Beyond first detection: Instrumental challenges of gravitational wave interferometry

Advanced Virgo

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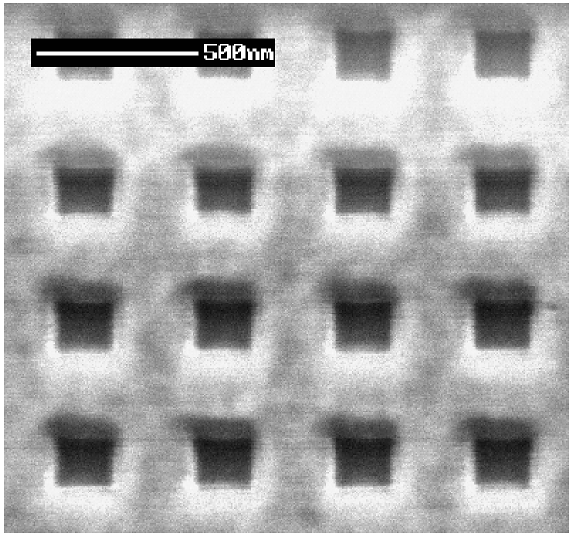
Cascina, Italy

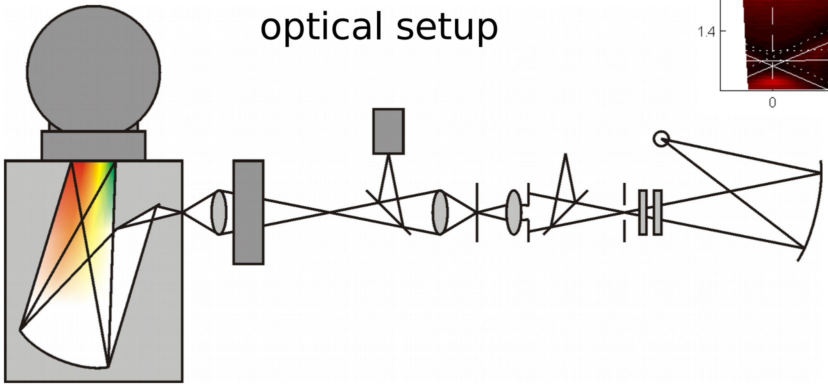
Nikhef Colloquium, 05/07/2017

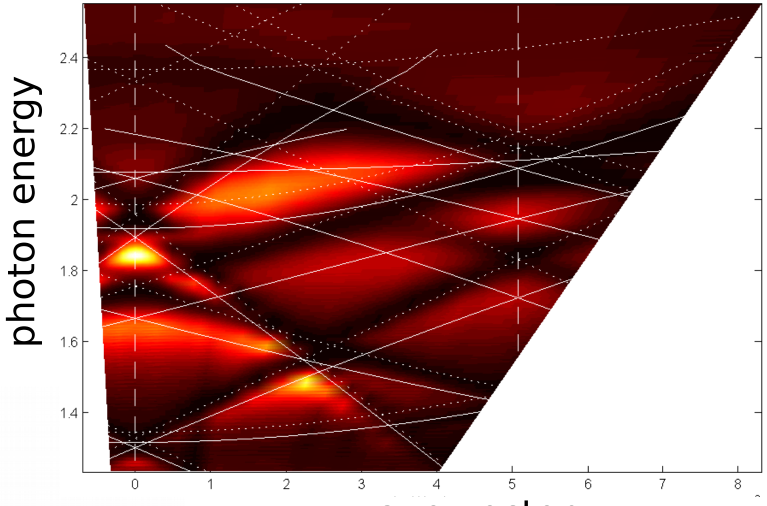
MSc at Twente University (2001)

