Gravitational Wave Detectors

Gravitational waves: a new messenger to explore the universe
3-4 March 2021

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MIT LIGO/LISA

Thanks to…

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- The LIGO Lab – MIT, Caltech, Hanford and Livingston Observatories
- The LIGO Scientific Collaboration; Virgo and KAGRA
- LISA Consortium and Pulsar Timing Array Collaborations
- The US National Science Foundation for extraordinary support and perseverance for LIGO



References

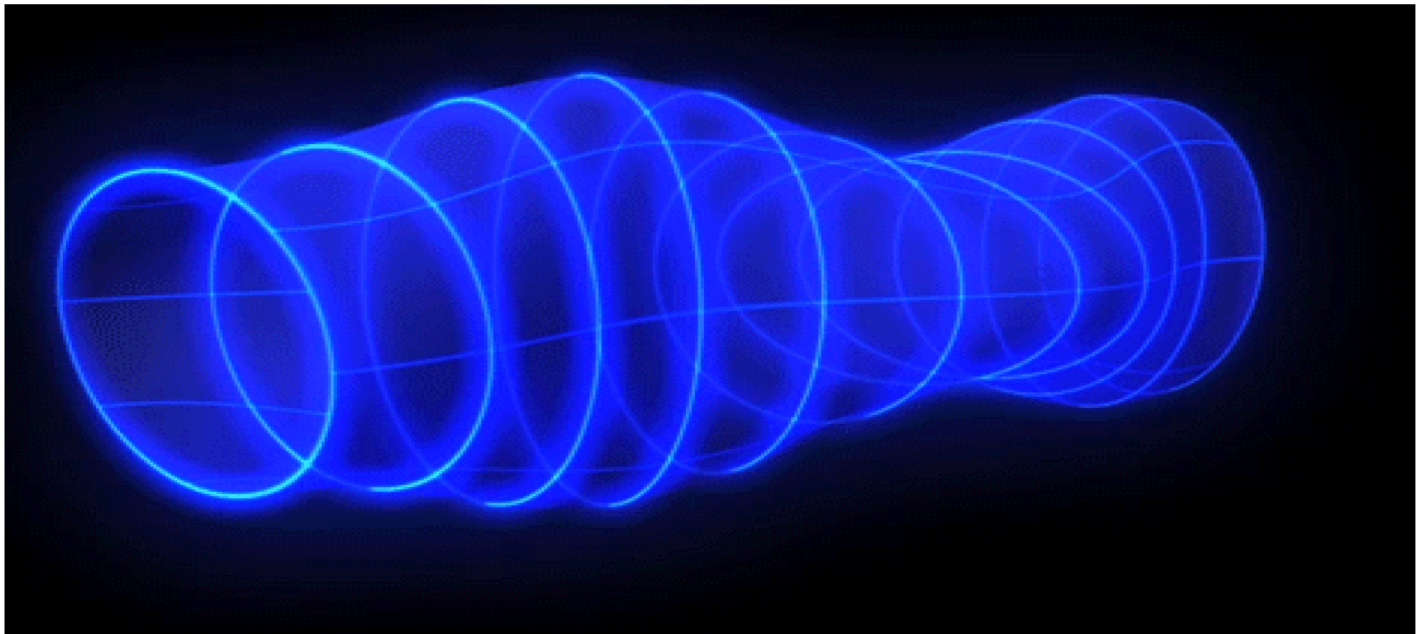
- Weiss R. Electromagnetically coupled broadband gravitational antenna, 1972 – historical interest. https://dcc.ligo.org/LIGO-P720002/public
- Advanced LIGO The LIGO Scientific Collaboration https://arxiv.org/pdf/1411.4547
- Saulson PR. Fundamentals of interferometric gravitational wave detectors (second edition). World Scientific, 2017 – good general introduction
- Siegman AE. Lasers (revised). University Science Books; 1986
- Reitze D, Saulson P, Grote H. Advanced interferometric gravitational-wave detectors. World Scientific Publishing; 2019.
- Harms J. Terrestrial gravity Fluctuations. Living Reviews in Relativity. 2019 https://link.springer.com/article/10.1007/s41114-019-0022-2
- Harry G, Bodiya T, DeSalvo R. Optical coatings and thermal noise in precision measurement. Cambridge
- Heinert D, Hofmann G, Nawrodt R. Fluctuation dissipation at work: Thermal noise in Reflective optical coatings for GW detectors. In: 2014 IEEE Metrology for Aerospace (MetroAeroSpace); 2014. p. 293
- Martynov D, Hall E, Abbott B, et al. Sensitivity of the advanced LIGO detectors at the beginning of gravitational wave astronomy https://arxiv.org/abs/1604.00439
- McCuller L, Whittle C, Ganapathy D, et al. Frequency-dependent squeezing for Advanced LIGO https://export.arxiv.org/pdf/2003.13443
- 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 is the only talk in the Workshop addressing the practical issues of detectors
  - » GWs creating a real, measurable strain in space already discussed
  - » Data analysis with real-world constraints coming in a later lecture
- Designed to give those interested in the theory and astrophysics an idea of the techniques, challenges, and opportunities
- Some discussion of detection approaches for all frequency domains
- Deeper focus on ground-based detectors for stellar-mass events
- Qualitative in orientation; references for deeper study

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° to each other
- Ring of free 'test masses' is deformed by a passing GW – this enables observation

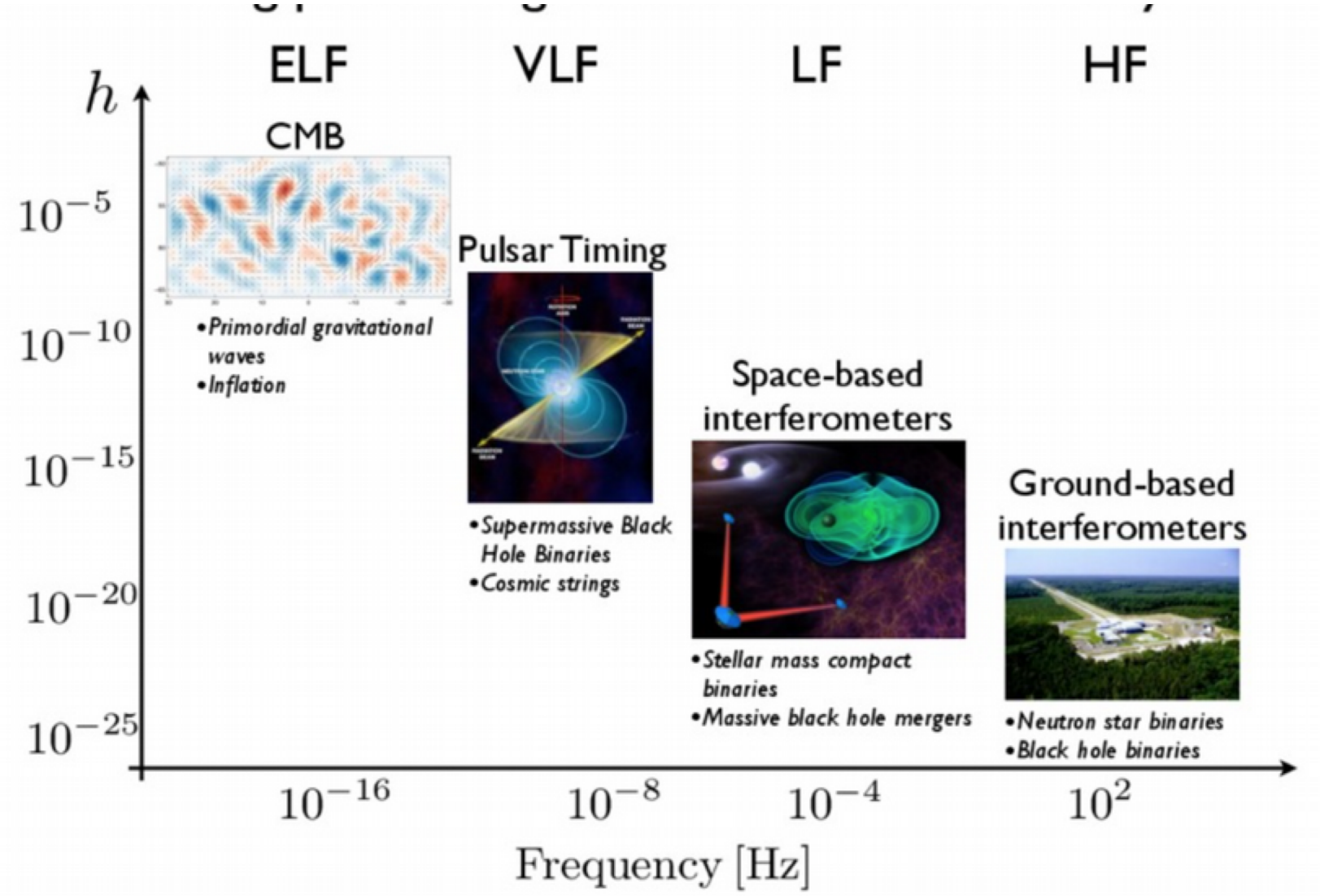


ESA

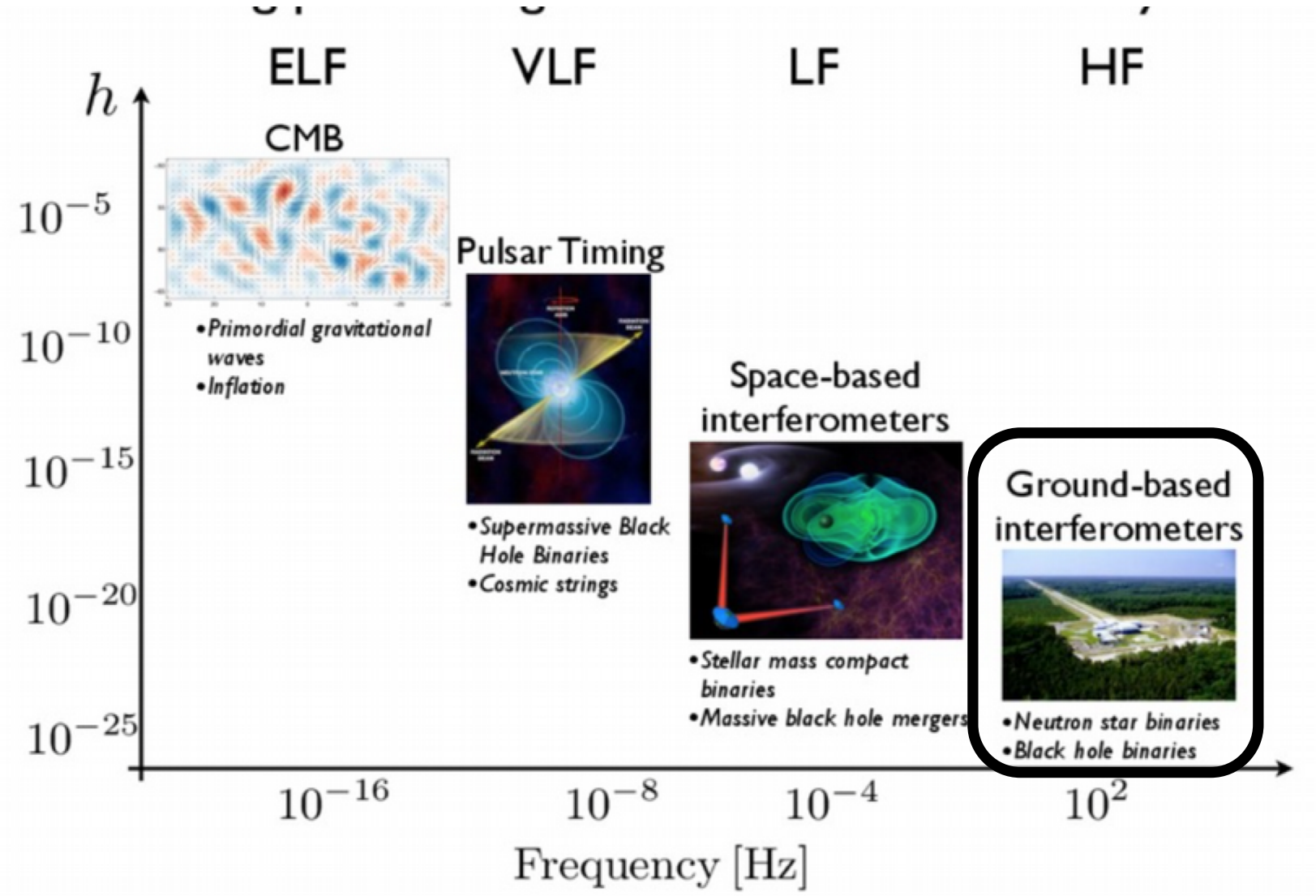
Detection methods, Projects

- 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
  - » 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
  - » LISA for example (launch in mid-2030's)
  - » Science target ~10^3 – 10^7 $M_\odot$ systems; 2.5x10^6 km arms
  - » and: DECIGO concept targeting primordial Background around 0.1 Hz
- Ground-based laser interferometric detectors
  - » LIGO, Virgo, KAGRA Current; 3 – 4 km arms
  - » Einstein Telescope, Cosmic Explorer future; 10 – 40 km arms
  - » Science target ~ <1 – 10^3 $M_\odot$ systems

Detection methods, Projects



Detection methods, Projects

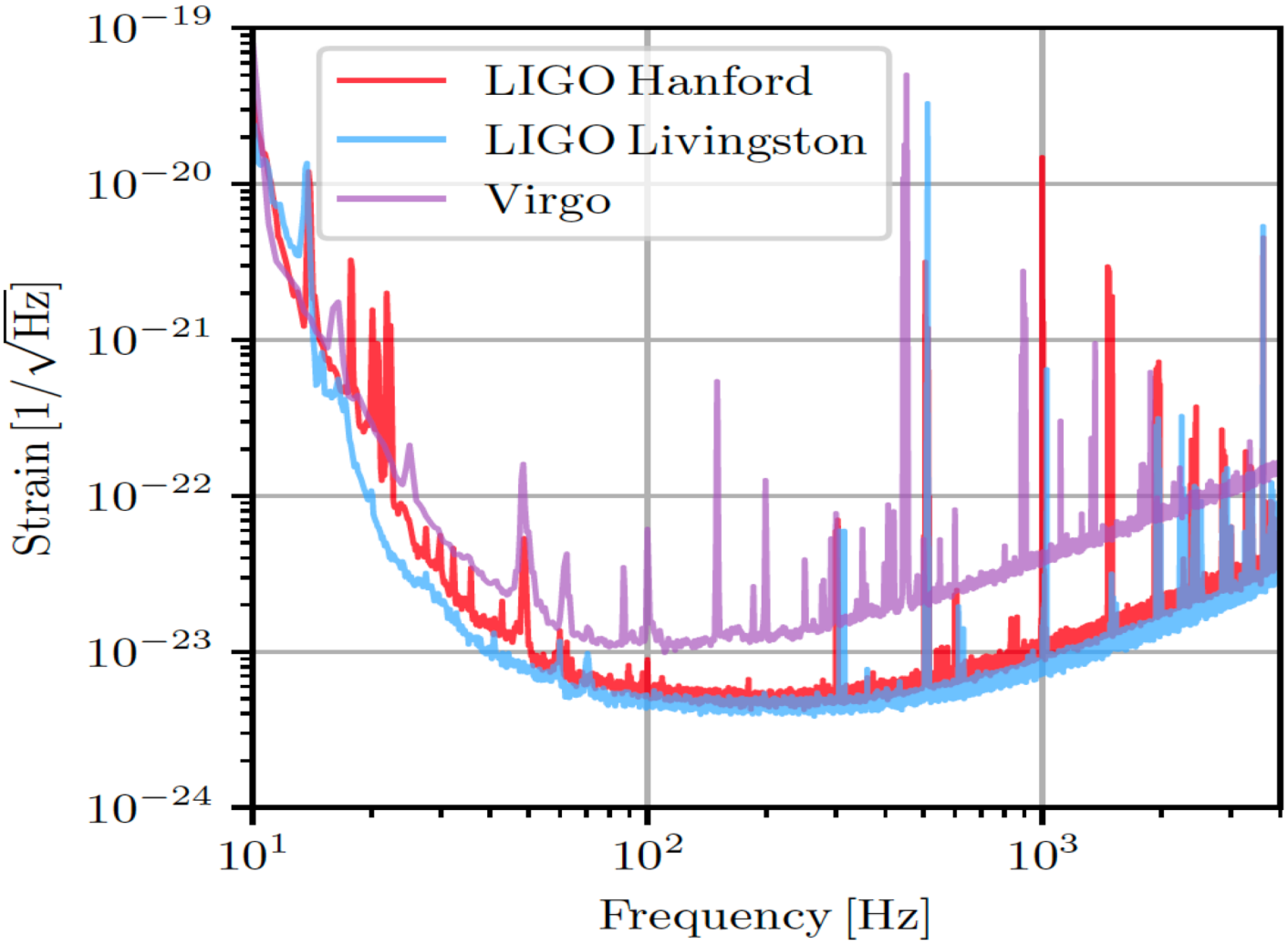


Ground-based Detector ~~requirements~~ → specifications

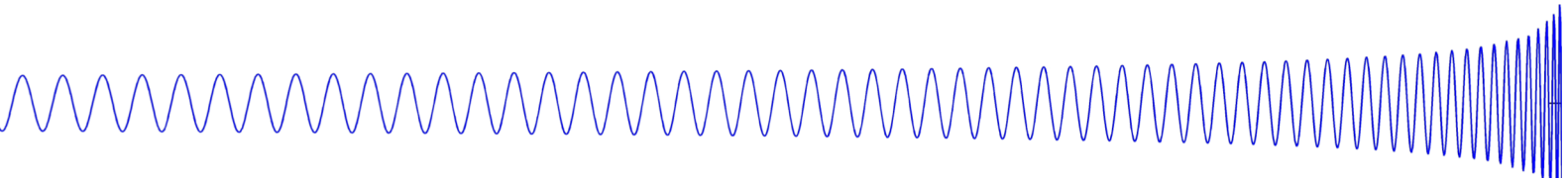
- Ground-based detectors: *presently* best-effort technically
  - » Where were optical or radio telescopes, X-ray satellites, etc. 5 years after their first successful operation? That's where GW detectors are!
  - » Seek observational science enabled with what can be built now
  - » Parallel development 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

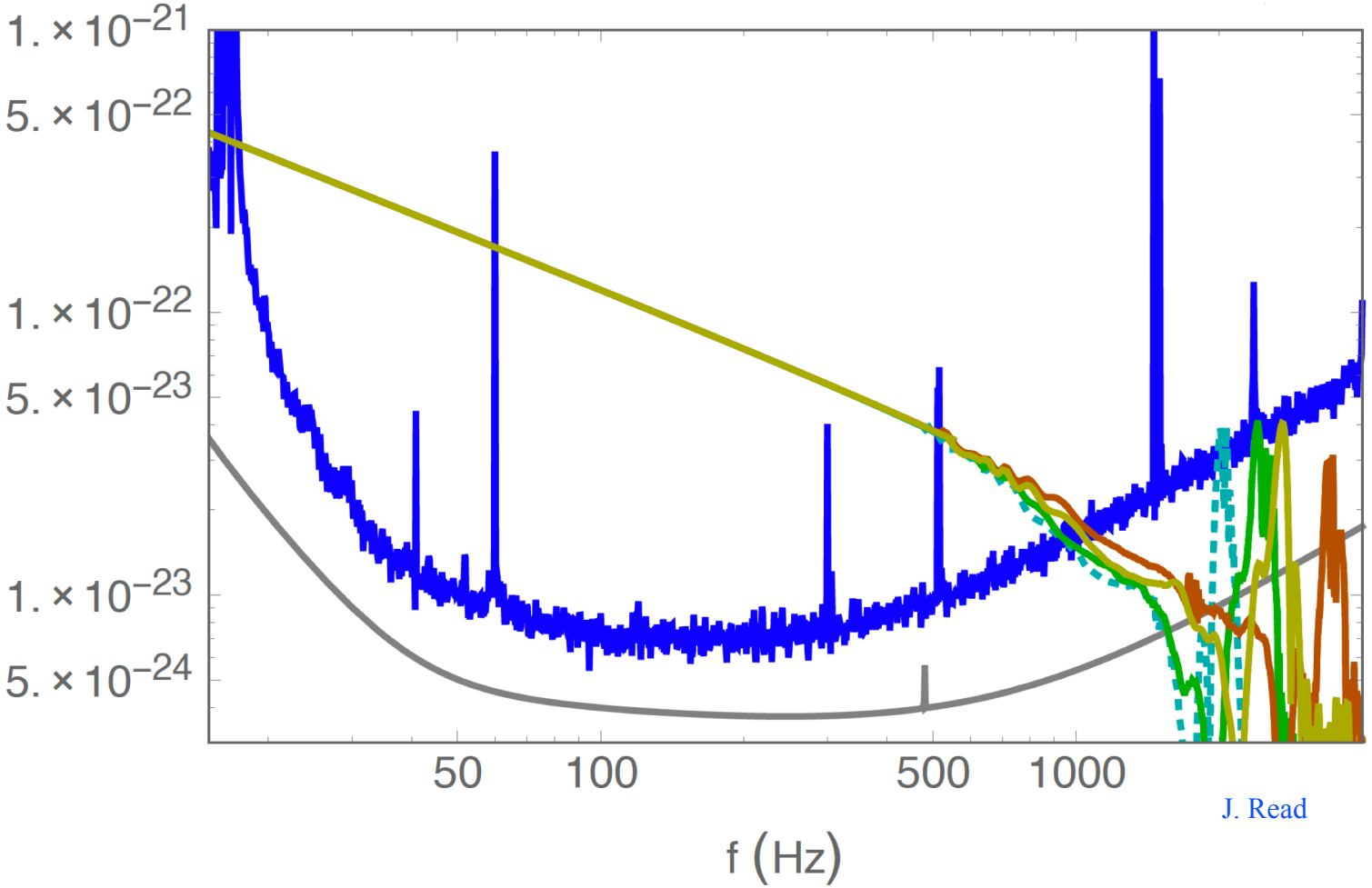
Current sensitivity

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



NS-NS inspiral mapped onto detector sensitivity





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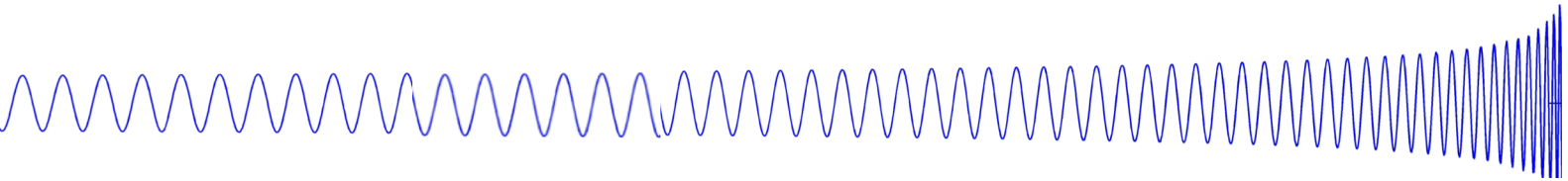

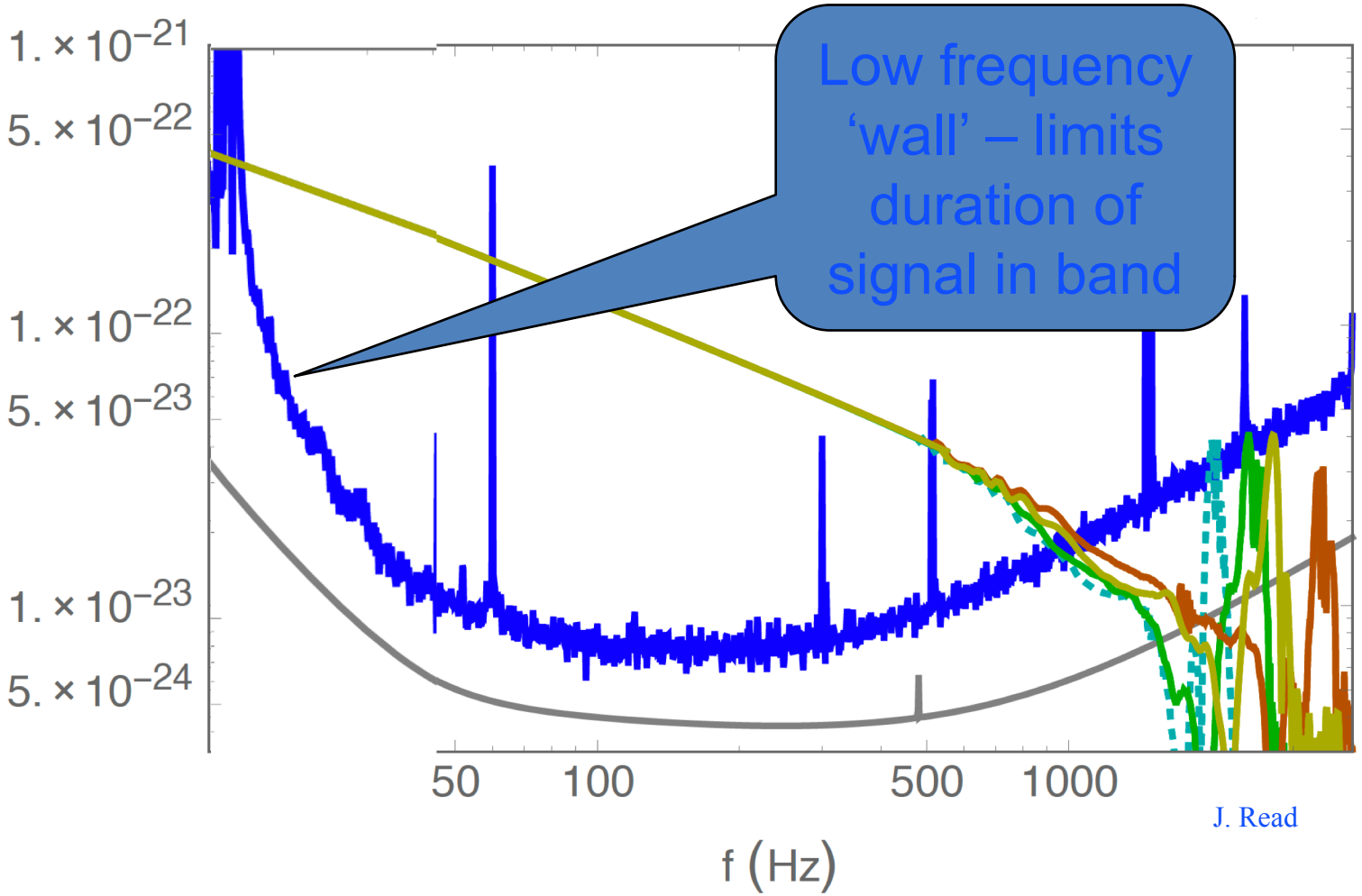

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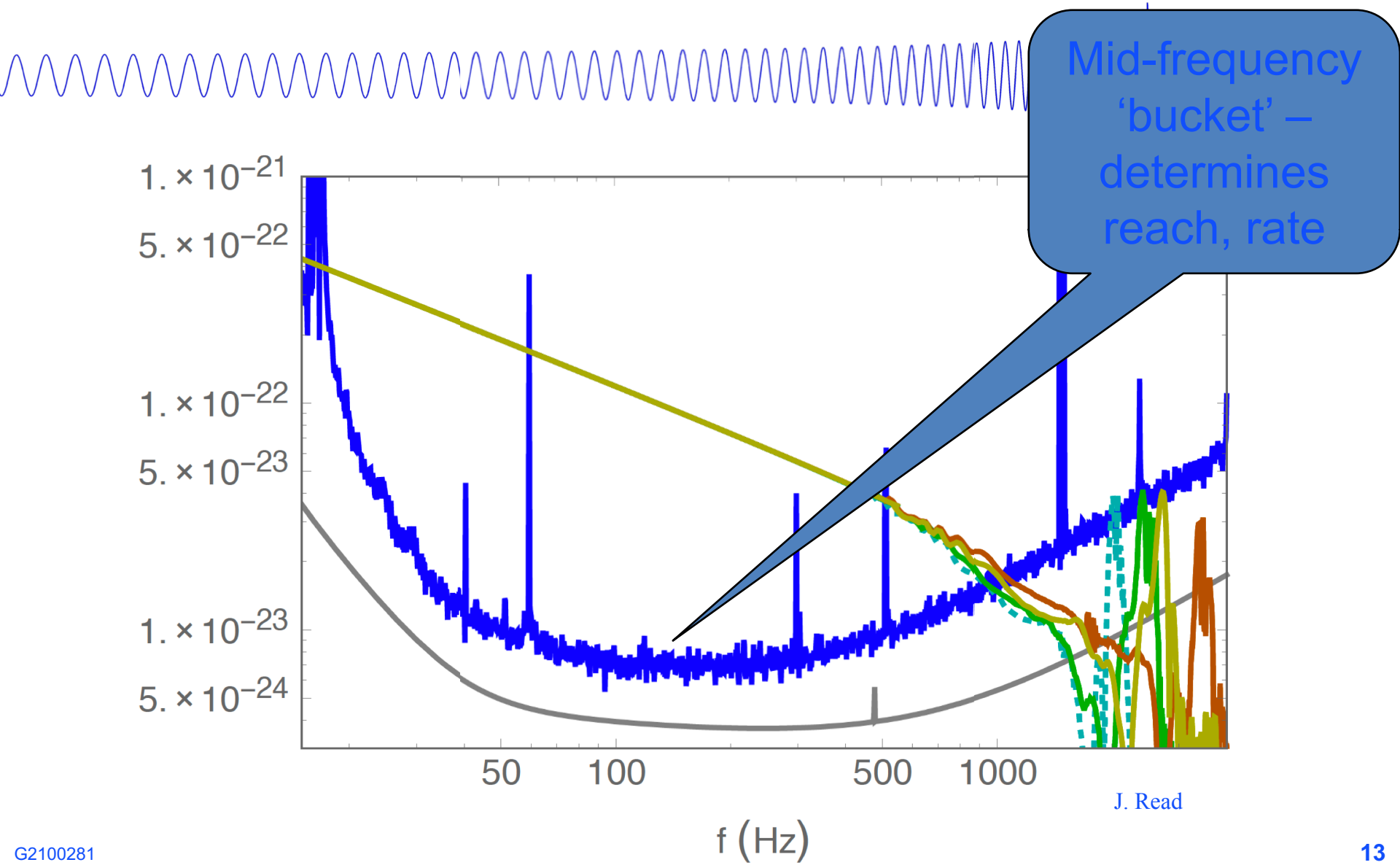

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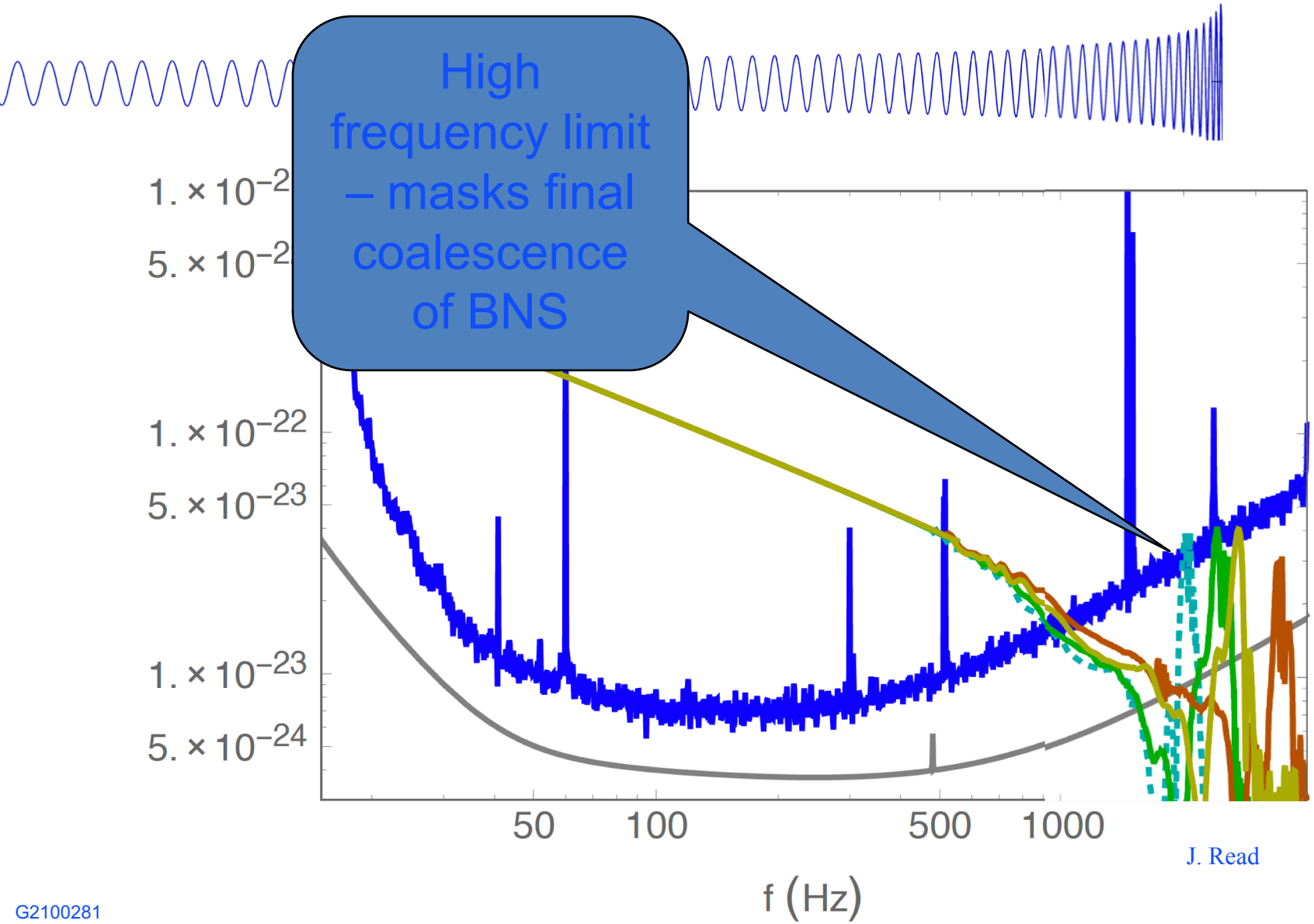
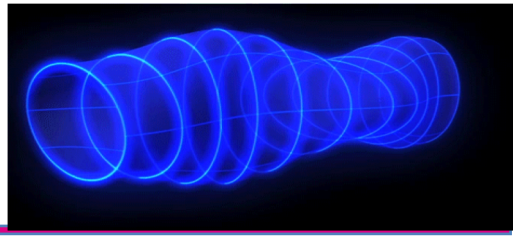
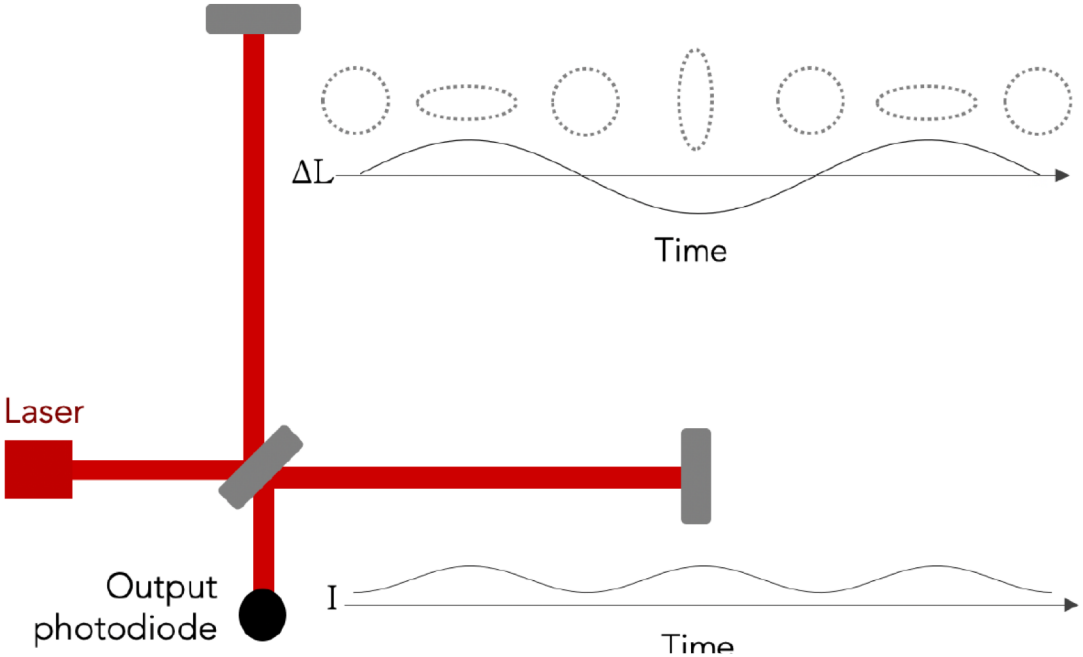


What is our measurement technique?

