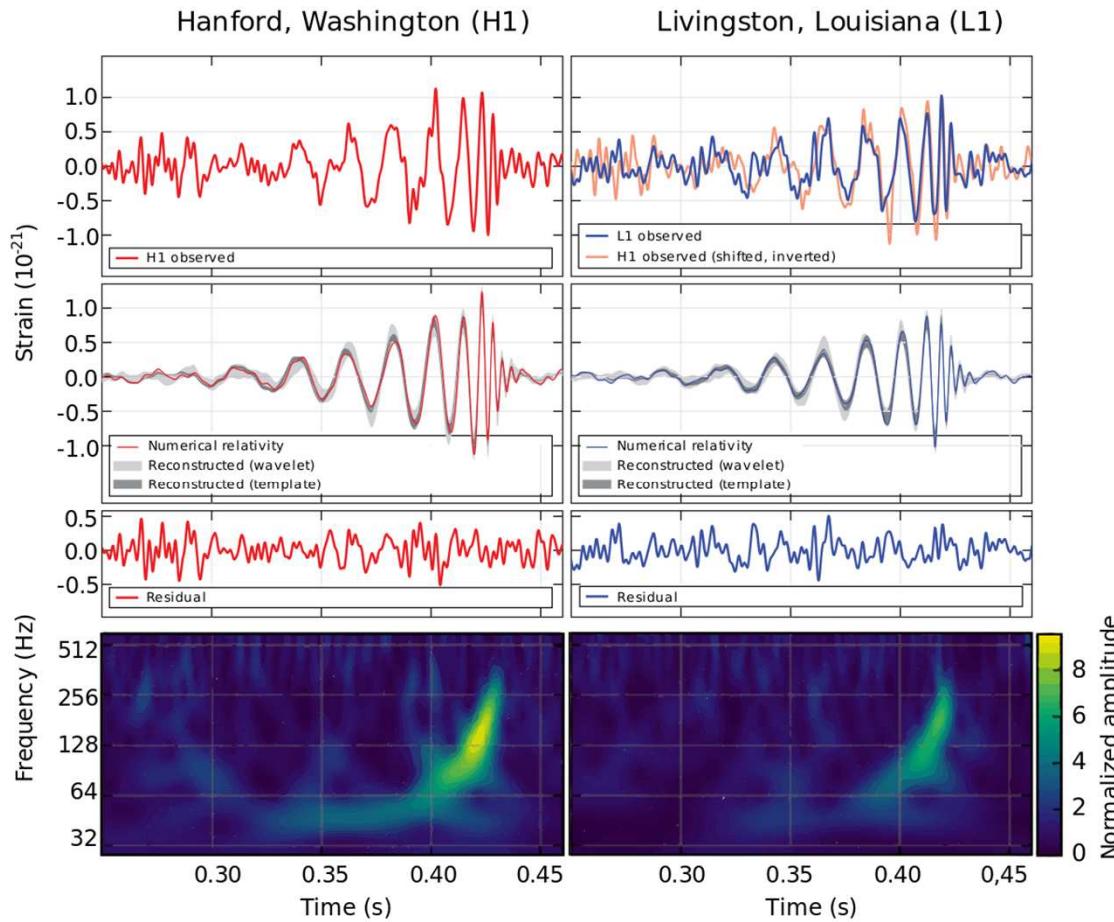


A detailed 3D rendering of a gravitational wave detector, likely the LIGO or Virgo interferometer. The detector consists of several large, dark grey cylindrical pipes connected by various mechanical components, valves, and sensors. A small white figure stands near one of the vertical support structures to provide a sense of scale. The background is a dark, star-filled space with a prominent central star.

Gravitational Wave Detector

June Gyu Park

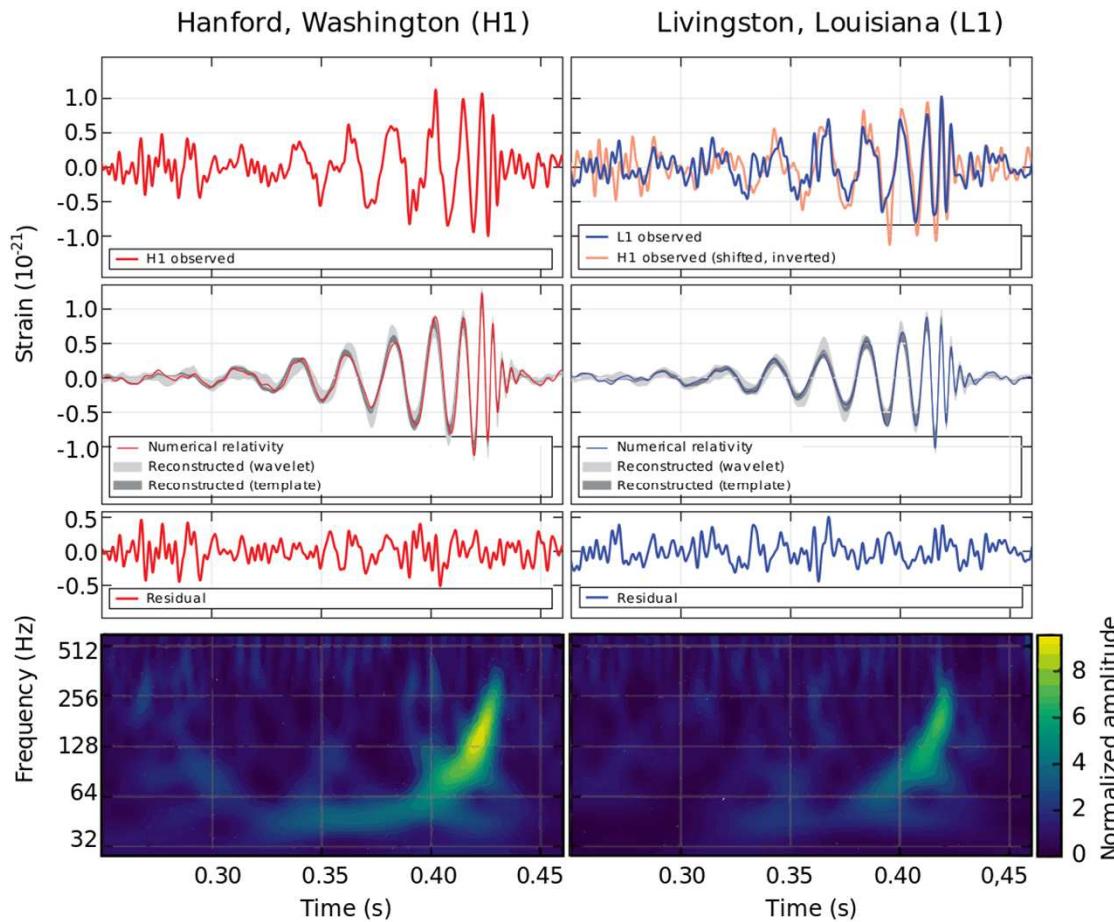
First observation of gravitational wave



GW150914

2015-09-14

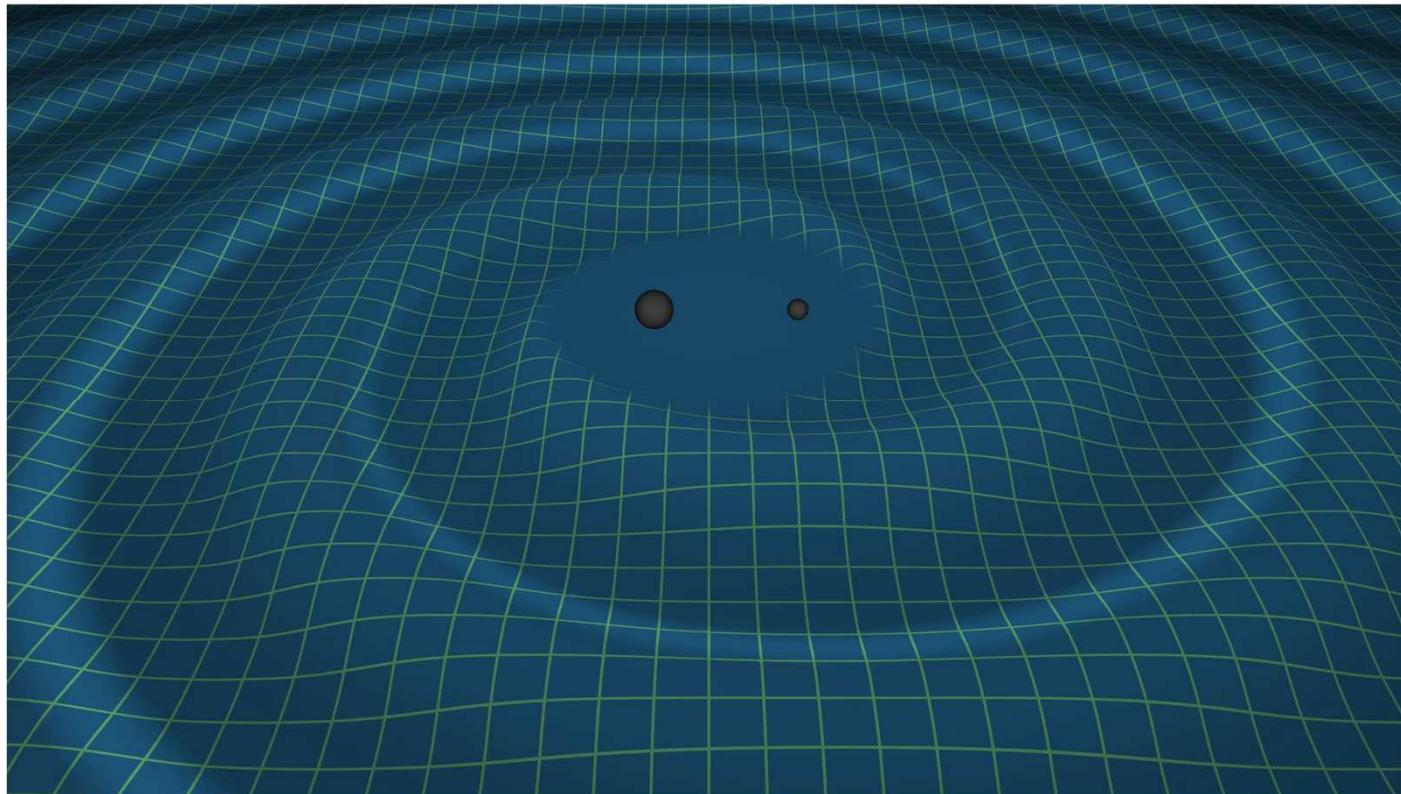
First observation of gravitational wave



GW150914

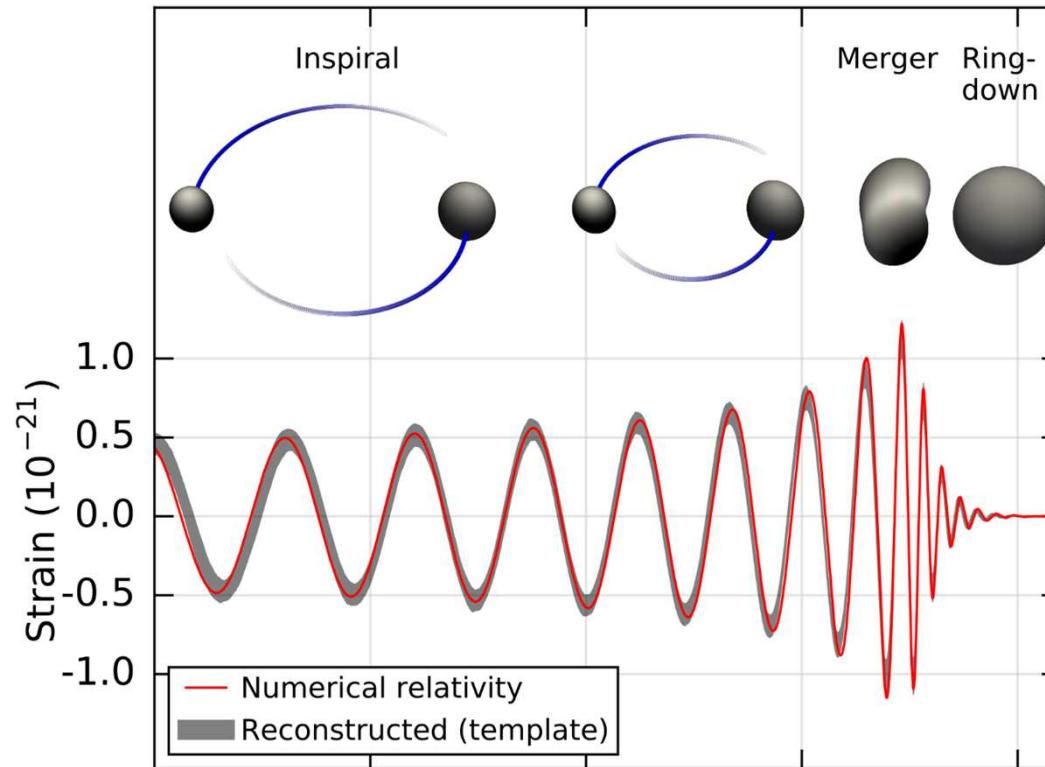
2015-09-14

Gravitational wave

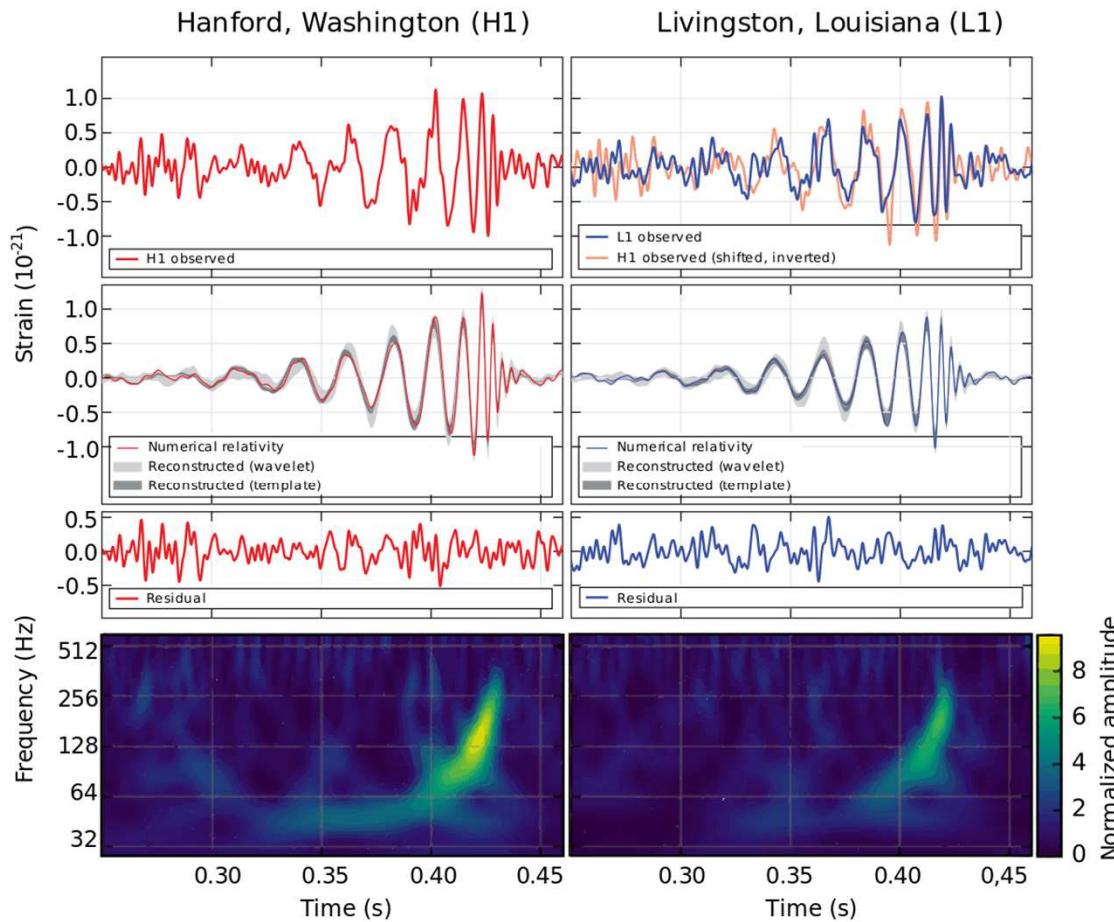


R. Hurt - Caltech / JPL

Inspiral, merger, ring-down



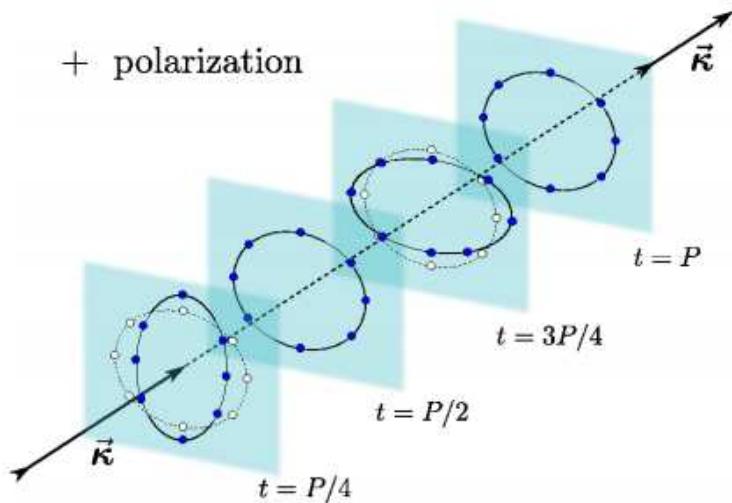
First observation of gravitational wave



GW150914

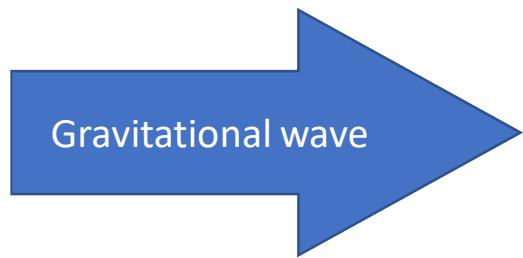
2015-09-14

Gravitational wave

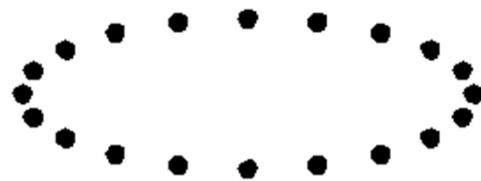
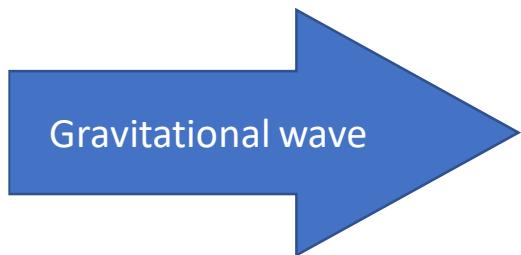


