Einstein Telescope

Technology development for new generation of gravitational wave detectors

Artem Basalaev, GWD group at UHH

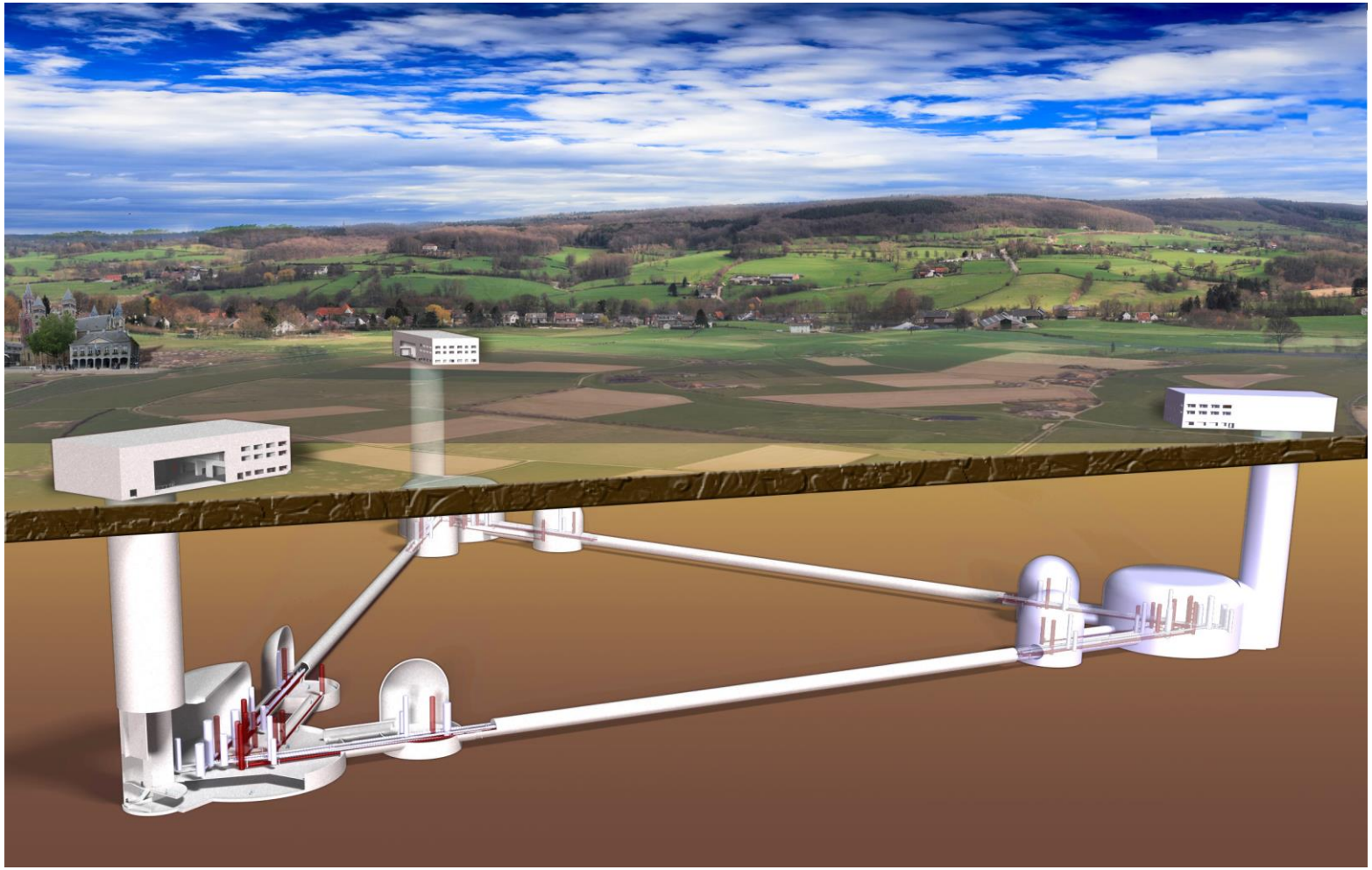
(in this talk: also highlighting collaborations with HSU, DESY, GFZ, XFEL)

