Gravitational Wave Detectors

ISAPP Summer School on Gravitational Waves 2021
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G2101171

Thanks to…

- Persons loaning slides and more: S.L. Danilishin, B. Shapiro, and many others hopefully acknowledged on slides
- The LIGO Lab – MIT, Caltech, Hanford and Livingston Observatories
- The LIGO Scientific Collaboration; Virgo and KAGRA
- NASA; LISA Consortium and Pulsar Timing Array Collaborations
- The US National Science Foundation for extraordinary support and perseverance for LIGO

References

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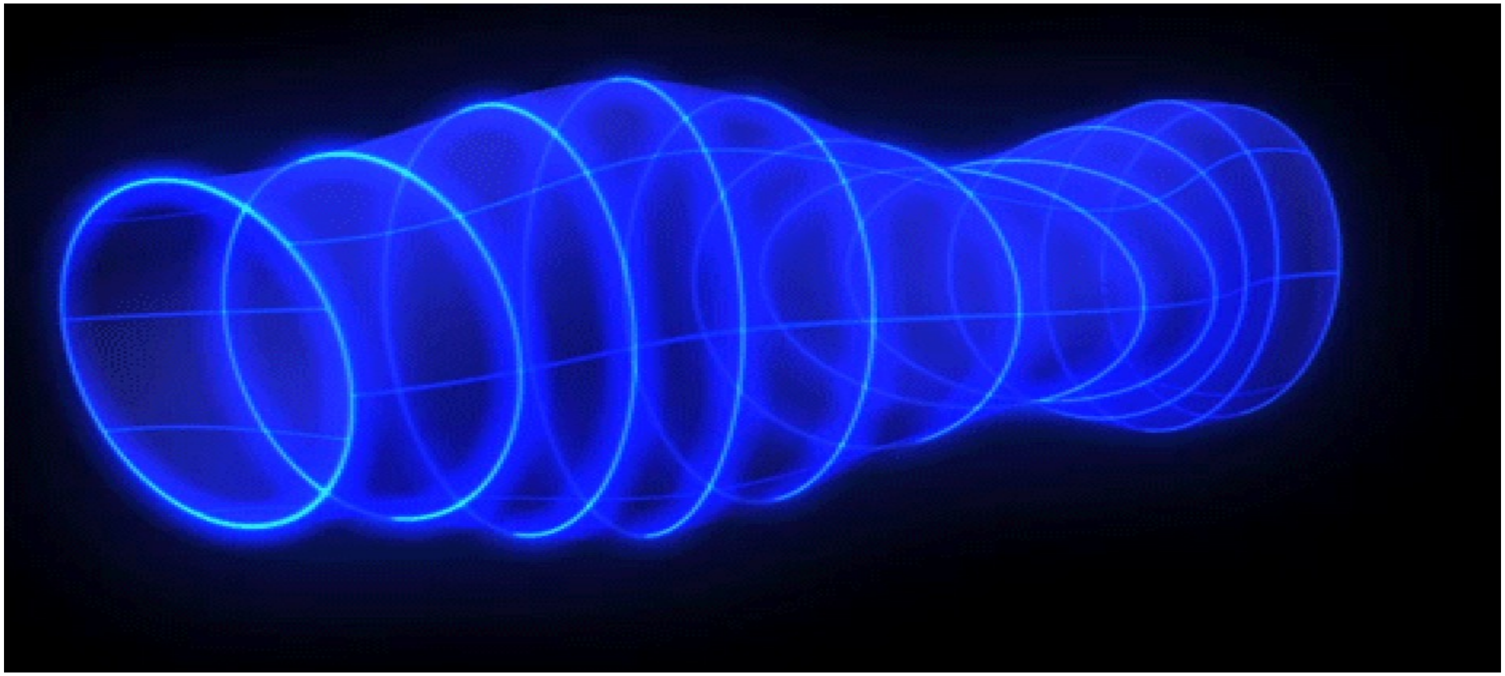
- A guide to LIGO-Virgo detector noise and extraction of transient gravitational-wave signals https://arxiv.org/pdf/1908.11170
- Einstein telescope http://www.et-gw.eu
- Cosmic explorer https://cosmicexplorer.org
- Hobbs G, Dai S. Gravitational wave research using pulsar timing arrays https://export.arxiv.org/pdf/1707.01615
- The NANOGrav 12.5-year Data Set: Search For An Isotropic Stochastic Gravitational-Wave Background https://arxiv.org/pdf/2009.04496
- LISA Mission Proposal https://dms.cosmos.esa.int/COSMOS/doc_fetch.php?id=3753414

Scope

- This talk is intended to present the basic concepts of laser interferometry for gravitational-wave observation
- Focus on ground-based detectors for stellar-mass events
  - I’ll mostly refer to LIGO due to familiarity
- Qualitative in orientation; references for deeper study
- Other talks will cover the current realization (Virgo, LIGO, KAGRA) and the future plans (Einstein Telescope, Cosmic Explorer) in detail.

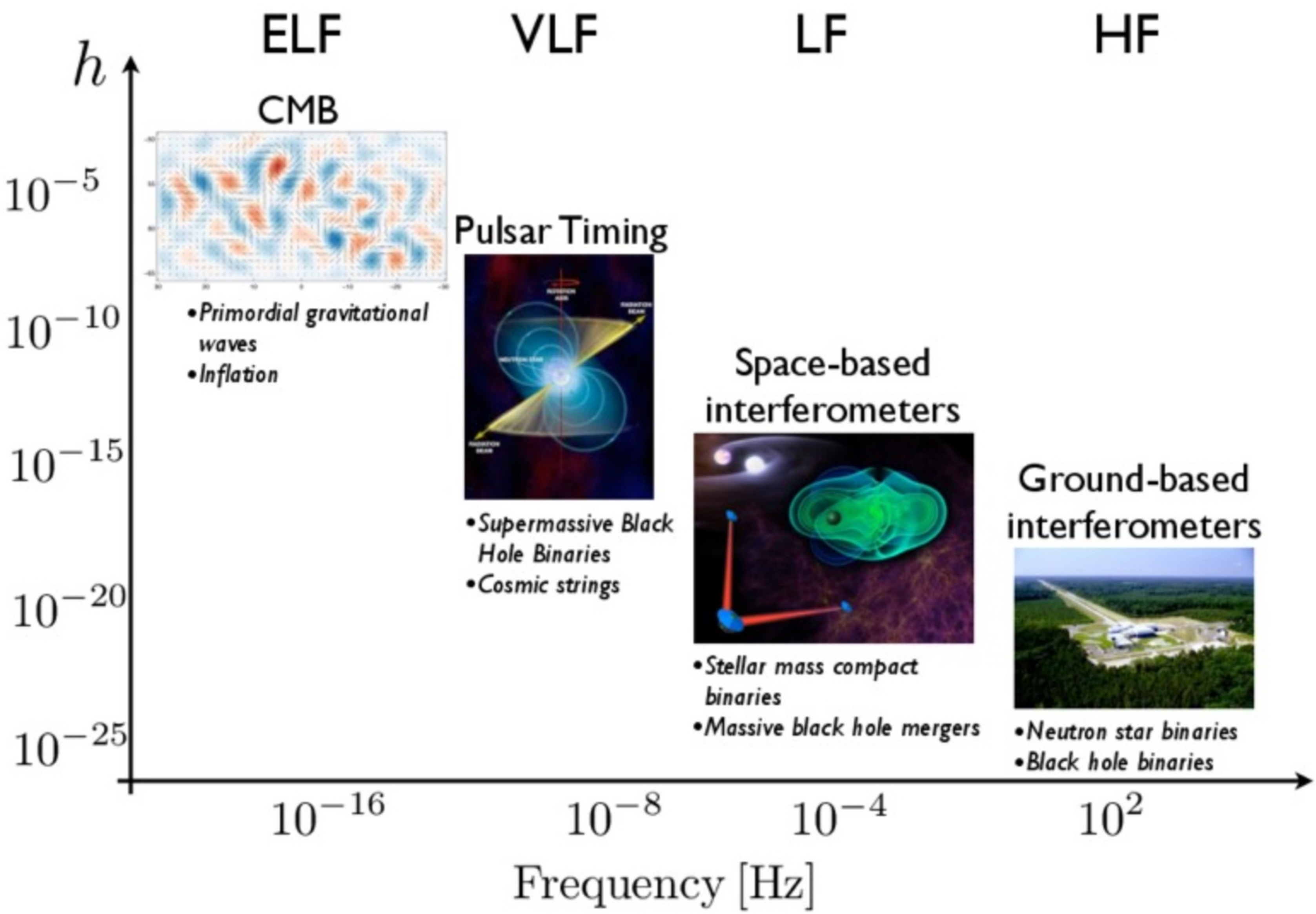
GWs in GR

- While tests of deviation from GR are important, the detectors I will discuss are built to be sensitive to GR-predicted signals, so assume waves:
- Propagating at the speed of light
- Creating strain $h = \Delta L / L$ in space with (in general) a time dependence $h(\mathrm{t})$
- Wavelengths $\lambda_{GW} = c / f_{GW}$ – ground based currently in short-antenna limit
- Two polarizations, 45^{o} to each other
- Ring of free 'test masses' is deformed by a passing GW – this enables observation



ESA

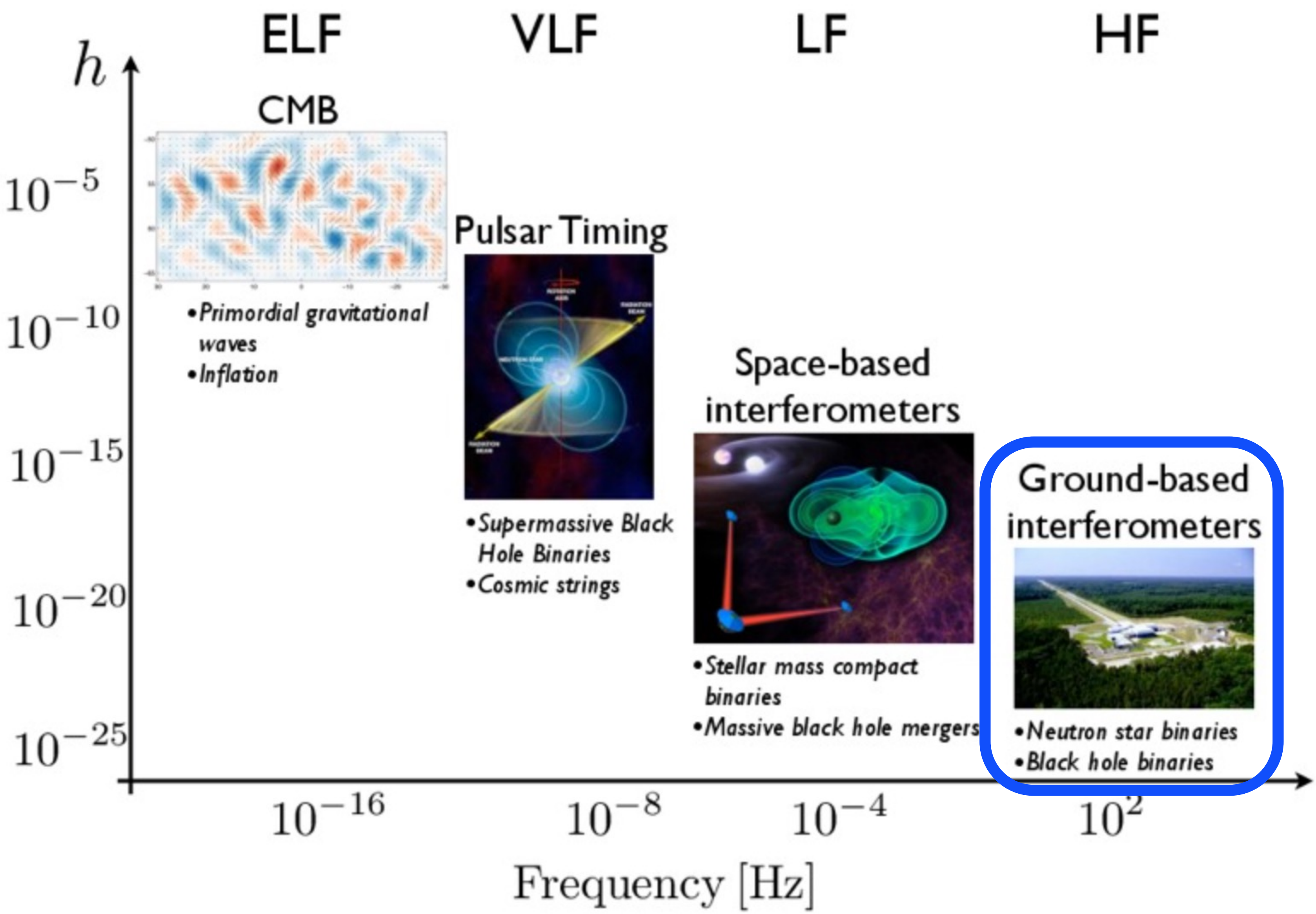
Detection methods, Projects



Detection methods, Projects

- B-mode Polarization of the Cosmic Microwave Background
  - » Search for a primordial GW Background: A very interesting target!
  - » Does not provide a time series $h(t)$ of strain; not discussed further here
- Pulsar timing arrays (Stanislav Babak)
  - » Use pulsars as test masses with clocks
  - » Look using radio telescopes for timing shifts in spatially-separated pulsars
  - » Astrophysical stochastic background the initial target
  - » Science target ~$10^7 – 10^{10}\ M_\odot$ systems
- Space-based laser interferometric detectors (Stanislav Babak)
  - » LISA for example (launch in mid-2030's)
  - » Science target ~$10^3 – 10^7\ M_\odot$ systems; 2.5×10^6 km arms
  - » and: DECIGO concept targeting primordial Background around 0.1 Hz
- Ground-based laser interferometric detectors
  - » LIGO (2xUS, LIGO-India), Virgo, KAGRA; 3 – 4 km arms
  - » Einstein Telescope, Cosmic Explorer future; 10 – 40 km arms
  - » Science target ~ <1 – $10^3\ M_\odot$ systems

Detection methods, Projects

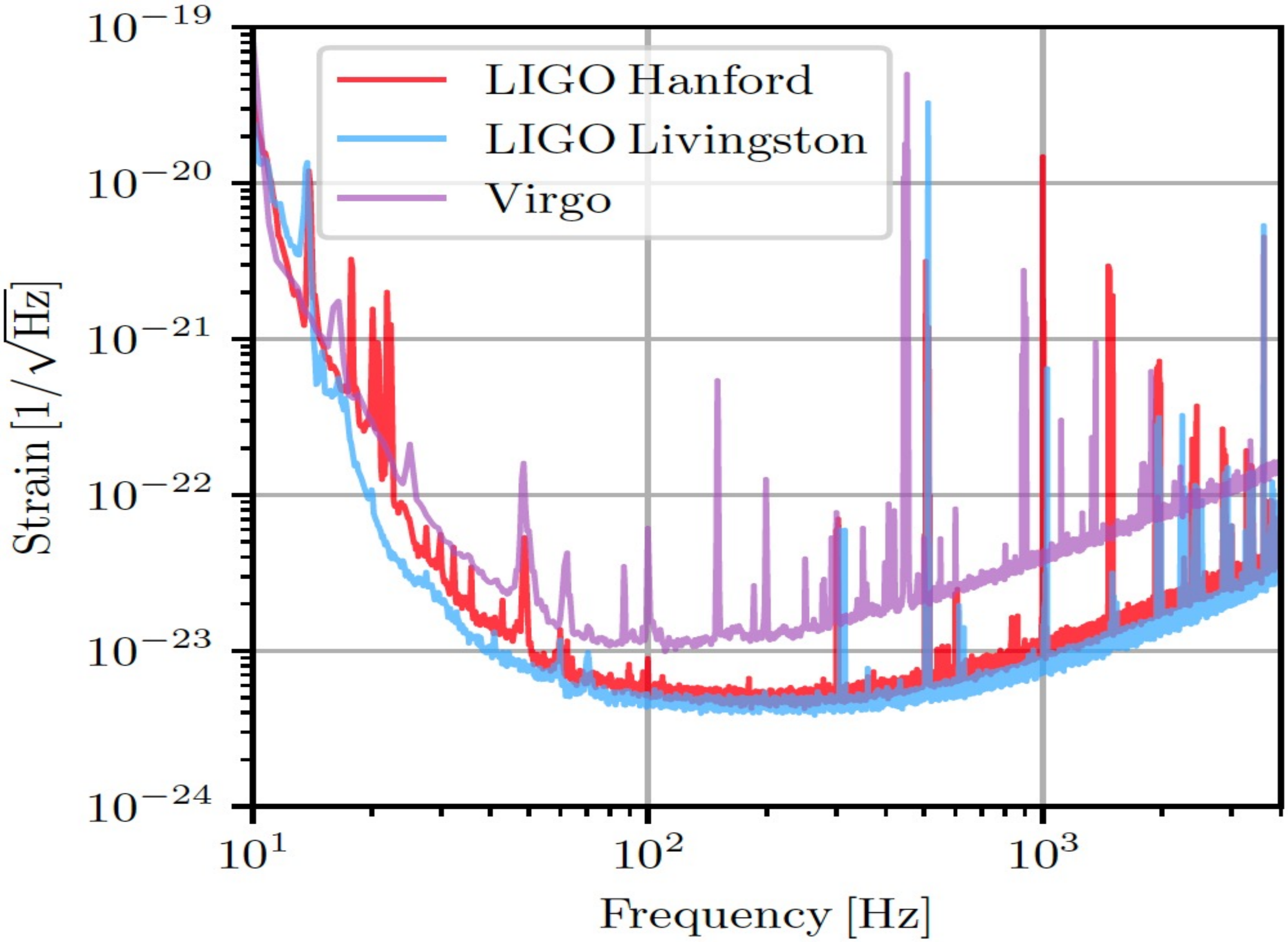


Ground-based Detector ~~requirements~~ → specifications

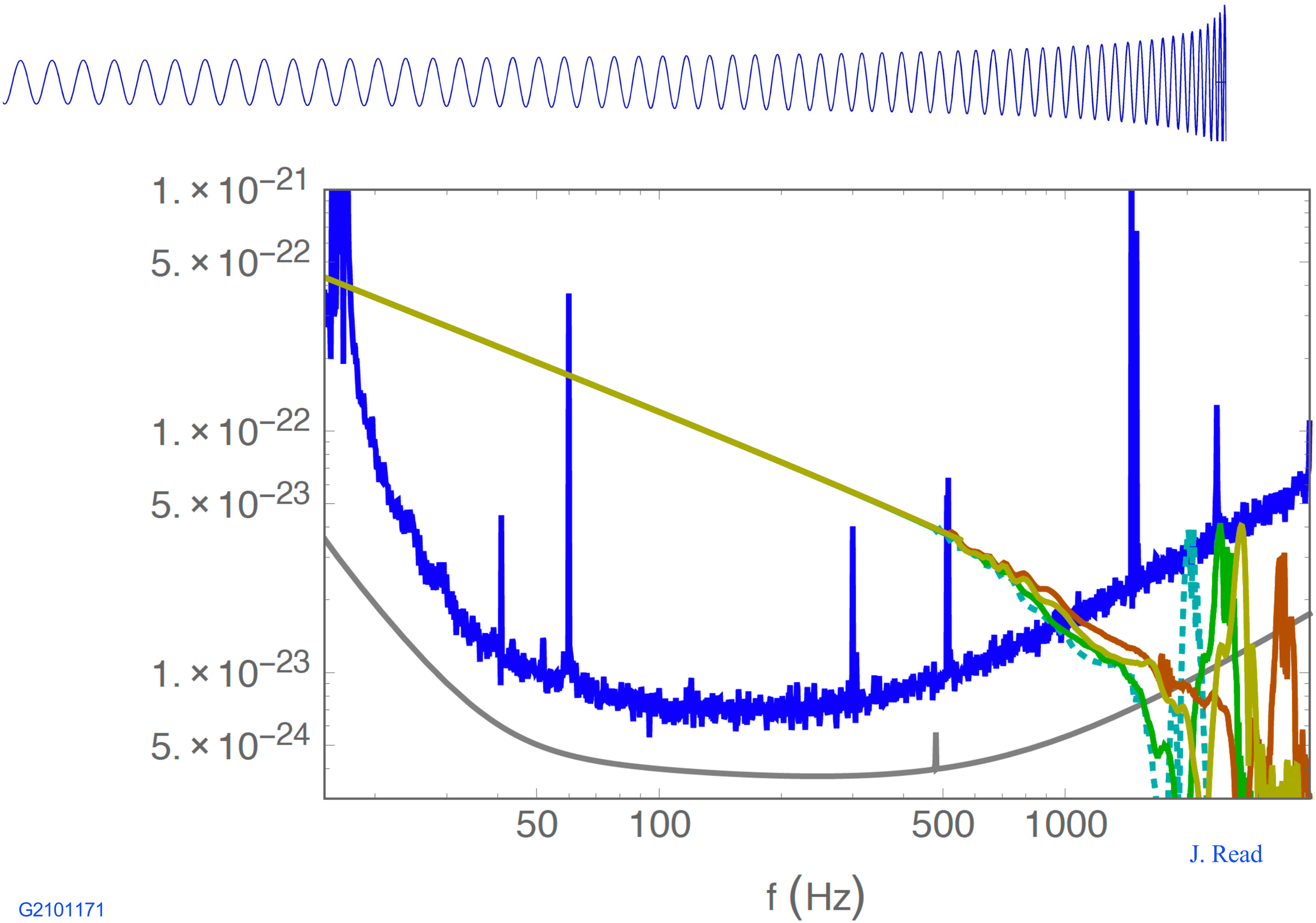
- Elegant to take a science case and use it to place *requirements* on a ground-based detector design
  - » The future ET and CE detectors can take this approach
- Ground-based detectors are *presently* best-effort technically
  - » Where were optical or radio telescopes, X-ray satellites, etc. 5 years after their first successful operation? That's where GW detectors are!
  - » Seek observational science enabled with what can be built now
  - » Parallel development of future science-driven observatories/detectors
- Low frequency limit enable studies of BH systems up to ~150$M_\odot$
  - » enables long observation times for lighter systems
  - » NSNS system seen for >30sec
- High frequency limit to enable studies of NS coalescence
  - » Ideally 3-4 kHz, currently more like 0.7-1 kHz
- Data must be sufficiently stationary and free of defects; good data segments significantly longer than transient signals
- Signal rate impedance matched to human impatience - ~1/week

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



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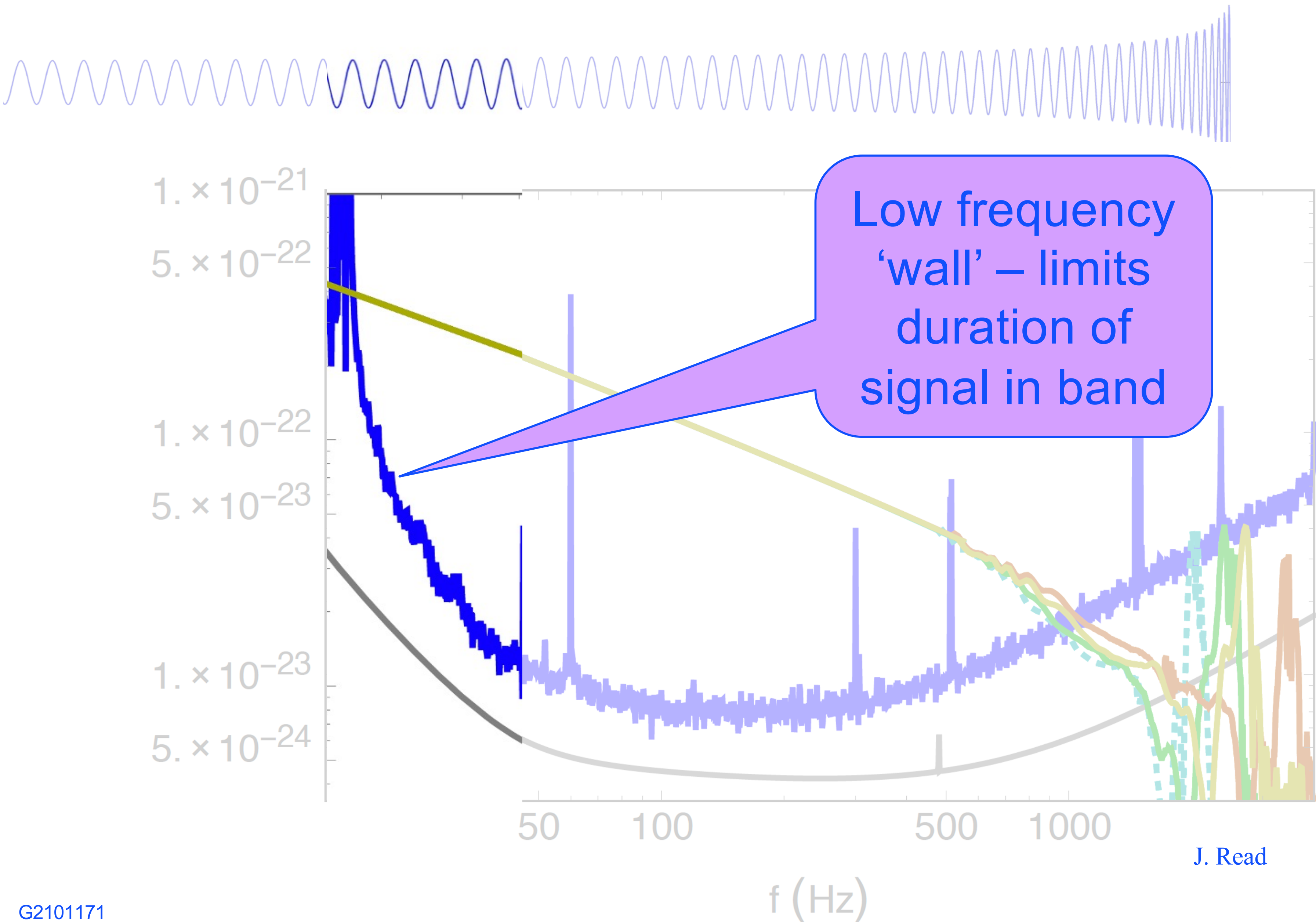

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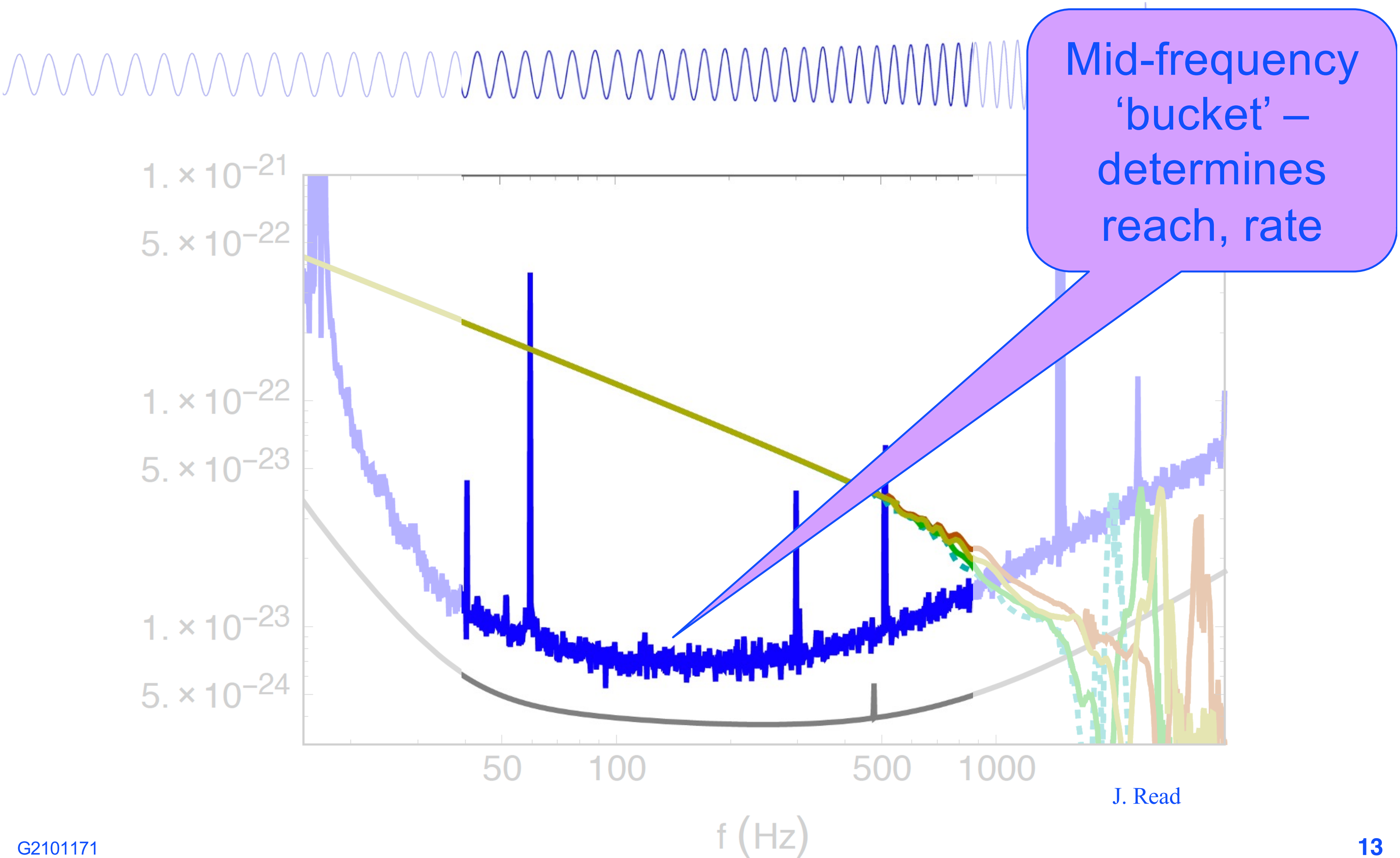

