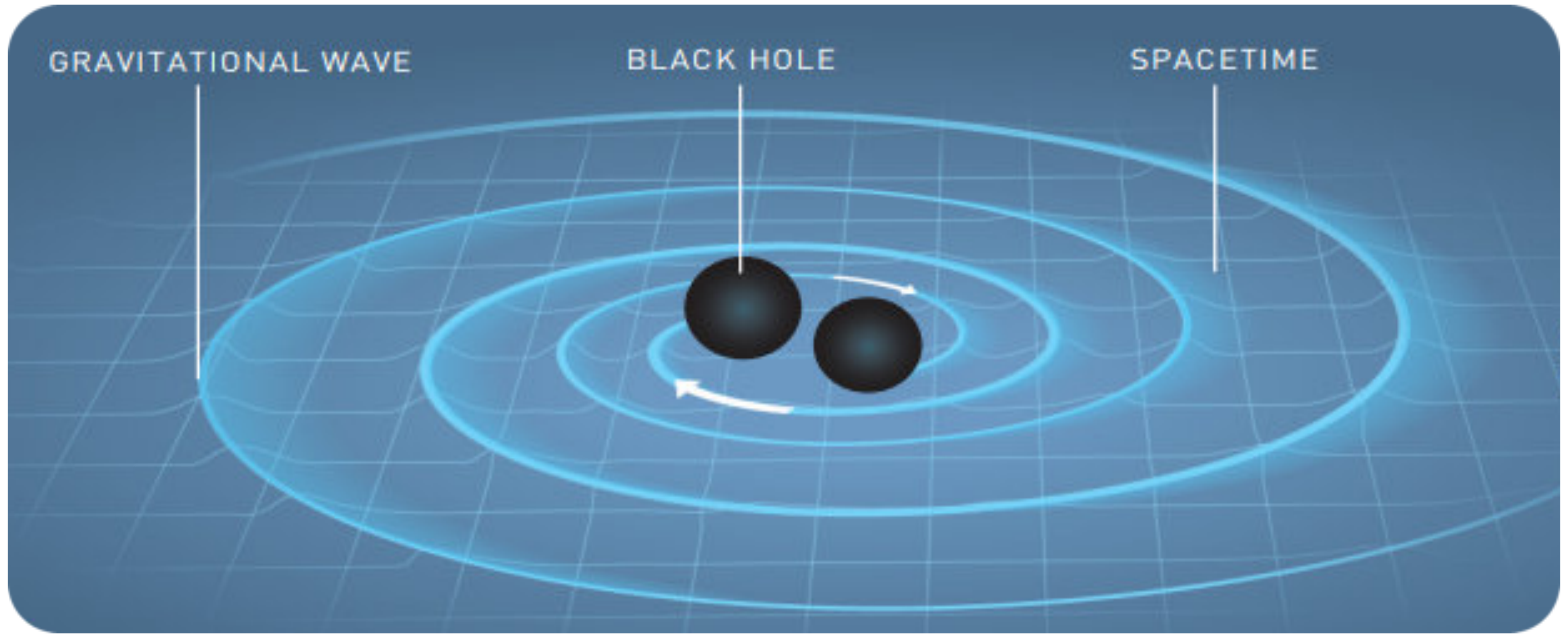
Katharina-Sophie Isleif
Junior-Prof. for Metrology
HSU, Institute for Automation Technology

Distributed seismic sensors

for Newtonian Noise Cancellation in Gravitational Wave Detectors

Gravitational wave detector

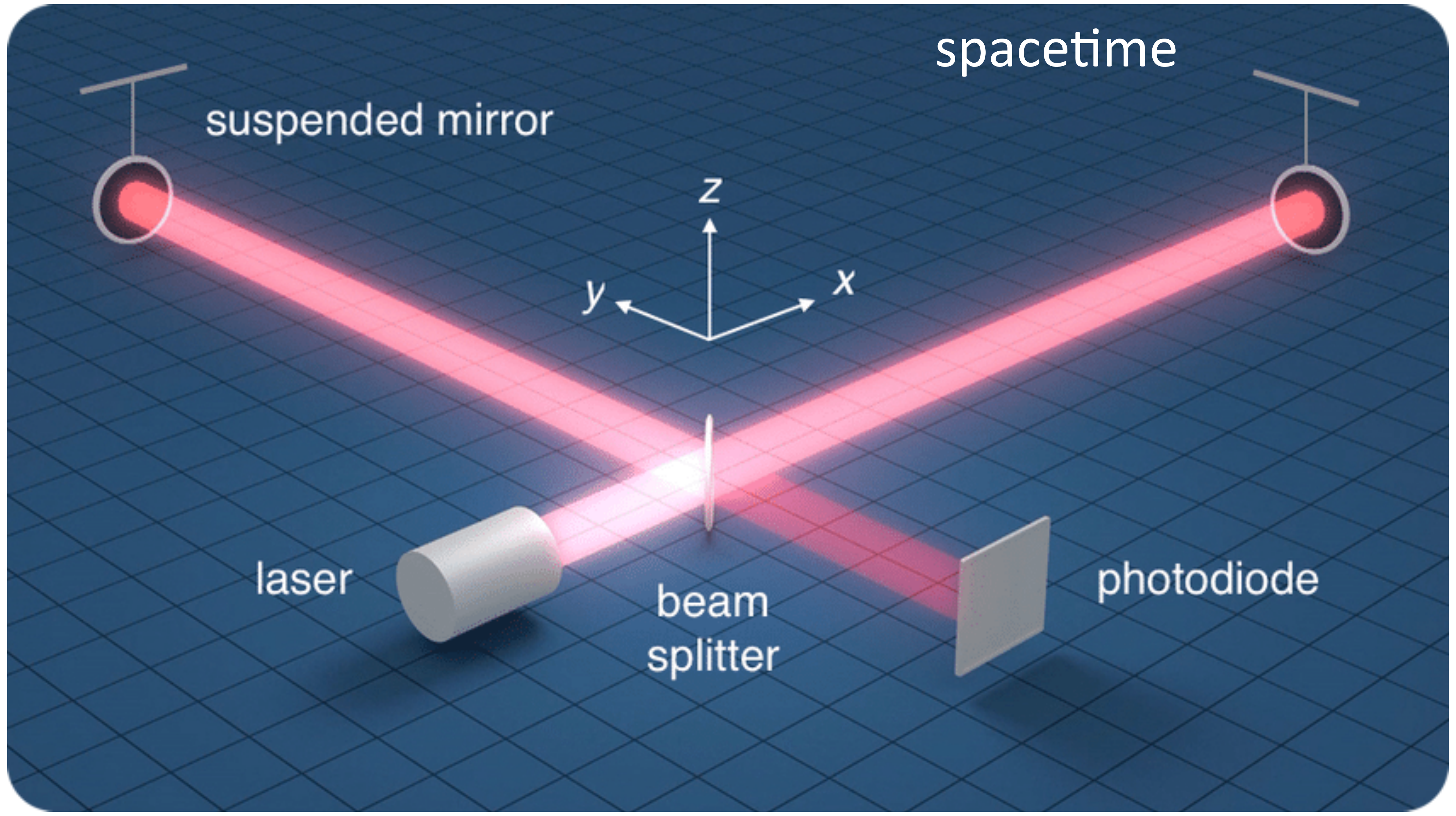
Gravitational wave (GW) source



https://spaceaustralia.com/news/new-technology-improve-gravitational-wave-detection

massive binary objects (e.g. **black holes**) orbiting each other produce **gravitational waves** (disturbances in spacetime)

GW detector using laser interferometry

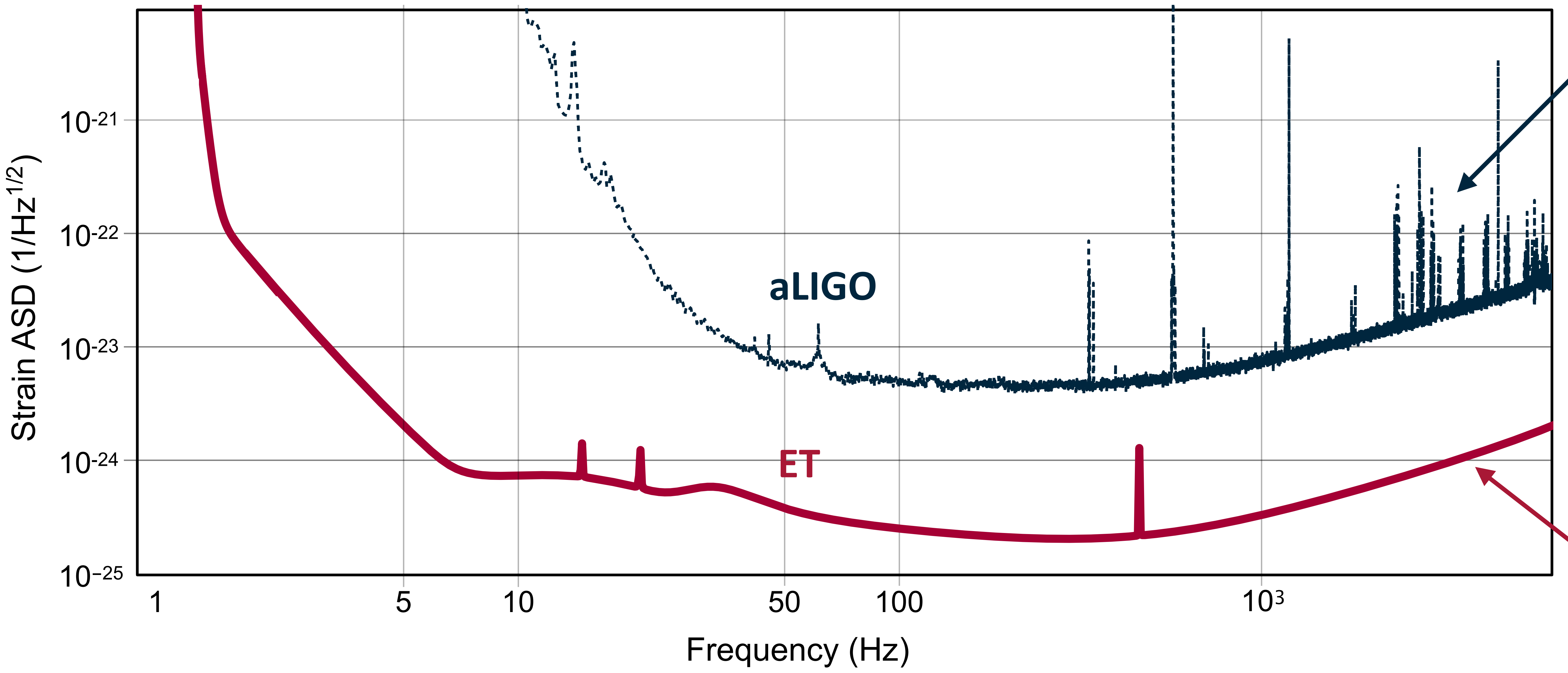


https://www.researchgate.net/publication/331246187

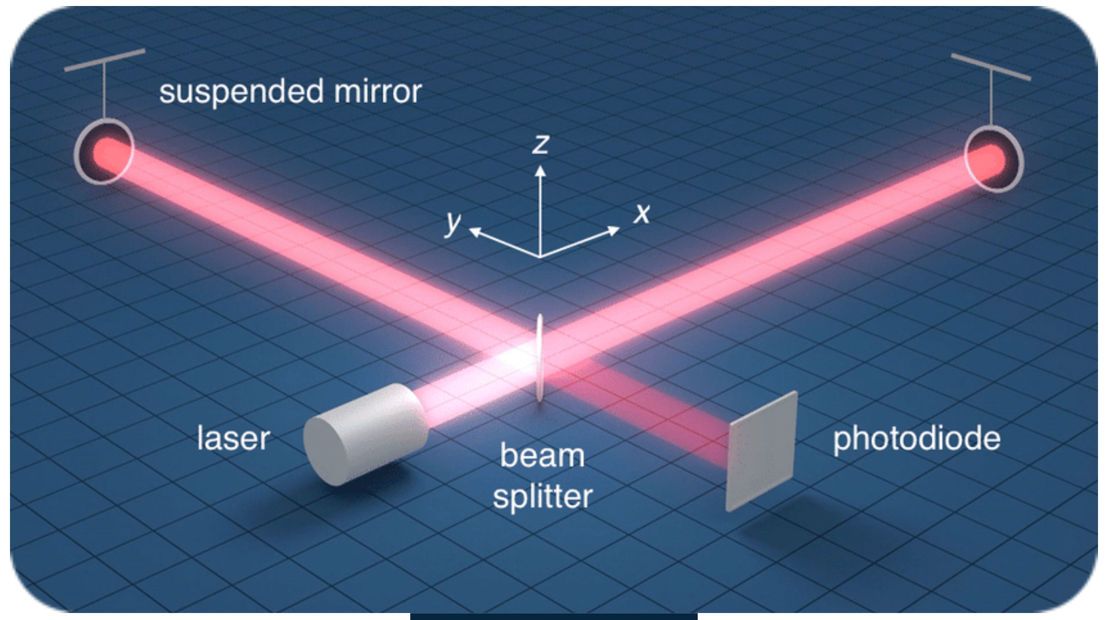
Interferometric **displacement measurement** between „free-falling“ mirrors:

$10^{-21}\,1/\sqrt{\mathrm{Hz}}$, baseline: $4 - 10\,\mathrm{km}$

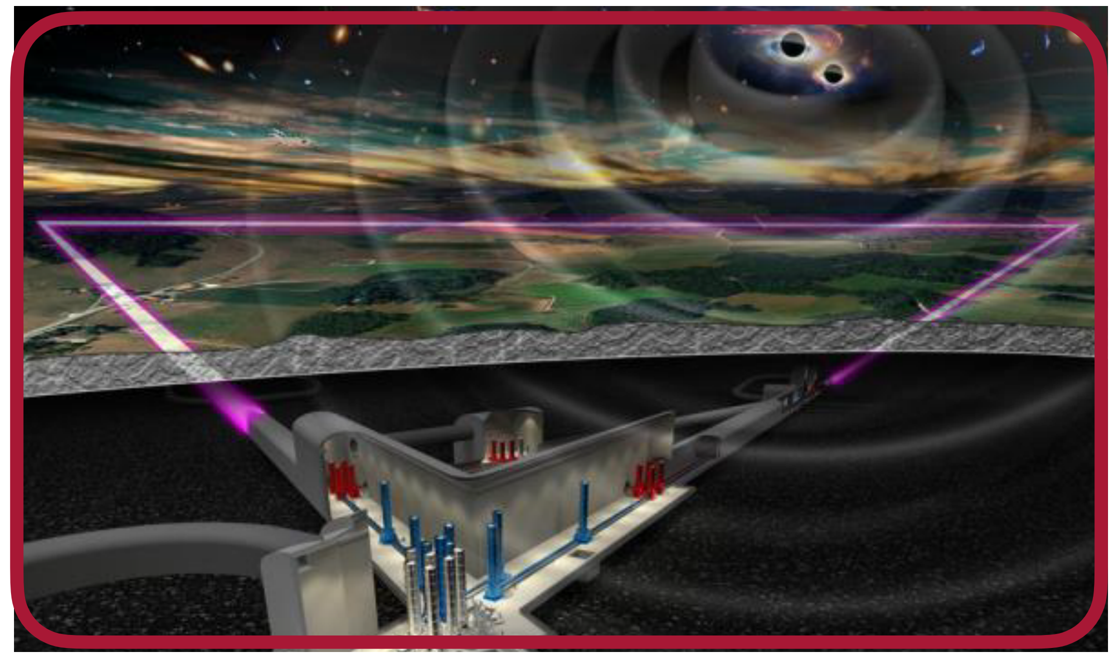
Future GW detectors



Current detectors (aLIGO, O3)



Einstein Telescope (planned in Europe)



ET design report 2020, https://gwic.ligo.org/3Gsubcomm/docs/ET-0007B-20_ETDesignReportUpdate2020.pdf

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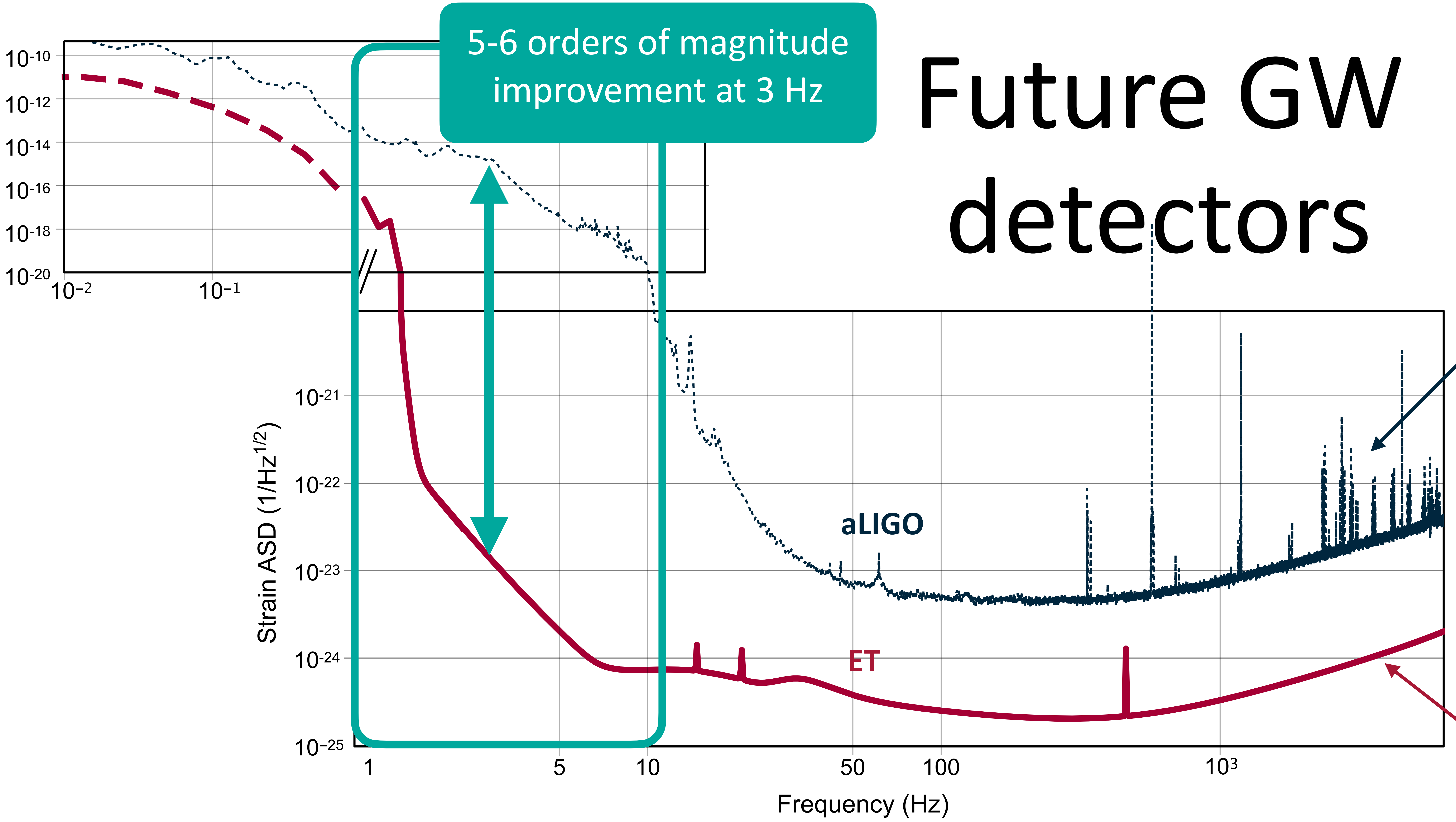

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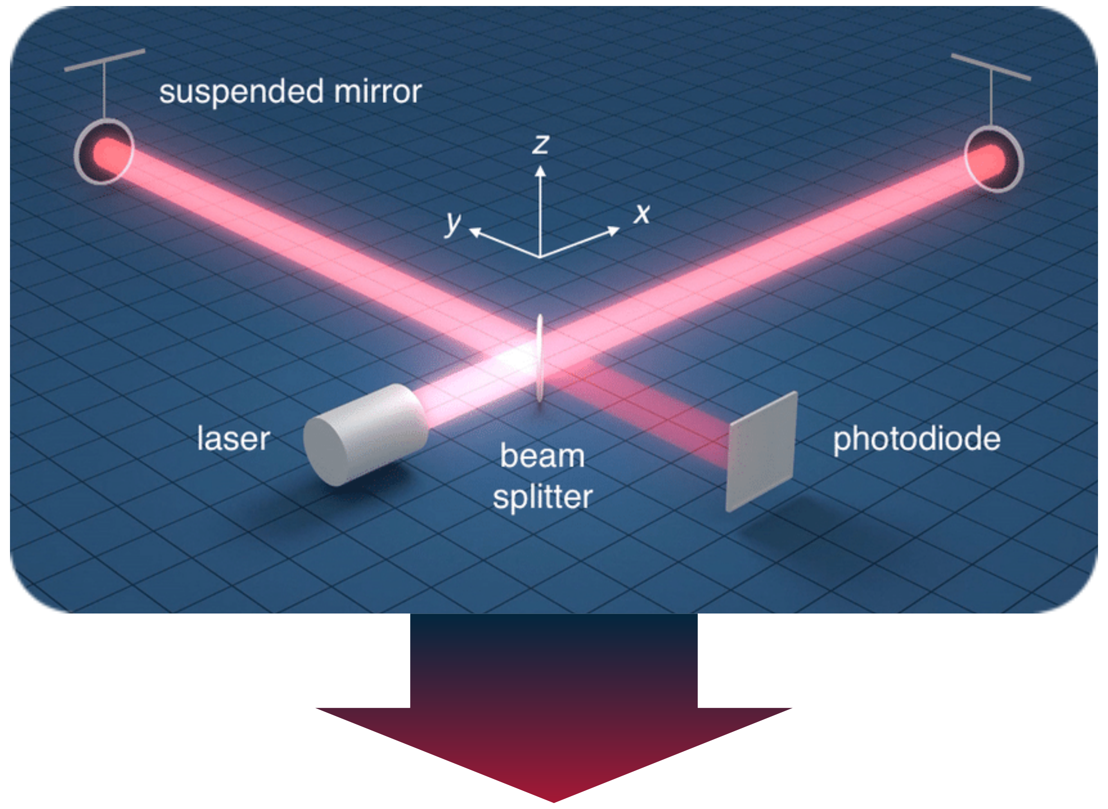

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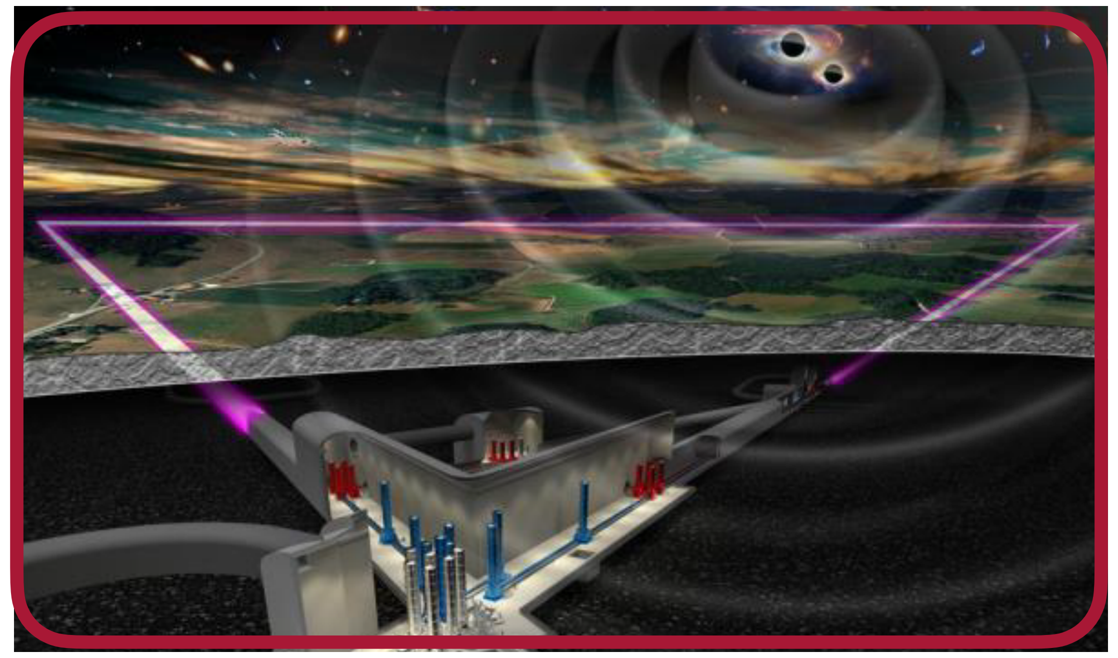

