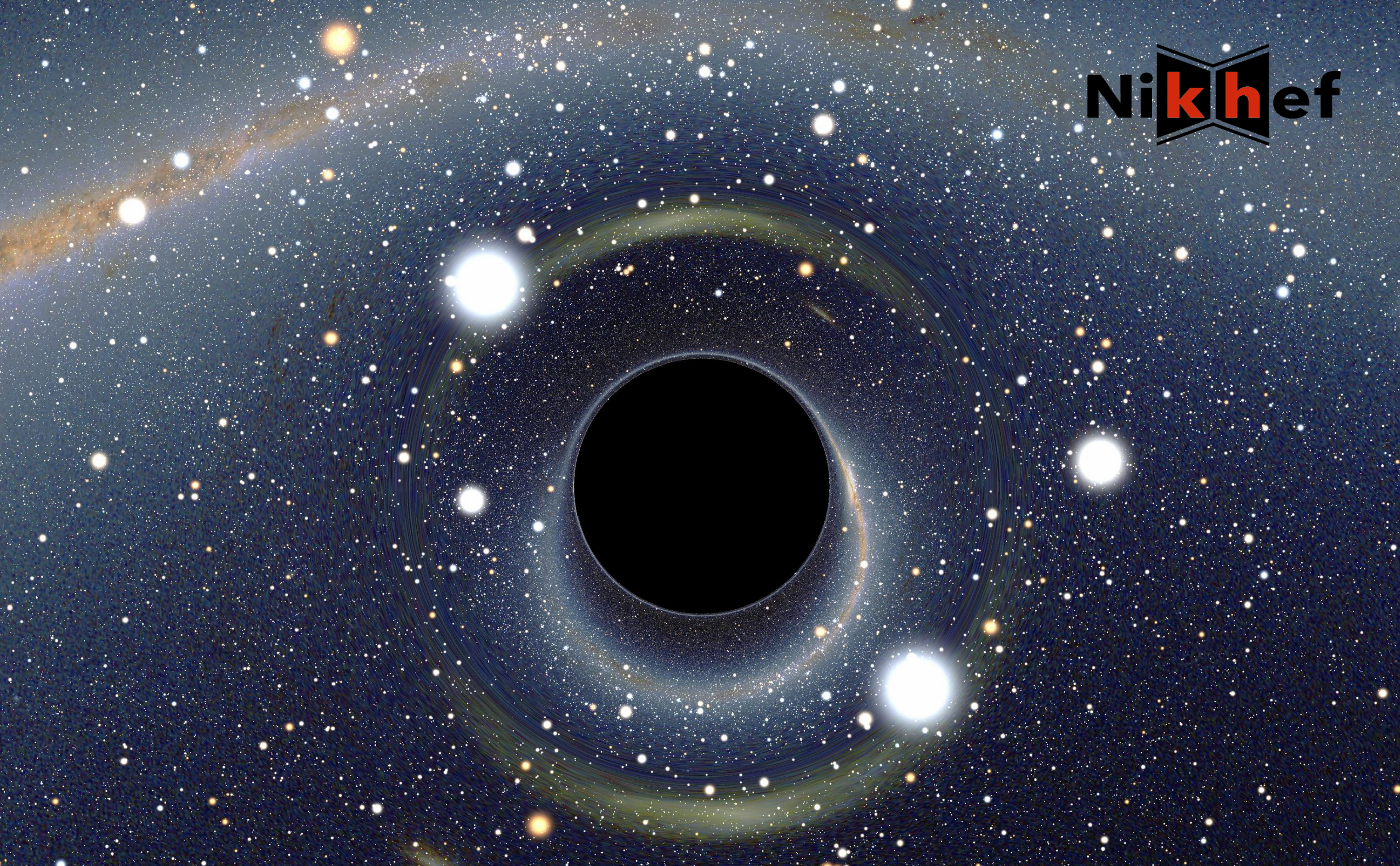


Nikhef

Connecting black hole collisions to seismic sensing

Jo van den Brand, Nikhef and VU Amsterdam

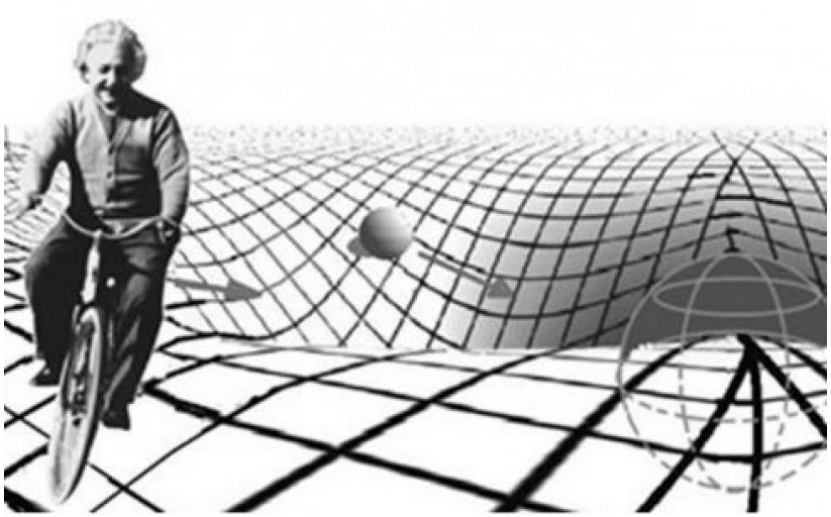
Connecting Strength of Big Science, June 10, 2016

Einstein's theory of general relativity

Einstein discovers deep connections between space, time, light, and gravity

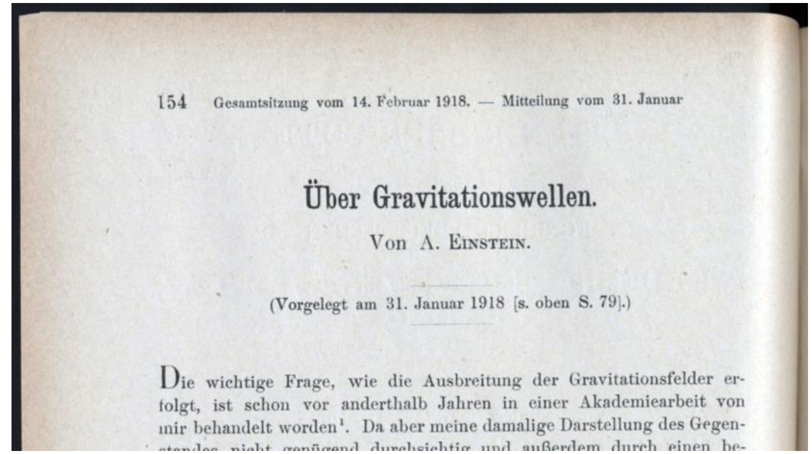
Einstein's Gravity

- Space and time are physical objects
- Gravity as a geometry



Predictions

- Gravitation is curvature of spacetime
- Light bends around the Sun
- Expansion of the Universe
- Black holes, worm holes, structure formation, …
- Gravitational waves



154 Gesamtsitzung vom 14. Februar 1918. — Mitteilung vom 31. Januar

Über Gravitationswellen.

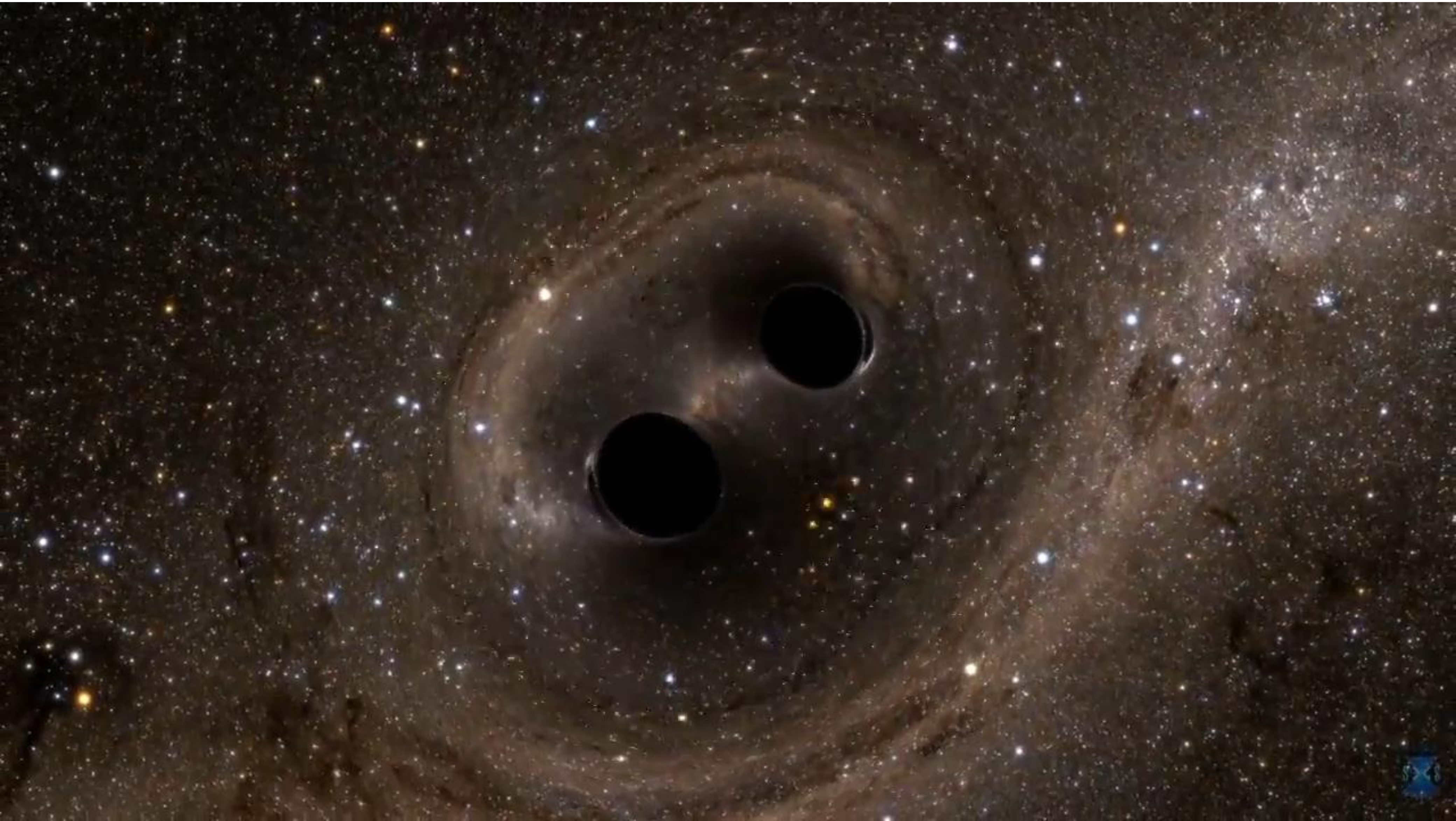
Von A. Einstein.

(Vorgelegt am 31. Januar 1918 [s. oben S. 79].)

