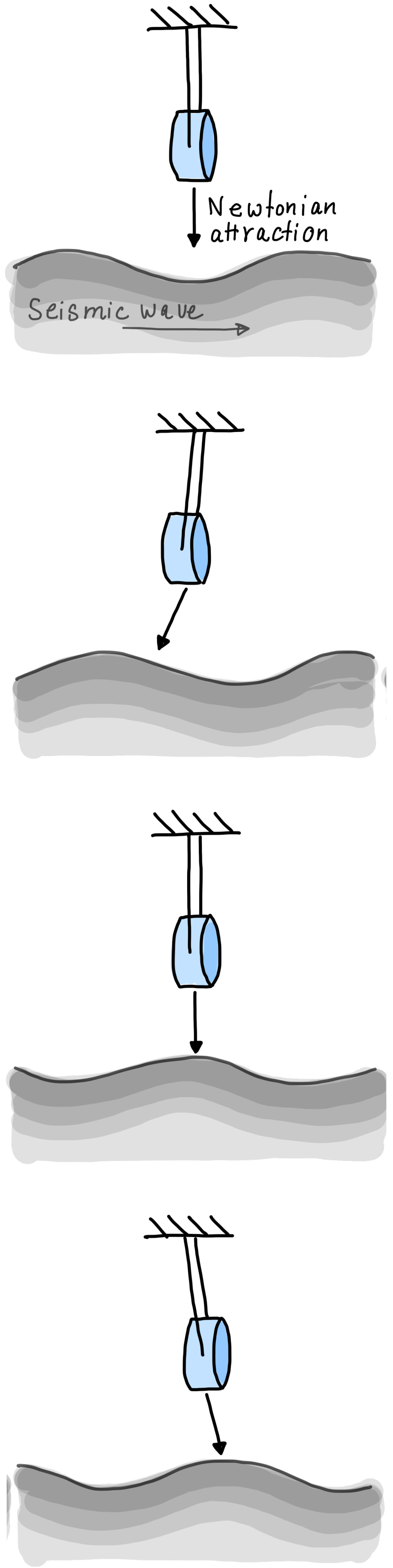
Katharina-Sophie Isleif
Junior-Prof. for Metrology
HSU, Institute for Automation Technology



Distributed seismic fiber networks for Newtonian noise cancellation in the Einstein Telescope

Katharina Isleif[1]

Reinhardt Rading[1], Julian Dietz[1]
Oliver Gerberding[2], Celine Hadziiaonnou[2]
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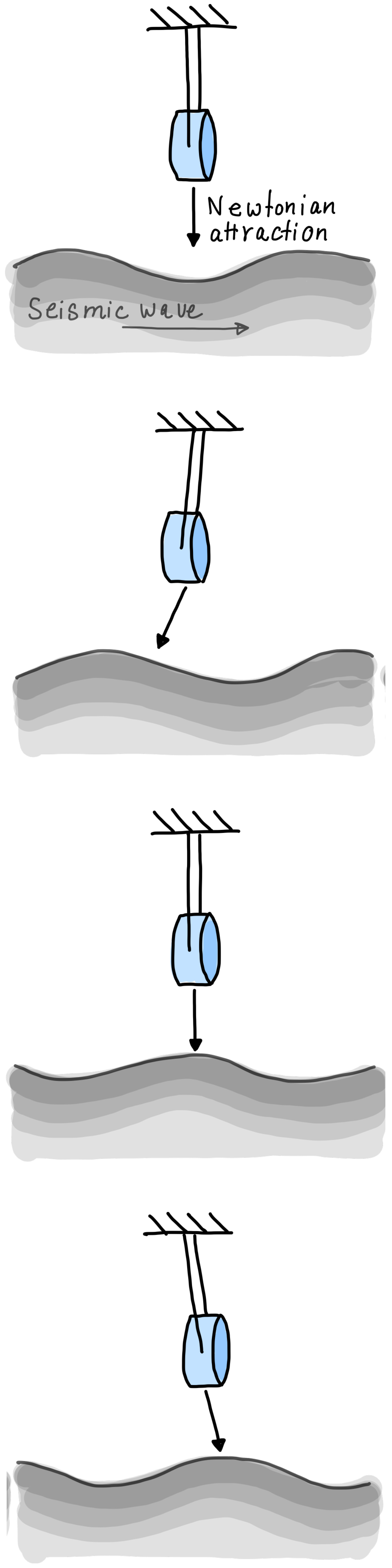


News, today 12pm

News

News from the DESY research centre

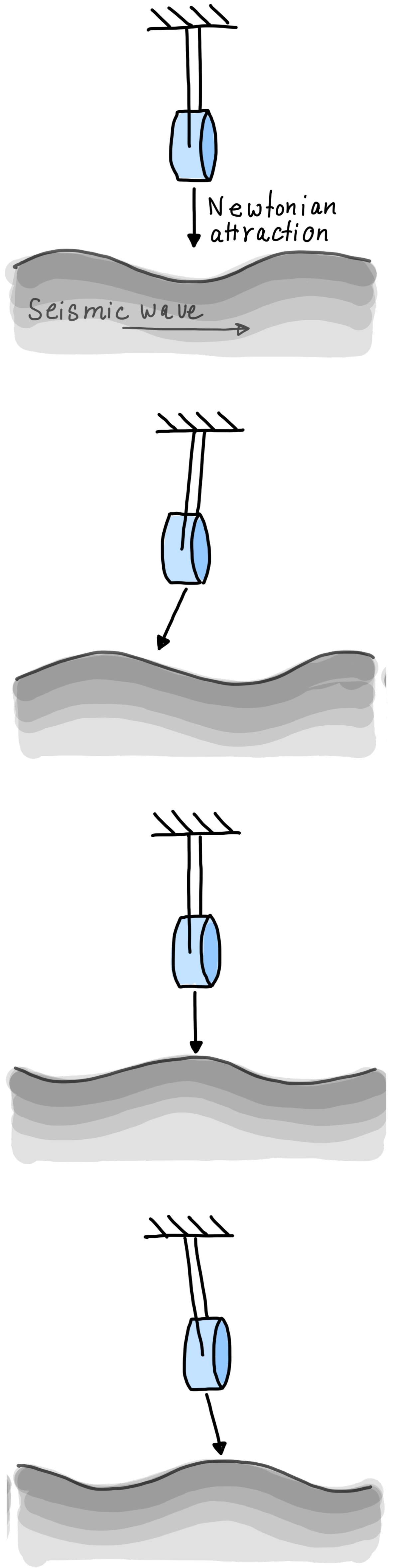
2023/05/23

Back

'Light shining through a wall' experiment ALPS starts searching for dark matter

World's most sensitive instrument of its kind is to produce axions

https://www.desy.de/news/news_search/index_eng.html?openDirectAnchor=2758



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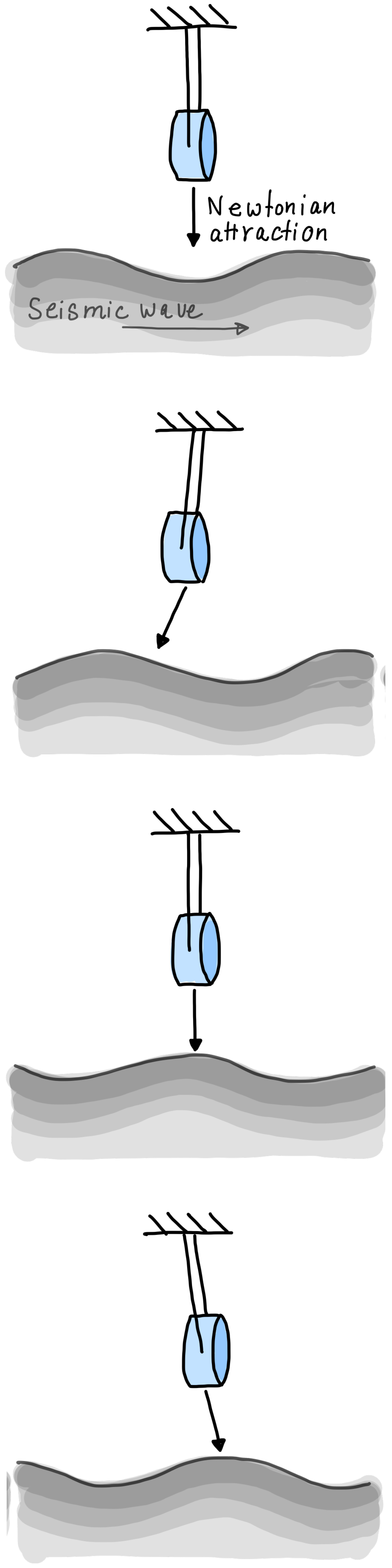
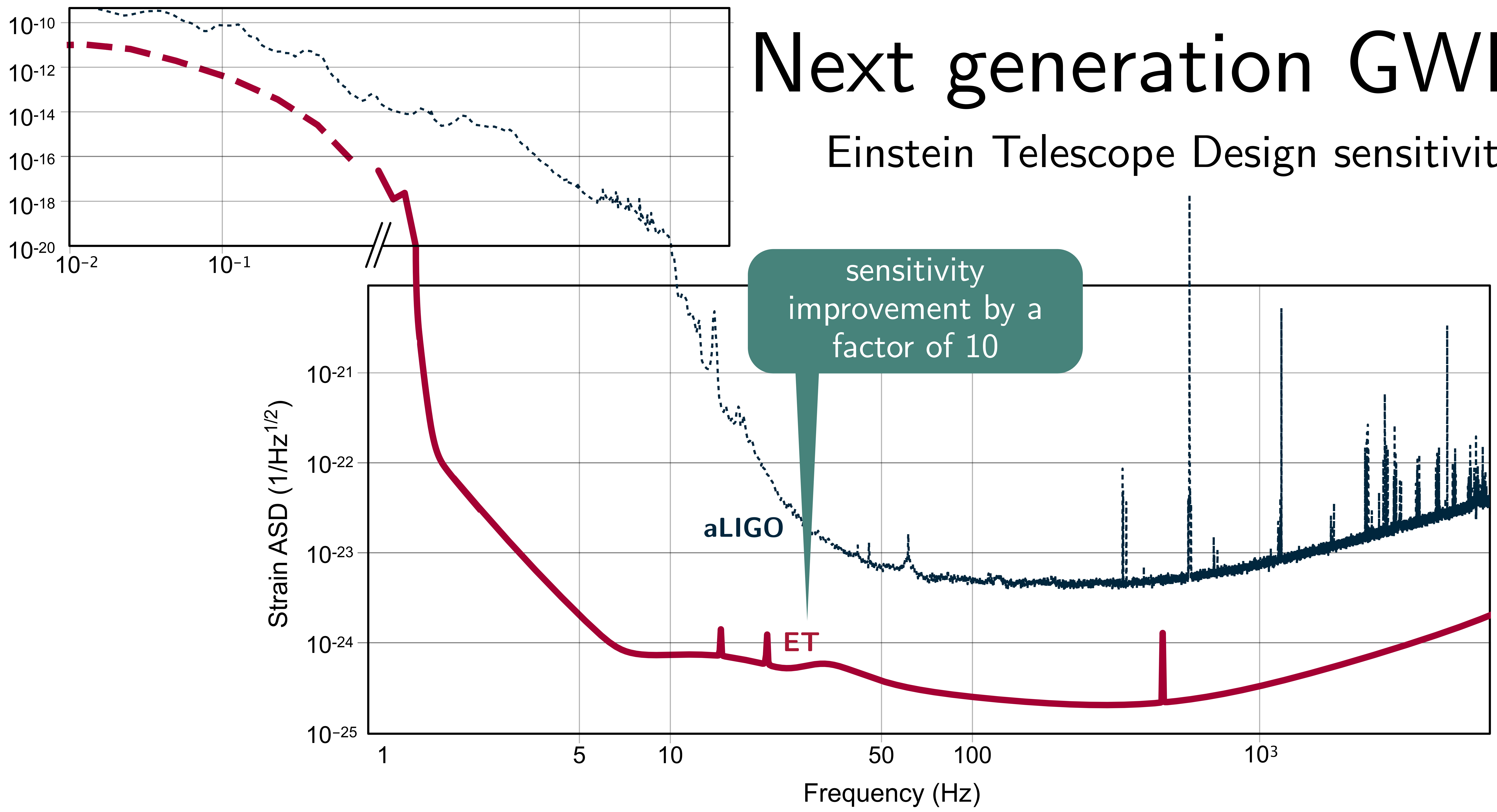


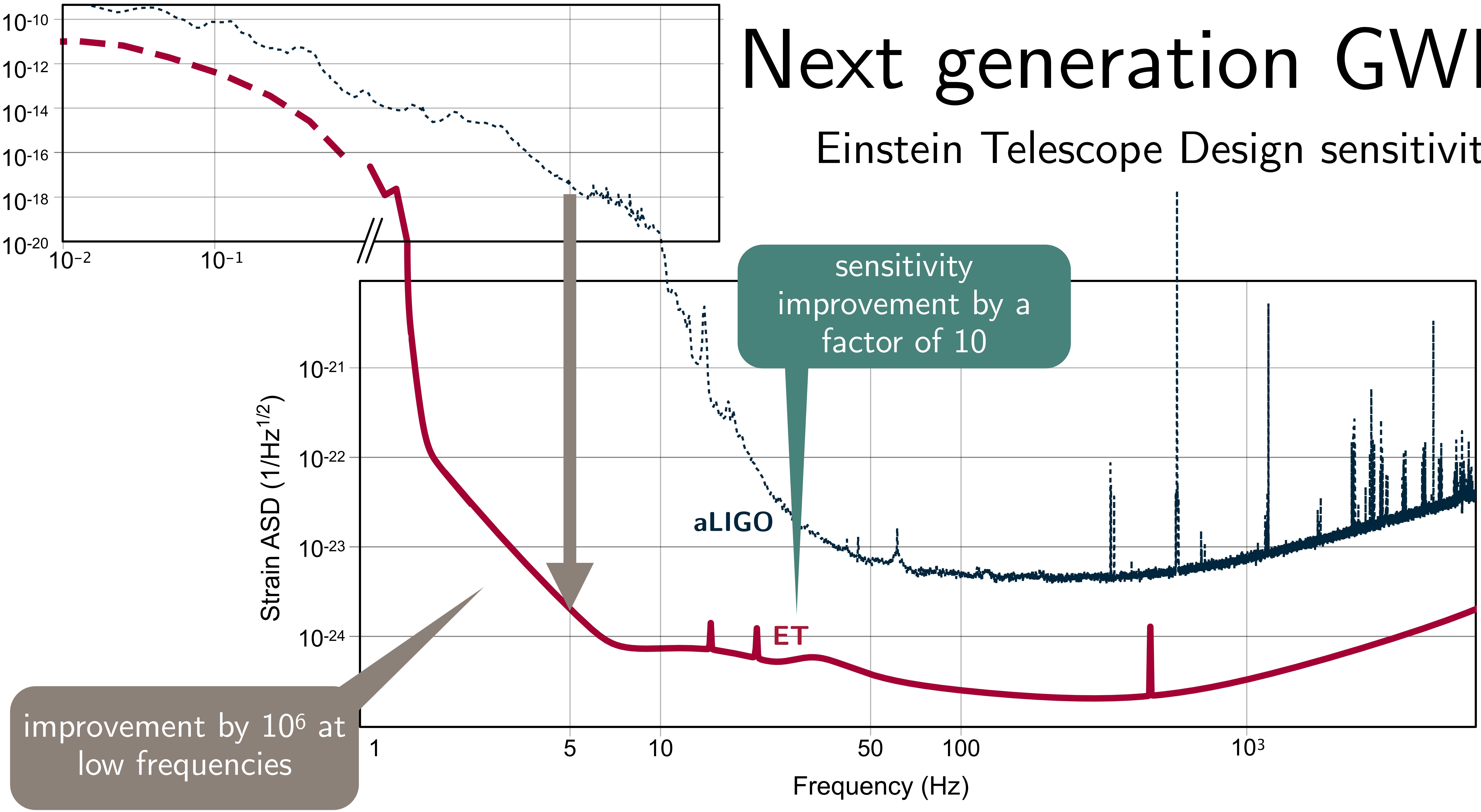
Next generation GWDs

Einstein Telescope Design sensitivity

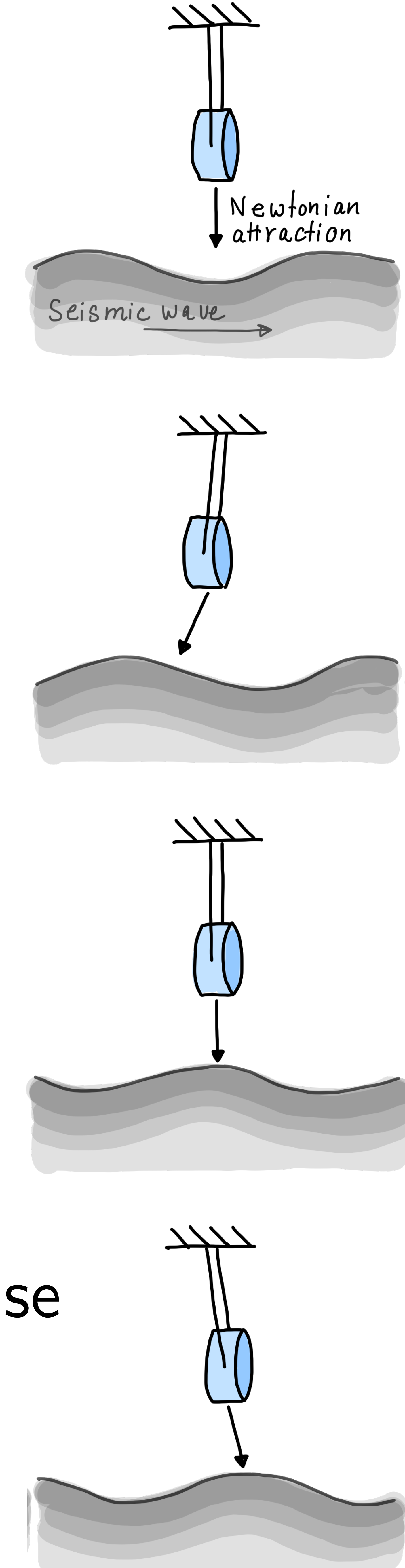


Next generation GWDs

Einstein Telescope Design sensitivity



Newtonian Noise (NN)



- Direct consequence of mass density fluctuations in the environment
- seismic noise, advected temperature and humidity fields, acoustic fields
- NN is a changing gravitational force accelerating the suspended test masses

