# An introduction to Terrestrial Gravitational Wave Detectors

First International Latin American Conference on Gravitational Waves

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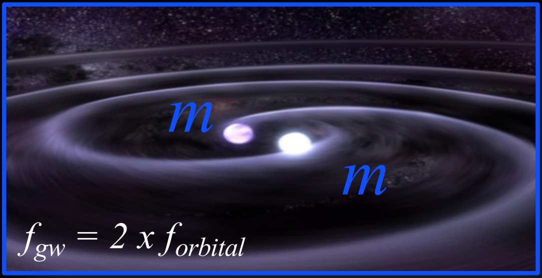
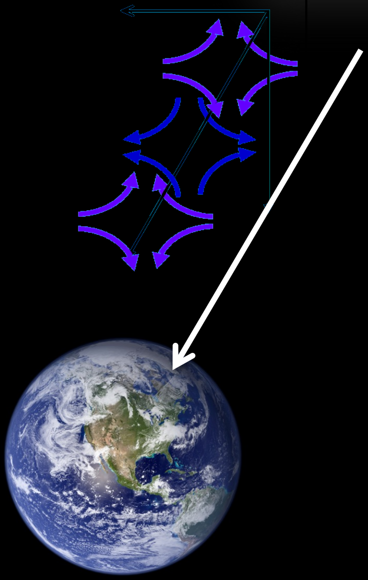
# Thanks to…

- The meeting organizers!
- Persons loaning slides and insights from the LIGO Scientific Collaboration; Virgo and KAGRA; and Cosmic Explorer
- The US National Science Foundation for extraordinary support and perseverance for LIGO

# Gravitational Wave Properties

Binary Coalescence of two compact objects





Distance $r$

Speed $c$

GW generation in GR:
lowest order radiation is quadrupole

*metric perturbation*

*quadrupole moment*

$$h = \frac{2\,G}{c^4\,r}\,\ddot{I}$$

Two masses m in a circular orbit at a distance $r$ create a periodic strain $h$ in space

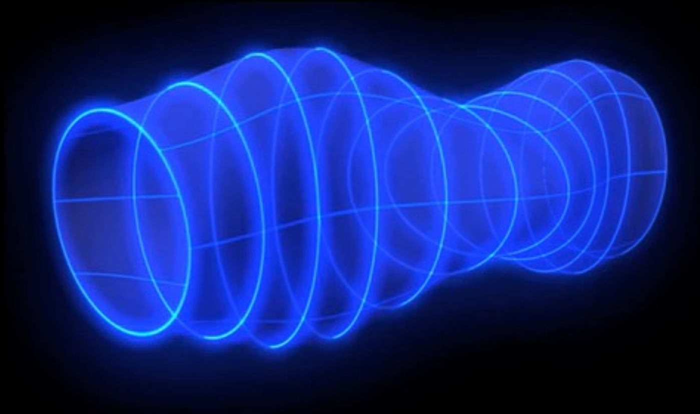
$$h = \frac{2\,G\,m}{c^4\,r}\,(2\pi f_{gw})^{2/3}$$

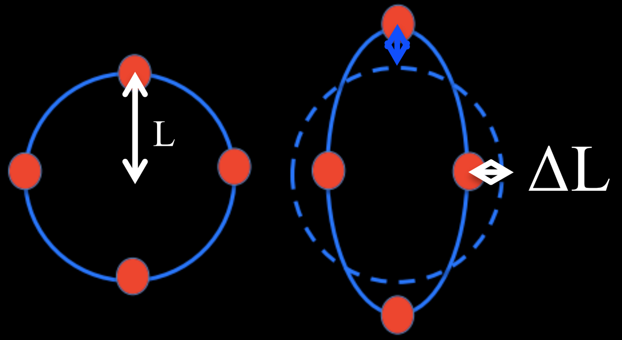
About once a week,
a wave passes with this characteristic strain:

$$\boxed{1.5 \times 10^{-21}}\left(\frac{m}{30 M_\odot}\right)\left(\frac{400\,\mathrm{Mpc}}{r}\right)\left(\frac{f_{gw}}{50\,\mathrm{Hz}}\right)^{2/3}$$

$h$ ~ (1 hair thickness) / (distance to Alpha Centuri)

# Stretching and squeezing of space-time





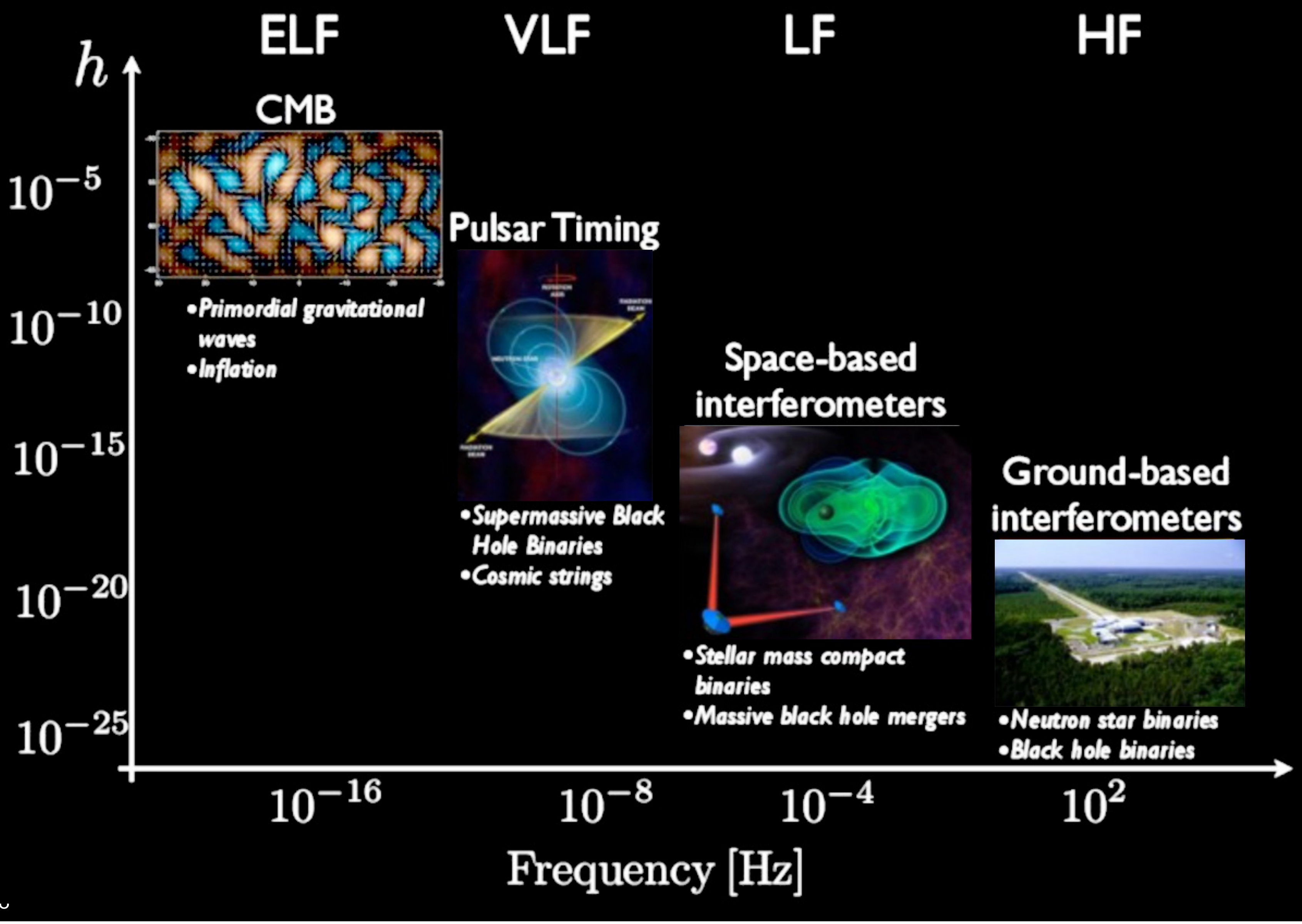
Amplitude of the gravitational wave strain is $h = \Delta L/L$

$\Delta L = h\, L$

Big $L$ makes $\Delta L$ easier to measure; current detectors have $L$ = 4 km, so from our two-mass example

$\sim 10^{-21} \text{ x } \sim 10^{3} = \boxed{\sim 10^{-18}\text{ m}}$

# Detection methods, Projects



**CMB**

- *Primordial gravitational waves*
- *Inflation*

**Pulsar Timing**

- *Supermassive Black Hole Binaries*
- *Cosmic strings*

**Space-based interferometers**

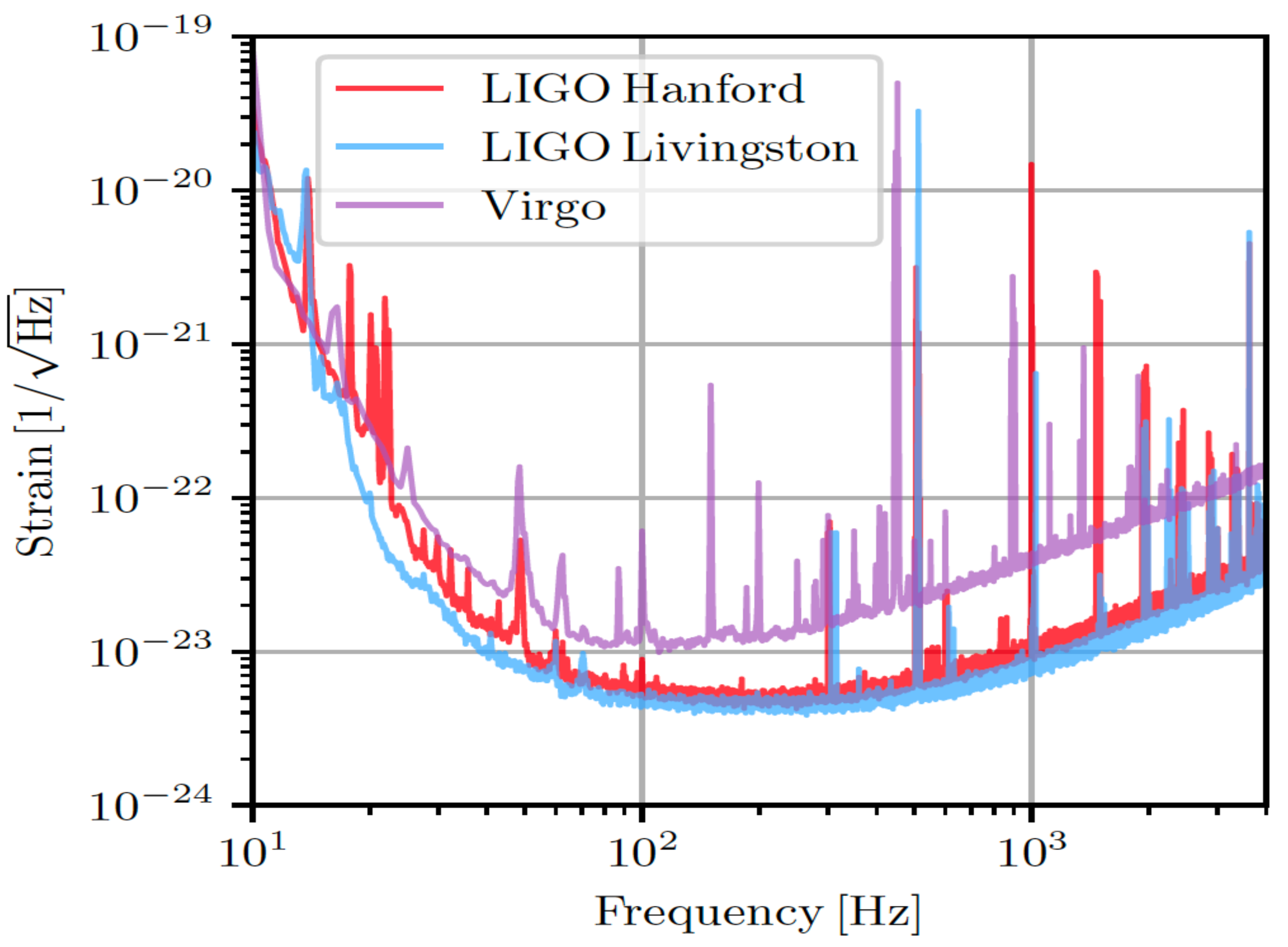
- *Stellar mass compact binaries*
- *Massive black hole mergers*

**Ground-based interferometers**

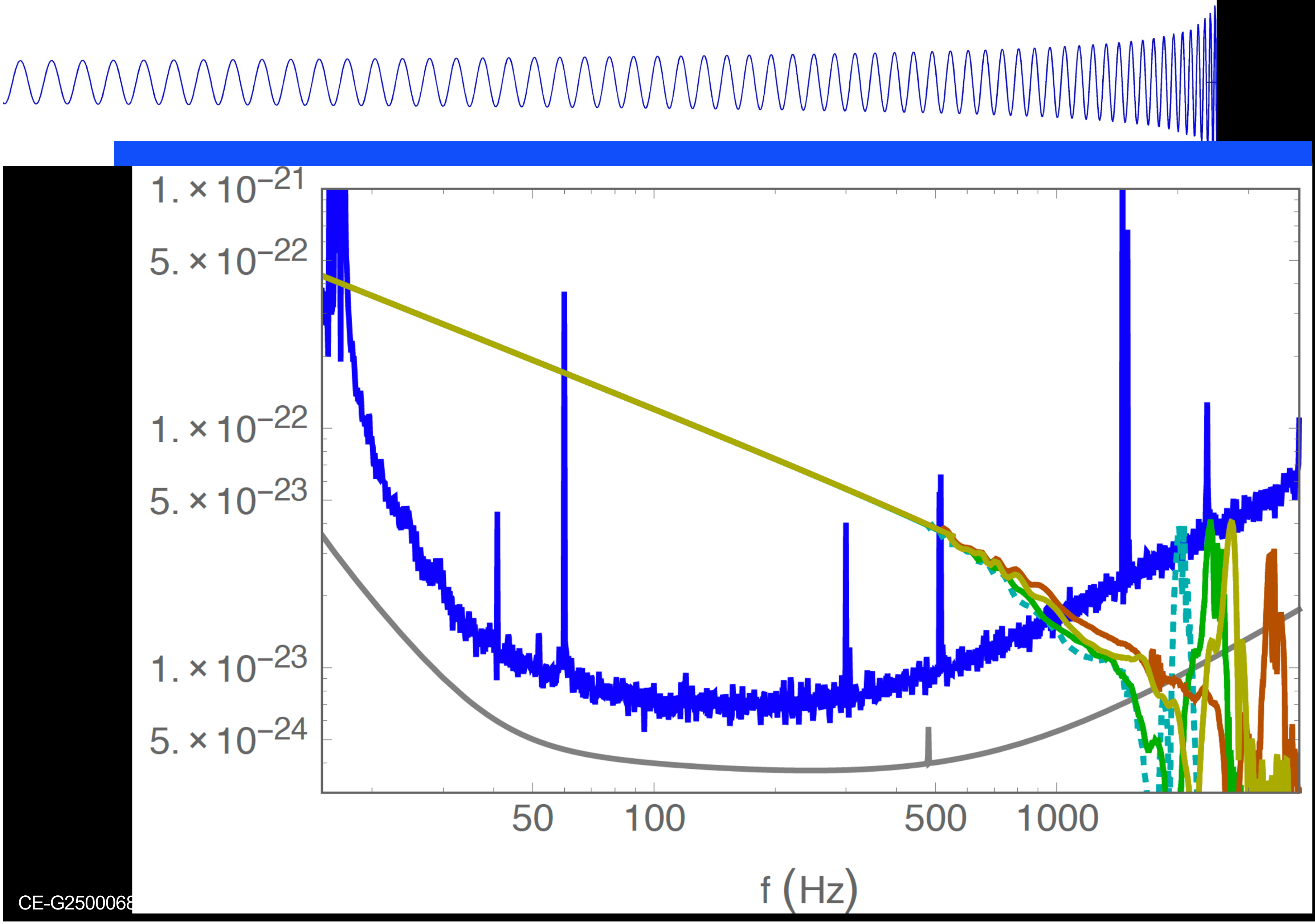
- *Neutron star binaries*
- *Black hole binaries*

# LIGO and Virgo sensitivity

- LIGO-Virgo noise floor *h = ΔL/L* ~$10^{-23}$ in a 1 Hz bandwidth



# NS-NS inspiral mapped onto detector sensitivity



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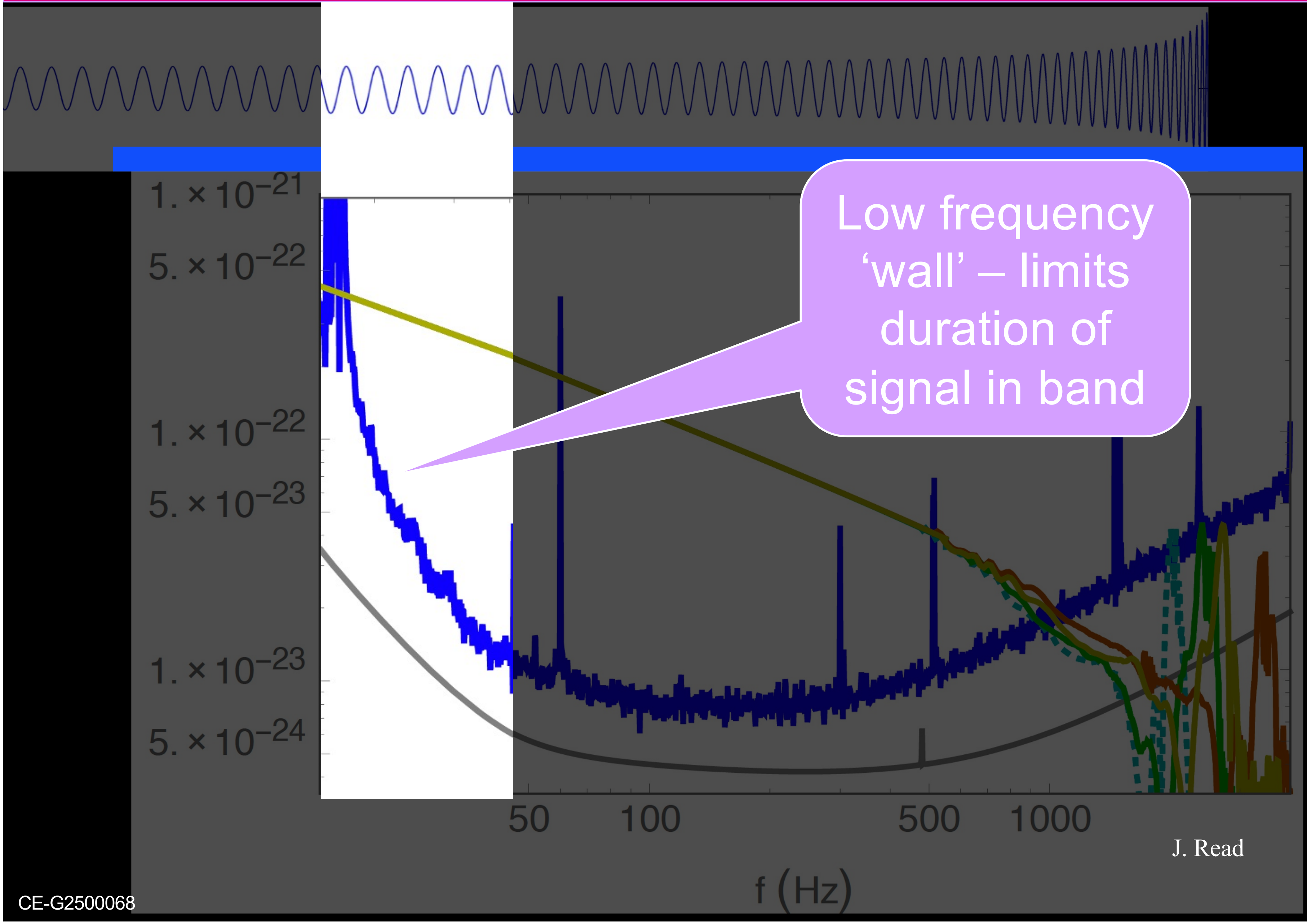
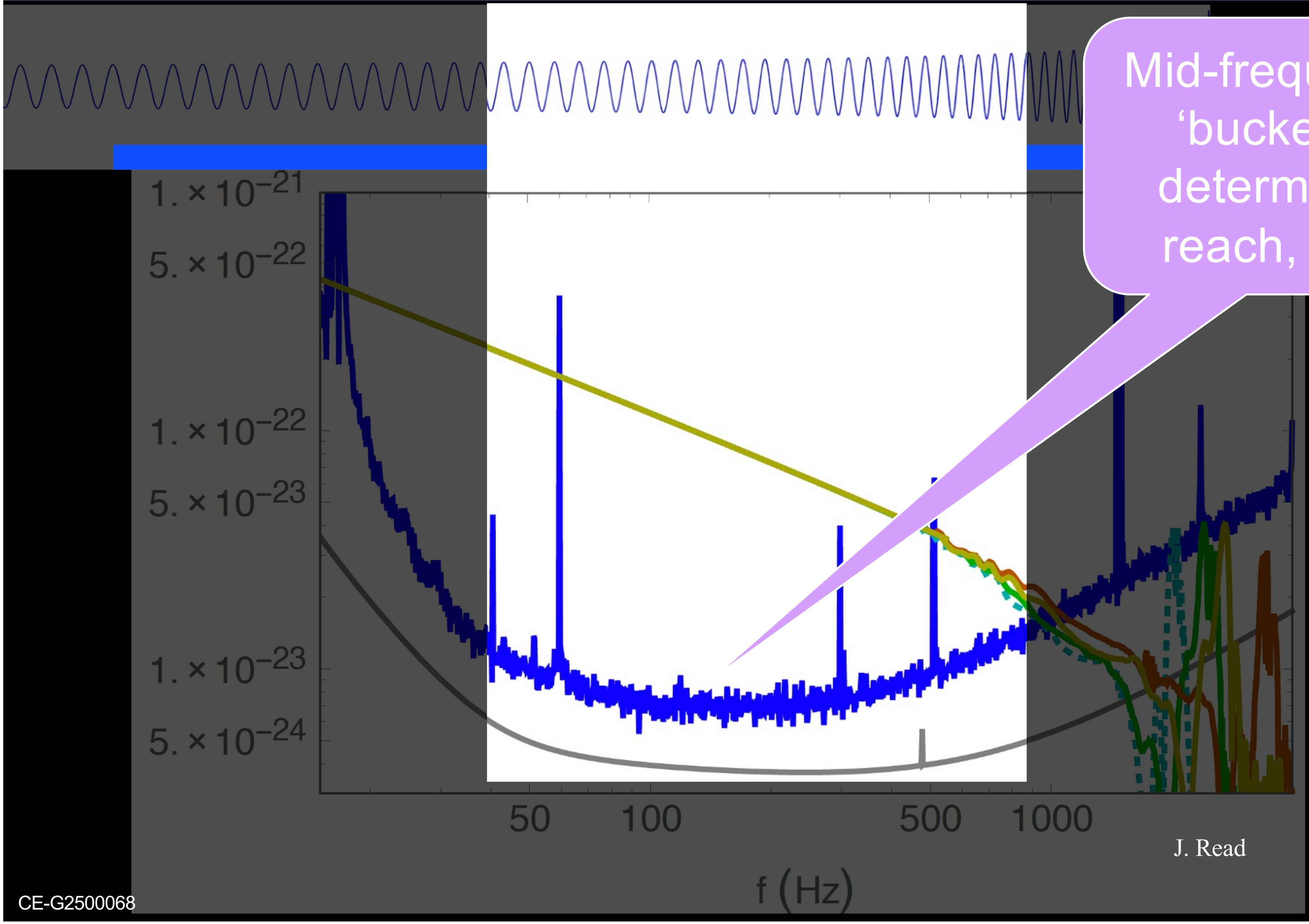


