Title: Gravitational Waves Experiments 3

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Abstract:

Gravitational Waves: Experimental Techniques 3

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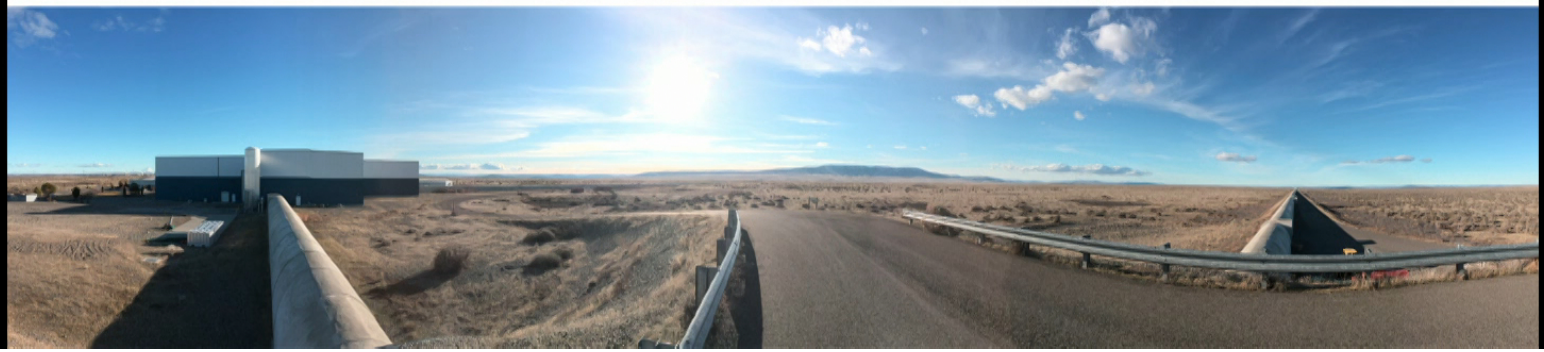
TRISEP 2018 - Perimeter Institute

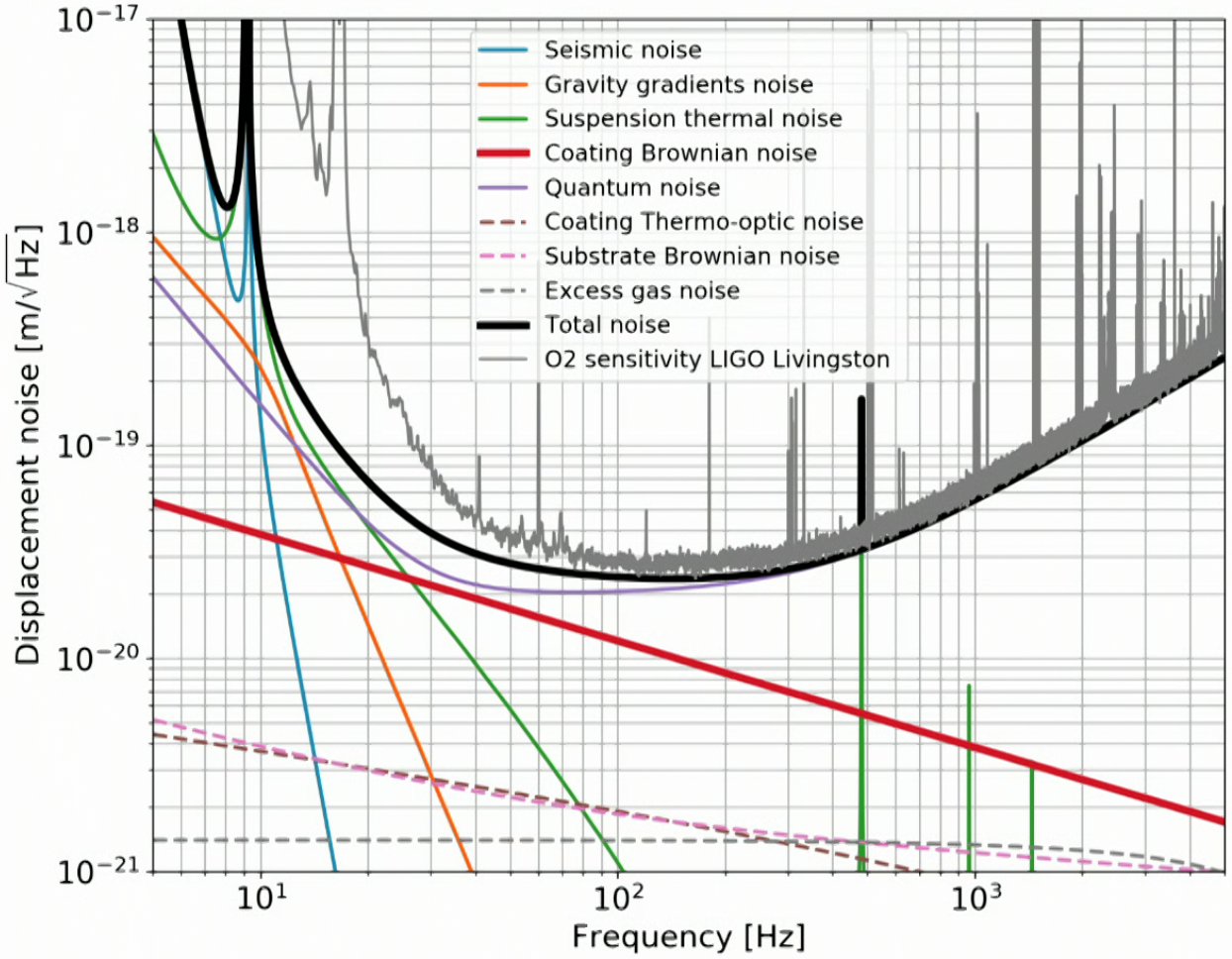


Outline

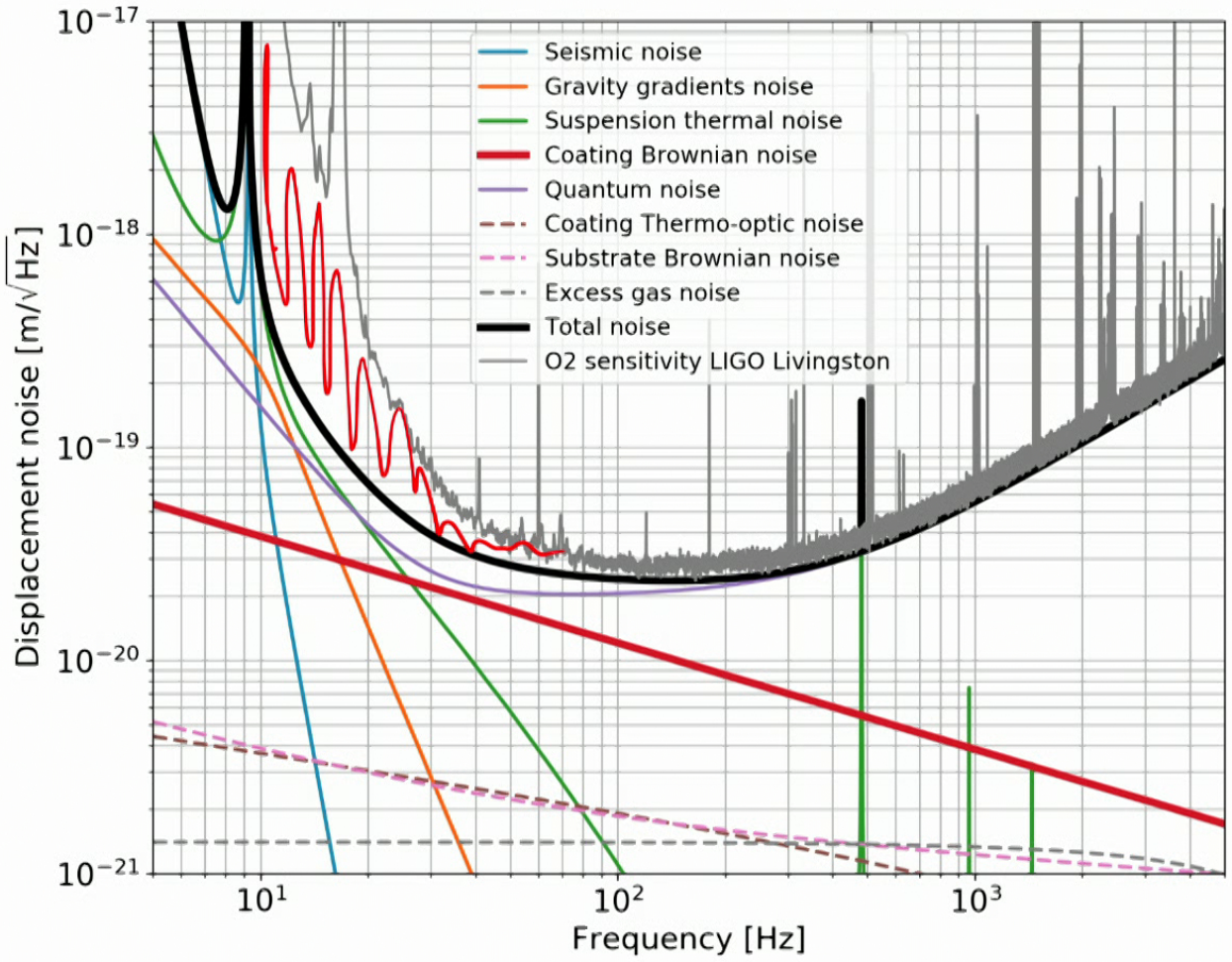
- **Lecture 1**: the basics of interferometric detection of gravitational waves
- **Lecture 2**: fundamental noise sources (seismic, thermal and quantum noises)
- **Lecture 3**: the dirty reality of ”technical noises” (scattered light, control noise, etc…) and prospects for the future

TECHNICAL NOISE SOURCES

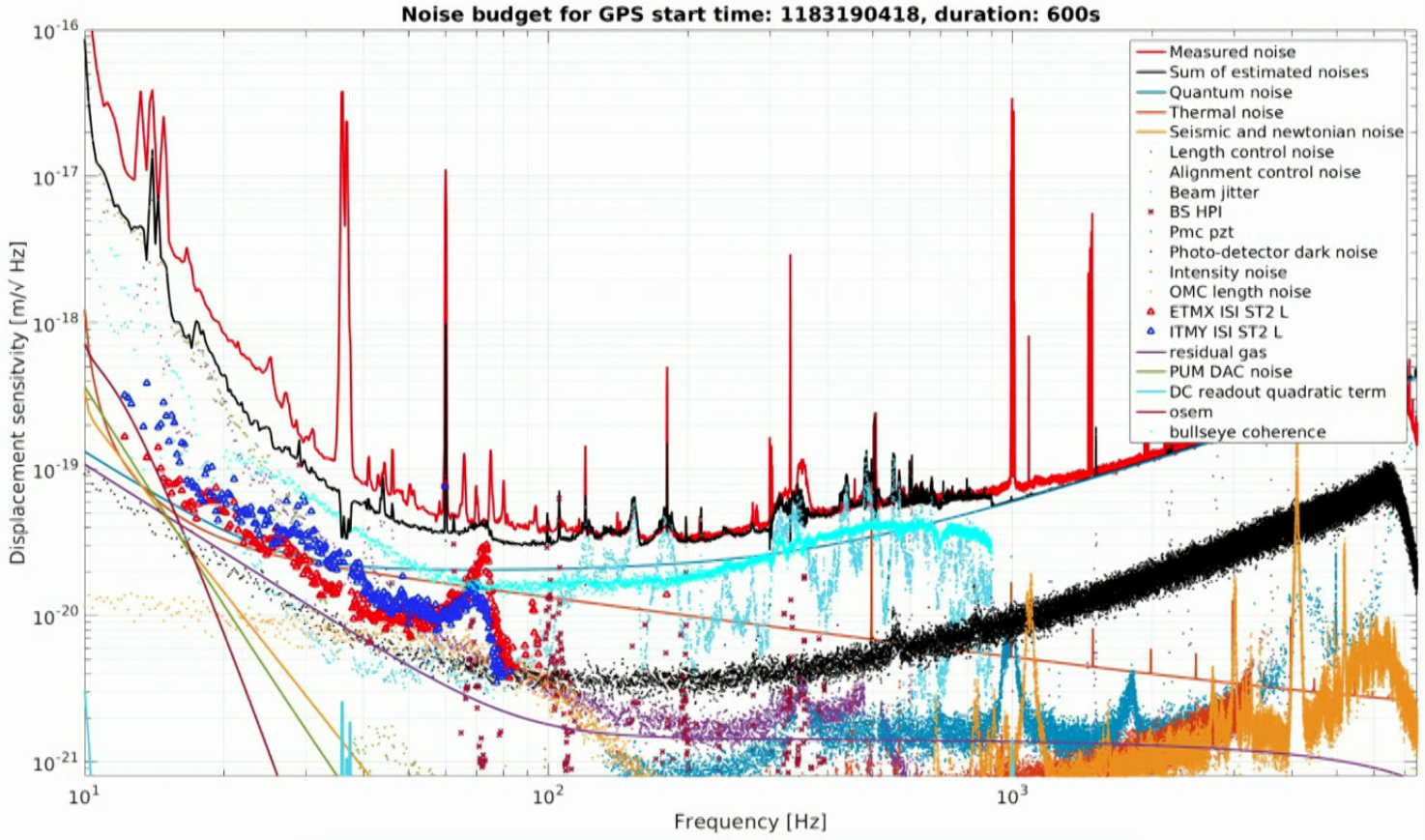
Advanced LIGO design



Advanced LIGO design



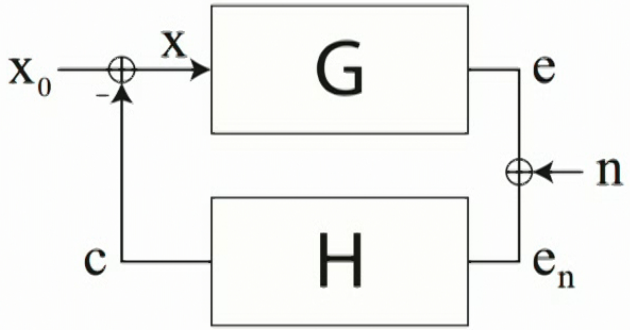
LIGO


Noise budget for GPS start time: 1183190418, duration: 600s
Displacement sensitvity [m/√ Hz]
Frequency [Hz]
Measured noise
Sum of estimated noises
Quantum noise
Thermal noise
Seismic and newtonian noise
Length control noise
Alignment control noise
Beam jitter
BS HPI
Pmc pzt
Photo-detector dark noise
Intensity noise
OMC length noise
ETMX ISI ST2 L
ITMY ISI ST2 L
residual gas
PUM DAC noise
DC readout quadratic term
osem
bullseye coherence

Technical noises

- Feedback control noise: longitudinal and angular
- Laser noises: frequency, intensity, jitter
- Electronic noises
- Scattered light
- Environmental noises: acoustic, electromagnetic, seismic

Feedback control noise



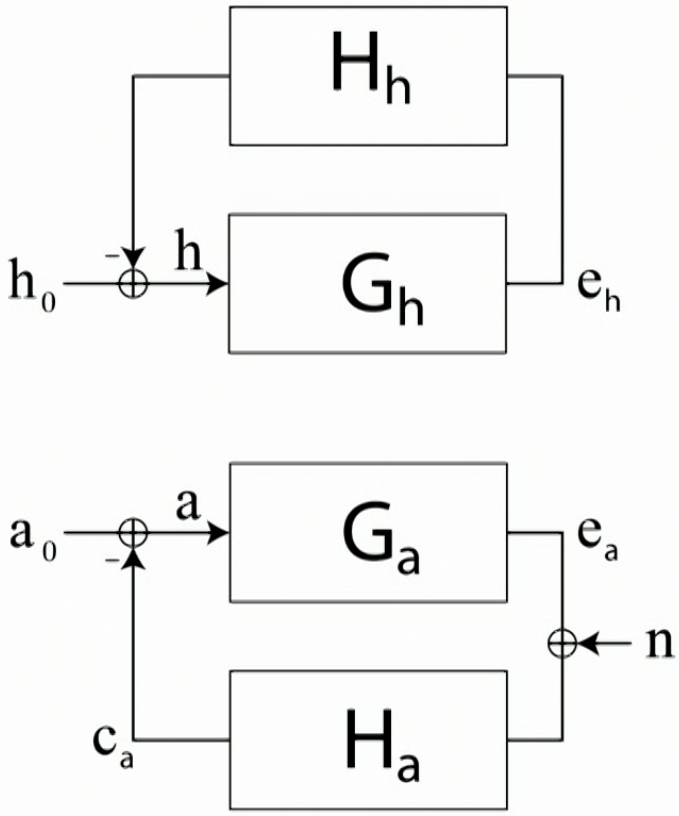
$$\hat{x} = \frac{\hat{x}_0}{1+HG} - \frac{HG}{1+HG}\left(\frac{\hat{n}}{G}\right)$$

$$\hat{e} = \hat{x}_0 \frac{G}{1+HG} - \frac{HG}{1+HG}\hat{n}$$

$$\hat{e}_n = \frac{G\hat{x}_0 + \hat{n}}{1+HG}$$

Why does it matter?

- Our system is not completely diagonal: auxiliary degrees of freedom couple into the main GW channel



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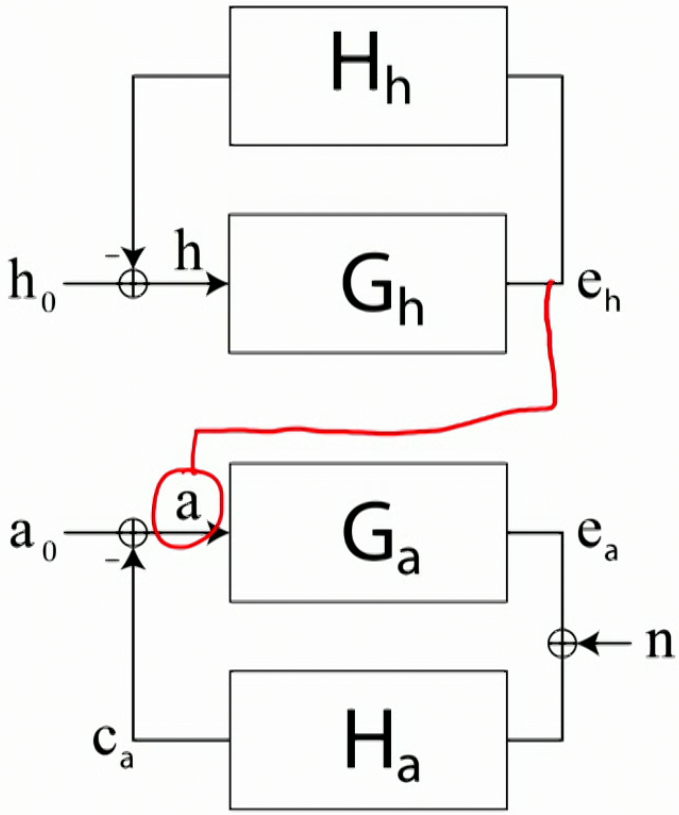

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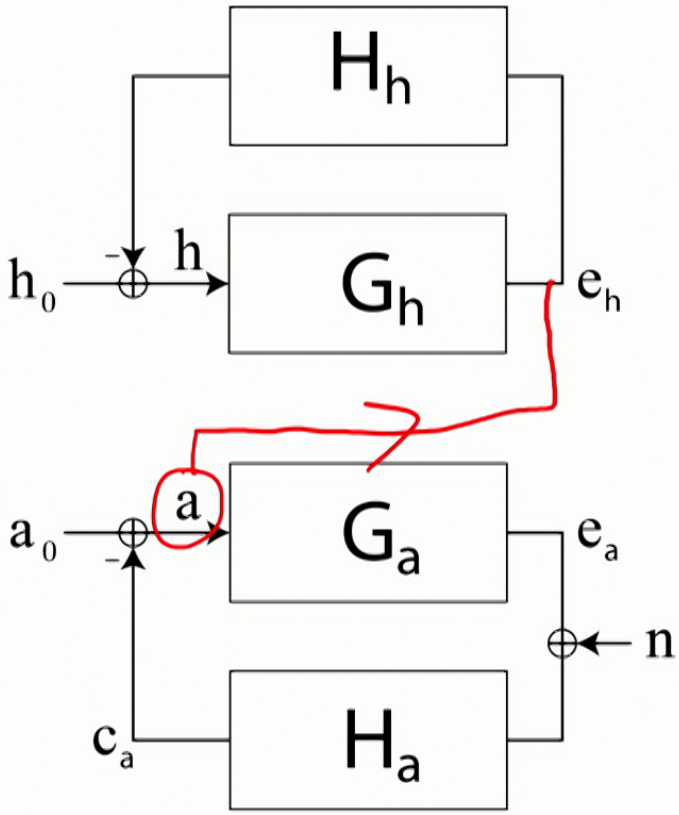

