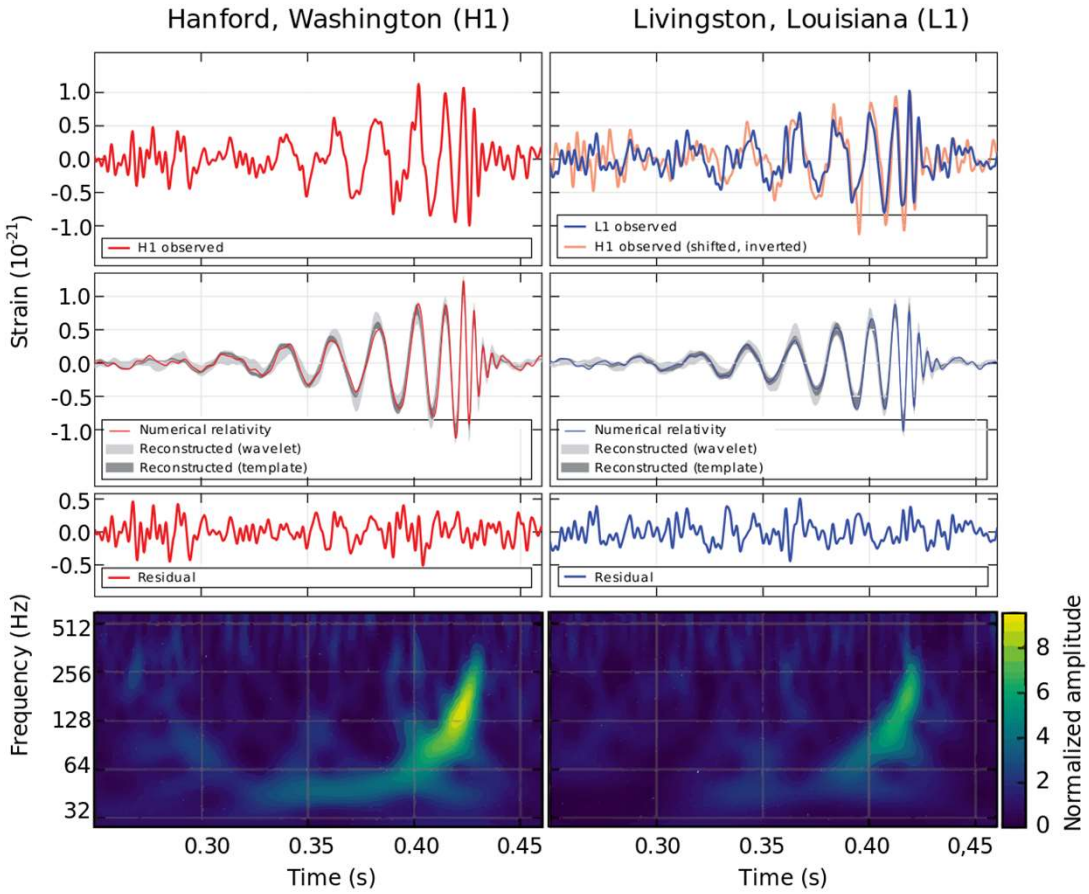
GW170104

+ pol

x pol



First detection of gravitational wave



First detection of gravitational wave

Gravitational W… Prediction

News Release • February 11,

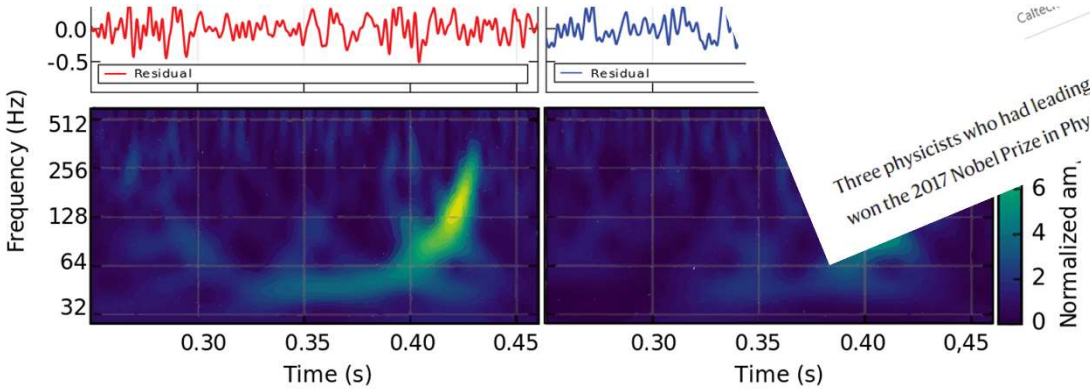
The Nobel Prize in Physics 2017 | Press Release

"for decisive contribut…

…Kip Thorne share the 2017 prize for their work at LIGO to

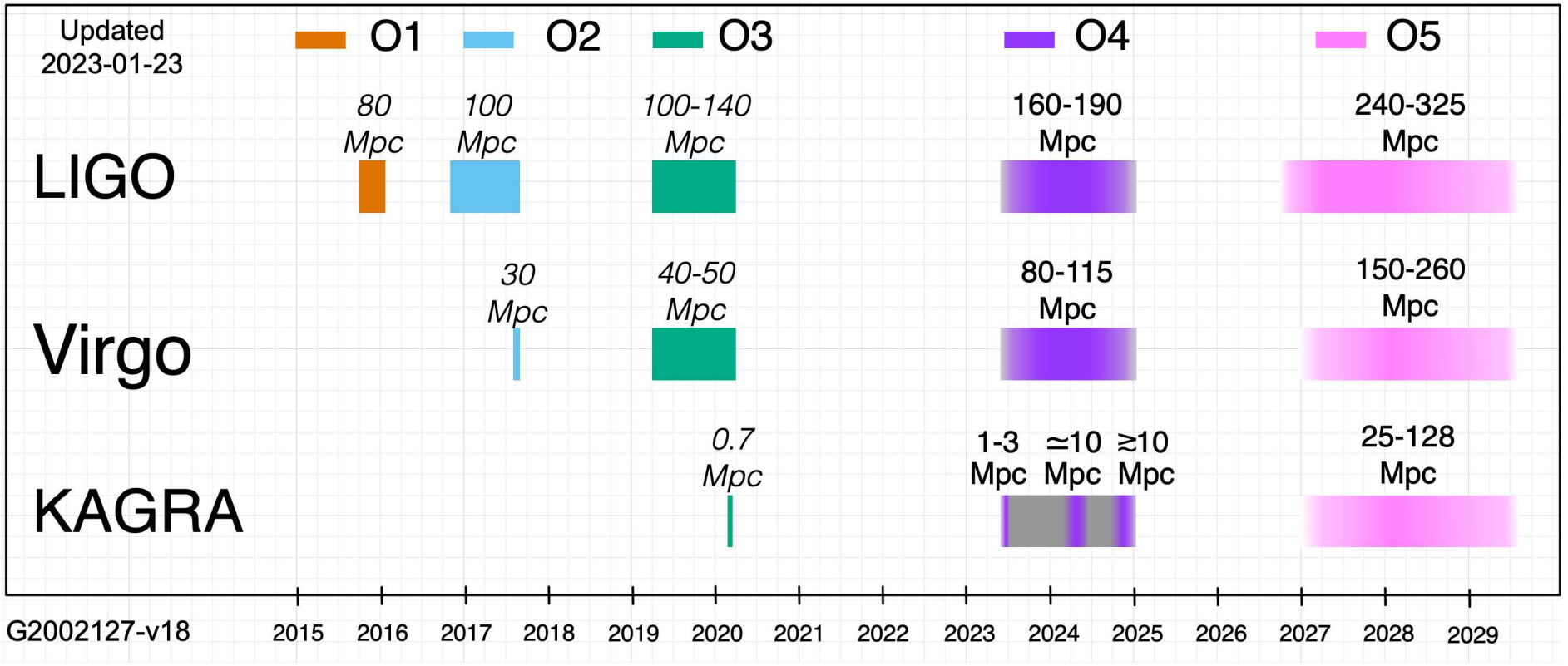
CNN health | Life, But Better | Fitness | Food | Sleep | Mindfulness | Relationships

Nobel Prize in Physics goes to 'black hole telescope' trio



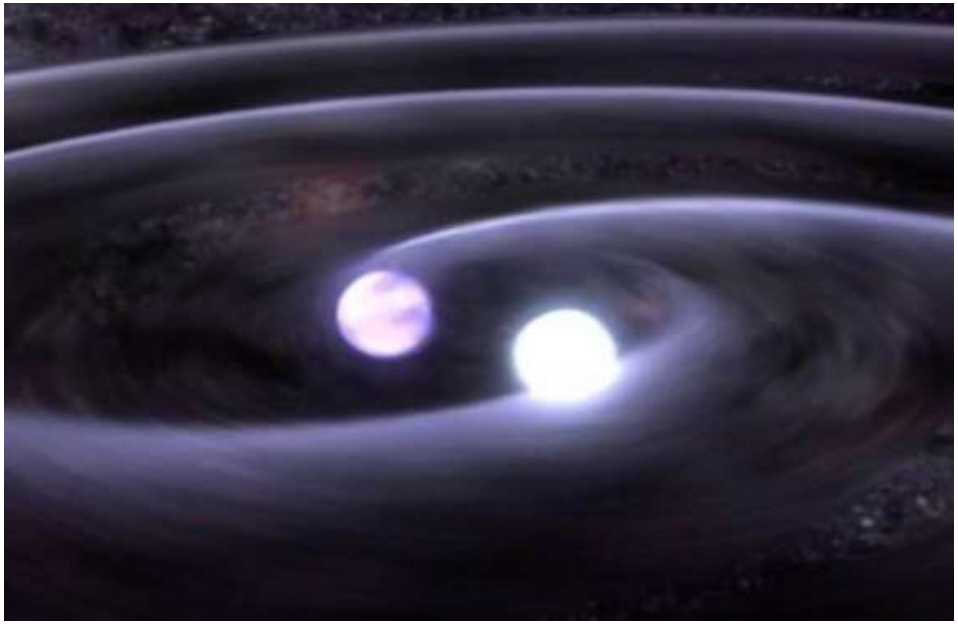
Three physicists who had leading roles in the first direct de… won the 2017 Nobel Prize in Physics.

LVK Observation plan



BNS range

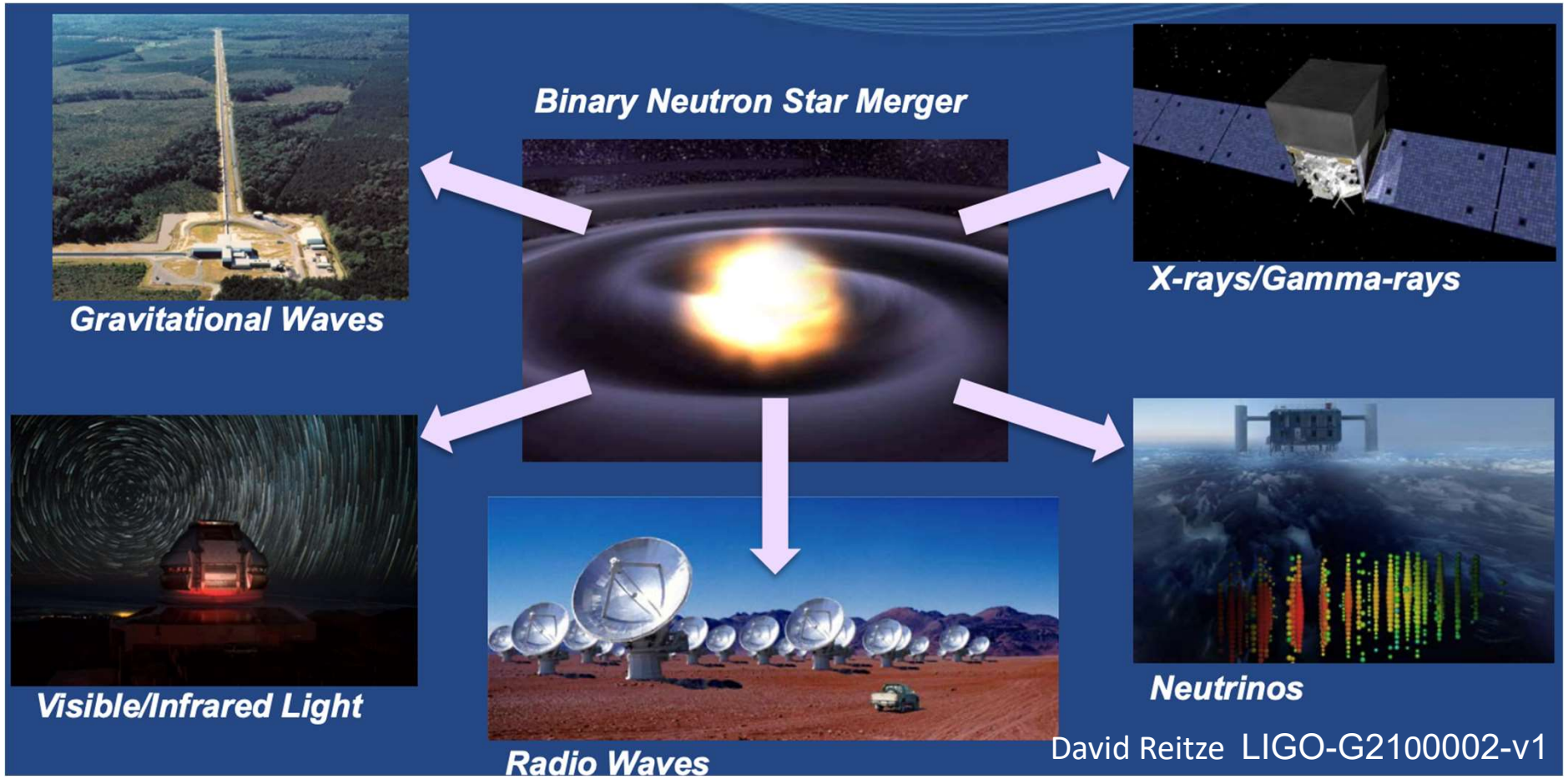
- Binary-neutron-star range
- Common benchmark of sensitivity
- Made up of two 1.4 solar mass neutron stars
- Signal-to-noise ratio of 8

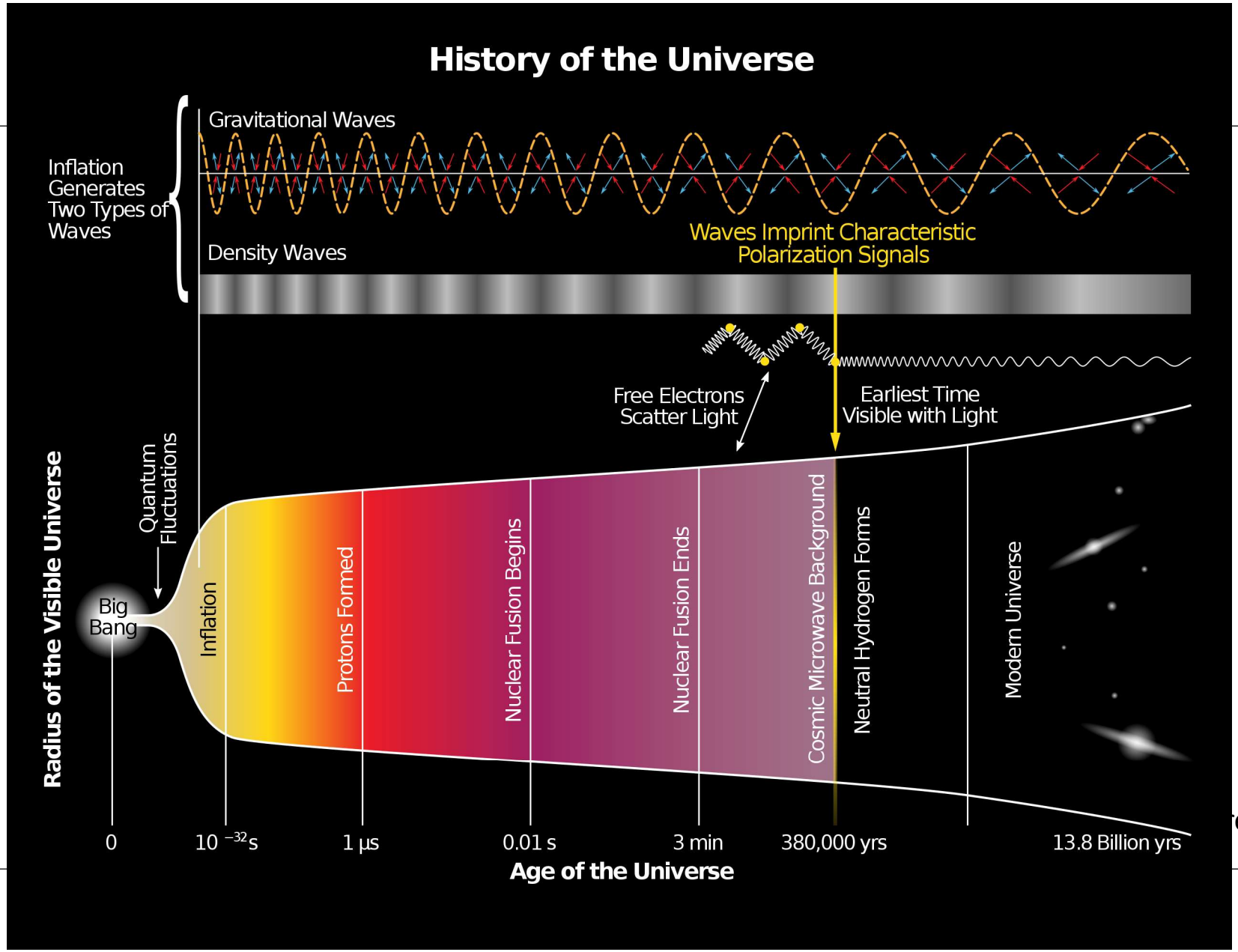


https://svs.gsfc.nasa.gov/10543

Maximum distance at which an event can be detected

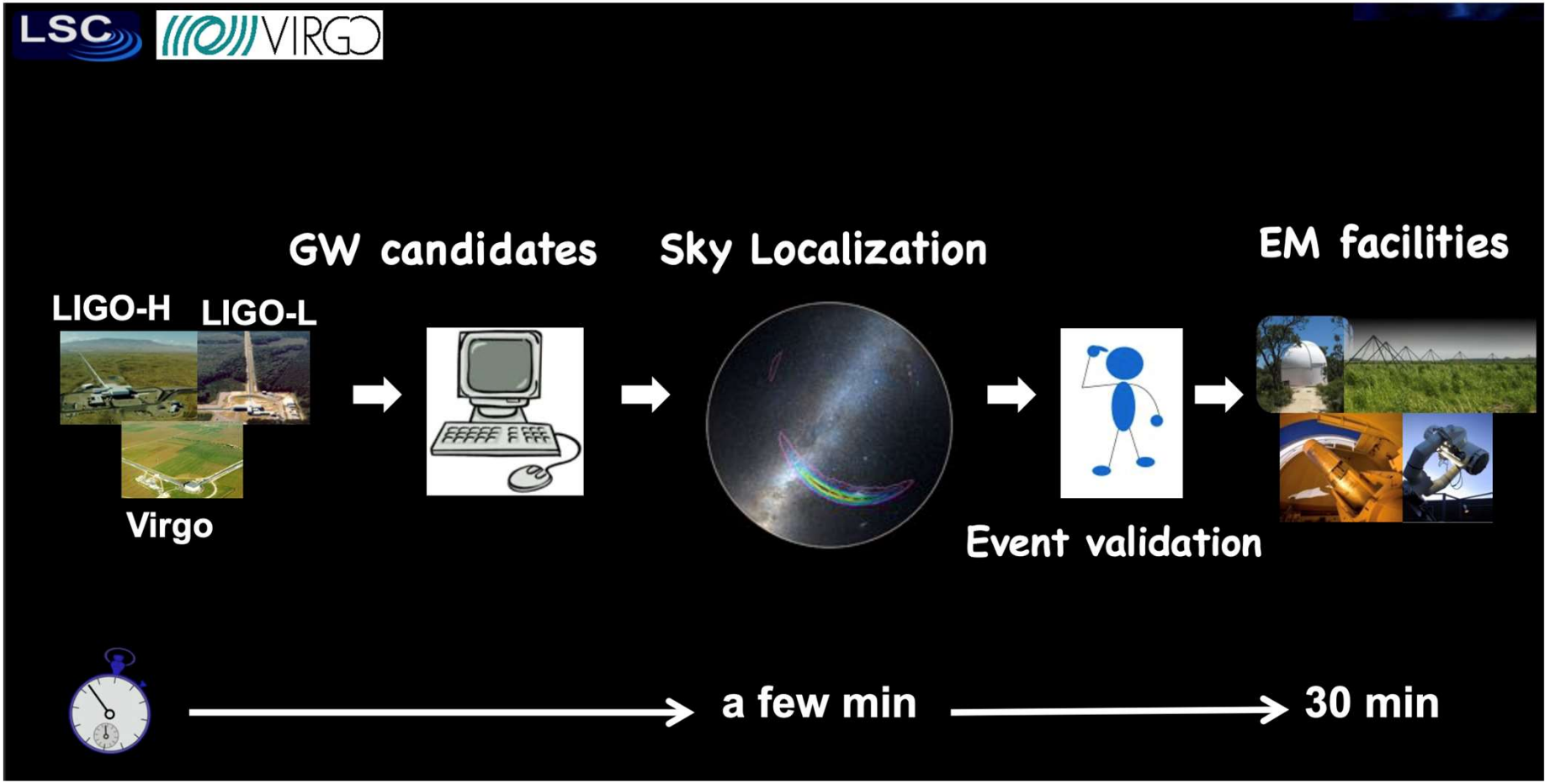
Multi-messenger astronomy with gravitational waves



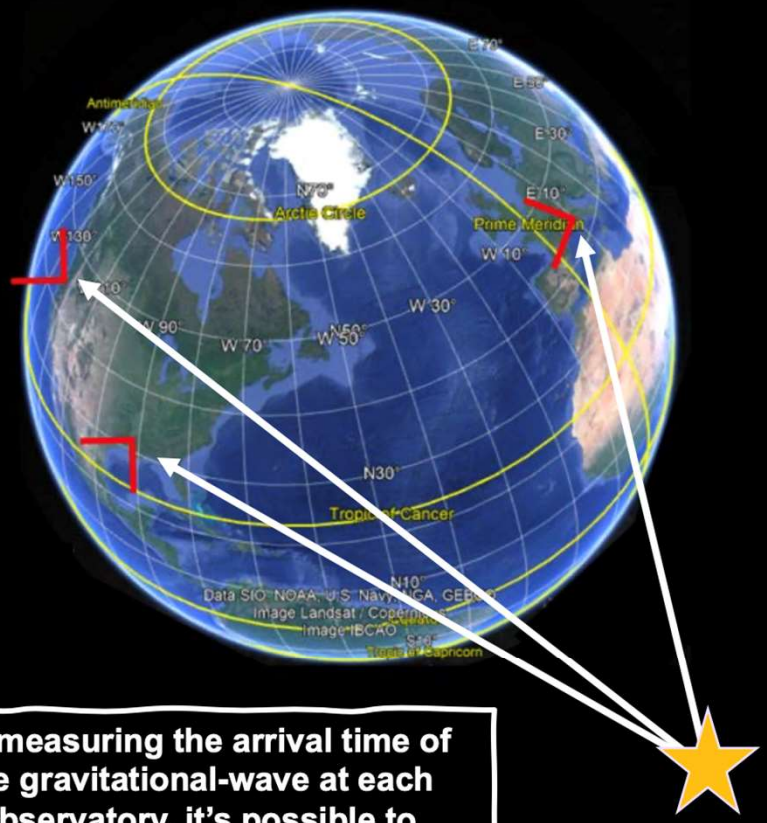

History of the Universe
Gravitational Waves
Inflation Generates Two Types of Waves
Density Waves
Waves Imprint Characteristic Polarization Signals
Free Electrons Scatter Light
Earliest Time Visible with Light
Radius of the Visible Universe
Quantum Fluctuations
Big Bang
Inflation
Protons Formed
Nuclear Fusion Begins
Nuclear Fusion Ends
Cosmic Microwave Background
Neutral Hydrogen Forms
Modern Universe
0
10 −32s
1 µs
0.01 s
3 min
380,000 yrs
13.8 Billion yrs
Age of the Universe

edit : BICEP2

GW alert procedure



Localizing Gravitational-wave Events

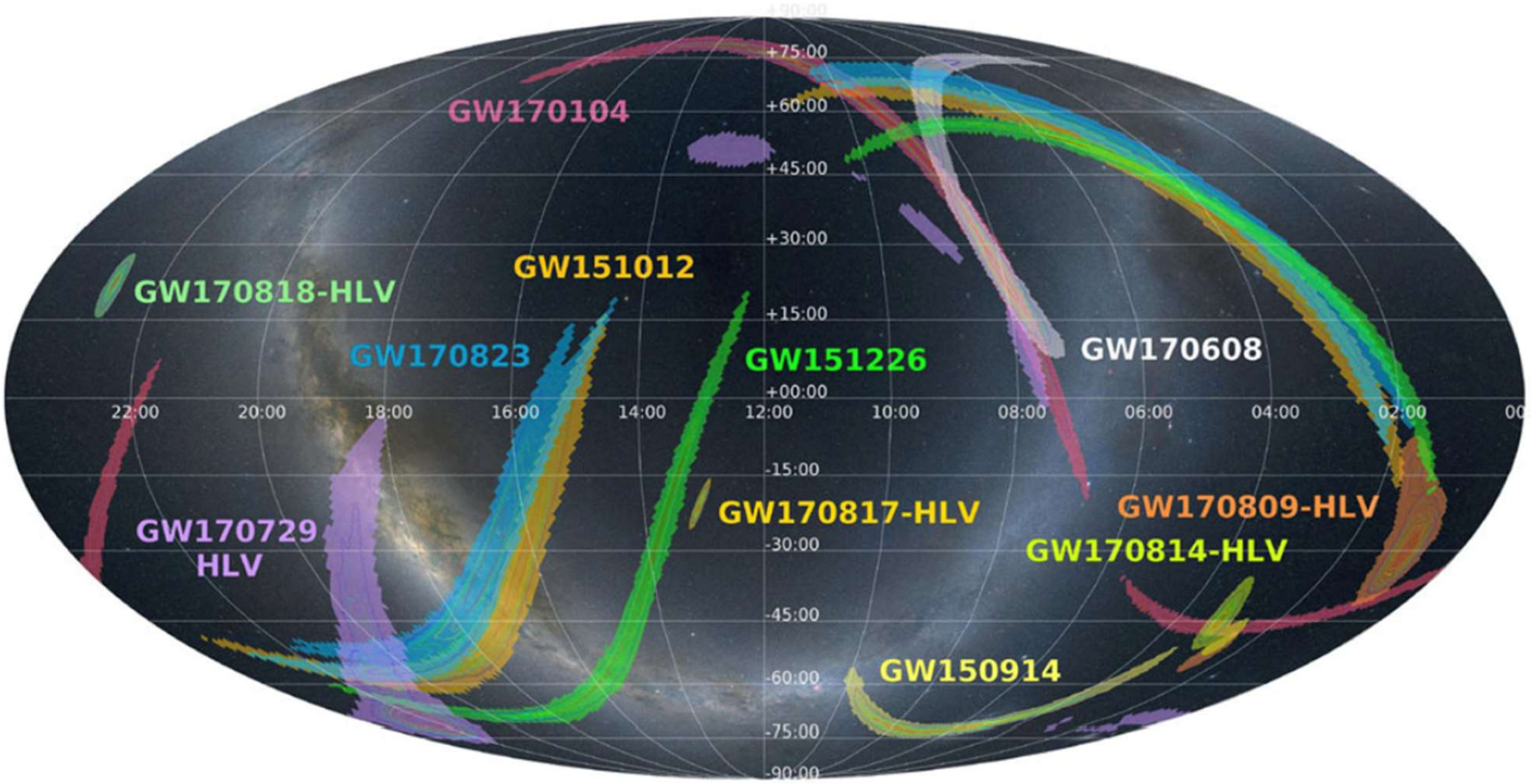


By measuring the arrival time of the gravitational-wave at each observatory, it's possible to identify its location on the sky

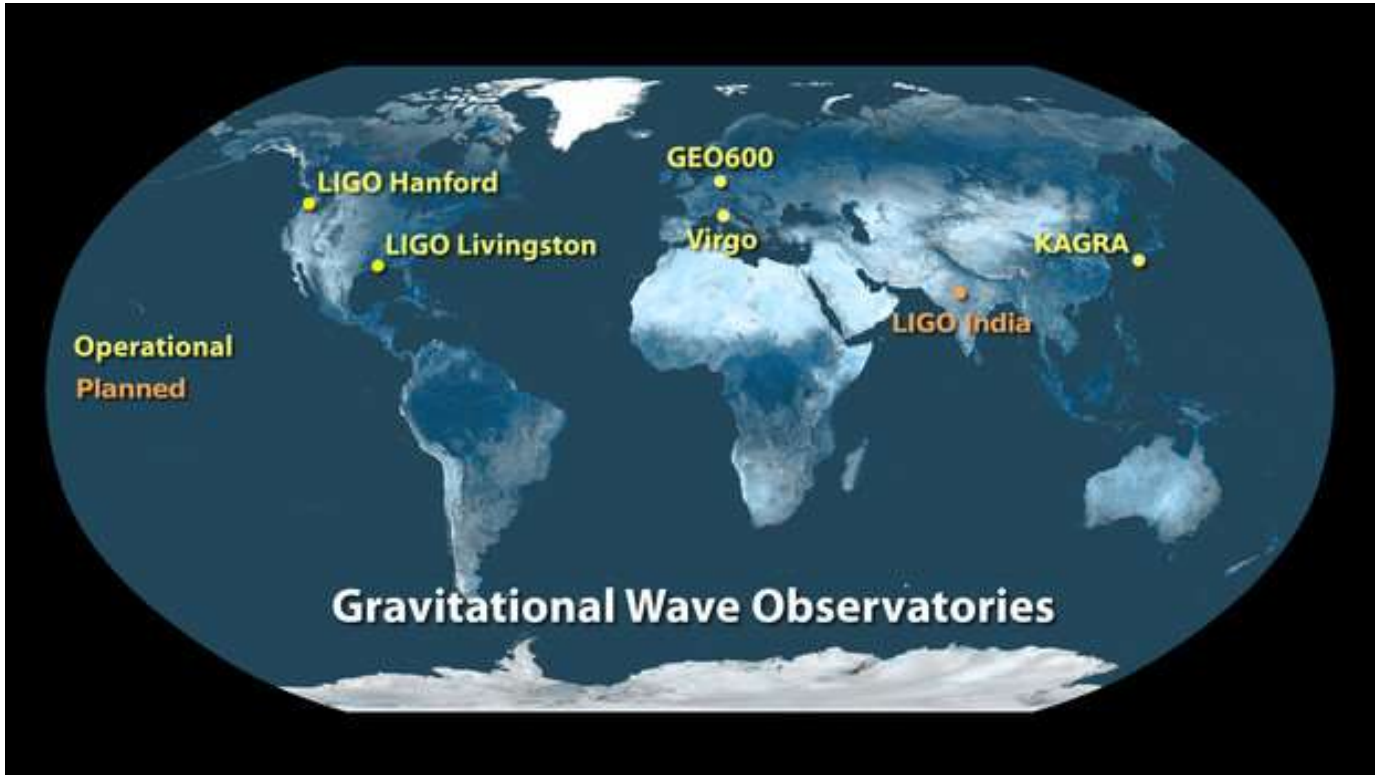
A single GW observatory is mostly insensitive to the sky location; we want two and preferably three or more observatories

