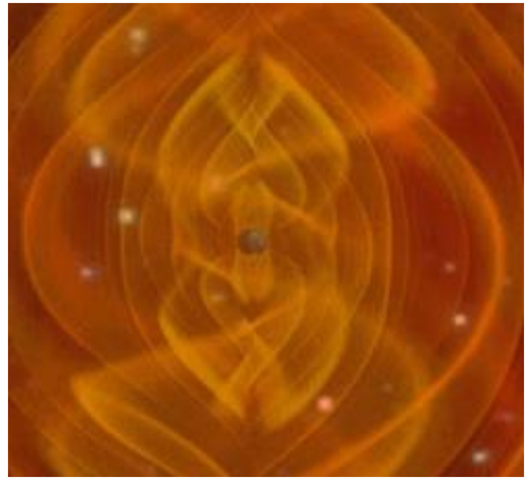
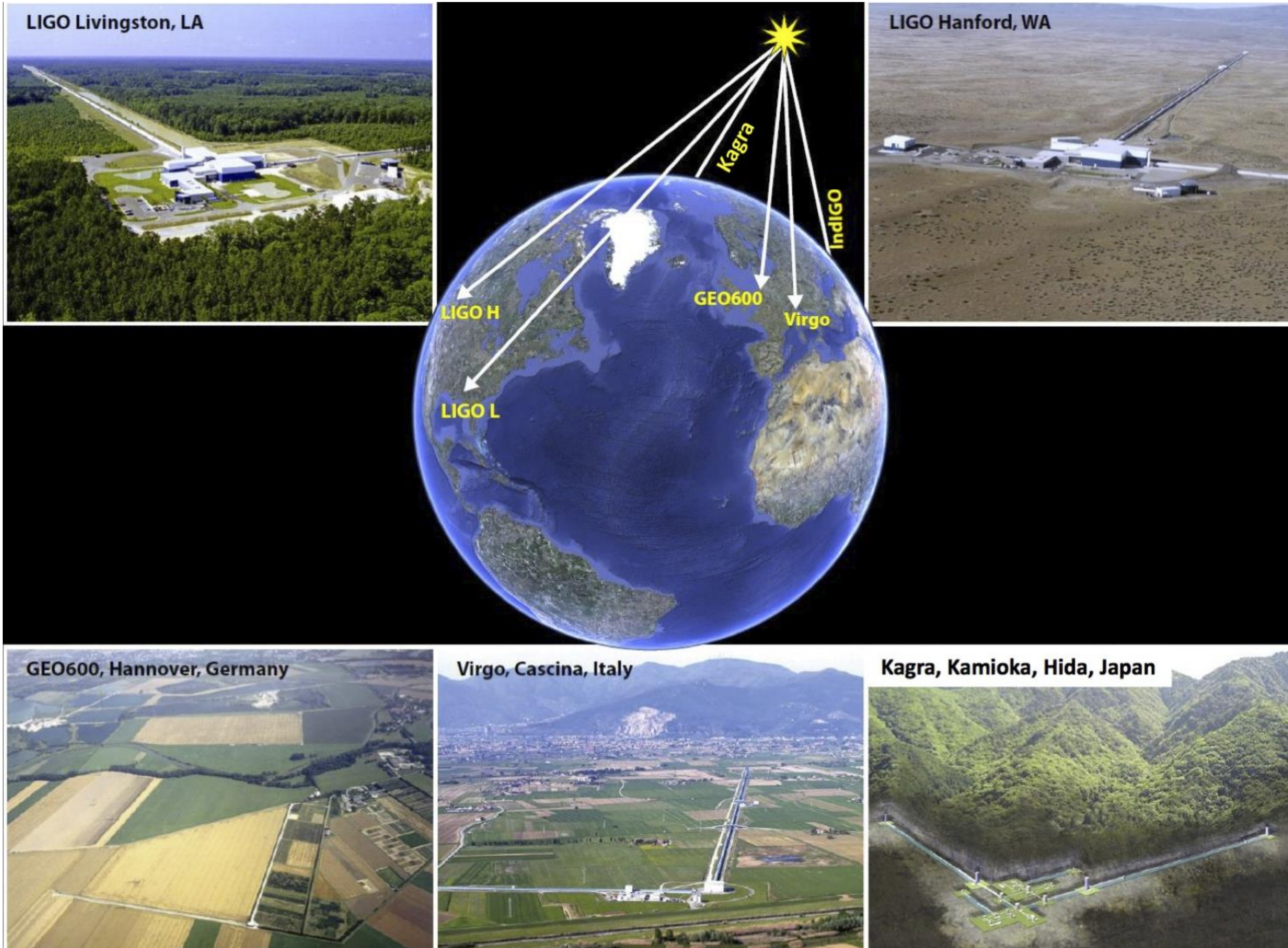