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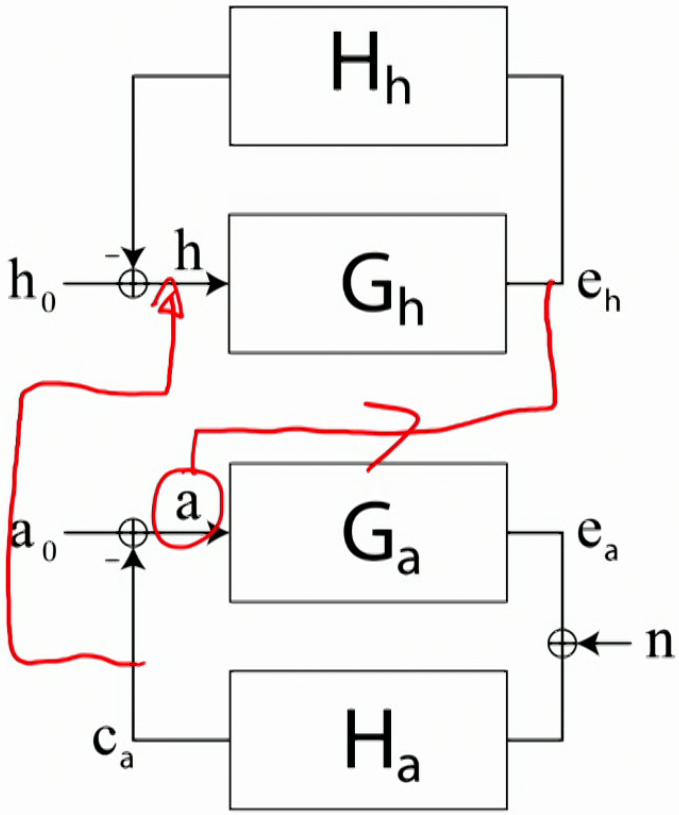
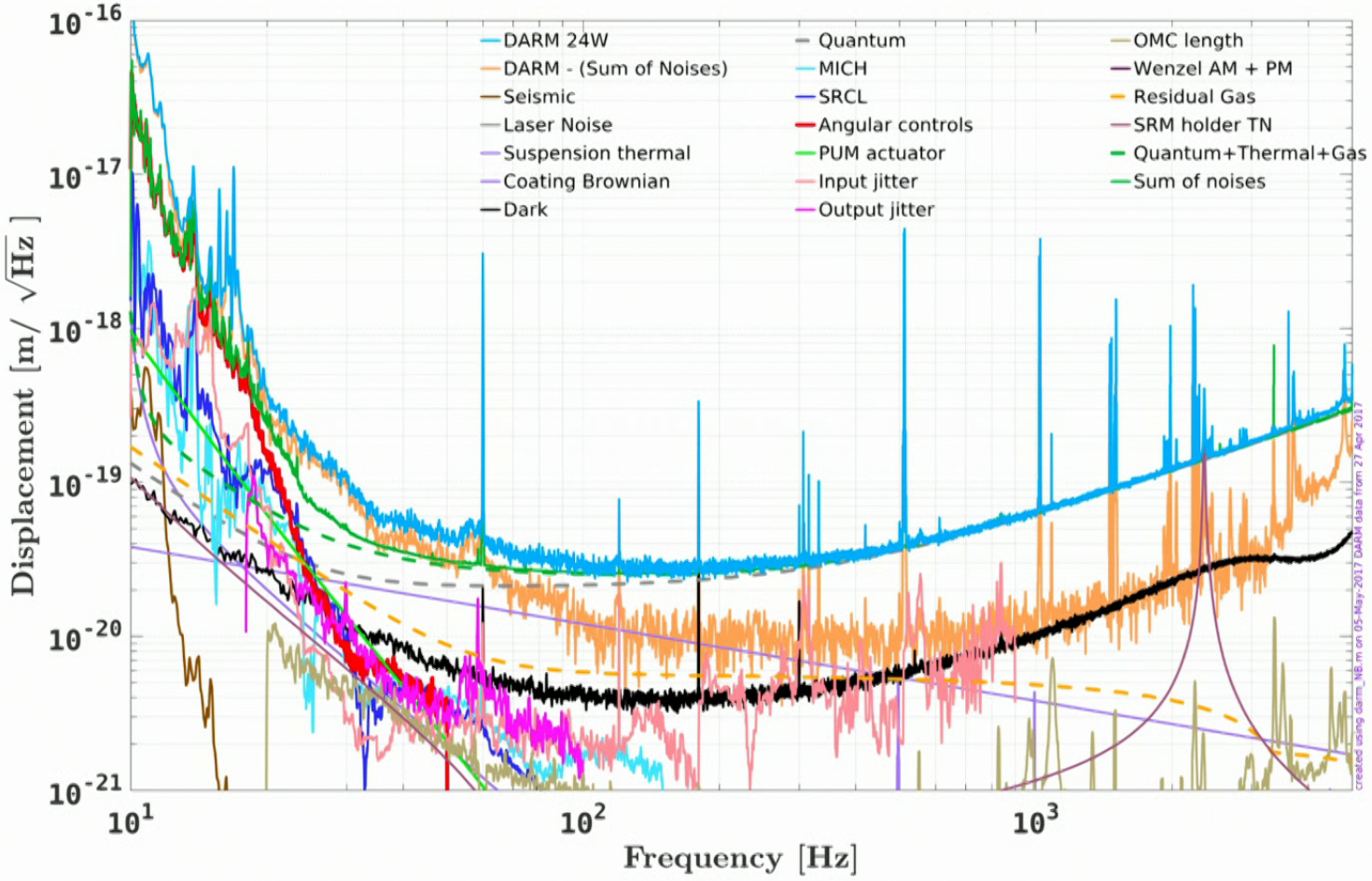
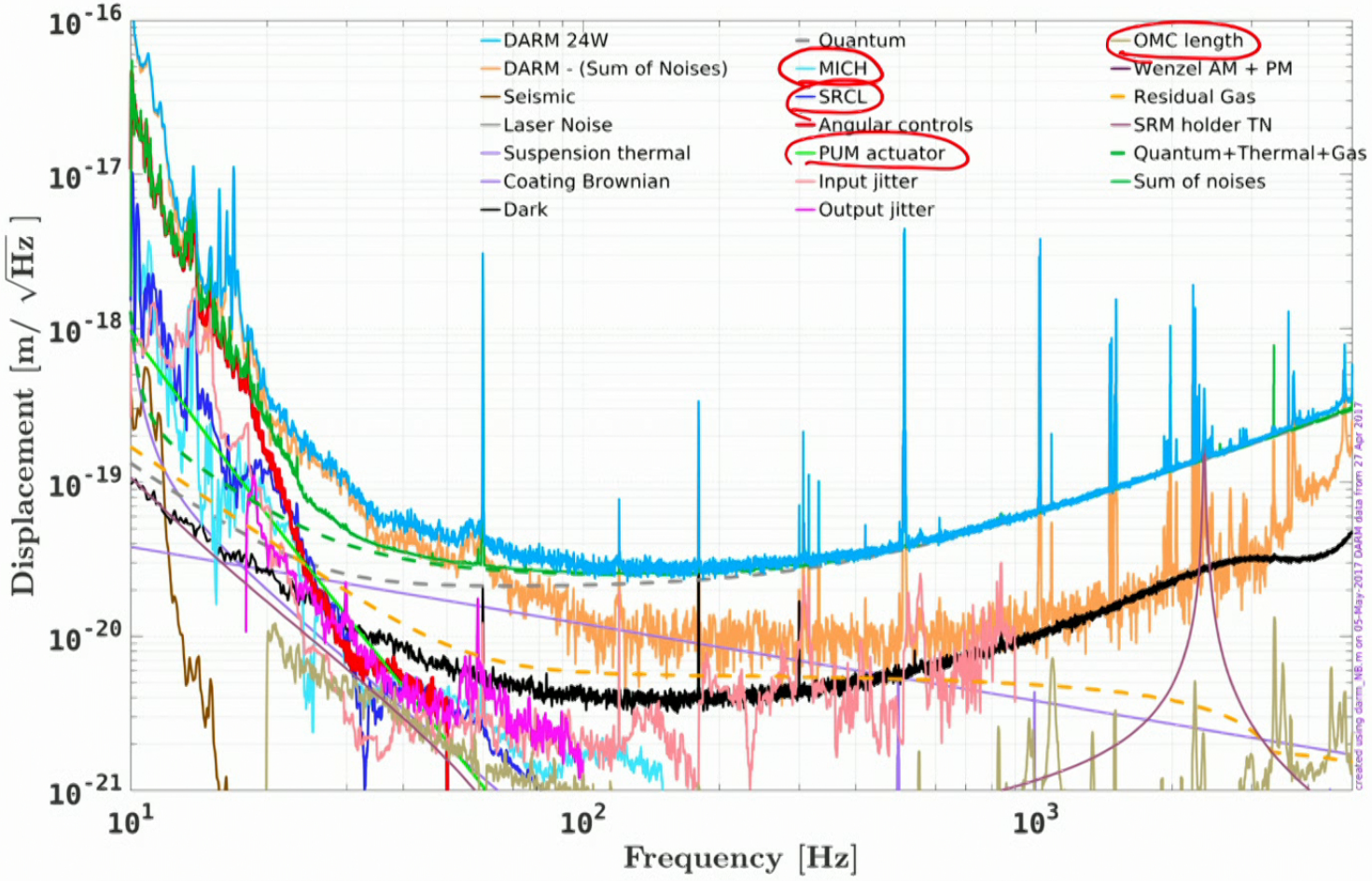


LIGO


DARM 24W
DARM - (Sum of Noises)
Seismic
Laser Noise
Suspension thermal
Coating Brownian
Dark
Quantum
MICH
SRCL
Angular controls
PUM actuator
Input jitter
Output jitter
OMC length
Wenzel AM + PM
Residual Gas
SRM holder TN
Quantum+Thermal+Gas
Sum of noises
Displacement [m/ √Hz]
Frequency [Hz]
10^-16
10^-17
10^-18
10^-19
10^-20
10^-21
10^1
10^2
10^3
created using darm_NB.m on 05-May-2017 DARM data from 27 Apr 2017

LIGO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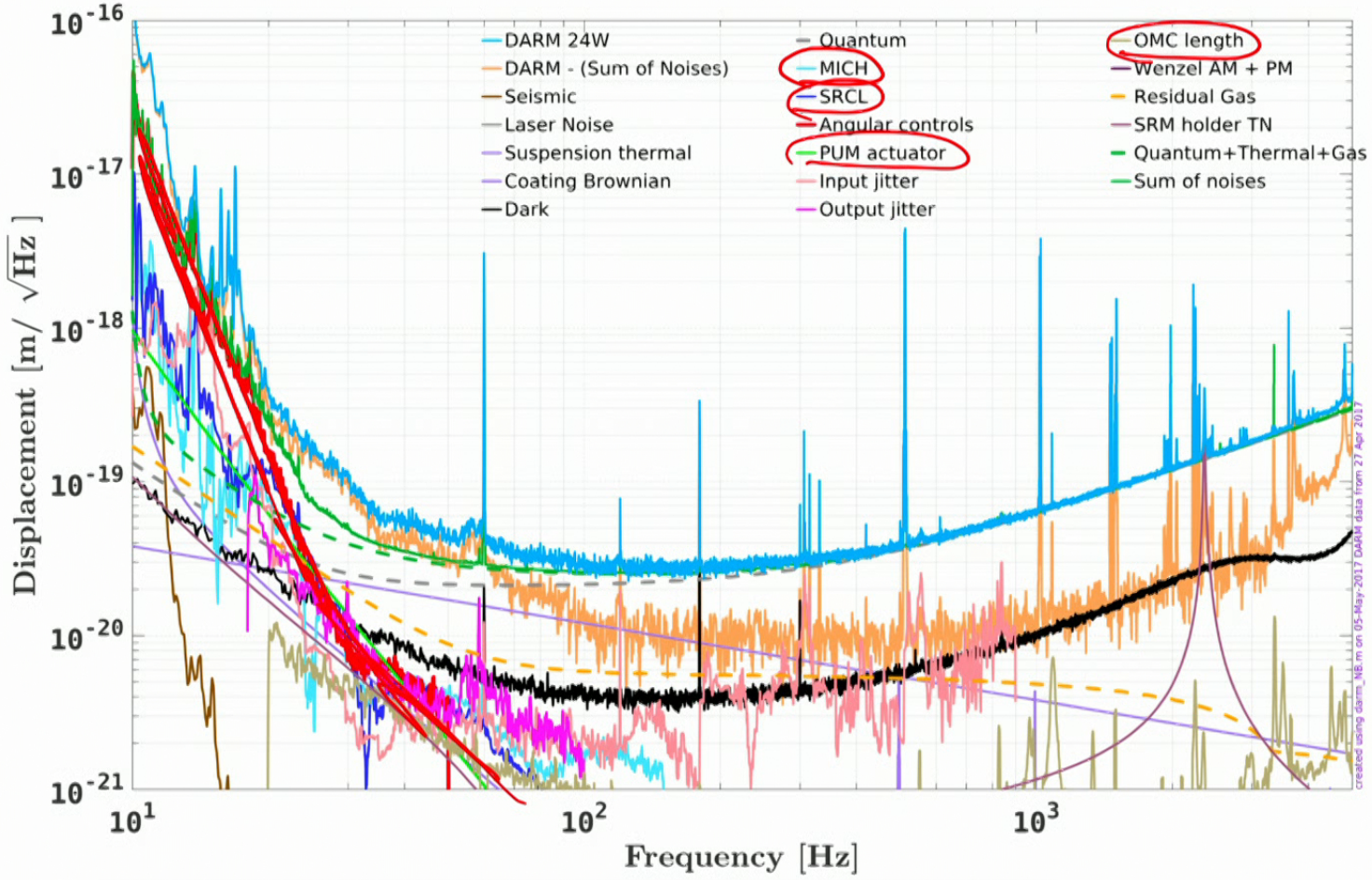
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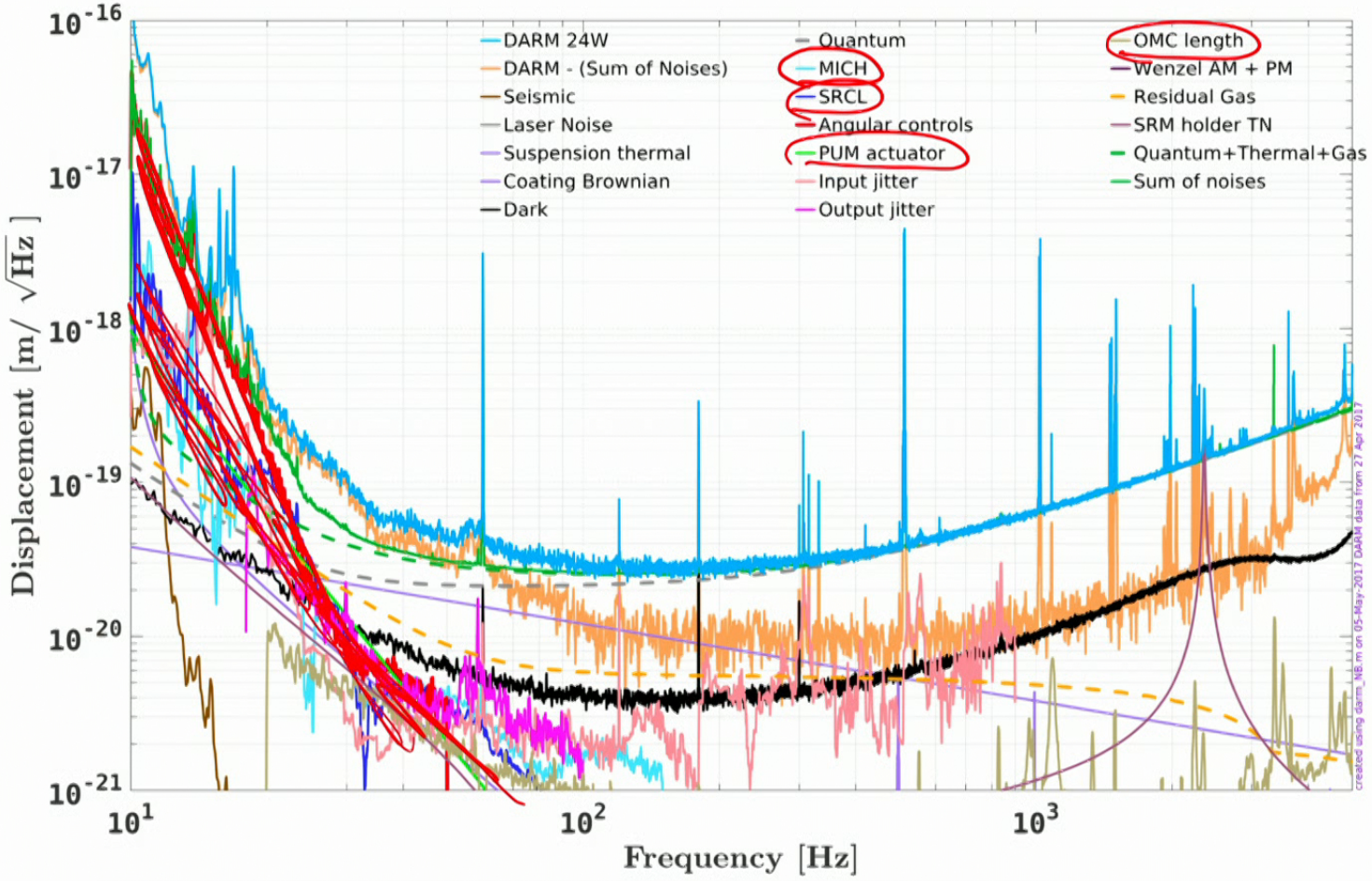
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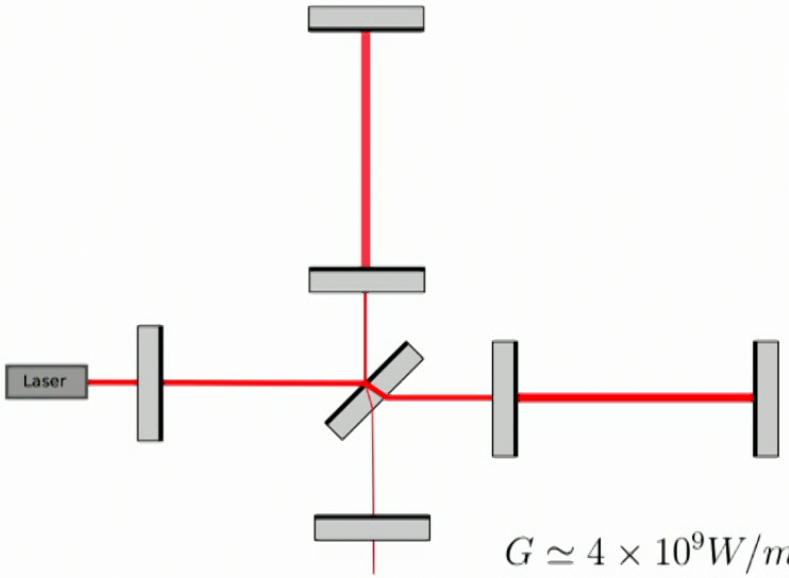
Laser noises: intensity

- We measure the GW signal in a Michelson interferometer by measuring power fluctuations at the anti-symmetric port



$G \simeq 4 \times 10^9 W/m$
for 10 mW of power on the PD

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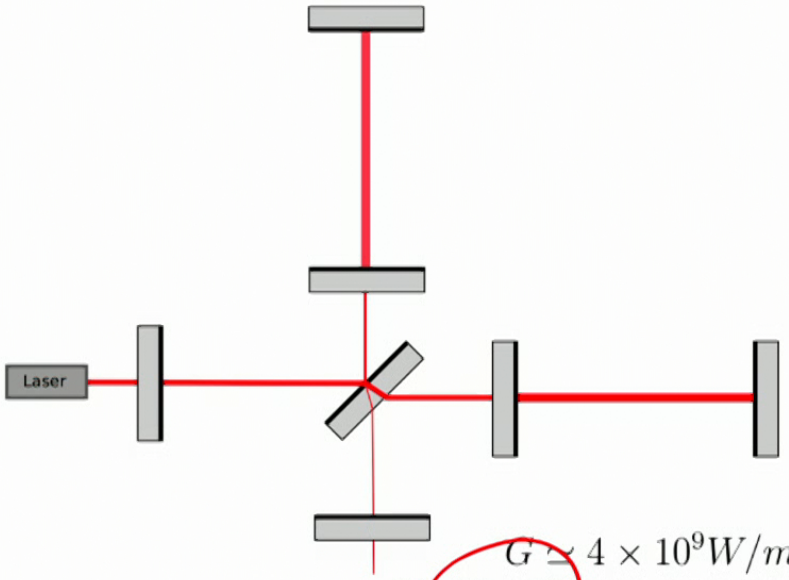

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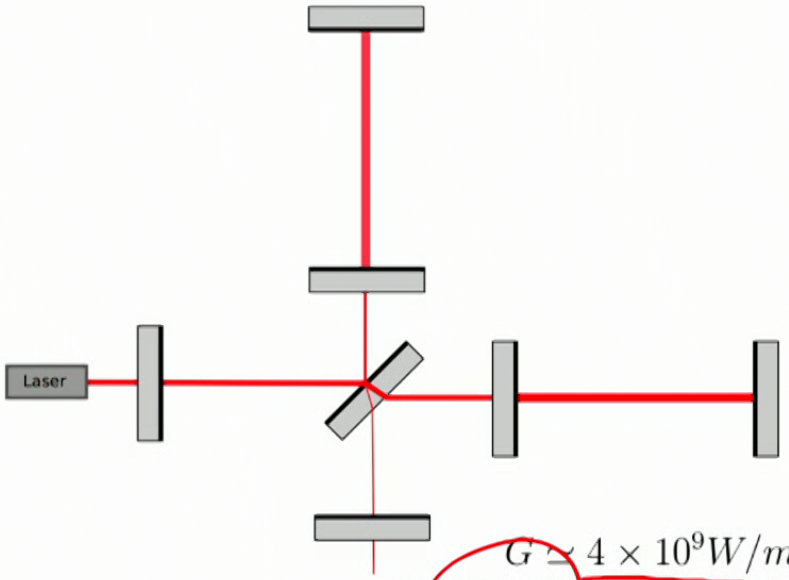

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Laser noises: intensity

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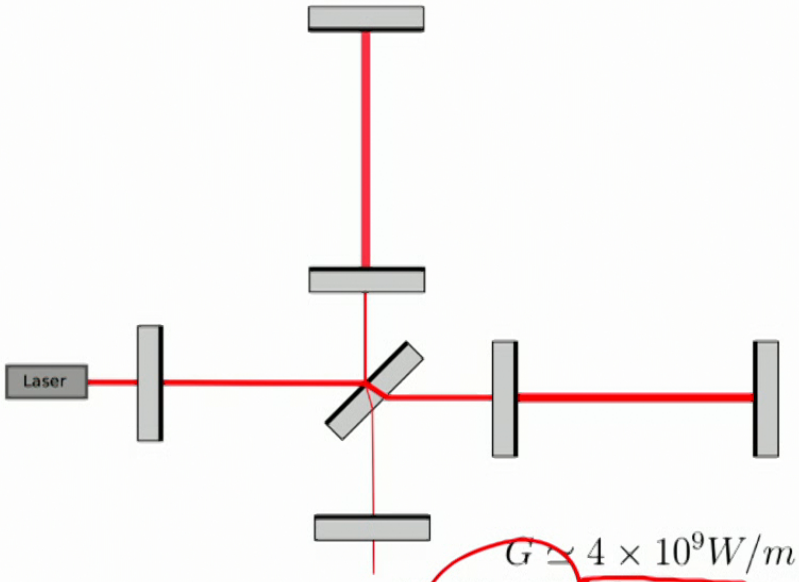
$z = 10^{-18}\ m$



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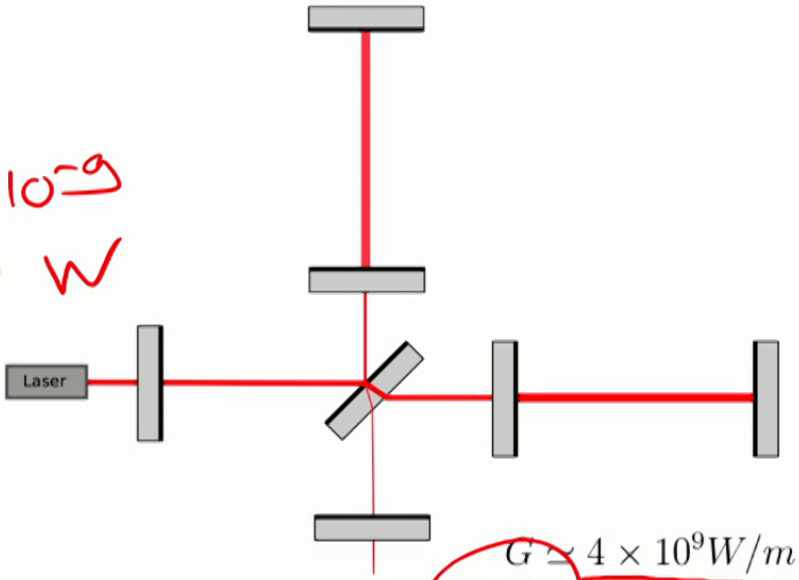

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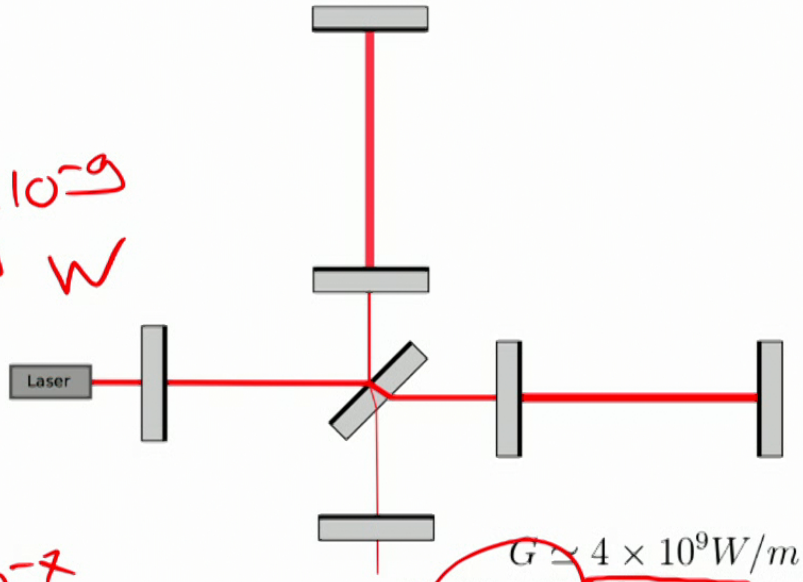
$h = 10^{-18}\ m$

$\delta P = 10^{-18} \times 4 \times 10^{-9}$

$= 4 \times 10^{-9}\ W$

$\frac{\delta P}{P} = \frac{4 \times 10^{-9}}{10^{-2}}$

$\simeq 4 \times 10^{-7}$



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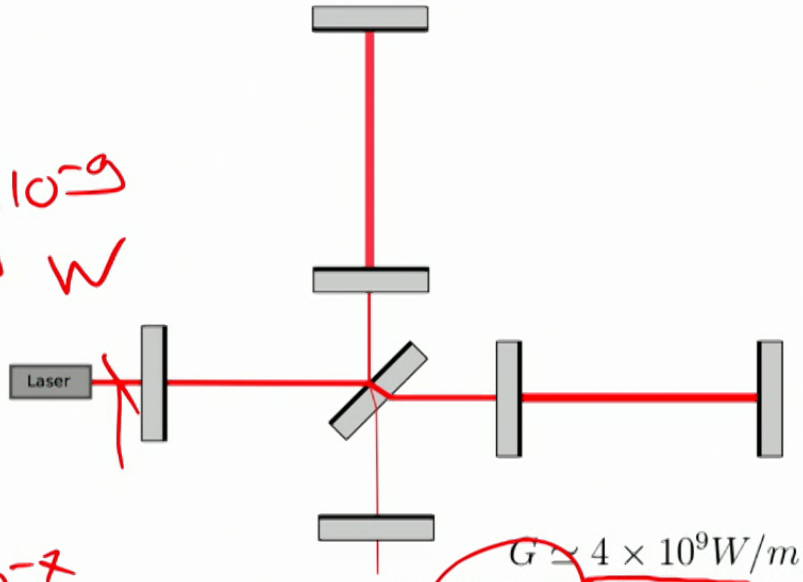

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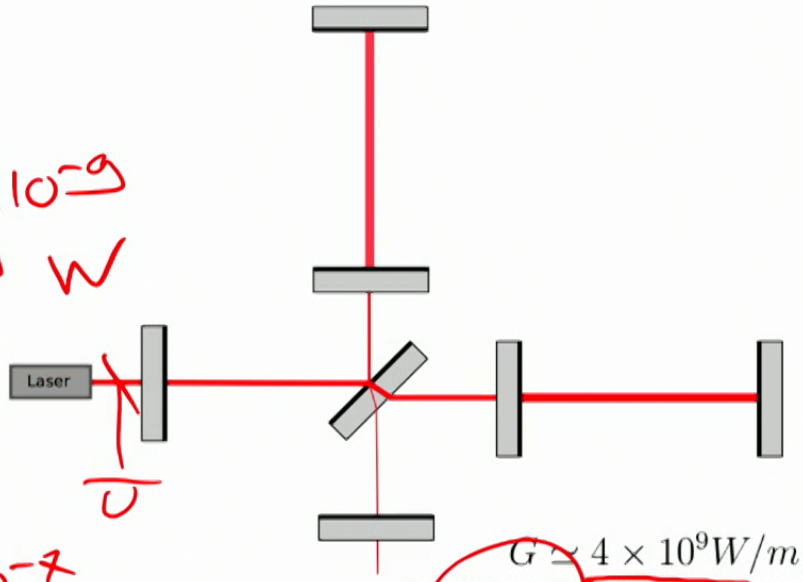

