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Gravitational waves, how to detect these silent messengers from our universe.

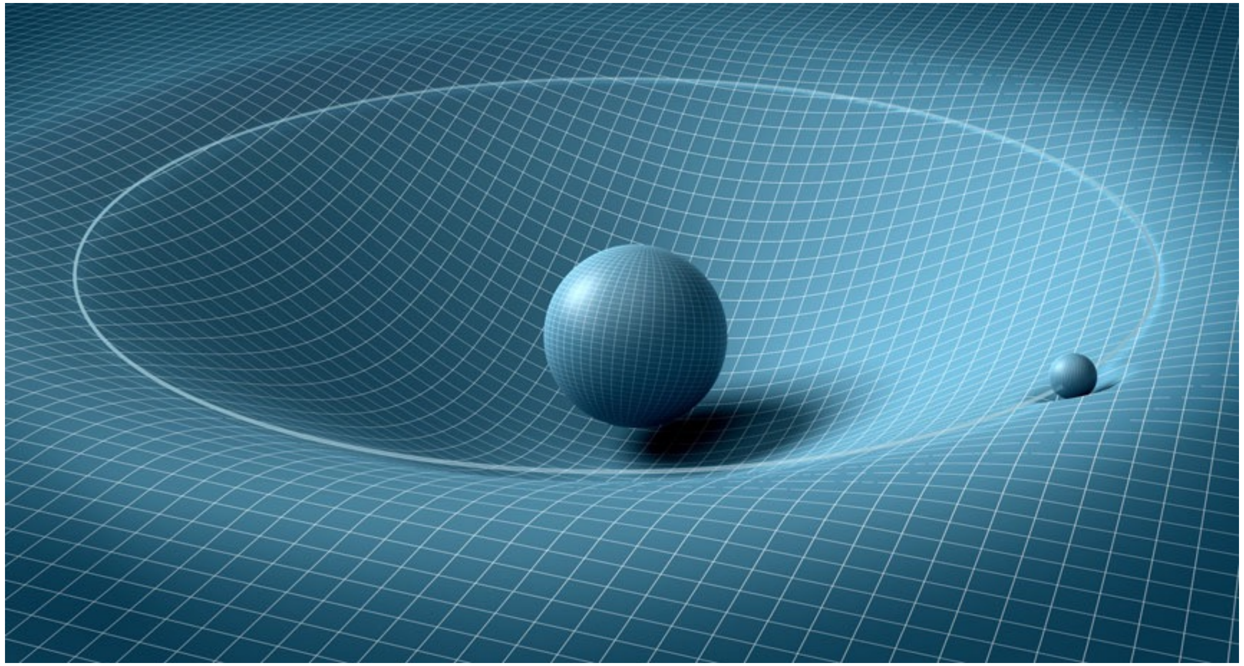
Hans Van Haevermaet

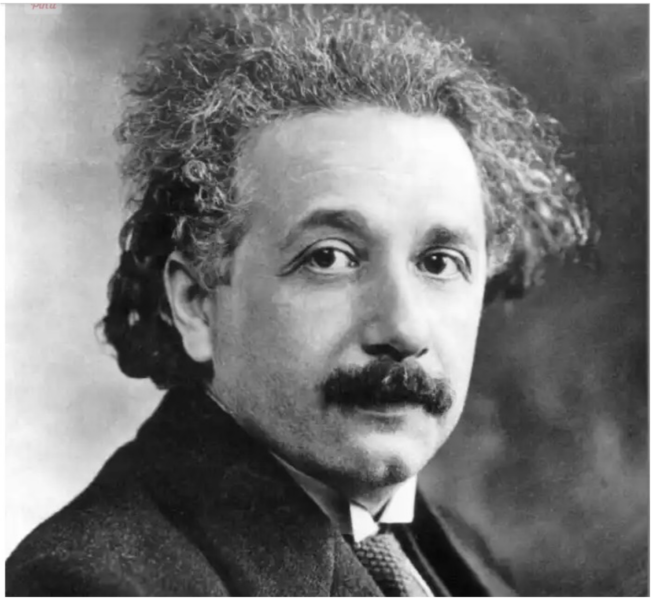
Particle Physics research group, Department of Physics

Advanced Engineering – 7/5/2026

Gravitational waves

The theory of General Relativity (1915) describes gravity





Gravity is not a force,
but a manifestation of **spacetime curvature!**

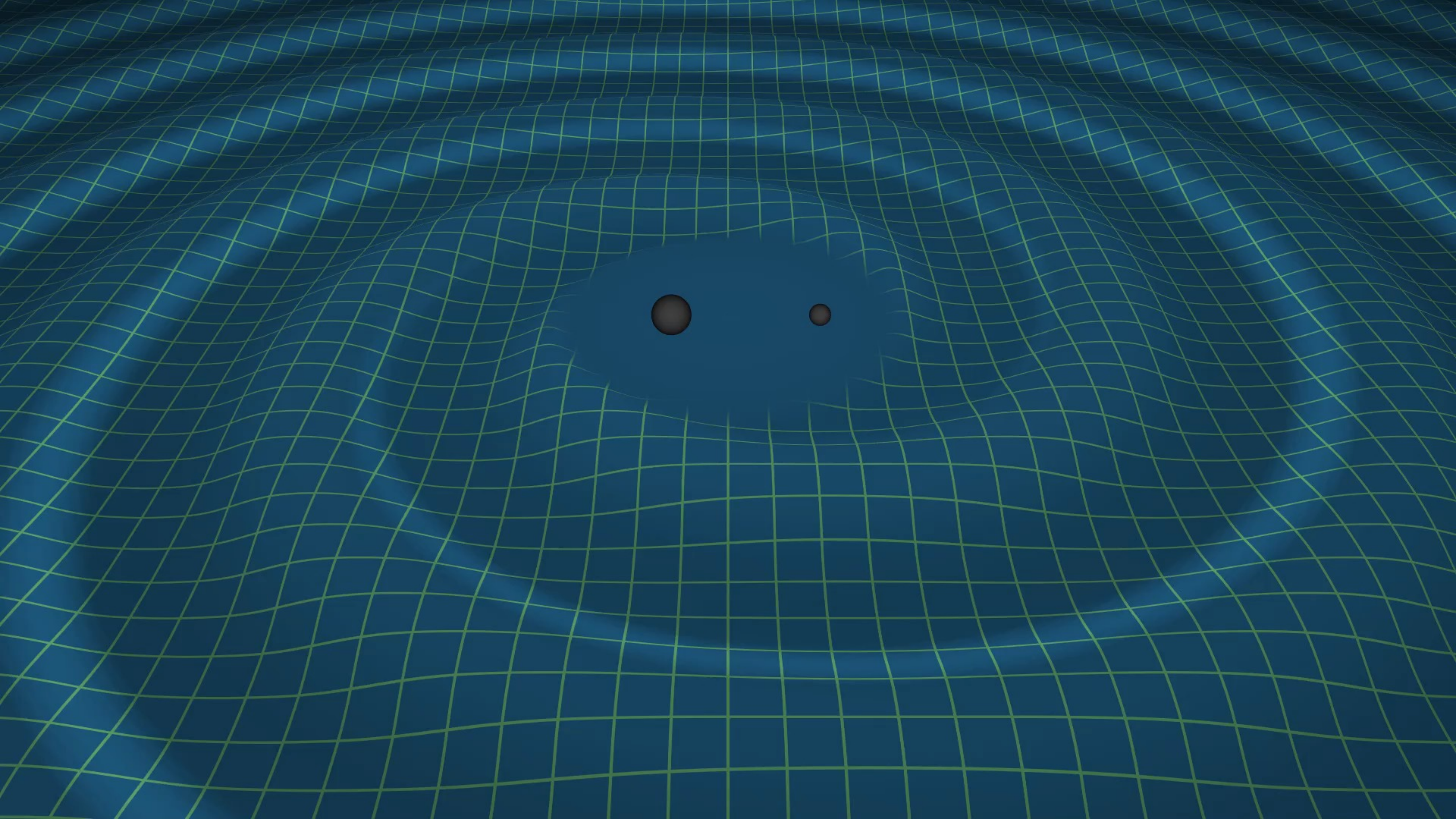
Einstein's field equations

$$G_{\mu\nu} \equiv R_{\mu\nu} - \frac{1}{2} R \, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Describes curvature