Die wichtige Frage, wie die Ausbreitung der Gravitationsfelder erfolgt, ist schon vor anderthalb Jahren in einer Akademiearbeit von mir behandelt worden[1]. Da aber meine damalige Darstellung des Gegen-

Event GW150914

Chirp-signal of gravitational waves from two merging black holes has been observed by the LIGO-Virgo Consortium on September 14, 2015



Observation of GW from the merger of two black holes

At least five major discoveries were reported on February 11, 2016 by the LIGO Virgo Consortium

Discoveries

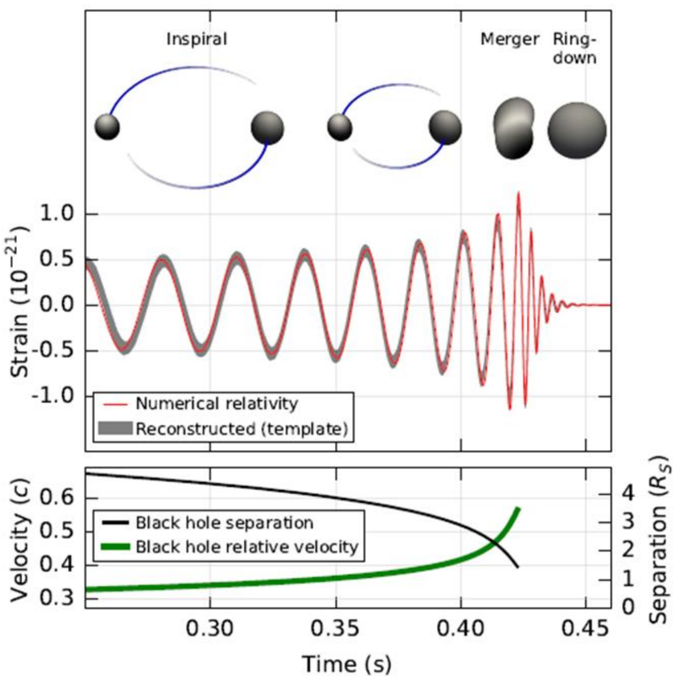
Gravitational waves were detected directly for the first time

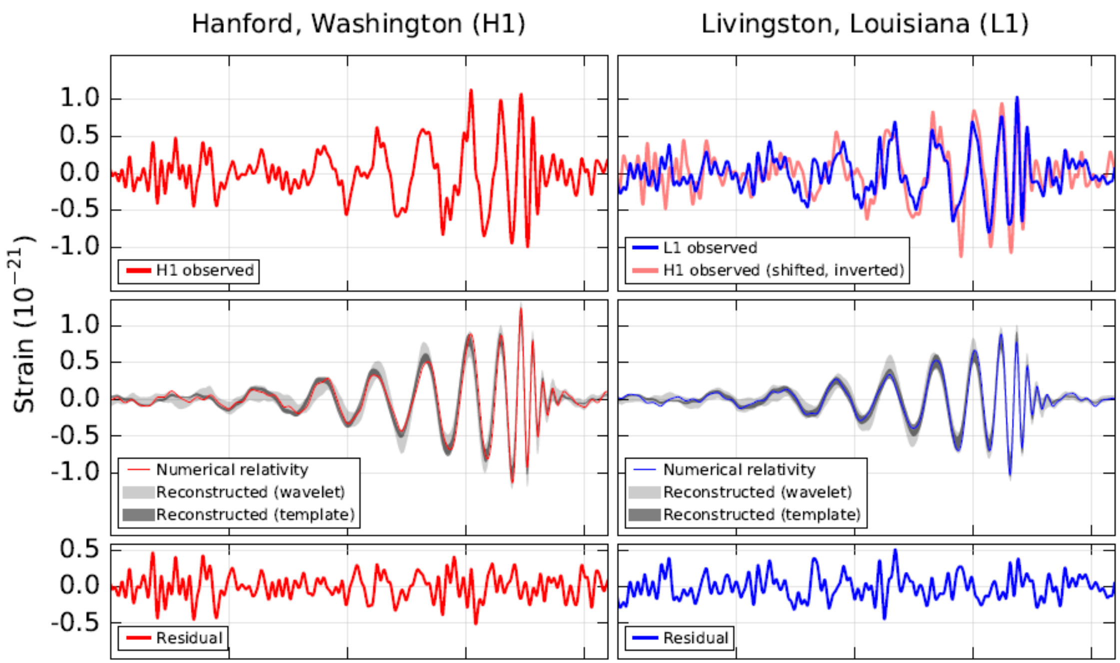
A black hole binary was observed

The creation and ring-down of a single black hole could be studied

Einstein's theory of general relativity could be tested in the strong-field gravity regime

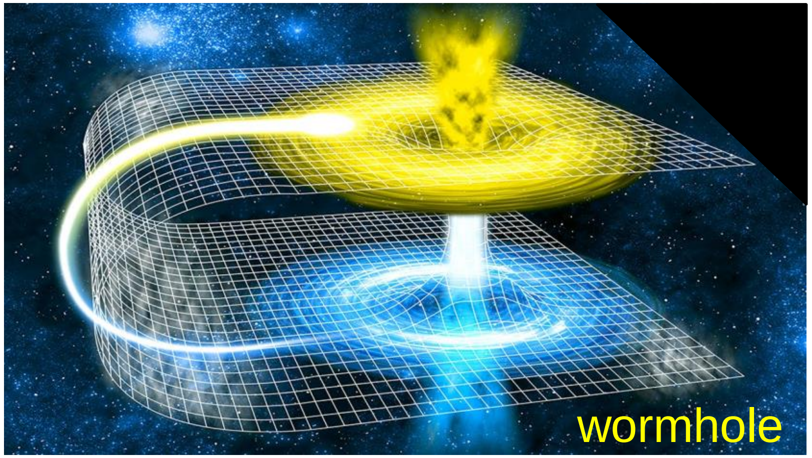
The most powerful event ever was observed: at the peak of the merger more power was emitted than all galaxies in the universe combined

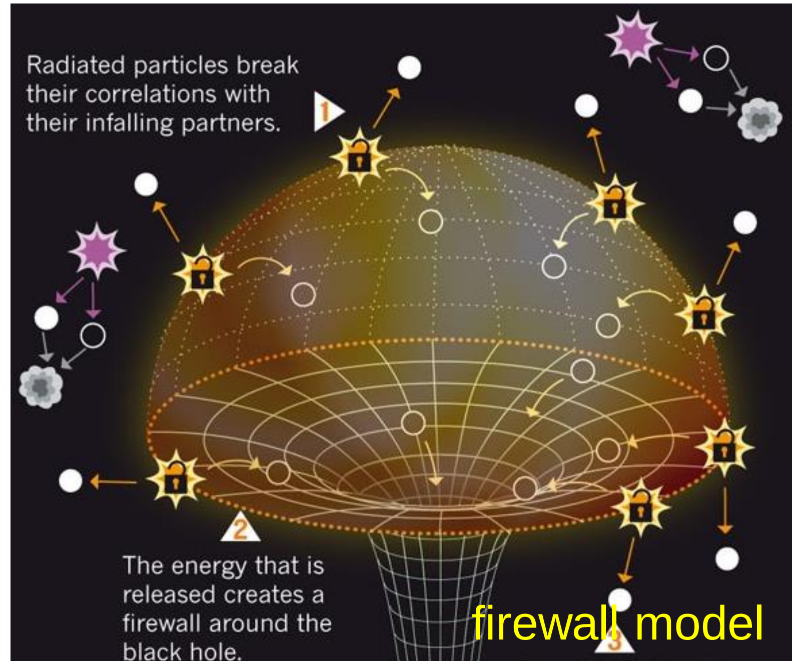


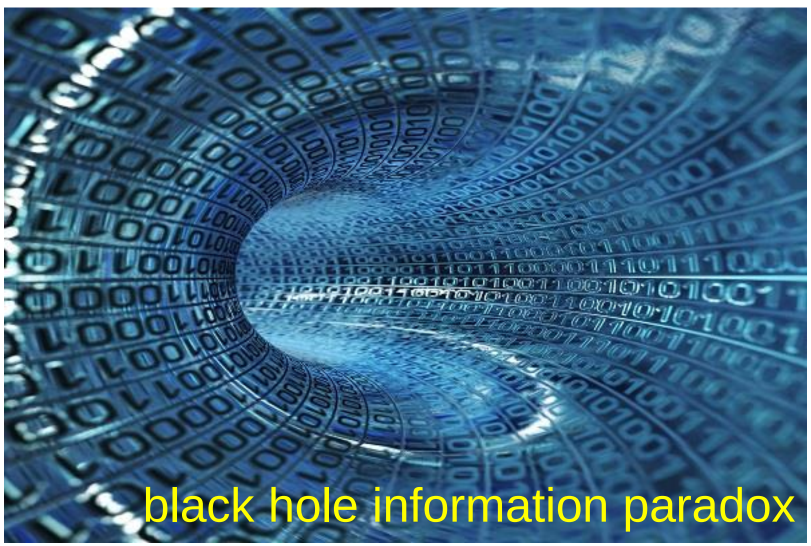


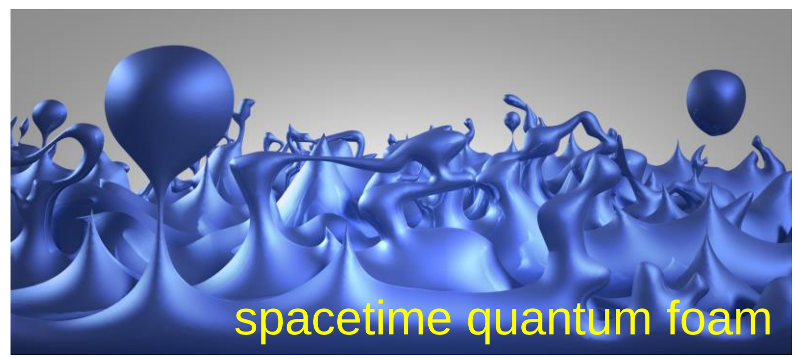
Did we observe black holes?