gold sample



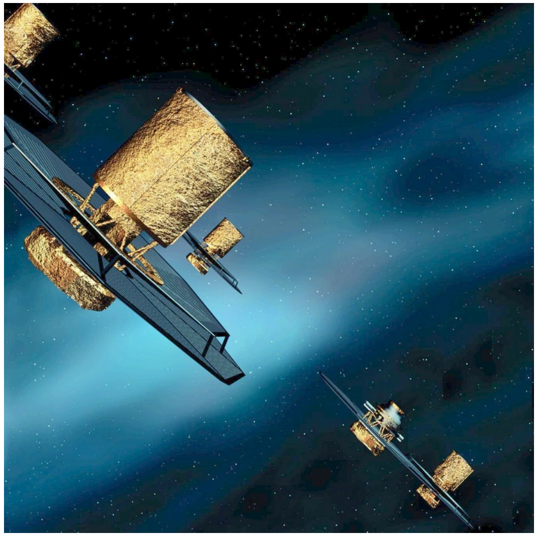
optical setup

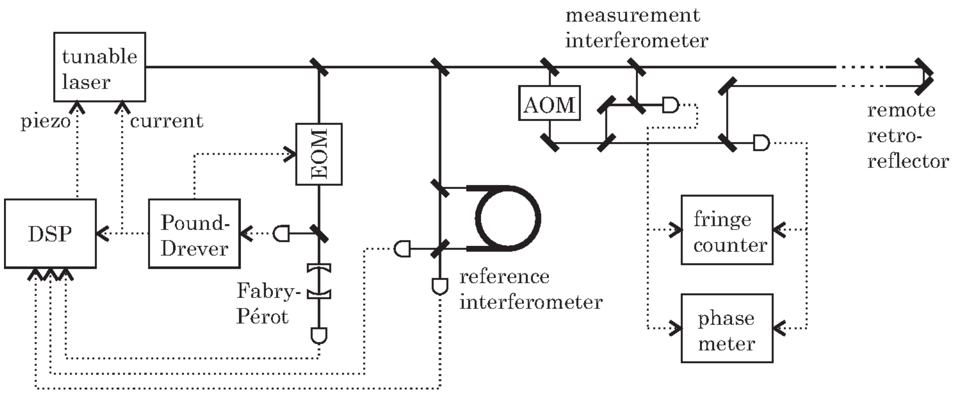


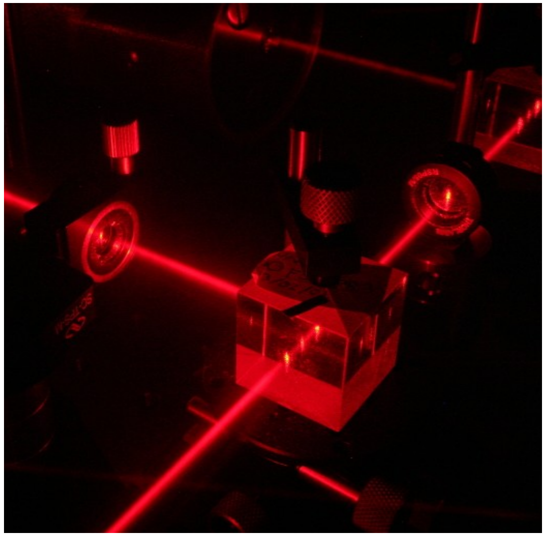


- MSc in Applied Physics, specialization in optics, minor in digital electronics
- Internship in Melbourne, built an erbium-doped fiber laser with fiber Bragg gratings
- Graduated in the nano-optics group of Prof. N. van Hulst / Dr. L. Kuipers
- Thesis project on extraordinary transmission of sub-wavelength hole arrays. Made gold samples, milled hole arrays using a Focused Ion Beam, built spectroscope/microscope to analyze optical properties of the samples.

PhD at Delft University (2006)

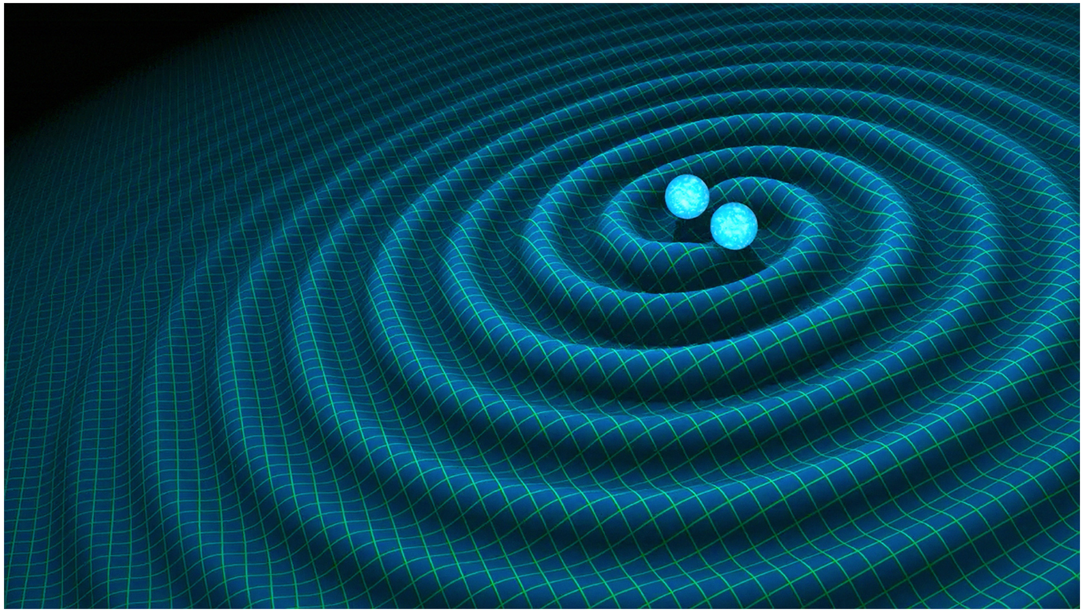


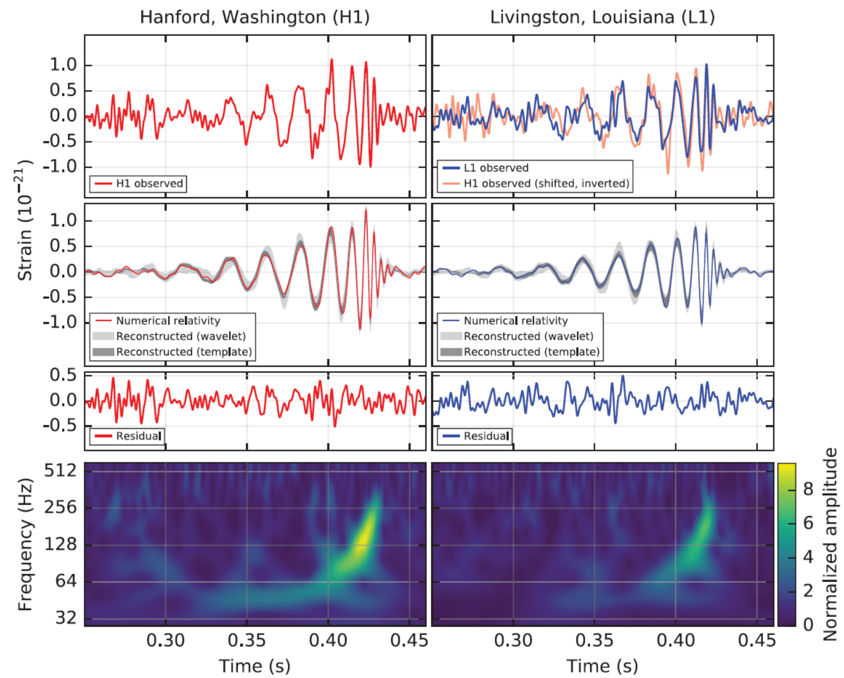




- PhD in Applied Physics, Optics group of Prof. J. Braat, collaboration with TNO Space
- Background: Darwin space mission aimed at detecting exo-planets, optical aperture synthesis using free-flying telescopes separated by ~200 meter.
- White light interferometry: optical path lengths must be equal to within micrometers, needs complex metrology system to make this work
- Goal was to measure absolute distances with high accuracy. Used new scheme of Frequency Sweeping Interferometry, scanning range of a tunable laser fixed on a monolithic Fabry-Perot cavity
- Built optical setup, implemented real-time control system, performed calibration and error characterization. Achieved 100 um repeatability over 100 meter in final results.
- Used Pound-Drever-Hall modulation scheme for stabilizing laser, technique from GW field