Yokohama GRB 2019
Marci Branchesi

Sky localization



Gravitational wave observatories

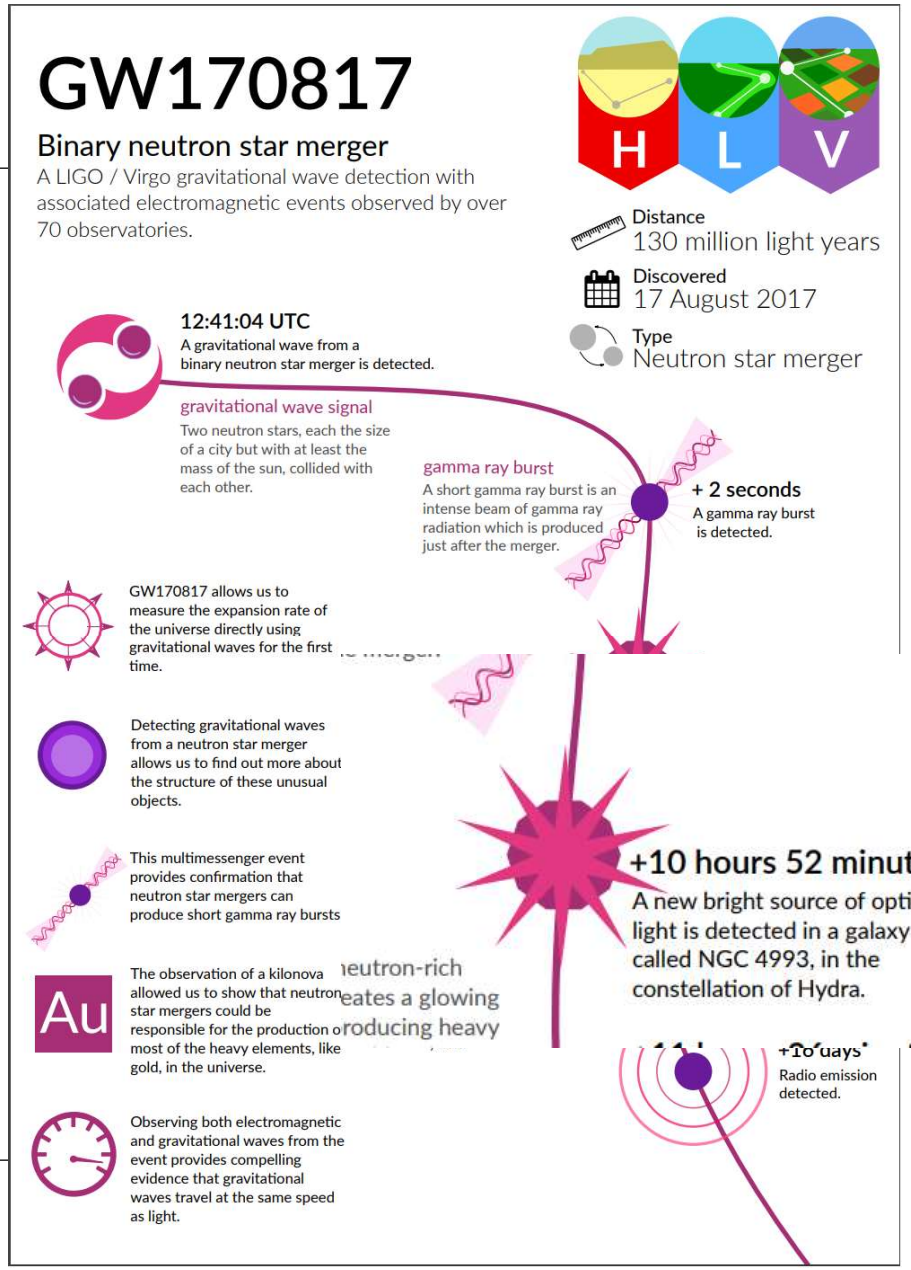


First multi-messenger detection

Binary neutron star merger

Gamma ray burst detection with Fermi-detector

Kilonova detection using telescope

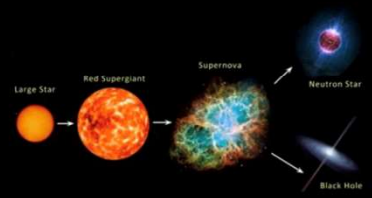


Radioactively powered transients

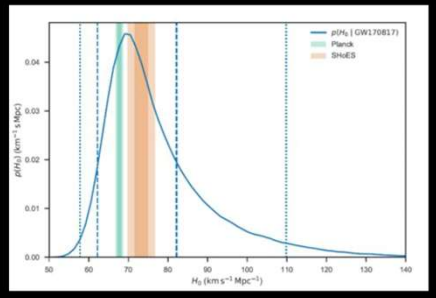
Relativistic astrophysics

Nucleosynthesis and enrichment of the Universe

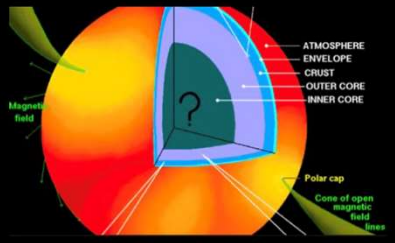
Compact object formation and evolution



Cosmology

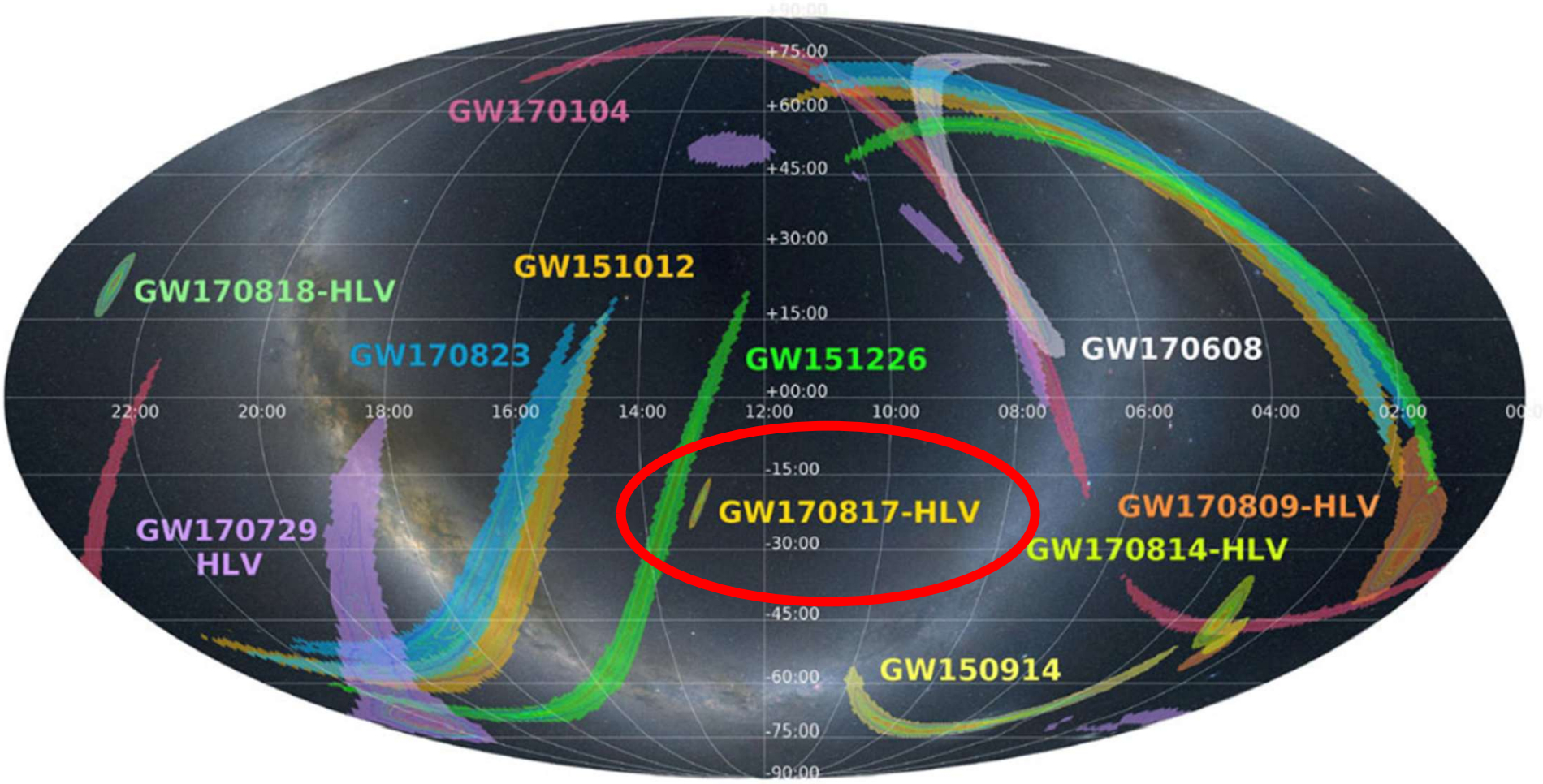


Nuclear matter physics

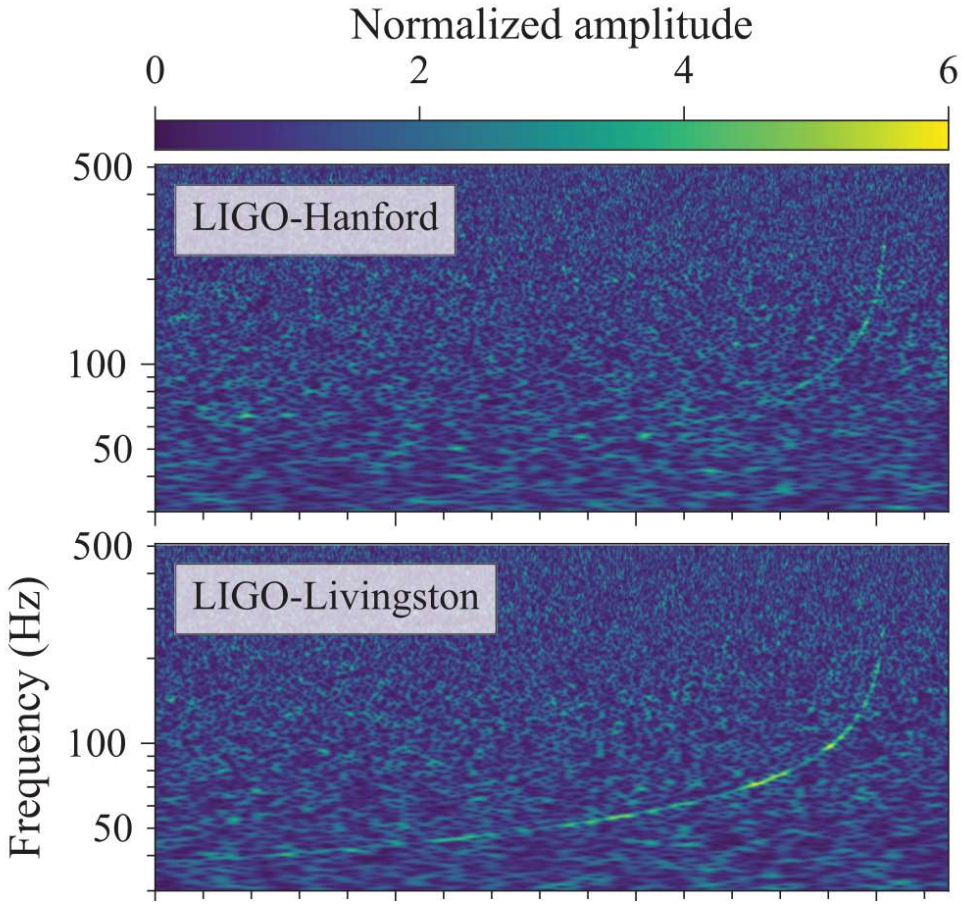


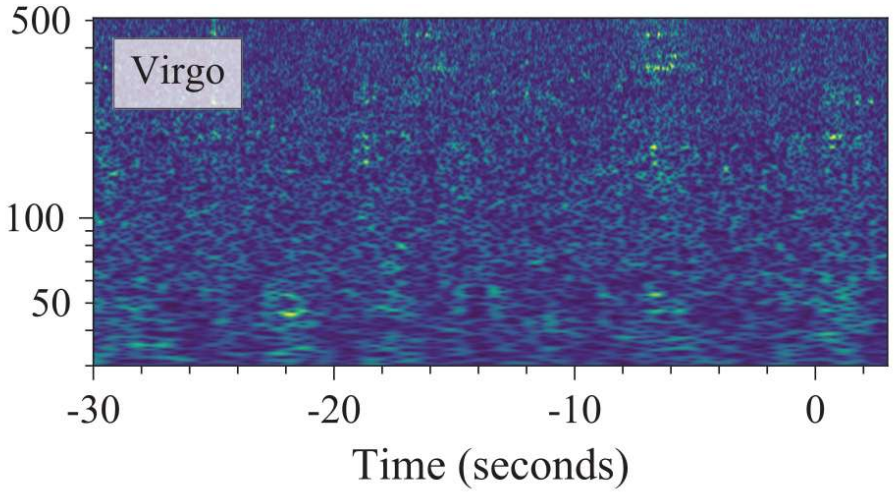
Yokohama GRB 2019
Marci Branchesi

Sky localization



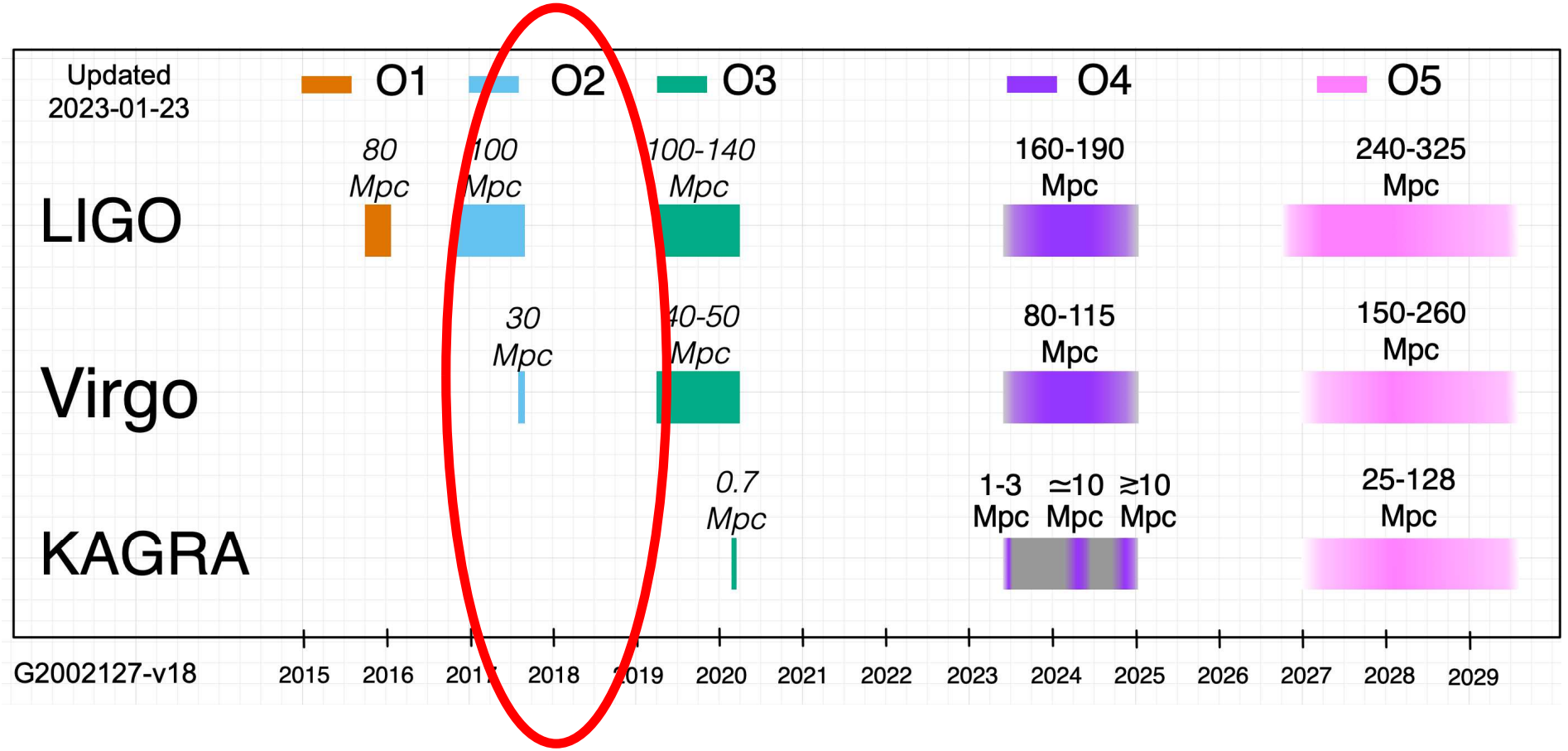
GW170817





No Signal at VIRGO ???

LVK Observation plan



LIGO-VIRGO joint observation

VIRGO JOINS LIGO FOR THE O2 DATA-TAKING PERIOD

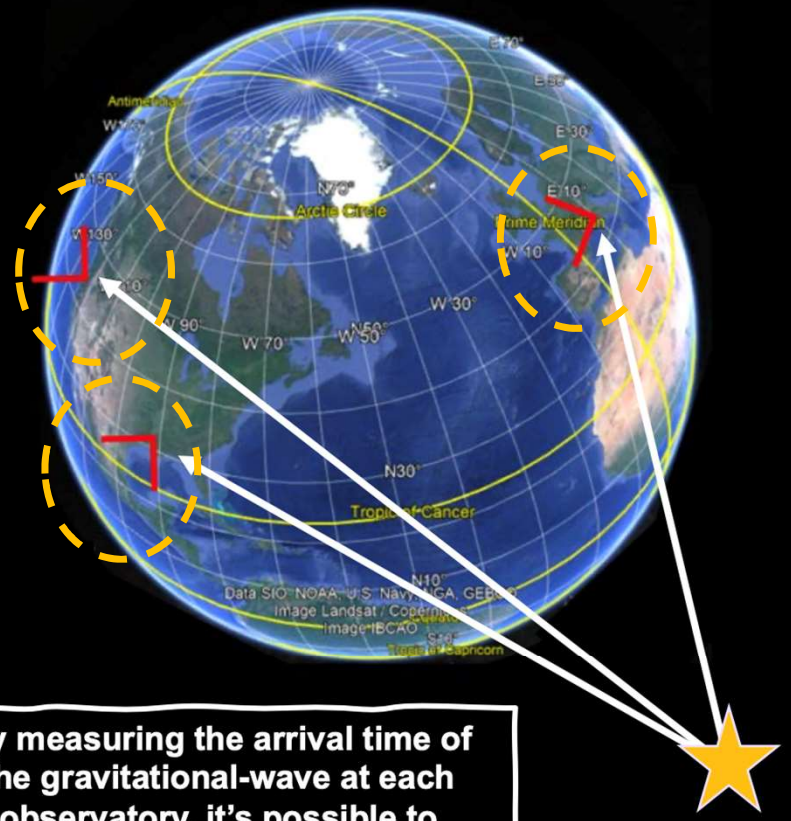
Warning: Use of undefined constant multiple - assumed 'multiple' (this will throv
content/themes/

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.

Localizing Gravitational-wave Events

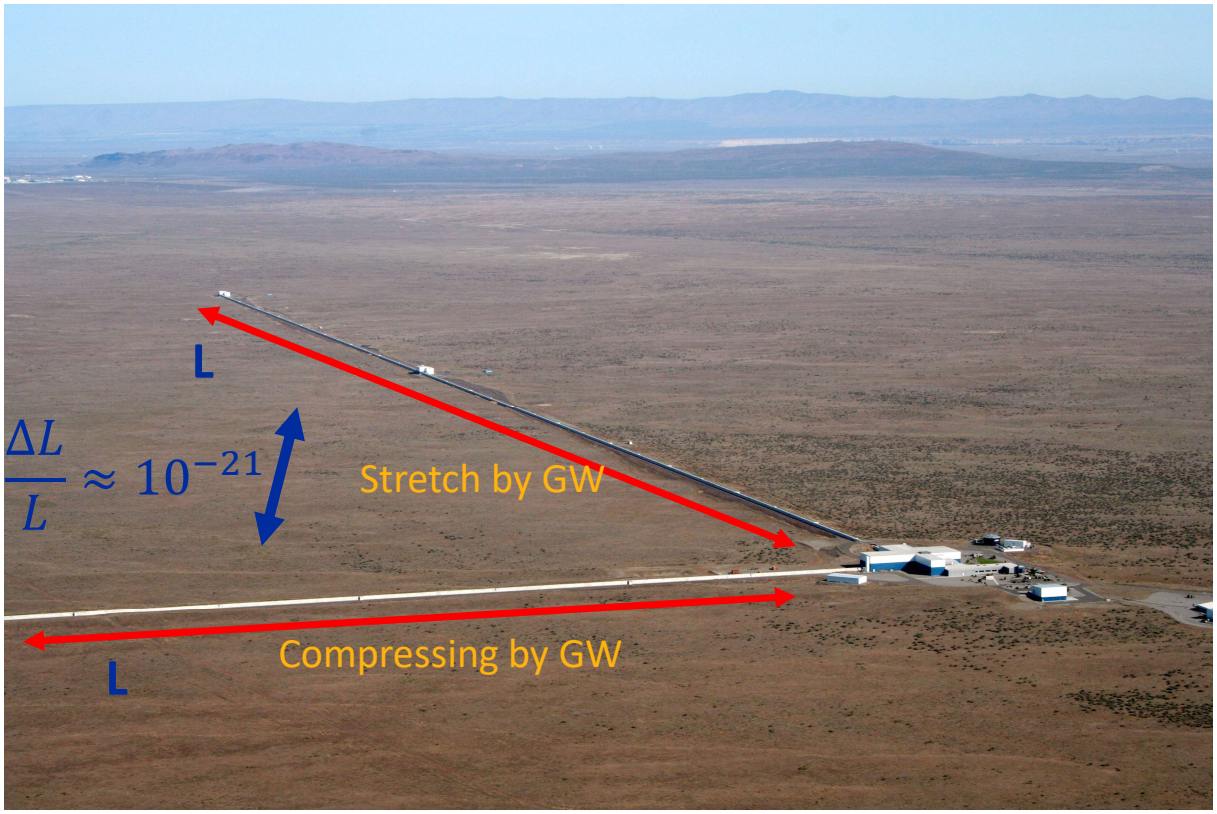


By measuring the arrival time of the gravitational-wave at each observatory, it's possible to identify its location on the sky

A single GW observatory is mostly insensitive to the sky location;
we want two and preferably three or more observatories