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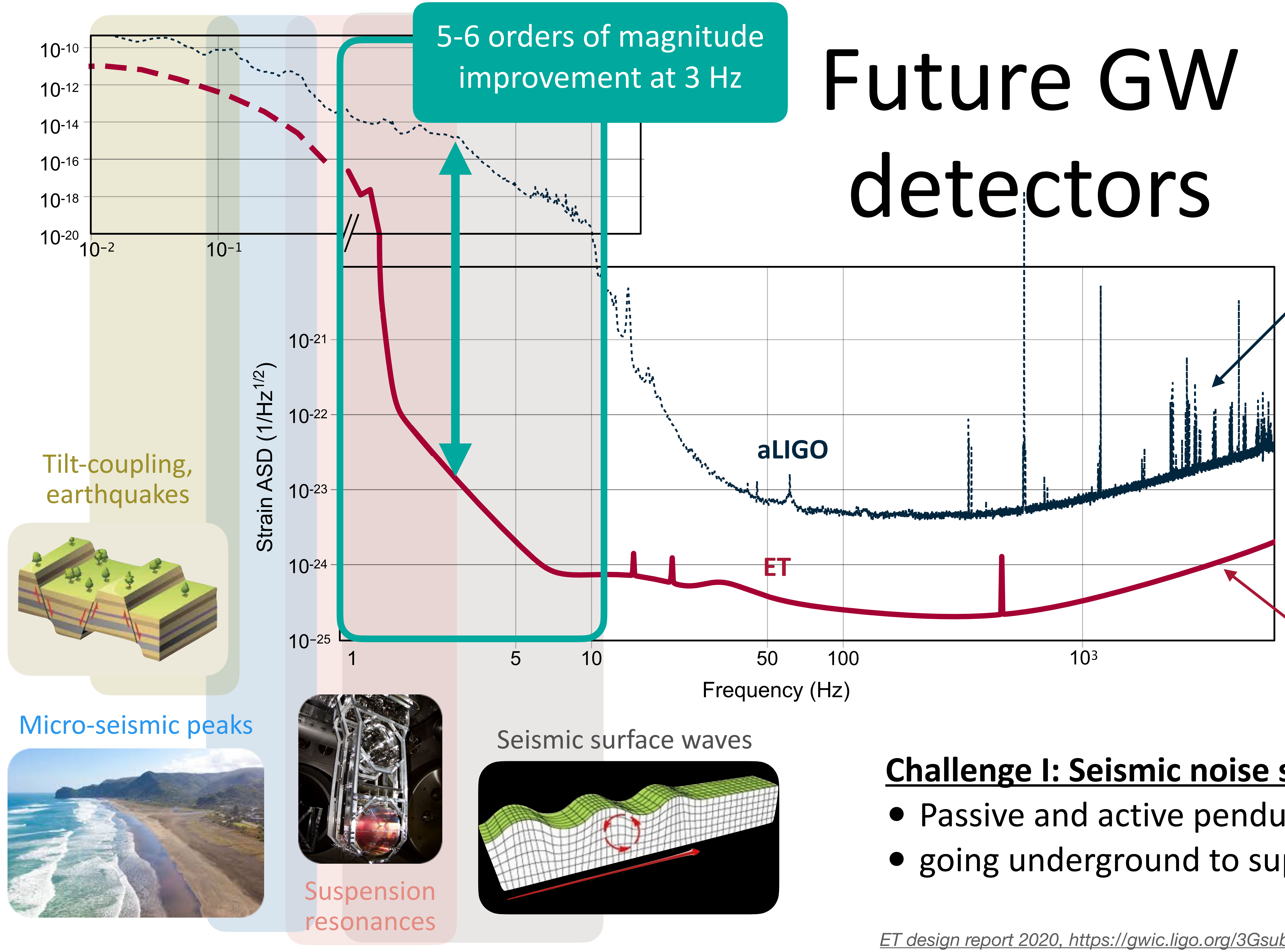

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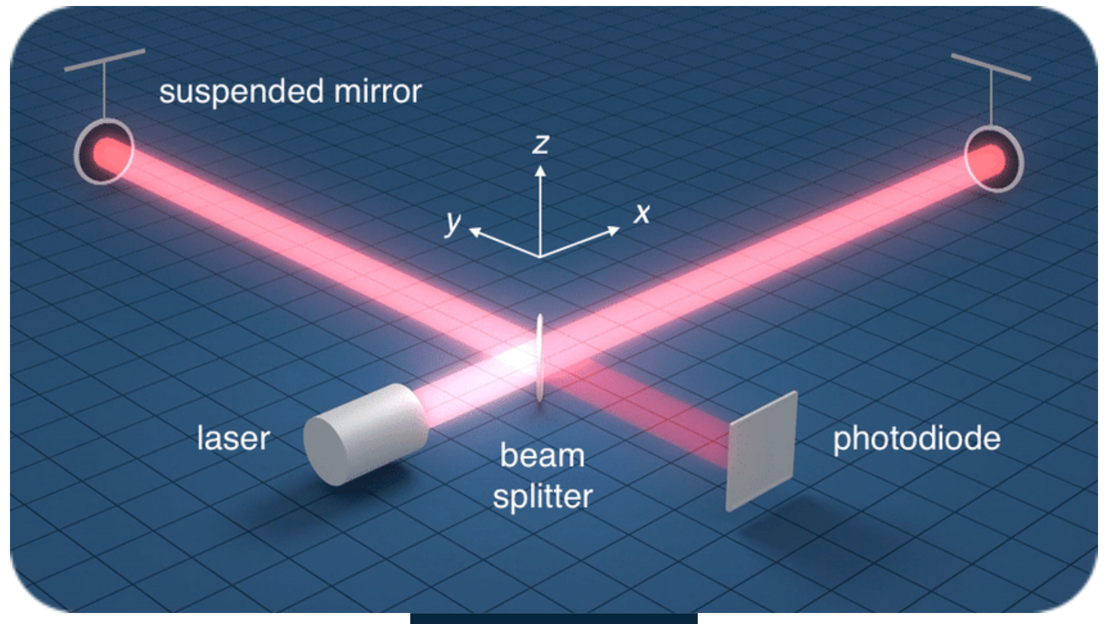

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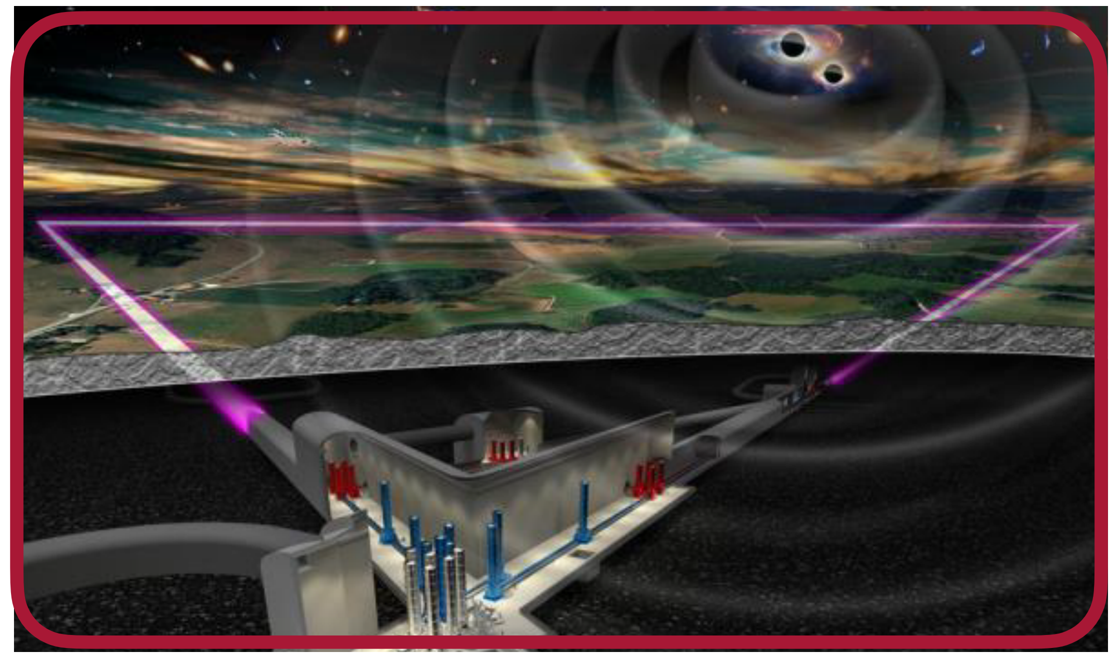
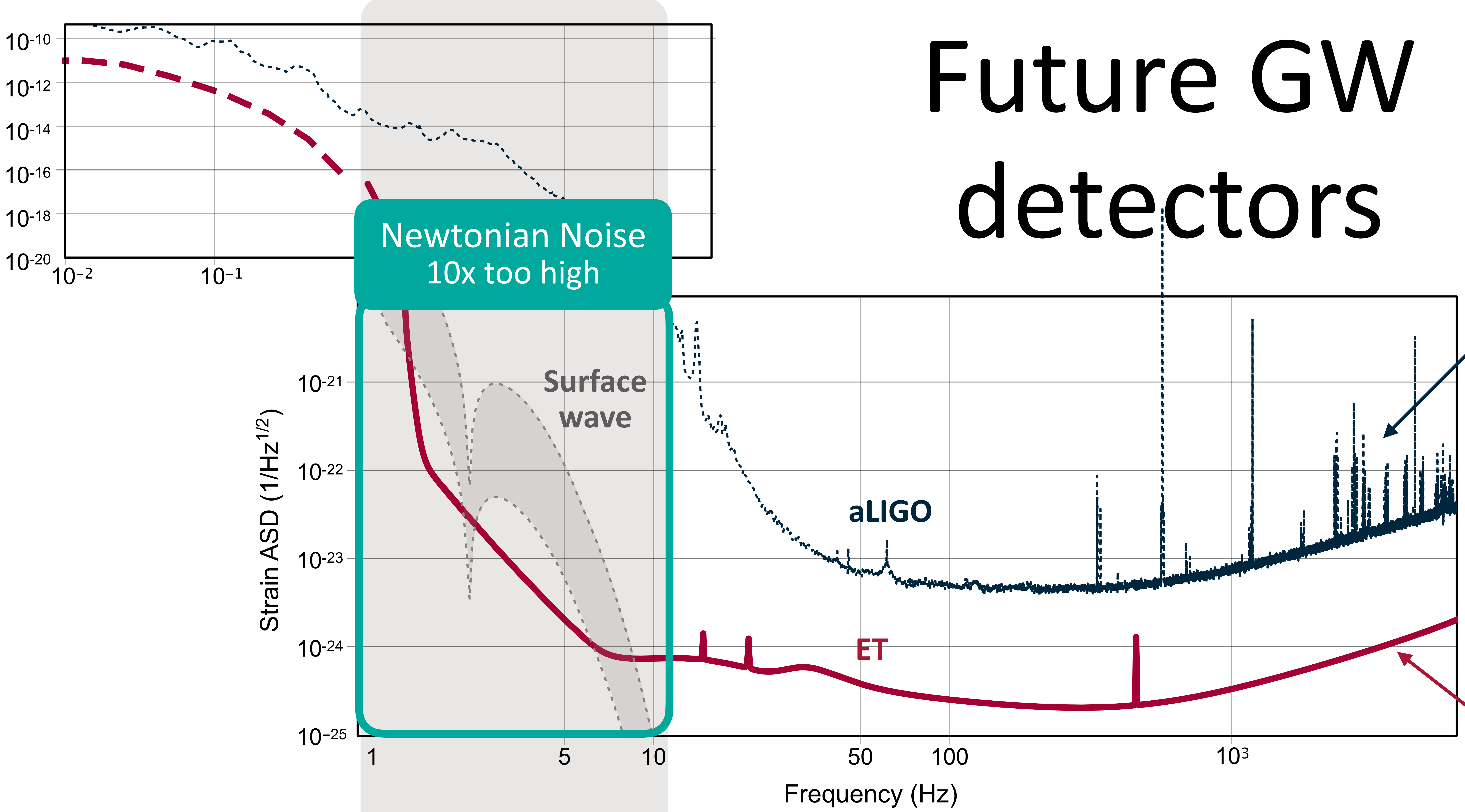


Challenge I: Seismic noise suppression:

- Passive and active pendulum isolation
- going underground to suppress seismic surface waves

ET design report 2020, https://gwic.ligo.org/3Gsubcomm/docs/ET-0007B-20_ETDesignReportUpdate2020.pdf

Future GW detectors



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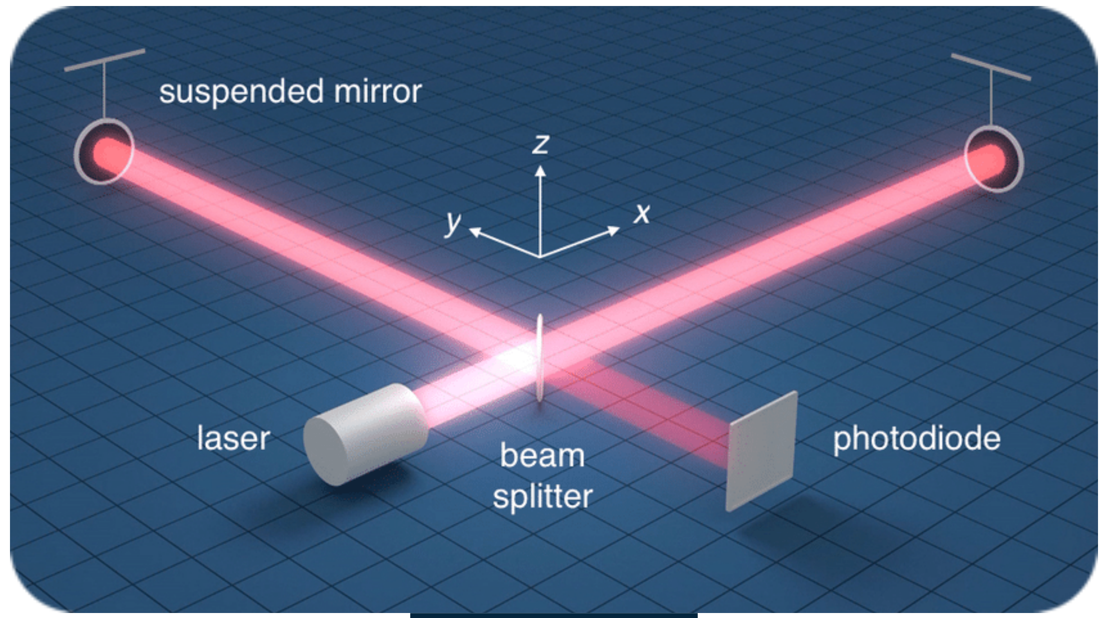

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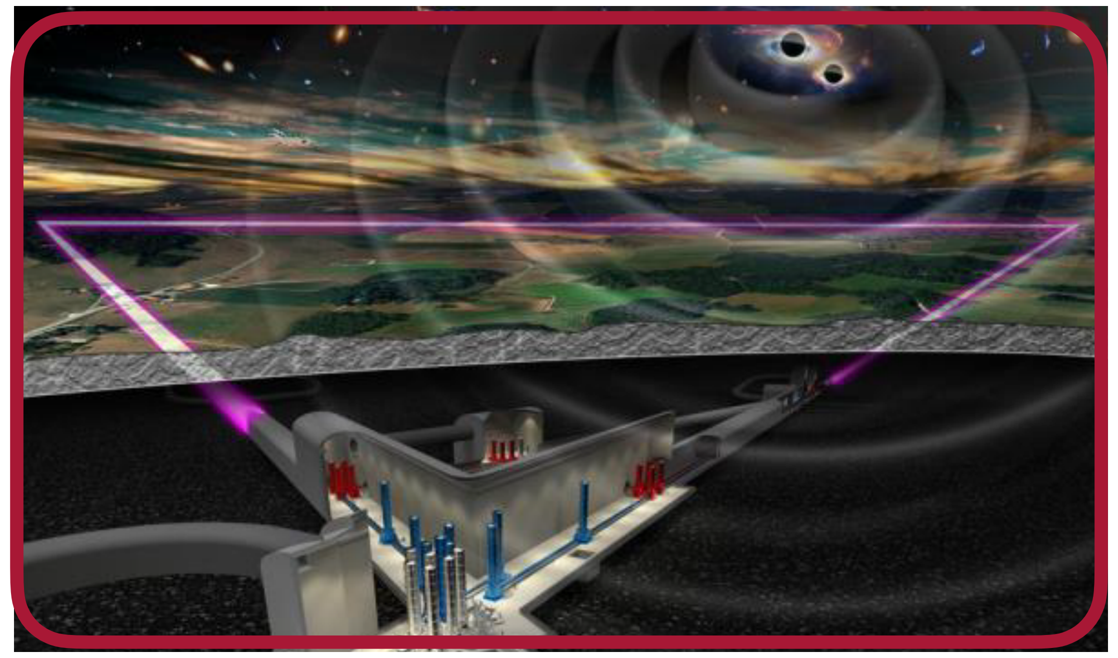
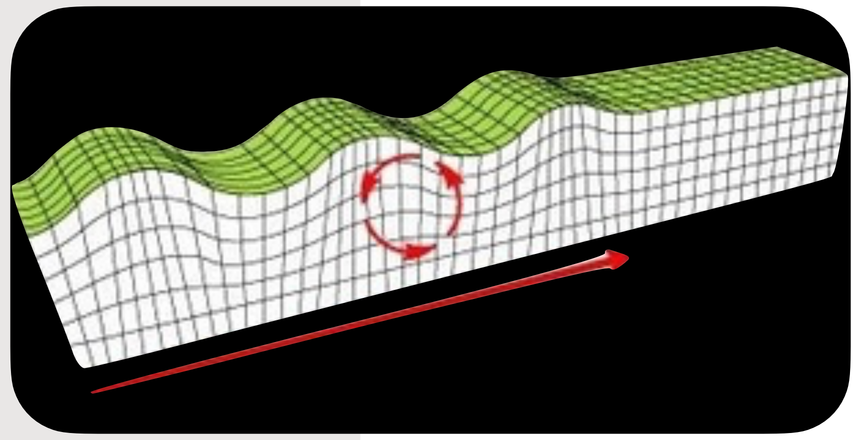


Seismic surface waves

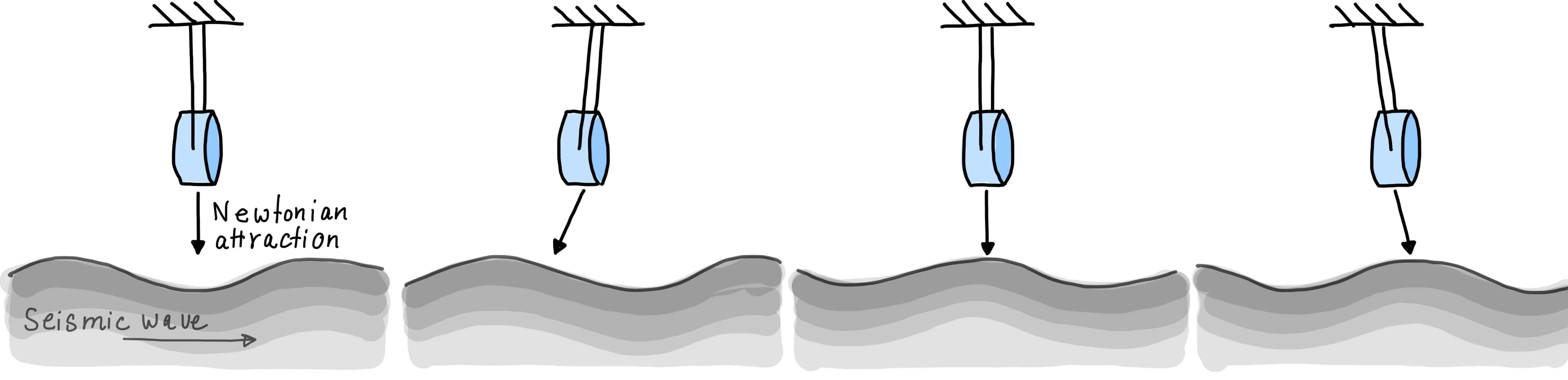


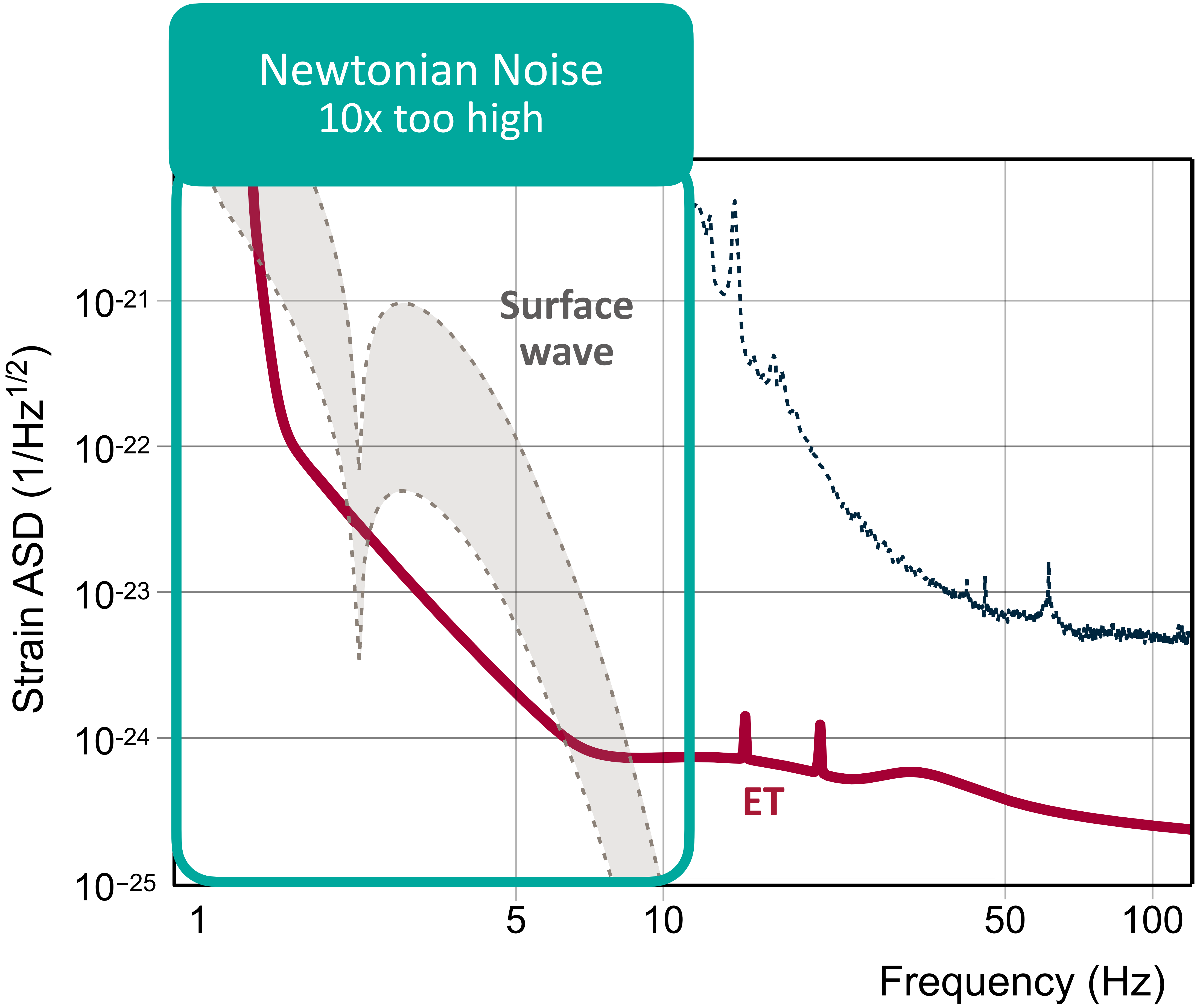
<u>Challenge II: Newtonian Noise (NN)</u>

Harms et al. 2015 https://link.aps.org/doi/10.1103/PhysRevD.92.022001

Newtonian Noise

in the Einstein Telescope





Test mass acceleration:

$$\delta\vec{a}(\vec{r}_0, t) = -\,G \int \underbrace{dV\rho(\vec{r})}_{\text{density \& volume of ground}} \Big(\overbrace{\vec{\xi}(\vec{r}, t)}^{\text{seismic displacement}} \cdot \nabla_0 \Big) \frac{\vec{r} - \vec{r}_0}{|\vec{r} - \vec{r}_0|^3}$$

