Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

GRAVITATIONAL WAVE DETECTION

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

DESY FH SEMINAR

OCTOBER 24TH 2025

EINSTEIN TELESCOPE - THE 3RD GENERATION OF LASER INTERFEROMETRIC GRAVITATIONAL WAVE DETECTION IN EUROPE

O. GERBERDING

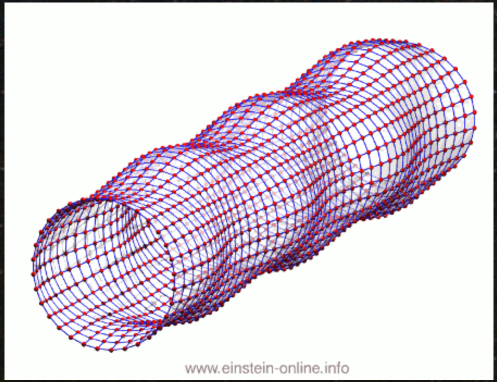
EINSTEIN TELESCOPE

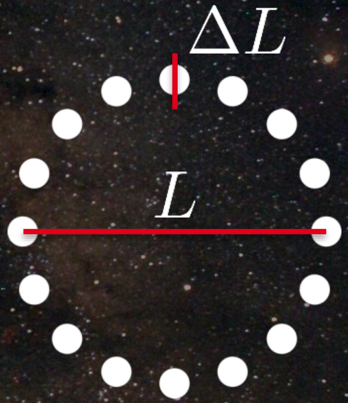
GRAVITATIONAL WAVES

- CONSEQUENCE OF GENERAL RELATIVITY
- SOURCED BY AN ACCELERATED QUADRUPOL MOMENT
- PROPAGATE WITH THE SPEED OF LIGHT
- TWO POLARISATIONS: + & X
- STRECH & COMPRESS SPACE-TIME TRANSVERSALLY

STRAIN FROM A BINARY

$$h = \frac{\Delta L}{L} \propto \frac{1}{r} m^{5/3} f^{2/3}$$





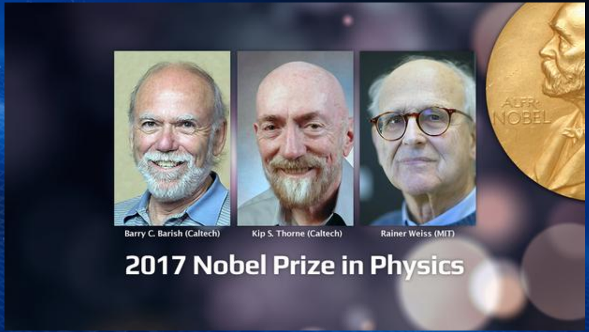
BACKGROUND: THE MILKY WAY GALAXY BY DEREK ROWLEY

GRAVITATIONAL WAVE ASTRONOMY

STRAIN FROM A BINARY

$$h = \frac{\Delta L}{L} \propto \frac{1}{r} m^{5/3} f^{2/3}$$

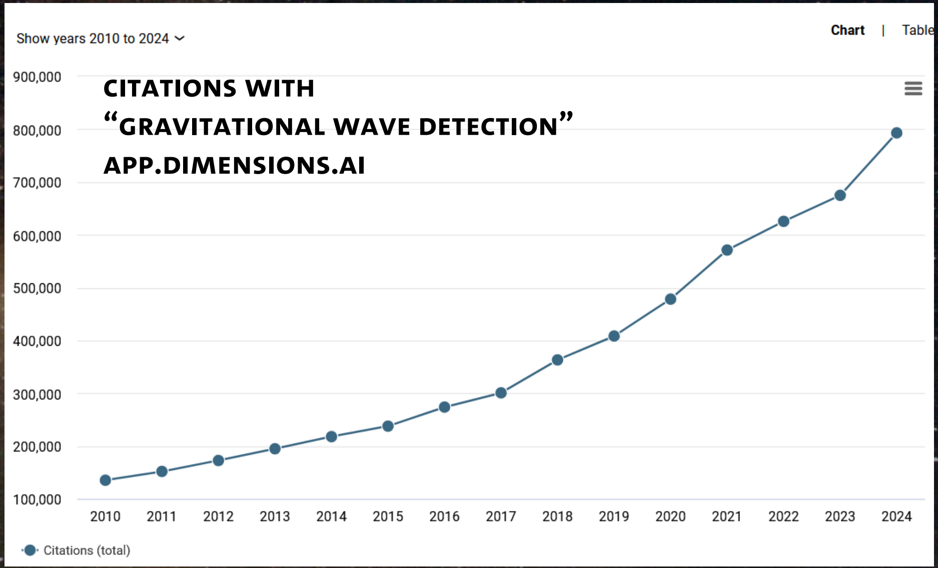
HULSE-TAYLOR BINARY-DISCOVERY 1974
ORBITAL DECAY FITS GRAVITATIONAL WAVES
NOBEL PRIZE 1993



FIRST DIRECT DETECTION BY LIGO IN 2015
LASER INTERFEROMETRY MEASURES STRAIN
NOBEL PRIZE 2017

CREDIT: ESO/L. CALÇADA

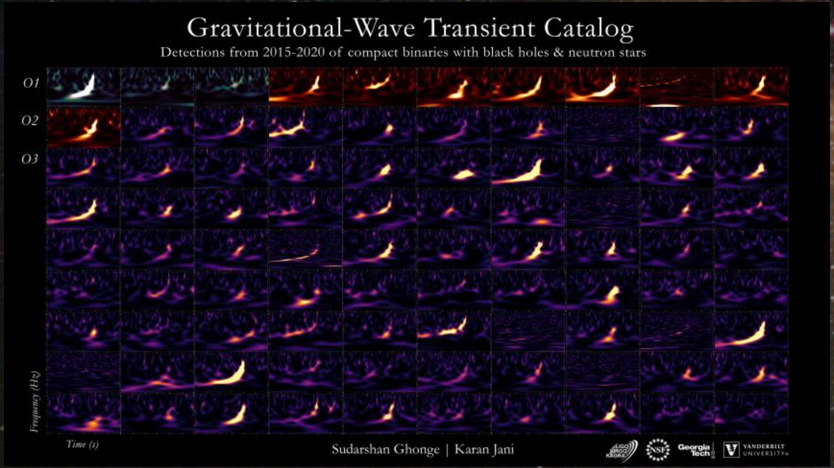
A NEW ERA IN GRAVITATIONAL PHYSICS

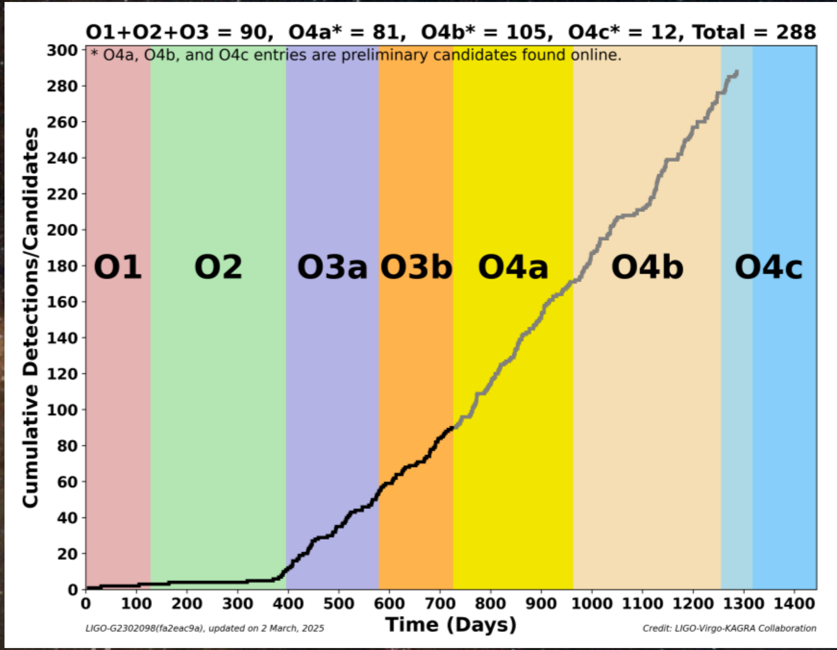


BACKGROUND: THE MILKY WAY GALAXY BY DEREK ROWLEY

A NEW ERA IN GRAVITATIONAL PHYSICS

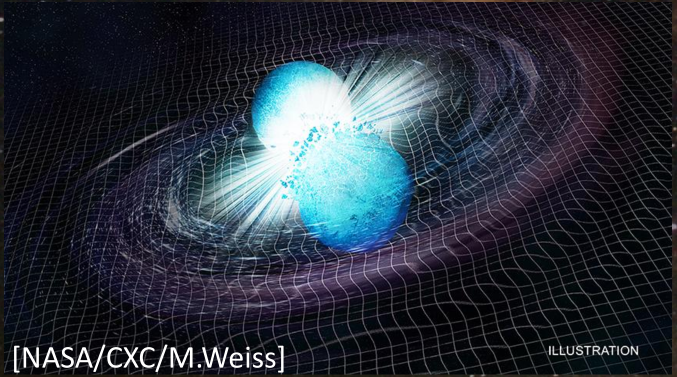
- Almost **daily** gravitational wave BBH, BNS & BHNS detections during observing runs



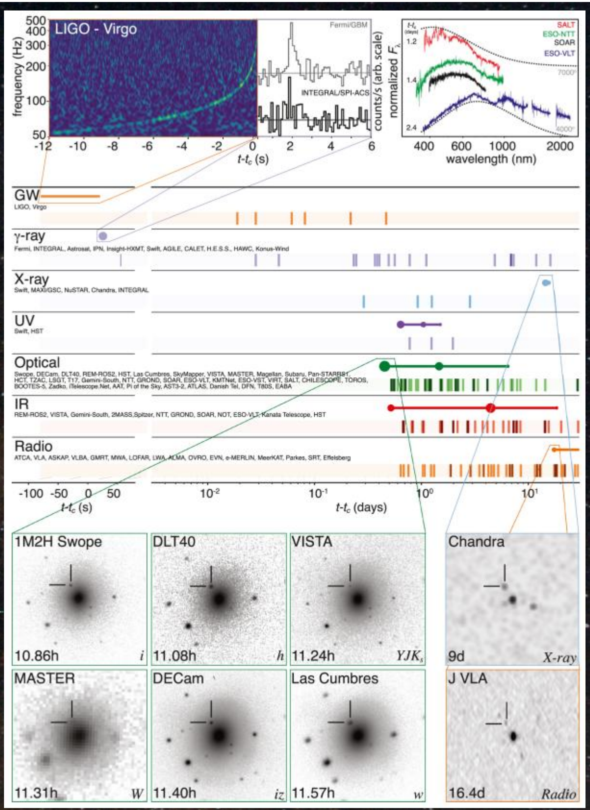


A NEW ERA IN GRAVITATIONAL PHYSICS

- Almost **daily** gravitational wave BBH, BNS & BHNS detections during observing runs
- Multi-messenger astronomy (GW170817, Kilonova)
- Precision tests of GR, black hole mass function, GW speed, Hubble constant via standard siren, mass-gap objects, Hawking area theorem



[NASA/CXC/M.Weiss]

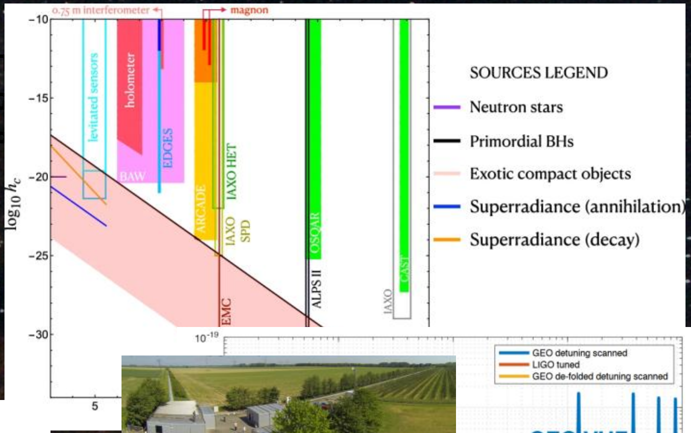


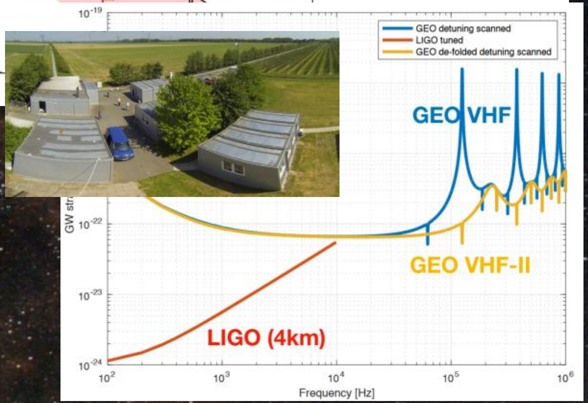
Abbott, Benjamin P., et al. *Astrophys. J. Lett* 848.2 (2017): L12.

A NEW ERA IN GRAVITATIONAL PHYSICS

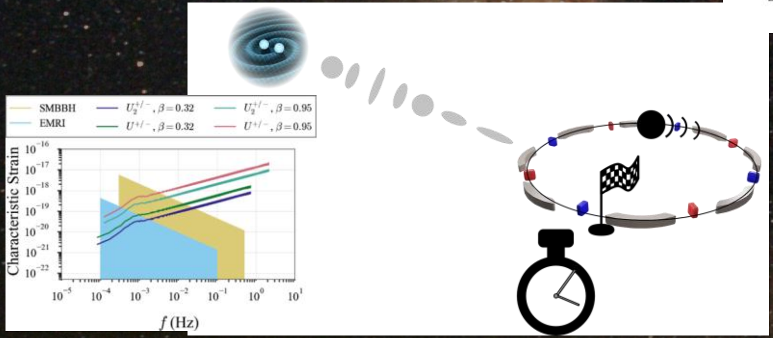
- Almost **daily** gravitational wave BBH, BNS & BHNS detections during observing runs
- Multi-messenger astronomy (GW170817, Kilonova)
- Precision tests of GR, black hole mass function, GW speed, Hubble constant via standard siren, mass-gap objects
- New GWD concepts from mHz to THz

Aggarwal, Nancy, et al, *Living reviews in relativity* 24 (2021): 1-74.