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

test mass position

Gravitational constant

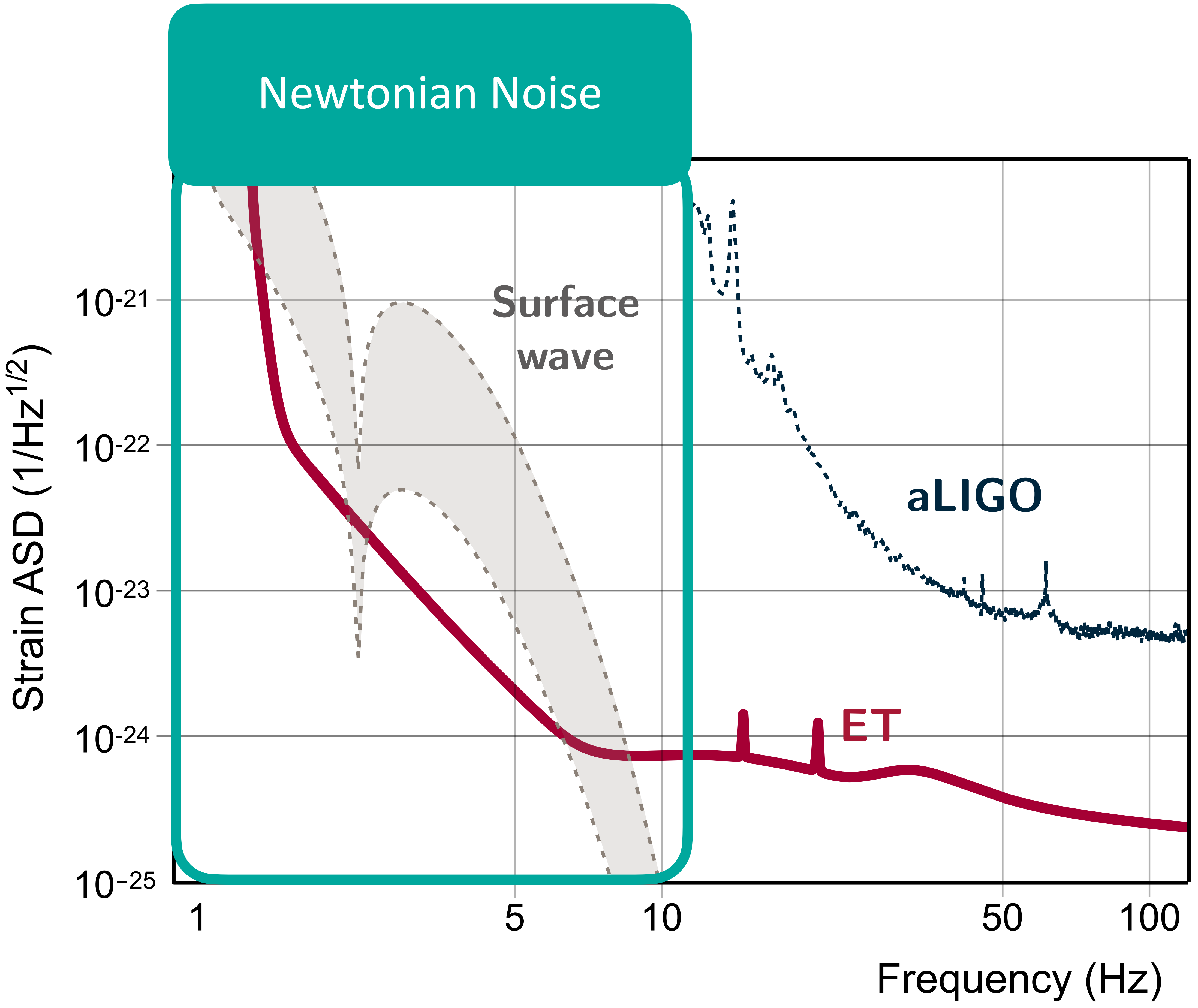
points inside medium

- NN bypasses isolation systems designed to suppress environmental/seismic noise

Harms, 2015 https://doi.org/10.1007/lrr-2015-3

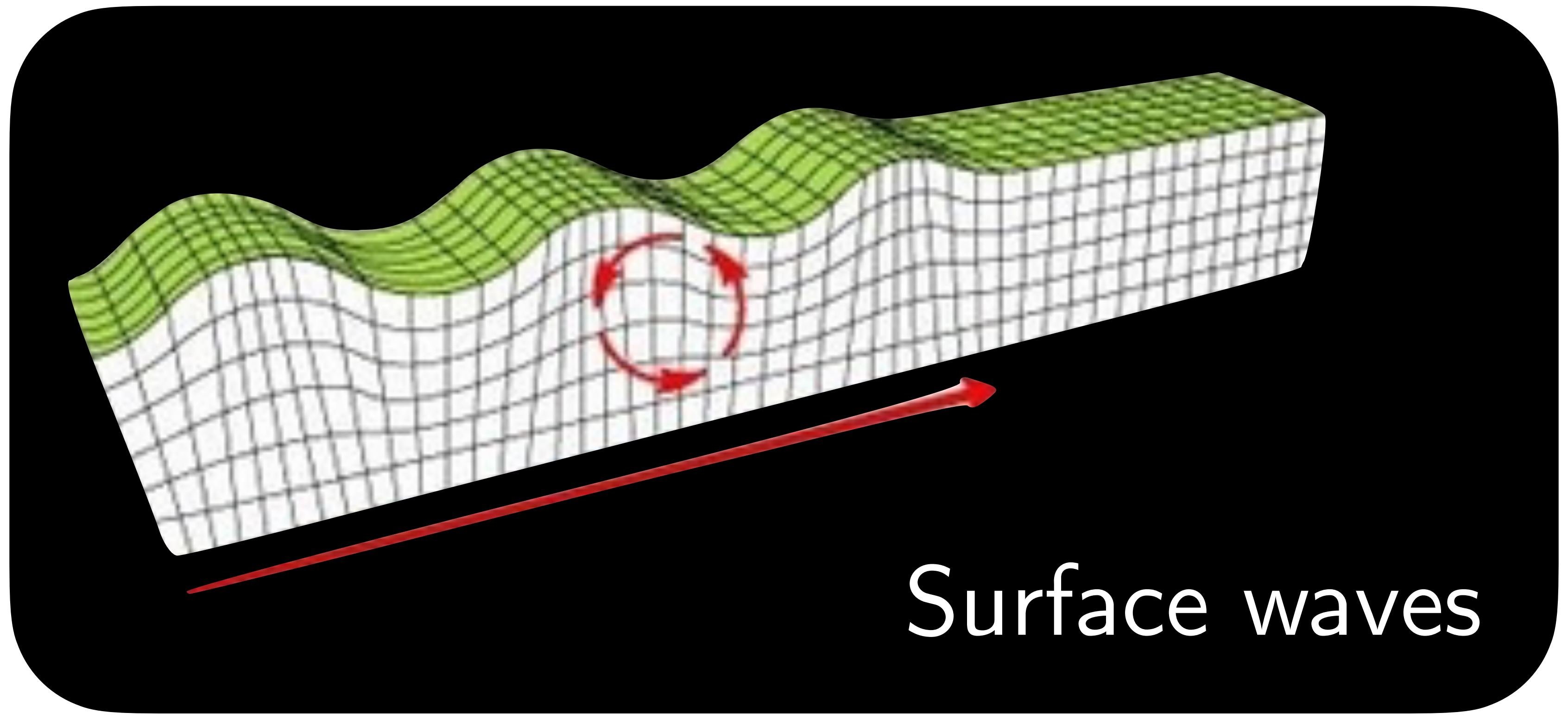
Newtonian Noise (NN) Model

From seismic fields



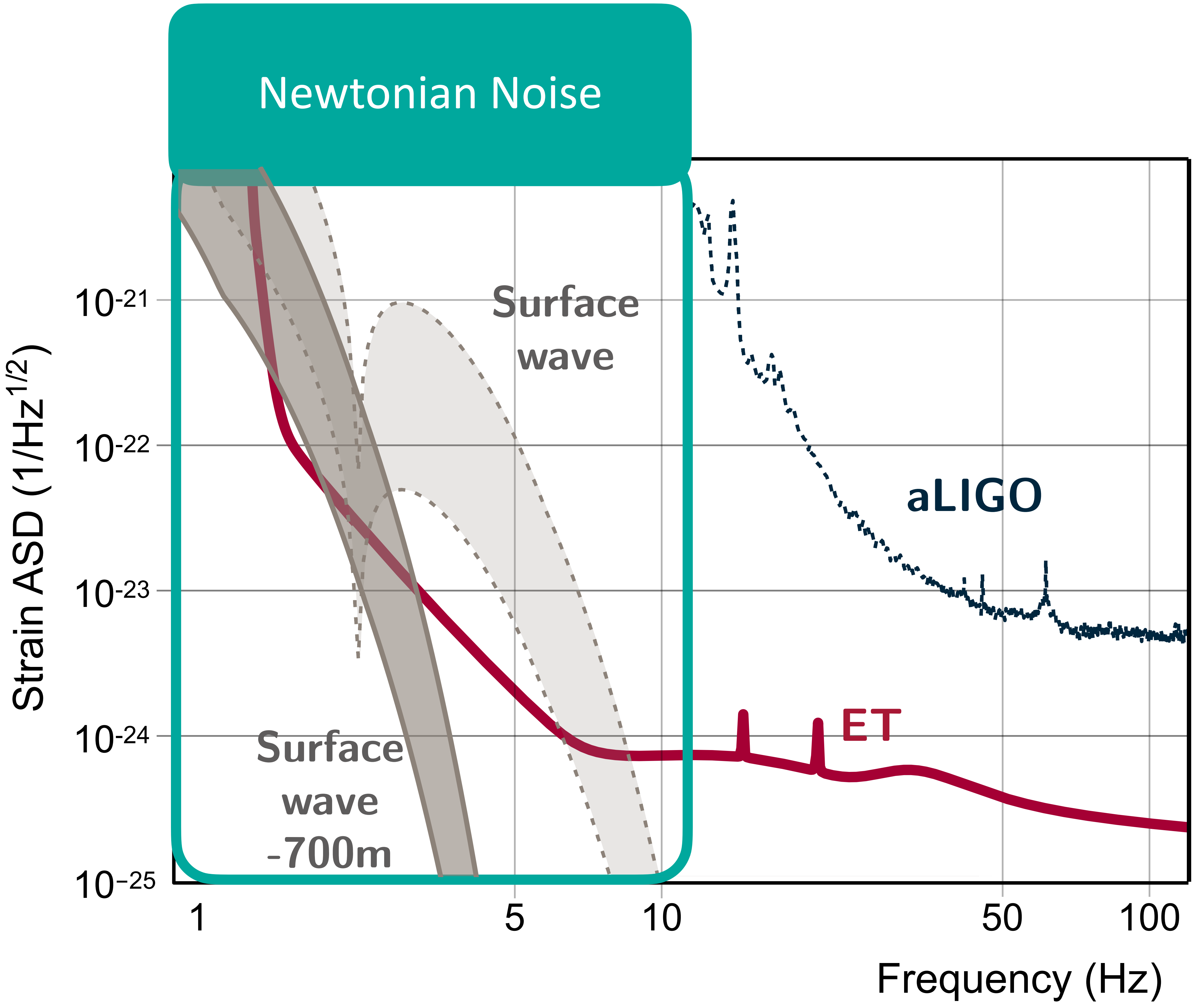
Harms, 2015 https://doi.org/10.1007/lrr-2015-3

- Surface waves dominate Newtonian Noise $\rightarrow$ underground detector



Newtonian Noise (NN) Model

From seismic fields



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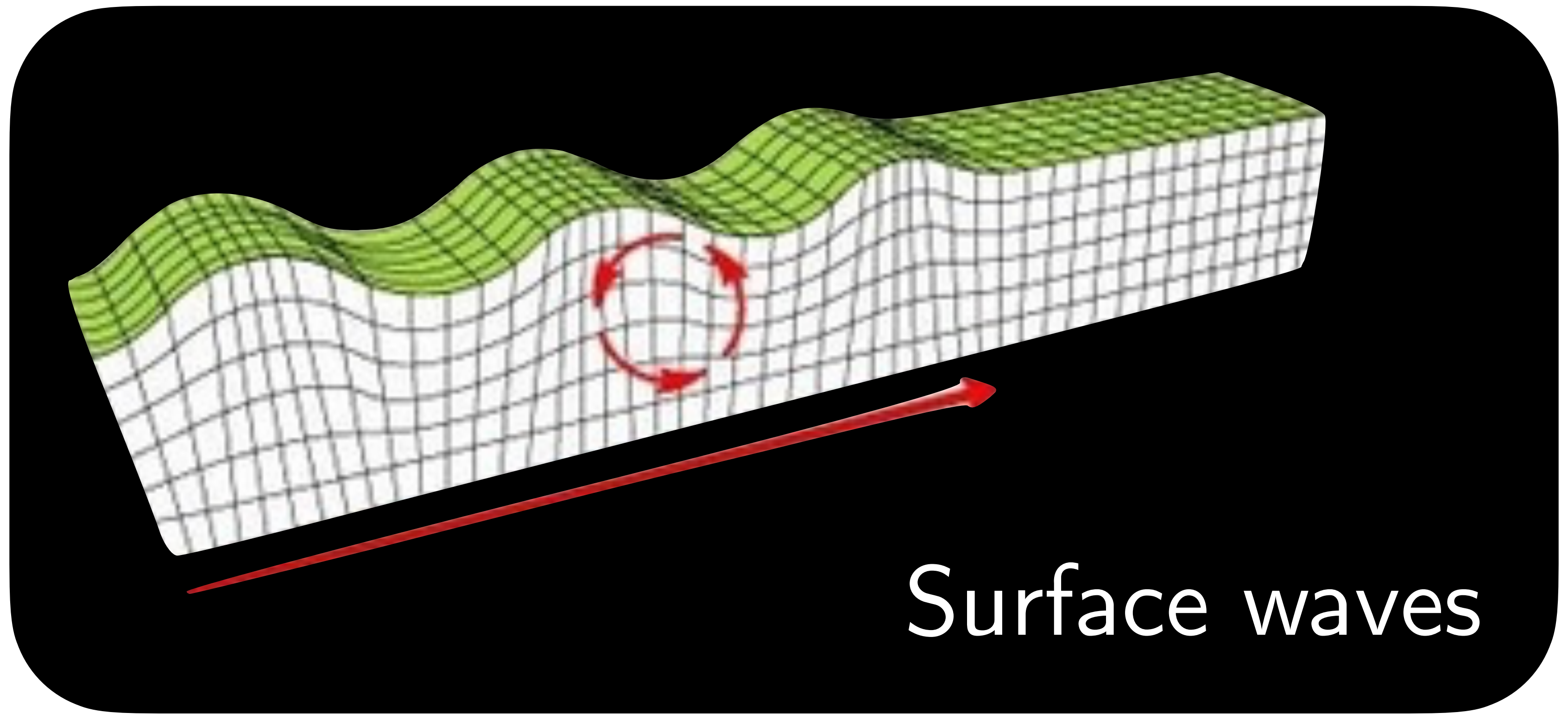

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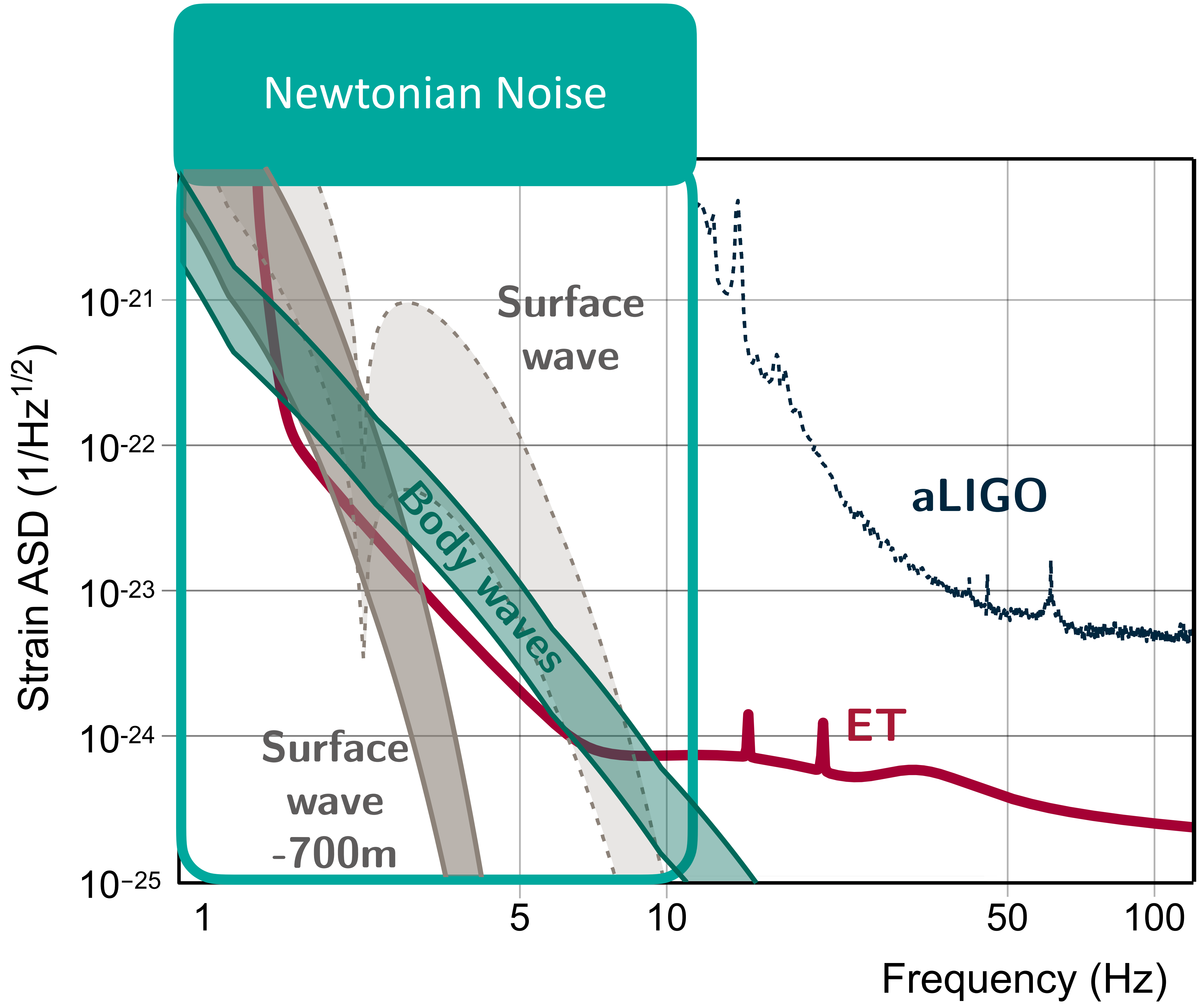
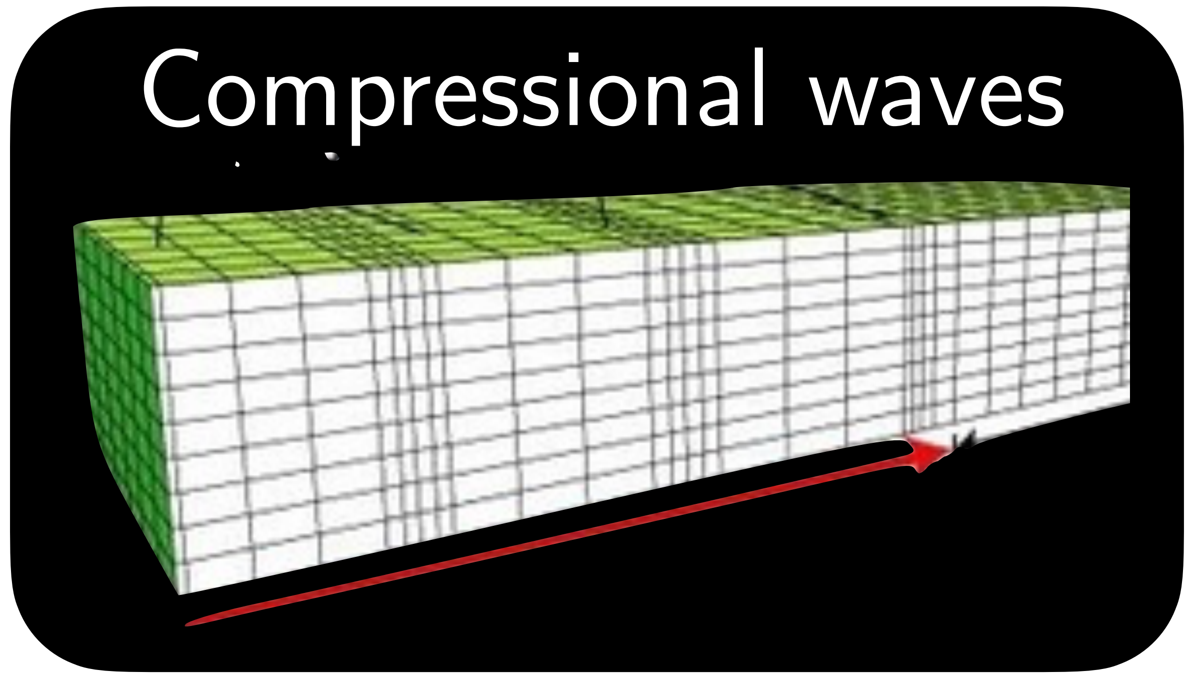
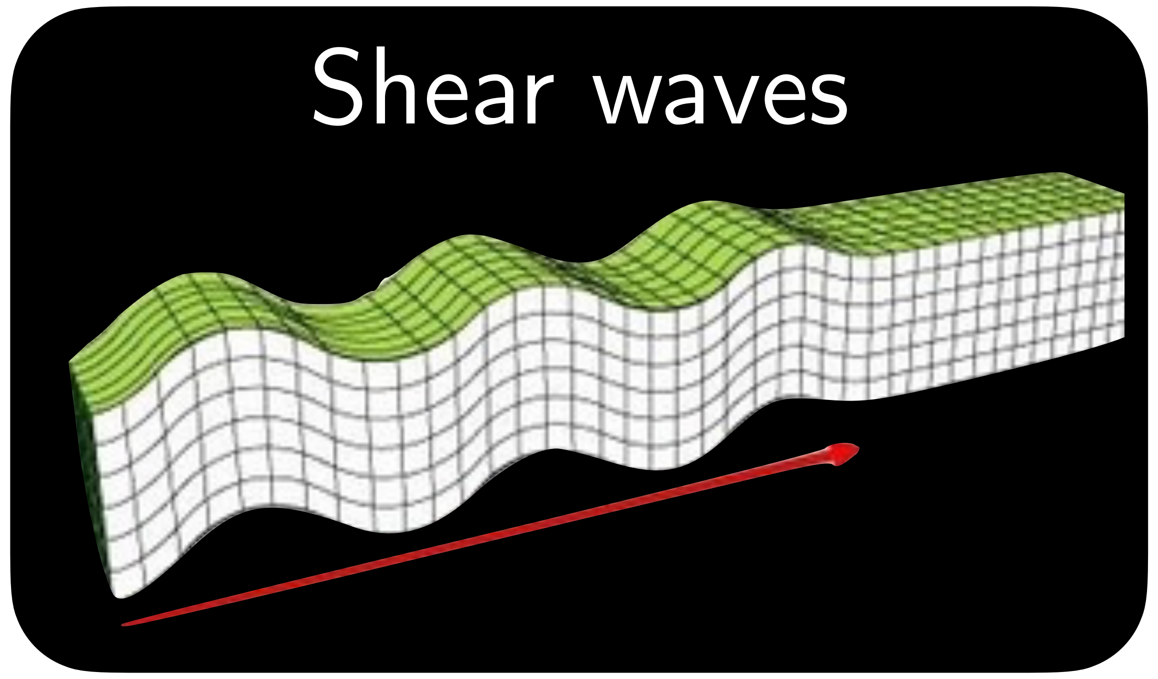


