An introduction to Terrestrial Gravitational Wave Detectors

First International Latin American Conference on Gravitational Waves

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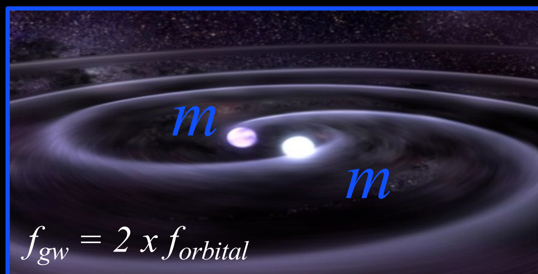
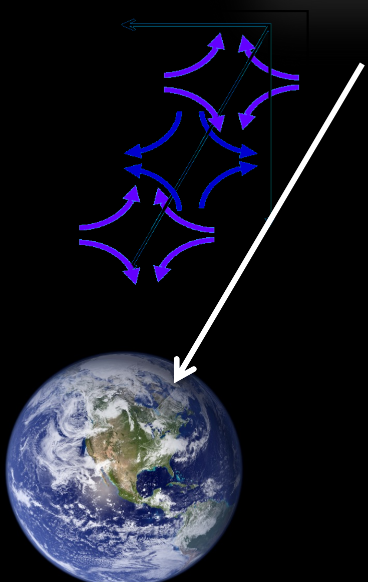
Thanks to…

- Persons loaning slides and insights from the LVK
- The LIGO Lab – MIT, Caltech, Hanford and Livingston Observatories
- The LIGO Scientific Collaboration; Virgo and KAGRA
- 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 → $h = \frac{2G}{c^4 r}\ddot{I}$ ← *quadrupole moment*

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

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

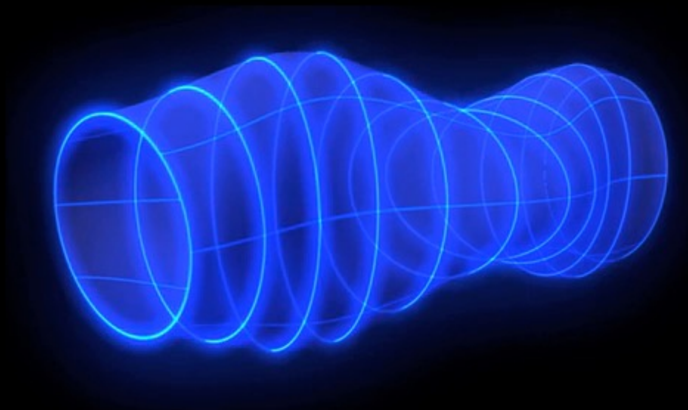
About once a week,
a wave passes with this characteristic strain:

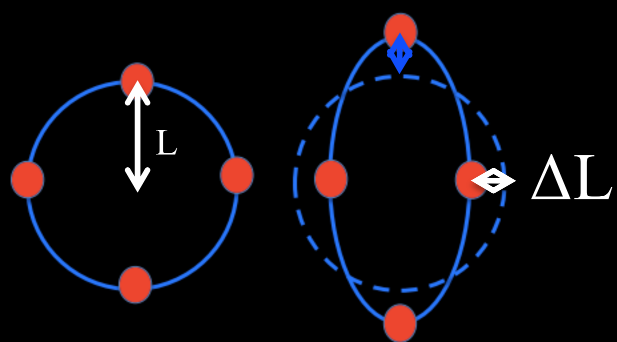
$$1.5 \times 10^{-21} \left(\frac{m}{30 M_\odot}\right)\left(\frac{400\,\mathrm{Mpc}}{r}\right)\left(\frac{f_{gw}}{50\,\mathrm{Hz}}\right)^{2/3}$$

3

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

Stretching and squeezing of space-time





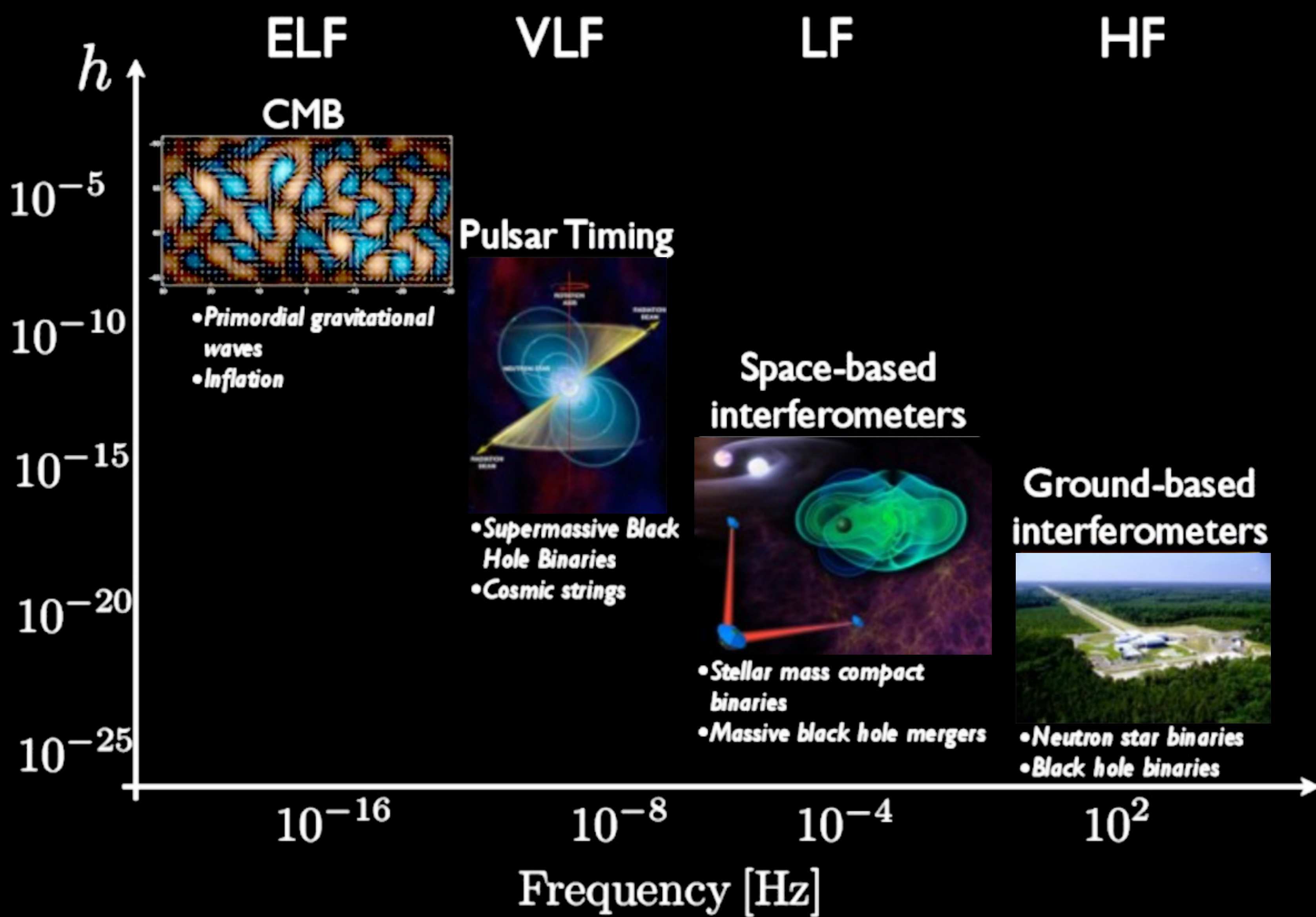
Amplitude of the gravitational wave strain is $h = \Delta L/L$

$\Delta L = h\,L$

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

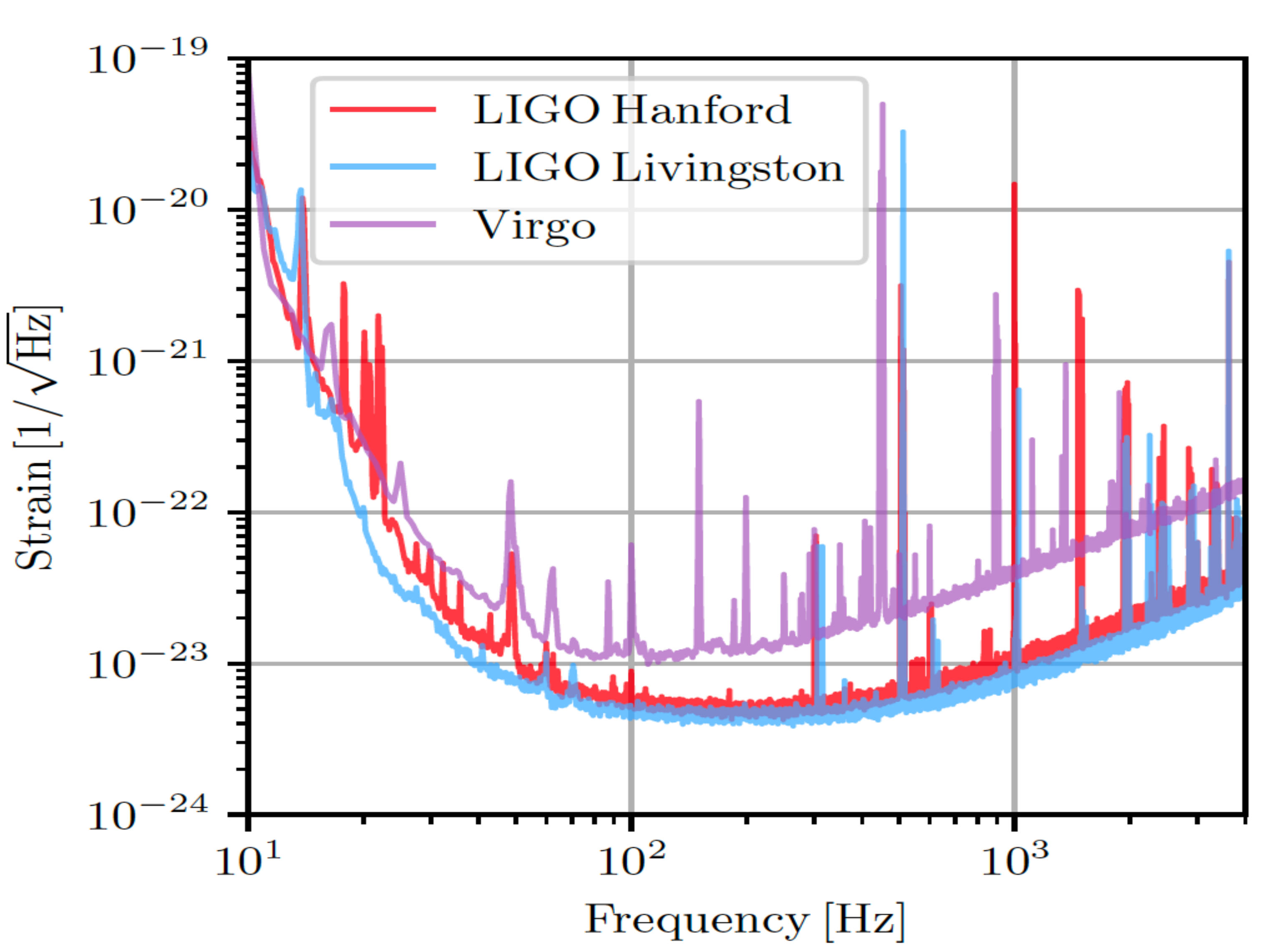
$\sim 10^{-21} \times \sim 10^{3} = \sim 10^{-18}$ m

Detection methods, Projects

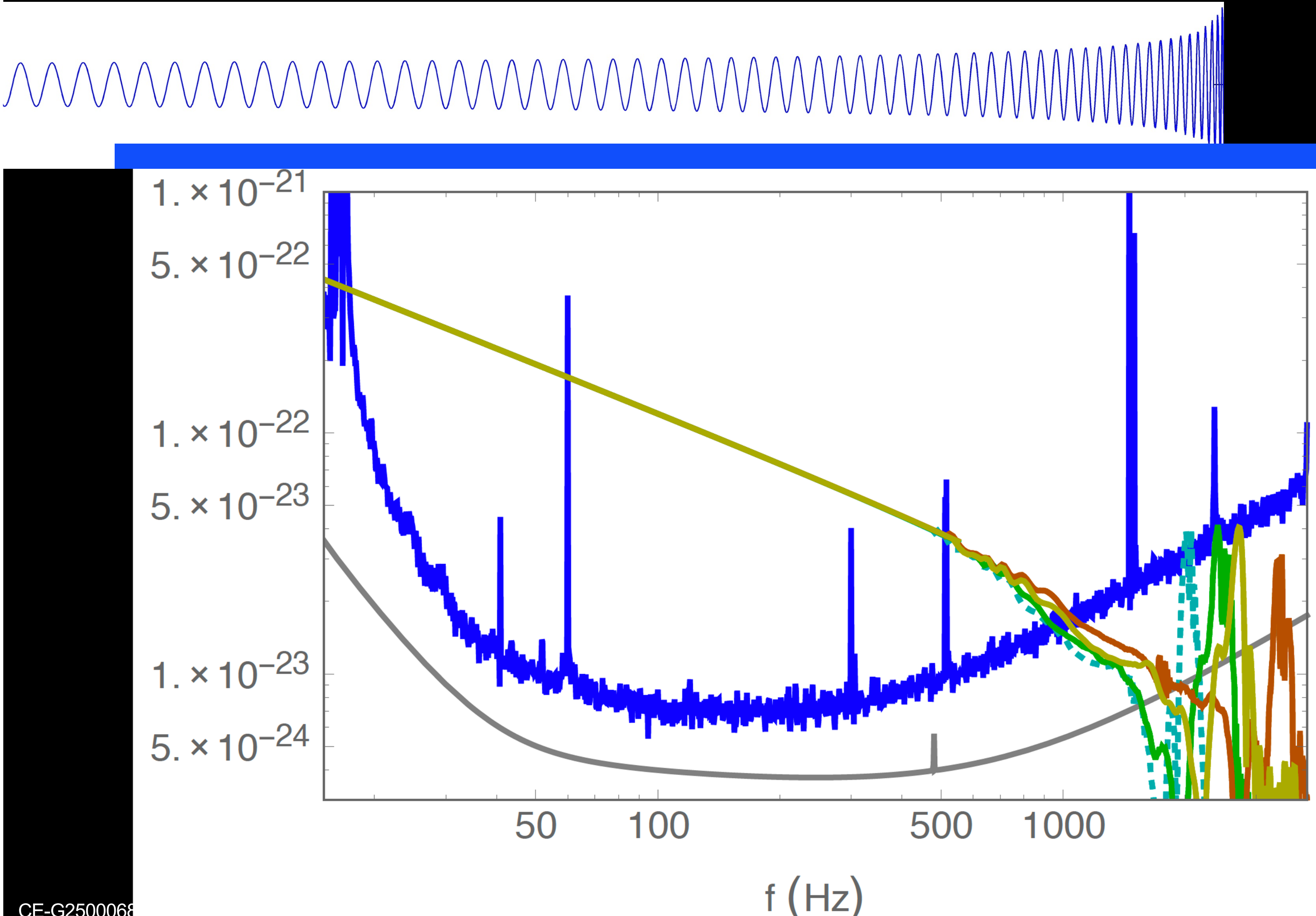


LIGO and Virgo sensitivity

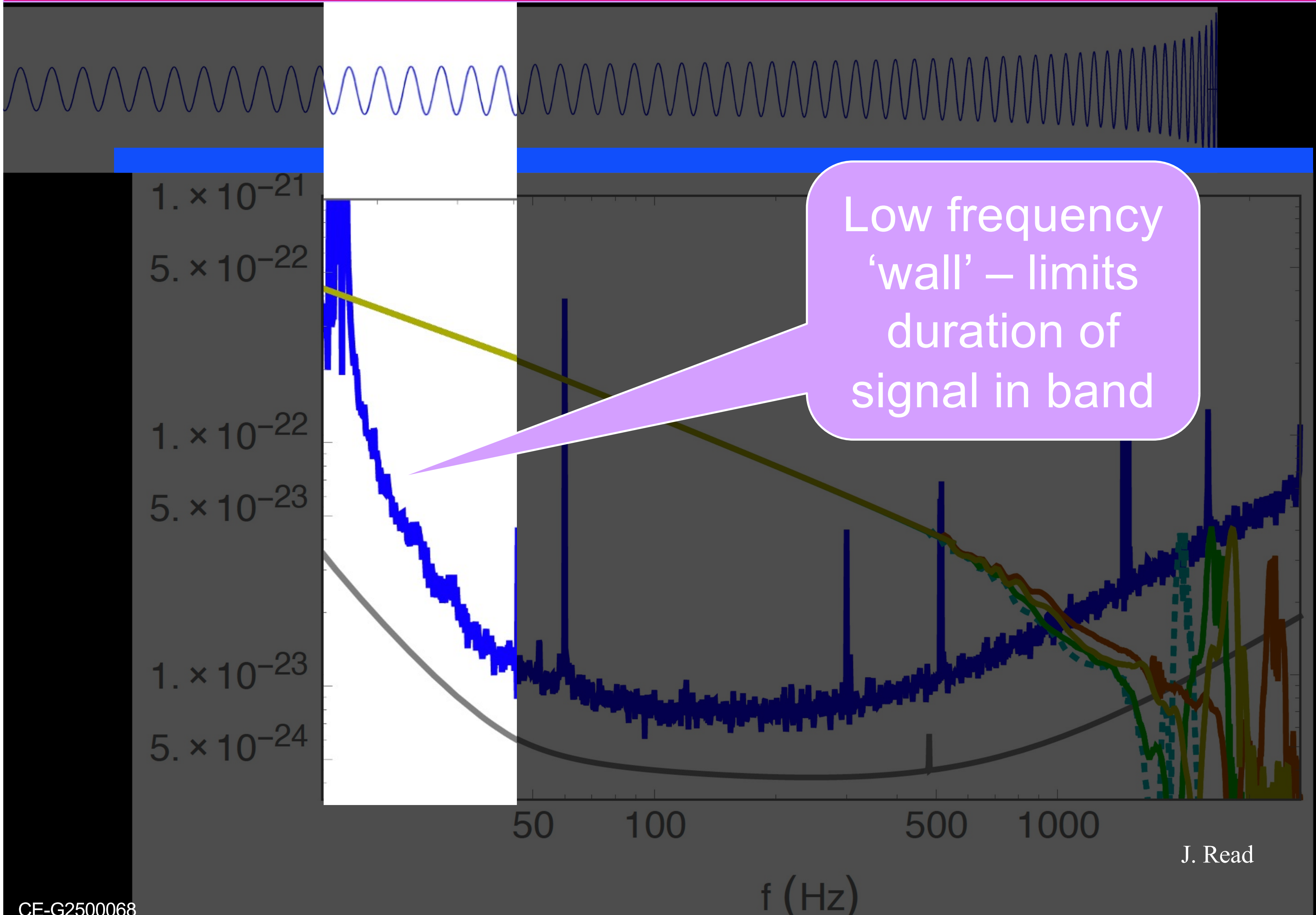
- LIGO-Virgo noise floor $h = \Delta L/L \sim 10^{-23}$ in a 1 Hz bandwidth