Low frequency ‘wall’ – limits duration of signal in band

J. Read

# NS-NS inspiral mapped onto detector sensitivity



Mid-frequency ‘bucket’ – determines reach, rate

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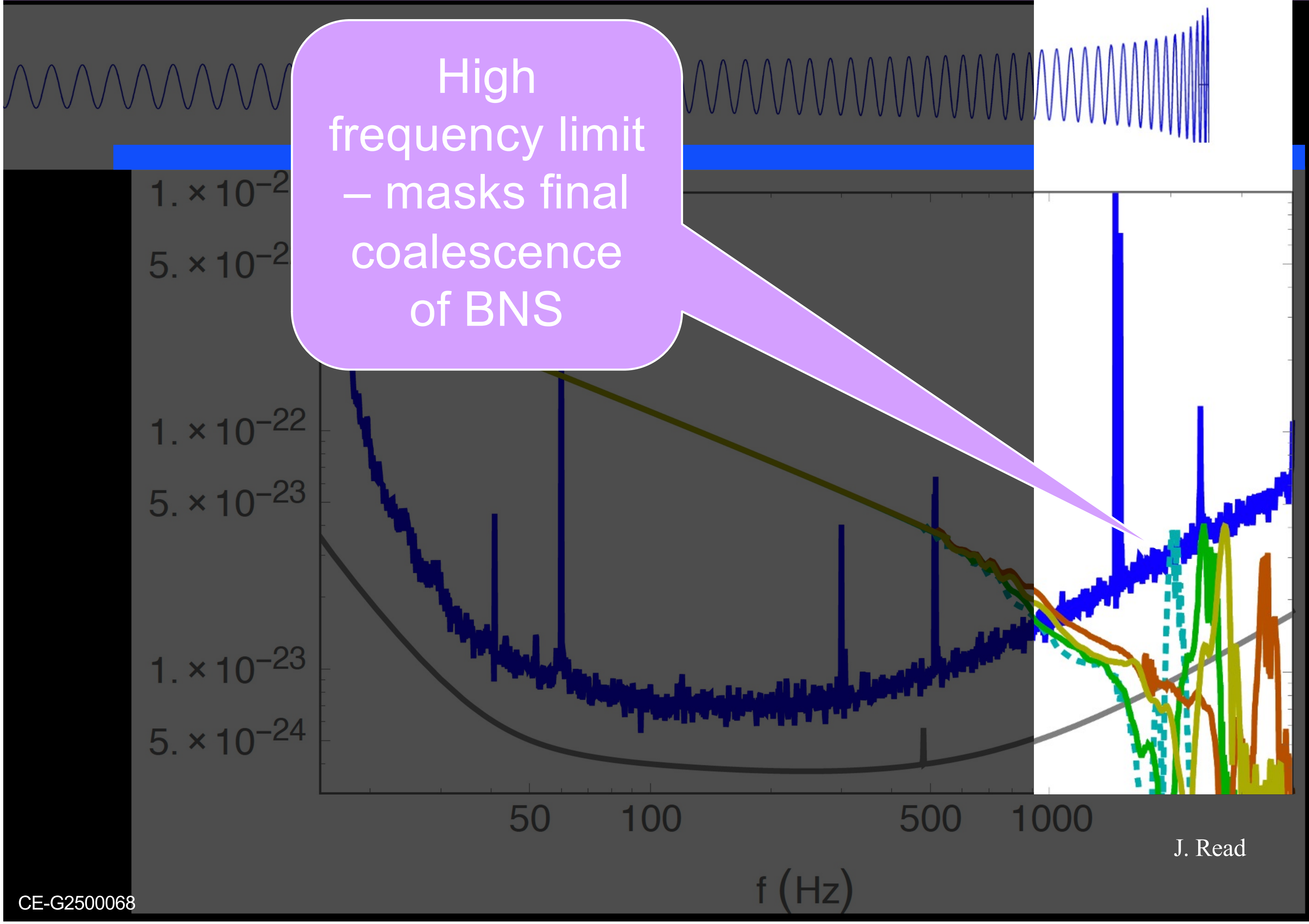
# NS-NS inspiral mapped onto detector sensitivity



High frequency limit – masks final coalescence of BNS

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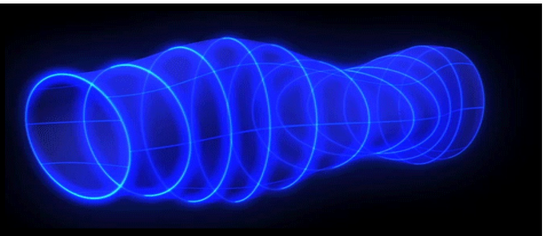
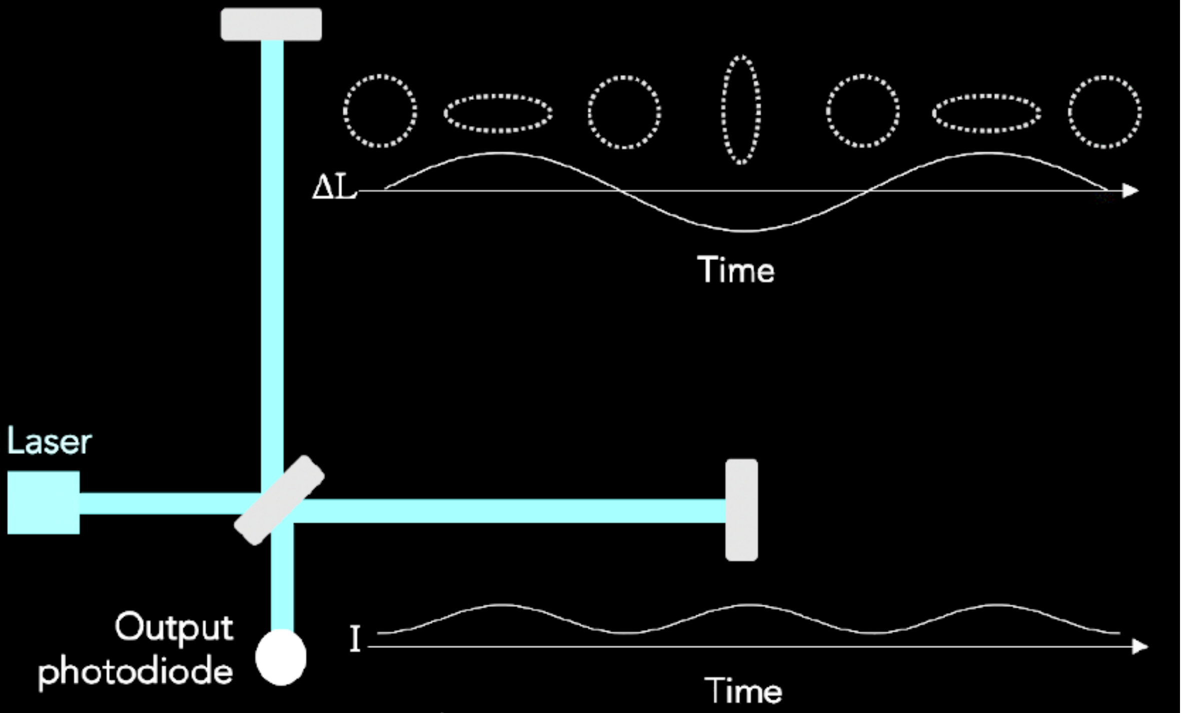
# What is our measurement technique?

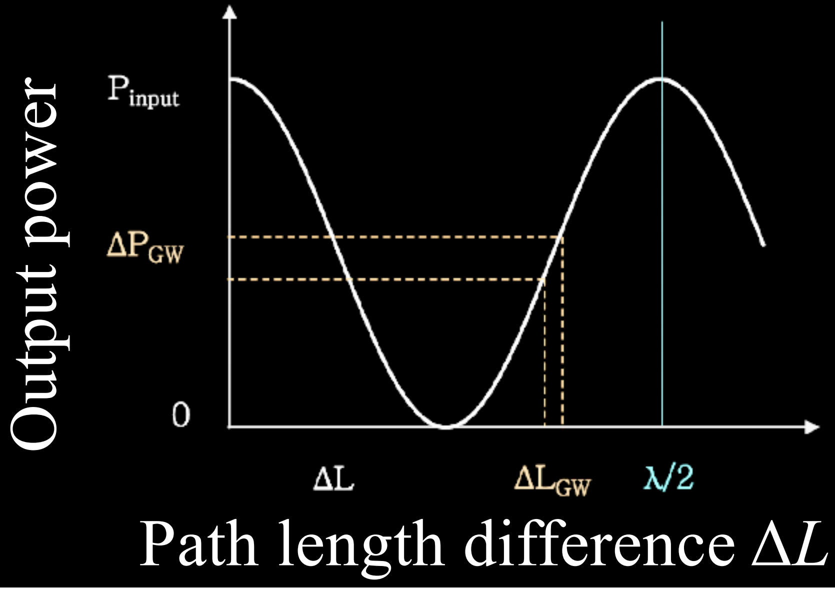


- Enhanced **Michelson interferometers**
- GWs modulate the distance between the end test mass optic and the beam splitter
- The interferometer acts as a transducer, turning GWs into photocurrent proportional to the strain amplitude



- For a given strain $h = \Delta L/L$,

$$\Delta P_{\rm GW} \sim h L P_{\rm laser}/\lambda_{\rm laser}$$



# What are the ‘fundamental’ limits to sensitivity?

# Useful paradigm in considering limits to detector sensitivity

- **Ability to measure** the position of our test mass
  - **Shot noise**
  - Scattered light
  - Laser light defects – intensity, position, mode shape, frequency noise
  - Electronics noise

- **True noise motions** of the reference surface on our ‘free test mass’ which can mask GWs
  - **Thermal noise**
  - Radiation pressure
  - Environmental mechanical forces – seismic, anthropogenic, weather
  - Stray electric, magnetic fields
  - Accidental noise forces from our control systems and sensors

**We’ll start with noise motions**

# Measuring $\Delta L = 4\text{x}10^{-18}$ m

- **Thermal noise** – kT of energy per mechanical mode
  - *A. Einstein, 1905*

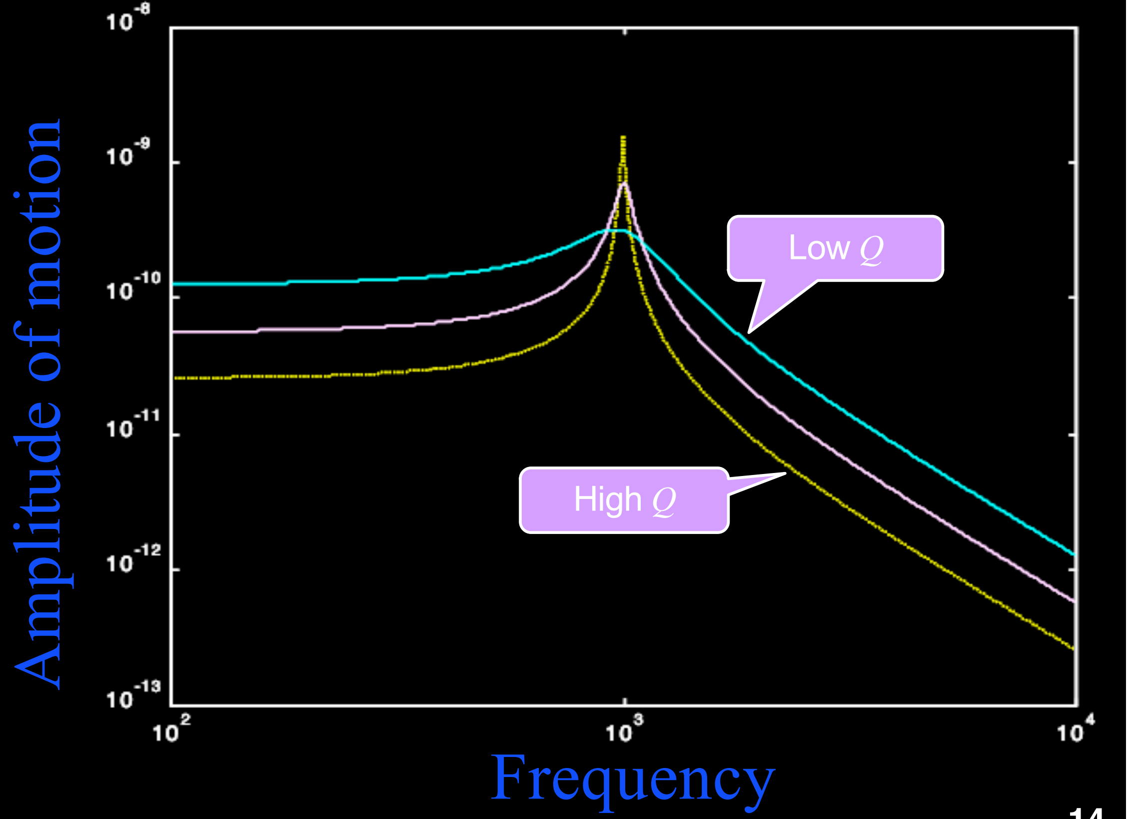
- Simple Harmonic Oscillator:

$$x_{rms} = \sqrt{\left\langle (\delta x)^2 \right\rangle} = \sqrt{k_B T / k_{spring}}$$

- Distributed in frequency according to real part of impedance $\Re(Z(f))$

$$\tilde{x}(f) = \frac{1}{\pi f}\sqrt{\frac{k_B T}{\Re(Z(f))}}$$

- Gather the $x_{rms}$ Into a narrow region around resonance
- Push down thermal noise above and below resonance



# Measuring Δ*L*= 4x10$^{-18}$ m
## Internal motion

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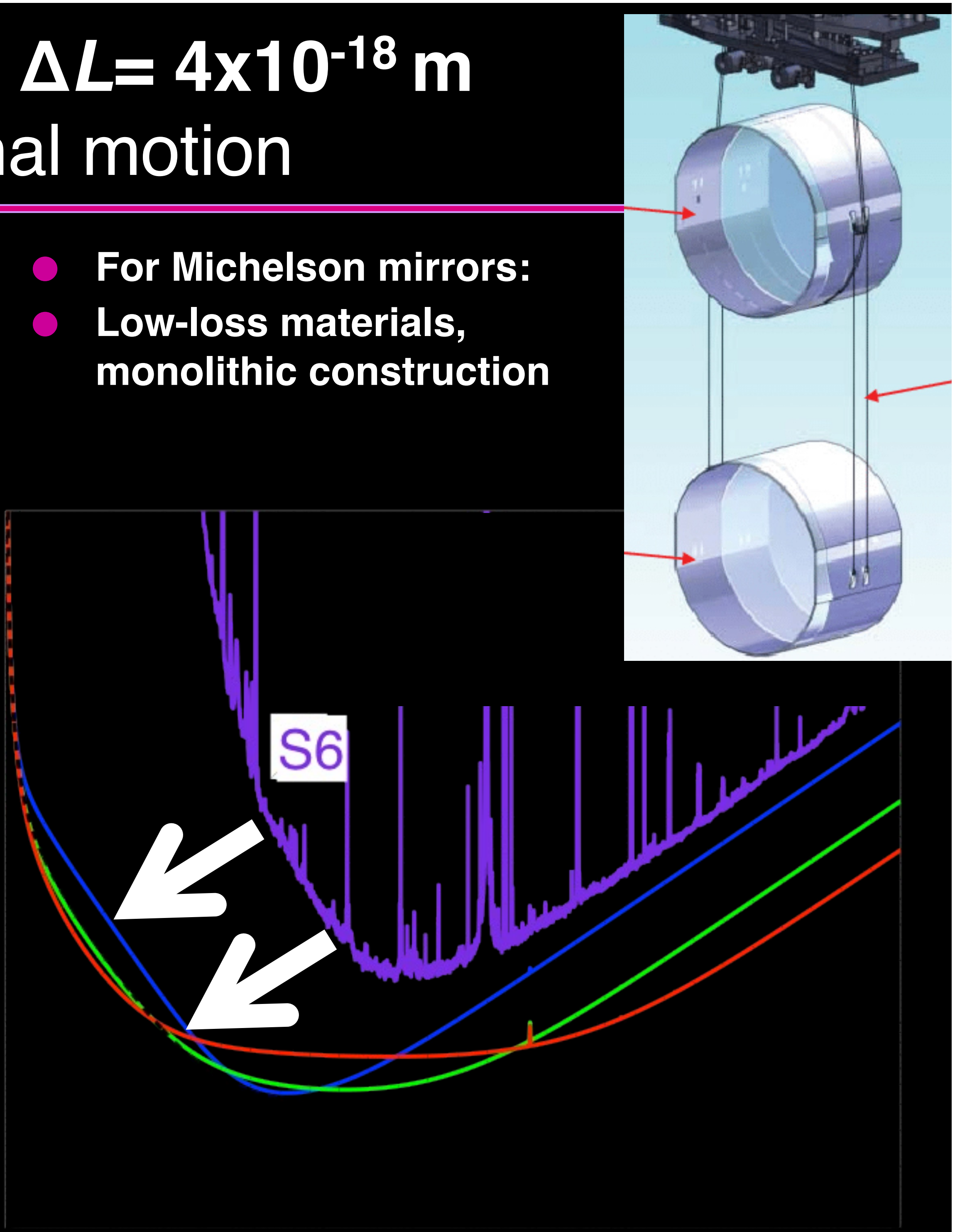
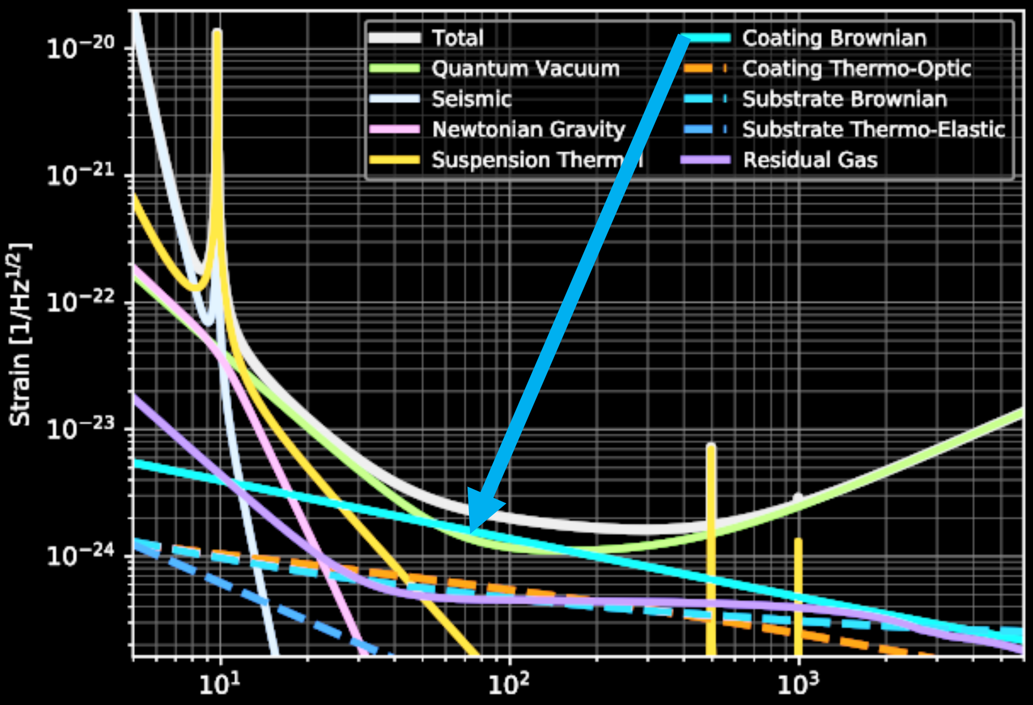
- **For Michelson mirrors:**
- **Low-loss materials, monolithic construction**