Yokohama GRB 2019
Marci Branchesi

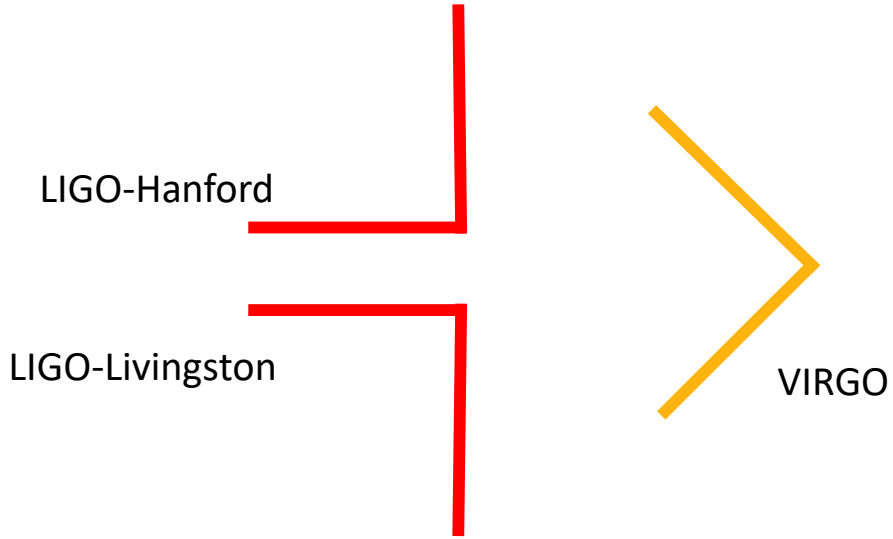
Strain sensitivity



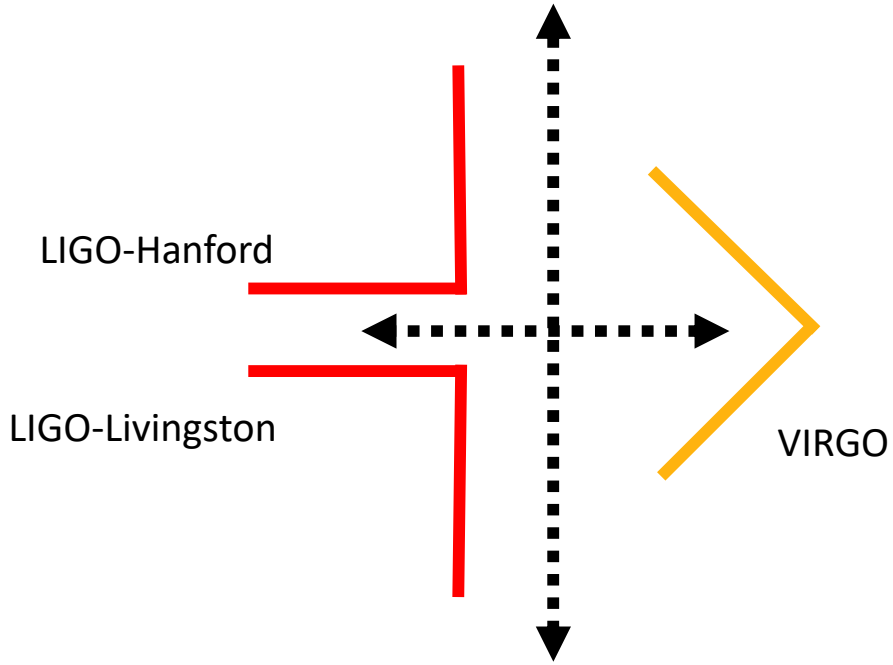
Minimum sensitivity

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

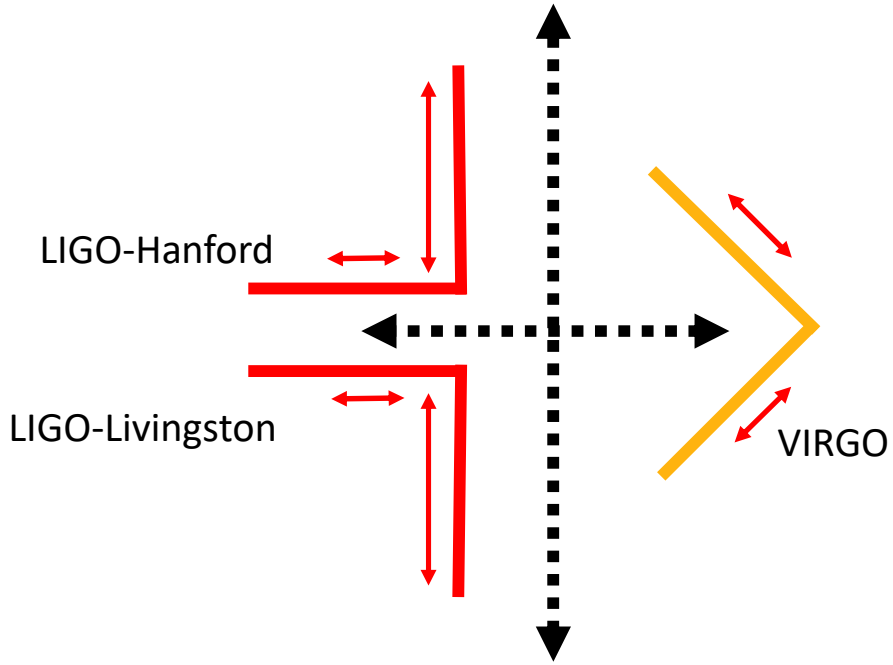
Polarization of gravitational wave

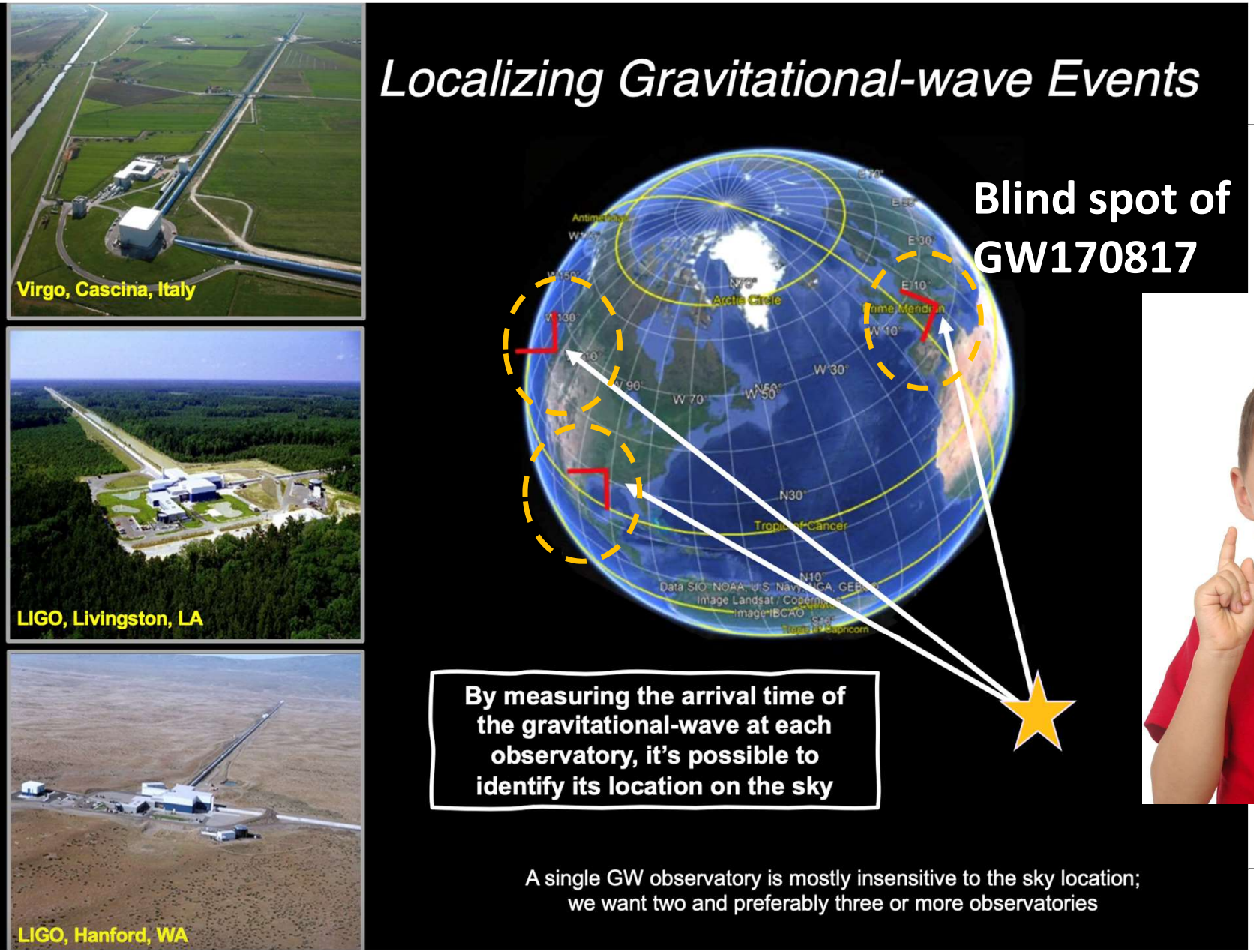


Polarization of gravitational wave

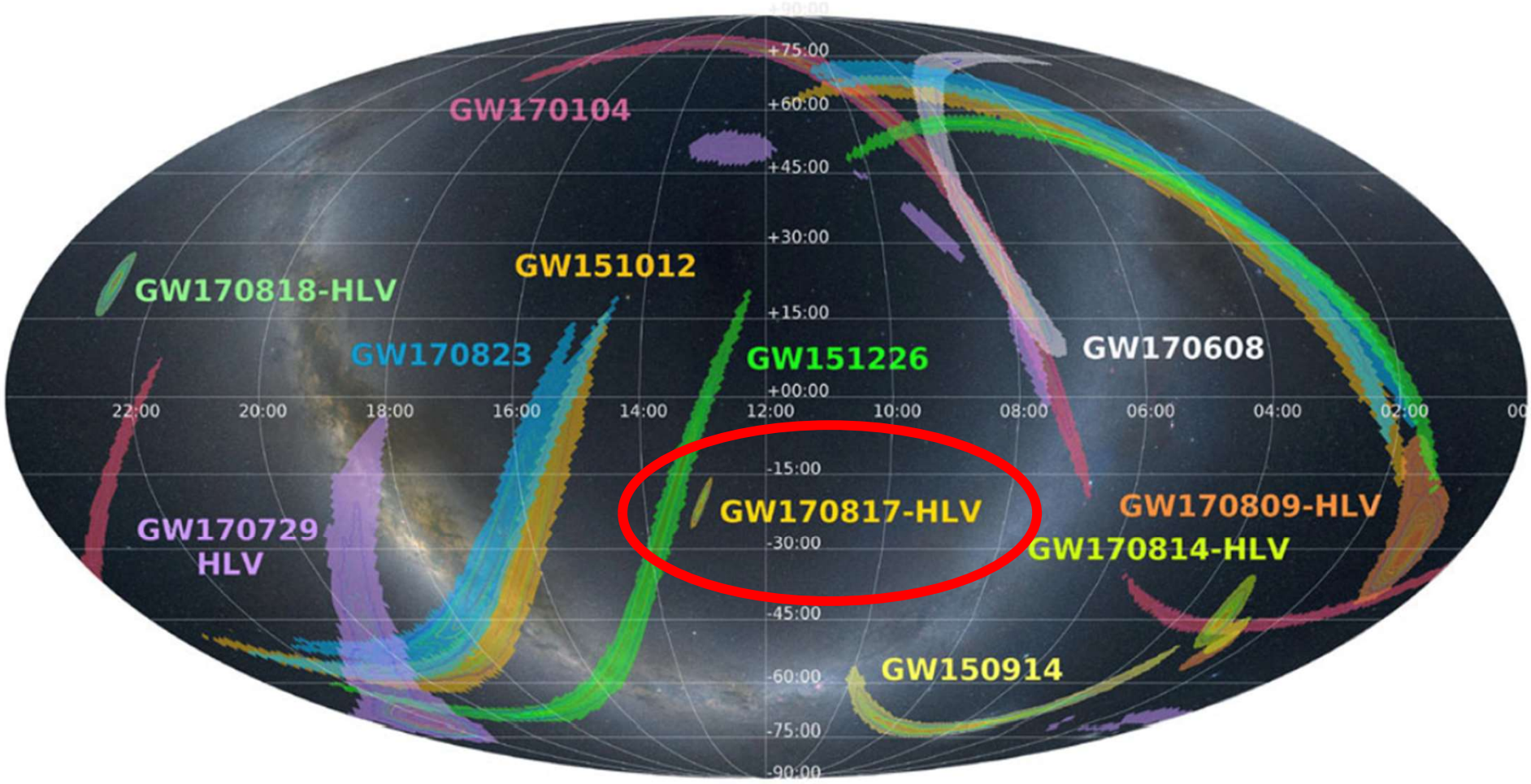


Polarization of gravitational wave




Localizing Gravitational-wave Events
Virgo, Cascina, Italy
LIGO, Livingston, LA
LIGO, Hanford, WA
Blind spot of GW170817
By measuring the arrival time of the gravitational-wave at each observatory, it's possible to identify its location on the sky
A single GW observatory is mostly insensitive to the sky location; we want two and preferably three or more observatories

Sky localization

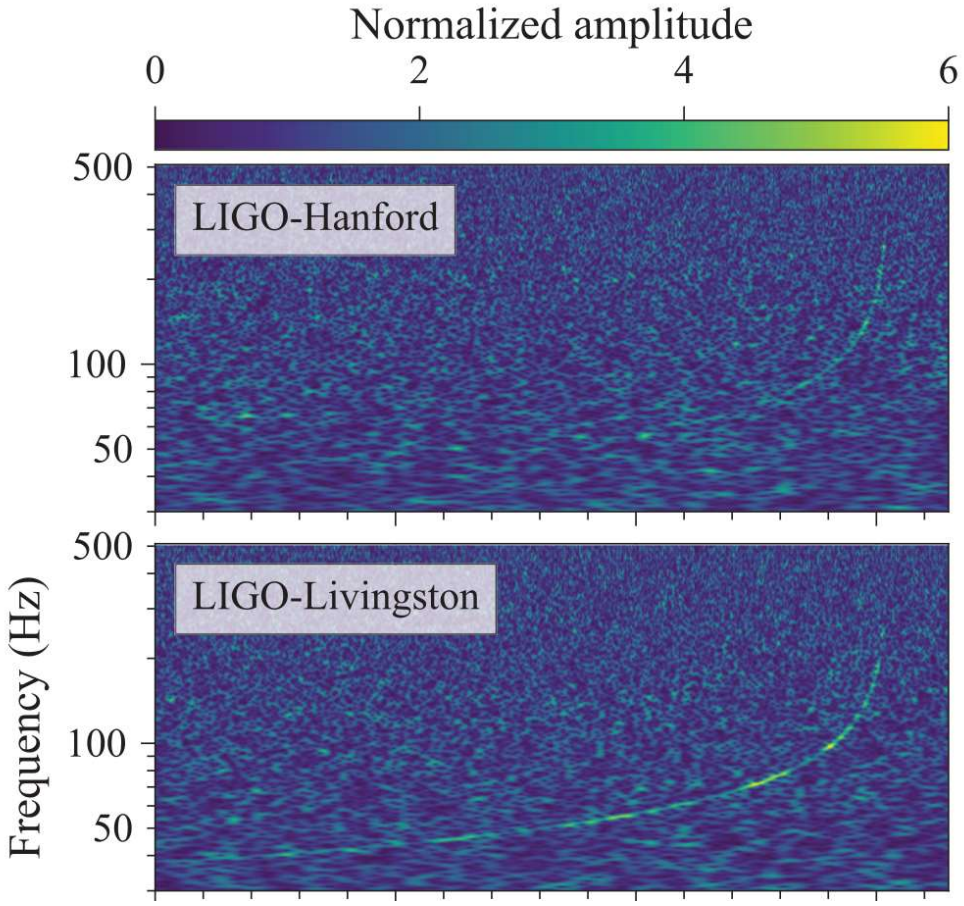


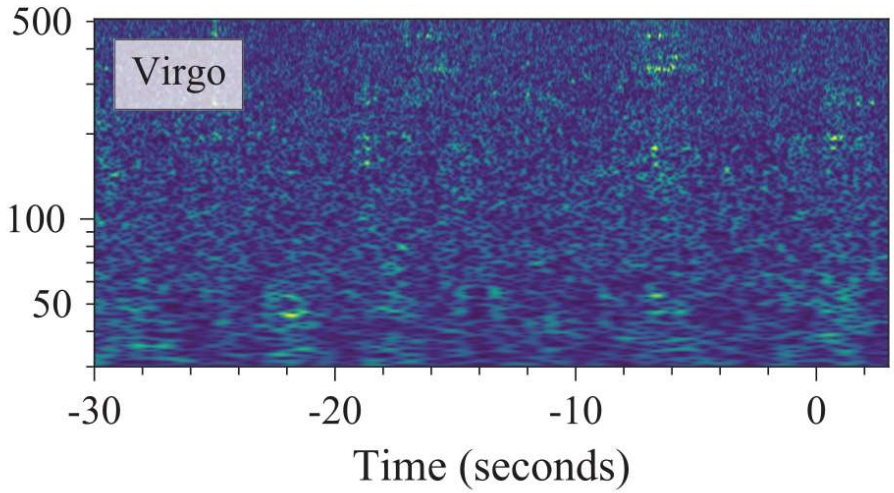
GW170817


SSS17a
August 17, 2017


August 21, 2017
Swope & Magellan Telescopes

GW170817

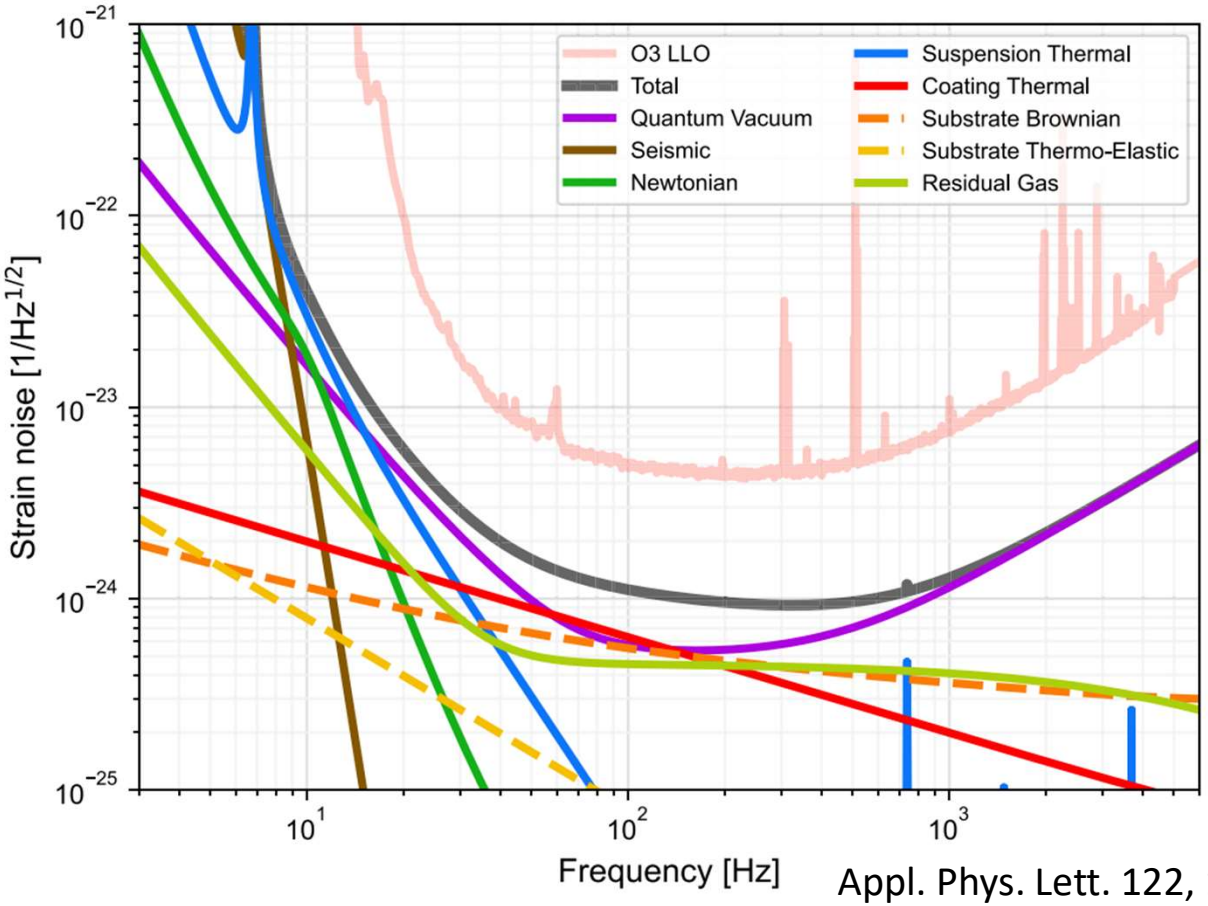

Normalized amplitude
0
2
4
6
500
LIGO-Hanford
100
50
500
LIGO-Livingston
100
50
Frequency (Hz)


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


VIRGO

2. Sensitivity curve of gravitational wave detector

LIGO sensitivity

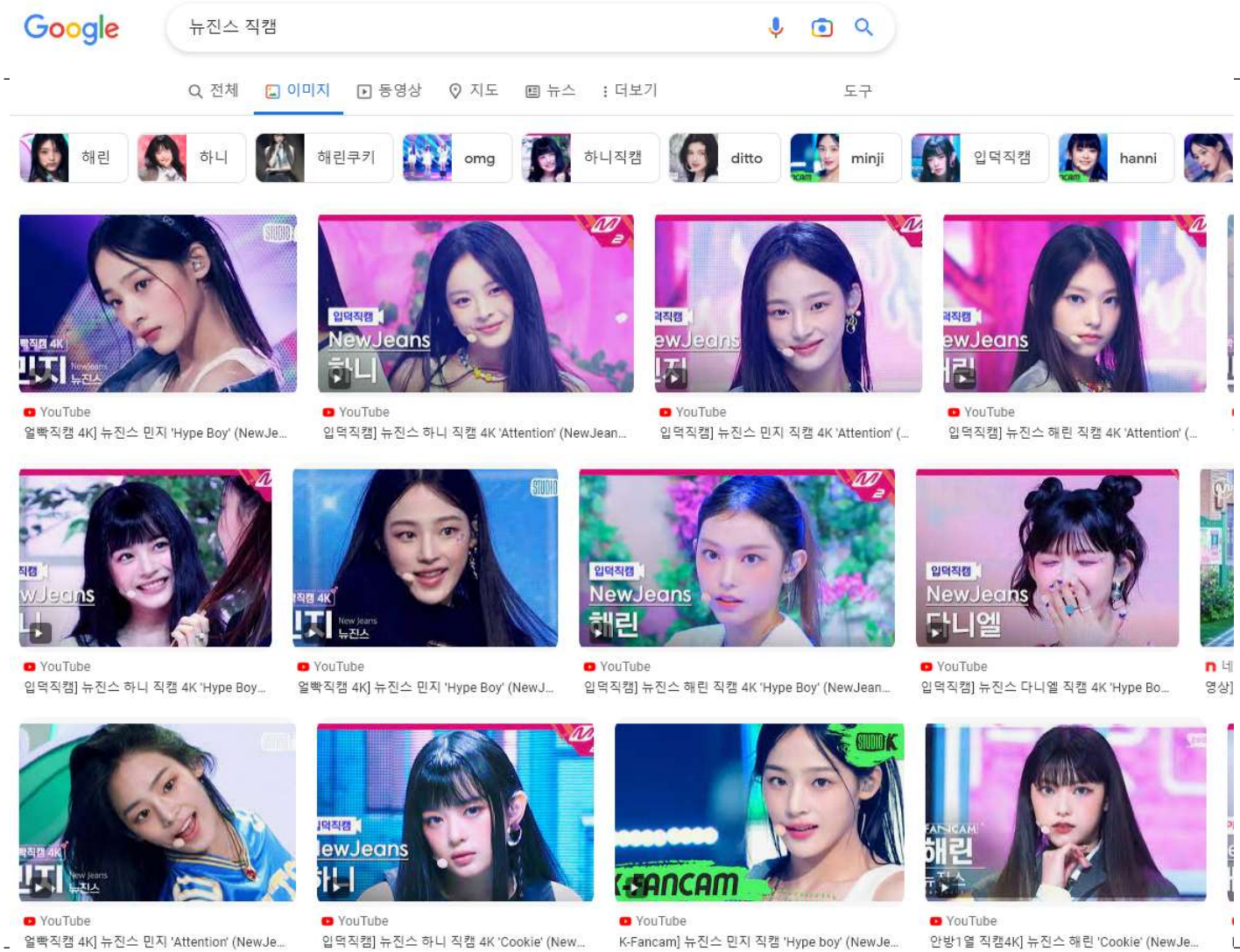


Appl. Phys. Lett. 122, 110502 (2023)

Signal and noise

Signal : 전달하고 자 하는 것

Noise : 시그널을 제외한 나머지


Google
뉴진스 직캠
전체
이미지
동영상
지도
뉴스
더보기
도구
해린
하니
해린쿠키
omg
하니직캠
ditto
minji
입덕직캠
hanni
YouTube
얼빡직캠 4K] 뉴진스 민지 'Hype Boy' (NewJe...
YouTube
입덕직캠] 뉴진스 하니 직캠 4K 'Attention' (NewJean...
YouTube
입덕직캠] 뉴진스 민지 직캠 4K 'Attention' (...
YouTube
입덕직캠] 뉴진스 해린 직캠 4K 'Attention' (...
YouTube
입덕직캠] 뉴진스 하니 직캠 4K 'Hype Boy...
YouTube
얼빡직캠 4K] 뉴진스 민지 'Hype Boy' (NewJ...
YouTube
입덕직캠] 뉴진스 해린 직캠 4K 'Hype Boy' (NewJean...
YouTube
입덕직캠] 뉴진스 다니엘 직캠 4K 'Hype Bo...
YouTube
얼빡직캠 4K] 뉴진스 민지 'Attention' (NewJe...
YouTube
입덕직캠] 뉴진스 하니 직캠 4K 'Cookie' (New...
YouTube
K-Fancam] 뉴진스 민지 직캠 'Hype boy' (NewJe...
YouTube
안방1열 직캠4K] 뉴진스 해린 'Cookie' (NewJe...

아이돌 직캠?

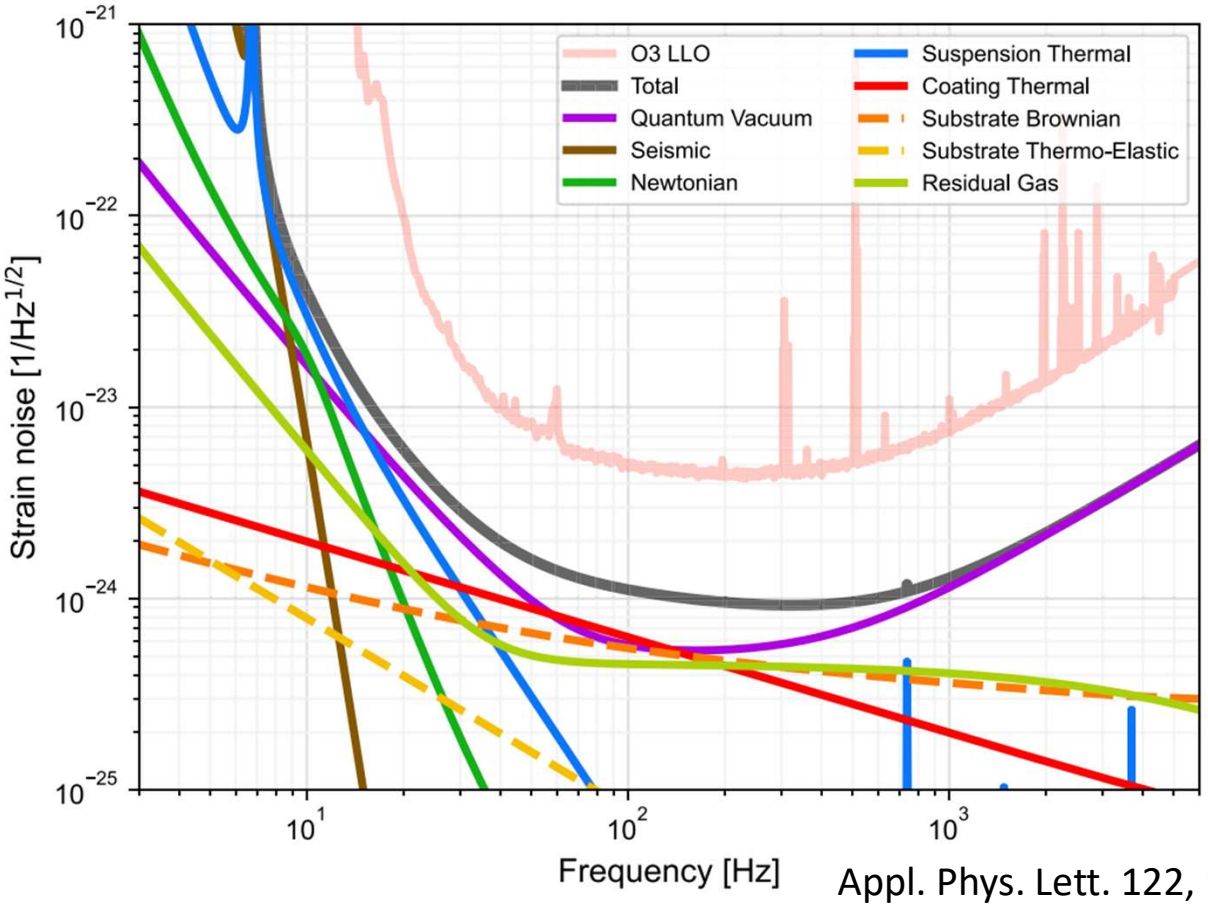
왜??

Signal and noise

Signal : 내가보고 싶은 멤버

Noise : 내가 보고싶은 멤버 뺀 나머지

LIGO sensitivity



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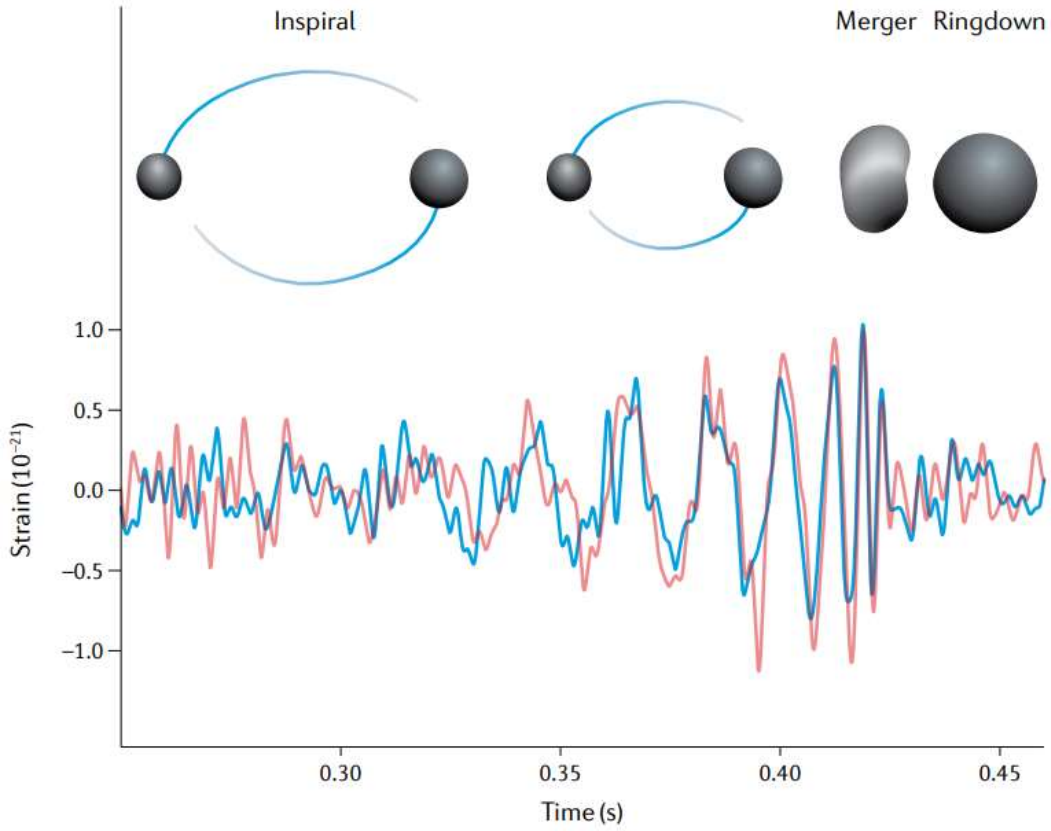
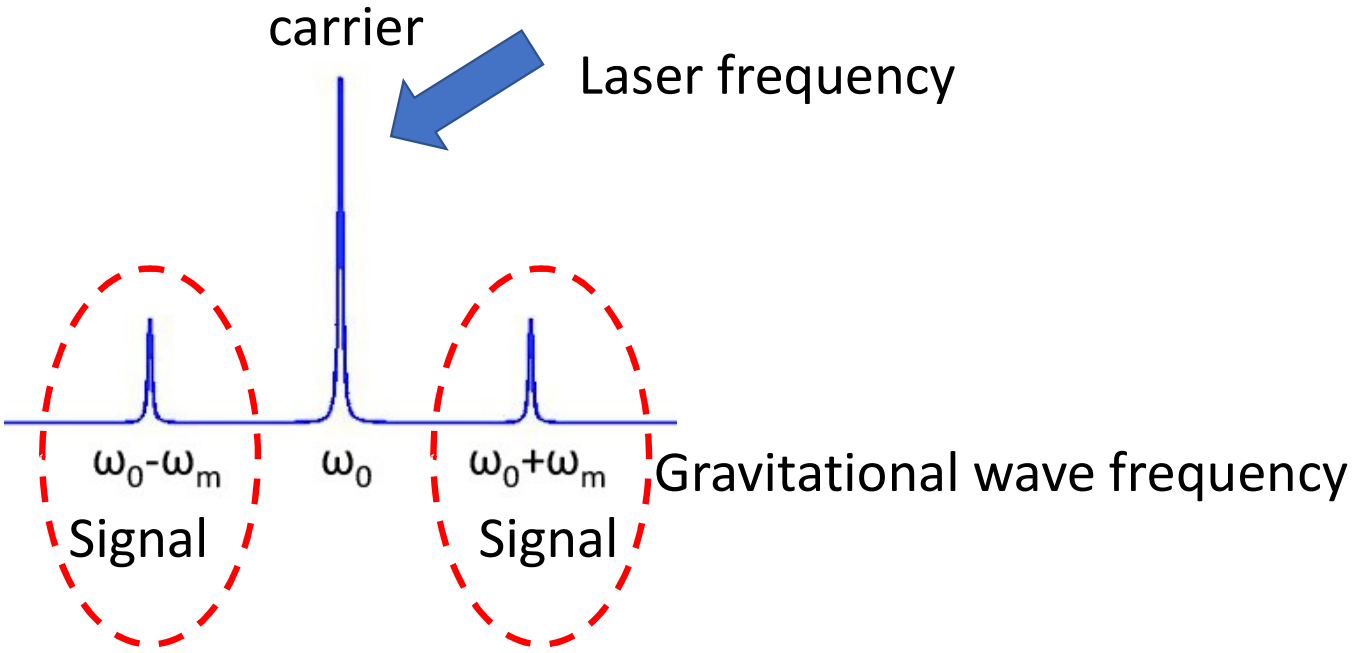
Inspiral–Merger–Ringdown



