LIGO-G1000642-V1

Technologies of Gravitational Wave Detection

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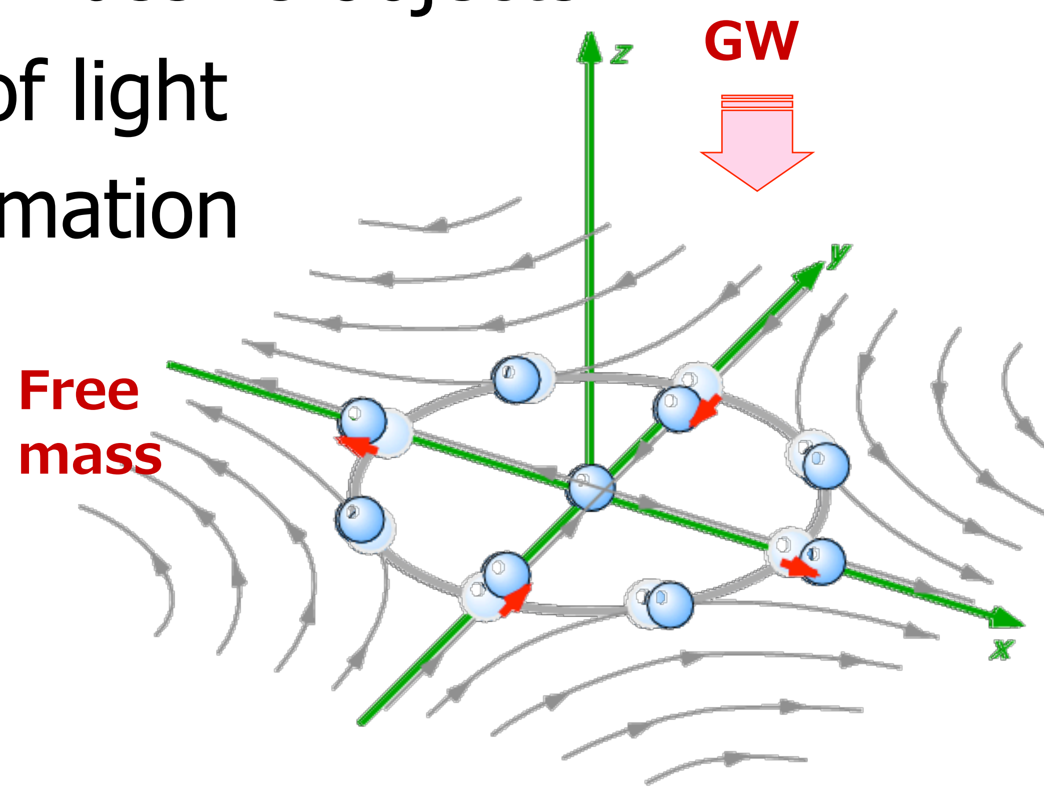
Background / Overview

- Introduce common technologies / terminologies
- Brief review of GW / GW detection
- Interferometer GW detectors
- Interferometry
- Sensing & Control

Interferometer GW detection

Gravitational wave

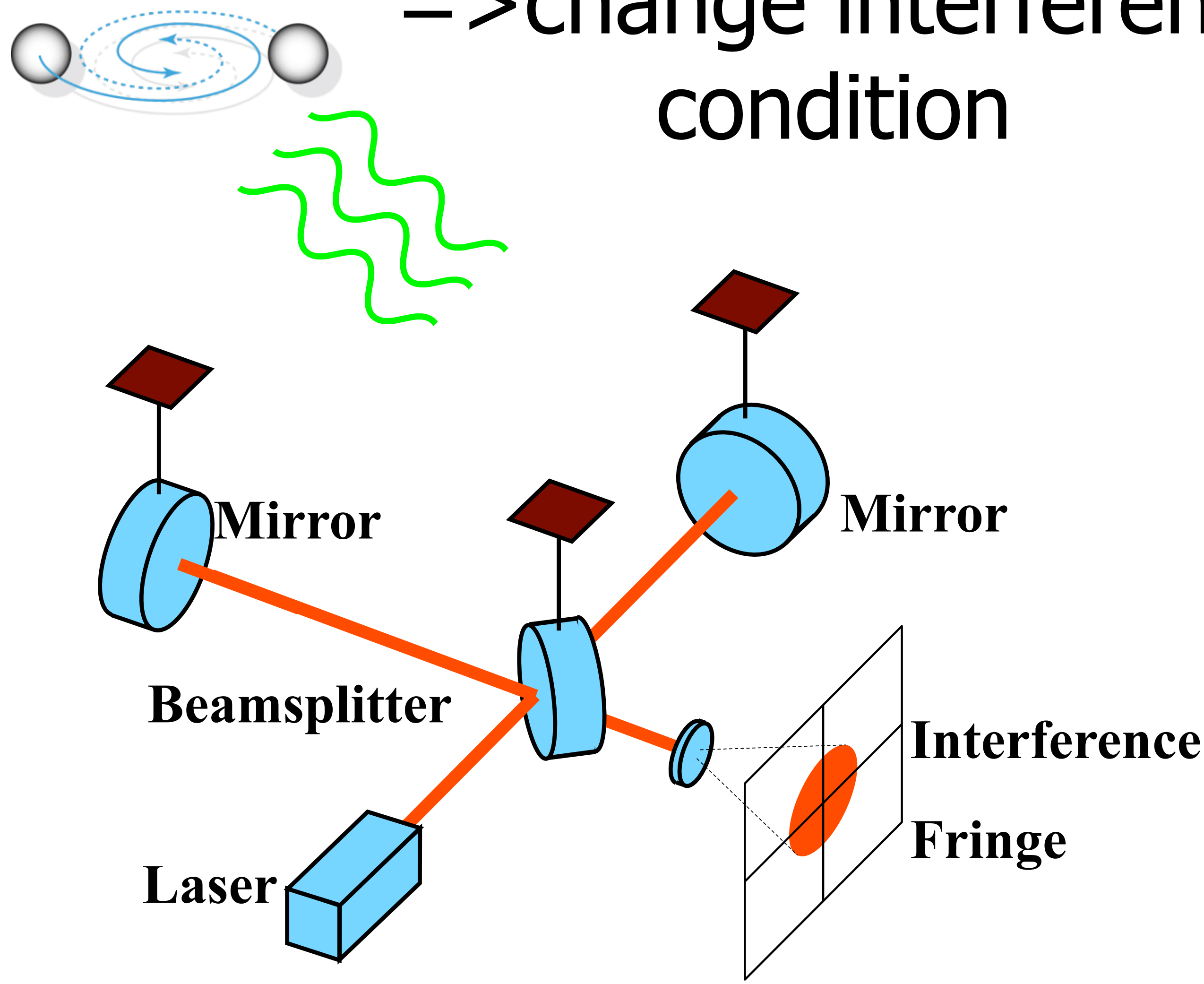
- General Relativity
  - Gravity = Spacetime curvature
  - Gravitational Wave = Wave of spacetime curvature
- GW
  - Generated by motion of massive objects
  - Propagates with speed of light
  - Cause quadrupole deformation of the spacetime



Interferometer GW detection

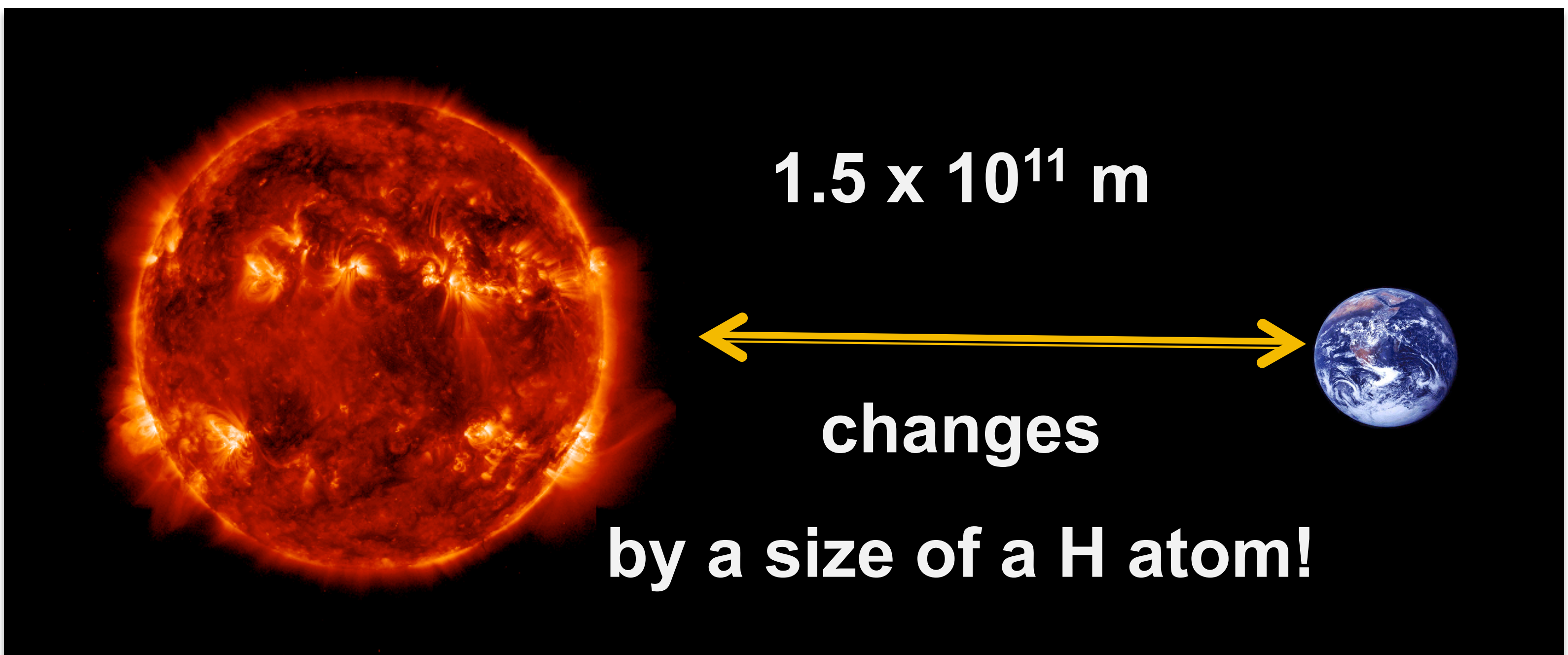
- Michelson-type interferometers are used
- Differential change of the arm path lengths

=>change interference condition



Amplitude of GWs

- The effect of GW is very small
- $h \sim 10^{-21}$ => distance of 1m changes 10^{-21}m
- Corresponds to:
  change by **~1 angstrom**
  for distance between the sun and the earth