Our theories “predict” the existence of other objects, such as worm holes, boson-stars, gravastars, firewalls, etc. The ring-down signals contain important information



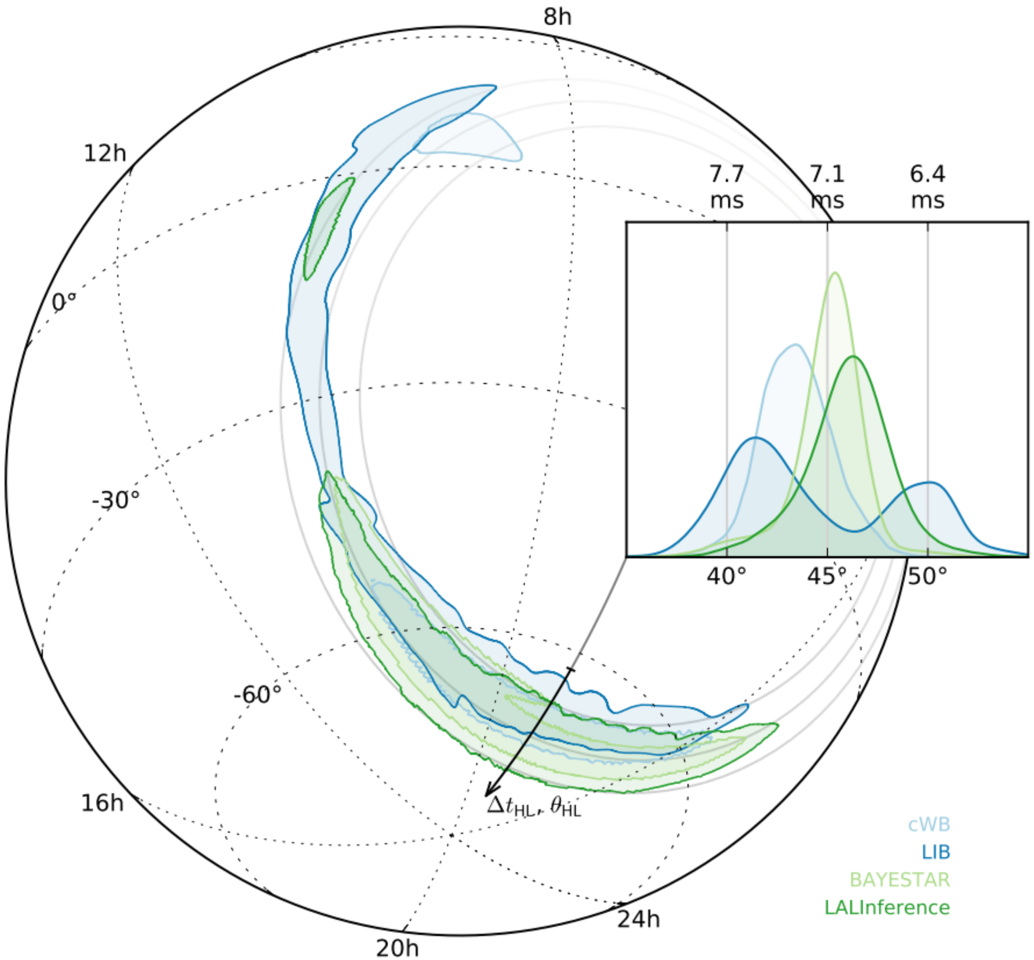


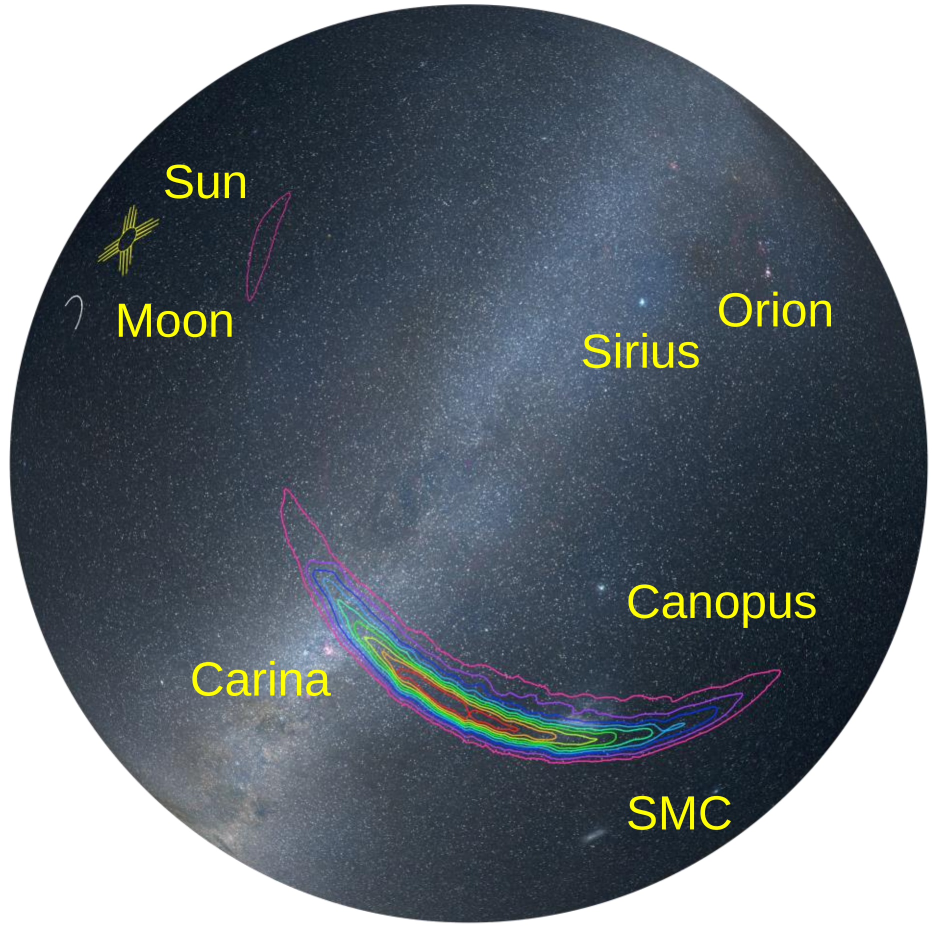




Sky localization probability maps

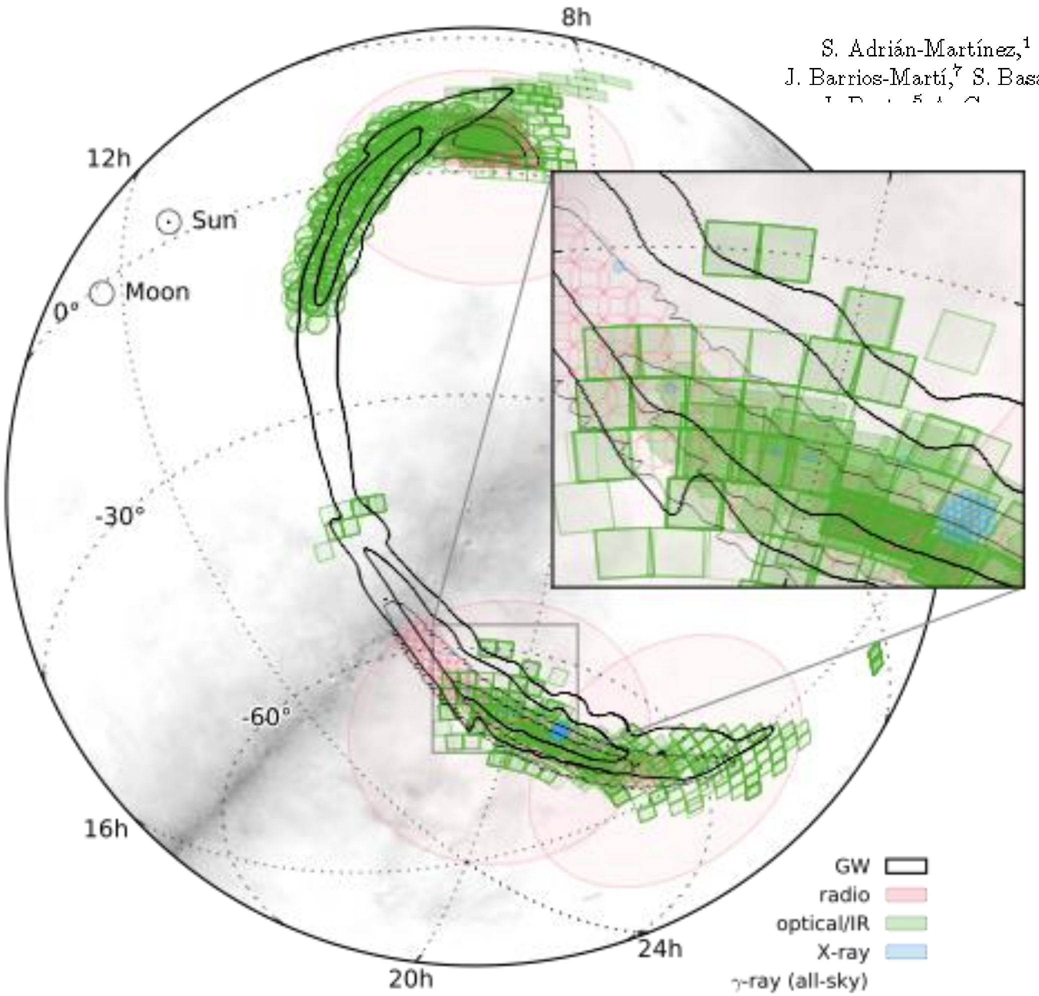
Sky at the time of the event, with 90% credible level contours. View is from the South Atlantic Ocean, North at the top, with the Sun rising and the Milky Way diagonally from NW to SE





Towards multi-messenger astronomy

Sky map for GW150914 was sent to astronomers (agreements with 74 groups), and they looked.
However, we do not expect any EM emission from binary black holes



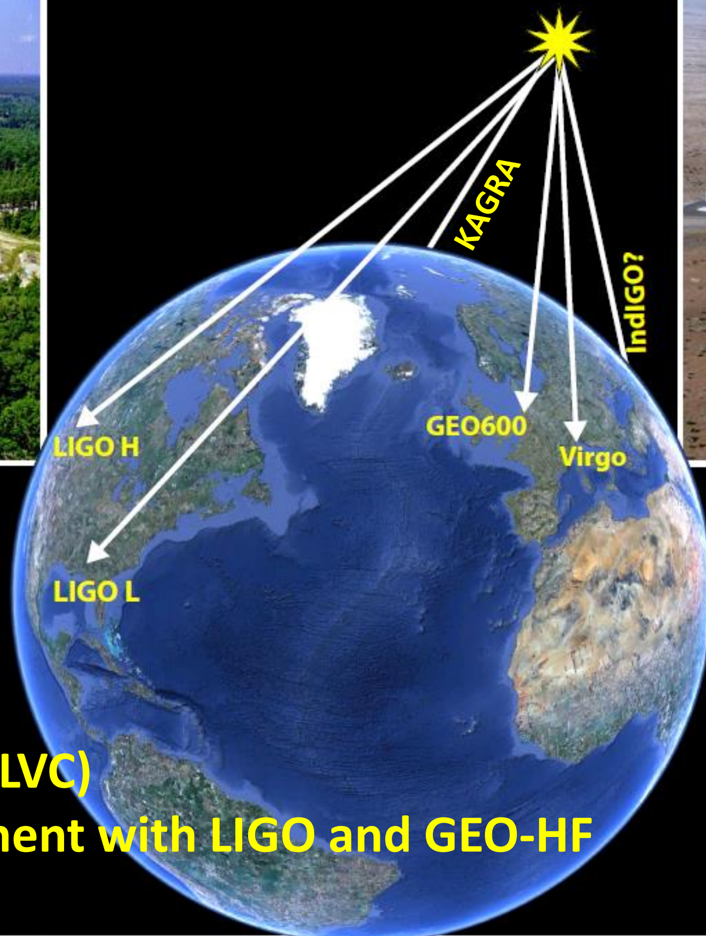
High-energy Neutrino follow-up search of Gravitational Wave Event GW150914 with ANTARES and IceCube

S. Adrián-Martínez,[1] A. Albert,[2] M. André,[3] G. Anton,[4] M. Ardid,[1] J.-J. Aubert,[5] T. Avgitas,[6] B. Baret,[6] J. Barrios-Martí,[7] S. Basa,[8] V. Bertin,[5] S. Biagi,[9] R. Bormuth,[10,11] M.C. Bouwhuis,[10] R. Bruijn,[10,12] J. Brunner,[5]

arXiv 1602.05411

Footprints of Tiled Observations

Group	Area (deg^2)	Contained probability (%) cWB[a]	LIB[b]	LALInf[c]
Swift	2	0.6	0.8	0.1
DES	94	32.1	13.4	6.6
INAF	93	28.7	9.5	6.1
J-GEM	24	0.0	1.2	0.4
MASTER	167	9.3	3.3	6.0
Pan-STARRS	355	27.9	22.9	8.8
SkyMapper	34	9.1	7.9	1.7
TZAC	29	15.1	3.5	1.6
ZTF	140	3.1	2.9	0.9
(total optical)	759	76.5	46.8	23.9
LOFAR-TKSP	103	26.6	1.3	0.5
MWA	2615	97.8	71.8	59.0
VAST	304	25.3	1.7	6.3
(total radio)	2623	97.8	71.8	59.0
(total)	2730	97.8	76.8	62.1



LIGO Virgo Collaboration (LVC)
Completed first measurement with LIGO and GEO-HF

KAGRA in 2020
LIGO India approved!