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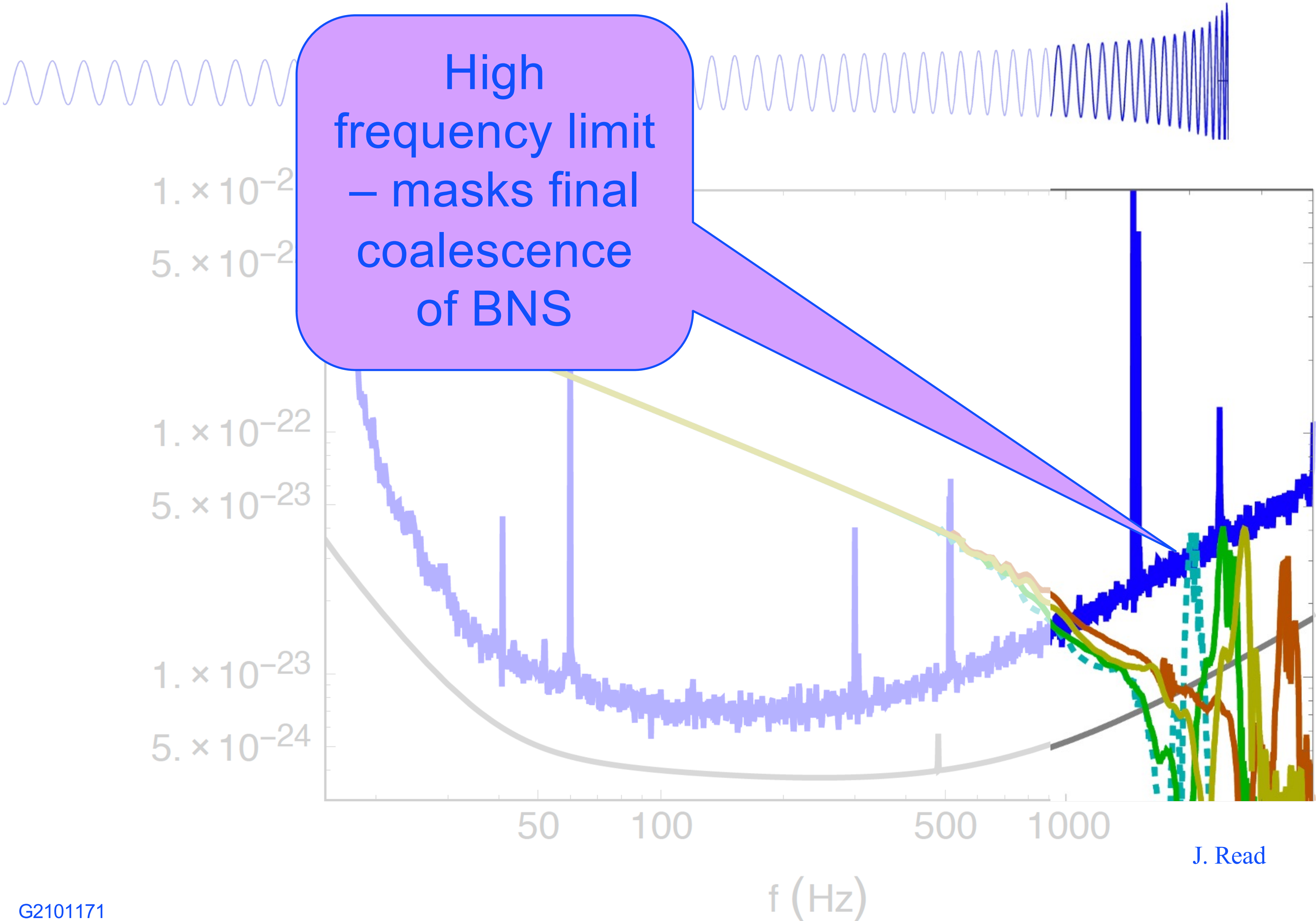
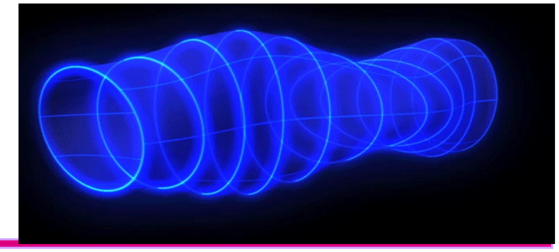
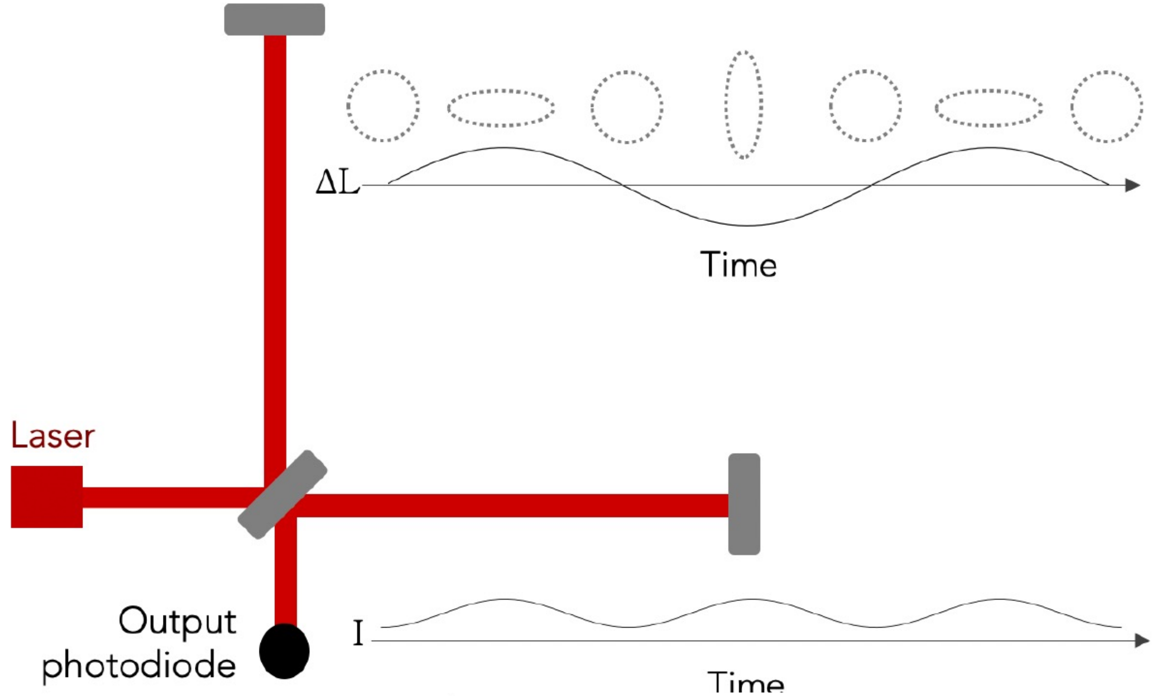


J. Read

What is our measurement technique?

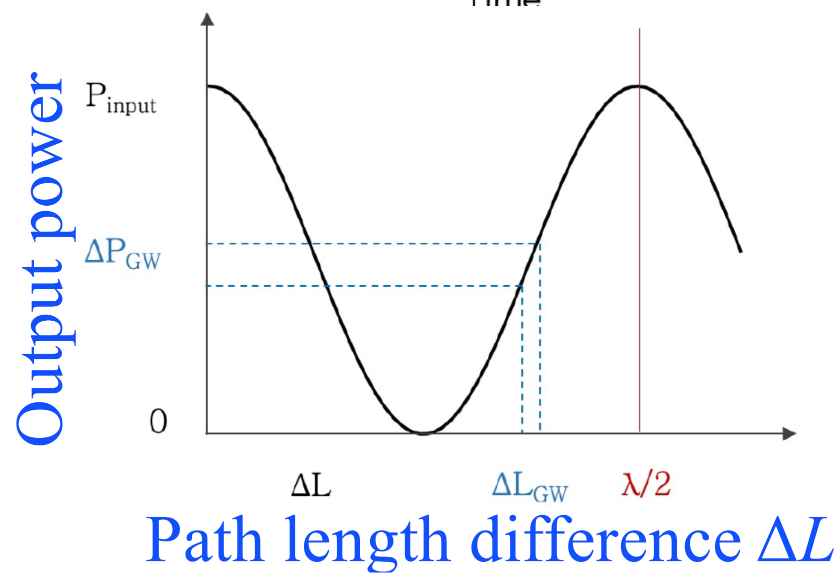


- Enhanced **Michelson interferometers**
- GWs modulate the distance between the end test mass optic and the beam splitter
- The interferometer acts as a transducer, turning GWs into photocurrent proportional to the strain amplitude



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

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



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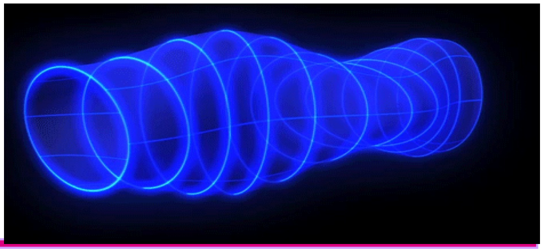

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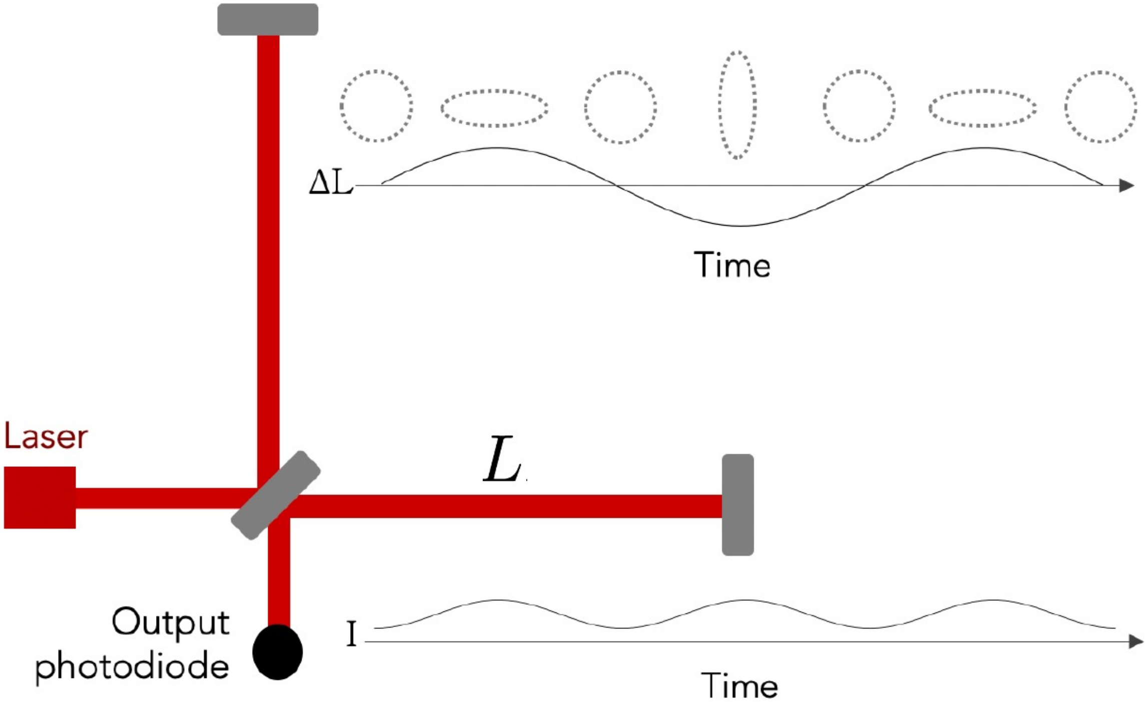


$$\Delta P_{\mathrm{GW}} \sim h L P_{\mathrm{laser}} / \lambda_{\mathrm{laser}}$$

- Increase arm length L
- Increase P_{laser}
- Use short wavelength laser λ_{laser}

Magnitude of h at Earth:
Detectable signals h ~ 10^{-21}
(1 hair / Alpha Centauri)
For L = 1 m, ΔL= 10^{-21} m
For L = 4km, **ΔL= 4x10^{-18} m**

What are the ‘fundamental’ limits to sensitivity?

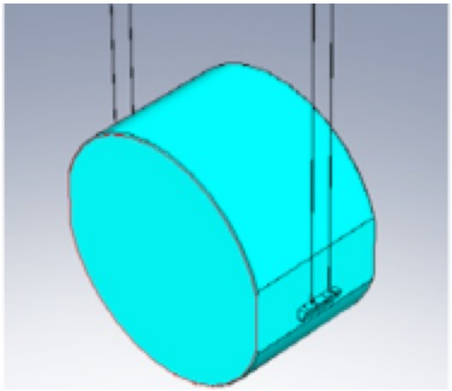
Useful paradigm in considering limits to detector sensitivity

- **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
Internal motion



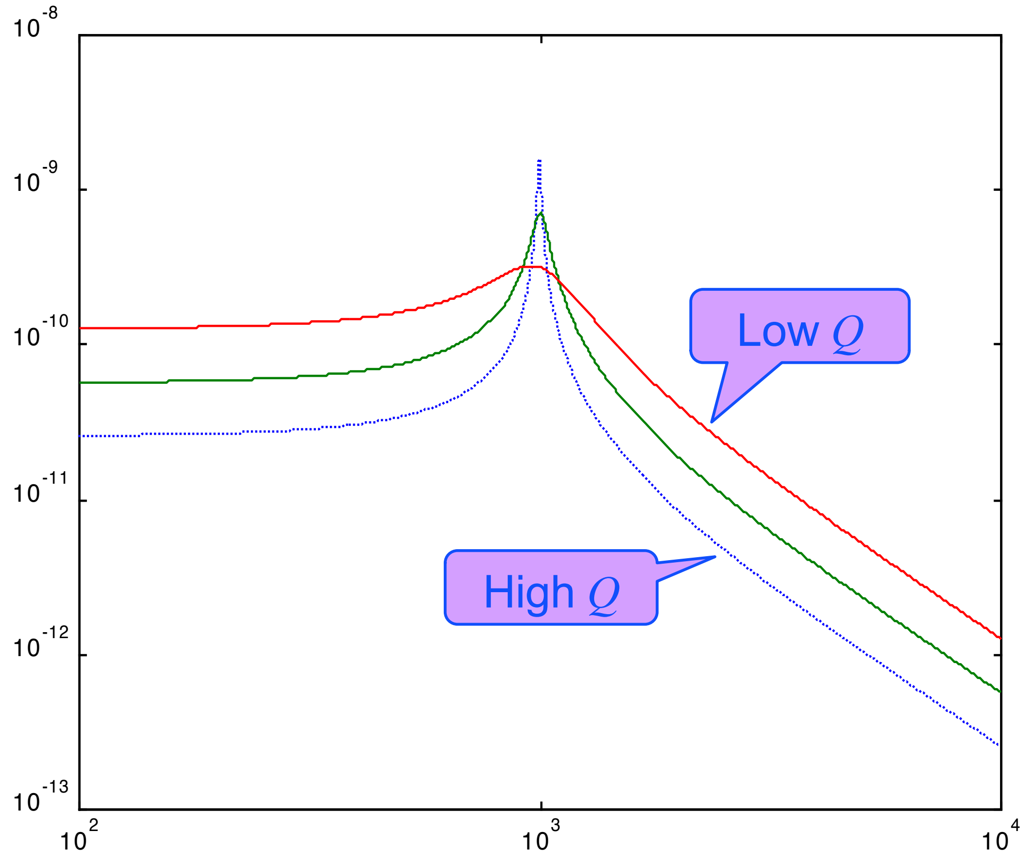
- **Thermal noise** – kT of energy per mechanical mode
- *Über die von der molekularkinetischen Theorie der Wärmegeforderte Bewegung von in ruhenden Flüssigkeiten suspendierten Teilchen,*
  A. Einstein, 1905
- Simple Harmonic Oscillator:

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

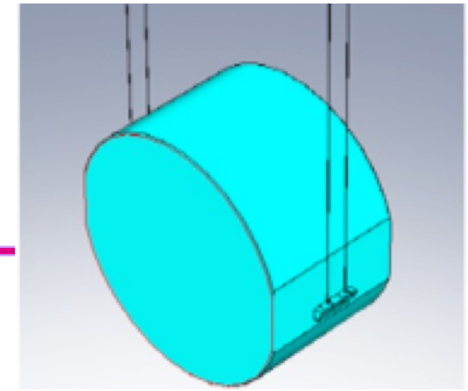
- Distributed in frequency according to real part of impedance $\Re(Z(f))$

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

- **Low-loss materials, monolithic construction**



Measuring ΔL= 4x10^{-18} m
Internal motion



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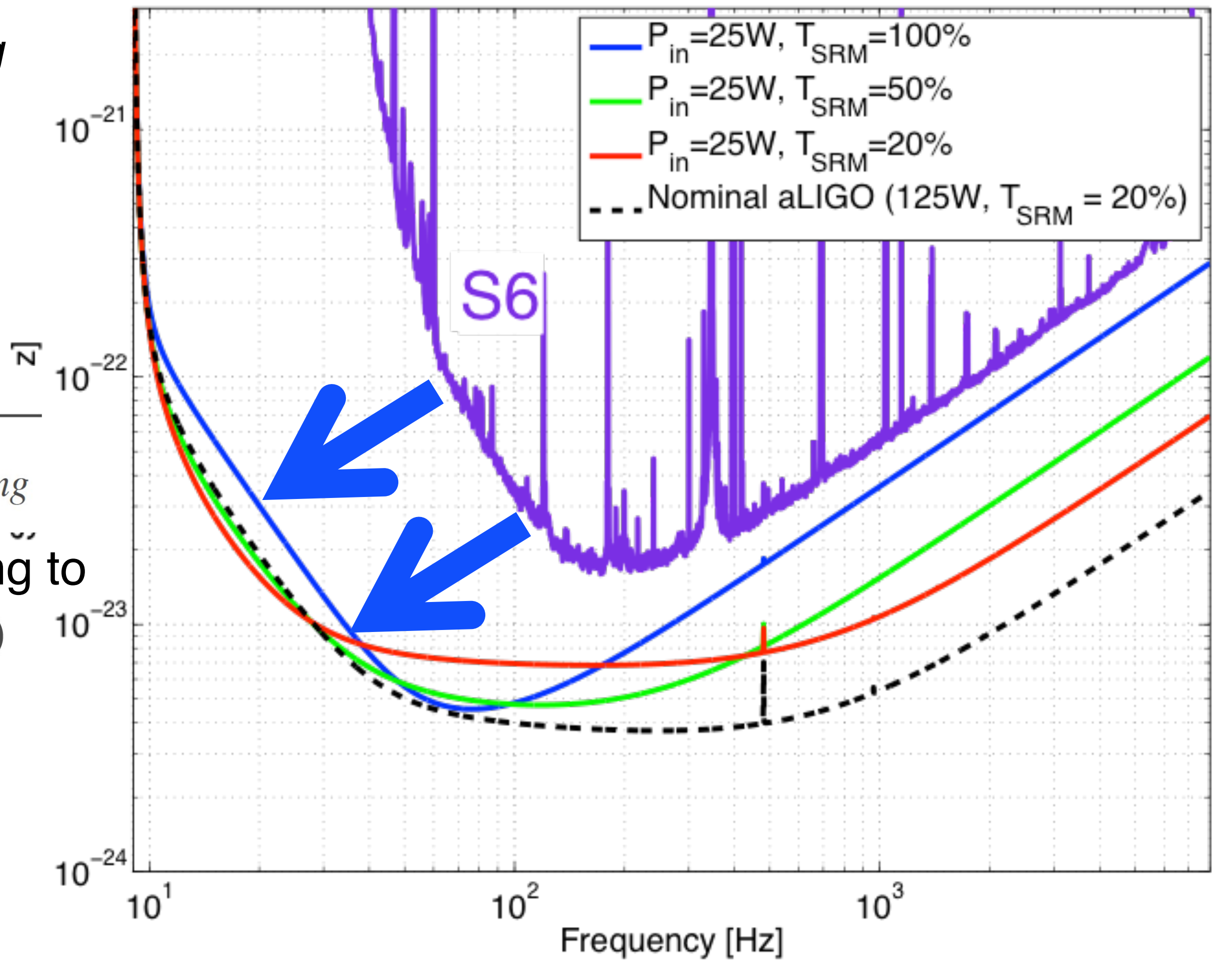
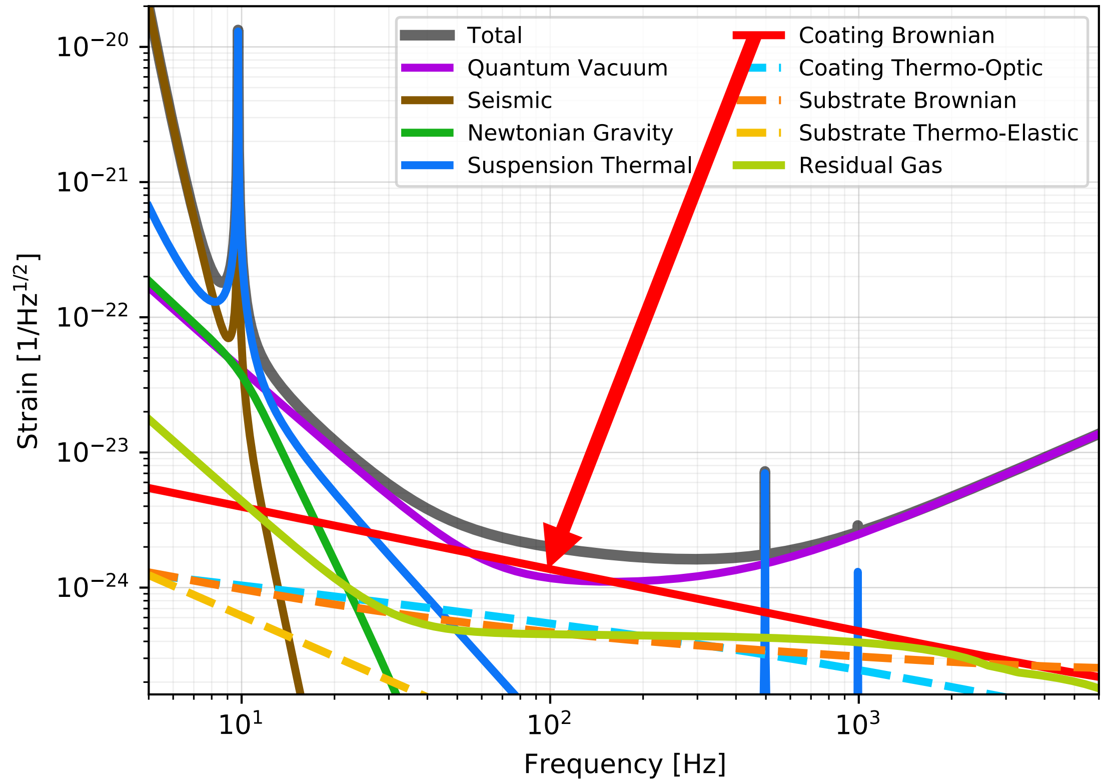


Measuring Δ*L*= 4x10^{-18} m
Internal motion

- In in the best coatings, the dielectric optical coating has a rather 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

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

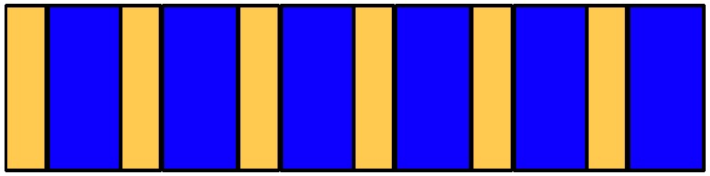
beam radius

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

Basic Coating Concepts

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

$\lambda/4n_H$ - $\lambda/4n_L$



- Dielectric mirror
  - alternating high/low index ~¼ wavelength-thick layers
  - large index contrast ⇒ fewer, thinner required layers

$$\text{FoM (roughly)} \propto \frac{(n_H / n_L)\ln(n_H / n_L)}{\phi_H}$$

- Key optical properties
  - absorption < 0.5 ppm, scatter – ppm's, point absorbers ↓
  - industry standard: ion-beam sputtering

    R.T. deposition followed by 300 C – 500 C annealing
  - scaling to >30 cm nontrivial

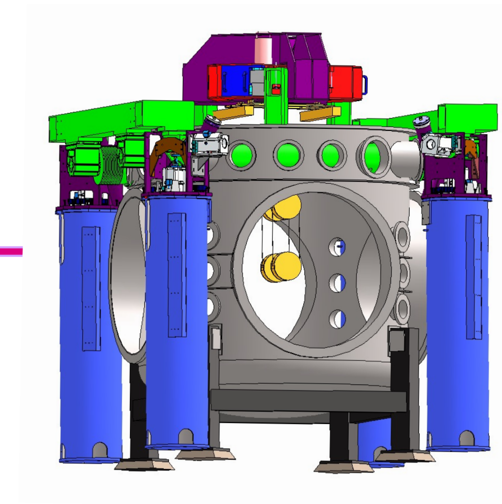
    with ~1 nm RMS figure: LMA, Lyon

- Current LIGO mirrors:
  - Ti(20%):Ta_2O_5: $n = 2.07$, $\phi = 3 \text{ x } 10^{-4}$

    SiO_2: $n = 1.45$, $\phi = 4 \text{ x } 10^{-5}$

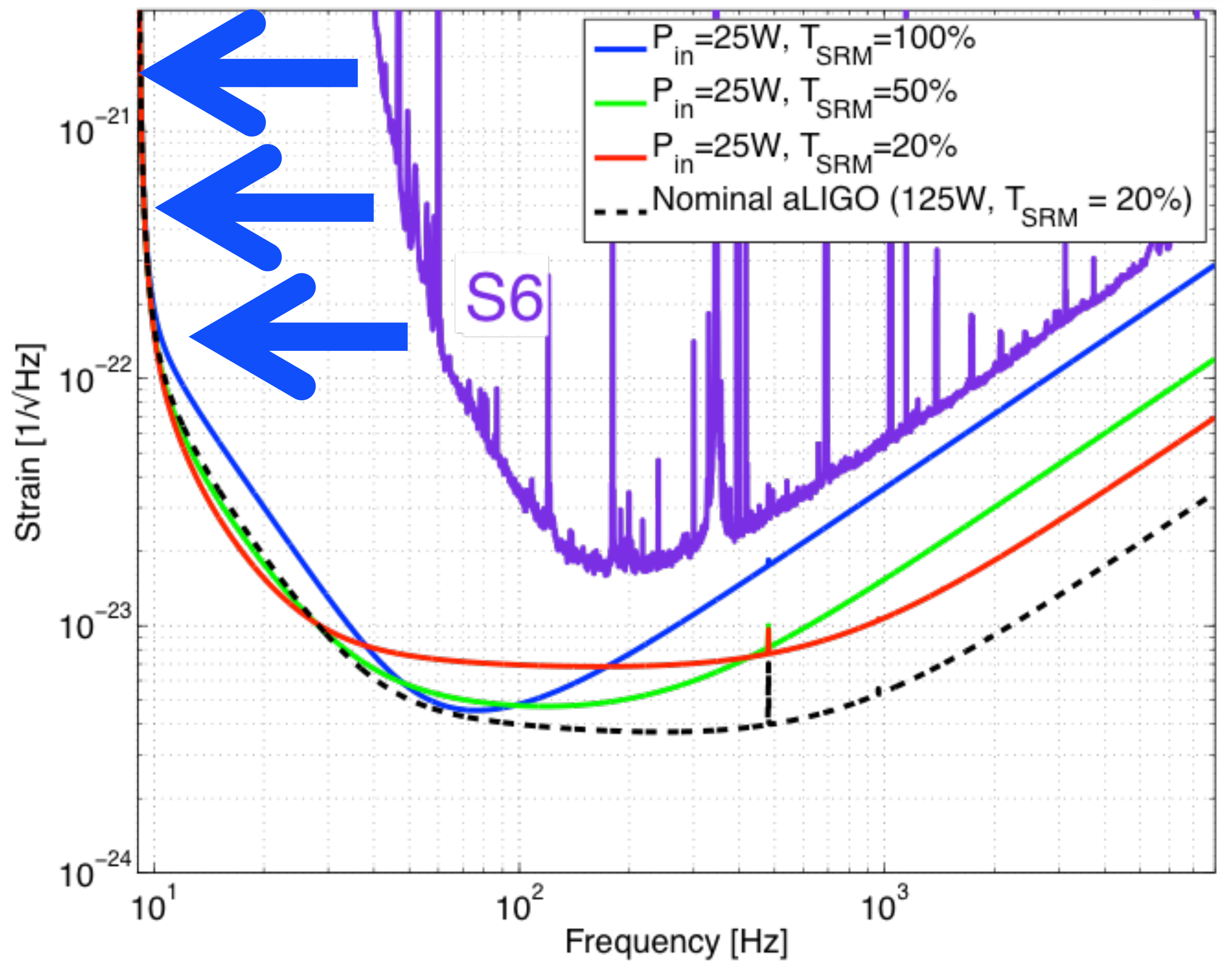
$$\frac{d_{Ta_2O_5}}{d_{Ta_2O_5} + d_{SiO_2}} \sim 40\%$$