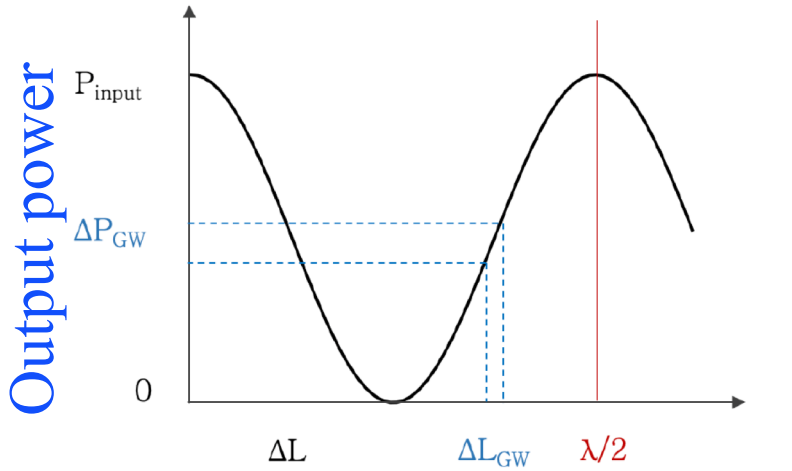


- Enhanced **Michelson interferometers**
- GWs modulate the distance between the end test mass optic and the beam splitter
- The interferometer acts as a transducer, turning GWs into photocurrent proportional to the strain amplitude



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

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



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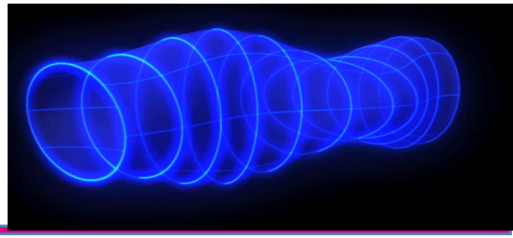

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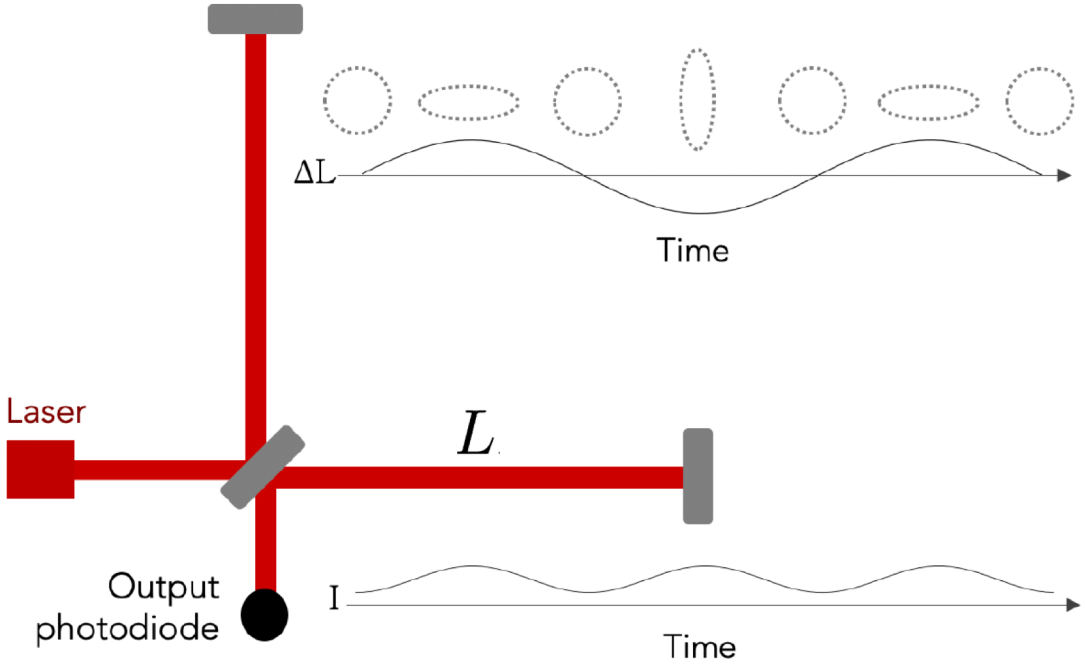
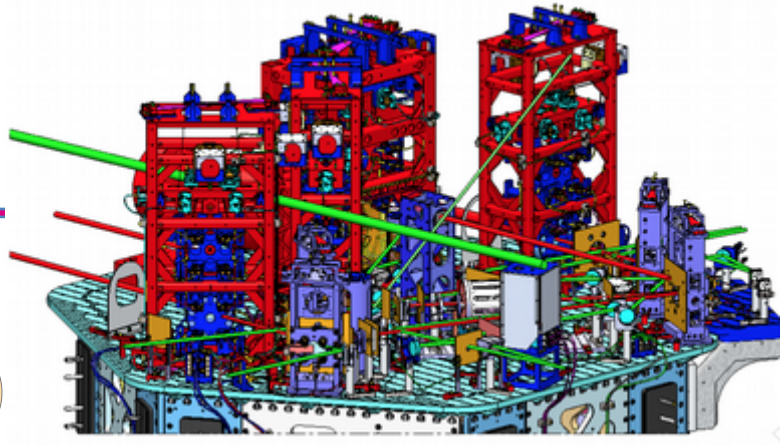
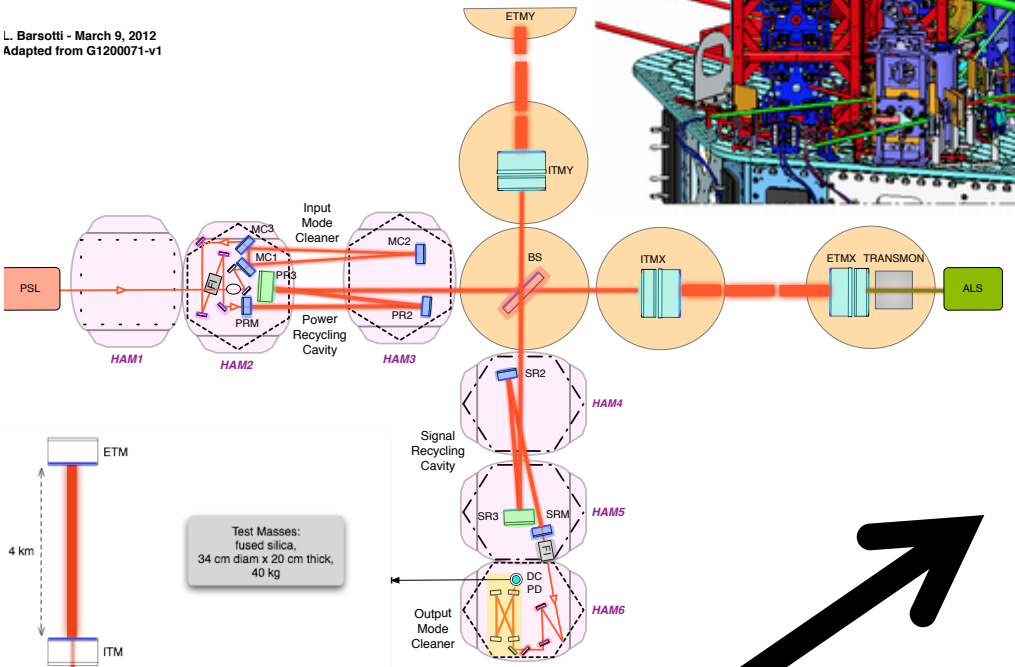


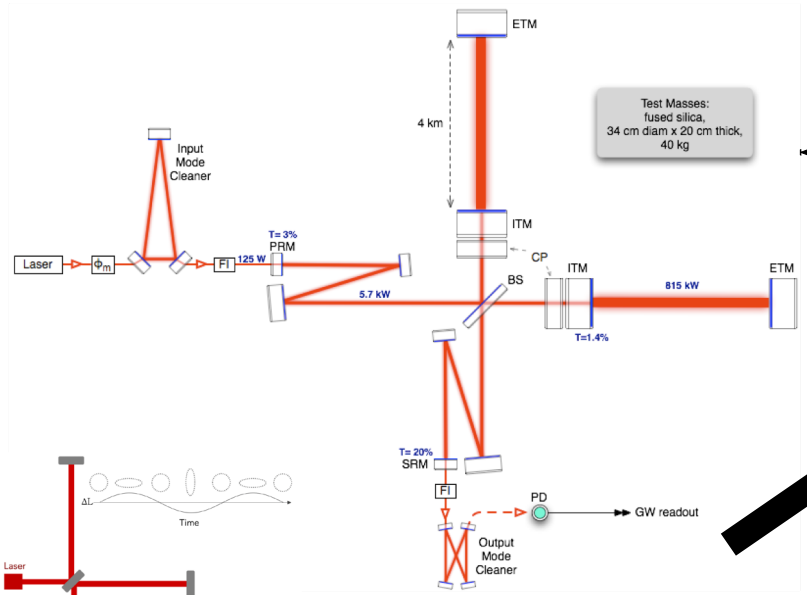
$$\Delta P_{\mathrm{GW}} \sim hLP_{\mathrm{laser}}/\lambda_{\mathrm{laser}}$$

- 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**





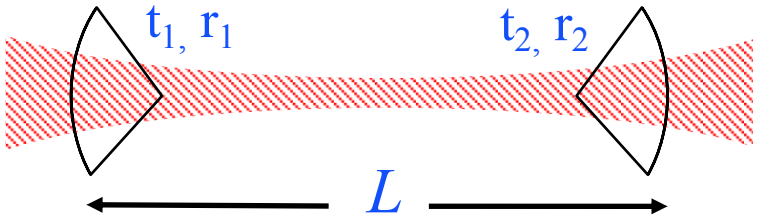


Reality axis

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

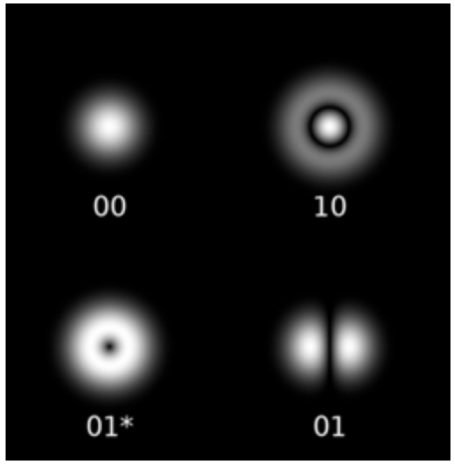
Basic building blocks: Optical Resonant Cavities

- Provides spatial and frequency boundary conditions for laser light
  - » If the length is constant, the resonant frequency is also; provides a frequency reference
  - » For a given mirror separation and radius of curvature, fixed transverse modes are resonant; others anti-resonant (so acts as a 'mode cleaner')
    - – Need to 'focus' the light to match the supported spatial mode
  - » Provides 'optical gain' *G* – stores photons; typically 10^2 – 10^3 for LIGO



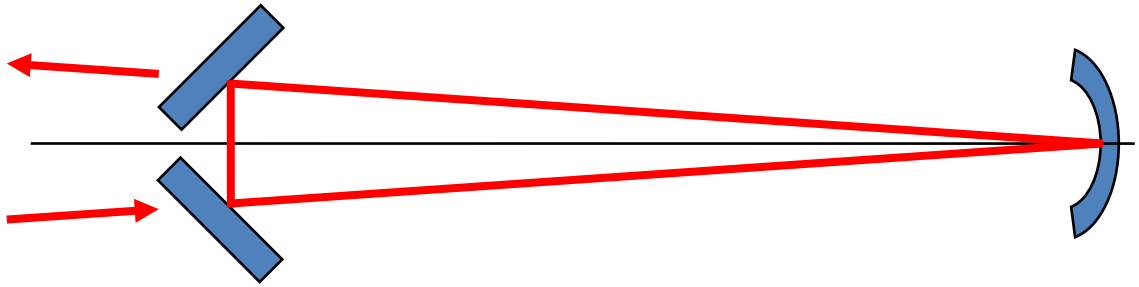
$$\nu \Rightarrow \nu + FSR, \quad FSR = \frac{c}{2L}$$

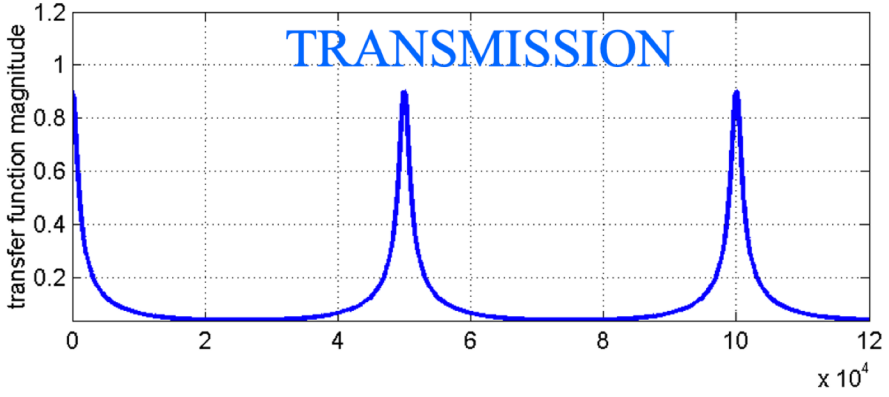
$$G = \left(\frac{t_1}{1 - r_1 r_2} \right)^2$$

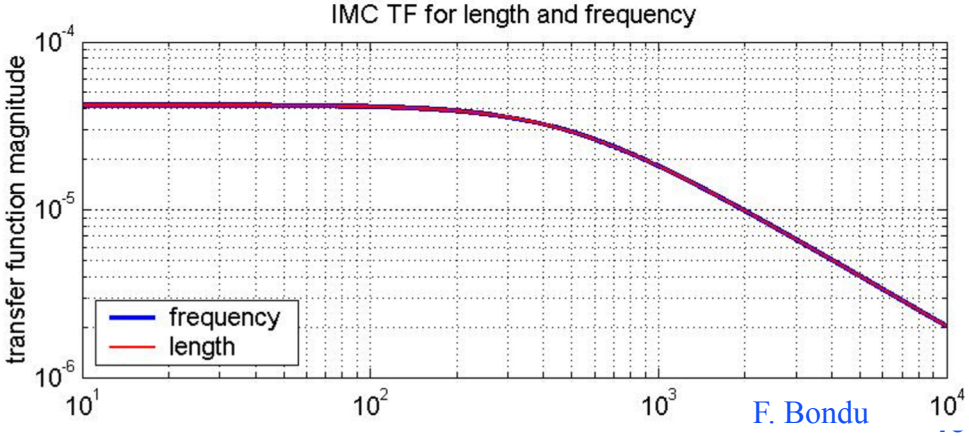


Basic building blocks: Optical Resonant Cavities

- Triangular cavities are practical for use in transmission
- Defines an optical axis; rejects light not in Gaussian fundamental mode
- Acts as a ‘low pass filter’ for intensity fluctuations

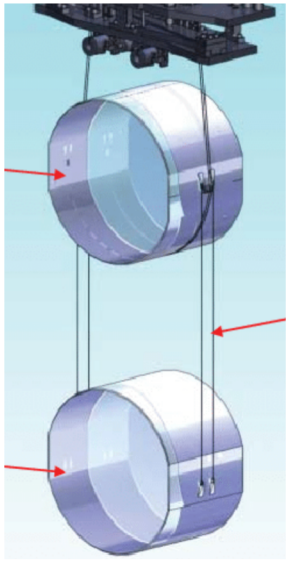


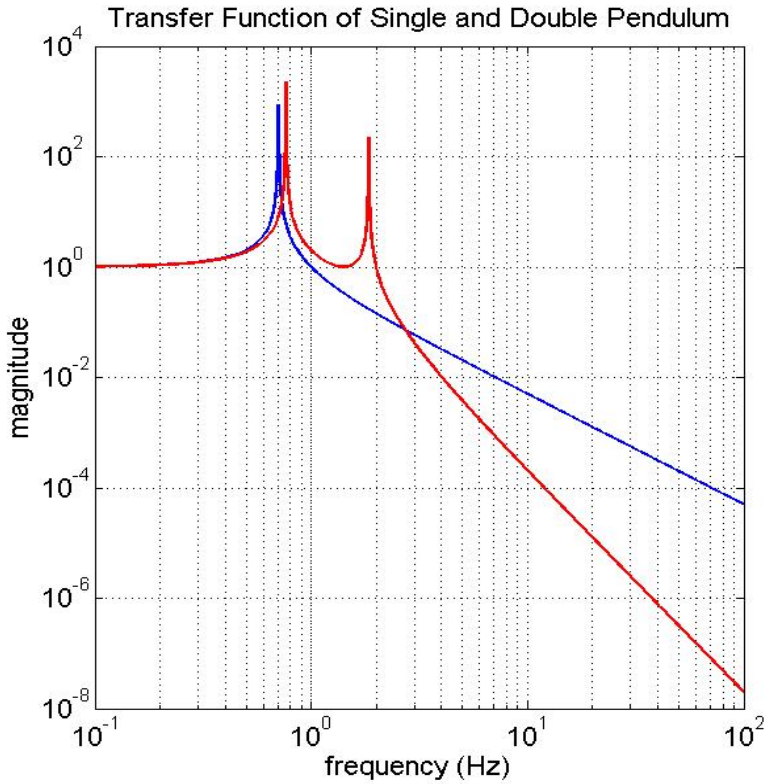




Basic Building Blocks: Pendulums

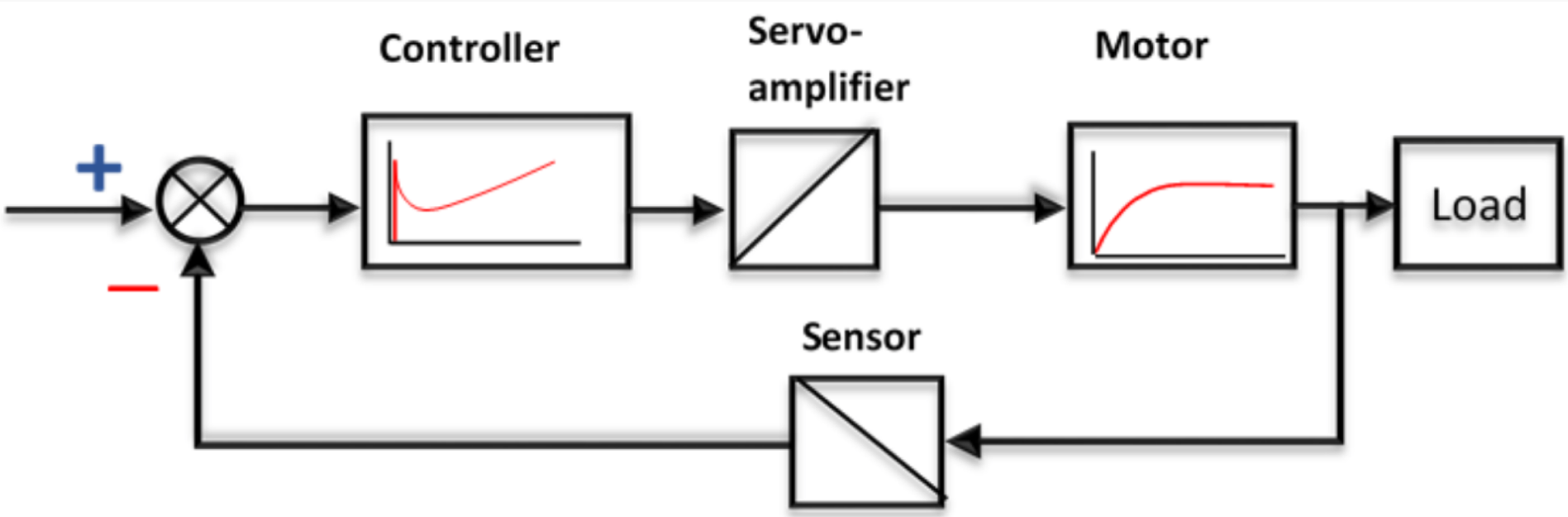
- Pendulum suspensions for optics which serve as test masses
- Need test masses to be ‘free’ in along the relevant measurement axis
- Ground-based detectors operate in Earth’s gravitational field
- Hang optics like a clock pendulum;
  above the resonant frequency, mirror is ‘free’
- Inertia of the mass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





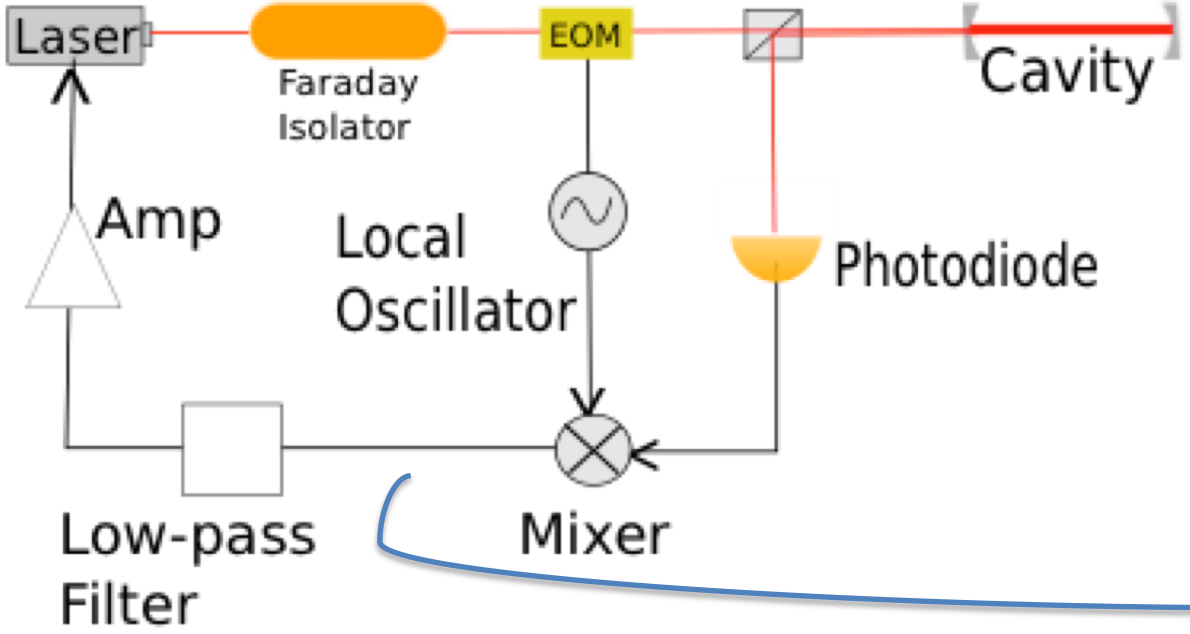
Basic Building Blocks: Servo control systems

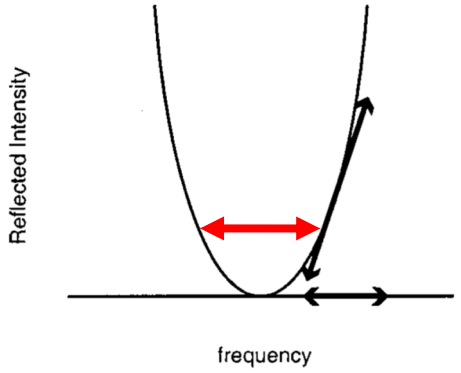
- Used throughout gravitational-wave detectors
- Longitudinal control: holding optical cavities on resonance
  - » Maintaining laser frequency compatible with reference cavity
- Angular controls: keeping optical cavities aligned with optical axes
- Suppressing noise – 'Null' servoes maintaining measured quantity to zero, and reading out control signal as measure of system

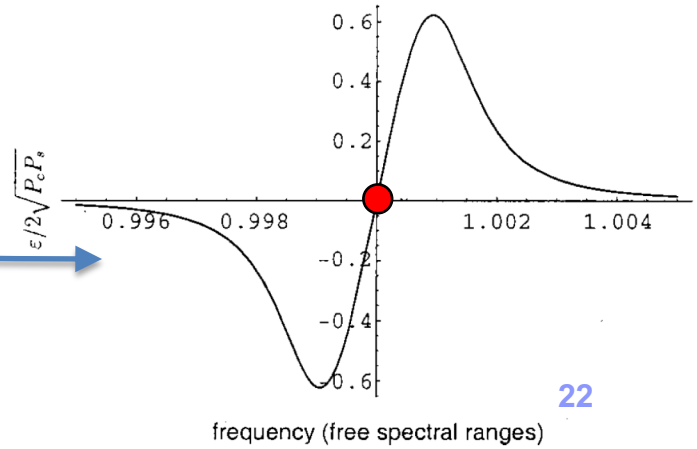


Basic Building Blocks: Pound-Drever-Hall Cavity control

- Modulation (Electro-Optic Modulator) effectively sweeps the frequency back and forth over cavity resonance
- Mixer effectively takes difference of signal above and below resonance
  - Equals zero if on resonance
- Send this 'error signal' back to control laser frequency – or cavity length







E.Black,AJP 69-79, 2001

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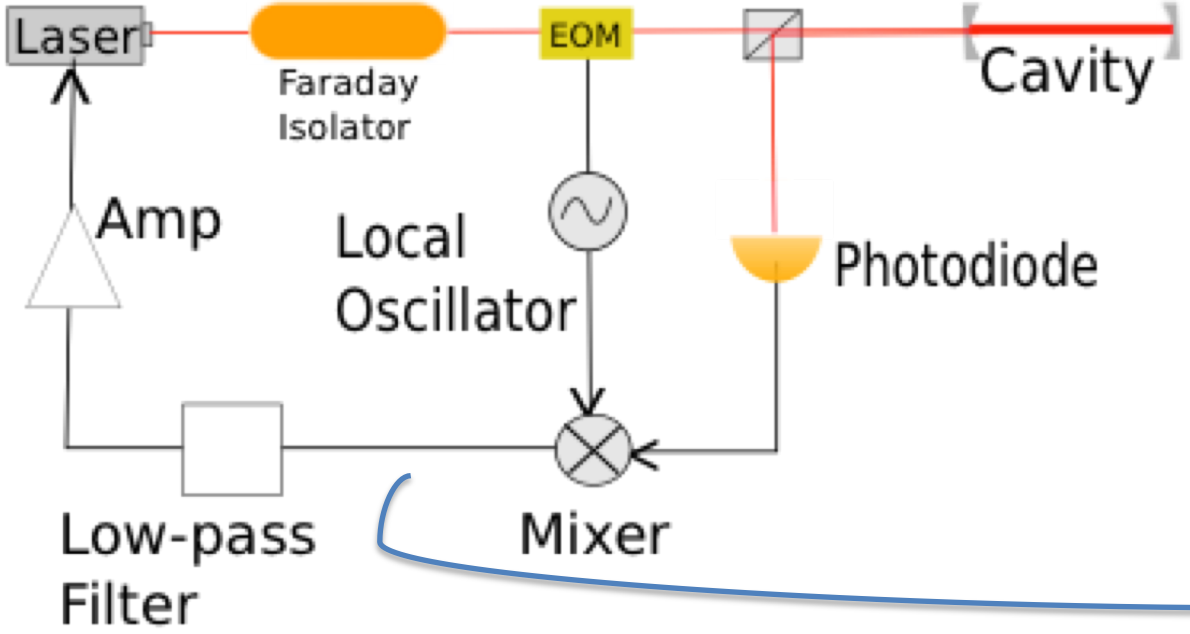

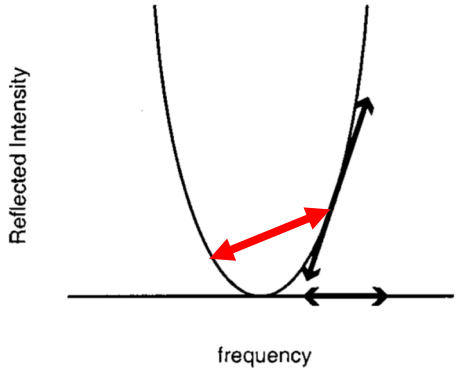

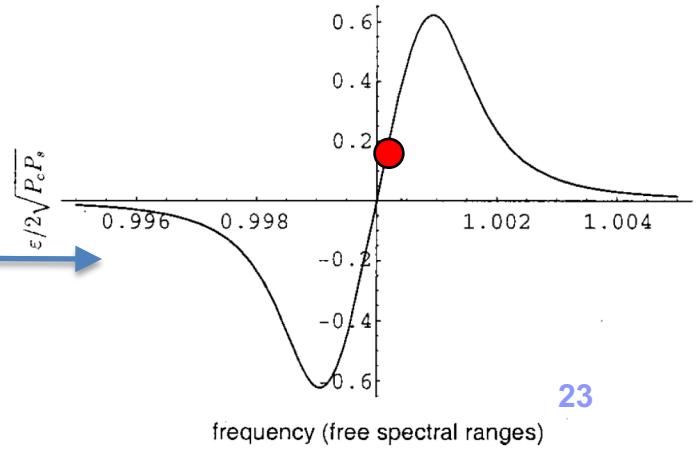

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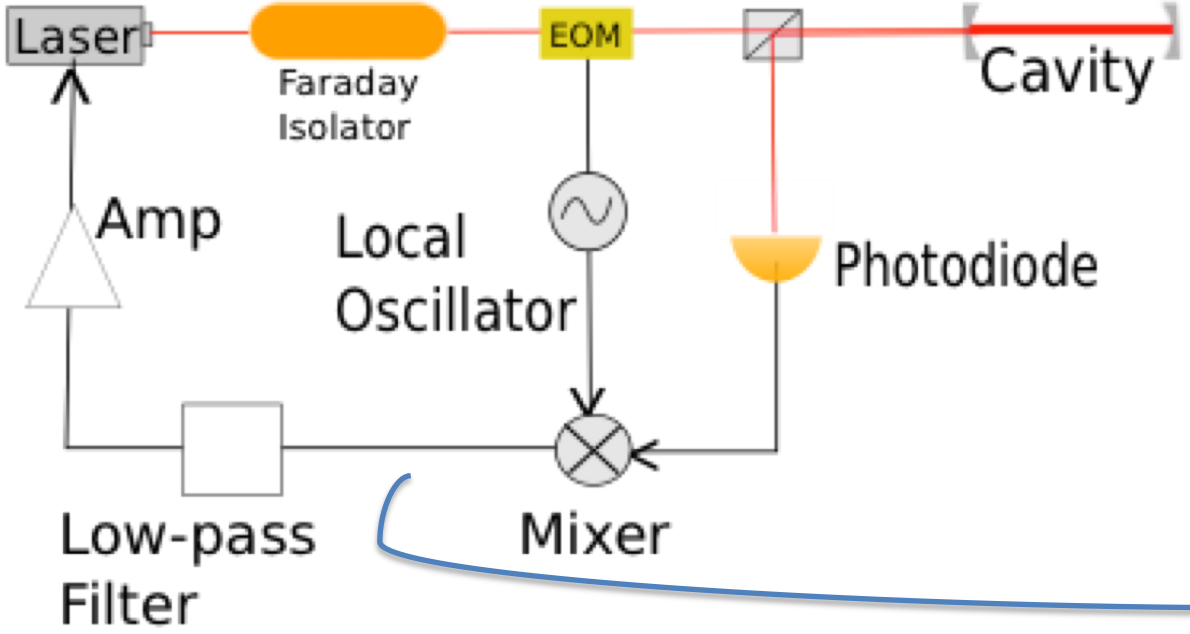
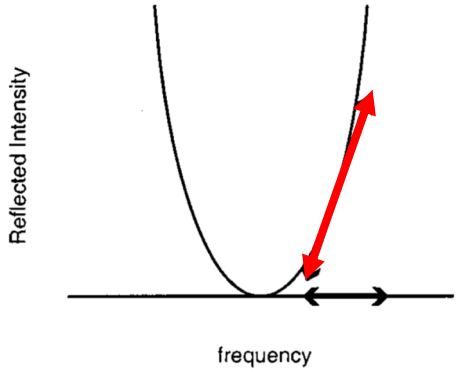
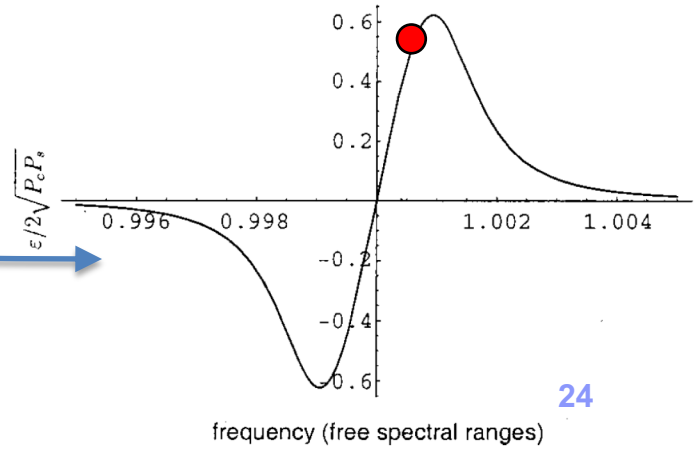






E.Black,AJP 69-79, 2001

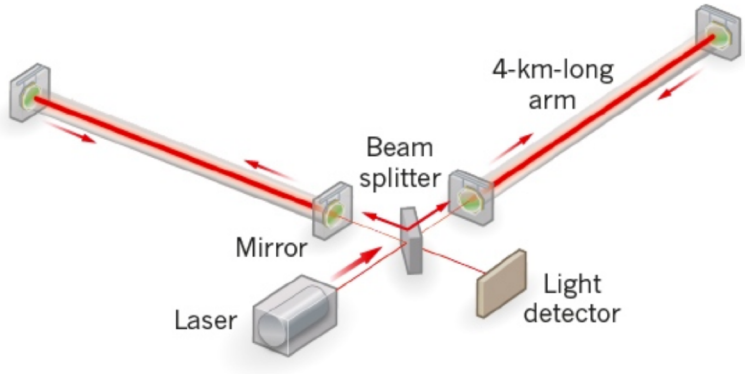
Useful paradigm in considering limits to detector sensitivity

- **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

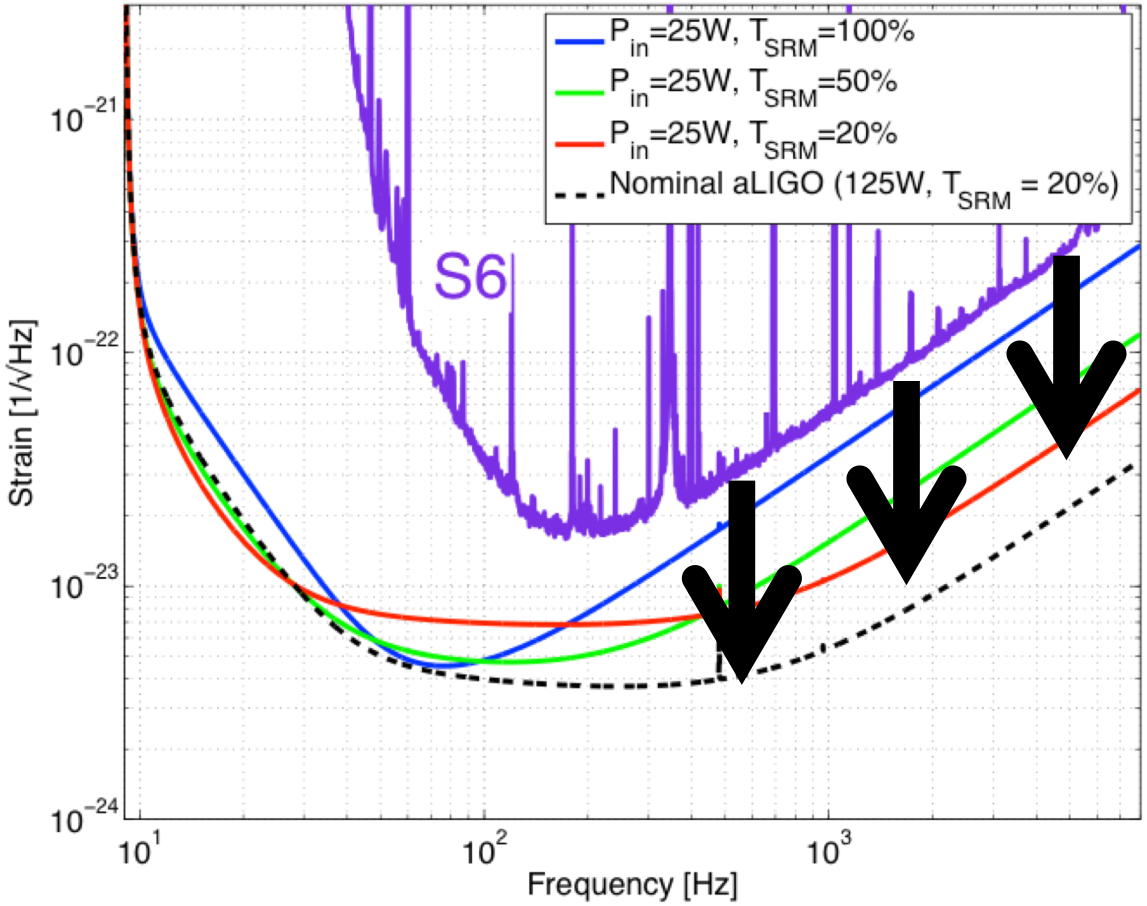
What are the ‘fundamental’ limits to sensitivity?

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)$^{1/2}$

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



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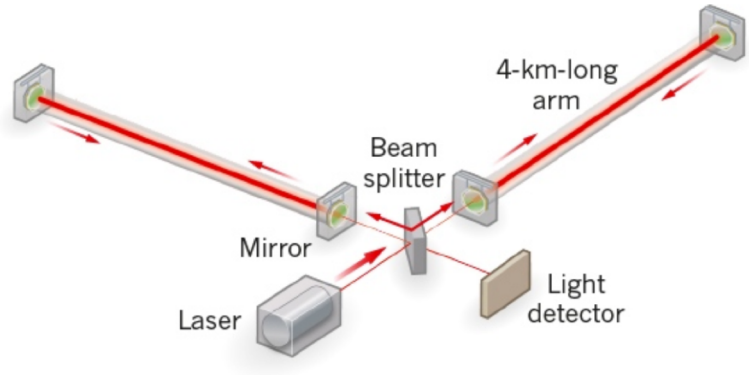
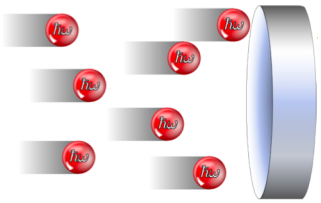


- Shot noise – ability to resolve a fringe shift due to a GW (counting statistics)

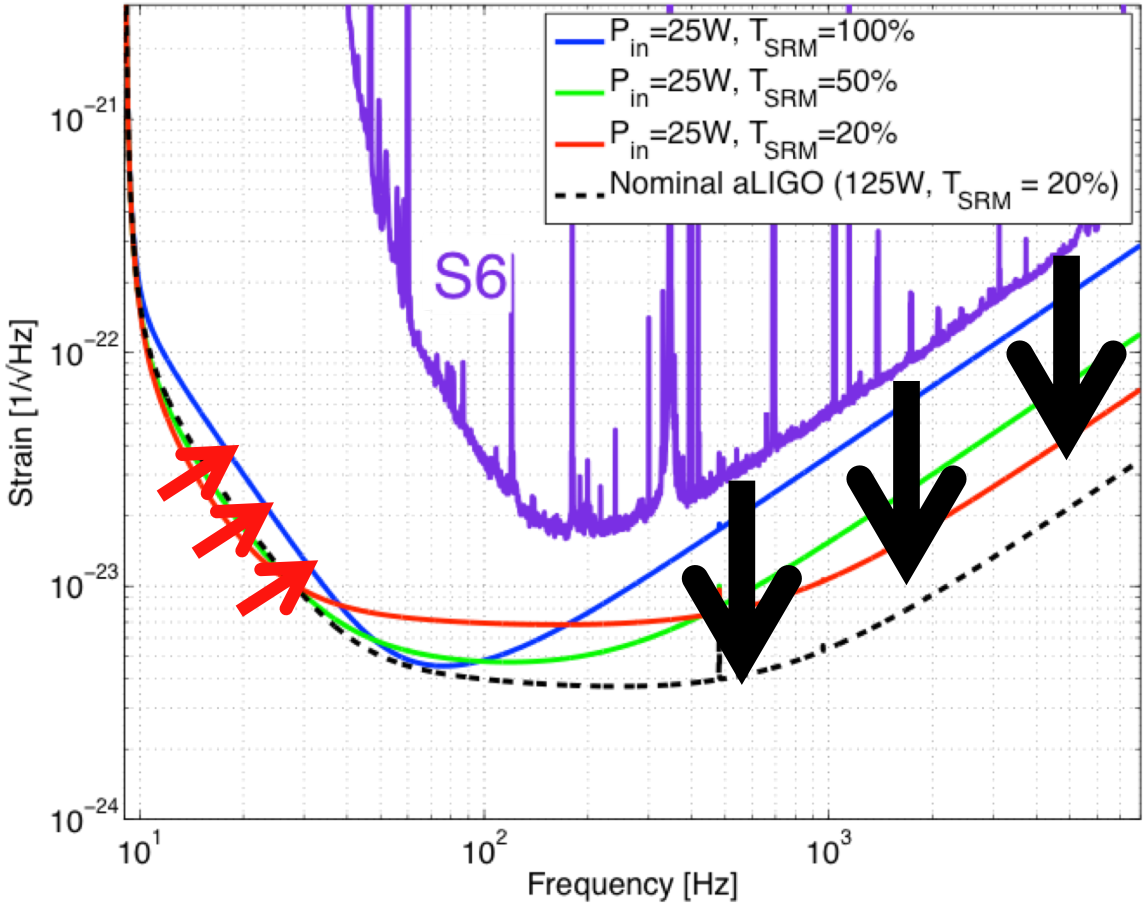
$$h_{\rm sn}(f) = \frac{1}{L}\sqrt{\frac{\hbar c\lambda}{2\pi P}}$$

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

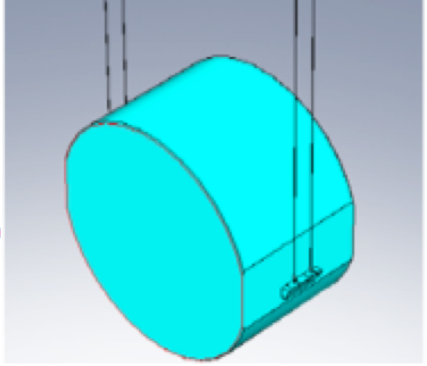


$$h_{\rm rp}(f) = \frac{1}{mf^2L}\sqrt{\frac{\hbar P}{2\pi^3 c\lambda}}$$

- **'Standard Quantum Limit'**



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



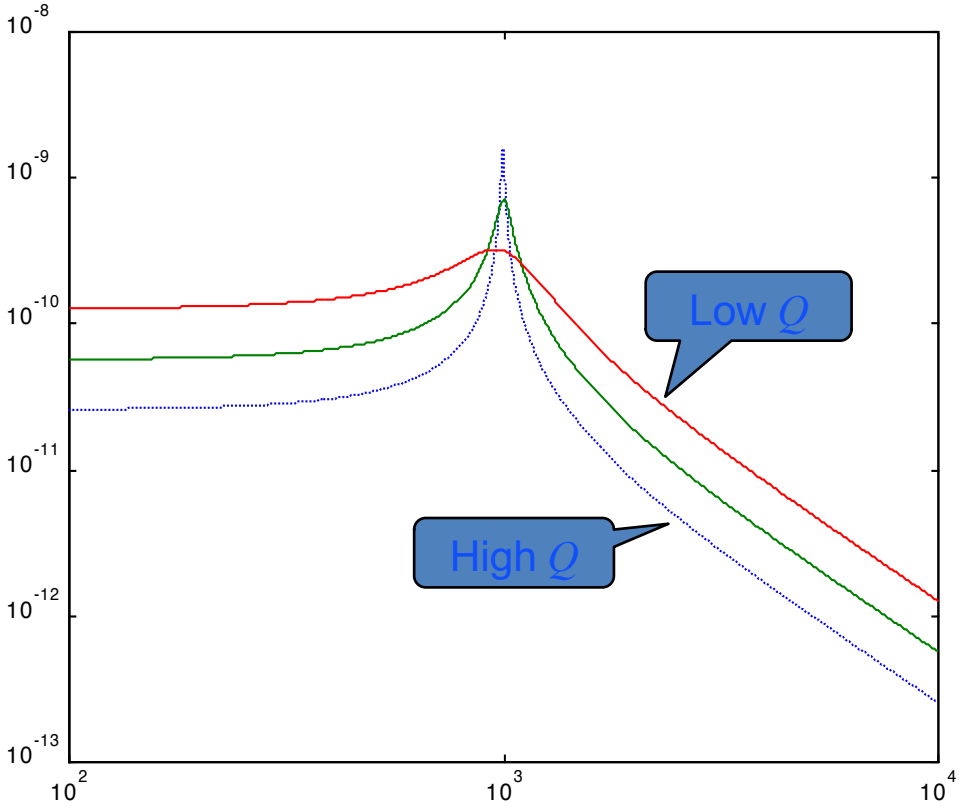
- **Thermal noise** – kT of energy per mechanical mode
- *Über die von der molekularkinetischen Theorie der Wärmegeforderte Bewegung von in ruhenden Flüssigkeiten suspendierten Teilchen*, A. Einstein, 1905
- Simple Harmonic Oscillator:

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

- 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**



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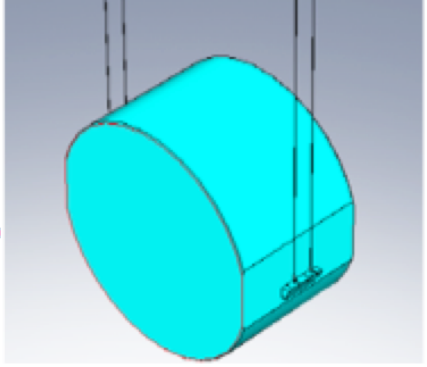

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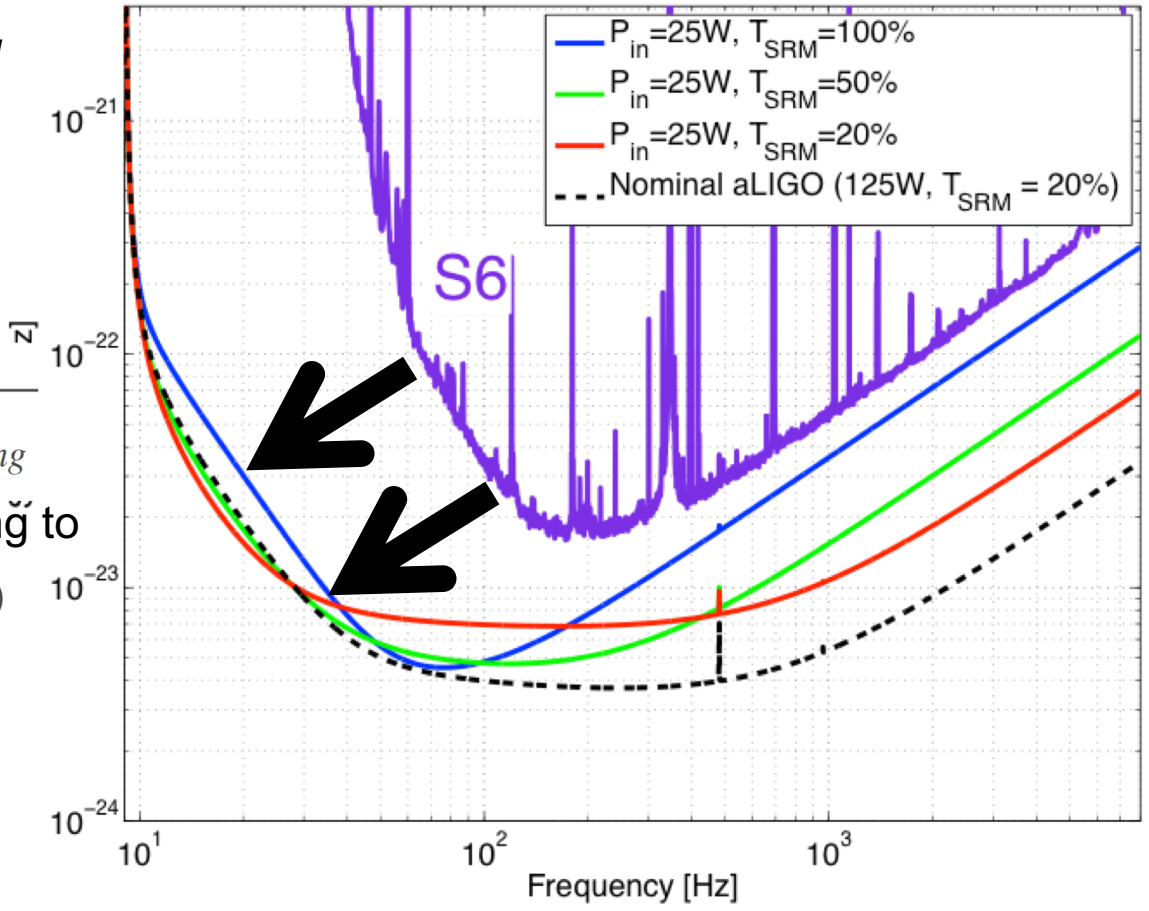