NS-NS inspiral mapped onto detector sensitivity



NS-NS inspiral mapped onto detector sensitivity



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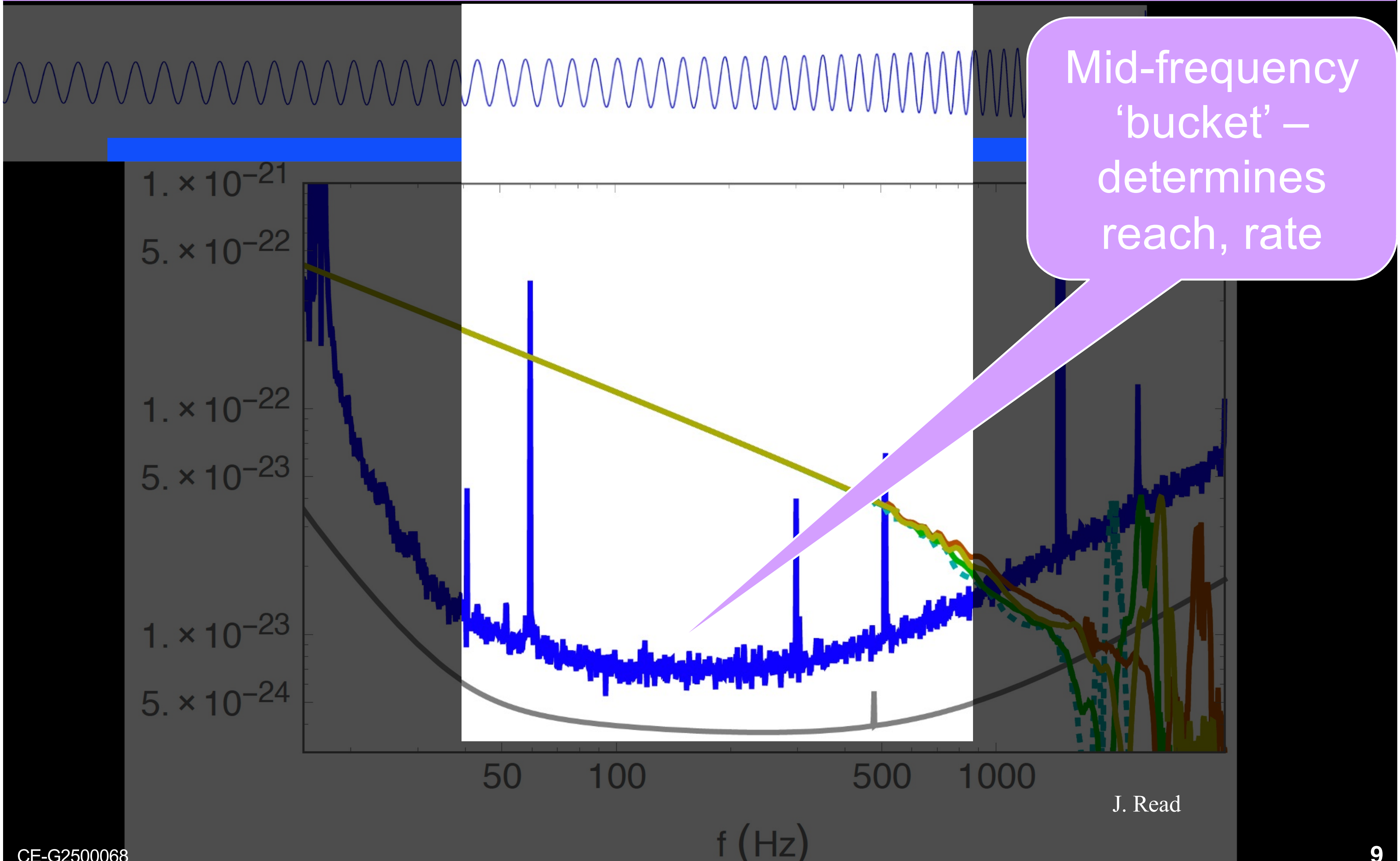
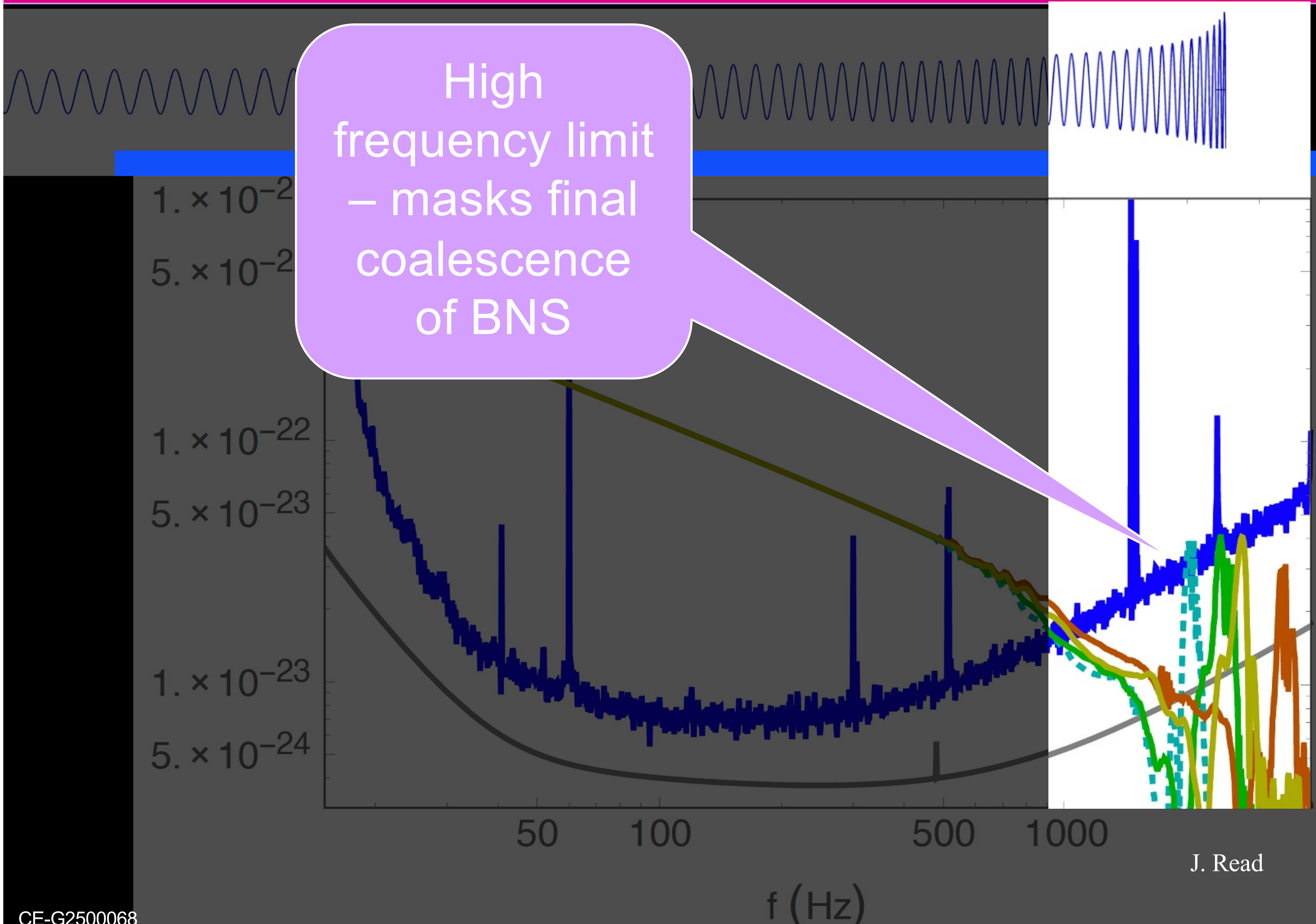
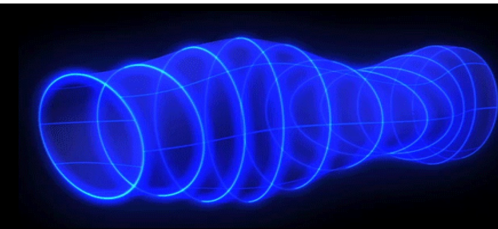


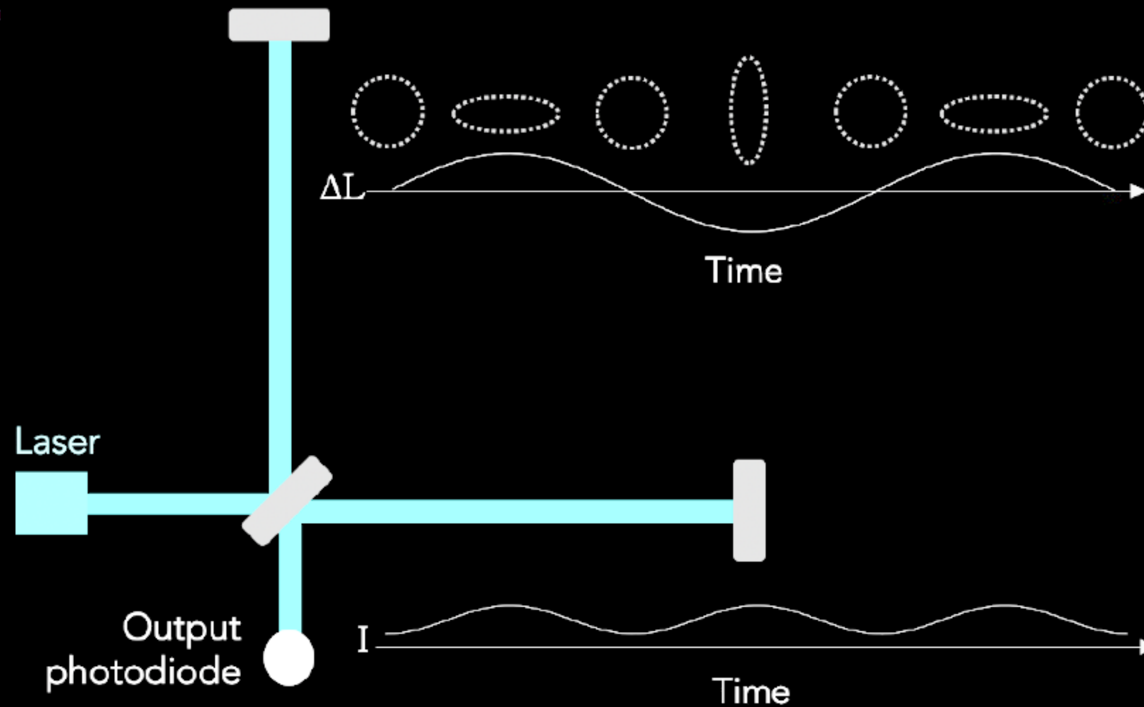
NS-NS inspiral mapped onto detector sensitivity



What is our measurement technique?

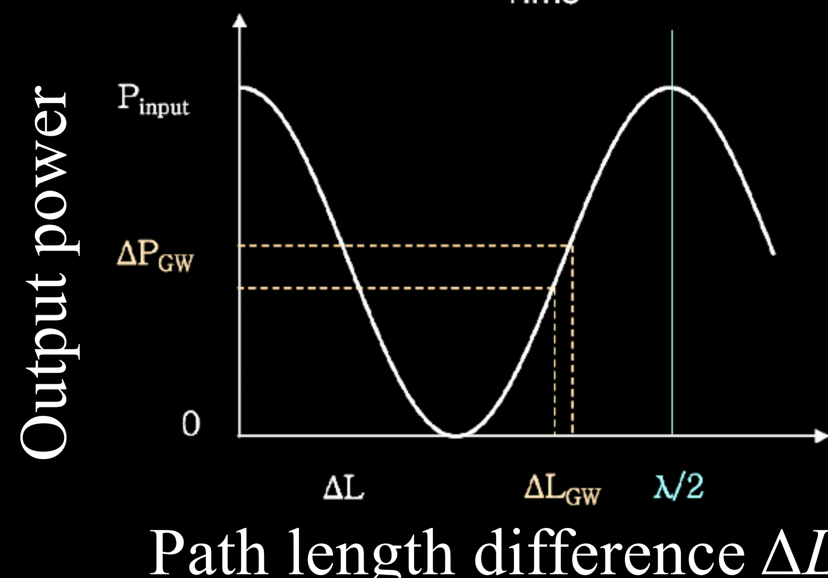


- Enhanced **Michelson interferometers**
- GWs modulate the distance between the end test mass optic and the beam splitter
- The interferometer acts as a transducer, turning GWs into photocurrent proportional to the strain amplitude



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

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



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 $\Delta L = 4 \times 10^{-18}$ m

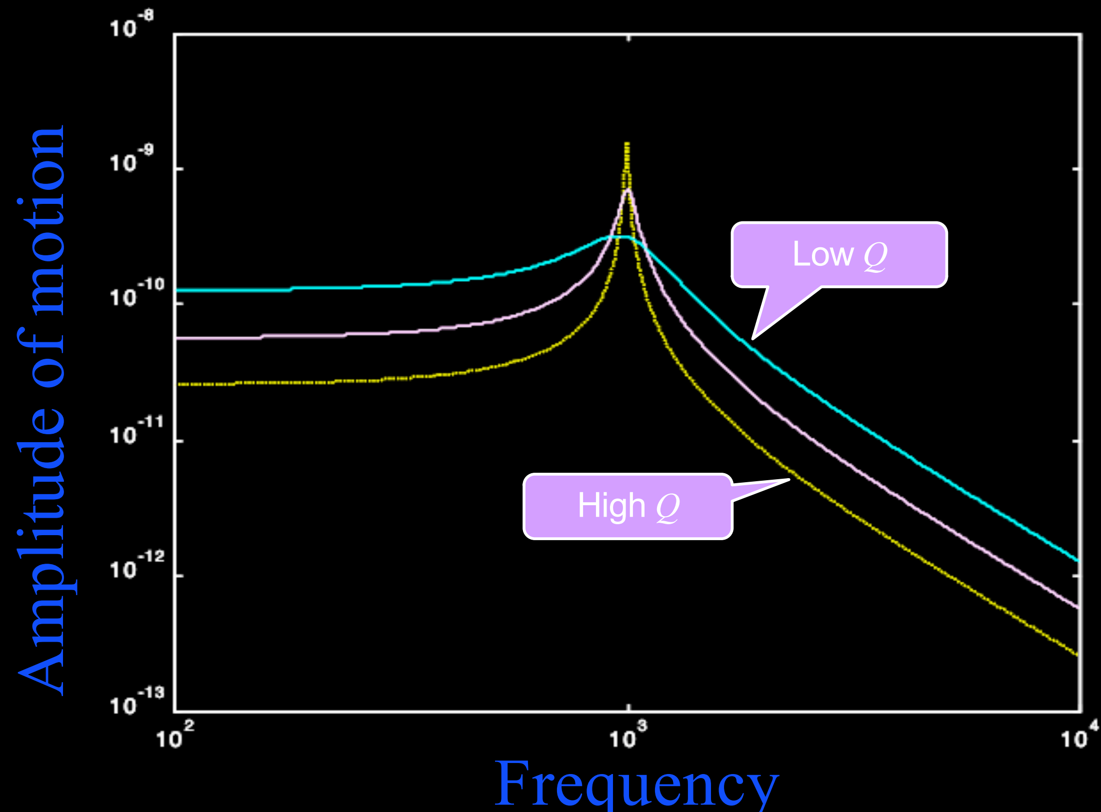
- **Thermal noise** – kT of energy per mechanical mode
  - *A. Einstein, 1905*
- Simple Harmonic Oscillator:

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

- 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 $\Delta L = 4\times10^{-18}$ m
Internal motion

