Earth-based Gravitational-Wave Experiments
Part I: Detectors

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SIGRAV International School 2024 - Measuring Gravity

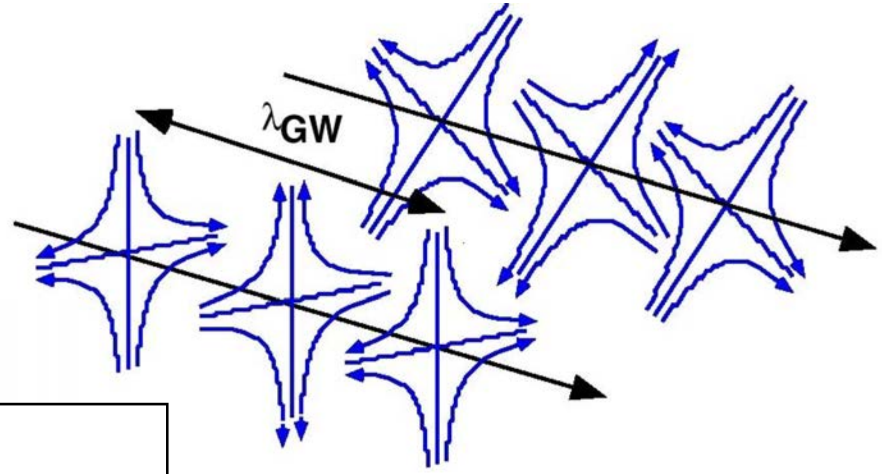
GRAVITATIONAL WAVES AND INTERFEROMETRIC DETECTORS

Gravitational Waves

- ❑ A prediction of General Relativity (Einstein, 1916)
- ❑ Perturbations in space-time metric
  - ➢ Generated by mass acceleration
  - ➢ Transverse, quadrupolar,
    2 orthogonal polarizations
  - ➢ Propagate at speed of light
    - ▪ Amplitude decreases with distance
- ❑ Source luminosity

$$\frac{c^5}{G} \quad \epsilon^2 \quad \left(\frac{R_S}{R}\right)^2 \quad \left(\frac{v}{c}\right)^6$$

asymmetric compact relativistic



$$h = 2\,\frac{\delta L}{L}$$

➔ Astrophysical sources
$h < 10^{-21}$ on Earth

Science Impact

Gravitation

Sources

High-energy phenomena

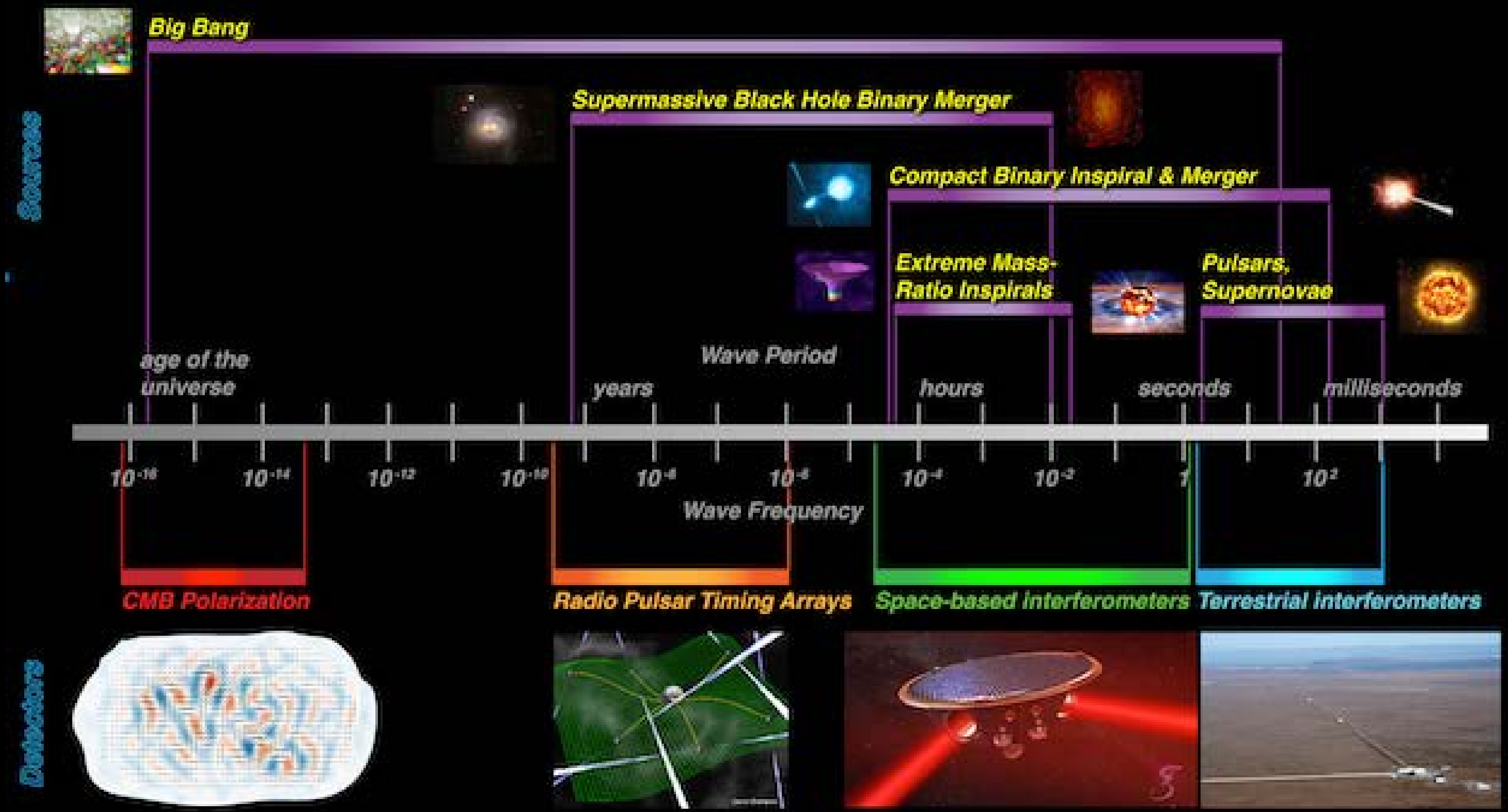
- Gravitational waves are generated in some of the most energetic events in the Universe
  - Direct probe of the event dynamics
- Gravitational waves are a tool to probe gravitation in a new regime
  - Gravitation at the heart of some of the great enigma of modern physics

General Relativity

Astrophysics

Cosmology

Gravitational-wave spectrum



Ground-based detectors: history

1960s & 1970s

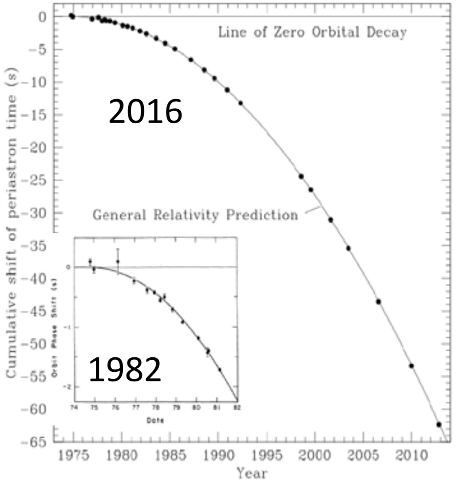
- Pioneering experimental work

Insufficient sensitivity

1980s & 1990s

- Design and construction of long-baseline interferometers

Gravitational waves exist!



2016

1982

2000s : 1st generation

- LIGO, Virgo

Sensitivity not quite good enough

2010s & 2020s : 2nd generation

- Advanced LIGO, Advanced Virgo
- + KAGRA

Discovery!

Toward routine GW observation
Multi-messenger astronomy

Deep observation of Universe with GW

3rd generation

A network of detectors


LIGO Hanford, 4 km (US)


LIGO Livingston, 4 km (US)


Virgo, 3 km (Italy)


KAGRA, 3 km (Japon)

GW coupling to Michelson interferometer

See movie

GW coupling to Michelson interferometer (cont.)

- ❑ Space-time metric $g_{\mu\nu} \simeq \eta_{\mu\nu} + h_{\mu\nu}$
- ❑ Perturbation to metric due to GW

$$h_{\mu\nu}(z,t) = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & -h_+ & h_\times & 0 \\ 0 & h_\times & h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

$$ds^2 = \Sigma\, g_{\mu\nu}\, dx^\mu dx^\nu = 0 \text{ for light}$$

- ❑ Accumulated round-trip phase along *x* axis $\Phi_{\mathrm{rt}}(t_{\mathrm{rt}}) = \int_0^{t_{\mathrm{rt}}} 2\pi\nu dt$
  - ➢ For GW with period >> round-trip light travel time

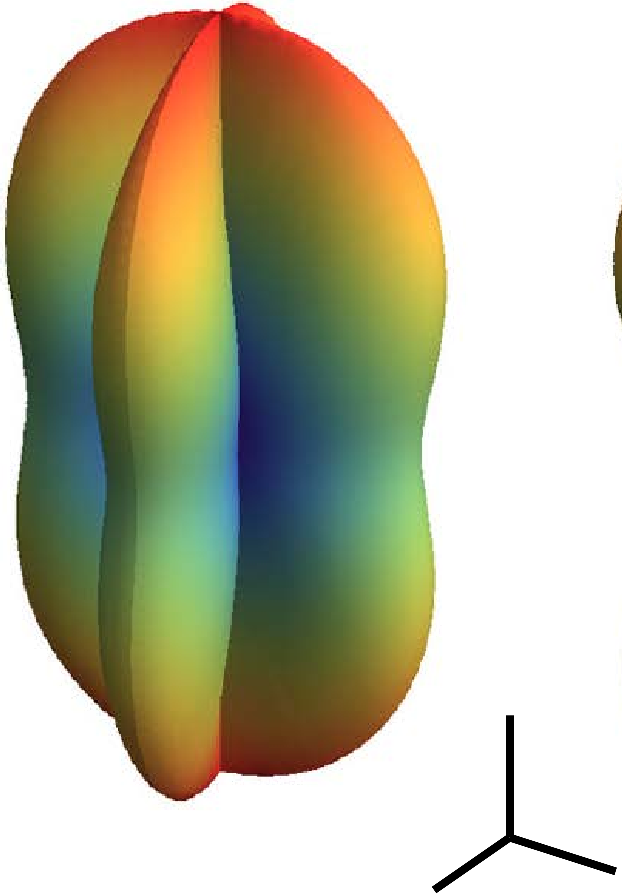
$$\Phi_{\mathrm{rt}}(t_{\mathrm{rt}}) = 2\frac{2\pi\nu}{c}\int_0^L \sqrt{|g_{xx}|}dx \simeq 2(1 - h_+/2)\frac{2\pi L}{\lambda}$$

  - ➢ General case includes term $\mathrm{sinc}\left(\pi f_{GW}\frac{2L}{c}\right)$
- ❑ Accumulated round-trip phase along *y* axis $\Phi_{\mathrm{rt}} \simeq 2(1 + h_+/2)(2\pi L/\lambda)$
- ❑ Difference in phase shift between *x* and *y* arms

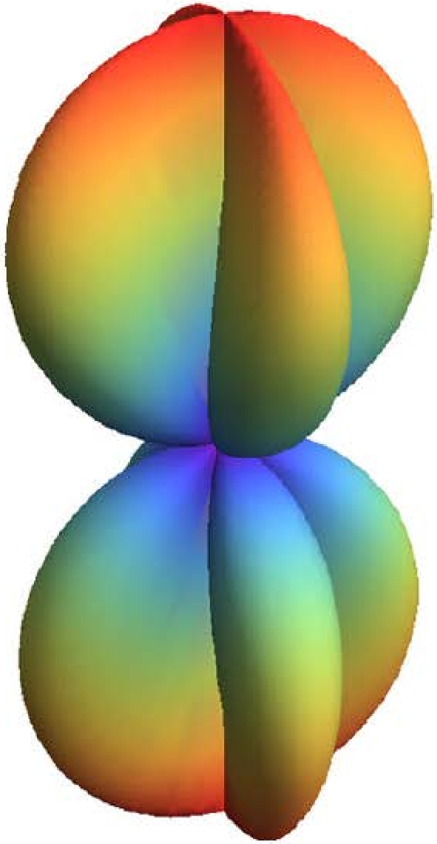
$$\Delta\Phi \simeq 2h_+(2\pi L/\lambda) \quad \leftrightarrow \quad \Delta L = h\, L$$

$L = 3\ \mathrm{km} \quad h < 10^{-21} \quad \rightarrow \Delta L < 10^{-18}\ \mathrm{m}$

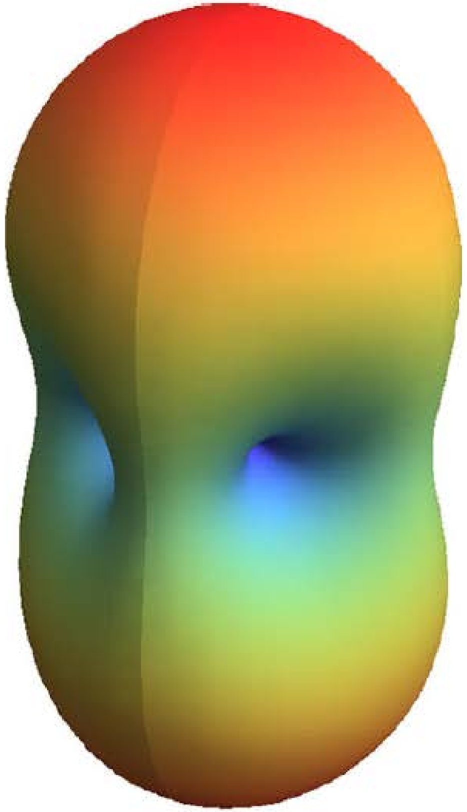
Detector antenna pattern



+ polarization



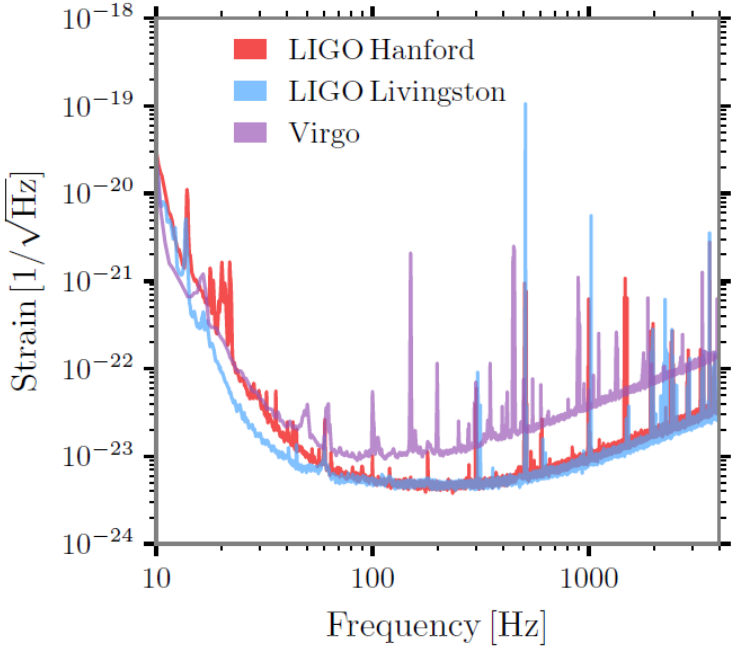
x polarization

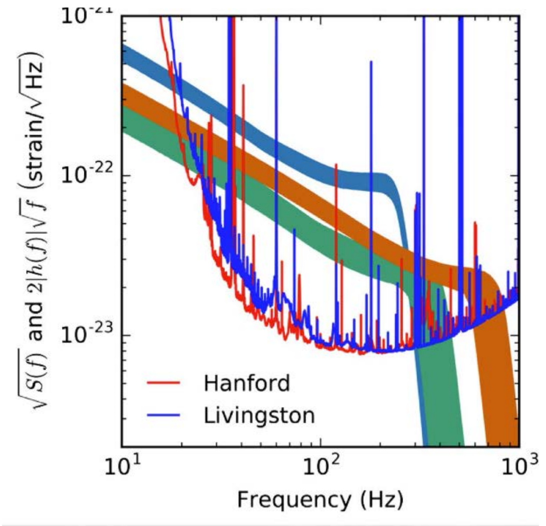


unpolarized GWs

- ☐ GW interferometric detector has
  - Broad angular response
  - Blind spots

Sensitivity curve





- Frequency-domain characterization of (stationary) noise: noise power spectrum, aka (one-sided) power spectral density (PSD)

$$S_n(f) = 2 \lim_{T\to\infty} \frac{1}{T} \left| \int_{-T/2}^{+T/2} e^{-i2\pi f t}\, n(t)\, dt \right|^2$$

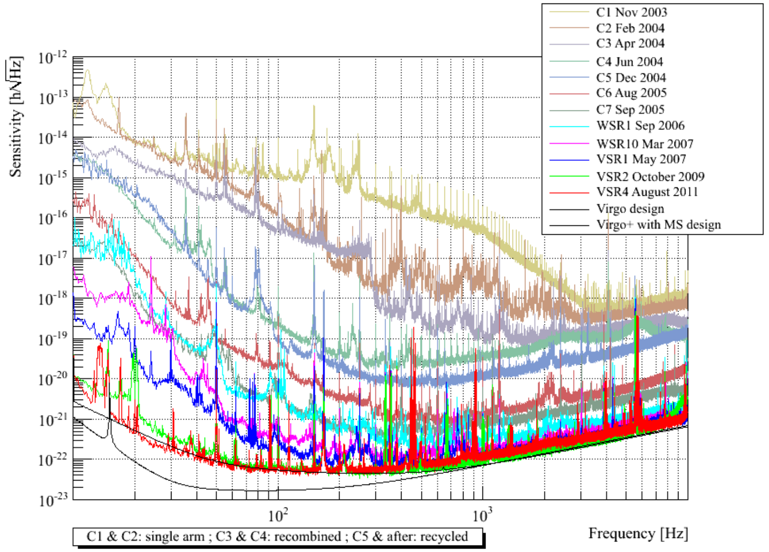
- Noise power spectrum is Fourier transform of noise autocorrelation

$$C(\tau) = E[n(t)n(t+\tau)] = \lim_{T\to\infty} \frac{1}{T} \int_{-T/2}^{+T/2} n(t)n(t+\tau)dt$$