J. Hough et al., Talk at MG17, 2024, Indico Link



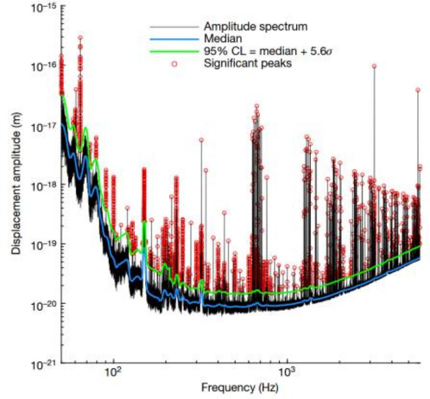
Schmirander, Thorben, et al. Physical Review D 110.8 (2024): 082002.

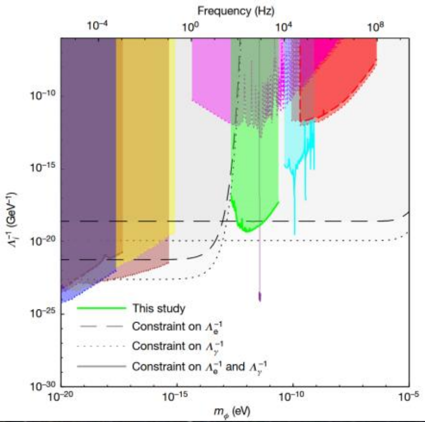
BACKGROUND: THE MILKY WAY GALAXY BY DEREK ROWLEY

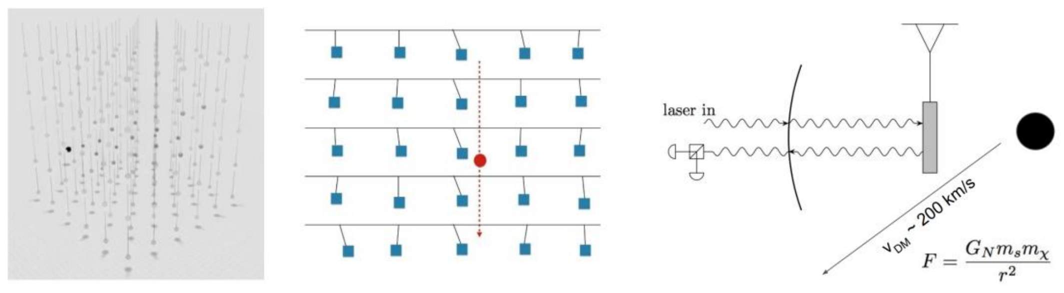
A NEW ERA IN GRAVITATIONAL PHYSICS

- Almost **daily** gravitational wave BBH, BNS & BHNS detections during observing runs
- Multi-messenger astronomy (GW170817, Kilonova)
- Precision tests of GR, black hole mass function, GW speed, Hubble constant via standard siren, mass-gap objects
- New GWD concepts from mHz to THz
- Gravitational dark matter detection

Vermeulen, Sander M., et al., Nature 600.7889 (2021): 424-428.







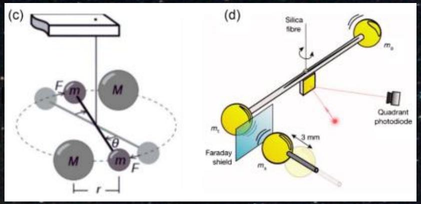
Attanasio, Alaina, et al. arXiv preprint arXiv:2203.07242 (2022).

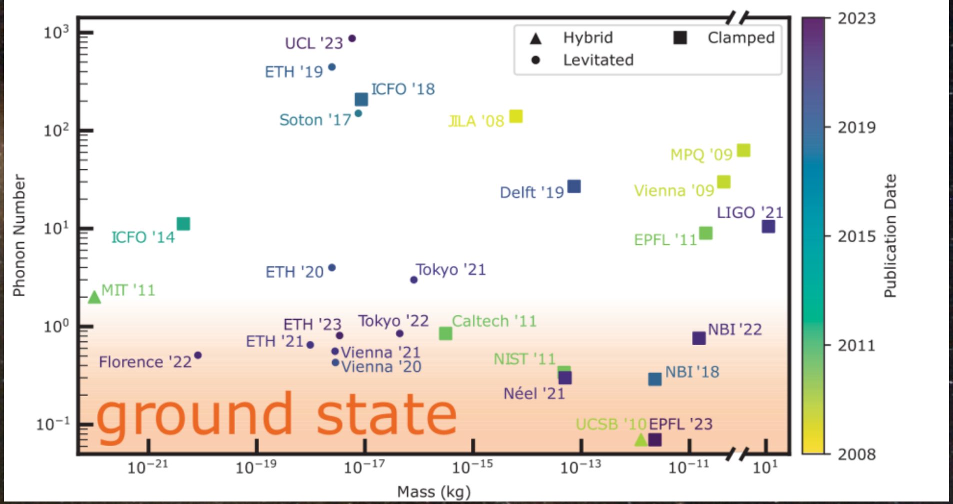
BACKGROUND: THE MILKY WAY GALAXY BY DEREK ROWLEY

A NEW ERA IN GRAVITATIONAL PHYSICS

- Almost **daily** gravitational wave BBH, BNS & BHNS detections during observing runs
- Multi-messenger astronomy (GW170817, Kilonova)
- Precision tests of GR, black hole mass function, GW speed, Hubble constant via standard siren, mass-gap objects
- New GWD concepts from mHz to THz
- Gravitational dark matter detection
- Table-top quantum-gravity experiments with macroscopic entangled masses

CITATIONS WITH
"GRAVITATIONA
APP.DIMENSION

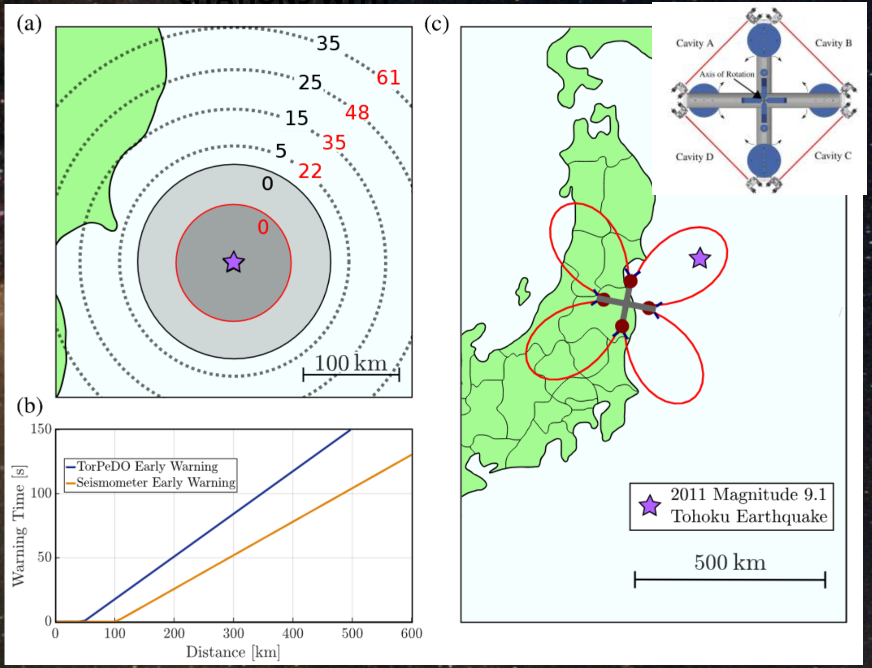




Bose, Sougato, et al., Reviews of Modern Physics 97.1 (2025): 015003.

A NEW ERA IN GRAVITATIONAL PHYSICS

- Almost **daily** gravitational wave BBH, BNS & BHNS detections during observing runs
- Multi-messenger astronomy (GW170817, Kilonova)
- Precision tests of GR, black hole mass function, GW speed, Hubble constant via standard siren, mass-gap objects
- New GWD concepts from mHz to THz
- Gravitational dark matter detection
- Table-top quantum-gravity experiments with macroscopic entangled masses
- Gravitational sensing of Earth



McManus, D. J., et al. arXiv preprint arXiv:1809.04787 (2018).

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

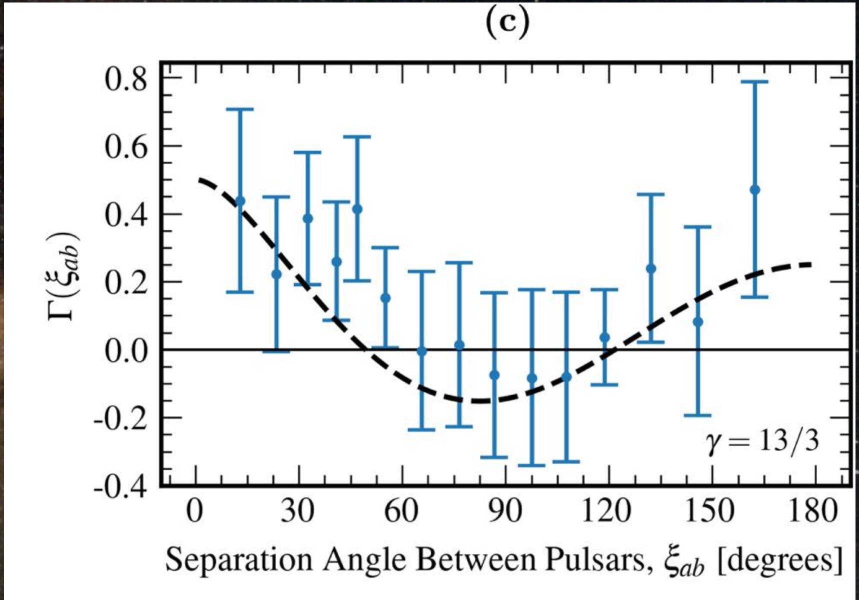
GRAVITATIONAL WAVE DETECTION

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

A NEW ERA IN GRAVITATIONAL PHYSICS

- Almost **daily** gravitational wave BBH, BNS & BHNS detections during observing runs
- Multi-messenger astronomy (GW170817, Kilonova)
- Precision tests of GR, black hole mass function, GW speed, Hubble constant via standard siren, mass-gap objects
- New GWD concepts from mHz to THz
- Gravitational dark matter detection
- Table-top quantum-gravity experiments with macroscopic entangled masses
- Gravitational sensing of Earth
- Evidence for nano Hz GWs from Pulsar timing arrays

CITATIONS WITH



Agazie, Gabriella, et al. , The Astrophysical Journal Letters 951.1 (2023): L8.

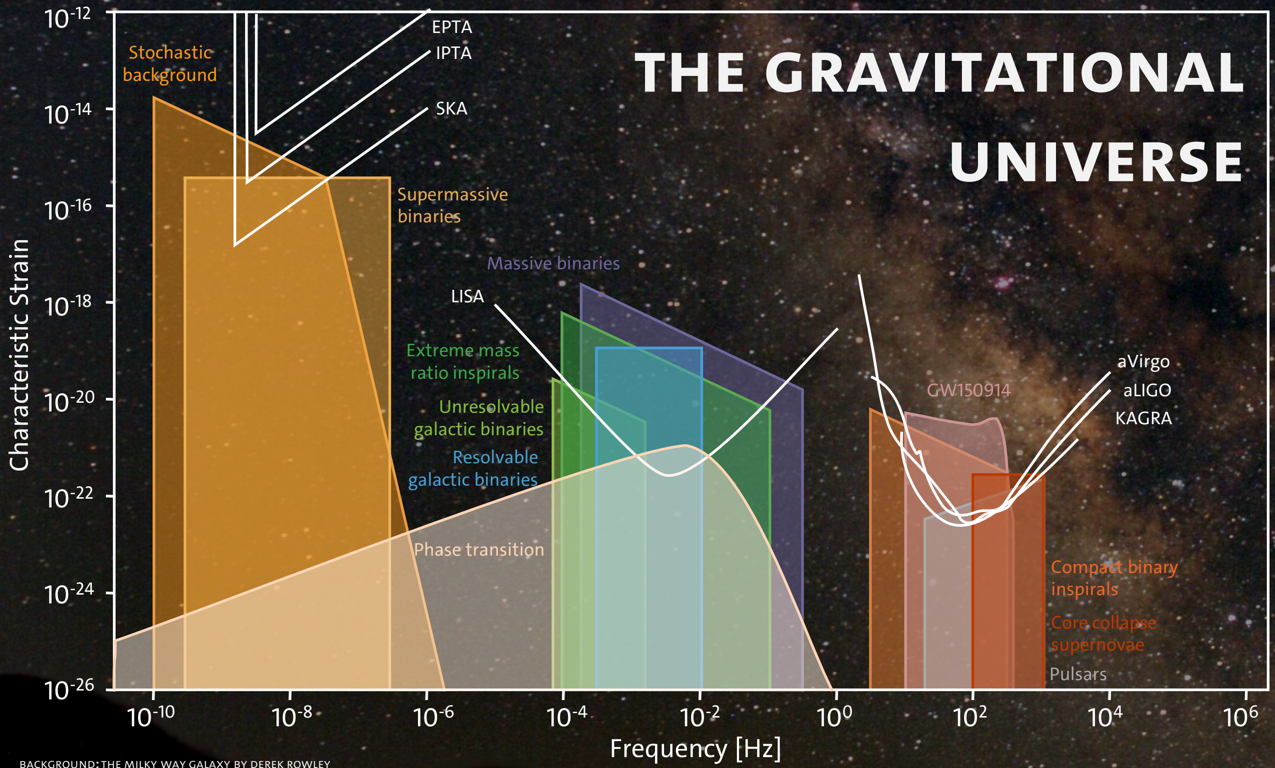
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

GRAVITATIONAL WAVE DETECTION

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

THE GRAVITATIONAL UNIVERSE

ADAPTED FROM GWPLOTTER.COM BY C. MOORE, R. COLE, AND C. BERRY.