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

Side band figure



Side band figure

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

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

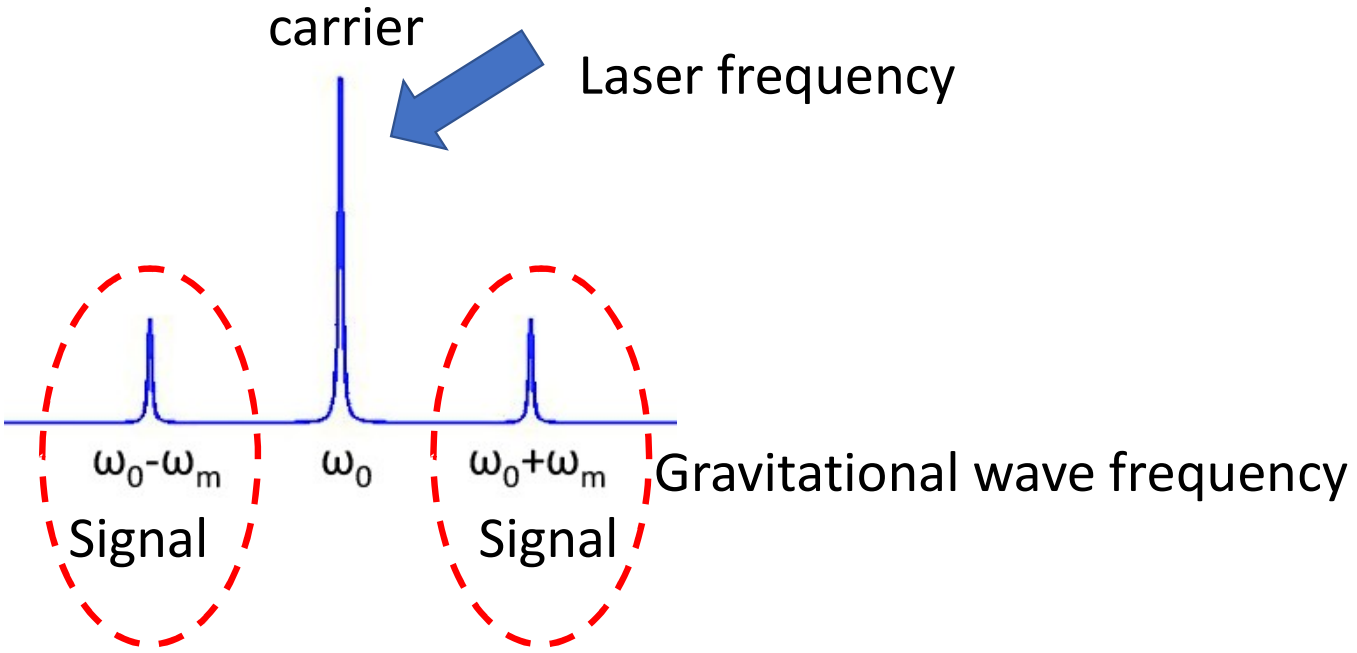
Adding $\cos(A)$ to both sides:

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

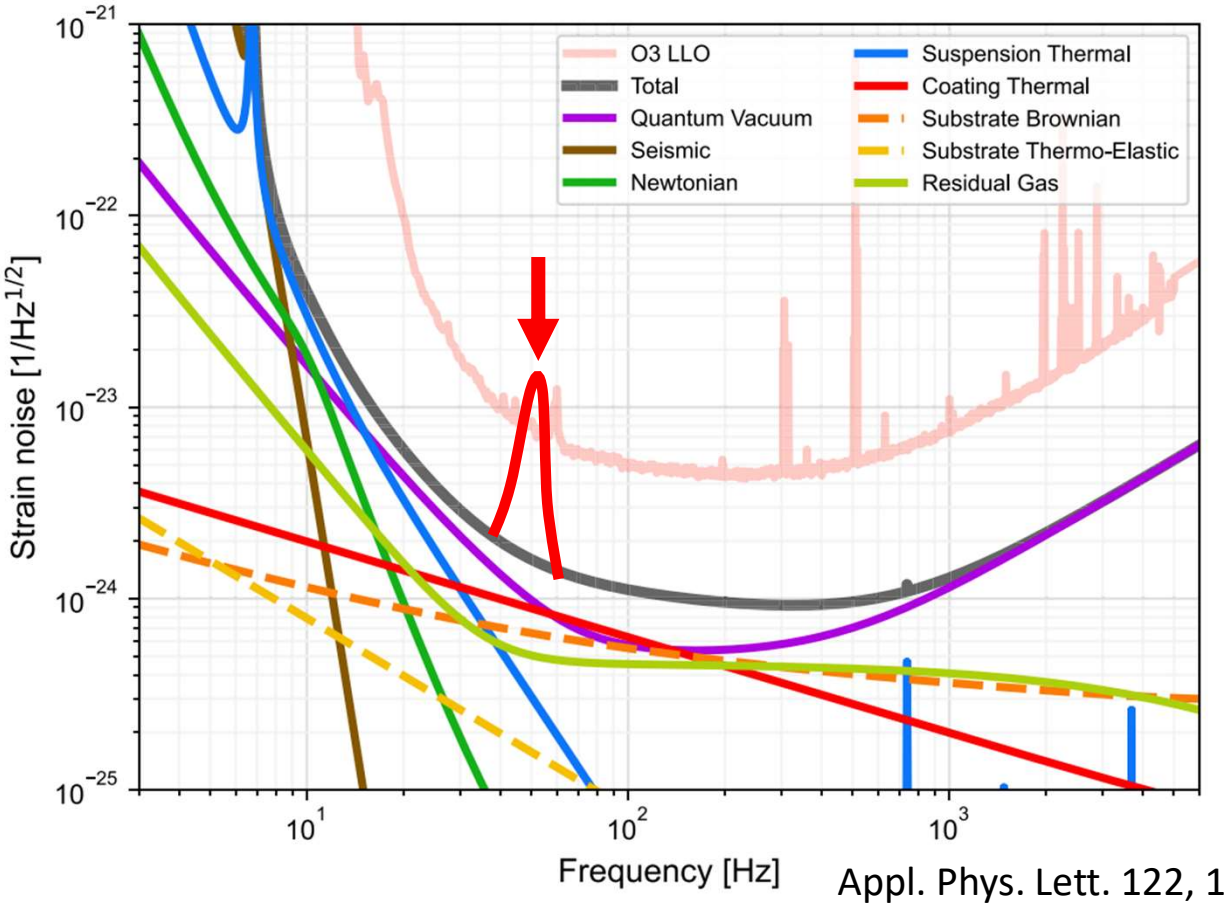
Substituting (for instance) $A \triangleq 1000\cdot t$ and $B \triangleq 100\cdot t$, where t represents time:

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

Side band figure



LIGO sensitivity



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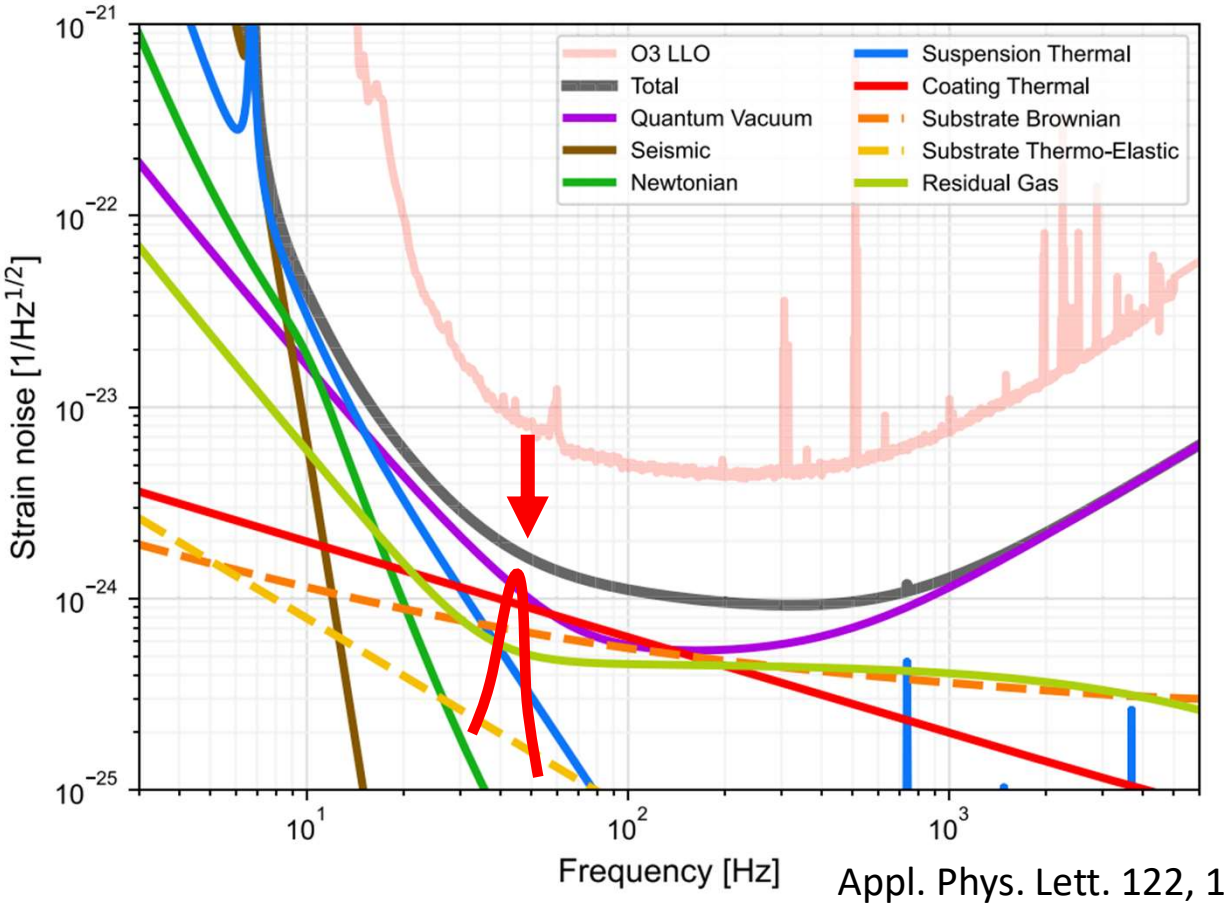
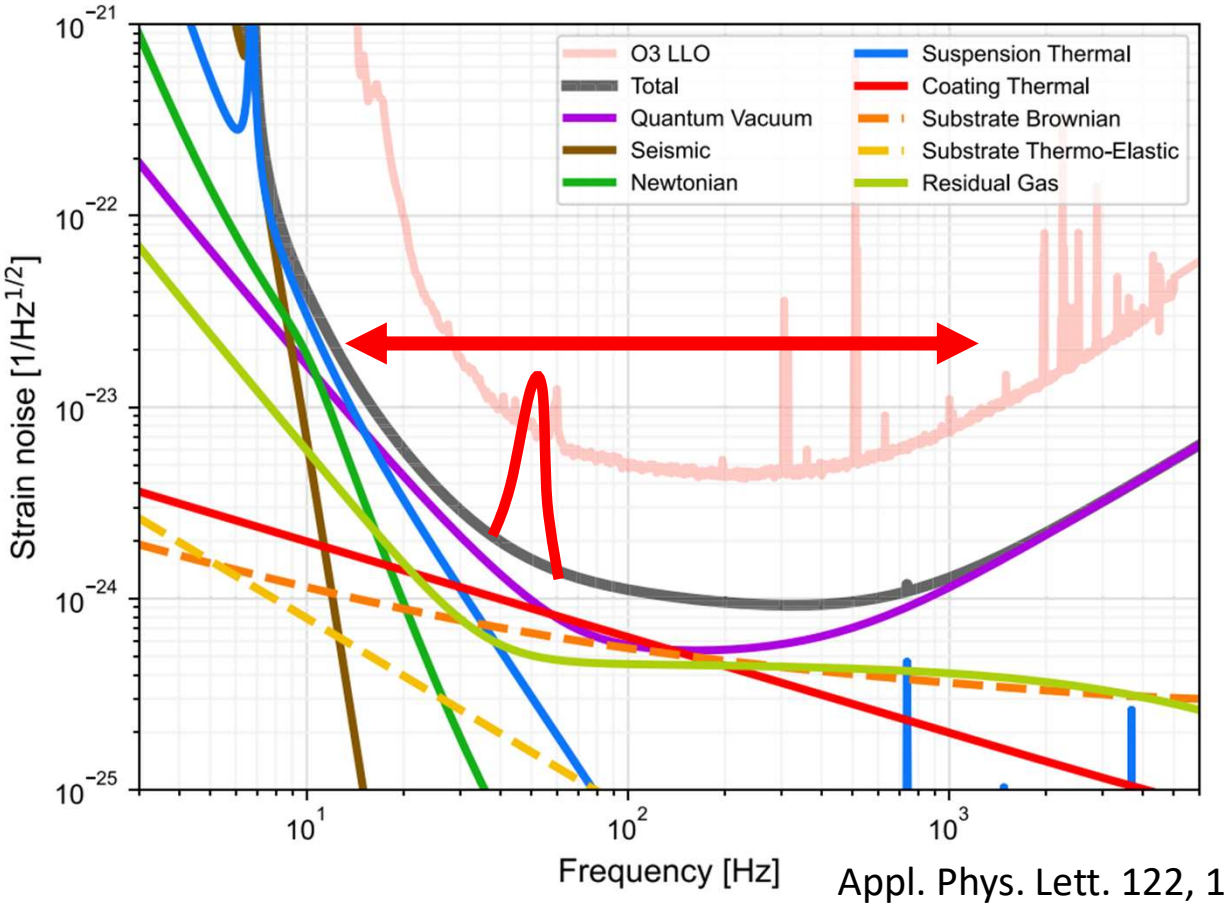
LIGO sensitivity



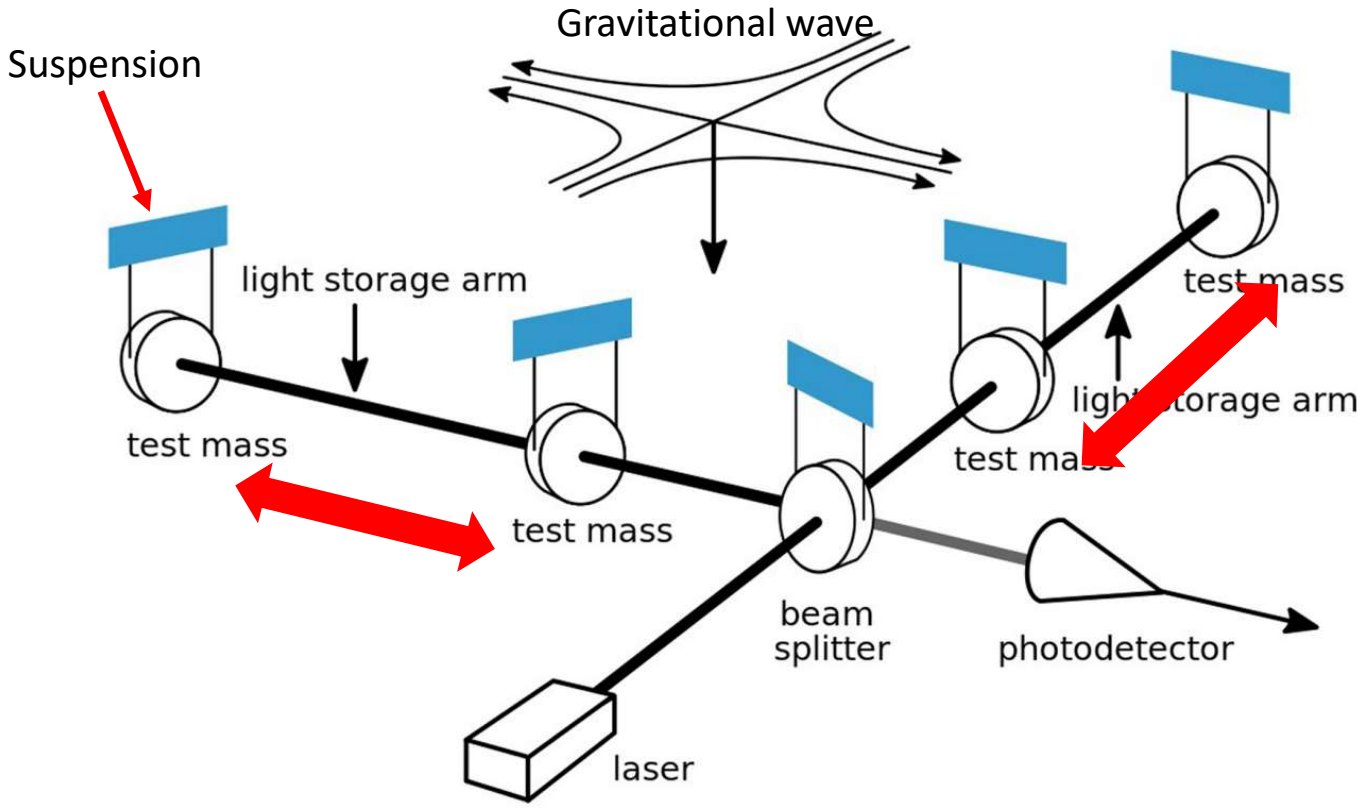
Appl. Phys. Lett. 122, 110502 (2023)

LIGO sensitivity



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

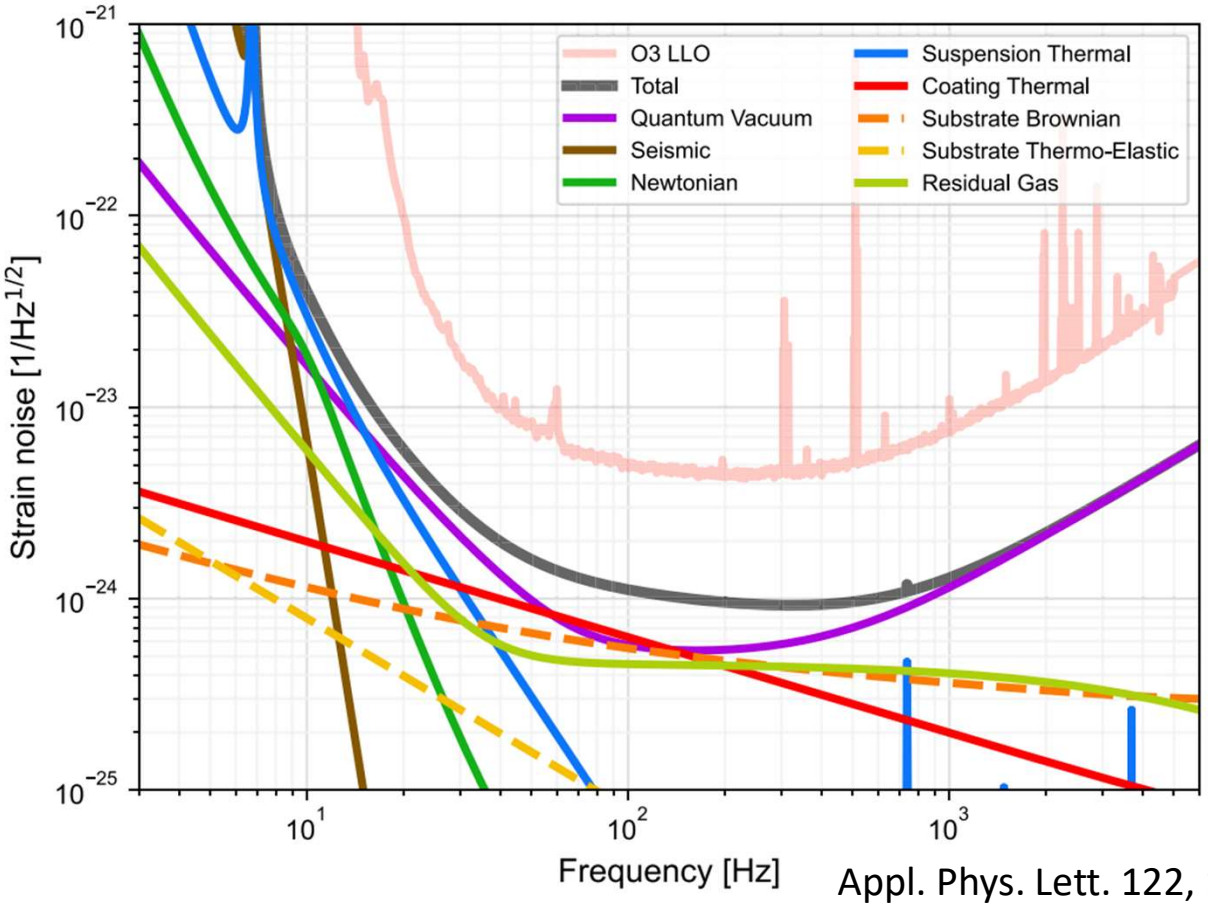
Gravitational wave and GW detector



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

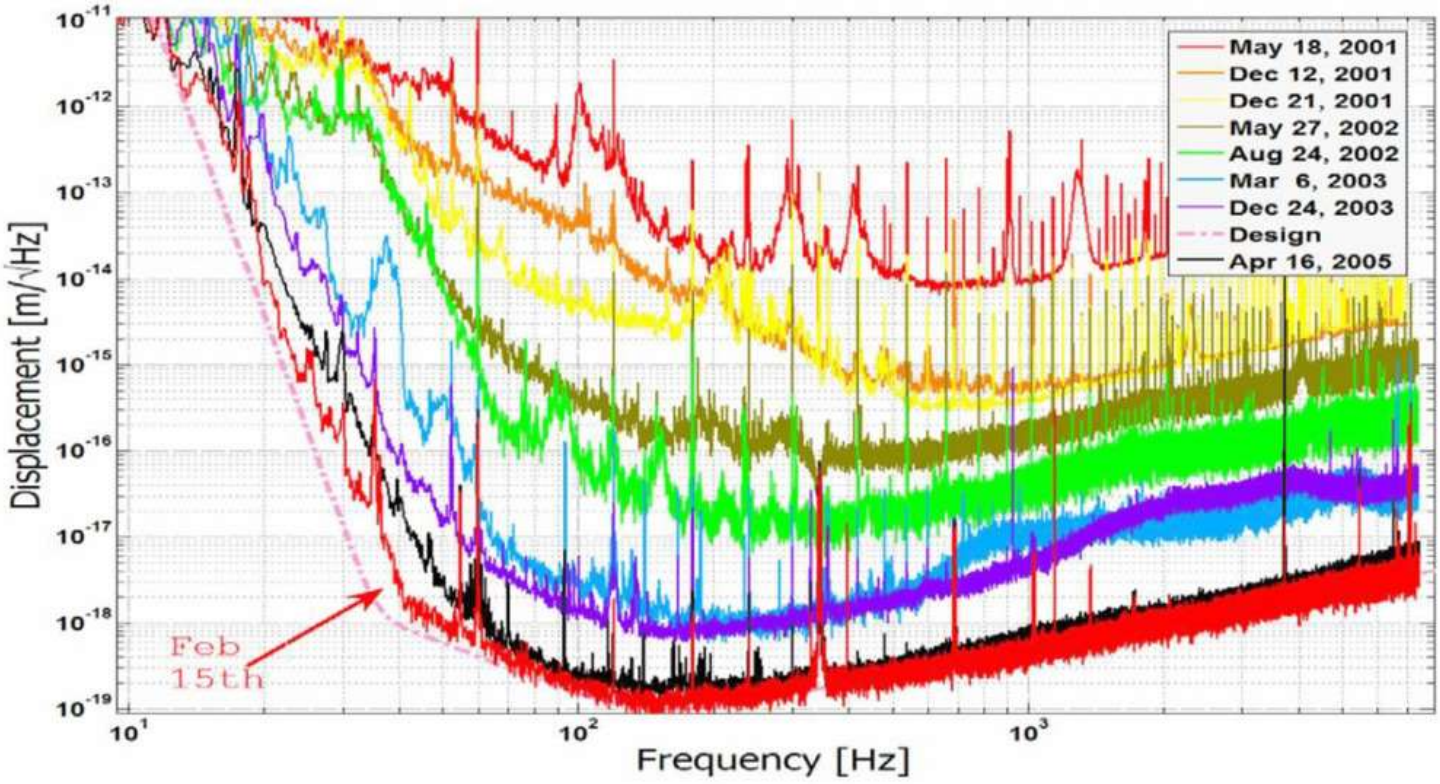
Swing out of gravitational wave frequency

LIGO sensitivity

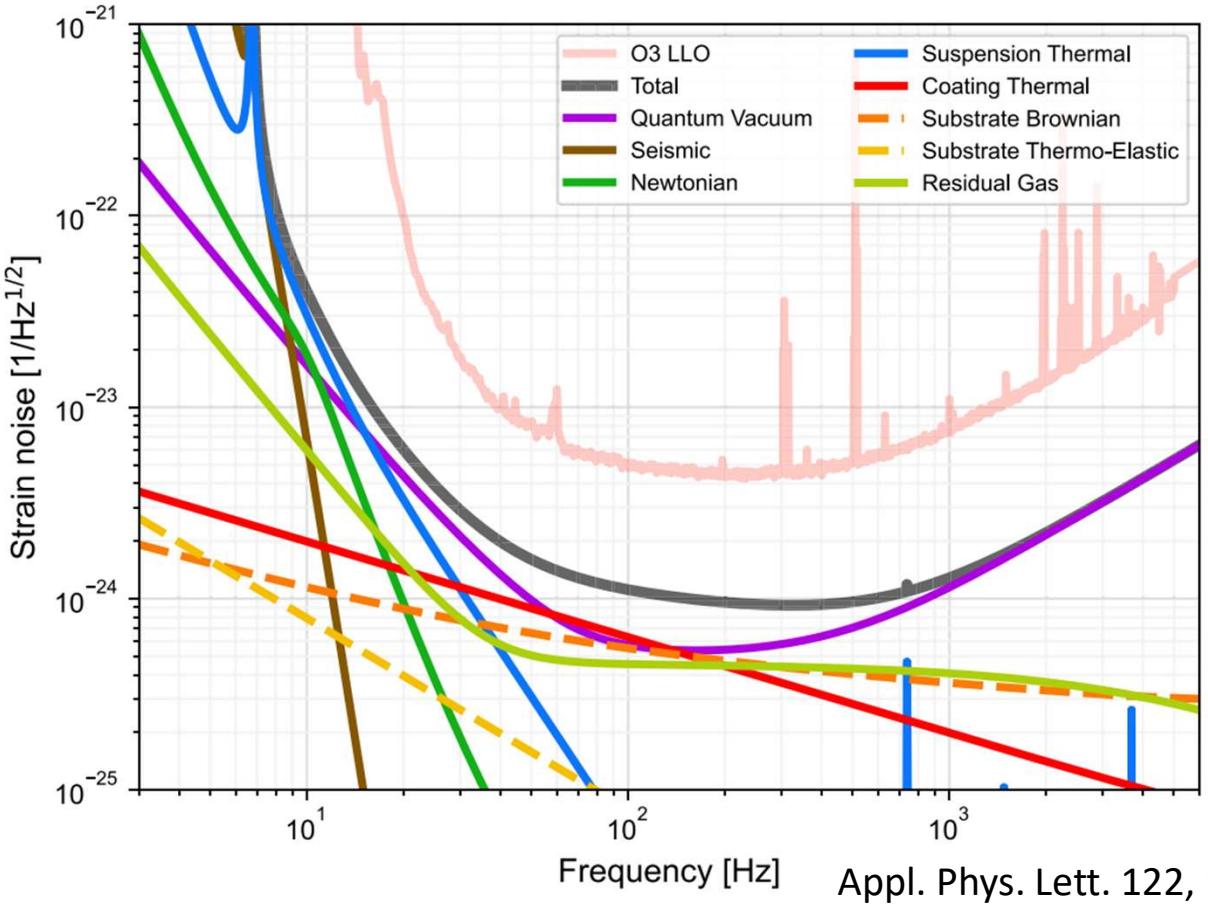


Appl. Phys. Lett. 122, 110502 (2023)

Sensitivity during science run

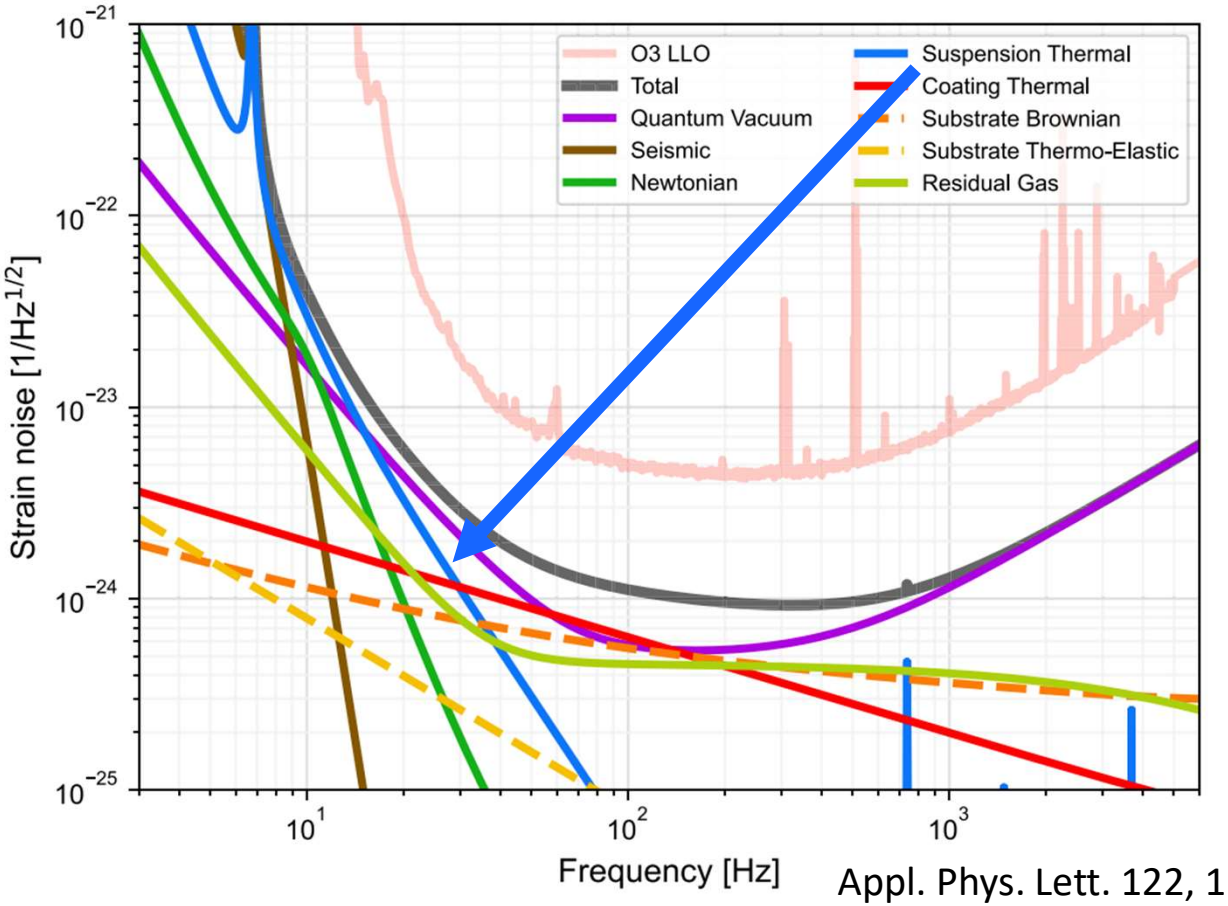


LIGO sensitivity



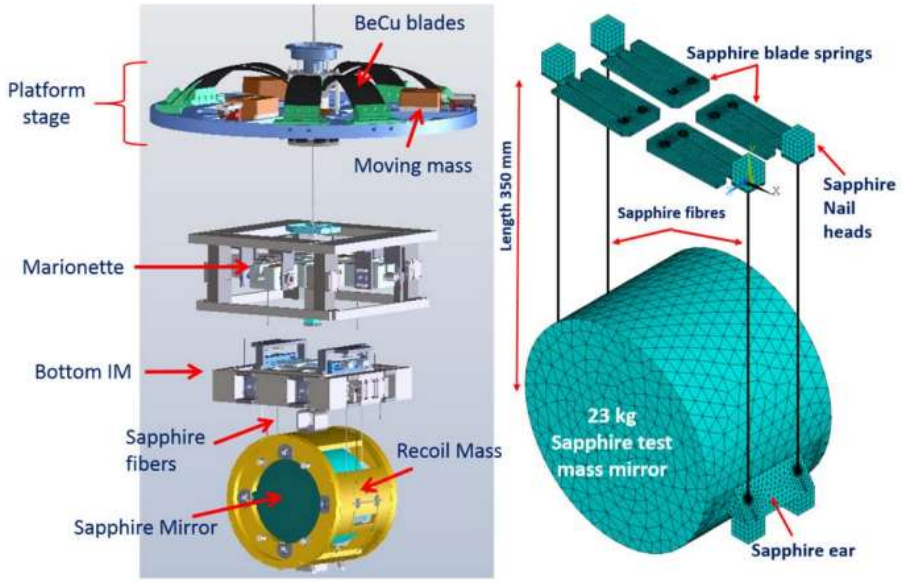
Appl. Phys. Lett. 122, 110502 (2023)

