



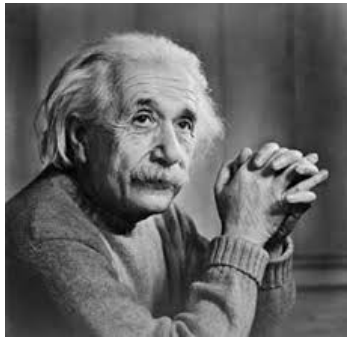
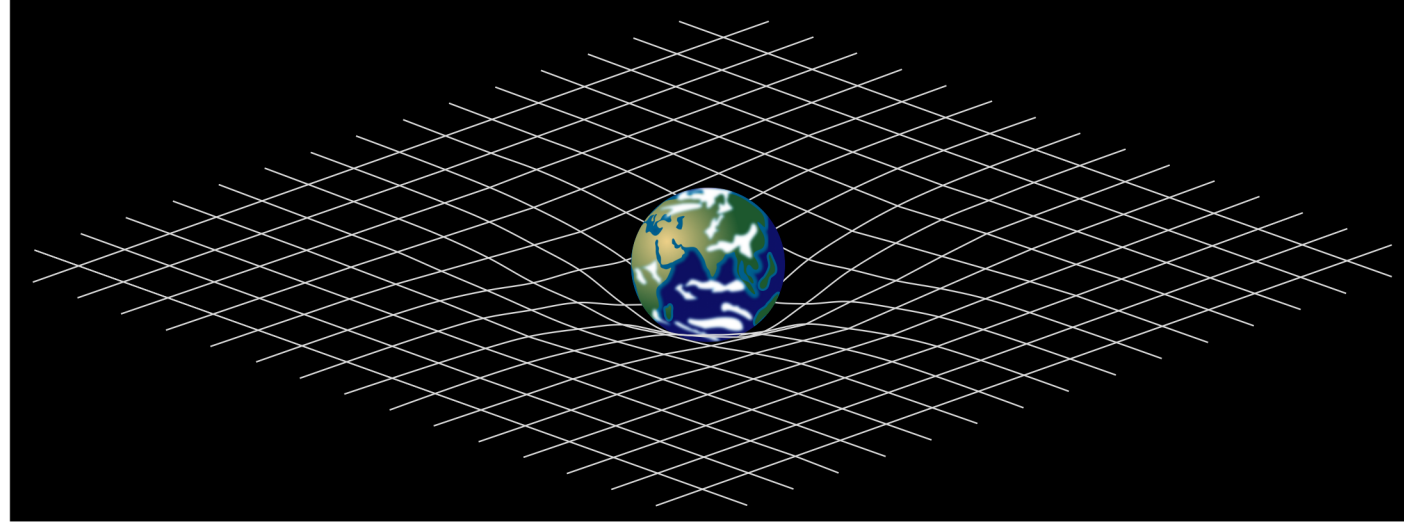
# Gravitational Wave Detector

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**June Gyu Park**

# Gravity and general relativity

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

Local space time curvature

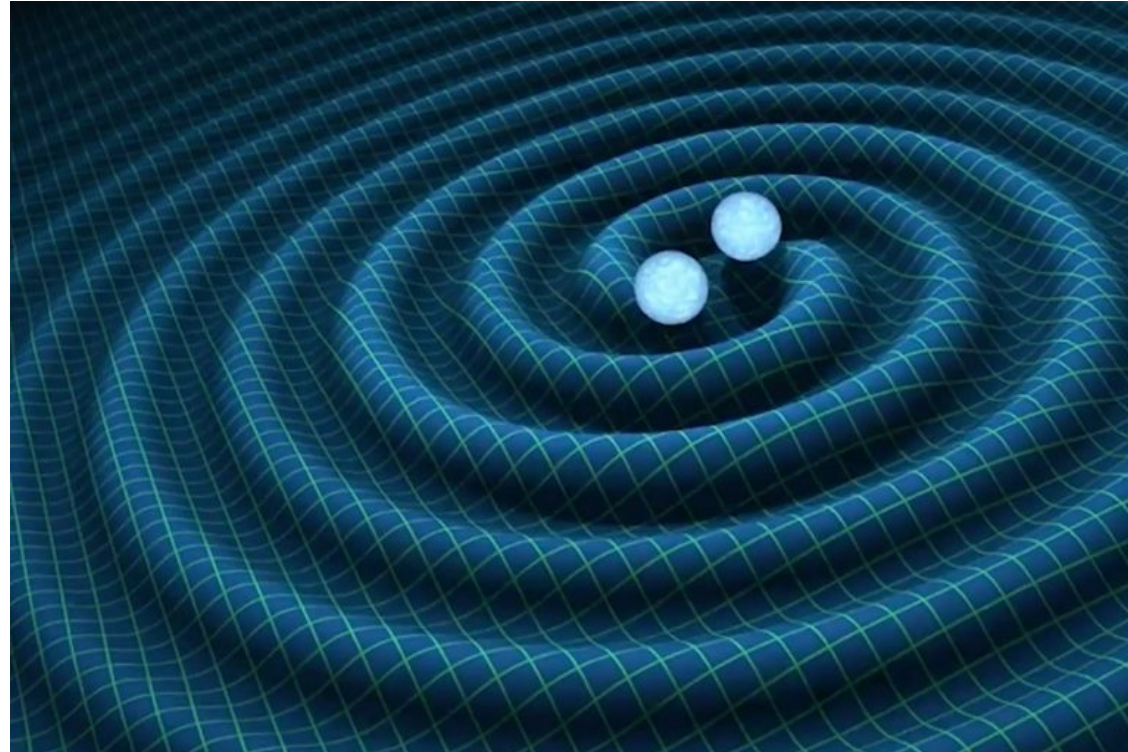
Local energy, momentum stress

Mass of object



# ■ Gravitational wave

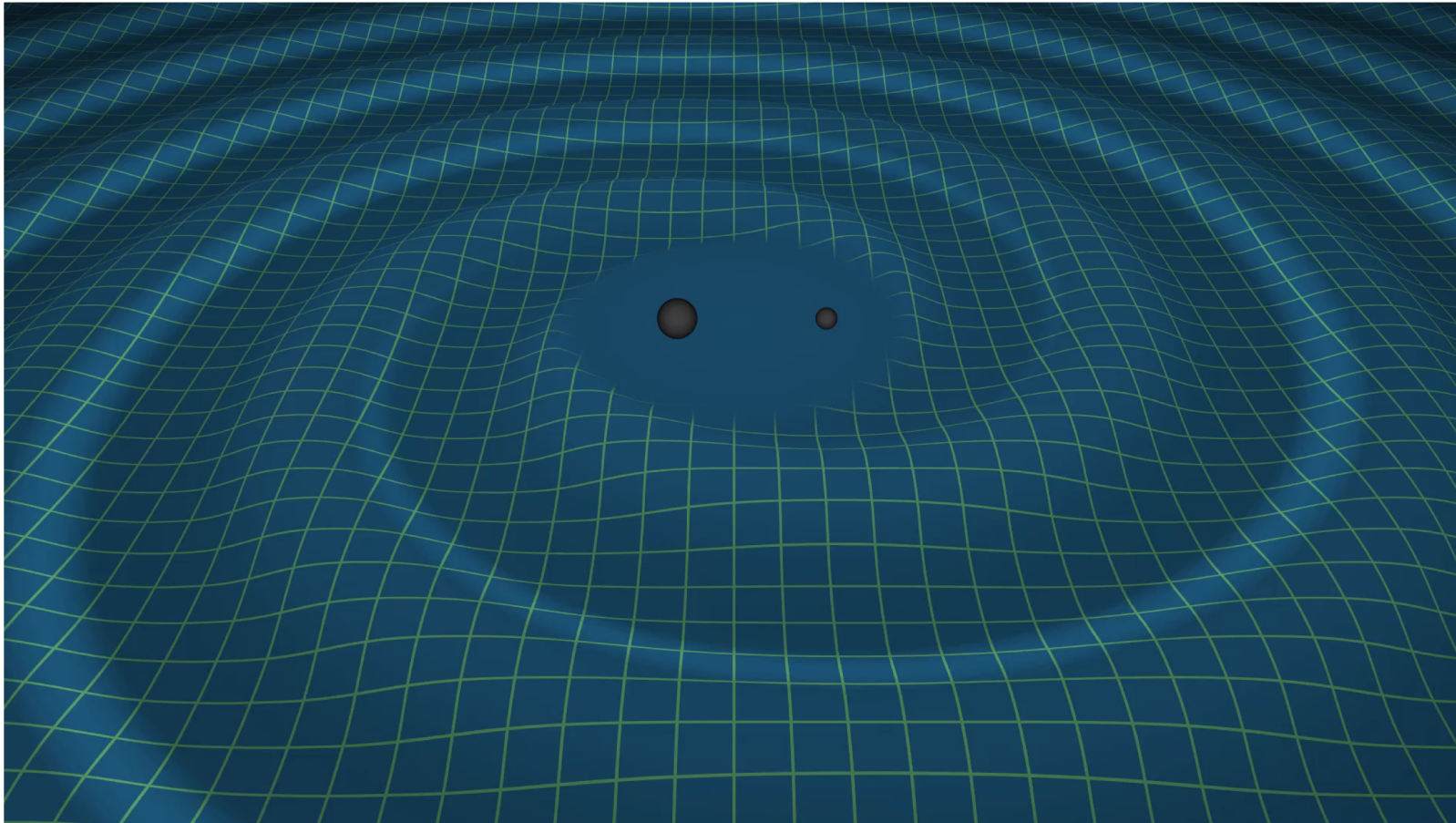
---



Propagation of ripples in space-time by massive objects moving with extreme accelerations  
= gravitational wave

# ■ Gravitational wave

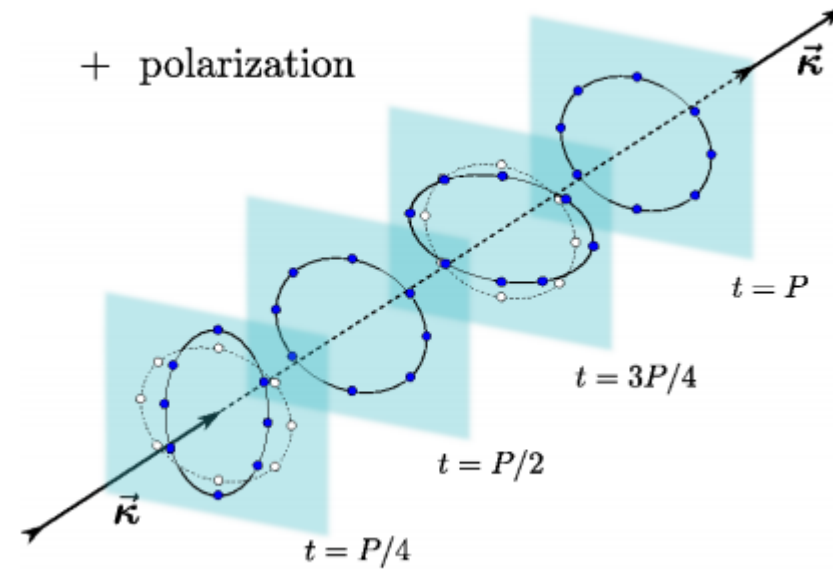
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R. Hurt - Caltech / JPL



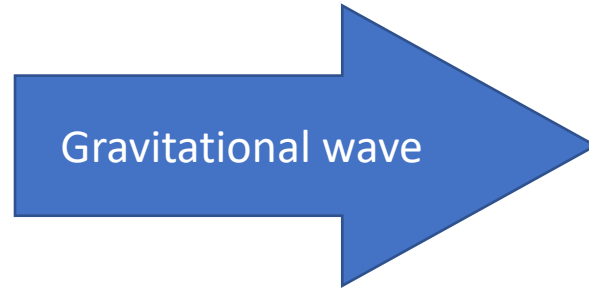
# Gravitational wave



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

# ■ Propagation of gravitational wave

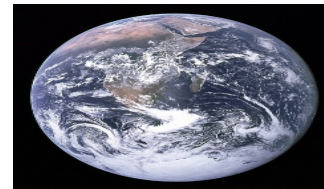
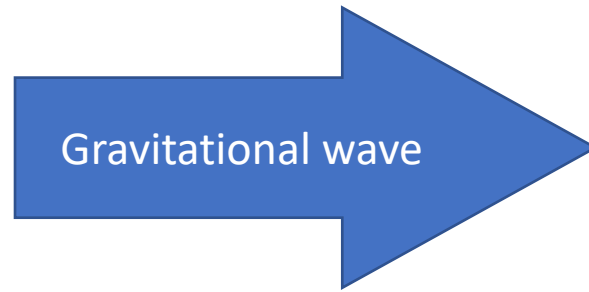
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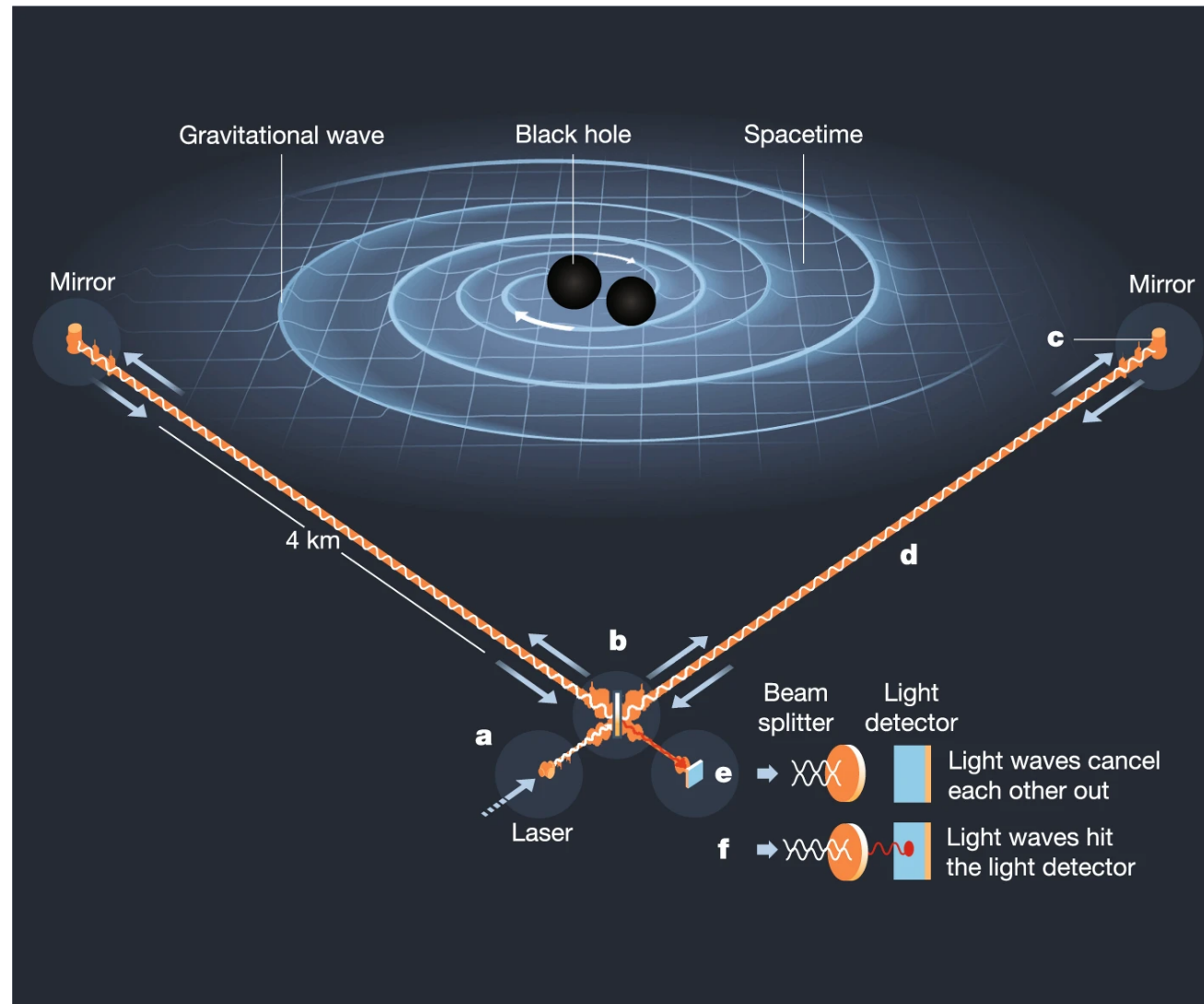


