INTERFEROMETRIC GRAVITATIONAL WAVE DETECTION – A (QUANTUM) METROLOGICAL CHALLENGE

Nuclear Physics in Astrophysics XI 2024, Dresden

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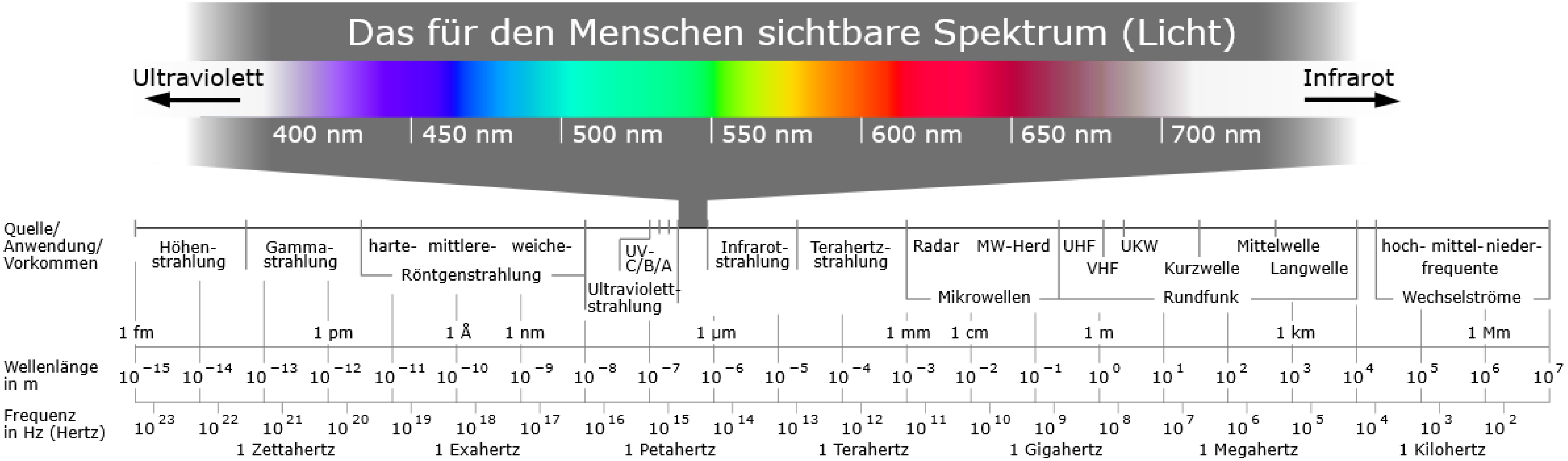
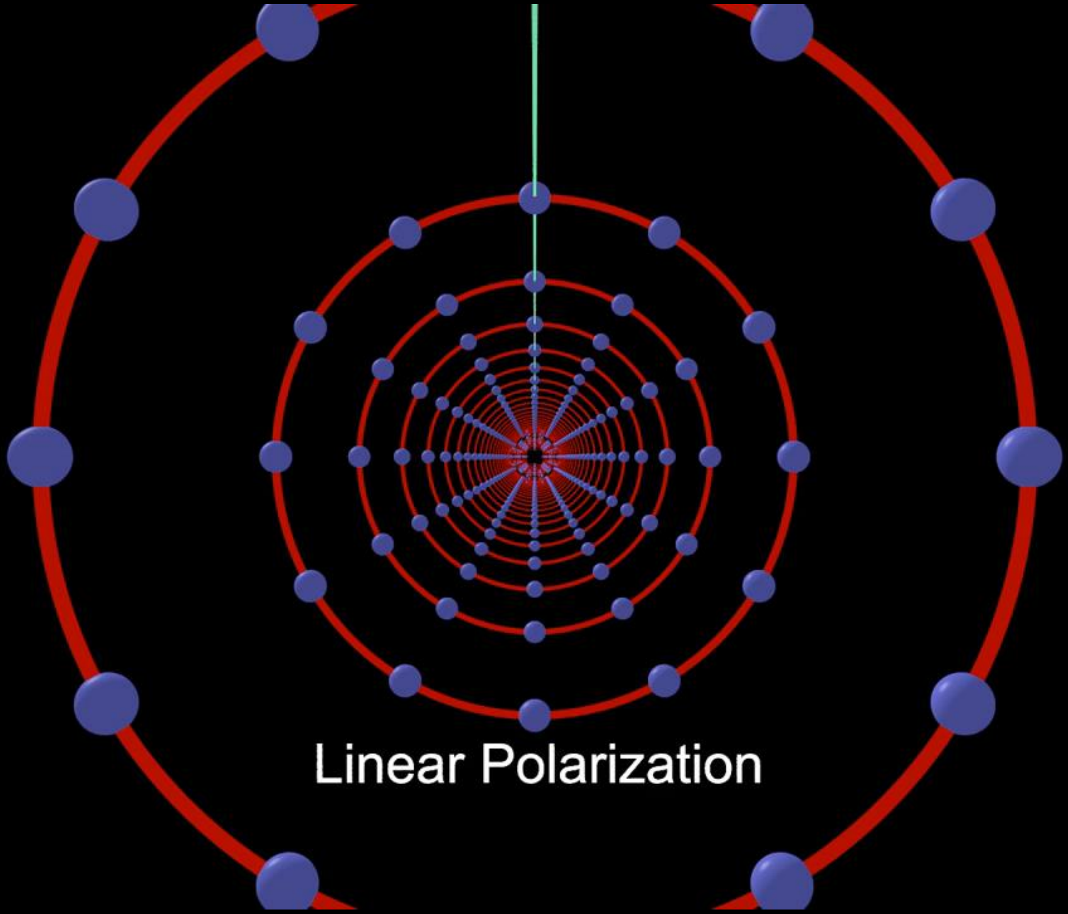
THE ELECTROMAGNETIC SPECTRUM

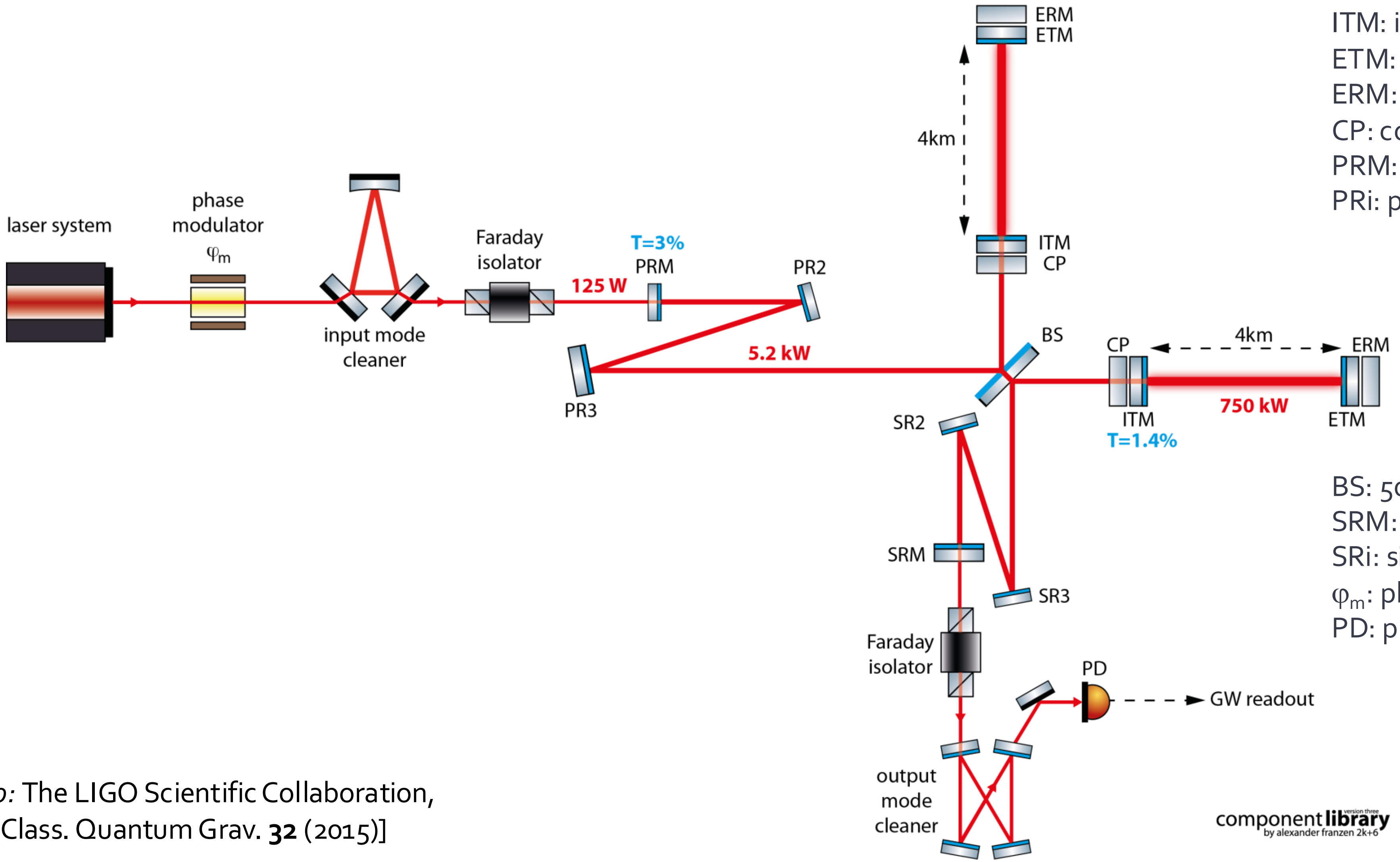


PROPAGATION OF GWS THROUGH SPACETIME



https://www.youtube.com/watch?v=F4stTzxYrNo

SIMPLIFIED OPTICAL SETUP OF ADVANCED LIGO

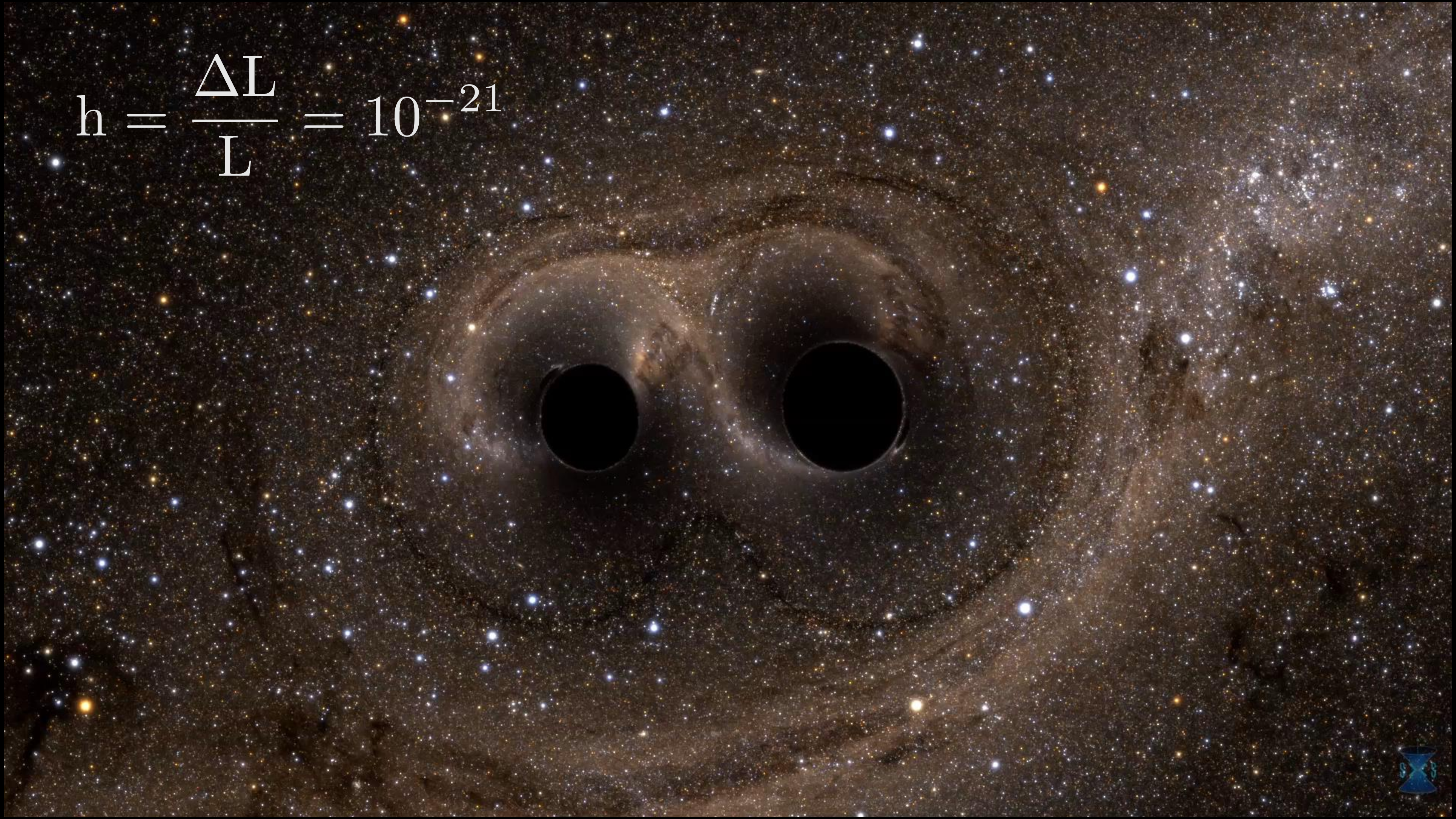


ITM: input test mass
ETM: end test mass
ERM: end reaction mass
CP: compensation plate
PRM: power recycling mirror
PRi: power recycling mirror I