MPA Lectures on Gravitational Waves in Cosmology
Azadeh Maleknejad
Max-Planck-Institute for Astrophysics

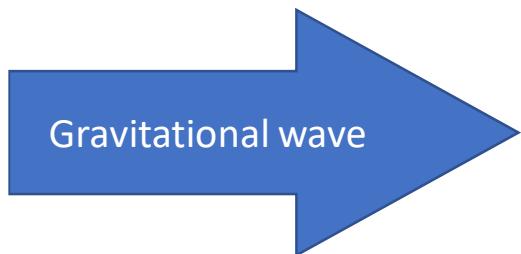
Propagation of gravitational wave



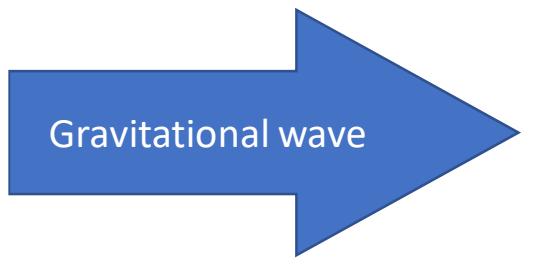
Effect of gravitational wave



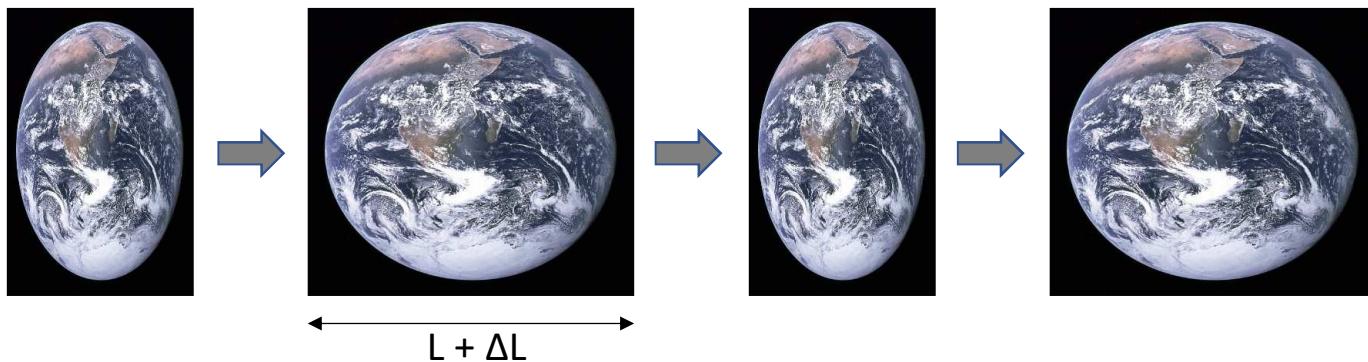
Effect of gravitational wave



Effect of gravitational wave

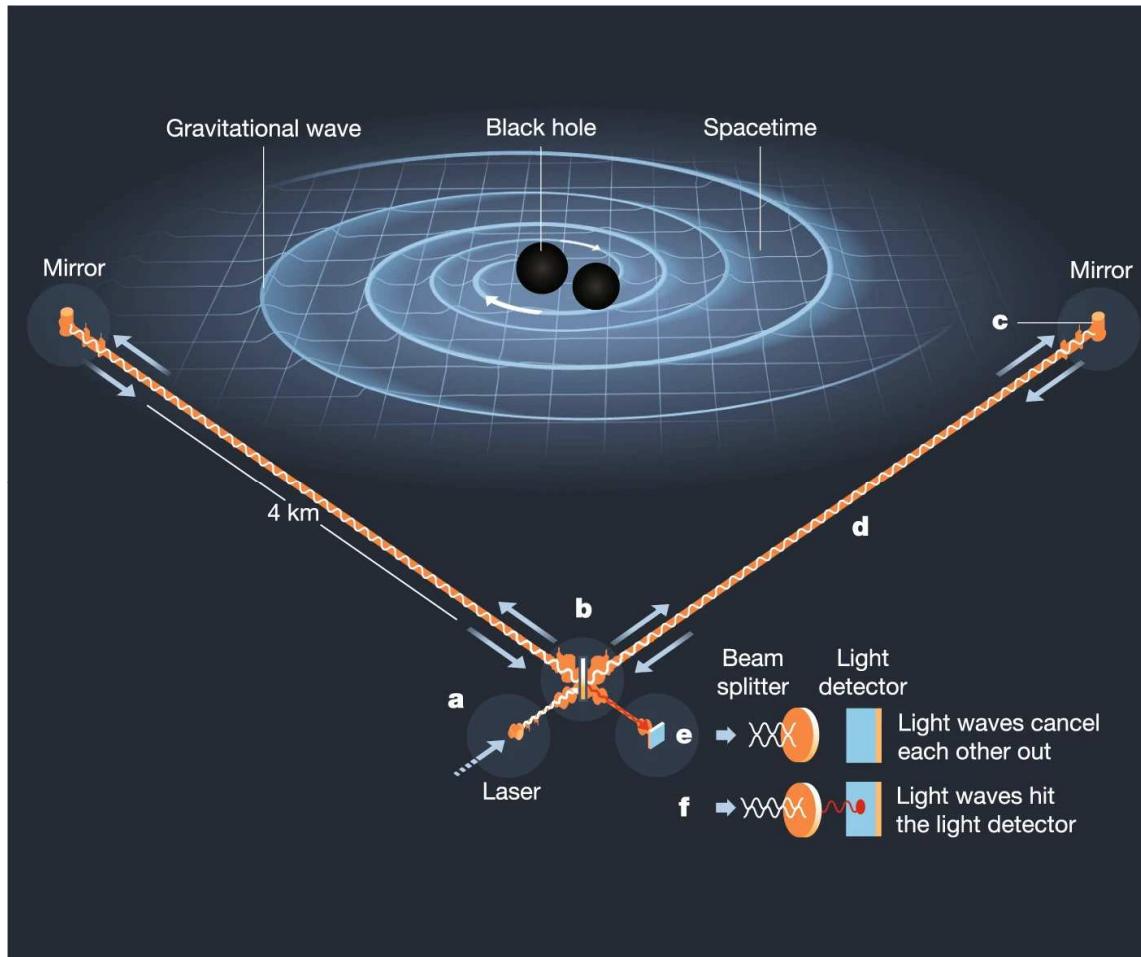


L



$L + \Delta L$

Gravitational wave detector

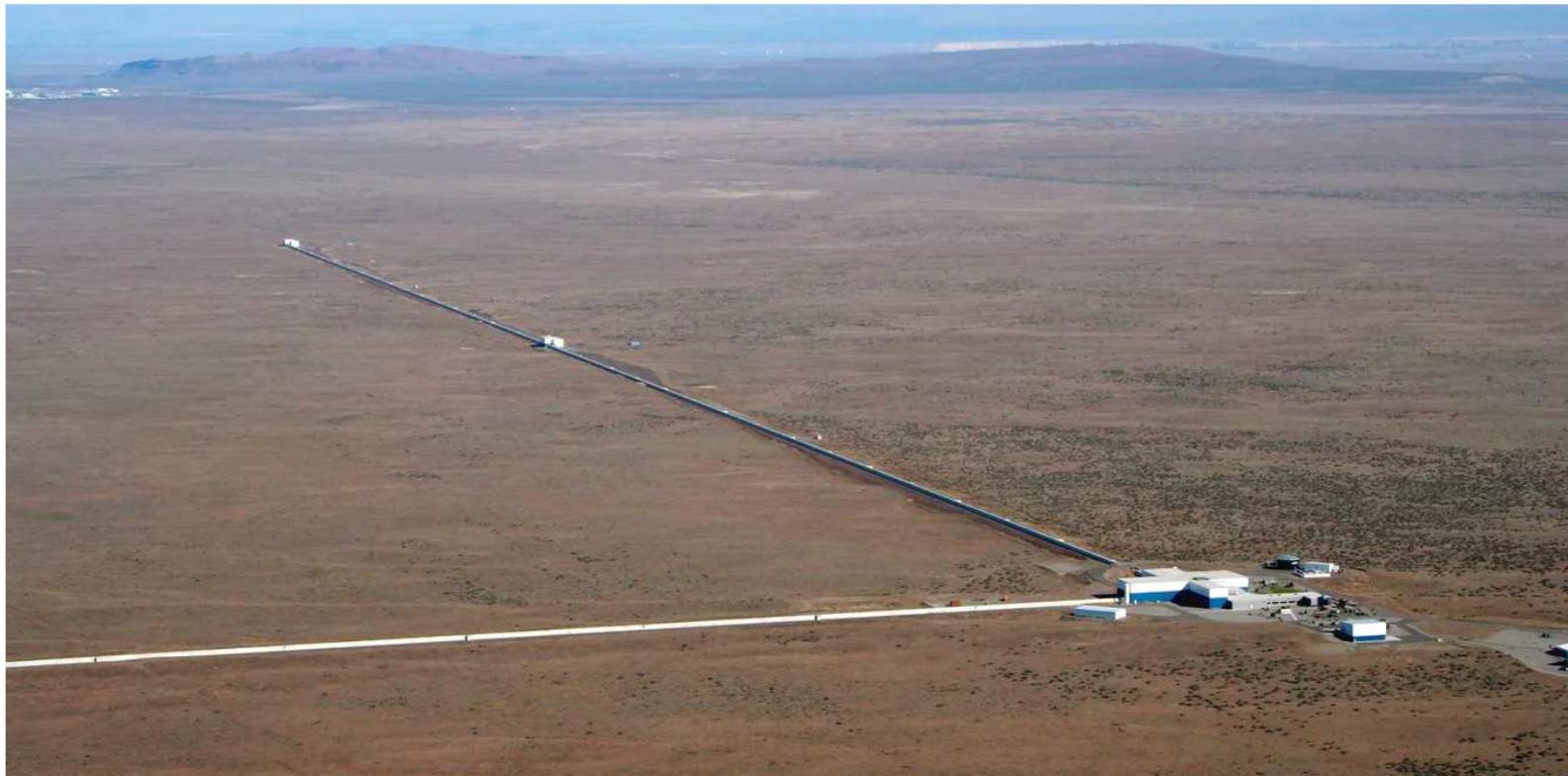


Gravitational wave detector



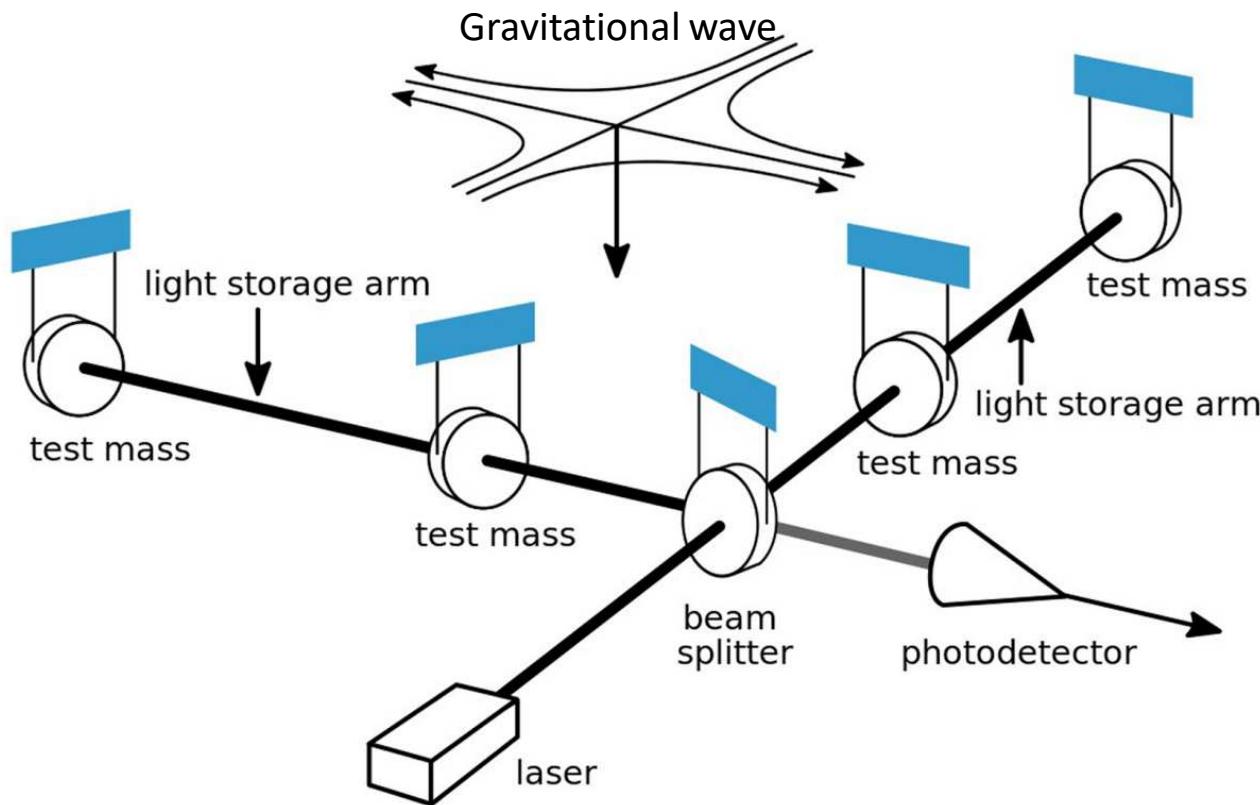
LIGO interferometer / Livingston

Gravitational wave detector



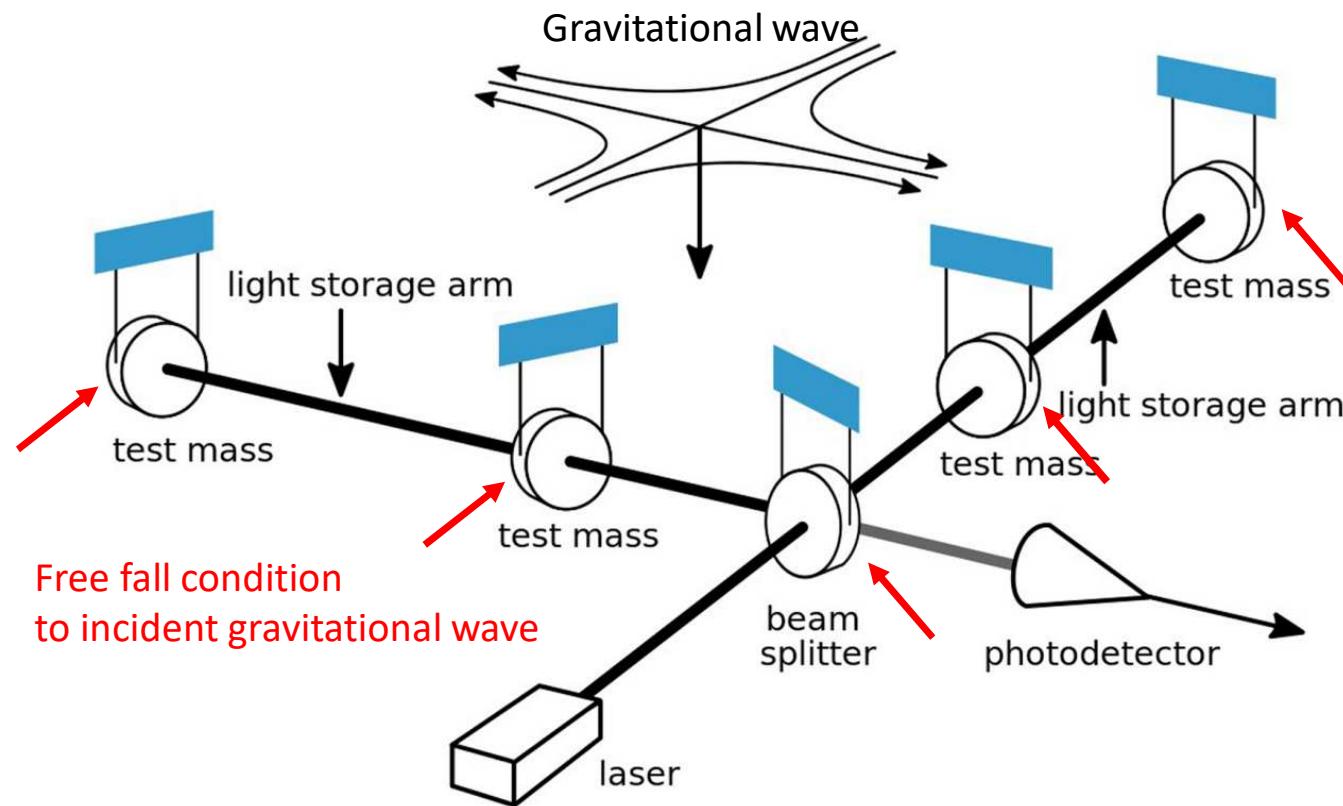
Gravitational waves are ripples in the fabric of spacetime caused by some of the most violent and energetic processes in the Universe, such as the collision of black holes.