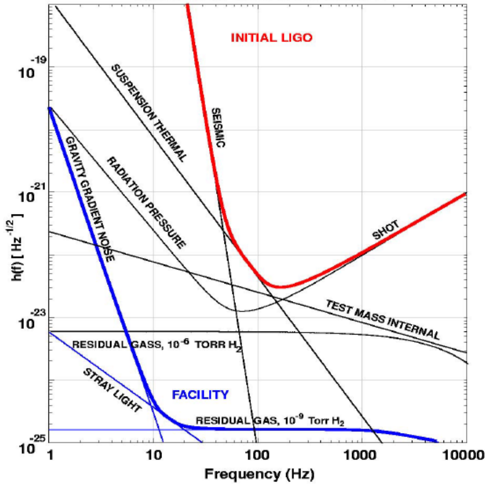
- PSD has unit Hz^{-1}, amplitude spectral density (ASD) has unit [strain]$/\sqrt{\mathrm{Hz}}$
- Related to mean square of noise $\mathrm{RMS}^2_{\Delta f} = \int_{\Delta f} S_n(f)\, df$
- Related to signal-to-noise ratio (SNR) $\mathrm{SNR}^2 = 4 \int_0^\infty \frac{|\tilde{h}(f)|^2}{S_n(f)}\, df$
- Usually characterized by BNS range
  - Typical detection reach for binary neutron star mergers with SNR 8

Anatomy of sensitivity curves

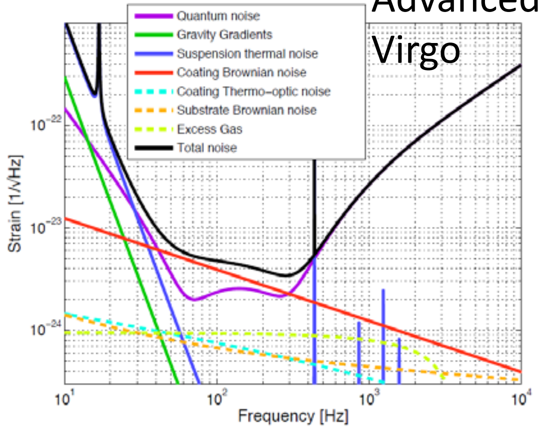
Constantly evolving
e.g.
Initial Virgo
2003-2011



Limited by
fundamental noise
sources…

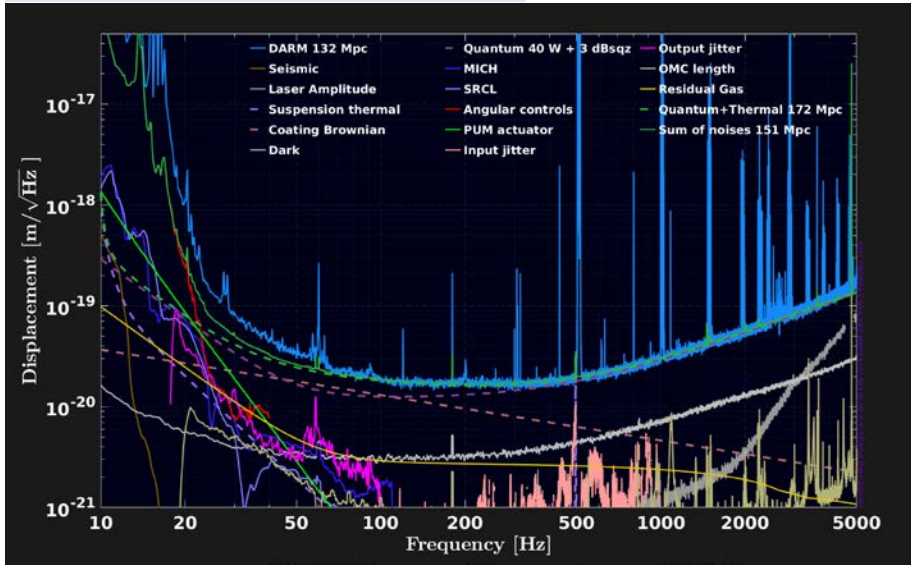


Advanced
Virgo



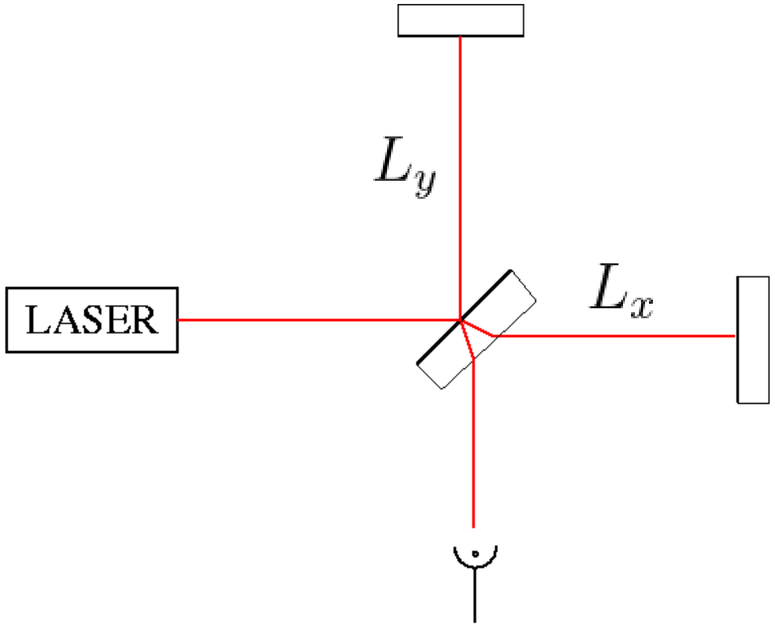
… but not only !

LIGO Livingston 2020



THE MAIN NOISE SOURCES AND HOW THEY DRIVE THE BASIC FEATURES OF DETECTORS

Quantum noise (i)



- Power at the output port of Michelson interferometer

$$P_{\text{out}} = \frac{P_{\text{in}}}{2}\left(1 + C\ \cos\Delta\phi\right)$$

$$\Delta\phi = \frac{4\pi}{\lambda}(L_x - L_y) \qquad \text{Contrast } C = \frac{P_{\text{out,max}} - P_{\text{out,min}}}{P_{\text{out,max}} + P_{\text{out,min}}}$$

$$\Delta\phi \to \Delta\phi + \delta\phi \ \Rightarrow P_{\text{out}} \to P_{\text{out}} + \delta P_{\text{out}}$$

$$\delta P_{\text{out}} = \frac{P_{\text{in}}}{2} C \sin\Delta\phi\ \delta\phi$$

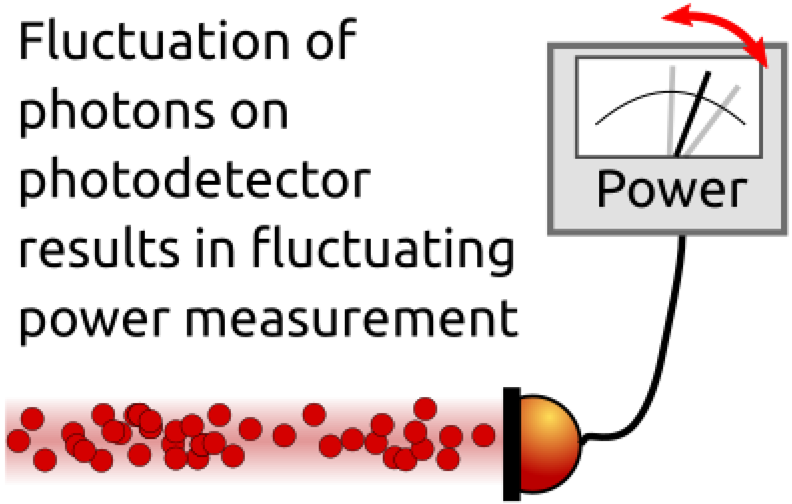
- How small a change in output power can be detected?
  - Photon counting statistics follows Poisson distribution
  - Arrival rate of photons

$$\bar{n} = \frac{\lambda}{2\pi\hbar c} P_{\text{out}} \qquad \sigma_n = \sqrt{\bar{n}}$$

  - Shot noise spectrum

$$\tilde{P}_{\text{out, shot}}(f) = \sqrt{\frac{4\pi\hbar c}{\lambda} P_{\text{out}}}\ [\text{W}/\sqrt{\text{Hz}}]$$

Fluctuation of photons on photodetector results in fluctuating power measurement



Minimizing shot noise

- ❑ Shot noise limit to phase difference measurement

$$\tilde{\delta\phi}(f) = \sqrt{2}\sqrt{\frac{4\pi\hbar c}{\lambda P_{\mathrm{in}}}}\,\frac{\sqrt{1+C\ \cos\Delta\phi}}{C\sin\Delta\phi}\ [\mathrm{rad}/\sqrt{\mathrm{Hz}}]$$

  - ➢ When $C = 1$, $\tilde{\delta\phi}$ is minimal for $\Delta\phi = \pi$
    - Michelson tuned on the dark fringe

$$\tilde{\delta\phi}_{\mathrm{min}}(f) = \sqrt{\frac{4\pi\hbar c}{\lambda P_{\mathrm{in}}}}\ [\mathrm{rad}/\sqrt{\mathrm{Hz}}]$$

  - ➢ In practice, $C < 1$ and we want the signal δP_{out} to vary linearly with $\delta\phi$
    - Small offset with respect to dark fringe

- ❑ Sensitivity to GW signal

$$\tilde{h}_{\mathrm{shot}}(f) = \frac{1}{L}\sqrt{\frac{\hbar c\lambda}{4\pi P_{\mathrm{in}}}}\ [/\sqrt{\mathrm{Hz}}]$$

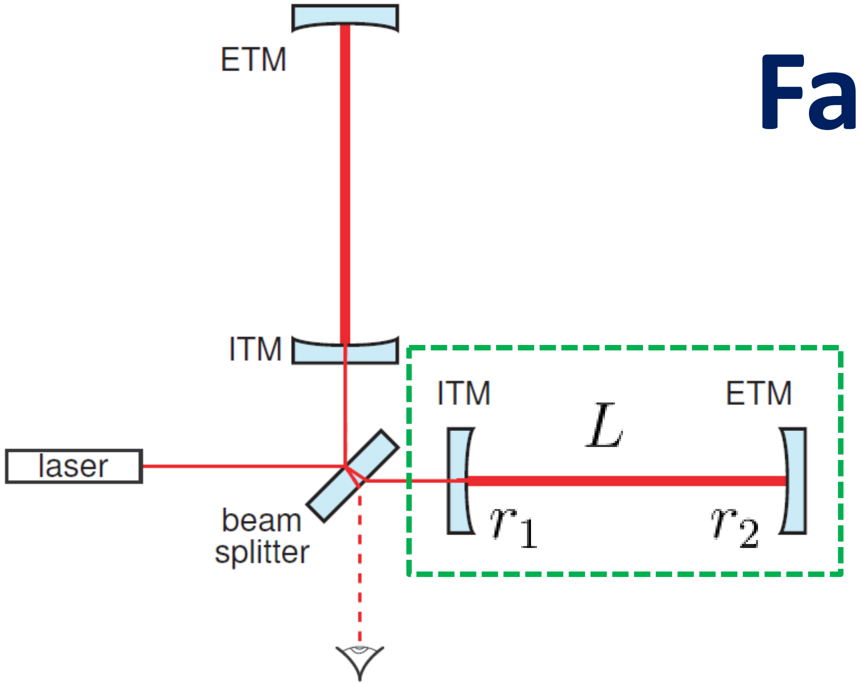
Wavelength set by availability of high-power lasers and optics

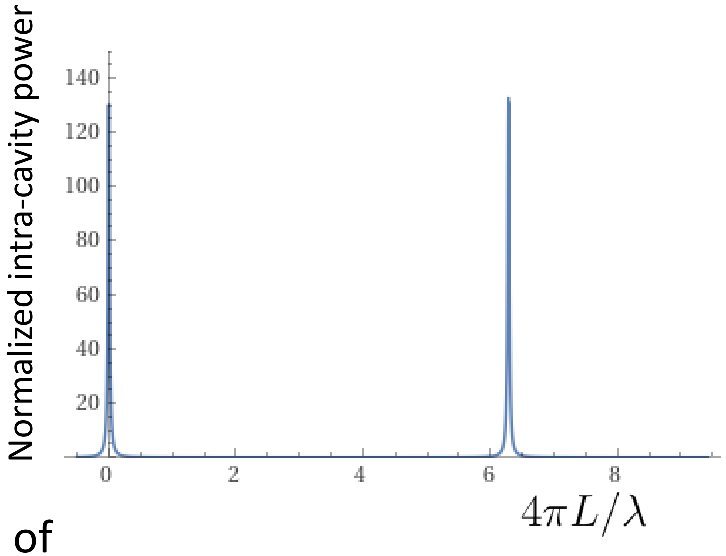
Arm length set by infrastructure (money) and configuration tweaks

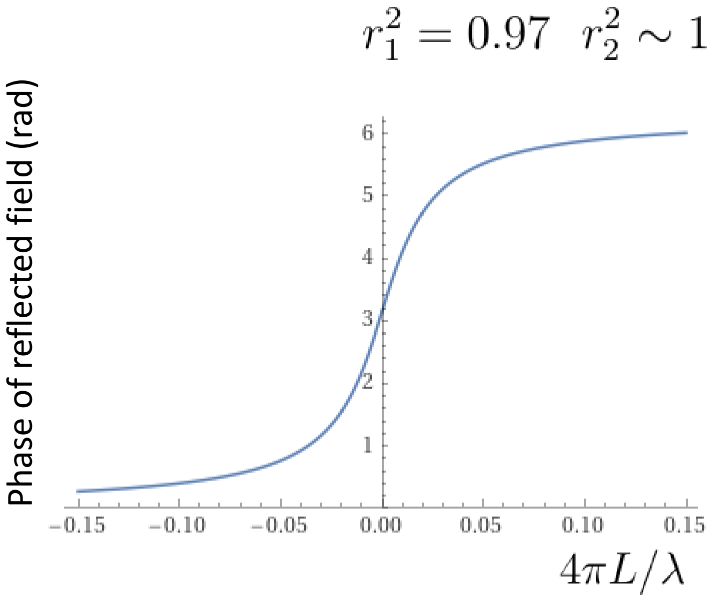
Input optical power set by laser and configuration tweaks

$$\lambda = 1064\ \mathrm{nm}$$
$$L = 3\ \mathrm{km}$$
$$P_{\mathrm{in}} = 20\ \mathrm{W}$$
$$\tilde{h}_{\mathrm{shot}}(f) \sim 4\times10^{-21}/\sqrt{\mathrm{Hz}}$$

Fabry-Perot cavities





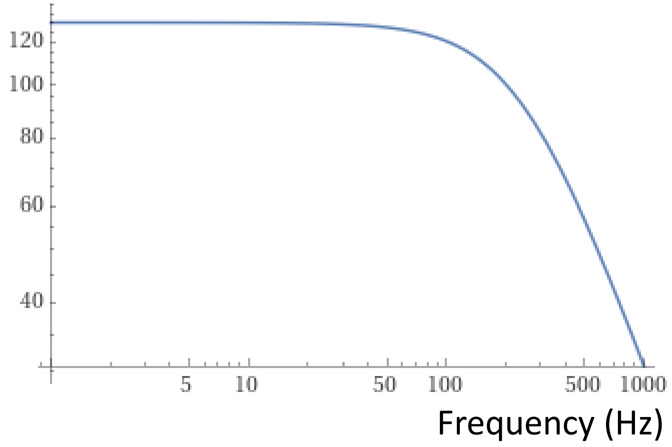

$r_1^2 = 0.97 \quad r_2^2 \sim 1$

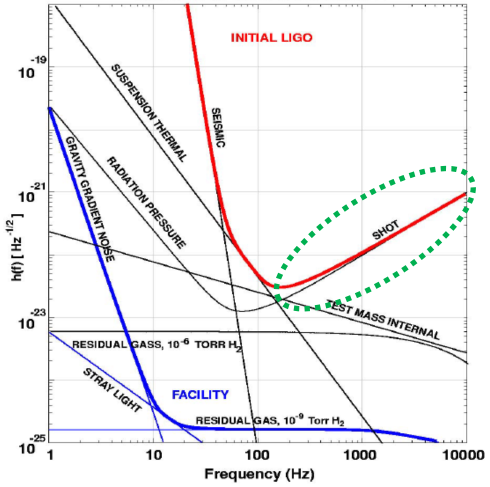
- ❑ Two mirrors with $r_2 \sim 1, r_1 < 1$ in the case of GW detectors
- ❑ Cavity characterized by its finesse $\mathcal{F} = \dfrac{\pi\sqrt{r_1 r_2}}{1 - r_1 r_2}$
- ❑ Resonance when $4\pi L/\lambda = n\,2\pi$
  - ➢ The storage time increases from $2L/c$ to $\tau_{\text{storage}} = \dfrac{2L}{c}\dfrac{\mathcal{F}}{2\pi}$
  - ➢ The phase shift of the reflected field around the resonance is amplified by factor $\dfrac{2\mathcal{F}}{\pi}$
- ❑ Cavity acts as low-pass filter, with cutoff frequency

$$f_c = 1/(4\pi\tau_{\text{storage}})$$

  - ➢ Explains high-frequency shape of sensitivity curve

Cavity response



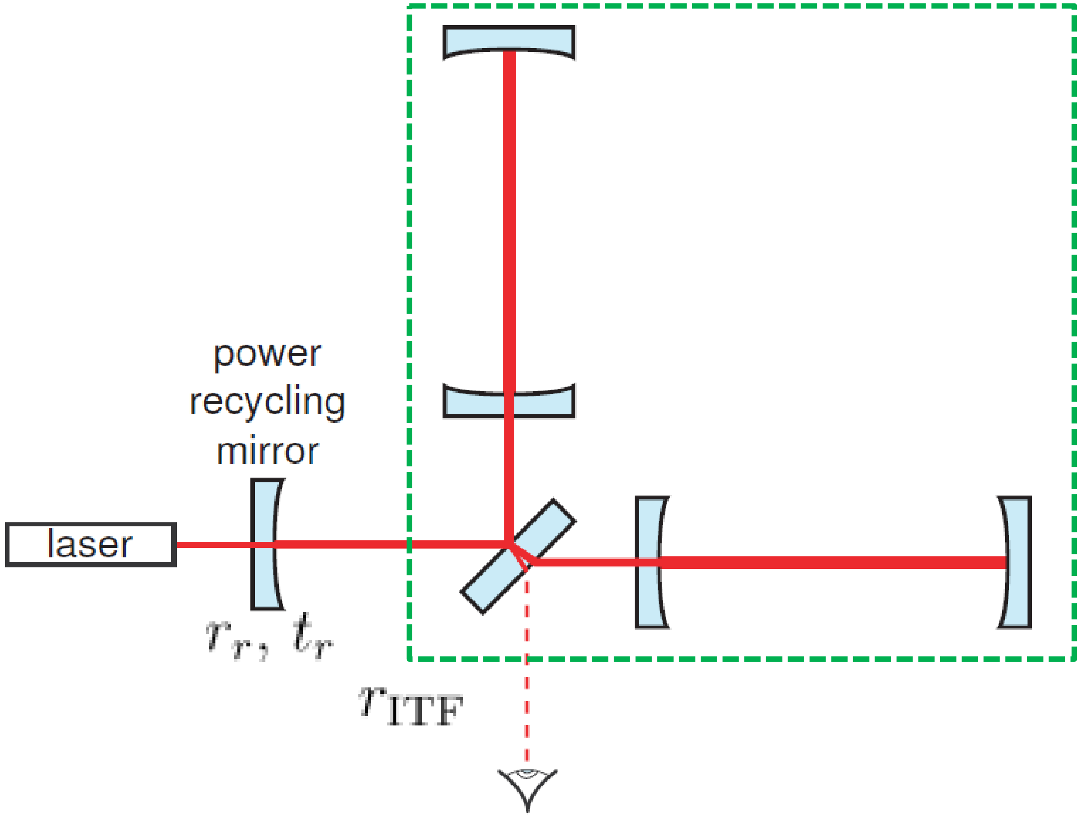


Power recycling

- With interferometer on dark fringe, input power is reflected back
- Add recycling mirror to make resonant cavity with interferometer

