Gravitational wave science – Virgo and Einstein Telescope

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YKIS2022a "Gravity – The Next Generation"
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LSC LIGO Scientific Collaboration

KAGRA

Advanced Virgo

Einstein Telescope

Gravity

Gravity is the least understood fundamental interaction with many open questions. Should we not now investigate general relativity experimentally, in ways it was never tested before?

Gravity

- Main organizing principle in the Universe
  - Structure formation
- Most important open problems in contemporary science
  - Acceleration of the Universe is attributed to Dark Energy
  - Standard Model of Cosmology features Dark Matter
  - Or does this signal a breakdown of general relativity?

Large world-wide intellectual activity

- Theoretical: combining GR + QFT, cosmology, …
- Experimental: astronomy (CMB, Euclid, VRO), particle (LHC), Dark Matter searches (Xenon1T), …

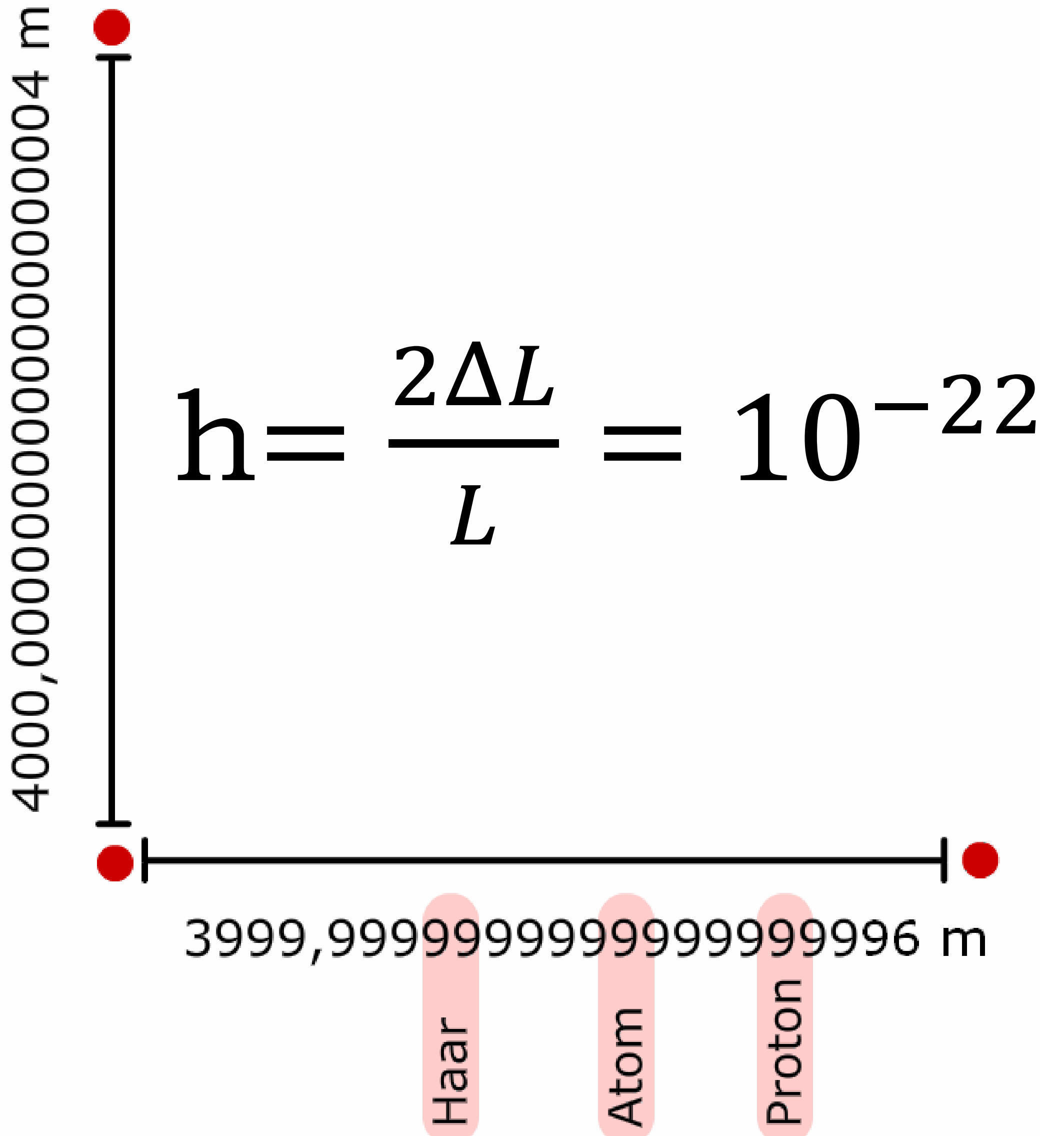
Gravitational waves

- Dynamical part of gravitation, all space is filled with GW
- Ideal information carrier, almost no scattering or attenuation
- The entire universe has been transparent for GWs, all the way back to the Big Bang

Gravitational wave science can impact

- Fundamental physics: black holes, spacetime, horizons, matter under extreme conditions
- Cosmology: Hubble parameter, Dark Matter, Dark Energy

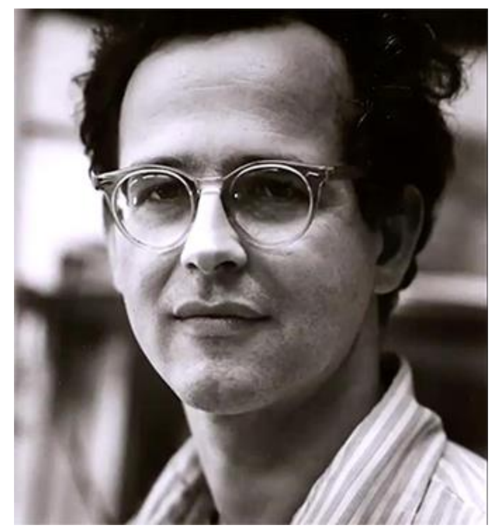
Gravitational waves can be measured with an ITF



$$h = \frac{2\Delta L}{L} = 10^{-22}$$

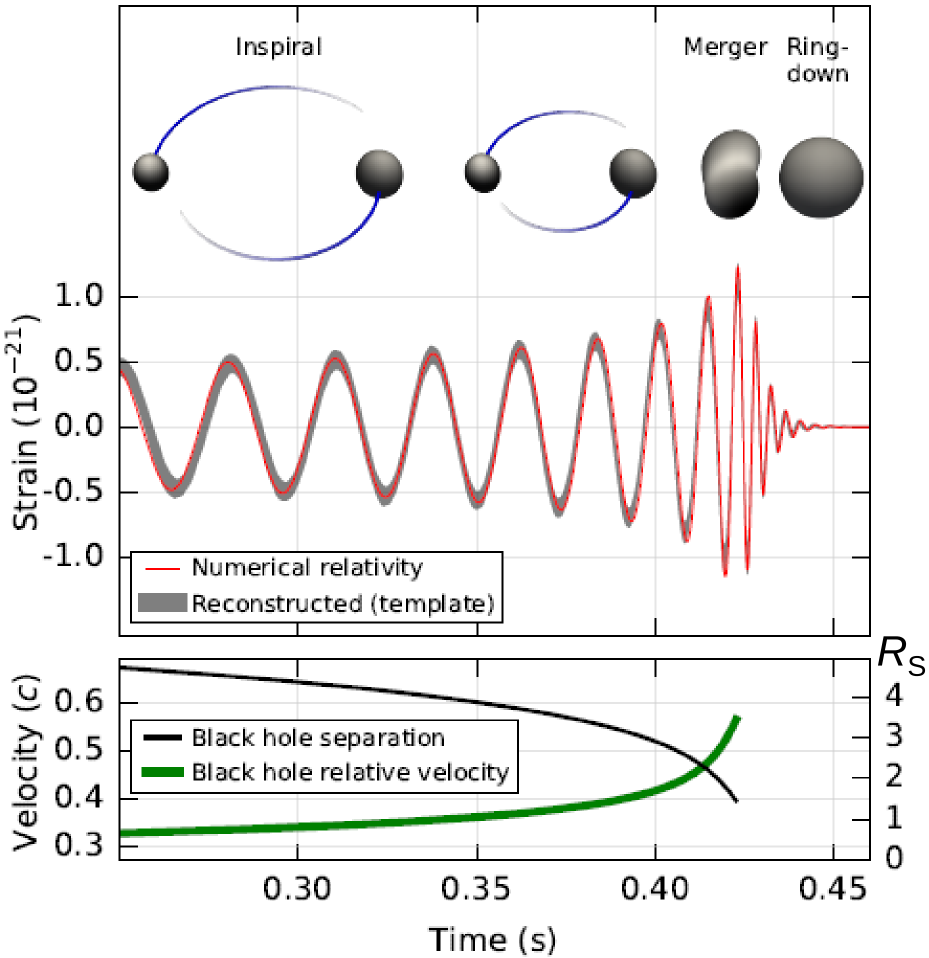
In 1964, Rai Weiss was at MIT as a professor, and assigned to teach general relativity.

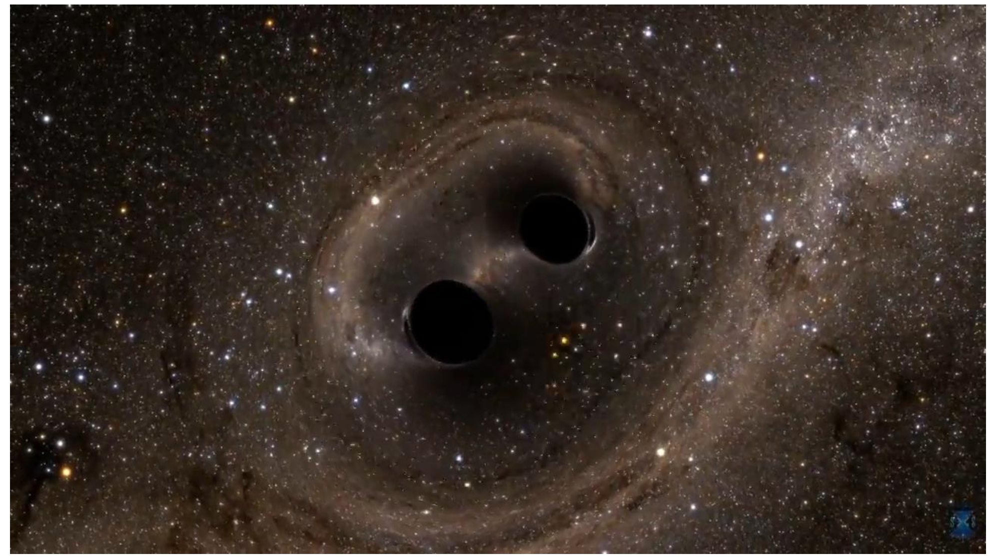
He asked, What’s really measurable in general relativity? He found the answer in Pirani’s papers presented at Chapel Hill in 1957



Binary black hole merger GW150914

The system will lose energy due to emission of gravitational waves. The black holes get closer and their velocity speeds up. Masses and spins can be determined from inspiral and ringdown phase





- Chirp $\dot{f} \approx f^{11/3} M_S^{5/3}$
- Maximum frequency $f_{\text{ISCO}} = \frac{1}{6^{3/2}\pi M}$
- Orbital phase (post Newtonian expansion)

$$\Phi(v) = \left(\frac{v}{c}\right)^{-5} \sum_{n=0}^{\infty} \left[\varphi_n + \varphi_n^{(l)} \ln\left(\frac{v}{c}\right)\right] \left(\frac{v}{c}\right)^n$$

- Strain $h \approx \frac{M_S^{5/3} f^{2/3}}{r} = \frac{\dot{f}}{r f^3}$

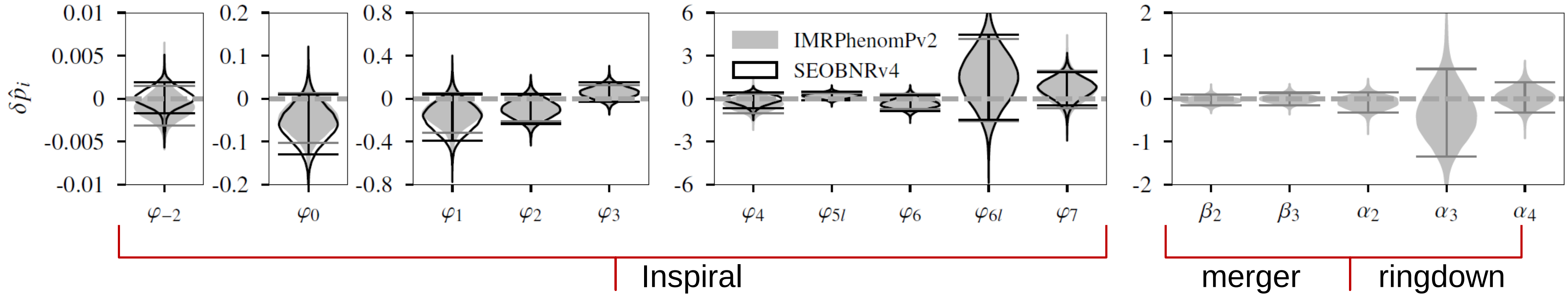
Precision tests of GR with BBH mergers

Bayesian analysis increases accuracy on parameters by combining information from multiple events

Inspiral and PN expansion

Inspiral PN and logarithmic terms:
Sensitive to GW back-reaction, spin-orbit, spin-spin couplings, …

LIGO Virgo Collaboration
arXiv:1903.04467v2



Orbital phase (post Newtonian expansion): $h^{\alpha\beta}(f) = h^{\alpha\beta} e^{i\Phi(f)}$

$$\Phi(v) = \left(\frac{v}{c}\right)^{-5} \sum_{n=0}^{\infty} \left[\varphi_n + \varphi_n^{(l)} \ln\left(\frac{v}{c}\right)\right] \left(\frac{v}{c}\right)^n$$

Merger terms: numerical GR

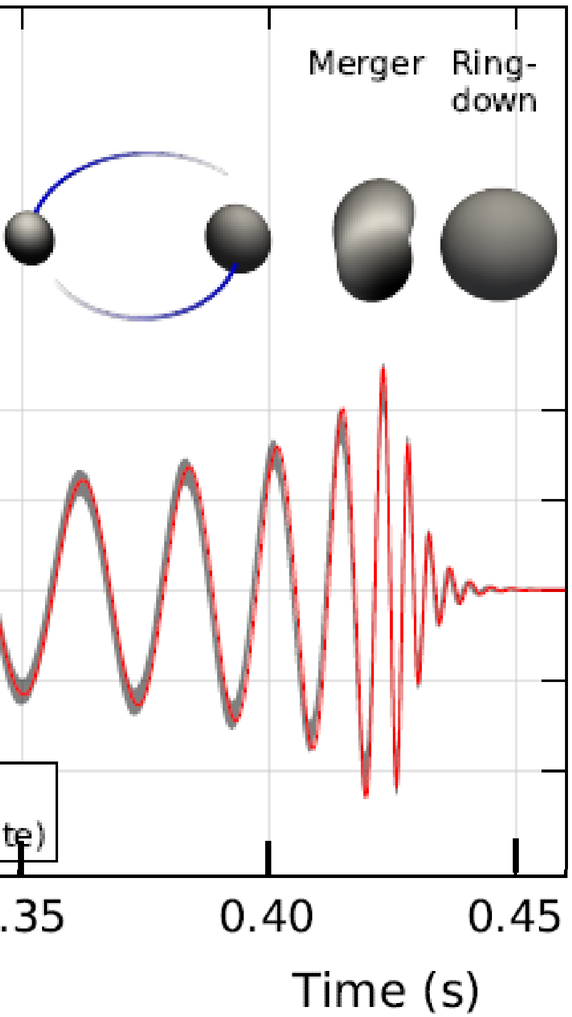
Ringdown terms: quasi-normal modes; do we see Kerr black holes?

