Measuring Thermoelastic Noise

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Thanks to

Caltech

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LIGO

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TAMA

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Thermal Noise Interferometer Crew

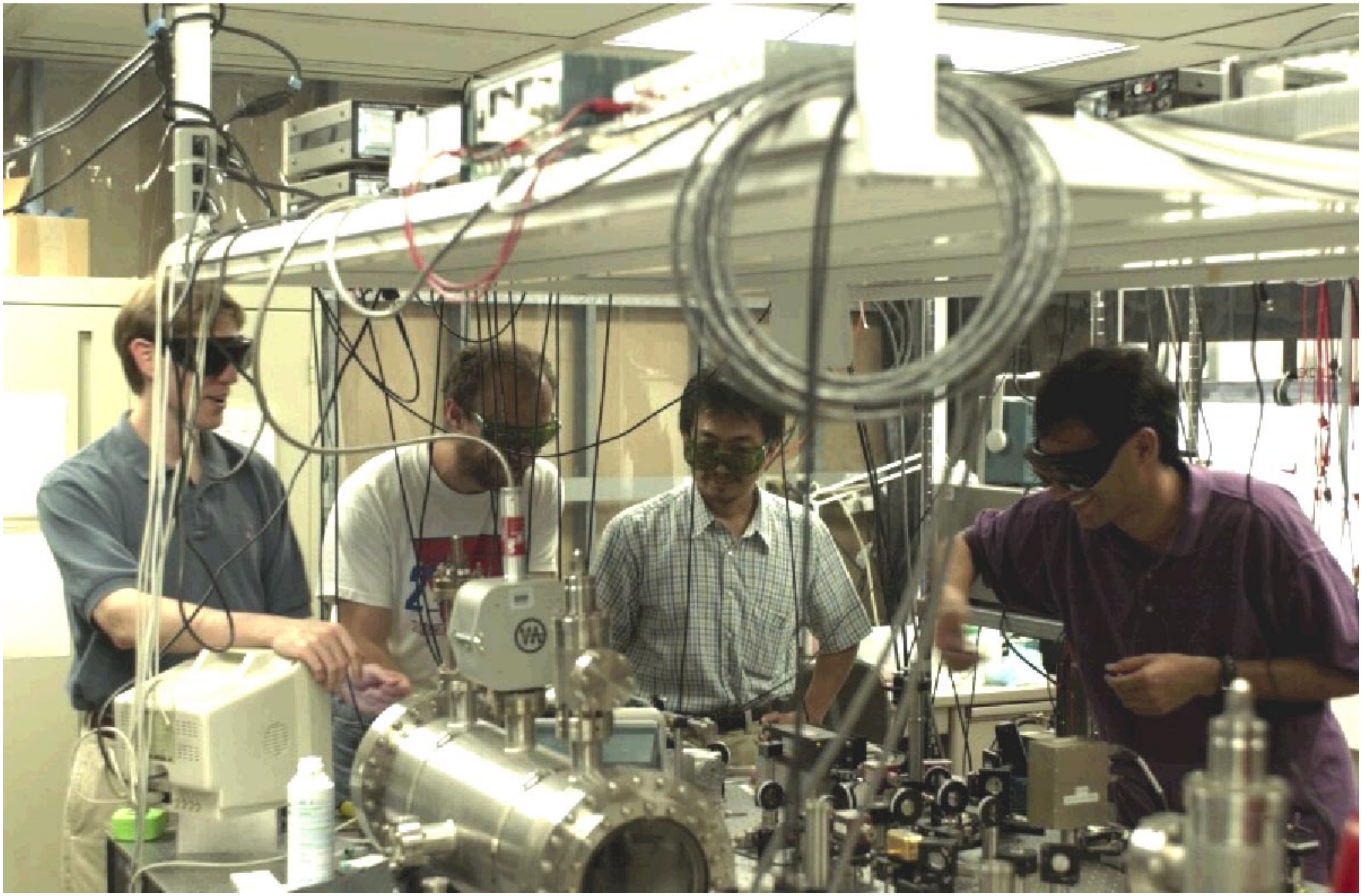


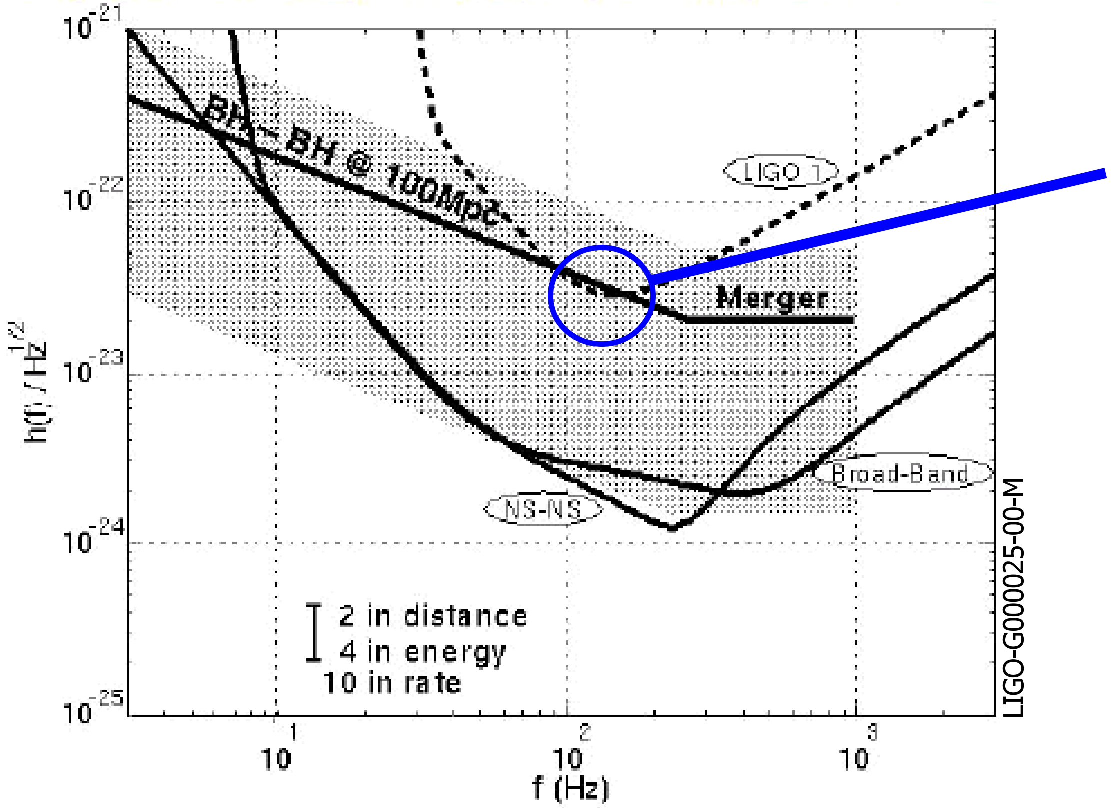
Photo by Ken Libbrecht

Eric Black **Luca Matone** **Seiji Kawamura** **Shanti Rao**

Thermal Noise Affects Event Rate

Rates Highly Uncertain. Optimistic estimates:

» LIGO-I: 100 Mpc, ~1/year. LIGO-II: z=0.5, ~1/hour



Thermal Noise

Limits event rate

Hard to measure with LIGO

Need to verify models

The TNI (Thermal Noise Interferometer) program measures thermal noise for LIGO I and II

Thermal Noise Sources

Brownian motion

Mirror recoils against internal phonons

$\propto (\phi\, k_B T / \omega\, r_0)^{1/2}$

$\phi \propto (1/Q)$ **"Quality factor"**

Thermoelastic damping

Thermodynamic noise from thermal expansion dissipation

$\propto (\alpha^2 k_B T^2 / \omega^2 r_0^3)^{1/2}$

Other

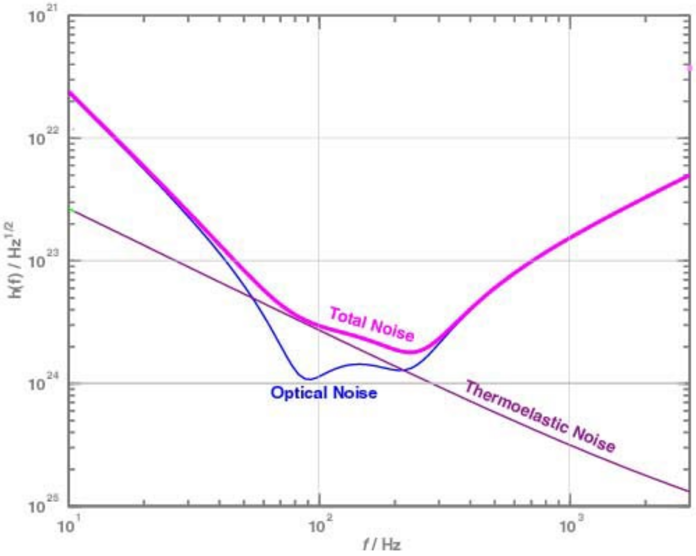
Thermorefractive

Photothermal

Non-Gaussian noise

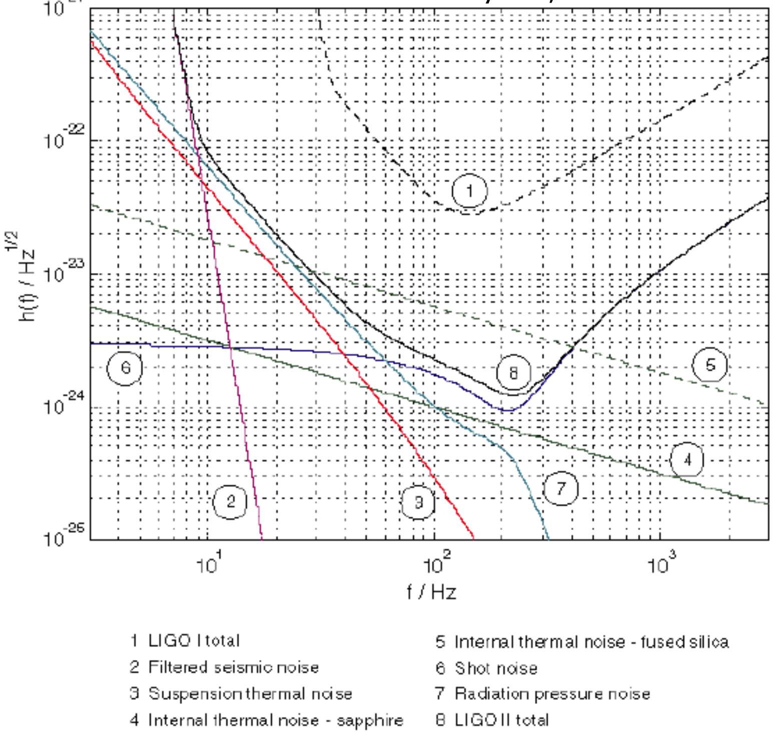
Unknown?