BS: 50/50 beam splitter
SRM: signal recycling mirror
SRi: signal recycling mirror i
φ_m: phase modulator
PD: photodetector

[Image according to: The LIGO Scientific Collaboration, "Advanced LIGO", Class. Quantum Grav. **32** (2015)]

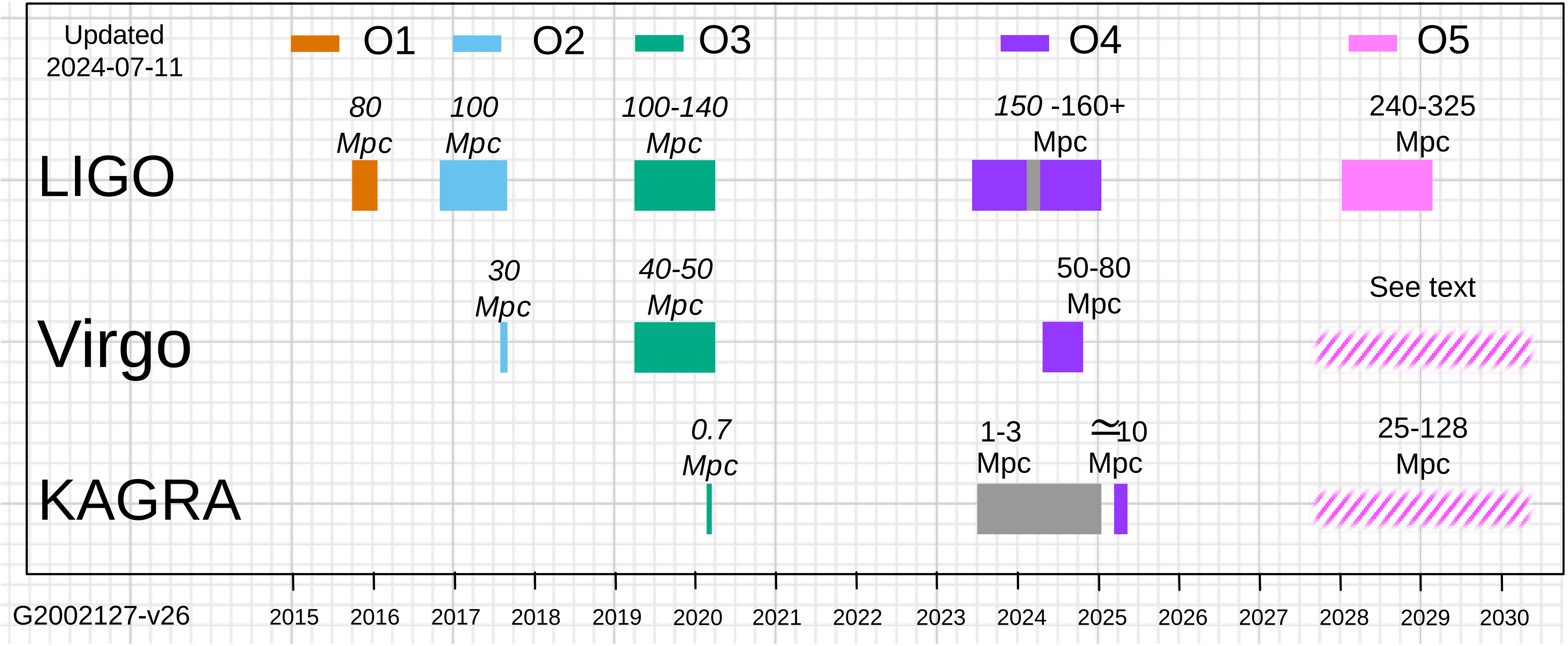
TWO BLACK HOLES BECOME ONE



TWO NEUTRON STARS MERGE

Credit: NASA's Goddard Space Flight Center/CI Lab

OBSERVATION RUNS AND RANGES

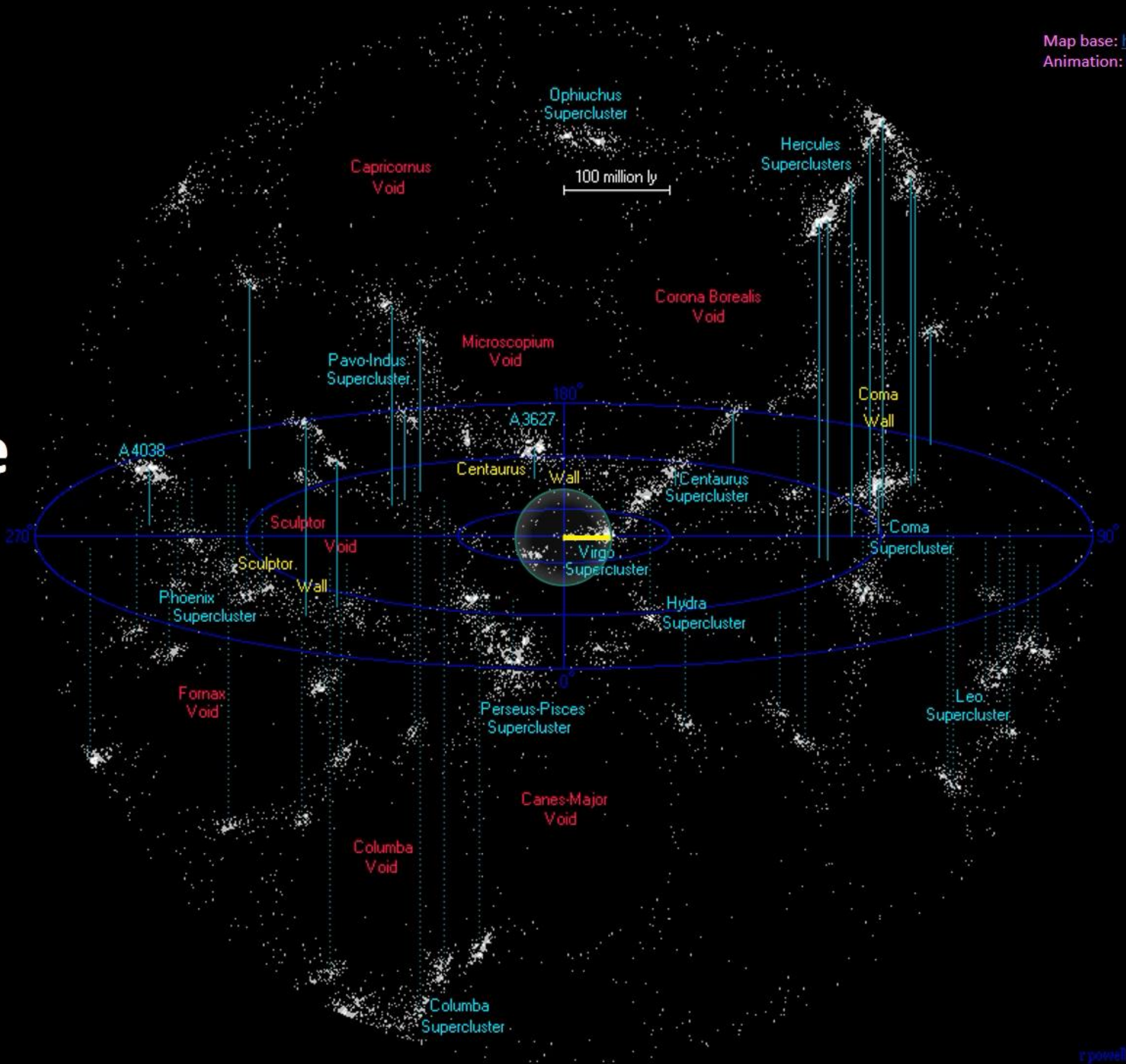


[Source: https://dcc.ligo.org/LIGO-G2002127/public]

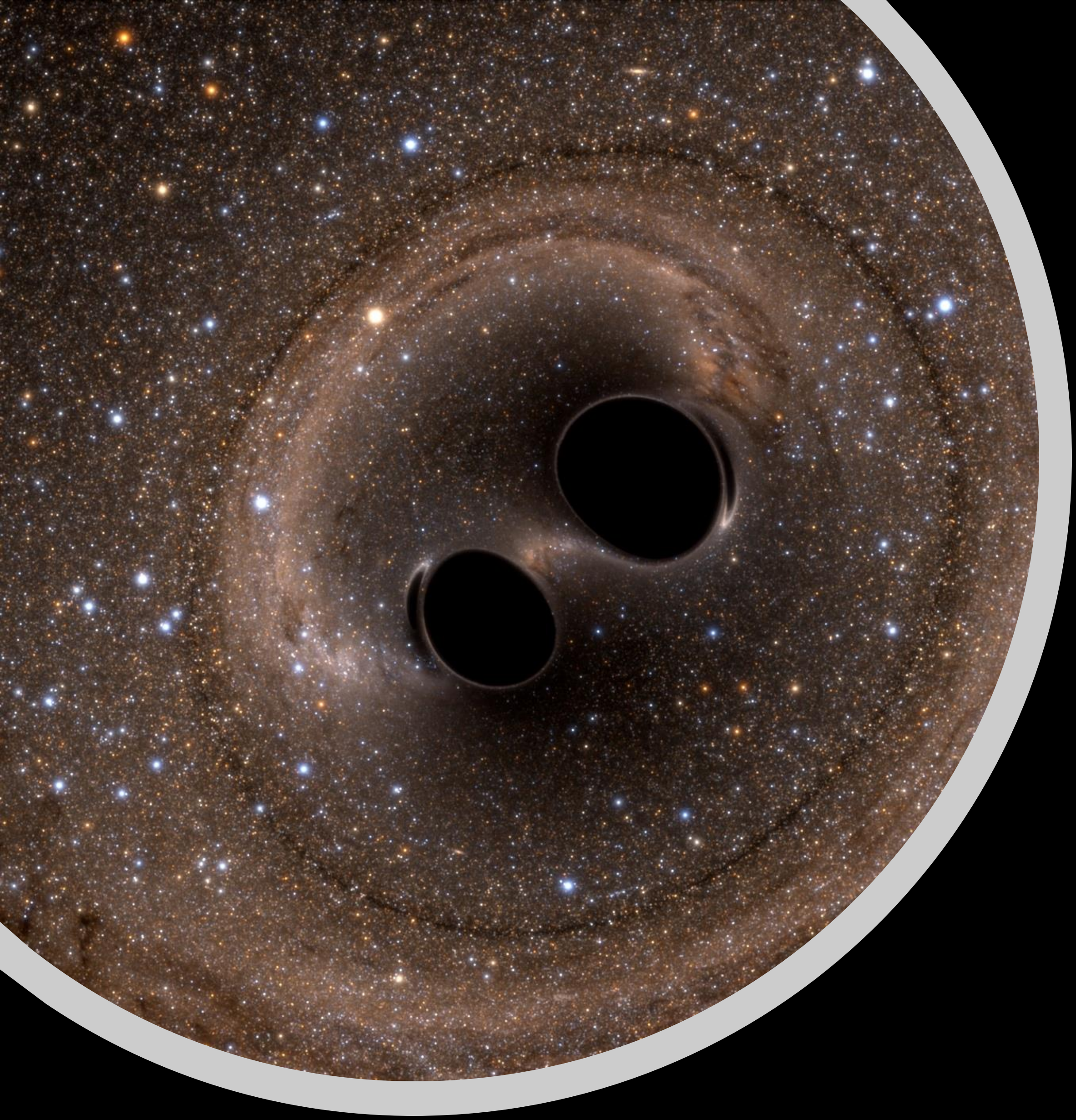
OBSERVATION RANGE

Map base: http://www.atlasoftheuniverse.com/index.html
Animation: Caltech/MIT/LIGO Lab/Kim Burtnyk