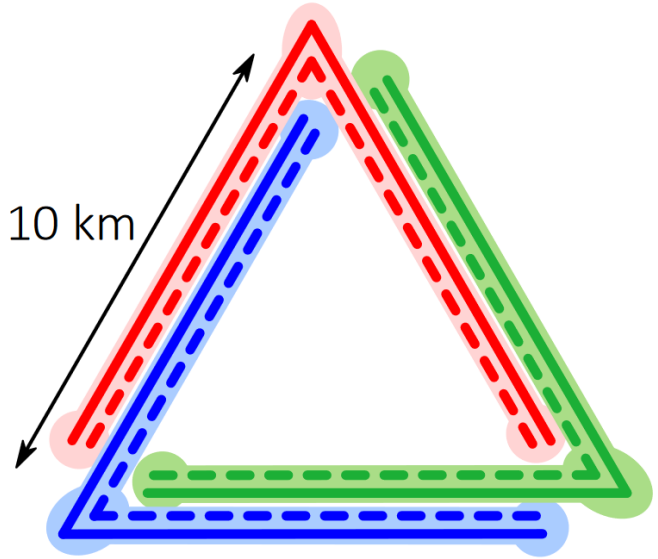
Perspectives in detector research workshop

1 June 2023

Einstein Telescope

https://www.et-gw.eu/

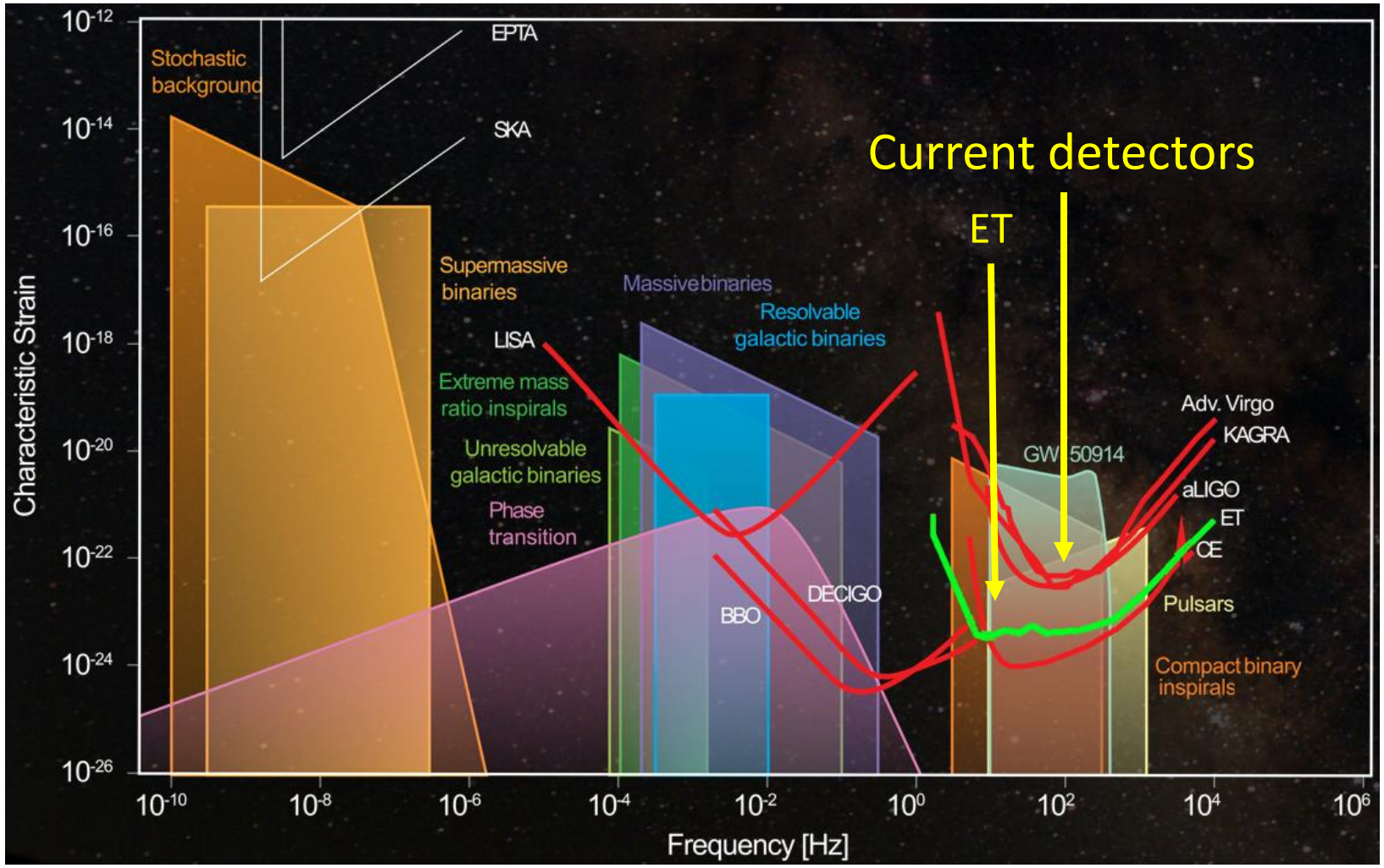




- Deep underground: better seismic isolation
- 6 interferometers
  - 3 cryo low-frequency
  - 3 room-temperature high frequency