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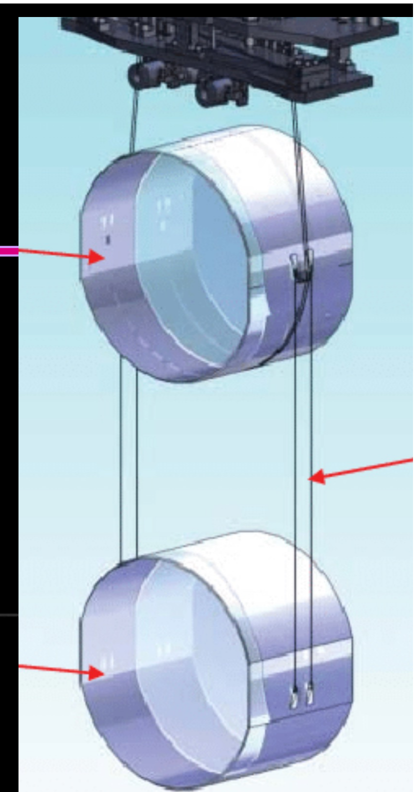
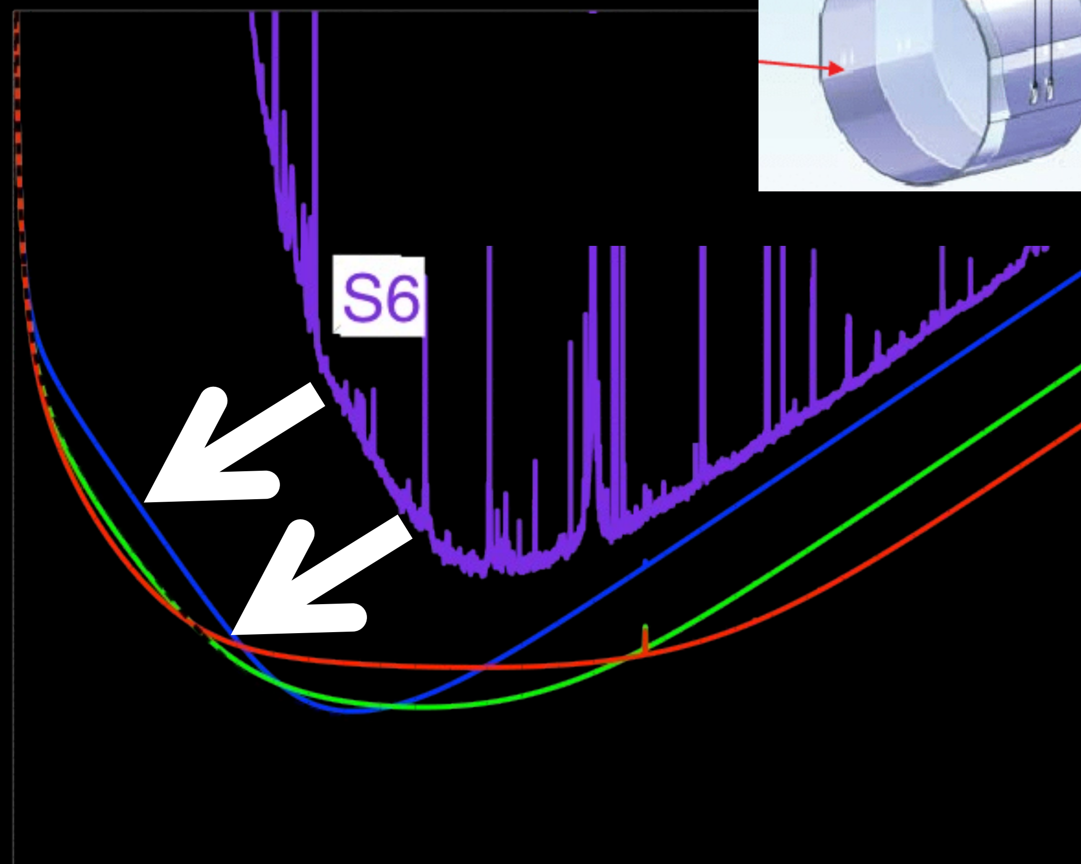
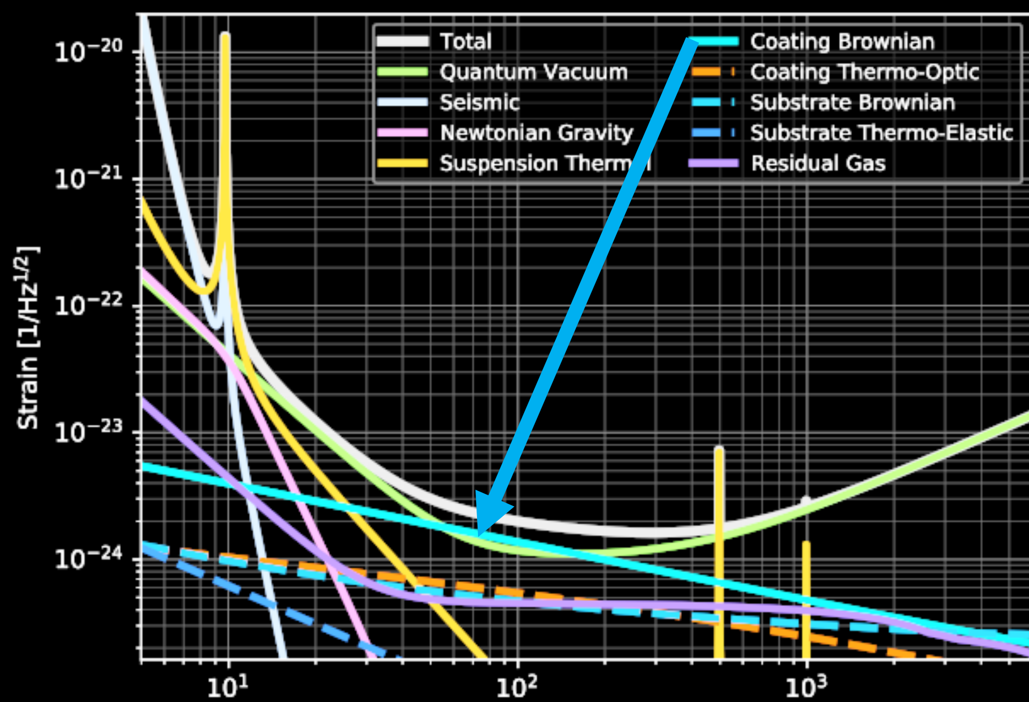
- **For Michelson mirrors:**
- **Low-loss materials, monolithic construction**





Measuring ΔL= 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

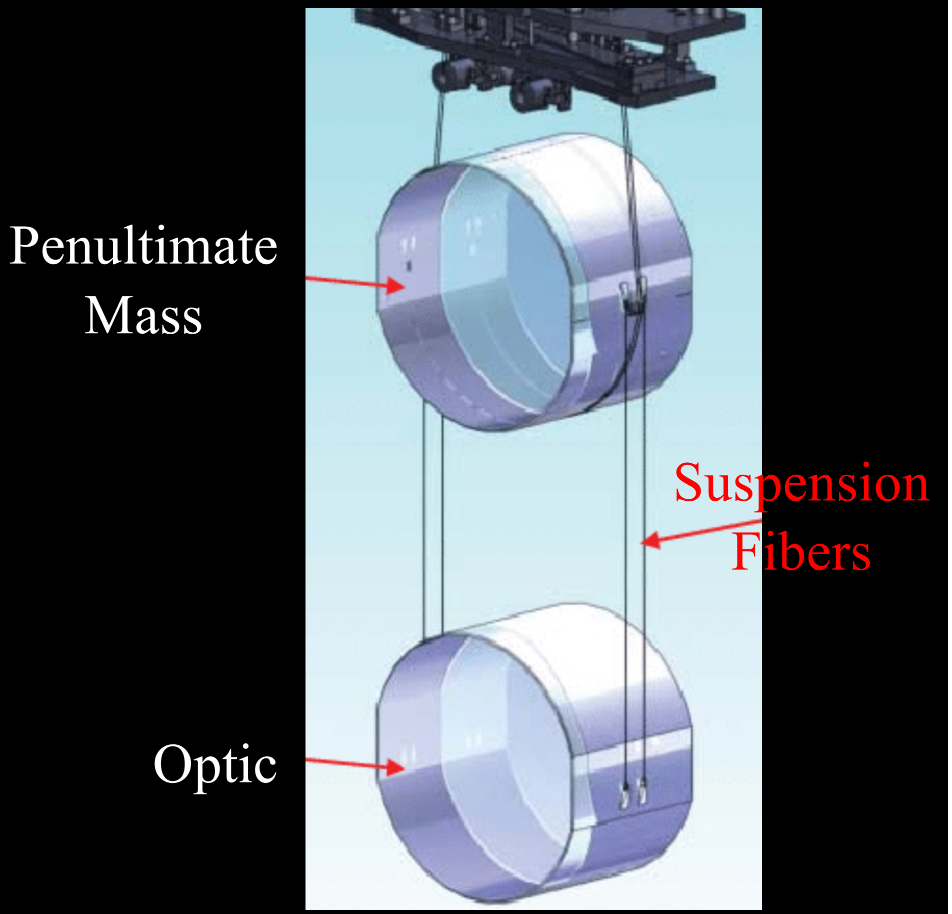
$$\left\langle \Delta x(f,T)^2 \right\rangle \approx \frac{2k_BT}{\pi^2 f}\frac{d}{w^2 Y}\phi(f)$$

beam radius

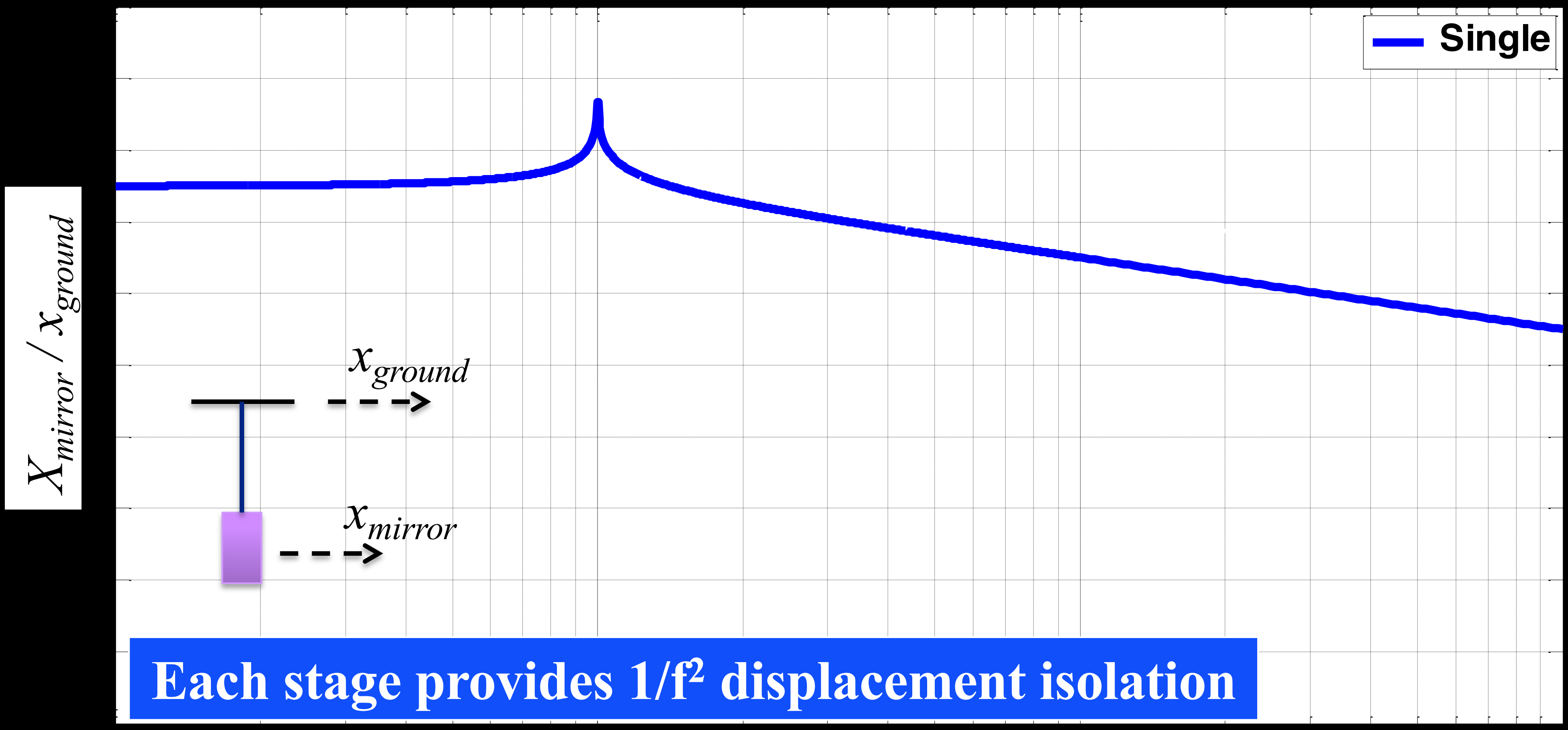
Y Levin *Phys. Rev. D* **57** 659 (1998)

Basic Building Blocks: Pendulums

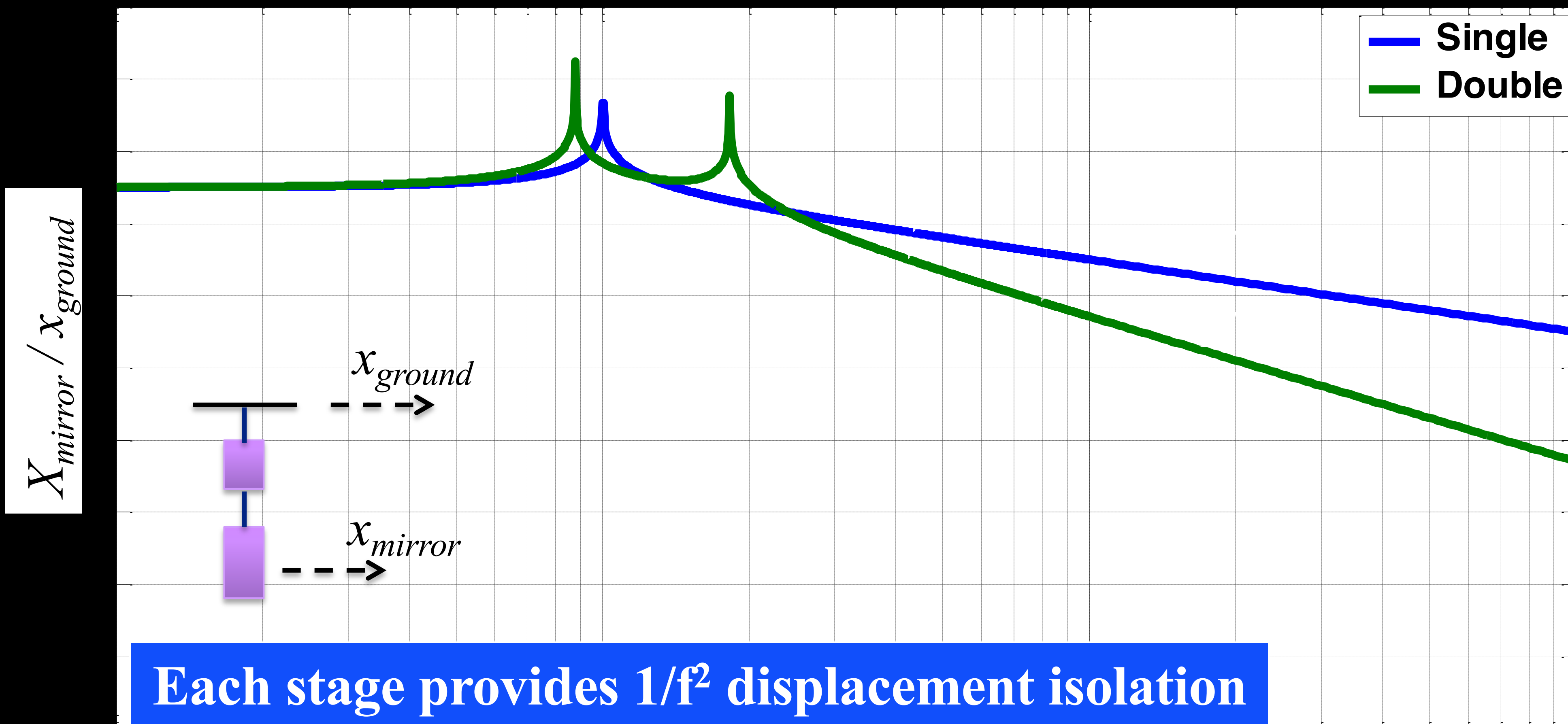
- Pendulum suspensions for optics which serve as test masses
- Need test masses to be 'free' in along the relevant measurement axis
- Terrestrial detectors operate in Earth's gravitational field
- Hang optics like a clock pendulum; above the resonant frequency, mirror is 'free'
- Inertia of the mass provides seismic isolation
  - Single stage $(f_0/f)^2$; two stages $(f_0/f)^4$…
- Provides flexibility for alignment and actuation



Multi-stage Isolation Performance
'Transfer function'