iLIGO Range Radius:
15 Mpc



Initial LIGO Range: 15 Mpc

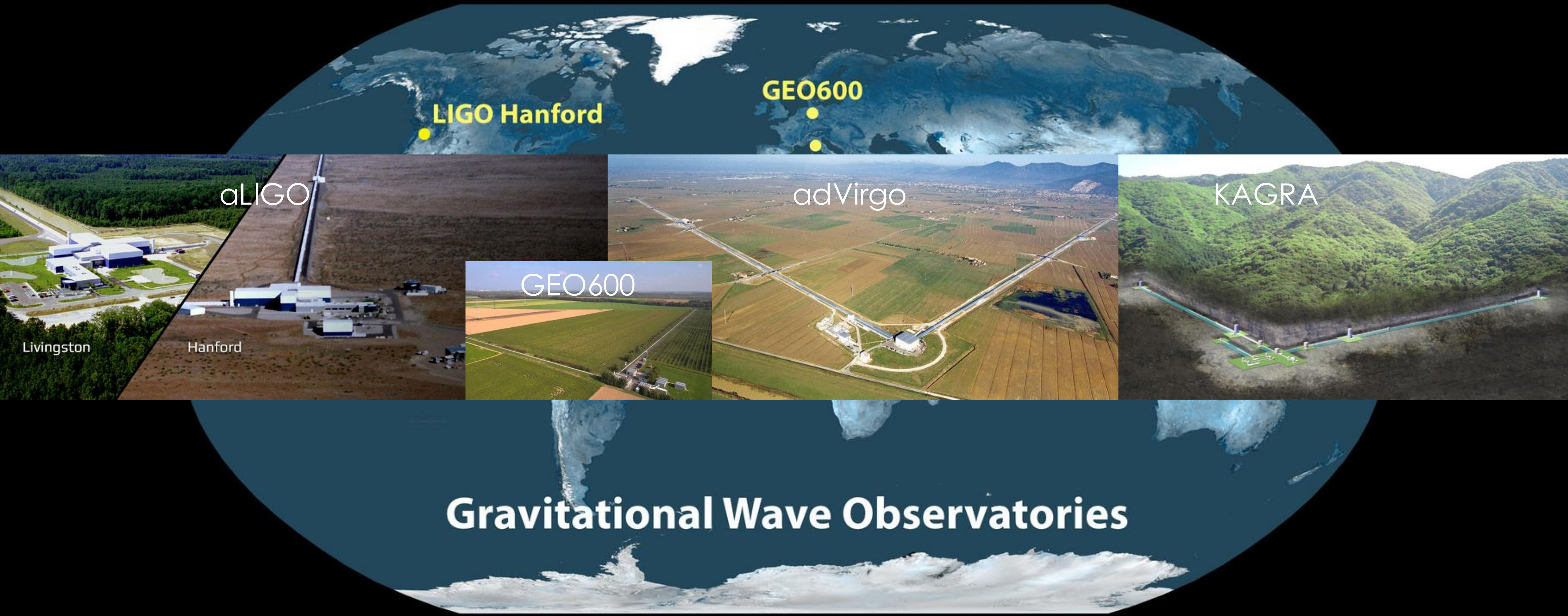


WHAT HAVE WE ALREADY LEARNED?

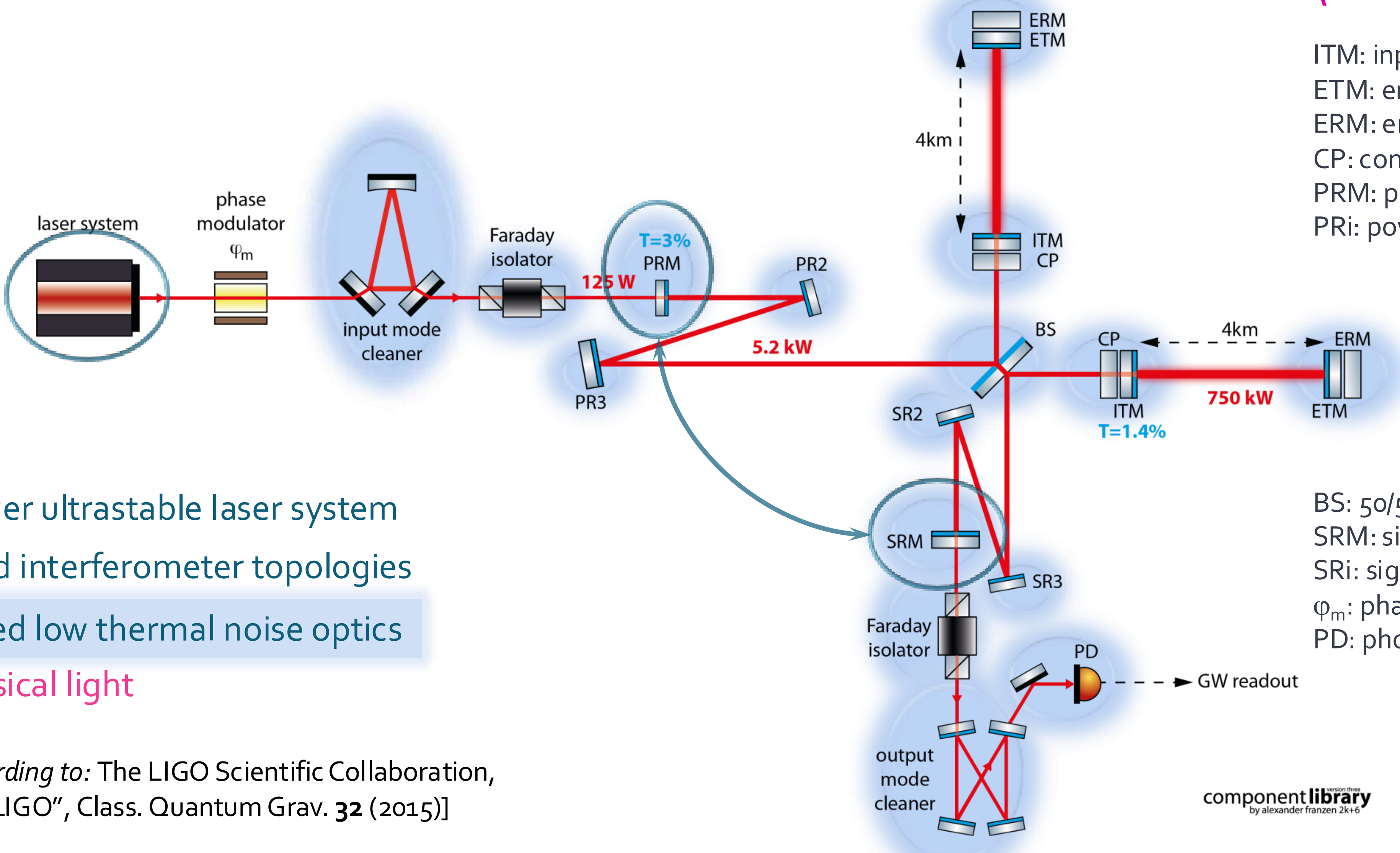
- **First detection of GWs** from a BBH system (GW150914)
  - Physics of BHs
- First detection of **GWs from a BNS** system (GW170817)
  - Birth of multimessenger astronomy with GWs
  - Constraining the equations of state of neutron stars
- **Localisation** capabilities of a GW source
- Measurement of the GW propagation speed
- **Test of General Relativity**
- Alternative measurement of the **Hubble constant**
- GW polarisations
- **Intermediate mass black hole** (GW190521)

[Slide modified from M. Punturo, APS Talk 2022 „GW Perspectives"]

THE GLOBAL GWD NETWORK (CURRENT STATUS, 2G)



ADVANCED TECHNOLOGY FOR aLIGO (EXAMPLES)



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High power ultrastable laser system