Measuring $\Delta L = 4\times10^{-18}$ m
Forces on test mass

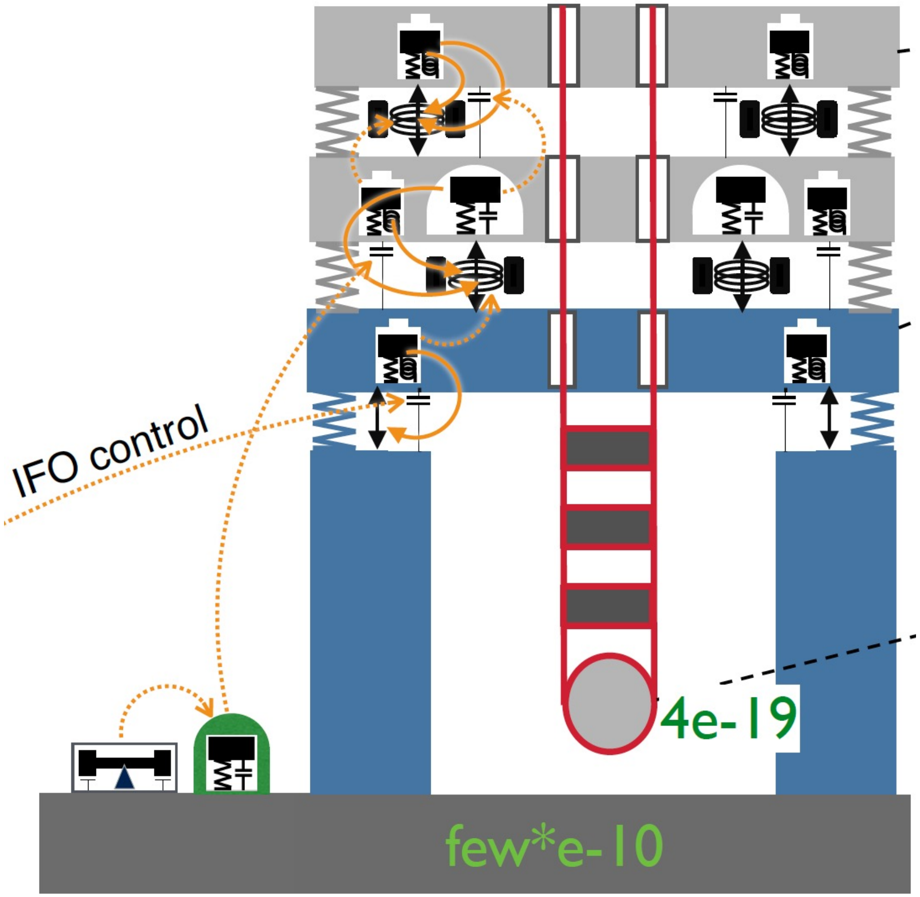


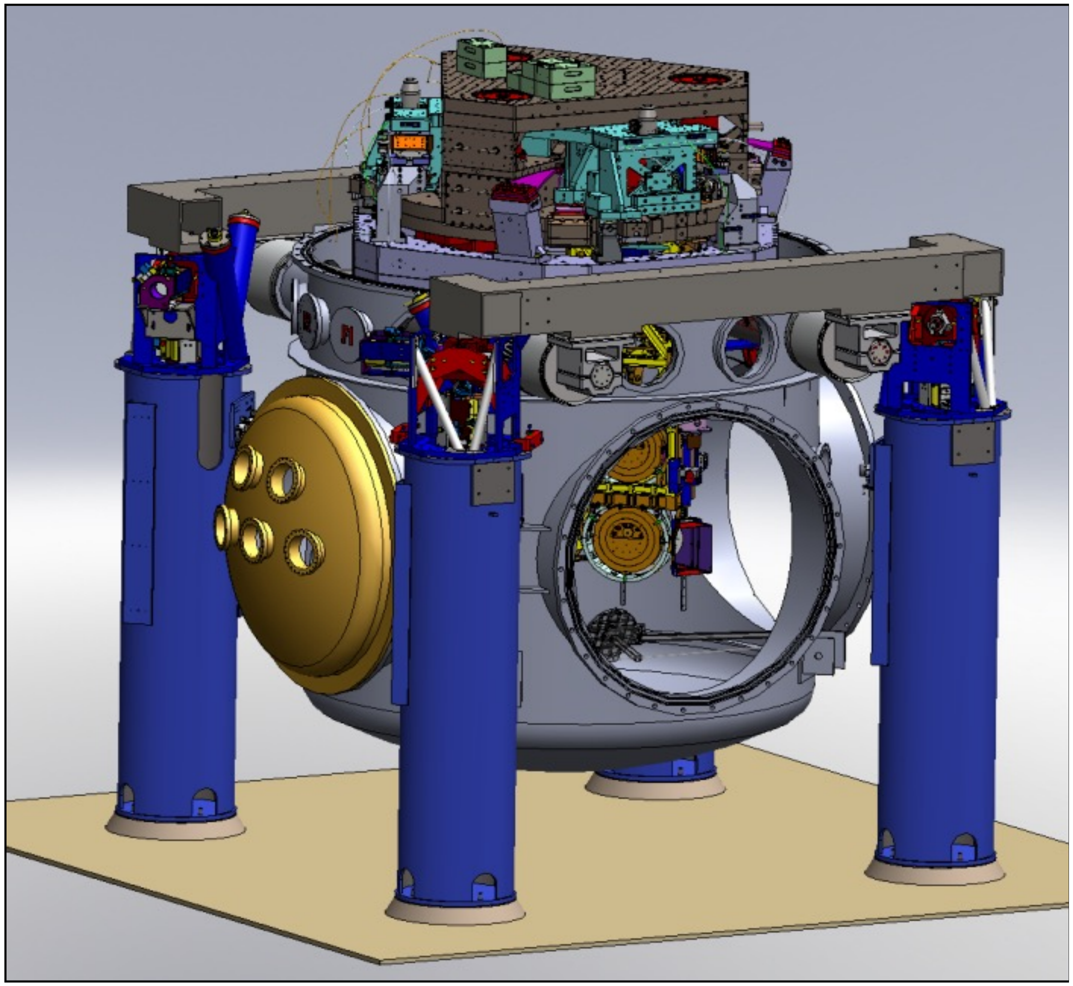
- **Seismic noise** – must prevent masking of GWs, enable practical control systems
- Not ‘fundamental physics’, but ‘fundamental to success’

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



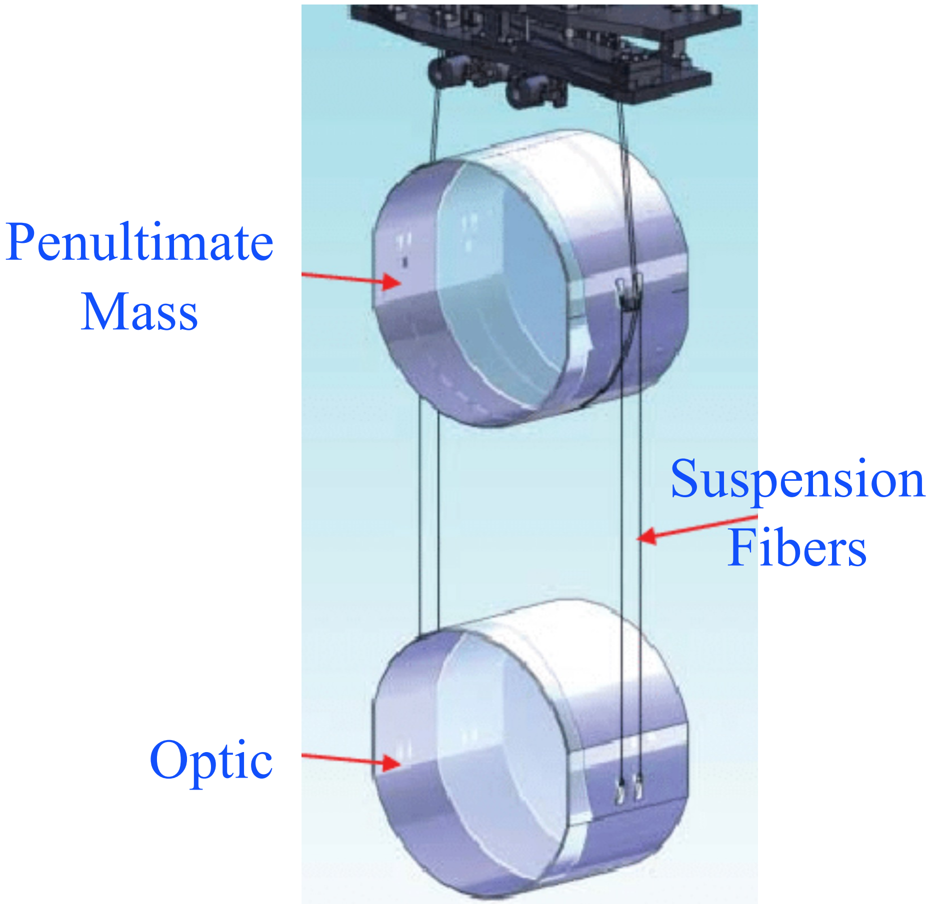
Active and passive seismic isolation



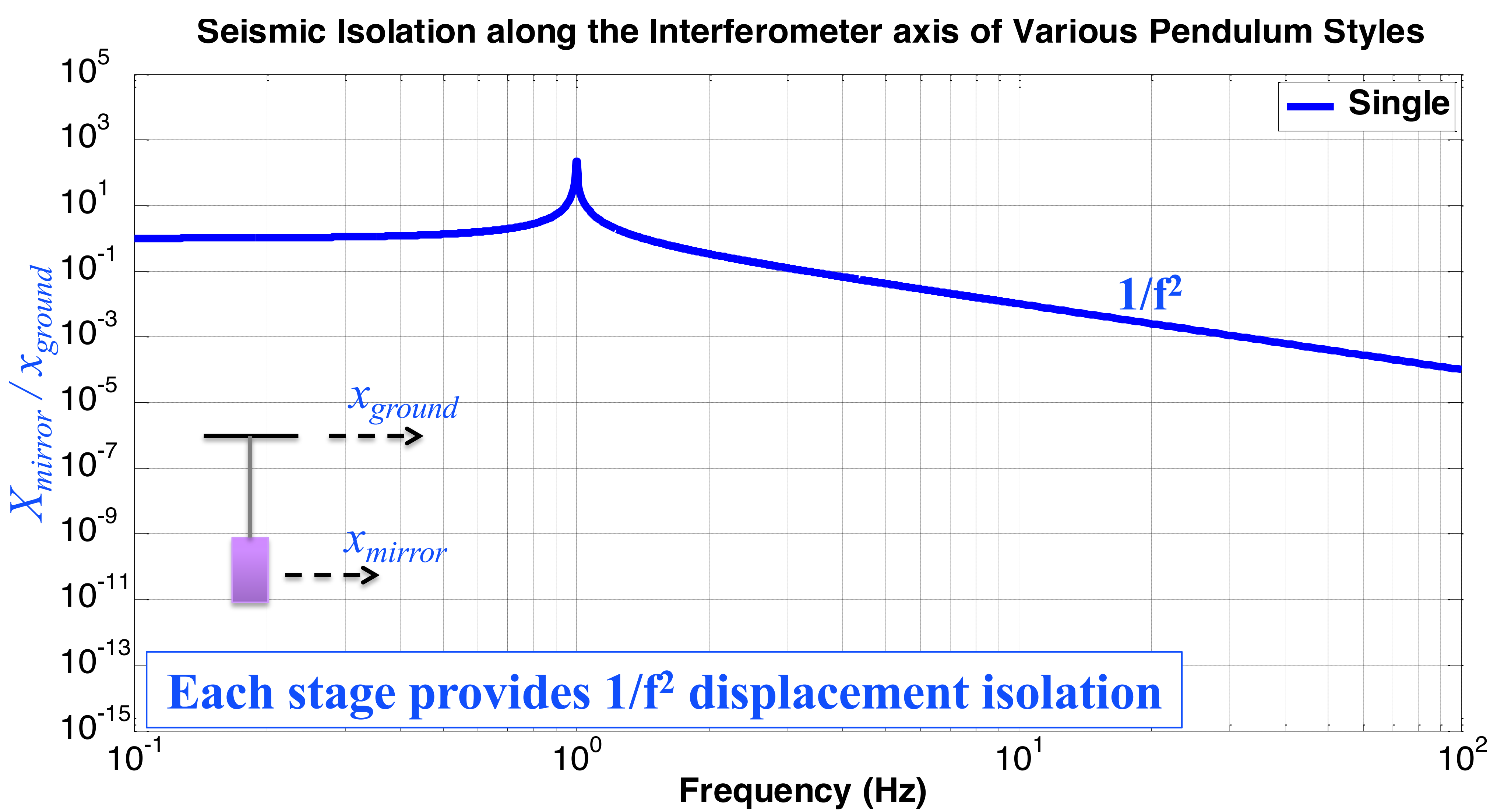


Basic Building Blocks: Pendulums

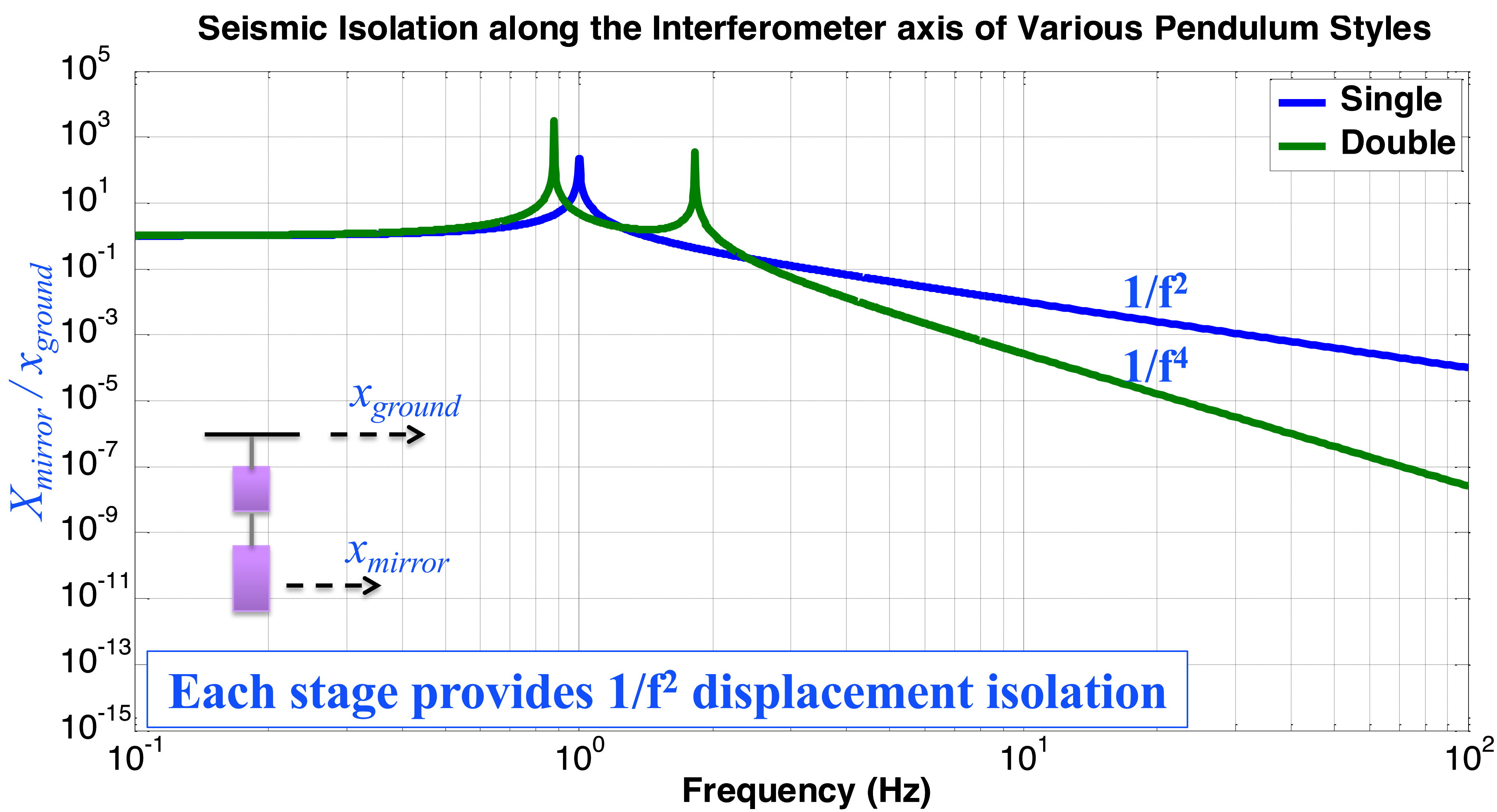
- Pendulum suspensions for optics which serve as test masses
- Need test masses to be 'free' in along the relevant measurement axis
- Ground-based detectors operate in Earth's gravitational field
- Hang optics like a clock pendulum; above the resonant frequency, mirror is 'free'
- Inertia of the mass 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'



Multi-stage Isolation Performance



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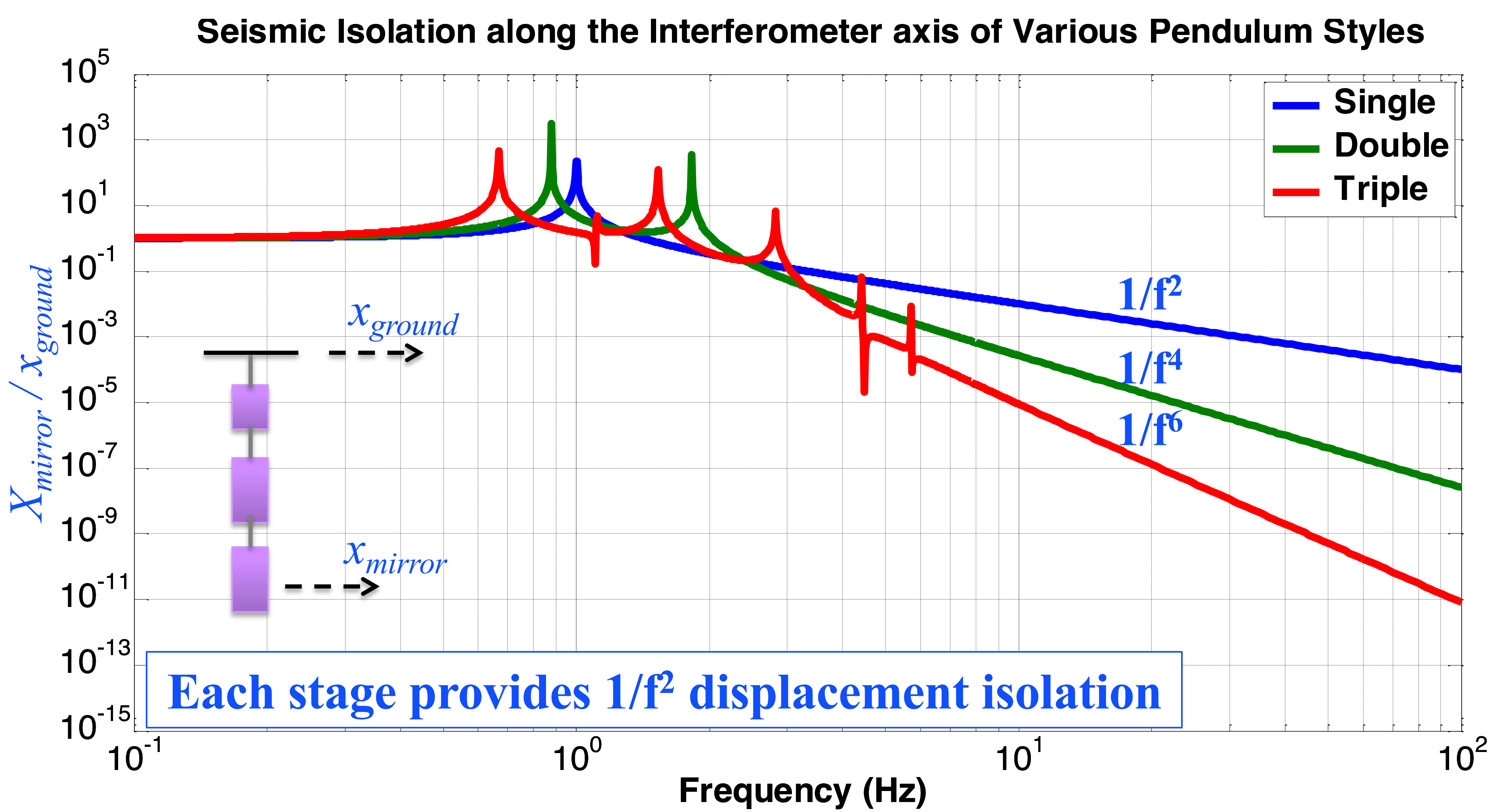

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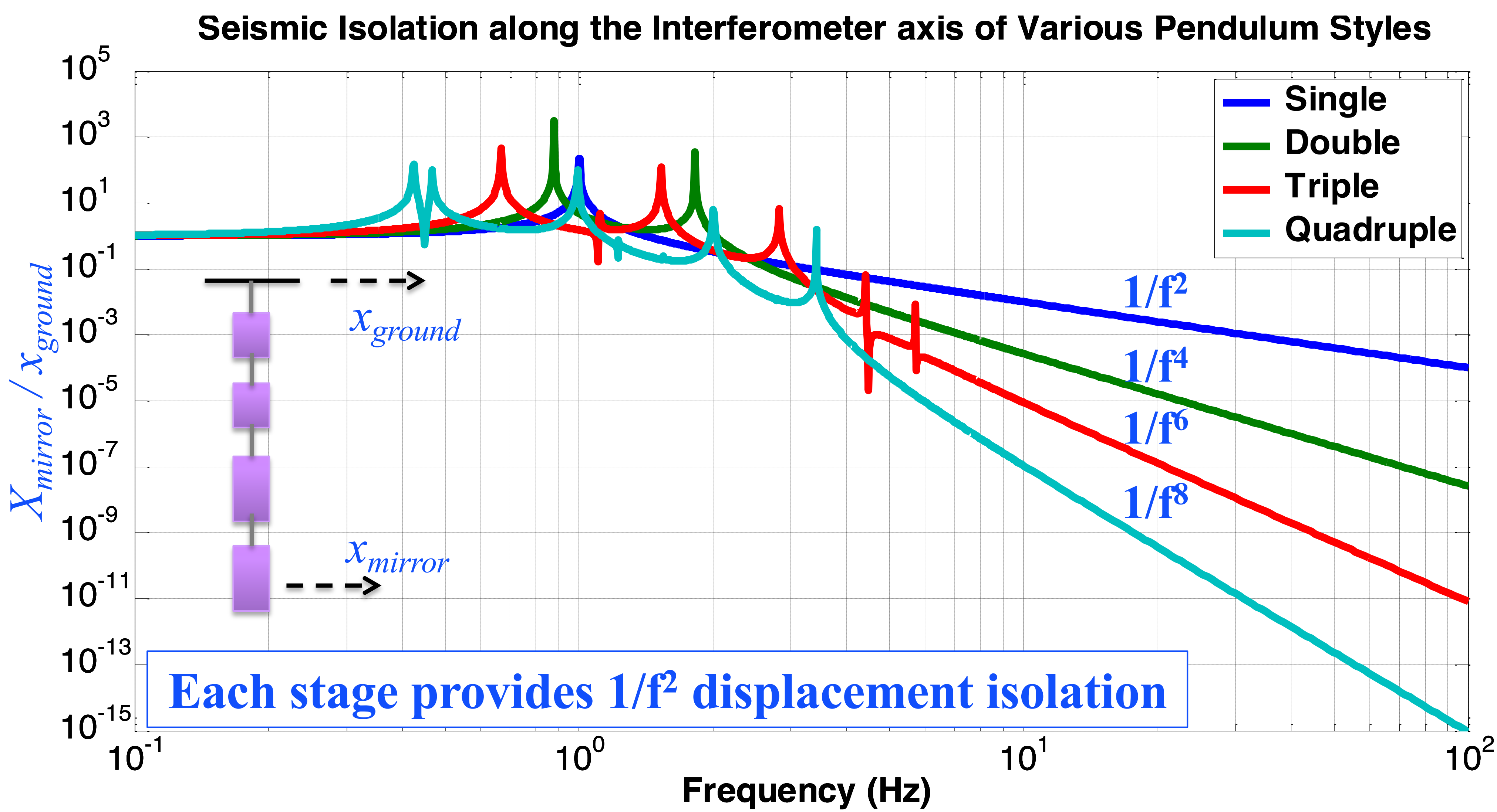
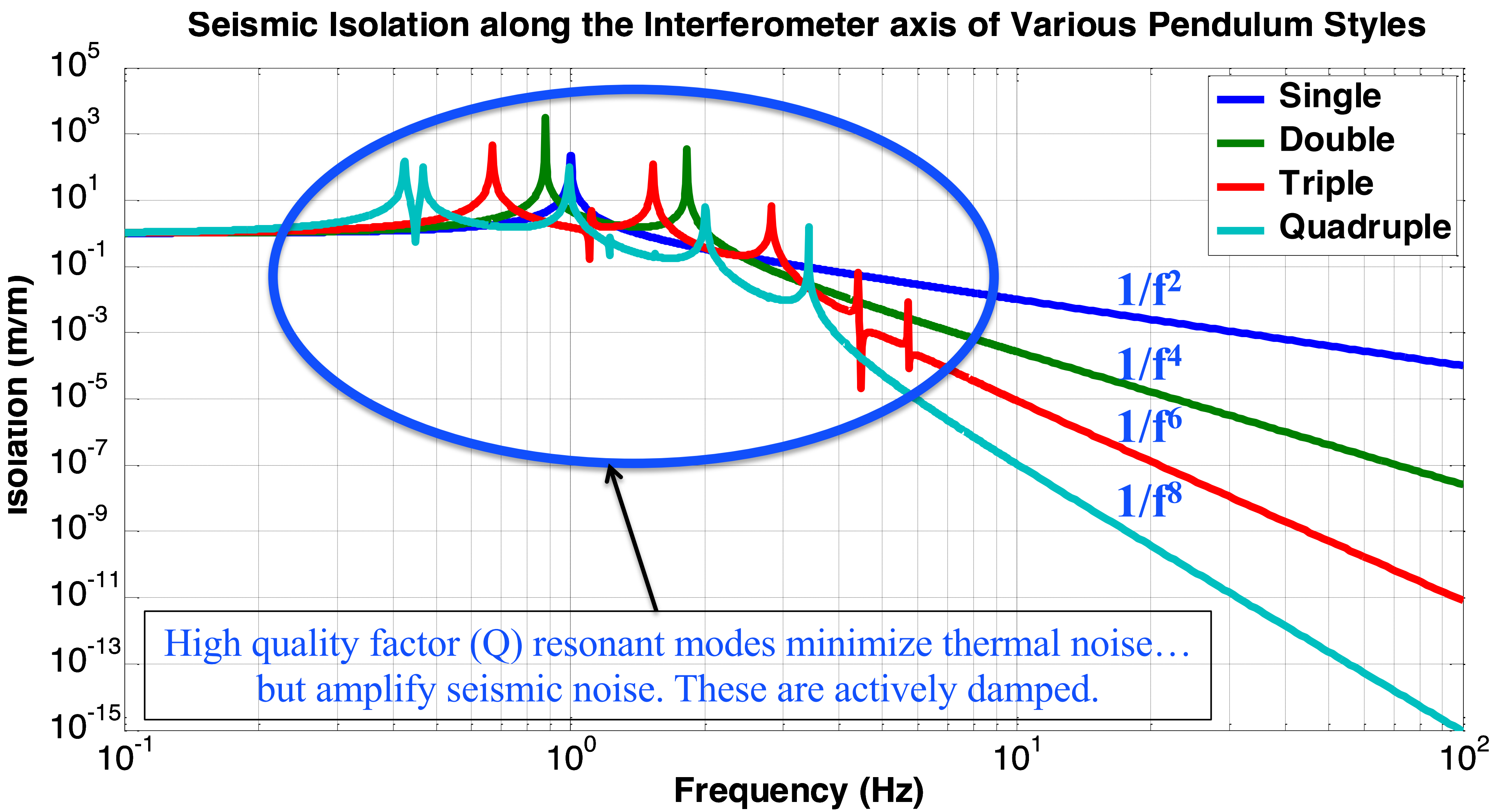


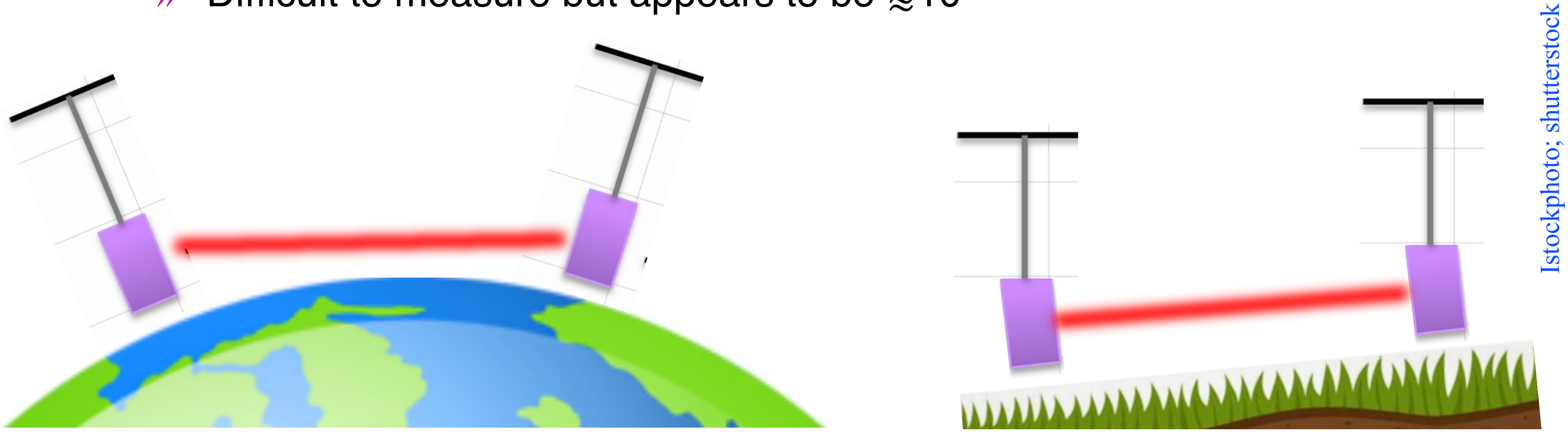
Brett Shapiro

Multi-stage Isolation Performance



Vertical Degree-of-Freedom

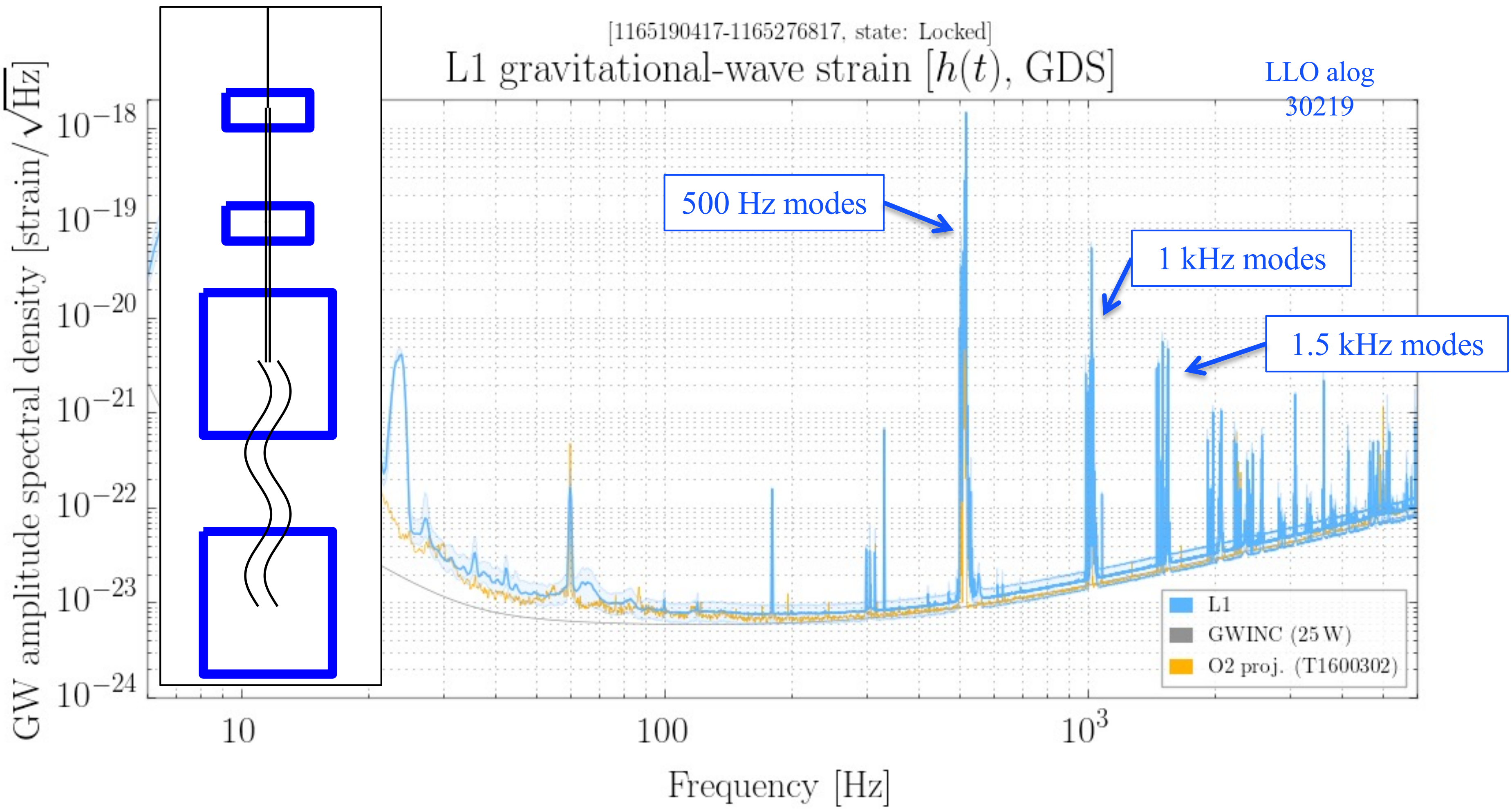
- Projection of 'vertical' motion along the optical axis if mirror is not normal to the laser beam
  - » → requirement on 'levelness' of the Observatory site
    - – Typ. 3-4 x 10^{-4} radians
  - » → coupling growing linearly with length of detector
    - – (but GW sensitivity also grows linearly; not a worry!)
- Coupling due to imperfections in suspension design
  - » E.g., unbalanced suspension fiber diameters, actuators which have an internal cross coupling, etc.
  - » Difficult to measure but appears to be $\lessapprox 10^{-3}$



