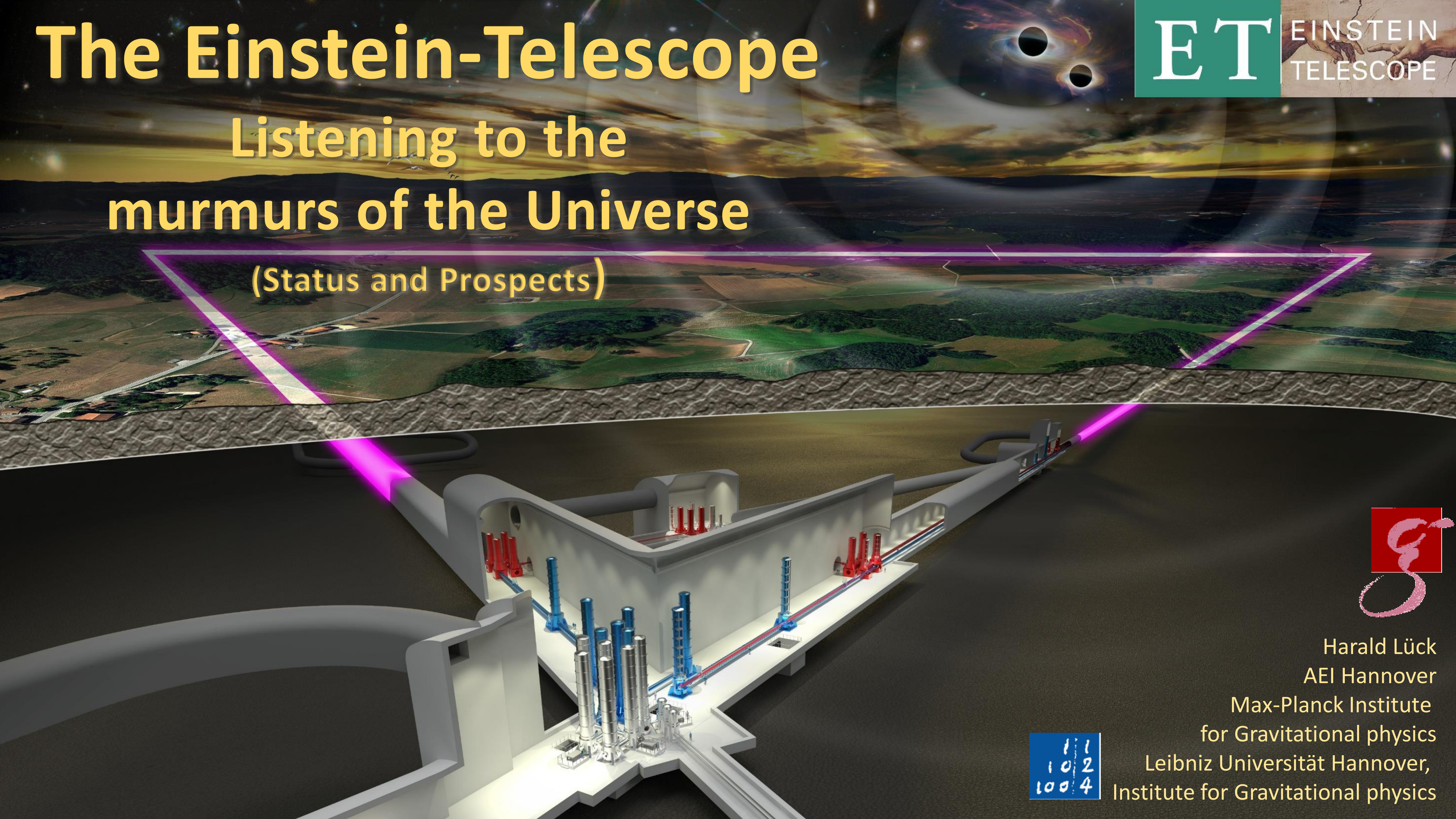
The Einstein-Telescope

Listening to the murmurs of the Universe

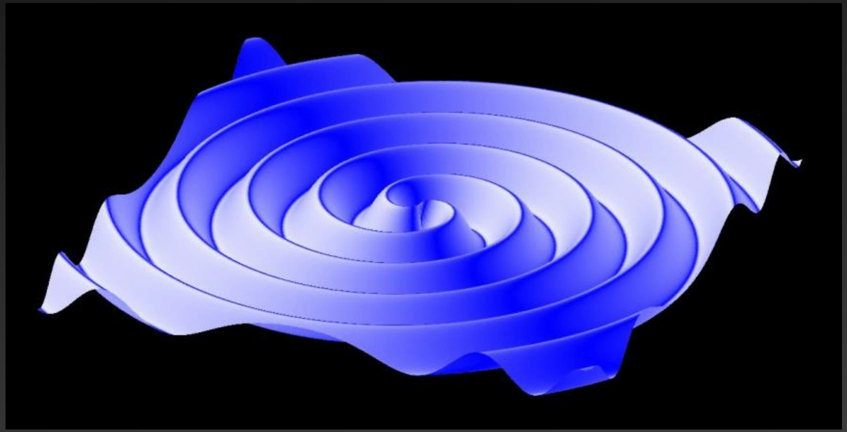
(Status and Prospects)



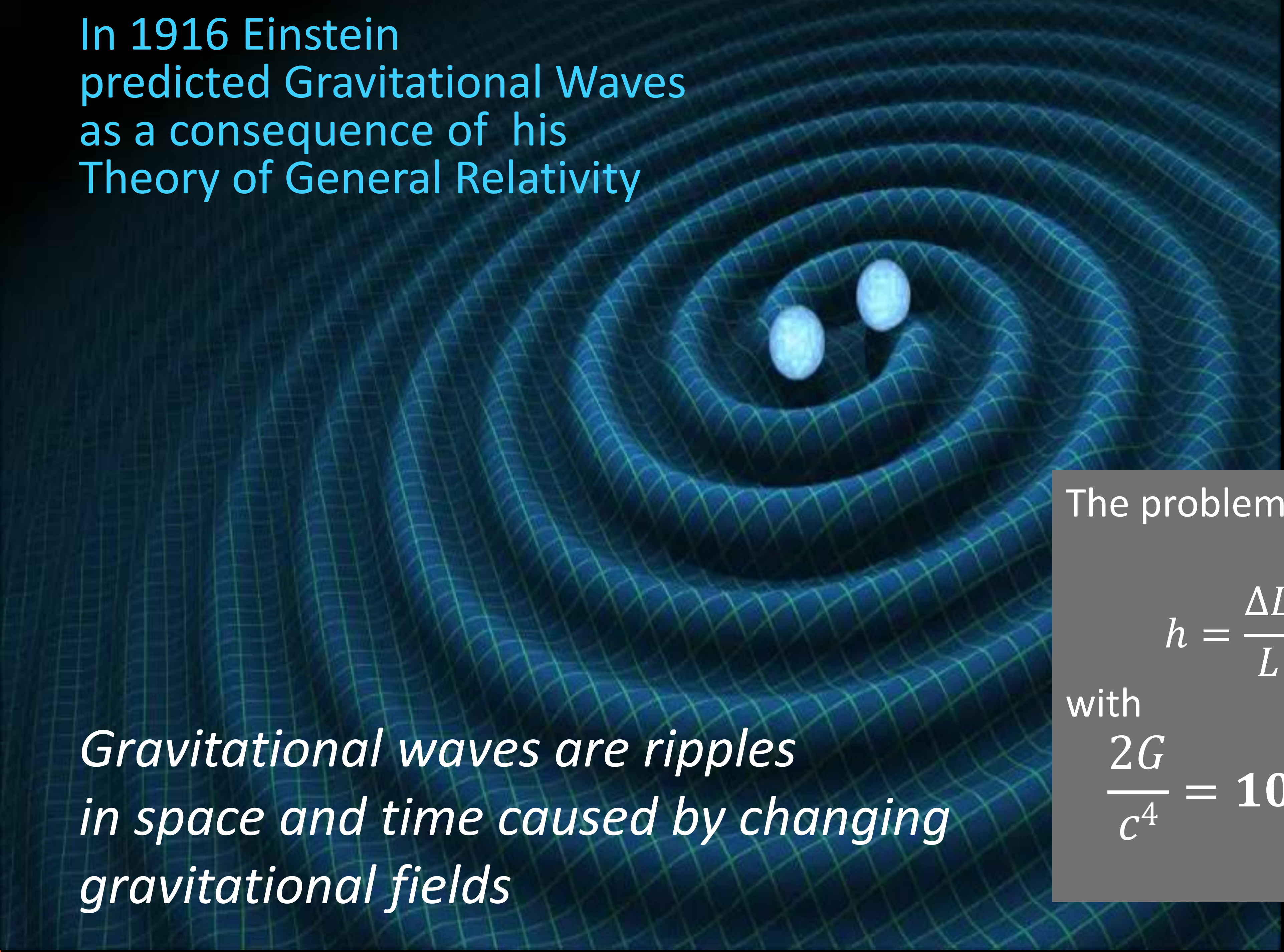
Harald Lück
AEI Hannover
Max-Planck Institute
for Gravitational physics
Leibniz Universität Hannover,
Institute for Gravitational physics

Content

- Gravitational waves
  - What are we talking about?
  - What have we detected so far?
  - What do we intend to measure?



- GW Detectors
  - How do they work?
  - What have we got?
  - How to improve?
  - Einstein Telescope!



In 1916 Einstein
predicted Gravitational Waves
as a consequence of his
Theory of General Relativity

Gravitational waves are ripples in space and time caused by changing gravitational fields

The problem is:

$$h = \frac{\Delta L}{L} = \frac{2\,G}{c^4}\,\frac{d^2Q}{dt^2}\,\frac{1}{d}$$

with

$$\frac{2G}{c^4} = \mathbf{10^{-44}}\,s^2 kg^{-1} m^{-1}$$

How big is ΔL caused by a Gravitational wave?

4000,0000000000000000004 m

Effect of a gravitational wave
on a length of 4km

$$h = 10^{-22}$$

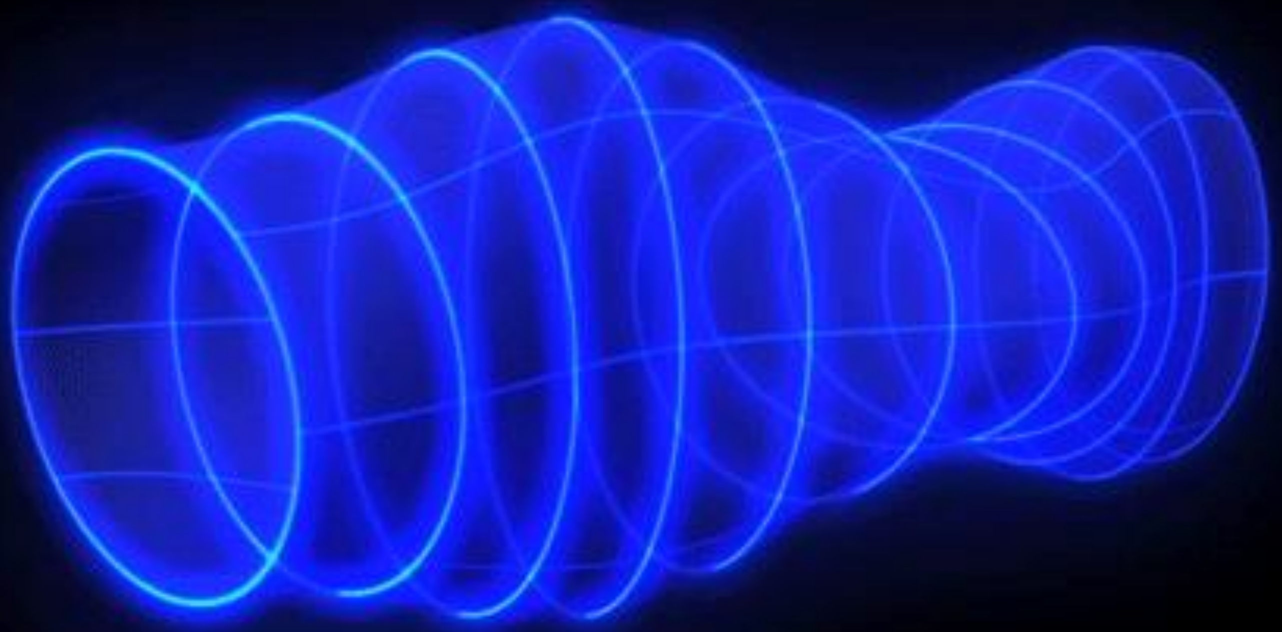
3999,9999999999999999996 m

Haar

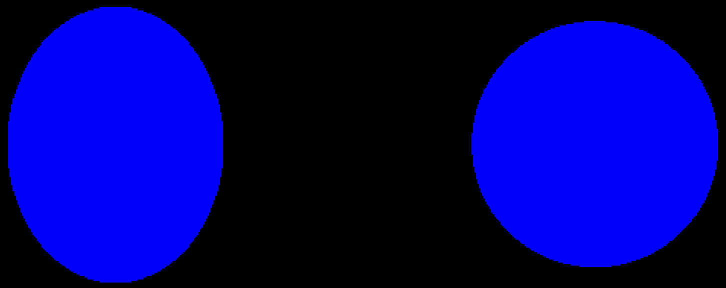
Atom

Proton

Gravitational waves propagate at the speed of light and cause measurable changes in the distance between objects



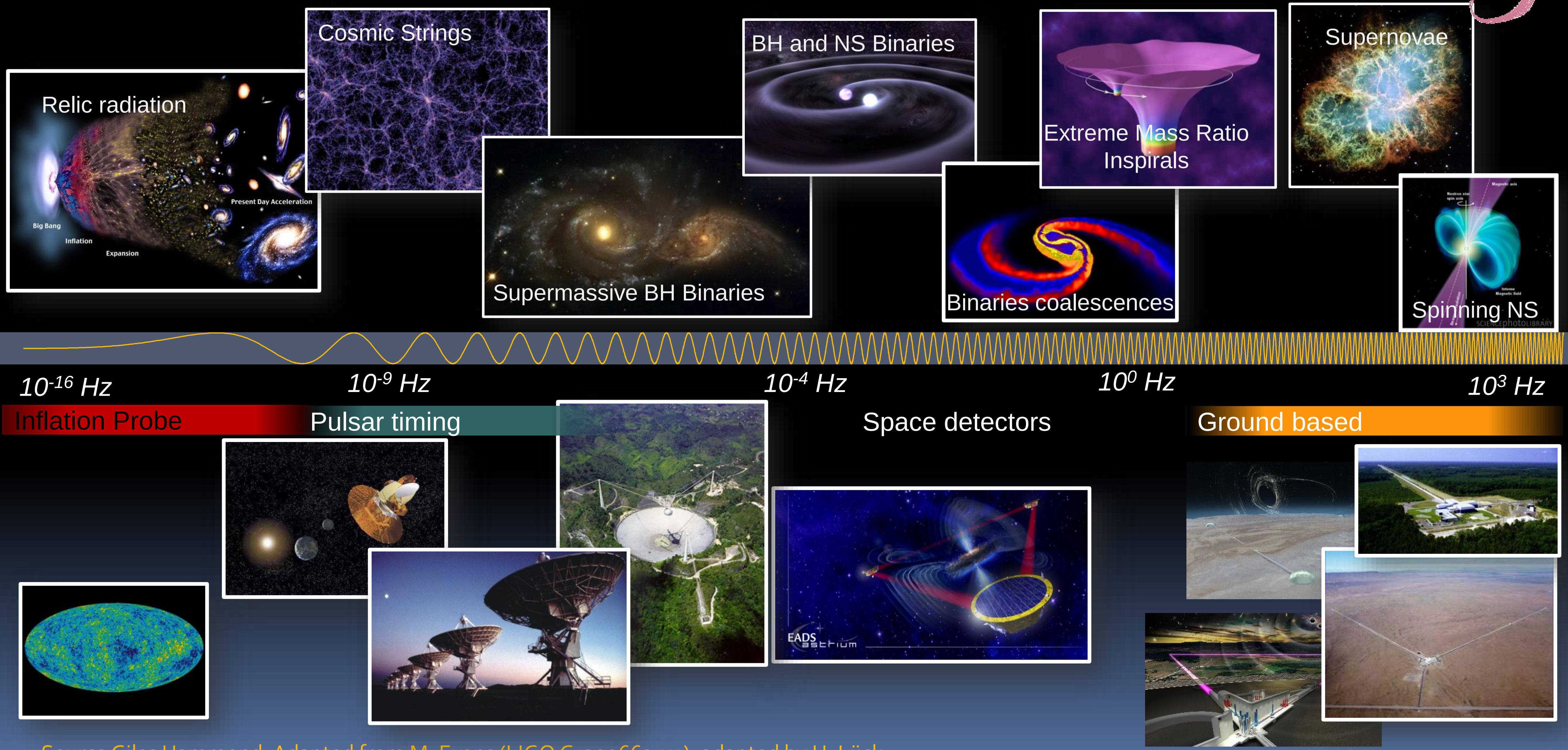
Credit: ESA–C.Carreau



"Plus" polarization

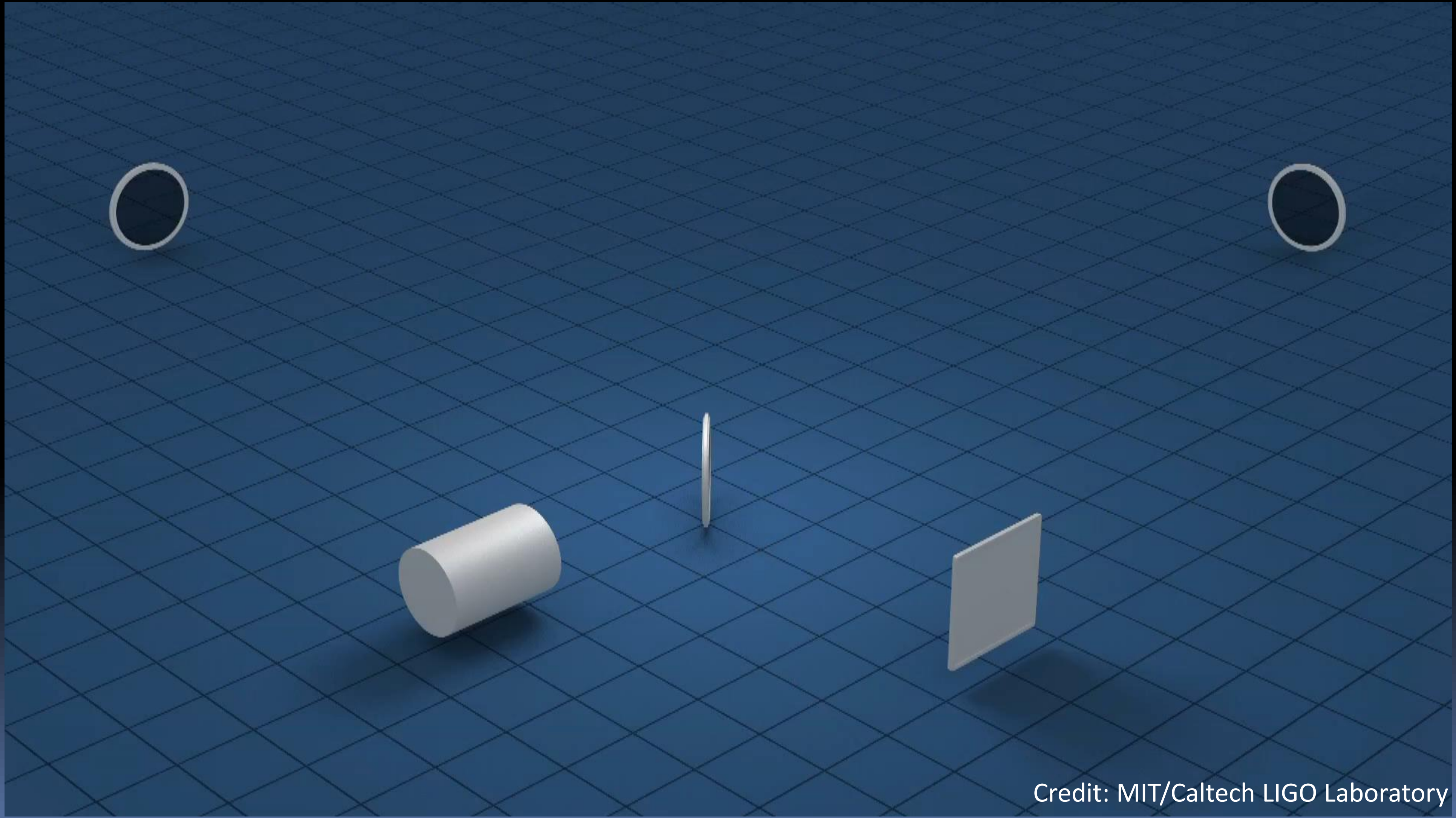
"Cross" polarization

The Gravitational Wave Spectrum



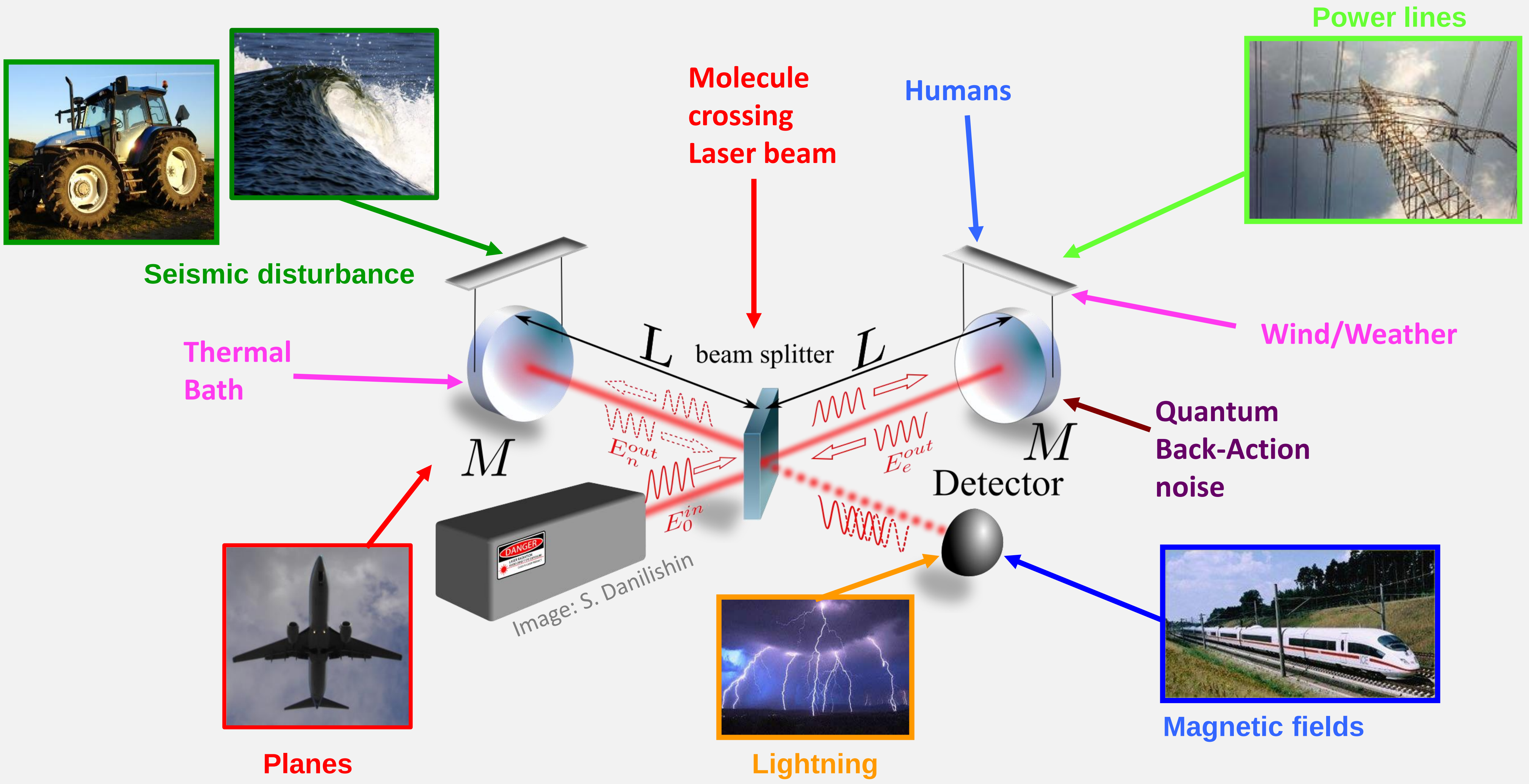
Source Giles Hammond: Adapted from M. Evans (LIGO G1300662-v4); adapted by H. Lück