Gravitational wave and GW detector



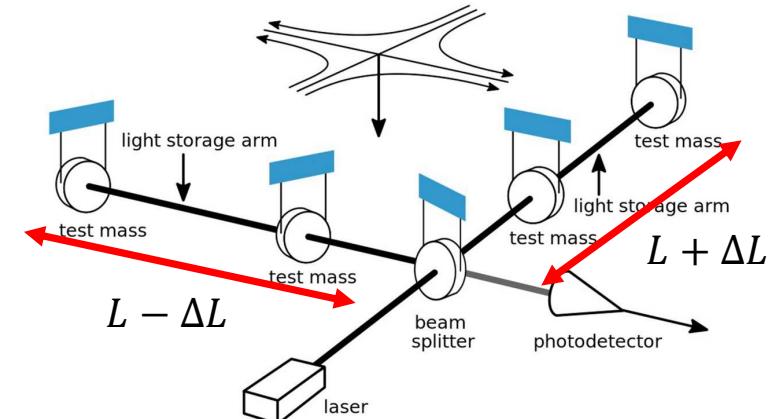
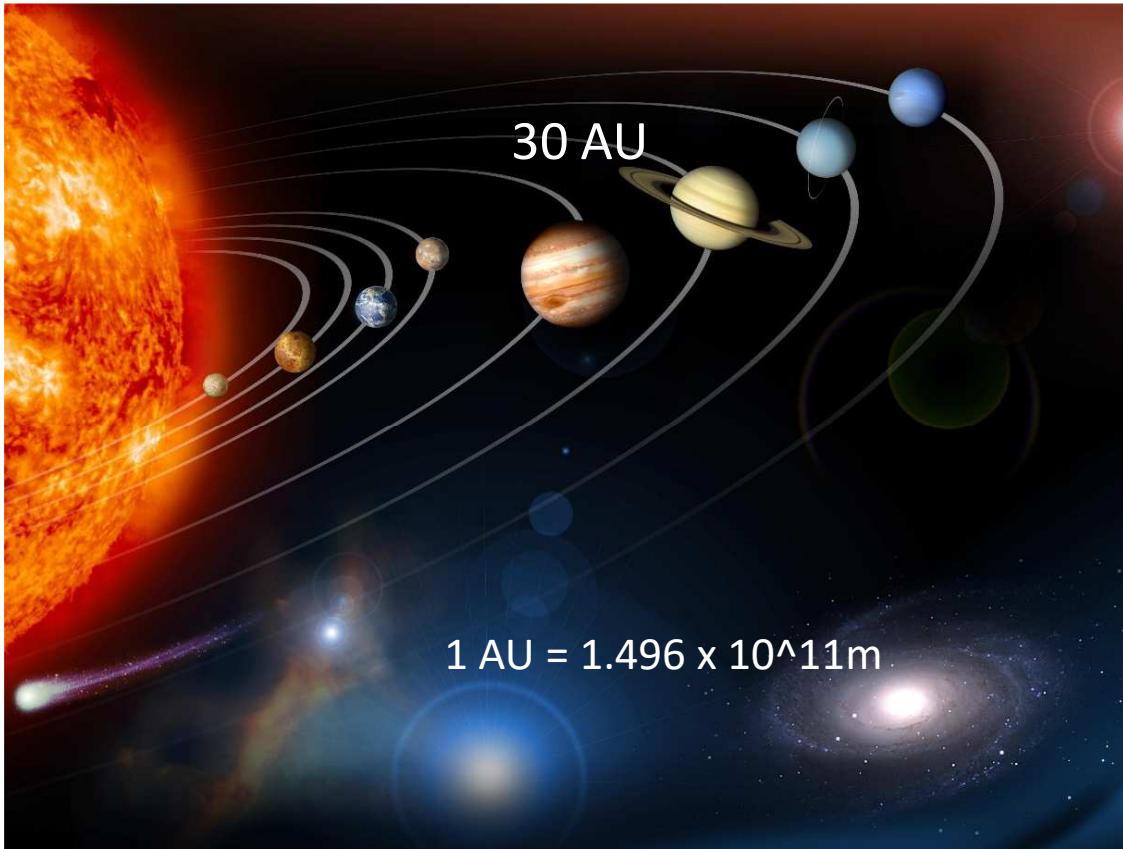
<https://www.ligo.caltech.edu/>

Gravitational wave and GW detector



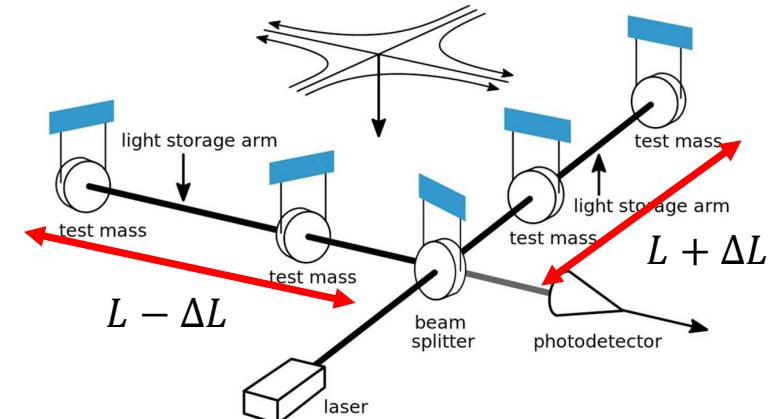
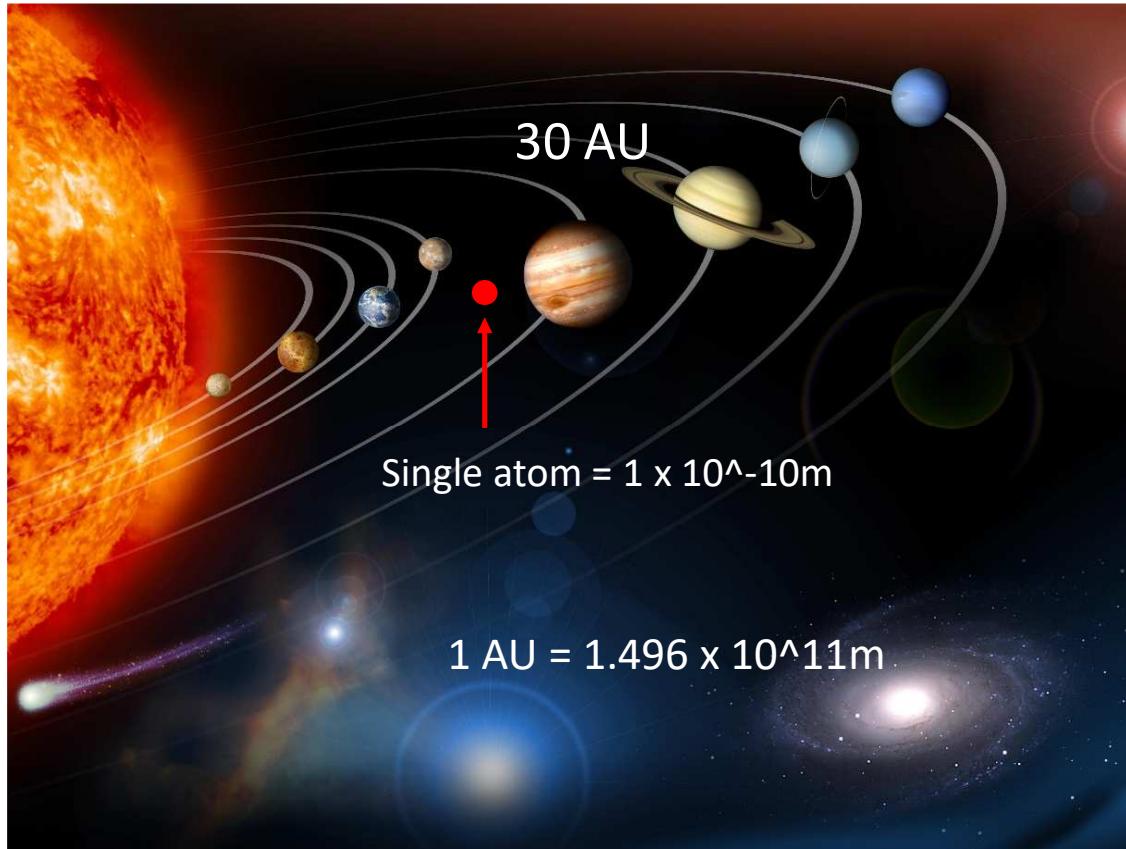
<https://www.ligo.caltech.edu/>

Strain of gravitational wave



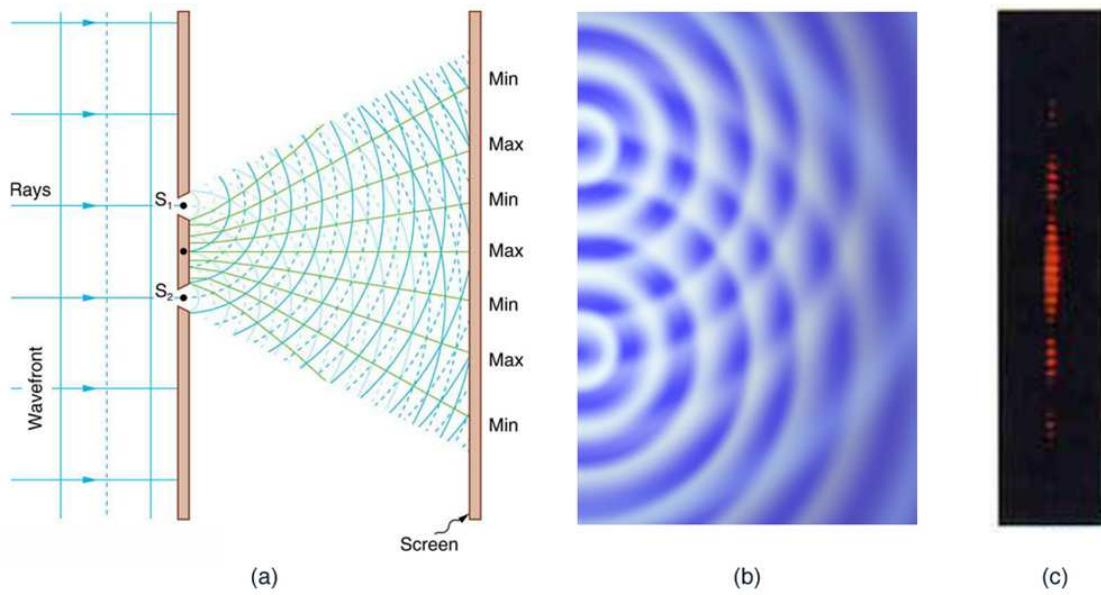
$$\frac{\Delta L}{L} \approx 10^{-21}$$

Strain of gravitational wave



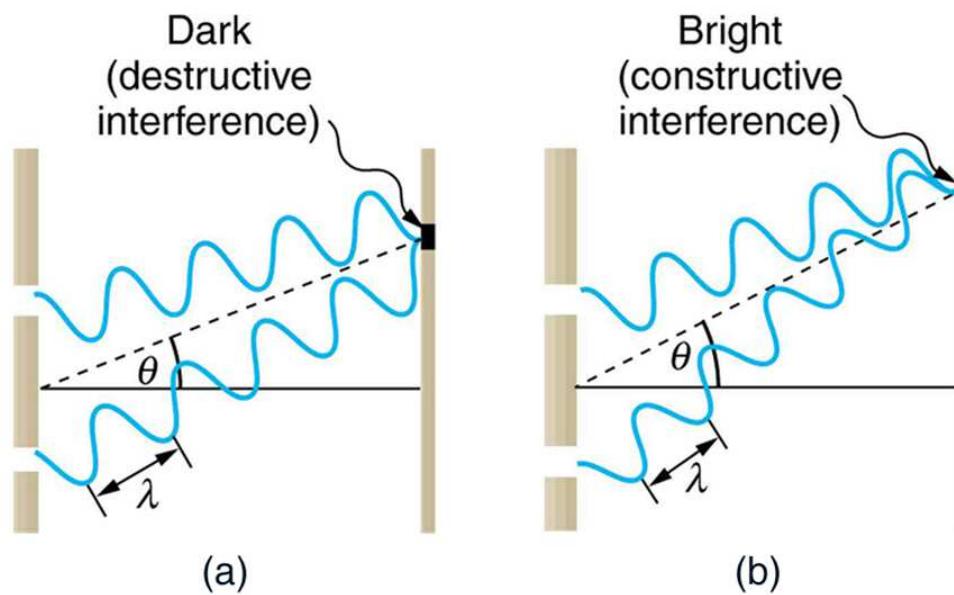
$$\frac{\Delta L}{L} \approx 10^{-21}$$

Double slit interference



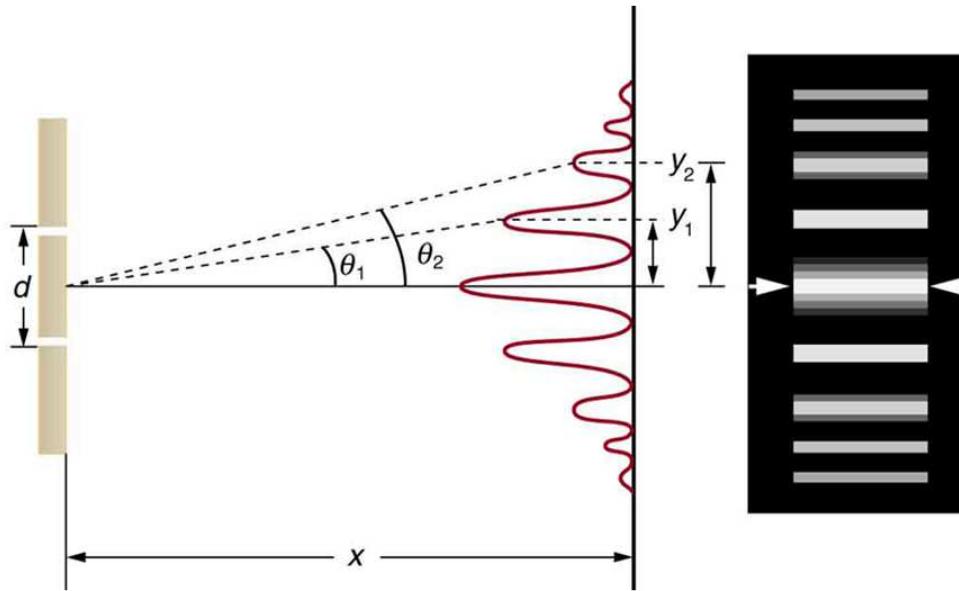
College Physics
OpenStaxCollege

Double slit interference



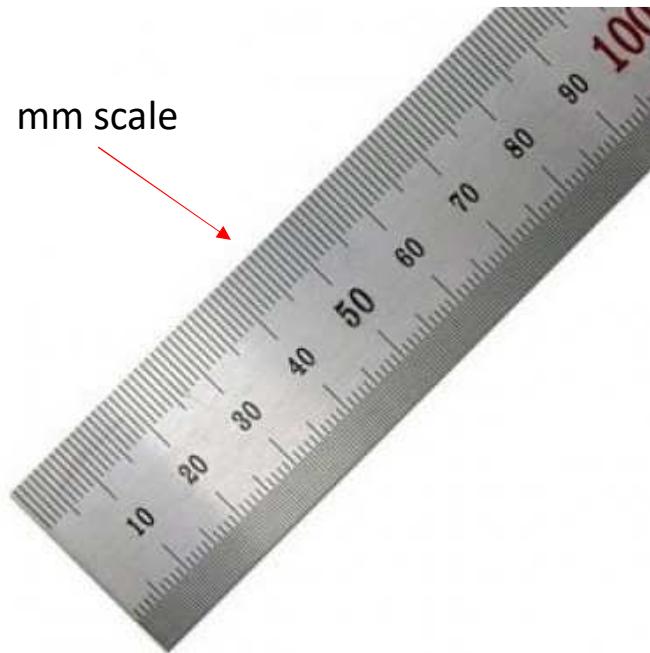
College Physics
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Double slit interference