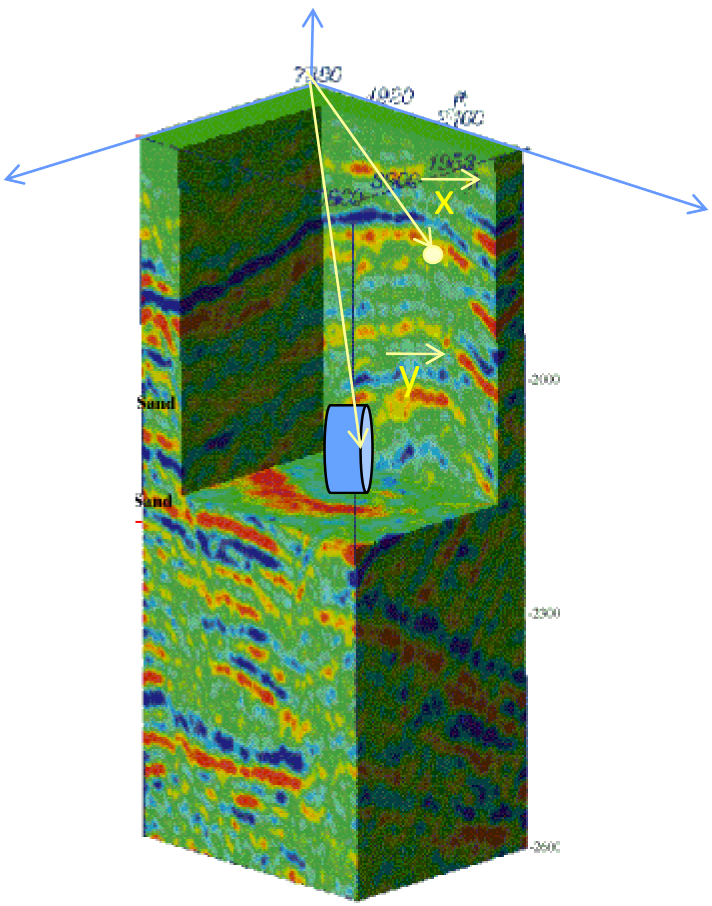
Technological innovation in opto/mechanics, and sensors

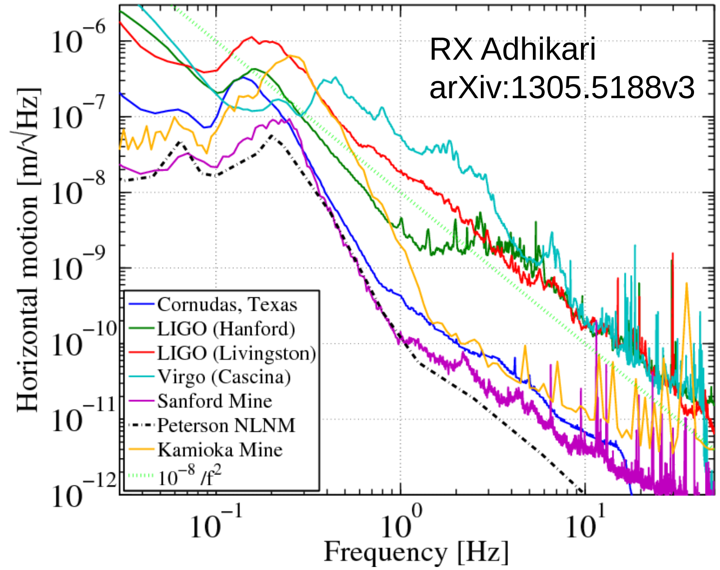
Developments in large optical components, coatings, interferometer controls, and vibration isolation. Here we discuss an example on sensor development and from spin-off activities at Nikhef

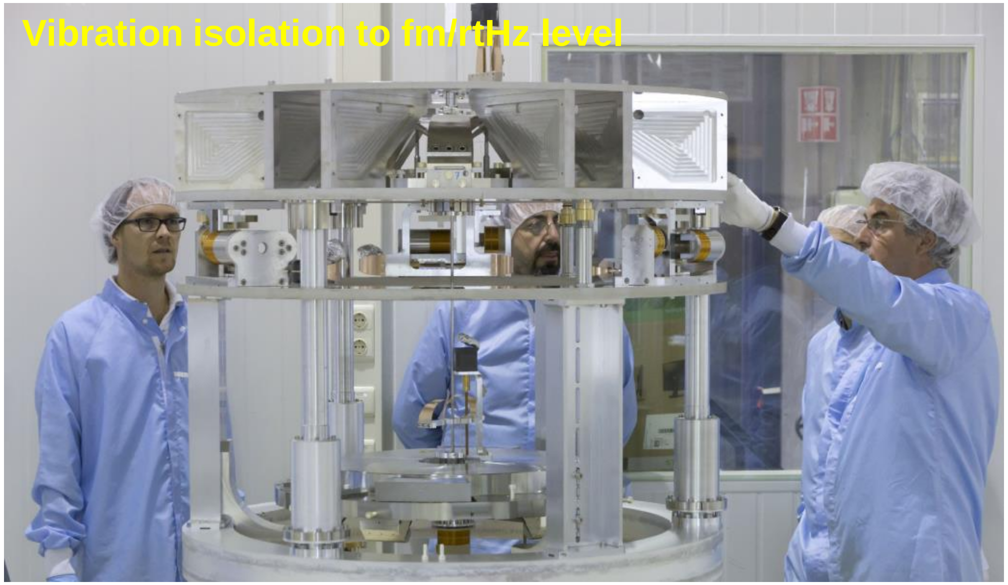
Issues

Seismic ground motion is about 10^{12} times higher than the GW effects. Thus vibration isolation systems are needed

Moreover gravity gradient noise can only be subtracted by sensor networks. This triggered sensor development

