Current and future ground-based gravitational-wave detectors

Haixing Miao

University of Birmingham

Key reference: LIGO Instrument Science White Paper (2015-2016)

Outline

- **Background**
  - Gravitational waves and their detection
- **Basic of noise**
  - Noise spectral density and transfer function
- **Environmental noise**
  - Passive isolation and active cancellation
- **Thermal noise**
  - Fluctuation-dissipation theorem
  - How to reduce thermal noise
- **Quantum noise**
  - Standard Quantum Limit
  - Frequency-dependent squeezing
- **Current and future detectors**
  - Timeline and sensitivity

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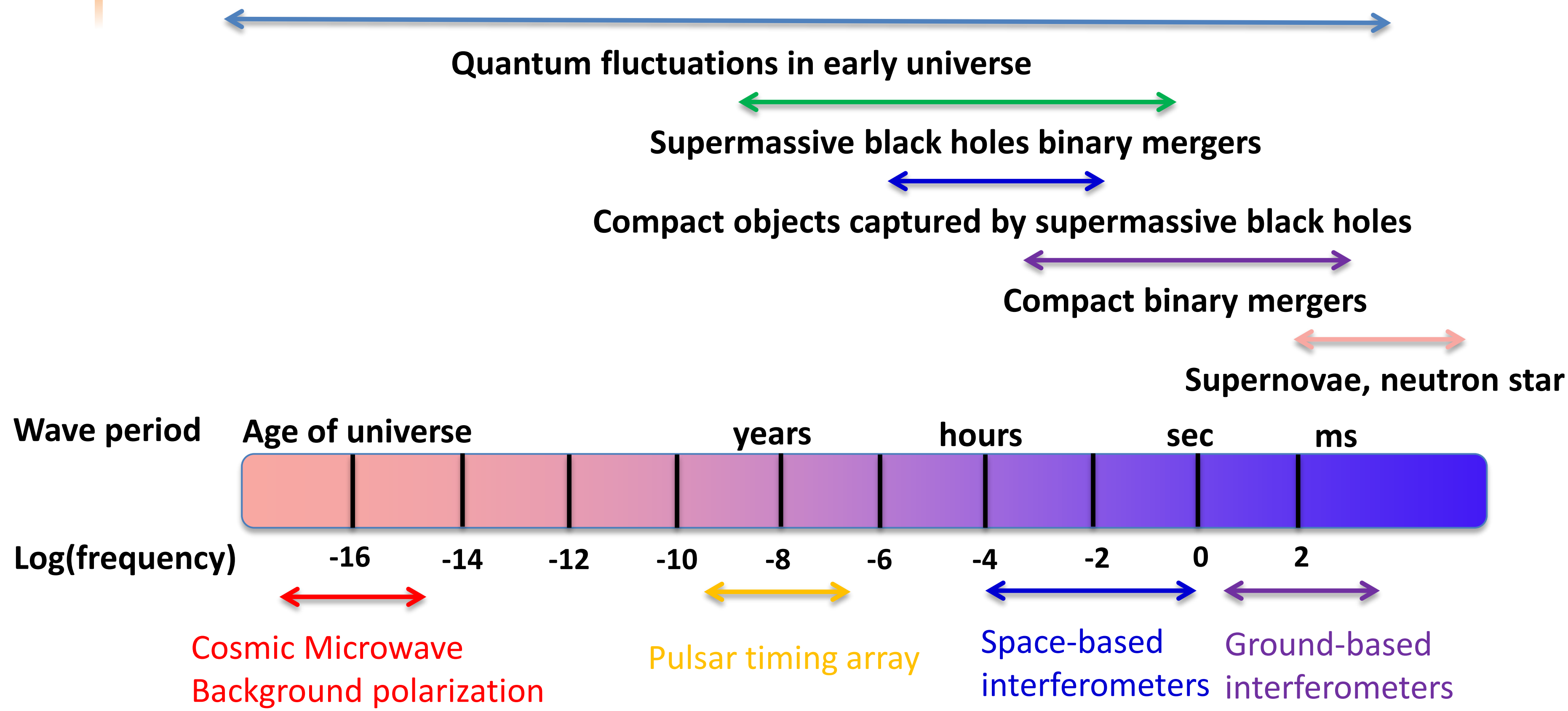
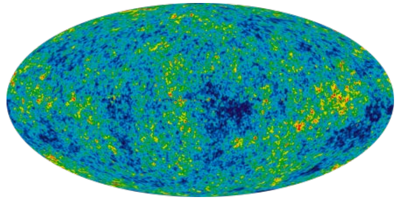
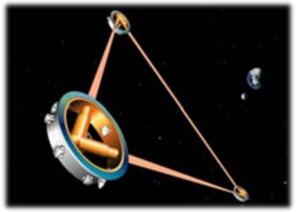
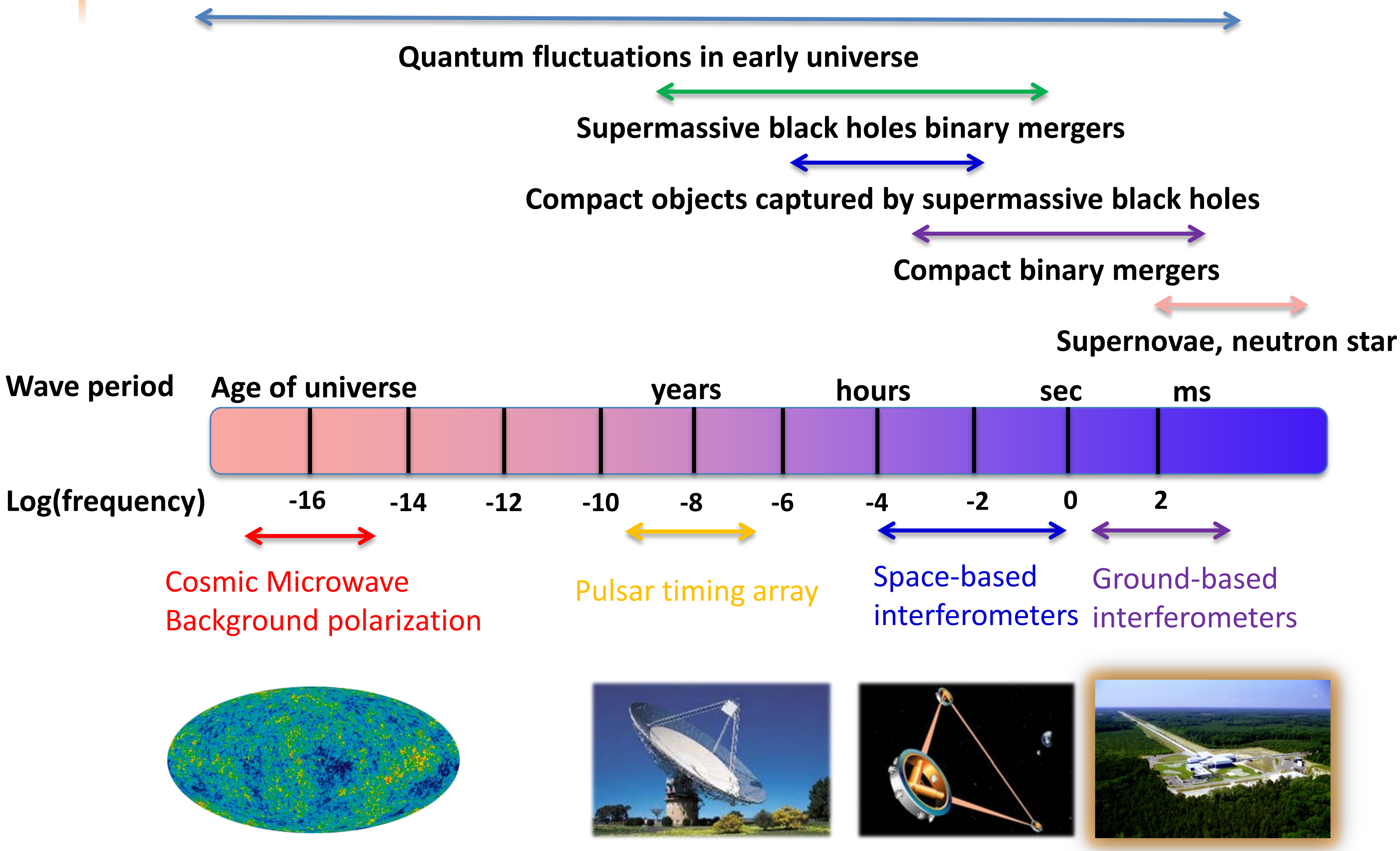
Gravitational waves and their detection