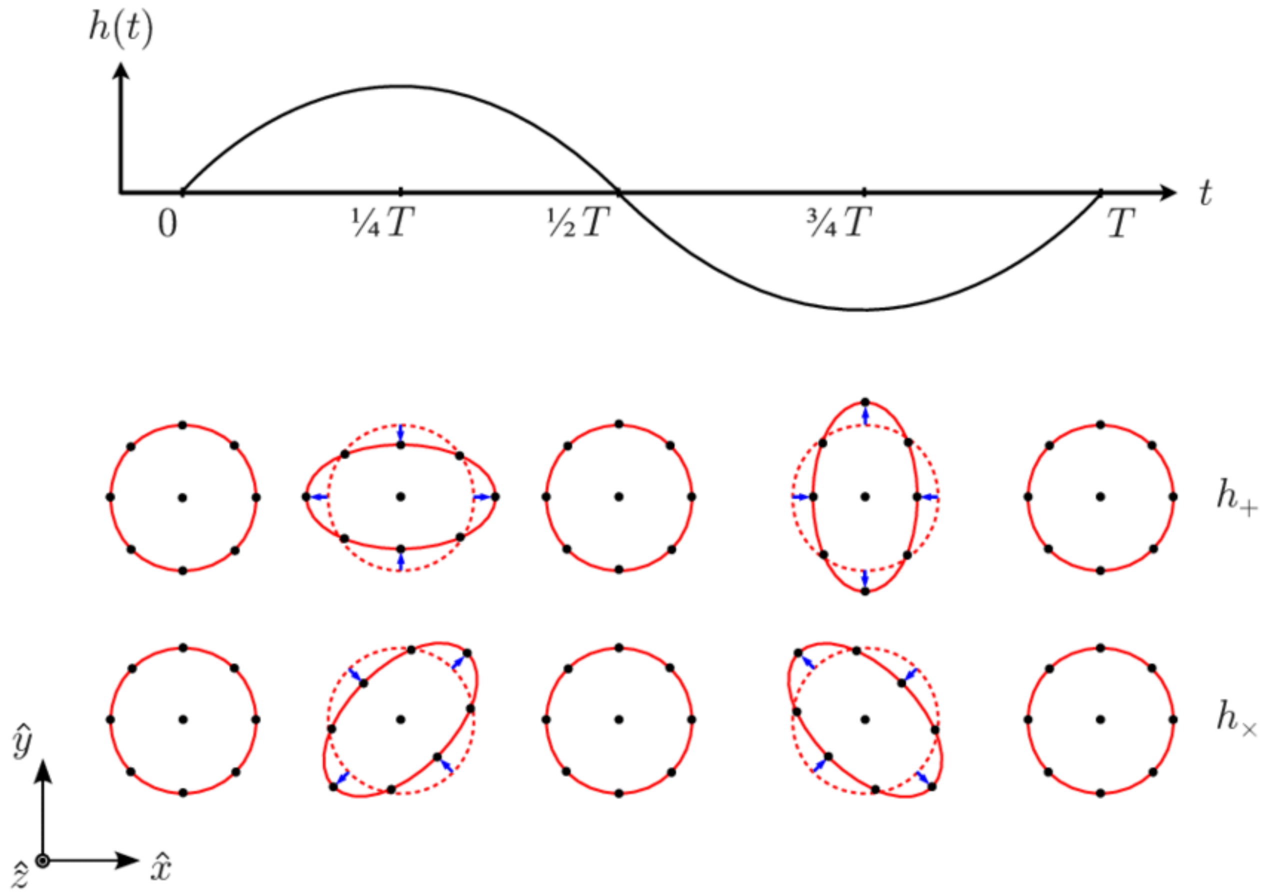
Describes spacetime

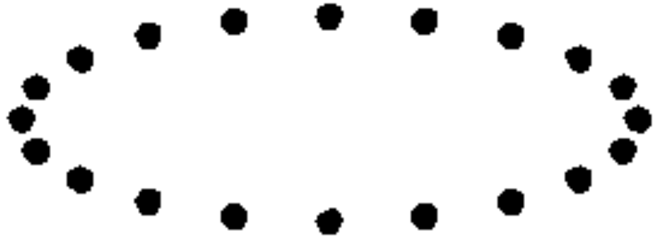
Describes energy/momentum



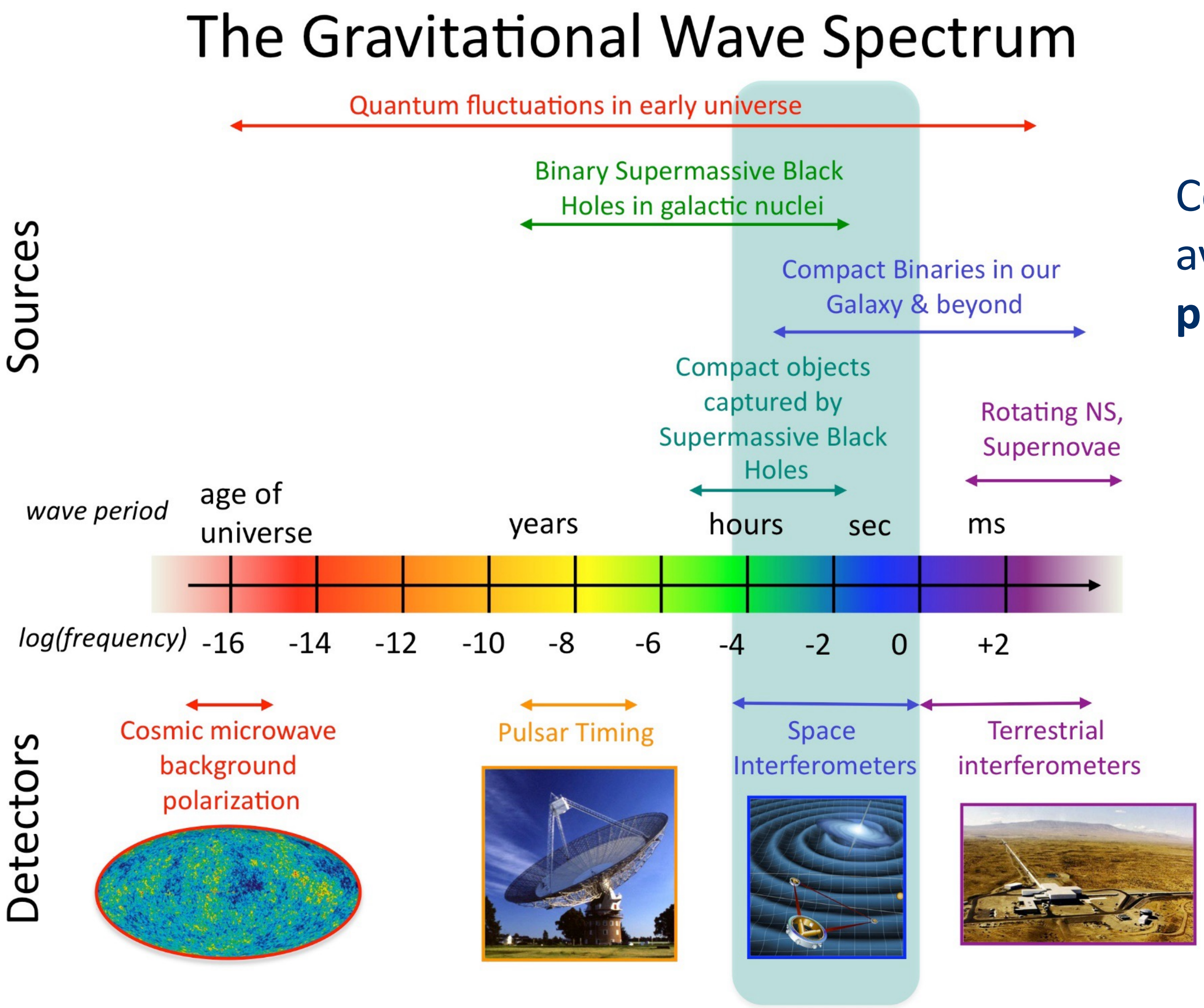
Gravitational waves

Ripples of spacetime curvature propagating at the speed of light

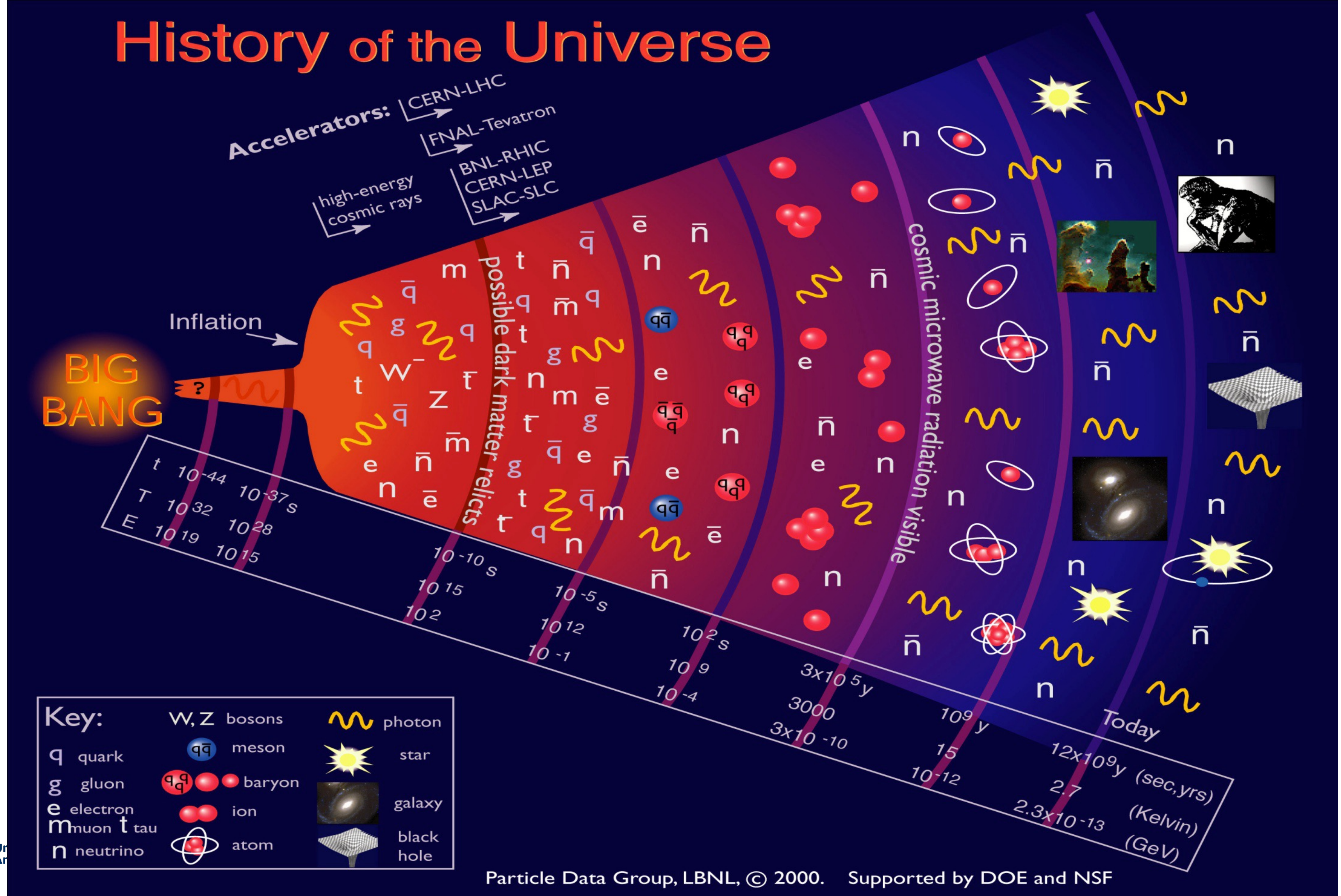




New window to observe the universe

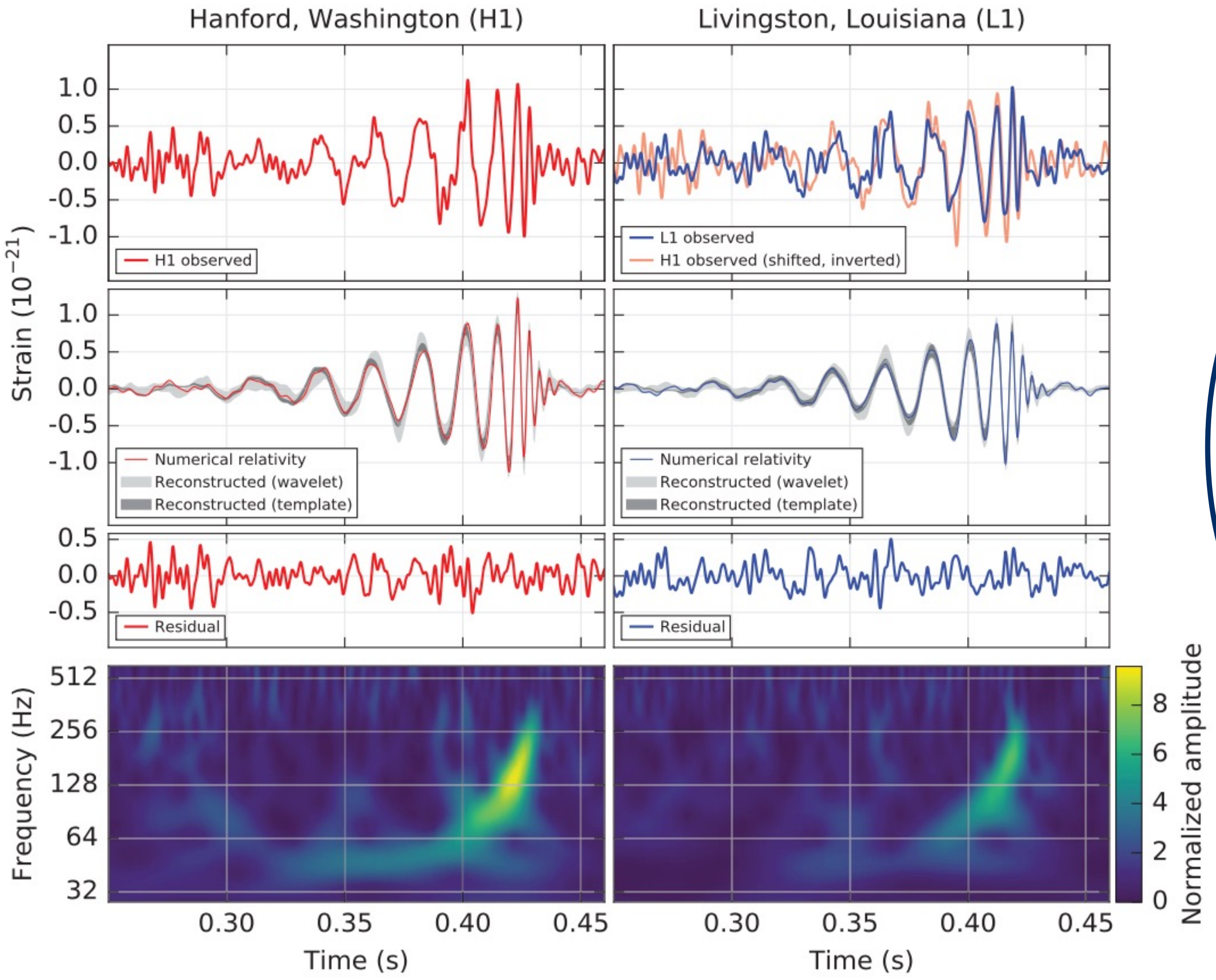


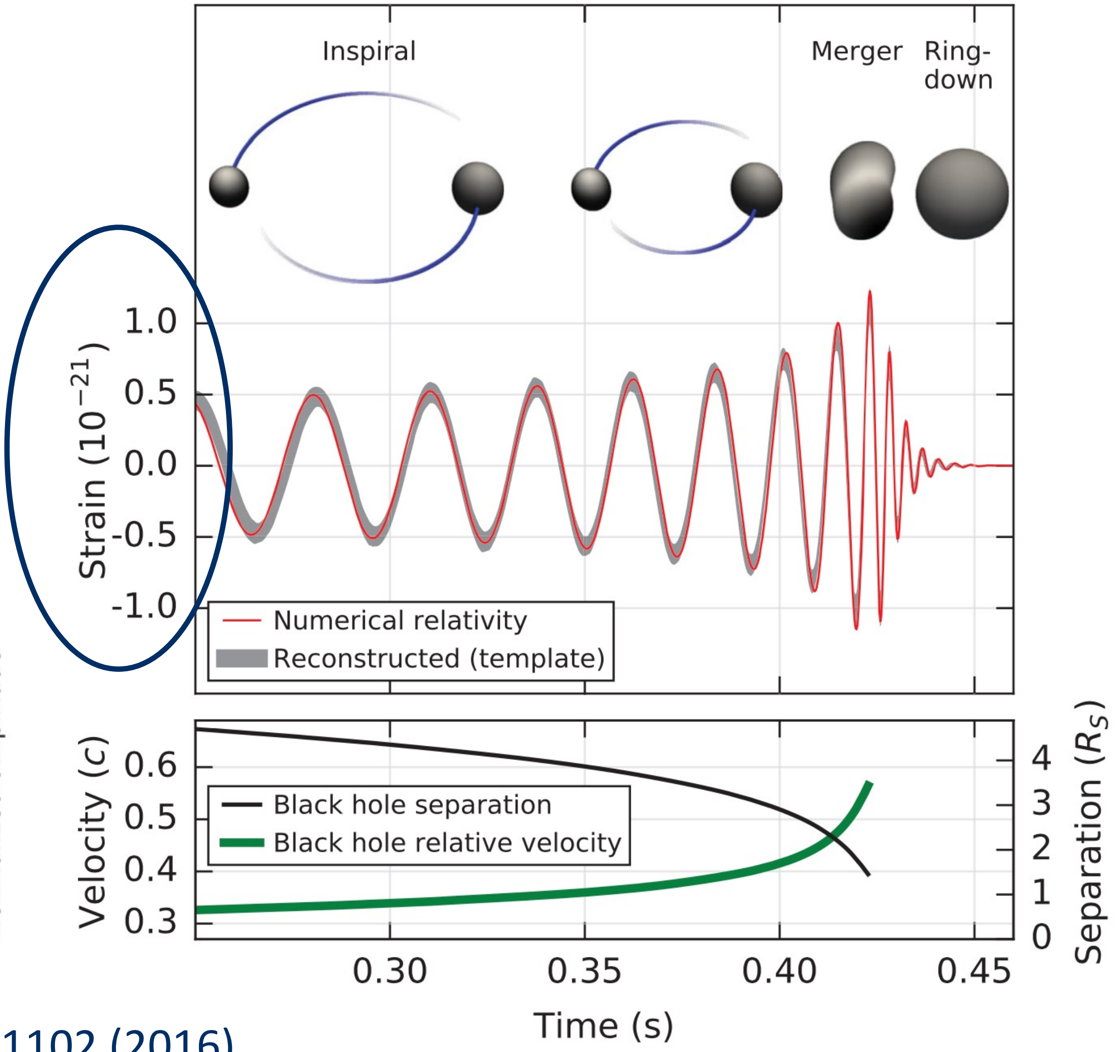
Completely new information carrier available to study the **fundamental physics** of the universe