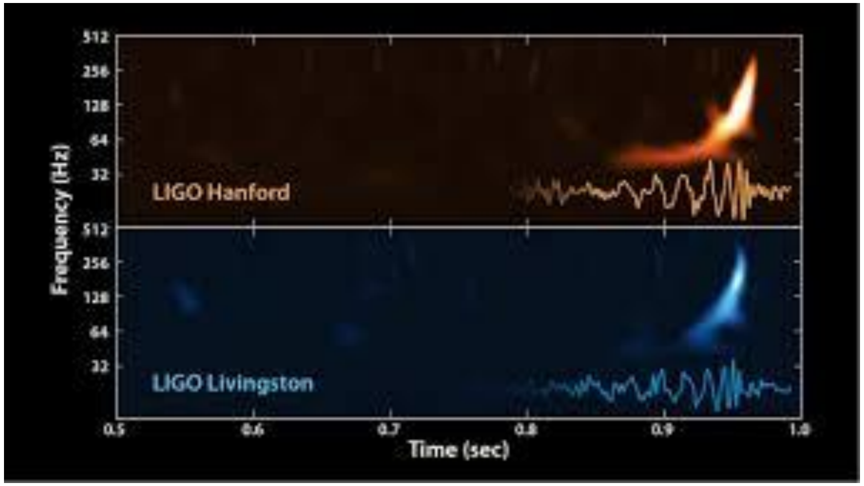
Gravitational Waves

Chris Van Den Broeck

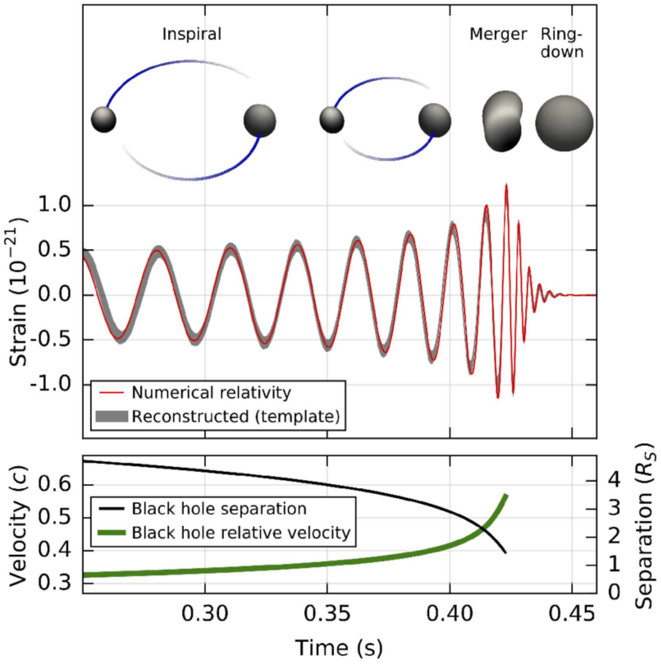
29th Symposium on Astroparticle Physics in the Netherlands
Soesterberg, 12-13 June 2025

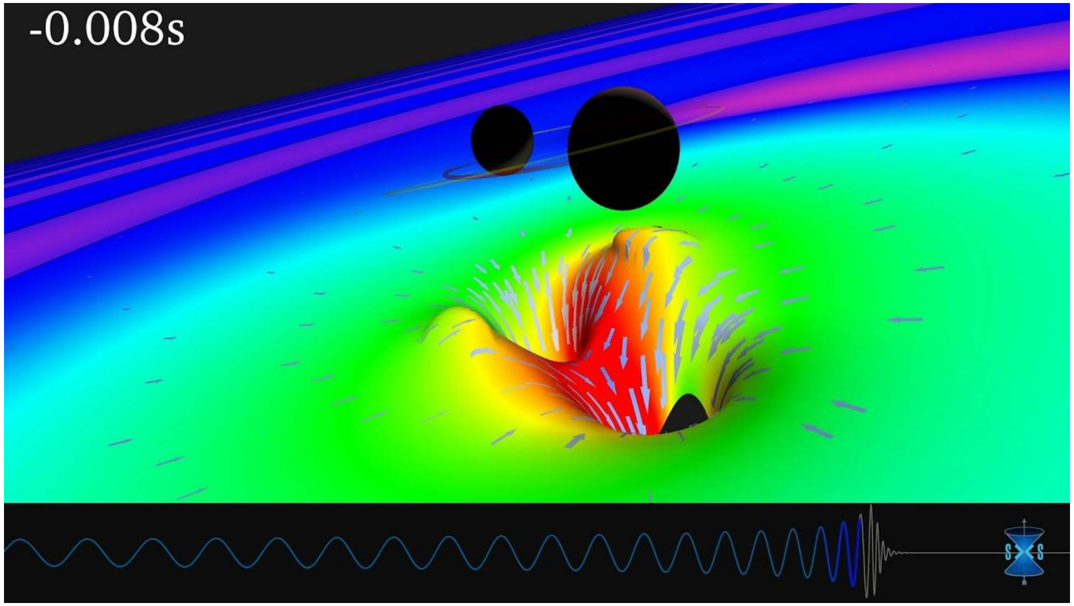

LIGO Livingston, LA
Kagra
IndIGO
LIGO H
GEO600
Virgo
LIGO L
LIGO Hanford, WA
GEO600, Hannover, Germany
Virgo, Cascina, Italy
Kagra, Kamioka, Hida, Japan

This September: *Happy Anniversary GW150914!*

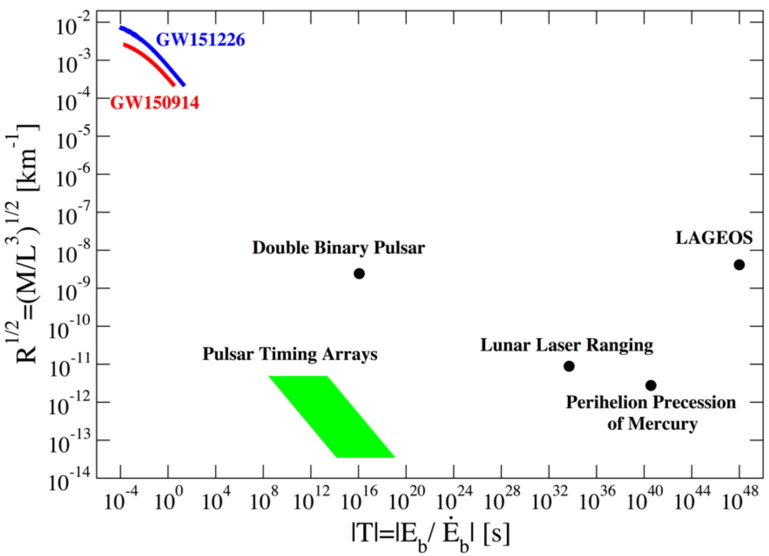


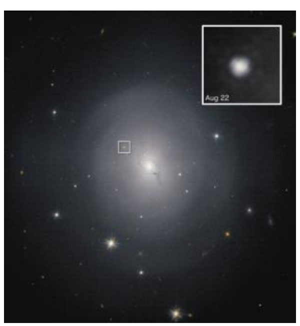
- **First direct detection of gravitational waves**
  - Signal from a binary black hole merger
  - Detected by the two LIGO interferometers