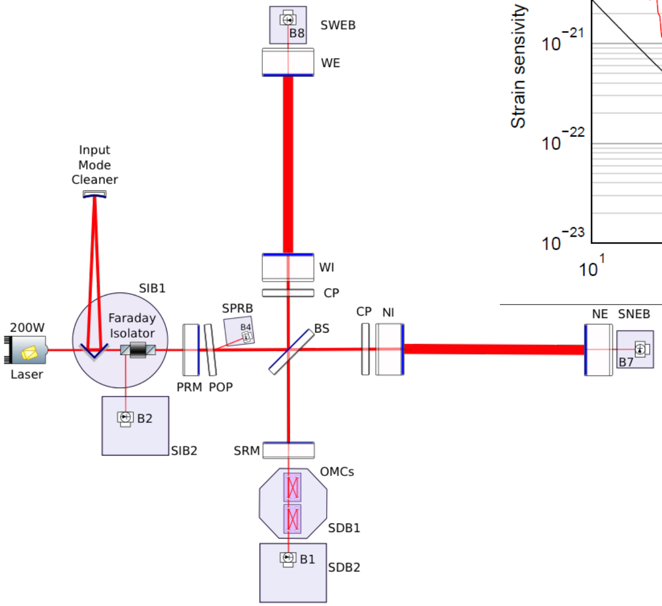
Gravitational waves (GW)

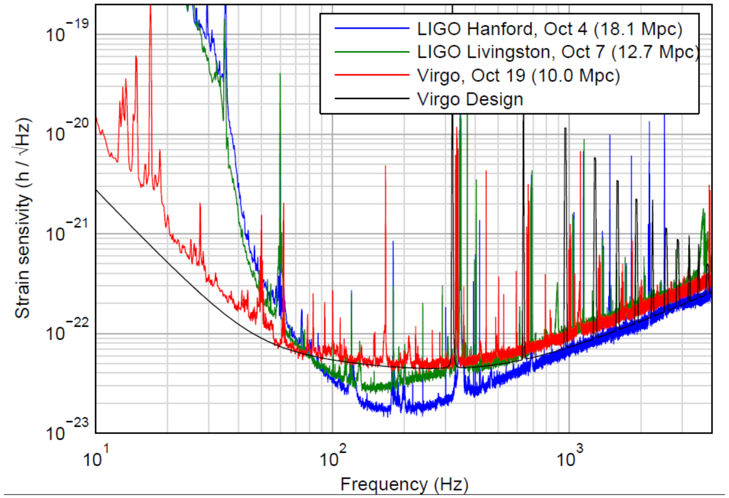




- Natural wave solutions to Einstein's General Relativity, generated when astronomical masses are accelerated to extreme speeds
- New astrophysics: properties of back holes, neutron stars not accessible by telescopes
- Fundamental physics: first tests of General Relativity in the strong-field regime
- **Challenging instrument science**: measure ~10^{-18} m using optical interferometry
- First direct detection of a black hole merger by the 2 LIGO interferometers in 2015