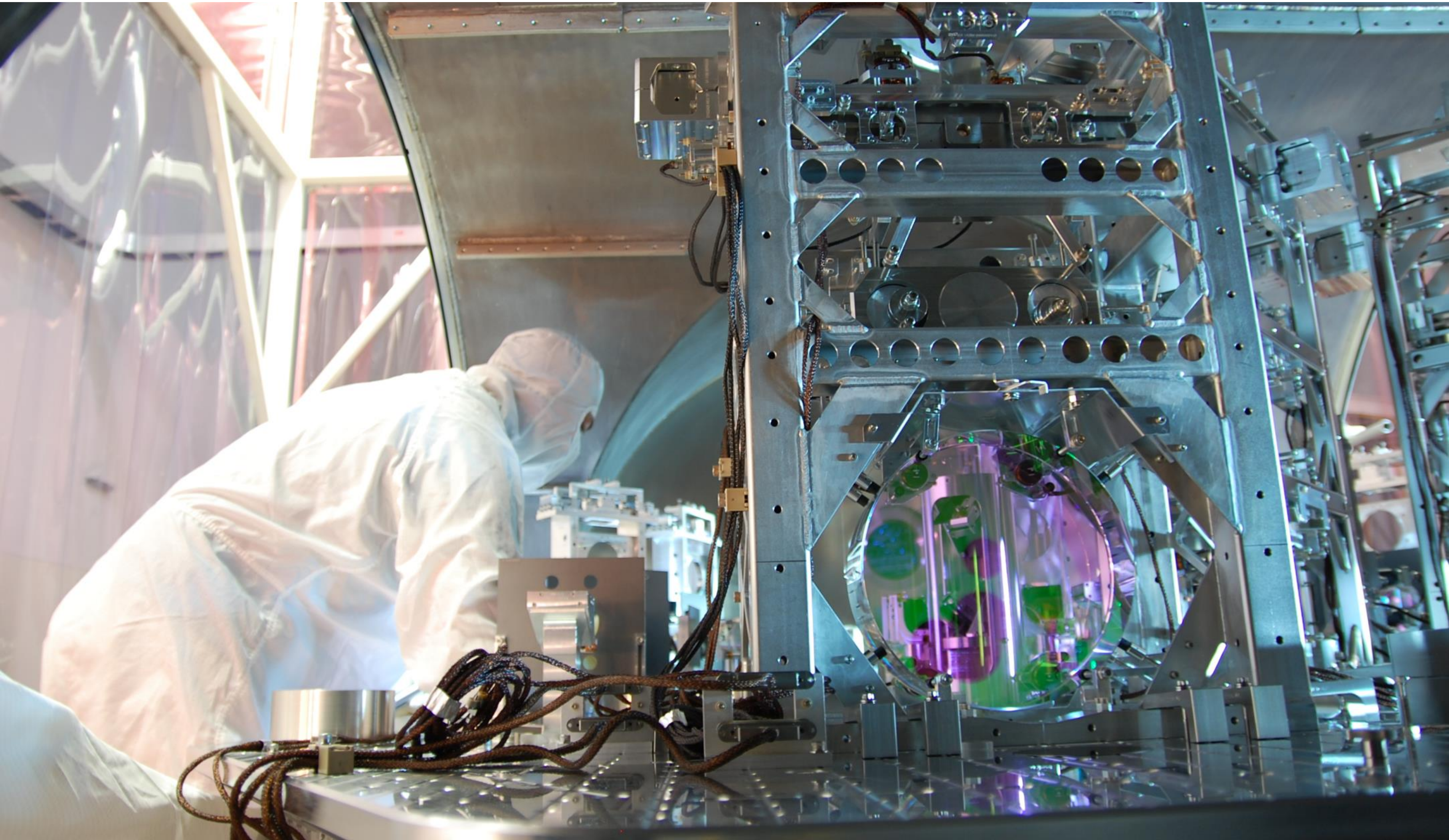


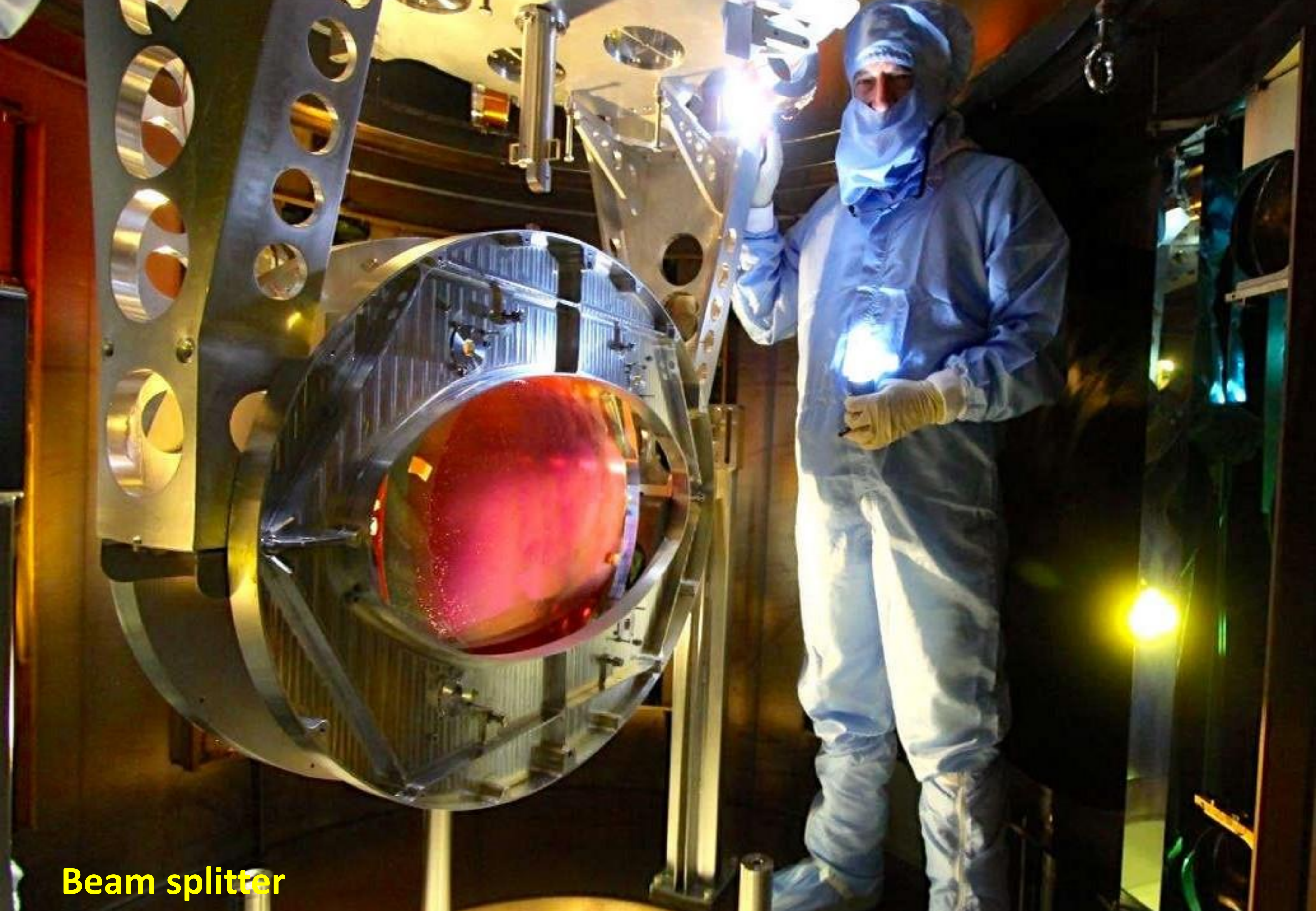




Optics, mechanics, electronics, controls, vacuum

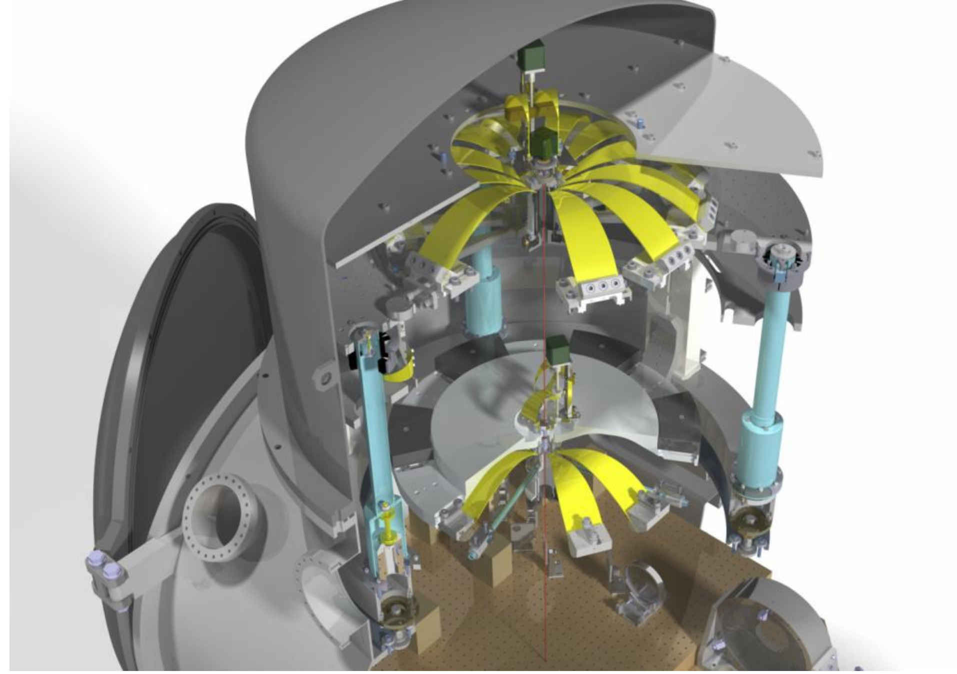
Mirror for “power recycling”





Beam splitter


Suppress vibrations up to a factor billion



Examples of spin-off from gravitational wave research

Stanford Photo-Thermal Solutions

- LIGO and Virgo optics must have very low loss. The company "Stanford Photo-Thermal Solutions" markets the device developed for LIGO. It sells primarily to the basic optics and homeland security markets.

See: http://www.ligo.org/science/faq.php#spinoffs

Prof Stuart Reid (Univ of West of Scotland)

- Working with cell biologists on adapting sensing techniques from GW technology to control stem cell differentiation for bone healing - spin-off company in progress.

See: http://www.bbc.com/news/uk-scotland-glasgow-west-22035696

Dr Siong Heng and OPTOS Ltd ("*The* Retina Company" acquired by NIKON)

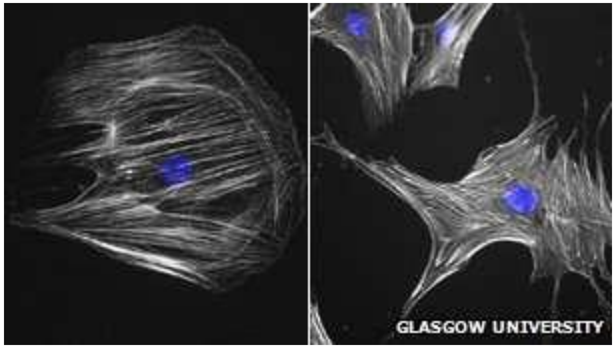
- Working with OPTOS Ltd developing algorithms for automated artefact detection for scanning laser ophthalmoscopes - potential to make significant savings by adopting new automated Quality Assurance processes during the manufacturing process.

See: http://censis.org.uk/censis_projects/optos2_gu/

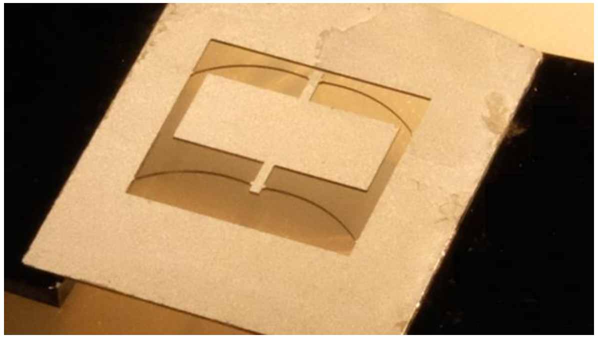
Dr Giles Hammond, (Univ of Glasgow)

- Working with several industrial partners on utilising spin-offs from core GW technology research to build low frequency ultra-sensitive MEMS gravimeters with applications in the energy, security and geophysics fields. Patent filed (GB Parent Application No: 1415087.4).

See: http://www.bbc.com/news/science-environment-35926147



Stem cell control: After the stem cells are "nanokicked" they turn into bone cells



MEMS gravimetry: Carved from a sheet of silicon, the sensor contains a weight (the central slab) suspended by thin, curved shafts

Seismic noise determines low frequency sensitivity

Gravitational wave astronomy requires seismically quiet sites in order to minimize both seismic and Newtonian noise (also called gravity gradient noise)

Nikhef has strong role in site selection

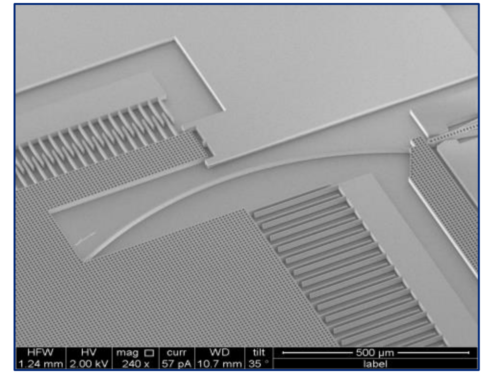
- Seismic and Newtonian noise
- Global seismic noise characterization
- Subtraction of seismic effects

