Detection of 10^{-21} strain of space-time with an optical interferometer

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Acknowledgment

- National Science Foundation
- Louisiana Board of Regents
- LIGO* Livingston Observatory
- LIGO Scientific Collaboration
- Southeastern Louisiana University

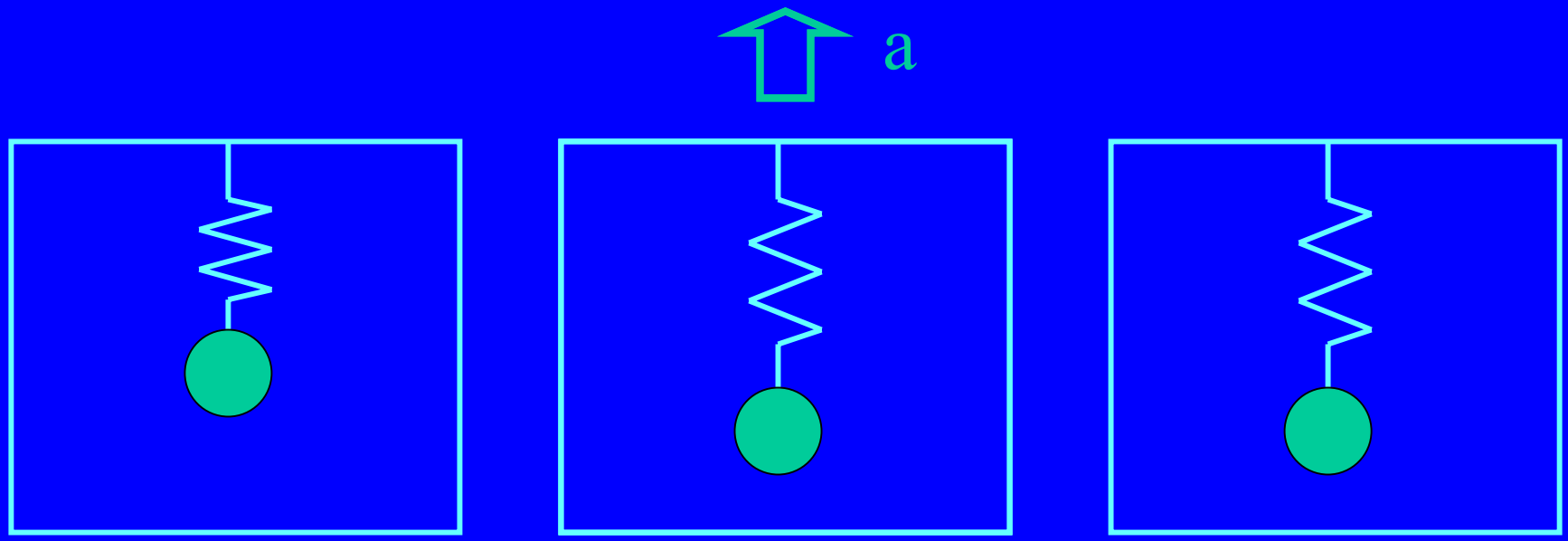
*LIGO: Laser Interferometer Gravitational-wave Observatory

Contents of talk

1. Gravitational wave?
2. LIGO I* detector overview
3. Technical issues
   - Suspended optics and local damping
   - Length sensing control and signal readout
   - Other control systems

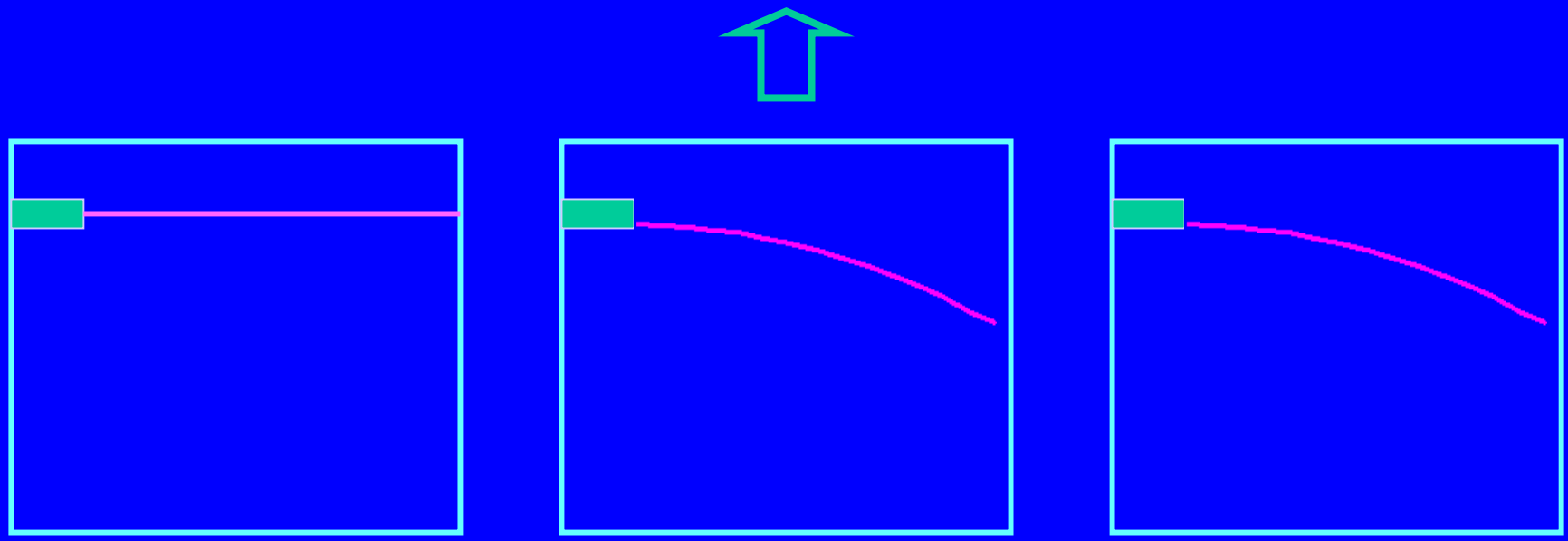
•First generation of LIGO detector
www.ligo.caltech.edu

General relativity (1)



Acceleration ⇔ Gravity

General relativity (2)

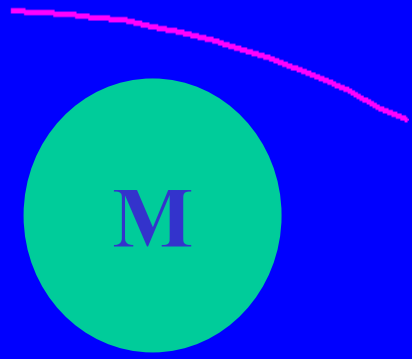


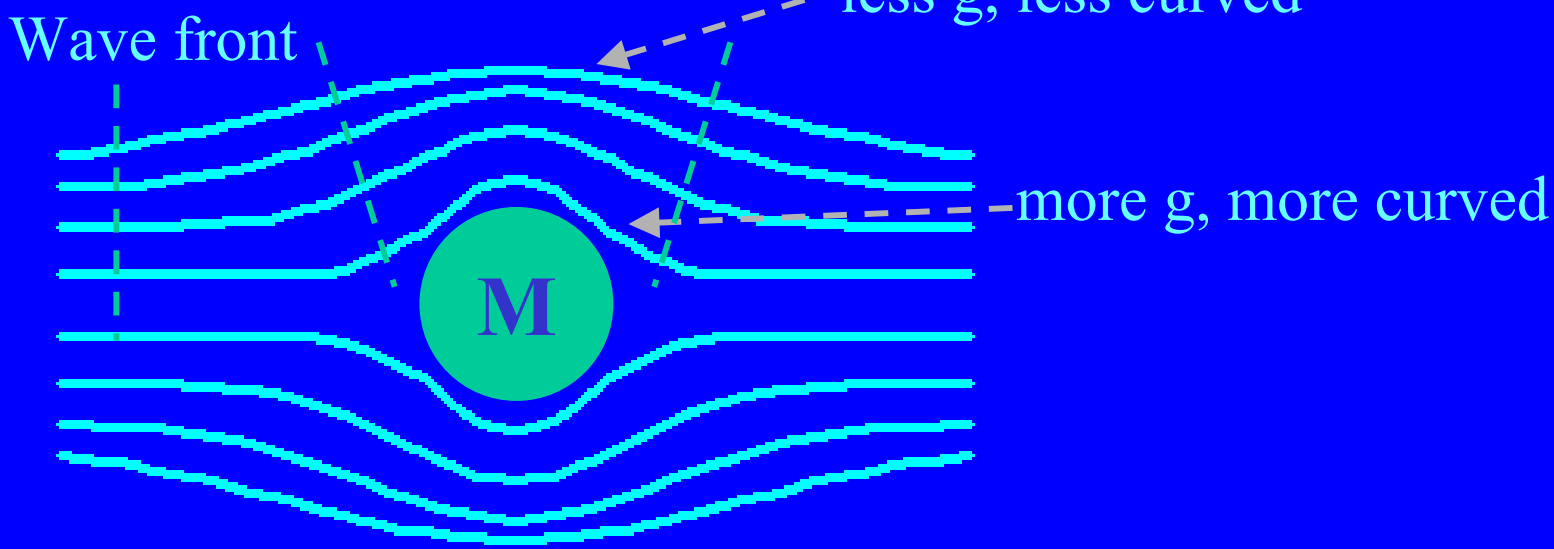
Acceleration ⇔ Gravity

M

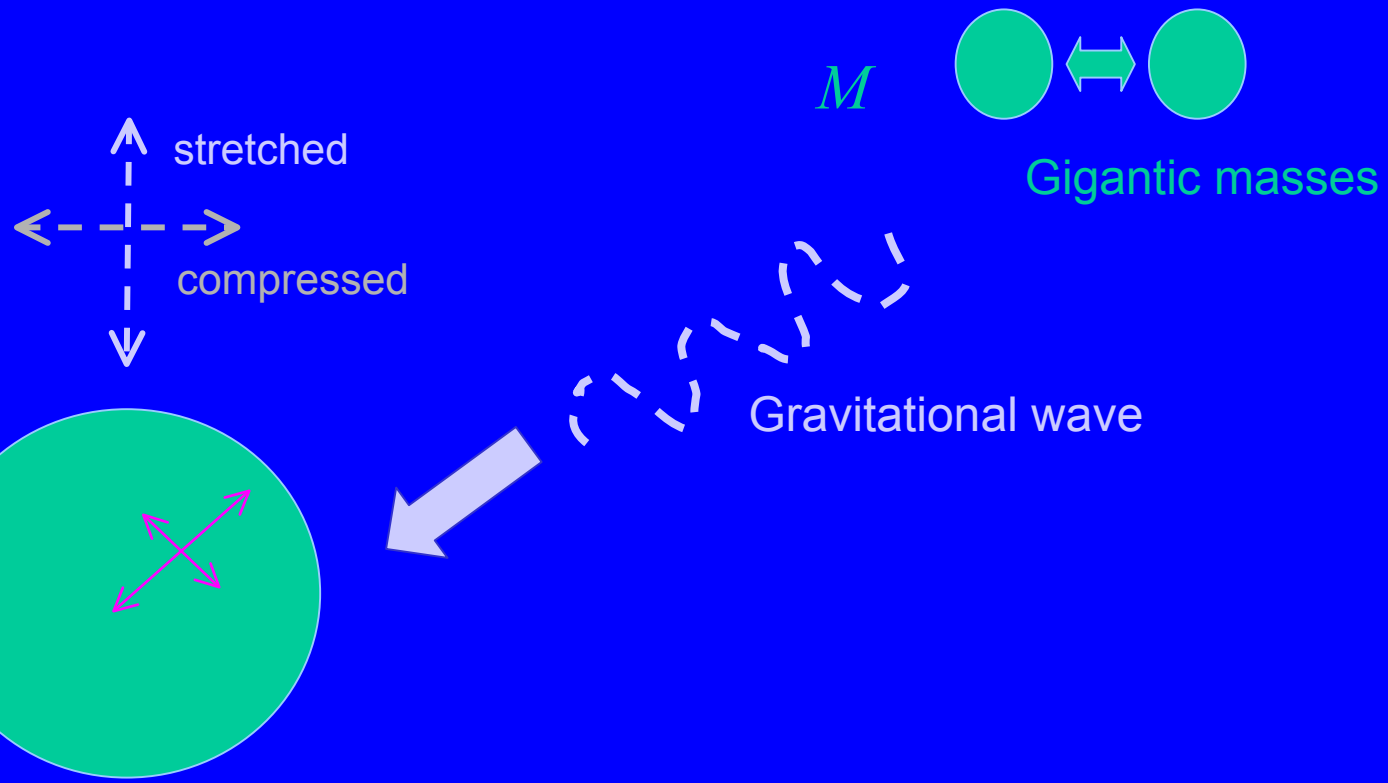
General relativity (3)