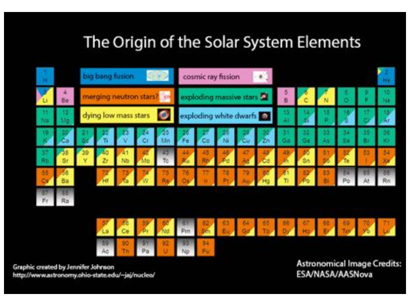


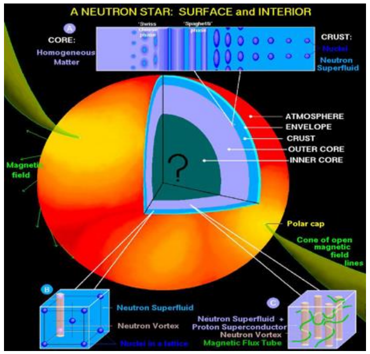


10 years of rich scientific harvest









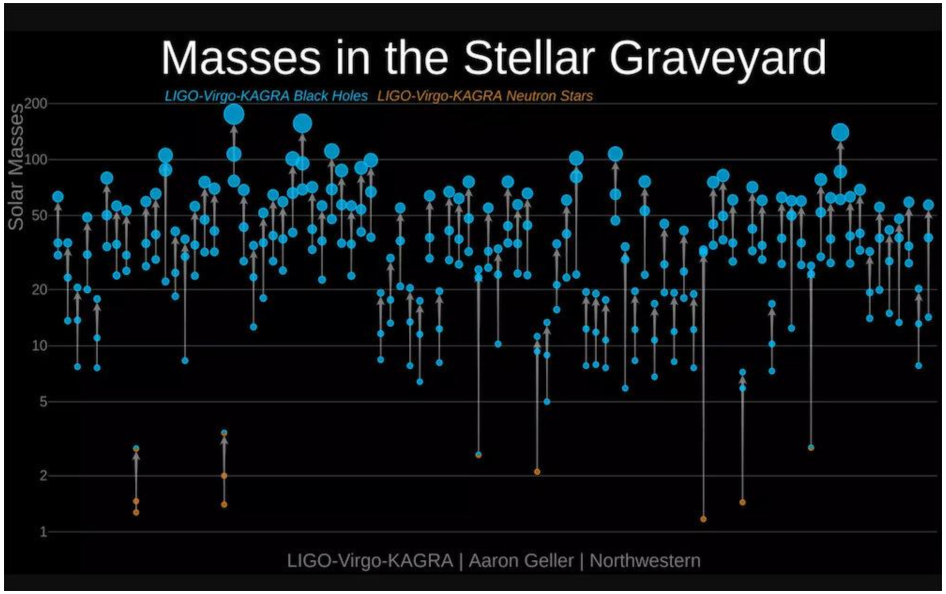
- First empirical access to the genuinely **strong-field dynamics of spacetime**
- Ultra-high precision bounds on dispersion of gravitational waves
  - **Bound on graviton mass**:

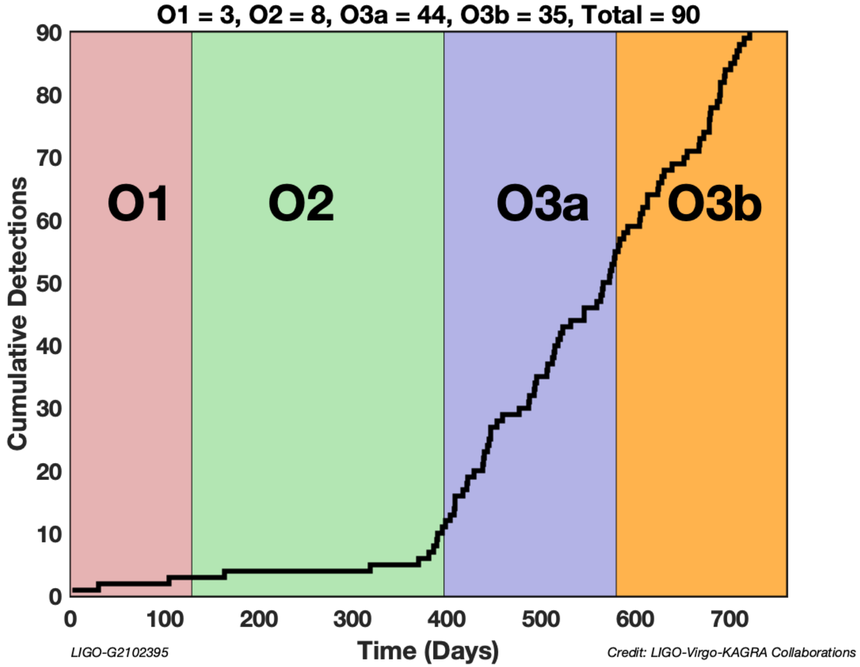
$$m_g \leq 1.76 \times 10^{-23}\,\mathrm{eV}/c^2$$

- First (indirect) empirical tests of the **no-hair theorem**
  - By looking at the "ringdown" from the black hole resulting from the merger
- **Binary neutron star mergers** (2017, 2019): **Multi-messenger astronomy**
  - New way of doing cosmology
  - Origin of heavy elements
  - Matter under extreme conditions

The first observing runs of LIGO, Virgo, KAGRA

- First three observing runs led to 90 detections
  - Binary black holes, binary neutron stars, neutron star-black hole





- Now in the fourth observing run, **O4**
  - Already total **200+ detections**
  - *First comprehensive release of results around August this year!*

The run-up to O5

- Possible start at the beginning of 2028

- Significant upgrades for LIGO, Virgo, KAGRA

- Virgo in a technologically critical phase
  - Upgrade from marginally stable cavities to **stable cavities**