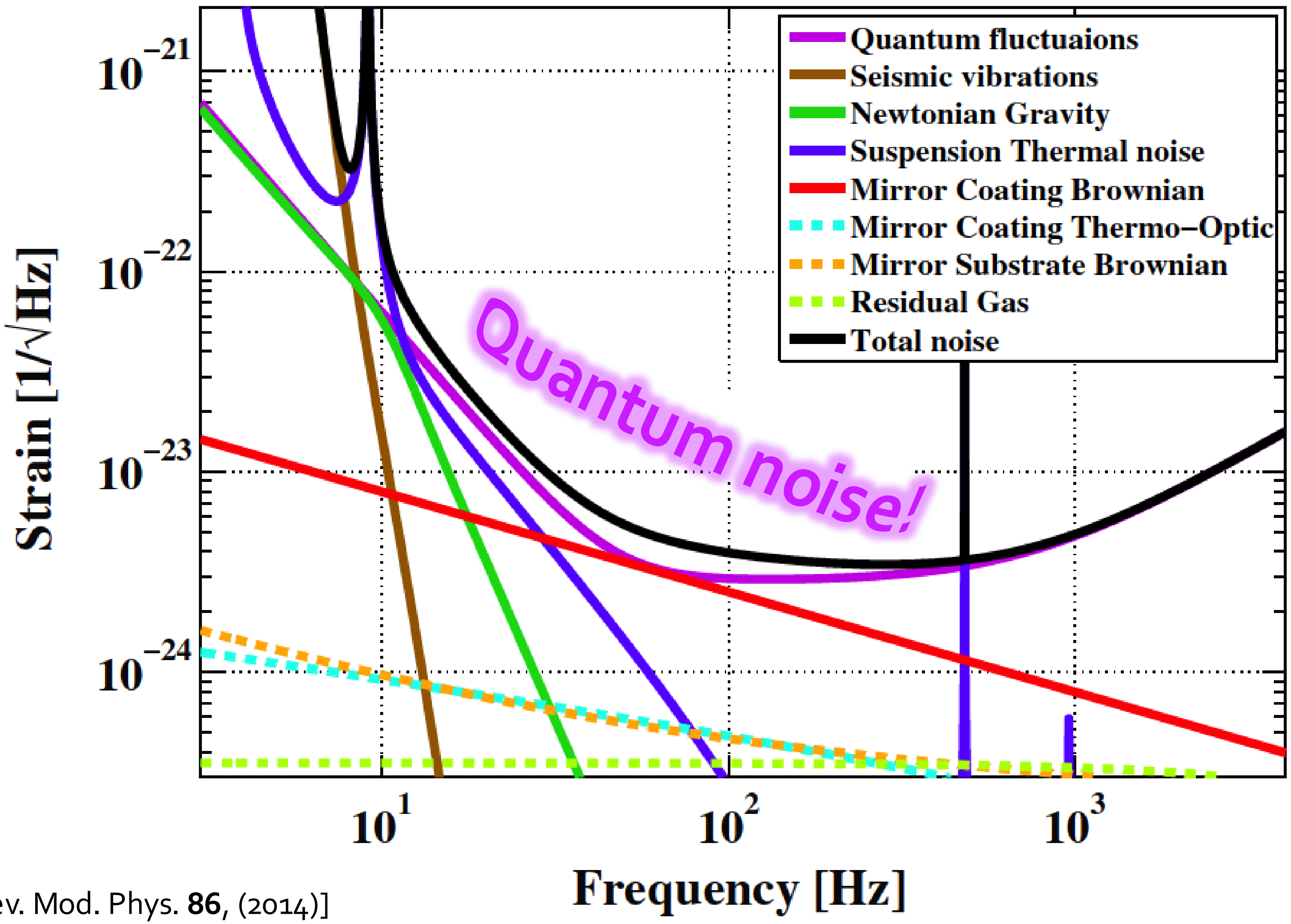
Advanced interferometer topologies

Suspended low thermal noise optics

Non-classical light

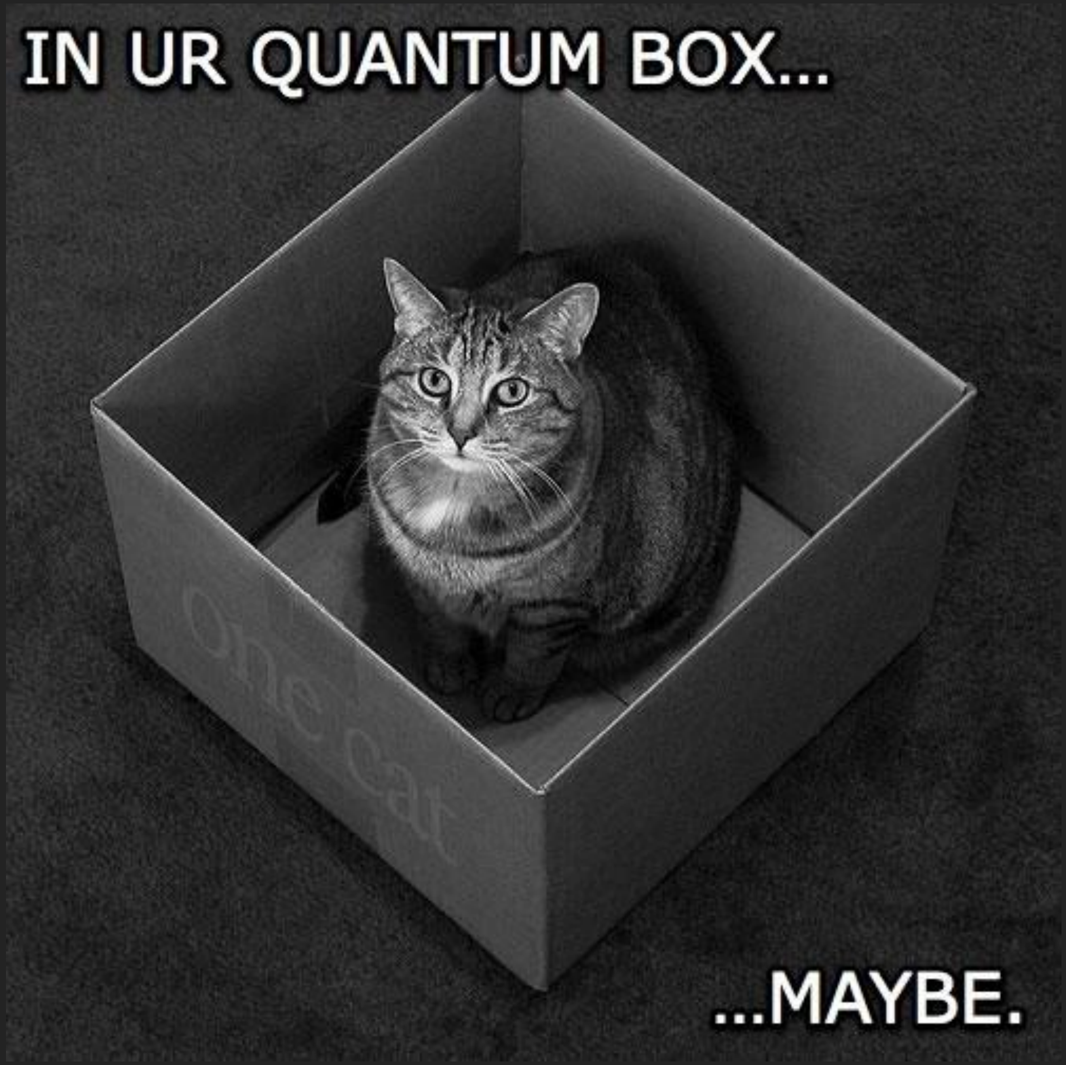
[Image according to: The LIGO Scientific Collaboration, "Advanced LIGO", Class. Quantum Grav. **32** (2015)]

DESIGN SENSITIVITY OF aLIGO

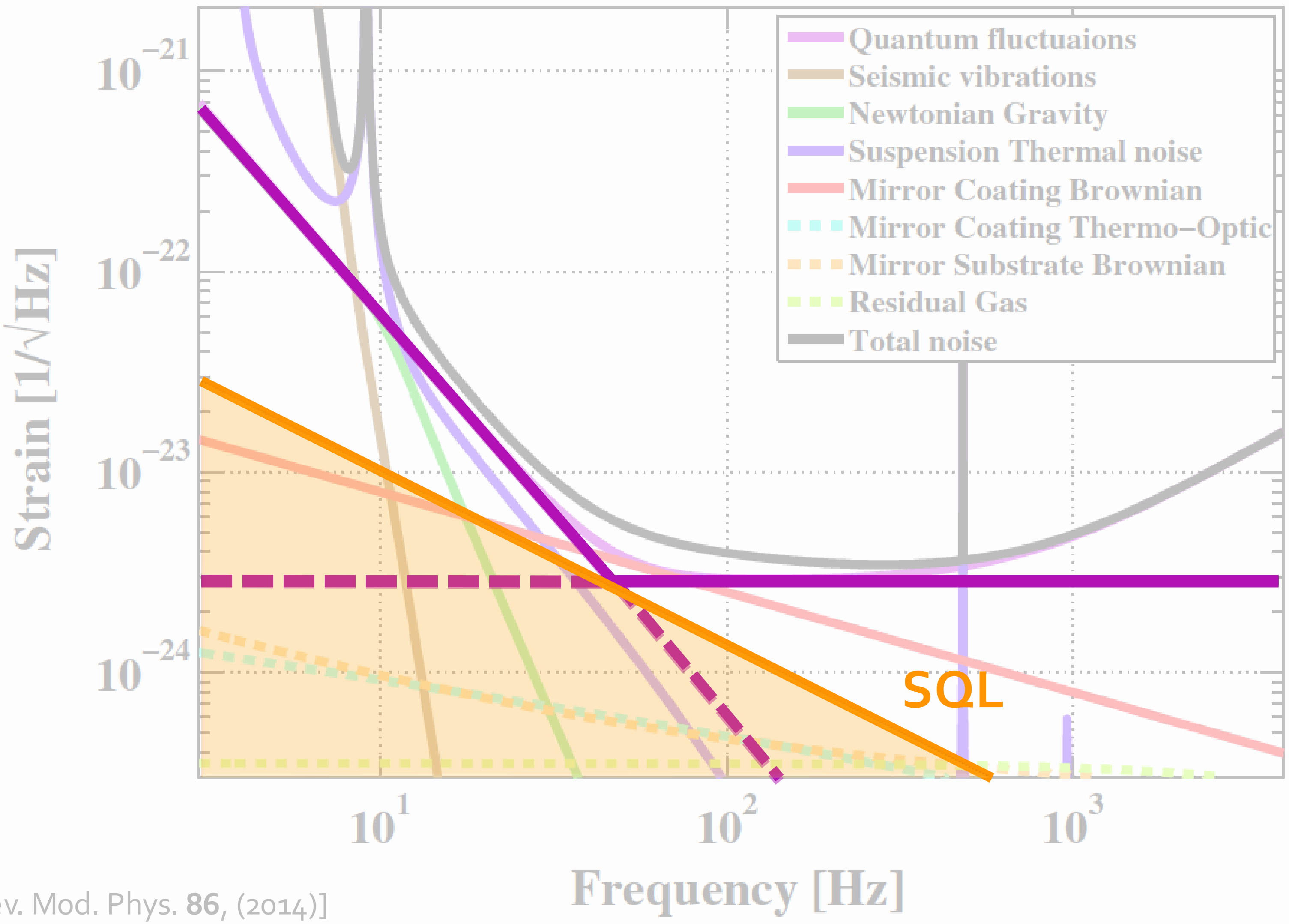


[*Image:* R. X. Adhikari, Rev. Mod. Phys. **86**, (2014)]

QUANTUM NOISE: HEISENBERG & CO.