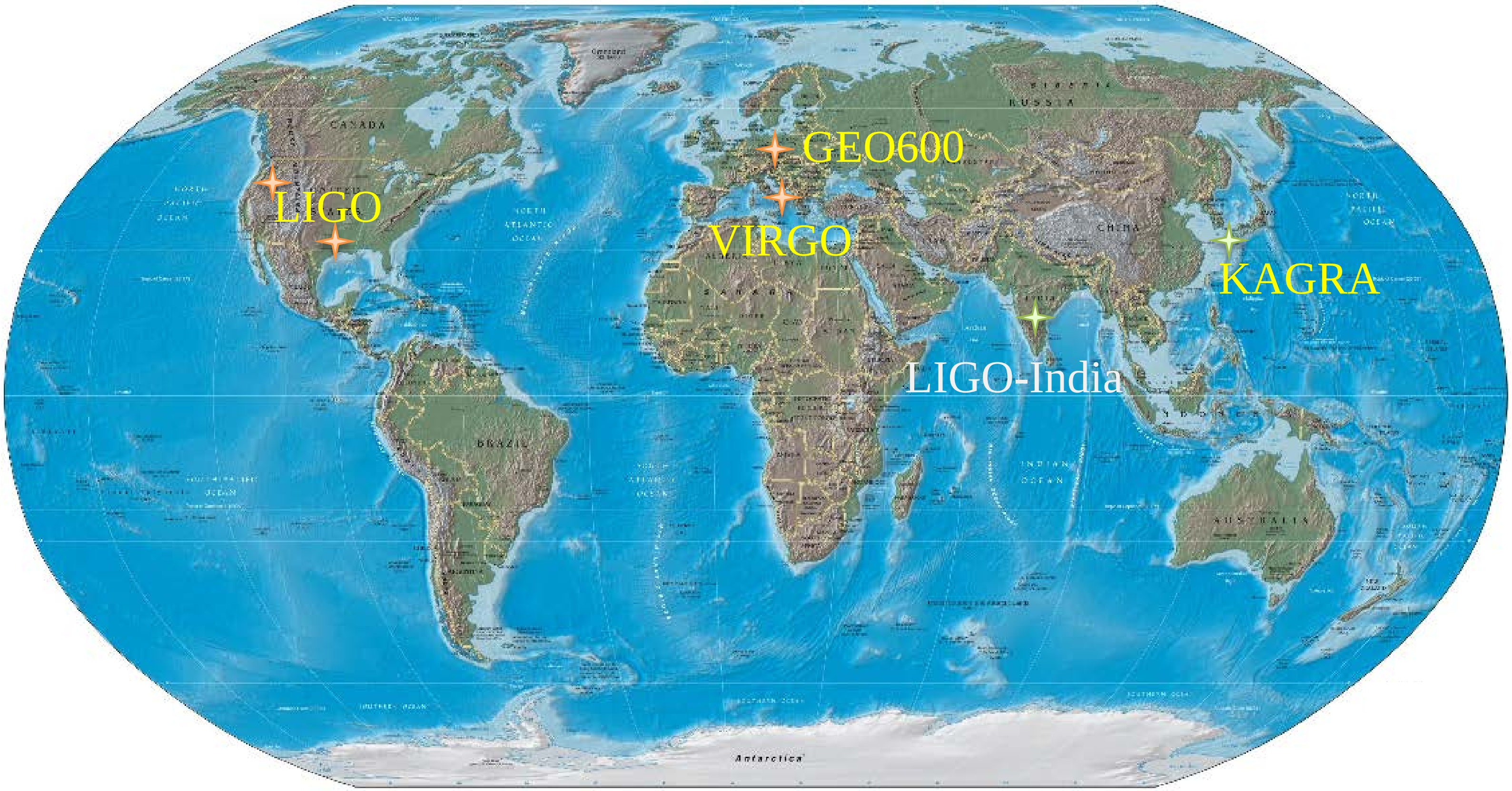




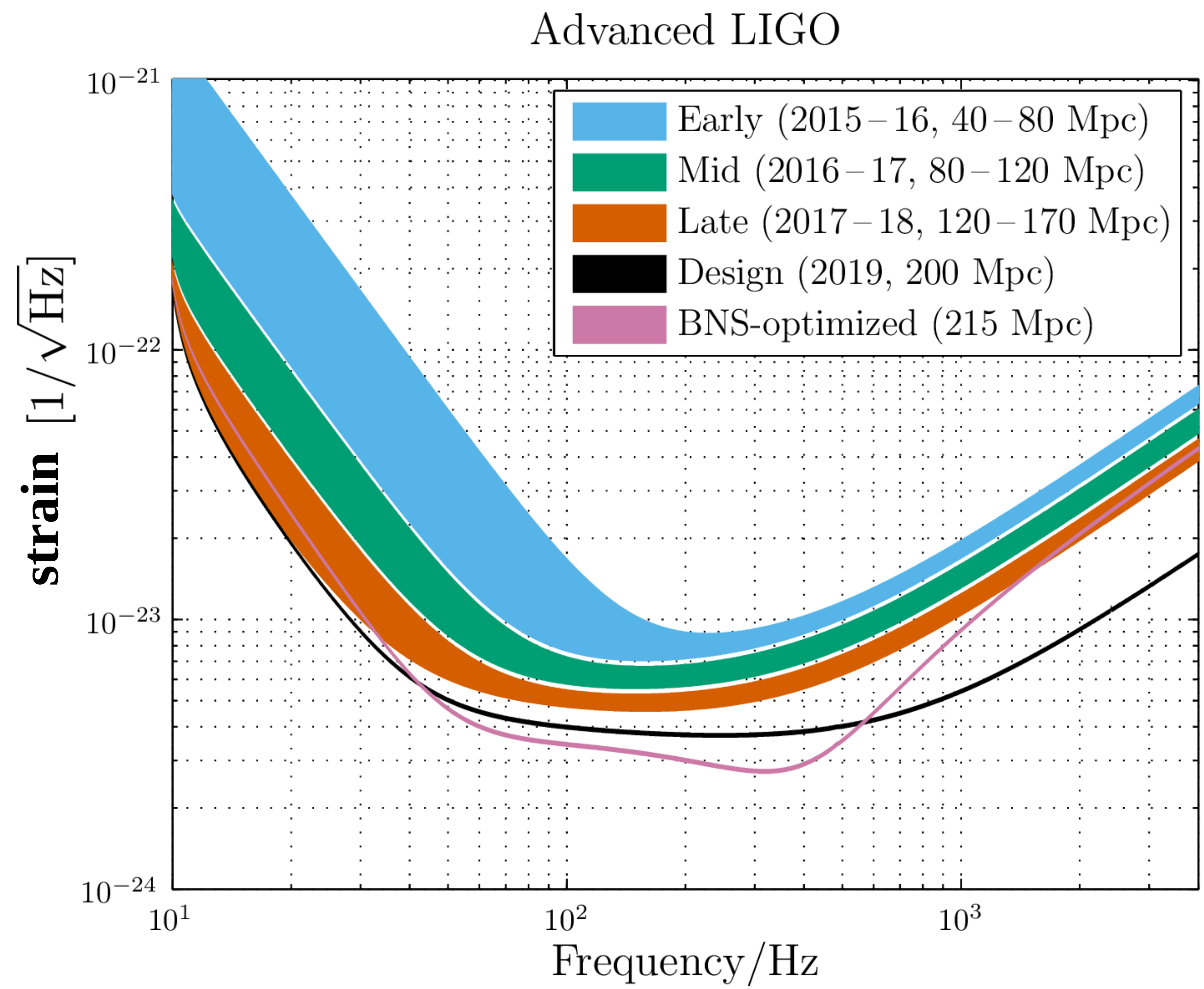
Gravitational waves and their detection



A Global Network

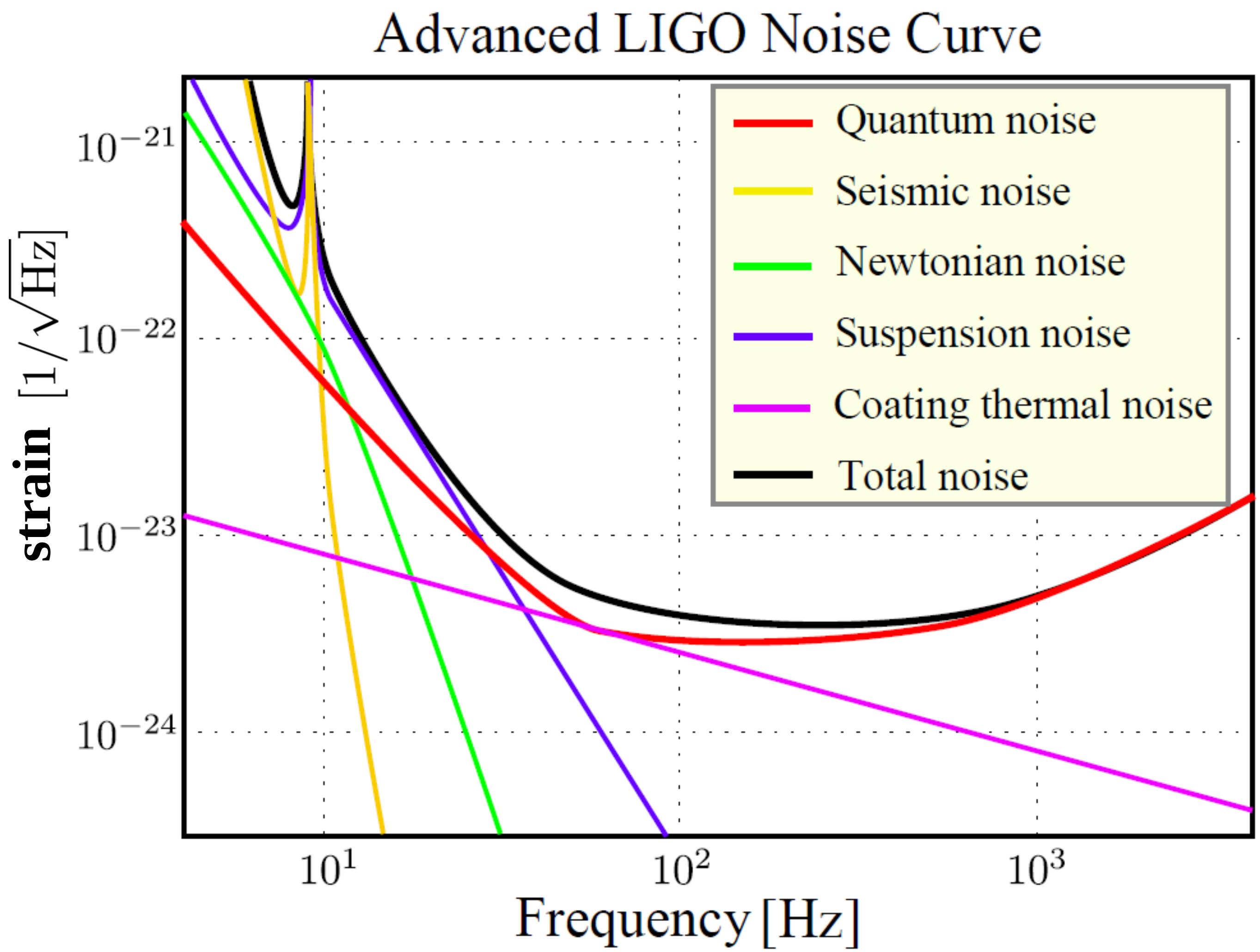


Different stages of Advanced LIGO



LSC, Living Reviews in Relativity 19, 1 (2016)

Design sensitivity of Advanced LIGO



LSC, Class. Quantum Grav. 32, 074001 (2015)

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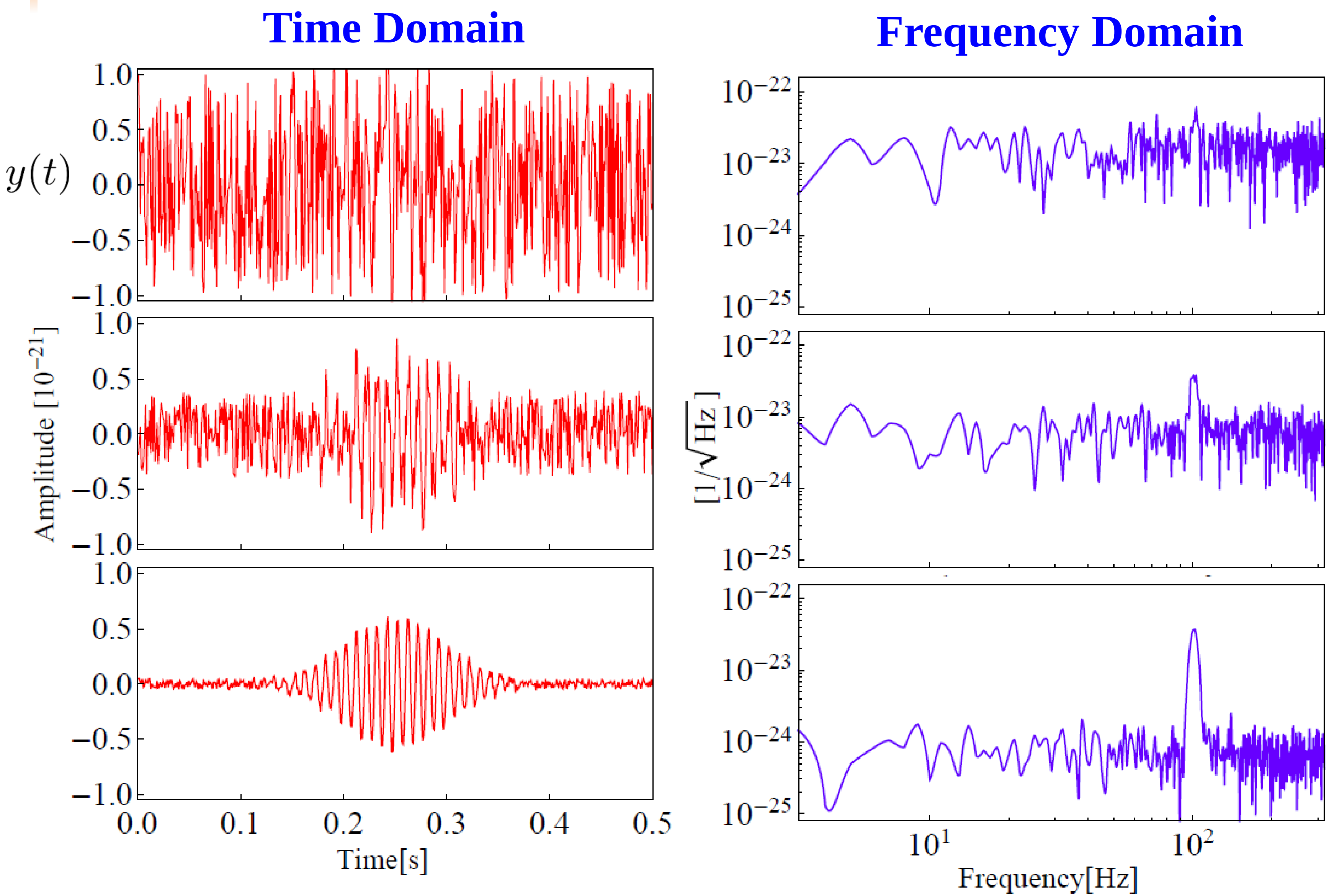
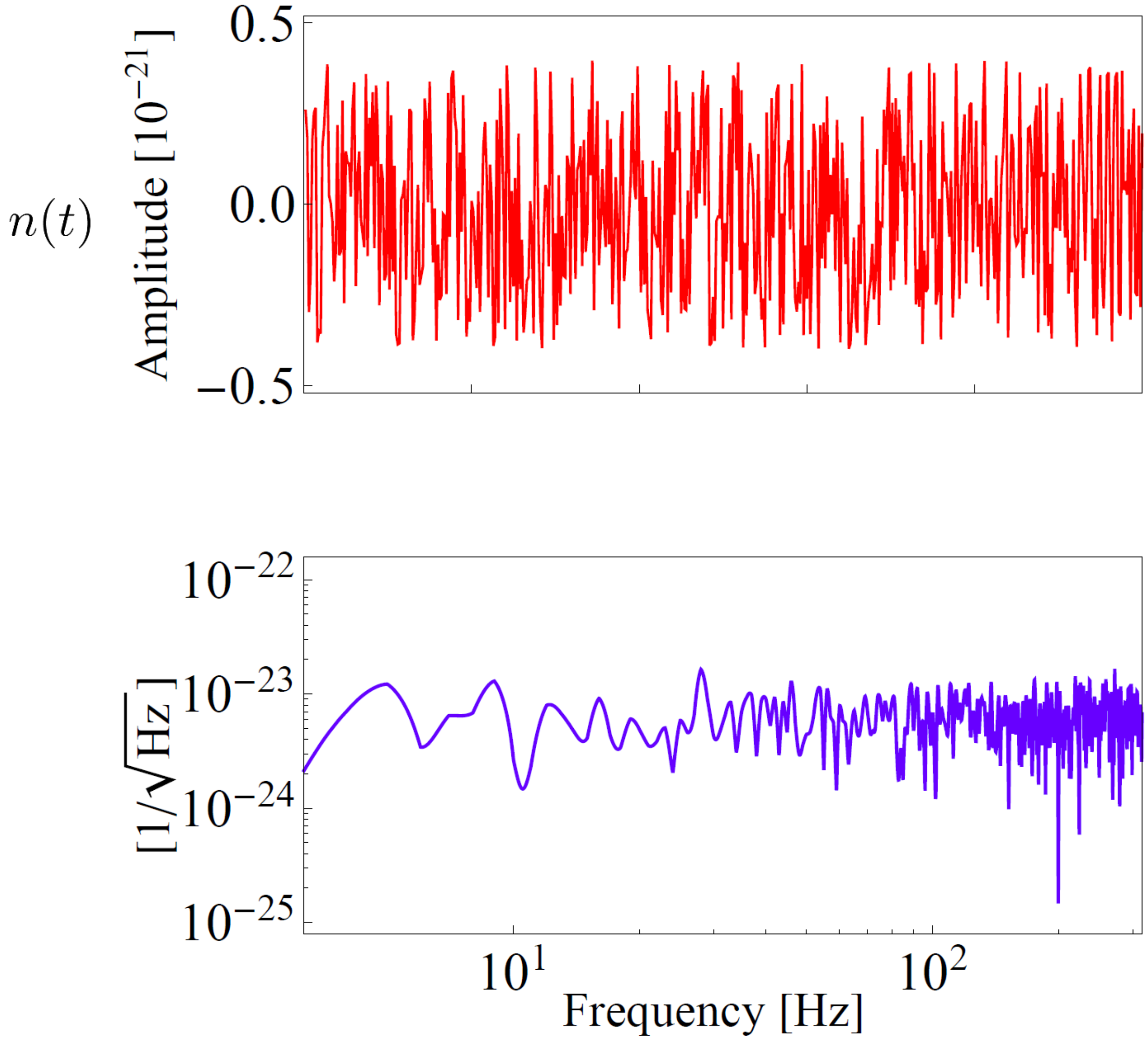
Signal and noise $y(t) = n(t) + h(t)$



Noise spectral density (spectrum)



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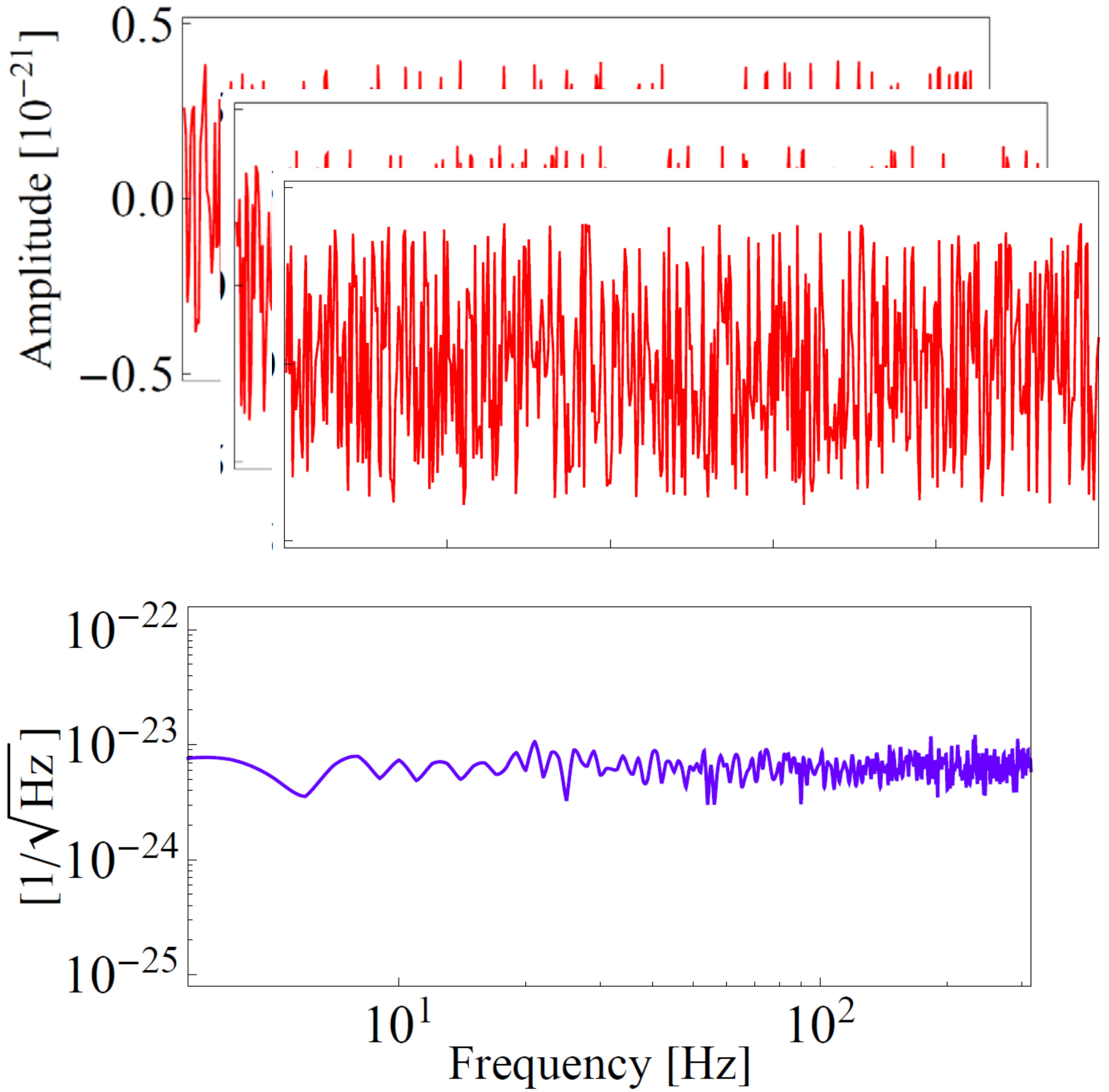

