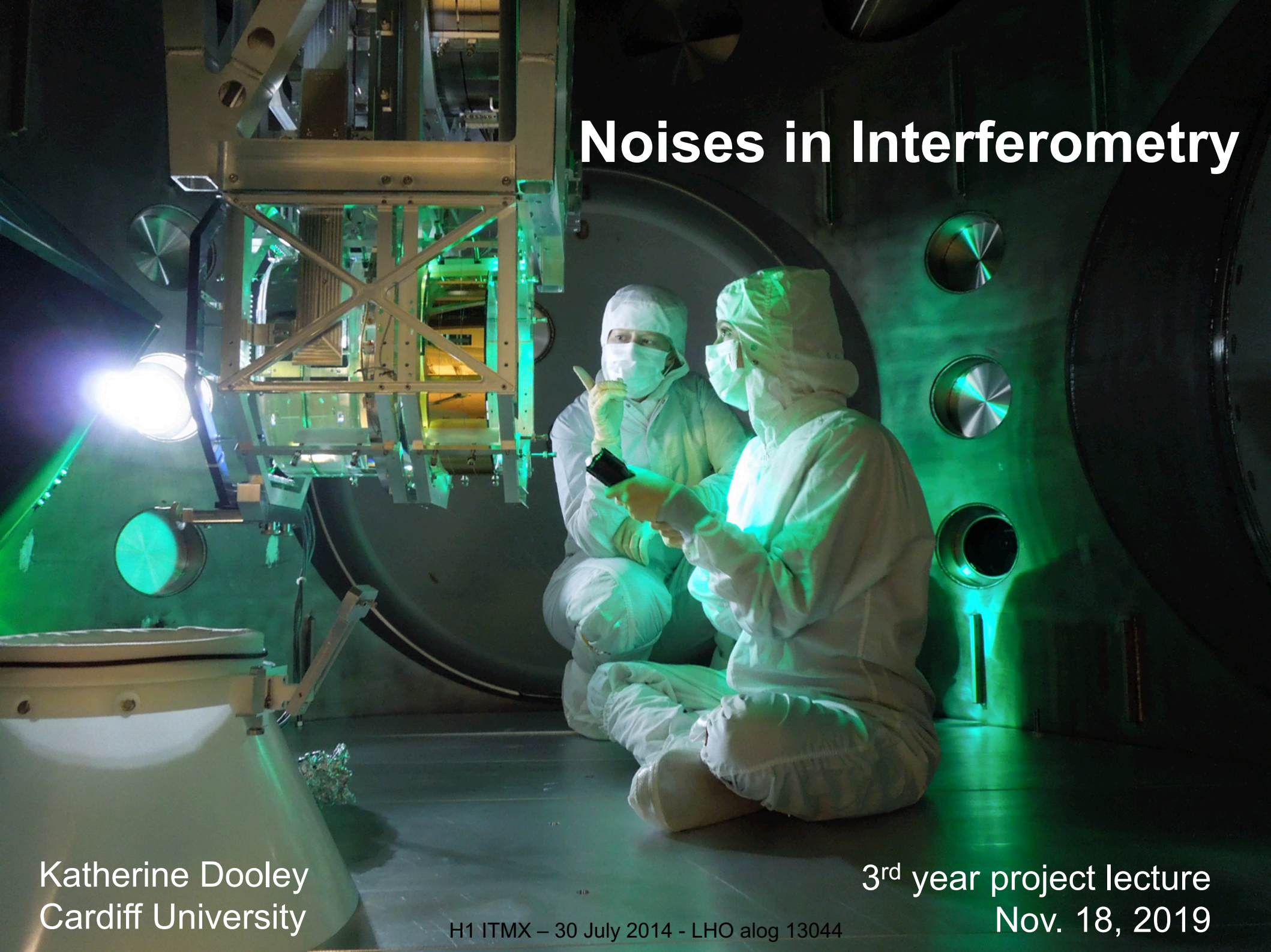
Noises in Interferometry

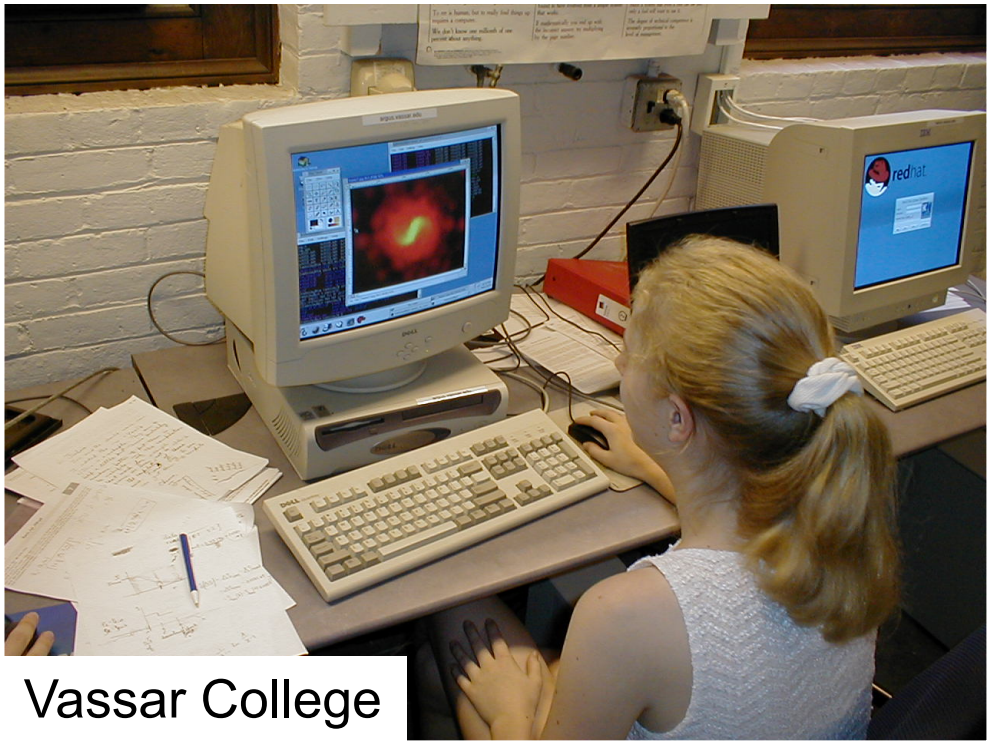


Katherine Dooley
Cardiff University

3rd year project lecture
Nov. 18, 2019

H1 ITMX – 30 July 2014 - LHO alog 13044

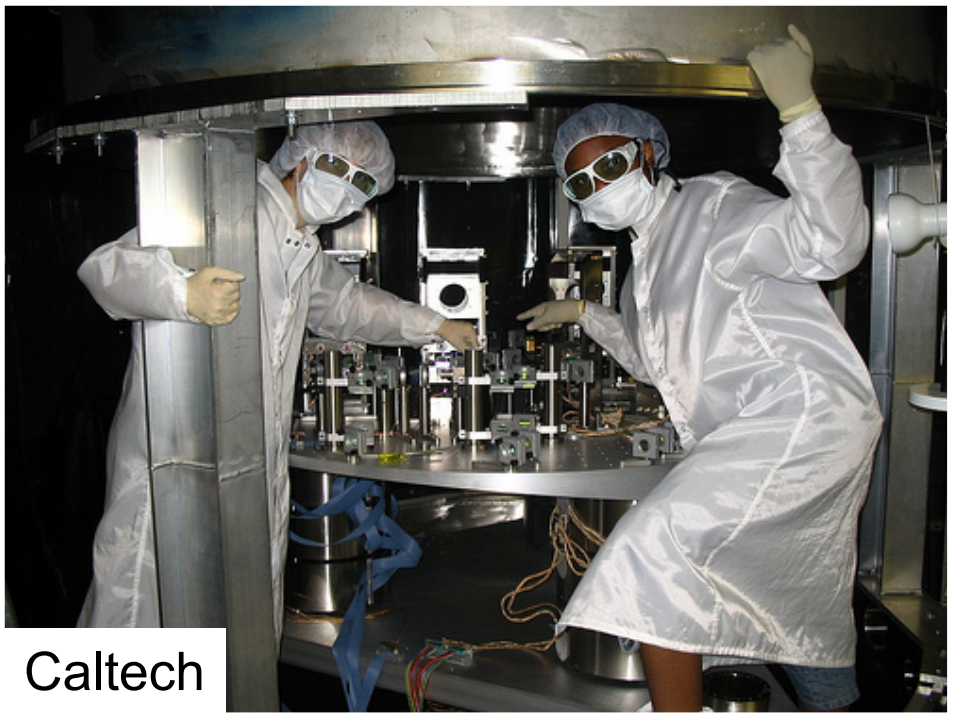
Undergraduate summer research experiences



Vassar College

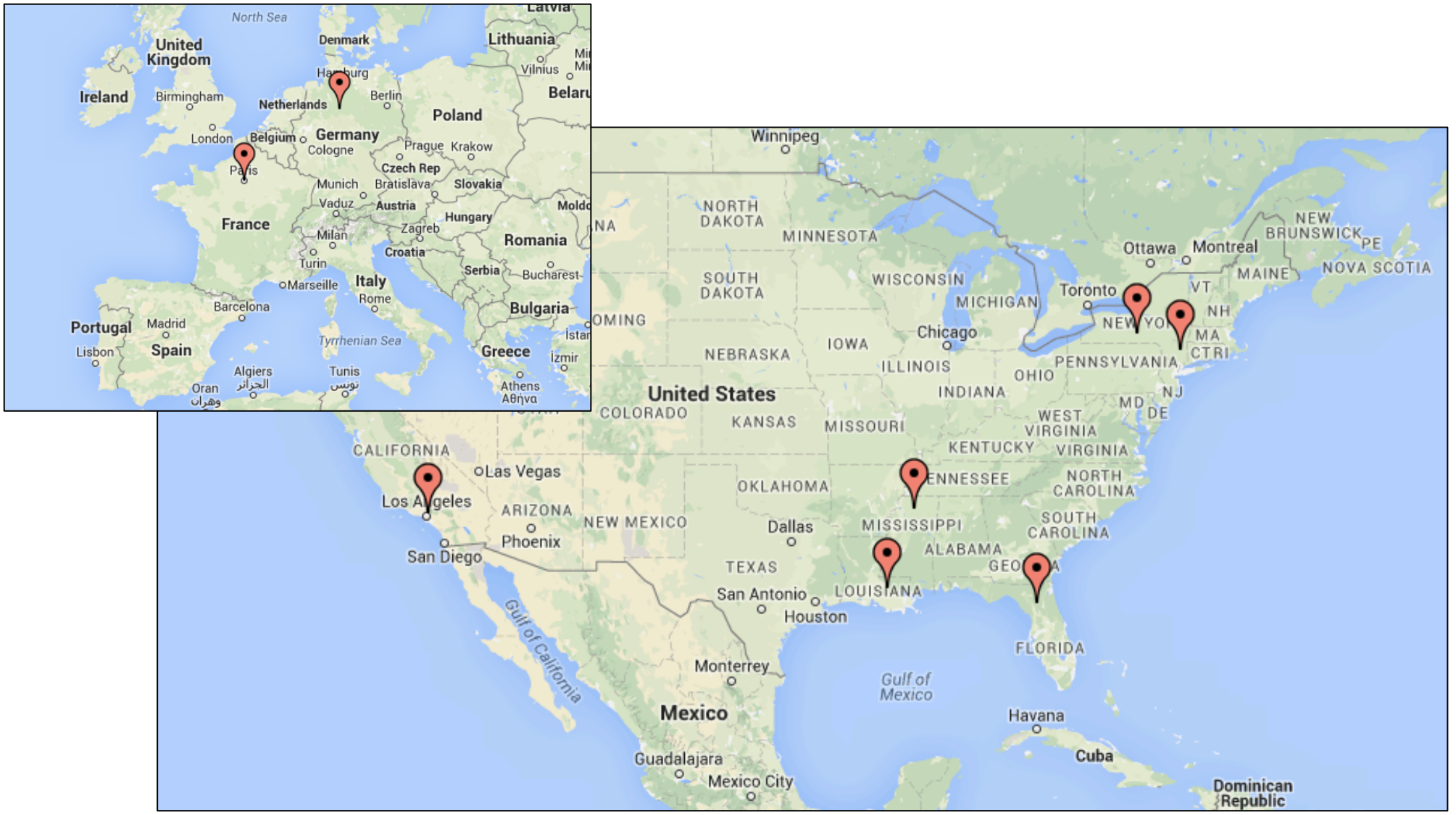
- Modeling
- Data analysis
- Experiment

Cornell University



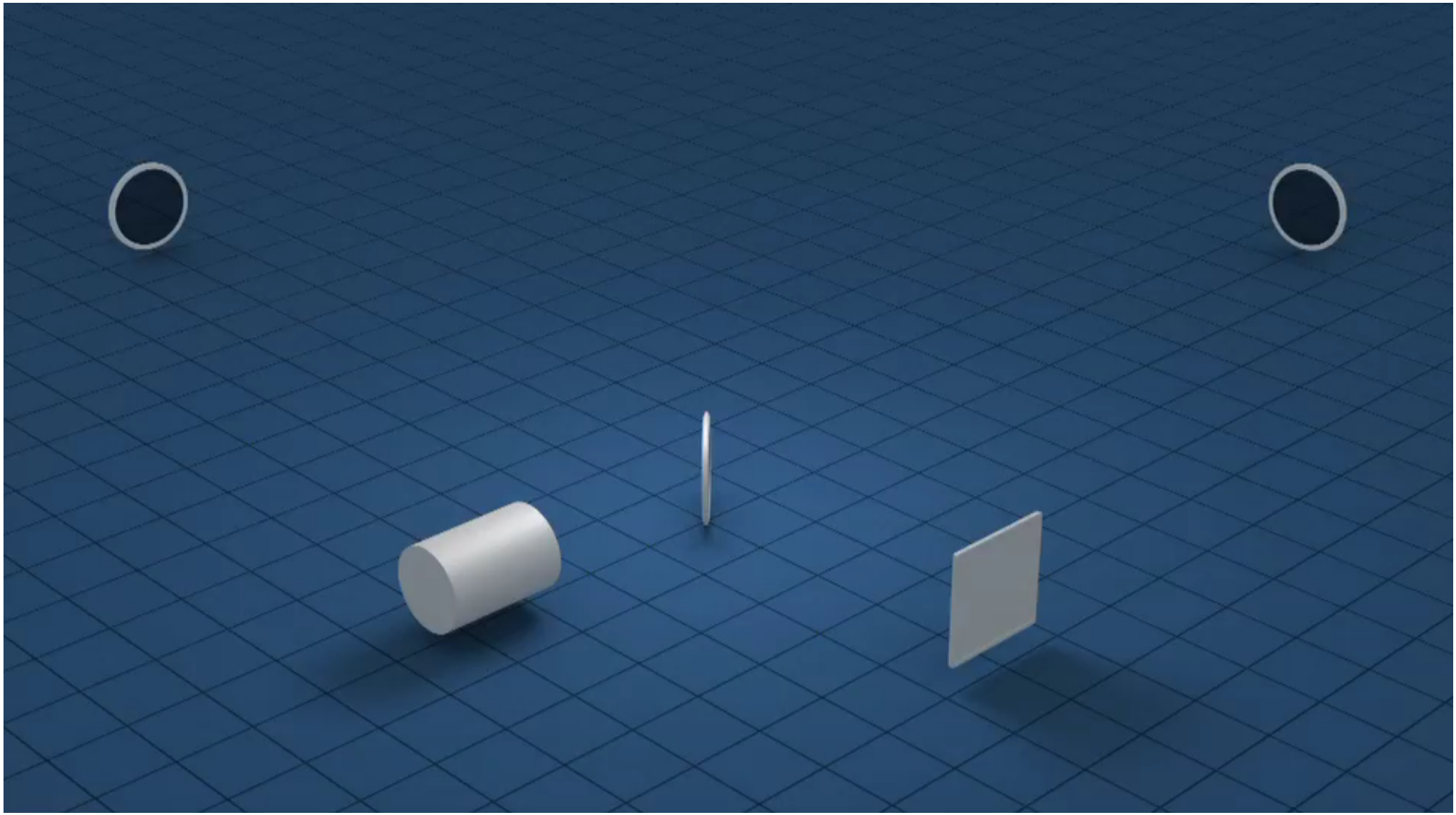
Caltech

A career for travel lovers!