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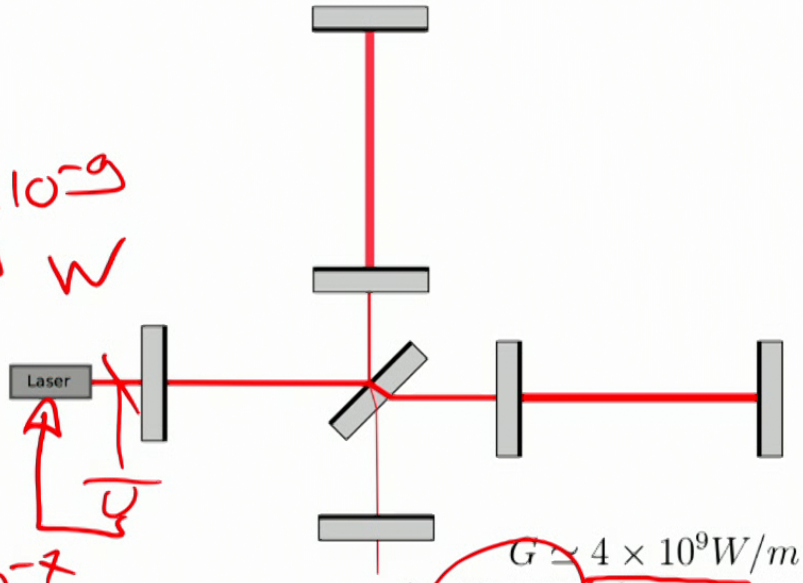

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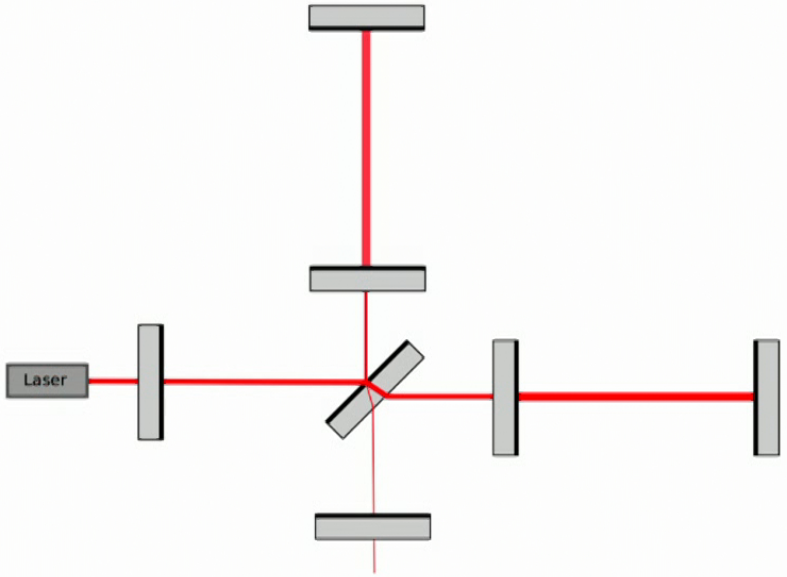
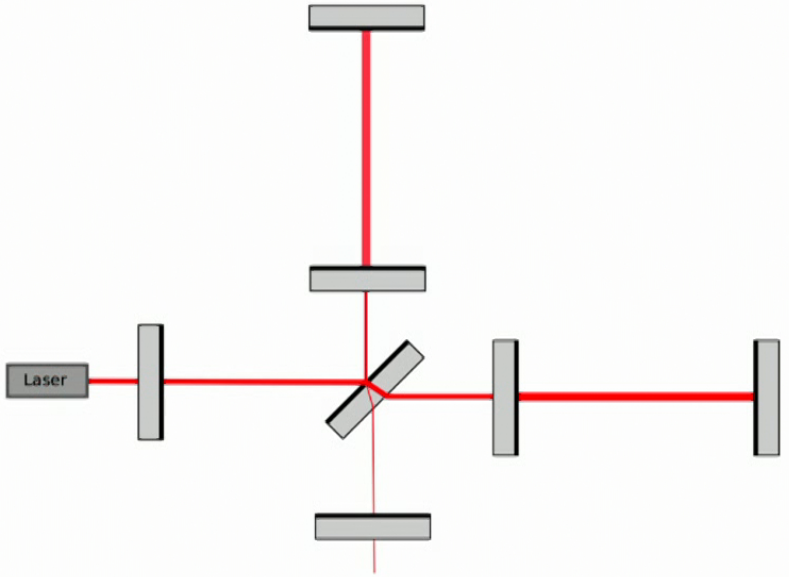
Laser noises: frequency



Laser noises: frequency

$E_0 e^{ikL}$



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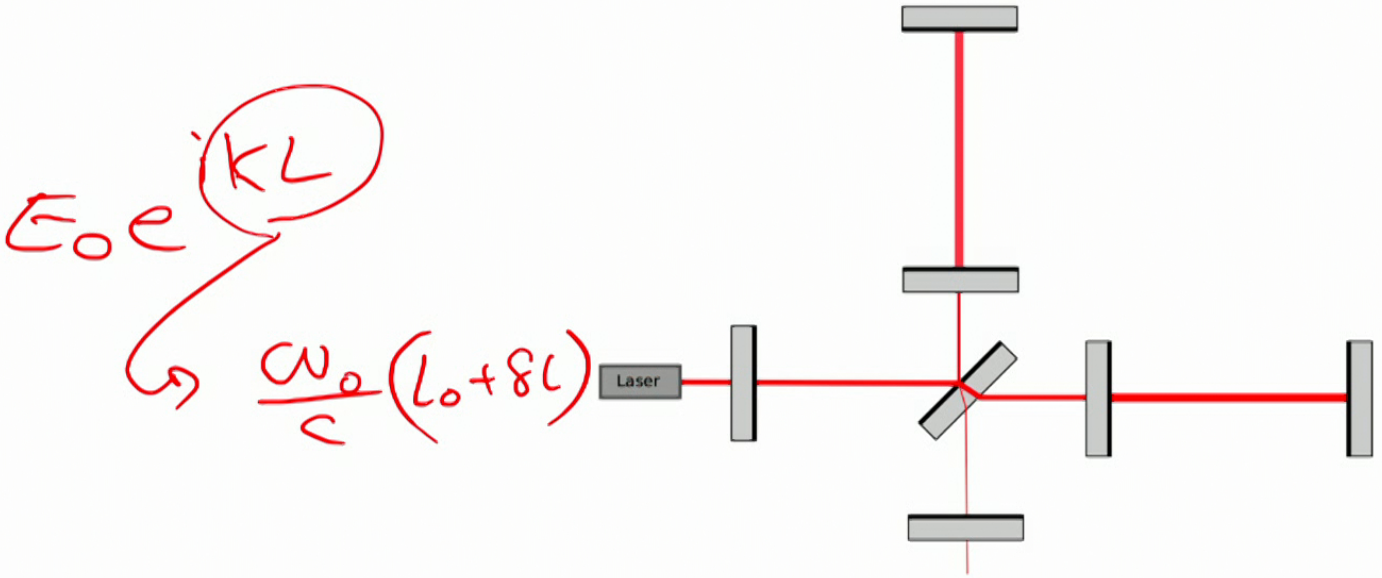

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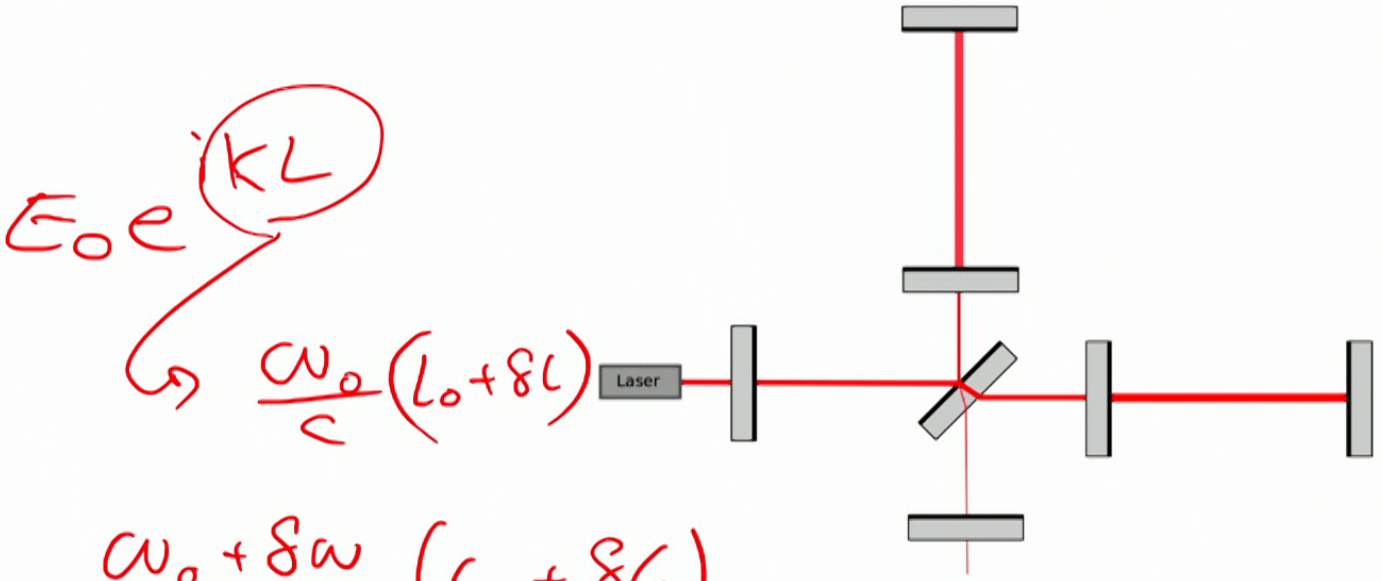

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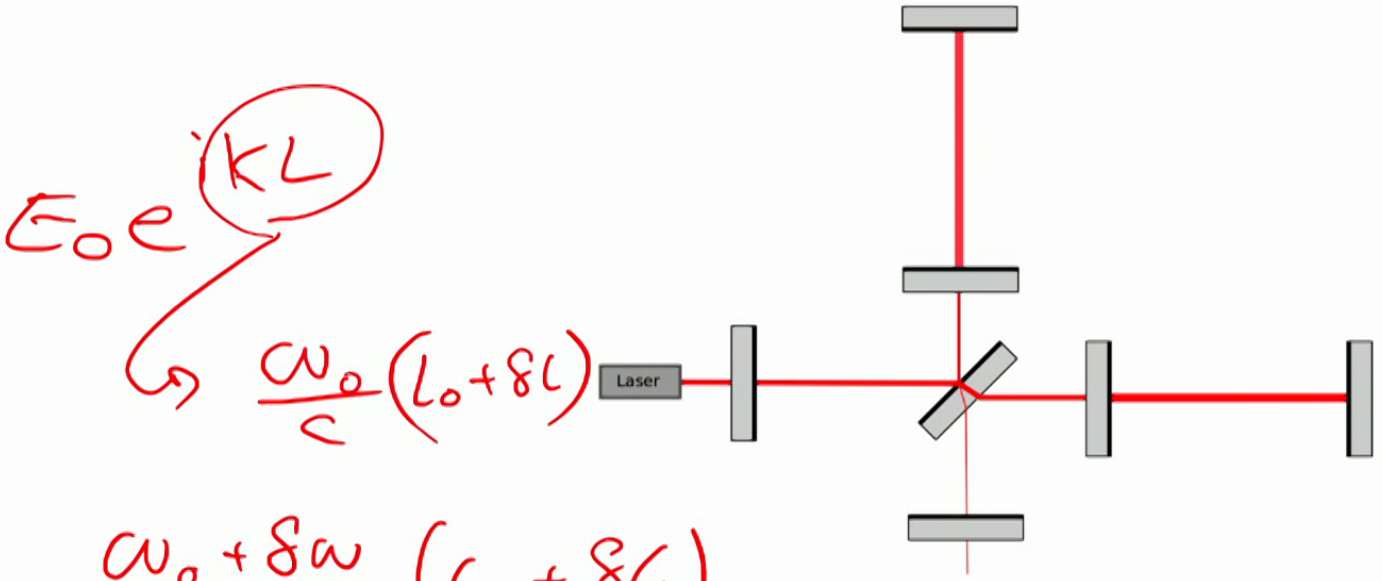


$E_0 e^{ikL}$

$\frac{\omega_0}{c}(L_0+\delta L)$

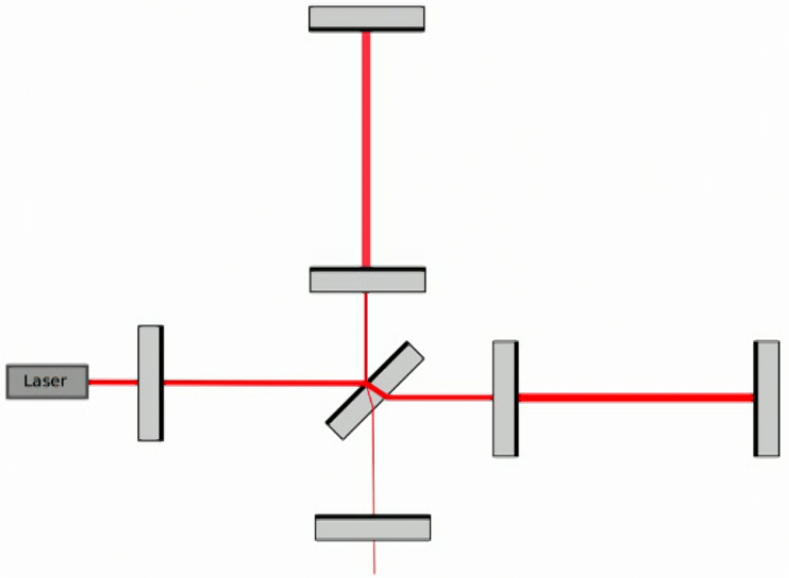
$\frac{\omega_0+\delta\omega}{c}(L_0+\delta L)$

$\frac{\delta\omega L_0}{c}$ $\frac{\omega_0 \delta L}{c}$

Laser noises: frequency

$$E \rightarrow Ee^{ikL} = Ee^{i\frac{\omega L}{c}}$$

$$\frac{\delta L}{L} = \frac{\delta \omega}{\omega}$$



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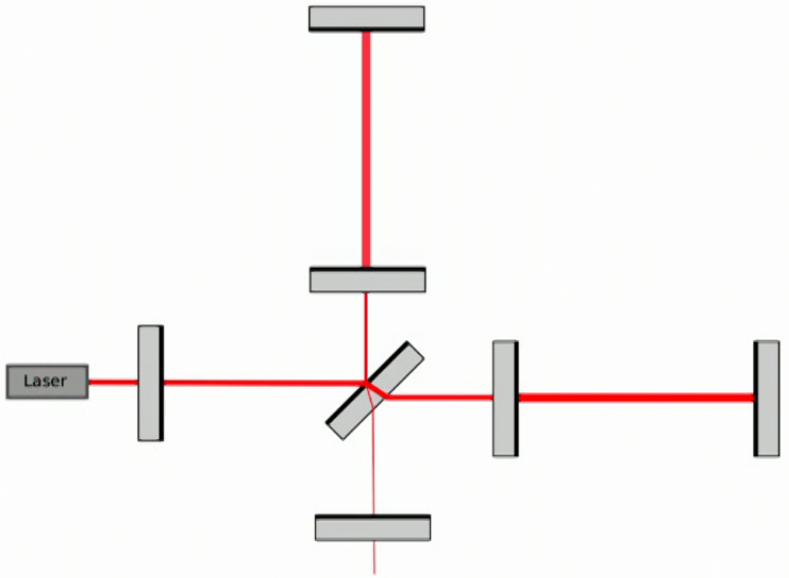
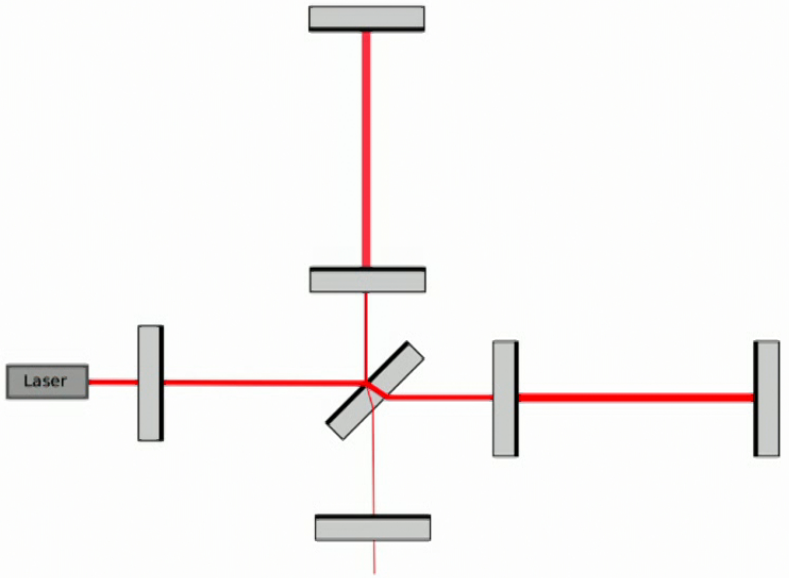


Laser noises: frequency

$$E \to Ee^{ikL} = Ee^{i\frac{\omega L}{c}}$$

$$\frac{\delta L}{L} = \frac{\delta \omega}{\omega_0}$$



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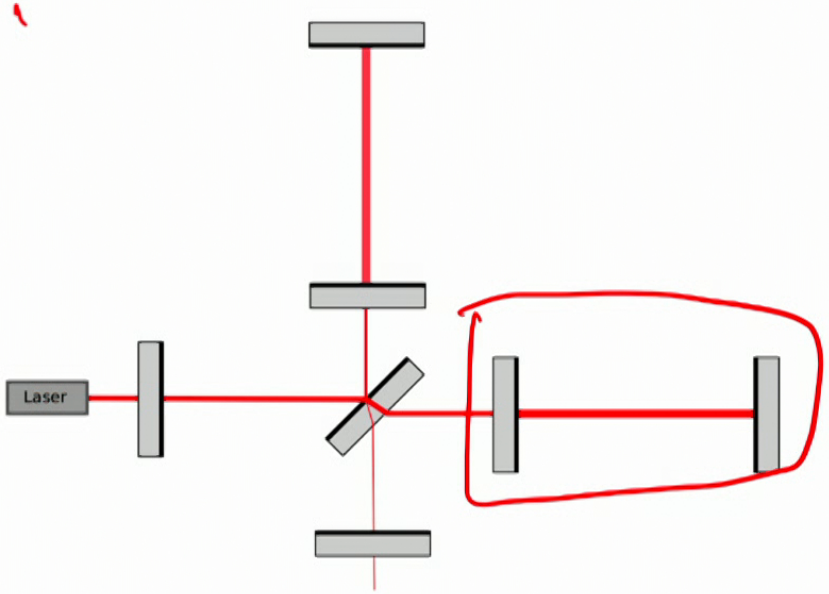

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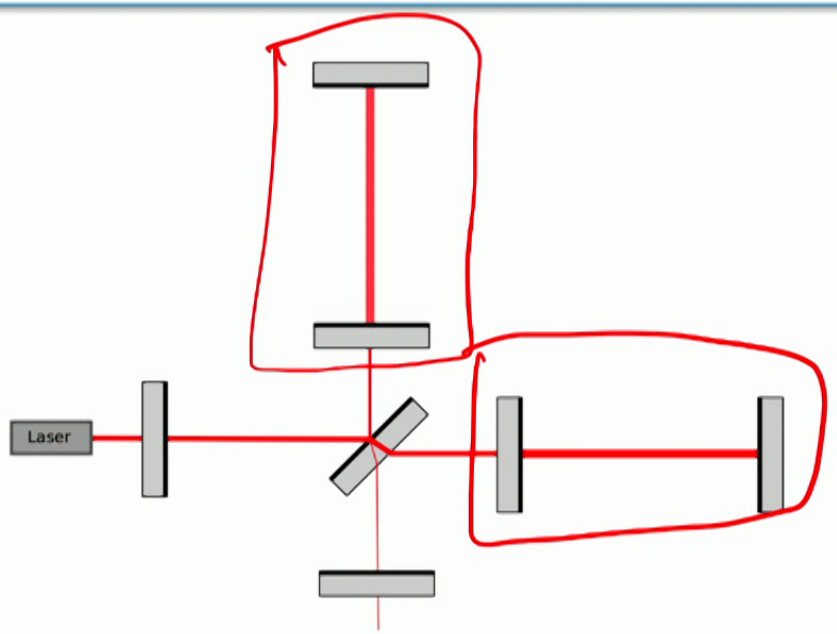
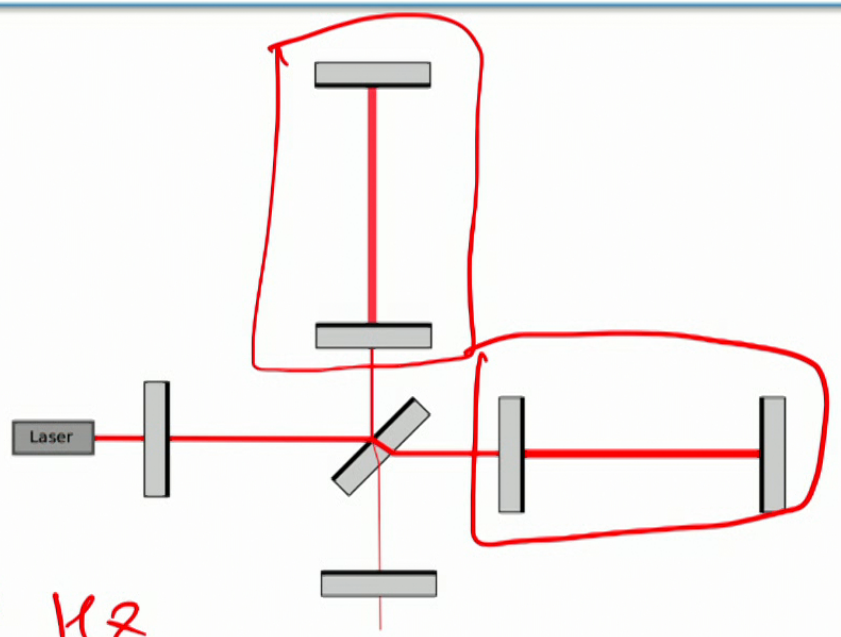


Laser noises: frequency

$$E \to E e^{ikL} = E e^{i\frac{\omega L}{c}}$$

$$\frac{\delta L}{L} = \frac{\delta \omega}{\omega_o}$$



$\delta f \sim 10^{-3}$ Hz

$f_o = 3 \times 10^{14}$ Hz $\quad \lambda = 1\mu m$

~ 10

Laser noises: frequency

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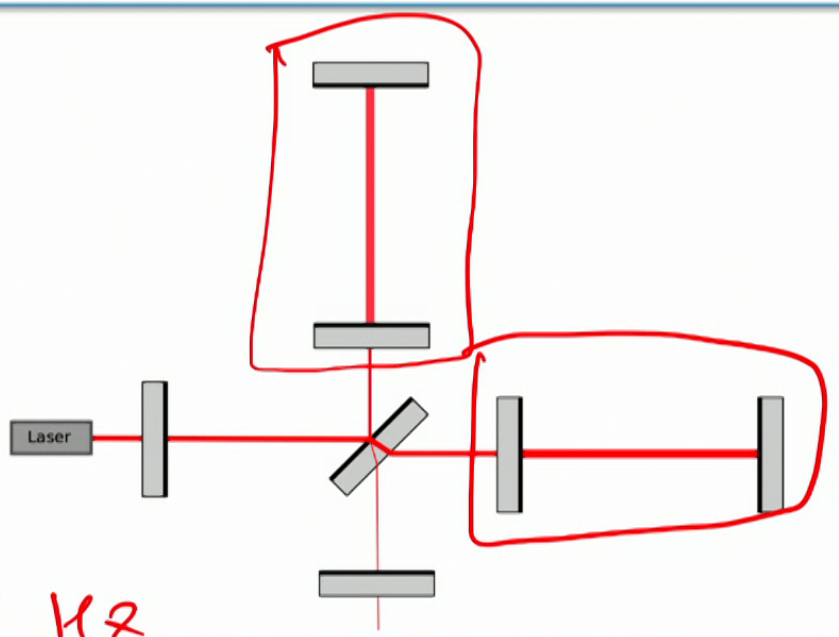
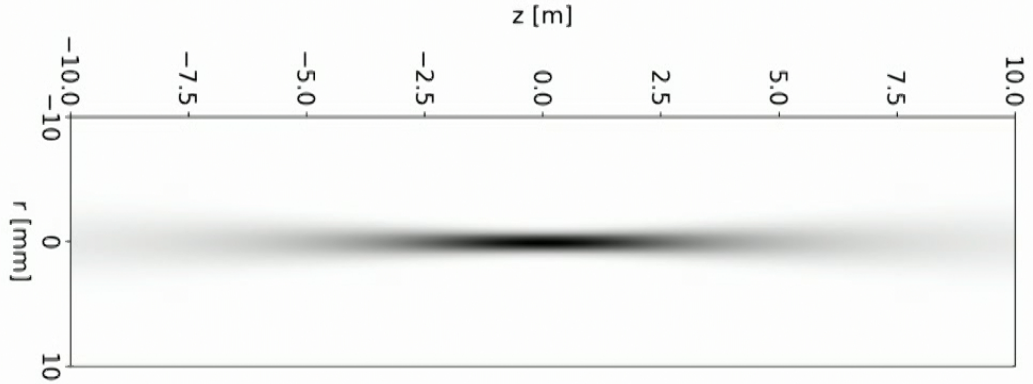