Einstein Telescope: science case

https://www.et-gw.eu/



Instrument:

- Increase sensitivity by several orders of magnitude
- Push lower bound of sensitivity down to ~3 Hz

Science:

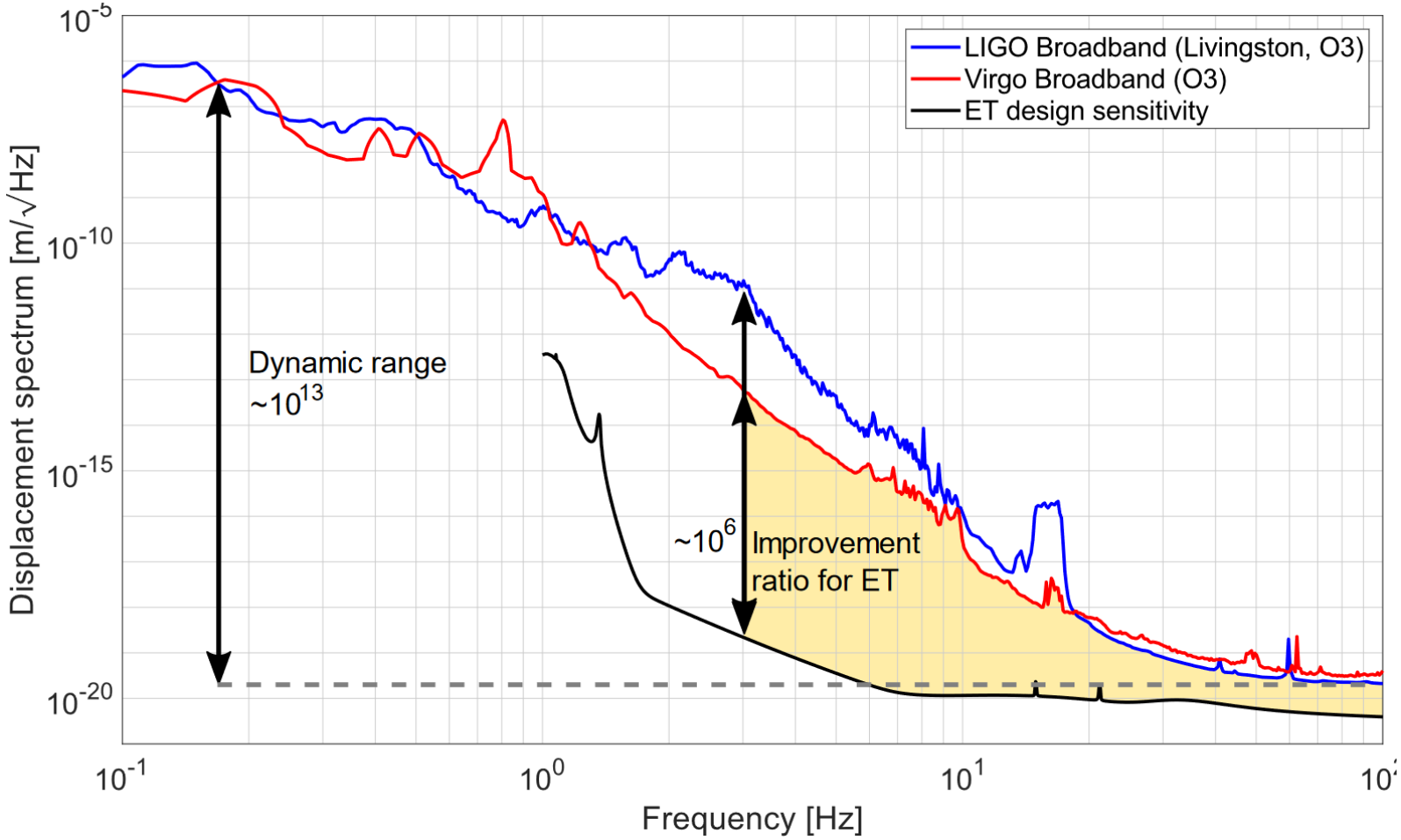
- Precise measurements of parameters of compact binaries
- Long pre-merger tracking, minutes to many hours
- As a result, rich multi-messenger opportunities for neutron stars