Gravity curves space-time

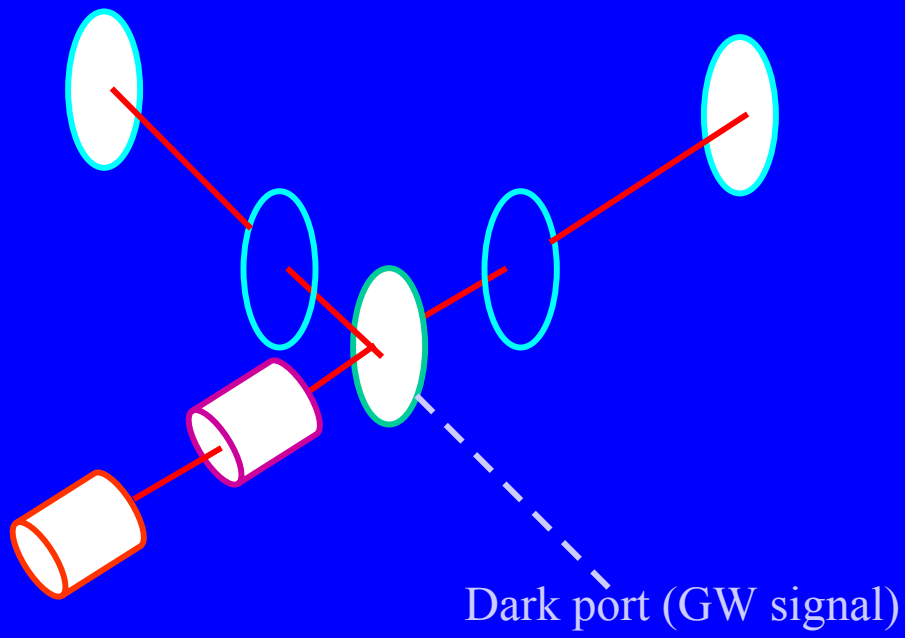




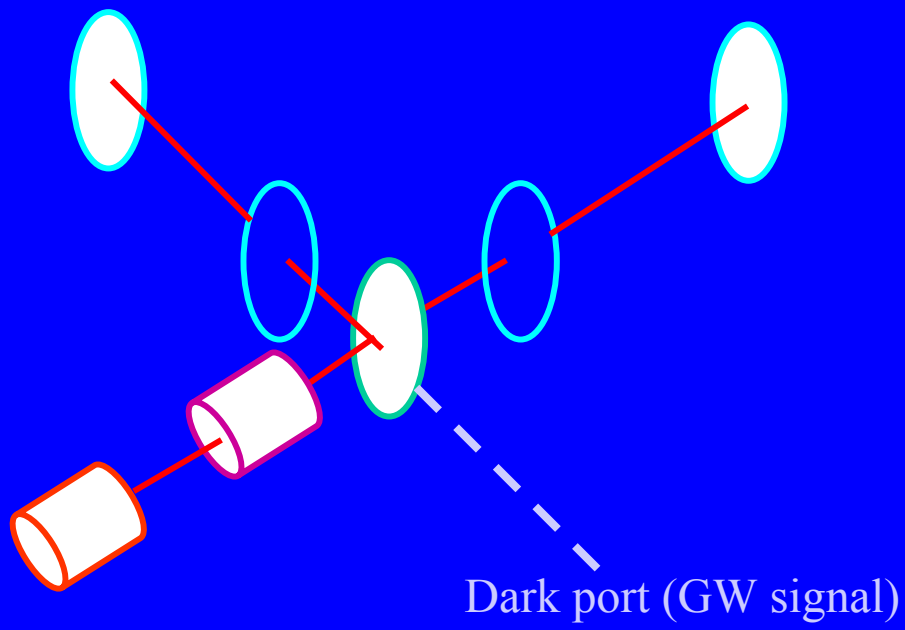
Conceptual picture of gravitational wave's propagation