Gravitational constant

test mass position

points inside medium

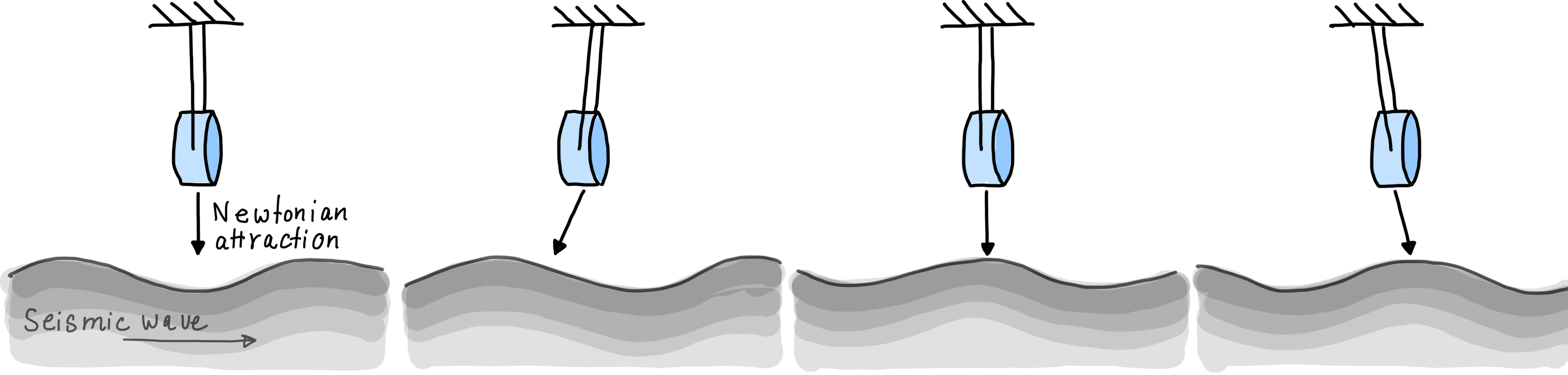
<u>Challenge II: Newtonian noise (NN) cancellation of factor 10</u>

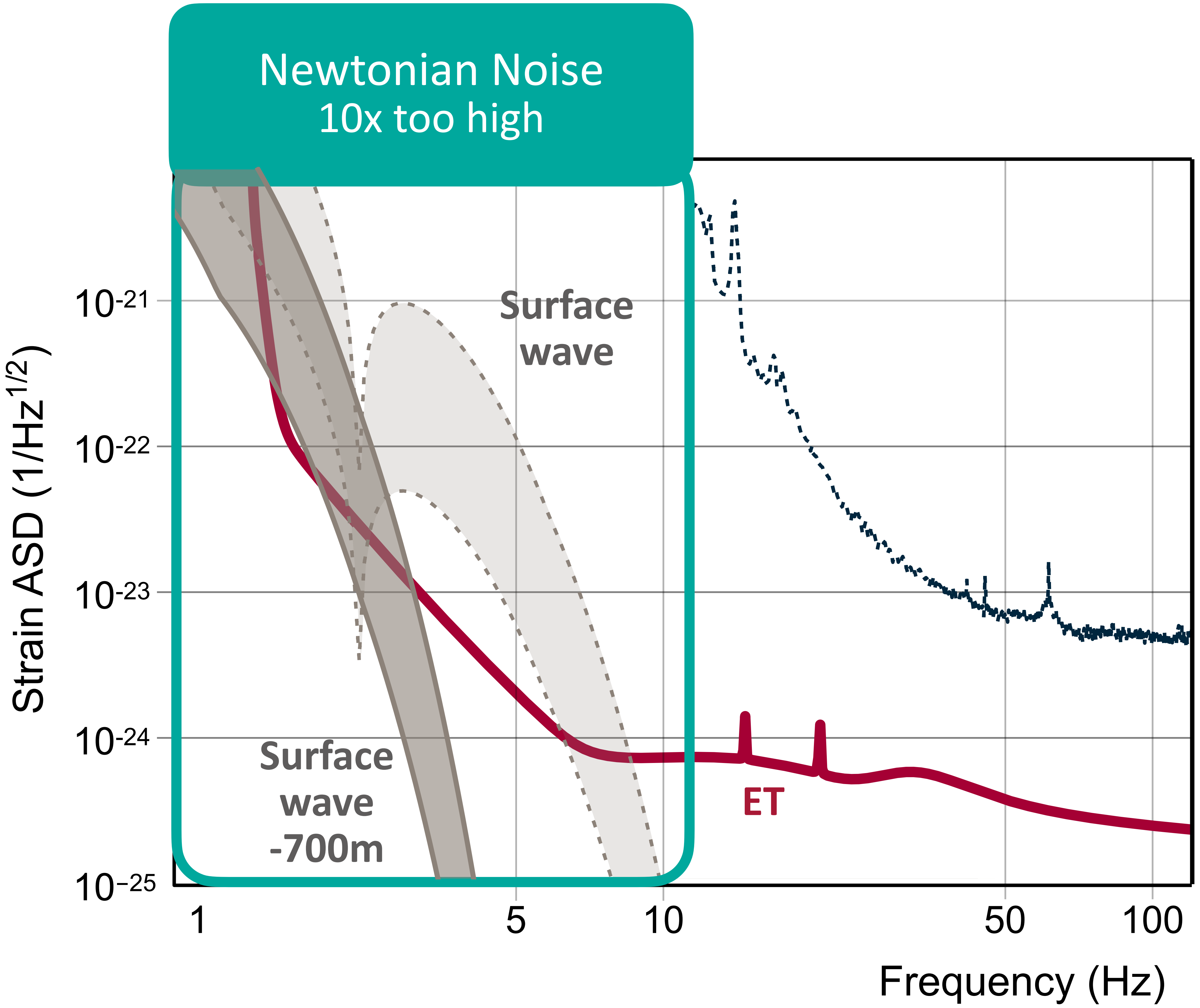
- NN is a direct consequence from seismic waves

Harms et al. 2015 https://link.aps.org/doi/10.1103/PhysRevD.92.022001

Newtonian Noise

in the Einstein Telescope





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Gravitational constant

test mass position

points inside medium

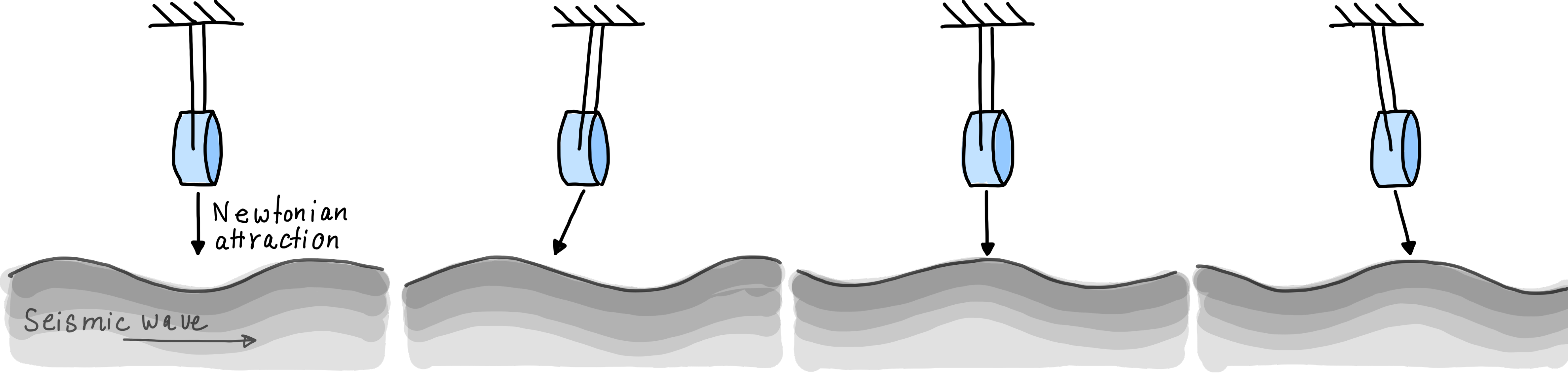
Challenge II: Newtonian noise (NN) cancellation of factor 10

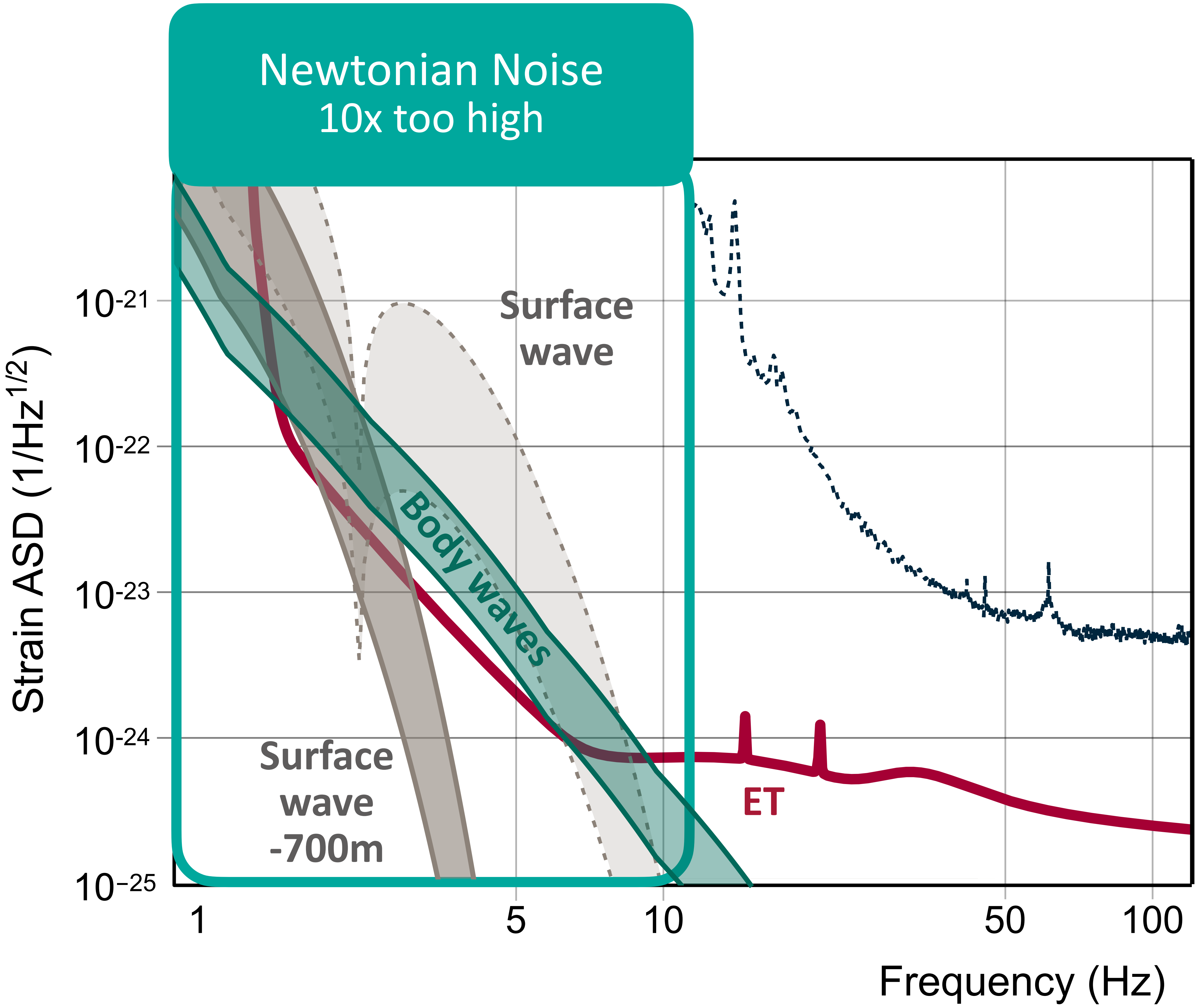
- NN is a direct consequence from seismic waves
- underground detector construction suppresses surface wave NN

Harms et al. 2015 https://link.aps.org/doi/10.1103/PhysRevD.92.022001

Newtonian Noise

in the Einstein Telescope





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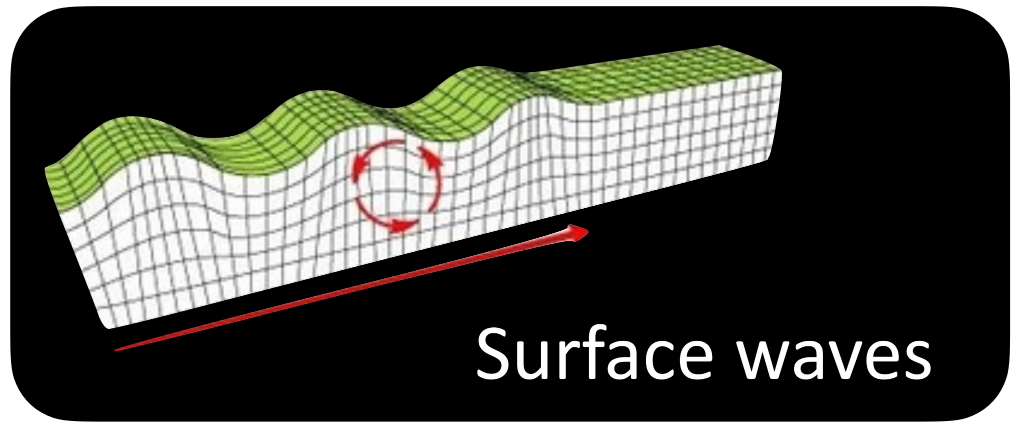
Gravitational constant

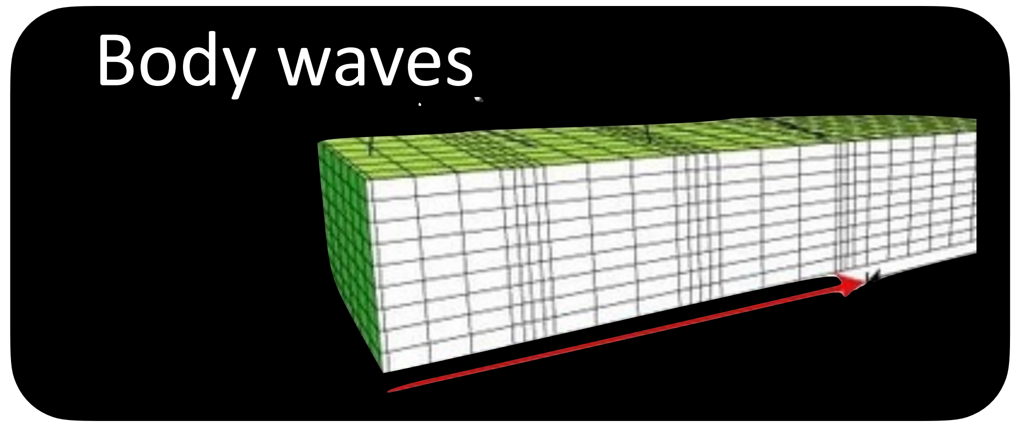
test mass position

points inside medium

Challenge II: Newtonian noise (NN) cancellation of factor 10

- NN is a direct consequence from seismic waves
- underground detector construction suppresses surface wave NN
- NN from body waves **is not suppressed in underground** detectors

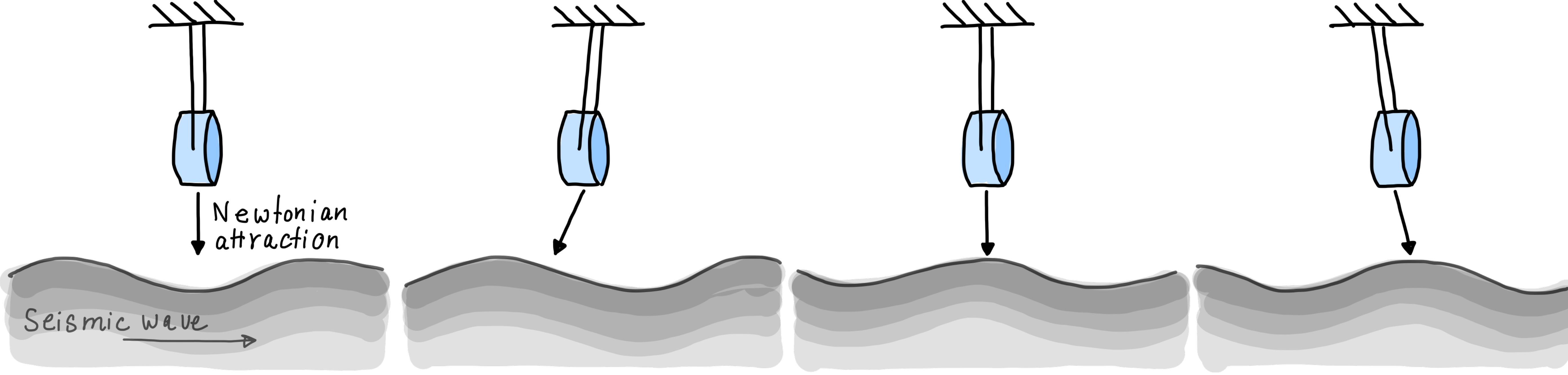


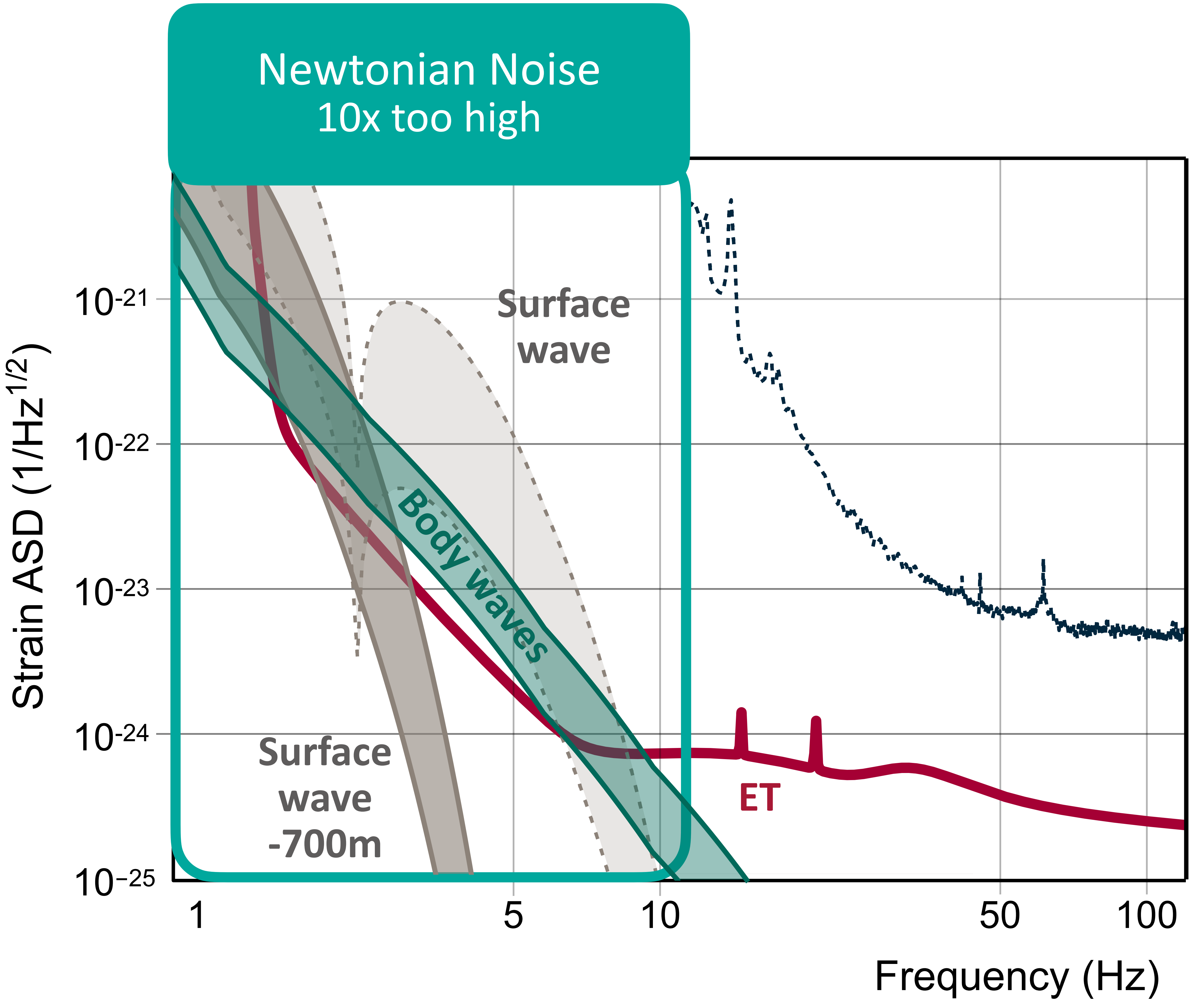


Harms et al. 2015 https://link.aps.org/doi/10.1103/PhysRevD.92.022001

Newtonian Noise

in the Einstein Telescope





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test mass position

points inside medium

<u>Challenge II: Newtonian noise (NN) cancellation of factor 10</u>

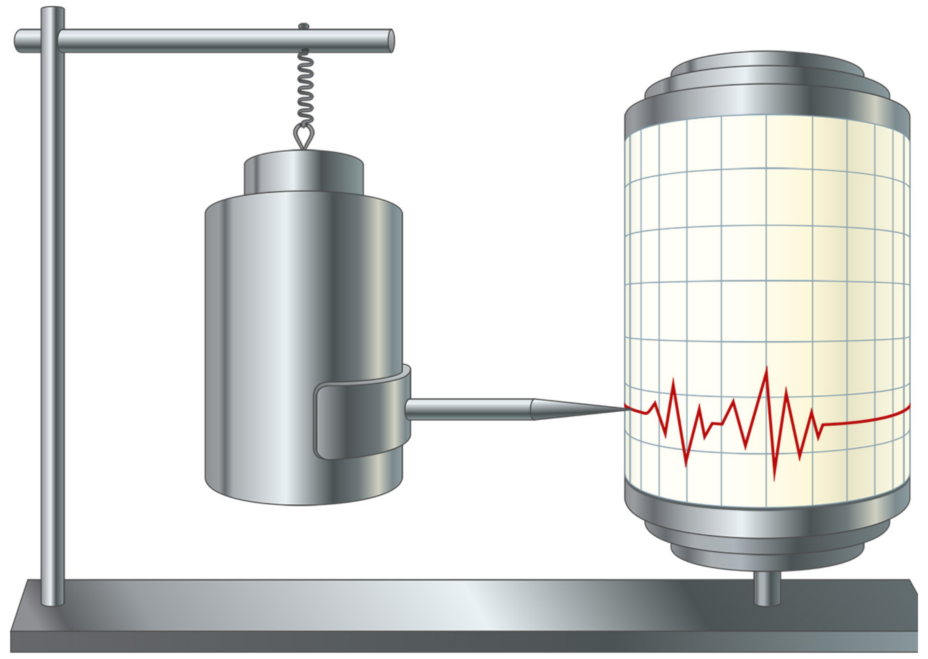
- NN is a direct consequence from seismic waves
- underground detector construction suppresses surface wave NN
- NN from body waves **<u>is not suppressed in underground</u>** detectors
- interacts gravitationally:

→ NN cannot be shielded ⚡

→ NN measurement + cancellation in post-processing 💡

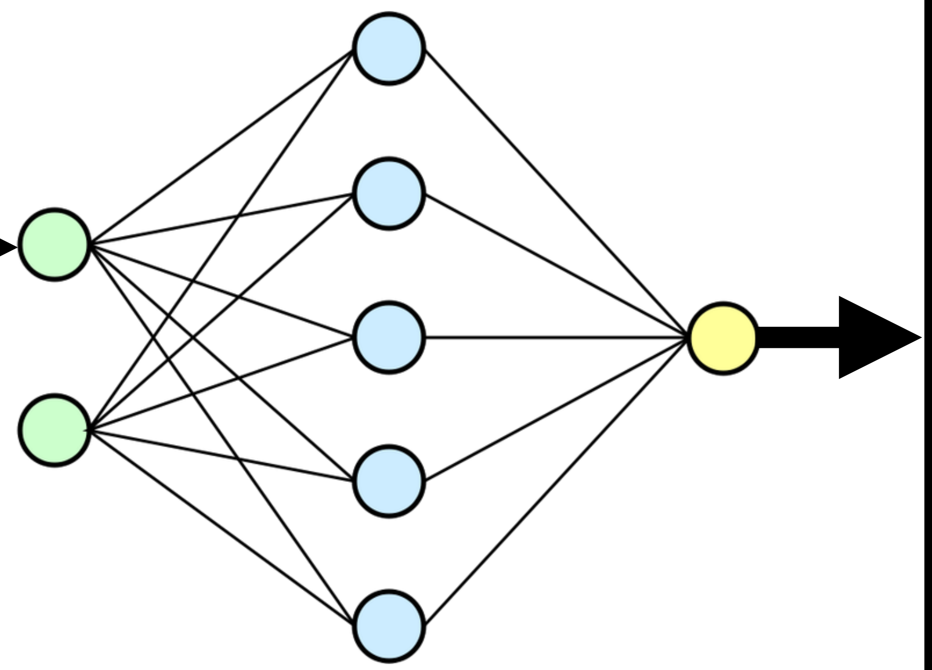
Harms et al. 2015 https://link.aps.org/doi/10.1103/PhysRevD.92.022001