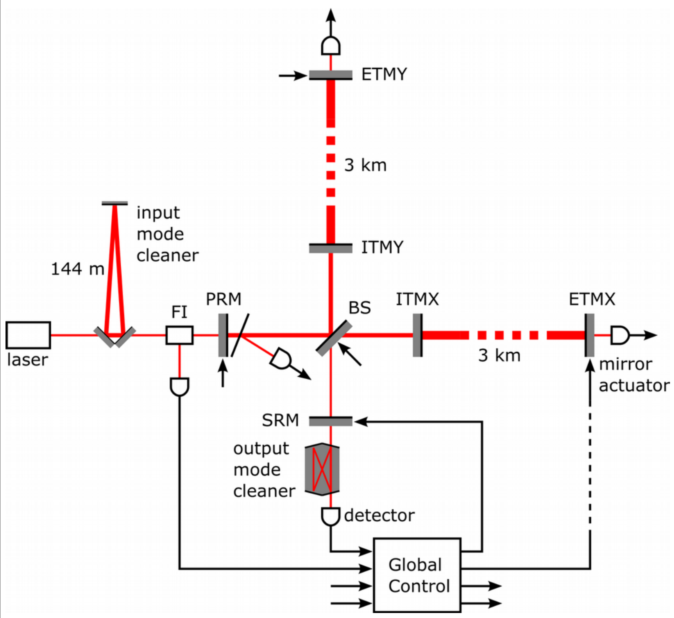
Virgo Interferometer

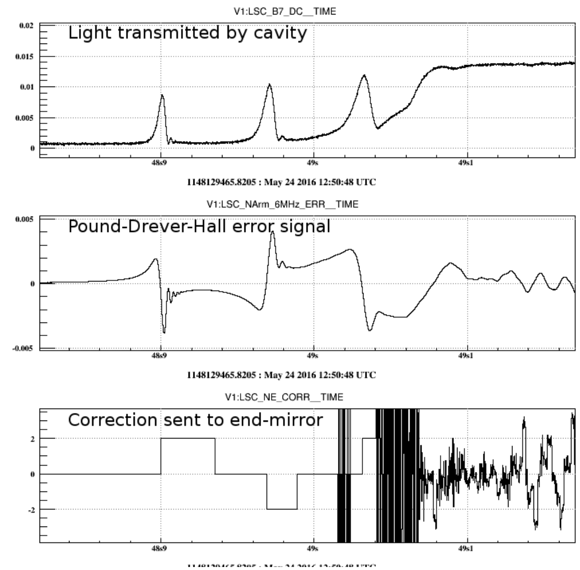


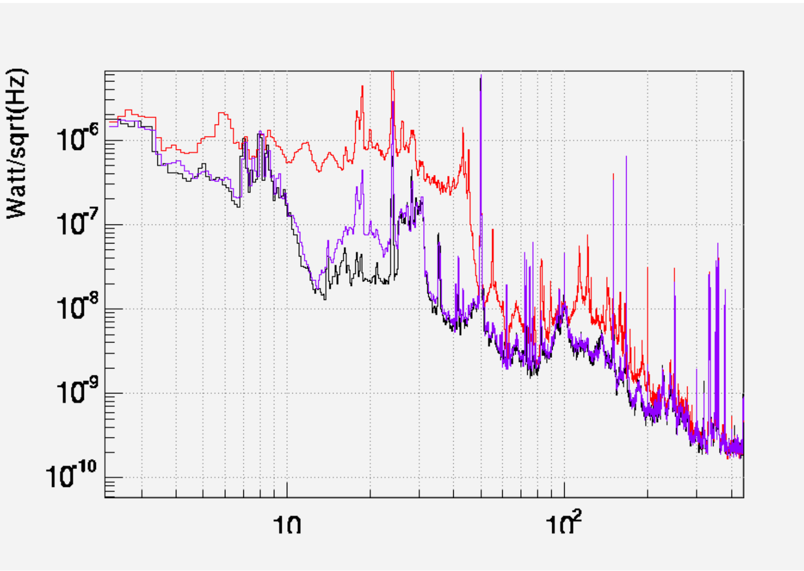


- 3 km long Michelson interferometer with Fabry Perot cavities. Located near Pisa, Italy.
- Worked here as Post-doc and later Staff Scientist (2006-now) on many parts of the experiment
- 4 science runs 2007-2011 together with LIGO, Virgo was better at low frequencies thanks to the advanced seismic isolation system
- Shut down in 2011 for Advanced Virgo upgrade, busy with restart since 2016
- About to start science run together with LIGO next month

Interferometer control

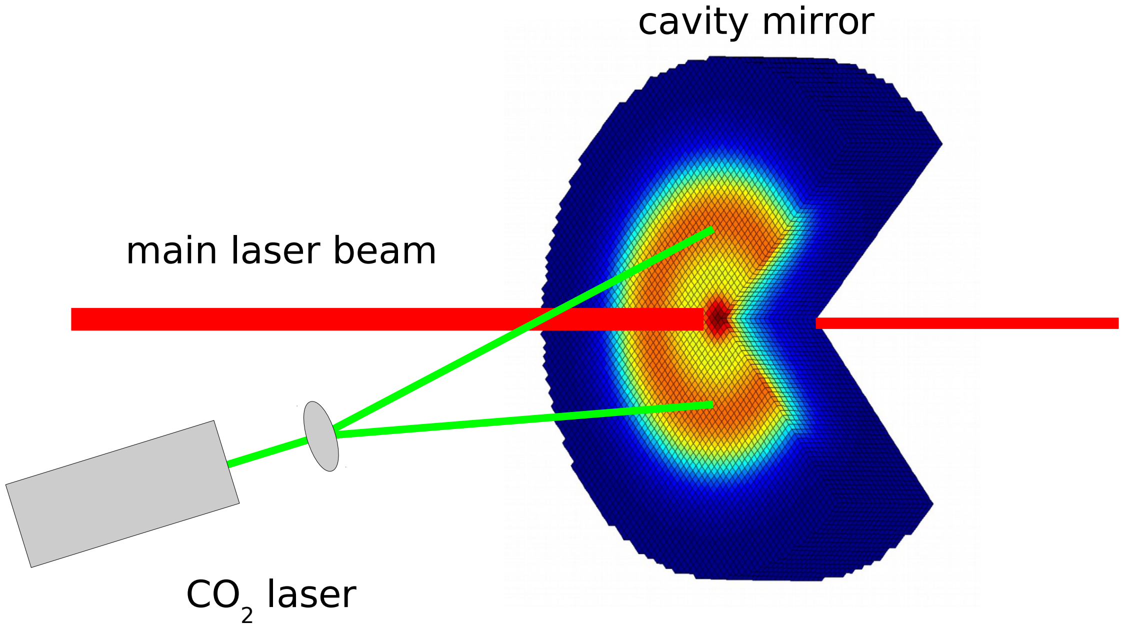






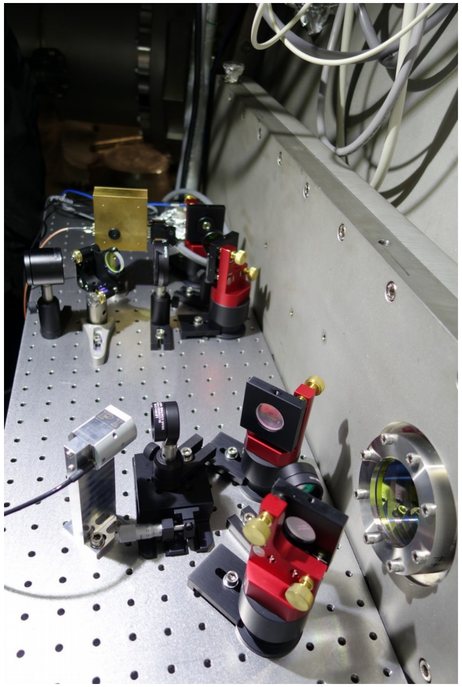
- Interferometer can only detect GW when multiple cavities are all on resonance, requires real-time control of mirror positions with picometer accuracy
- Central to the operation principle of interferometers, the GW signal is suppressed by the feedback of the main loop!
- Non trivial lock acquisition sequence, start with all mirrors freely swinging, error signals that are only linear in a small region: Guided lock technique (see thesis D. Bersanetti)
- Control system with multiple degrees of freedom, suppressing the noise from auxiliary loops is crucial. Subtraction technique enabled unmatched sensitivity at low frequencies