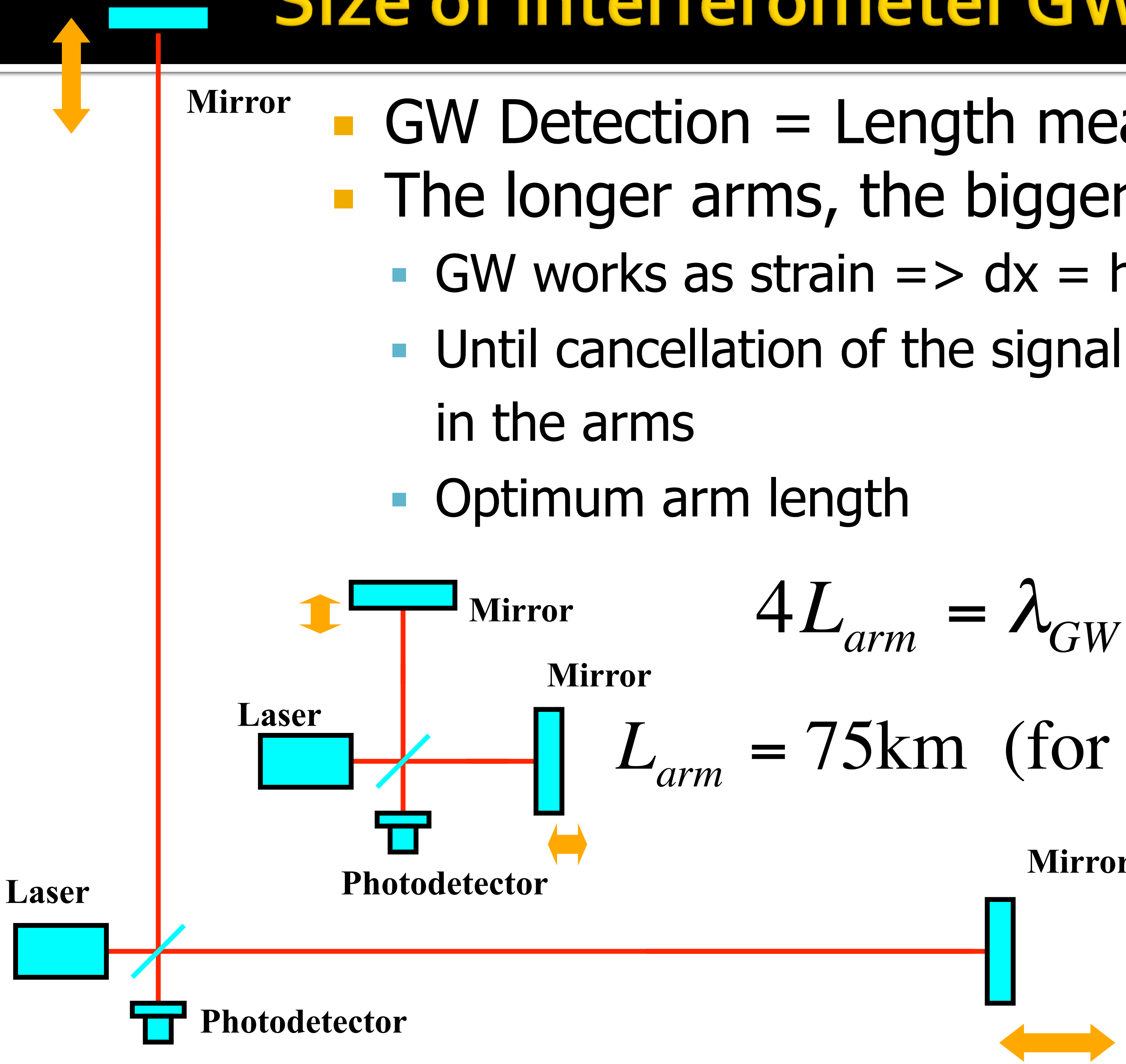


Size of interferometer GW detectors

- GW Detection = Length measurement
- The longer arms, the bigger the effect
  - GW works as strain => $dx = h_{GW} \times L_{arm}$
  - Until cancellation of the signal happens in the arms
  - Optimum arm length

$$4L_{arm} = \lambda_{GW} (= c / f_{GW})$$

$$L_{arm} = 75\text{km} \quad (\text{for } f_{GW} = 1\text{kHz})$$



Size of interferometer GW detectors

- **LIGO Observatories**

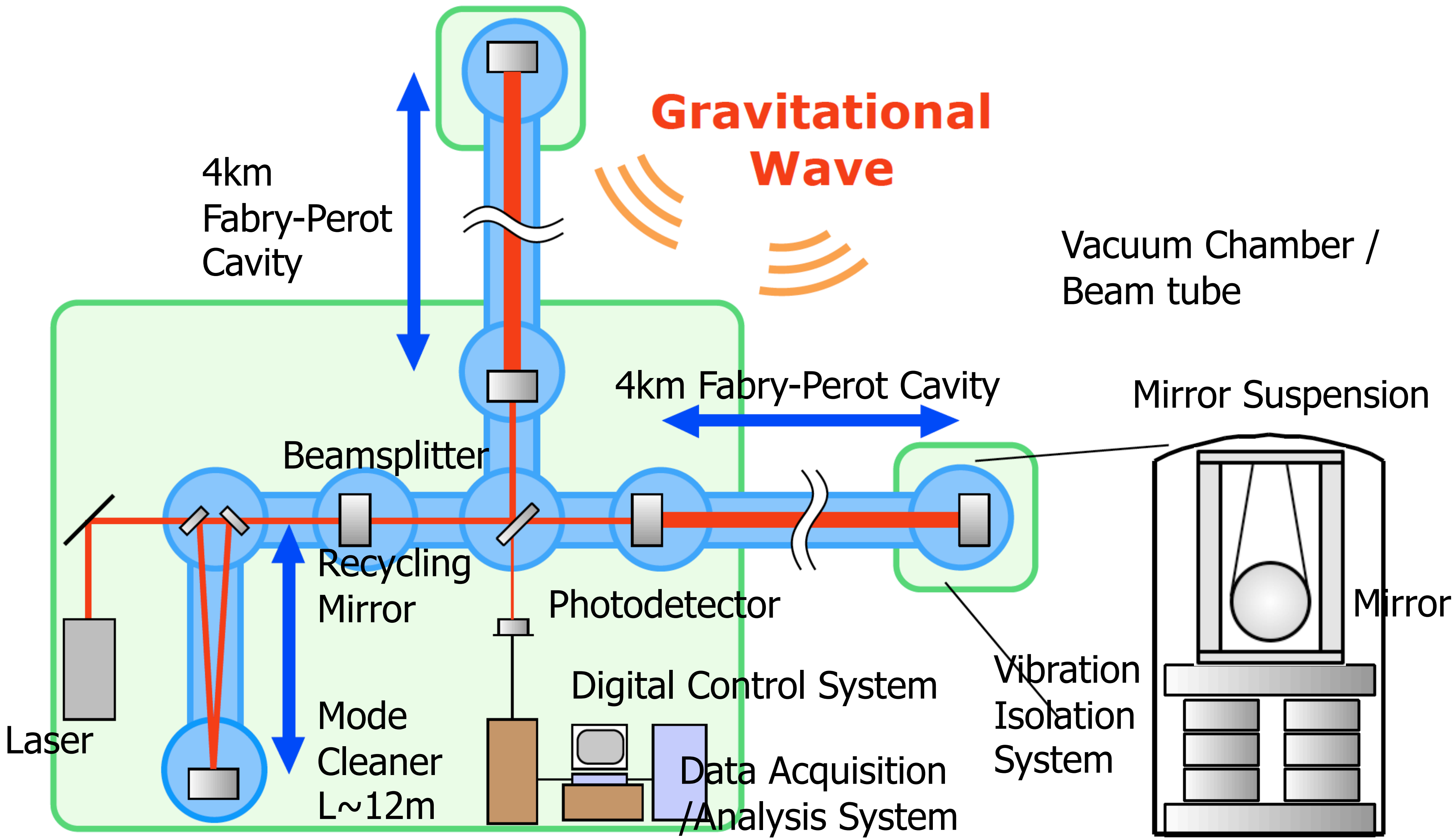
  Hanford (4km&2km)　Livingston (4km)

  Still shorter than the optimum length
  => Use optical cavity to increase life time of the photons in the arm

c.f. Virgo (FRA/ITA) 3km, GEO (GER/GBR) 600m, TAMA (JPN) 300m

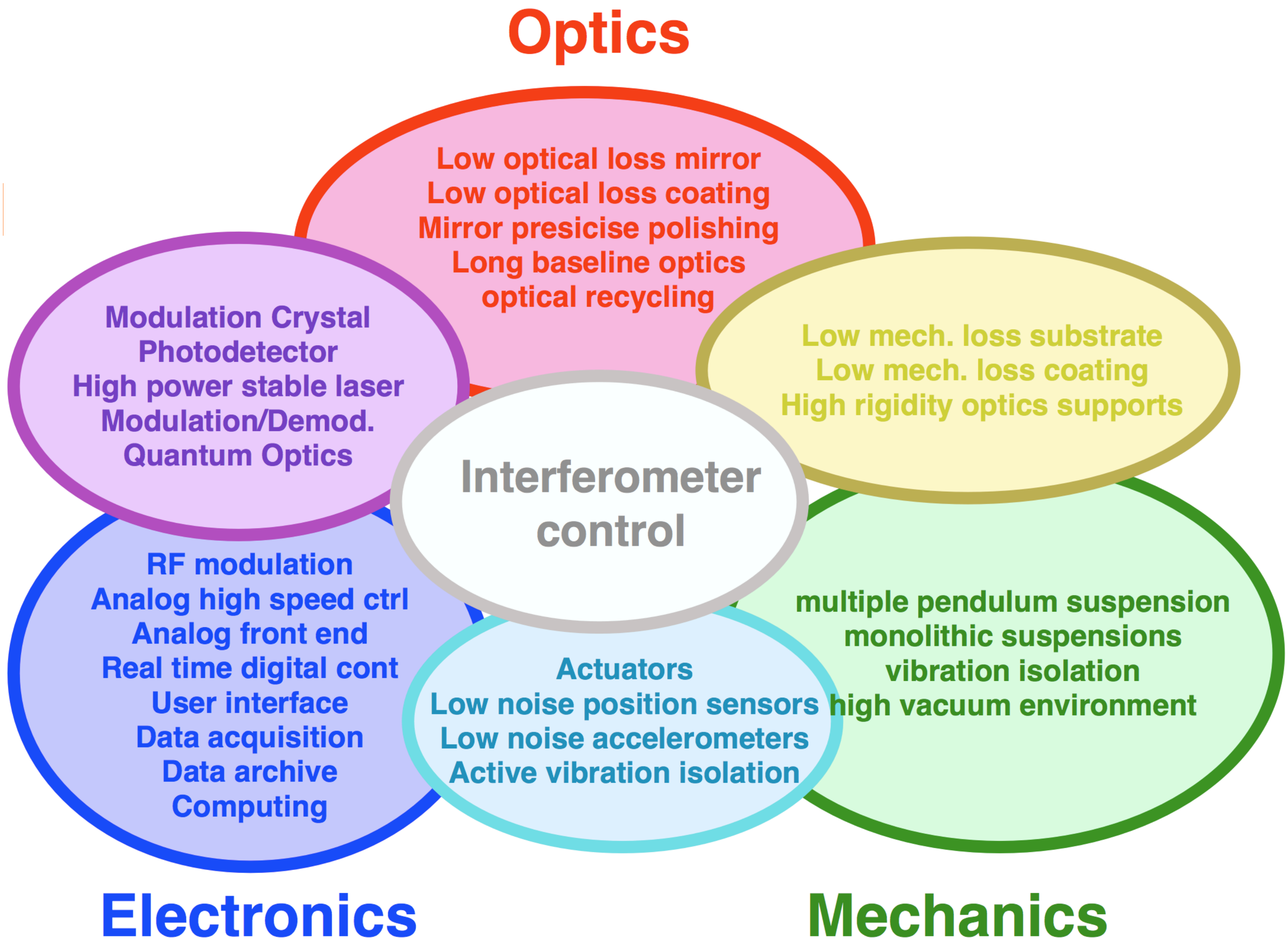
Components of the interferometer

- "Still simplified" LIGO Interferometer



Components of the interferometer

- 3
- O
- M
- El



What can we do for the detection?