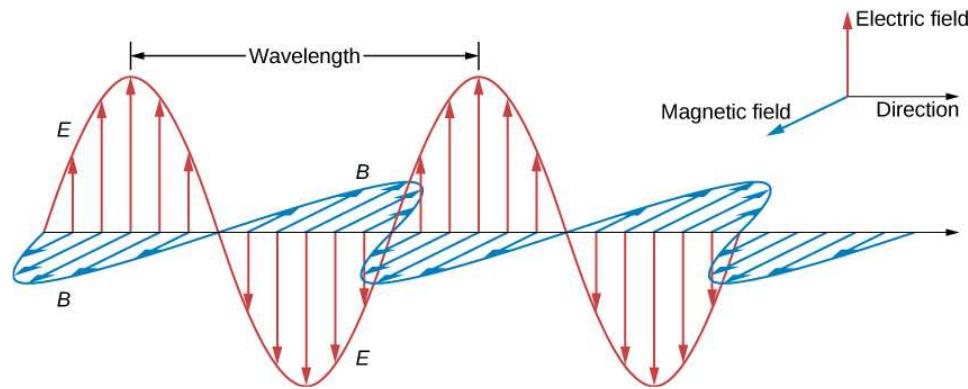
College Physics
OpenStaxCollege

Interferometer



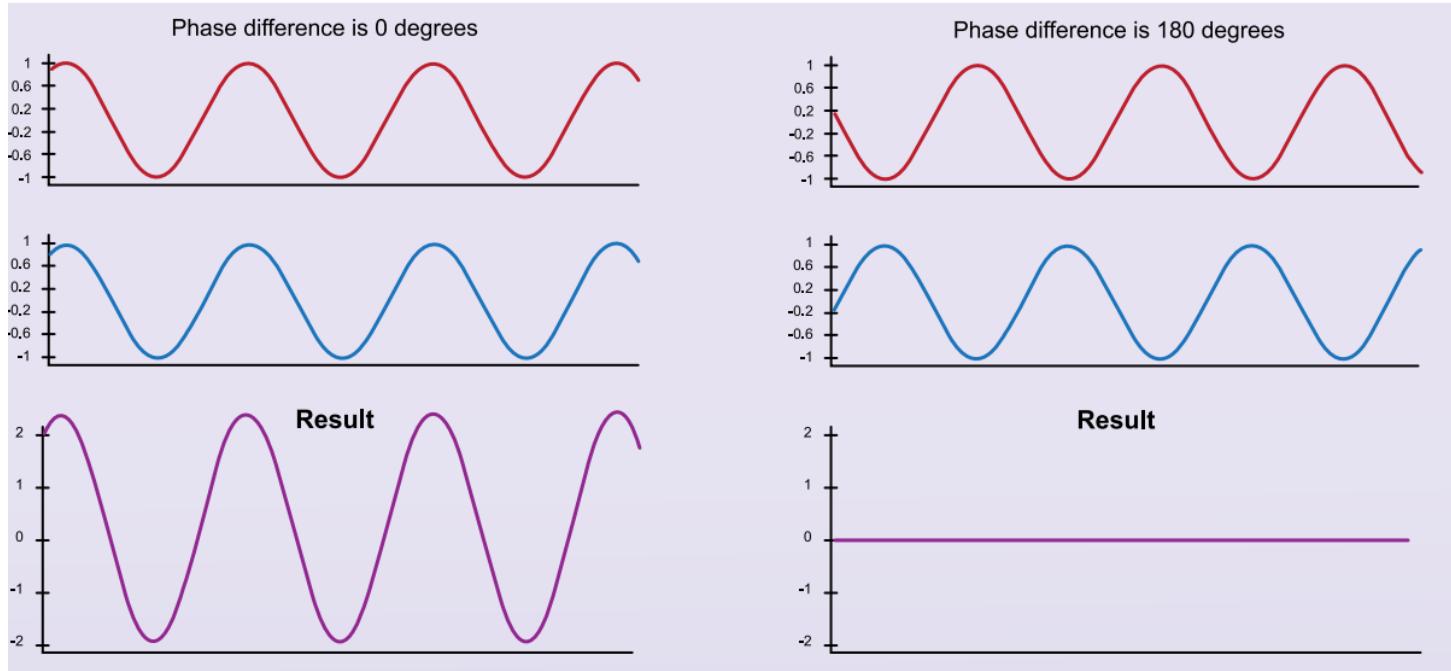
mm scale

Interferometer

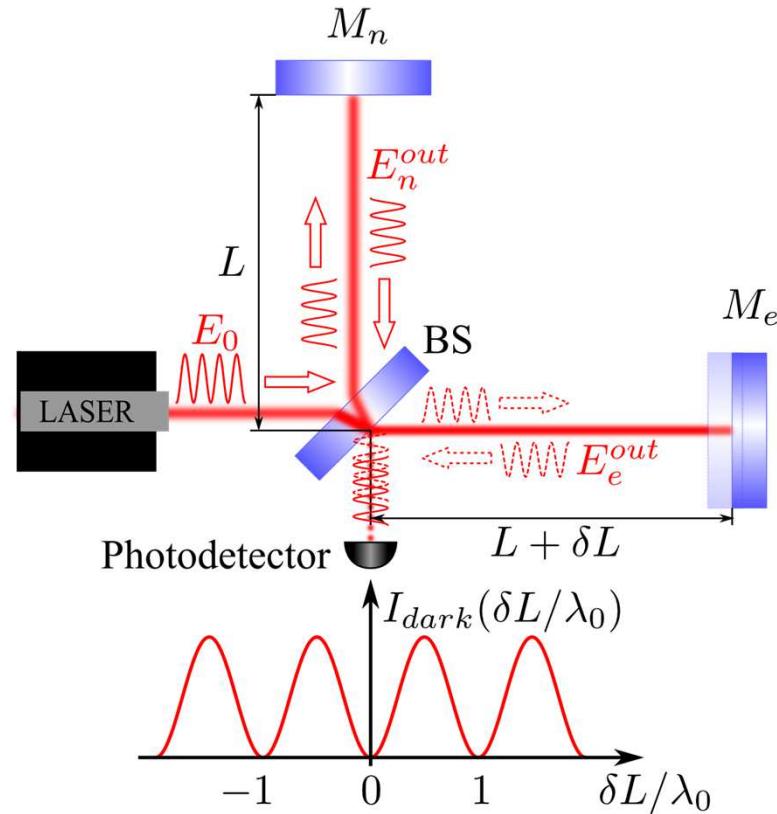


$$E = E_0 \cos(kx - \omega t)$$

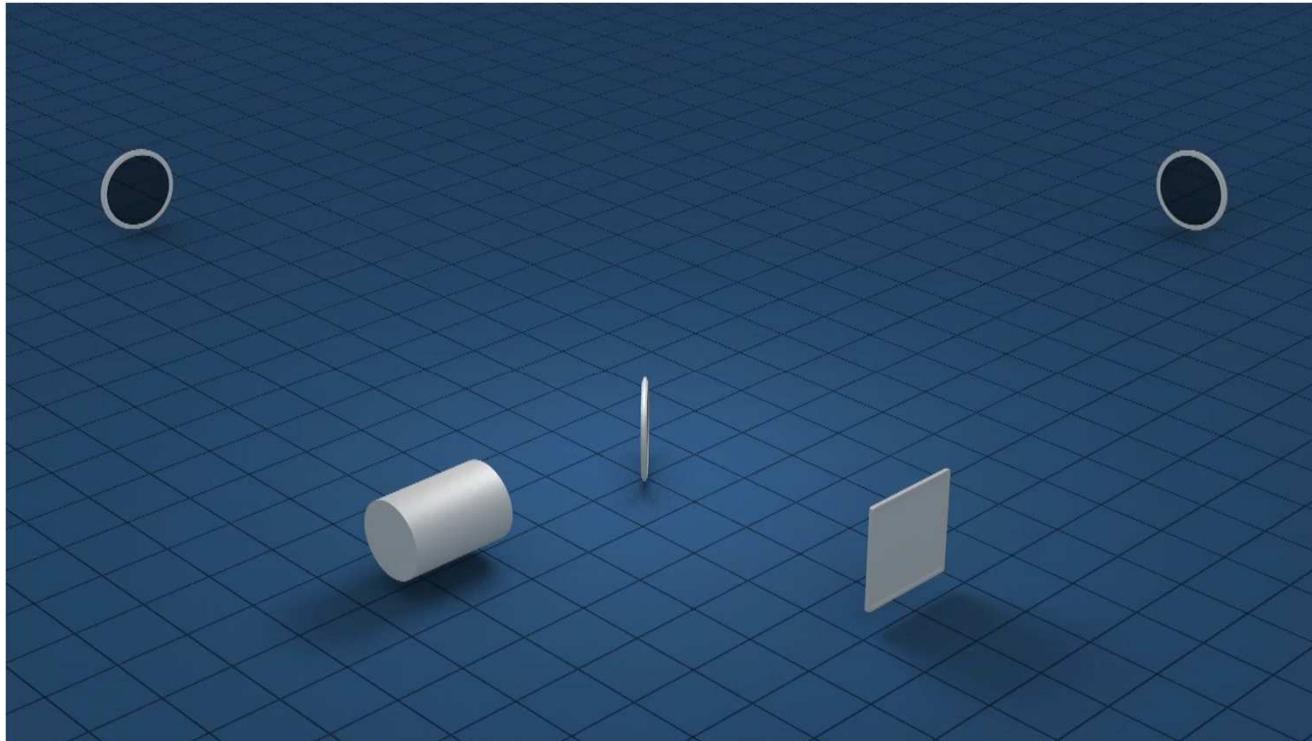
Construct & Destructive interference



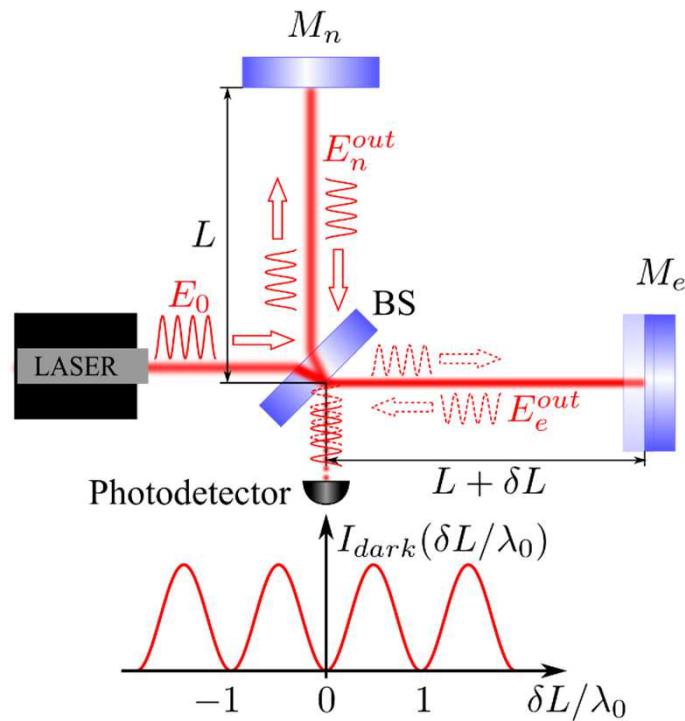
Michelson interferometer



Michelson interferometer



Sensitivity of Michelson interferometer



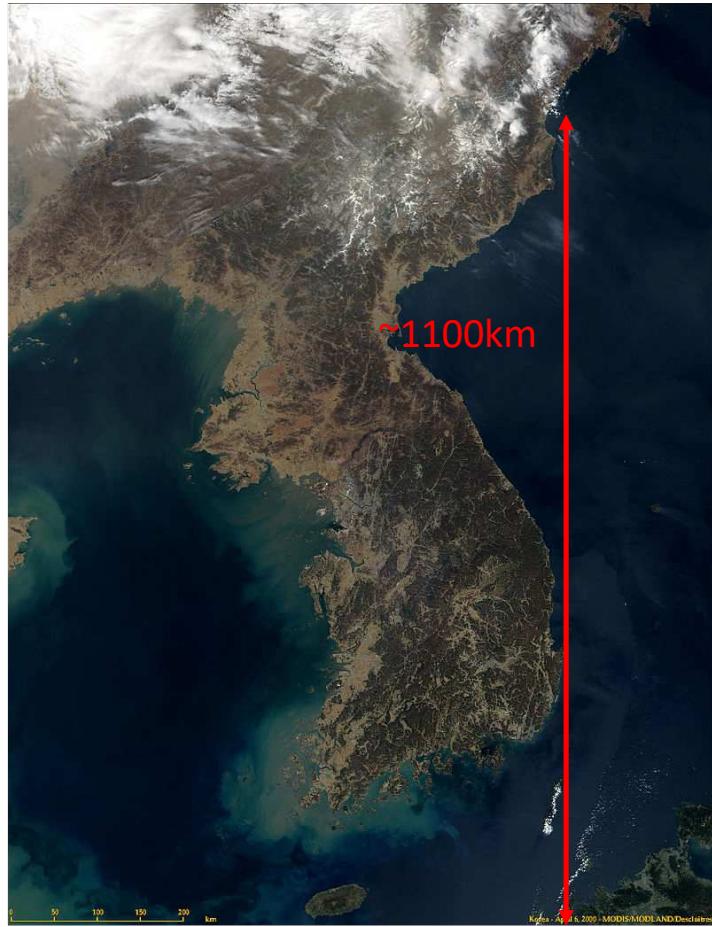
When $L = 1\text{m}$

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

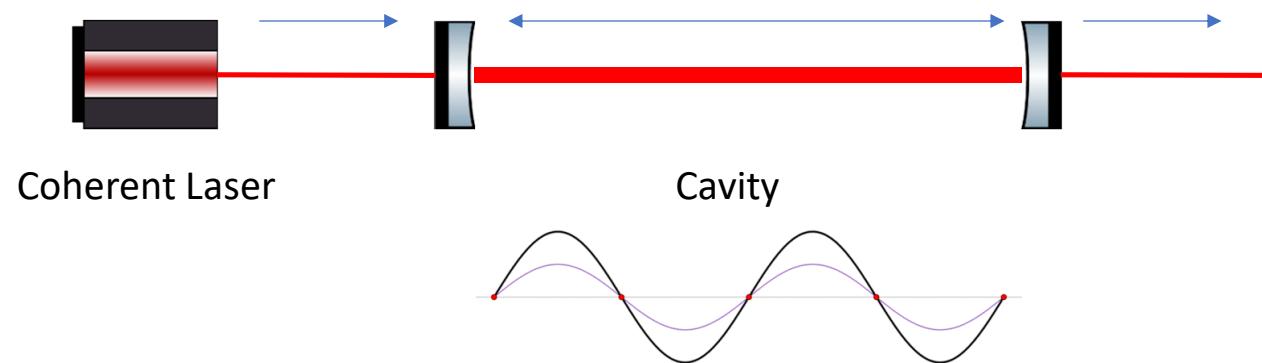
If $L = 1000\text{km}$

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

1000km interferometer is available?