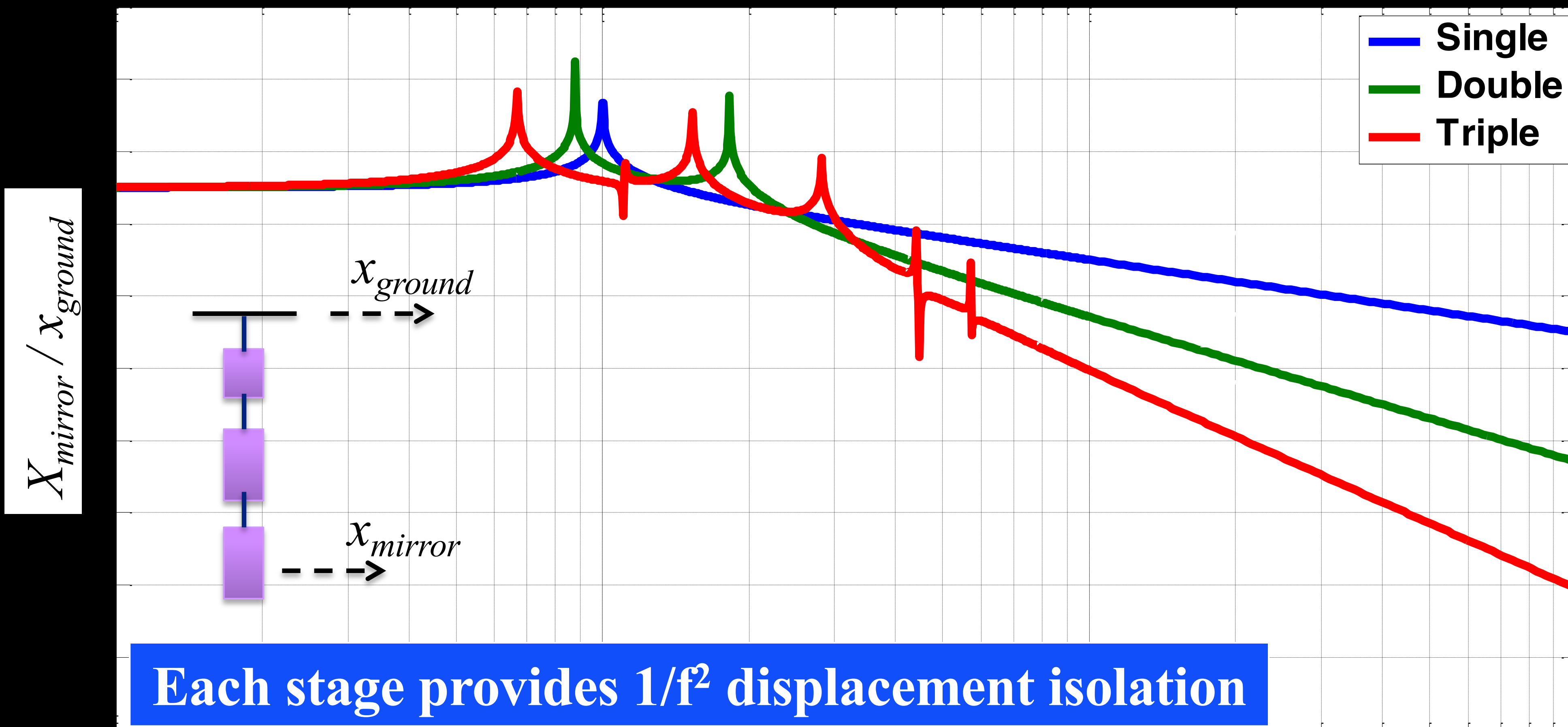


Multi-stage Isolation Performance



Each stage provides 1/f² displacement isolation

Multi-stage Isolation Performance



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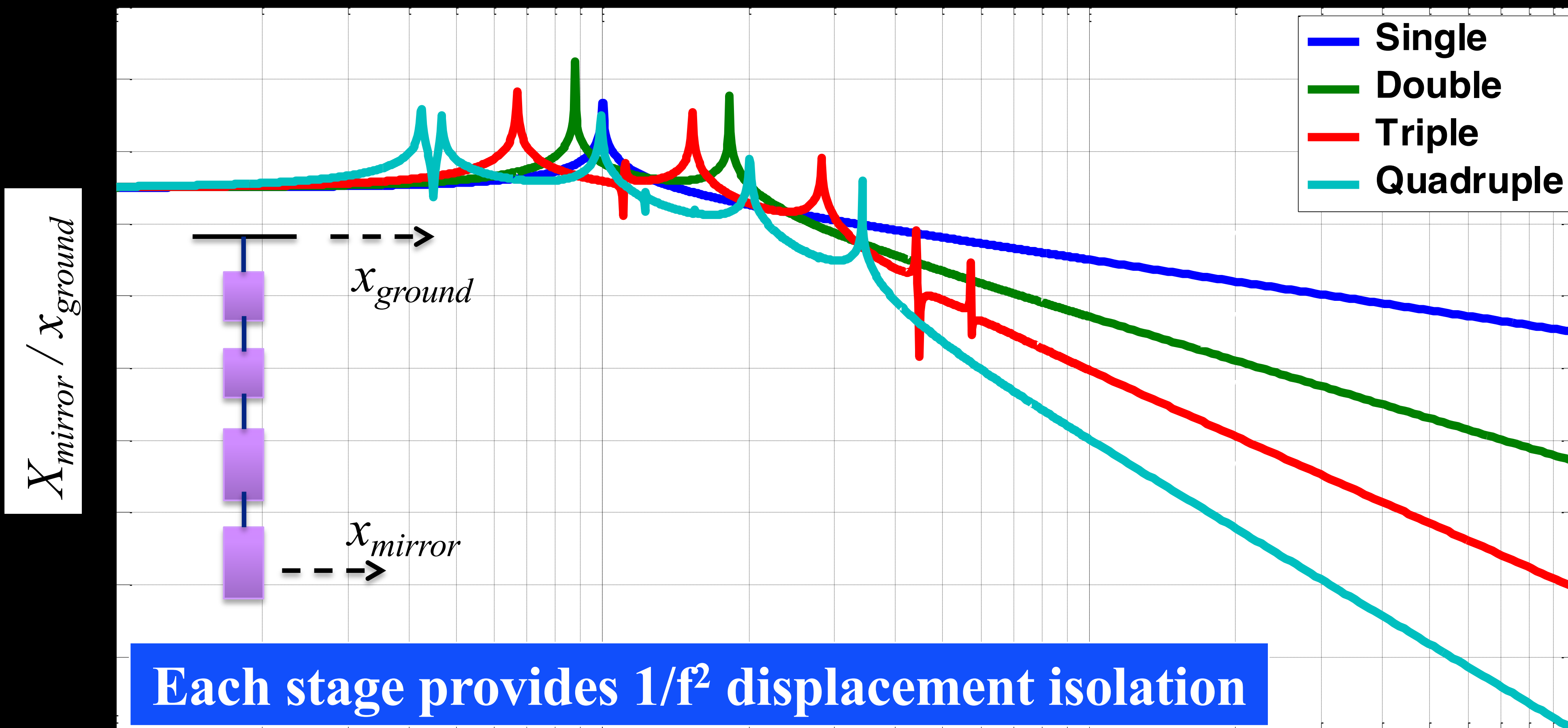
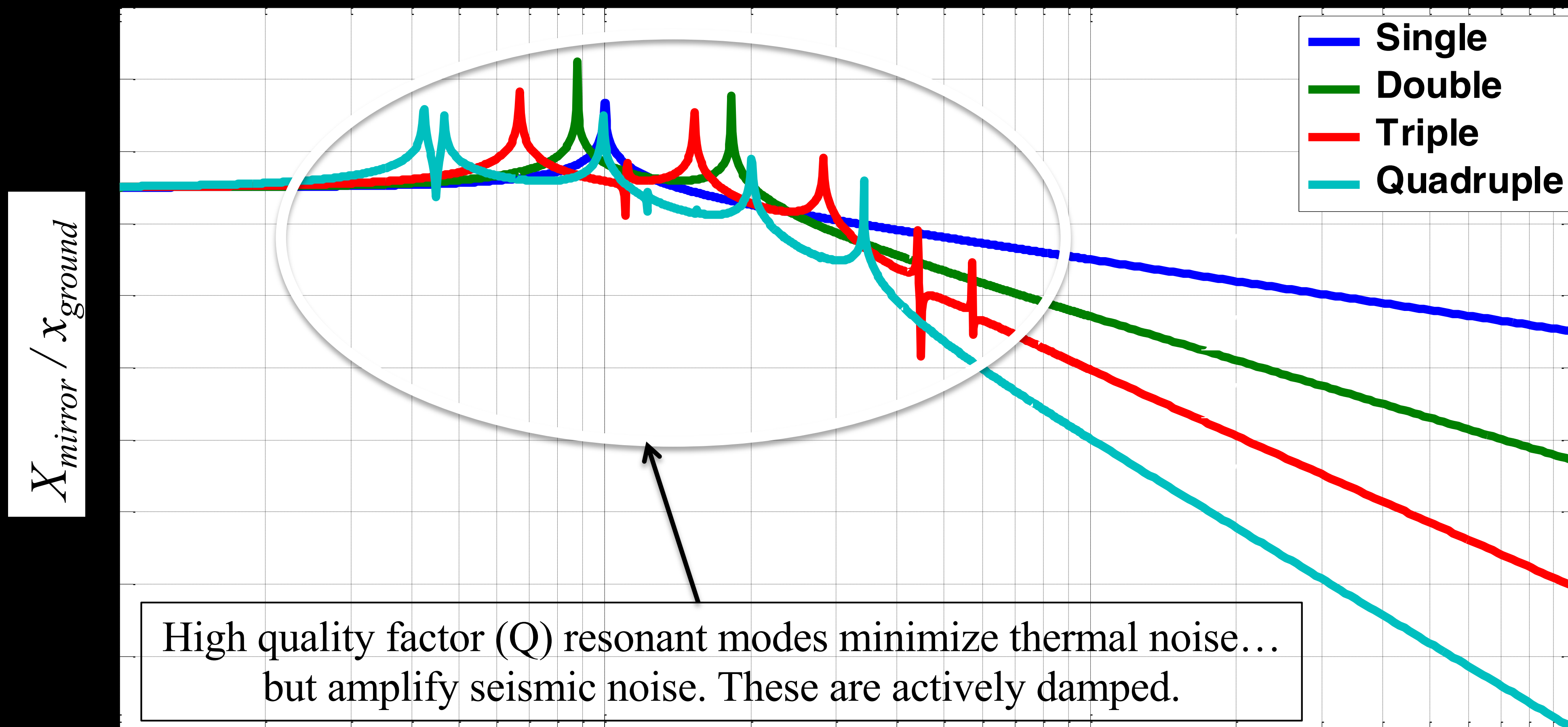
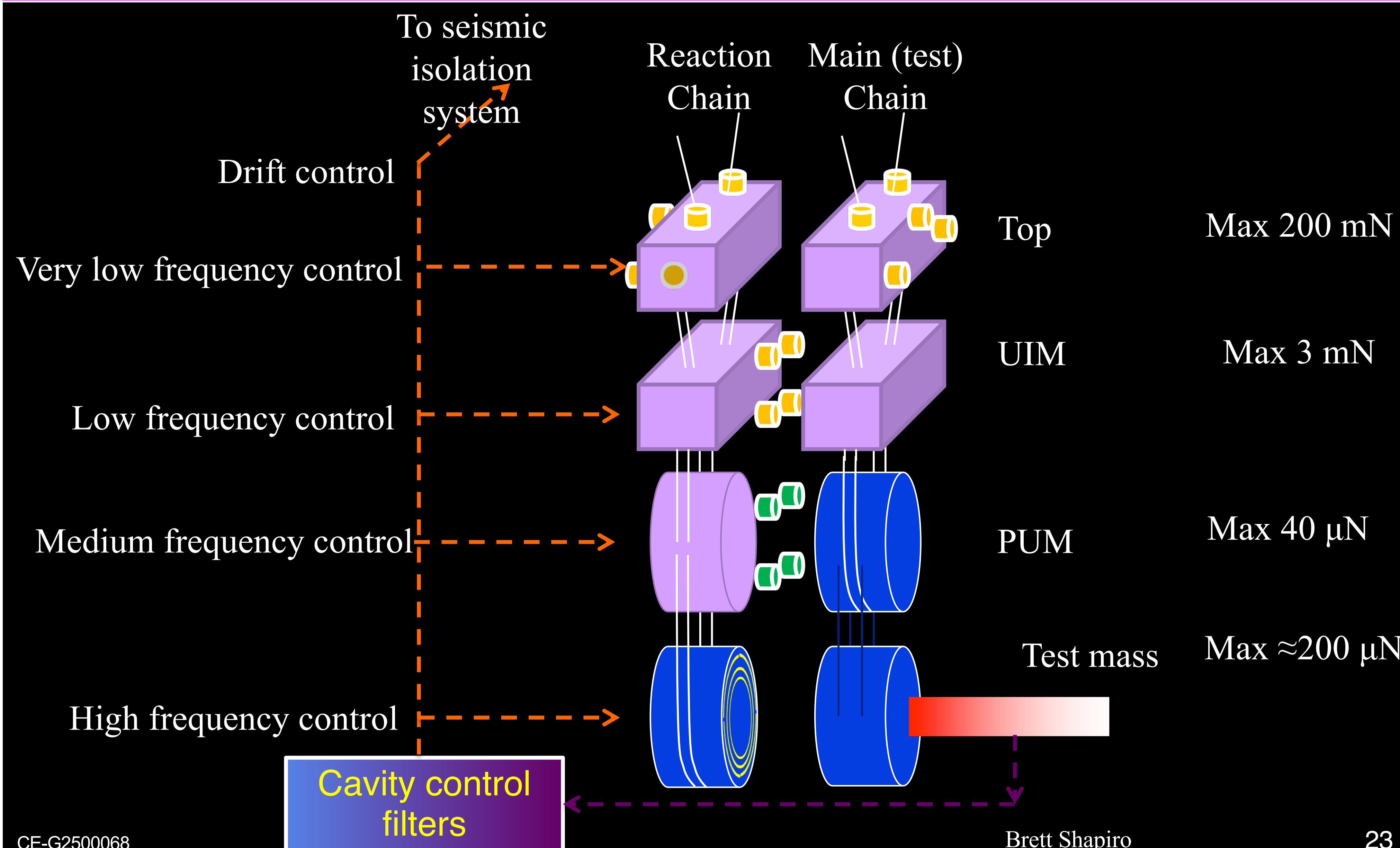


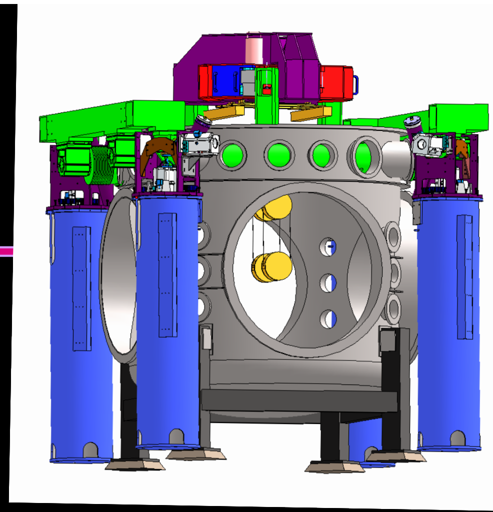
Multi-stage Isolation Performance



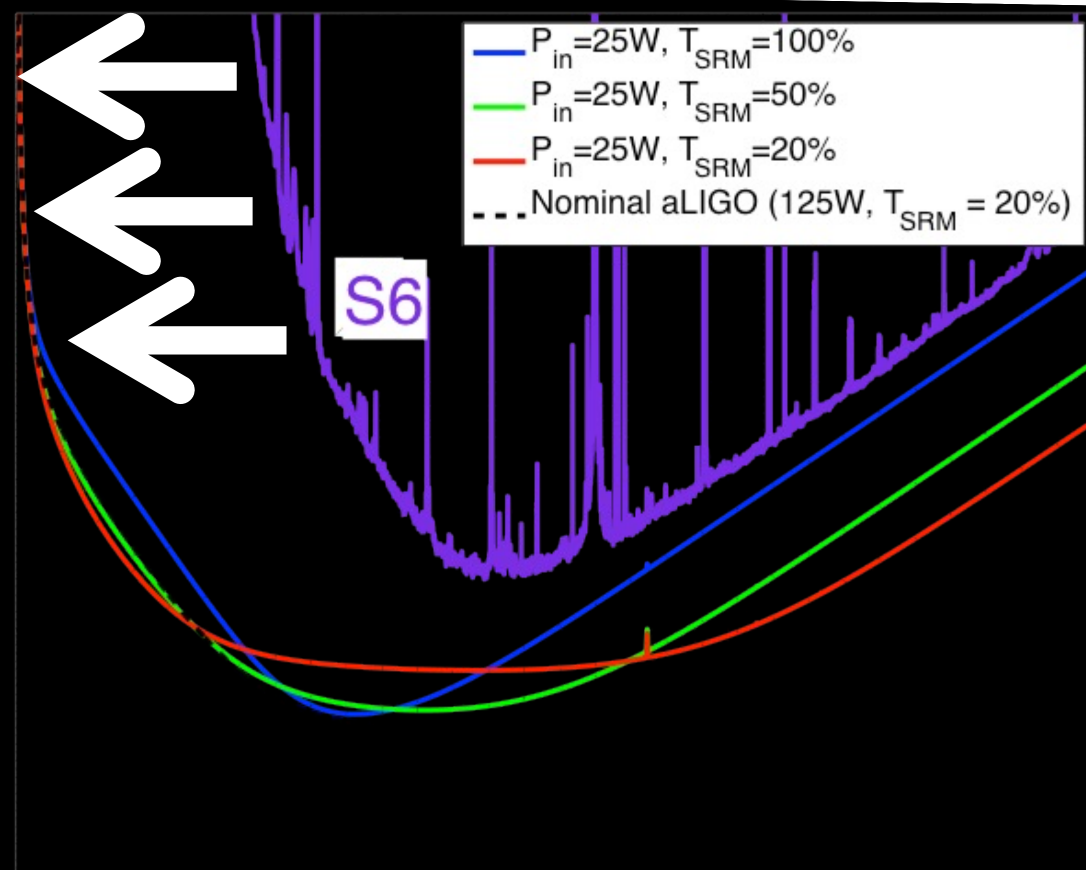
Cavity Length Control



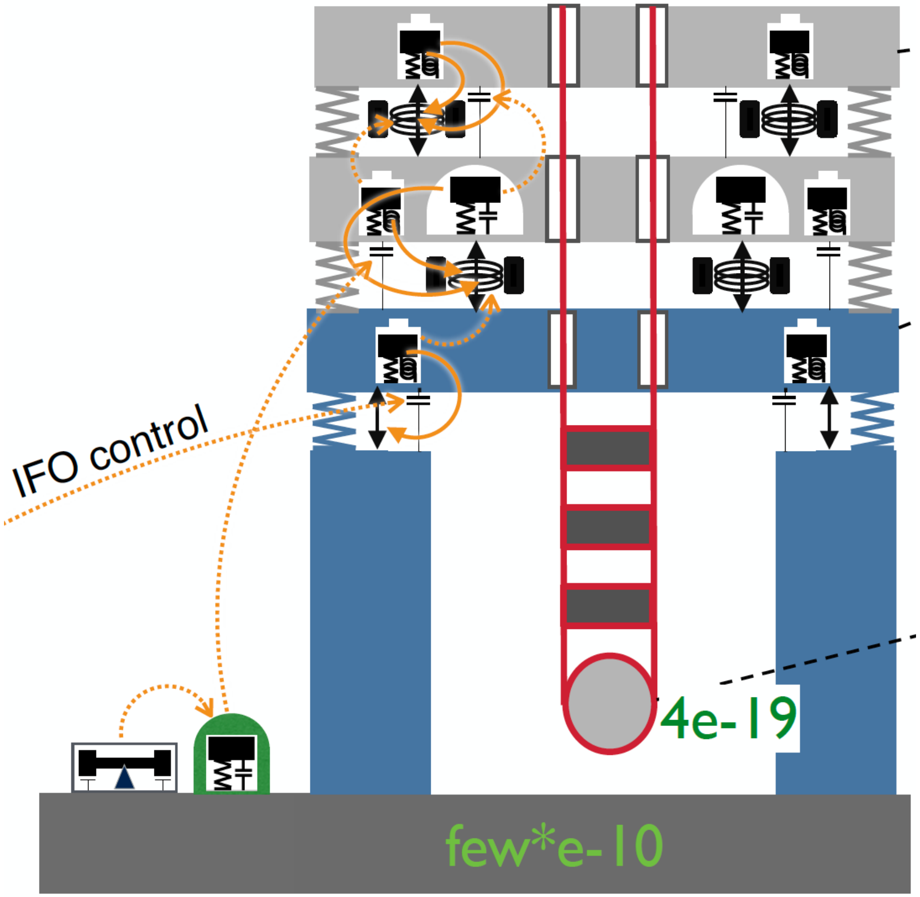
Measuring ΔL= 4x10⁻¹⁸ m
External Forces on test mass

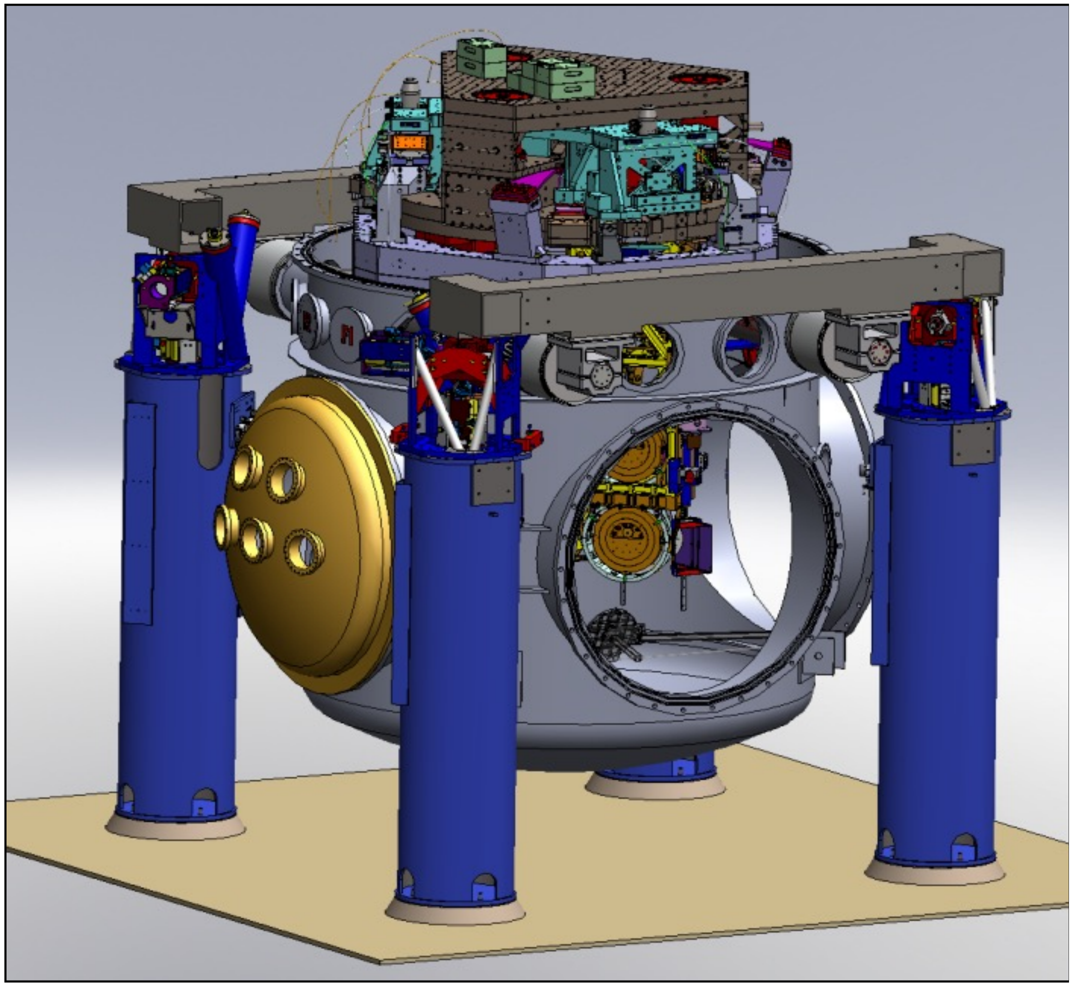


- **Seismic noise** – must prevent masking of GWs, enable practical control systems
- Not ‘fundamental physics’, but ‘fundamental to success’
- aLIGO uses **active servo-controlled platforms, multiple pendulums**