LIGO II Sensitivity Plot, 2000

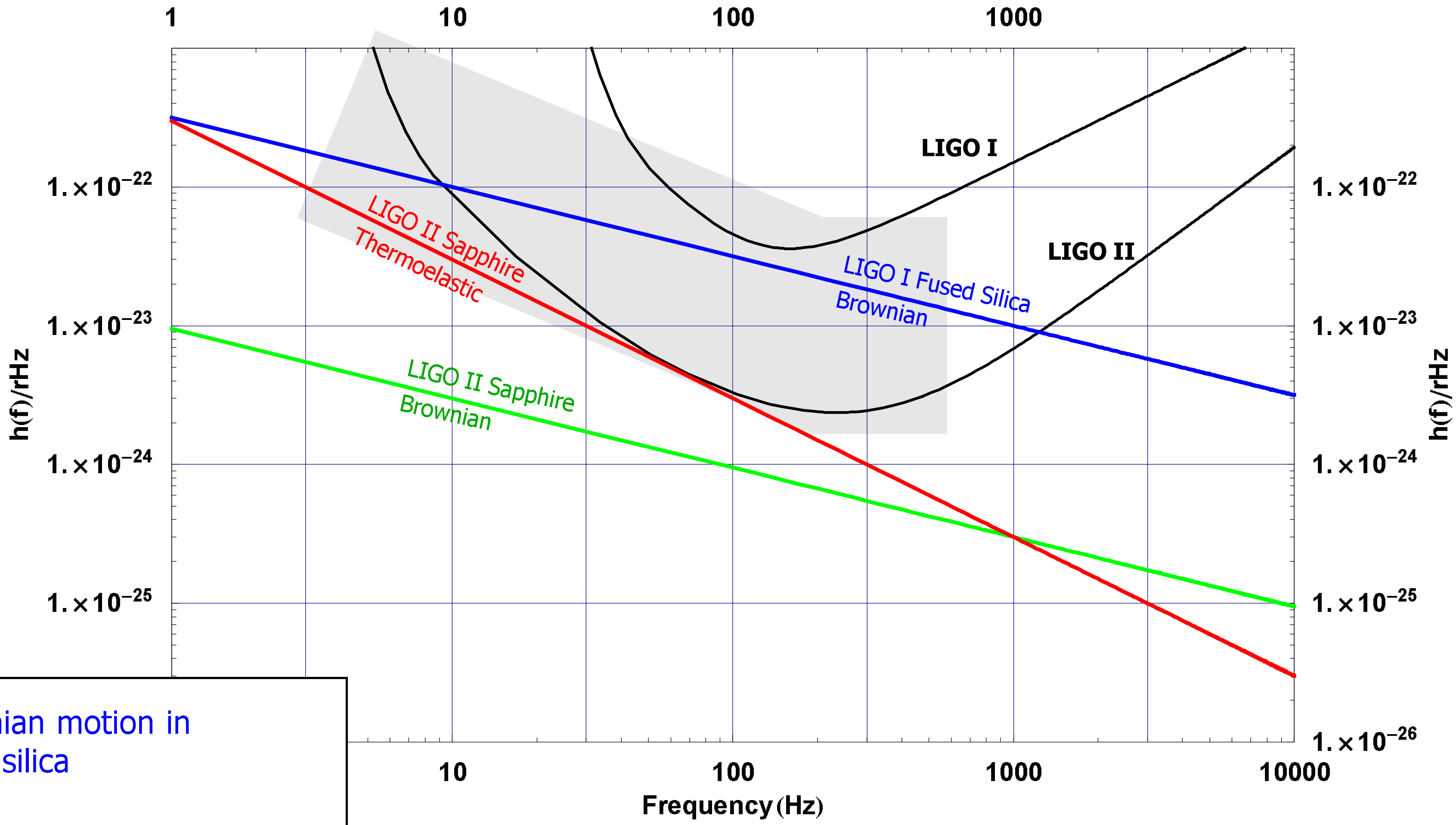


Source: Peter Fritschel Oct/2000

LIGO II Sensitivity Plot, c. 1998



Thermal Noise and LIGO



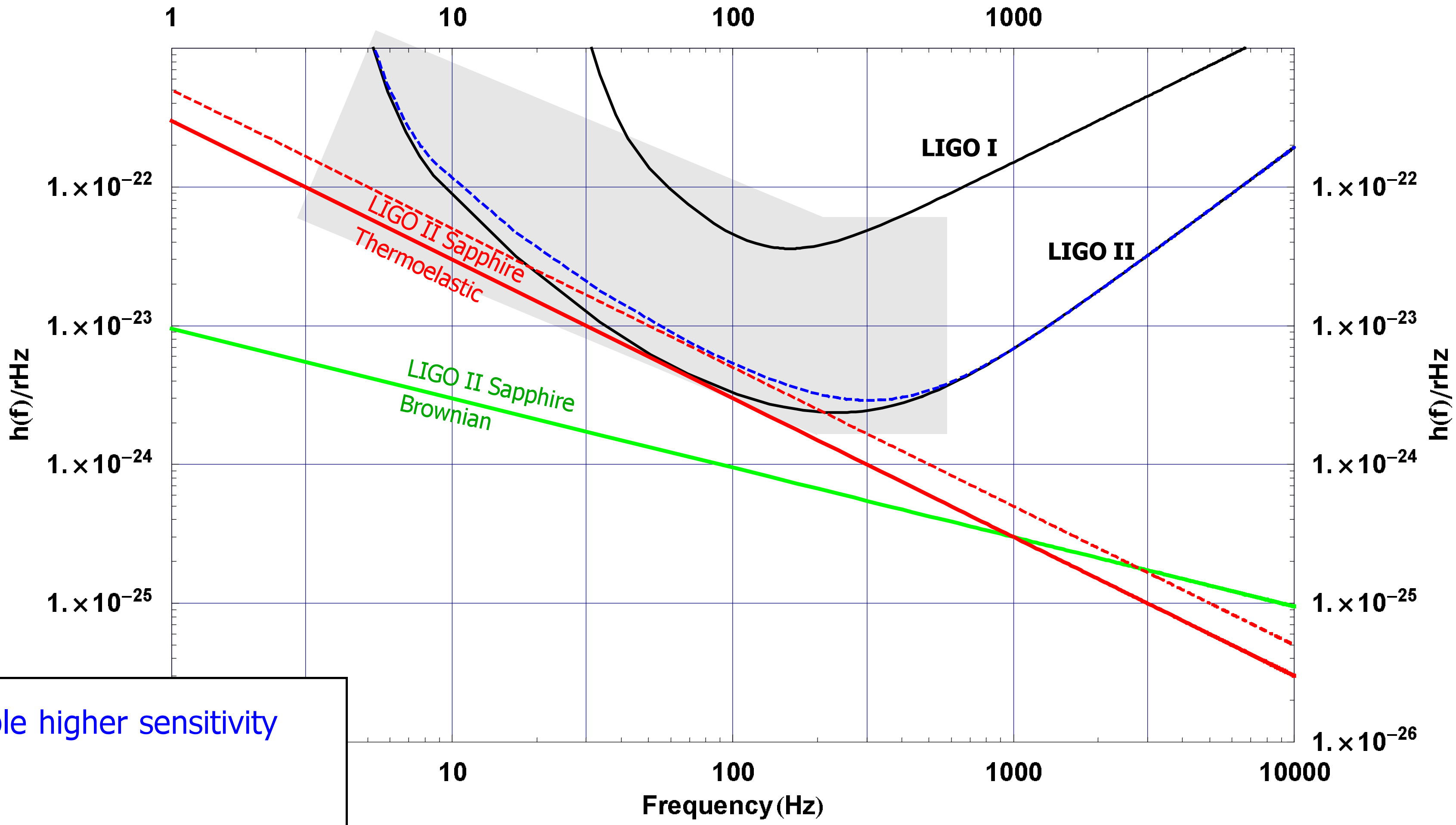
Brownian motion in fused silica

Thermoelastic damping in sapphire

Brownian motion in sapphire

Thermoelastic and Brownian noise are poorly measured at these levels

LIGO II with Sapphire Mirrors



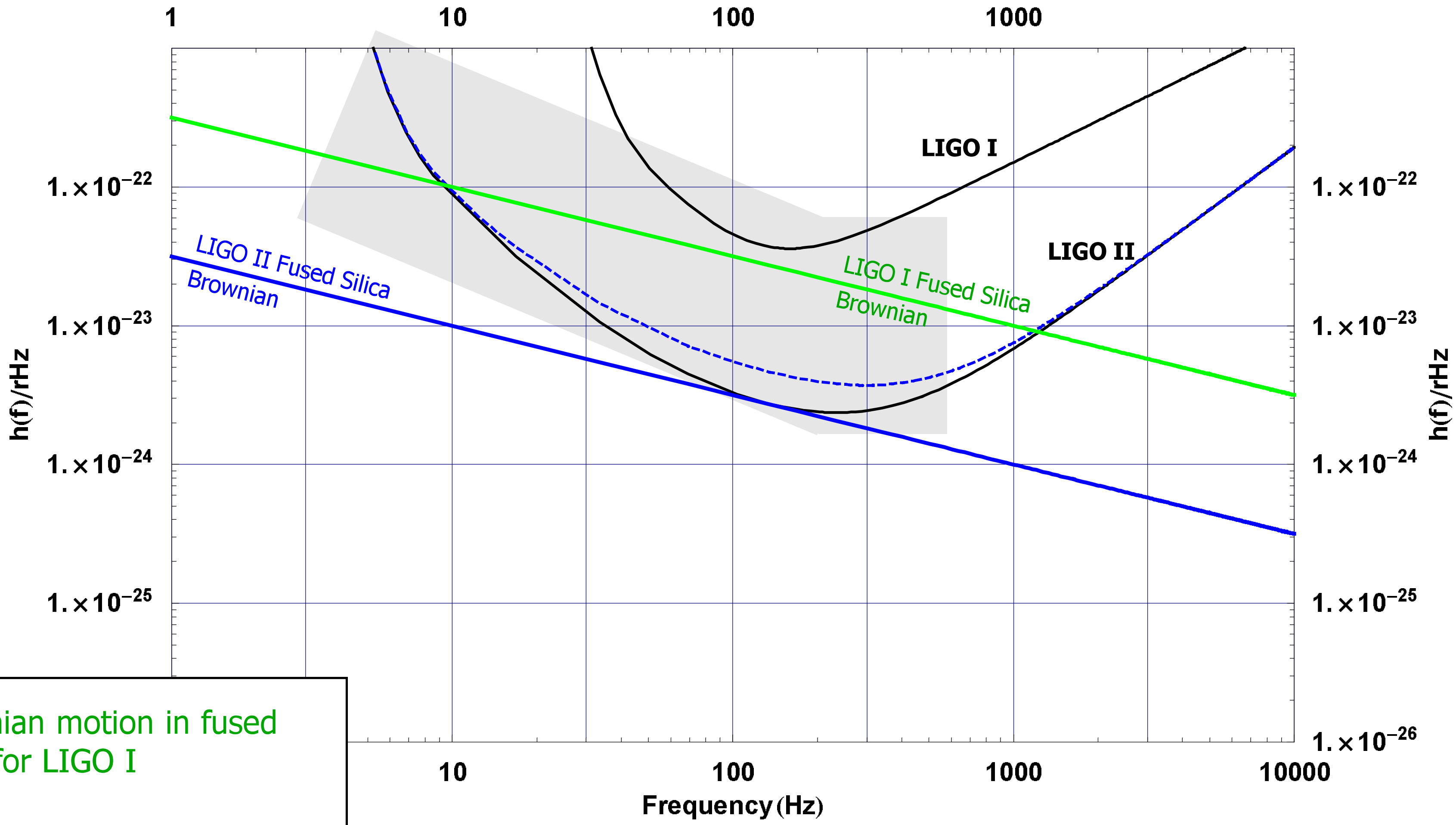
Possible higher sensitivity curve

Thermoelastic damping in sapphire

Brownian motion in sapphire

What if thermoelastic damping is bigger than we expect?