Harms, 2015 https://doi.org/10.1007/lrr-2015-3

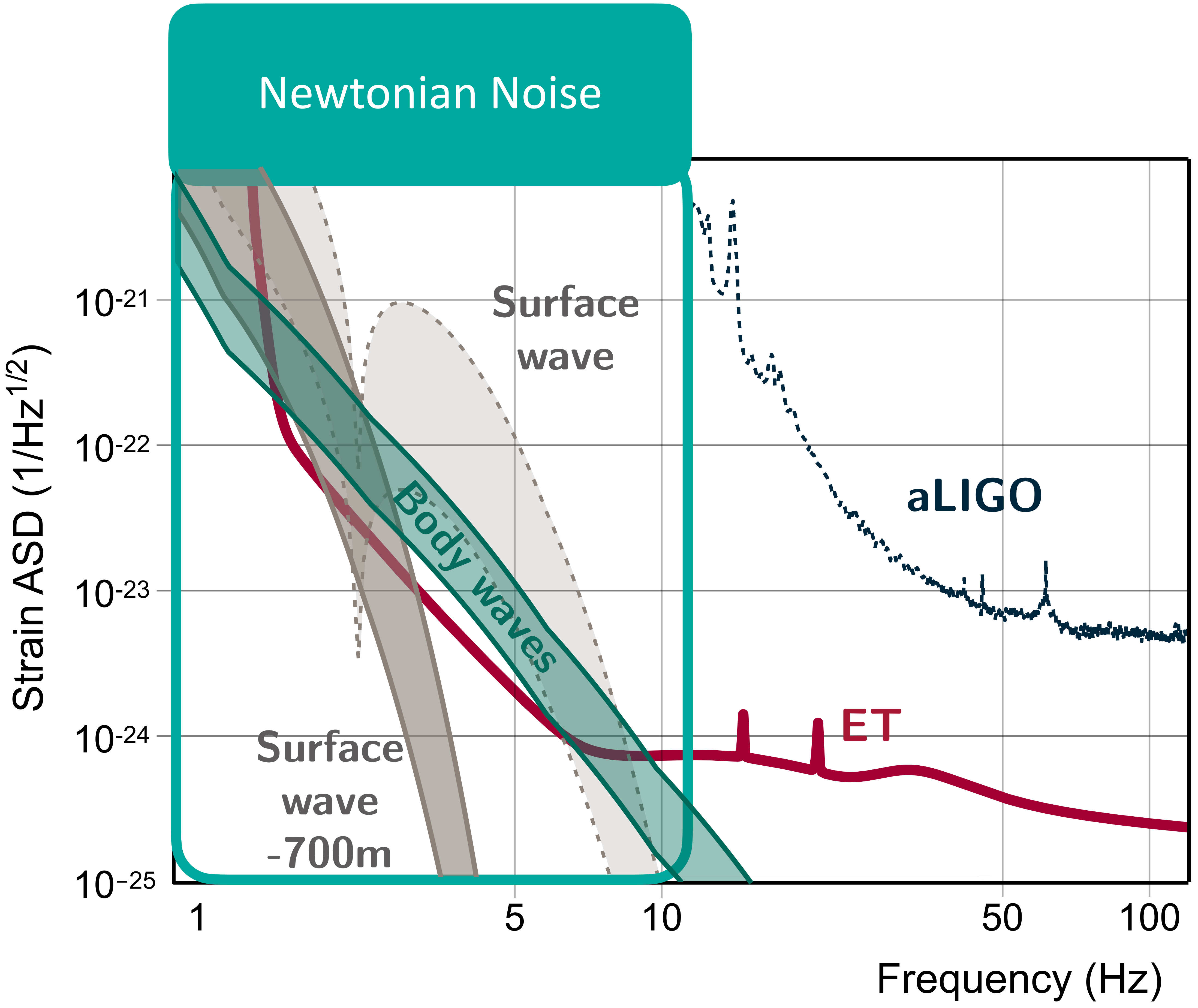
- Surface waves dominate Newtonian Noise → underground detector
- Body waves (compressional and shear waves) are not suppressed with depth





Newtonian Noise (NN) Model

From seismic fields



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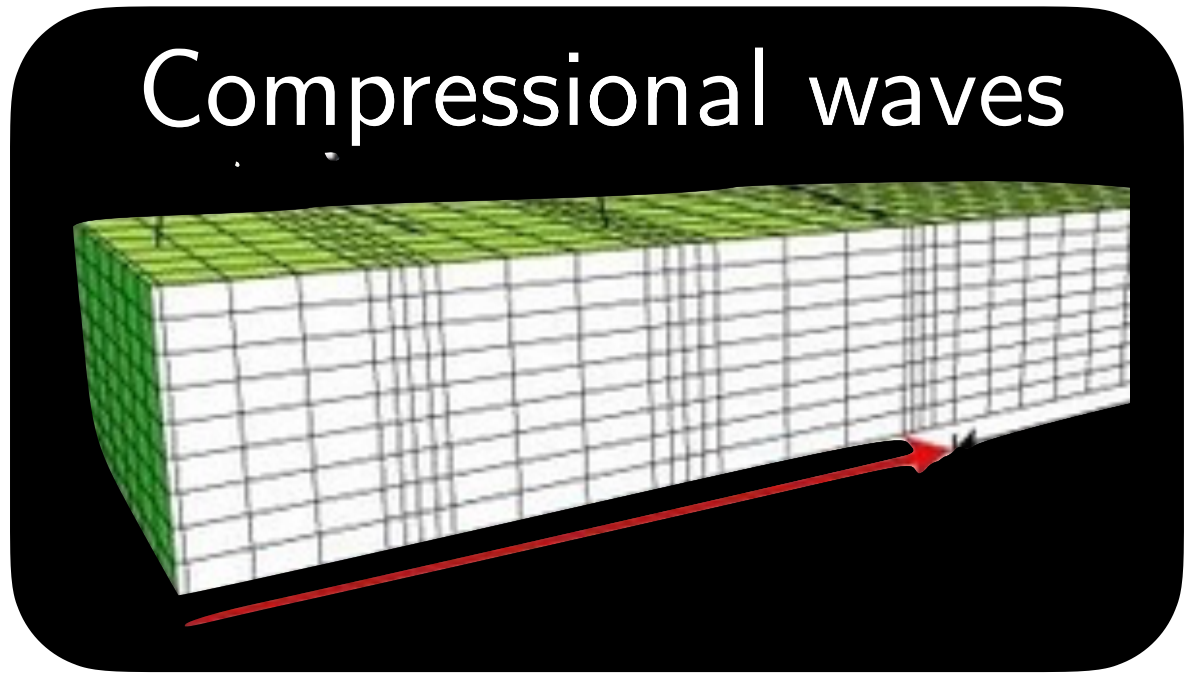
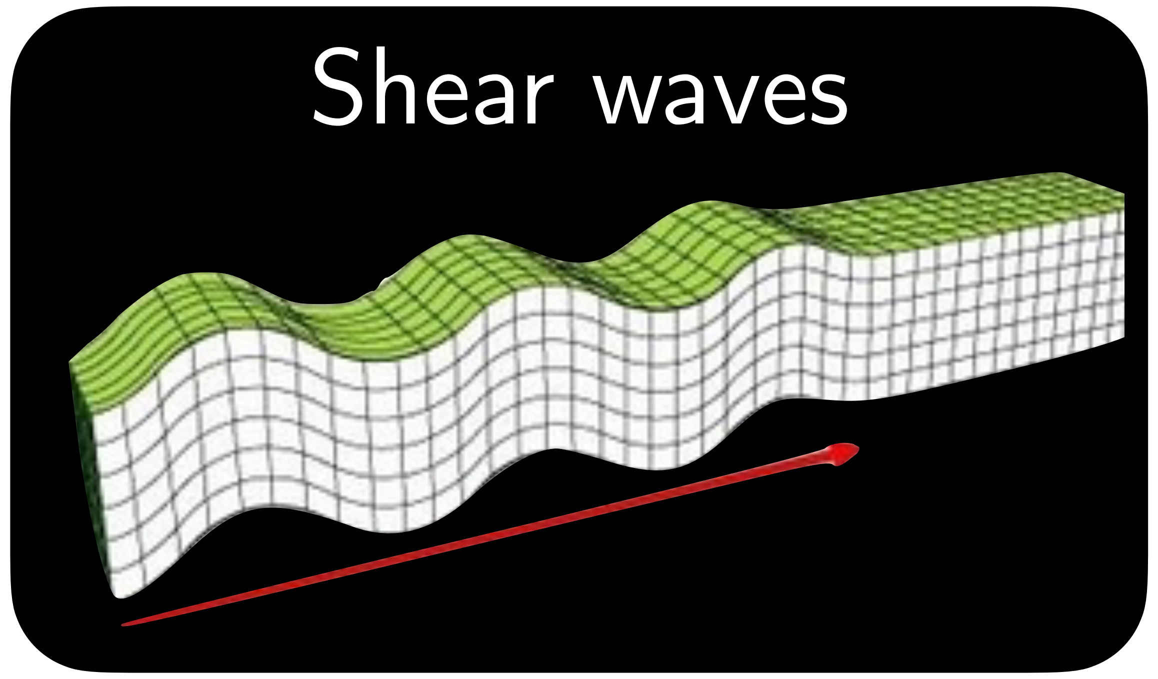




➡Site characterization for future detectors

➡NN cancellation (NNC) system

NN cancellation

NN cancellation

NN cancellation

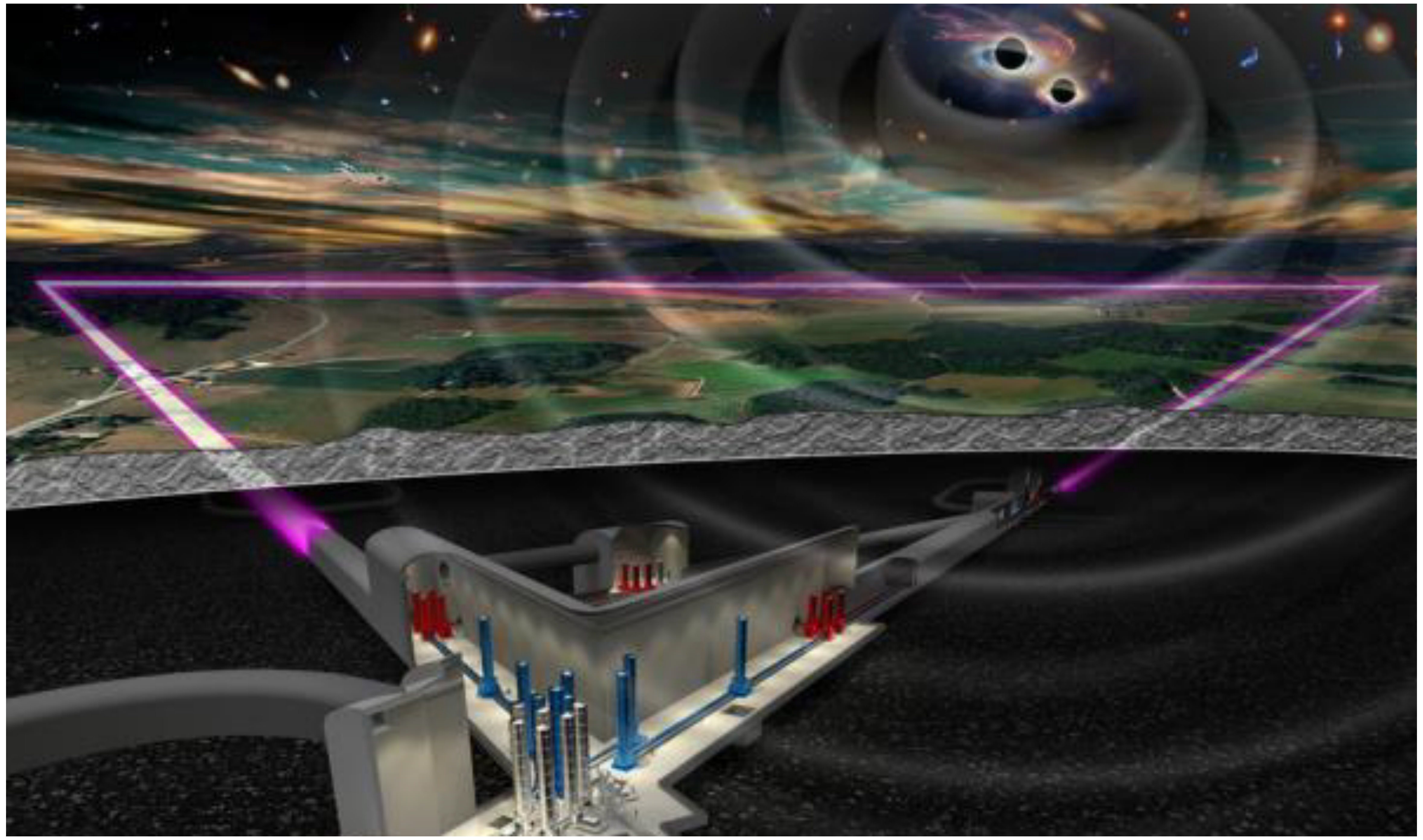
$$\delta\vec{a}(\vec{r}_0,t) = -G\int dV\rho(\vec{r})\Big(\overbrace{\vec{\xi}(\vec{r},t)}^{\text{seismic displacement}}\cdot\nabla_0\Big)\frac{\vec{r}-\vec{r}_0}{|\vec{r}-\vec{r}_0|^3}$$

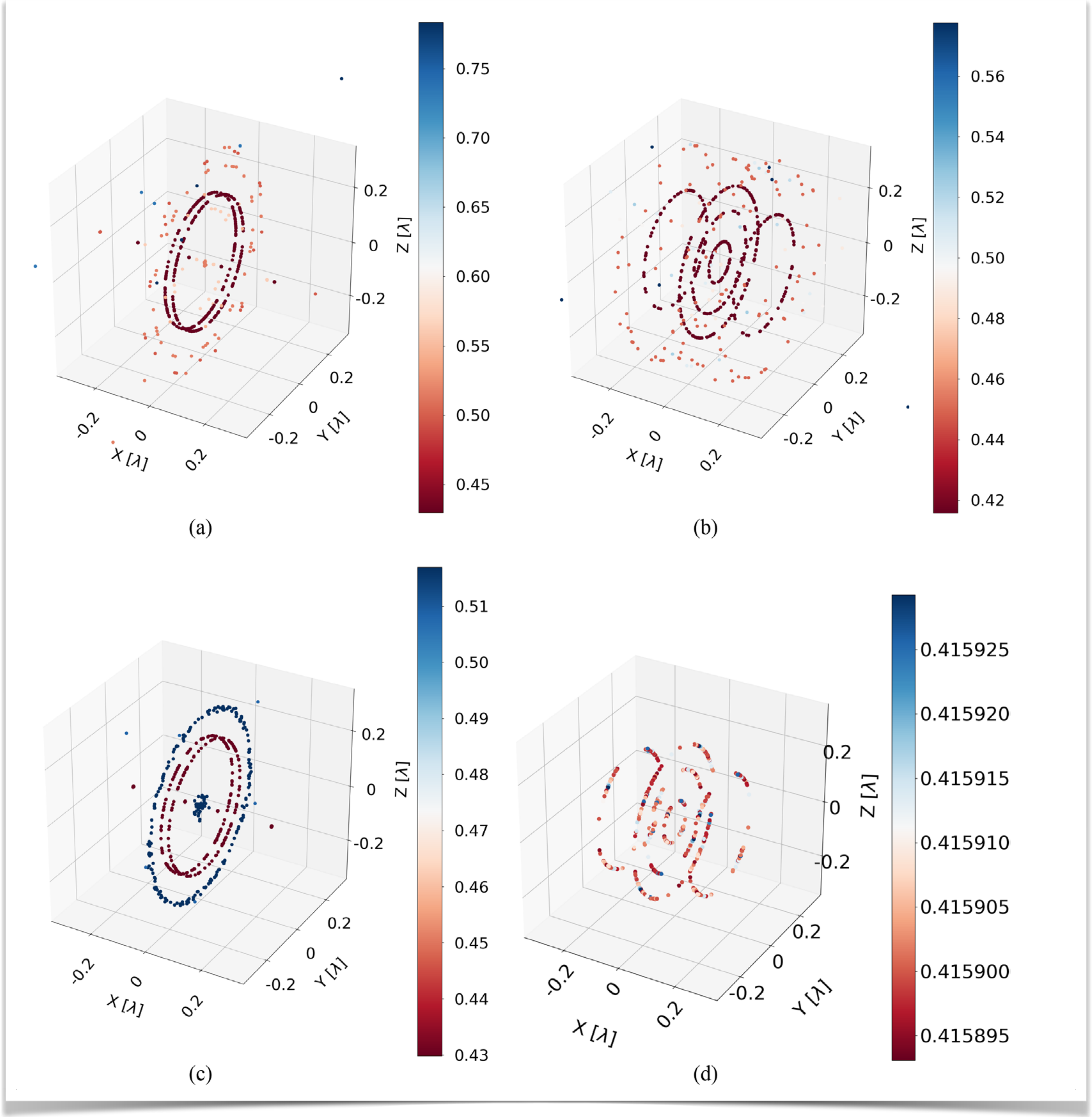
NN cancellation

NN cancellation

NNC system for ET

Simulation results for body wave NN





(a) (b) (c) (d)

- 12 TMs require NNC
- 20 seismometers per TM

} = 240 borehole sensors (Very expensive)

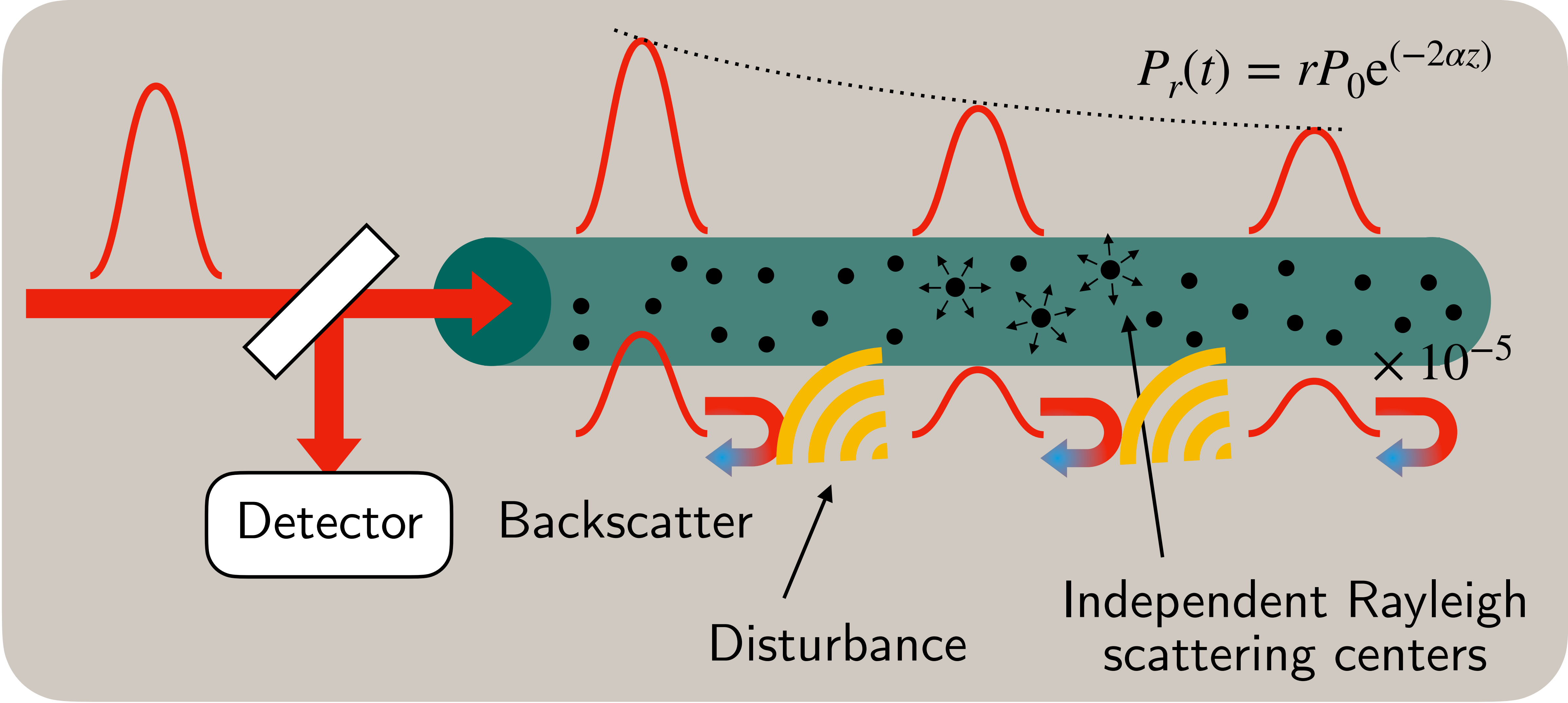
- Seismometers: high sensitivity, high SNR, <10Hz