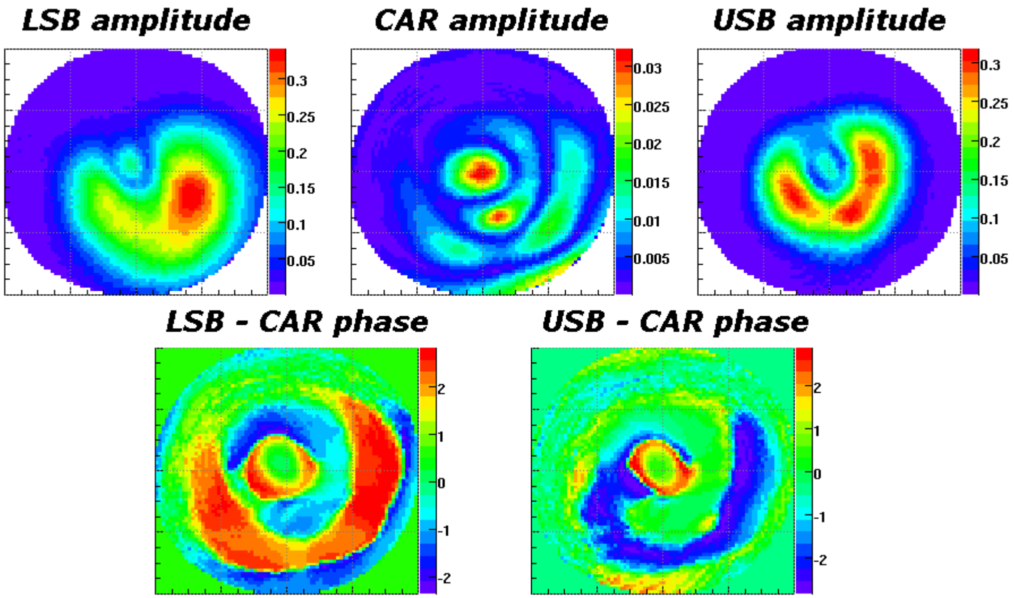
Thermal effects



- State-of-the-art mirrors with low loss coatings, but even a tiny absorption becomes relevant when there is 500 kW of light stored in the resonant arm cavities
- Heating of the coating causes a 'thermal lens', which can disturb resonant optical fields inside cavities. Effect can be mitigated using a Thermal Compensation System
- Finite element simulations of mirror heating, could correctly predict time constants, sensitivity to beam shape
- Fine-tuning thermal effects is crucial for obtaining a good sensitivity and robustness

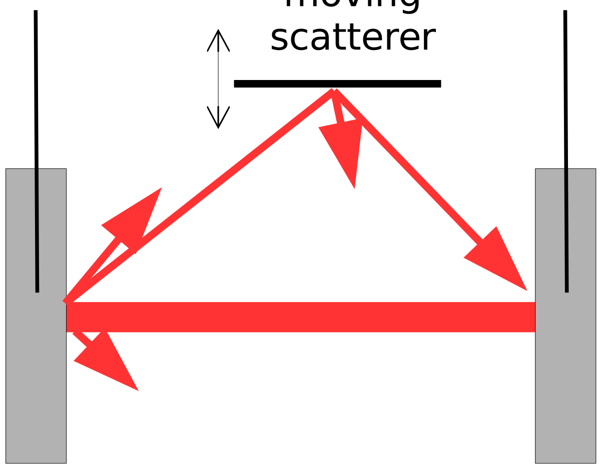
Phase camera

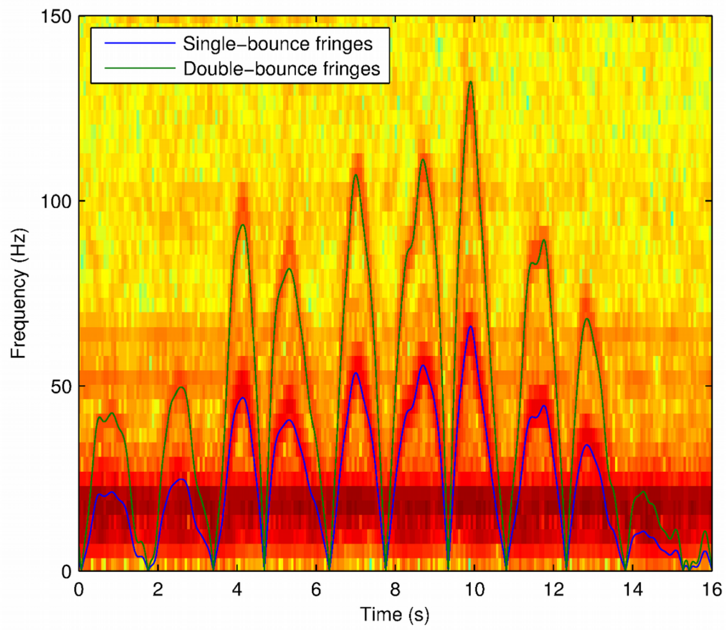




- The main sensor for observing thermal aberrations is the *phase camera*: use scanning mirror and demodulation techniques to spatially resolve individual sideband fields resonating in the interferometer
- Previous analog version was built by Pisa group, use online software to convert time-domain signals into images
- New digital version built by Nikhef, improving the optical design based on previous experience, extract more information in the signal analysis
- System in operation since recently, now trying to characterize the performance of the interferometer based on these signals