Advanced Virgo +

Advanced Virgo Plus for O5

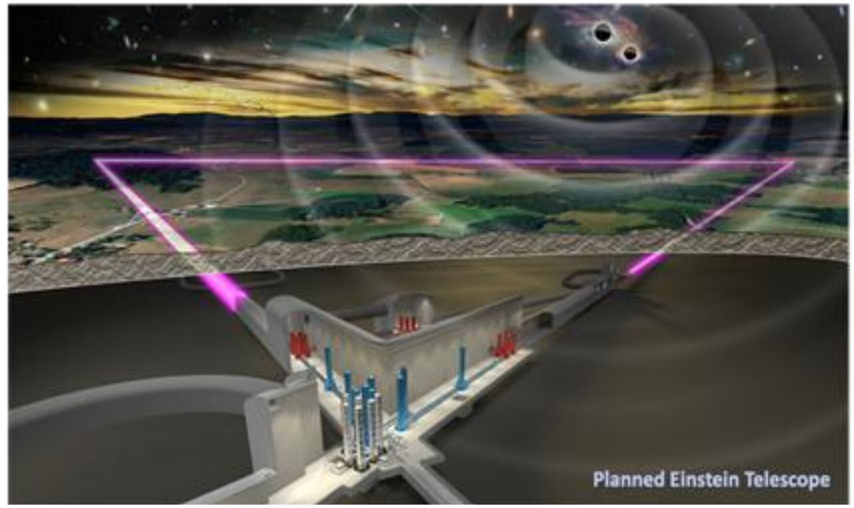
Technical Design Report

The Virgo Collaboration

VIR - 0499A - 25

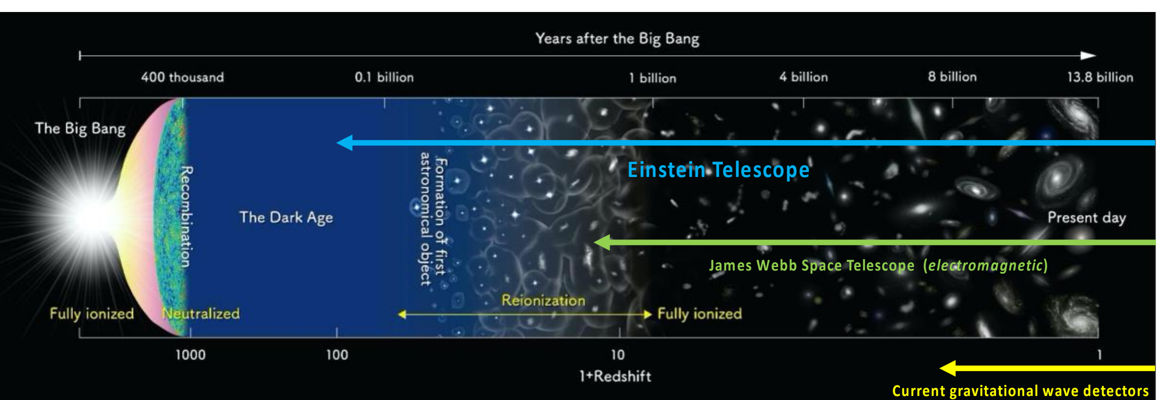
5 May 2025

From current detectors to Einstein Telescope



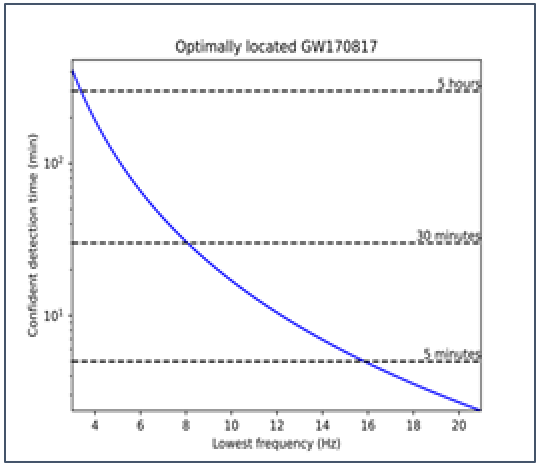
Baseline design:

- 3 detectors arranged in a triangle, 10 km arm length
- Factor 10 more sensitivity at mid-frequencies, > 1000 at low frequencies
- Candidate sites: Euregio Meuse-Rhine, Sardinia, Saxony (?)

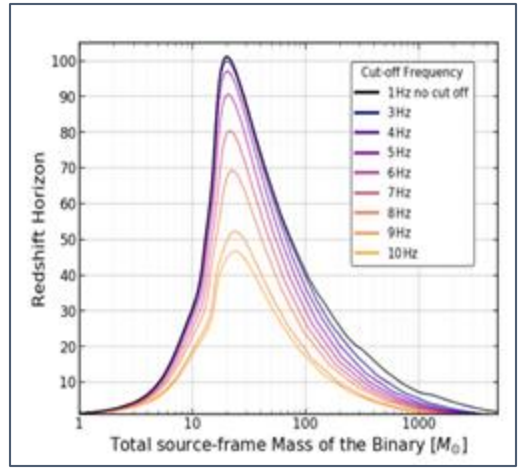


- Access to entire visible universe
  - *What happened before the first stars?*
- 100,000 signals per year
  - *Map out formation history of compact objects*
- Loud signals
  - *Precision science!*