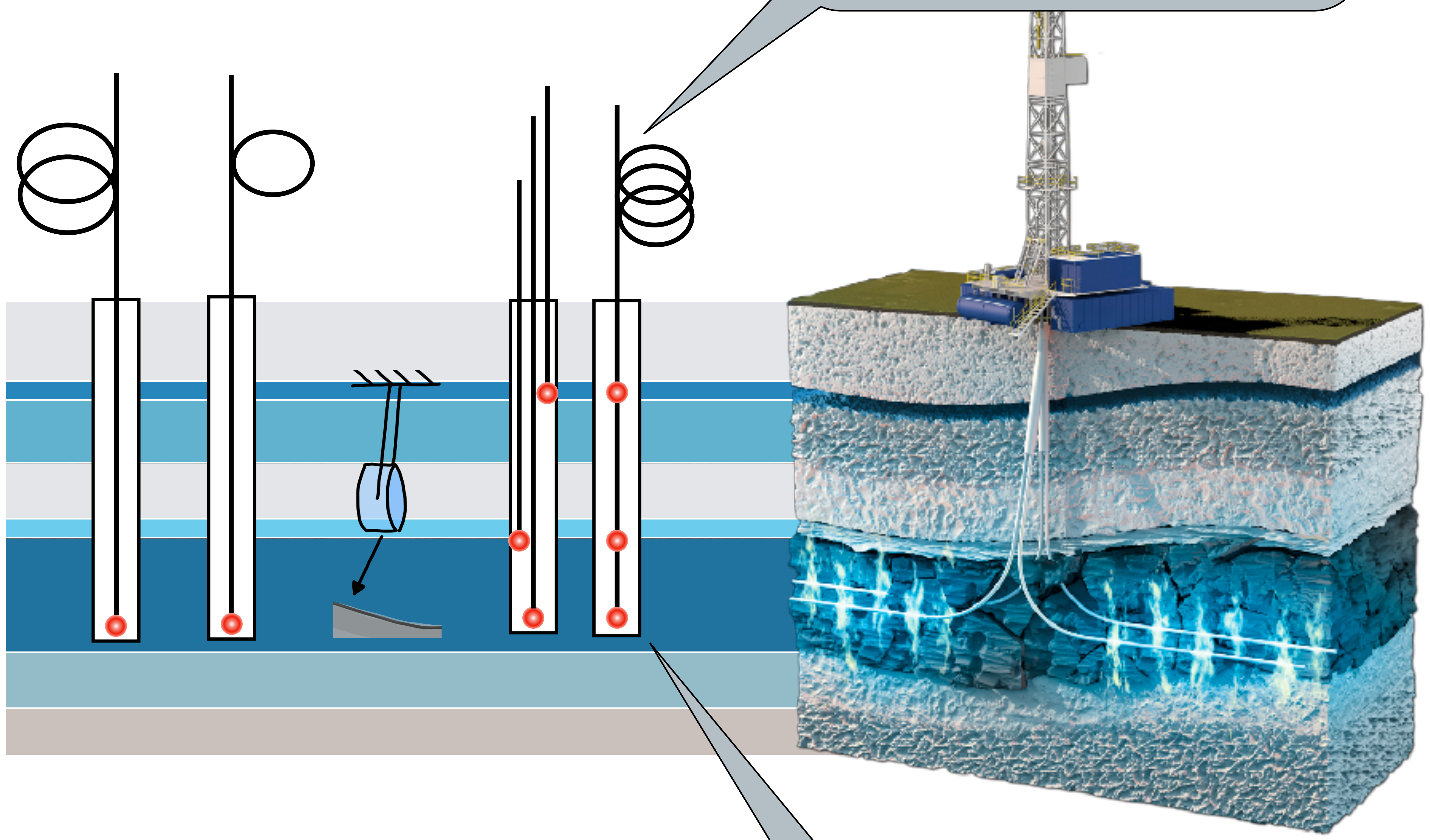
Badaracco, Harms. 2019, https://doi.org/10.1088/1361-6382/ab28c1

Distributed acoustic sensing (DAS)

Fibers are very sensitive seismic **strain sensors**

OTDR: optical time domain reflectometry



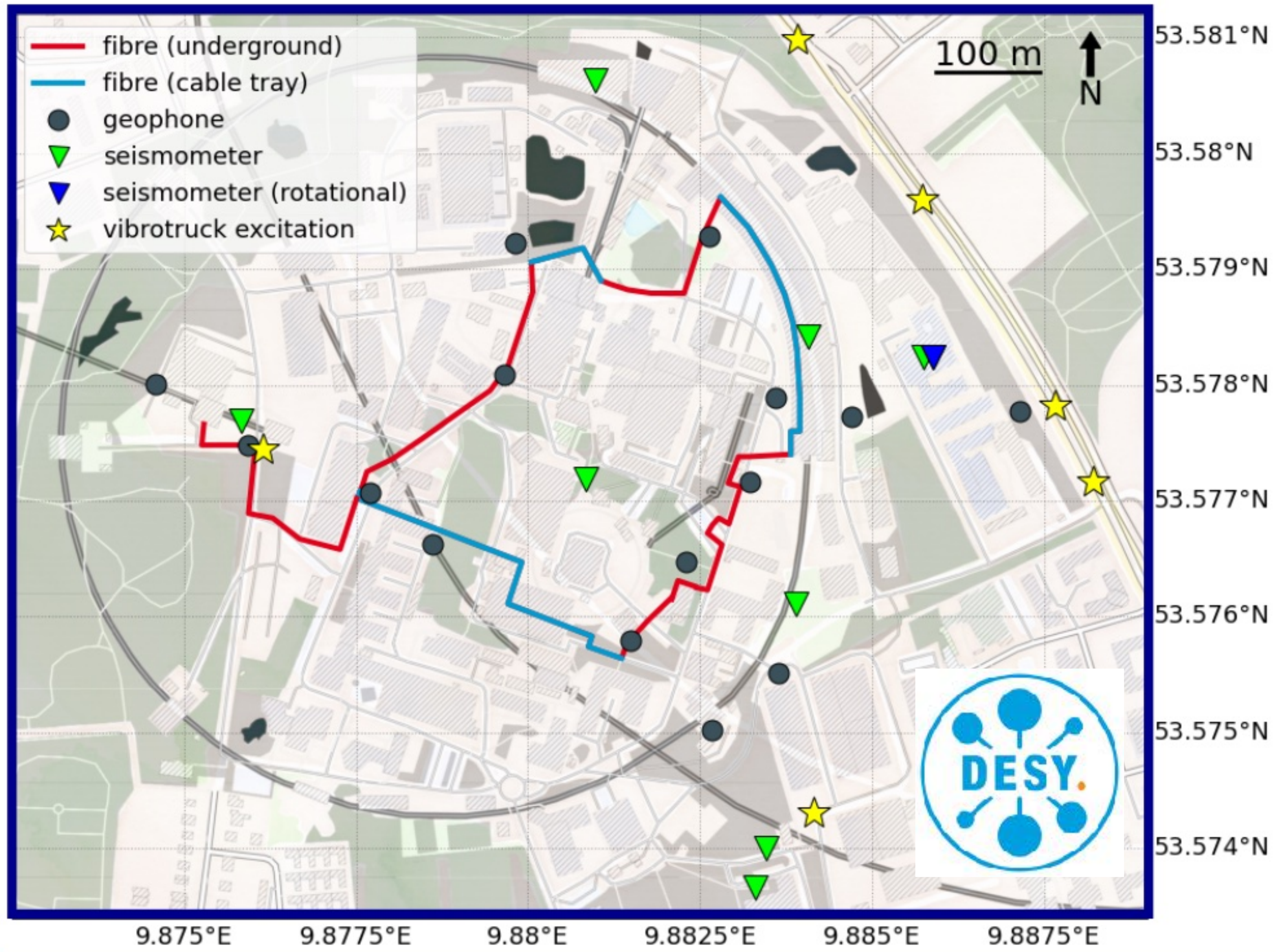


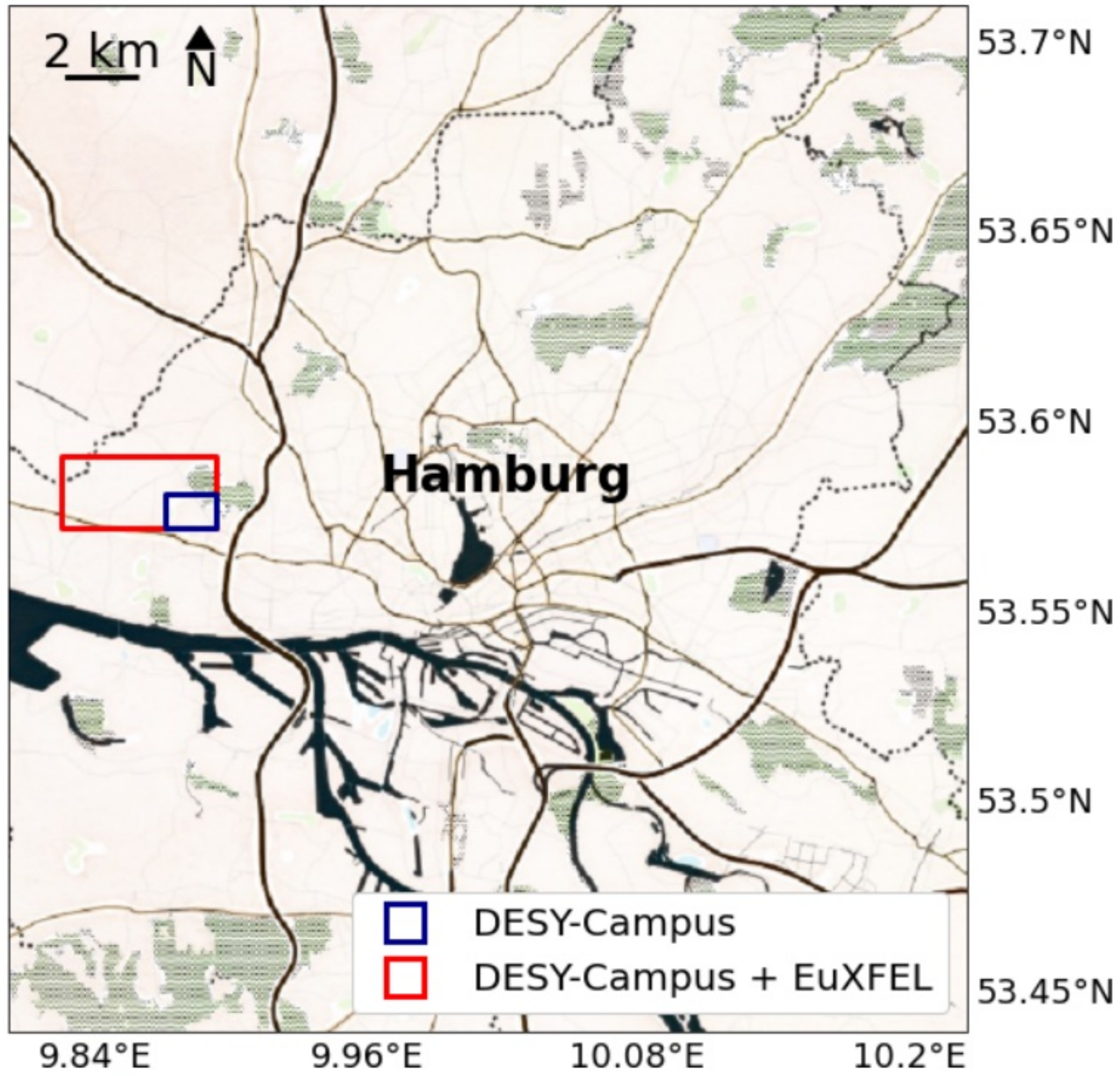
Rayleigh backscatter intensity: $I \propto \frac{1}{\lambda^4} \propto \mathrm{ppm/m}$

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

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

<u>**Multiple fibers**</u> in individual boreholes and along 10km interferometer arms

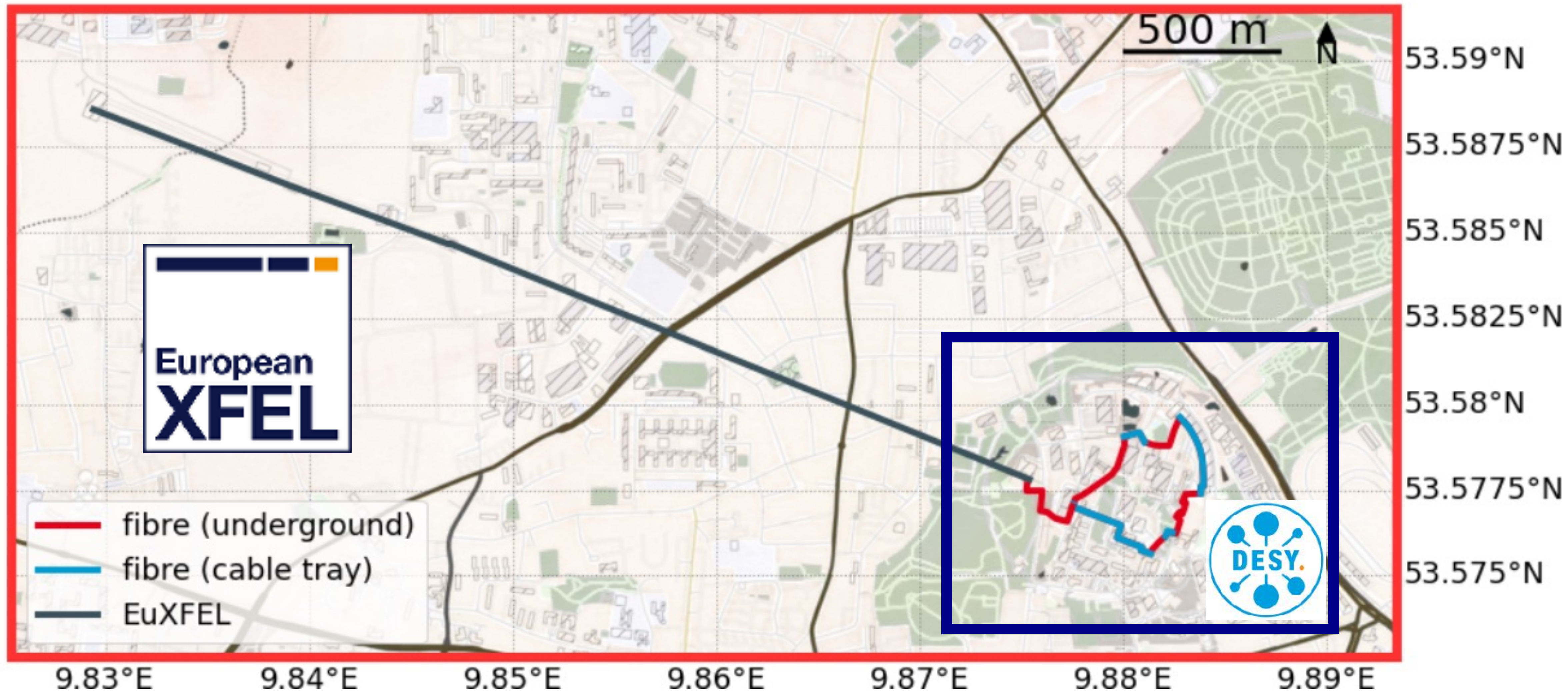




WAVE

Seismic network in Hamburg

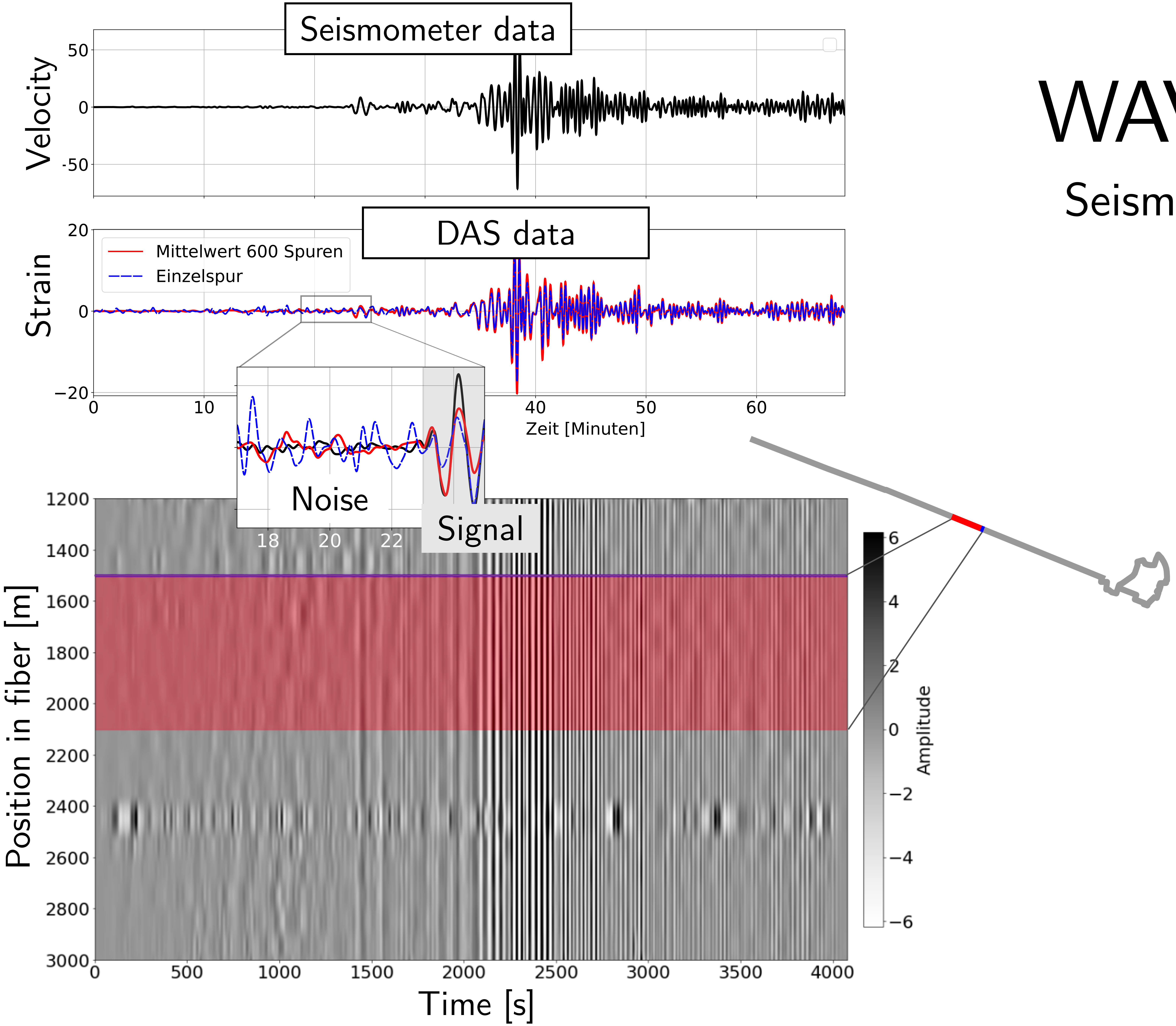
(*http://wave-hamburg.eu*)



- Large research campus
  physics, seismology, engineering, informatics, ...
- May 2021, 2 weeks, 60TB
- Sensors:
  - 12.6km fiber readout with 2x DAS Systems, 1m gauge (= **12,600 seismic strain sensors**)
  - Seismometers, Geophones, Rotational seismometer