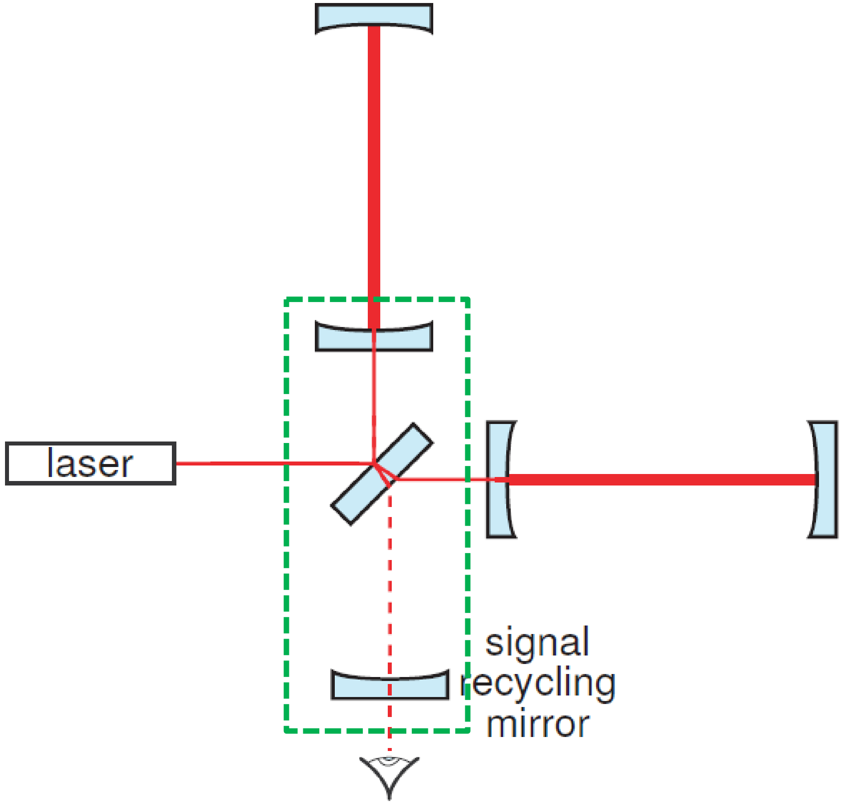
$$P_{\text{in}} = \frac{t_r^2}{(1 - r_r r_{\text{ITF}})^2} P_{\text{laser}}$$

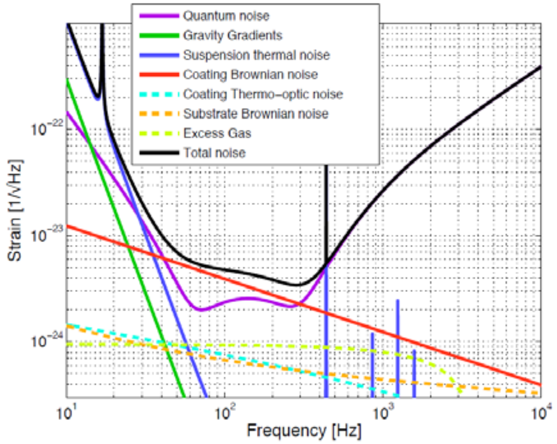
- With $P_{\text{laser}} = 20\,\text{W}$ and gain of ~50, on beam-splitter $P_{\text{in}} = 1\,\text{kW}$



Signal recycling

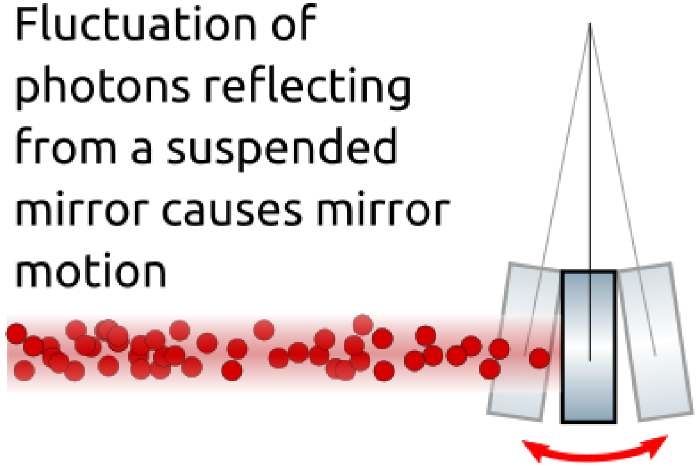
- Signal recycling or resonant sideband extraction
- To reach given optical power in Fabry-Perot cavities, high finesse desirable
    - Reduce absorption in input mirrors and associated thermal distortions ☺
    - Reduce bandwidth ☹
- Phase modulation due to GW signal creates sidebands in optical field at GW frequency, which do not cancel out at output port
    - Add mirror to form resonant cavity with input mirrors for GW sidebands
    - Cavity increases effective transmission of input mirrors for GW signal
    - Broaden bandwidth ☺





Quantum noise (ii)

Fluctuation of photons reflecting from a suspended mirror causes mirror motion

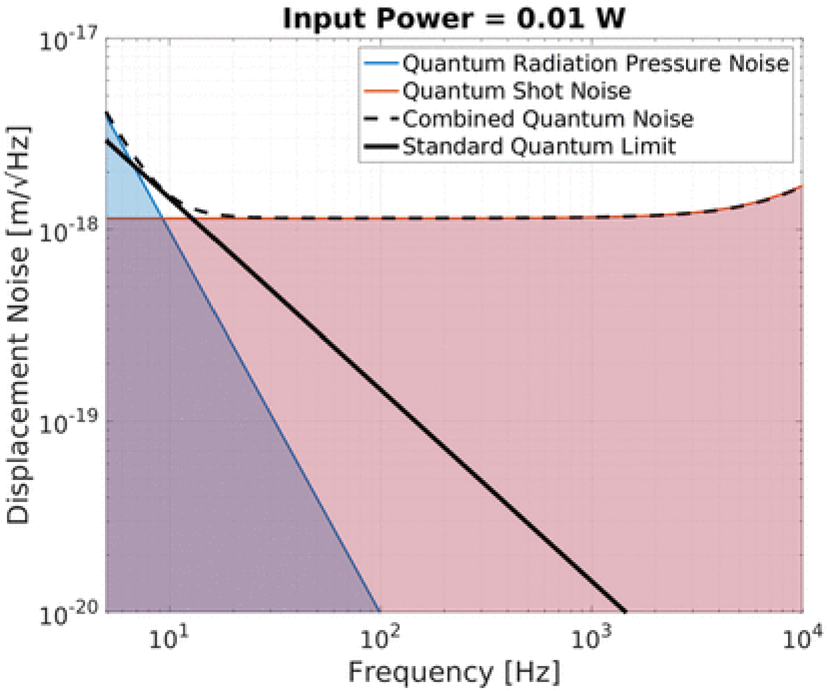


- ❑ Radiation pressure fluctuations
  - ➢ Displacement noise for simple Michelson

$$\tilde{x}_{\mathrm{rad}}(f) = \frac{1}{m f^2}\sqrt{\frac{\hbar P_{\mathrm{in}}}{8\pi^3 c\lambda}}$$

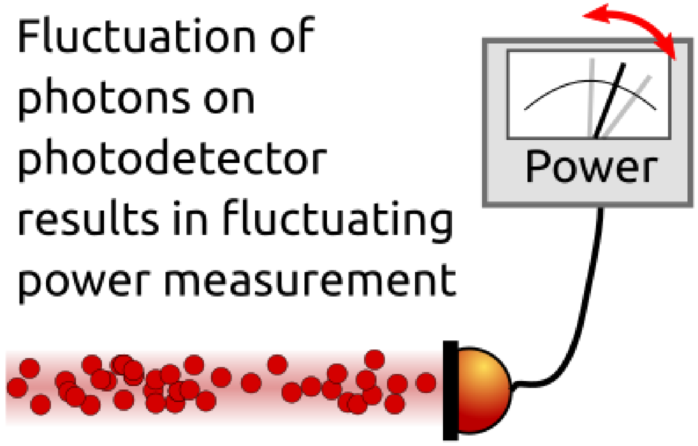
Mirror mass

https://10m.aei.mpg.de/standard-quantum-limit-sql/



Shot noise decreases with $\sqrt{P_{\mathrm{in}}}$
Radiation pressure noise increases with $\sqrt{P_{\mathrm{in}}}$

Fluctuation of photons on photodetector results in fluctuating power measurement

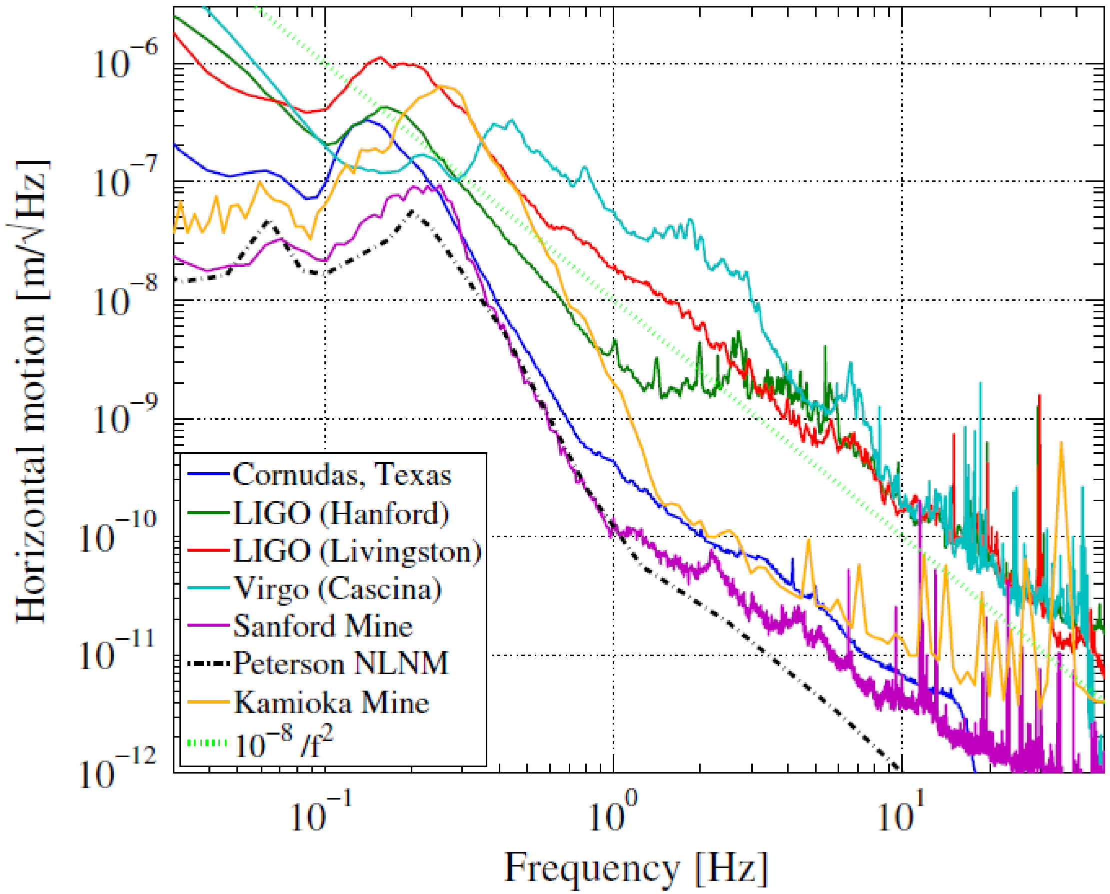


- ❑ Envelope of minima in quadratic sum of shot noise and radiation pressure noise as input power varies defines standard quantum limit (SQL)

$$\tilde{x}_{\mathrm{SQL}}(f) = \frac{1}{\pi f}\sqrt{\frac{\hbar}{2m}}$$

- ❑ SQL can be overcome with quantum optics techniques…

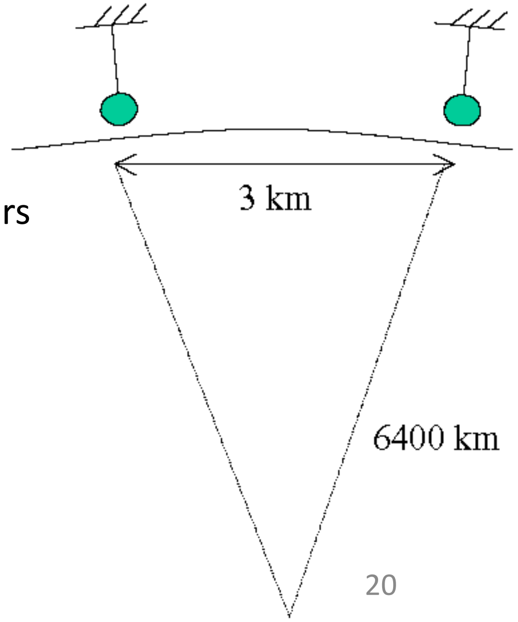
Seismic noise



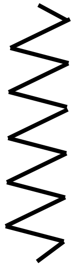
- ❑ Low-frequency limit to all ground-based interferometers
- ❑ Earth tides
  - ➢ Length changes of ~100 μm over 3 km baseline
  - ➢ Compensated by long-range actuators
- ❑ Secondary microseism
  - ➢ Amplitude ~1 μm
  - ➢ Canceled by feedback systems
- ❑ Spectrum above ~1 Hz

$$\tilde{x}_{\text{ground}}(f) = 10^{-7} - 10^{-8}\left(\frac{1\ \text{Hz}}{f}\right)^2 \text{m}/\sqrt{\text{Hz}}$$

  - ➢ High-performance isolation needed
    - ▪ Active, based on seismic vibration sensors
    - ▪ Passive
- ❑ Horizontal-vertical couplings
  - ➢ $\sim 10^{-4}$ for 3 km baseline