# Measuring $\Delta L$= 4x10$^{-18}$ m

## Internal motion

- **Optical reflective coatings on the mirrors introduce thermal noise**
- Even in the best coatings, the dielectric optical coating has a large loss tangent
  - Some $10^{-4}$ , compared to $10^{-8}$ for fused silica
- The Fluctuation-Dissipation theorem says this is where the greatest motion is found
- And: the coating is the surface that is sensed by the laser
- **This is the dominant limit in the critical 50-200 Hz band**



coating elastic loss

$\phi \equiv \mathrm{Im}\,Y\,/\,\mathrm{Re}\,Y$

coating thickness

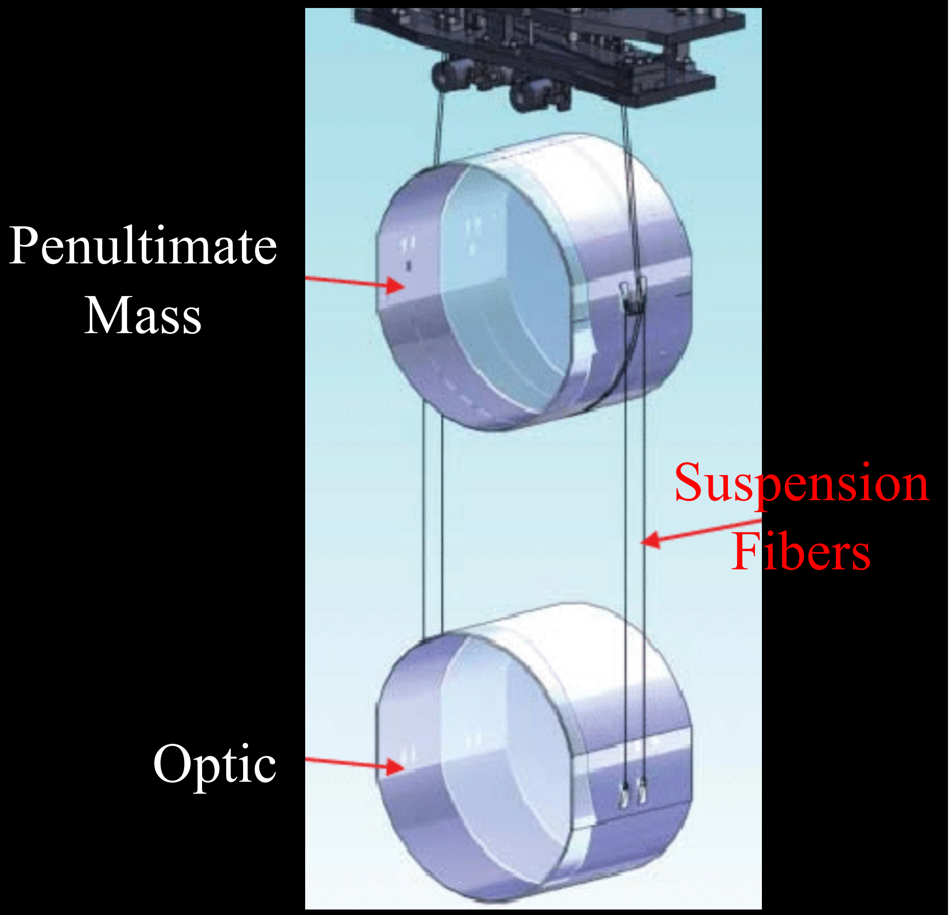
$$\left\langle \Delta x(f,T)^2 \right\rangle \approx \frac{2k_BT}{\pi^2 f}\frac{d}{w^2Y}\phi(f)$$

beam radius

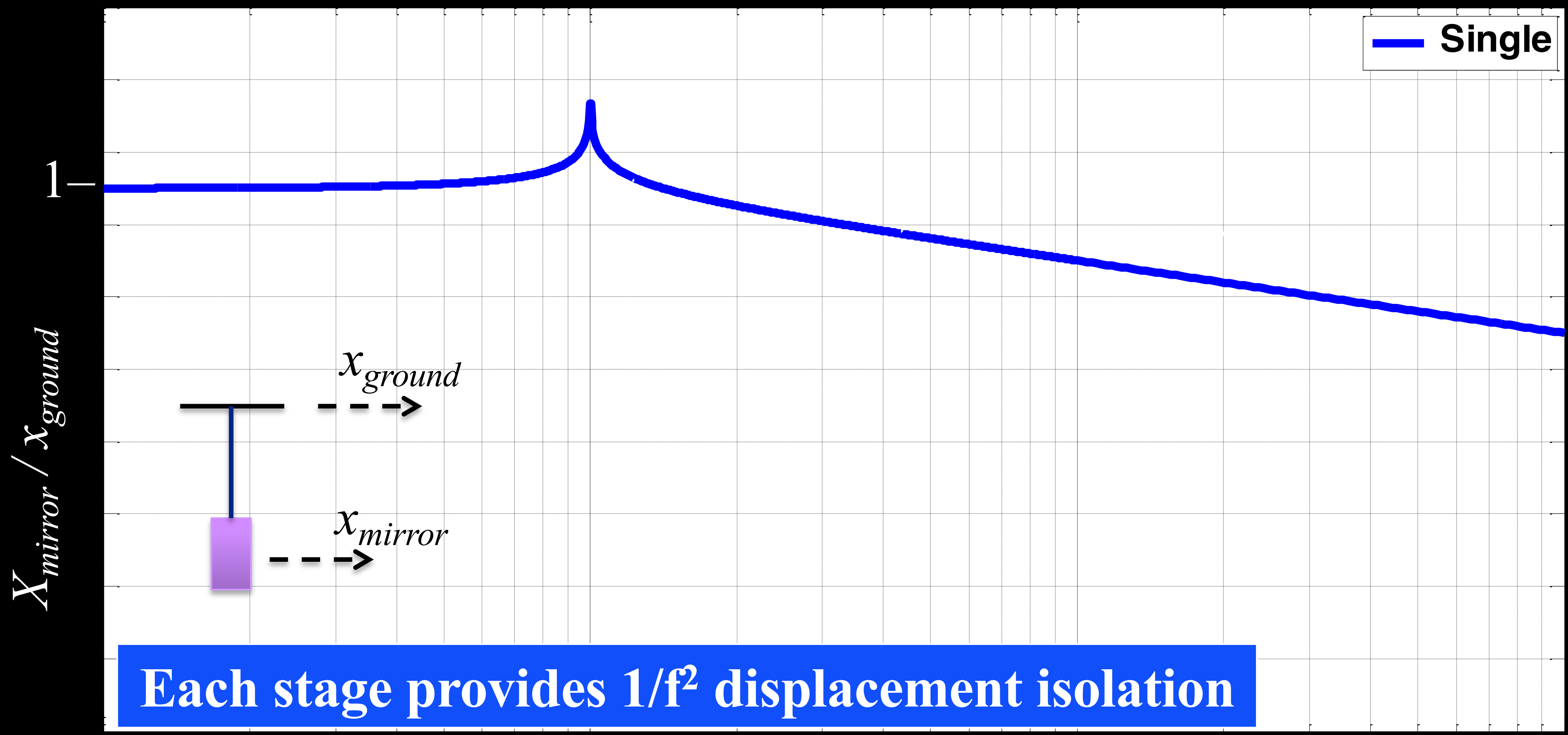
Y Levin *Phys. Rev. D* **57** 659 (1998)

# Basic Building Blocks: Pendulums

- Pendulum suspensions for optics which serve as test masses
- Need test masses to be ‘free’ along the relevant measurement axis
- Terrestrial detectors operate in Earth’s gravitational field
- Hang optics like a clock pendulum; above the resonant frequency, mirror is ‘free’
- Inertia of the mass provides seismic isolation
  - Single stage $(f_o/f)^2$; two stages $(f_o/f)^4$…
- Provides flexibility for alignment and actuation

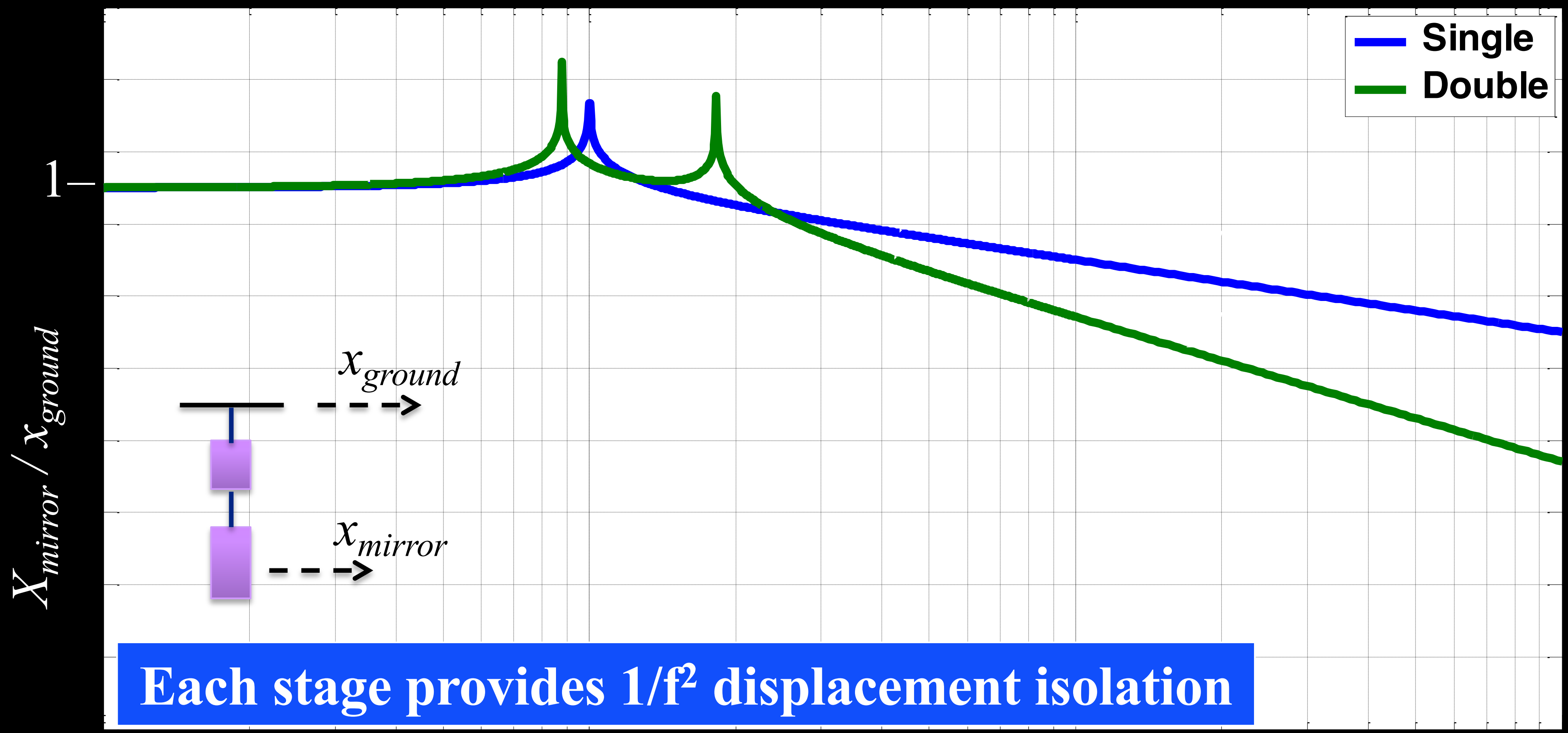


# Multi-stage Isolation Performance
# ‘Transfer function’



**Each stage provides 1/f² displacement isolation**

# Multi-stage Isolation Performance



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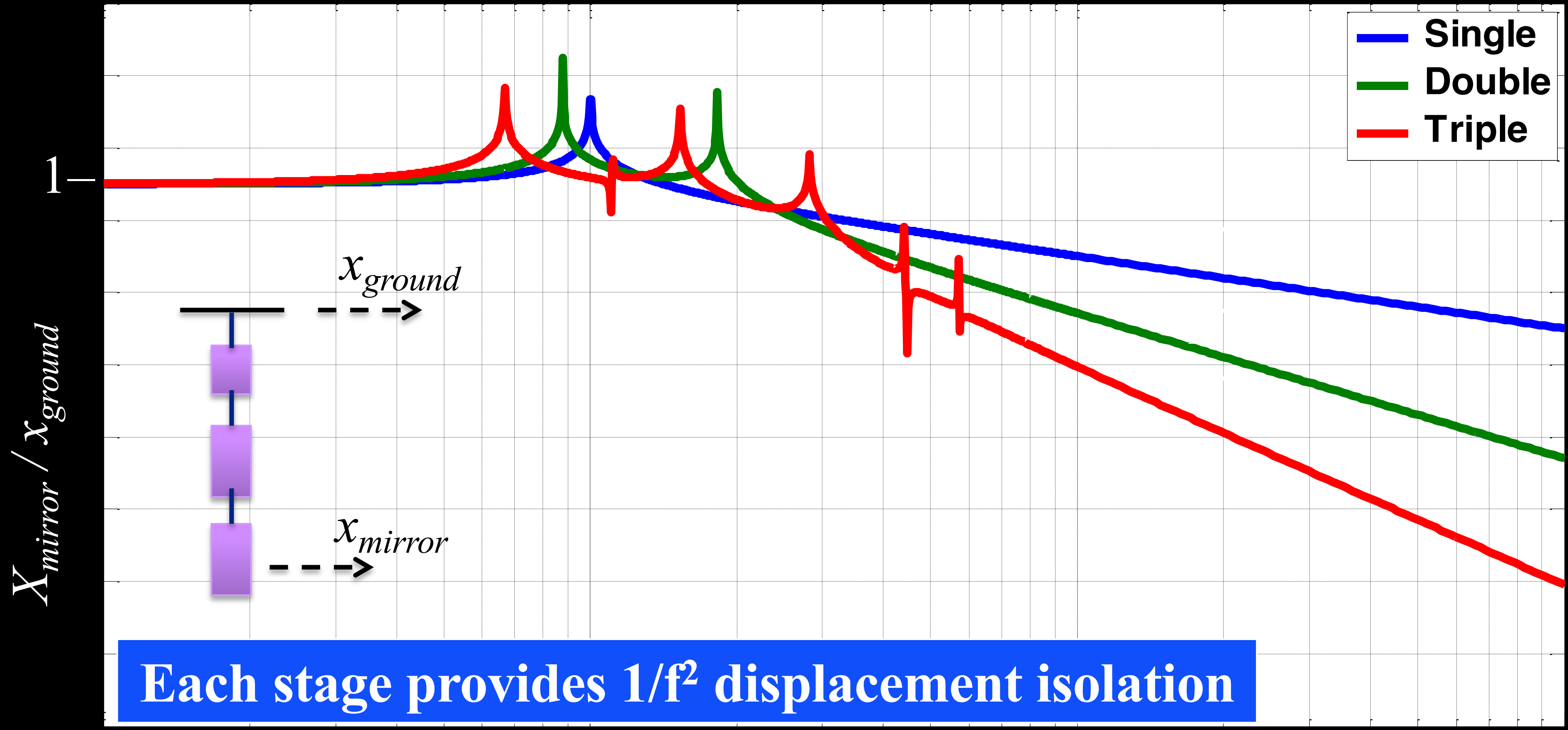
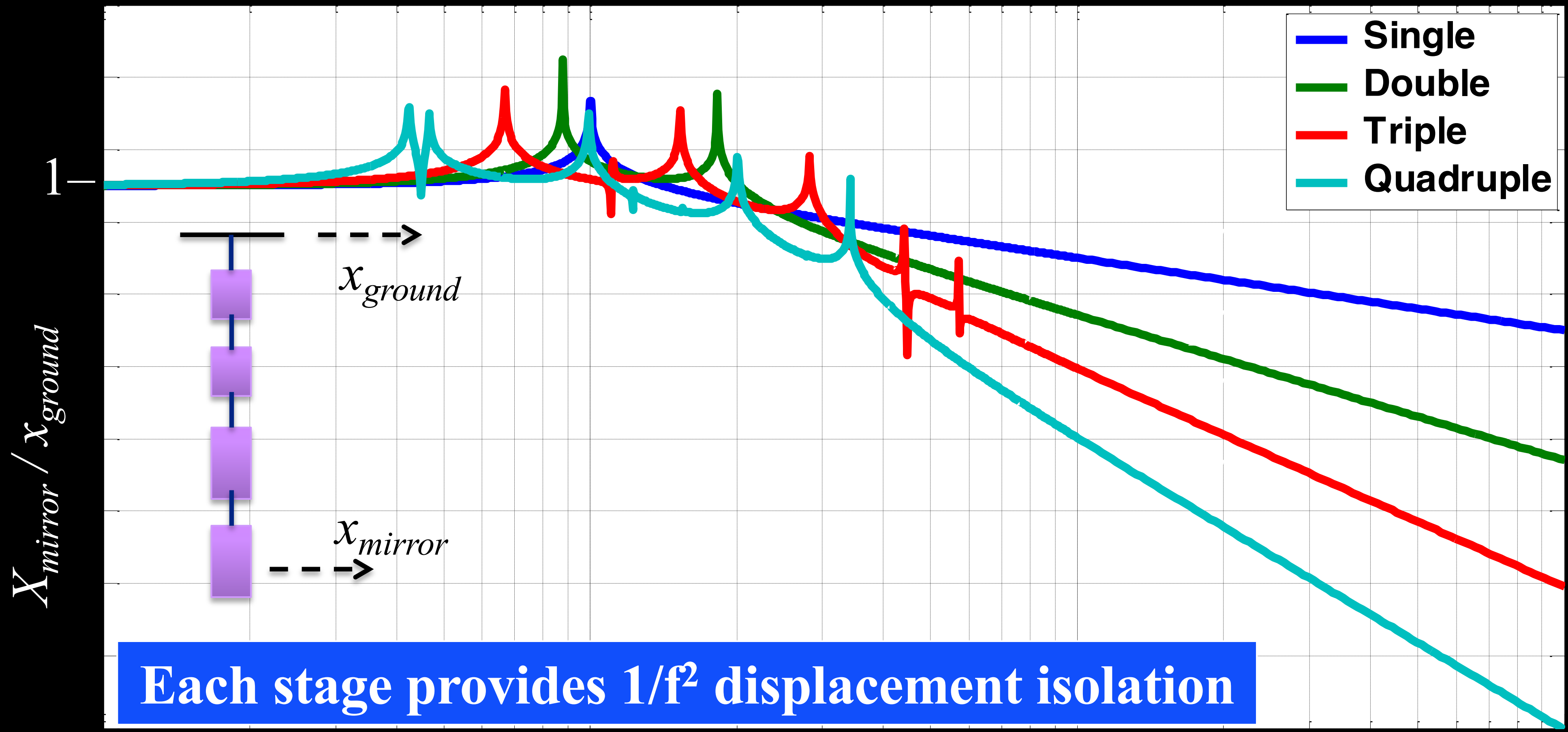