2^{ND} GENERATION

LIGO

LISA

VIRGO

KAGRA

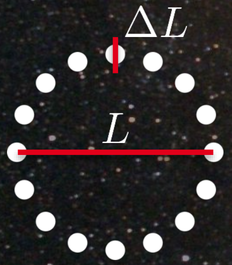
GEO600

BACKGROUND: THE MILKY WAY GALAXY BY DEREK ROWLEY

GROUND BASED GRAVITATIONAL WAVE DETECTION VIA LASER INTERFEROMETERS

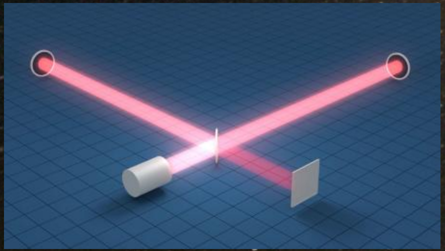
Free masses

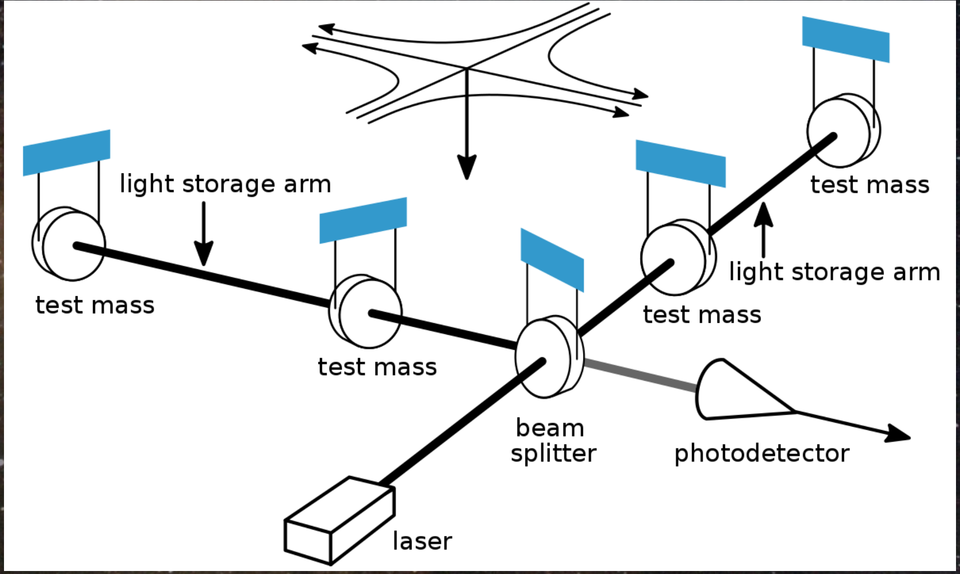
$$h = \frac{\Delta L}{L}$$



Laser displacement measurements

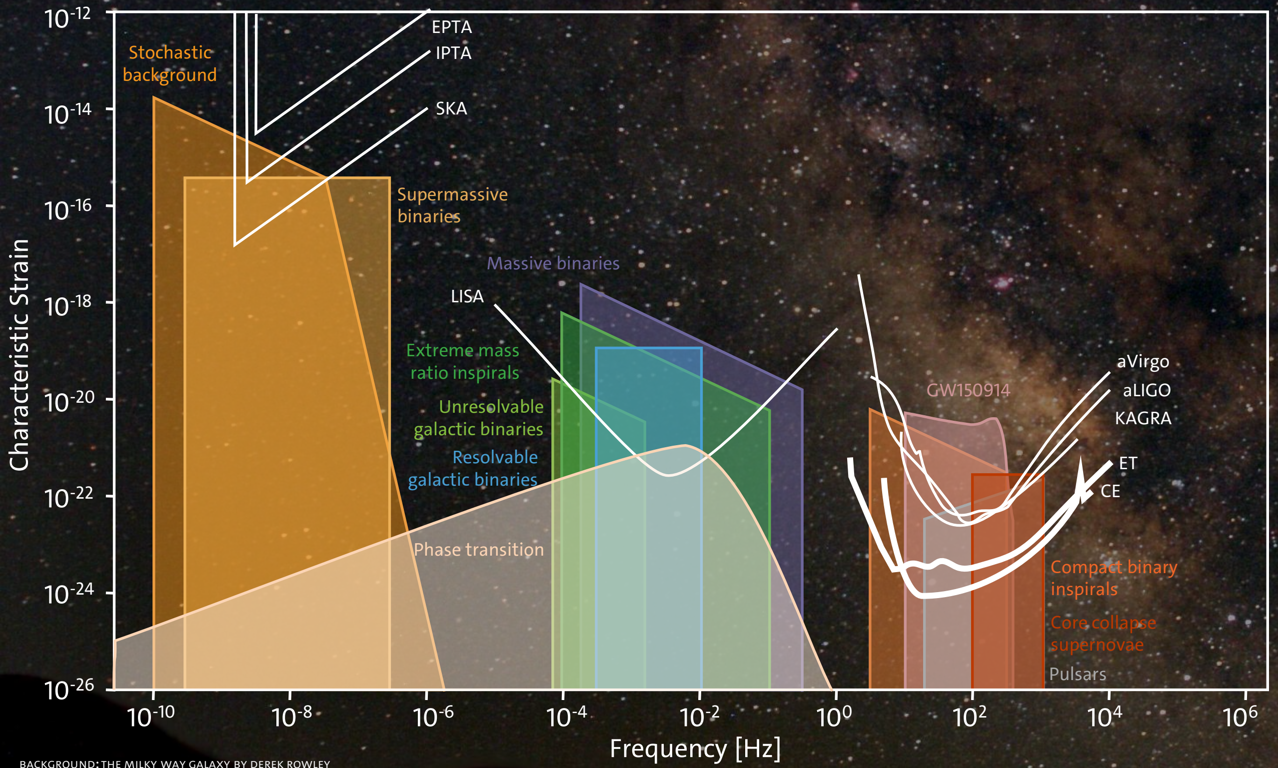
$$\Delta\varphi = \frac{2\pi\Delta L}{\lambda} \approx \Delta L \cdot 10^7$$



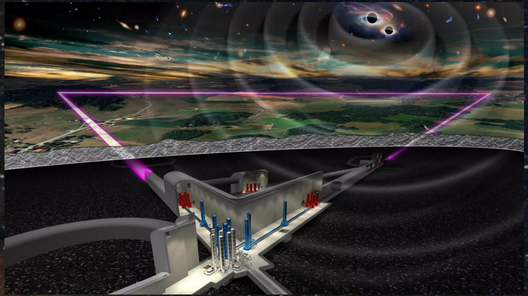


3RD GENERATION

ADAPTED FROM GWPLOTTER.COM BY C. MOORE, R. COLE, AND C. BERRY.



EINSTEIN TELESCOPE

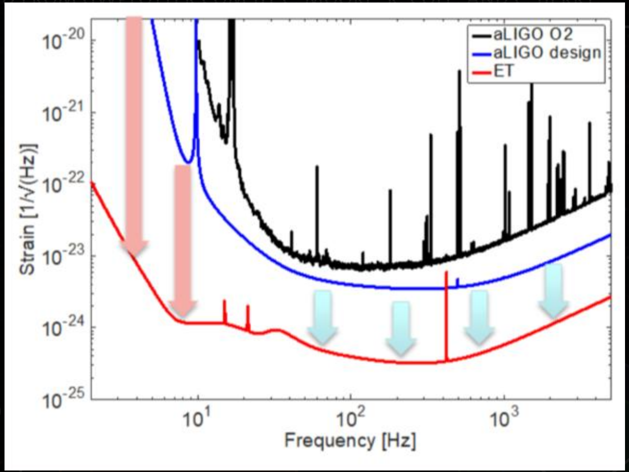


COSMIC EXPLORER

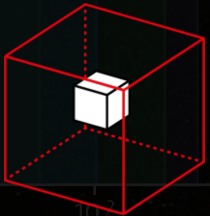
BACKGROUND: THE MILKY WAY GALAXY BY DEREK ROWLEY

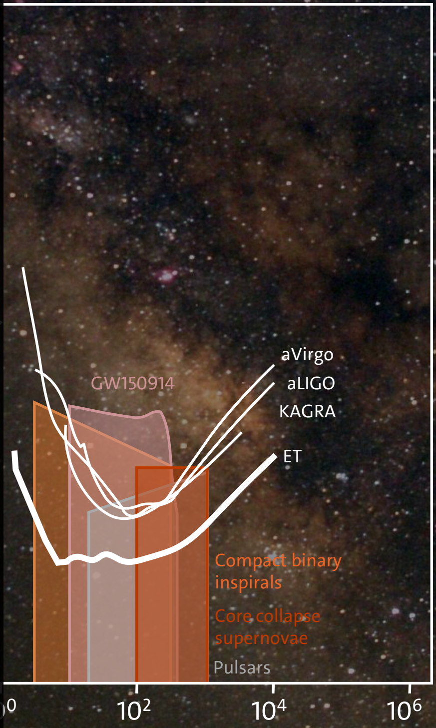
x10 broadband sensitivity increase

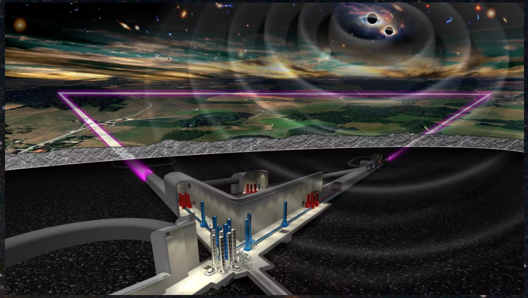
EINSTEIN TELESCOPE

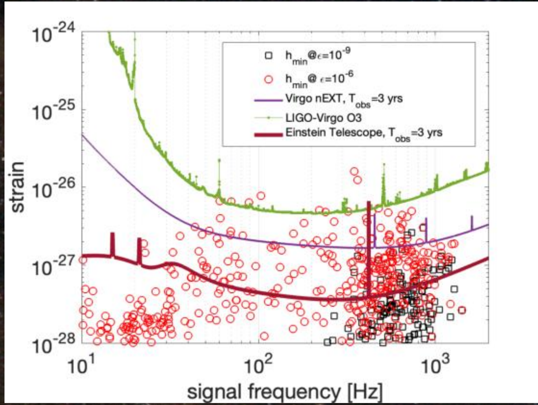


- x1000 more detections
- higher SNR (precision)
- Continuous GWs from known NSs





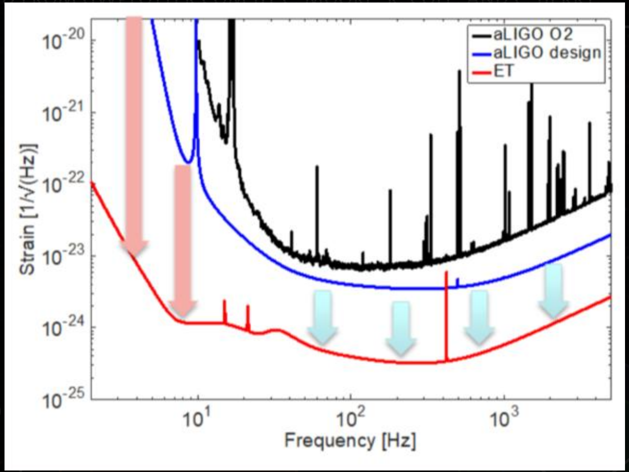




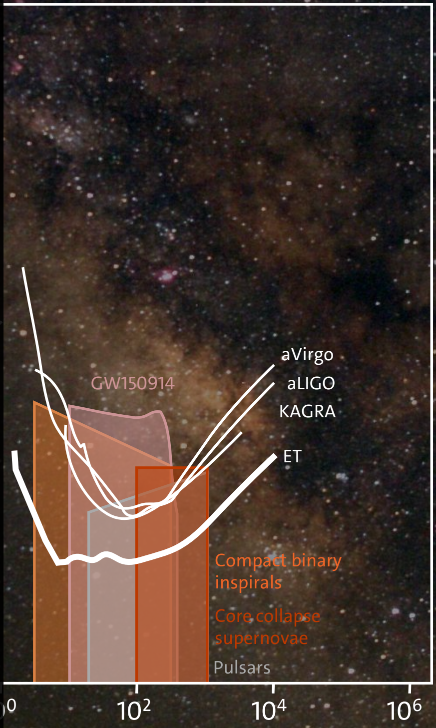
Credit: Palombo; Virgo Post O5 Report: VIR-0497D-2

x10^6 noise reduction below 10 Hz

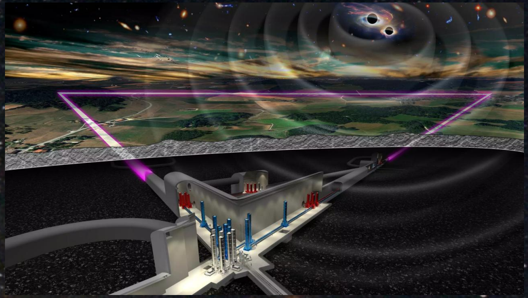
ADAPTED FROM GWPLOTTER.COM BY C. MOORE, R. COLE AND C. BERRY

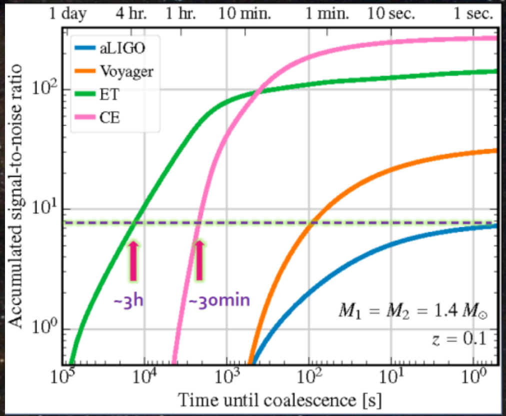


- Higher redshift detections
- Higher mass events
- Early warning for Multi-Messenger Astronomy