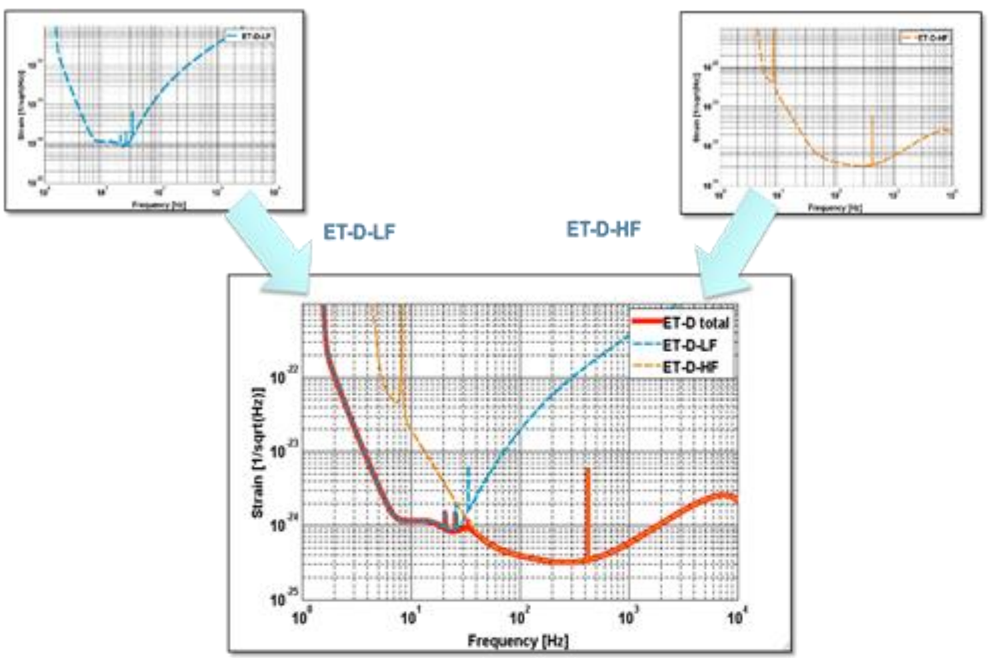
Extending the reach to low frequencies



Pre-warning time for impending binary neutron star mergers



High-mass and redshifted binaries



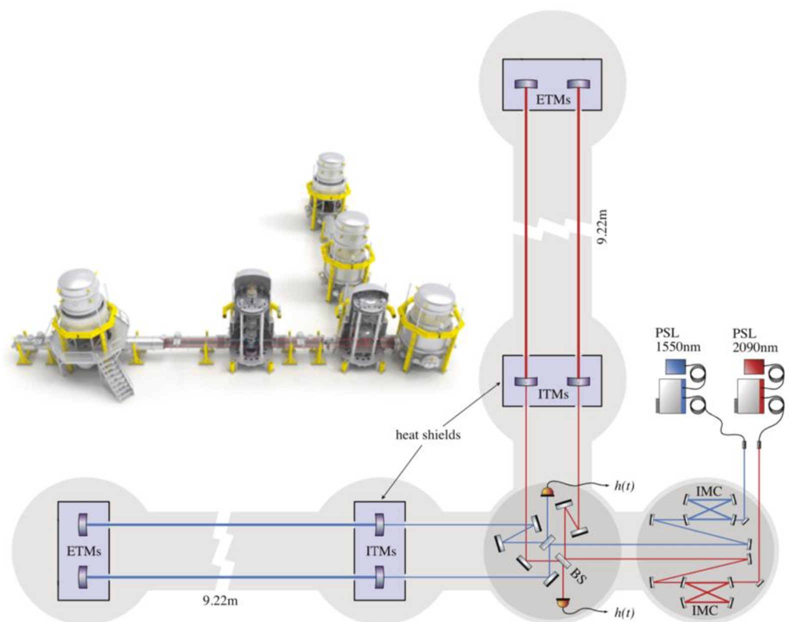
- Broadband sensitivity through a **xylophone concept**
  - Each detector consists of a high frequency (HF) and low frequency (LF) interferometer
    - Factor ~10 improvement at HF
    - Factor > 1000 improvement at LF
  - **Needs fundamental changes in technology and concepts**
    - Testing & prototyping needed

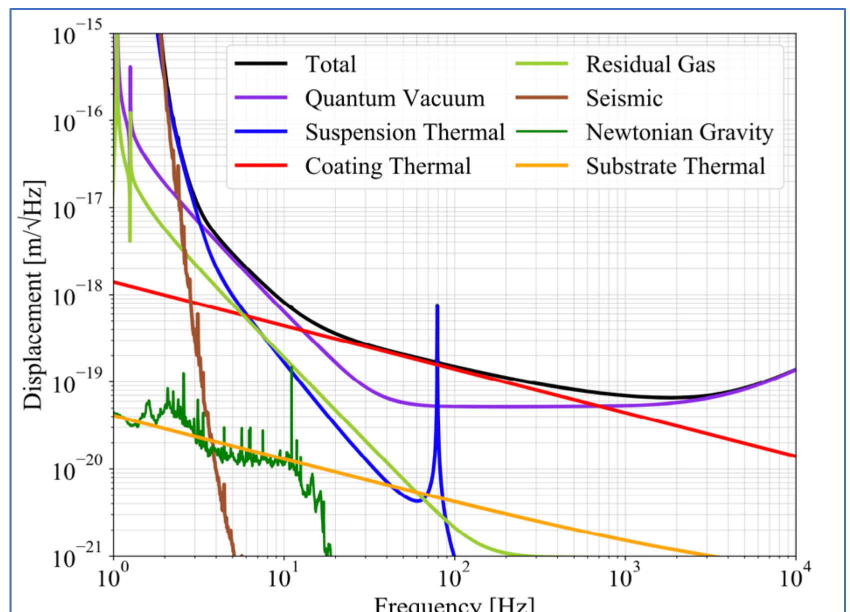
ETpathfinder (Maastricht)