Working principle of a GW Detector: Michelson Interferometer



Credit: MIT/Caltech LIGO Laboratory

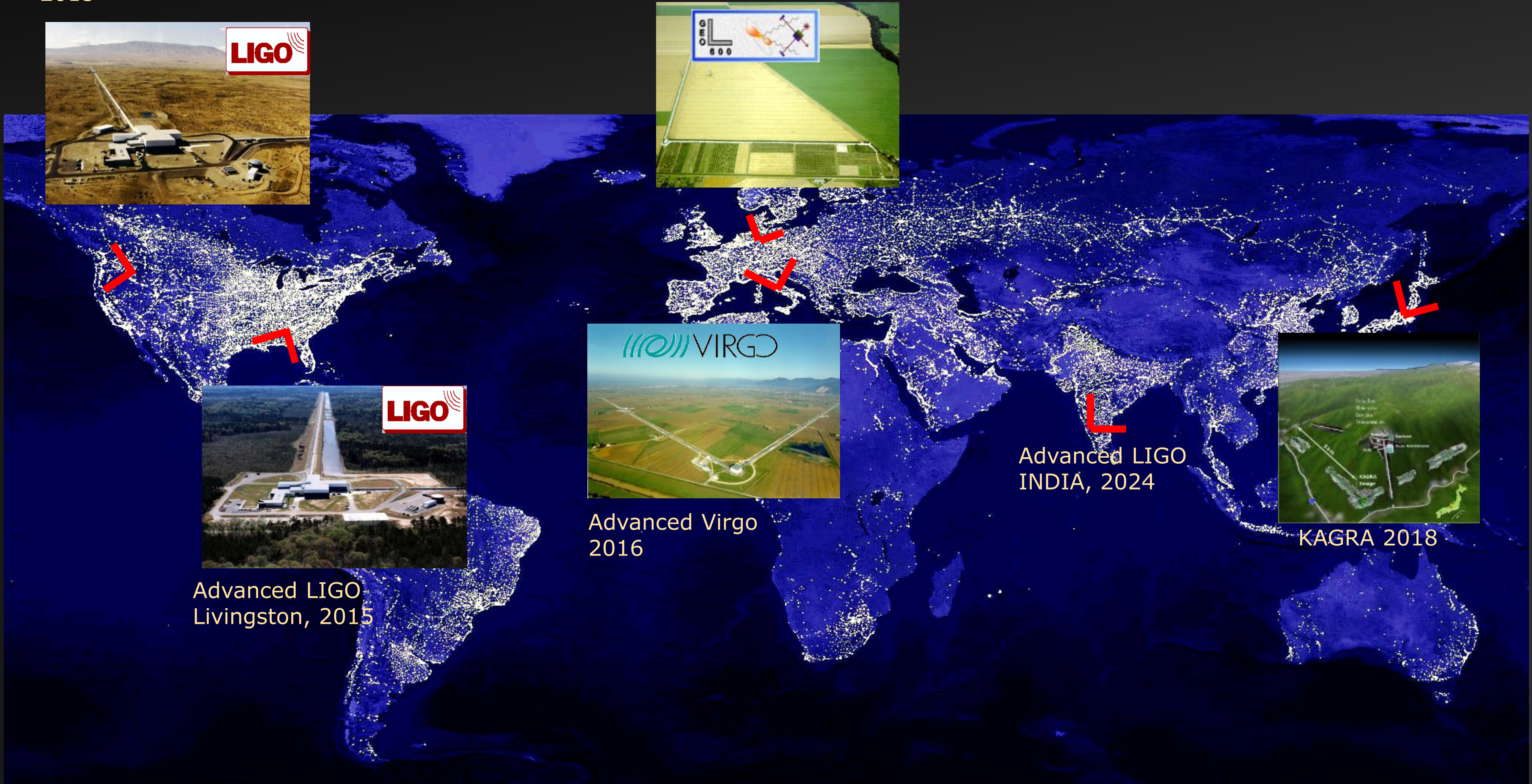
Lots of external disturbances



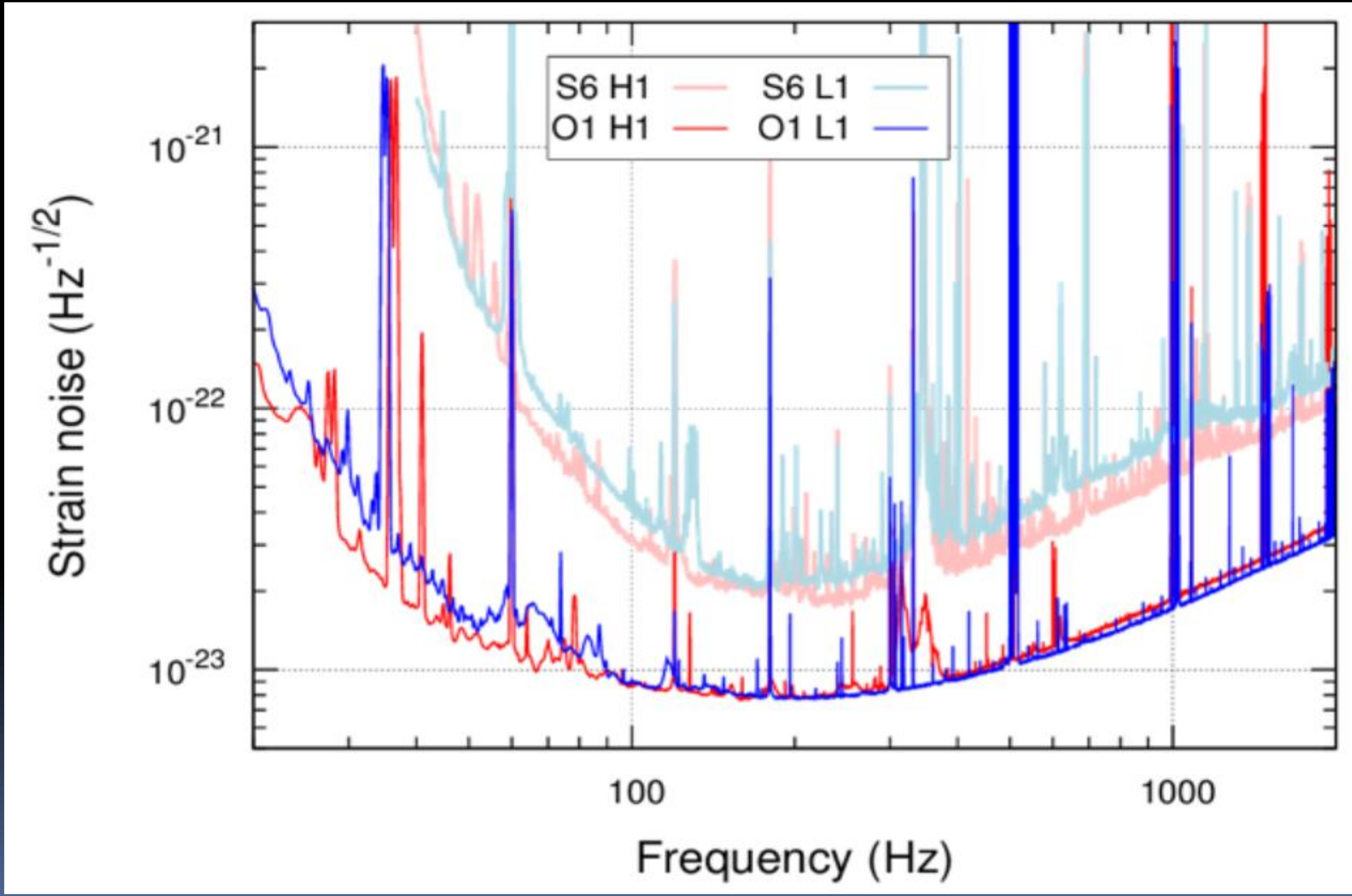
The advanced GW Network

Advanced LIGO Hanford, 2015

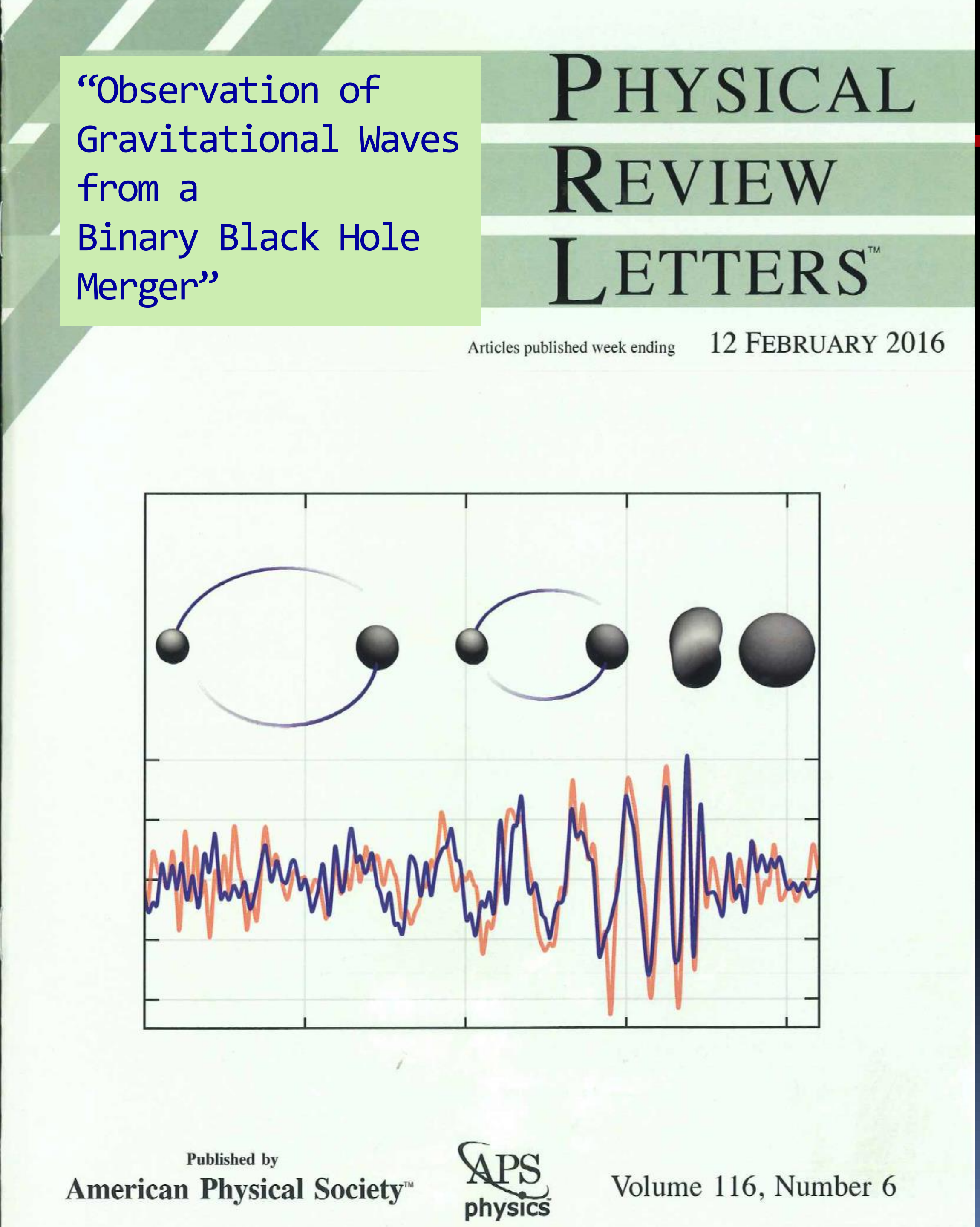
GEO600, 2011



Sensitivity improvement LIGO <-> aLIGO



“Observation of Gravitational Waves from a Binary Black Hole Merger”

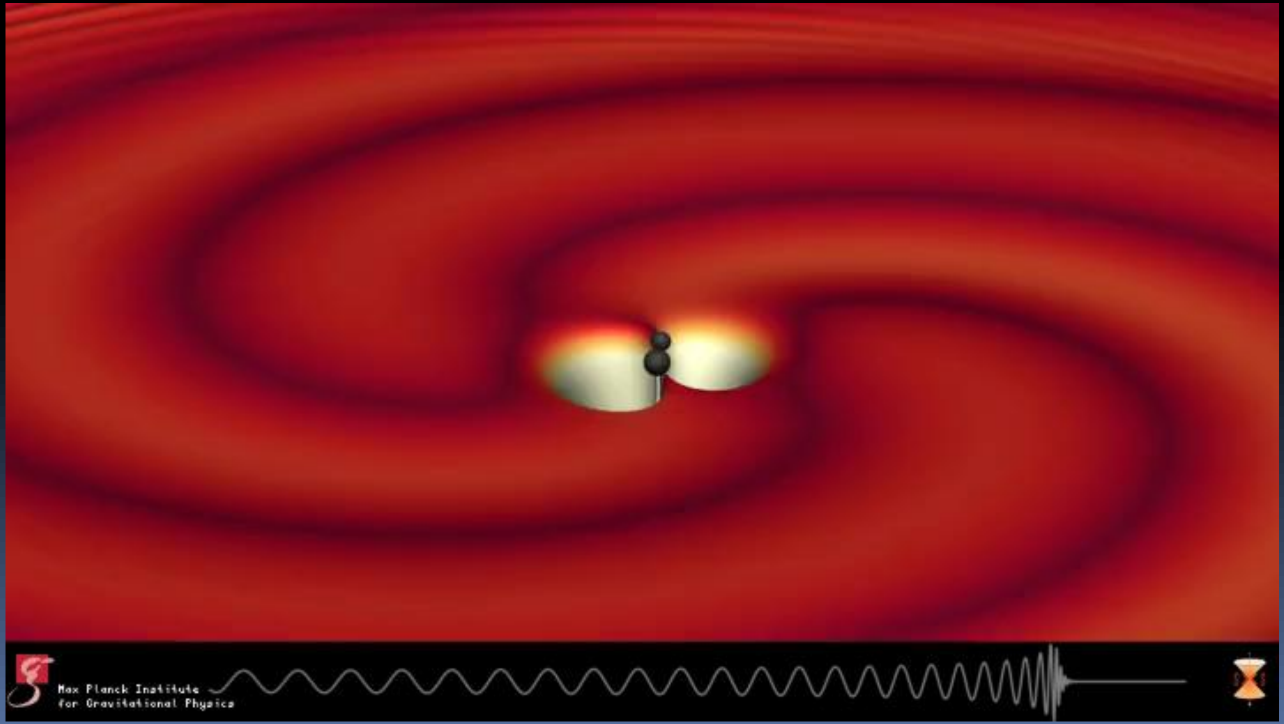


THE Detection

GW150914

14. September 2015
09:50:45 UTC
= 11:50:45 CEST

Detection of a transient signal in **both** advanced LIGO detectors



Preise

- Breakthrough Prize fundamental Physics 3M$
- Shaw Prize in Astronomy 1.2 M$
- Gruber Cosmology Prize 0.5 M$
- Kalvi Prize 1 M$
- OSA team engineering award

Nobel Preis 2017 !

Körber Stiftung

Karsten Danzmann erh

2017

Der deutsche Physiker Karsten Danzmann und sein Tea
denen 2015 in Amerika erstmals der direkte Nachweis v
Astronomen buchstäblich ein neues Fenster zum Kosm

Bislang kon
Wellen erfo
Gammastra
eigenen Bo
Danzmann.
Astronomie
99 Prozent

Karsten Danzmann

ASTROPHYSICS LAUREATES

2014 Alan H. Guth, Andrei D. Linde, Alexei A. Starobinsky

2012 David C. Jewitt, Jane X. Luu, Michael Edwards Brown

2016 KAVLI PRIZE IN ASTROPHYSICS

Otto-Hahn-Preis für
Forscher

ze Press Release

FOR IMMEDIATE RELEASE

Gruber Cosmology Prize for Detection of Gravitational Waves

Ronald W. P. Drever

Kip Thorne

Rainer Weiss

Professor Karsten Danzmann (Bild), Direktor am Max-Planck-Institut für Gravitationsphysik hat mit seinen Kollegen Alessandra Buonanno und B
Staatspreis gewo

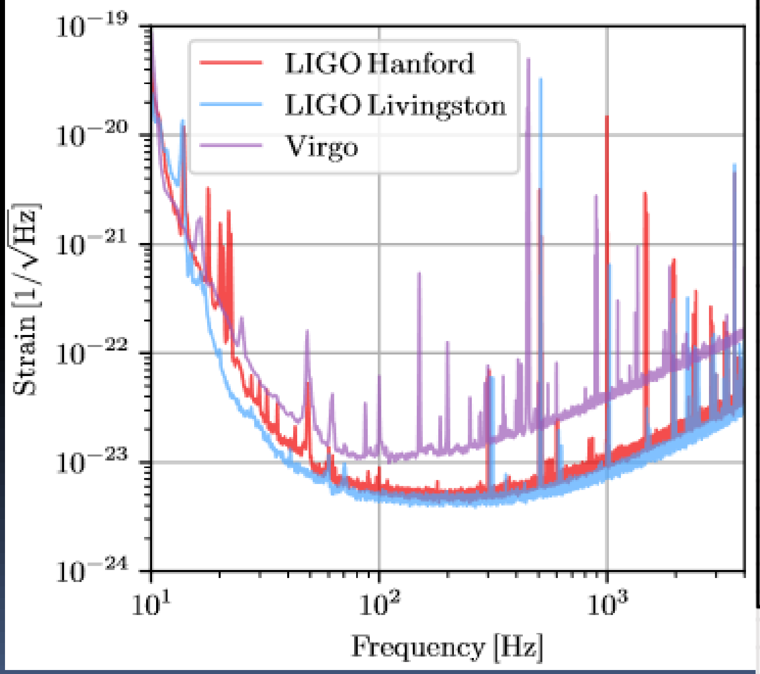
07 September 2016

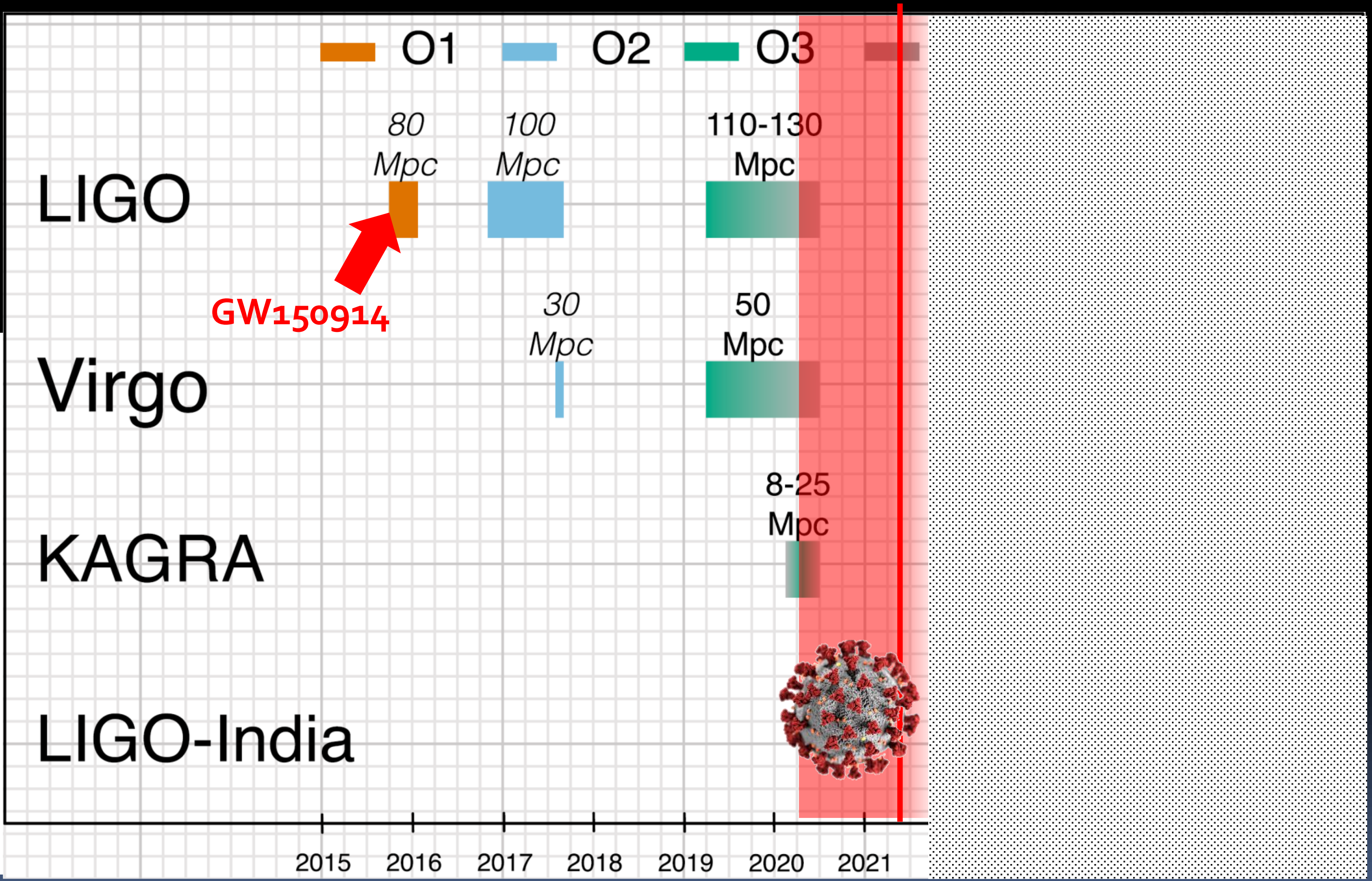
Advanced LIGO Engineering Team Receives OSA's 2016 Paul F. Forman Team Engineering Excellence Award

Overcoming a daunting list of engineering challenges; LIGO team connected optical, electrical and mechanical elements of advanced interferometry to find engineering success at the limits of human endeavor

LVK Observation runs

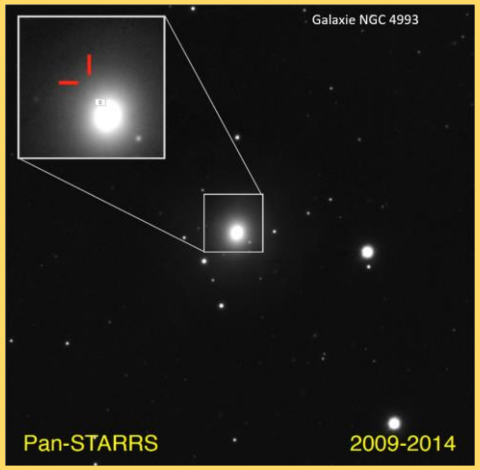
Median O3a:
LHO: 108MPc (1.64xO2)
LLO: 135 MPc (1.53xO2)
Virgo: 45 MPc (1.73XO2)