Newtonian Noise Sensor



Measurement data
from seismic field

reconstruction of seismic field
(12 degrees of freedom)

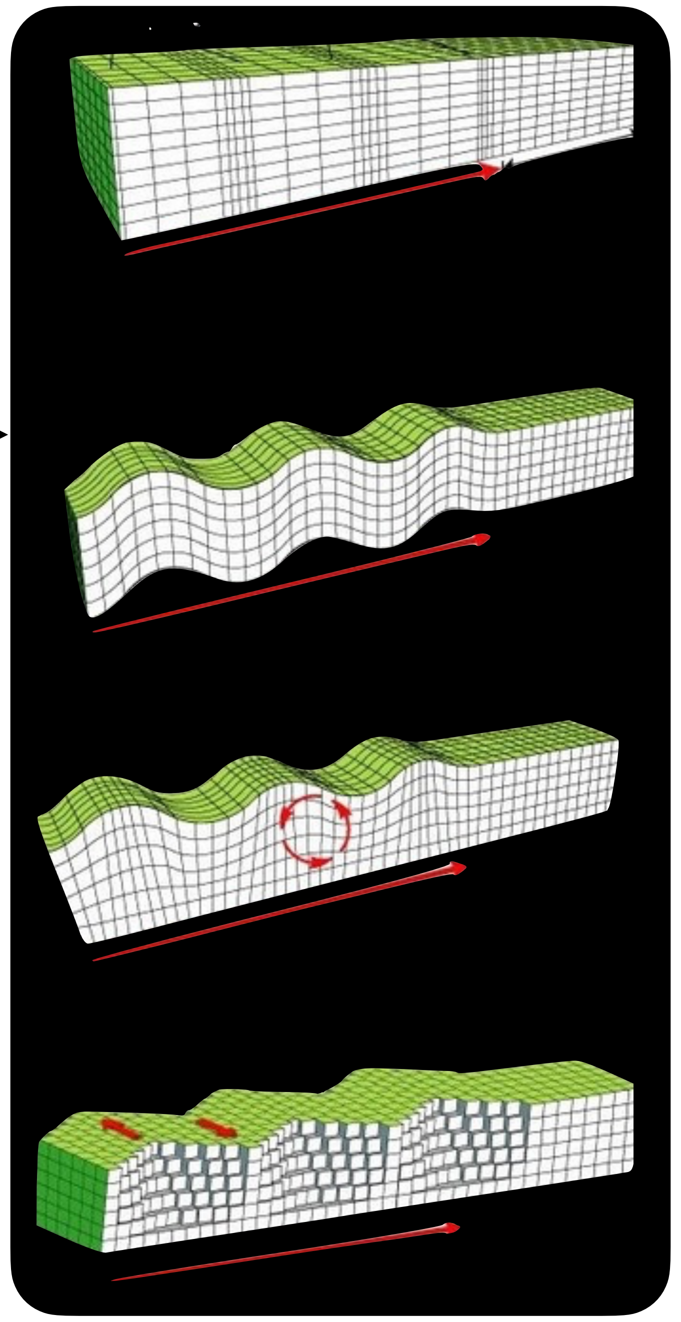


Wiener filter

Couglin et al. 2016, https://doi.org/10.1088/0264-9381/33/24/244001

(Surrogate model)

Badaracco et al. 2020, https://doi.org/10.1088/1361-6382/abab64



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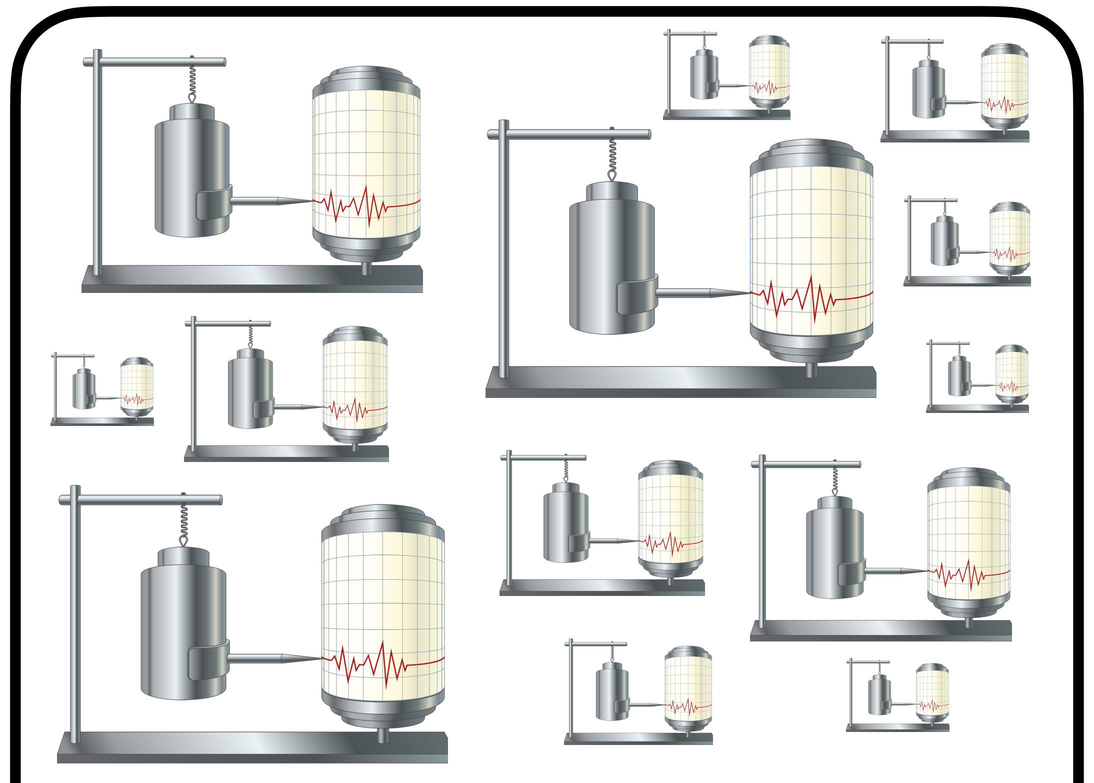

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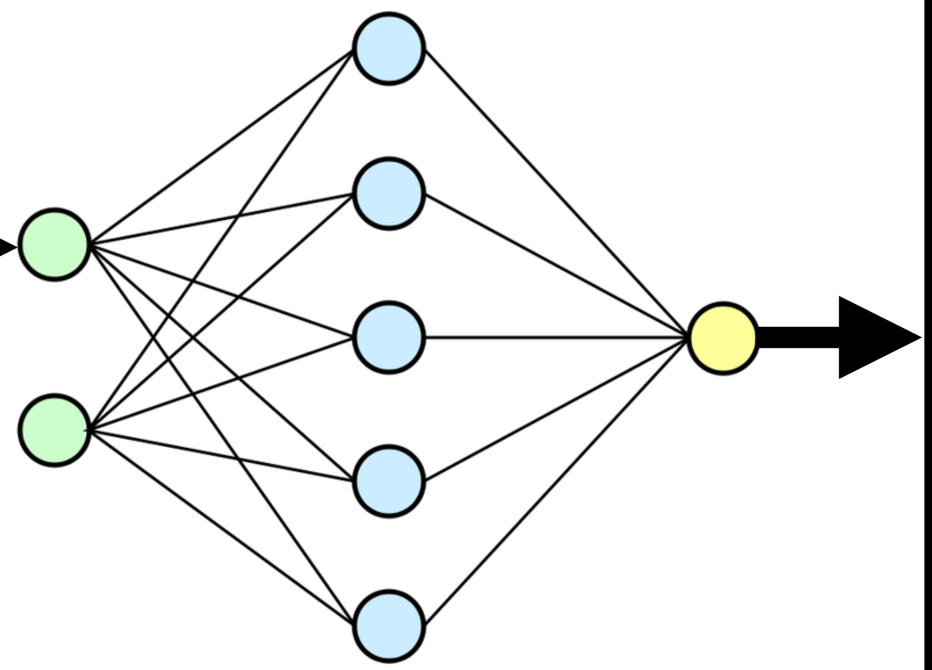

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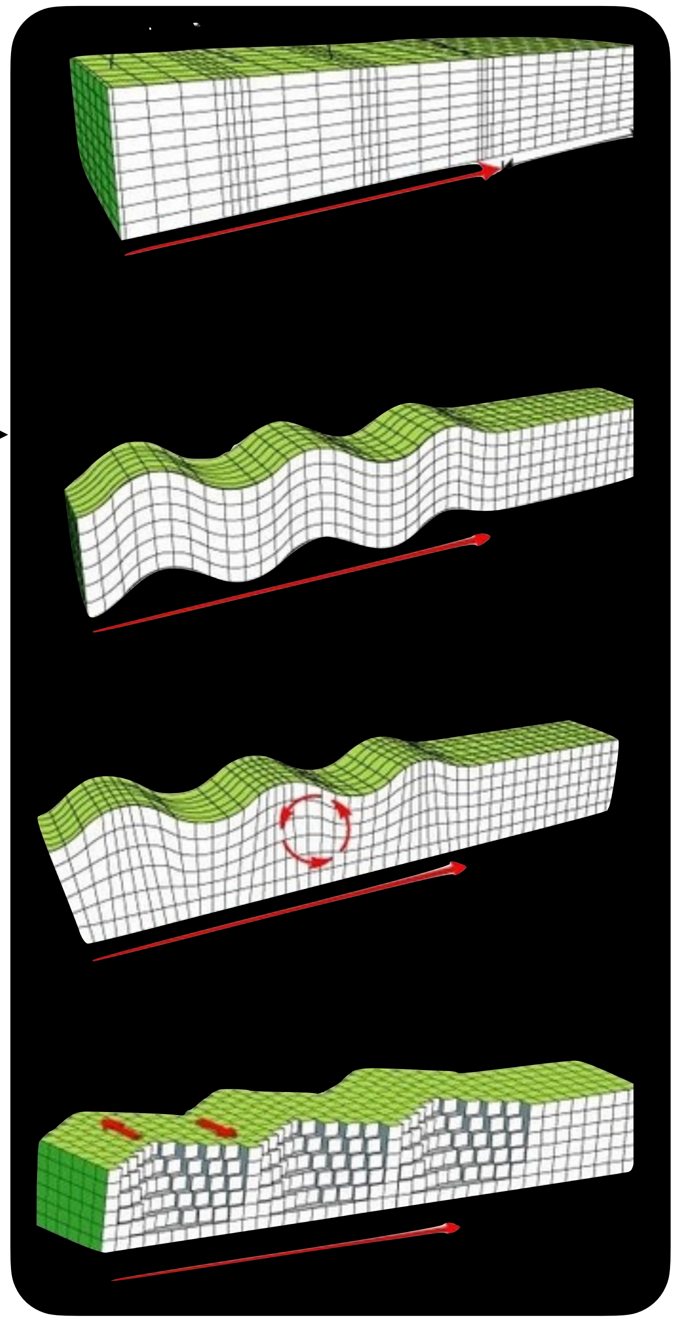

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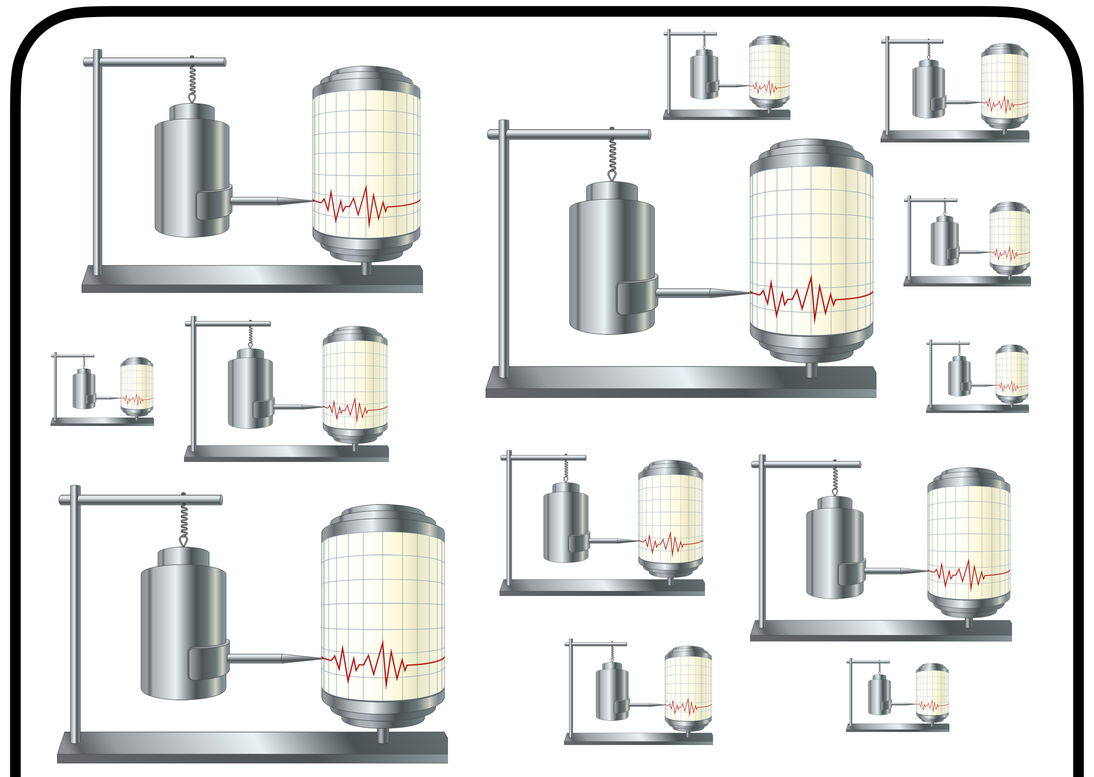

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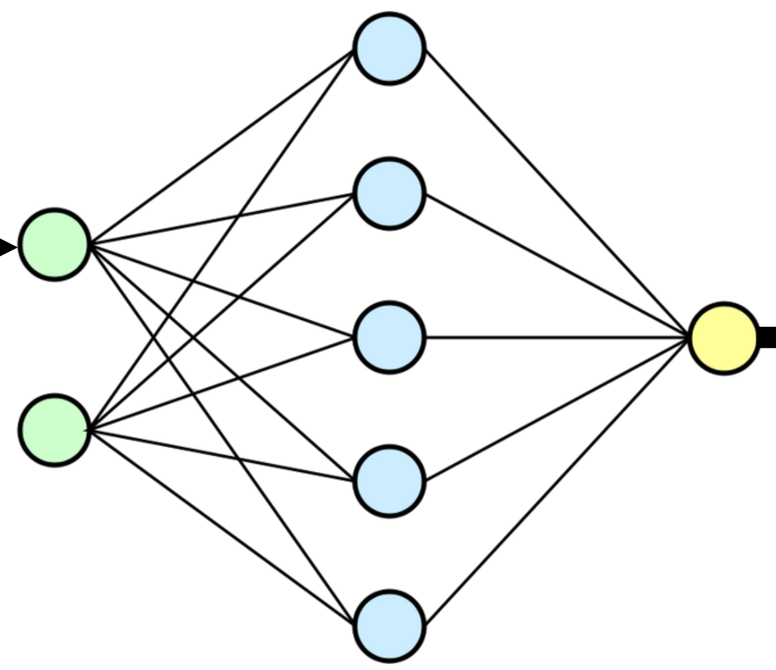

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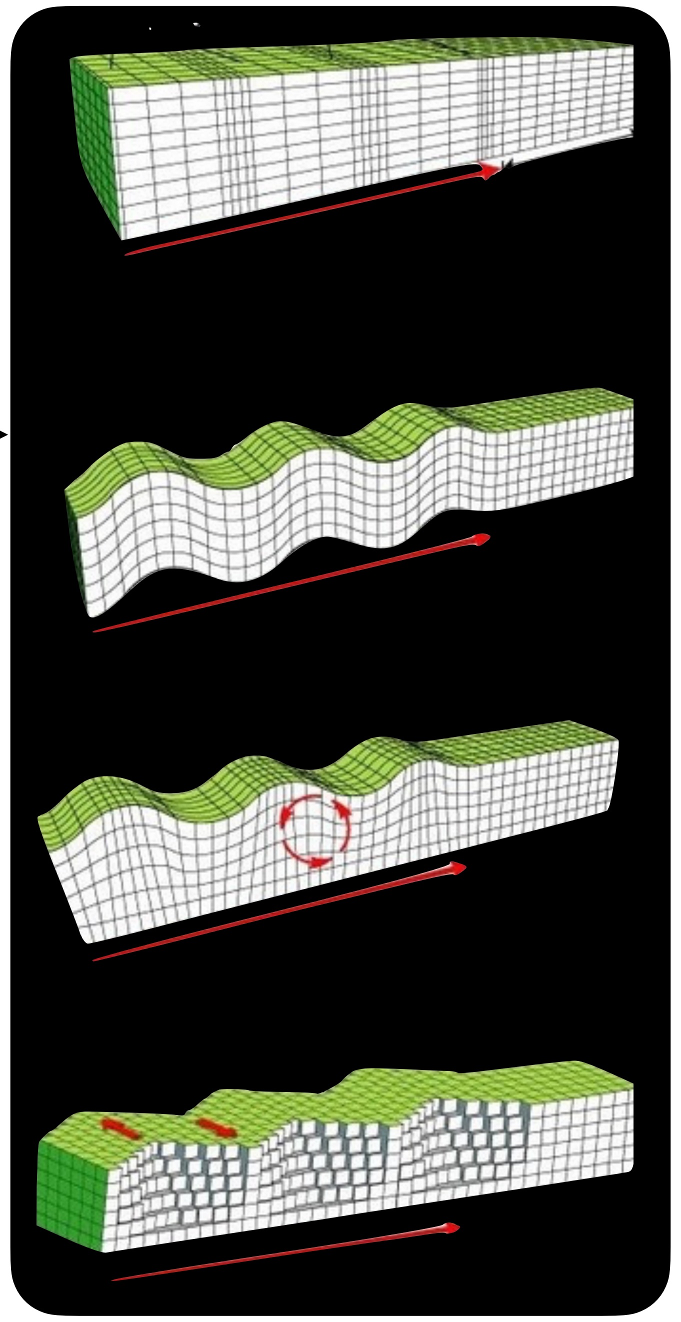

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Newtonian Noise prediction on the test mass

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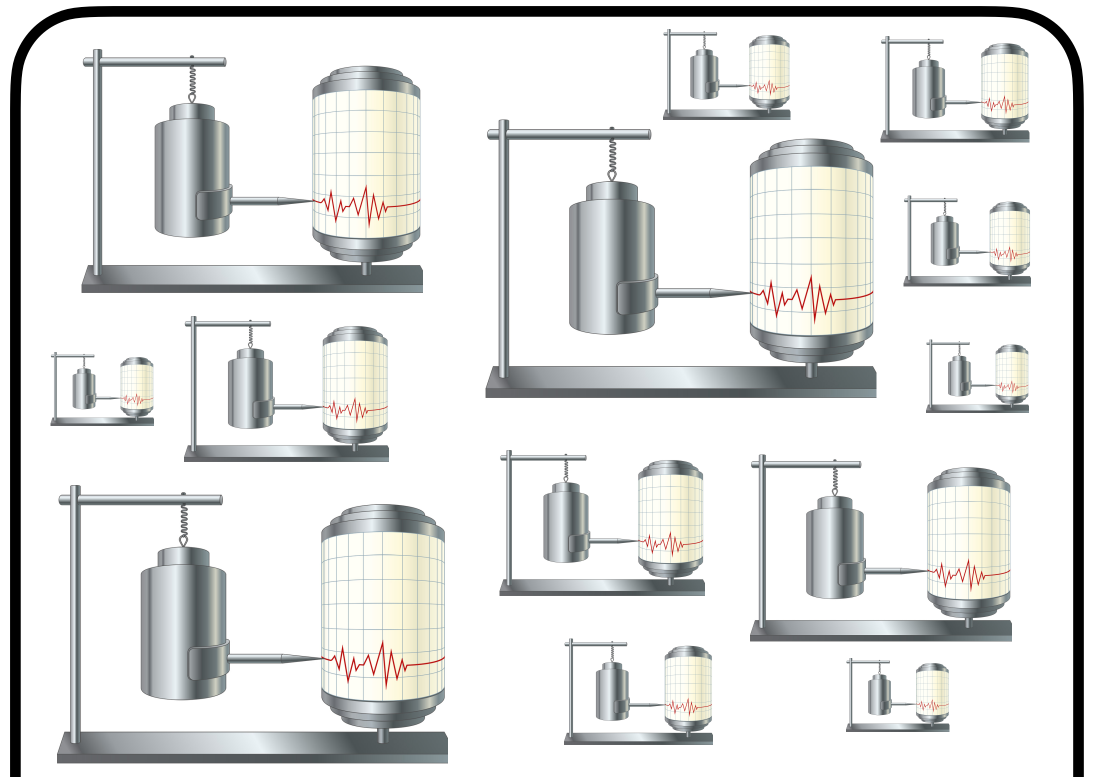

Measurement data
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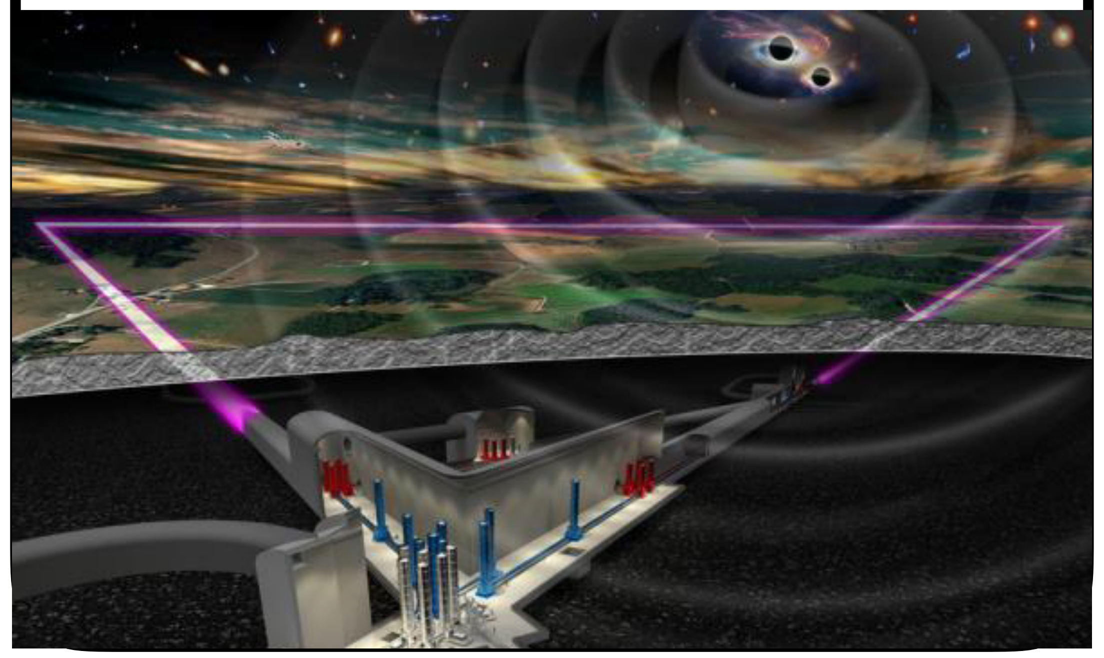
Science Data



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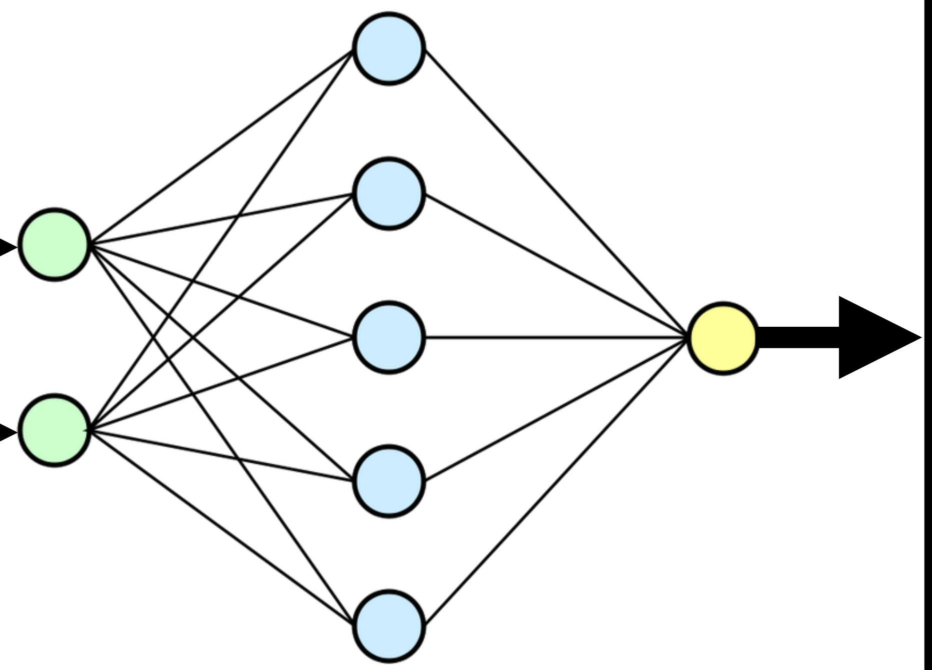