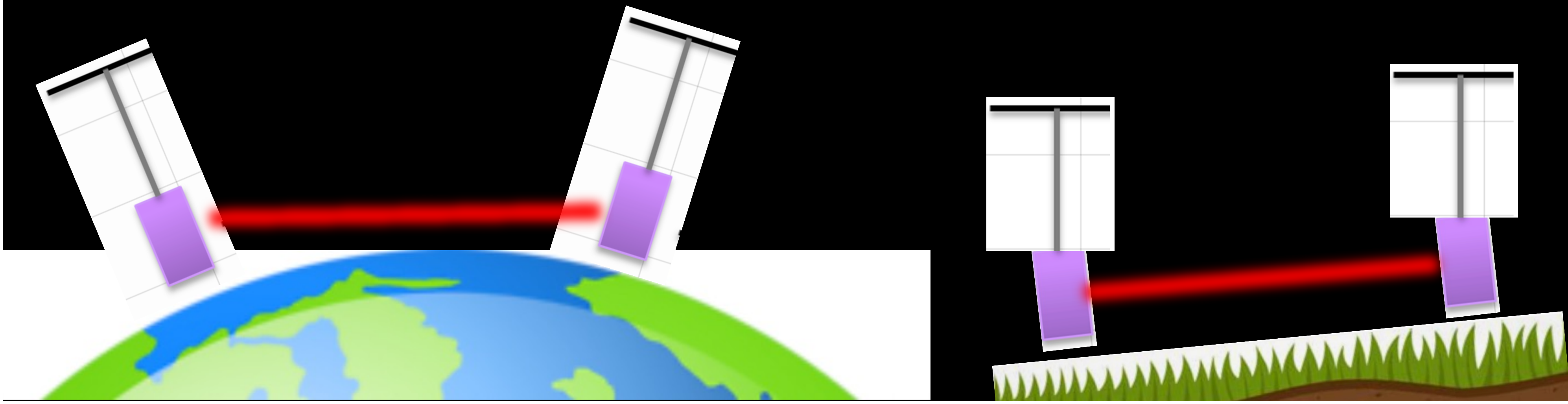
Active and passive seismic isolation





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

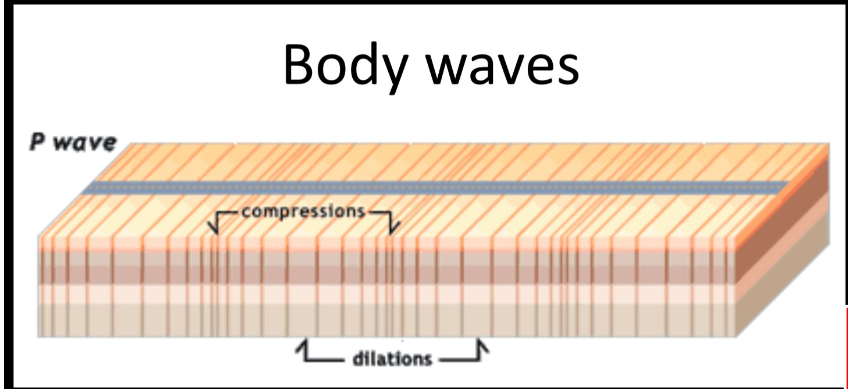
LIGO Facility
Beam Tube Alignment

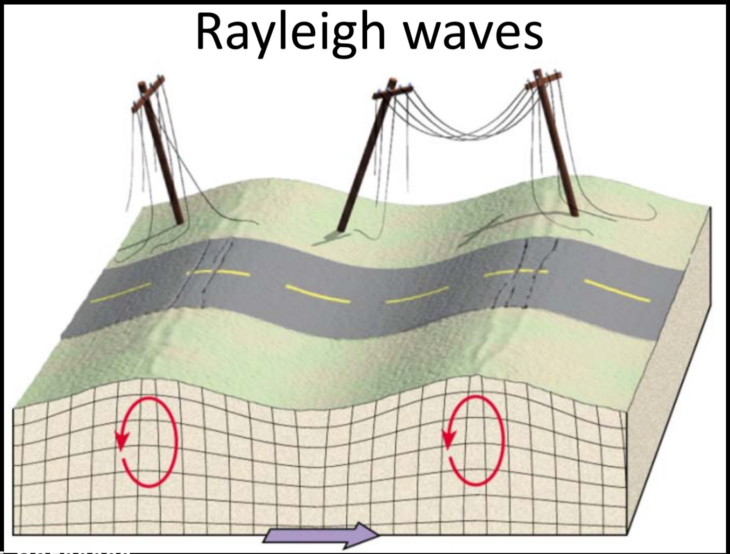
- Requirement to maintain a 1m clear aperture through the 4 km long arms
- A straight line in space varies in Earth height by 1.25 m over a 4km baseline
- A maximum deviation from straightness in inertial space of 5 mm rms
- Average angle with respect to local gravity of $3x10^{-4}$ radians

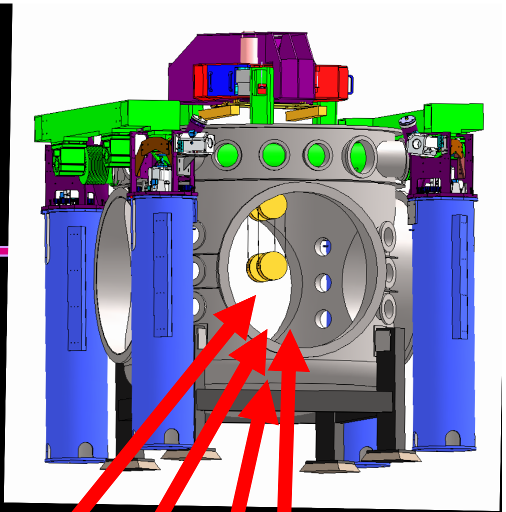
Measuring $\Delta L = 4 \times 10^{-18}$ m
External Forces on test mass

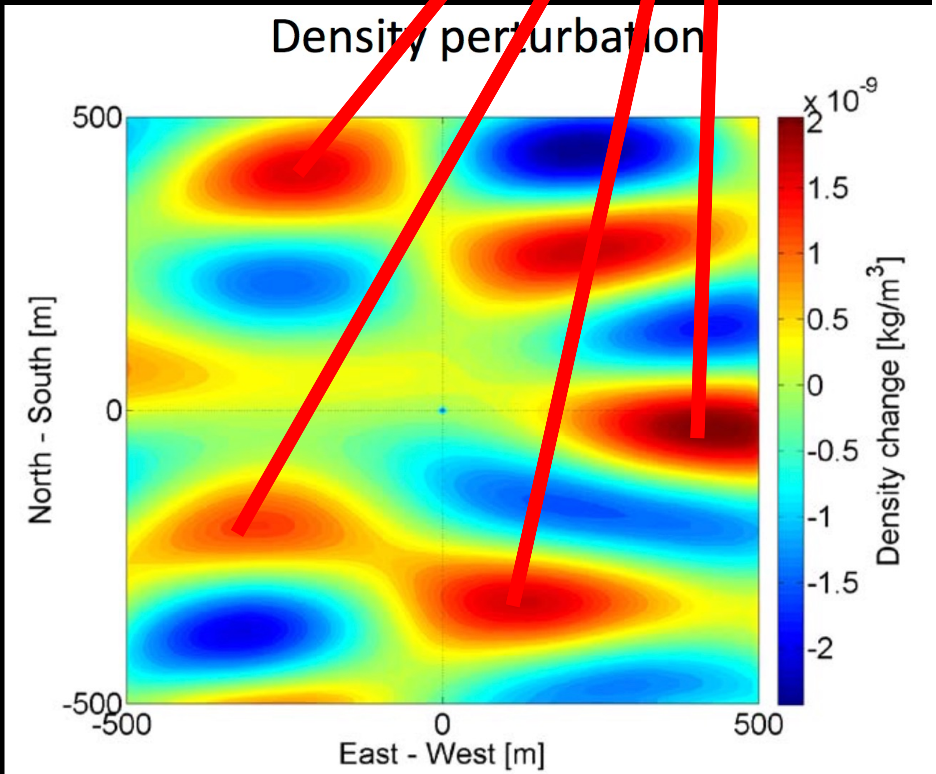
Ultimate limit on the lowest frequency detectors
on- or under-ground:

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





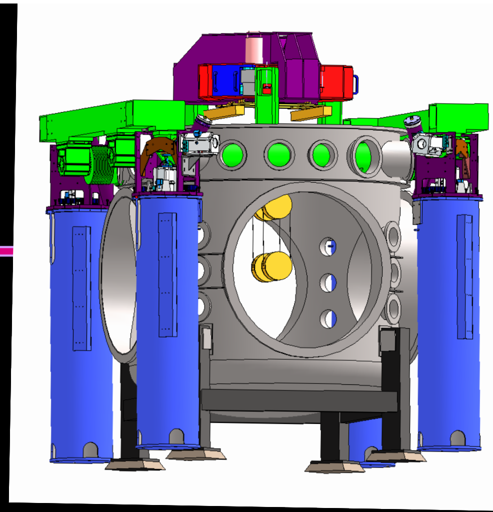




Density perturbations
cause gravity perturbations.

Images: J. Harms

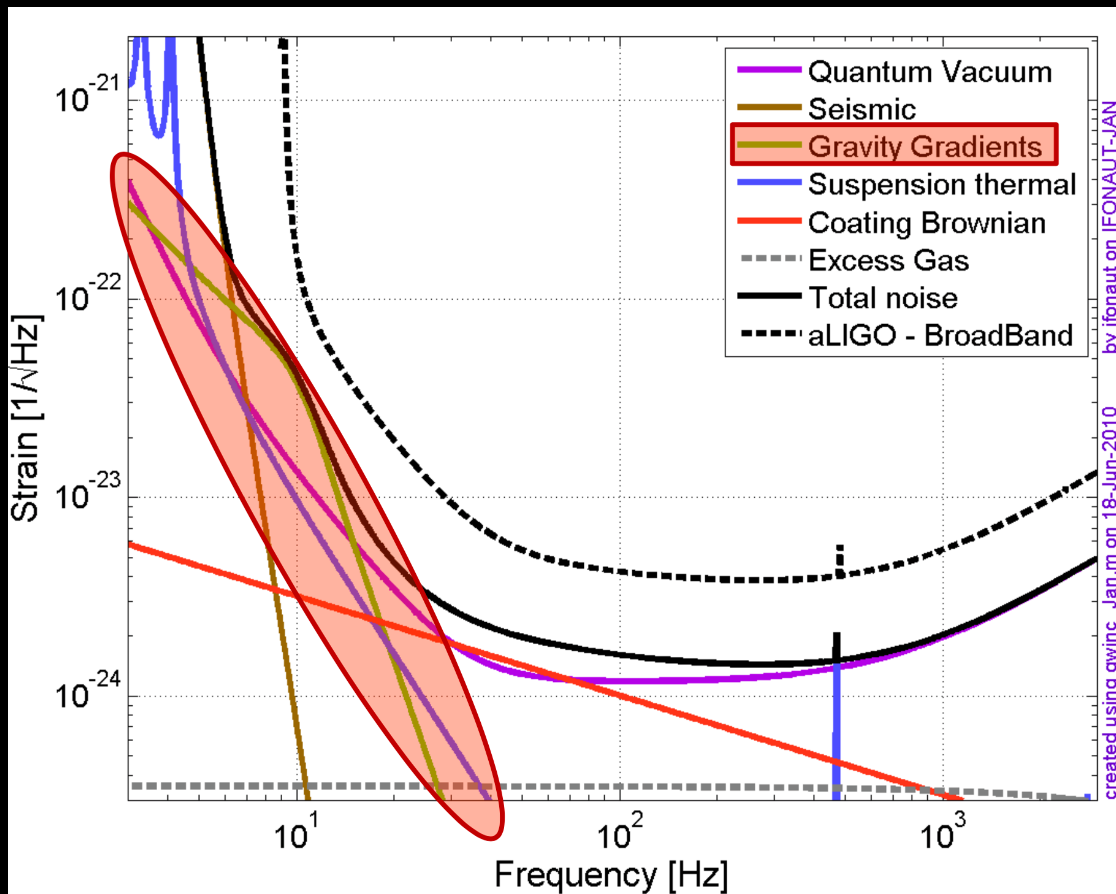
Measuring $\Delta L = 4 \times 10^{-18}$ m
External Forces on test mass



- 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

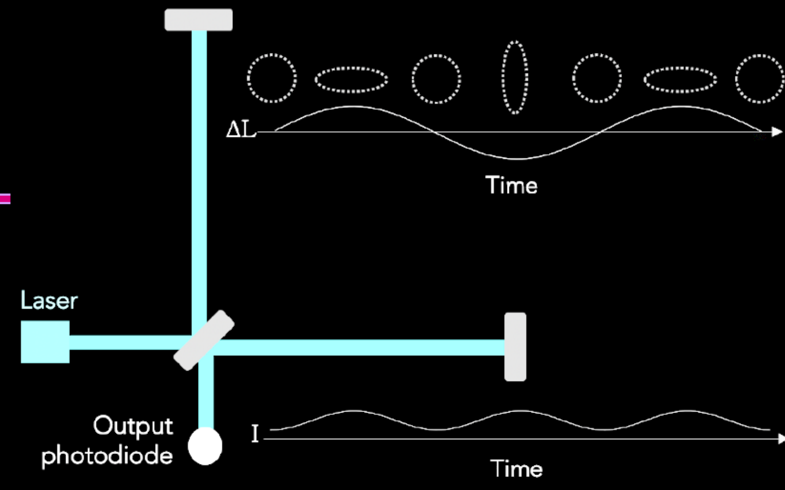
- Interferometry comparing the light travel time along (more or less) orthogonal arms can measure a passing gravitational wave
- The limits to sensitivity come from
  - Undesired motions of the interferometer mirrors
  - Limitations in our ability to measure the positions of the mirrors
- Thermal noise 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

Interferometry

- Quantum measurement effects present both limits to sensitivity **and** means to improve the sensitivity
- First, increase the light power to reduce shot noise
  - High power laser
  - Low loss, high-precision optical components
  - Optical topologies to increase circulating light power
  - Optical topologies to distribute light power optimally
  - …until radiation pressure starts to dominate
    - **Standard Quantum Limit**
  - …and our selected topologies couple shot noise and radiation pressure
- Second, use squeezed light to improve sensitivity
  - Manage coupling between light intensity and light phase (pondermotive squeezing)
  - Sneak around Heisenberg’s uncertainty principle

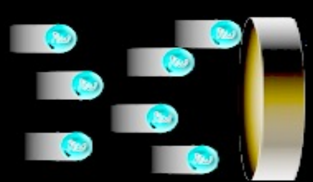
Resolution of the optical sensing



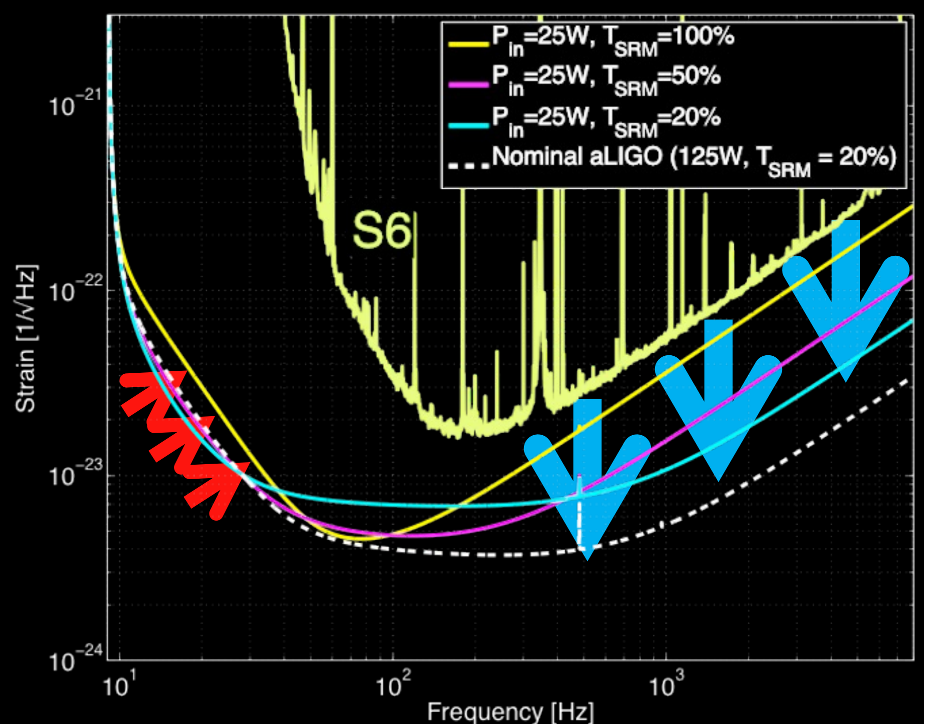
- **Shot noise** – ability to resolve a fringe shift due to a GW (counting statistics; *A. Einstein, 1909*)