EINSTEIN TELESCOPE





Credit: Evan Hall

BACKGROUND: THE MILKY WAY GALAXY BY DEREK ROWLEY

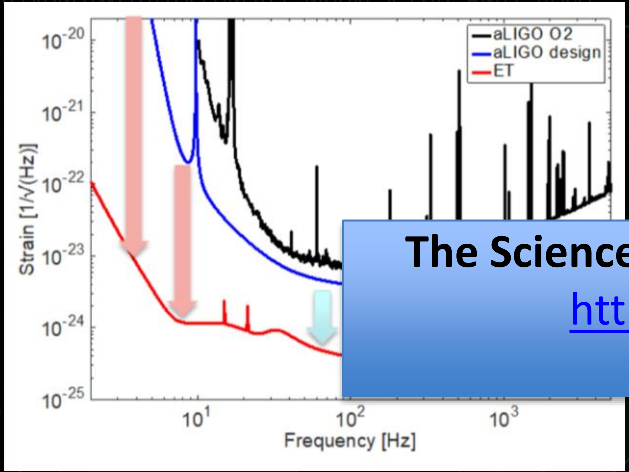
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

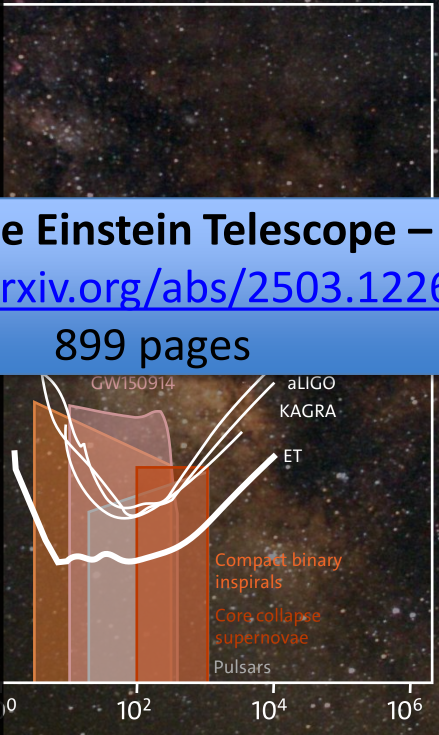
GRAVITATIONAL WAVE DETECTION

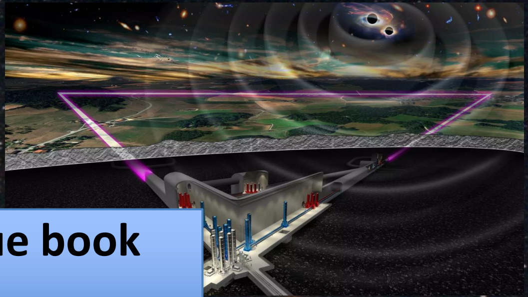
CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

x10^6 noise reduction below 10 Hz

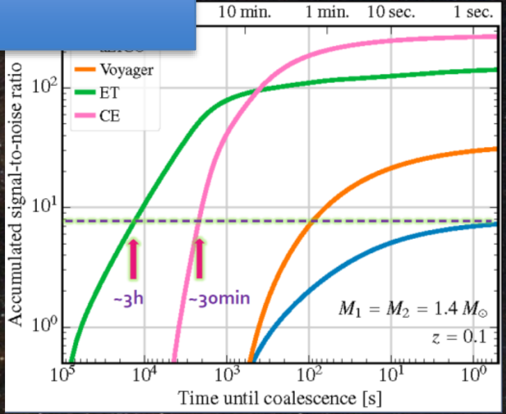
EINSTEIN TELESCOPE







The Science of the Einstein Telescope – Blue book
https://arxiv.org/abs/2503.12263
899 pages



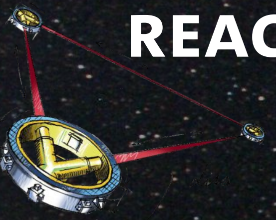
- Higher redshift detections
- Higher mass events
- Early warning for Multi-Messenger Astronomy

Credit: Evan Hall

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

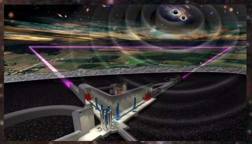
GRAVITATIONAL WAVE DETECTION

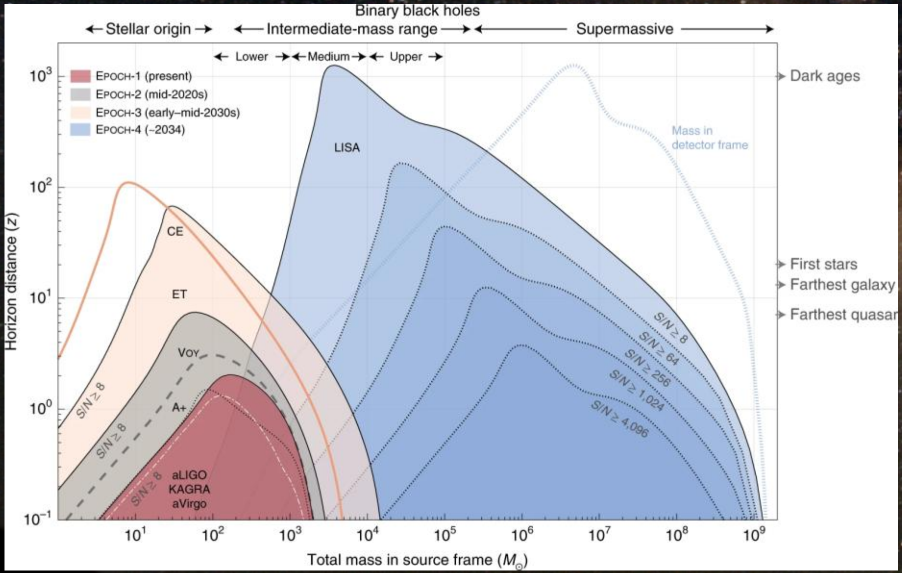
CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

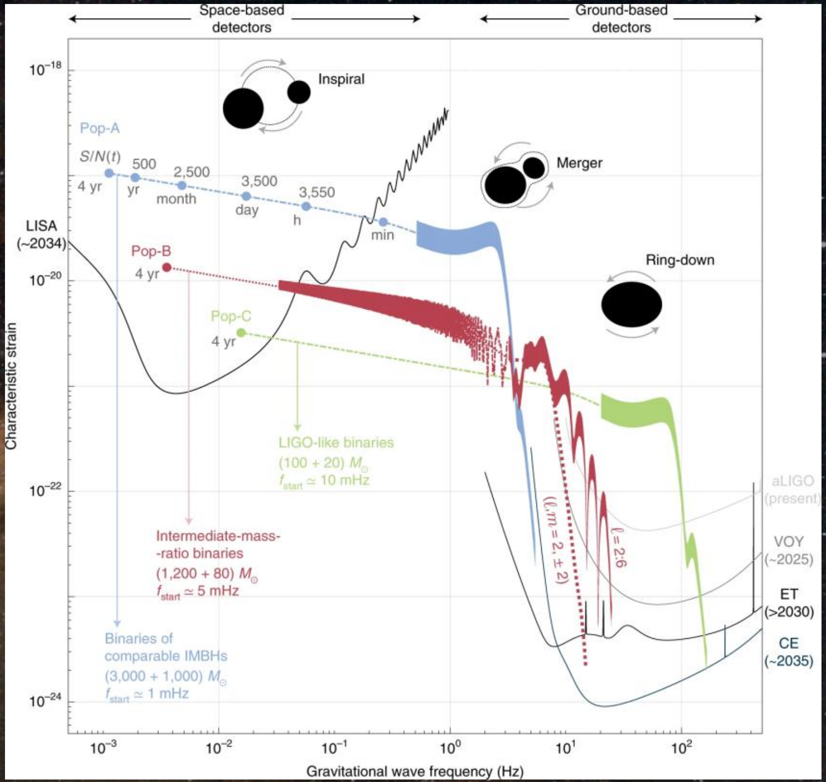


REACH & MULTI-BAND

LISA + ET

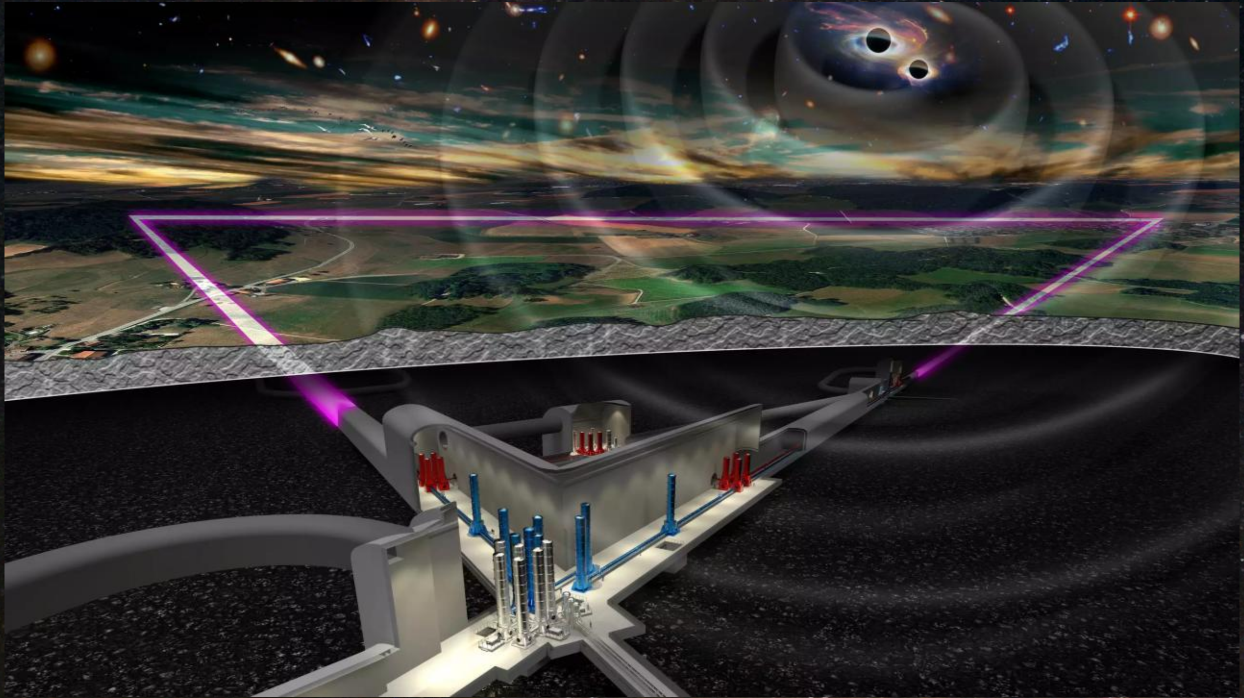




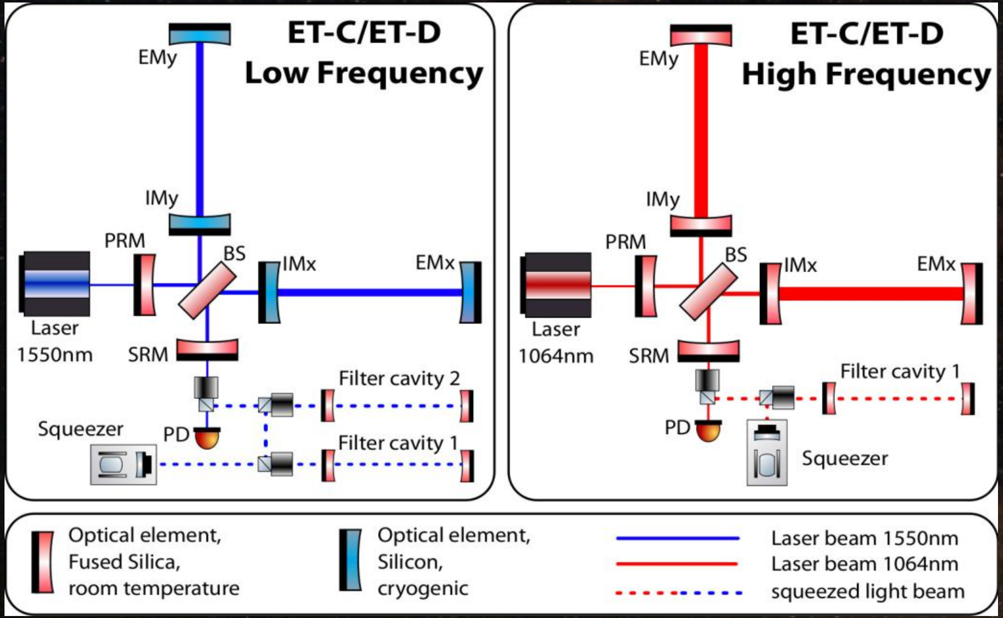


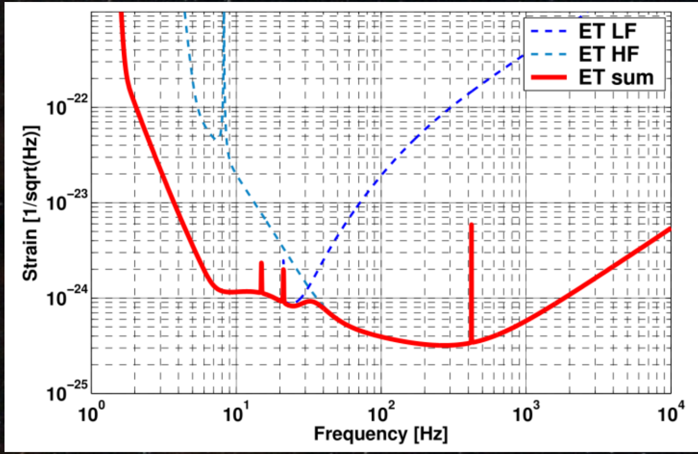
K. Jani et al. Nature Astronomy volume 4, pages 260–265 (2020)