New facility for testing ET technology in a low-noise, full-interferometer setup

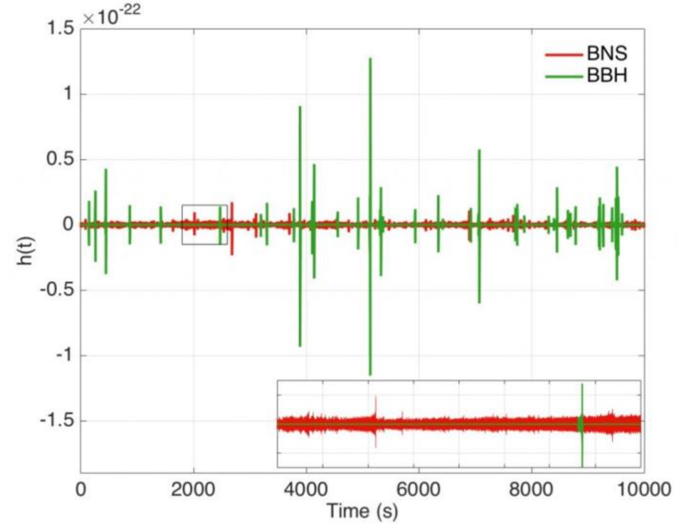
- Silicon mirrors: 3 to 100+ kg
- Cryogenics
  - Cryogenic liquids and sorption coolers
  - Water/ice management
- New wavelengths: 1550 and 2090 nm

… which cannot be tested by LIGO/Virgo





Data analysis development

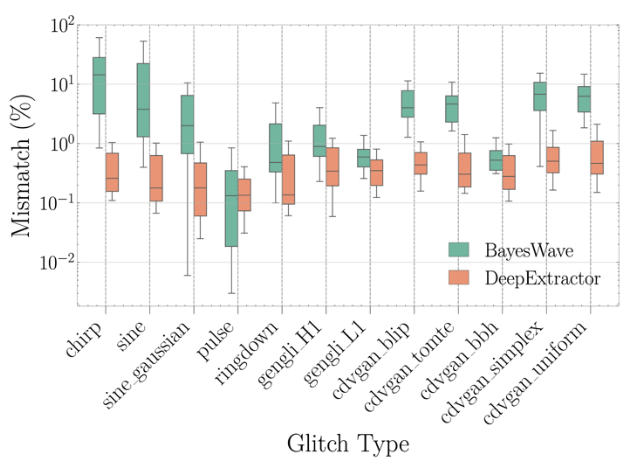


Completely new data analysis setting:

- Long signals
- Overlapping signals
- Loud signals
- Every stretch of data contains signal
  - How to characterize underlying noise?

	kWh	CO_2 [kg]	Trees†
JIM	34	11	0.55
PBILBY	3599	1180	59.02

Wouters, Pang, Dietrich, Van Den Broeck, PRD 110, 083033



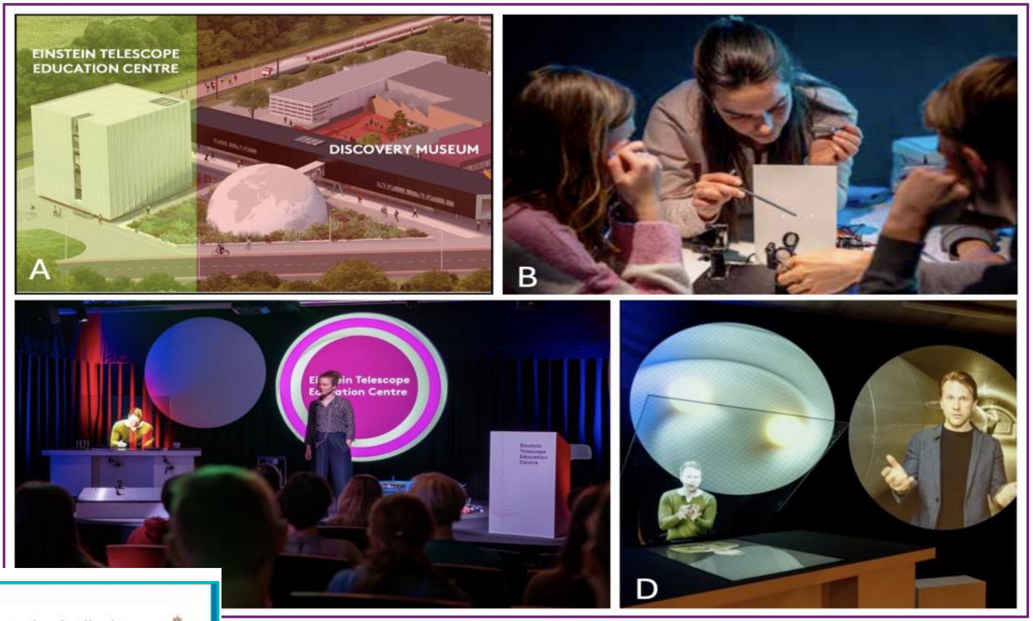
Dooney, Narola, Bromuri, Courier, Van Den Broeck, arXiv:2501.18423

Machine learning to the rescue!

- Estimating the parameters of the source
  - Same accuracy as “classical” tools
  - Minutes (incl. training) rather than hours
  - Much more ecologically friendly
- Real-time instrumental glitch characterization
  - Sub-second rather than hours
  - Sub-percent accuracy
- Glitch mitigation using the null stream
  … or without it
- Learning how to deal with overlapping signals
  - *Also a problem for LISA!*
  - “Global fit” as a solution for both?