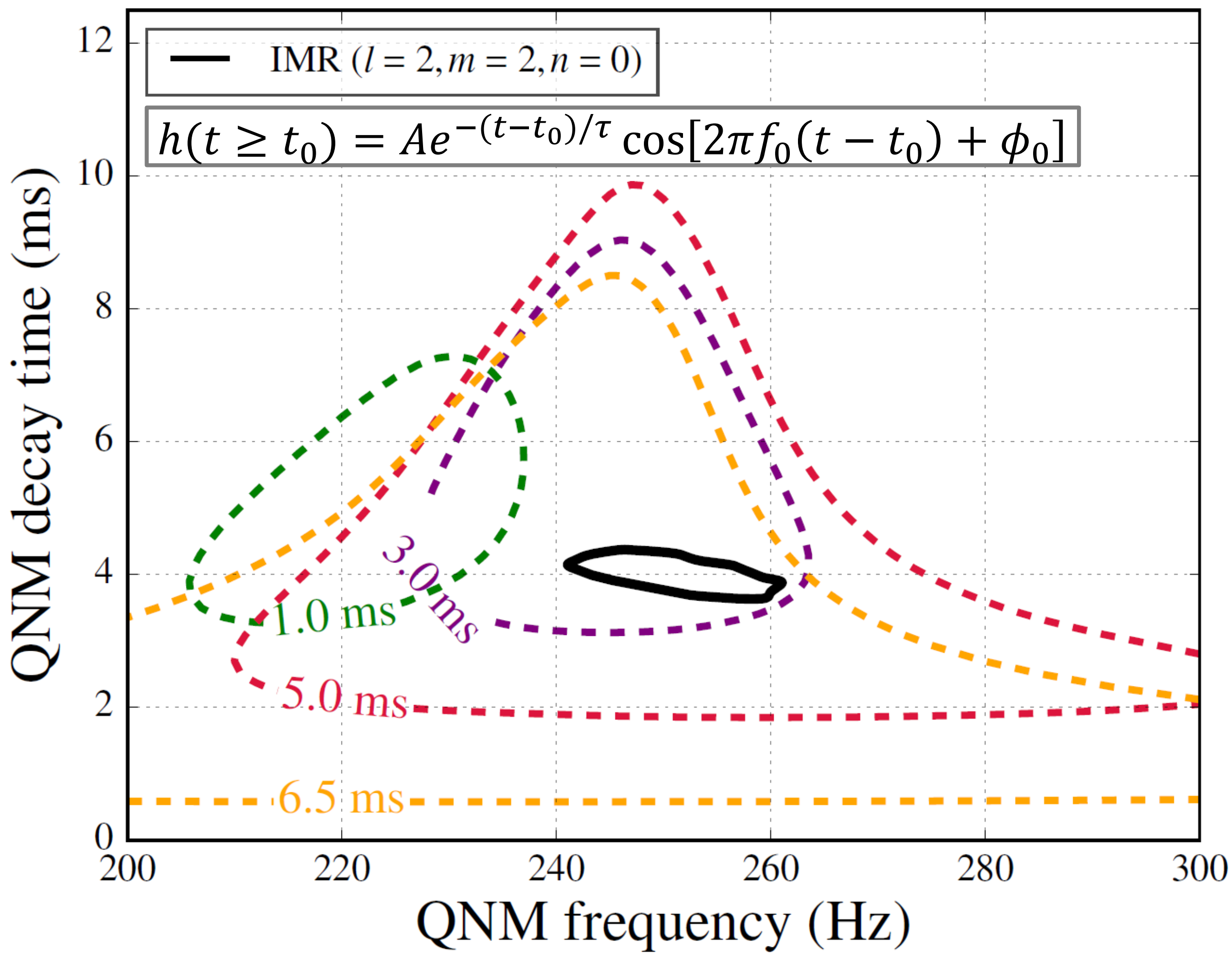
Towards high precision tests of gravity

Combining information from multiple events and having high-SNR events will allow unprecedented tests of GR and other theories of gravity

Is a black hole created in the final state?

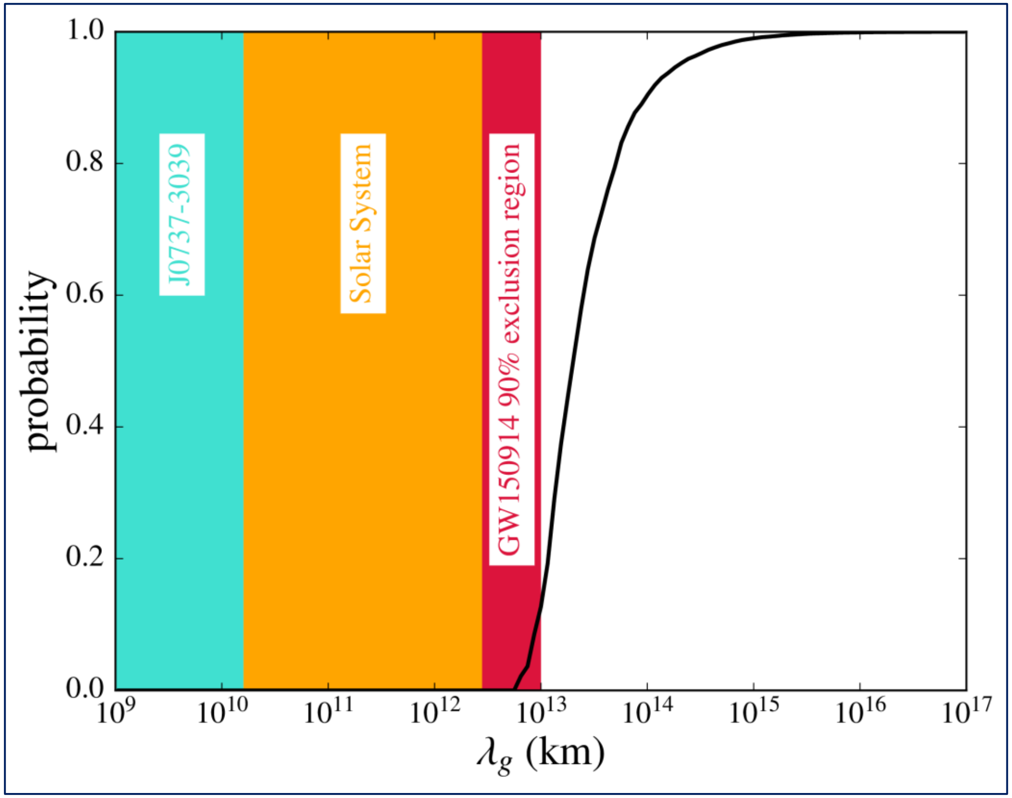
From the inspiral we can predict that the ringdown frequency of about 250 Hz and 4 ms decay time. This is what we measure (http://arxiv.org/abs/1602.03841). We will pursue this further and perform test of no-hair theorem. This demands good sensitivity at high frequency





Limit on the mass of the graviton

Bounds on the Compton wavelength $\lambda_g = {}^{h}/_{m_g c}$ of the graviton compared to Solar System or double pulsar tests. Some cosmological tests are stronger (but make assumptions about dark matter)



See "*Tests of general relativity with GW150914*"
http://arxiv.org/abs/1602.03841

$$\delta\Phi(f) = -\frac{\pi D c}{\lambda_g^2(1+z)} f^{-1}$$

Will, Phys. Rev. D **57**, 2061 (1998)

Massive-graviton theory dispersion relation $E^2 = p^2c^2 + m_g^2 c^4$

We have $\lambda_g = h/(m_g c)$

Thus frequency dependent speed
$\frac{v_g^2}{c^2} \equiv \frac{c^2 p^2}{E^2} \cong 1 - h^2c^2/(\lambda_g^2 E^2)$

$\lambda_g > 10^{13}$ km
$m_g \leq 10^{-22} \mathrm{eV}/c^2$

Virgo Collaboration

Virgo Collaboration

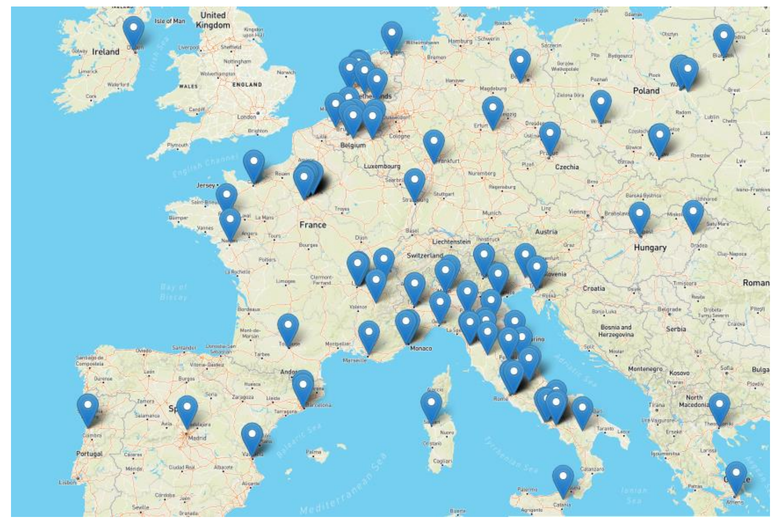
Virgo is a European collaboration with 741 members, 514 authors from 129 institutions in 16 different countries. Virgo has more that doubled its size in the last few years

Virgo is a 2nd generation GW detector in Europe

- EGO Council composed of France, Italy and the Netherlands
- Participation by scientists from Belgium, China, Czechia, Denmark, France, Germany, Greece, Hungary, Ireland, Italy, Japan, Monaco, Poland, Portugal, Spain, The Netherlands

Gravitational wave science: steep learning curve

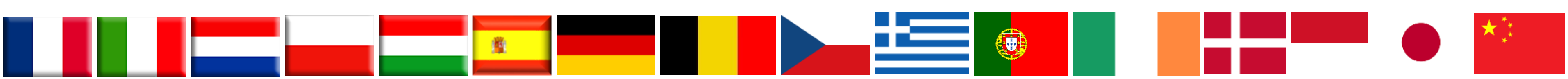
- Join gravitational wave science
- Learn about instrumentation and data analysis
- Path to third generation: Einstein Telescope
- Many members traditionally from CERN community



Virgo develops advanced and innovative technology

- Quantum technologies: frequency dependent squeezing
- Large test masses and advanced coatings
- Scattered light mitigation
- Low frequency risk reduction

14 European countries + China + Japan



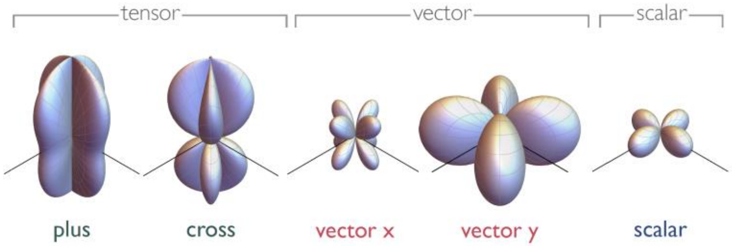
The Virgo interferometer joined observation in 2017

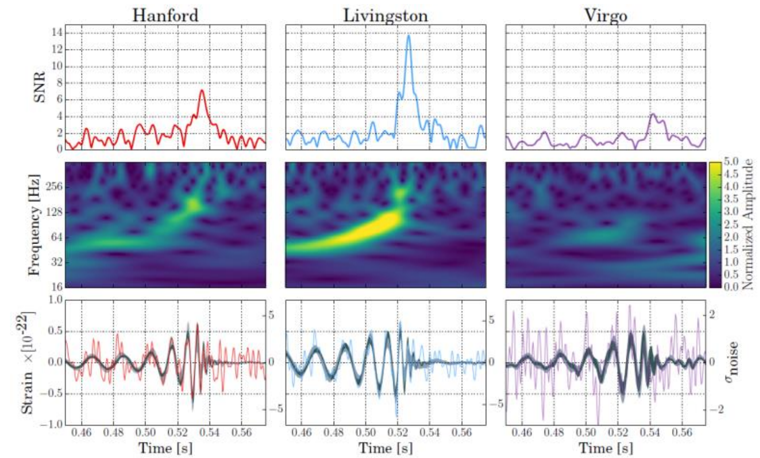
GW170814: first test of polarizations of GW

According to Einstein's General Relativity there exist only two polarizations. General metric theories of gravity allow six polarizations. GW170814 confirms Einstein's prediction

Angular dependence (antenna-pattern) differs for T, V, S

LIGO and Virgo have different antenna-patterns
This allows for fundamental test of the polarizations of spacetime





Our analysis favors tensor polarizations in support of General Relativity

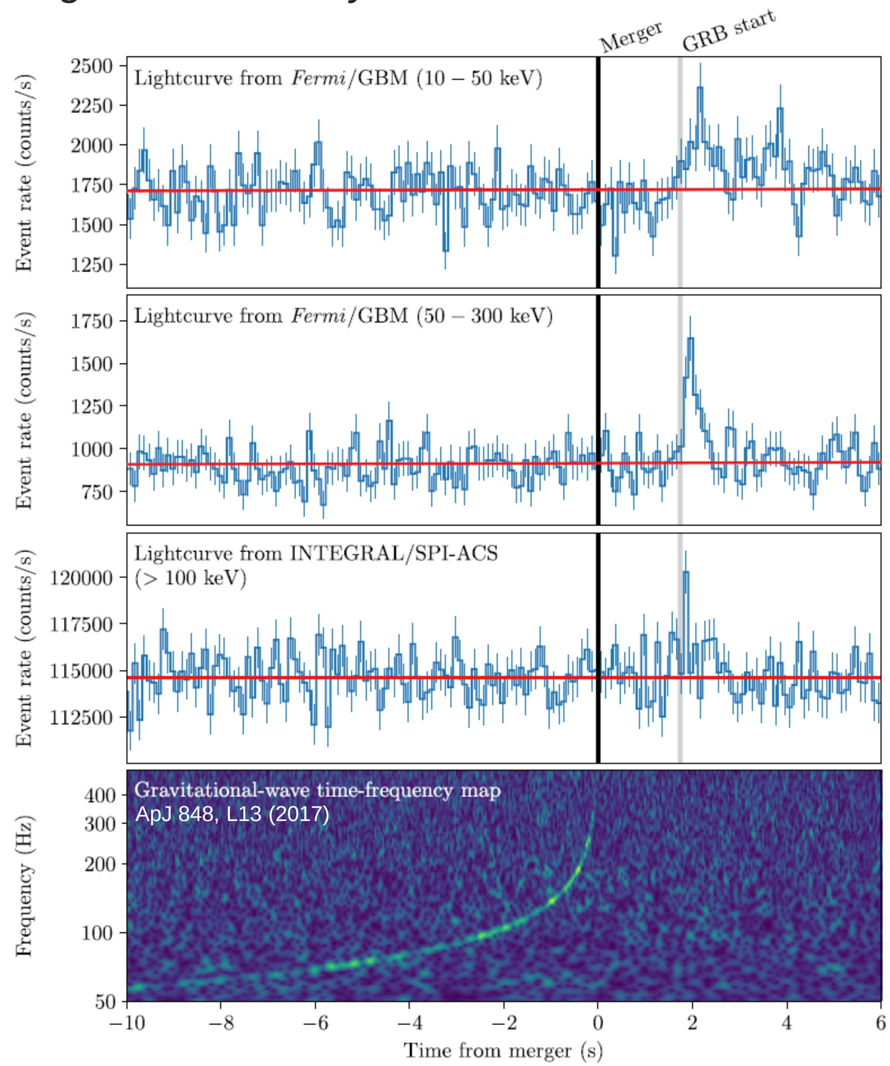
Our data favor tensor structure over vector by about a (Bayes) factor 200

And tensor over scalar by about a factor 1000

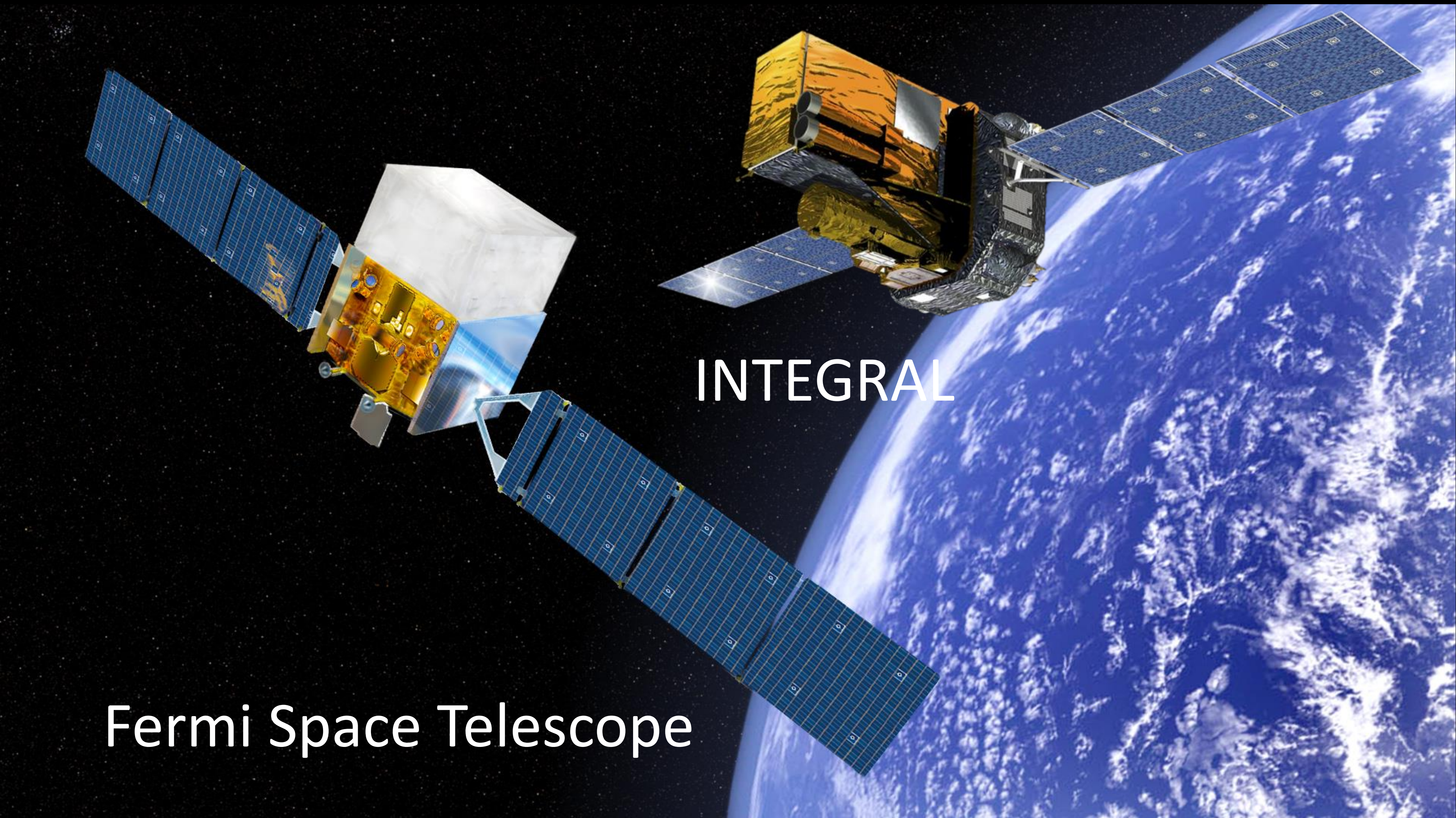
This is a first test, and for BBH we do not know the source position very well