**Each stage provides 1/f² displacement isolation**

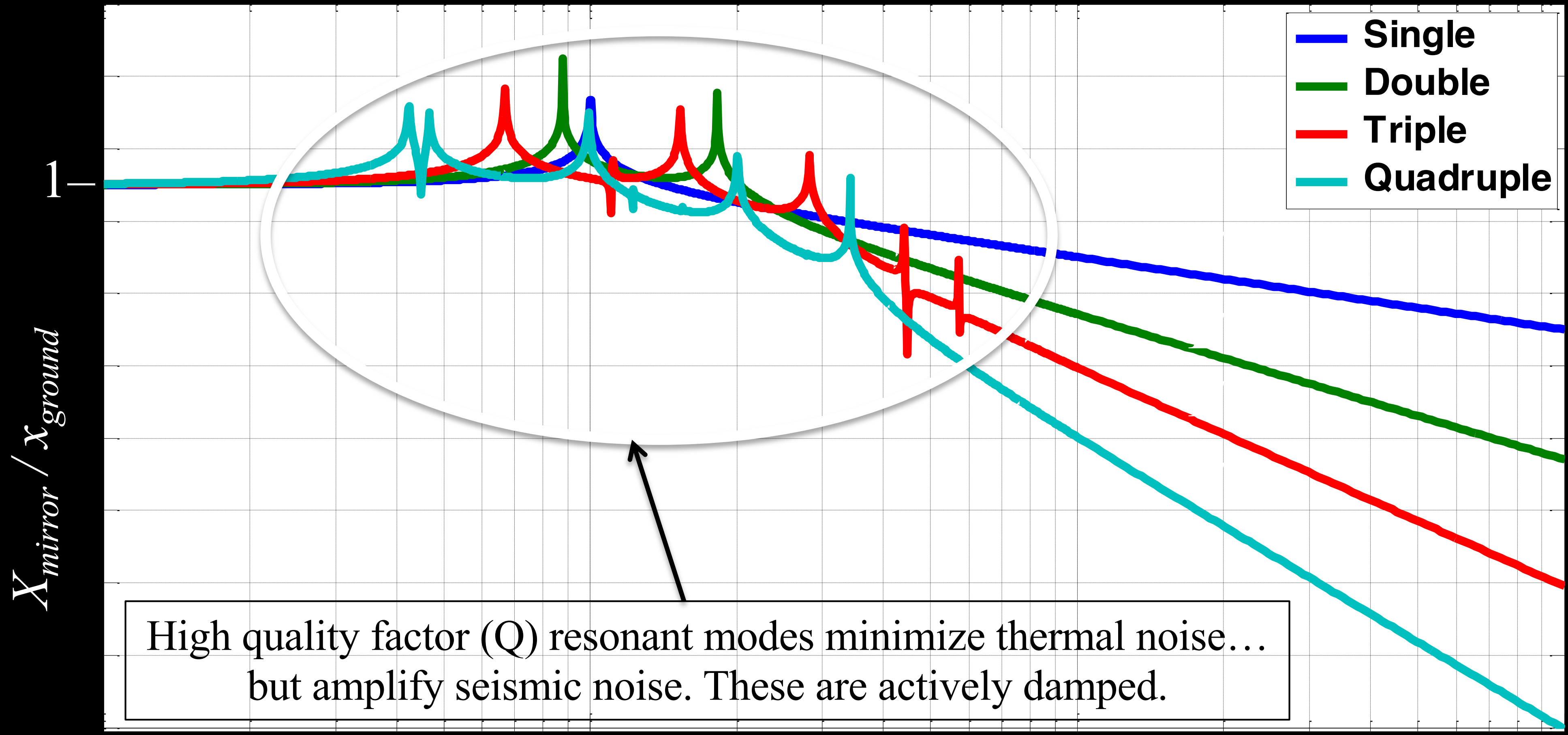
# Multi-stage Isolation Performance



Each stage provides 1/f² displacement isolation

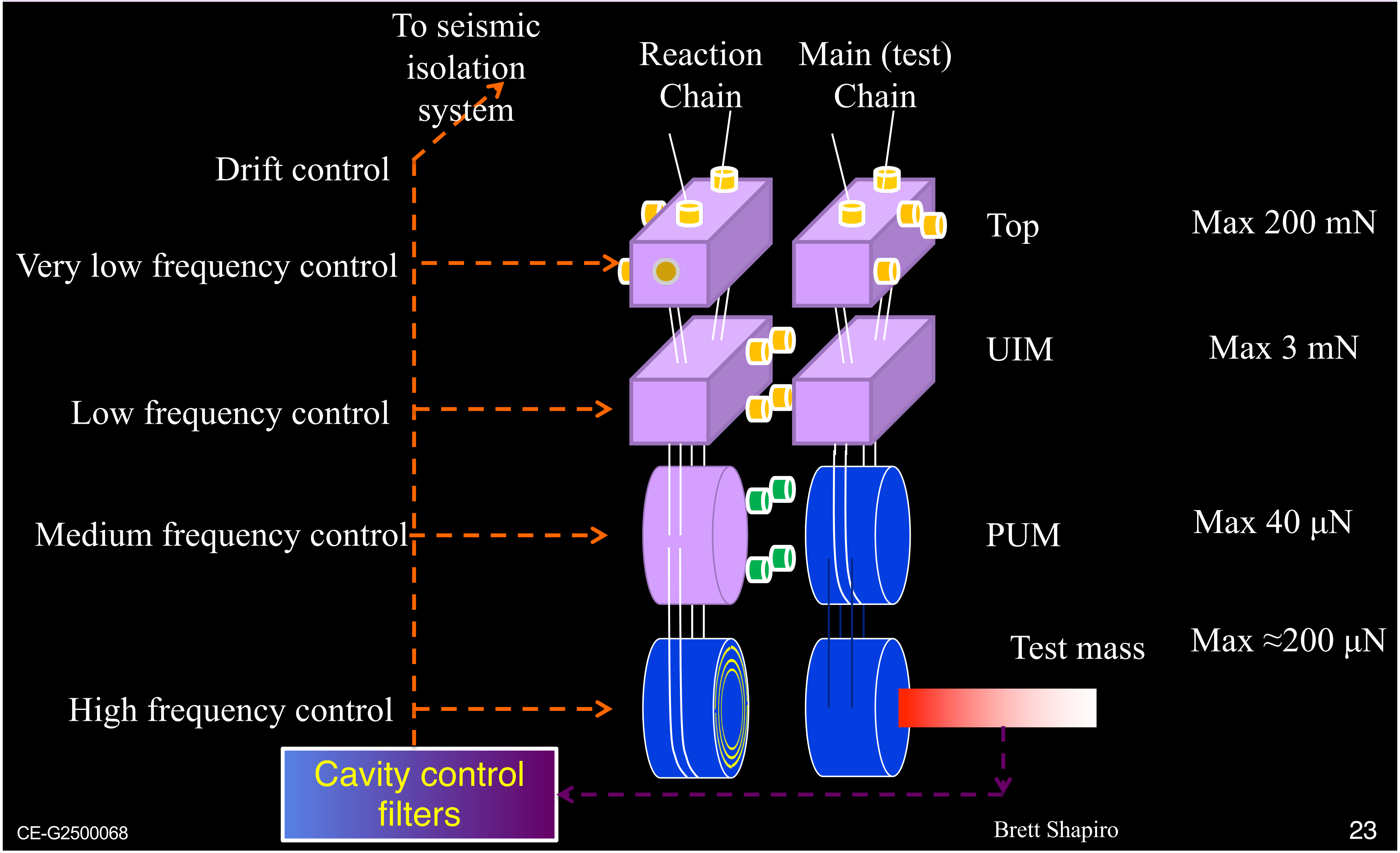
Brett Shapiro

# Multi-stage Isolation Performance



High quality factor (Q) resonant modes minimize thermal noise… but amplify seismic noise. These are actively damped.

# Cavity Length Control



To seismic isolation system

Reaction Chain

Main (test) Chain

Drift control

Very low frequency control

Low frequency control

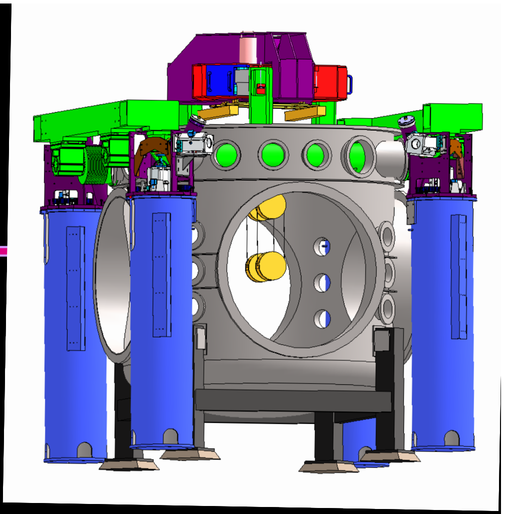
Medium frequency control

High frequency control

| | |
|---|---|
| Top | Max 200 mN |
| UIM | Max 3 mN |
| PUM | Max 40 μN |
| Test mass | Max ≈200 μN |

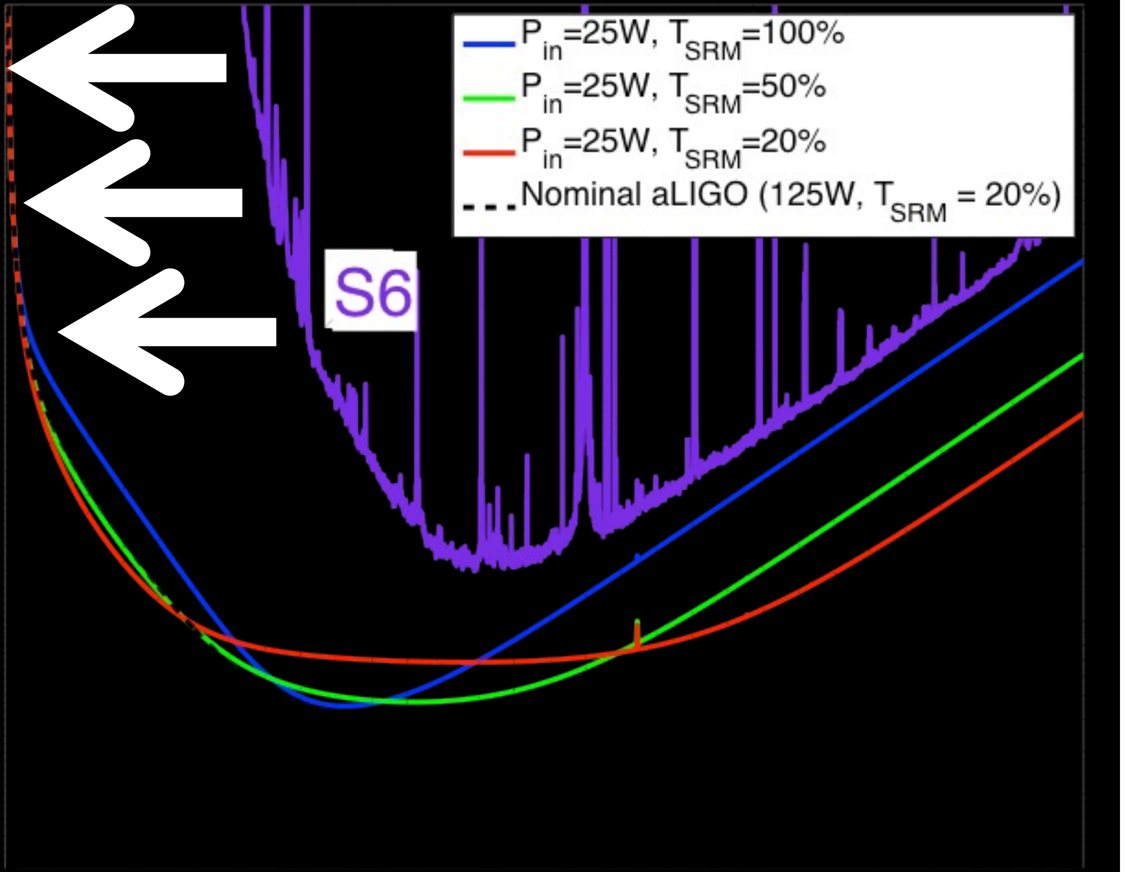
Cavity control filters

# Measuring Δ*L*= 4x10$^{-18}$ m
# External Forces on test mass

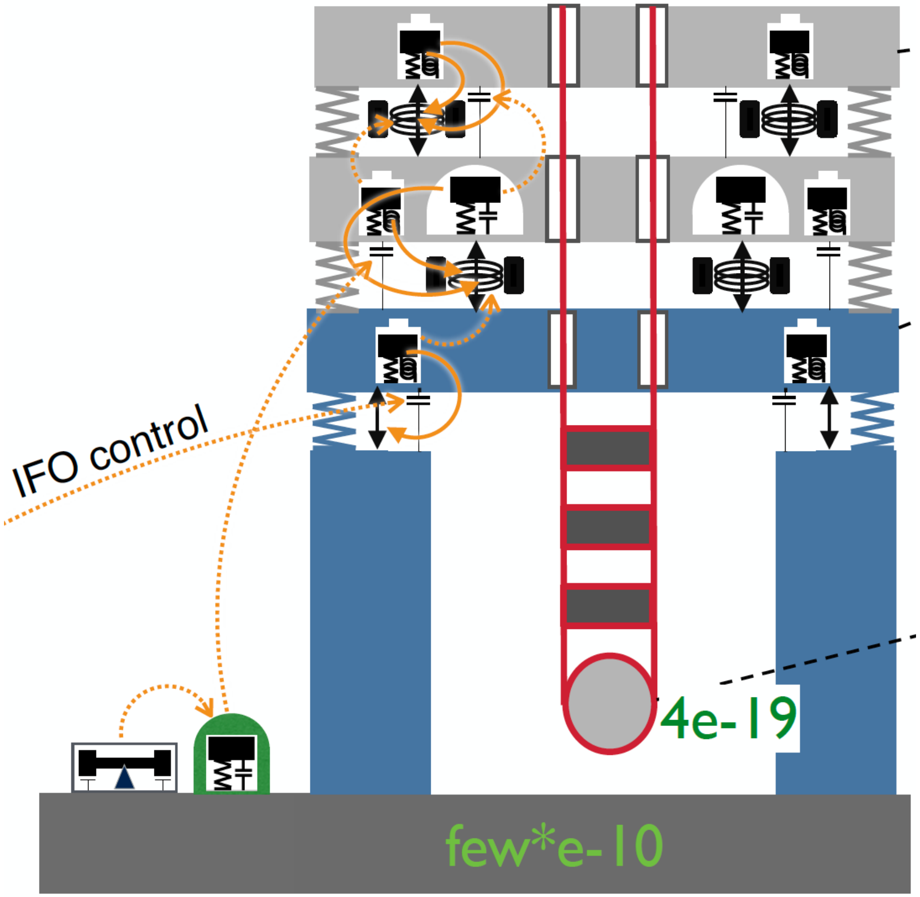


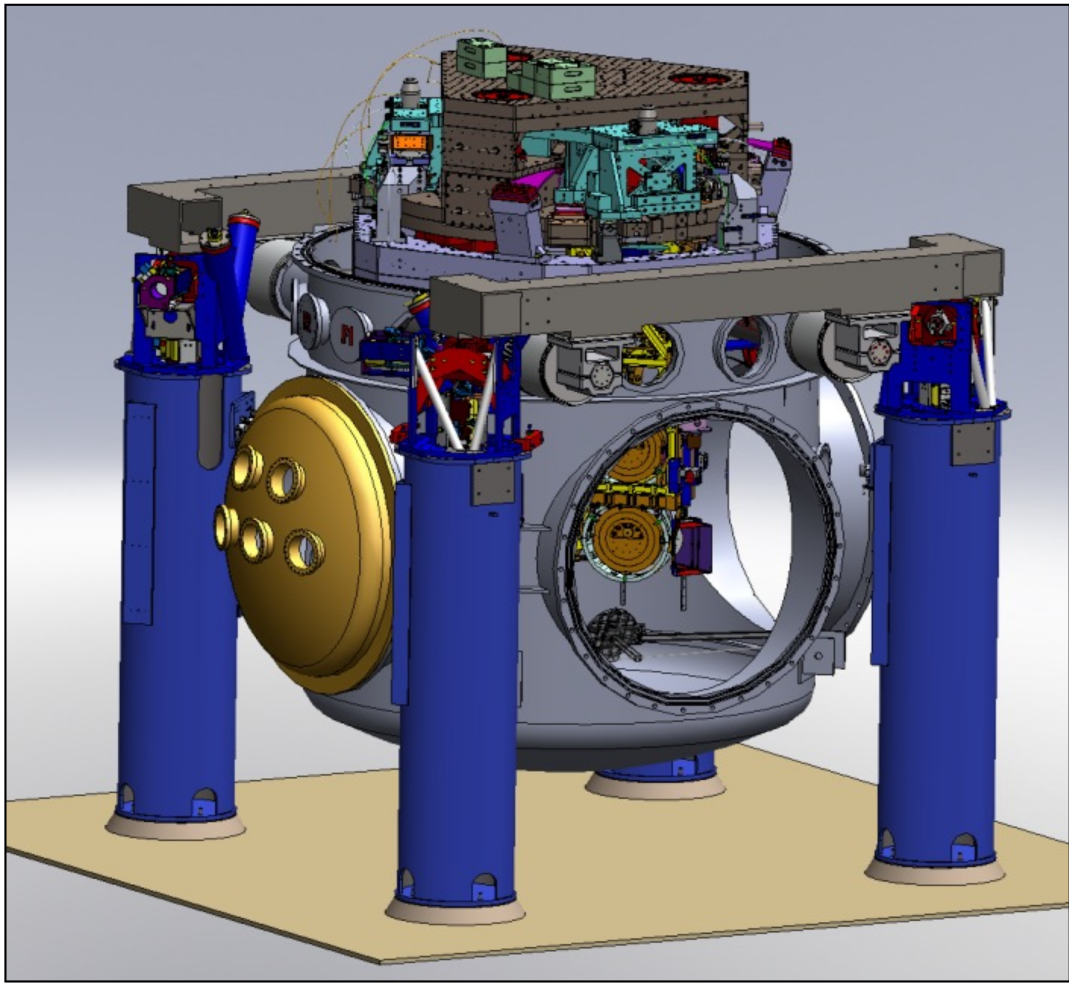
- **Seismic noise** – must prevent masking of GWs, enable practical control systems
- Not ‘fundamental physics’, but ‘fundamental to success’

- aLIGO uses **active servo-controlled platforms, multiple pendulums**



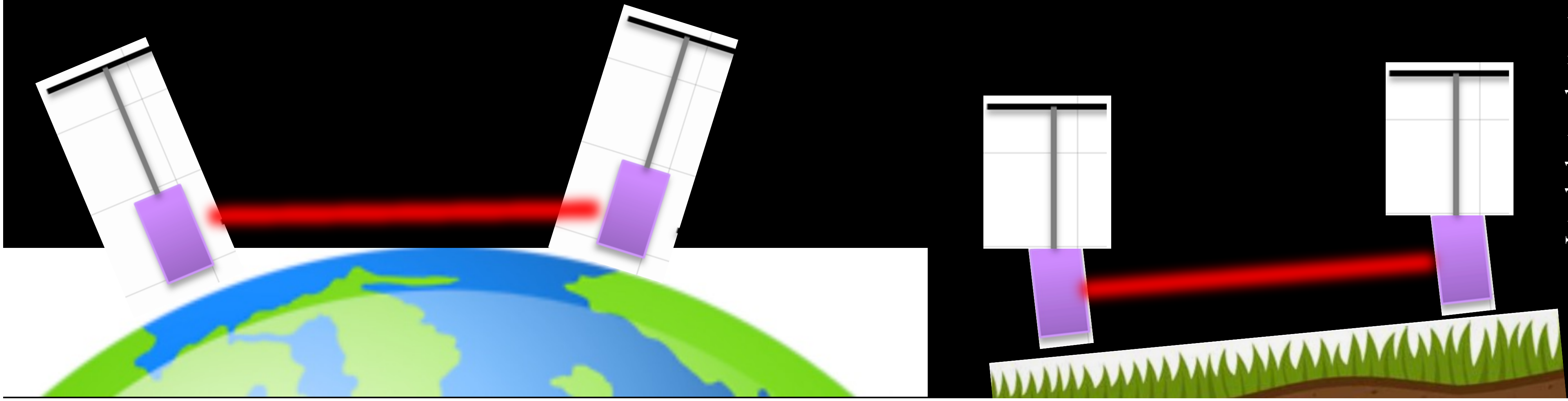
# Active and passive seismic isolation





# Vertical Degree-of-Freedom

- Projection of ‘vertical’ motion along the optical axis if mirror is not normal to the laser beam
  - Both from seismic noise AND from vertical thermal noise
  - → requirement on ‘levelness’ of the Observatory site
  - → coupling growing linearly with length of detector
    - (but GW sensitivity also grows linearly; not a worry!)
- Coupling due to imperfections in suspension design
  - E.g., unbalanced suspension fiber diameters, actuators which have an internal cross coupling, etc.