LIGO sensitivity

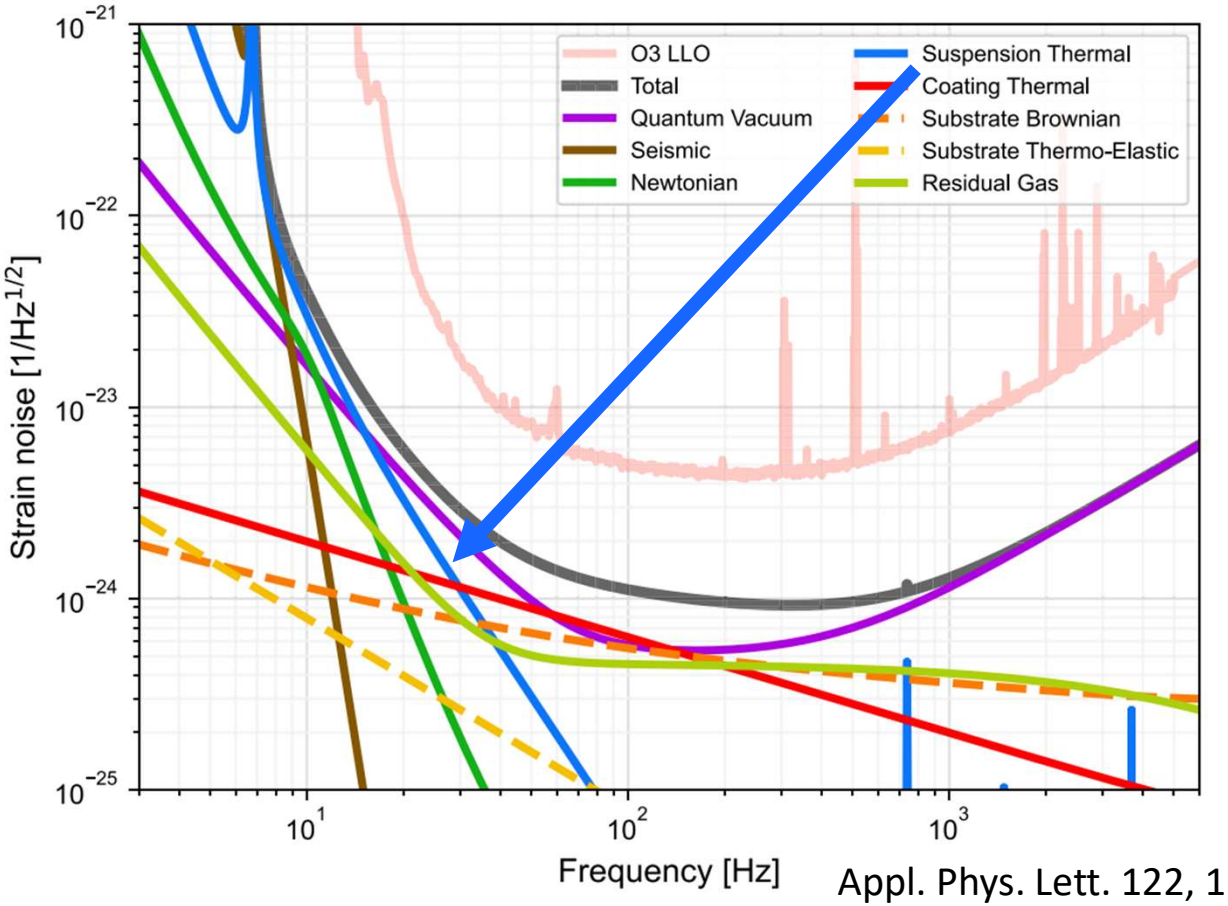


Appl. Phys. Lett. 122, 110502 (2023)

Suspension

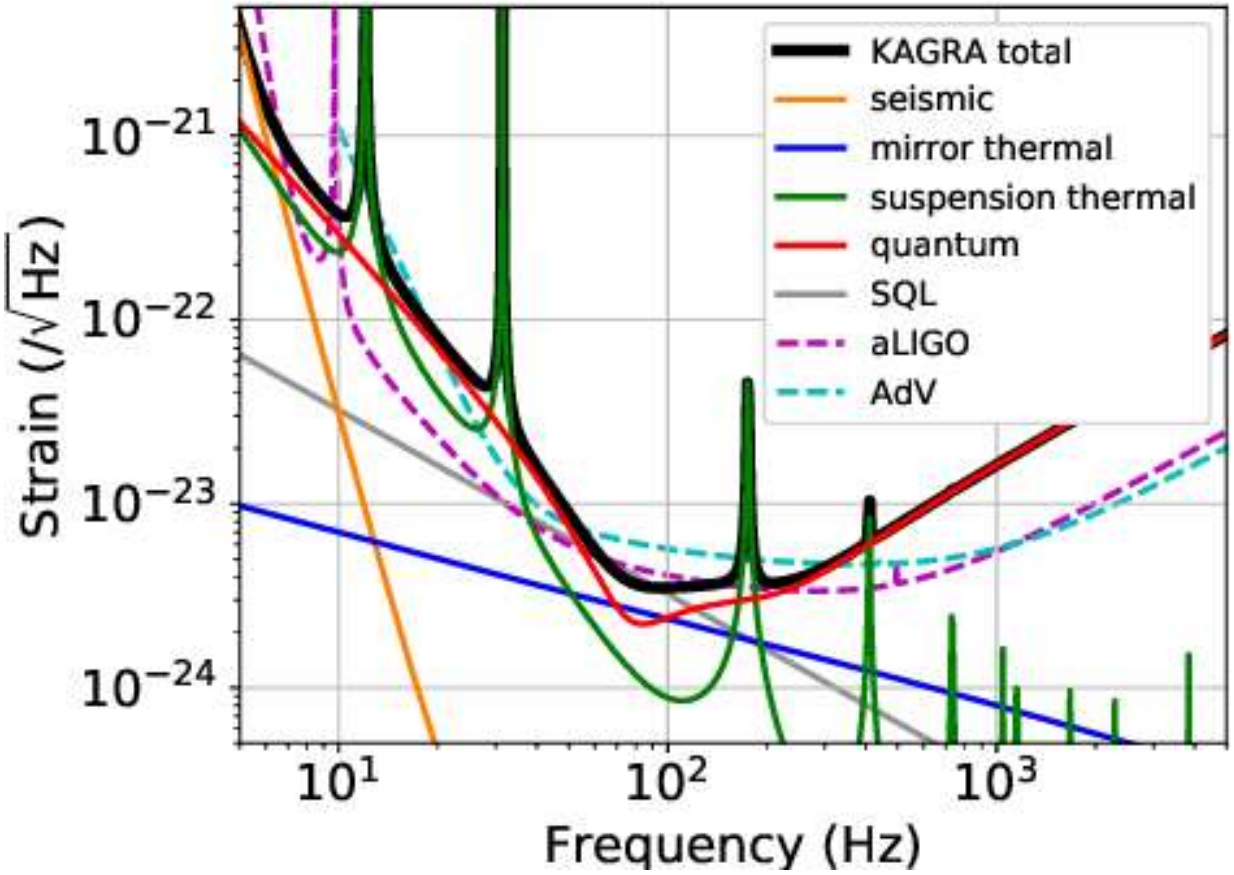

BeCu blades
Platform stage
Moving mass
Marionette
Bottom IM
Sapphire fibers
Recoil Mass
Sapphire Mirror
Length 350 mm
Sapphire blade springs
Sapphire Nail heads
Sapphire fibres
23 kg Sapphire test mass mirror
Sapphire ear

LIGO sensitivity

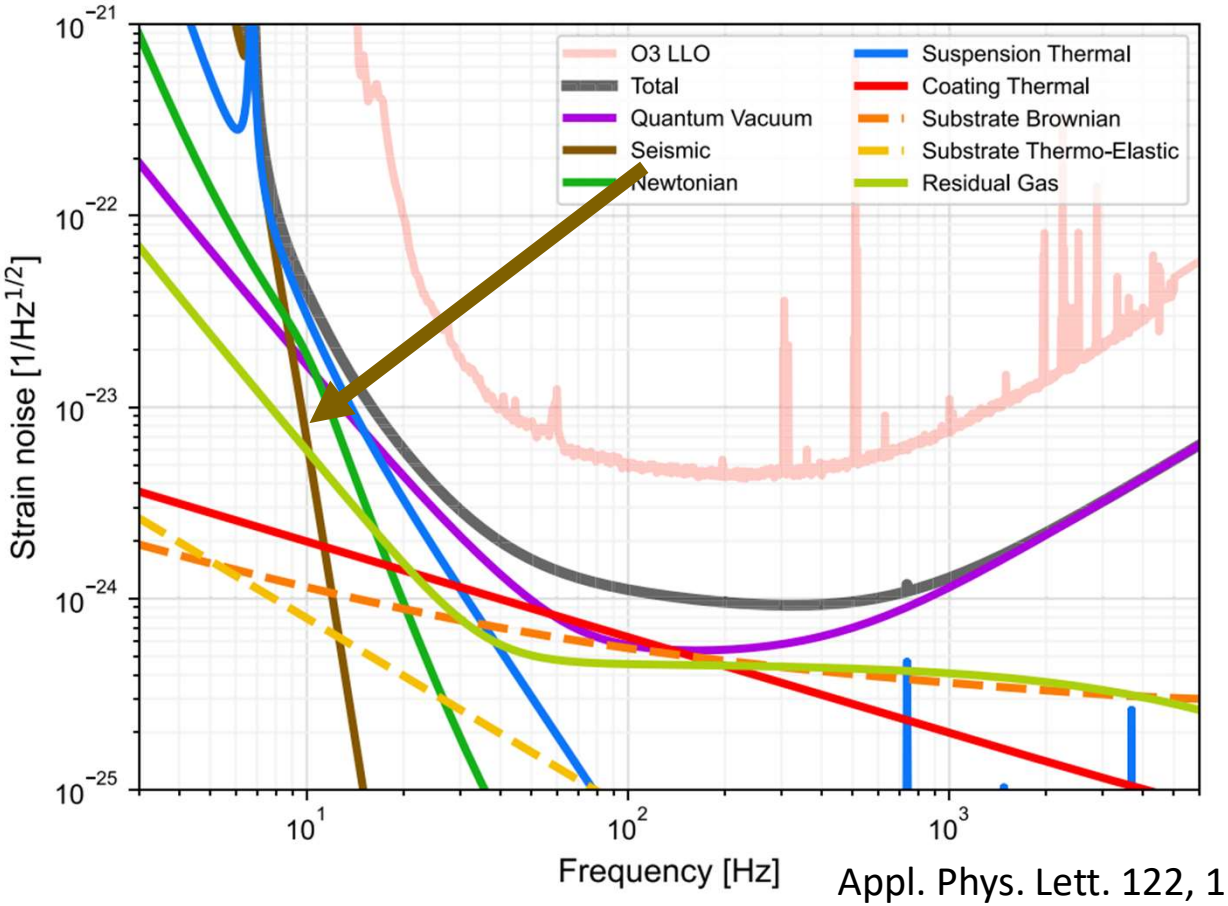


Appl. Phys. Lett. 122, 110502 (2023)

Sensitivity curve of KAGRA

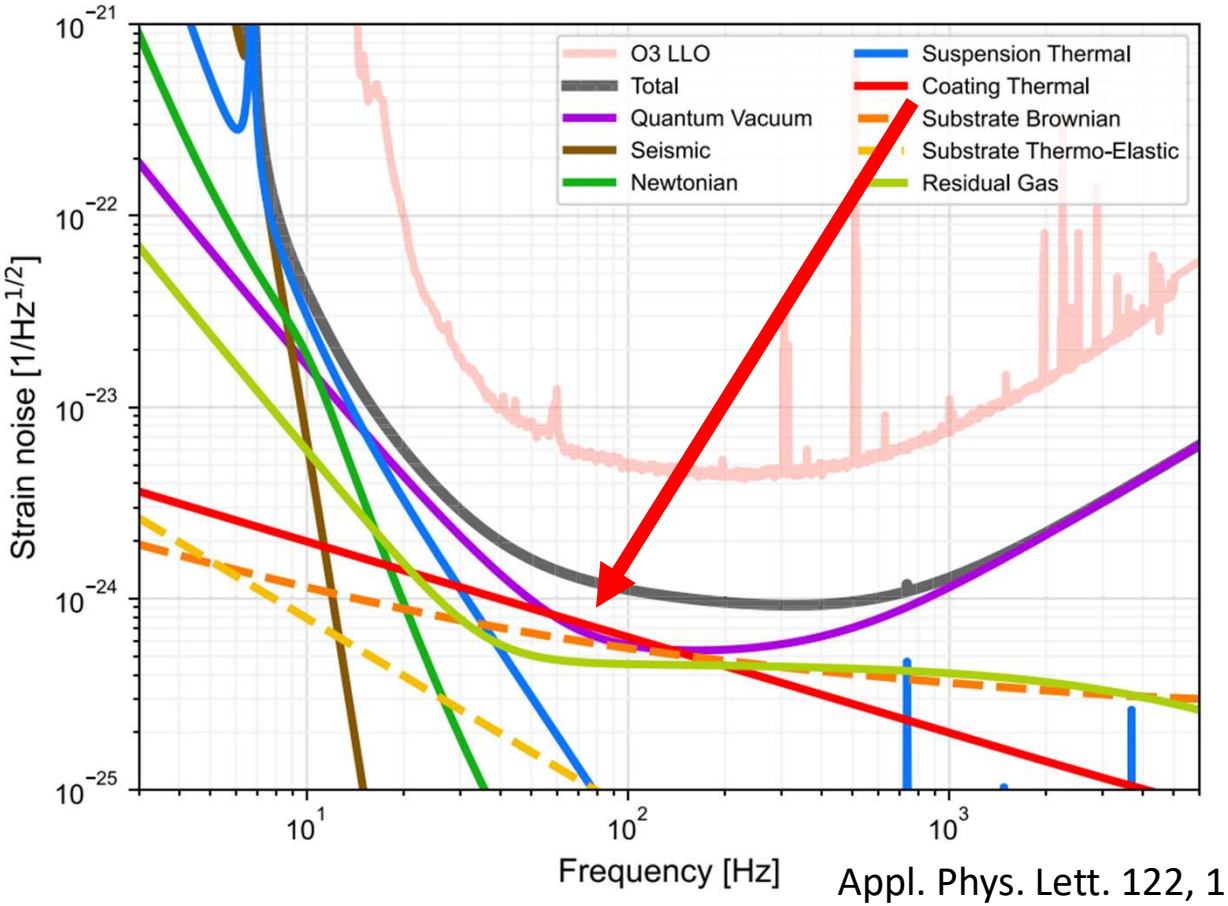


LIGO sensitivity



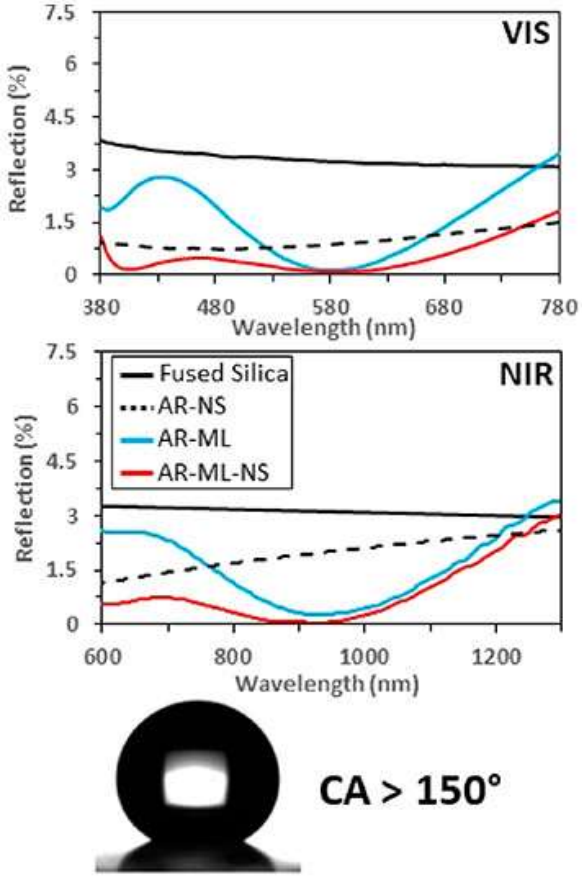
Appl. Phys. Lett. 122, 110502 (2023)

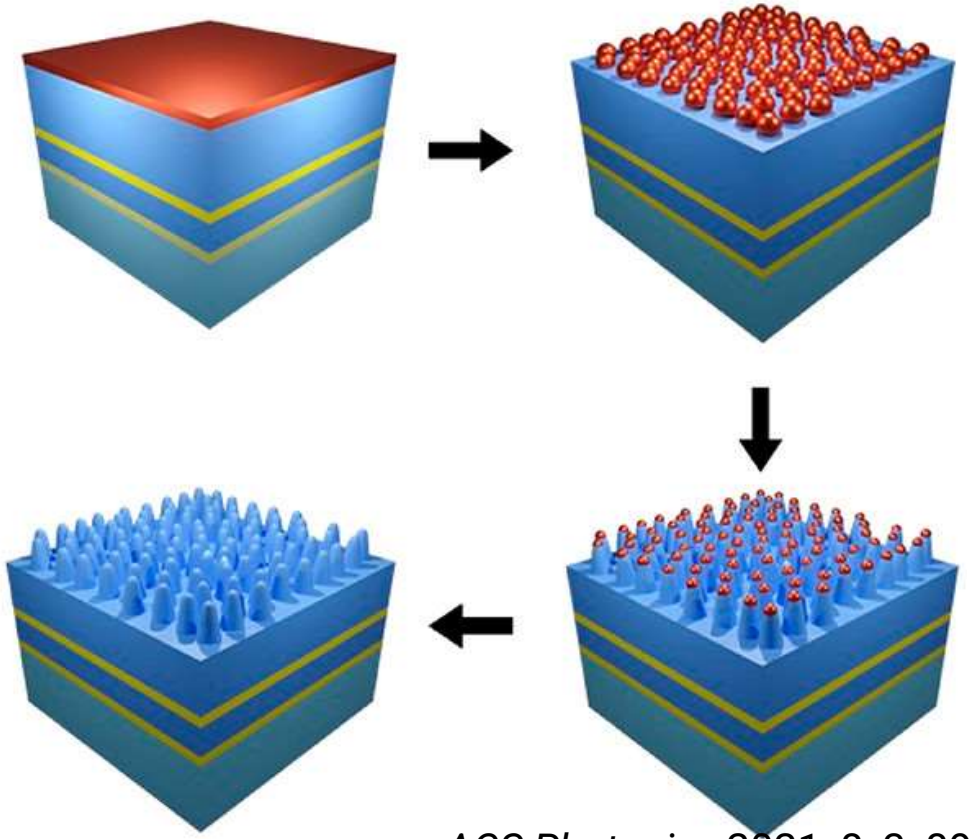
LIGO sensitivity



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

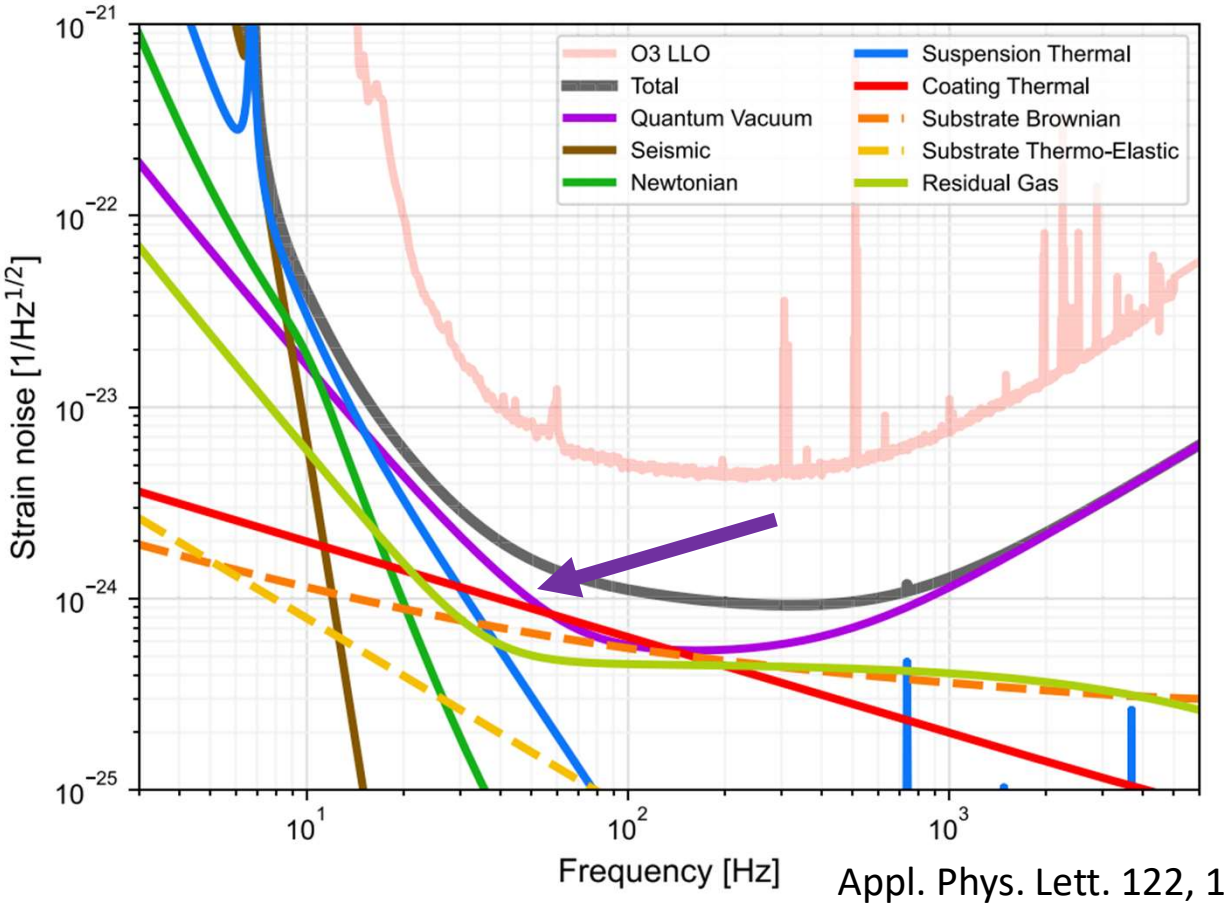
Optical coating





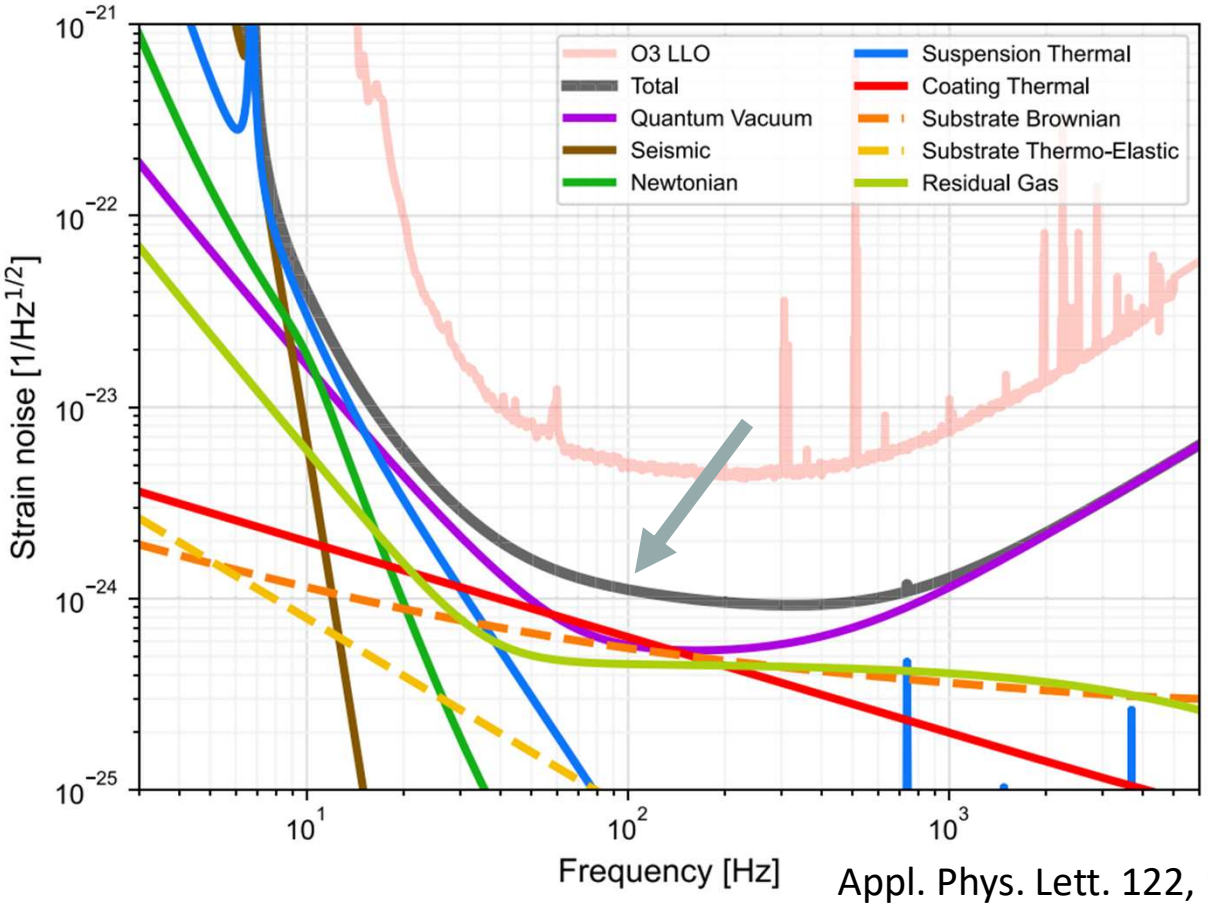
ACS Photonics 2021, 8, 3, 894−900
Publication Date:February 17, 2021
https://doi.org/10.1021/acsphotonics.0c01909

LIGO sensitivity

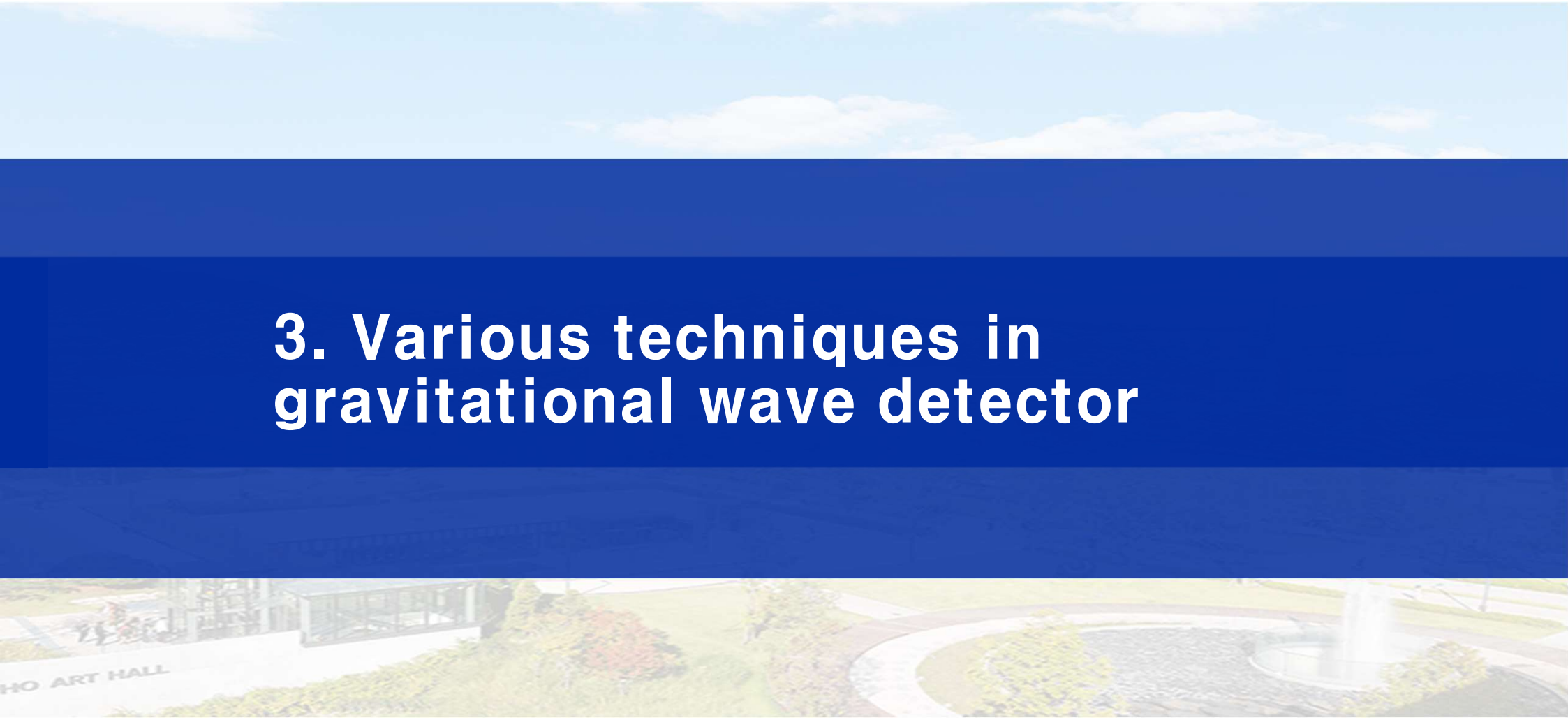


Appl. Phys. Lett. 122, 110502 (2023)