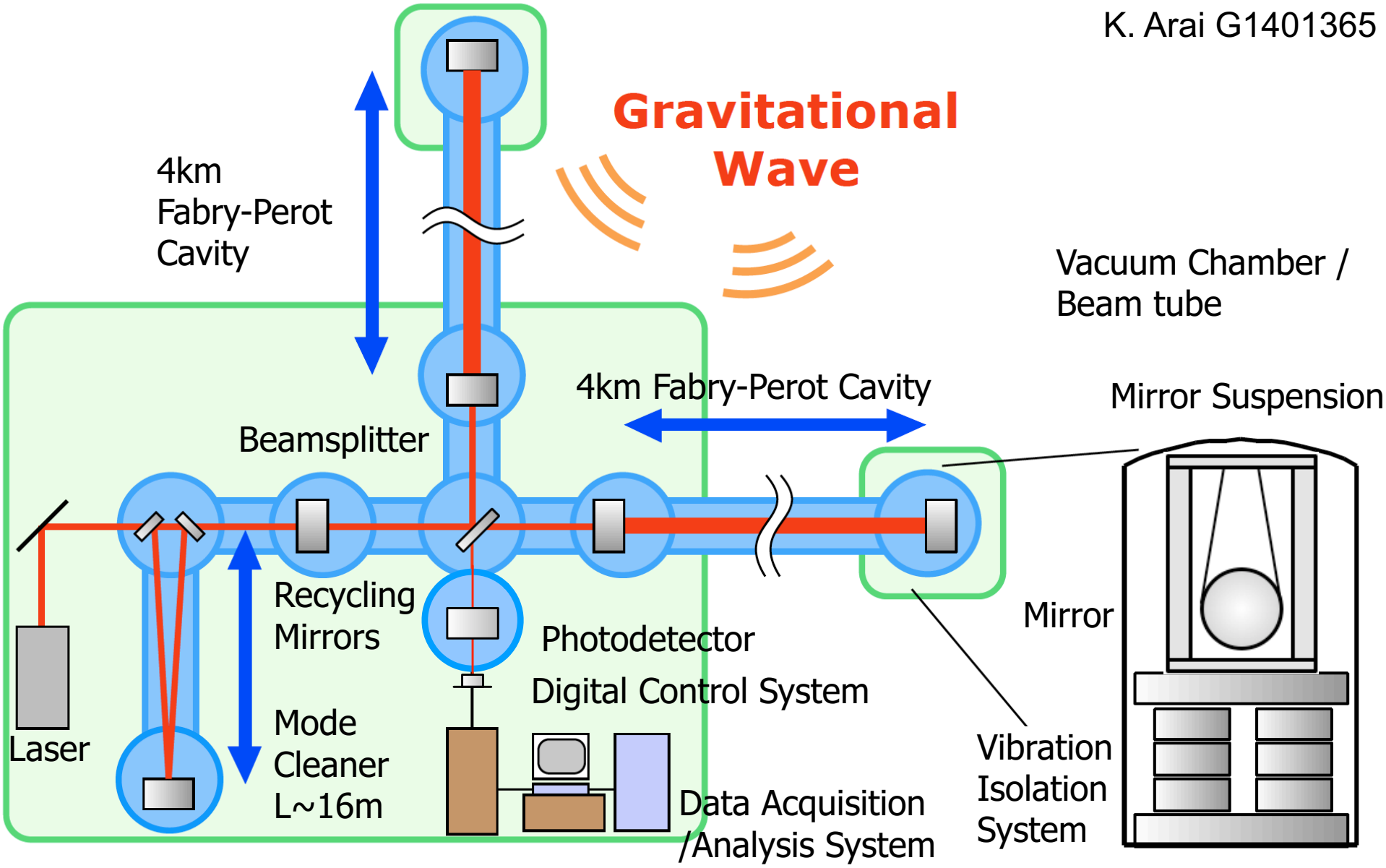
The places I've lived (+ Cardiff!)

The gravitational wave detectors

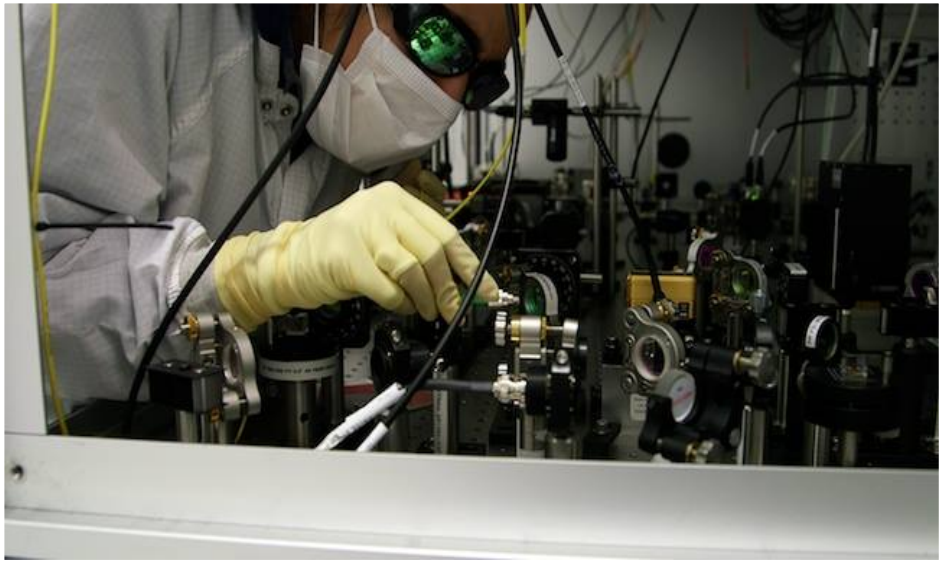


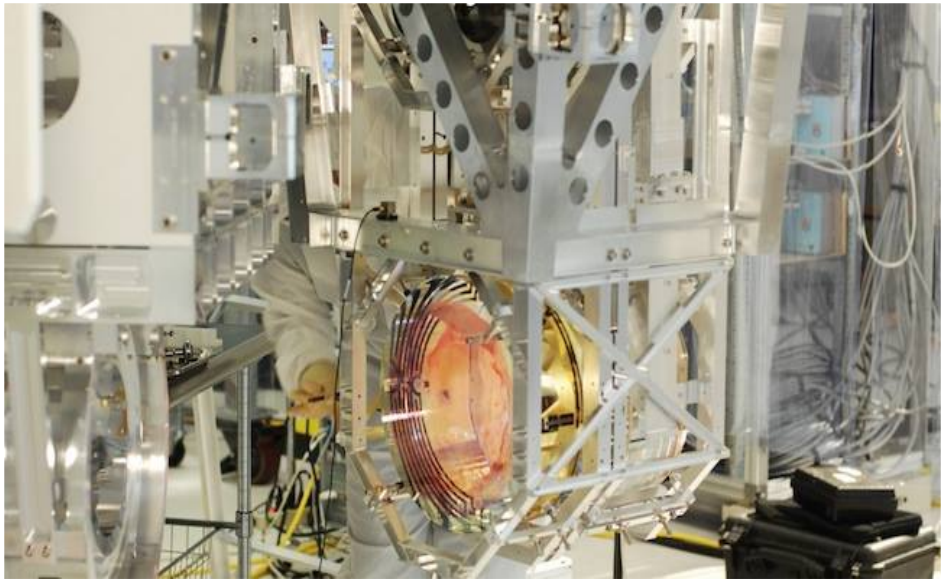
The most precise ruler ever constructed.