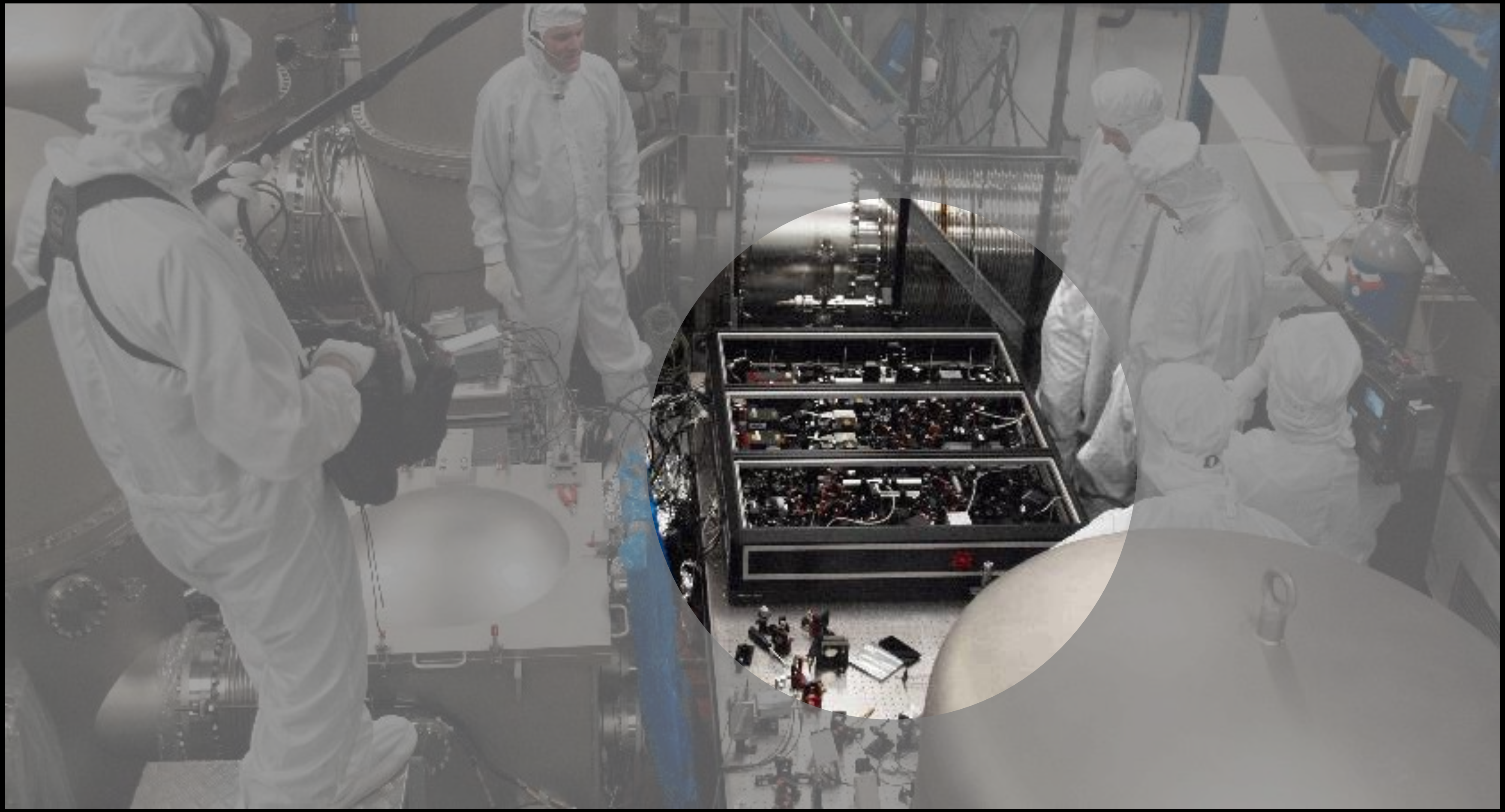


THE STANDARD QUANTUM LIMIT (SQL)
OF INTERFEROMETRY



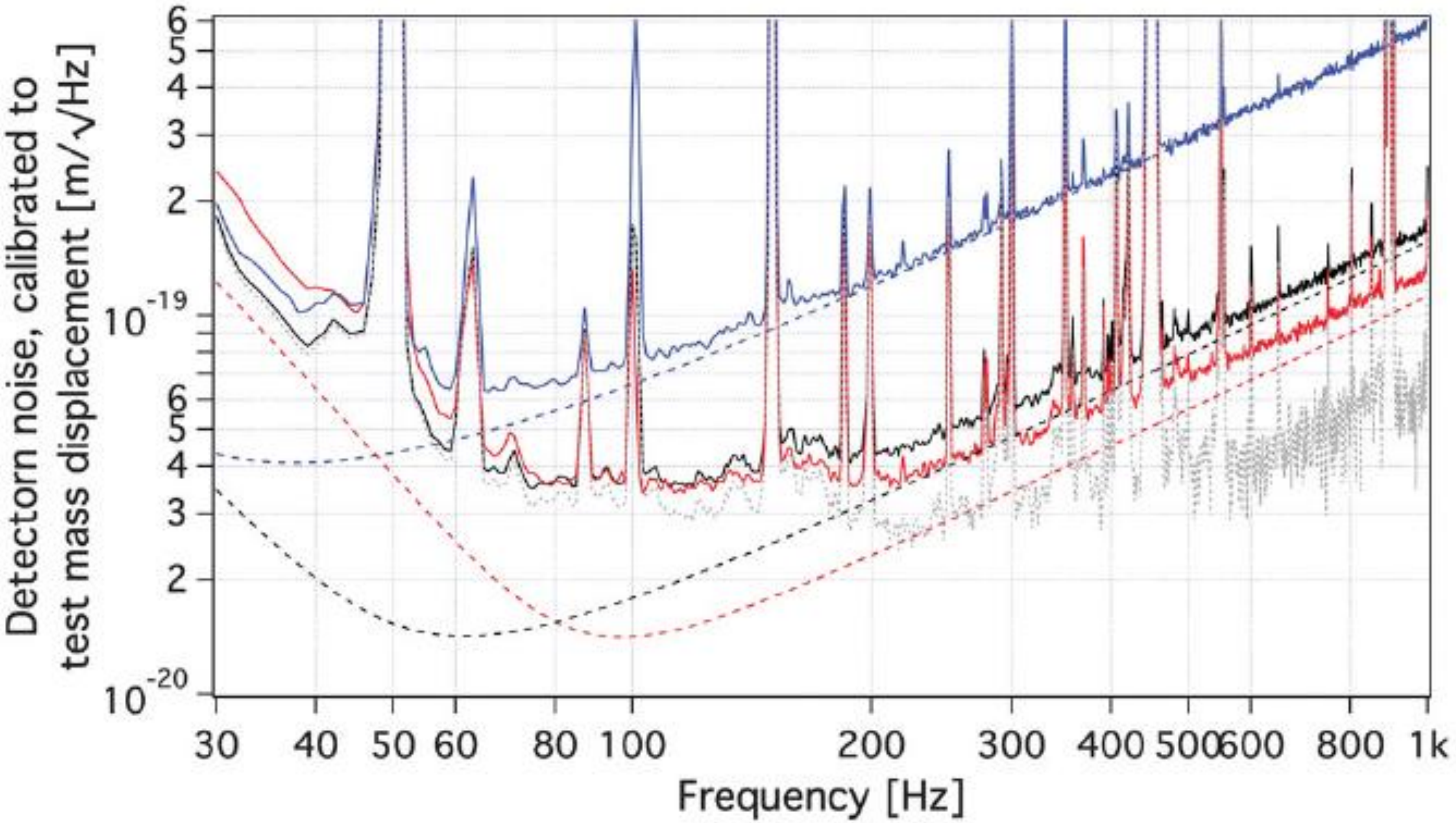
[*Image:* R. X. Adhikari, Rev. Mod. Phys. **86**, (2014)]

GEO600: THE FIRST GWD TO USE SQUEEZED LIGHT (SINCE 2010!)!



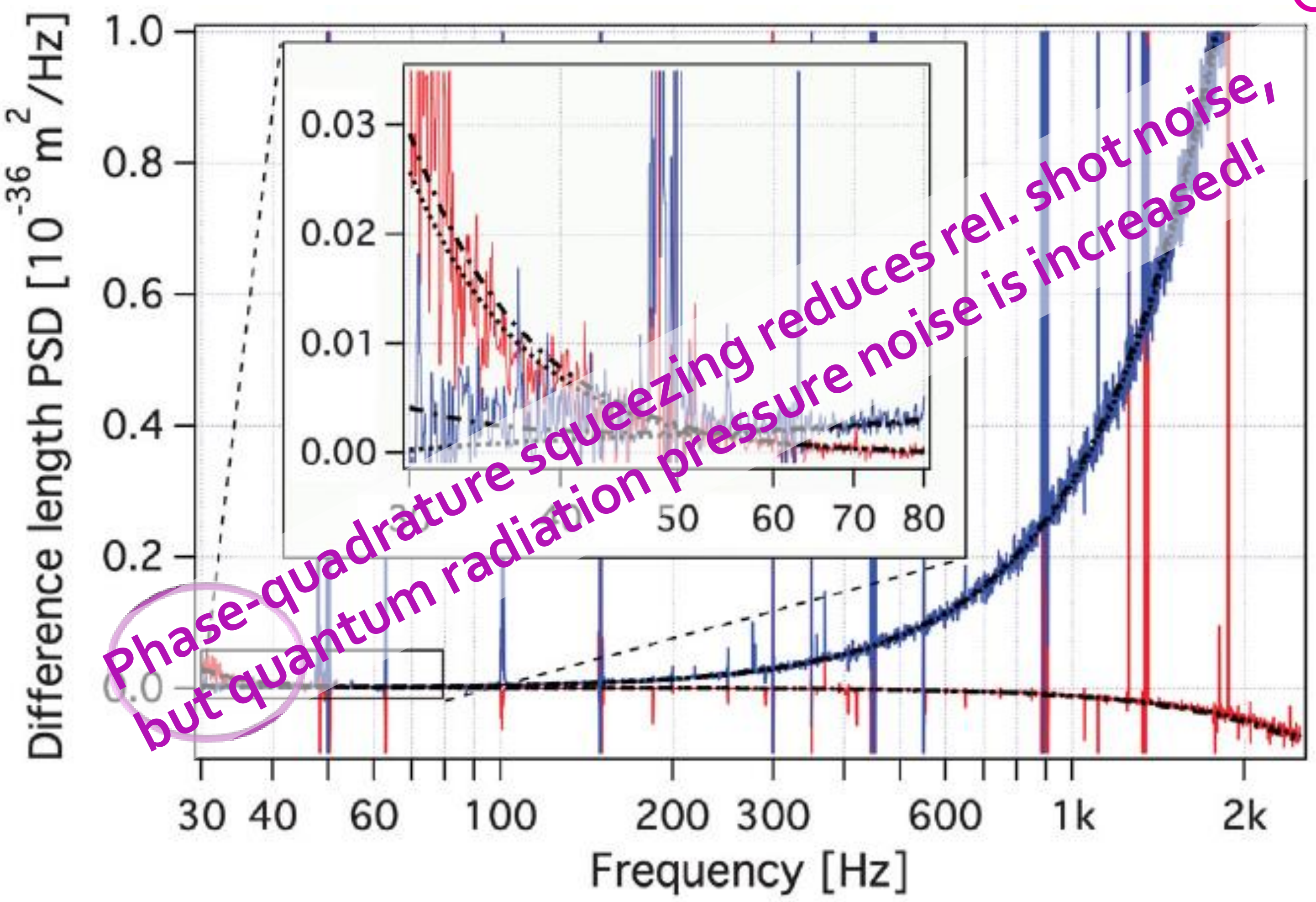
[Nat. Phys. **7**, 962–965 (2011)]

FIXED-QUADRATURE SQUEEZING AT adVIRGO



[The Virgo Collaboration & Mehmet et al. „Quantum Backaction on Kg-Scale Mirrors: Observation of Radiation Pressure Noise in the Advanced Virgo Detector " Phys. Rev. Lett. **125**, 131101 (2020)]

FIXED-QUADRATURE SQUEEZING AT adVIRGO



Fixed ampl. quadr. SQZ (normalised)

Fixed phase-quadr. SQZ (normalised)

[The Virgo Collaboration & Mehmet et al. „Quantum Backaction on Kg-Scale Mirrors: Observation of Radiation Pressure Noise in the Advanced Virgo Detector " Phys. Rev. Lett. **125**, 131101 (2020)]

adVIRGO TEST MASS (42 kg, ϕ = 350 mm, D = 200 mm)

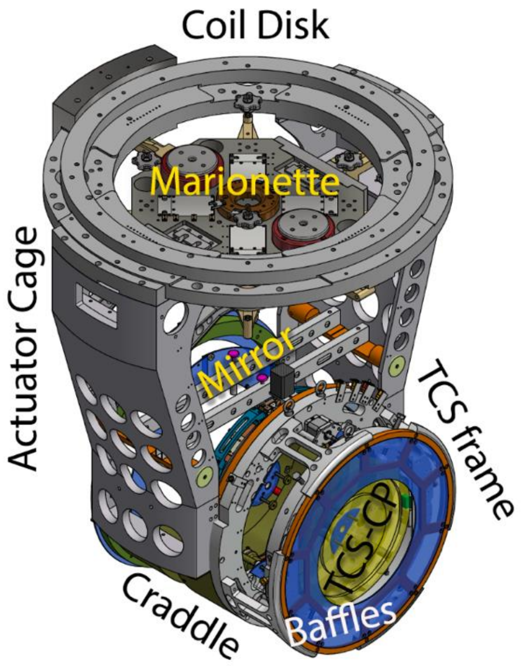


Figure 3. Input Payload, CAD drawing.