LIGO sensitivity



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

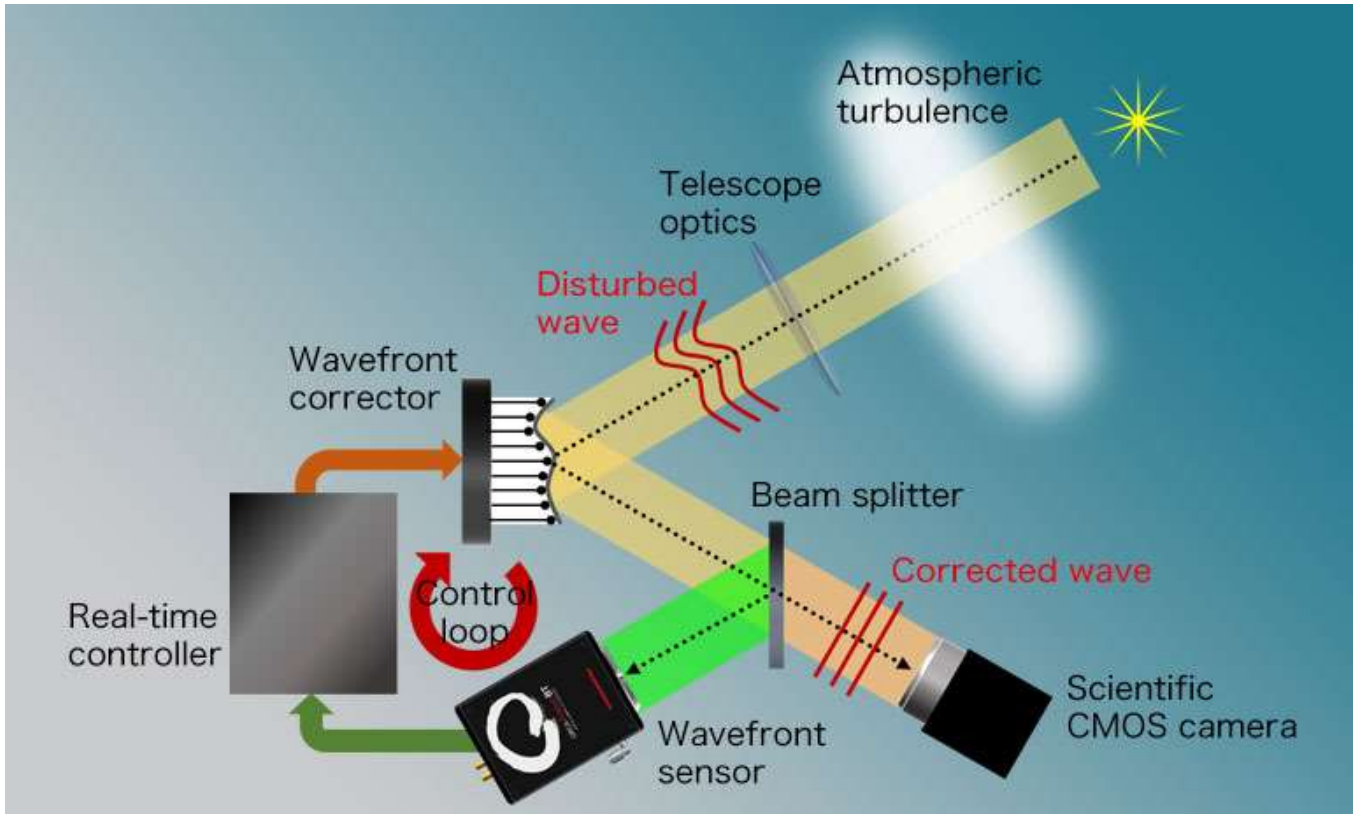


3. Various techniques in gravitational wave detector

Vacuum tunnel

Air turbulence, scattering from air

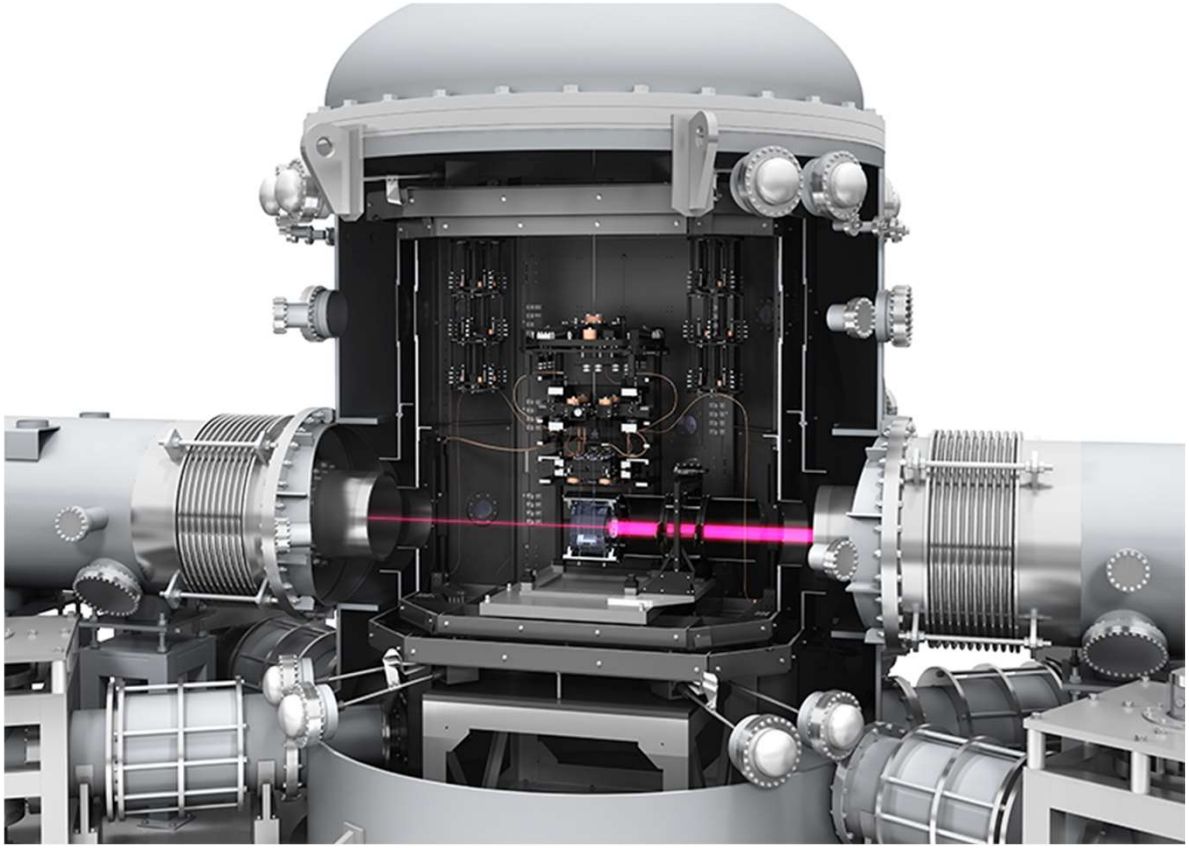
Atmospheric turbulence



Vacuum tunnel

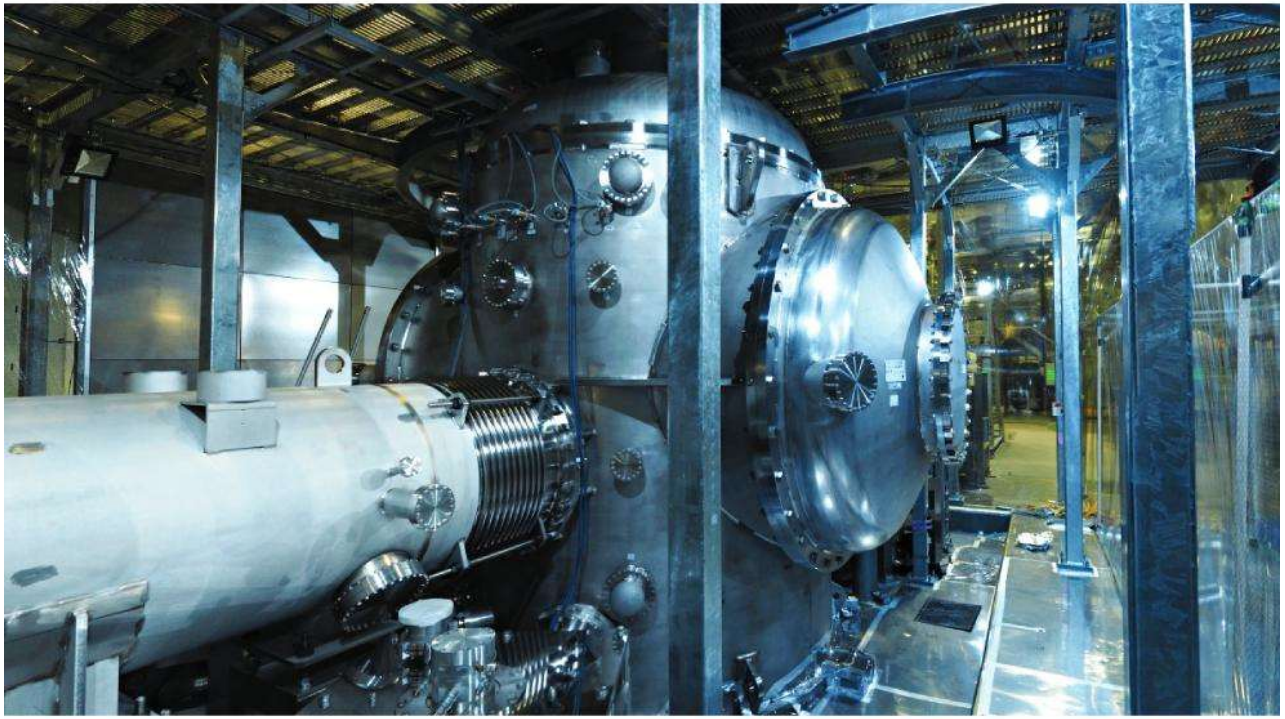
Air turbulence, scattering from air

Test mass chamber

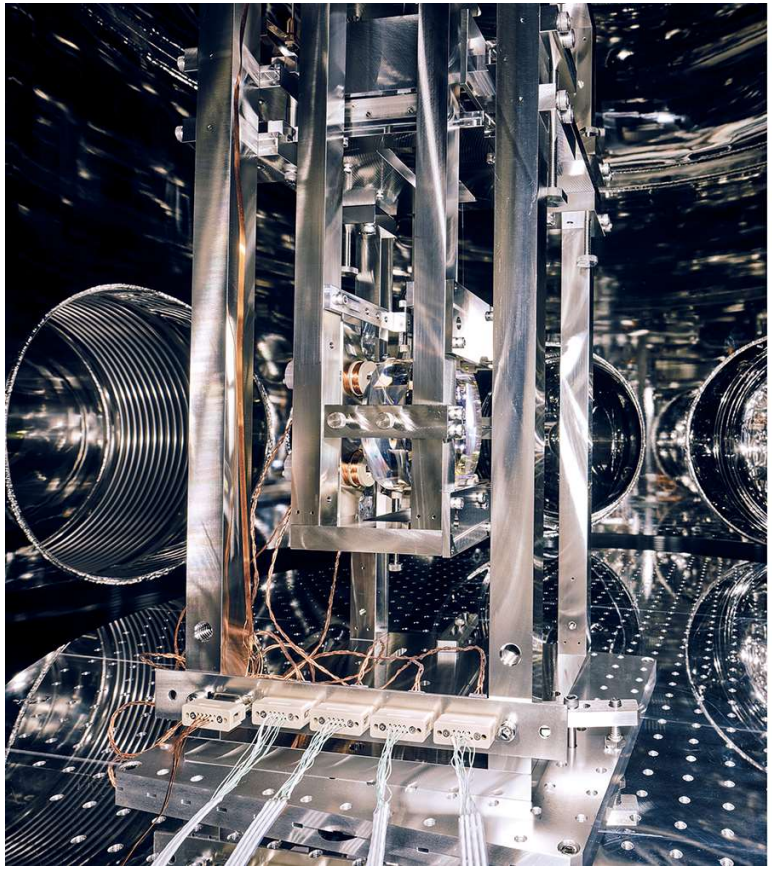


Rey.Hori

KAGRA vacuum chamber

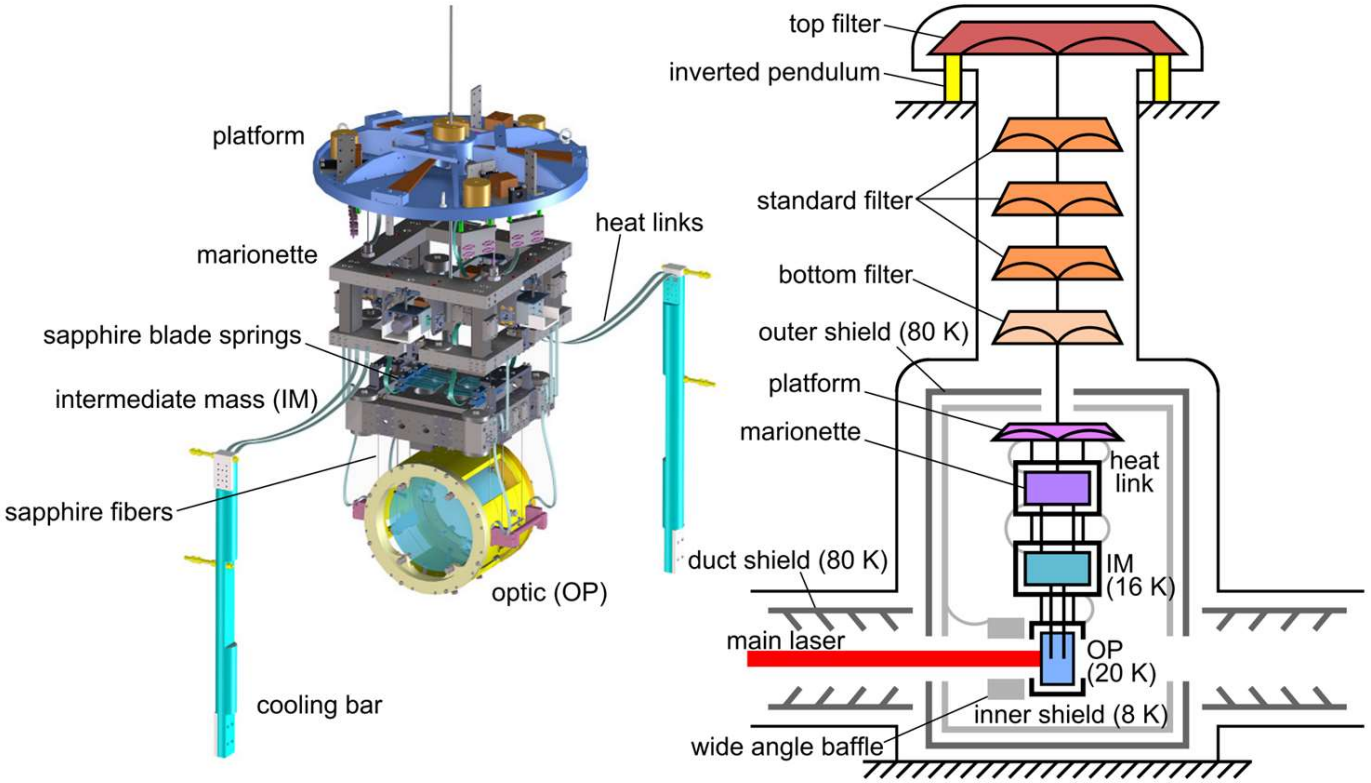


KAGRA vacuum chamber

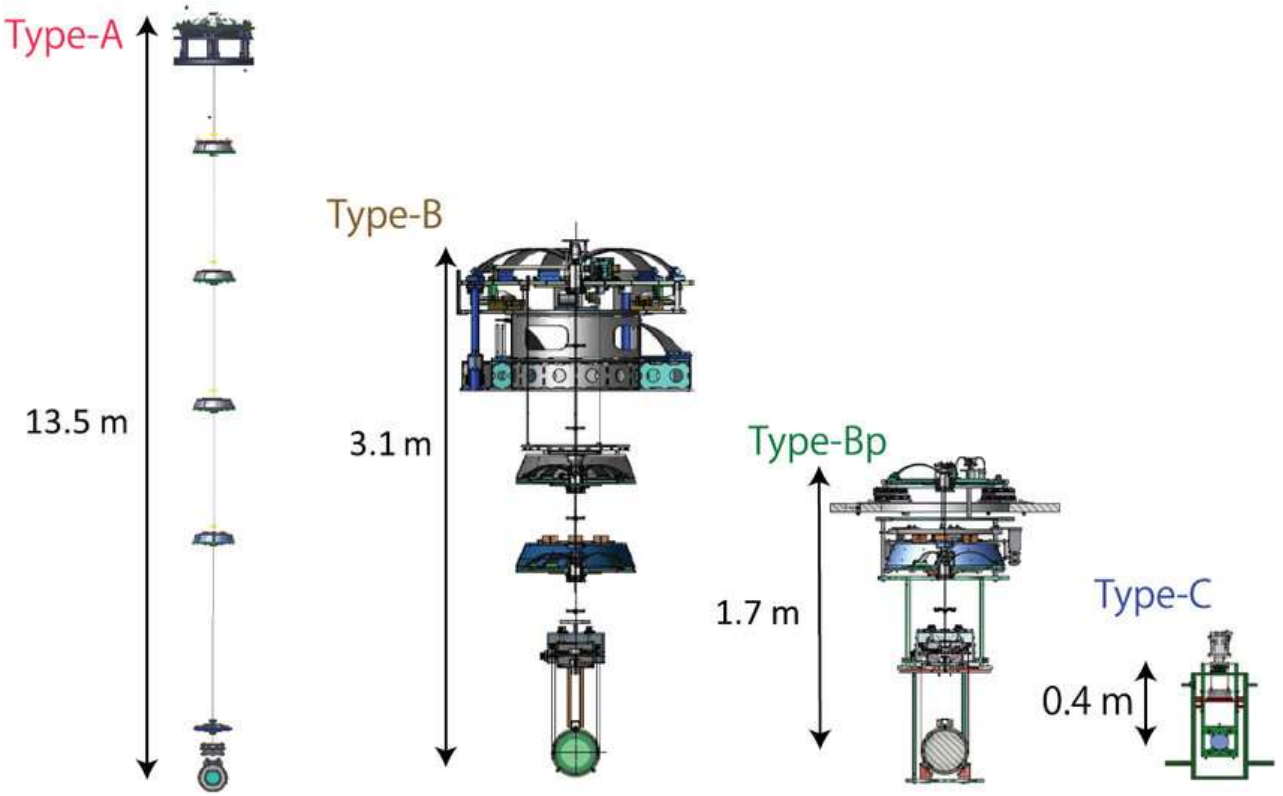


Cryocooler of KAGRA

KAGRA cryostat

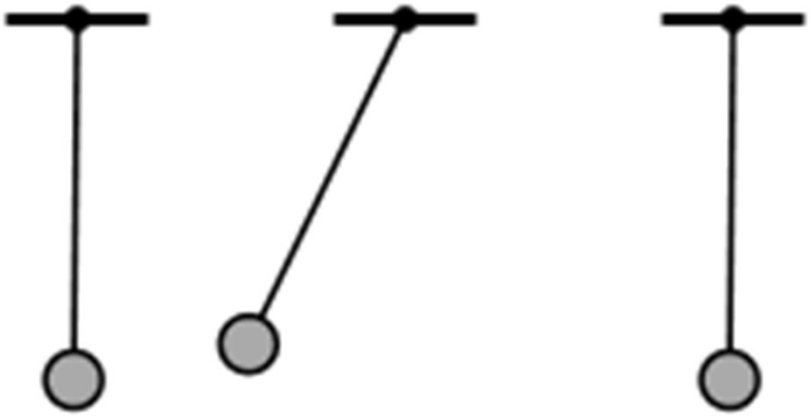


Vibration isolation

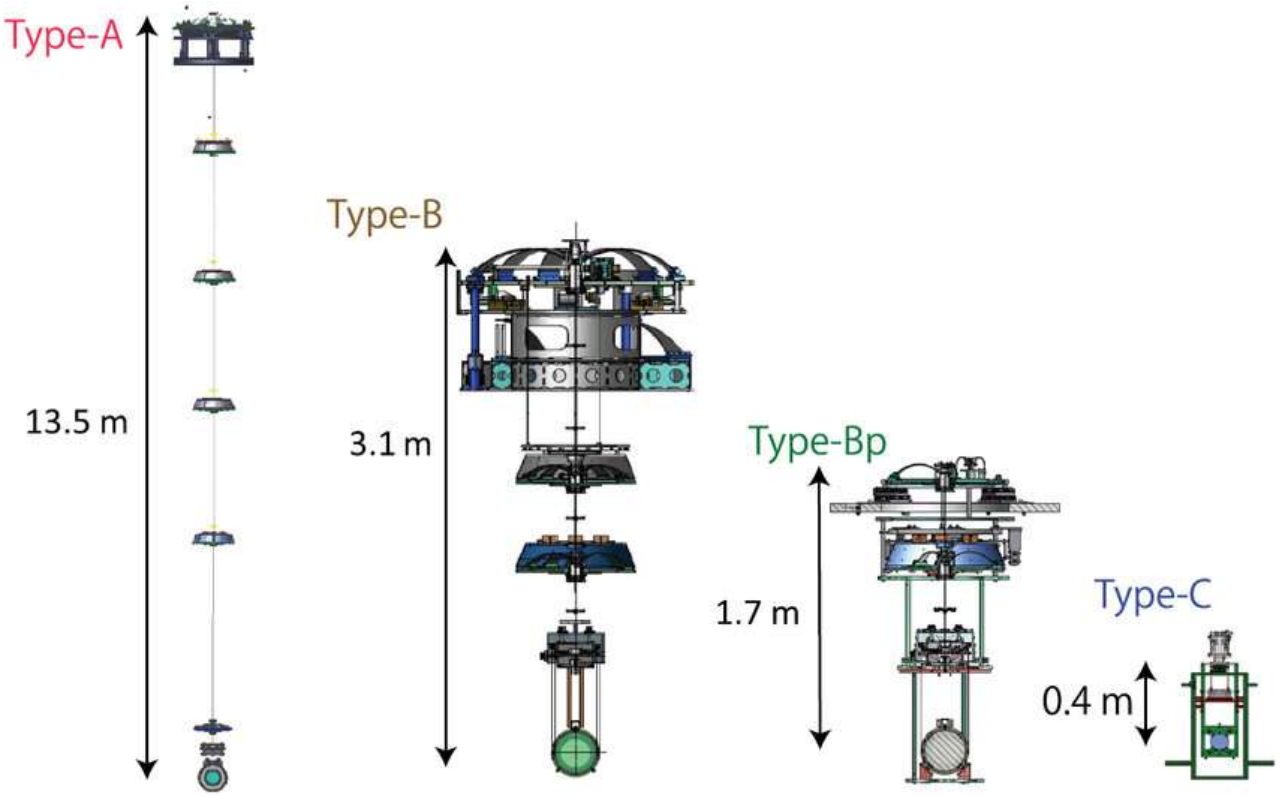


[Vibration isolation system with a compact damping system for power recycling mirrors of KAGRA]
T.Akuts et al.,