Components of the interferometer

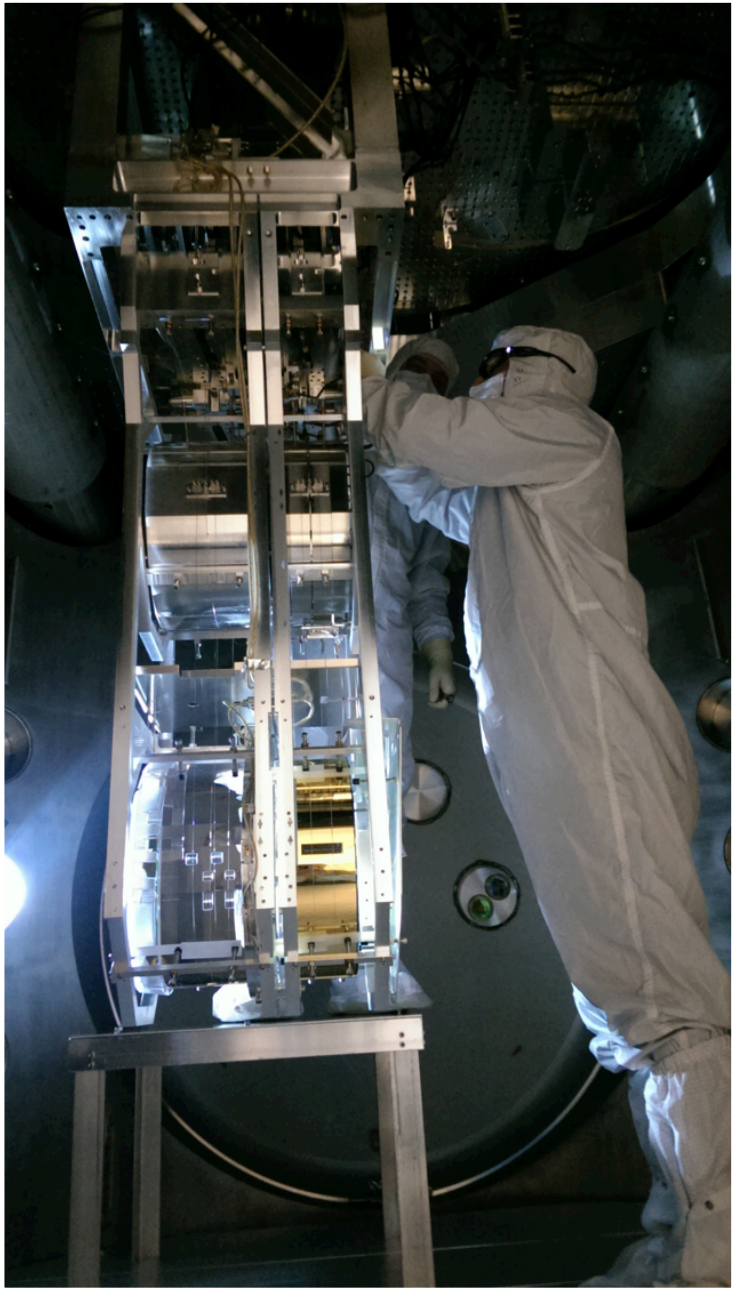


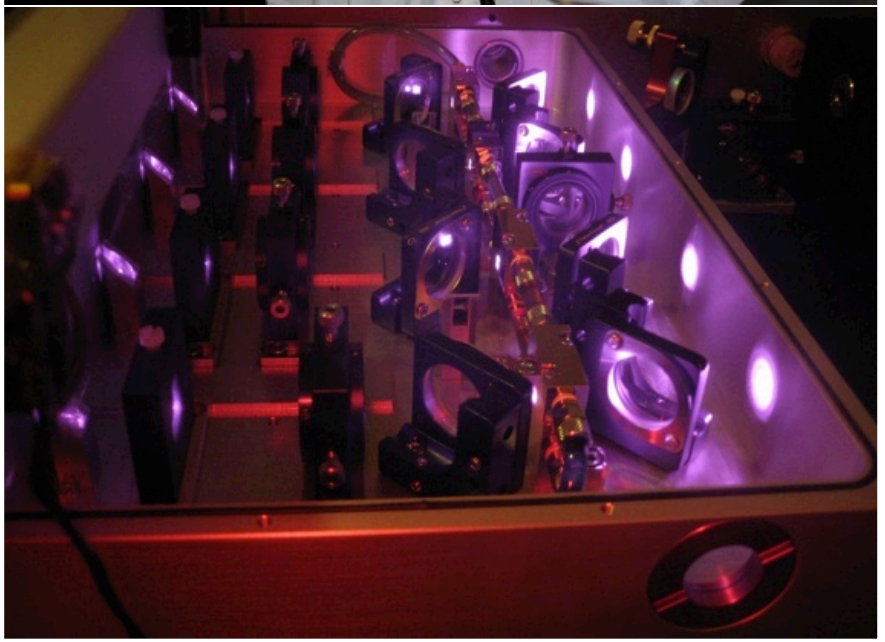
What the detectors really look like



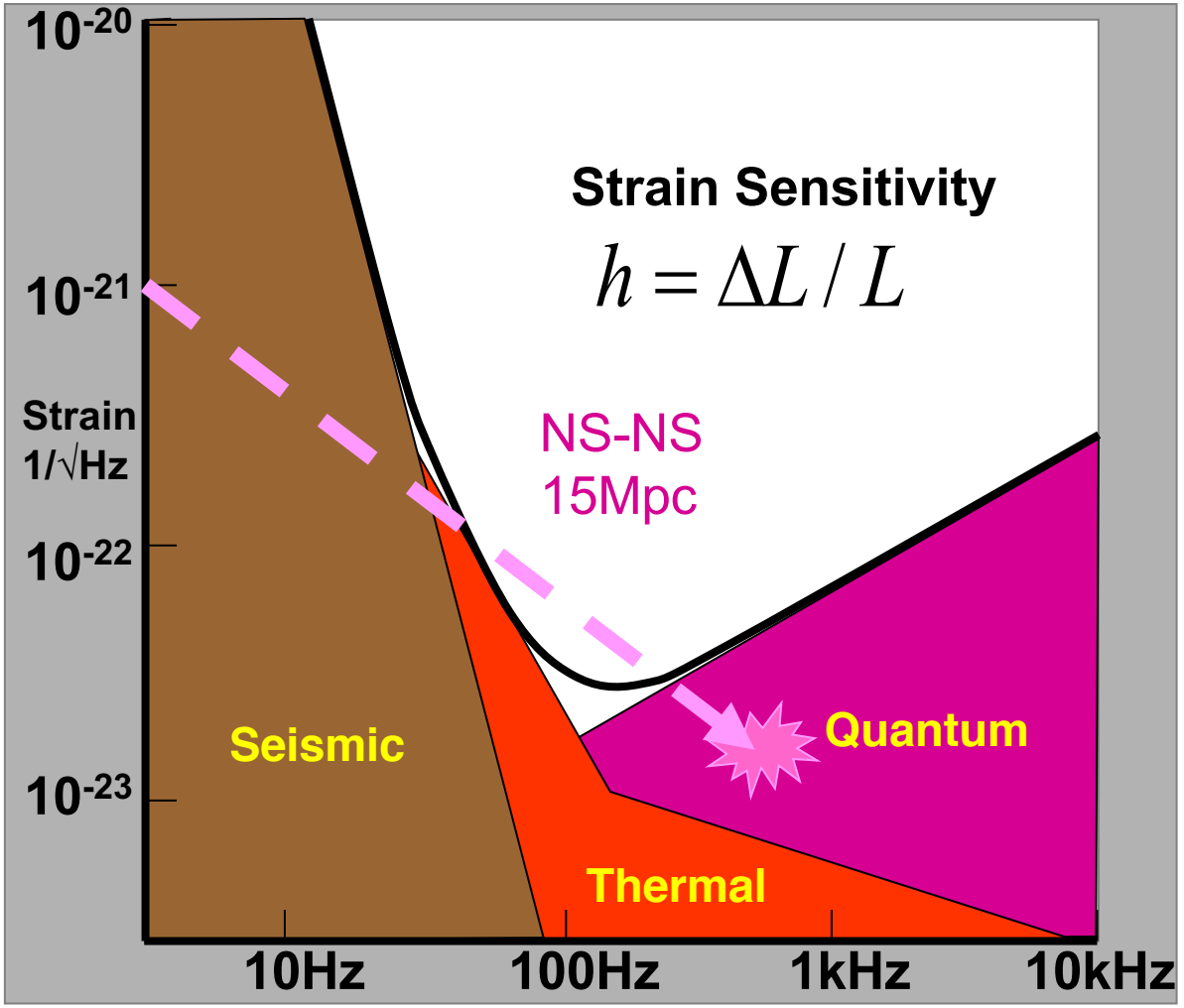


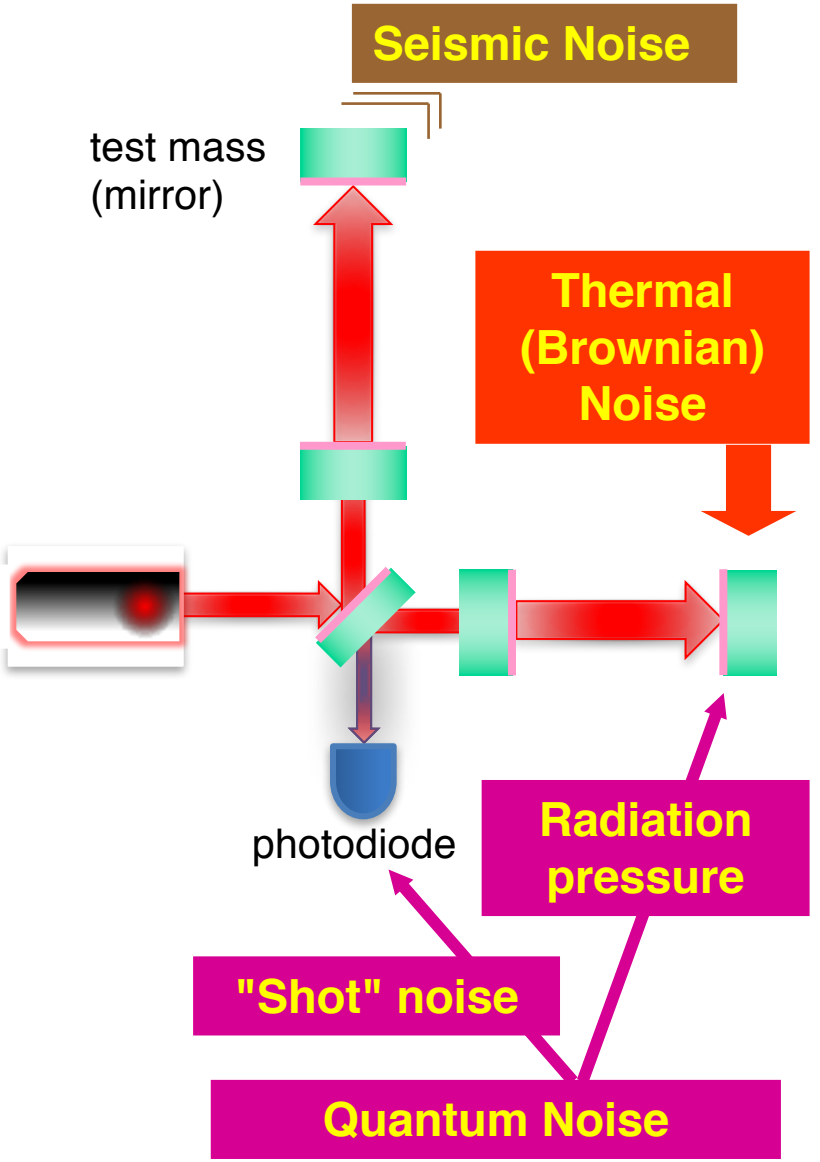
What the detectors really look like





Noise categories





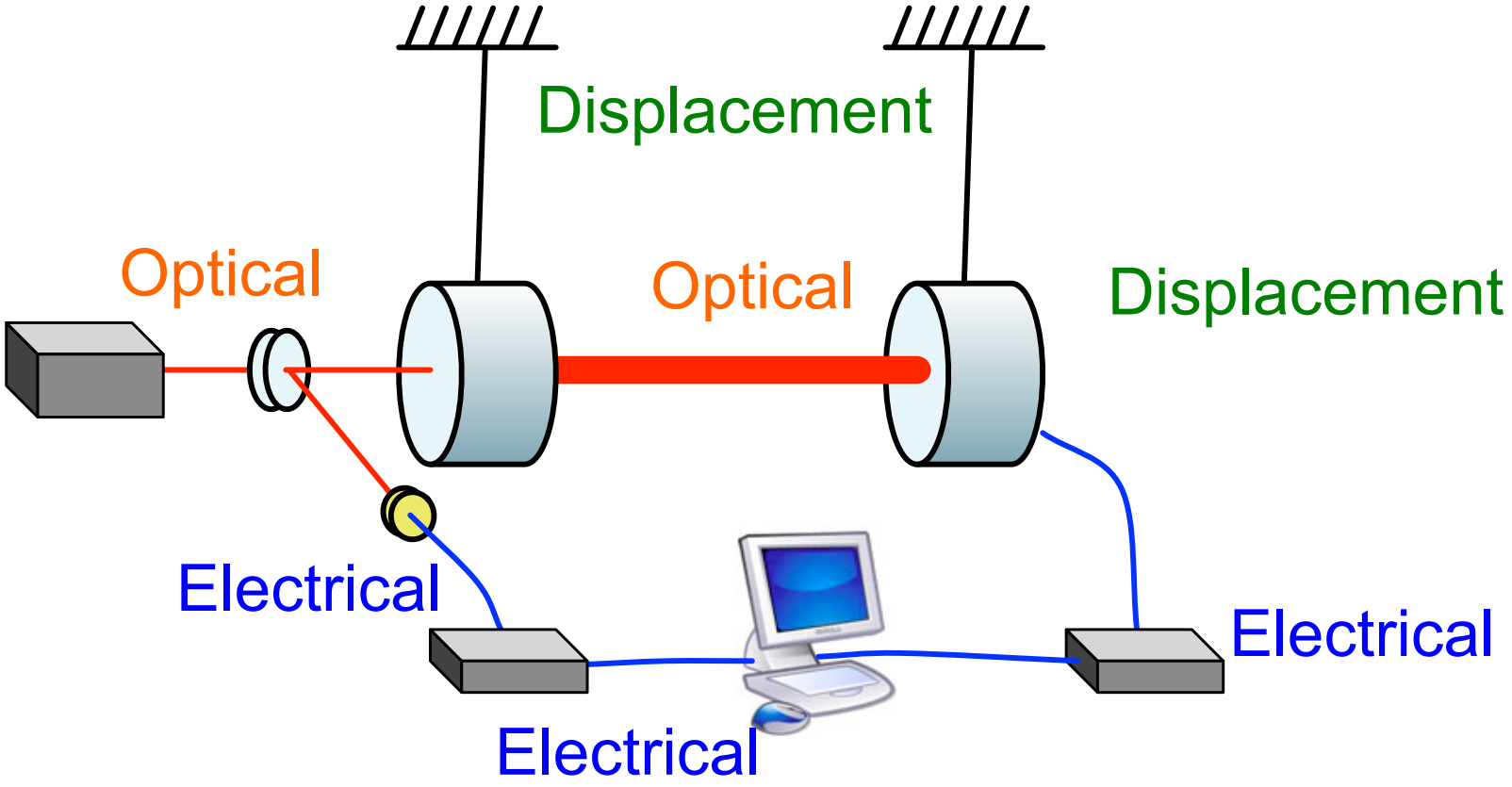
Noise categories

3 fundamental types of noises:

Mechanics → Displacement noises

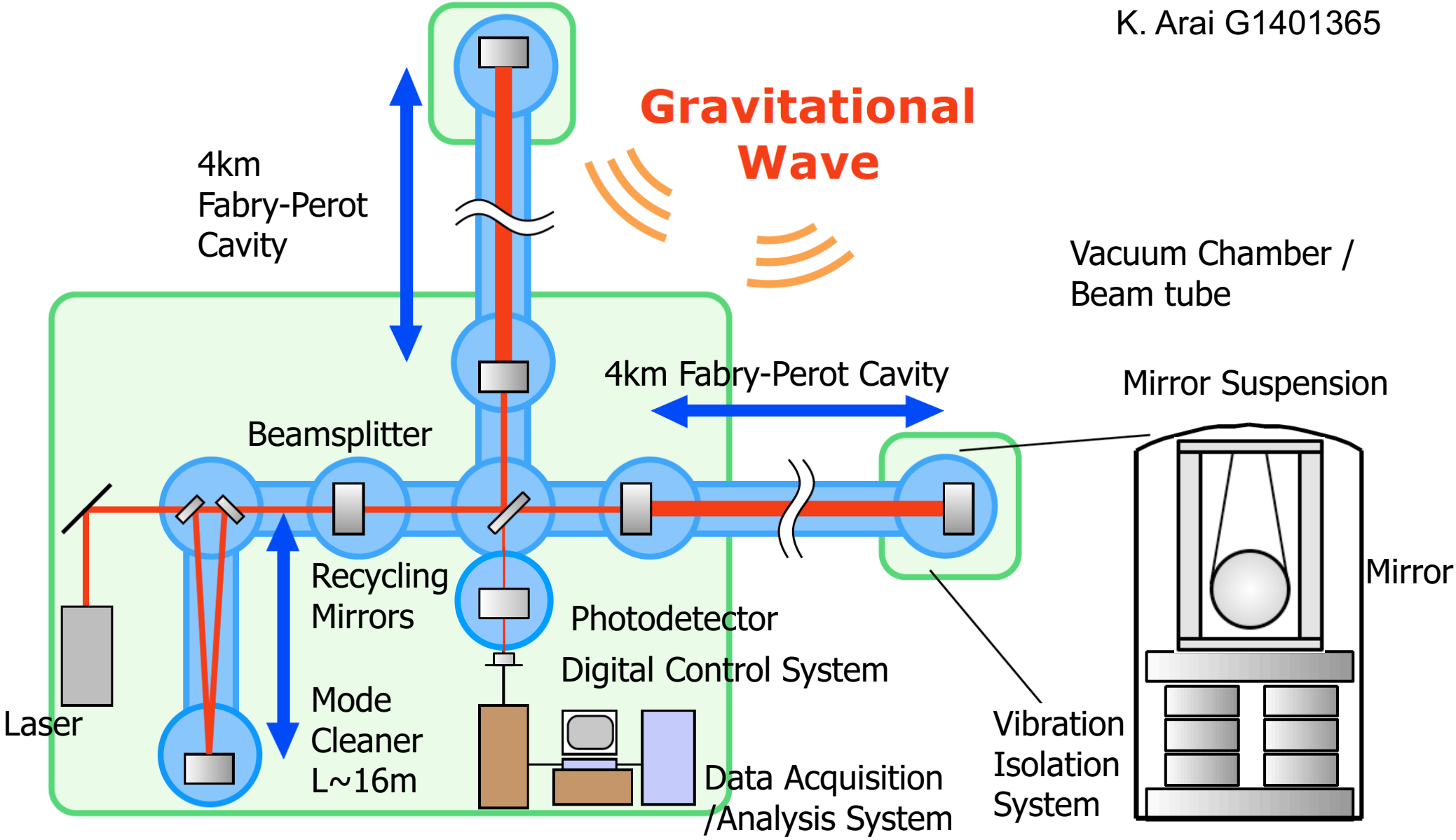
Optics → Optical noises

Electronics → Electrical noises



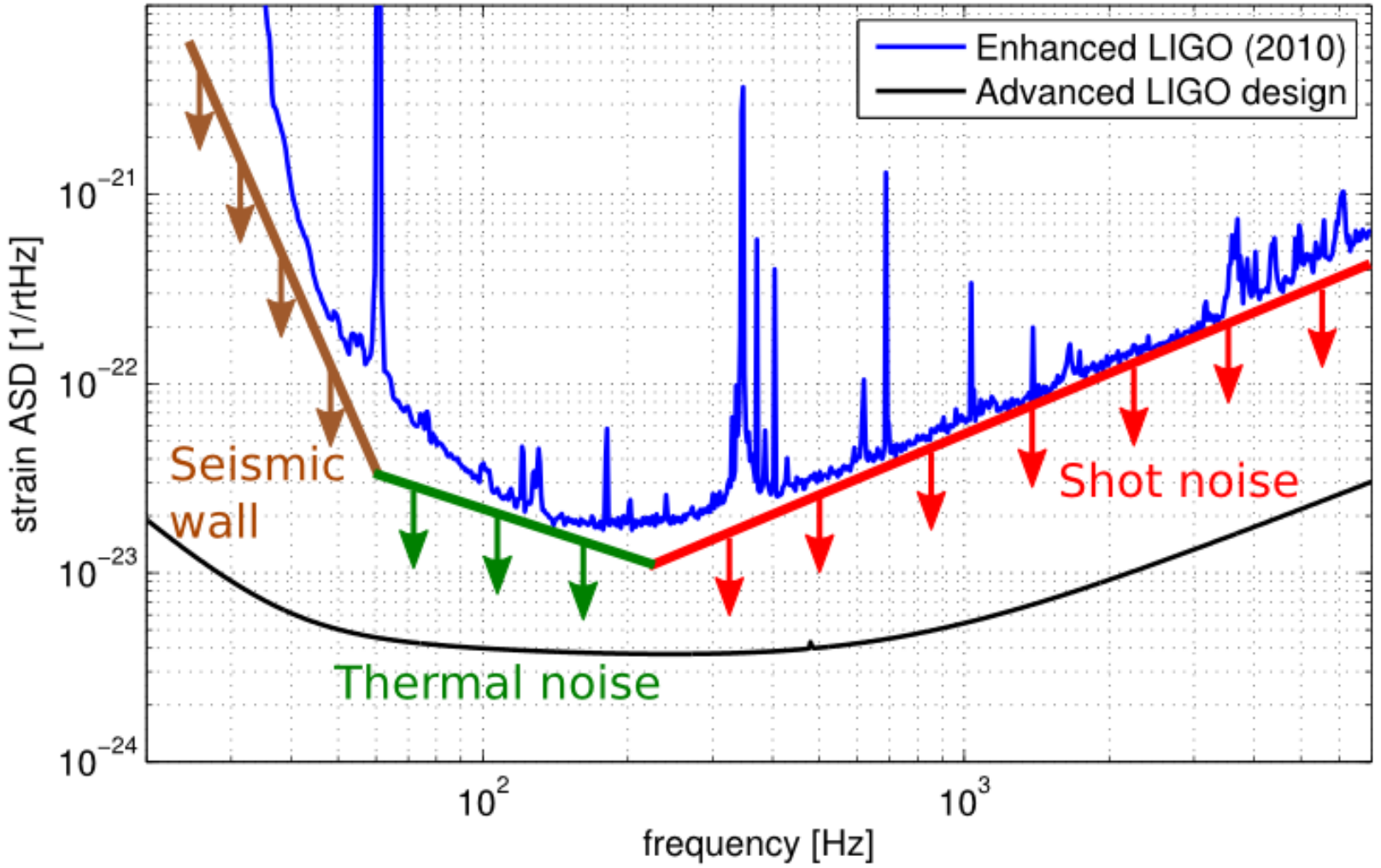
Components of the interferometer

K. Arai G1401365

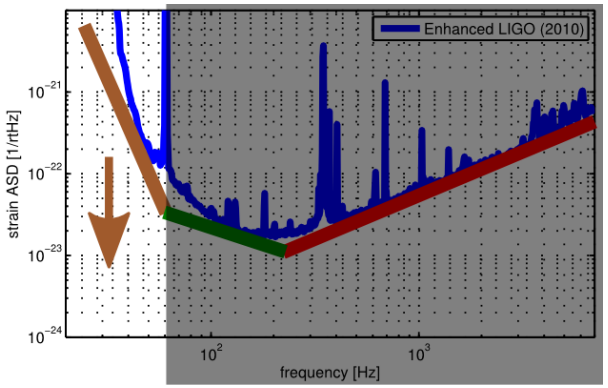


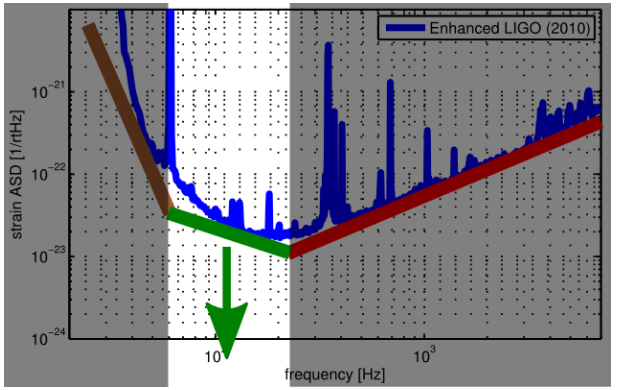
Experimental challenge: noises

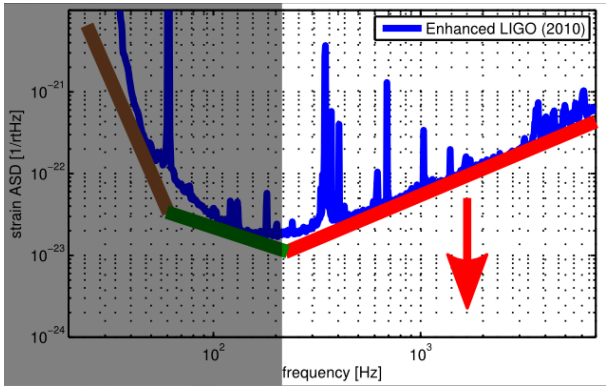
$h = \Delta L / L$



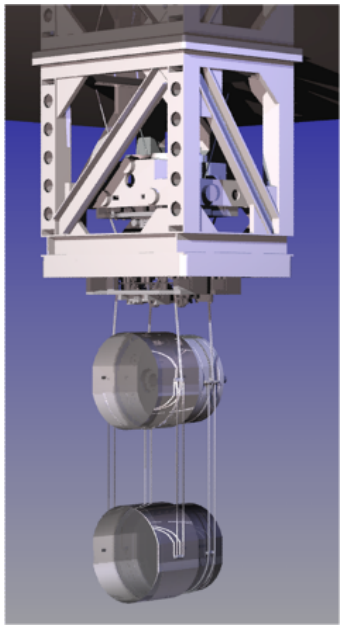
Background: From Initial to Advanced LIGO