- An IFO produces a continuous signal in the GW channel

- The detector is fixed on the ground
=> can not be directed to a specific angle

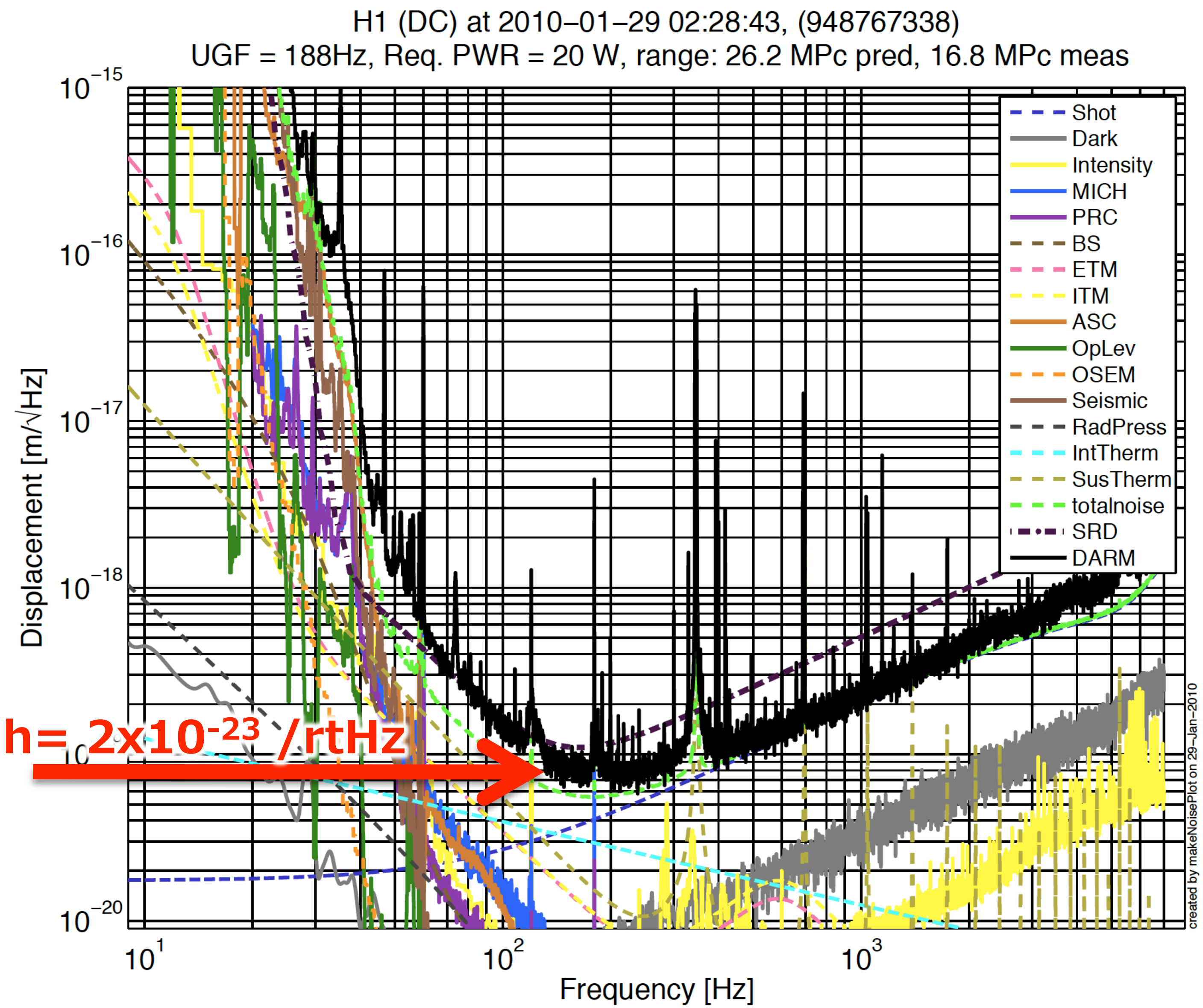
- GWs and noises are, in principle, **indistinguishable**
=> Anything we detect is GW

- **Reduce noises!**

- Obs. distance is inv-proportional to noise level
- x10 better => x10 farther => x1000 more galaxies

Recent sensitivity of LIGO

- Sensitivity (=noise level) of Enhanced LIGO



Laser shot noise
Laser radiation pressure noise
thermal noise
seismic noise
Laser intensity /frequency noise

electronics noise
digitization noise
angular control noise

......

Summary

- GWs ~ ripples of the spacetime
- **Not yet** directly detected
  ~ the effect is so small ($h<10^{-21}$)
- **Michelson**-type interferometers are used
- GW detection is a **precise** length
  (=displacement) measurement!
- GW effect is very small

Summary

- Essentially, **the larger, the better.**
  LIGO has two largest interferometers
  in the world

- **IFO consists of many components**
  Optics / Mechanics / Electronics
  and their combinations (e.g. Opto-Electronics)

- noise and signal are, in principle,
  indistinguishable.
  Noise reduction is the matter.

Interferometry

Laser interferometry

- GW detection
  = High sensitive detection of displacement

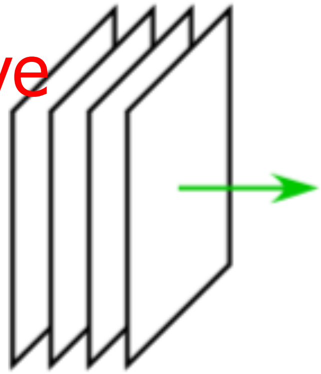
- Laser interferometry is an indispensable technology (lambda ~ 1um)

- **We use optical cavities in many places**
  What is an optical cavity?

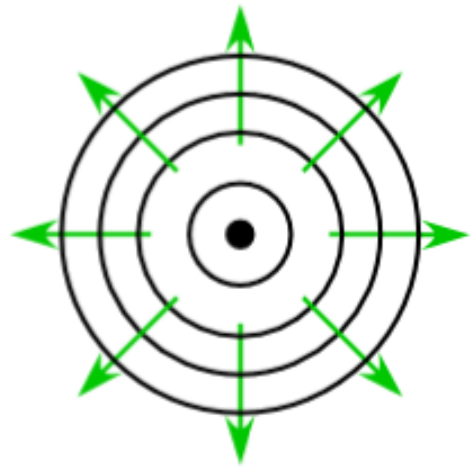
Gaussian beam

- Propagation of EM waves
  - Plane wave

Equiphase Planes



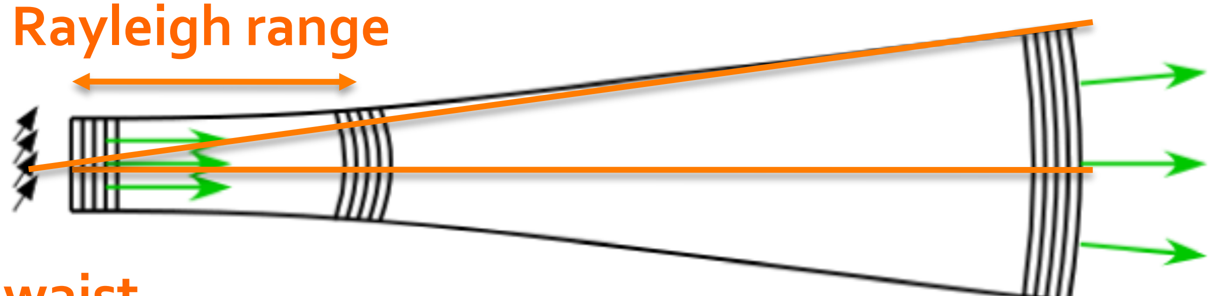
Spherical wave



- Gaussian beam:

Any laser beam does diverge

Amplitude distribution of the beam is Gaussian



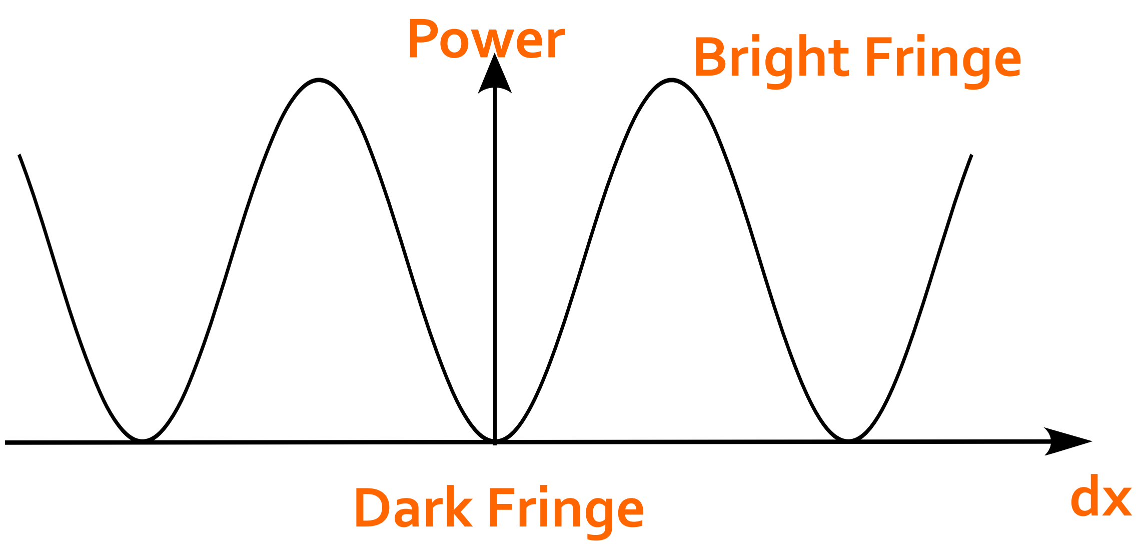
Fringes

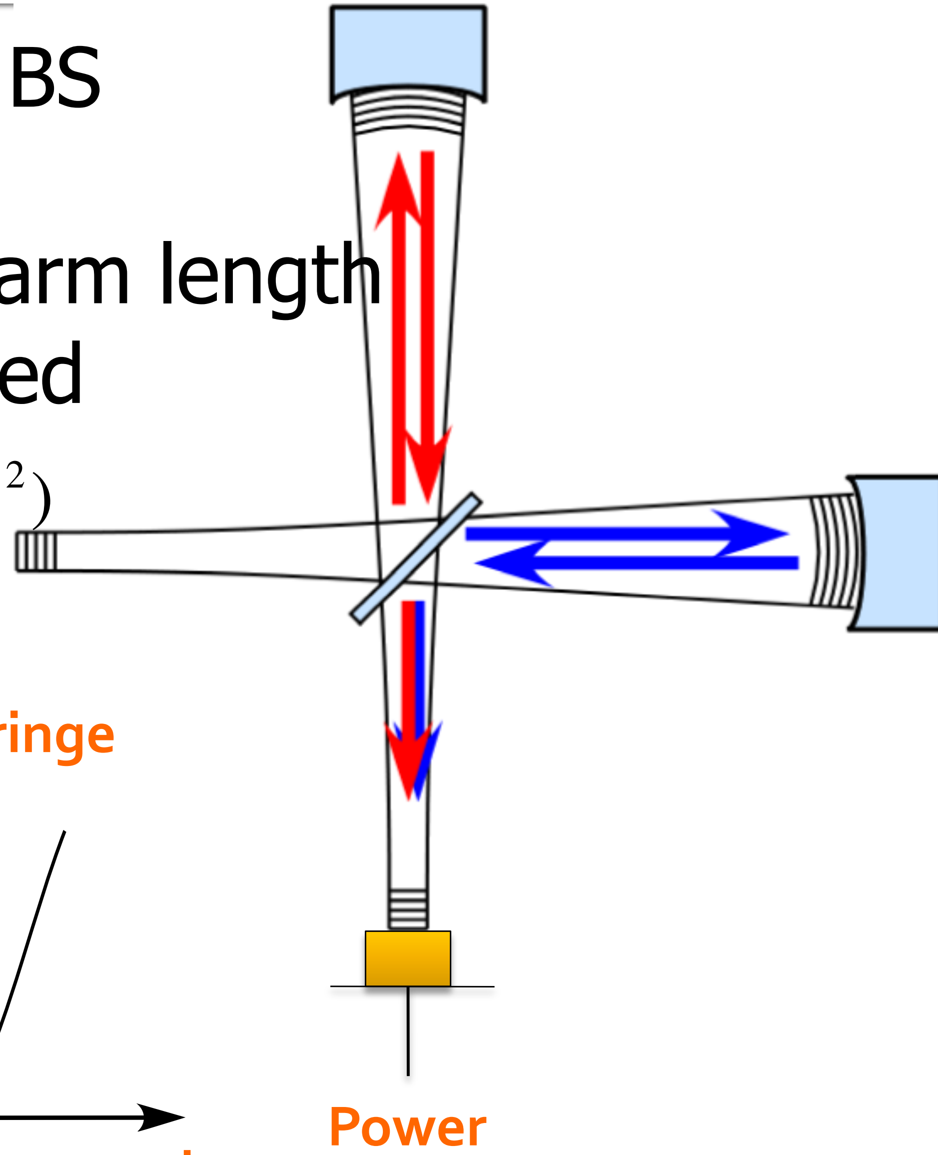
- Two beams overlap at the BS

- Differential change of the arm length => fringe condition changed

$$P = E \cdot E^{*} = P_0 (e^{i\phi 1} - e^{i\phi 2})(e^{-i\phi 1} - e^{-i\phi 2})$$