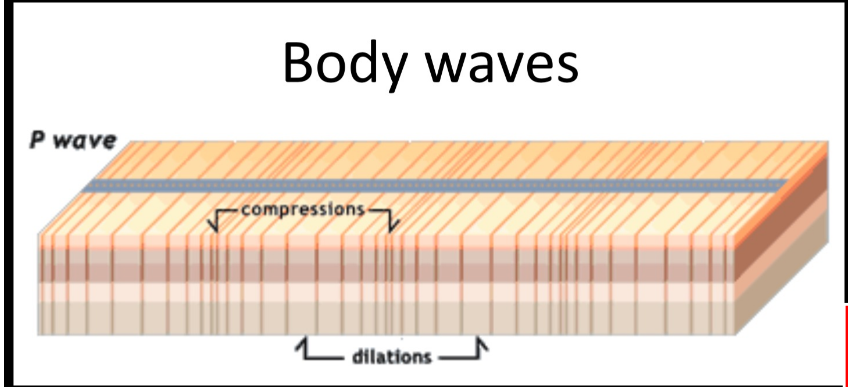
Istockphoto; shutterstock

# Measuring Δ*L*= 4x10$^{-18}$ m
# External Forces on test mass

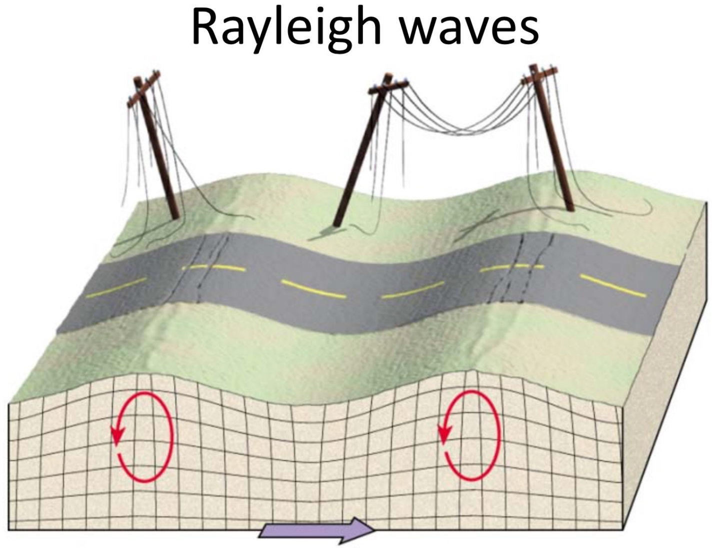
Ultimate limit on the lowest frequency detectors
on- or under-ground:

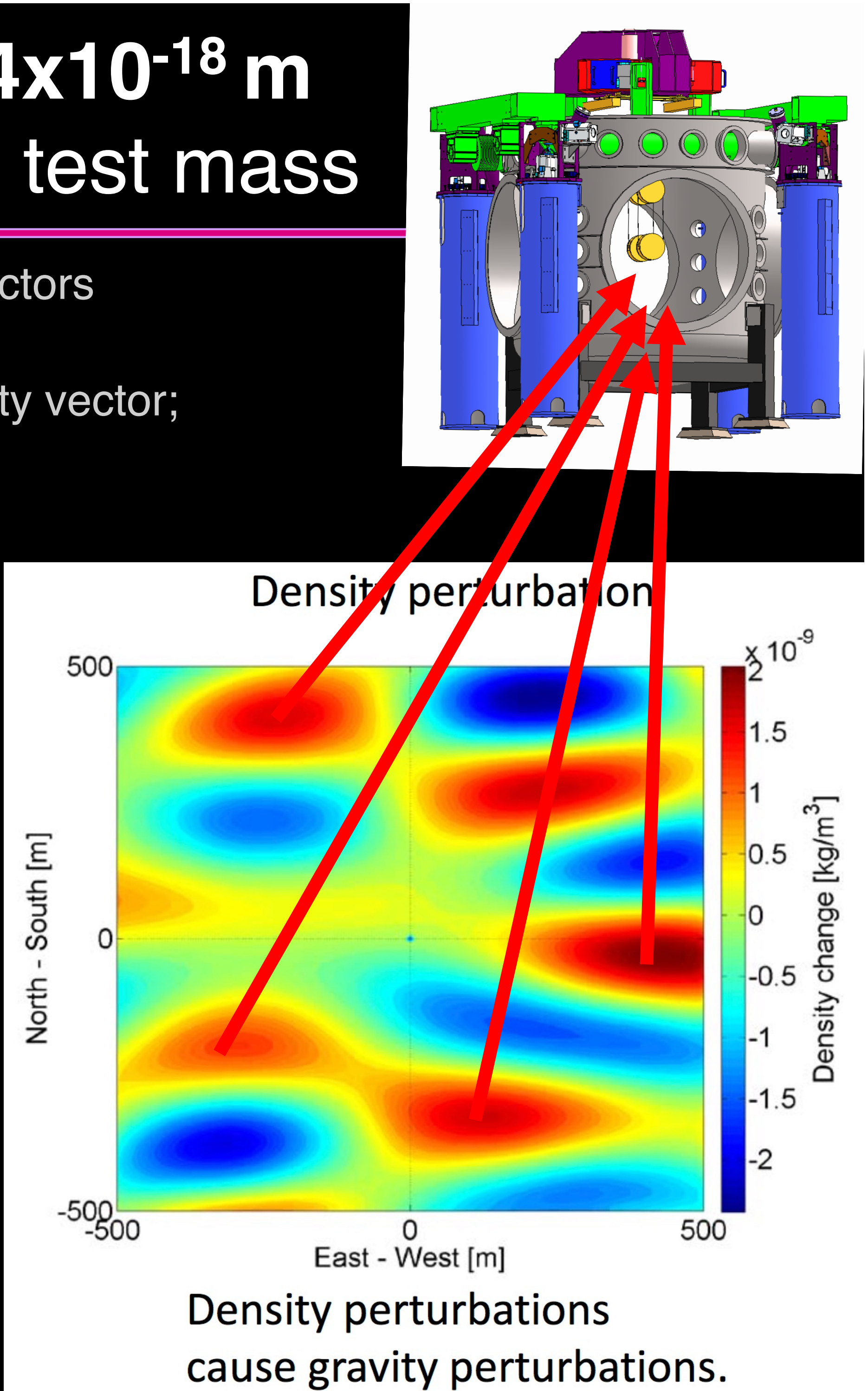
- **Newtonian background** – wandering net gravity vector; Forbiddingly large for ~3Hz and lower

Body waves



Rayleigh waves

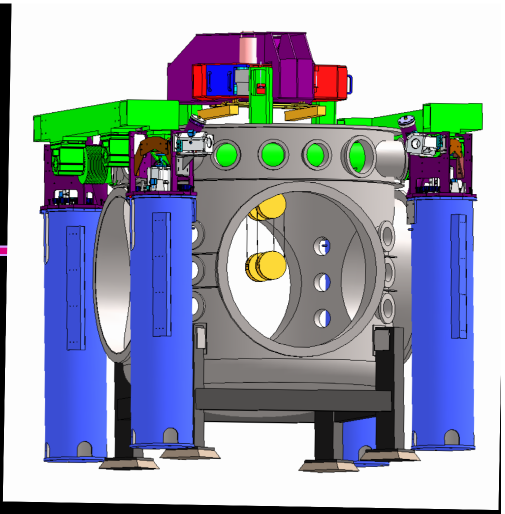




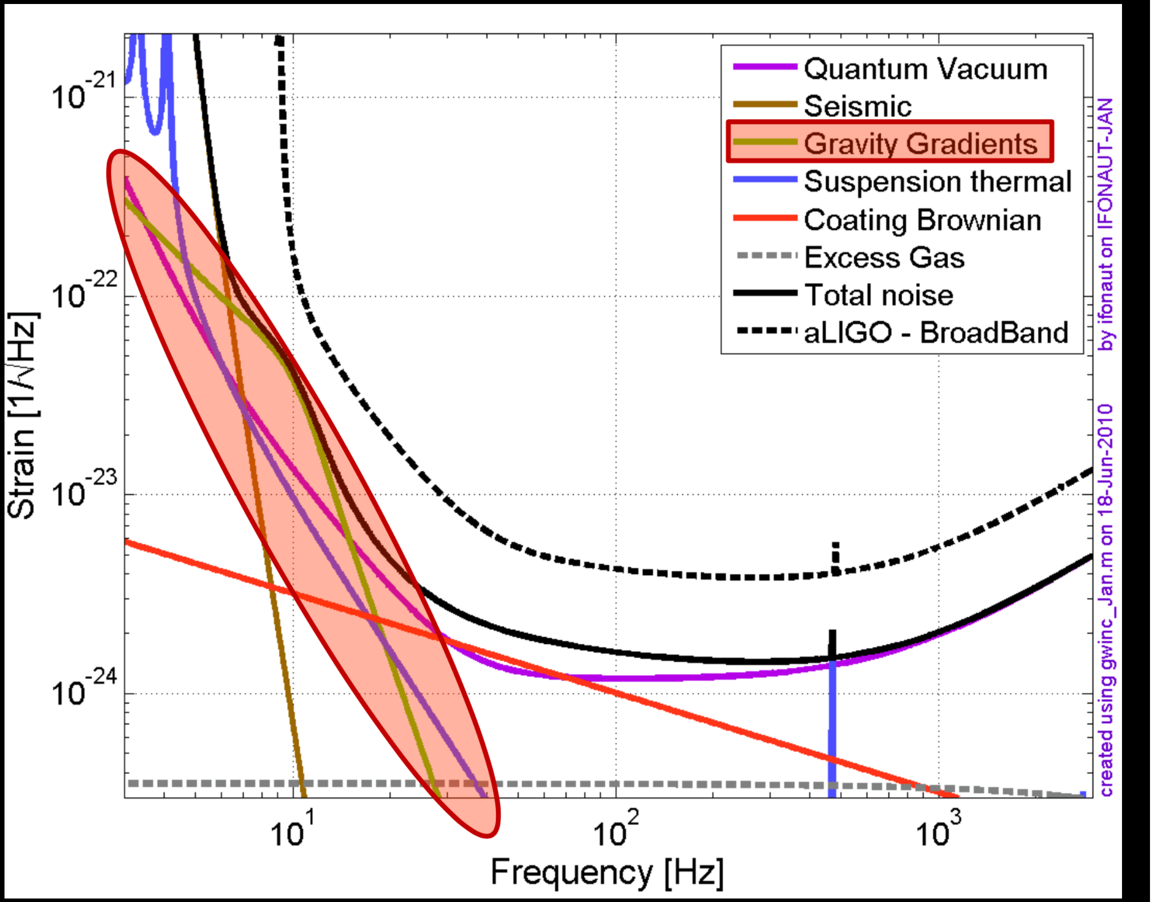
Density perturbations cause gravity perturbations.

Images: J. Harms

# Measuring Δ*L*= 4x10$^{-18}$ m
## External Forces on test mass



- Advanced LIGO (and Virgo) expect to be limited by this noise source –
  - After all technical noise sources beaten down
  - At low optical power (no radiation pressure noise)
  - In the 10-30 Hz range
- **We would *love* to be limited only by this noise source!**
- Want to go a bit lower? Go underground.
- Want to go much lower? Go to space. **LISA MIssion**



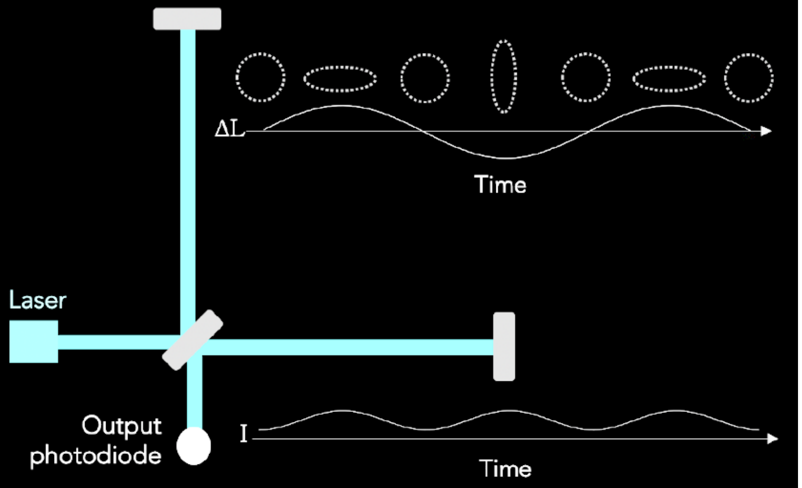
Images: J. Harms

# Mid-path summary

- Interferometry comparing the light travel time along (more or less) orthogonal arms can measure a passing gravitational wave
- The limits to sensitivity come from
  - Undesired motions of the interferometer mirrors
  - Limitations in our ability to measure the positions of the mirrors
- Thermal noise is one cause of undesired motions, managed through use of low-mechanical-loss materials and concentrating motion in a narrow band
- External forces must be very strongly filtered to make those forces negligible; pendulums are a very useful approach, complemented with servo-control systems
- Time-varying Newtonian gravity fields remain, and cannot be filtered – only reduced through facility design (including underground) or sensed and subtracted (with limited success)

- …Now: sensing the position of the masses

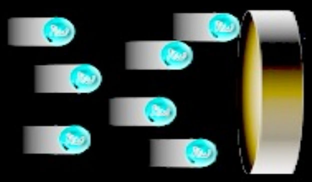
# Resolution of the optical sensing



- **Shot noise** – ability to resolve a fringe shift due to a GW (counting statistics; *A. Einstein, 1909*)

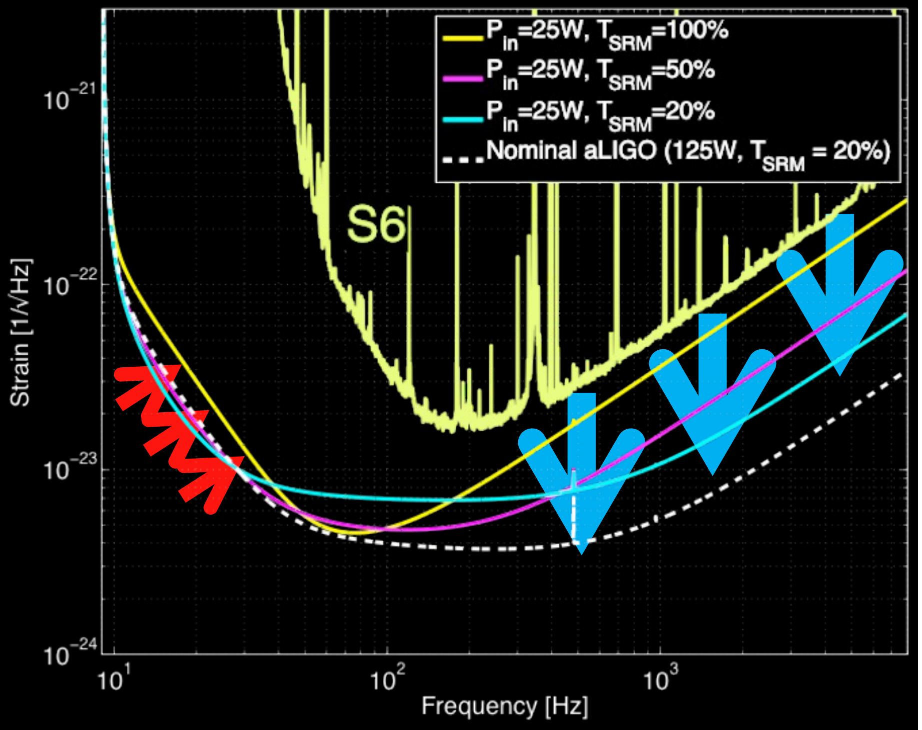
$$h_{\rm sn}(f) = \frac{1}{L}\sqrt{\frac{\hbar c\lambda}{2\pi P}}$$

- **Radiation Pressure noise** –buffeting of test mass by photons increases low-frequency noise – use heavy test masses!



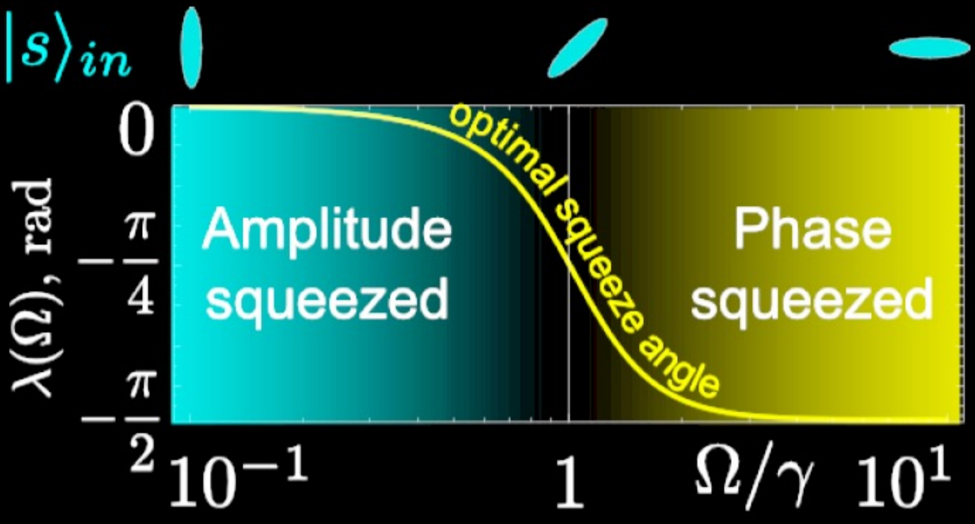
$$h_{\rm rp}(f) = \frac{1}{mf^2L}\sqrt{\frac{\hbar P}{2\pi^3 c\lambda}}$$

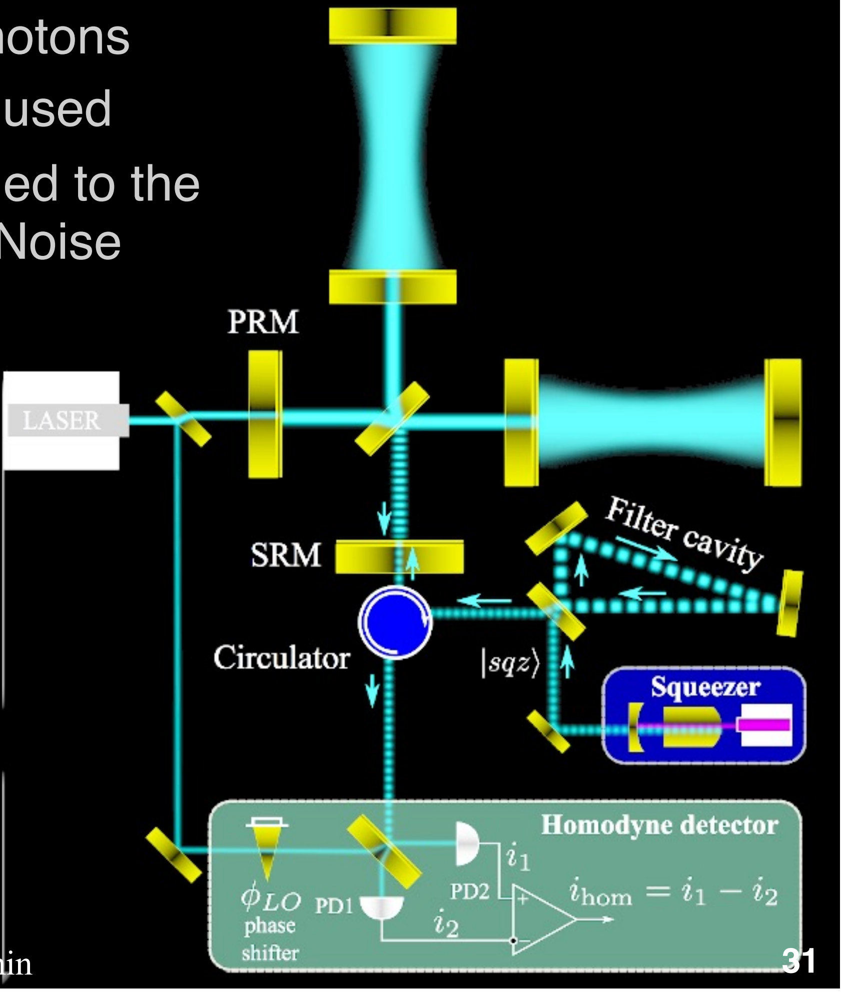
- **Standard Quantum Limit**



# Frequency Dependent Squeezing

- Heisenberg's principle still holds at any given frequency, but we may look more carefully at the amplitude at low frequencies
  -- and at the phase at high frequencies
- Use squeezed light to trade between precision in phase and amplitude
  - » Playing with the Poisson statistics of the photons
- We can adjust the phase of the squeezed light used
  - » Optical resonant cavity acting as a filter tuned to the transition from Radiation Pressure to Shot Noise