THE EINSTEIN TELESCOPE



THE EINSTEIN TELESCOPE

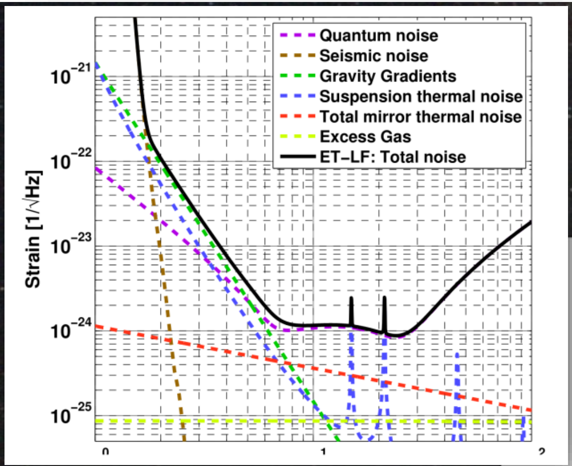


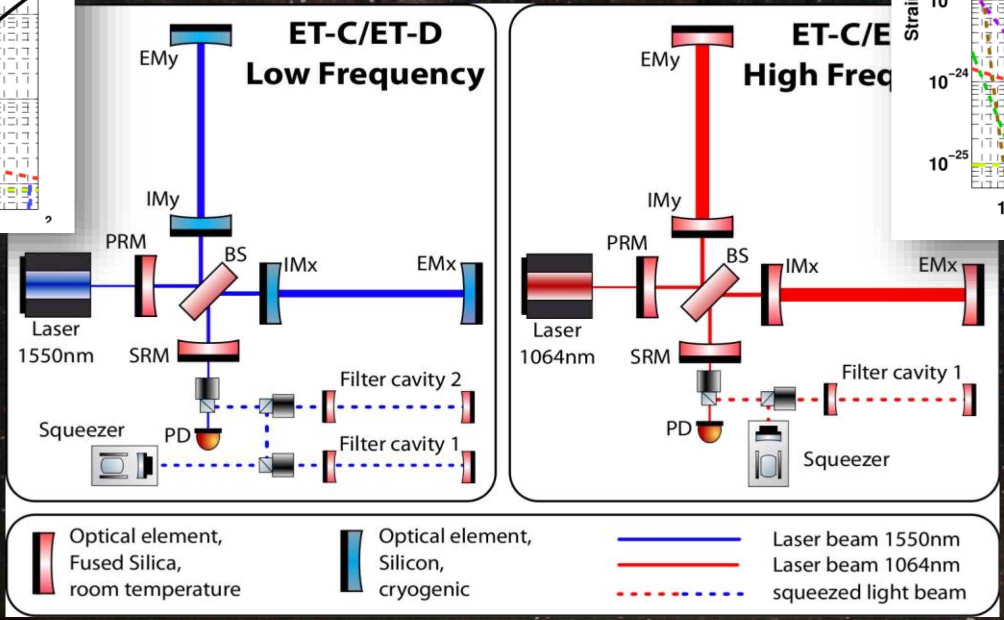


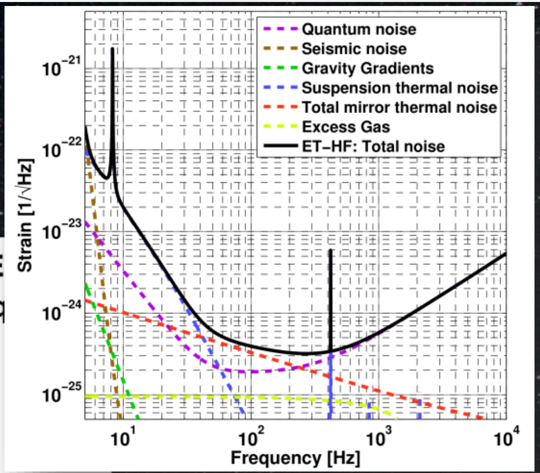
Einstein Telescope Conceptual Design Study 2011 ET-0106C-10

CREDIT: THE MILKY WAY GALAXY BY DEREK ROWLEY

EINSTEIN TELESCOPE SENSITIVITY







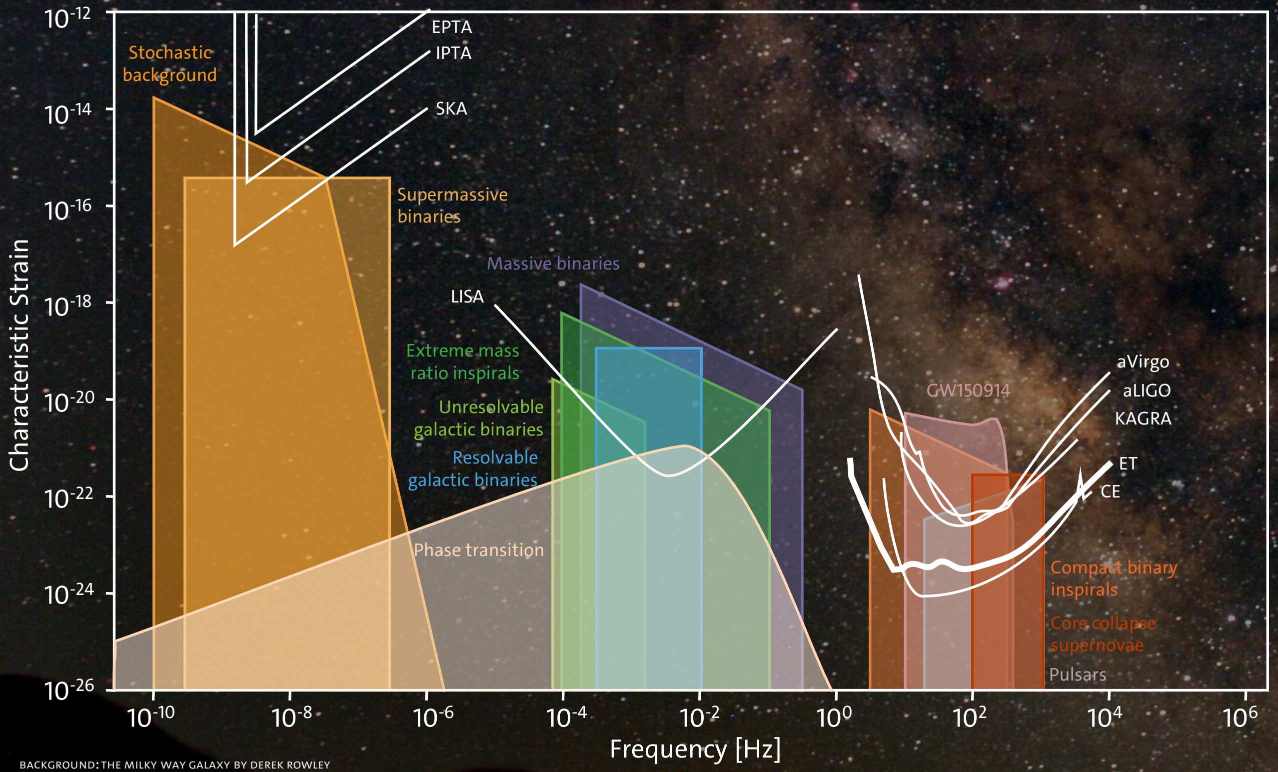
ET LOW FREQUENCY

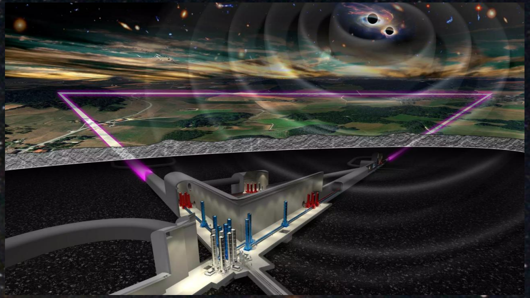
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

GRAVITATIONAL WAVE DETECTION

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

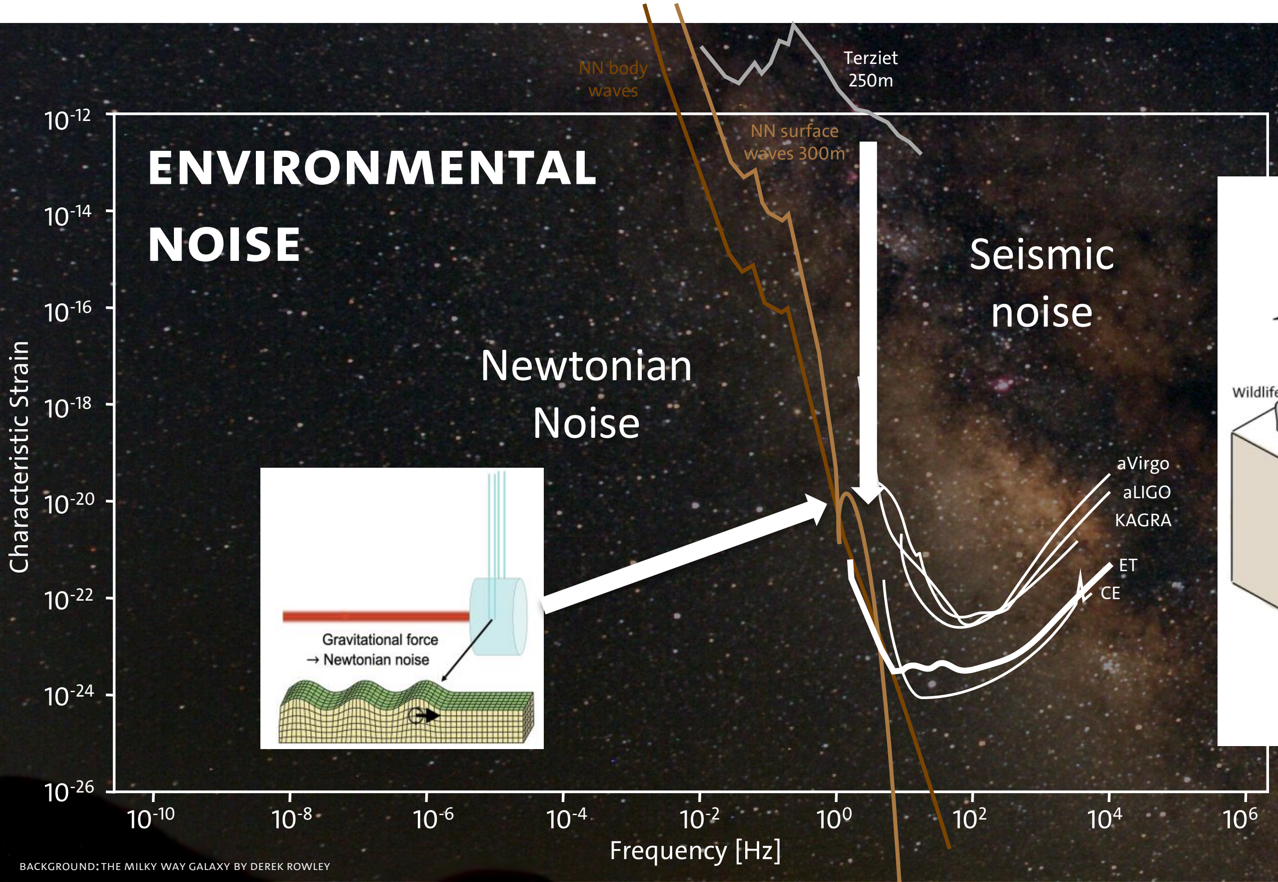
ADAPTED FROM GWPLOTTER.COM BY C. MOORE, R. COLE, AND C. BERRY.