LIGO Facility
Beam Tube Alignment

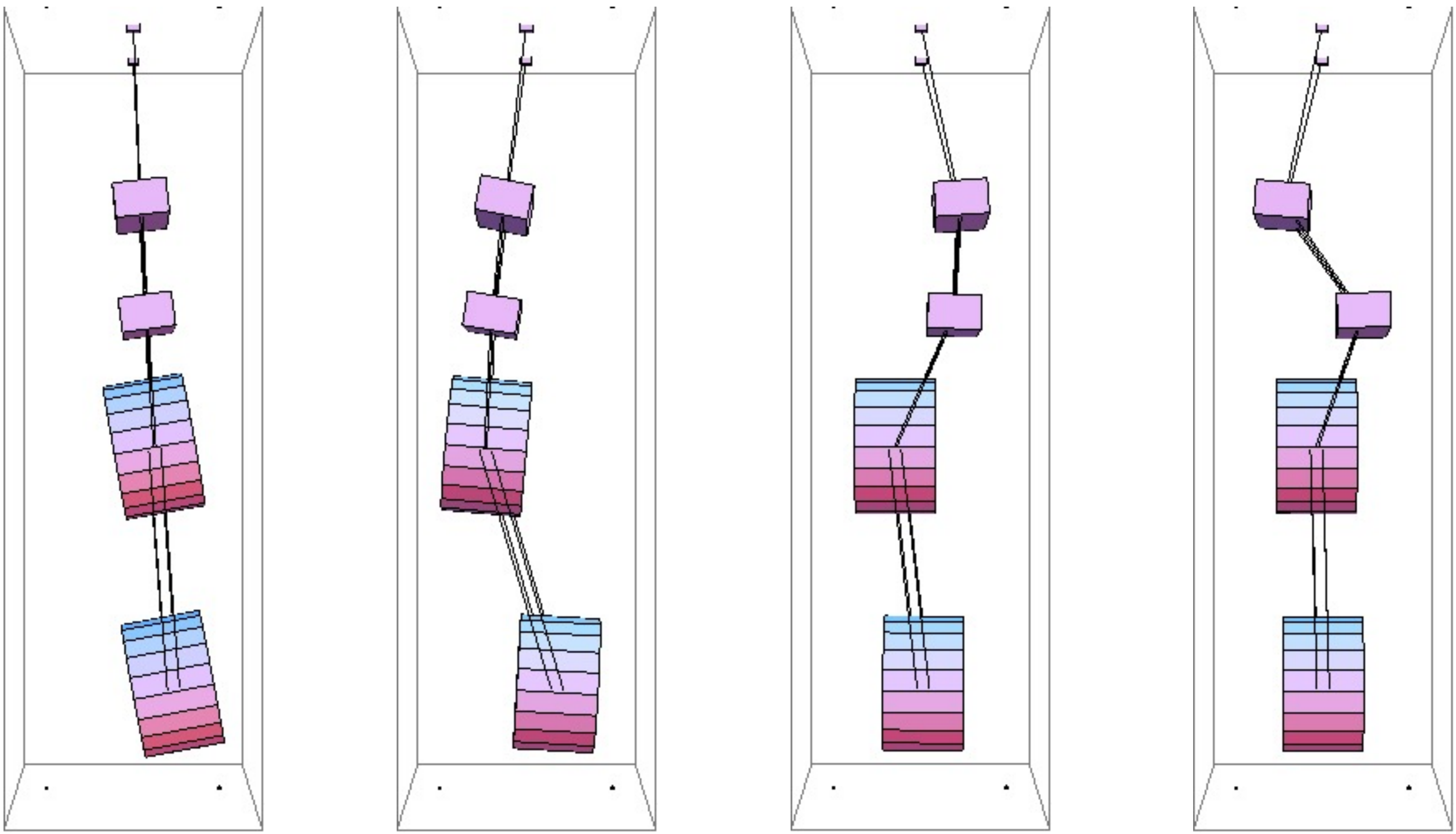
- Requirement to maintain a 1m clear aperture through the 4 km long arms
- A straight line in space varies in ellipsoidal height by 1.25 m over a 4km baseline
- A maximum deviation from straightness in inertial space of 5 mm rms
- Average angle with respect to local gravity of $3x10^{-4}$ radians

Suspension violin modes



Very high Q (~1 billion) silica fiber violin modes at 500 Hz and higher harmonics, excited by thermal noise

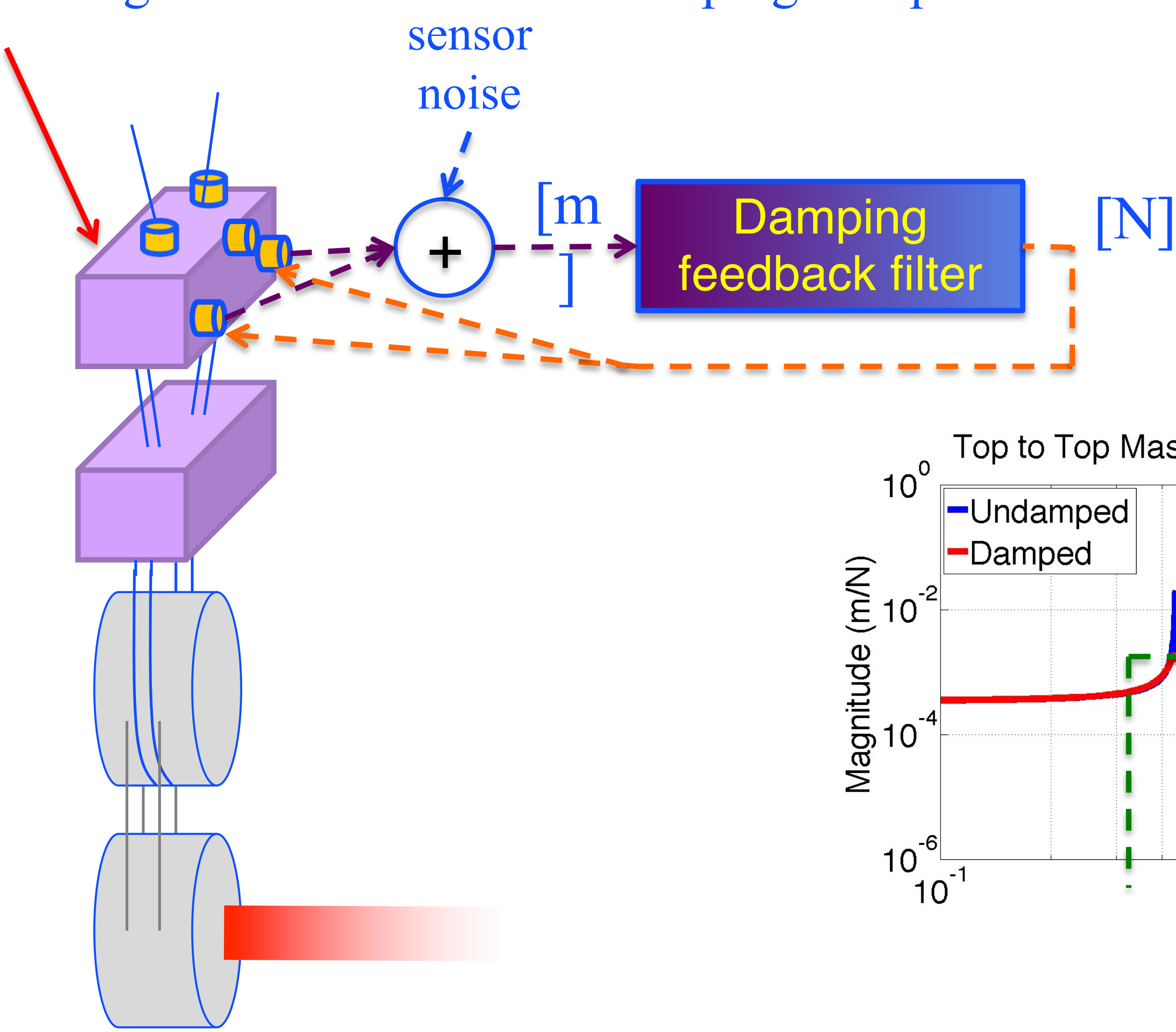
Some of the many modes of a quadruple pendulum

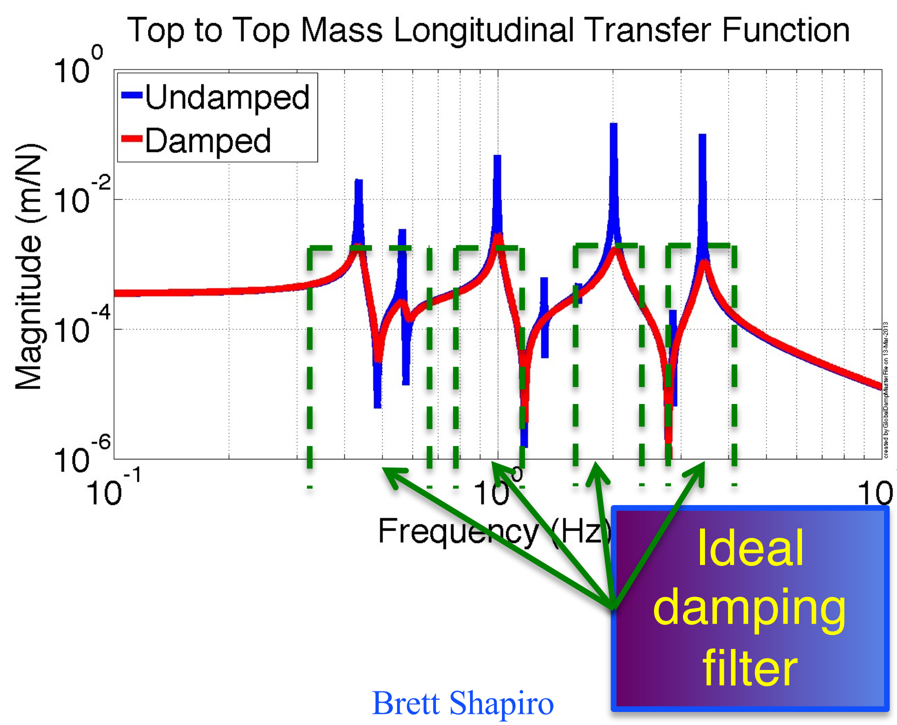


0.43 Hz **1.0 Hz** **2.0 Hz** **3.4 Hz**

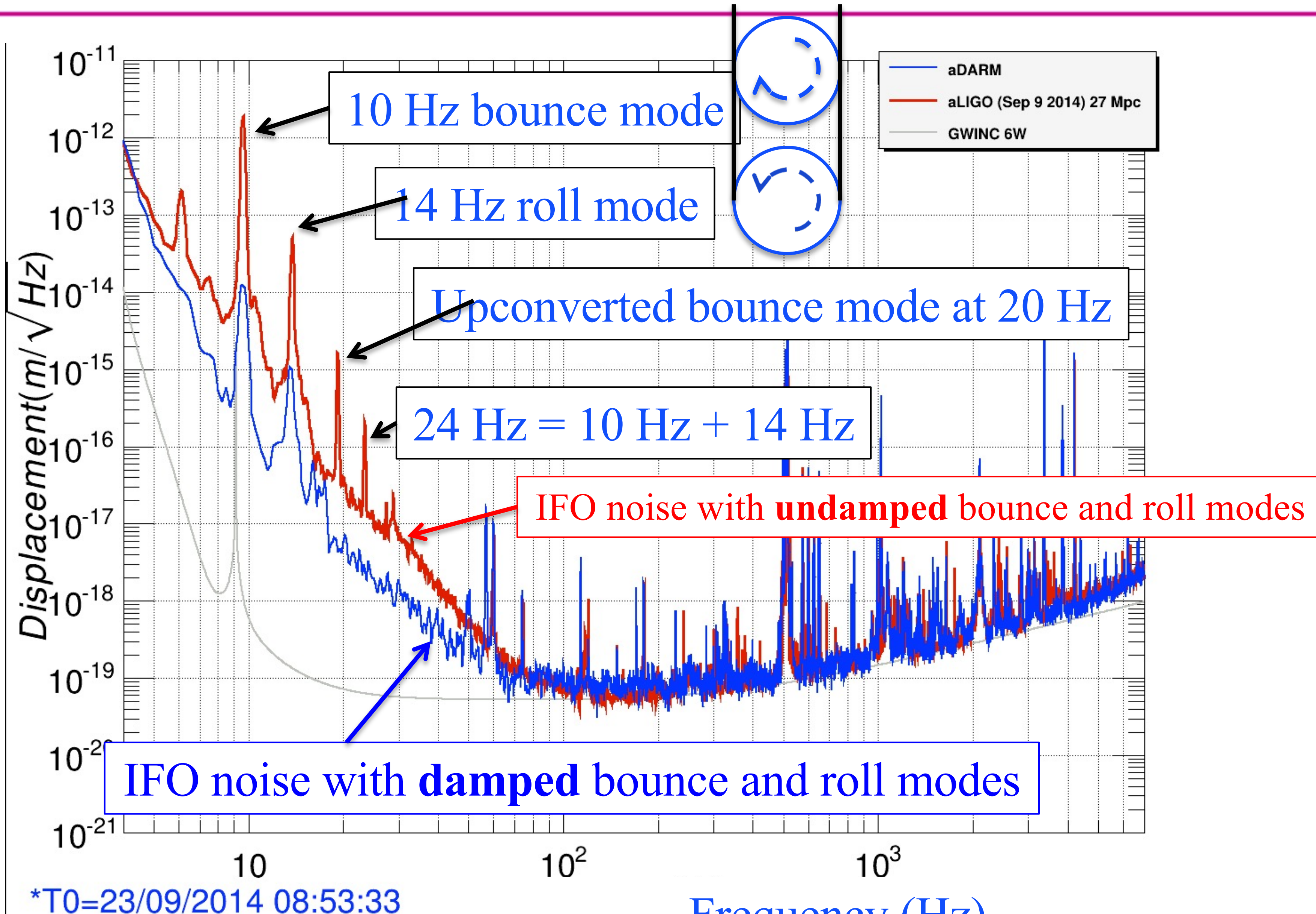
Top Mass Damping

High sensor noise limits damping to top mass

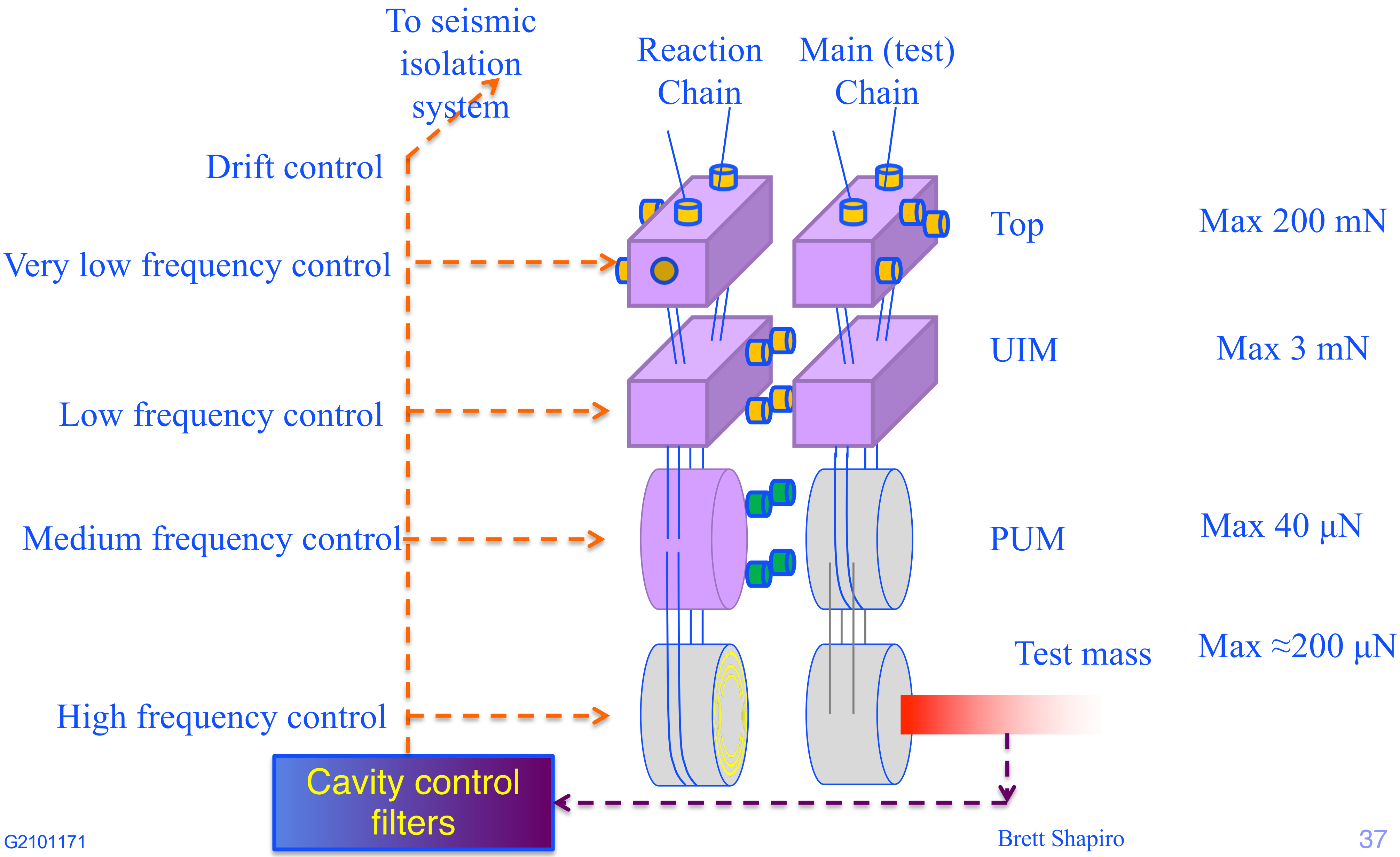




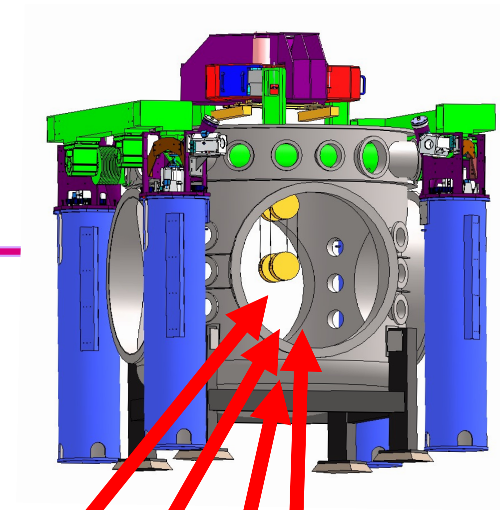
Other DOF;
Nonlinear Upconversion



Cavity Length Control

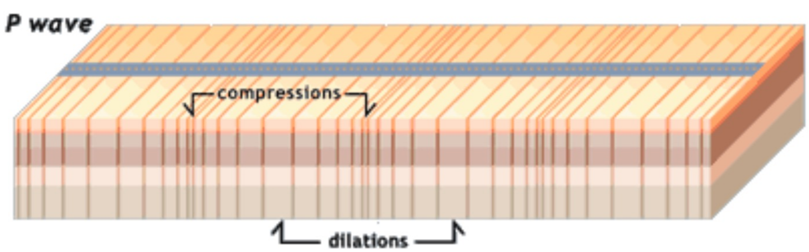


Measuring $\Delta L = 4 \times 10^{-18}$ m
External Forces on test mass

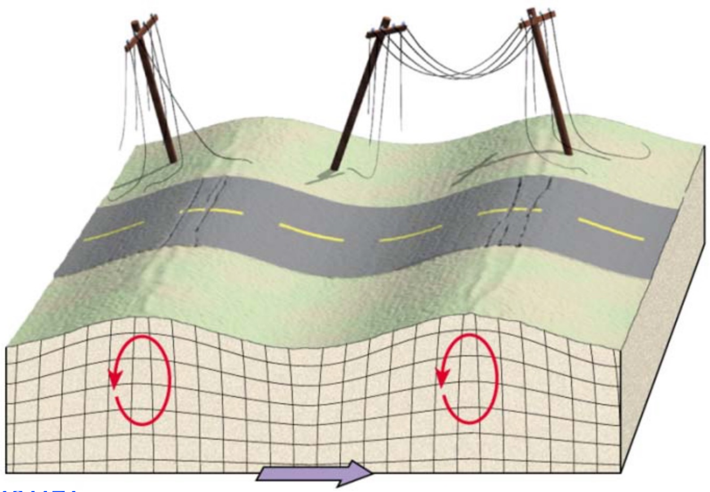


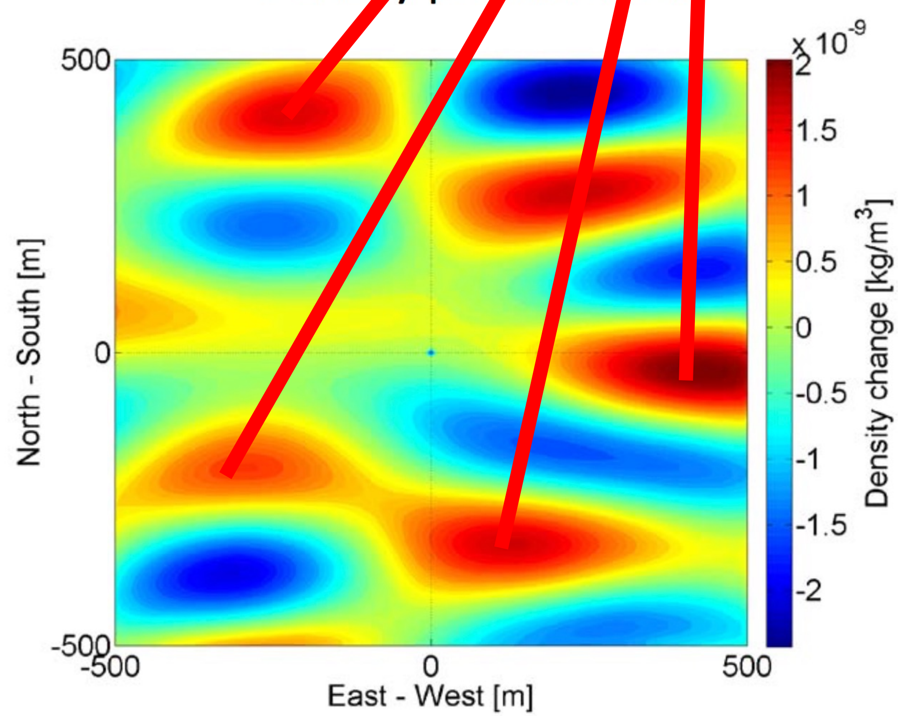
- Ultimate limit on the lowest frequency detectors on- or under-ground:
- **Newtownian background** – wandering net gravity vector; Forbiddingly large for ~3Hz and lower

Body waves



Rayleigh waves

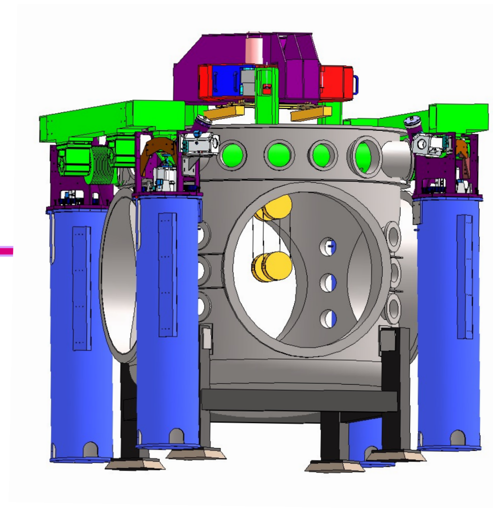




Density perturbations cause gravity perturbations.

Images: J. Harms

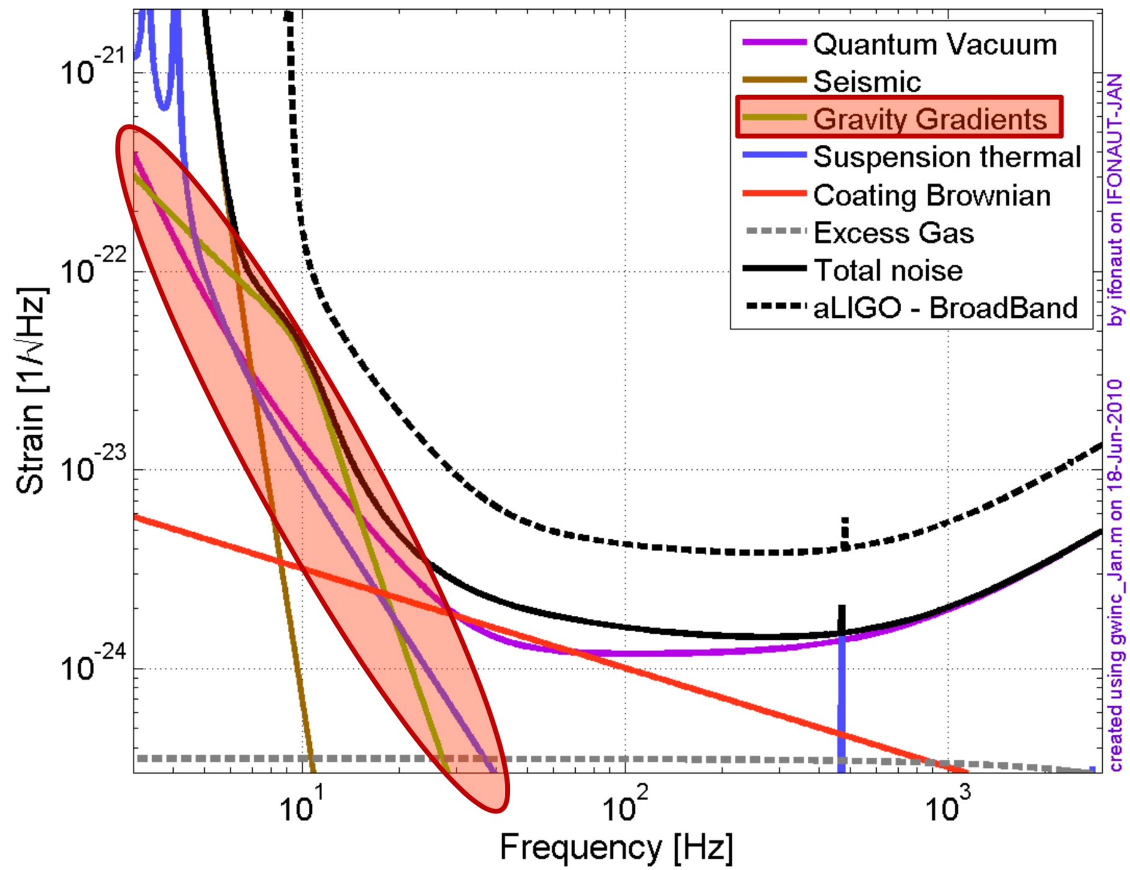
Measuring $\Delta L = 4\times10^{-18}$ m
External Forces on test mass



- 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.