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s
T 10 32 10 28
E 10 19 10 15
10 -10 s
10 15
10 2
10 -5 s
10 12
10 -1
10 2 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
10 9 y
15
10 -12
Today
12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

First direct observation

14 September 2015





PRL 116, 061102 (2016)

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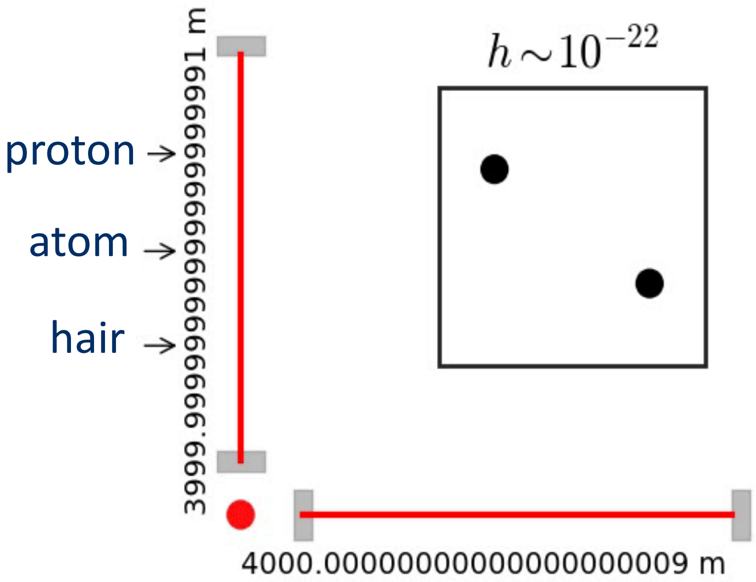
Gravitational wave detectors: interferometers