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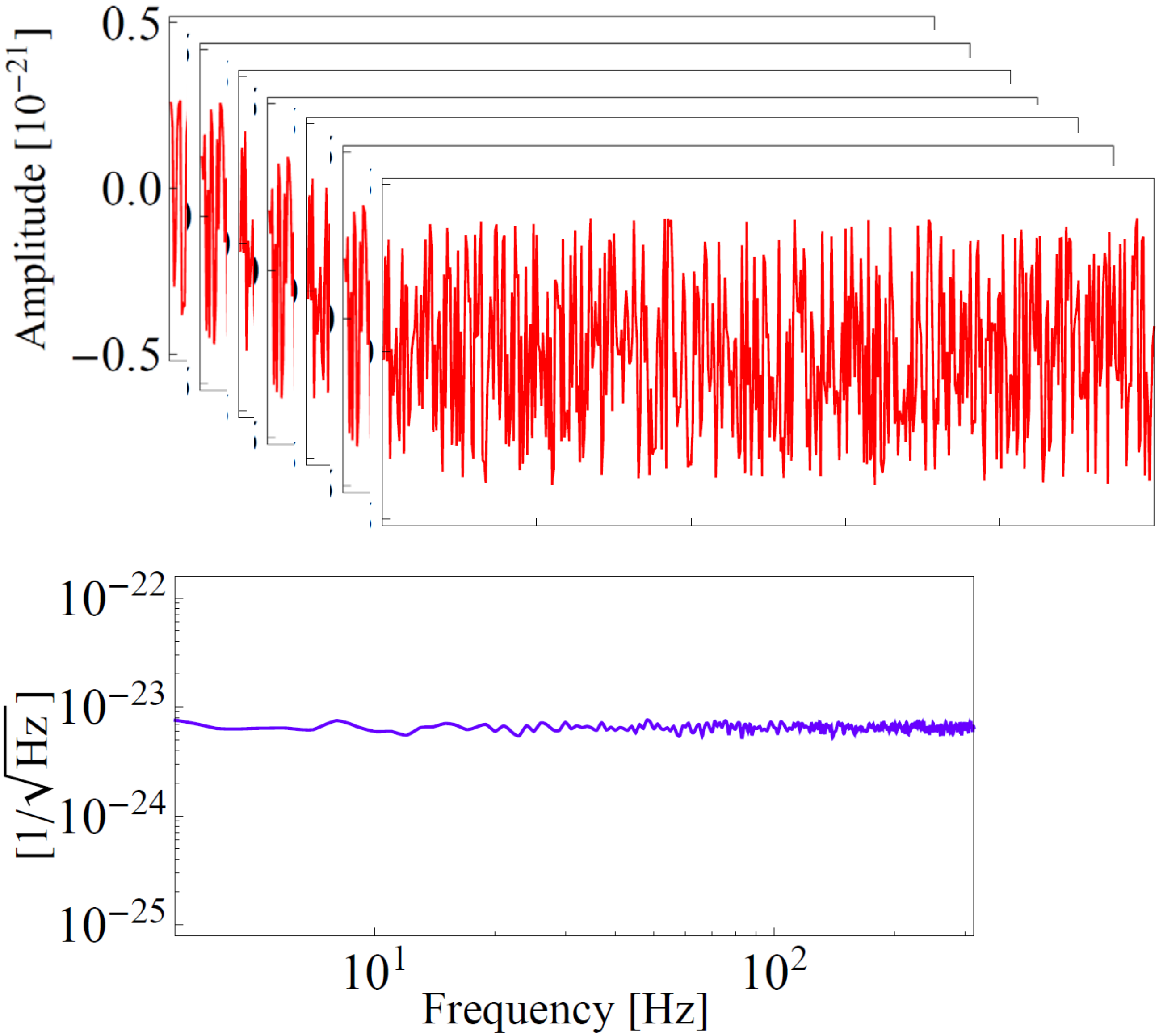

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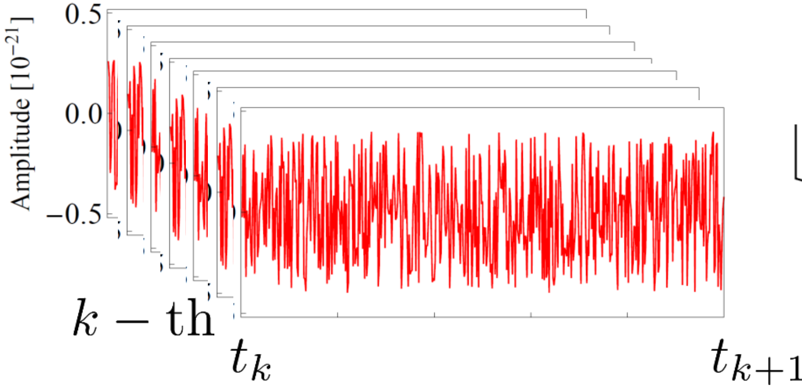
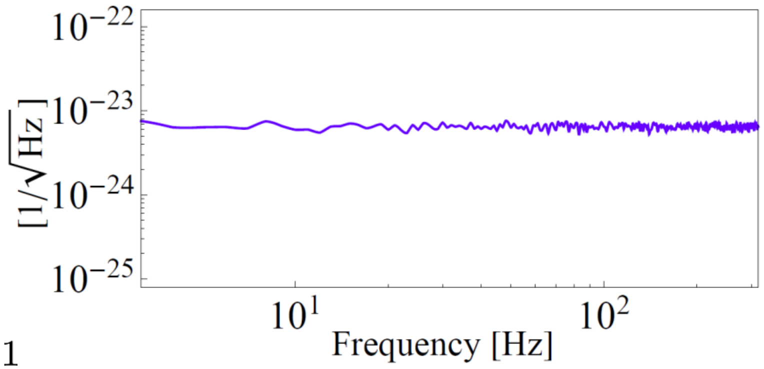




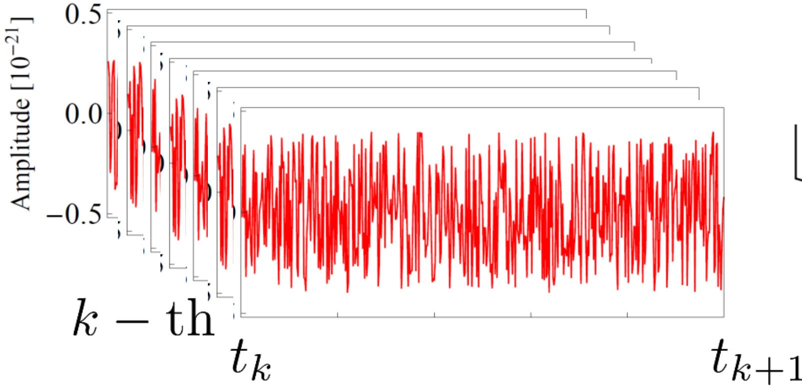
$$\tilde{n}_k(f) \equiv \int_{t_k}^{t_{k+1}} \mathrm{d}t\,[n(t)-\langle n\rangle]e^{2\pi i f t}$$

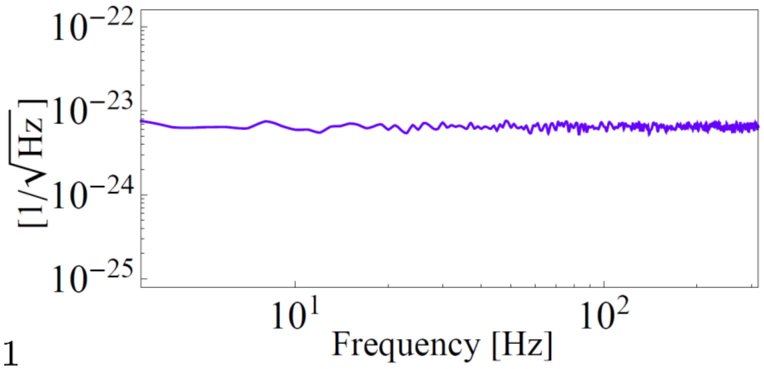
Spectral density: $S_{nn}(f) \equiv \lim_{N\to\infty} \frac{1}{N}\sum_{k=1}^{N}\frac{1}{\Delta t}|\tilde{n}_k(f)|^2$ $\quad \Delta t = t_{k+1} - t_k$

$$\approx \lim_{\tau\to\infty}\frac{1}{\tau}|\tilde{n}(f)|^2 \qquad \tau \equiv N\Delta t$$

$$\tilde{n}(f) \equiv \int_{-\tau/2}^{+\tau/2} \mathrm{d}t\,[n(t)-\langle n\rangle]e^{2\pi i f t}$$

Noise spectral density (spectrum)





$$\tilde{n}_k(f) \equiv \int_{t_k}^{t_{k+1}} \mathrm{d}t\,[n(t) - \langle n \rangle] e^{2\pi i f t}$$

Spectral density: $S_{nn}(f) \equiv \lim_{N\to\infty} \frac{1}{N} \sum_{k=1}^{N} \frac{1}{\Delta t} |\tilde{n}_k(f)|^2 \approx \lim_{\tau\to\infty} \frac{1}{\tau} |\tilde{n}(f)|^2$

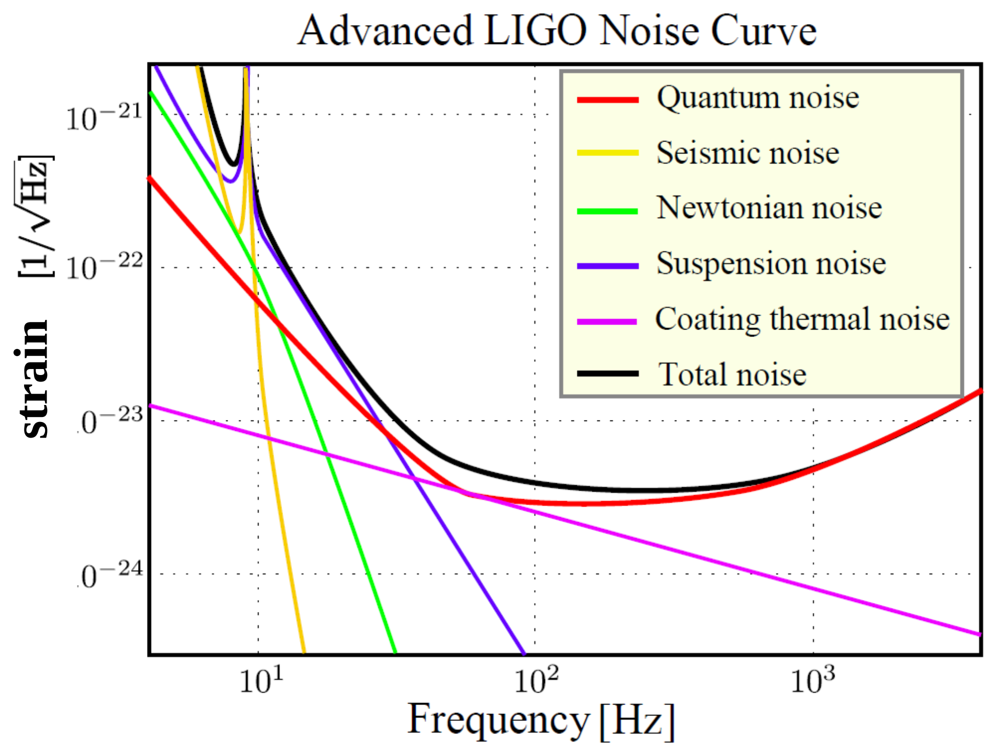
Linear version: $\sqrt{S_{nn}(f)}$ $[1/\sqrt{\mathrm{Hz}}]$

resolution bandwidth

Order of magnitude: $h_{\min}|_{f_0} \approx \sqrt{S_{nn}(f_0)\Delta f}$ $\Delta f \equiv 1/\Delta t$

Chap 6: Random Process in *Applications of Classical Physics* by Blandford & Thorne

Noise spectral density (spectrum)