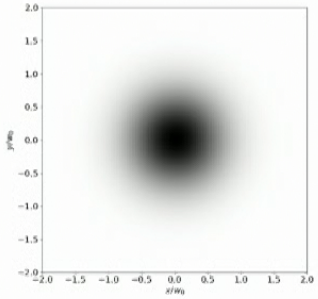
$\delta f \sim 10^{-3}$ Hz

$f_o = 3 \times 10^{14}$ Hz $\quad \lambda = 1\mu m$

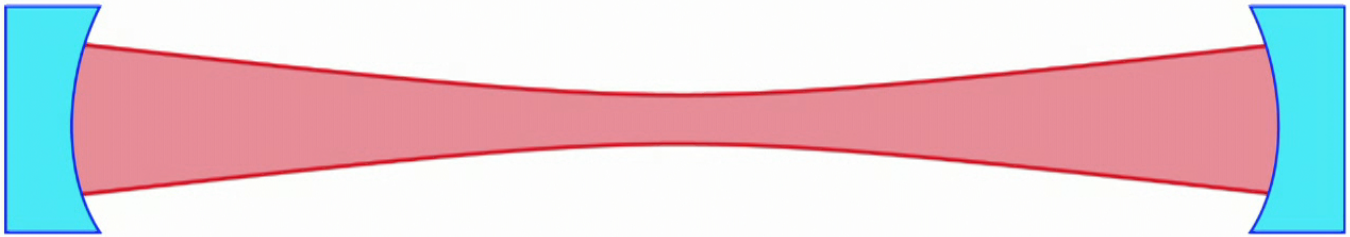
$\sim 10^{-17}$

Laser noises: jitter





- Change in pointing direction and size of the laser beam



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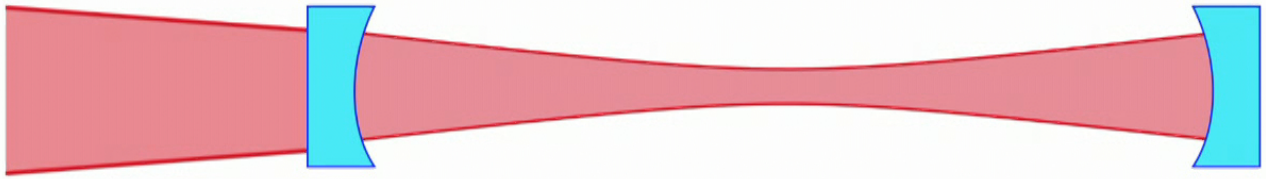

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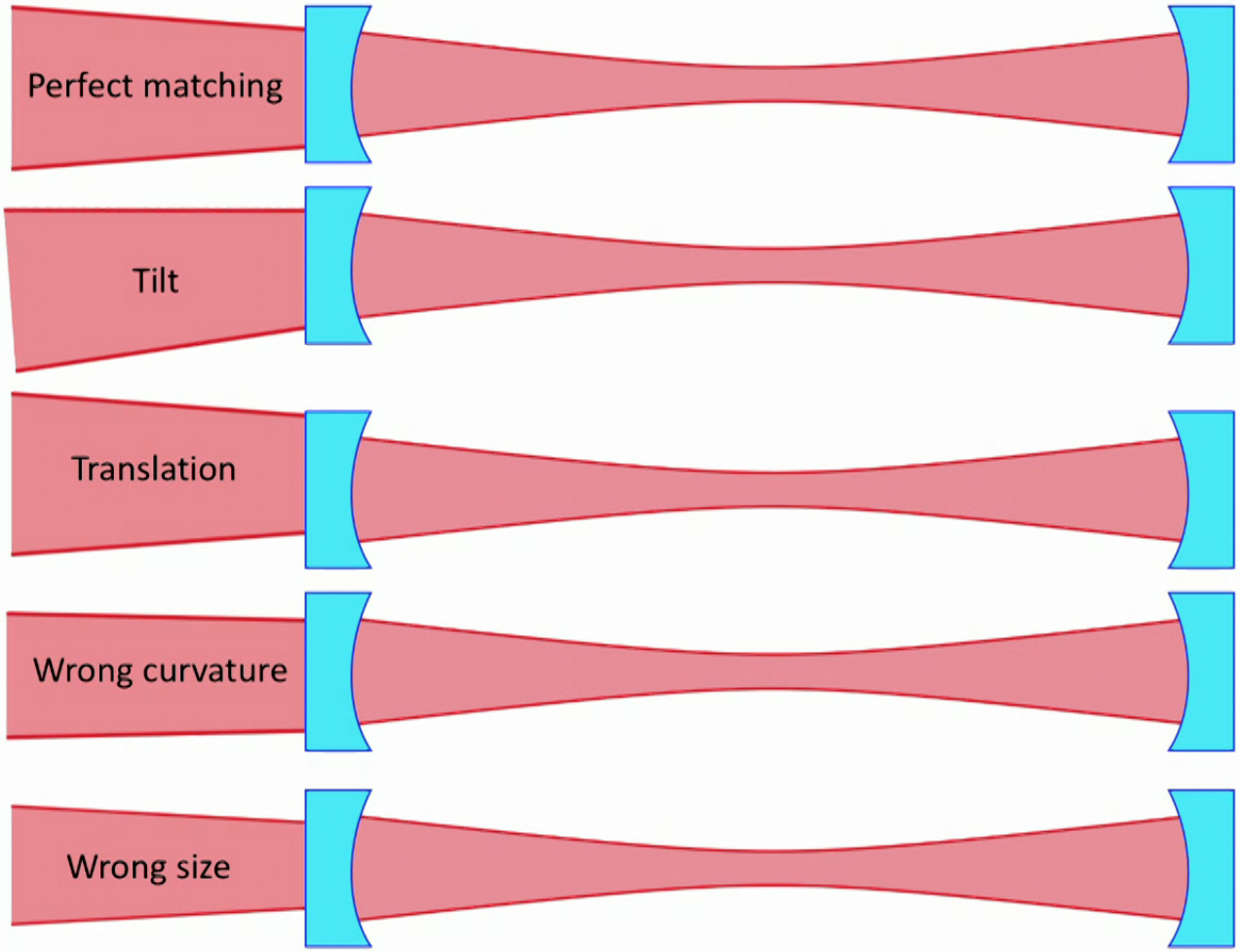
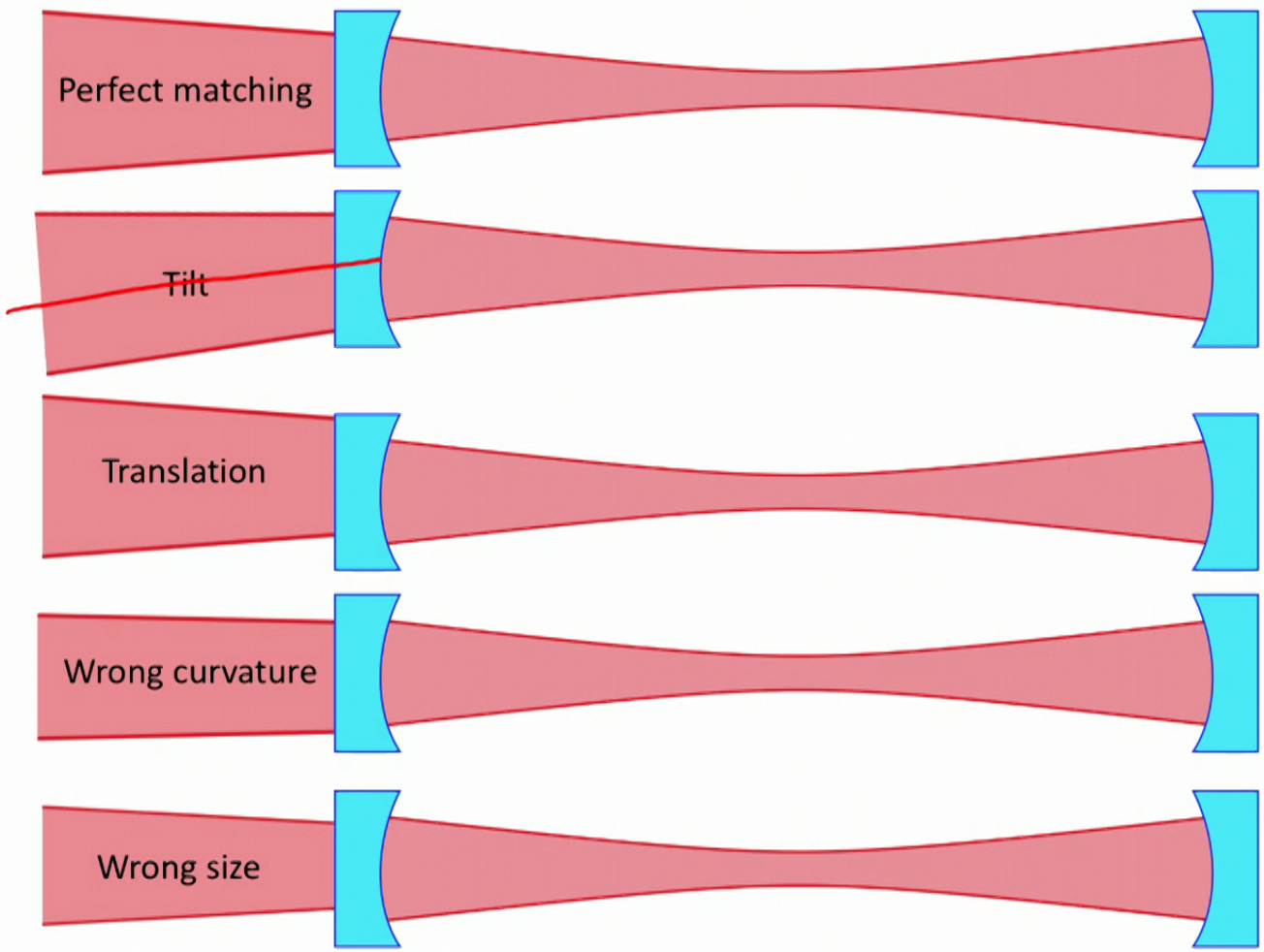

Perfect matching
Tilt
Translation
Wrong curvature
Wrong size

LIGO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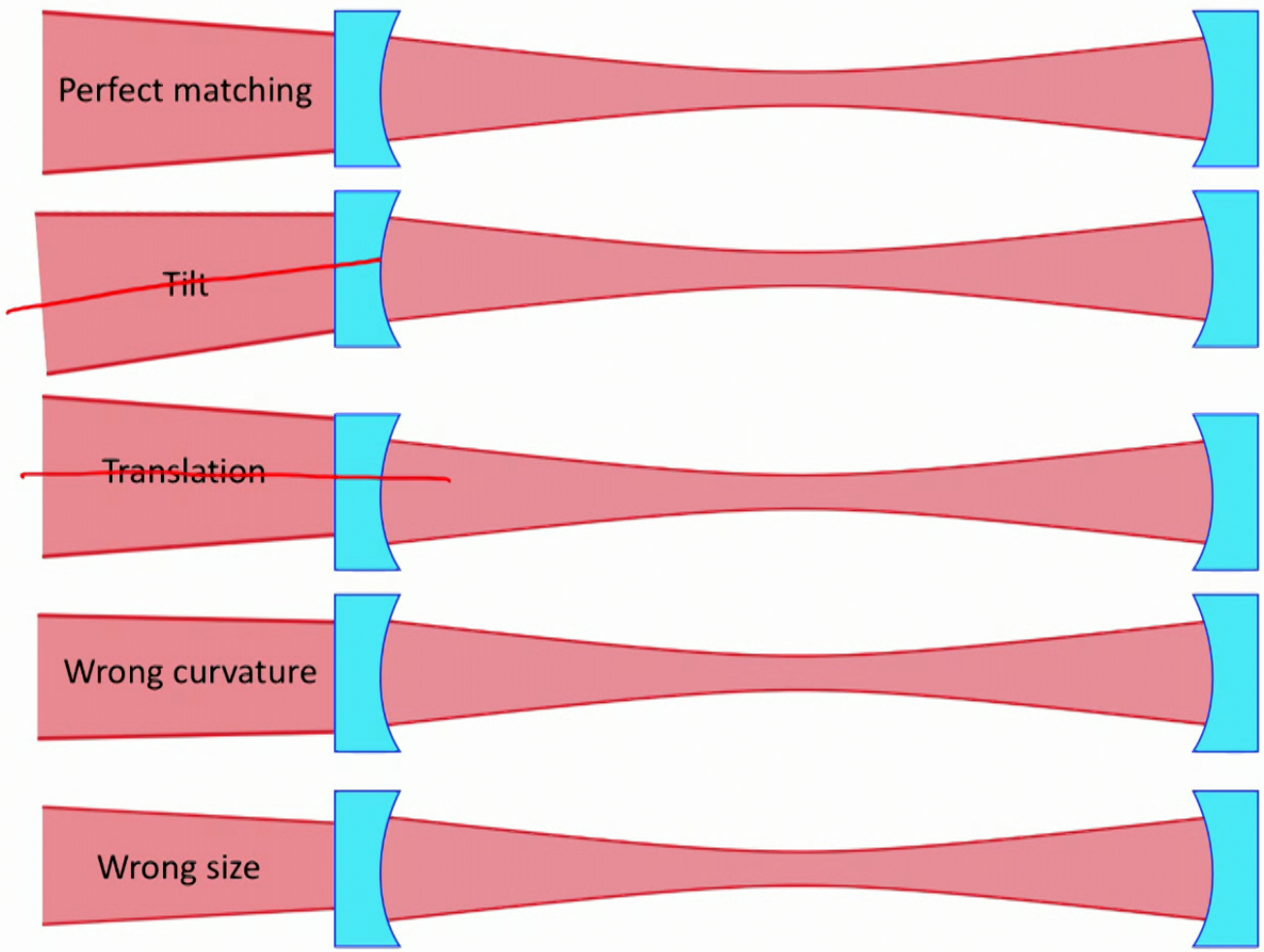
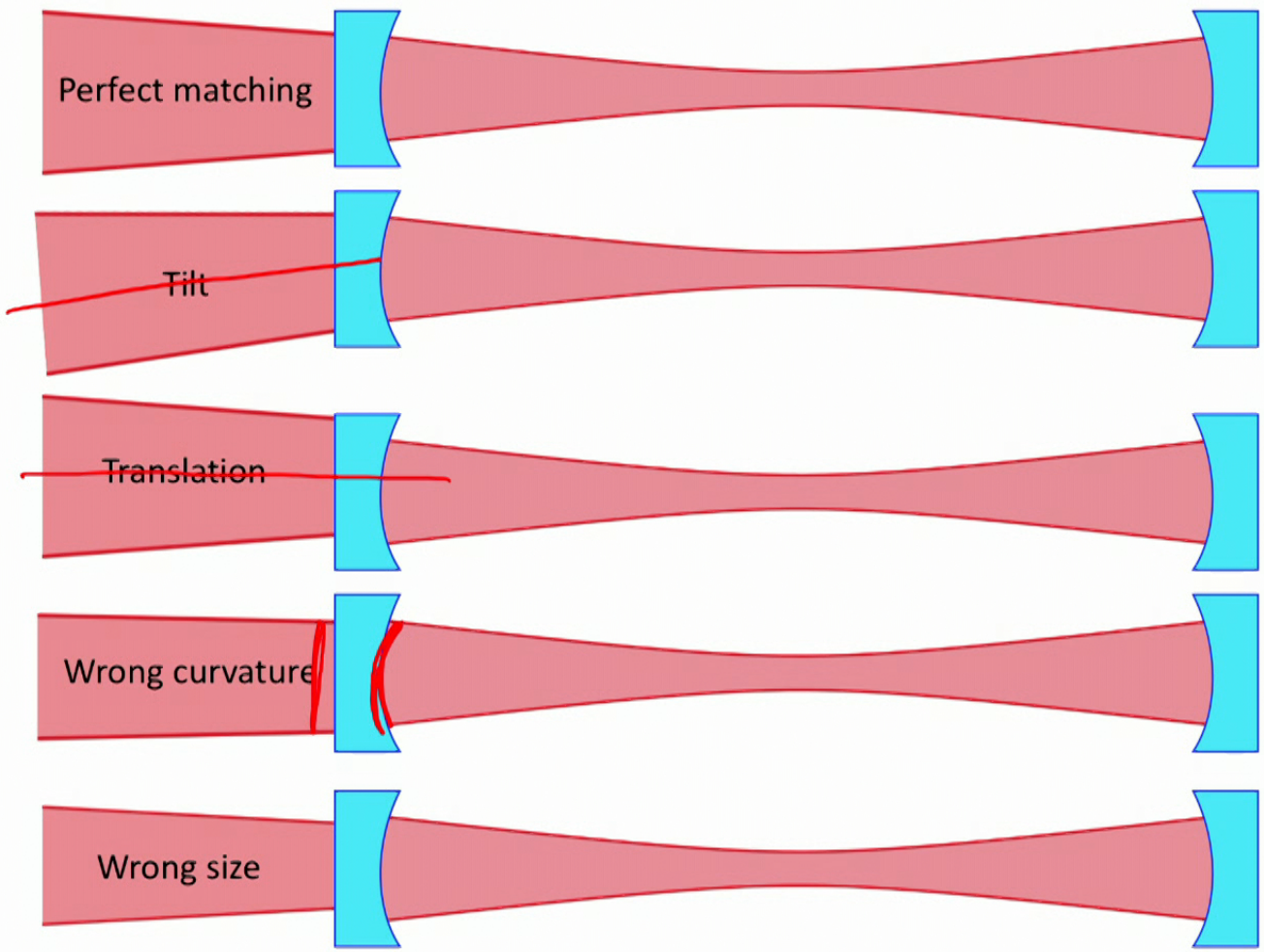
Wrong size