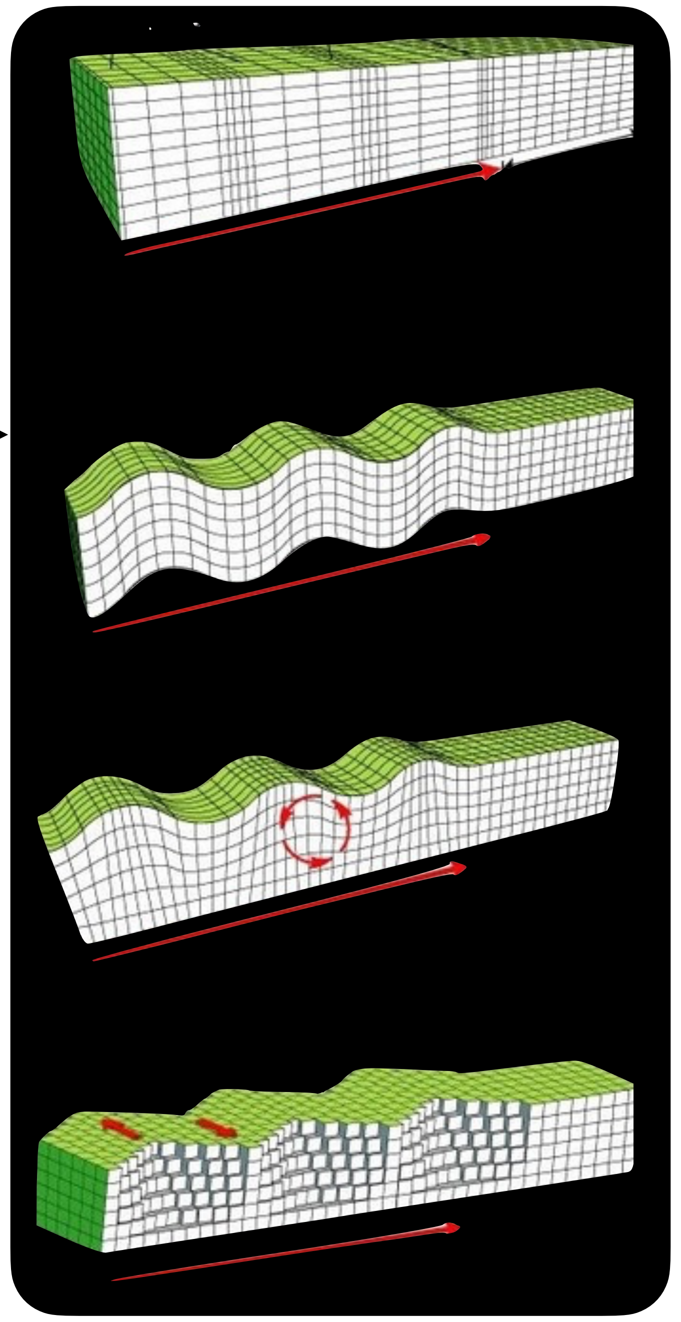

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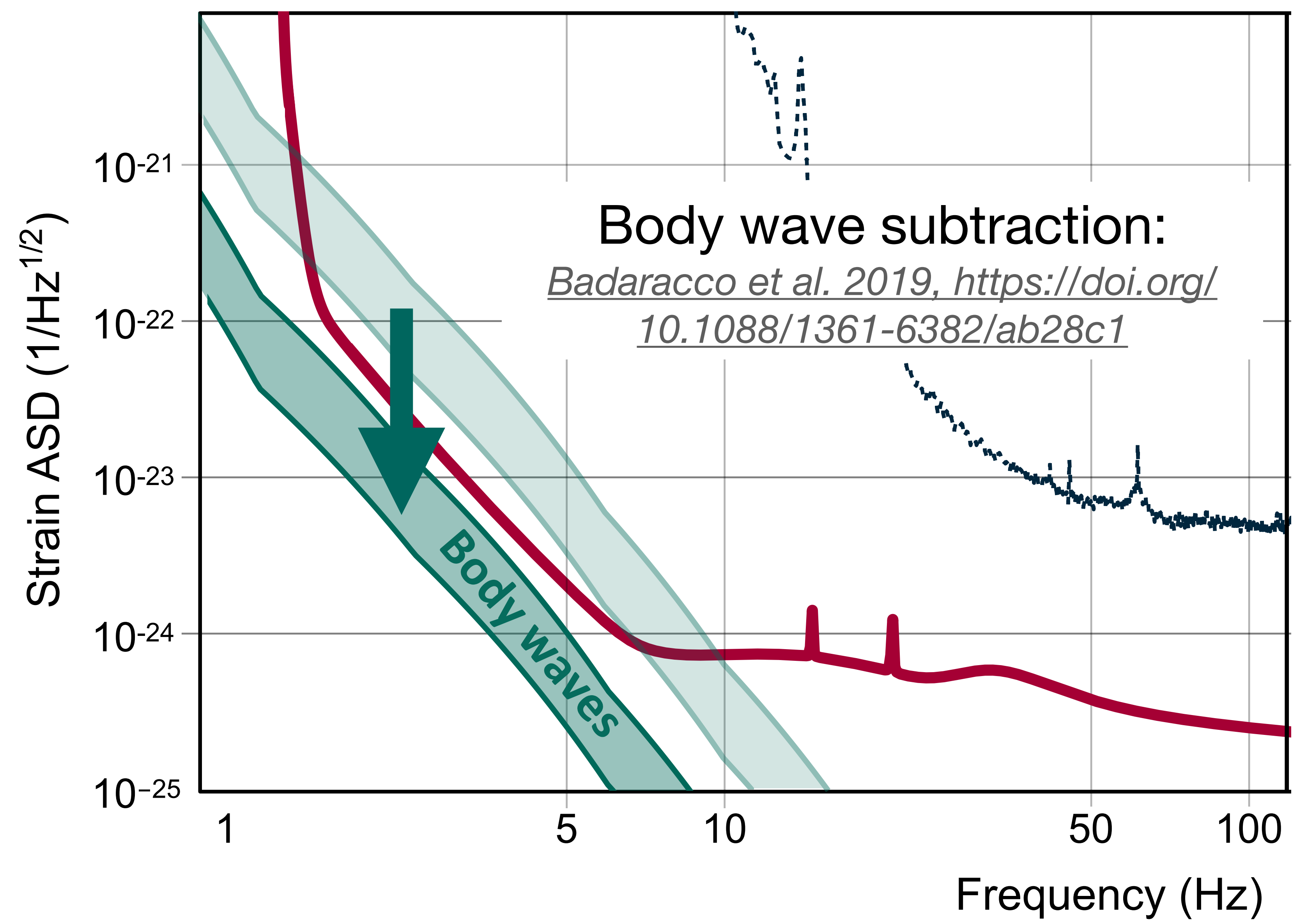
Subtraction in post-processing



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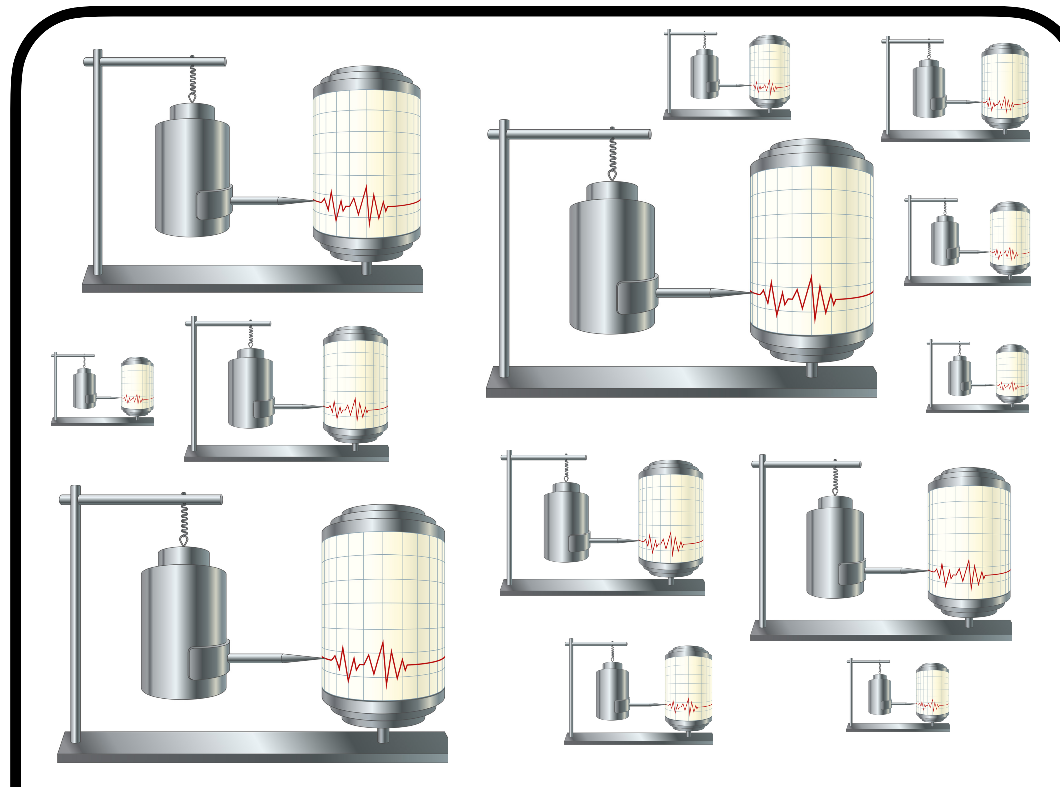


Measurement data from seismic field

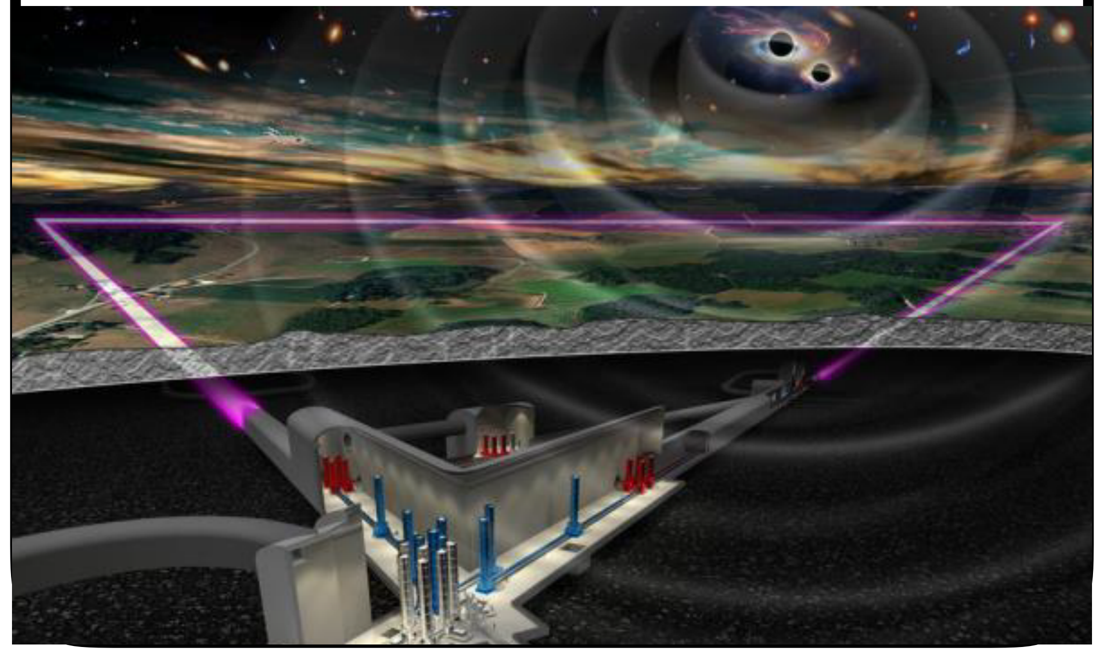
N = 20 x 12 = **240** sensors = boreholes

seismometers (boreholes)

test masses

High precision < 10 Hz

Science Data



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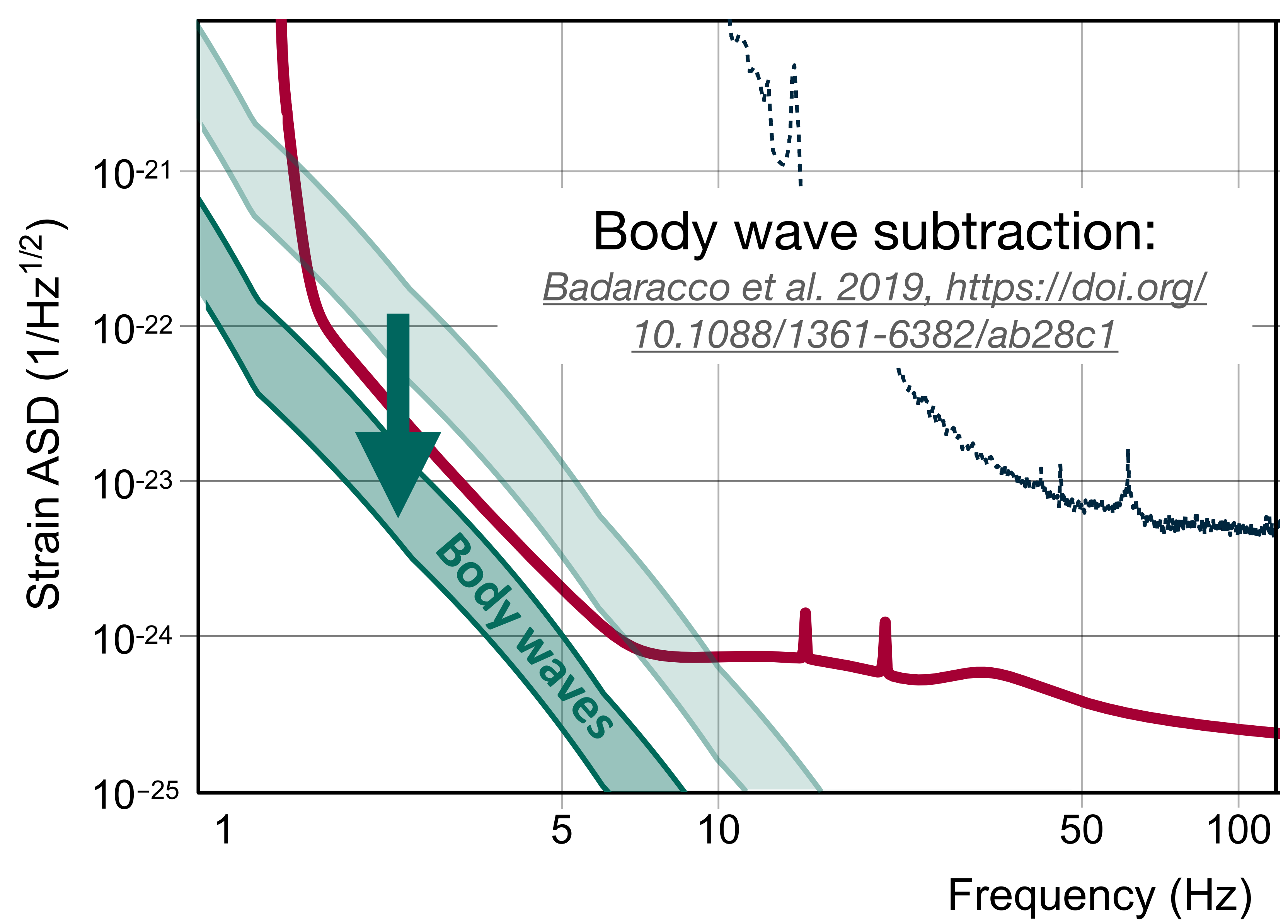

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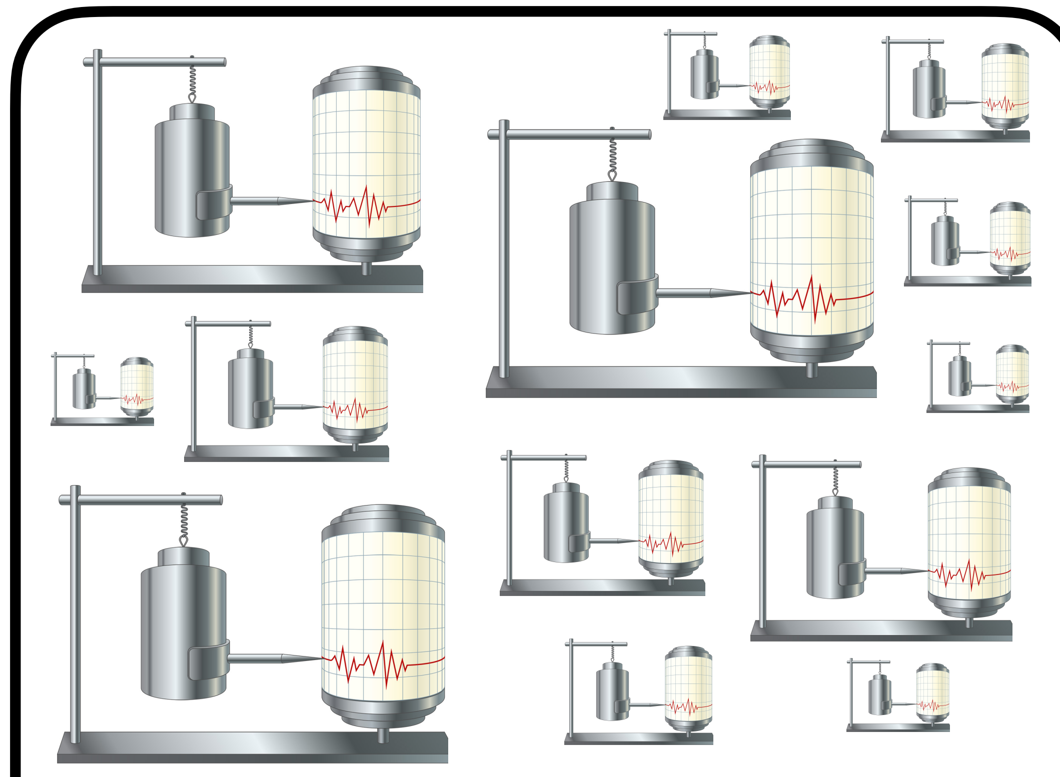

Measurement data from seismic field

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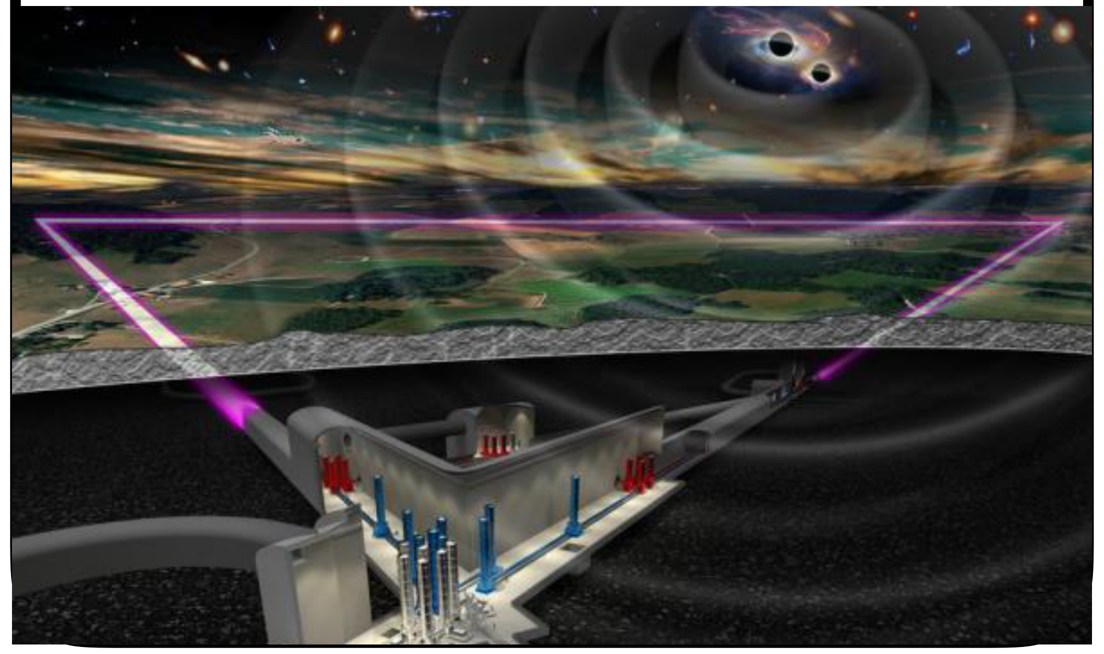

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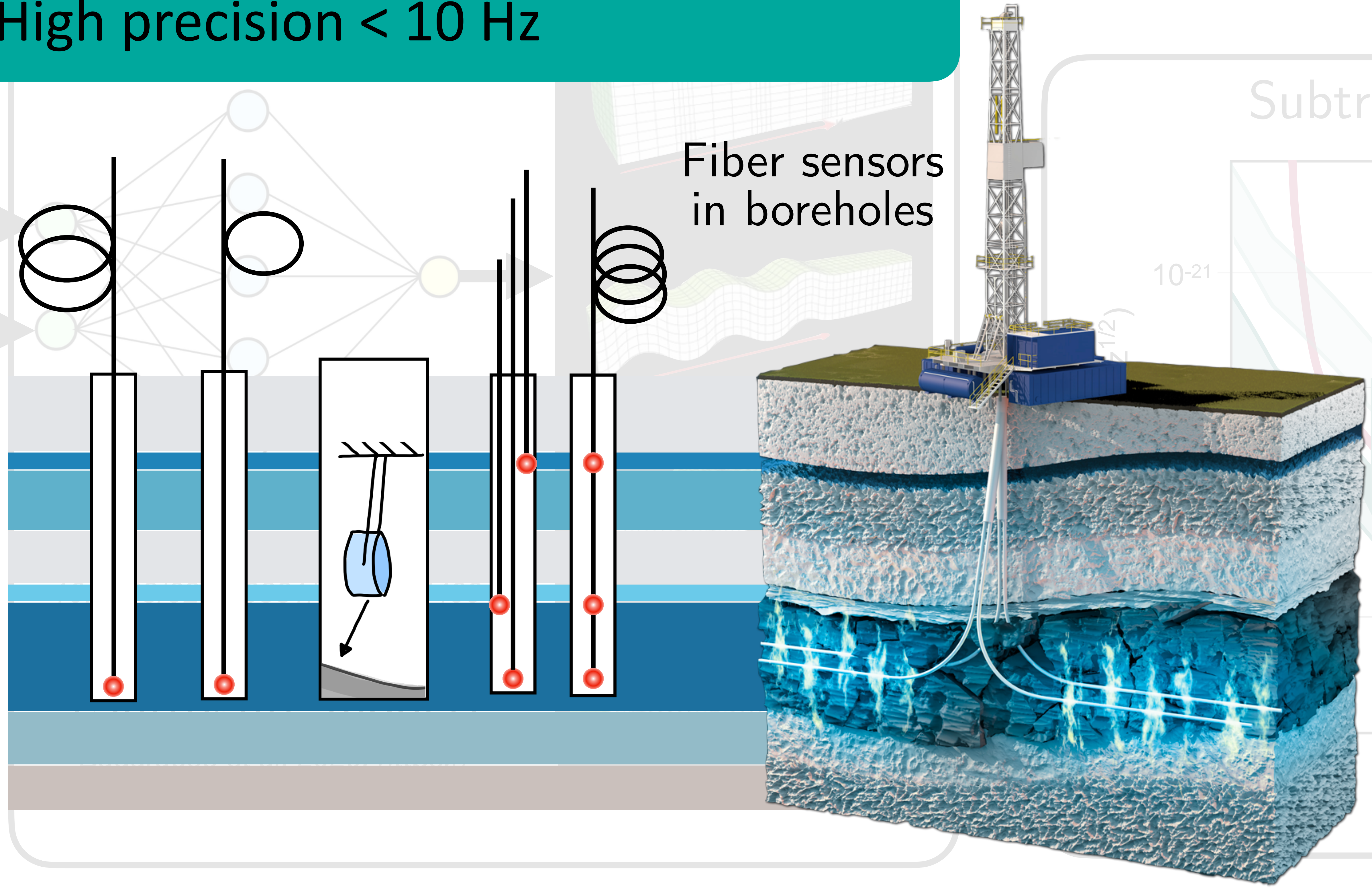