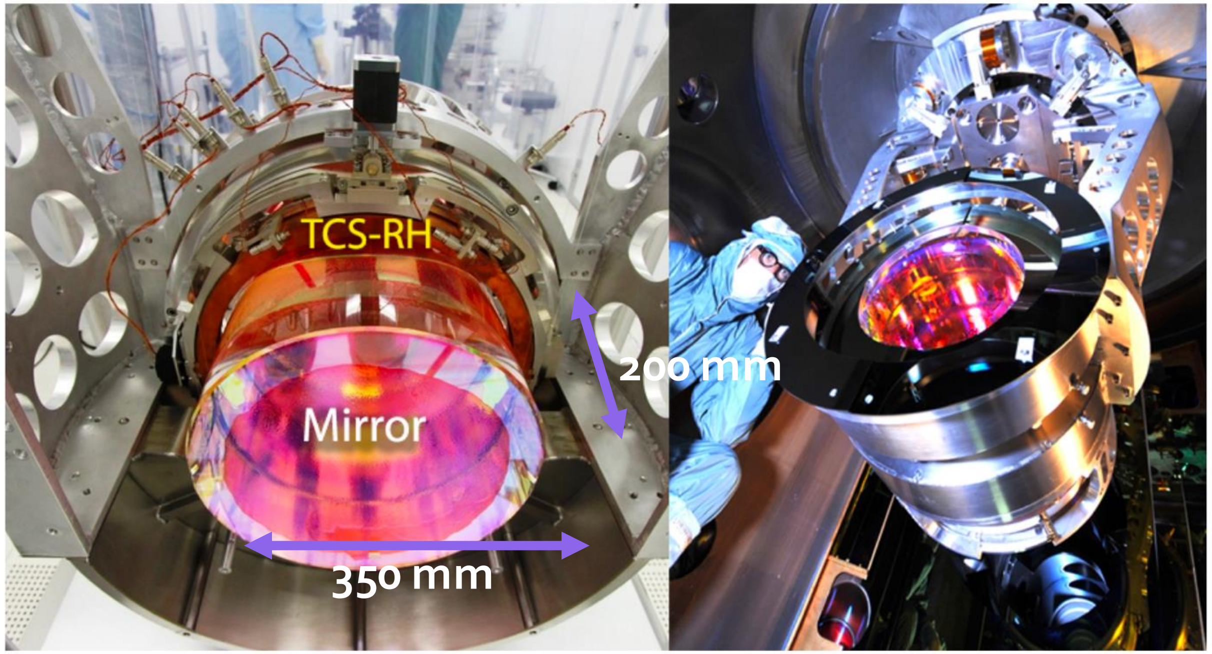
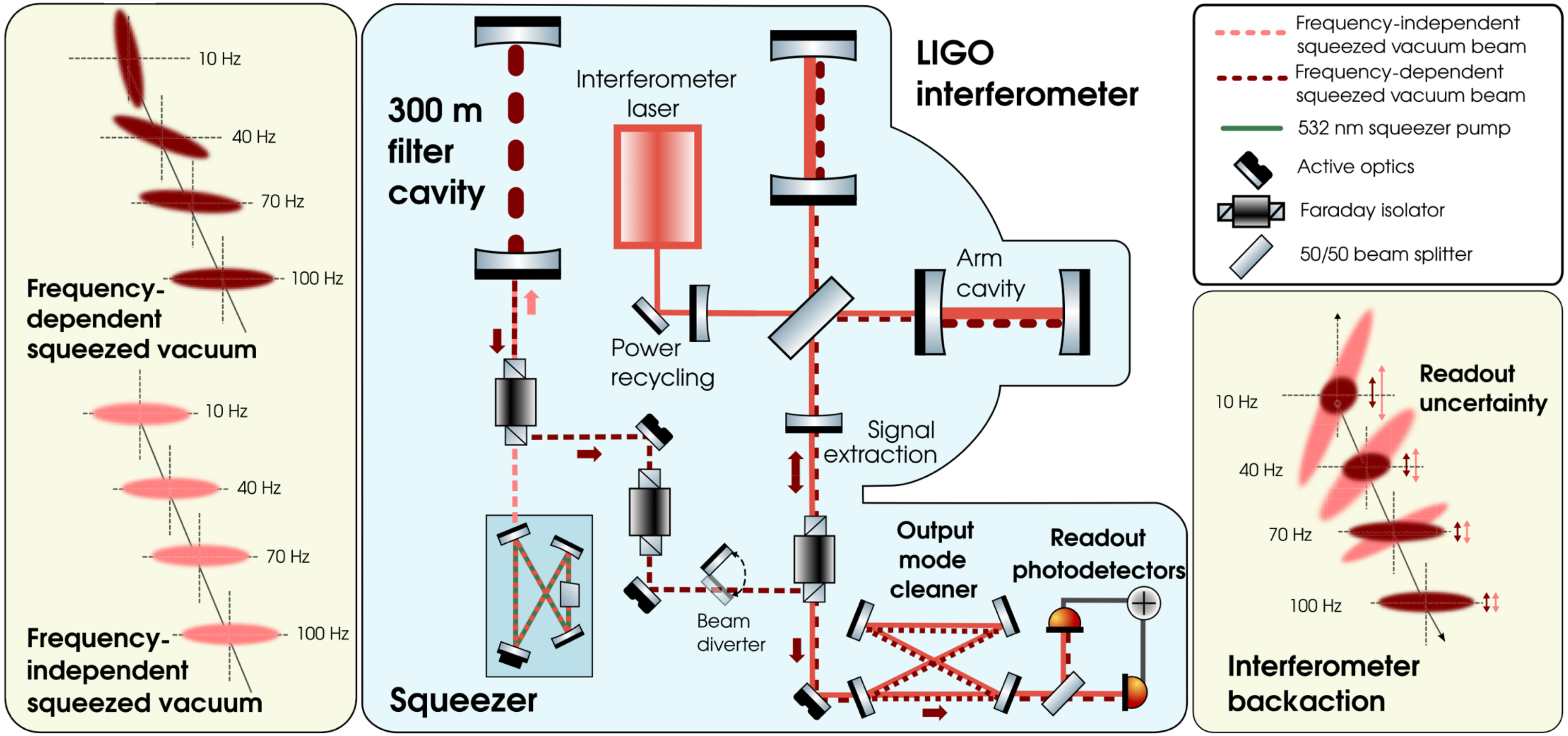


Figure 4. Input Payload during assembly (left) and its integration with SA (right).

[modified from: L. Naticchioni and on behalf of the Virgo Collaboration, J. Phys.: Conf. Ser. **957** 012002 (2018)]

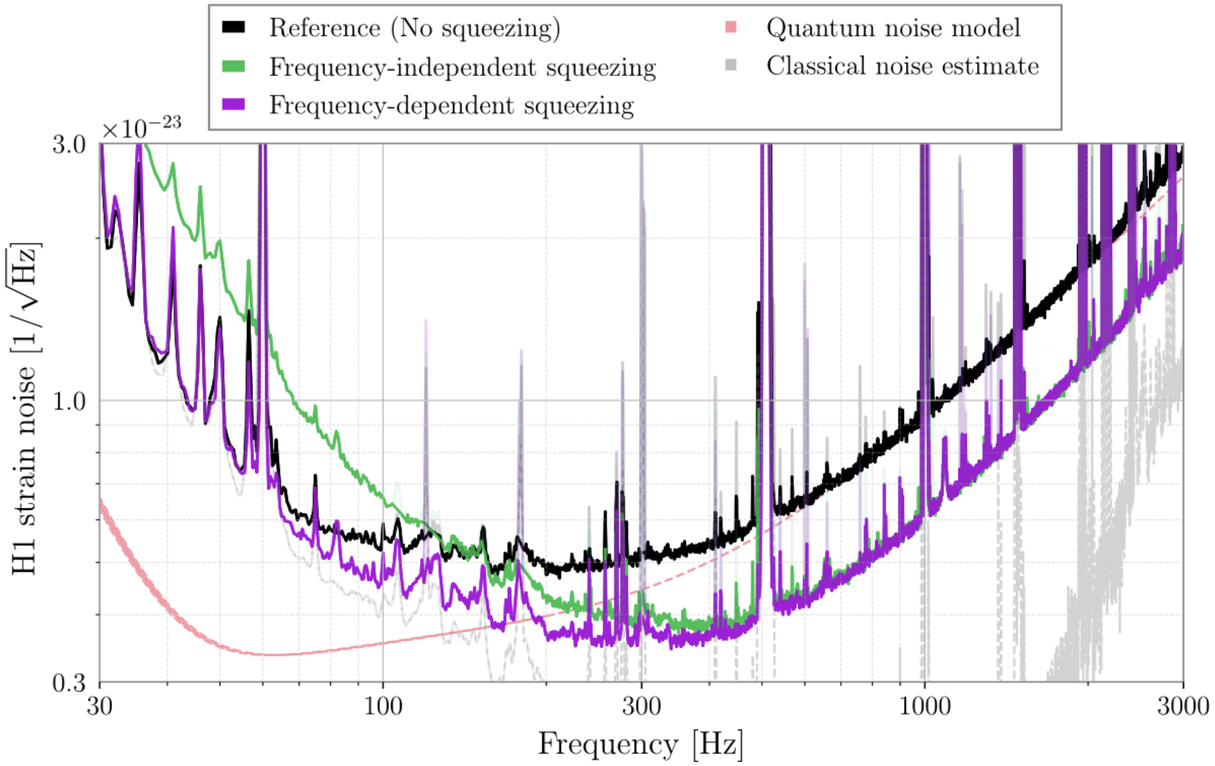
FREQUENCY-DEPENDENT SQUEEZING AT aLIGO (O4)



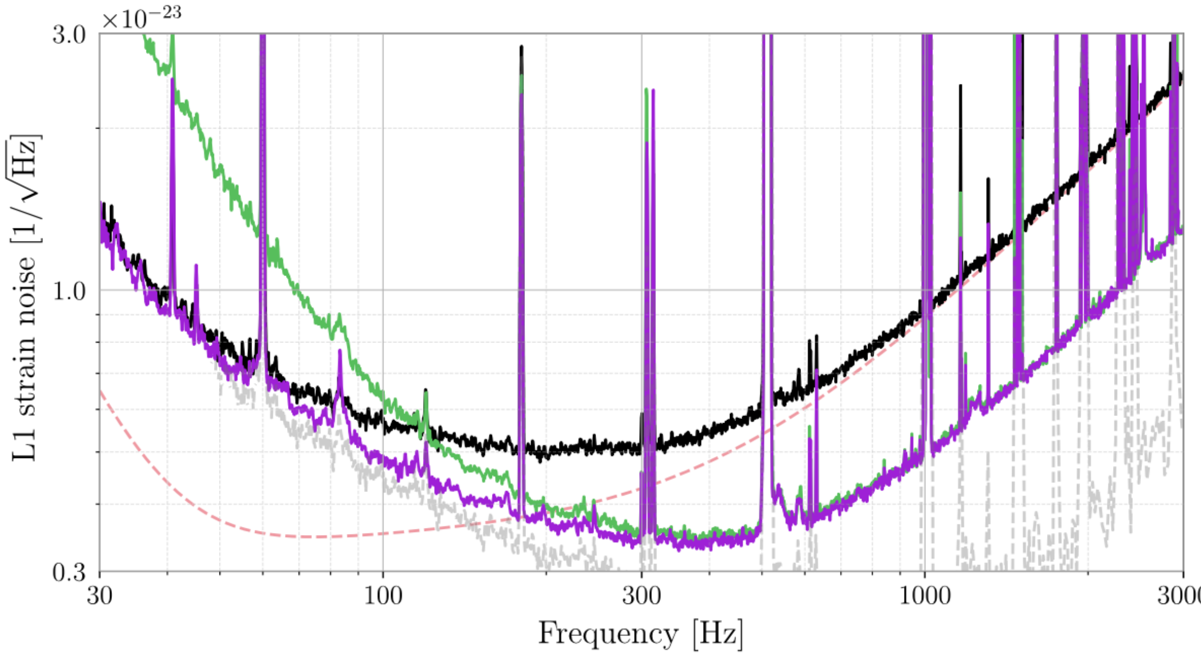
D. Ganapathy et al. (The LIGO O4 Detector Collaboration), „Broadband Quantum Enhancement of the LIGO Detectors with Frequency-Dependent Squeezing", Phys. Rev. X **13**, 041021 (2023)]

FREQUENCY-DEPENDENT SQUEEZING AT aLIGO (O4)

LIGO Hanford



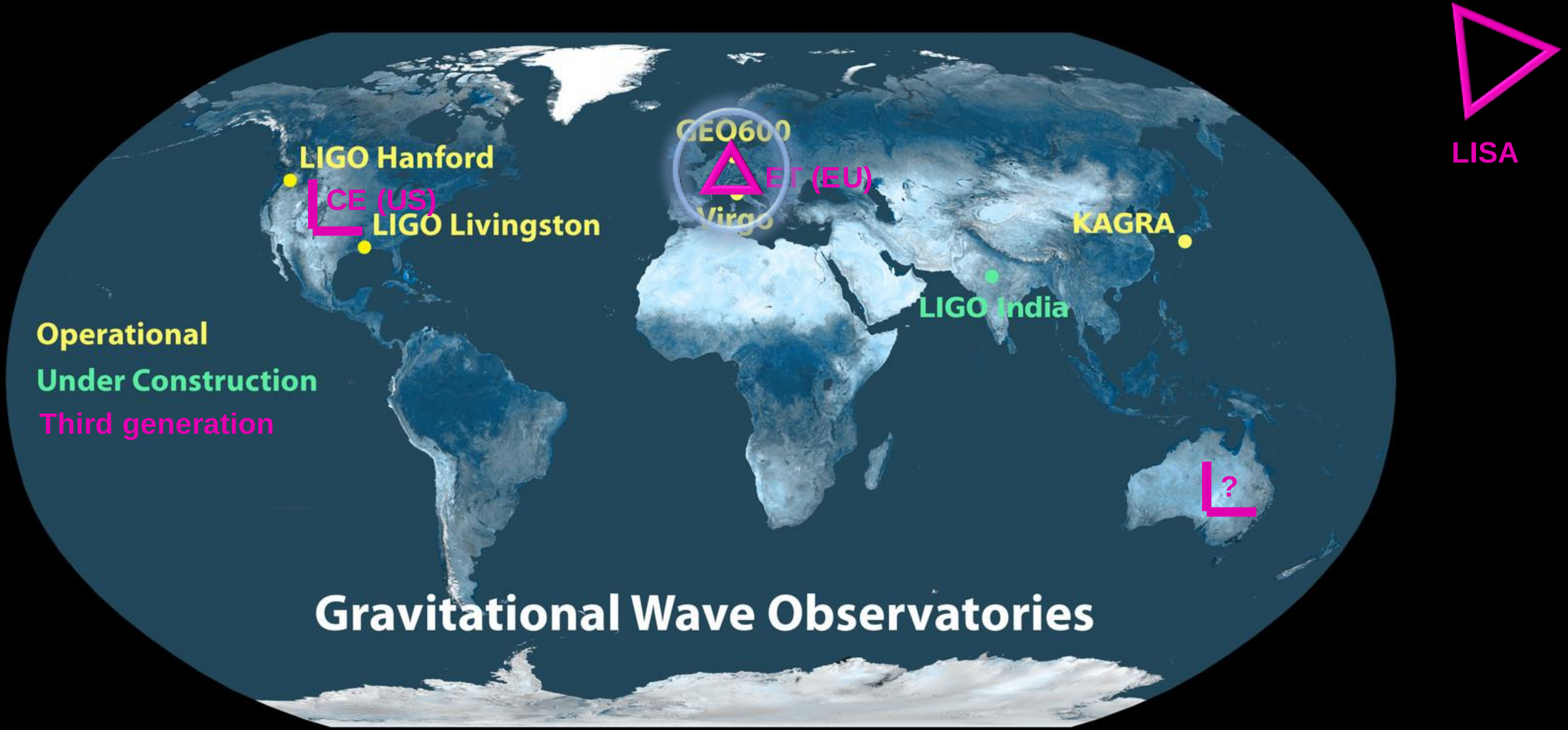
LIGO Livingston



D. Ganapathy et al. (The LIGO O4 Detector Collaboration), „Broadband Quantum Enhancement of the LIGO Detectors with Frequency-Dependent Squeezing“, Phys. Rev. X **13**, 041021 (2023)]