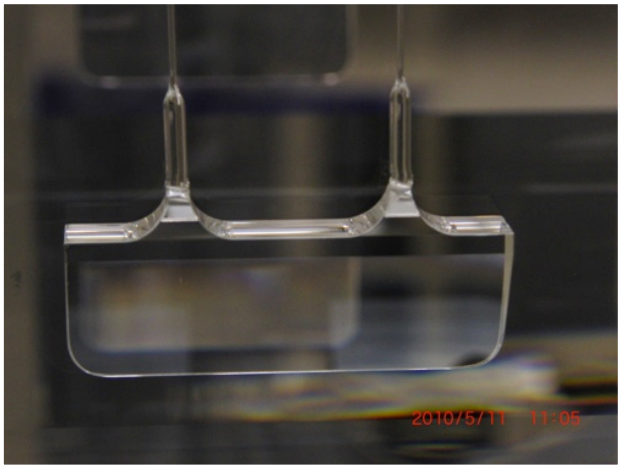




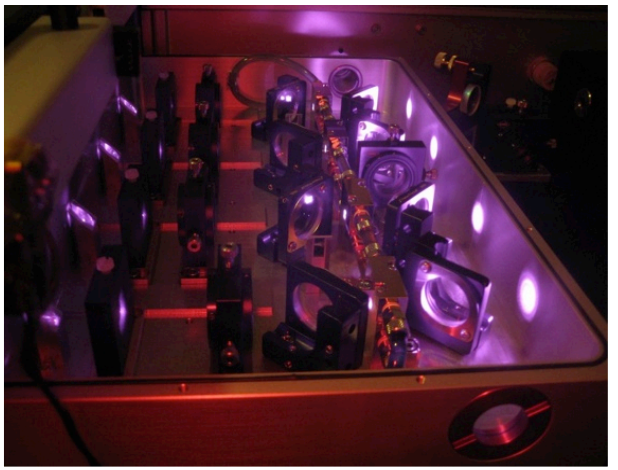
Extreme isolation



Better optics

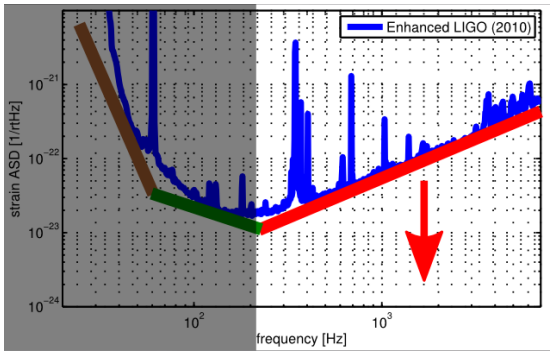


Higher power

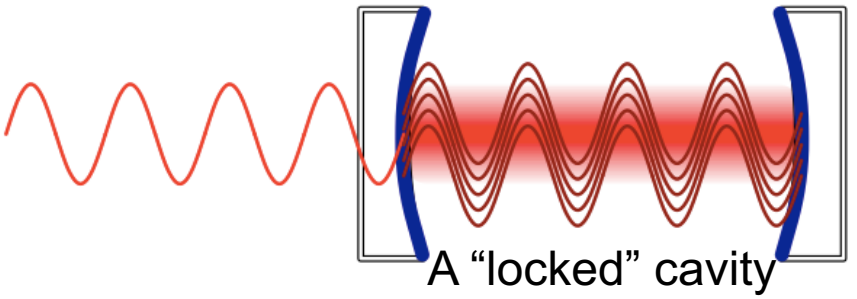


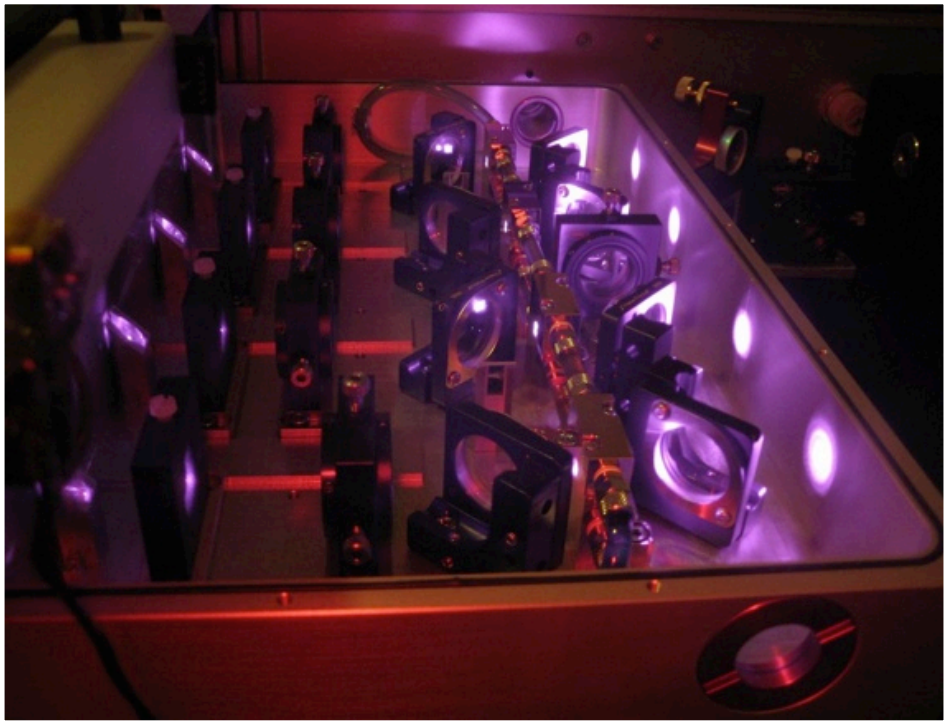
A. Effler

More power…

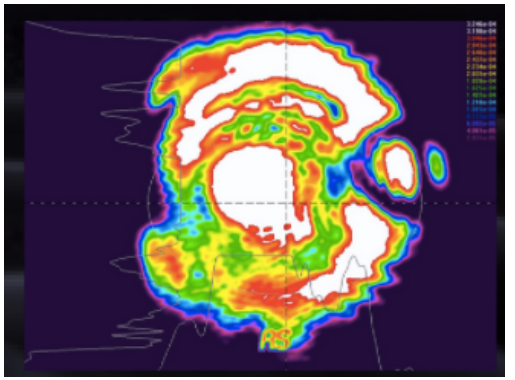


- 100 W input power
- 5 kW on beam-splitter
- 1 MW in arm cavities

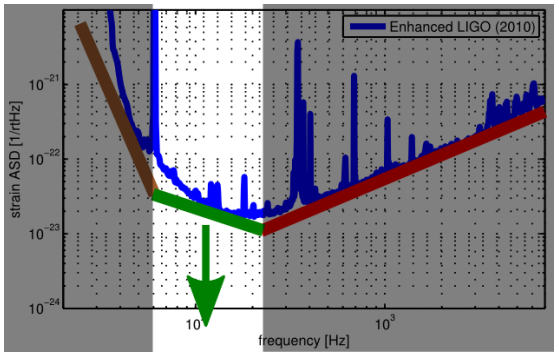




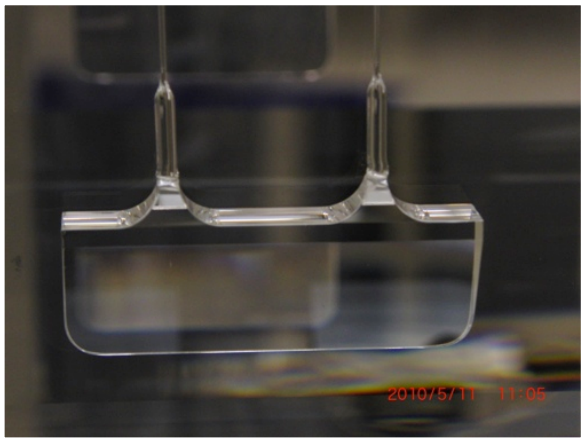
Radiation pressure and thermal effects become a serious problem

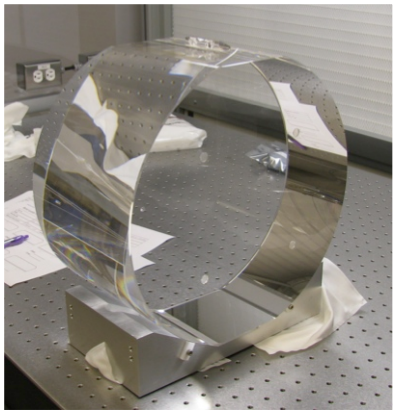


…better optics…

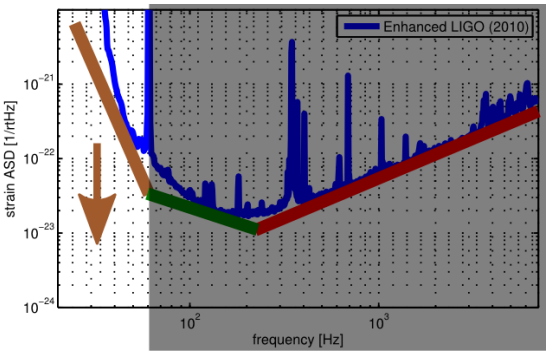


- Better coatings (titania-doped layers)
- Monolithic suspensions
- Larger beam spots

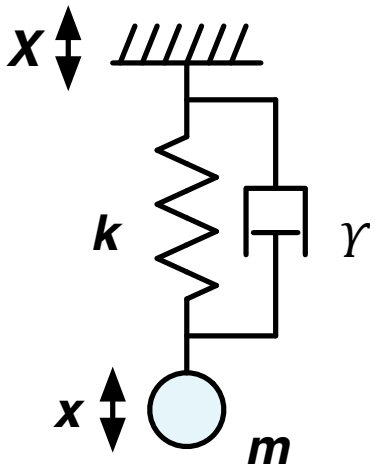


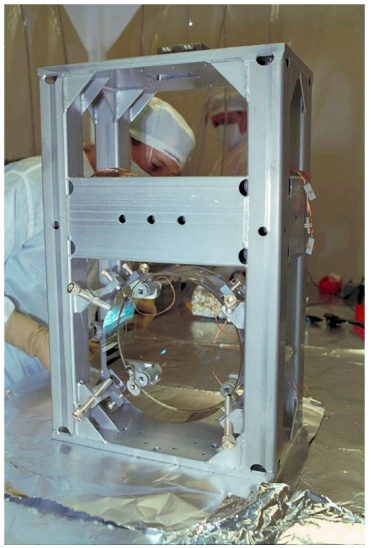


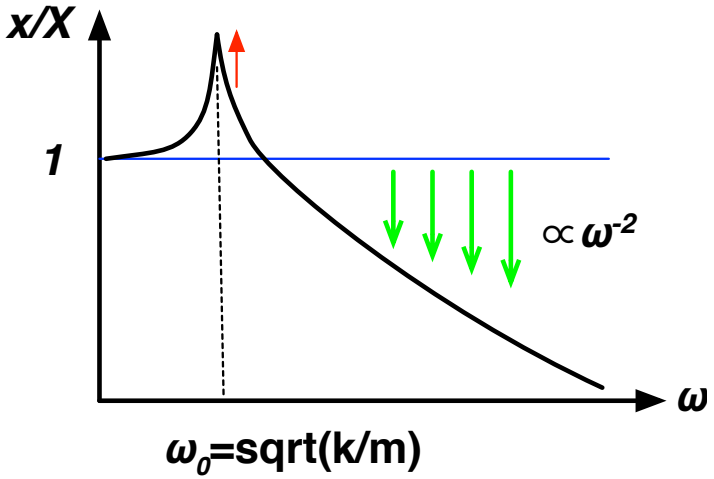
…extreme isolation



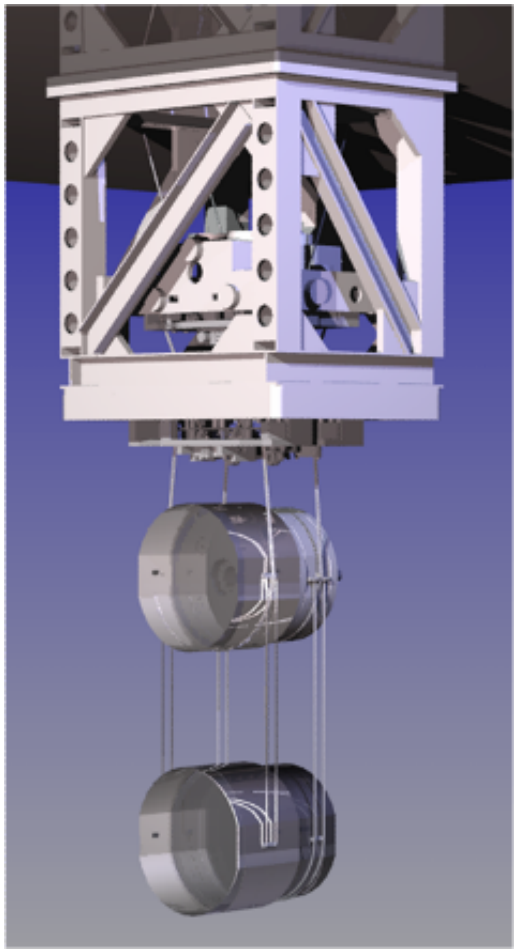
Initial LIGO: single-stage suspensions





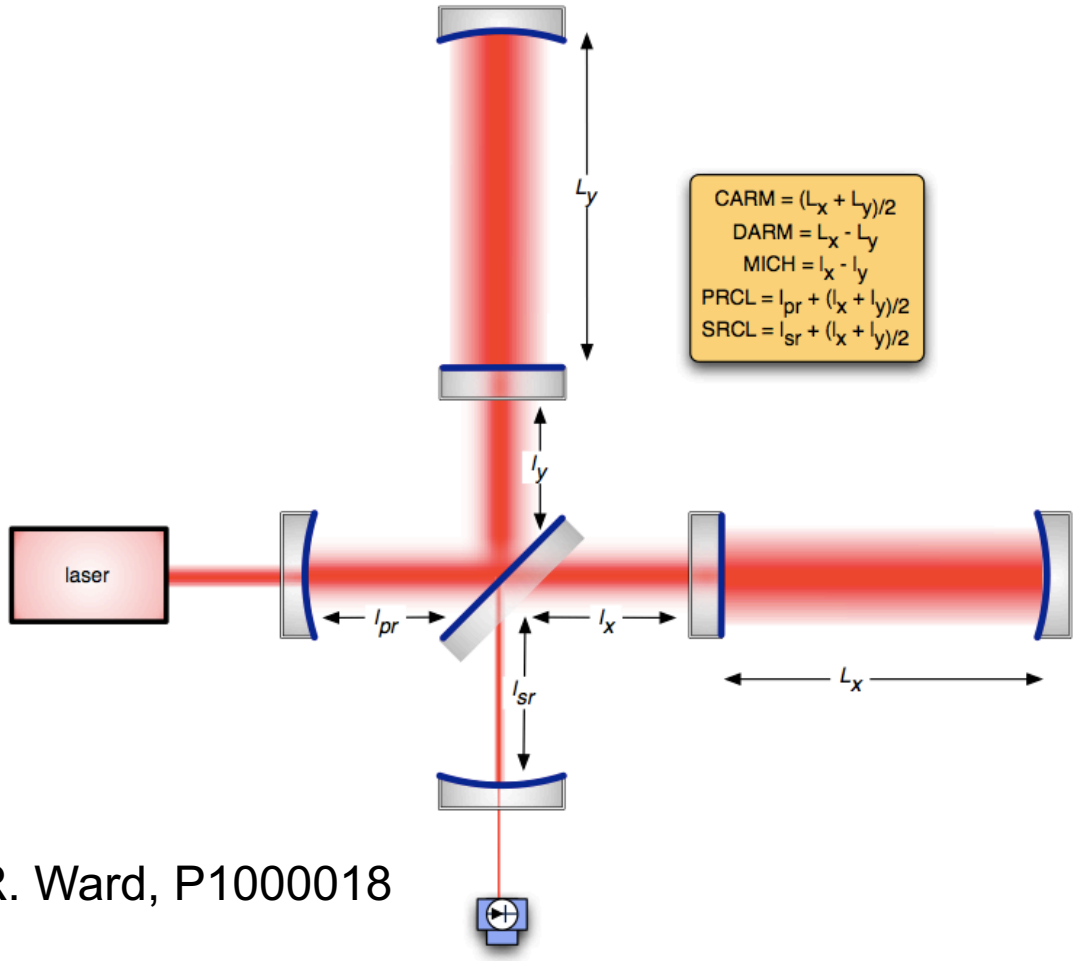


Advanced LIGO: quadruple-stage suspensions

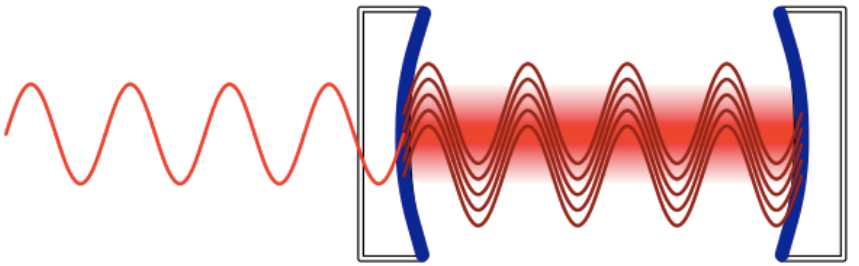


Why mirror motion is not tolerable

- 5 cavities → 5 length degrees of freedom



R. Ward, P1000018

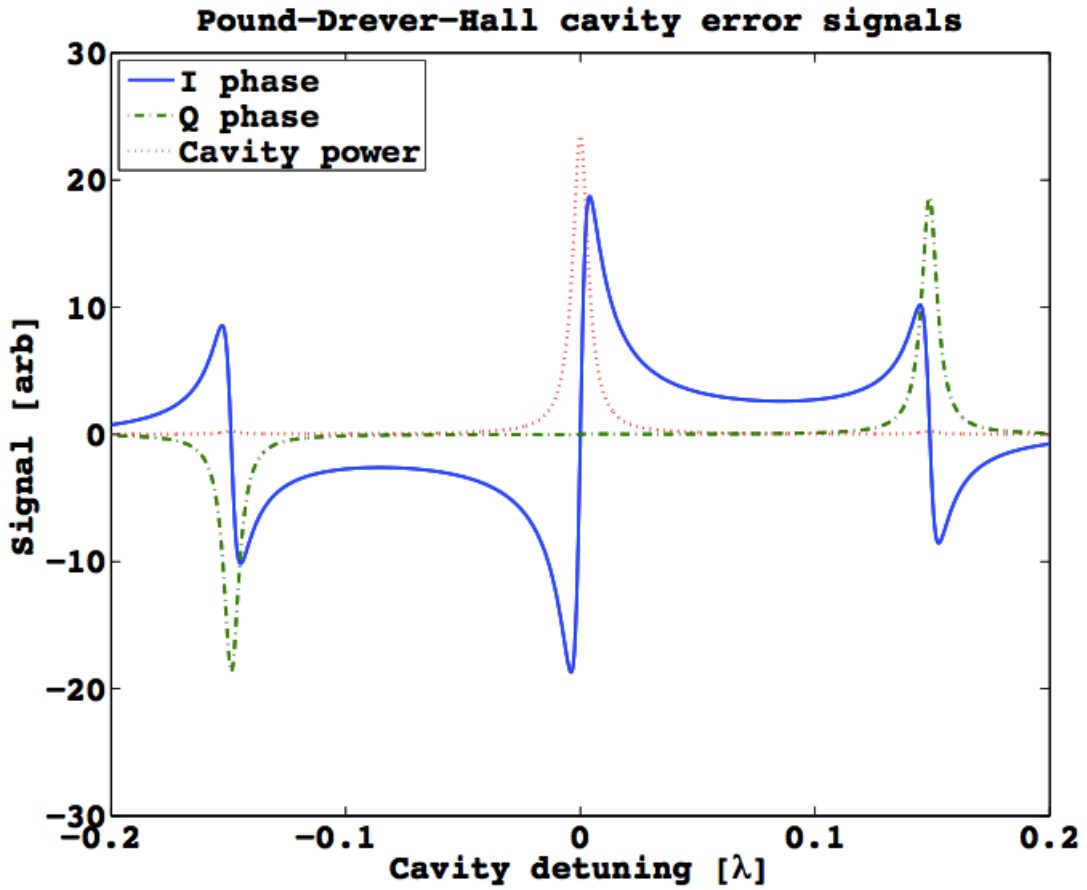


A “locked” cavity.

All cavities must be locked simultaneously.