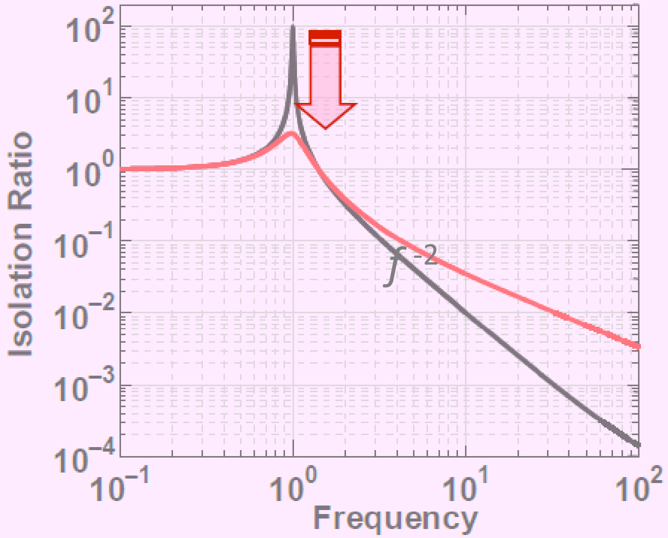


Passive vibration isolation



Damping

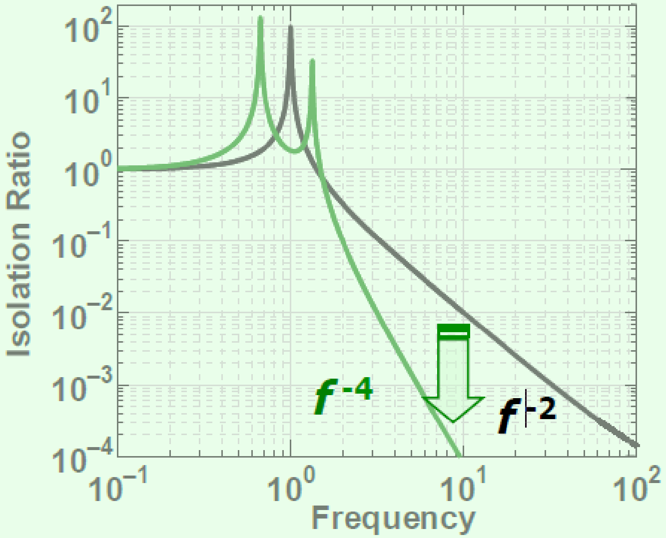
Lower the peak height



Worse isolation

Multi stage

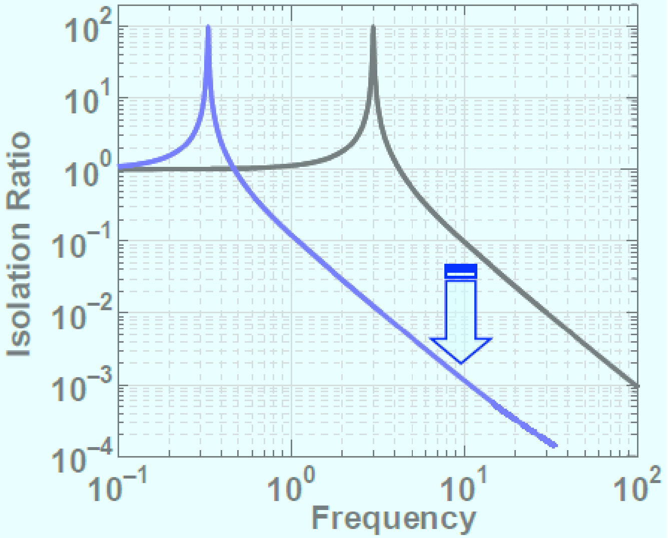
Steeper isolation curve



More peaks

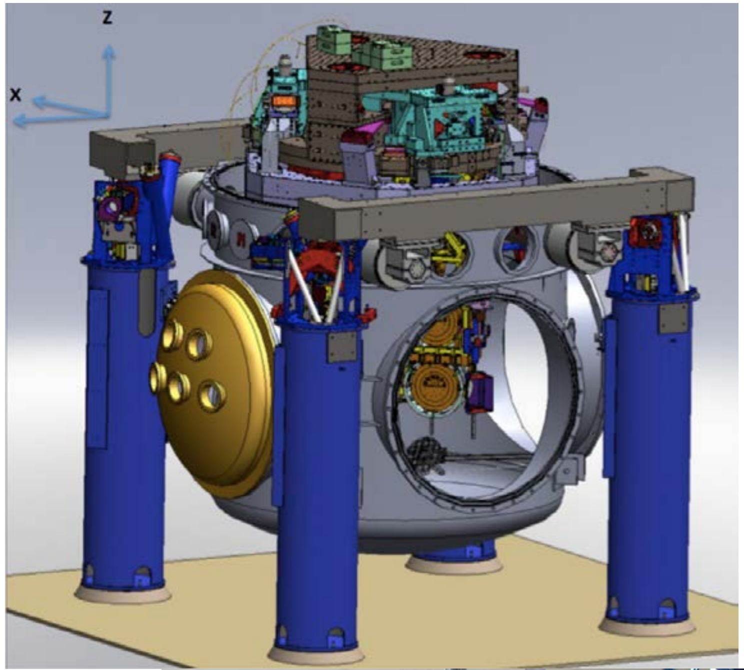
Lower resonant freq

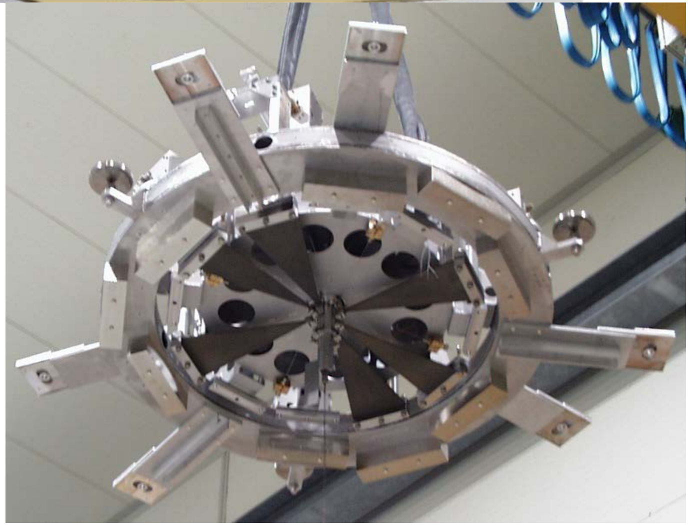
Better isolation

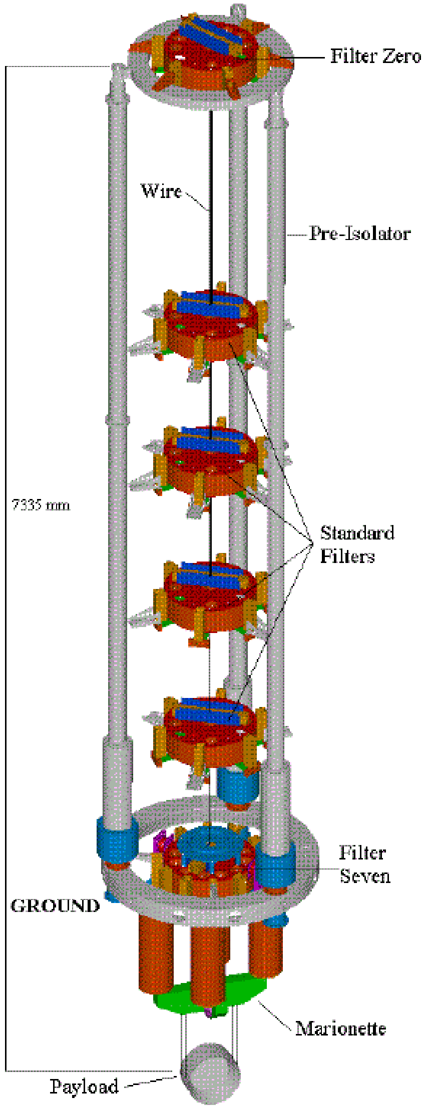


Complex to realize

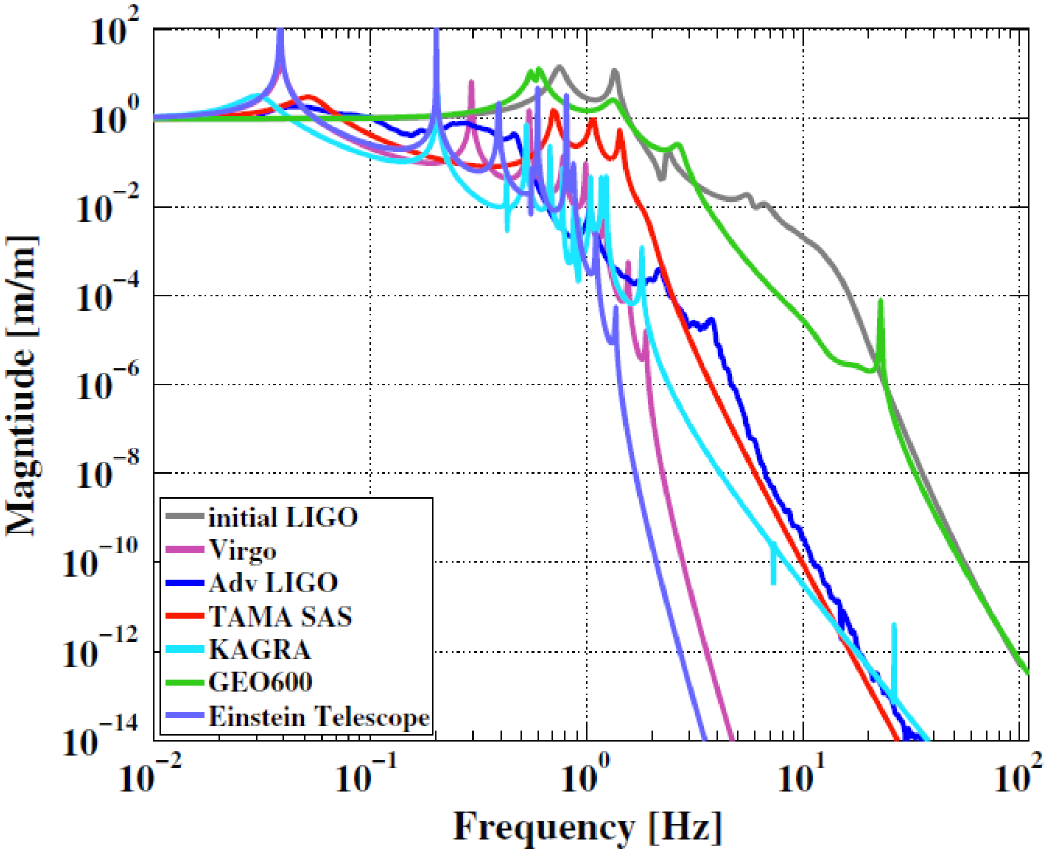
Vibration isolation







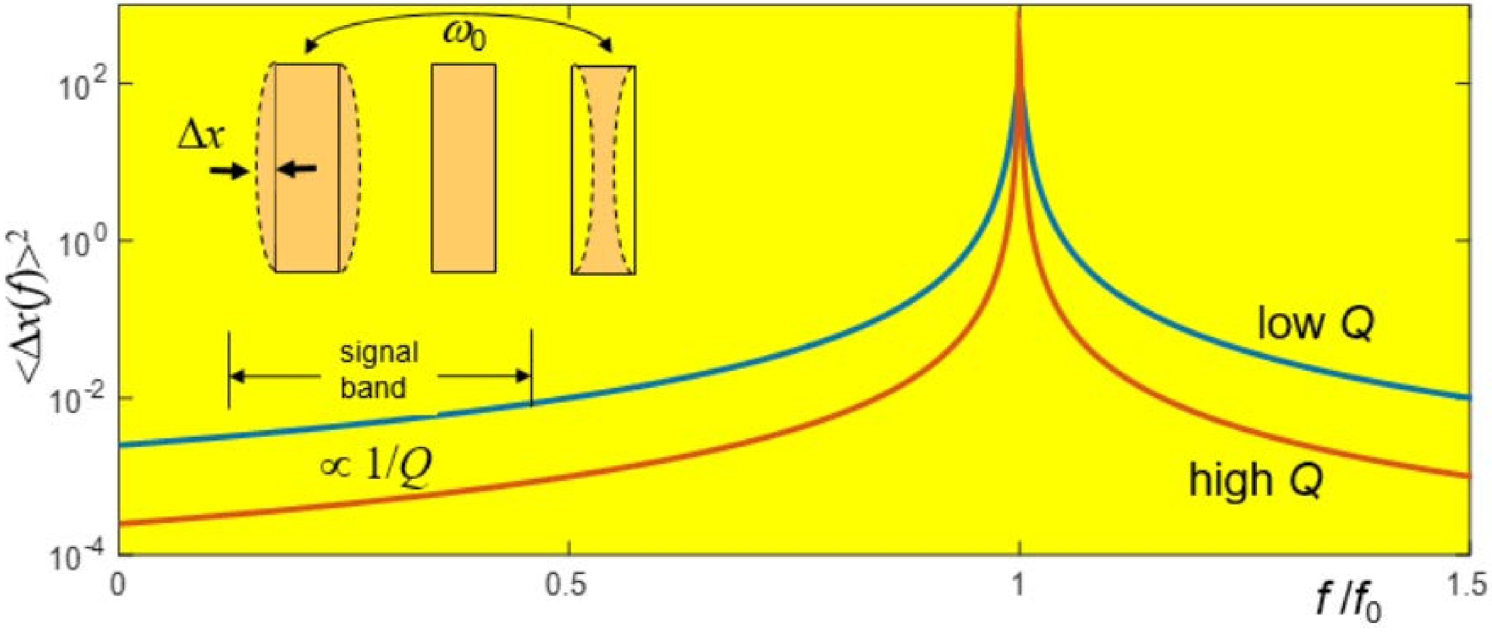
Horizontal ground to mirror motion transfer functions



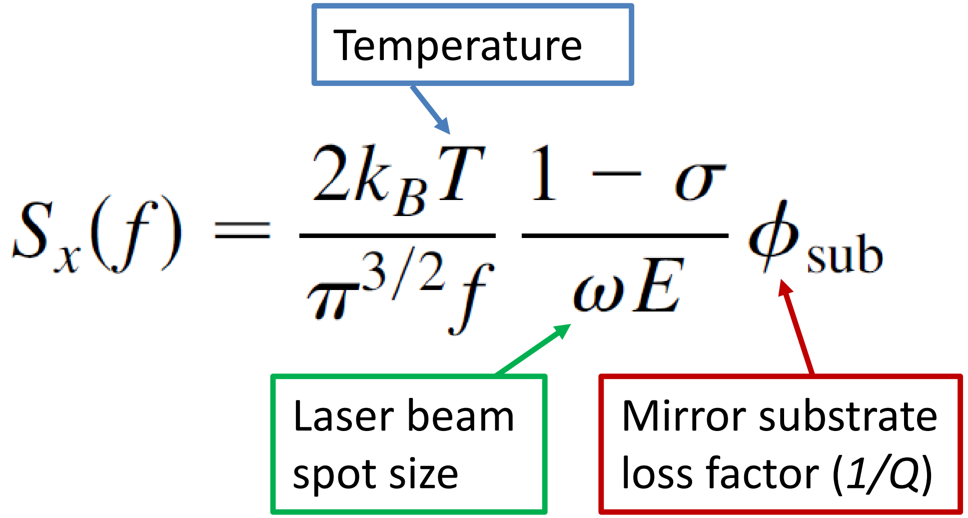
Thermal noise

- Mirrors in thermal equilibrium
- Dissipation-fluctuation relationship → noise
- Multiple sources of noise
  - Mirror thermal noise – bulk and coating
    - Brownian noise
    - Thermo-optic noise due to temperature fluctuations
      - Random thermal expansion
      - Random change in refractive index
  - Suspension thermal noise

Mirror thermal noise



- Displacement noise power spectrum



$$S_x(f) = \frac{2k_BT}{\pi^{3/2}f}\frac{1-\sigma}{\omega E}\phi_{\mathrm{sub}}$$

Temperature

Laser beam spot size

Mirror substrate loss factor (*1/Q*)

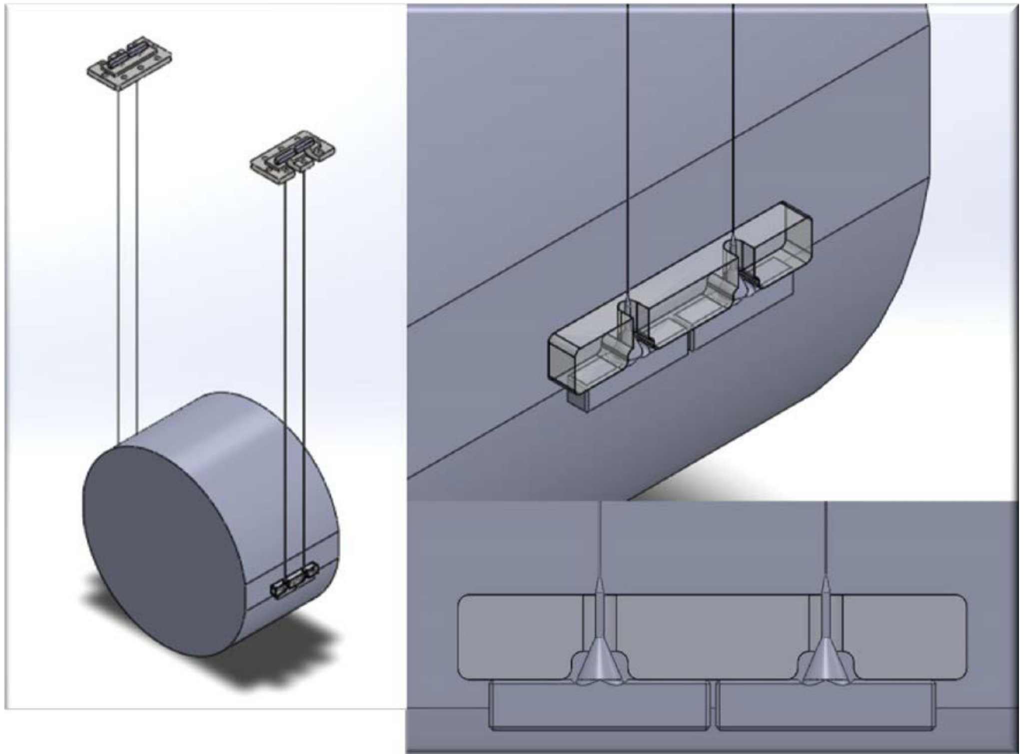
- Best substrates have $\phi_{\mathrm{sub}} \leq 10^{-8}$
- Interfaces are critical

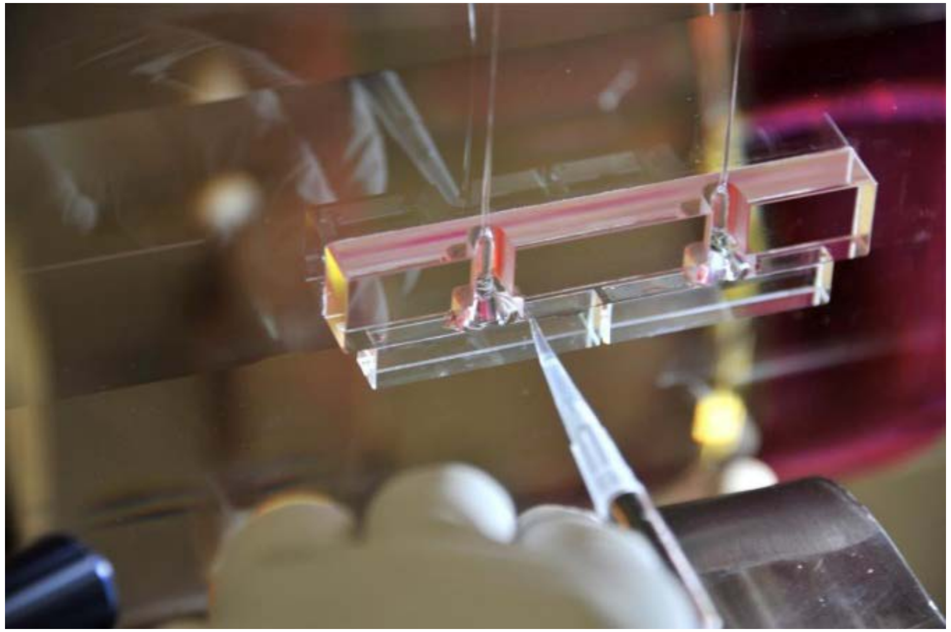
Suspension thermal noise

- For a pendulum of mass *m* and length *l*, suspended by 4 wires/fibers
- Mirrors held by thin glass fibers
  - Monolithic suspensions

tension

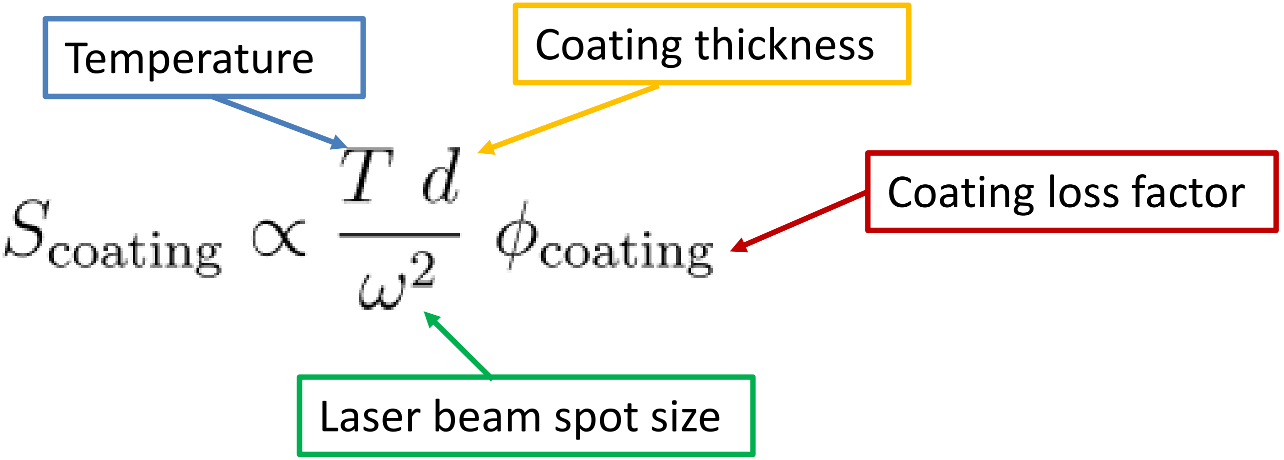
$$\phi_{\text{pendulum}} = \phi_{\text{wire}} \frac{4\sqrt{T\ E\ I}}{m\ g\ l}$$