Strain h is relative change in distance between two objects: h = δL/L
With h = 10^{-21} and L = 1000 m ➔ **δL = 10^{-18} m !** Nucleus size: ~1 fm = 10^{-15} m

So, we must be able to measure insanely small distance changes!



animation by Jeroen Meidam

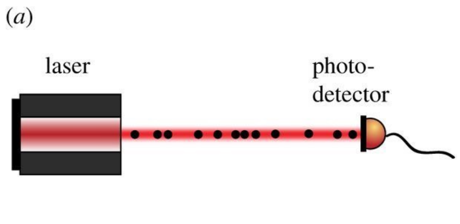
Gravitational wave detectors

Use very large high-precision Fabry-Perot Michelson interferometers

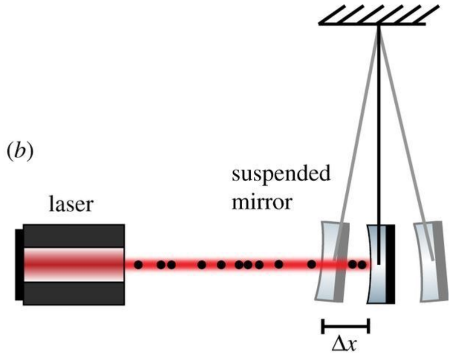
Obviously, many sources of noise…

- Seismic noise
- Thermal noise
- Laser instability
- Residual particles in vacuum
- Electronics noise

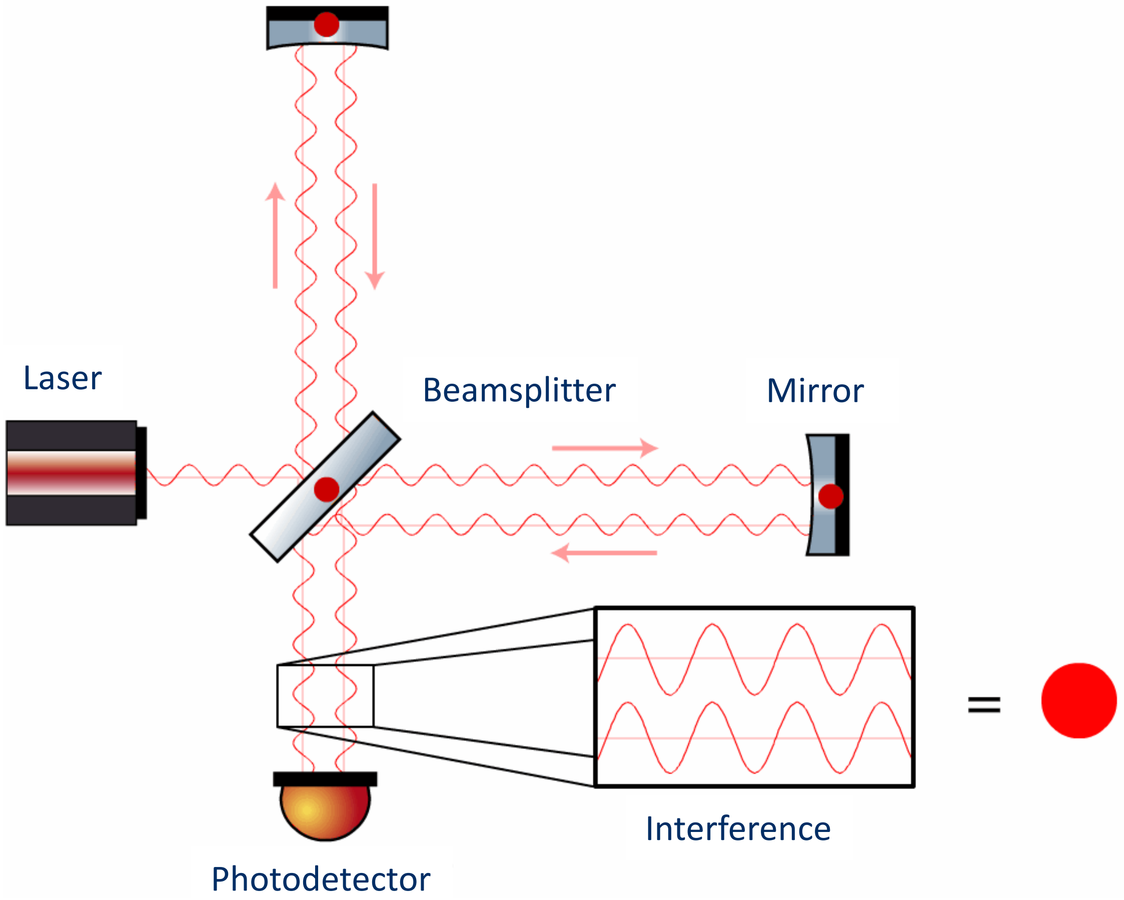
Quantum noise:



visualization of shot noise

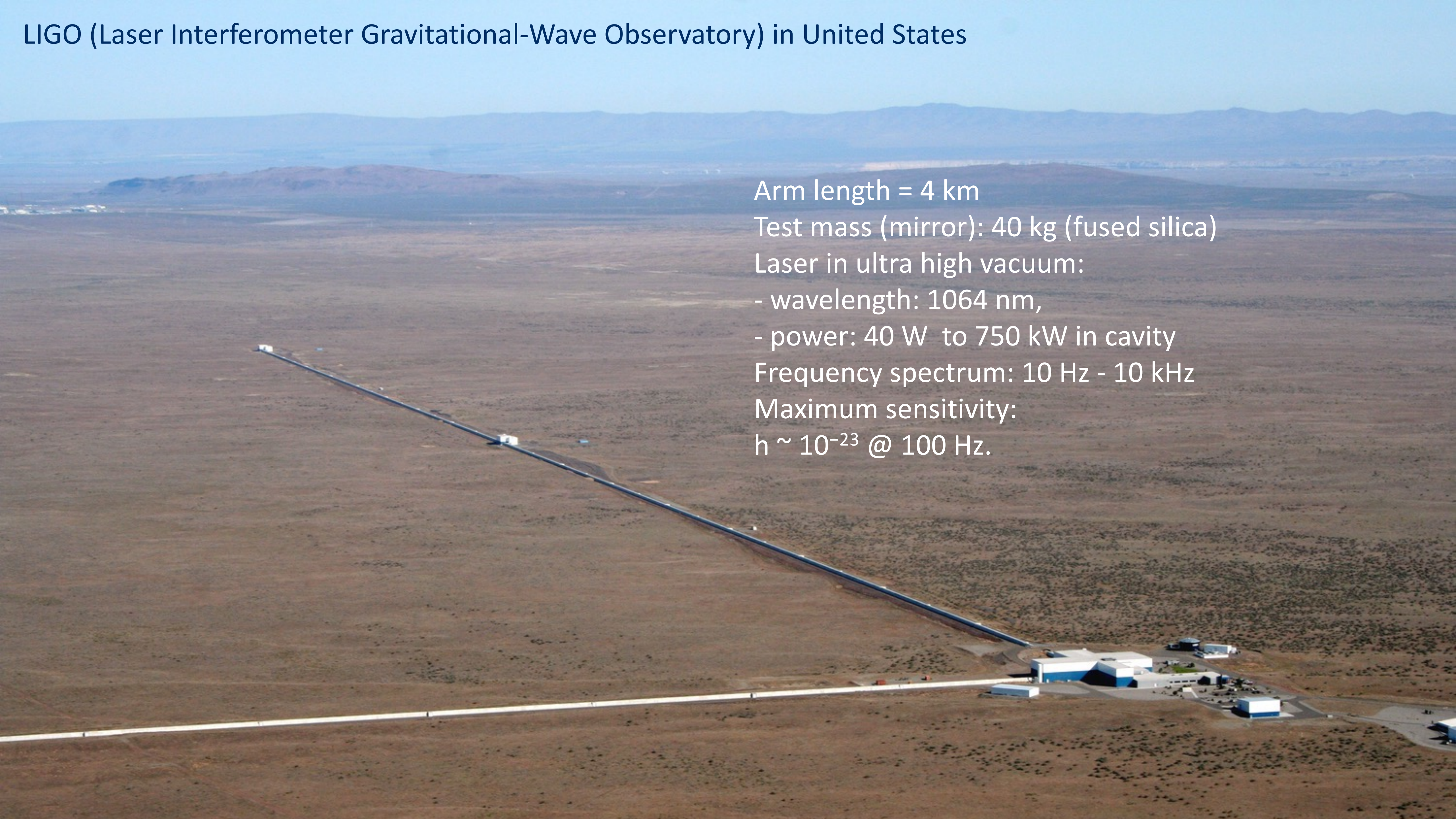


visualization of radiation pressure noise



animation by Harald Lück

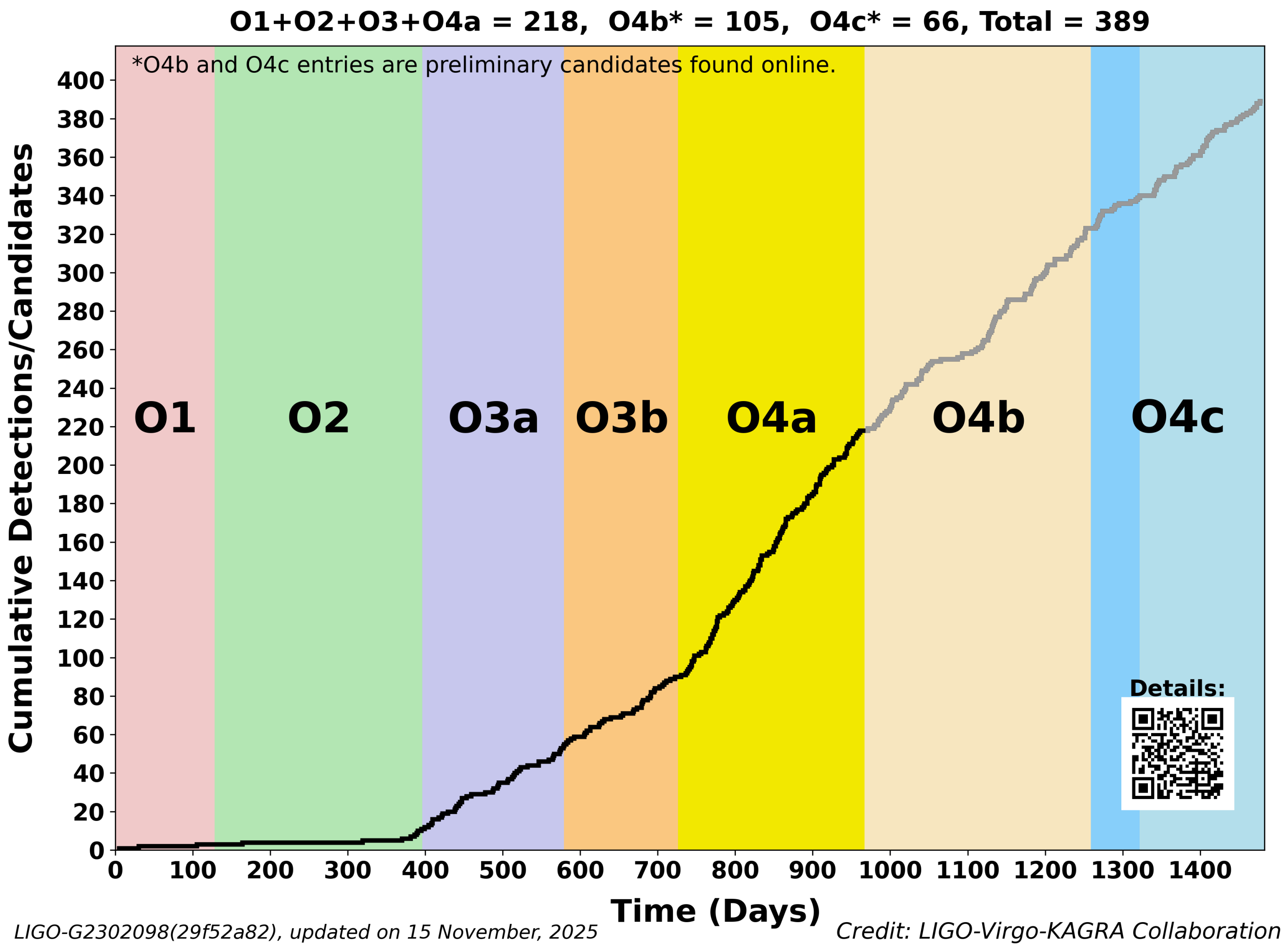
LIGO (Laser Interferometer Gravitational-Wave Observatory) in United States



Arm length = 4 km
Test mass (mirror): 40 kg (fused silica)
Laser in ultra high vacuum:
- wavelength: 1064 nm,
- power: 40 W to 750 kW in cavity
Frequency spectrum: 10 Hz - 10 kHz
Maximum sensitivity:
h ~ 10^{-23} @ 100 Hz.


VIRGO in Cascina, Italy

Total number of observations until today



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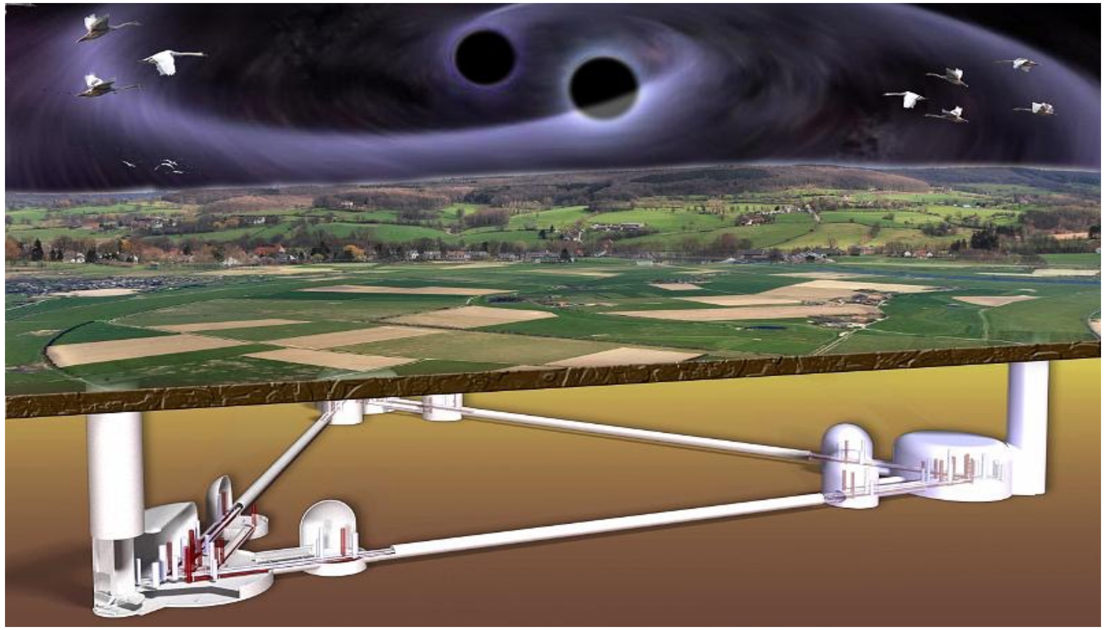
The Einstein Telescope

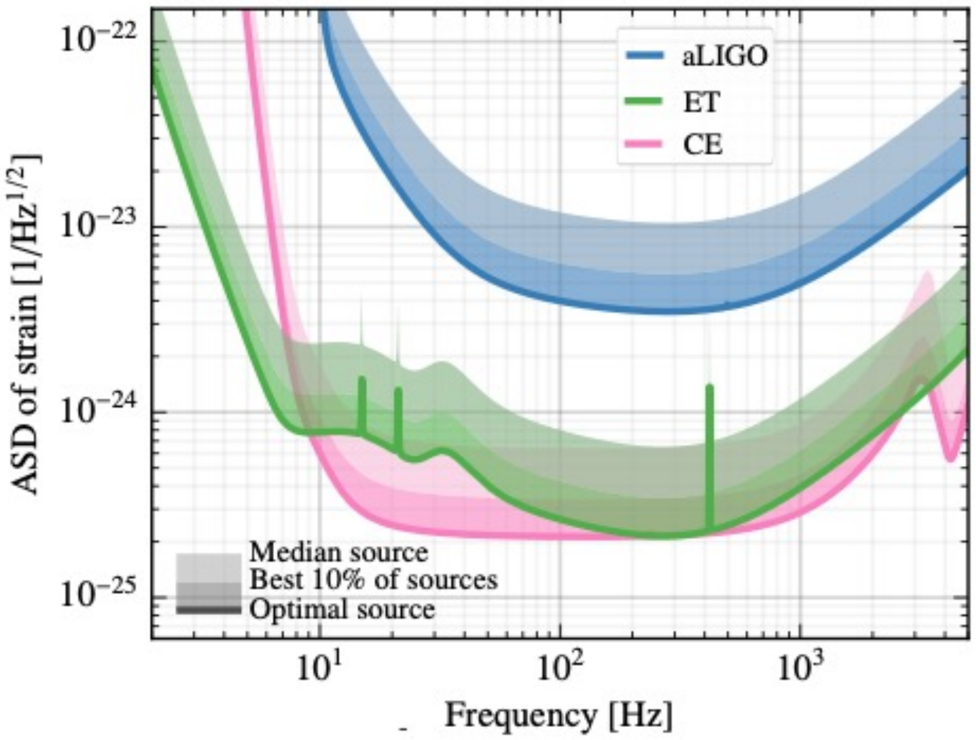
New generation of detectors needed to discover full potential of gravitational waves!