Measuring $\Delta L = 4 \times 10^{-18}$ m
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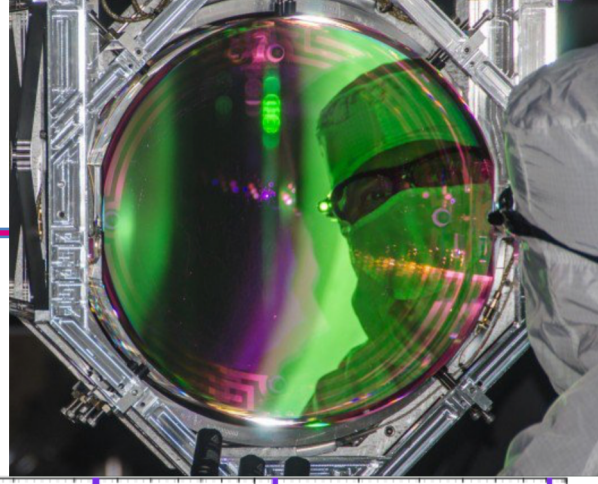
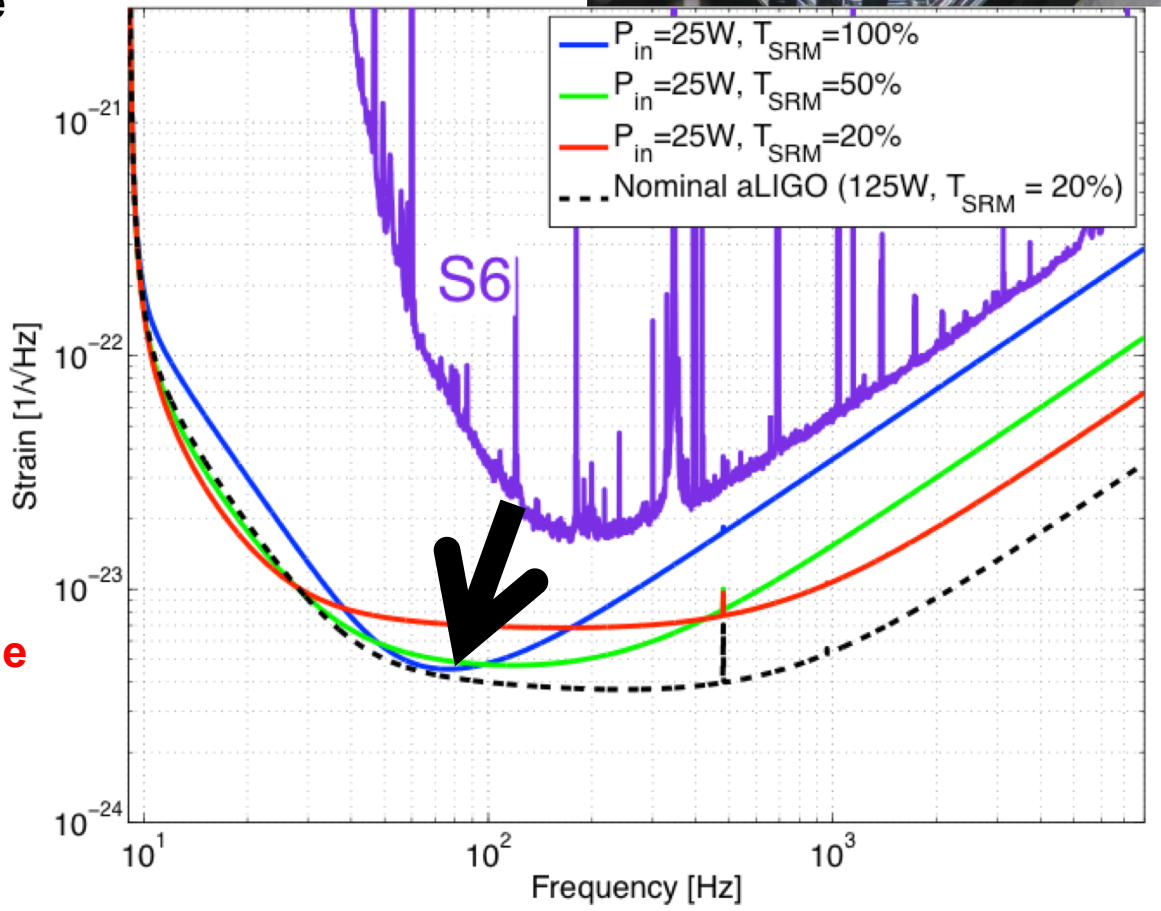
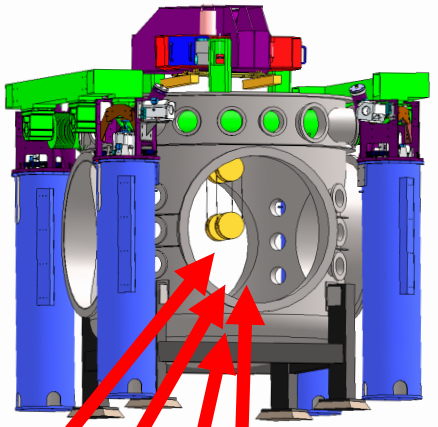


- In Advanced LIGO, the dielectric optical coating has a rather large loss tangent
  - » Some 10^{-4} , compared to 10^{-8} for fused silica
- The Fluctuation-Dissipation theorem says this is where the greatest motion is found
- And: the coating is the surface that is sensed by the laser



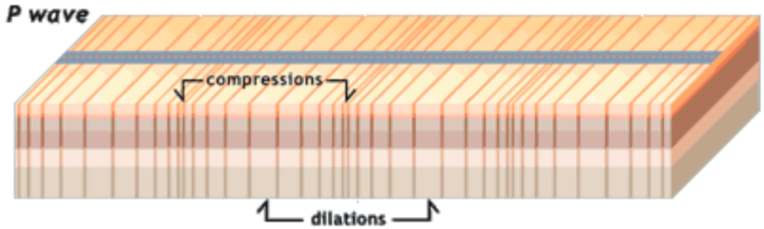
- **This is the dominant limit in the critical 50-200 Hz band**

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

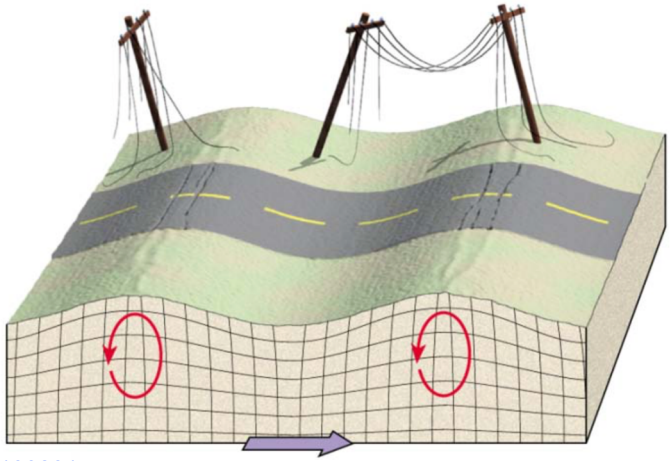


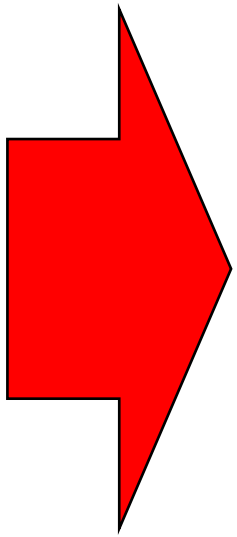
- Ultimate limit on the lowest frequency detectors on- or under-ground:
- **Newtownian background** – wandering net gravity vector; Forbiddingly large for ~3Hz and lower

Body waves

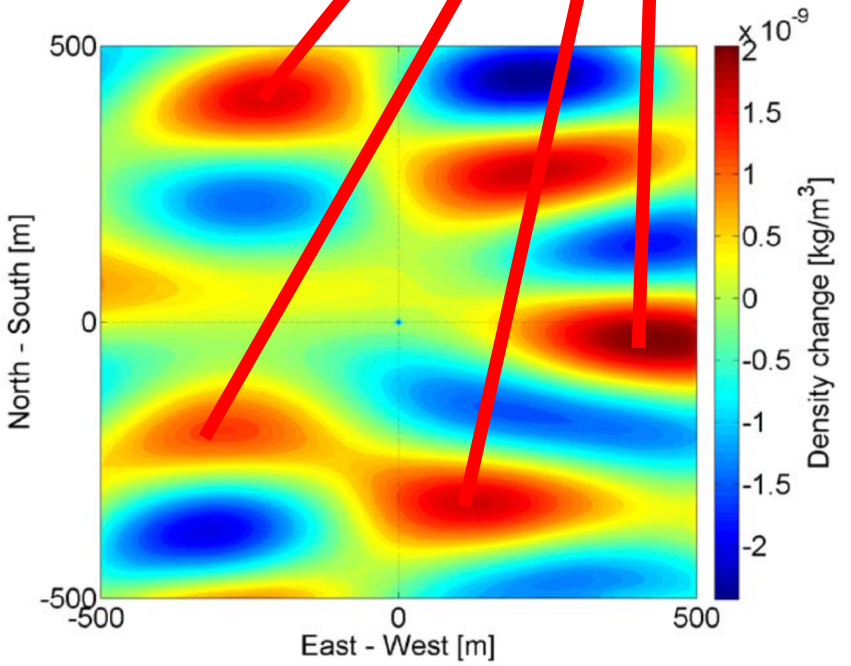


Rayleigh waves





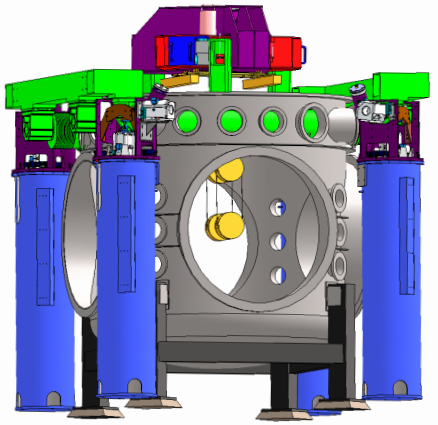
Density perturbation



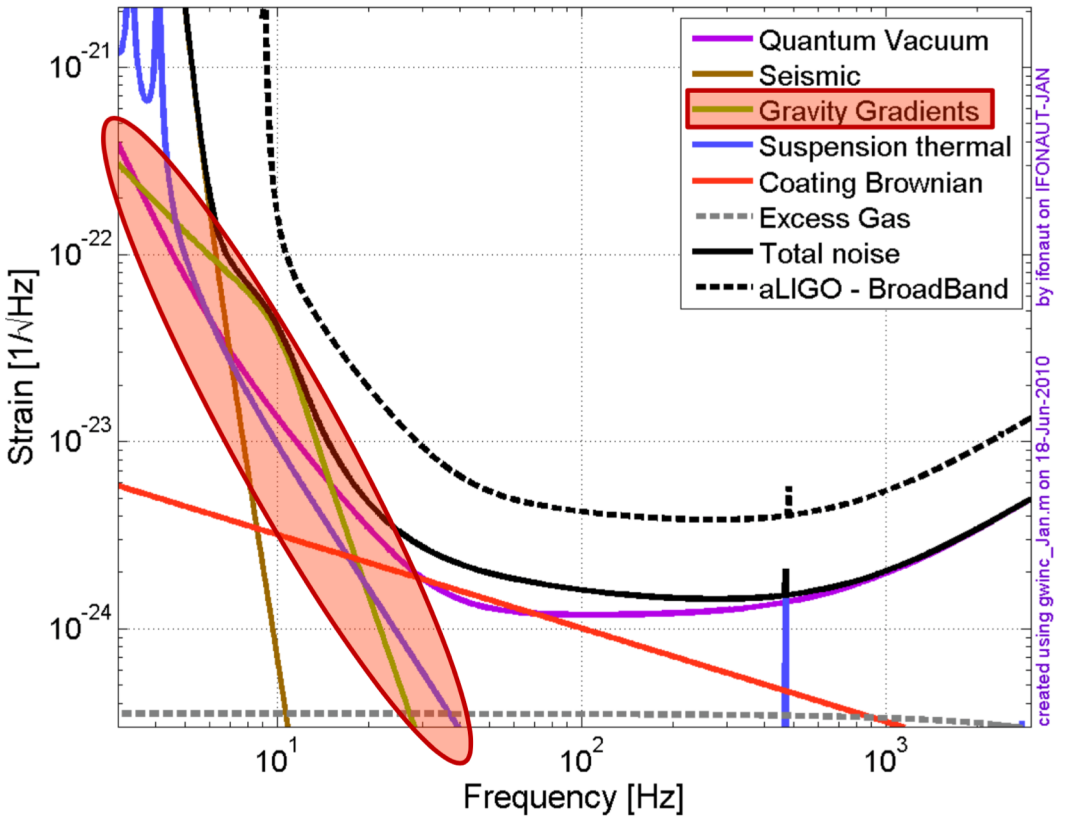
Density perturbations cause gravity perturbations.

Images: J. Harms

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



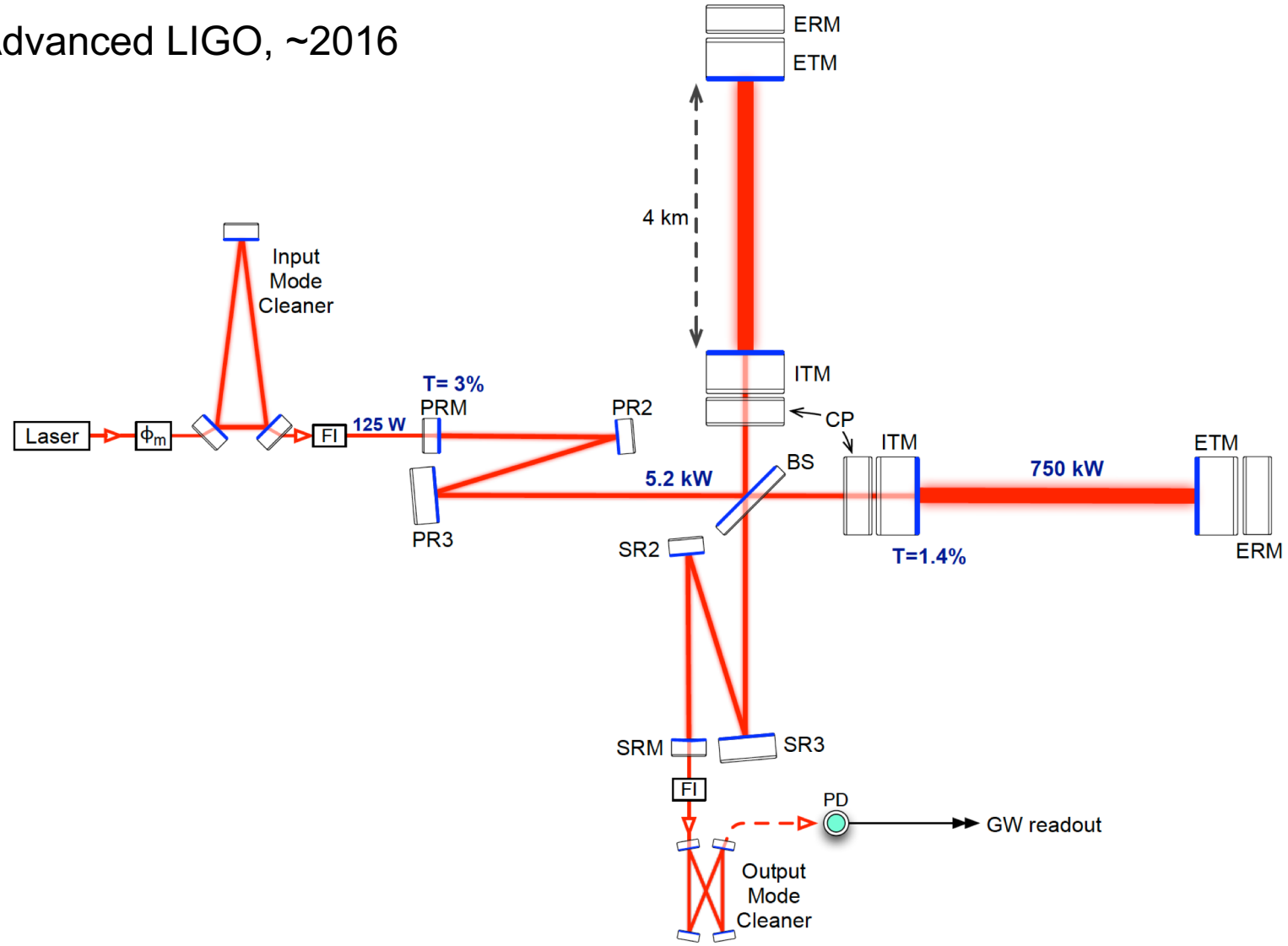
Images: J. Harms

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
- Second, use squeezed light to improve sensitivity
  - » Manage coupling between light intensity and light phase (pondermotive squeezing)
  - » Sneak around Heisenberg's uncertainty principle

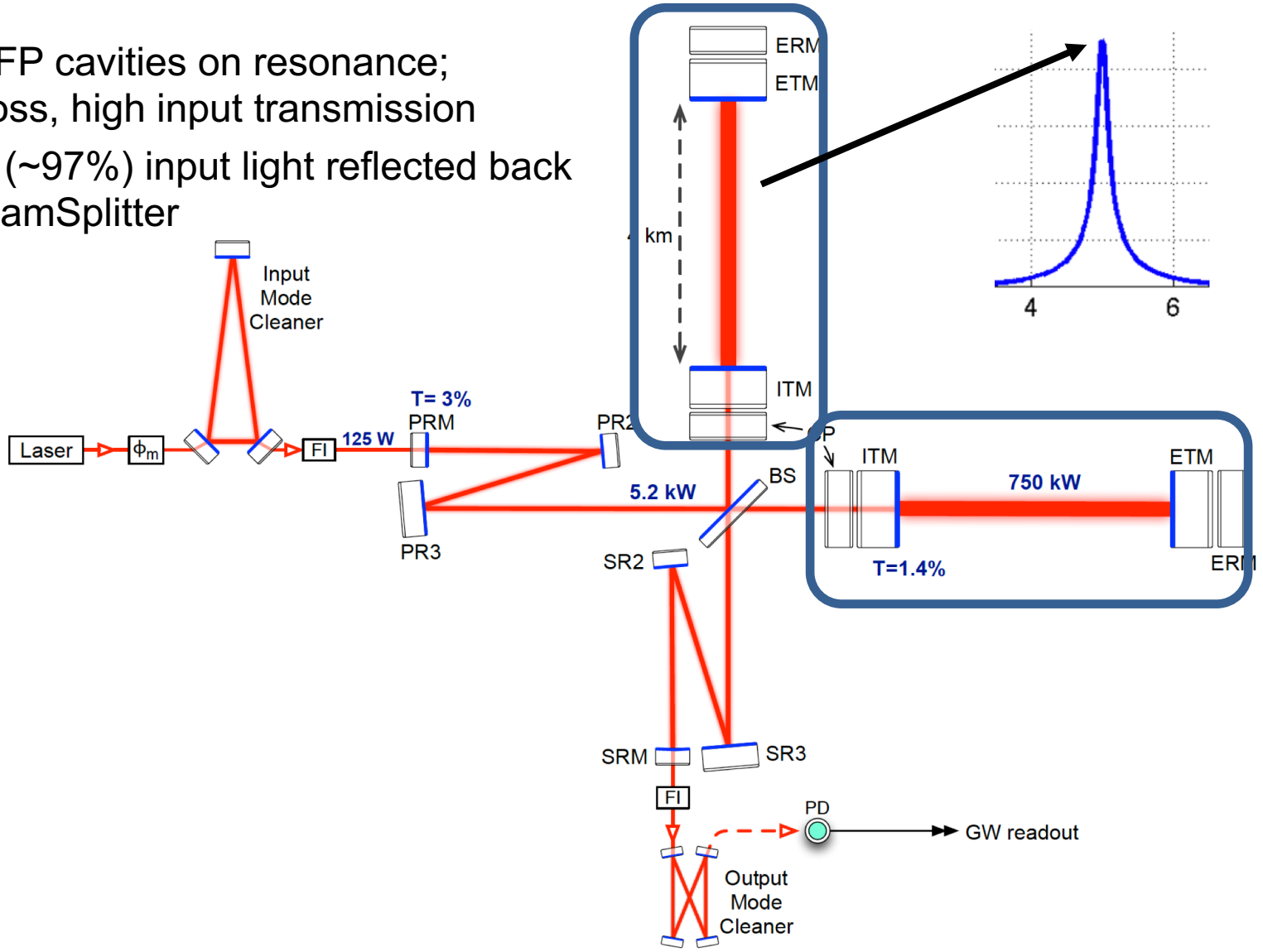
Power and Signal Recycling

- Advanced LIGO, ~2016



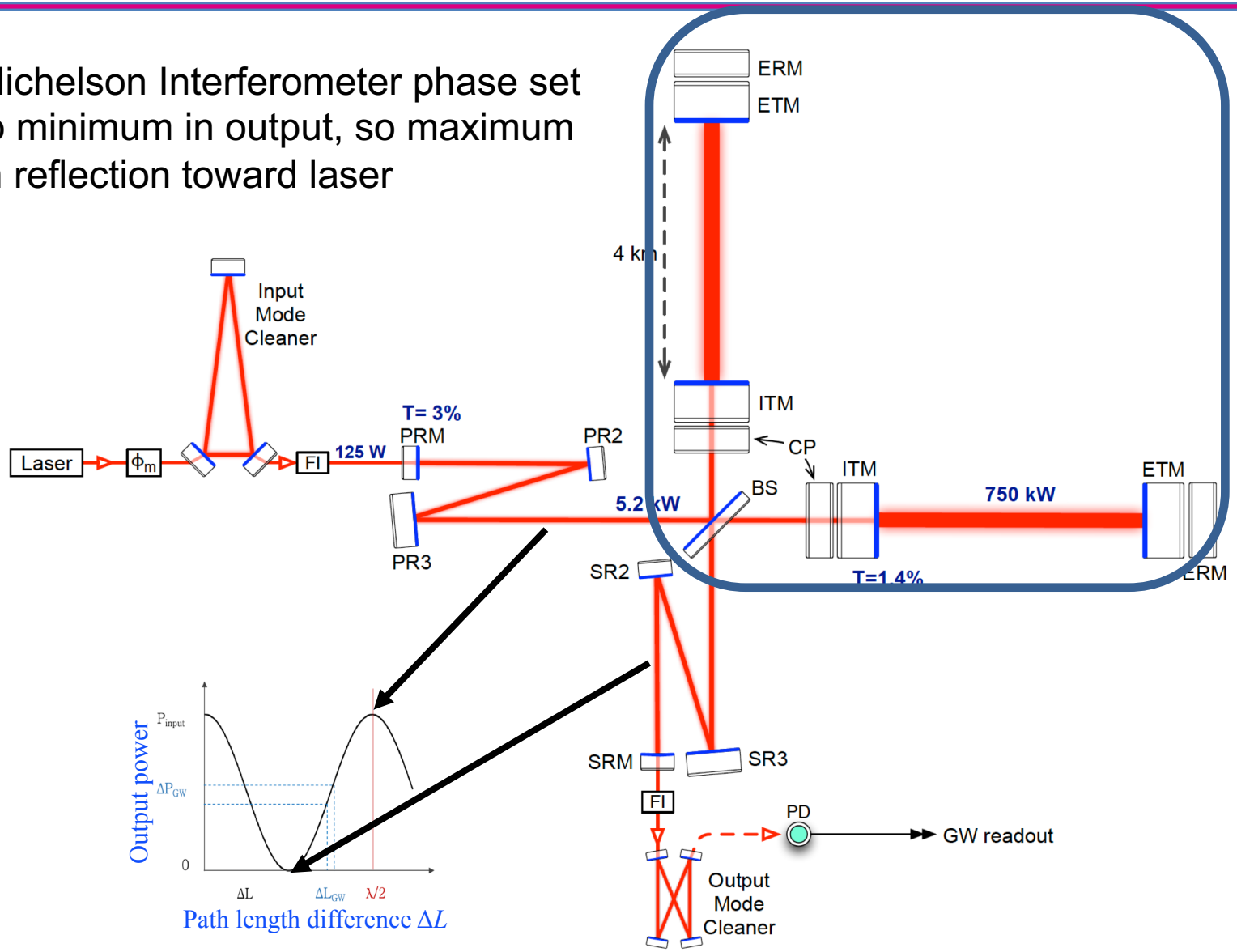
Power and Signal Recycling

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



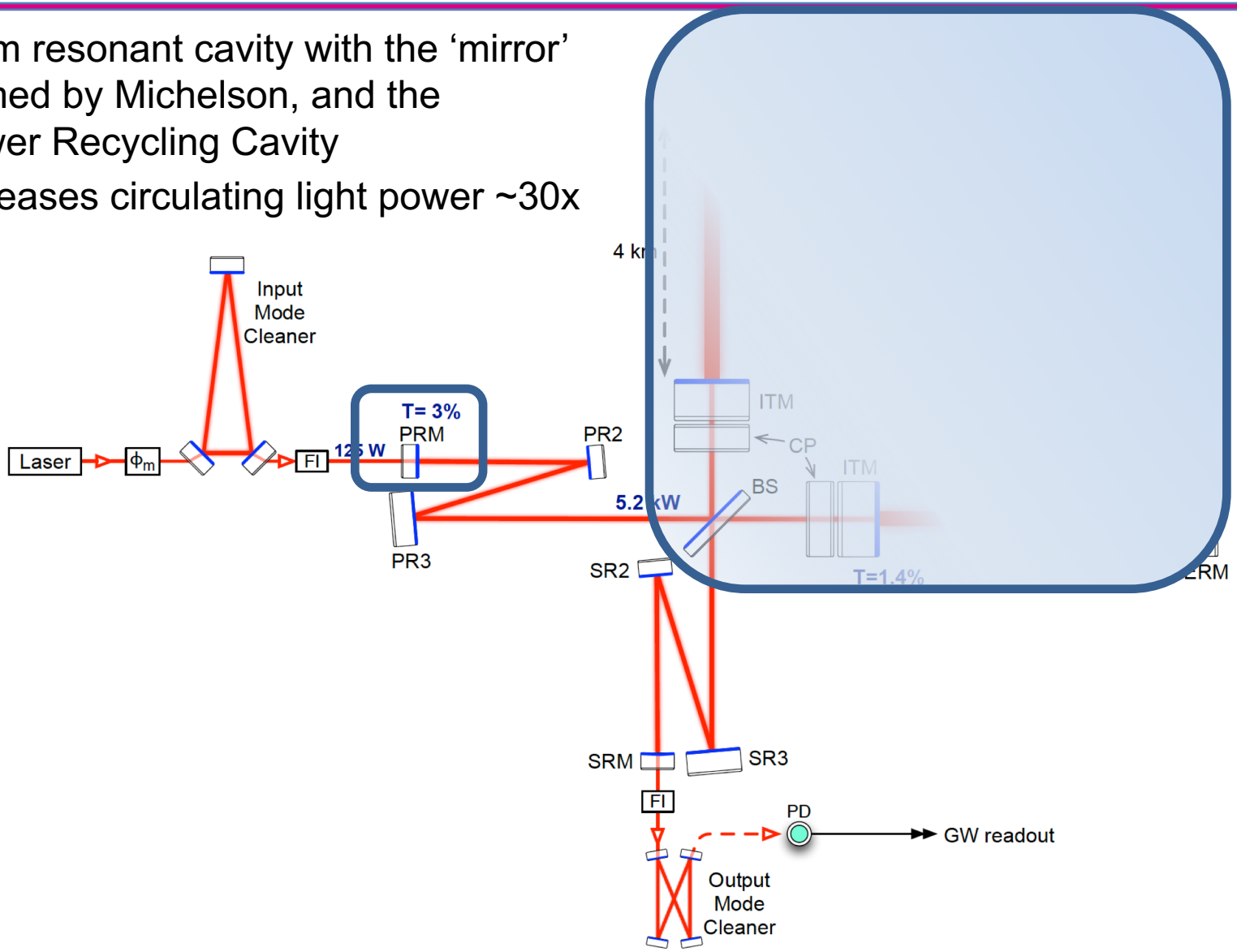
Power and Signal Recycling

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

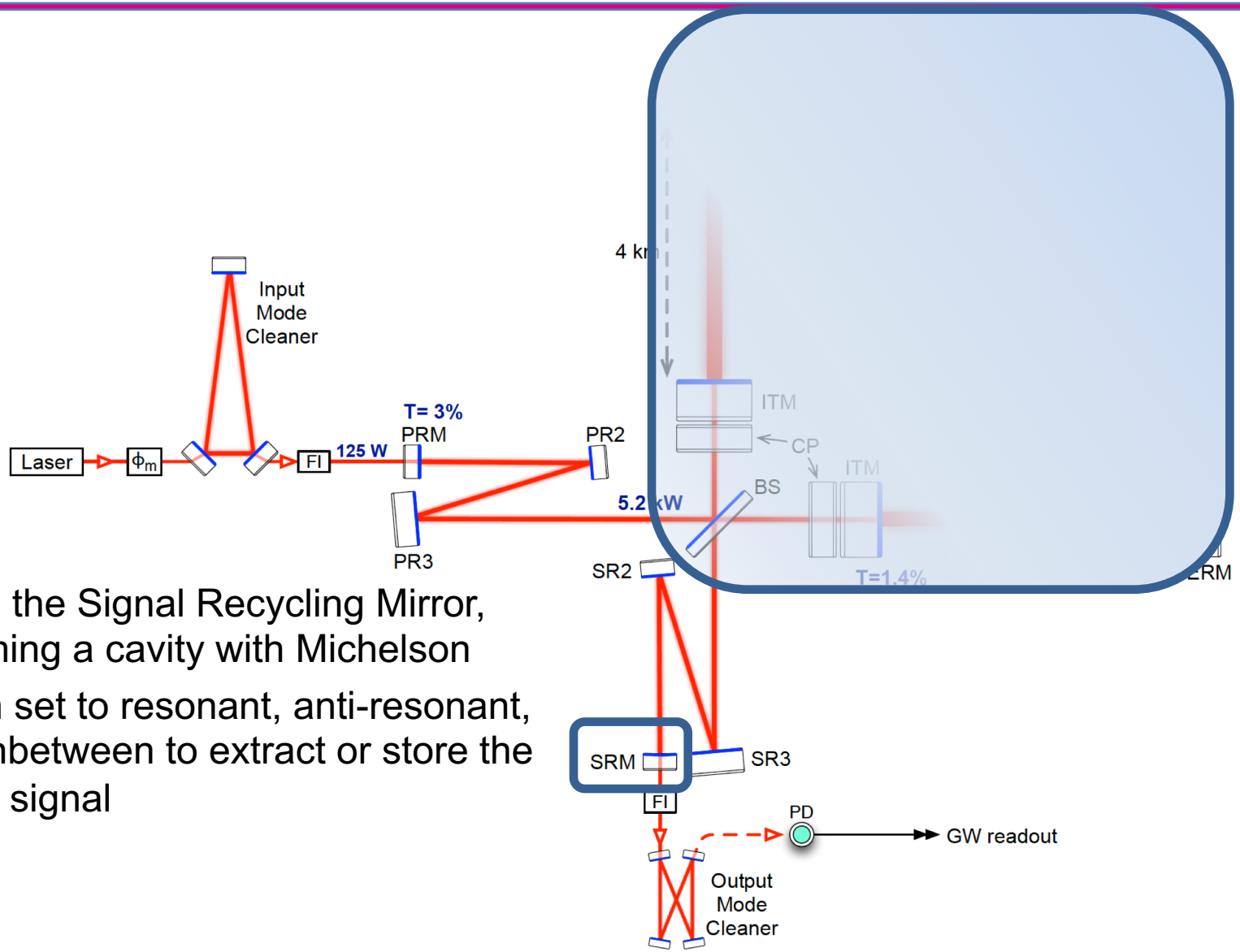


Power and Signal Recycling

- 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

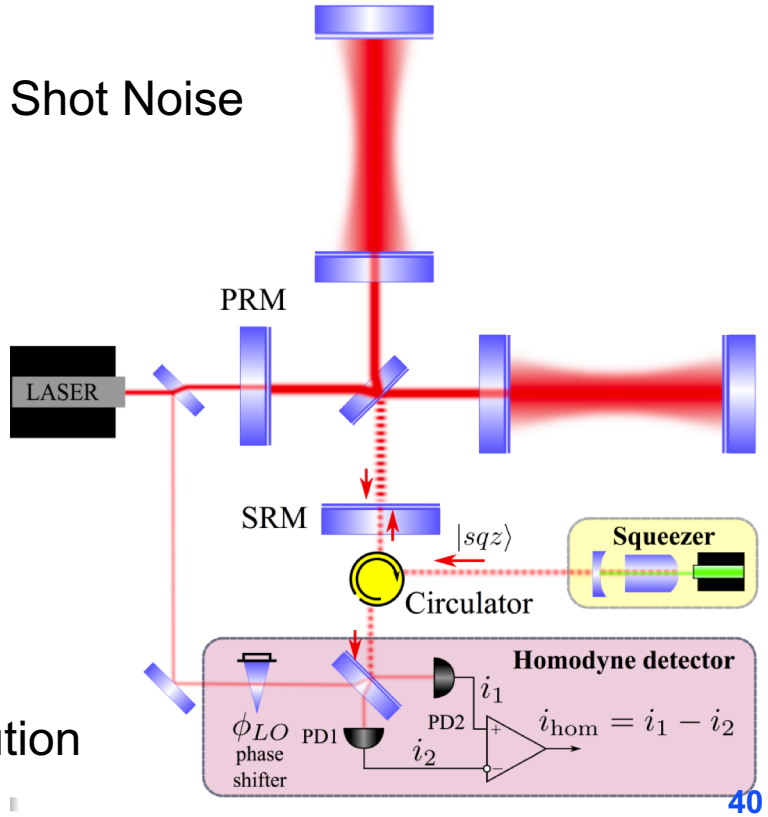
Squeezed light to reduce quantum noise

- 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

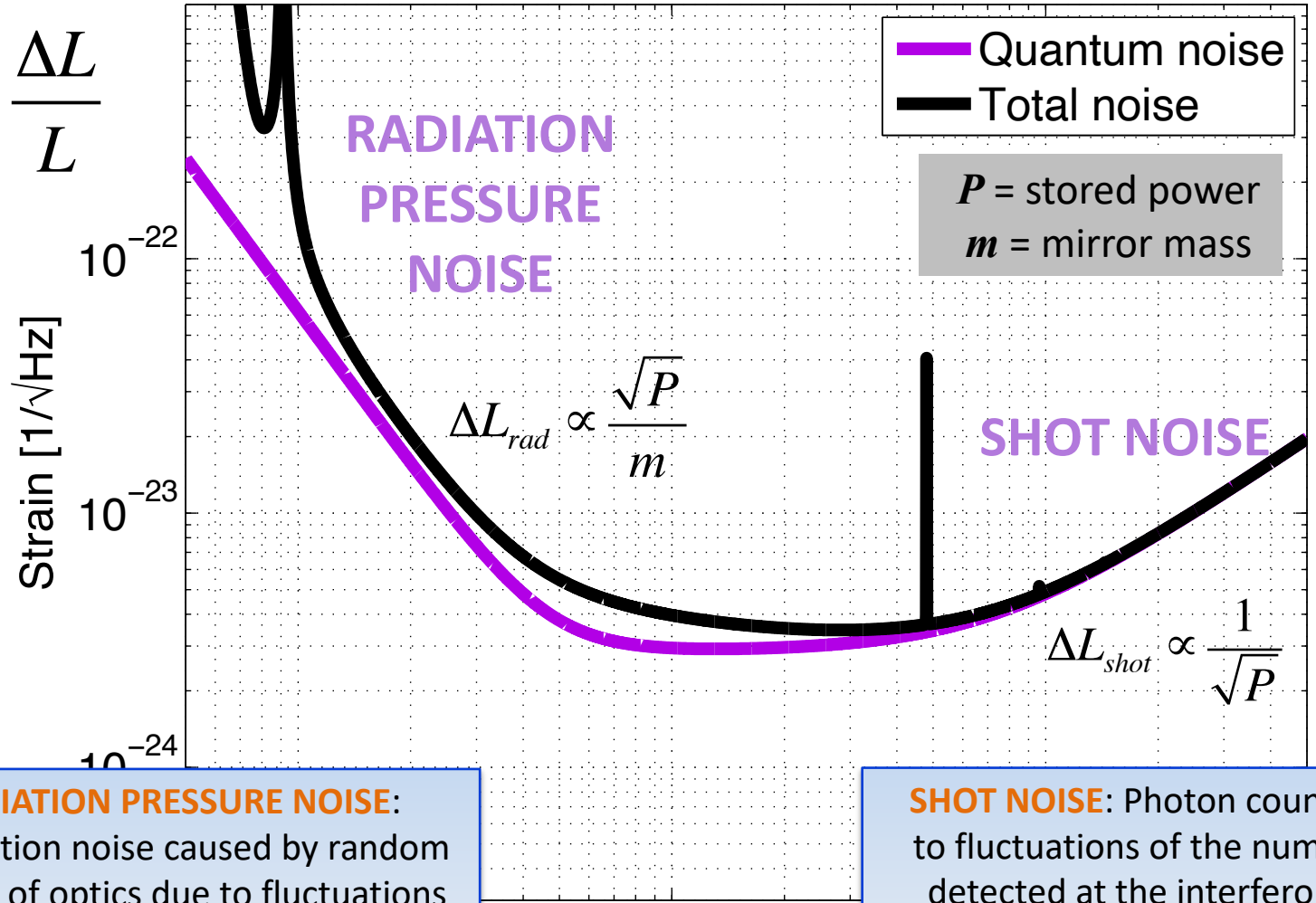
- Squeezing is made by creating pairs of photons using an optical parametric oscillator
- The pairs are quantum-mechanically entangled and have correlated arrival times at the detector
- This reduces the randomness of the time distribution



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

Quantum shot noise limits the high frequency sensitivity

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



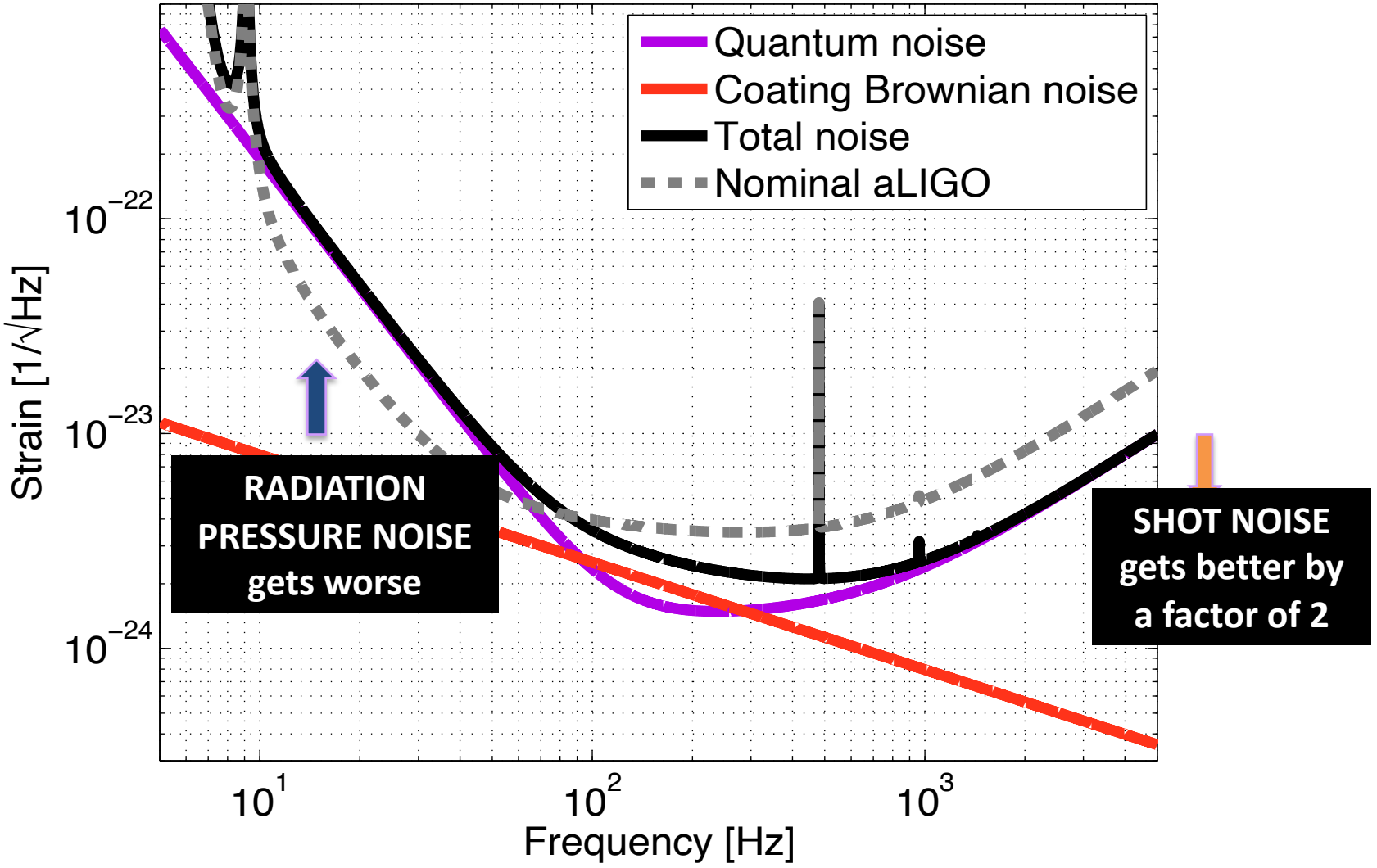
RADIATION PRESSURE NOISE: Back-action noise caused by random motion of optics due to fluctuations of the number of impinging photon
→ *Additional displacement noise*