# ■ Effect of gravitational wave

---

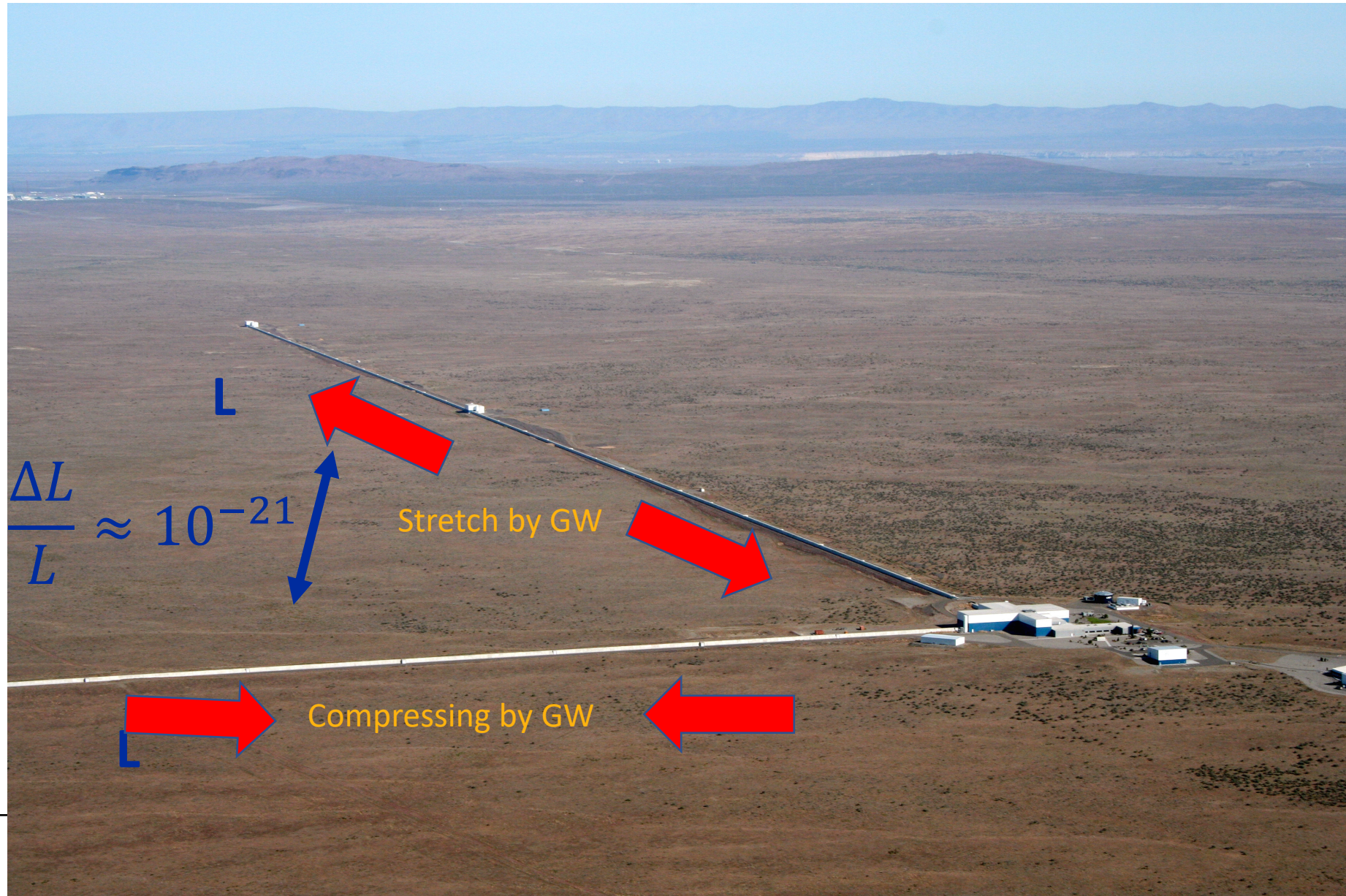


# Gravitational wave detector



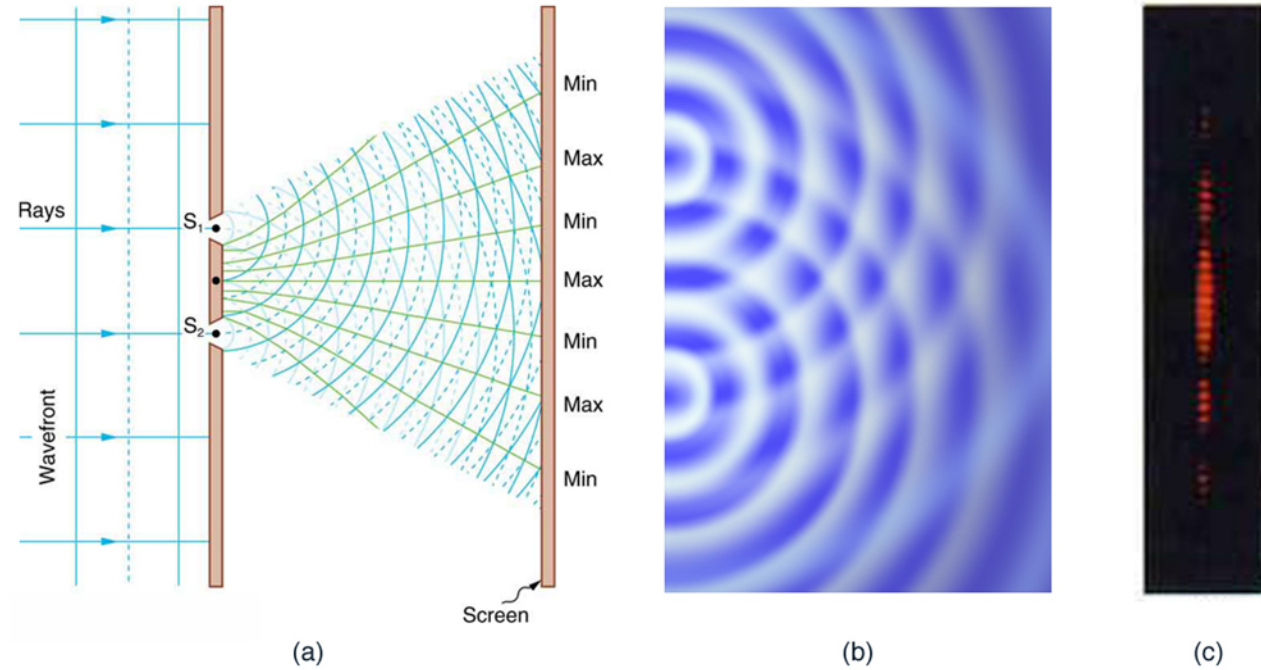


# ■ Strain sensitivity





# Double slit interference

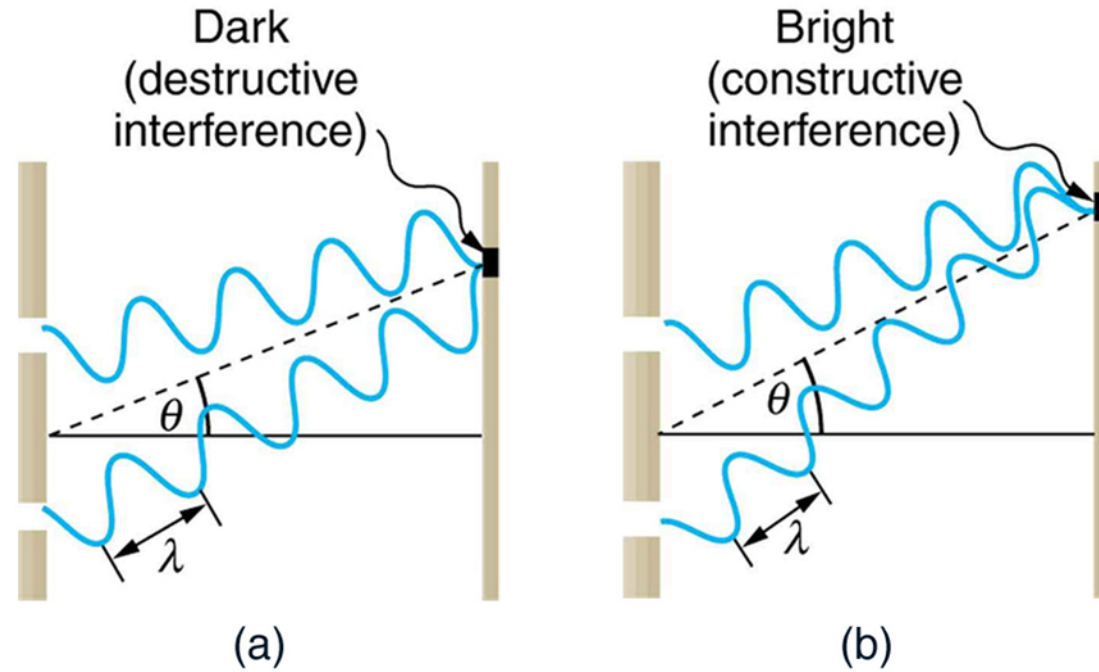


College Physics  
OpenStaxCollege



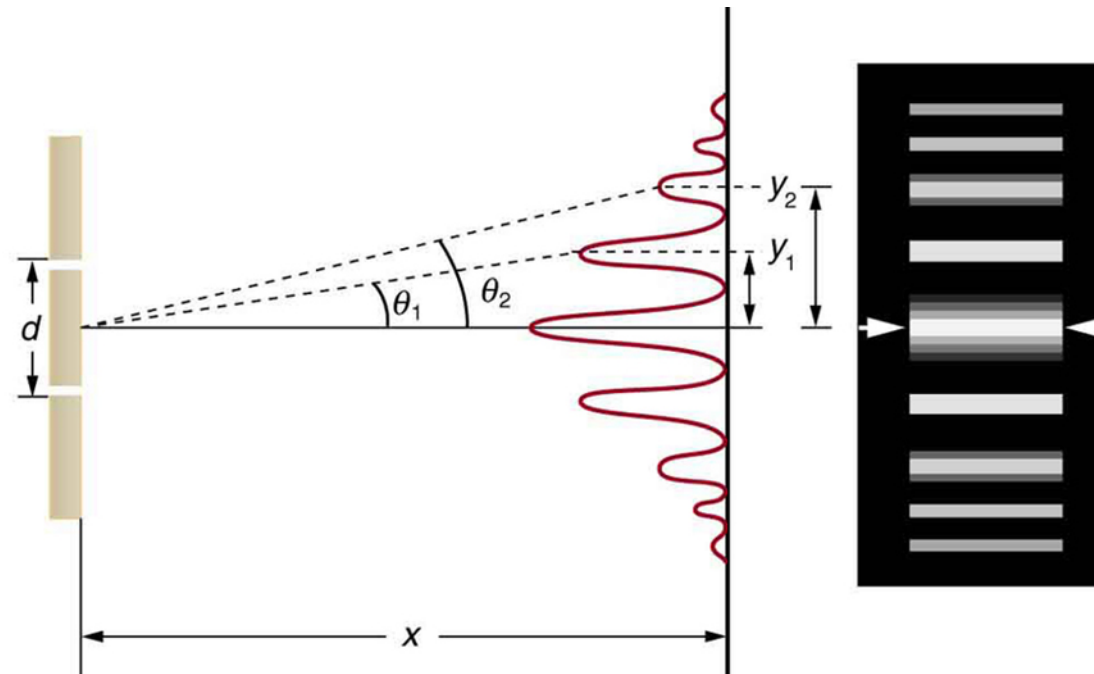
# ■ Double slit interference

---



College Physics  
OpenStaxCollege

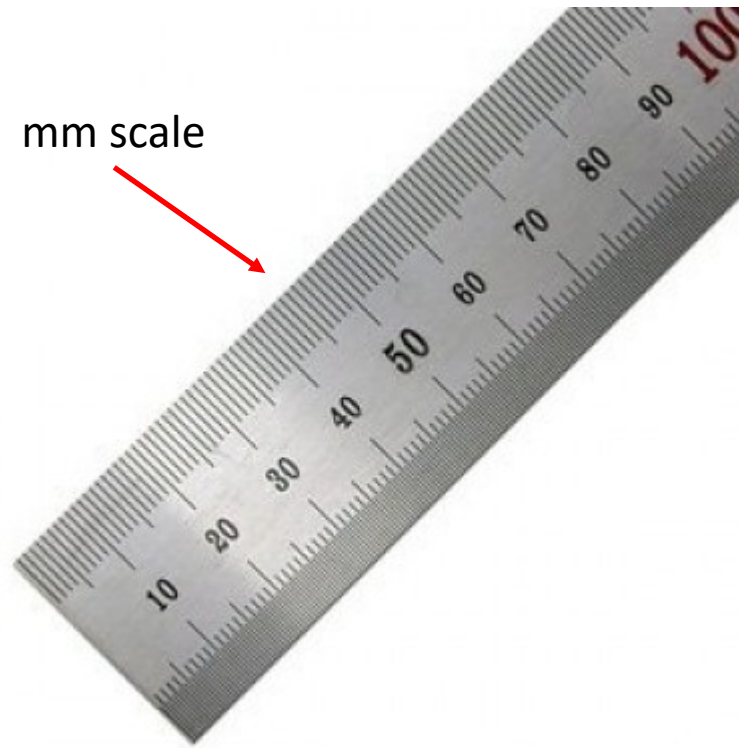
# Double slit interference



College Physics  
OpenStaxCollege

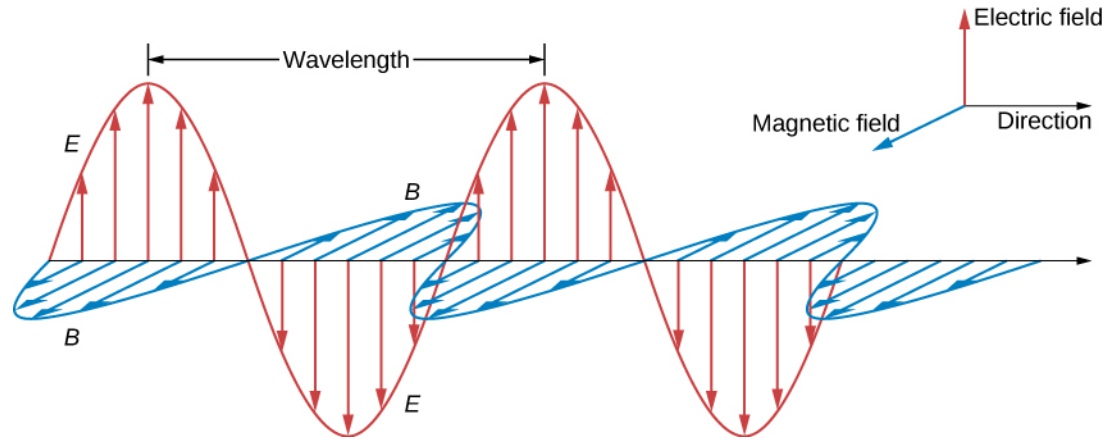
# ■ Interferometer

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# ■ Interferometer

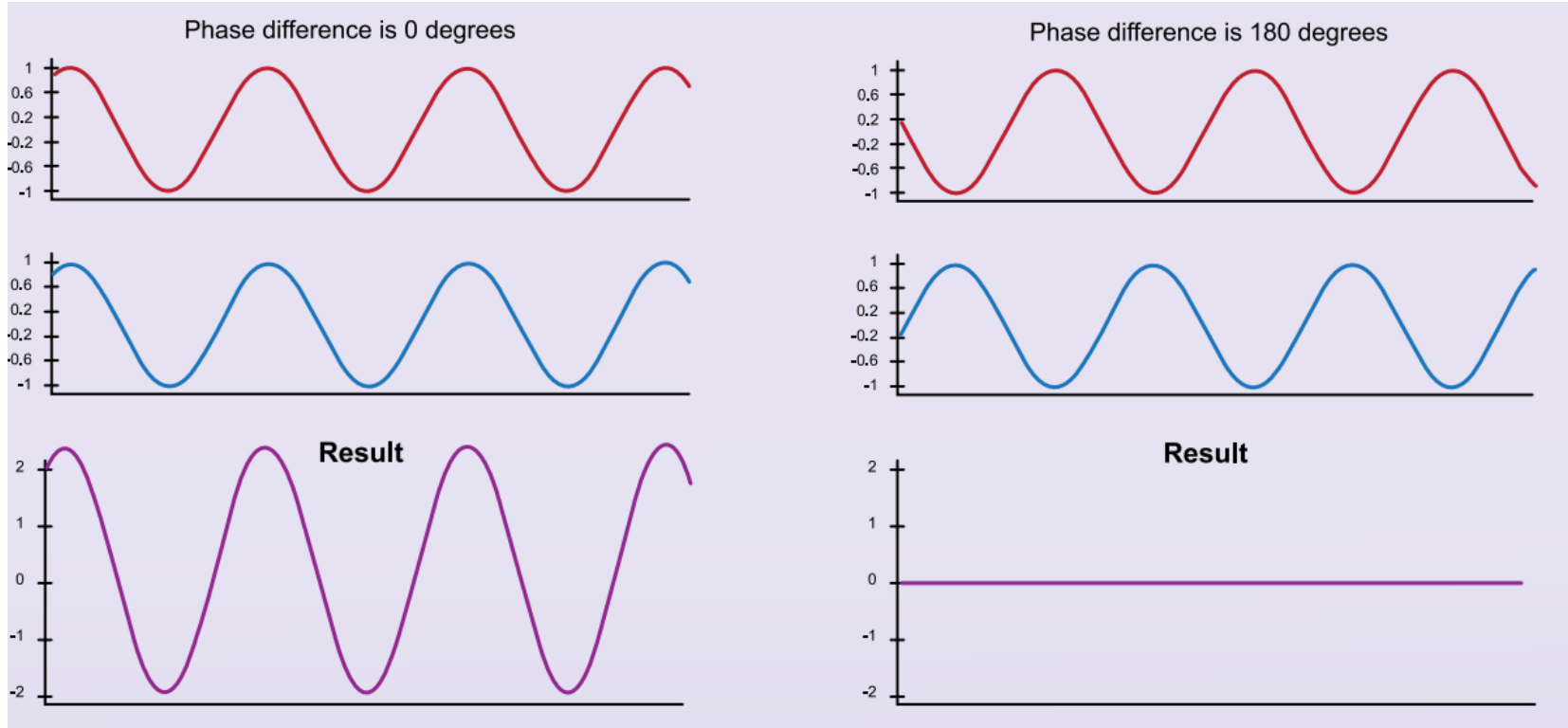
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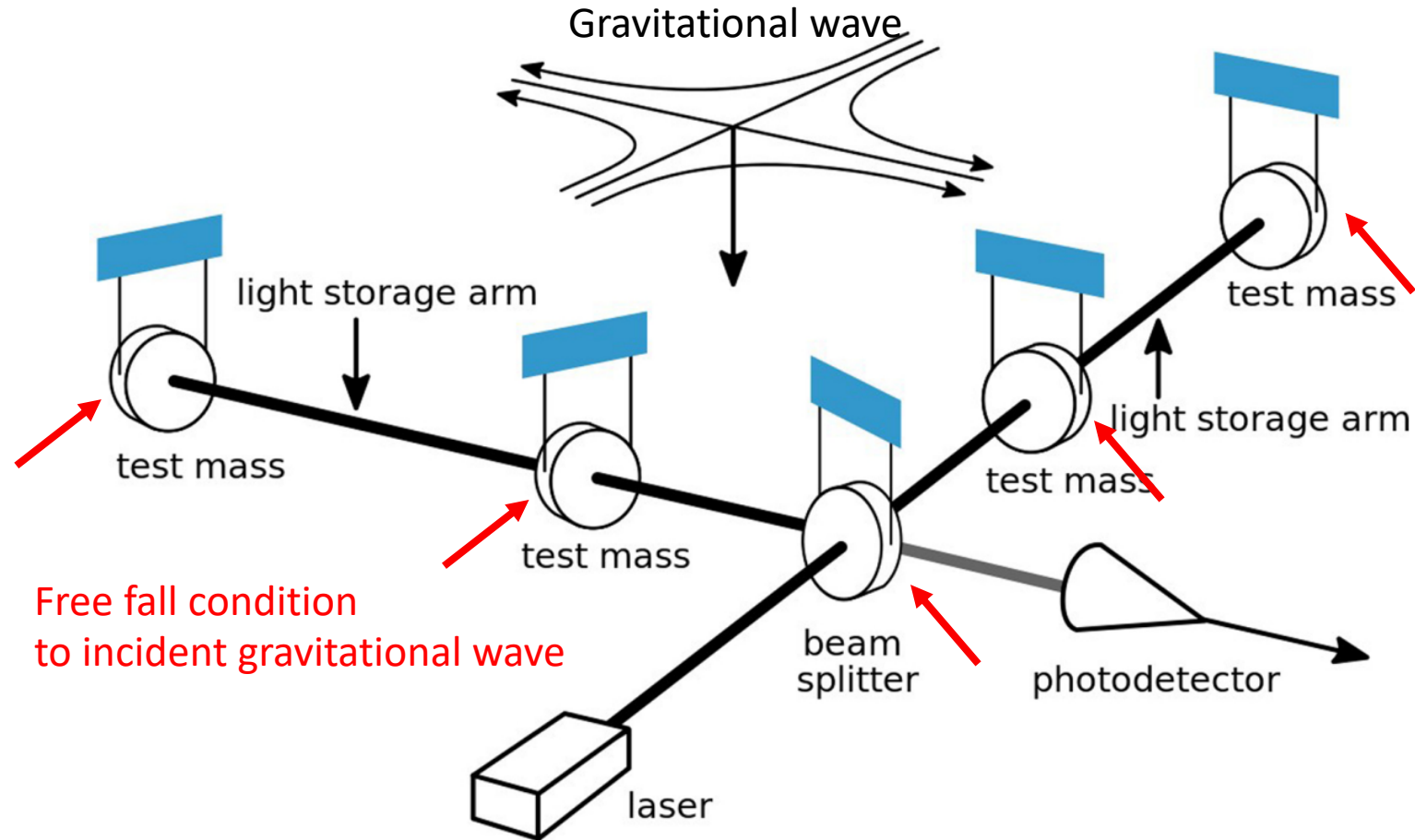
$$E = E_0 \cos(kx - \omega t)$$