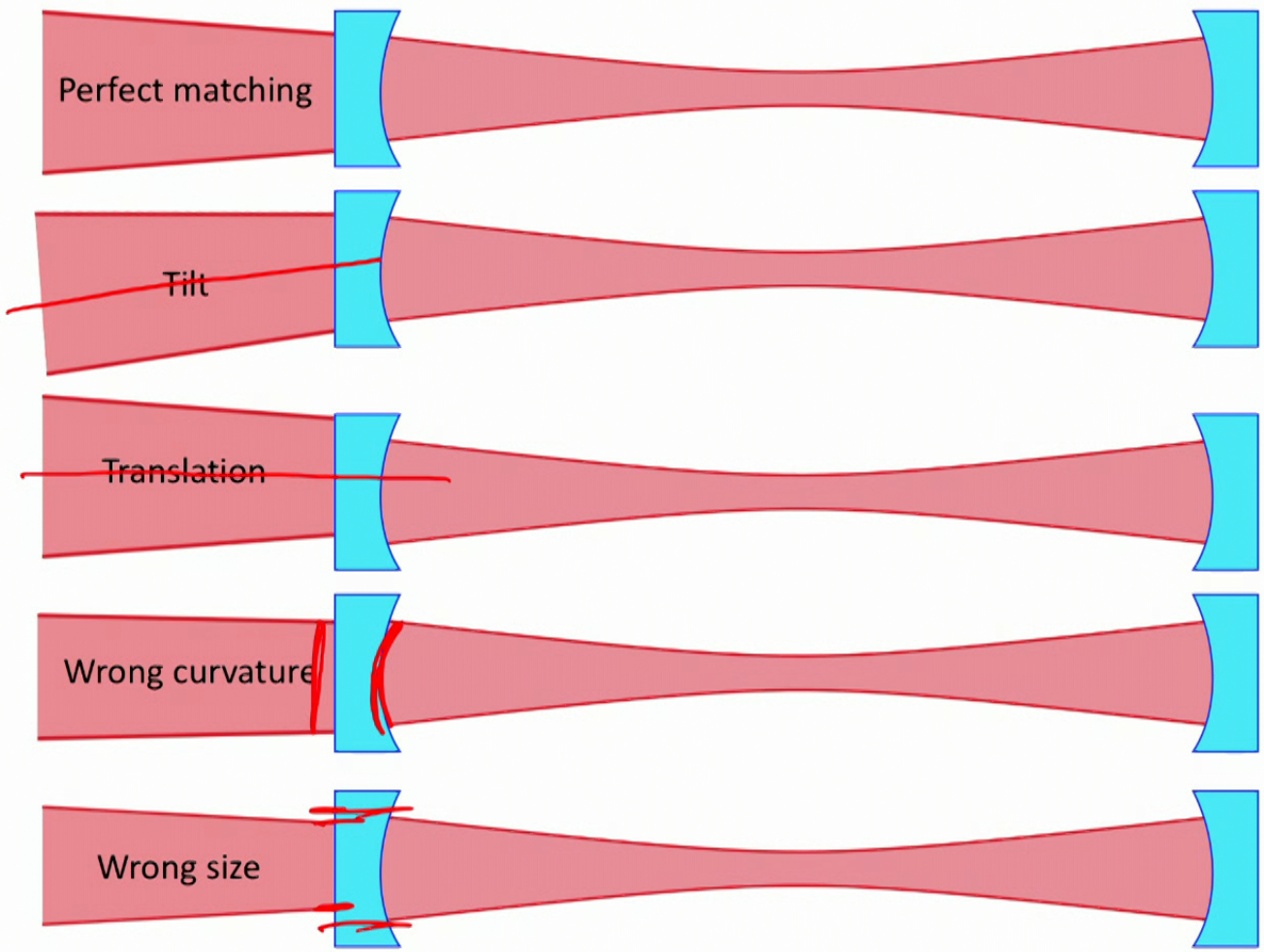
LIGO


Perfect matching
Tilt
Translation
Wrong curvature
Wrong size

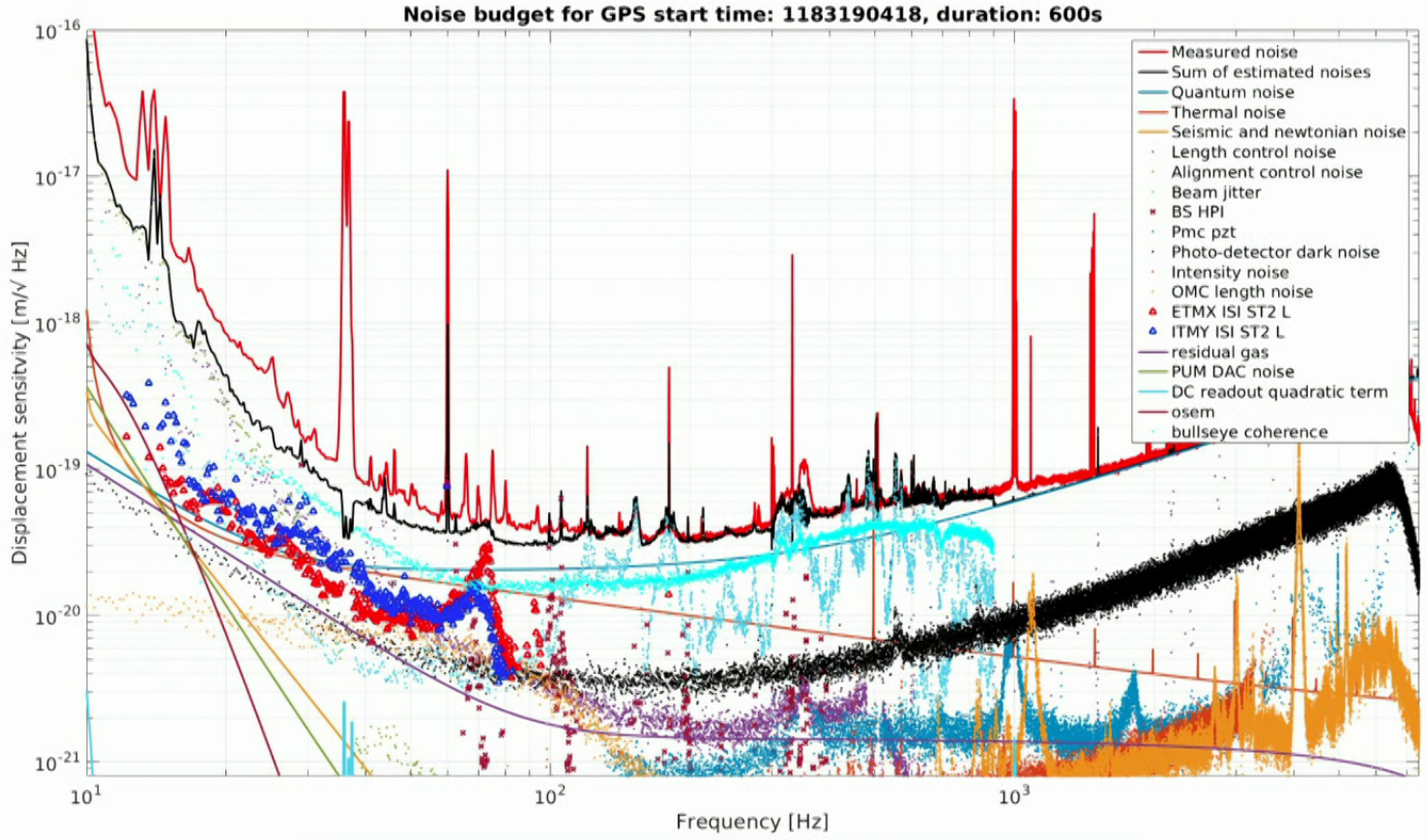
LIGO


Perfect matching
Tilt
Translation
Wrong curvature
Wrong size

LIGO


Perfect matching
Tilt
Translation
Wrong curvature
Wrong size

LIGO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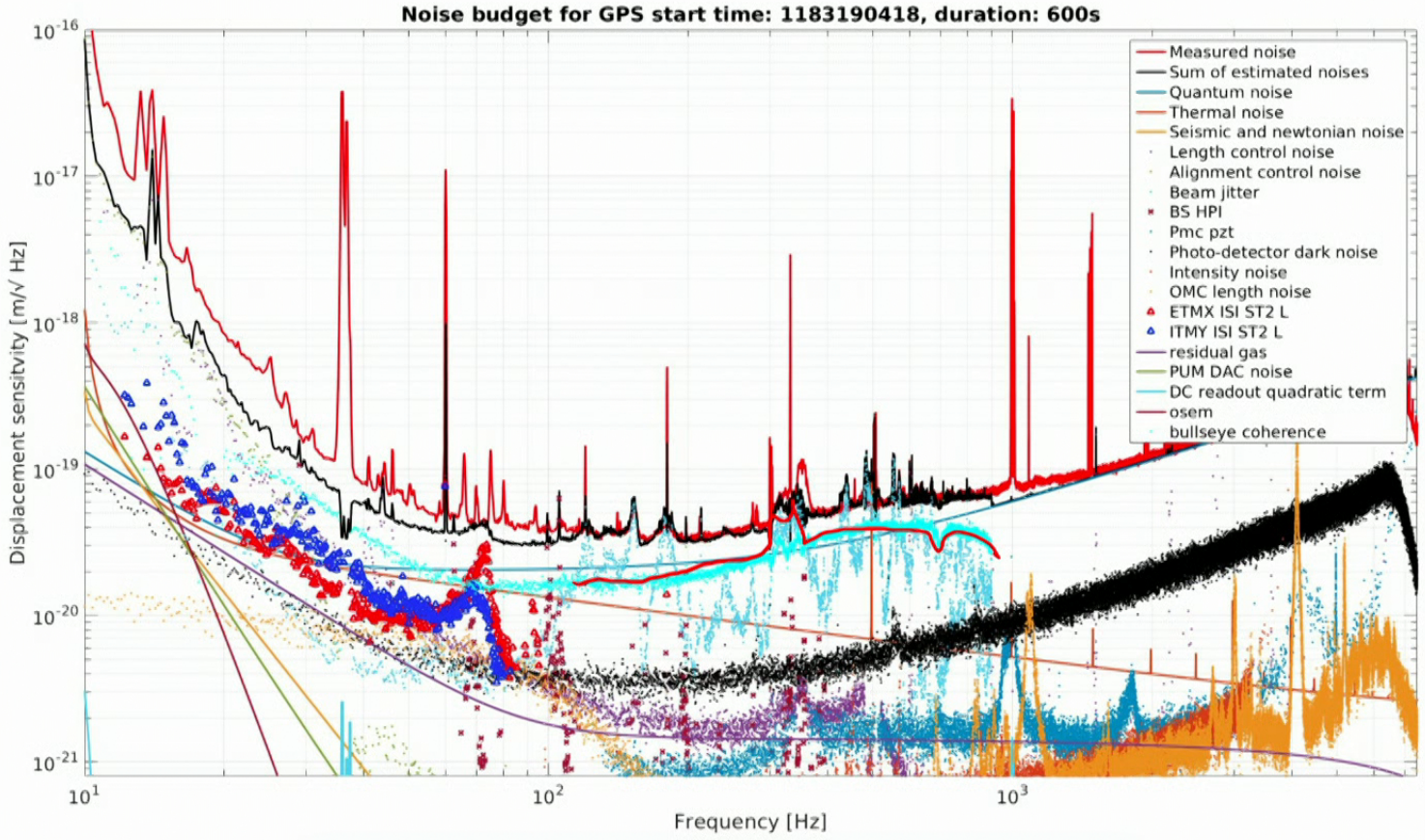
Displacement sensitvity [m/√ Hz]
Frequency [Hz]
Measured noise
Sum of estimated noises
Quantum noise
Thermal noise
Seismic and newtonian noise
Length control noise
Alignment control noise
Beam jitter
BS HPI
Pmc pzt
Photo-detector dark noise
Intensity noise
OMC length noise
ETMX ISI ST2 L
ITMY ISI ST2 L
residual gas
PUM DAC noise
DC readout quadratic term
osem
bullseye coherence

LIGO


Noise budget for GPS start time: 1183190418, duration: 600s
Displacement sensitvity [m/√ Hz]
Frequency [Hz]
Measured noise
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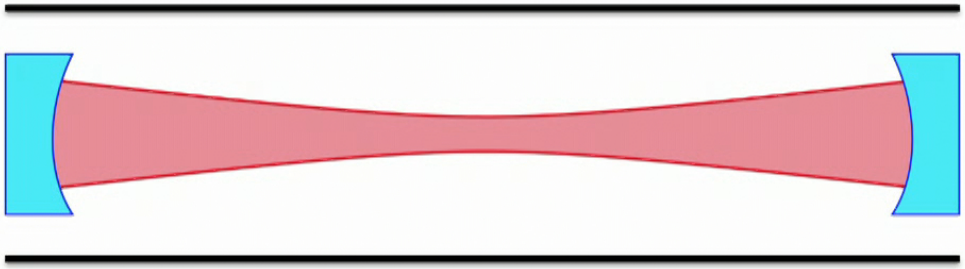
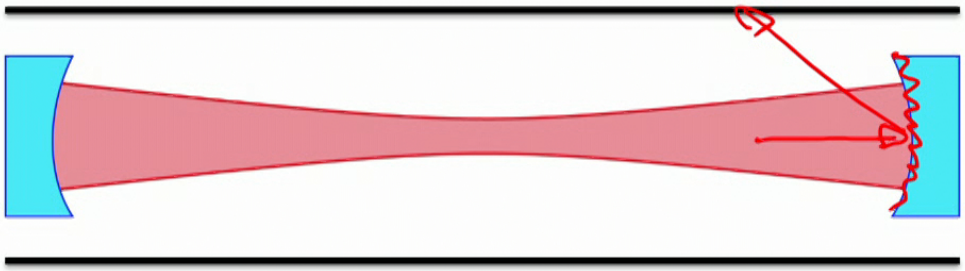
OMC length noise
ETMX ISI ST2 L
ITMY ISI ST2 L
residual gas
PUM DAC noise
DC readout quadratic term
osem
bullseye coherence

Scattered light

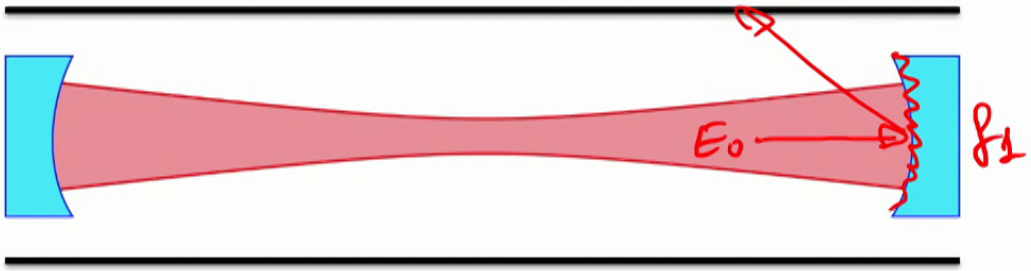


LIGO

Scattered light

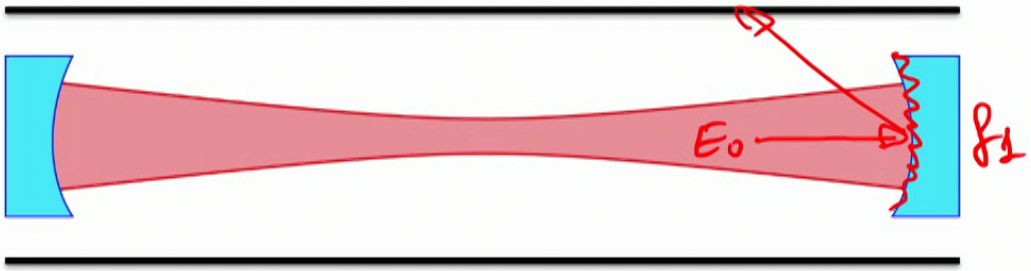


Scattered light



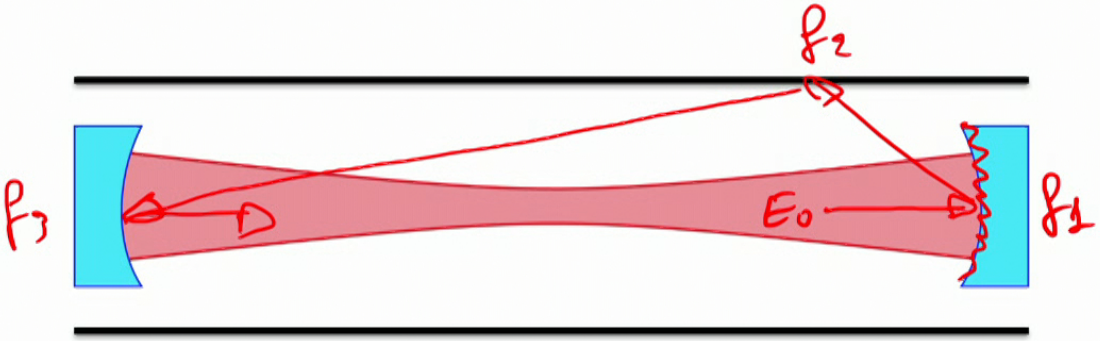
δ

Scattered light



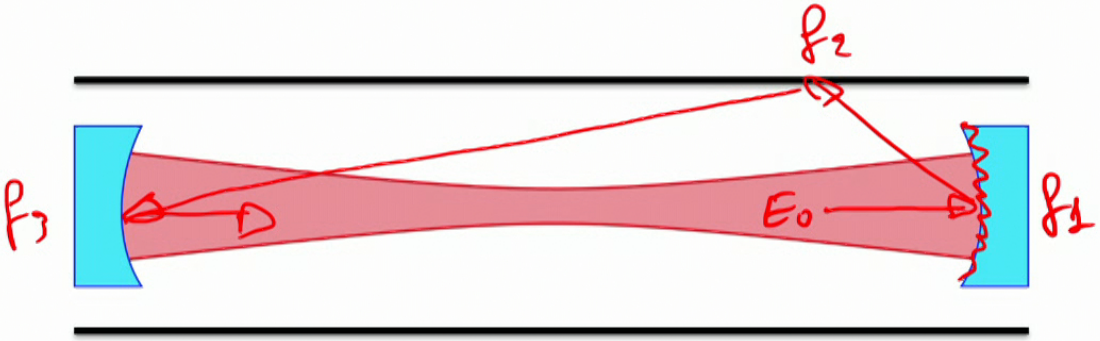
$\rho_1 E_0$

Scattered light



$f_1 E_0 \times f_2 \times f_3$

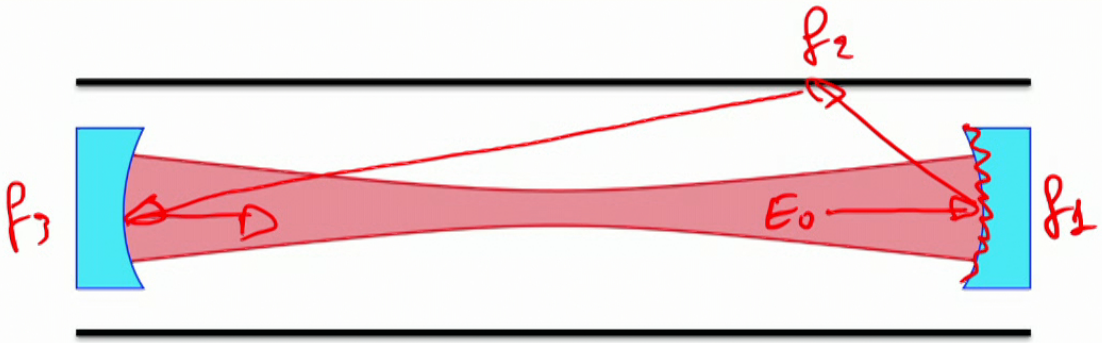
Scattered light



$\beta_1 E_0 \times \beta_2 \times \beta_3$

$E_0 + \beta_{sc} E_0$

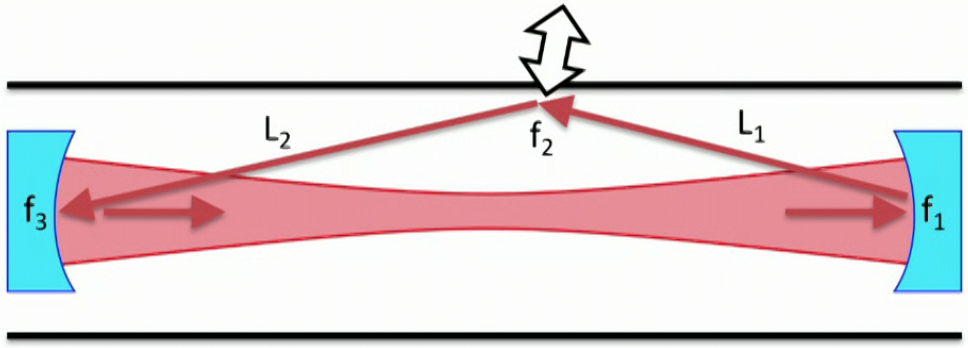
Scattered light



$$\rho_1 E_0 \times \rho_2 \times \rho_3$$

$$E_0 + \rho_{sc} E_0 \, e^{i\phi(t)}$$

Scattered light



$$f_1 E_0 \times e^{ikL_1} \times f_2 \times e^{ikL_2} \times f_3 \times e^{ikL} = (f_1 f_2 f_3)\, e^{ik(L_1+L_2+L_3)}$$

$$E_0 \rightarrow E_0 + \delta E = E_0 \left[1 + f_{sc} e^{ikz_{sc}}\right]$$

$$E' = E_0 \left[1 + f_{sc} \cos kz_{sc} + i f_{sc} \cos kz_{sc}\right]$$

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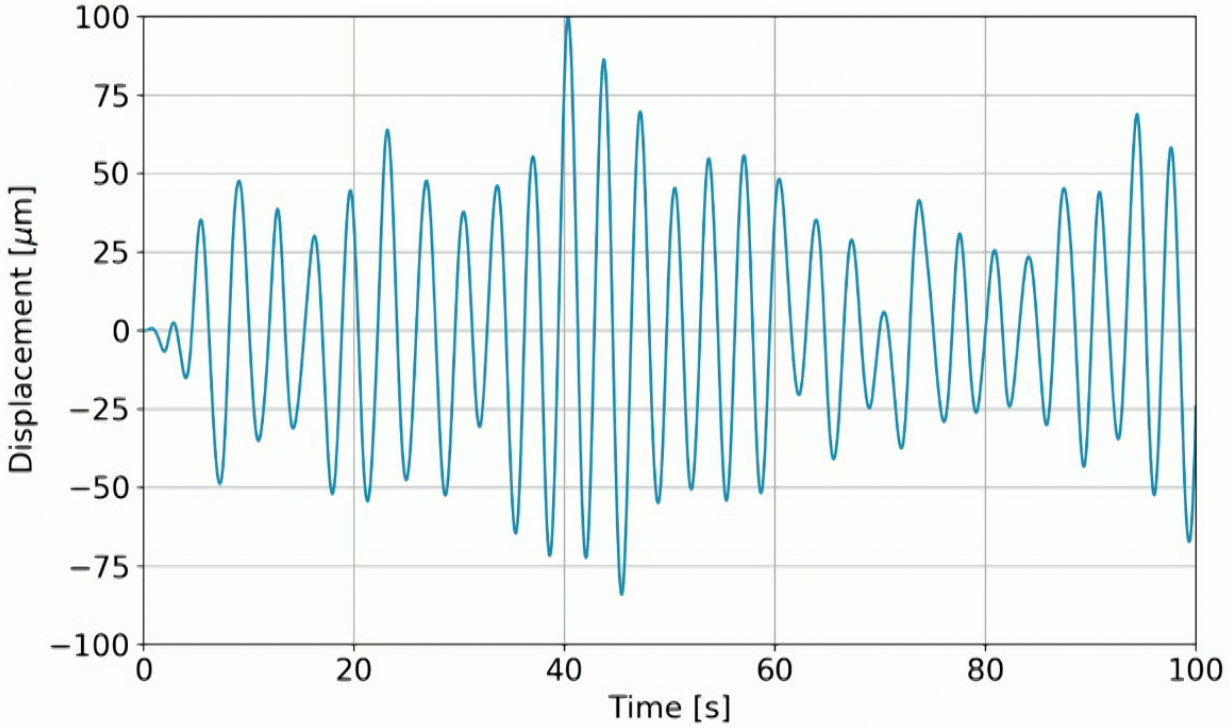
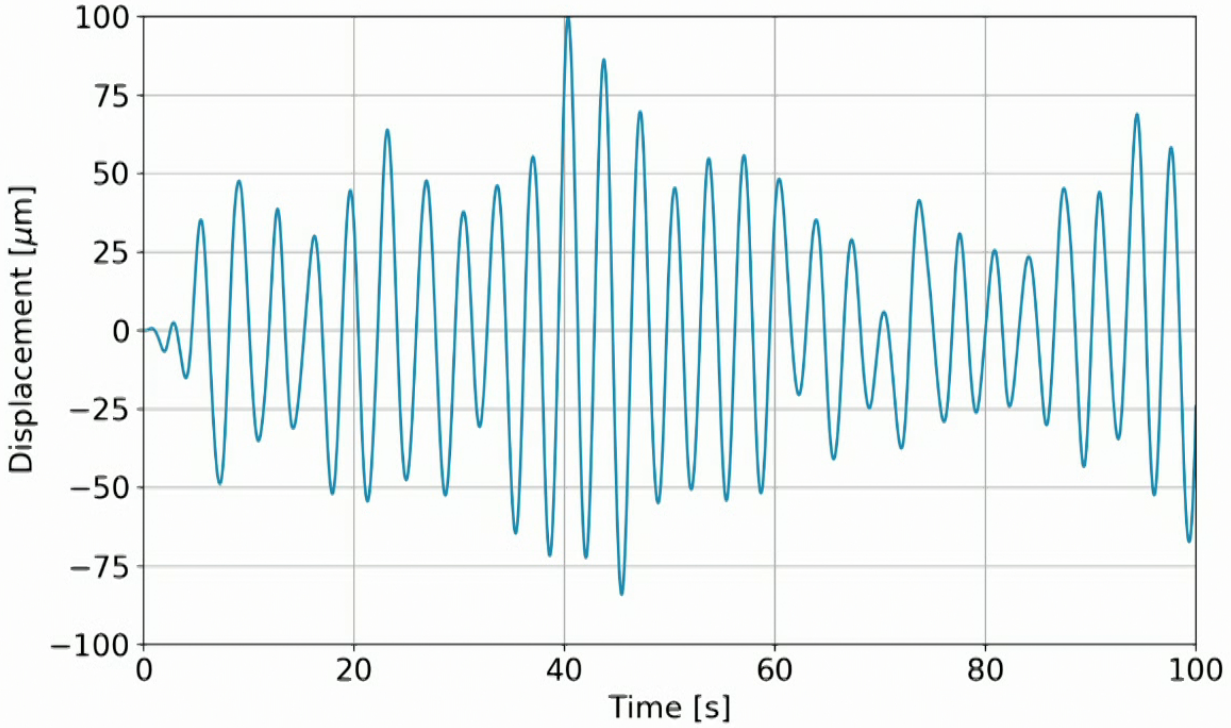
Scattered light