M. Evans, Amaldi 11

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

Frequency Independent Squeezing

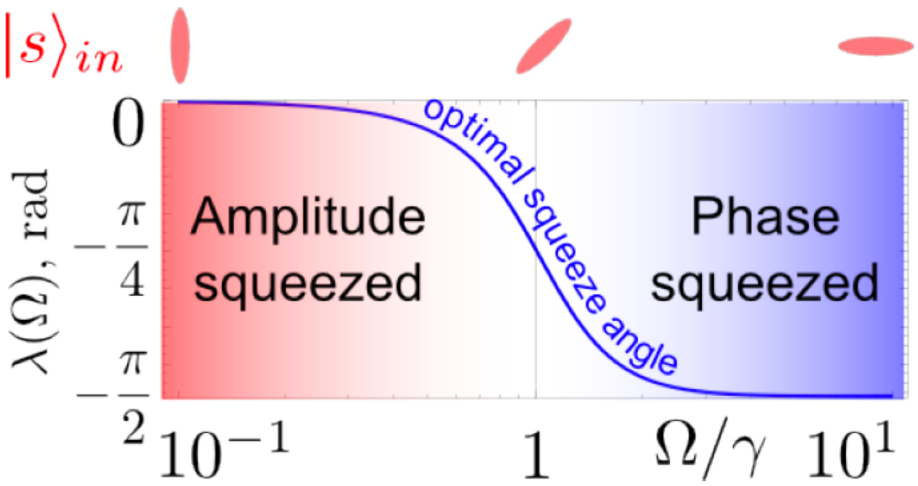
M. Evans

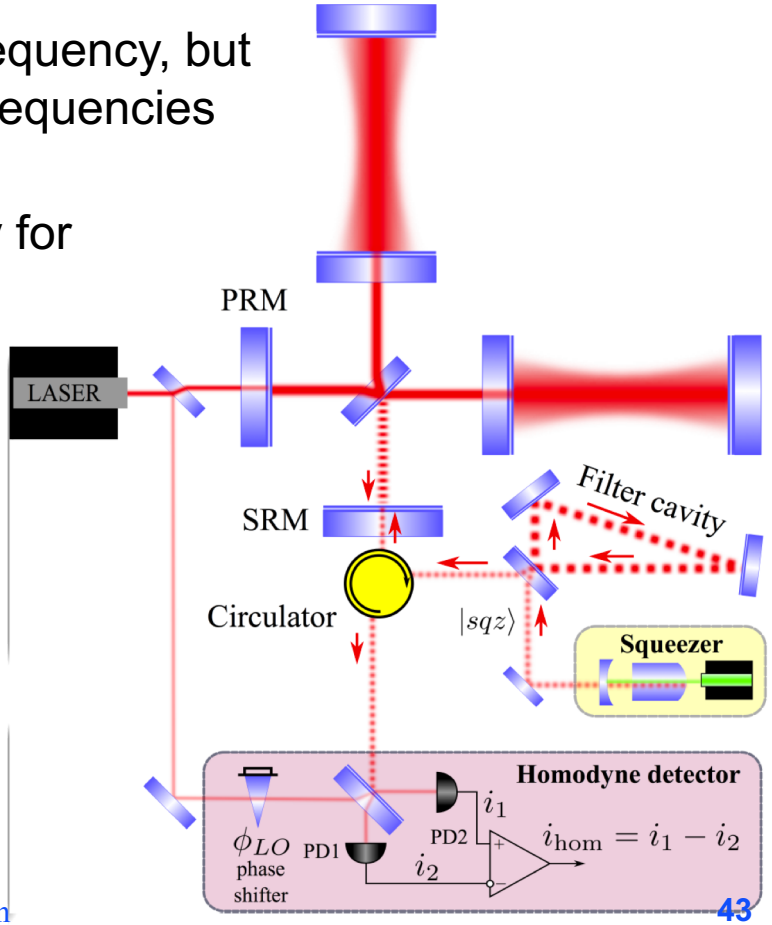


➔ High frequ M. Evans, Amaldi 11 fit in BNS-BNS range

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



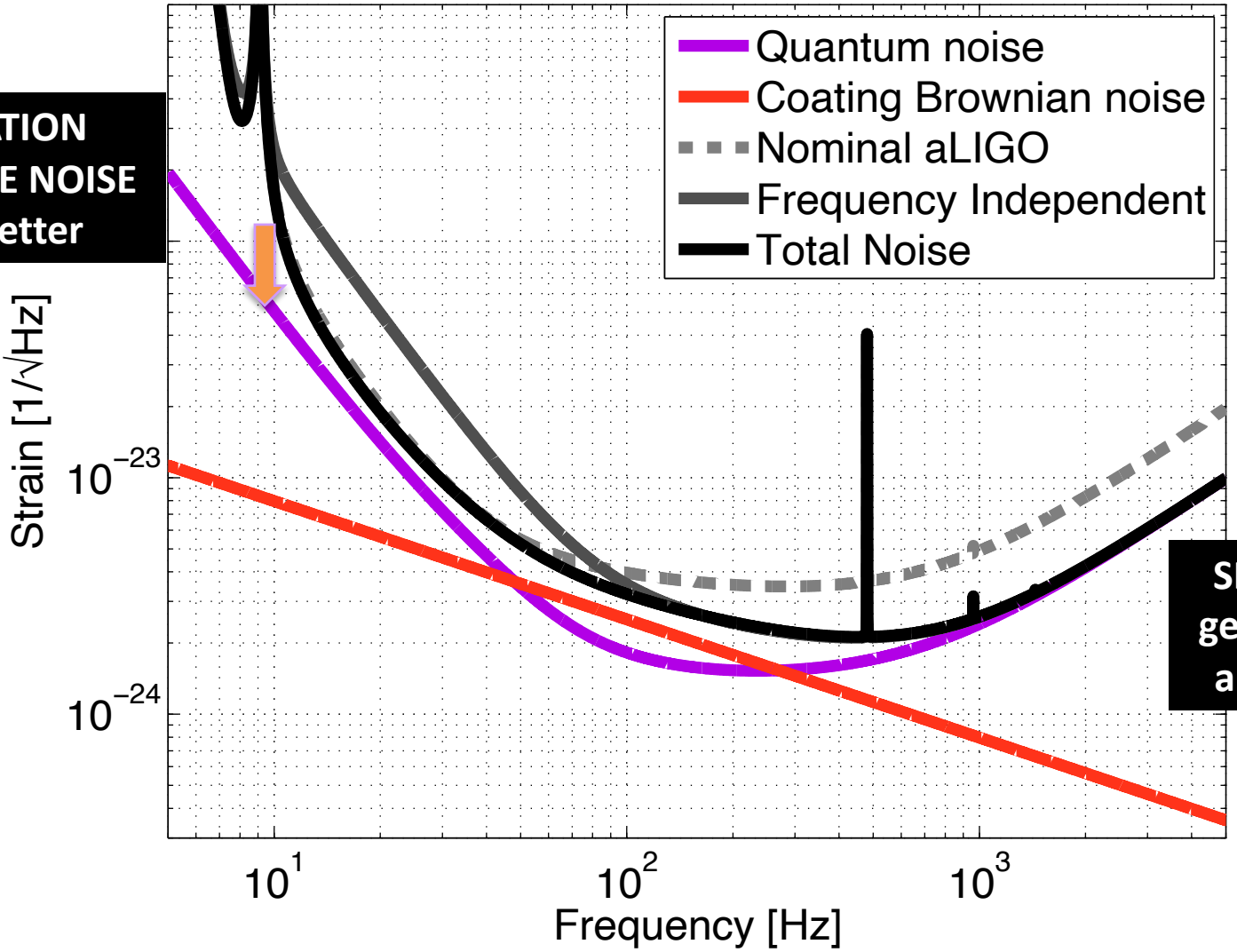


J. Kimble et al., PRD 65, 022002 (2001); S.L. Danilishin

Frequency Dependent Squeezing

M. Evans

RADIATION PRESSURE NOISE gets better



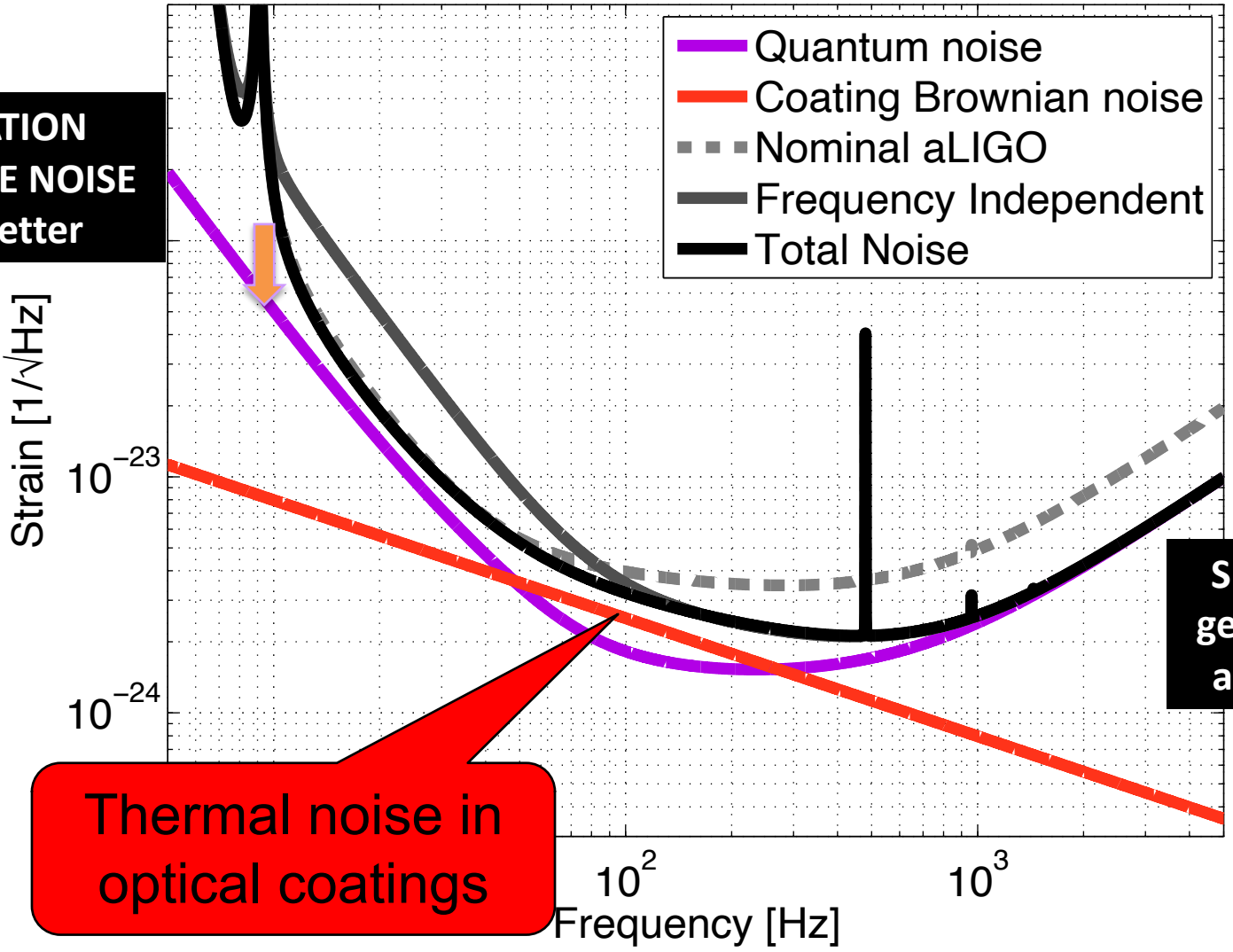
SHOT NOISE gets better by a factor of 2

➔ High freque M. Evans, Amaldi 11 range (200 → 250 Mpc)

Frequency Dependent Squeezing

M. Evans

RADIATION PRESSURE NOISE gets better

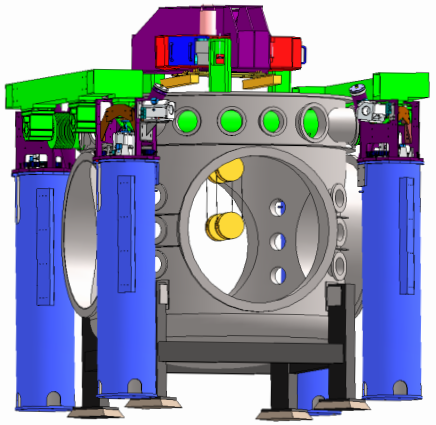


SHOT NOISE gets better by a factor of 2

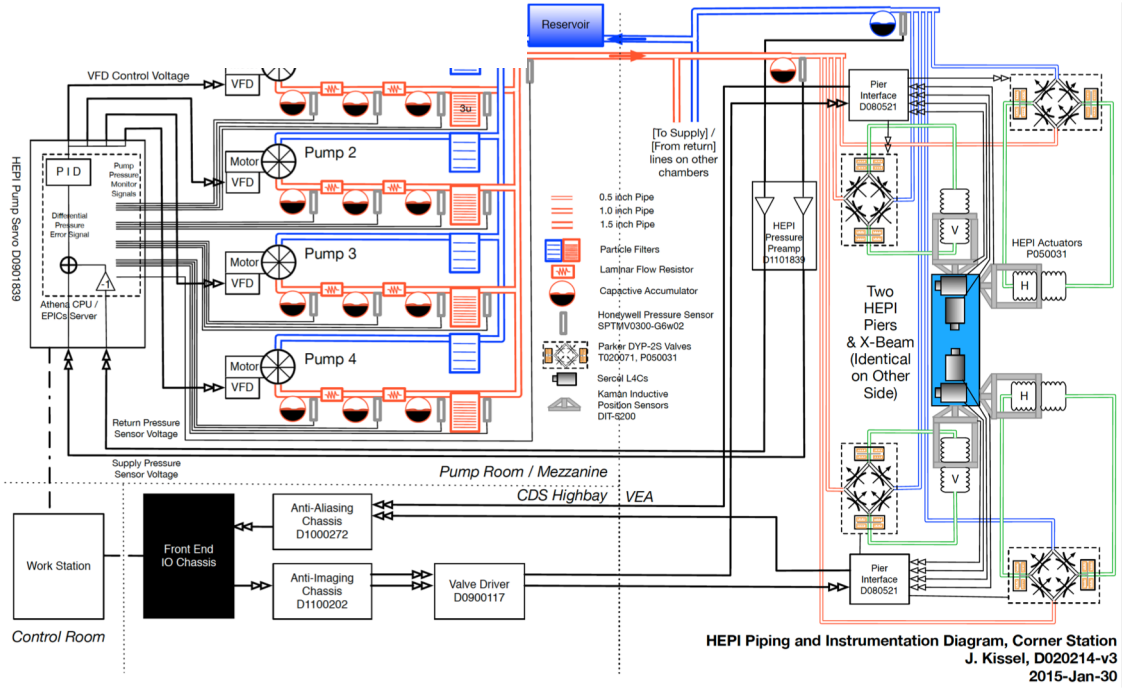
Thermal noise in optical coatings

➔ High freque M. Evans, Amaldi 11 range (200 → 250 Mpc)

Keeping it all aligned



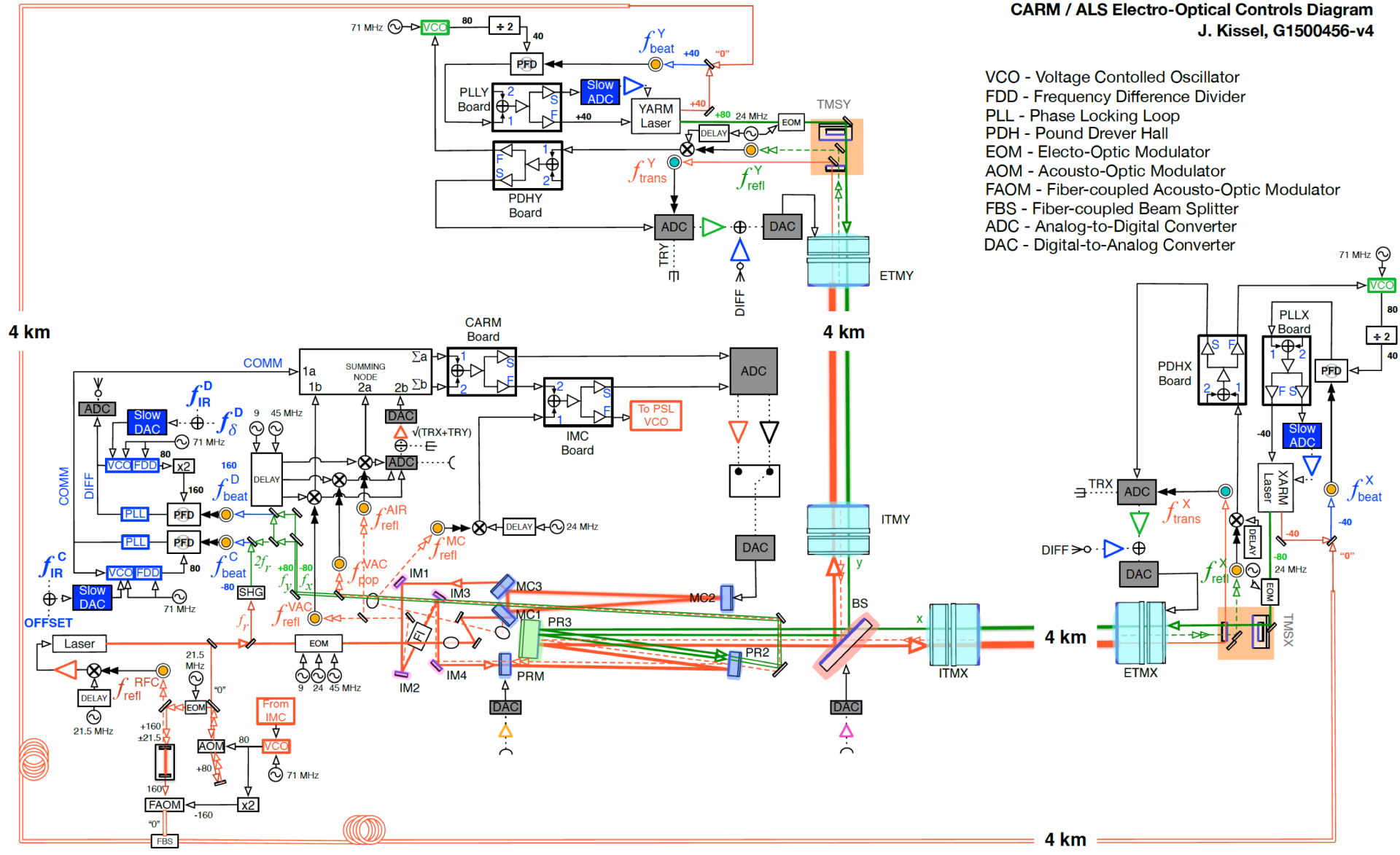
- **All cavities require precision alignment**
- 4 cavity optics – ‘Test Masses’ as pendulums, but also…
- Beamsplitter, ‘recycling’ mirrors, filter cavities all suspended
- Over 4km baseline
- 10^{-5} m motions at 1 Hz, 10^{-20} m at 20 Hz; dynamic range challenge
- Nanoradian alignment
- Guided control from micron to picometer motion, coupled cavities on resonance
- Fully digital distributed system
- 15μsec delay over 4km a limit to servo bandwidth



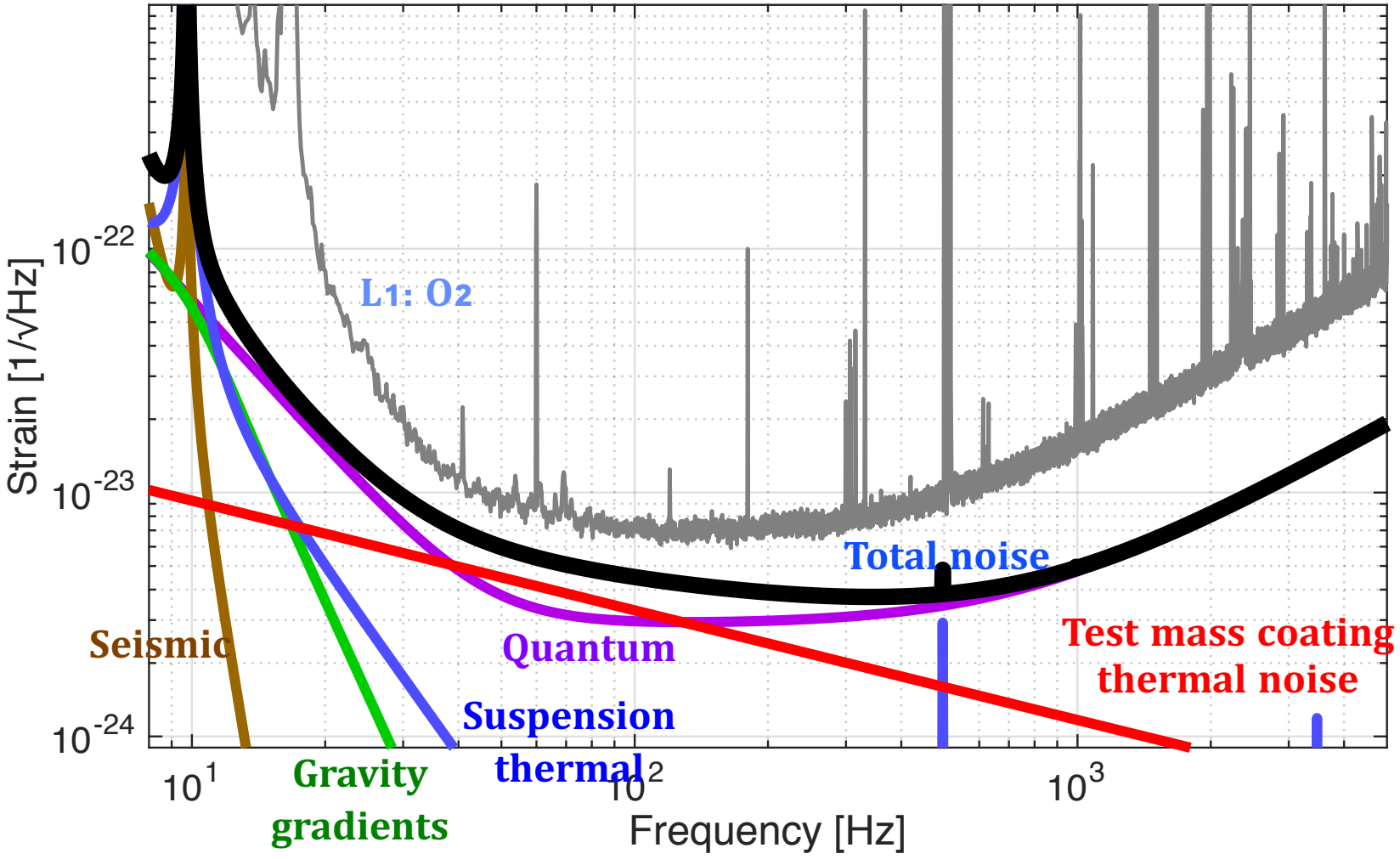
- **Control system demands are extraordinary**

1/3 of Seismic controls:
The external laminar flow hydraulic positioning system

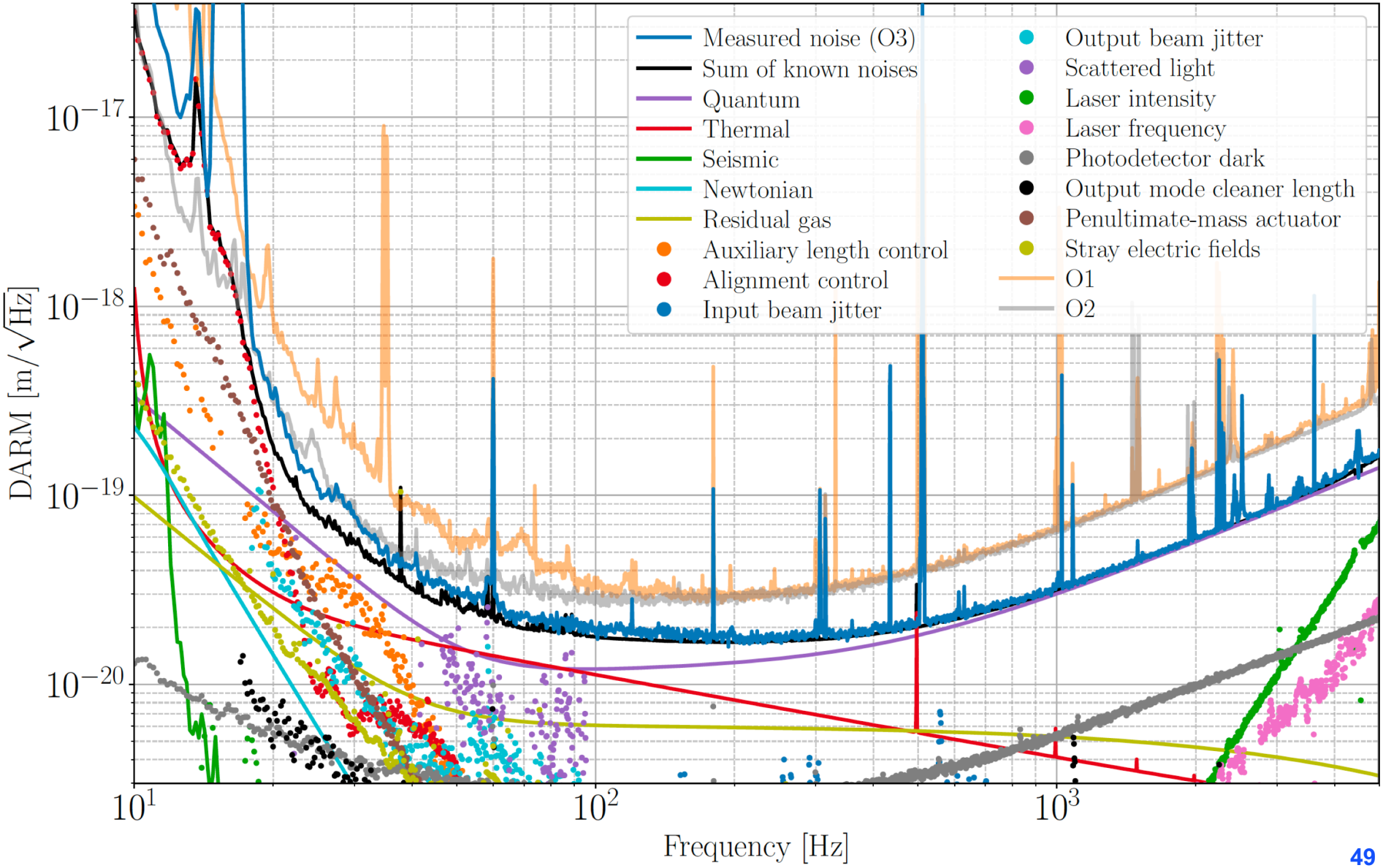
Partial Servo-control diagram for interferometer control



Adv LIGO Target Design
Sensitivity, basic noise sources



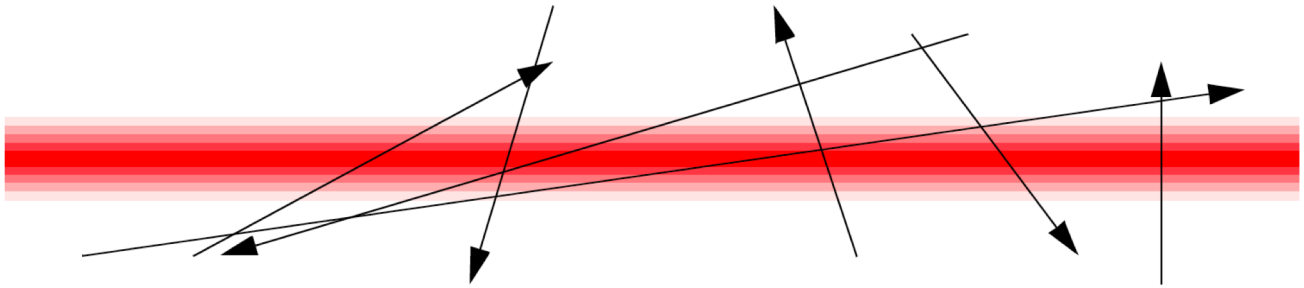
Then there are the technical noise sources….



Observatory Infrastructure

Vacuum System

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



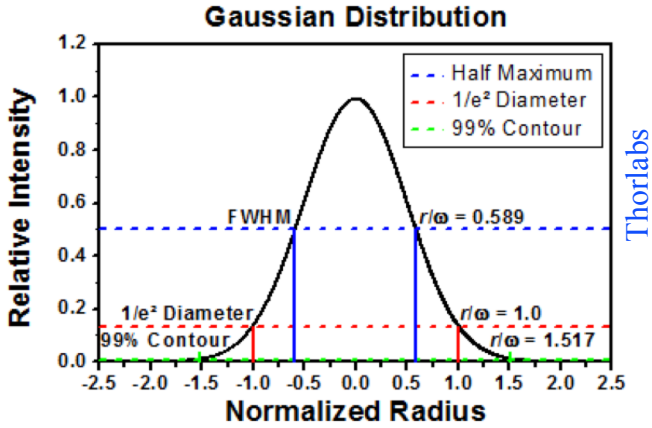
- Polarizability α of the remaining gas molecules induces path-length fluctuations; again, Poisson Statistics, and an effect proportional to square root of density $\rho^{1/2}$ along the path

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

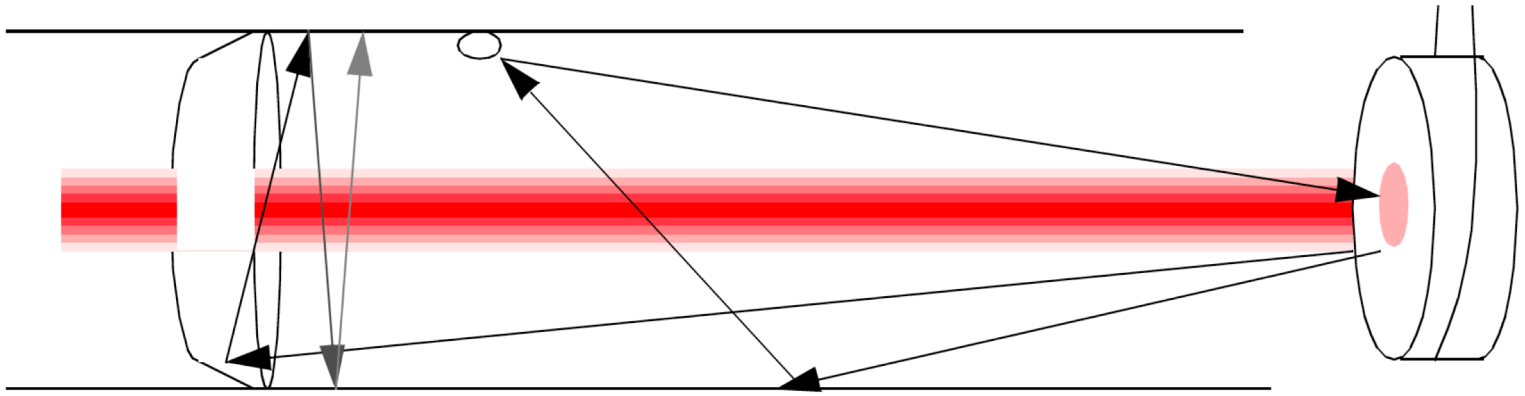
- Connect locomotive transformer to tubing for I^2R heating to outgas
- 1 pump every 2km **(We just spent ~$50M!)**

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



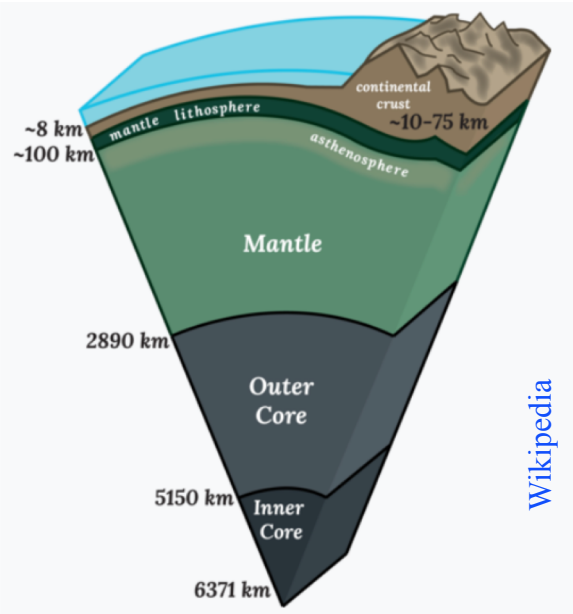
Civil Construction

- Light travels in straight lines (when far from black holes)
  - » The Earth is not flat (whatever some political partisans may say)
  - » Sagitta for 4km is some 1/3m – some earthmoving needed
- Also need stable foundation to support 1.2m beam tube
- And some weather protection for the beam tube
  - » Turns out that there are are stainless-steel eating microbes
  - » Also wasps and black-widow spiders
  - » And rodents
  - » …and, worst of all, humans

(We just spent another ~$60M)



fantasticpestcontrol.co.uk, terro.com



Wikipedia

Civil Construction:
Beam Tube cover, foundation, earthmoving

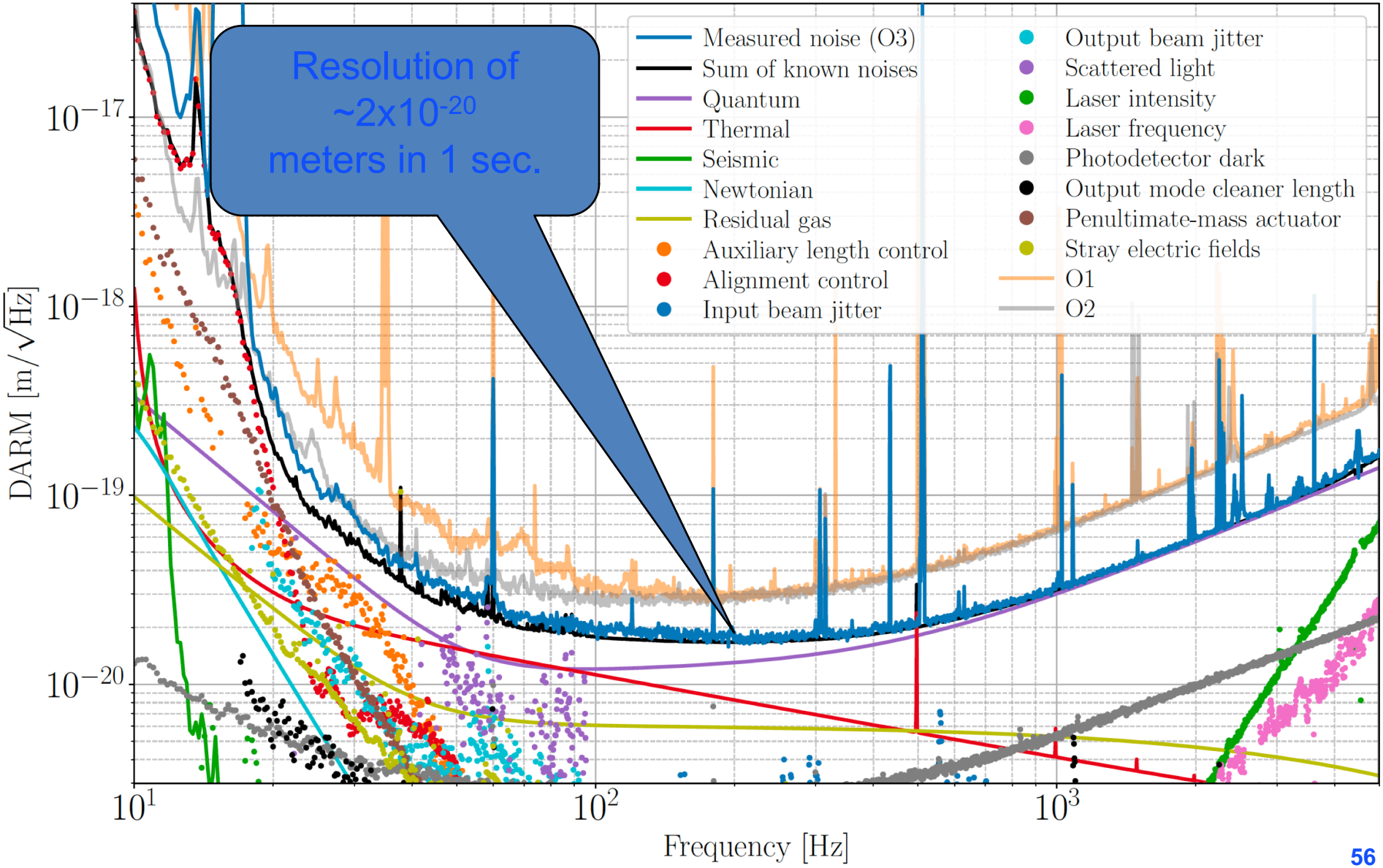


photo credit M. Zucker?

…and worst of all, humans



Then there are the technical noise sources….