Low-frequency noise

- Especially challenging to improve in low frequency
- Can't make the "noise wall" arbitrarily steep → need good improvement even below detection band

Where it comes from? Sources include:

- Seismic/control noise
- Newtonian noise
- Others out of scope of this talk

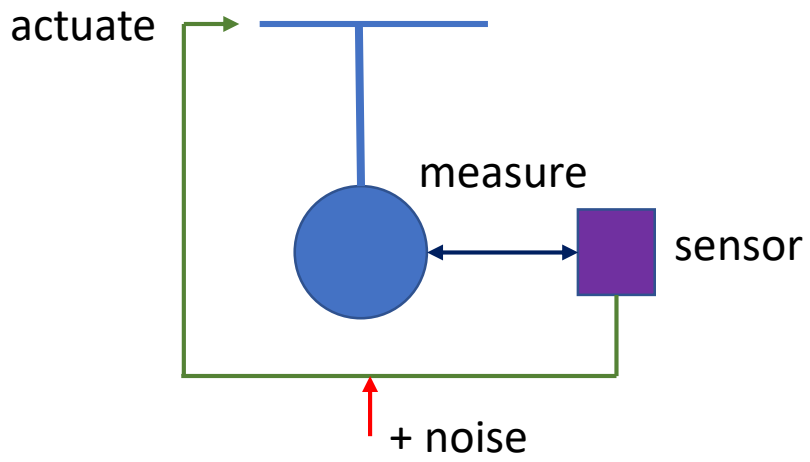


Source: Conor Mow-Lowry, taken from Jan Harms talk at ET-ISB workshop

Low-frequency noise sources

Seismic/control noise

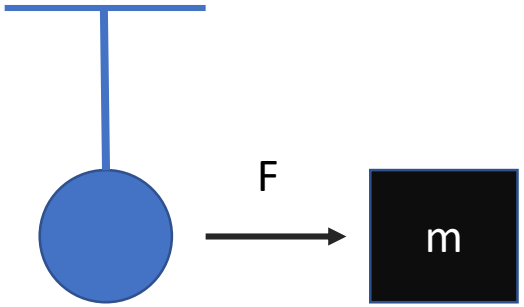
- Imperfect measurement of seismic motion in active isolation (noisy sensors)
- Gets imprinted onto optics motion and eventually differential measurement



Solution: **better displacement sensors**

Newtonian noise

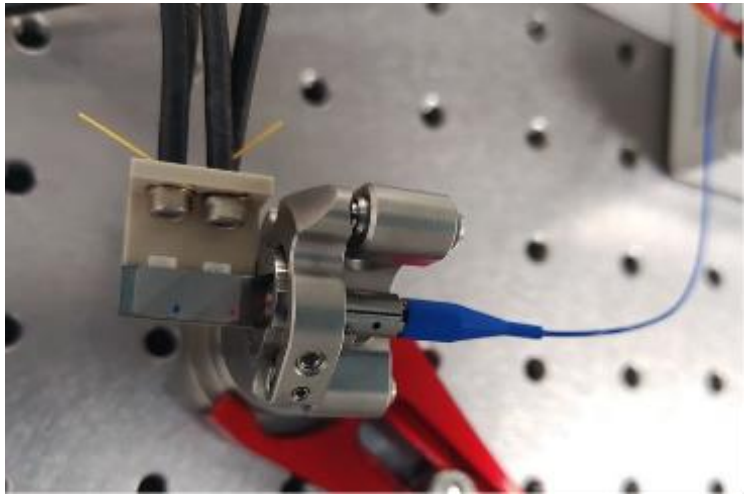
- Moving masses near interferometer produce gravity gradient
- Moves the mirror & produces differential measurement