Understanding scattered light

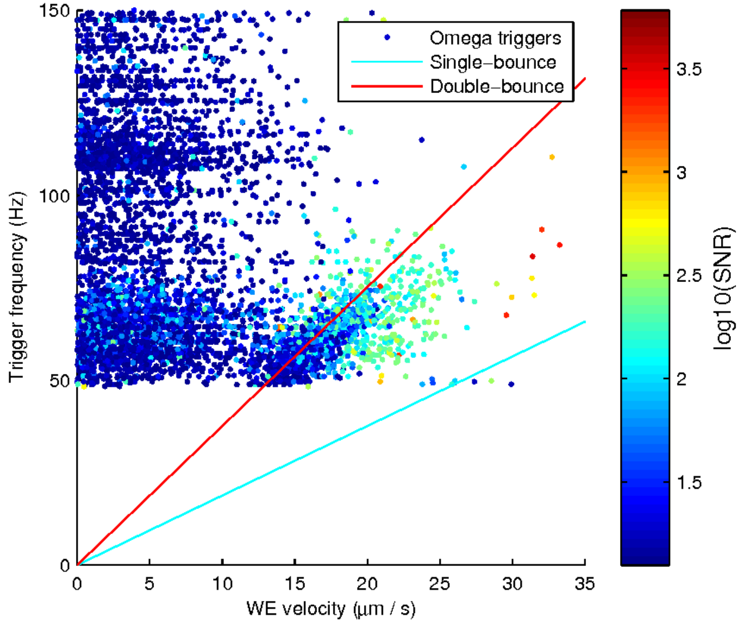


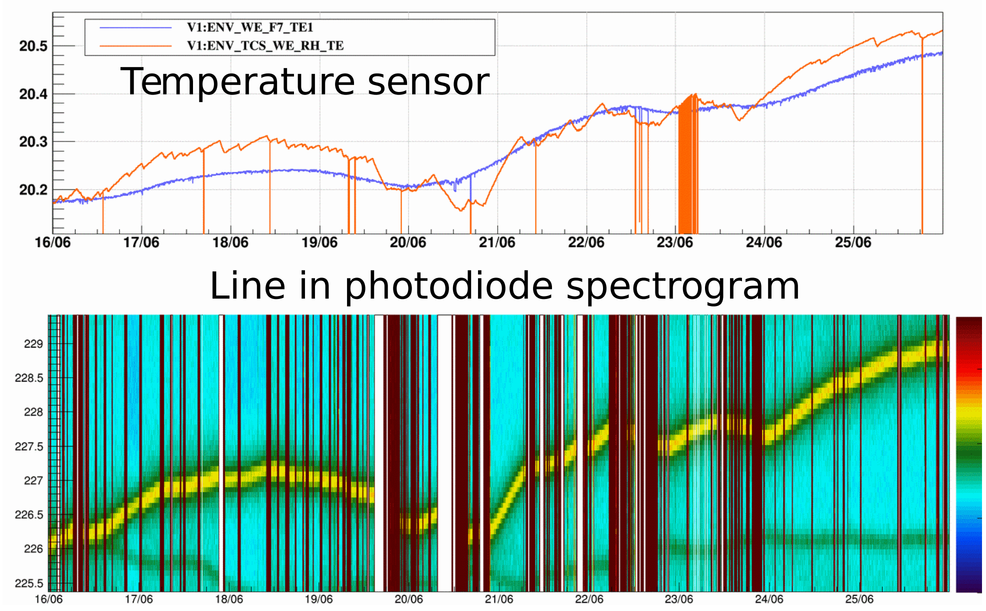


- Mirrors are unfortunately not perfect, tiny fraction of the light scatters out of the beam, hits a vibrating wall and scatters back
- One of the biggest technical challenges: non-linear process that can completely spoil the sensitivity at low frequencies
- Developed theoretical model for understanding this noise, can accurately predict frequency of scattered light 'arches' in the spectrogram
- Two ways to mitigate this noise: reduce amount of scattered light, reduce movement of scatterer

Finding technical noise sources

Koley, Flood, Fiori



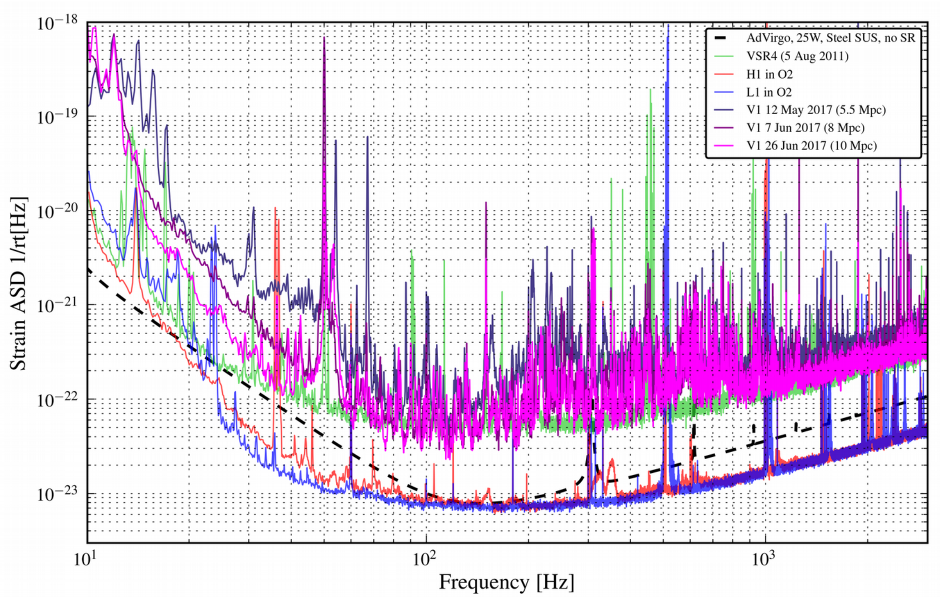


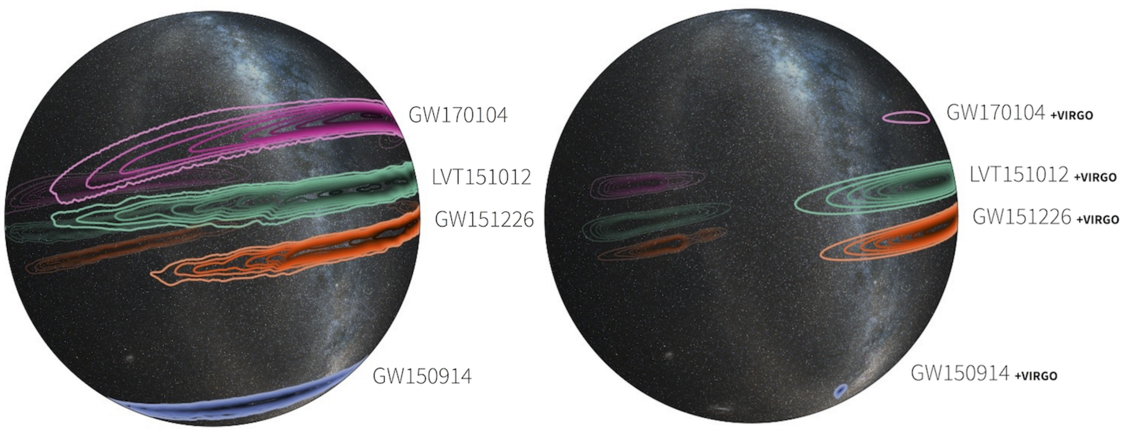
- Sensitivity of the interferometry initially limited by broadband noise, spectral lines and glitches due to technical problems (scattered light, electronic problems, software bugs)
- GW interferometers are very complex: > 1000 control loops, recording ~40000 channels: finding a needle in a haystack. Takes considerable commissioning time to understand and resolve all of them
- Finding the origin of a problem requires a detailed understanding of the machine
- Better to automate this: wrote several tools that look for correlation between glitches or other issues and all channel values, in a brute-force way