Coating thermal noise

- ❑ Displacement noise power spectrum



Temperature

Coating thickness

Coating loss factor

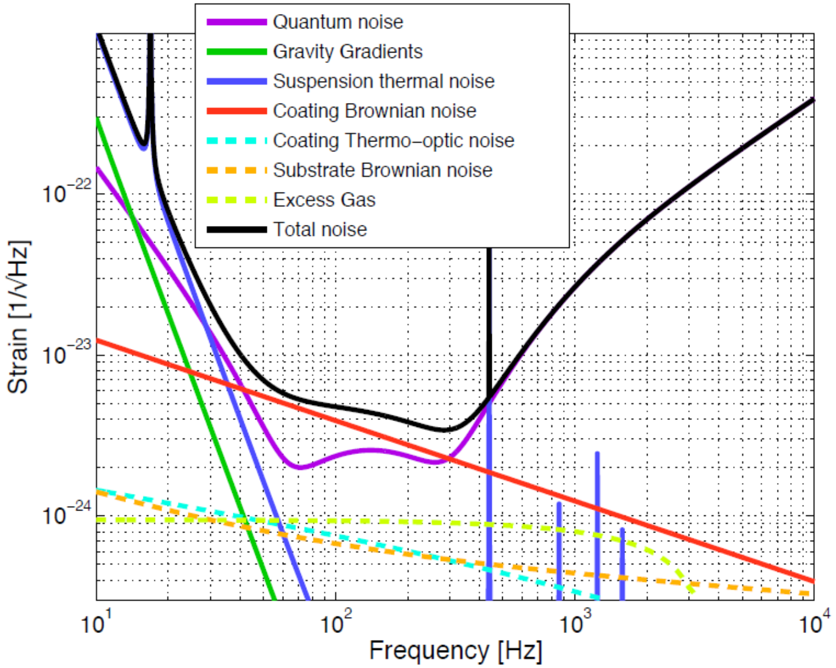
$$S_{\text{coating}} \propto \frac{T\ d}{\omega^2}\ \phi_{\text{coating}}$$

Laser beam spot size

- ❑ Coatings have excellent optical properties but poor mechanical properties
  - ➢ Dominant source of thermal noise
    - ▪ Level comparable to quantum noise around 100 Hz
  - ➢ Major R&D effort

Residual Gas Noise

- ❑ Phase noise from fluctuations in column density of gas along interferometer arms
  - ➢ Ultra-high vacuum needed $\sim 10^{-9}\ \mathrm{mbar}$
  - ➢ Residual pressure dominated by out-gassing of H_2 from beam tubes after bake-out to remove H_2O



Recap of basic features

- ❑ Interferometer
  - ➢ Michelson interferometer on ~ dark fringe
  - ➢ Fabry-Perot cavities
  - ➢ Power and signal recycling cavities

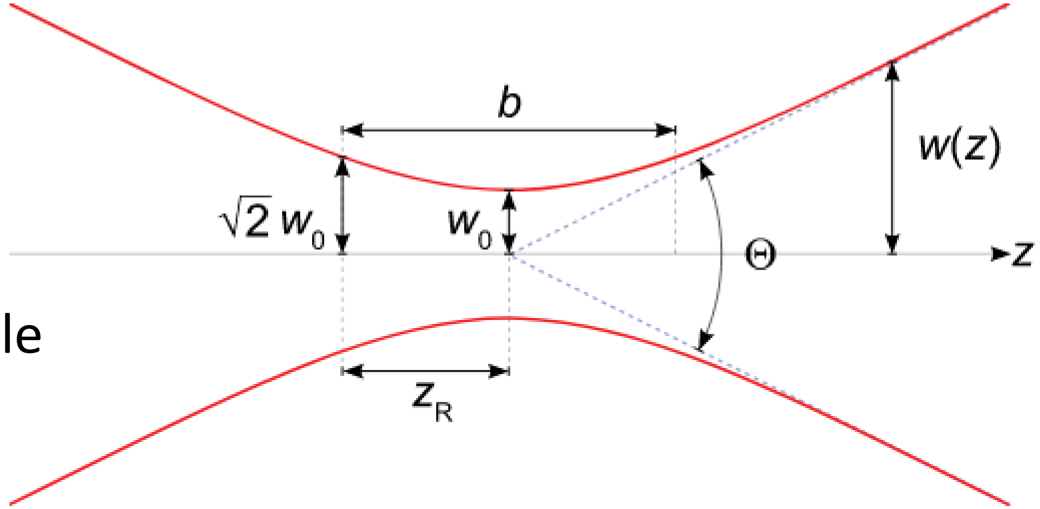
- ❑ Suspensions
  - ➢ Decouple mirrors from ground to allow free response to GW
  - ➢ Isolate mirrors from ground vibrations
  - ➢ Hold mirrors without introducing extra thermal noise

- ❑ Infrastructure
  - ➢ Ultra-low pressure in beam tubes and vacuum chambers

- ❑ Test masses
  - ➢ Low mechanical loss factors
  - ➢ Shape: high frequencies for internal resonances
  - ➢ Large: accommodate laser beam spot without losses
  - ➢ Massive: mitigate response to radiation pressure fluctuations
  - ➢ Near-perfect mirrors

OTHER ASPECTS AND CHALLENGES

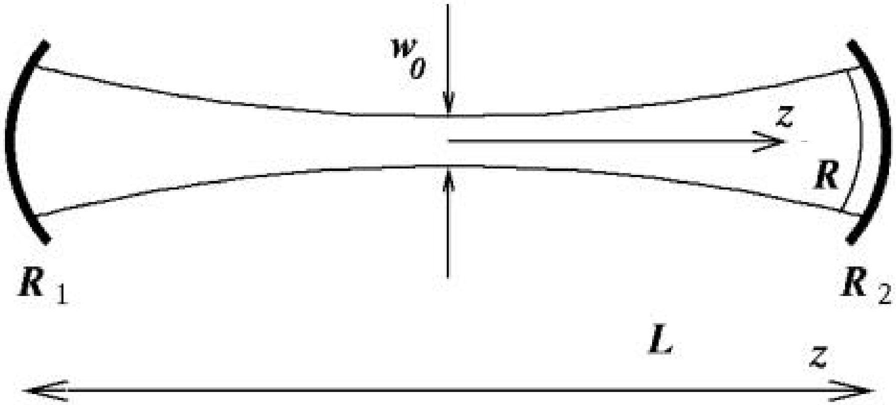
Gaussian beams



- Laser beam is fundamental mode of transverse electromagnetic mode TEM_{00}

$$E(r,z) = E_0 \frac{w_0}{w(z)} \exp\left(\frac{-r^2}{w^2(z)}\right) \exp\left(-ikz - ik\frac{r^2}{2R(z)} + i\zeta(z)\right)$$

  - Amplitude in transverse plane follows Gaussian profile
  - Shape of beam driven by waist w_0
  - Beam radius $w(z) = w_0\sqrt{1+\left(\frac{z}{z_R}\right)^2}$ $\qquad z_R = \frac{\pi w_0^2}{\lambda}$
  - Wavefront radius of curvature $R(z) = z\left[1+\left(\frac{z_R}{z}\right)^2\right]$

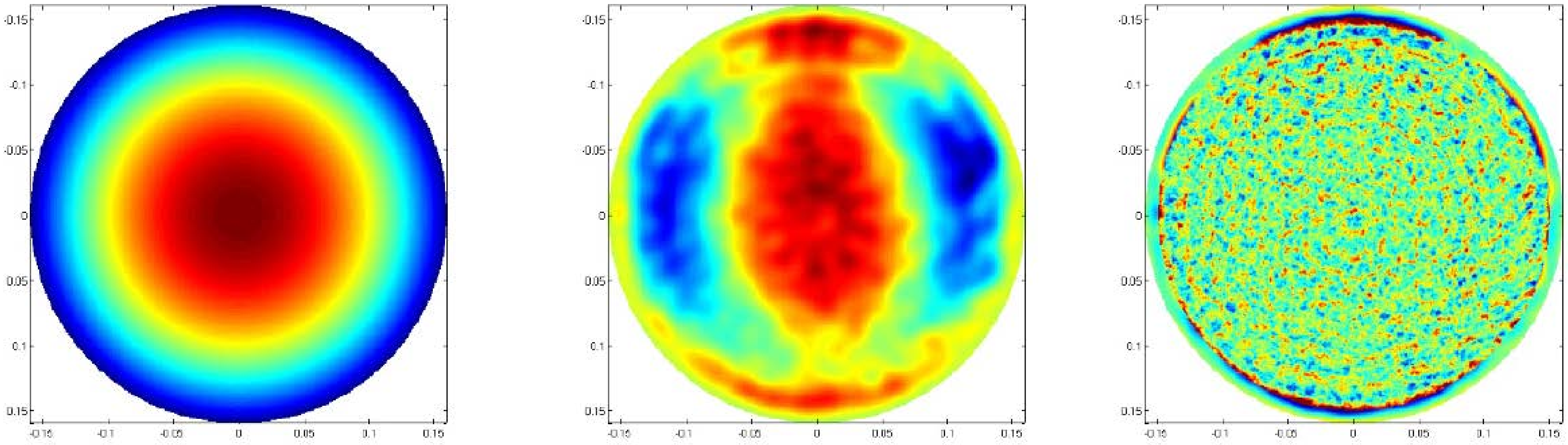


- Fabry-Perot geometry needs to match beam mode $R_1 \sim R_2 \sim R(\pm\frac{L}{2})$
- Bi-concave geometry allows large beams on mirrors (minimize thermal noise)

Mirrors

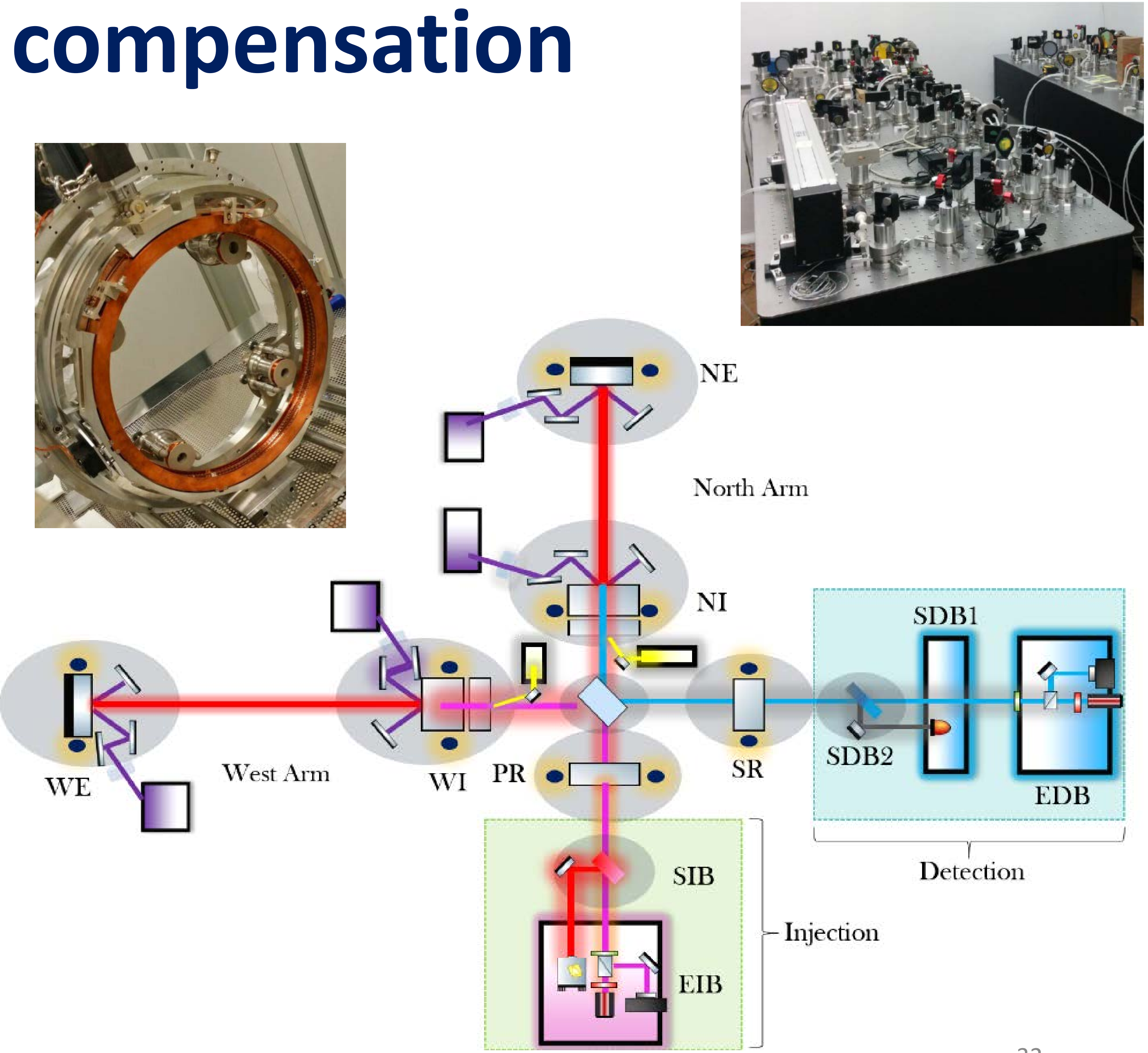
- Large and heavy optics
  - ~ 35 cm diameter, 40 kg
- Right geometry
- Near-perfect surface quality
  - Flatness < 1 nm, roughness < 1 Å
  - Uniform coatings
- Low absorption < 1 ppm

- Blanks of ultra-pure fused silica
  - Sapphire in KAGRA
- Stringent polishing requirements
- Coating uses ion beam sputtering
- Metrology
- Clean environment

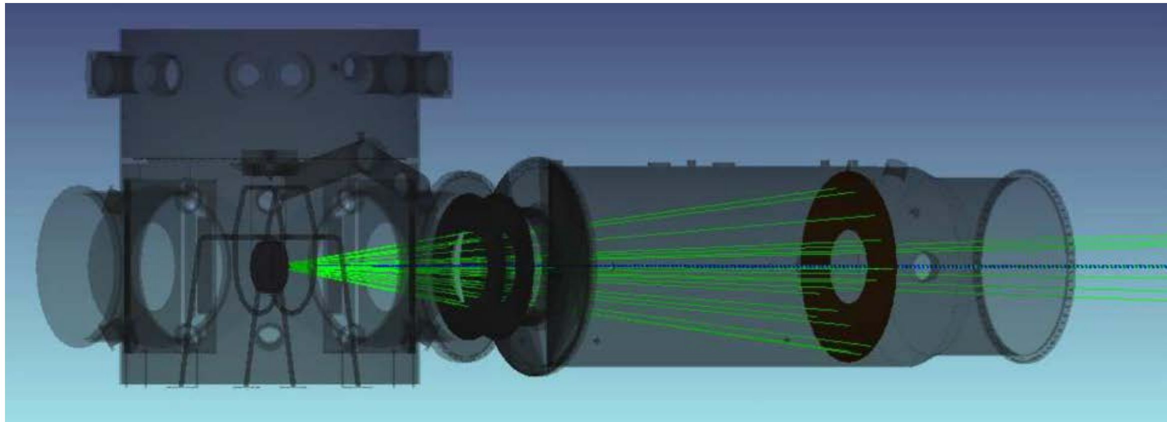


Thermal compensation

- Aberrations in the optics
  - Manufacturing errors in mirror curvature
  - High optical power ➔ thermal lensing, thermal expansion of mirrors
    - Substrate/coating absorption, point absorbers
- Need a thermal compensation system
  - Sensors to measure wavefront distortions
  - Actuators
    - Ring heaters to tune mirror curvature
    - CO_2 lasers to shine compensating heating pattern
      - Shining onto mirrors would introduce noise ⇨ compensation plates



Scattered light



- ❑ Even high-quality optics will scatter small amount of light
- ❑ Part of scattered light may recombine with main beam
  - ➢ Light scattered by mirrors reflected off beam tube
  - ➢ Backscattering from auxiliary optics
- ❑ Noise due to phase modulation by movement of reflective or scattering surface
  - ➢ Non-linear coupling if movement > wavelength ➔ high-frequency conversion of seismic noise
  - ➢ Broadband excess noise and transient noise

Minimize amount of scattered light

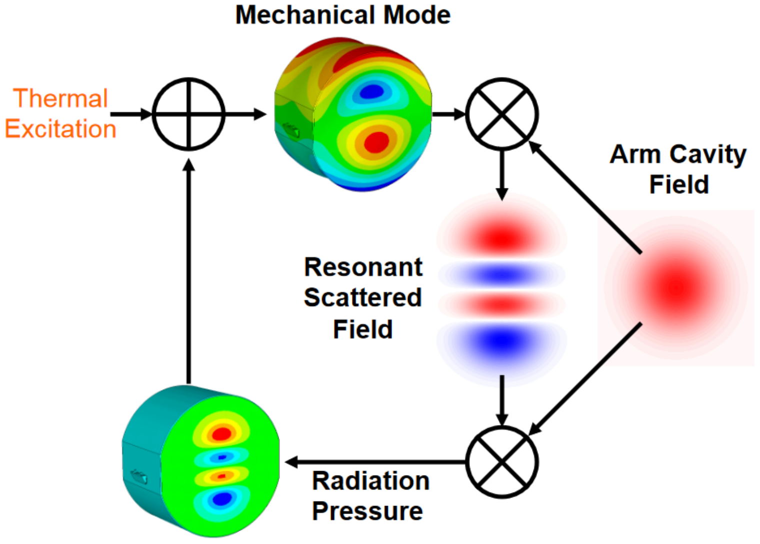
- ❑ Baffles to trap scattered light
- ❑ Model and dump spurious beams
- ❑ Size and quality of optics
- ❑ Clean environment