Binary neutron star merger on August 17, 2017

Gamma rays reached Earth 1.7 s after the end of the gravitational wave inspiral signal. The data are consistent with standard EM theory minimally coupled to general relativity



Gamma rays reached Earth 1.7 seconds after GW170817



Neutron stars are laboratories for extreme physics

Mass: from about 1.1 to about 2.2 solar mass

Density: up to several times nuclear density

Temperature: up to 10^{12} K

Magnetic field: up to 10^{11} T

Held together by gravity and supported by degeneracy pressure and NN repulsion

Extrapolate behavior of QCD, superconductivity, and superfluidity

Equation Of State: many models

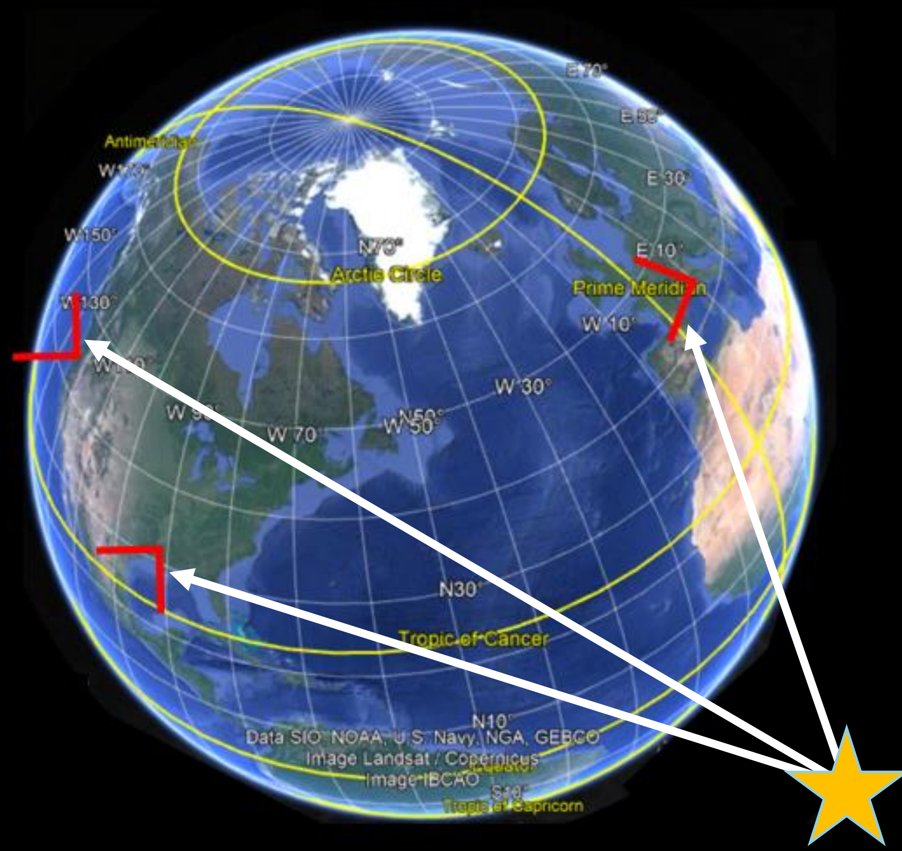
Source location via triangulation

GW170817 first arrived at Virgo, after 22 ms it arrived at LLO, and another 3 ms later LLH detected it

Virgo, Cascina, Italy

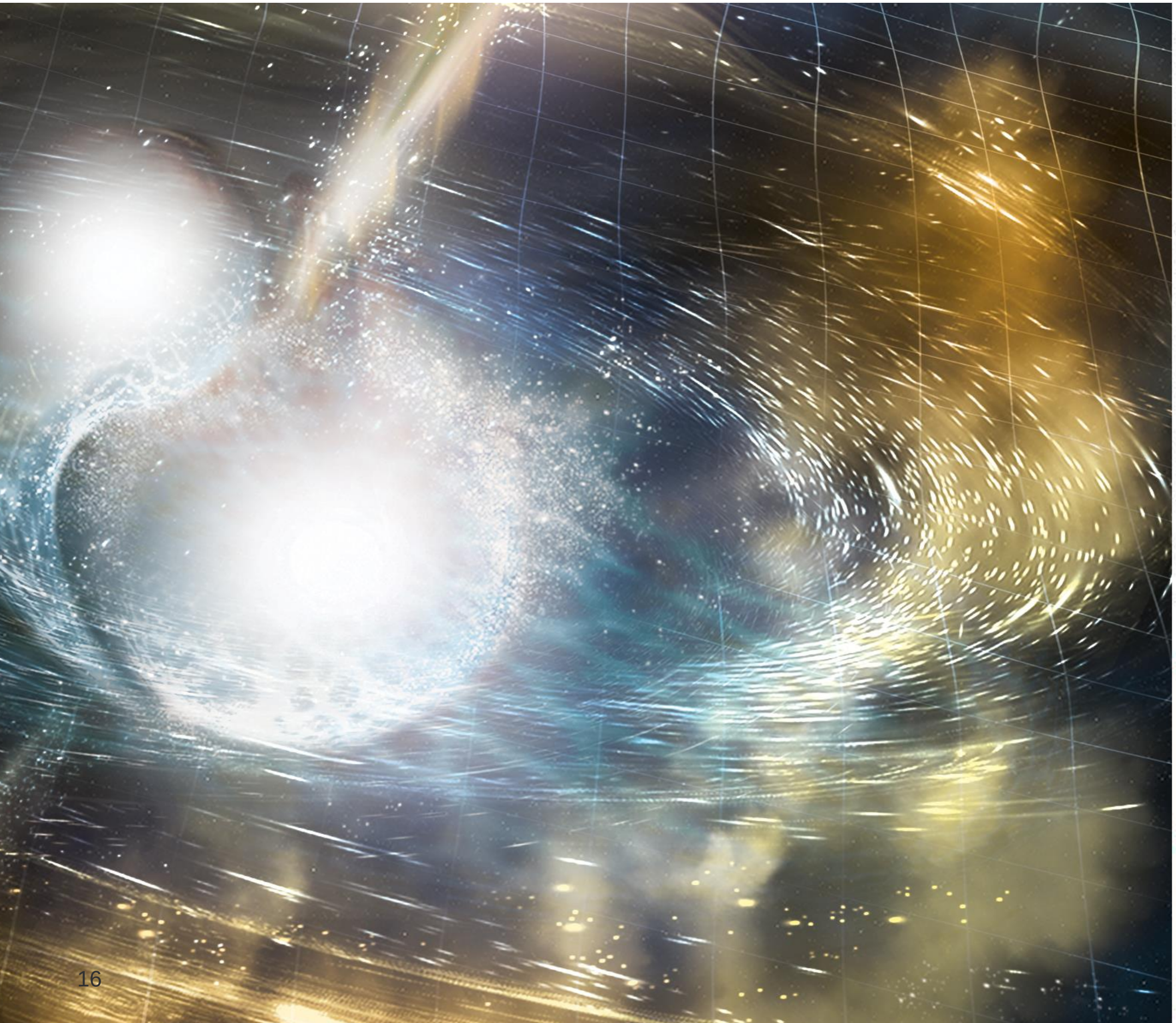
LIGO, Livingston, LA

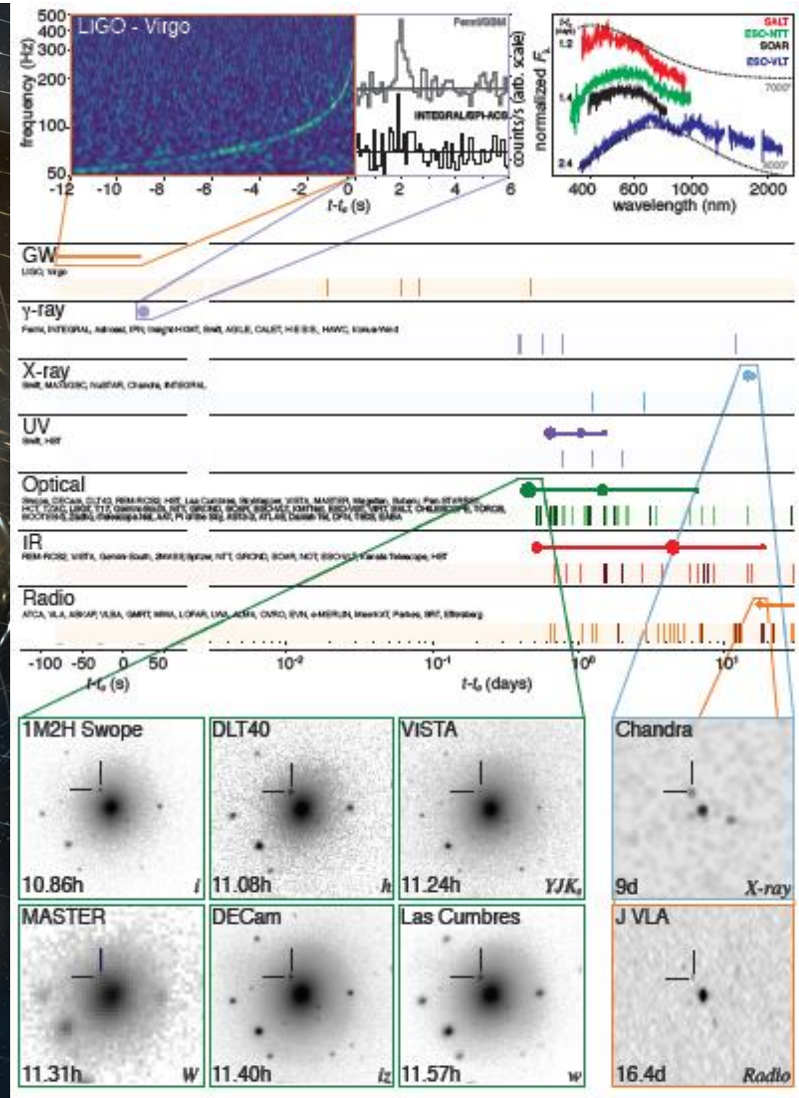
LIGO, Hanford, WA



GW170817: start of multi-messenger astronomy with GW

Many compact merger sources emit, besides gravitational waves, also light, gamma- and X-rays, and UV, optical, IR, and radio waves, as well as neutrino's or other subatomic particles. Our three-detector global network allows identifying these counterparts



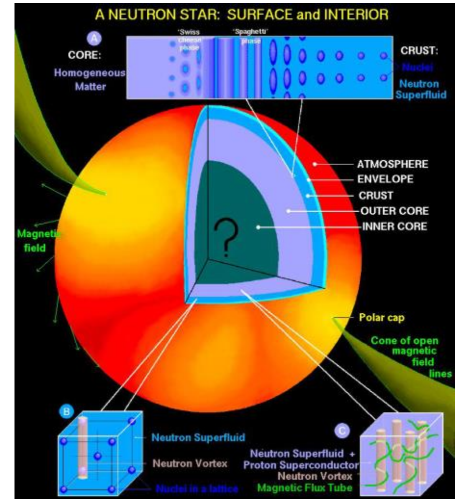


Solving an astrophysical conundrum

Neutron stars are rich laboratories with extreme matter physics in a strong gravitational environment. Stability is obtained due to quantum physics

Structure of neutron stars?

- Structure of the crust?
- Proton superconductivity
- Neutron superfluidity
- “Pinning” of fluid vortices to crust
- Origin of magnetic fields?
- More exotic objects?

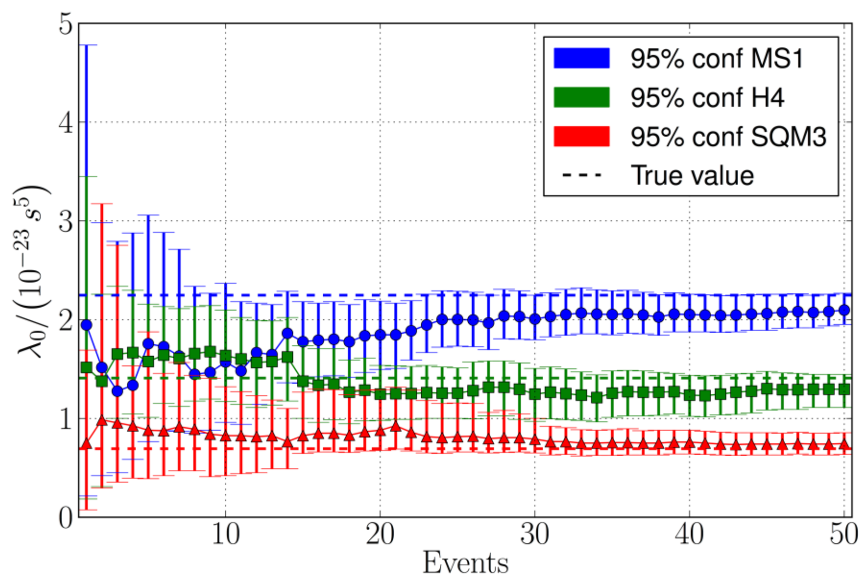


Gravitational waves from inspiraling neutron stars

- Stars induce tidal deformations in each other
- These affect orbital motion
- Tidal effects imprinted upon gravitational wave signal
- Tidal deformability maps directly to neutron star equation of state

Demorest *et al*., Nature 467, 1081 (2010)

Bernuzzi *et al*., PRL 115, 091101 (2015)

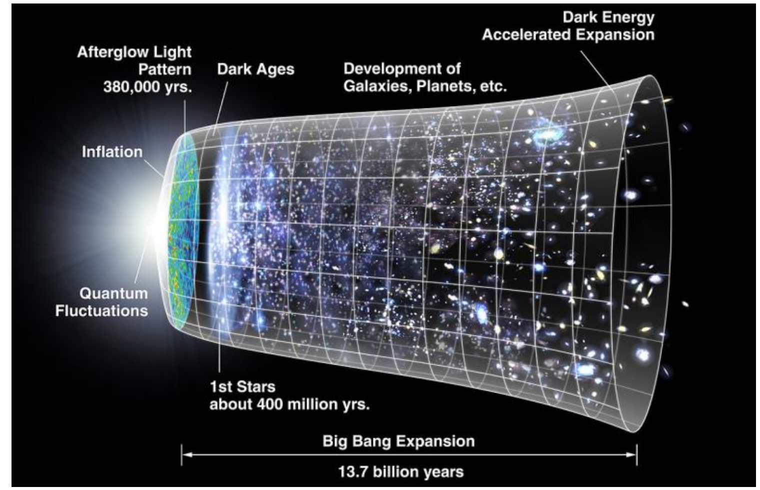


A new cosmic distance marker

Binary neutron stars allow a new way of mapping out the large-scale structure and evolution of spacetime by comparing distance and redshift

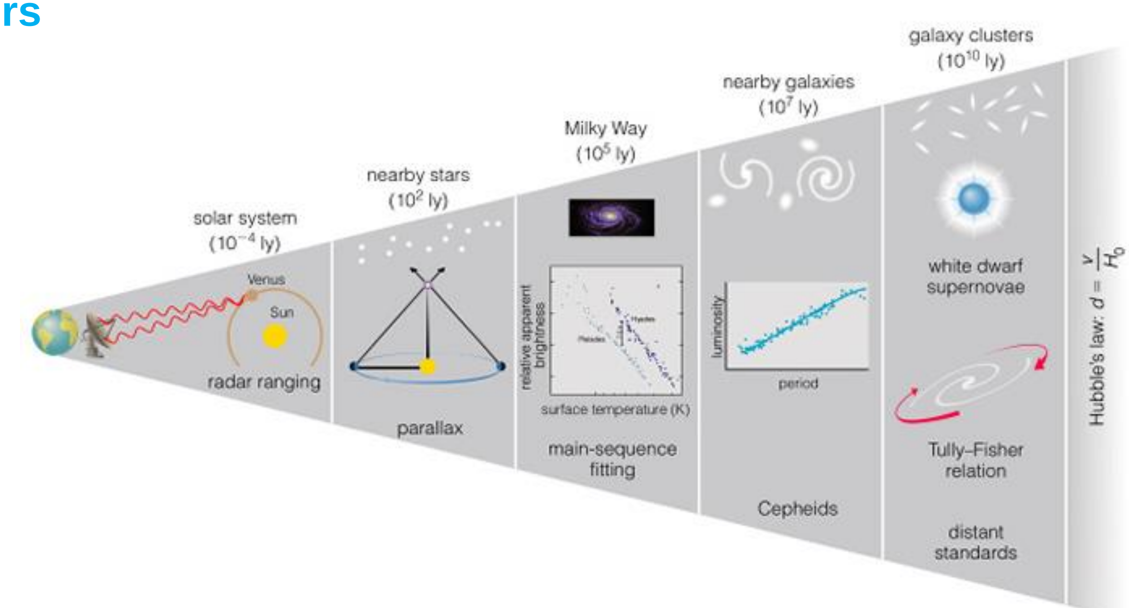
Current measurements depend on cosmic distance ladder

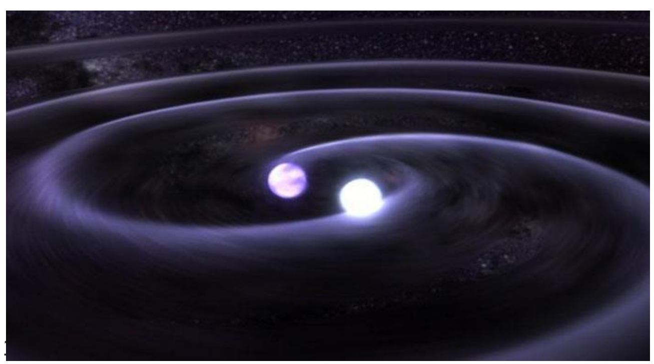
- Intrinsic brightness of *e.g.* supernovae determined by comparison with different, closer-by objects
- Possibility of systematic errors at every “rung” of the ladder



Gravitational waves from binary mergers

Distance can be measured directly from the gravitational wave signal!