Commissioning Coordinator

- Was elected as commissioning coordinator from 2013-2017, lead the initial startup of the interferometer after the Advanced Virgo upgrade
- During this period, went from empty towers to complete integration of most subsystems, all main control loops closed and a fully automated lock acquisition sequence. Challenging time: broken blade springs, constant breaking of fibers that suspend the mirrors, serious software issues
- Pre-alignment: devised system of jigs, laser-diode and screens, geodetic measurements to get beam through tube. Helped discover issue of BS wedge that was installed in the wrong way, solved by redesign of some output optics.
- Reached a horizon of 10 mega-parsec since then

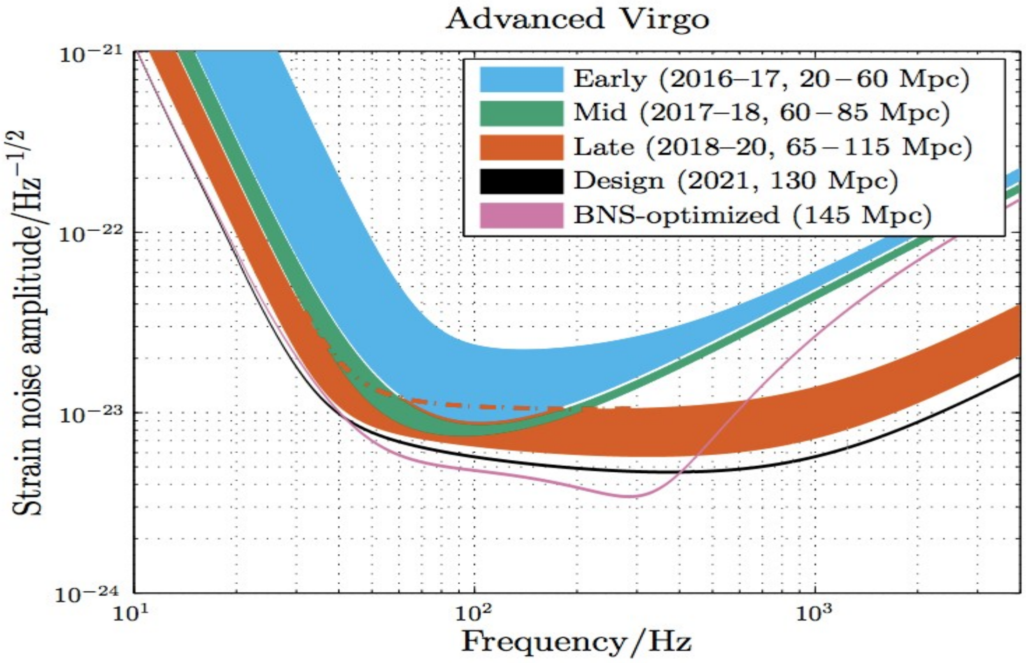
Now: detect GW with Virgo!





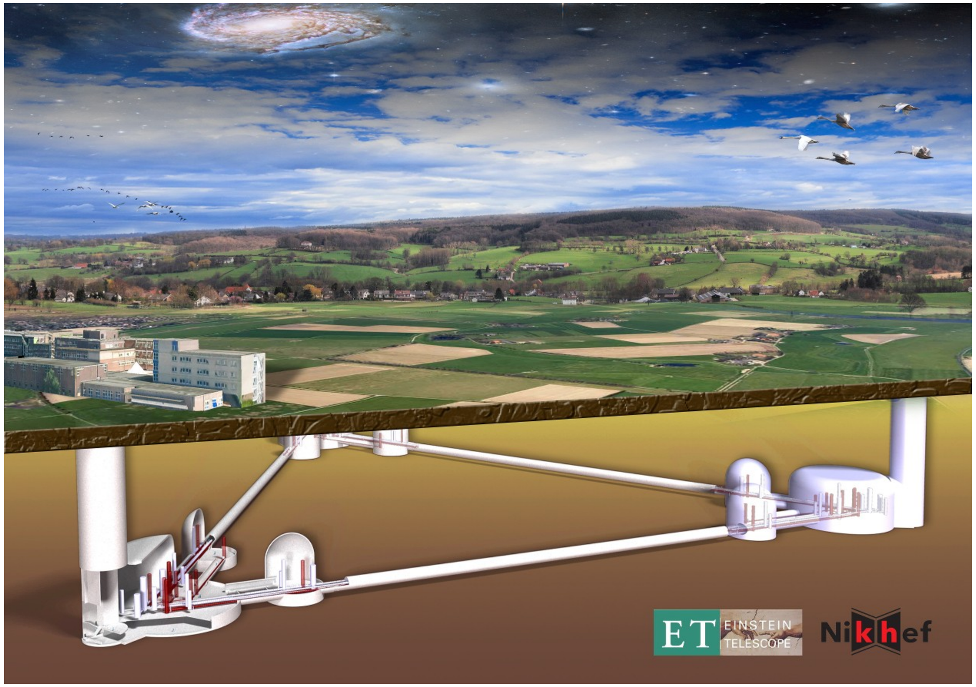
- In the short term: do everything possible so that Advanced Virgo obtains promised range of 20 mega-parsec and detects its first GW
- Aiming to join LIGO's O2 science run in 1 month, operate as a network
- 3rd interferometer is important for sky localization, parameter estimation, improving confidence due to triple coincidence
- Making a detection now is crucial for future of GW community in Europe