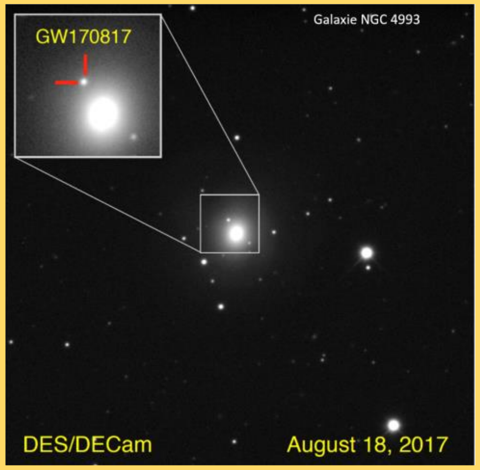




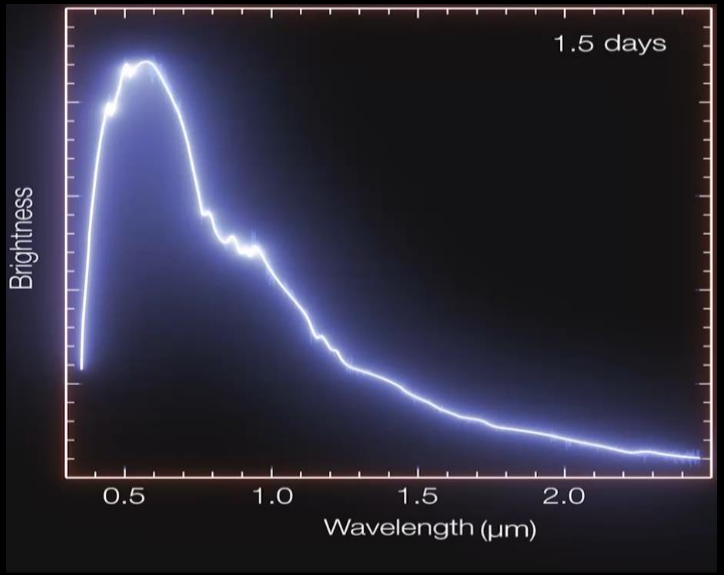
https://arxiv.org/pdf/2010.14527.pdf

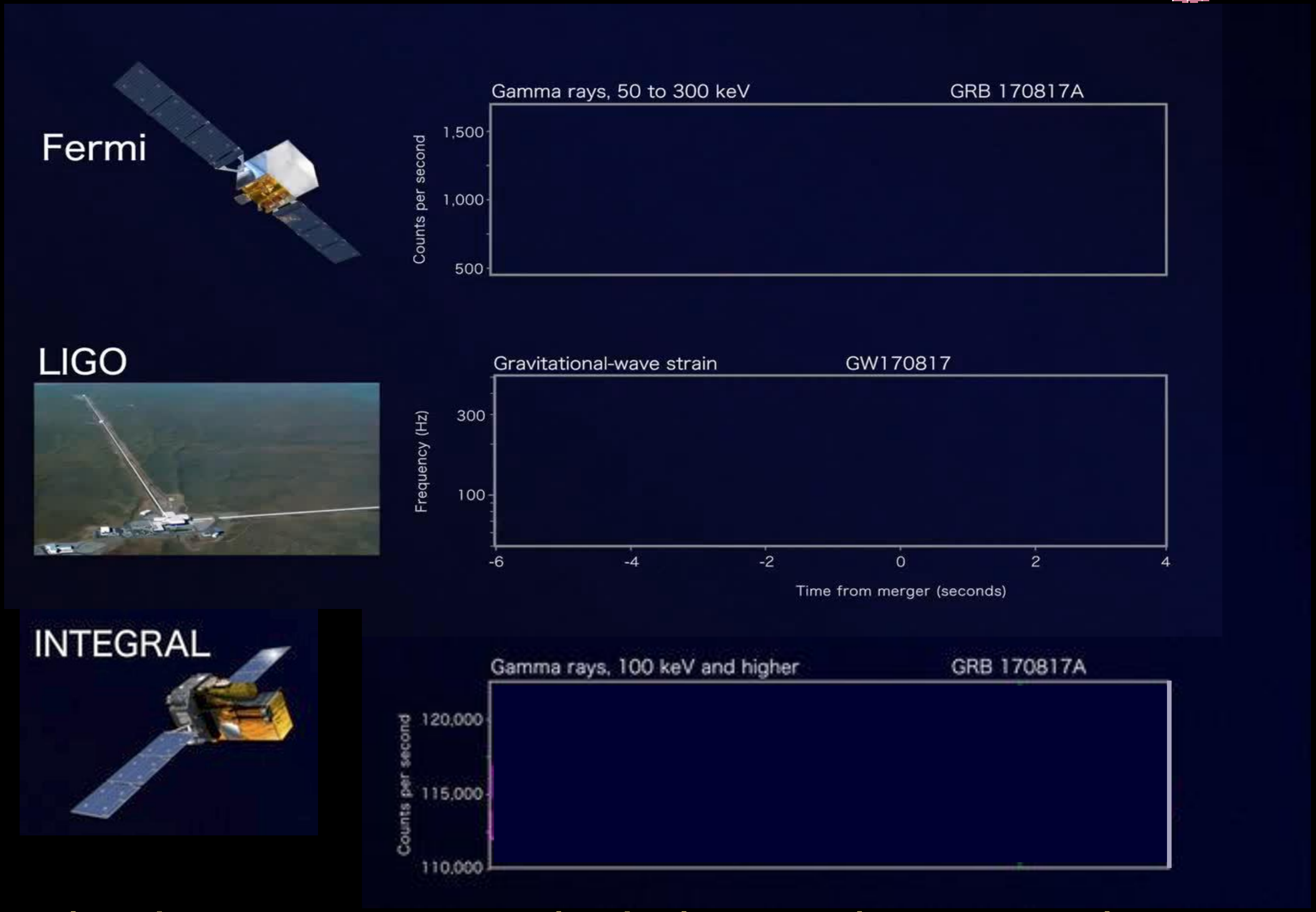
GW170817: A Binary Neutron star merger





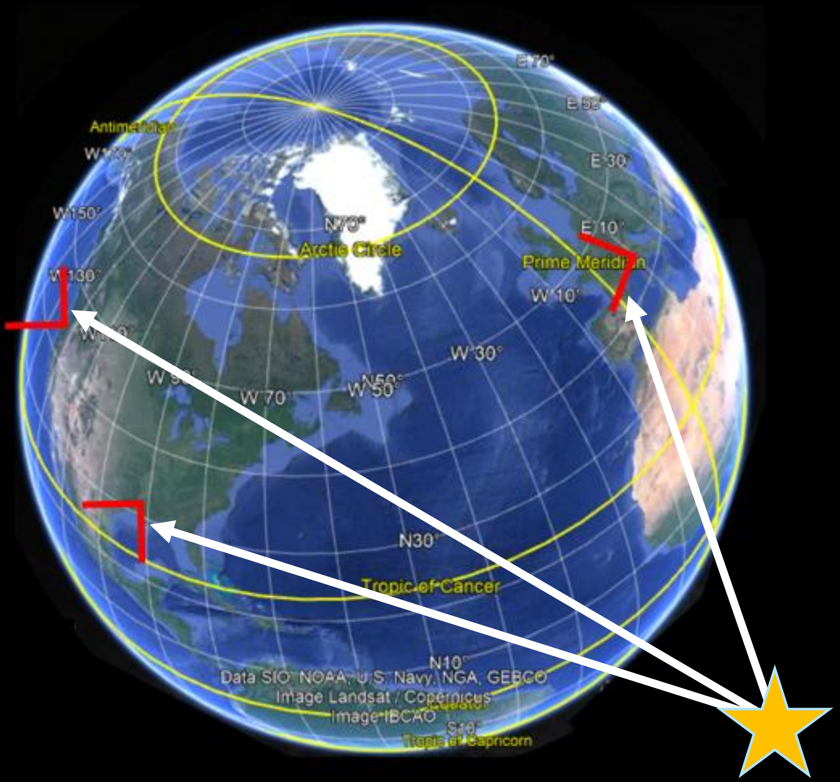
Electromagnetic follow-up





Led to largest astronomical observation campaign

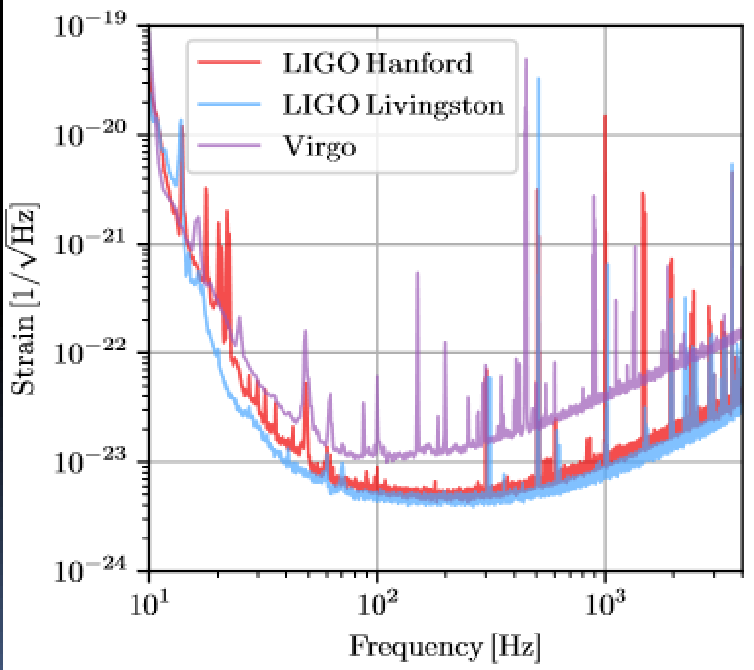
Localisation by Trilateration

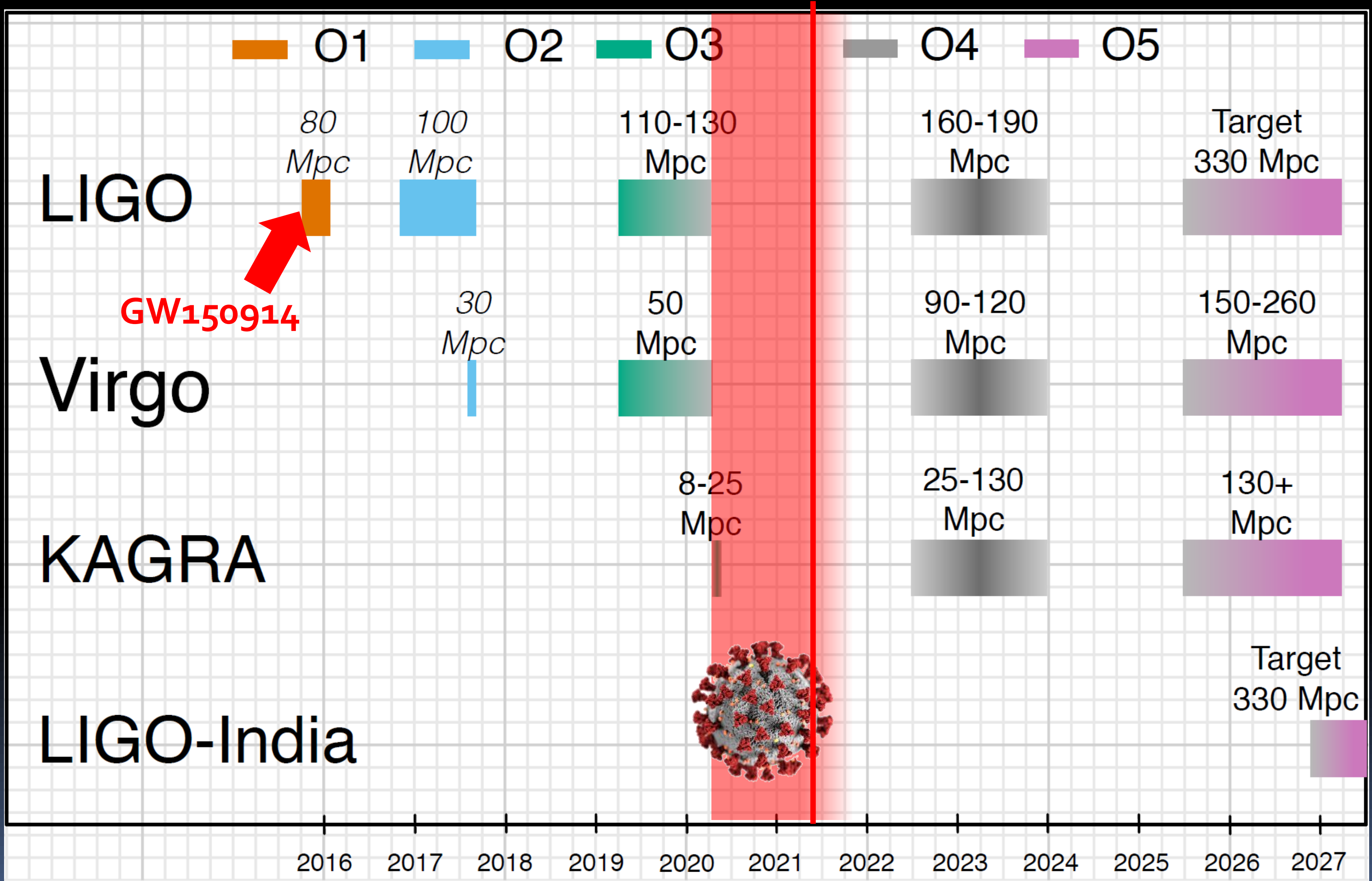


Slide: Stefan Hild (modified)

LVK Observation runs

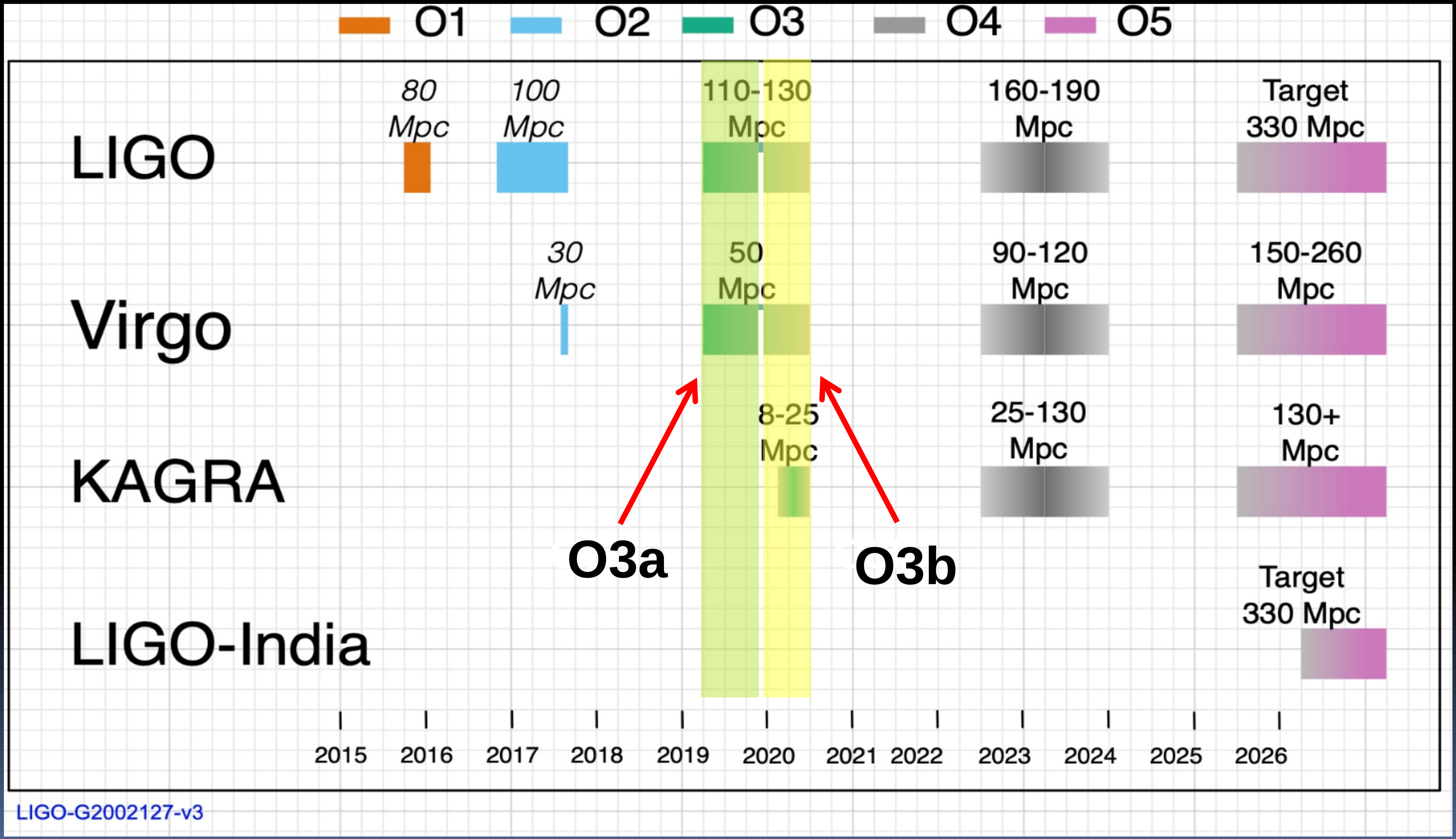
Median O3a:
LHO: 108MPc (1.64xO2)
LLO: 135 MPc (1.53xO2)
Virgo: 45 MPc (1.73XO2)





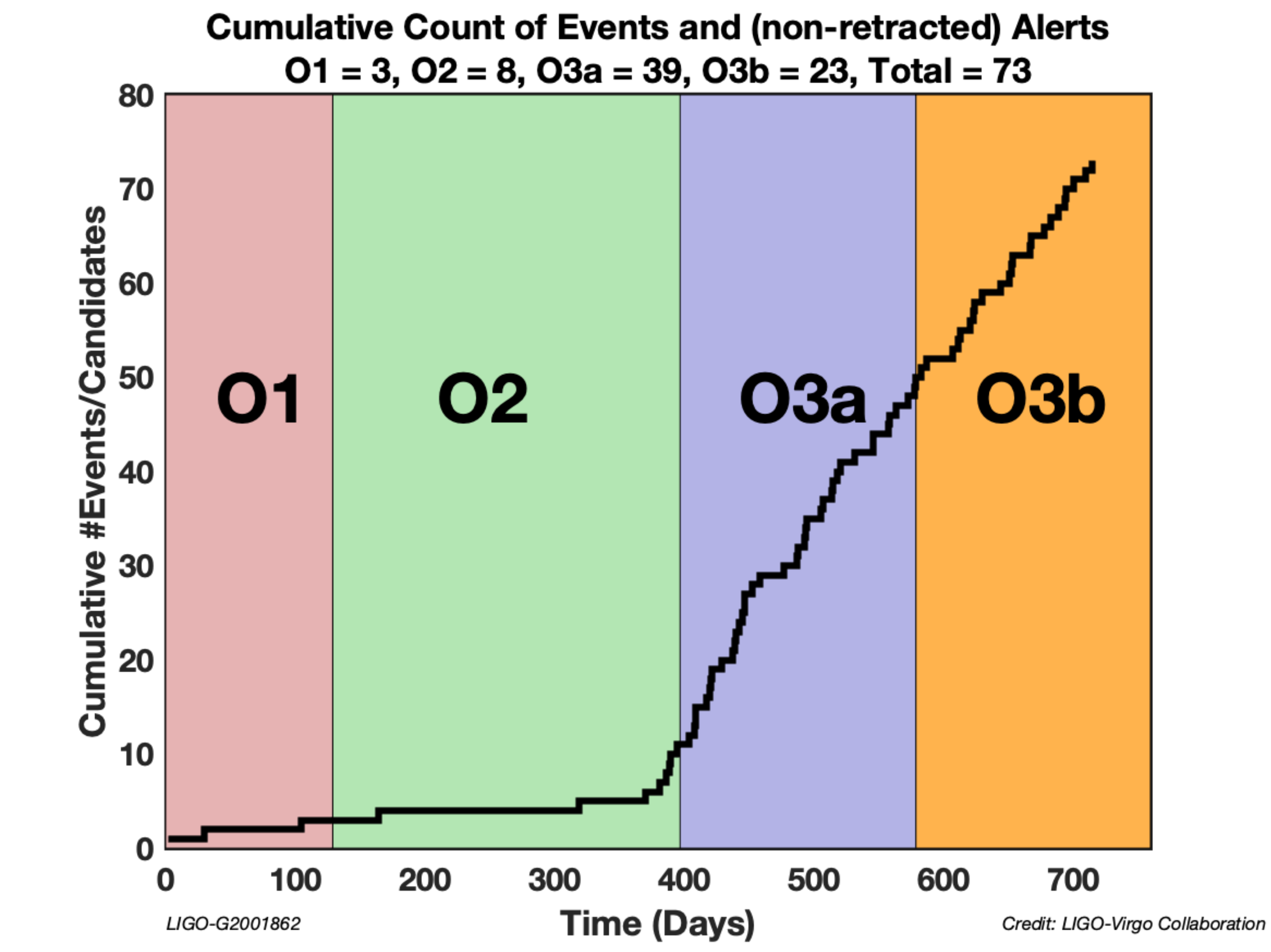
https://arxiv.org/pdf/2010.14527.pdf

O4 („not before June 2022")



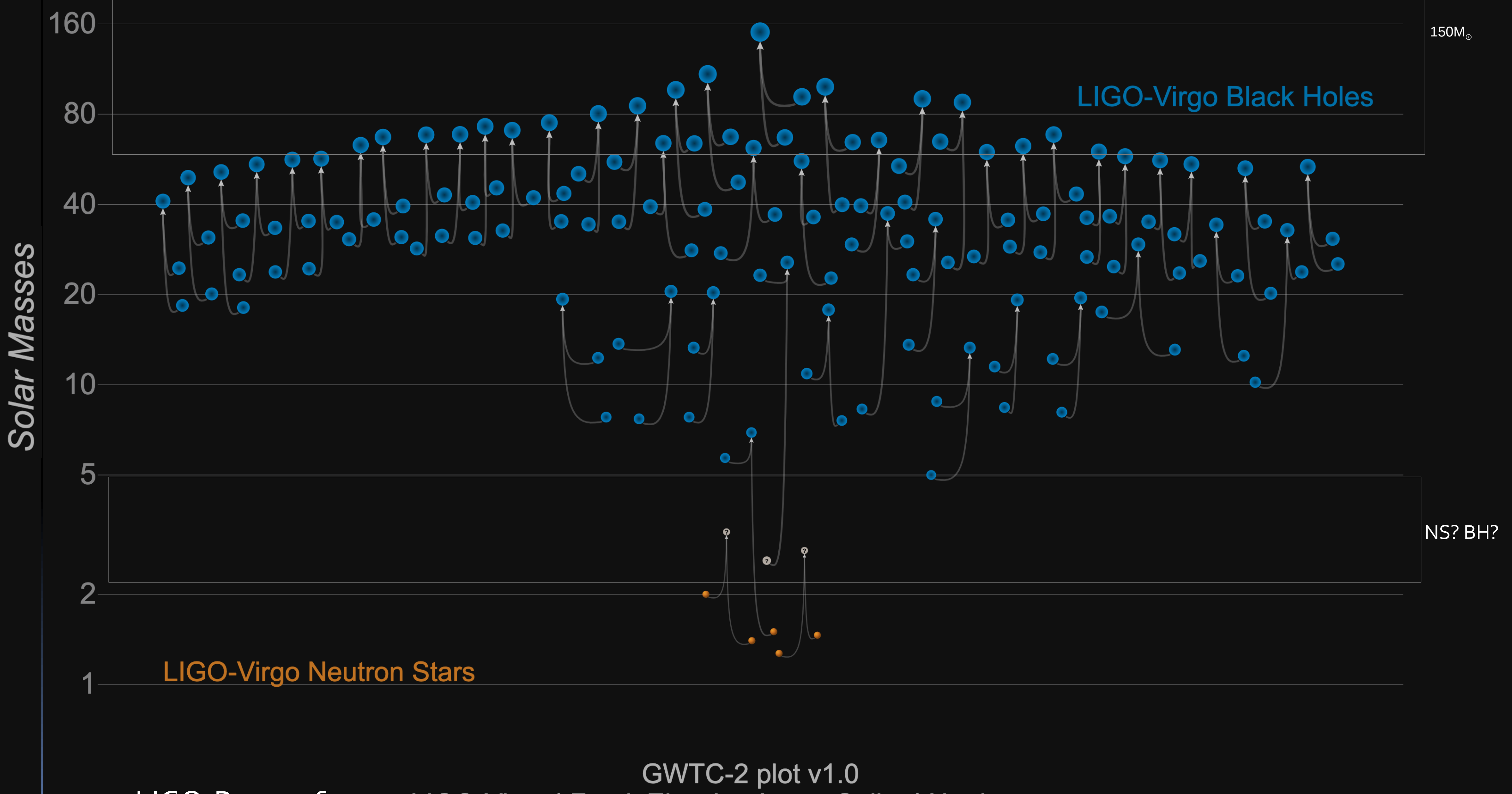
Observing plans and public alerts: https://www.ligo.org/scientists/GWEMalerts.php

Gravitationswellendetektionen



https://dcc.ligo.org/LIGO-G2001862/public

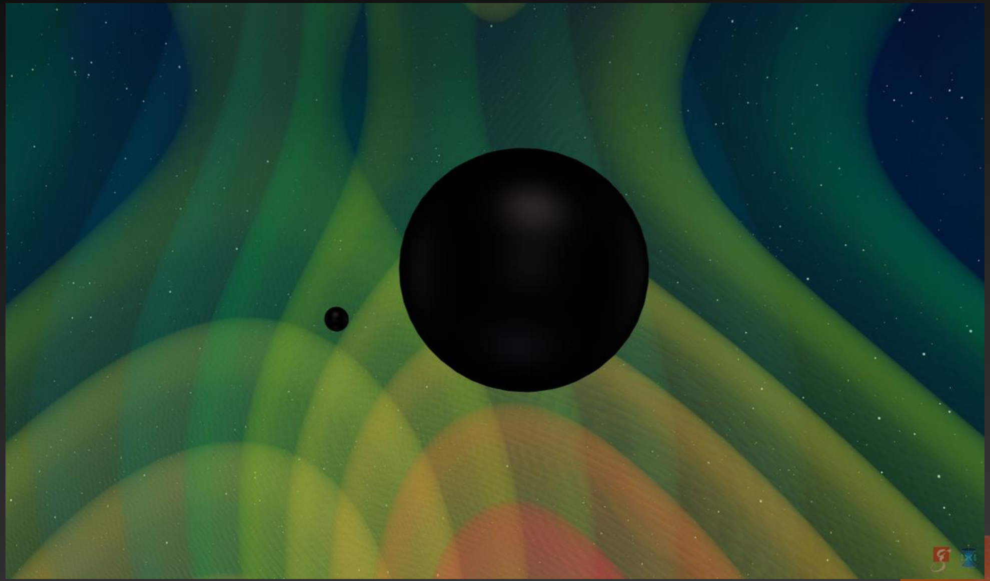
Coalescing binaries observed so far O1 – O3a

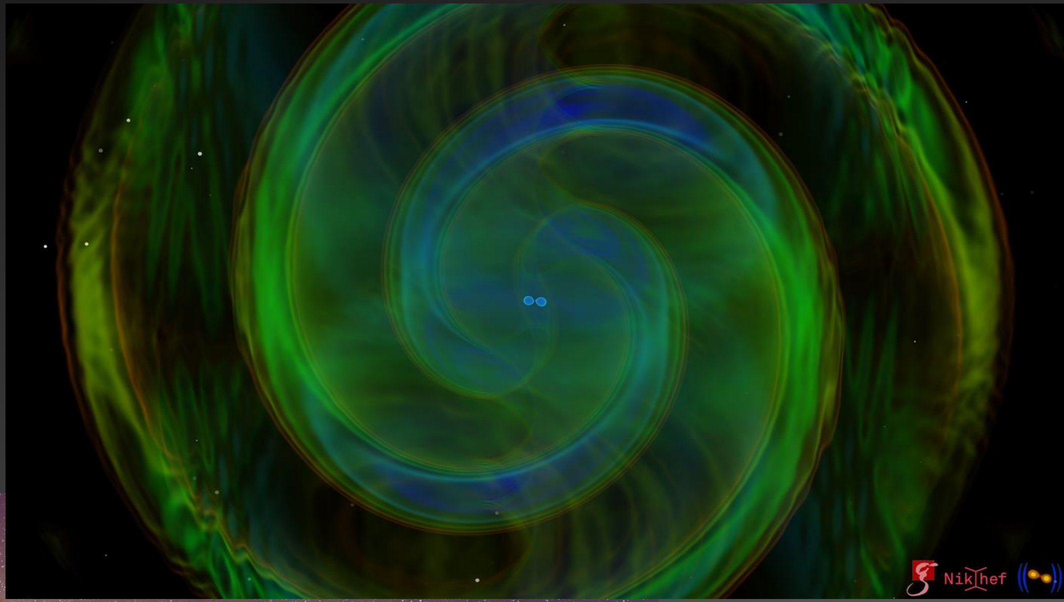


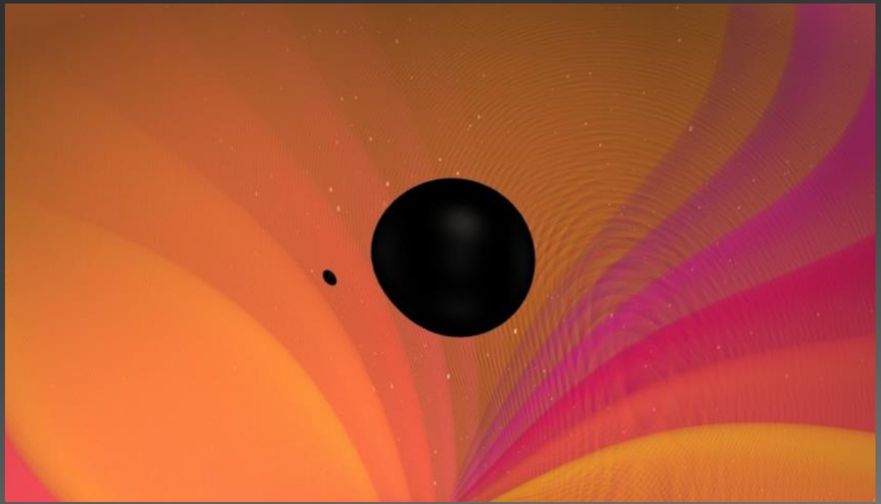
LIGO-P2000061-v14 LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