$$= 2P_0 (1 - \cos d\phi)$$





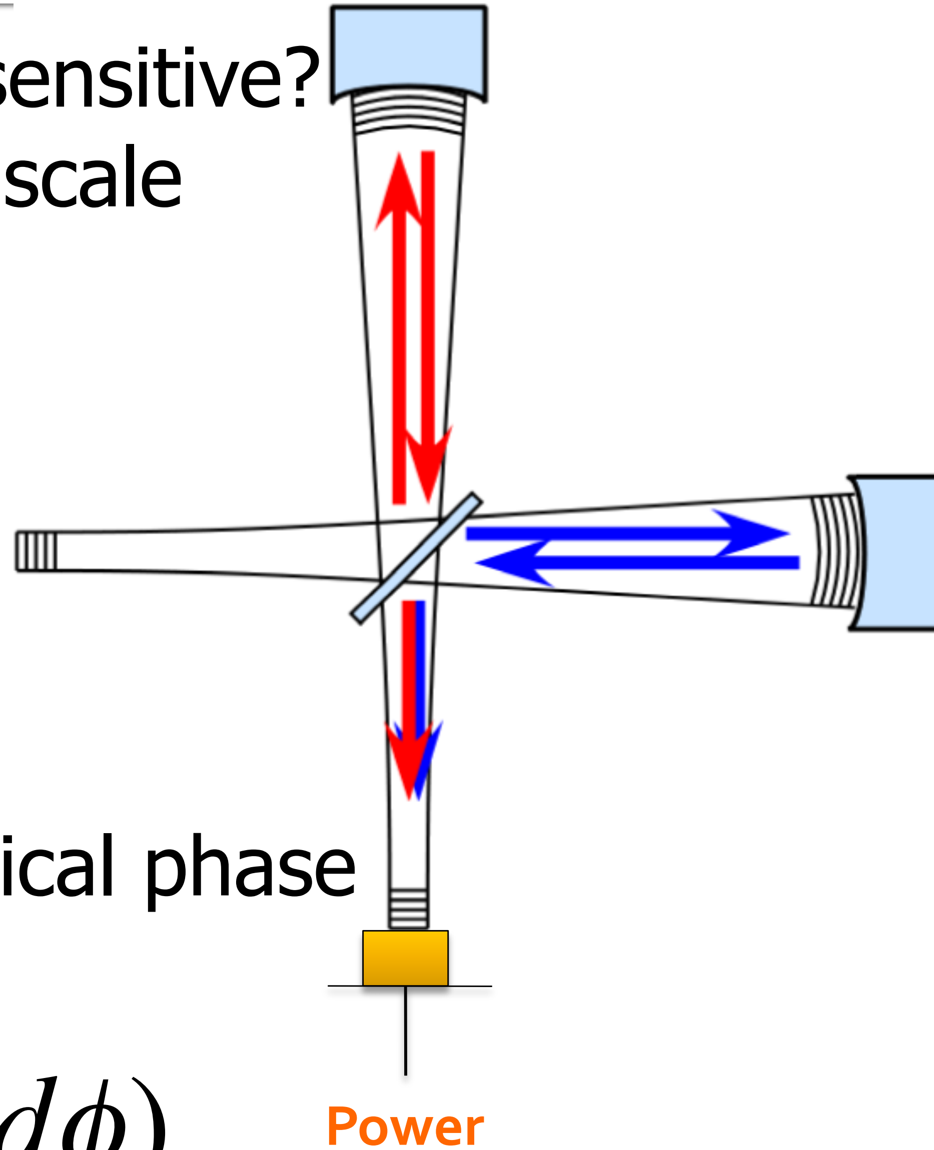
Phase measurement

- Why an interferometer is sensitive?
the wavelength is used as a scale

- We can not directly read
phases of the E-field
=> What we can use is
the detected power

- Power depends on the optical phase by using interference

$$P = 2P_0(1 - \cos d\phi)$$



Fringes

- Contrast

$$C = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

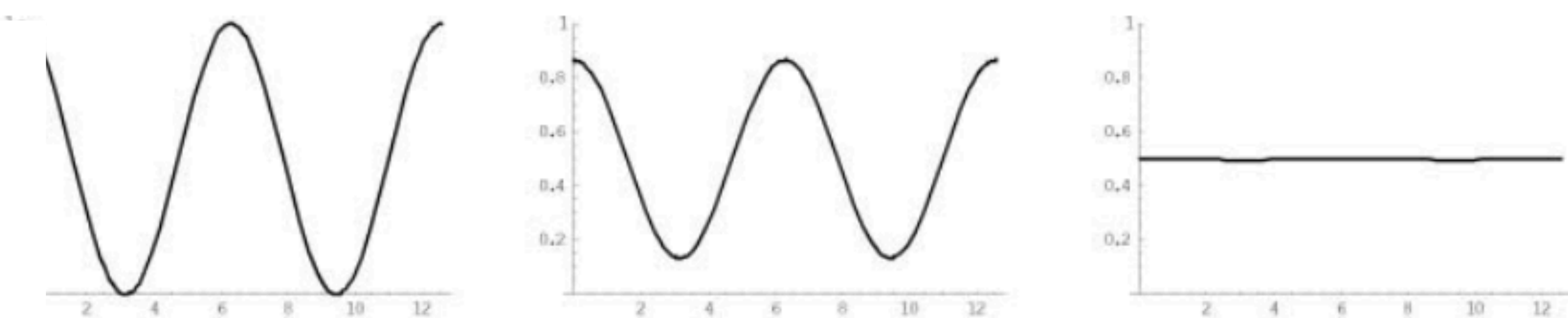
Contrast Defect with mirror tilting

Dar

If you really see fringe stripes, that's BAD!

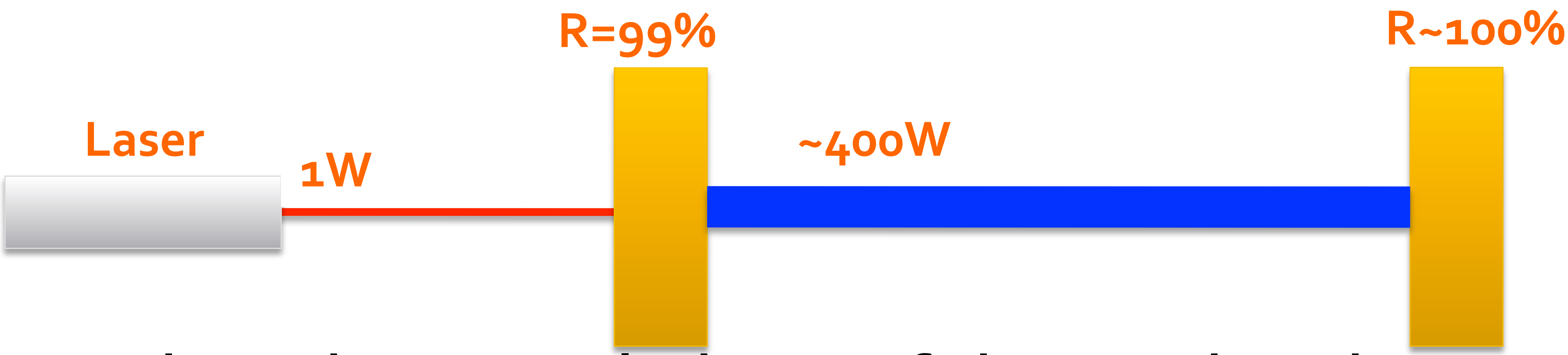
Contrast — C = 1 — C ~0.7 — C ~ 0

Light intensity at PD with the mirror swept

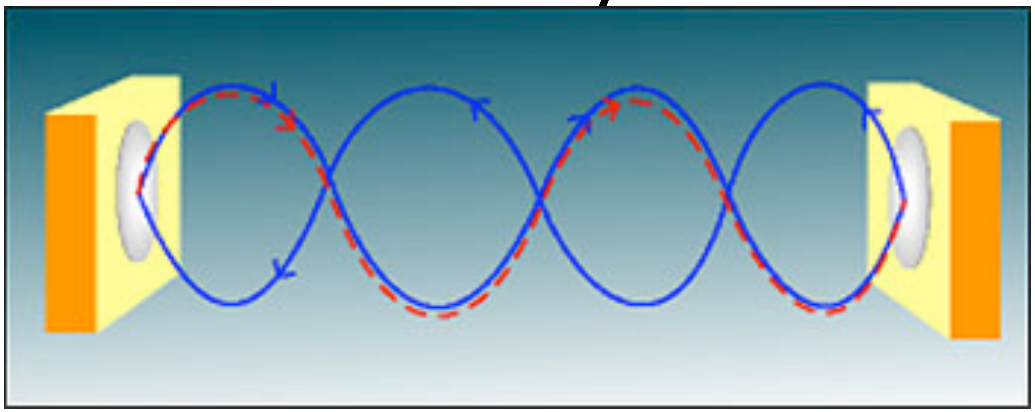


Fabry-Perot Optical Resonator Cavities

- Two facing high reflective mirror

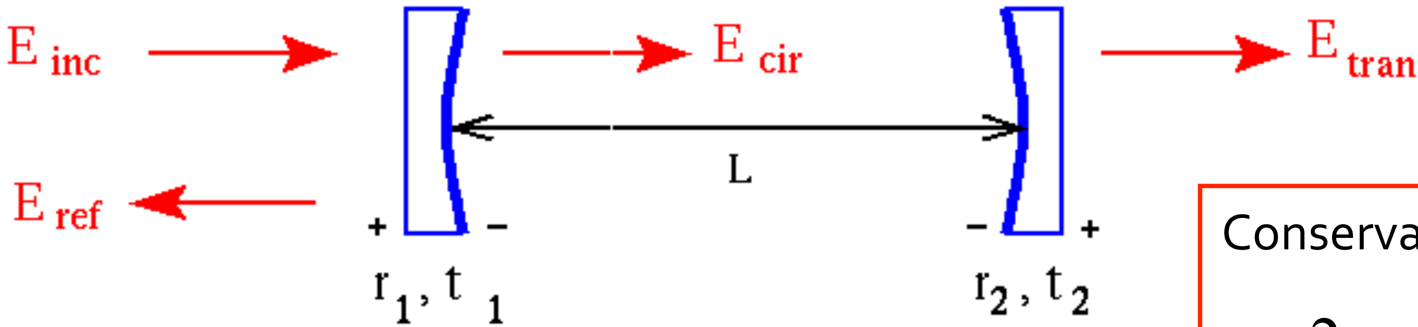


- When the optical phase of the incident beam matches the phase in the cavity => **resonance**



- 2 mirror cavity = Fabry-Perot (FP)
  more mirrors = ring cavity
  not much difference

Fabry-Perot Optical Resonator Cavities



$$E_{cir} = t_1 E_{inc} + r_1 r_2 e^{-2ikL} E_{cir} = \frac{t_1}{1 - r_1 r_2 e^{-2ikL}} E_{inc}$$

$$E_{ref} = r_1 E_{inc} - t_1 r_2 e^{-2ikL} E_{cir} = \frac{r_1 - r_2 (1 - L) e^{-2ikL}}{1 - r_1 r_2 e^{-2ikL}} E_{inc}$$

$$E_{tran} = t_2 \; e^{-ikL} E_{cir} = \frac{t_1 t_2 e^{-ikL}}{1 - r_1 r_2 e^{-2ikL}} E_{inc}$$