# Construct & Destructive interference

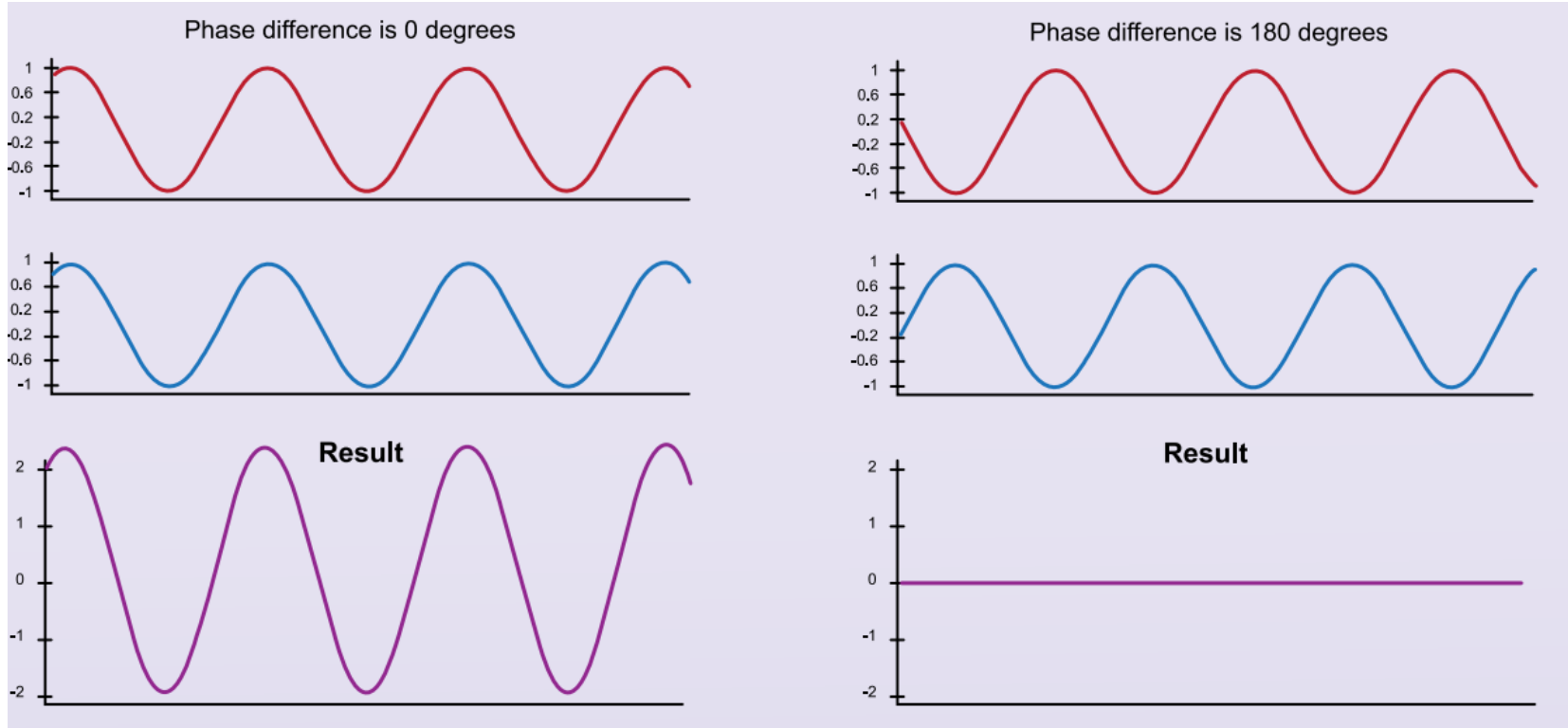


# Gravitational wave and GW detector

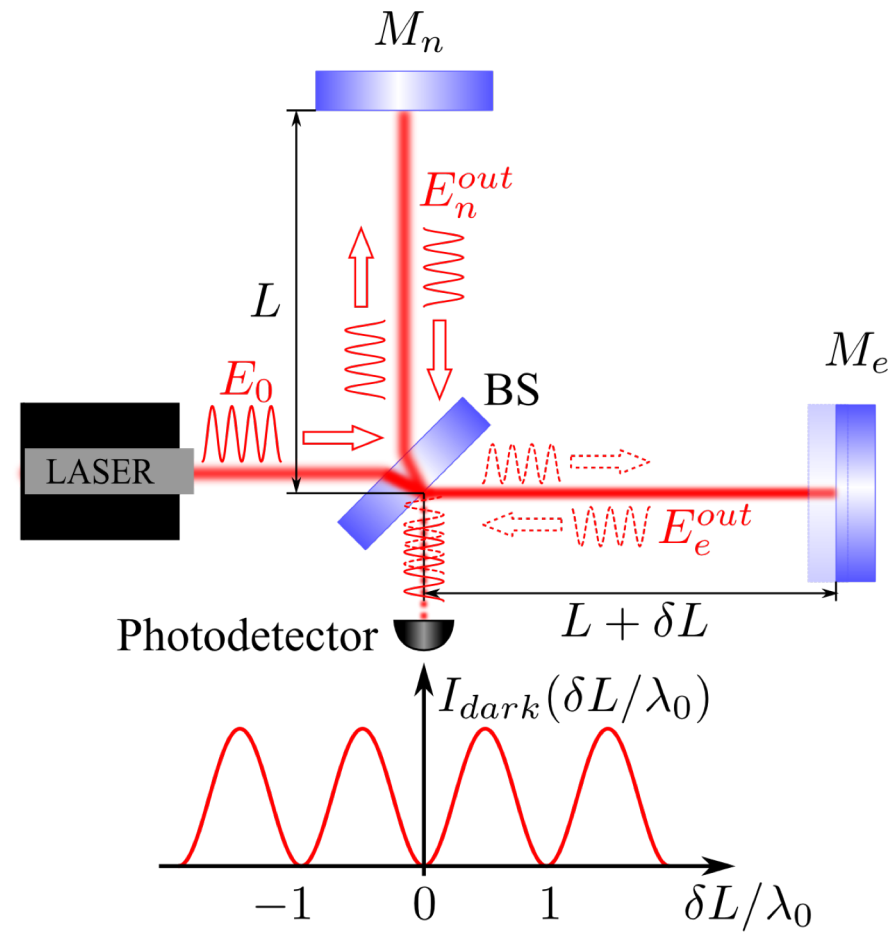


<https://www.ligo.caltech.edu/>

# Construct & Destructive interference



# ■ Michelson interferometer

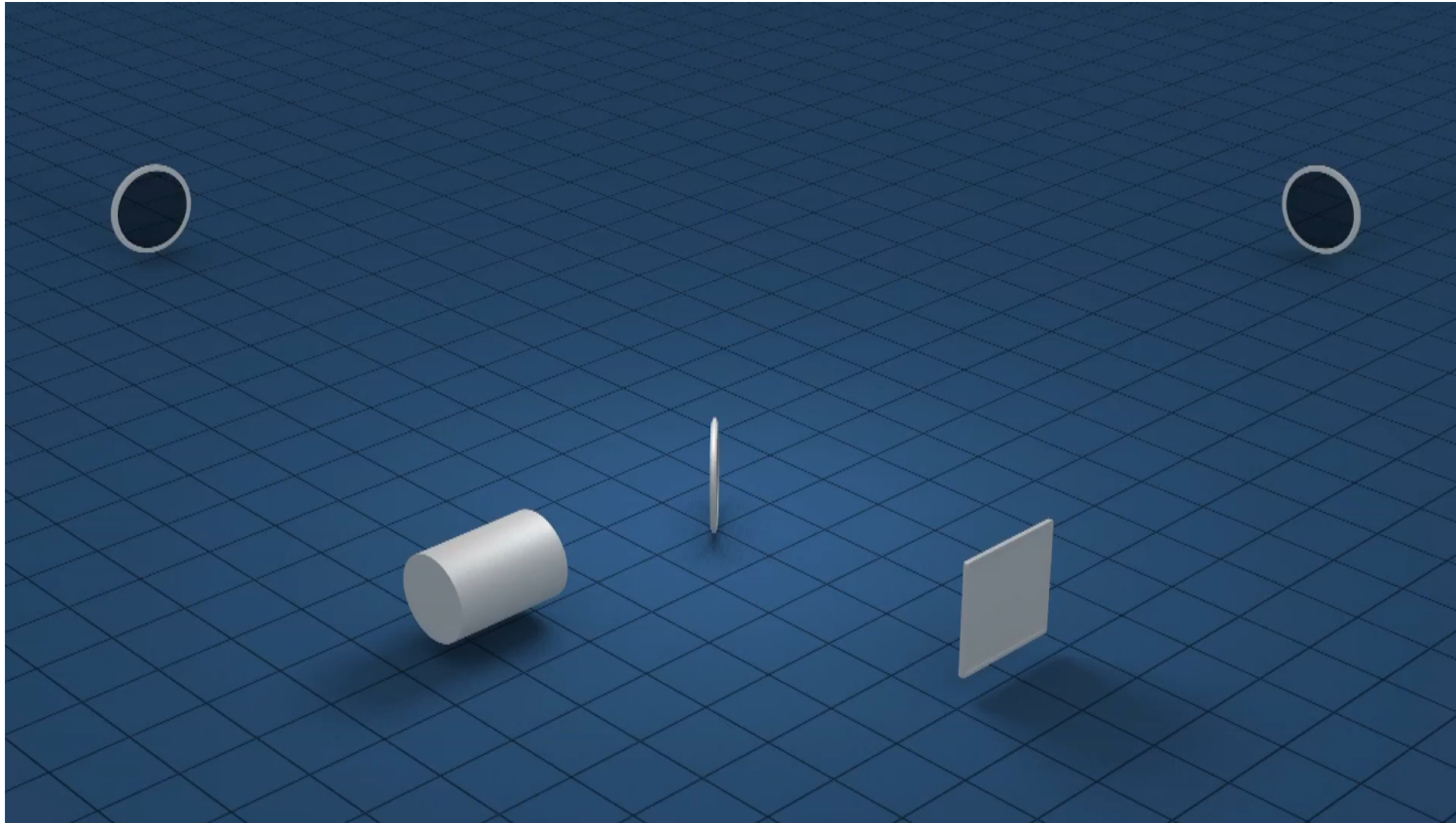


Danilishin, Stefan L. et al. Living Rev.Rel. 15 (2012) 5 arXiv:1203.1706

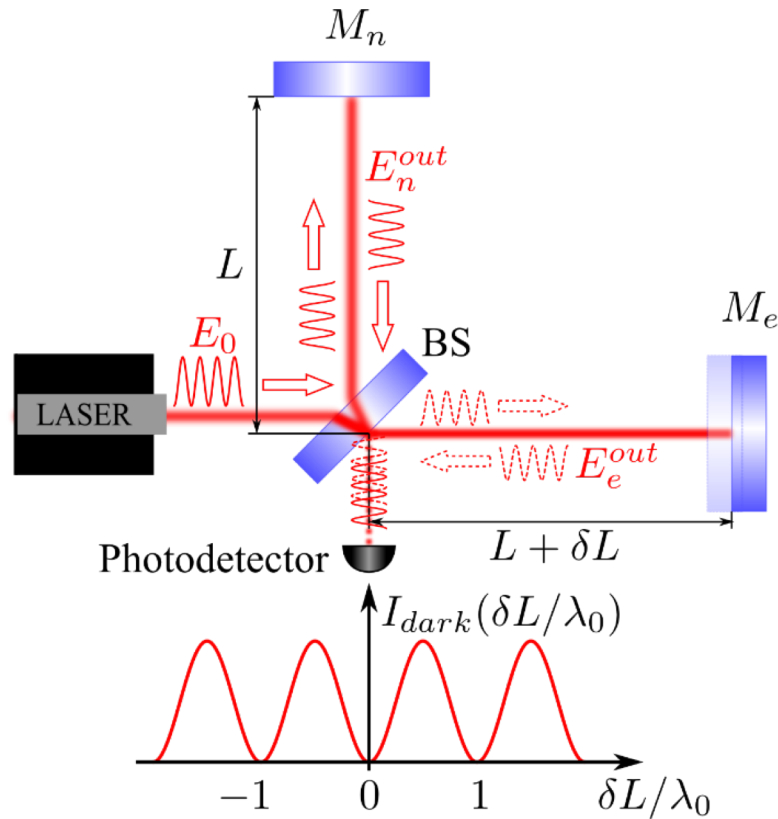


# ■ Michelson interferometer

---



# ■ Sensitivity of Michelson interferometer



When  $L = 1\text{m}$

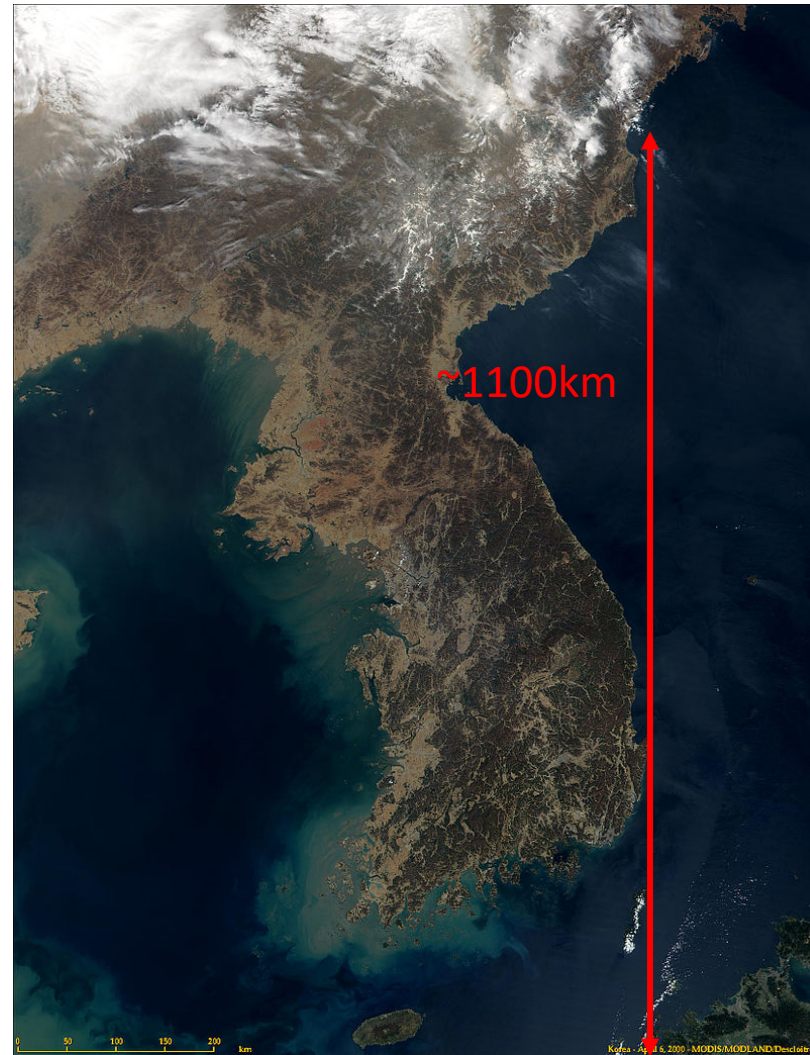
$$\frac{\Delta L}{L} \approx 10^{-16}$$

IF  $L = 1000\text{km}$

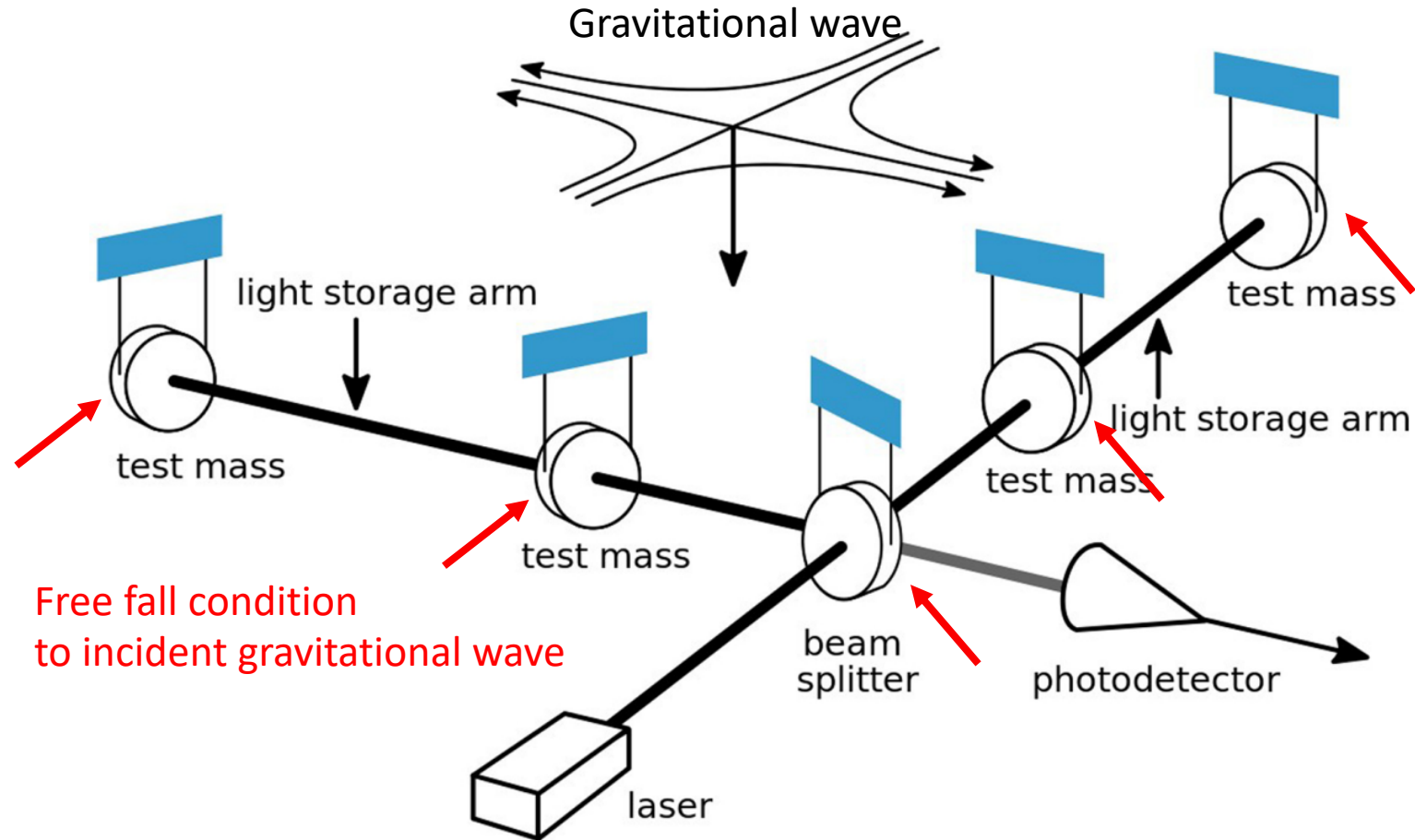
$$\frac{\Delta L}{L} \approx 10^{-21}$$

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

- 1000km interferometer is available?
- 



# Gravitational wave and GW detector

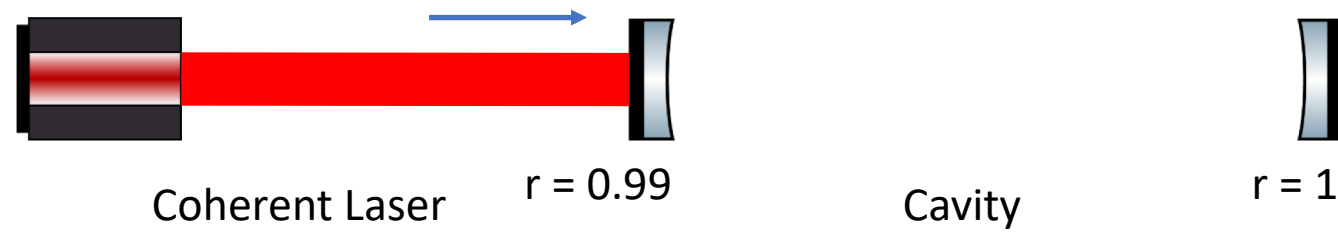


<https://www.ligo.caltech.edu/>



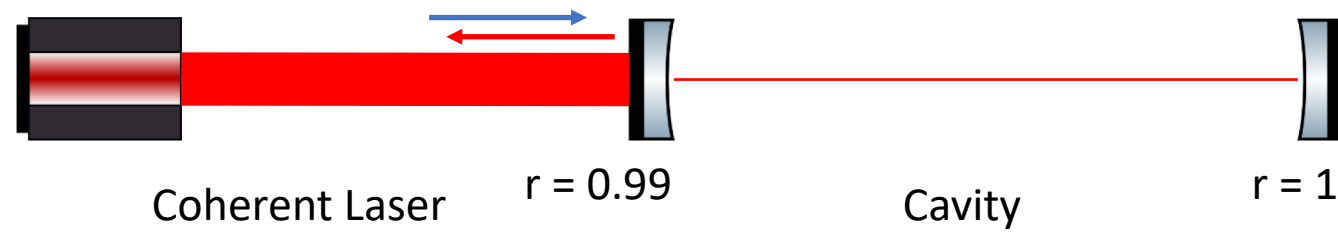
# ■ Fabry-Perot cavity

---



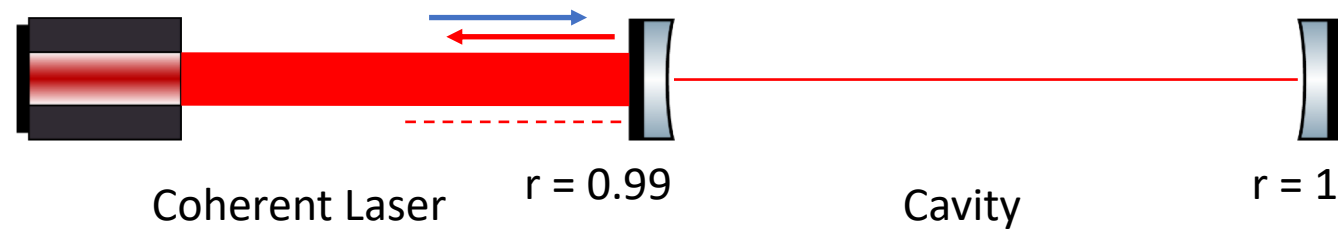
# ■ Fabry-Perot cavity

---



# ■ Fabry-Perot cavity

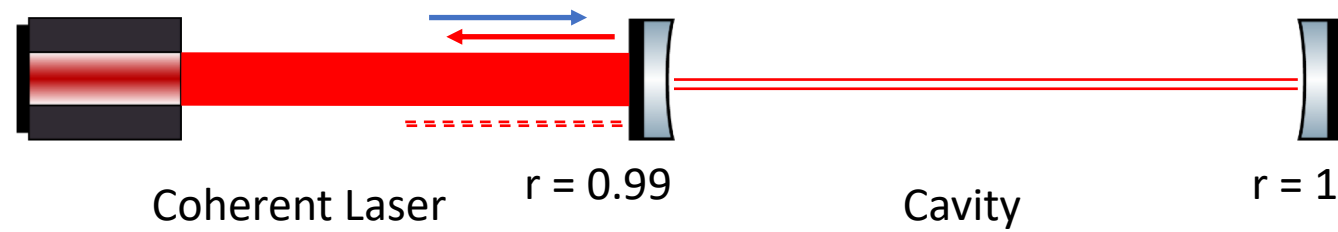
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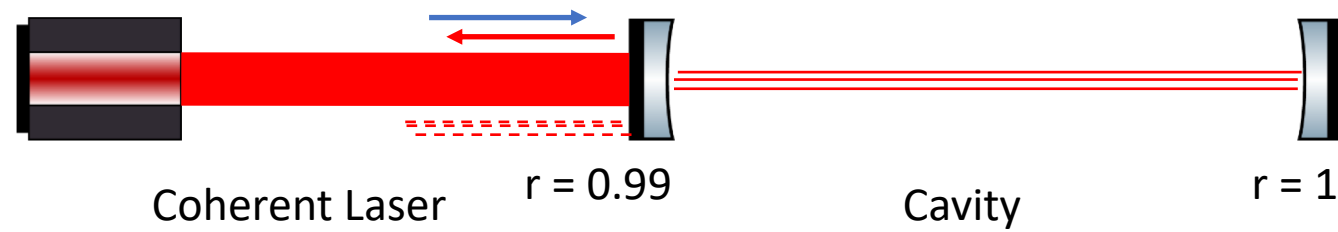
# ■ Fabry-Perot cavity