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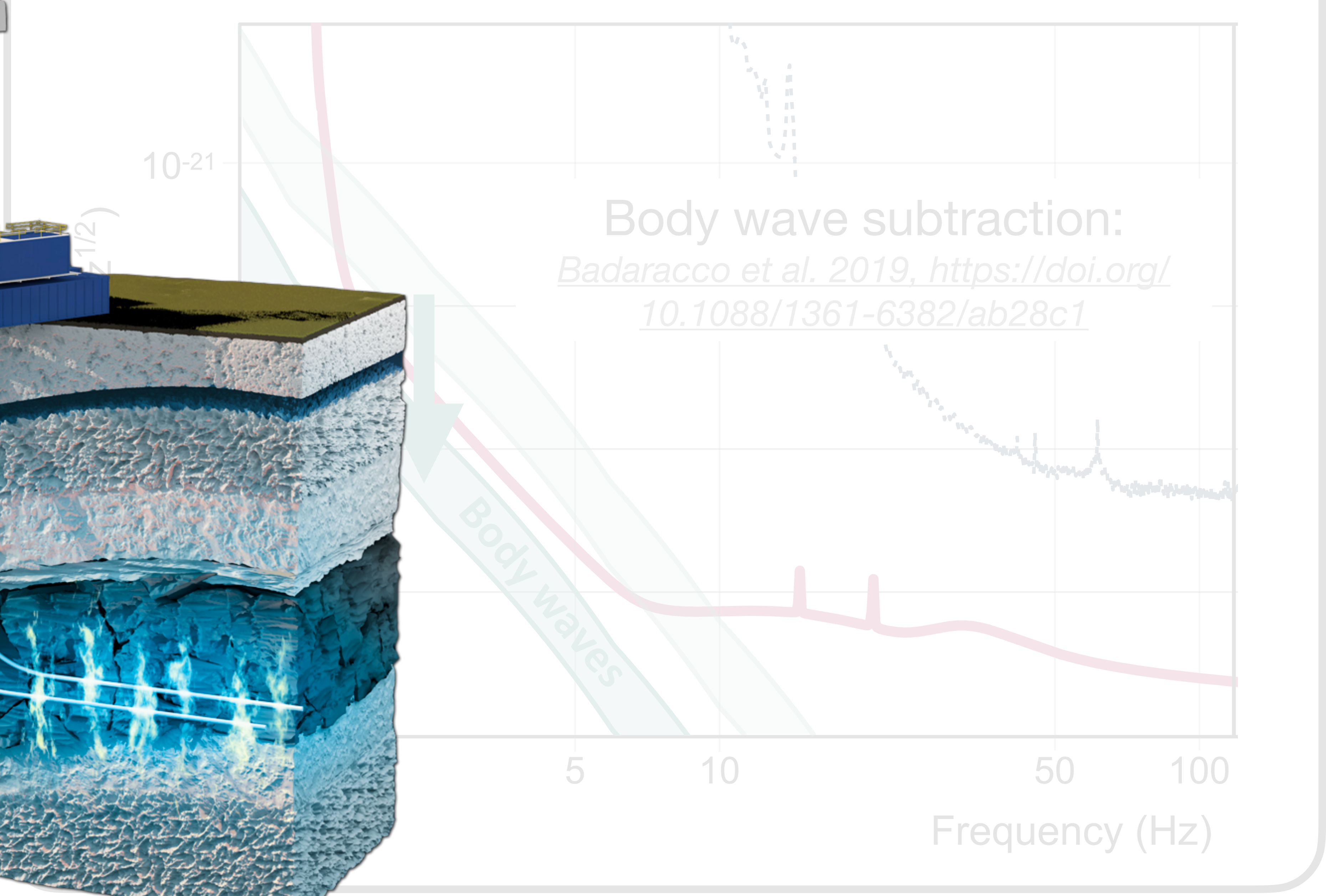
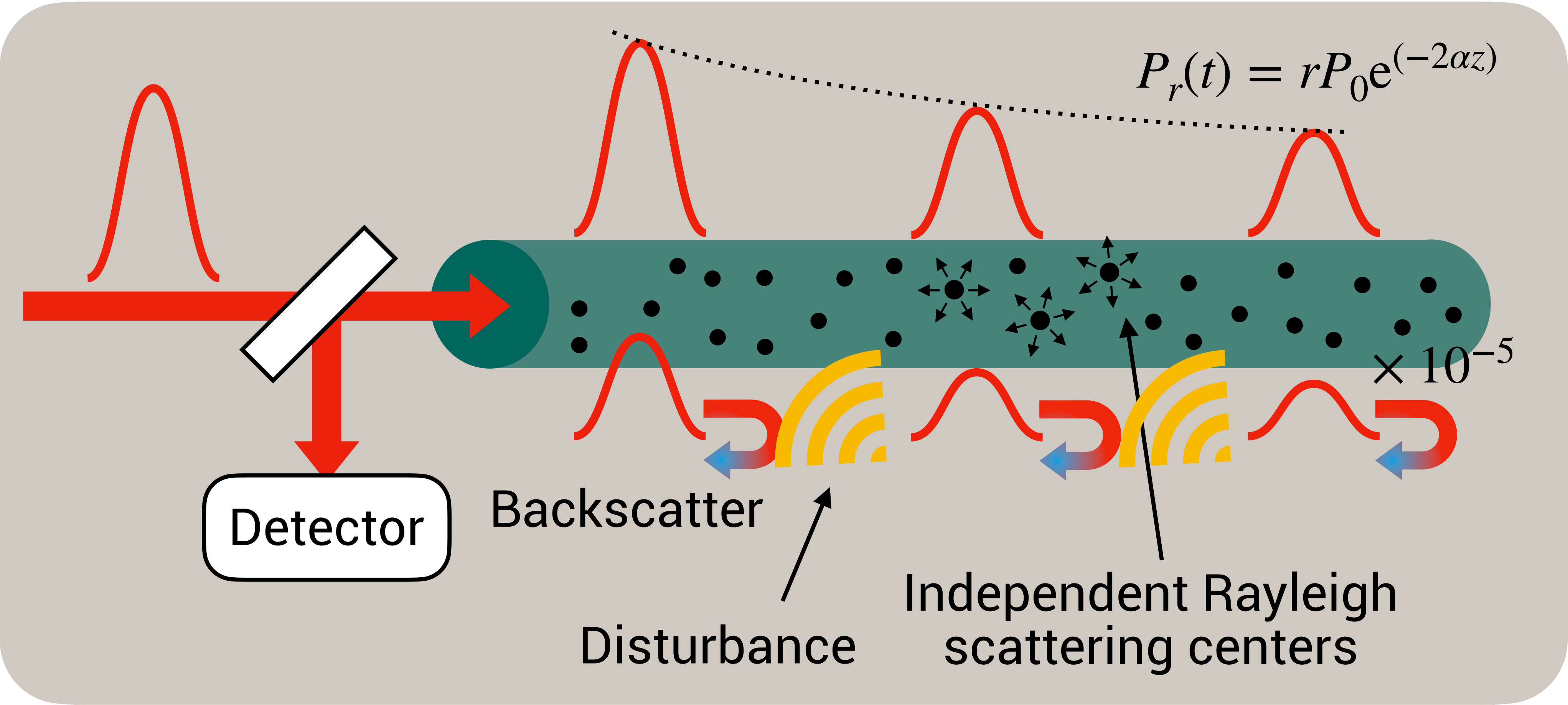
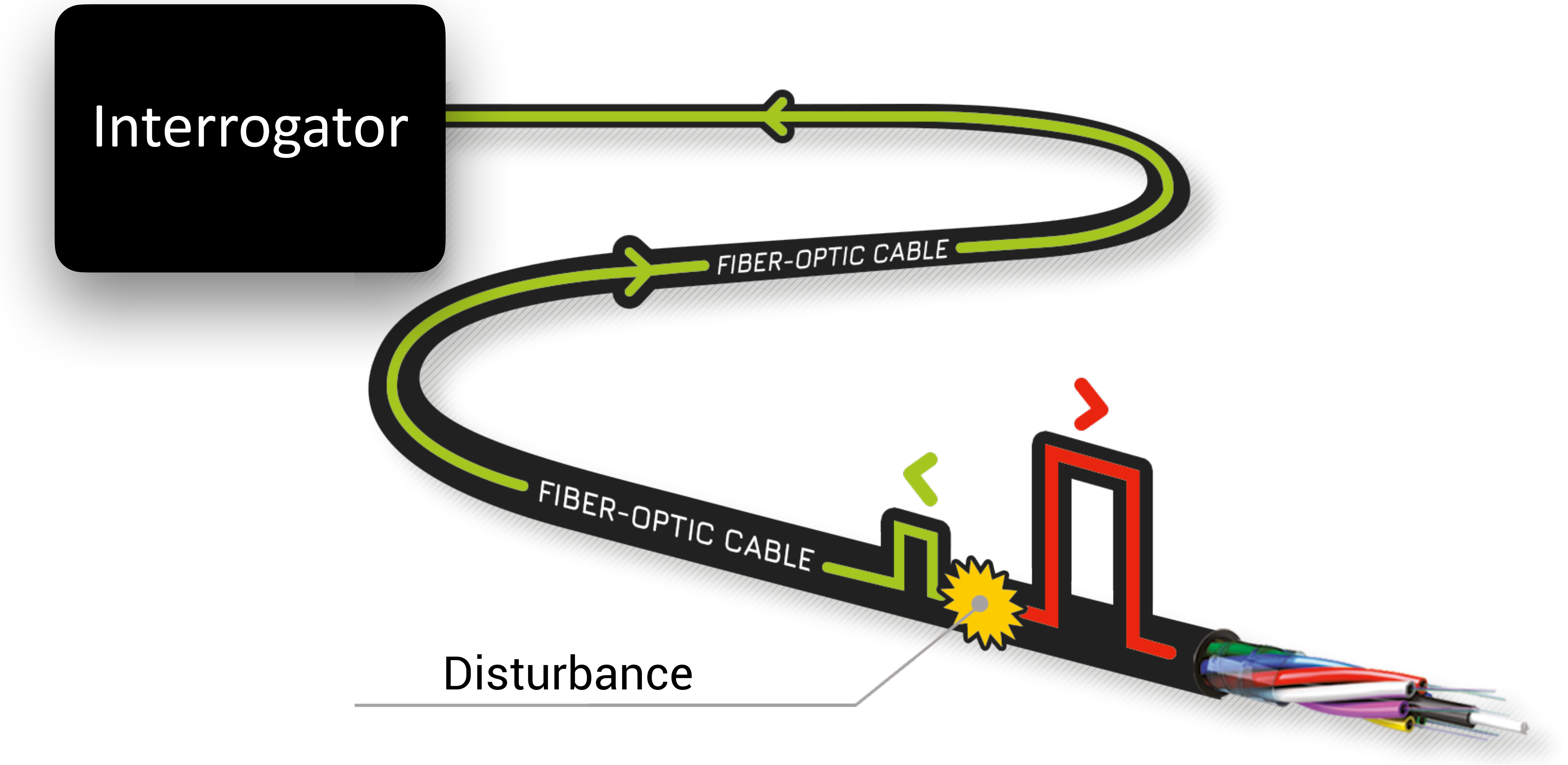


Distributed acoustic sensing (DAS)

Readout principle

OTDR: optical time domain reflectometry





Rayleigh backscatter intensity: $I \propto \frac{1}{\lambda^4} \propto \mathrm{ppm/m}$

Pulse width, $l = 10\,\mathrm{m}$ resolution: $t = \frac{n \cdot l}{c} = 50\,\mathrm{ns}$

Roundtrip in $1\,\mathrm{km}$ fiber: $t = \frac{n \cdot 2z}{c} = 10\,\mu s \mathrel{\hat=} 100\,\mathrm{kHz}$

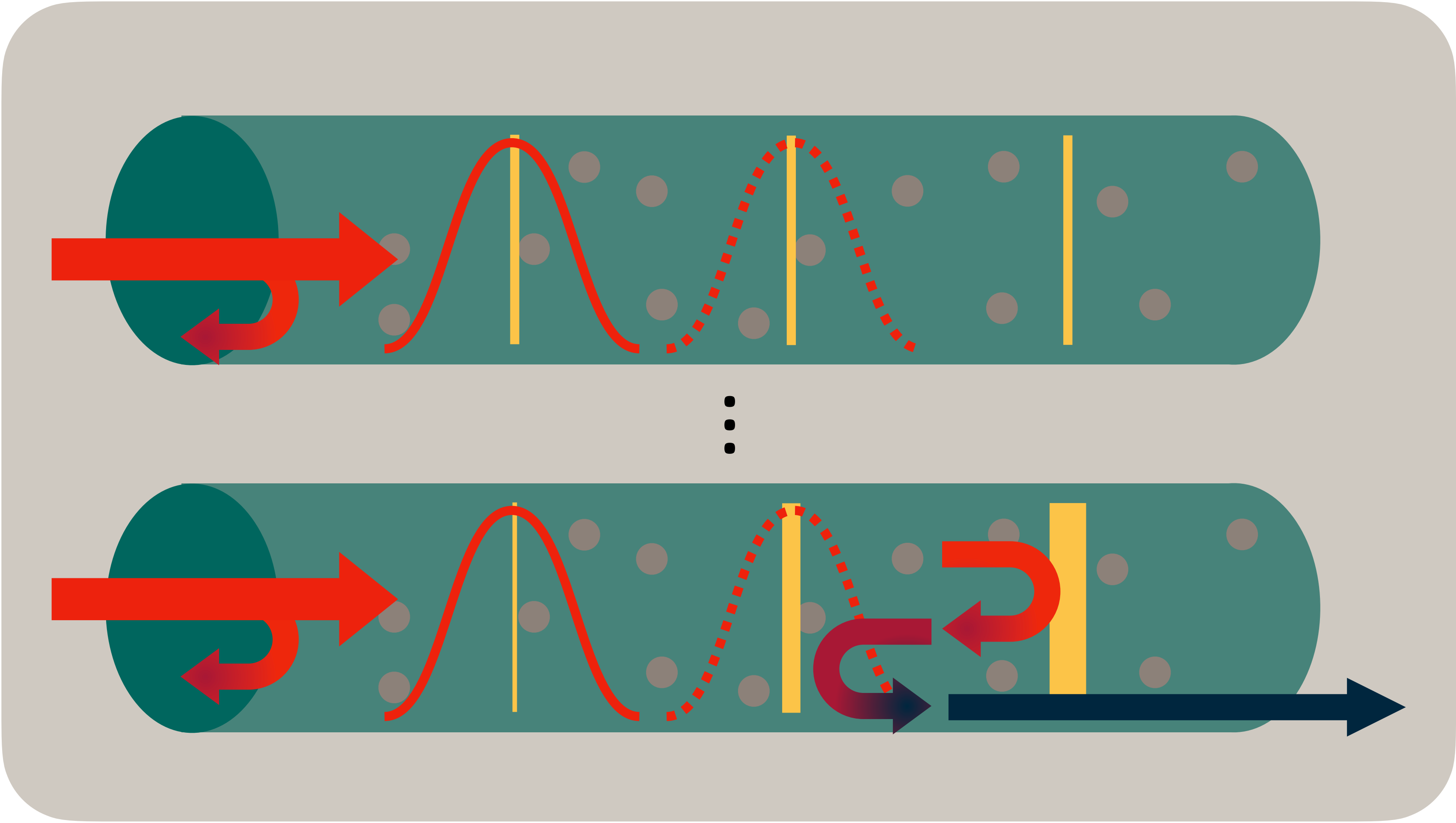
- **<u>> 1000</u>** distributed **<u>sensors</u>** along fiber
- Fiber lengths up to several **<u>10 kilometers</u>**
- Very sensitive to
  - **<u>Seismic</u>**: traffic / ocean waves / micro-seismic / earthquake / …
  - **<u>Vibration</u>**: e.g. due to vacuum pumps / water cooling / high power transformers / broken devices / construction work / cranes / …
  - **<u>Temperature and Humidity</u>**

https://www.febus-optics.com

High precision fiber sensing

Special fibers

Engineered fibers

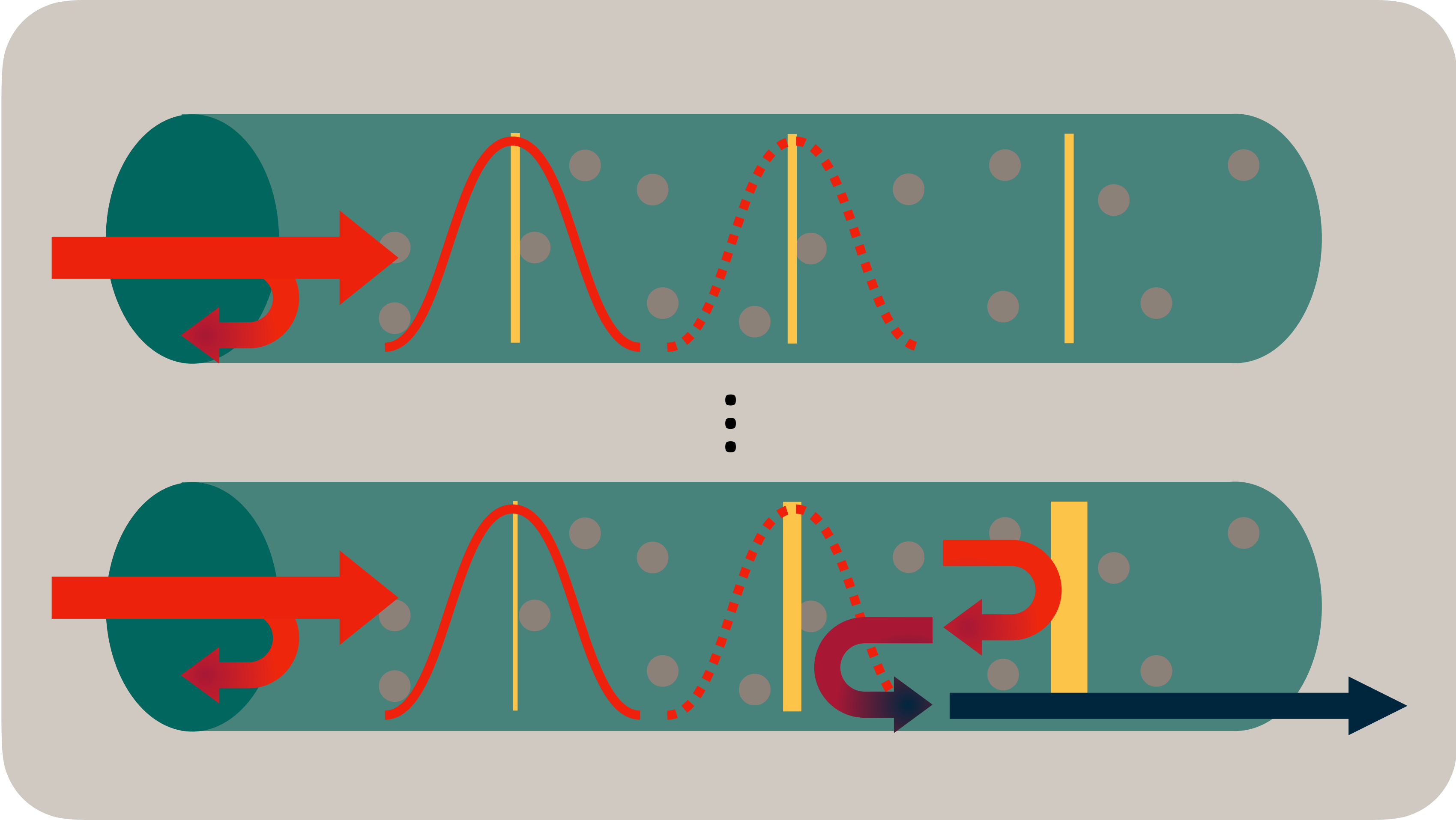


- Much higher signal
- Reasonable losses
- Less fading (control of phase)
- ***Highly-precise interrogator required to use extra light & reduce the noise floor***

High precision fiber sensing

With digitally-enhanced interferometry

Engineered fibers



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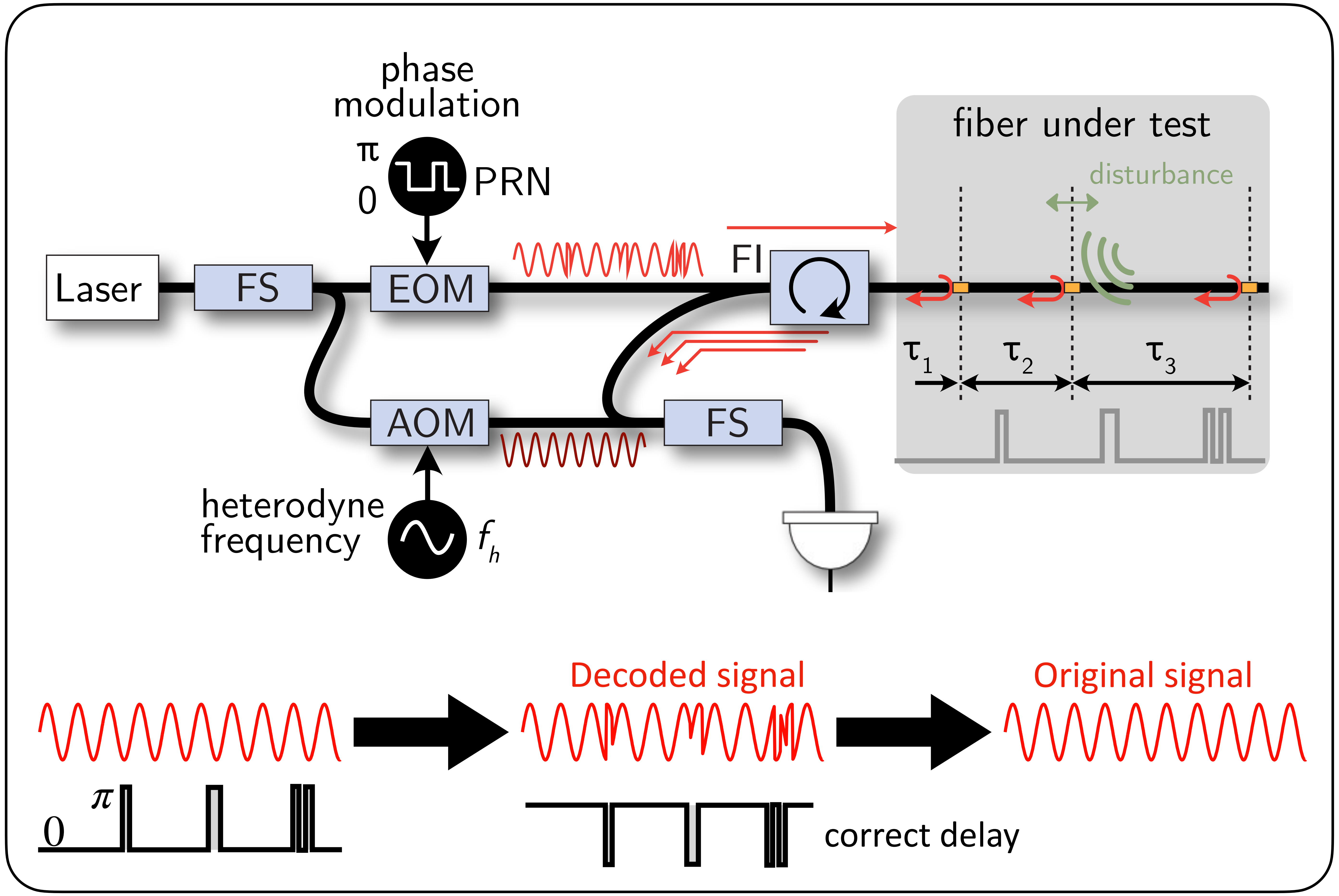
- ***Highly-precise interrogator required to use extra light & reduce the noise floor***