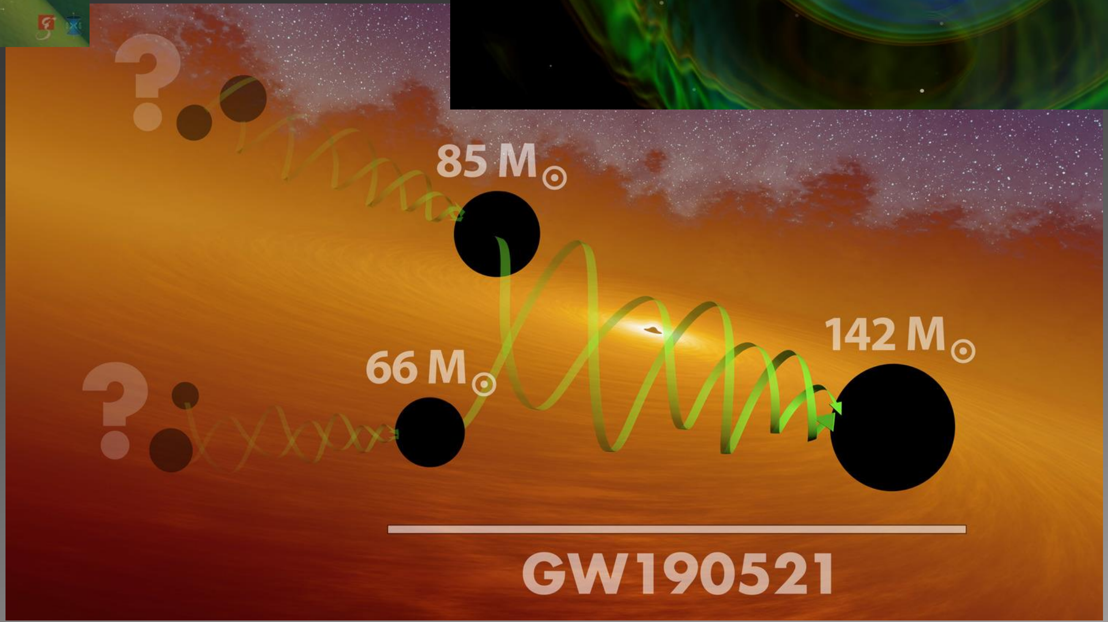
Source: https://ligo.northwestern.edu/media/mass-plot/index.html

Detection Highlights from O3a









GW190425 - 2nd neutron star merger

Astrophys. J. Lett. 892, L3 (2020)

- Only measured by two detectors (LLO and Virgo)
  - Poorer localisation compared to GW170817
- No EM counterpart found
- Unexpectedly heavy pair: total mass of $3.4_{+0.3\ -0.1}\ M_\odot$ is 5σ from galactic mean

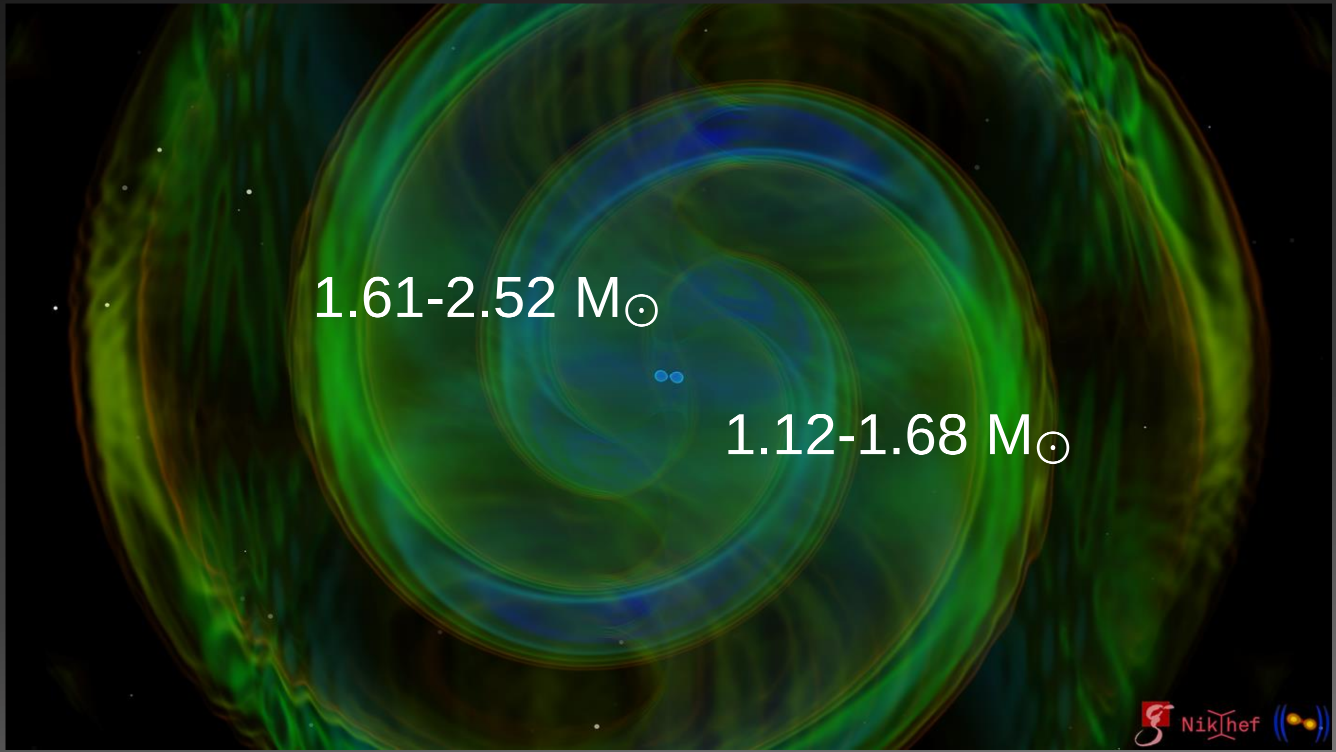
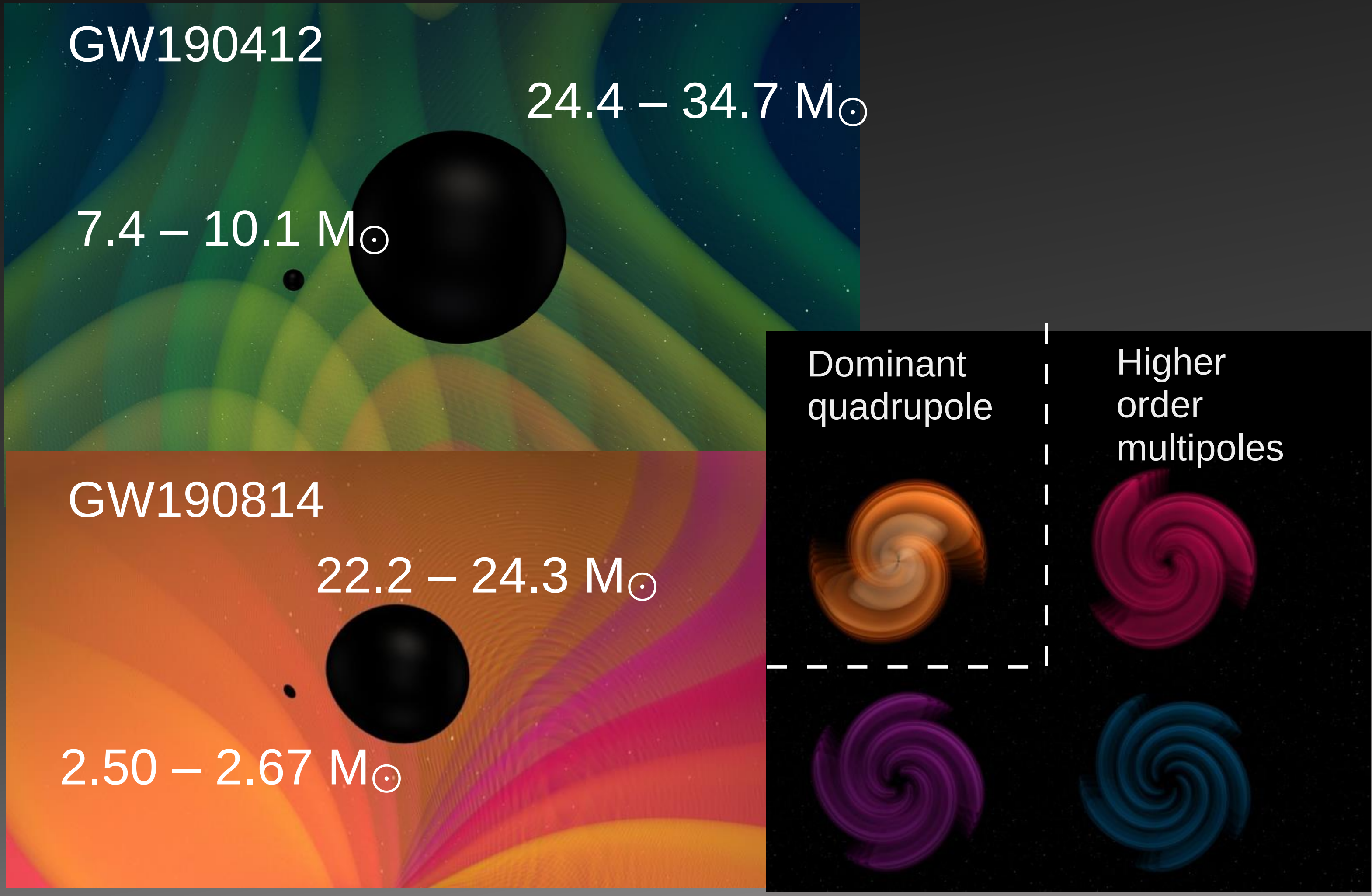


Image: T. Dietrich (Nikhef), S. Ossokine, A. Buonanno (MPI for Gravitational Physics), W. Tichy (Florida Atlantic University) and the CoRe-collaboration

GW190412 & GW190814 – the “odd couples”

Phys. Rev. D 102, 043015 (2020) Astrophys. J. Lett. 896, L44 (2020)

- First detections of a large mass imbalance, mass ratio (q ~ 0.28 and 0.11)
- First evidence of higher order GW modes.
- Additional info from higher order modes allowed better parameter constraints
- GW190814: what was the smaller object?



Images: N. Fischer *et al.* Max Planck Institute for Gravitational Physics, Simulating eXtreme Spacetimes project

GW190521 – the “big fish”

[1] Phys. Rev. Lett. 125, 101102 (2020) [2]

- Most massive system observed: objects 85 and 66 $M_\odot$ [1]
- Remnant intermediate mass black hole - first direct observation of IMBH
- One or both components in the *pair instability mass gap* (50 - 120 $M_\odot$)

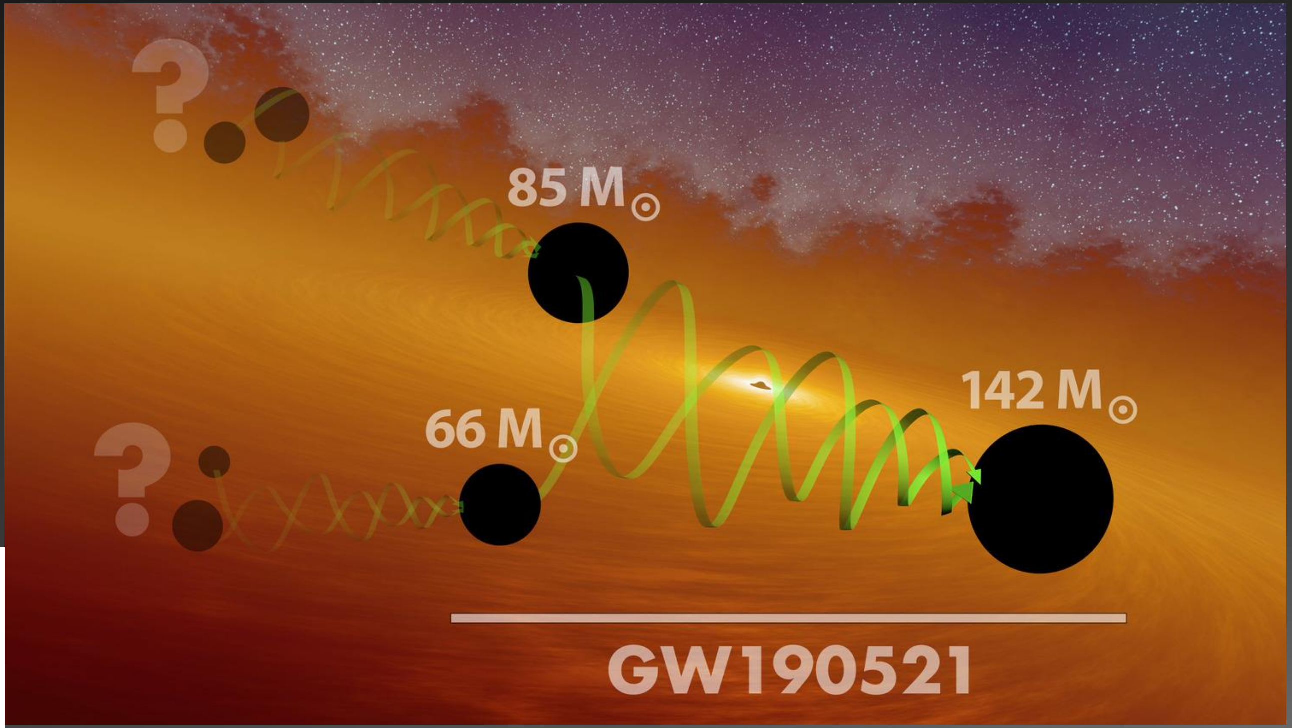
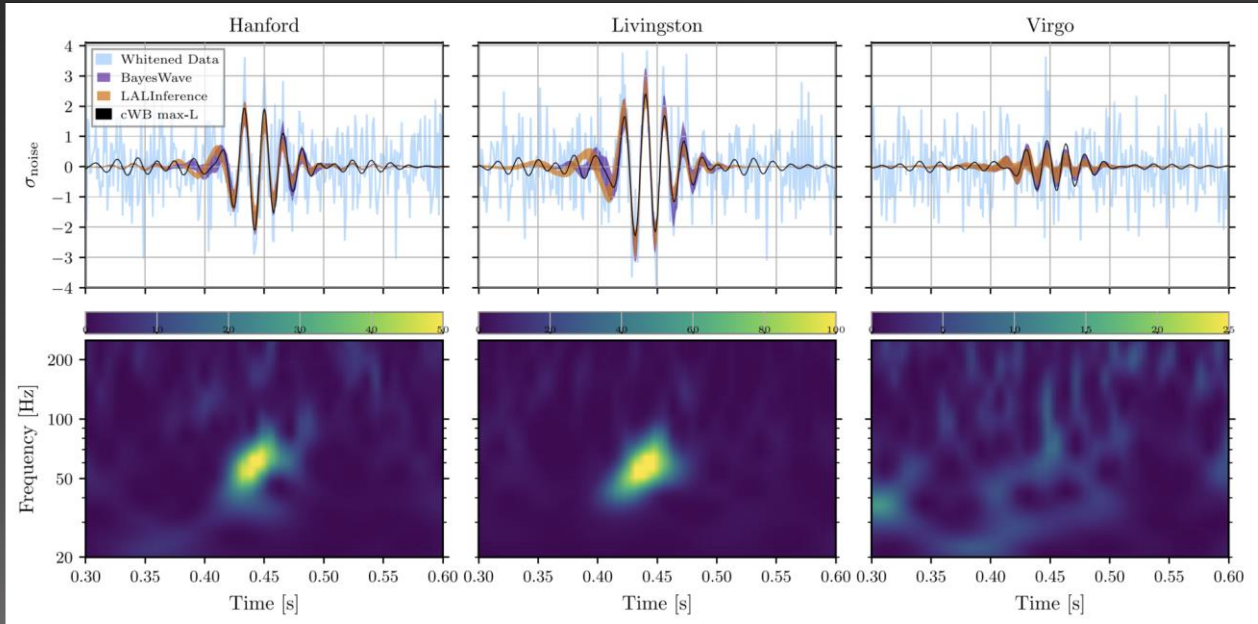
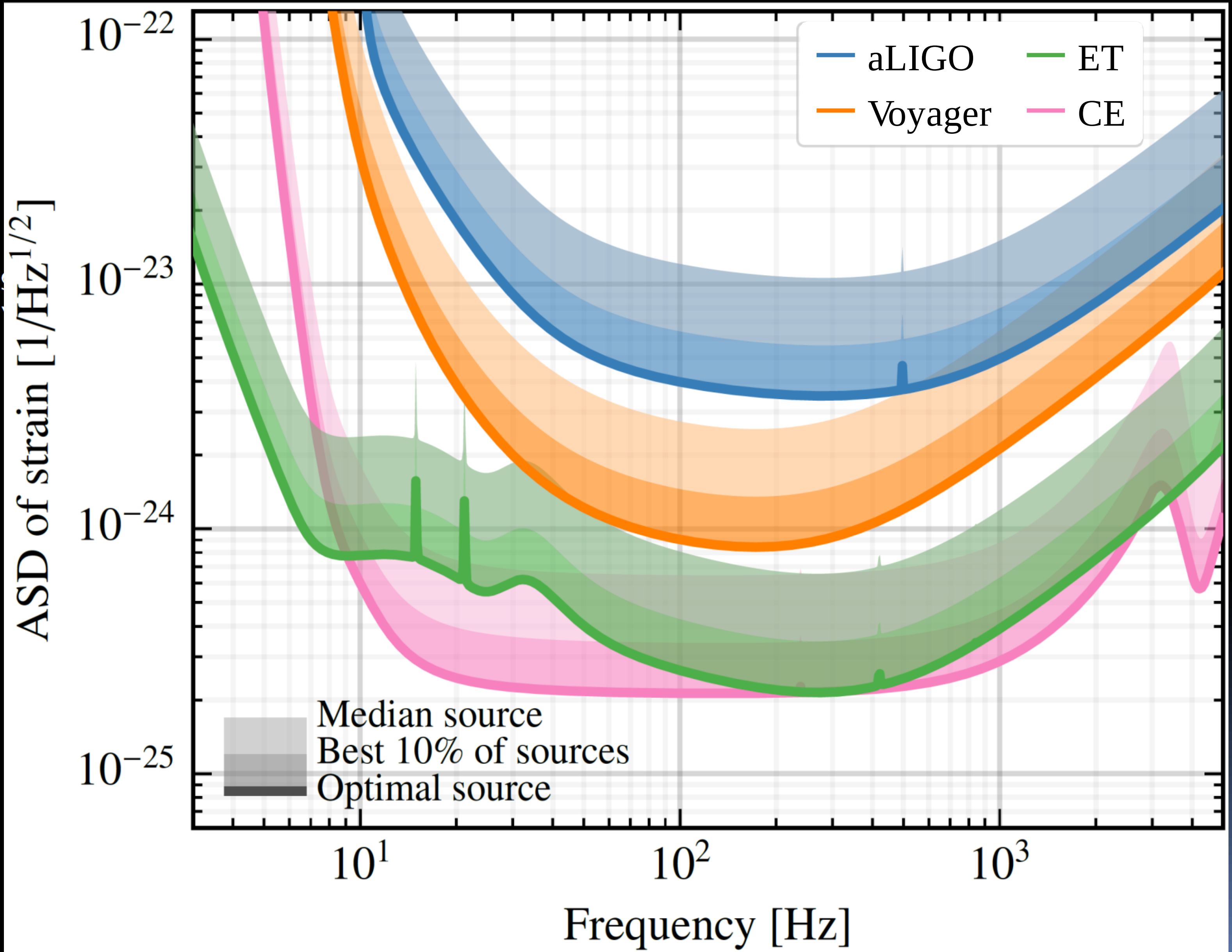


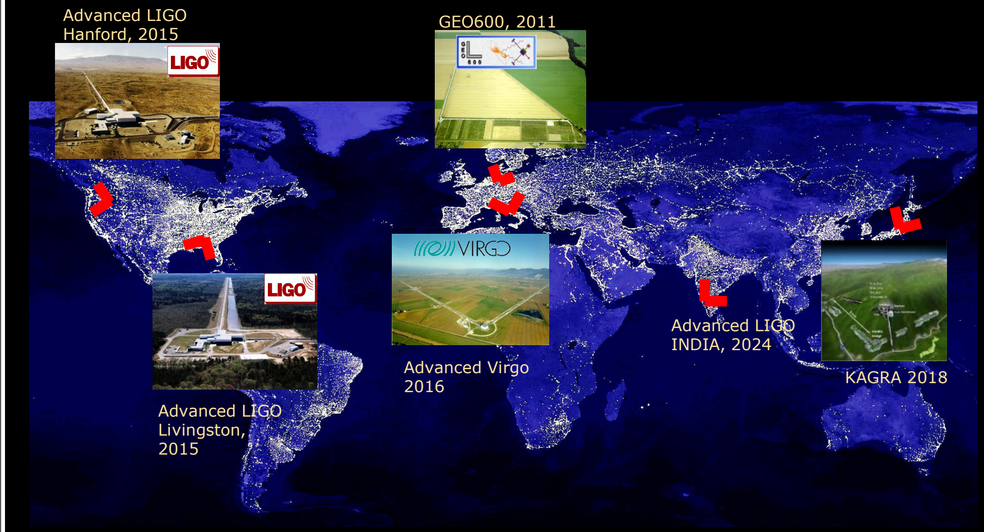
Image: LIGO/Caltech/MIT/R. Hurt (IPAC)



Slide from David Wu, AEI, modified

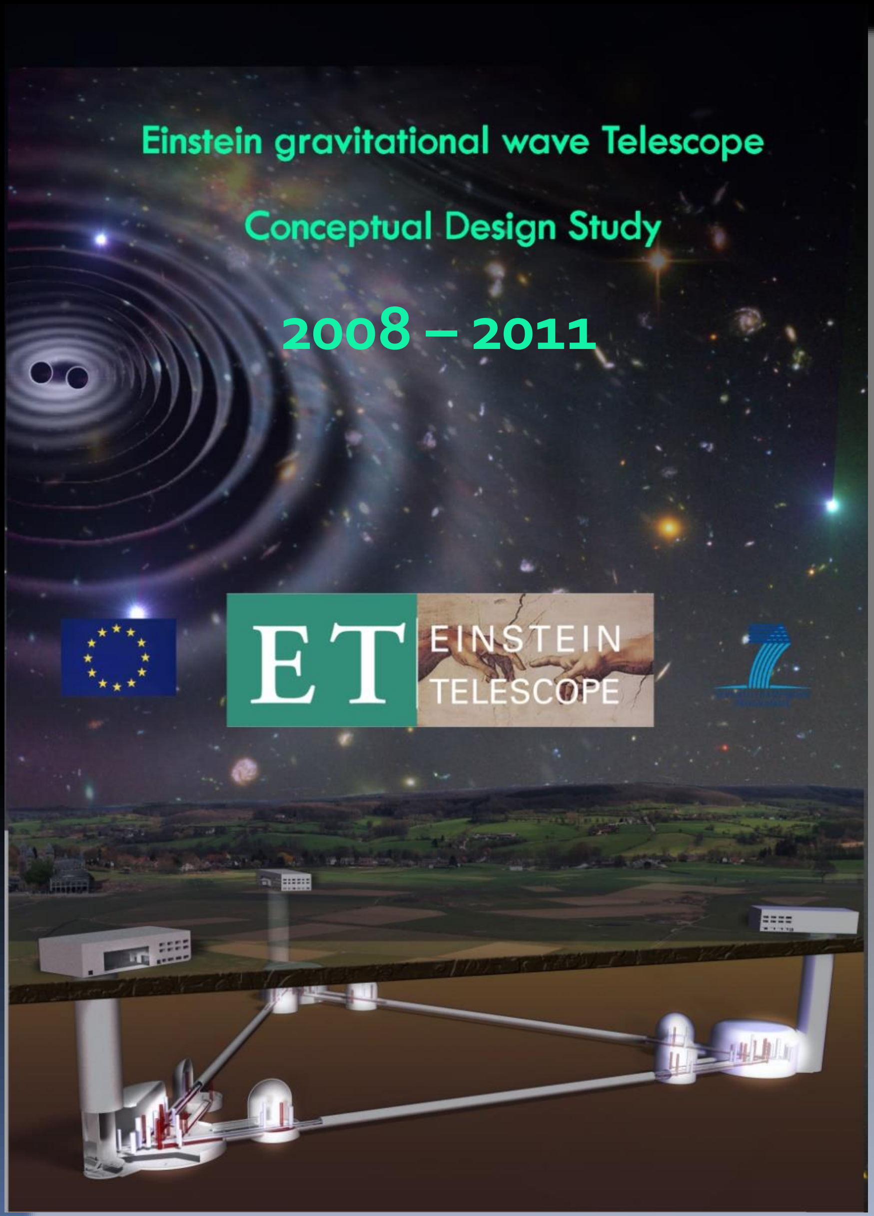
Sensitivities of the 2nd Generation

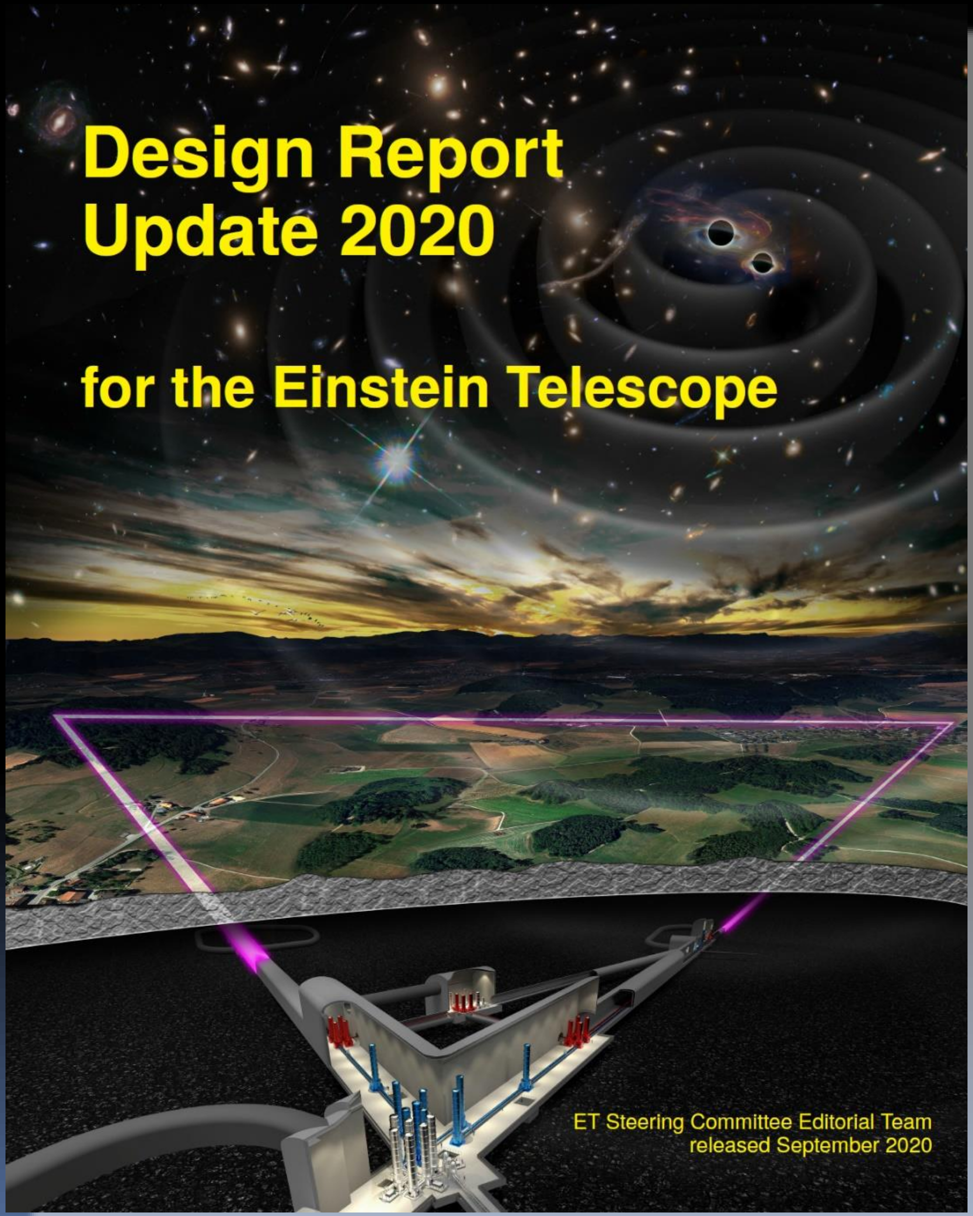




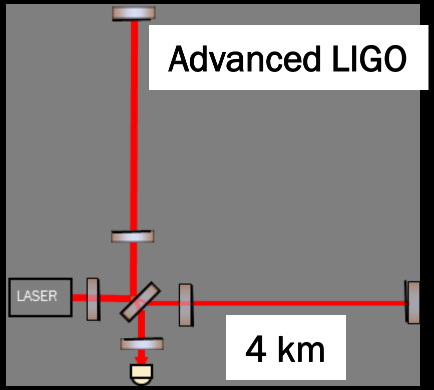
Infrastructure will reach an end of lifetime and
a limit in performance
(self noise, size)
→ New infrastructures