J. Kimble et al., PRD 65, 022002 (2001); S.L. Danilishin

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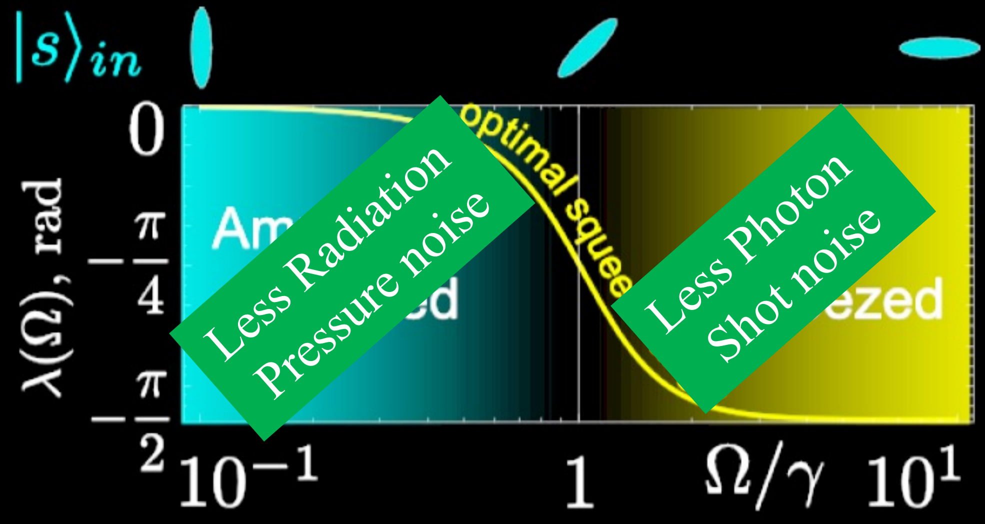

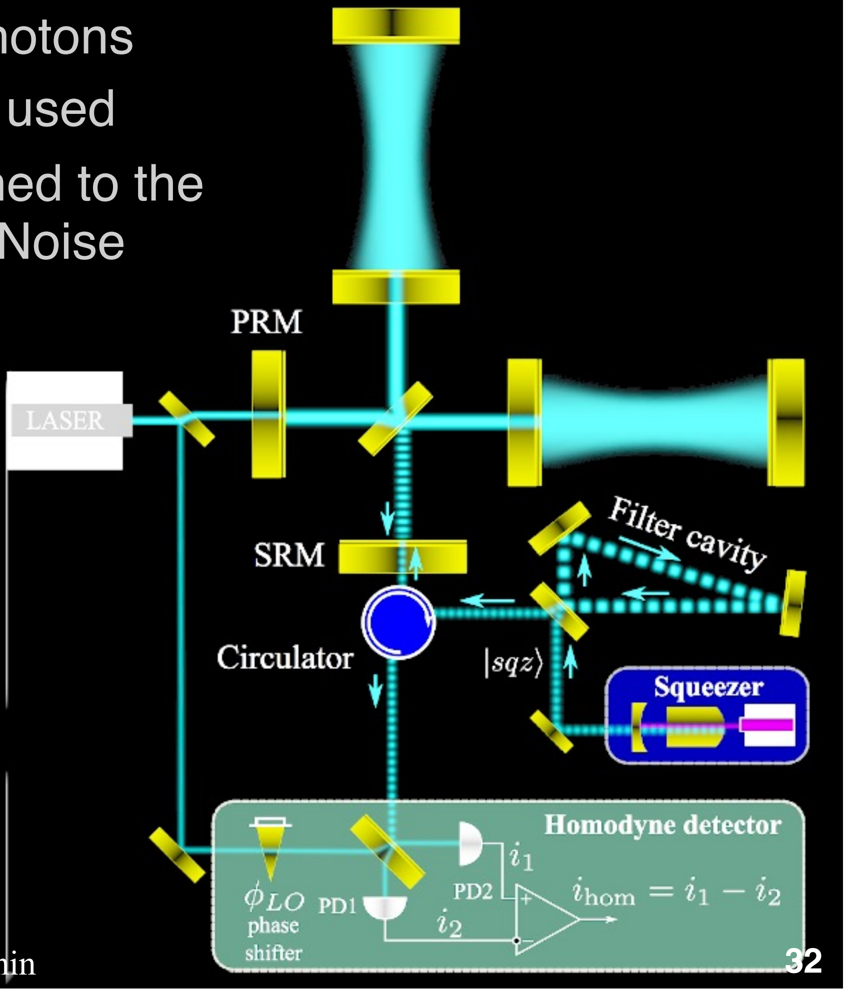

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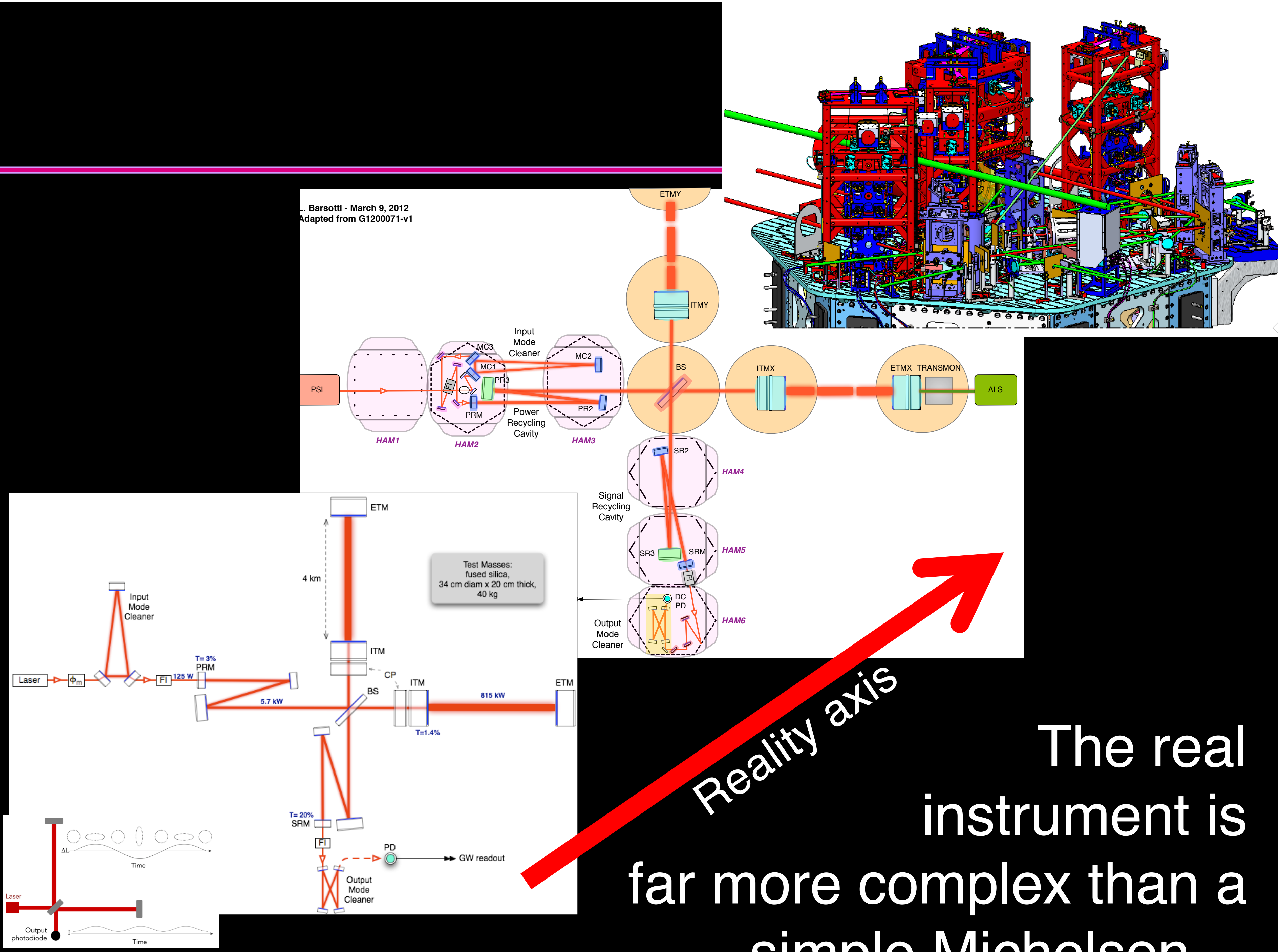
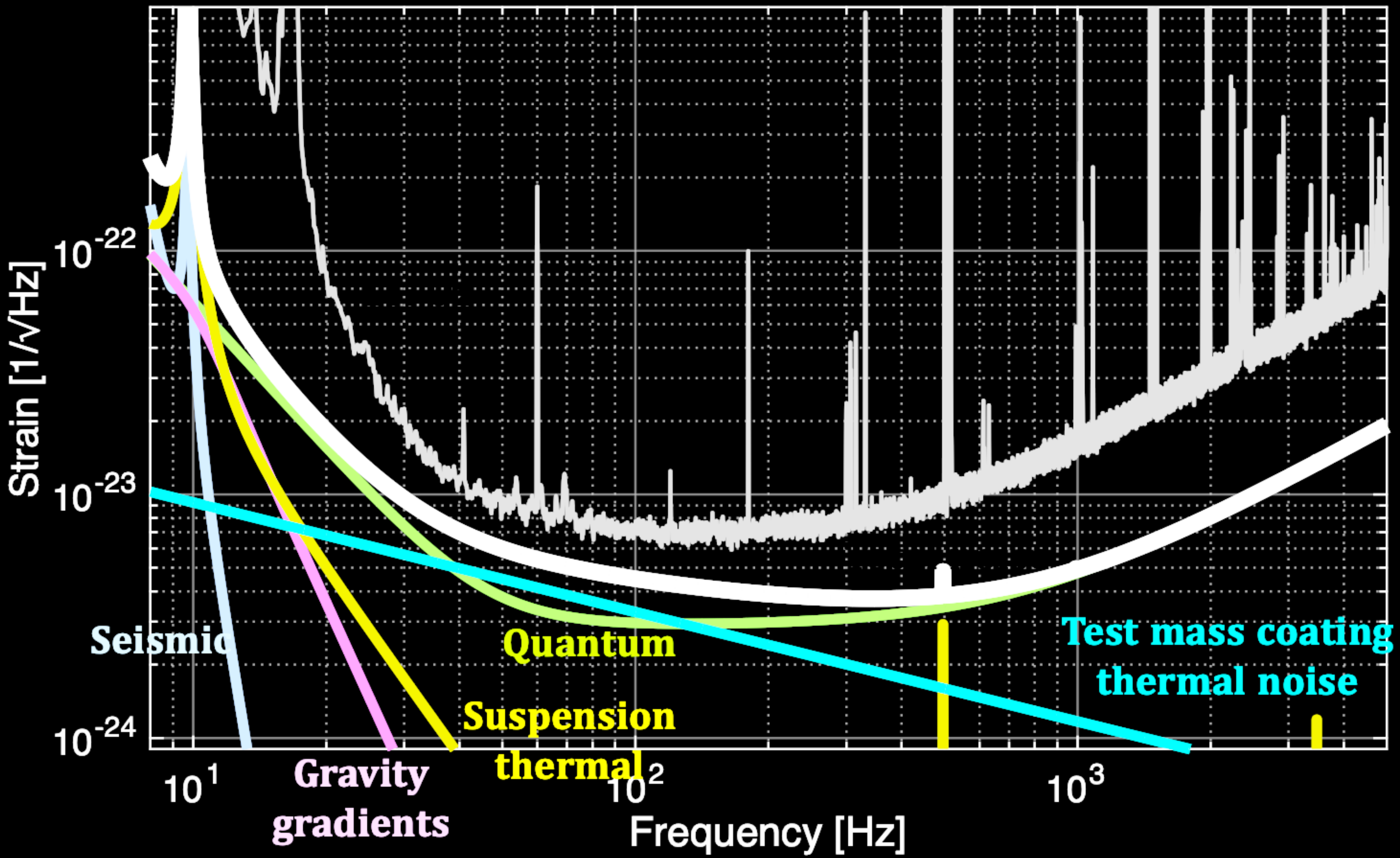


The real
instrument is
far more complex than a
simple Michelson…

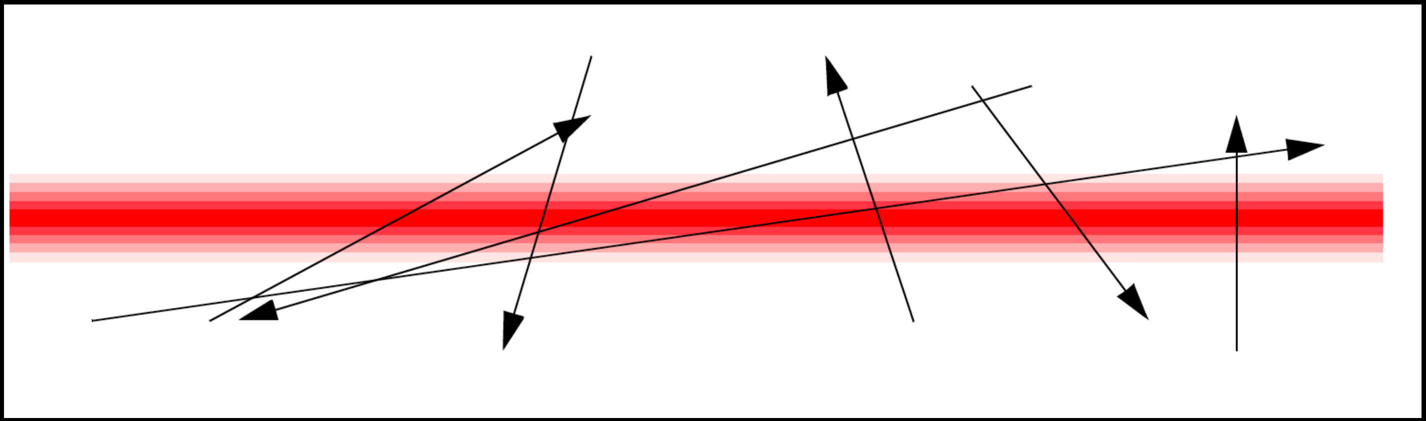
# Adv LIGO Target Design Sensitivity, basic noise sources



# Observatory Infrastructure

# Vacuum System

- The 3 or 4km path of the laser from BeamSplitter to end mirror must be in an excellent vacuum



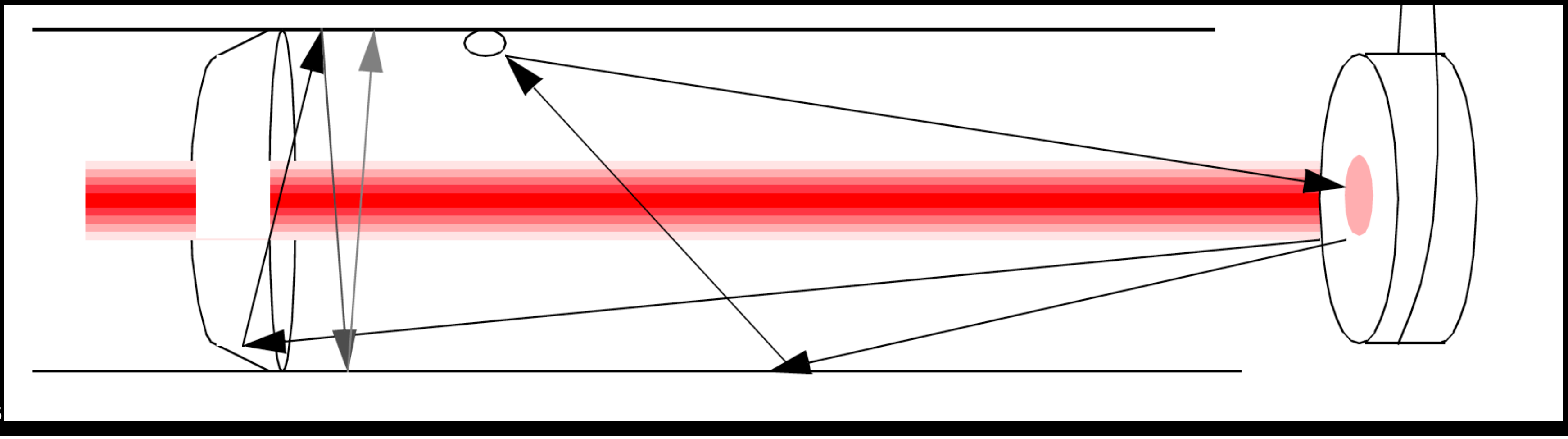
- Polarizability α of the remaining gas molecules induces path-length fluctuations; again, Poisson Statistics, and an effect proportional to square root of density $\rho^{1/2}$ along the path

$$h(f) \approx 4\pi\alpha\left(\frac{2\rho}{v_0 w_0 L}\right)^{\frac{1}{2}}$$

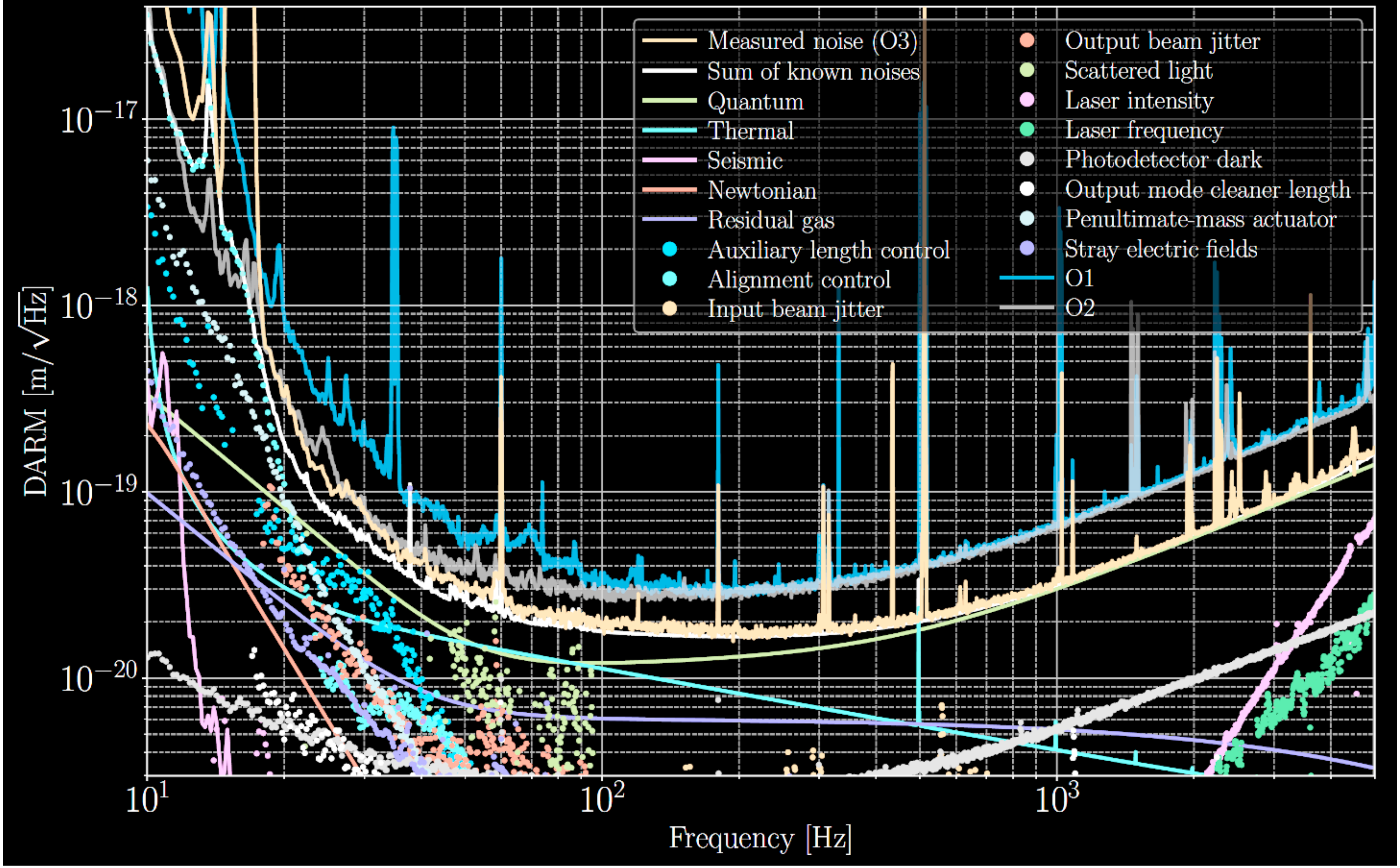
- Connect locomotive transformer to tubing for $I^2R$ heating to outgas
- 1 pump every 2km suffices!