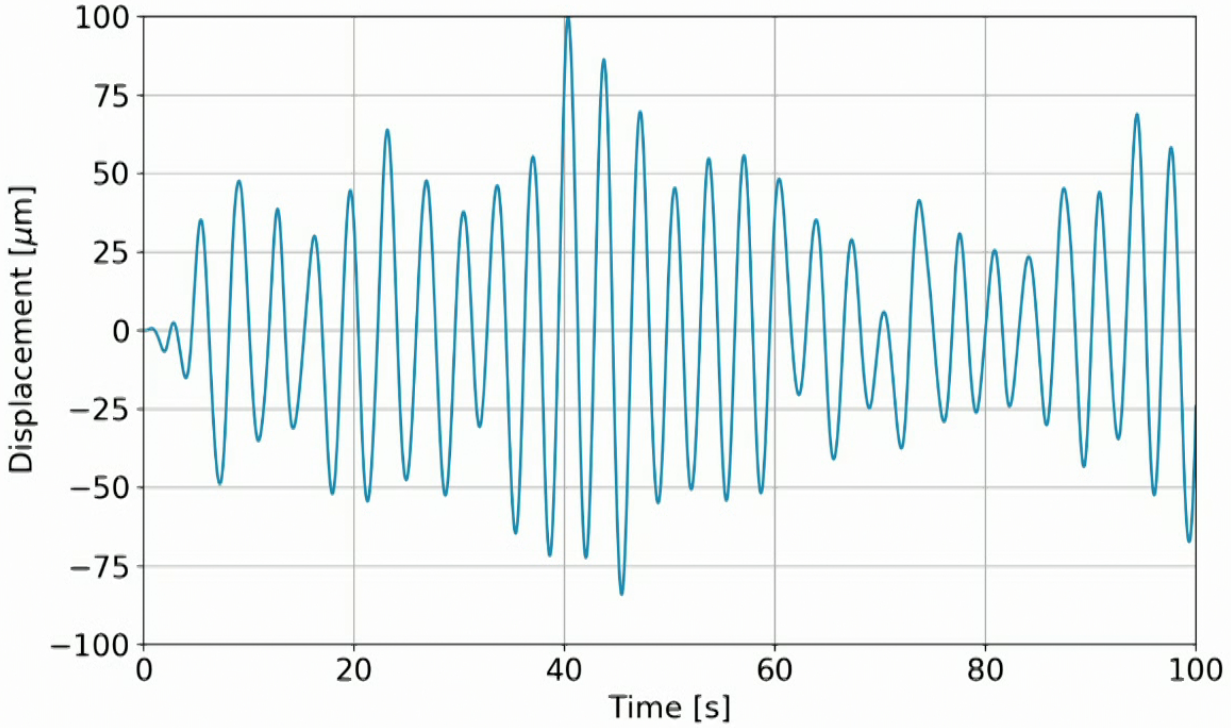
Scattered light

sin kz



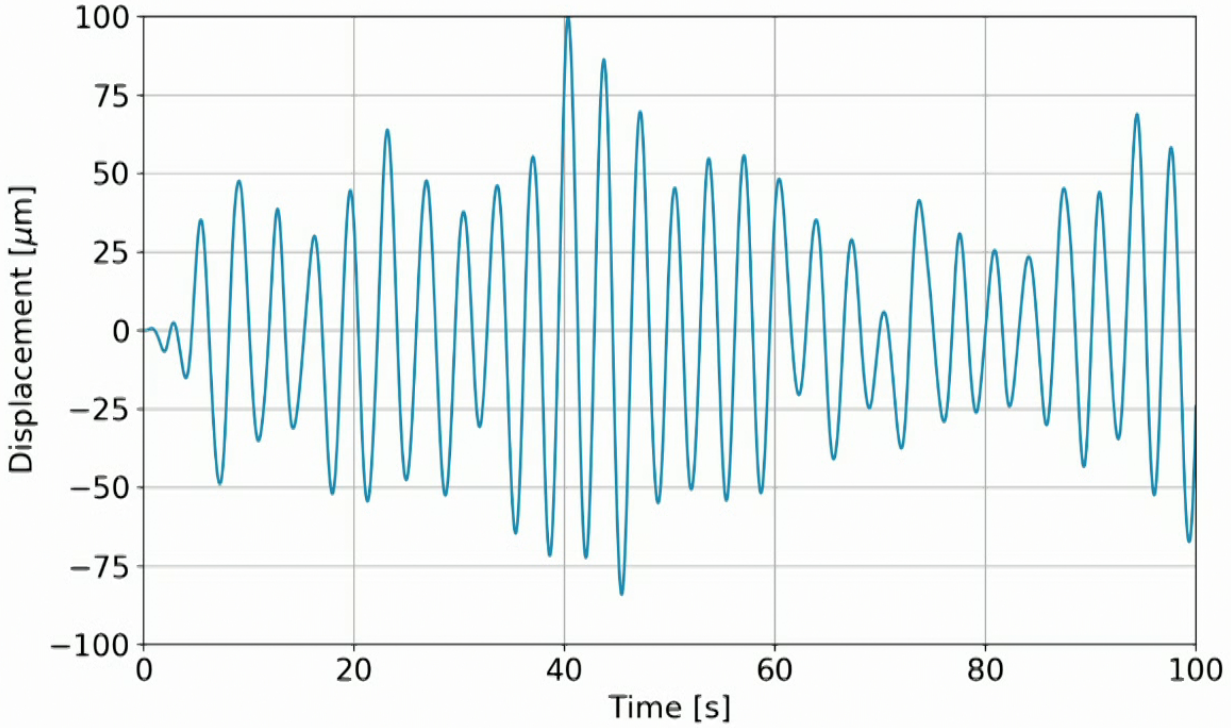
Scattered light

$\sin kz = \sin \frac{2\pi}{\lambda} z$

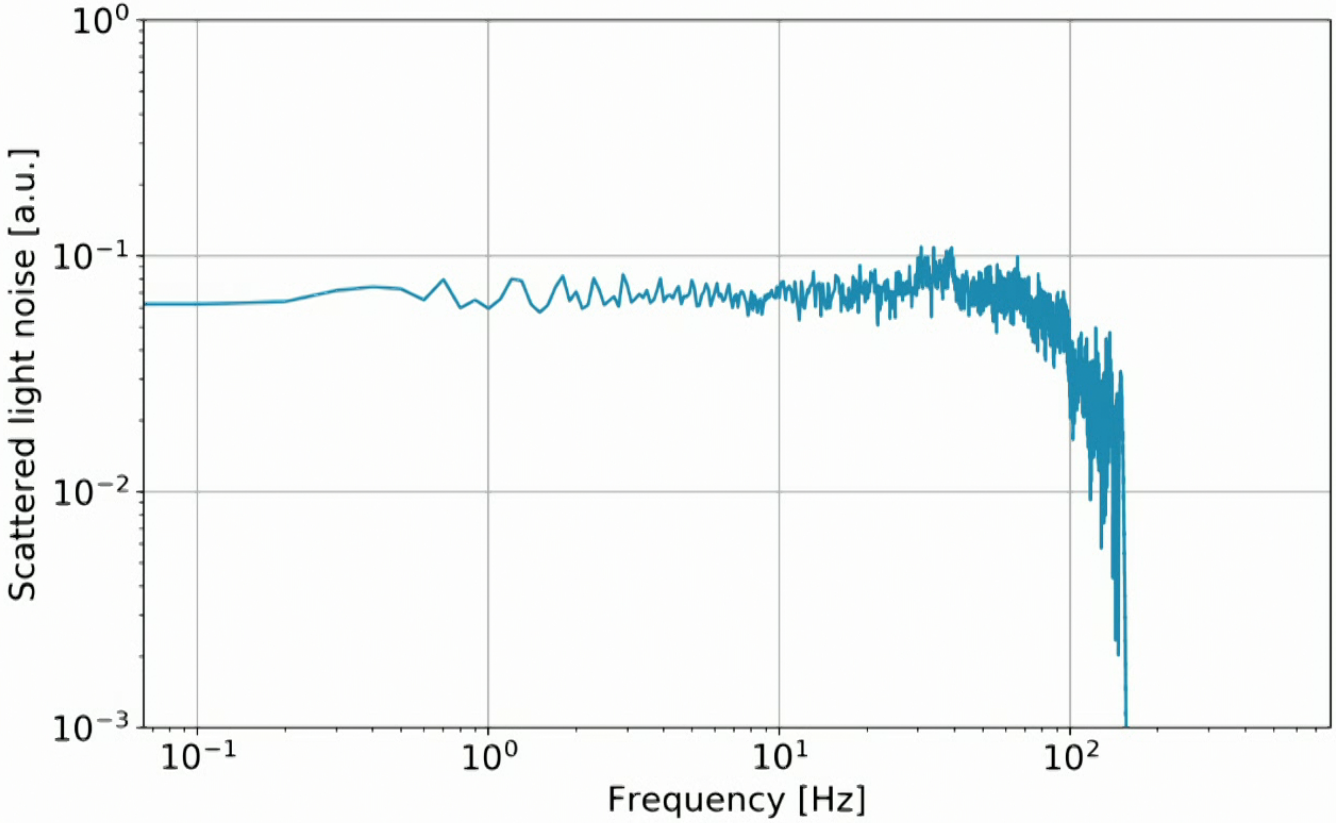


Scattered light

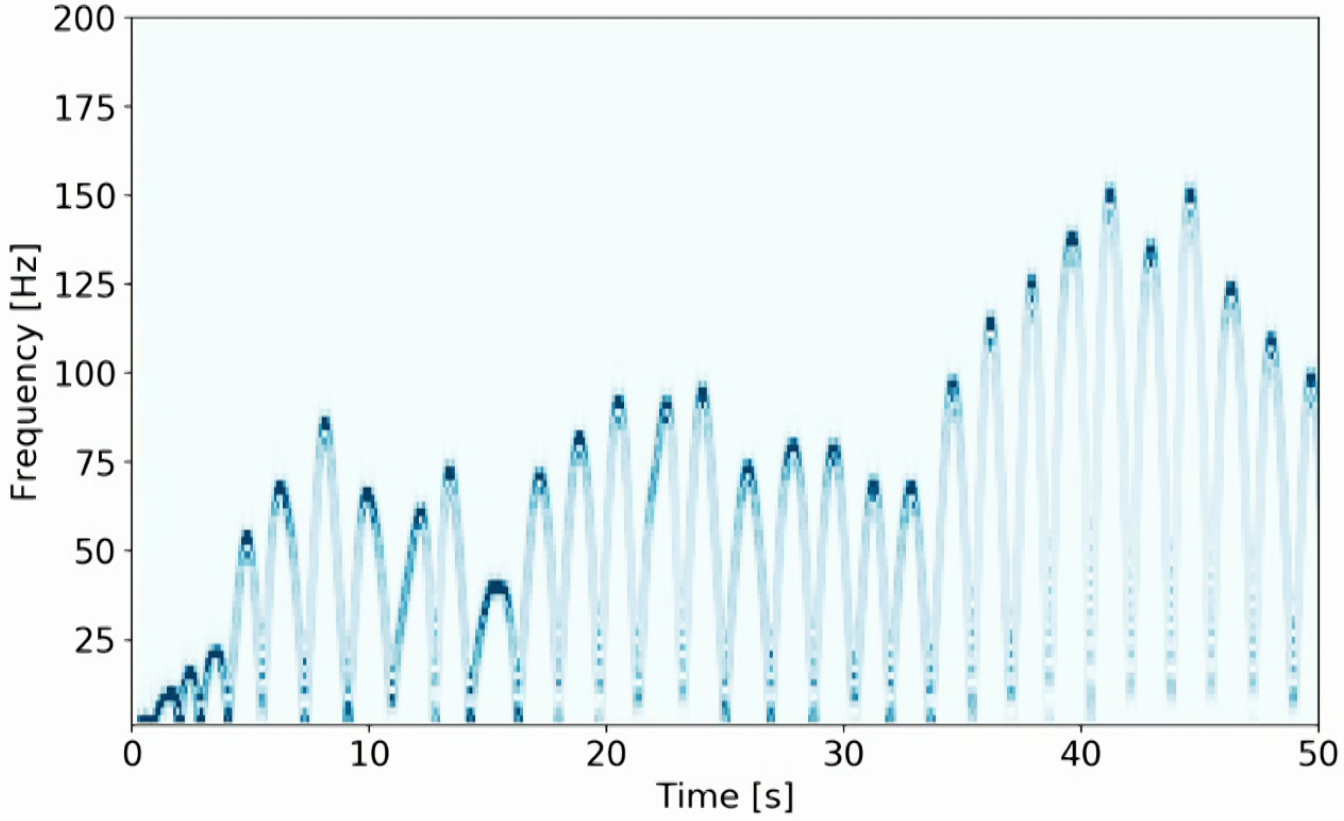
$\sin kz = \sin\left(\frac{2\pi}{\lambda} z\right)$



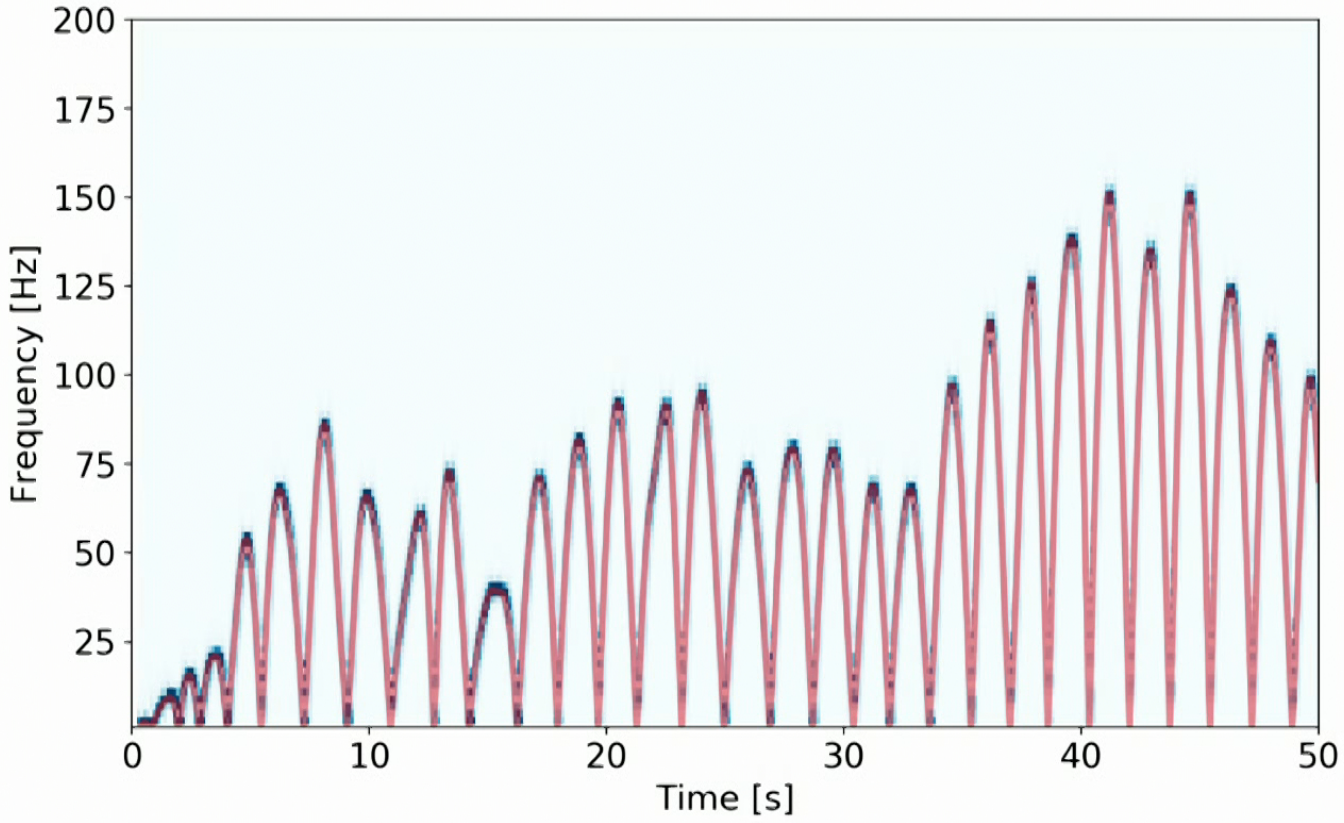
Scattered light



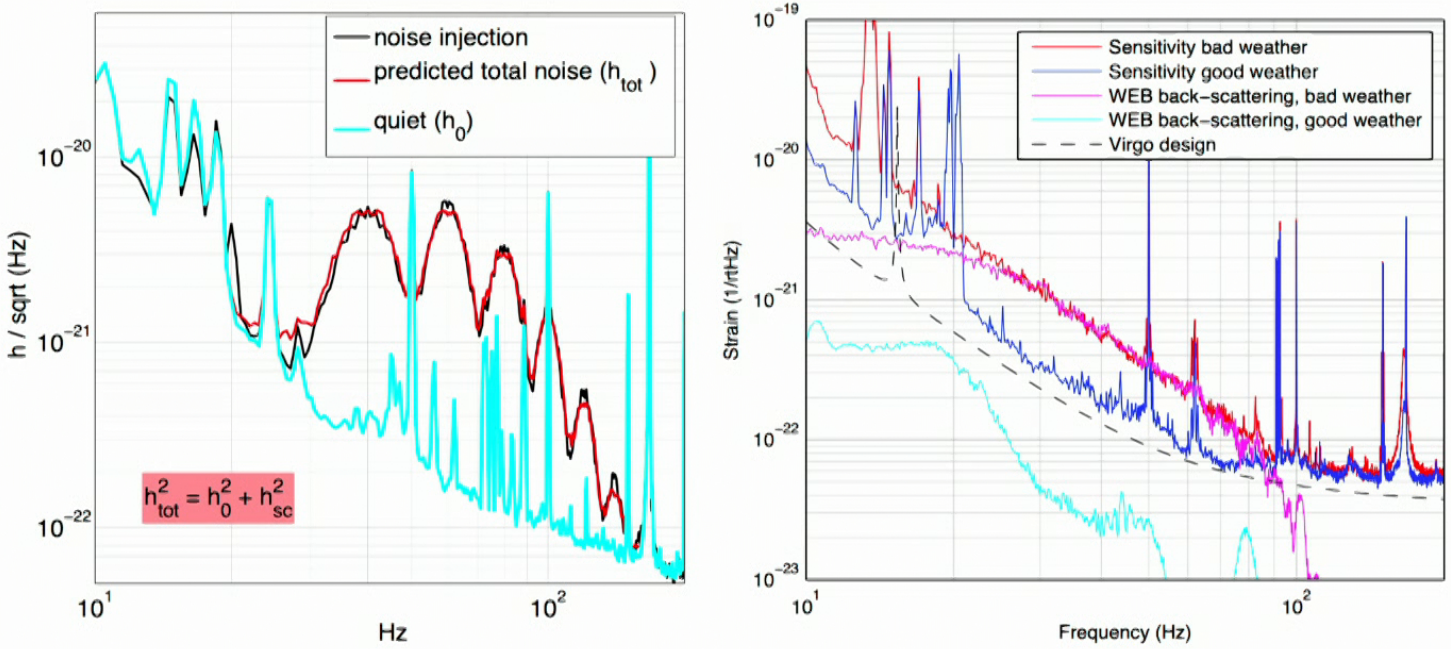
Scattered light



Scattered light



Examples from 1st generation detectors



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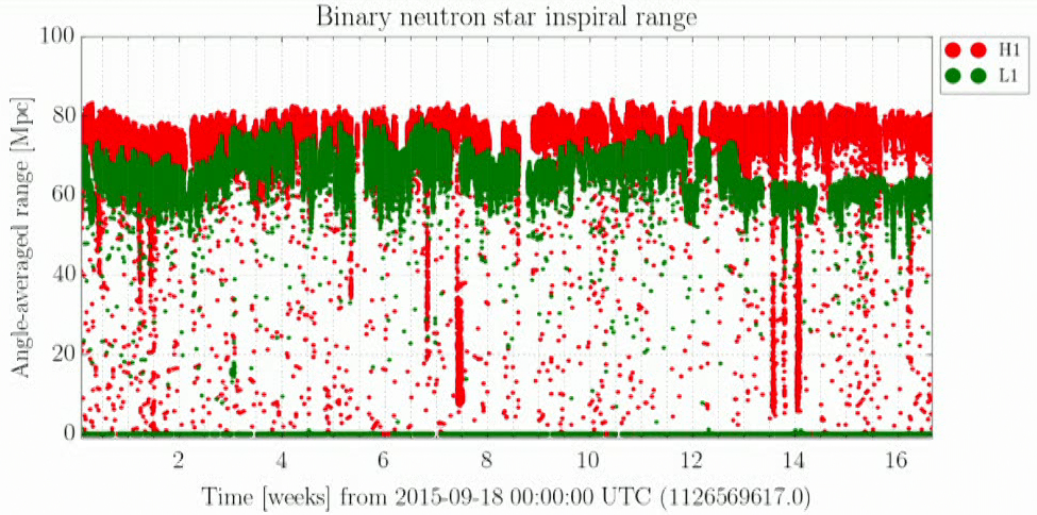
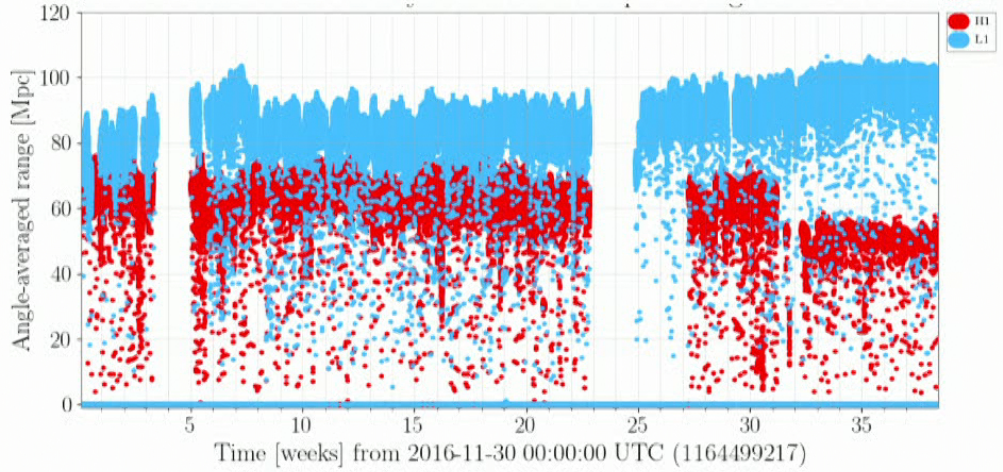
CURRENT STATUS

Observation runs: O1 and O2

O1: 2015-2016



O2: 2016-2017

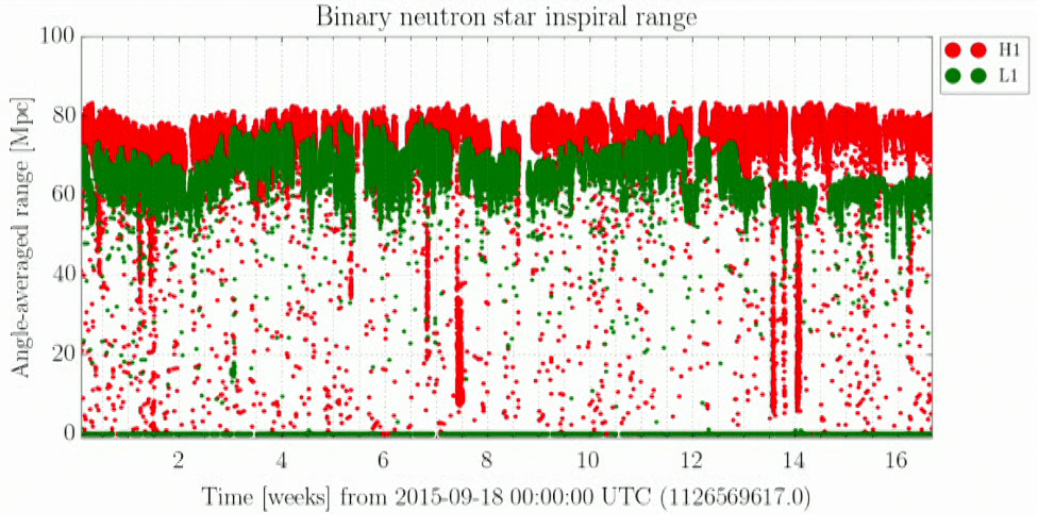


Going into O3

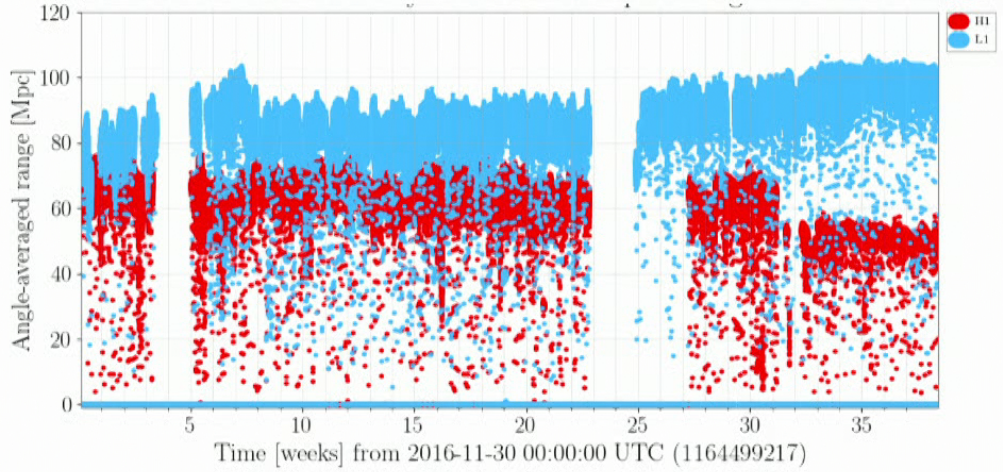
- Many improvements:
  - **New test mass mirrors**: to reduce scattering of light and simplify control
  - **Annular** reaction masses: to reduce gas damping
  - New laser: lower shot noise with **more power**
  - Frequency independent **squeezing**: lower shot noise without more power
  - **Baffles** to catch and damp spurious beams, to reduce scattered light noise
- Fine tuning of control system and noise studies will follow
- Stay tuned for next year's observing run O3