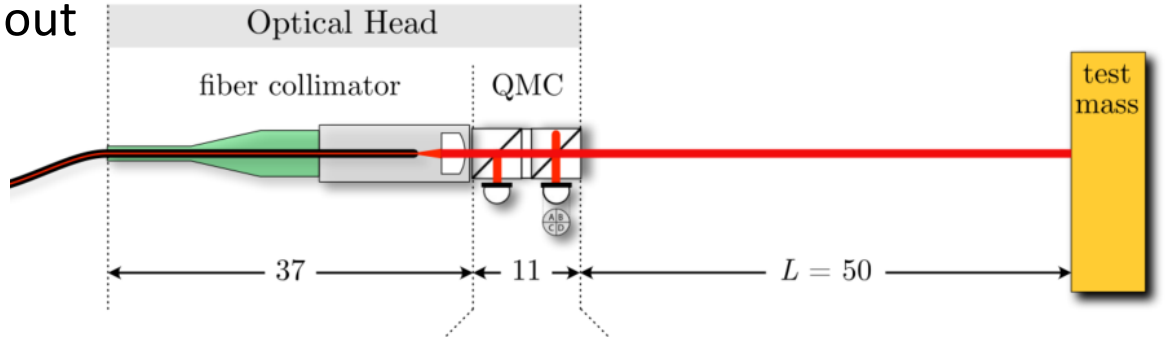


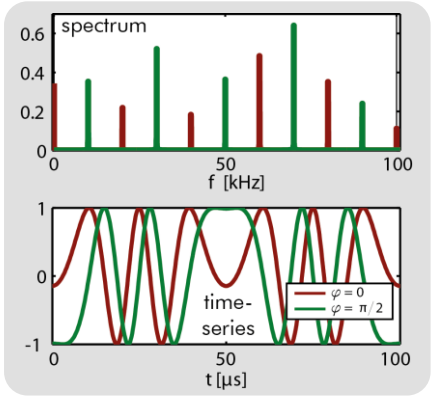
Solution: **better measurement of seismic field with distributed sensor network**, calculating force real-time

Compact Balanced Readout Interferometer (COBRI) sensors

- Local displacement readout or inertial sensors
- Based on **Deep Frequency Modulation Interferometry (DFMI)**
- Very compact: fits into half inch mirror mount
- Expected sensitivity **~10^{-14} m/ √Hz**
- Two other readout techniques currently investigated to go below **10^{-15}/√Hz**:
  - Resonantly enhanced DFMI
  - Heterodyne cavity readout



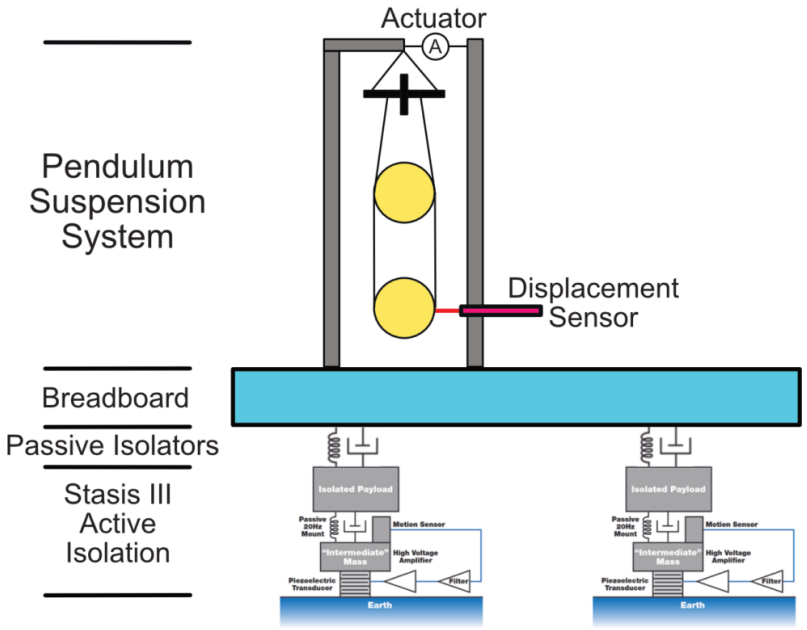




See also Prof. O. Gerberding talk at ET Symposium 2023

VATIGrav: seismically isolated platform for testing sensor designs in vacuum

Better isolation = better sensors



Need to model:

- Effects of couplings between different DOFs in sensing and actuation
- Effects of sensor noise; optimize sensor placement
- Optimize the controller

Spicypy project

Combining several tools to facilitate **signal processing**, **control systems modelling**, and the **interface between the two**.

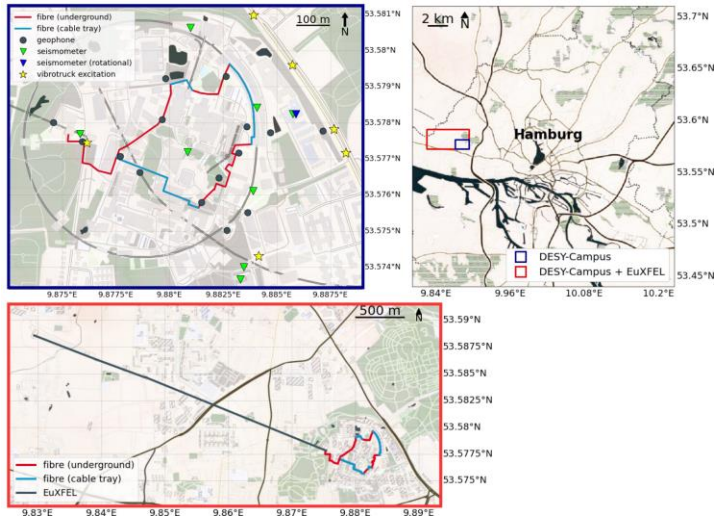
LVK | Einstein Telescope | LISA | Laser physics, material science, ...