Conservation of energy:

$$r_i^2 + t_i^2 + L_i = 1$$

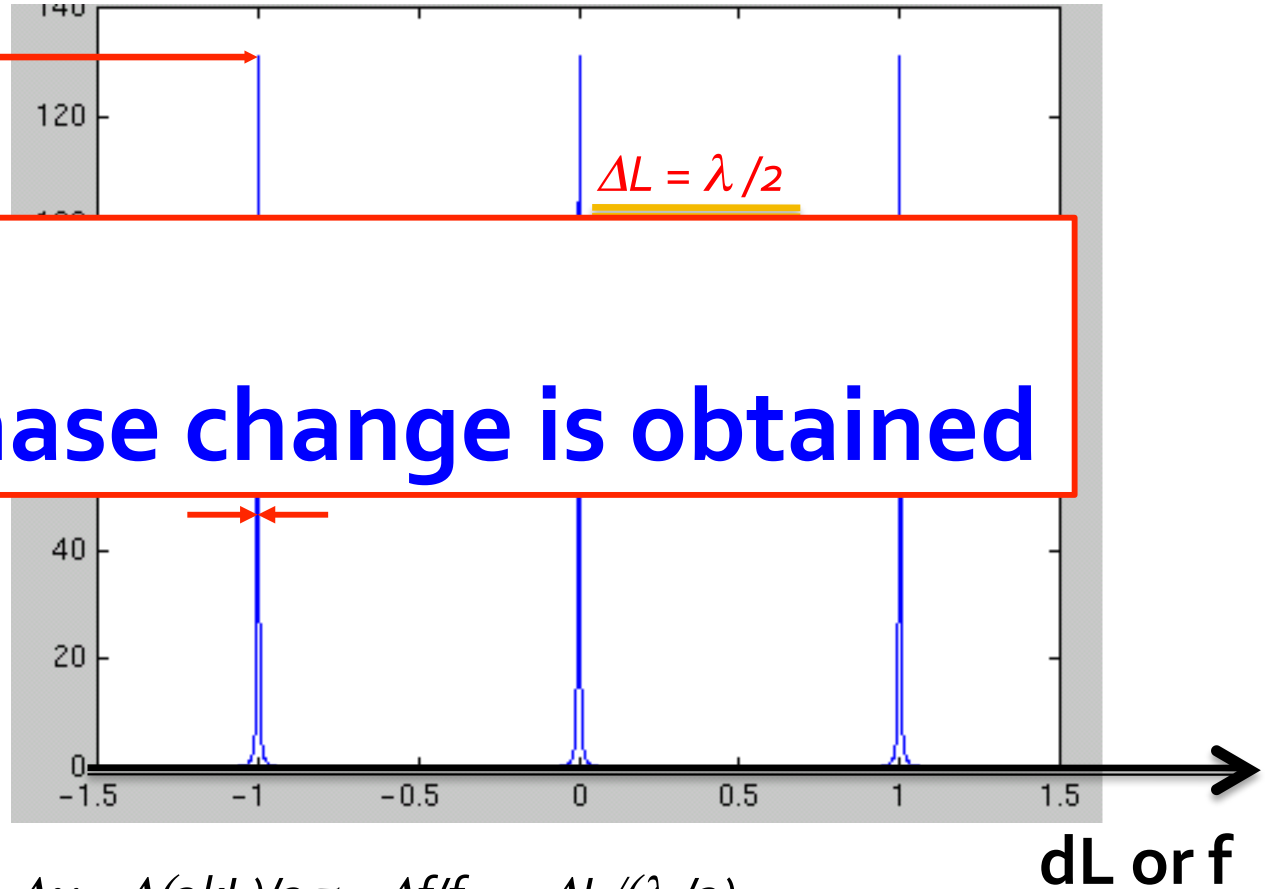
$$R_i + T_i + L_i = 1$$

When $2kL = n(2\pi)$, (ie, $L = n\lambda/2$),

E_{cir}, E_{tran} maximized $\Rightarrow$ resonance!

FP circulating field

Power Gain



Cavity:
a larger phase change is obtained

Free Spectral Range:
$f_{FSR} = c/2L$

Finesse $= \delta f / f_{fsr}$

$\Delta\nu = \Delta(2kL)/2\pi = \Delta f/f_{fsr} = \Delta L/(\lambda/2)$

$$F = \frac{\pi\sqrt{r1 \cdot r2}}{1 - r1 \cdot r2}$$

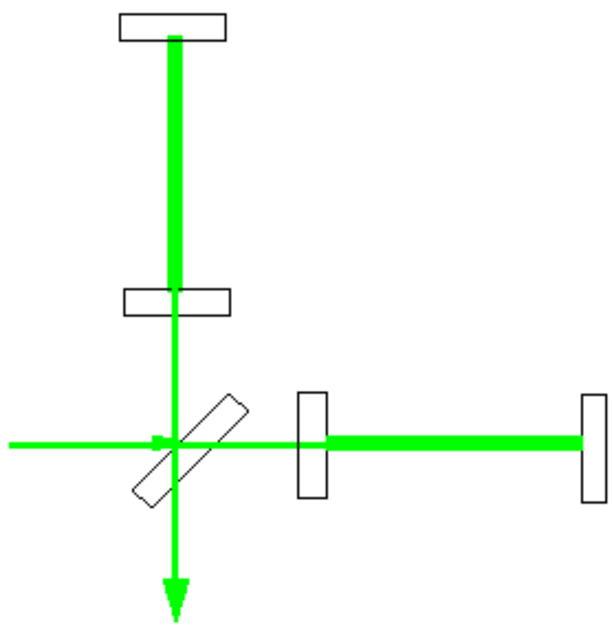
Phase enhancement factor N_{FP}=2F/Pi

Optical cavity

- How useful are the optical cavities?

- **FP arms:**

Enhance the phase change in the MI arm
= larger response to GWs

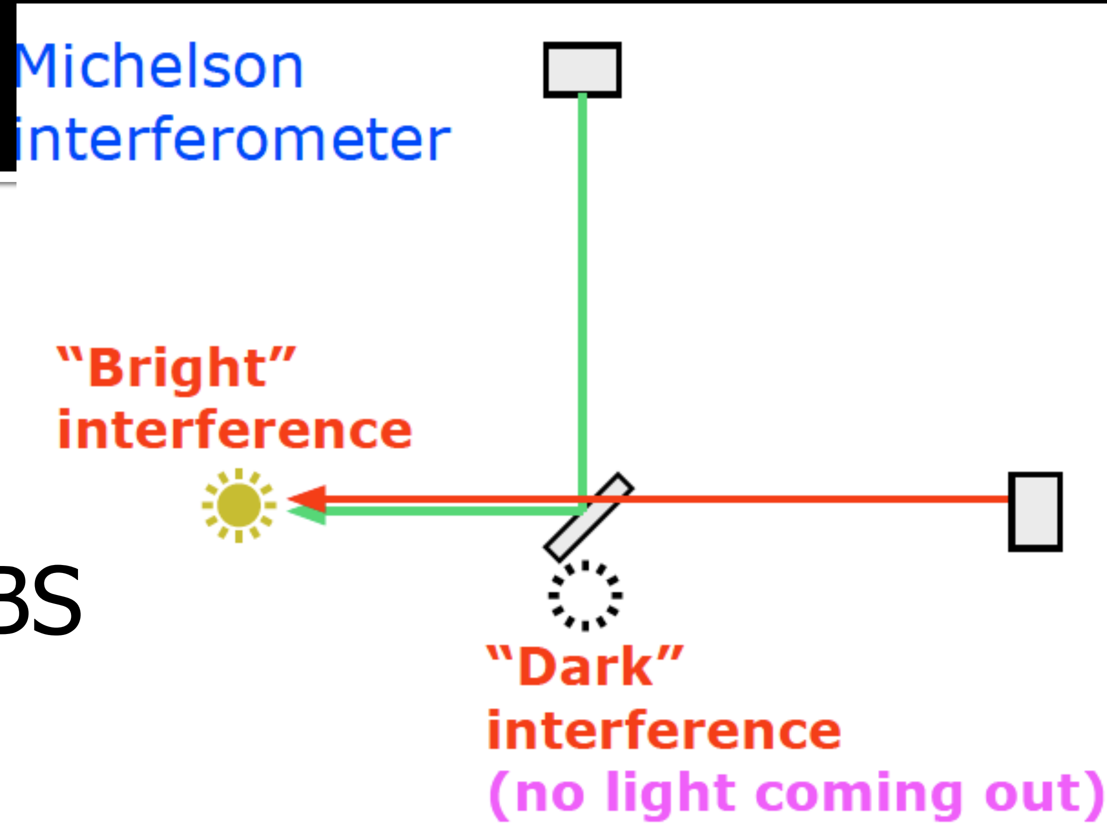


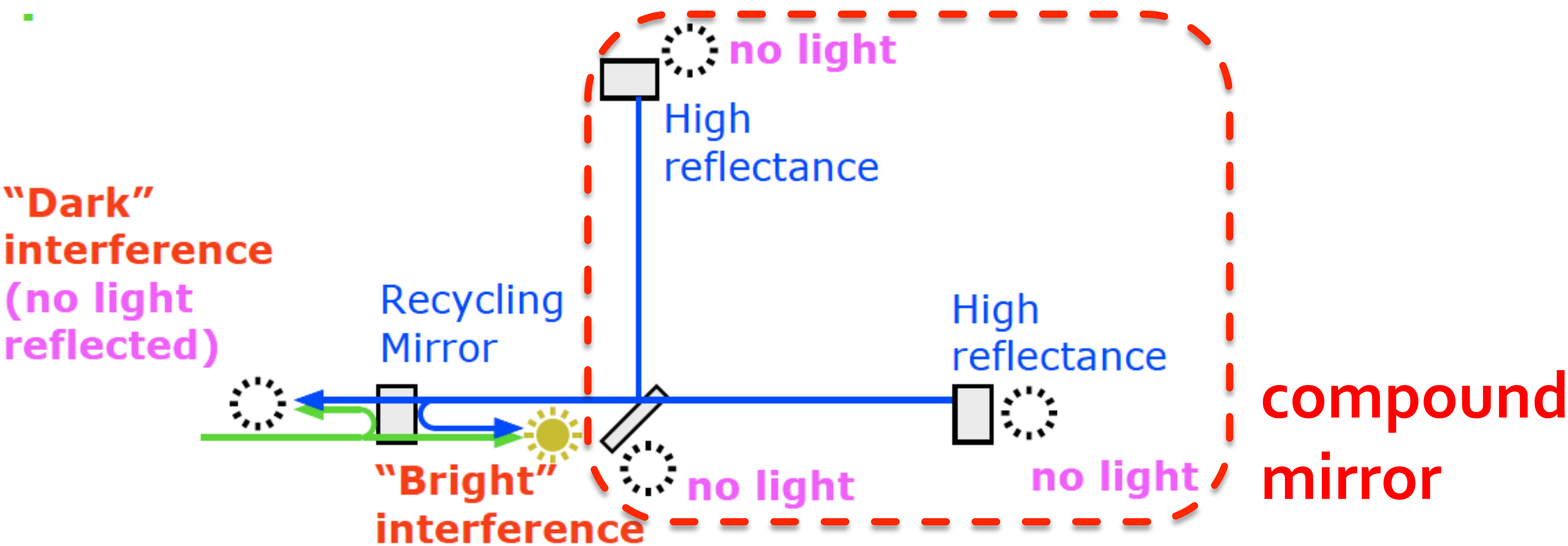
Fabry Perot interferometer

Optical cavity

- **Power recycling**

  Increase the light power towards the BS





Optical cavity

- **Freq Stabilization** (Mode Cleaner/Ref Cav)

$$\phi_{cav} = 4\pi Lf / c$$

Cavity length (L) and Laser freq (f) are equivalent
=>**Use L as a reference of f**

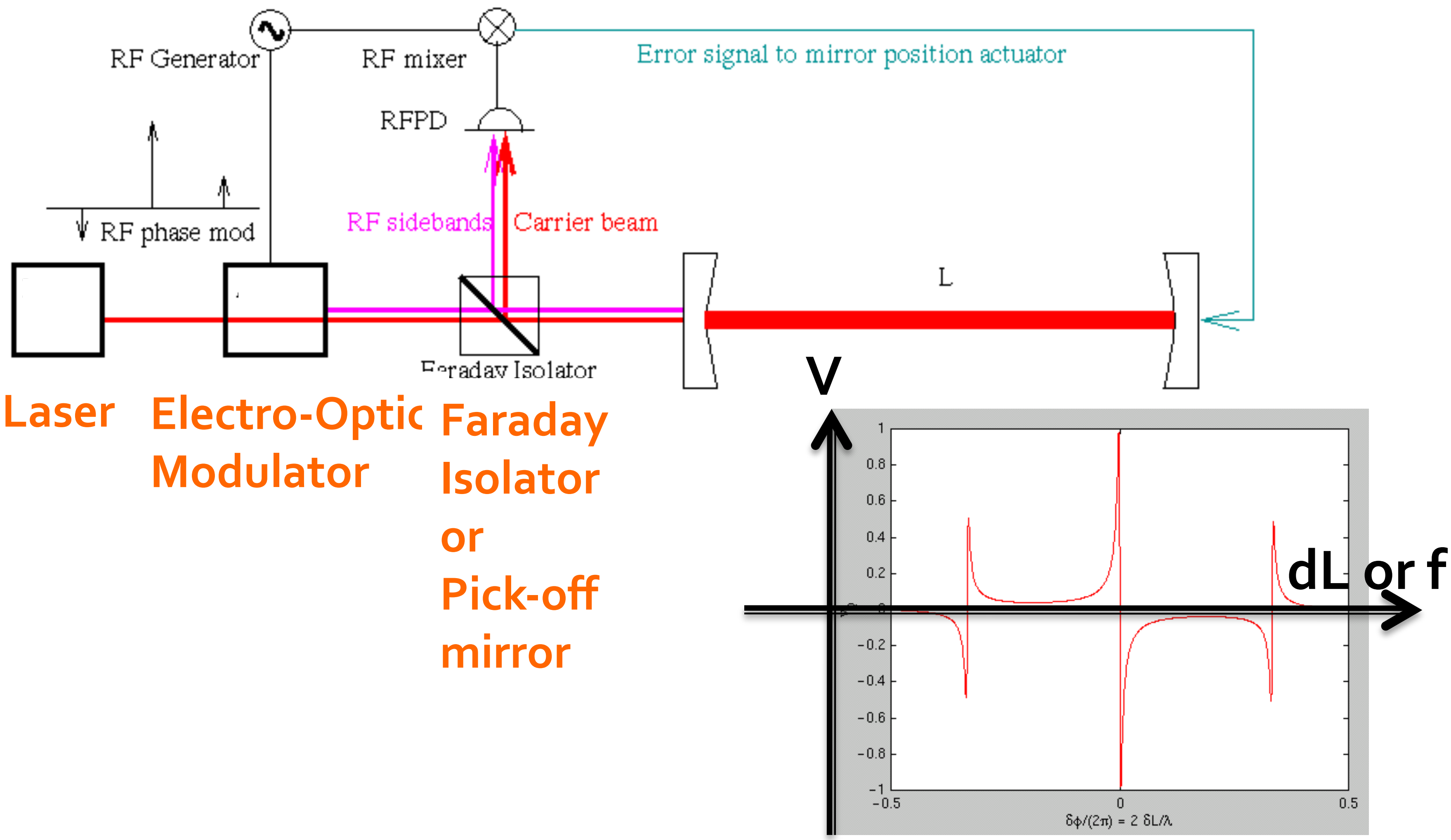
$$\frac{dL}{L} = \frac{df}{f}$$

e.g.
dL~1pm, L~0.1m
=> freq stability of 10^{-11} (df=3kHz for f~300THz)