---



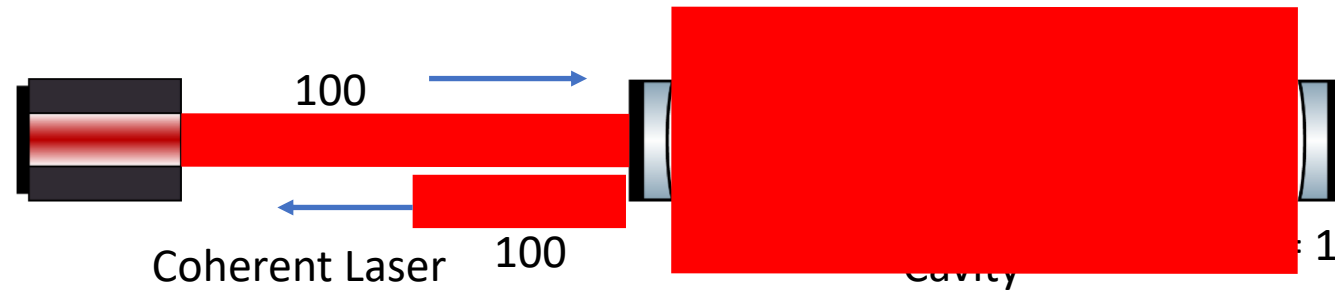
# ■ Fabry-Perot cavity

---



# Fabry-Perot cavity

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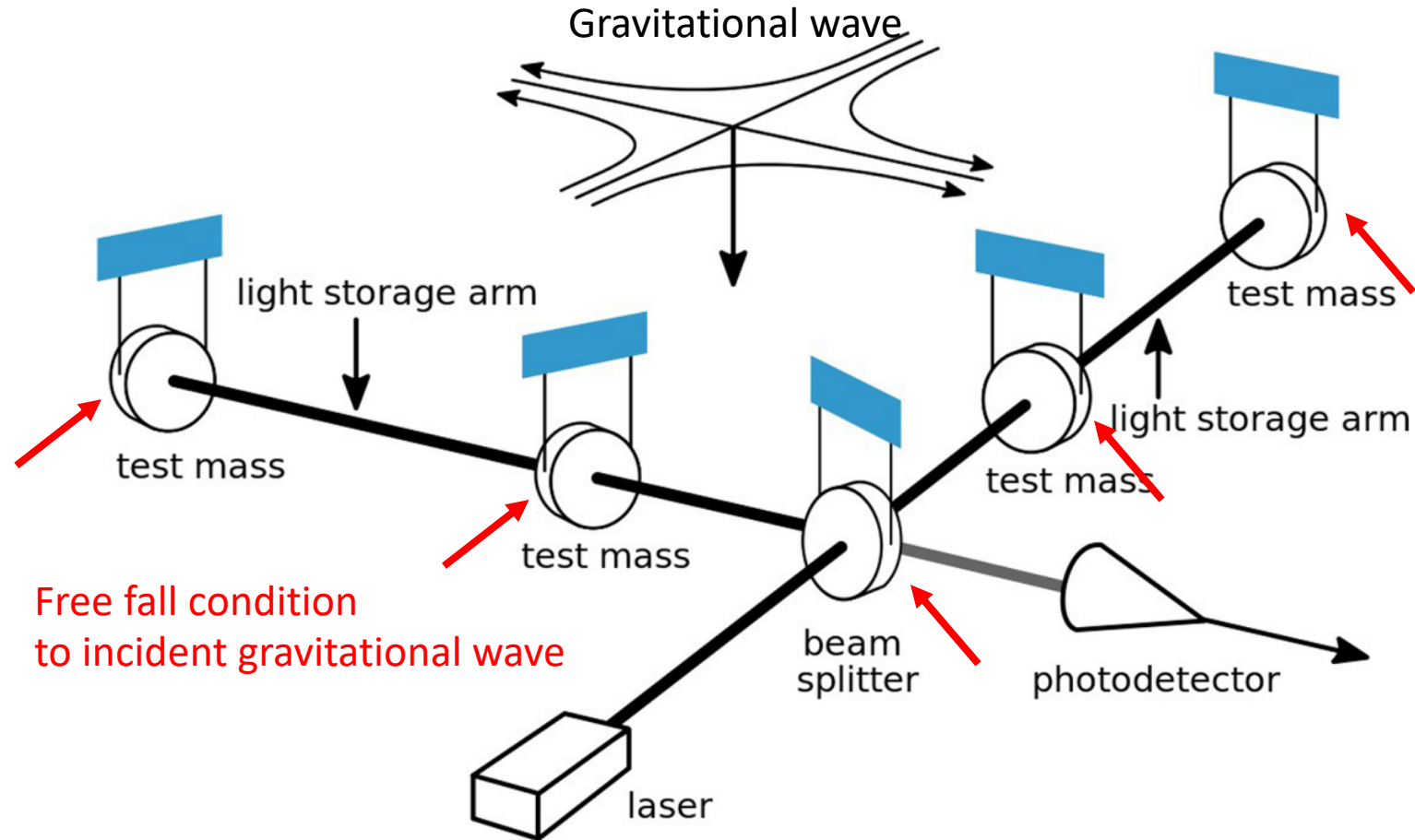


# Fabry-Perot cavity

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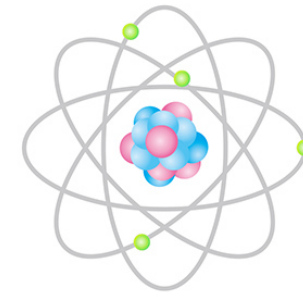
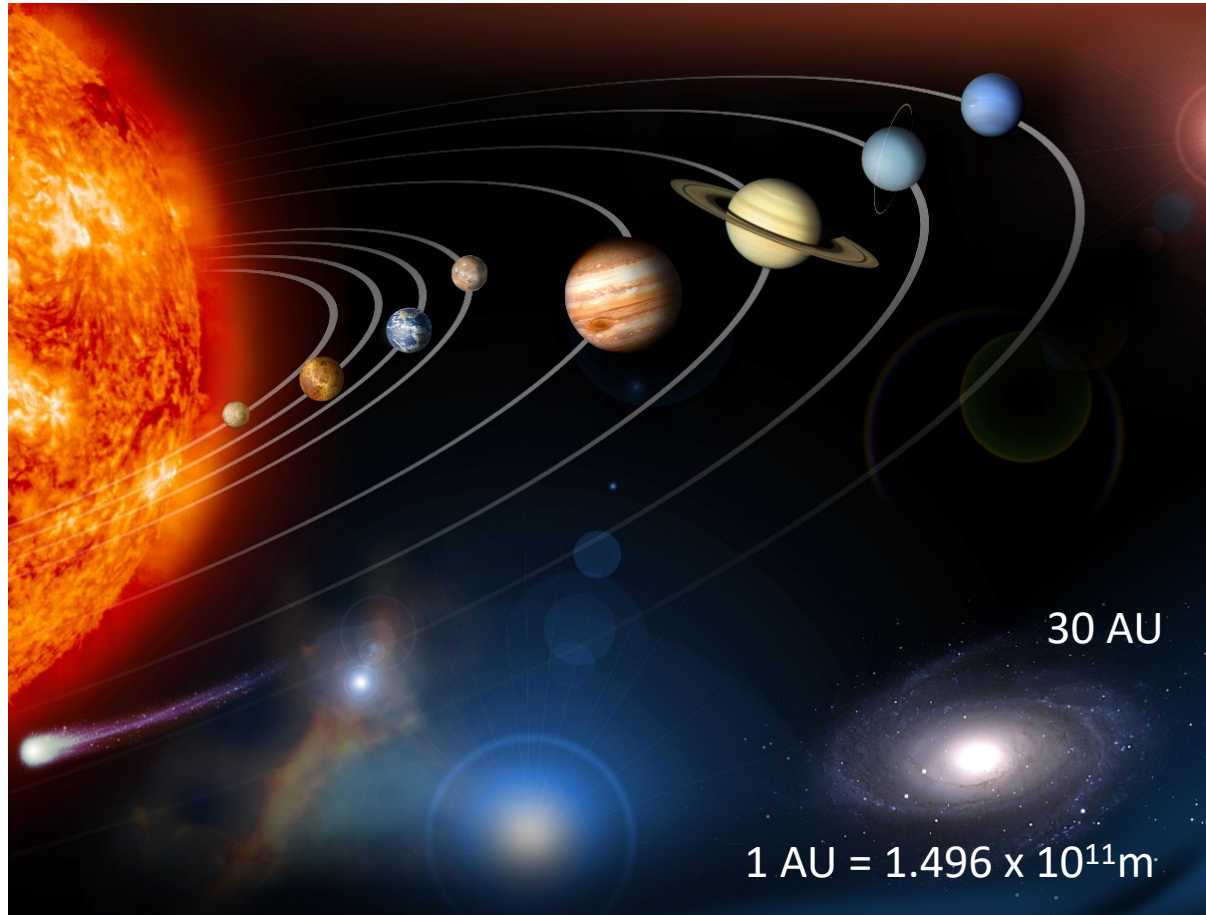
# Gravitational wave and GW detector



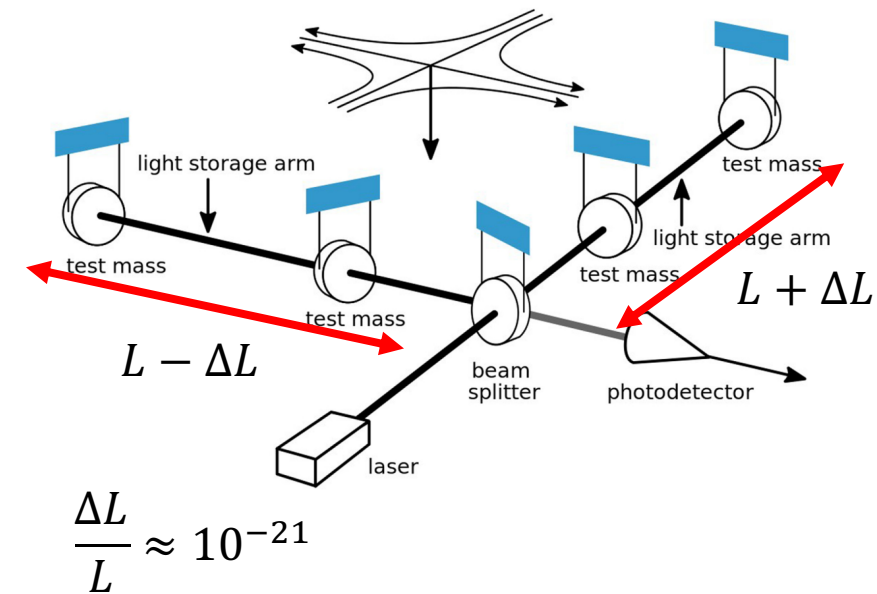
<https://www.ligo.caltech.edu/>



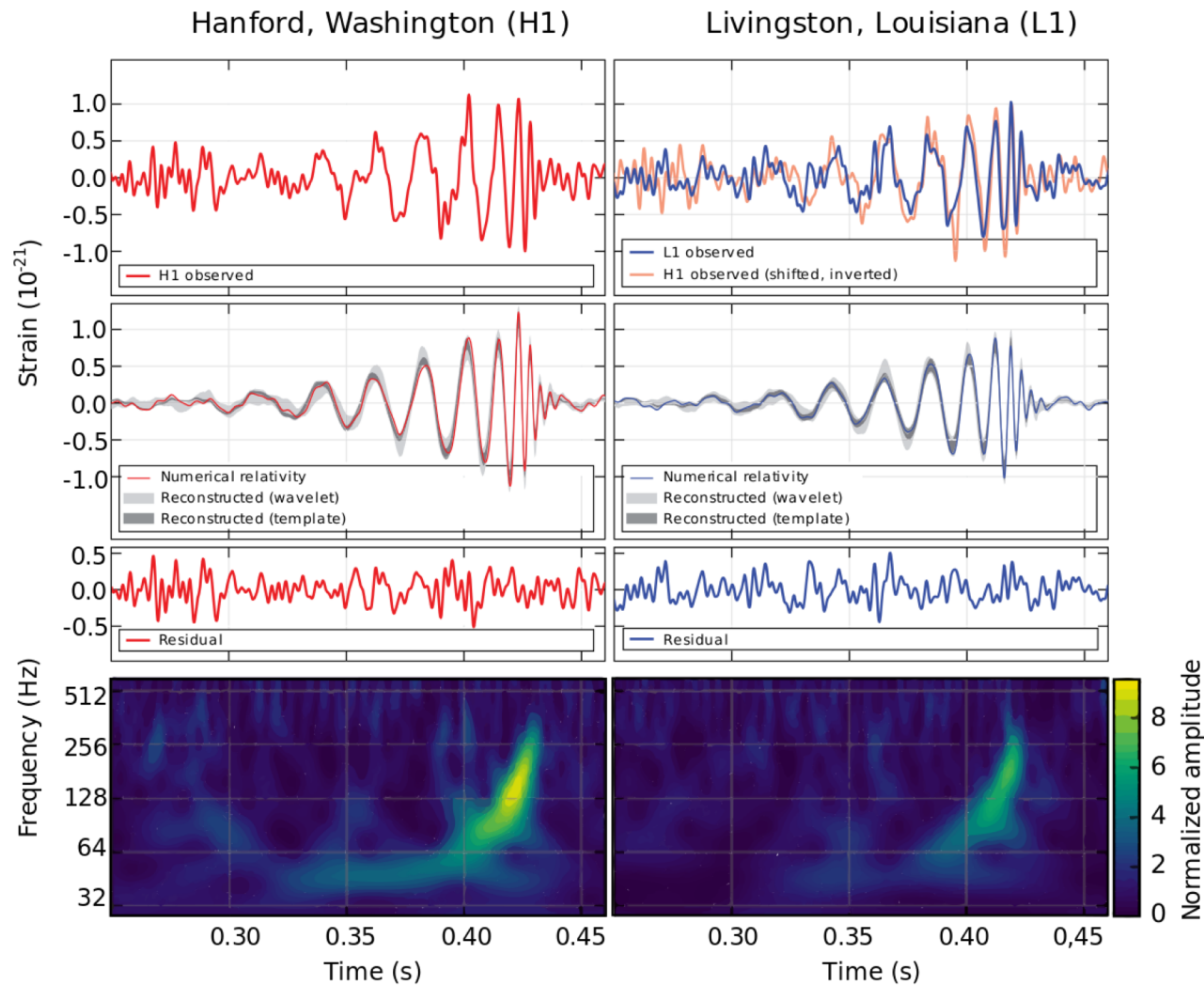
# Strain due to gravitational wave



Size of atom =  $1 \times 10^{-10} \text{m}$



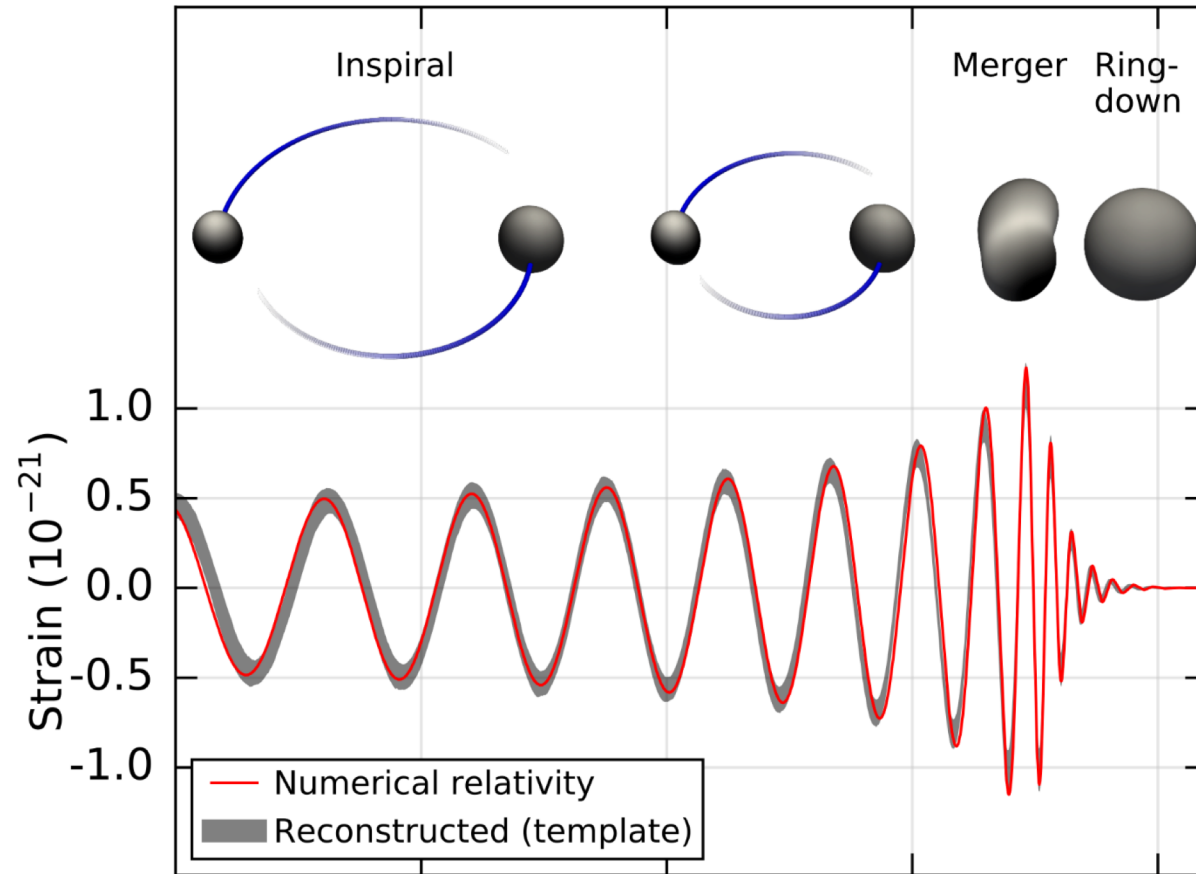
# ■ First observation of gravitational wave