Why mirror motion is not tolerable

- GW detection relies on operation in the linear regime



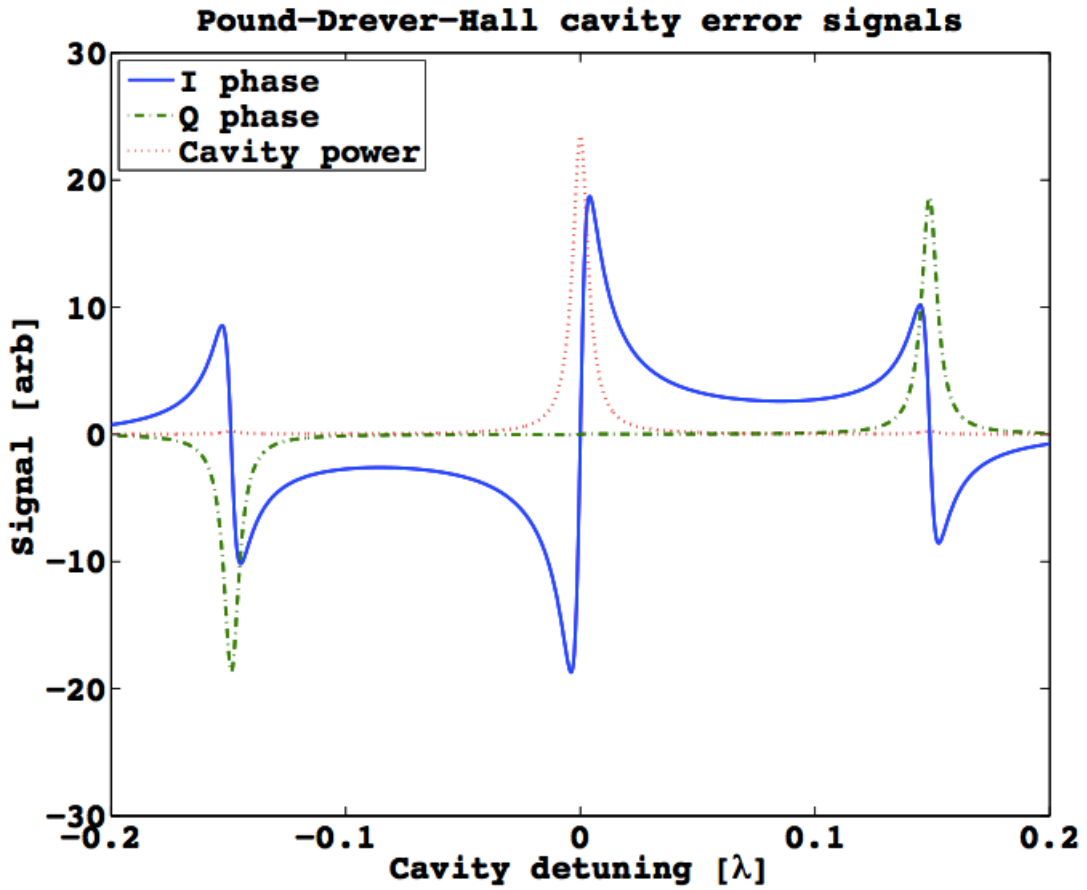
R. Ward, P1000018

- Relative mirror motion requirement:

$< 1 \times 10^{-15}$ m RMS

Why mirror motion is not tolerable

- 5 cavities → 5 length degrees of freedom



R. Ward, P1000018

- Relative mirror motion requirement:

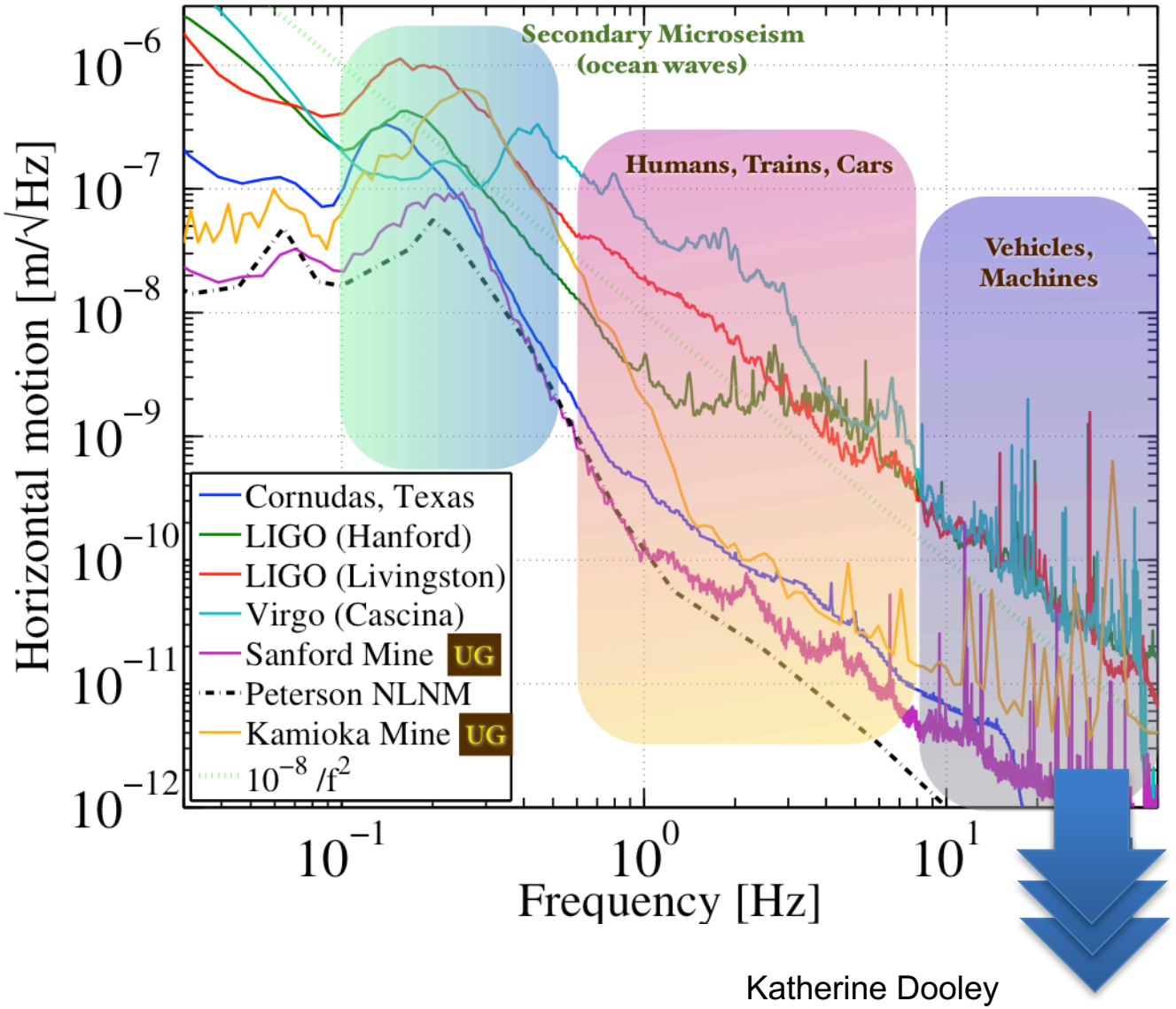
$< 1 \times 10^{-15}$ m RMS

- But the ground motion is:

1×10^{-6} m RMS !

Seismic noise

Even when there is no noticeable earth quake…



Need:

- 10 orders of magnitude isolation at 30 Hz
- 9 orders of magnitude isolation at 0.15 Hz

Target displacement noise:

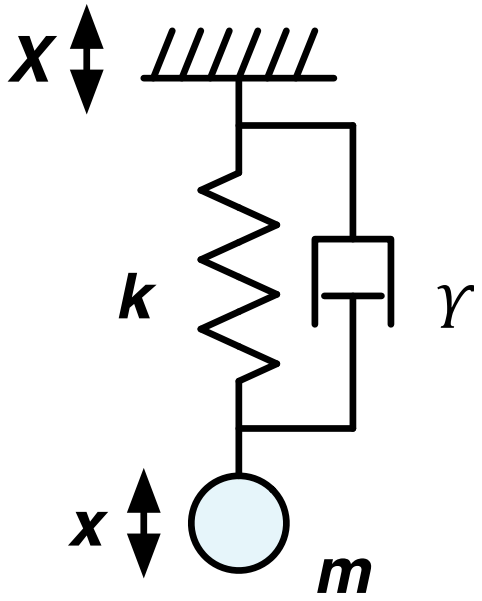
10^{-20} m/rtHz at 30 Hz

http://link.aps.org/doi/10.1103/RevModPhys.86.121 (http://arxiv.org/abs/1305.5188)

Passive isolation

Vibration isolation ~ use a harmonic oscillator

A harmonic oscillator provides vibration isolation above its resonant frequency



$$m\ddot{x} = -k(x - X) - \gamma(\dot{x} - \dot{X})$$

$$\left(\omega_0^2 + i\frac{\gamma}{m}\omega - \omega^2\right)\tilde{x} = \left(\omega_0^2 + i\frac{\gamma}{m}\omega\right)\tilde{X}$$

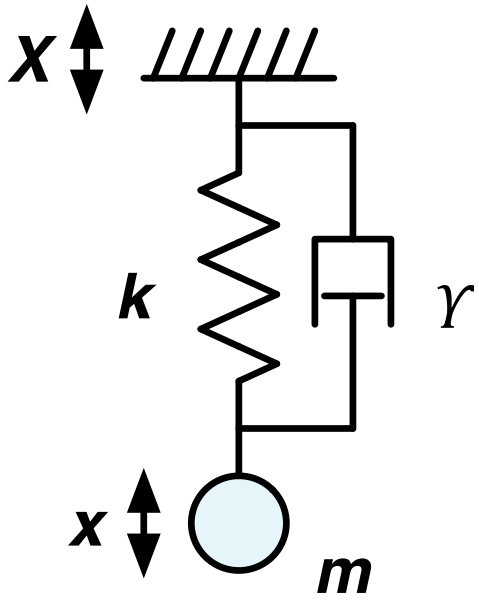
$$\frac{\tilde{x}}{\tilde{X}} = \frac{\omega_0^2 + i\frac{\gamma}{m}\omega}{\omega_0^2 + i\frac{\gamma}{m}\omega - \omega^2}$$

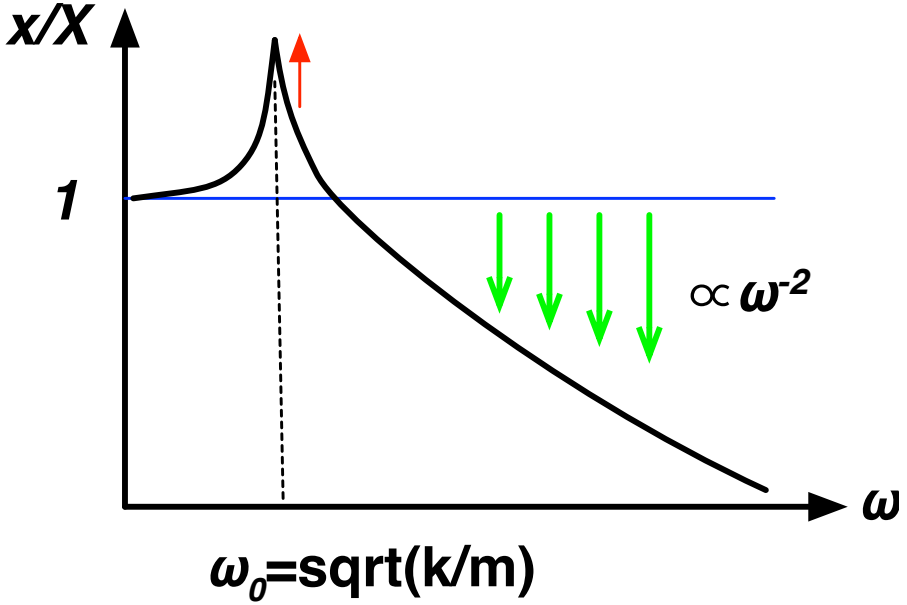
Recall:
F[d/dt f(t)] = i w F(w)

Passive isolation

Vibration isolation ~ use a harmonic oscillator

A harmonic oscillator provides vibration isolation above its resonant frequency



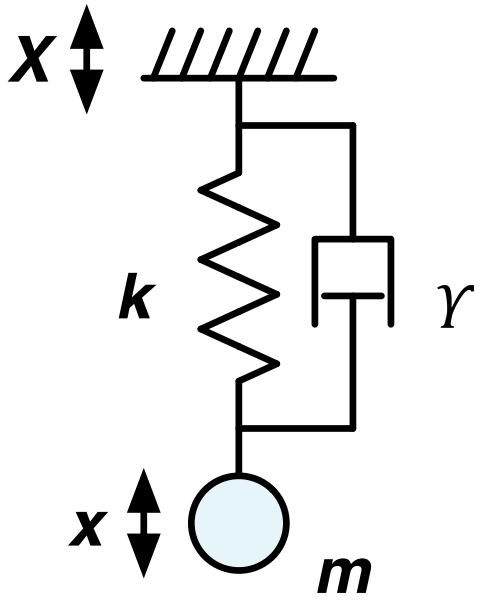


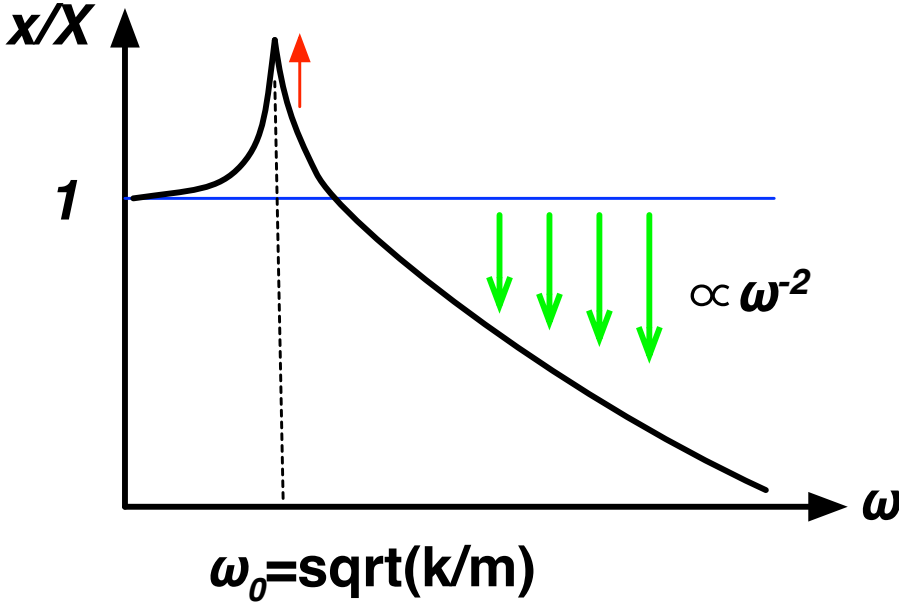
$$\frac{\tilde{x}}{\tilde{X}} = \frac{\omega_0^2 + i\frac{\gamma}{m}\omega}{\omega_0^2 + i\frac{\gamma}{m}\omega - \omega^2}$$