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

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



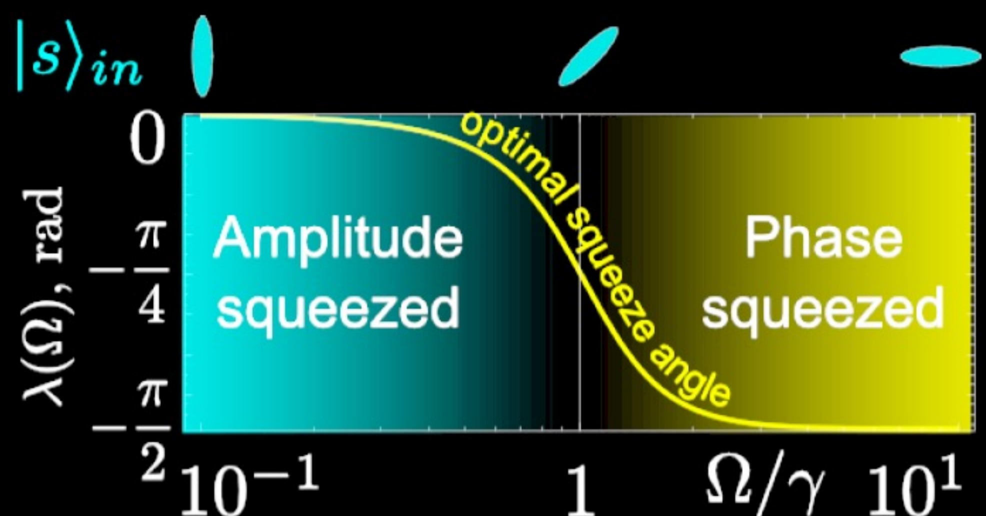
$$h_{\rm rp}(f) = \frac{1}{m f^2 L}\sqrt{\frac{\hbar P}{2\pi^3 c \lambda}}$$

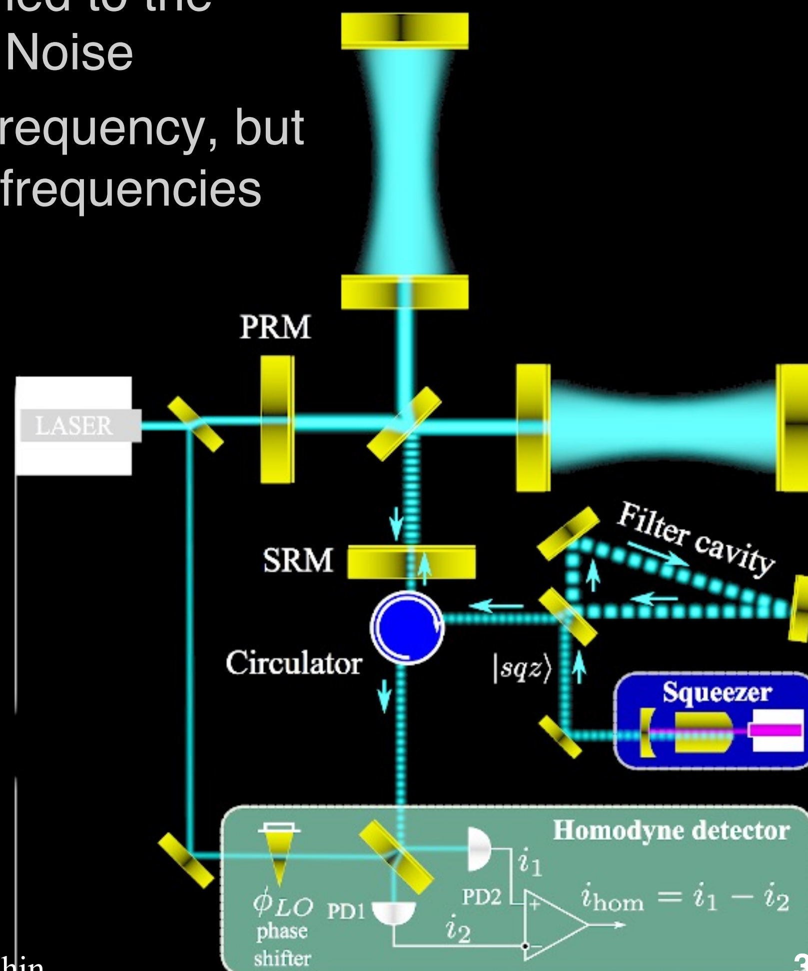


- **Standard Quantum Limit**

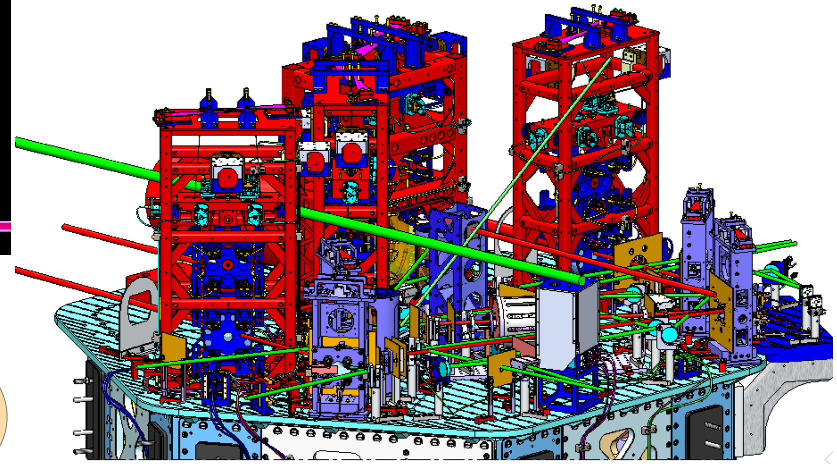
Frequency Dependent Squeezing

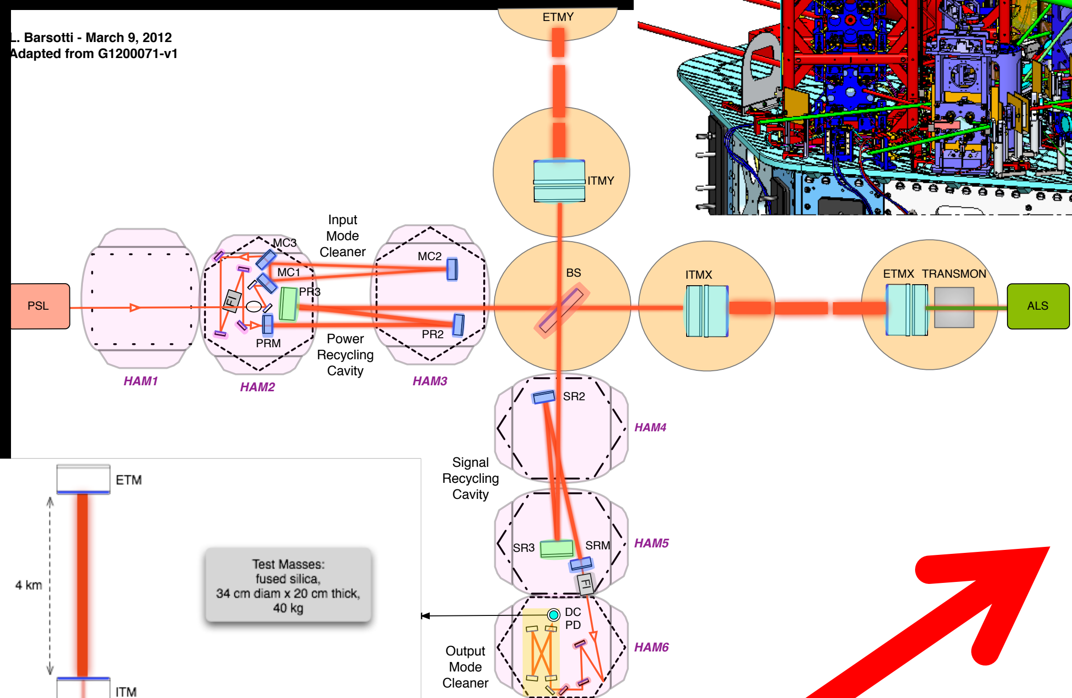
- Use squeezed light to balance precision in phase and amplitude
  - » Playing with the Poisson statistics of the photons
- We can adjust the phase of the squeezed light used
  - » Optical resonant cavity acting as a filter tuned to the transition from Radiation Pressure to Shot Noise
- Heisenberg's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

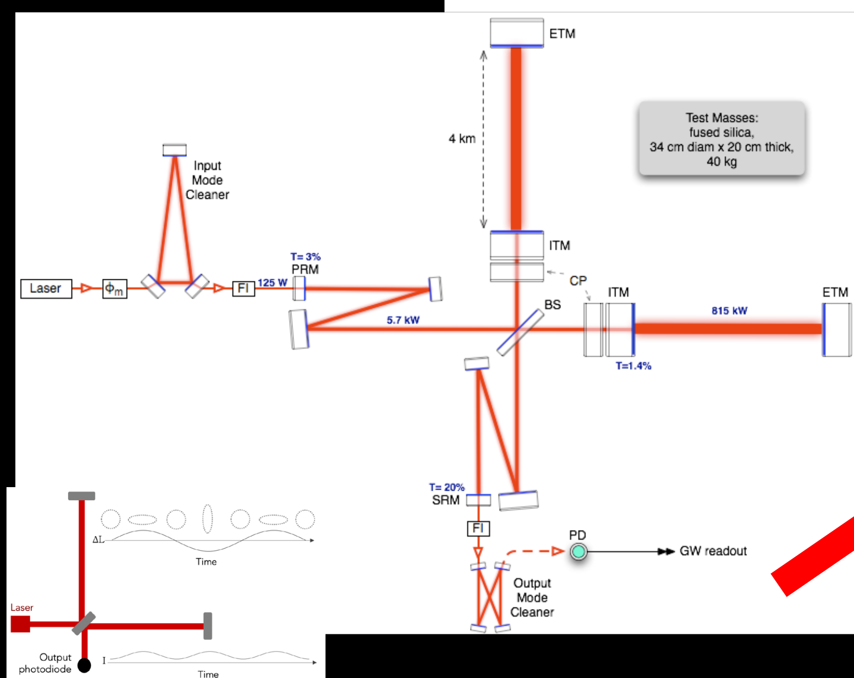




J. Kimble et al., PRD 65, 022002 (2001); S.L. Danilishin



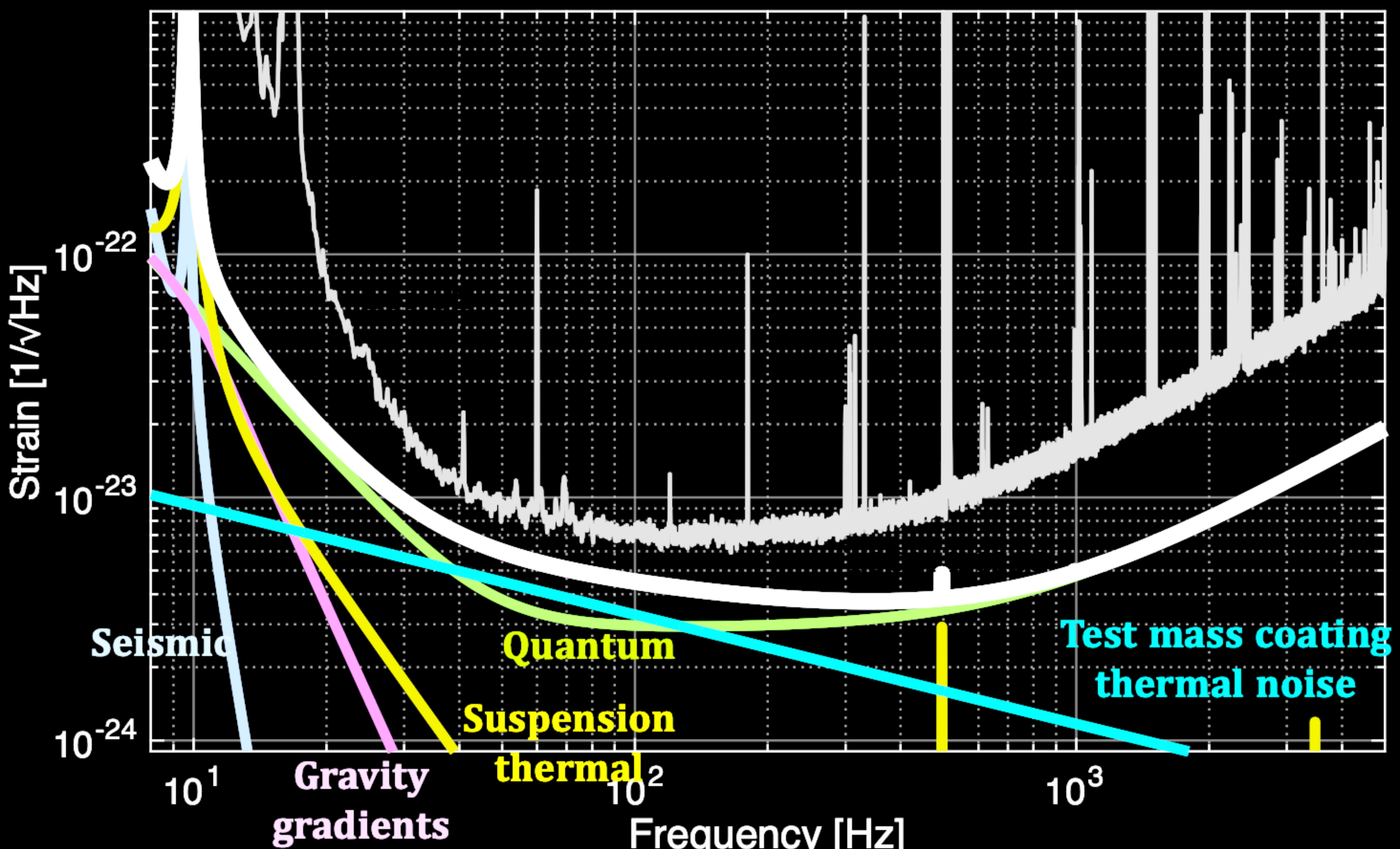




Reality axis

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

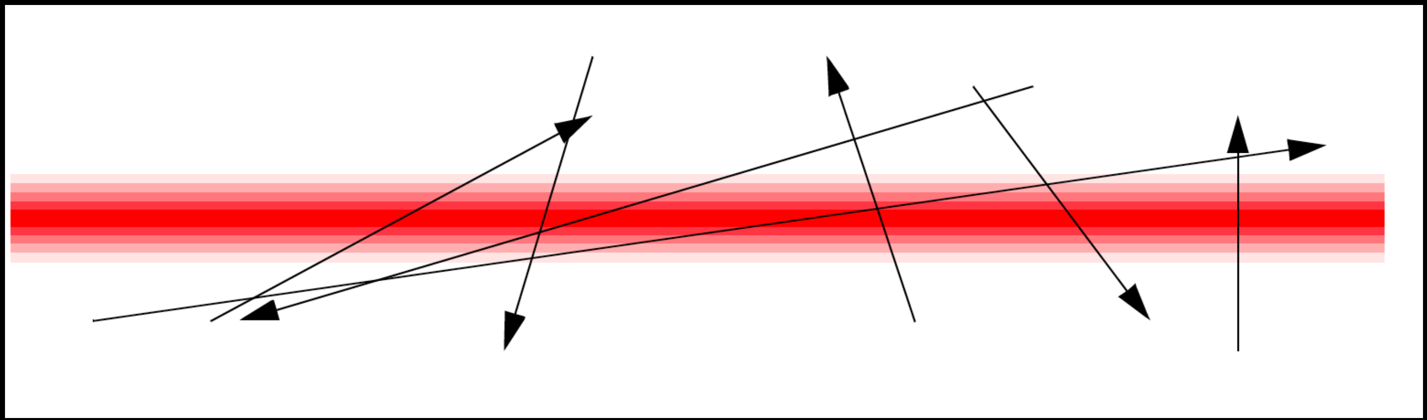
Adv LIGO Target Design Sensitivity, basic noise sources



Observatory Infrastructure

Vacuum System

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



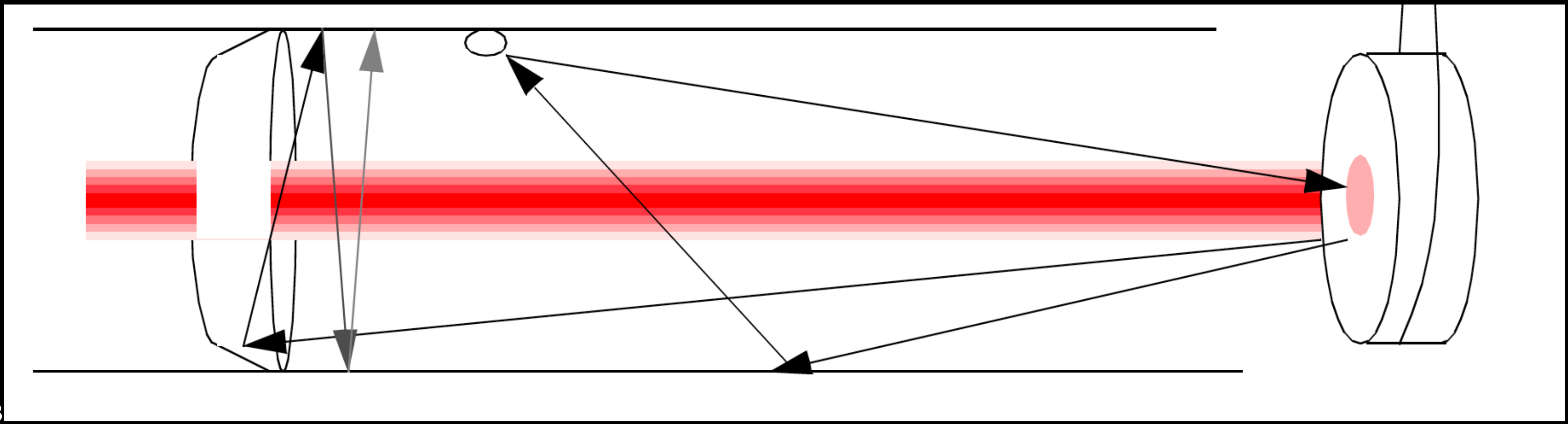
- Polarizability α of the remaining gas molecules induces path-length fluctuations; again, Poisson Statistics, and an effect proportional to square root of density $\rho^{1/2}$ along the path