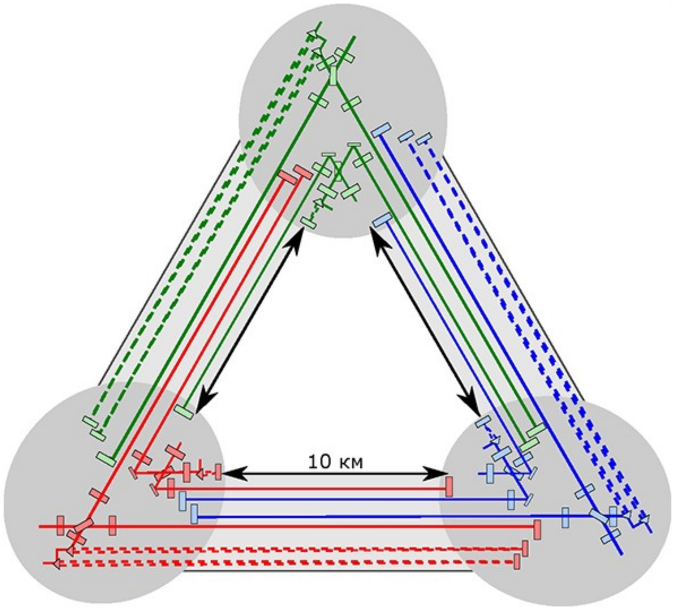
Near future: make Virgo more sensitive



- **Mitigate thermal effects** by using Nikhef's phase cameras as sensor and the Thermal Compensation System as actuator
- **Mitigate scattered light noise**, possibly by developing interferometric distance measurements between suspended benches and mirrors to damp the relative velocity
- **Add signal recycling mirror** to get a sensitivity similar to LIGO. This requires a new lock acquisition method, using an auxiliary laser system. Complex system, Nikhef could contribute to the complex electronics

Long term: make ET possible

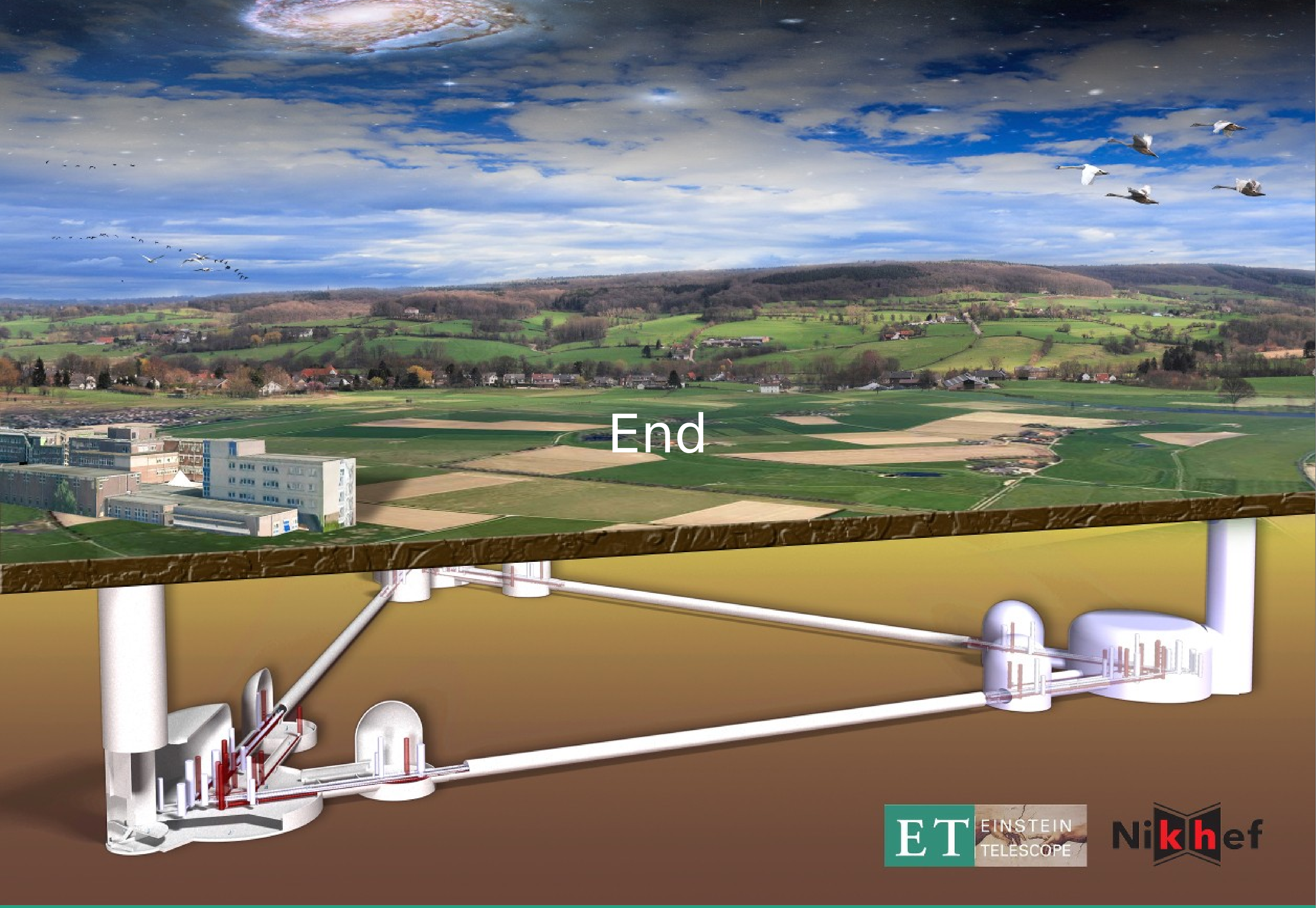




- To significantly increase sensitivity, third generation facility like the Einstein Telescope (ET) need to be realized: longer, underground, cryogenic, and possibly in the Netherlands!
- Advanced sensors: phase camera, digital demodulation of photodiodes
- More advanced distance metrology systems: control velocities between suspended objects to reduce scattered light, interferometric readout of seismometers, auxiliary laser systems for making lock acquisition more robust
- Construct test facilities for integrated testing of sub-systems: reduce 'machine time'
- Very large scale project: need to involve industry in the construction

Concluding

- Gravitional waves were recently detected for the first time
- Only the beginning of an era, many known and unknown science is still to be done
- Advancing requires multiple, more sensitive observatories: very challenging instrument science
- Short time goals: make existing facilities work at their promised sensitivity, take data as a network and detect more GW
- Long term goals: realize third generation facilities, need to invest in development of advanced hardware and test facilities now
- Huge opportunity for Nikhef and the Netherlands to play a leading role in the future of the GW field
- My knowledge of optics, GW interferometers and signal analysis, and my contacts in the GW field and Dutch optics industry would be valuable for realizing these ambitions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ET
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