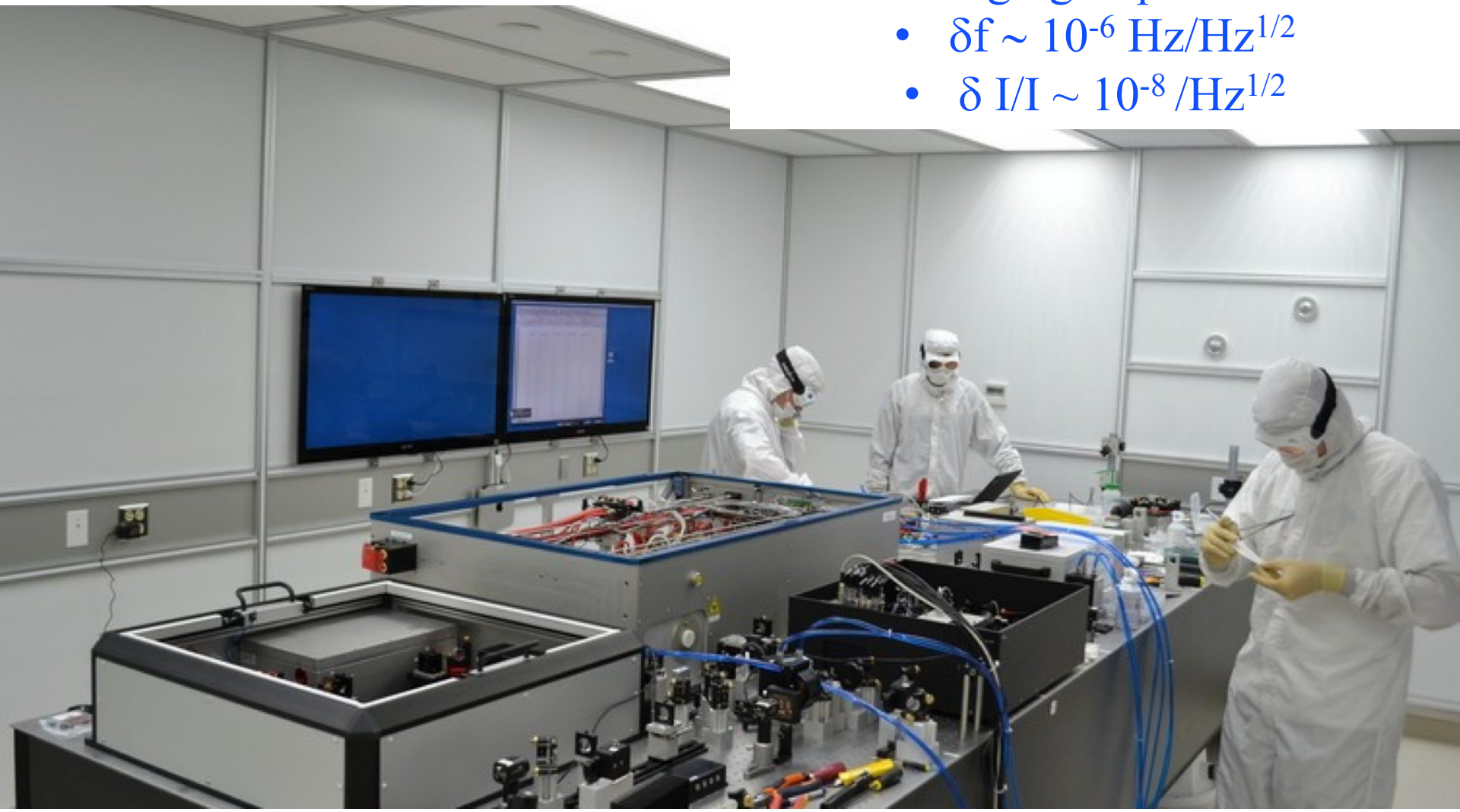
Let’s look at the actual LIGO layout and hardware

Laser Clean Room; extraterrestrials for scale

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

Challenging requirements:

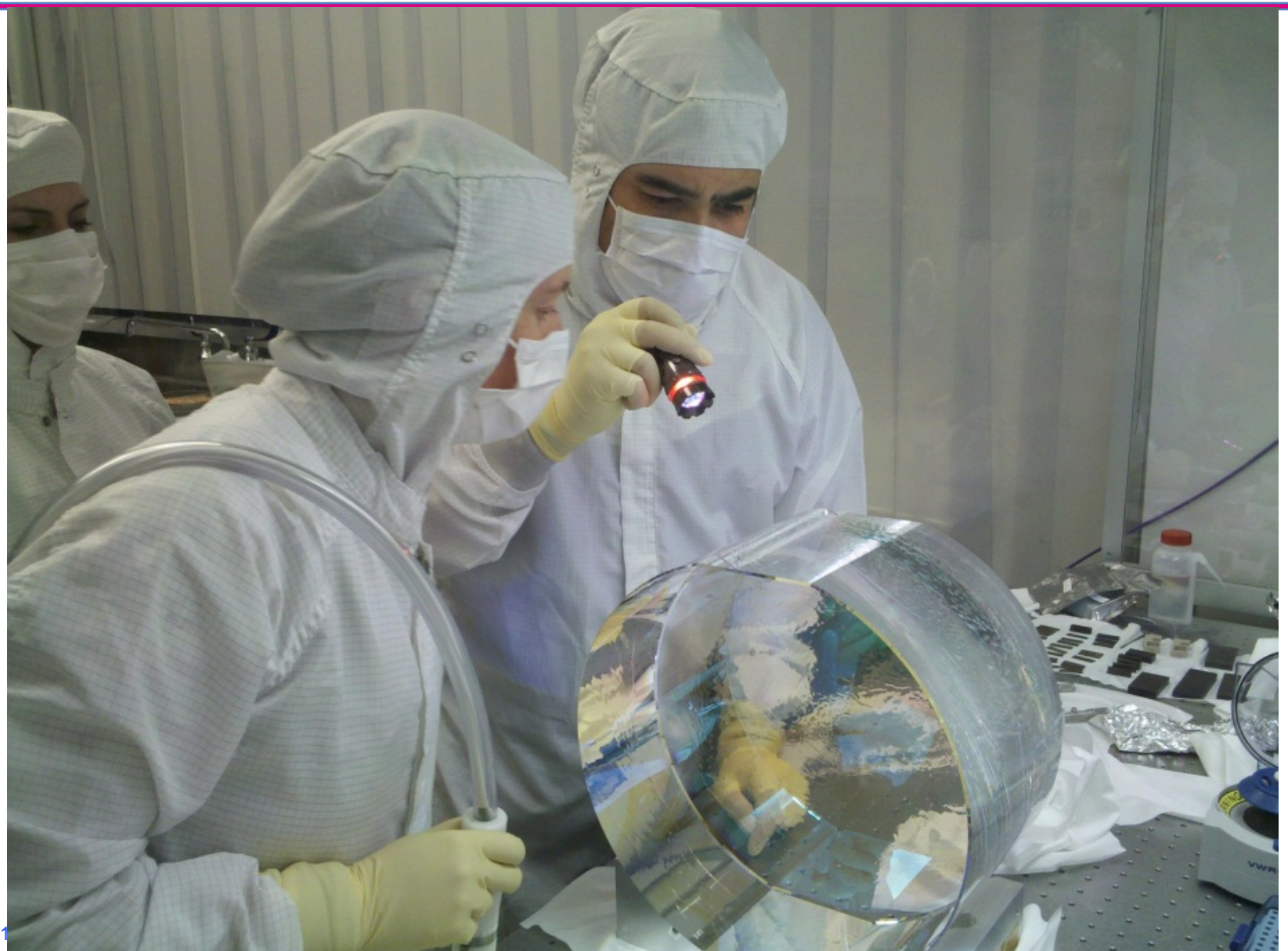
- $\delta f \sim 10^{-6}$ Hz/Hz$^{1/2}$
- $\delta I/I \sim 10^{-8}$ /Hz$^{1/2}$

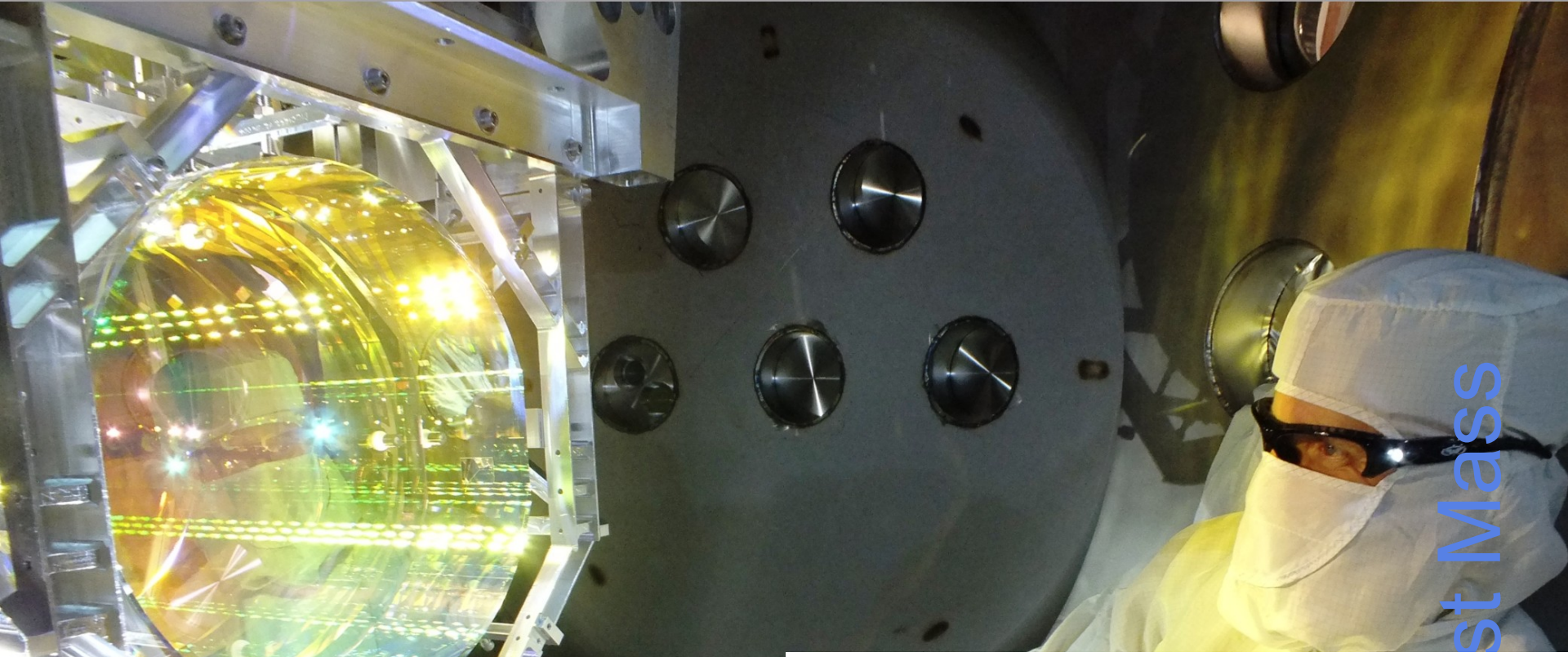


Vacuum chambers to protect and isolate optics



Inspecting mirror during fabrication





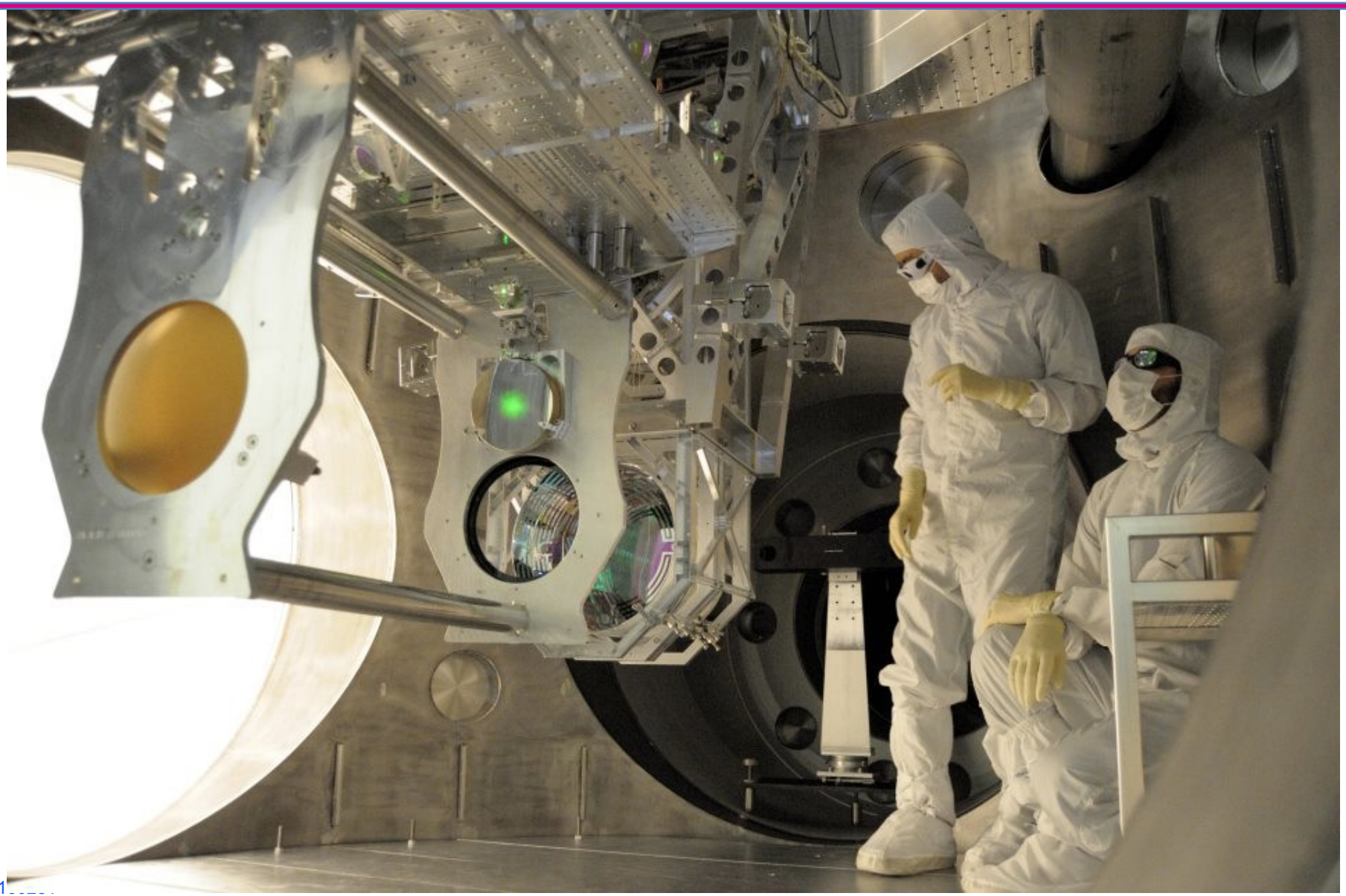
st Mass

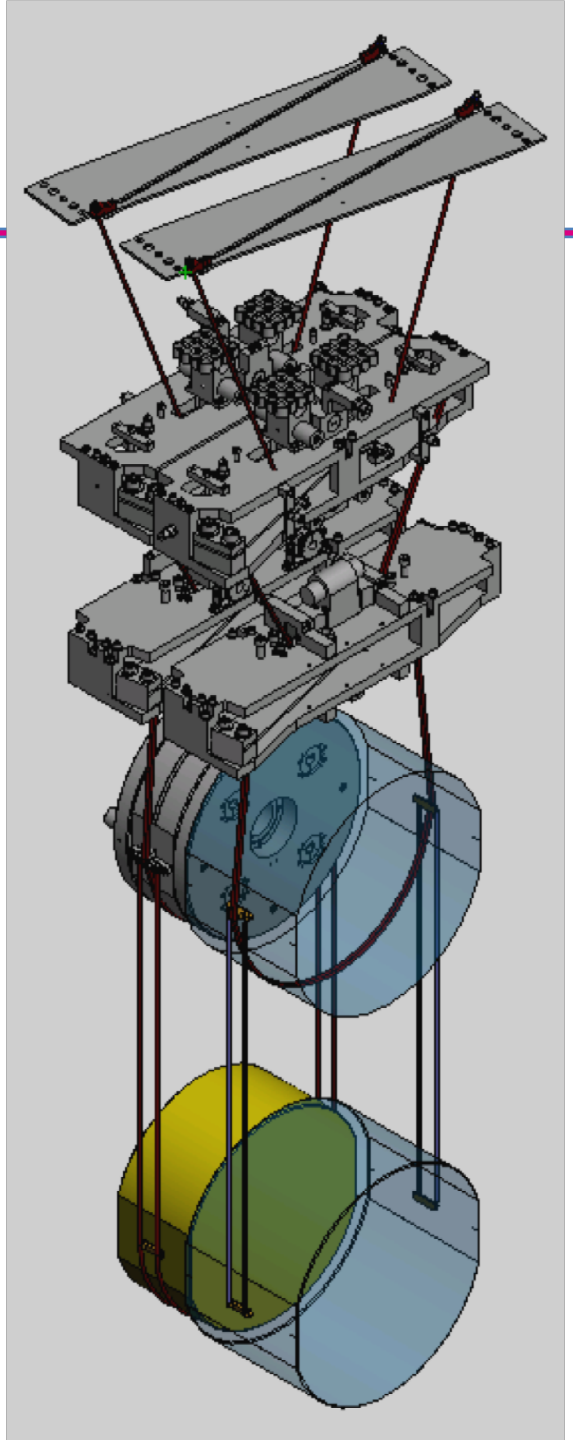
~35 cm diameter, 40 kg
Ultra-high purity fused silica

Challenging requirements:

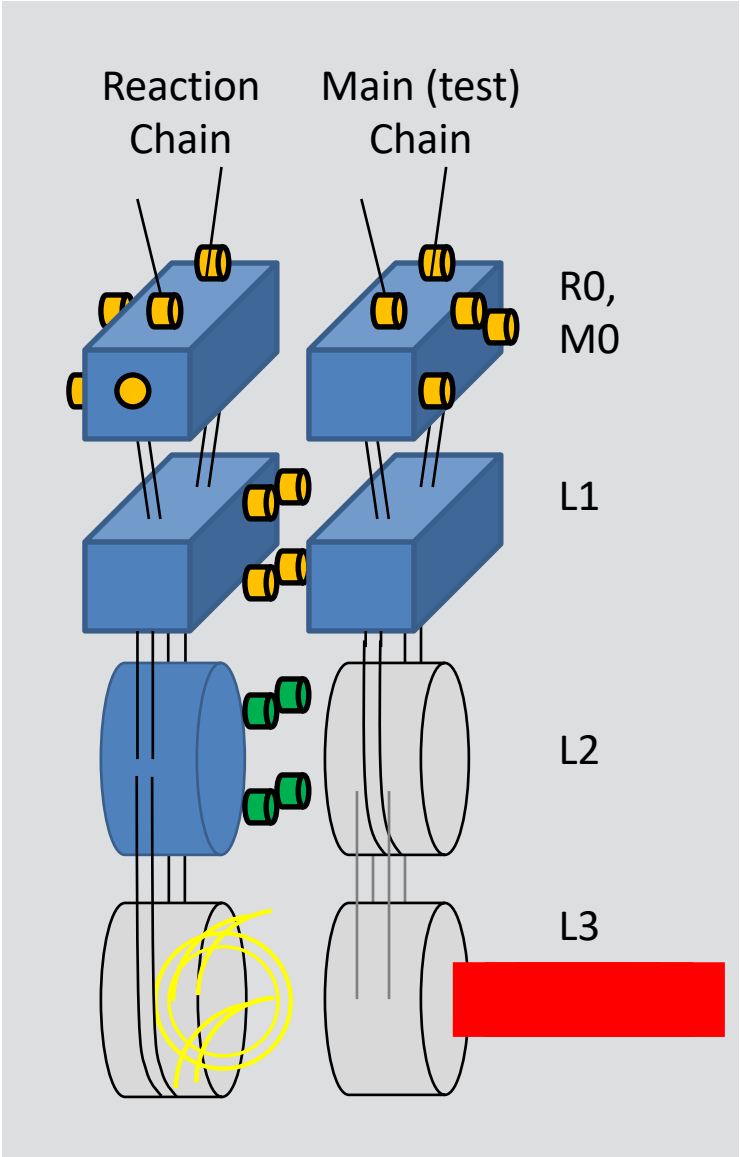
- λ/1000 surface figure
- < 1 ppm absorption
- ~10 ppm scatter
- 0.1 % coating uniformity

End-mirror assembly (humans removed before pumpdown)





Optic Suspensions

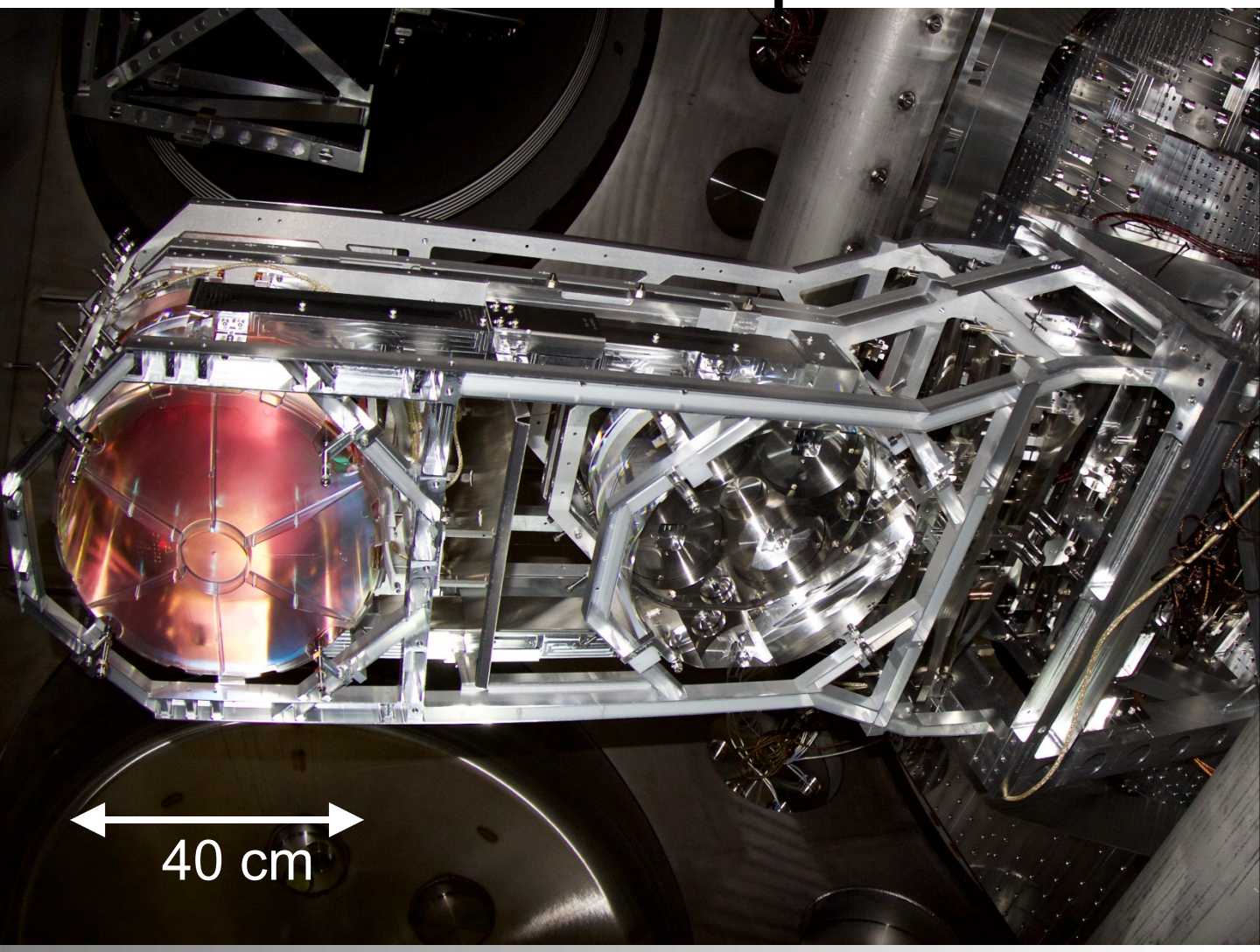


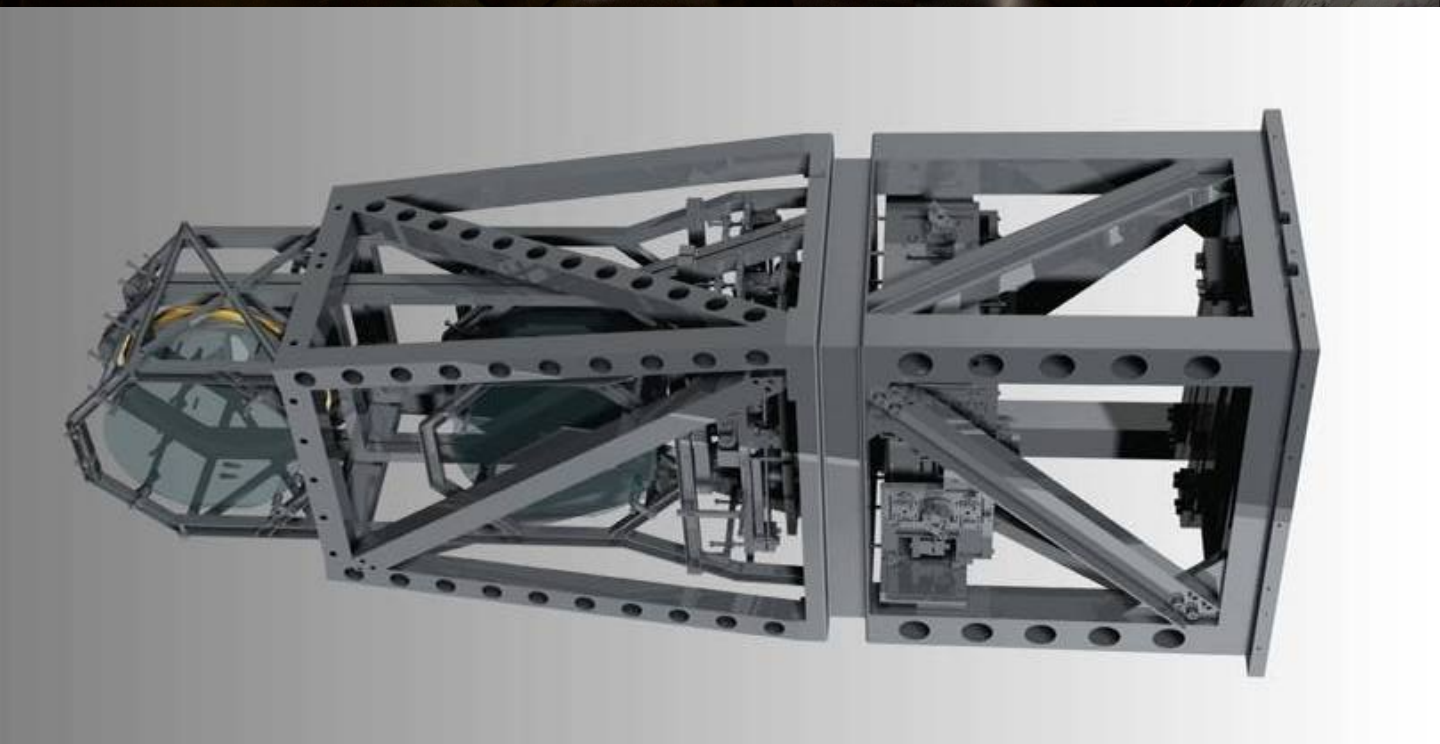
Electromagnetic sensors/actuators measure position relative to a reaction chain that is also passively isolated

Lower stage actuators used to control/maintain optic cavity length and alignment

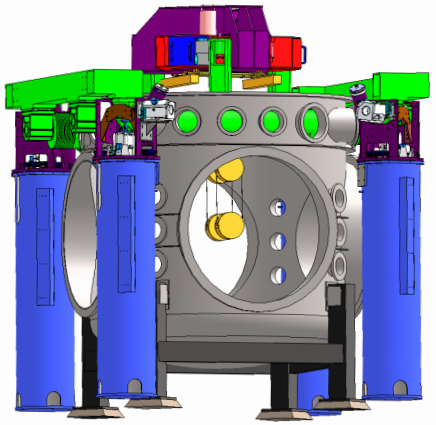
'Monolithic' – optic, penultimate mass, and suspension fibers welded together

Test Mass Suspension

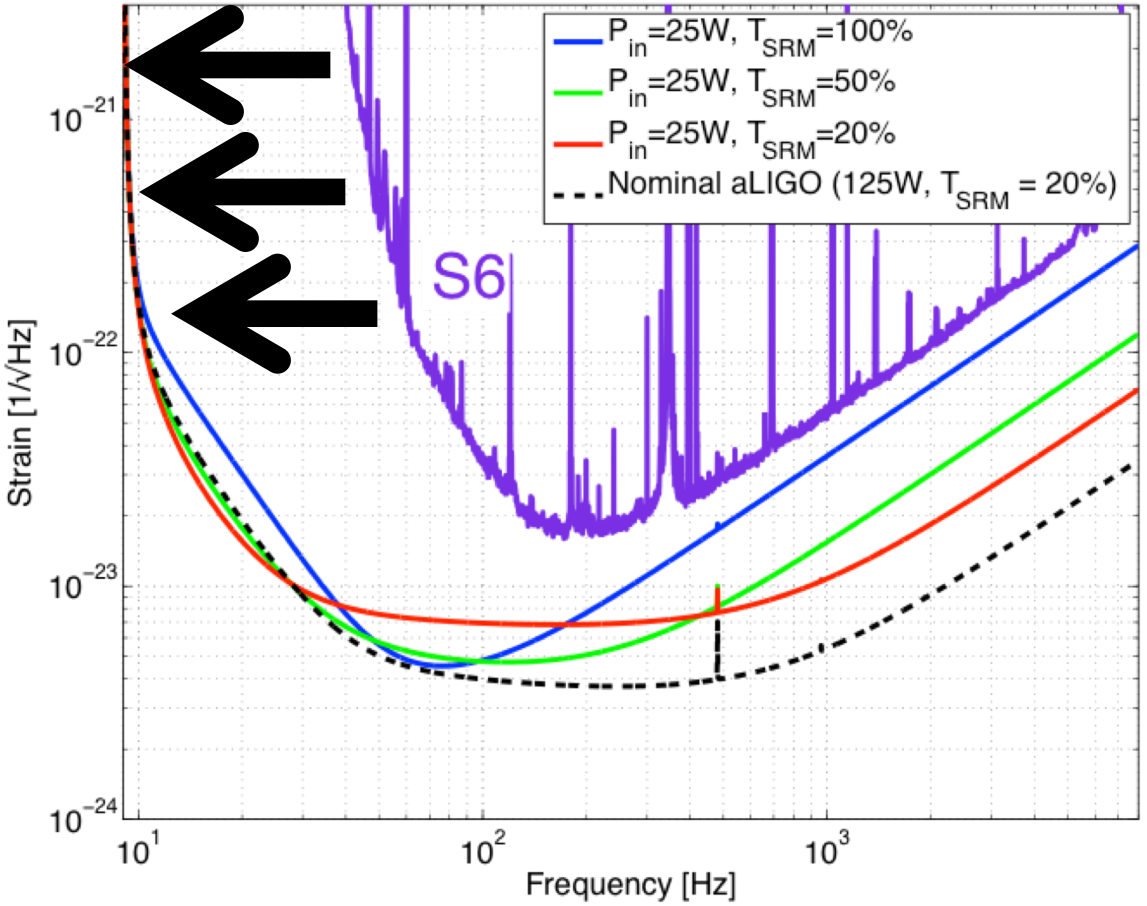




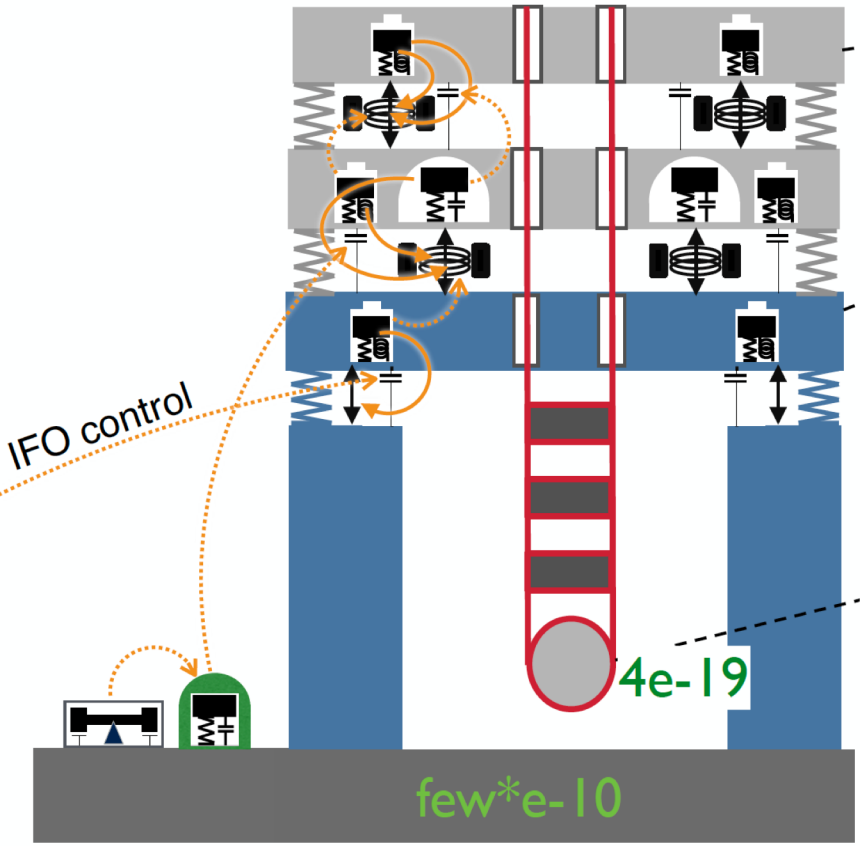
Measuring $\Delta L = 4 \times 10^{-18}$ m
Forces on test mass

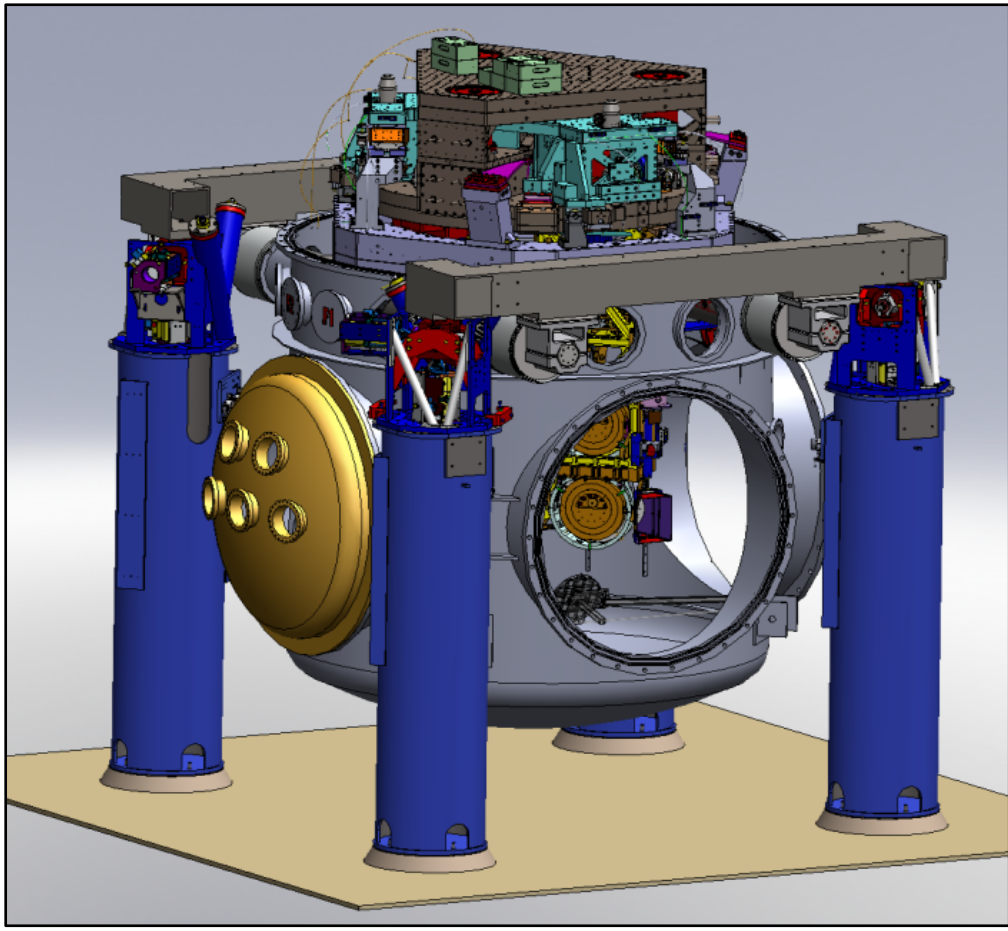


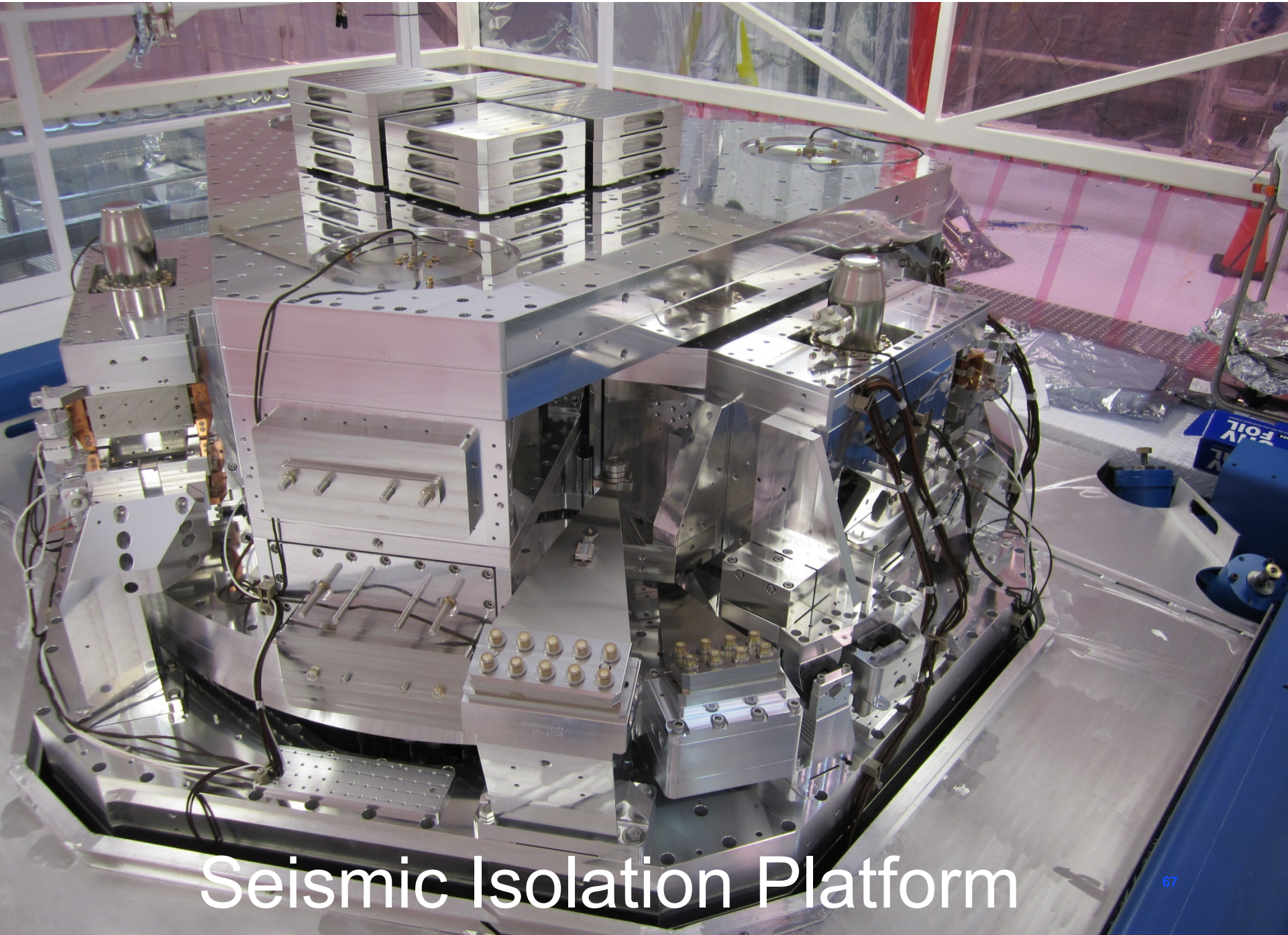
- Not ‘fundamental physics’, but ‘fundamental to success’
- **Seismic noise** – must prevent masking of GWs, enable practical control systems
- aLIGO uses **active servo-controlled platforms, multiple pendulums**
- 3 layers, each of 6 degrees-of-freedom



Active and passive seismic isolation







Seismic Isolation Platform

Getting from electronic signals to gravitational-wave data

Enabling Scientific Interpretation: Calibration

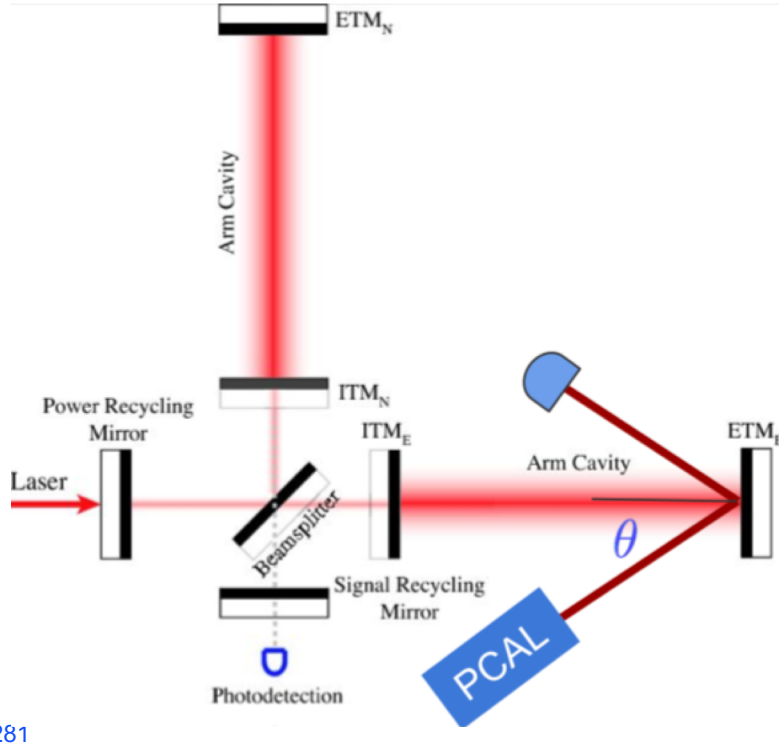
- GR makes predictions for the luminosity of coalescing binaries
  - » Signal at the detector depends on the distance as $1/r$
    - – Not as $1/r^2$!
    - – Degeneracy with inclination of orbit

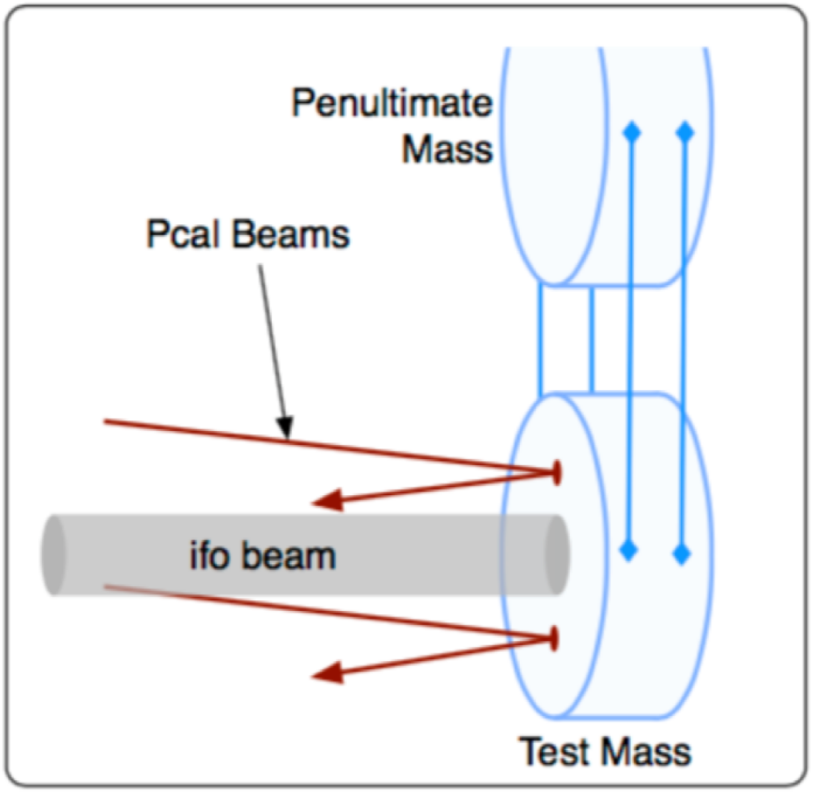
- Can obtain a measure of distance to source from the best-fit amplitude
  - » But this requires **absolute calibration** of the detector in Strain

Calibration technique

- LIGO's calibration method uses photon pressure on the test masses
- 1W laser sinusoidally modulated makes an easy-to-see motion of the mirror

$$x(f) = \frac{2\cos\theta}{c}\left[1 + \frac{M}{I}(\vec{a}\cdot\vec{b})\right] S(f)\,P(f)$$

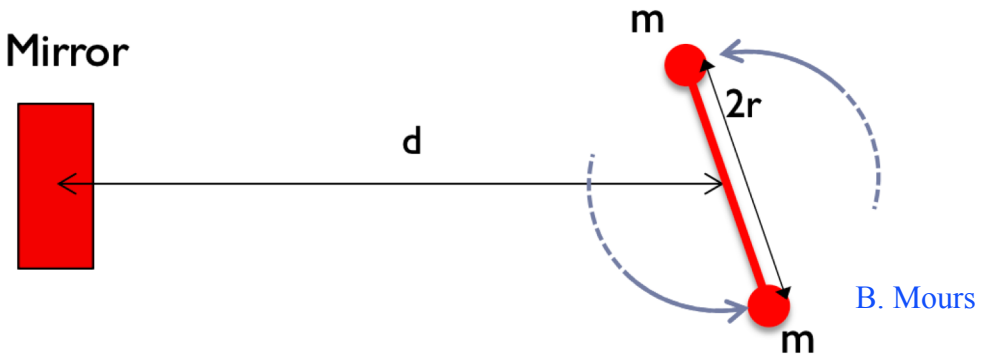




Karki et al., Review of Scientific Instruments **87**, 114503 (2016)

Calibration

- Accuracy is ~5% and ~3° currently
  - » May be able to improve by ~factor 2
  - » Uncertainty in the world standards for light intensity a real limit!
- Secondary system based on 'gravitational attraction' in development
  - » A dynamic Cavendish experiment
  - » Signal depends mainly on the rotor geometry, mass and position
  - » Need to ensure no cross-coupling from mechanical, magnetic, electrostatics, electronics



- **The ability of GW detectors to give distance to source is very nice!**

Enabling Scientific Interpretation: Data Quality

Output of detector

is not frequency-independent Gaussian Stationary noise!