A new cosmic distance marker

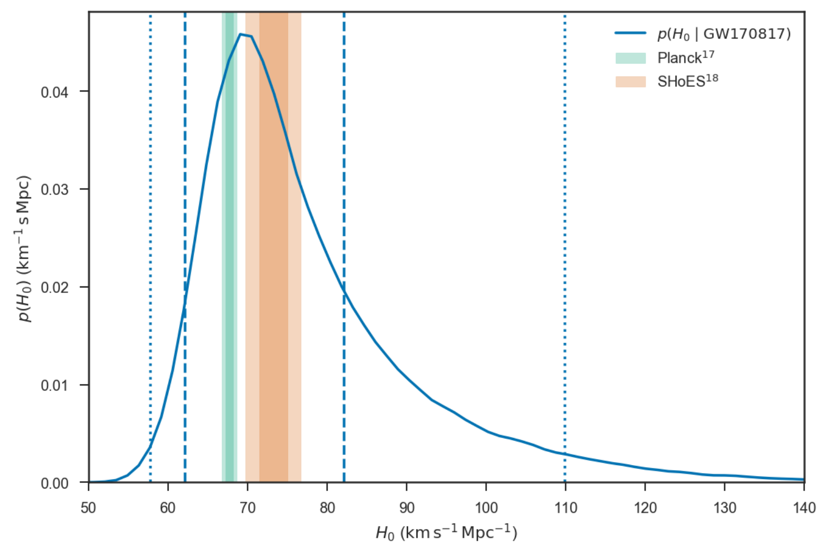
A few tens of detections of binary neutron star mergers allow determining the Hubble parameters to about 1-2% accuracy

Measurement of the local expansion of the Universe

The Hubble constant

- Distance from GW signal
- Redshift from EM counterpart (galaxy NGC 4993)

LIGO+Virgo *et al*., Nature 551, 85 (2017)

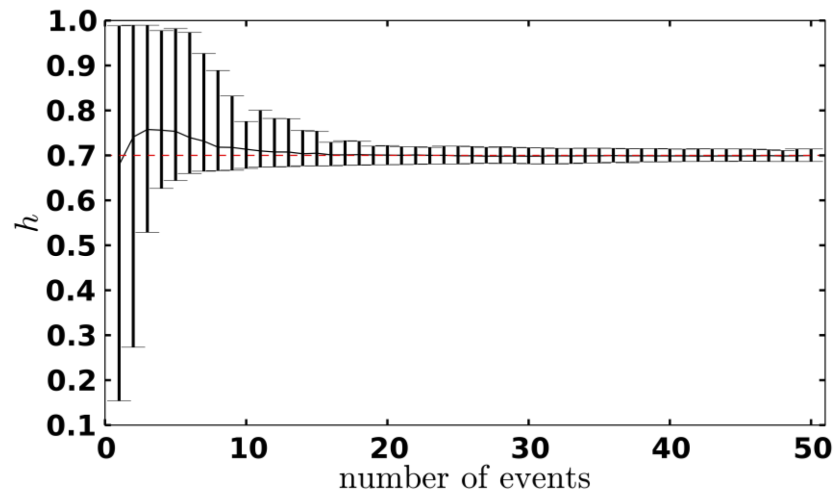


GW170817

- One detection: limited accuracy
- Few tens of detections with LIGO/Virgo will be needed to obtain O(1-2%) accuracy

Bernard Schutz, Nature 323, 310–311 (1986)

Walter Del Pozzo, PRD 86, 043011 (2012)



Third generation observatories allow studies of the Dark Energy equation of state parameter

Scientific impact of gravitational wave science

Multi-messenger astronomy started: a broad community is relying of detection of gravitational waves
Scientific program is limited by the sensitivity of LVC instruments over the entire frequency range

Fundamental physics
Access to dynamic strong field regime, new tests of General Relativity
Black hole science: inspiral, merger, ringdown, quasi-normal modes, echo's
Lorentz-invariance, equivalence principle, polarization, parity violation, axions

Astrophysics
First observation for binary neutron star merger, relation to sGRB
Evidence for a kilonova, explanation for creation of elements heavier than iron

Astronomy
Start of gravitational wave astronomy, population studies, formation of progenitors, remnant studies

Cosmology
Binary neutron stars can be used as standard “sirens”
Dark Matter and Dark Energy

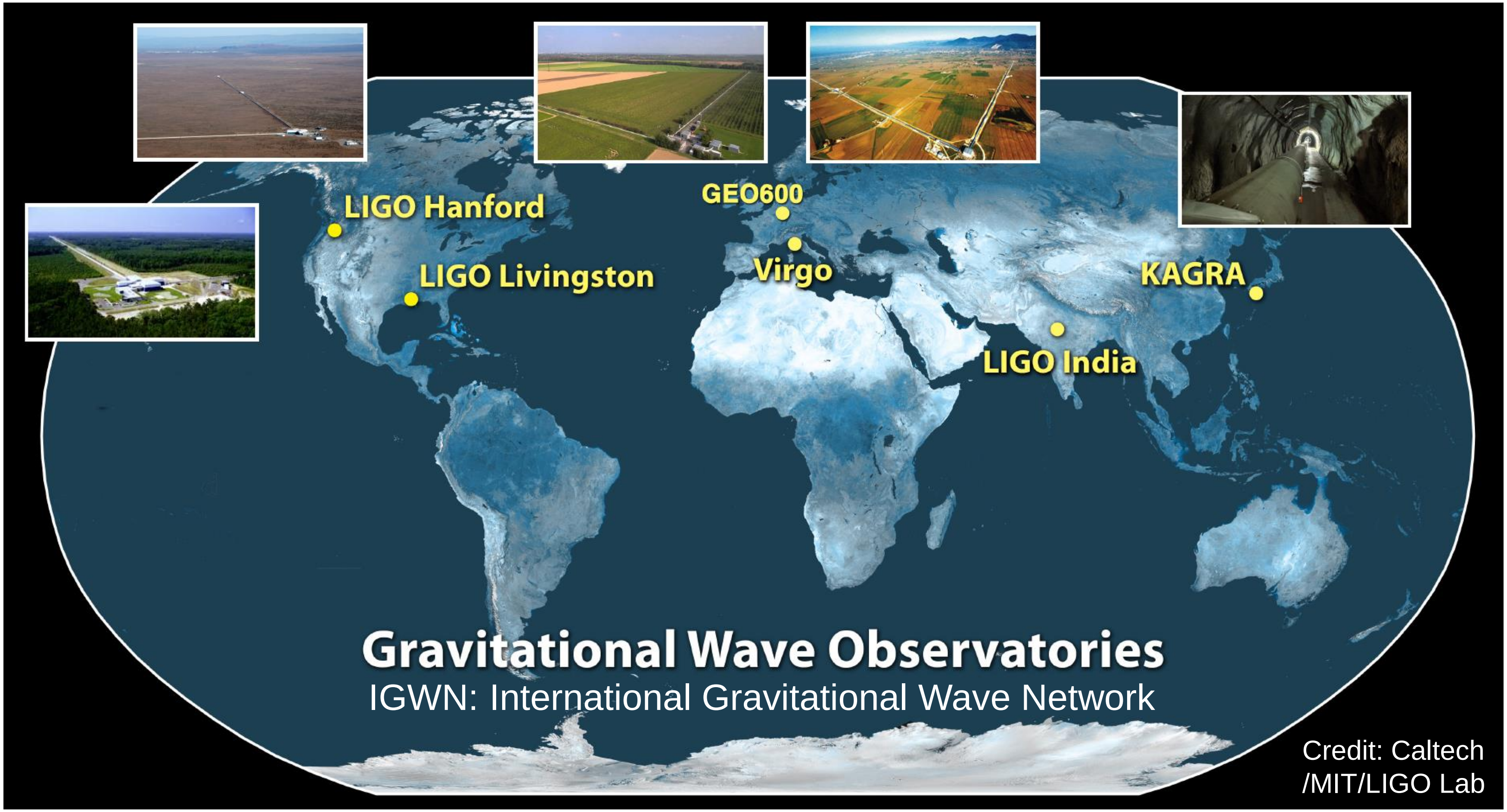
Nuclear physics
Tidal interactions between neutron stars get imprinted on gravitational waves
Access to equation of state

KAGRA joins LIGO and Virgo

LVK: LIGO Scientific, Virgo and KAGRA Collaborations

Observe together as a network of GW detectors. LVK have integrated their data analysis

LIGO and Virgo have coordinated data taking and analysis, and release joint publications
LIGO and Virgo work under an MOU already for more than a decade
KAGRA in Japan joined in February 2020



LIGO - Virgo - KAGRA observations

LIGO and Virgo coordinate science data taking. In between the observation runs, the instruments are upgraded and commissioned to achieve better sensitivity

Observing run 1

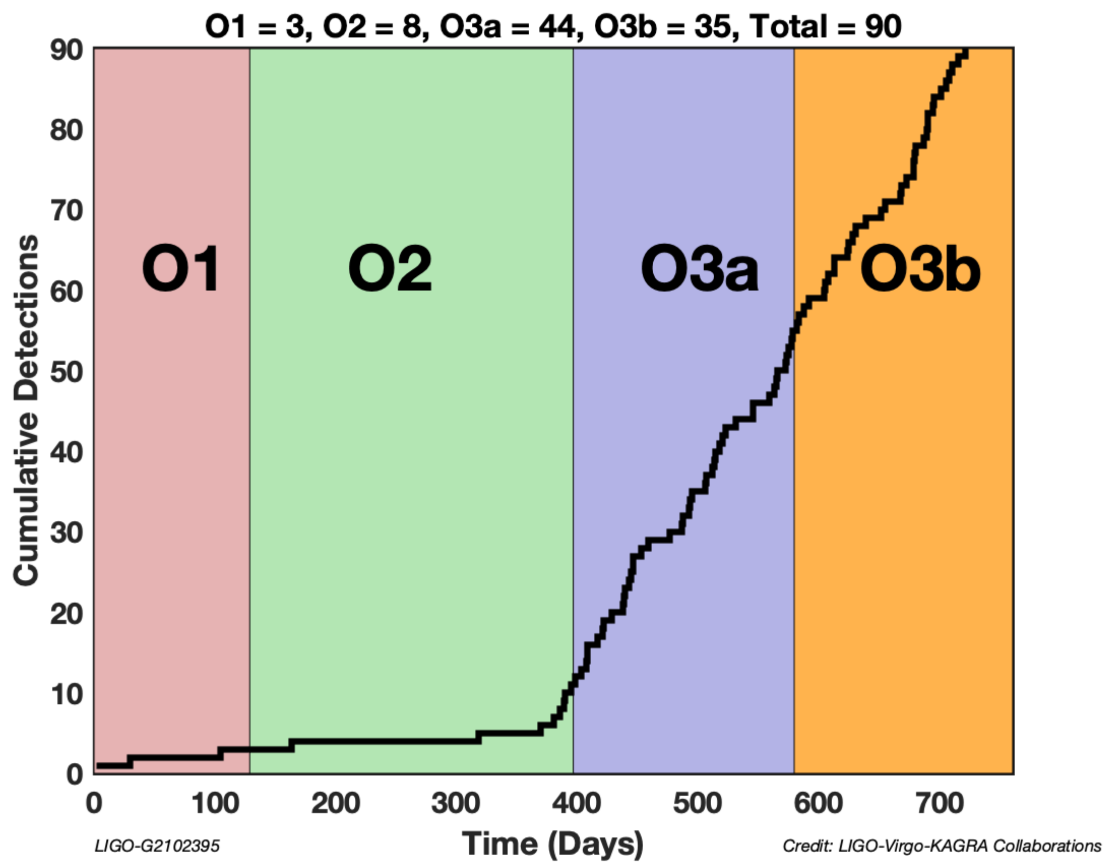
- September 2015 to January 2016
- LIGO interferometers
- Most notable: first BBH GW150914
- Every few months

Observing run 2

- November 2016 to August 2017
- LIGO + Virgo (August 2017 only) ITFs
- Most notable: first BNS GW170817

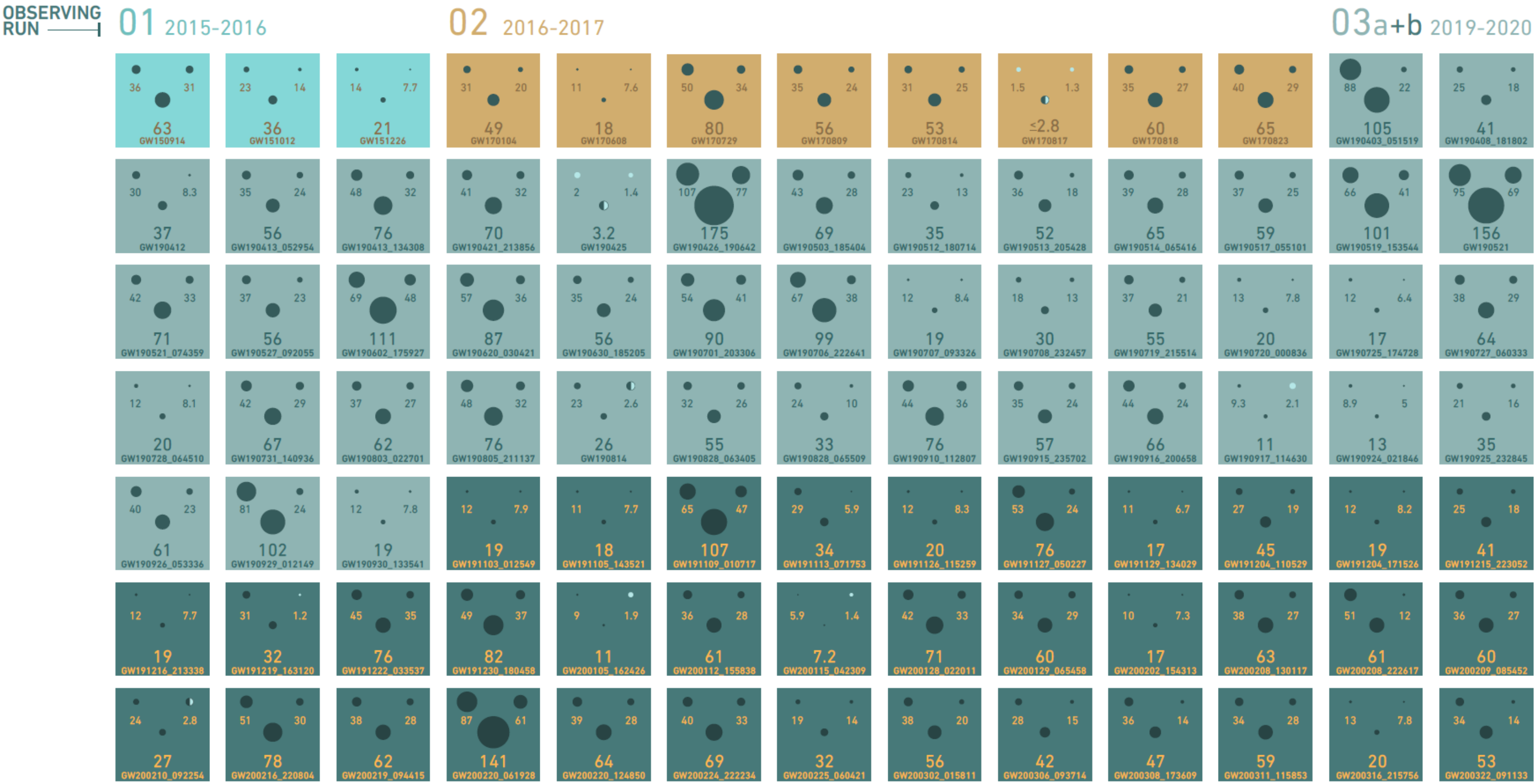
Observing run 3

- April 2019 to March 2020
- LIGO + Virgo interferometers
- O1 - O3a: 50 significant detections
  Abbott et al. Phys. Rev. X 11, 021053 (2021)
- O3b LVK Collaboration, arXiv:2111.03606v2 (2021))
- Weekly detections



Gravitational wave merger detections

SINCE 2015



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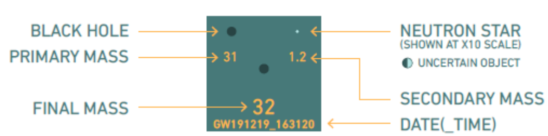


UNITS ARE SOLAR MASSES
1 SOLAR MASS = 1.989 x 10^{30}kg

Note that the mass estimates shown here do not include uncertainties, which is why the final mass is sometimes larger than the sum of the primary and secondary masses. In actuality, the final mass is smaller than the primary plus the secondary mass.