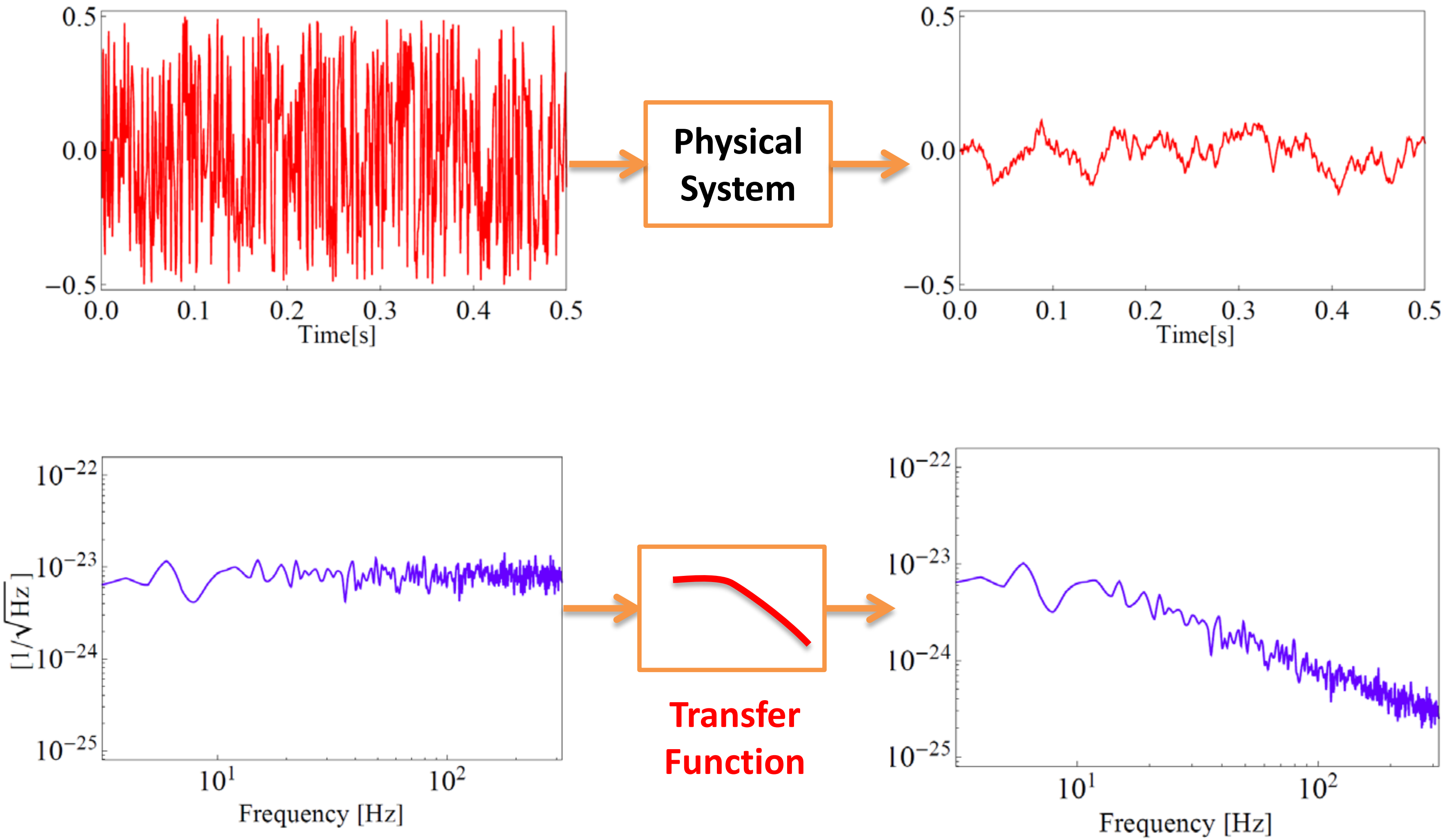


100Hz signal (1sec long): $h_{\min}|_{100\mathrm{Hz}} \approx \sqrt{S_{nn}(100\mathrm{Hz})\Delta f}$

$\Delta f = 1/\Delta t = 1\mathrm{Hz}$ $\approx 10^{-23}$

In general: $\mathrm{SNR} \equiv \int_{f_{\min}}^{f_{\max}} \mathrm{d}f \, \frac{|\tilde{h}(f)|^2}{S_{nn}(f)}$ **(with matched filtering)**

Transfer function



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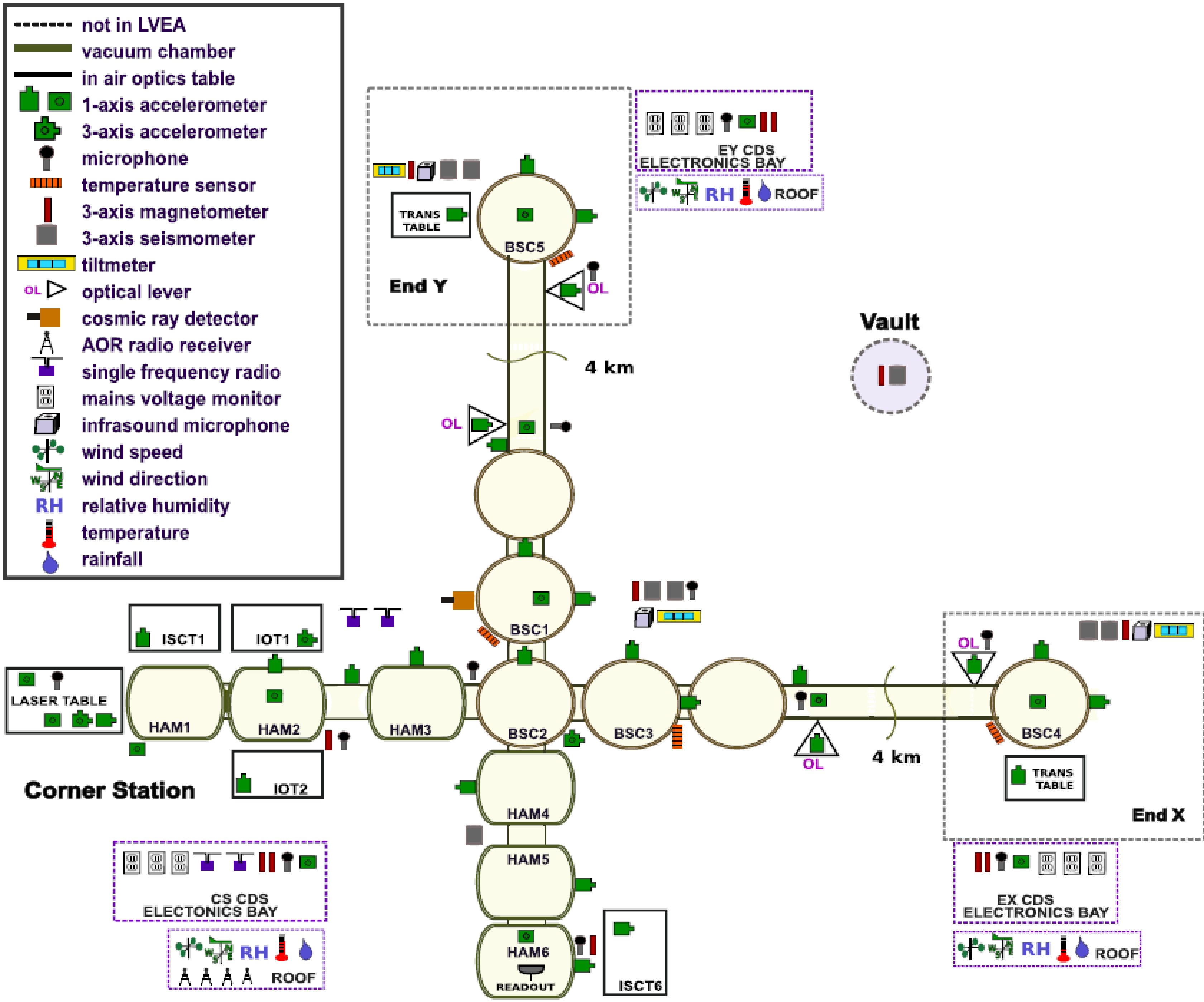
Environmental noise

- Seismic noise
- Newtonian noise
- Acoustic noise
- EM interference



not in LVEA
vacuum chamber
in air optics table
1-axis accelerometer
3-axis accelerometer
microphone
temperature sensor
3-axis magnetometer
3-axis seismometer
tiltmeter
OL
optical lever
cosmic ray detector
AOR radio receiver
single frequency radio
mains voltage monitor
infrasound microphone
wind speed
wind direction
RH
relative humidity
temperature
rainfall
EY CDS
ELECTRONICS BAY
RH
ROOF
TRANS
TABLE
BSC5
End Y
OL
Vault
4 km
OL
BSC1
ISCT1
IOT1
LASER TABLE
HAM1
HAM2
HAM3
BSC2
BSC3
BSC4
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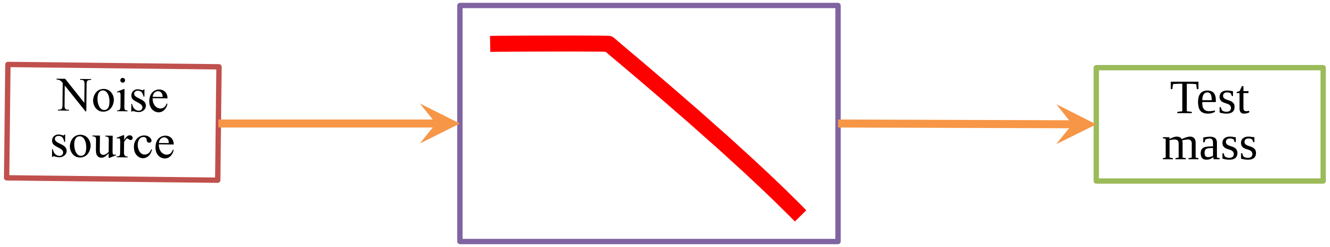
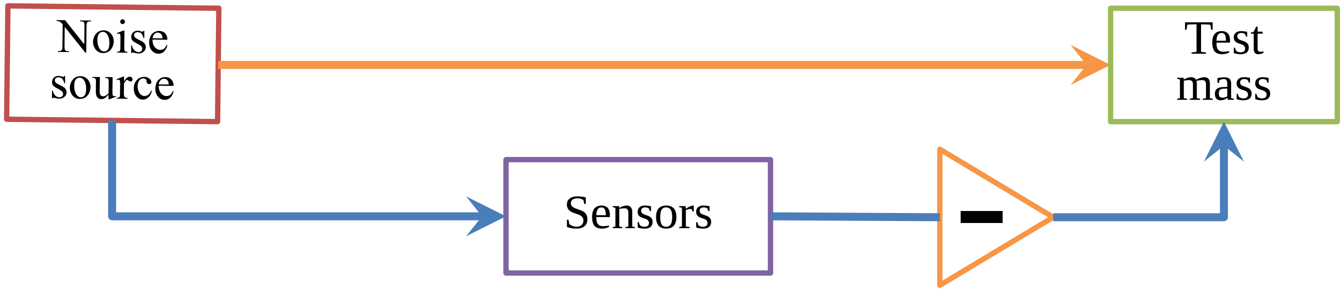
4 km
TRANS
TABLE
End X
IOT2
Corner Station
HAM4
HAM5
HAM6
READOUT
ISCT6
CS CDS
ELECTONICS BAY
RH
ROOF
EX CDS
ELECTRONICS BAY
RH
ROOF

How to reduce environmental noise

1. Passive isolation:

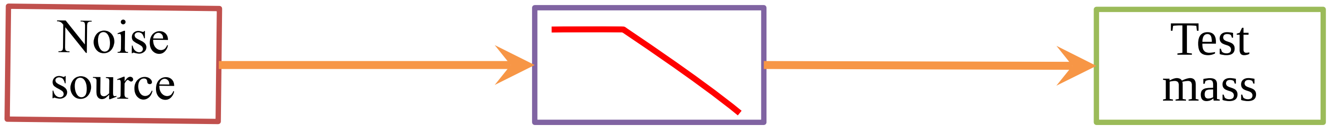


2. Active cancelation: (on-line or off-line)

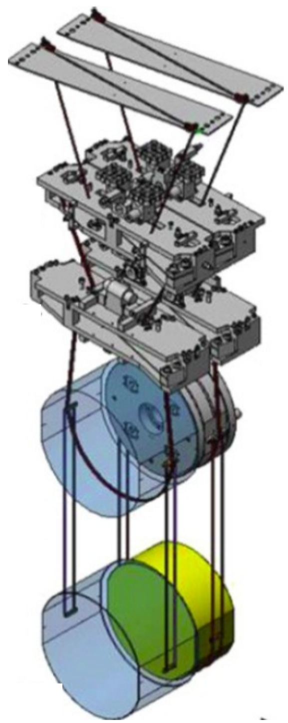


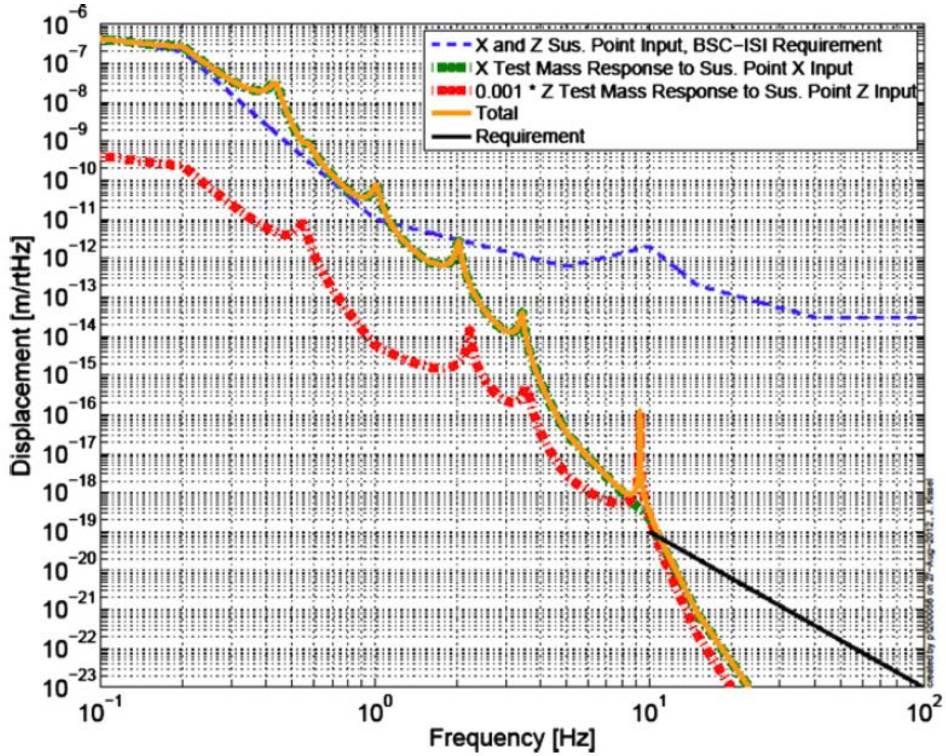
Example: Seismic noise

1. Passive isolation:



Advanced LIGO quadruple suspension:

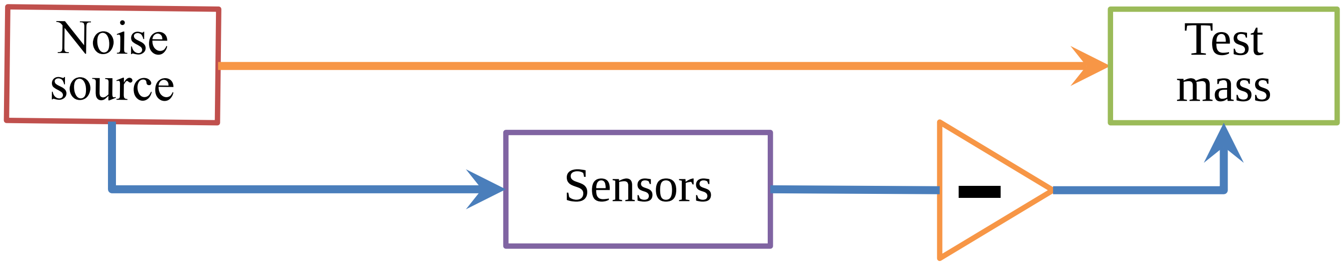


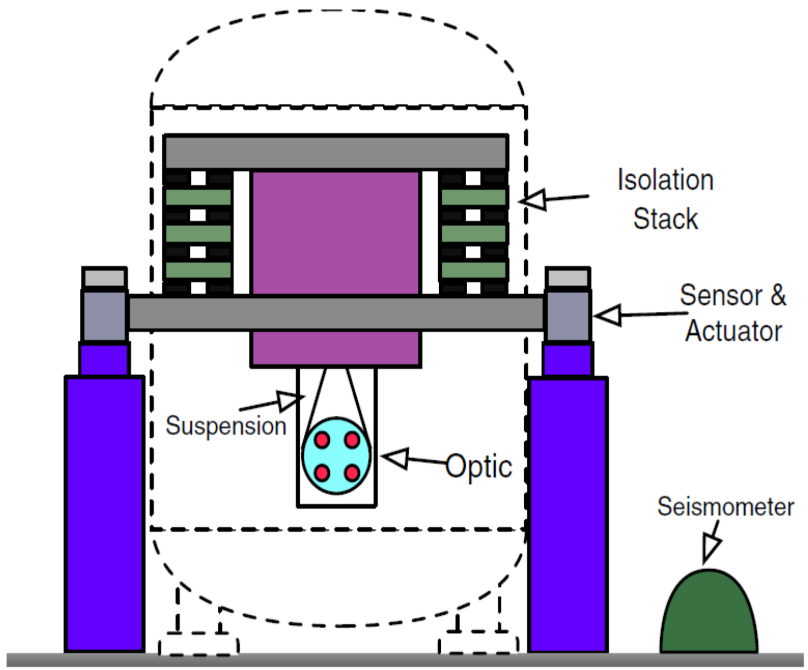


Seven orders of magnitude passive isolation

Example: Seismic noise

2. Active cancelation: **(on-line or off-line)**





Similar technique can be used for cancelling Newtonian noise

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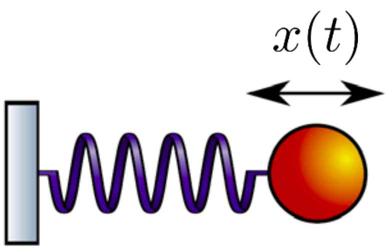
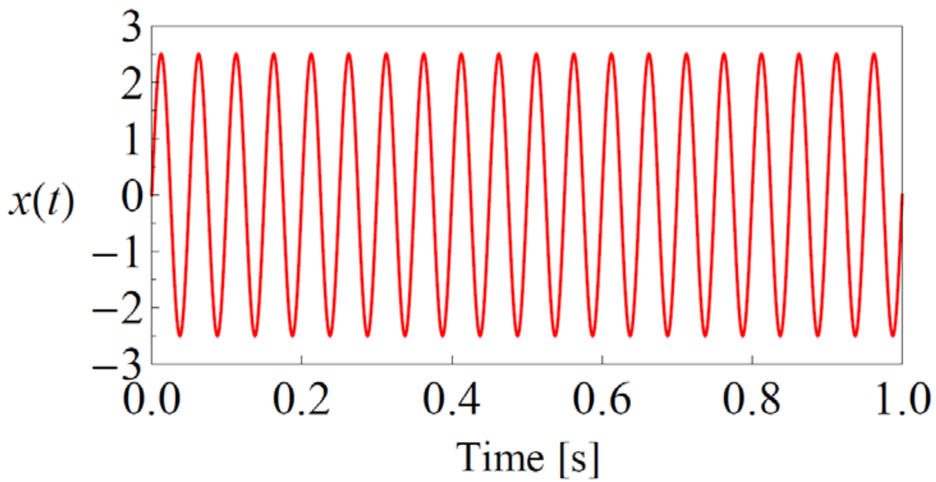
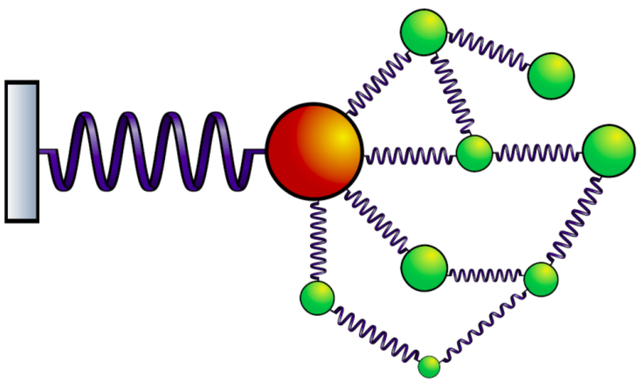
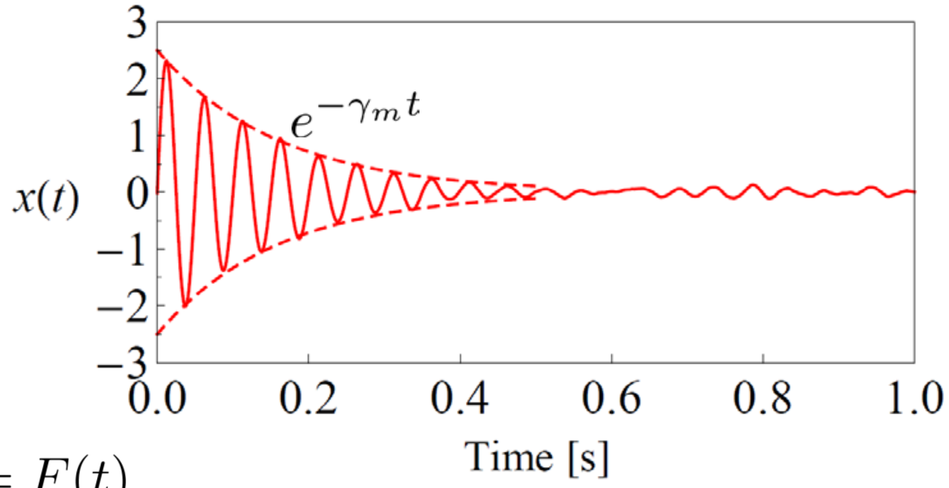
Fluctuation-dissipation theorem (FDT)





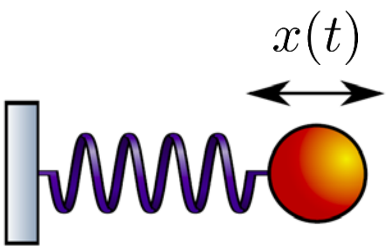
$$m[\ddot{x}(t) + \omega_m^2 x(t)] = F(t)$$

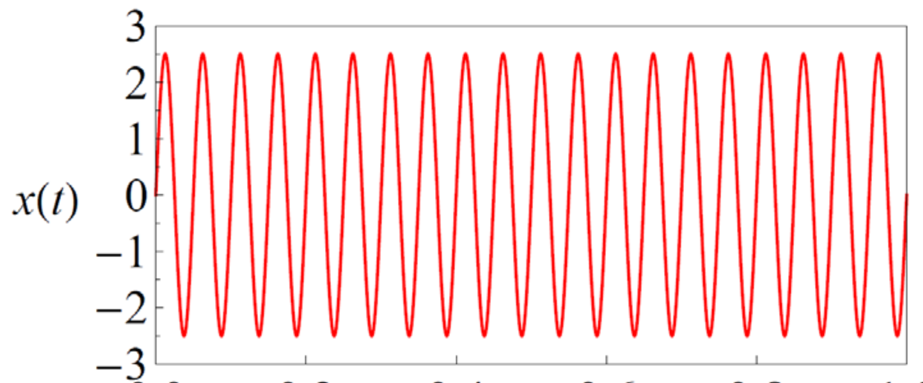




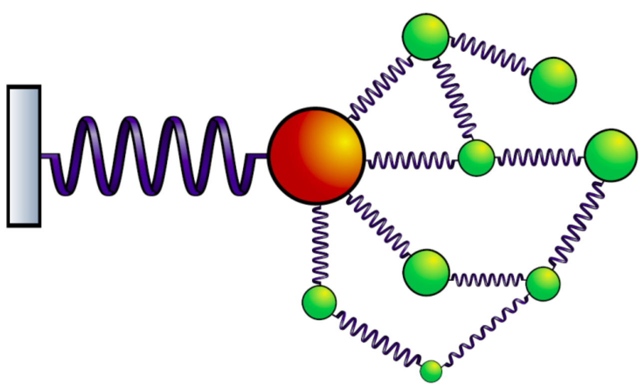
$$m[\ddot{x}(t) + \gamma_m \dot{x}(t) + \omega_m^2 x(t)] = F(t)$$

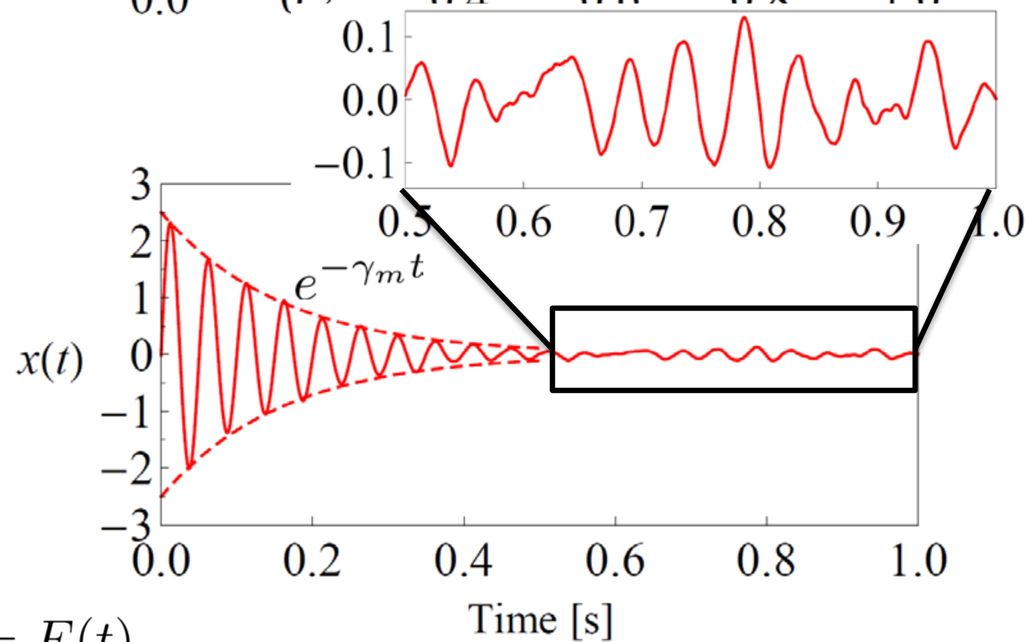
Fluctuation-dissipation theorem (FDT)





$$m[\ddot{x}(t) + \omega_m^2 x(t)] = F(t)$$



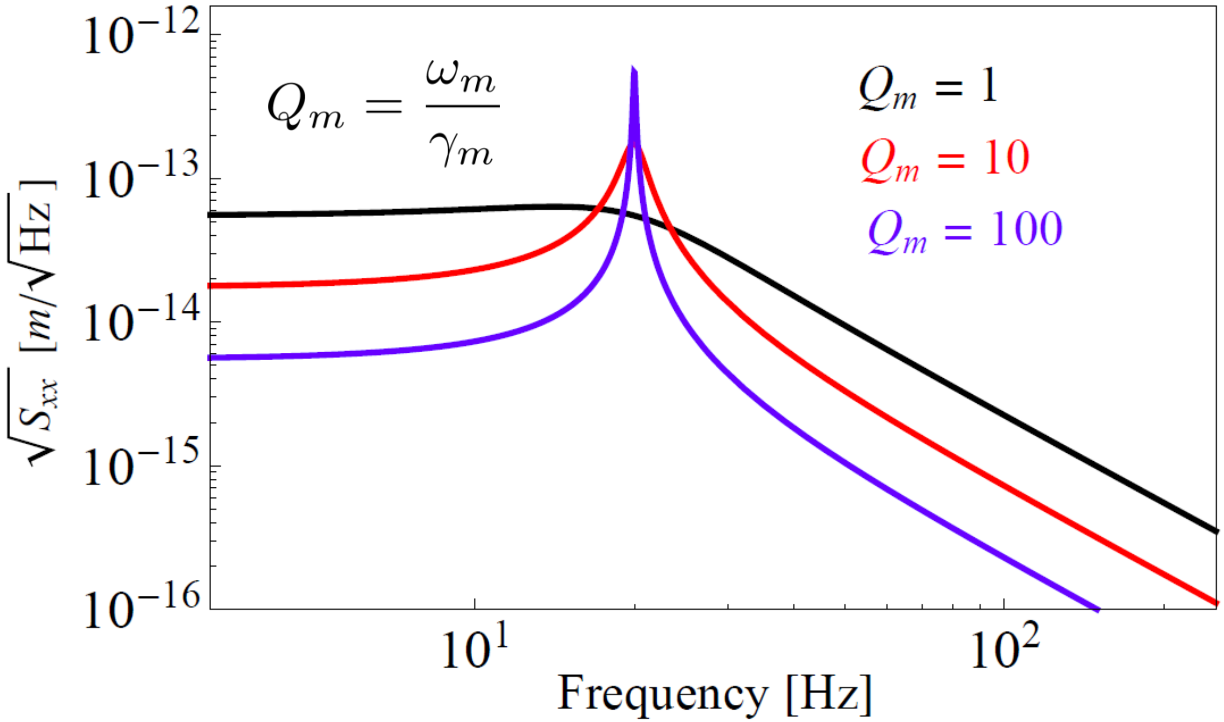


$$m[\ddot{x}(t) + \gamma_m \dot{x}(t) + \omega_m^2 x(t)] = F(t)$$

Fluctuation-dissipation theorem (FDT)

FDT: $$S_{xx}(f) = \frac{k_B T}{2\pi f} \mathrm{Im}[\chi_{xx}(f)]$$

Susceptibility: $$\chi_{xx}(f) = \frac{\tilde{x}(f)}{\tilde{F}(f)} = \frac{1}{m[-(2\pi f)^2 - i\gamma_m(2\pi f) + \omega_m^2]}$$