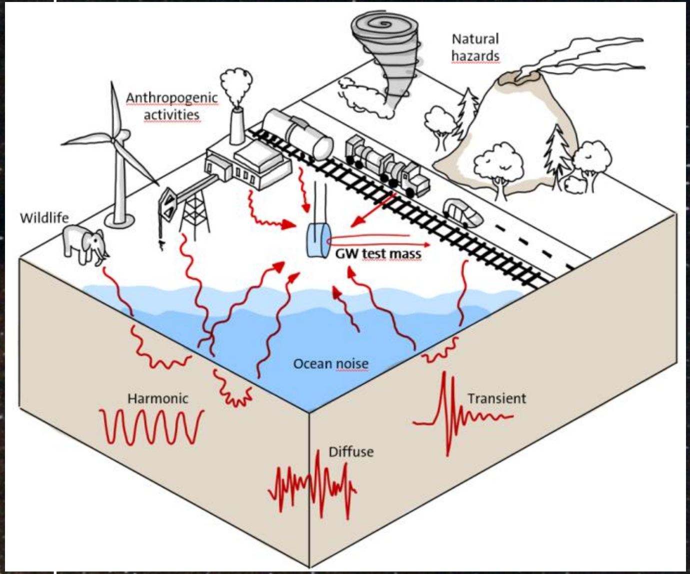




BACKGROUND: THE MILKY WAY GALAXY BY DEREK ROWLEY

ET LOW FREQUENCY



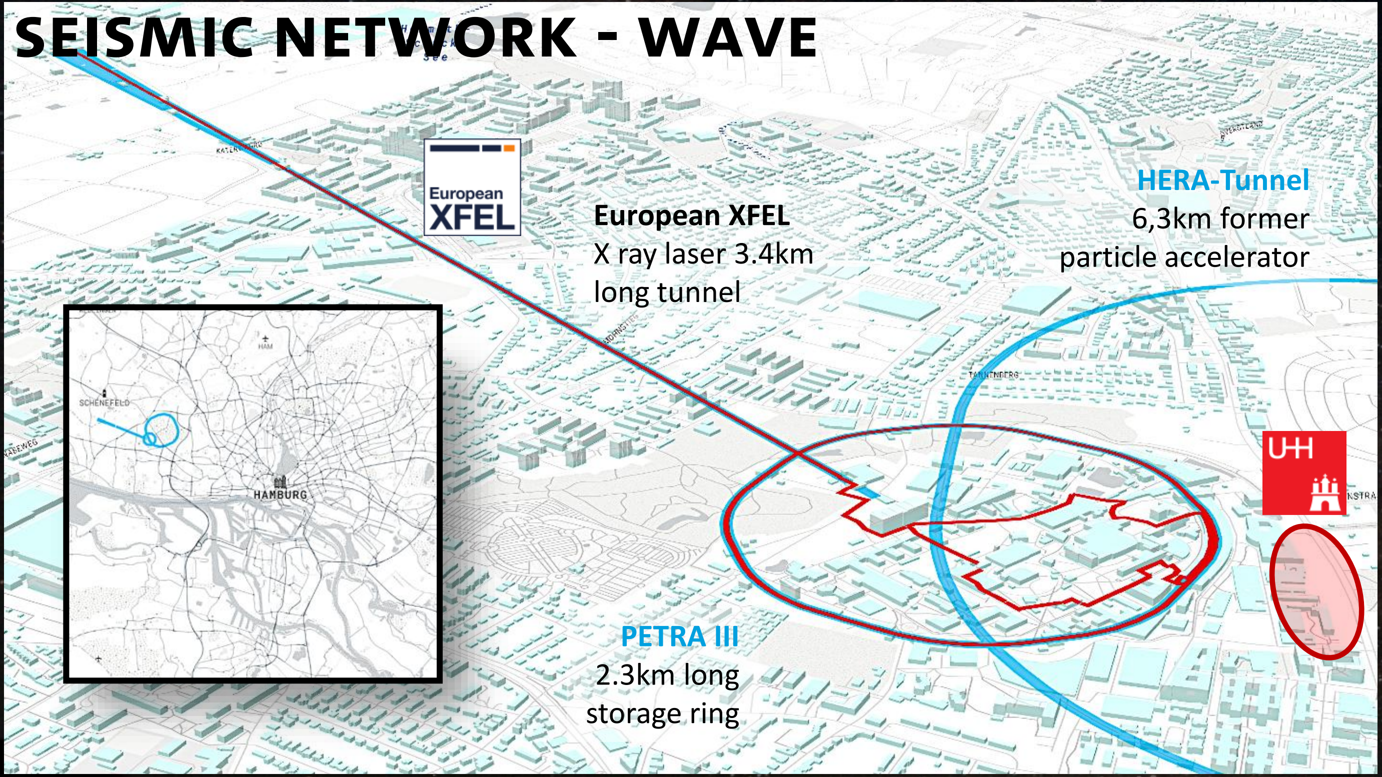


Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

GRAVITATIONAL
WAVE DETECTION

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

SEISMIC NETWORK - WAVE



19 km glass fibre
are turned into
19.000 sensors

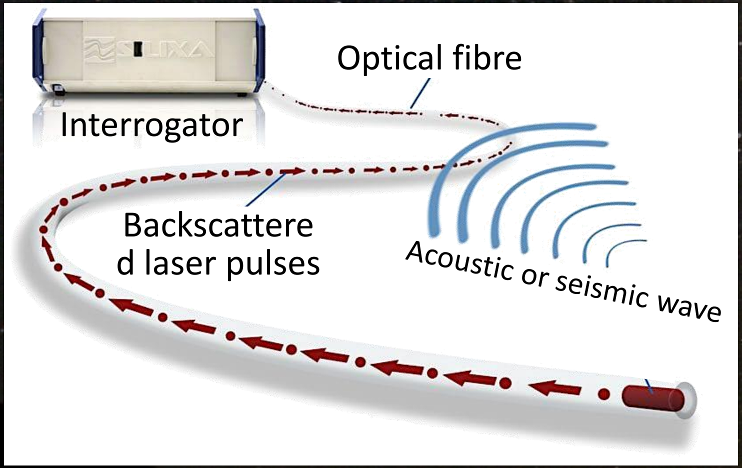
Campus-wide seismic sensor network

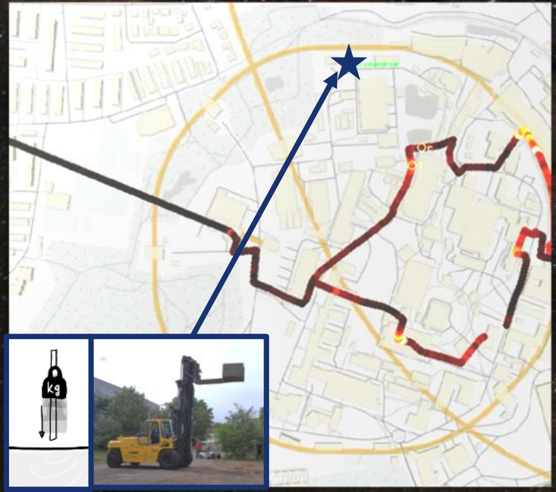
wave-hamburg.eu

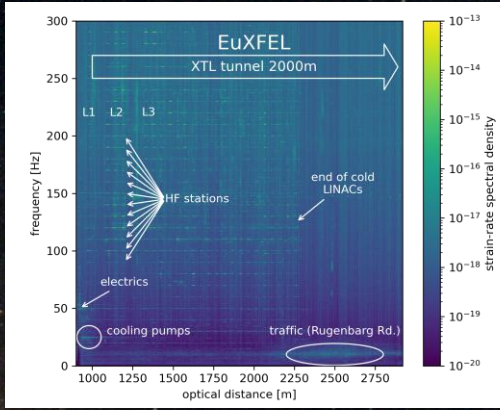
BACKGROUND: THE MILKY WAY GALAXY BY DEREK ROWLEY

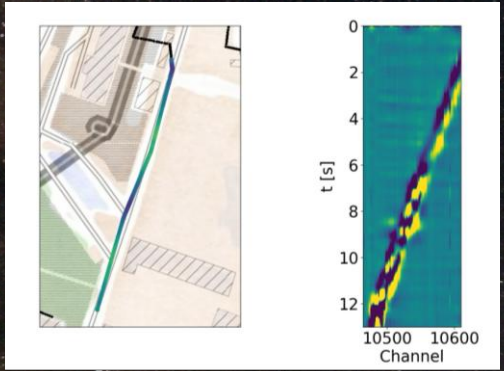
SEISMIC NETWORK - WAVE

- Distributed acoustic sensing (DAS)
- Sensitive to all infrastructure noise
- Sensitive to traffic, events, temperature, airplanes and more









Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

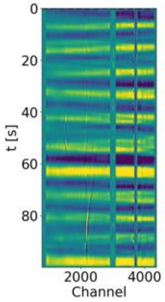
GRAVITATIONAL WAVE DETECTION

CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

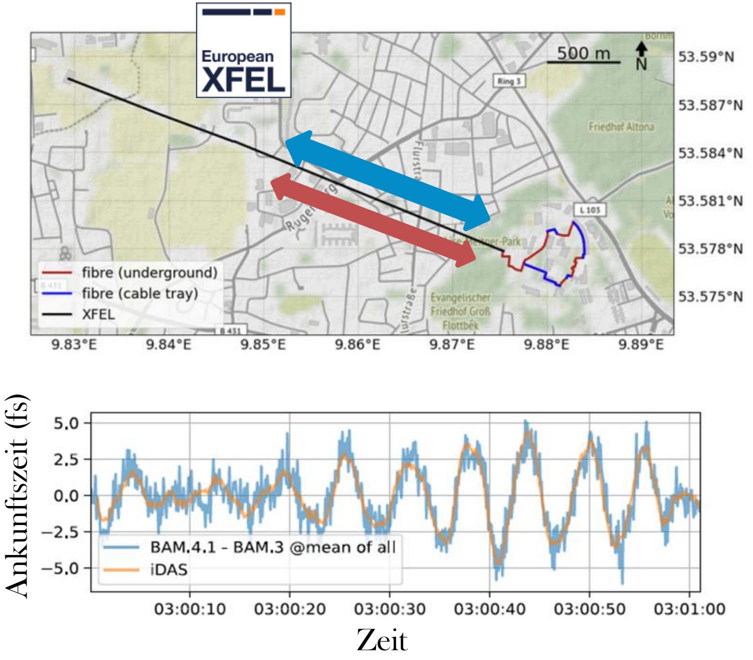
SEISMIC NETWORK - WAVE

- Directional detection of long wavelength signals from e.g. Earthquakes

- Identified ocean microseism as limiting noise in European XFEL timing system
  -> can now correct fs variations using DAS



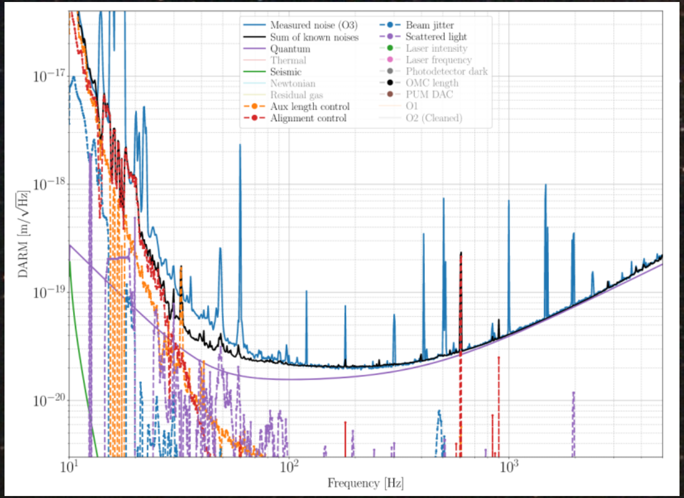
European XFEL: Earthquake from China measured with distributed fiber sensor

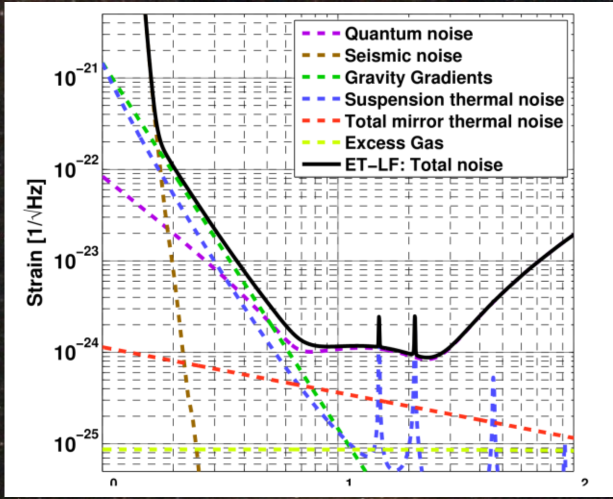


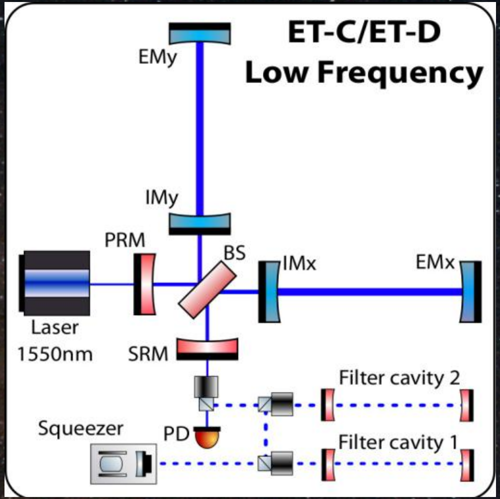
Genthe E. et al., accepted in High power laser science and engineering (2025)