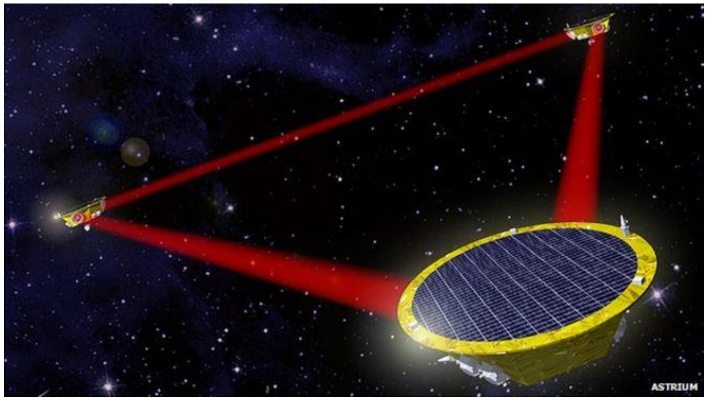
Education and outreach

- Einstein Telescope Education Center (ETEC) in Kerkrade
  - For school classes

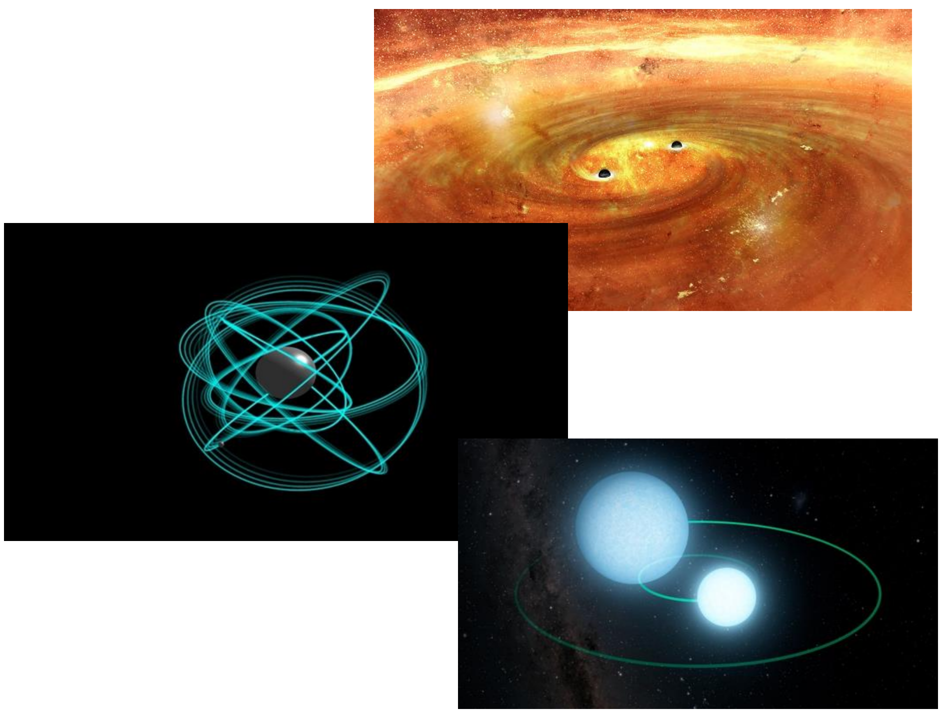


- Maastricht Gravitational Education Curriculum (MAGIC)
  - For high school teachers

LISA: A gravitational wave detector in space (2034)



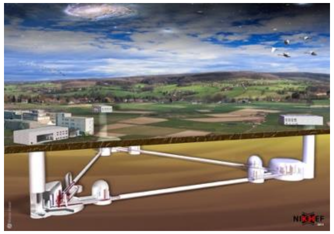
- Laser Interferometer Space Antenna
- Three probes in orbit around the Sun, exchanging laser beams
  - Triangle with sides of 2.5 million kilometers
  - Sensitive to low frequencies (10^{-4} Hz - 0.1 Hz)
  - **January 2024: definitive approval by ESA!**
- Different kinds of sources:
  - Merging *supermassive* binary black holes ($10^5 – 10^{10}\ M_{sun}$)
  - Smaller objects in complicated orbits around supermassive black hole
  - White dwarf binaries throughout the Milky Way
  - Primordial gravitational waves from right after the Big Bang?

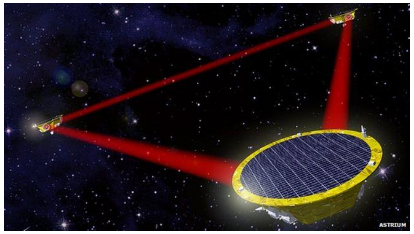


Einstein Telescope and LISA

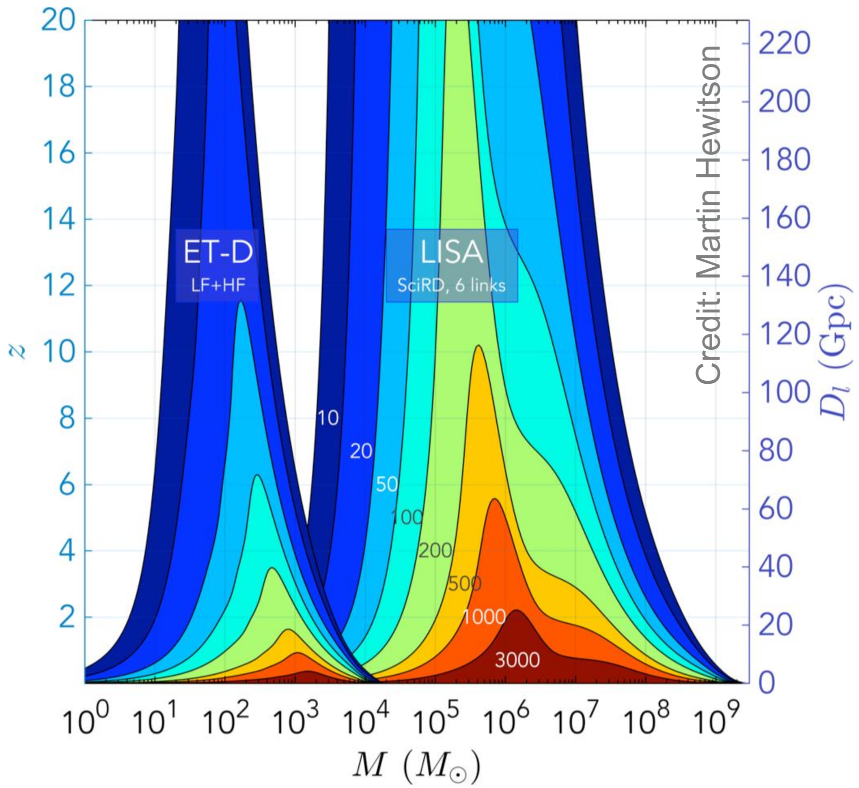
- Together unravel how black holes of all sizes came into being