Passive isolation

Vibration isolation ~ use a harmonic oscillator

A harmonic oscillator provides vibration isolation above its resonant frequency

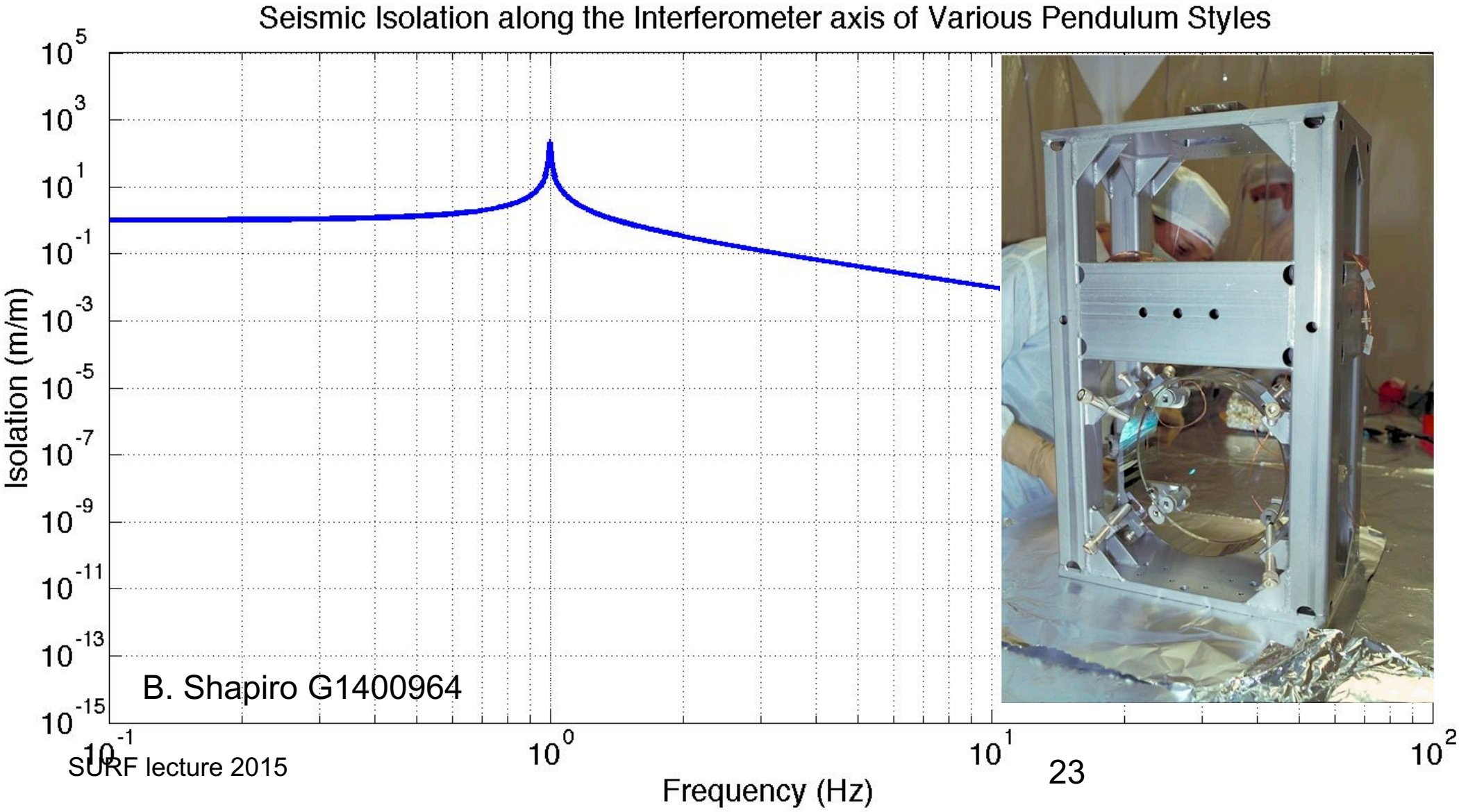




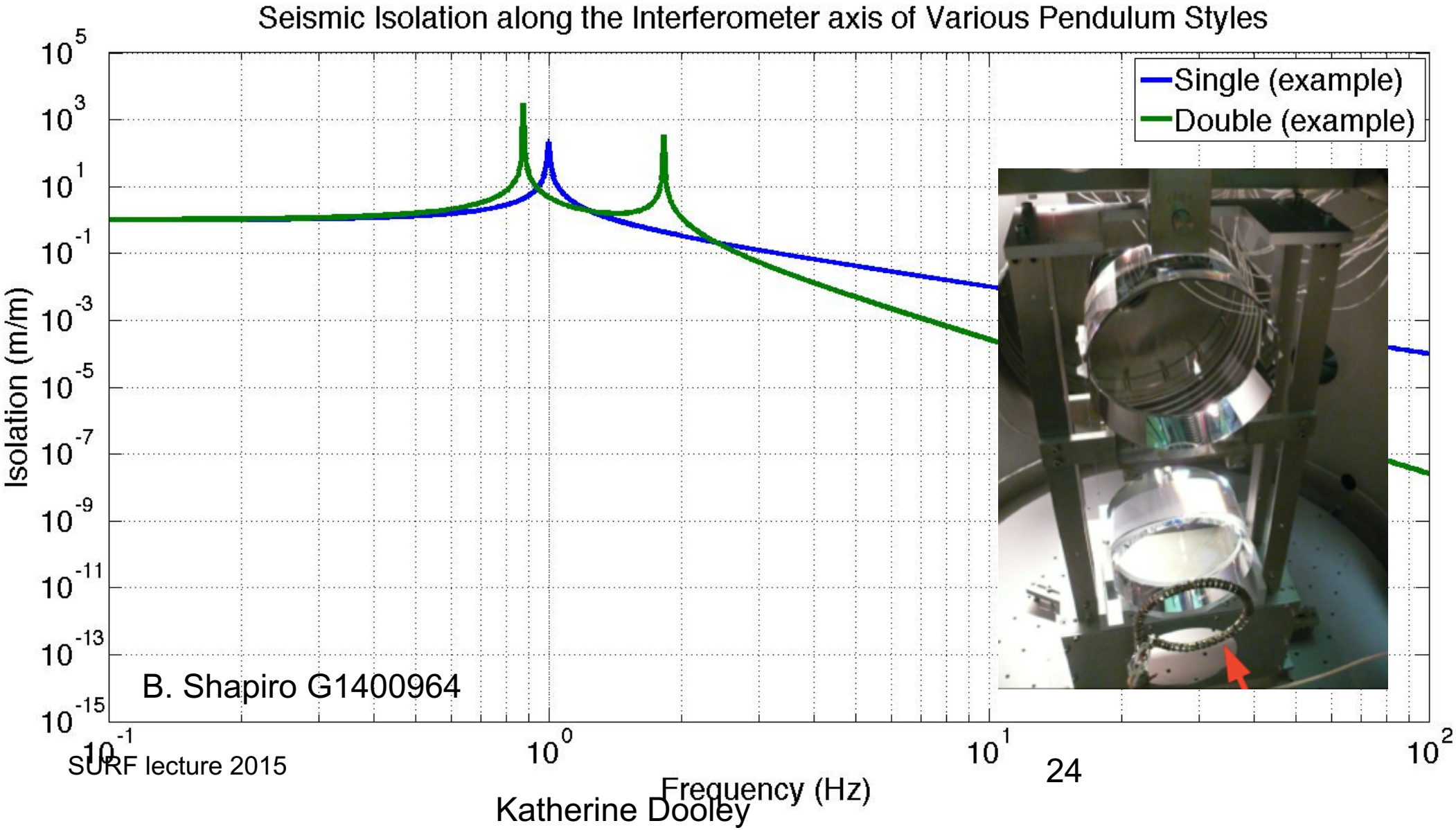
For w_0 = 1Hz,
|x/X|~1/1000 @ 30Hz

$$\frac{\tilde{x}}{\tilde{X}} = \frac{\omega_0^2 + i\frac{\gamma}{m}\omega}{\omega_0^2 + i\frac{\gamma}{m}\omega - \omega^2}$$

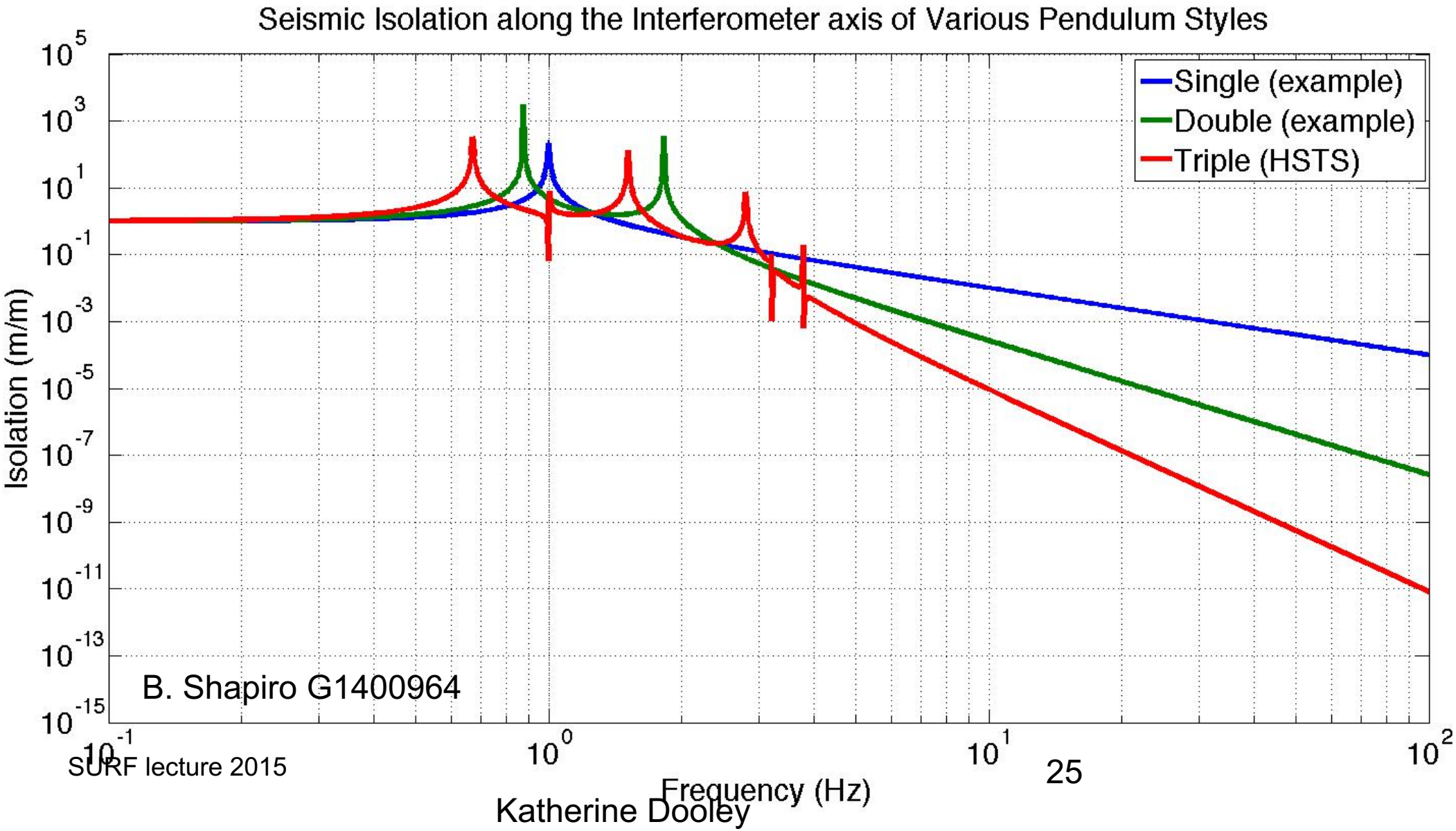
Suspension Isolation: Initial LIGO (~2005)



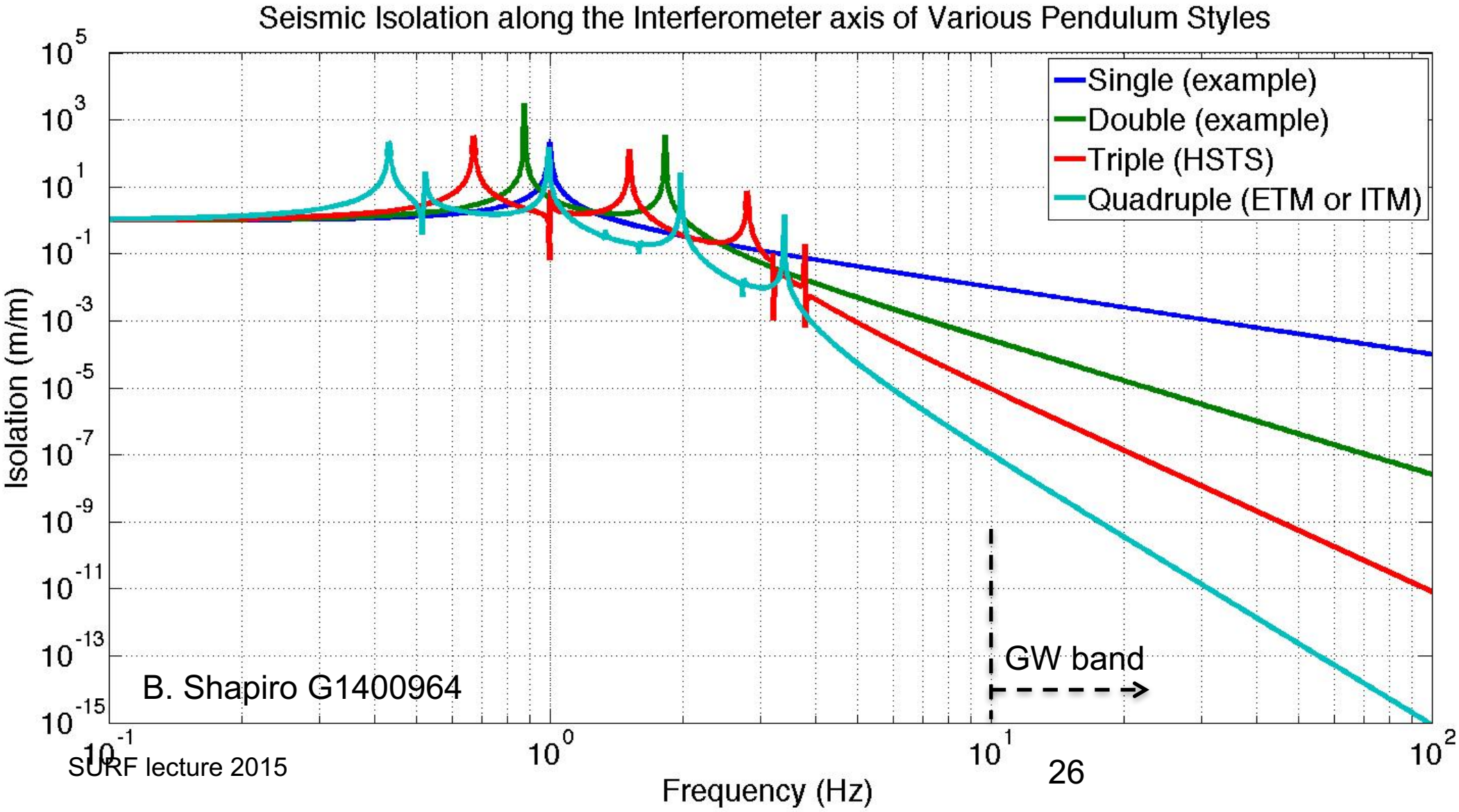
Suspension Isolation: Initial LIGO (~2005) to …



Suspension Isolation: Initial LIGO (~2005) to …



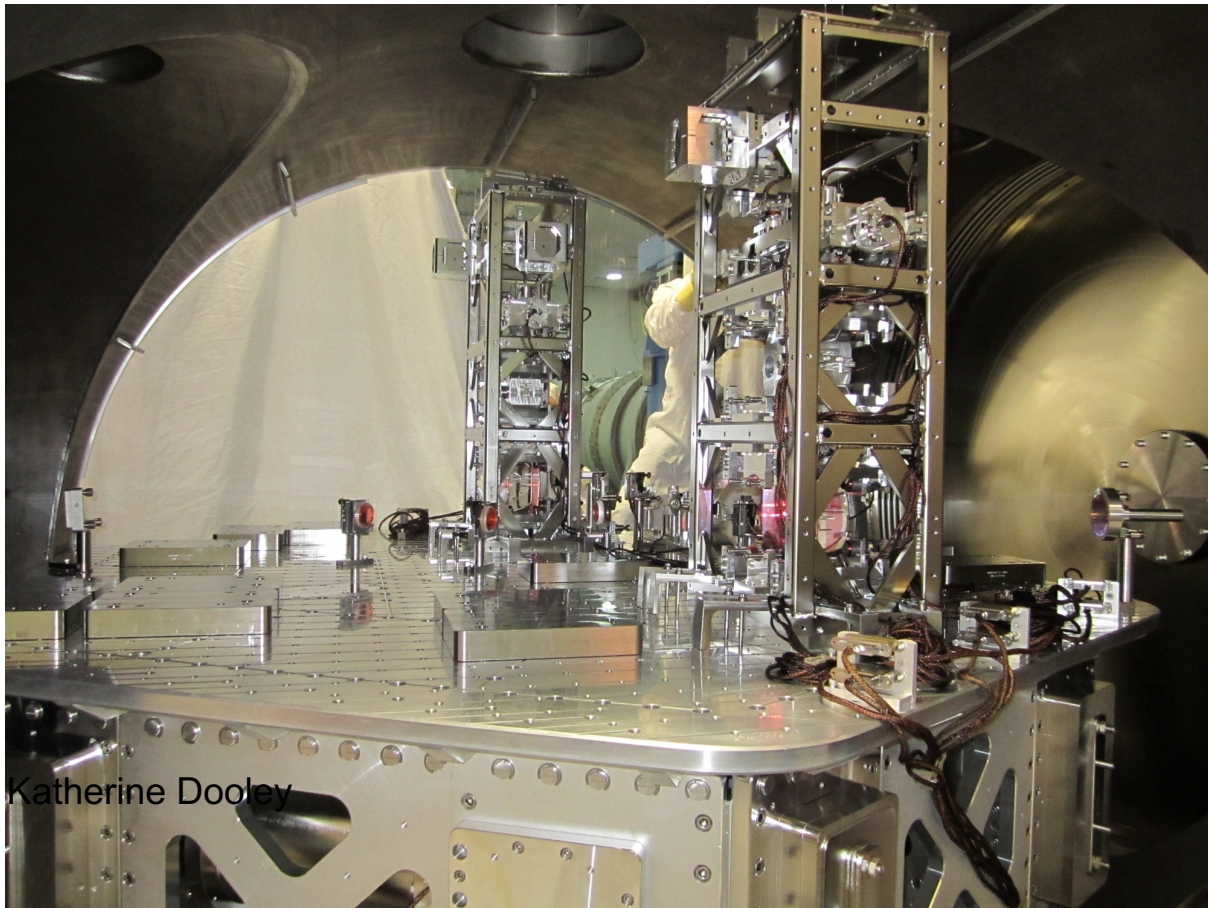
Suspension Isolation: Initial LIGO (~2005) to Advanced LIGO (~2014)



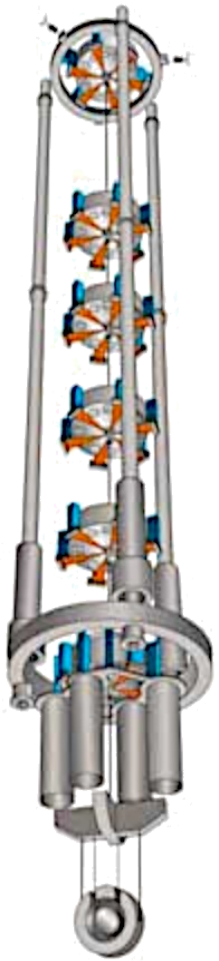
Advanced LIGO quadruple suspension

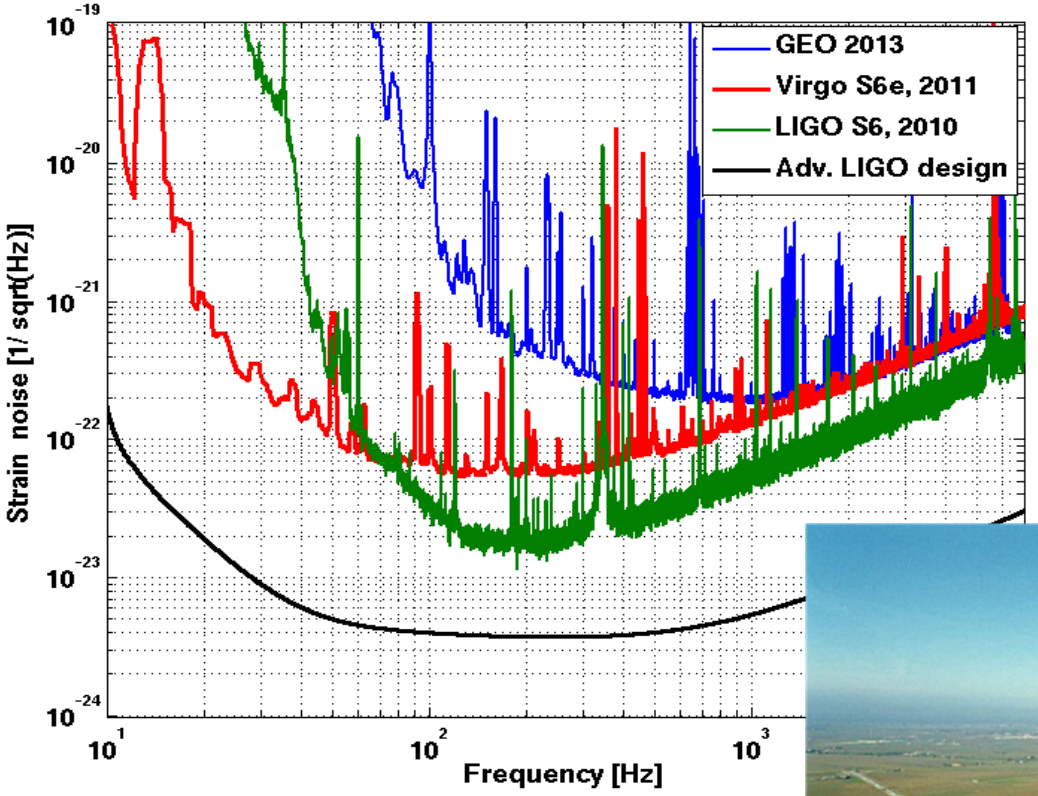
Test mass suspension on 2-stage in-vacuum isolation table