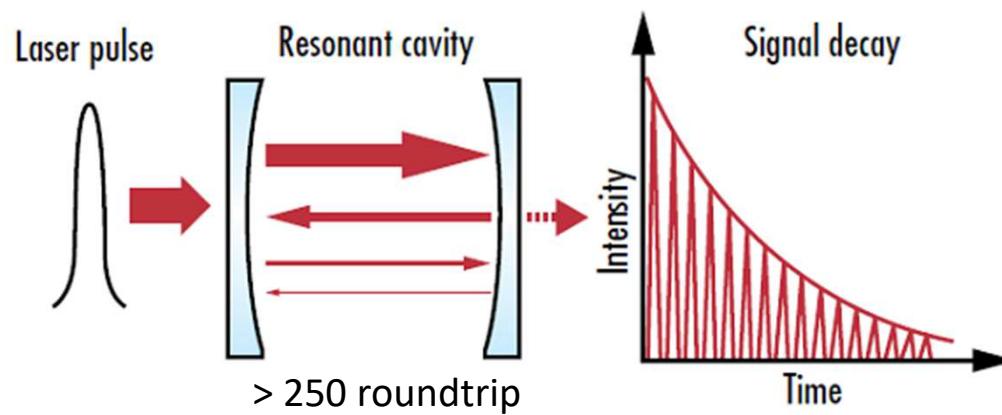
Fabry–Perot cavity



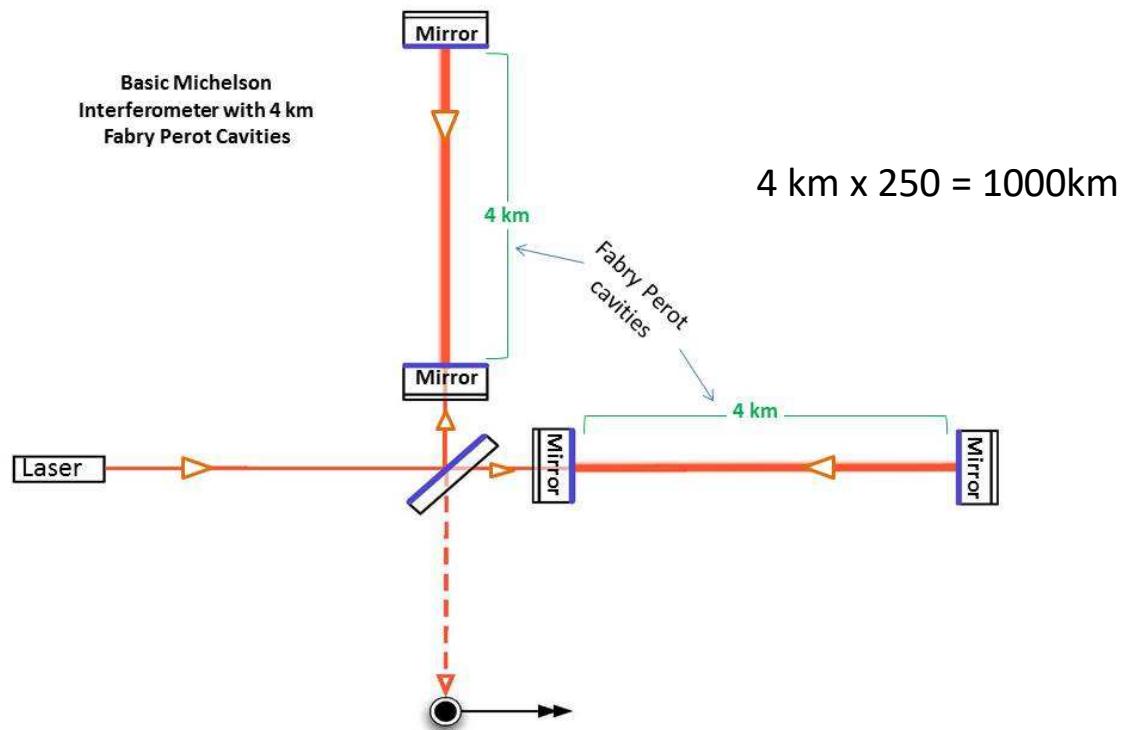
Fabry–Perot cavity



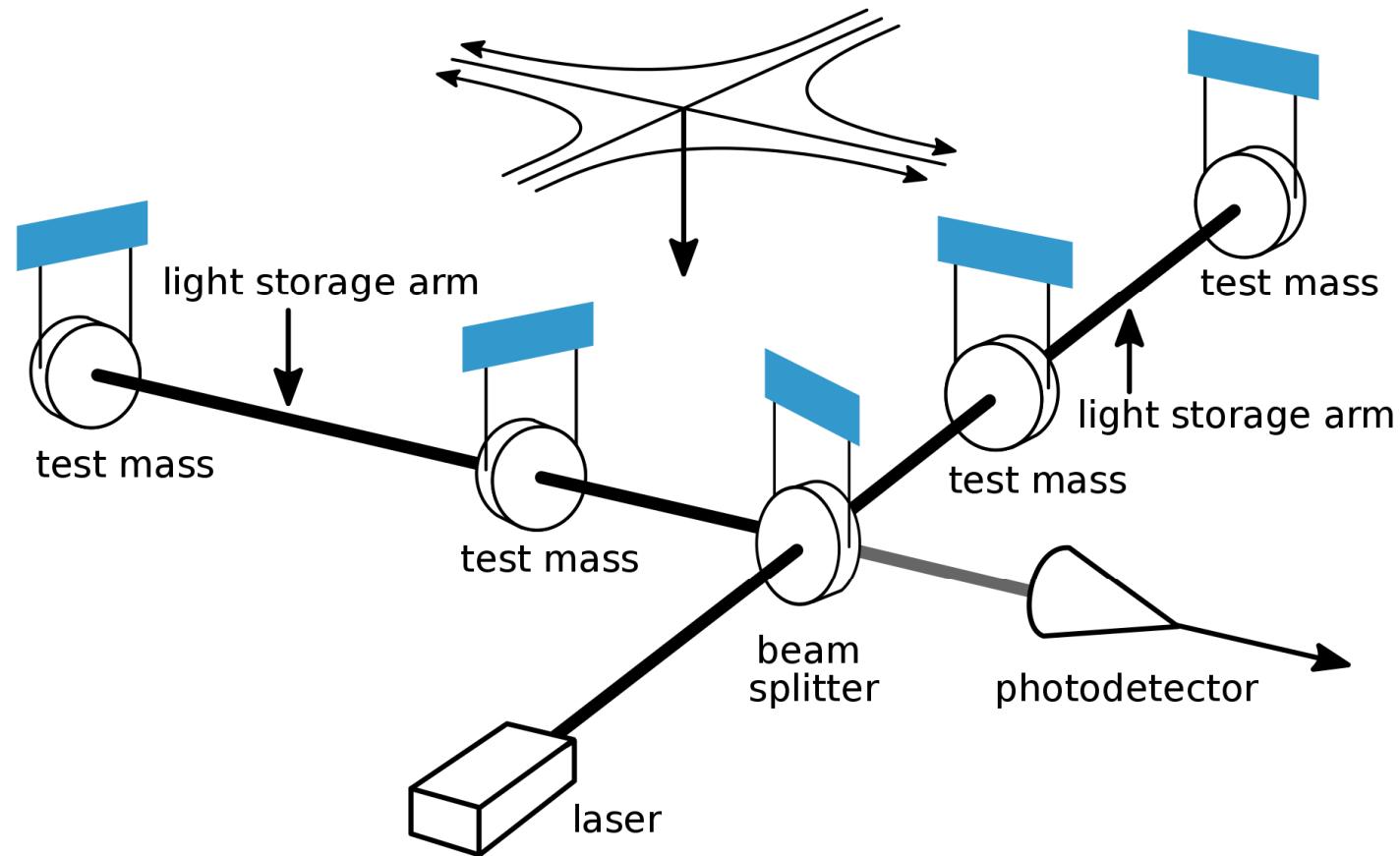
Coherent Laser Cavity



Fabry–Perot Michelson interferometer



Interferometer of LIGO





Interferometer of GW detector



KAGRA interferometer



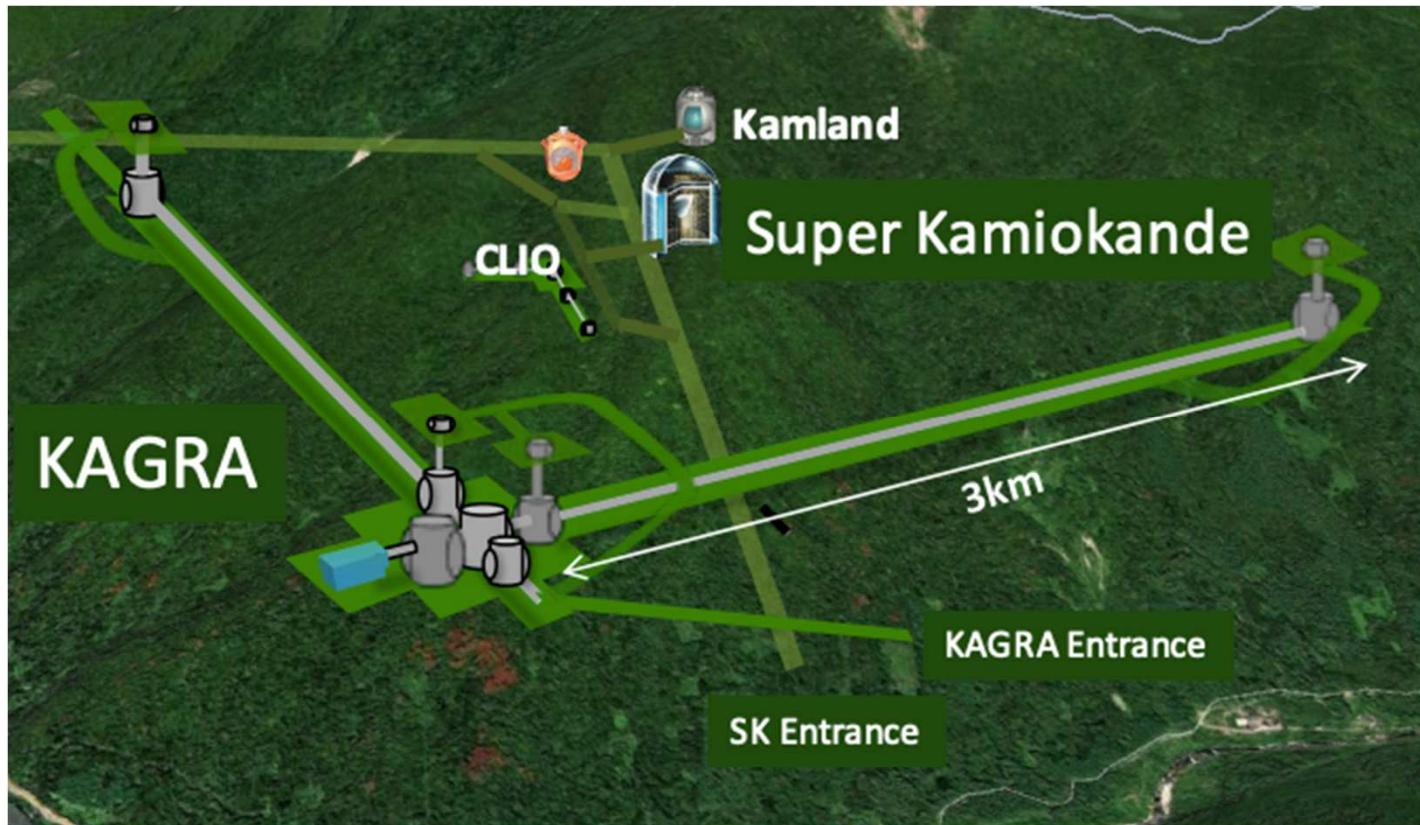
Rey.Hori

Location of KAGRA



Nature Astronomy, 3 (2019) 35–40

Avoid seismic noise

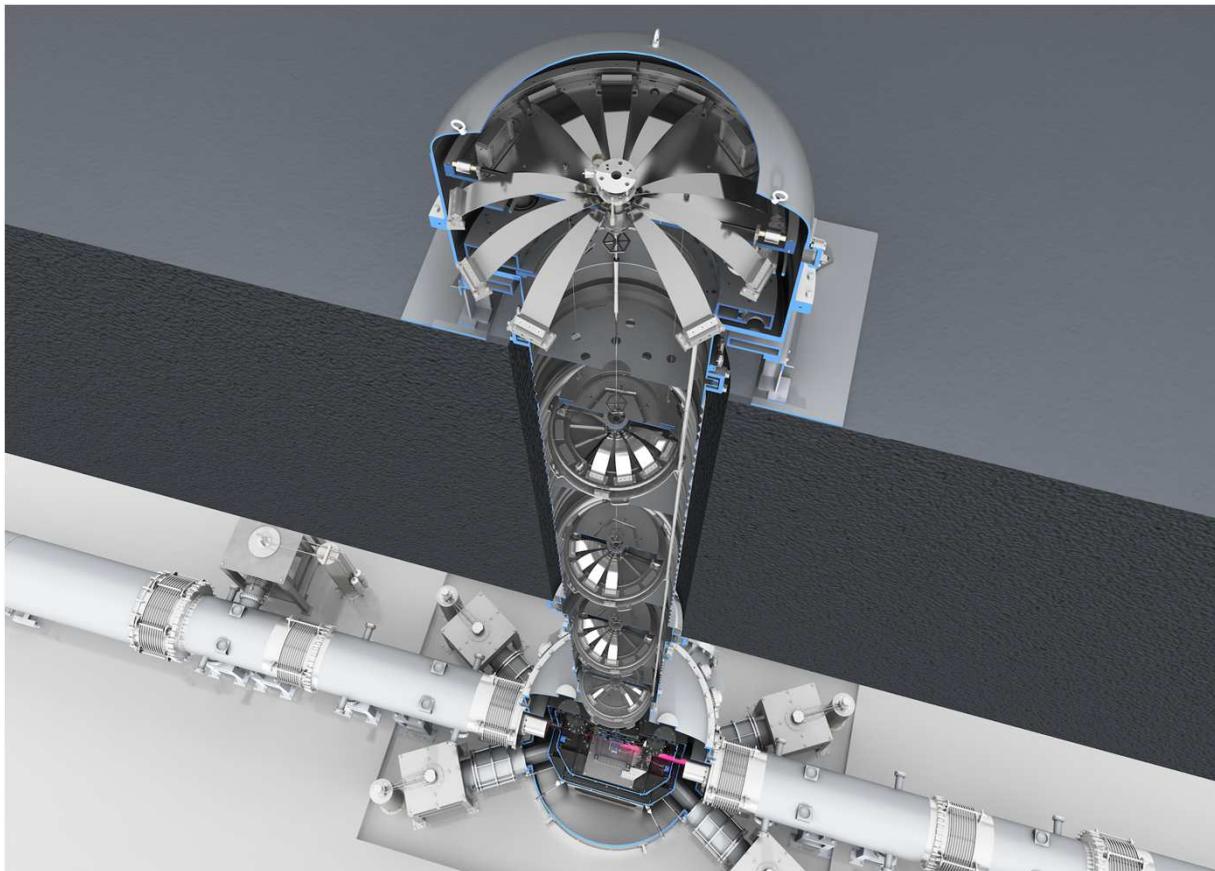


KAGRA tunnel



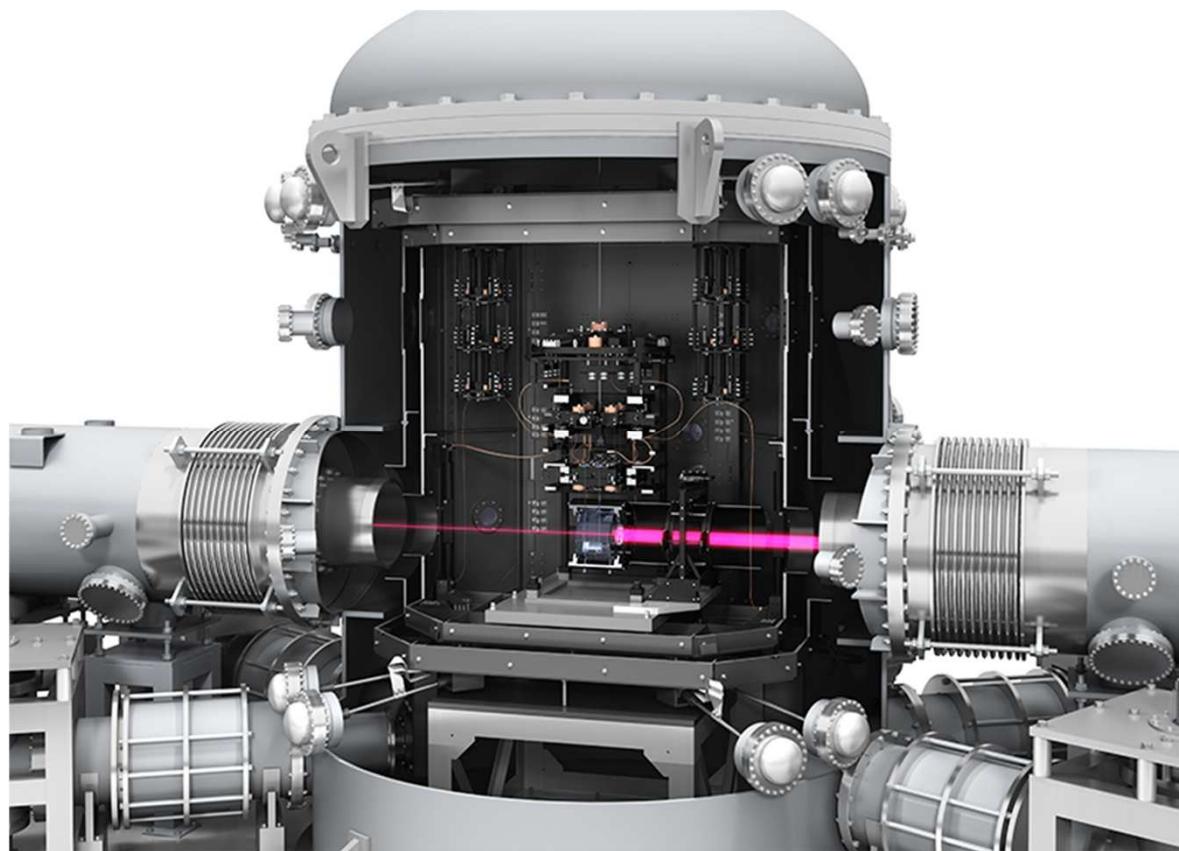
Photo credit: KAGRA

Vibration isolation system of KAGRA



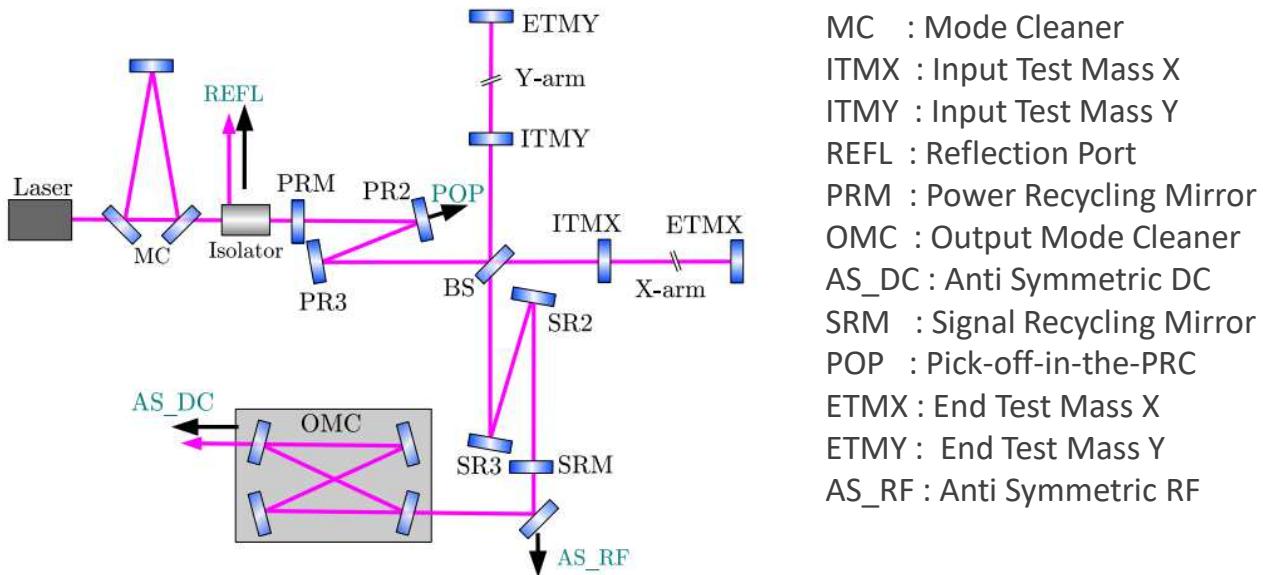
Rey.Hori

Test mass chamber



Rey.Hori

Interferometer of KAGRA

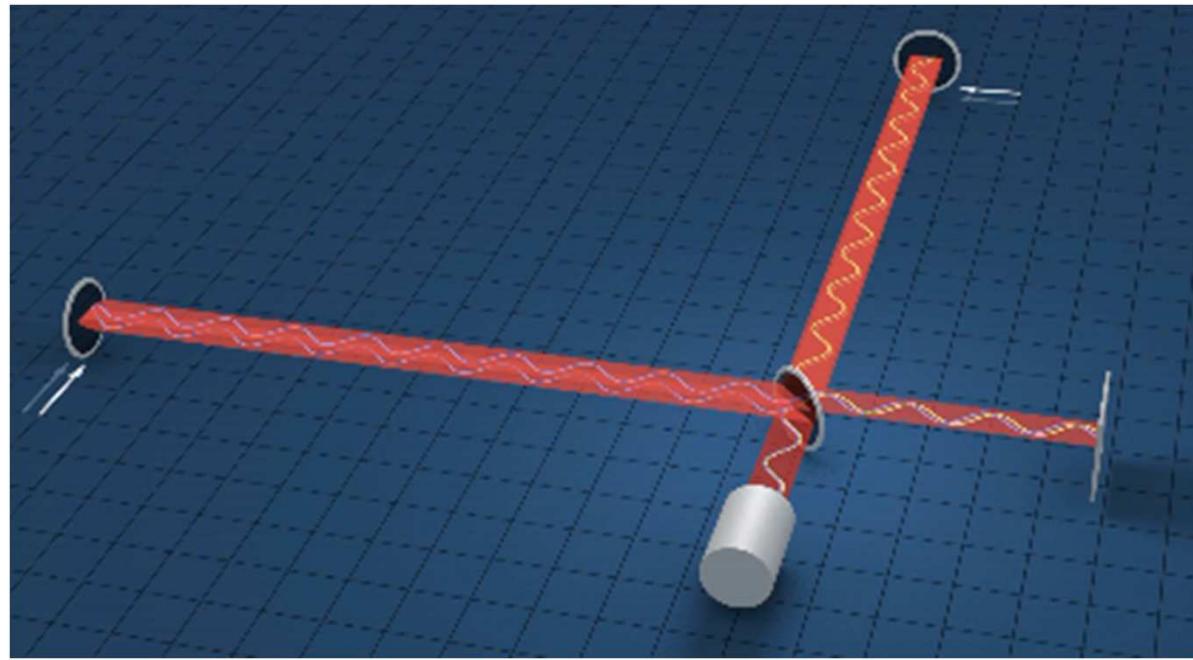


MC : Mode Cleaner
ITMX : Input Test Mass X
ITMY : Input Test Mass Y
REFL : Reflection Port
PRM : Power Recycling Mirror
OMC : Output Mode Cleaner
AS_DC : Anti Symmetric DC
SRM : Signal Recycling Mirror
POP : Pick-off-in-the-PRC
ETMX : End Test Mass X
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AS_RF : Anti Symmetric RF