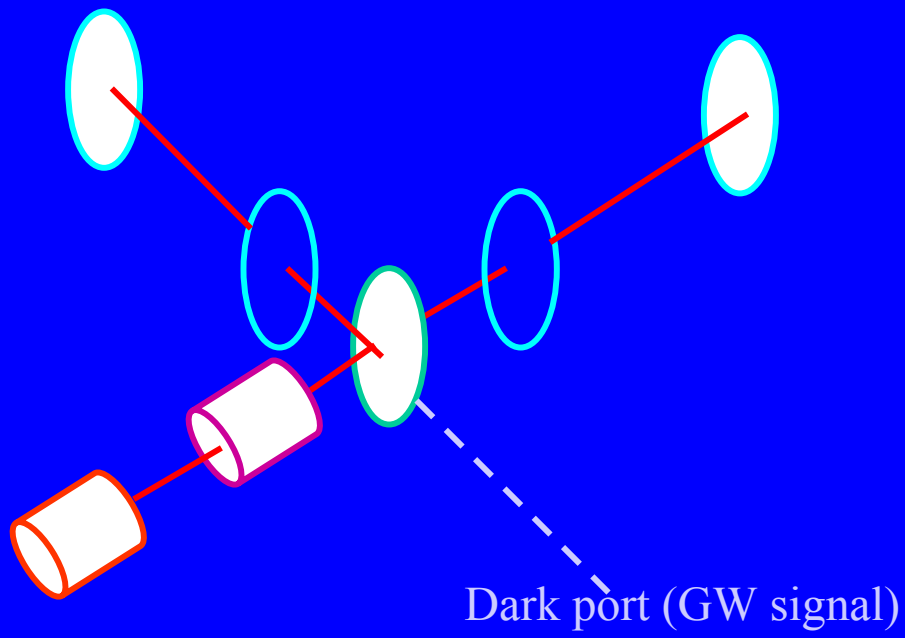
Gravitational Wave detection



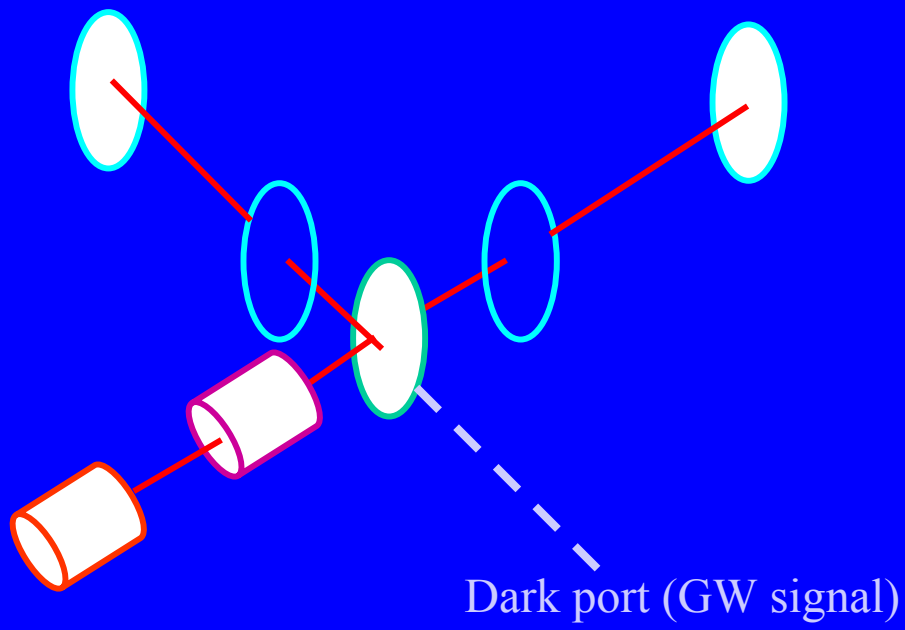
Gravitational Wave detection



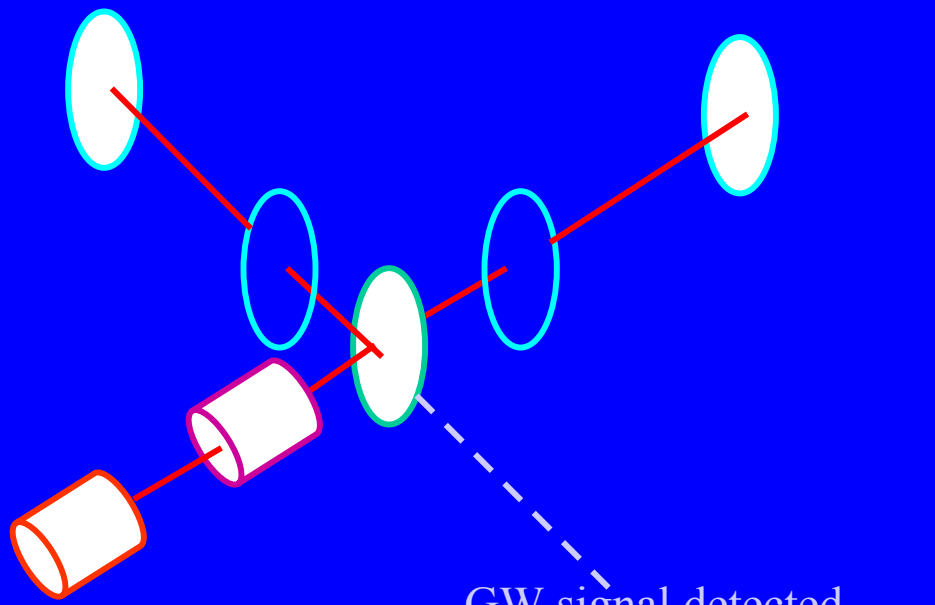
Gravitational Wave detection



Gravitational Wave detection



Gravitational Wave detection



Schematic illustration of relative phase difference

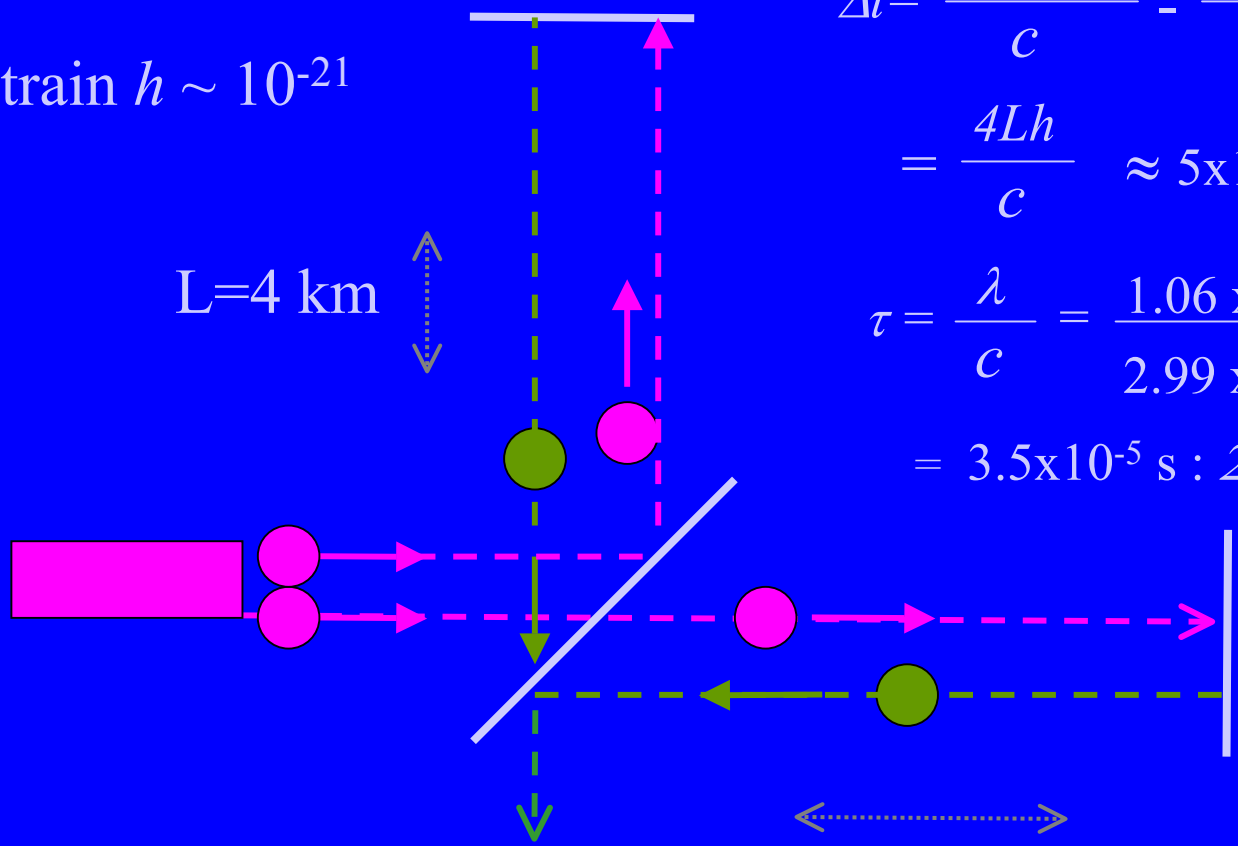
Space strain $h \sim 10^{-21}$

$$\Delta t = \frac{2L(1+h)}{c} - \frac{2L(1-h)}{c}$$

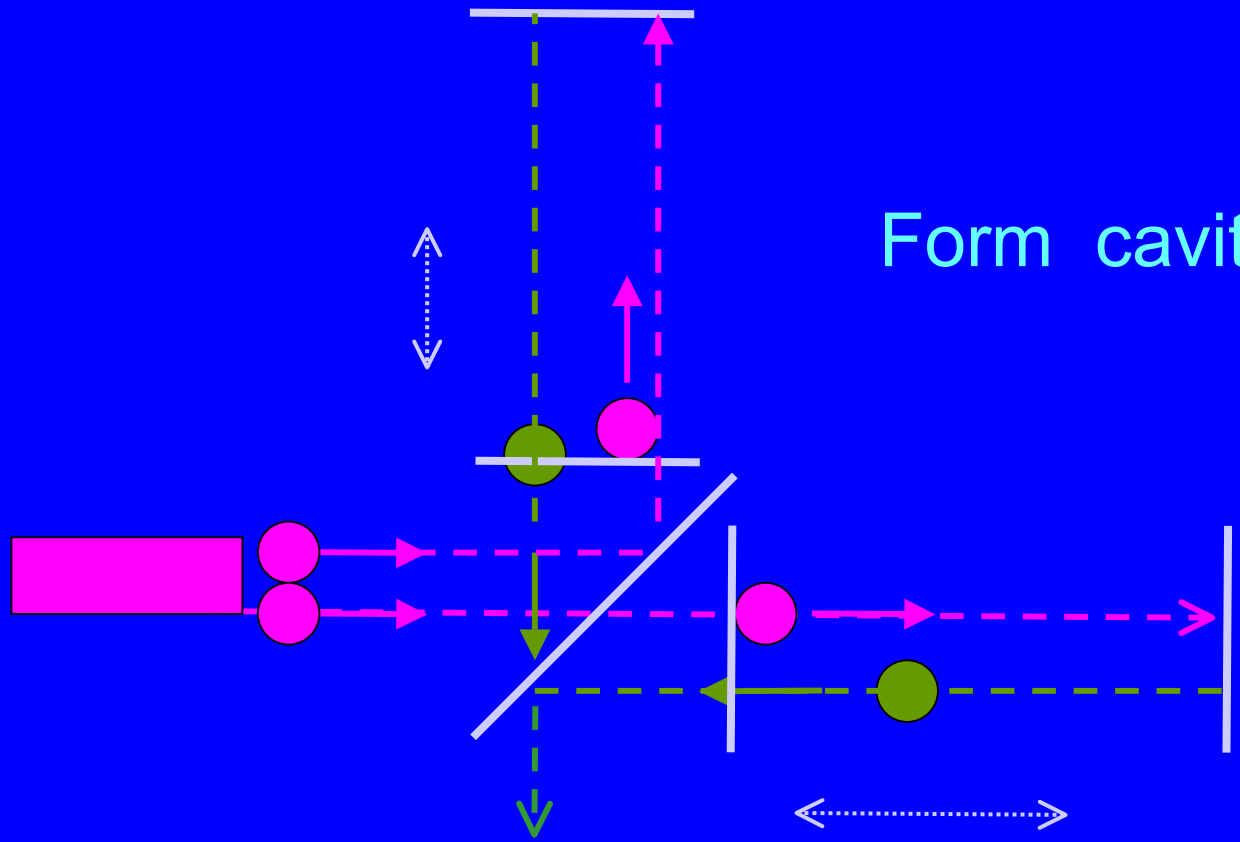
$$= \frac{4Lh}{c} \approx 5\text{x}10^{-26}\ \text{s} : \Delta\phi$$

$$\tau = \frac{\lambda}{c} = \frac{1.06\ \text{x}10^{-6}}{2.99\ \text{x}10^{8}}$$

$$= 3.5\text{x}10^{-5}\ \text{s} : 2\pi$$

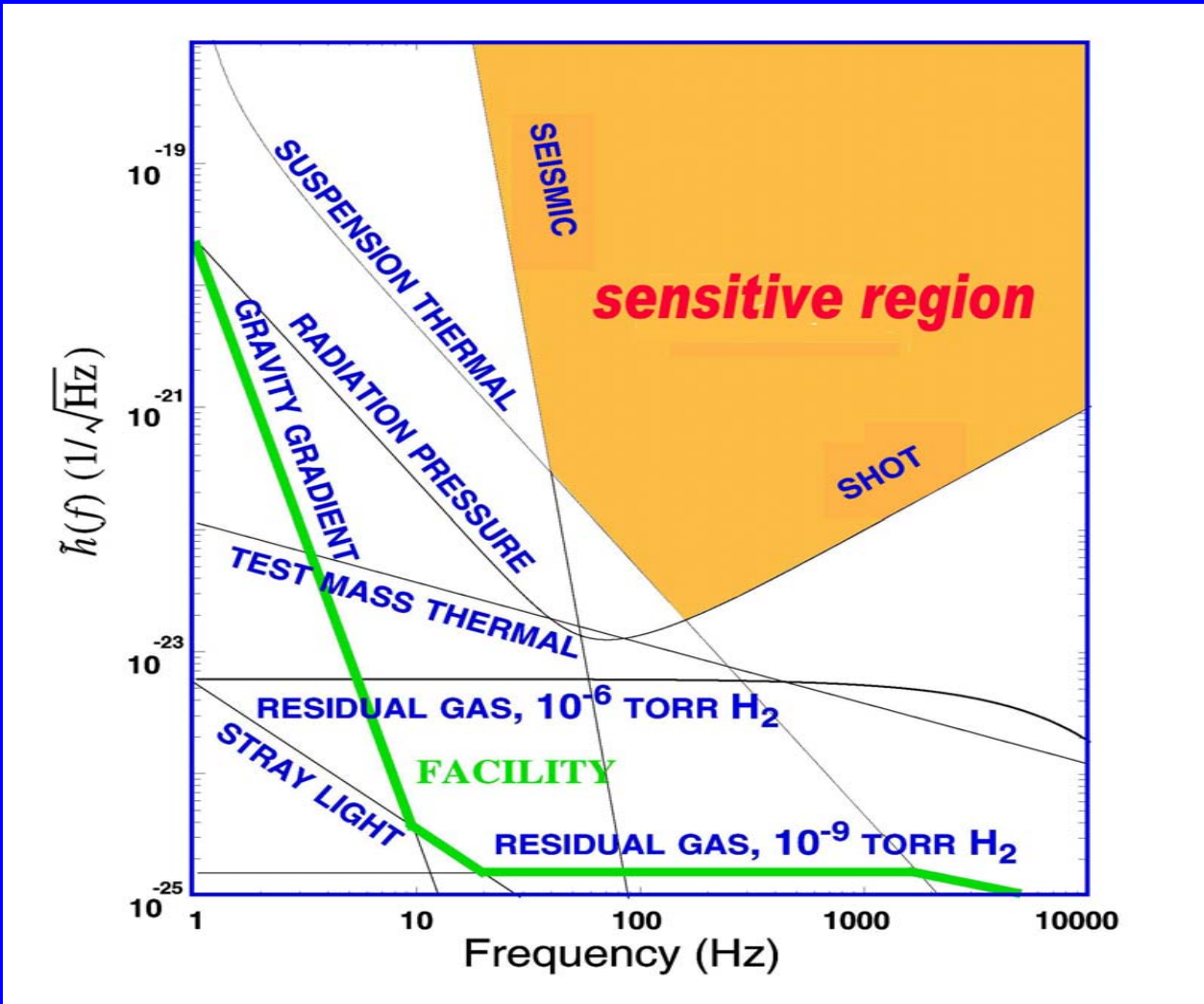


Need to increase L!



Form cavities

Make it quiet at GW signal frequency

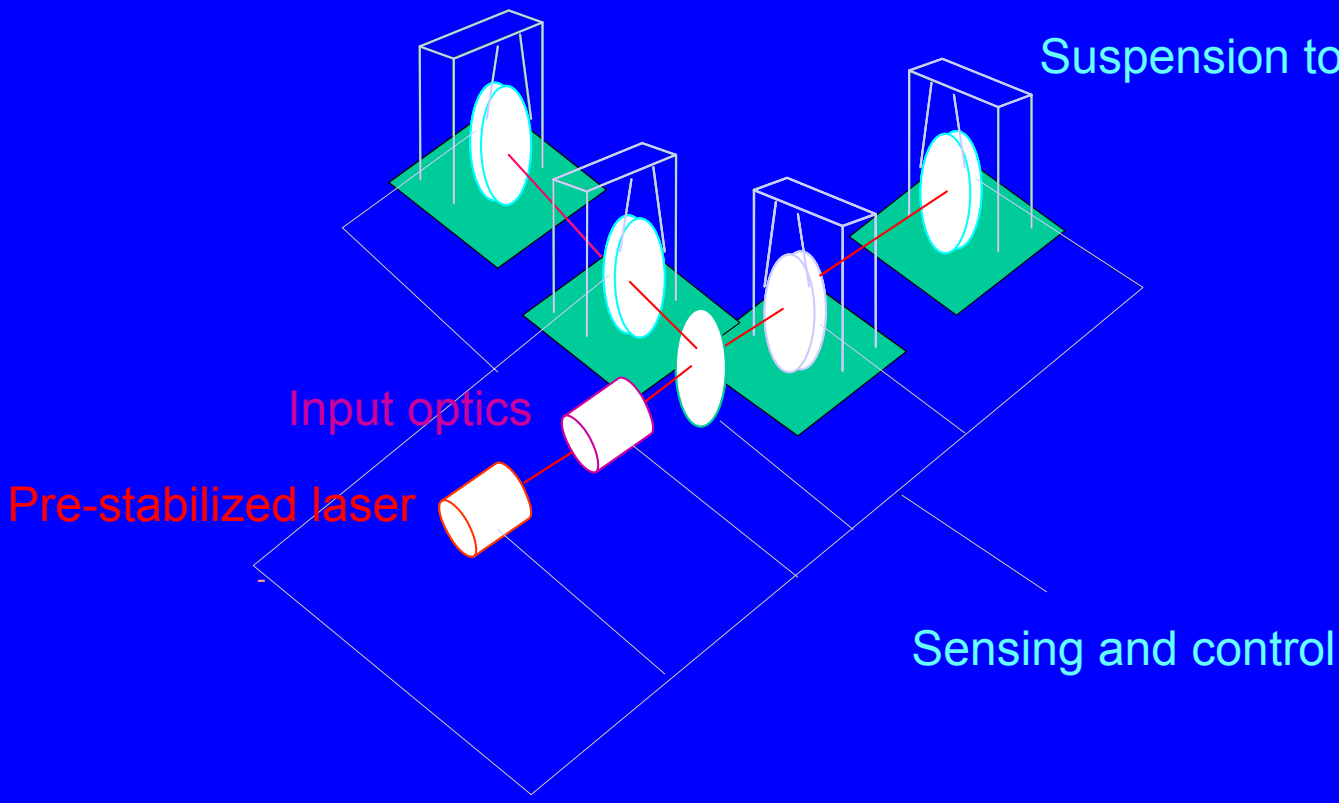


B. Barish, .LIGO-G030535-00-M

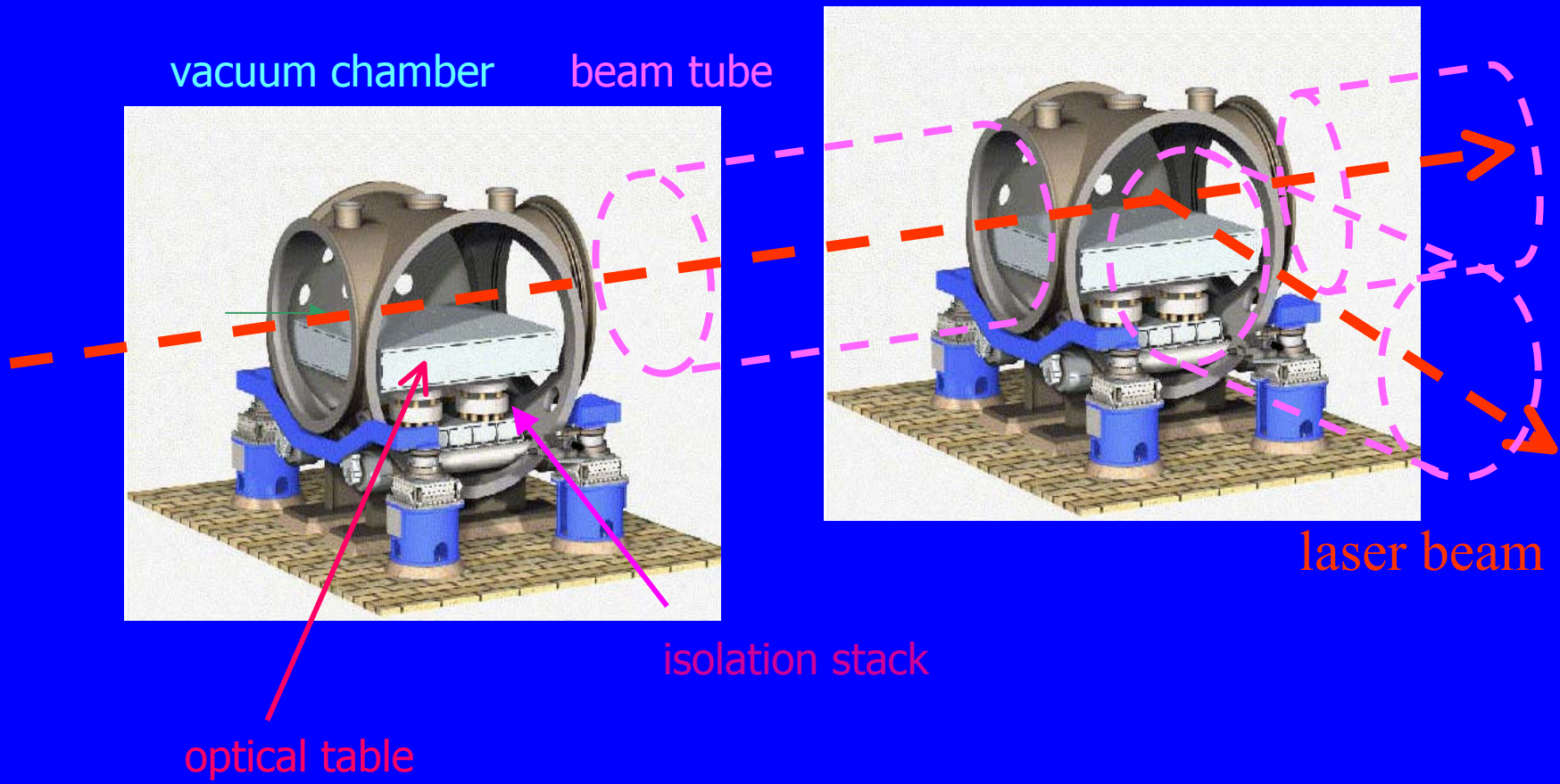
Limited by:

Seismic noise (low ν), Thermal Noise (middle ν), Shot Noise (high ν)

Schematic view of LIGO I interferometer



Suspended optics on optical tables

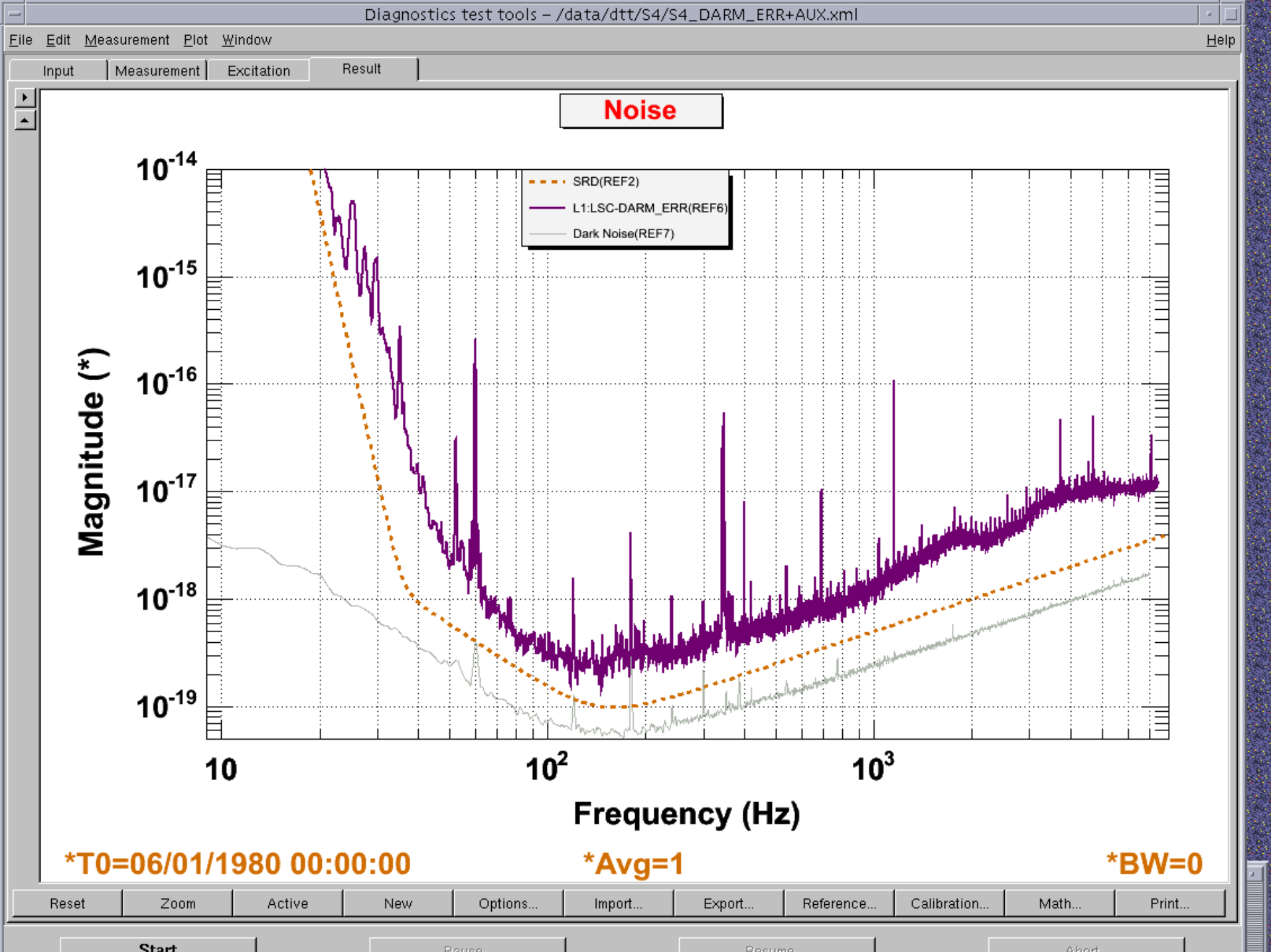


LIGO Hanford WA

LIGO Livingston LA

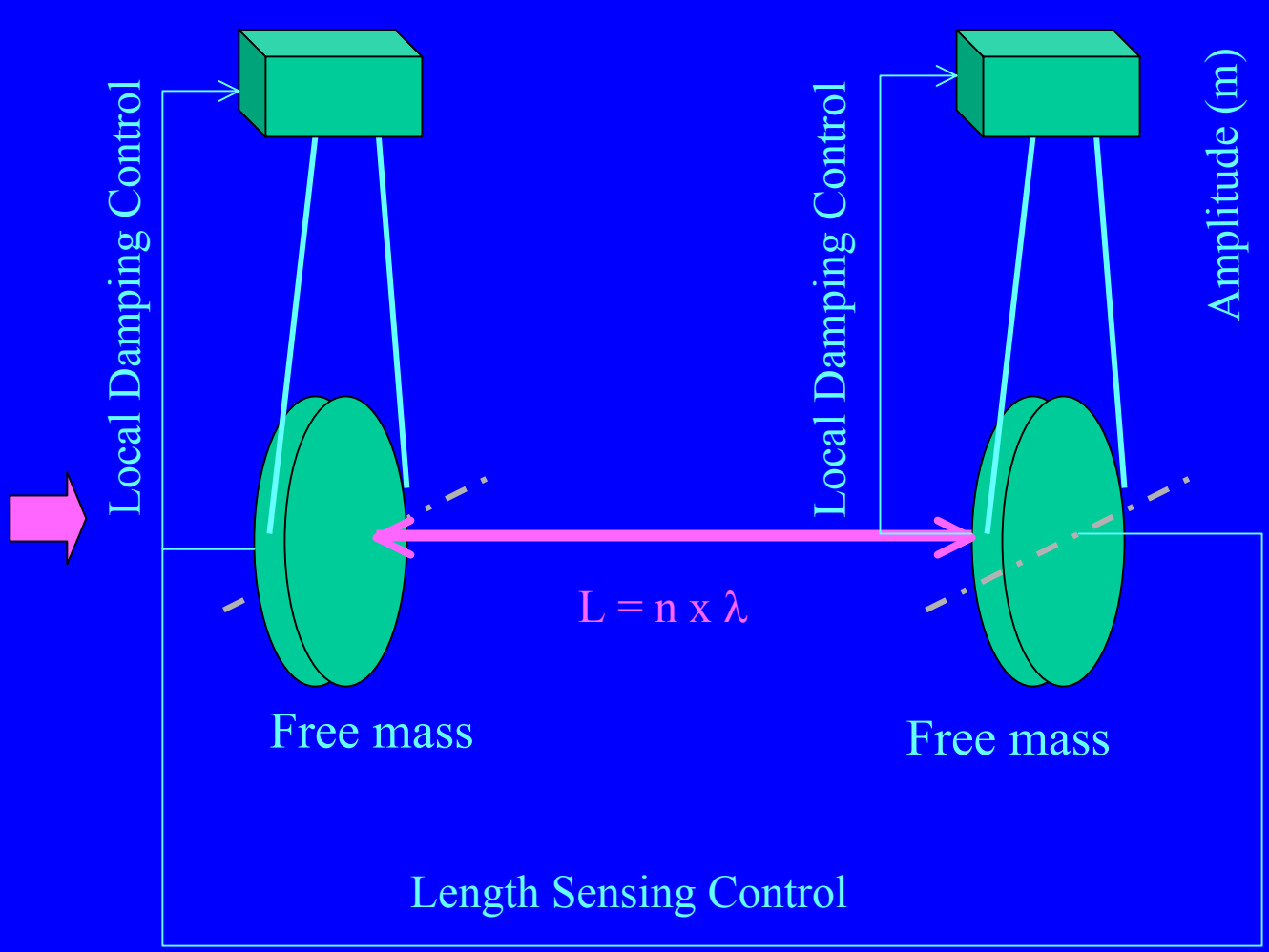
Horizontally accessible module (HAM)

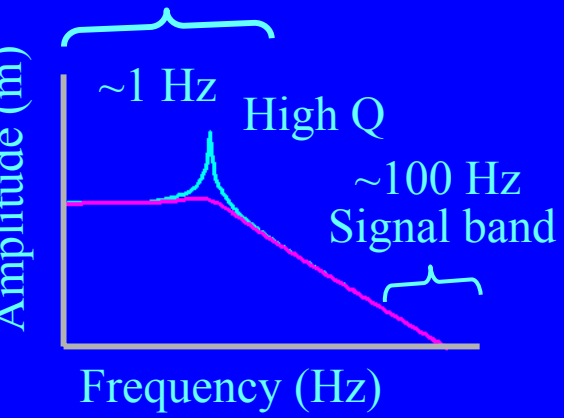
Large optics suspension

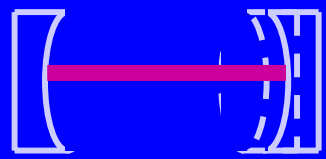

Diagnostics test tools – /data/dtt/S4/S4_DARM_ERR+AUX.xml
File Edit Measurement Plot Window Help
Input Measurement Excitation Result
Noise
SRD(REF2)
L1:LSC-DARM_ERR(REF6)
Dark Noise(REF7)
Magnitude (*)
10^-14
10^-15
10^-16
10^-17
10^-18
10^-19
10
10^2
10^3
Frequency (Hz)
*T0=06/01/1980 00:00:00
*Avg=1
*BW=0
Reset Zoom Active New Options... Import... Export... Reference... Calibration... Math... Print...
Start Pause Resume Abort