LIGO II with Fused Silica Mirrors

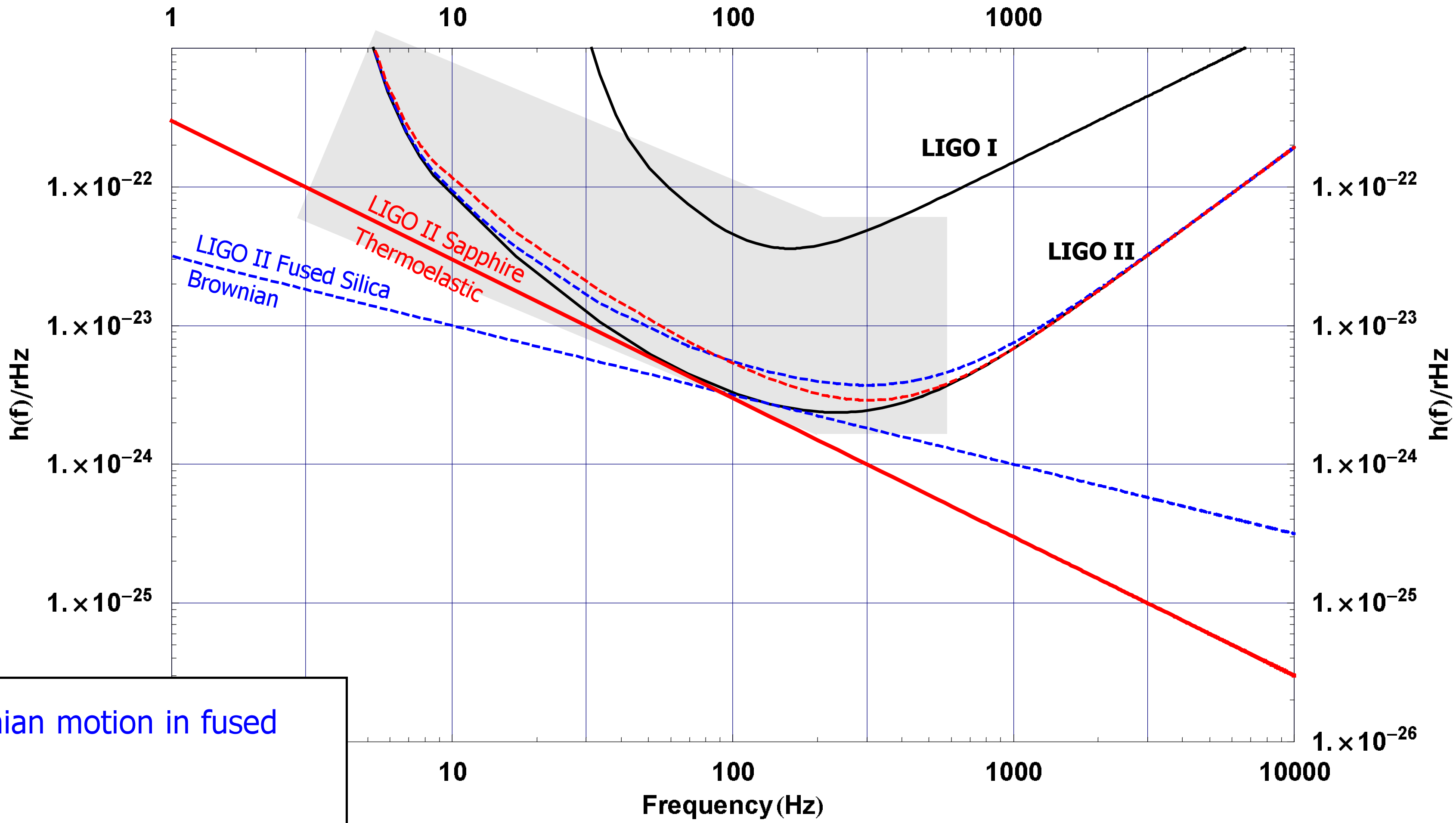


Brownian motion in fused silica for LIGO I

Brownian motion in fused silica for LIGO II

Fallback plan for LIGO II uses fused silica instead of sapphire

LIGO II Material Selection



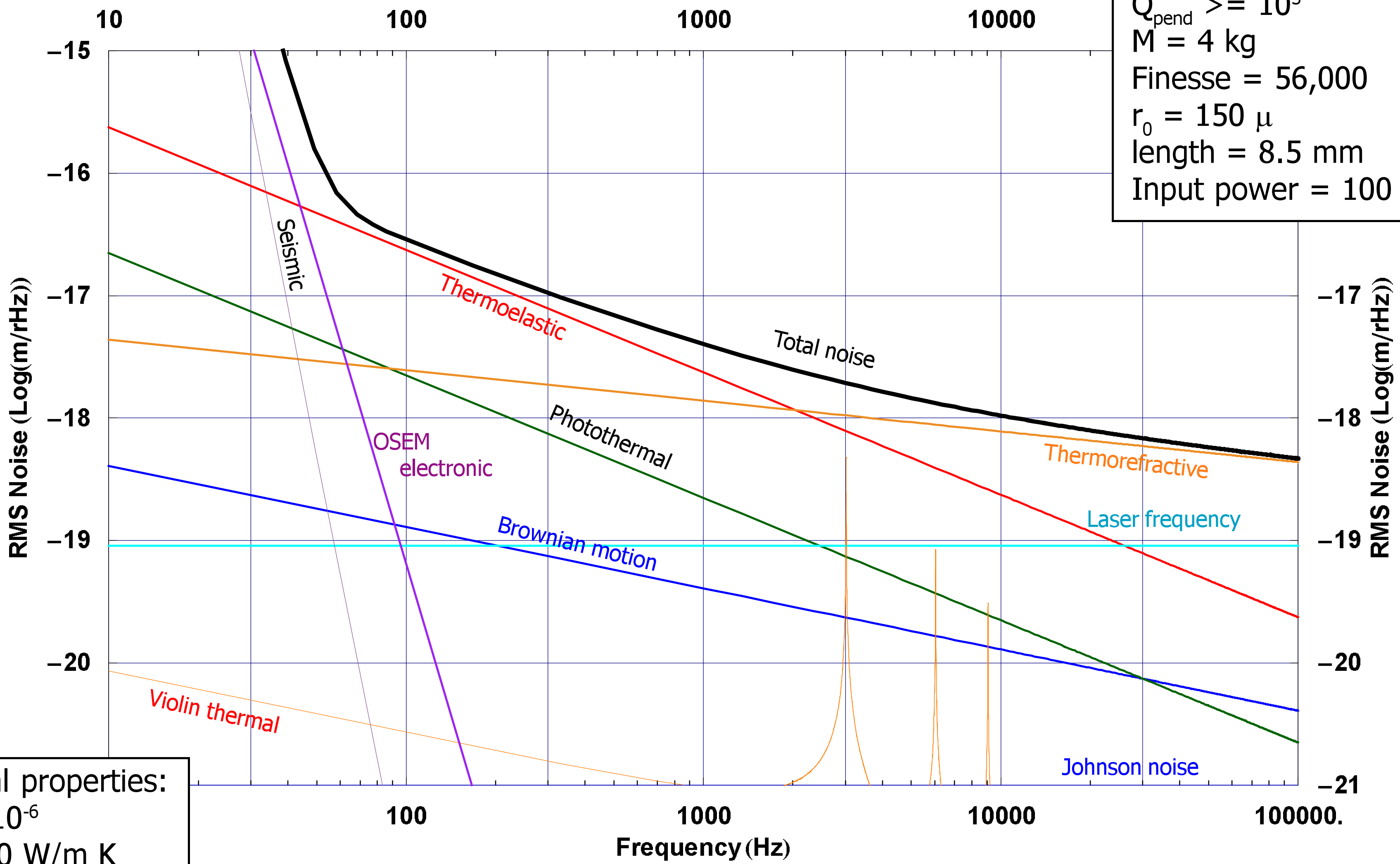
Brownian motion in fused silica

Thermoelastic noise in sapphire

Need to determine the tradeoff between LIGO II test mass materials

TNI Expected Spectrum - Sapphire

10cm x 10cm Al_3O_2
$Q >= 10^6$
$Q_{pend} >= 10^3$