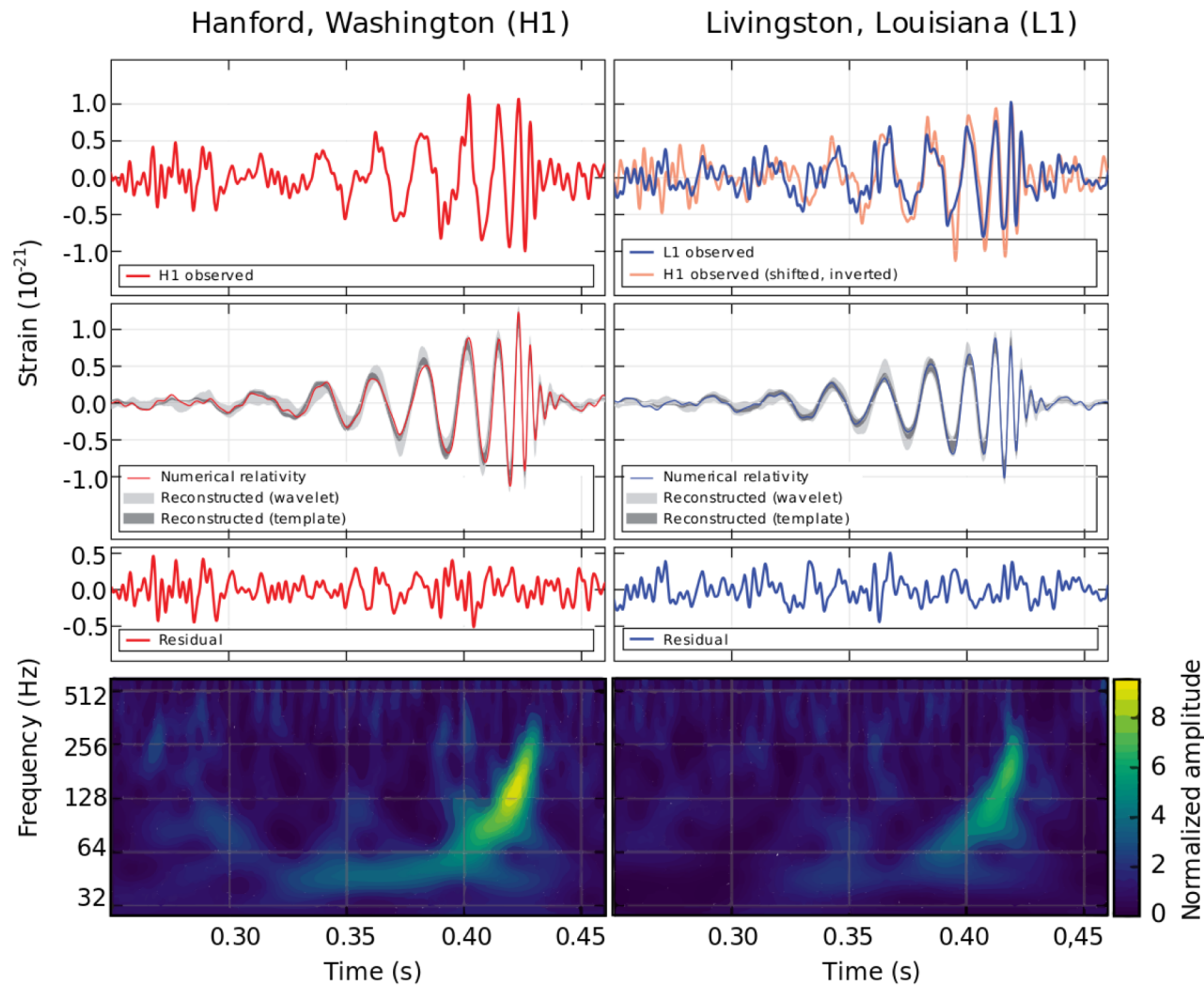
GW150914

2015-09-14

# ■ Inspiral, merger, ring-down



# ■ First observation of gravitational wave

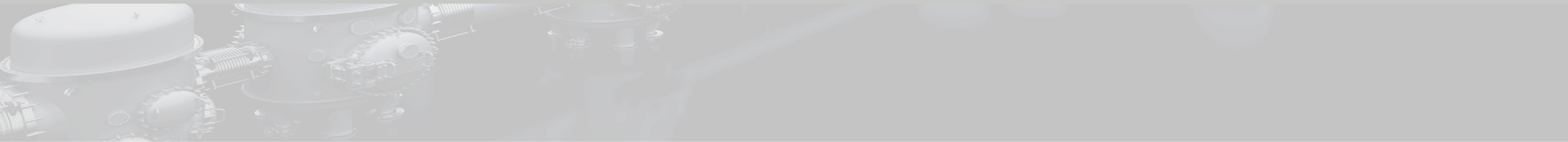


GW150914

2015-09-14



# Interferometer of GW detector





# ■ KAGRA interferometer

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# Location of KAGRA

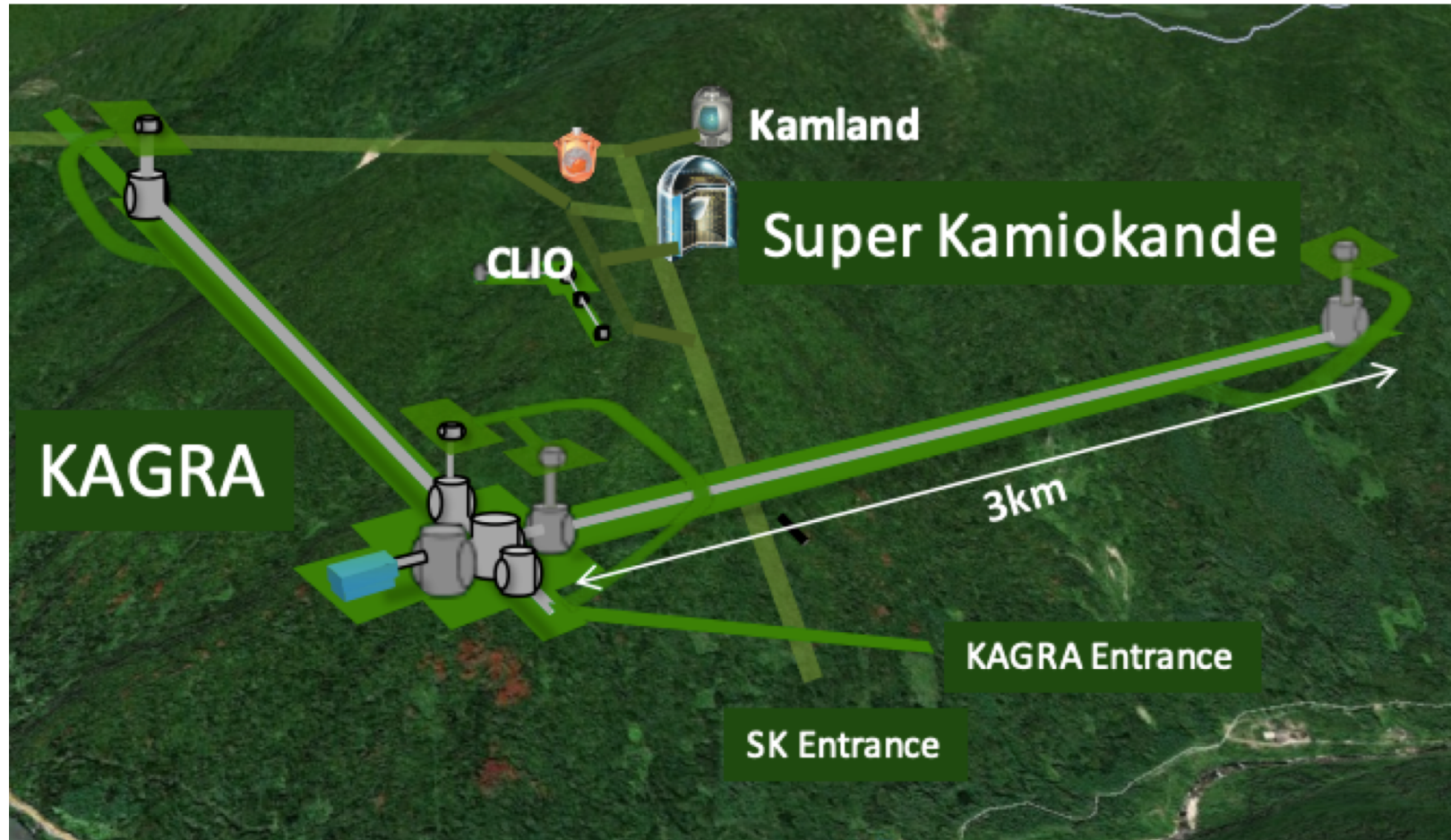


Nature Astronomy, 3 (2019) 35–40



## ■ Avoid seismic noise

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# ■ KAGRA tunnel

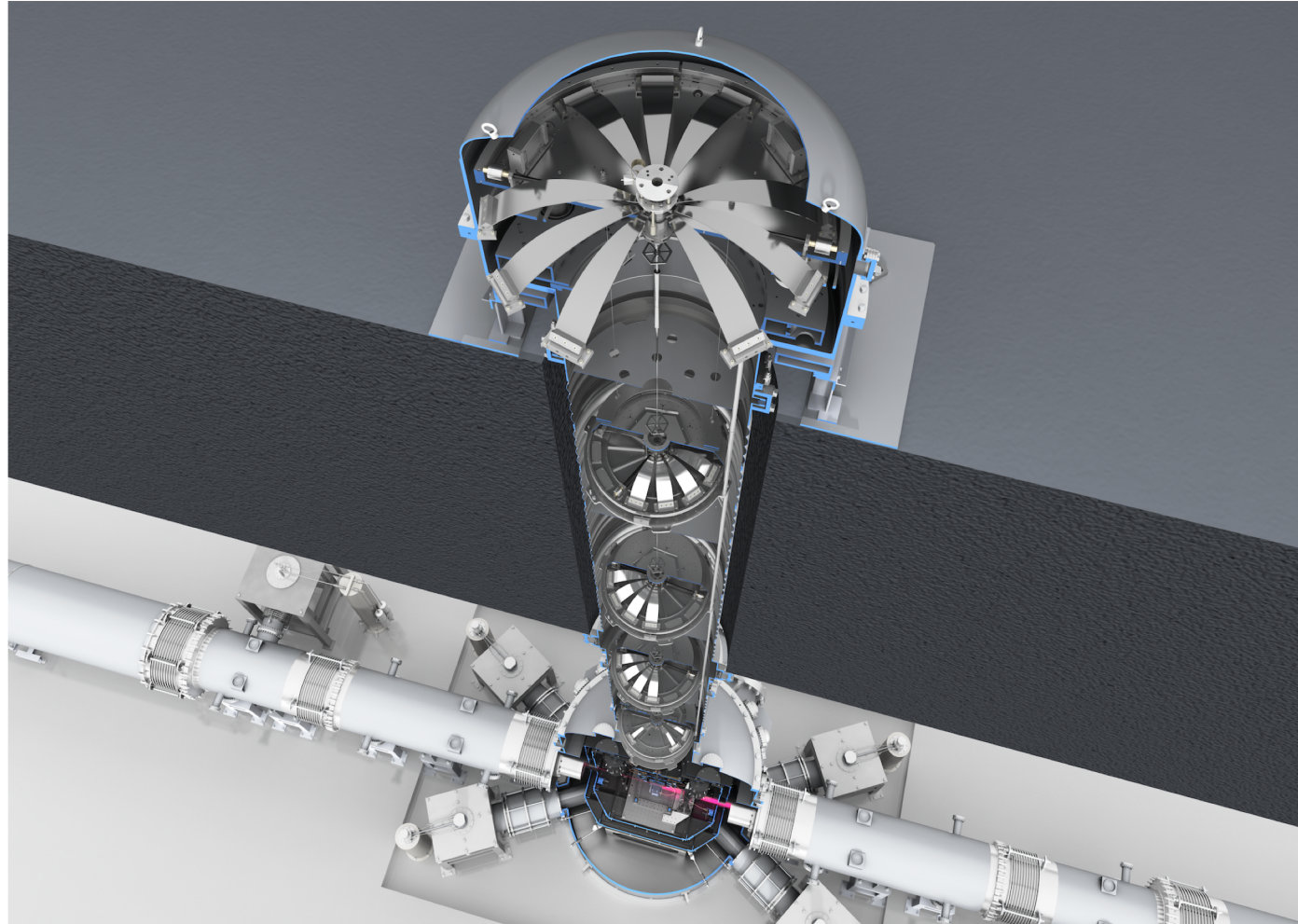
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# ■ Vibration isolation system of KAGRA

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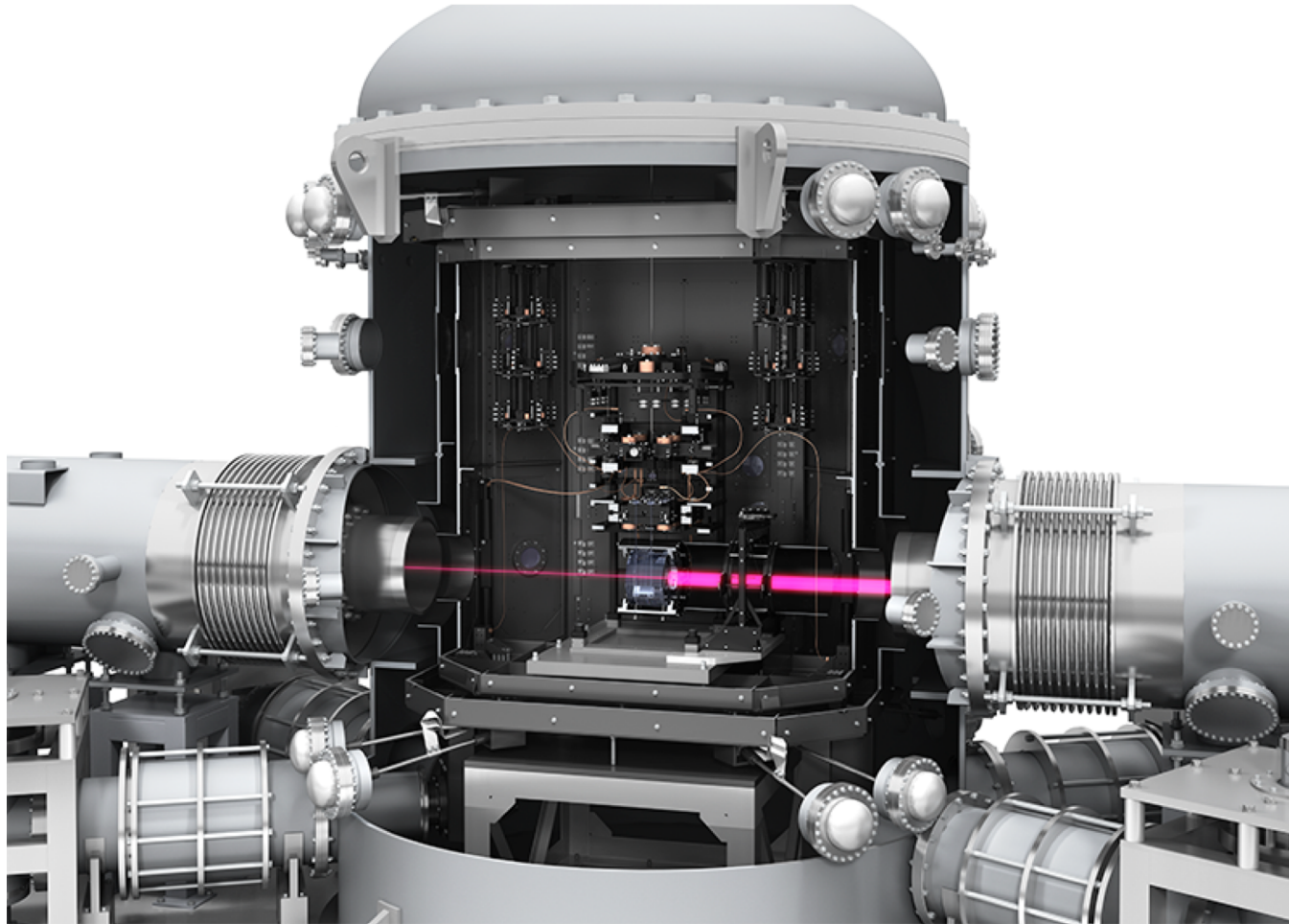


Rey.Hori

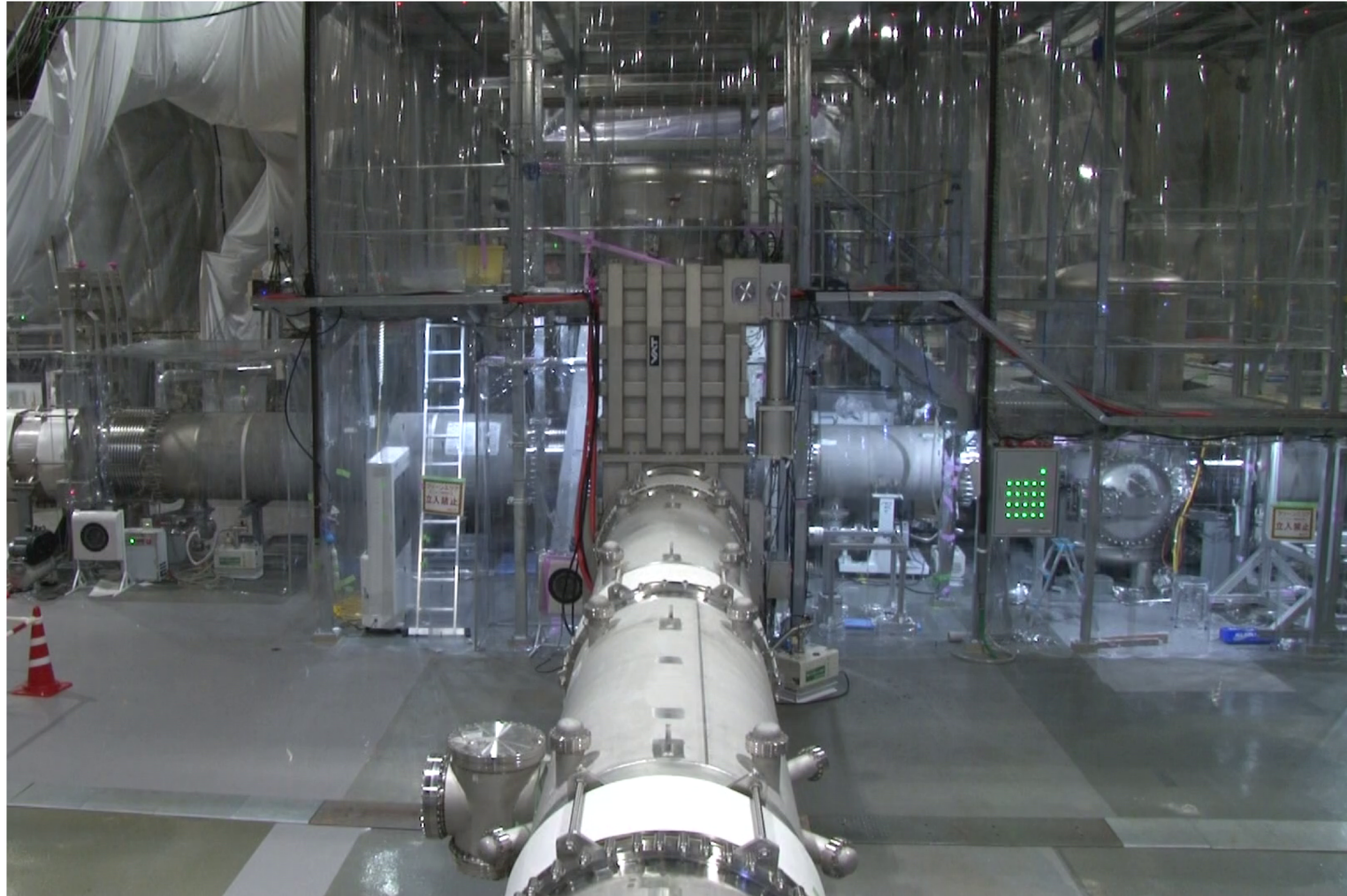


# ■ Test mass chamber

---



Rey.Hori



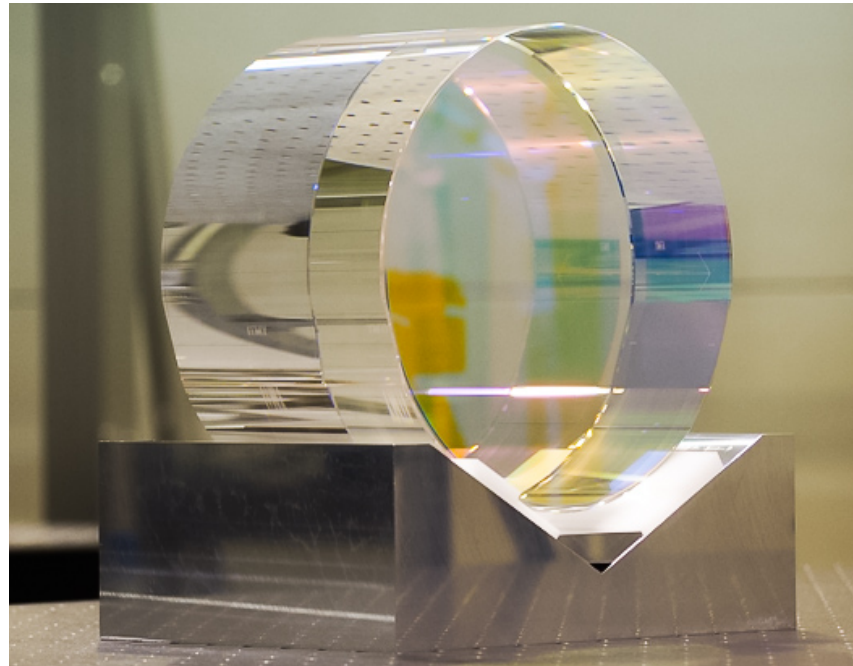


# KAGRA



# ■ KAGRA

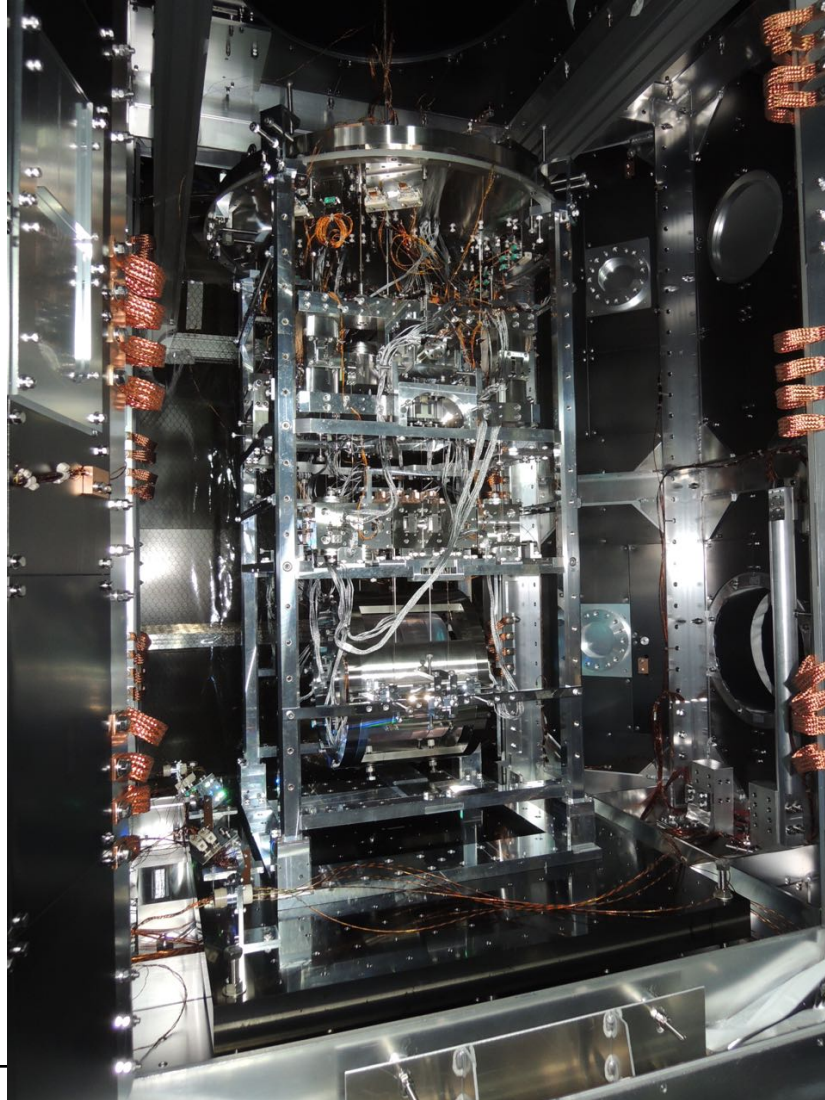
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# KAGRA