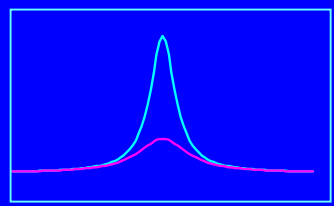
Technical issues

Technical issues overview



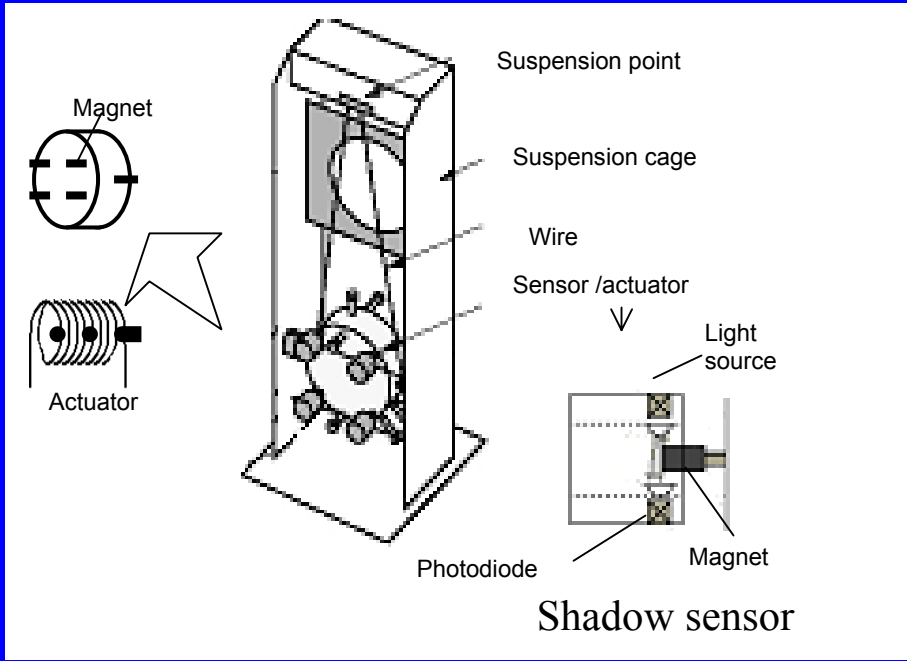




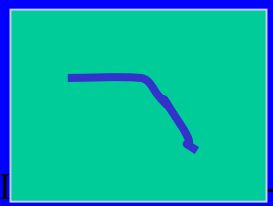


Suspended optic
and
Local damping control

Suspended optics

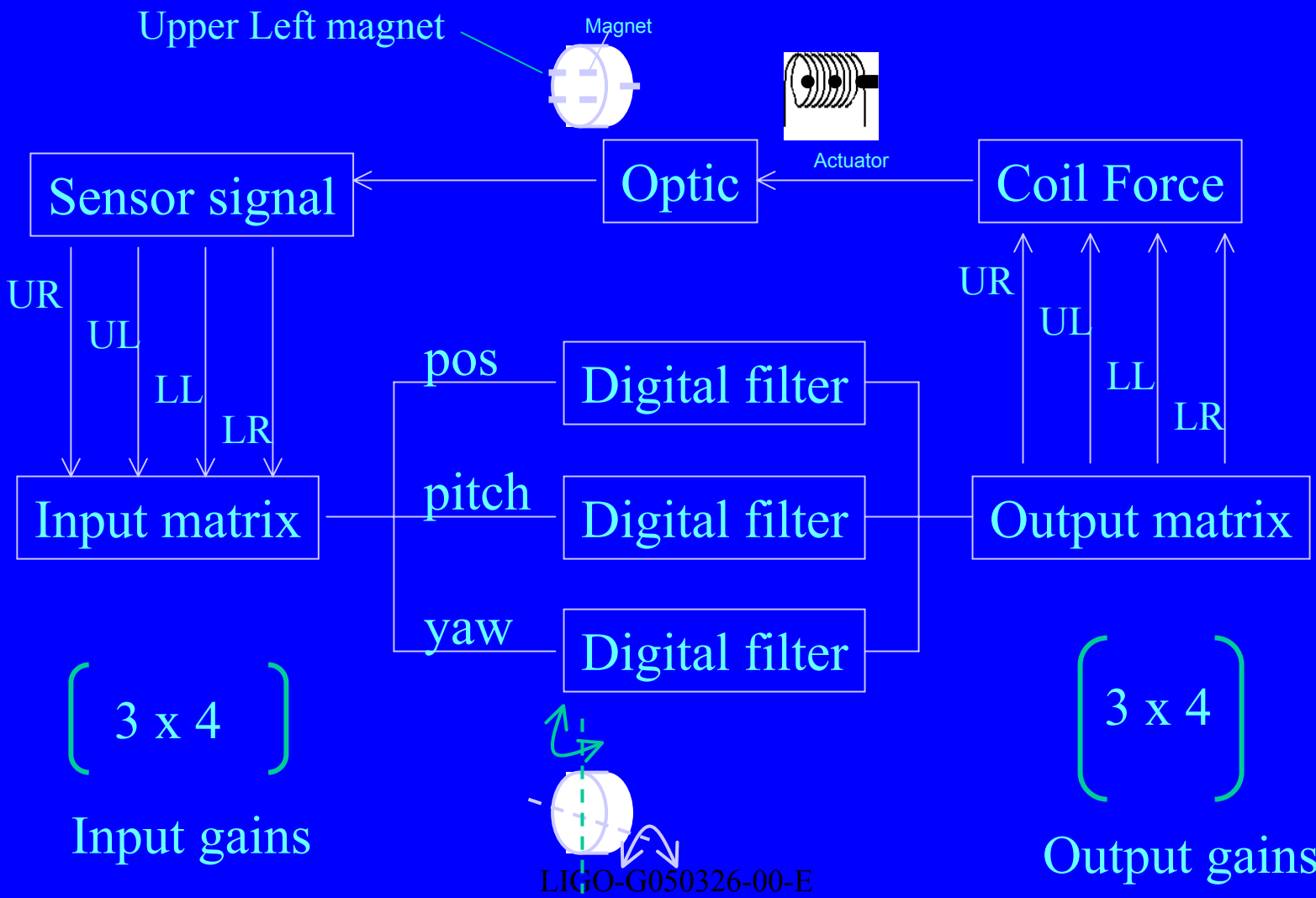


Sensor signal → Digital filter → Coil Force



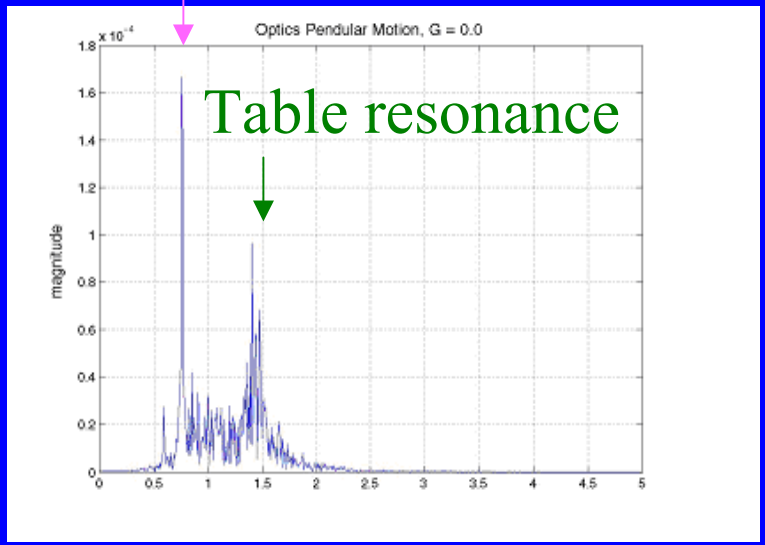
Free mass at signal band!

Suspended optics local damping servo



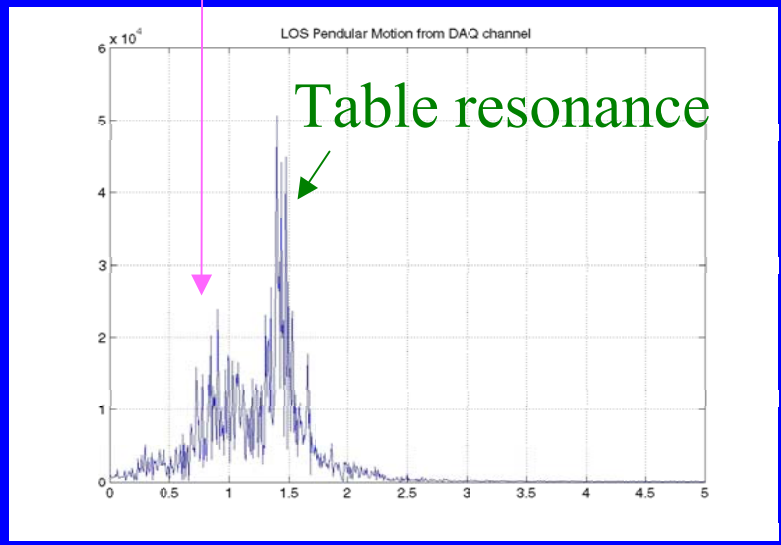
Suspended optics sensor signals

Optic's resonance



Local damp off

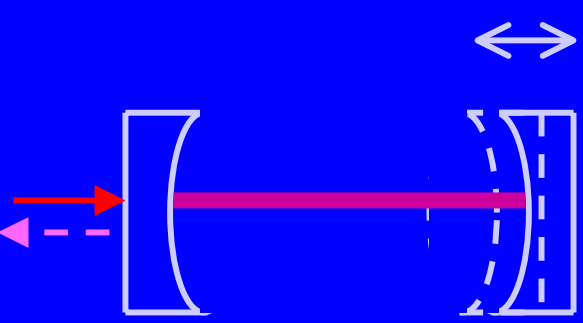
Optic's resonance



Local damp on

Locking cavity
by
Length sensing control

Cavity response to length change

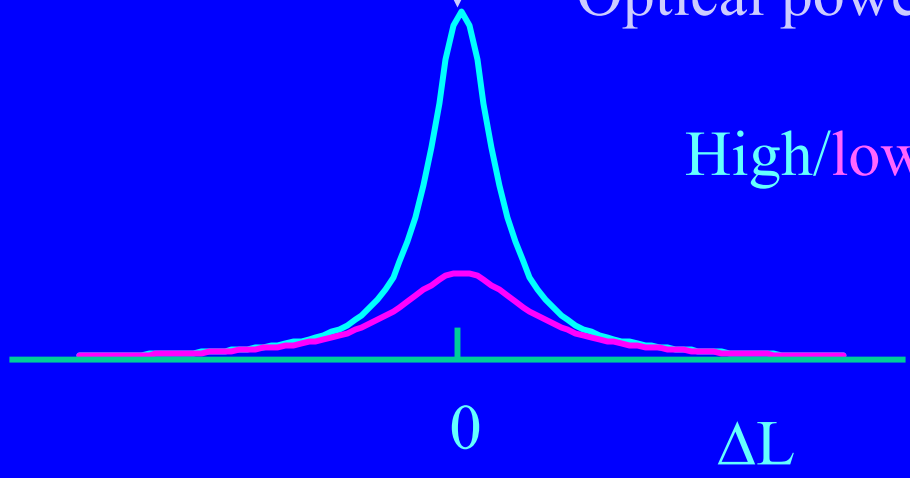


Optical power
Rejected by cavity

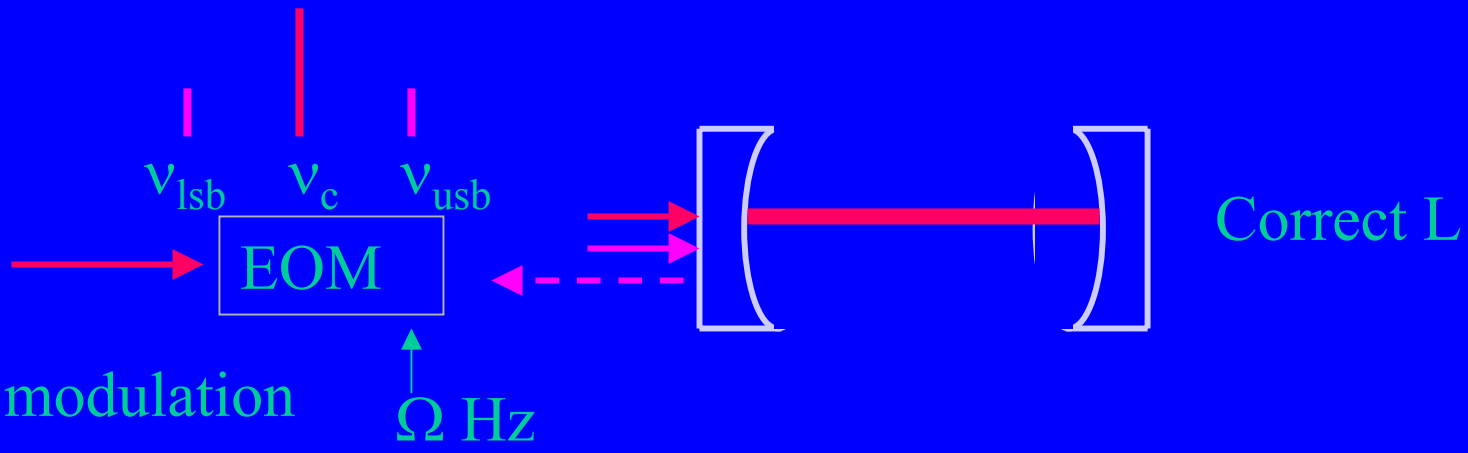
Correct length

Optical power coupled into cavity

High/low Q factor

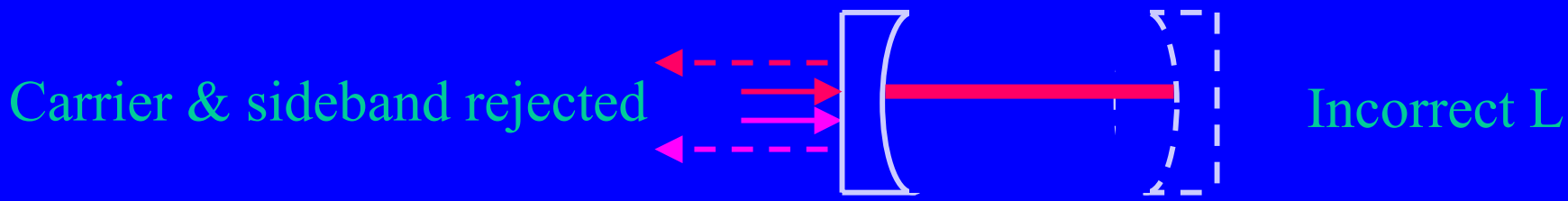


How to detect rejected light?
- Pound-Drever-Hall Method -



ν_c: carrier frequency (resonant)