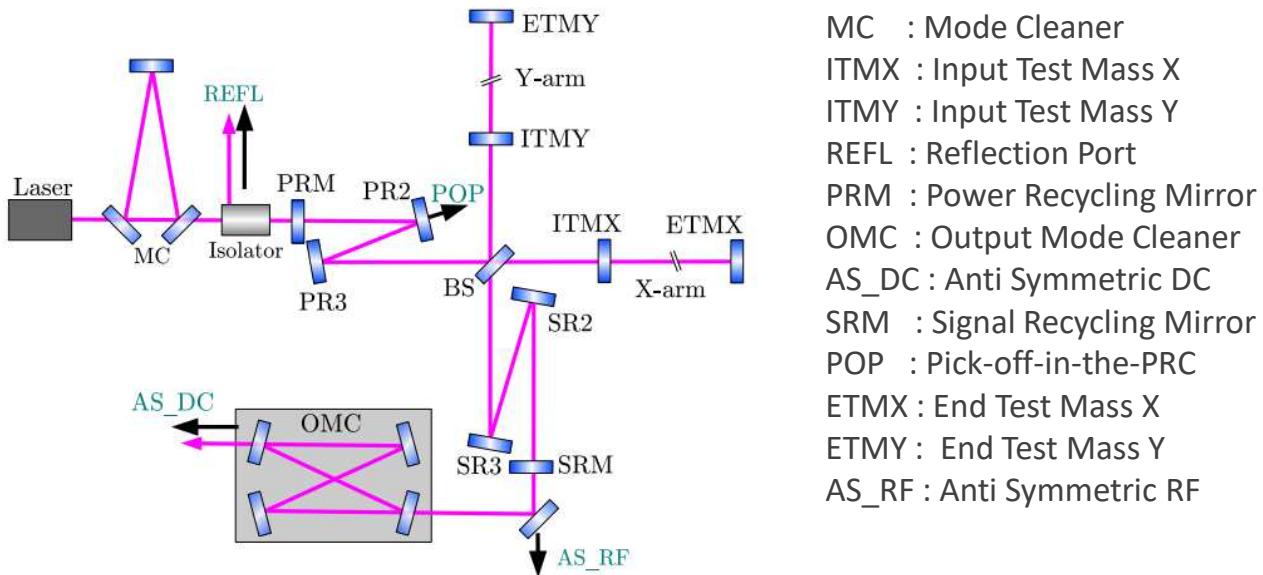
Y. Aso et al. (KAGRA Collaboration), Phys.Rev. D88, 043007 (2013)

Interferometer of KAGRA
(gravitational wave detector)

Michelson interferometer



Interferometer of KAGRA

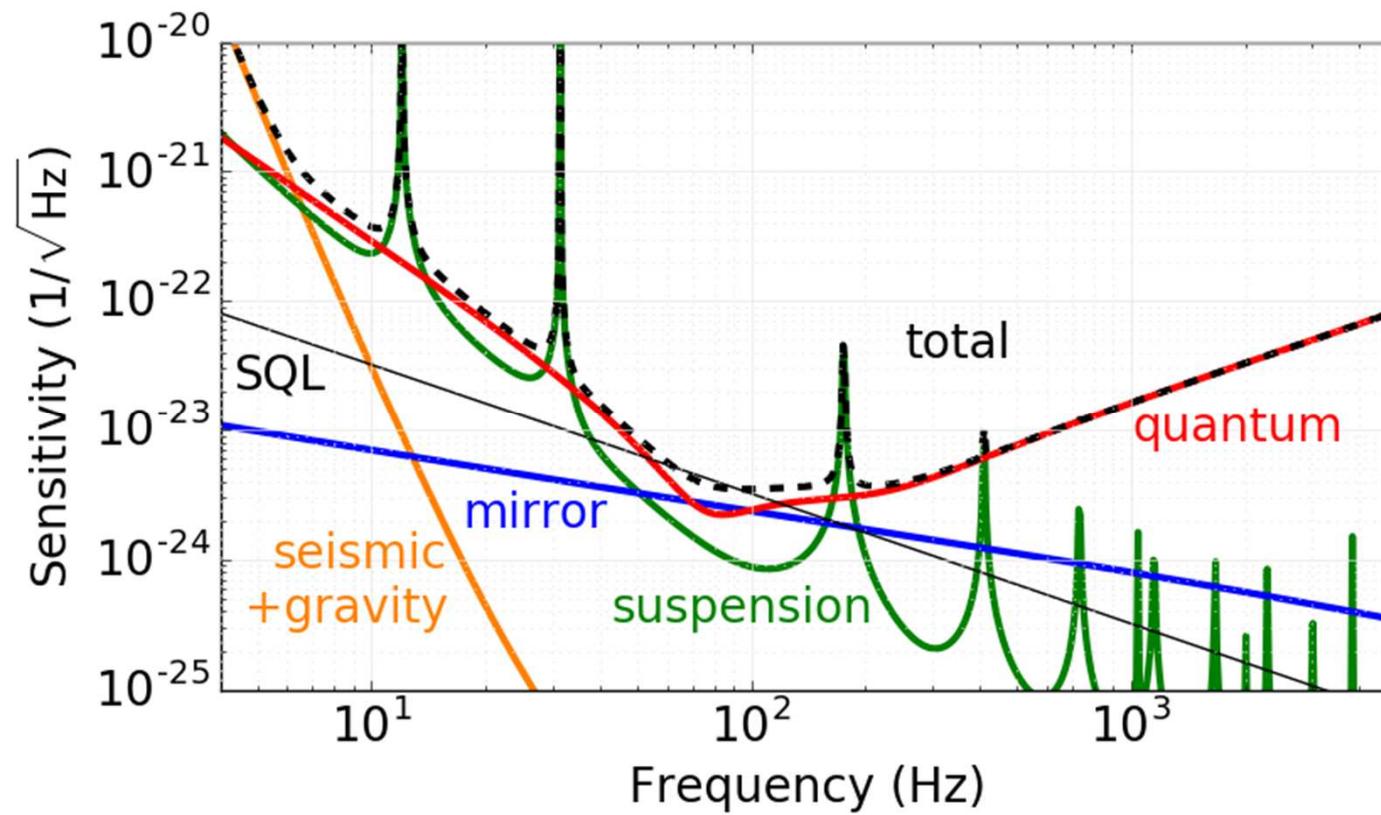


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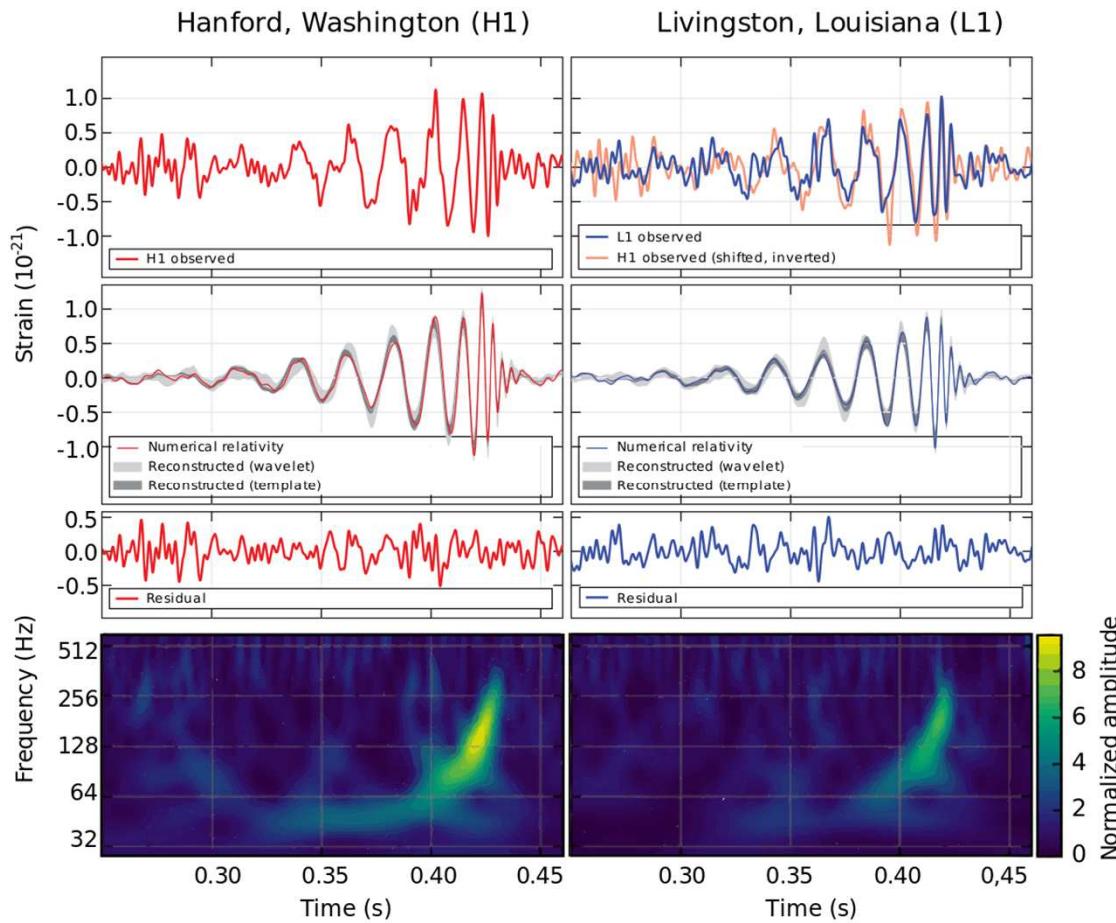
Interferometer of KAGRA
(gravitational wave detector)

Sensitivity curve of gravitational wave detector

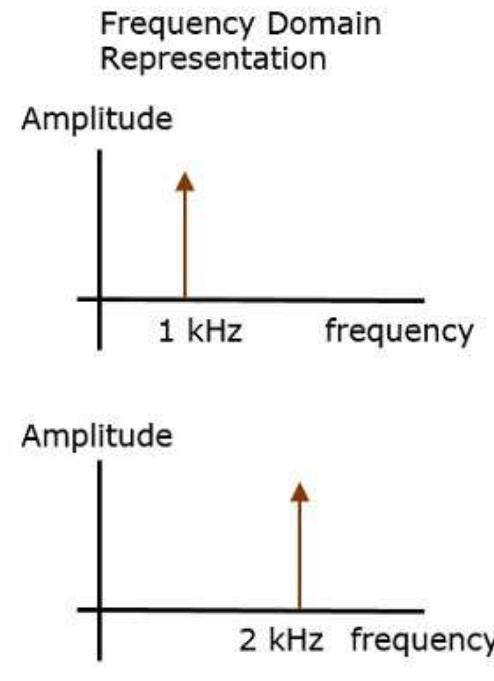
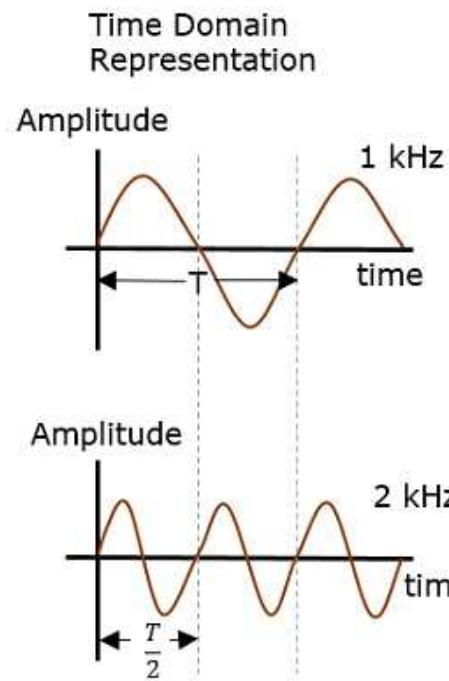