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

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

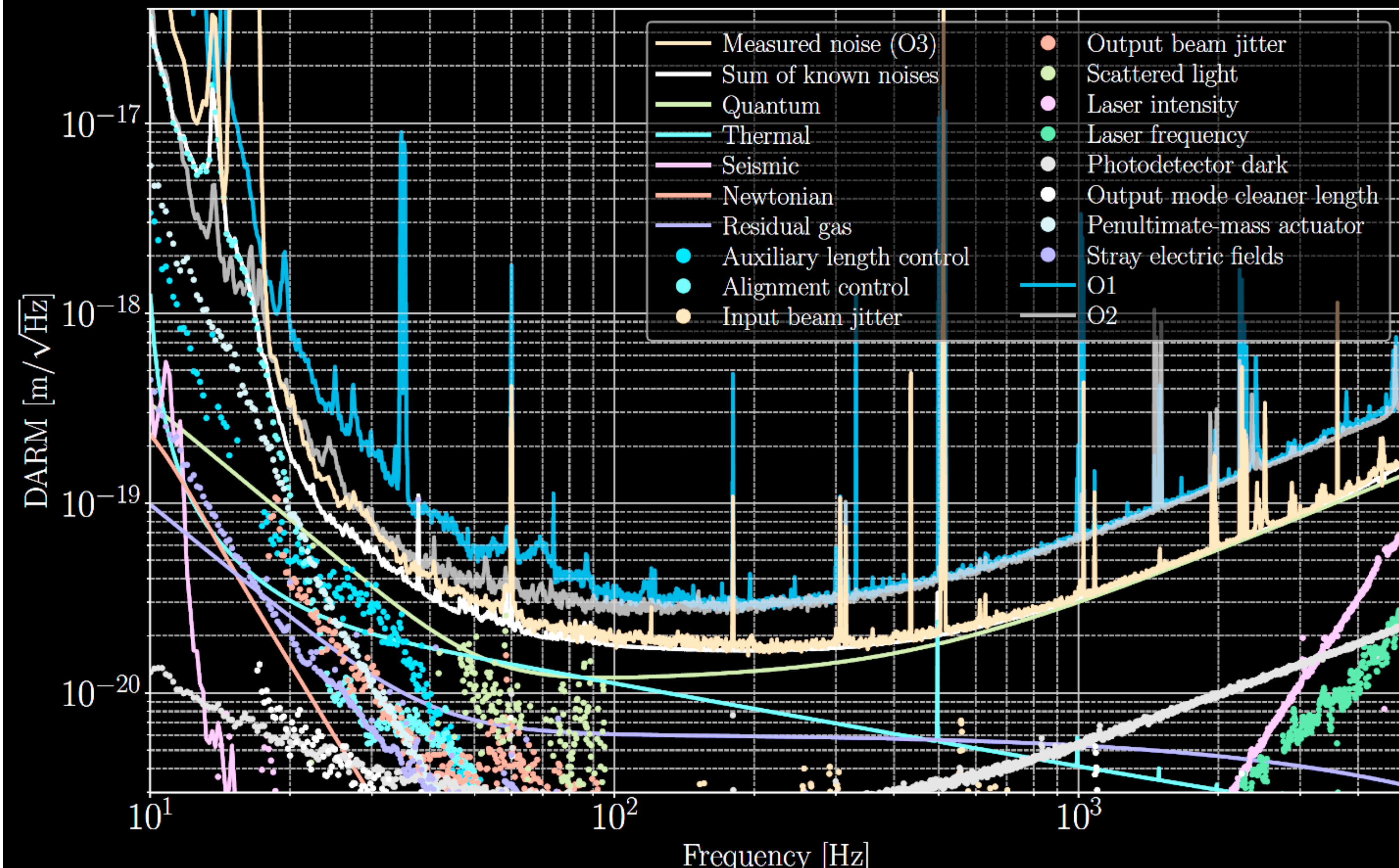
Beam Tube Scattered Light

- 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



Thorlabs

Many other 'technical' noise sources….



Some considerations for future Observatories

Length: The ultimate solution

- Design for low thermal noise, quantum limits, Newtonian and seismic noise
  - 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)
- One disadvantage: **Cost.**
- Length scaling dominates the cost for a detector

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	$1/L^{3/2}$

Terrestrial detectors: Surface, or Underground?

- 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 present very difficult puzzles to solve

Risk

- Different projects can adopt different risk levels
- Also different cultures, funding agencies, collaborations have different levels of tolerable risk
- More ambitious designs require more R&D to be successful to be realized, and may
  - Take more time to get working
  - Lead to a more sensitive detector
  - Make more significant steps forward in measurement science
  - And be risky!
- Safety
  - A different kind of risk, but human safety is very important
  - One person seriously injured or worse is not only a human tragedy – it can also kill a project

System Engineering

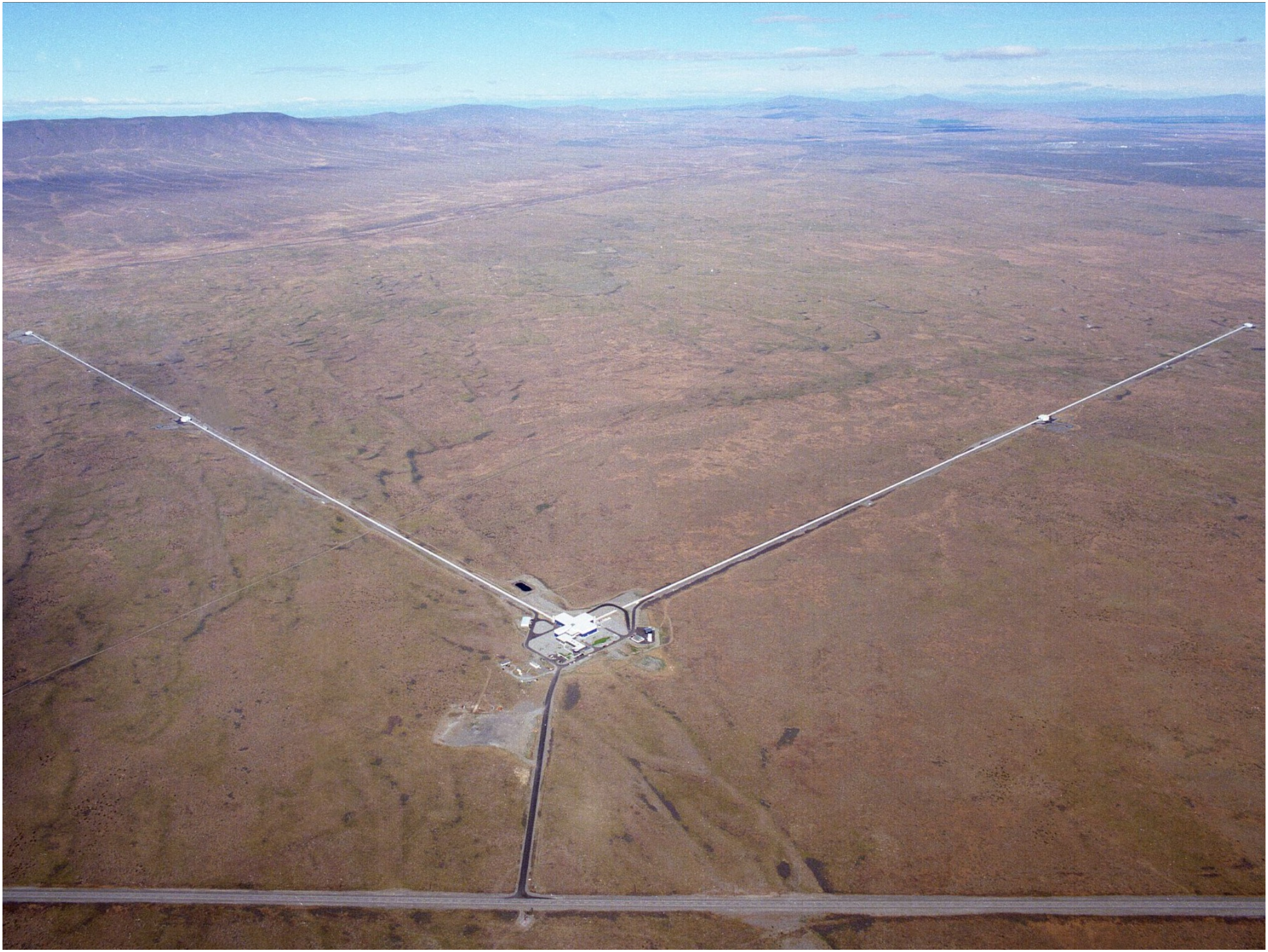
- To find solutions which meet the observational science goals, and which fit in the other constraints just discussed, is challenging
- Requires compromises both in the initial design, and dynamically as the project advances
- Constant modeling of the sensitivity is crucial, along with modeling of schedule and cost
- A mixture of engineering, instrument science, observational science, and project management is needed to succeed

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 LIGO Scientific Collaborations all sharing data
  - » The science that is possible is qualitatively greater
  - » The sociology of a (mostly) non-competitive environment nurturing and supportive
- LISA and Pulsar Timing also in collaborations/consortia
- Now perhaps 3000 persons worldwide
- Ready for the next generation of Observatories