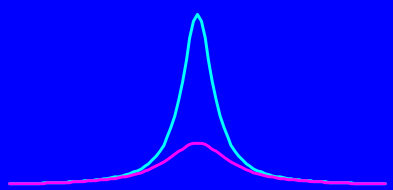
ν_{sb}: sideband frequency (non-resonant)

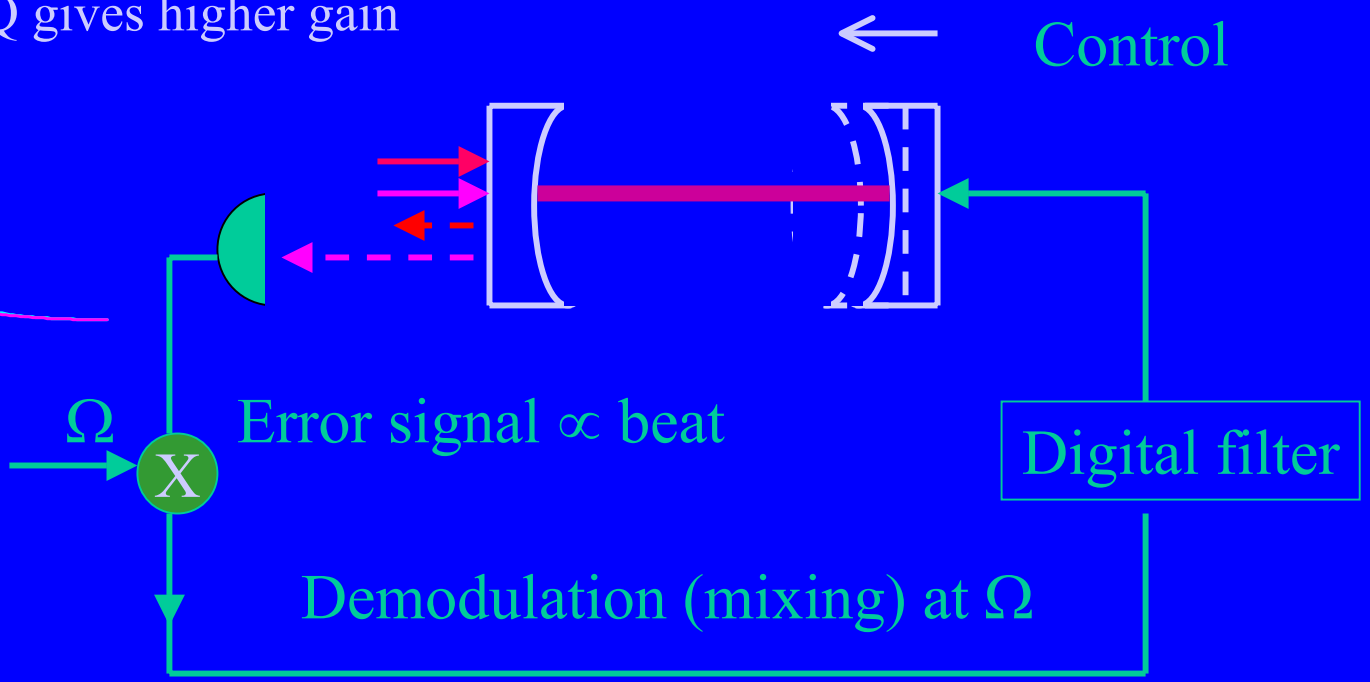


Pound-Drever-Hall Method

Higher the Q gives higher gain

Cavity Q

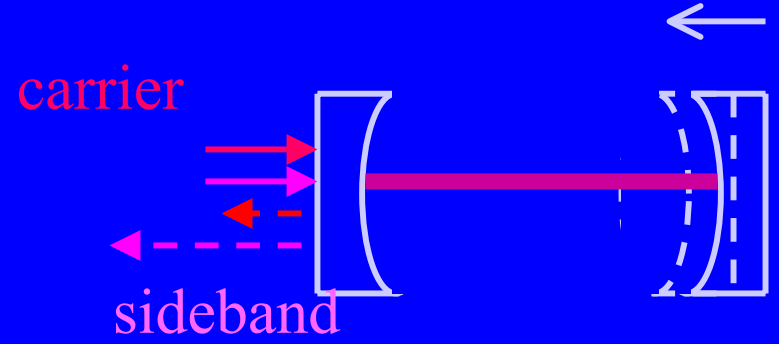




$PD_{signal} \propto P \propto E_c E_s e^{jn\Omega t}$: PD_{signal} =0 only when E_c=0

Apply control till PD_{signal} = 0! : High cavity Q → high gain

Pound-Drever-Hall Method



PD_{signal}

Set phase
$\phi = \pi/2$

$$PD_{signal} \propto \boxed{\cos(\omega t \pm \Omega t)}\ \boxed{\cos(\omega t + \phi + \delta)}$$

$$= (1/2)\{\cos[2\omega t \pm \Omega t + (\phi+\delta)] + \cos[\Omega t \mp (\phi+\delta)]\}$$

$$\cos[\Omega t \mp (\phi+\delta)] = \cos(\phi+\delta)\cos(\Omega t) \pm \sin(\phi+\delta)\sin(\Omega t)$$

$$= \cos(\pi/2+\delta)\cos(\Omega t) \pm \sin(\pi/2+\delta)\sin(\Omega t) = \sin\delta\cos(\Omega t) \pm \cos\delta\sin(\Omega t)$$

$$\approx \boxed{\delta\cos(\Omega t)} \pm \underline{\sin(\Omega t)}$$

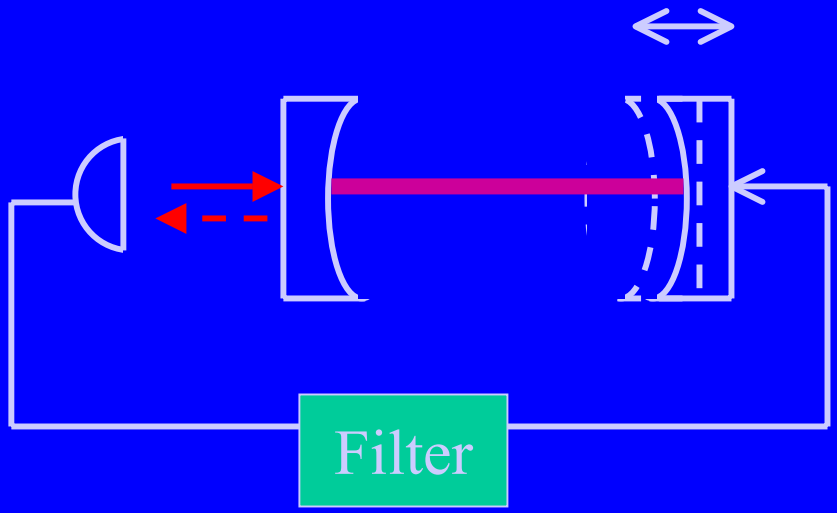
In-phase

cf.) quad-phase

demodulation

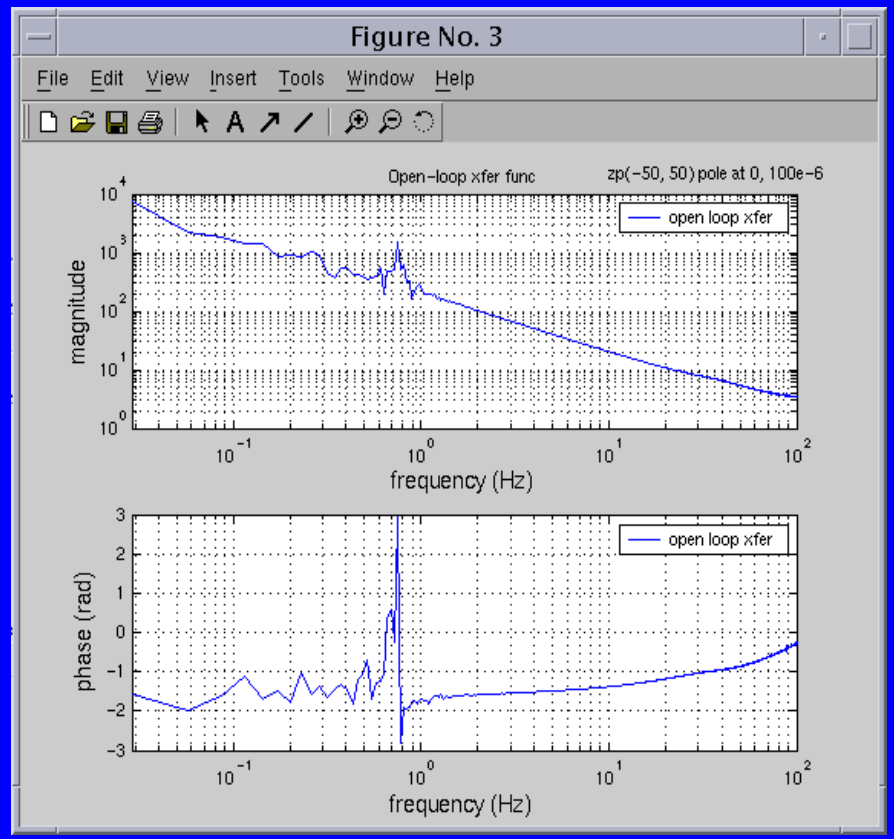
$$\int P(t)\cos(\Omega t)\,dt \propto \delta$$

Cavity response to length change



Design filter to cancel amplitude/
Phase frequency dependence.