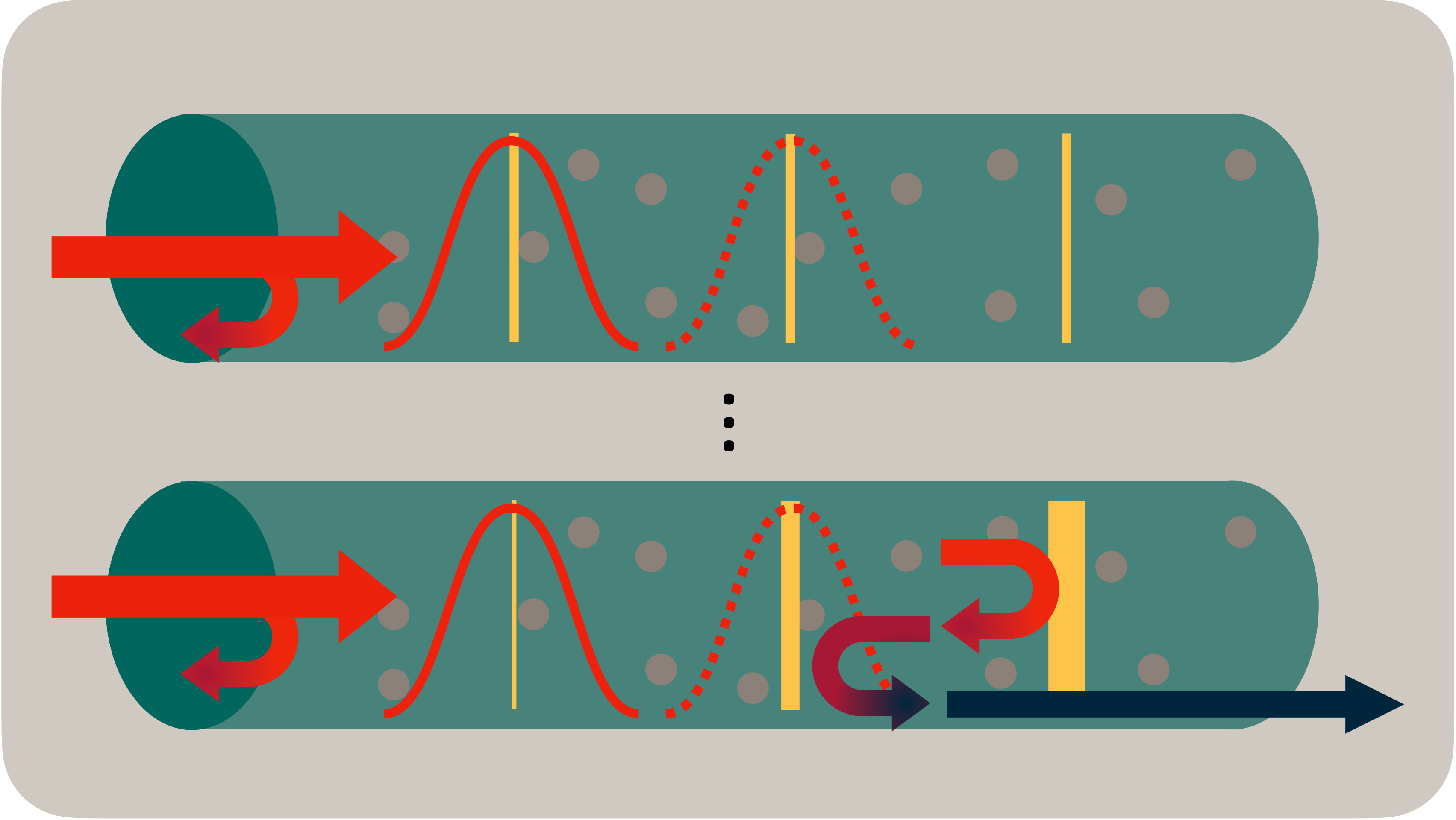
Digitally-enhanced interferometry



High precision fiber sensing

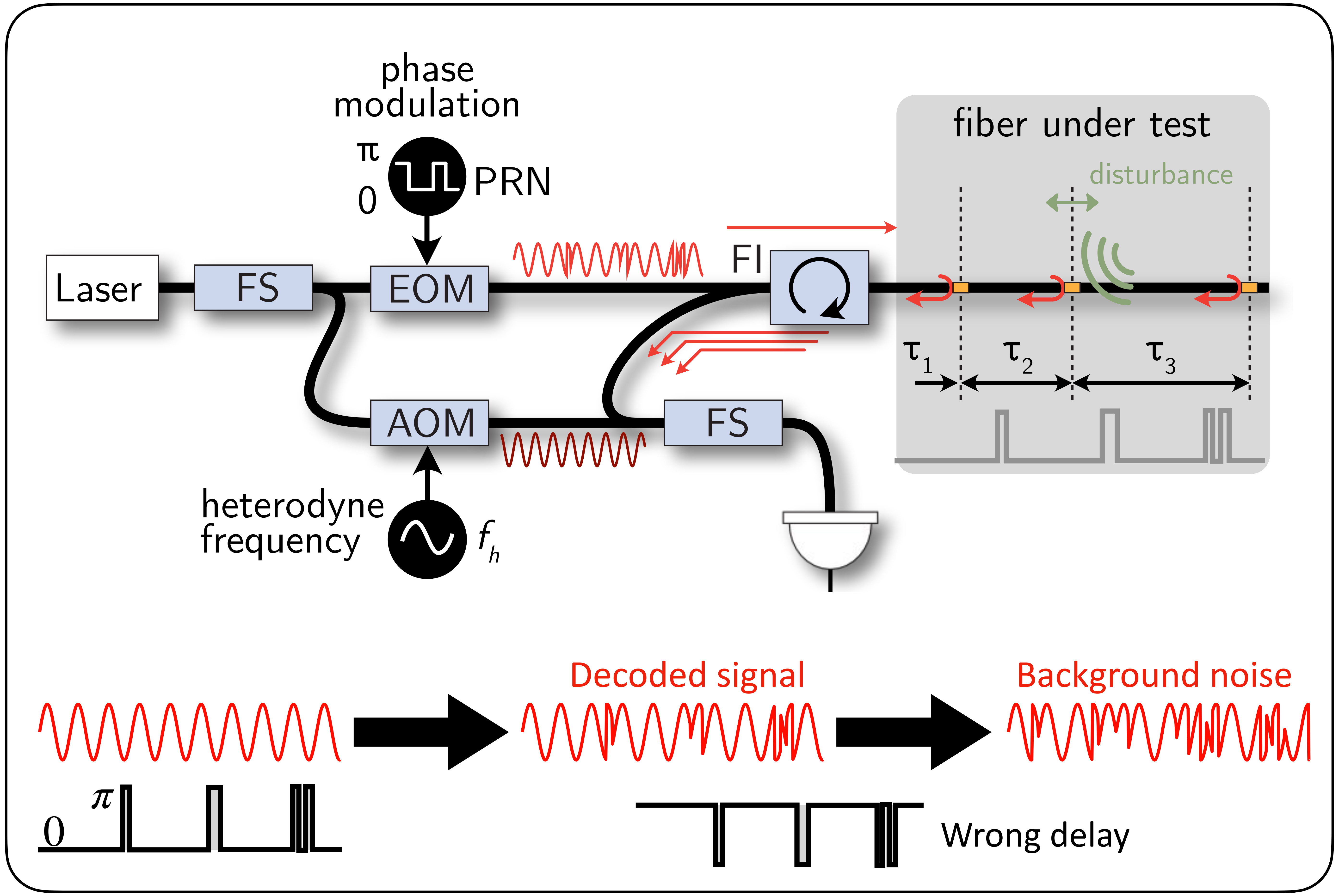
With digitally-enhanced interferometry

Engineered fibers



- Much higher signal
- Reasonable losses
- Less fading (control of phase)
- ***Highly-precise interrogator required to use extra light & reduce the noise floor***

Digitally-enhanced interferometry



Results

Digitally-enhanced distributed fiber readout for seismic noise

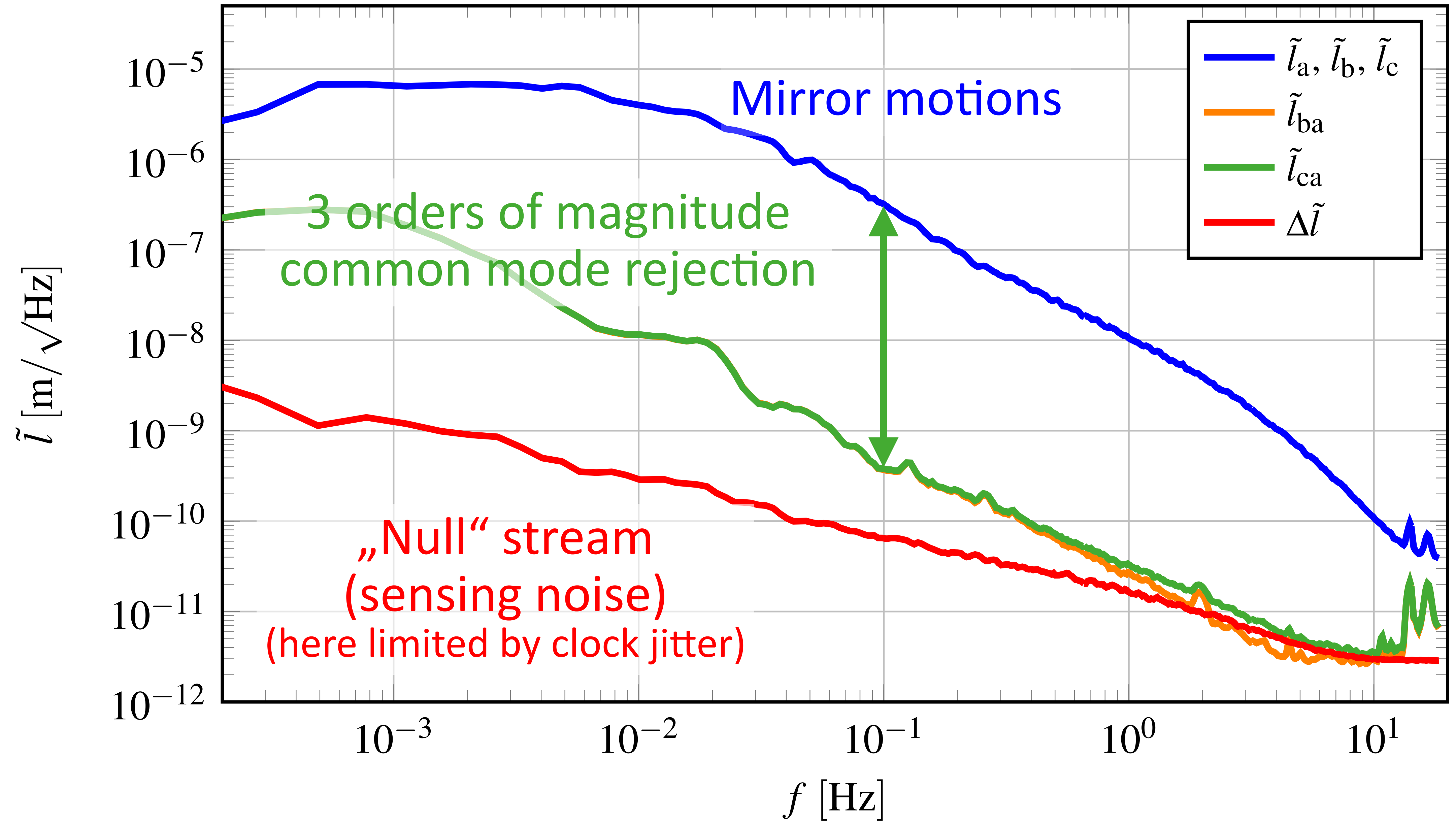
- High speed free beam setup (Hannover)

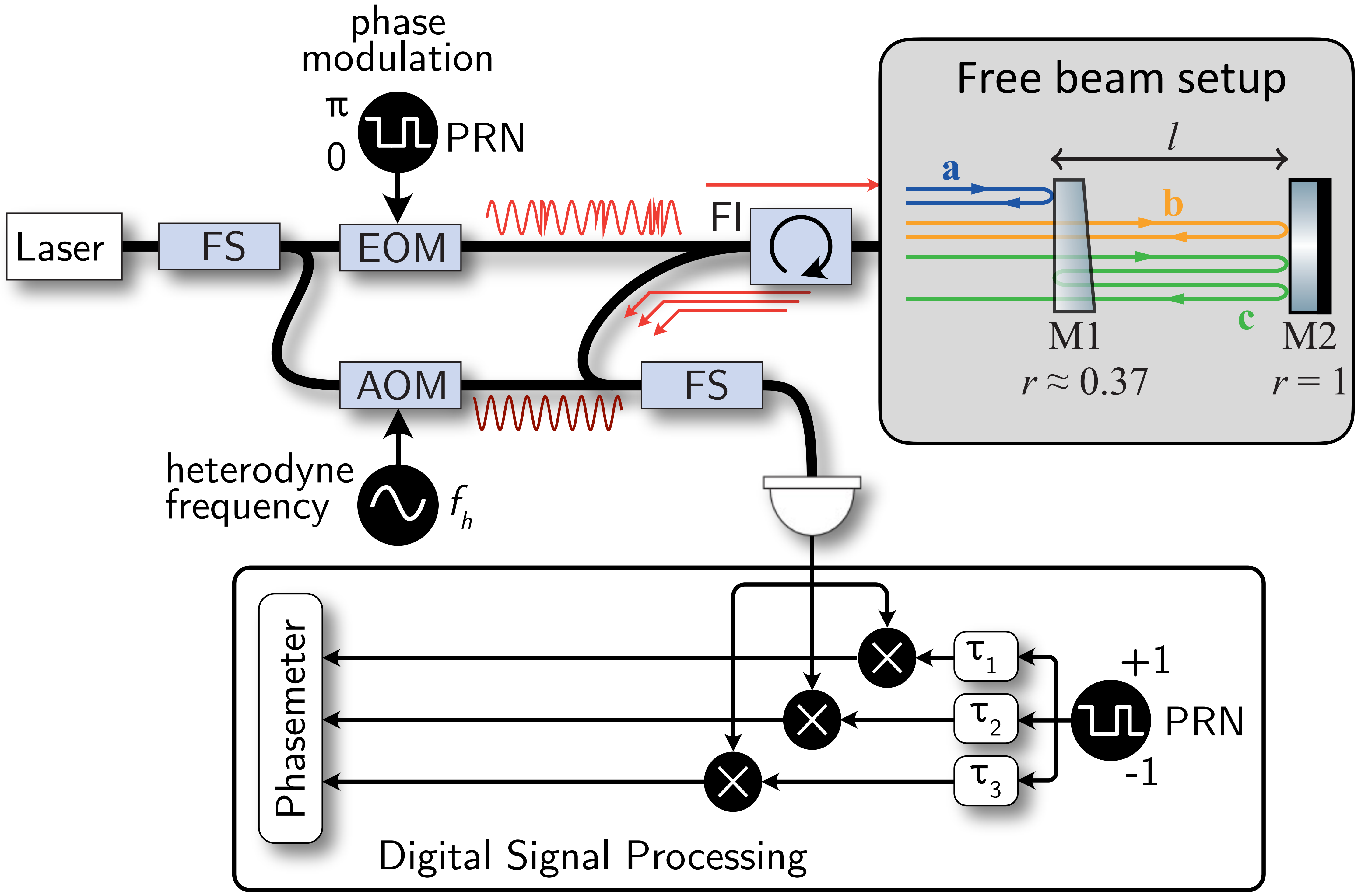
$f_{\mathrm{PRN}} \approx 1.25\,\mathrm{GHz}$ → $12\,\mathrm{cm}$ spatial resolution

$2\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ @ 10 Hz →

$20\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ @ 1 Hz →

$1 - 10\,\mathrm{p}\epsilon/\sqrt{\mathrm{Hz}}$





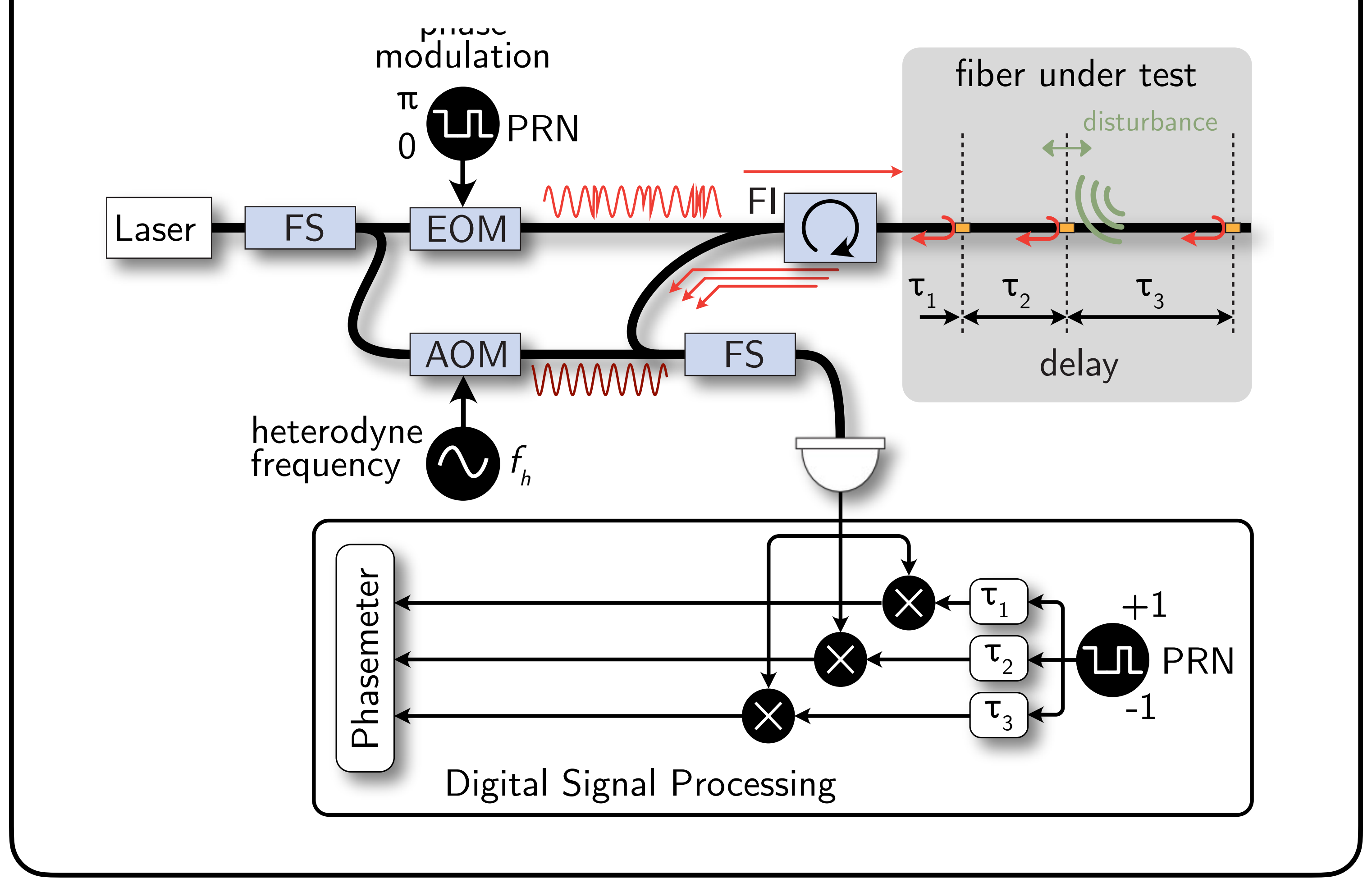
Isleif et al. 2014, DOI:10.1364/OE.22.024689 | OPTICS EXPRESS 24689

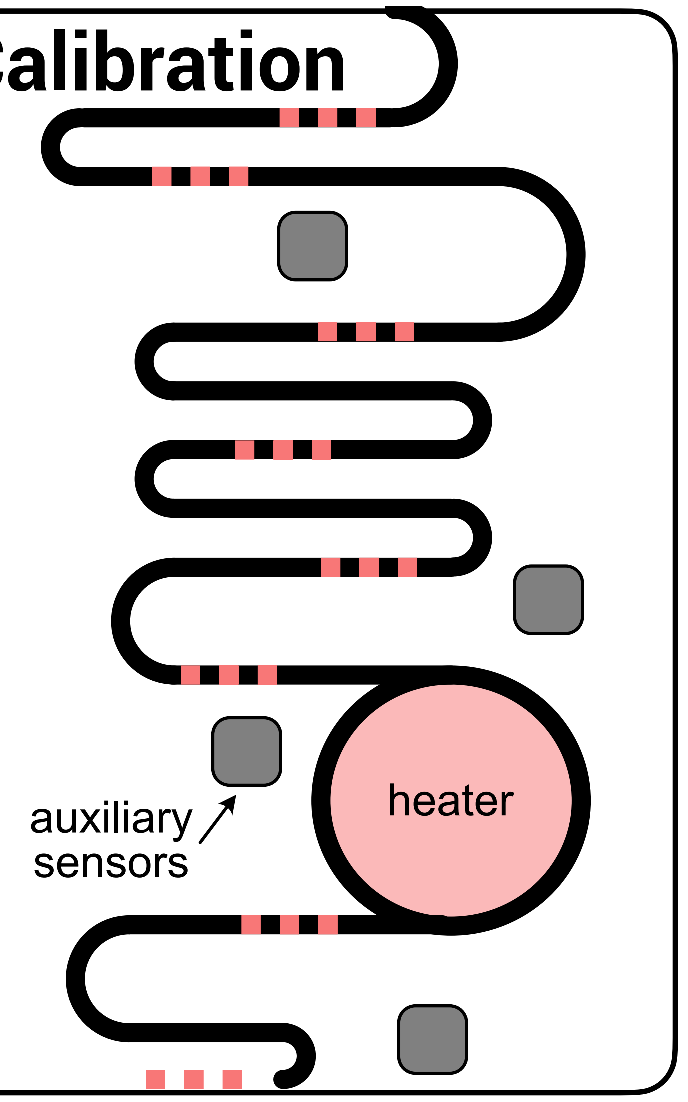
Status and outlook

Digitally-enhanced distributed fiber readout for seismic noise

Fiber setup at HSU in Hamburg and DESY:

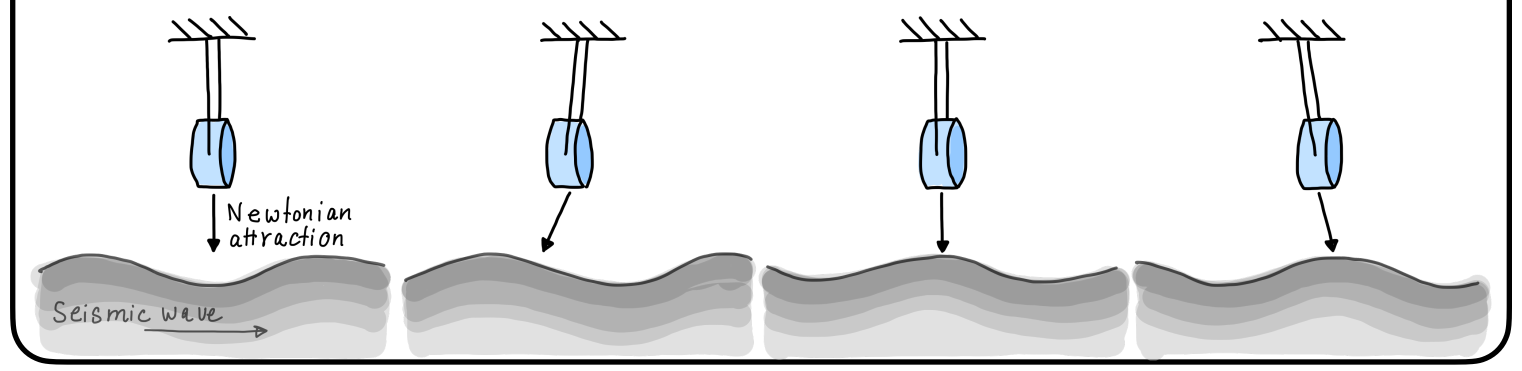
- Setup of the laser lab and **fiber setup**
- **Digital signal processing**
  - 100 of channels in FPGA
- Fiber **calibration** and **characterization**
  - Direction, routing, shape, loop, meander
  - Fiber Bragg gratings, mating sleeves, …
- Potential Applications:
  - **Newtonian Noise** simulations for ET
  - Control of research facilities: feedback, feedforward, early warning system
  - Geophysics: large seismic wavelengths
- **Analysis** of commercial distributed seismic data within the WAVE initiative (following talk by Céline)



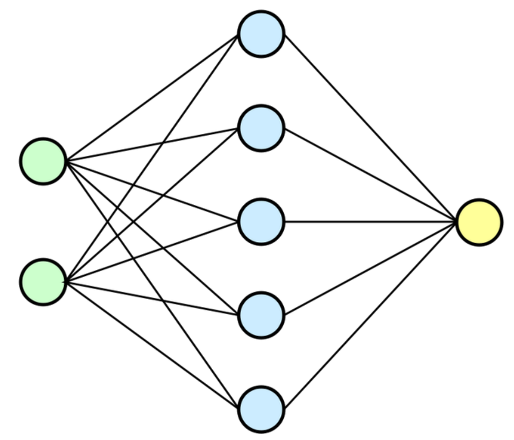


Modelling

$$\delta\vec{a}(\vec{r}_0,t) = -G\int dV\rho(\vec{r})\Big(\underbrace{\vec{\xi}(\vec{r},t)}_{\text{seismic displacement}}\cdot\nabla_0\Big)\frac{\vec{r}-\vec{r}_0}{|\vec{r}-\vec{r}_0|^3}$$