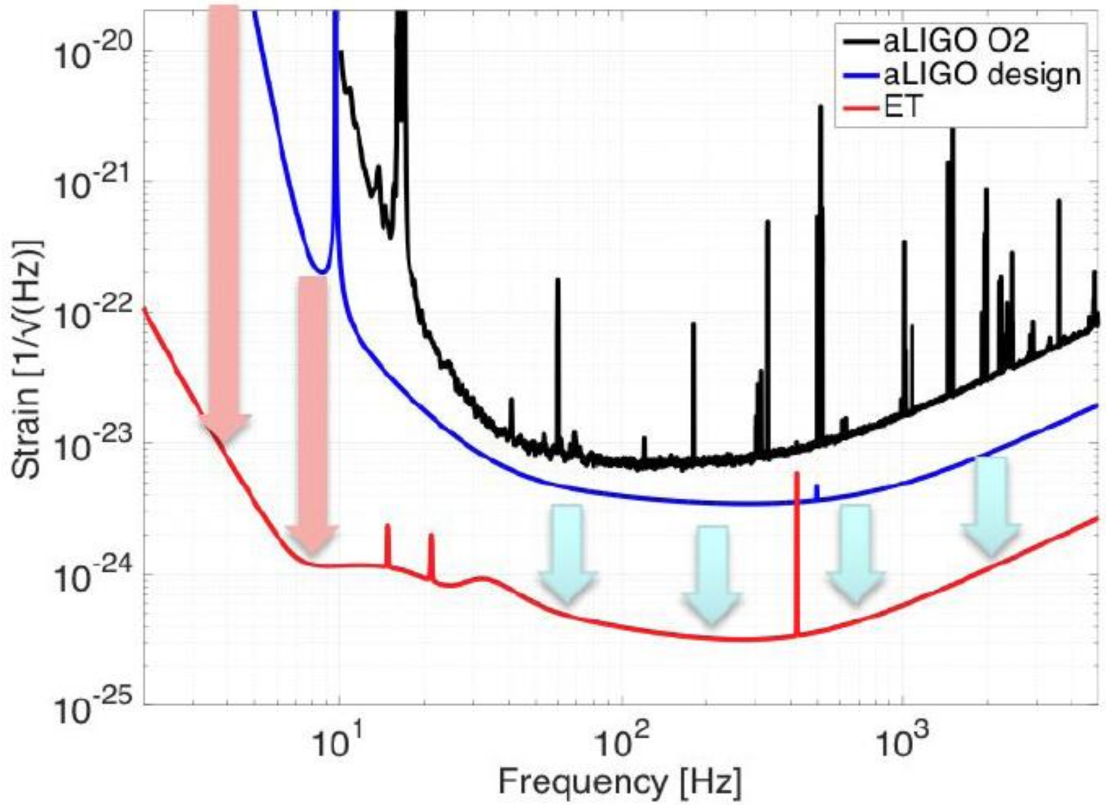
THE NEXT GENERATION

THE WORLDWIDE DETECTOR NETWORK OF THE FUTURE



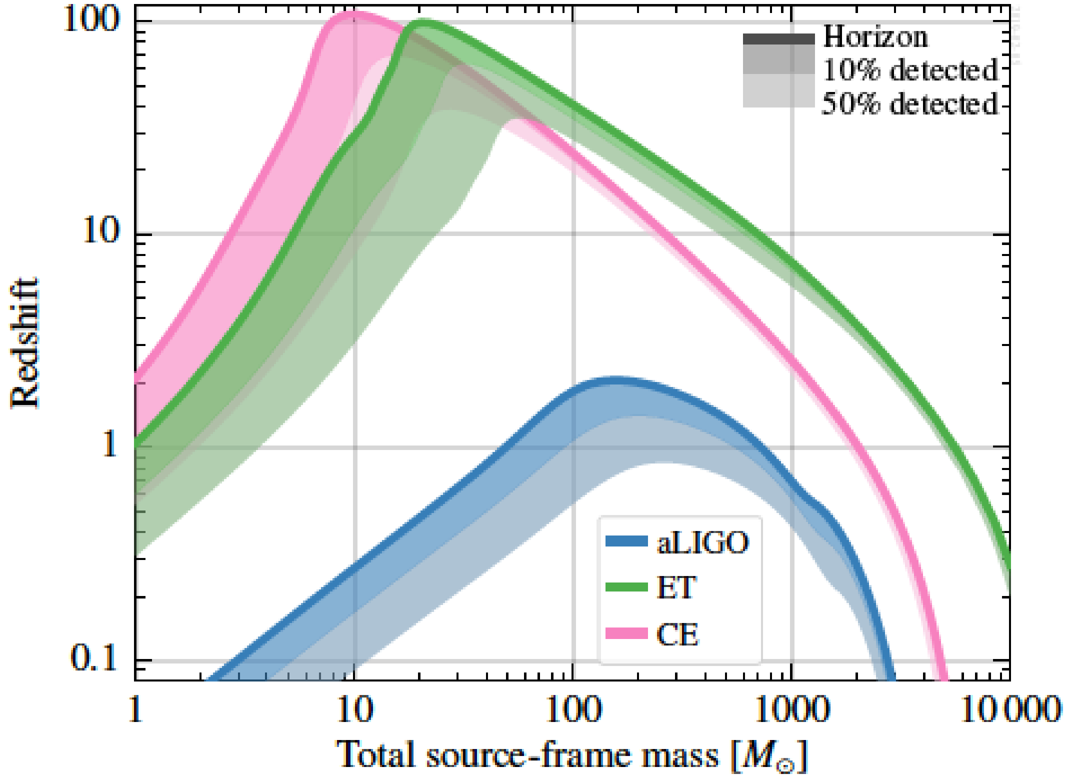
SENSITIVITIES OF 3G GWDS

Sensitivity comparison of Advanced LIGO and Einstein Telescope (design)



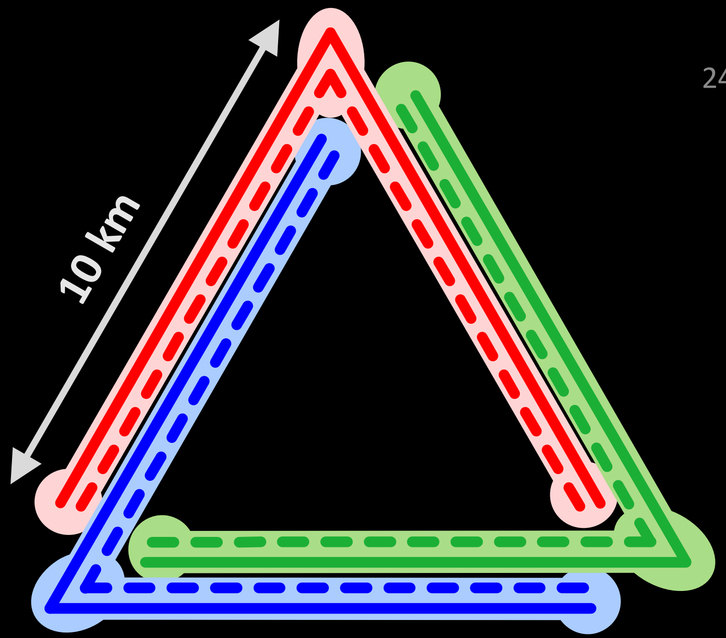
[source: Einstein Telescope Design Report Update 2020]

Astrophysical reach for equal-mass, nonspinning binaries for Advanced LIGO, Einstein Telescope and Cosmic Explorer

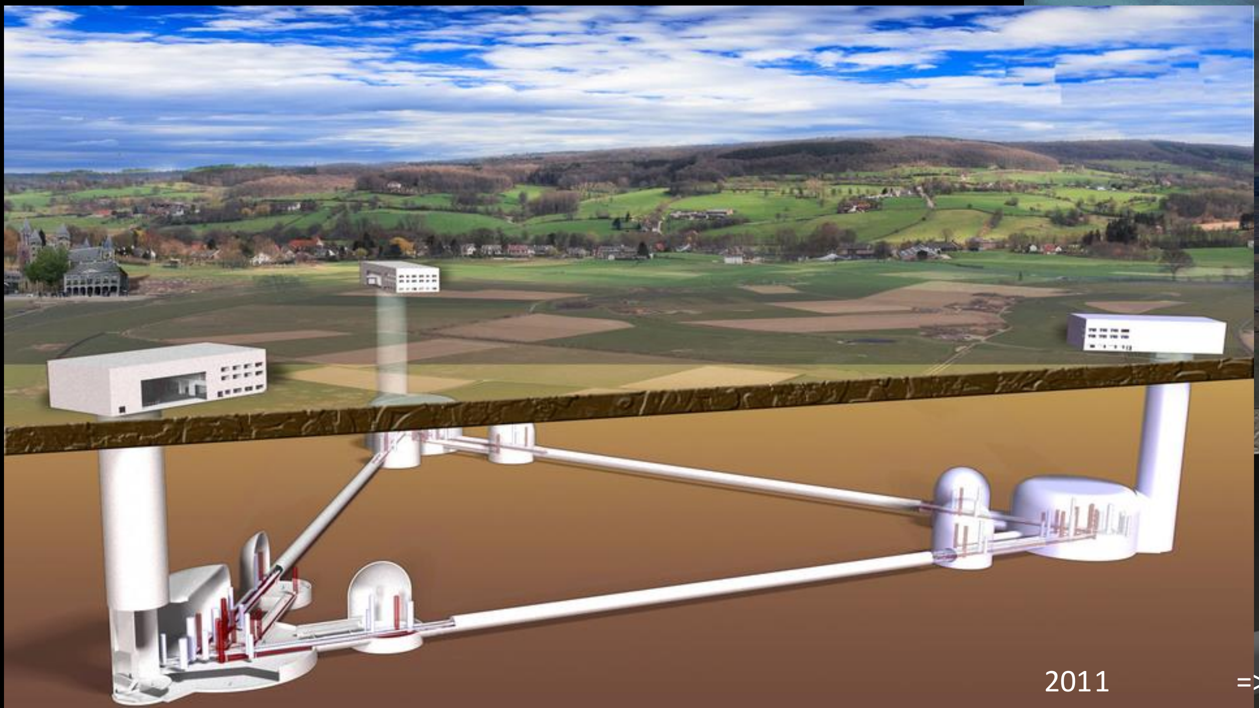


[source: ET Design Report Update 2020, and references therein].