Observation runs: O1 and O2

O1: 2015-2016

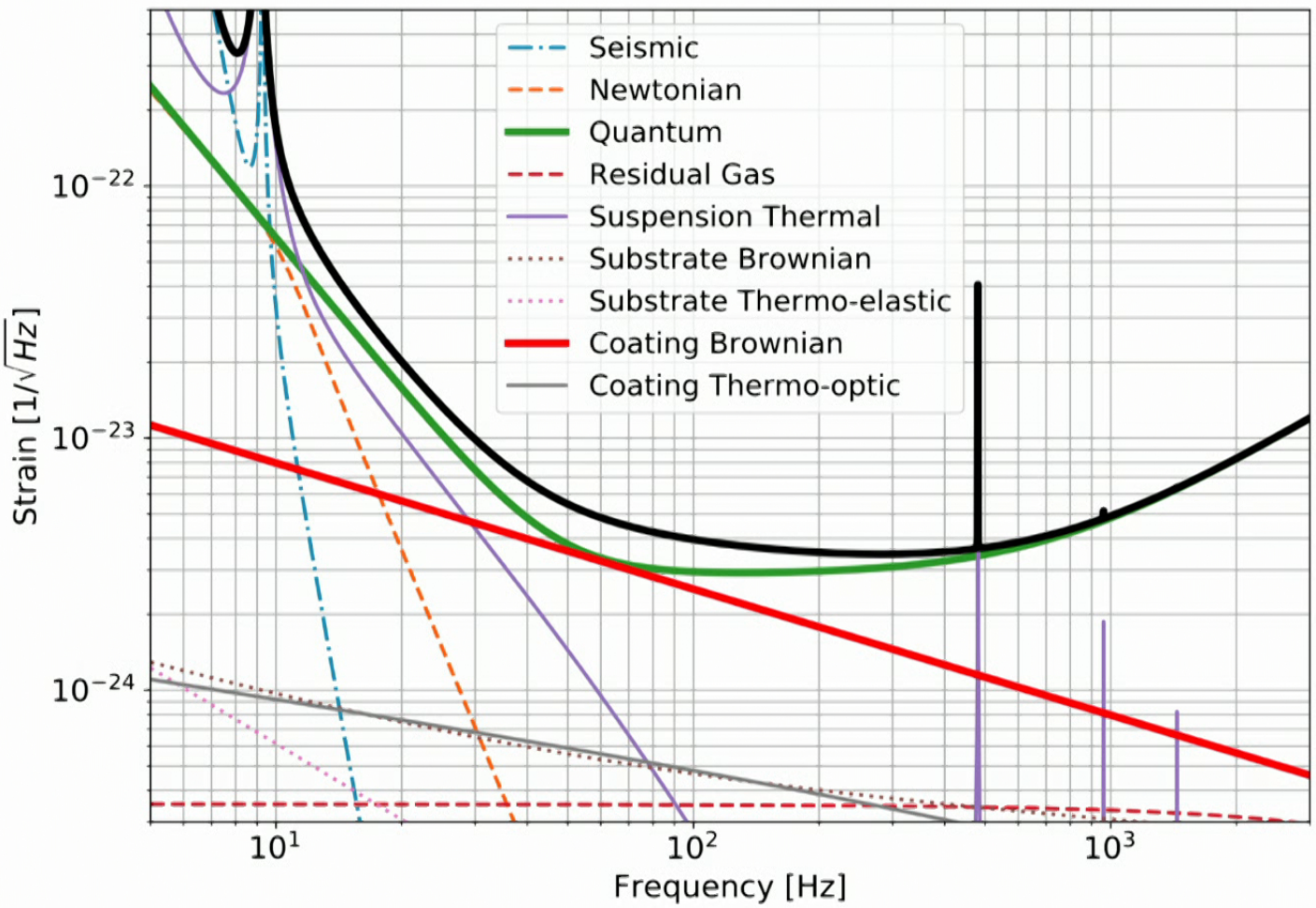


O2: 2016-2017

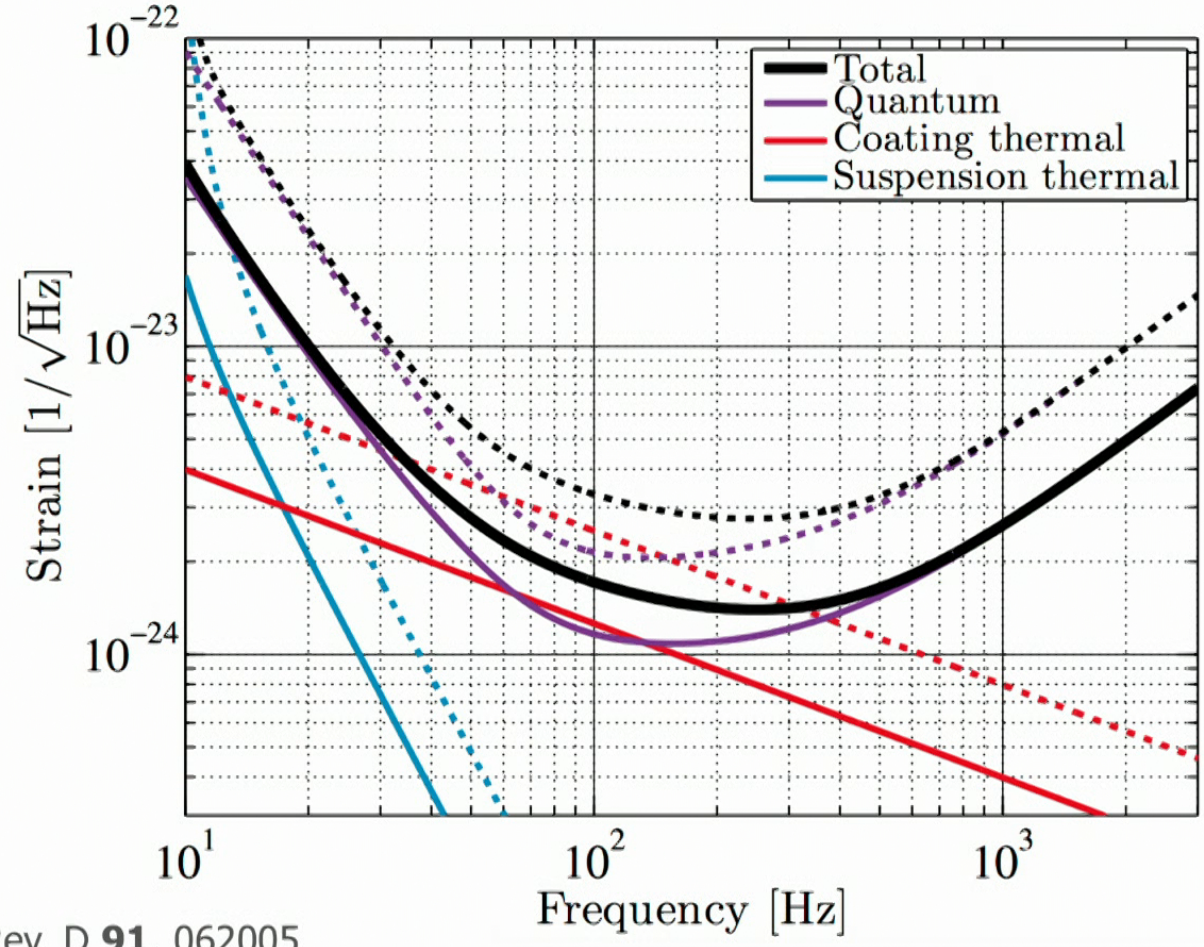


NEAR TERM

The near future: Advanced LIGO+

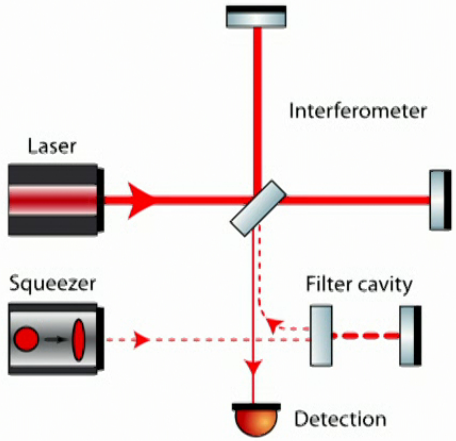


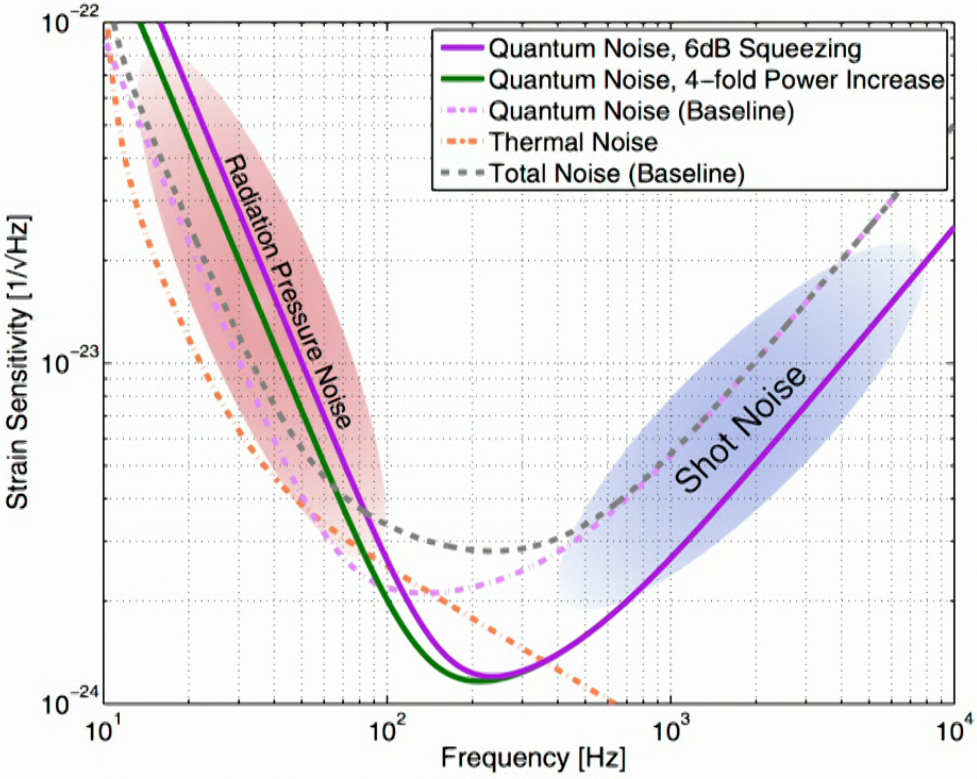
LIGO



Phys. Rev. D **91**, 062005

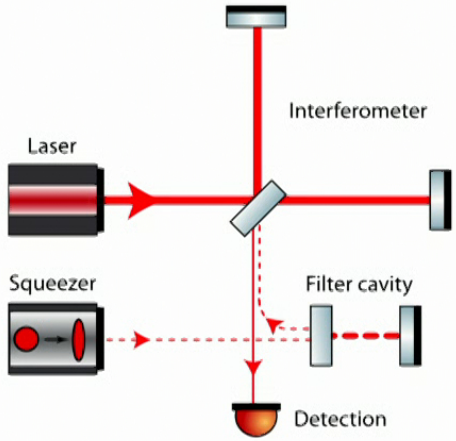
Frequency dependent squeezing

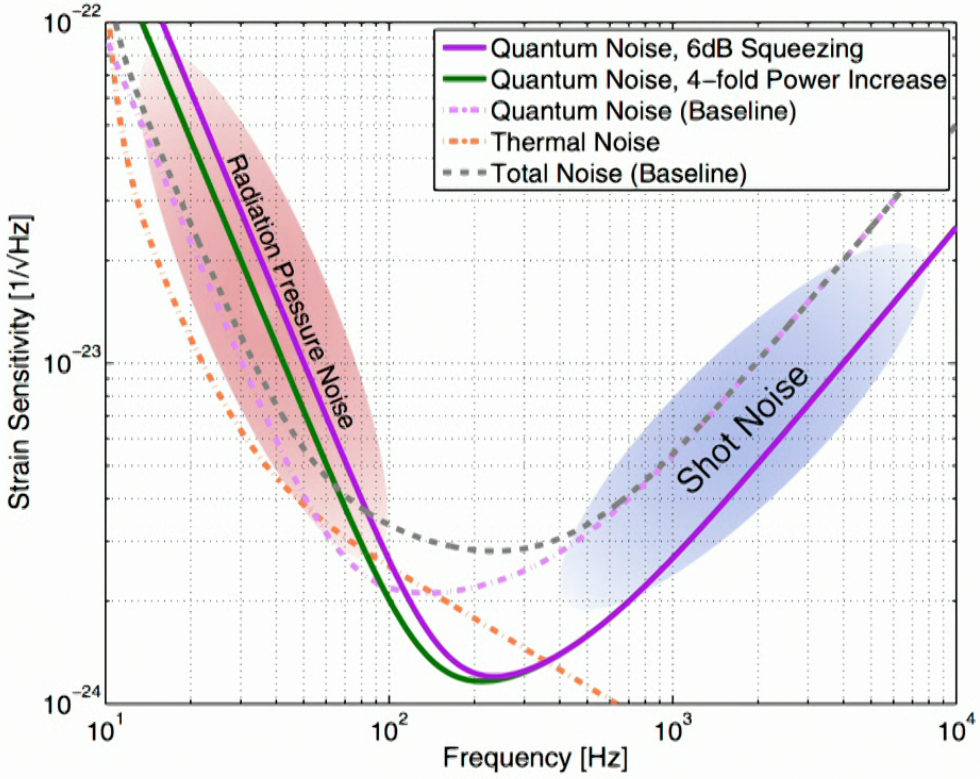




PHYSICAL REVIEW D 88, 022002 (2013)

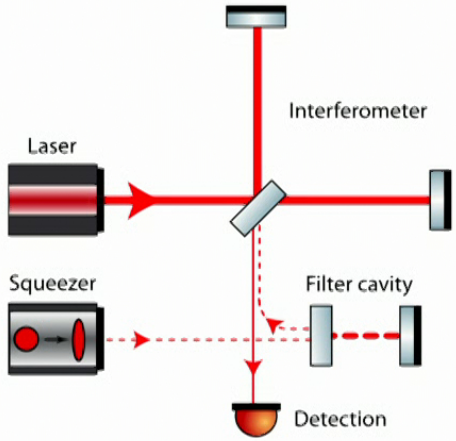
Frequency dependent squeezing

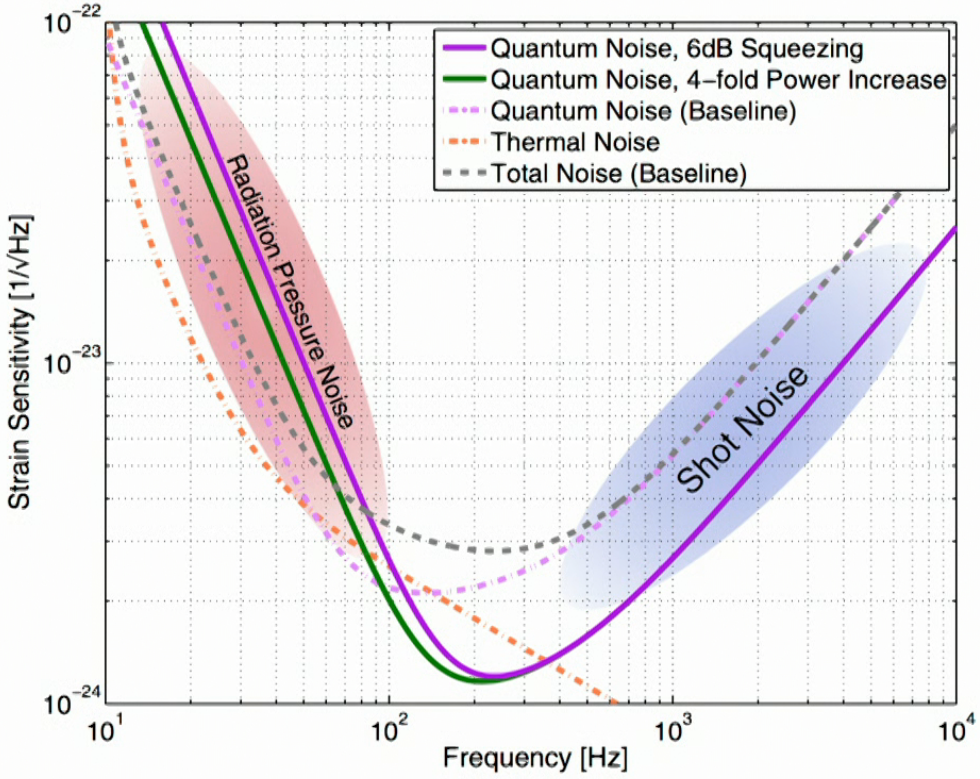




PHYSICAL REVIEW D 88, 022002 (2013)

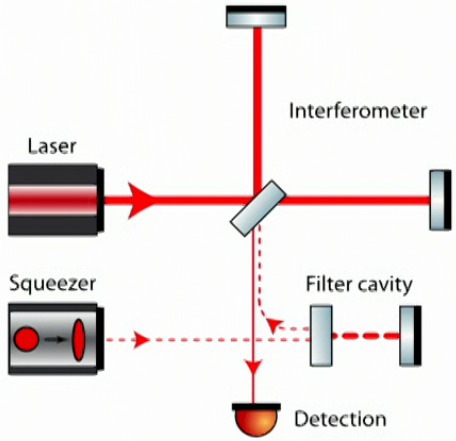
Frequency dependent squeezing

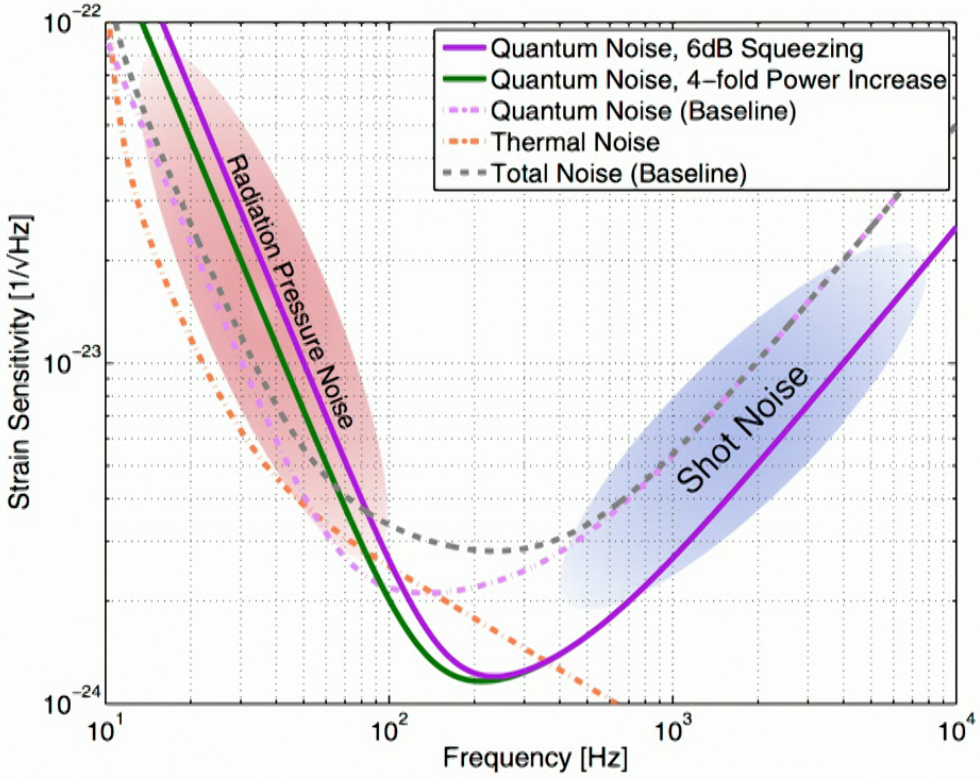




PHYSICAL REVIEW D 88, 022002 (2013)

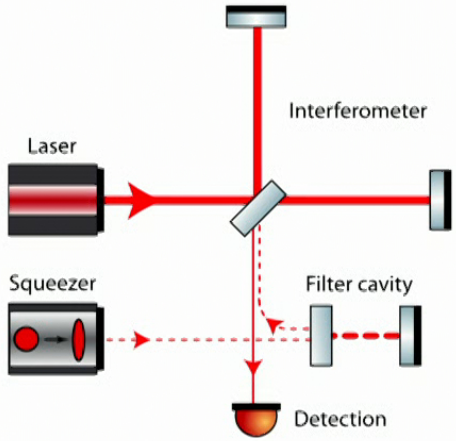
Frequency dependent squeezing

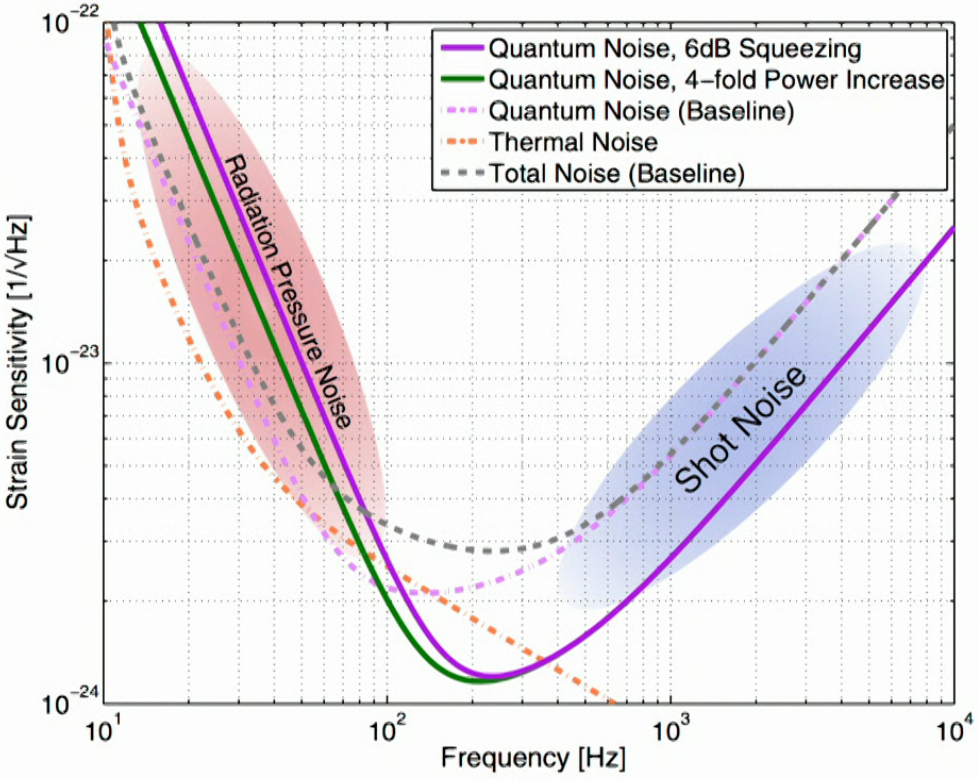




PHYSICAL REVIEW D 88, 022002 (2013)

Frequency dependent squeezing

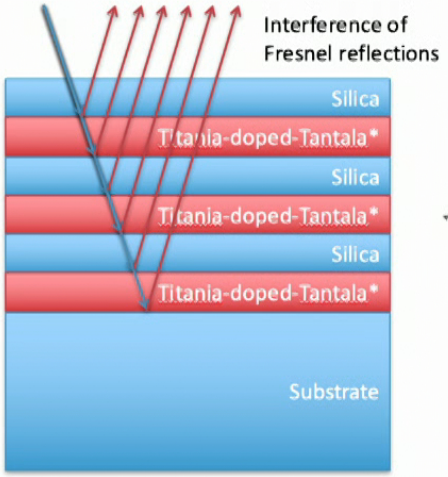


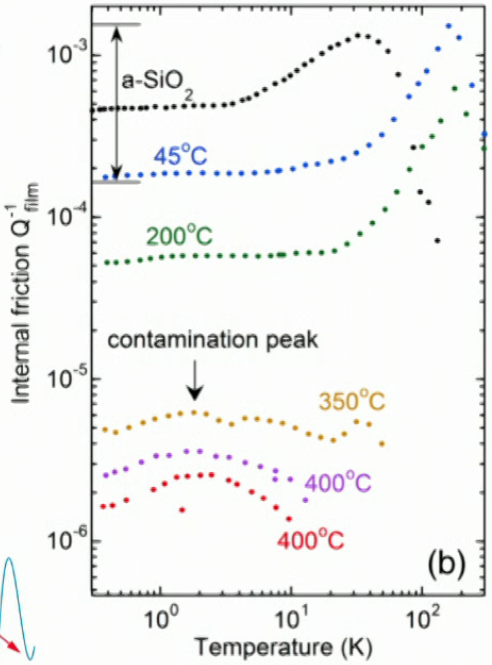


PHYSICAL REVIEW D 88, 022002 (2013)

Lower thermal noise

Material	Refractive index	Loss angle
Silica SiO_2	1.45	0.4×10^{-4}
Tantala Ta_2O_5	2.03	3.4×10^{-4}
Titania-doped tantala Ta_2O_5-TiO_2	2.07	**2.3×10^{-4}**





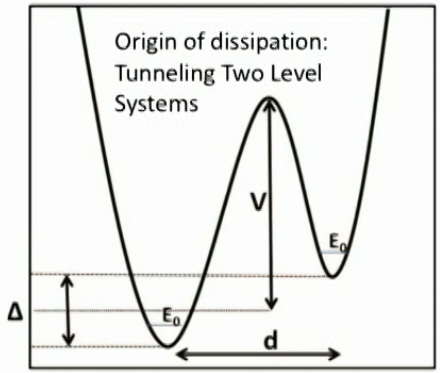
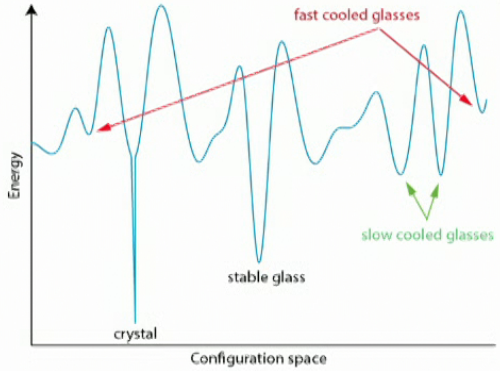


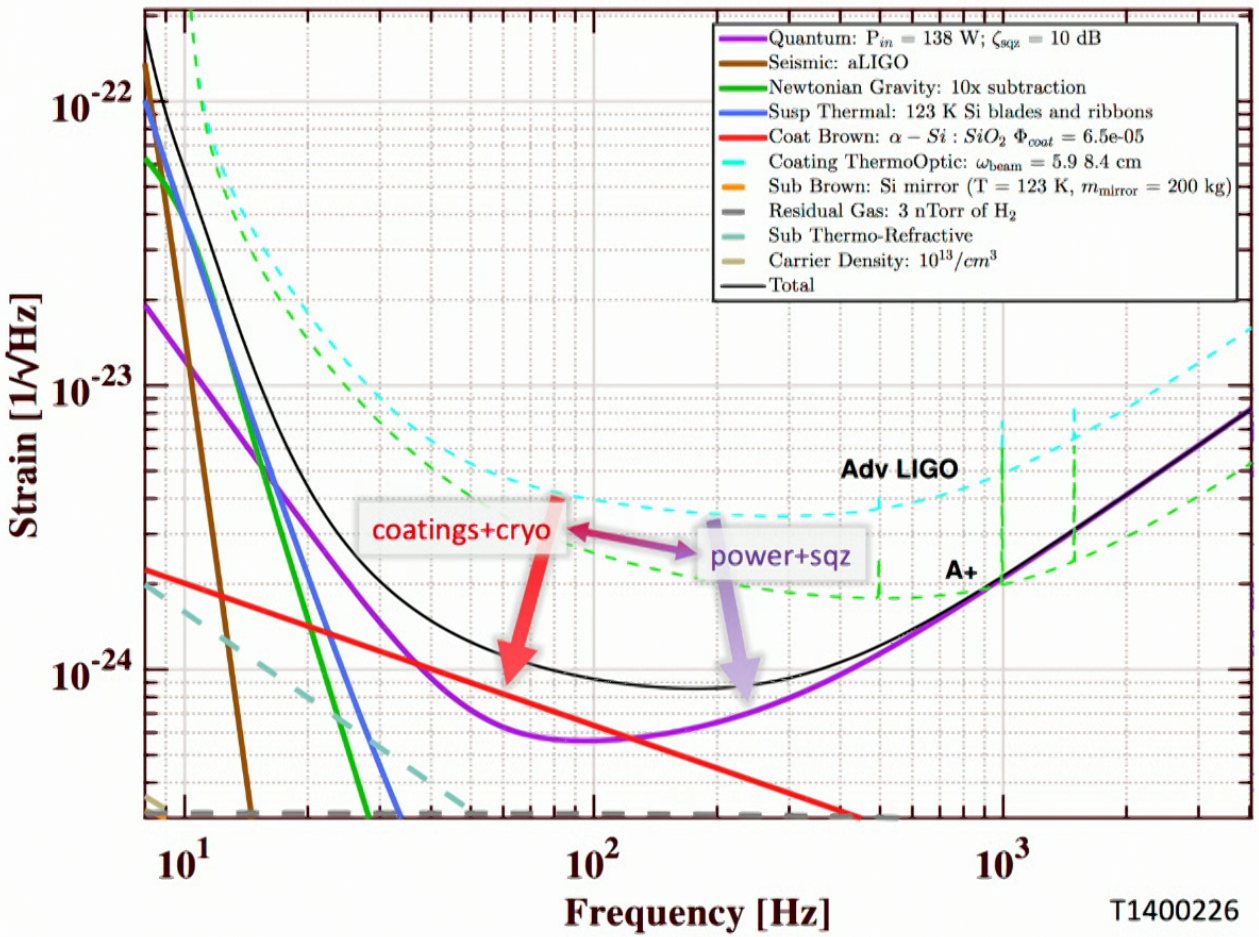
FIG. 1. Representation of the double-well potential. d is the configurational distance between the two wells, Δ is the energy asymmetry, E_0 is the ground state energy, and V is the barrier height.