Low power seismic sensing and MEMS accelerometers

- Innoseis founded in 2013

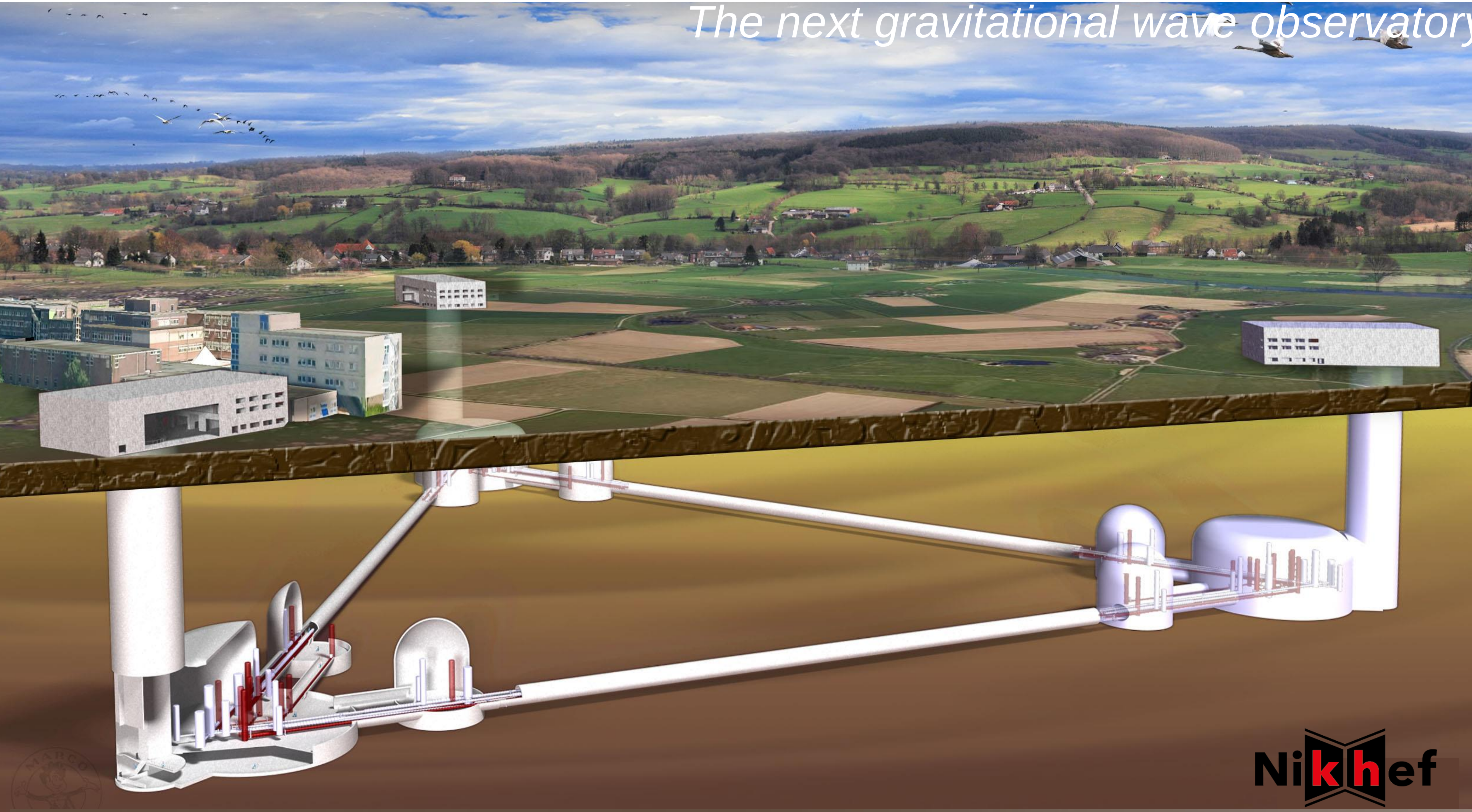
Relationship to oil & gas exploration

- Partnership with Shell
- Computing Science Energy Research



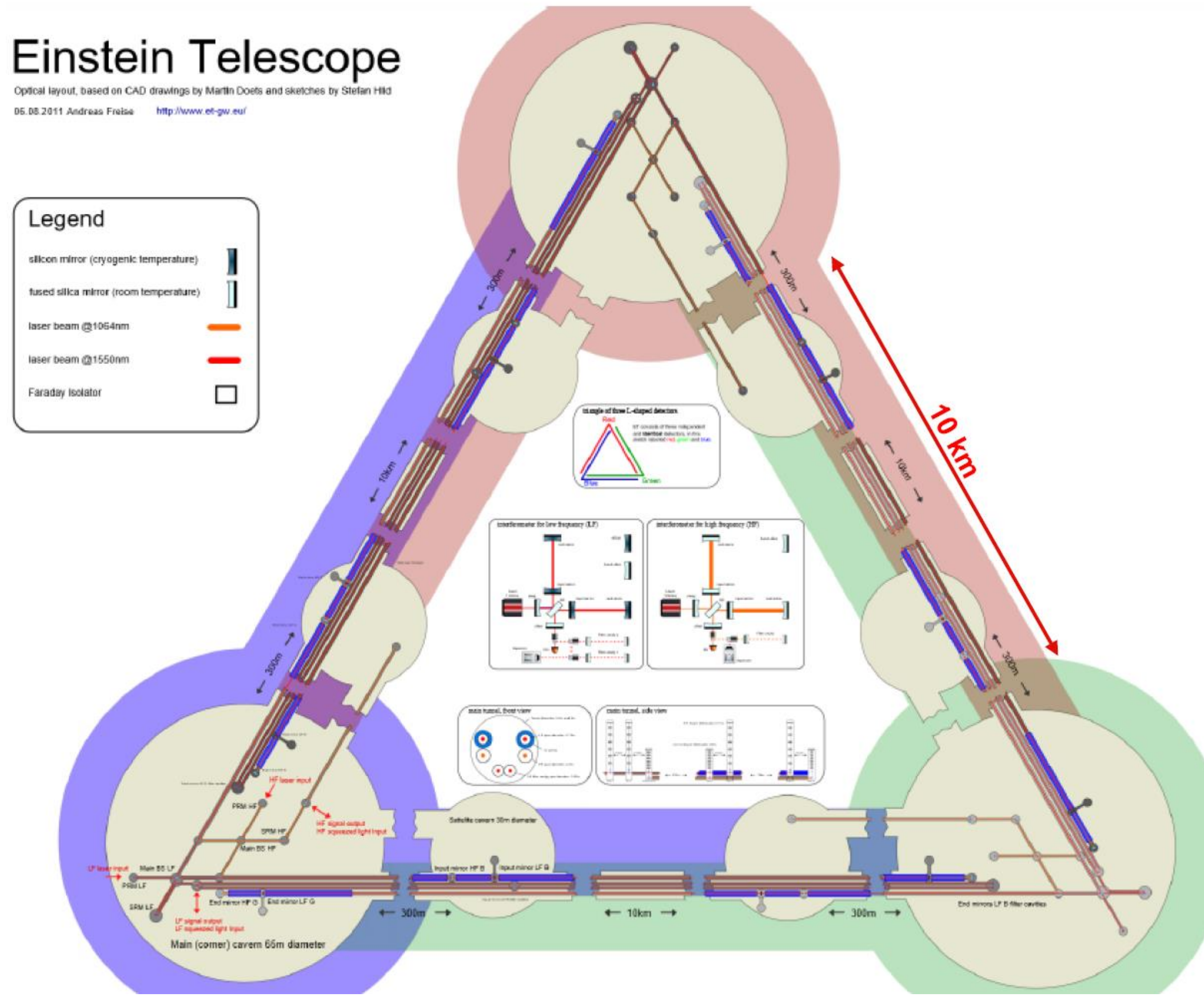
Einstein Telescope

Ultimate facility to study gravity: dark ages, (primordial) black holes, cosmography, early Universe



Technology

Einstein Telescope will be at the frontier of technology. Innovations are required in mechanics, optics, controls, computing, etc.



Einstein Telescope: cosmography

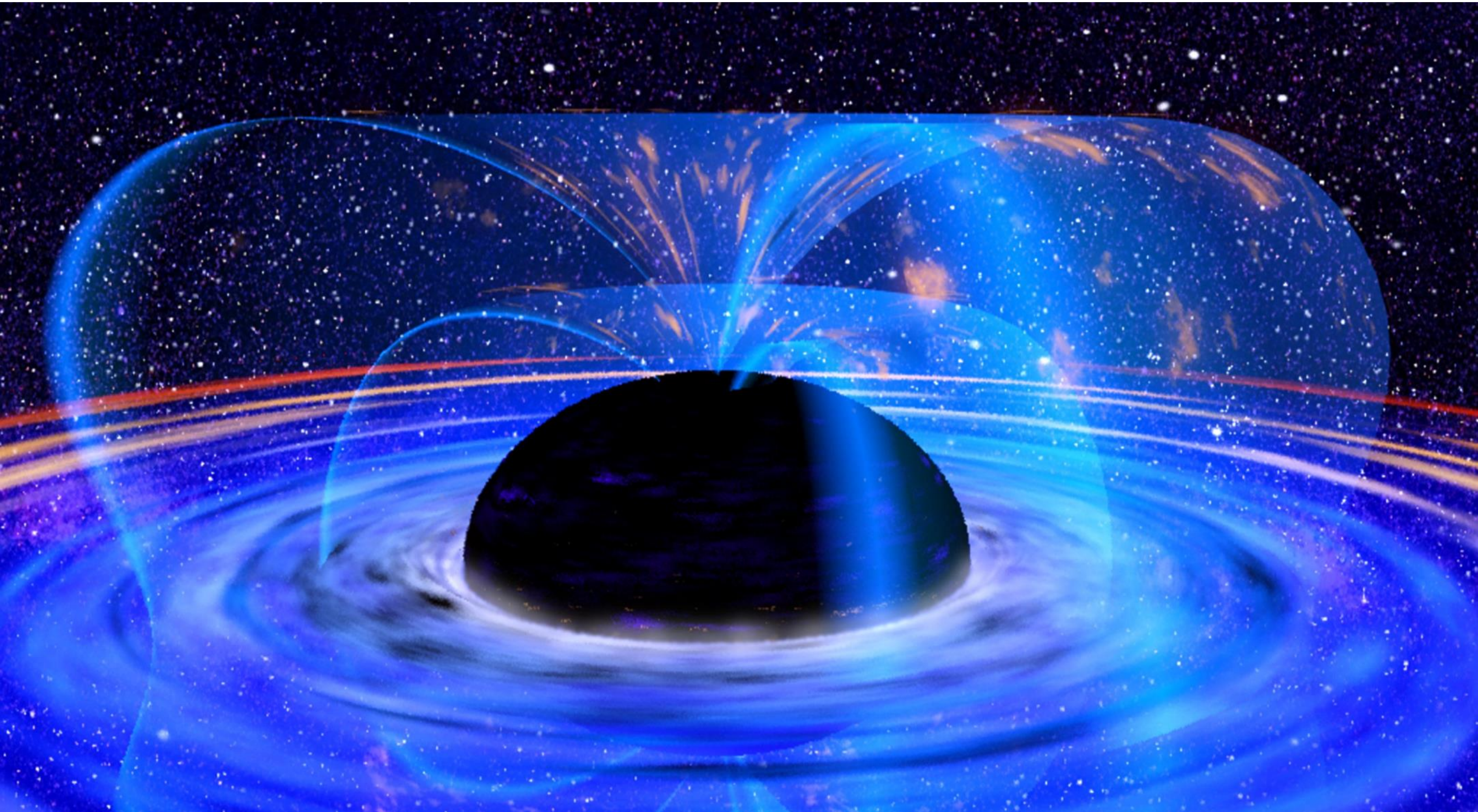
What is this mysterious dark energy that is tearing the Universe apart?

Use BNS and BBH as standard “candles” (so-called “sirens”)

Einstein Telescope: fundamental physics

What happens at the edge of a black hole?