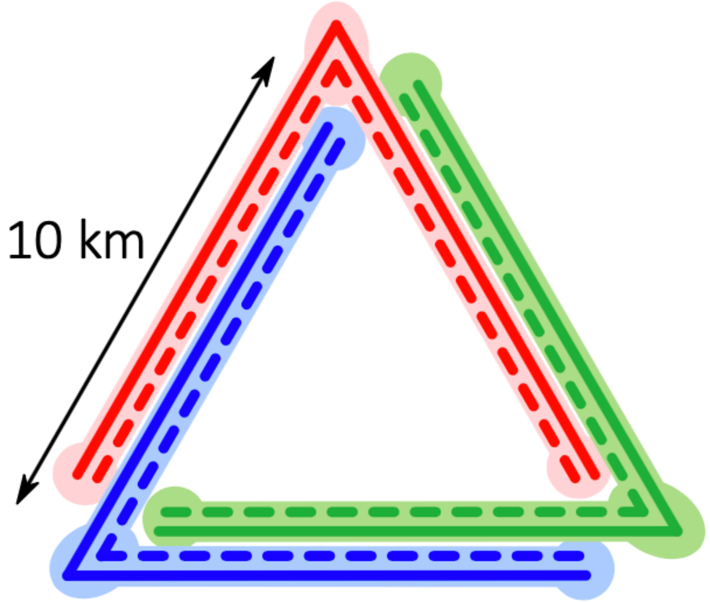


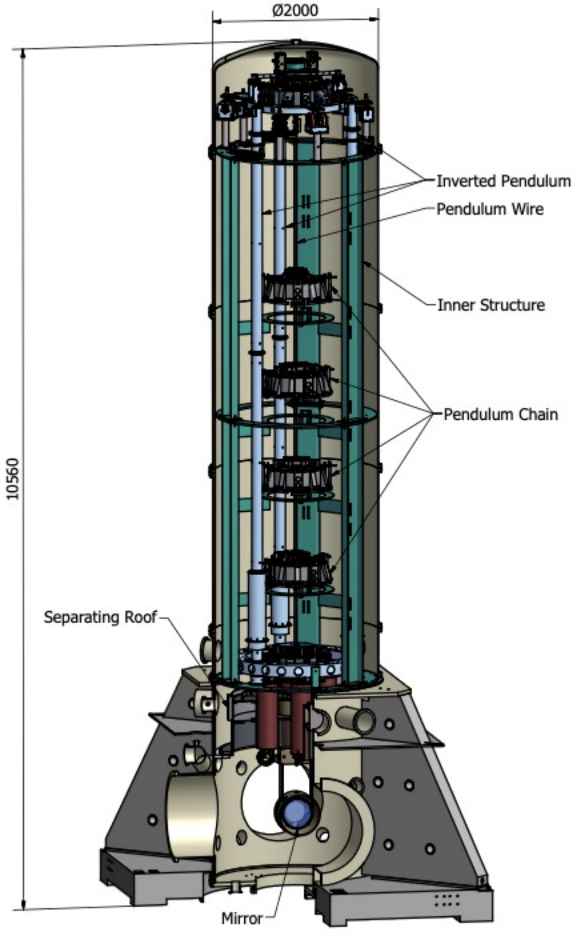
Larger (10km arms), underground (seismic noise suppression), 6 interferometers (low, high freq), cryogenic Silicon optics (thermal noise suppression) → **100 to 1000 observations per day**

The Einstein Telescope

Improvement of sensitivity: several orders of magnitude, especially at low frequencies.



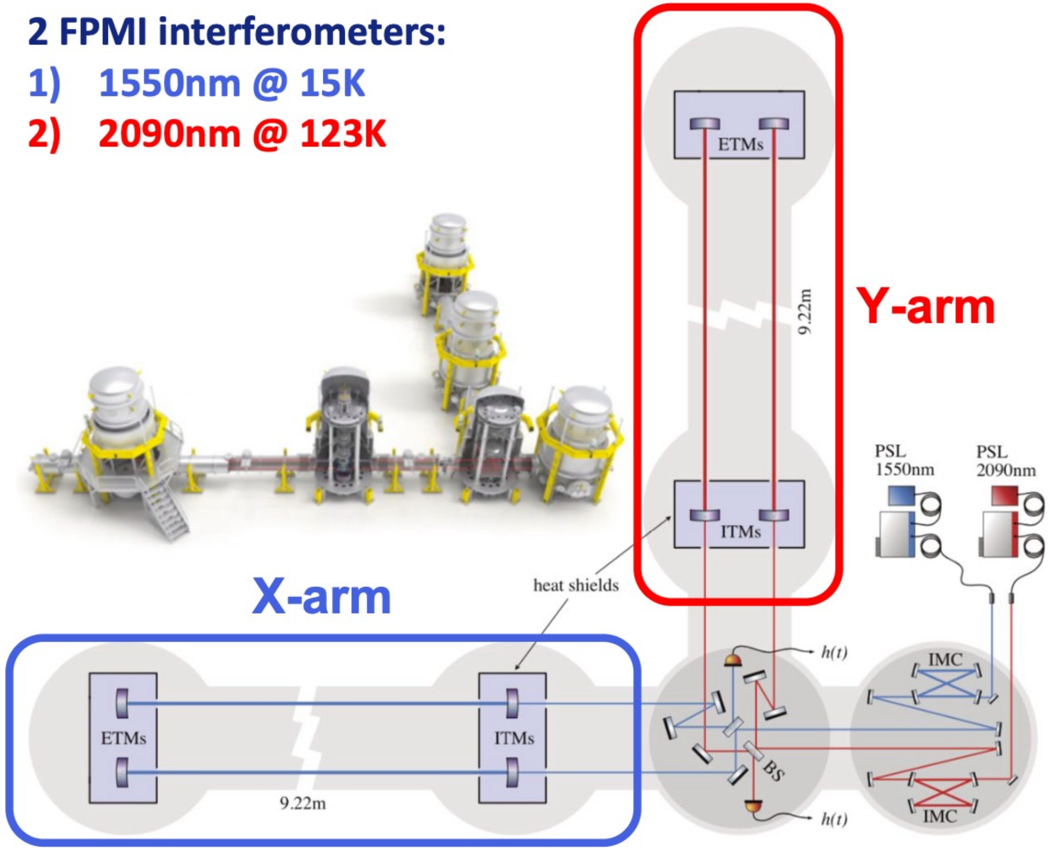




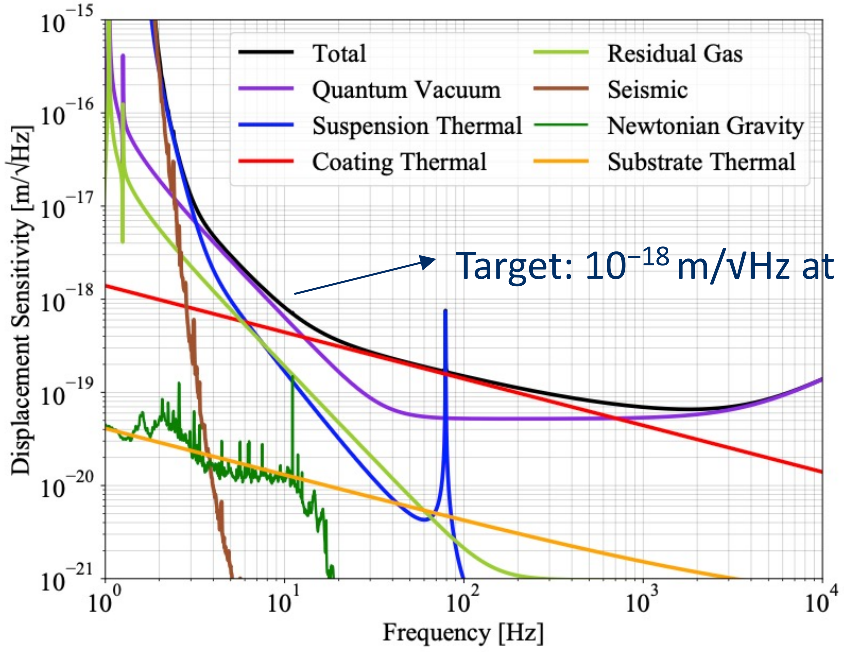
ETpathfinder

R&D infrastructure for testing new ET technologies in a low-noise full interferometer environment

2 FPMI interferometers:
1) **1550nm @ 15K**
2) **2090nm @ 123K**



- Cryogenic temperatures: 15K & 123K
- New Mirror Material: Silicon
- New Wavelengths: 1550nm & 2090nm
- Advanced Quantum Noise Reduction Techniques