M = 4 kg
Finesse = 56,000
$r_0 = 150\ \mu$
length = 8.5 mm
Input power = 100 mW



Physical properties:
$\alpha = 5\ 10^{-6}$
$\lambda^* = 40$ W/m K
$\rho = 4\ g/cm^3$
C = 790 J/kg K
E = 400 GPa

Reduce technical noise to improve sensitivity to thermal noise

Thermal Noise Interferometer (TNI)

Characterize GW detectors

Measure Brownian noise in 2000

Measure thermoelastic noise in 2001

Measure non-Gaussian noise

Design choices

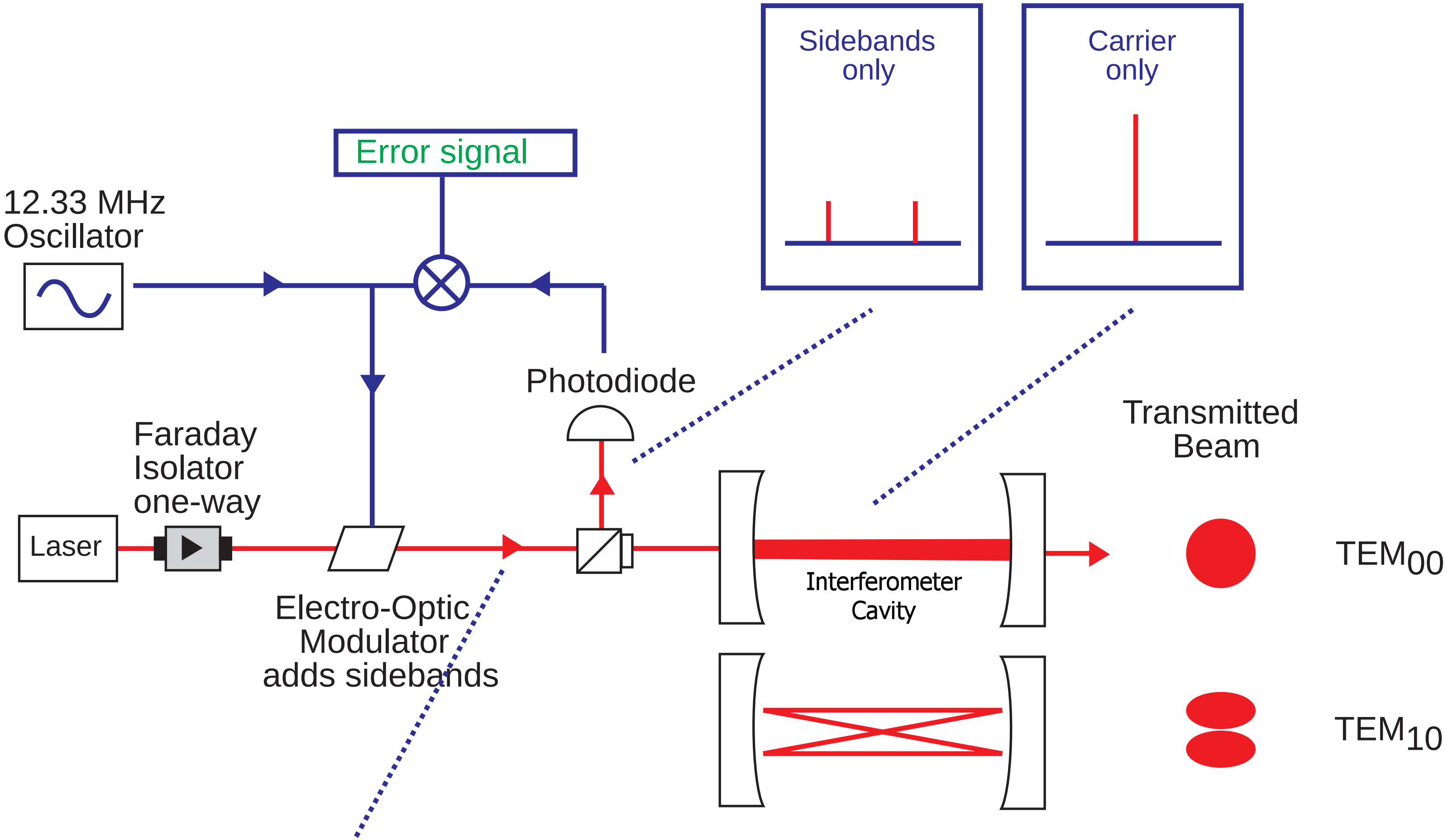
Short interferometers (~1 cm) are easier to build