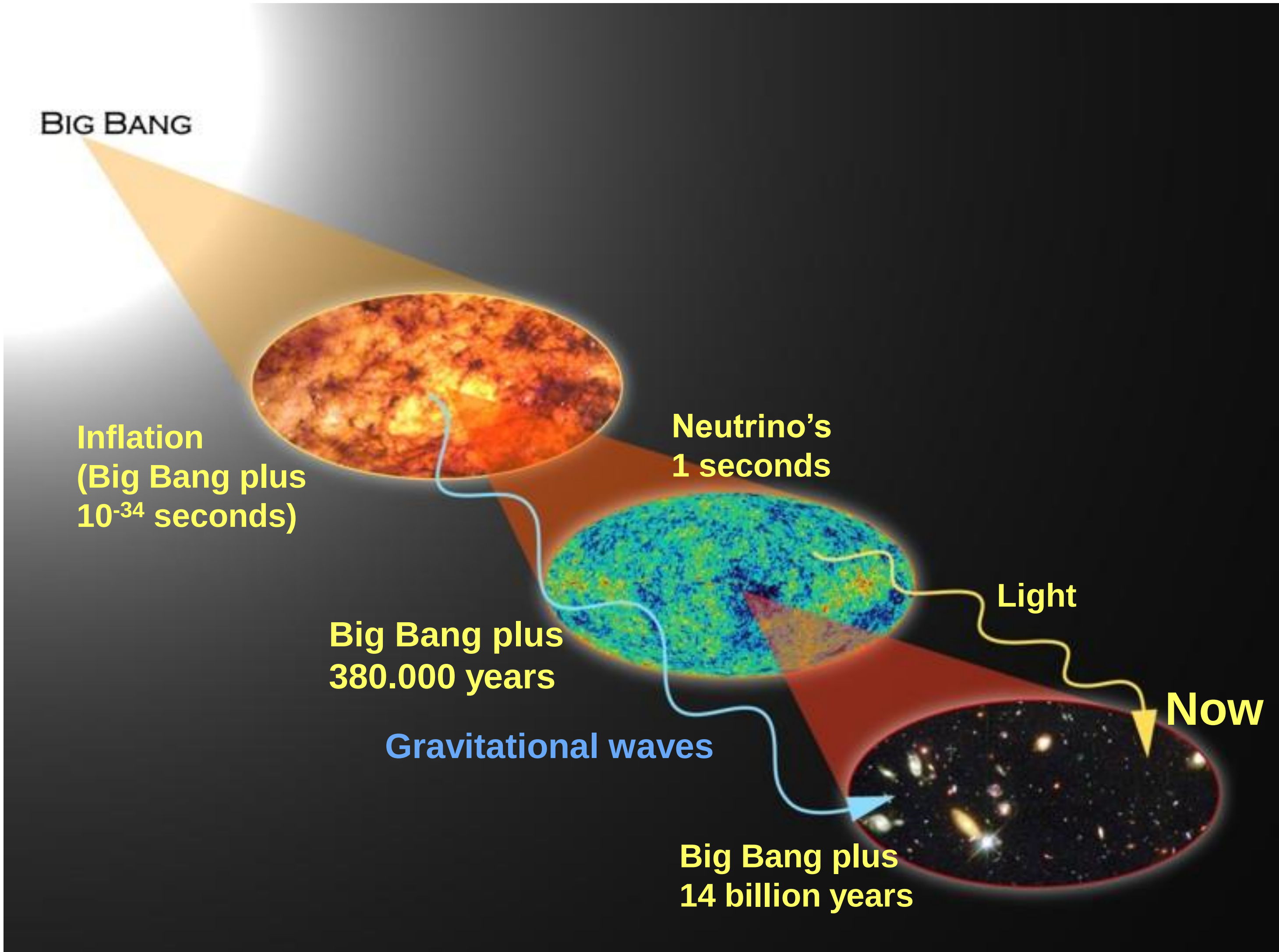
Is Einstein's theory correct in conditions of extreme gravitation? Of does new physics await?



Einstein Telescope: physics of early universe

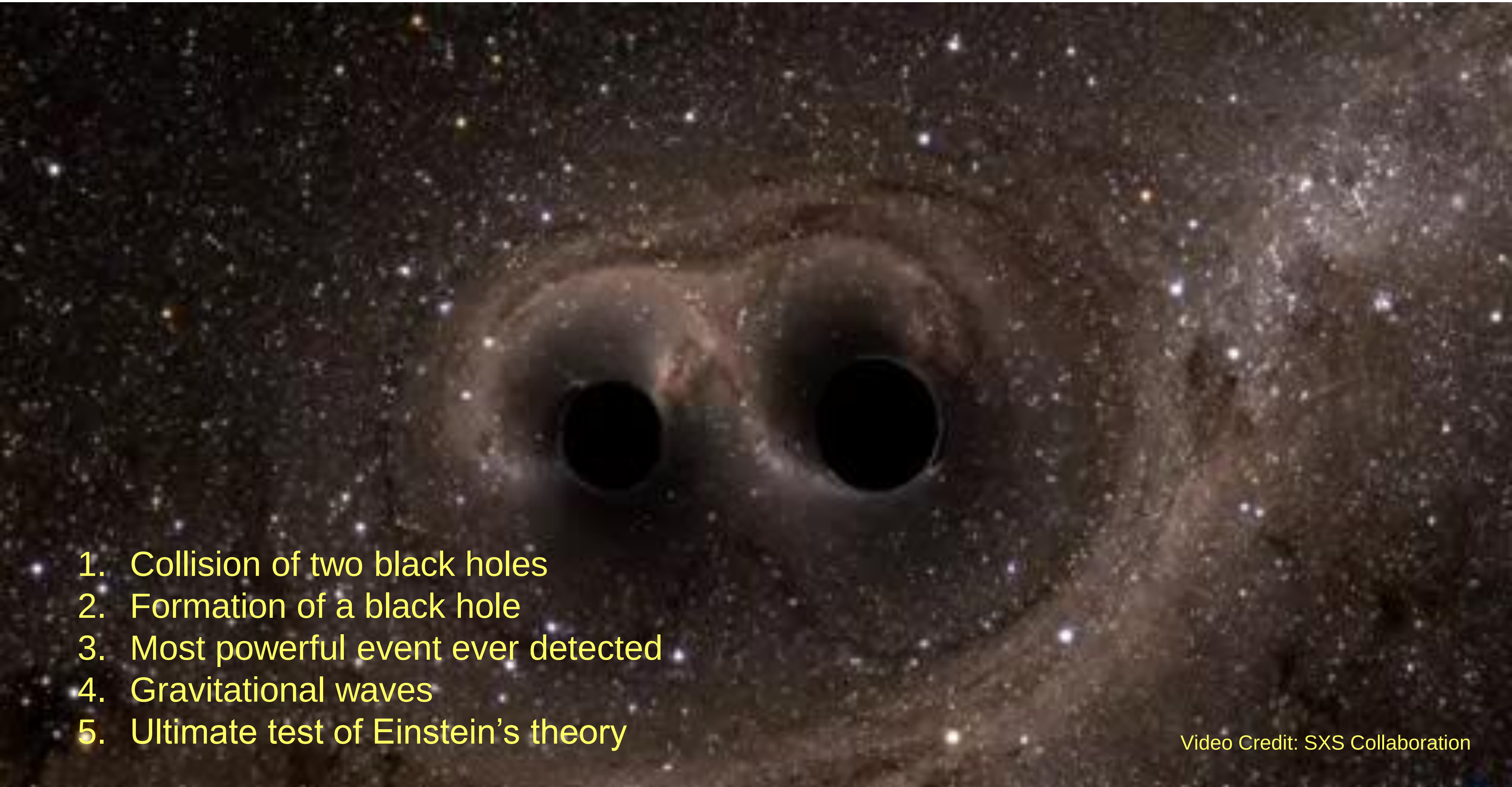
What is powering the Big Bang?

Gravitational waves can escape from the earliest moment of the Big Bang



Stay tuned … more to come

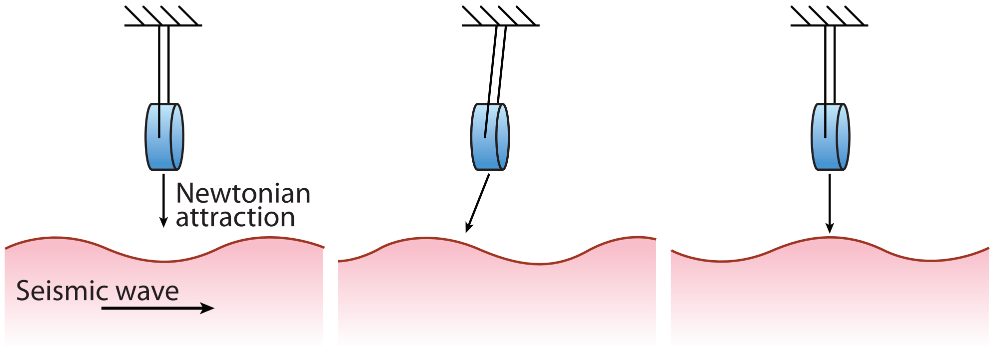
Science observation will restart this summer. We expect more collisions of black holes and/of neutron stars. Perhaps more surprises



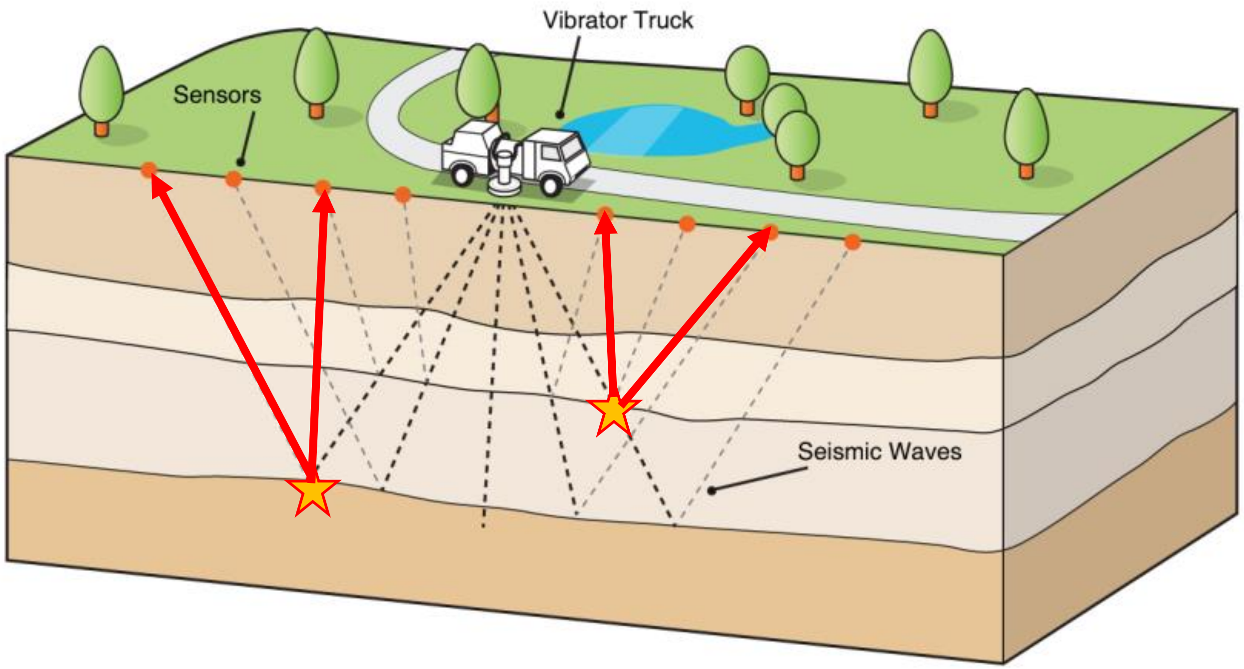
From black holes to innovation in seismic sensing

EUNL16 Big Science, Dwingeloo

Valorization opportunity from Gravitational Physics



Measure seismic noise to improve gravitational wave detector



Valorization opportunity!