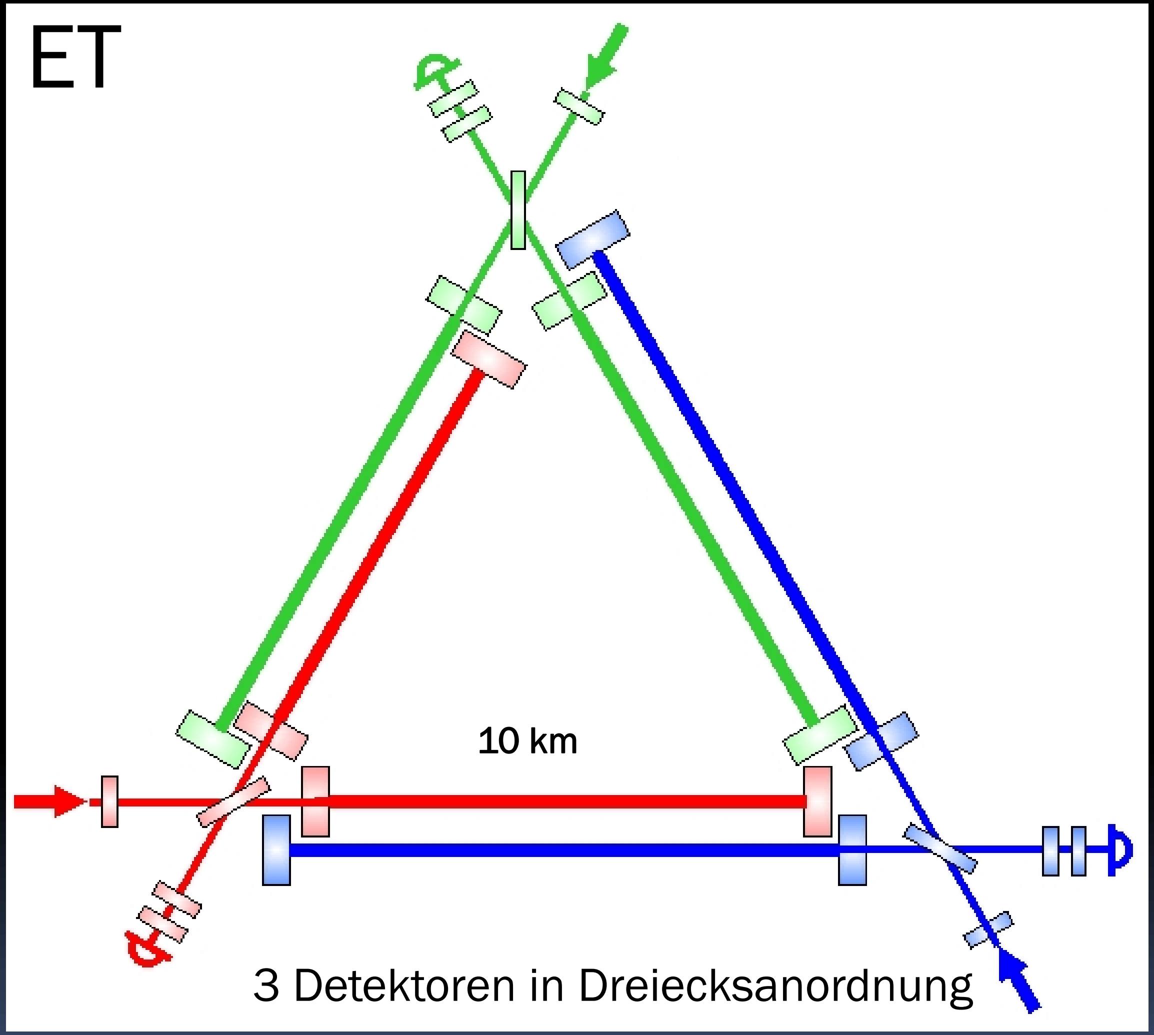
Design Pläne





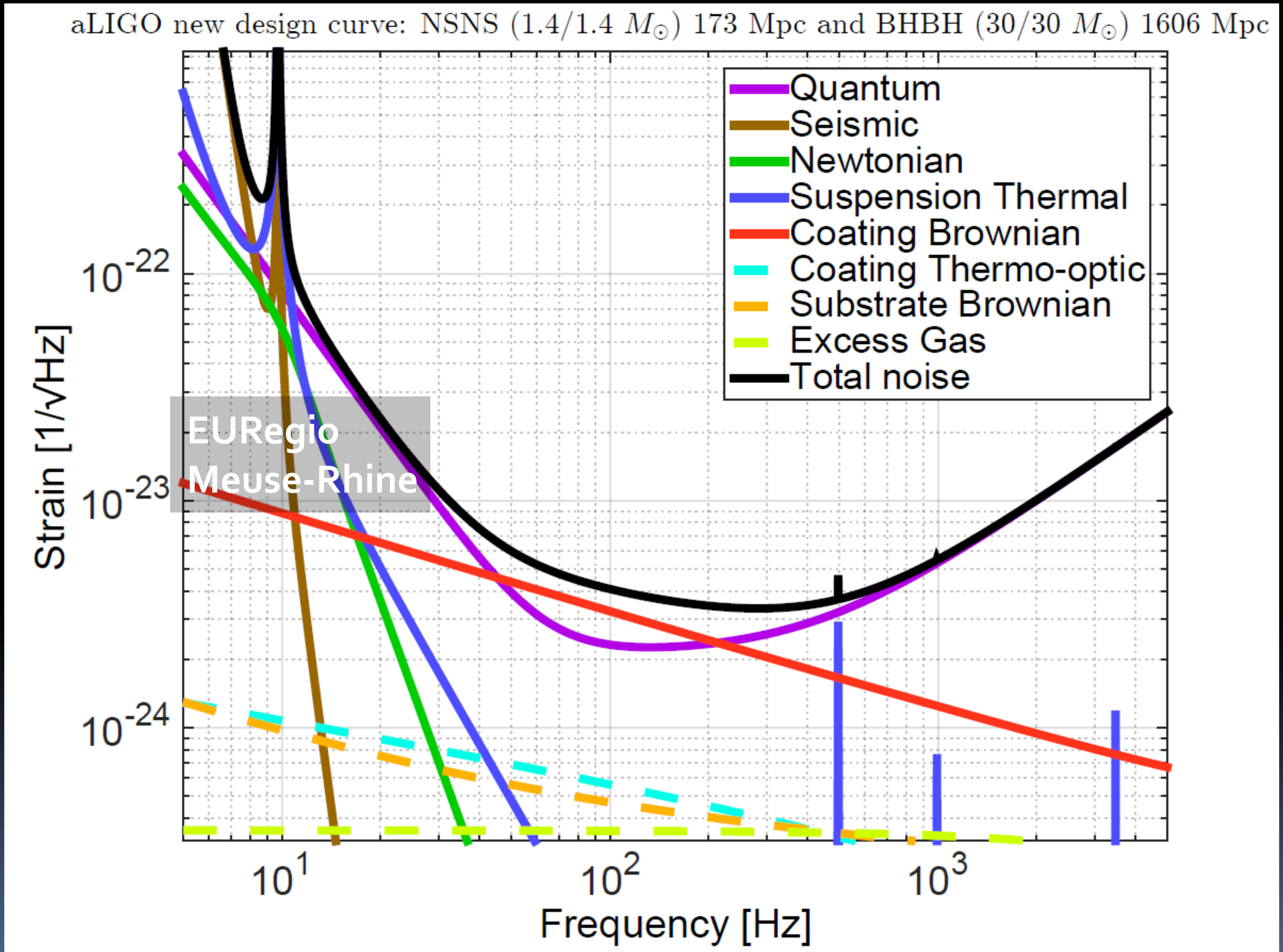
Increase size 4km → 10 km





rel. Längenänderung : $\Delta L/L$ = 2%

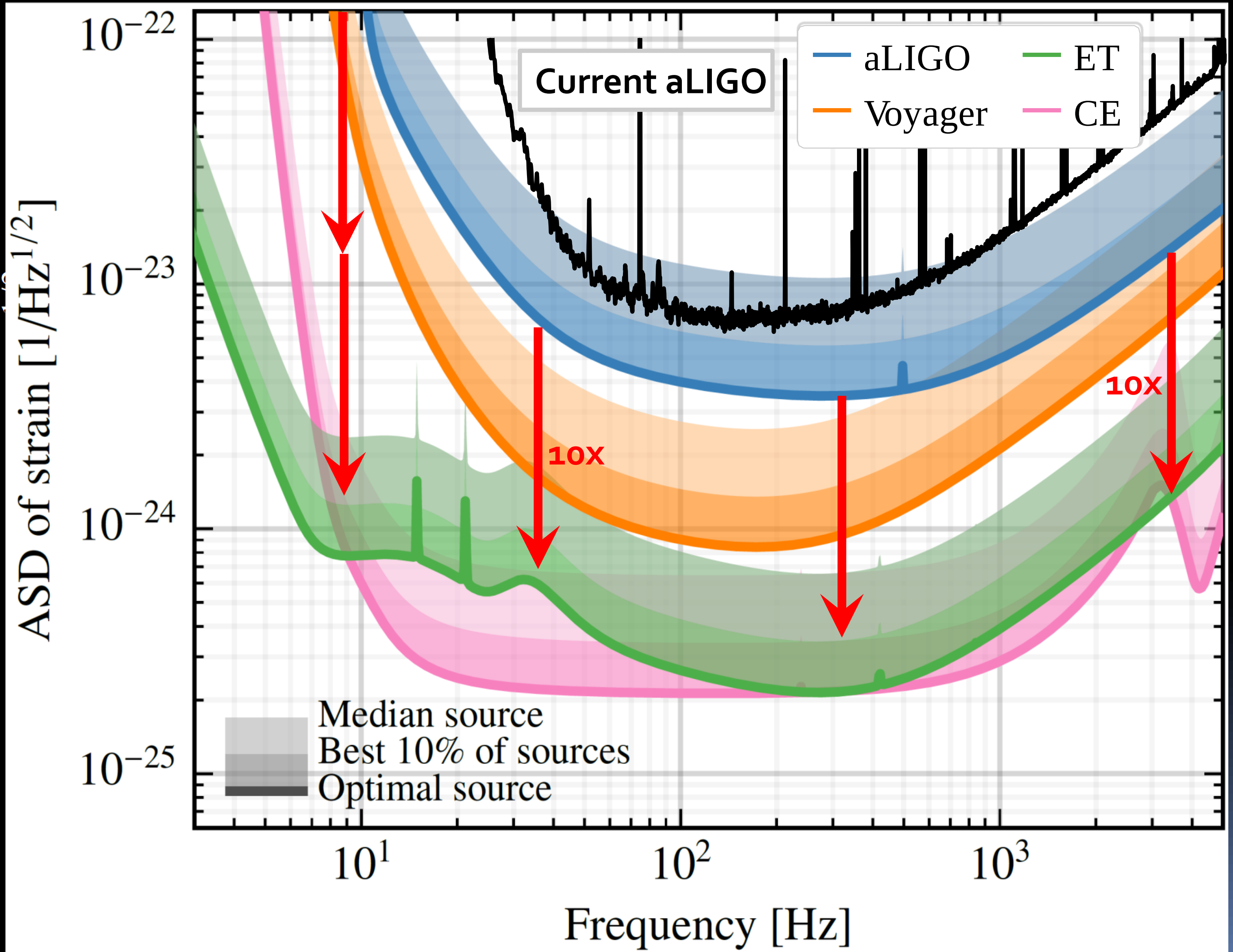
Noise Budget (aLIGO example)

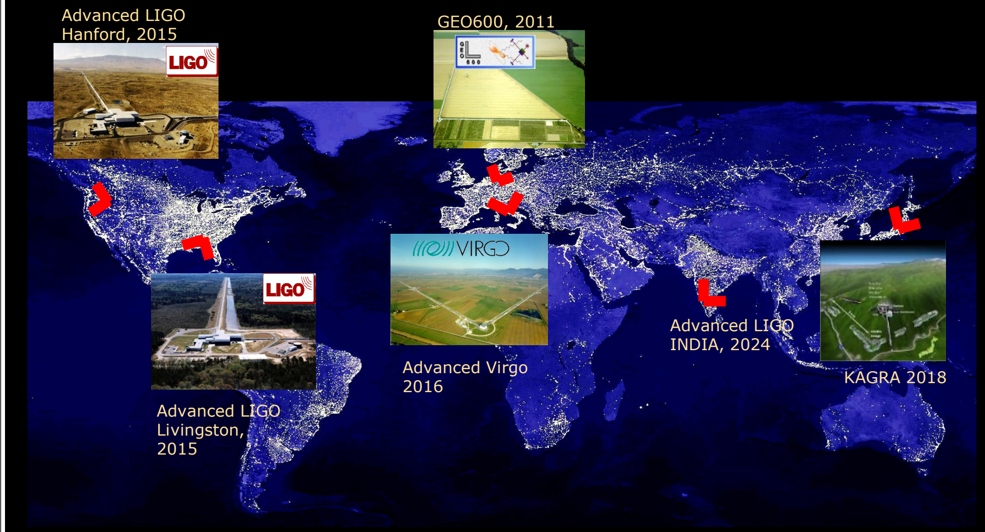


Noise Sources:

- High Frequencies
  - High laser power/squeezing
- Mid Frequencies
  - Squeezing
  - Better coatings/ cryogenic operation
- Low frequencies
  - Low Laser Power
  - Better suspensions
  - Longer suspensions
  - Newtonian noise
  - New control signals

Sensitivities of the 2nd Generation

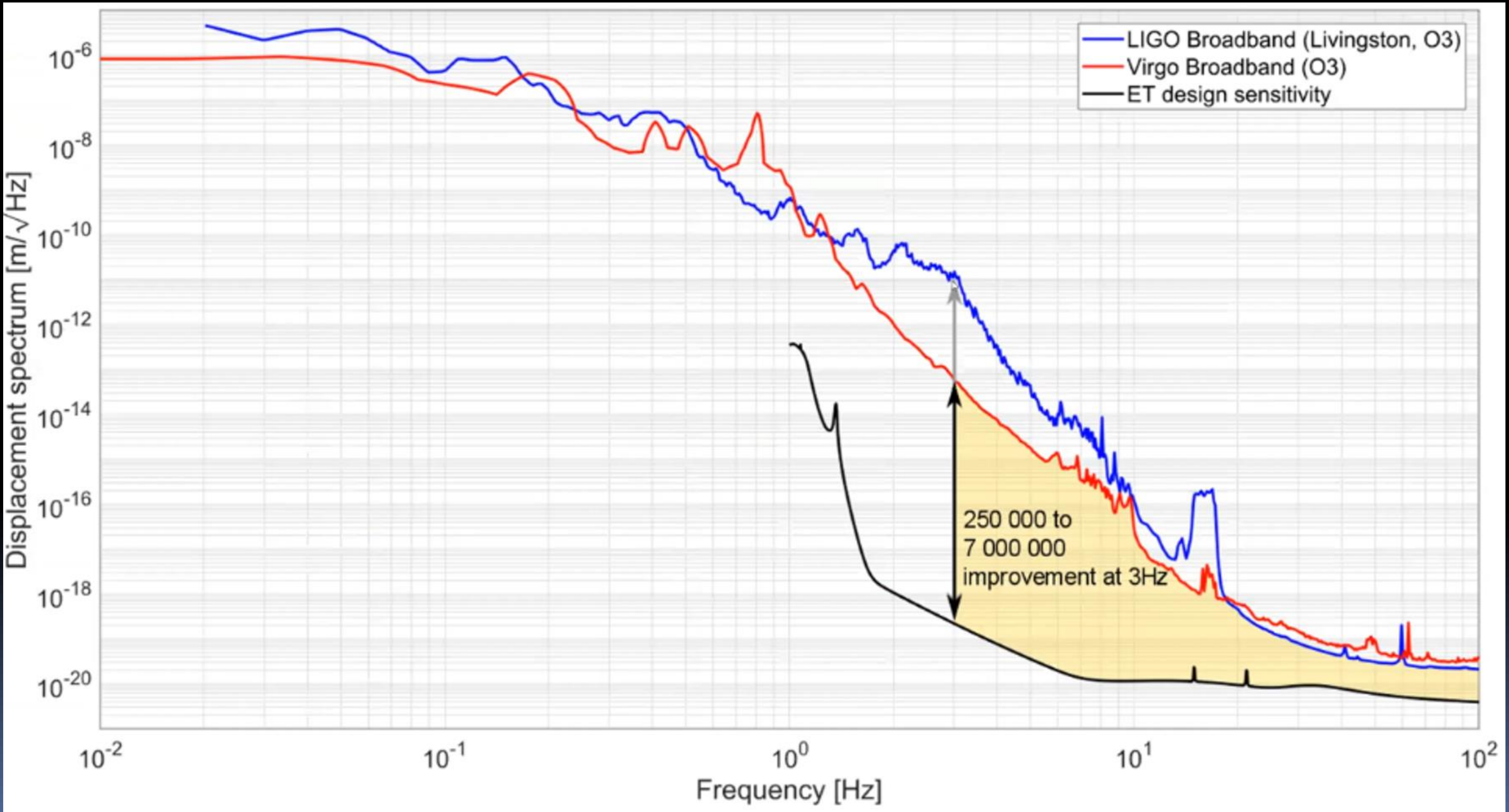




Infrastructure will reach an end of lifetime and a limit in performance (self noise, size)

→ New infrastructures

Challenge: Low Frequency improvement factor

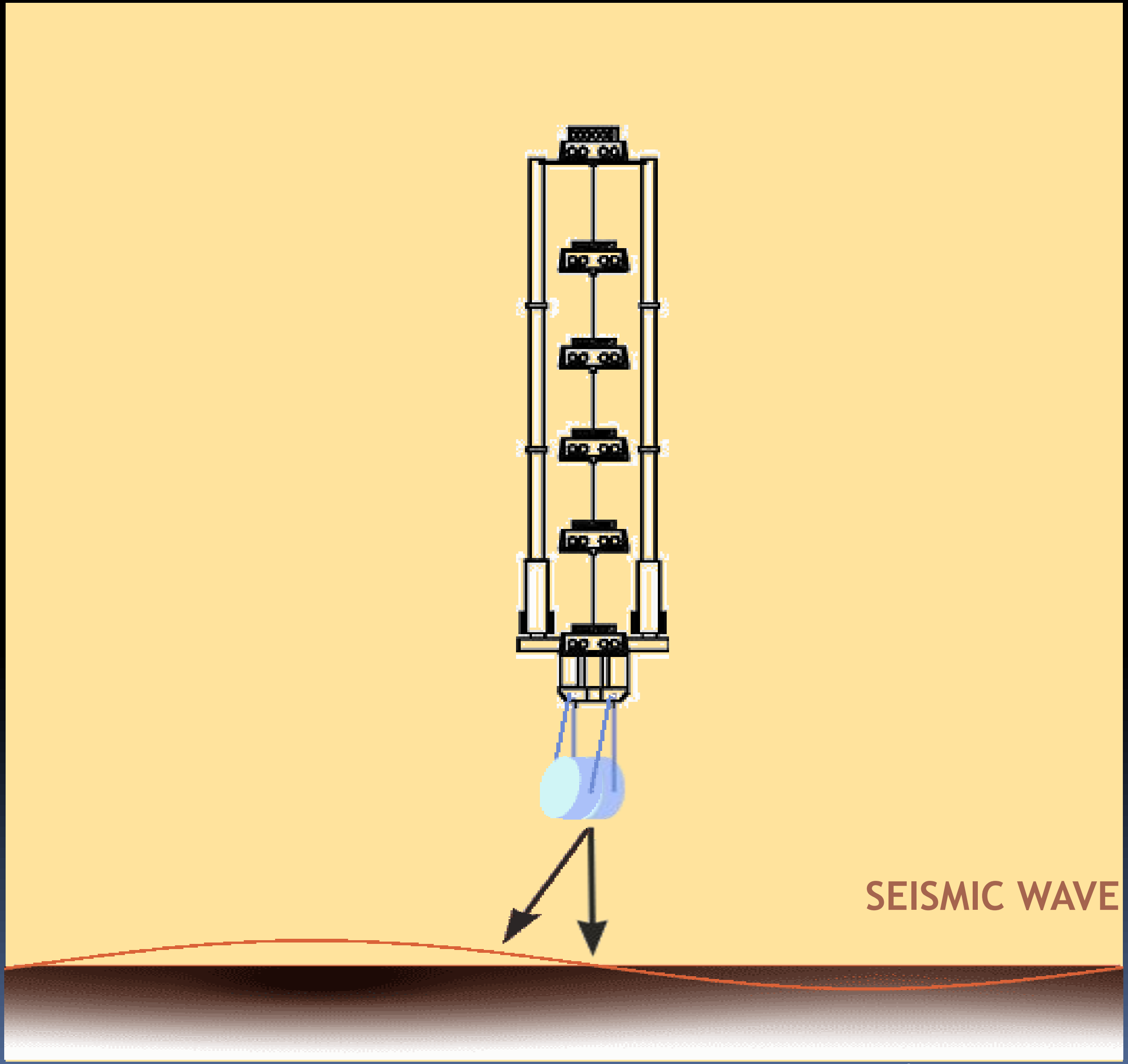


Newtonian Noise

- The Virgo suspension is almost good enough for filtering the seismic disturbances and keeping the mirrors quiet enough
  - A longer suspension is needed to improve filtering at low frequencies