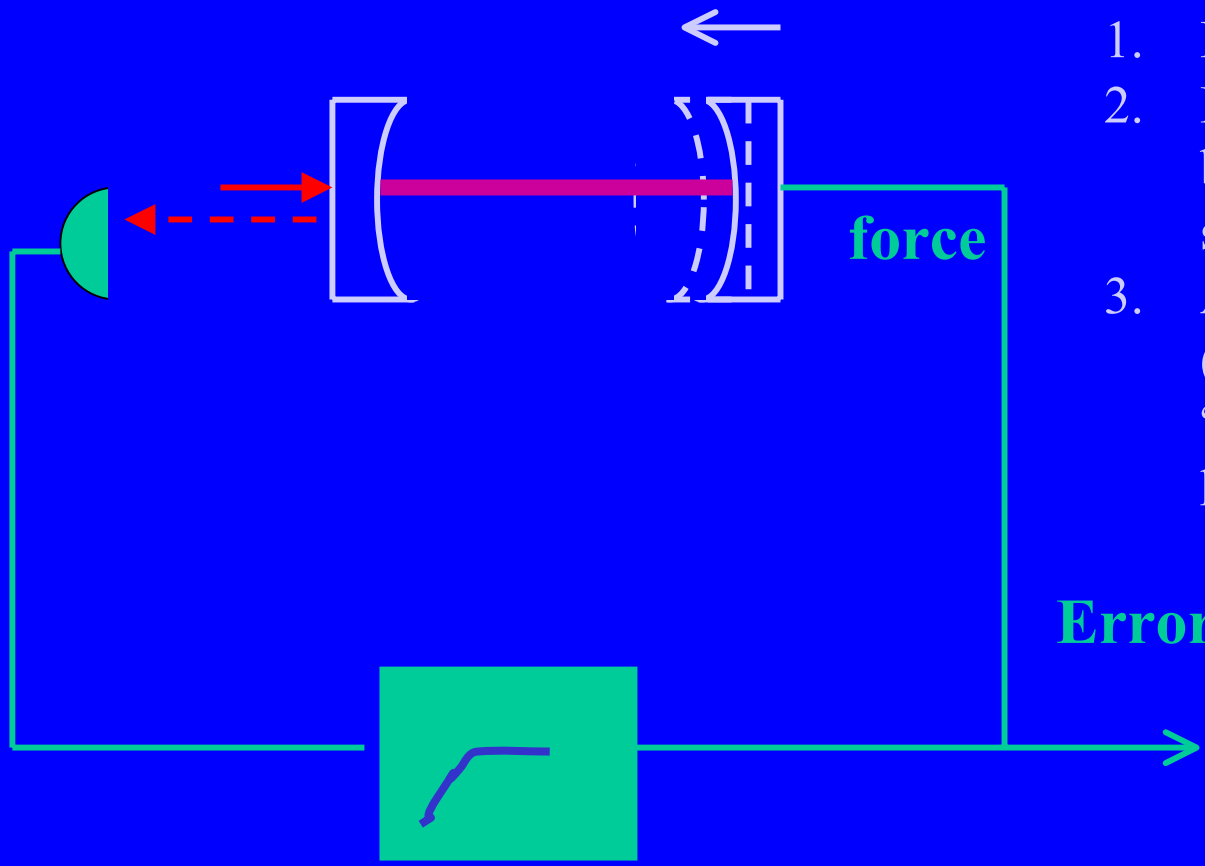
Force to ΔL transfer function



Force: COIL force
ΔL: mirror distance

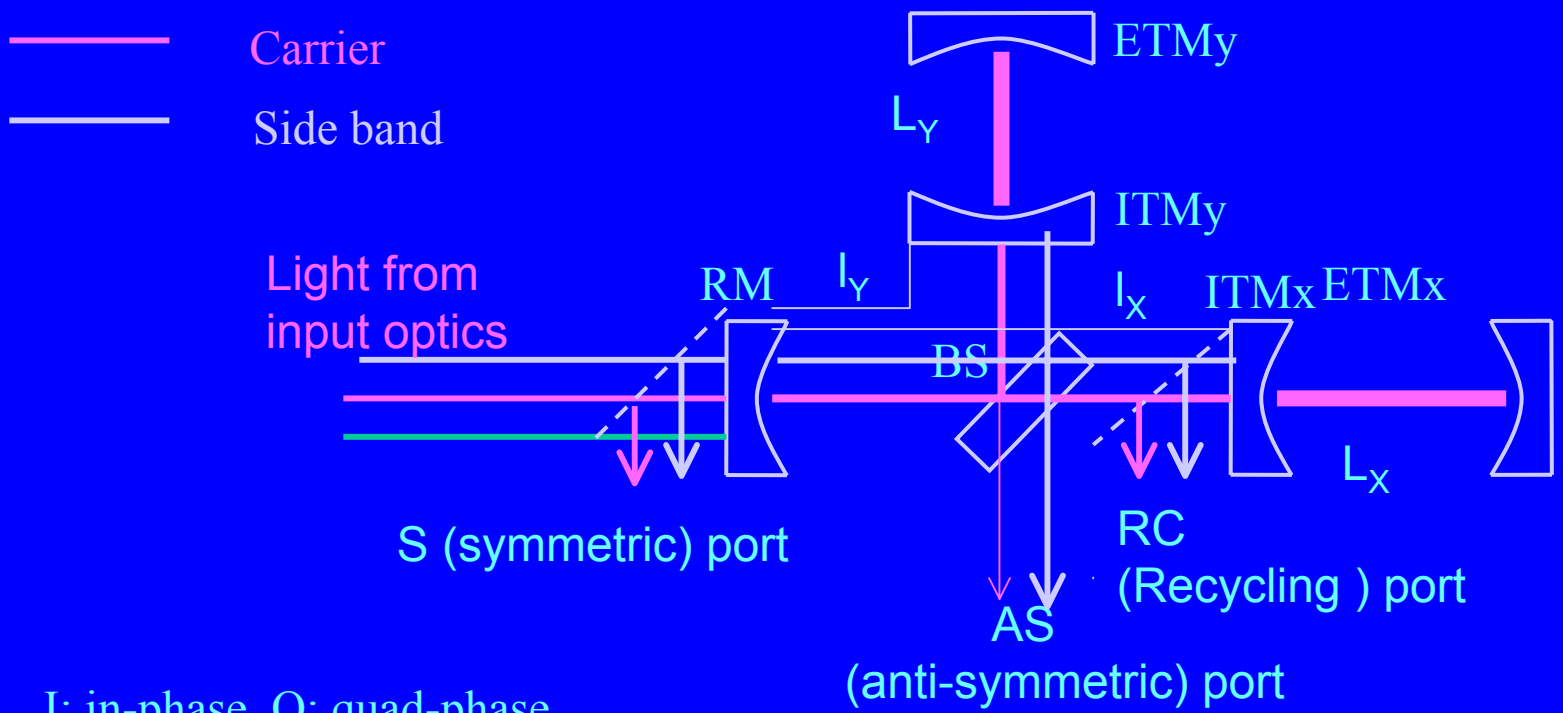
Cavity length change readout and GW signal detection

How to detect cavity length change?



1. Lock the cavity.
2. Detect and correct ΔL by Pound-Drever-Hall scheme.
3. Analyze feedback (error) signal. "Use templates of known GW signals."

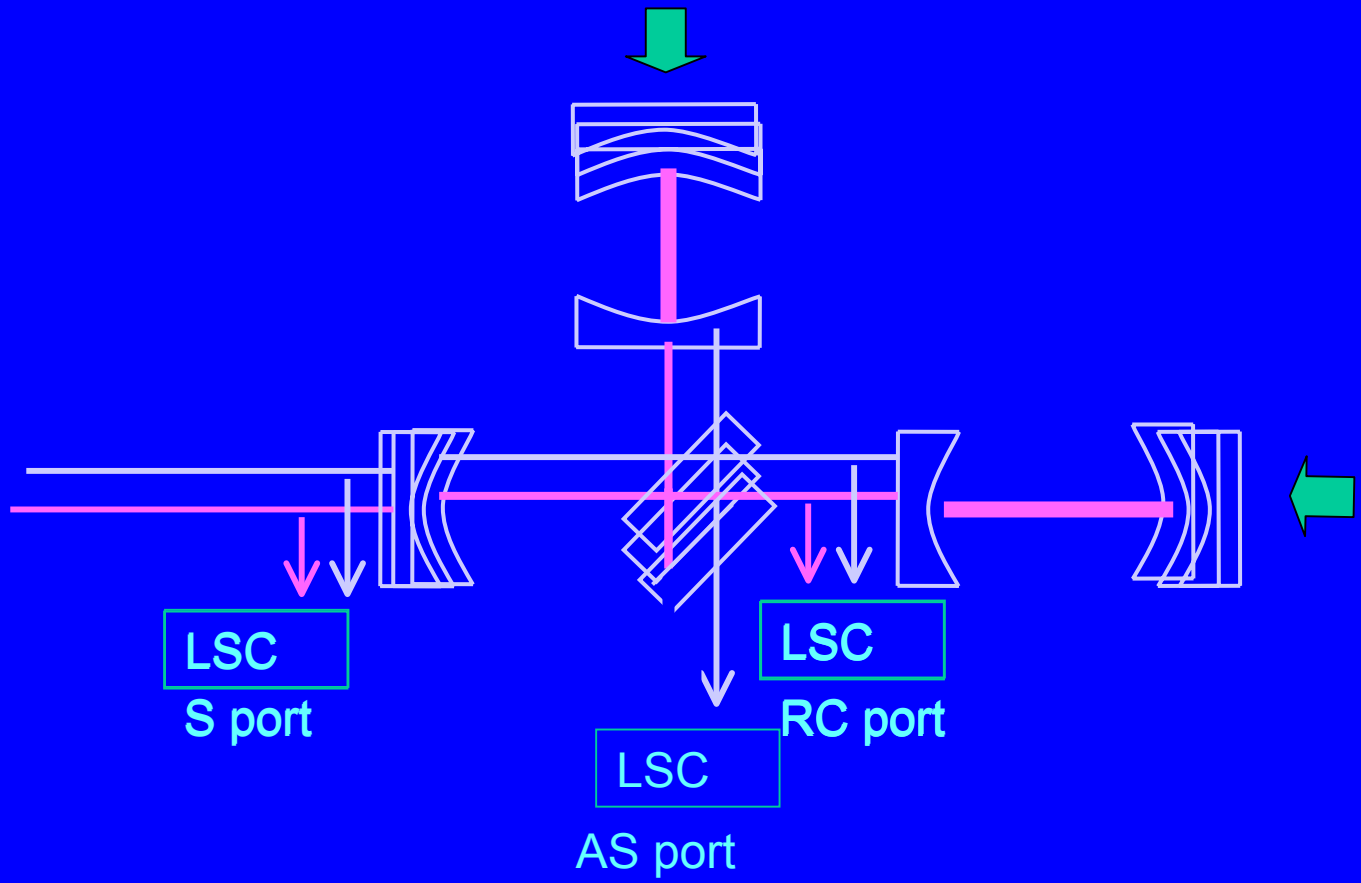
LIGO I coupled cavity & 4 degrees of freedom



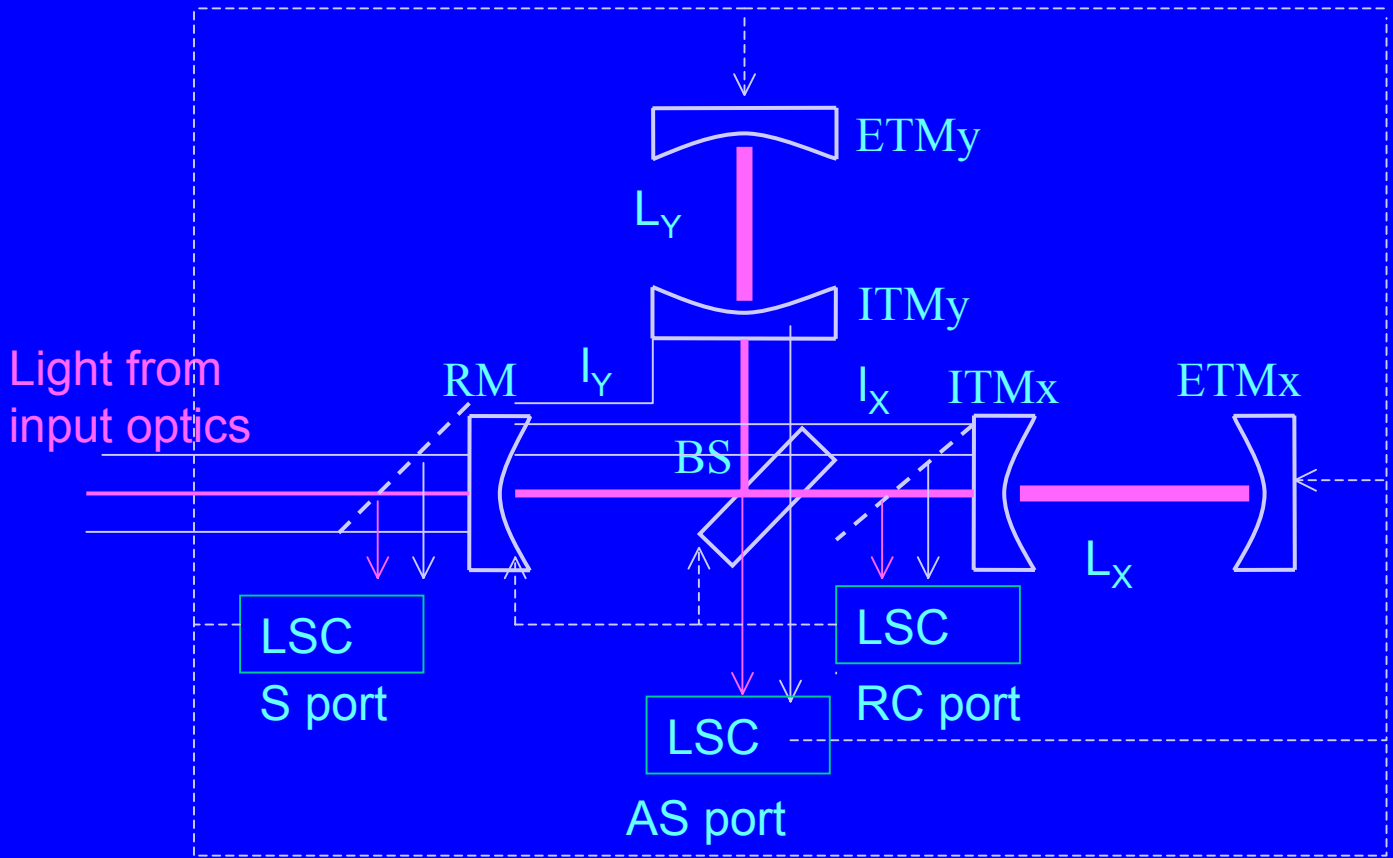
I: in-phase, Q: quad-phase

DOF	signal	Controlled optics
L_+ (common mode) $= (L_X + L_Y)/2$	S-port-I, RC-port-I	ETMx, ETMy
L_- (differential mode) $= (L_X - L_Y)/2$	AS-port-Q	ETMx, ETMy
l_+ (recycling cavity) $= (l_X + l_Y)/2$	S-port-I, RC-port-I	RM
l_- (Michelson cavity) $= (l_X - l_Y)/2$	RC-port-Q	BS

LIGO I cavities LSC



LIGO I cavities LSC



Dark port signal

$P_{AS} \propto 1+\cos 2(\phi_0+\phi_{gw}+\Gamma \sin\Omega t)$: Intensity at Dark Port

$=1+\cos(2\phi_0+2\phi_{gw})\cos(2\,\Gamma\sin\Omega t)-\sin(2\phi_0+2\phi_{gw})\sin(2\Gamma\sin\Omega t)$

$\cos(2\,\Gamma\sin\Omega t)=J_0(2\,\Gamma)+J_2(2\,\Gamma)\cos(2\Omega t)$

$\sin(2\,\Gamma\sin\Omega t)=2J_1(2\,\Gamma)\sin(\Omega t)$

$\Phi_0=\pi/2$, $\cos(2\phi_{gw})\cong 1$, and $\sin(2\phi_{gw})\cong 2\phi_{gw}$

$=1-[J_0(2\,\Gamma)+J_2(2\,\Gamma)\cos(2\Omega t)] + (2\phi_{gw})\,2J_1(2\,\Gamma)\sin(\Omega t)$