Measure seismic signal to study geophysical properties

Earthquake monitoring

INNOSEIS

Technology to revolutionize the seismic industry

INNOSEIS

- The industries lightest seismic recording system
- High signal fidelity
- Long battery life

Our technology caught the industry's attention

Applications for onshore seismic data acquisition

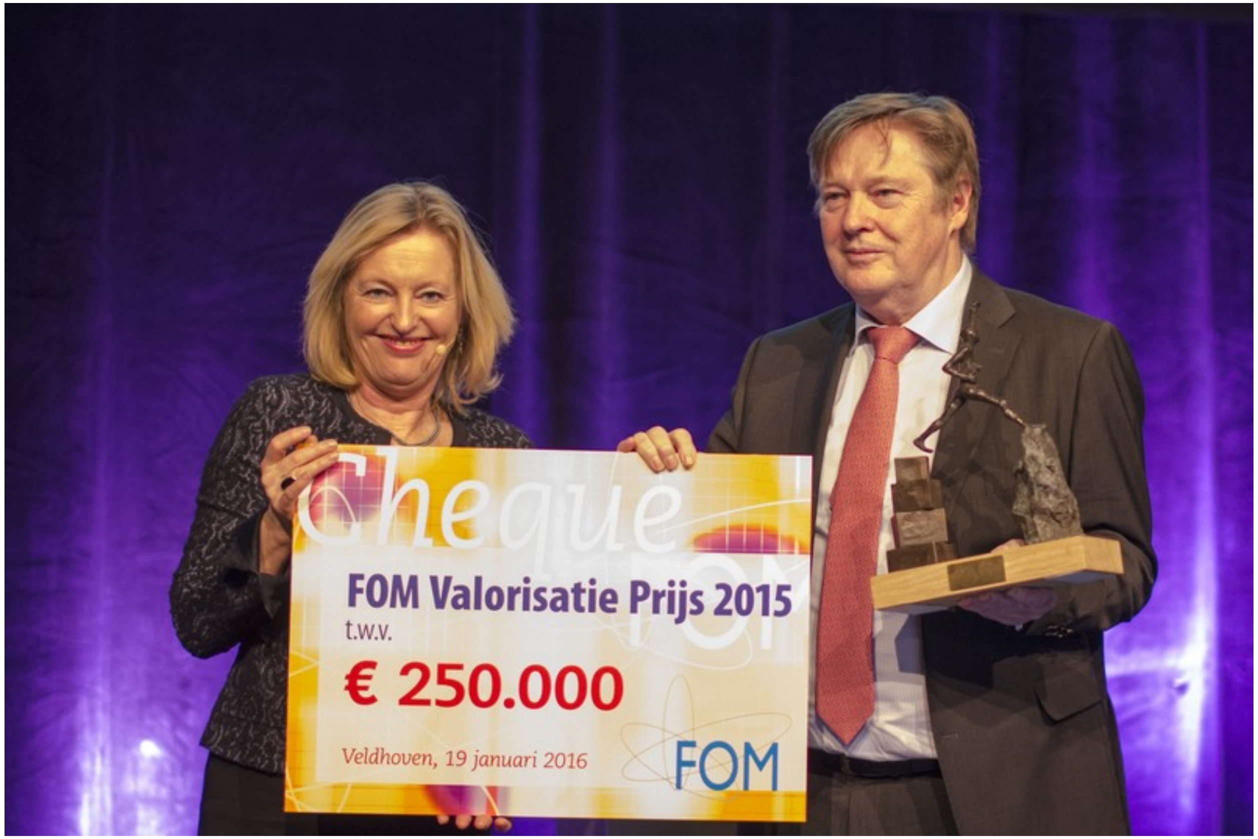
Industrial cooperation

- Networks scalable up to 1 million nodes
- Definition of requirements
- Technology audits
- Field trials, The Netherlands / Oman

INNOSEIS

FOM Valorization prizes

FOM Valorization chapter prize 2014
FOM Valorizaiton prize 2015



FOM

Autonomous compact intelligent seismic sensor nodes

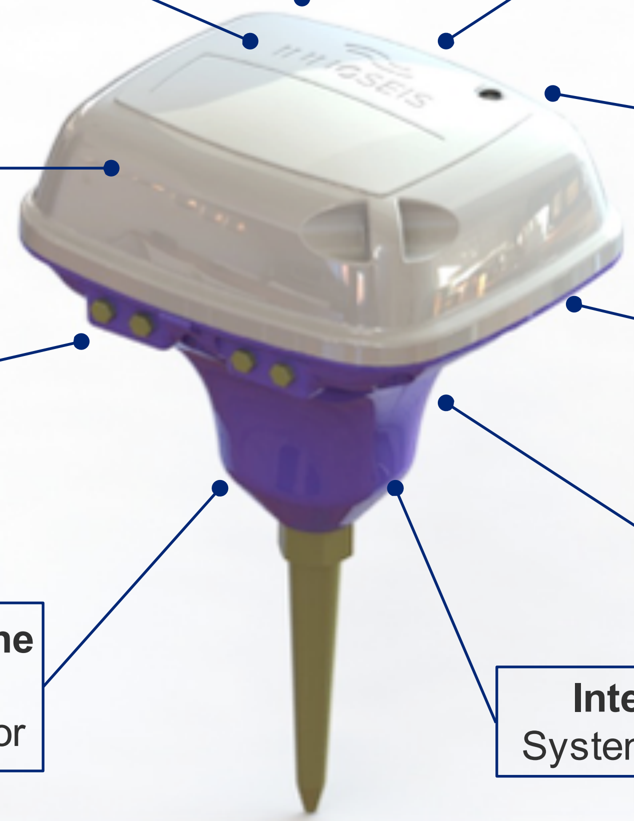
GPS
GNSS/GLONAS/Galileo
Timing precision ±10 μs

Ultra-low power
42+ days operating life
continuous recording

Bluetooth Low Energy
Quality control
Configuration and proximity

High dynamic range
up-to 137 dB

Highly visible LED
Health status feedback



Connectors
High-speed USB interface
Battery charging

Internal batteries
Rechargeable Li-ion
Charge time 3 hours

Robust enclosure
Watertight IP68

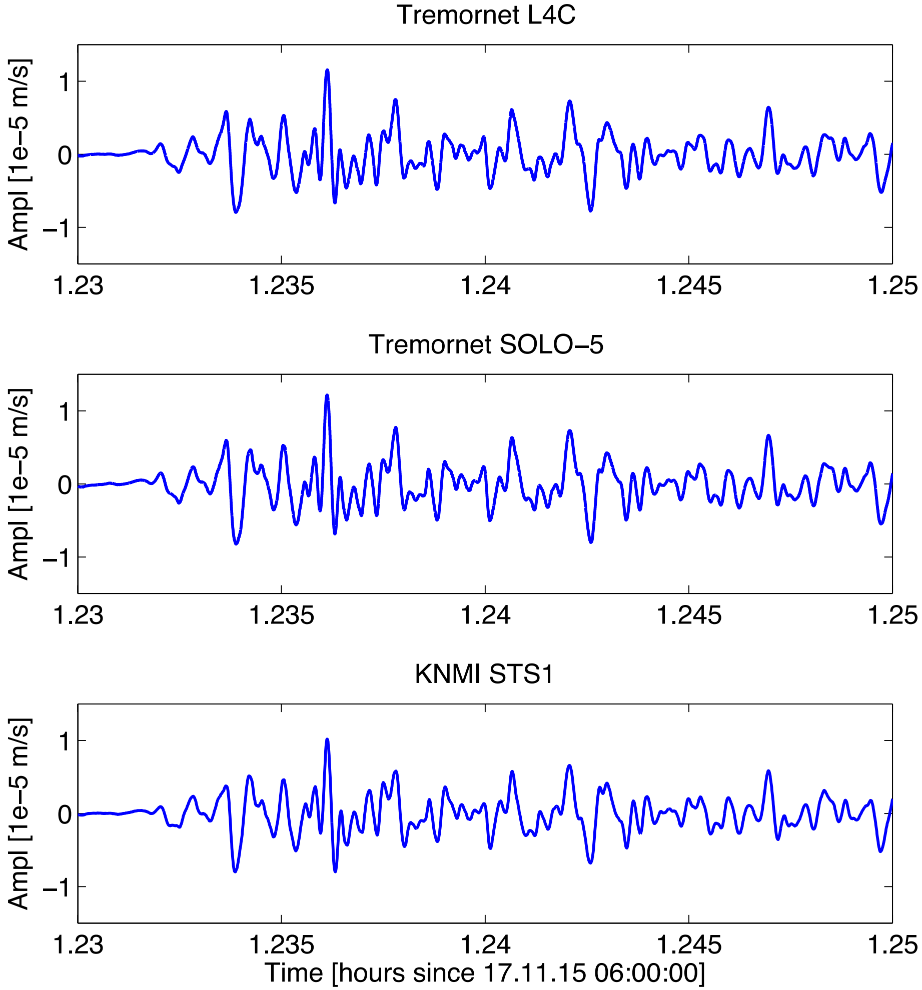
High sensitivity geophone
10 or 5 Hz
optional external connector

Internal calibration
System and sensor check

INNOSEIS

Validation with KNMI

Greece Earthquake measured on 17 November 2016



Easy deployment

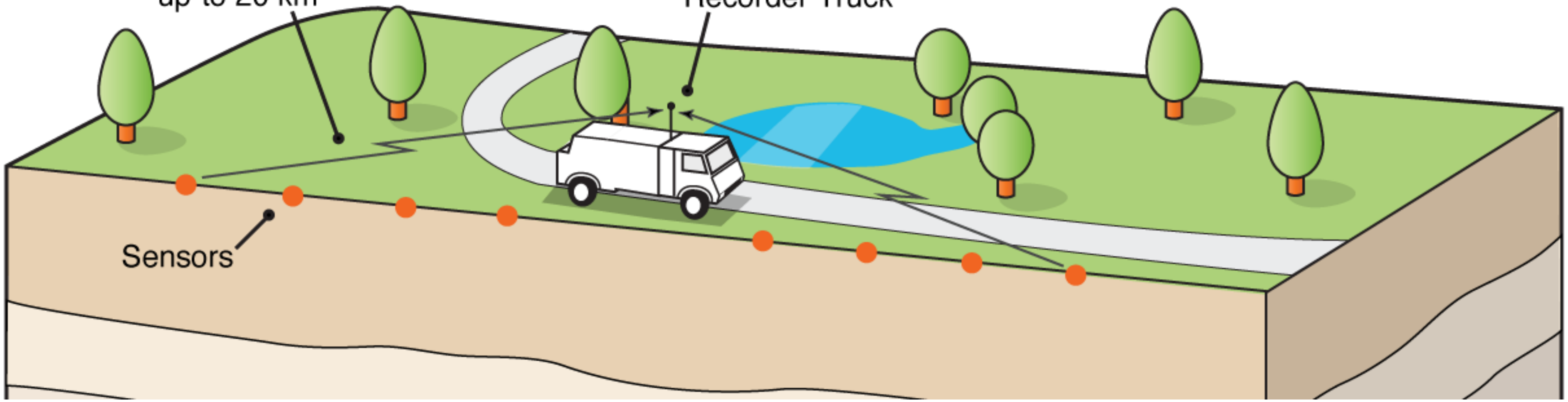
INNOSEIS

Easy deployment

INNOSEIS

Future: Internet of Things

Innoseis see's the potential of LoRa as an effective communication protocol for Quality Control information of a seismic sensor network



Concluding remarks

- Excellent example of commercial application of fundamental physics research
- We have developed the latest sensor technology in land seismic
  - Highest precision
  - Lightest package
  - Highly cost effective
  - Longest battery life
  - Robust system
  - Suitable for automated deployment
- Field proven technology
- Applications in geophysics surveying and Earthquake monitoring
- And potentially other future applications..
- Questions?

INNOSEIS