- Newtonian Noise circumvents this isolation chain

→ ET EINSTEIN TELESCOPE Go underground

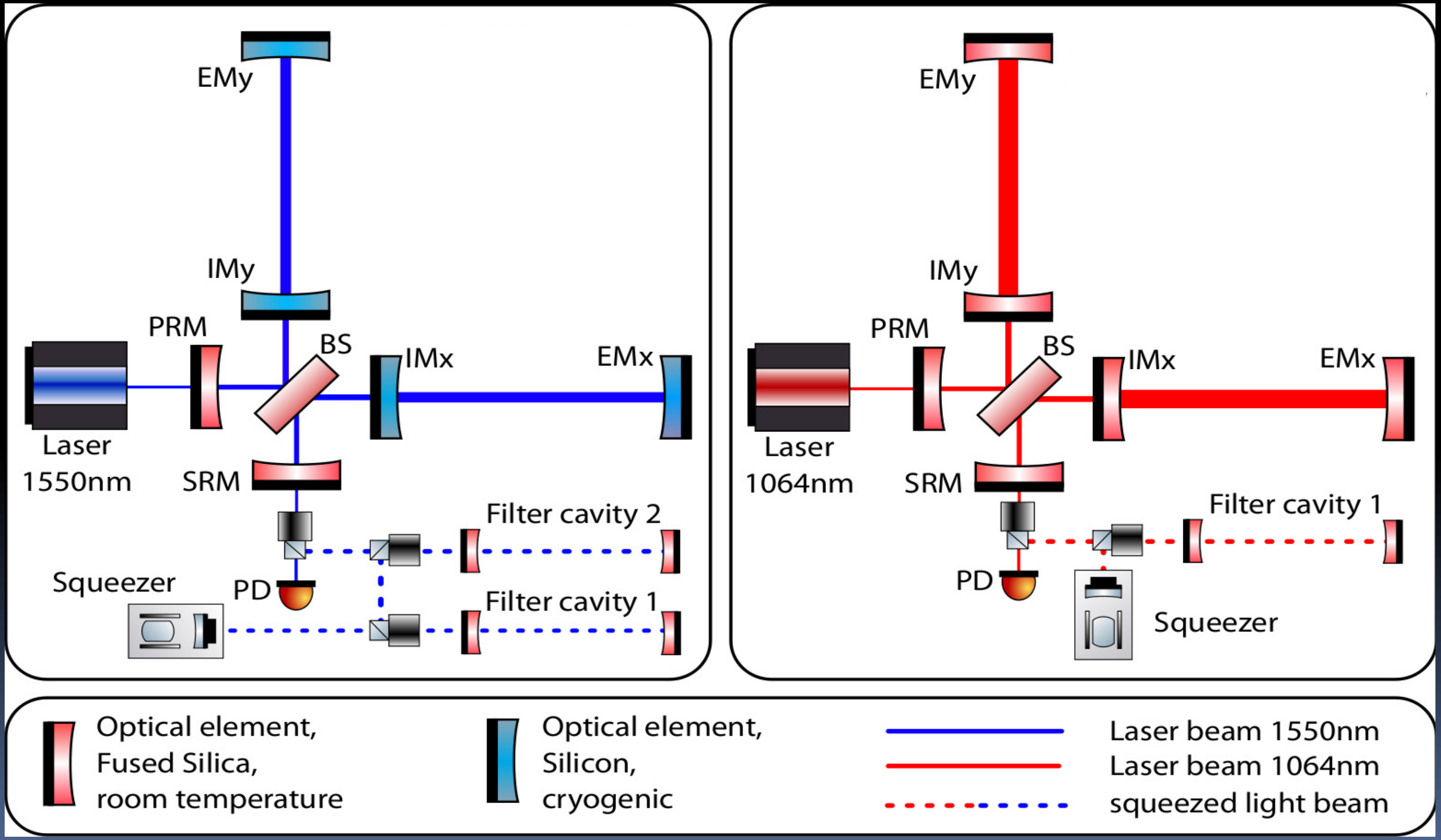


Credit M.Lorenzini

ET - Xylophone Concept

ET - LF
low-power, cryogenic
low-frequency detector

ET – HF
high-power, room-temperature
high-frequency detector



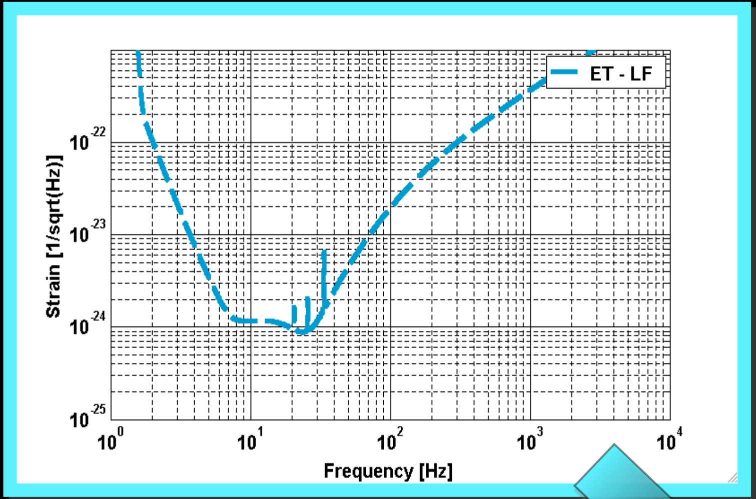
ET-HF: 300 K

- High power laser
- High circulating light power
- Thermal compensation
- Large test masses
- New coatings
- Frequency dependent squeezing

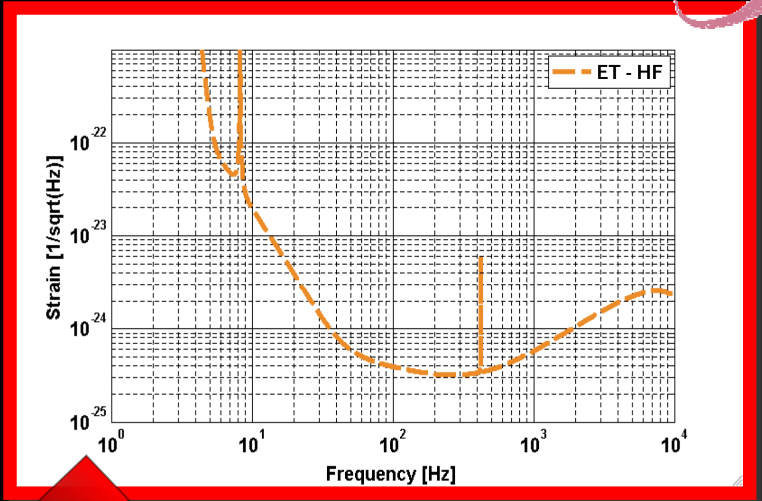
ET-LF: 10 – 20 K

- Cryogenics
- Seismic suspensions
- Silicon (Sapphire) test masses
- Large test masses
- New coatings
- New laser wavelength
- Frequency dependent squeezing, Filter cavities

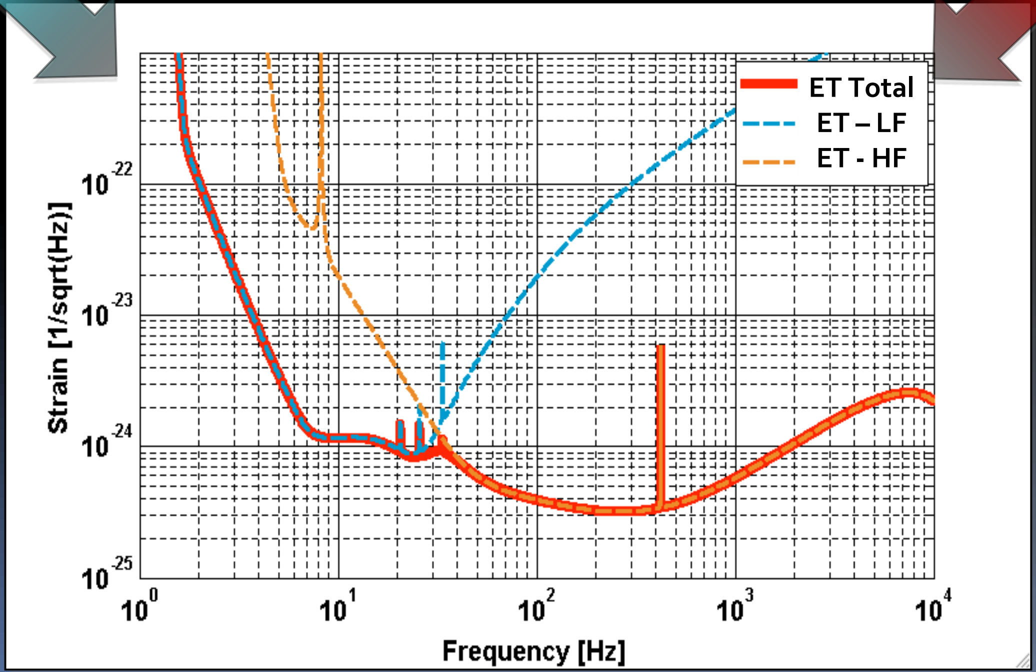
ET Xylophone Sensitivity



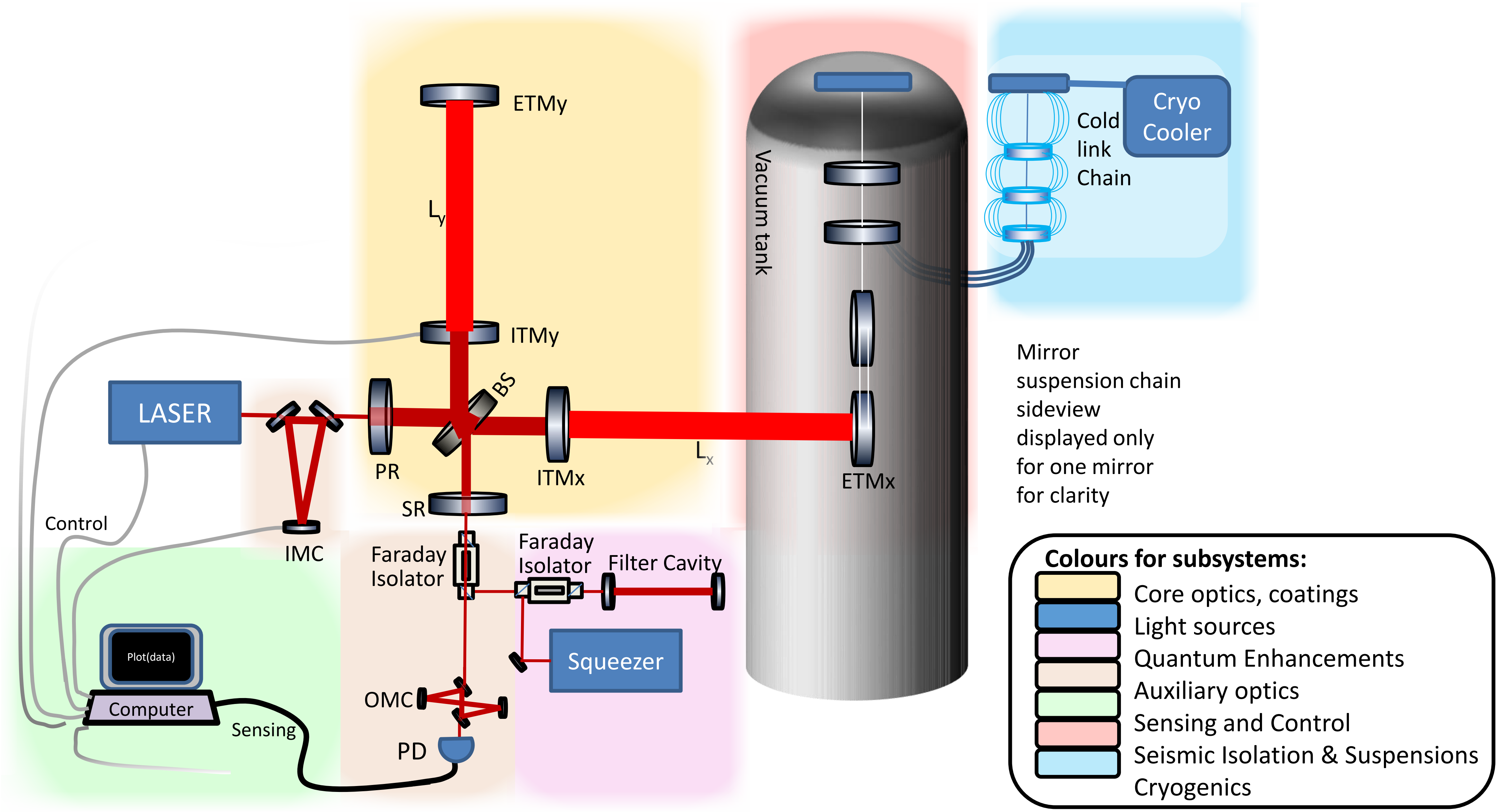
ET-LF



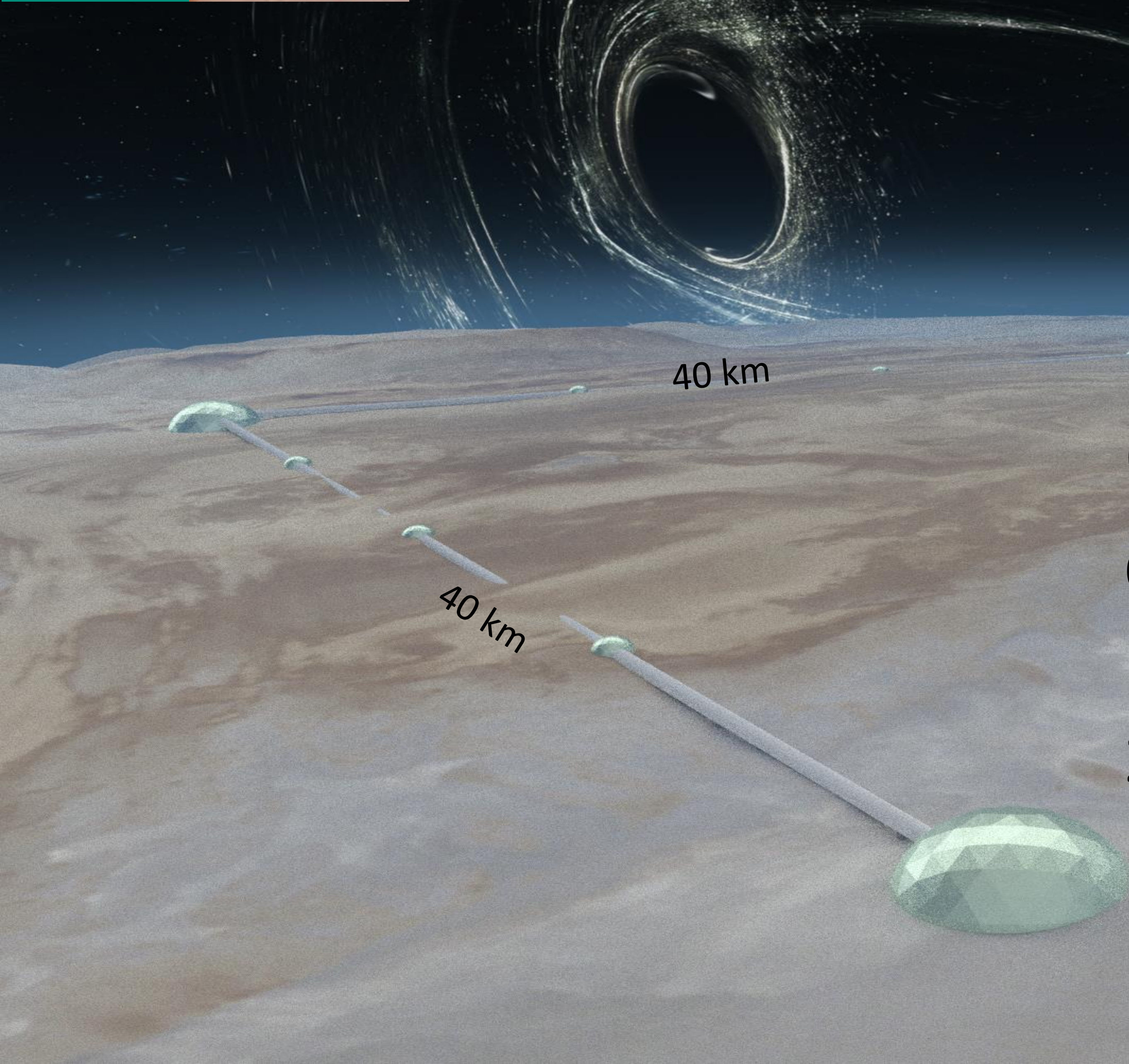
ET-HF



Detector Subsystems



ET EINSTEIN TELESCOPE



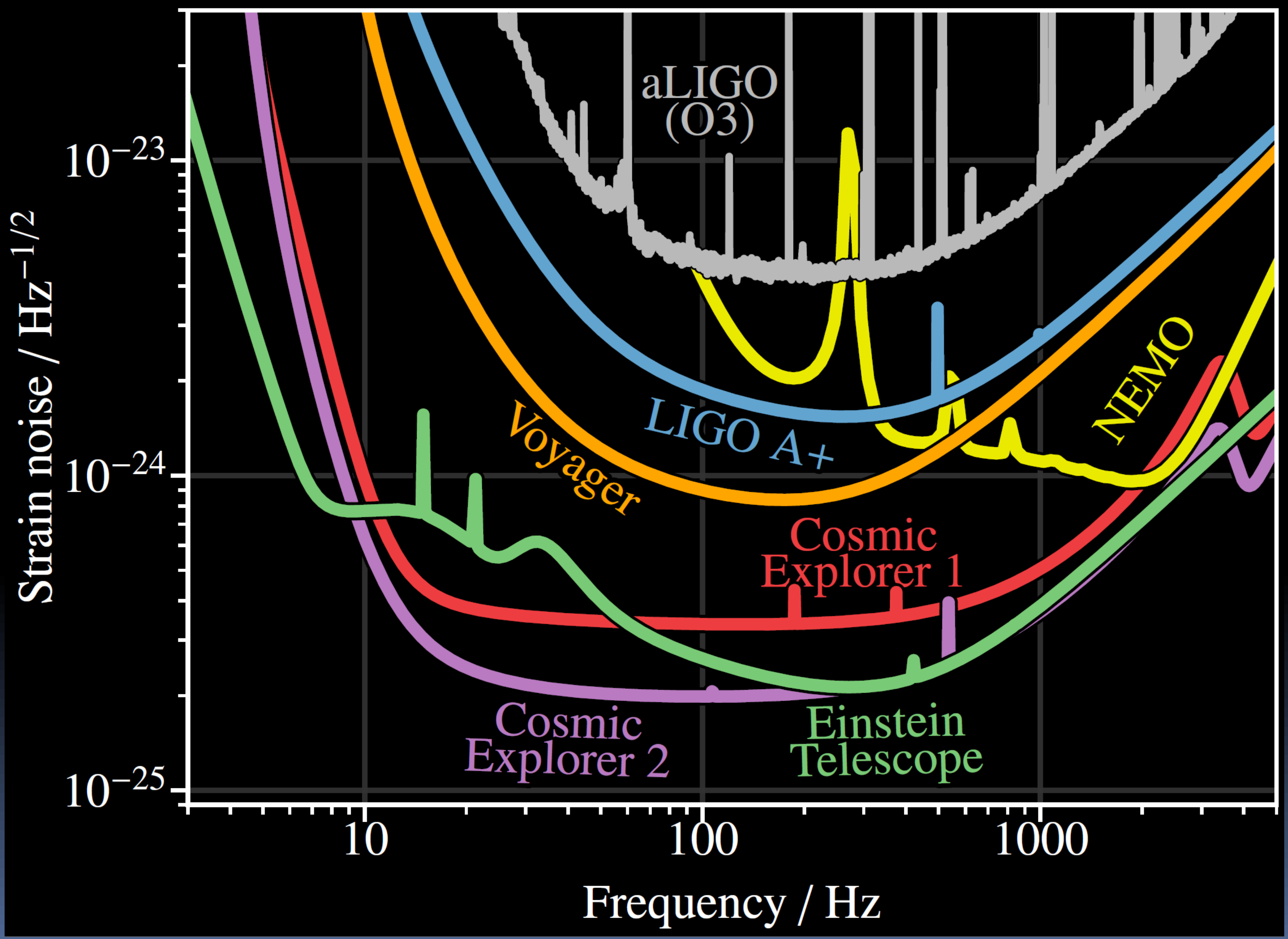
Cosmic Explorer (USA)

Oberirdisch

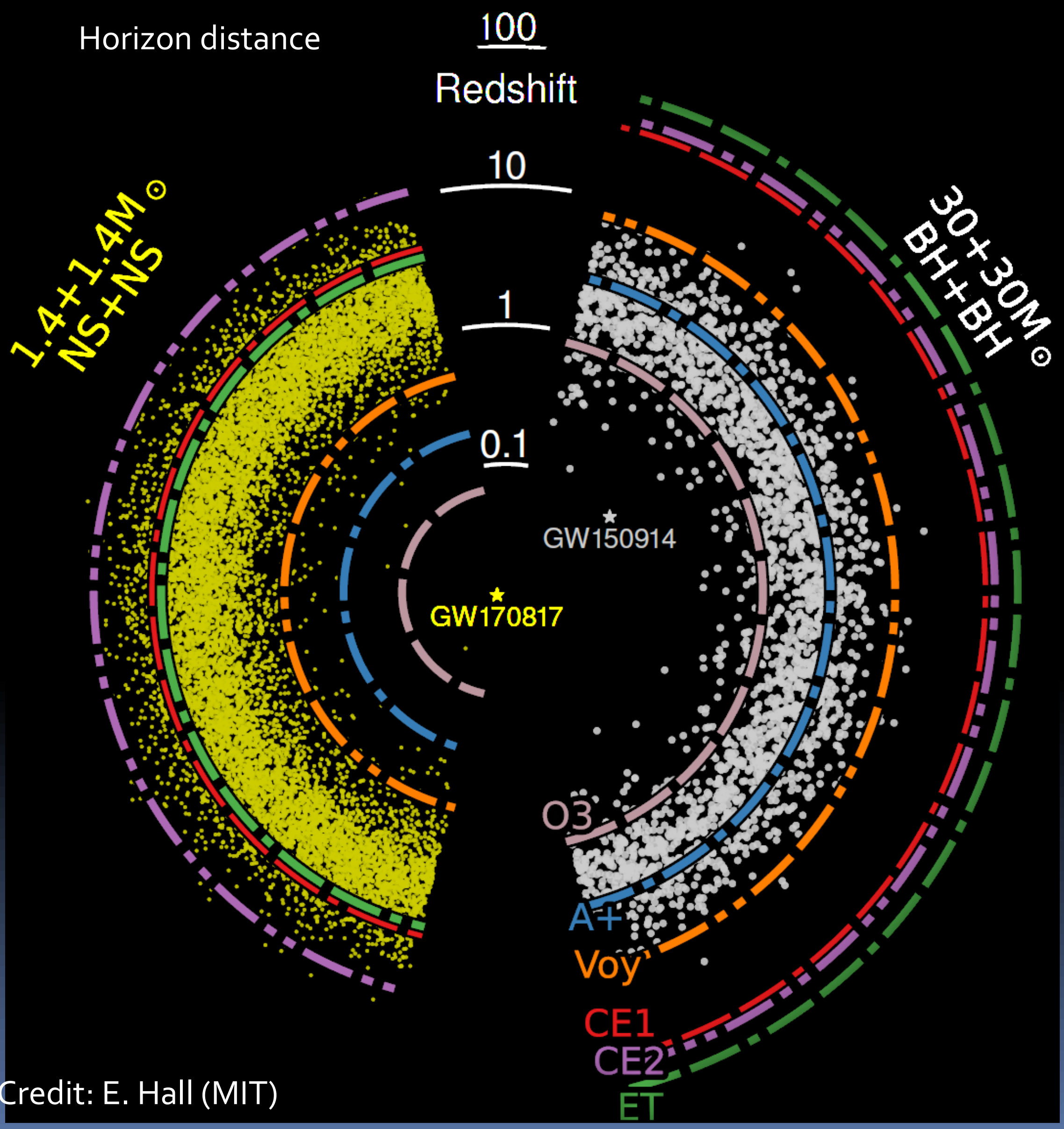
Empfindlichkeit 10x advanced Det.

2 Phasen

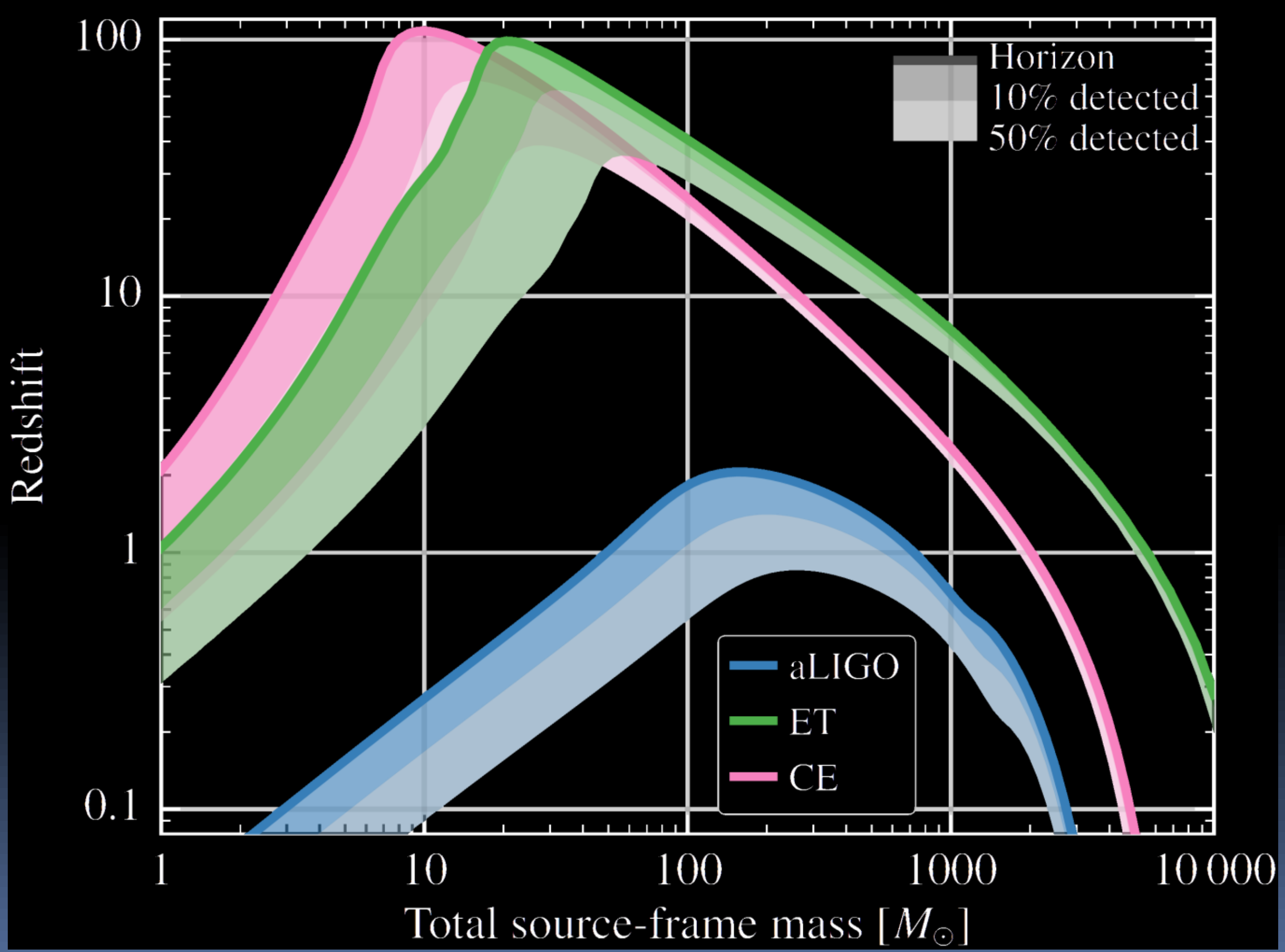
Sensitivities in the 3G era



Reaching for the „whole universe"...