https://gitlab.com/pyda-group/spicypy

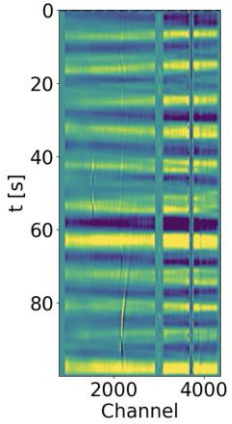
See also Prof. O. Gerberding talk at ET Symposium 2023

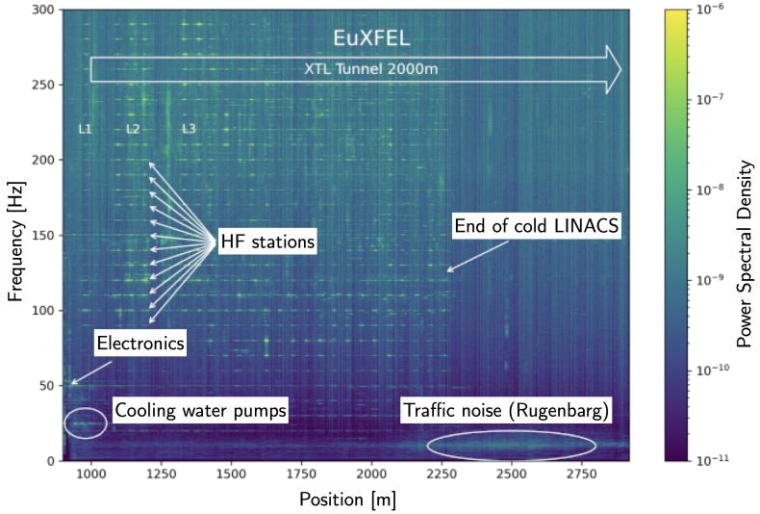
Seismic fiber network on campus: WAVE initiative

- Geophones, seismometers, and distributed acousting sensing (DAS):
  - Optic fiber as sensitive seismic sensors
  - High spatial sensor density over large distances (12.6km, 1m gauge lengths = 12600 sensors)



http://wave-hamburg.eu





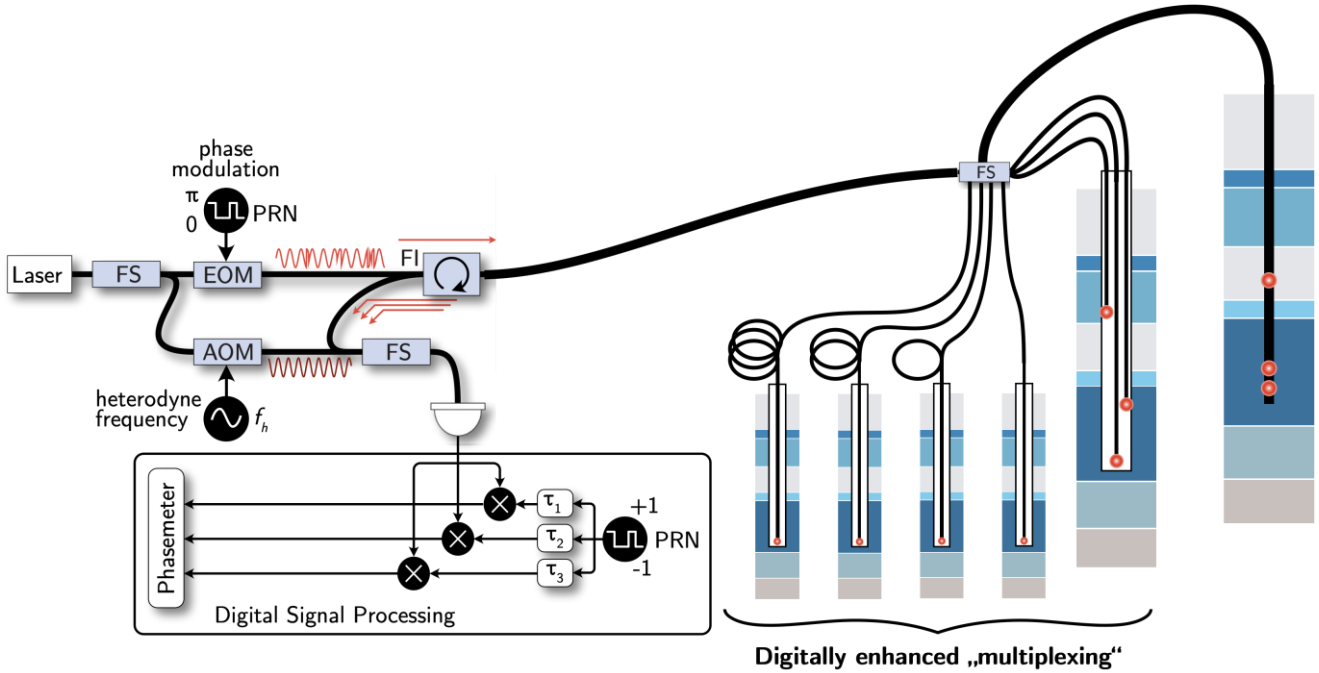
Seismic fiber network for Newtonian noise cancellation in ET