The events listed here pass one of two thresholds for detection. They either have a probability of being astrophysical of at least 50%, or they pass a false alarm rate threshold of less than 1 per 3 years.

OzGrav
ARC Centre of Excellence for Gravitational Wave Discovery

LIGO VIRGO KAGRA

Release of Open Public Alerts

LIGO and Virgo Collaborations release Open Public Alerts, with low latency, for all interesting signal triggers, and follow-up information sufficient for non-GW observers to find hosts. We also release data and data analysis software

For a quick overview of all our new papers

See our Science Summaries available in multiple languages:
https://www.ligo.org/science/outreach.php

You can also find tutorials, GW data analysis software and other tools

at our Gravitational Wave Open Science Center:
https://www.gw-openscience.org/about/

If you'd like to receive alerts about new GW detections

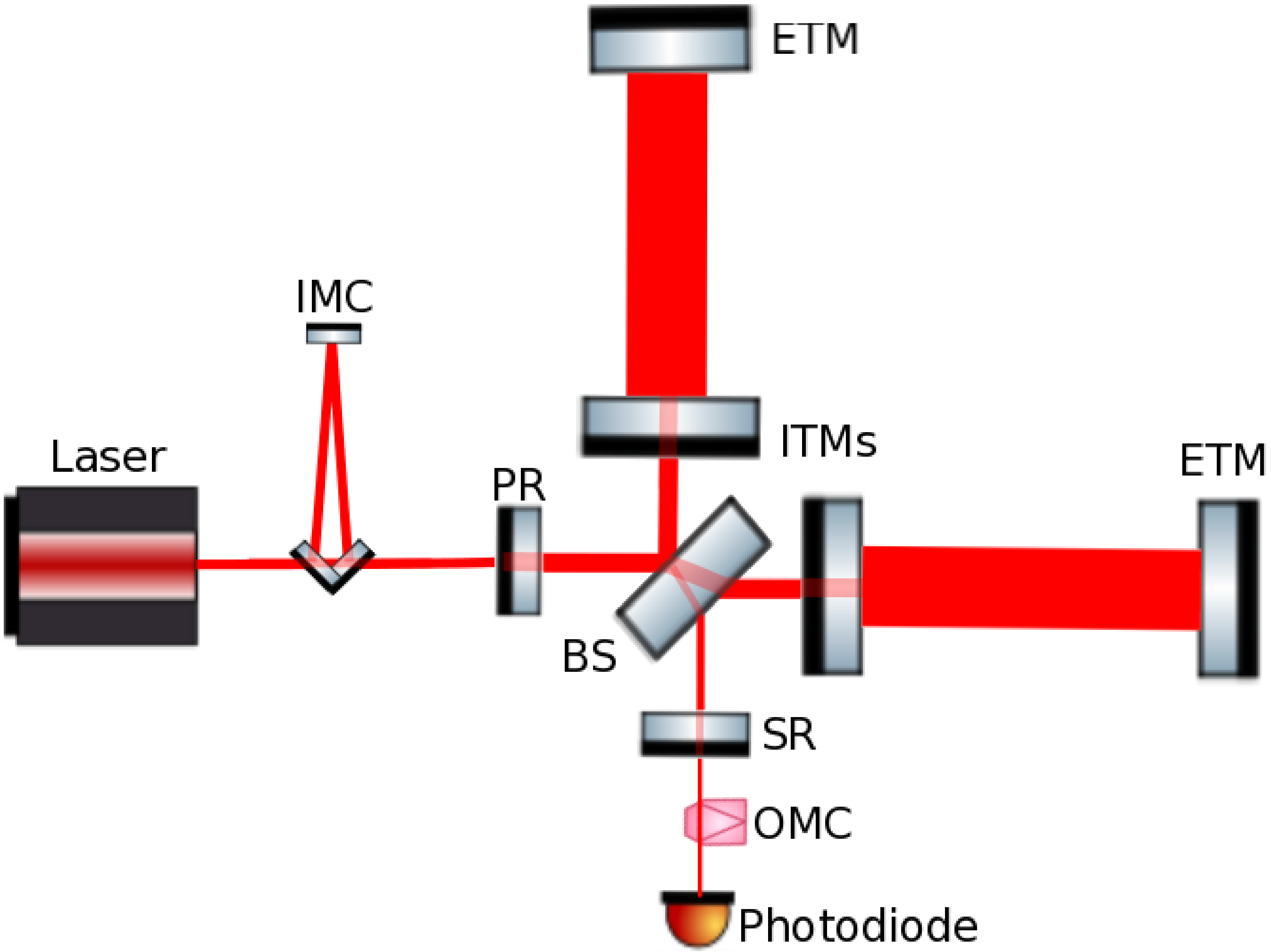
Check out our LIGO/Virgo Public Alerts User Guide:
https://emfollow.docs.ligo.org/userguide/

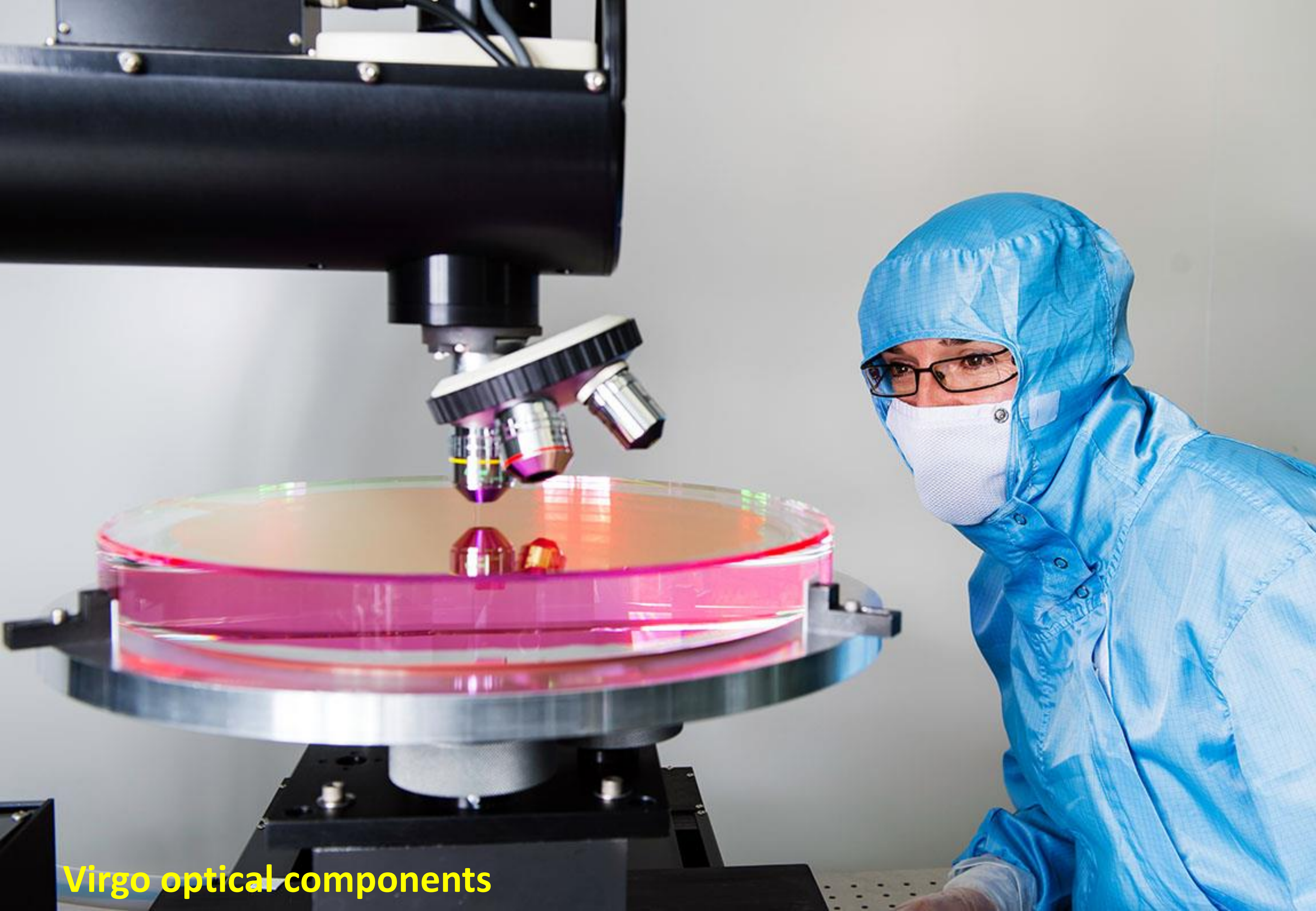
Outlook

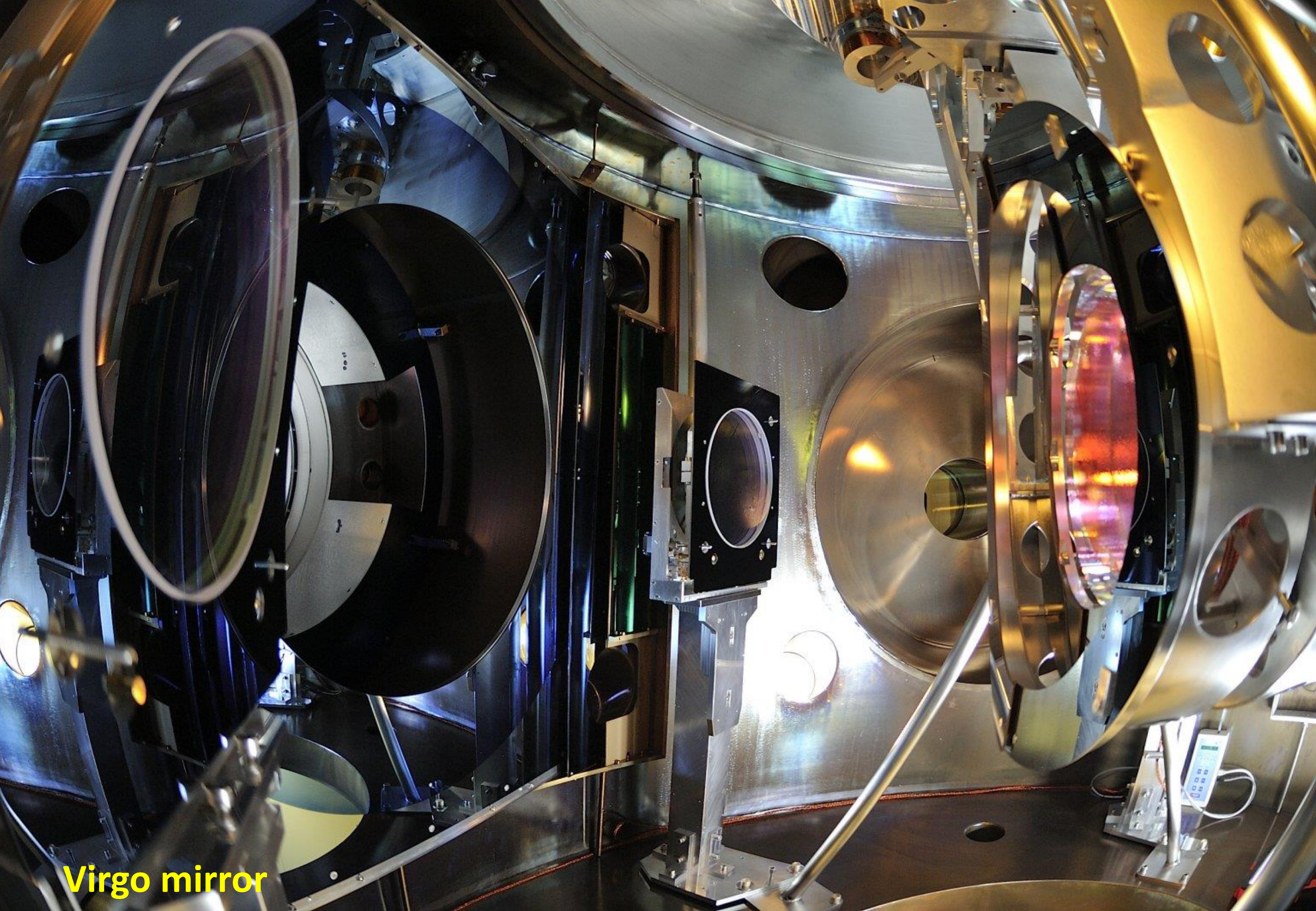
Virgo interferometer

Dual recycled Fabry-Perot interferometer

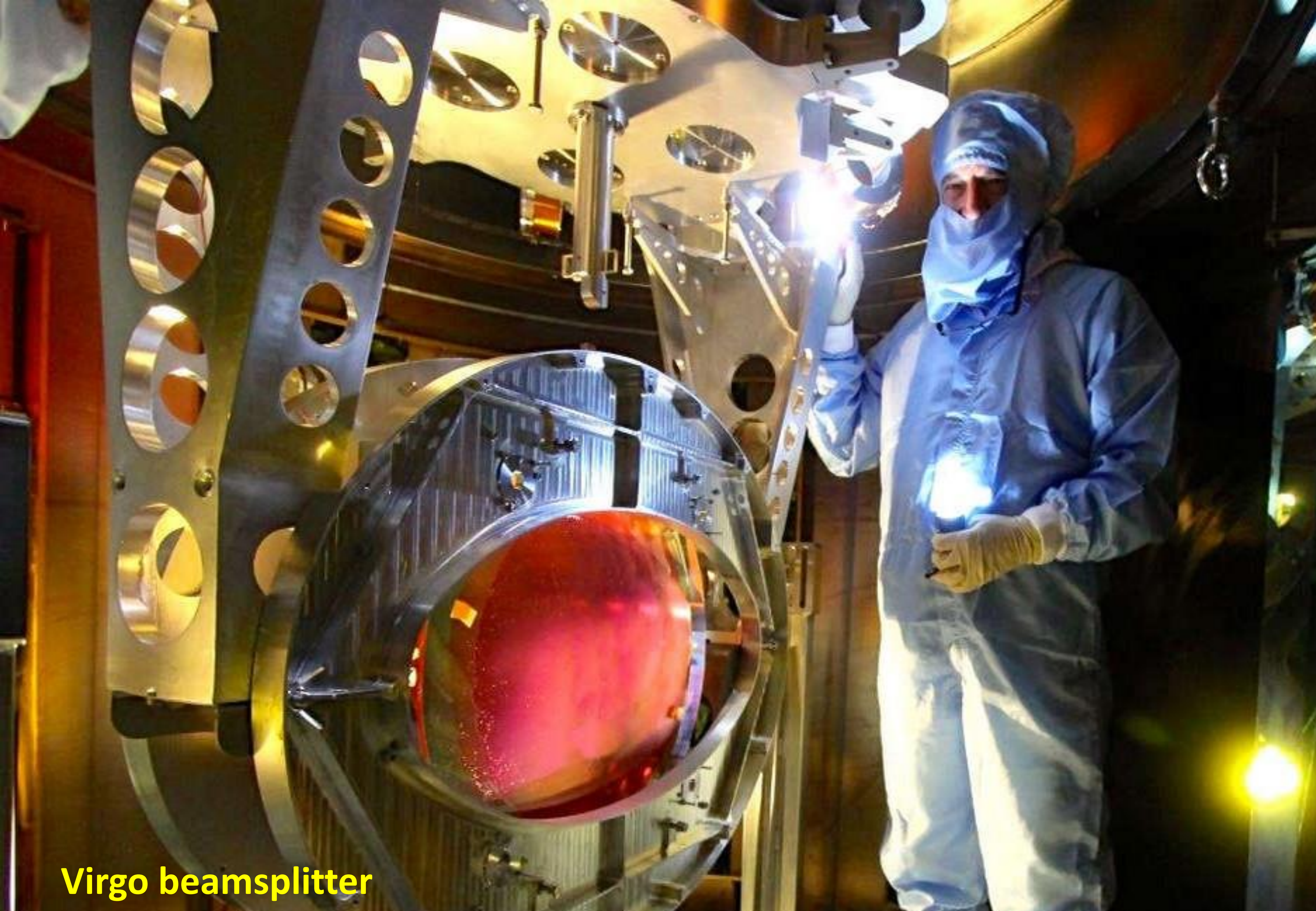
LIGO and Virgo will use dual recycled Fabry-Perot interferometers including input mode cleaner and output mode cleaner