# Beam Tube Scattered Light

- Laser wavelength determines the minimum beam size after 4km propagation – for 1064nm Nd:YAG, this leads to 10-12cm diameter for $1/e^2$ – but in fact must be much further in the tails of Gaussian to $10^{-6}$
- In addition, the mirrors are not perfect
  - ‘dust’ and point defects
  - Large-scale ‘waviness’ (~10 nm over 10 cm)
- → 1.2m diameter beam tube
- → baffles to catch scattered light



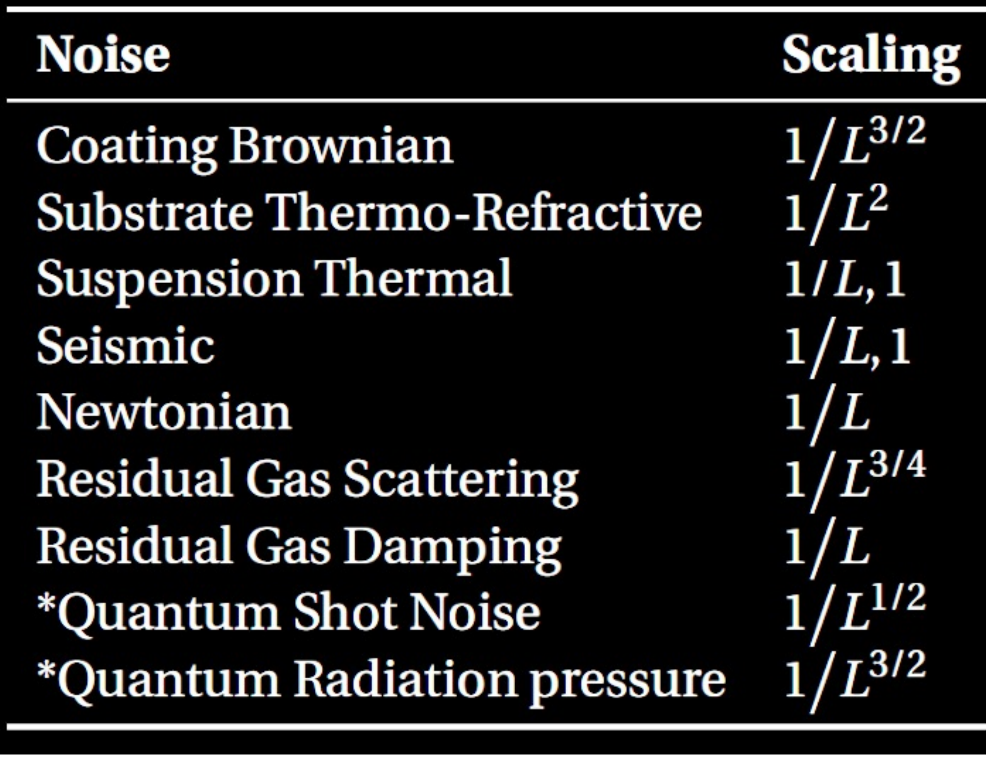
# Many other
# 'technical' noise sources….



# Some considerations for future Observatories

# Length: The ultimate solution

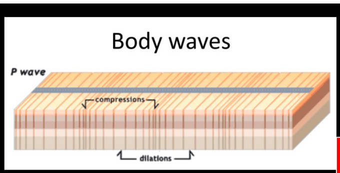
- Design for low thermal noise, quantum limits, seismic noise, controls/servos…
  - Subtle, difficult instrument design challenges
- **Length** is great for sensitivity! Technically *much* easier than lowering noises
  - Signals get larger, noises tend not – until one is comparable to $\lambda_{GW}/2$
    - (Optimum for coalescence of BNS around 20km)

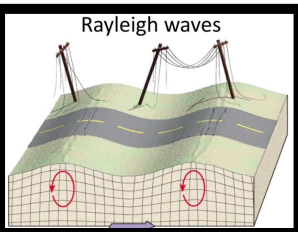


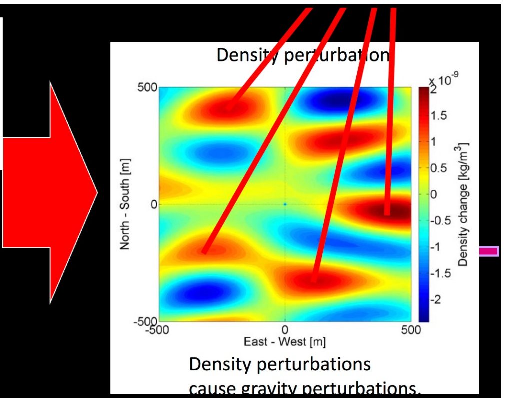
| **Noise** | **Scaling** |
|---|---|
| Coating Brownian | $1/L^{3/2}$ |
| Substrate Thermo-Refractive | $1/L^2$ |
| Suspension Thermal | $1/L, 1$ |
| Seismic | $1/L, 1$ |
| Newtonian | $1/L$ |
| Residual Gas Scattering | $1/L^{3/4}$ |
| Residual Gas Damping | $1/L$ |
| *Quantum Shot Noise | $1/L^{1/2}$ |
| *Quantum Radiation pressure | $1/L^{3/2}$ |

- One disadvantage: **Cost.**
  - Vacuum system
  - Earthmoving
  - concrete
- Length scaling dominates the cost for a detector

# Terrestrial detectors: Surface, or Underground?







Density perturbations cause gravity perturbations.

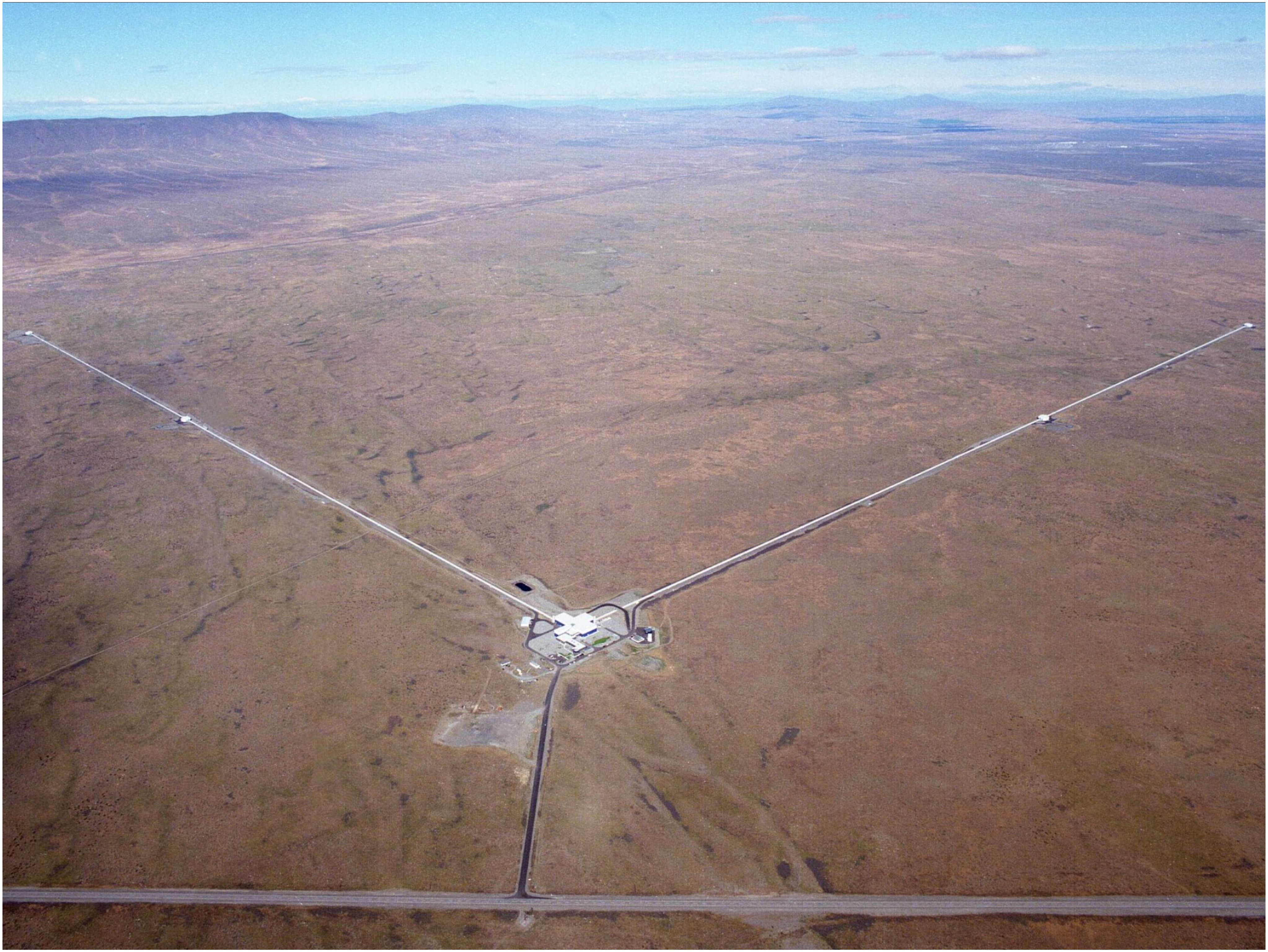
- Burying the detector has unique advantages to improve the low-frequency sensitivity; esp. reducing the Newtonian background
- The Science Case should drive the design decisions, modulated by cost
- Asking for both an optimal length **and** and a buried detector is probably unrealistic from a cost standpoint
- Next-generation observatories are a wonderful illustration
  - Cosmic Explorer: 40km, surface detector, best reach
  - Einstein Telescope: 10km, underground, best low-frequency
- Also practical considerations:
  - Working underground, safely, is hard! Can expect slower progress in activities leading up to observation
  - On the surface, Blocking migratory paths, occupying land belonging to indigenous peoples and present use present very difficult puzzles to solve

# One more fundamental element in interferometer designs

# Collaboration

- Table-top scientists – precision measurement, laser, atomic – started the field; tradition of small groups, small projects, and some competition
- Early general relativists, theorists, astrophysicists much the same
- Transformation when High Energy Physics types got involved
  - Engineering, project organization, computing, analysis
- Funding agencies also saw a need for a shift
  - There is a real skill in spending hundreds of millions of dollars!
- Goal pre-discovery was crystal-clear: Make a detection
- After the Collaborations formed and were stable, meta-collaborations: ‘The LVK’ – KAGRA, Virgo, and LSC
  - The science that is possible is qualitatively greater
  - The sociology of a (mostly) non-competitive environment nurturing and supportive
- Big Questions now that the field is established:
  - Should the data be private?
  - Are ever bigger Collaborations best for people? Science?

# LIGO ‘Virtual’ Tour

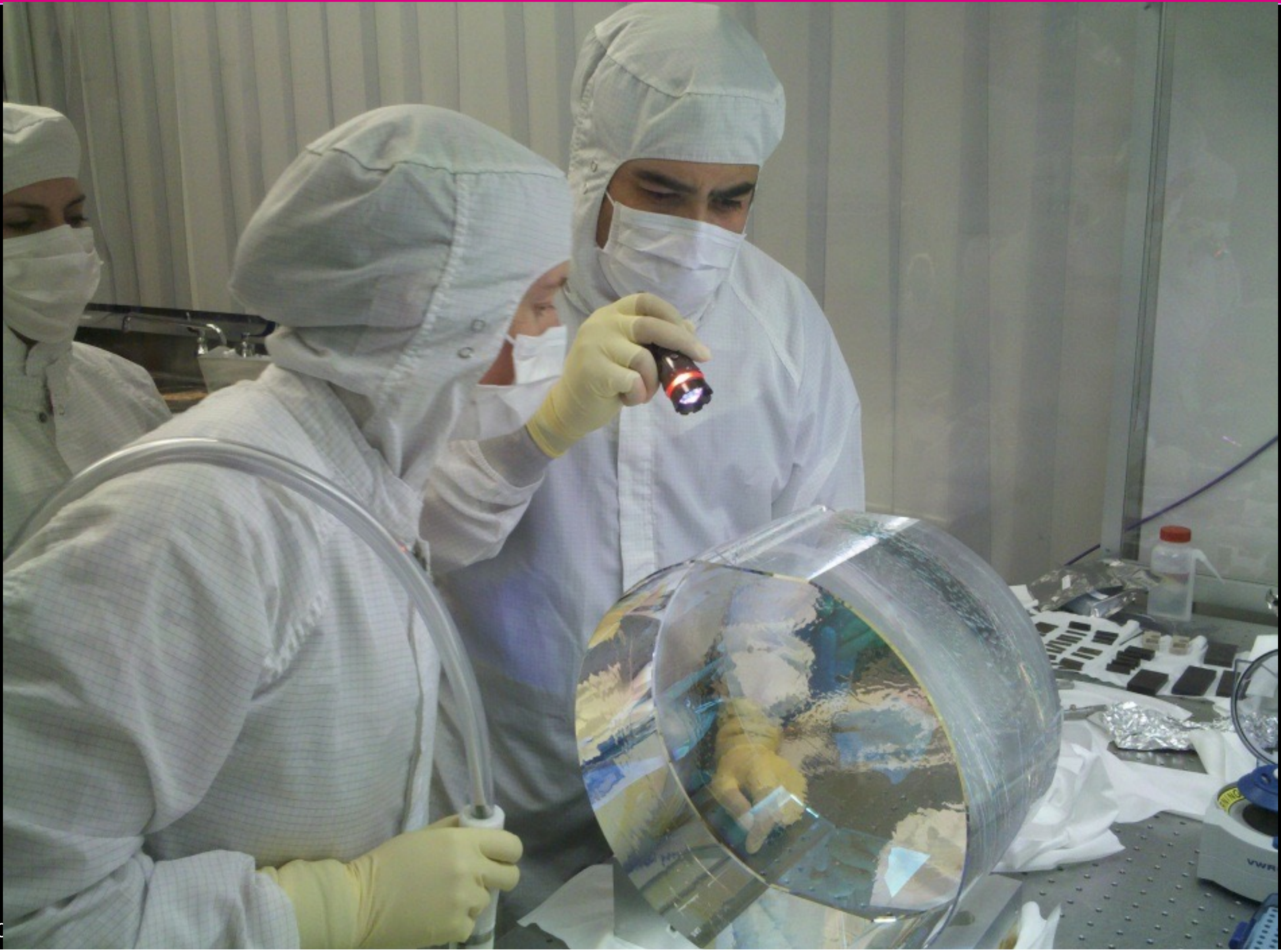


# Hanford Corner building

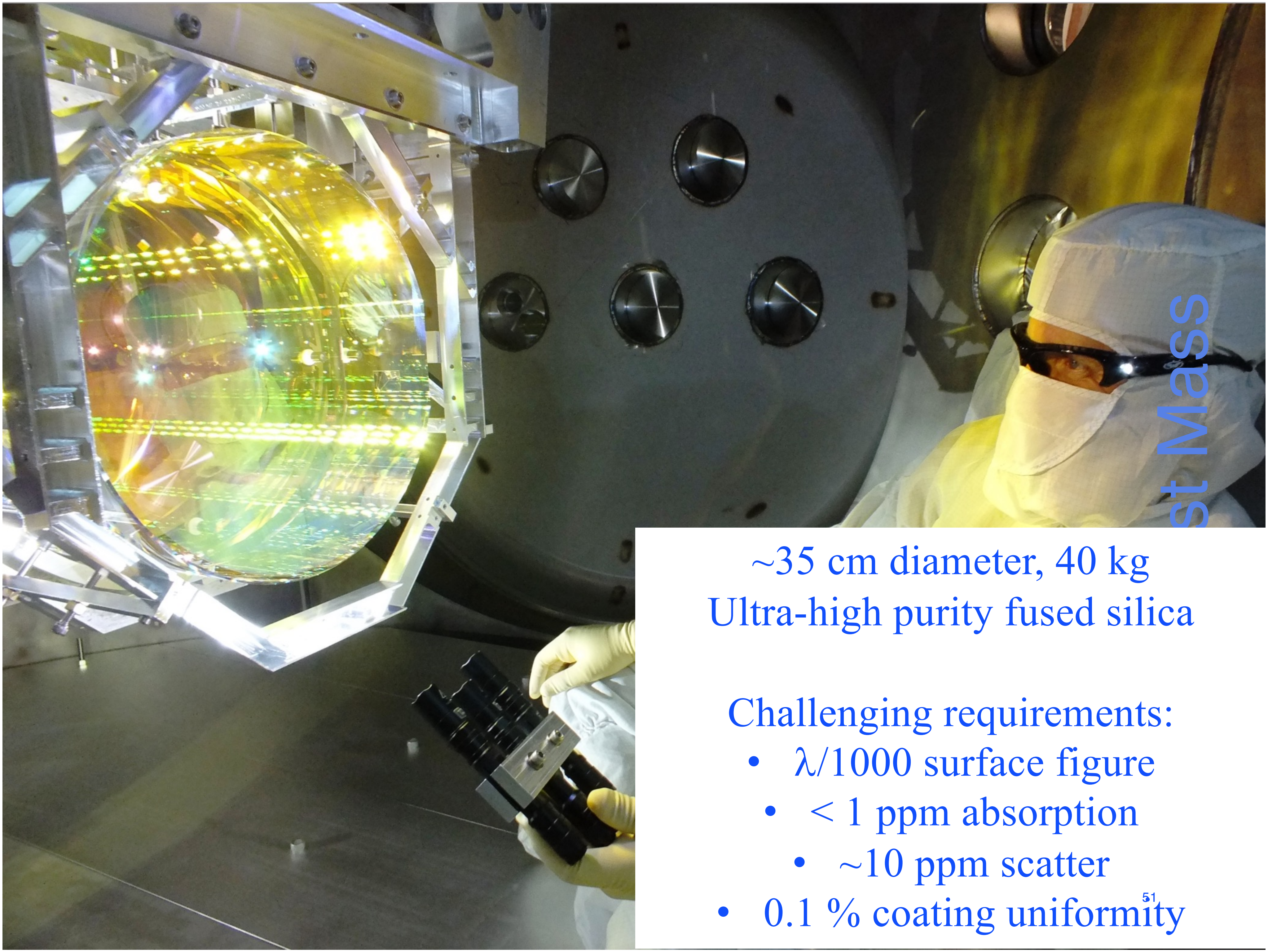
# Laser Clean Room; extraterrestrials for scale