Vibration isolation



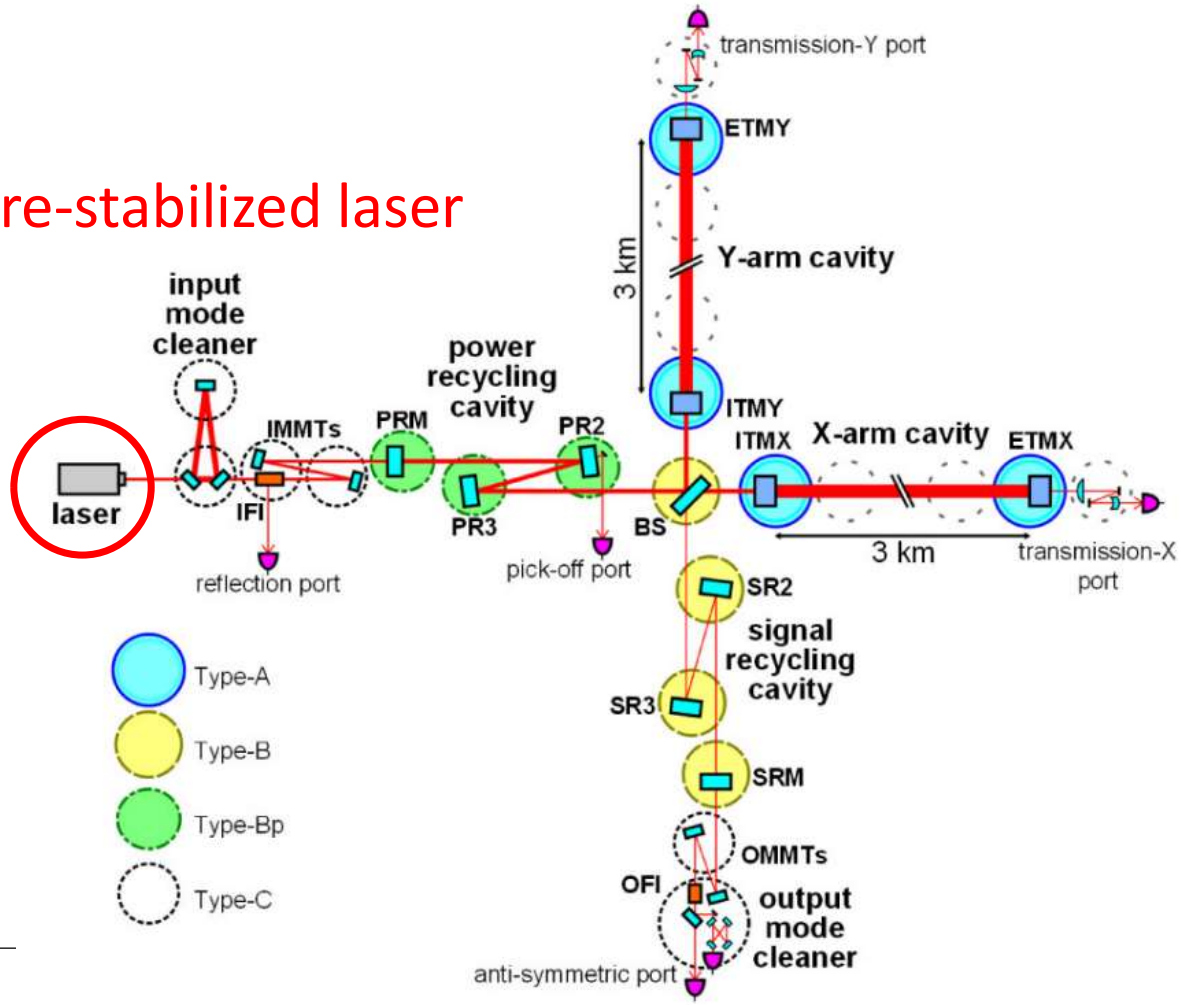
Vibration isolation



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

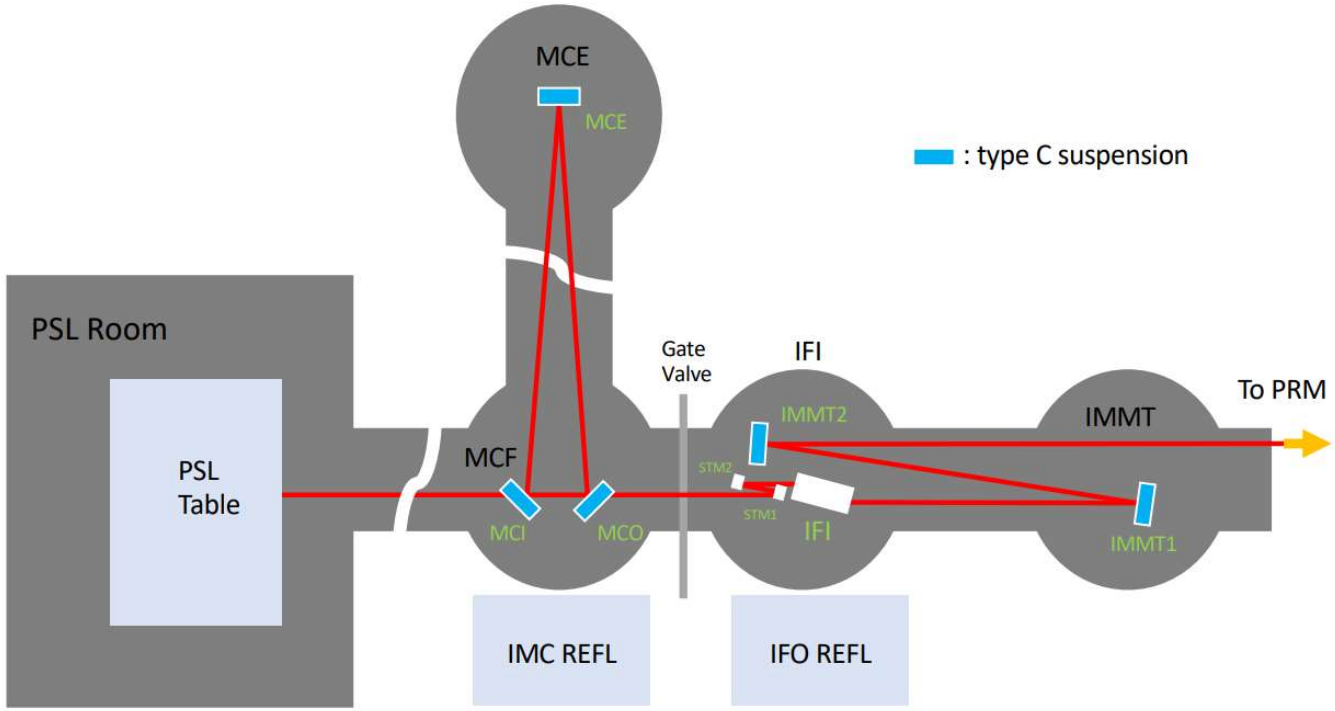
KAGRA interferometer

Pre-stabilized laser

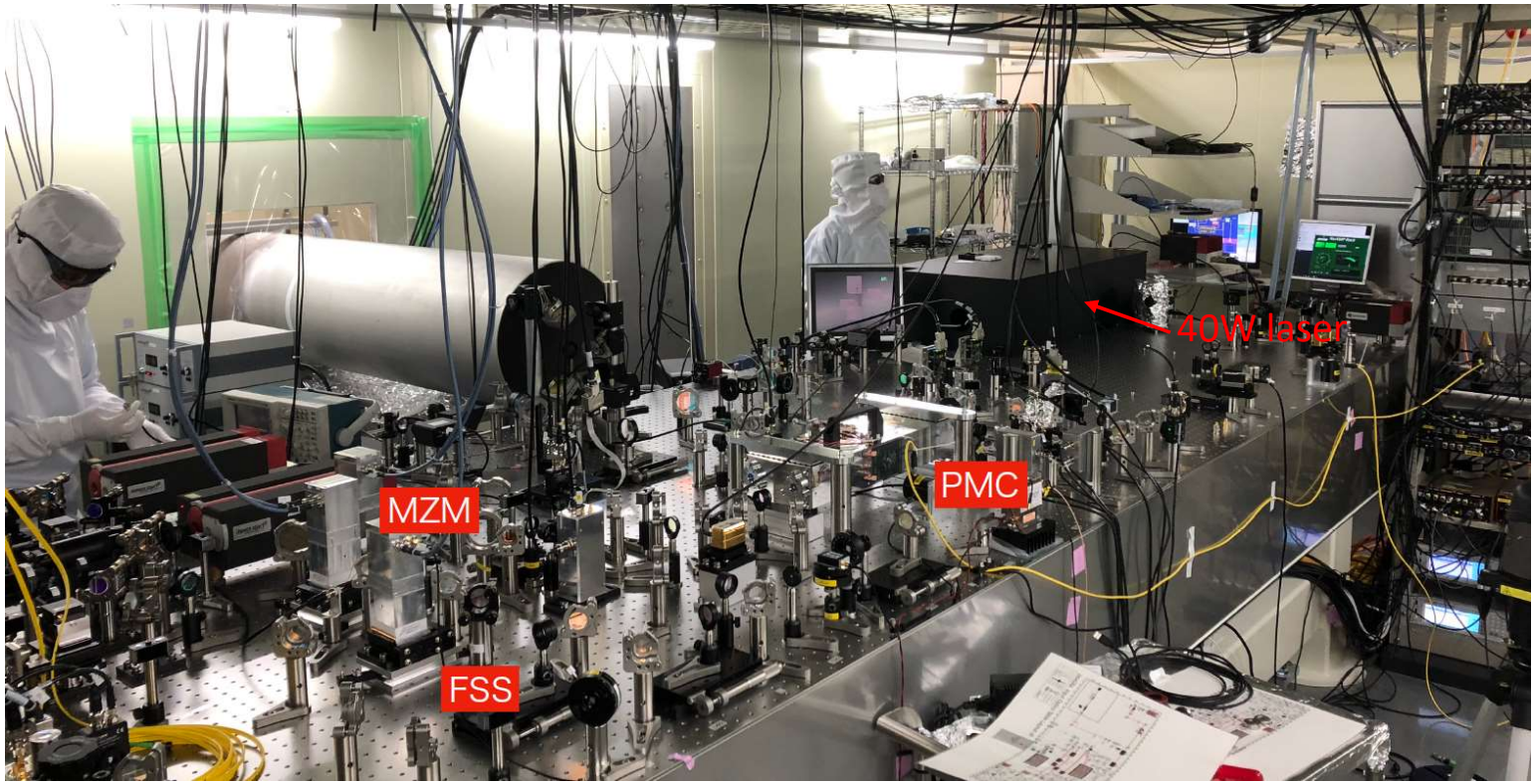


IOO : Input output optics
MIF : Main interferometer
MIR : Mirror
MMT : Mode matching telescope
OMC : Output mode cleaner

IOO of KAGRA


MCE
MCE
: type C suspension
PSL Room
PSL
Table
Gate
Valve
IFI
IMMT2
IMMT
To PRM
MCF
STM2
STM1
IFI
MCI
MCO
IMMT1
IMC REFL
IFO REFL

PSL room of KAGRA



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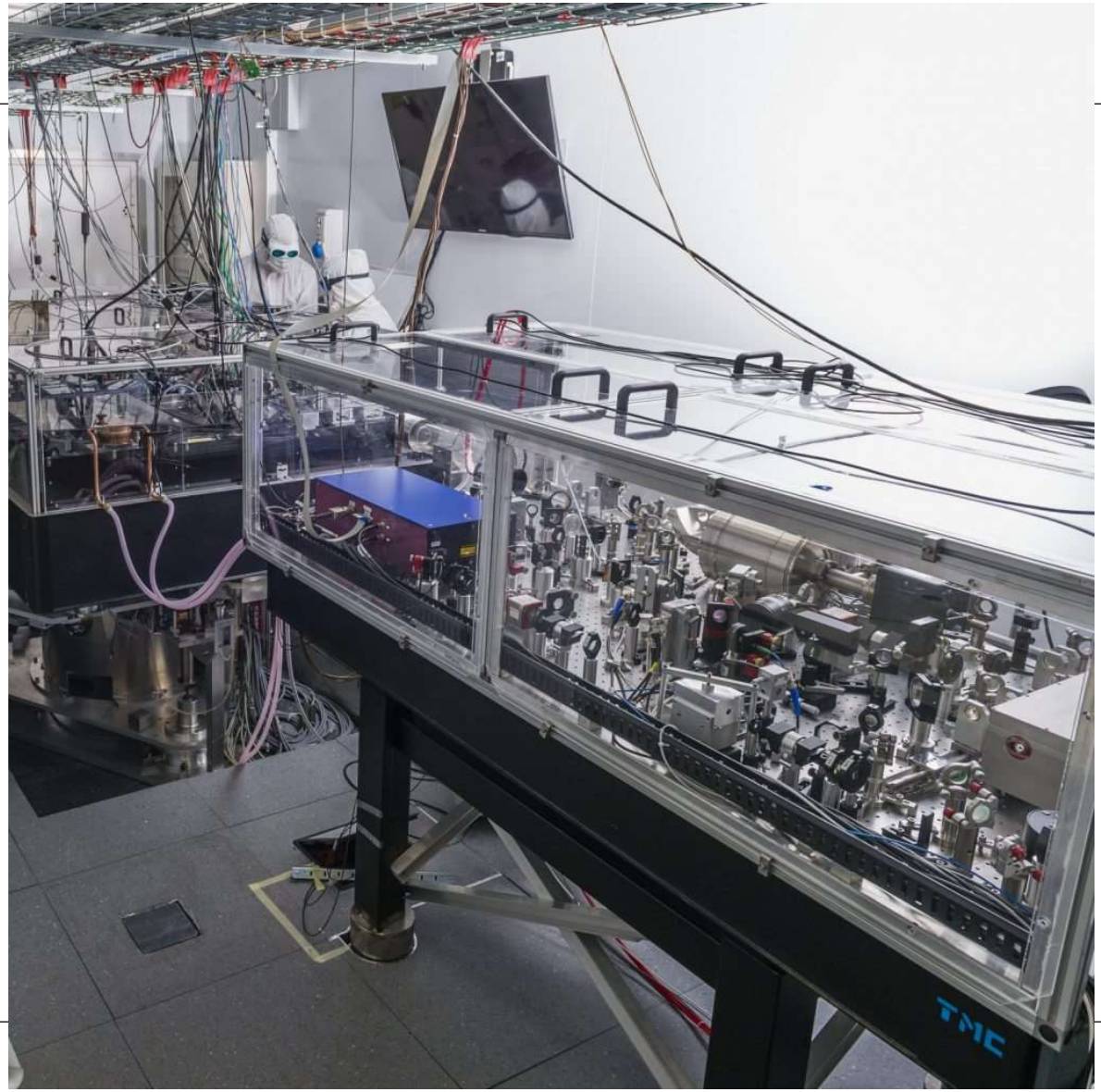
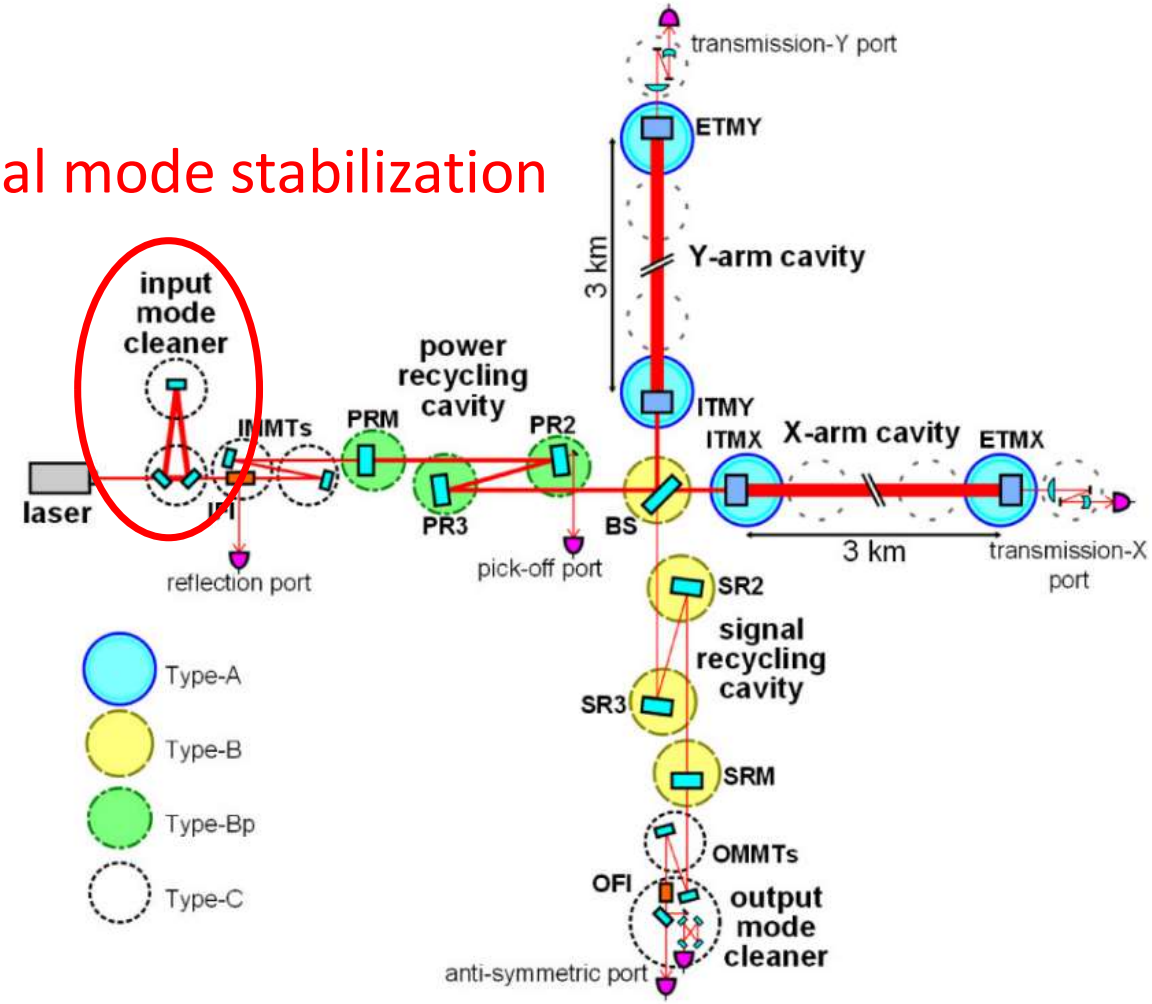

TMC

KAGRA interferometer

Spatial mode stabilization



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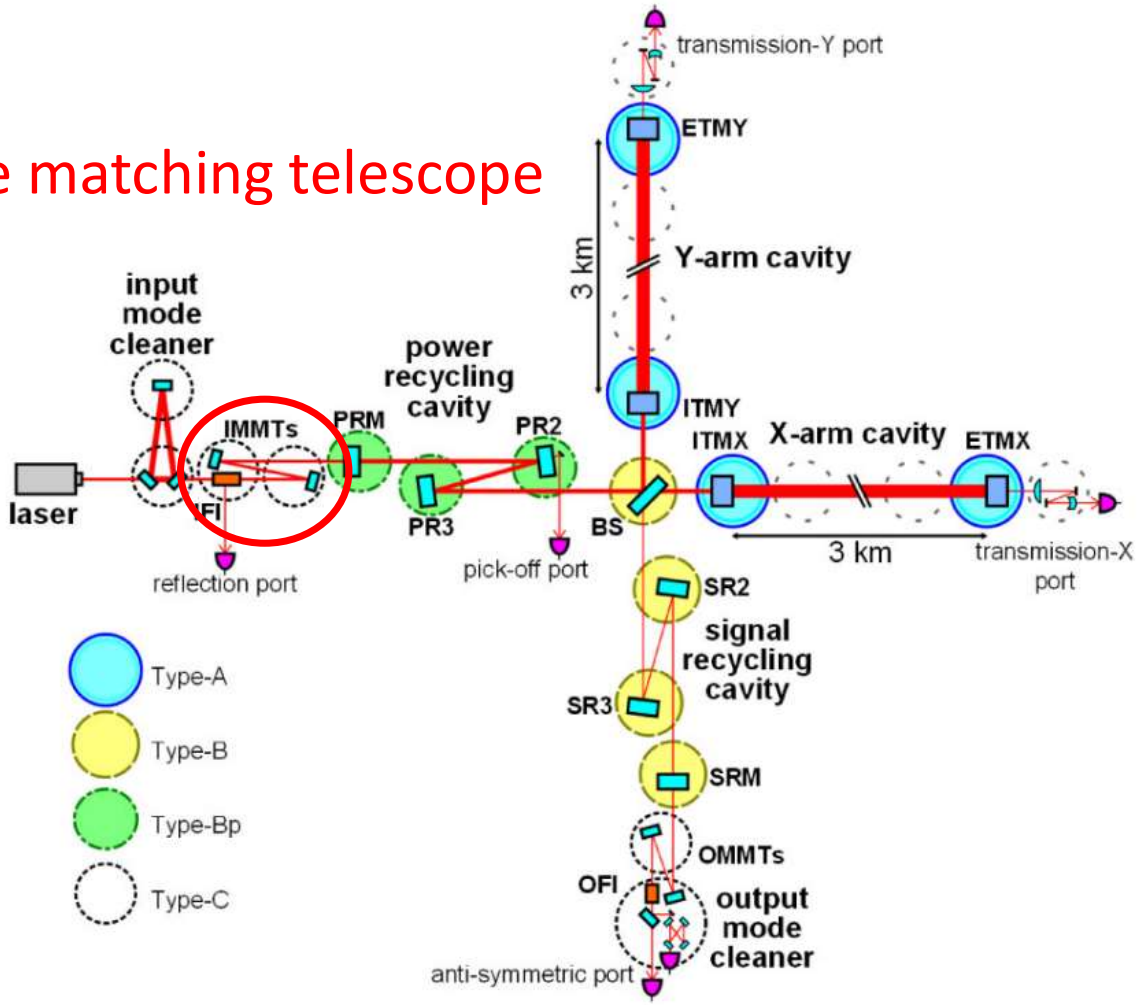
KAGRA interferometer

Mode matching telescope



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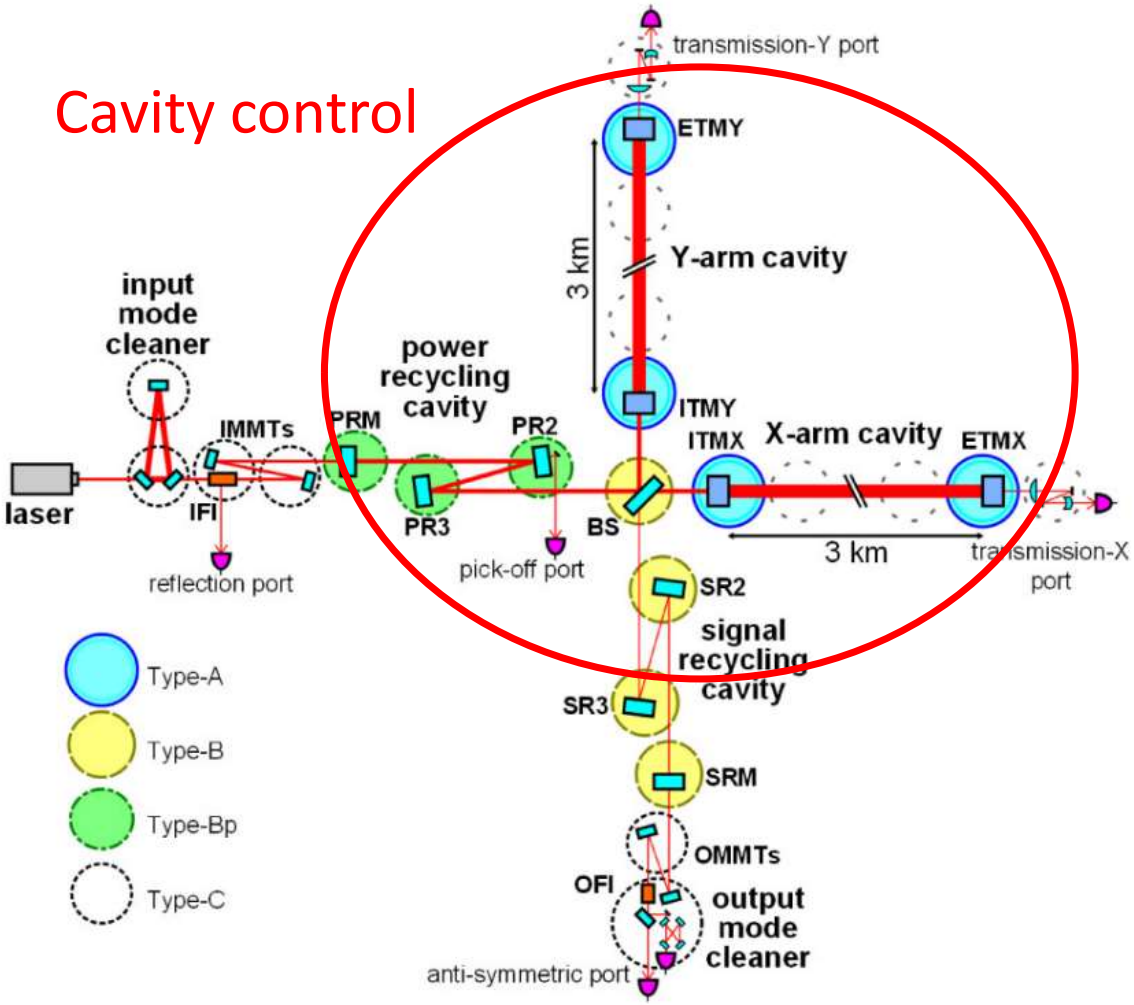
KAGRA interferometer



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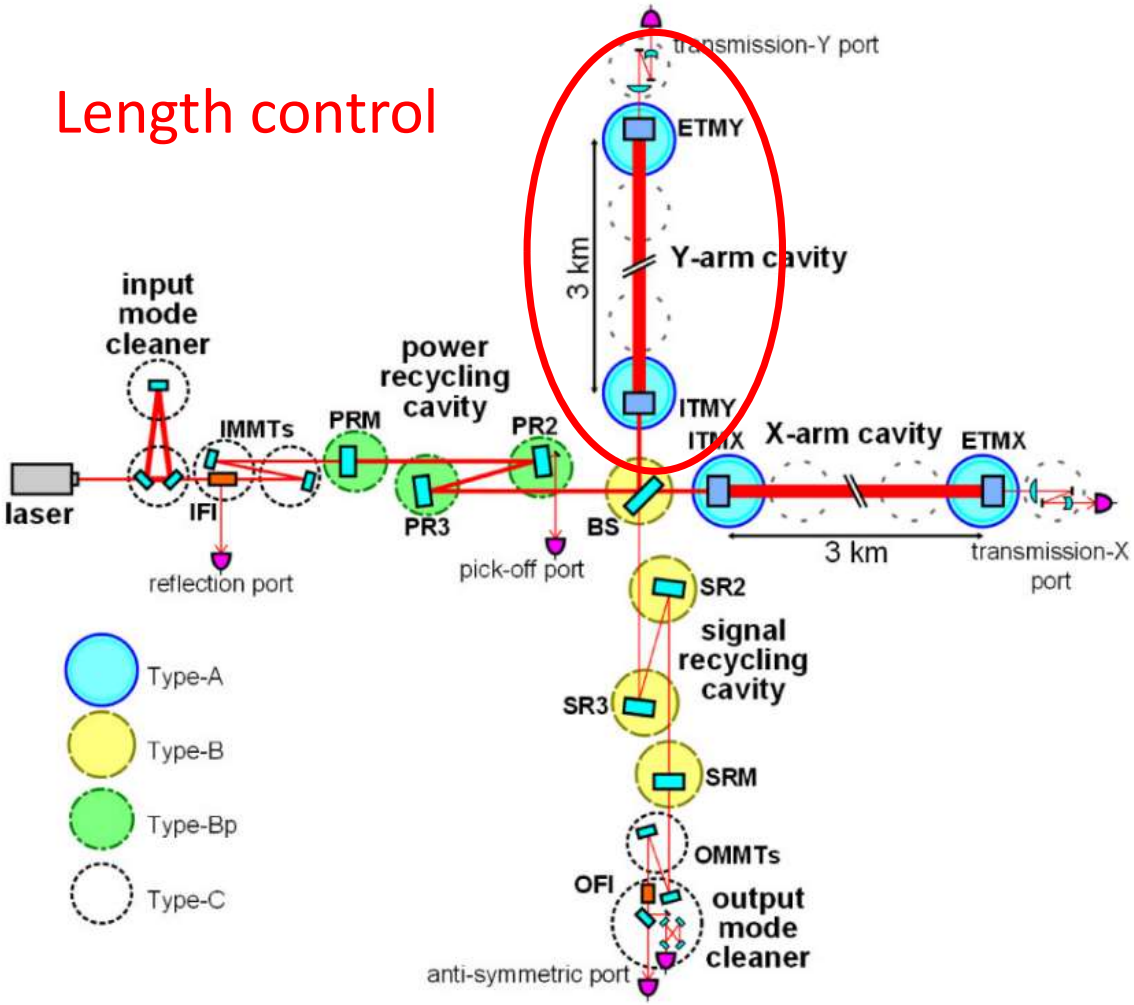
KAGRA interferometer



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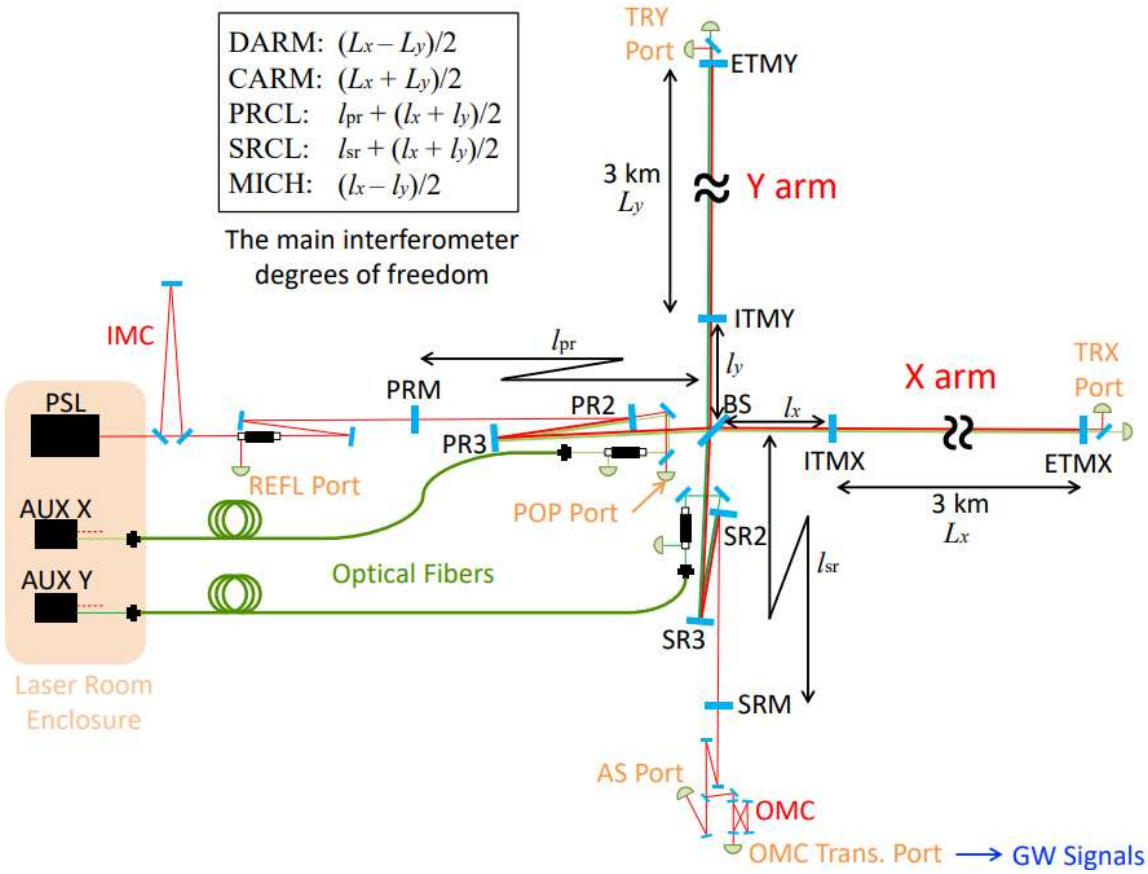
Arm length stabilization of KAGRA



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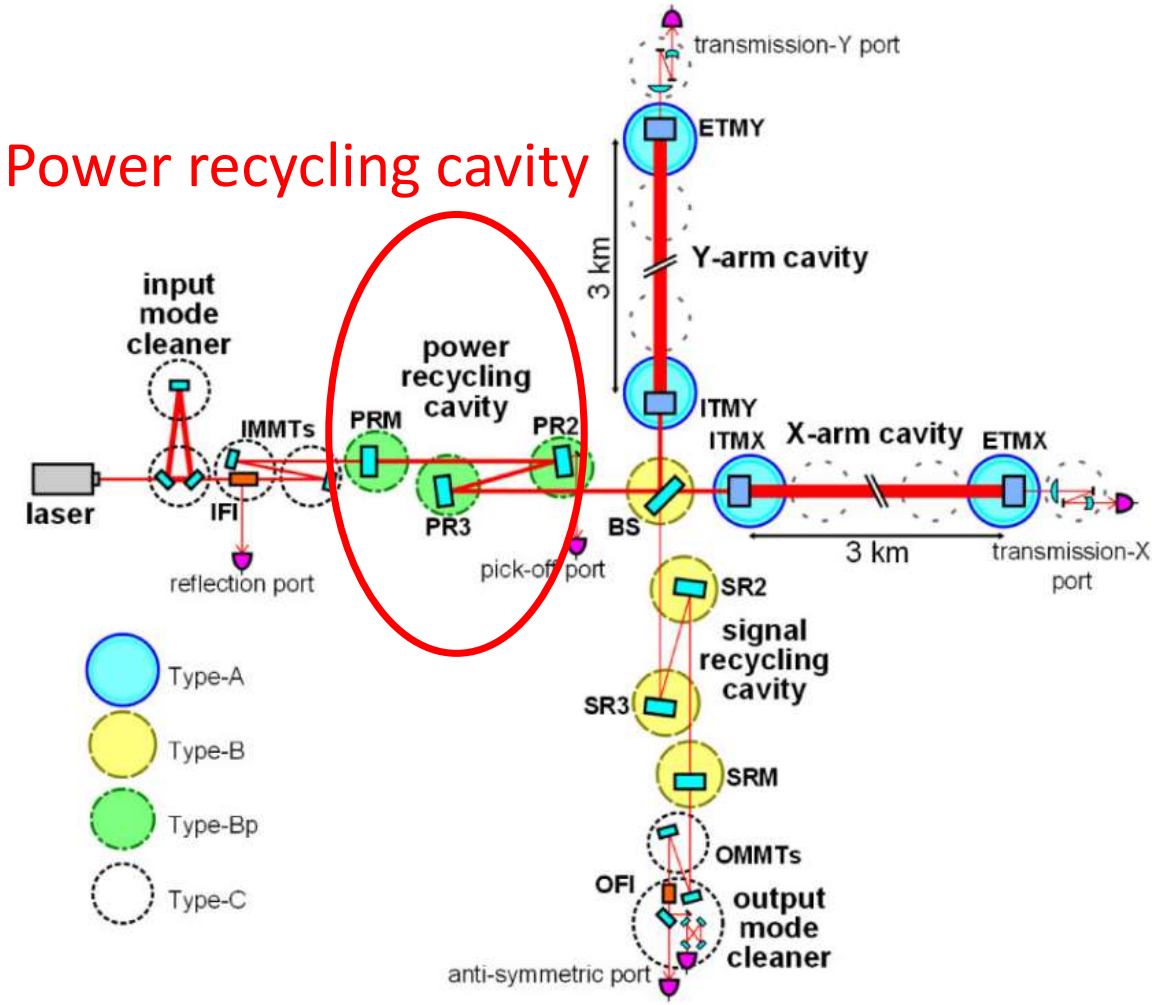
KAGRA interferometer