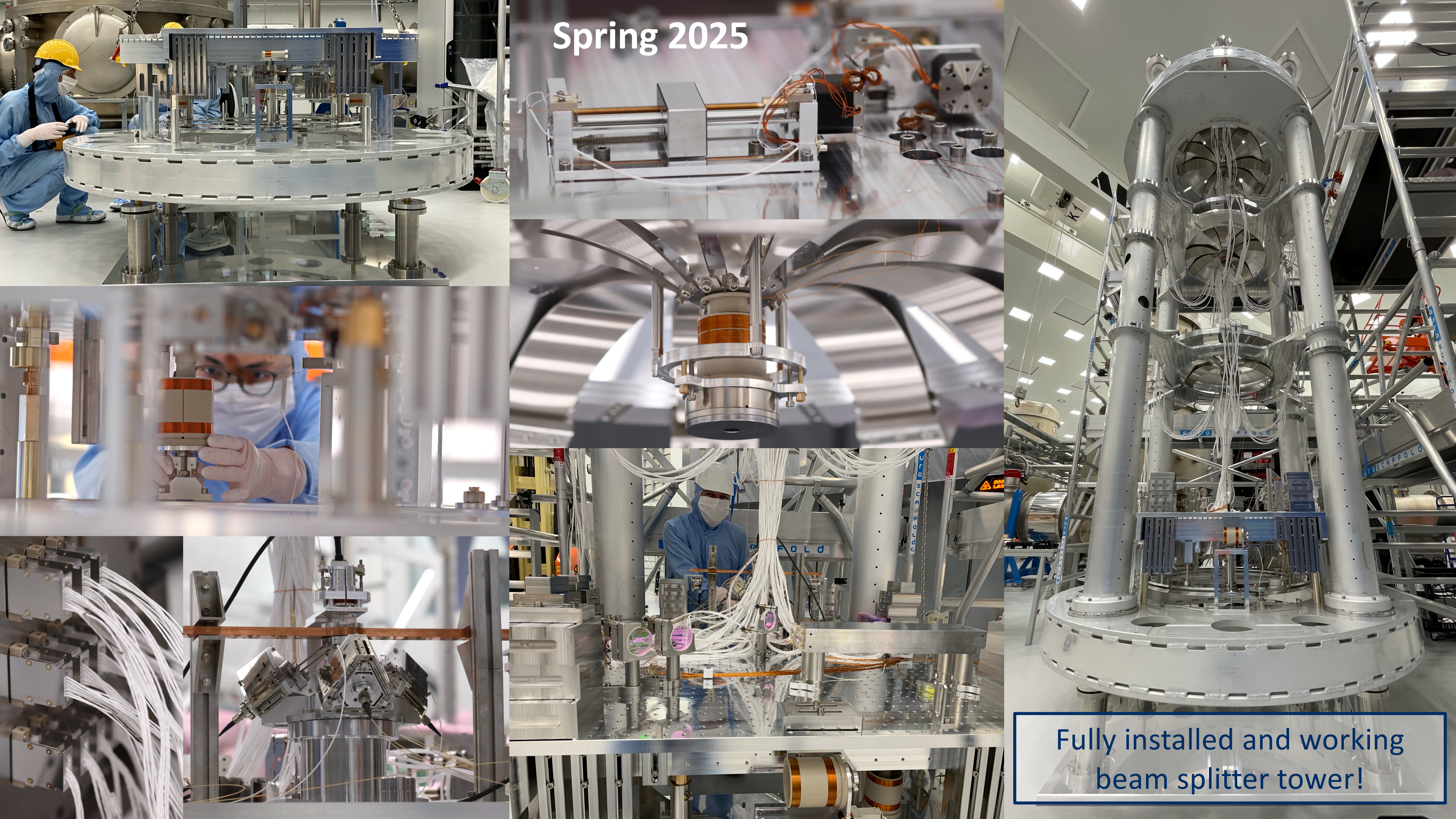


Target: 10^{-18} m/√Hz at 10Hz

[Class. Quantum Grav. 39 (2022) 215008]

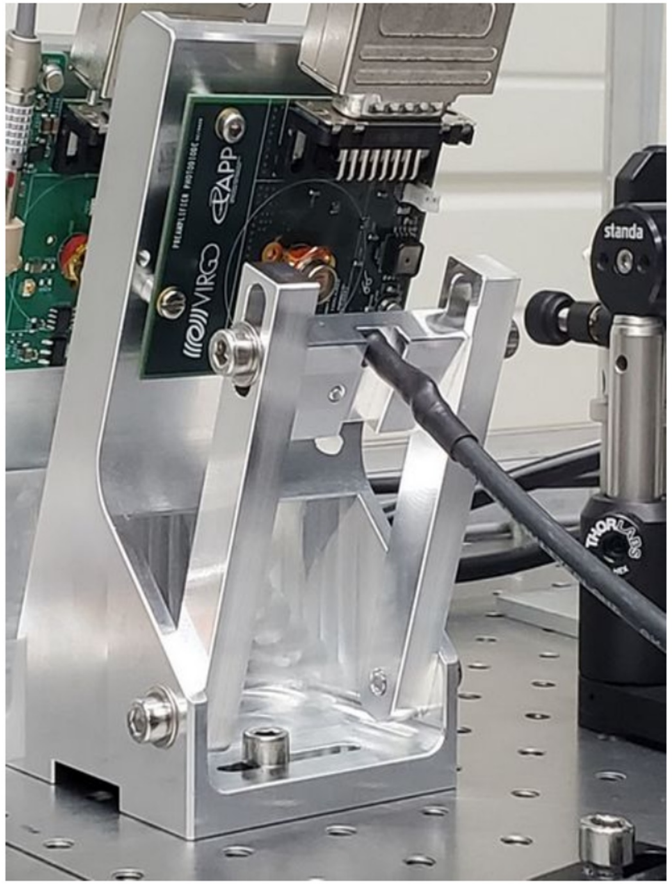
Summer 2021


Spring 2024


Spring 2025
Fully installed and working beam splitter tower!

Optical sensors

Gravitational wave detector: complex optical system



Use **photodiode detectors** and **beam cameras** to control and read-out laser beams.

Especially for 2090nm photodiode detectors unknown territory.
Need for development and (noise) characterization.

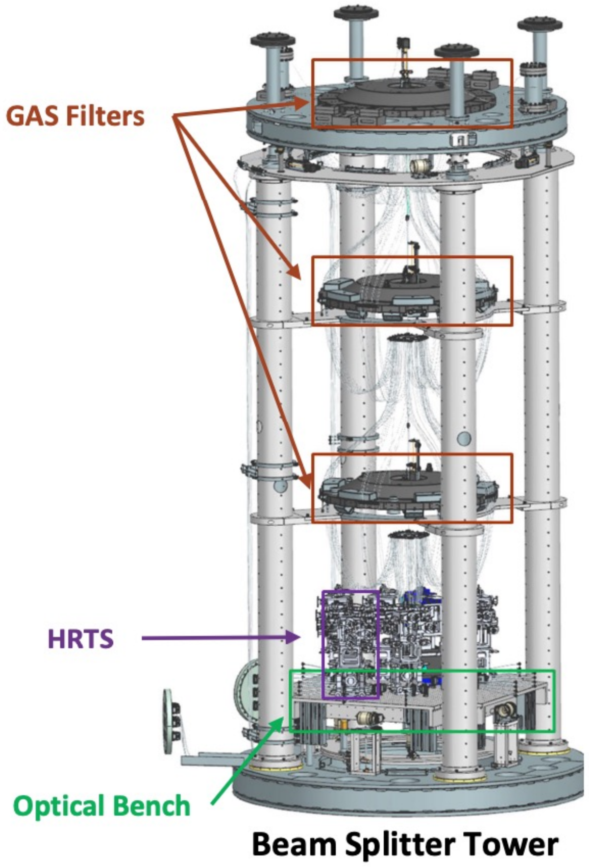
Beam cameras are used for alignment, beam profile monitoring, etc.

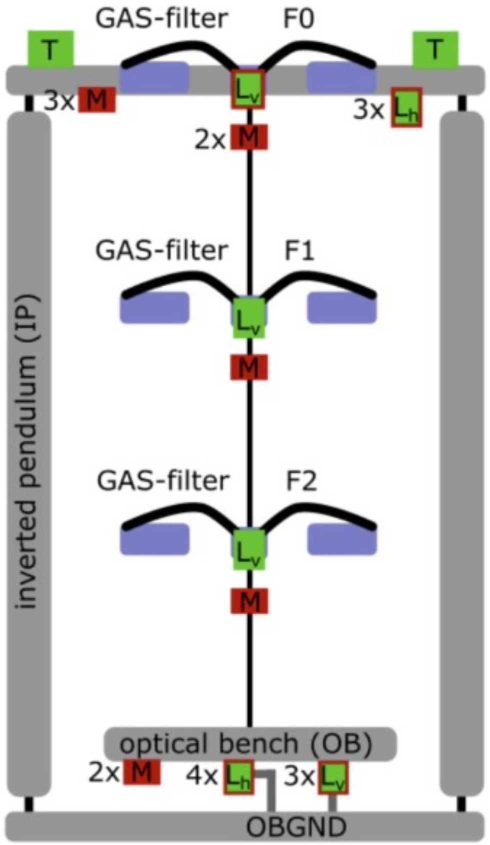
ETpathfinder: uses Xenics Wildcat 640 U3V 100.
(InGaAs photodiode array, 640 x 512 pixels, 900 – 1700 nm)

Use advanced real-time image processing techniques to control optics?
(with piezo elements)

Inertial and position sensors

Key components of seismic isolation: suspensions, sensors, actuators





- Passive attenuation
- Active control

- Inertial sensors (seismometers) (T)
- Position sensors (LVDT) (L)
- Voice coil actuators
- Stepper motors (M)

Sensing and control:

- Provide precise alignment of payload

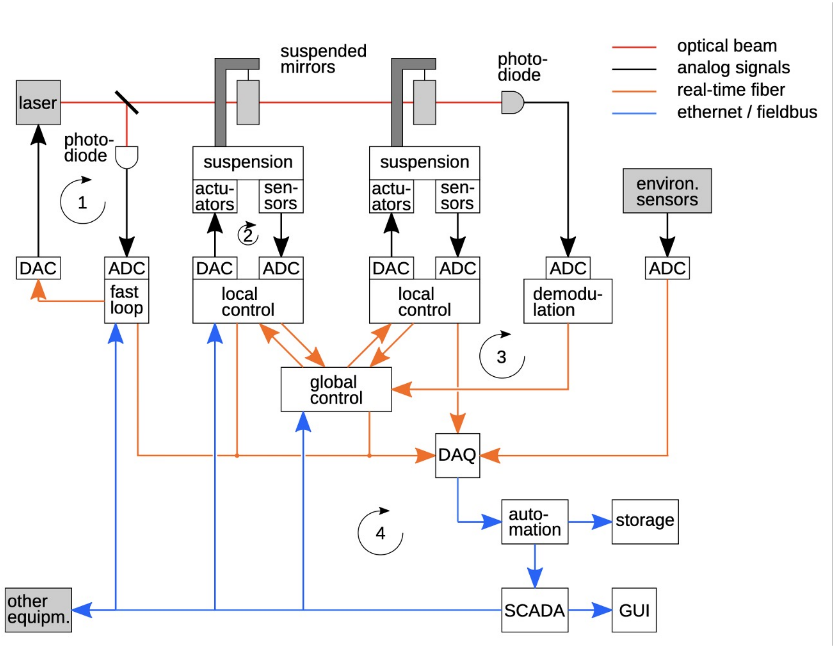
Environmental sensors

Crucial to monitor external disturbances at surface, tunnels, underground caverns

- In a wider area around ET: highly sensitive **seismometers** and accelerometers
- **Sensitive microphones:** Acoustic sensors measure sounds of the surface propagating in the caves and tunnels.
- **Pressure** sensors, **temperature** gauges:
  measure variations in air pressure, weather conditions
- **Lightning detectors:** ET expected to be affected by lightning strikes from all over the world. EM waves can be picked up by coils of the vibration dampers in the vacuum towers and cause vibrations on the mirrors.
- **Flow meters:** measure water drained from the tunnels.
- **Magnetometers:** measure eddy currents and EM fields in underground caverns.