LIGO data in time and frequency

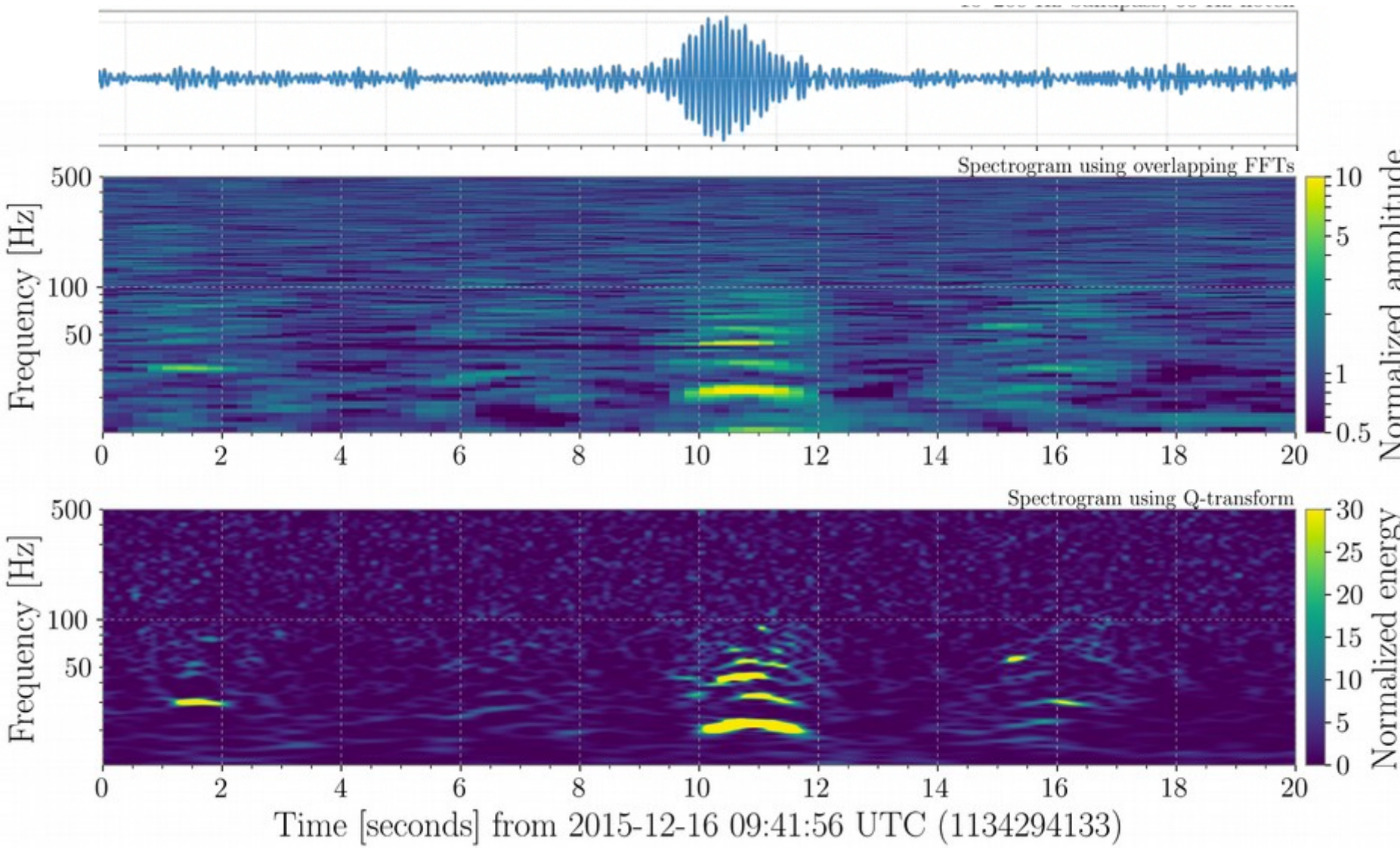
LIGO-Hanford h(t)

Made with GWpy by Duncan Macleod. Code: https://git.io/gwpy-ligo-scattering-animation

0.5 second FFT; 5 averages covering 1.5 seconds; 50% overlap

G2100281

Time-frequency spectrograms



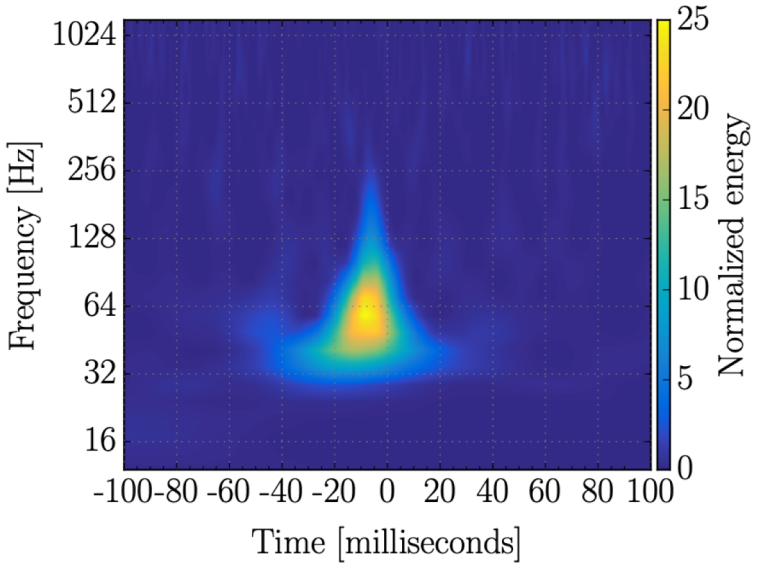
G2100281

Made with GWpy by Duncan Macleod

Examples of spectrograms of data defects

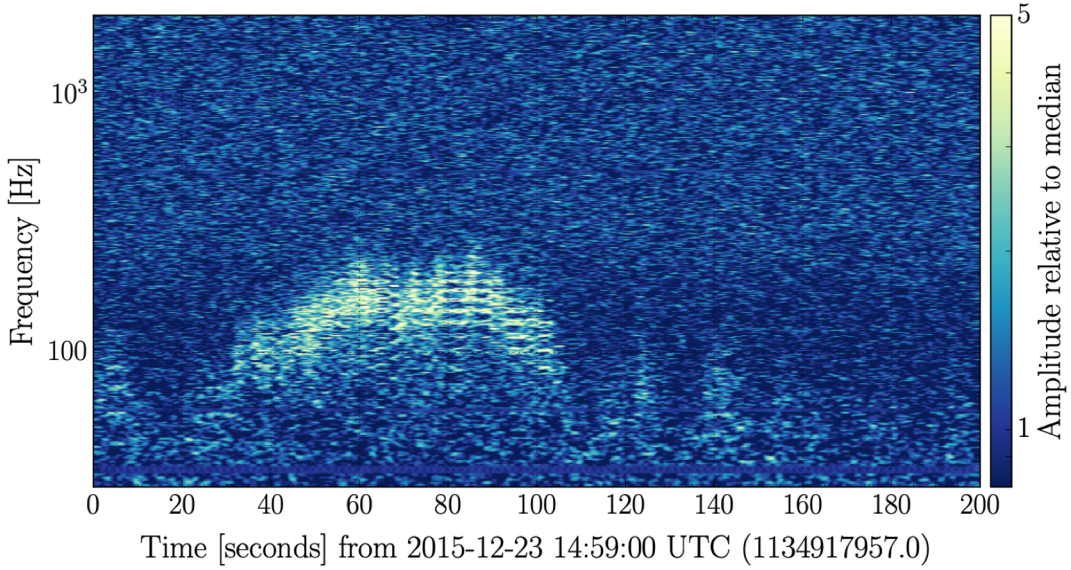
Blip glitches

- The biggest contributor to the transient GW search backgrounds
- Seen in both LIGO detectors
- Non-coincident…2 detectors good!
- No known correlation with instrument behavior or environment.



60-200 Hz non-stationary noise

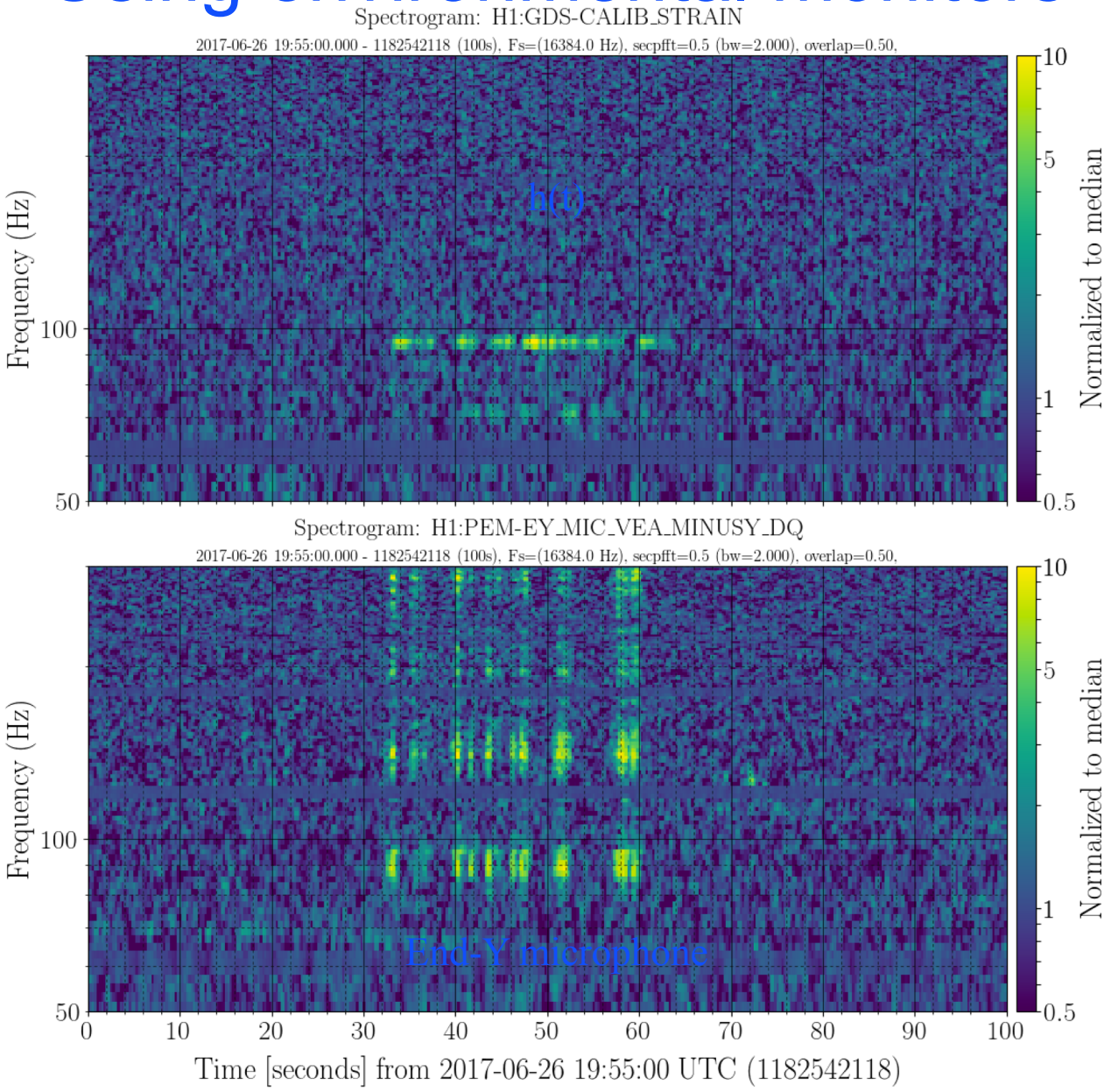
- Pollutes LIGO-Livingston data in a critical frequency range (~50-500Hz)
- Longer duration (10s or 100s of seconds)
- Major contributor to CBC and burst backgrounds



Tracking down strain defects: Using environmental monitors

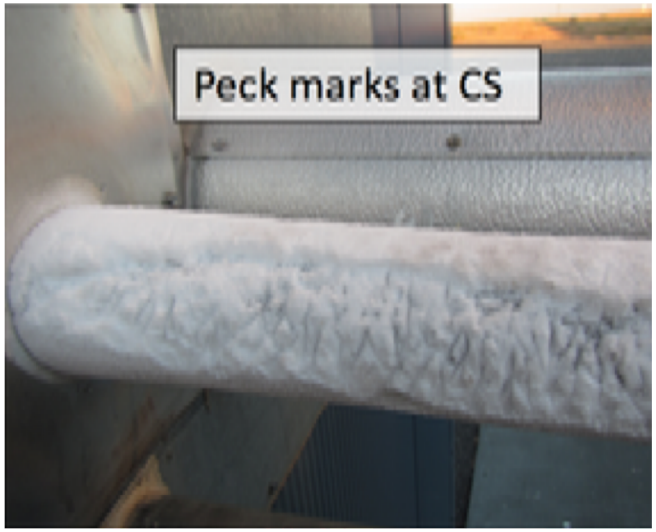
$h(t)$

Microphone end station



Ravens!



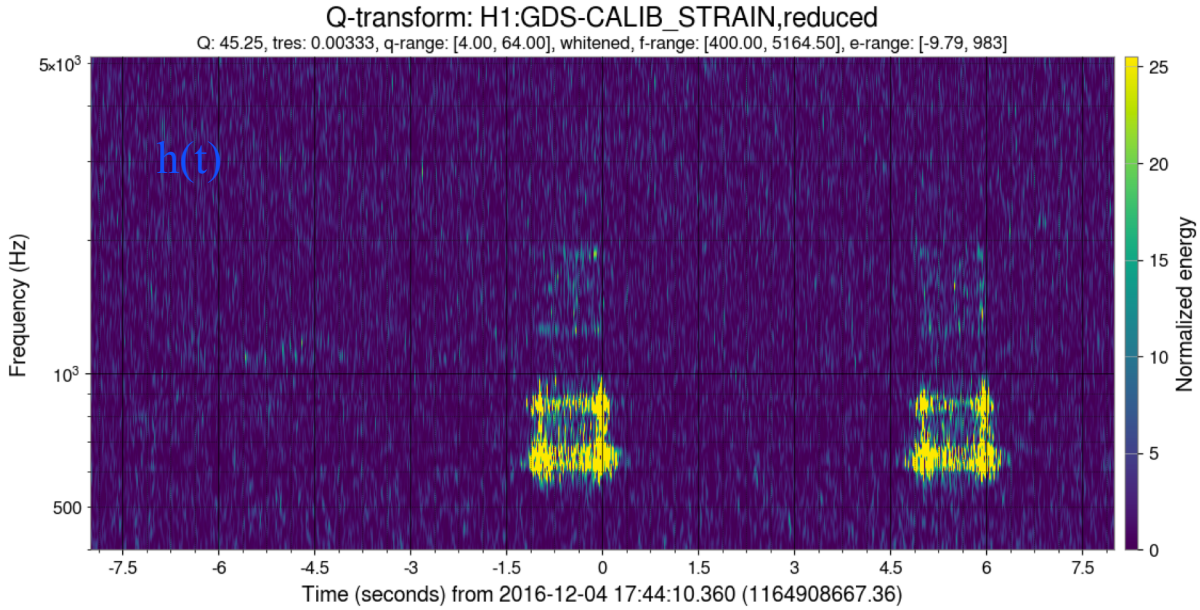




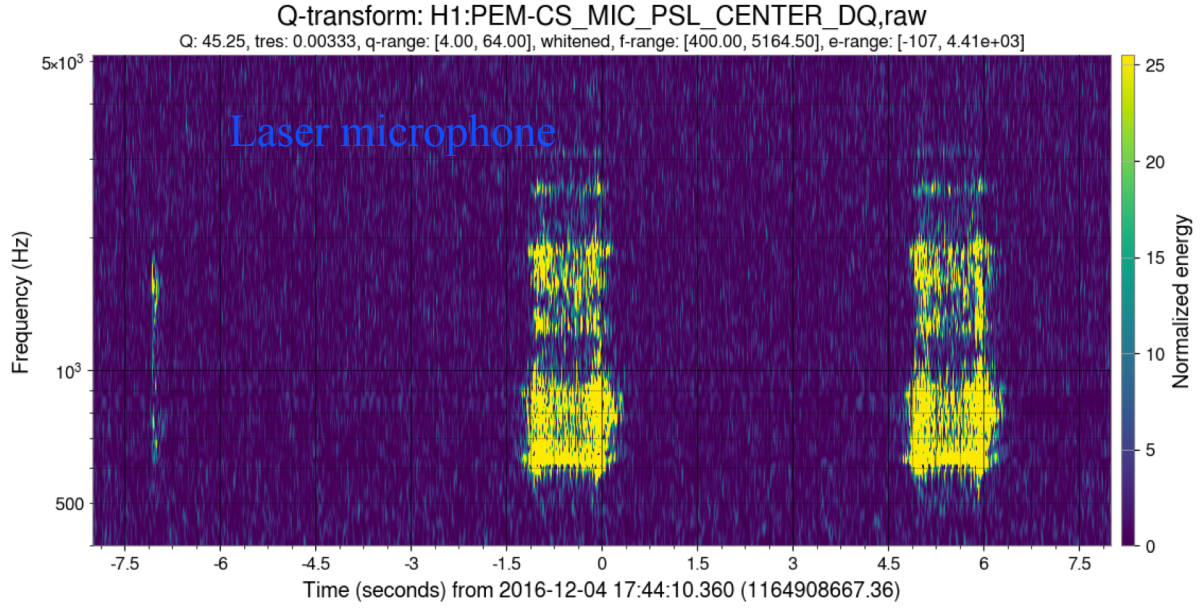


Hanford alog https://alog.ligo-wa.caltech.edu/aLOG/# 37630

Tracking down data defects



Spectrogram of *h(t)* – the interferometer output

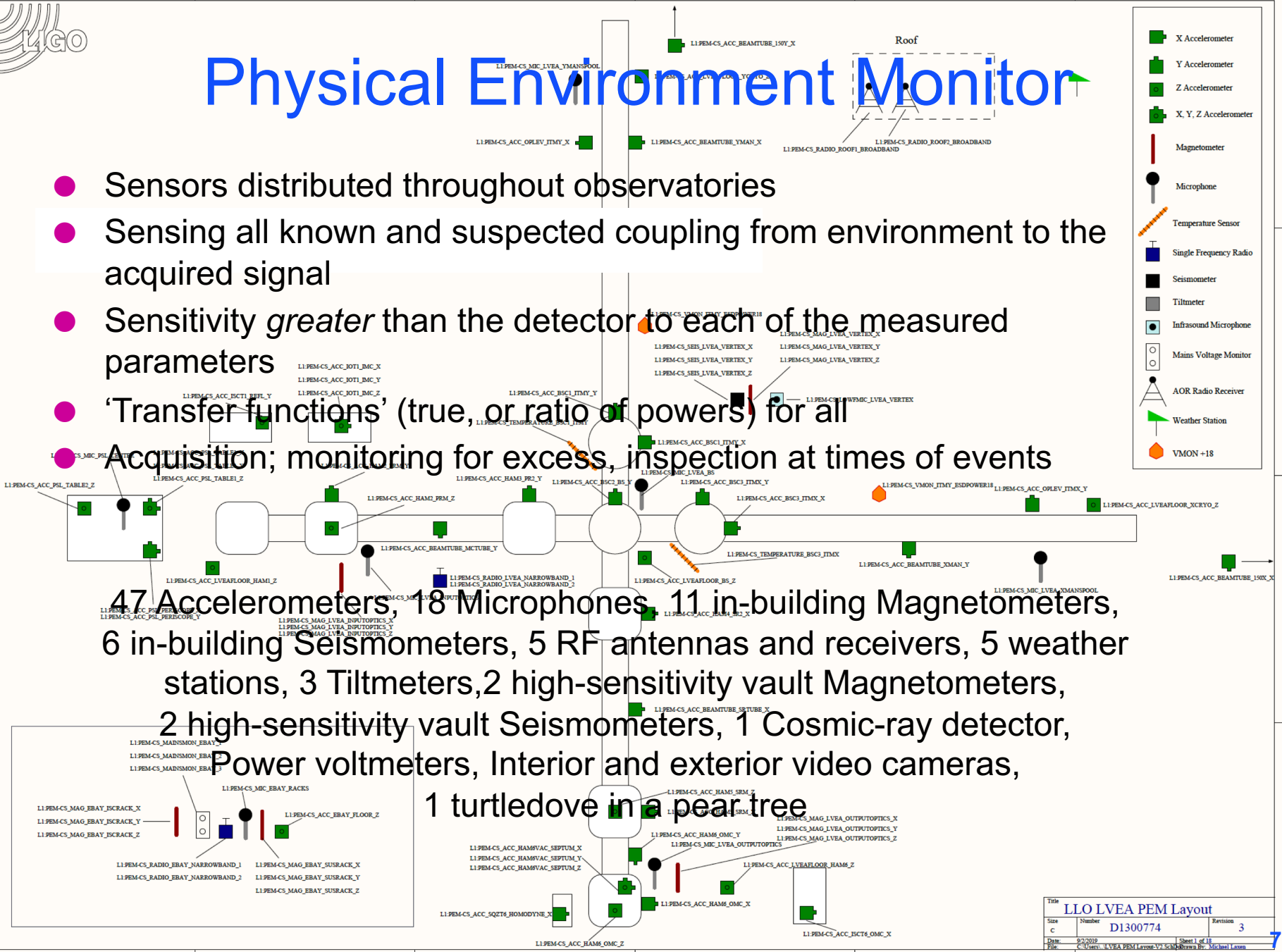


Noise monitoring microphone in Laser enclosure

LHO alog #32503: https://alog.ligo-wa.caltech.edu/aLOG/index.php?callRep=32503

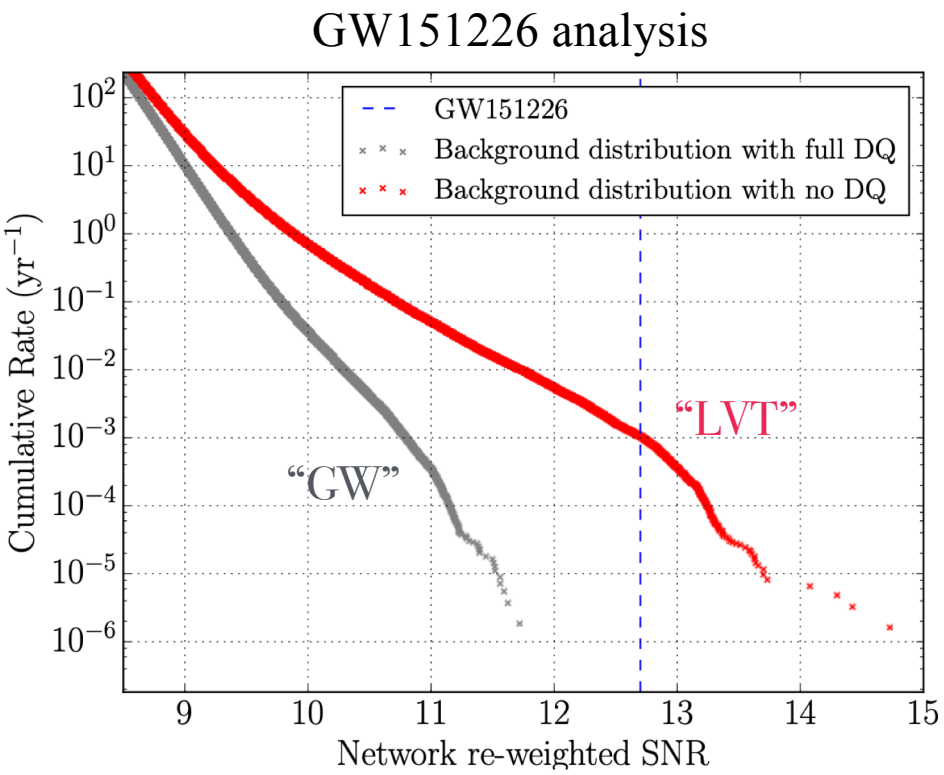
Physical Environment Monitor

- Sensors distributed throughout observatories
- Sensing all known and suspected coupling from environment to the acquired signal
- Sensitivity *greater* than the detector to each of the measured parameters
- ‘Transfer functions’ (true, or ratio of powers) for all
- Acquisition; monitoring for excess, inspection at times of events

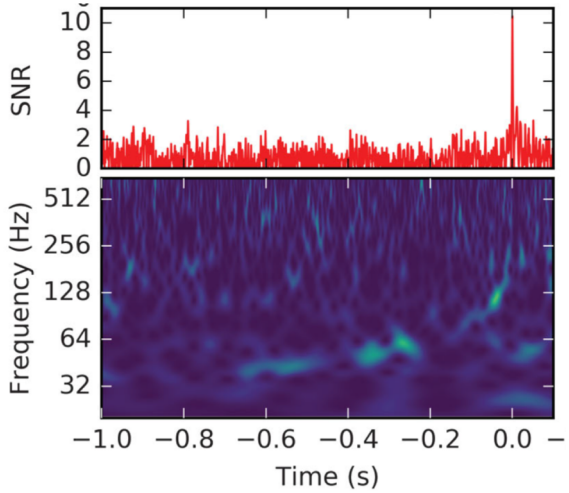


47 Accelerometers, 18 Microphones, 11 in-building Magnetometers, 6 in-building Seismometers, 5 RF antennas and receivers, 5 weather stations, 3 Tiltmeters,2 high-sensitivity vault Magnetometers, 2 high-sensitivity vault Seismometers, 1 Cosmic-ray detector, Power voltmeters, Interior and exterior video cameras, 1 turtledove in a pear tree

The impact of detector characterization



LIGO-Virgo collaboration (2017) - arXiv 1710.02185



$14.2^{+8.3}_{-3.7}M_{\odot}$ and $7.5^{+2.3}_{-2.3}M_{\odot}$

The false alarm rate of GW151226:

- 1 in 320 years with raw data
- 1 in 183000 years with data quality information applied

Gravitational-wave detector networks

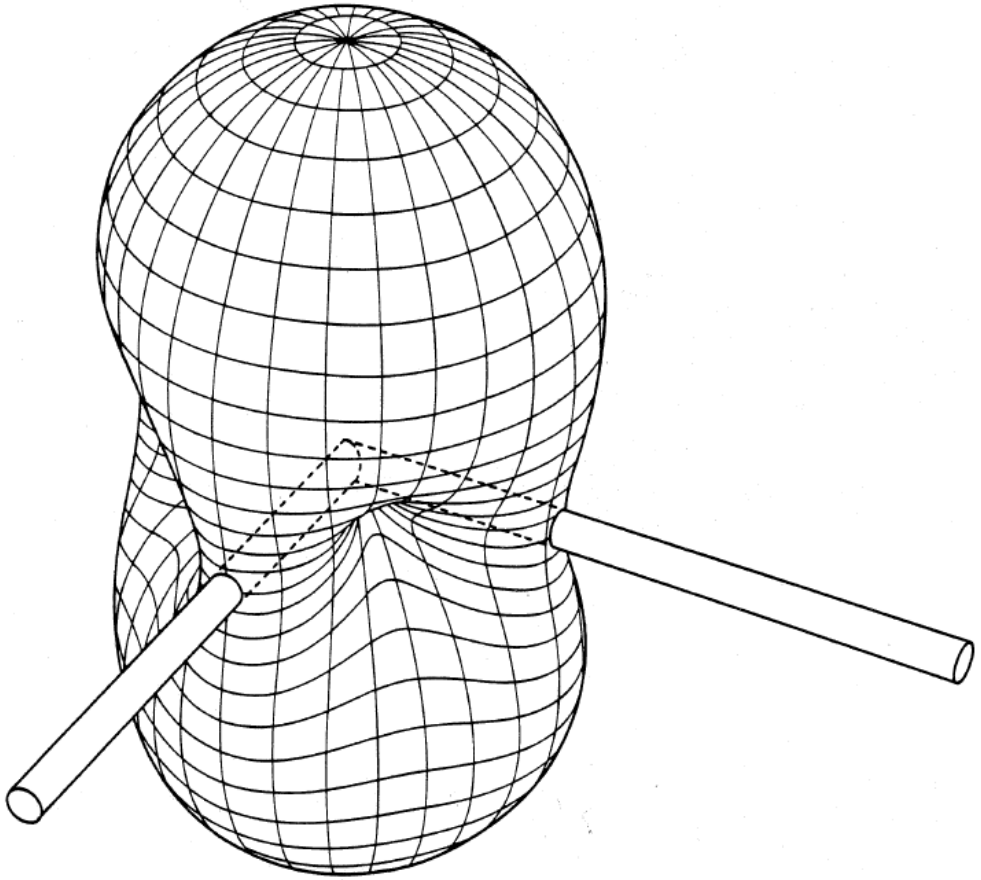
GW170817

LIGO-Virgo/Geoffrey Lovelace, Duncan Brown, Duncan Macleod, Jessica McIver, Alex Nitz

https://doi.org/10.1103/PhysRevLett.119.161101

Antenna pattern for a single detector

- Maximal for overhead or underfoot source
- 1/2 for signals along one arm
- …and zero at 45 degrees
- Good: A detector sees almost the entire sky with good sensitivity
- Bad: A single detector gives very limited information on the source direction
- Solution: Use multiple detectors working together to perform ‘triangulation’

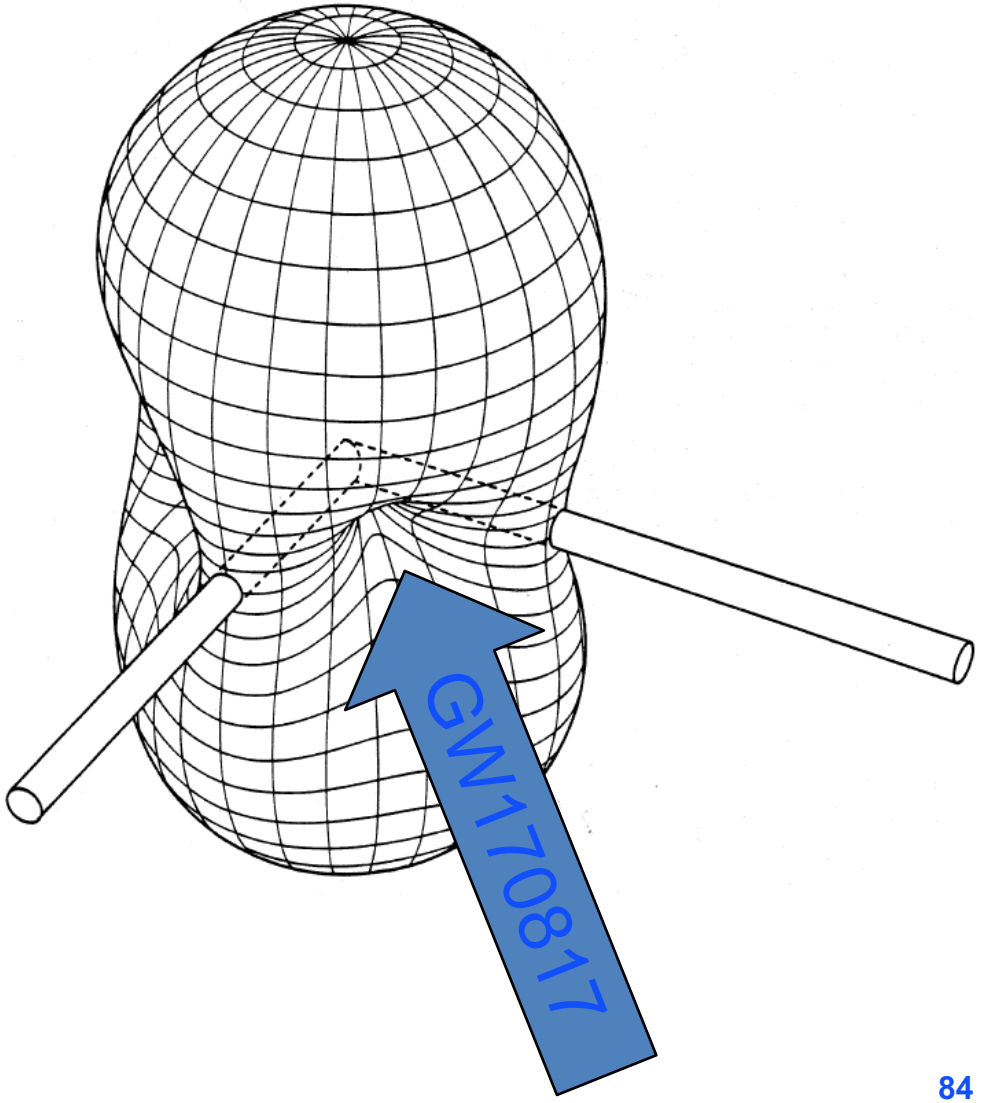


Antenna pattern for a single detector

- Maximal for overhead or underfoot source
- 1/2 for signals along one arm
- …and zero at 45 degrees

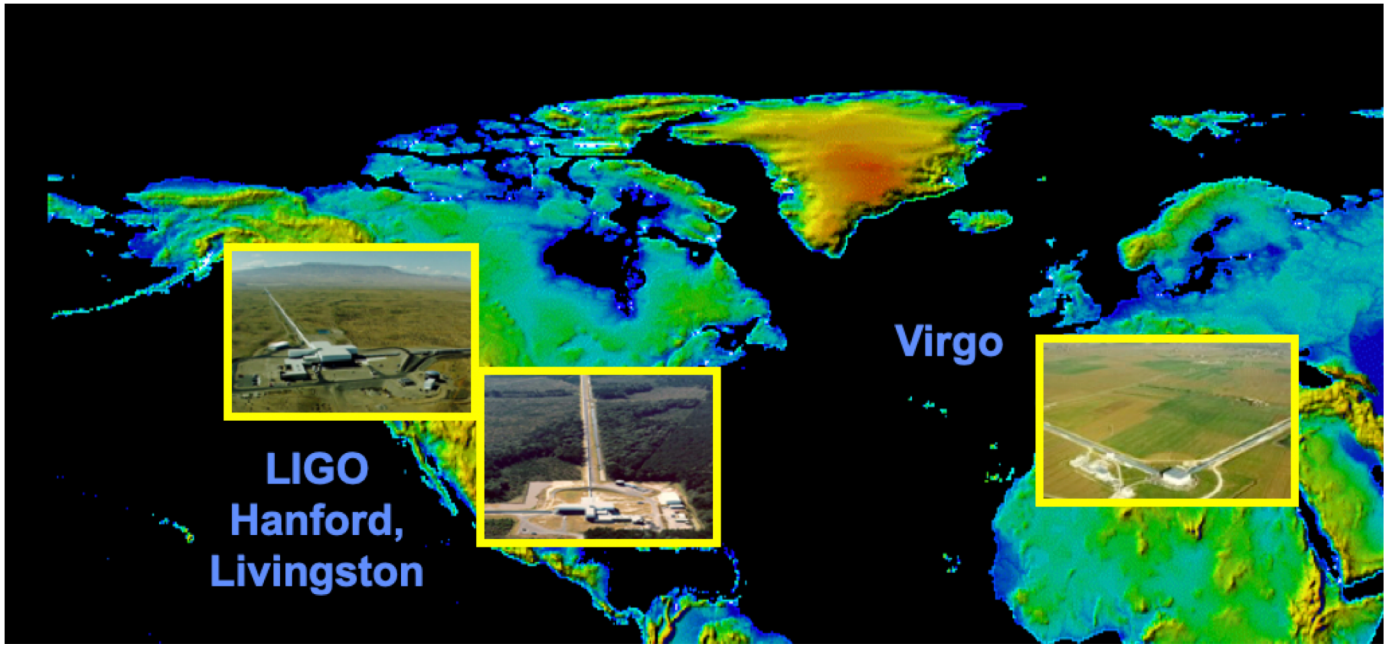
- GW170817 fell on Virgo close to 45 degrees!

- Virgo data were critical for localization; knowledge of ~zero signal carries very good position information



LIGO and Virgo

- Similar instruments in concept; differences in details
  - » Virgo: 3km arms, LIGO: 4km arms, 2 detectors
  - » Different starting dates for upgrades, so sensitivity a bit out of synch
- Instruments observe together, share data in real time, perform position identification
- Collaborations share all data, analysis tasks, and publications
- Win-win-win (win win win win….)

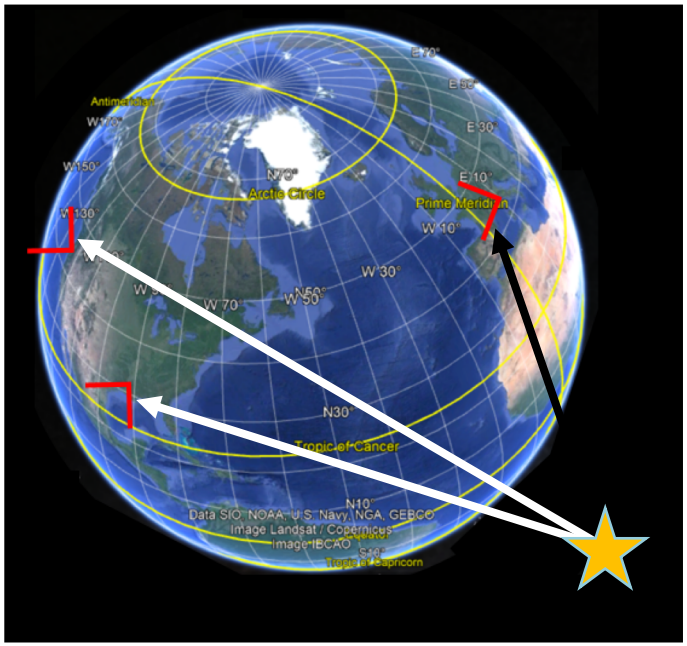


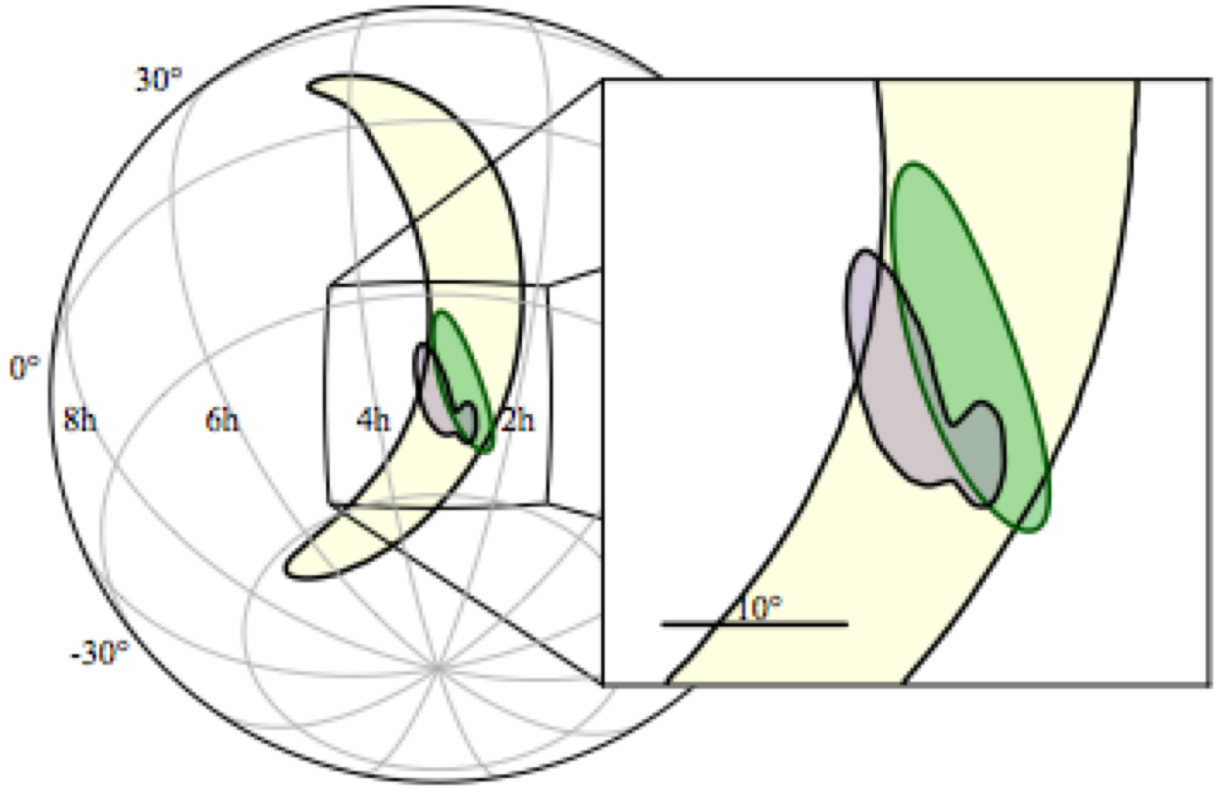
Localization by the GW detector network

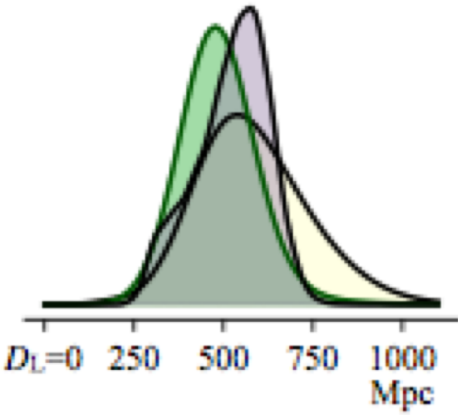




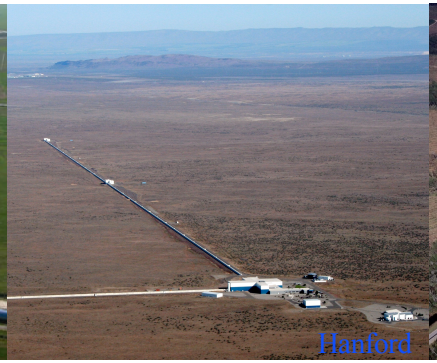









Virgo


Hanford


Livingston

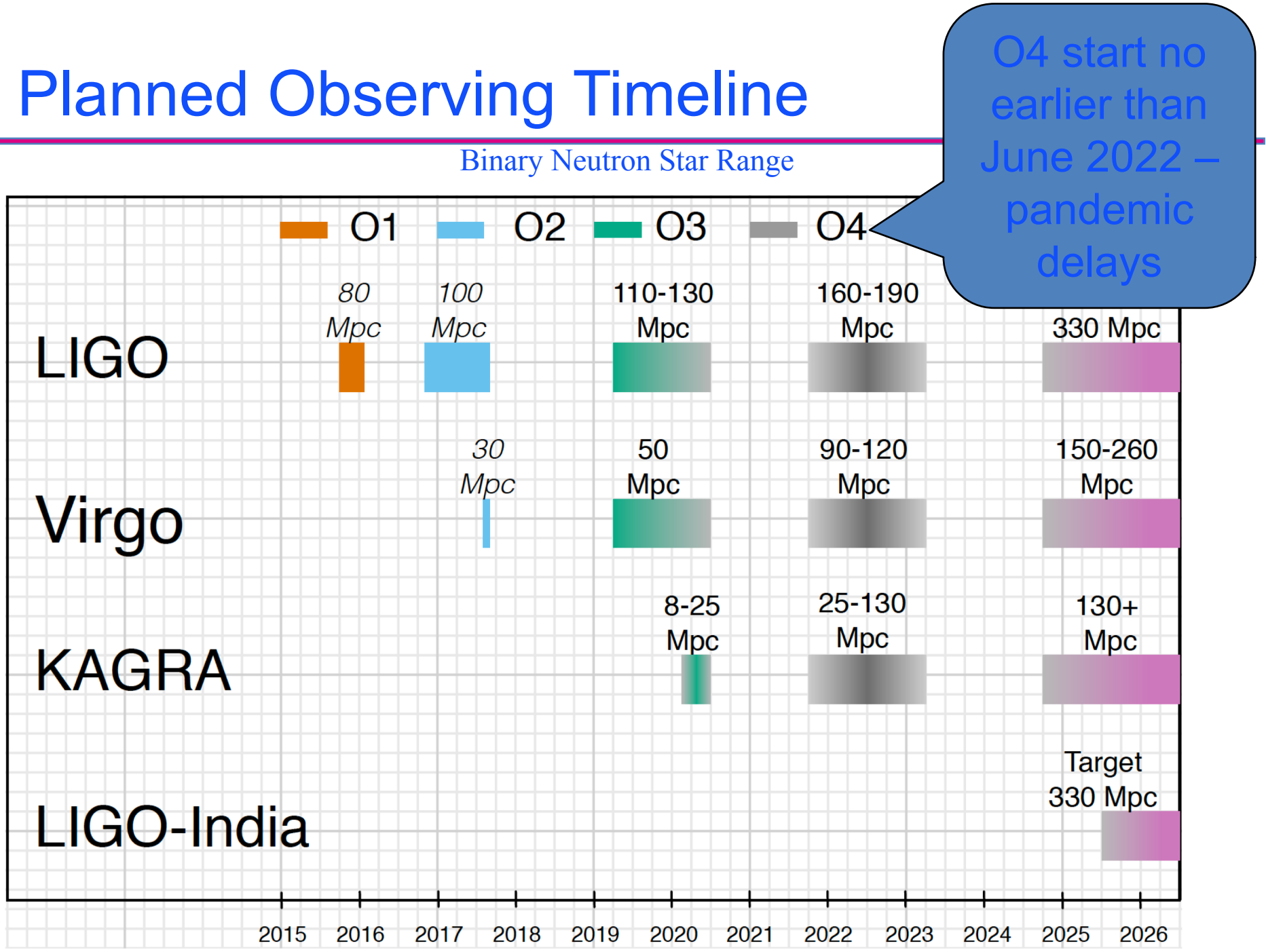
What enabled the remarkable achievements in this new field?