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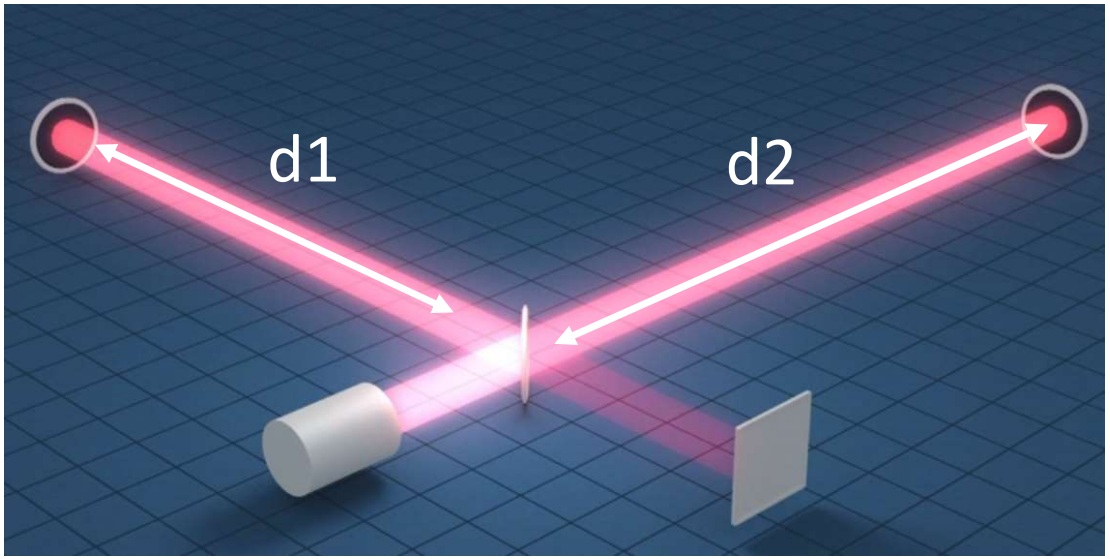
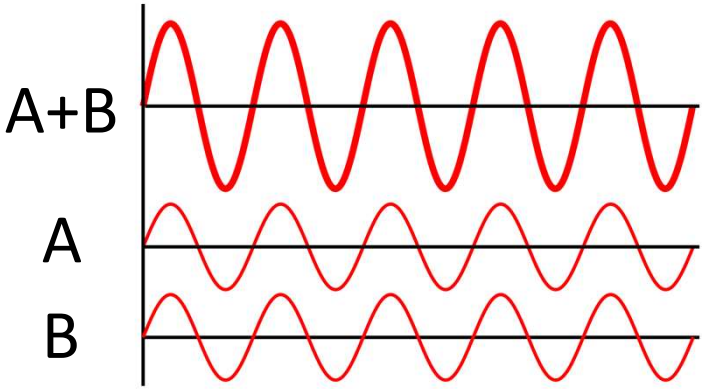
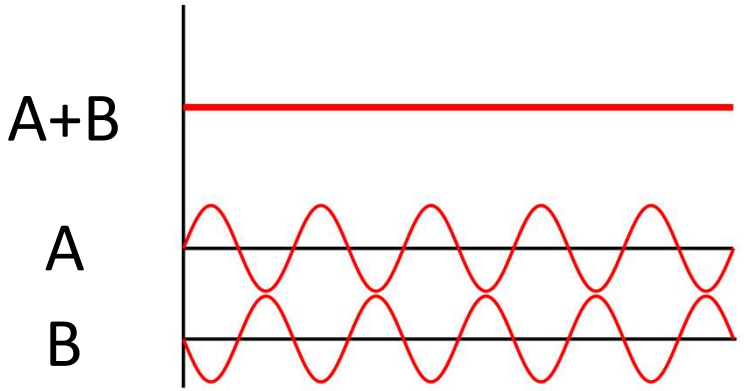
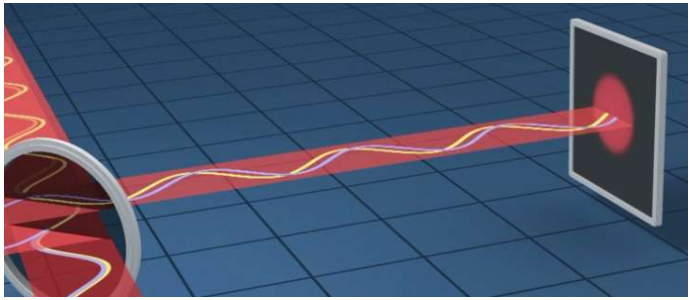
Power recycling cavity

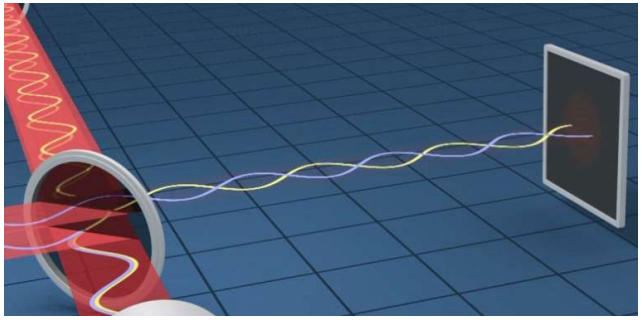


Power recycling cavity





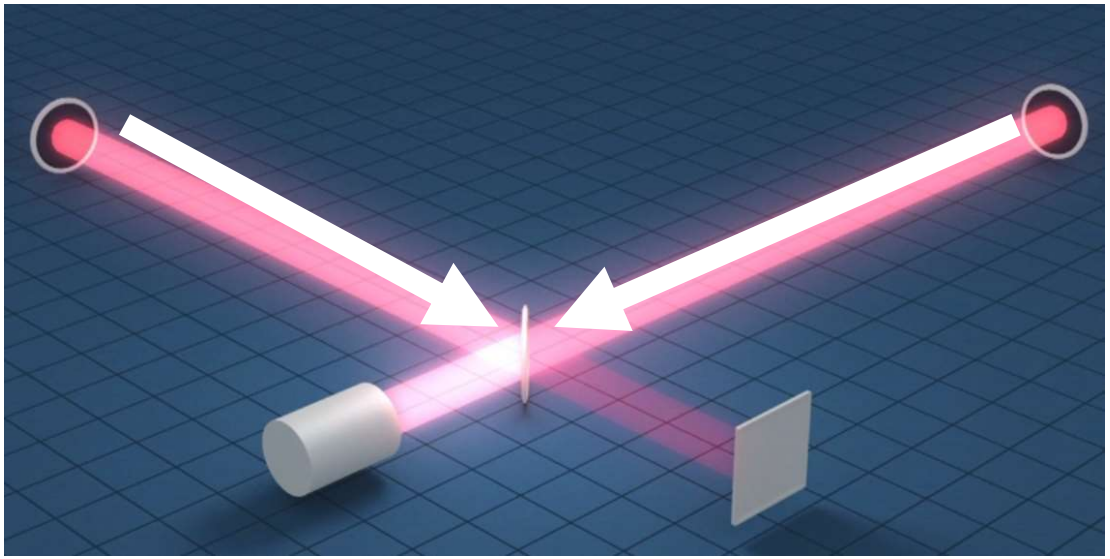




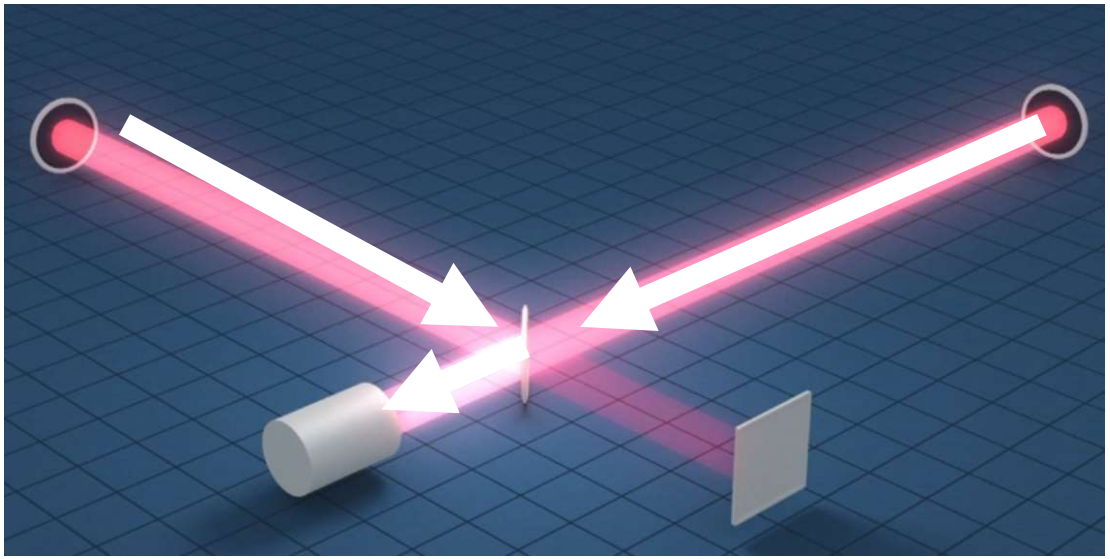
Constructive

Destructive

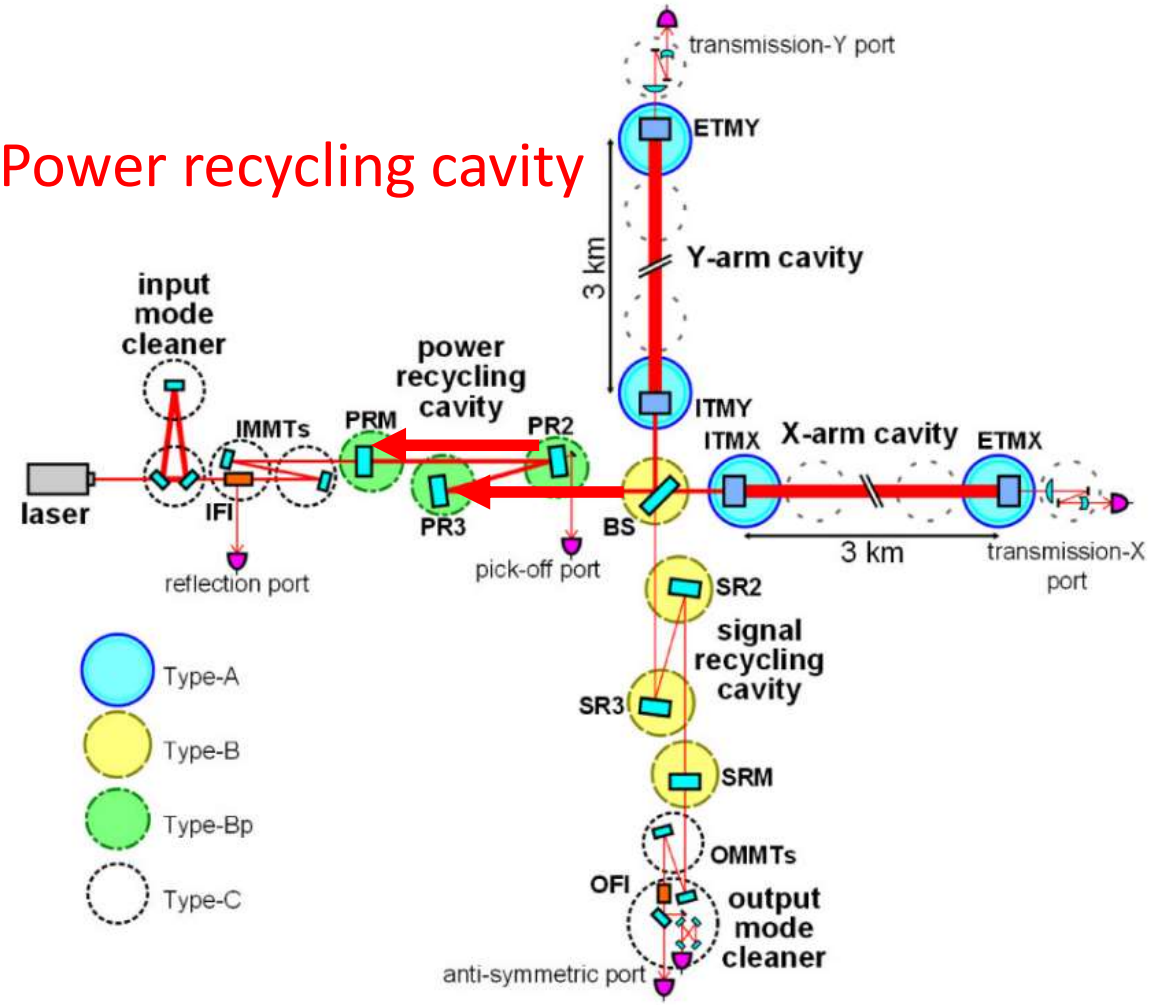
Power recycling cavity



Power recycling cavity



KAGRA interferometer



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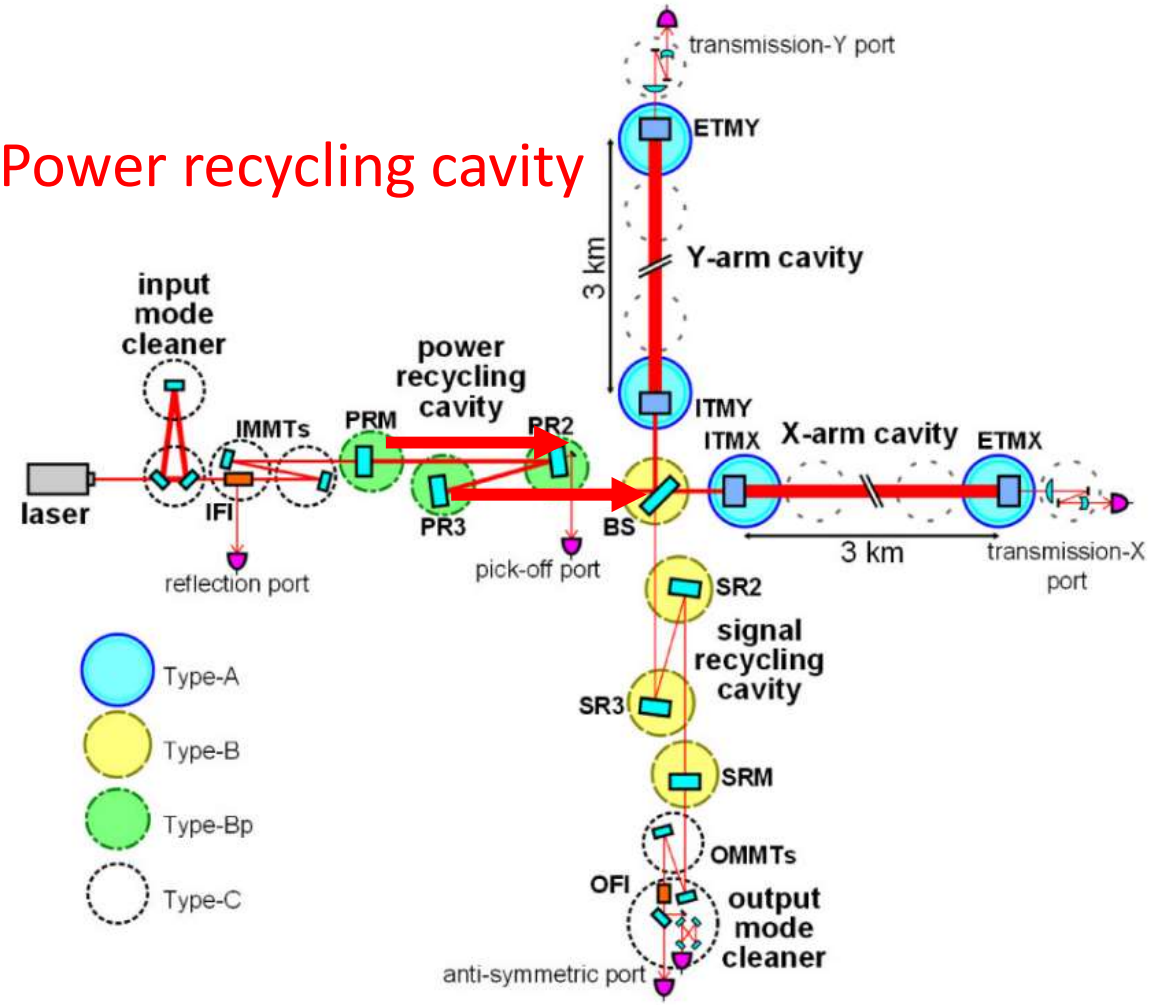
KAGRA interferometer



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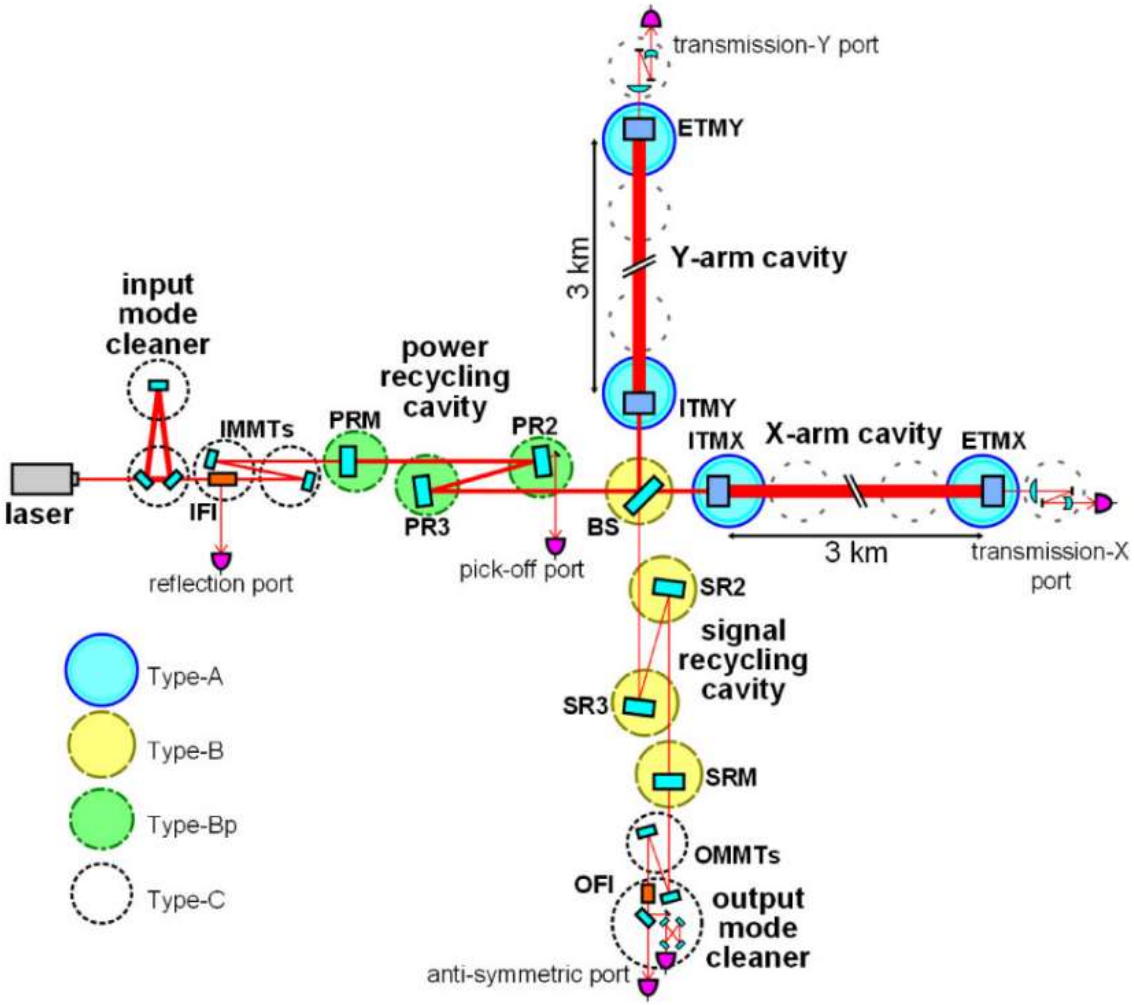

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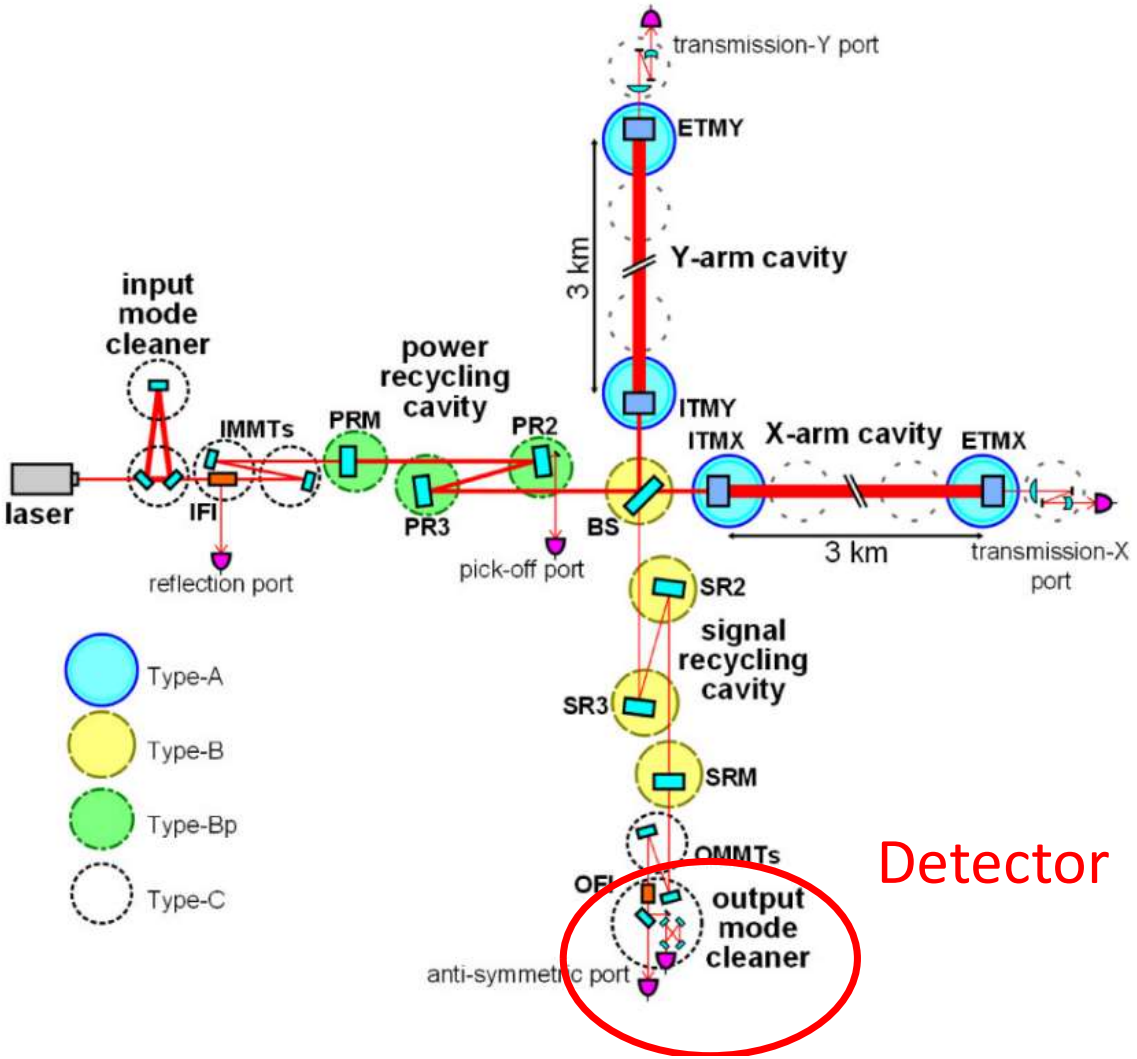

Detector

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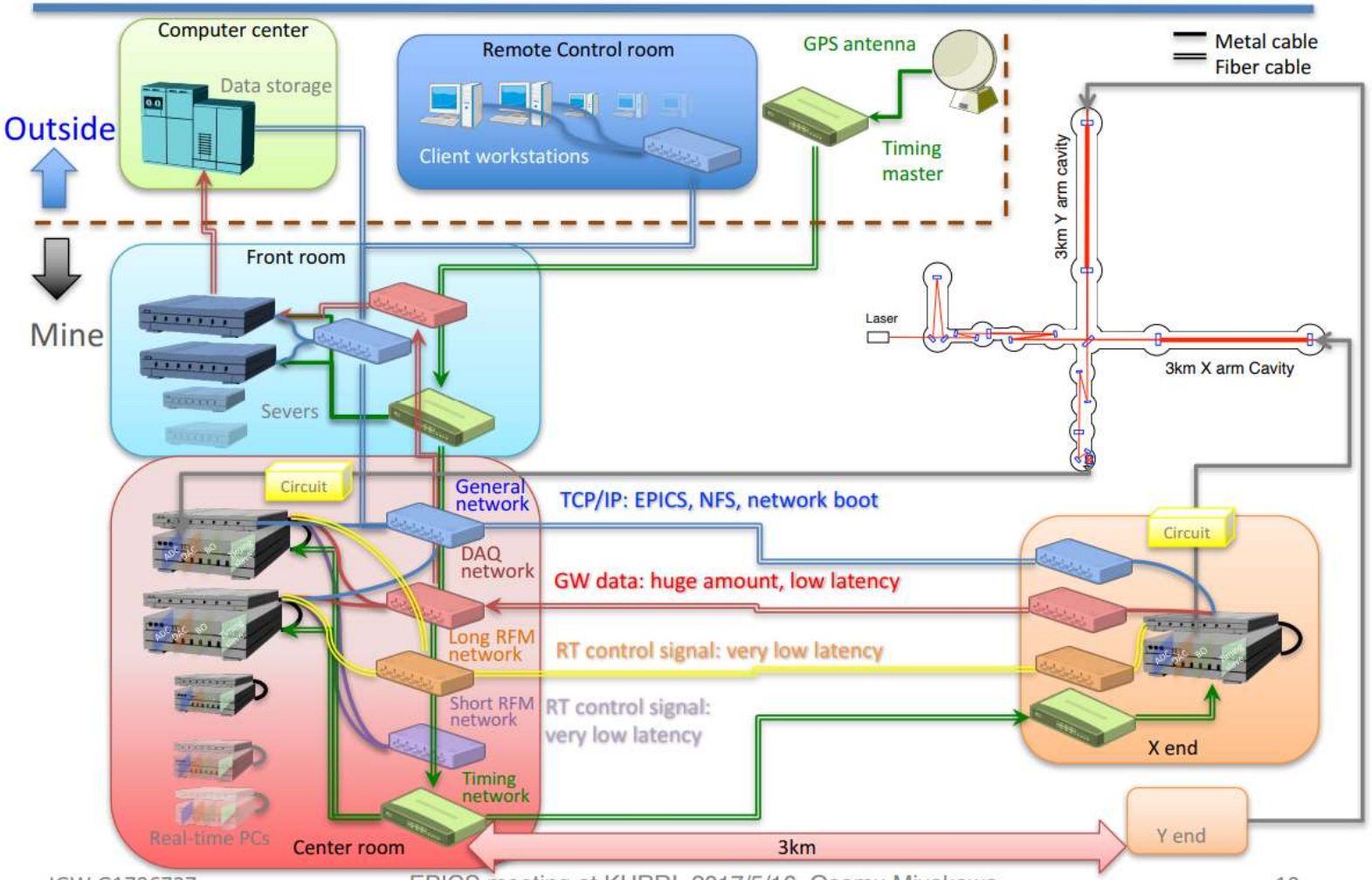
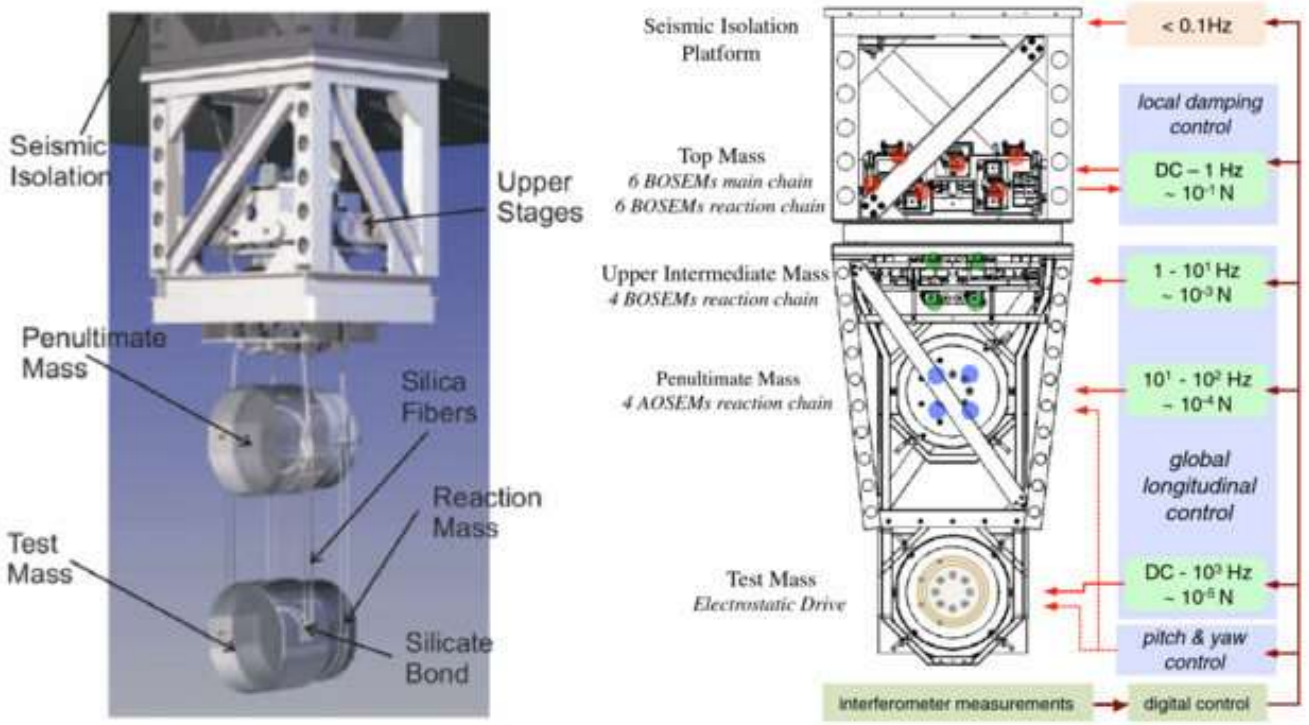
KAGRA control network design



Sensors in gravitational wave detector



Calibration instrument