Auxiliary optics on 1-stage in-vacuum isolation table



Virgo seismic isolation



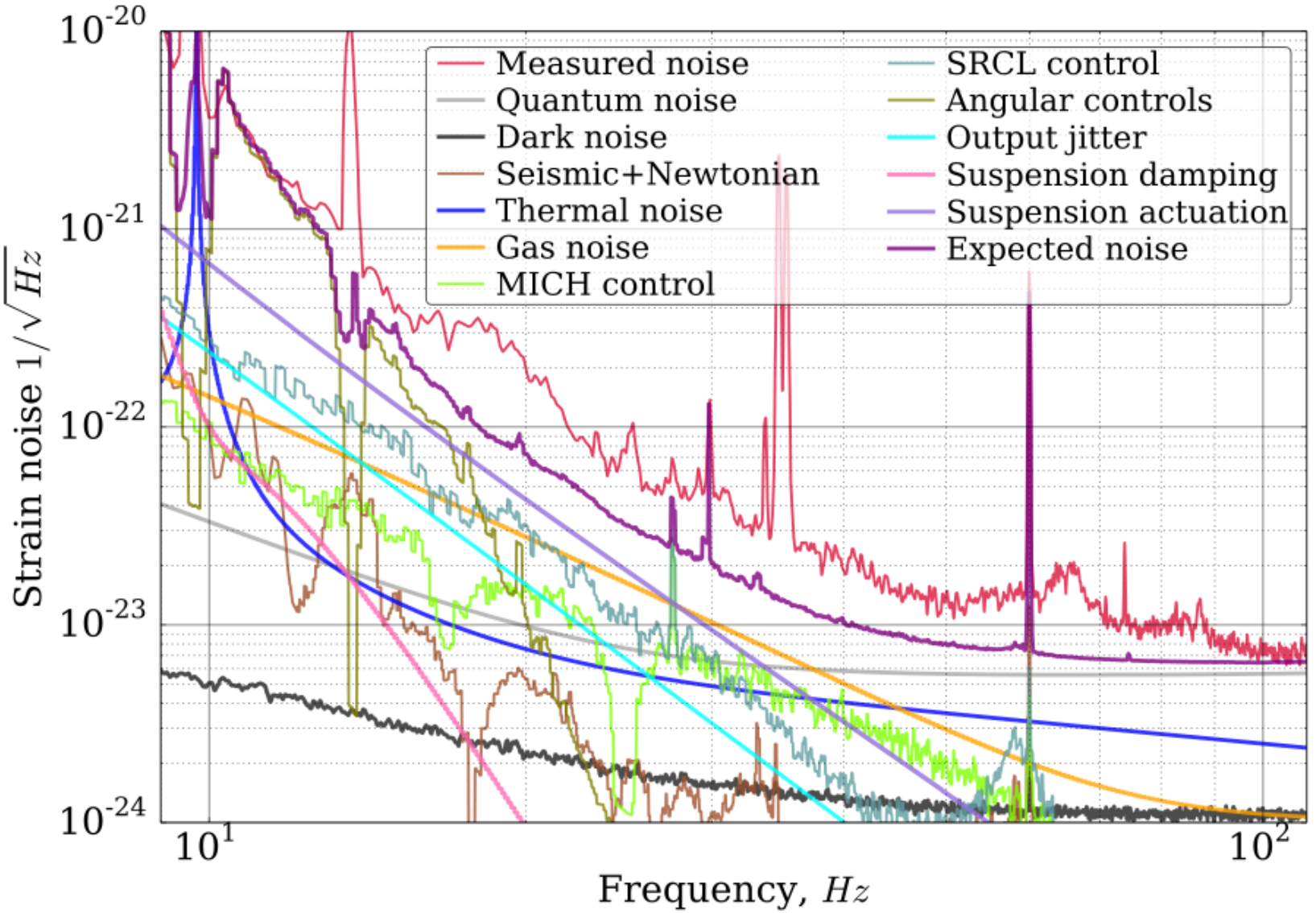


Managed by suspending the mirrors from extreme vibration isolators

Virgo Super attenuator:
8 stages

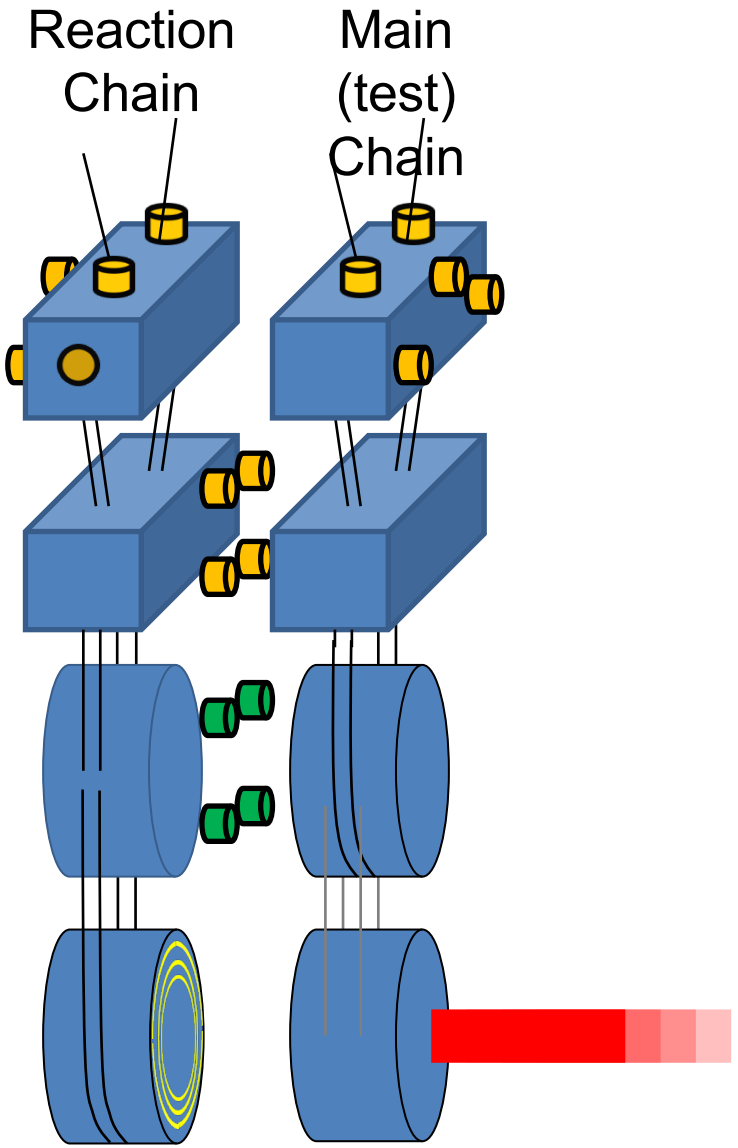
Virgo super-attenuators being upgraded

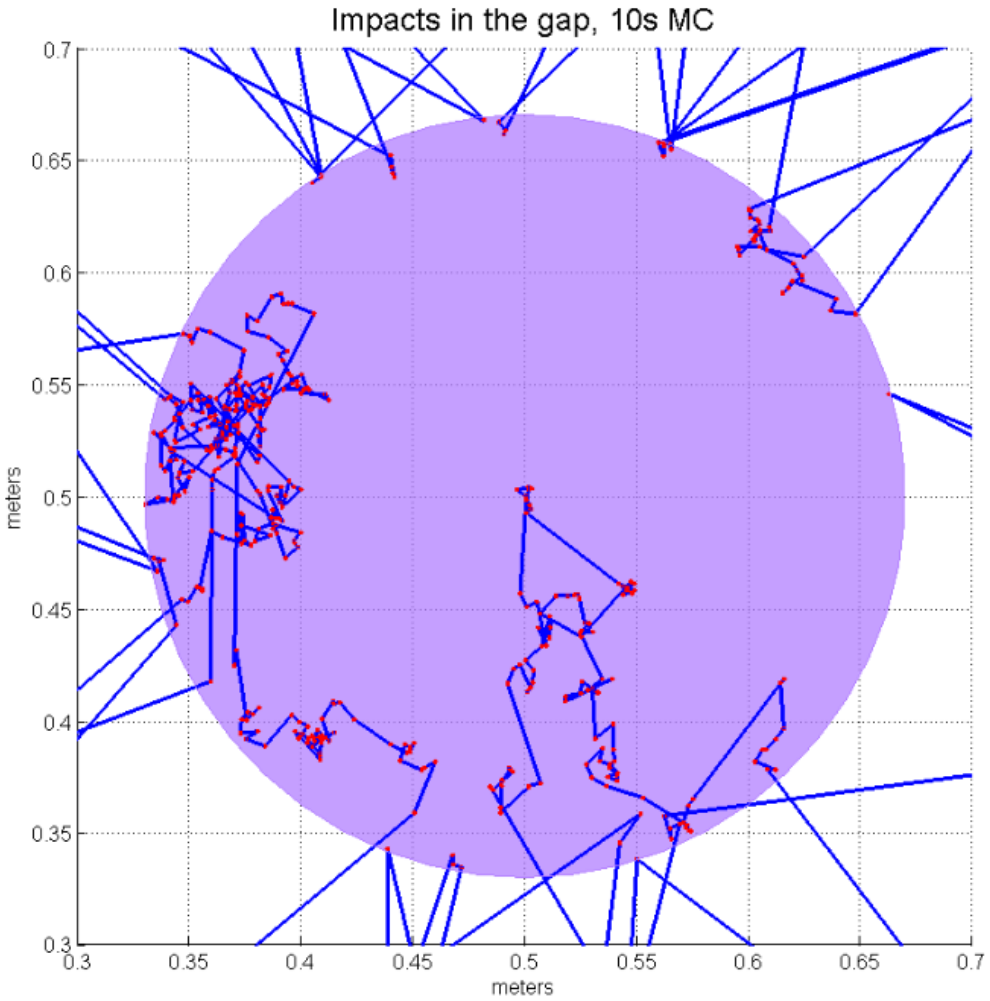
Advanced LIGO Noise budget



Phys. Rev. D **93**, 112004

Challenges: squeezed film damping



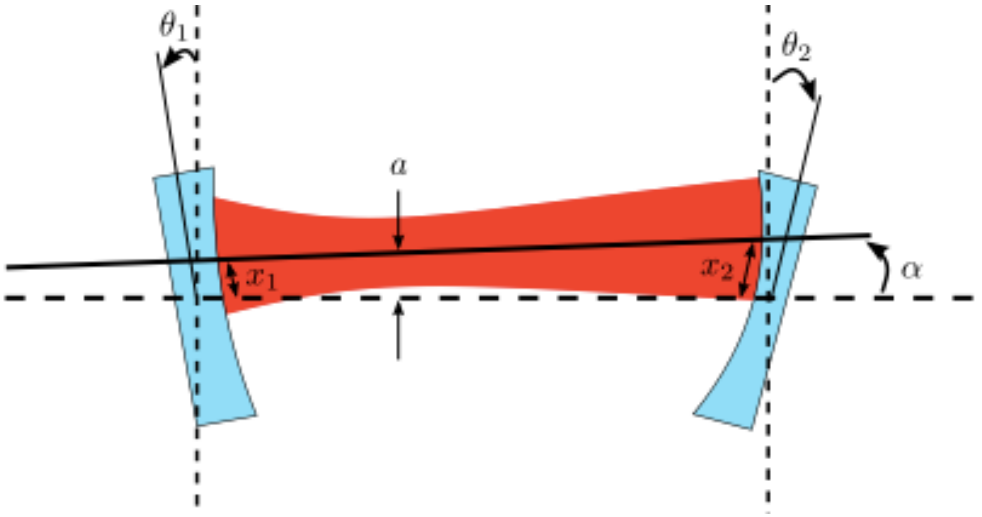


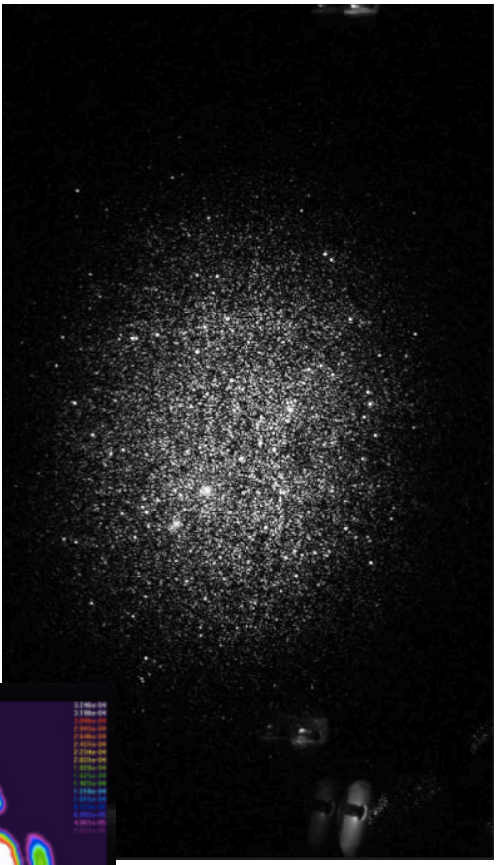
View onto test mass 'through' reaction mass

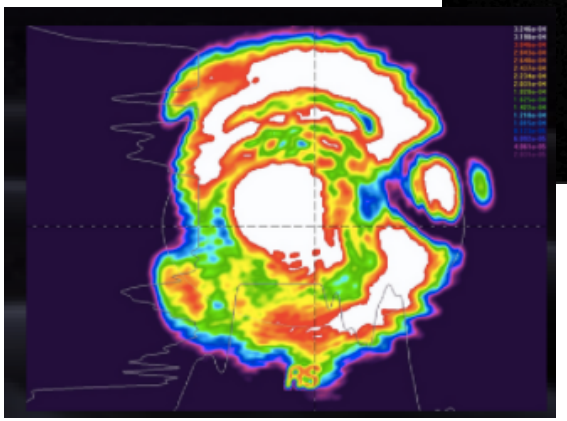
LIGO-T0900582

Challenges: higher power

Radiation pressure and thermal effects become a technical challenge



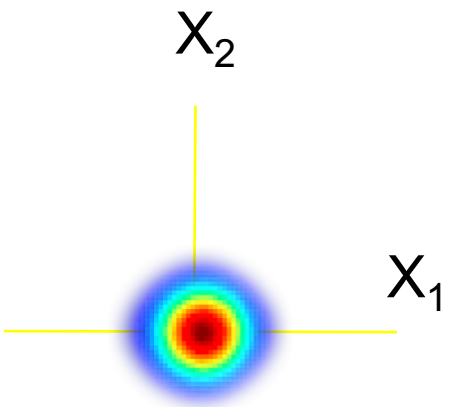




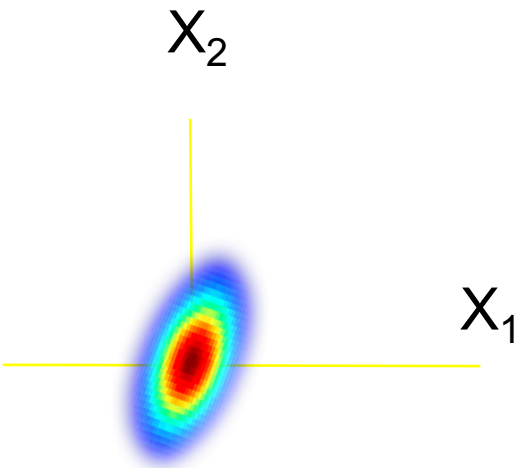
Dooley et al. J. Opt. Soc. Am. A 30 (2013)

SNR scales with sqrt(power)

Squeezed vacuum…



Vacuum fluctuations



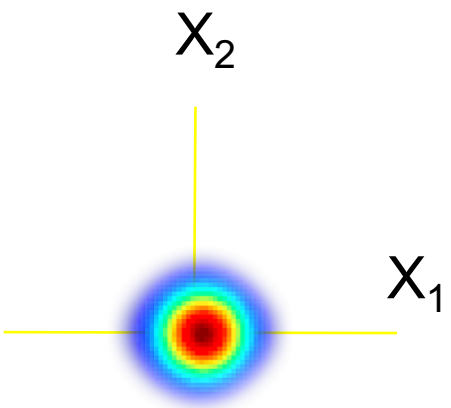
Squeezed vacuum

The uncertainty principle:

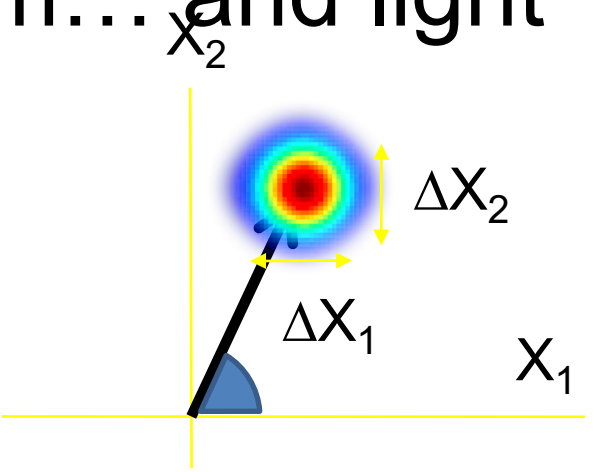
$$\Delta X_1 \, \Delta X_2 \geq 1$$

Image: S. Dwyer

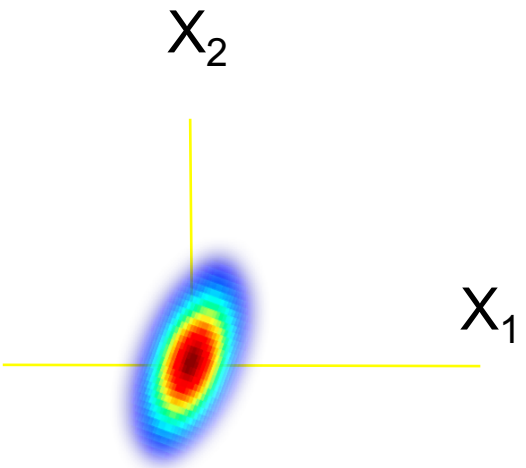
Squeezed vacuum… and light



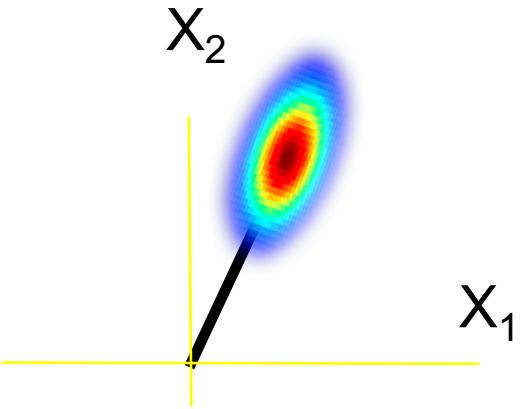
Vacuum fluctuations



Coherent state of light



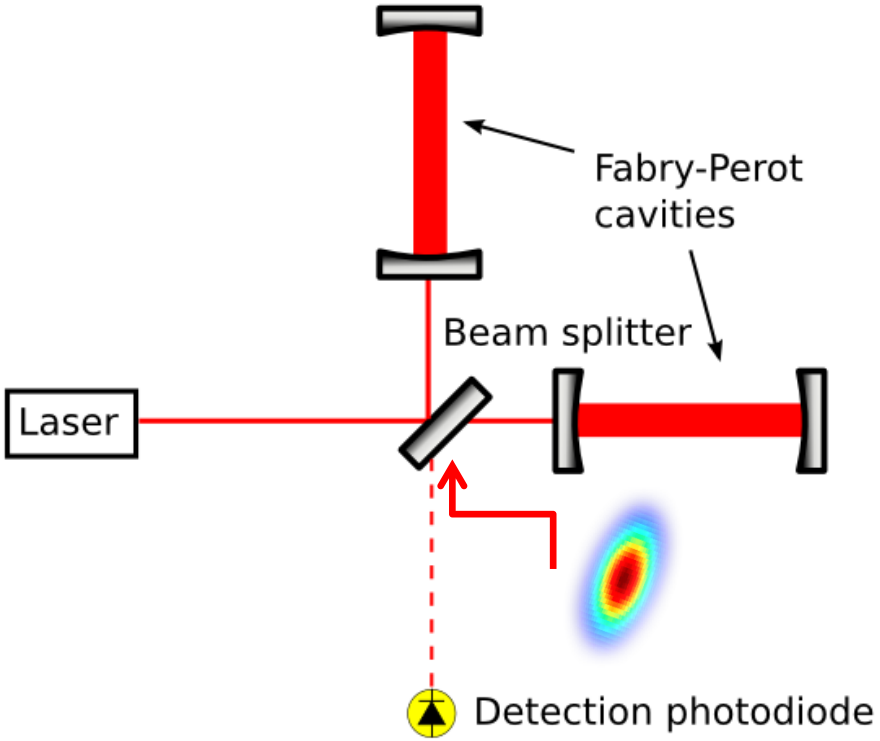
Squeezed vacuum

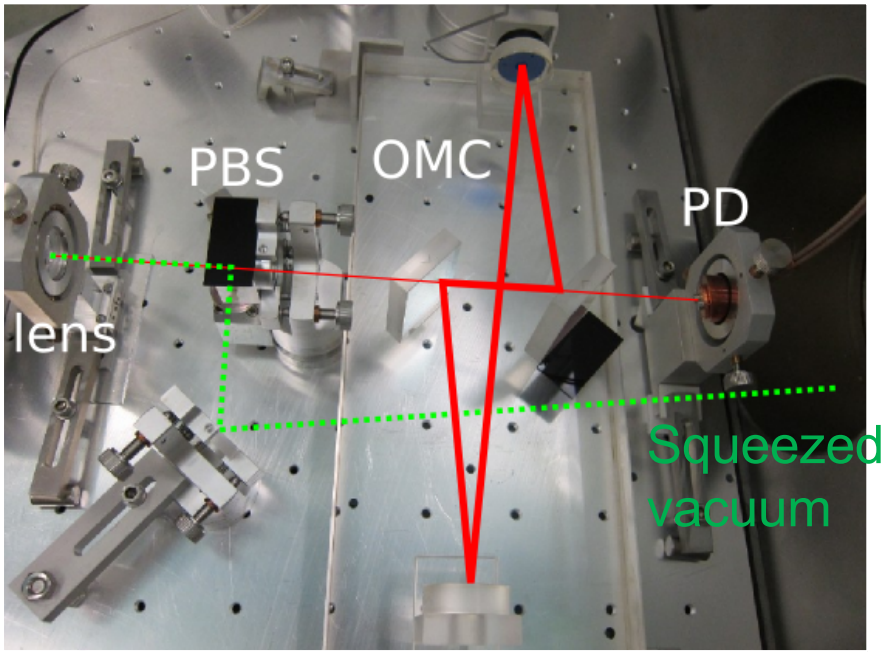


Squeezed light

Squeezing in an interferometer

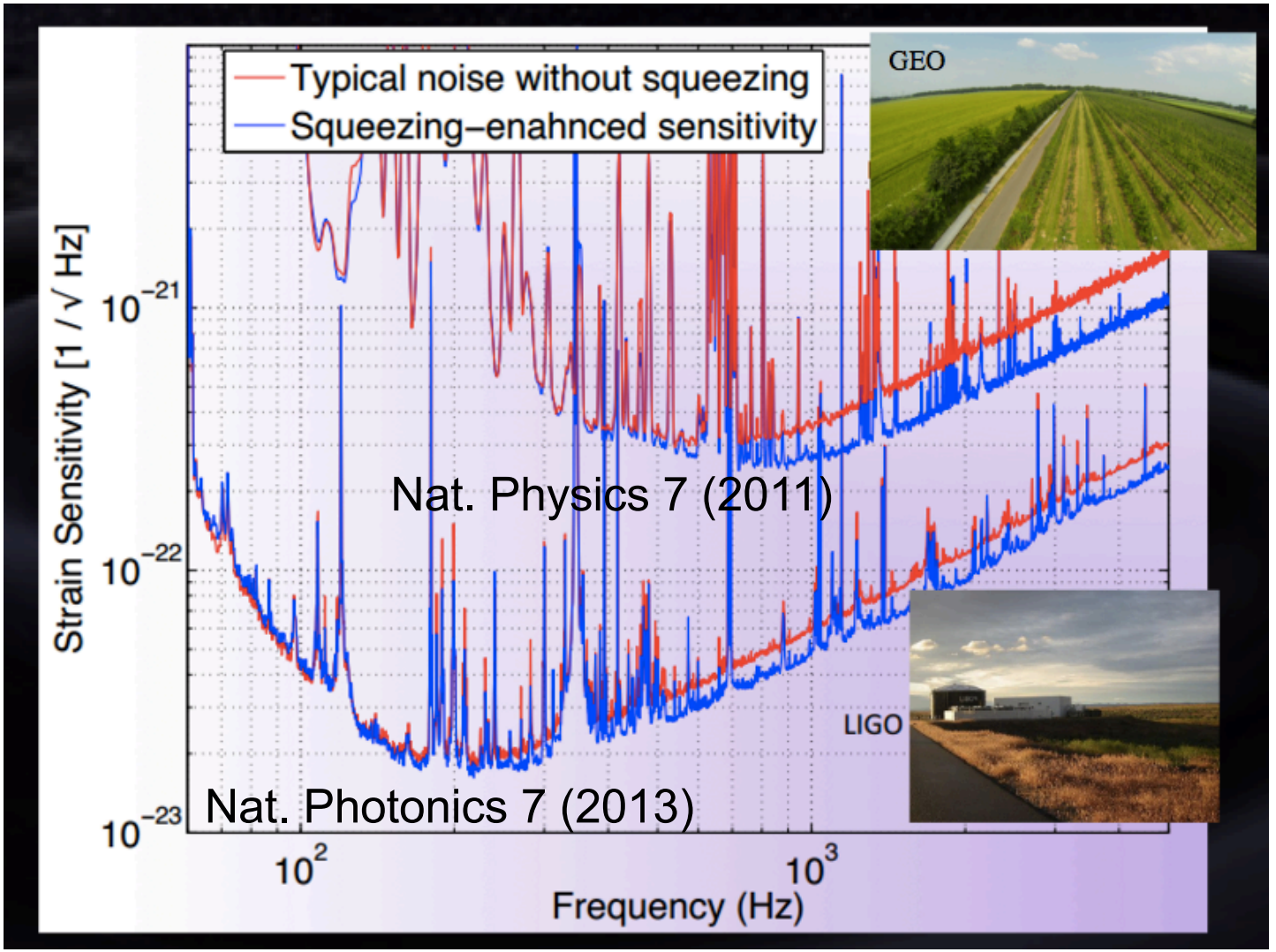
Vacuum fluctuations enter the interferometer from all ports where no classical field exists.



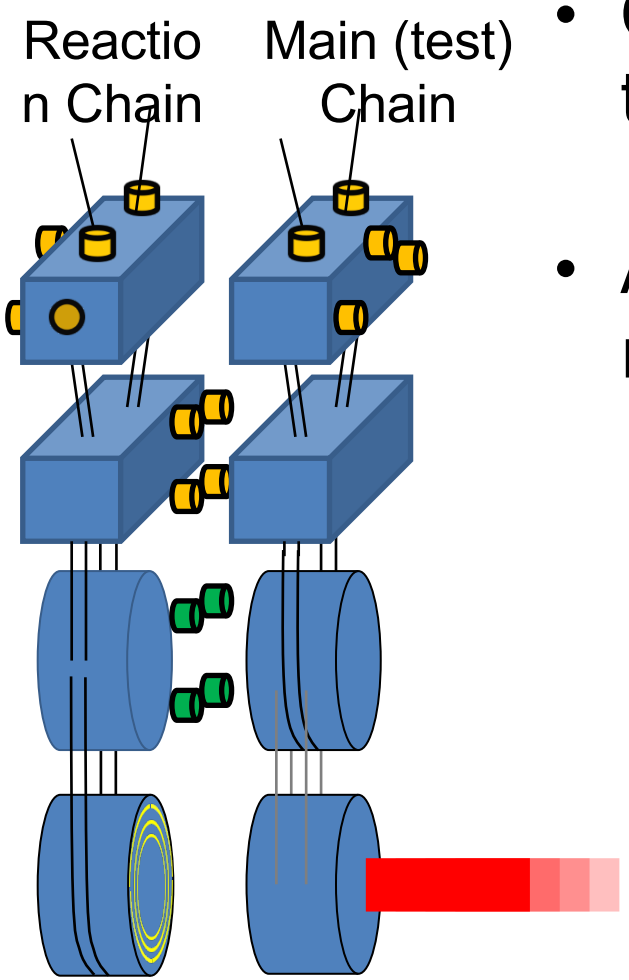


C Caves (1981) Phys. Rev. D **23**, 1693

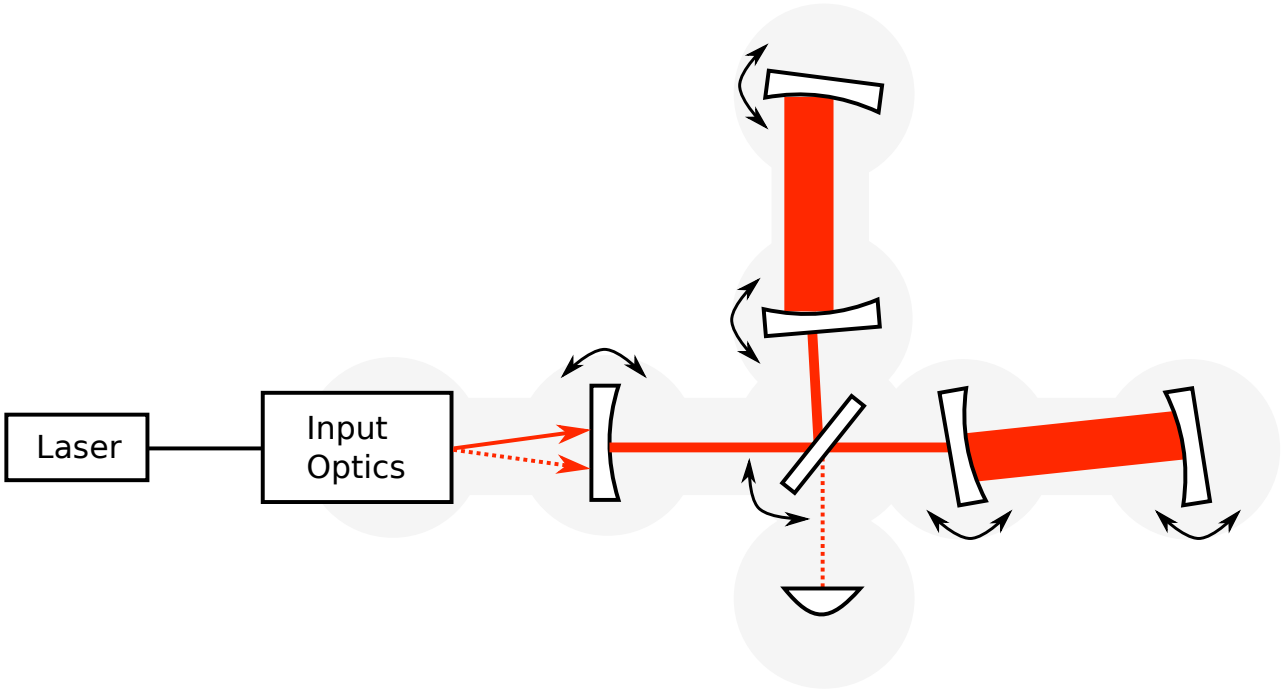
Squeezing demonstration



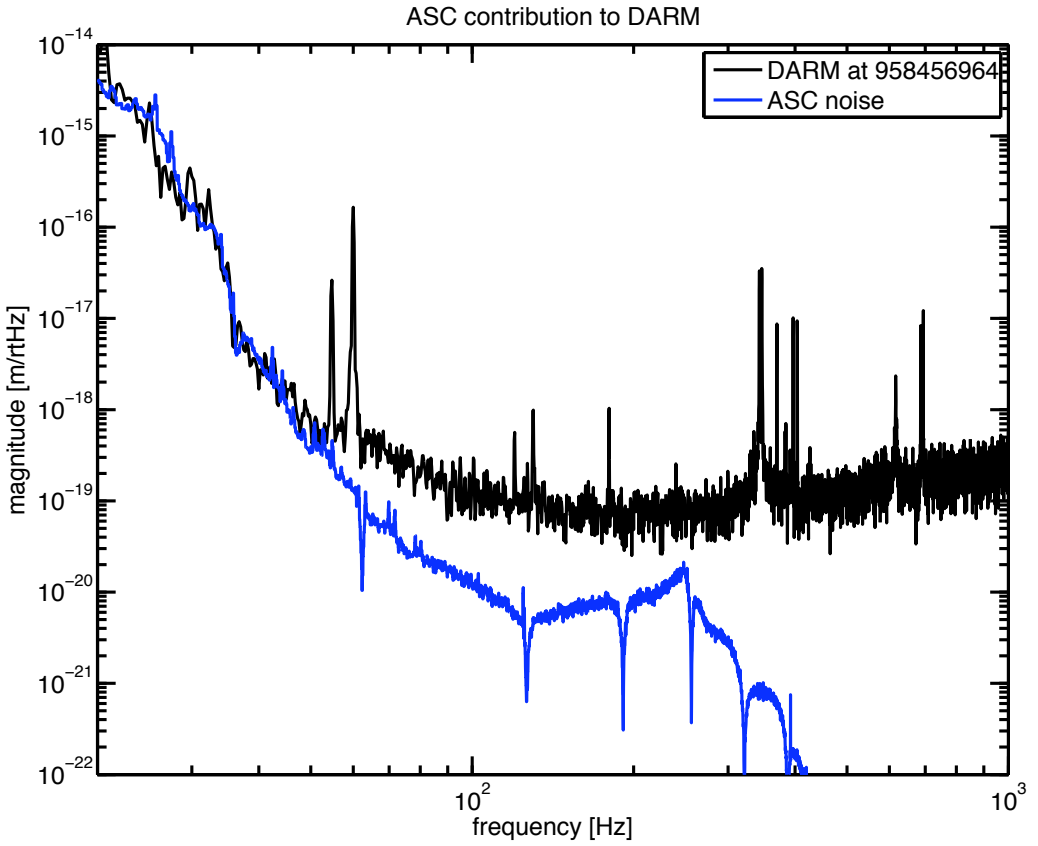
Challenge: length-to-angle coupling



- Control of relative mirror motion goes to upper two suspension stages
- Angular motion induced due to the many length-to-angle coupling paths.



Alignment feedback is a limiting noise source



Angular sensors impress noise onto the gravitational-wave signal

Dooley et al. J. Opt. Soc. Am. A 30 (2013)

Livingston pre-mode cleaner reflected beam, 2011

Thanks for your attention and good luck!