Collaboration

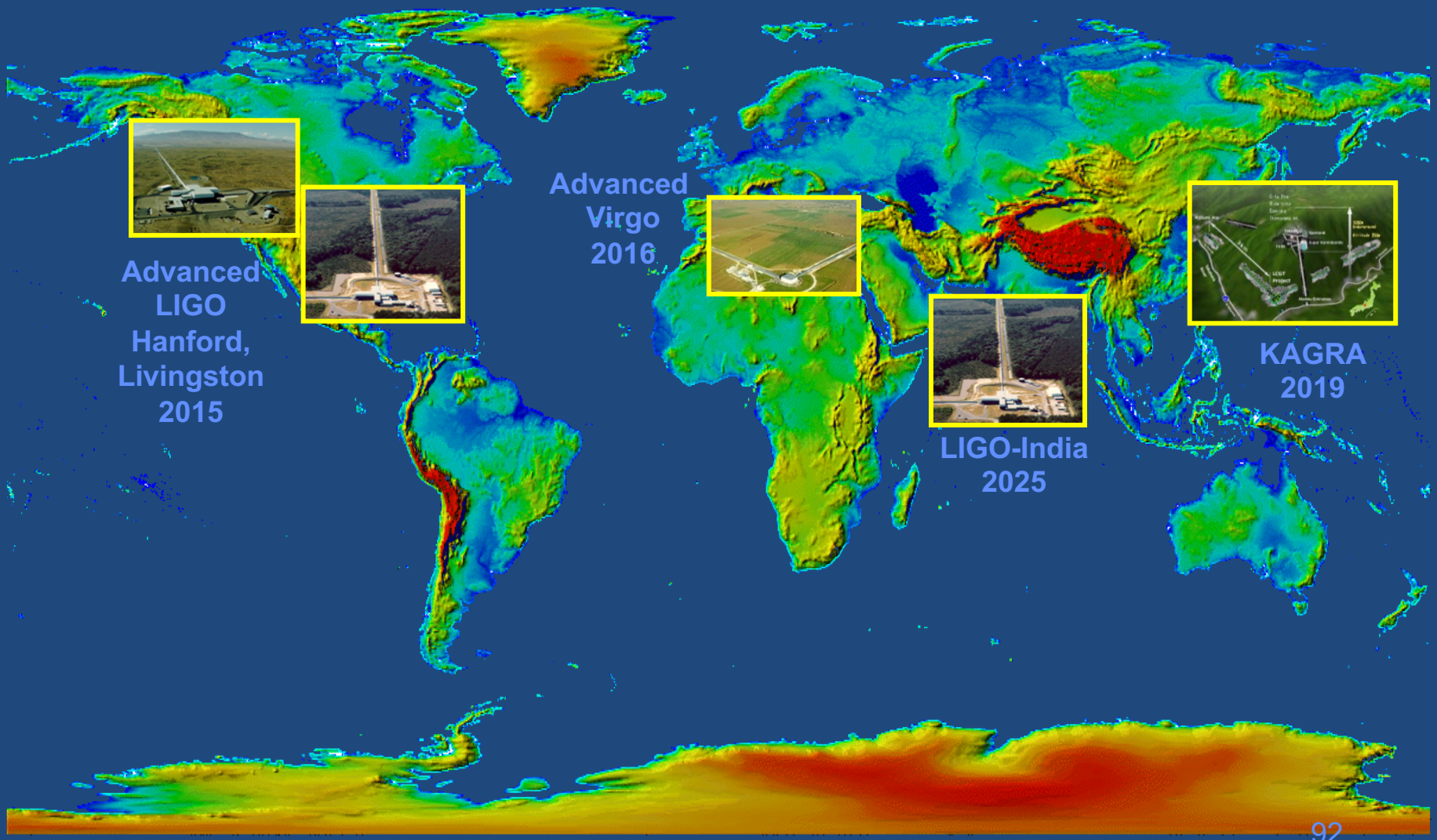
- Table-top scientists – precision measurement, laser, atomic – started the field; tradition of small groups, small projects, and some competition
- Early general relativists, theorists, astrophysicists much the same
- Transformation when High Energy Physics types got involved
  - » Engineering, project 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

What does the future hold?

Planned Observing Timeline

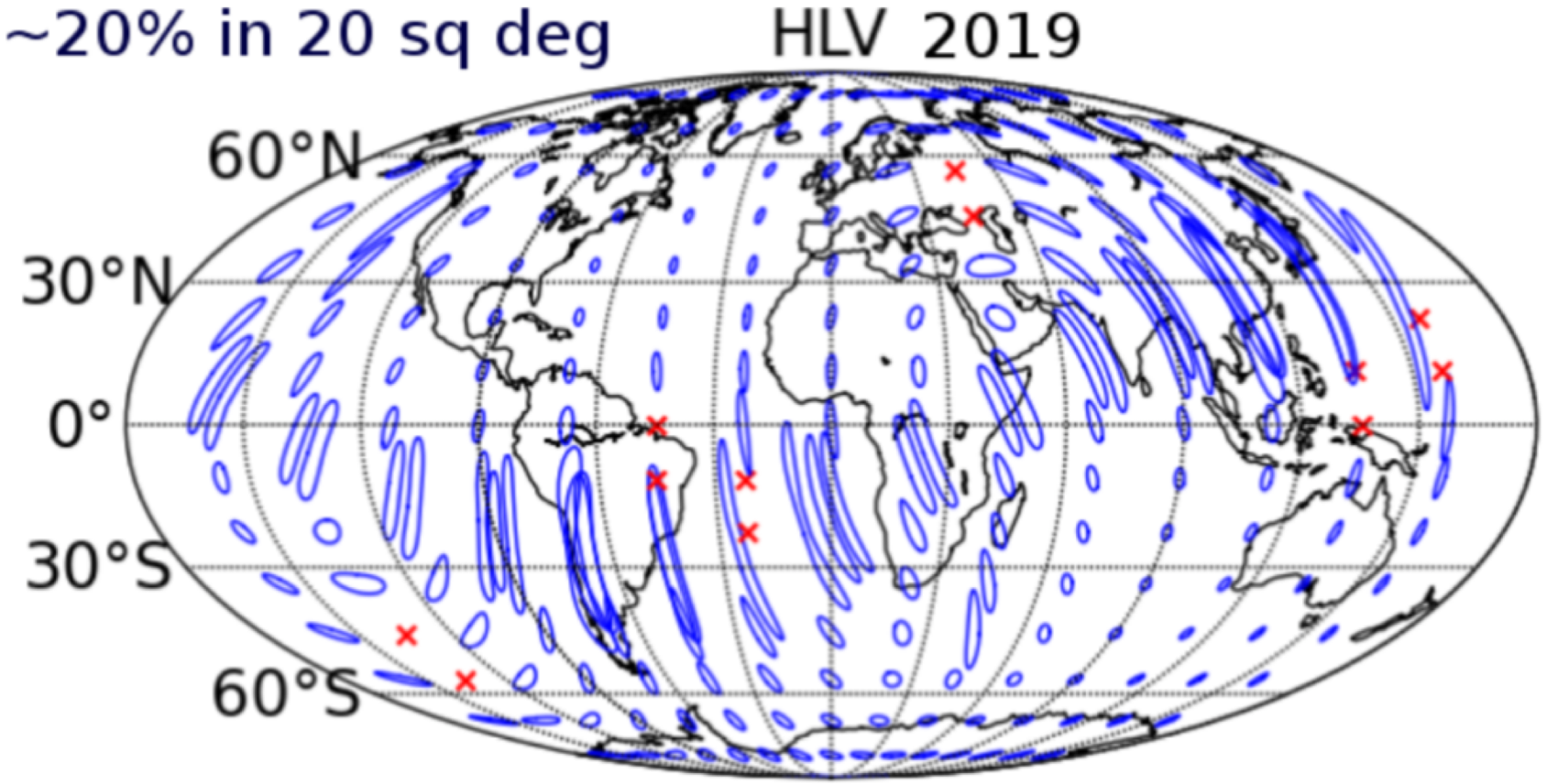


The advanced GW detector network



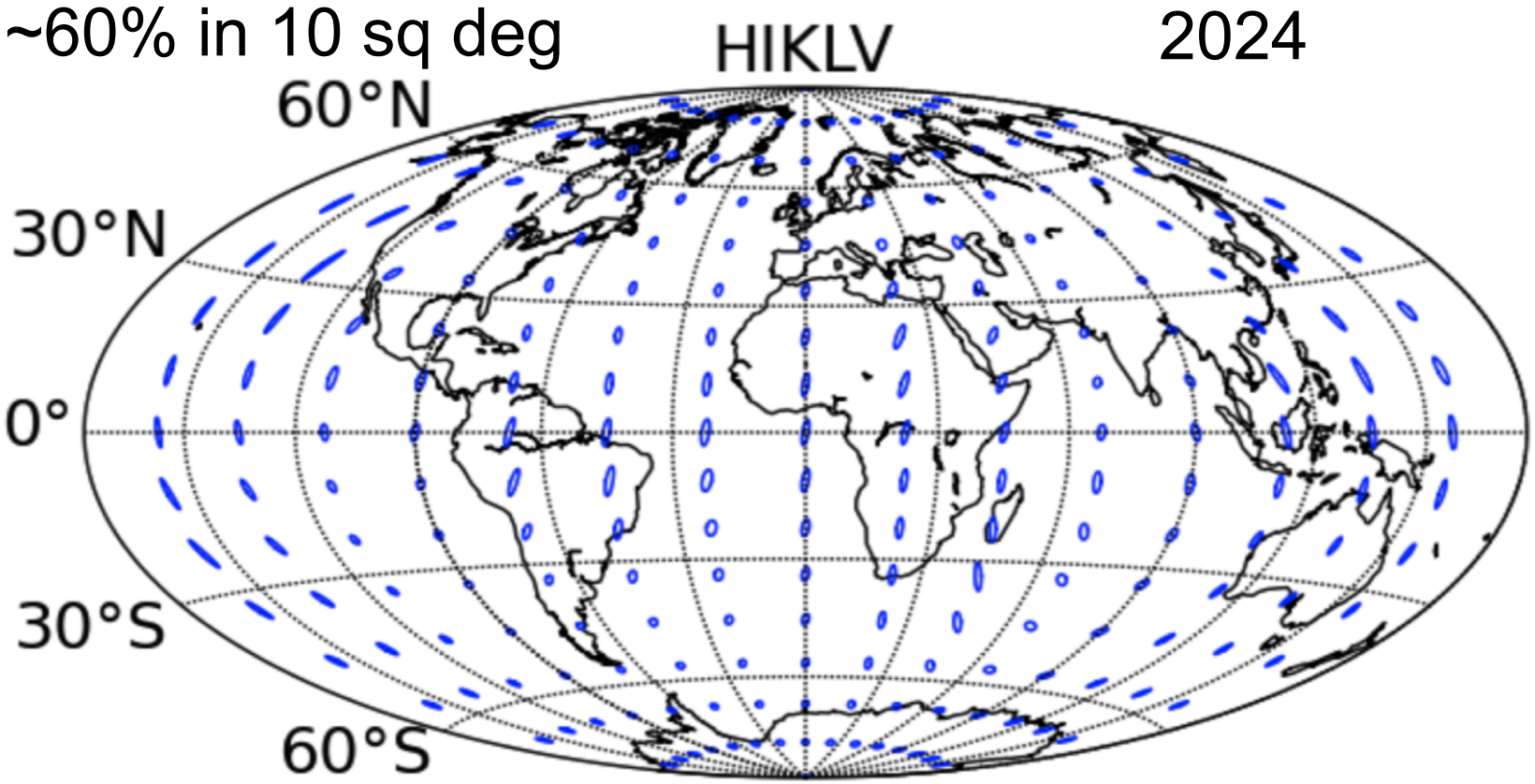
2018-19 Sensitivity/configuration:

3 detectors
~1 signal per week



~2025 Sensitivity/configuration:

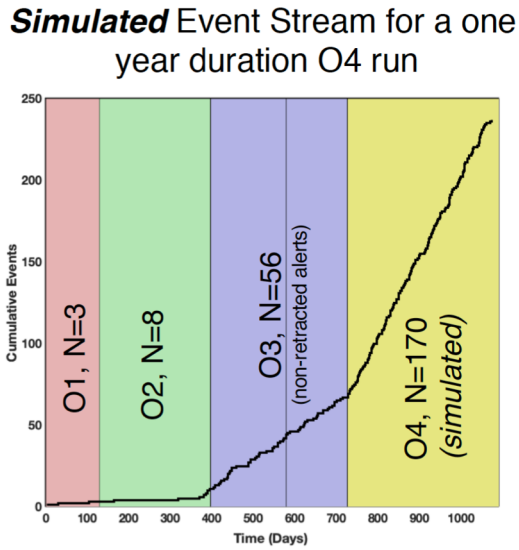
5 detectors (add India and Japan)
far improved source localization

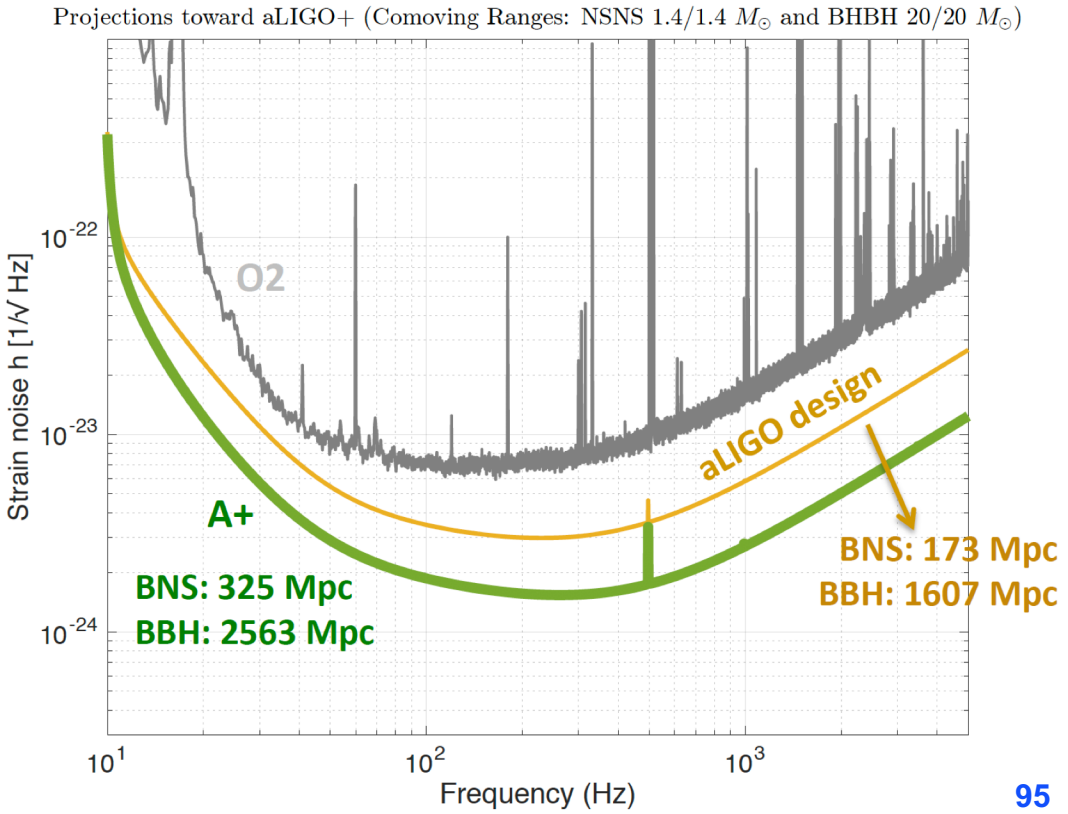


Sensitivity improvements are *very* well rewarded

- 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 ~2024 (plus pandemic delay)





Then…

- One of my early slides had the headline:

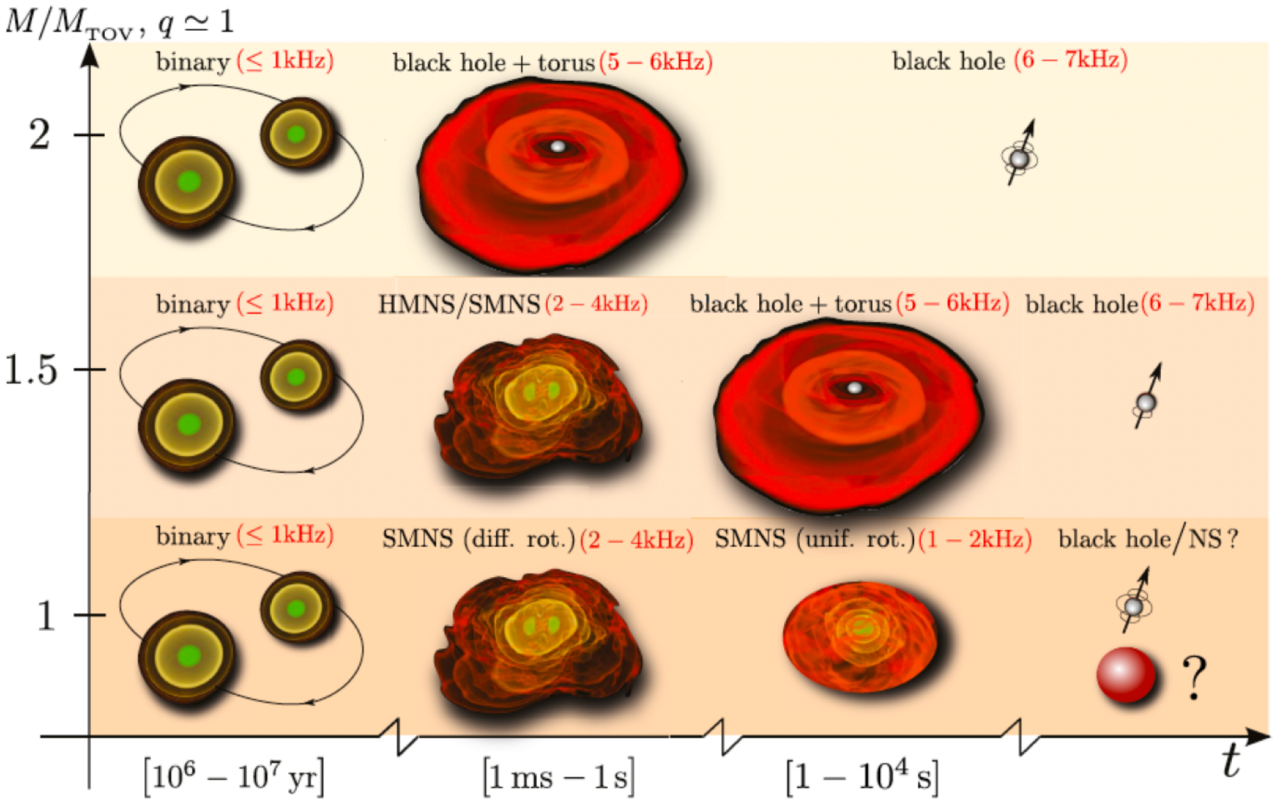
Ground-based Detector
~~requirements~~ → specifications

- Now can envision the transition:

Ground-based Detector
~~specifications~~ → **requirements**

Designing instruments for Astrophysical goals

- Suppose we want to focus on the nuclear physics of Neutron Stars –



L. Baiotti, and L. Rezzolla (2017)

Merger remnants:

Hyper-massive neutron star (HMNS) or Super-massive neutron star (SMNS)

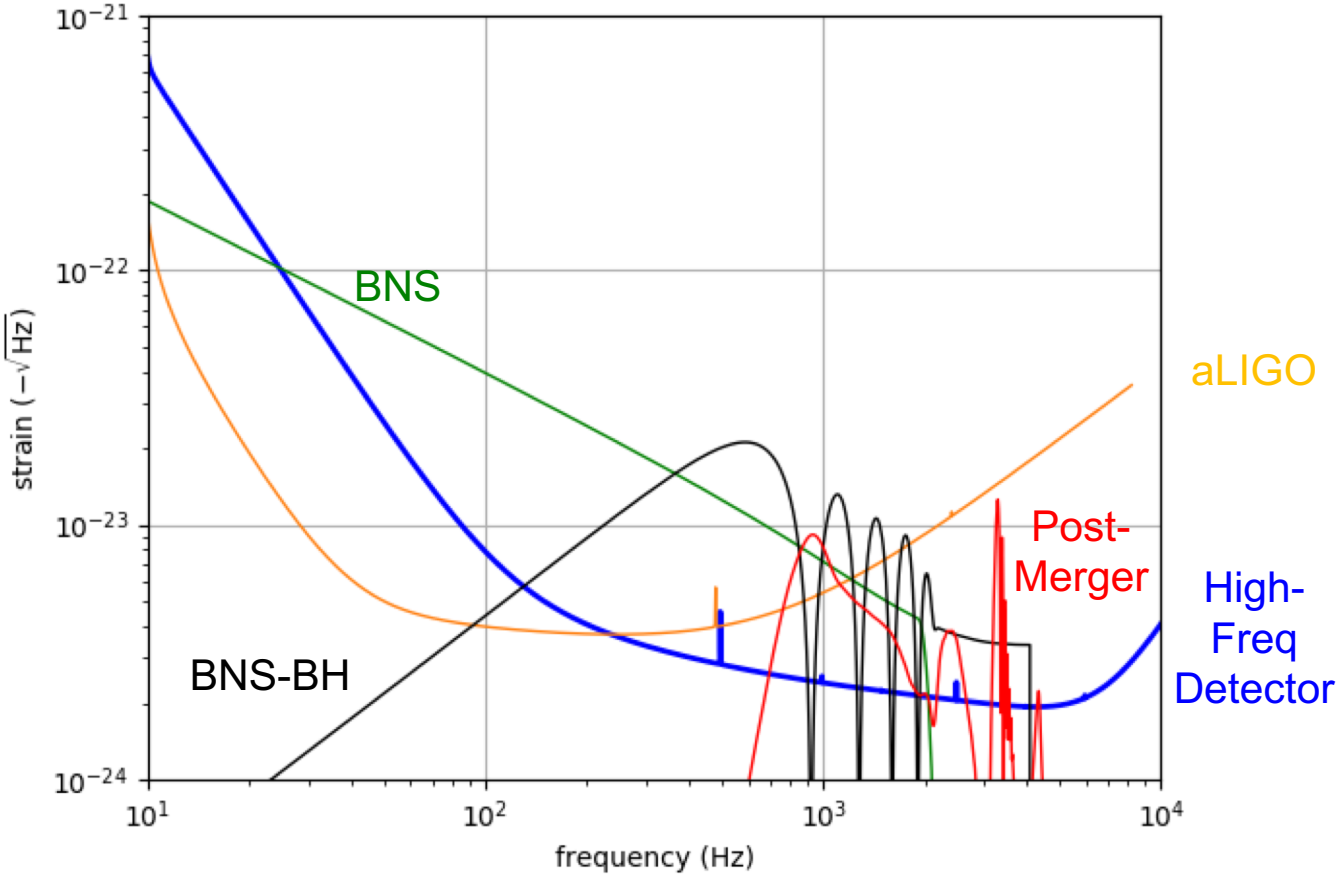
Oscillation mode (or GW) frequency is around 2kHz - 4kHz

Encoding rich information about equation of state (EOS) of hot, dense nuclear matter

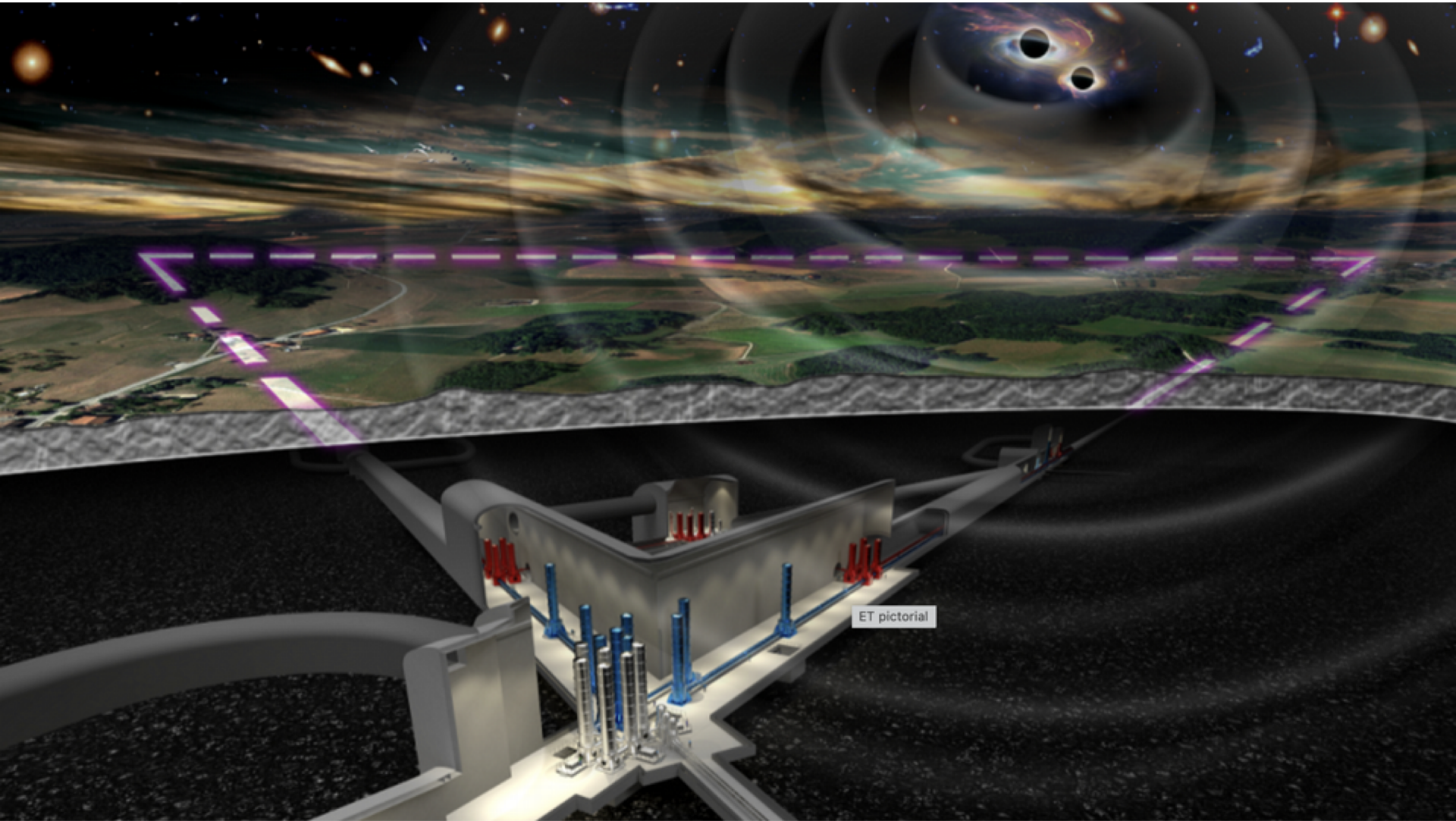
Having EM counterpart (multi-messenger observation)

NEMO: A ‘Neutron Star Explorer’

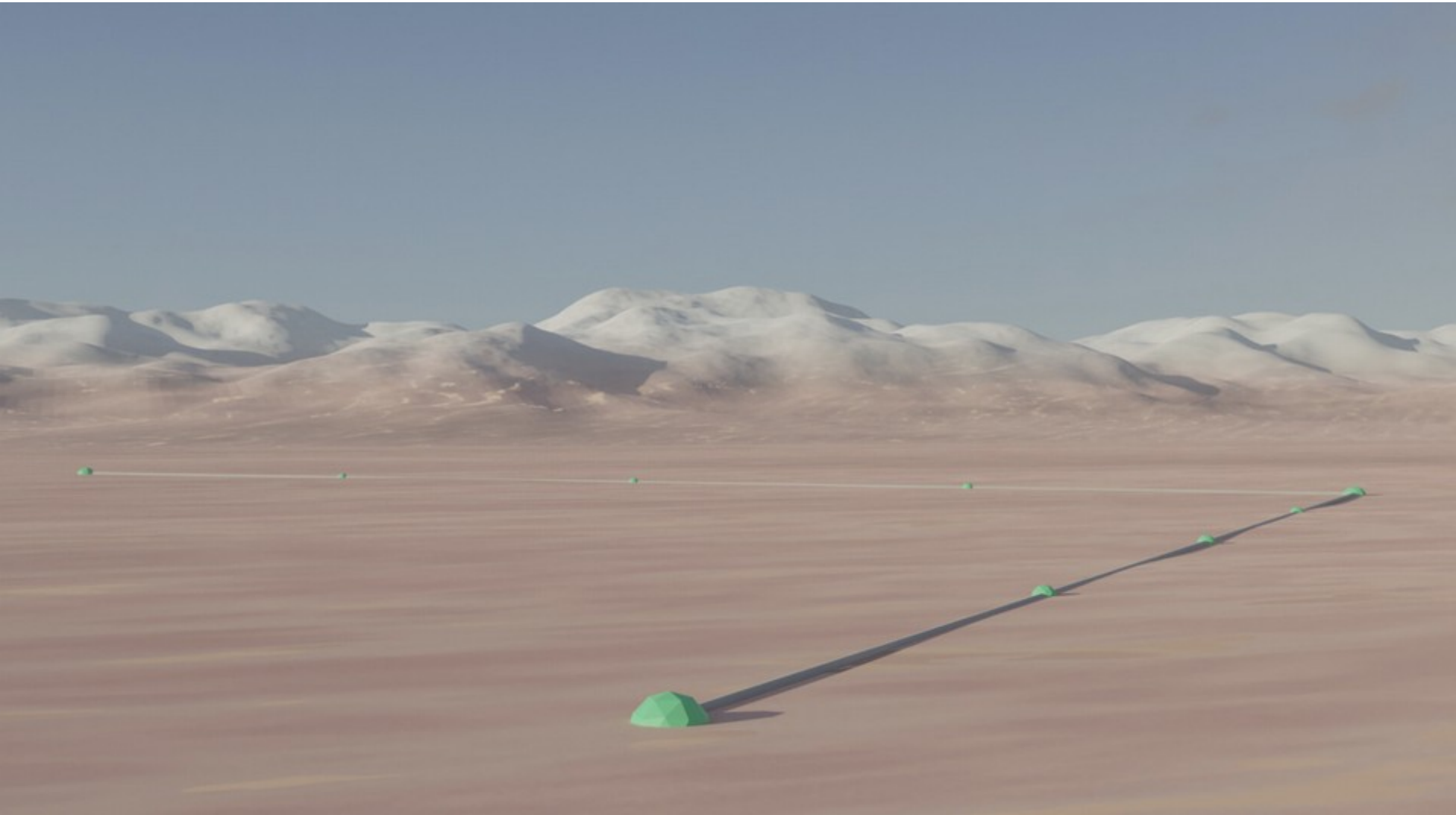
- Target the 1-5 kHz range
- Modest length requirements – 3-4 km
- Stressful on the optical design (high circulating power)
- …easy on the $1/f^n$ noise sources
- Australian future detector working group



Next Generation Observatories: Einstein Telescope

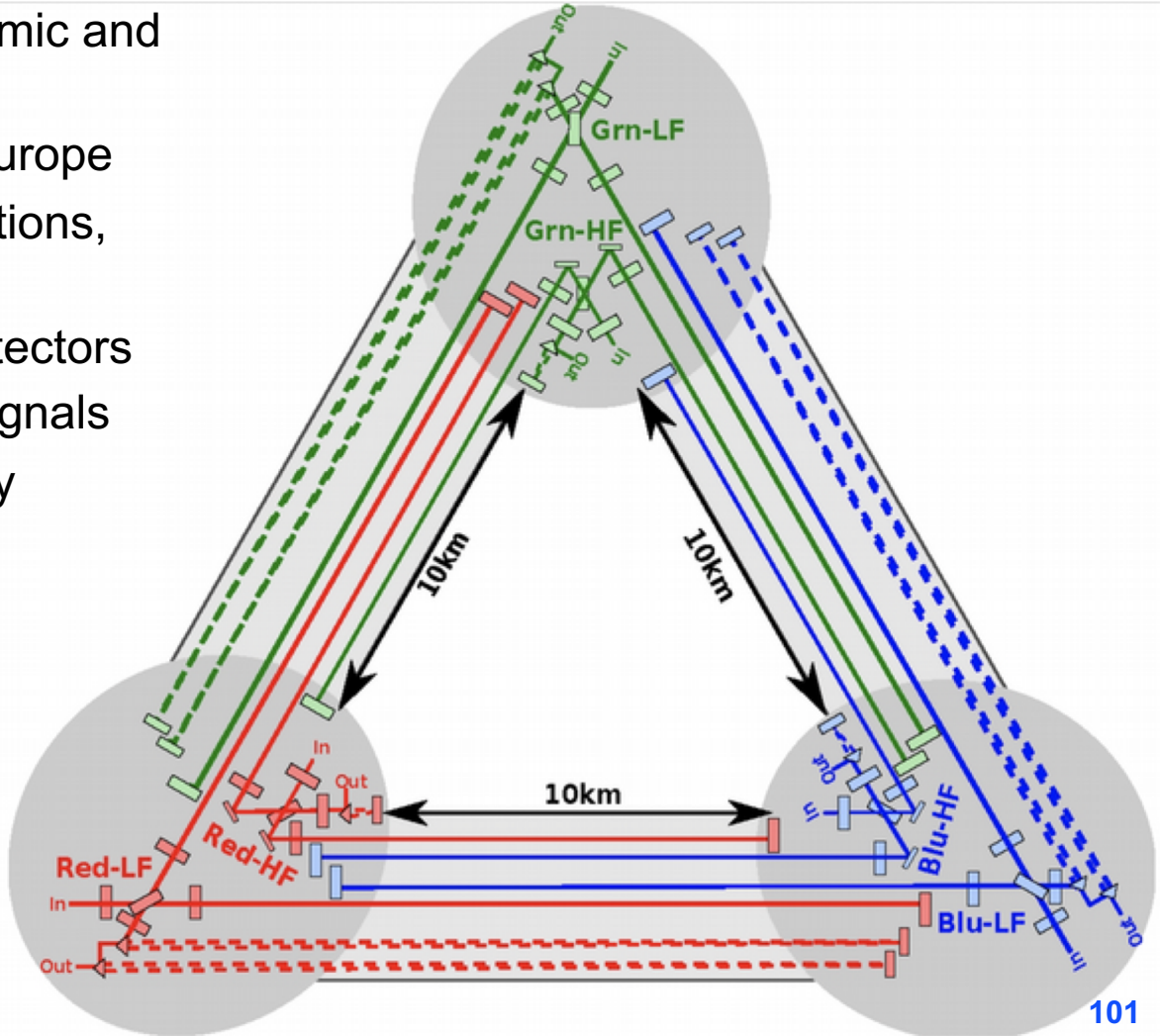


Next Generation Observatories: Cosmic Explorer



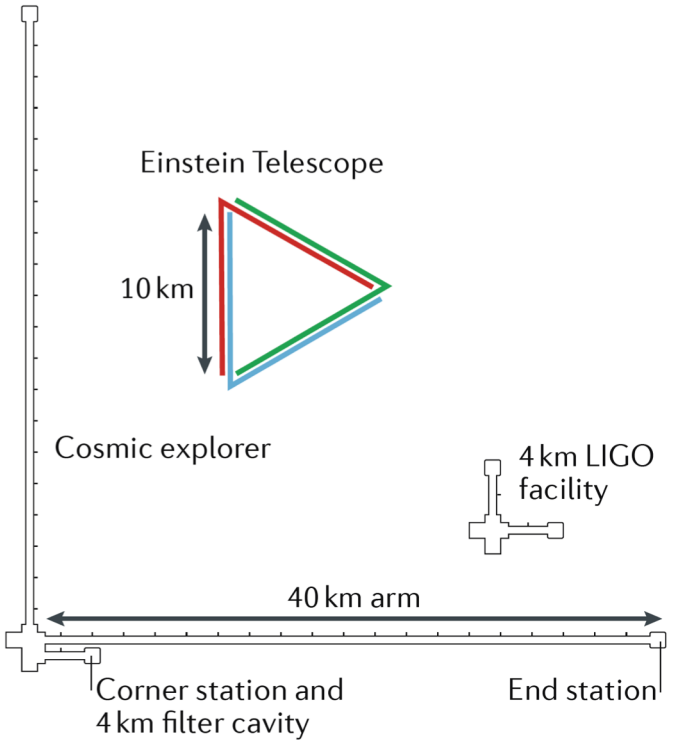
Einstein Telescope: Underground multi-ifo Triangle

- 10km arms – philosophy is to stretch technologies to overcome test-mass motions
- Underground to reduce seismic and Newtonian noise
  - » Also helps with site in Europe
- Triangular to give 2 polarizations, 'null stream'
- High- and low-frequency detectors
  - » High-power for NSNS signals
  - » Cryogenic low-frequency for BHBH