LIGO ‘Virtual’ Tour

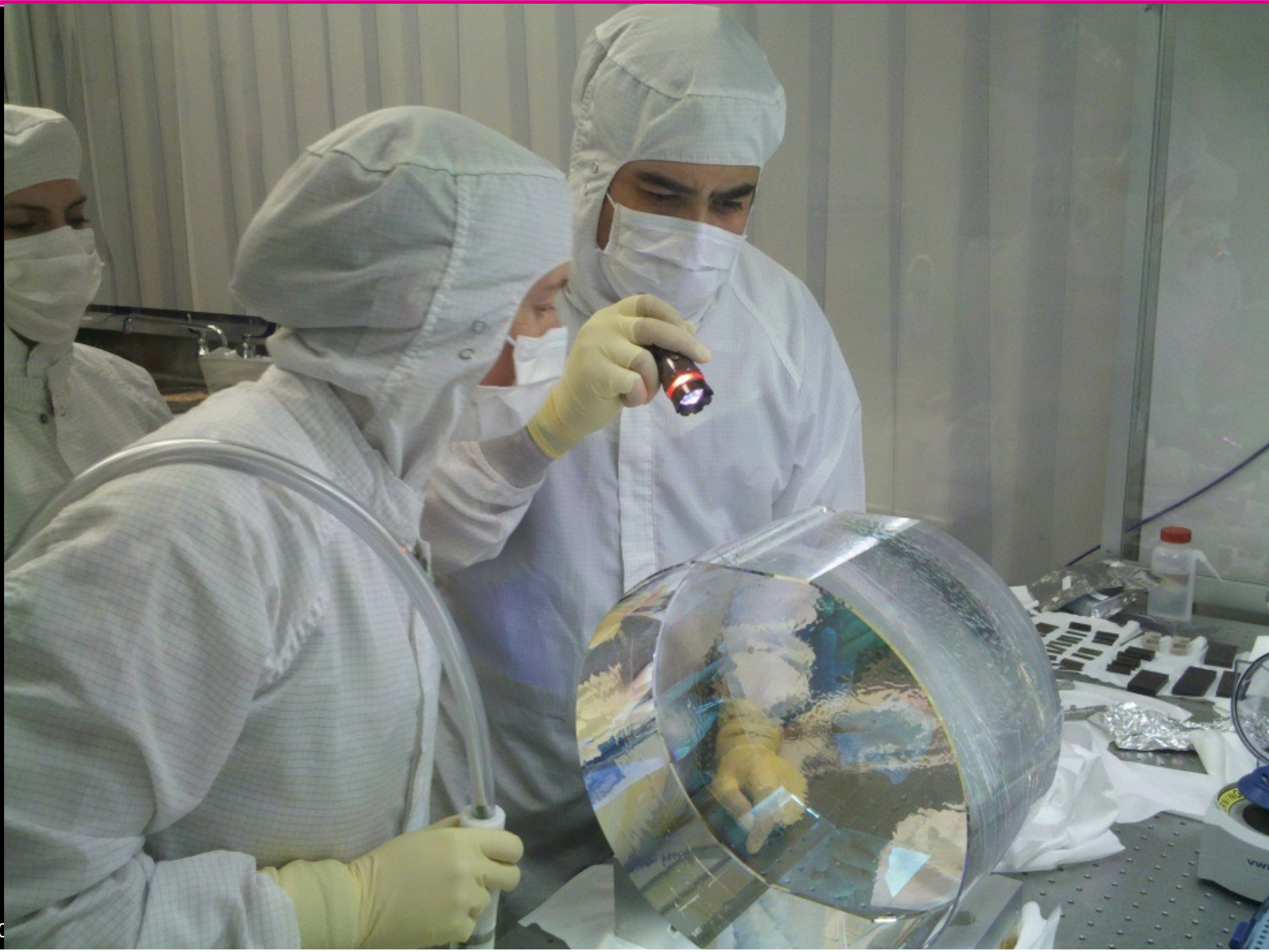


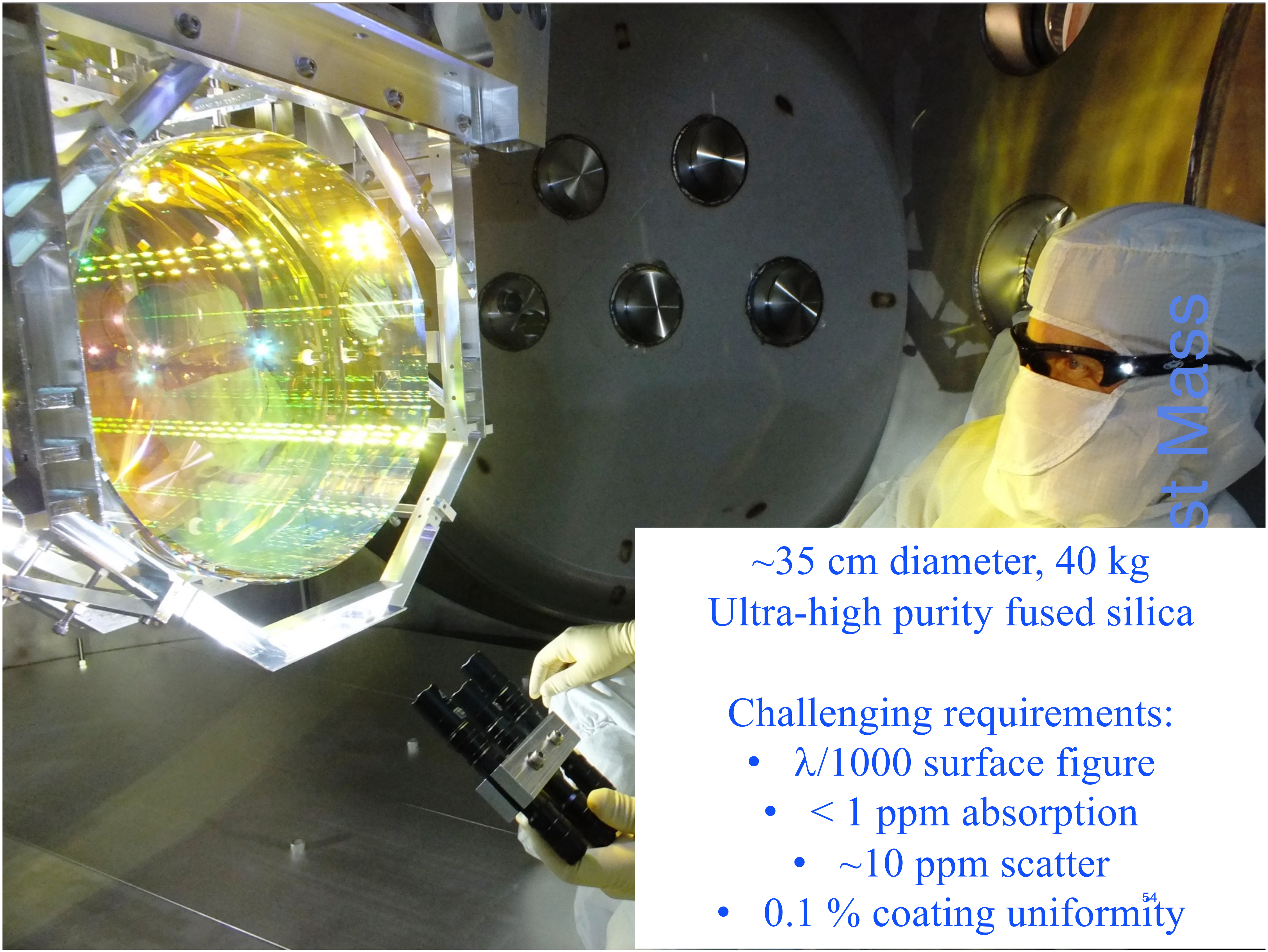
Hanford Corner building

Laser Clean Room; extraterrestrials for scale

Vacuum chambers to protect and isolate optics

Inspecting mirror during fabrication





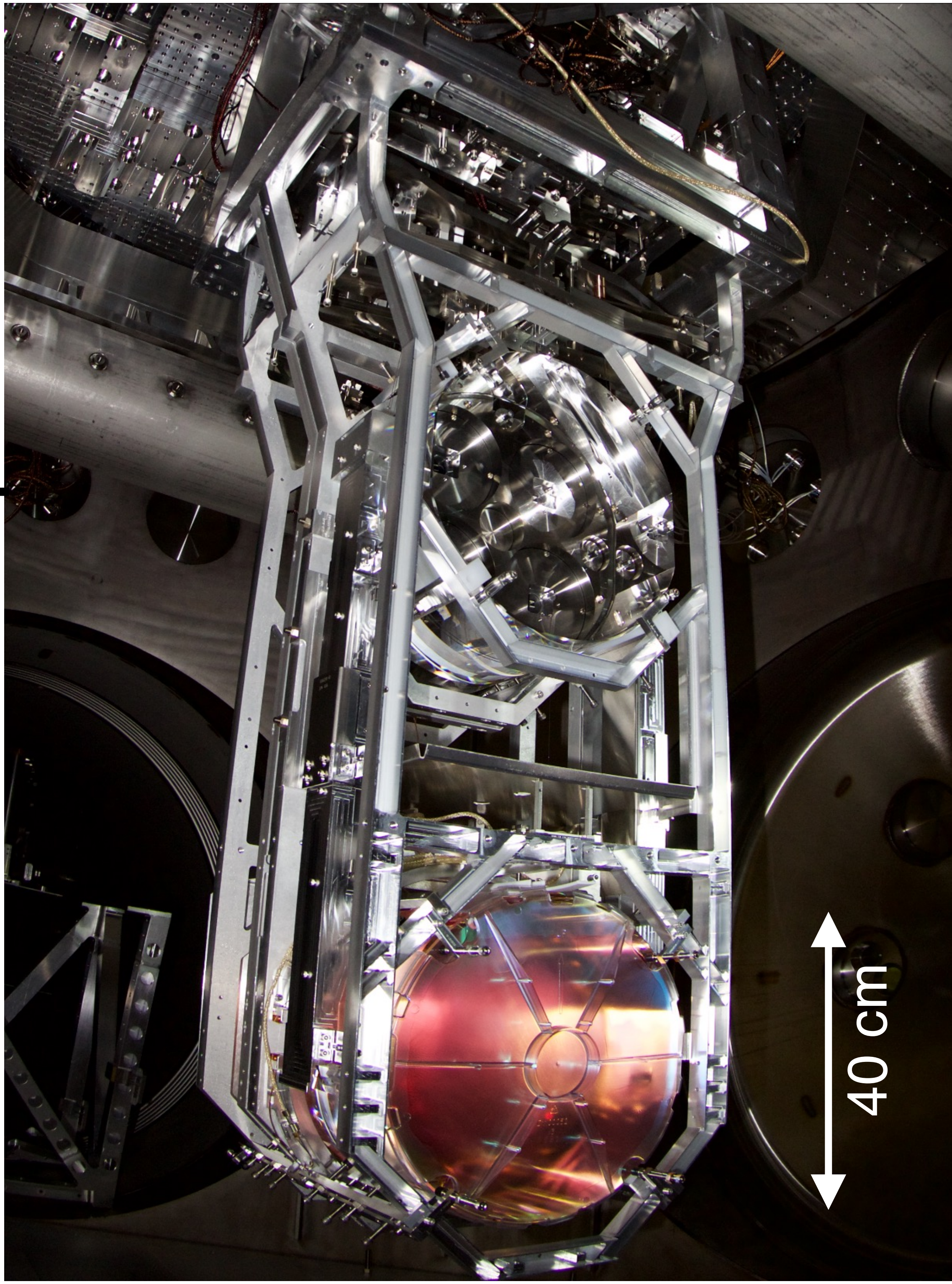
~35 cm diameter, 40 kg

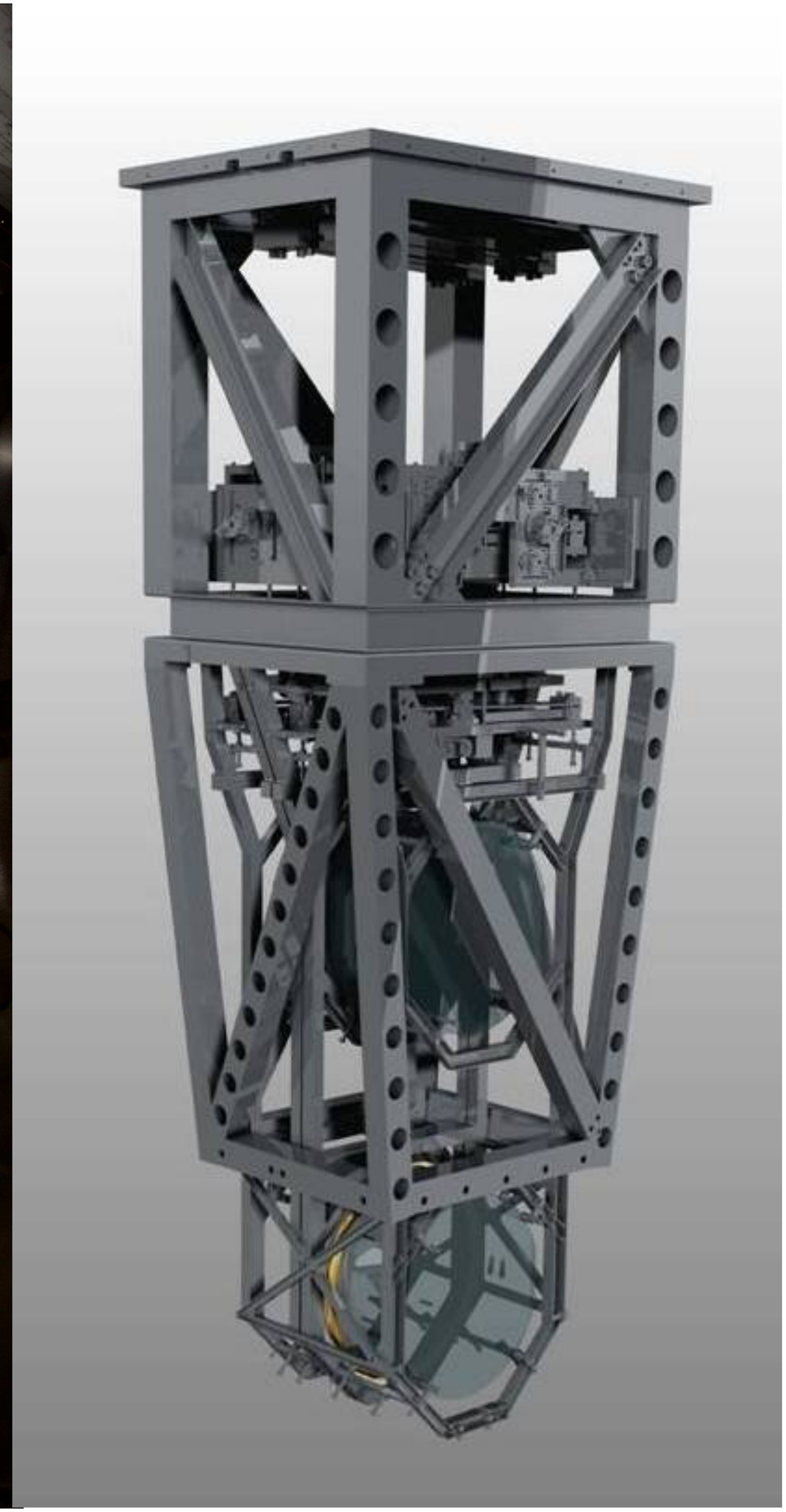
Ultra-high purity fused silica

Challenging requirements:

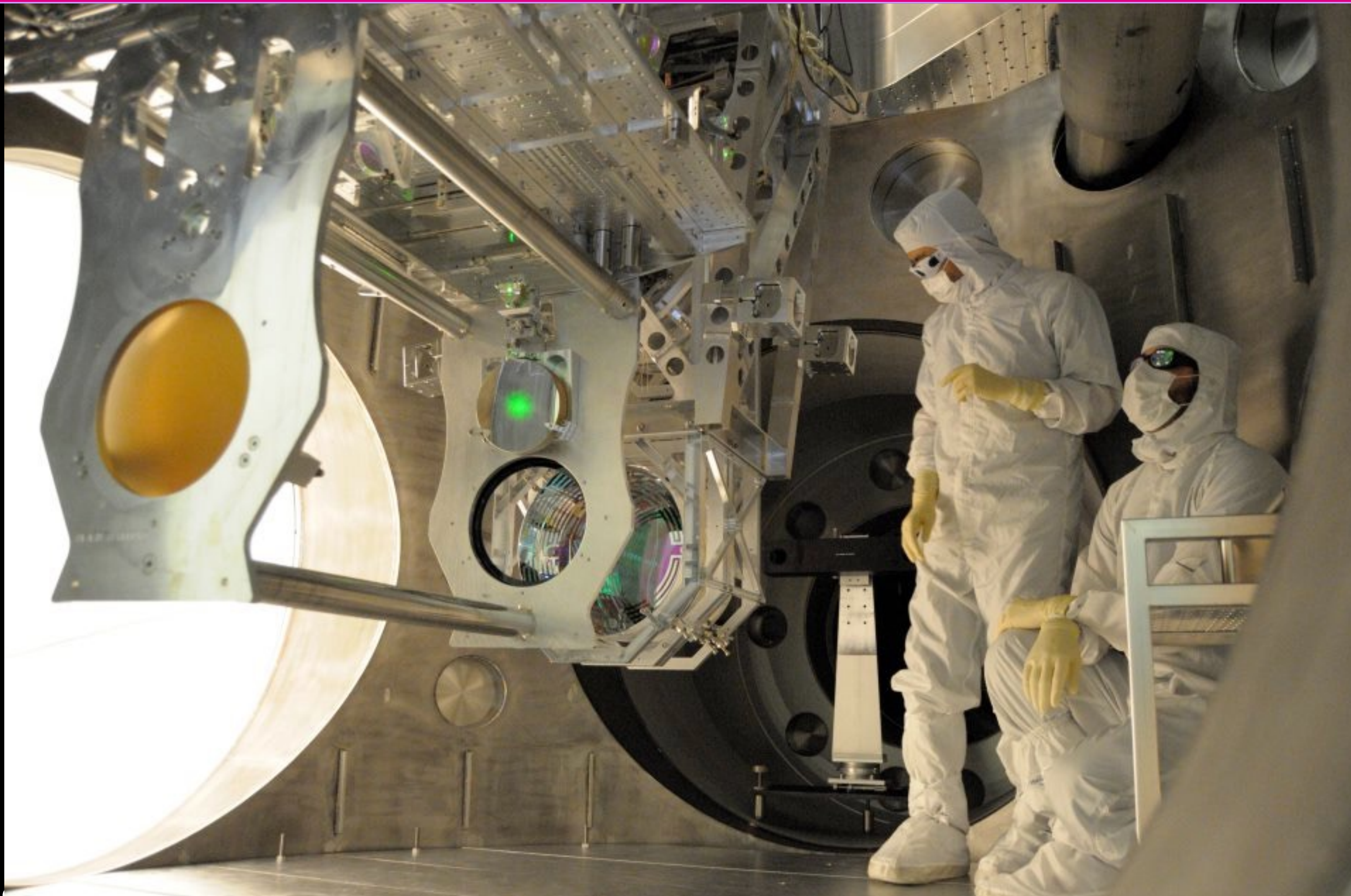
- $\lambda/1000$ surface figure
- < 1 ppm absorption
- ~10 ppm scatter
- 0.1 % coating uniformity

Test Mass Suspension

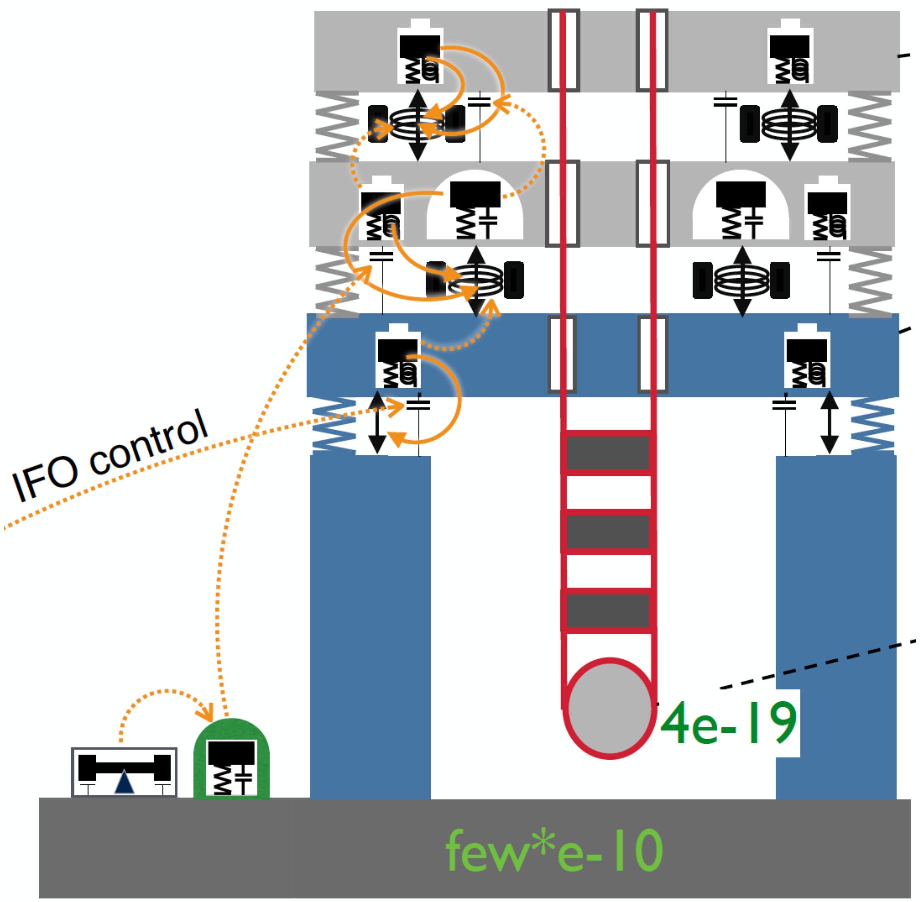


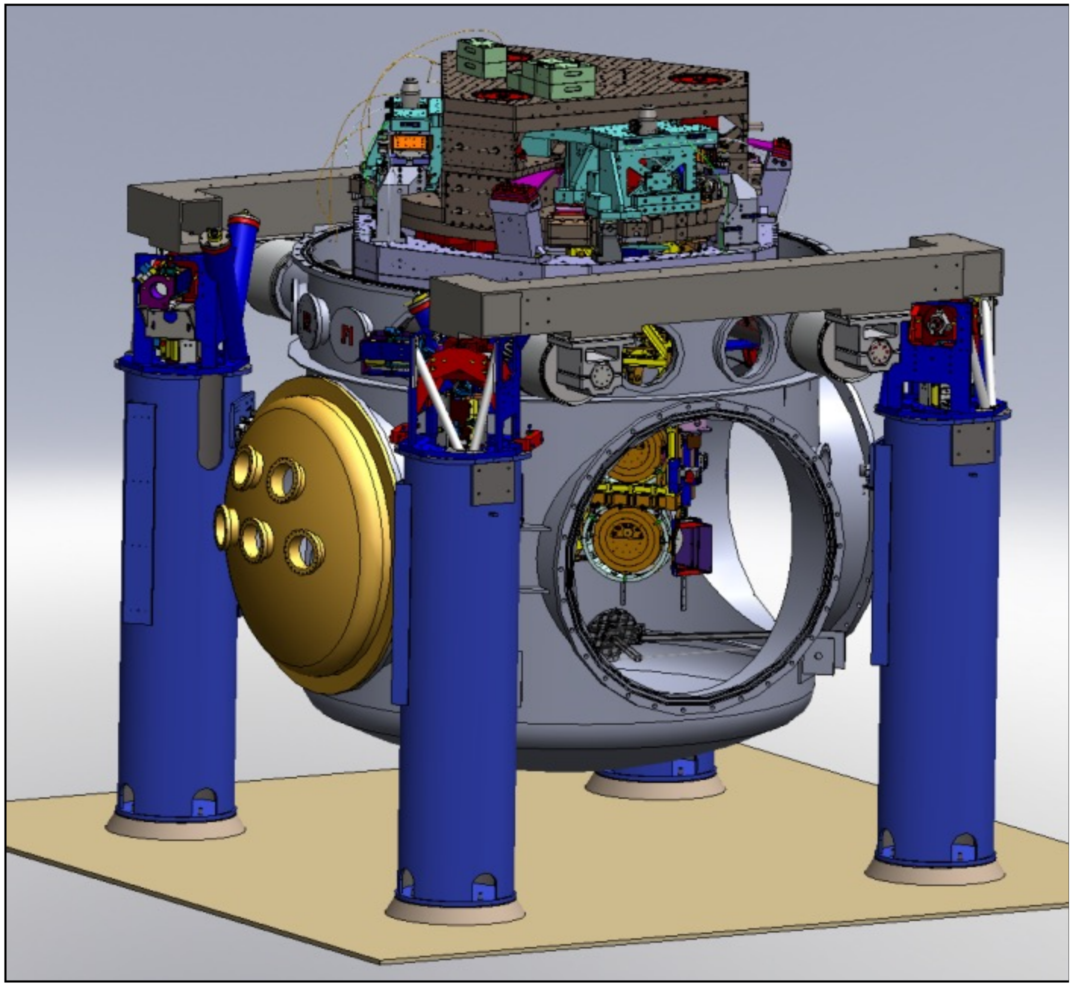


End-mirror assembly (humans removed before pumpdown)

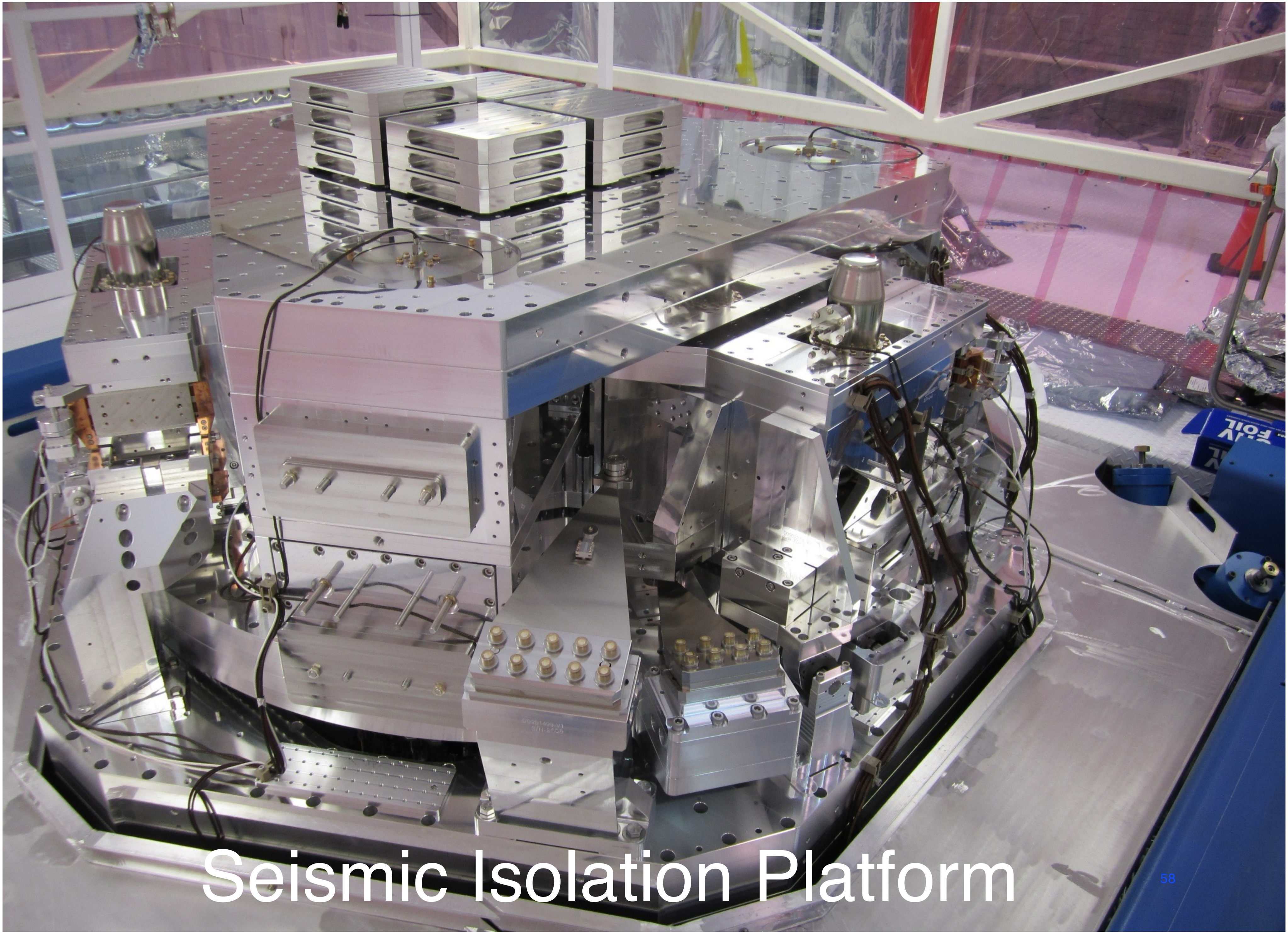


Active and passive seismic isolation





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

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)