Minimize coupling of scattered light

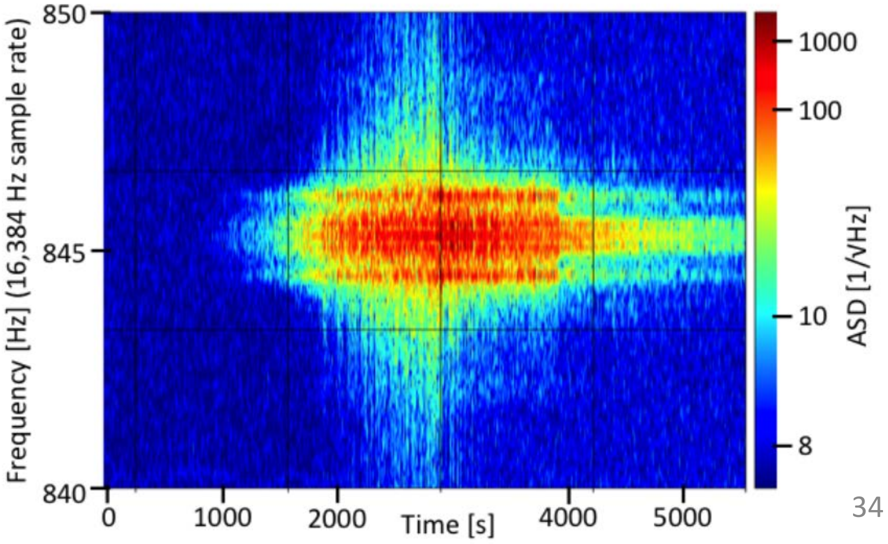
- ❑ Seismic and acoustic isolation of sensitive optics
- ❑ Optical benches suspended in vacuum

Parametric instabilities

- ❑ Opto-mechanical interaction
  - ➢ Energy transfer from interferometer fundamental optical mode into mirror mechanical mode
    - Radiation pressure
    - Modulation of fundamental field by excited mechanical mode
  - ➢ Risk of instability if mechanical mode and optical mode have coincident resonant frequencies
    - Risk increases with optical power
- ❑ Observed in advanced LIGO
- ❑ Various strategies possible
  - ➢ Tune cavity geometry to avoid instability
  - ➢ Passive or active damping of mechanical modes

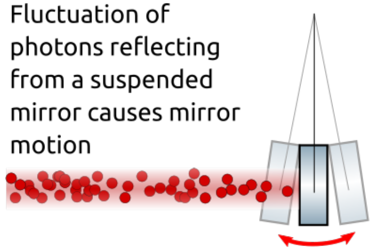


Phys. Rev. Lett. 114, 161102 (2015)

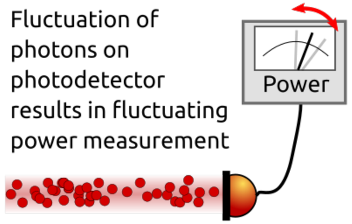


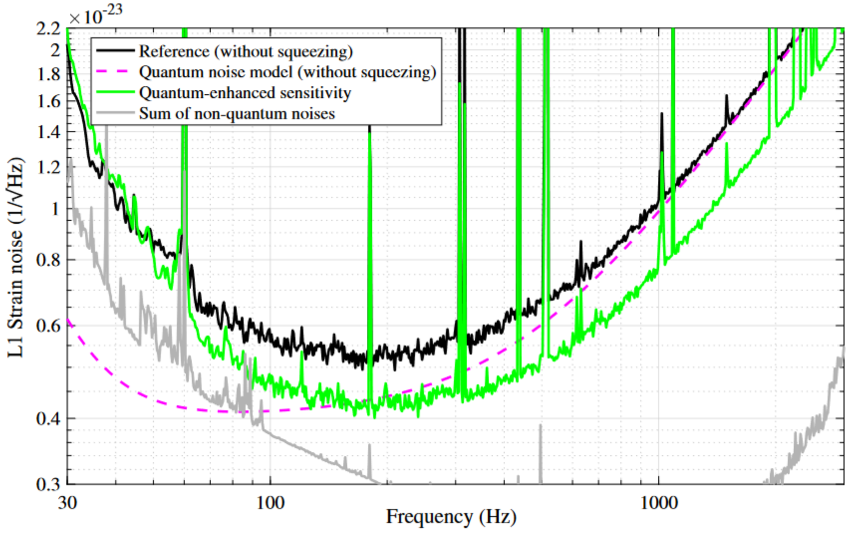
Quantum noise (iii)

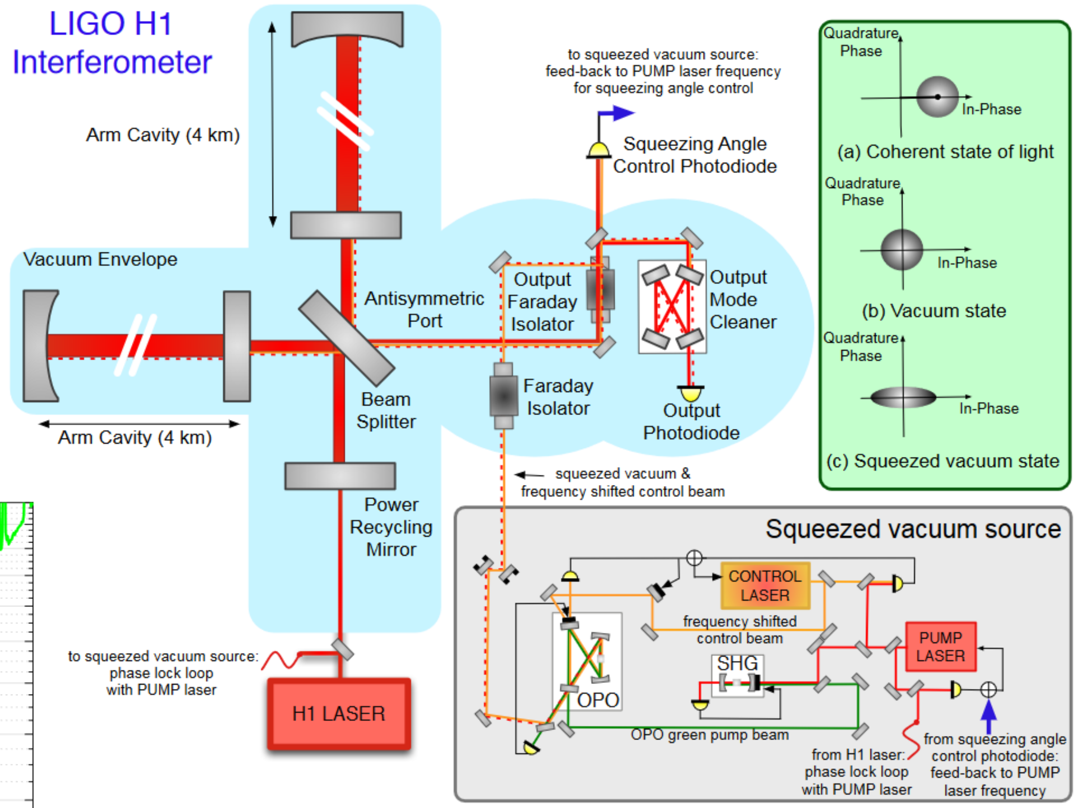
Fluctuation of photons reflecting from a suspended mirror causes mirror motion



Fluctuation of photons on photodetector results in fluctuating power measurement







- ❑ SQL can be beaten by reducing noise in one of the two quadratures of vacuum field, at the expense of the other
  - ➢ Phase: reduce shot noise
  - ➢ Amplitude: reduce radiation pressure noise

NEW

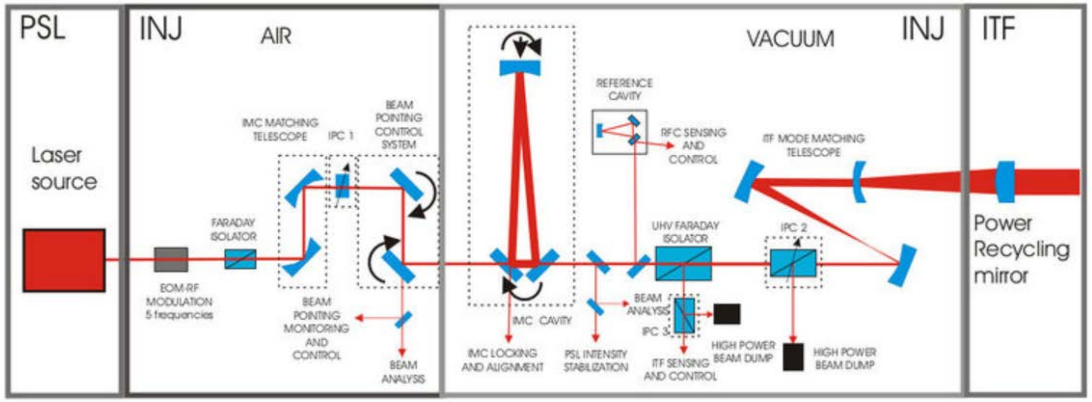
- ❑ Use filtering cavity to apply frequency-dependent phase shift to provide phase squeezing at high frequency and amplitude squeezing at low frequency

High optical power : recap

- ❑ High power needed to lower shot noise

- ❑ High-power laser
  - ➢ Mono-mode
  - ➢ Power stabilized $\delta P/P \sim 10^{-9}\ /\sqrt{\mathrm{Hz}}$
  - ➢ Frequency stabilized $\delta\nu \sim 10^{-6}\ \mathrm{Hz}/\sqrt{\mathrm{Hz}}$
  - ➢ Controlled beam pointing
  - ➢ Achieved through combination of active and passive stabilization

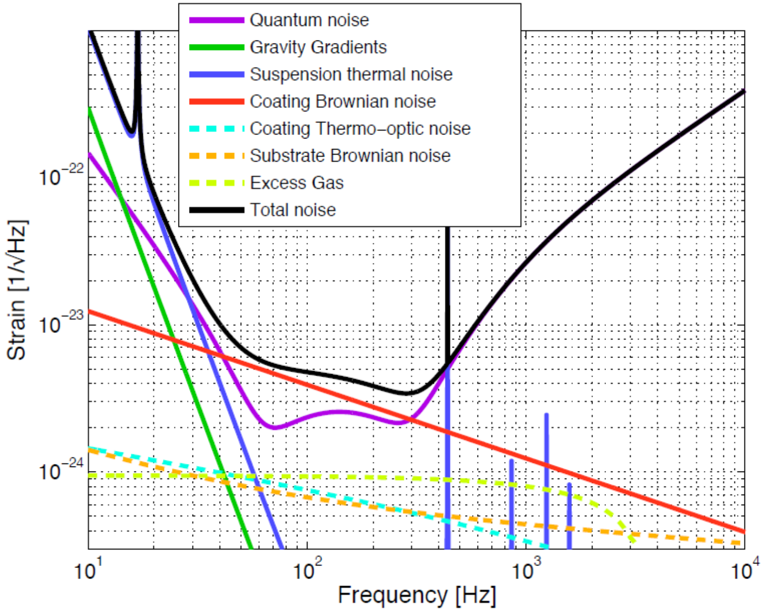
- ❑ Challenges of high power
  - ➢ Thermal aberrations
  - ➢ Scattered light
  - ➢ Parametric instabilities
  - ➢ Radiation pressure noise
  - ➢ Mirror alignment control

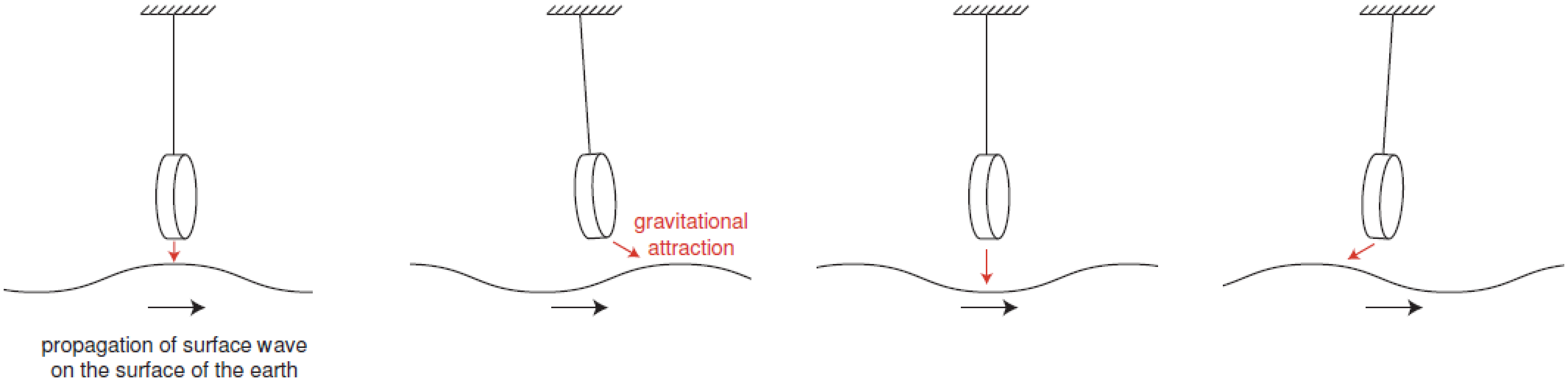


- ❑ Squeezing is alternative/complementary approach to lower shot noise
  - ➢ Needs to be frequency-dependent to avoid increasing radiation pressure noise

Gravity gradient noise

- ❑ Also called Newtonian noise
- ❑ Direct gravitational coupling of mass density fluctuations to suspended mirrors
  - ➢ Dominated by seismic surface waves
- ❑ Not limiting in current detectors, but will be for next generation
- ❑ Cannot be shielded
  - ➢ Monitor with array of seismometers, model and subtract
  - ➢ Quieter underground





Real-time control

- Suspended mirrors still have low-frequency movements comparable to laser wavelength
- Interferometer must be kept at right working point
  - Cavities on resonance, ~dark fringe
  - Mirror longitudinal and angular degrees of freedom must be controlled in real time – aka locking and alignment
- Complex set of feedback loops
  - Error signals
    - Laser beam is phase modulated to create sidebands with behavior different from carrier
    - Sidebands beating with carrier provides error signals
  - Electromagnetic actuators
    - Coil-magnet pairs

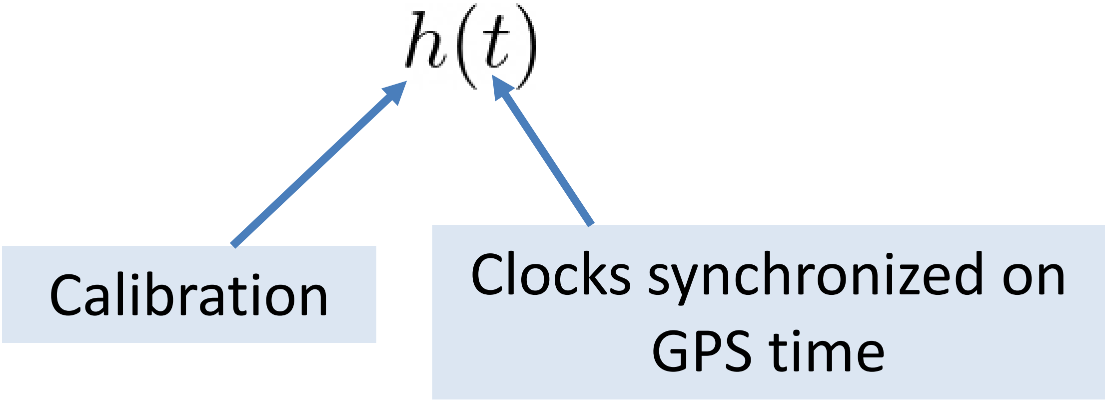
Detector calibration

- Data analysis needs phase measurement to be translated into gravitational-wave strain signal

- Part of GW signal is in control signals
  - Due to feedback loops maintaining interferometer at working point

- Typical accuracy
  - ~2-5% on amplitude, ~2-4 deg on phase

- *h(t)* reconstruction typically includes some noise subtraction, aka *data cleaning*



$$h(t)$$

Calibration

Clocks synchronized on GPS time

- Interferometer response calibrated against known mirror displacements
  - Laser wavelength as a reference
  - Radiation pressure from auxiliary laser beams reflected off mirrors, aka *photon calibrator (PCal)*
  - Gravitational coupling to nearby rotating masses, aka *Newtonian calibrator (NCal)*

FROM CURRENT DETECTORS TO THE NEXT GENERATION WHY? HOW?