- **Spacial mode filtering**
- **Signal Recycling**

Pound-Drever-Hall technique (PDH)

- **Signal extraction scheme for the cavities**
  - Phase modulation -> RF optical sidebands
  - Reflected beam -> detected / demodulated



Summary

- Interferometer is a sensitive device
  - Because we are reading the phase of the light
- Optical cavity is more sensitive
  - Because the phase change is enhanced by the cavity
- Optical cavities are useful!
- The PDH technique

Sensing & Control

Sensing and Control

- Feedback controls are a common technique in the instruments and measurements

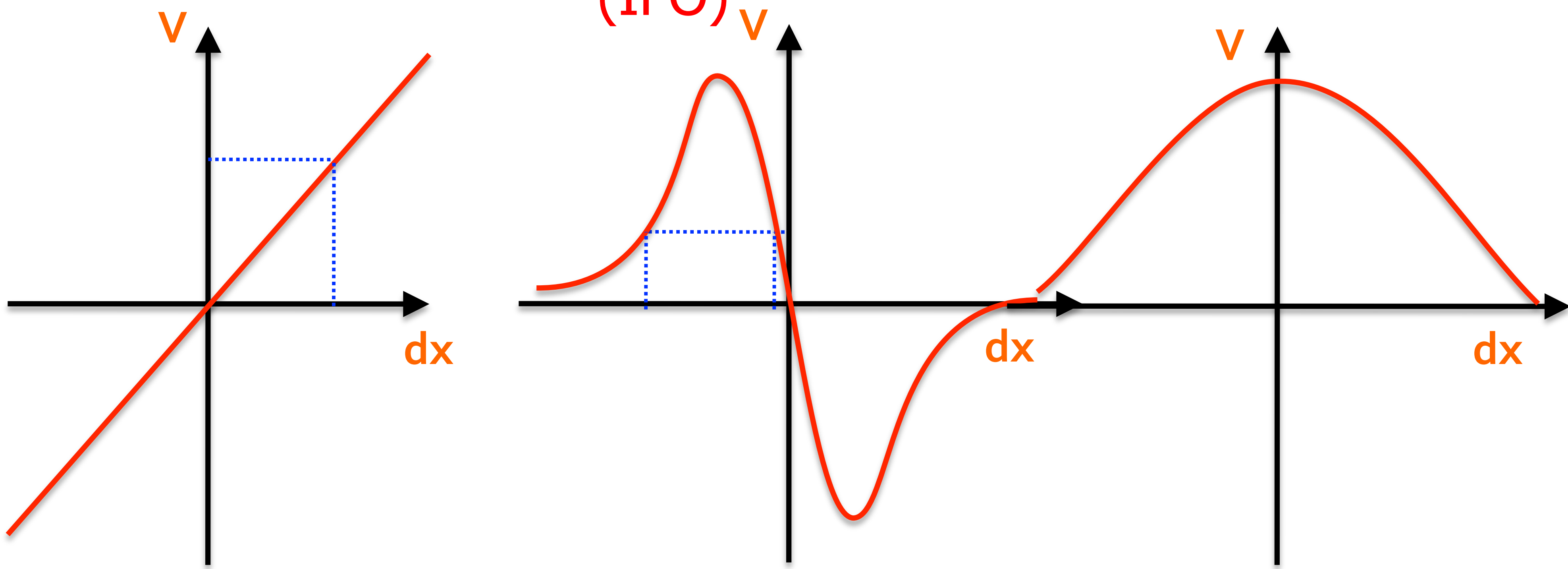
- For high sensitivity, we use interferometry.
  The response of the interferometers are nonlinear
  Michelson: moderately
  Fabry-Perot: highly nonlinear

- **Presence of seismic disturbance**
  We need to control the mirror positions

Sensor

- A sensor is an instrument to convert a physical quantity to a signal --- mostly a voltage signal

- linear sensor   nonlinear sensor (IFO)   (almost) useless

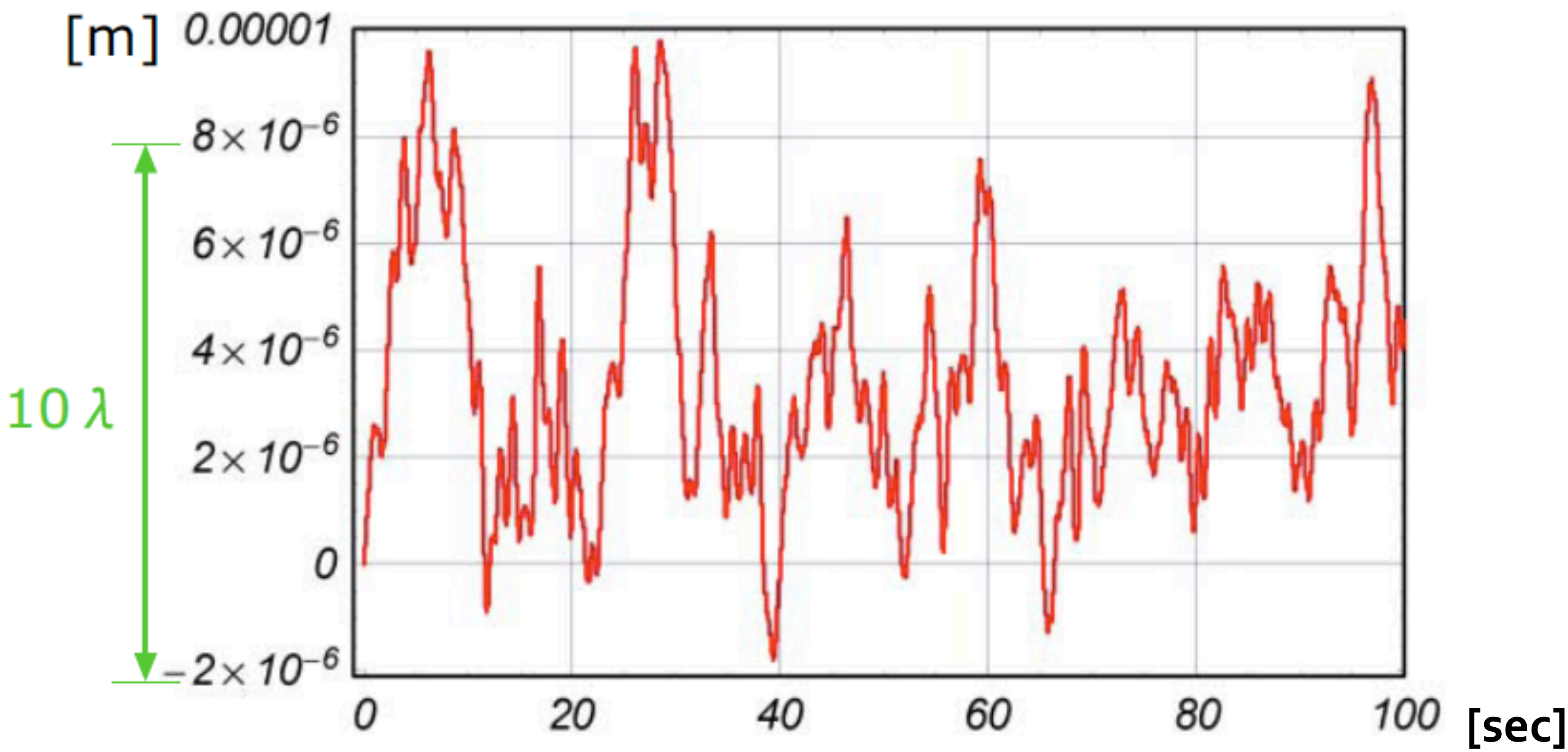


No control needed

control needed

Mirror motion

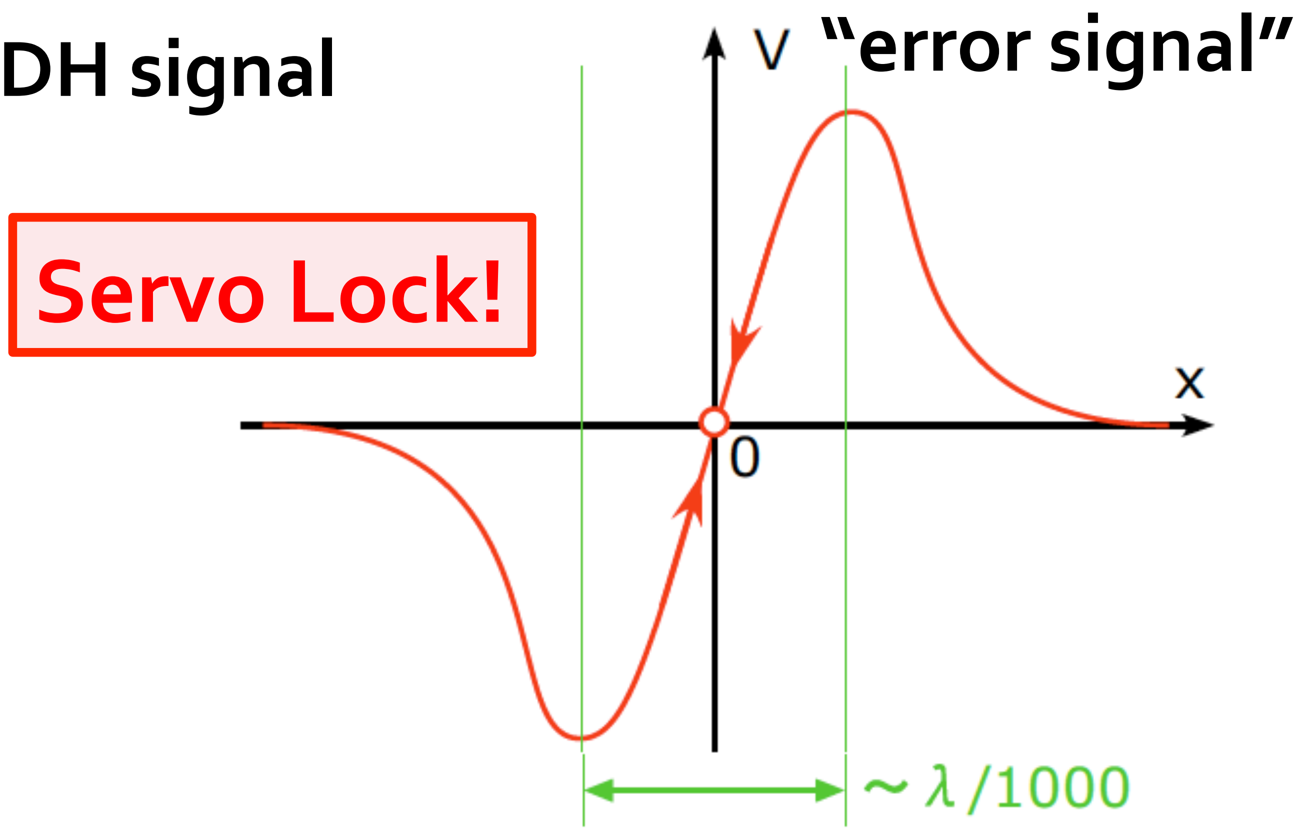
- The mirrors of the interferometer is suspended
- At low frequency (f<1Hz), the vibration isolation is not effective
- Mirror swings an order of lambda (~um)