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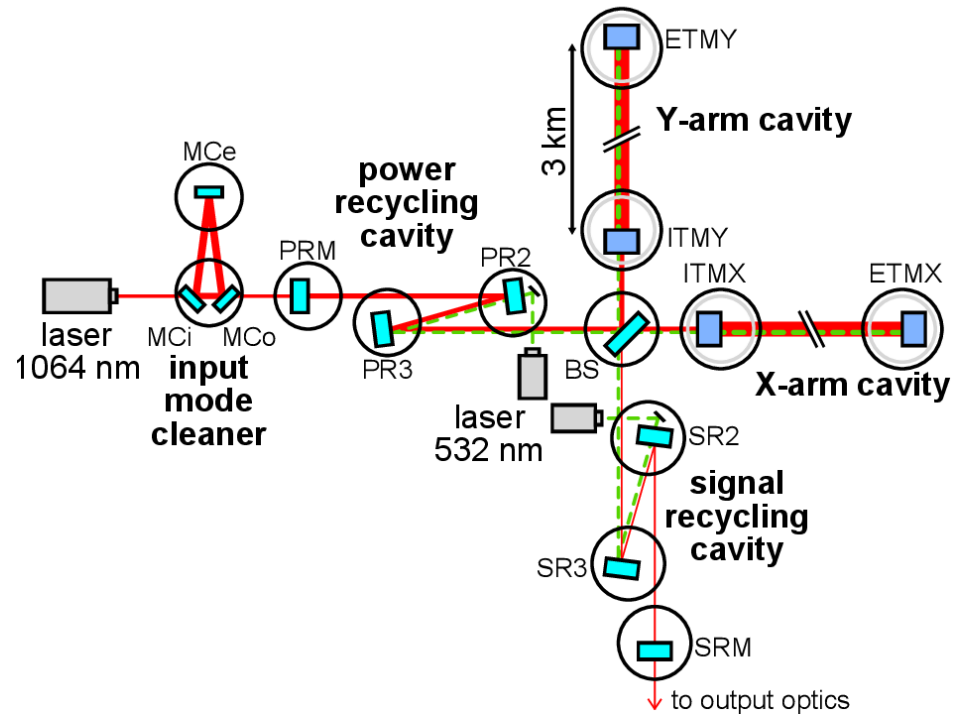


# ■ KAGRA

---



# Interferometer of KAGRA

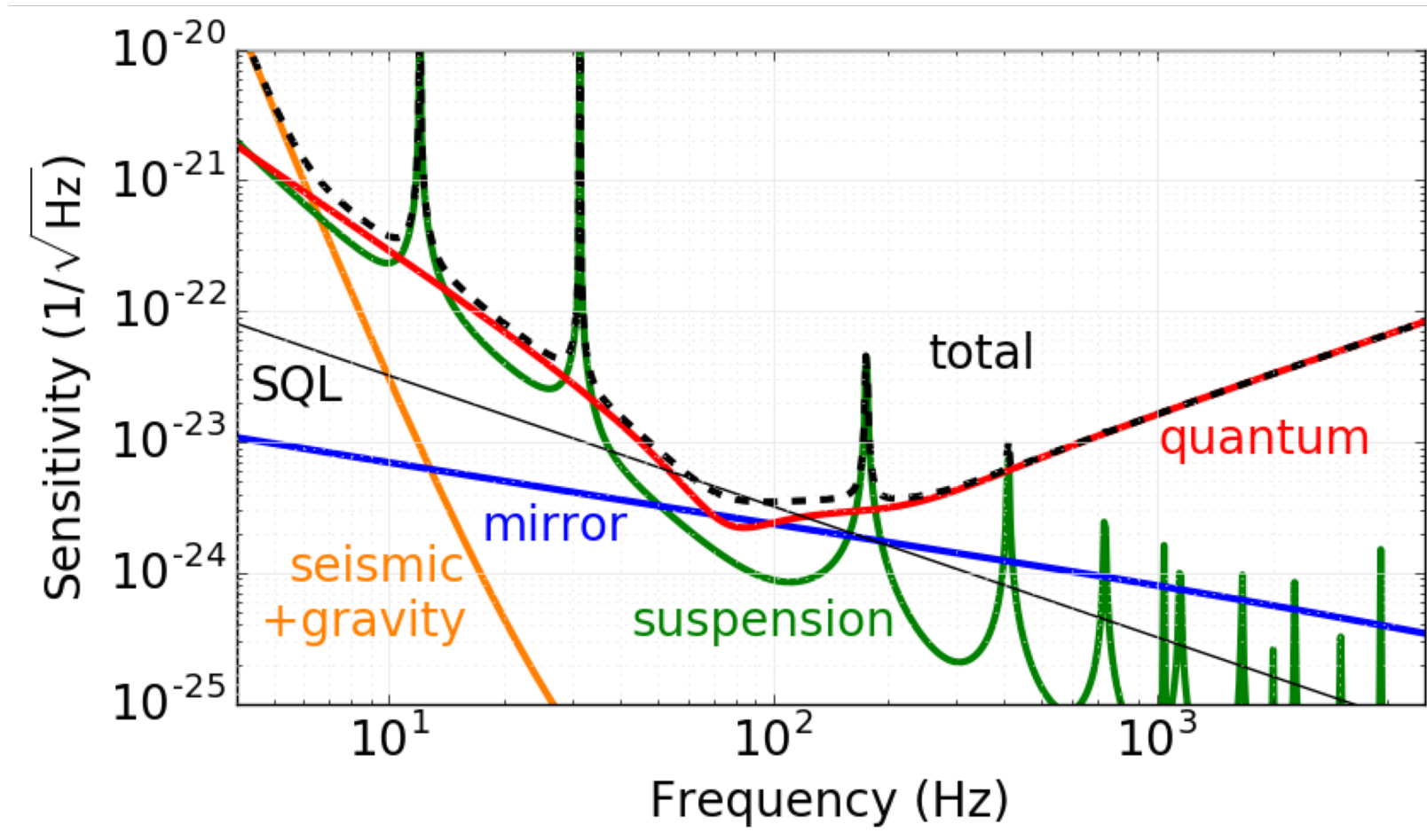


- MC : Mode Cleaner
- ITMX : Input Test Mass X
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- REFL : Reflection Port
- PRM : Power Recycling Mirror
- OMC : Output Mode Cleaner
- AS\_DC : Anti Symmetric DC
- SRM : Signal Recycling Mirror
- POP : Pick-off-in-the-PRC
- ETMX : End Test Mass X
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-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

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

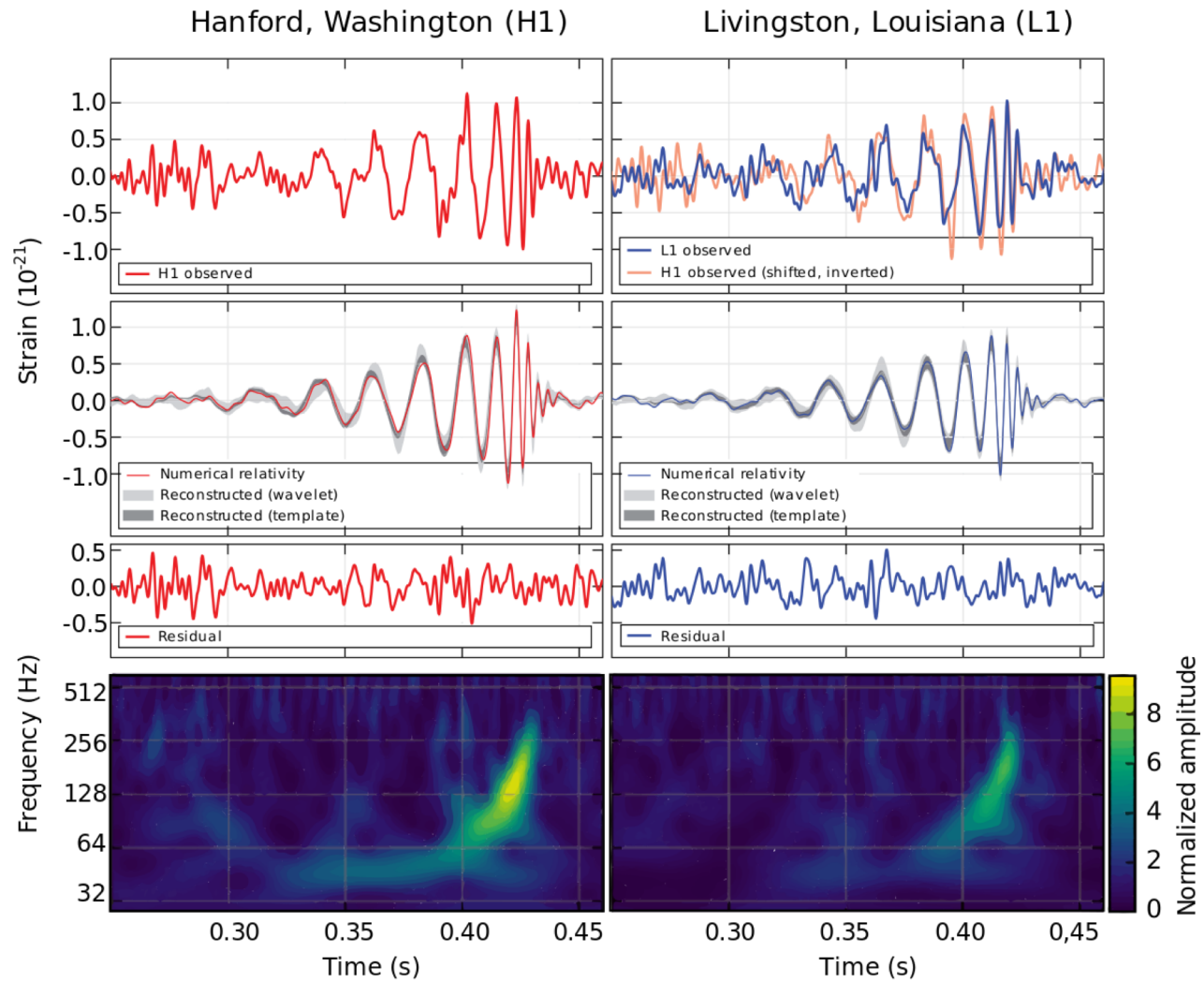
Interferometer of KAGRA  
(gravitational wave detector)

# ■ Sensitivity curve of gravitational wave detector

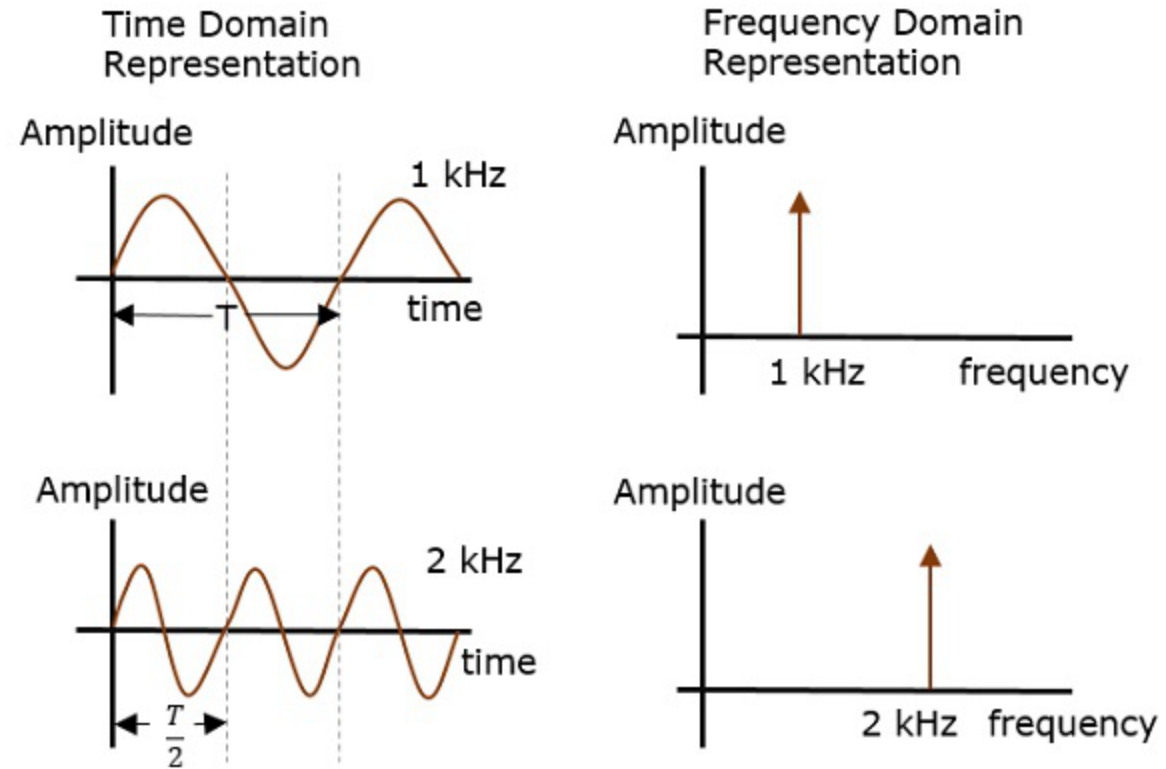


Sensitivity curve of KAGRA

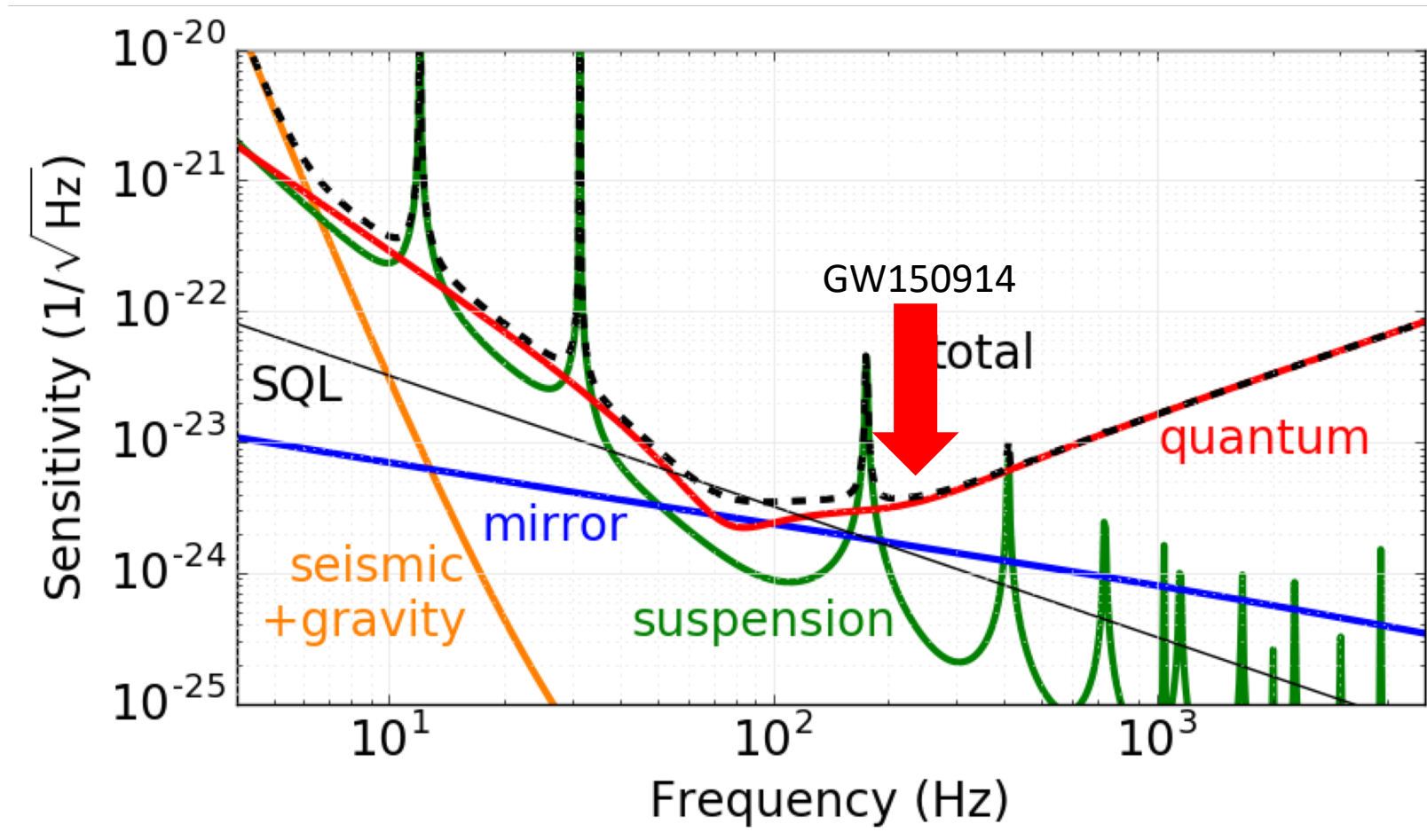
# Measurement



# Time domain and frequency domain



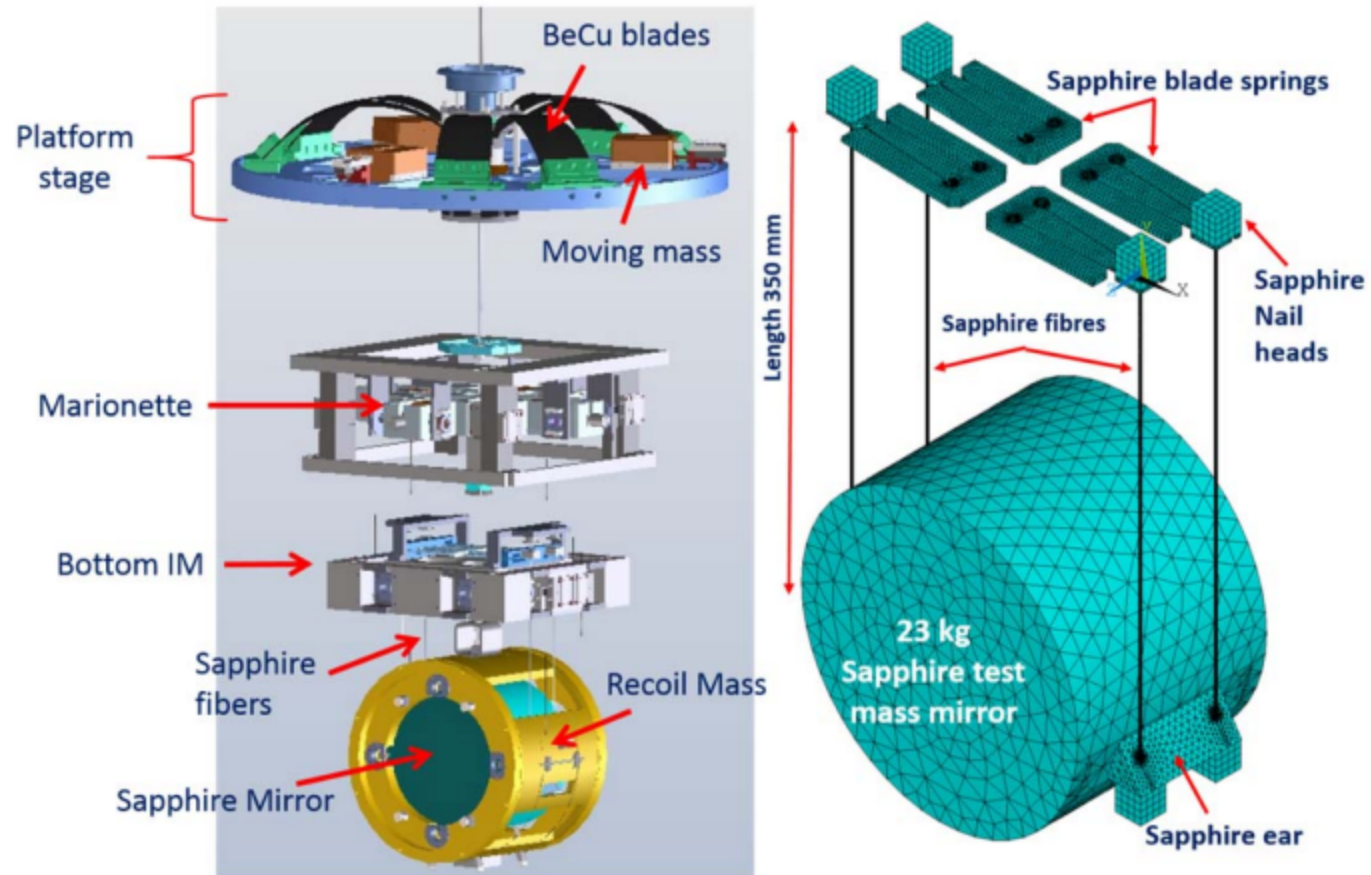
# ■ Sensitivity curve of gravitational wave detector



Sensitivity curve of KAGRA

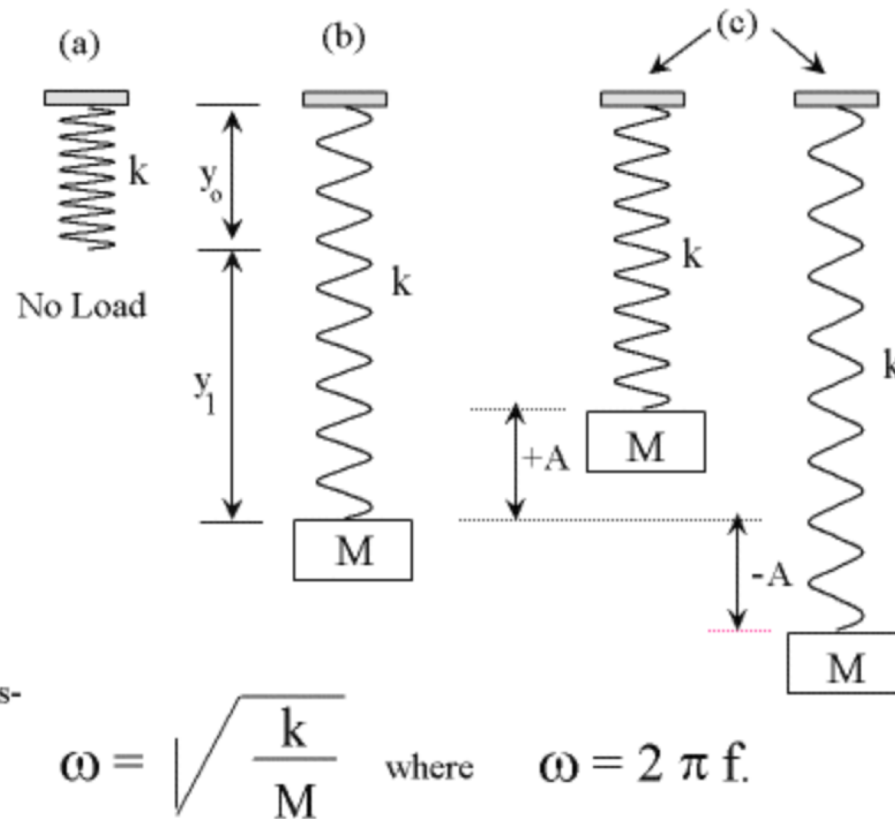


# ■ Test mass of KAGRA



# 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  $\omega$ , the angular frequency of oscillations of the mass-spring system is given by