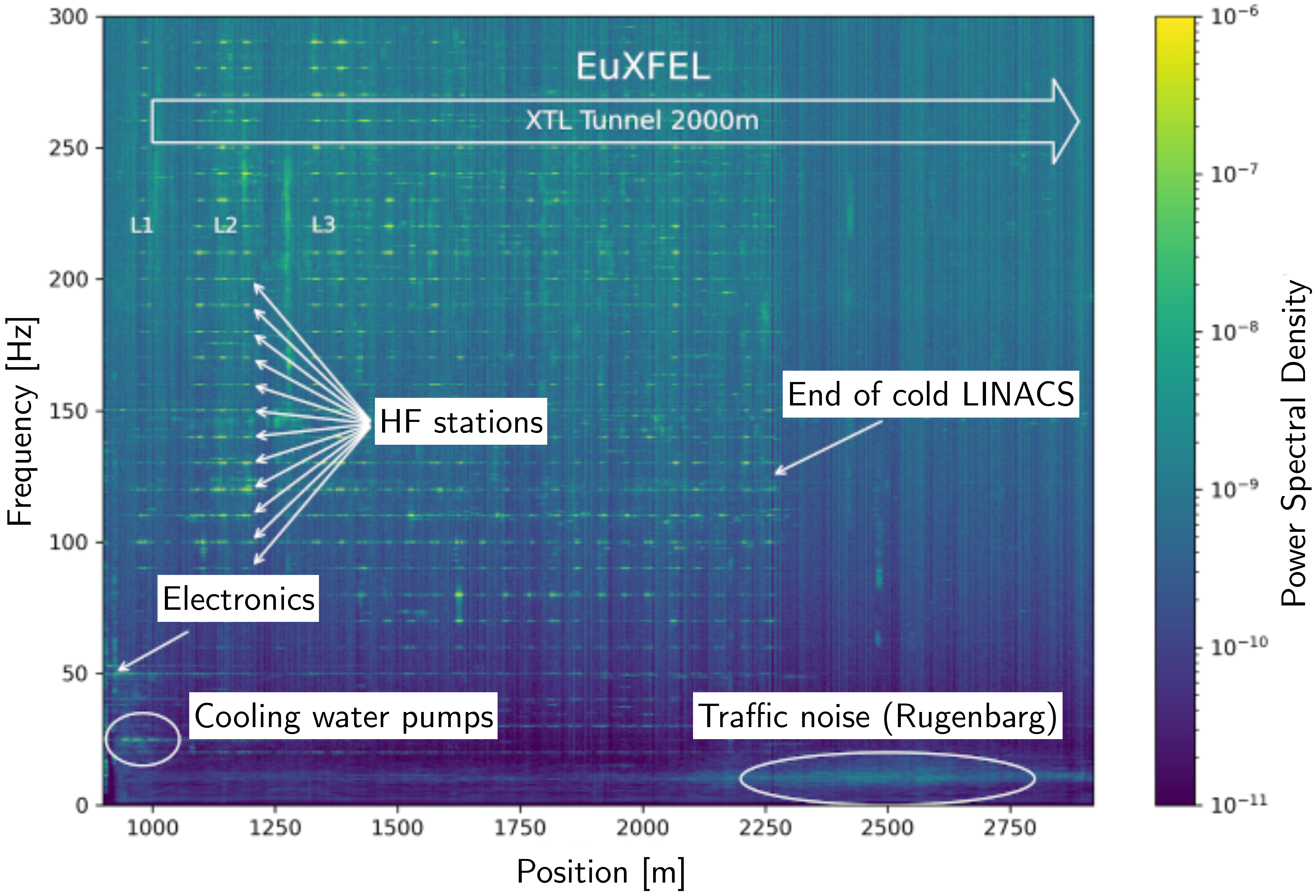
WAVE data analysis

Seismometer vs. DAS measurements

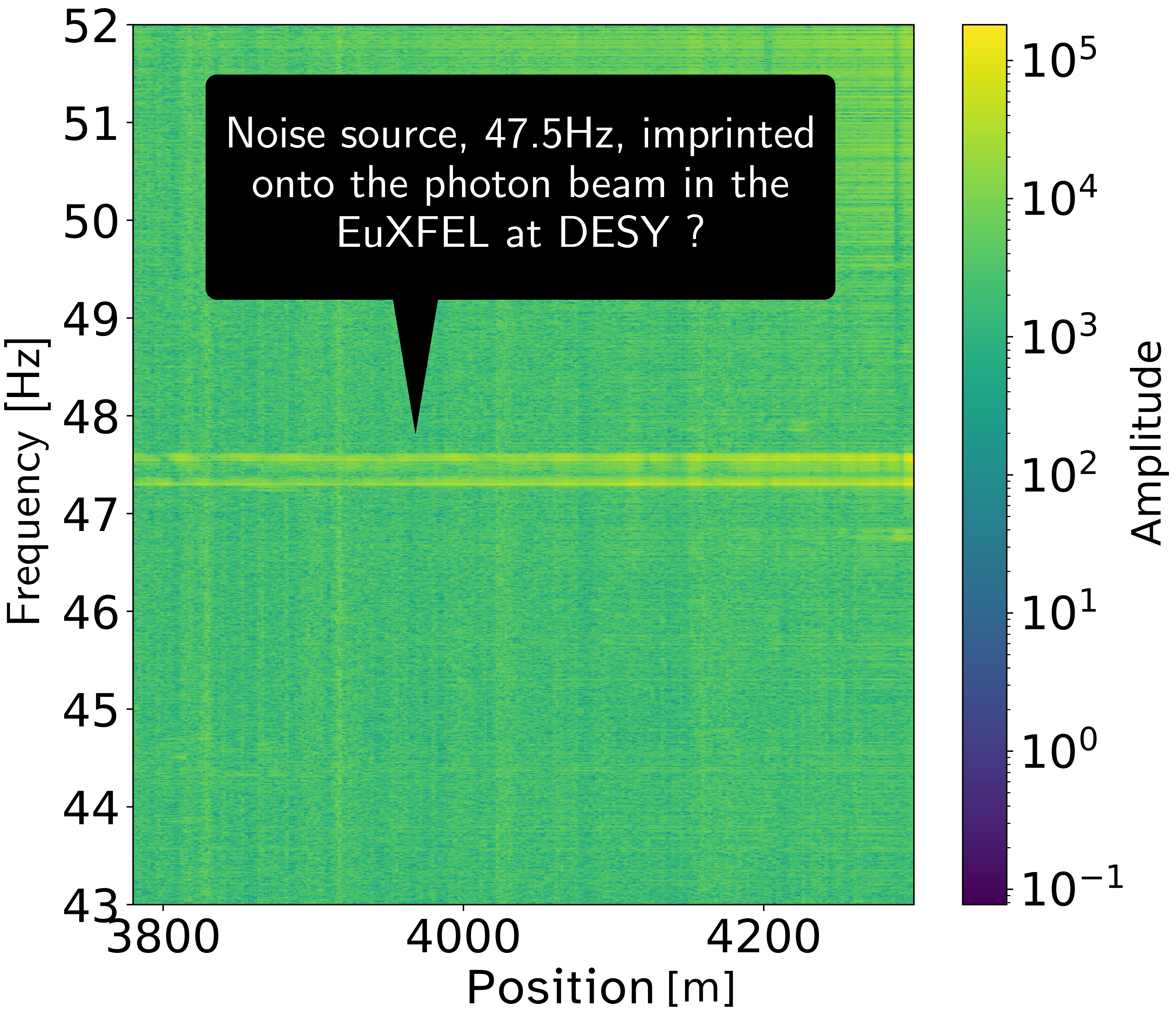


- Earthquake Magnitude 7.4, May 2021, Qinghai, China
- Comparison between seismometer (displacement) and DAS (strain)
- Coherent seismic wavefront propagating through the EuXFEL tunnel
- Spatial variations of the oscillation: due to inhomogeneous subsurface structure?
- More results online: http://wave-hamburg.eu

WAVE data analysis



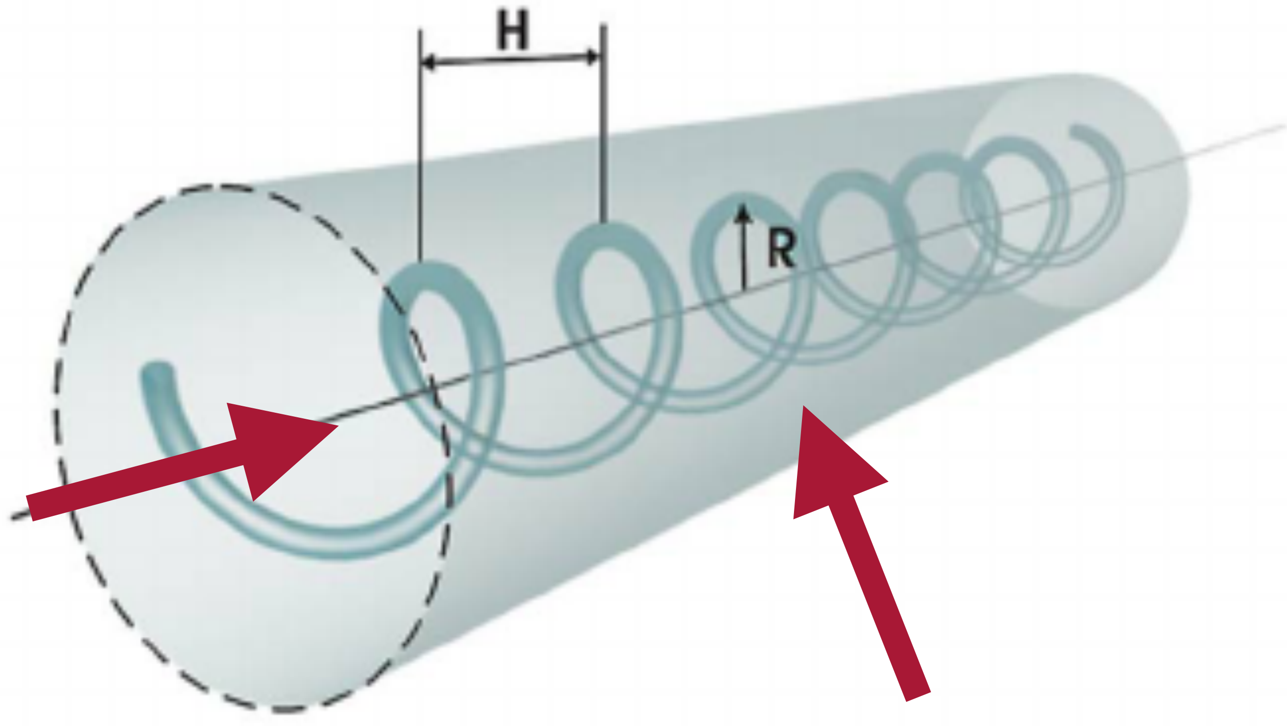
WAVE data analysis

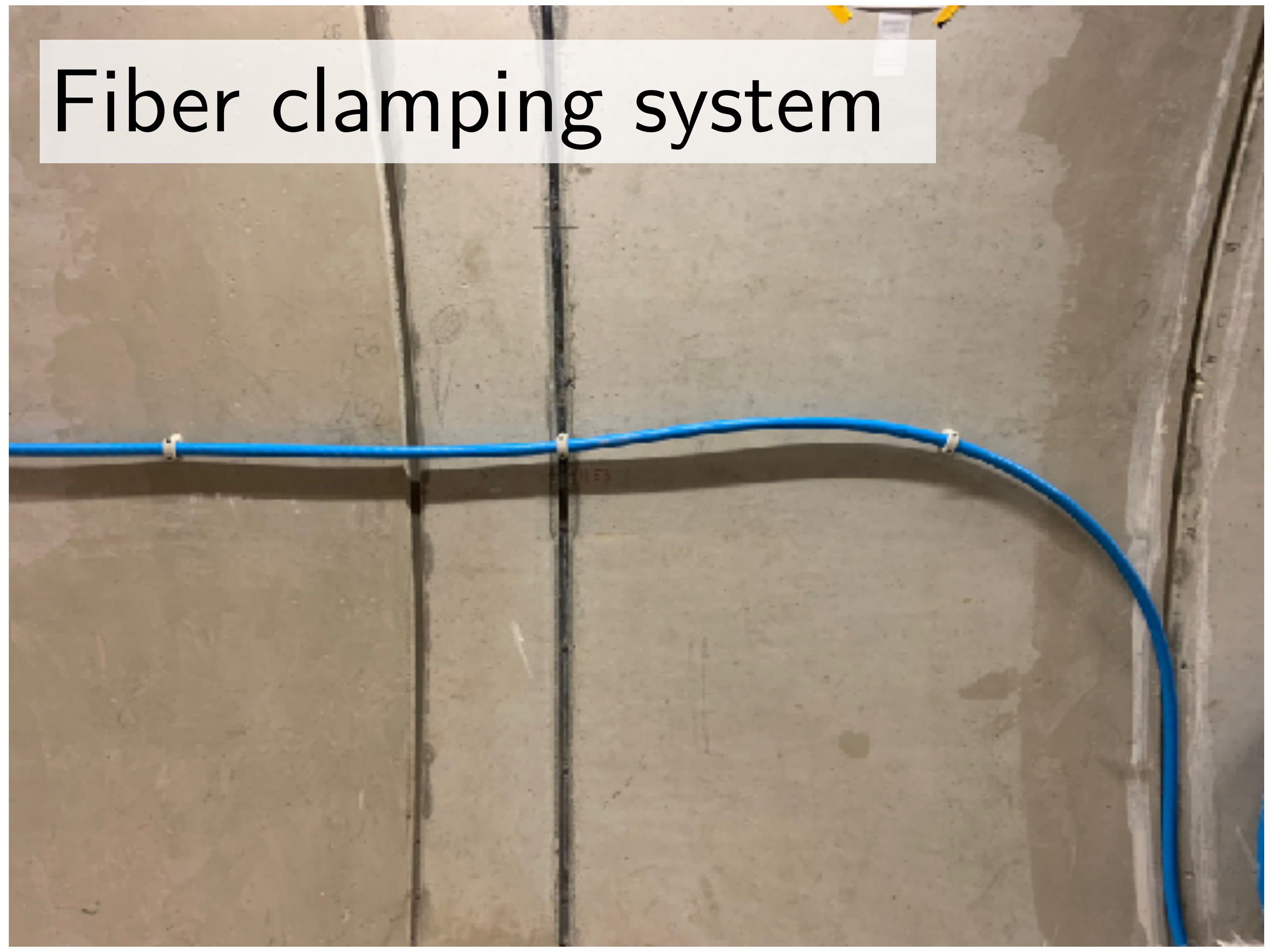


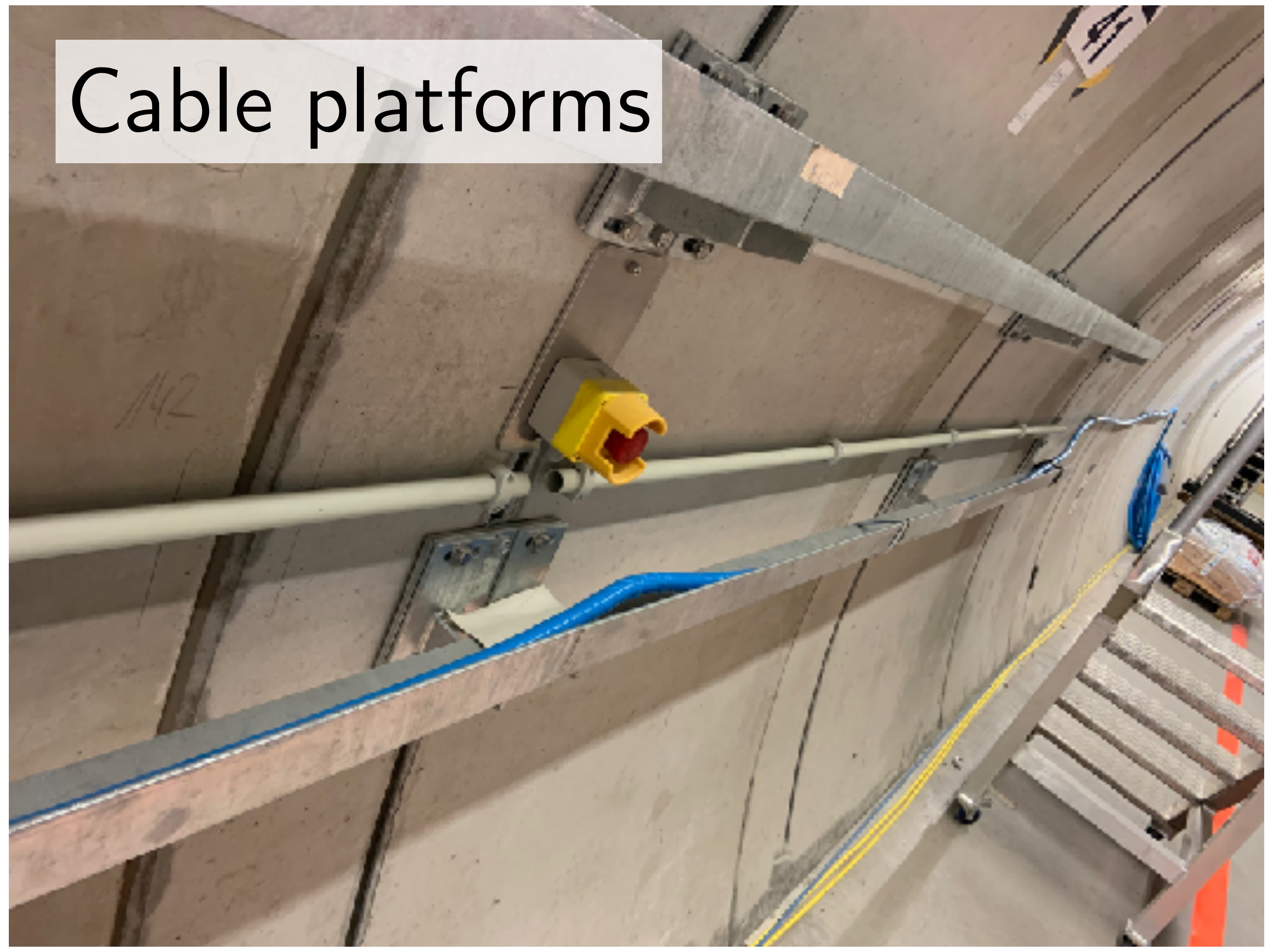
- The **spatial resolution of the DAS system** could identify the noise source:
  - classified to be acoustic noise
  - **Identification of origin of noise sources** (Helium compressor)
- More examples and animations online: http://wave-hamburg.eu

DAS investigations

- Sensor self-noise measurements
- Comparison with seismometers
- Coupling tests to ground
- Investigation of special fibers (engineered and helic)
- **Limitations for ET:**
  - Interrogator is a black box
  - Fiber lengths ⚡ pulse repetition rate and backscatter power
  - High optical input power for high spatial resolution and long distance
  - No multiple fiber readout
  - dynamic range ⚡, fading, LFN
- **Own sensor development**