Hamdan et al. J. Chem. Phys. 141, 054501 (2014) Parisi et al. Nature Materials 12, 94 (2013)

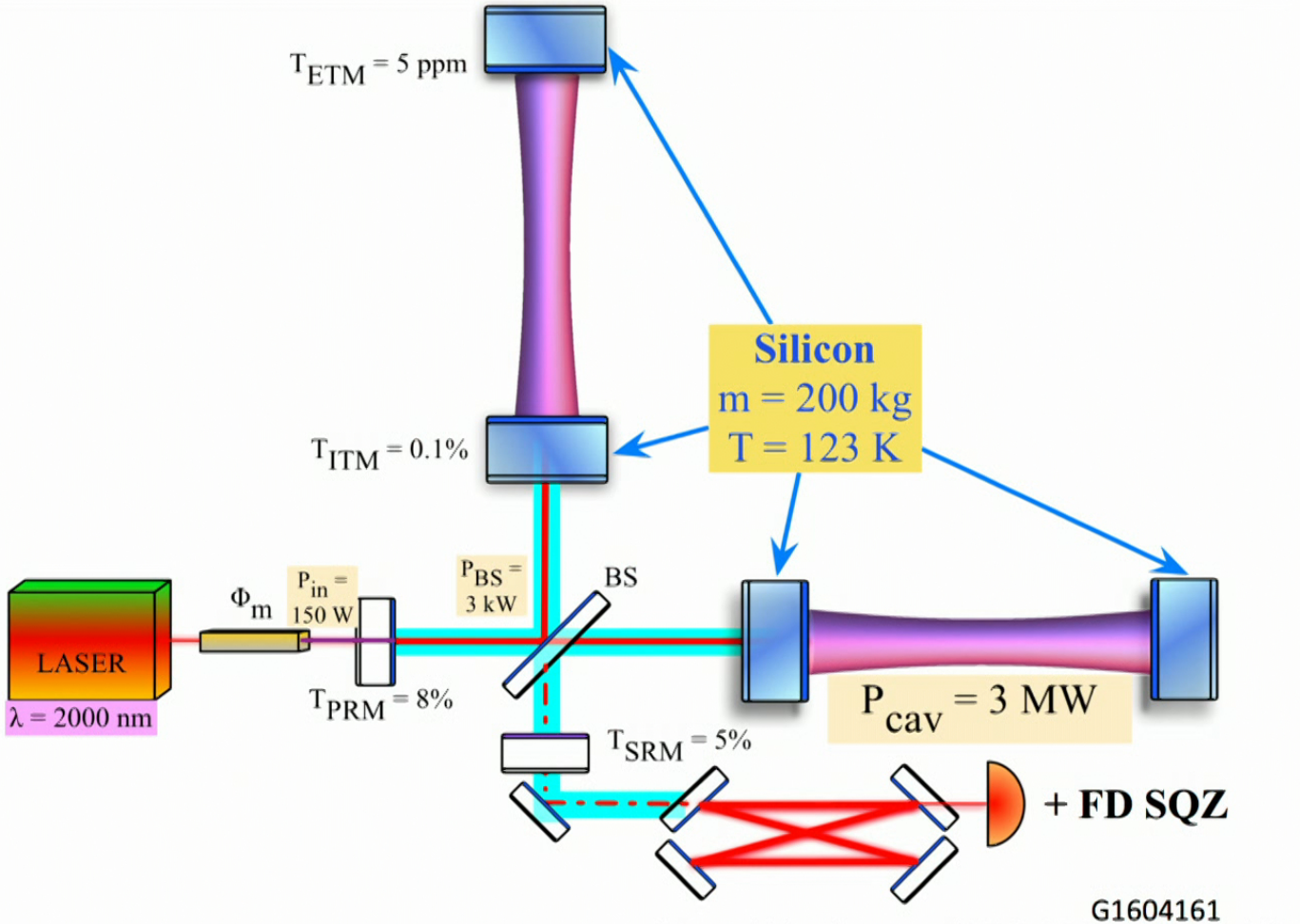
LONG TERM UPGRADES

Pushing the facilities to the limit: Voyager

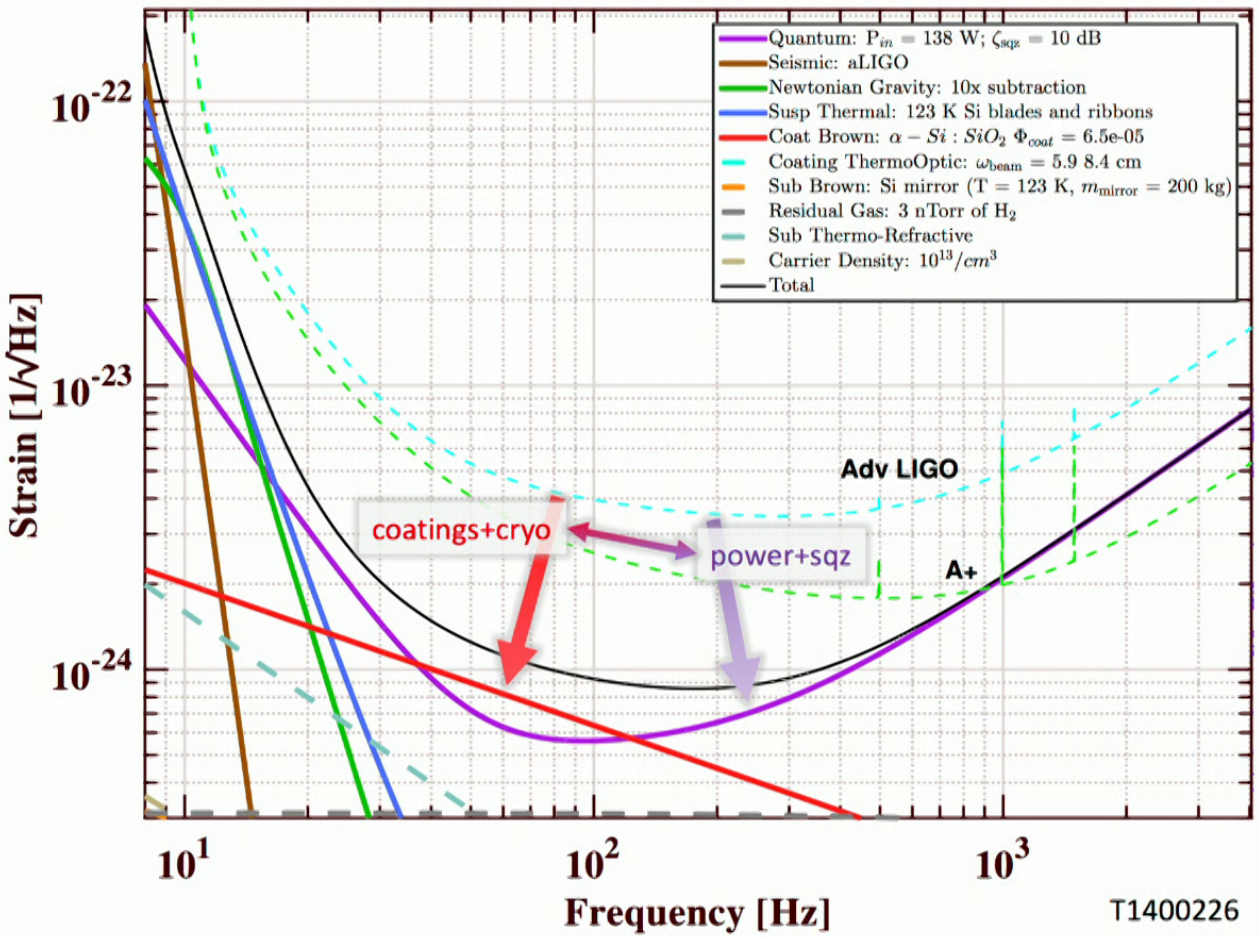


https://dcc.ligo.org/LIGO-G1700848/public

Pushing the facilities to the limit: Voyager

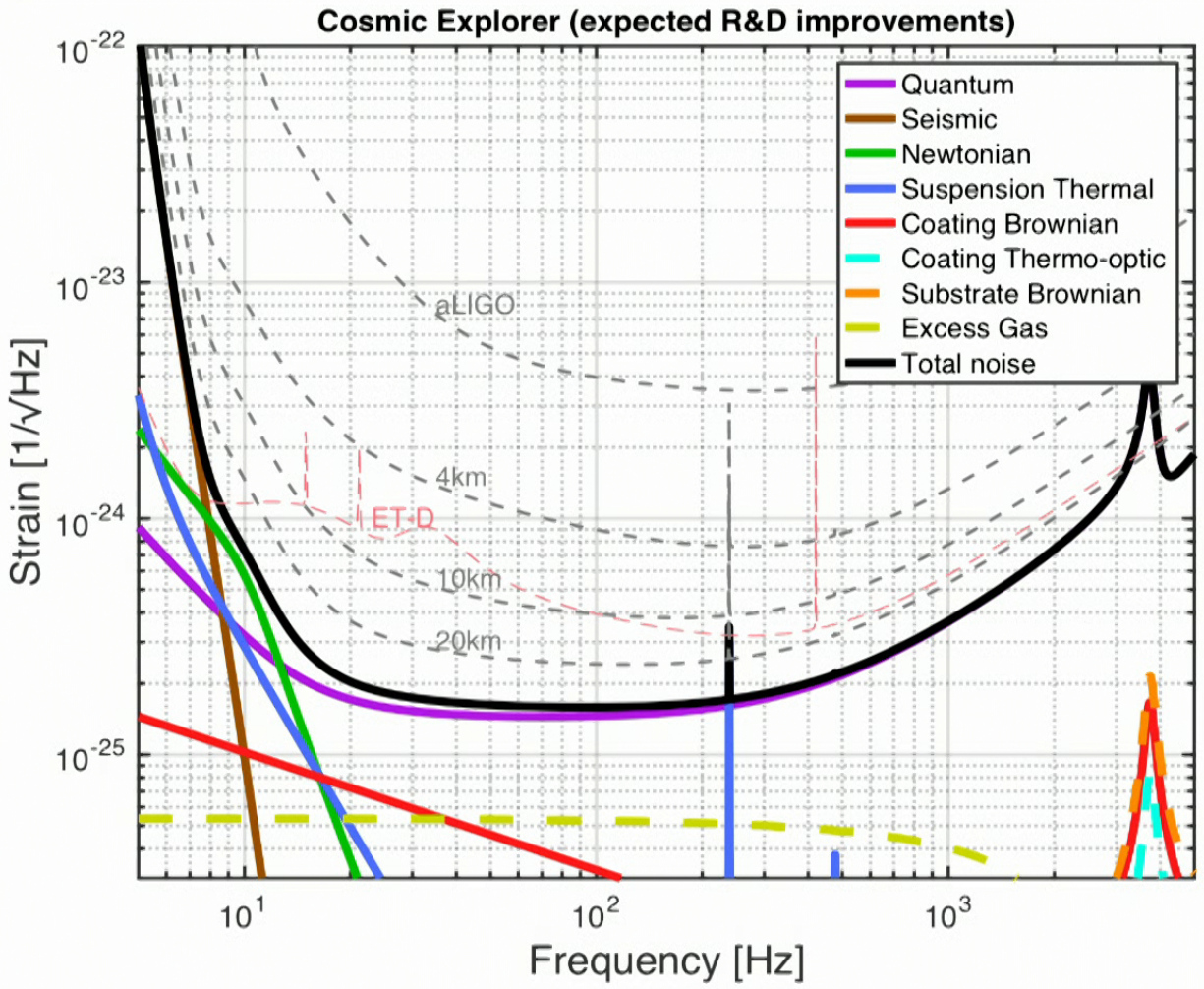


Pushing the facilities to the limit: Voyager



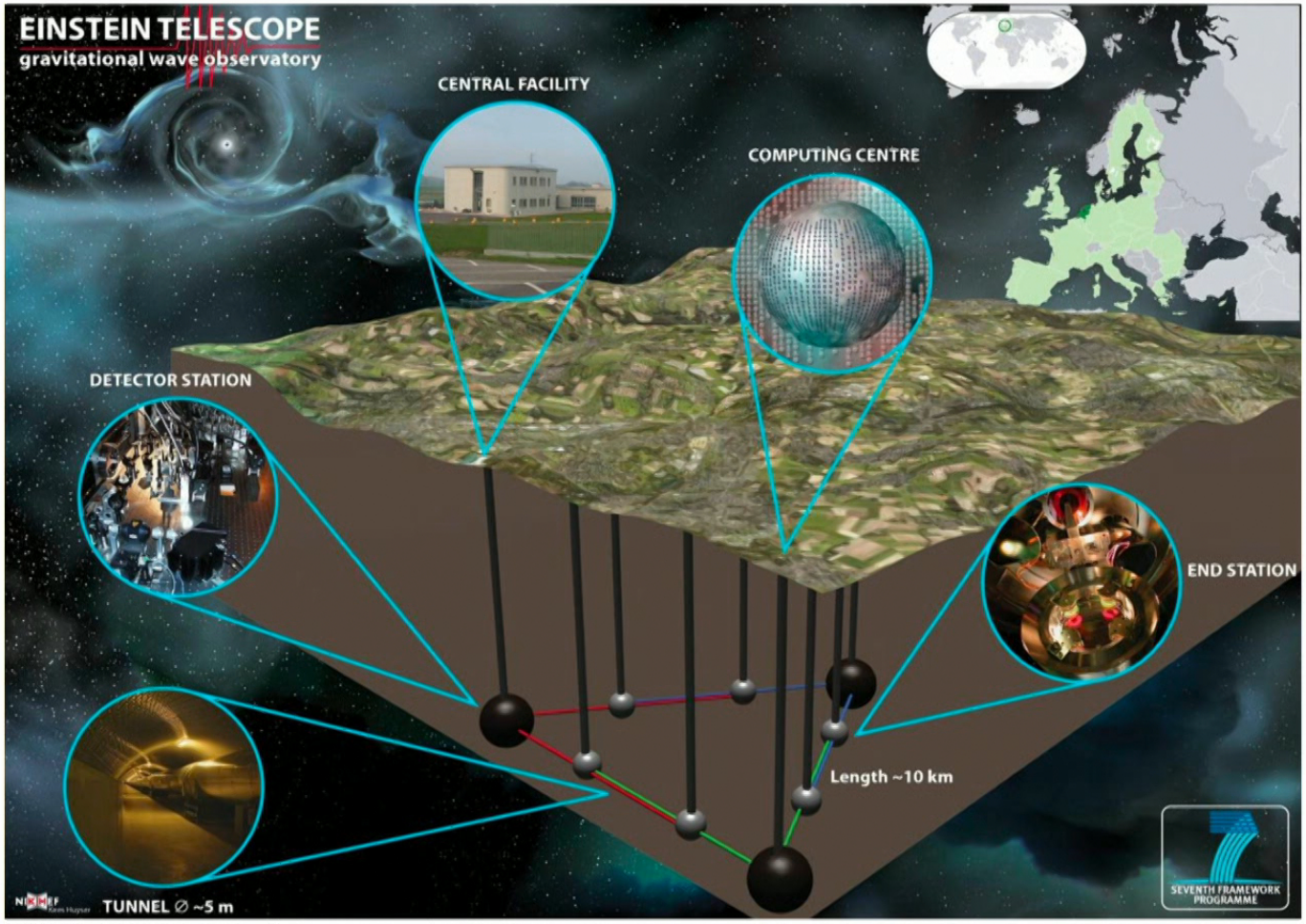
https://dcc.ligo.org/LIGO-G1700848/public

New facilities: Cosmic Explorer



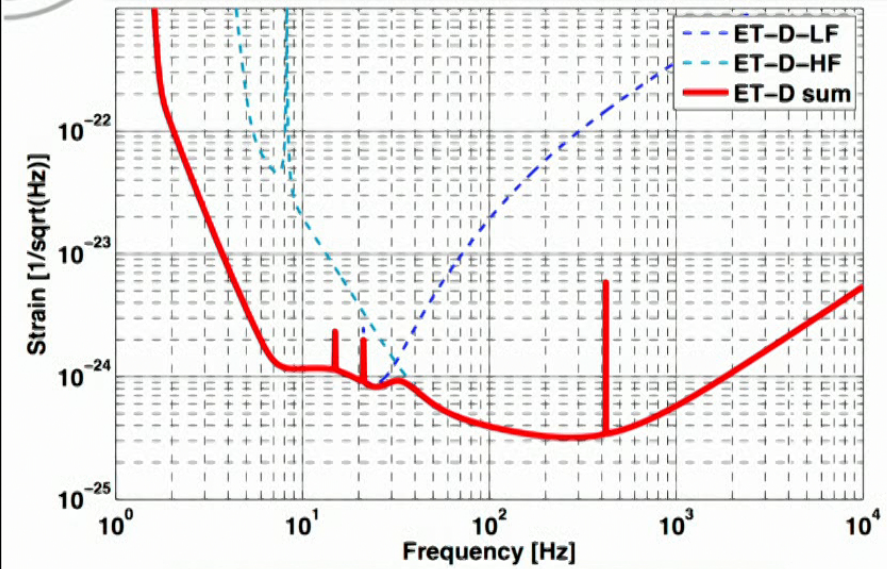
https://dcc.ligo.org/LIGO-G1800983/public

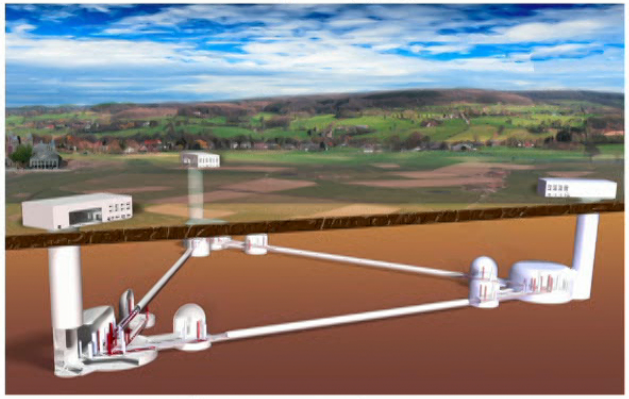
New facilities: Einstein Telescope



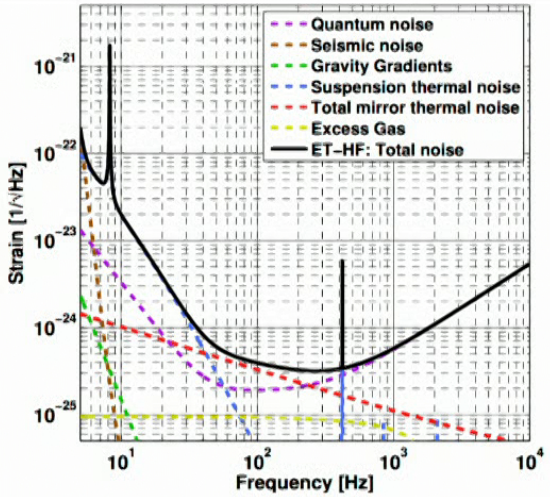
http://www.et-gw.eu/index.php/etdsdocument

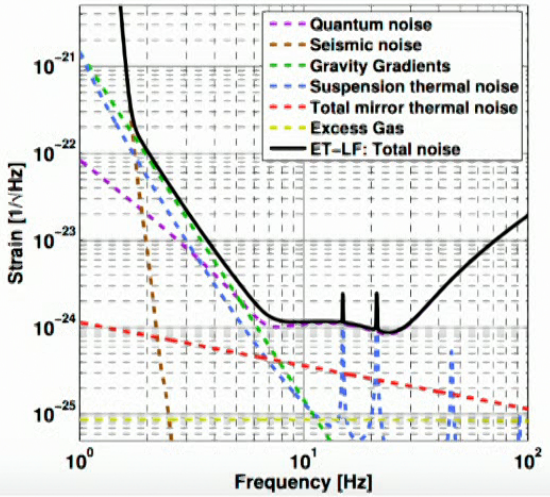
Einstein Telescope



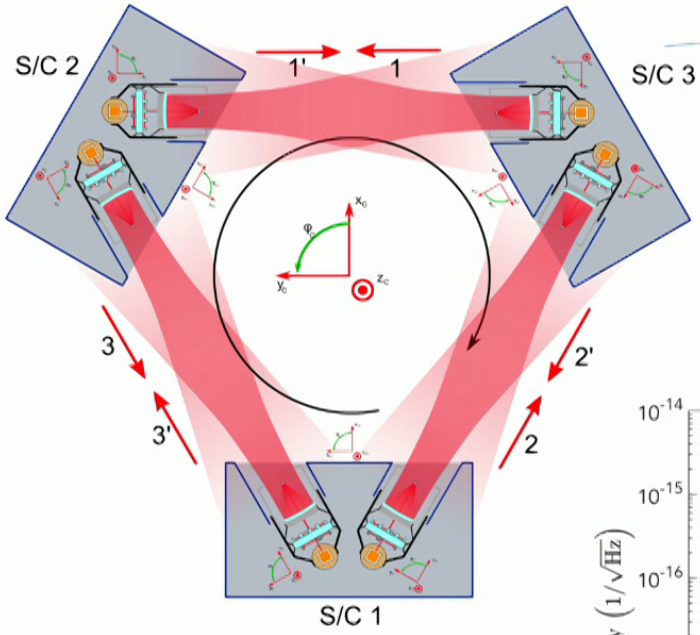


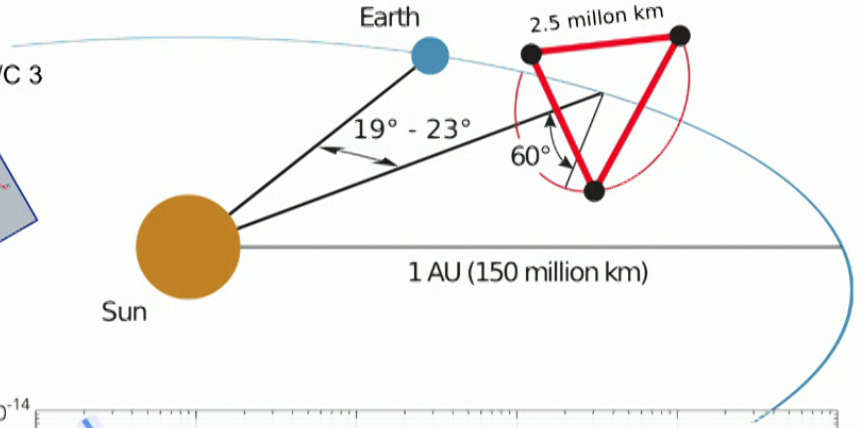
http://www.et-gw.eu/index.php/etdsdocument

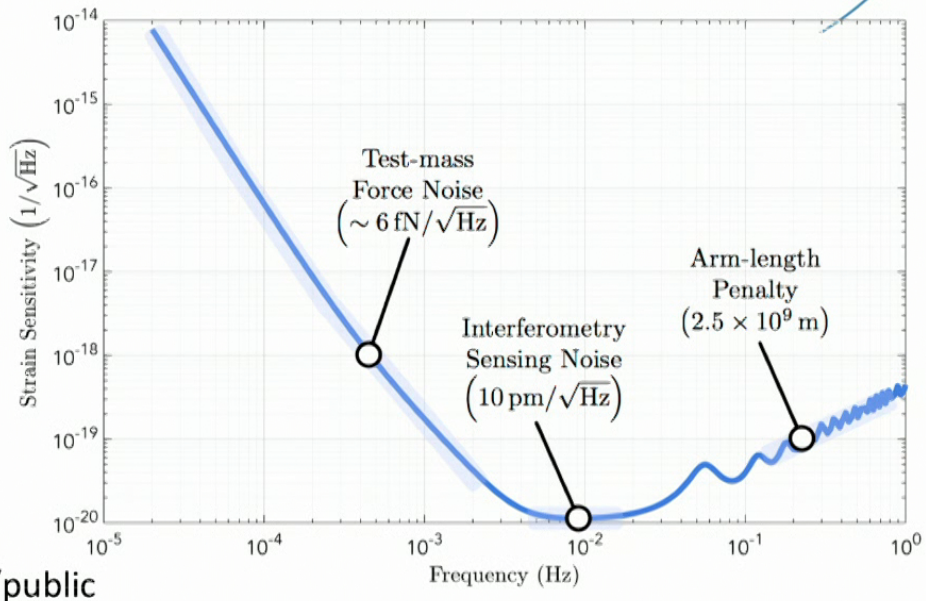




Going large and far: LISA







https://dcc.ligo.org/LIGO-G1800974/public

An old but still good introduction to GW detectors:
Peter R. Saulson "**Fundamentals of Interferometric Gravitational Wave Detectors**",
World Scientific (1994)

A collection of lectures on more advanced and recent topics:
Massimo Bassan, editor "**Advanced Interferometers and the Search for Gravitational Waves**",
Springer (2014)

The first discovery paper:
B. P. Abbott et al. "**Observation of Gravitational Waves from a Binary Black Hole Merger**"
PRL 116, 061102 (2016)

The binary neutron star discovery paper:
B. P. Abbott et al. "**GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral**",
PRL 119, 161101 (2017)

A good and brief introduction to the Advanced LIGO detectors
B. P. Abbott et al. "**GW150914: The Advanced LIGO Detectors in the Era of First Discoveries**",
Phys. Rev. Lett. 116, 131103

Another introduction to GW detectors, with a bit of historical perspective
Pitkin, M., Reid, S., Rowan, S. et al.
"**Gravitational Wave Detection by Interferometry (Ground and Space)**",
Living Rev. Relativ. (2011) 14: 5.

Work-in-progress notes:

https://tinyurl.com/GW-notes-2018

They cover all of lecture 1, some of lecture 2, none of lecture 3. May contains mistakes, typos
And are updated continuously

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