H. Callen, and T. Welton, Phys. Rev. 83, 34 (1951)

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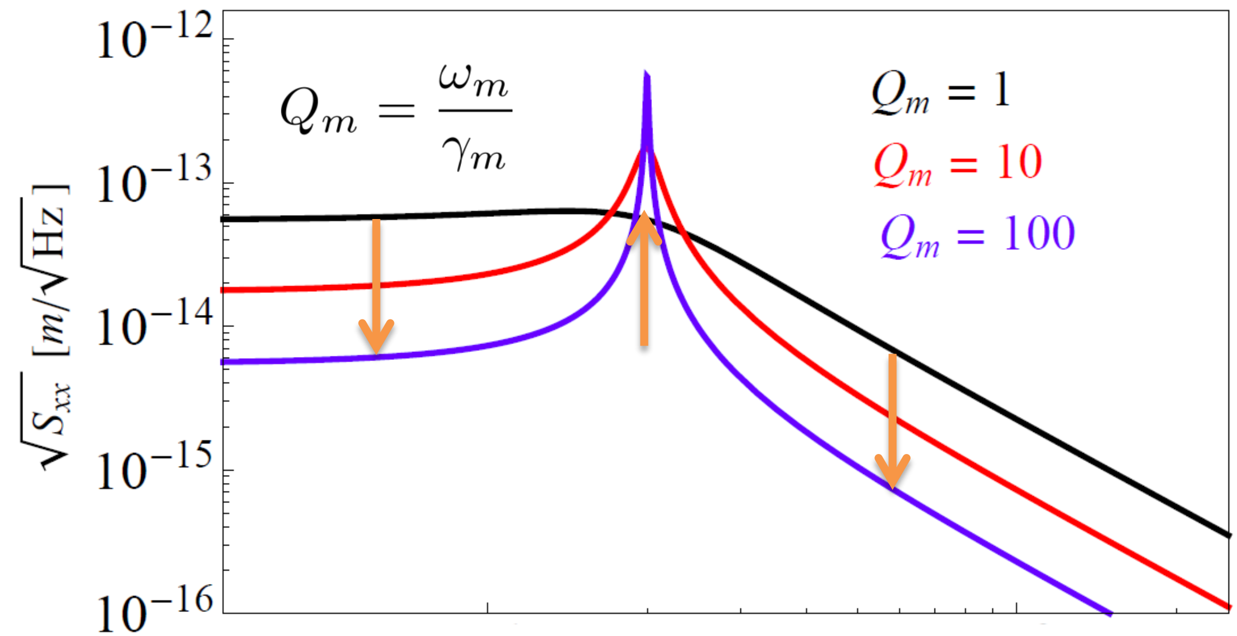

$$\frac{1}{2}m\omega_m^2\langle x^2\rangle = \frac{1}{2}m\omega_m^2\int \mathrm{d}f\, S_{xx}(f) = \frac{1}{2}k_B T$$ **(Equipartition)**

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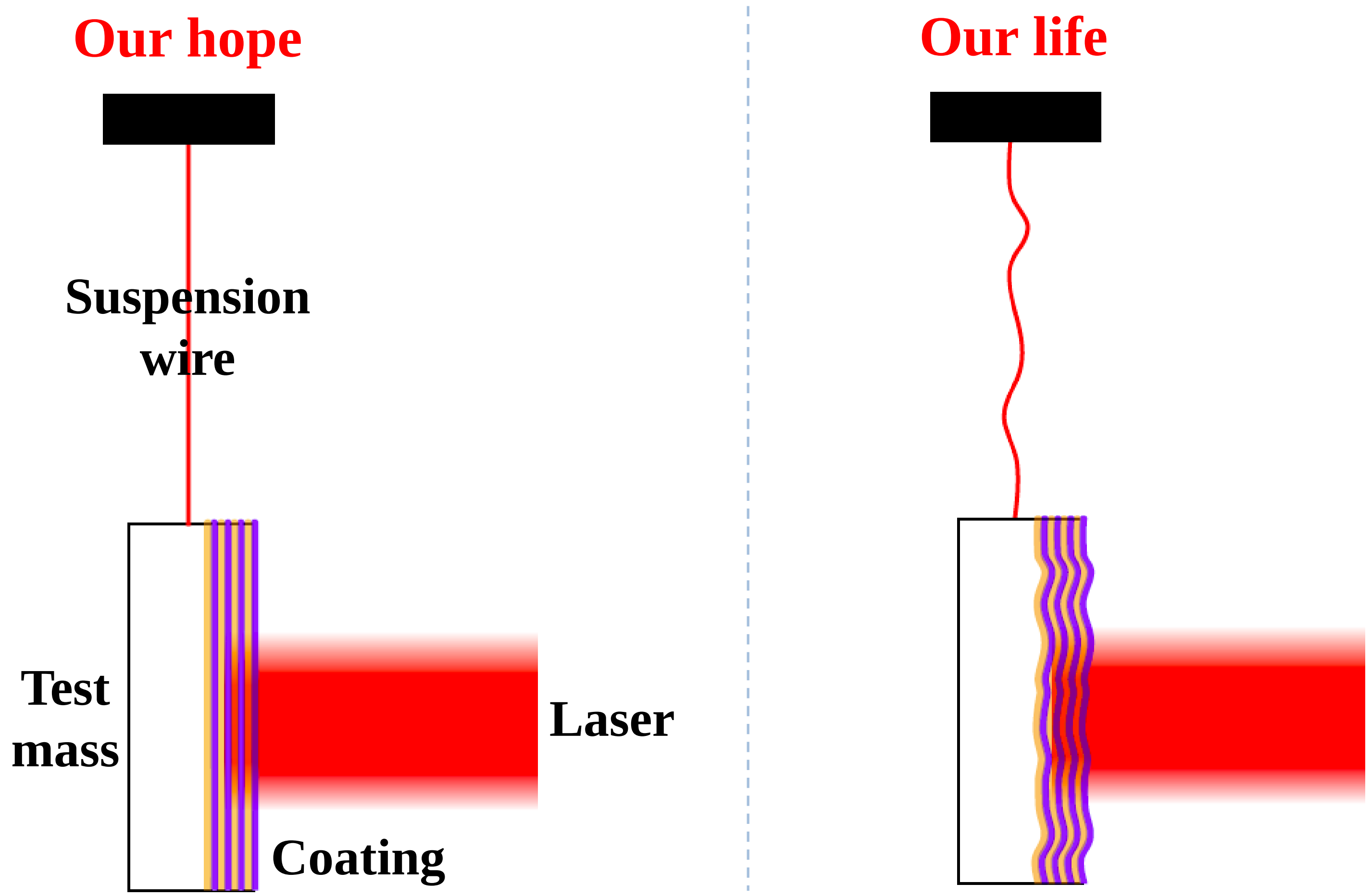
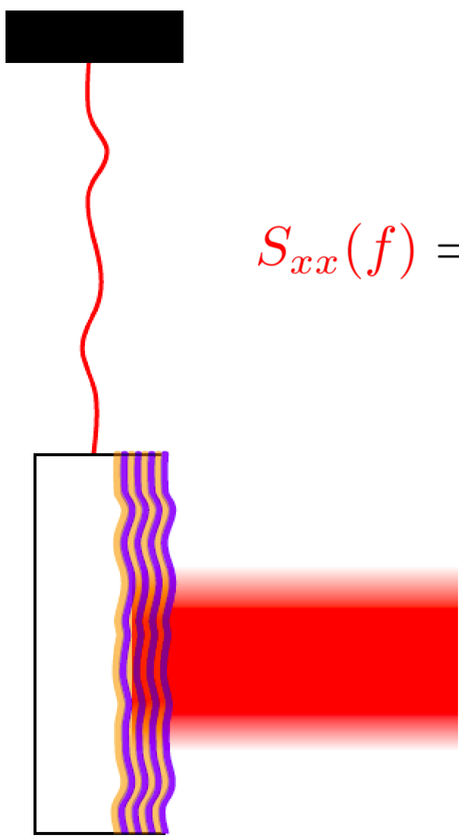
Sources of thermal noise



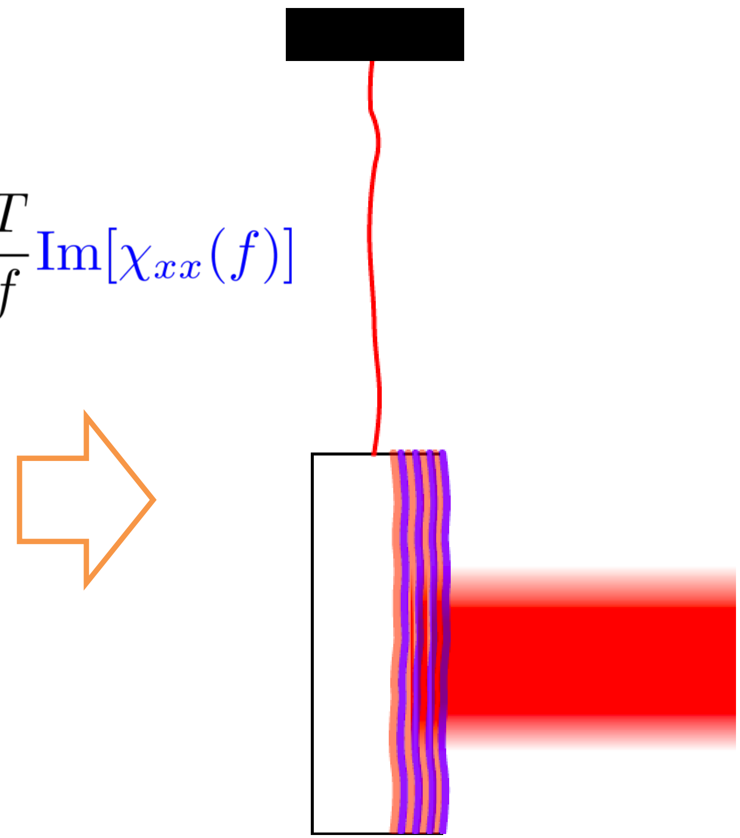
Thermal noises are ubiquitous. Dominant: suspension and coating.

How to reduce thermal noise

1. Using low temperature



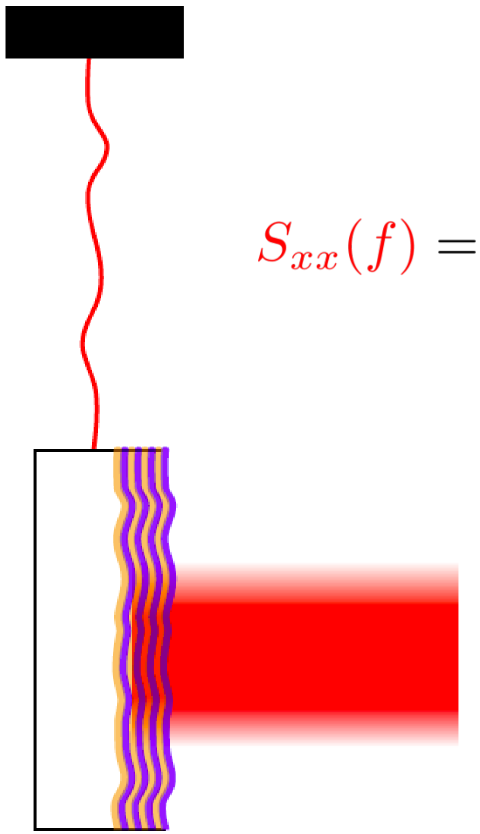
$$S_{xx}(f) = \frac{k_B T}{2\pi f}\mathrm{Im}[\chi_{xx}(f)]$$



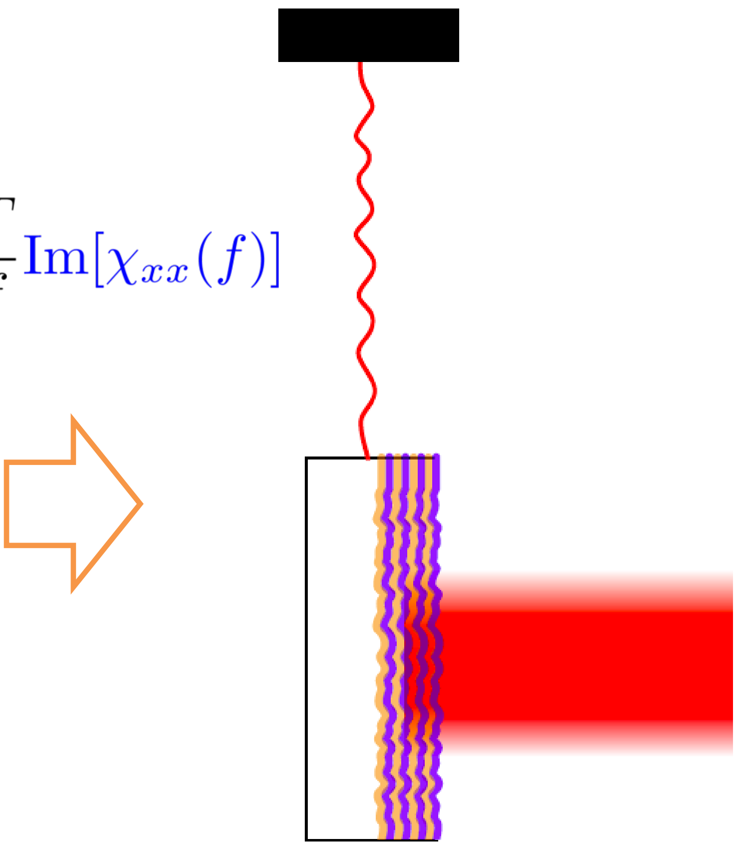
KAGRA in JAPAN will operated at cryogenic temperature.
Some designs of future detectors also incorporates cryogenic.

How to reduce thermal noise

2. Using high-quality material



$$S_{xx}(f) = \frac{k_B T}{2\pi f}\mathrm{Im}[\chi_{xx}(f)]$$

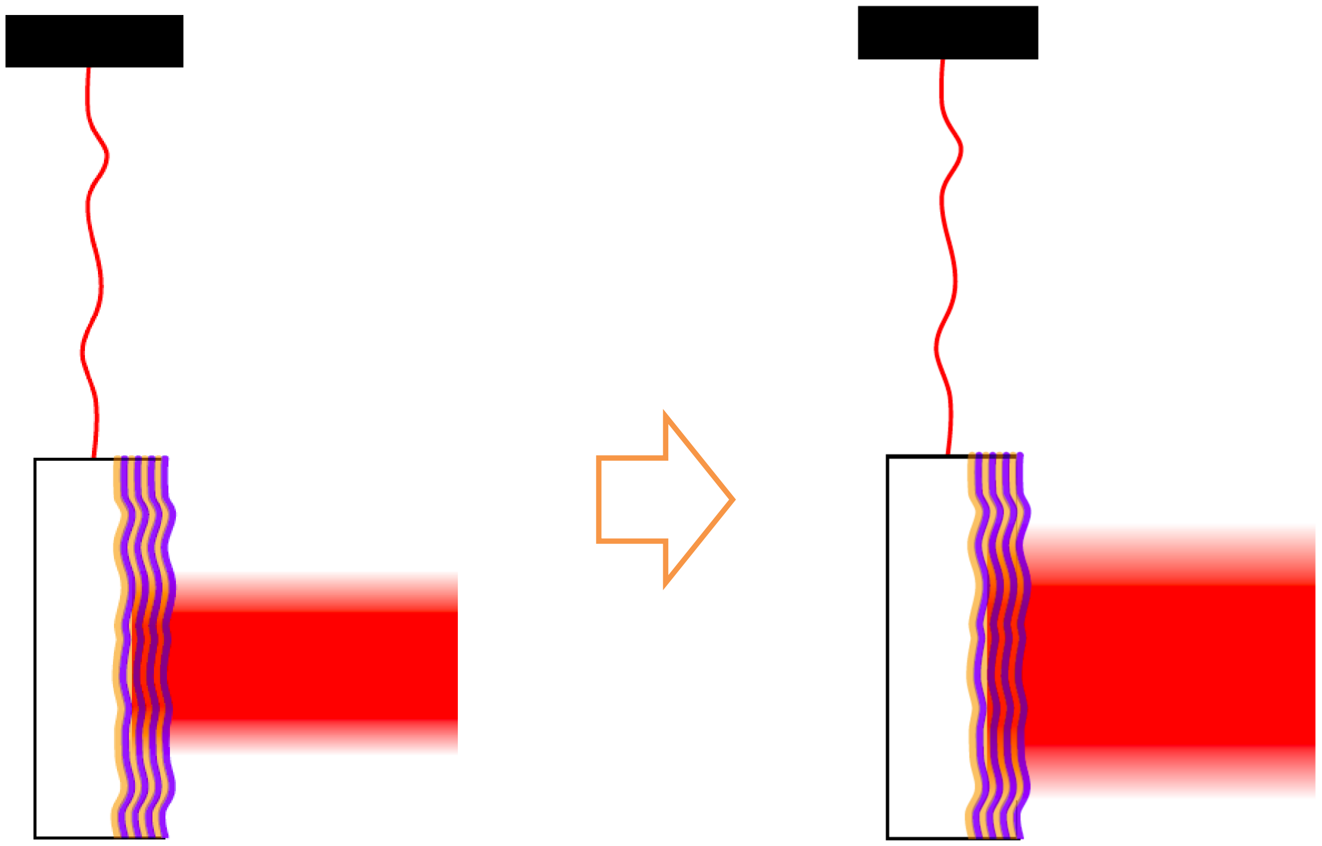


FDT

Concentrating thermal energy; pushing noise outside band of interest.