Group of Prof. K.-S. Islief

HELMUT SCHMIDT UNIVERSITÄT
Universität der Bundeswehr Hamburg

Goal: Optimal (cost-effective) NNC system for ET

- R&D of distributed fiber sensors using digitally-enhanced interferometry, providing high broadband performance
- Optimal sensor positioning for fiber strain sensors



See Prof. K.-S. Islief talk at GWADW 2023

Summary

- To achieve science goals of Einstein Telescope, current best achievable **sensitivity has to be improved**, especially **at low frequency**
- A lot of RND on campus to help achieve this target:
  - **Compact Balanced Readout Interferometer (COBRI)** sensors for better local displacement sensitivity, resulting in **better seismic isolation & control**
  - WAVE initiative testing technologies for **optical fiber seismic network**
  - Study of application of such network together with digitally-enhanced interferometry for **Newtonian noise cancellation**

N.B.: for time constraints, this talk focused on Einstein Telescope

- All mentioned RND is **also relevant for other next-gen detectors**: LIGO A#, Cosmic Explorer, etc…
- **There's more RND** for other detectors and applications (LISA, …)

Thank you!

Backup

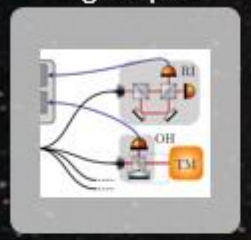
DFMI Concept

Deep-Frequency Modulation Interferometry (DFMI)

Laser modulation

$$f(t) = f_0 + f_\Delta \cos(\omega_m t)$$
$$f_m = 1\,\mathrm{kHz}$$
$$f_\Delta = 3\,\mathrm{GHz}$$

Light split

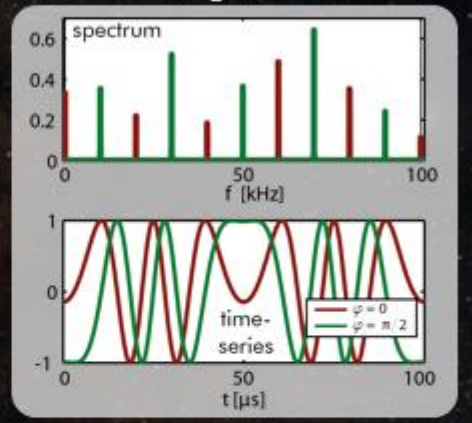


$$f_1(t) = f_2(t) = f_N(t)$$
$$f_R(t) \approx \mathrm{const} + f_\Delta(t)$$

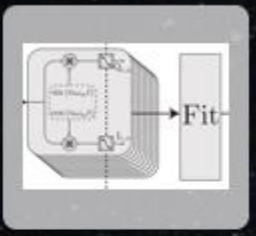
Interferometer

$$L_\Delta = 0.1\,\mathrm{m}$$
$$m = 2\pi \frac{L_\Delta}{c} f_\Delta \approx 7$$