THE EINSTEIN TELESCOPE (ET)



- A **European** project!
- Triangular* underground GW observatory (at 200 – 300 m depth) with 10 km arm length



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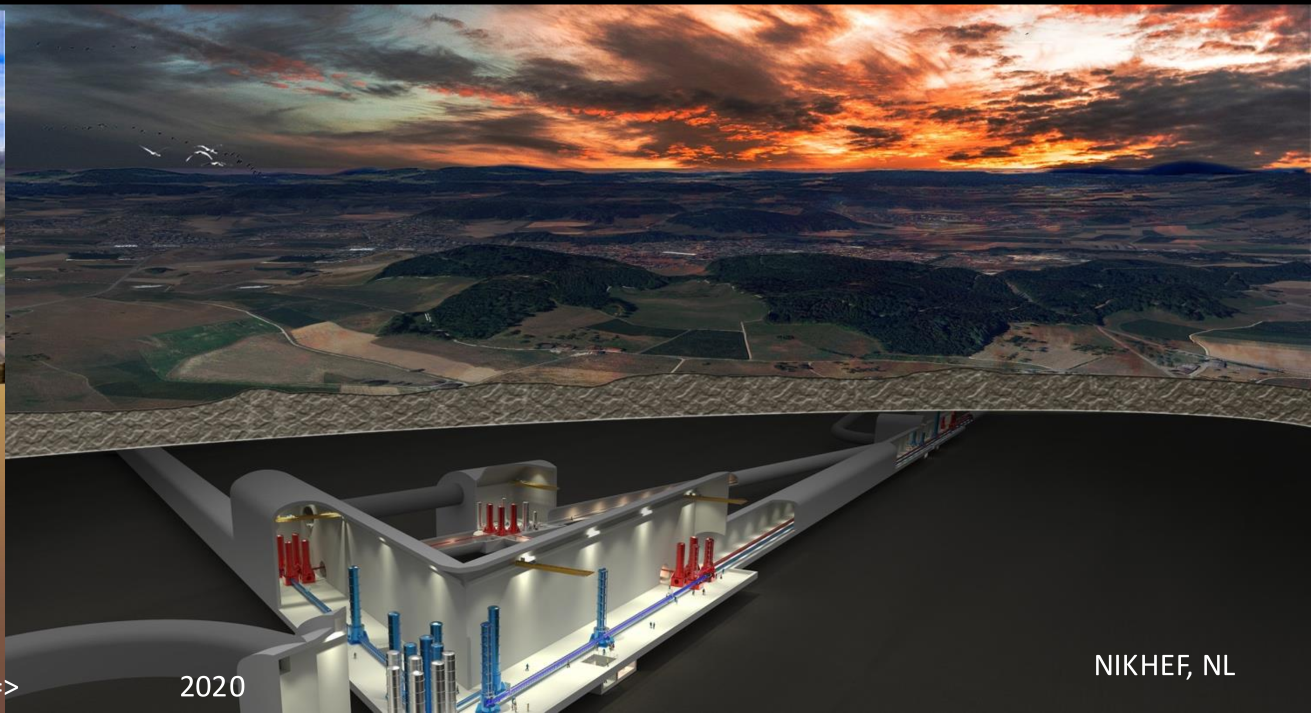

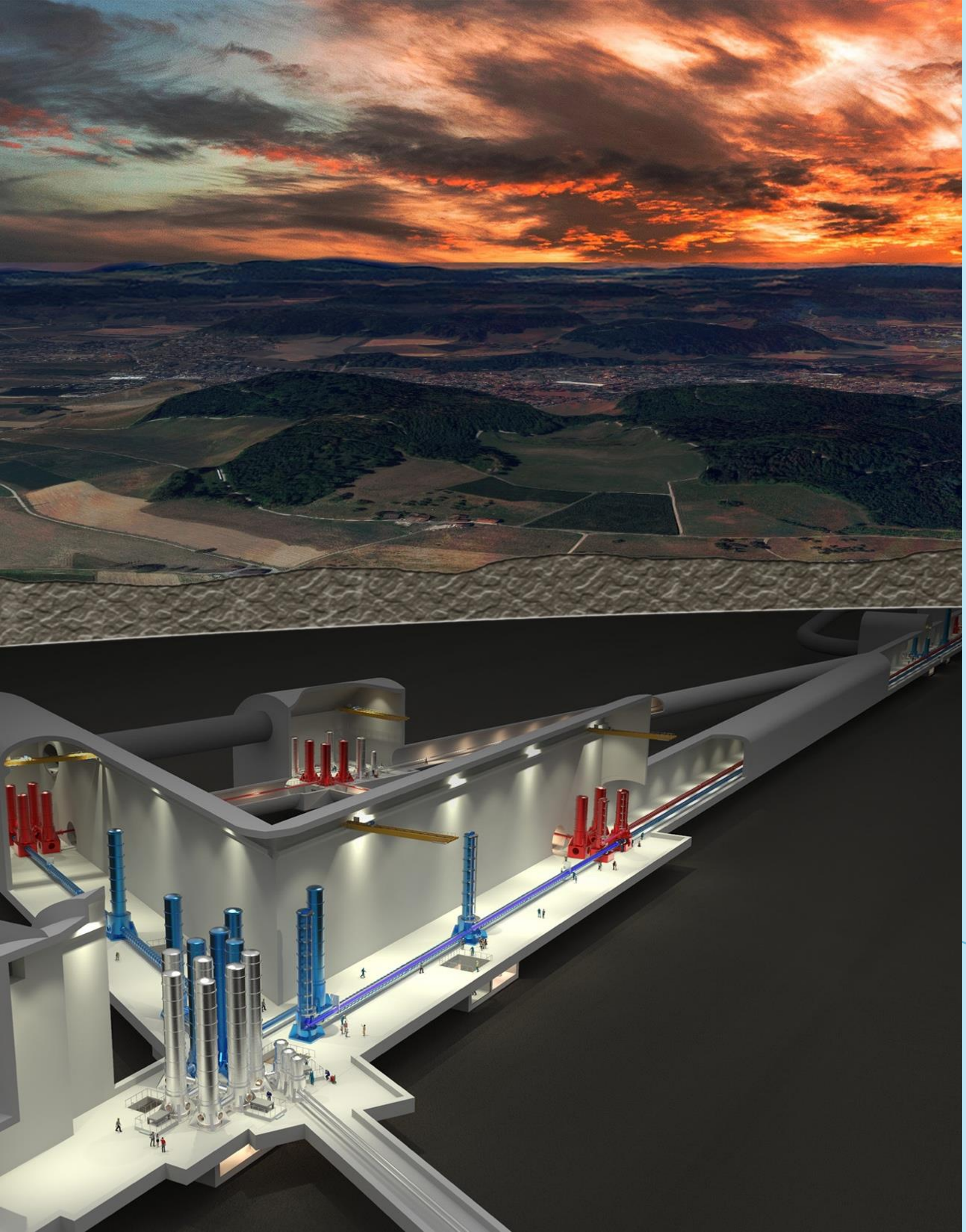

Atlantic Ocean
North Sea
Celtic Sea
Bay of Biscay
Ligurian Sea
Balearic Sea
Tyrrhenian Sea
Adriatic Sea
Mediterranean Sea
IRELAND
Dublin
Belfast
UNITED KINGDOM
Glasgow
Edinburgh
Isle of Man (U.K.)
Leeds
Liverpool
Manchester
Birmingham
Cardiff
London
Guernsey (U.K.)
Jersey
DENMARK
Copenhagen
Göteborg
Malmö
Bornholm
Amsterdam
NETH.
Rotterdam
Brussels
Luxembourg
LUX.
Hamburg
Bremen
Berlin
Poznań
Essen
Leipzig
Bonn
GERMANY
Frankfurt
Stuttgart
Munich
Prague
Brno
Vienna
AUSTRIA
LIECH.
Vaduz
Zürich
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SWITZ.
SLOVENIA
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Toulouse
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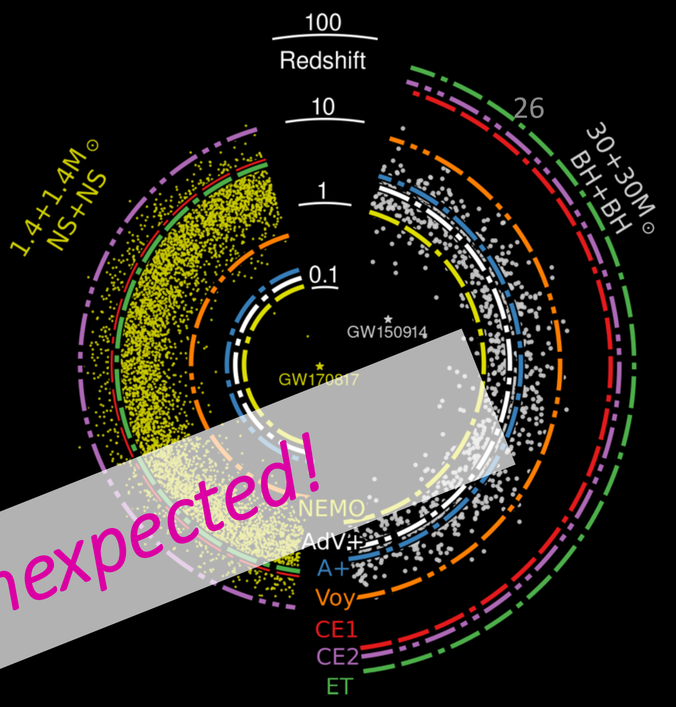
Andorra la Vella
ANDORRA
Milan
Venice
Turin
Genoa
SAN MARINO
Florence
ITALY
Rome
VATICAN CITY
Naples
Corsica
Sardinia
Càgliari
Palermo
SPAIN
PORTUGAL
A Coruña
Porto
Lisbon
Bilbao
Zaragoza
Madrid
Barcelona
Valencia
BALEARIC ISLANDS
Sevilla
Málaga
Gibraltar (U.K.)
40
EU Regio Rhein-Maas
Lusatia?
Sardinia

WHAT SCIENCE CAN WE DO WITH ET?



Astrophysics

- Black hole properties
  - origin (stellar vs. primordial)
  - evolution, demography
- Neutron star properties
  - interior structure (QCD at ultra-high densities, exotic states of matter)
  - demography
- Multi-messenger astronomy
  - joint GW/EM observations (GRB, kilonova,…)
  - multiband GW detection (LISA)
  - neutrinos
- Detection of new astrophysical sources
  - core collapse supernovae
  - isolated neutron stars
  - stochastic background of astrophysical origin

Fundamental physics and cosmology

- The nature of compact objects
  - near-horizon physics
  - tests of no-hair theorem
  - exotic compact objects
- Tests of General Relativity
  - post-Newtonian expansion
  - strong-field regime
- Dark Matter
  - primordial Black Holes
  - Axion clouds, DM accreting on compact objects
- Dark Energy and modifications of gravity on cosmological scales
  - DE equation of state
  - modified GW propagation
- Stochastic backgrounds of cosmological origin and connections with high-energy physics
  - inflation
  - phase transitions
  - cosmic strings
  - …

But: ET will be a "discovery machine", so expect the unexpected!

Einstein Telescope

„All" BBH back to Big Bang

Nearly all BNS back to Big Bang

Many supernovae

View to the Dark Ages

[This list was taken verbatim from the talk by M. Maggiore at the 11th ET Symposium (2020)]

DZA TEAM AND NETWORK

AIP

DESY.

Max-Planck-Institut
für Radioastronomie

TECHNISCHE
UNIVERSITÄT
DRESDEN

R D S

KAT. Komitee für
Astro. Teilchen. Physik

VdR

HZDR
HELMHOLTZ ZENTRUM
DRESDEN ROSSENDORF

SKAO

ET EINSTEIN TELESCOPE

Nikhef

SILICON SAXONY
THE HIGH-TECH NETWORK

futureSAX
Idee. Transfer. Innovation.

LRT
SACHSEN/THÜRINGEN

Uniwersytet
Wrocławski

OHB
DIGITAL

IBM

DOMOWINA

Stadt Görlitz

THE QUANTUM CONTROL GROUP ☺

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Mariia Matiushechkina Lea Richtmann Tim Bartelsmeier Kirstin Tews M.H. Imke Niehoff Frauke Berger Roman Kossak Nived Johny