Virgo optical components



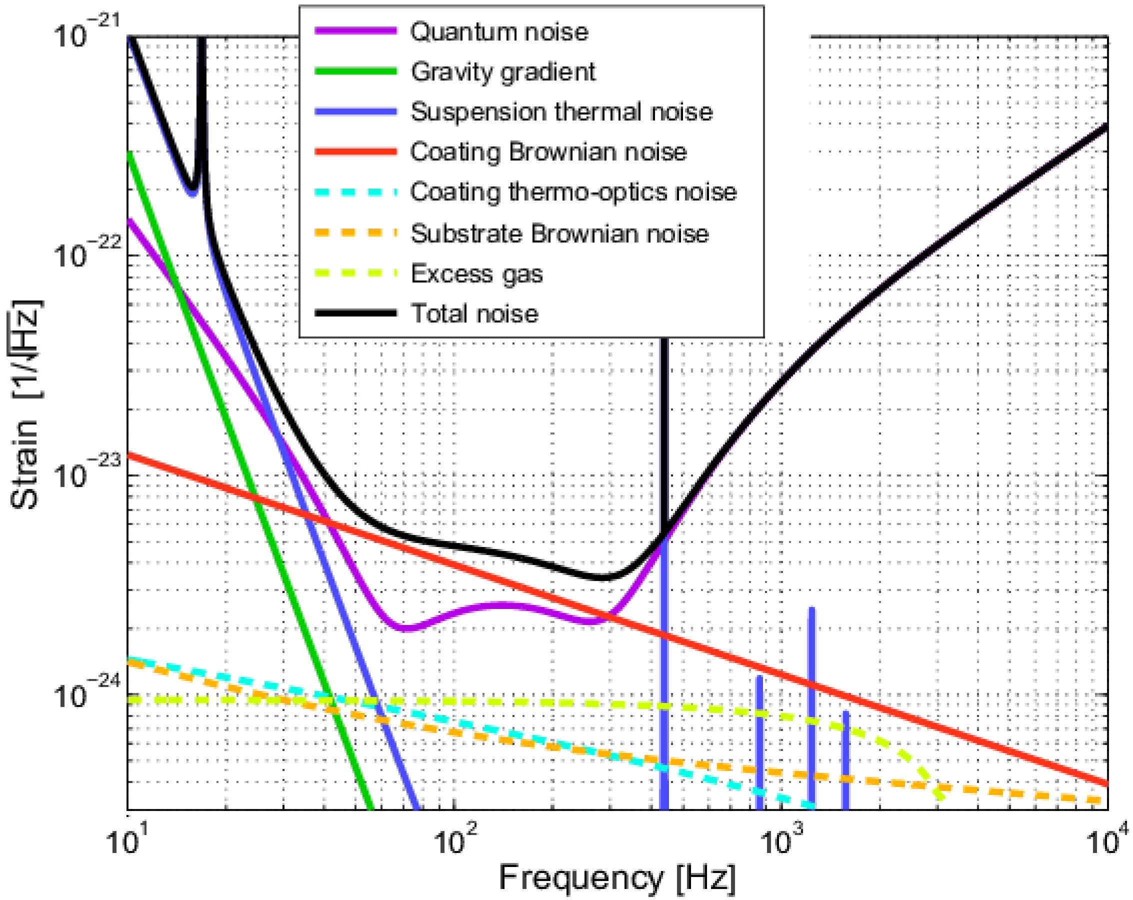
Virgo mirror



Virgo beamsplitter

Noise budget of Advanced Virgo

Solid curves show the main contributions to Virgo's sensitivity. Signal recycling and frequency dependent squeezing will be available for the next science run, O4. New optics with better coatings will be installed for run O5



AdV+ as the next step forward in Virgo sensitivity

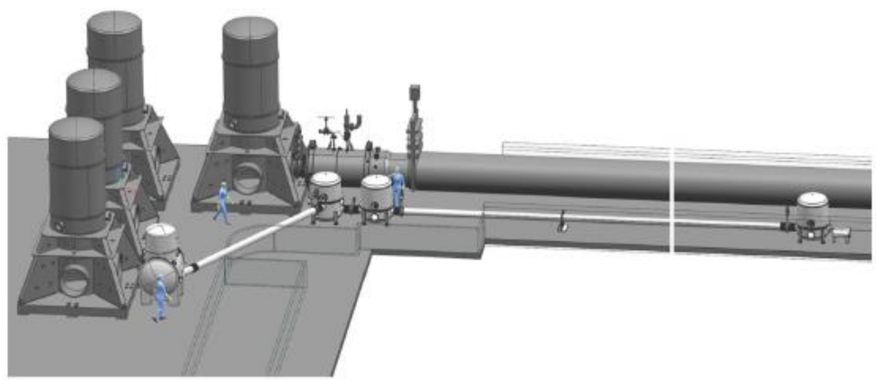
AdV+ will maximize Virgo’s sensitivity within the constrains of the EGO site. It has the potential to increase Virgo’s detection rate by up to an order of magnitude

AdV+ features

- Maximize science and secure Virgo’s scientific relevance
- Safeguard investments by scientists and funding agencies
- Implement new innovative technologies
- De-risk technologies needed for third generation observatories
- Attractive for groups wanting to enter the field

Upgrade activities: we now need to discuss Phase 2

- Tuned signal recycling and HPL: 120 Mpc
- Frequency dependent squeezing: 150 Mpc
- Newtonian noise cancellation: 160 Mpc
- Larger mirrors (105 kg): 200-230 Mpc
- Improved coatings: 260-300 Mpc



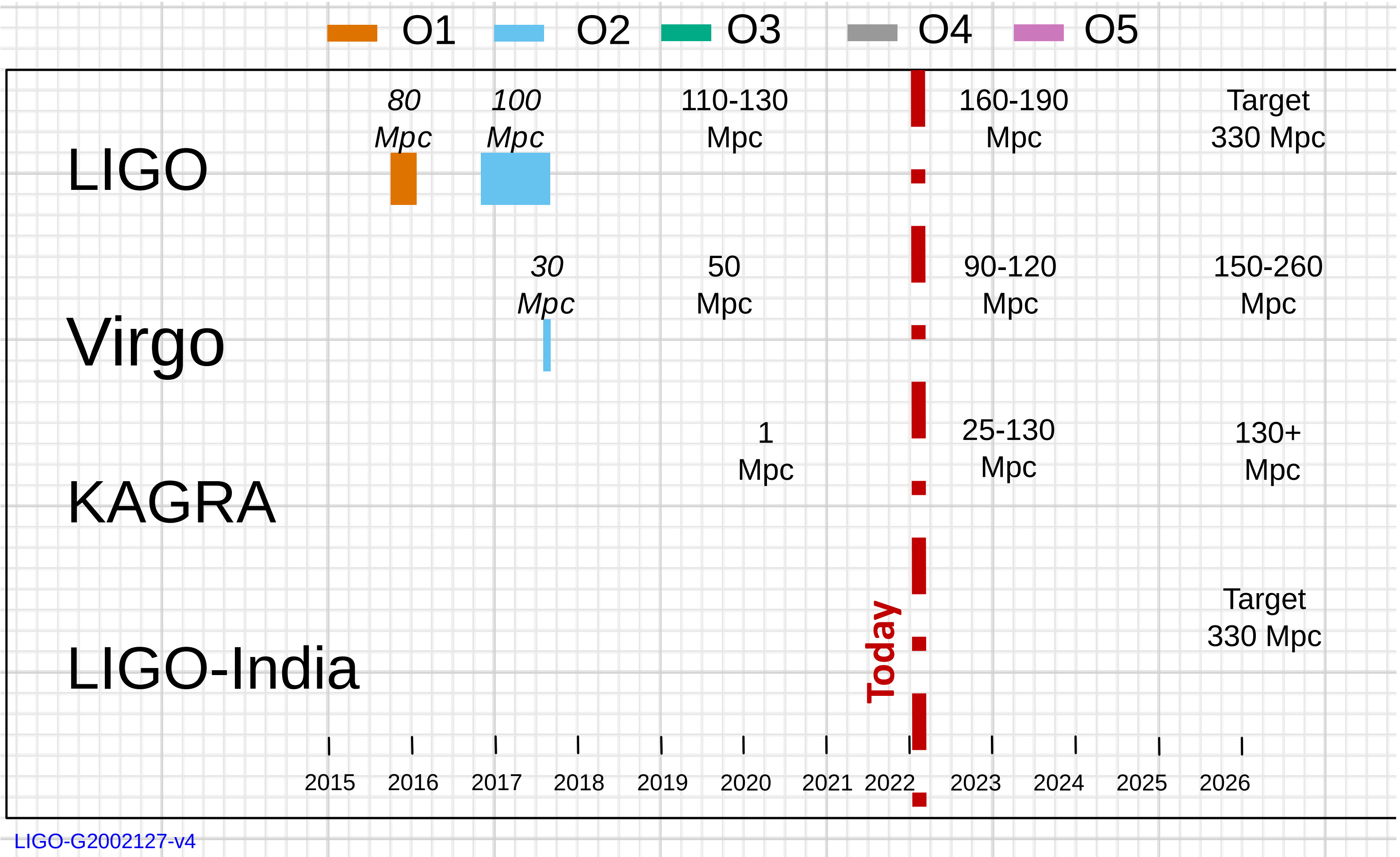
Phase 2 timeline

- Stringent time constrains due to international context: LIGO, Indigo, KAGRA

Timeline for past and future science runs

AdV+ and A+ will be carried out in two steps
This allows installation and commissioning in between O4 and O4

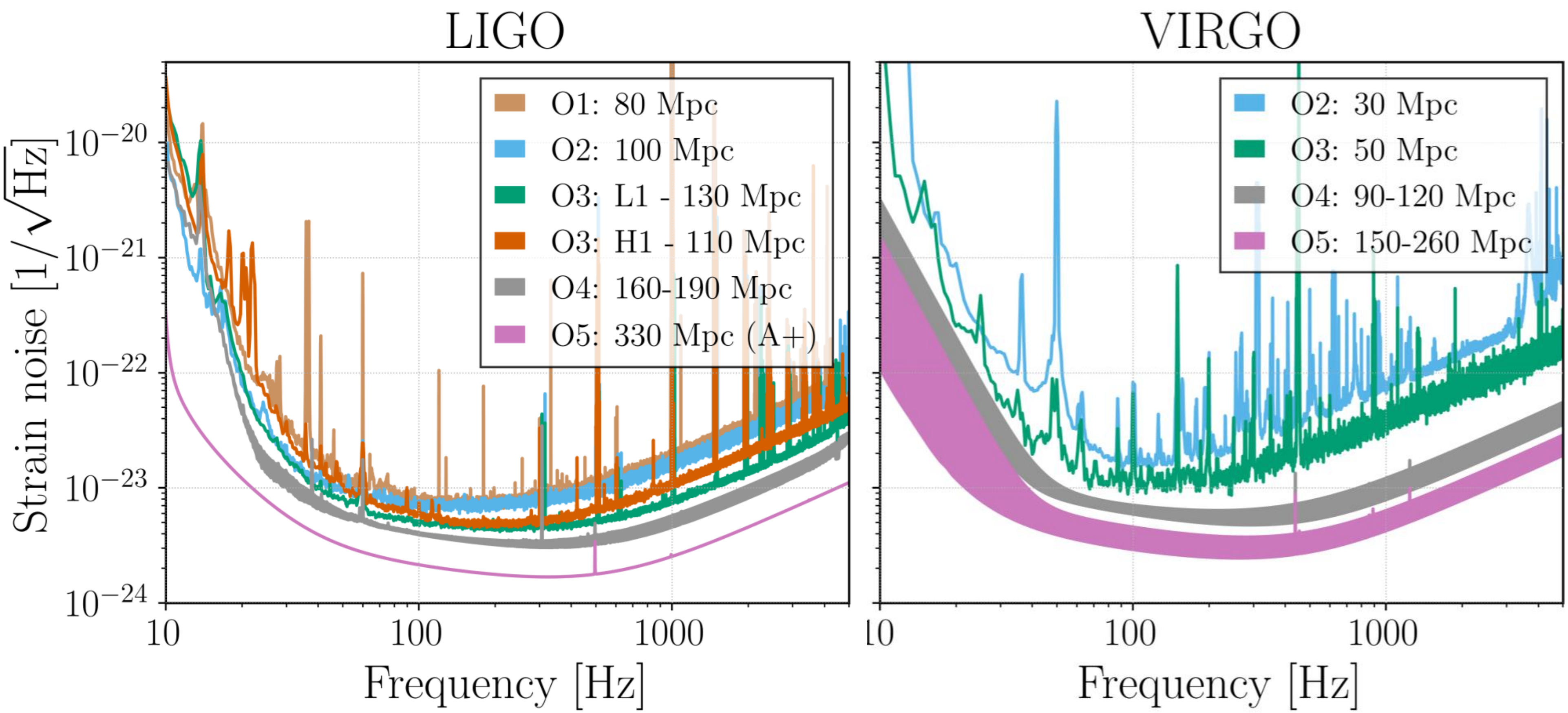
O4 is scheduled to start in second-half of 2022



LIGO-G2002127-v4

Sensitivity targets for LIGO's A+ and Virgo's AdV+

Detector noise expressed as equivalent GW strain



AdV+ phase 1

Signal recycling will be implemented after O3, higher laser power, and improved squeezing

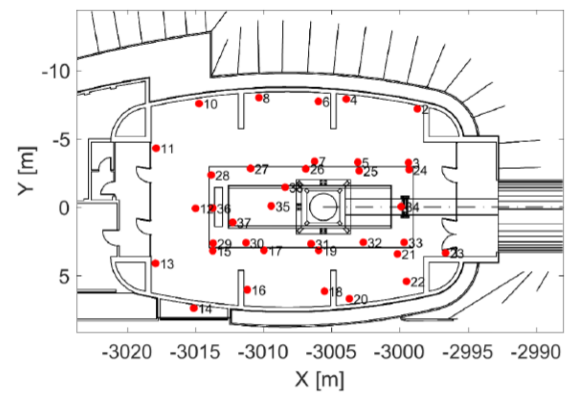
Frequency dependent squeezing

Filter cavity construction progressing

Newtonian noise cancellation

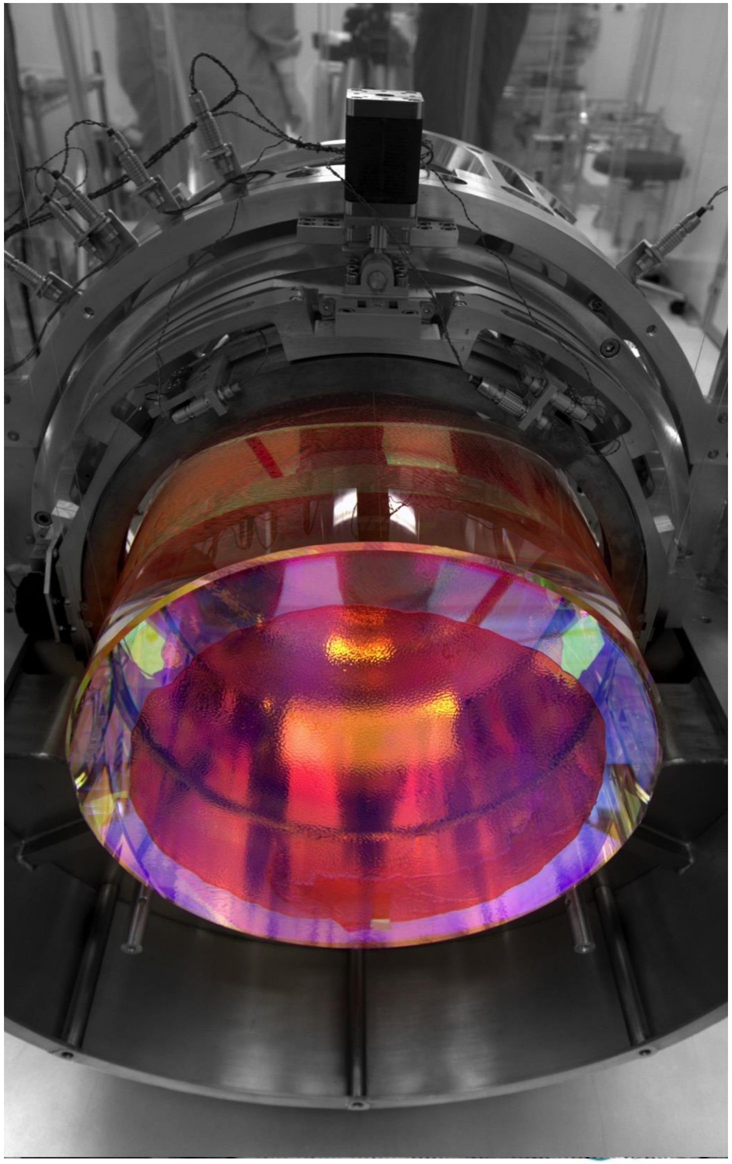
Smart sensor network (140 sensors) to monitor displacement field

Subtraction algorithms are under development



AdV+ phase 2 upgrade and extreme mirror technology

Laboratoire des Matériaux Avancés LMA at Lyon produced the coatings used on the main mirrors of the two working gravitational wave detectors: Advanced LIGO and Virgo. These coatings feature low losses, low absorption, and low scattering properties



Features

- Flatness < 0.5 nm rms over central 160 mm of mirrors by using ion beam polishing (robotic silica deposition was investigated)
- Ti:Ta_2O_5 and SiO_2 stacks with optical absorption about 0.3 ppm