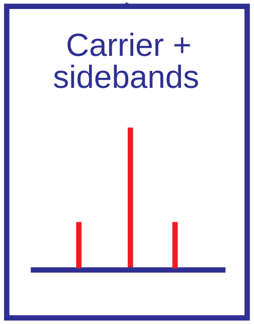
Small spot size increases thermal noise for low loss mirrors

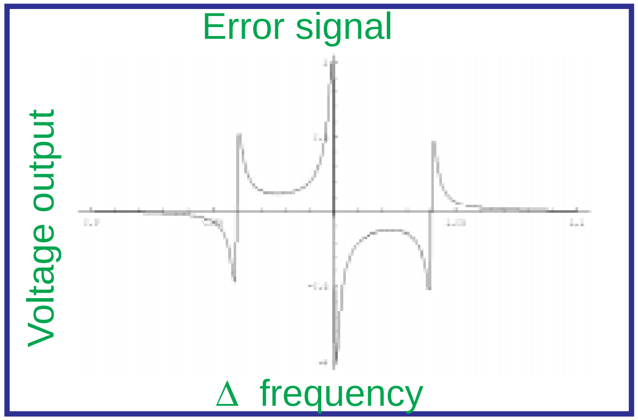
High finesse increases sensitivity

The TNI uses LIGO-like mirrors
and suspensions

How an Interferometer (IFO) works





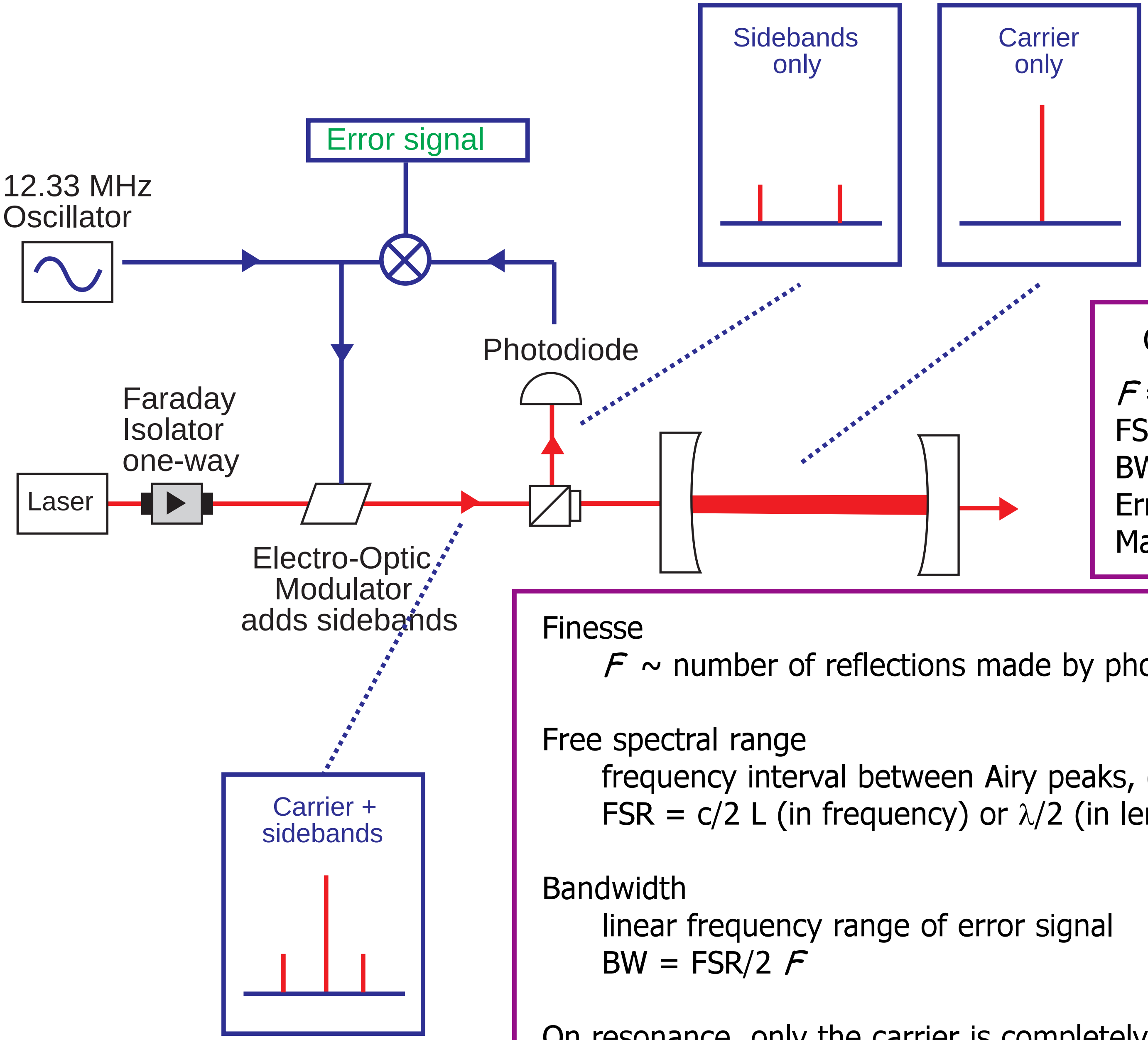


Buzzwords

Fabry-Perot
Two mirror cavity interferometer.

Pound-Drever-Hall
Lock-in method for measuring length changes, using reflected sidebands.