Observing runs and upgrades

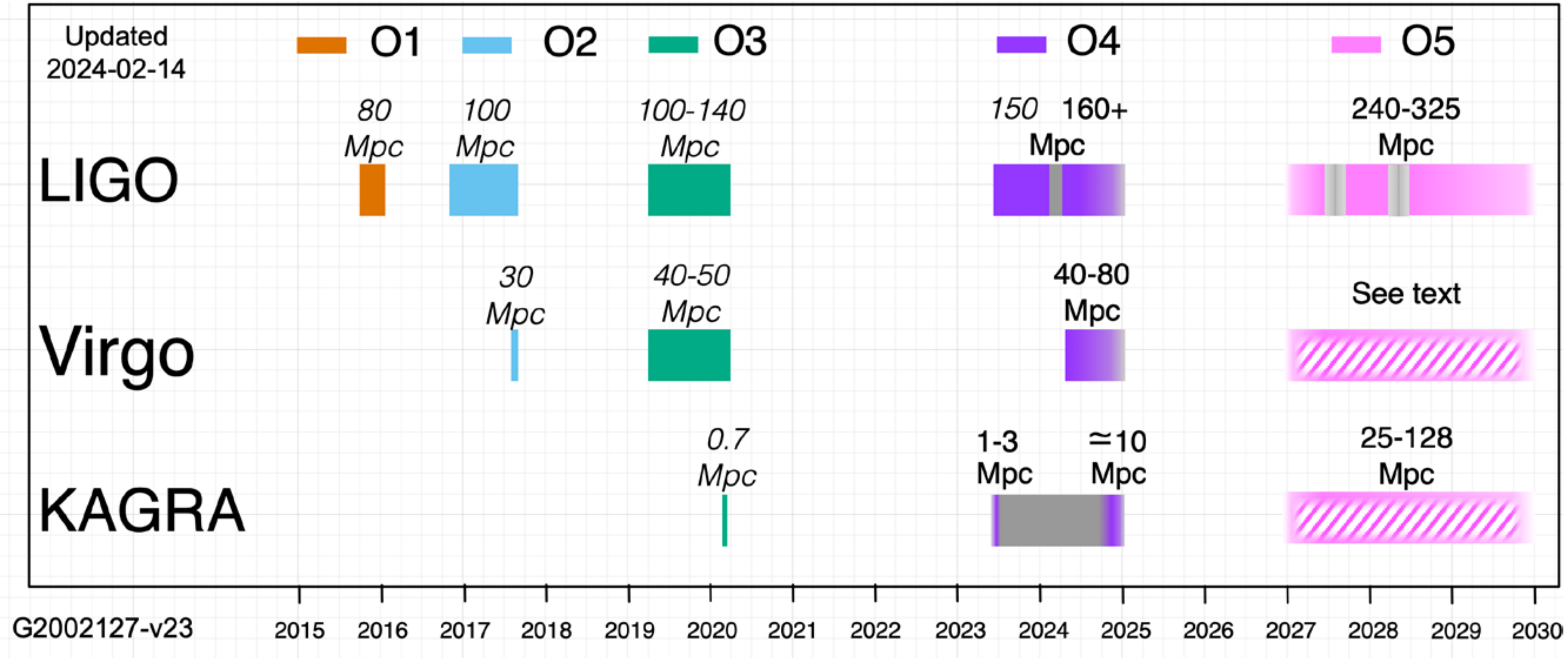
Advanced Virgo

AdV+ Phase I

AdV+ Phase II

aLIGO

A+



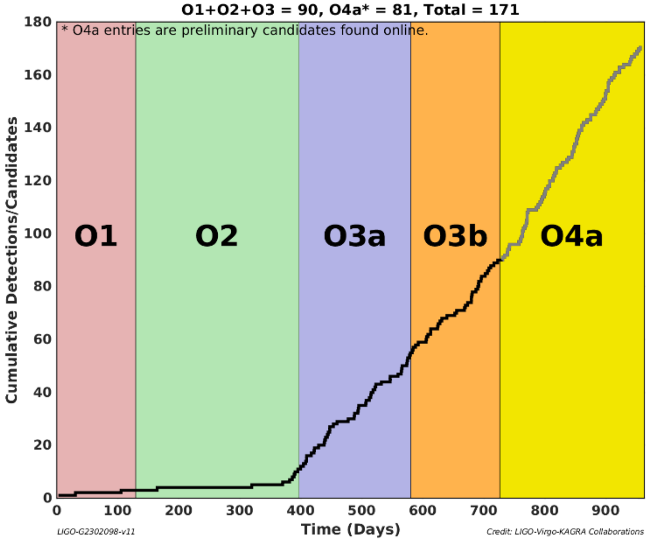
O6

A# concept

Virgo_nEXT concept

“Ultimate” upgrades to reach infrastructure limit

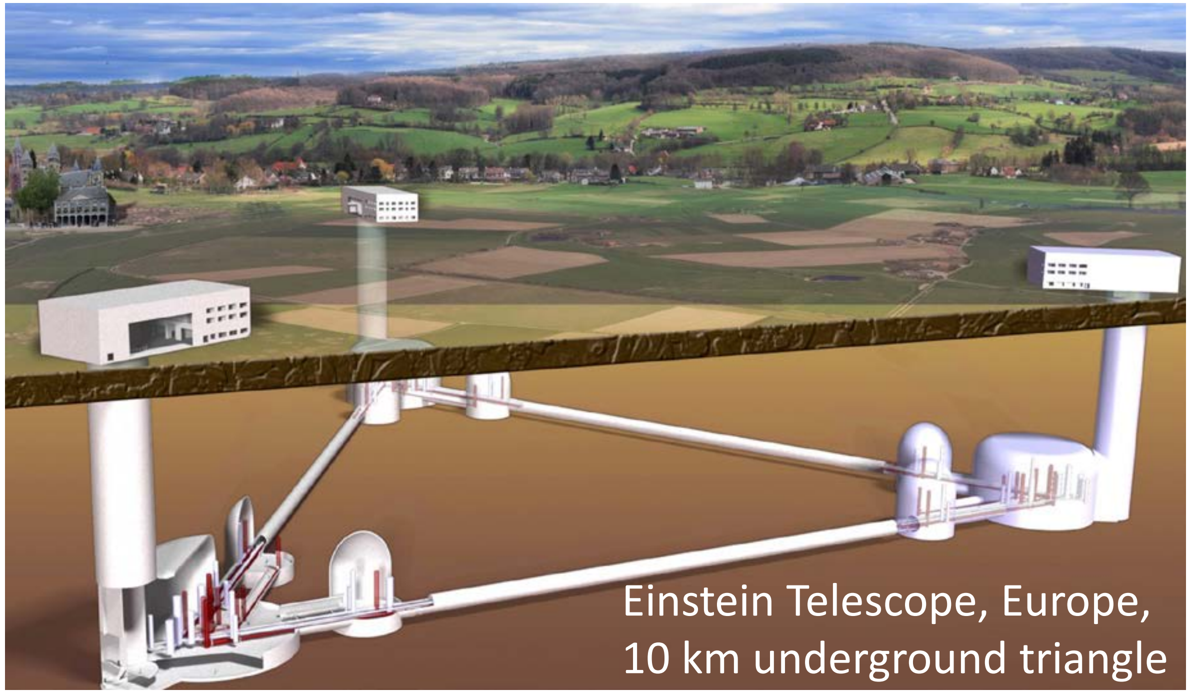
- ❑ Network alternates observing runs and upgrades
- ❑ Rate of detections increases with sensitivity
- ❑ Ultimately, efforts to improve sensitivity will approach infrastructure limits

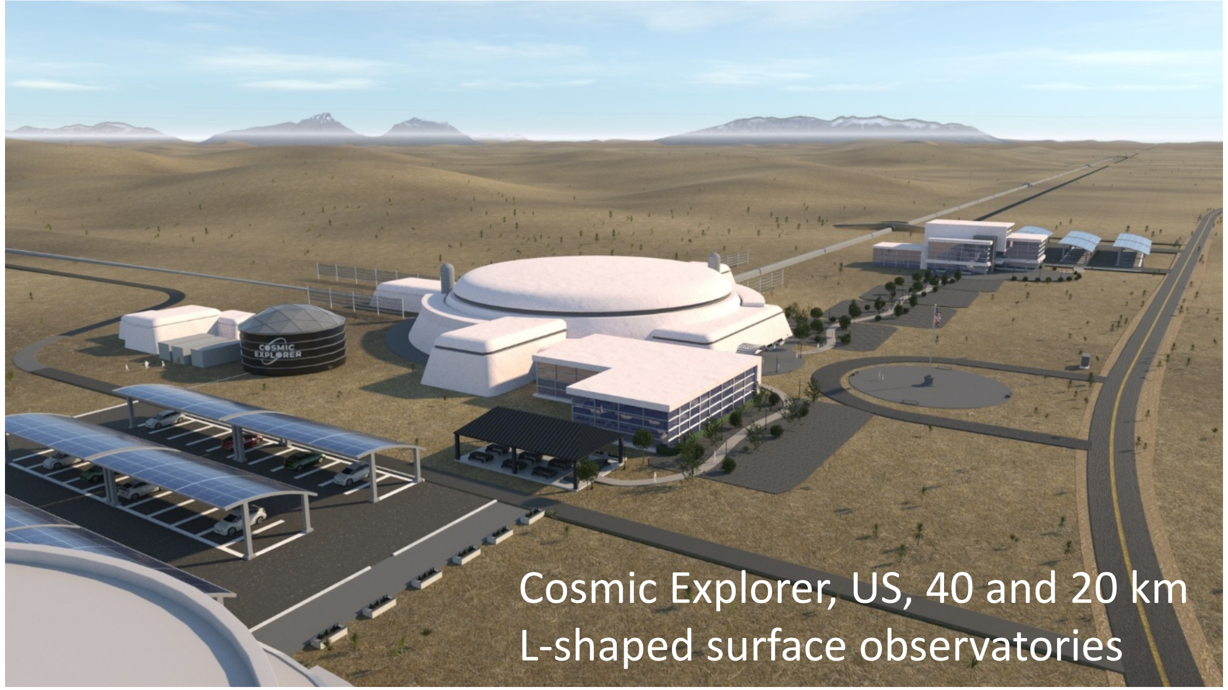


LIGO-G2302098-v11

Credit: LIGO-Virgo-KAGRA Collaborations

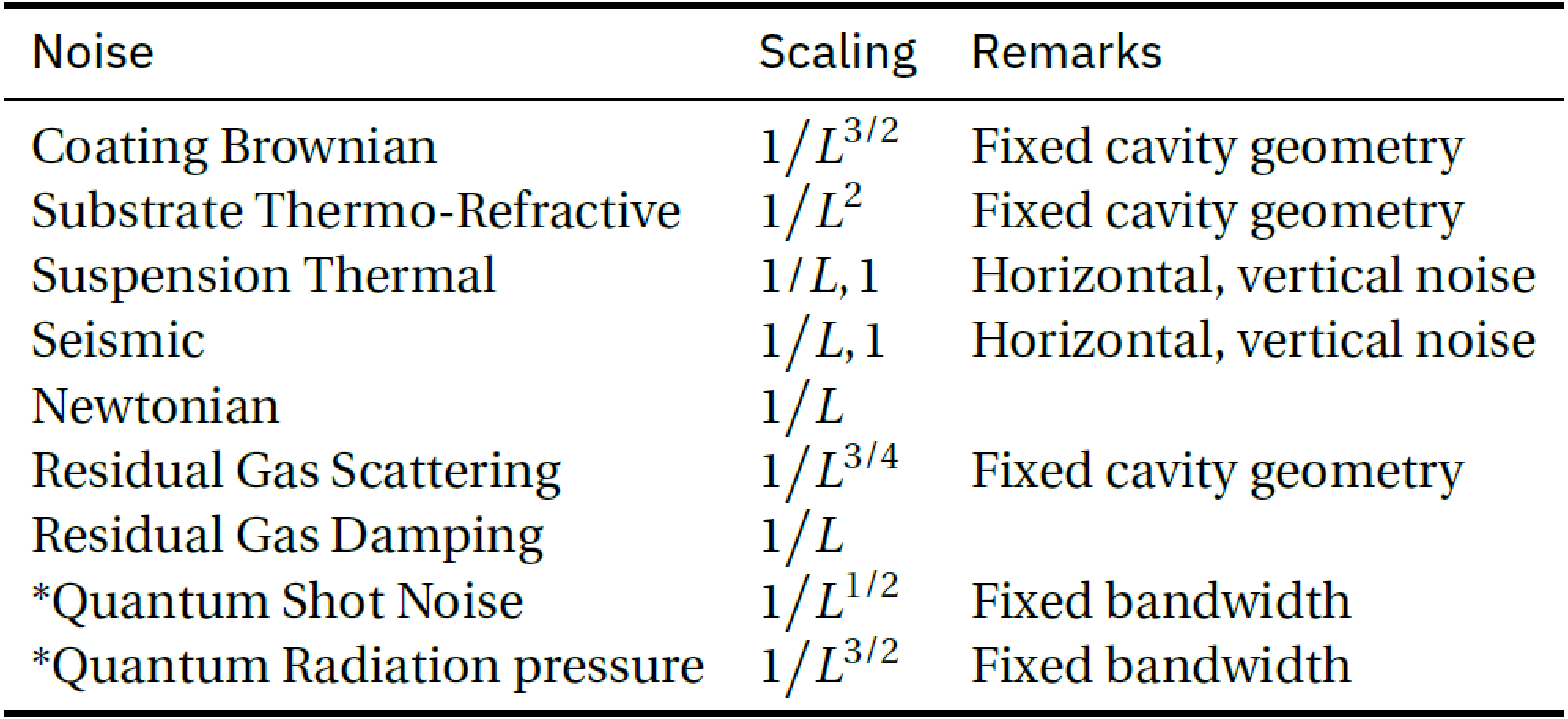
Projects in new infrastructures


Einstein Telescope, Europe, 10 km underground triangle


Cosmic Explorer, US, 40 and 20 km L-shaped surface observatories

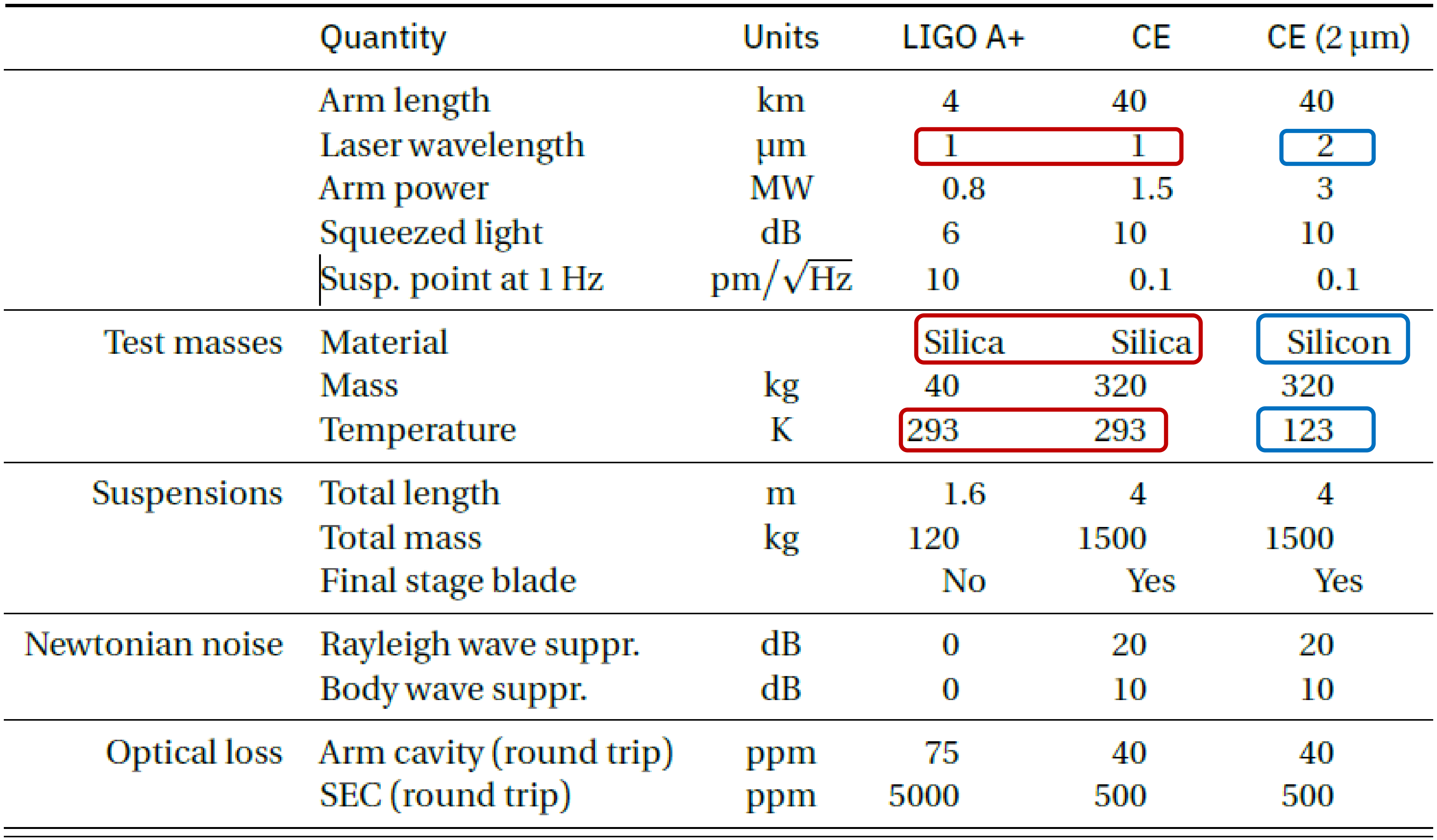
- New infrastructures allow baselines longer by an order of magnitude
  - GW signal increases with length
  - Interferometer response and therefore noise levels scale non-trivially with length

Scaling of fundamental noises with arm length



Noise	Scaling	Remarks
Coating Brownian	$1/L^{3/2}$	Fixed cavity geometry
Substrate Thermo-Refractive	$1/L^2$	Fixed cavity geometry
Suspension Thermal	$1/L, 1$	Horizontal, vertical noise
Seismic	$1/L, 1$	Horizontal, vertical noise
Newtonian	$1/L$	
Residual Gas Scattering	$1/L^{3/4}$	Fixed cavity geometry
Residual Gas Damping	$1/L$	
*Quantum Shot Noise	$1/L^{1/2}$	Fixed bandwidth
*Quantum Radiation pressure	$1/L^{3/2}$	Fixed bandwidth

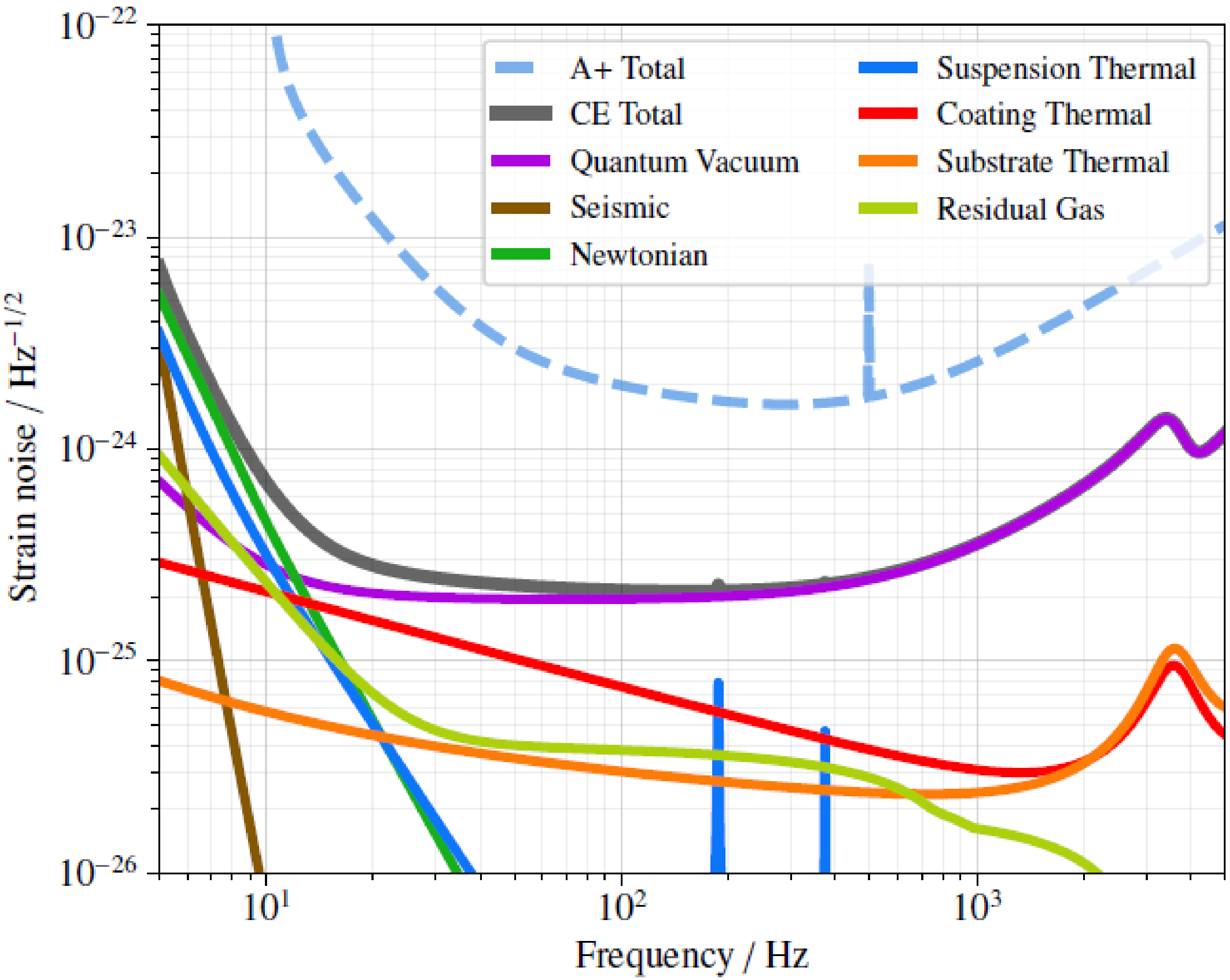
Cosmic Explorer: a bigger LIGO



	Quantity	Units	LIGO A+	CE	CE (2 μm)
	Arm length	km	4	40	40
	Laser wavelength	μm	1	1	2
	Arm power	MW	0.8	1.5	3
	Squeezed light	dB	6	10	10
	Susp. point at 1 Hz	$\mathrm{pm}/\sqrt{\mathrm{Hz}}$	10	0.1	0.1
Test masses	Material		Silica	Silica	Silicon
	Mass	kg	40	320	320
	Temperature	K	293	293	123
Suspensions	Total length	m	1.6	4	4
	Total mass	kg	120	1500	1500
	Final stage blade		No	Yes	Yes
Newtonian noise	Rayleigh wave suppr.	dB	0	20	20
	Body wave suppr.	dB	0	10	10
Optical loss	Arm cavity (round trip)	ppm	75	40	40
	SEC (round trip)	ppm	5000	500	500