Images: J. Harms

Mid-path summary

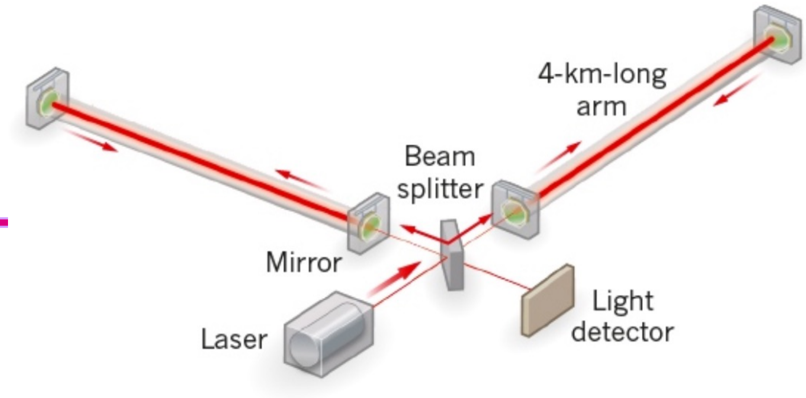
- Interferometry comparing the light travel time along (more or less) orthogonal arms can measure a passing gravitational wave
- The limits to sensitivity come from
  - Undesired motions of the interferometer mirrors
  - Limitations in our ability to measure the positions of the mirrors
- Thermal noise is one cause of undesired motions, managed through use of low-mechanical-loss materials and concentrating motion in a narrow band
- External motion 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

- …Tomorrow we continue with sensing limitations, some general considerations, and a tour of the facilities

Interferometry

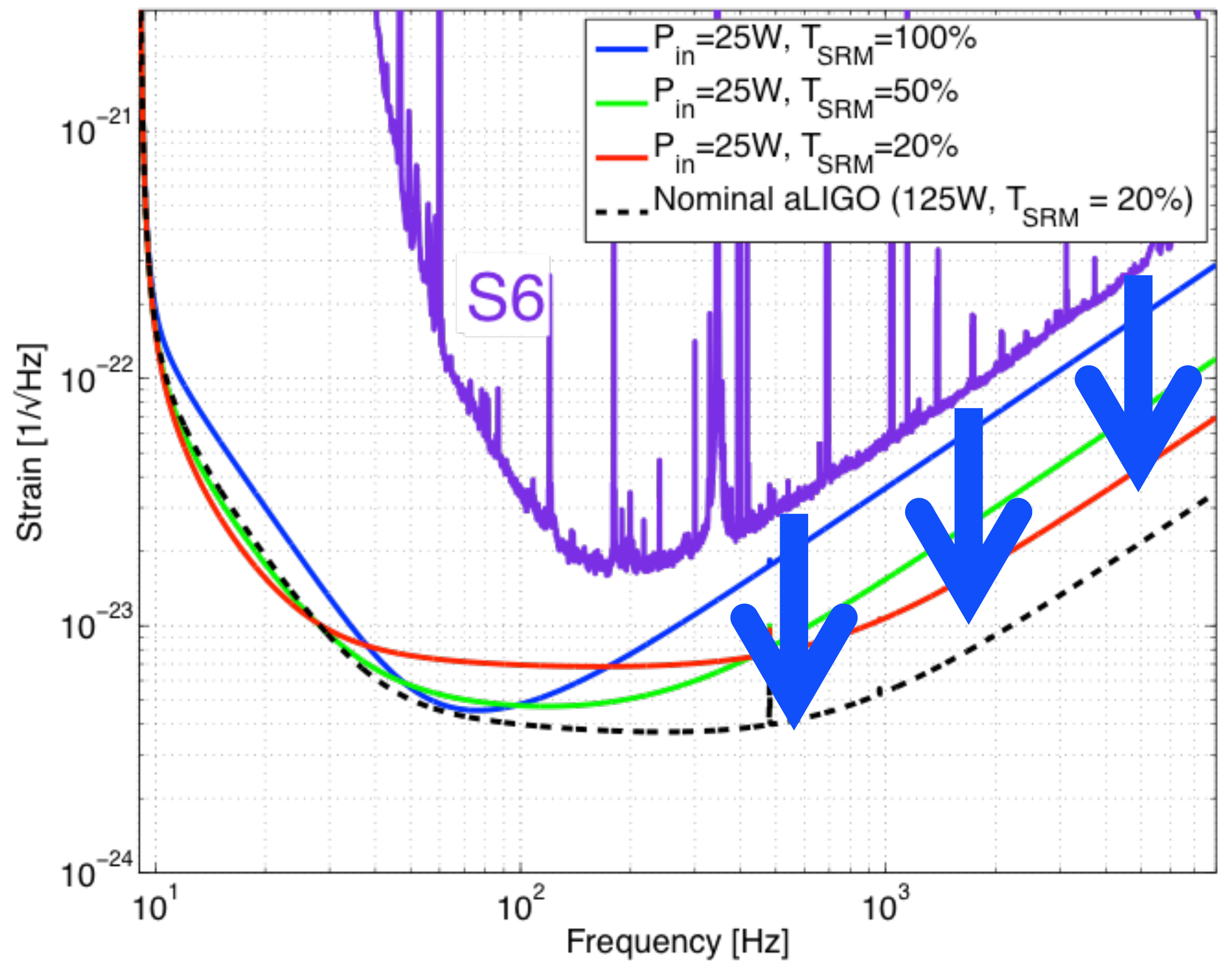
- Quantum measurement effects present both limits to sensitivity **and** means to improve the sensitivity
- First, increase the light power to reduce shot noise
  - » High power laser
  - » Low loss, high-precision optical components
  - » Optical topologies to increase circulating light power
  - » Optical topologies to distribute light power optimally
  - » …until radiation pressure starts to dominate
  - » …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

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

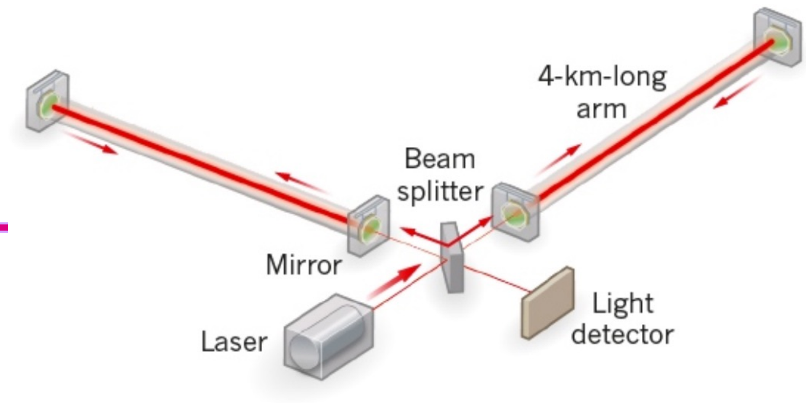


- **Shot noise** – ability to resolve a fringe shift due to a GW (Poisson counting statistics)
- *Zum gegenwärtigen Stand des Strahlungsproblems*, A. Einstein, 1909
- Fringe Resolution at high frequencies improves as as (laser power)$^{1/2}$

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



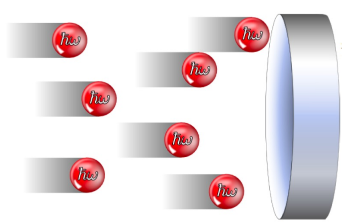
Measuring $\Delta L = 4\times10^{-18}$ m
Readout



- Shot noise – ability to resolve a fringe shift due to a GW (counting statistics)

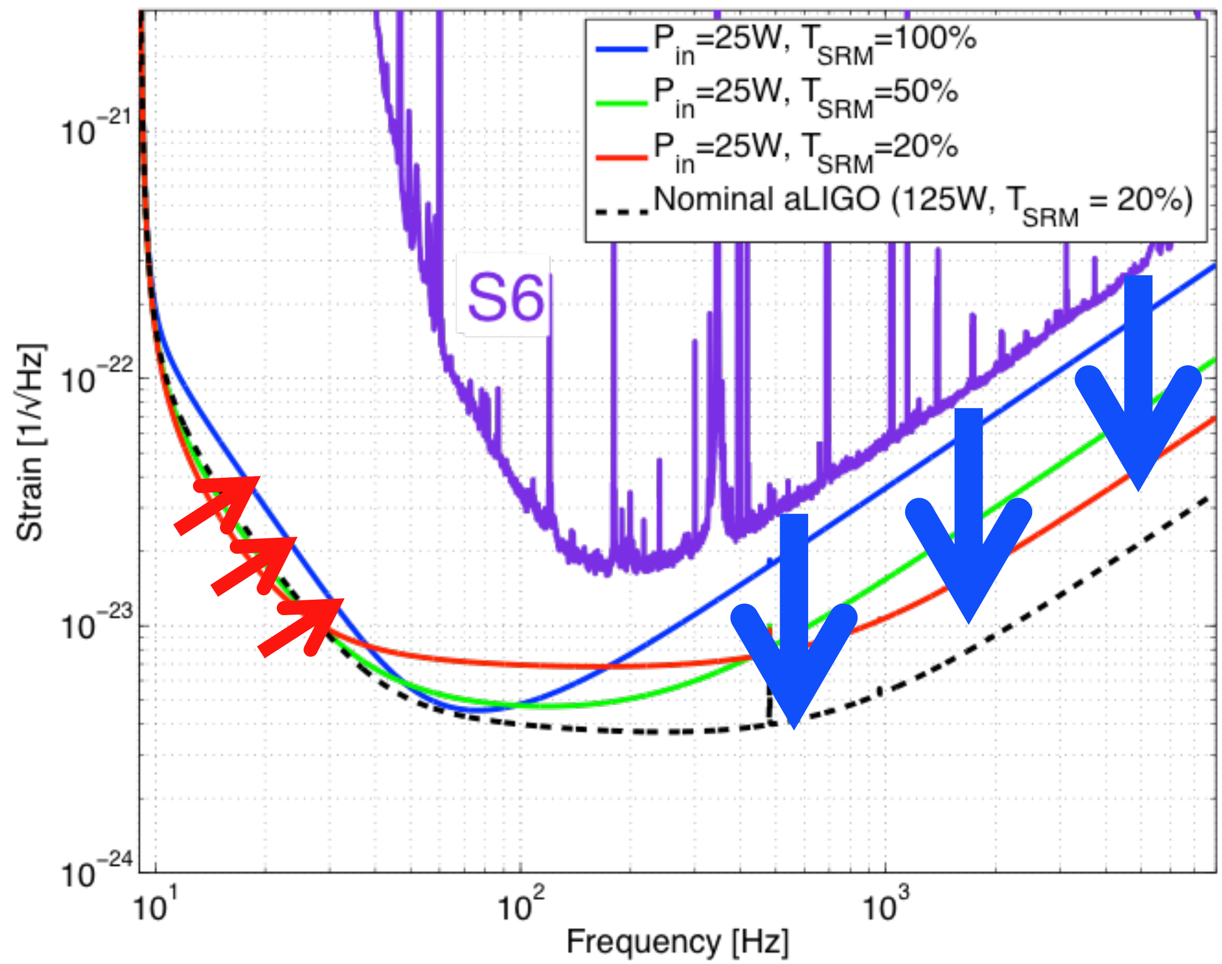
$$h_{\rm sn}(f) = \frac{1}{L}\sqrt{\frac{\hbar c \lambda}{2\pi P}}$$

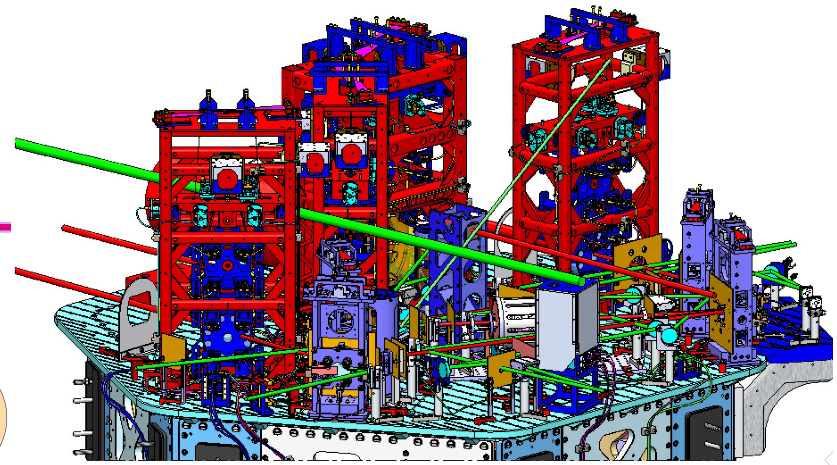
- **Radiation Pressure noise** – buffeting of test mass by photons increases low-frequency noise – use heavy test masses!

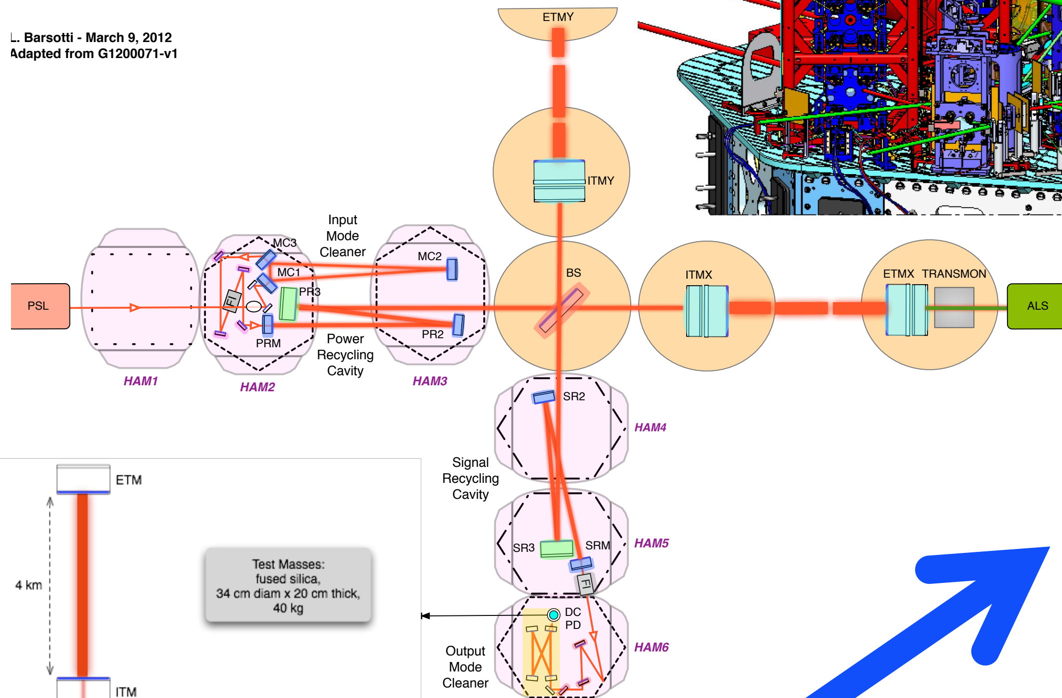


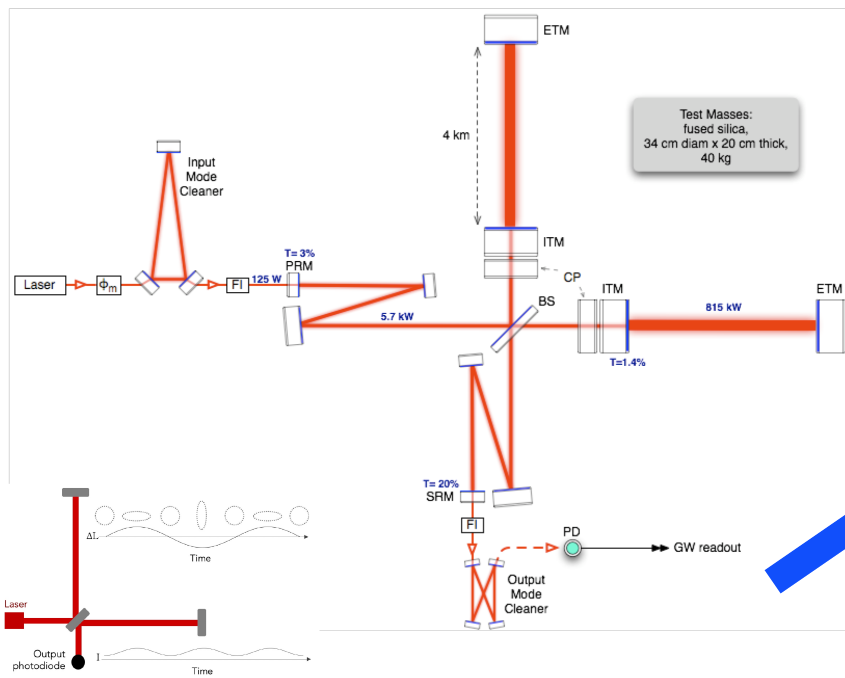
$$h_{\rm rp}(f) = \frac{1}{m f^2 L}\sqrt{\frac{\hbar P}{2\pi^3 c \lambda}}$$

- **'Standard Quantum Limit'**







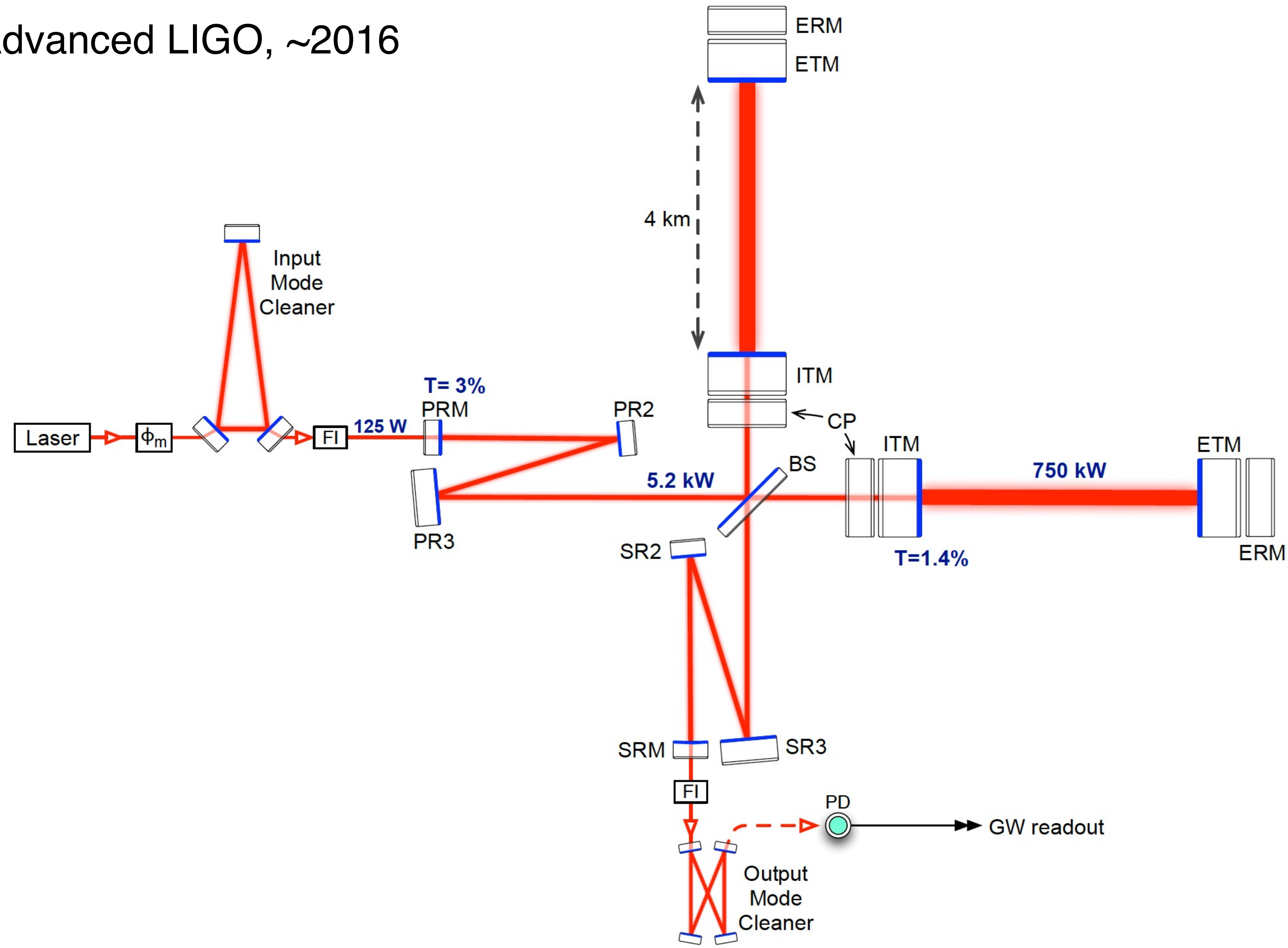


Reality axis

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

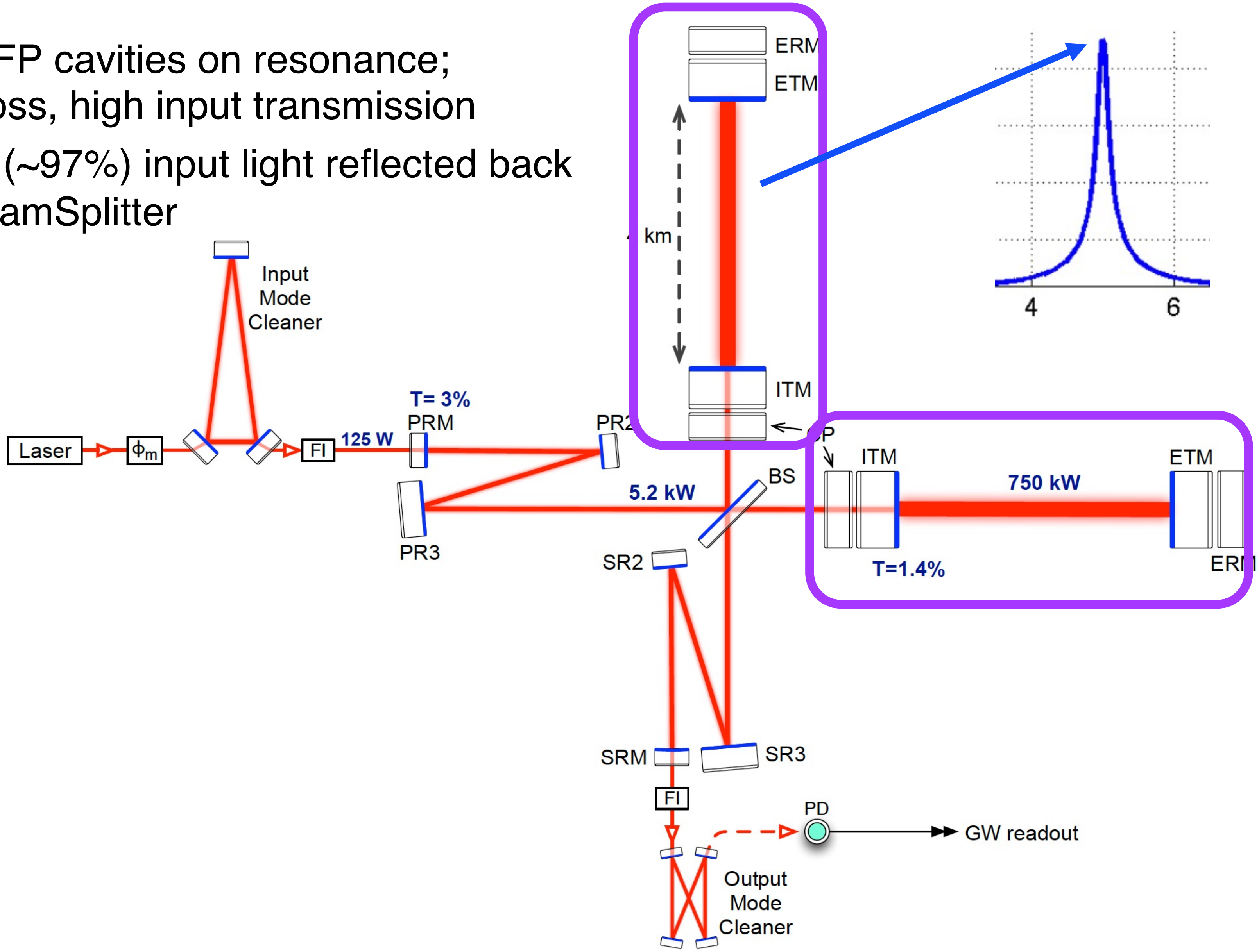
Power and Signal Recycling

- Advanced LIGO, ~2016



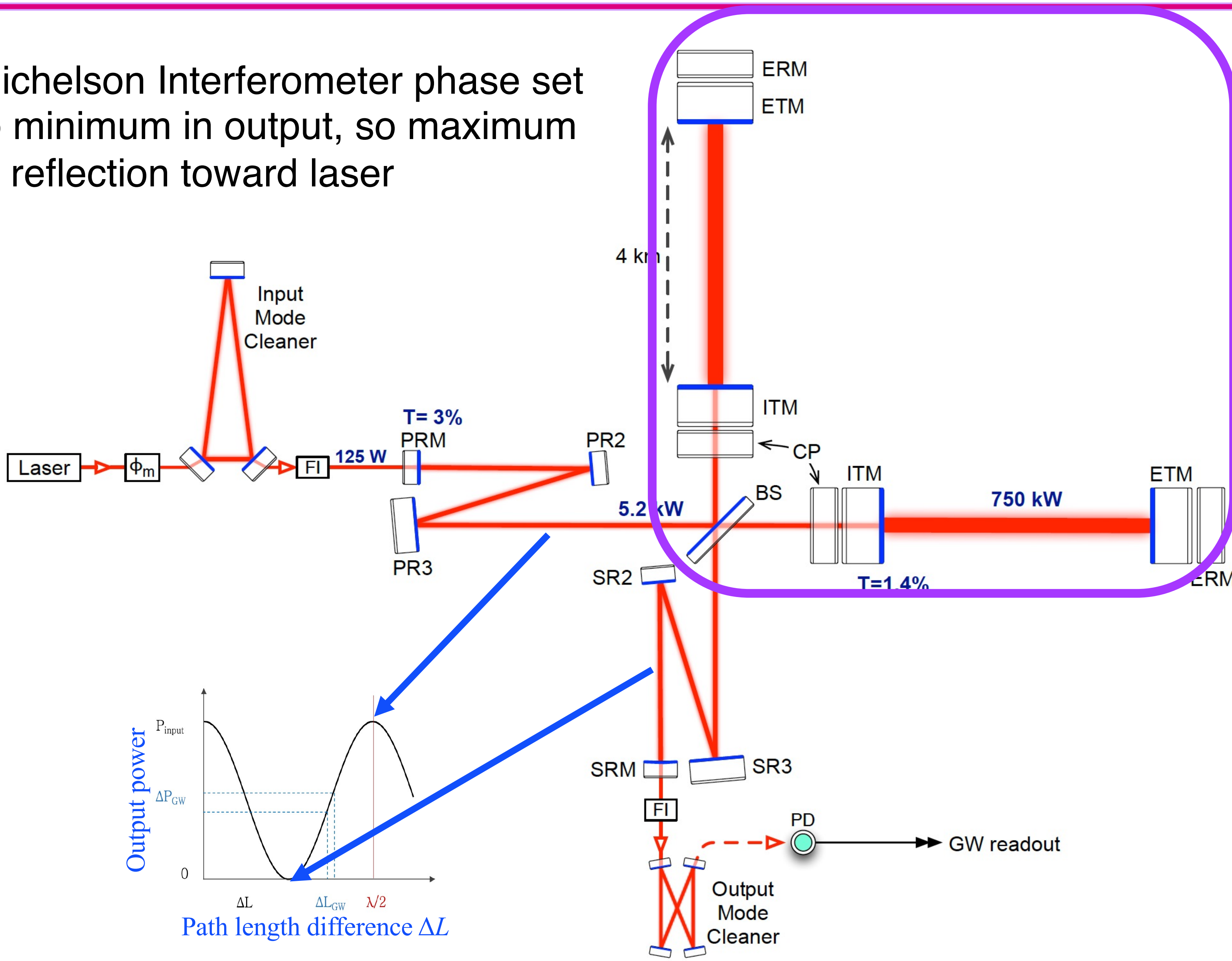
Power and Signal Recycling

- 4km FP cavities on resonance; low loss, high input transmission
- Most (~97%) input light reflected back to BeamSplitter



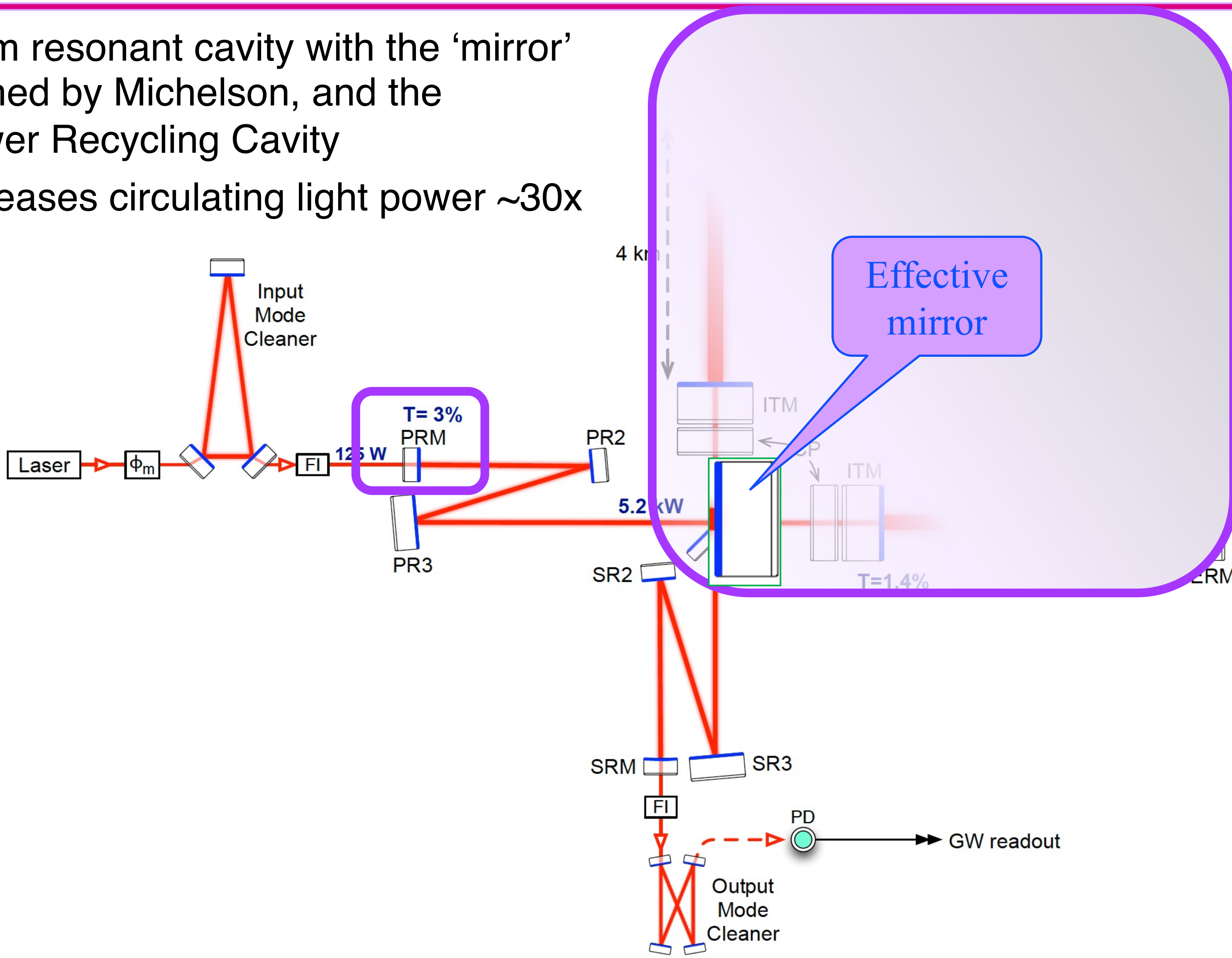
Power and Signal Recycling

- Michelson Interferometer phase set to minimum in output, so maximum in reflection toward laser