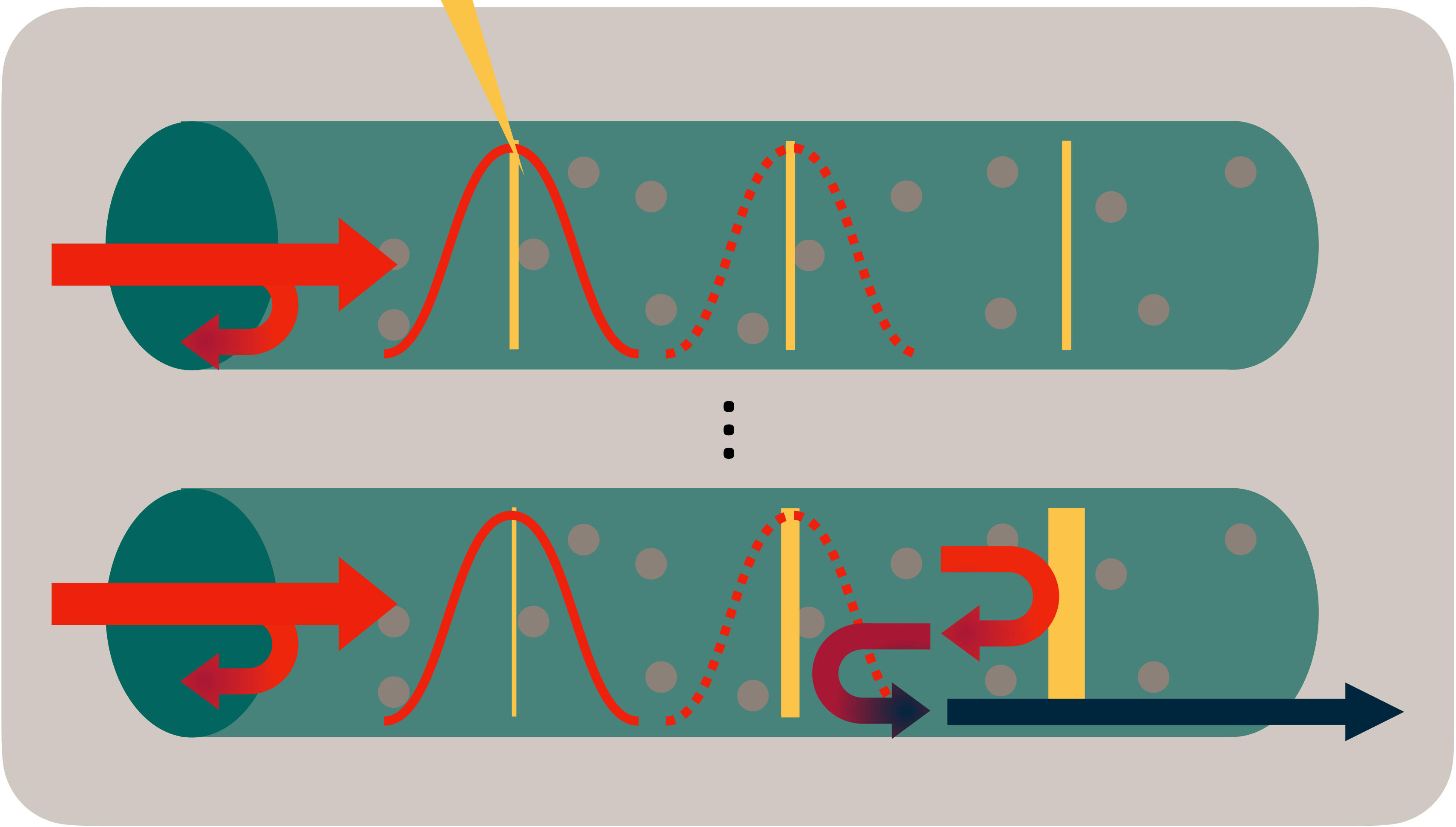
New distributed fiber sensors for ET

Using digitally-enhanced heterodyne interferometry

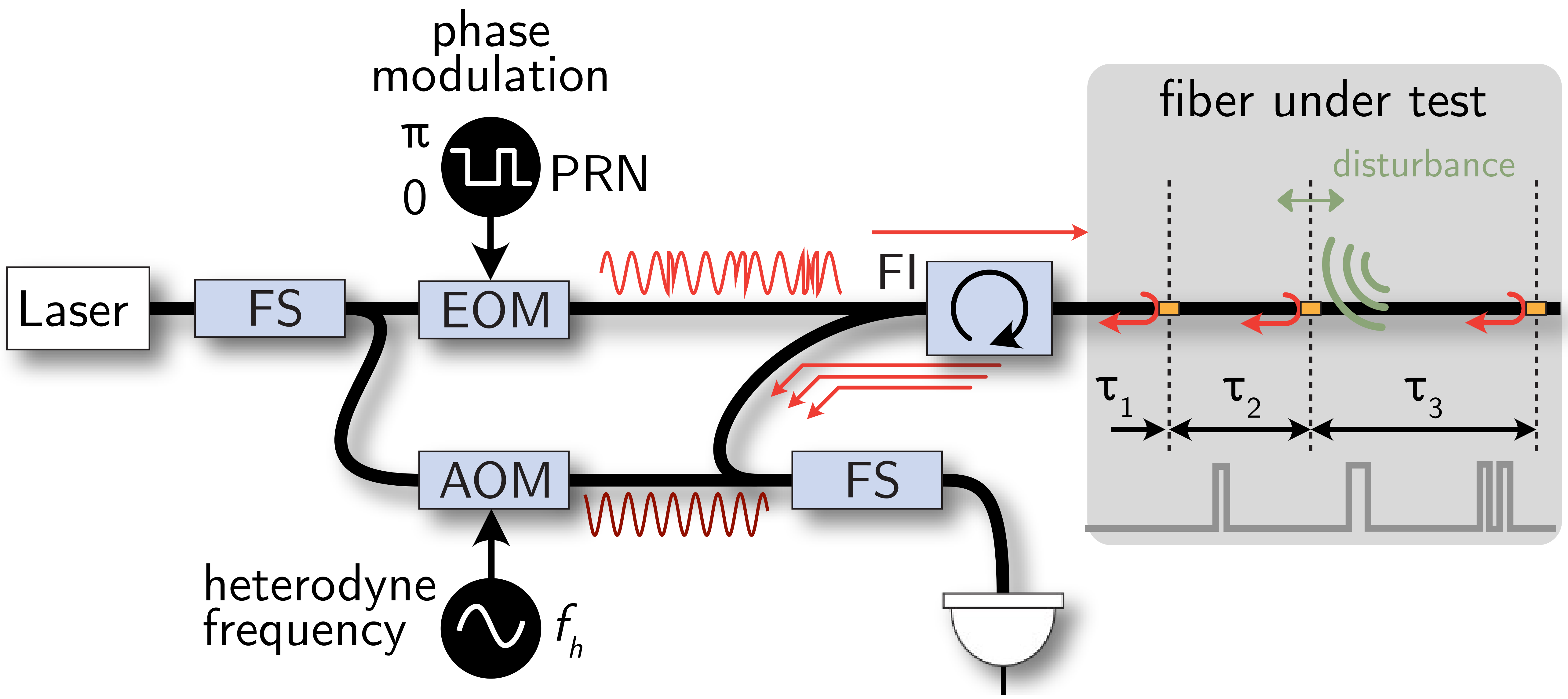
Shaddock, 2007, DOI: 10.1364/OL.32.003355

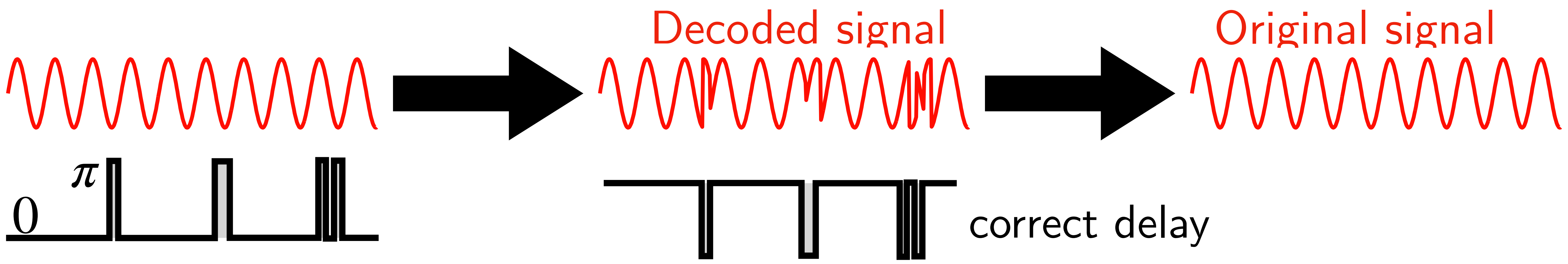
e.g. FBGs, accelerometers, ...

Engineered fibers



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





Results DI experiment

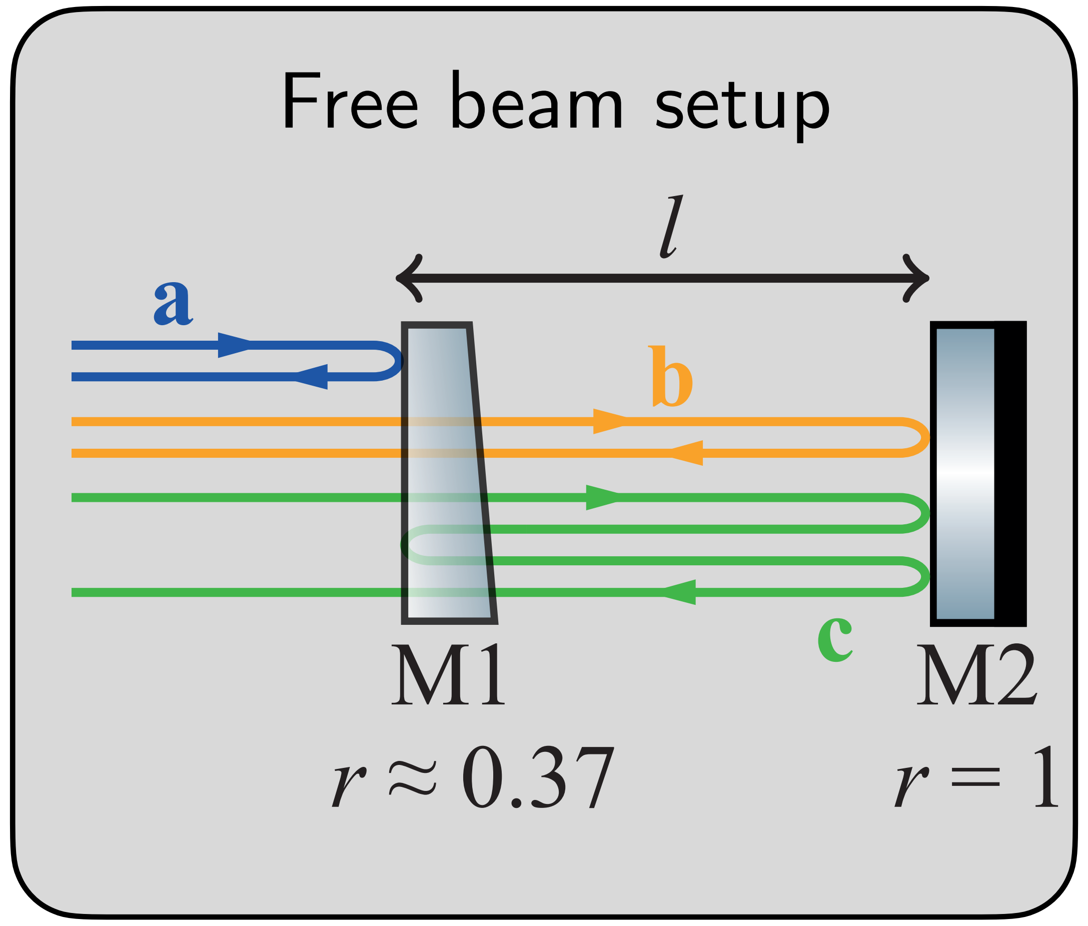
Isleif et al. 2014, DOI:10.1364/OE.22.024689

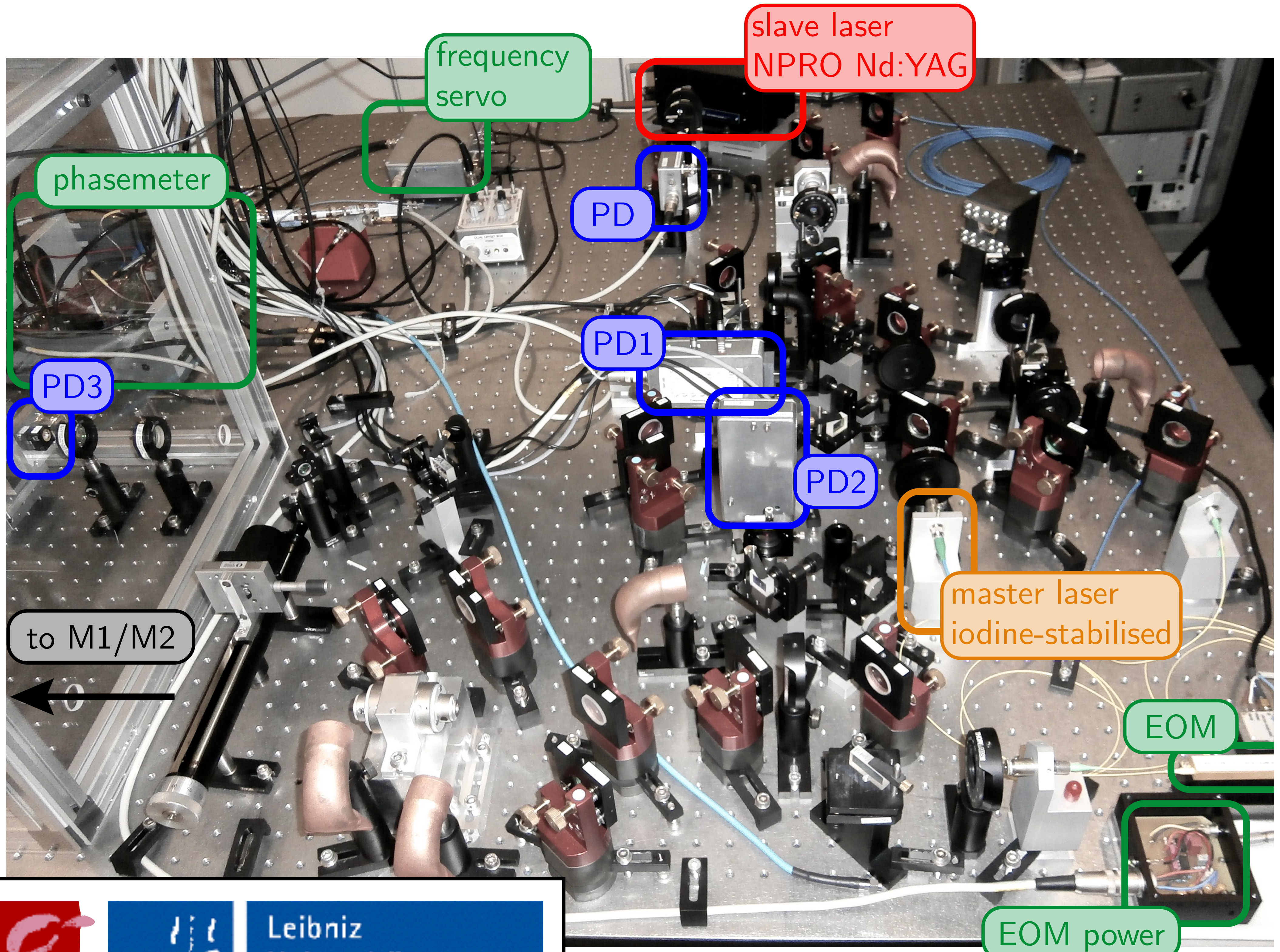
- High speed free beam setup in air

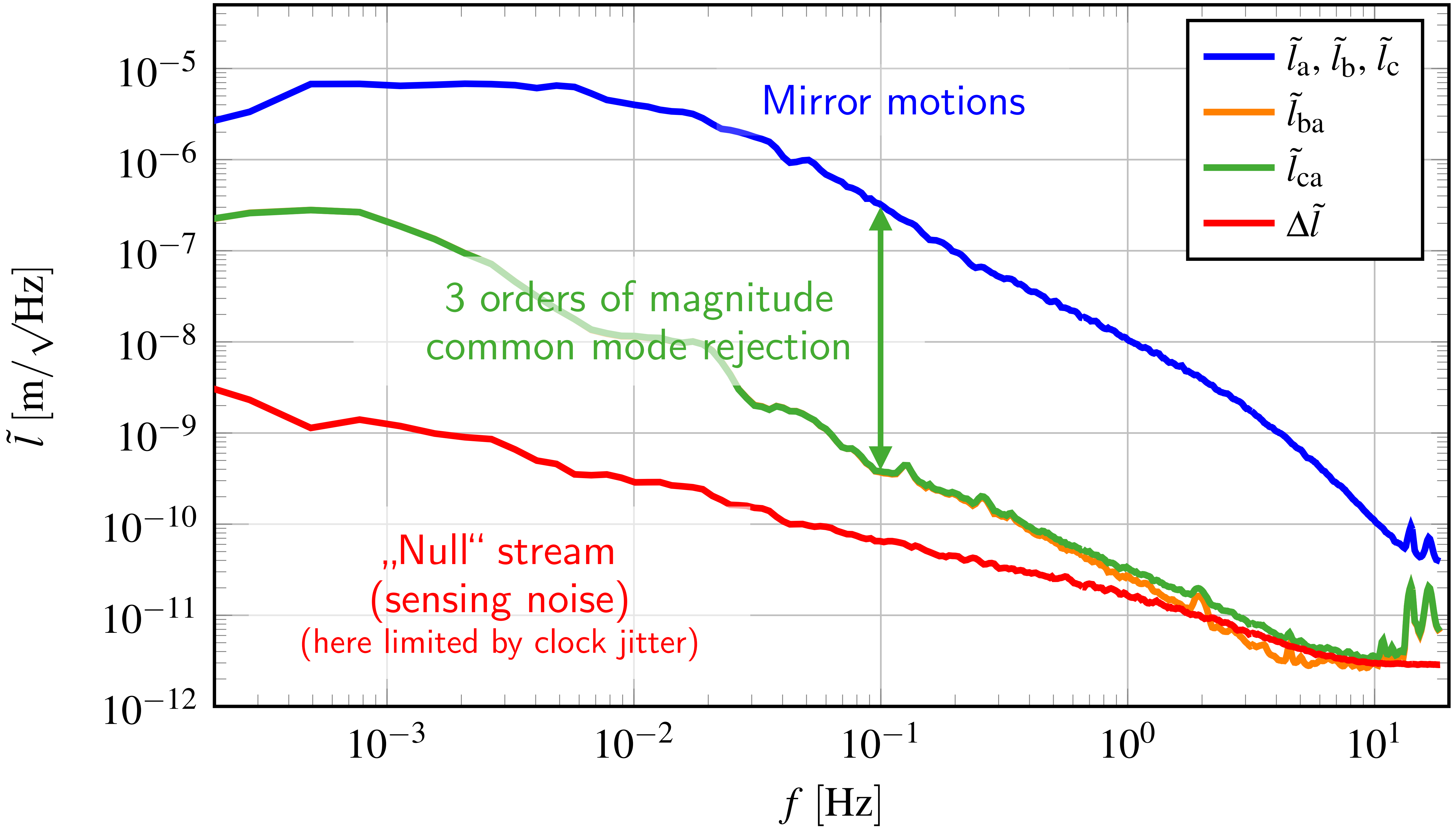
  $f_{\mathrm{PRN}} \approx 1.25\,\mathrm{GHz} \;\rightarrow$ 12 cm spatial resolution

  $2\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ @ 10 Hz | $20\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ @ 1 Hz

- Multiplexing capabilities
- High dynamic range
- High common mode rejection
- Flexible signal combinations







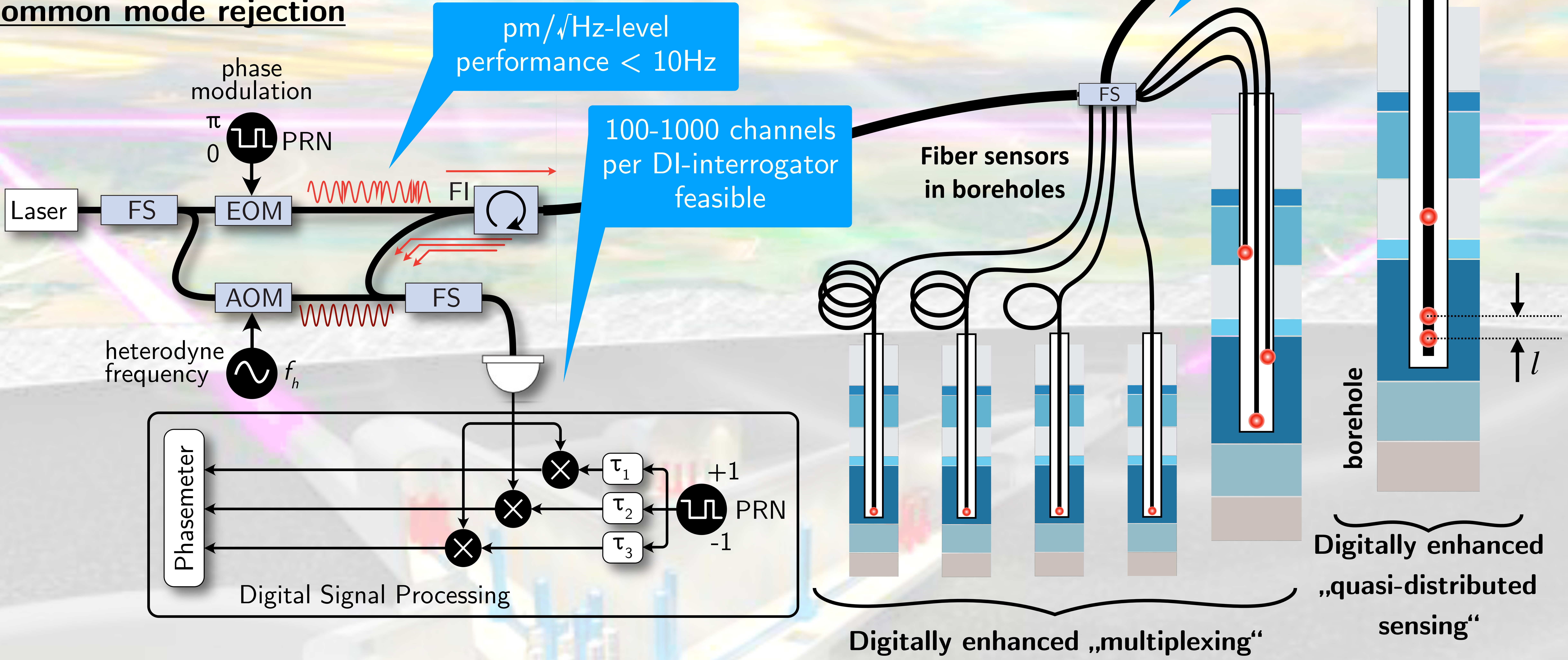
Spatial resolution: $l \approx 10\,\mathrm{cm}_{@1.25\,\mathrm{GHz}}$ $l \approx 10\,\mathrm{m}_{@12.5\,\mathrm{MHz}}$