How to reduce thermal noise

3. Using larger beam size



Averaging out the thermal fluctuation.

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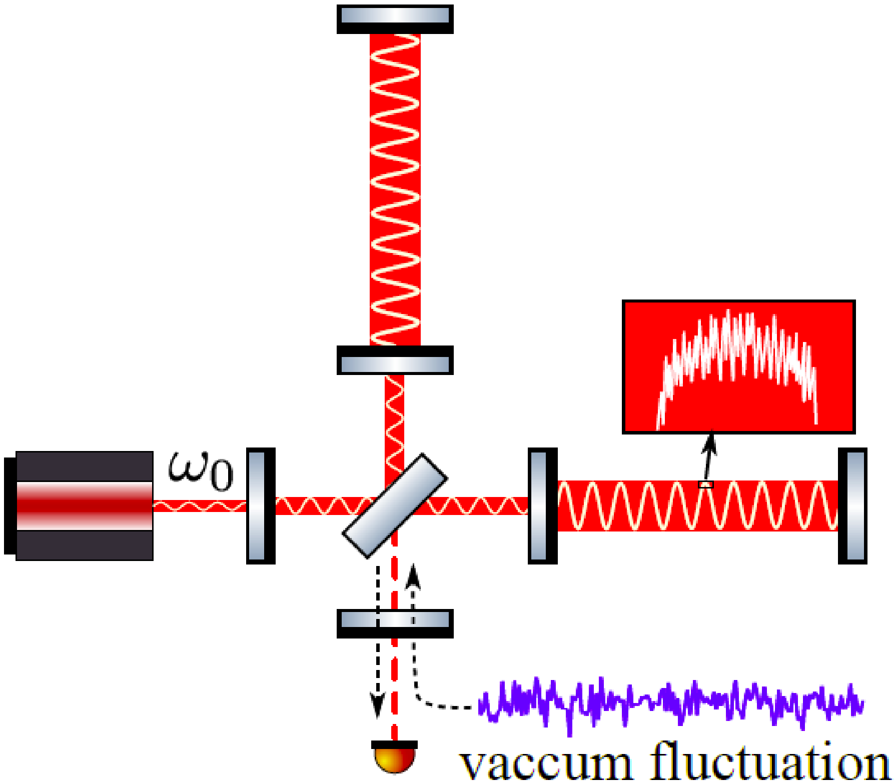
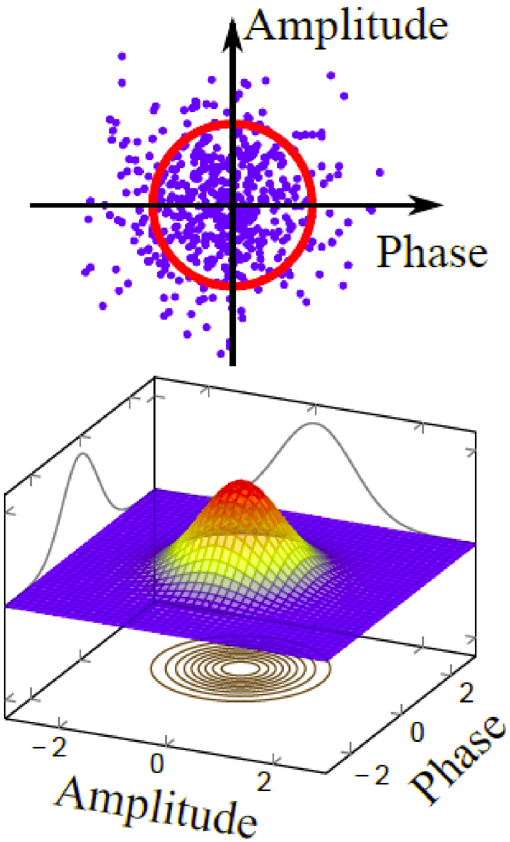
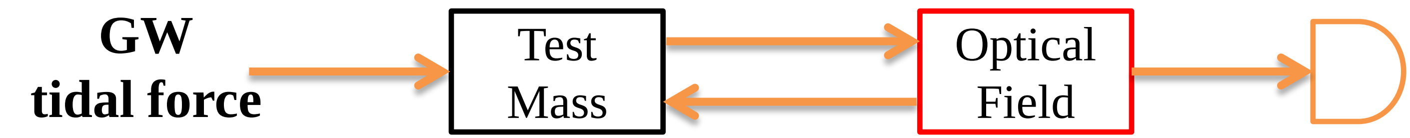
Origin of quantum noise





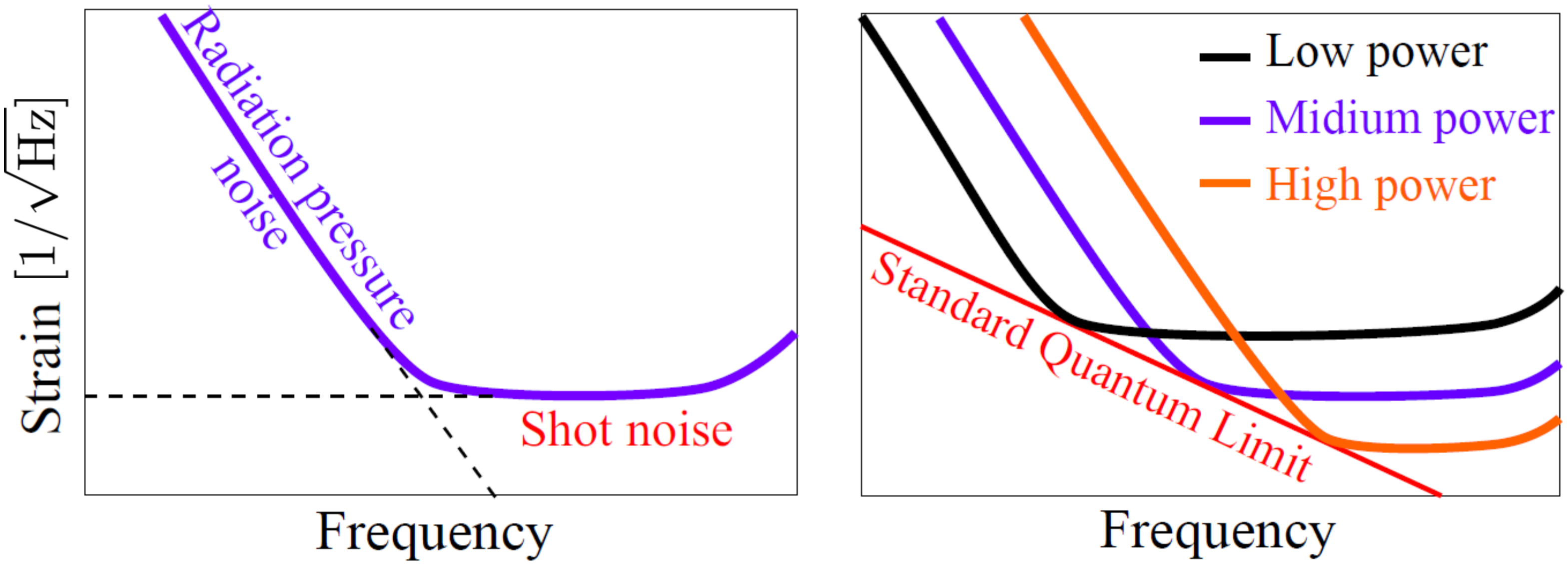
Standard quantum limit



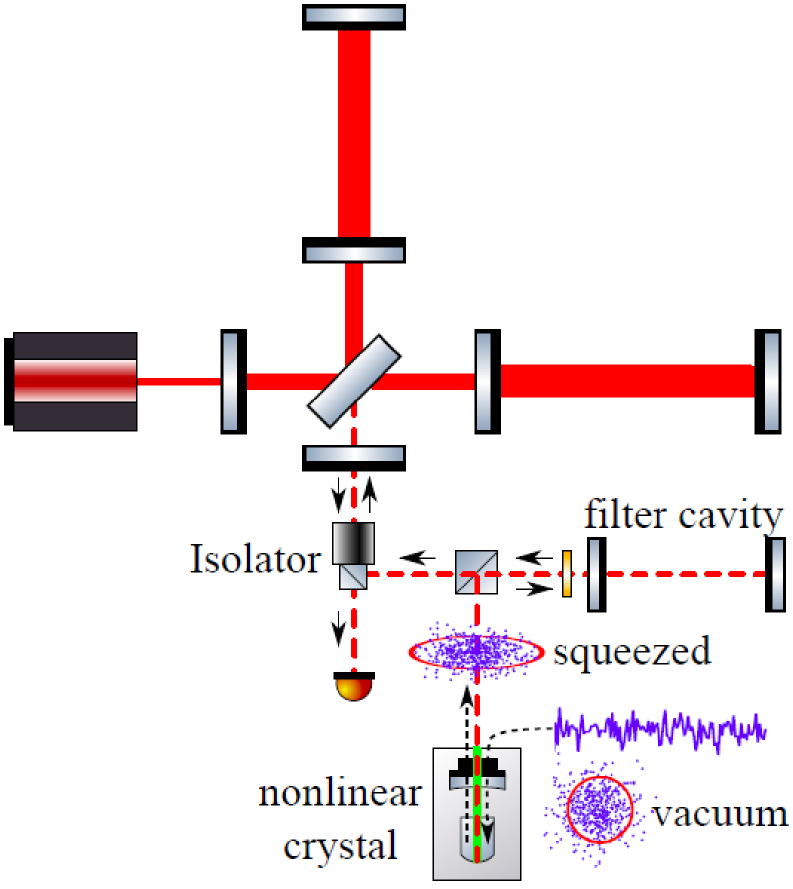
Quantum fluctuation in optical phase ⇨ **Shot noise**

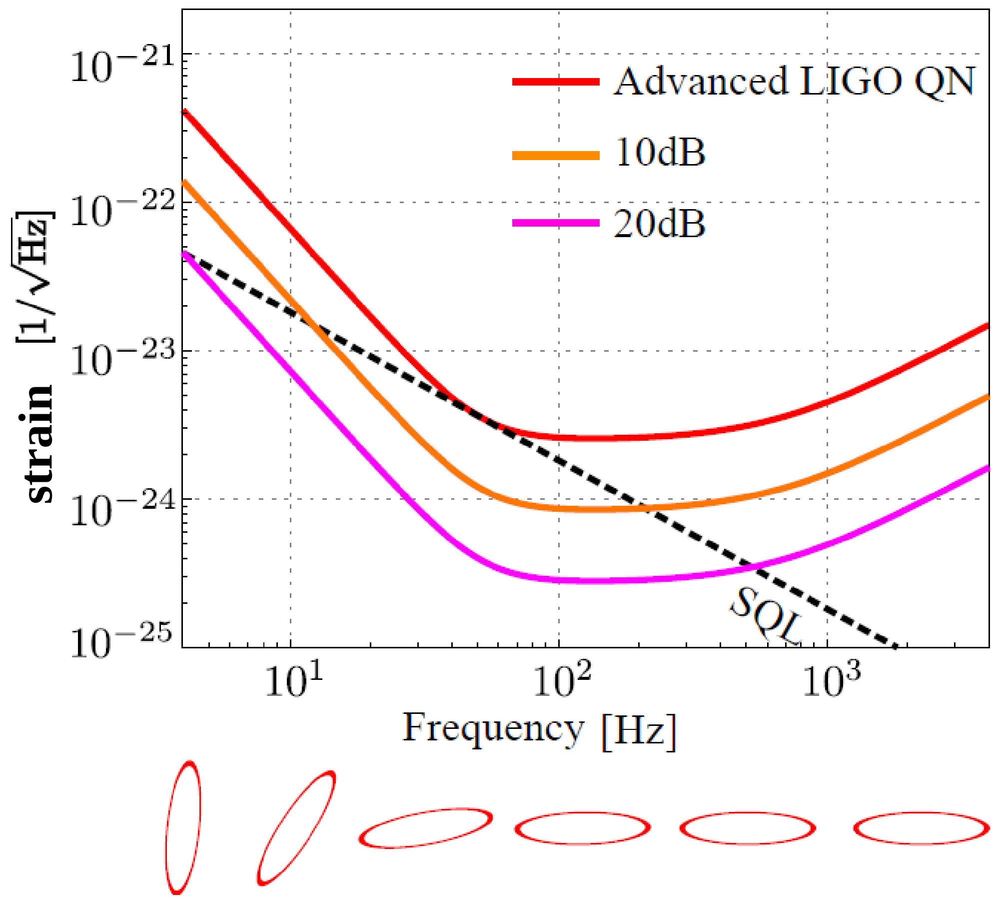
In optical amplitude ⇨ **Power fluctuation** ⇨ **Radiation pressure noise**

Standard Quantum Limit:



Frequency-dependent squeezing

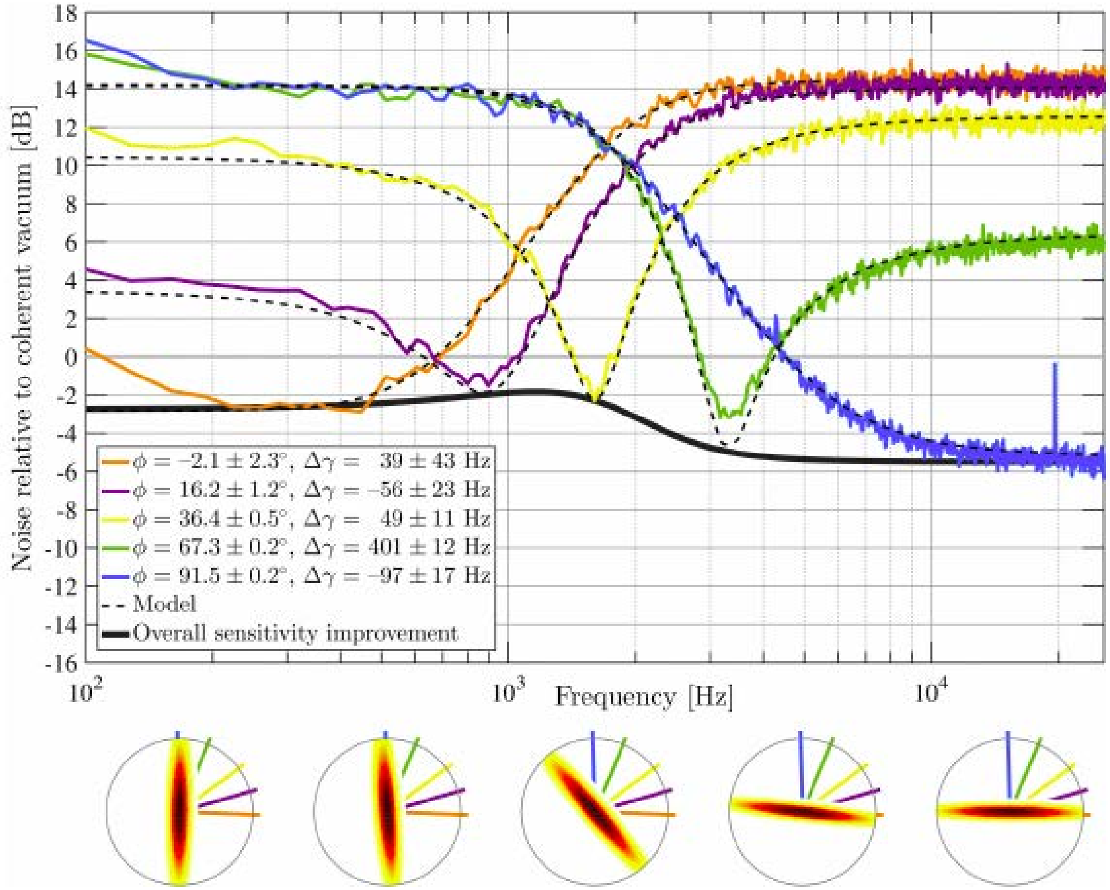




J. Kimble, ***et al. Conversion of conventional GW interferometers into QND by modifying their input and/or output optics,*** **PRD 65, 022002 (2001)**

State-of-the-art

MIT proof-of-principle demonstration



E. Oelker *et al.*, *Audio-Band Frequency-Dependent Squeezing for Gravitational-Wave Detectors*, PRL 116, 041102 (2016)

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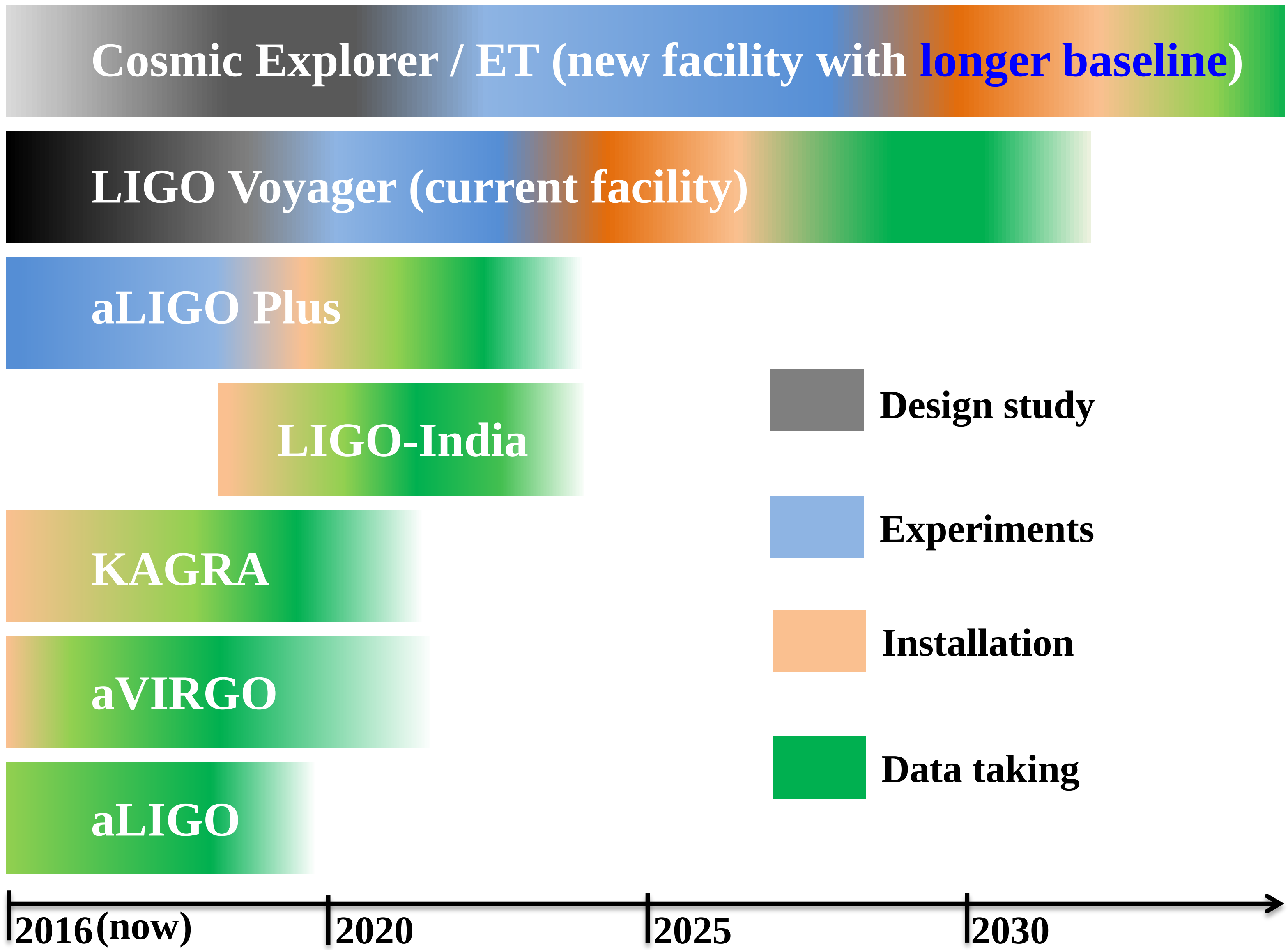
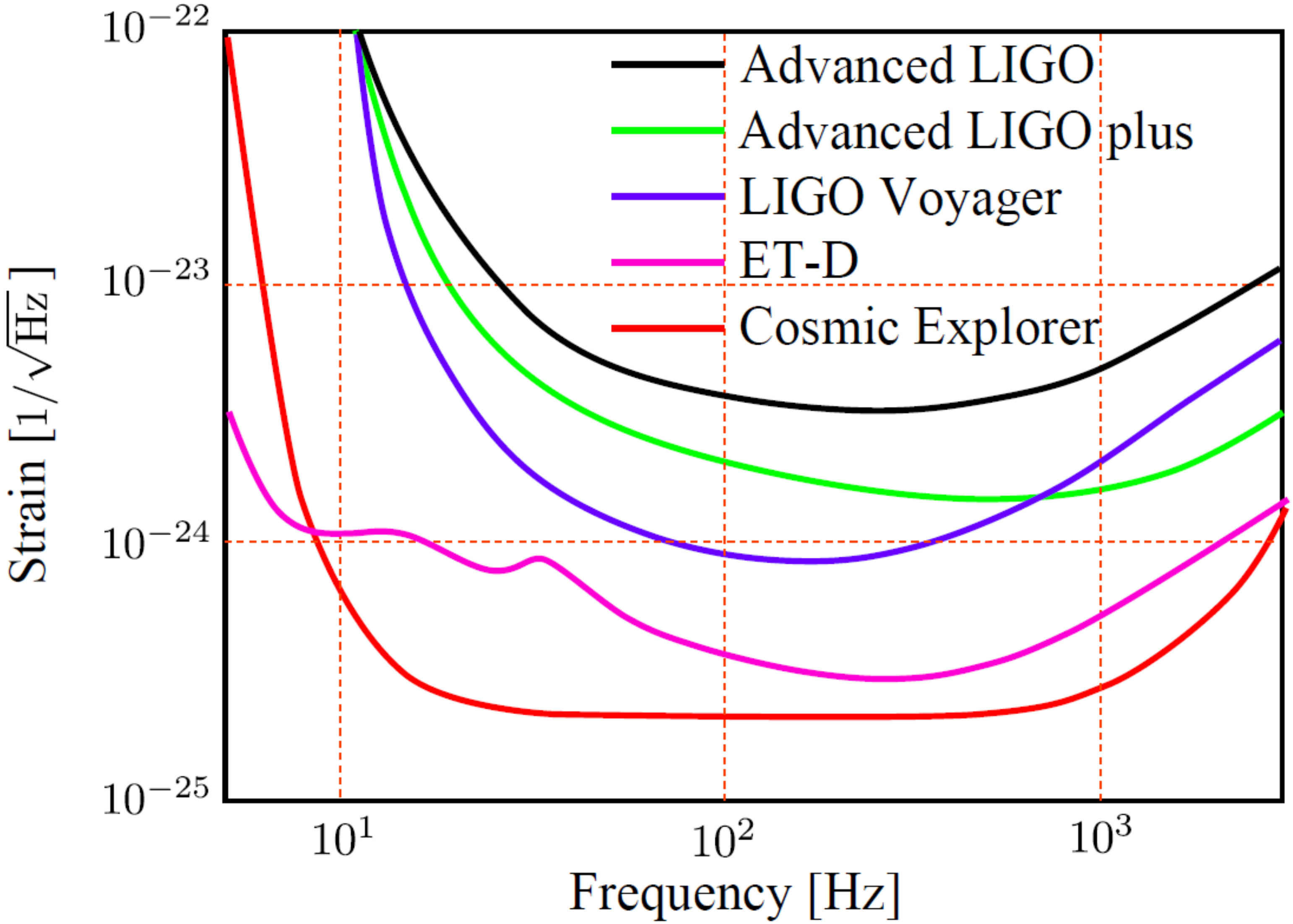
Timeline of current and future detectors



Sensitivity of future detectors



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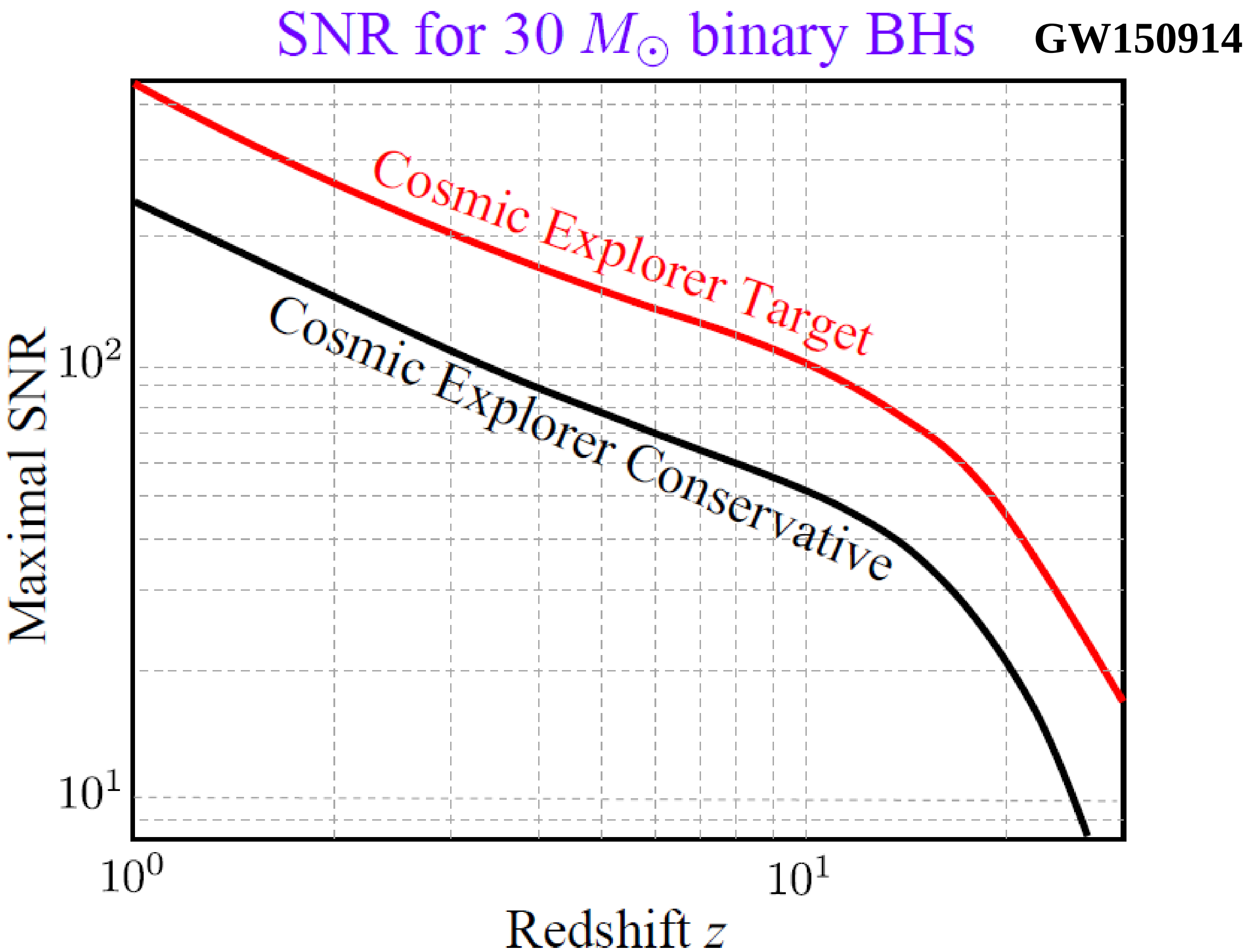

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- R. X. Adhikari *et al*, LIGO-DCC: T1400226 –v7 (2016)

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- ET science team, Einstein GW Telescope conceptual design study

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- S. Dwyer *et al*, Phys. Rev. D **91**, 082001 (2015)
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Finally, refer to LIGO Instrument Science White Paper (2015-2016)

Outline

- **Background**
  - Gravitational waves and their detection
- **Basic of noise**
  - Noise spectral density and transfer function
- **Environmental noise**
  - Passive isolation and active cancellation
- **Thermal noise**
  - Fluctuation-dissipation theorem
  - How to reduce thermal noise
- **Quantum noise**
  - Standard Quantum Limit
  - Frequency-dependent squeezing
- **Current and future detectors**
  - Timeline and sensitivity