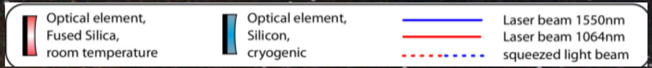
BACKGROUND: THE MILKY WAY GALAXY BY DEREK ROWLEY

GOAL FOR ET-LF: QUANTUM-THERMAL NOISE LIMIT



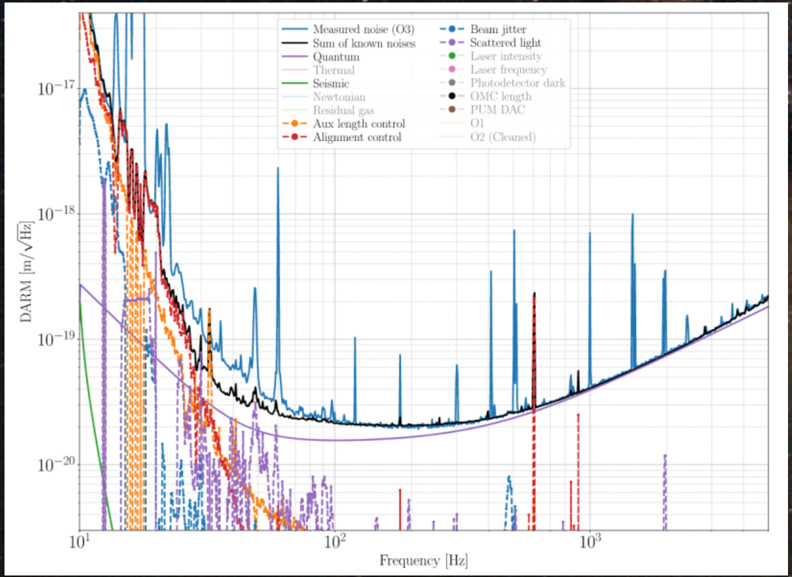






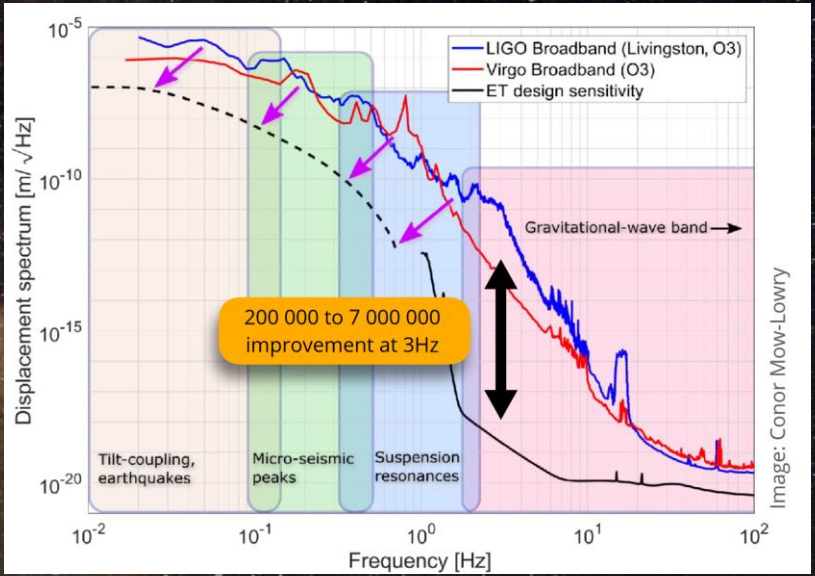
Fundamental technical noise

INTRINSIC LOW-FREQUENCY INSTRUMENT NOISE



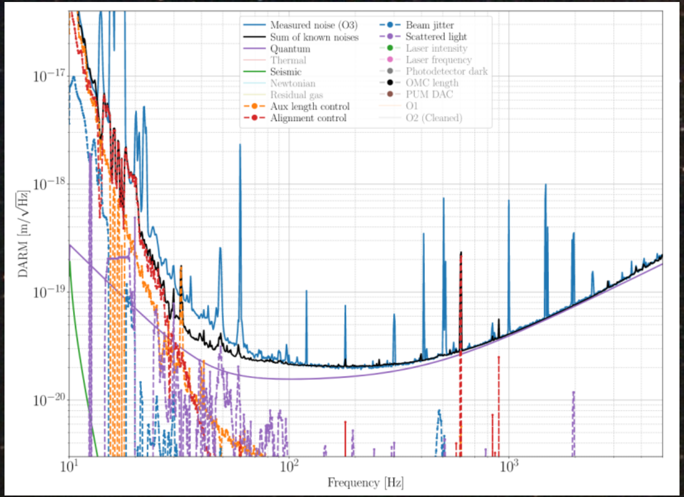
LIGO O3 noise budget

https://ccahilla.github.io/lho_noisebudget.svg

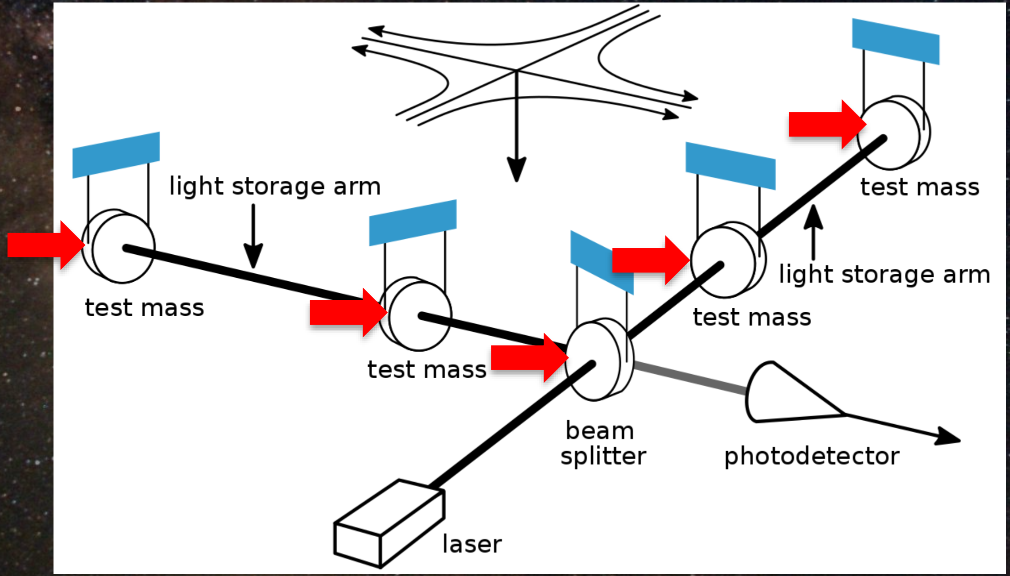


Einstein Telescope

INSTRUMENT SCIENCE CHALLENGE: CONTROL NOISE



Fundamental technical noise



Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

GRAVITATIONAL WAVE DETECTION

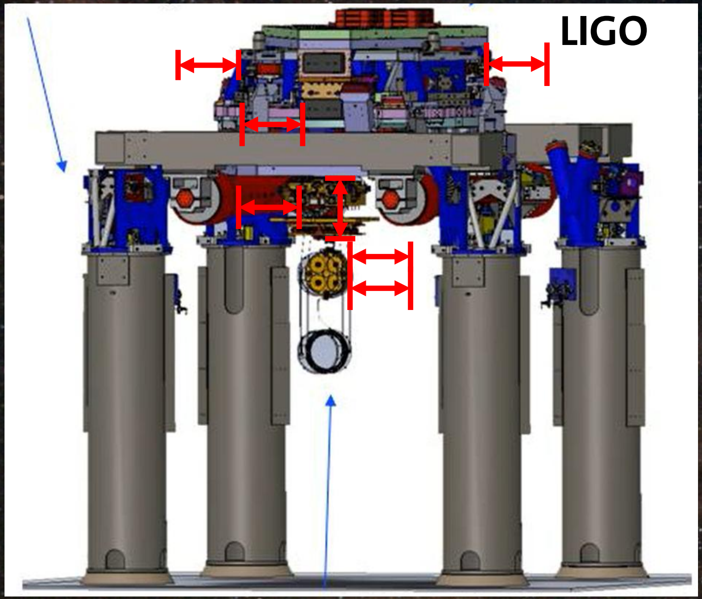
CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

SEISMIC ISOLATION

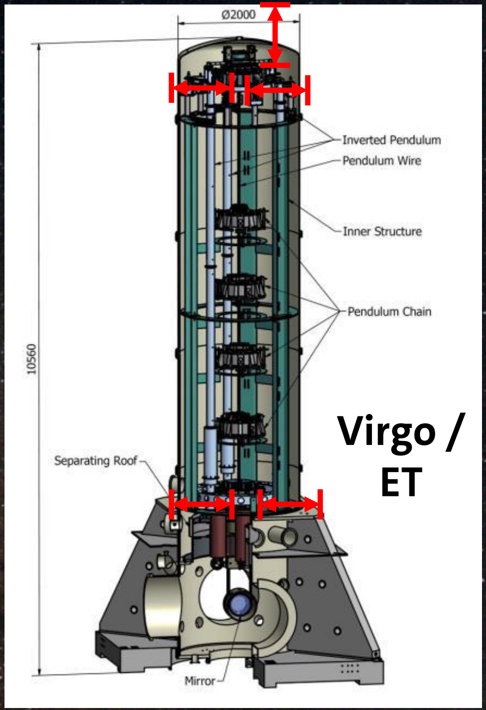
- Active & passive isolation
- Various control loops to
  - Supress seismic noise
  - Damp resonances
  - Align the mirrors
  - Position the mirrors
- Limited by local displacement and position sensor noise

Goal: <10fm/rtHz

Active platform



Passive suspension chain



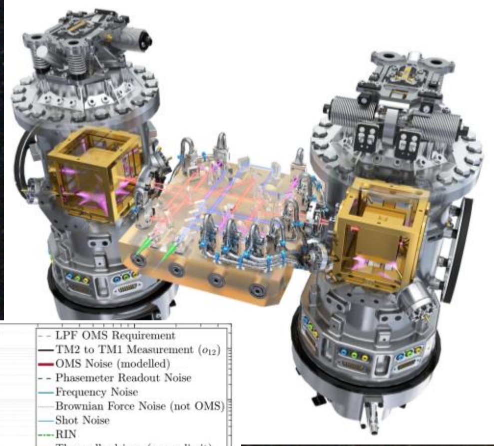
COMPACT INTERFEROMETRIC SENSORS

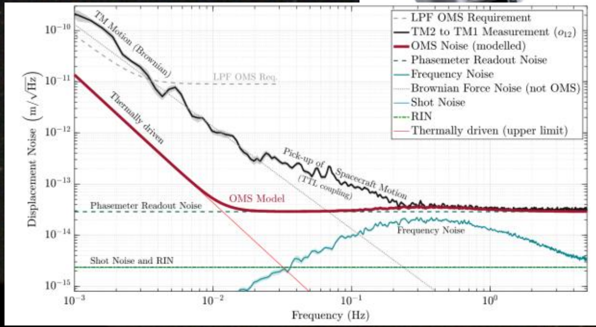
LIGO

LISA PATHFINDER

Test mass readout

30fm/rtHz
displacement noise





10X SIZE REDUCTION

10X MORE SENSORS

Armano, M., et al. PRL 126.13 (2021): 131103.

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

GRAVITATIONAL WAVE DETECTION

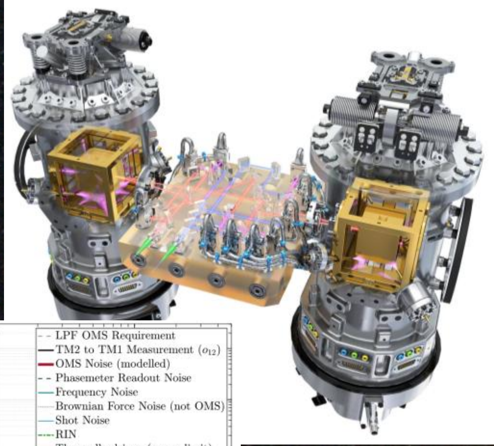
CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

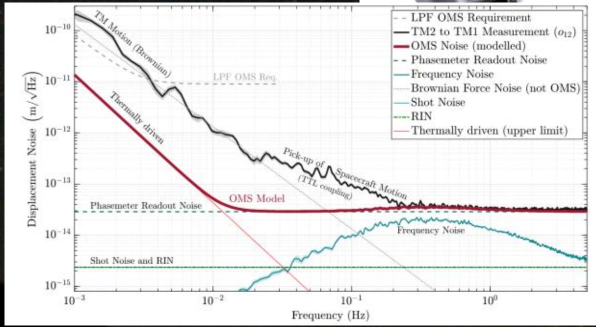
COMPACT INTERFEROMETRIC SENSORS

LIGO

LISA PATHFINDER
Test mass readout

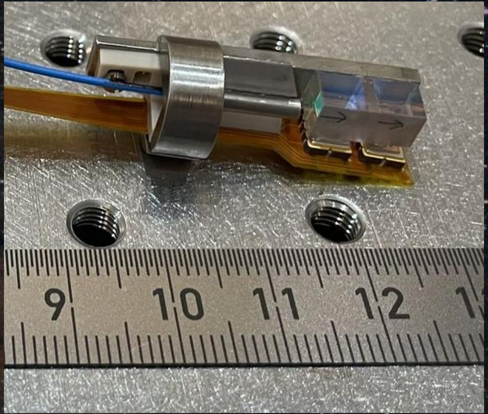
30fm/rtHz
displacement noise





Armano, M., et al. PRL 126.13 (2021): 131103.