Fiber lengths: „no“ limits, depends on back reflected power, number of sensors

Number of fibers: „no“ limits, depends on power, number of sensors, PRN code

Common mode rejection

Optimal strain sensor array for NNC with Jan & Francesca



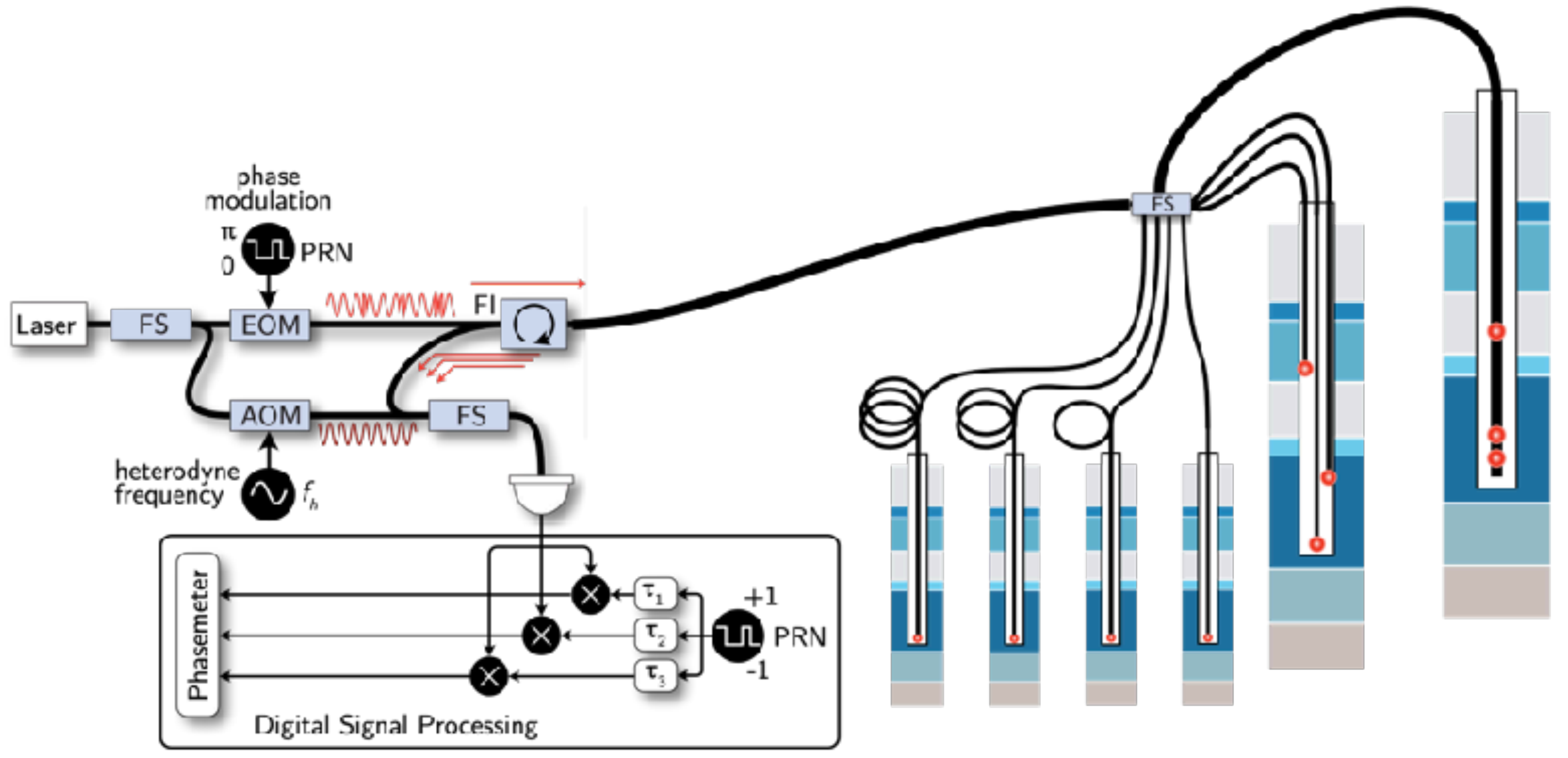
Conclusion & Outlook

Distributed seismic fiber network for NNC in ET

Katharina Isleif[1] (isleifk@hsu-hh.de)
Reinhardt Rading[1], Julian Dietz[1]
Oliver Gerberding[2], Celine Hadziiaonnou[2]
Francesca Badaracco[3], Jan Harms[4]

- Spatially and temporal resolved seismic DAS signals help to identify and eliminate noise sources
- Seismic data analysis and comparison between seismic sensors (WAVE seismic network) http://wave-hamburg.eu
- **NNC simulations for ET with strain sensors**
  - Vertical (boreholes) and horizontal (along 10km arms?)
  - Optimization of strain sensor positioning for ET
- **R&D of digitally-enhanced fiber strain sensors**
  - DI allows for high low-frequency sensitivity + multiplexing + common mode rejection (LFN, fiber noise, ...)
  - fiber sensors (gratings, mirrors, accelerometers) + fiber routing
- Optimal, efficient sensor array and sensor fusion concepts for ET and current GWDs to search for noise sources

$$\delta\vec{a}(\vec{r}_0, t) = -G\int dV\rho(\vec{r})\left(\vec{\xi}(\vec{r}, t)\cdot\nabla_0\right)\frac{\vec{r}-\vec{r}_0}{|\vec{r}-\vec{r}_0|^3}$$



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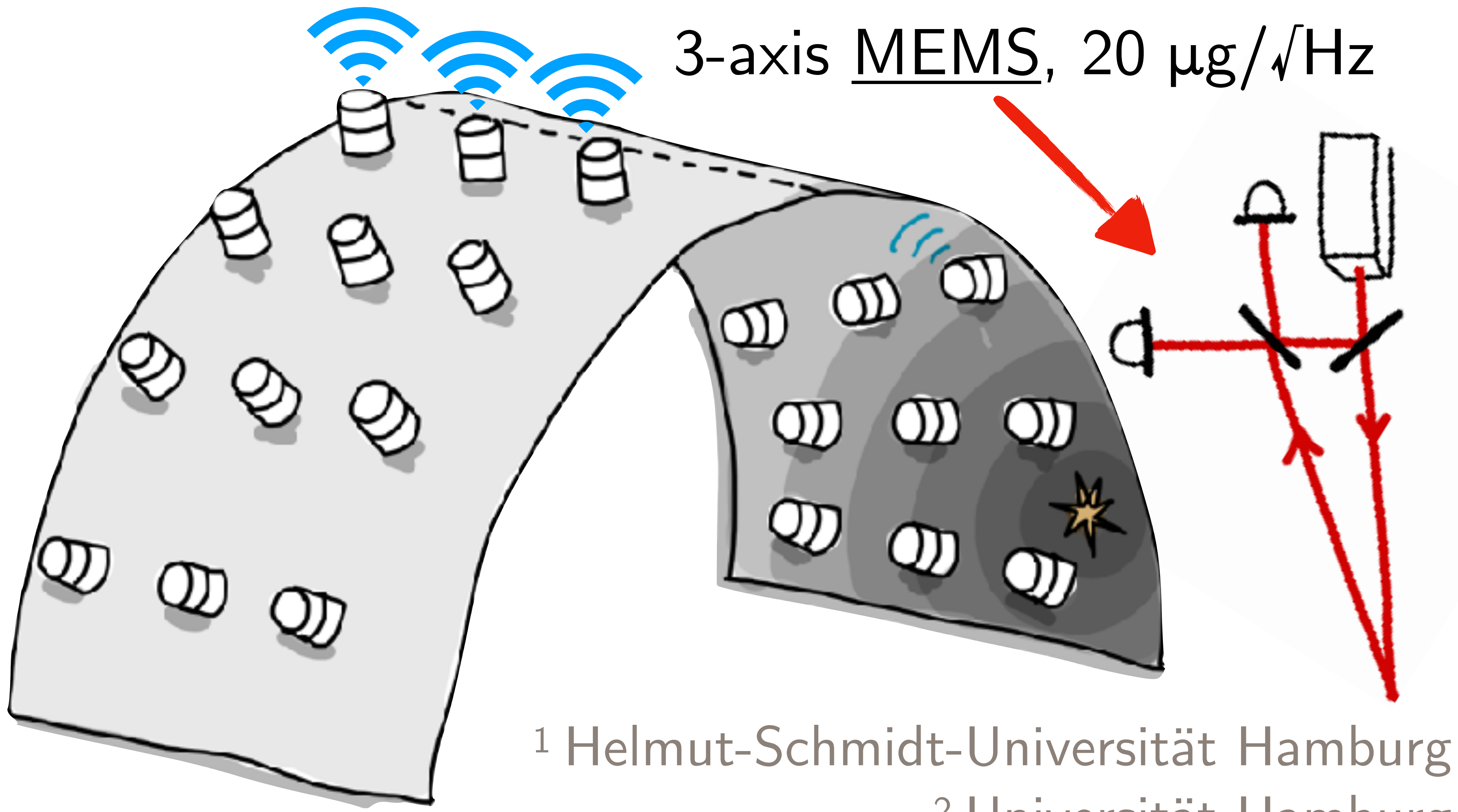
Wireless sensor networks
3-axis MEMS, 20 µg/√Hz



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Appendix

References I - Newtonian Noise

Models, Wiener Filter, Optimization

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Site characterization

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[11] „A Seismological Study of the Sos Enattos Area—the Sardinia Candidate Site for the Einstein Telescope | Seismological Research Letters | GeoScienceWorld“. https://pubs.geoscienceworld.org/ssa/srl/article-abstract/92/1/352/592415/A-Seismological-Study-of-the-Sos-Enattos-Area-the?redirectedFrom=fulltext

[12] „Characterization of the Sos Enattos site for the Einstein Telescope - IOPscience“. https://iopscience.iop.org/article/10.1088/1742-6596/1468/1/012242/meta

[13] „Temporal variations of the ambient seismic field at the Sardinia candidate site of the Einstein Telescope | Geophysical Journal International | Oxford Academic“. https://academic.oup.com/gji/article-abstract/234/3/1943/7143776?login=true

References II - DI & DAS

Digitally enhanced interferometry

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DAS

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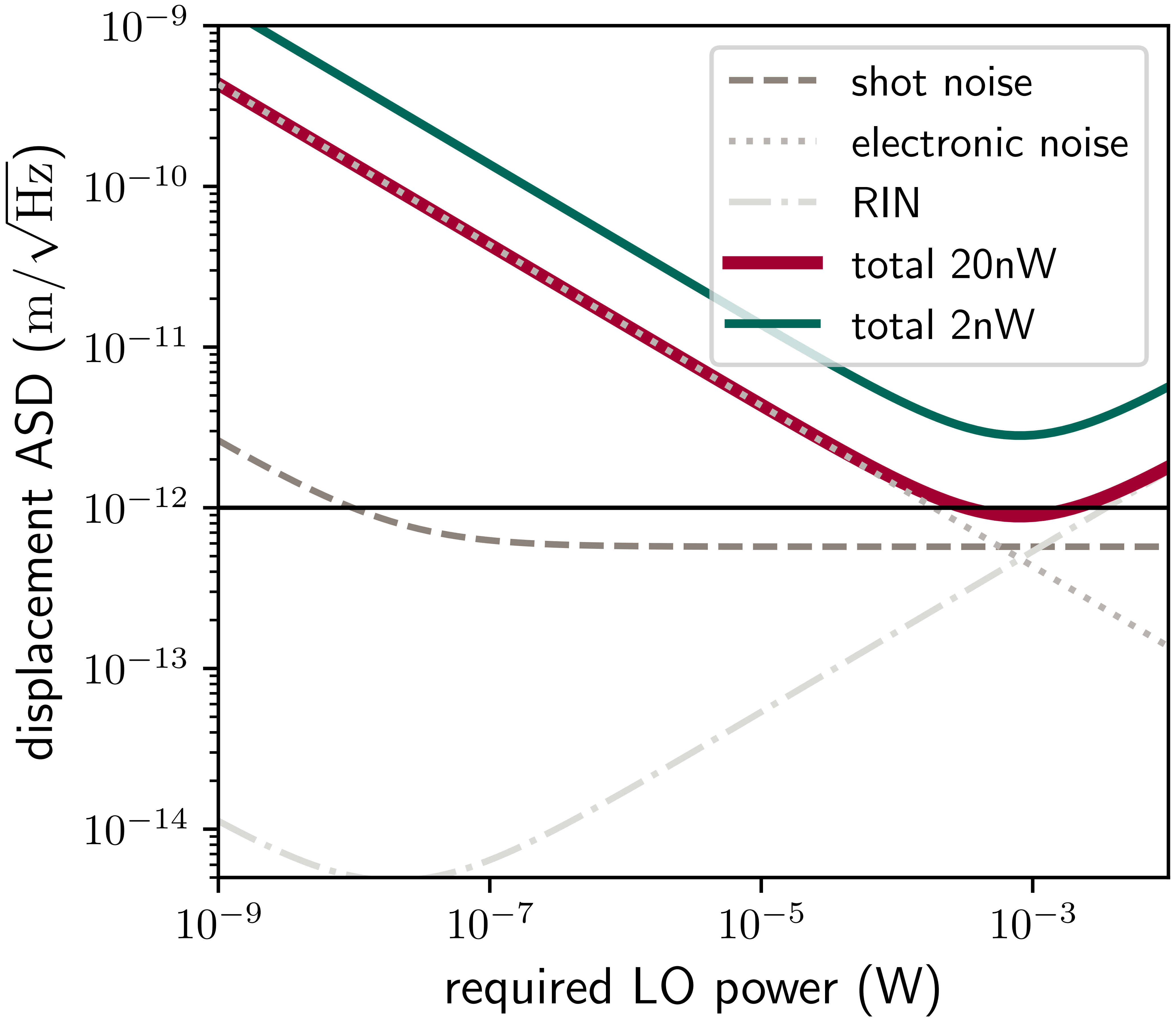
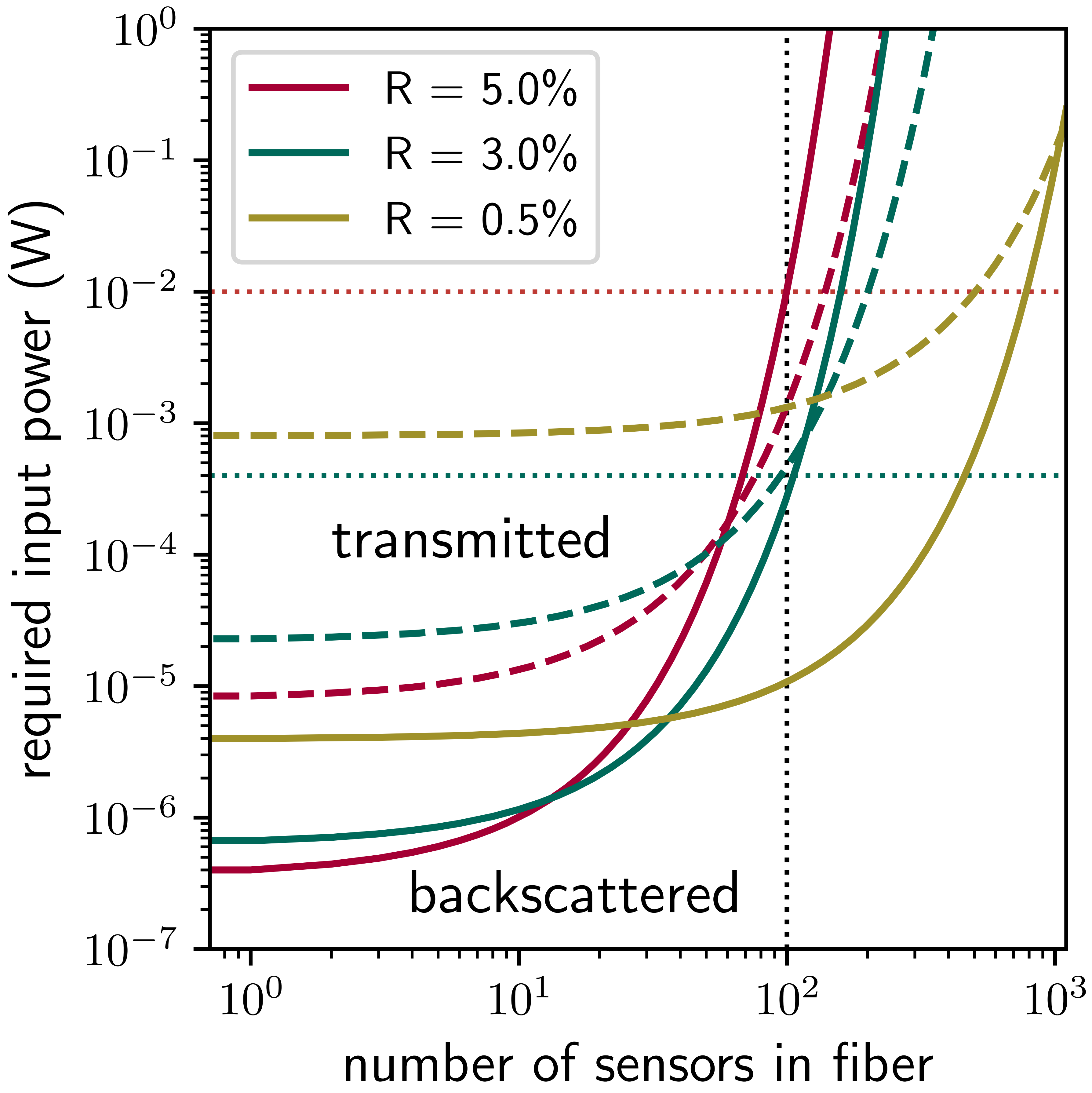
Power & channel limitations: DI distributed strain sensors

20nW back-reflection power is required as minimum to ensure pm (noise budget for 1550nm laser)



Input power to ensure pm in reflection and transmission



Noise sources

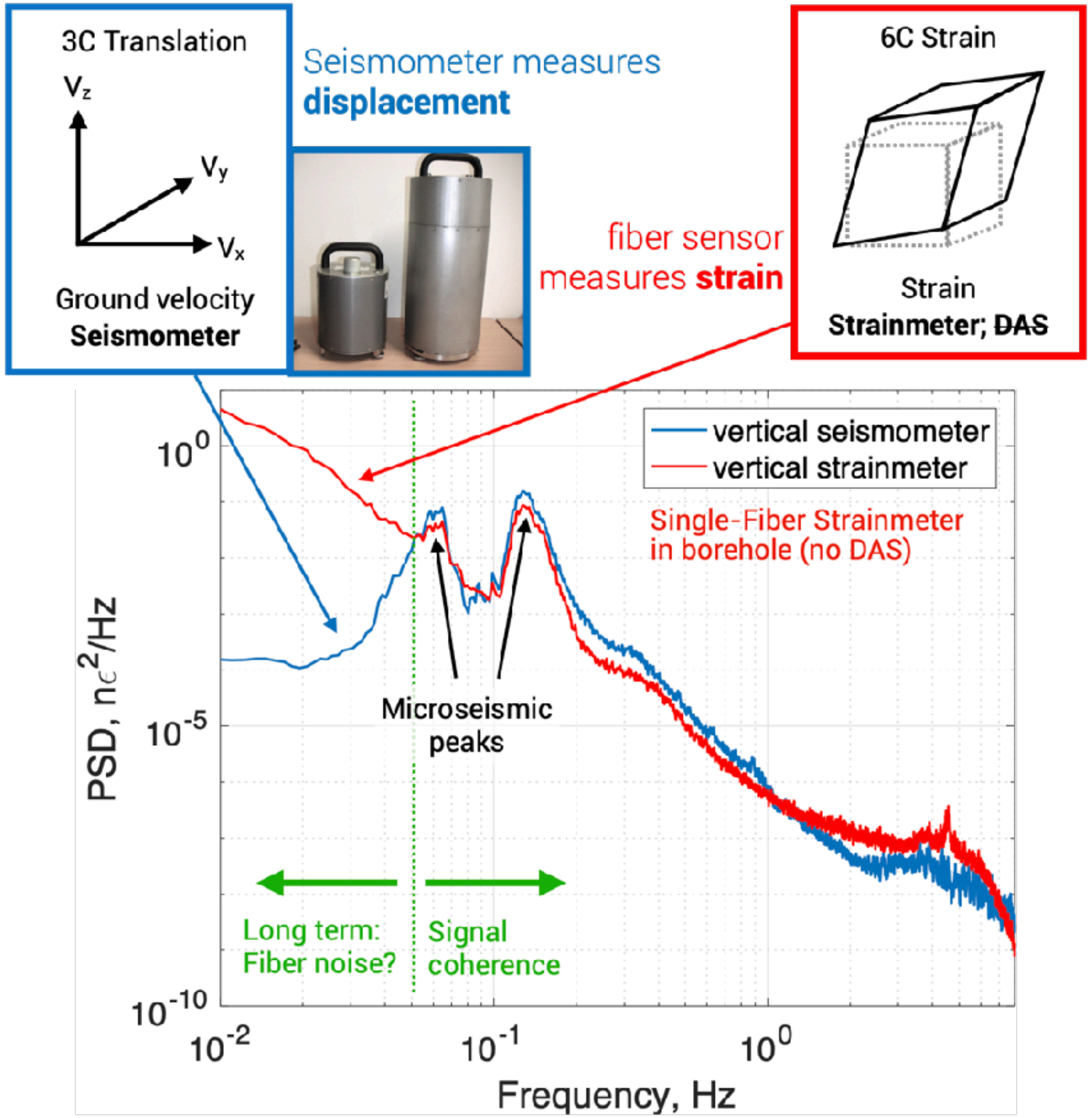
DI distributed strain sensors

- Fiber noise (length, temperature, humidity)
- Laser noise (laser frequency noise)[1]
- Clock jitter noise (high speed)
- Autocorrelation suppression (length of PRN code)
- Multiplexing channel noise (1000 channel limit?)[2,3]
- Sophisticated digital signal processing system: FPGA
- Costs? (polarization maintaining fibers, dedicated fibers, laser frequency reference)
- Coupling to seismic field