Signal



Phasemeter



$$\hat{i}_{DC}, \hat{i}_{AC}, \hat{m}, \hat{\varphi}, \hat{\psi}$$

power, contrast, ranging, displacement

$$i(t) = i_{DC} + i_{AC} \cos(\varphi + m \cos(\omega_m t + \psi))$$

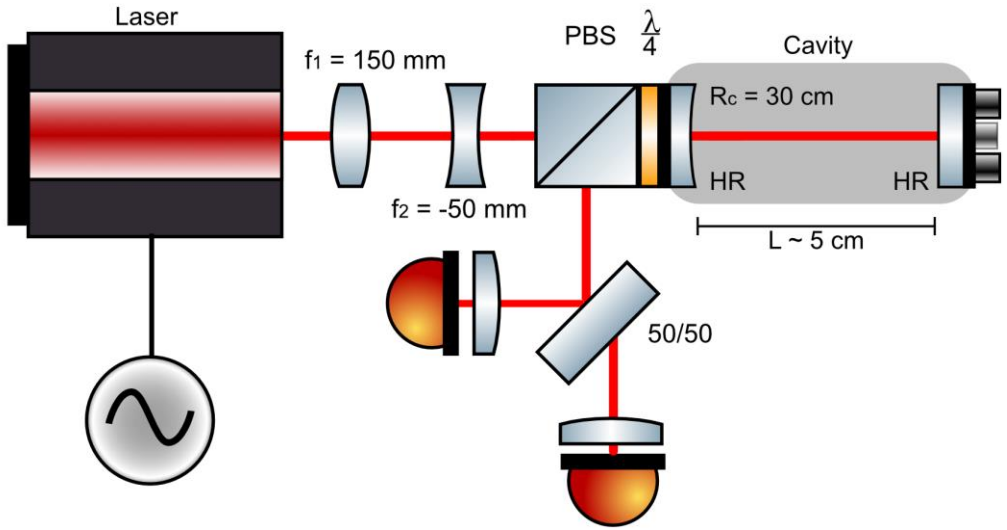
Main features:

- Signal is inherently non-linear and linearized by the phasemeter algorithm/estimator
- Each interferometer (optical head) has only one input beam and can be very compact
- Laser frequency noise is common mode (can be suppressed actively or in post-processing)
- Provides wide-range sensing of displacement & absolute ranging

O. Gerberding, Optics Express, 23, 11, (2015)
G. Heinzel et al., Optics Express, 18, 19, (2010)
K.-S. Isleif et al., Optics Express, 24, 2, (2016)
K.-S. Isleif et al., PRApplied 12, 034025 (2019)

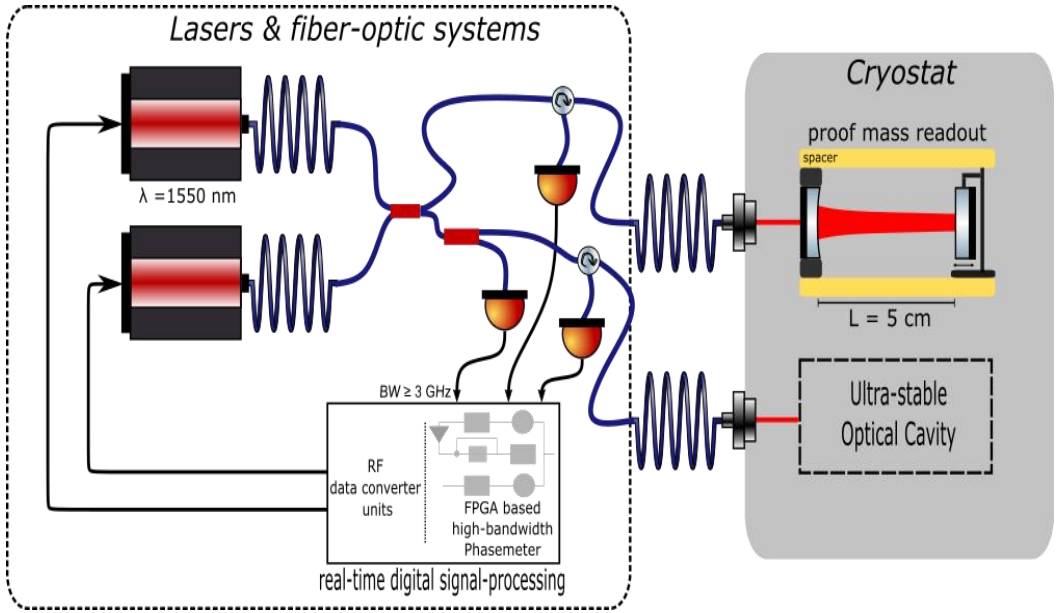
See Oliver Gerberding talk at ET Symposium

ReDFMI and Heterodyne cavity



Resonantly enhanced DFMI

<10^{-15}m/sqrt(Hz)
dozens of sensors per laser
absolute ranging



Heterodyne cavity tracking readout

<10^{-15}m/sqrt(Hz)
one sensor per laser
best possible performance

See Oliver Gerberding talk at ET Symposium