Asymptotically Linear Sensor

- Nonlinear sensor can also be used as a linear sensor by utilizing feedback control

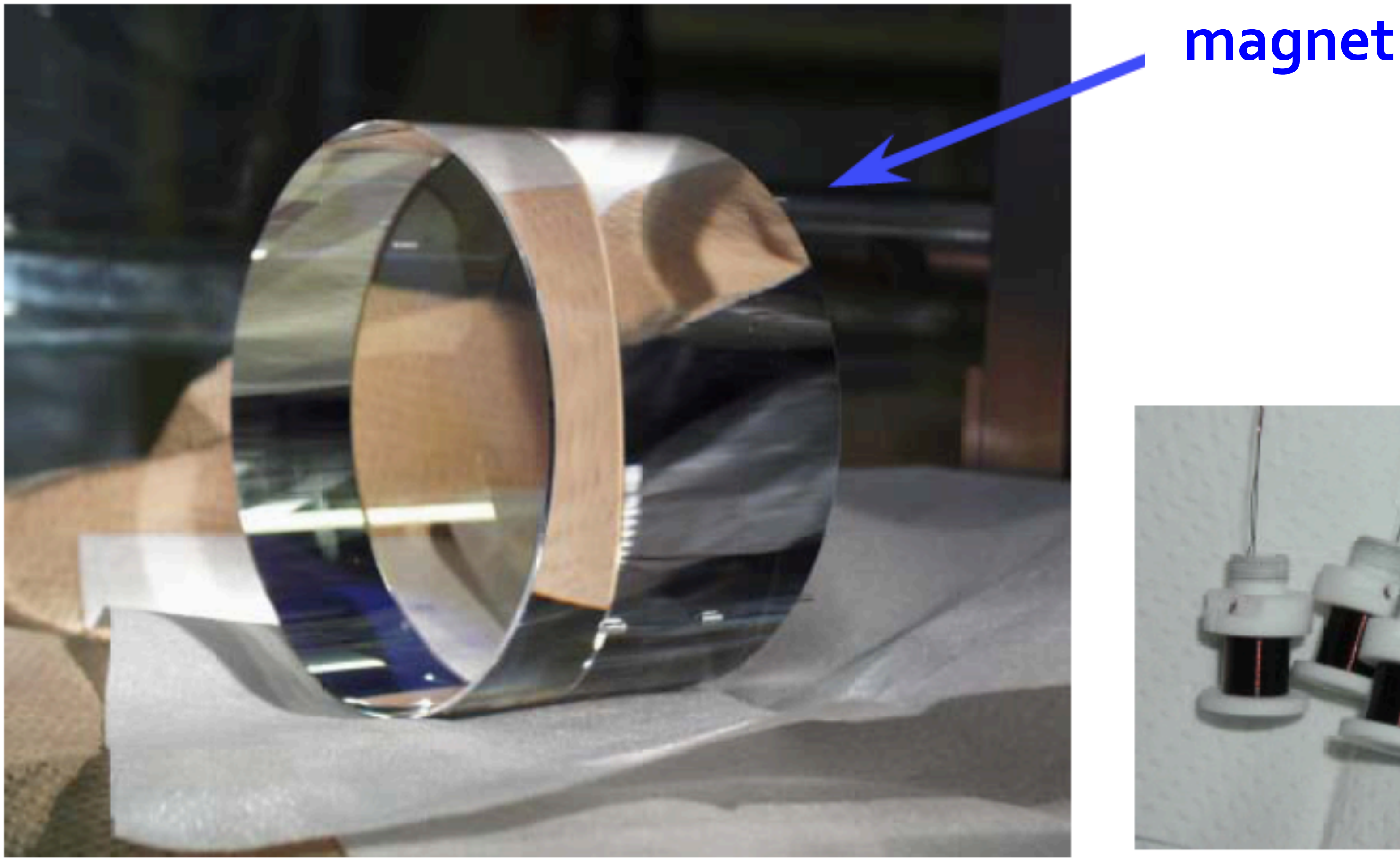
e.g. PDH signal



- The IFO is locked at its most sensitive state

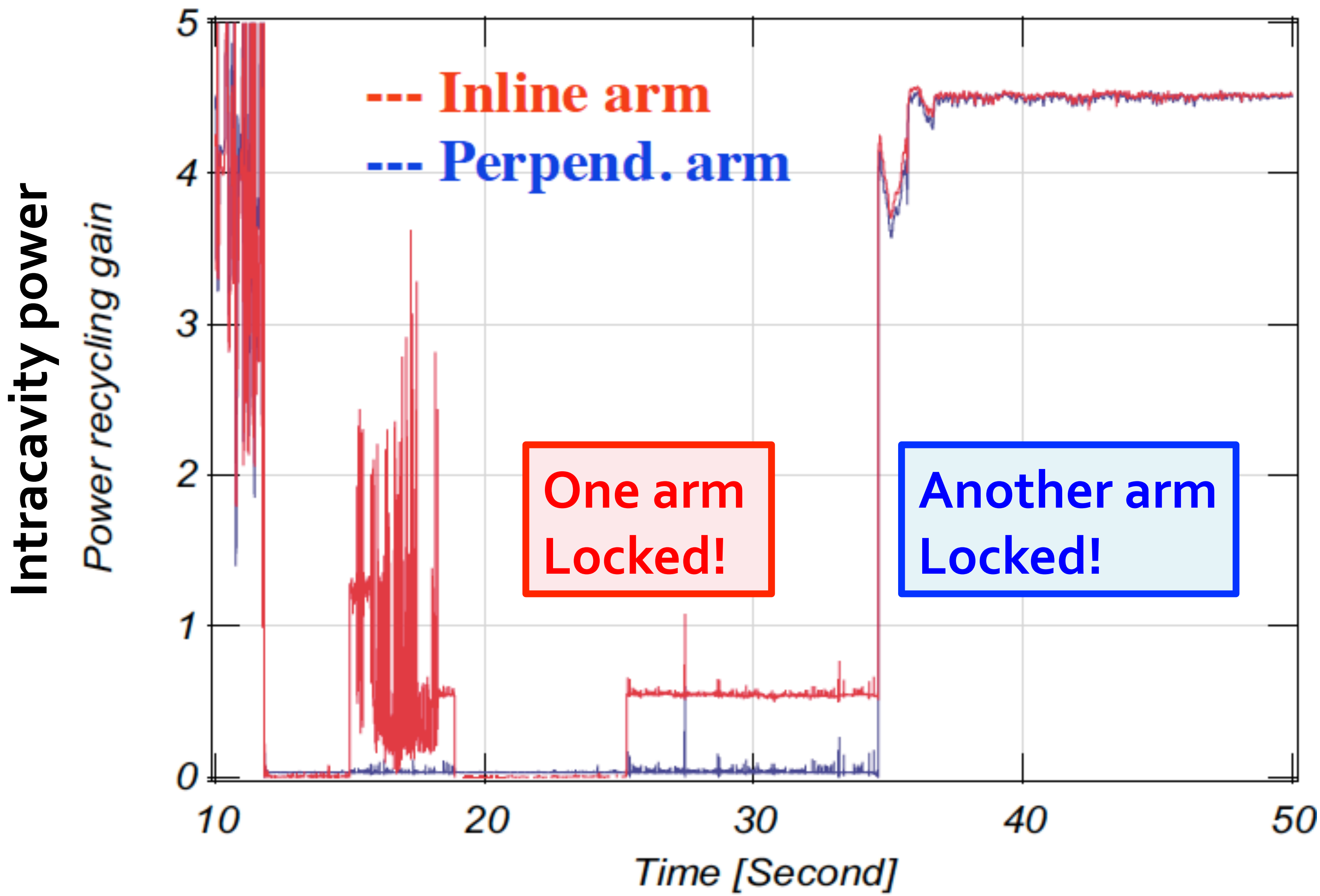
Actuators

- In particular for the current GW IFO case, **coil-magnet pairs** are used to actuate the position and angles of the mirrors



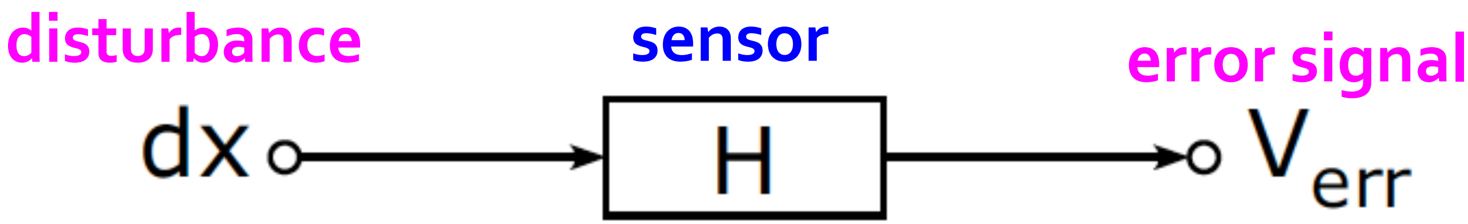
Lock Acqusition

- The moment of lock acquisition



Block diagram

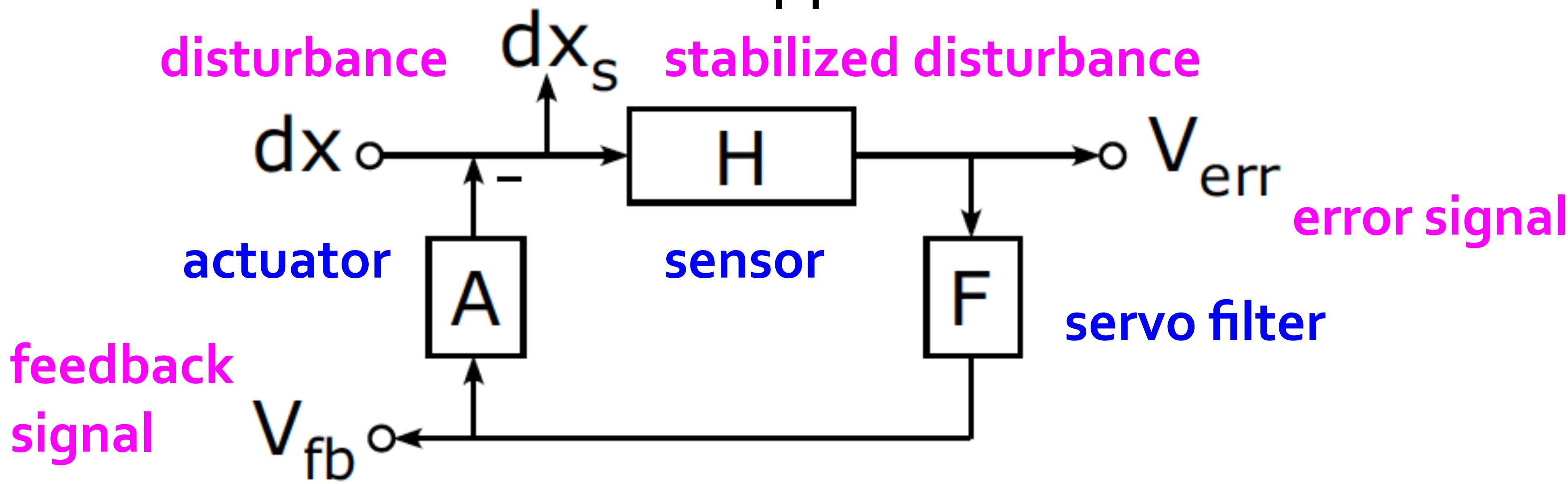
- If the sensor is linear we don't need feedback