Einstein Telescope

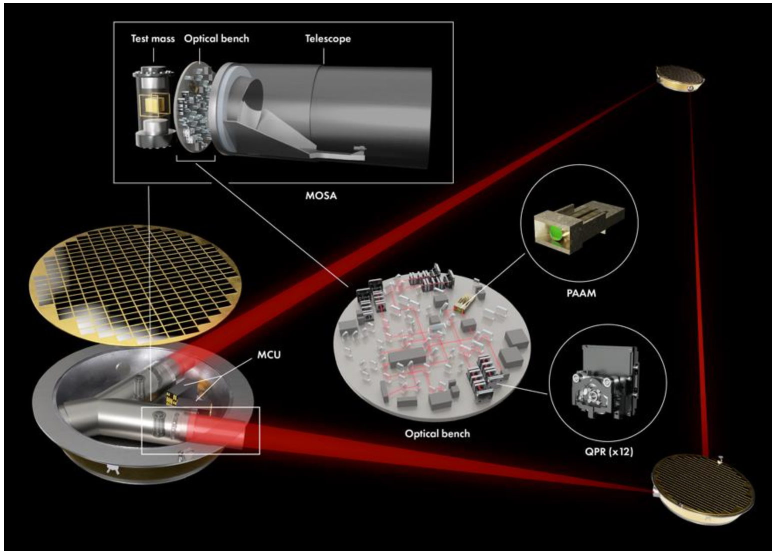


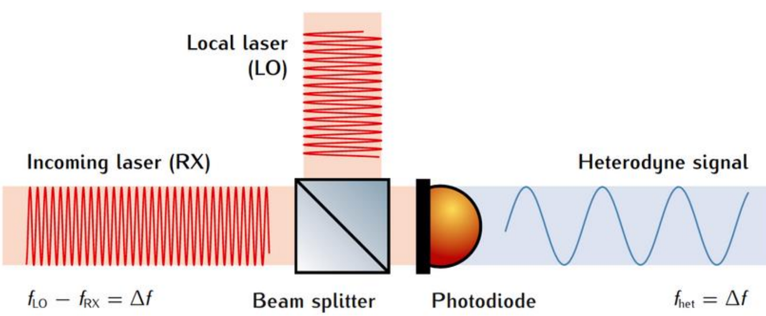


LISA



LISA: Key Dutch hardware contributions

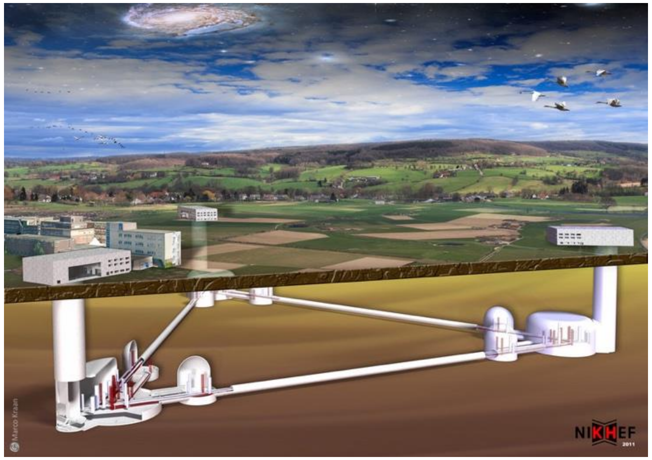


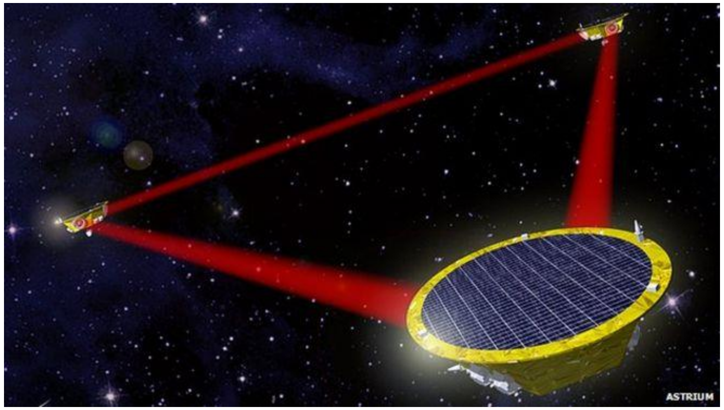


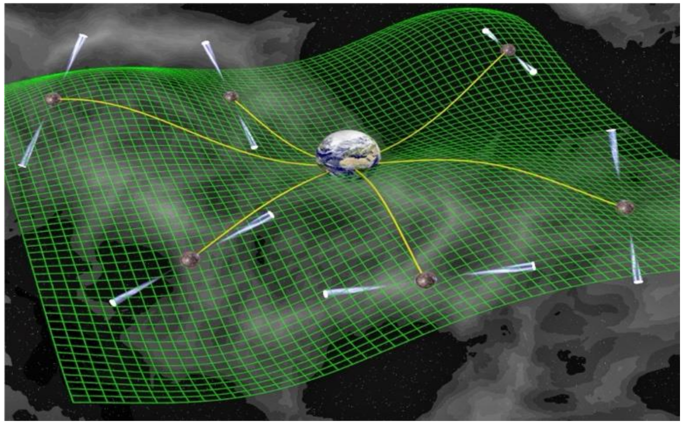
- Point Ahead Angle Mechanism (PAAM)
  - Pointing a laser beam to where the receiving spacecraft *will* be
- Mechanism Control Unit (MCU)
  - Responsible for controlling and monitoring mechanical actuators, including PAAM
- Quadrant Photo-Receiver (QPR)
  - Detecting the science signal!
  - Heterodyne beat signal between incoming laser beam & local laser

Near and long term future

- New discoveries to be expected…







… with new detectors and detection techniques!

Thank you!