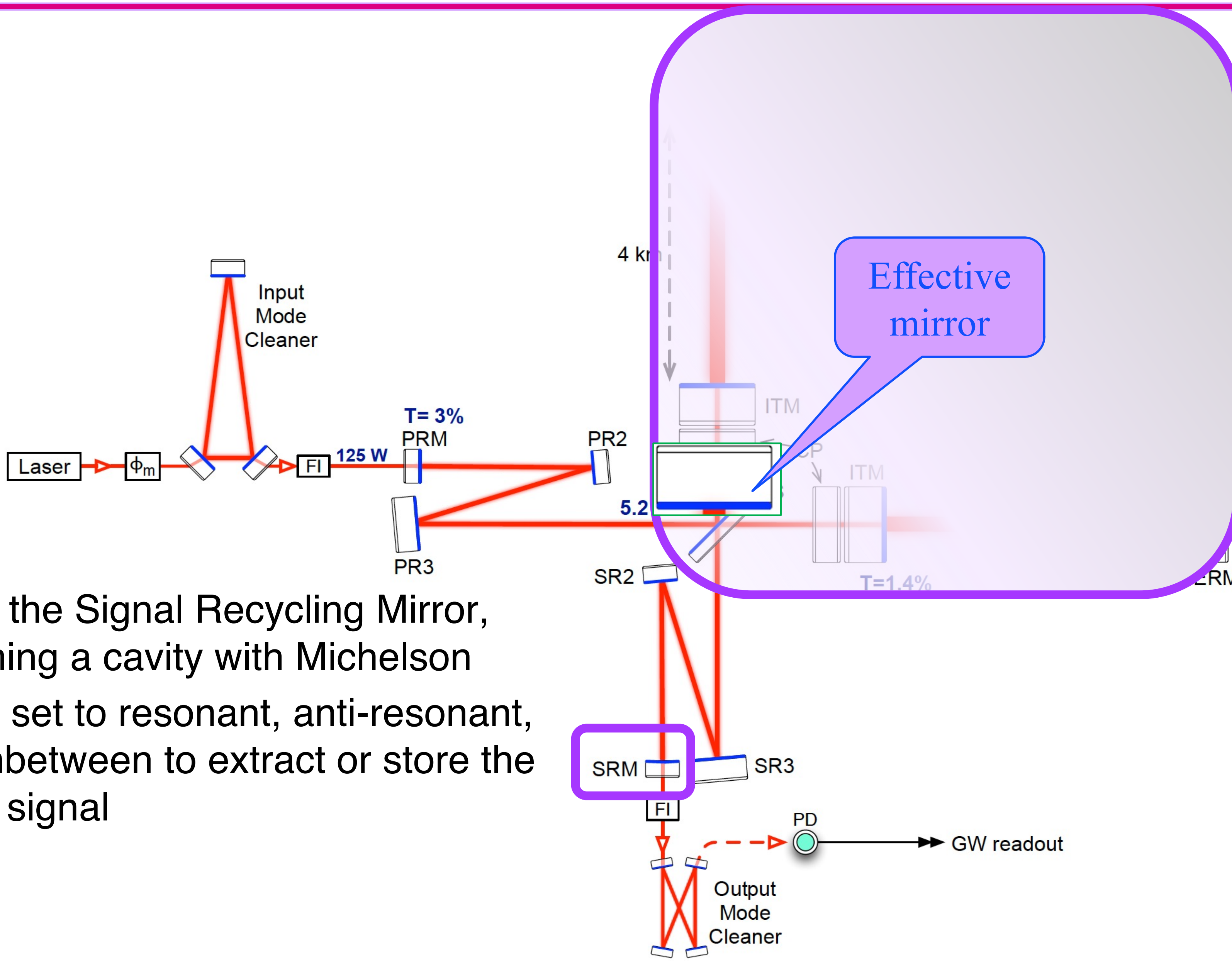


Power and Signal Recycling

- Form resonant cavity with the 'mirror' formed by Michelson, and the Power Recycling Cavity
- Increases circulating light power ~30x



Power and Signal Recycling



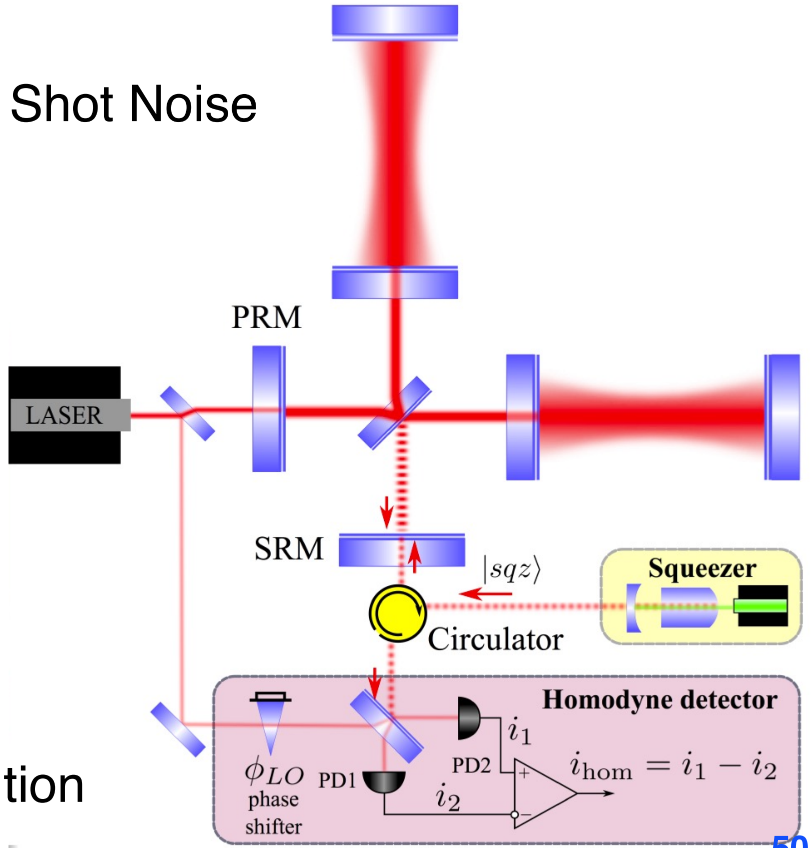
- Add the Signal Recycling Mirror, forming a cavity with Michelson
- Can set to resonant, anti-resonant, or inbetween to extract or store the GW signal

Squeezed light to reduce quantum noise

- Heisenberg Uncertainty Principle of QM dictates that precise values of phase, and amplitude, of light cannot be known at the same time:

$$\Delta \hat{X}_{\text{phase}} \Delta \hat{Y}_{\text{amp}} \geqslant \hbar/2$$

- We can choose however to e.g., know the amplitude less well and look more closely at the phase
- This corresponds to reducing the high-frequency Shot Noise in our interferometer noise budget
  - » BUT increasing the low-frequency Radiation Pressure noise
- This is frequency **in**dependent squeezing

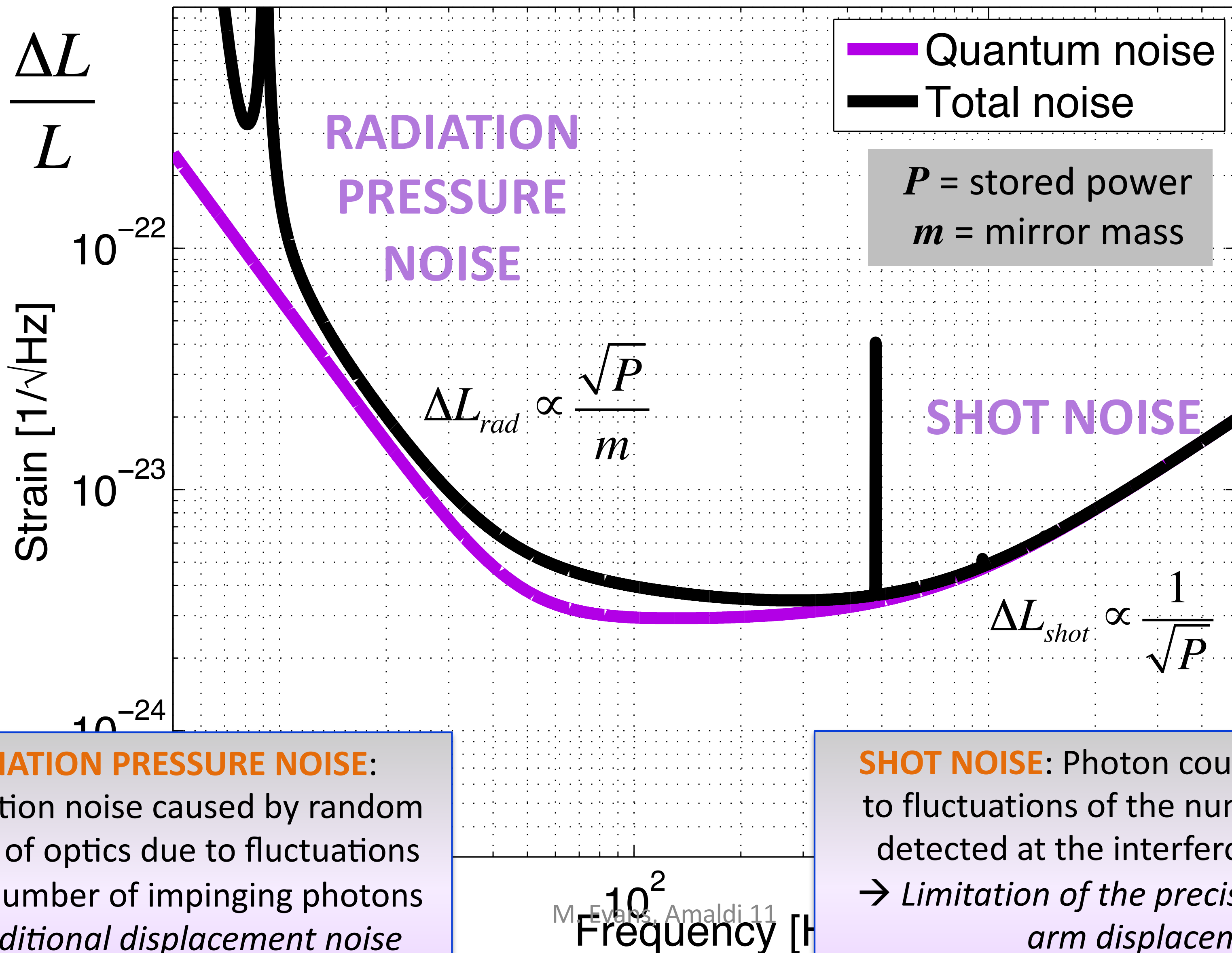


- Squeezing is made by creating pairs of photons using an optical parametric oscillator
- The pairs are quantum-mechanically entangled and have correlated arrival times at the detector
- This reduces the randomness of the time distribution

W. Unruh, PRD 19, 2888 (1979); S.L. Danilishin

Quantum shot noise limits the high frequency sensitivity

$$h = \frac{\Delta L}{L}$$

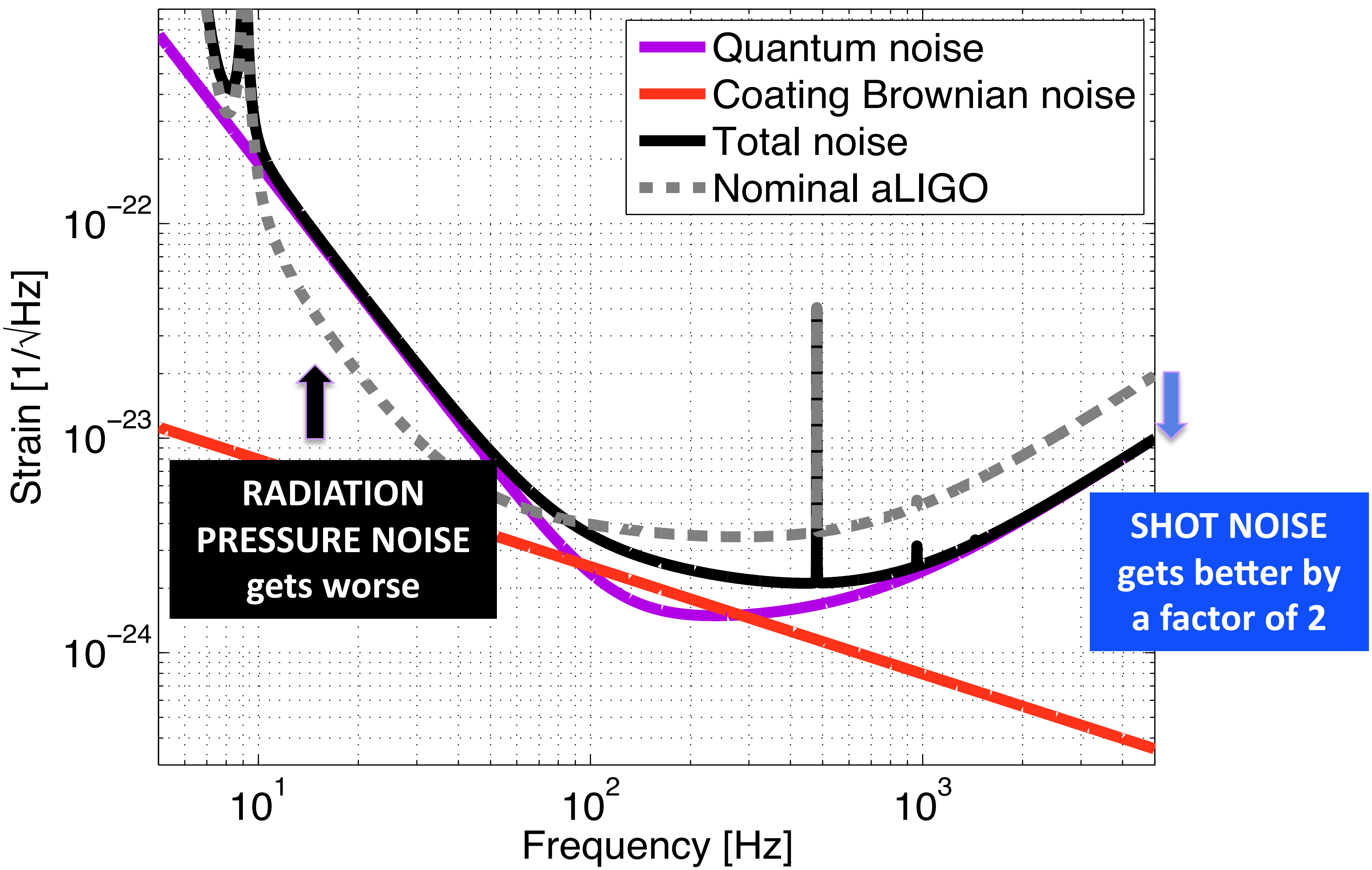


RADIATION PRESSURE NOISE: Back-action noise caused by random motion of optics due to fluctuations of the number of impinging photons
→ *Additional displacement noise*

SHOT NOISE: Photon counting noise due to fluctuations of the number of photon detected at the interferometer output
→ *Limitation of the precision to measure arm displacement*

M. Evans, Amaldi 11

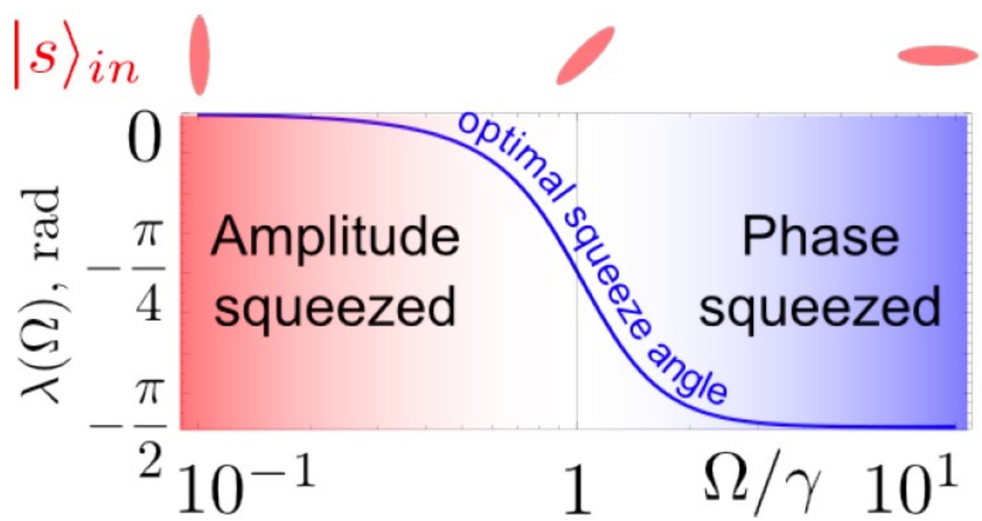
Frequency **In**dependent Squeezing

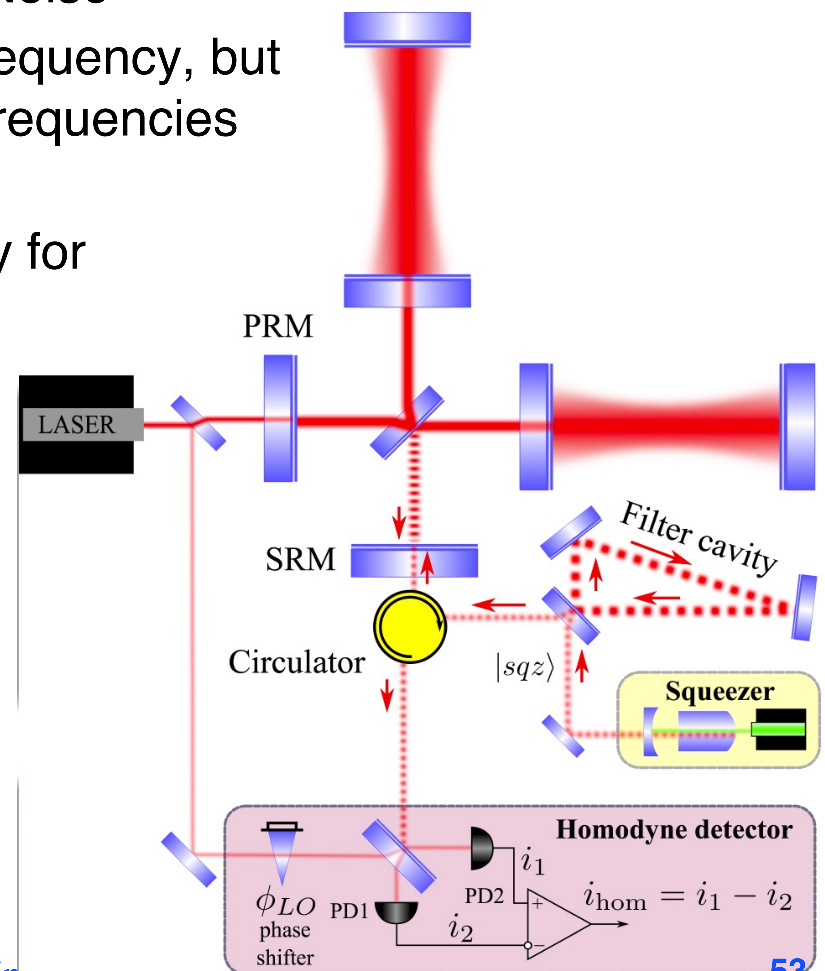


➔ High frequency improvement, no benefit in BNS-BNS range

Frequency Dependent Squeezing

- We can be more clever!
- We can adjust the phase of the squeezed light used
  - Pass through an 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
- Being implemented in Virgo and LIGO, probably for next observing run O5

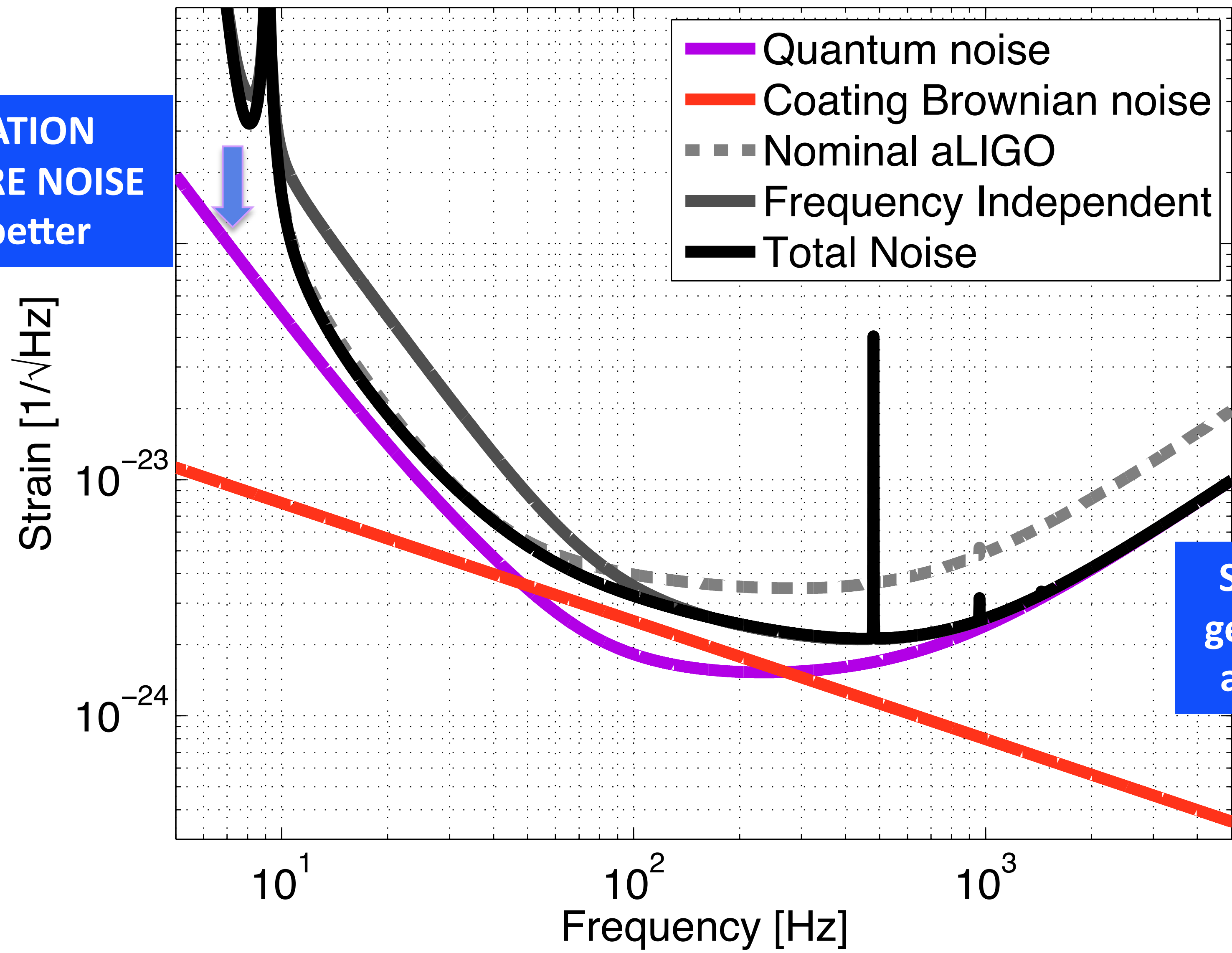




J. Kimble et al., PRD 65, 022002 (2001); S.L. Danilishin

Frequency Dependent Squeezing

RADIATION PRESSURE NOISE gets better



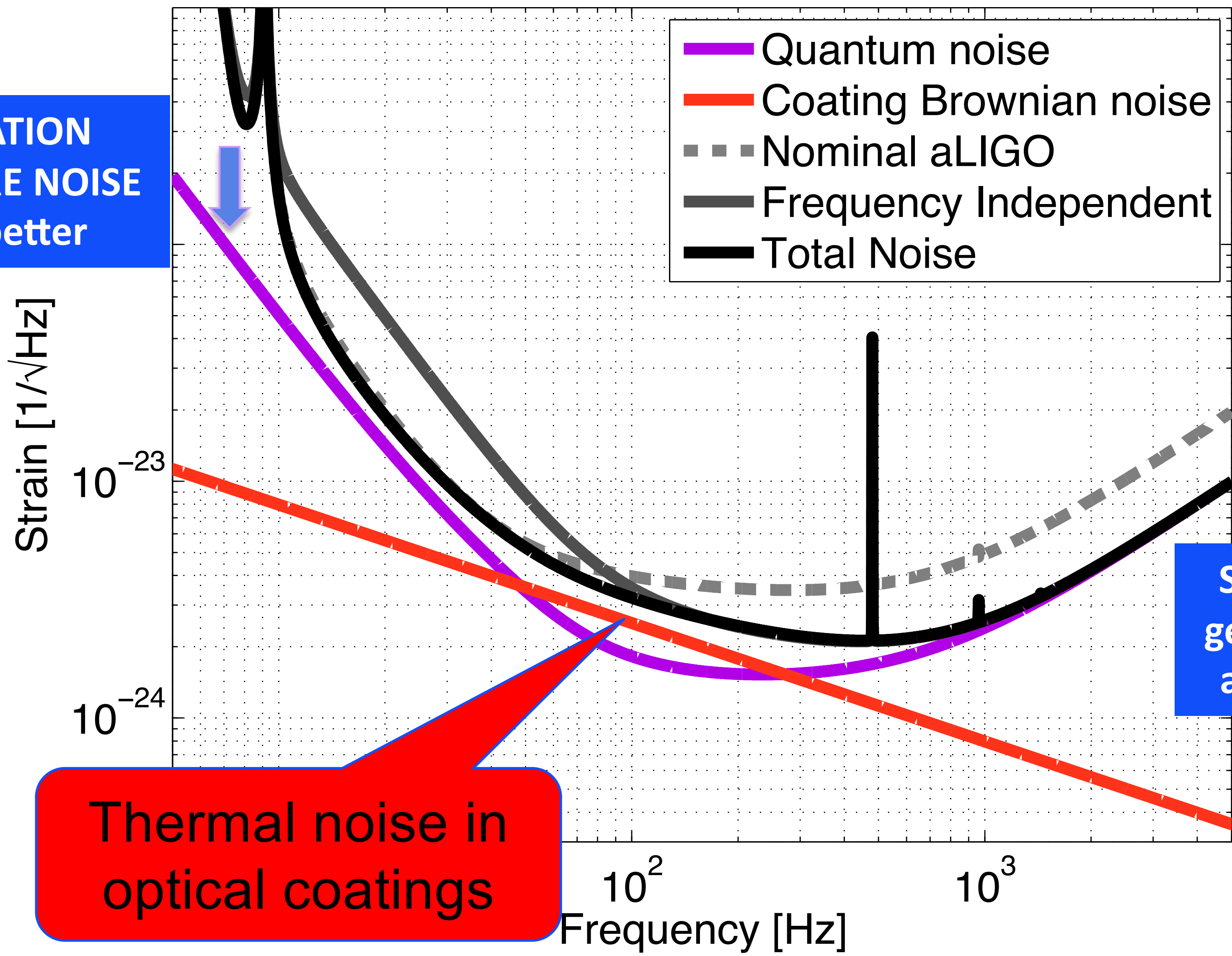
SHOT NOISE gets better by a factor of 2

→ High frequency improvement, + 25% BNS-BNS range (200 → 250 Mpc)

M. Evans, Amaldi 11

Frequency Dependent Squeezing

RADIATION PRESSURE NOISE gets better



SHOT NOISE gets better by a factor of 2

→ High frequency improvement, + 25% BNS-BNS range (200 → 250 Mpc)

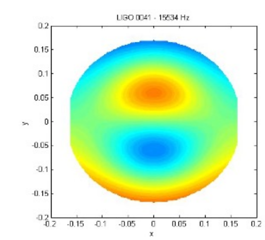
Cross coupling between motion and sensing: Parametric Instabilities

- A coupling between the optical sensing system and the mechanical system being sensed
- One limitation to the usable light power in a GW detector

Cavity fundamental mode ω_0

Radiation pressure driven opto-mechanical interaction

High order optical mode ω_1



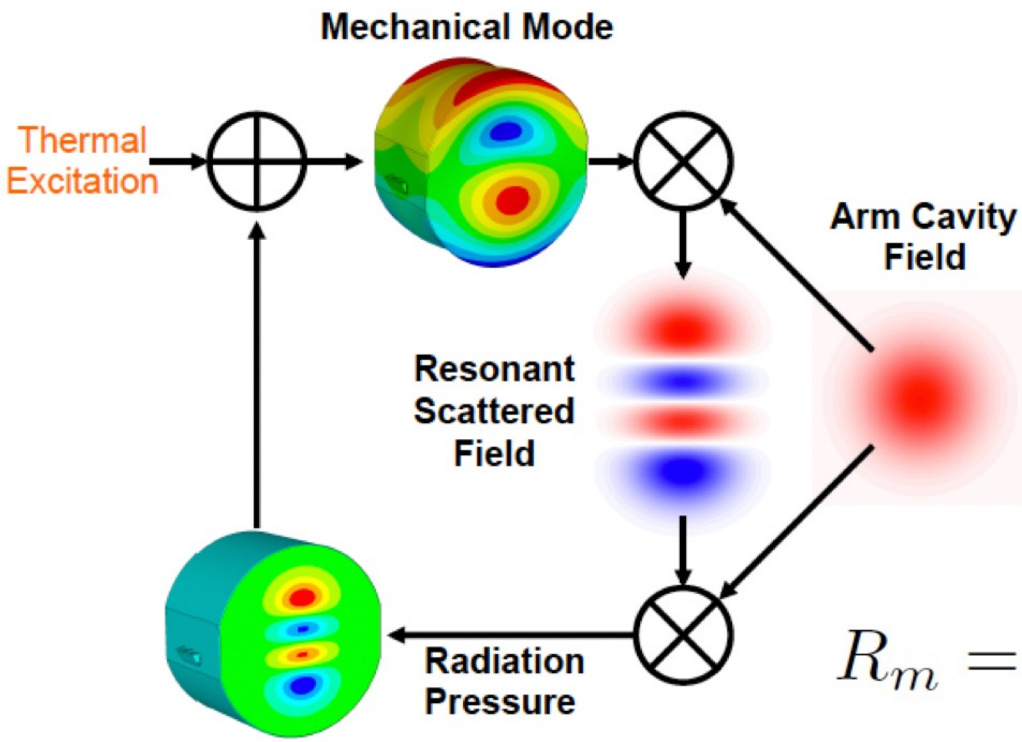
Mechanical mode ω_m

Thermally excited acoustic mode scatters TEM_{00} mode → sidebands $\omega_0 \pm \omega_m$

Resonance condition:

$\omega_o - \omega_1 = \omega_m$ & high spatial overlap

Parametric Instabilities



$$R_m = \frac{8\pi Q_m P_{\text{arm}}}{M \omega_m^2 \, c \, \lambda} \sum_{n=0}^{\infty} \Re[G_n] B_{m,n}^2$$