Verr = H dx
i.e. dx = Verr / H

Block diagram

- When the feedback is applied:



$$dx_s = dx - G\,dx_s$$

$$\Rightarrow dx_s = dx \,/\, (1+G)$$

$$\Rightarrow dx = V_{err} \;\; (1+G) \,/\, H$$

$$dx = V_{fb}\, A\, (1+G) \,/\, G$$

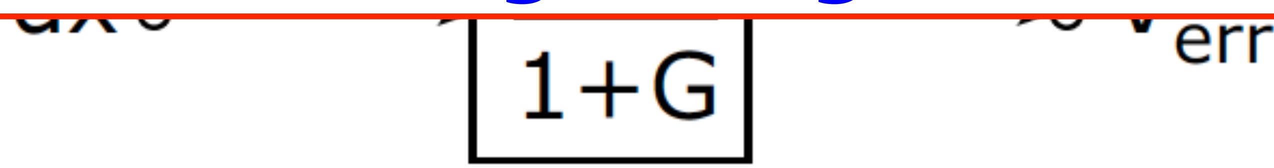
Open loop transfer function

$$G \stackrel{\text{def}}{=} H\, F\, A$$

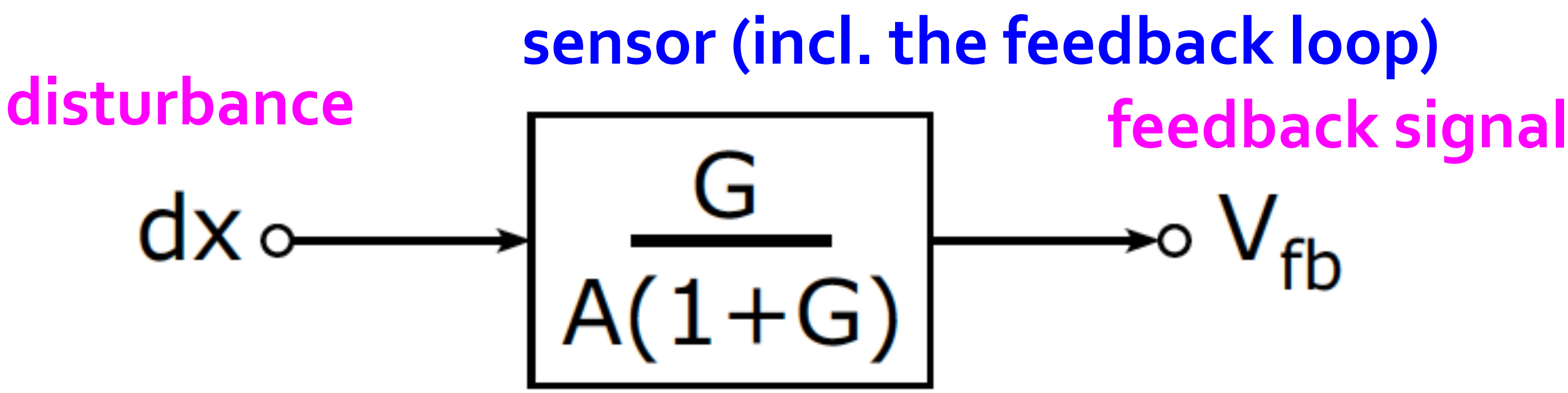
Effect of a feedback to the signals

the size of the signal depends on the fb gain (G)

G<<1 the error signal is good
G>>1 the fb signal is good



- Response with feedback (feedback signal)



For stable feedback control

stabilized

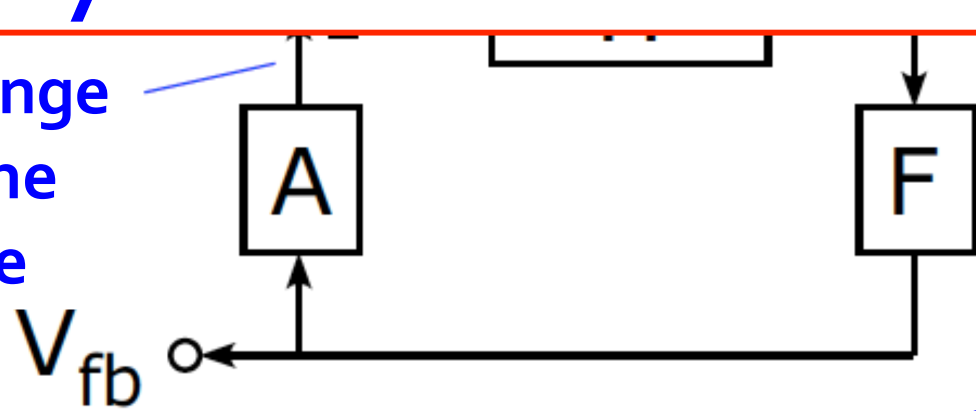
linear range
to accomodate

Modeling of a control loop helps you

signal

distu

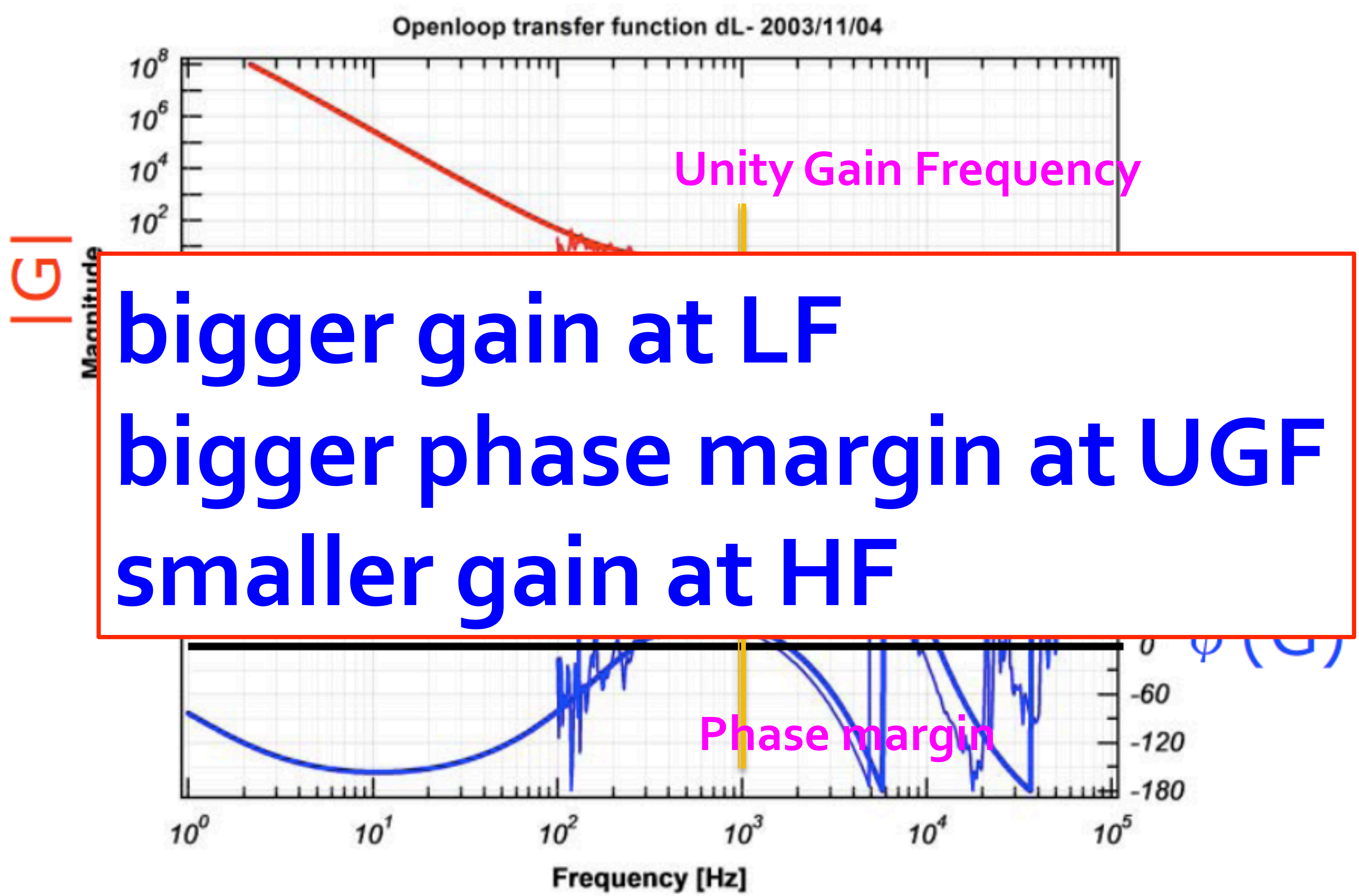
actuator range
to cancel the
disturbance



feedback
signal

servo filter
shape based on
a control theory

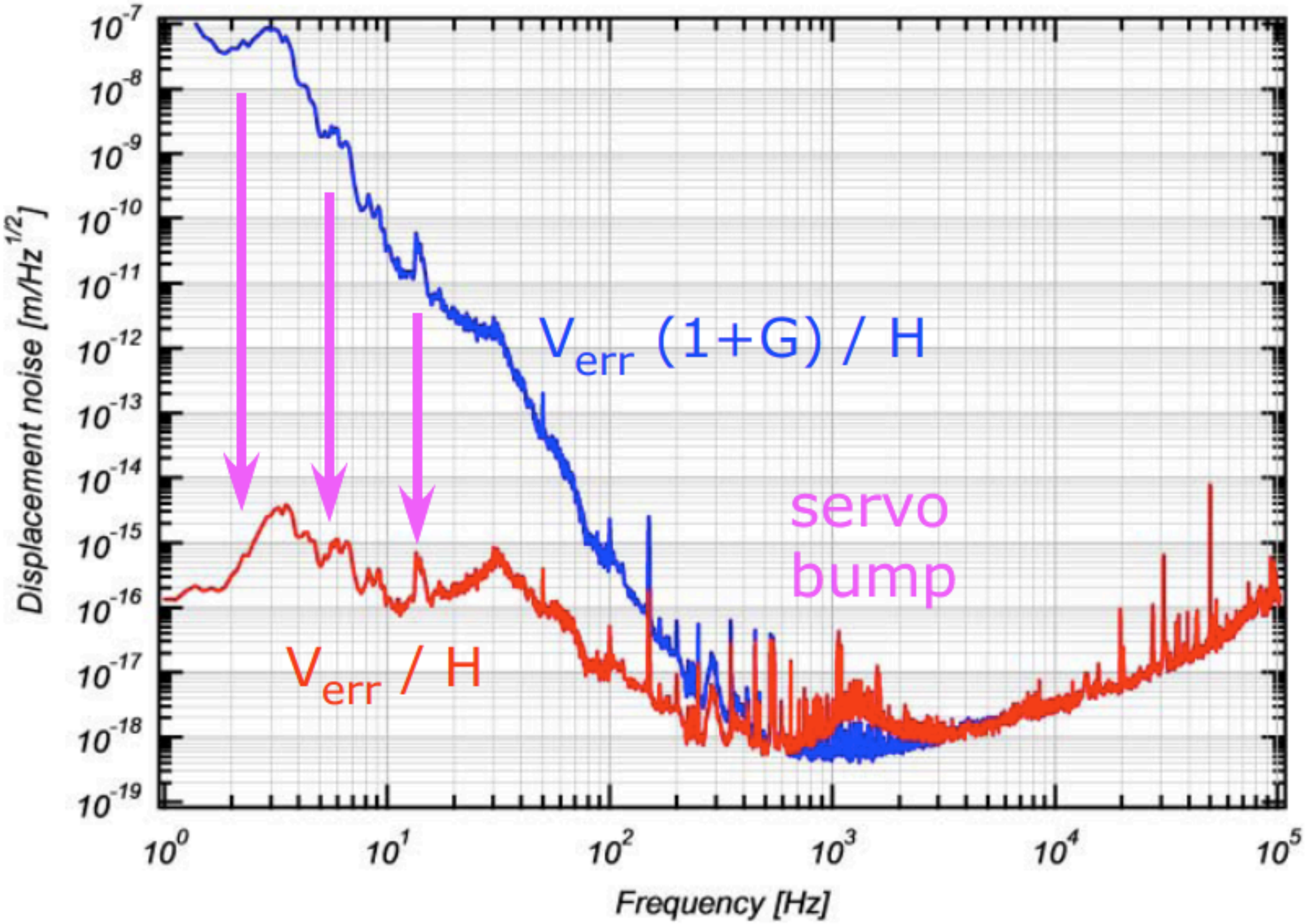
Example of an open loop TF



bigger gain at LF
bigger phase margin at UGF
smaller gain at HF

Supression of the error signal

- By knowing H, A, F, we can reproduce the original disturbance level



Summary

- With feedback control, we can treat a nonlinear system as a linear system
- **Feedback control is the key** for GW interferometers to keep their performance
- An openloop transfer function is to be designed in each case.
- Feedback control changes the signals from the system. Modeling always helps to understand how the original signals are.