Analysis of sensor networks



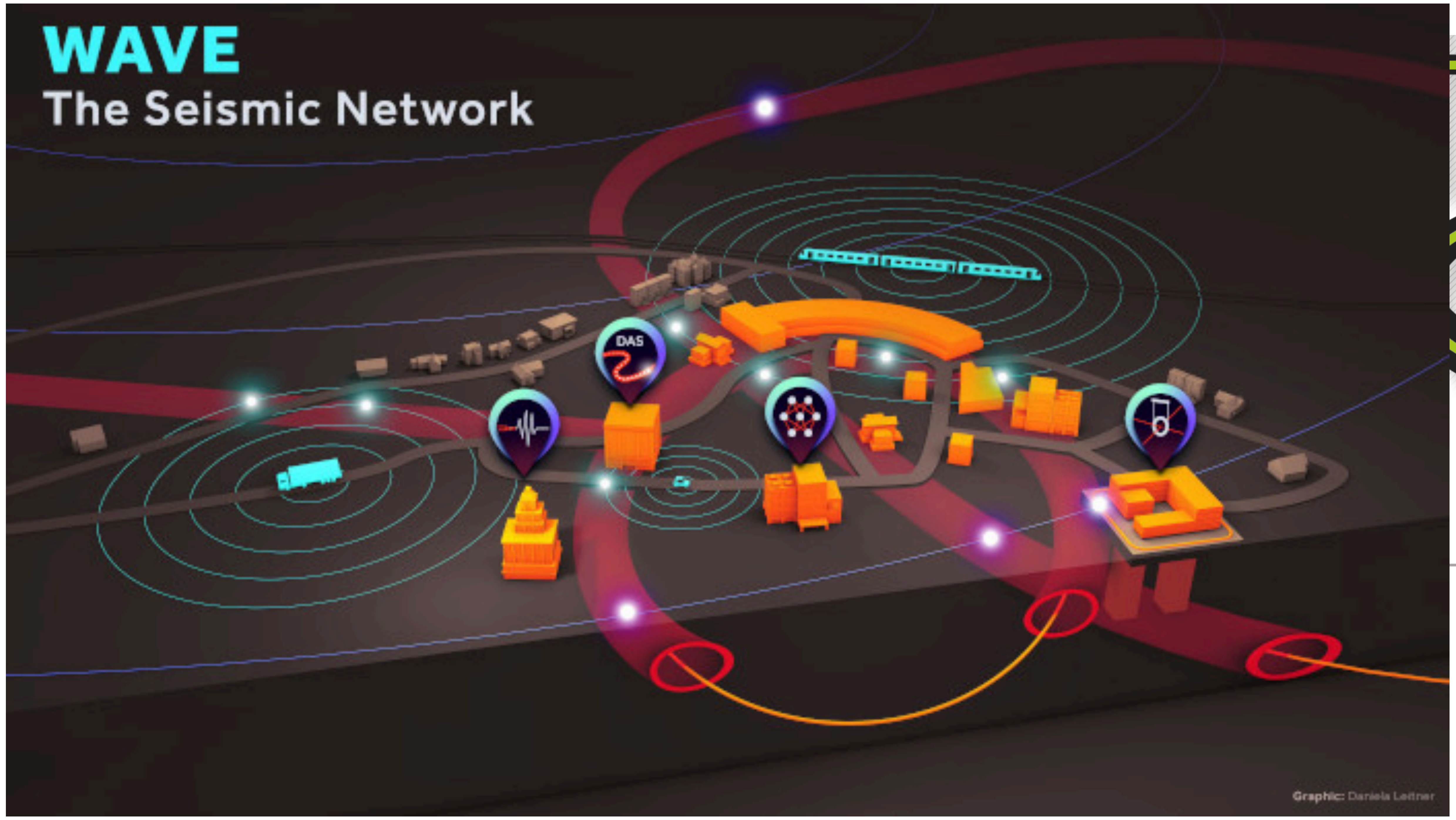
WAVE - a seismic network in Hamburg

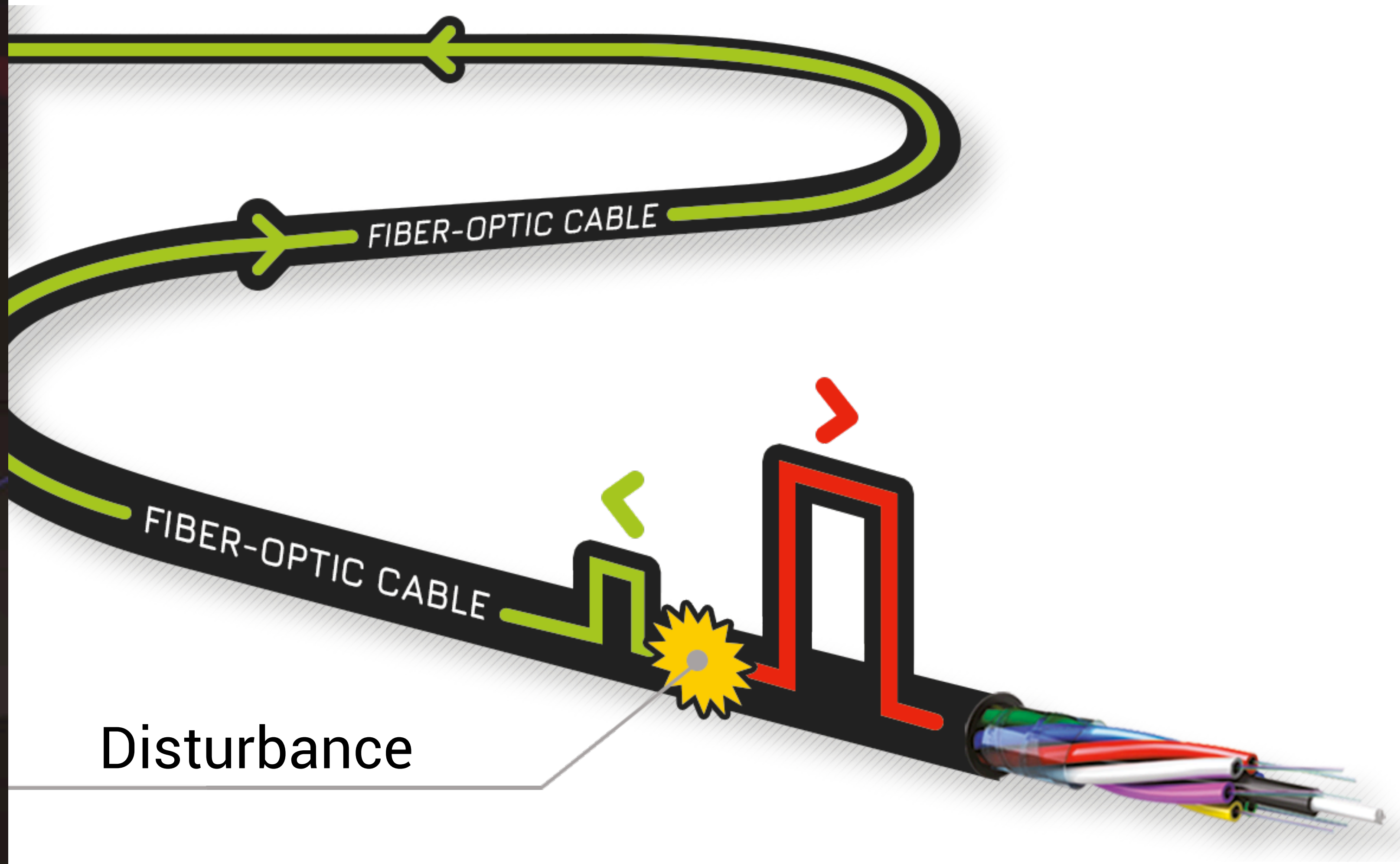
(http://wave-hamburg.eu)

O. Bölt*, L. Cristiano°, S. Croatto†, D. Gajewski*, E. Genthe†, O. Gerberding*, C. Hadziioannou*, M. Hoffmann†, K.-S. Isleif†, C. M. Krawczyk°, A. Lindner†, R. Maaß*, I. Malucelli Barbosa*, N. Meyners†, H. Schlarb†, R. Schnabel*, C. Wollin°

* Universität Hamburg, D-20148 Hamburg
† Deutsches Elektronen-Synchrotron (DESY), D-22607 Hamburg
° Helmholtz Zentrum Potsdam, GeoForschungsZentrum GFZ, D-14473 Potsdam

Geophysicists
Seismologists
Physicists (GW, particle physics, accelerators, ...)
Engineers
Computer scientists





Dark communication fibers on the Science Campus Bahrenfeld read out with commercial interrogator for distributed acoustic sensing

WAVE - a seismic network in Hamburg

(http://wave-hamburg.eu)

O. Bölt*, L. Cristiano°, S. Croatto†, D. Gajewski*, E. Genthe†, O. Gerberding*, C. Hadziioannou*, M. Hoffmann†, K.-S. Isleif†, C. M. Krawczyk°, A. Lindner†, R. Maaß*, I. Malucelli Barbosa*, N. Meyners†, H. Schlarb†, R. Schnabel*, C. Wollin°

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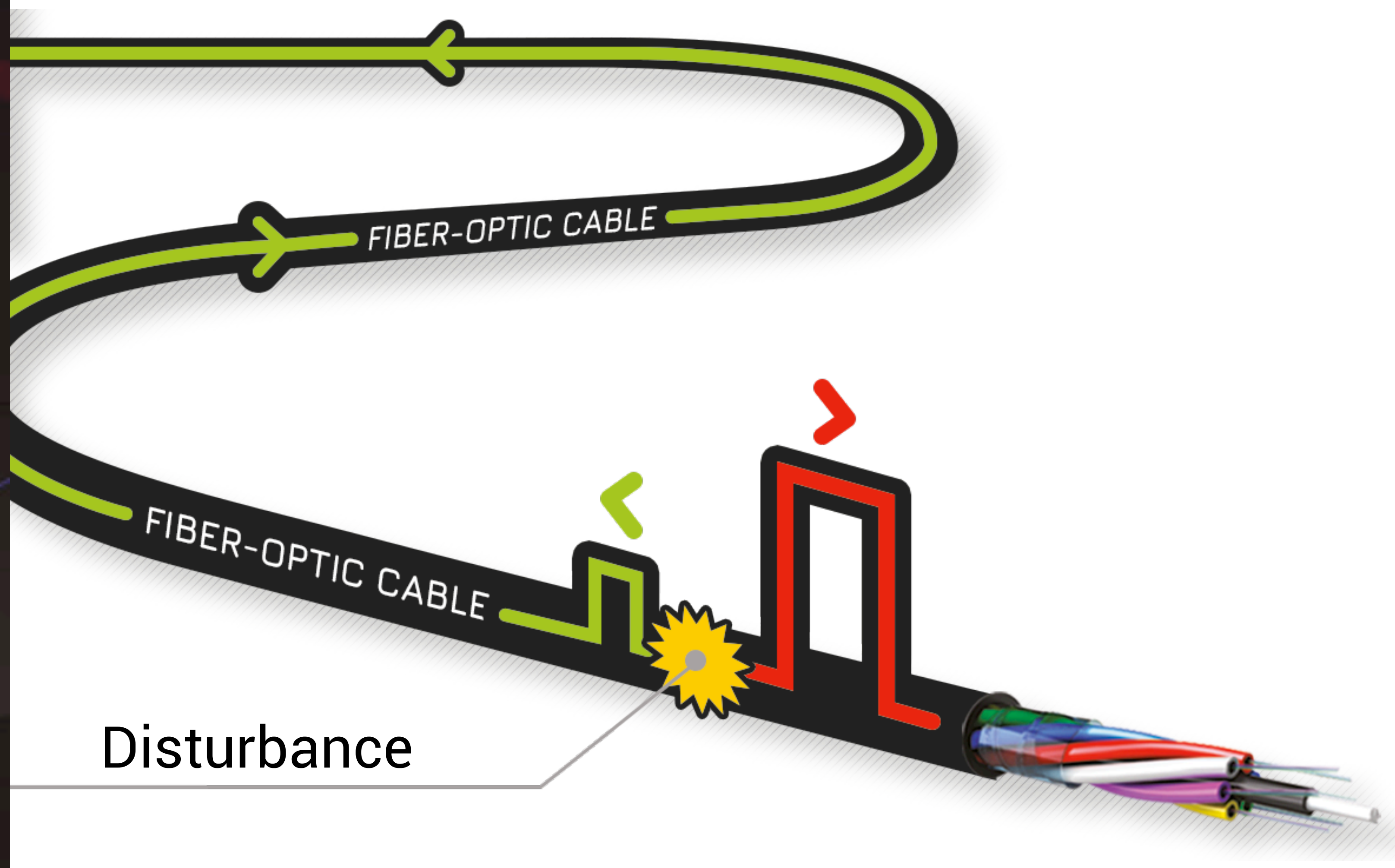
11:00

First WAVE results **TODAY (!)** after this talk

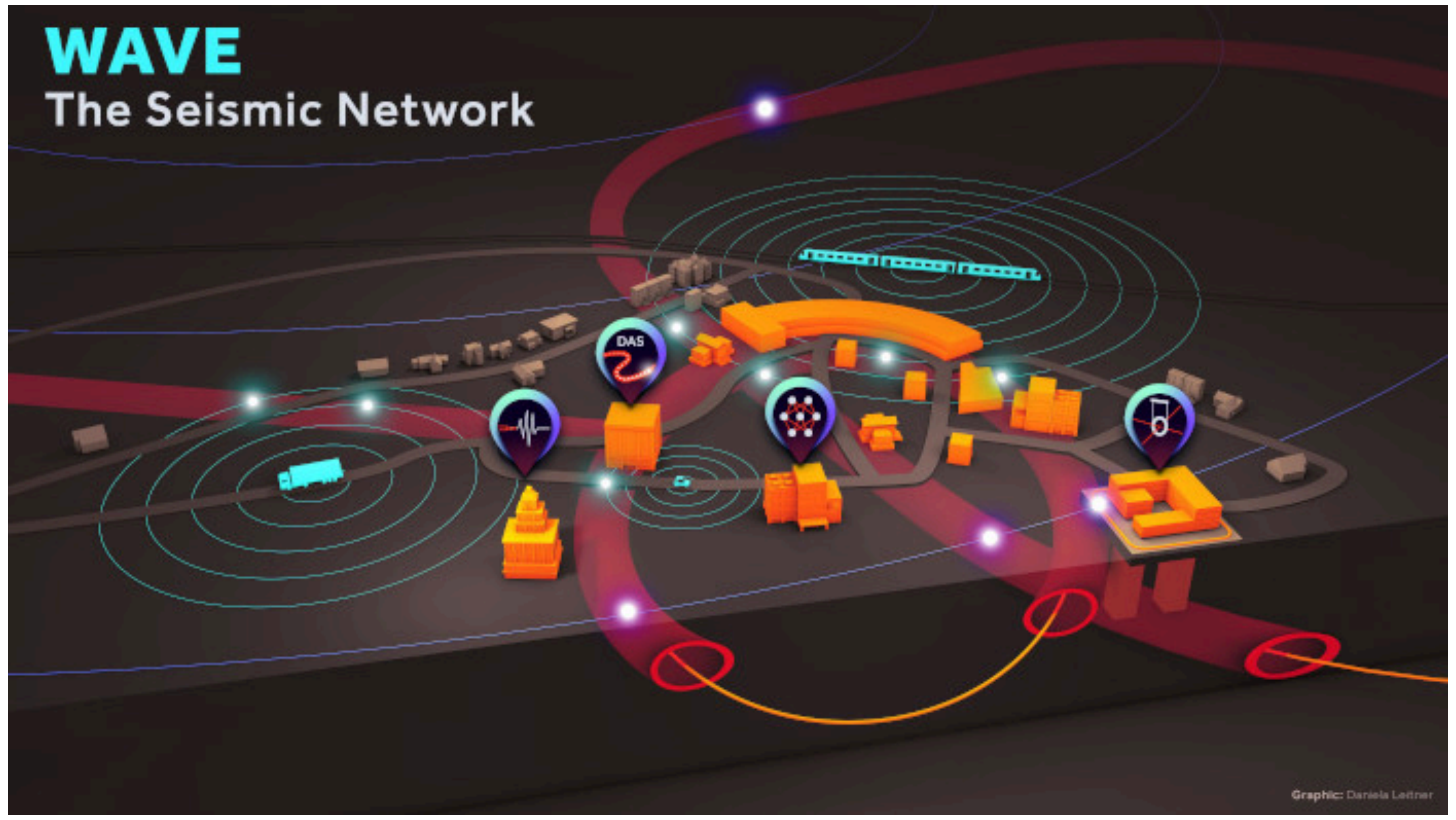
Keynote Physics Talks 1: Geophysics - Prof. Céline Hadziioannou, University of Hamburg

FTU Aula, KIT Campus North 11:00 - 11:45



Dark communication fibers on the Science Campus Bahrenfeld read out with commercial interrogator for distributed acoustic sensing

Thank you for your Attention.



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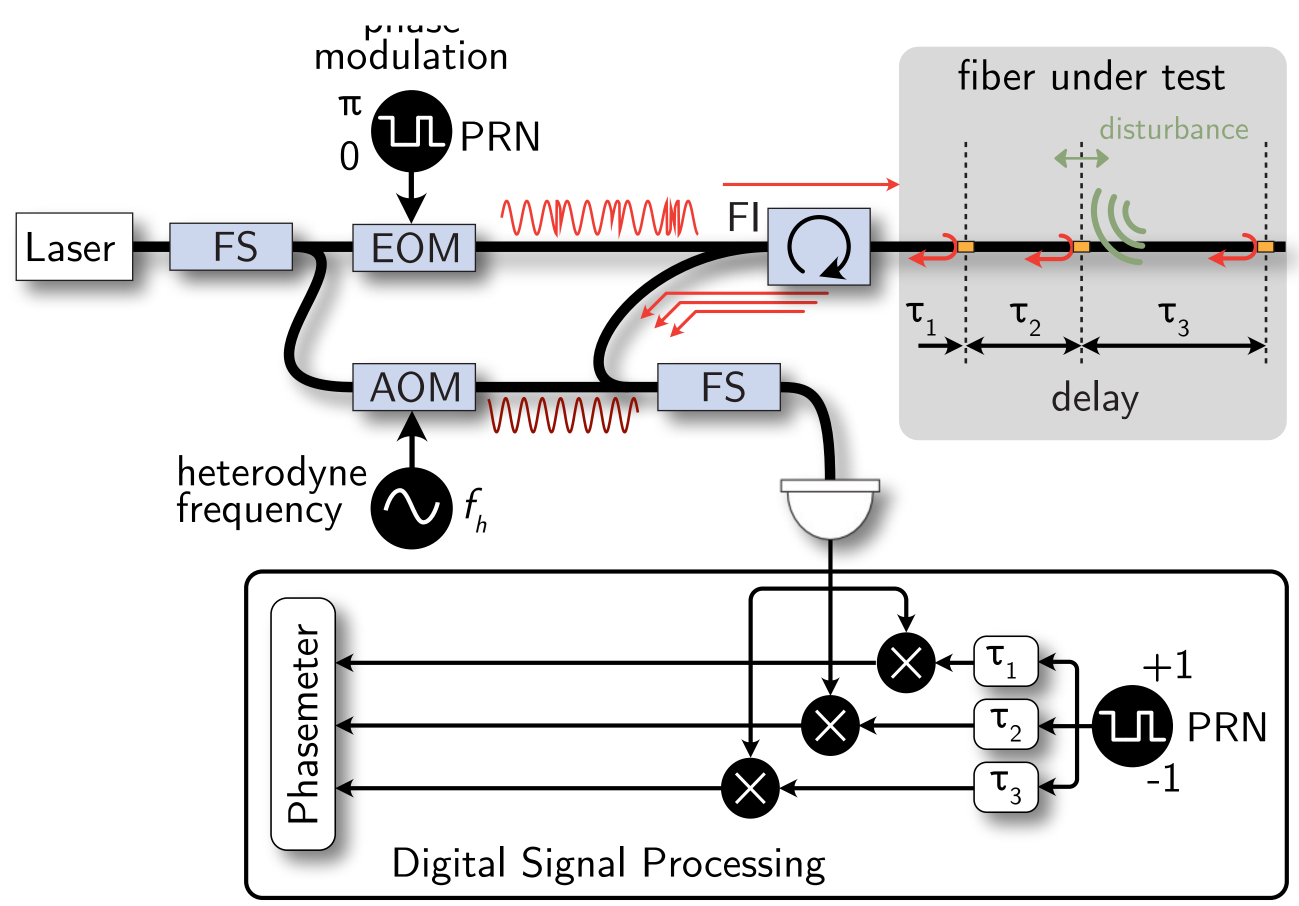
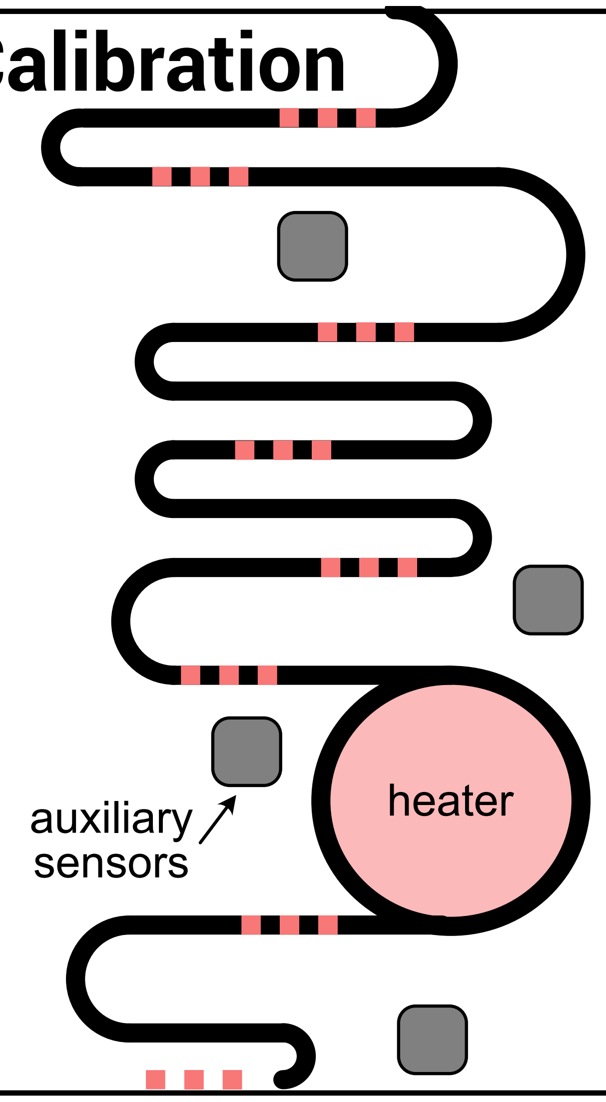


Calibration



Modelling

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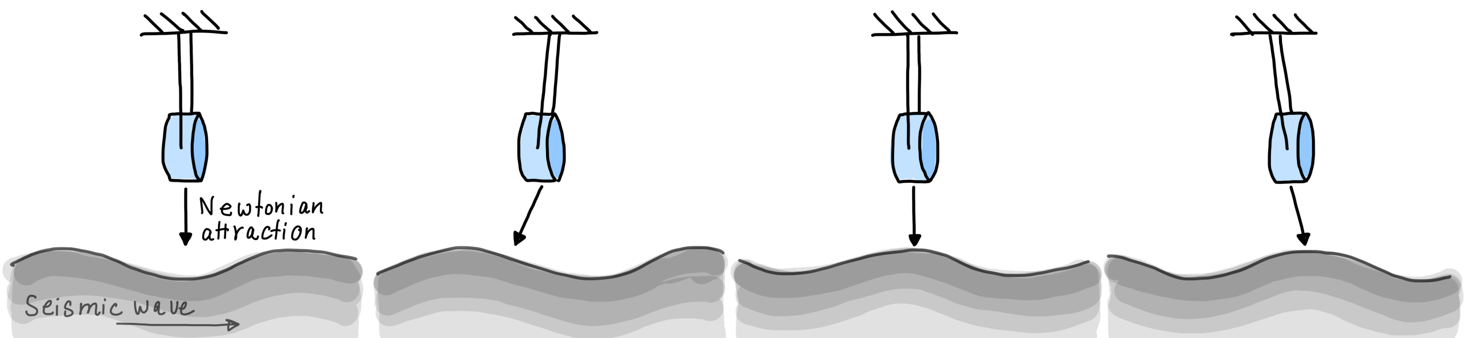

Analysis of sensor networks