10X SIZE REDUCTION
10X MORE SENSORS



COBRI
- 10fm/rtHz displacement noise
- absolute ranging

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

GRAVITATIONAL WAVE DETECTION

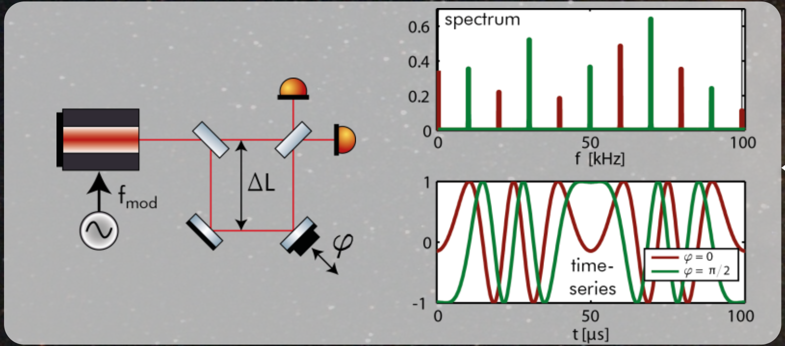
CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

COMPLEXITY FROM OPTICS TO DIGITAL

G. Heinzel et al., Optics Express, 18, 19, (2010)
O. Gerberding, Optics Express, 23, 11, (2015)
K.-S. Isleif et al., Optics Express, 24, 2, (2016)
K.-S. Isleif et al., PRApplied 12, 034025 (2019)
Gerberding O. et al., Sensors 21.5 (2021)
Smetana J. et al., PRApplied 18.3 (2022)
Eckhardt T. et al., Metrology 2.1 (2022)
Eckhardt T. et al., Scientific Reports 14.1 (2024)

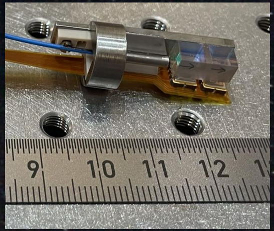
Deep frequency modulation interferometery DFMI

LIGO



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

Realtime laser control & stabilisation



COBRI

FPGA & CPU processing

Estimate parameters from non-linear function in real time

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

GRAVITATIONAL WAVE DETECTION

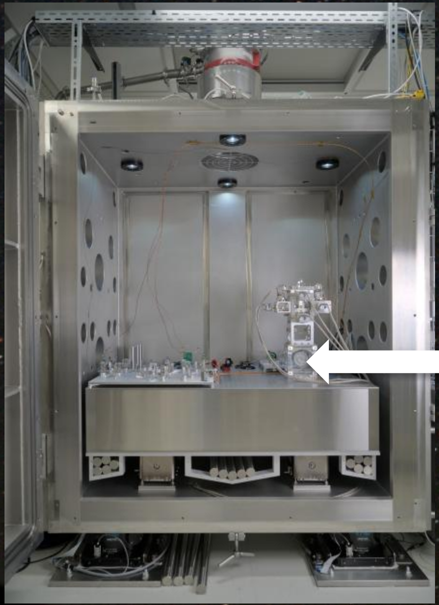
CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

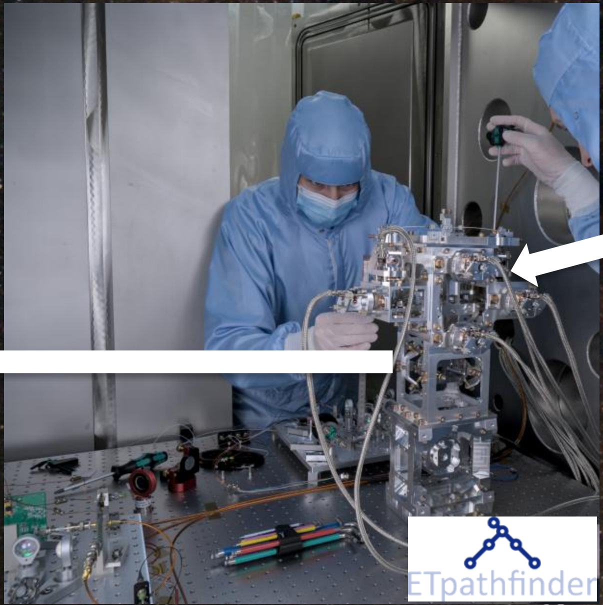
TEST IN RELEVANT ENVIRONMENT

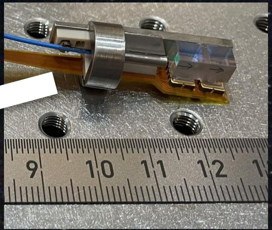
G. Heinzel et al., Optics Express, 18, 19, (2010)
O. Gerberding, Optics Express, 23, 11, (2015)
K.-S. Isleif et al., Optics Express, 24, 2, (2016)
K.-S. Isleif et al., PRApplied 12, 034025 (2019)
Gerberding O. et al., Sensors 21.5 (2021)
Smetana J. et al., PRApplied 18.3 (2022)
Eckhardt T. et al., Metrology 2.1 (2022)
Eckhardt T. et al., Scientific Reports 14.1 (2024)

Inertial testbed

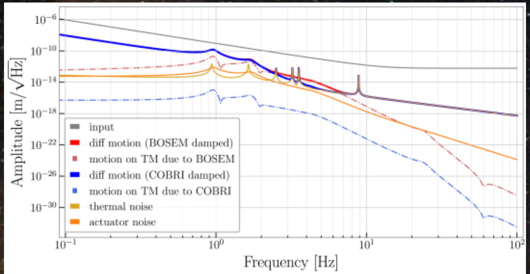
LIGO







COBRI



L. Weickhardt et al. In preparation

HAM Relay Triple Suspensions

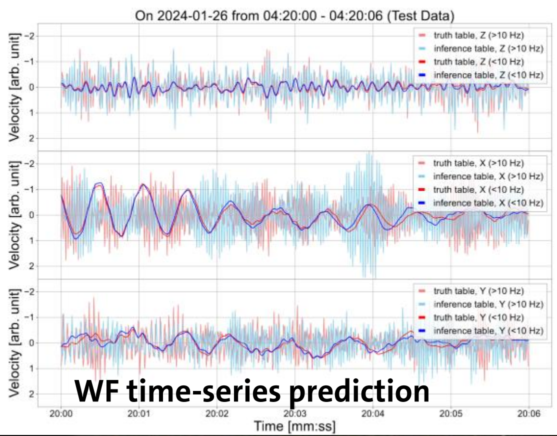
Demonstrate performance

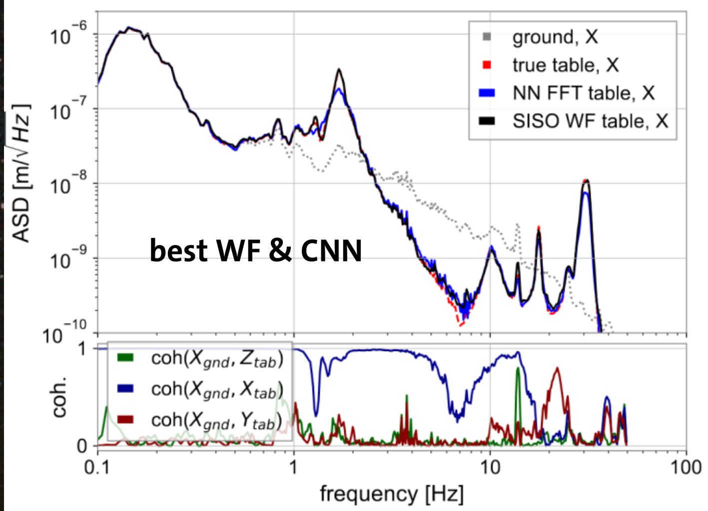
BACKGROUND: THE MILKY WAY GALAXY BY DEREK ROWLEY

MACHINE LEARNING FOR PREDICTION & CONTROL

Predict the table motion (3 DOF) with seismometer on ground

Can convolutional neural networks outperform (optimal) Wiener Filters for such a mostly linear, mechanical system??



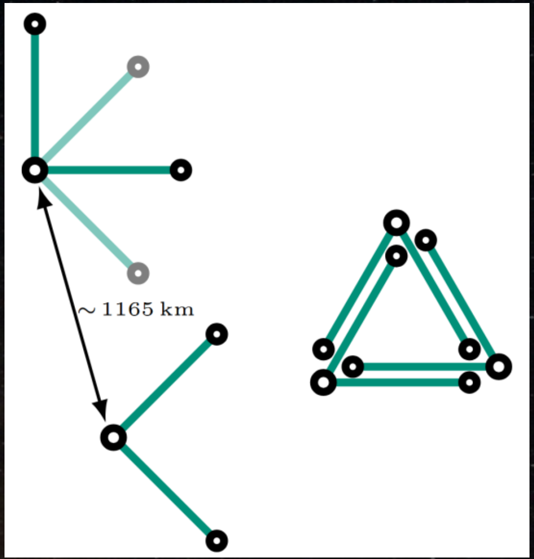


Basalaev A. et al, PRApplied (2025)

EINSTEIN TELESCOPE SITES AND CONFIGURATIONS

- There are now three candidate sites for the Einstein Telescope: Sardinia (Italy), Euregio-Meuse-Rhine (EMR) region (Netherlands, Belgium, Germany) and Lusatia (Germany)
- Two major configurations are being studied:
  - Triangle/Δ: 3 co-located detectors (6 interferometers)
  - 2L: 2 detectors on separated sites (4 interferometers)
- The configurations have various implications with regards to cost, risk, noise, science output and politics

By Tjonnie Li, https://indico.nikhef.nl/event/6639/attachments/9753/14692/TjonnieLi.pdf



The current goal is to come to a decision on the sites and the configurations around early 2027. Ongoing site studies are planned to conclude by the end of 2026.

1st detector operation is currently scheduled around the end of 2030s, assuming approval is happening shortly after site decision.

BACKGROUND: THE MILKY WAY GALAXY BY DEREK ROWLEY

EINSTEIN TELESCOPE IN GERMANY

- The current German government has shown great interest in the Einstein Telescope
- A preparatory phase for the Einstein Telescope was selected for the FIS Prioritisation of the federal government
- We are currently preparing for this funding
- Germany has a very active community and can play a leading role in the project going forward
(independent of the chosen configuration)

EINSTEIN TELESCOPE

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

GRAVITATIONAL WAVE DETECTION

CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

CREDIT:

- **GWD GROUP**
  + ALUMNI
- **COLLABORATORS**
- **FUNDING AGENCIES**

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

DFG Deutsche Forschungsgemeinschaft

Gefördert vom Bundesministerium für Bildung und Forschung

DLR

Gefördert durch: Bundesministerium für Wirtschaft und Energie aufgrund eines Beschlusses des Deutschen Bundestages

LISA CONSORTIUM

EINSTEIN TELESCOPE

LSC LIGO Scientific Collaboration

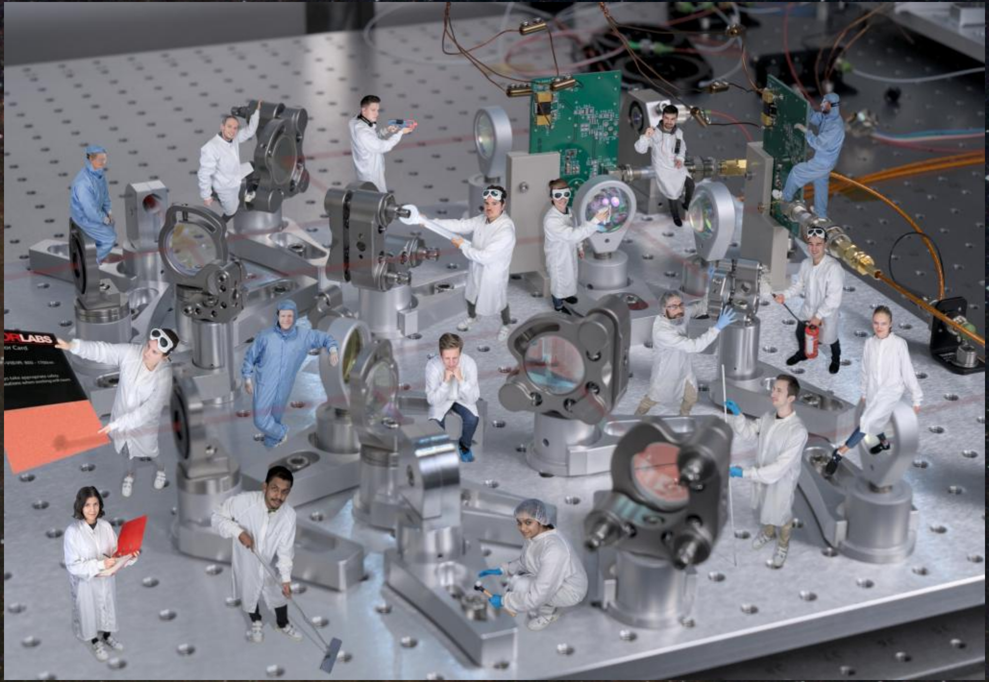
WAVE The Seismic Network

LGWA LUNAR GRAVITATIONAL WAVE ANTENNA

CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

DESY.

HELMUT SCHMIDT UNIVERSITÄT Universität der Bundeswehr Hamburg



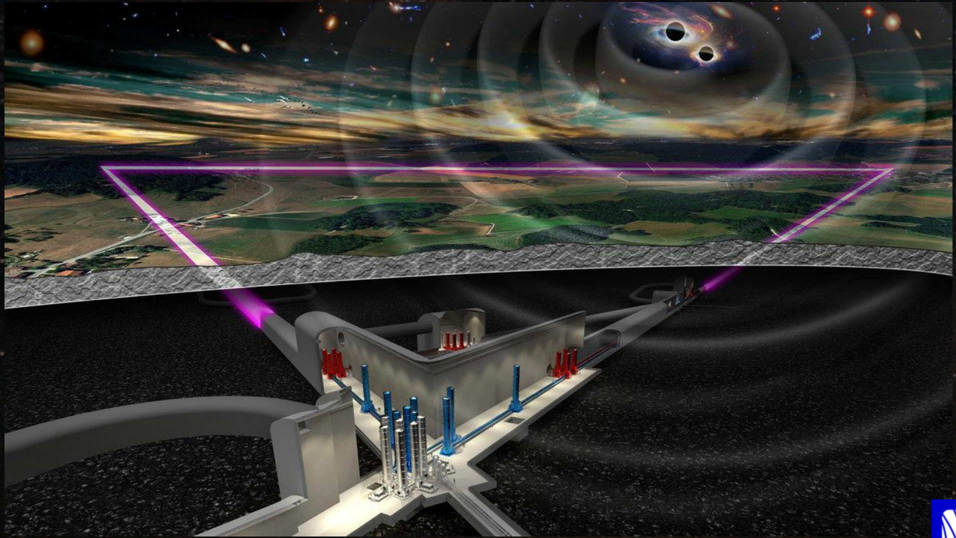
BACKGROUND: THE MILKY WAY GALAXY BY DEREK ROWLEY

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

GRAVITATIONAL
WAVE DETECTION

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

Thank you for your attention!



EINSTEIN
TELESCOPE

BACKGROUND: THE MILKY WAY GALAXY BY DEREK ROWLEY