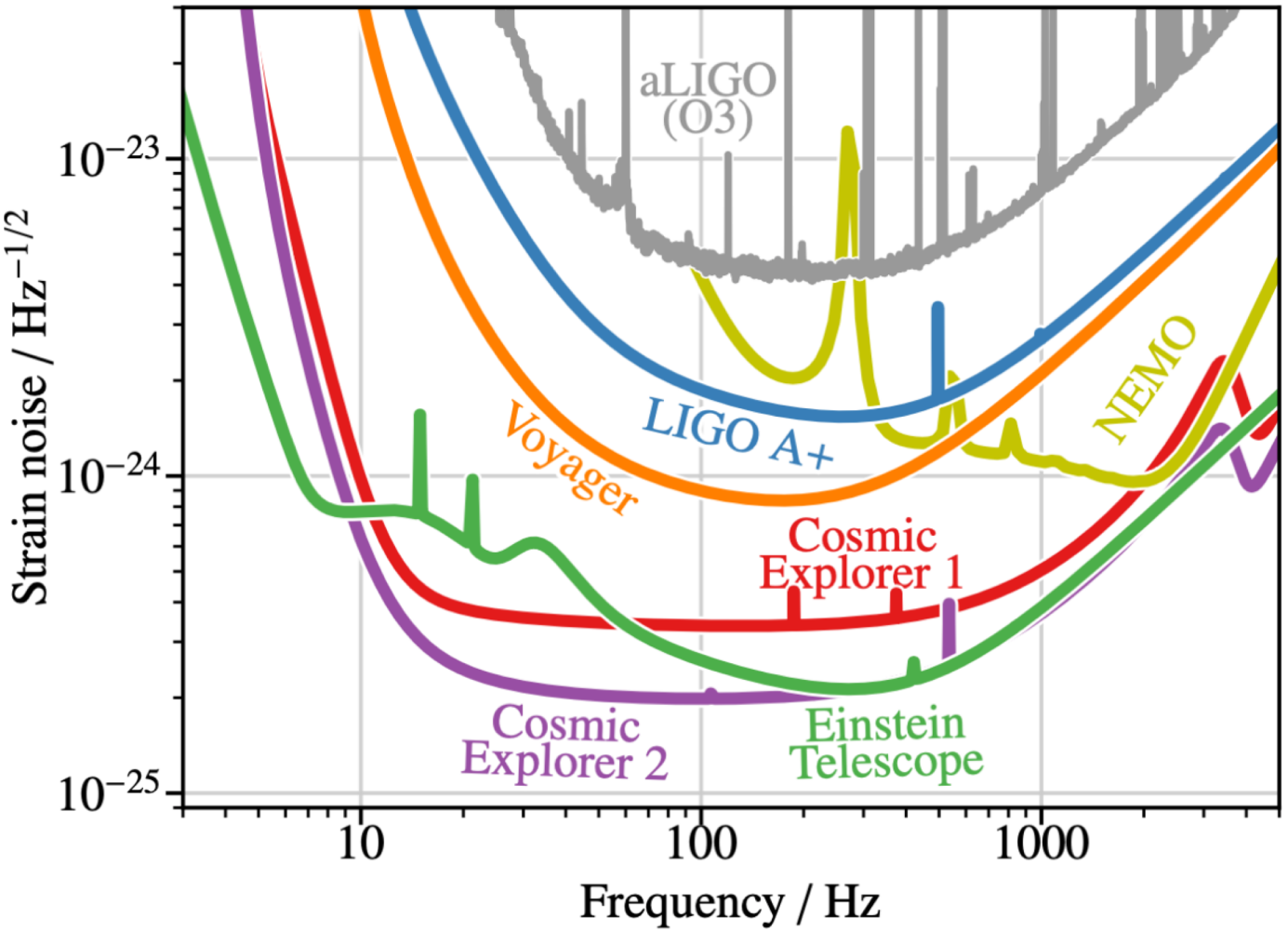


Cosmic Explorer: Make arms 10x longer

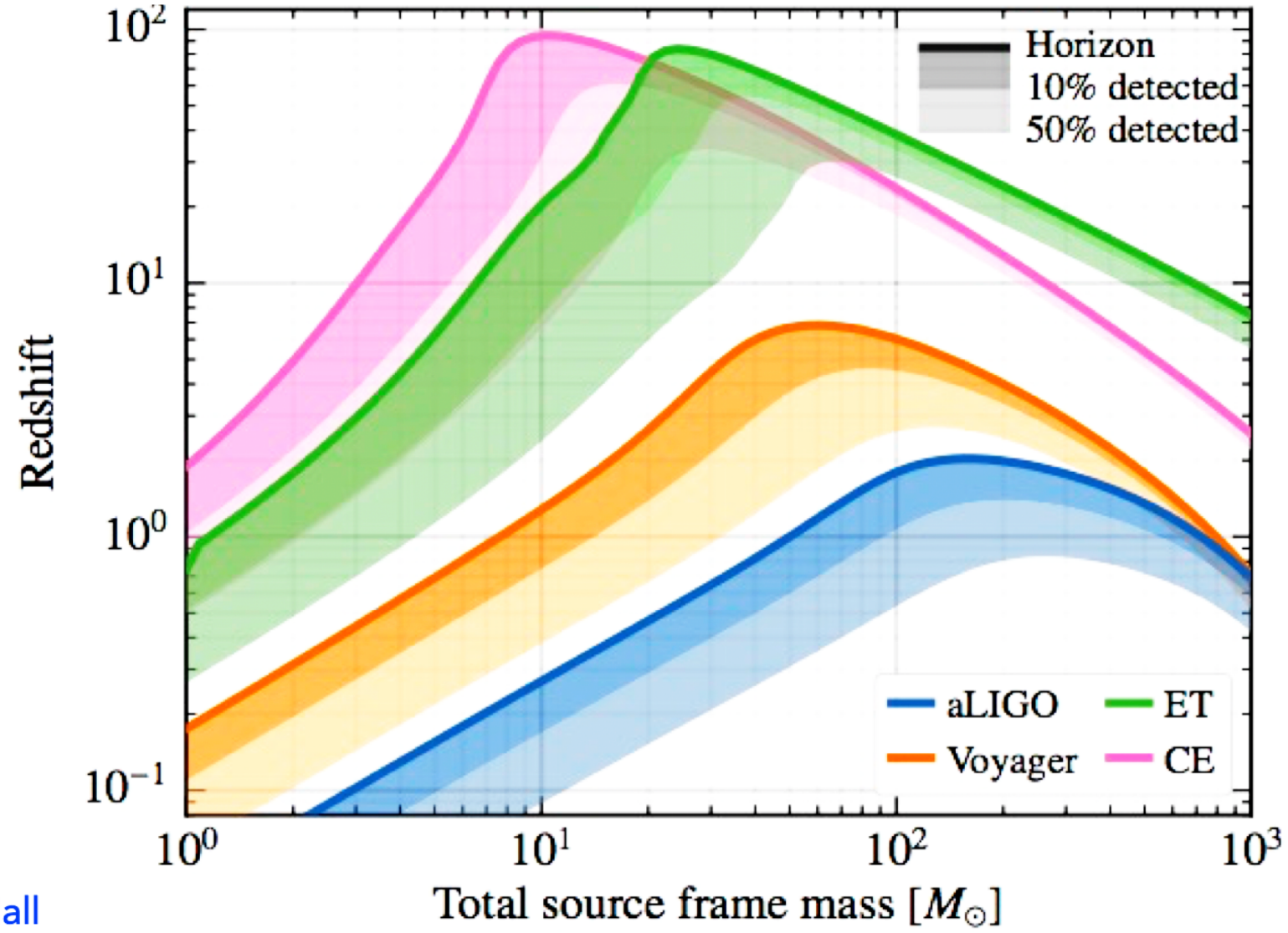
- Philosophy is the stretch the arms, and start with known technologies
- Signal $\Delta L = hL$ grows with length – *not* most noise sources
- Thermal noise, radiation pressure, seismic, Newtonian unchanged
- Coating thermal noise improves *faster* than linearly with length
- Concept offers sensitivity without new measurement challenges; start at room temperature, modest laser power, etc.
  - » Will install more challenging technologies when timely – Low initial risk is key
- Baseline of two detectors:
  - » 40km arms: maximize reach for cosmology
  - » 20km arms: focused on NSNS
- Have identified many possible sites
  - » Sagitta is 31 meters…
  - » Find 'bowls' which are in fact flat
    - – US; elsewhere, e.g., Australia
- Work on reducing cost of vacuum system



Sensitivity



Reach of 3G detectors for BH: Edge of the universe



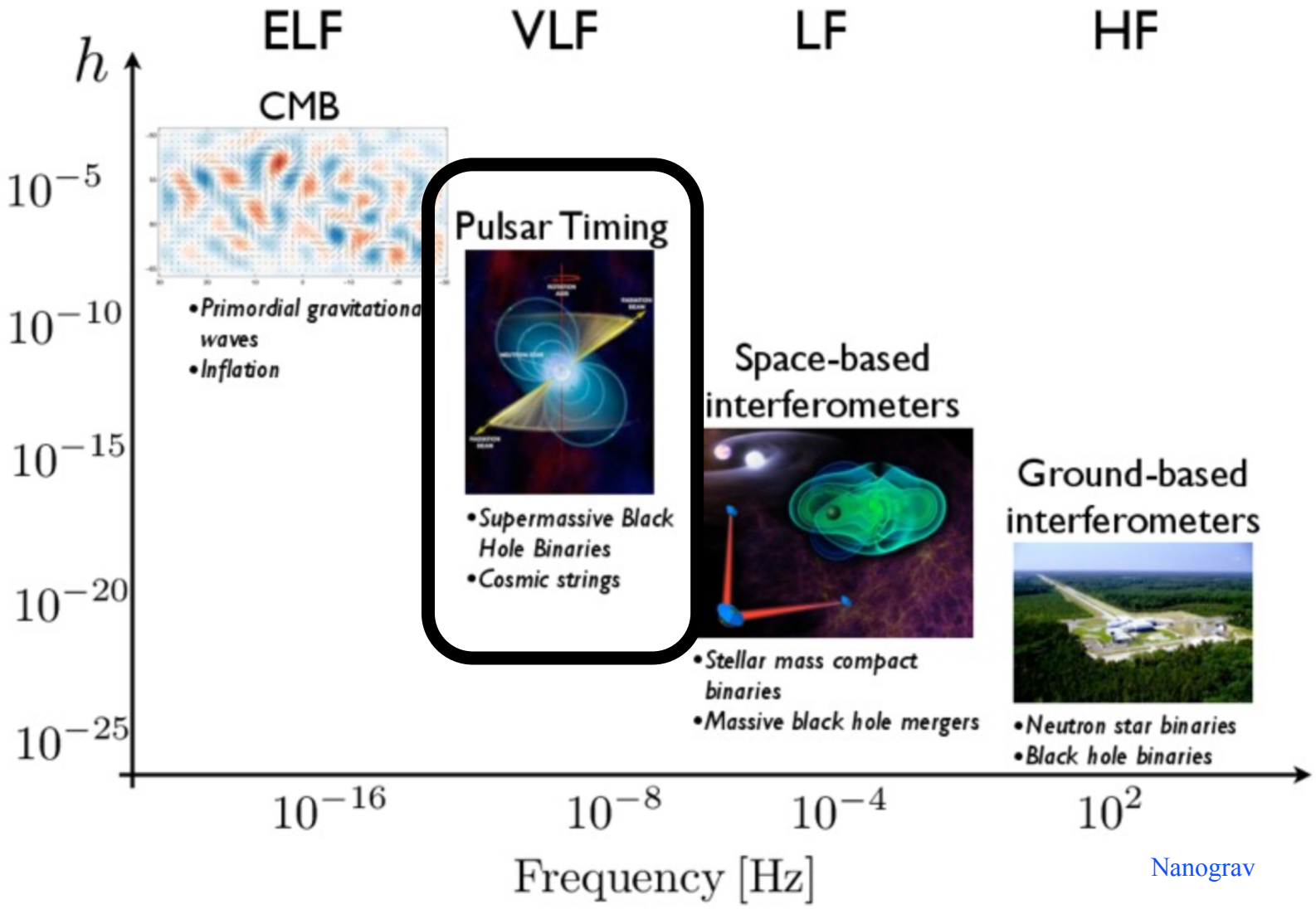
Evan Hall

Next Generation Observatories

- When could this new wave of ground instruments come into play?
- Appears 15 years from *t*=0 is a feasible baseline
  - » Initial LIGO: 1989 proposal, and at design sensitivity 2005
  - » Advanced LIGO: 1999 White Paper, GW150914 in 2015
- **Modulo funding, could envision 2030's**
- Should hope – and strive and plan – to have great instruments ready to 'catch' the end phase of binaries seen in space-based LISA
- Worldwide community working together on concepts and the best observatory configuration for the science targets, e.g.,
  - » GWIC https://gwic.ligo.org/3Gsubcomm/documents.shtml

- **Crucial for all these endeavors: to expand the scientific community planning on exploiting these instruments far beyond the GR/GW enclave**
  - » Costs are like TMT/GMT/ELT – needs a comparable audience
  - » Events like GW170817 help!

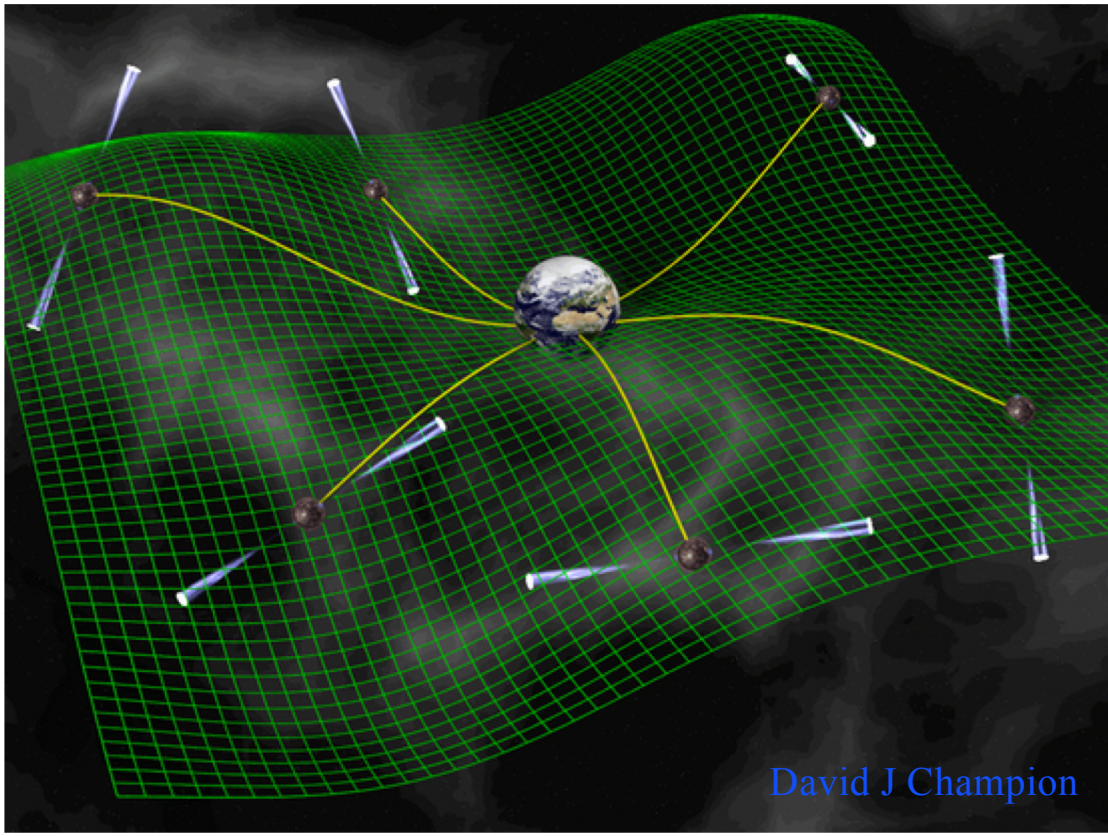
Broad spectrum of GW sources



Nanograv

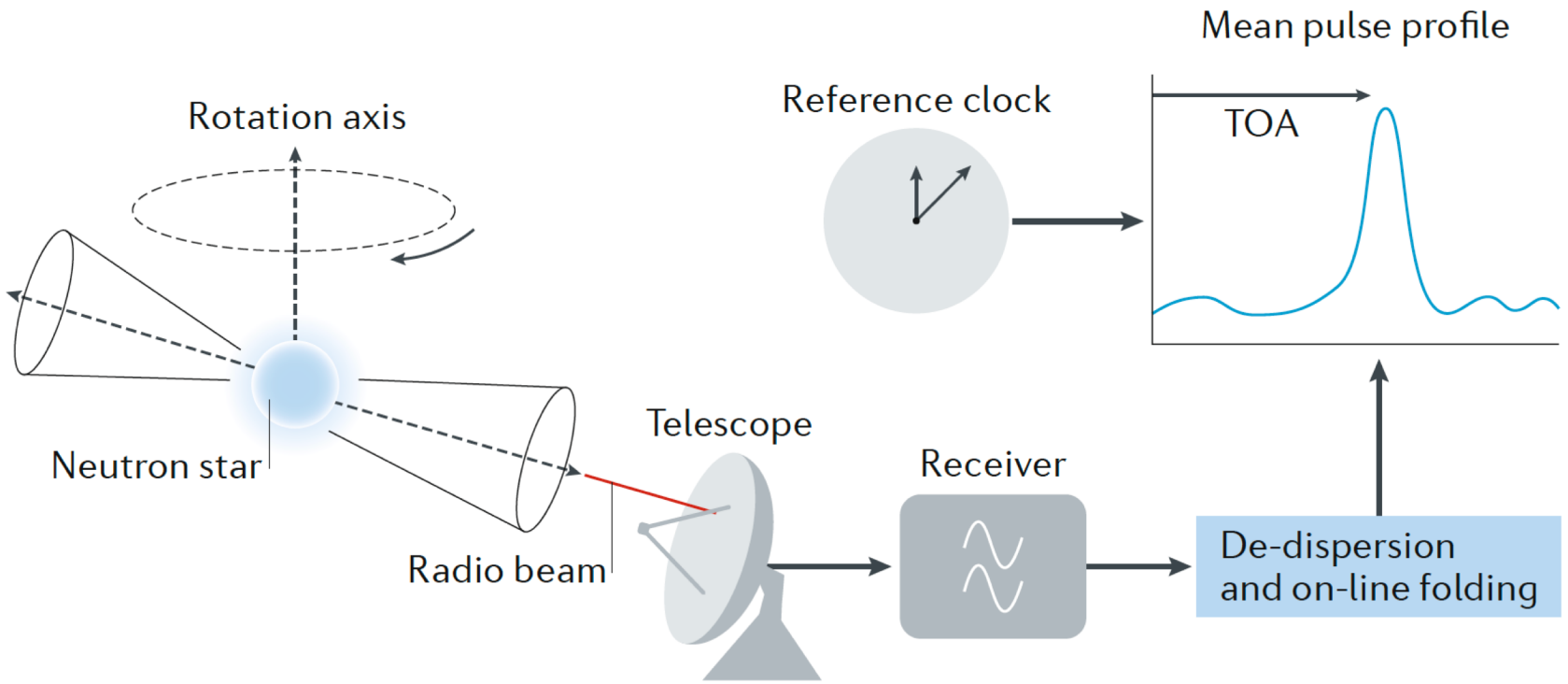
Pulsar Timing Arrays

- Pulsars: spinning Neutron Stars; magnetic fields lead to beamed EM emission
- Significant number have their ‘beacons’ pointing at Earth
- Form extremely stable clocks
- If a GW passes between us and the pulsar, the time-of-arrival of the clock pulse will be shifted
- Looking at a collection of pulsars scattered in space, unique signal corresponding to GWs can be inferred
- Sensitive to *very* massive BH
  - » ~10^7 - 10^{10} $M_\odot$
- Astrophysical stochastic background best candidate
- Some indication of a signal!
  - » Measurements continuing…



PTA ‘Instrument’

- Test Mass offered by the Pulsar and its rotation
- Radio Telescope catches many low-SNR ‘blips’
- De-dispersion (originating in the interstellar medium)
- Blips ‘folded’ on top of eachother to increase SNR
- ‘Fit’ of signals from multiple pulsars to models of passing GWs



The International Pulsar Timing Array: Radio telescopes



IPTA

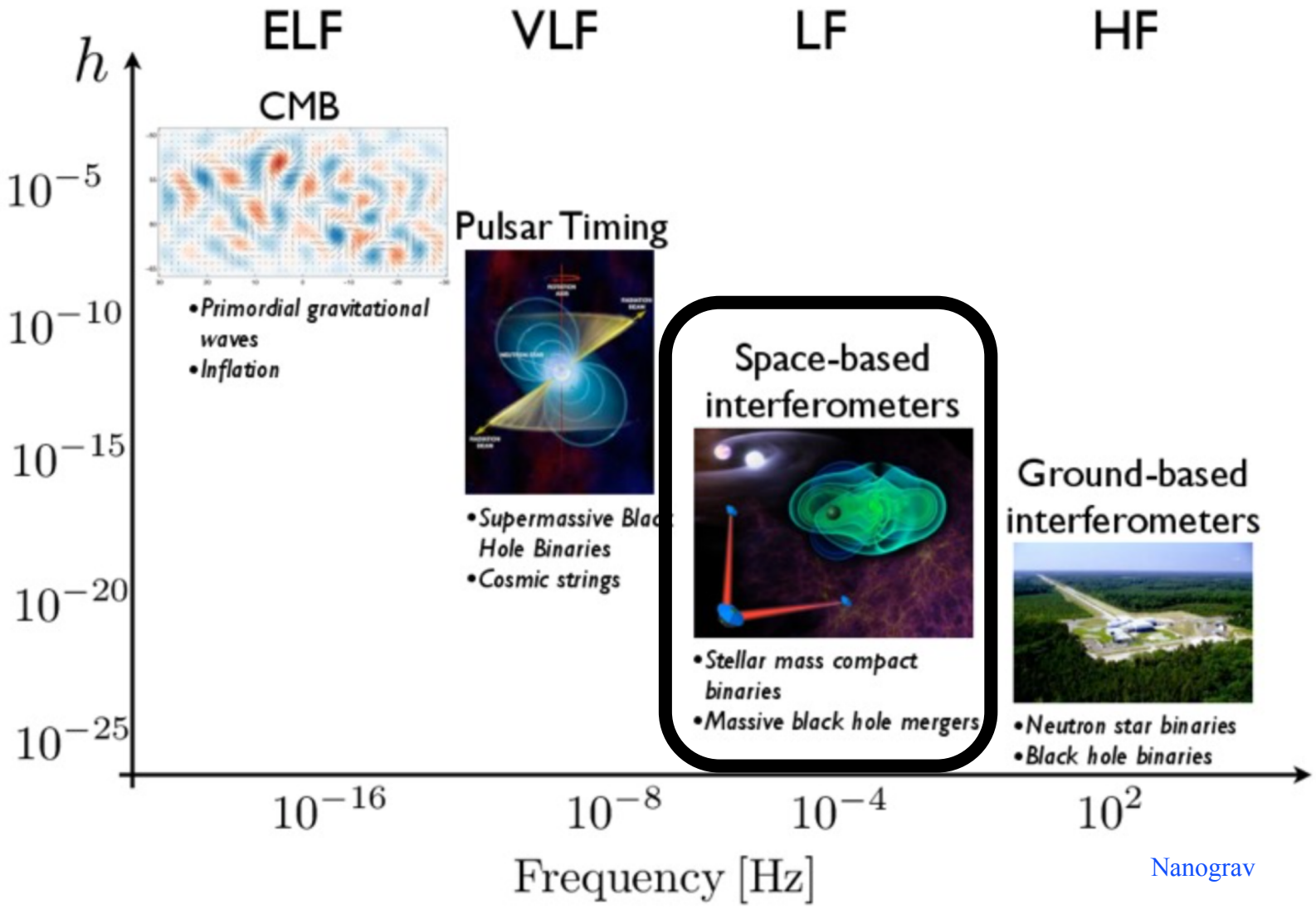
G2100281

The International Pulsar Timing Array: People



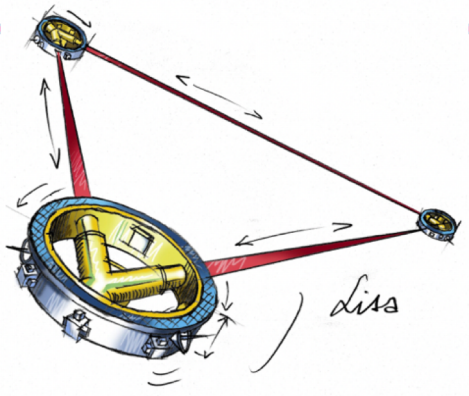
- Groups in Europe, India, Australia, US working together to join data
- Requires allocation of time on instruments worldwide, bringing data sets into common formats, and number crunching
- Pulsars also have personalities – glitches
- Finding additional pulsars also improves the sensitivity
- Ultimately, the $h(t)$ of some individual sources should be seen

Broad spectrum of GW sources

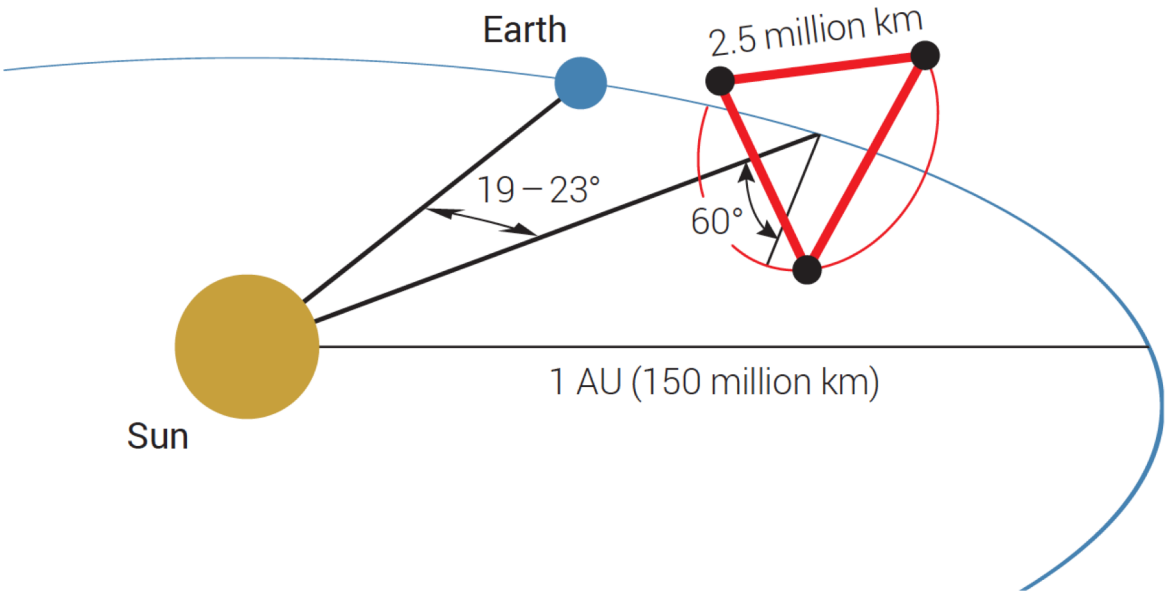


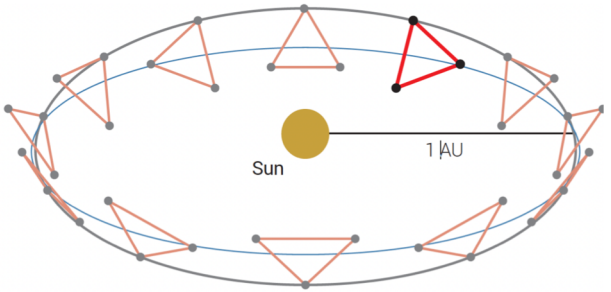
Nanograv

LISA, targeting super-massive Black Holes



- 2.5x10^6 km arms: moves best sensitivity to 0.01 Hz, target masses to 10^6 solar masses
- 'Servo' the shield satellites to follow the test masses, protecting against solar wind etc.
- Orbit scans sky; sources last years, viewed from 2AU baseline
- Use interferometry to sense path length changes due to passing GW

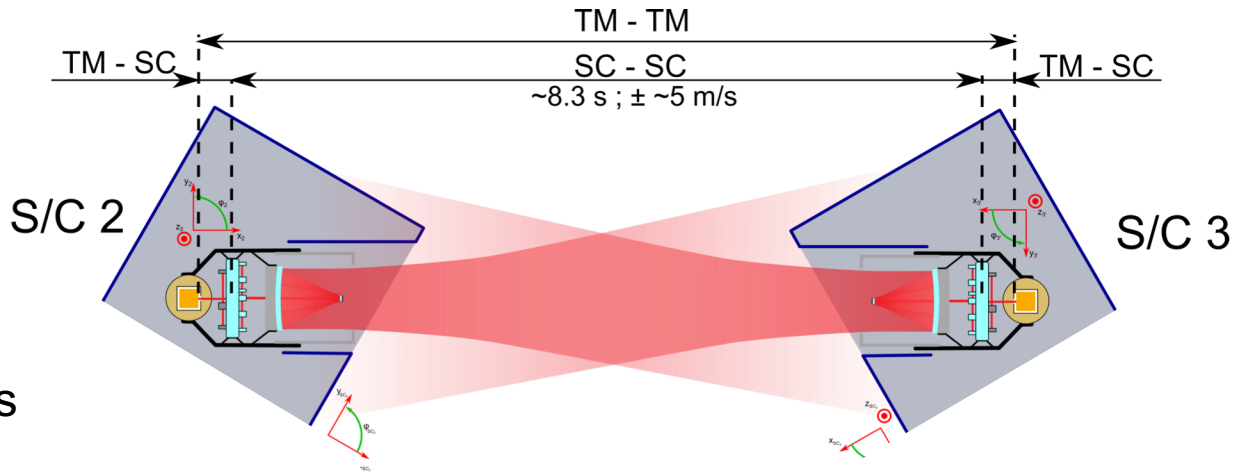




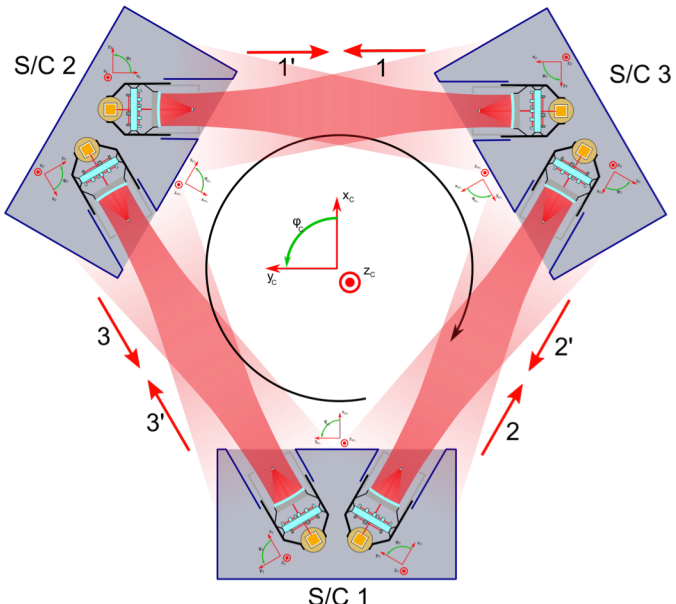
LISA Orbit

The measurement concept

- Test-mass to test-mass measurement is synthesized from:
- test-mass to spacecraft
- →spacecraft to spacecraft
- →→spacecraft to test-mass

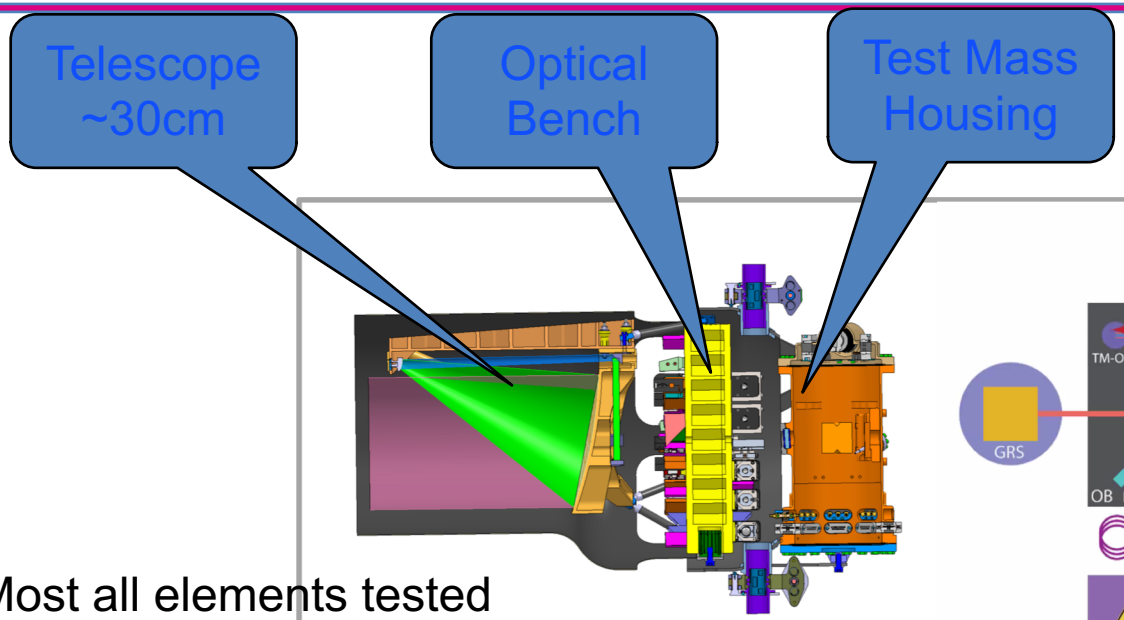


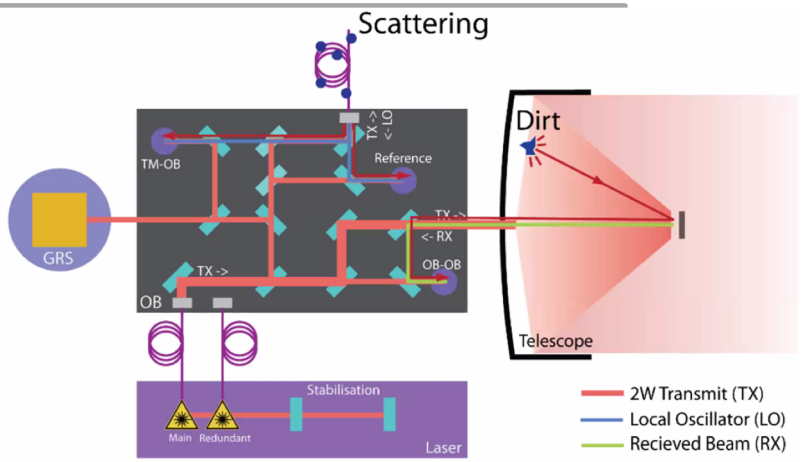
- 2 W broadcast, 10^{-10} W received
  - » *Not* LIGO-style interferometry!
  - » 6 independent lengths



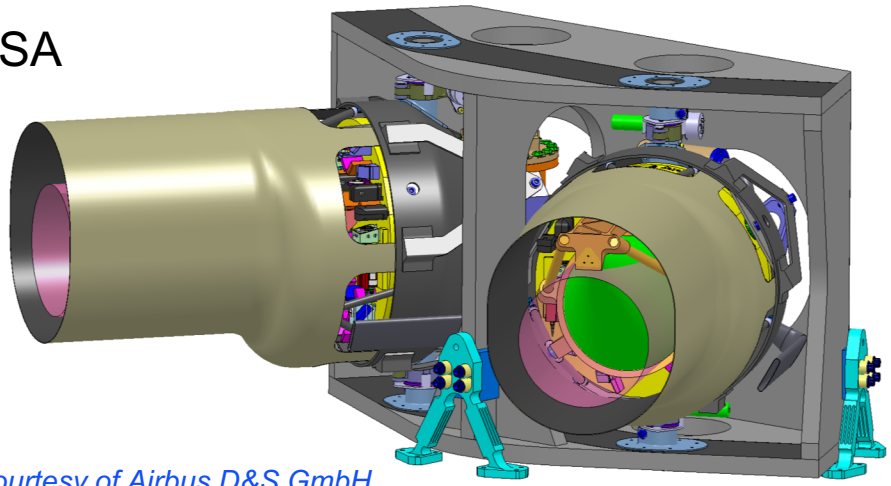
- Combine 6 links on ground
- 'Time Delay Interferometry' to reconstruct GW waveform, suppress technical noise

The basic sensing assembly





- Most all elements tested in the 'LISA Pathfinder'
- All requirements for LISA demonstrated with margin
- Telescope is one new element, along with the 2.5x10^6 km path



Images courtesy of Airbus D&S GmbH, Friedrichshafen

LISA Path Finder

- LPF was two test masses, separated by and optical bench of some tens of cm; LISA uses the same test mass setup
- Sensors measure distance from test mass to the cage
- Low-force thrusters push on spacecraft to keep the cage equidistant from the test mass



- Initial balancing is critical!
- The 'gravitational attraction'* of the test mass to a paperclip would be fatal, causing the spacecraft to chase the paperclip to oblivion…

*'gravitational attraction' = warpage of spacetime

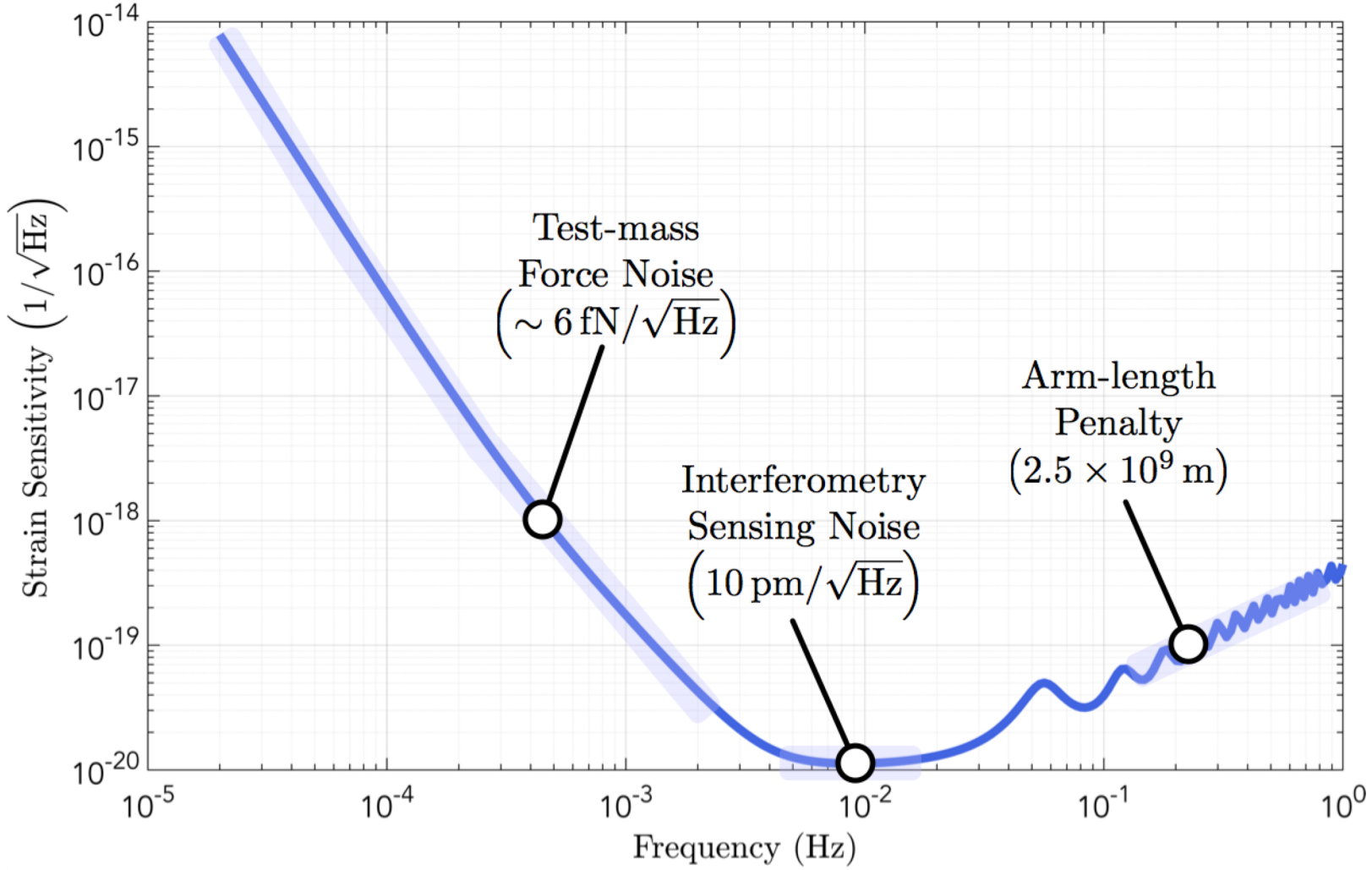
Comparison Ground and Space

- From a talk I gave in 1998…

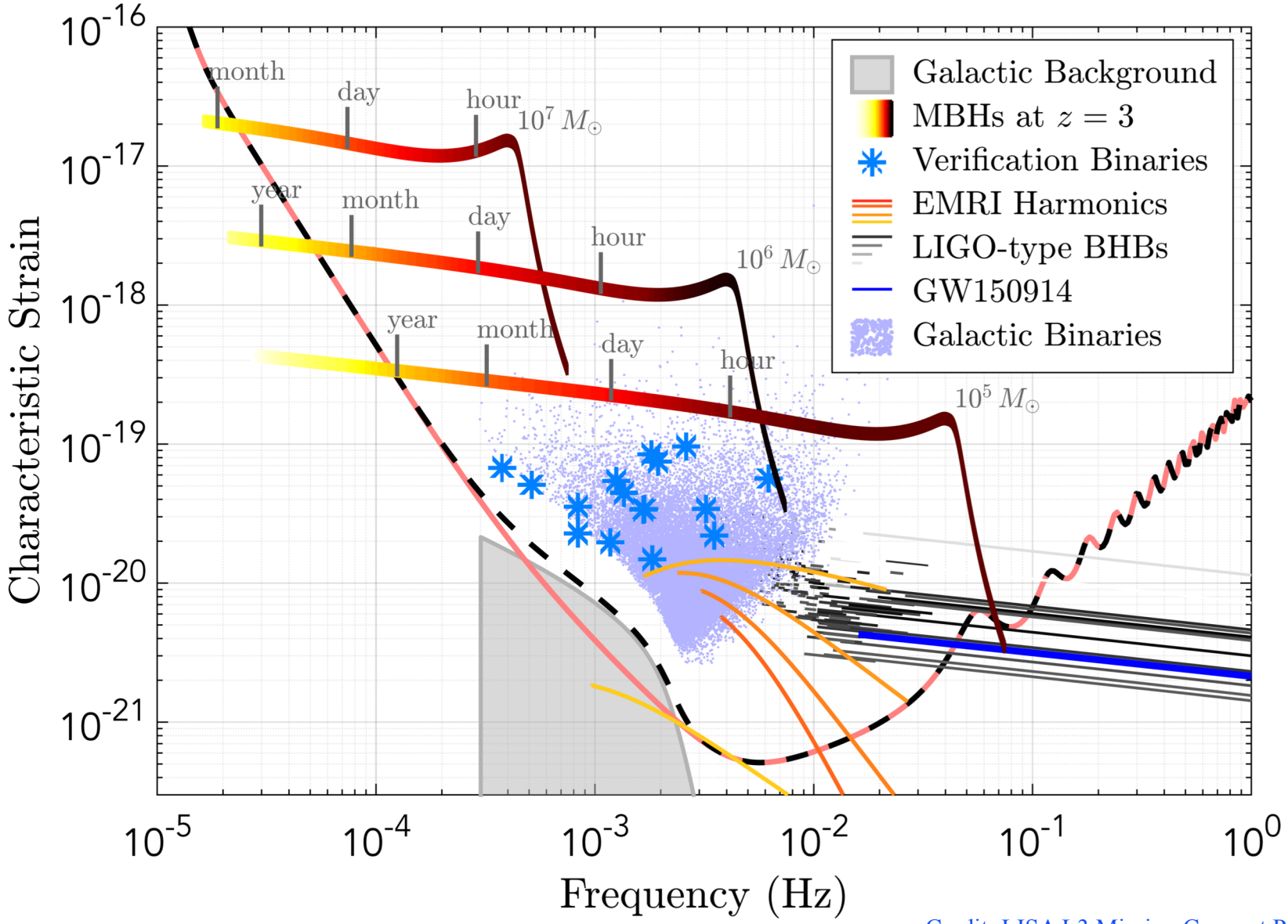
	Ground-based	LISA
Frequency Range	$10^{+1} - 10^{+4}$ Hz	$10^{-4} - 10^{-1}$ Hz
Burst/Integrated strain sensitivity	$\sim 10^{-23}$ (at ~100 Hz)	$\sim 10^{-23}$ (at ~1/100 Hz)
Arm Length	$\sim 10^{+3}$ m	$\sim 10^{+9}$ m
Displacement sensitivity	$\sim 10^{-19} \frac{\text{m}}{\sqrt{\text{Hz}}}$	$\sim 10^{-12} \frac{\text{m}}{\sqrt{\text{Hz}}}$
Stochastic forces	seismic isolation, suspensions, thermal noise	inertial sensing, drag-free technology, thermal distortions
Sensing system	laser power, optics development	clocks and corrections, transponding system

LISA Sensitivity curve

- Again: stray forces at low frequencies, shot noise at high frequency
- See the effect of GW wavelengths shorter than arms at HF



LISA Astrophysics



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Credit: LISA L3 Mission Concept Proposal

Done, at last!

- instrumentation touches fundamental physics in many domains
- systems are complex and rich
- all source domains are currently mostly or entirely unexplored
- all detector domains have clear paths to refinement, improvement, extensions
- An interesting environment from a social and career perspective

Just the beginning of a new field – new instruments, new discoveries, new synergies

Milliseconds	Minutes to Hours	Years to Decades	Billions of Years
LIGO/Virgo	LISA	Pulsar Timing Array	Cosmology Probes