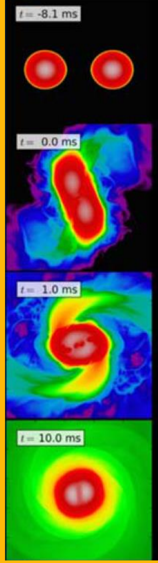
CBC Sources throughout the universe

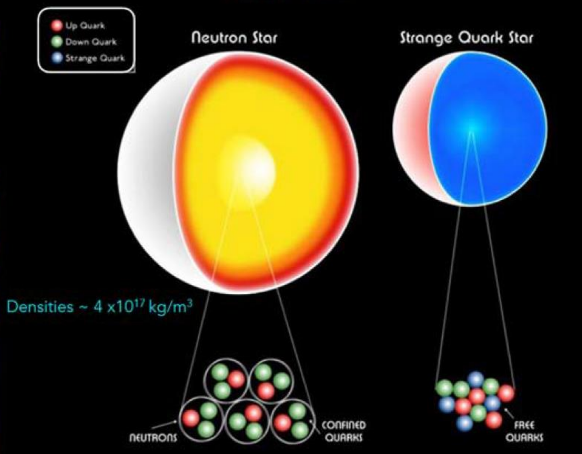


Slide layout: Sheila Rowan, modified

3G Gravitational Wave Science

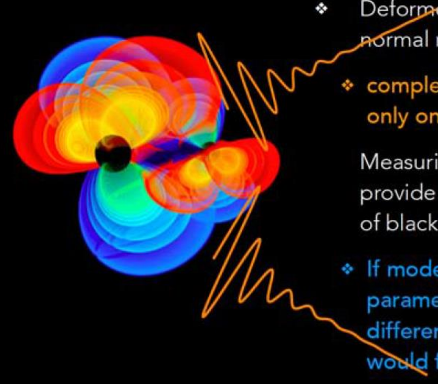
EQUATION OF STATE OF DENSE NUCLEAR AND OTHER EXTREME MATTER





9

EXTREME GRAVITY, DYNAMICAL SPACETIMES



- Deformed black holes emit quasi-normal modes
  - complex frequencies depend only on the mass and spin
- Measuring two or modes would provide a smoking gun evidence of black holes
  - If modes depend on other parameters, consistency between different mode frequencies would fail

Dreyer+ 2004, Berti+ 2006, Berti+ 2007, Kamaretsos+ 2012, Gossan+2012

talks by Vitale and Campanelli

10

PRECISION COSMOLOGY

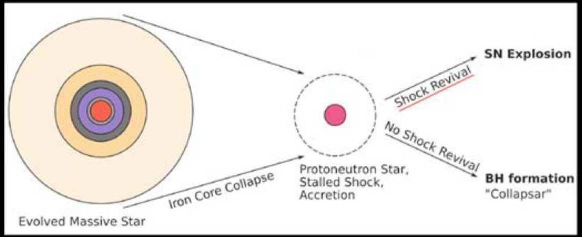
- Compact binaries are standard sirens; GW observations can measure the luminosity distance
- But can we measure distance and redshift both from GW observations alone?
- Tidal interactions between neutron stars have the opposite effect of cosmology; this helps break the mass-redshift degeneracy

Read and Messenger PRL 2012; Messenger+ PRX 2014

15

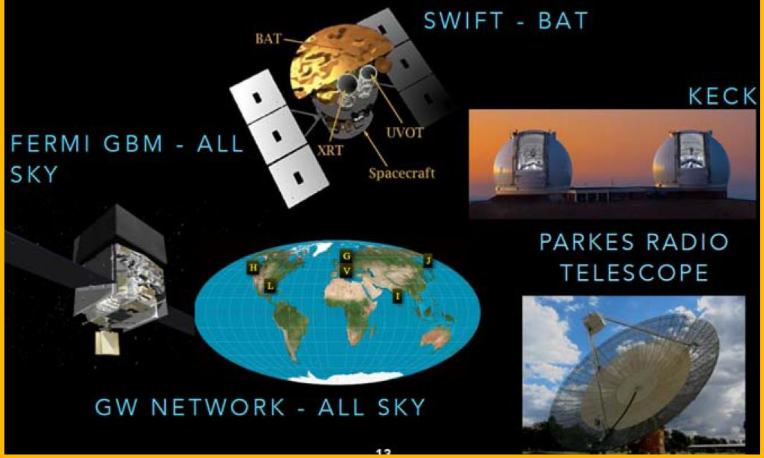
ASTROPHYSICS OF STELLAR COLLAPSE AND SUPERNOVAE

- Energy reservoir
  - few x 10^{53} erg
- Explosion energy
  - 10^{51} erg
- Time frame for explosion
  - 300 - 1500 ms after bounce
- Formation of black hole
  - At baryonic mass > 1.8-2.5 M



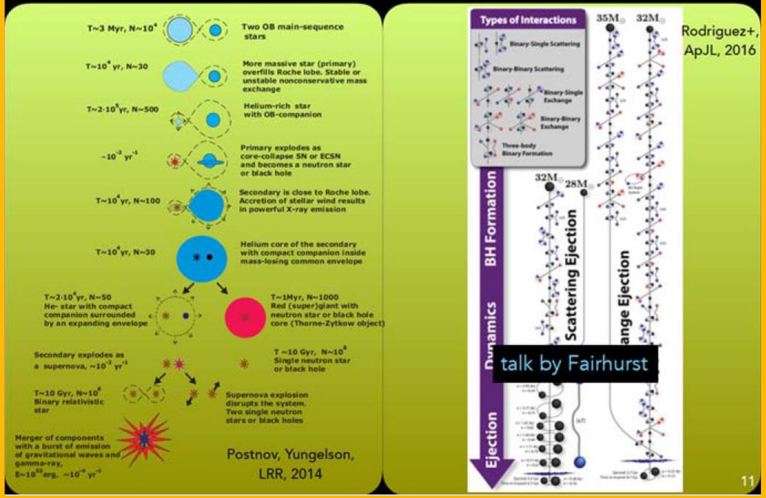
12

MULTI-MESSENGER ASTROPHYSICS: SYNERGY BETWEEN GW-EM



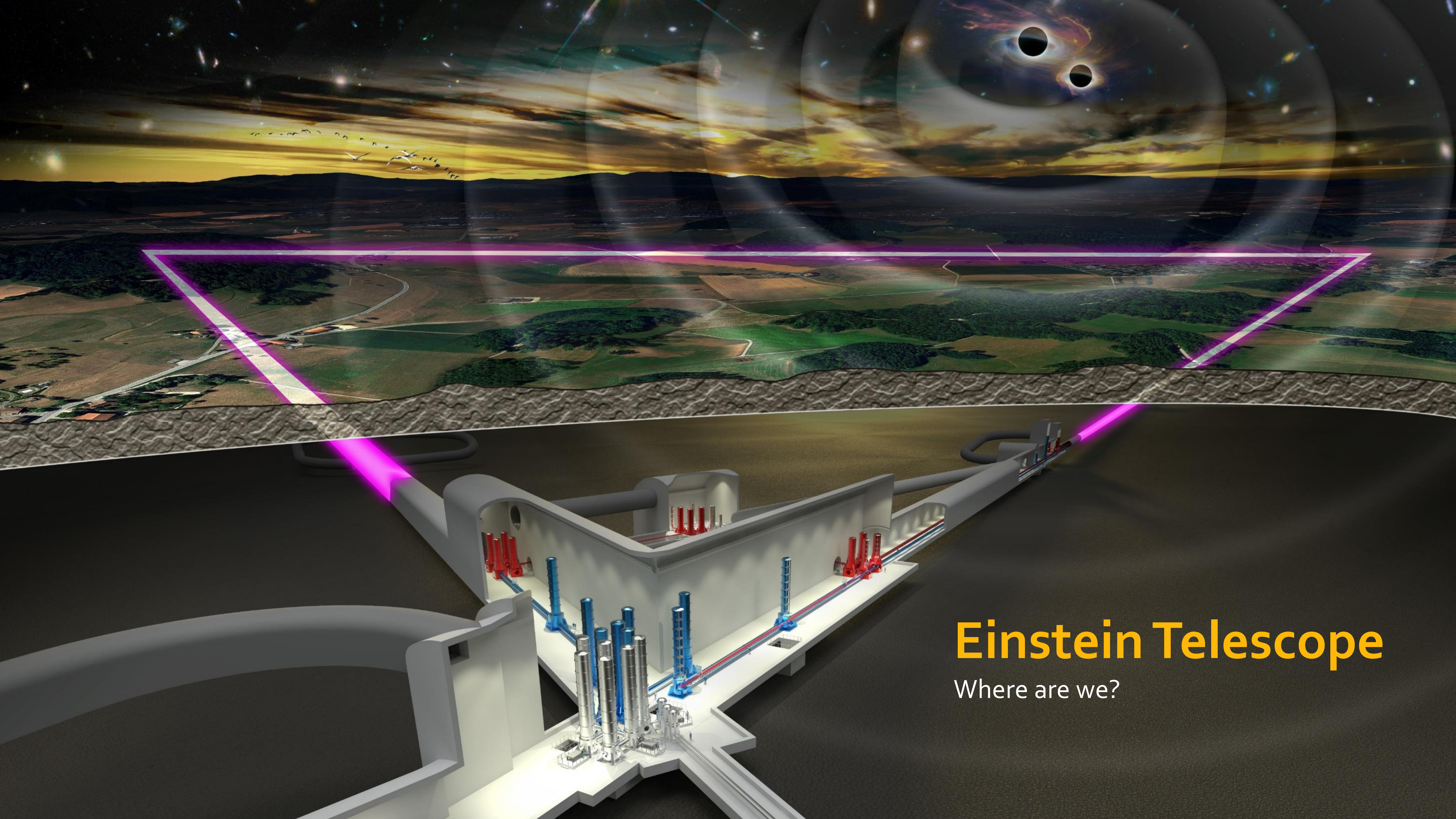
13

FORMATION AND EVOLUTION OF COMPACT BINARIES



11

Sub-slides credit: B. Sathyaprakash, Dawn III Workshop, https://wiki.ligo.org/LSC/LIGOworkshop2017/WebHome



Einstein Telescope

Where are we?

ESFRI Roadmap

European Strategy Forum
on Research Infrastructures

EINSTEIN TELESCOPE

Proposal submitted by:

- **Italy** (Lead Country)
- Netherlands
- Belgium
- Spain
- Poland

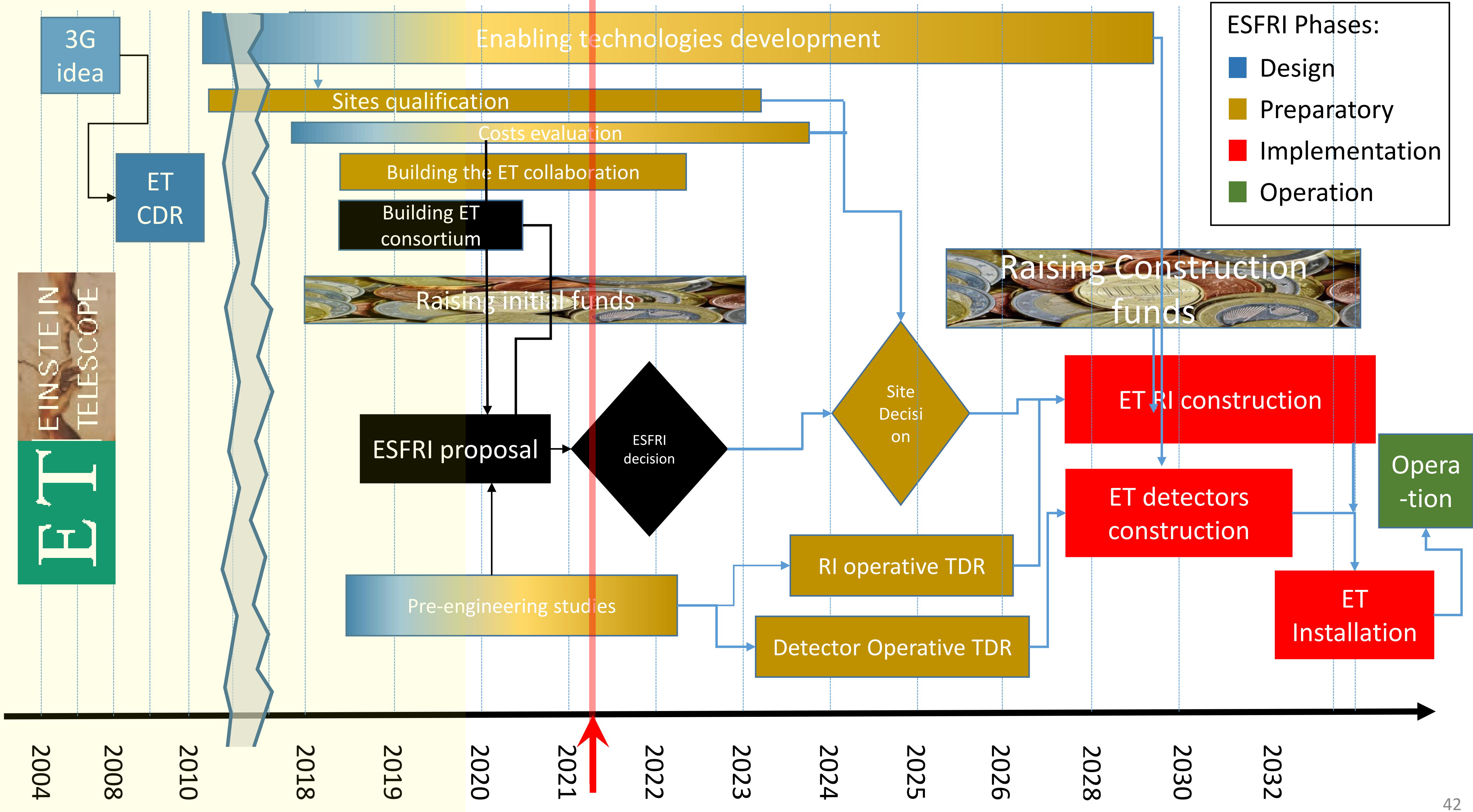
ET ESFRI Proposal:
the consortium level

- The ET ESFRI consortium is composed by the institutions signing the ET consortium agreement (CA)
  - Very light CA at this level
  - 41 Institutions signed the ET consortium
  - The ET consortium is coordinated by INFN and Nikhef
    (Stan Bentvelsen, Antonio Zoccoli)

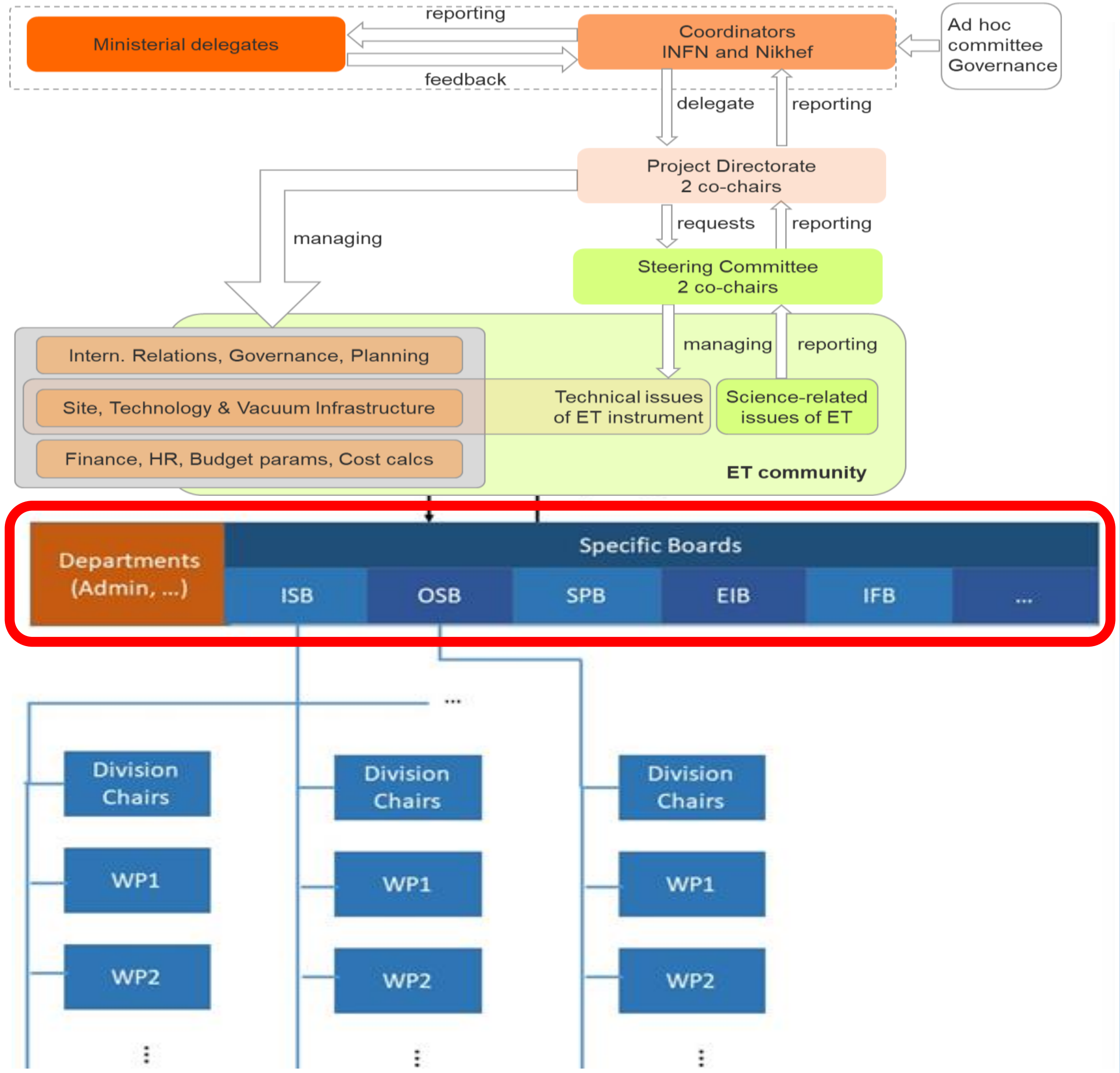
From LKV Sept2020, modified

https://www.google.com/maps/d/edit?mid=1ljTBCqTyCmVncbYaeUVcpQA3udceyg2b&usp=sharing

Slide: Michele Punturo



ET Governance Scheme (proposal)

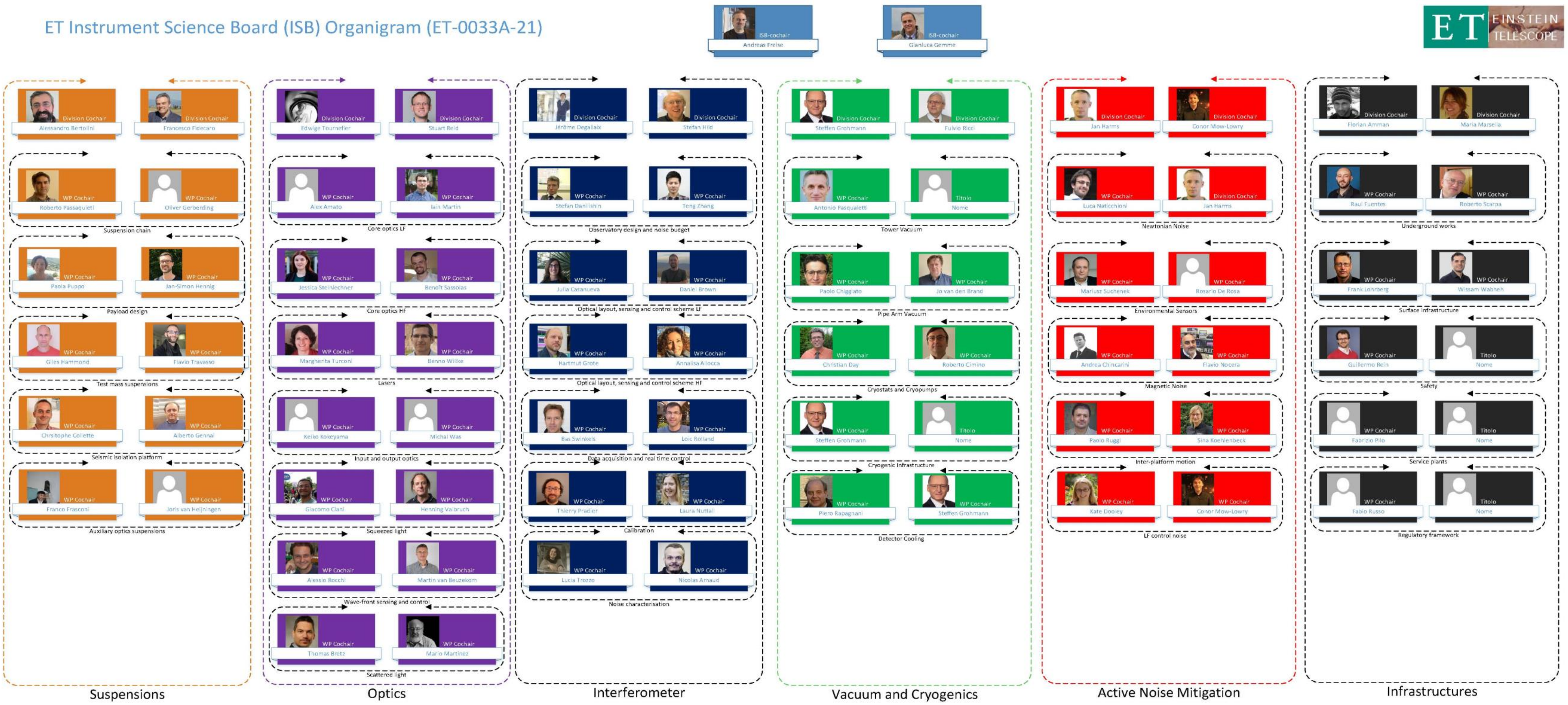


H. Lueck @ GWADW 2021

ET Boards

- **The Instrument Science Board (ISB)**
  - deliver the ET Technical Design Report (ET-TDR) for infrastructure and detectors
  - identify the missing technologies and suggest a (living) plan for R&D activities. first version ca. March 2021.
- **The Observational Science Board (OSB)**
  - will detail the ET science case
  - will prepare the data analysis requirements
  - will indicate the computing requirements for ET
- **The Site Preparation Board (SPB)**
  - will coordinate the effort on the site related activities
  - formulate the site specifications for Einstein Telescope
  - prepare the choice of the site for the Einstein Telescope observatory
- **The E-Infrastructures Board (EIB) -> Computing Infrastructure Board**
  - will define the computing and storage resources, networking, local and distributed e-infrastructures
  - will study the computing models that can be adopted in ET and the synergies with the e-infrastructures available or expected in Europe in the next decade.
- **The Internal Finance Board (IFB)**
  - will have the mandate to evaluate the financial needs
  - collecting and harmonizing the inputs received from the other technical boards
  - will suggest the funding tools needed to elaborate a financial strategy to be proposed to the Council.

ISB: Instrument Science Board



Like to join the Einstein Telescope project?

Check out the website of the ISB

Wiki.et-gw.eu/ISB/WelcomePage

and contact a working group chair or a division chair

They will assist you join the collaboration,
where you can **shape the next generation** of
gravitational wave observatories

OSB: Observational Science Board

Marica Branchesi - Michele Maggiore - Ed Porter

Fundamental physics
- Physics near BH horizons
- Tests of GR
- Exotic compact objects

Cosmology
- Dark Energy
- Dark matter
- Estimation of cosmological parameters
- Modifications of gravity at cosmological scales
- Stochastic background of cosmological origin

Population Studies
- Predictions of population of astrophysical origin
- Predictions of primordial BHs
- Stochastic backgrounds of astrophysical origin

MM observations
- ET / high-energy
- ET / optical
- ET / radio
- ET / neutrinos

Synergies w. other GW observ.
- Synergies with 2G+ detector
- Synergies with CE, 3G
- Synergies with LISA

Nuclear physics
- EoS of NSs in isolated systems
- EoS in NSs in binary systems
- Nucleo-synthesis in BNS mergers

Transient GW Sources
- Predictions for Supernovae
- Predictions for magnetars
- Predictions for cosmic string bursts

Waveforms
- Waveforms relevant for ET
- Improvement of waveforms for BBH
- Improvement of waveforms for NSBH
- Improvement of waveforms for BNS

Science Potential
- Science potential for various detector configurations
- Common tools

DA platform
- DA platform

Site Candidates

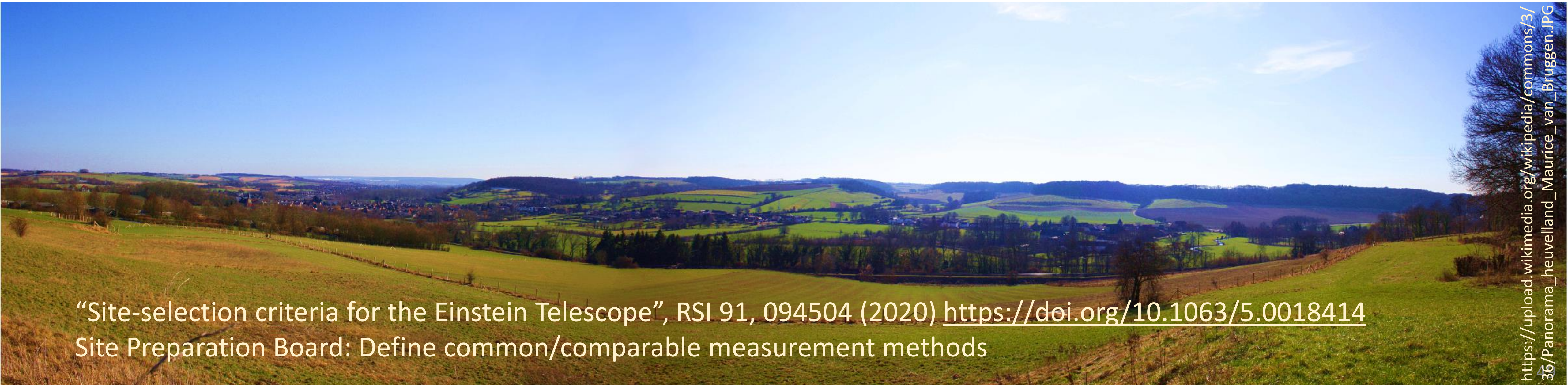
Two candidate sites in

- Italy and
- The Netherlands

Both sites geologically and seismically suited.
Investigations ongoing.