# Vacuum chambers to protect and isolate optics

# Inspecting mirror during fabrication



st Mass

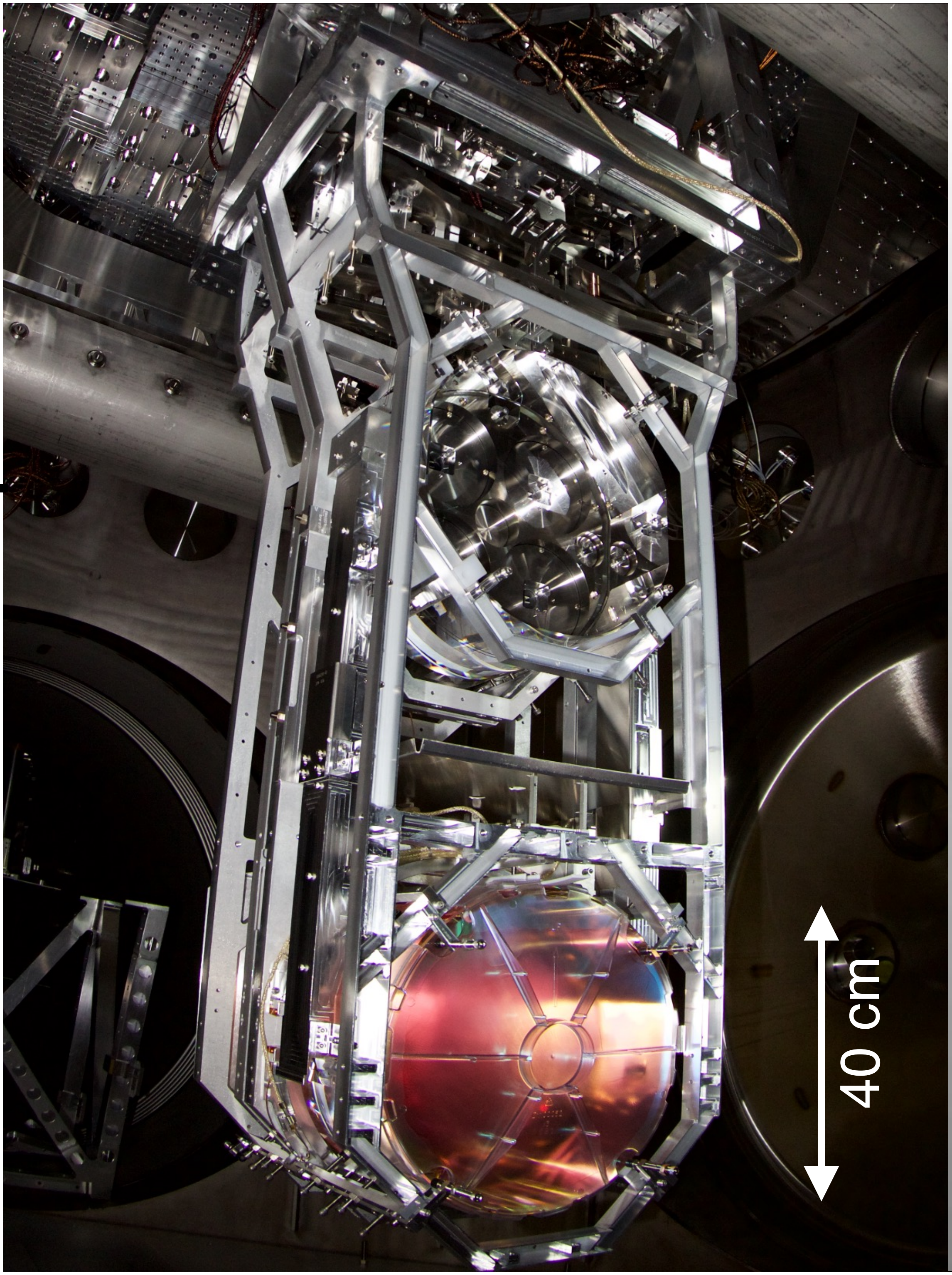


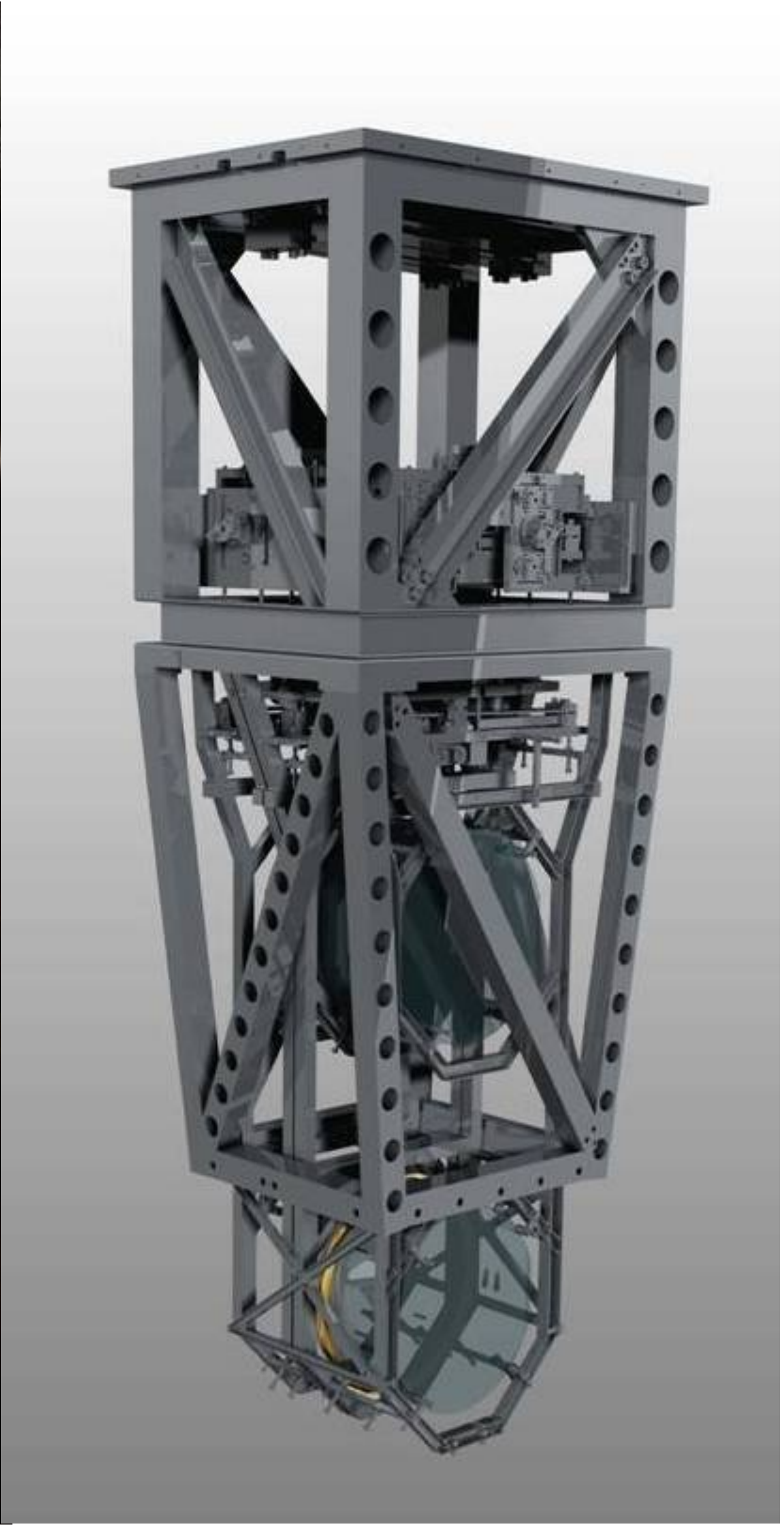
~35 cm diameter, 40 kg
Ultra-high purity fused silica

Challenging requirements:

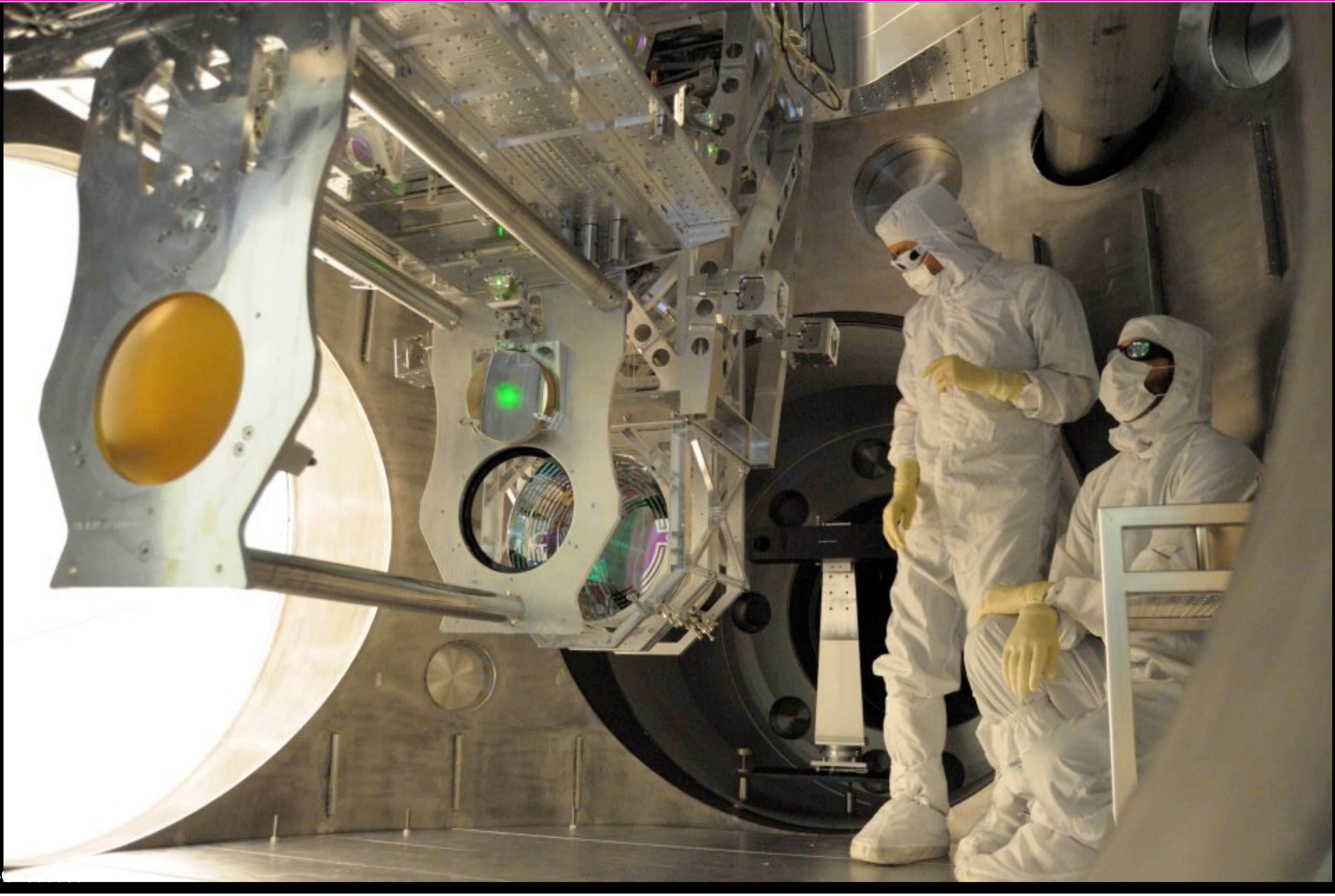
- λ/1000 surface figure
- < 1 ppm absorption
- ~10 ppm scatter
- 0.1 % coating uniformity

# Test Mass Suspension

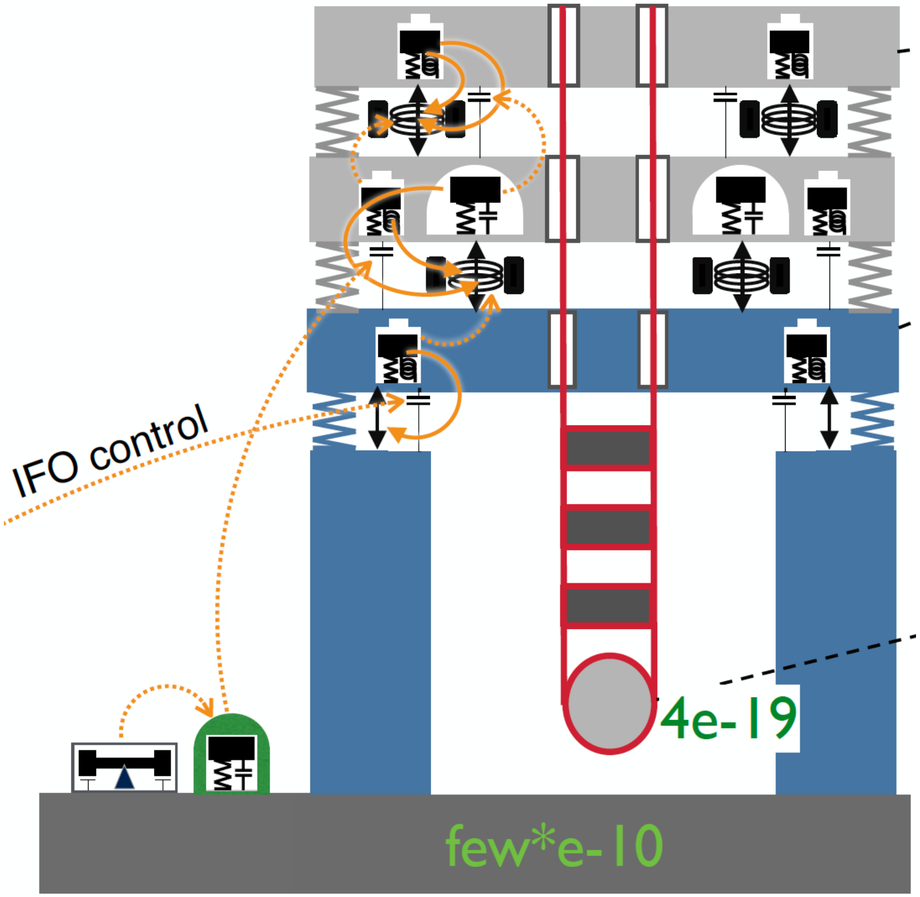


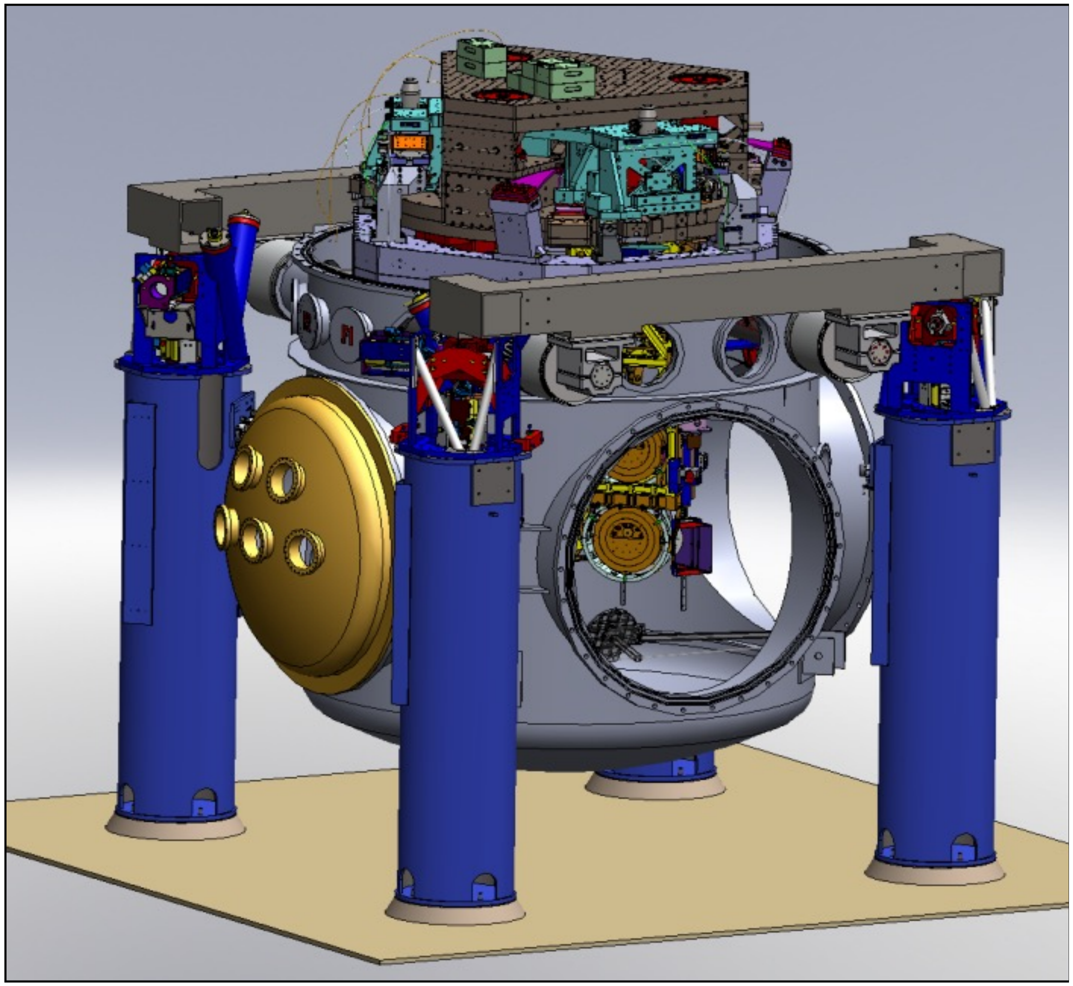


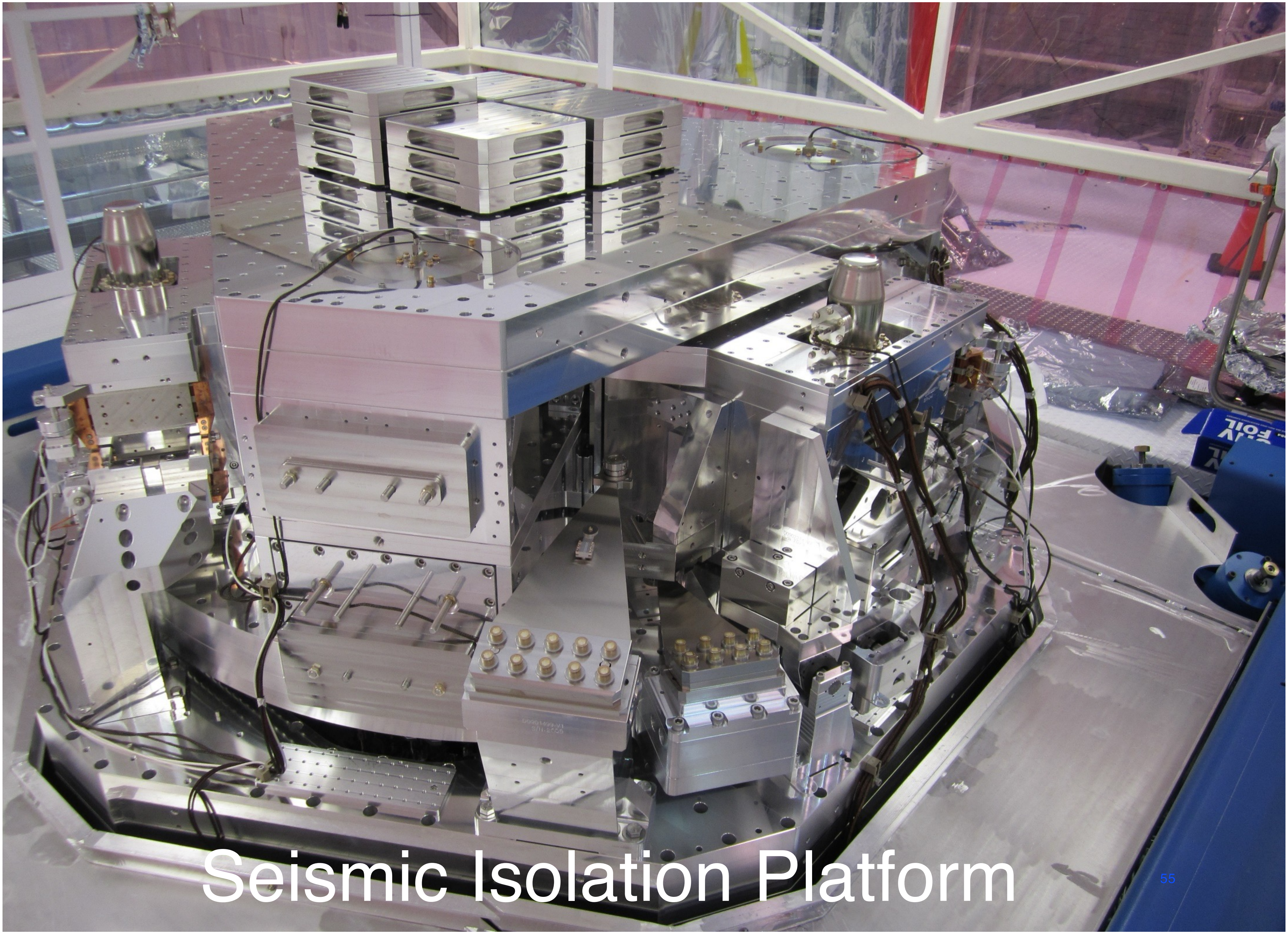
# End-mirror assembly
# (humans removed before pumpdown)



# Active and passive seismic isolation







# Seismic Isolation Platform

# Civil Construction: Beam Tube cover, foundation

photo credit M. Zucker?

# Cover useful to protect against 2-ton masses at 100 km/hour


ISCT1

# Onward

- Hope this introduction gives a good basis for the talks to follow
- Also email to dhs@mit.edu (but may need to be a bit patient for responses)