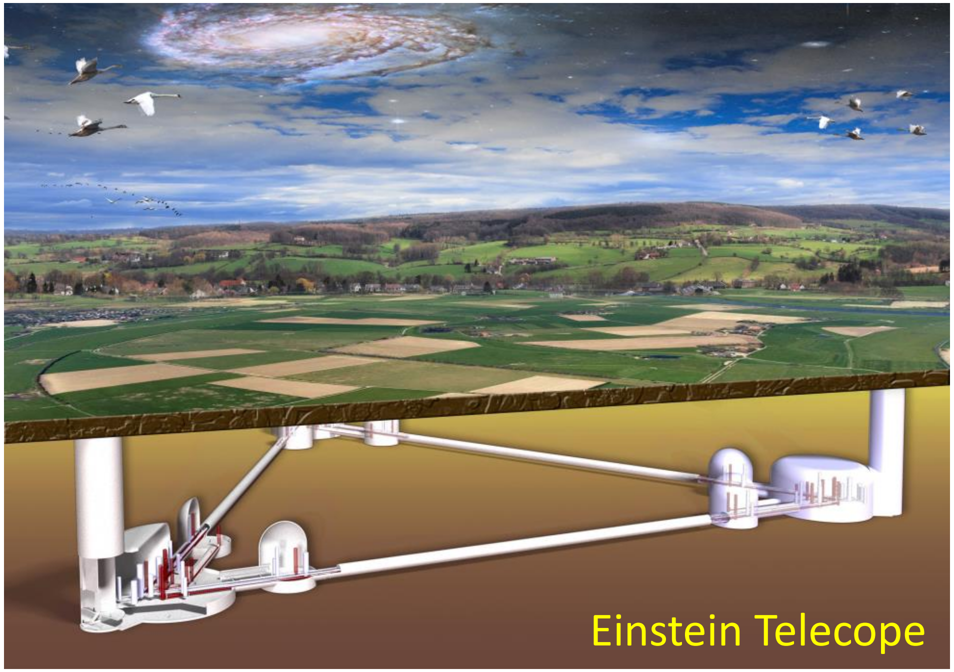
Expand LMA capabilities for next generation

LMA is the only coating group known to be capable of scaling up

Third-generation gravitational wave detectors

Third-generation gravitational wave detectors

Einstein Telescope was placed on Europe's ESFRI Roadmap on June 30, 2021
Cosmic Explorer submitted a conceptual design study to NSF in the USA



Einstein Telescope

The Einstein Telescope Consortium is composed of the institutions that signed the Consortium Agreement submitted to ESFRI (European Strategy Forum on Research Infrastructures)

ET Consortium Agreement

Agreement signed by 41 institutions

Coordinated by INFN and Nikhef

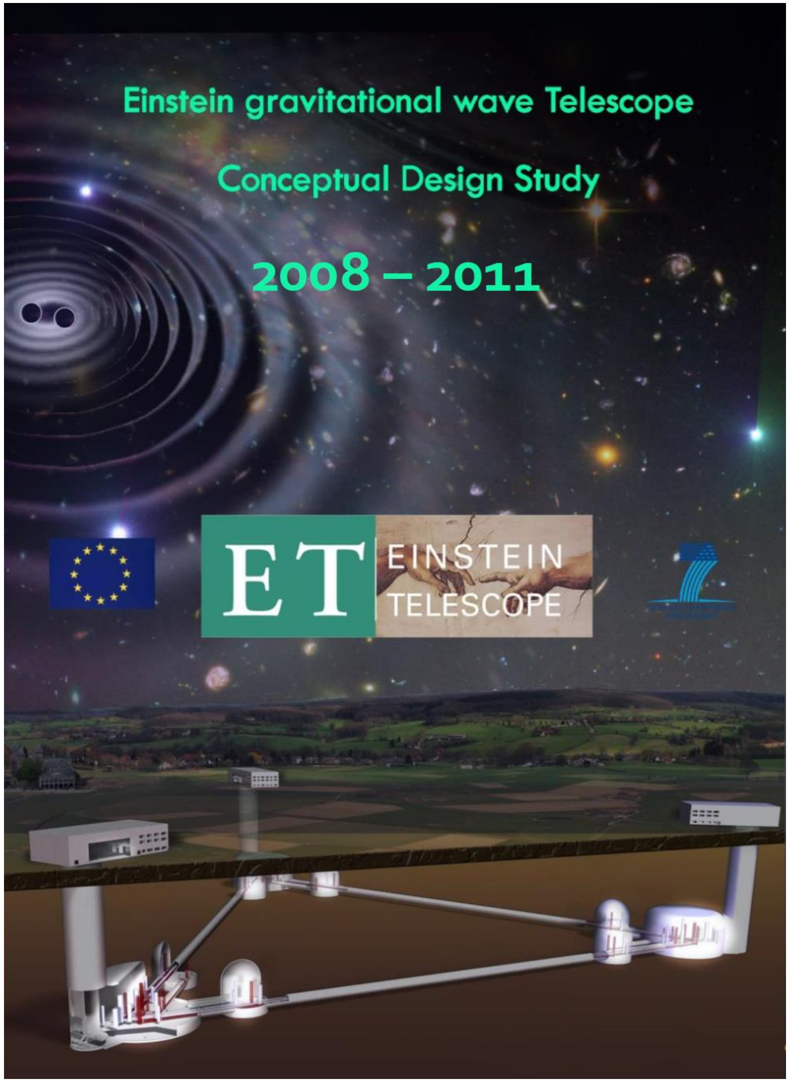
Milestones

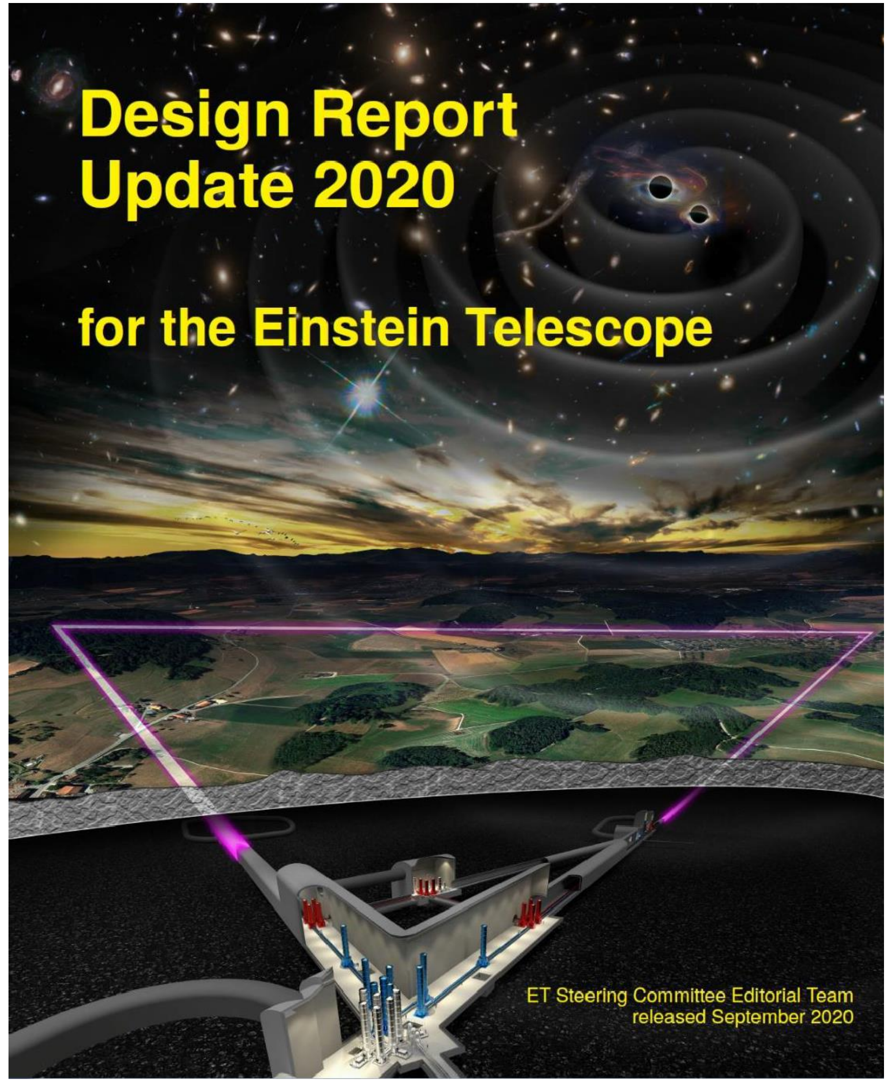
ESFRI approval: June 30, 2021

https://www.esfri.eu/latest-esfri-news/n

Einstein Telescope Design Studies

Conceptual Design Study: https://tds.virgo-gw.eu/?call_file=ET-0106C-10.pdf
Design Report Update: https://apps.et-gw.eu/tds/?content=3&r=17245

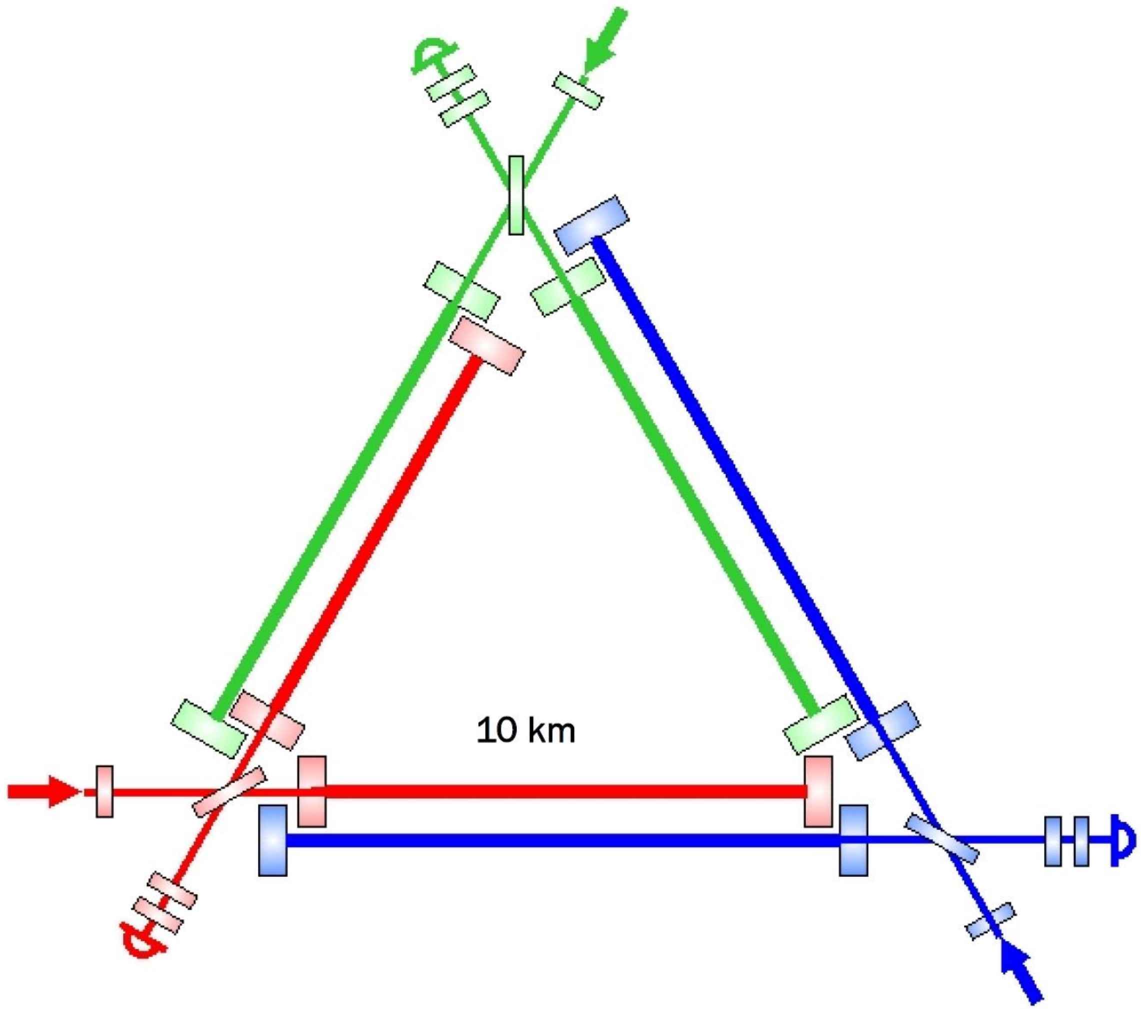




Triangular configuration

Three detectors with arm length of 10 km

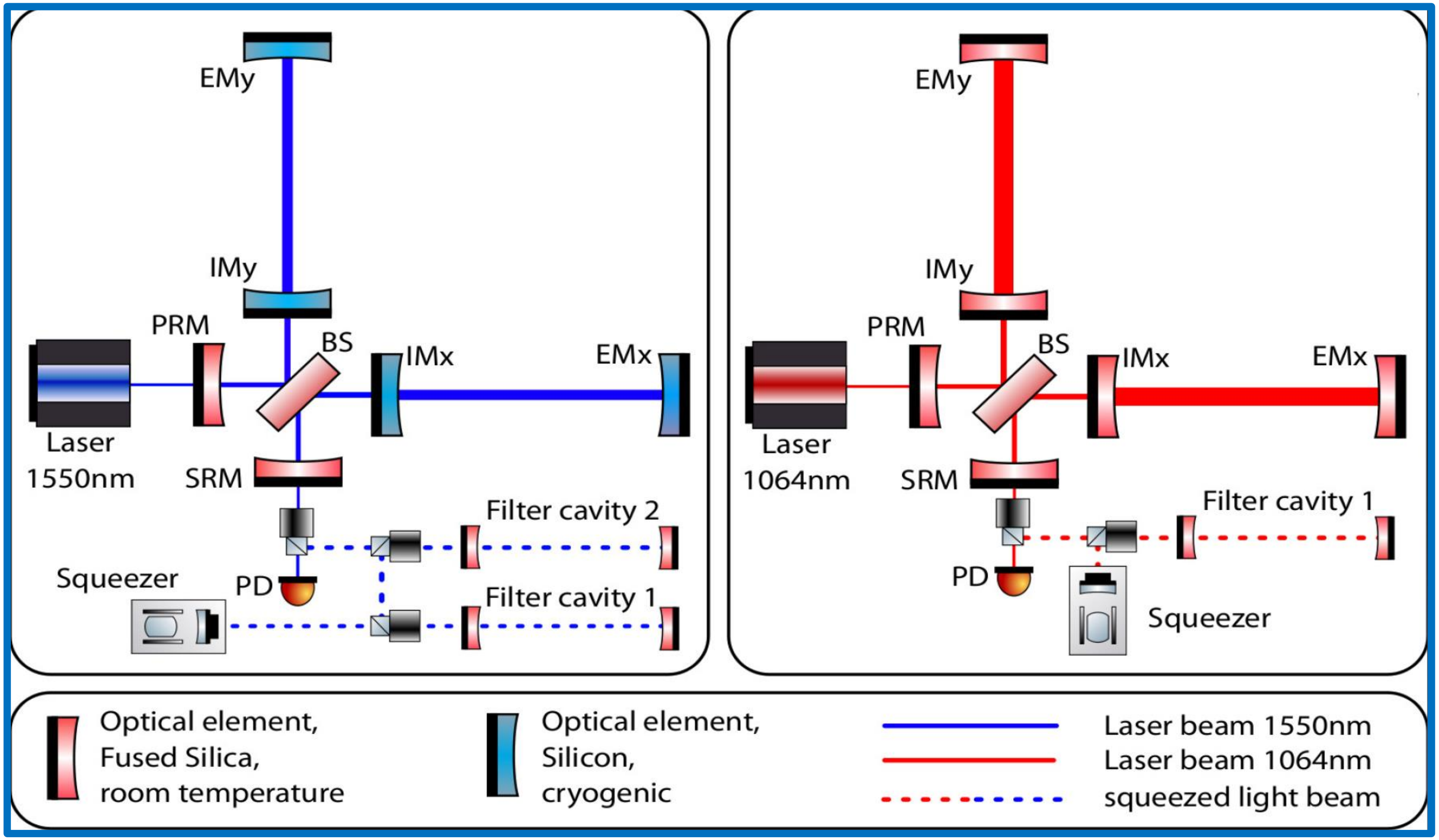
Detectors will be sited a few hundred meters underground in hard-rock



Xylophone detector design

Einstein Telescope splits the detection band over two instruments: an interferometer optimized for measuring low-frequency gravitational waves and an optimized high-frequency interferometer