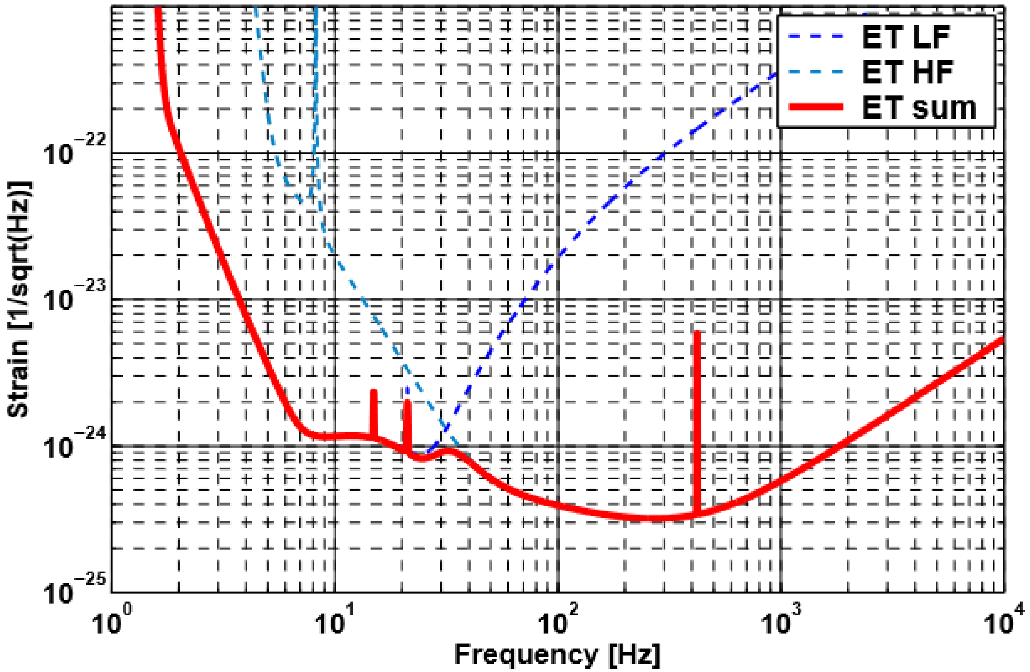
Alternative path if unexpected challenges in incremental approach based on current technology

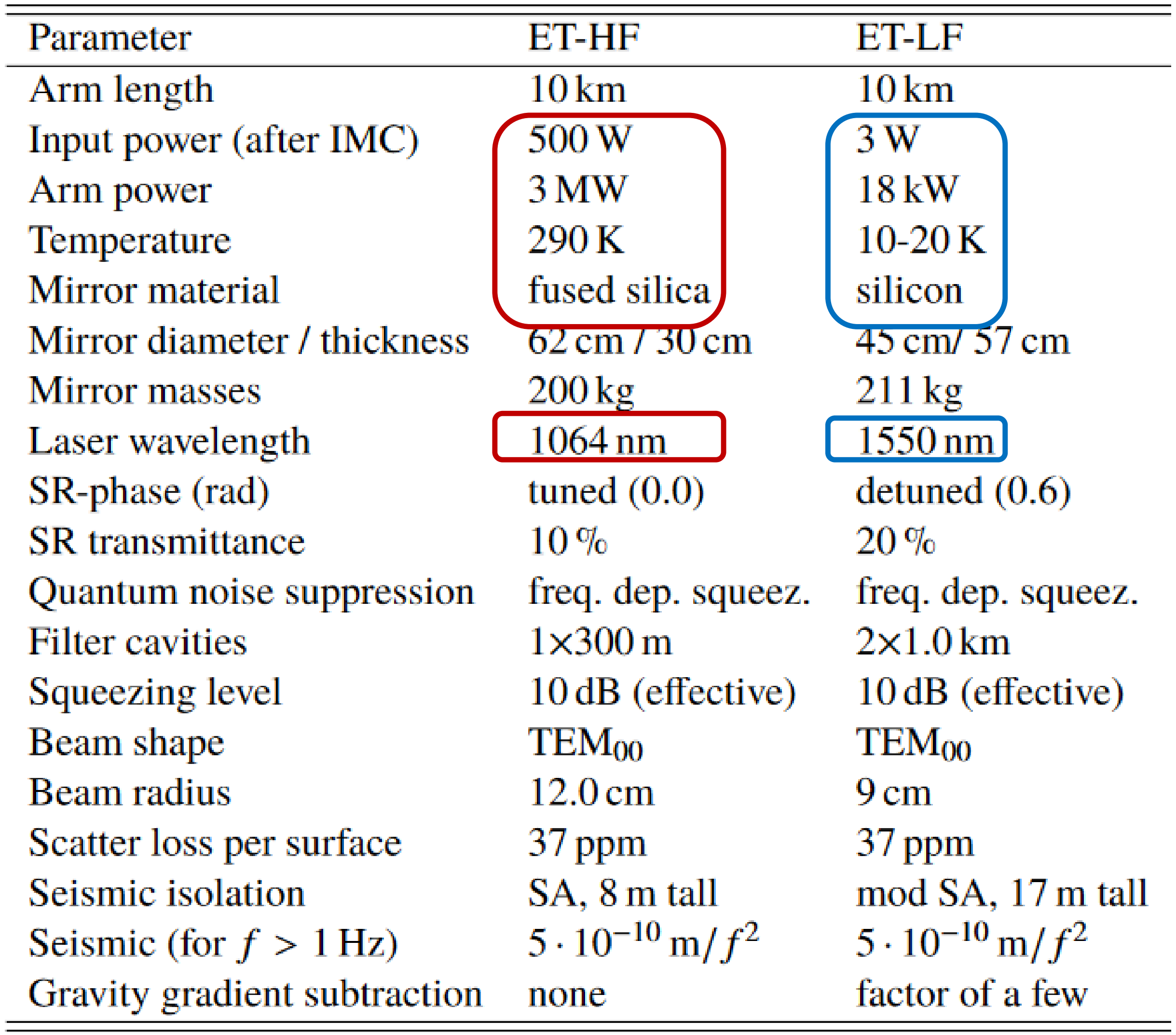
Cosmic Explorer target sensitivity



Einstein Telescope: xylophone strategy

- Low and high frequencies have conflicting requirements
  - High optical power needed to decrease shot noise but will increase radiation pressure noise
  - High power comes with challenges + not easily compatible with low-temperature operation
- Combine two detectors dedicated to LF and HF

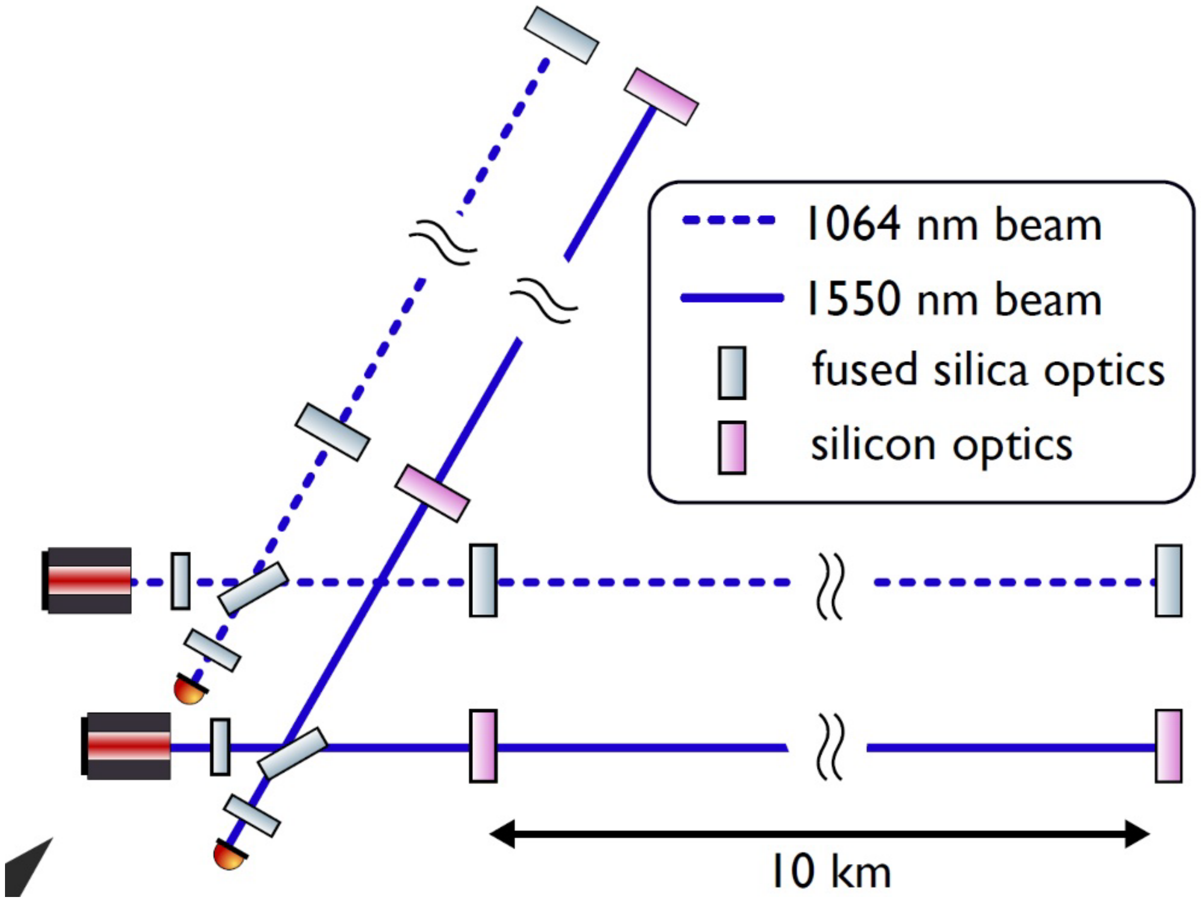


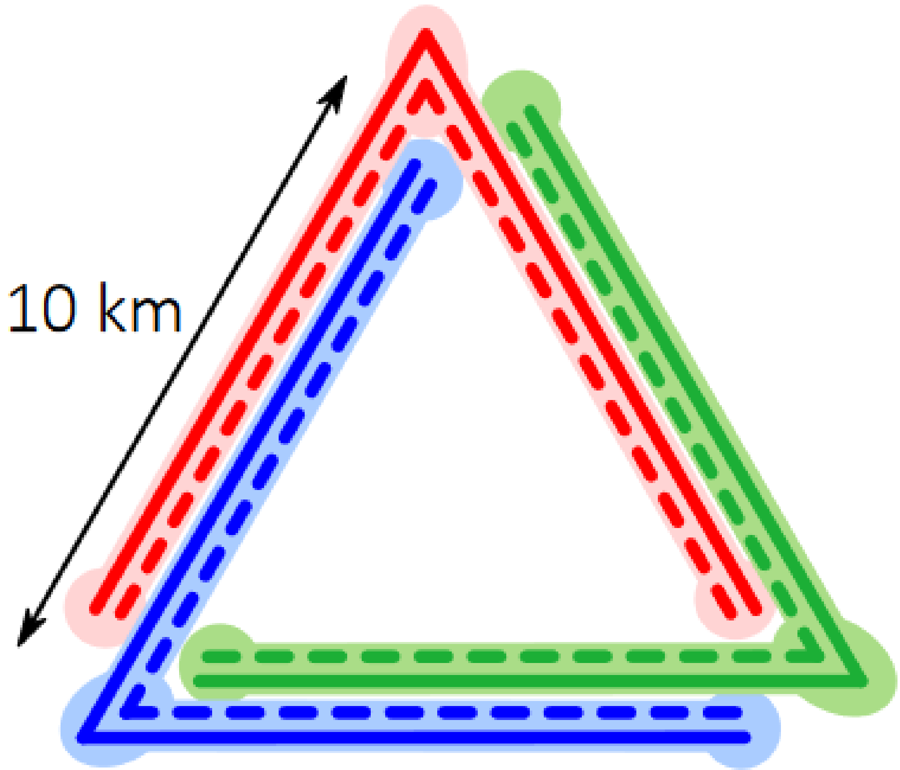


Parameter	ET-HF	ET-LF
Arm length	10 km	10 km
Input power (after IMC)	500 W	3 W
Arm power	3 MW	18 kW
Temperature	290 K	10-20 K
Mirror material	fused silica	silicon
Mirror diameter / thickness	62 cm / 30 cm	45 cm/ 57 cm
Mirror masses	200 kg	211 kg
Laser wavelength	1064 nm	1550 nm
SR-phase (rad)	tuned (0.0)	detuned (0.6)
SR transmittance	10 %	20 %
Quantum noise suppression	freq. dep. squeez.	freq. dep. squeez.
Filter cavities	1×300 m	2×1.0 km
Squeezing level	10 dB (effective)	10 dB (effective)
Beam shape	TEM_{00}	TEM_{00}
Beam radius	12.0 cm	9 cm
Scatter loss per surface	37 ppm	37 ppm
Seismic isolation	SA, 8 m tall	mod SA, 17 m tall
Seismic (for $f > 1$ Hz)	$5 \cdot 10^{-10}\,\mathrm{m}/f^2$	$5 \cdot 10^{-10}\,\mathrm{m}/f^2$
Gravity gradient subtraction	none	factor of a few

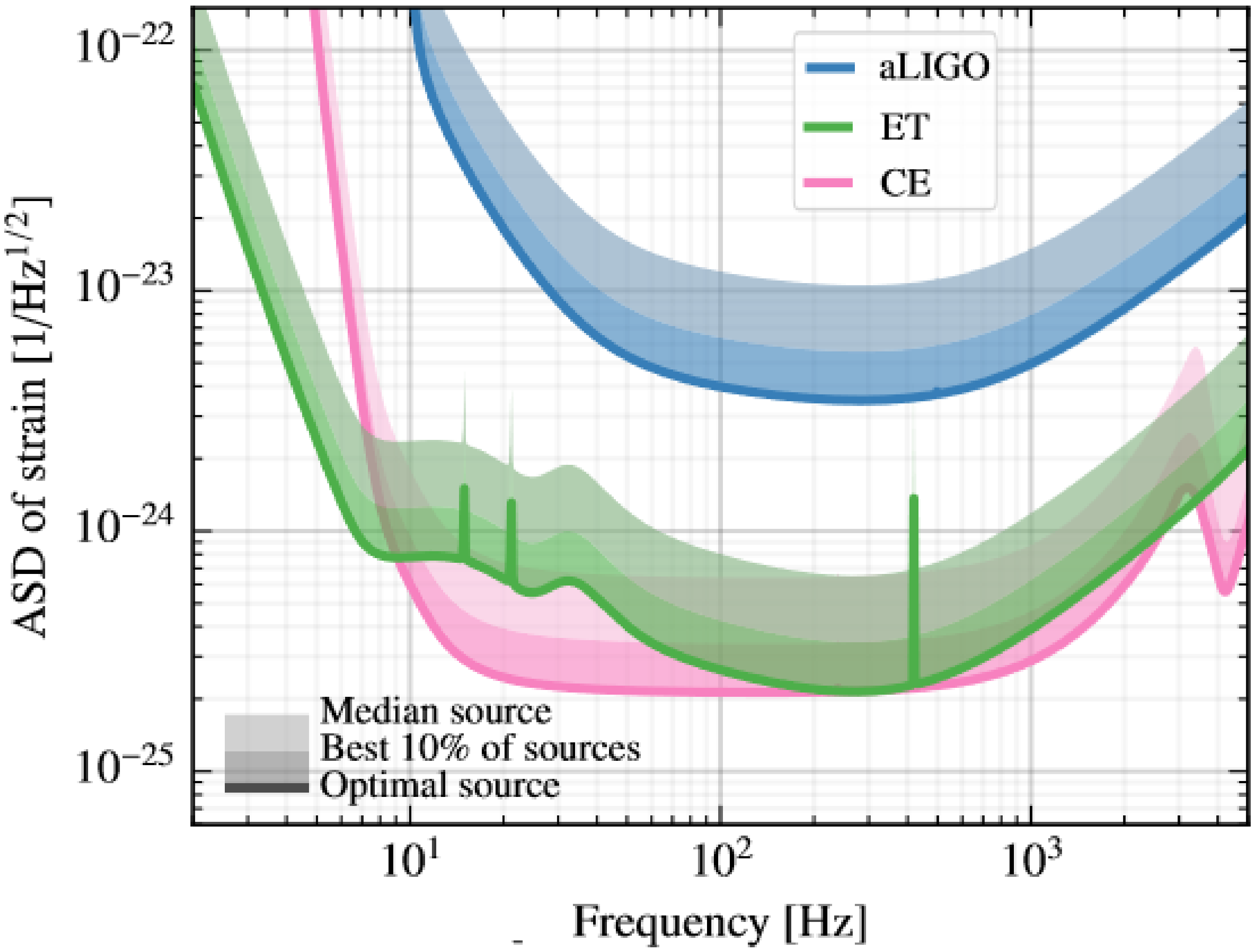
Einstein Telescope: multiple detectors

- Three (pairs of) detectors arranged in a triangle





Einstein Telescope: target sensitivity



Tomorrow…

PART II: SOURCES, DATA ANALYSIS, SCIENCE