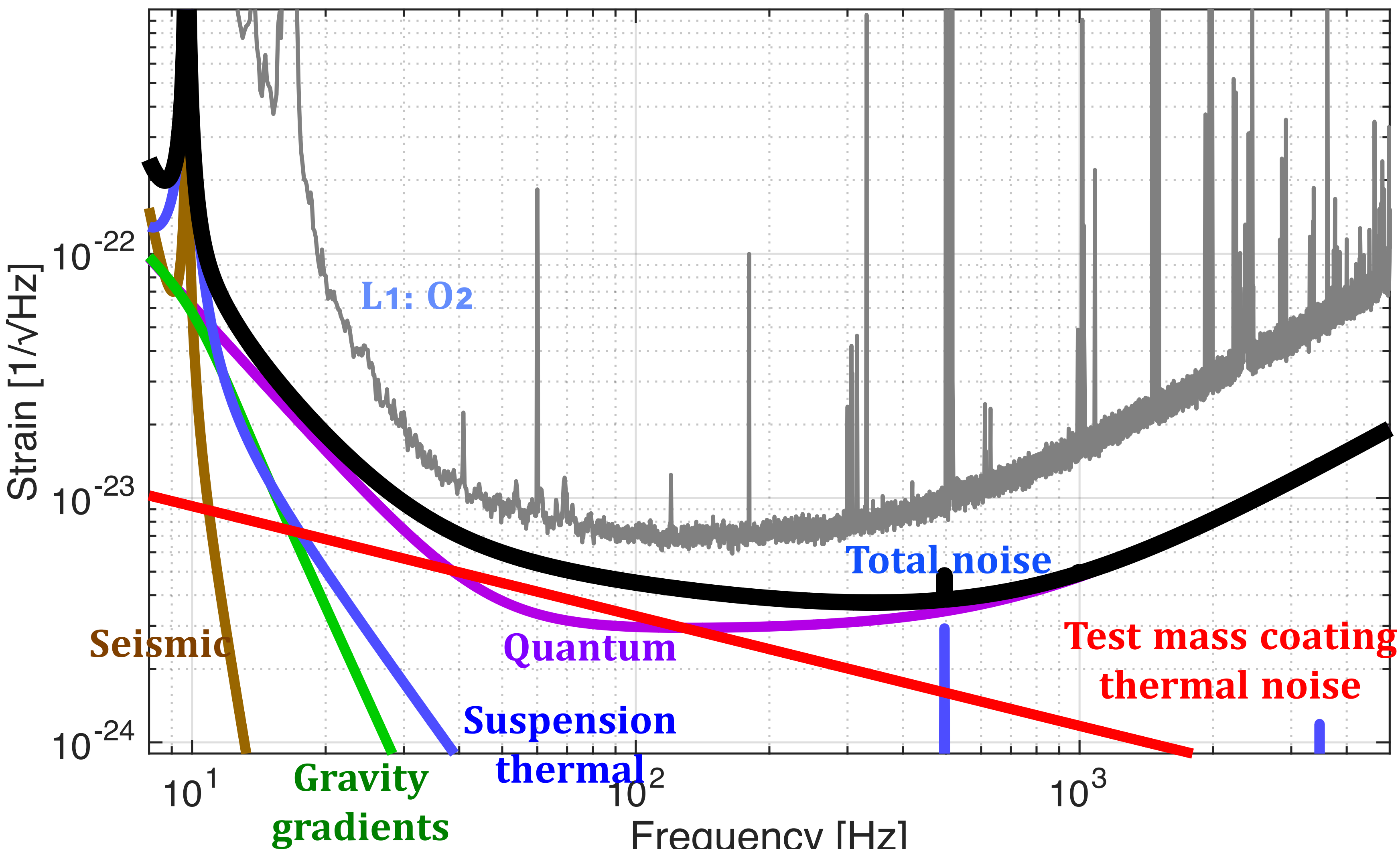
Related to the optical gain of the scattered field ($\Re[G_n]$)

Overlap between mechanical and optical modes ($B_{m,n}^2$)

- **Active and passive control scheme to suppress**

Evans et al, Phys. Lett. A, 374(4), 665-671 (2010)

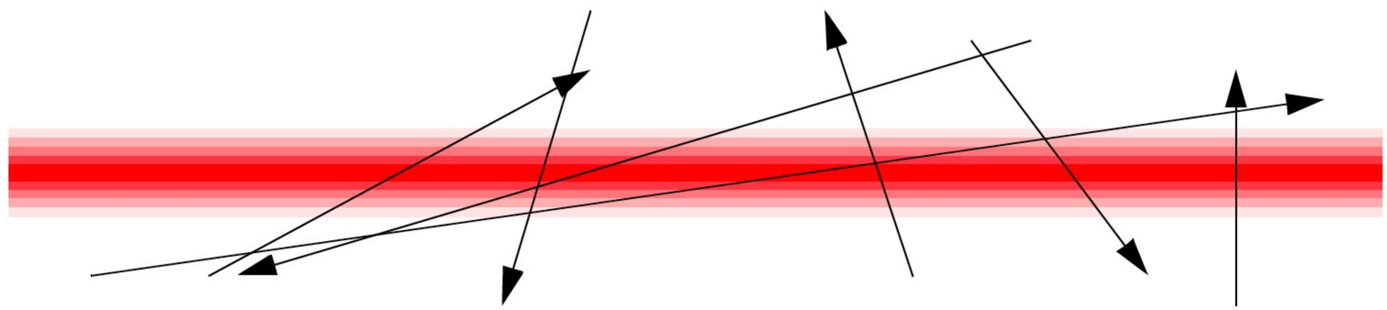
Adv LIGO Target Design
Sensitivity, basic noise sources



Observatory Infrastructure

Vacuum System

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



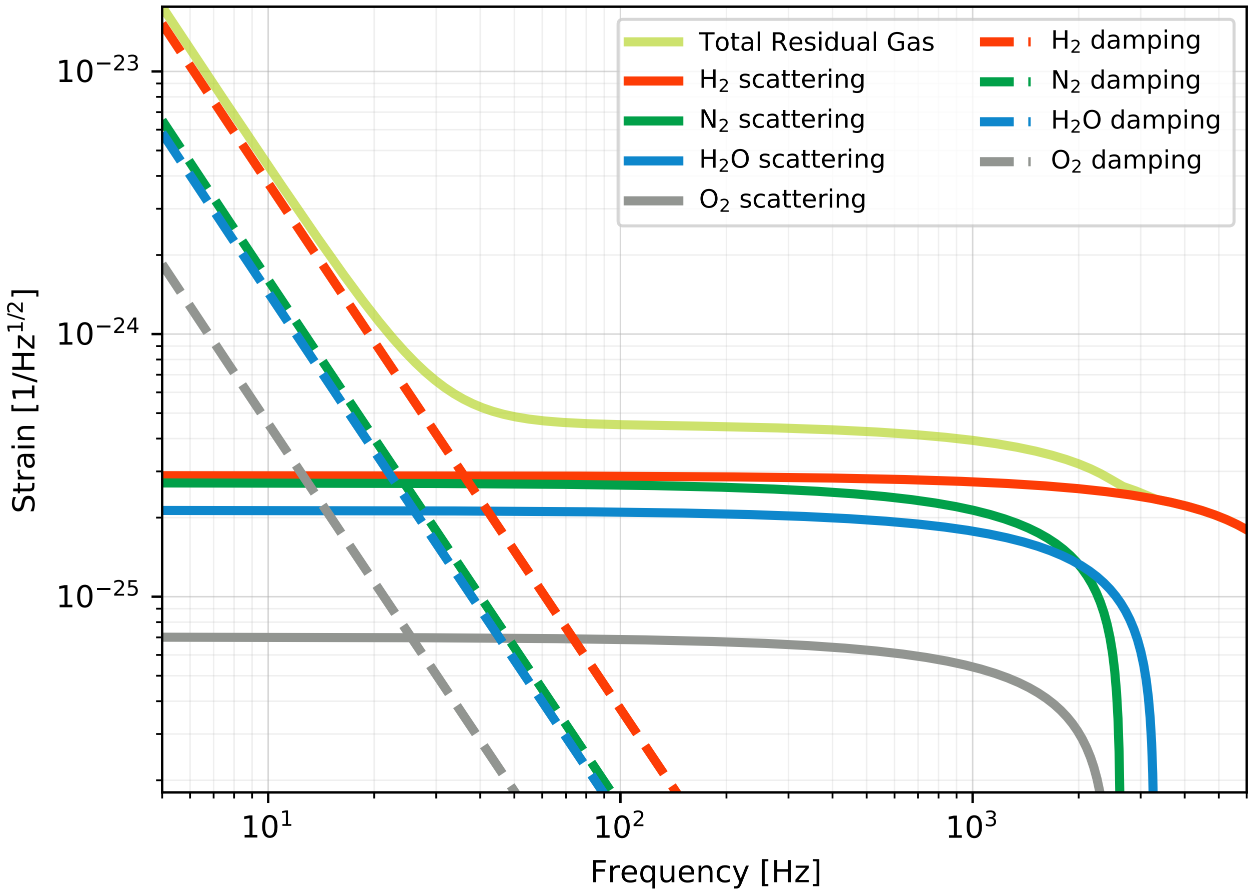
- Polarizability α of the remaining gas molecules induces path-length fluctuations; again, Poisson Statistics, and an effect proportional to square root of density $\rho^{1/2}$ along the path

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

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

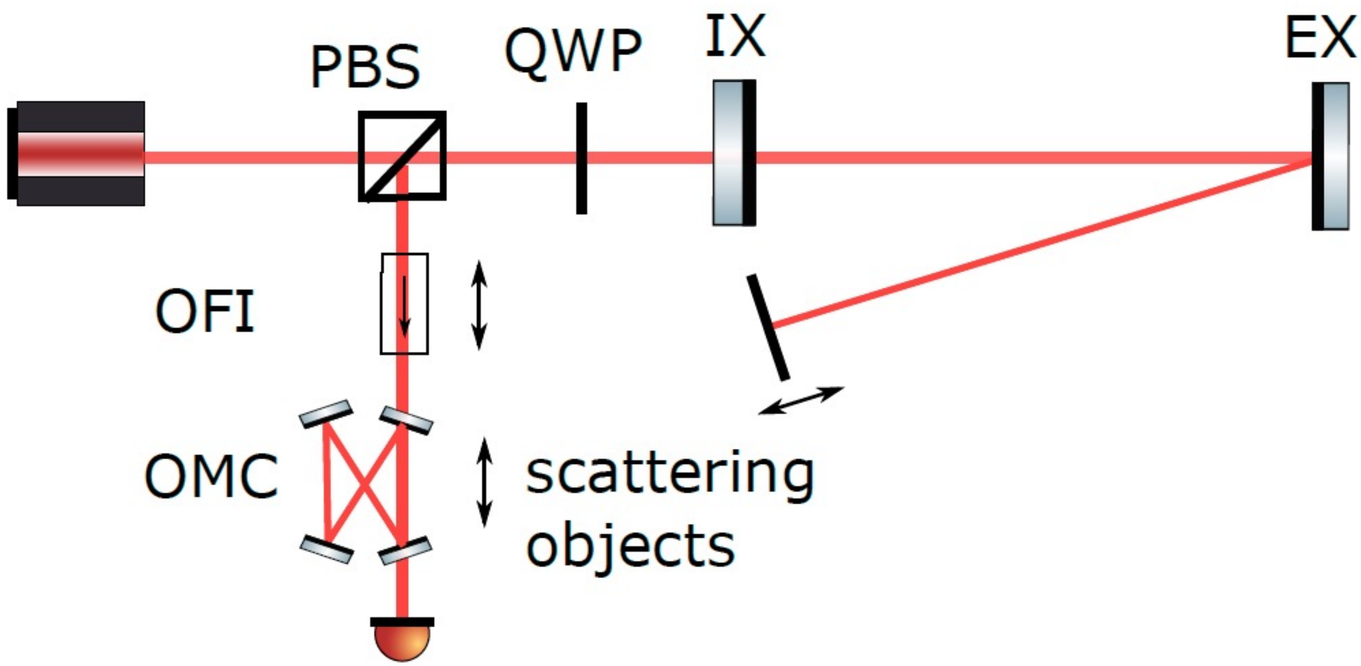
Residual gas: path-length fluctuations, pendulum damping

- Pygwinc model for residual gas, for
  - The path length fluctuations for gas along the n*km path
  - Pendulum suspension thermal noise due to transfer of momentum to/from gas molecules from/to test mass



How scattered light affects the IFO

- Scattered light is especially problematic if the light can re-enter the main beam path, scattered back from moving objects like baffles or chamber walls.

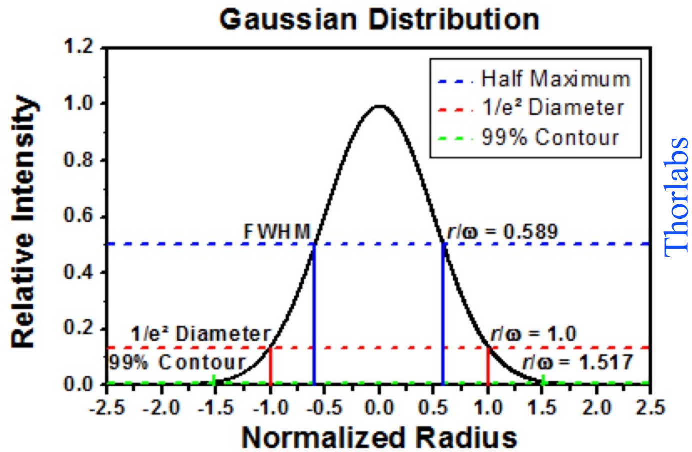


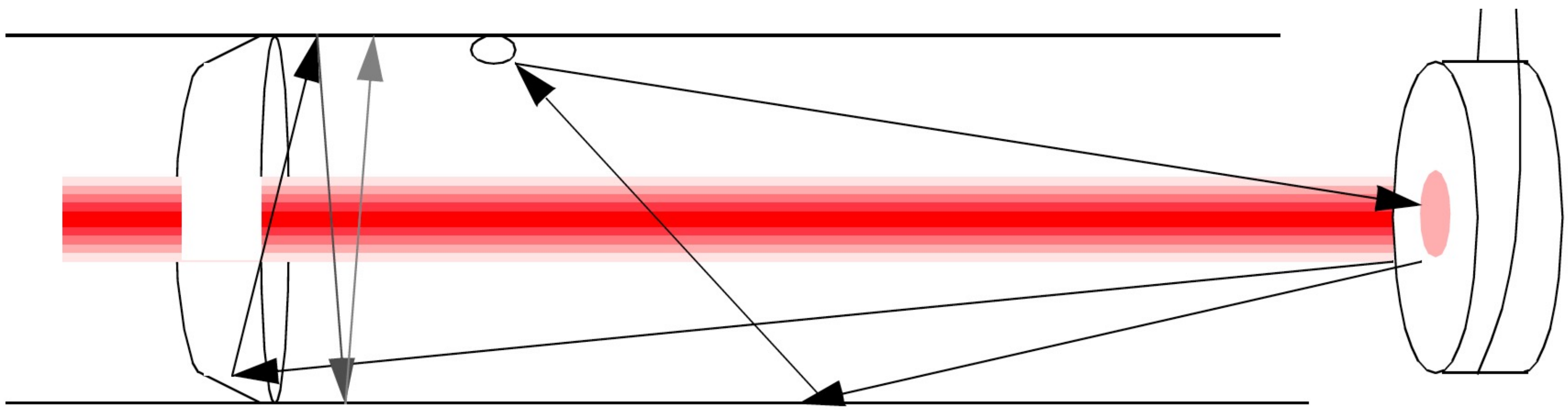
- Scattered light noise is seen in the DARM spectrum in the frequency range 10-200 Hz.
- Significant noise source.

REF: Denis Martynov thesis: https://dcc.ligo.org/DocDB/0119/P1500087/001/DenisMartynovThesis.pdf

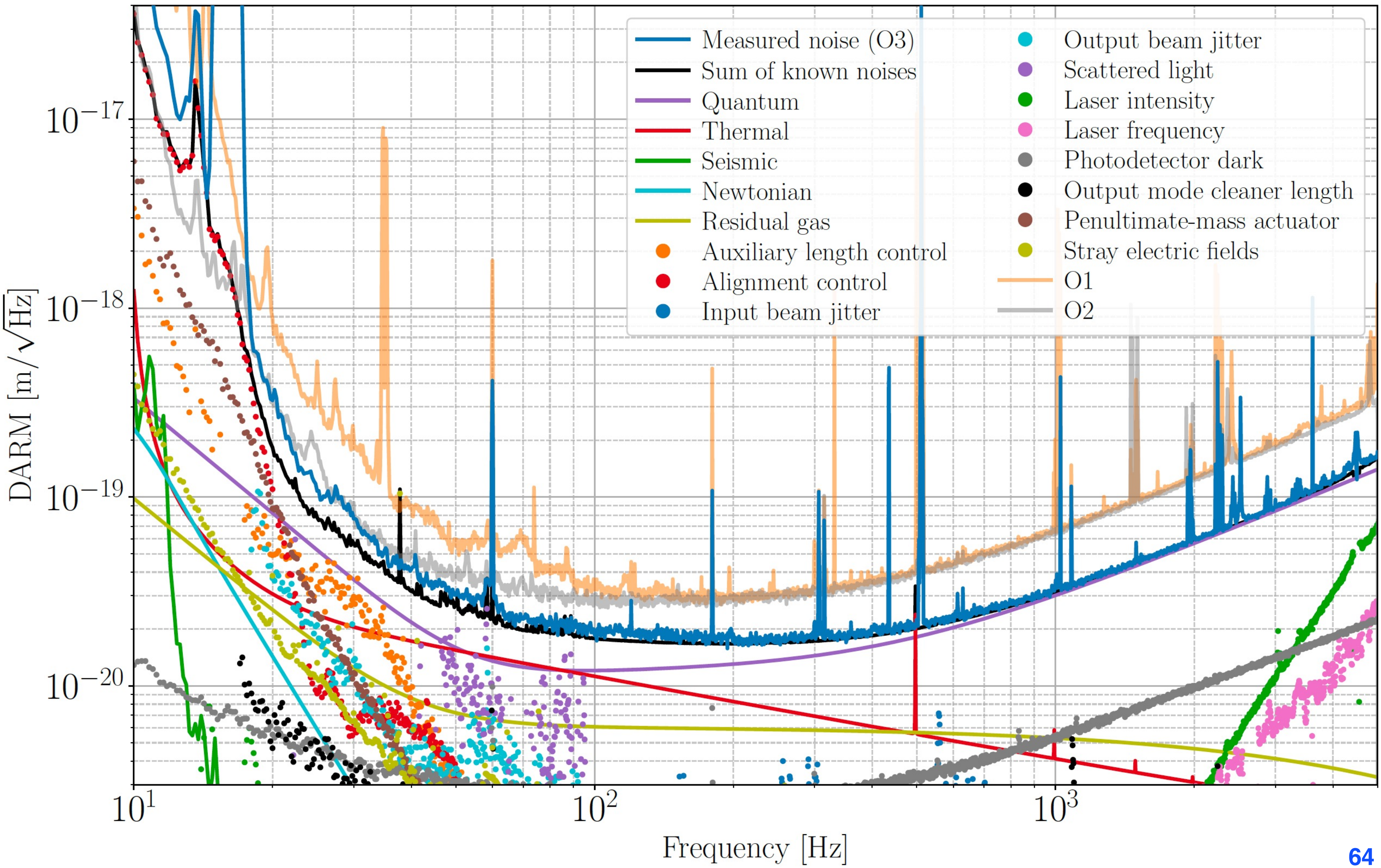
Beam Tube Scattered Light

- 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





And many other 'technical' noise sources….



Length: The ultimate solution

- In addition to understanding and adjusting the design for thermal noise, quantum limits, Newtonian background, seismic noise, there are important parameters to consider
- Length is good for sensitivity! Technically *much* easier than lowering noises
  - » Signals get larger, noises tend not – until one is comparable to λ/2
  - » Optimum for coalescence of BNS around 20km
- 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	$1/L^{3/2}$

Strain sensitivity as function of length L

Depth

- Burying the detector has unique advantages to improve the low-frequency sensitivity; esp. reducing the Newtonian background
- The Science Case should drive the design decision here, modulated by cost
- Asking for both an optimal length **and** and a buried detector is probably unrealistic from a cost standpoint
- Next-generation detectors 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
- GEO-600 is a great example of a situation where high risks can be taken
- 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

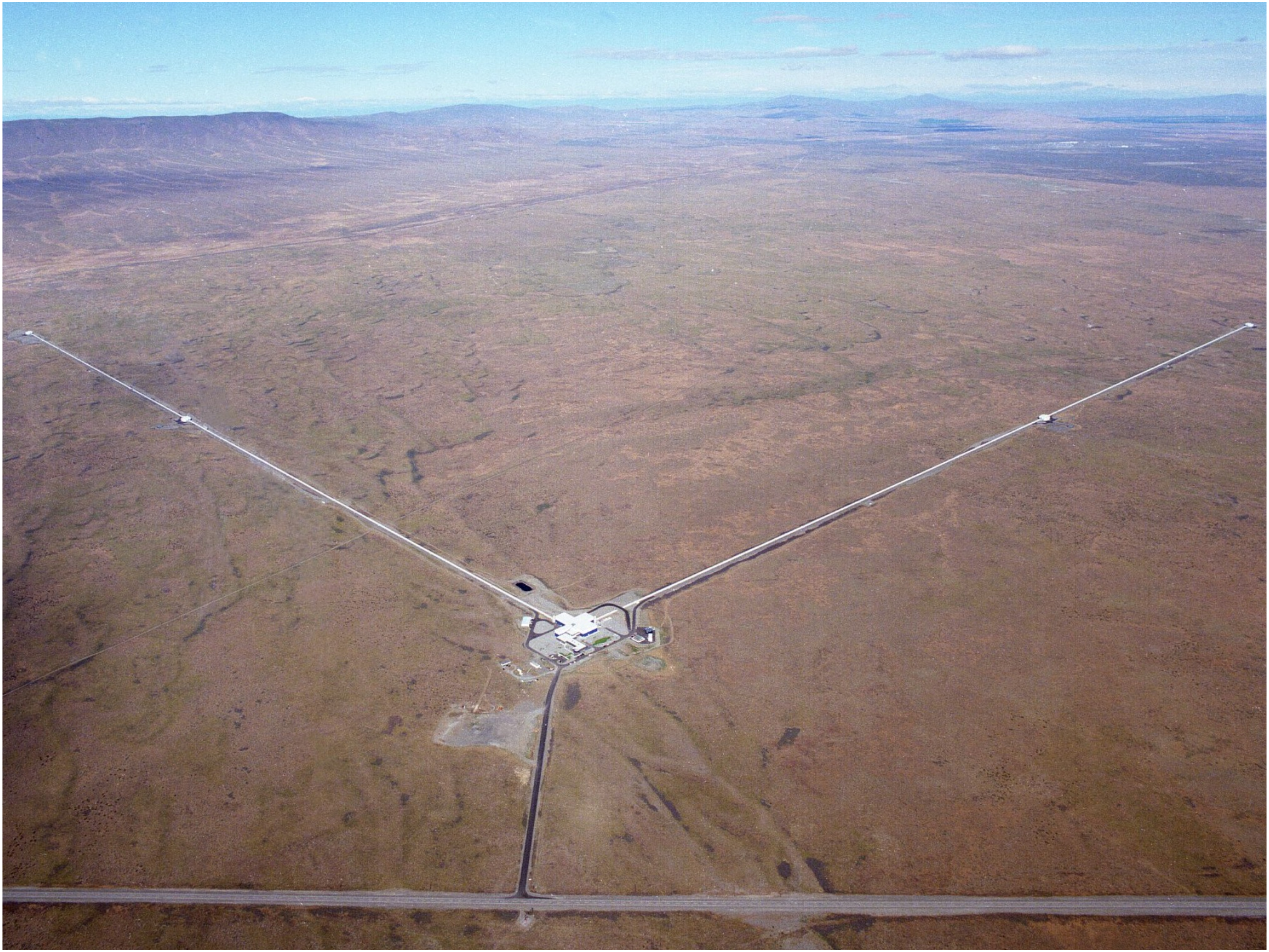
- To find solutions which meet the observational science goals, and which fit in the other constraints just discussed, is tricky
- Requires compromises both in the initial design, and dynamically as the project advances
- Constant modeling of the sensitivity is crucial, along with modeling of schedule and cost
- A mixture of engineering, instrument science, observational science, and project management is needed to succeed
- Just keep in mind that a full design process has a great deal of richness!

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 Euros!
- Goal pre-discovery was crystal-clear: Make a detection
- Afer 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
- Maybe you will join us!

LIGO ‘Virtual’ Tour



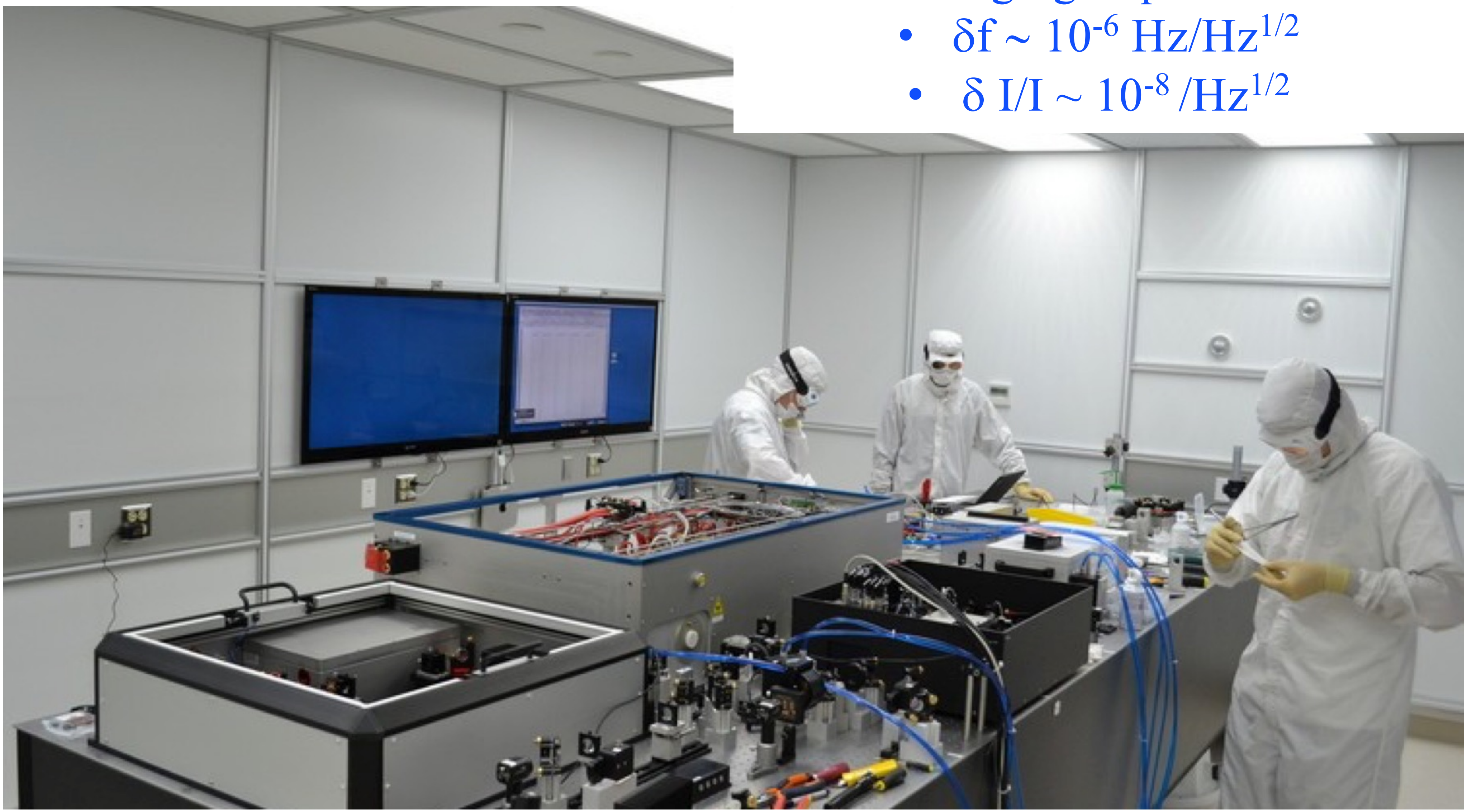
Hanford Corner building

Laser Clean Room; extraterrestrials for scale

200 W, single frequency, single mode, Nd:YAG laser

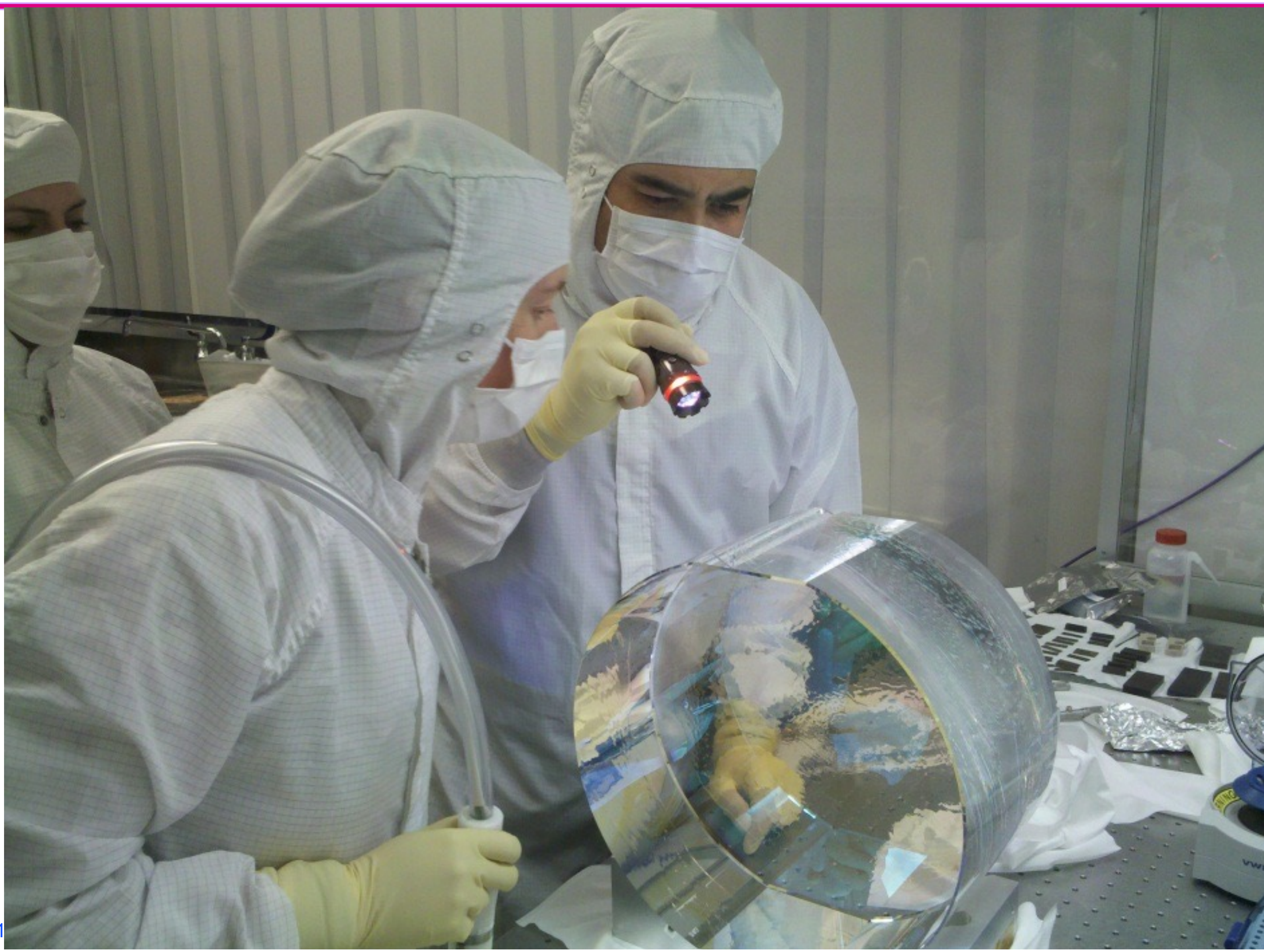
Challenging requirements:

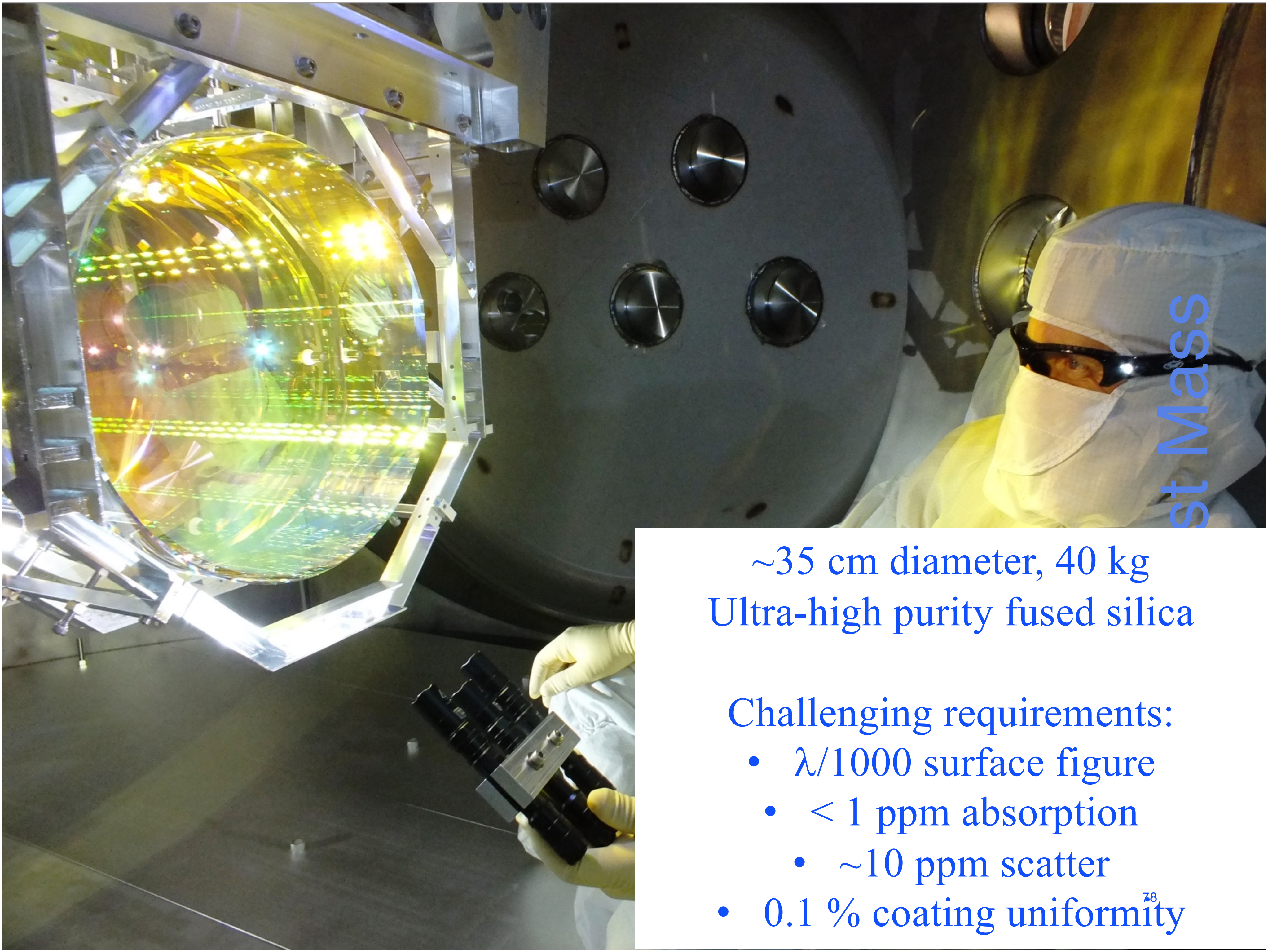
- $\delta f \sim 10^{-6}$ Hz/Hz$^{1/2}$
- $\delta I/I \sim 10^{-8}$ /Hz$^{1/2}$



Vacuum chambers to protect and isolate optics

Inspecting mirror during fabrication





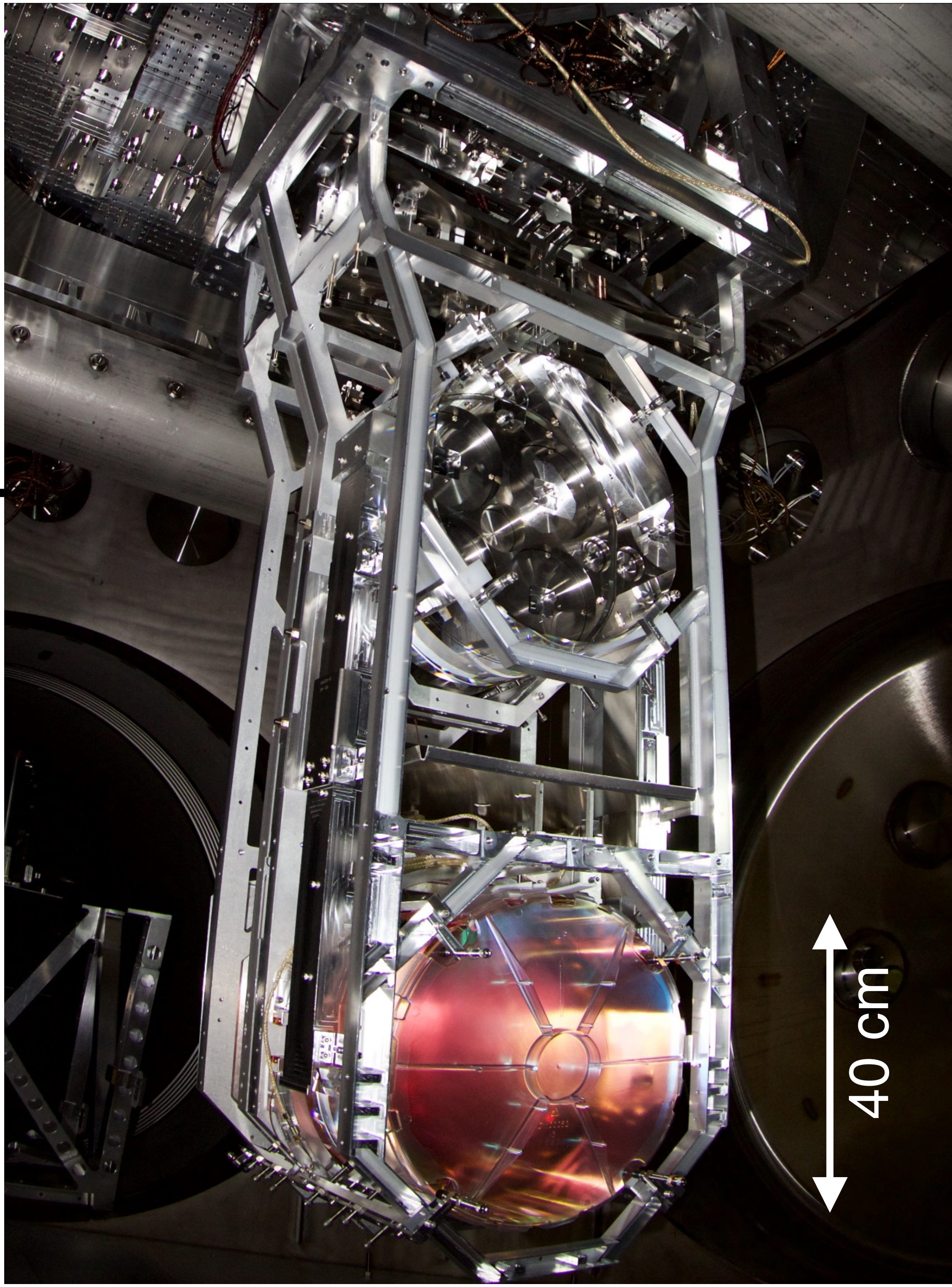
~35 cm diameter, 40 kg

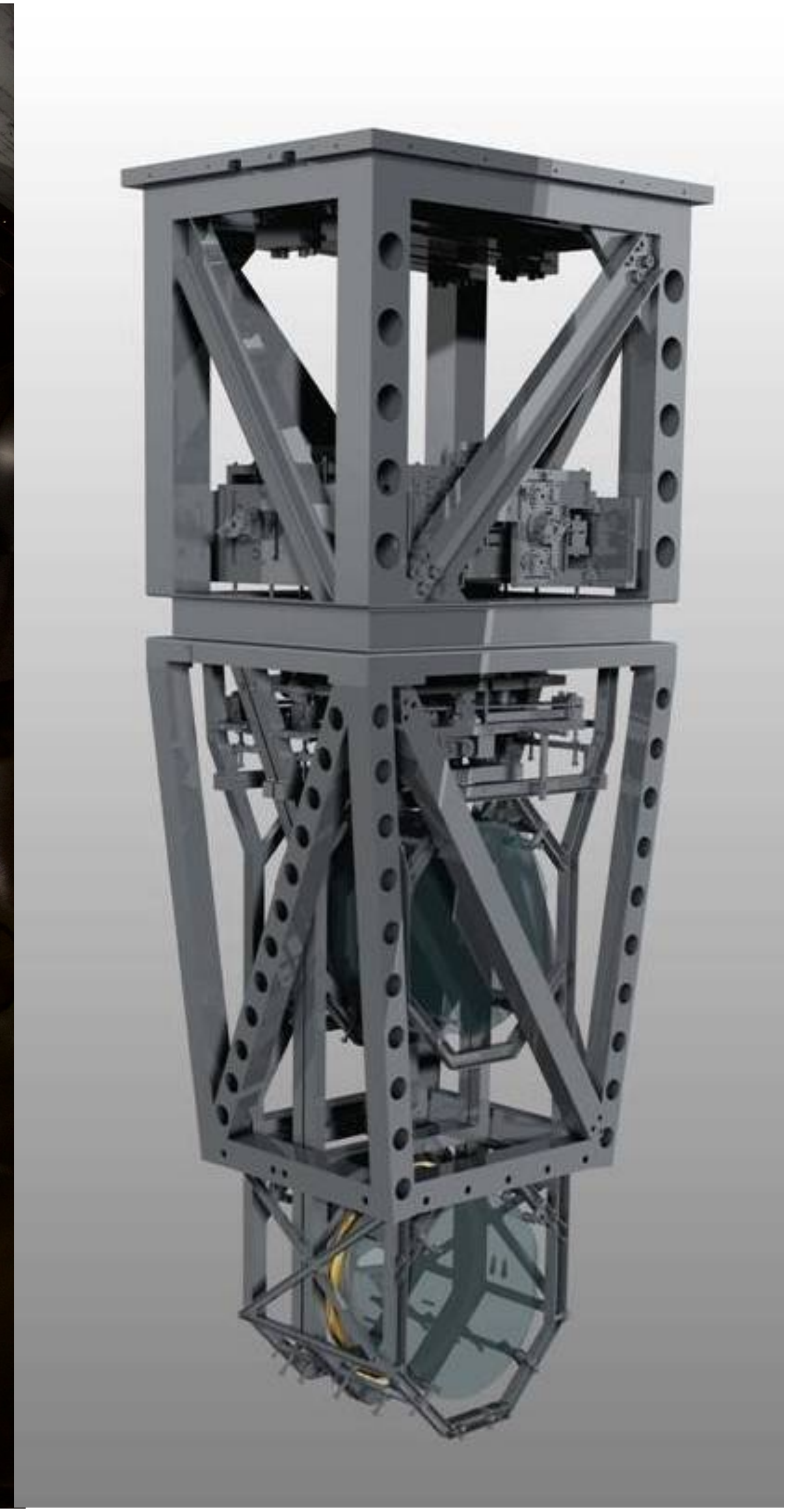
Ultra-high purity fused silica

Challenging requirements:

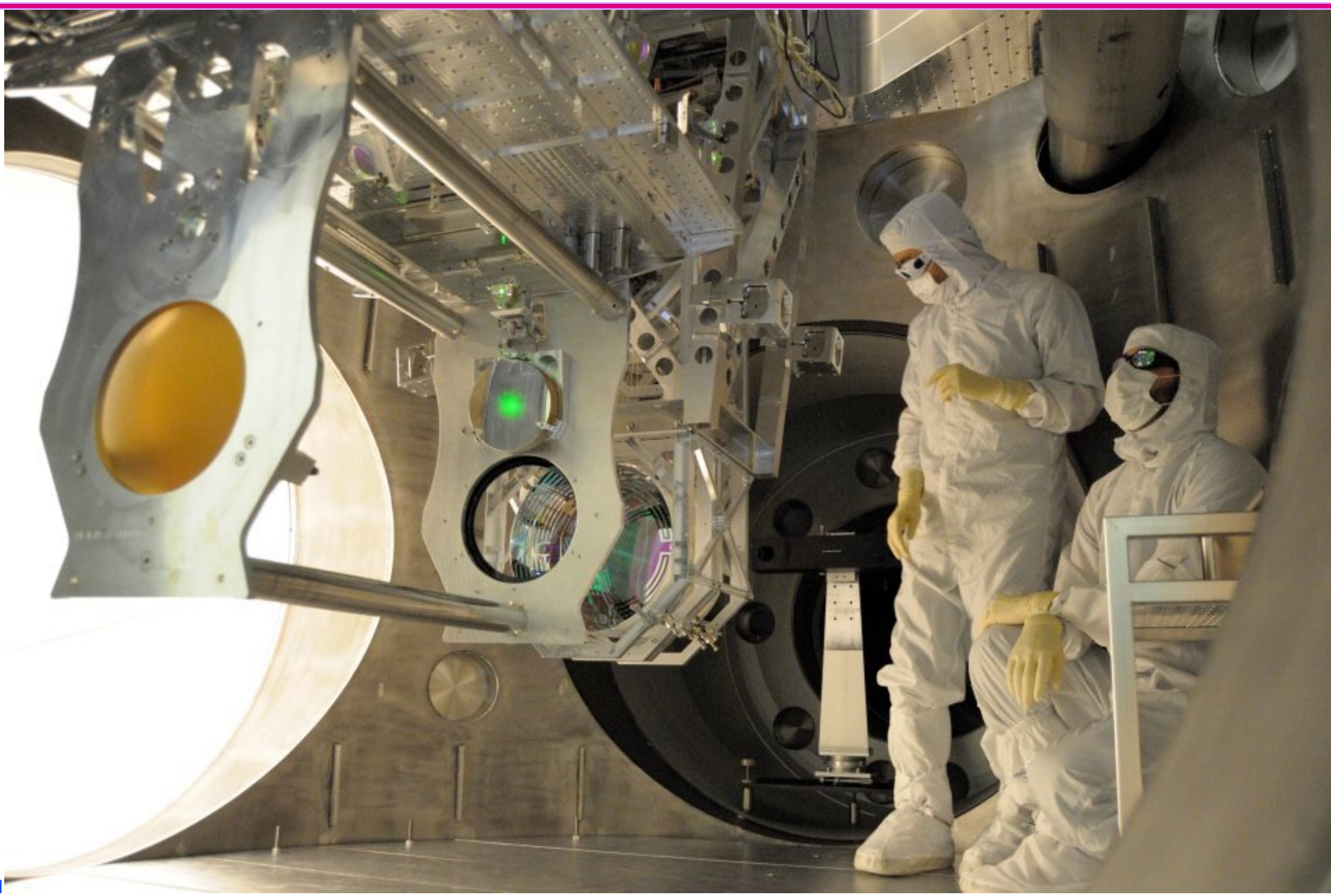
- λ/1000 surface figure
- < 1 ppm absorption
- ~10 ppm scatter
- 0.1 % coating uniformity

Test Mass Suspension

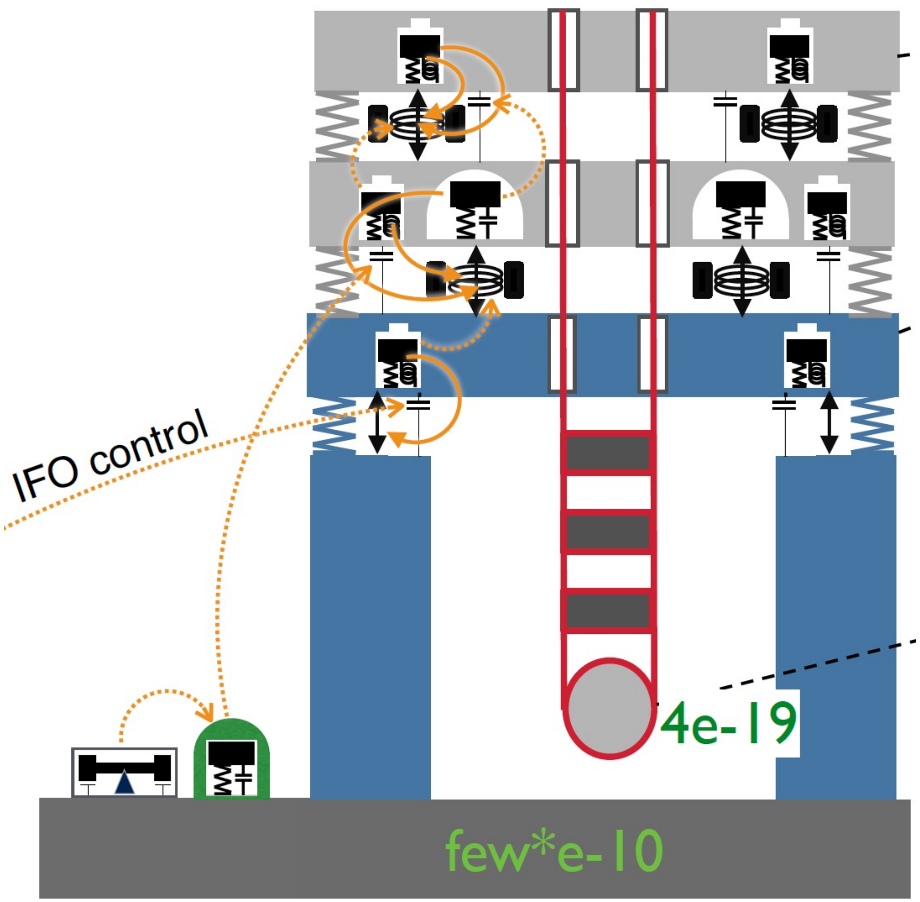


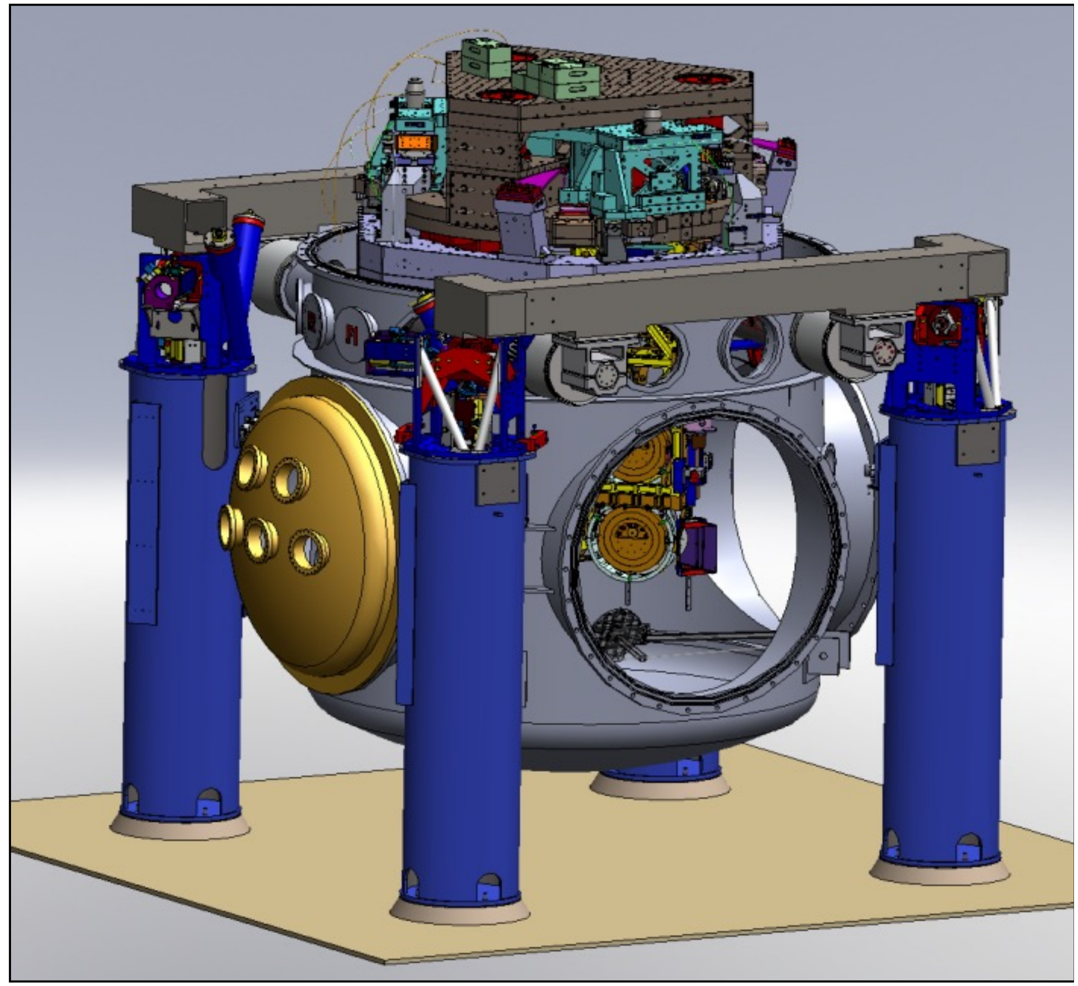


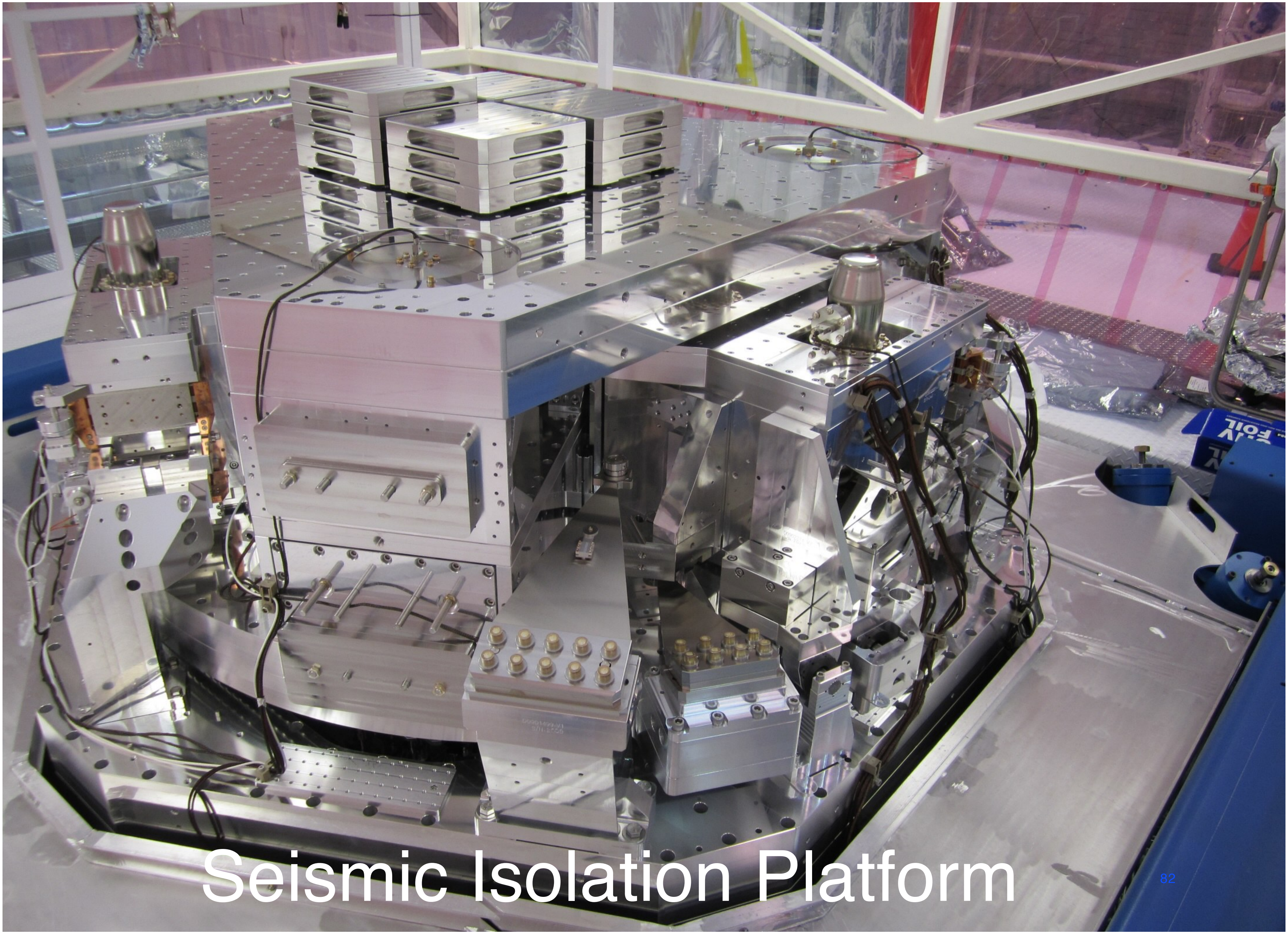
End-mirror assembly
(humans removed before pumpdown)



Active and passive seismic isolation






Seismic Isolation Platform

Civil Construction: Beam Tube cover, foundation

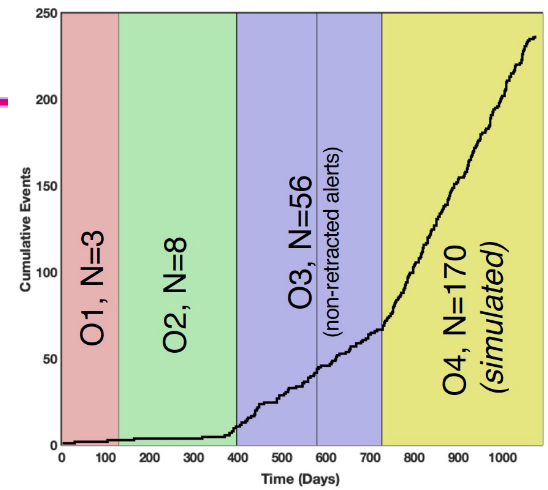
photo credit M. Zucker?

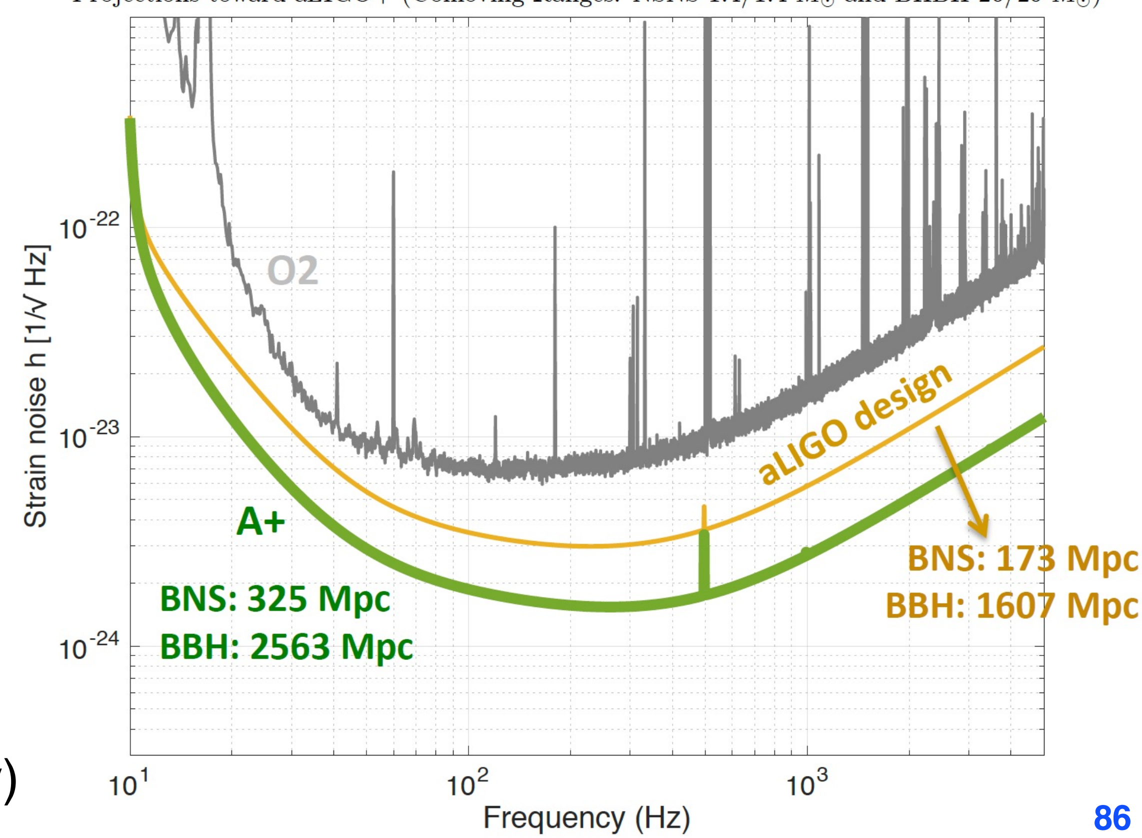
Cover useful to protect against 2-ton masses at 100 km/hour

Sensitivity improvements are *very* well rewarded

- LIGO 'A+' – Incremental changes to the Advanced LIGO design
  - Similar changes planned for Virgo
- Rough doubling of reach
  - $2^3 = 8$ greater volume
  - 8x higher rate
  - 17-300 BBH/month
  - 1-13 BNS/month
  - 2-11 BNS x SGRB coincidences/year
- Population studies
- Hubble Constant
- …higher SNR for e.g., tests of GR
- Plan to be observing ~2025 (uncertain pandemic delay)

Simulated Event Stream for a one year duration O4 run





Onward

- Hope this introduction gives a good basis for the talks to follow
- Do feel free to follow up with questions in the Office Hours
- Also email to dhs@mit.edu (but may need to be a bit patient for responses)