$J_0(2\,\Gamma)=1-\Gamma^2$, $J_1(2\,\Gamma)=\Gamma$, and $J_2(2\,\Gamma)=\Gamma^2/2$

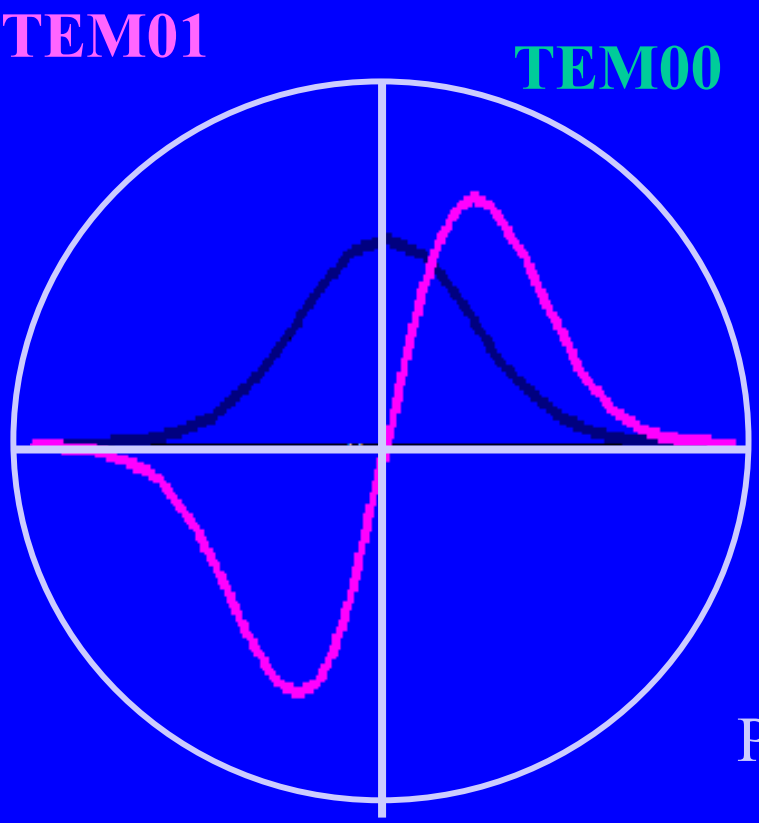
$=1-[(1-\Gamma^2)+(\Gamma^2/2)\cos(2\Omega t)] + 2\phi_{gw}\,2\,\Gamma\sin(\Omega t)$

$=\Gamma^2-(\Gamma^2/2)\cos(2\Omega t)+4\phi_{gw}\,\Gamma\sin(\Omega t)$

$\phi_{gw} \propto$ Q-phase demodulation at Ω

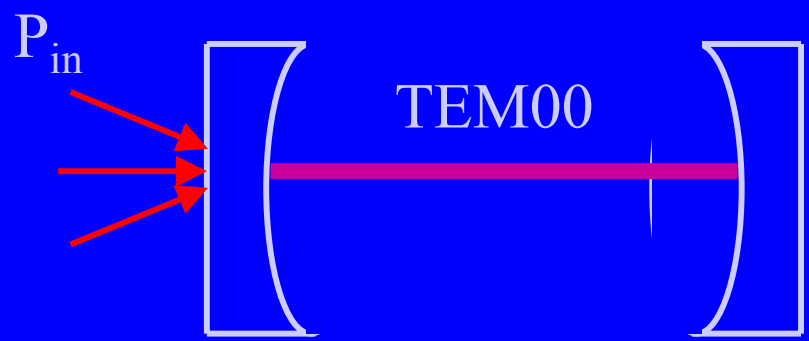
Other control systems

Wave front sensing

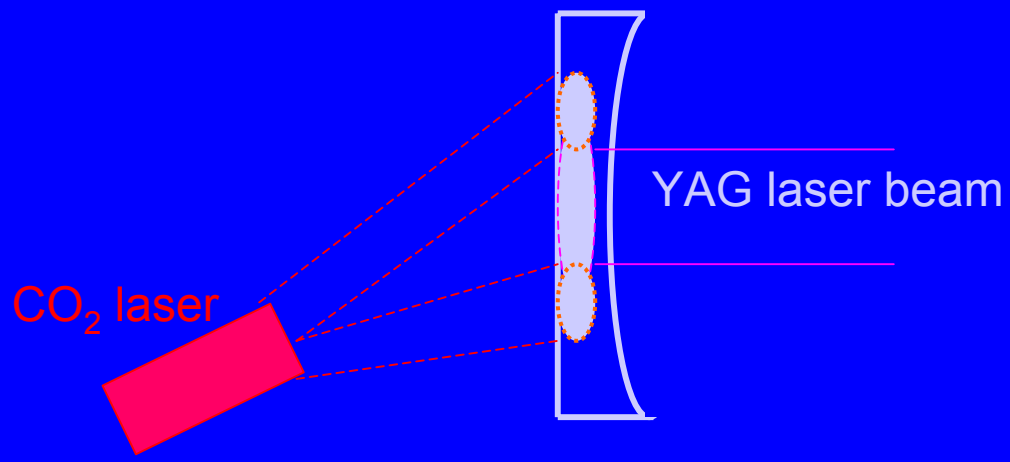


Quad sensor

Angular misalignment generates higher order modes



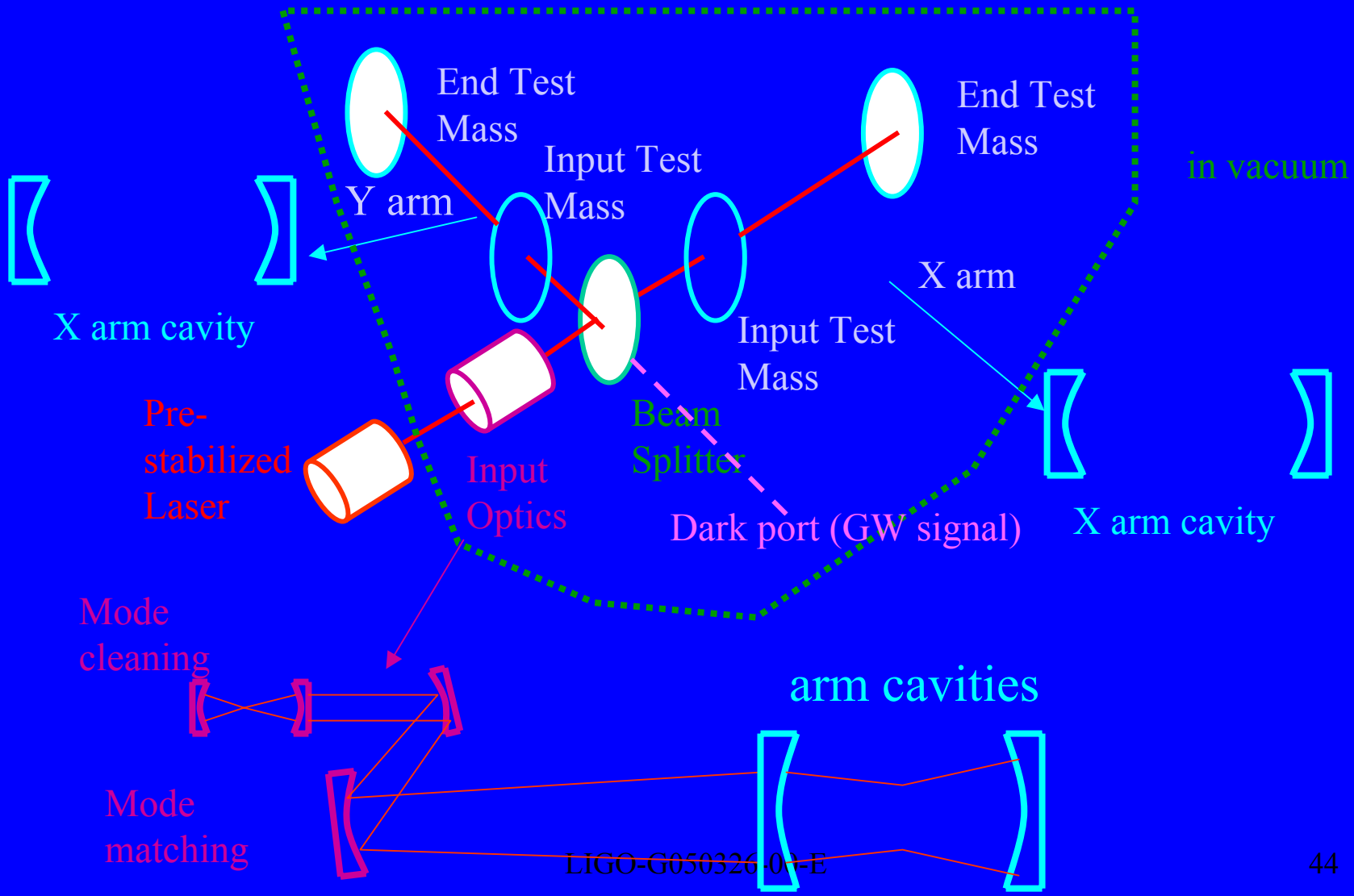
Thermal compensation



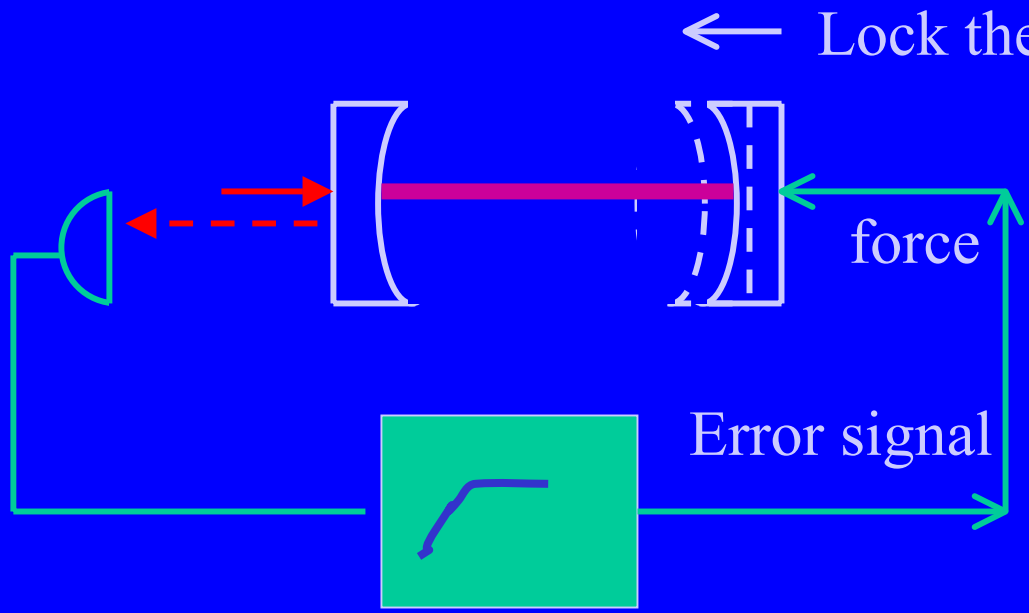
Better mode matching

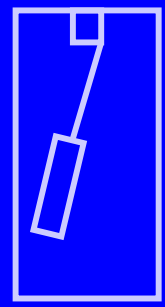
Thank you!

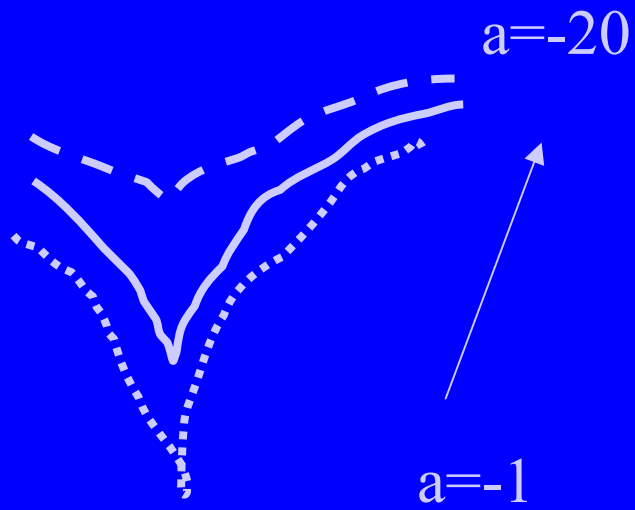
LIGO detector (Michelson Interferometer)

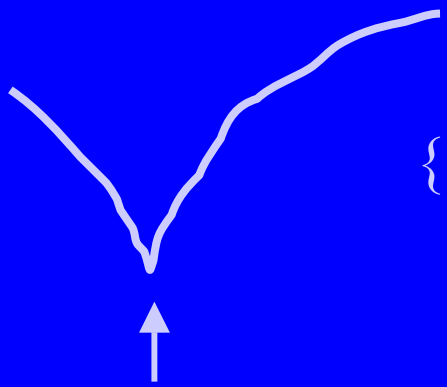


Design filter for length control









$\{s-(\underline{a}-bj)\}\{(s-(\underline{a}+bj)\}$

Dissipation term

Mirror resonance (1 Hz)

Small optics suspension