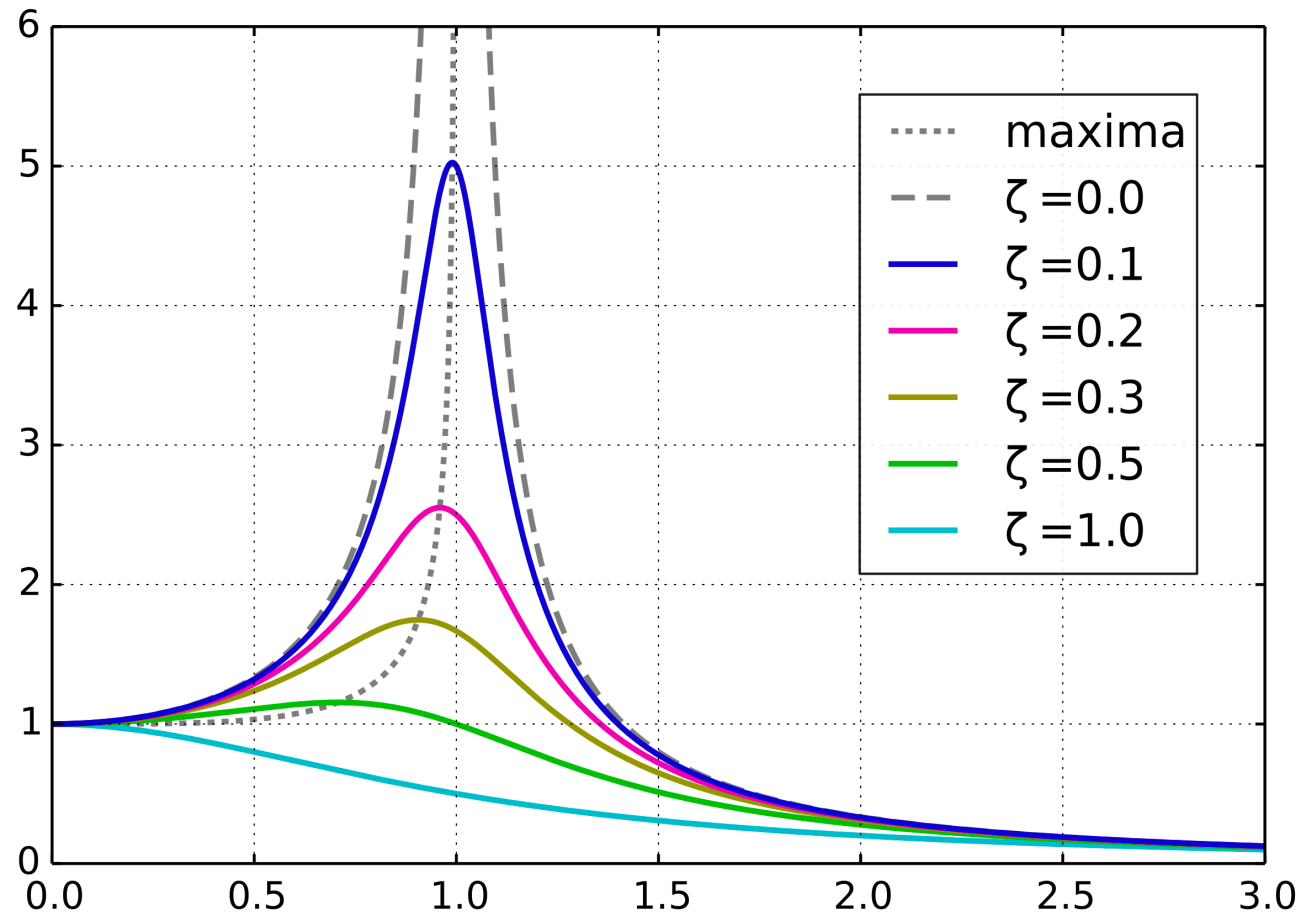


$$\omega = \sqrt{\frac{k}{M}} \quad \text{where} \quad \omega = 2\pi f.$$

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

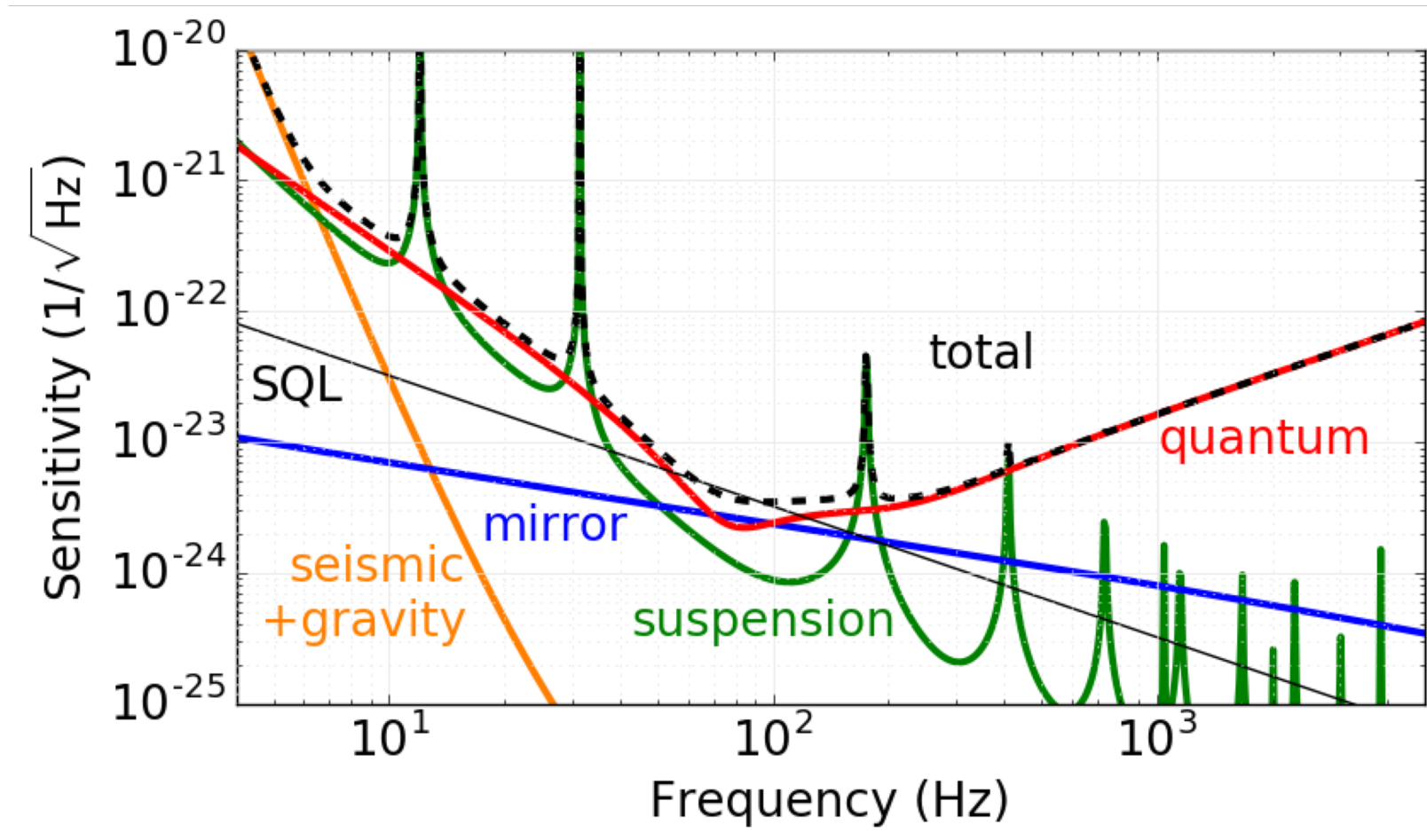
<http://www.pstcc.edu/nbs/WebPhysics/Expm%2001.htm>

# Resonance



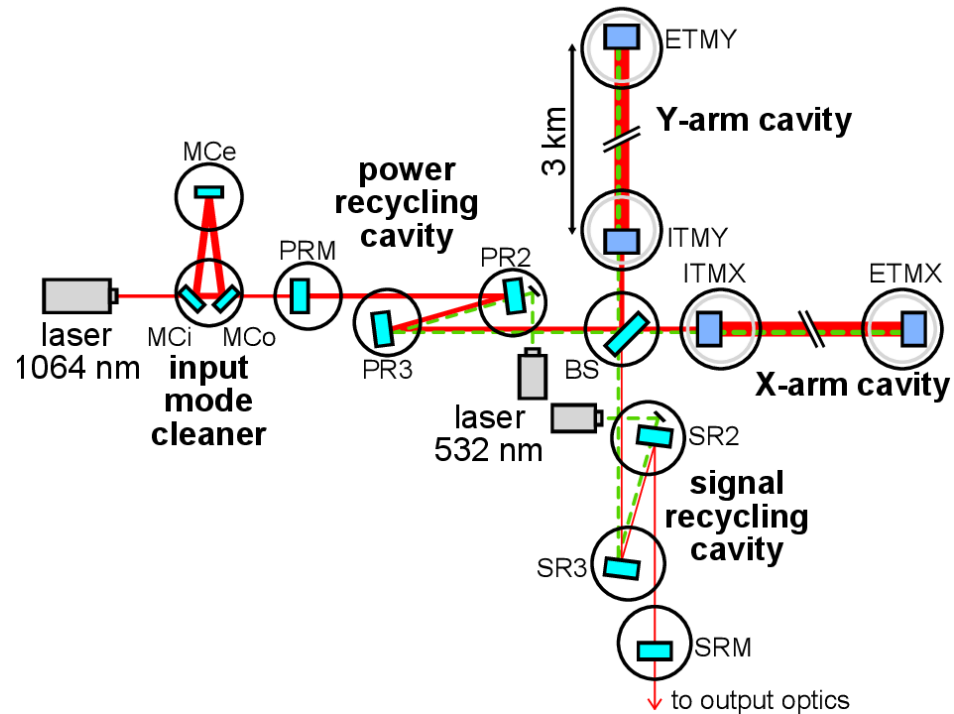
<https://en.wikipedia.org/wiki/Resonance>

# ■ Sensitivity curve of gravitational wave detector



Sensitivity curve of KAGRA

# Interferometer of KAGRA



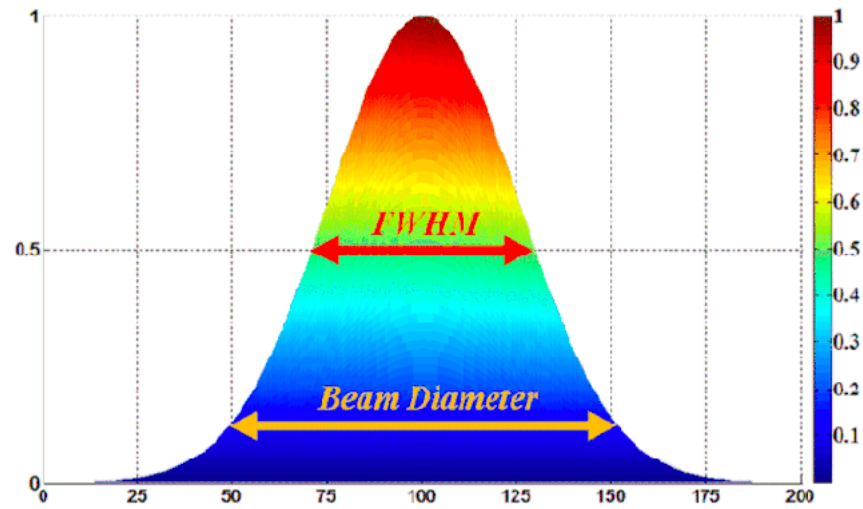
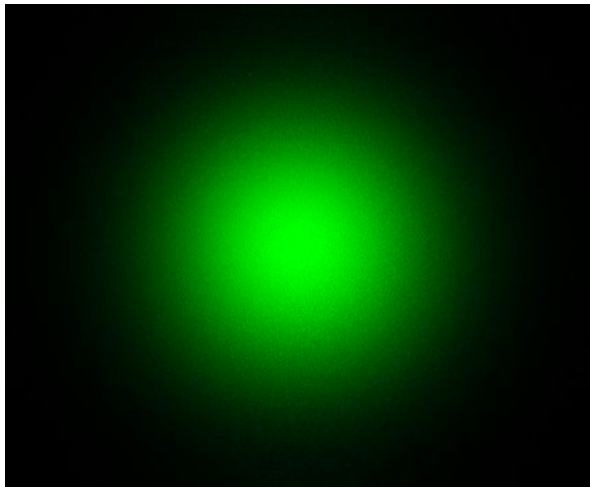
MC : Mode Cleaner  
ITMX : Input Test Mass X  
ITMY : Input Test Mass Y  
REFL : Reflection Port  
PRM : Power Recycling Mirror  
OMC : Output Mode Cleaner  
AS\_DC : Anti Symmetric DC  
SRM : Signal Recycling Mirror  
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Y. Aso et al. (KAGRA Collaboration), Phys.Rev. D88, 043007 (2013)

Interferometer of KAGRA  
(gravitational wave detector)

# ■ Gaussian beam

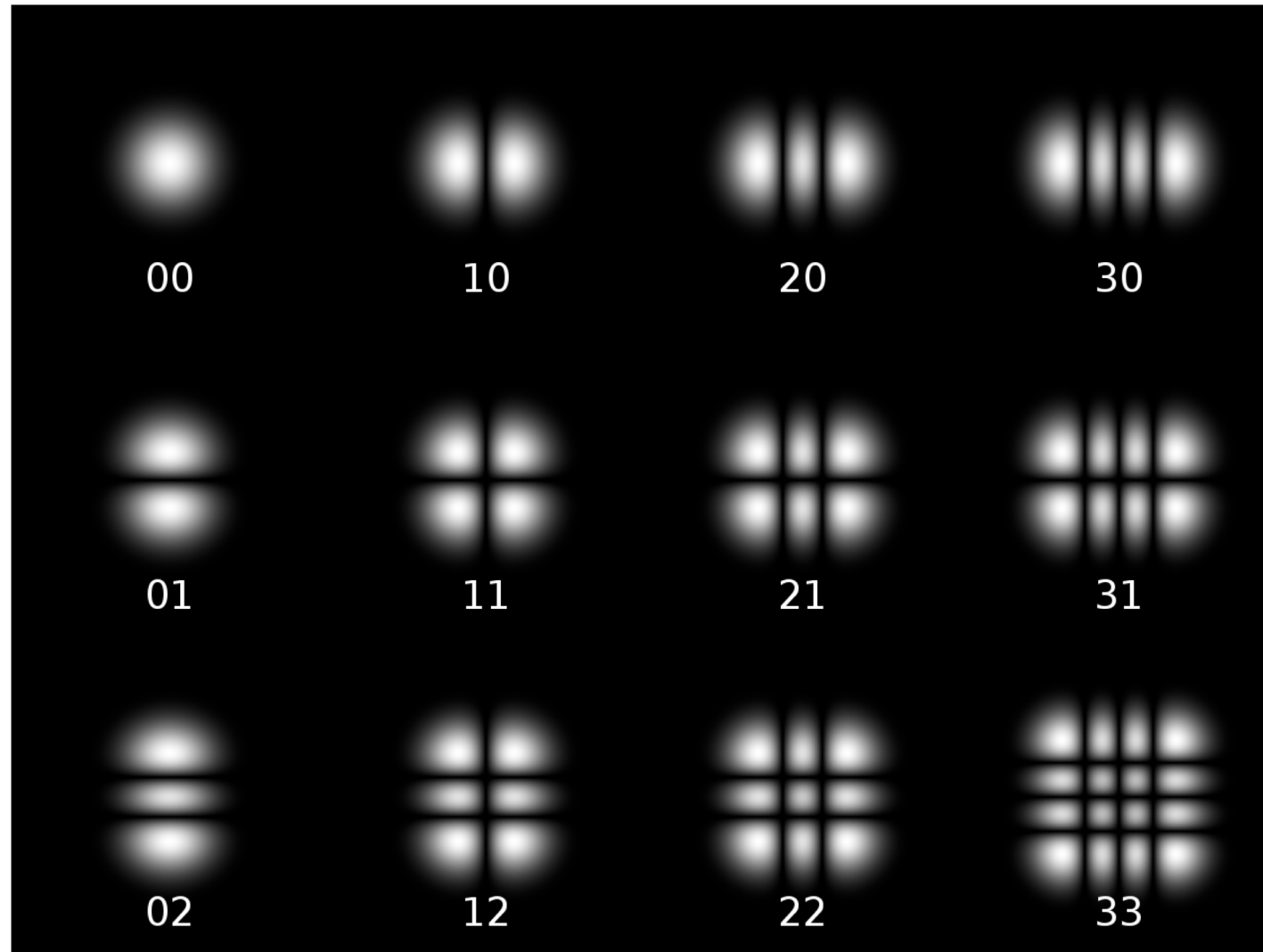
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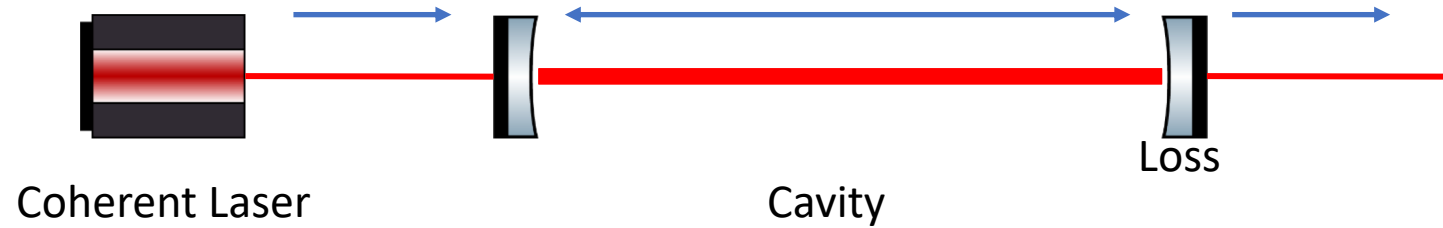
# ■ Spatial mode of gaussian beam

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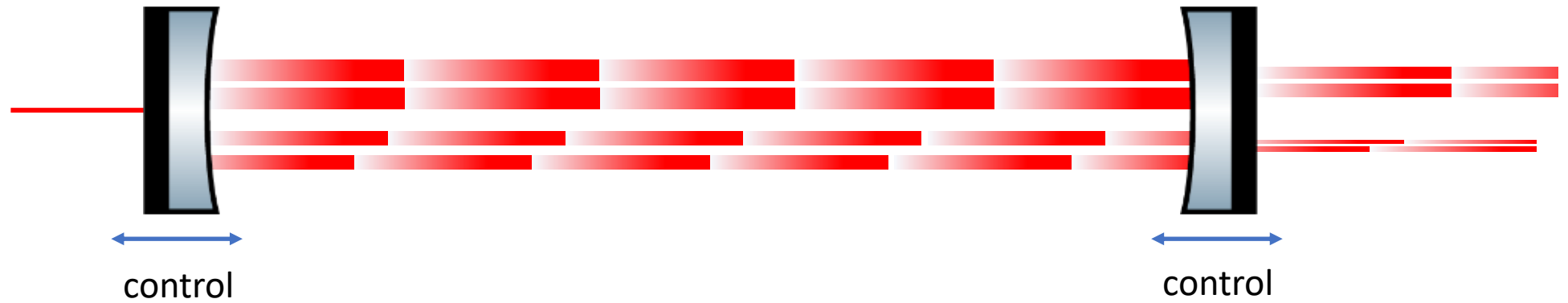
# Working principle of mode cleaning