Sensitivity curve of KAGRA

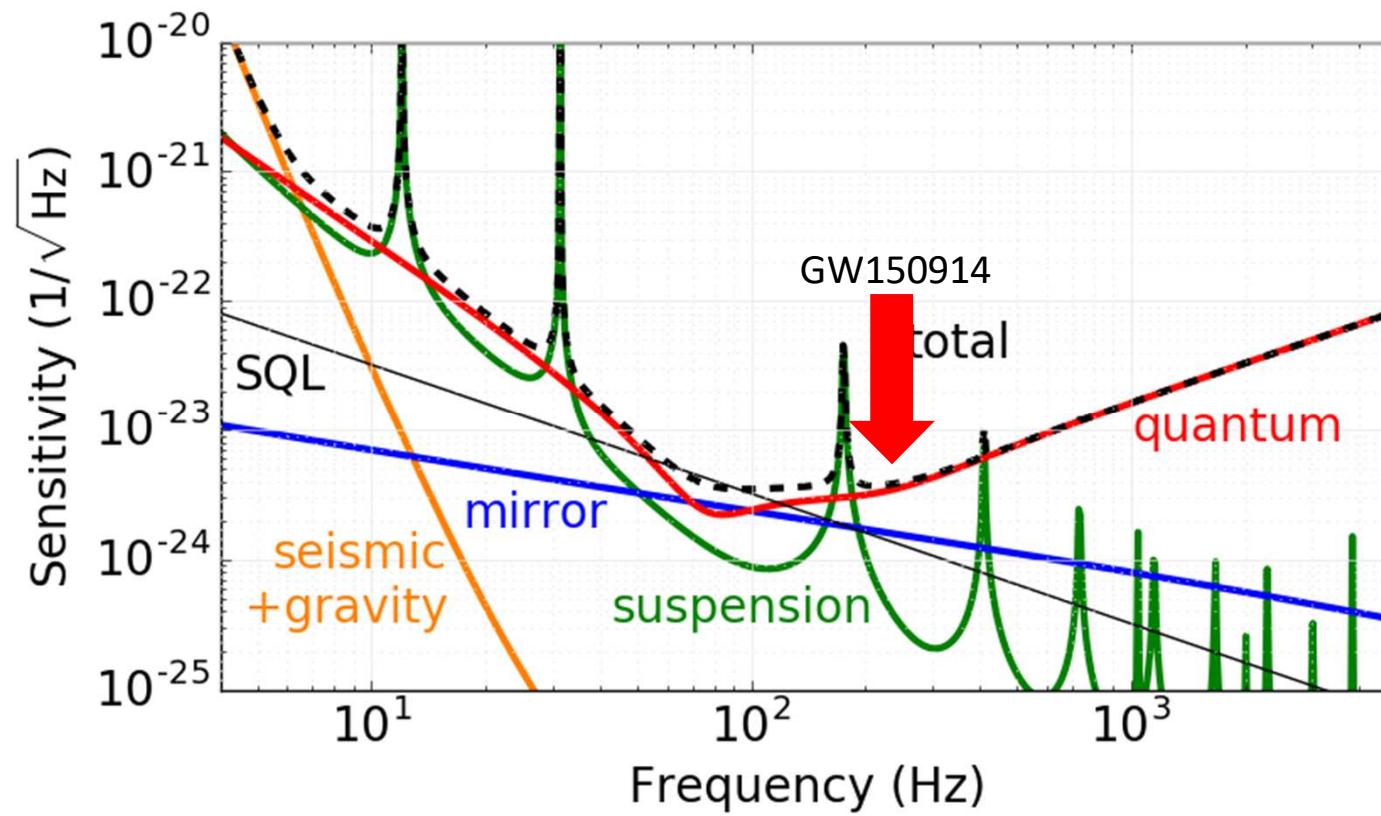
Measurement



Time domain and frequency domain

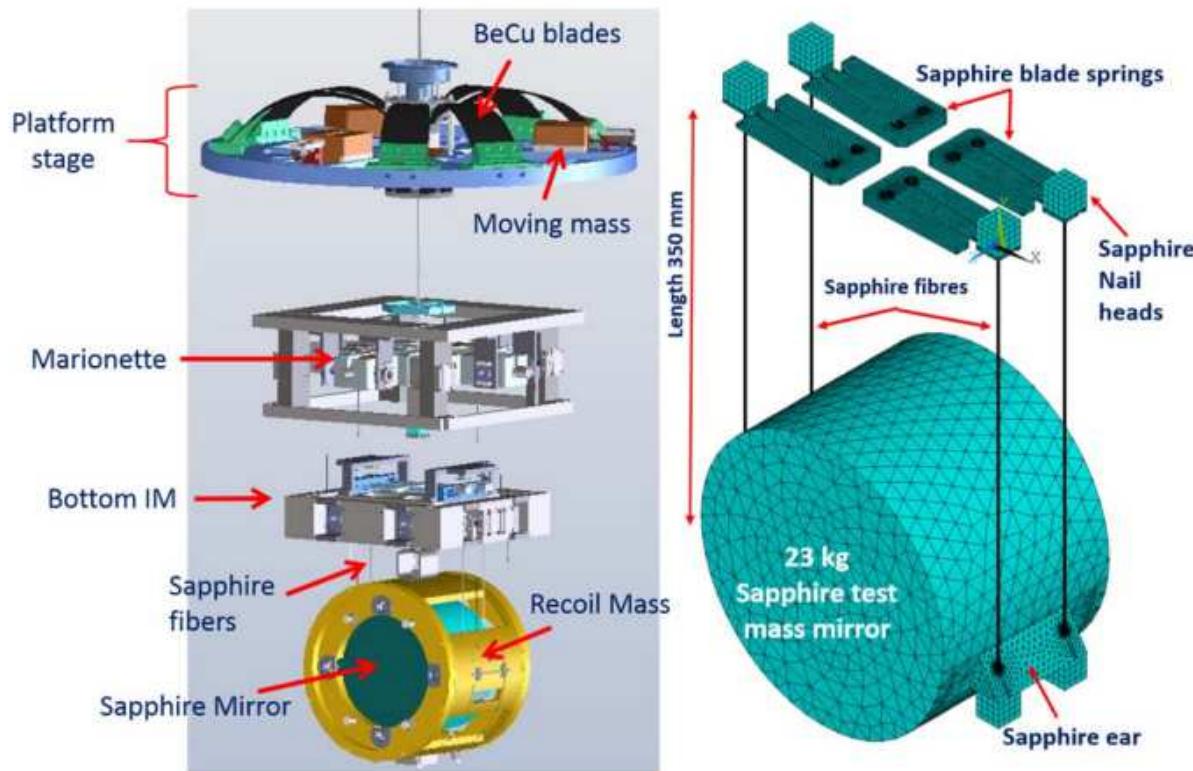


Sensitivity curve of gravitational wave detector



Sensitivity curve of KAGRA

Test mass of KAGRA



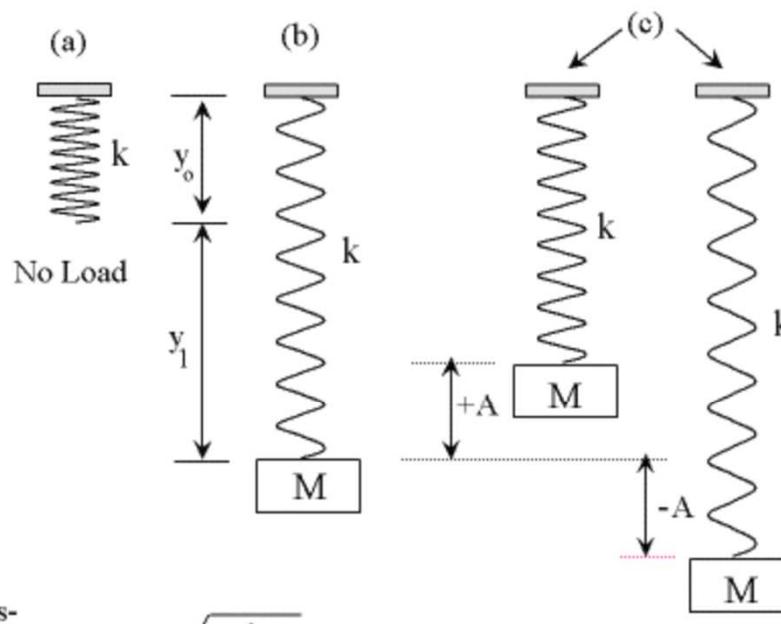
Test mass of KAGRA



High frequency component of vibration and seismic noise can be reduced

How suspension works

Note that the bottom of the spring or the top of the mass is chosen for our study of the oscillations. We could have drawn the dotted lines at the mid-level of mass M or any other point on the object consistent in all figures. Using a simple differential equation, it can be shown that ω , the angular frequency of oscillations of the mass-spring system is given by

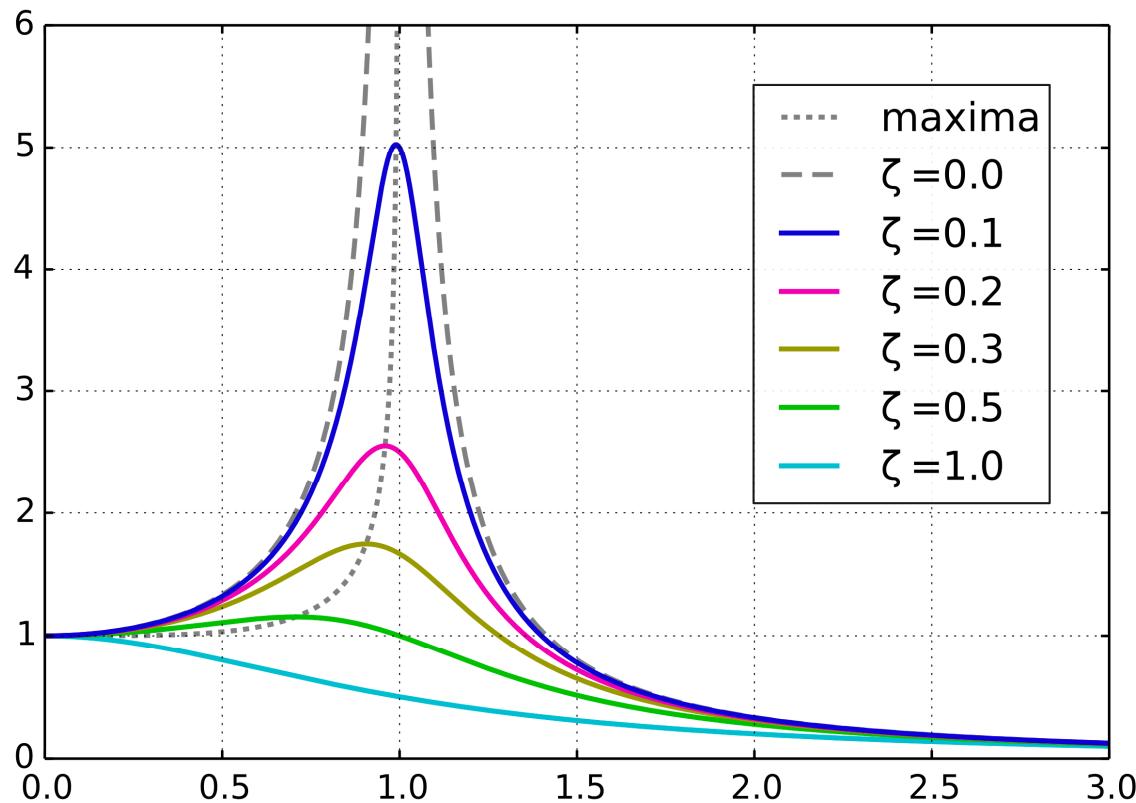


$$\omega = \sqrt{\frac{k}{M}} \quad \text{where} \quad \omega = 2\pi f.$$

From this equation the frequency, f , and period, T , can be calculated.

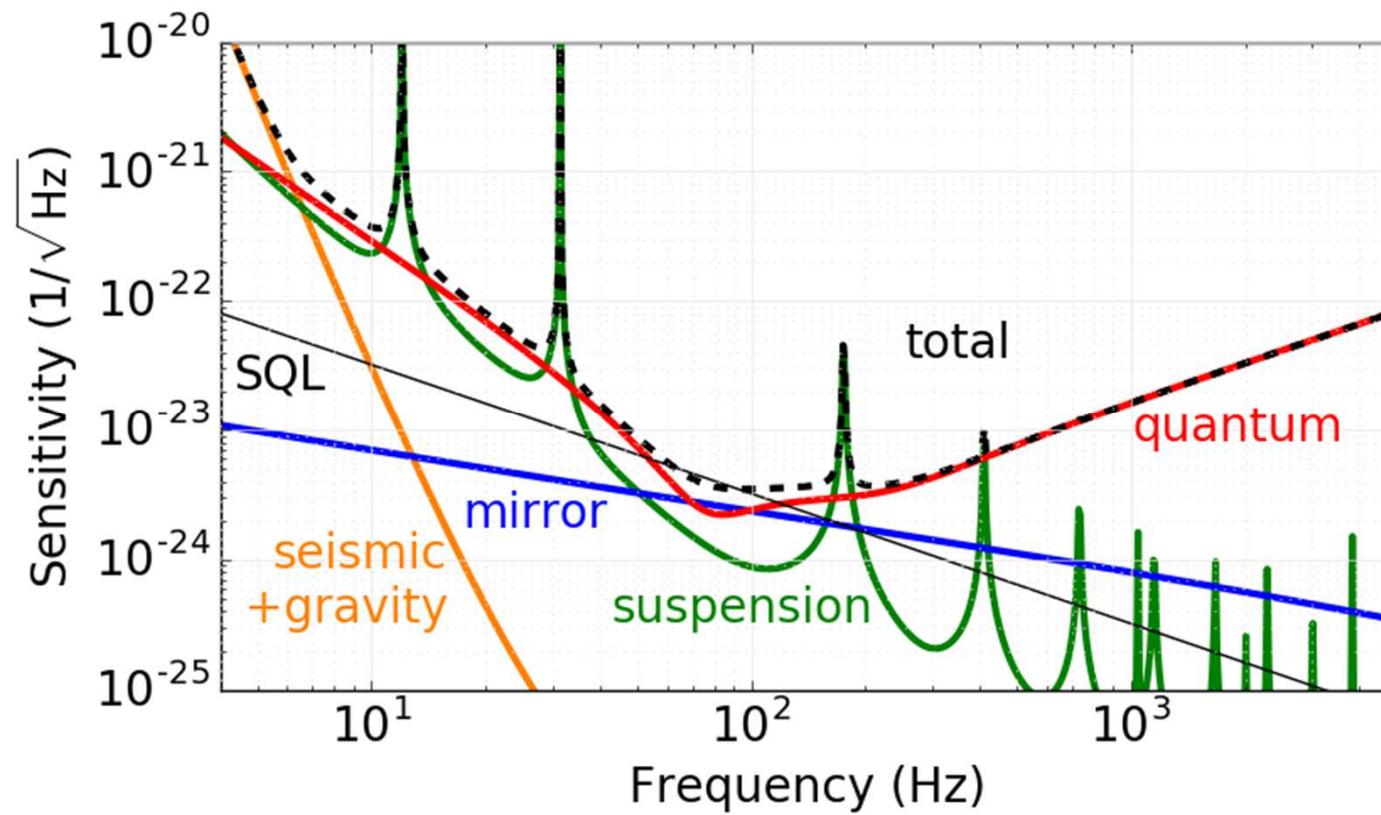
<http://www.pstcc.edu/nbs/WebPhysics/Expm%2001.htm>

Resonance



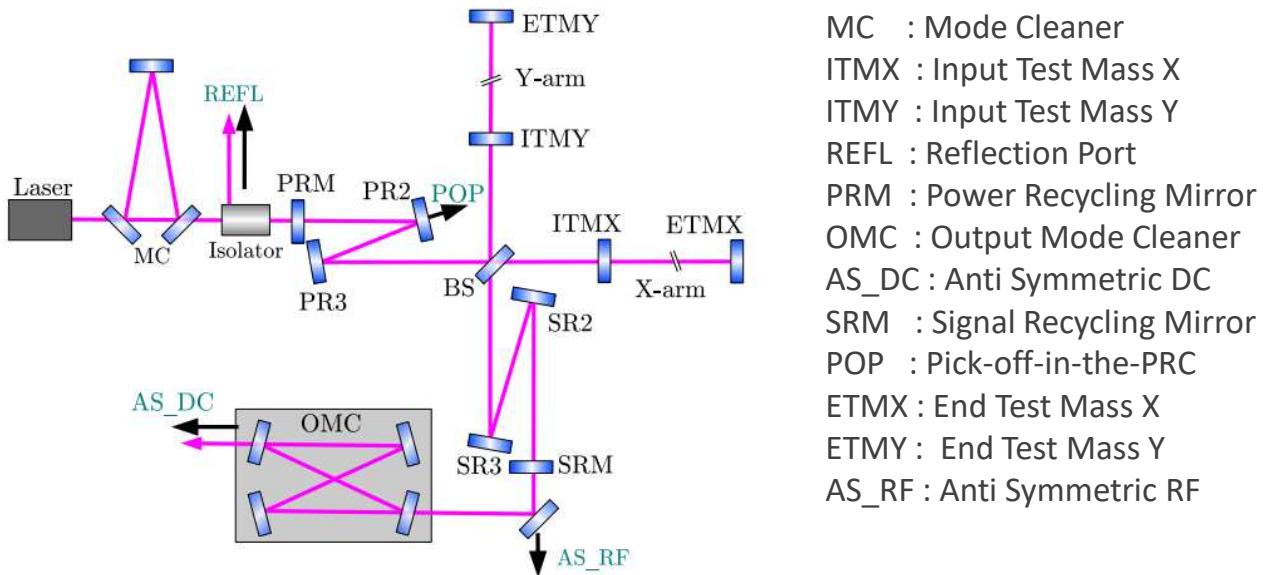
<https://en.wikipedia.org/wiki/Resonance>