How an IFO works



Our suspended cavities

$\mathcal{F}$ = 60,000
FSR = 15 GHz or 0.5 μ
BW = 125 kHz or 8.3 pm
Error signal = 0.2 mV/fm
Max stored power ~ 1 kW

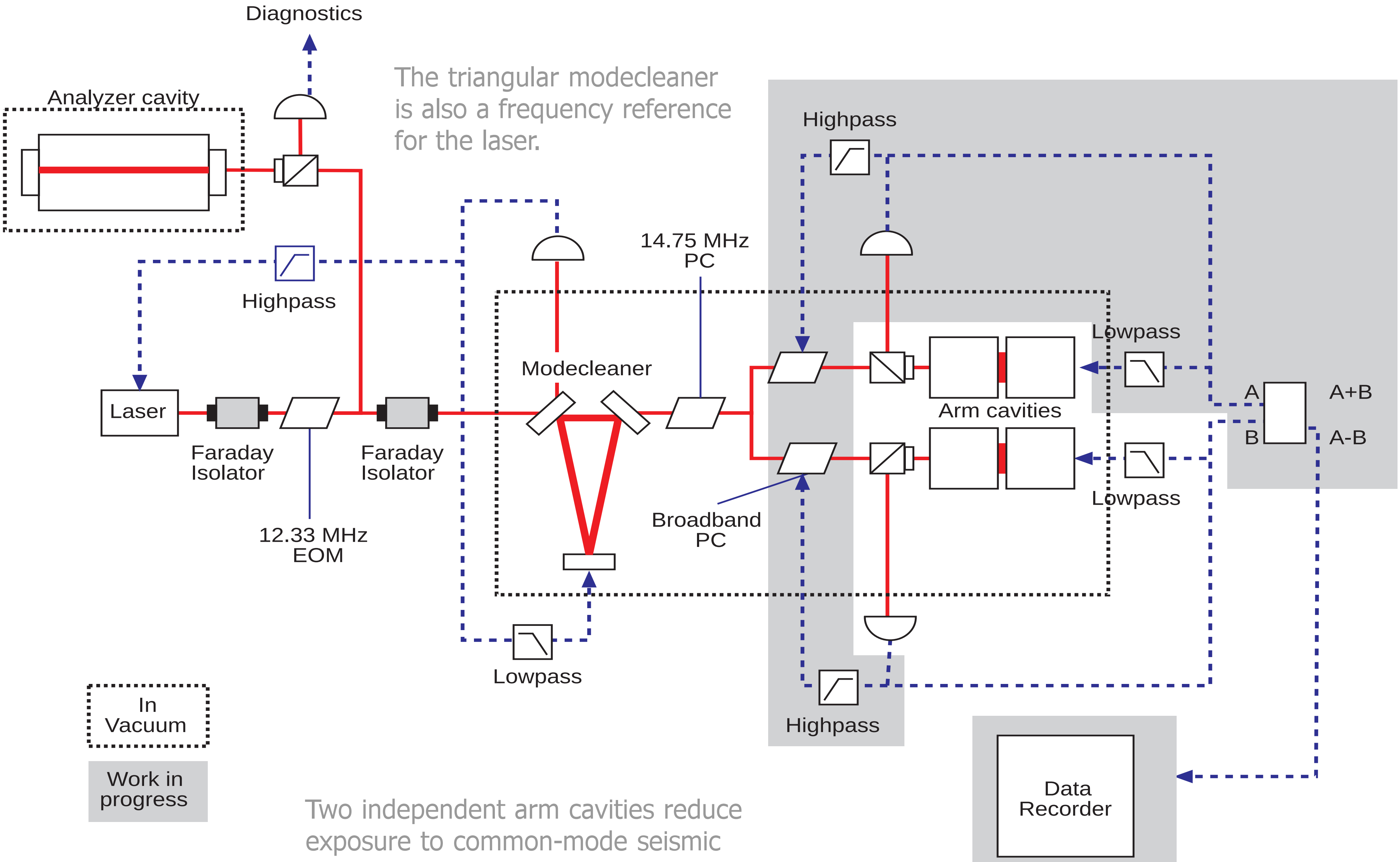
Finesse
$\mathcal{F}$ ~ number of reflections made by photons in the cavity

Free spectral range
frequency interval between Airy peaks, depends only on length
FSR = c/2 L (in frequency) or $\lambda/2$ (in length)

Bandwidth
linear frequency range of error signal
BW = FSR/2 $\mathcal{F}$

On resonance, only the carrier is completely transmitted, and only the sidebands are reflected, if the mirror reflectivities are the same

TNI Equipment



The triangular modecleaner is also a frequency reference for the laser.

Two independent arm cavities reduce exposure to common-mode seismic motion and laser frequency noise.

Major Thermal Noise Sources

Brownian motion

Limits LIGO I sensitivity
Test masses recoil against internal thermal phonons
Largest thermal noise contribution for fused silica
Quality factor determines noise

$$x(\omega) \propto (\phi\, k_B T / \omega\, r_0)^{1/2}$$

Thermoelastic damping

Fluctuations arise from thermal expansion dissipation
Large thermal noise contribution in sapphire
Material properties determine noise

$$x(\omega) \propto (\alpha^2 k_B T^2 / \omega^2\, r_0^3)^{1/2}$$

Thermorefractive noise

Mirror coatings’ index of refraction depends on temperature

$$x(\omega) \propto r^{-1} \omega^{-1/4}$$

Photothermal noise

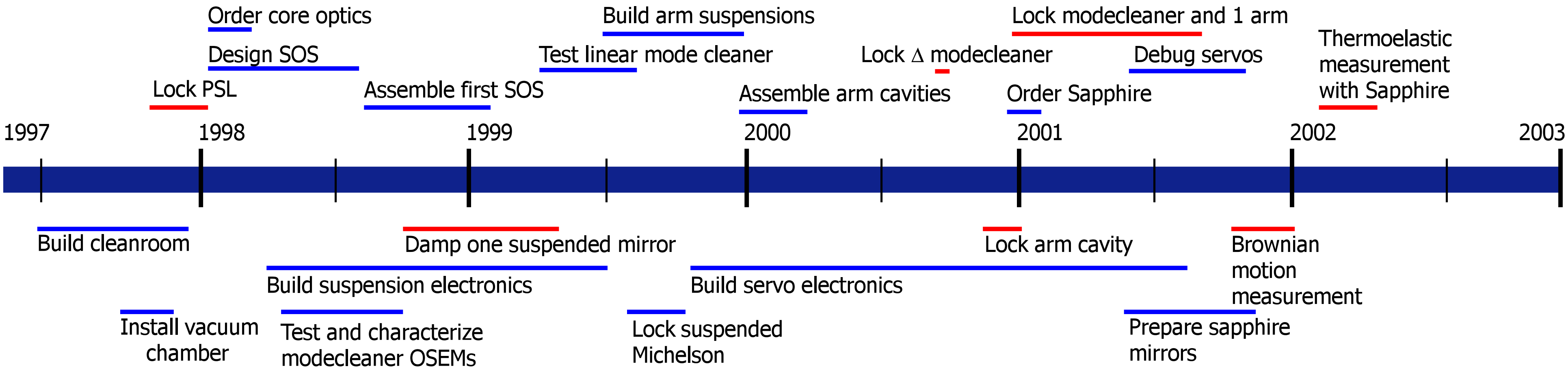
Light heats mirror, and thermal expansion changes IFO length