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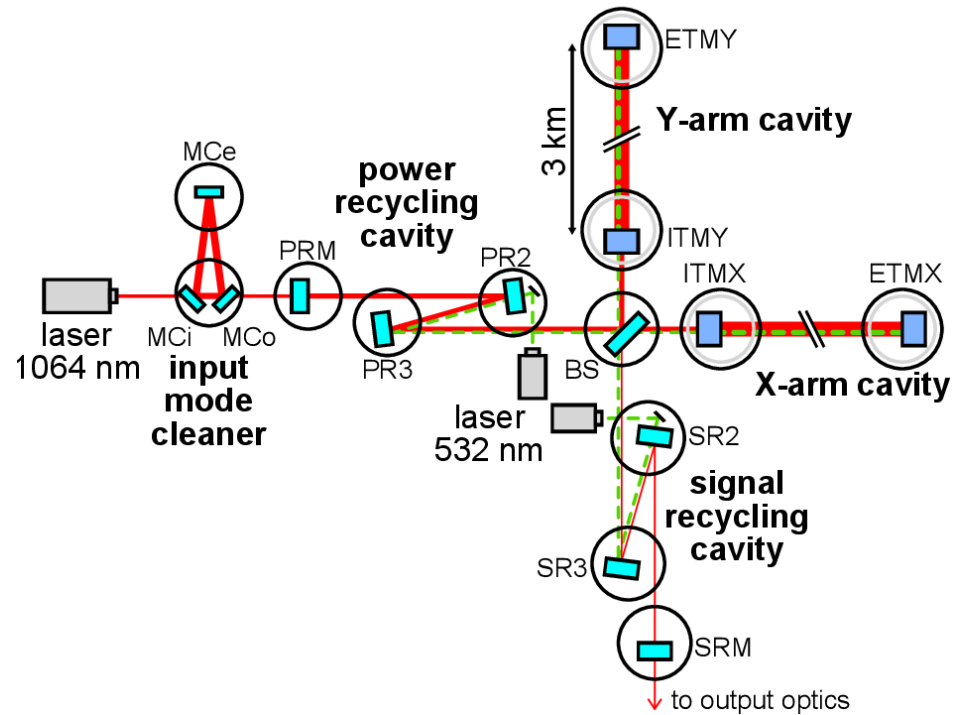


# Working principle of mode cleaning

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# Power and Signal recycling mirror

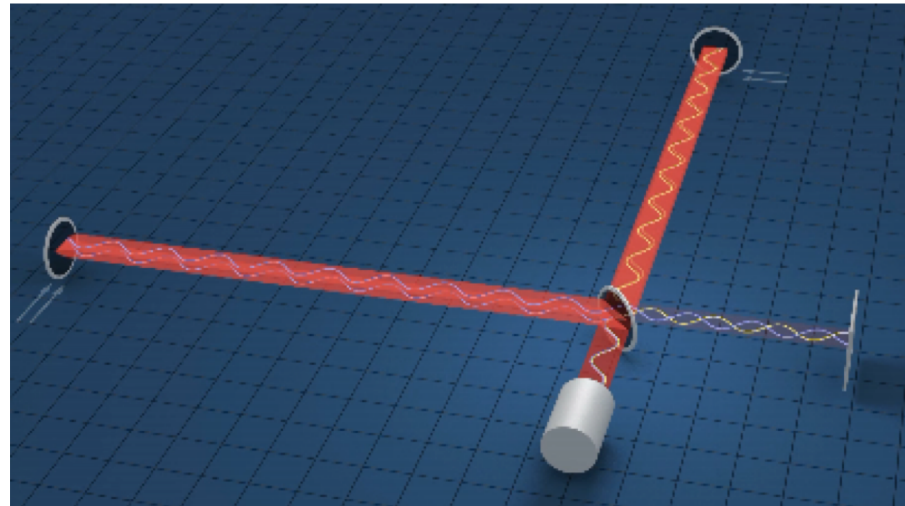
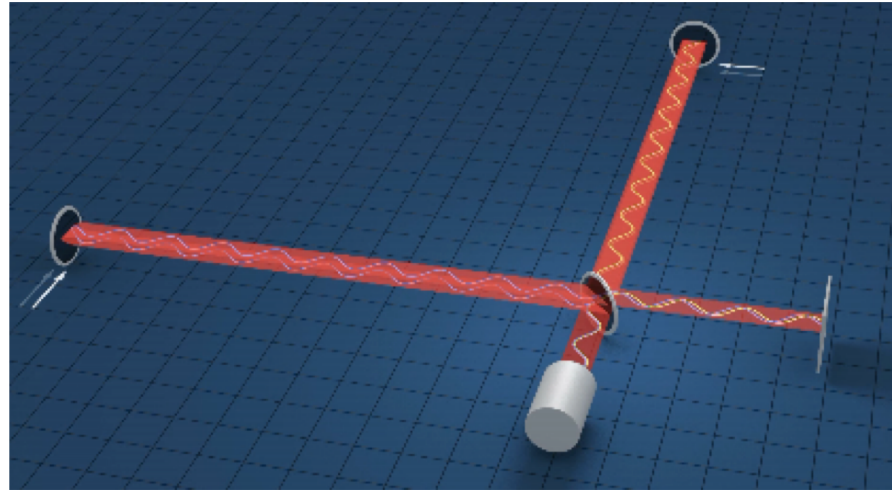


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Y. Aso et al. (KAGRA Collaboration), Phys.Rev. D88, 043007 (2013)

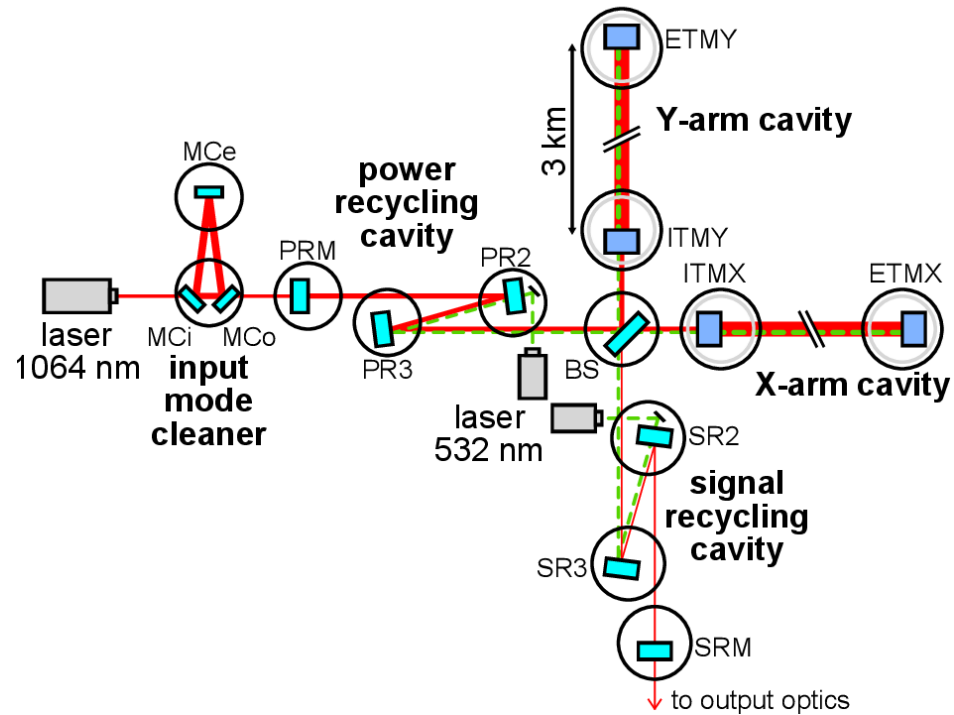
# ■ Energy conservation in Michelson interferometer

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# Power and Signal recycling mirror

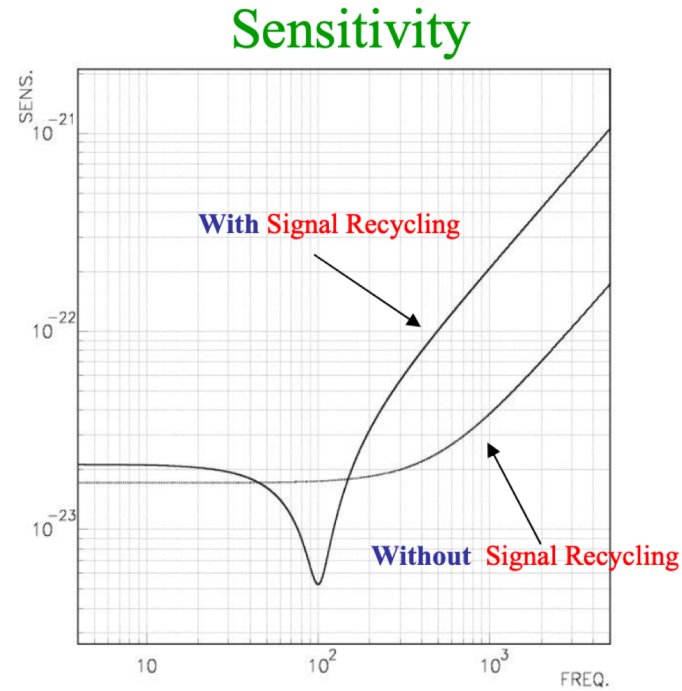
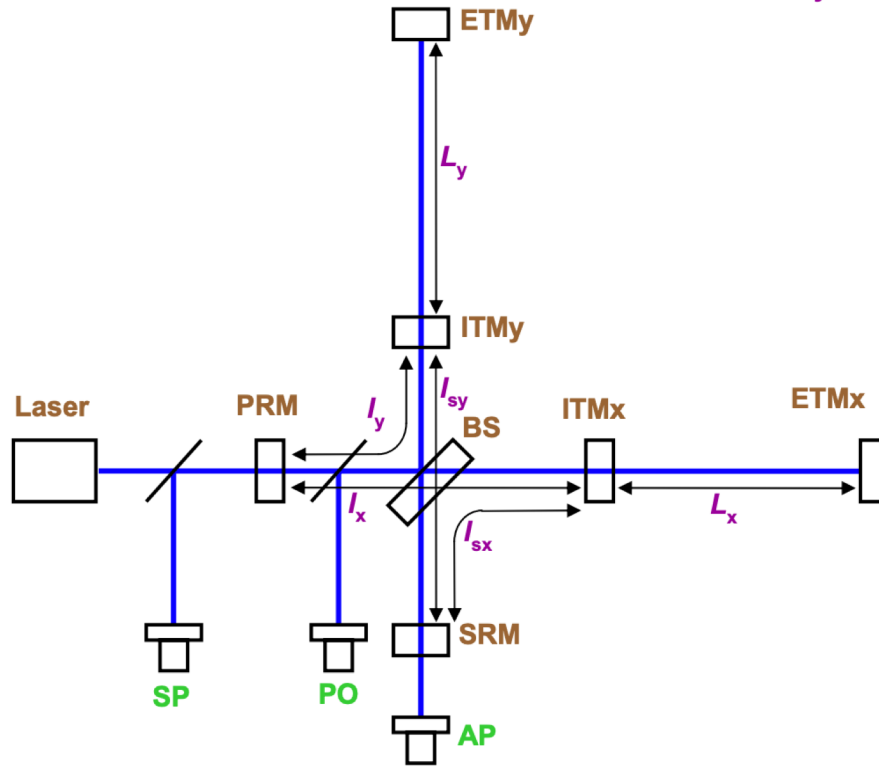


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Y. Aso et al. (KAGRA Collaboration), Phys.Rev. D88, 043007 (2013)

# DUAL-RECYCLED INTERFEROMETER

- Common of arms :  $L_+ = (L_x + L_y) / 2$
- Differential of arms :  $L_- = (L_x - L_y) / 2$
- Power recycling cavity :  $I_+ = (I_x + I_y) / 2$
- Michelson :  $I_- = (I_x - I_y) / 2$
- Signal recycling cavity :  $I_s = (I_{sx} + I_{sy}) / 2$

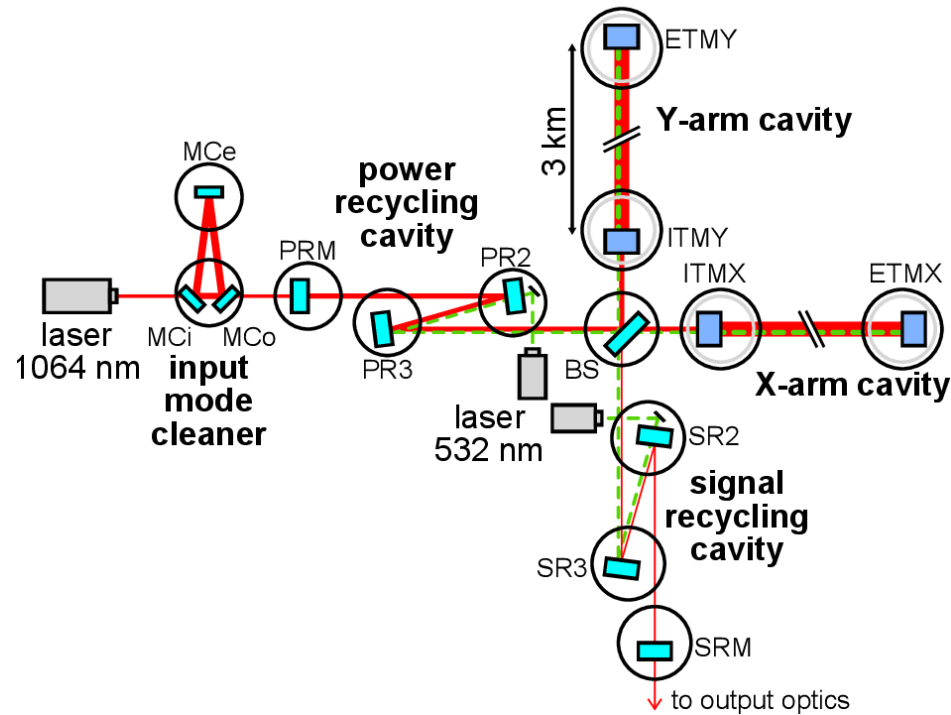


*better sensitivity in an optimized frequency band (naive view)*

01/06/2006

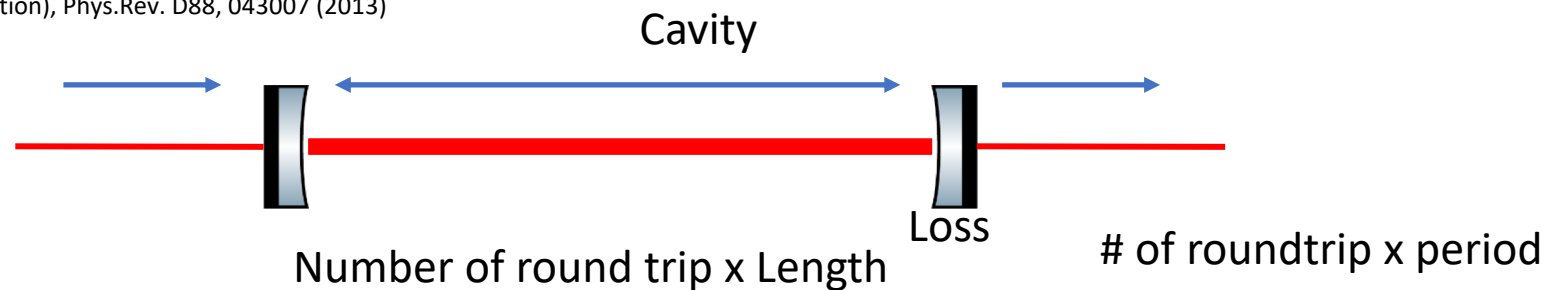
GWADW - Elba (Italy), ----  
M.Varvella

# Power and Signal recycling mirror



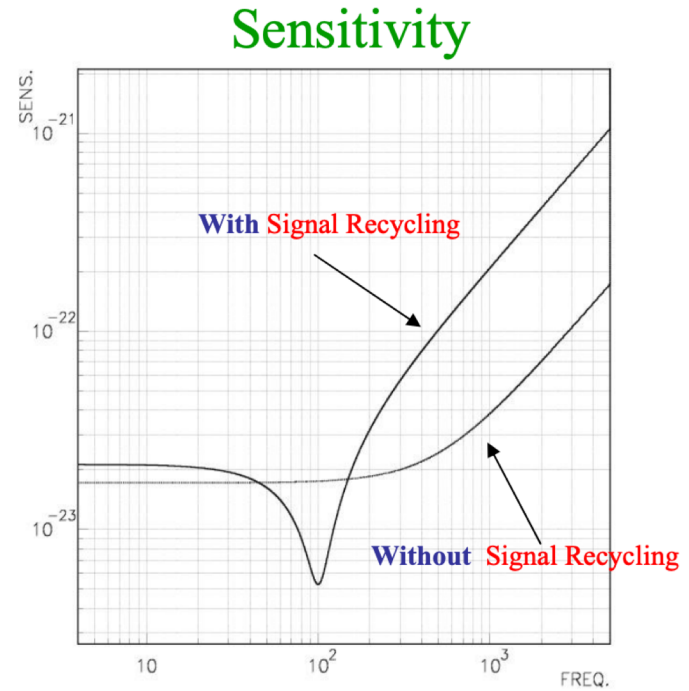
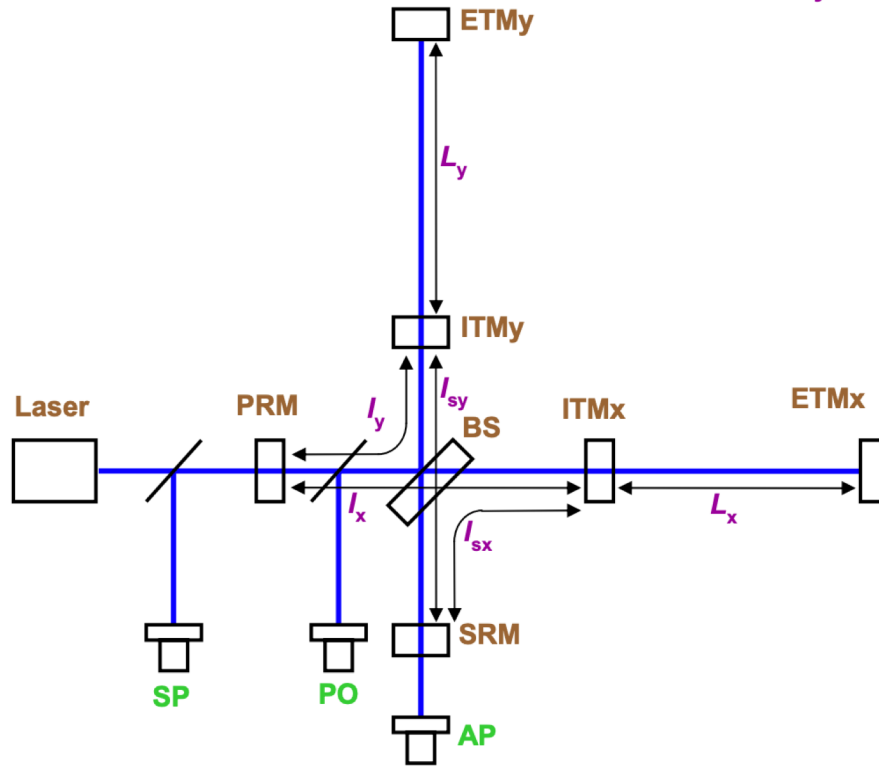
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Y. Aso et al. (KAGRA Collaboration), Phys.Rev. D88, 043007 (2013)



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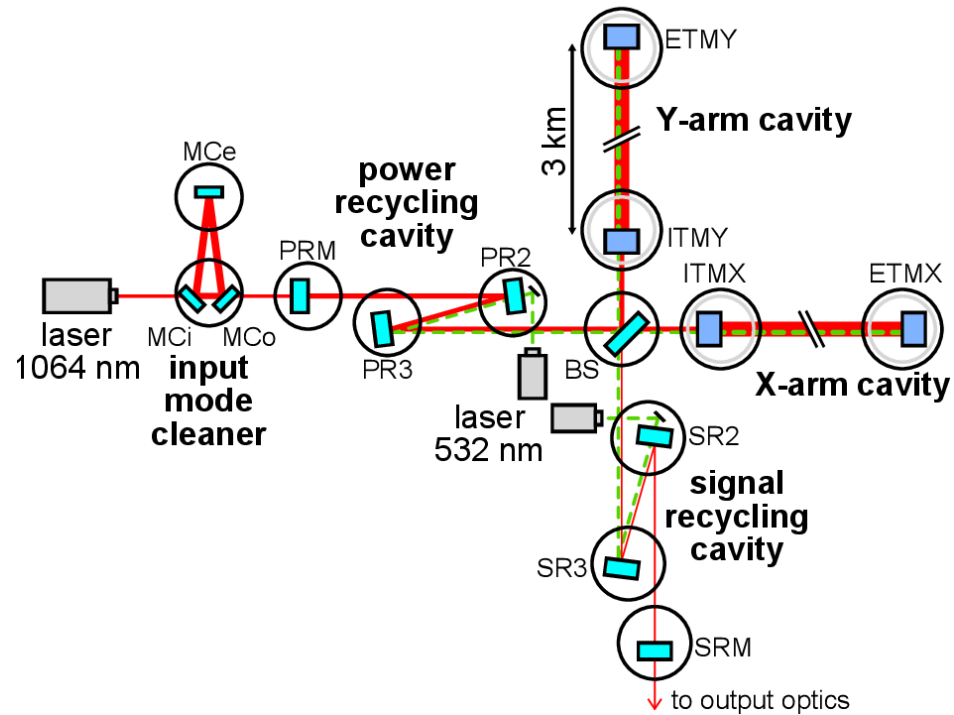


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01/06/2006

GWADW - Elba (Italy), ----  
M.Varvella

# Power and Signal recycling mirror



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- OMC : Output Mode Cleaner
- AS\_DC : Anti Symmetric DC
- SRM : Signal Recycling Mirror
- POP : Pick-off-in-the-PRC
- ETMX : End Test Mass X
- ETMY : End Test Mass Y
- AS\_RF : Anti Symmetric RF

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



# Control room