Data acquisition and control system

All these devices need to communicate with each other and control our detector to its working point



Data Acquisition Systems:

- Analog amplifier circuits
- Analog to digital conversion for real-time signal processing
- Custom hardware: FPGA, DSP modules (1MHz sampling rate, 18-bits)
- GPS time synchronization

Future:

- ADC @ sensor and transfer digital signals?
- Commercial solutions for Einstein Telescope DAQ?

Control systems:

- Usually PID based, MIMO system
- Sensor blending: LVDT + seismometer
- Required for real-time active control

Development of new algorithms: inspiration from robotics, AI, …?

Requirements

To achieve the projected Einstein Telescope sensitivity and enable stable operation

Sensors and actuators need to:

- Provide instant read-out or control
- Operate reliably 24/7 in a complex underground environment
- Have easy maintenance
- Generate minimal self-noise (thermal and electromagnetic)
- Meet the criteria for operation in ultra-high vacuum
- Have robust assembly and calibration methods

For industry, this means

- Innovation opportunities in high-tech and embedded systems
- Exploration of new markets (incl. aerospace, medical technology, quantum technology)
- Collaboration with leading institutes and access to European research programs

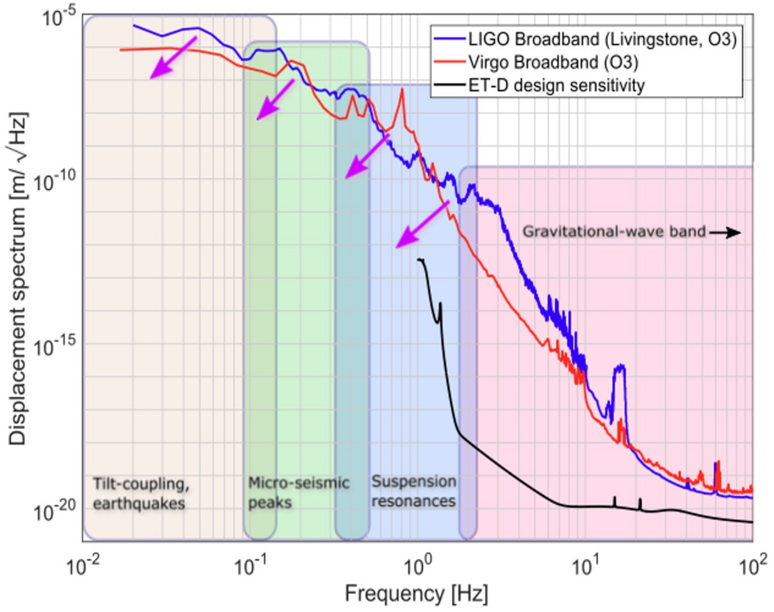
Requirements

From the Einstein Telescope Design Report Update 2020

6.10.1.5 Sensor development

The seismic isolation and suspension systems of ET will require the development of new sensors not currently deployed in-vacuum at observatories. The most important classes of sensor required are:

- Inertial sensors in rotation. Actively controlling the tilt of the isolated platforms is crucial, and a suitable sensor must have self-noise of $< 10^{-10}\,\mathrm{rad}/\sqrt{\mathrm{Hz}}$ at 10 mHz [494, 495].
- Advanced inertial sensors in translation. Reaching a sufficiently low vibration level will require sensors with a resolution of $\sim 10^{-13}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$ at 1 Hz.
- Precision non-contact displacement sensors for suspension damping. To actively extract energy from the suspension chain normal-modes without injecting noise, a non-contact sensor will need better resolution than the input platform motion, *i.e.* $< 10^{-13}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$ at 1 Hz [496].
- Inter-platform sensors for displacement and rotation. There are numerous potential technologies, but the key performance metric is to have RMS noise comparable to the linewidth of the suspended cavities, *i.e.* $\sim 10^{-10}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$ at 10 mHz.

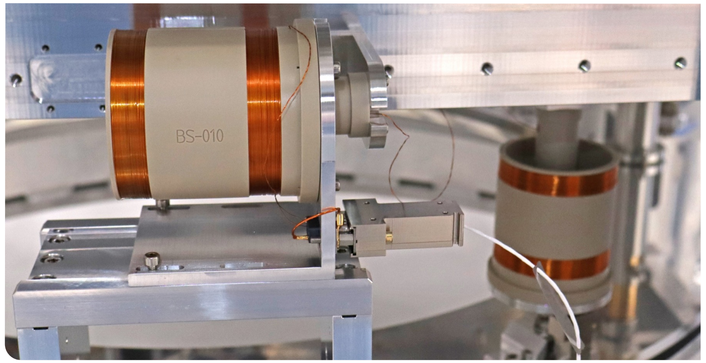


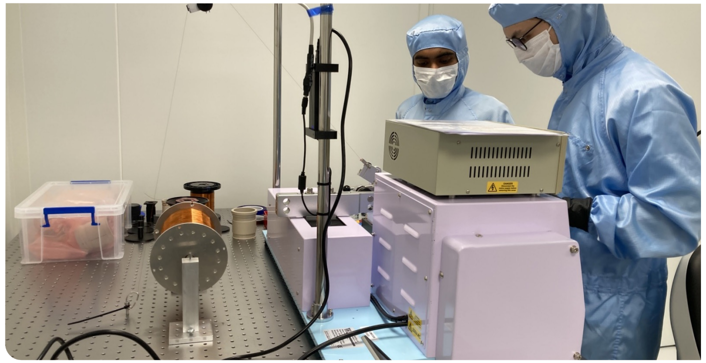
(these numbers might change depending on detector design updates)

Examples of ongoing research

LVDT position sensor (combined with voice coil actuator)

- Non-contact (inductive)
- Highly linear
- Noise determined by electronics
- UHV vacuum compatible
- Current noise level: ~1nm/√Hz

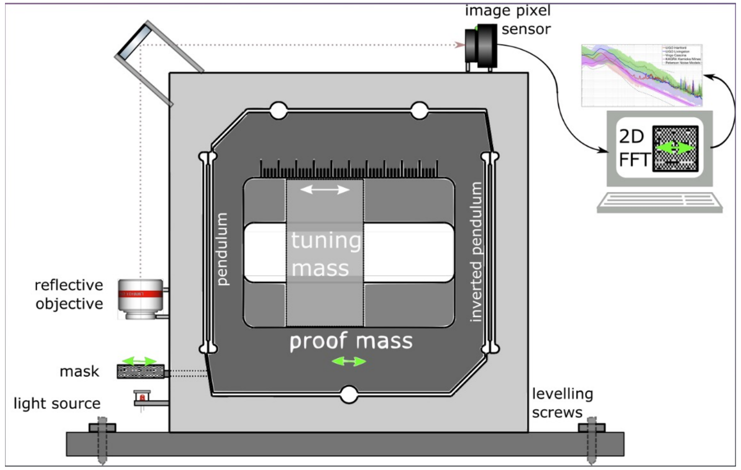


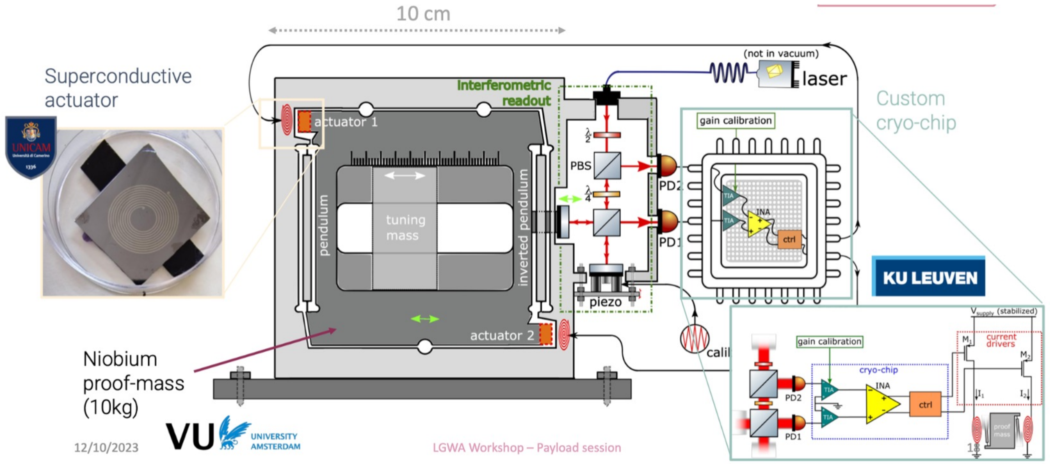


Research at UAntwerpen:

- Sensitivity optimization
- Readout electronics
- New design concepts
- Eddy current systems

Inertial sensors (noise levels pm/√Hz):





Summary

- To observe extremely weak gravitational wave signals, the Einstein Telescope must detect incredibly small spacetime distortions — far below the subatomic scale.
- The system is sensitive to any form of noise or interference, and therefore requires ultra-sensitive and highly stable sensing, actuation, and advanced control systems.
- This includes optical, seismic, inertial and environmental sensors. Information is collected in an instrumentation network and used in control systems with actuators, to e.g. achieve vibration damping.
- The challenges: sensitivity, robust assembly & operation, ultra-high vacuum, read-out electronics, data acquisition, real-time signal processing, …

More info/resources:

Einstein Telescope Design Report Update 2020: https://www.et-gw.eu/index.php/relevant-et-documents
ETpathfinder design report: https://www.etpathfinder.eu/wp-content/uploads/2020/03/ETpathfinder-Design-Report.pdf

Technology domain sensors: https://www.einsteintelescope-emr.eu/sensoren/