$$x(\omega) \propto (h\nu P / \omega^2\, r_0^4)^{1/2}$$

TNI Timeline

Deadline: June 4, 2002

Latest date to choose mirror materials for LIGO II



Order core optics

Design SOS

Lock PSL

Assemble first SOS

Build arm suspensions

Test linear mode cleaner

Assemble arm cavities

Lock Δ modecleaner

Lock modecleaner and 1 arm

Debug servos

Order Sapphire

Thermoelastic measurement with Sapphire

1997

1998

1999

2000

2001

2002

2003

Build cleanroom

Install vacuum chamber

Build suspension electronics

Test and characterize modecleaner OSEMs

Damp one suspended mirror

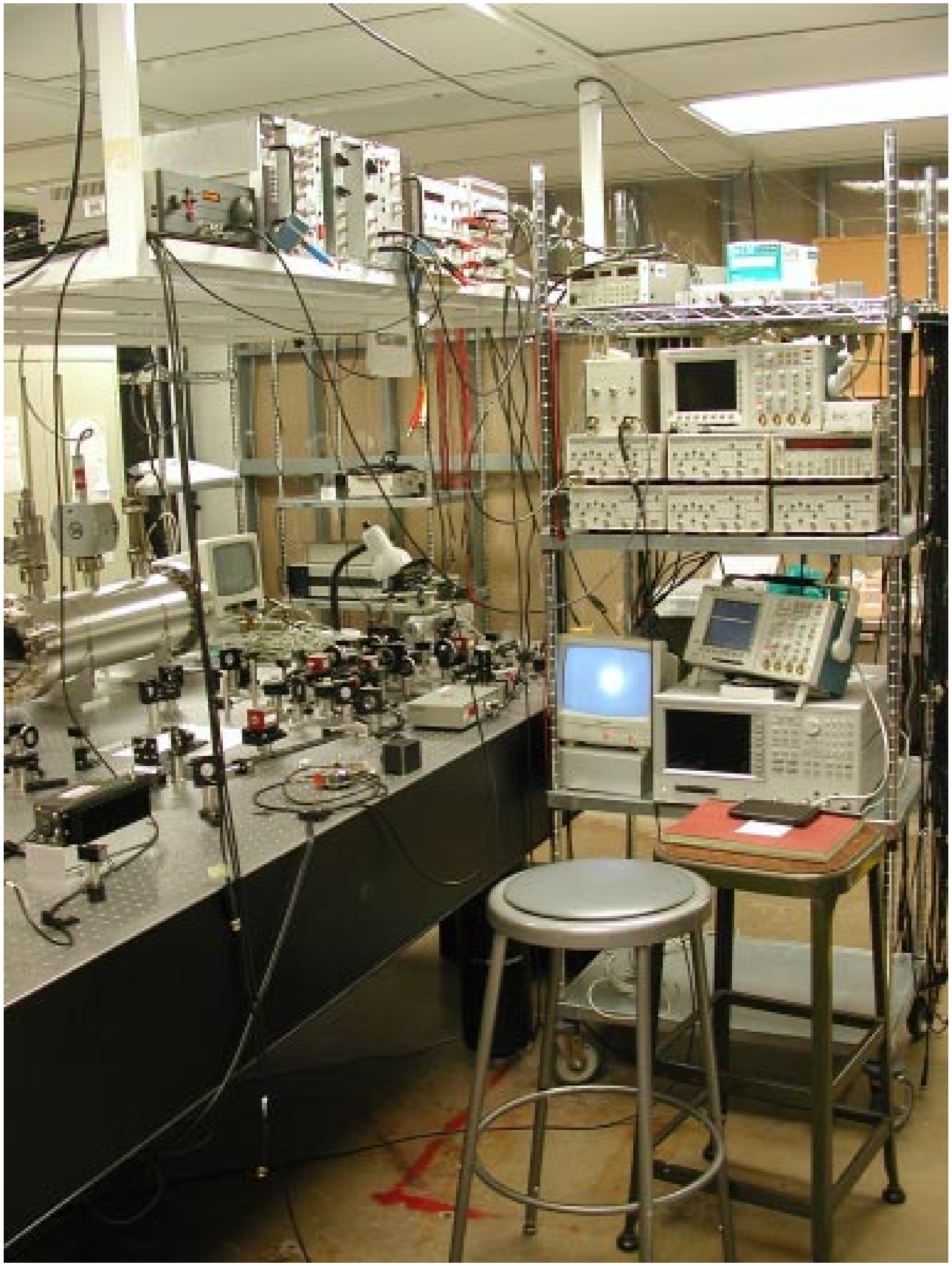
Lock suspended Michelson

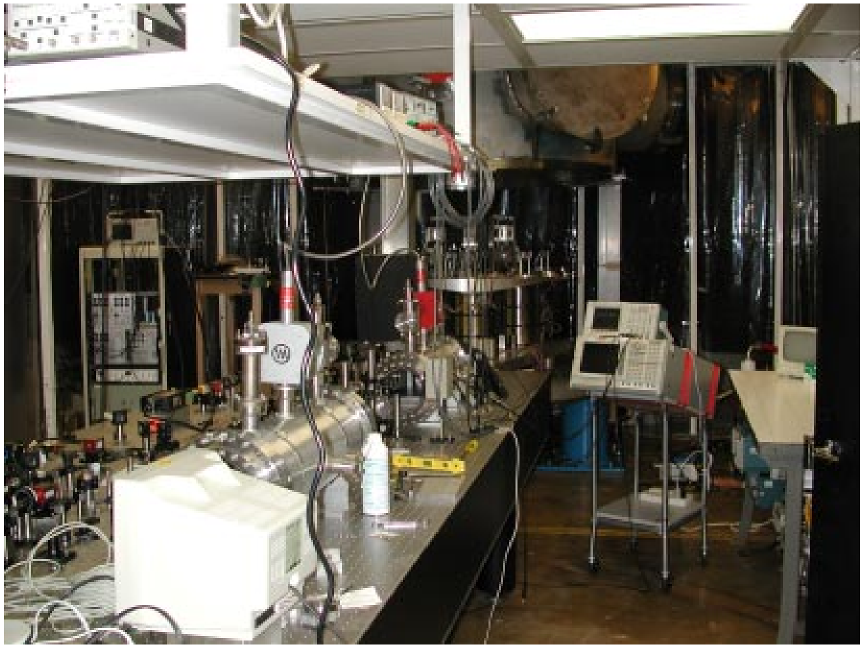
Build servo electronics

Lock arm cavity

Prepare sapphire mirrors

Brownian motion measurement



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