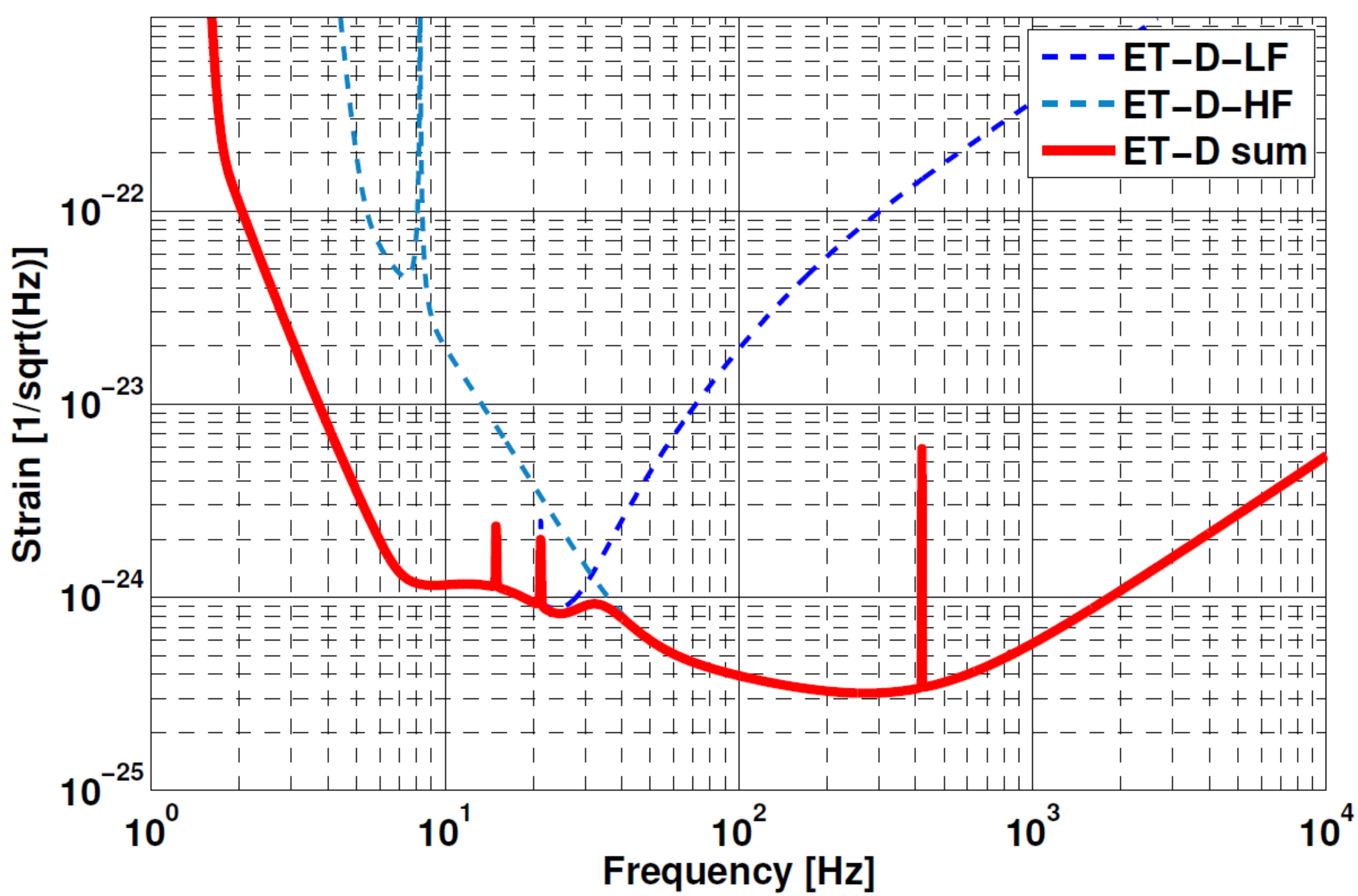
ET-LF: large cryogenic (10 - 20 K) silicon test masses, seismic suspensions, new wavelength, FDS, ..
ET-HF: high power laser, high circulating light power, thermal compensation, large test masses, FDS, ..



Einstein Telescope xylophone sensitivity

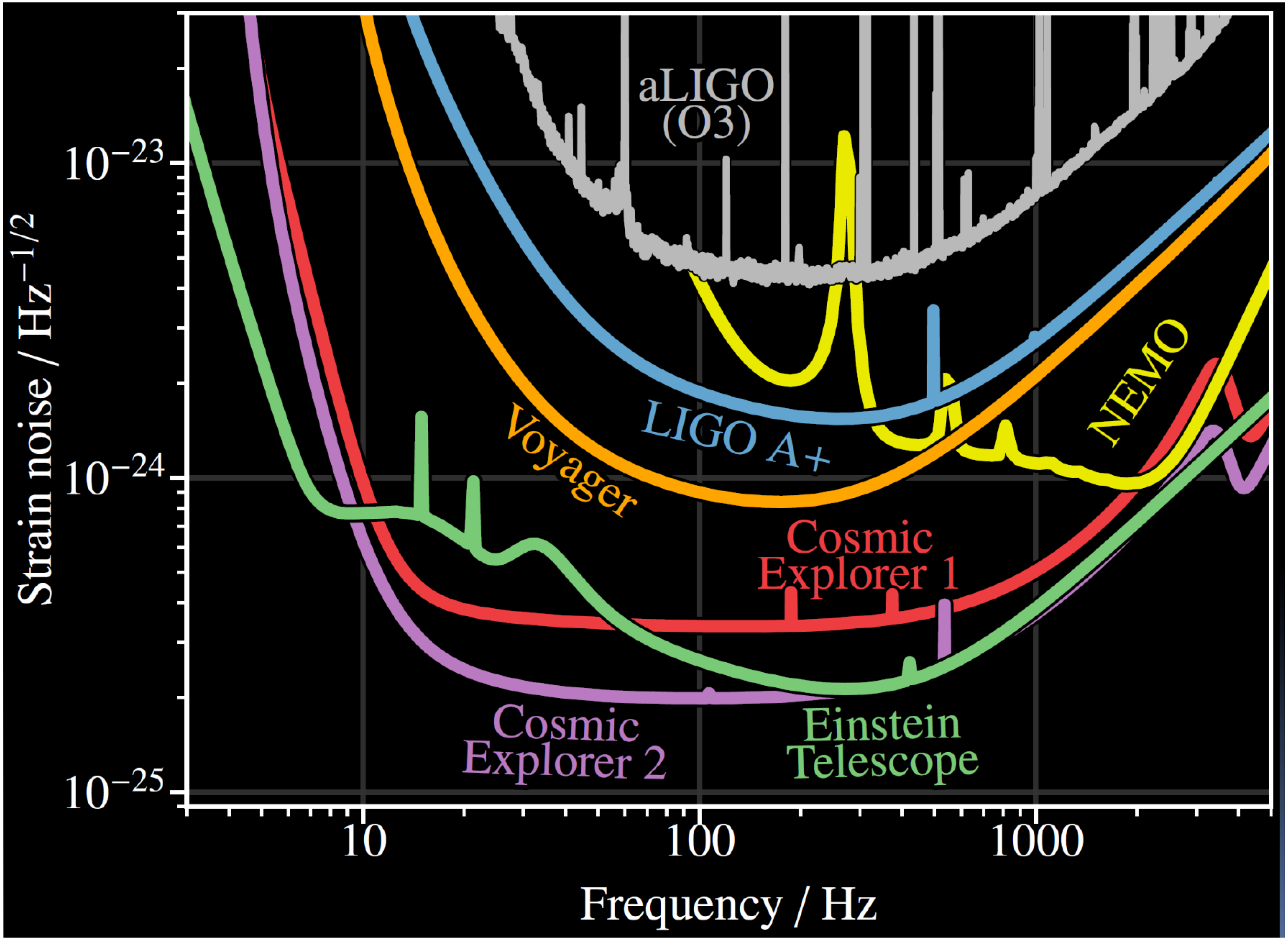
Three detectors with arm length of 10 km

Each detector consists of a low-frequency and a high-frequency interferometer
All six interferometers will be sited in hard-rock up to a few hundred meters underground



Sensitivities in the 3G era

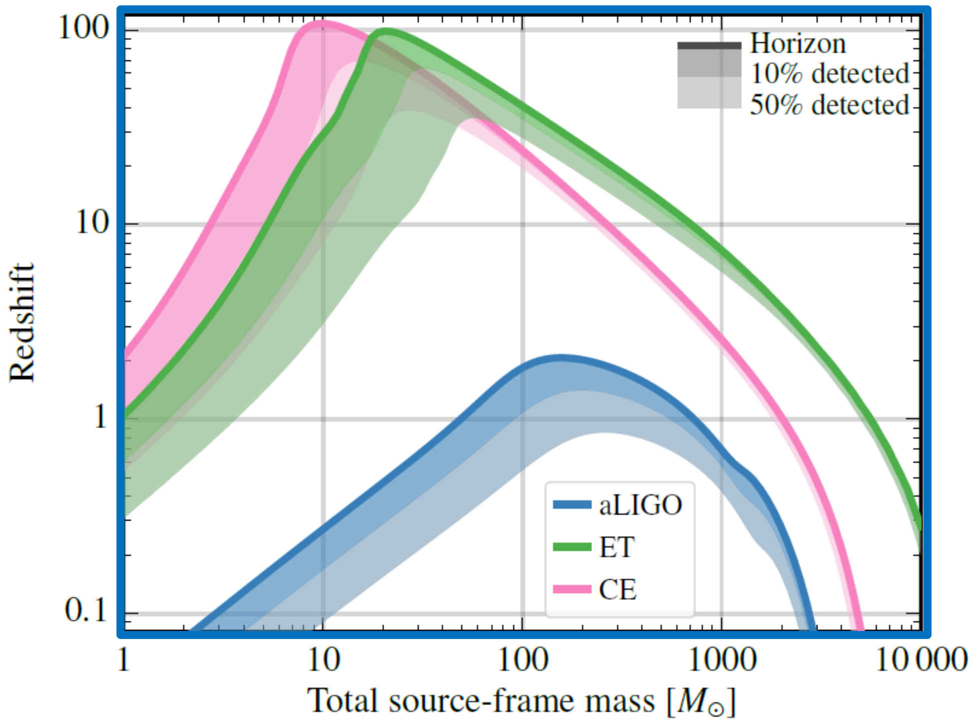
Sensitivity improvement by at least an order of magnitude compared to 2G design sensitivities



Science potential of 3G detectors

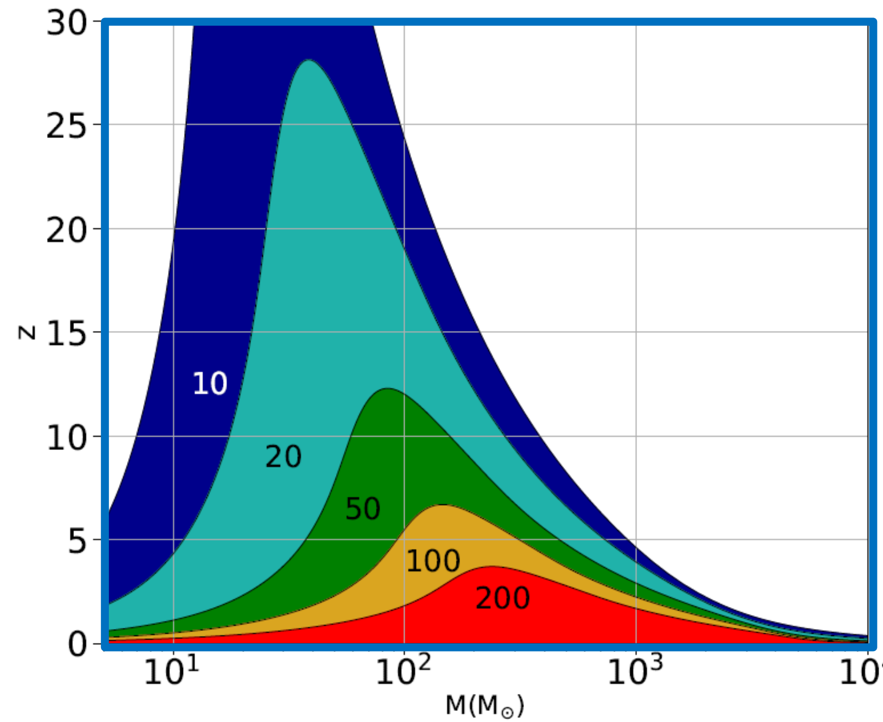
Sensitivity improvement by at least an order of magnitude compared to 2G design sensitivities

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



Credit: M. Maggiore *et al*., Science case for the Einstein Telescope, https://arxiv.org/abs/1912.02622

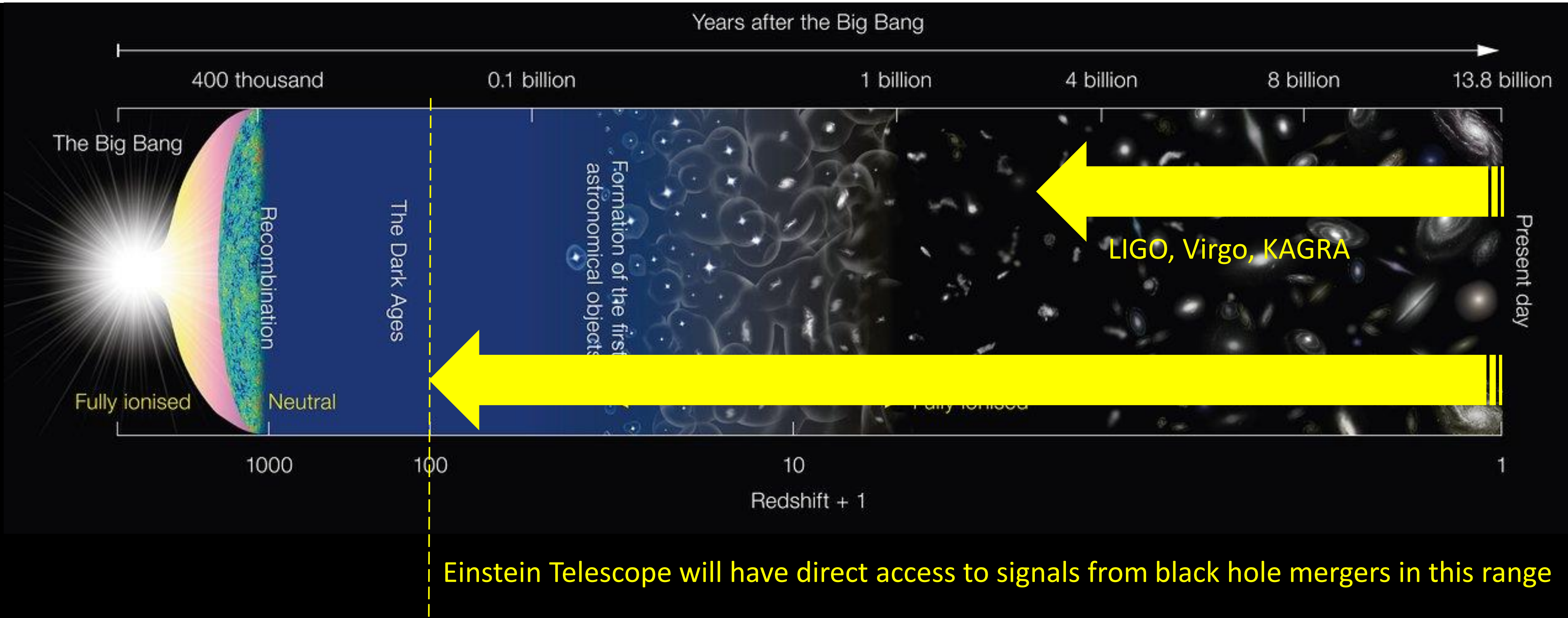
Curves of constant SNR in the (total mass, redshift) plane, for a network of one ET and two CE detectors



Credit: M. Colpi and A. Mangiagli

Detection horizon for black hole binaries

Einstein Telescope can observe BBH mergers to redshifts of about 100. This allows a new approach to cosmography. Study primordial black holes, BH from population III stars (first metal producers), *etc*.



Third-generation instruments will observe hundreds of thousands of black hole mergers per year

Many events will have signals with an SNR up to 1,000 allowing precision black hole science

Events are distributed through the entire Universe allowing cosmography

Einstein Telescope's science in a nutshell

ET will serve a vast scientific community: fundamental physics, astronomy, astrophysics, particle physics, nuclear physics and cosmology

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-band and -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 object**s
  - near-horizon physics
  - tests of no-hair theorem
  - exotic compact objects
- **Tests of General Relativity**
  - post-Newtonian expansion
  - strong field regime
- **Dark matter**
  - primordial BHs
  - axion clouds, dark matter accreting on compact objects
- **Dark energy and modifications of gravity on cosmological scales**
  - dark energy equation of state
  - modified GW propagation
- **Stochastic backgrounds of cosmological origin**
  - inflation, phase transitions, cosmic strings

Multi-messenger observatories

Einstein Telescope will operate in synergy with a new generation of innovative observatories

Einstein Telescope observatory

Bright future for gravitational wave research

LIGO and Virgo are operational. KAGRA in Japan joined in 2020, LIGO-India under construction. ESA launches LISA in 2034. Einstein Telescope on ESFRI roadmap. CE CDR financed by NSF

Gravitational wave research

- LIGO and Virgo operational
- KAGRA joined last year
- LIGO-India under construction (2025)
- ESA selects LISA, NASA rejoins
- Pulsar Timing Arrays, such as EPTA and SKA
- Cosmic Microwave Background radiation

Einstein Telescope and Cosmic Explorer

- Einstein Telescope on ESFRI roadmap (June 2021)
- Cosmic Explorer submitted CDR to NSF in USA

Next steps for 3G

- Organize the community and prepare a credible plan for EU funding agencies
- Support 3G: http://www.et-gw.eu/index.php/letter-of-intent