Sensitivity curve of gravitational wave detector



Sensitivity curve of KAGRA

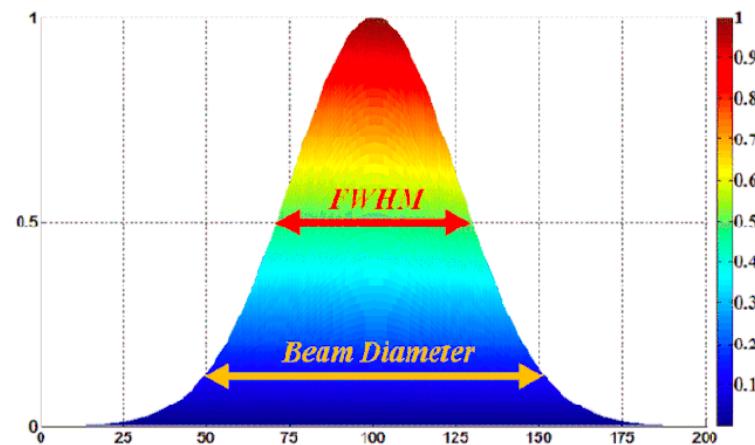
Interferometer of KAGRA



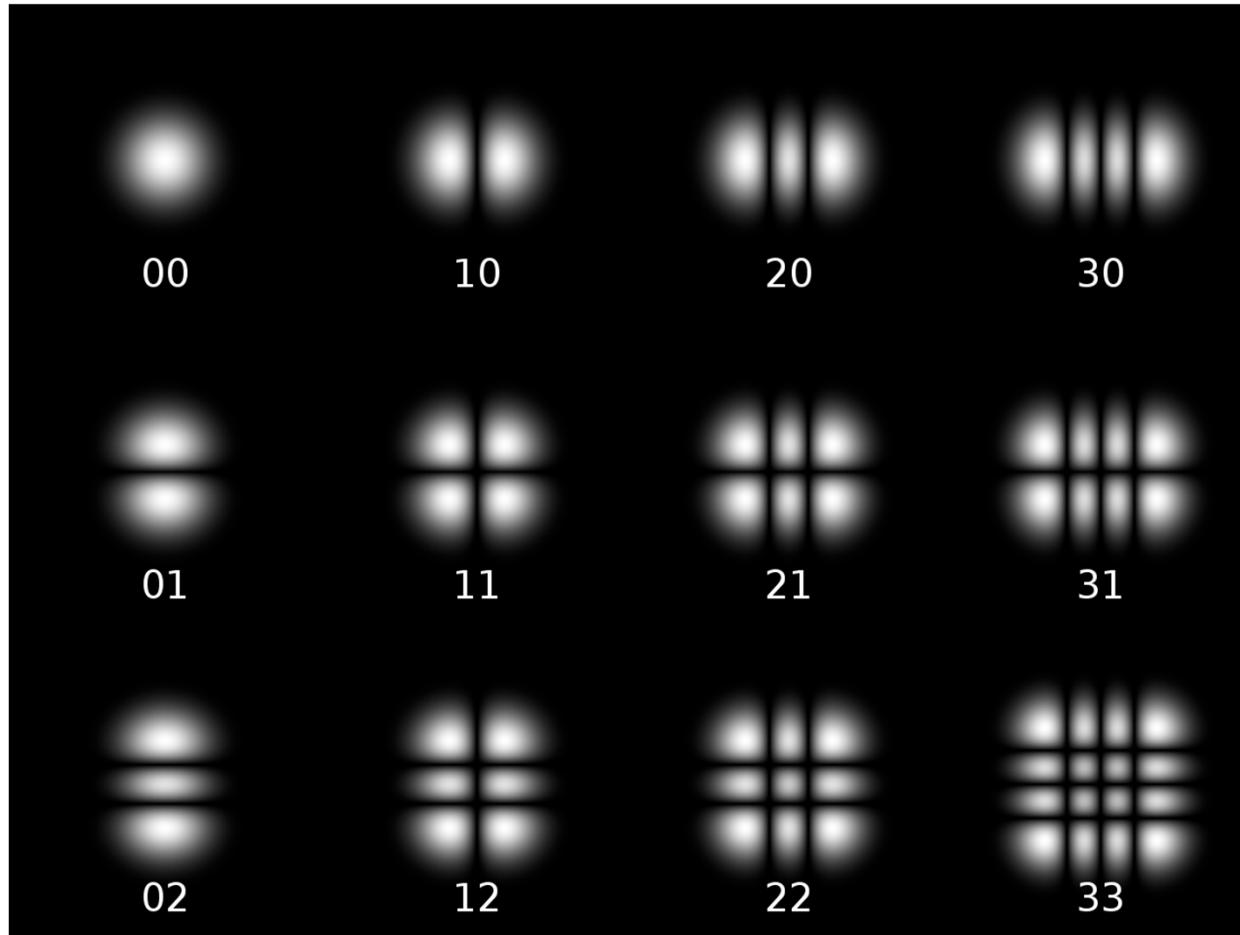
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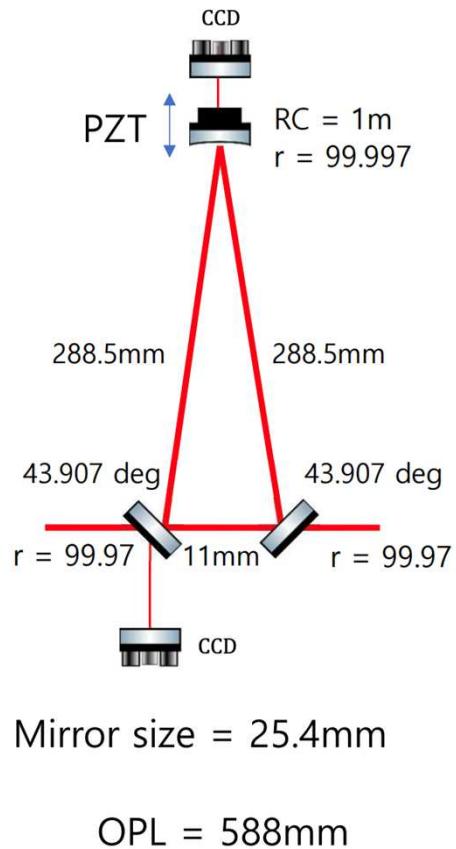
Gaussian beam



Spatial mode of gaussian beam

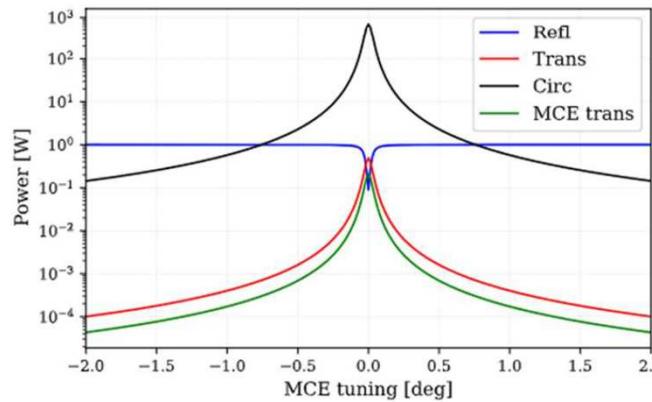


Design of mode cleaner

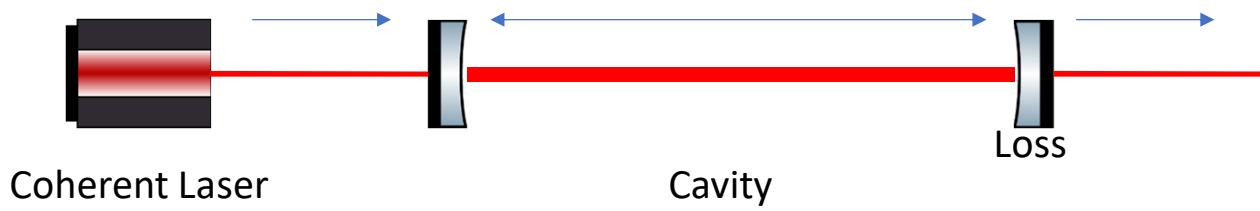


```
--- cavity tracing  
cavity IMC:  
cavity is stable! Eigenvalues:  
qx=-0.0055+0.45553j, w0x=392.785928485974um zx=-5.50000000000001m mx=-0.411893  
qy=-0.0055+0.455651j, w0y=392.83651358971um zy=-5.5m my=0.412107  
finesse : 3140.46, round-trip power loss: 0.0019987203 [/100]  
opt. length: 588m, FSR: 509.851119047619MHz, m: -411.893072289888m  
FWHM: 162.349119294022kHz (pole: 81.1745596470109kHz)  
(x) A: -0.42289507 B: -0.41515707 C: 2.0003637 D: -0.40089107  
(y) A: 0.42310491 B: 0.41521992 C: -1.9996364 D: 0.40110891  
(x) RT Gouy: -114.323810241722 deg, mode sep. -161.911451626471MHz  
(y) RT Gouy: 65.6627436253686 deg, mode sep. 92.9950647698086MHz
```

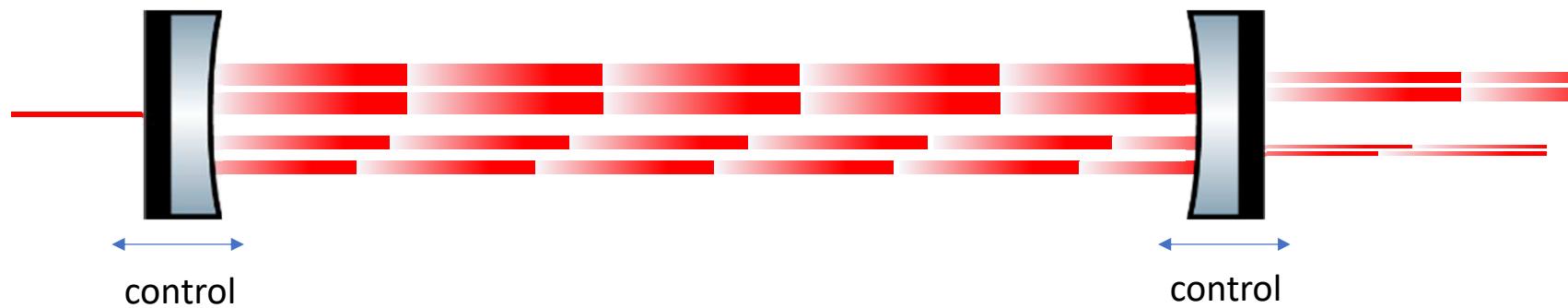
computation time: 0.0840034s



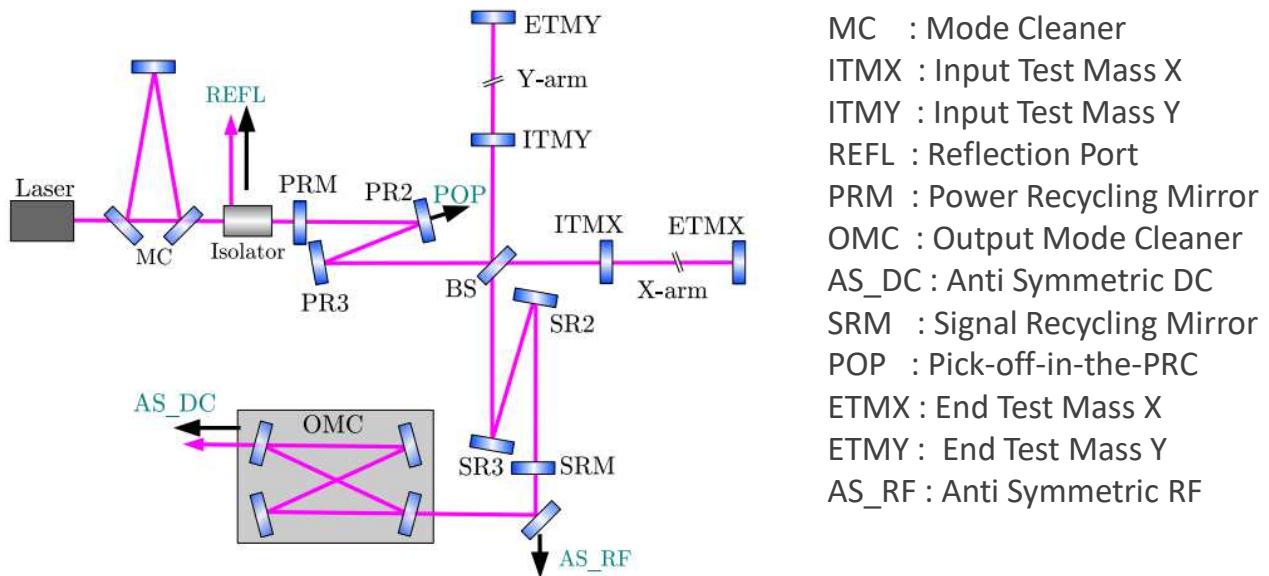
Working principle of mode cleaning



Working principle of mode cleaning



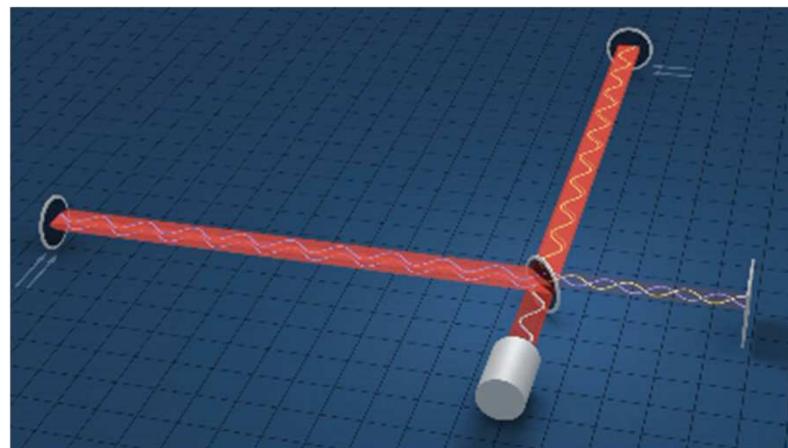
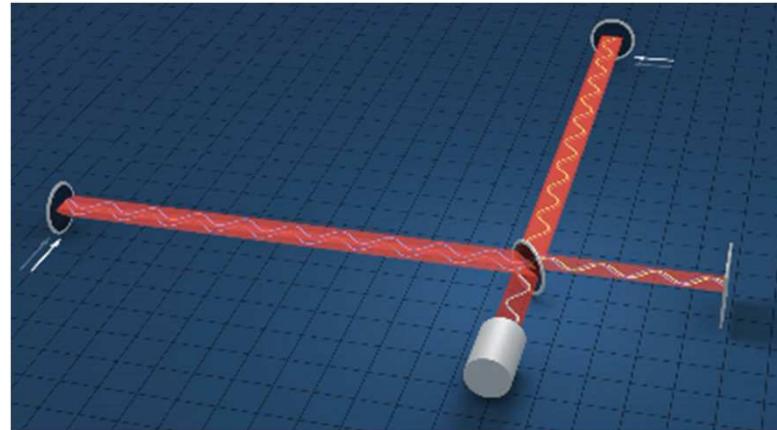
Power and Signal recycling mirror



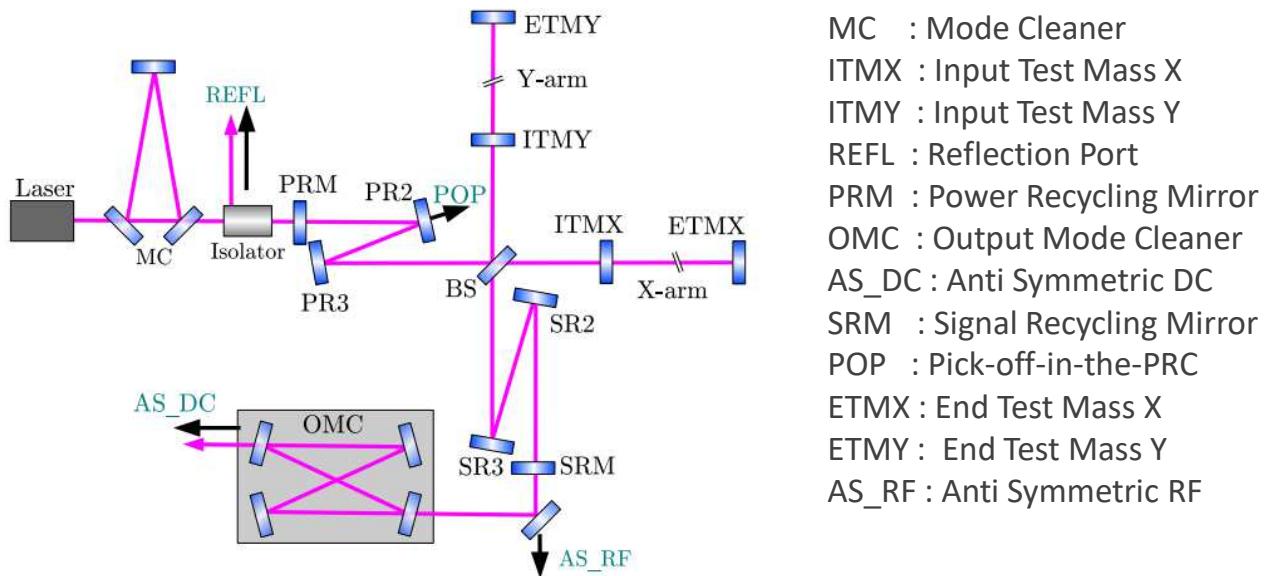
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Y. Aso et al. (KAGRA Collaboration), Phys.Rev. D88, 043007 (2013)

Energy conservation in Michelson interferometer



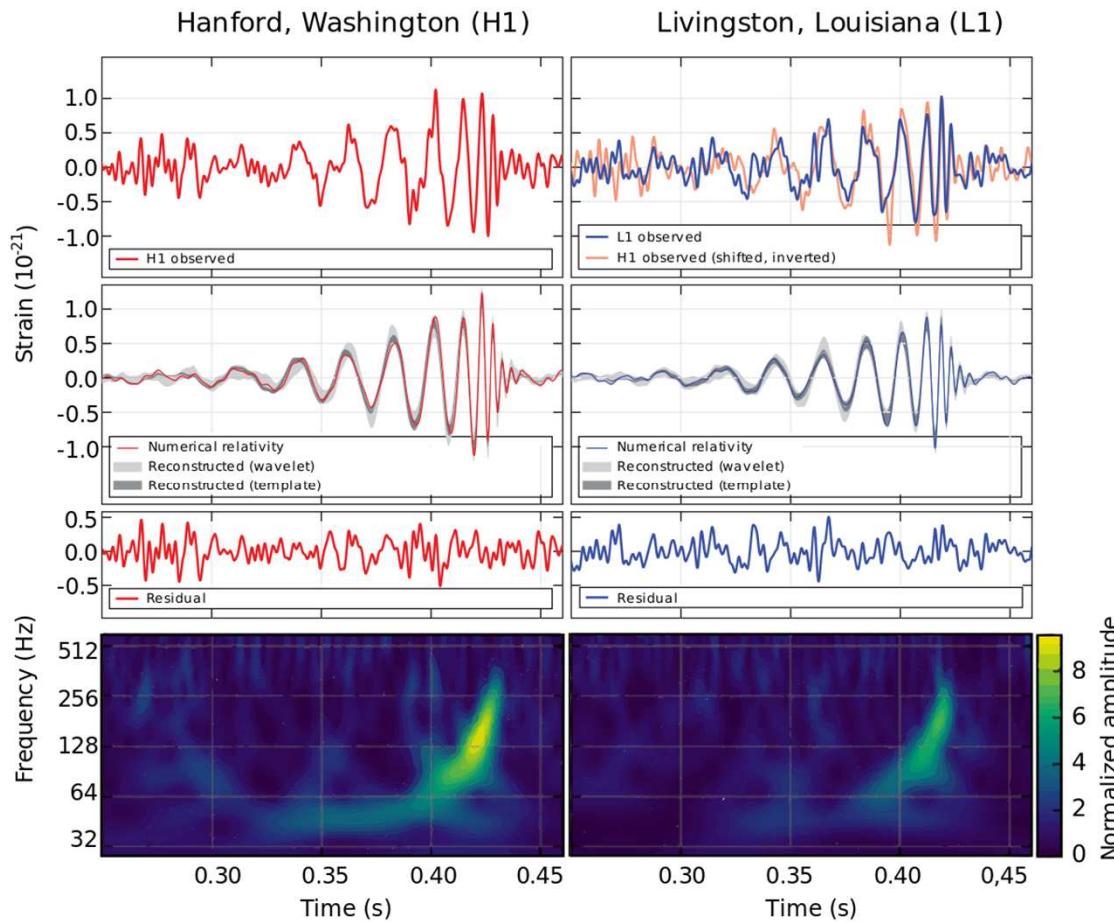
Power and Signal recycling mirror



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First observation of gravitational wave



GW150914

2015-09-14