[1] Gray et. al 2014, DOI: 10.1117/12.2059435

[2] Spollard et. al 2022: https://opg.optica.org/ol/abstract.cfm?uri=ol-47-7-1570

[3] Sibley etl al 2020: https://www.osapublishing.org/abstract.cfm?URI=oe-28-7-10400



Credit: Harald Lück, Jan Harms / Piñon Flat Observatory, Univ. of California
https://pfostrain.ucsd.edu/pfo/

Noise sources

DI distributed strain sensors

Displacement noise: $\tilde{x} = \frac{\tilde{\nu}}{\nu} x$

- Fiber noise (length, temperature, humidity)
- Laser noise (laser frequency noise)[1]
- Clock jitter noise (high speed)
- Autocorrelation suppression (length of PRN code)
- Multiplexing channel noise (1000 channel limit?)[2,3]
- Sophisticated digital signal processing system: FPGA
- Costs? (polarization maintaining fibers, dedicated fibers, laser frequency reference)
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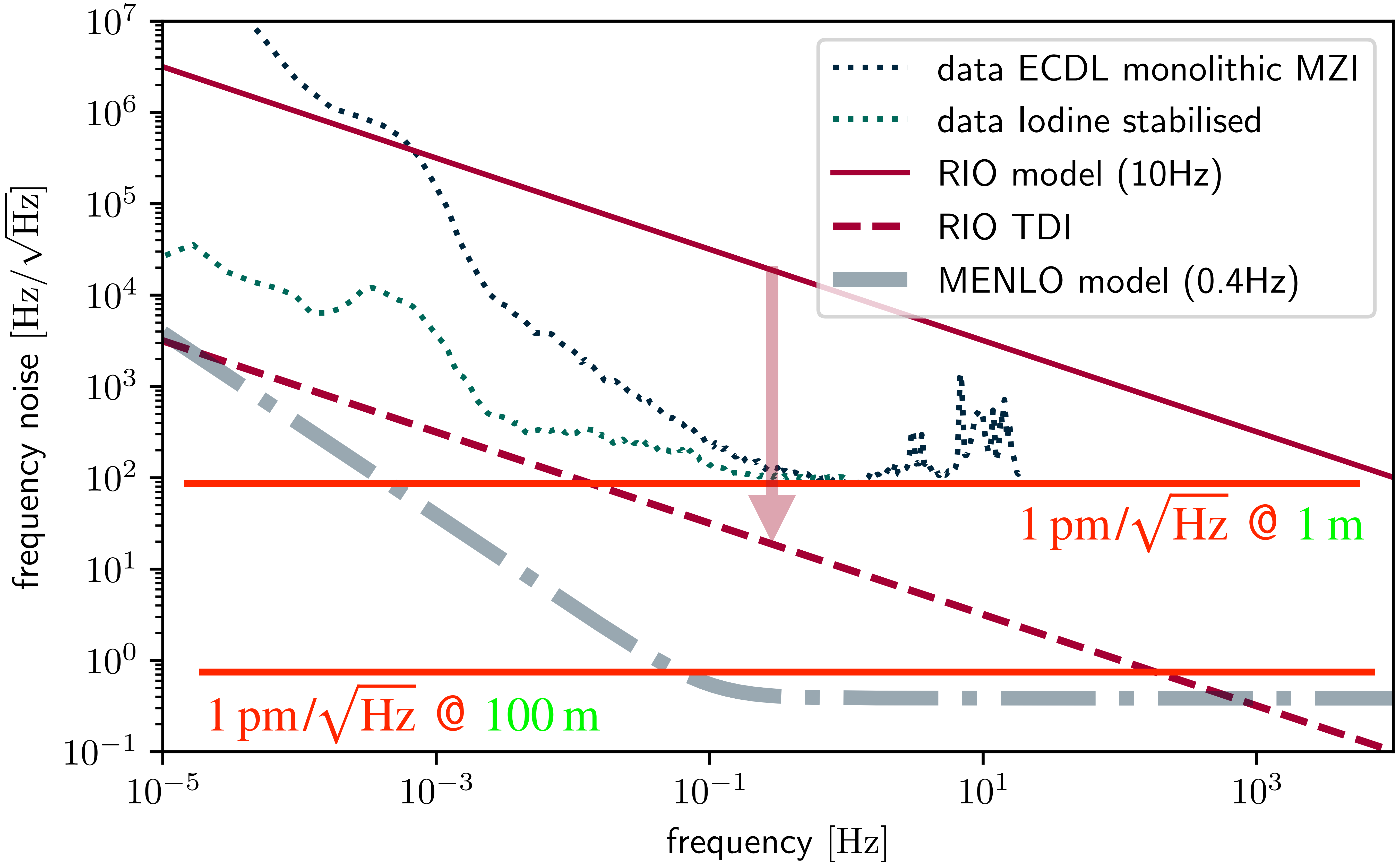
Laser frequency noise:



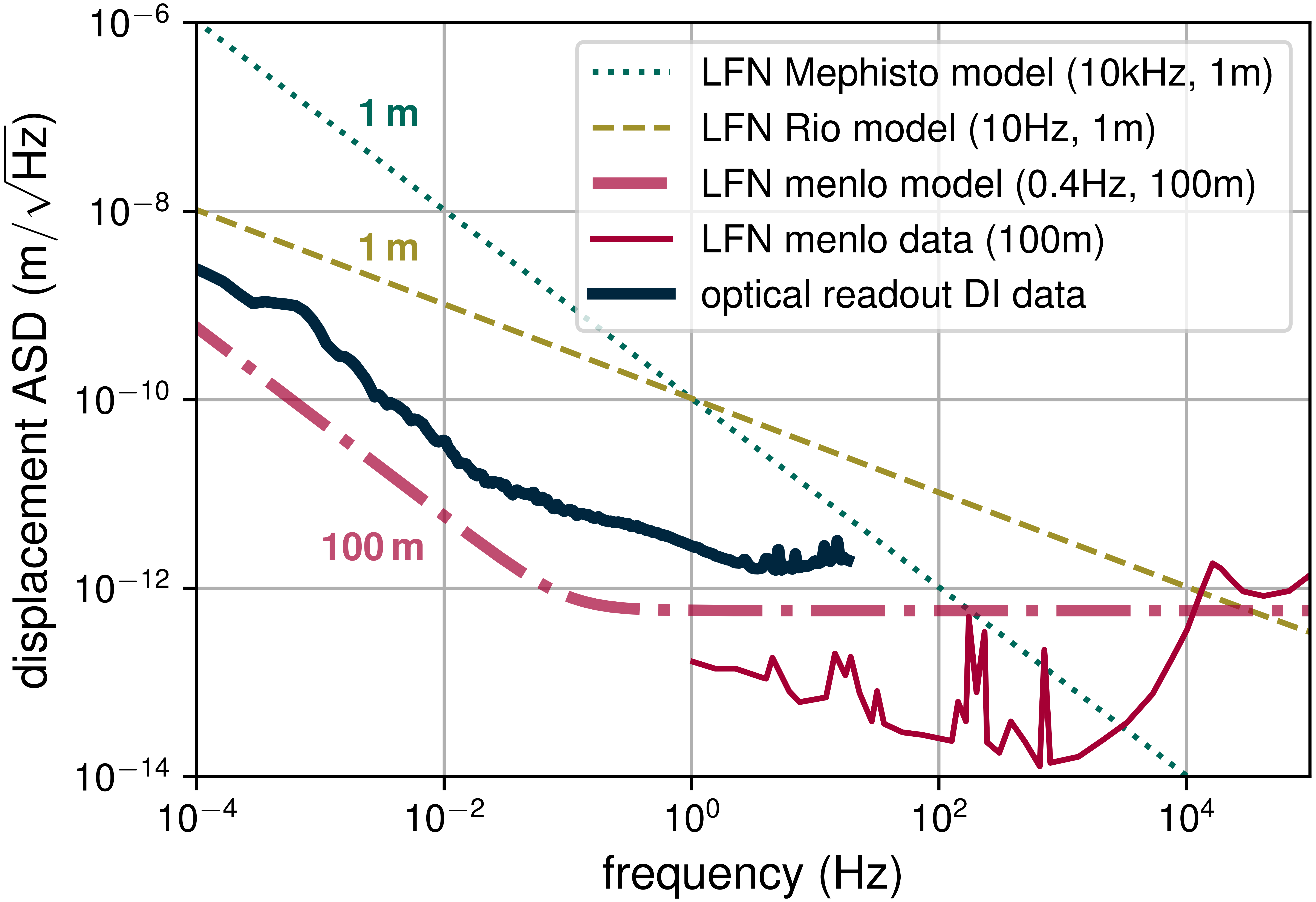
[1] Gray et. al 2014, DOI: 10.1117/12.2059435

[2] Spollard et. al 2022: https://opg.optica.org/ol/abstract.cfm?uri=ol-47-7-1570

[3] Sibley etl al 2020: https://www.osapublishing.org/abstract.cfm?URI=oe-28-7-10400

Limitations of strain sensors: laser frequency noise

- Depends on interferometric arm length mismatch dL
- Might be common mode in some signal combinations
- To ensure pico-strain:
  - Mephisto (1064nm, NPRO): dL = 1m @100Hz
  - Rio (1550nm, diode laser): dL = 1m @10kHz dL = 1cm @1Hz
  - Menlo (frequency comb): dL = 100m @100mHz



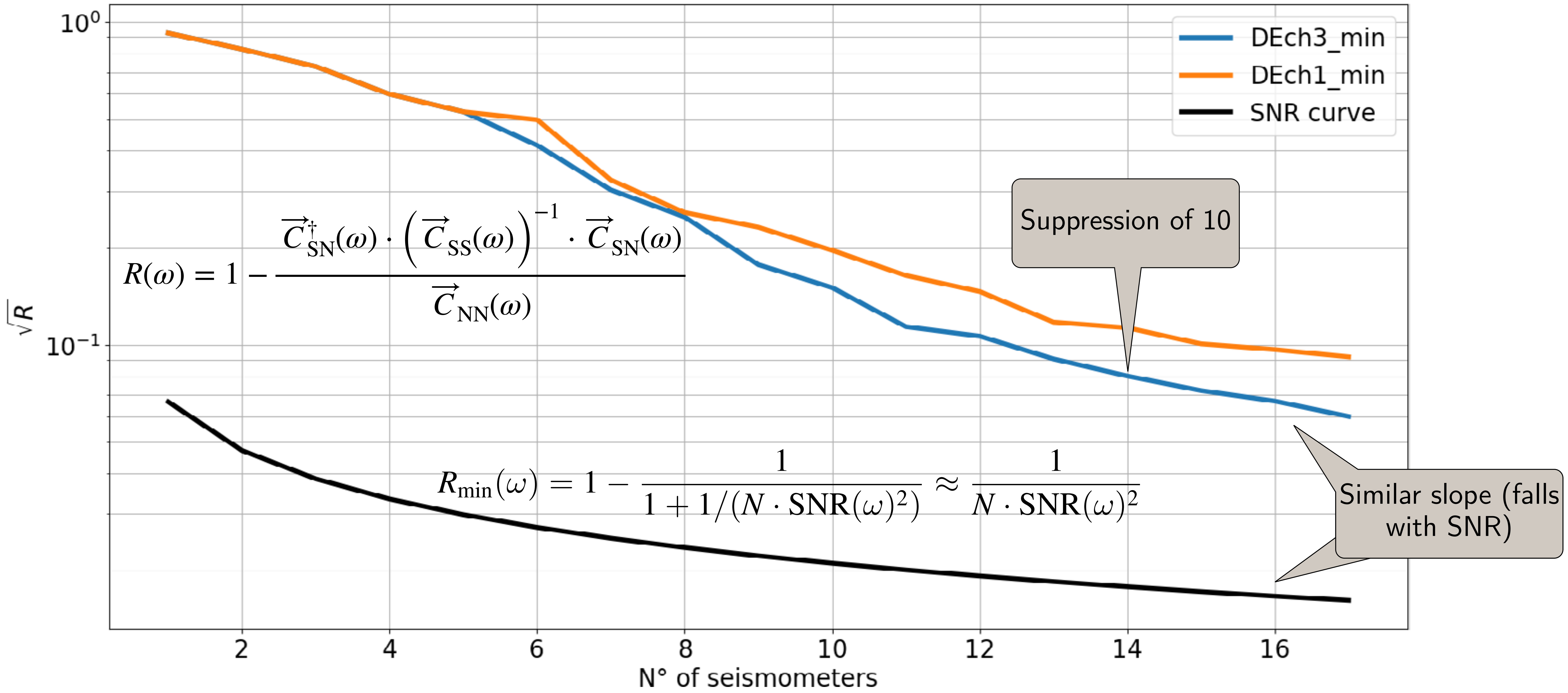
NNC for body waves

In underground detectors using seismometers

Jan Harms

Francesca Badaracco

Badaracco et al. 2019, https://doi.org/10.1088/1361-6382/ab28c1



$$R(\omega) = 1 - \frac{\vec{C}^{\dagger}_{\mathrm{SN}}(\omega) \cdot \left(\vec{C}_{\mathrm{SS}}(\omega)\right)^{-1} \cdot \vec{C}_{\mathrm{SN}}(\omega)}{\vec{C}_{\mathrm{NN}}(\omega)}$$

$$R_{\min}(\omega) = 1 - \frac{1}{1 + 1/(N \cdot \mathrm{SNR}(\omega)^2)} \approx \frac{1}{N \cdot \mathrm{SNR}(\omega)^2}$$

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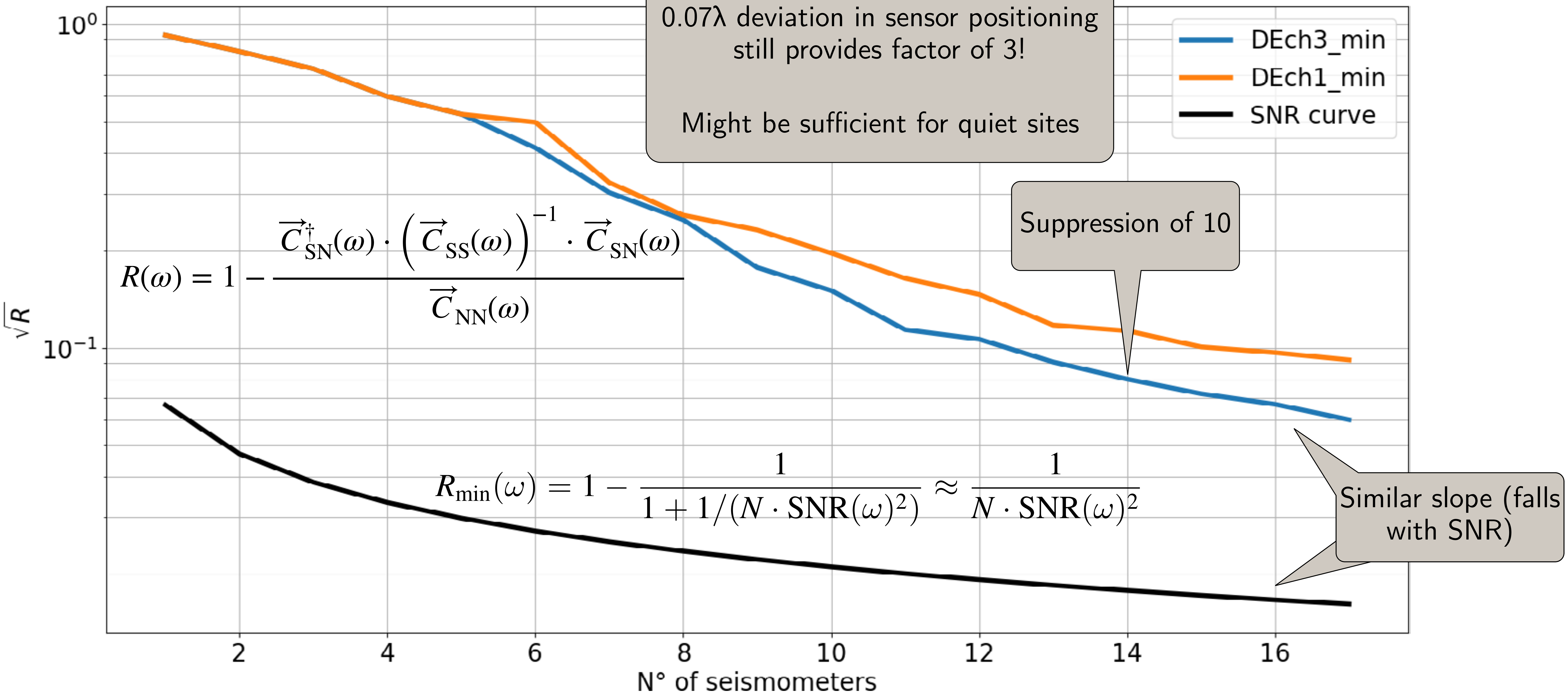
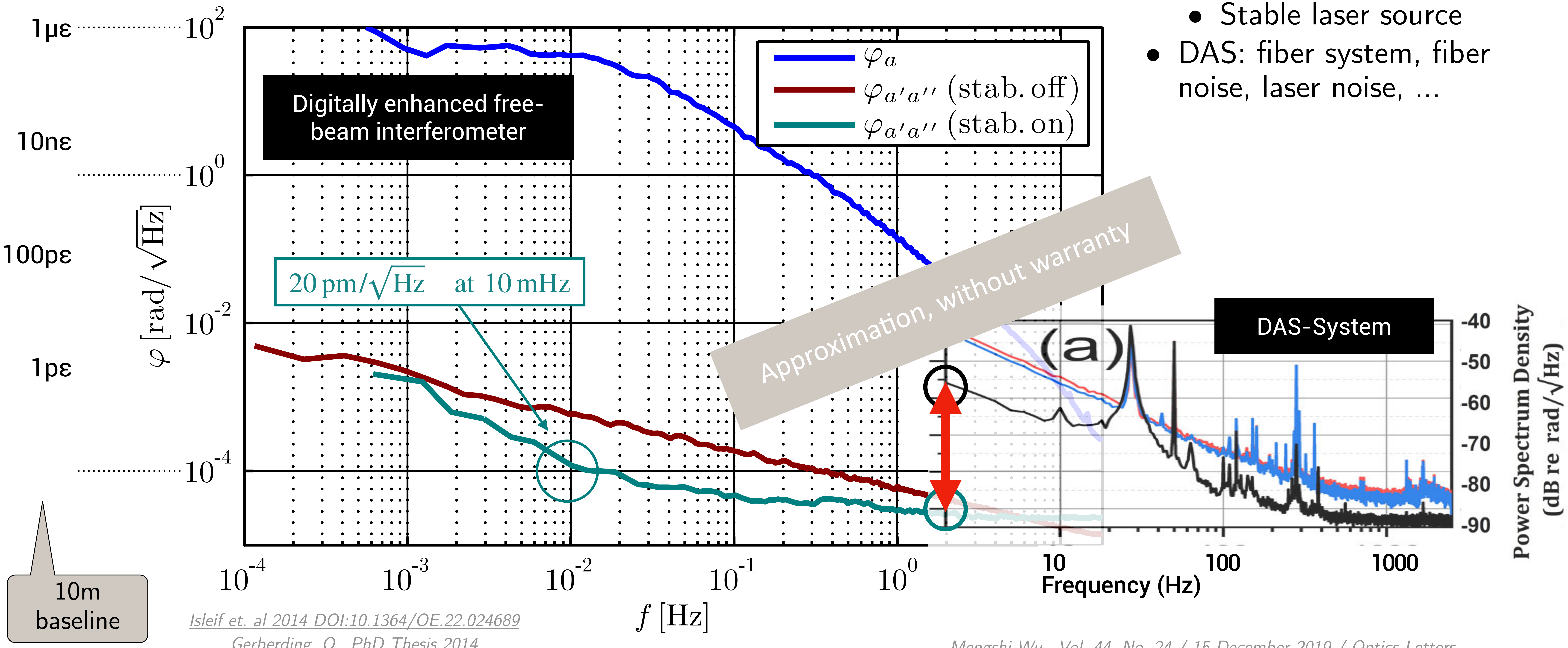


$$R(\omega) = 1 - \frac{\vec{C}^{\dagger}_{\mathrm{SN}}(\omega) \cdot \left(\vec{C}_{\mathrm{SS}}(\omega)\right)^{-1} \cdot \vec{C}_{\mathrm{SN}}(\omega)}{\vec{C}_{\mathrm{NN}}(\omega)}$$

$$R_{\mathrm{min}}(\omega) = 1 - \frac{1}{1 + 1/(N \cdot \mathrm{SNR}(\omega)^2)} \approx \frac{1}{N \cdot \mathrm{SNR}(\omega)^2}$$

Comparison „DAS“ vs. „DI“

- This DI experimental data:
  - Displacement measurement
  - Free beam setup (no fiber)
  - Stable laser source
- DAS: fiber system, fiber noise, laser noise, …



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Mengshi Wu,, Vol. 44, No. 24 / 15 December 2019 / Optics Letters