Activities in the Euregio Meuse-Rhine

- A 250-m deep borehole has been drilled and is equipped with
  - Seismic data under acquisition and analysis
- 3-5 more boreholes in 2021/22
- Extensive active and passive site characterisation with sensor arrays in 2021
- ET pathfinder lab under construction making good progress

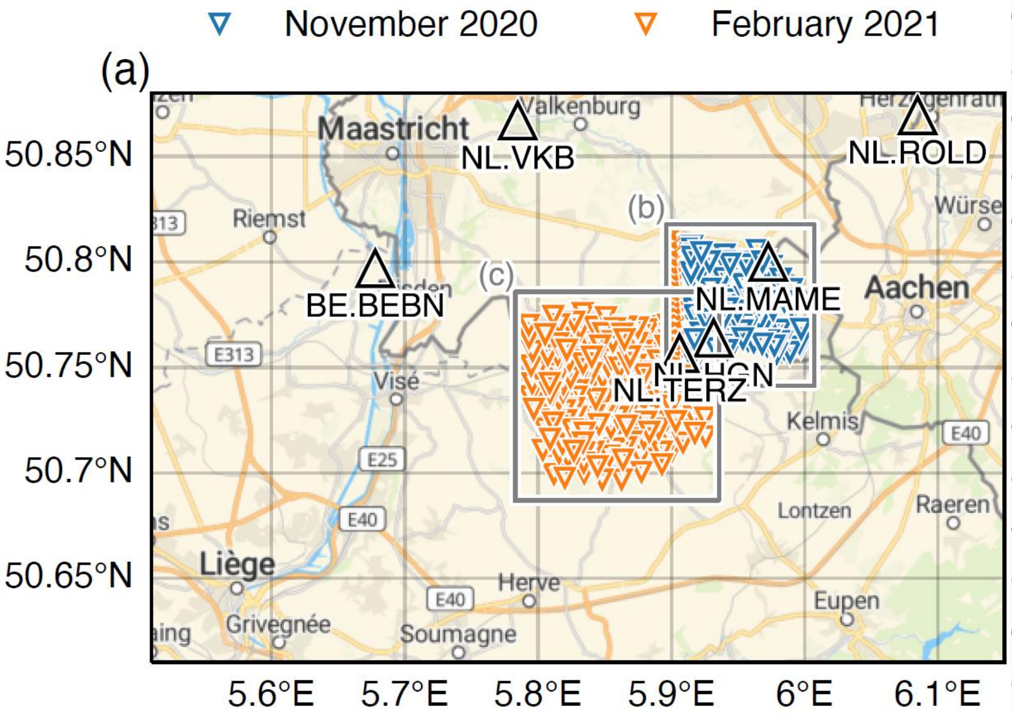


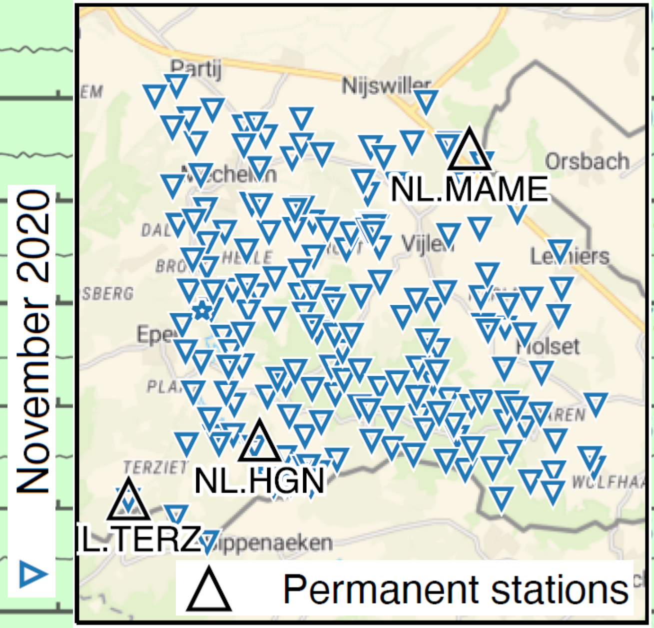
“Site-selection criteria for the Einstein Telescope”, RSI 91, 094504 (2020) https://doi.org/10.1063/5.0018414
Site Preparation Board: Define common/comparable measurement methods

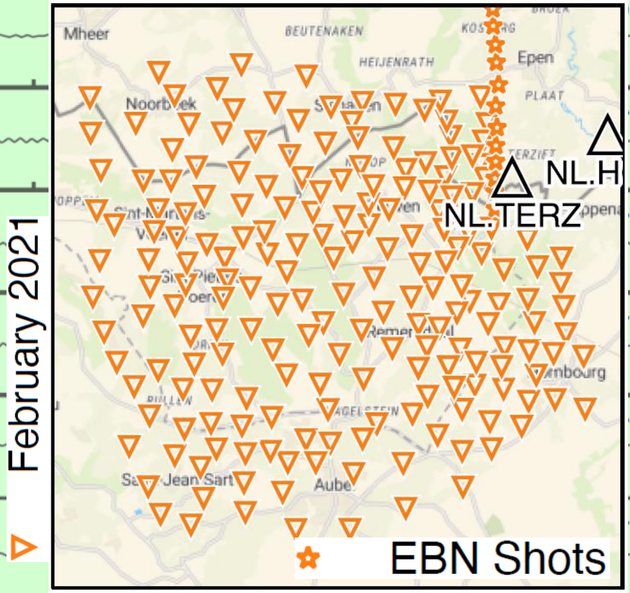
https://upload.wikimedia.org/wikipedia/commons/3/36/Panorama_heuvelland_Maurice_van_Bruggen.JPG

Measurements in the Euregio Meuse-Rhine

Data:
https://www.fdsn.org/networks/detail/3T_2020/

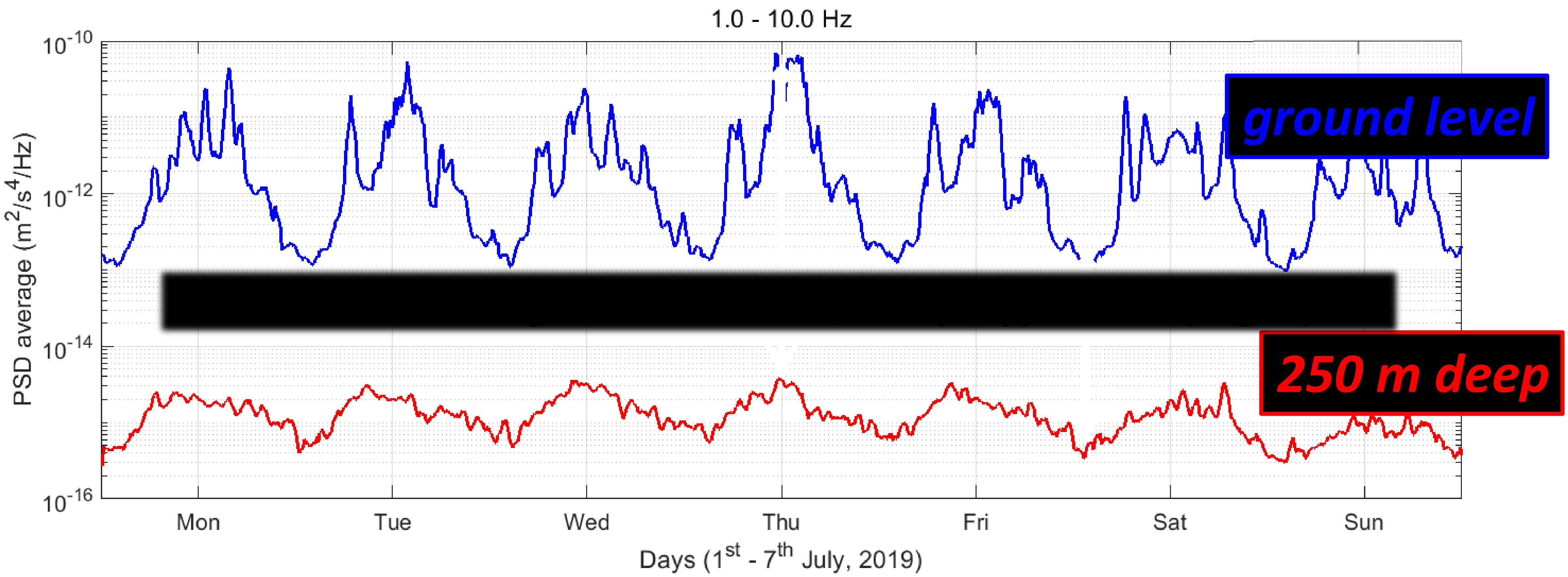






Terziet: Live data:
http://www.orfeus-eu.org/data/odc/realtime/?network=NL&station=TERZ
First three: on ground
Lower three: down hole sensor

Seismic noise at the Terziet site



soft top layer

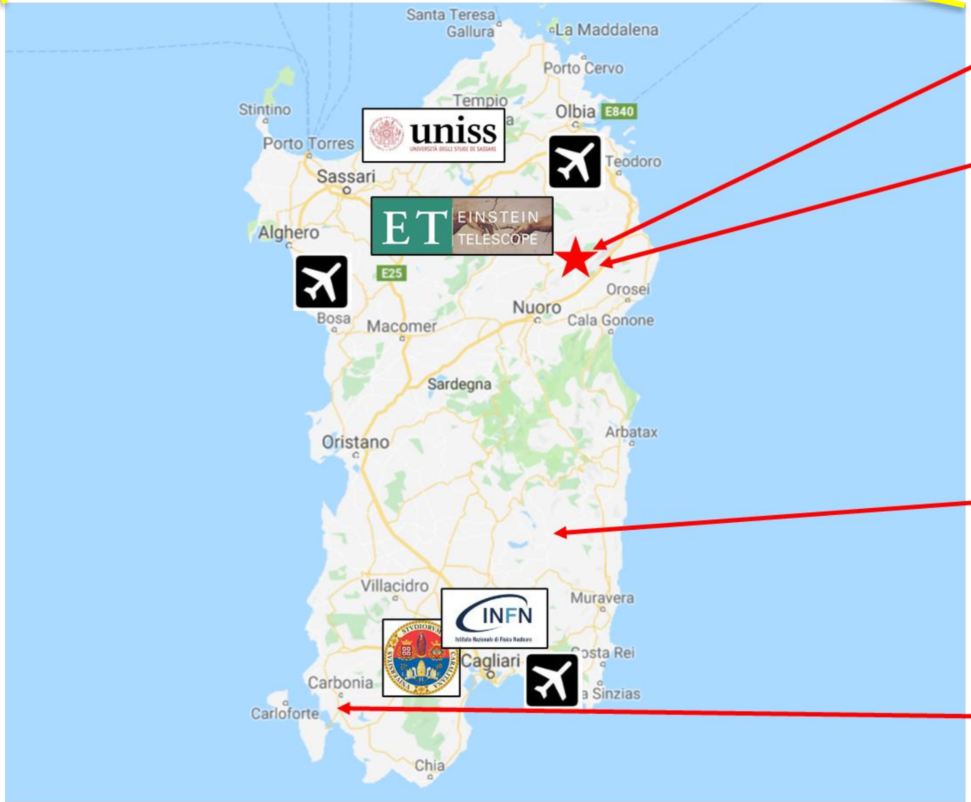
on hard rock

good for tunnel construction ☺

Sardinia Site Activities

Slide: Domenico D'Urso

The Sos Enattos site



Site access: 50’ (85km) drive from Olbia airport (highway)

SarGrav underground laboratory

Sardinia Radio Telescope

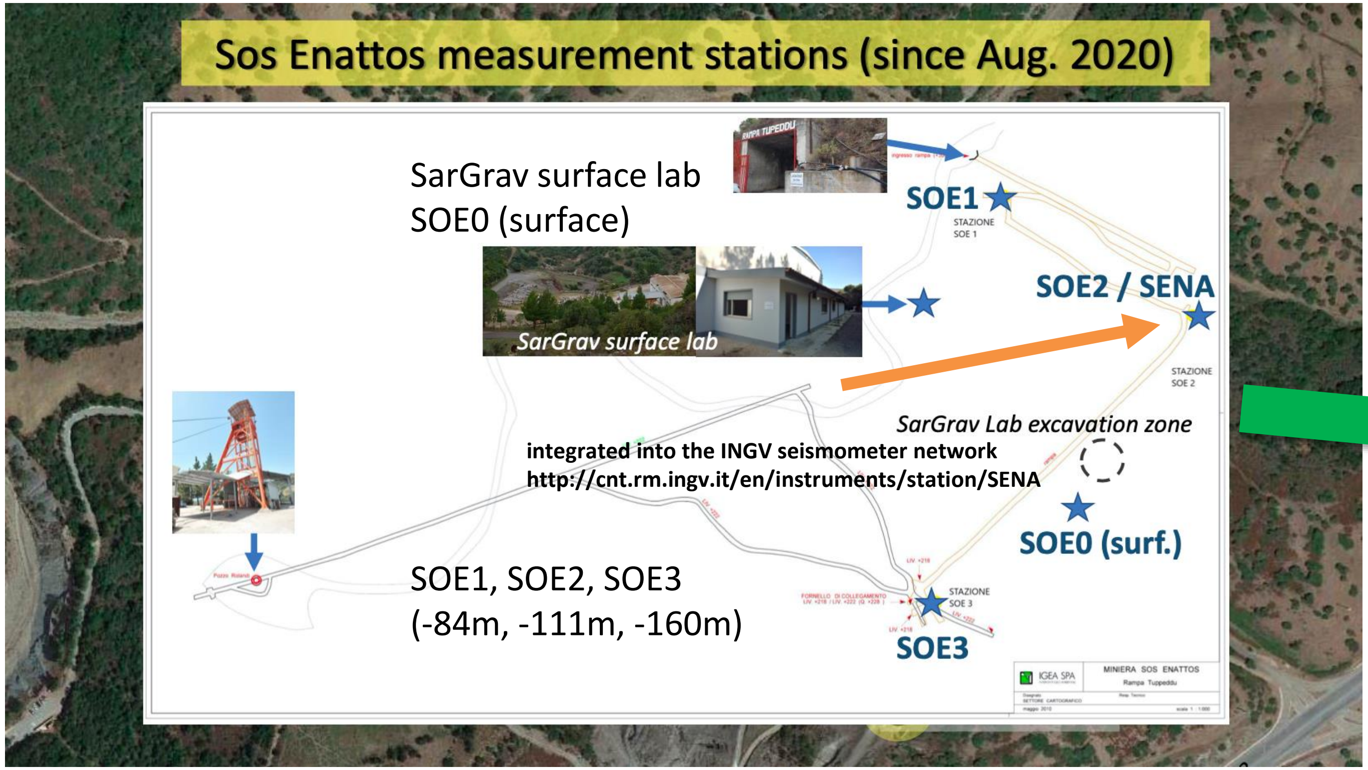
“ARIA” project (for Gran Sasso *Dark Side* DM det.)

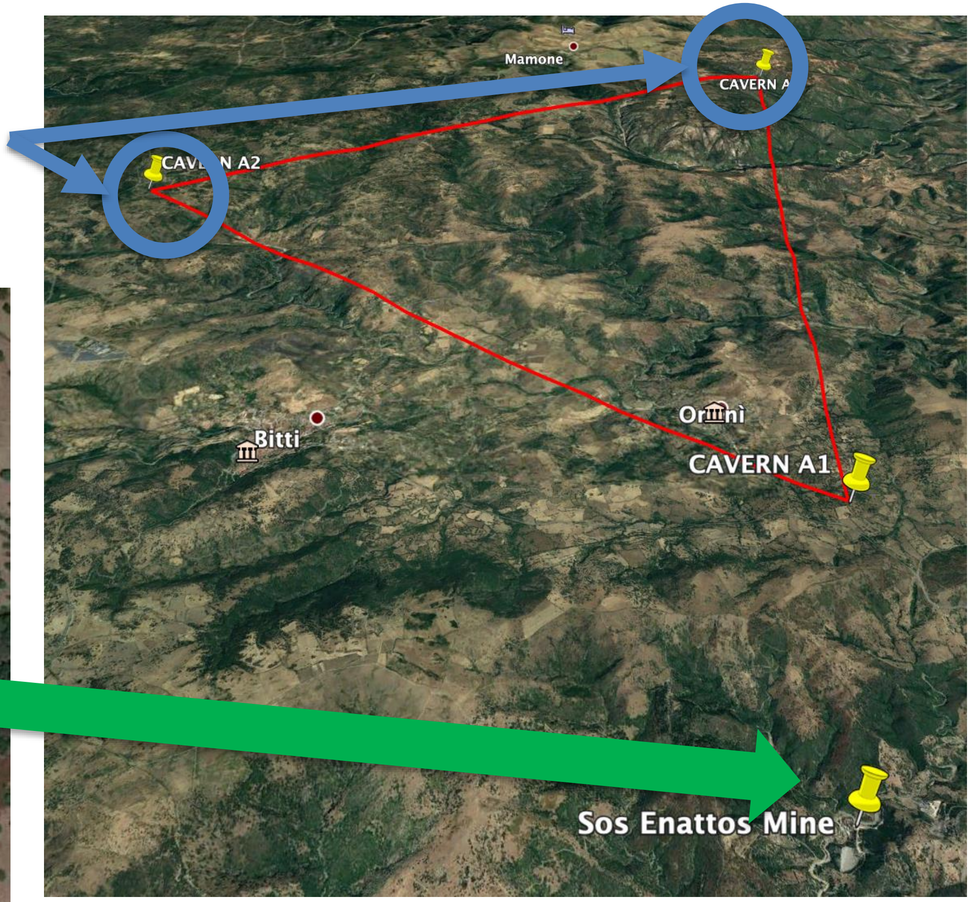
Slide: Domenico D'Urso

Slide: Domenico D'Urso

Measurement in Sardinia

Characterization of the Bitti and Onanì corners:
Surface and underground seismic and
environmental measurements will start soon

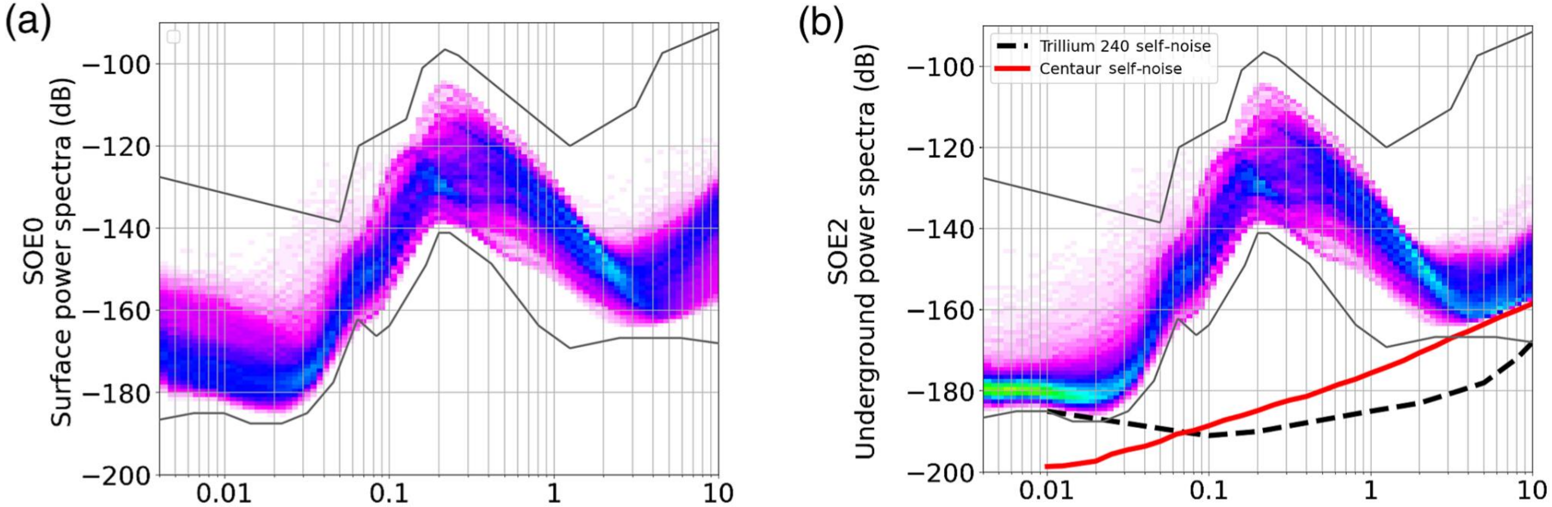




4 broadband seismometers, 3 short-period seismometers, 2 magnetometers,
1 tiltmeter distributed over underground and surface stations

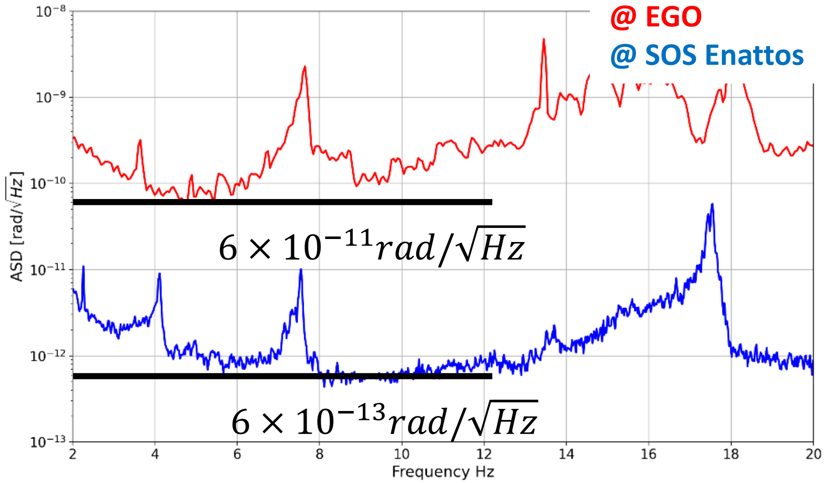
Credits to L. Naticchioni

Measurement Results



- First year of seismic characterization measurements at Sos Enattos published (JPCS 1468, 2020, SRL https://doi.org/10.1785/0220200186): extremely low-noise conditions in the range 2-10Hz. SOE2 measurements are biased by the low-gain setting of the ACQ (compliant to the national monitoring program).

- Preliminary sensitivity of Archimedes Prototype balance (tiltmeter) (https://doi.org/10.1103/PhysRevD.90.022002)



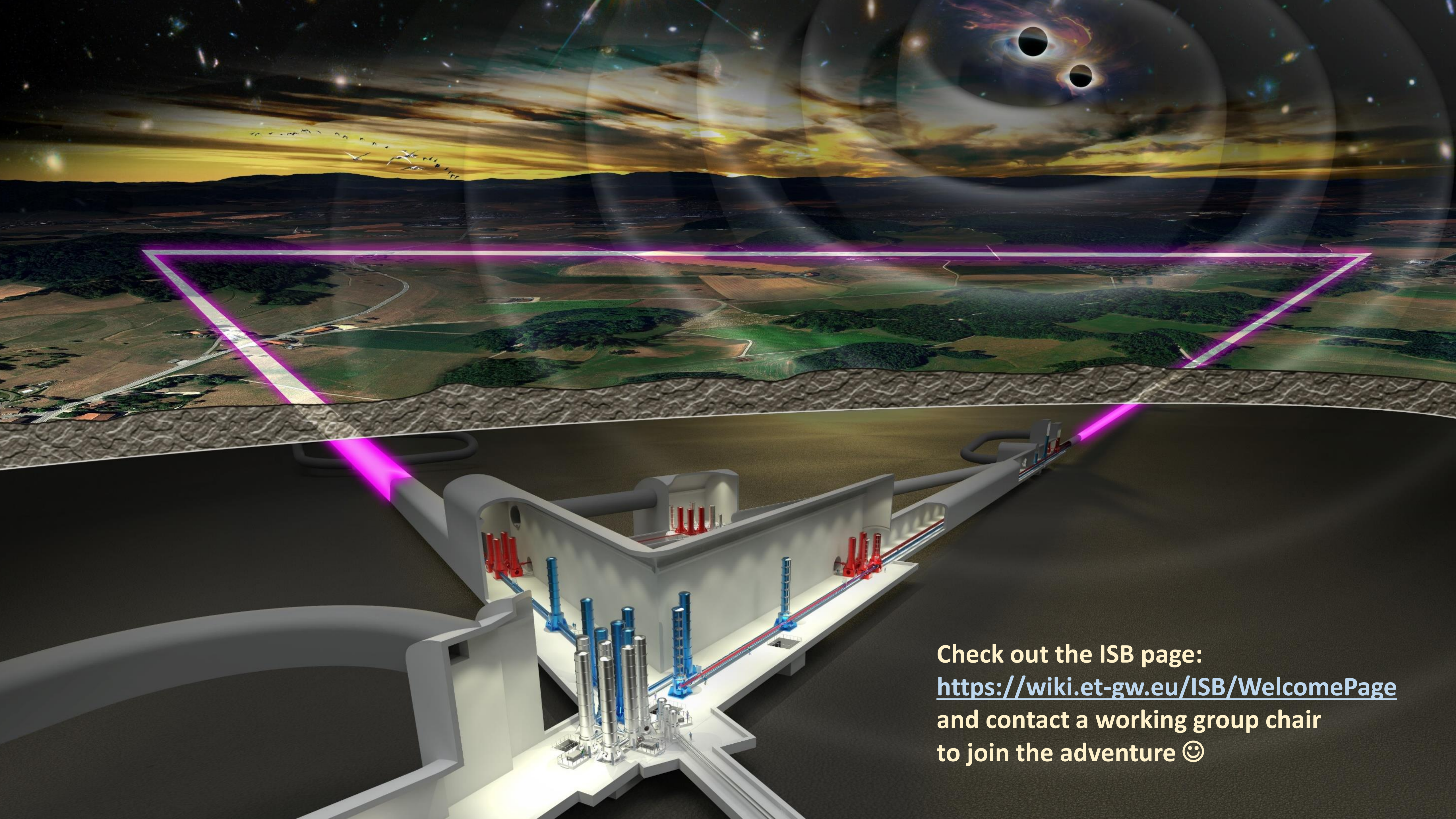
Slide: Domenico D'Urso

ET Community in Germany

ET activites are ramping up
in several countries in Europe,
e.g. in **Germany**
Joint Research Activity of 17 university partners
funded by BMBF

EINSTEIN TELESCOPE

Einstein Telescope Infrastructure


Check out the ISB page:
https://wiki.et-gw.eu/ISB/WelcomePage
and contact a working group chair
to join the adventure ☺