Gravitational wave science

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APPEC, Brussels, January 9, 2018

Towards a global GW research infrastructure

LSC and Virgo share data and do analysis jointly

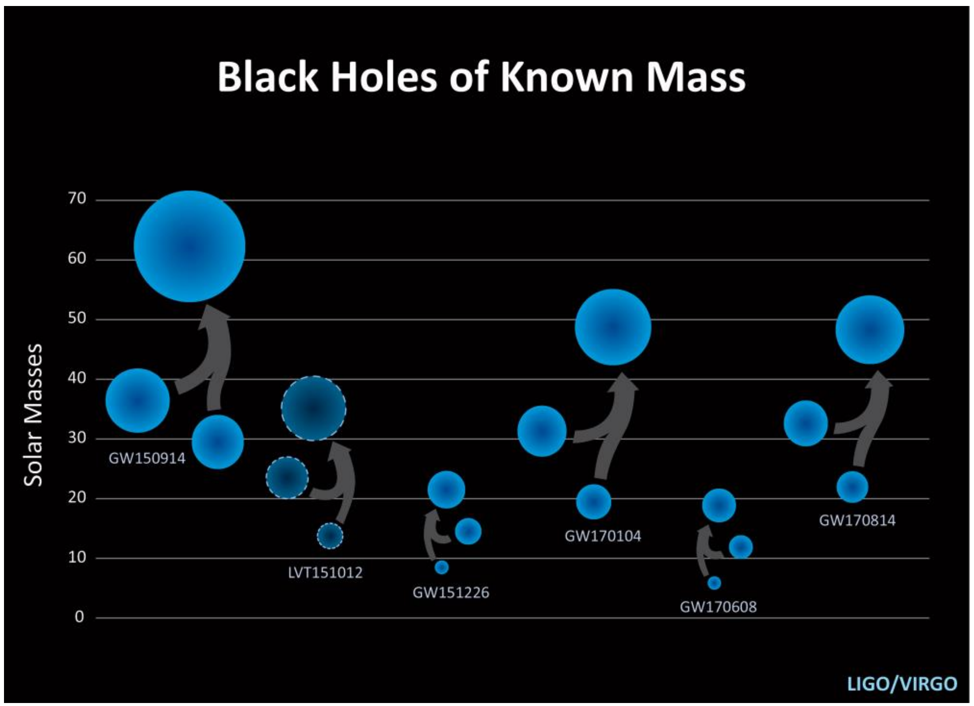
Scientific achievements: properties of black holes

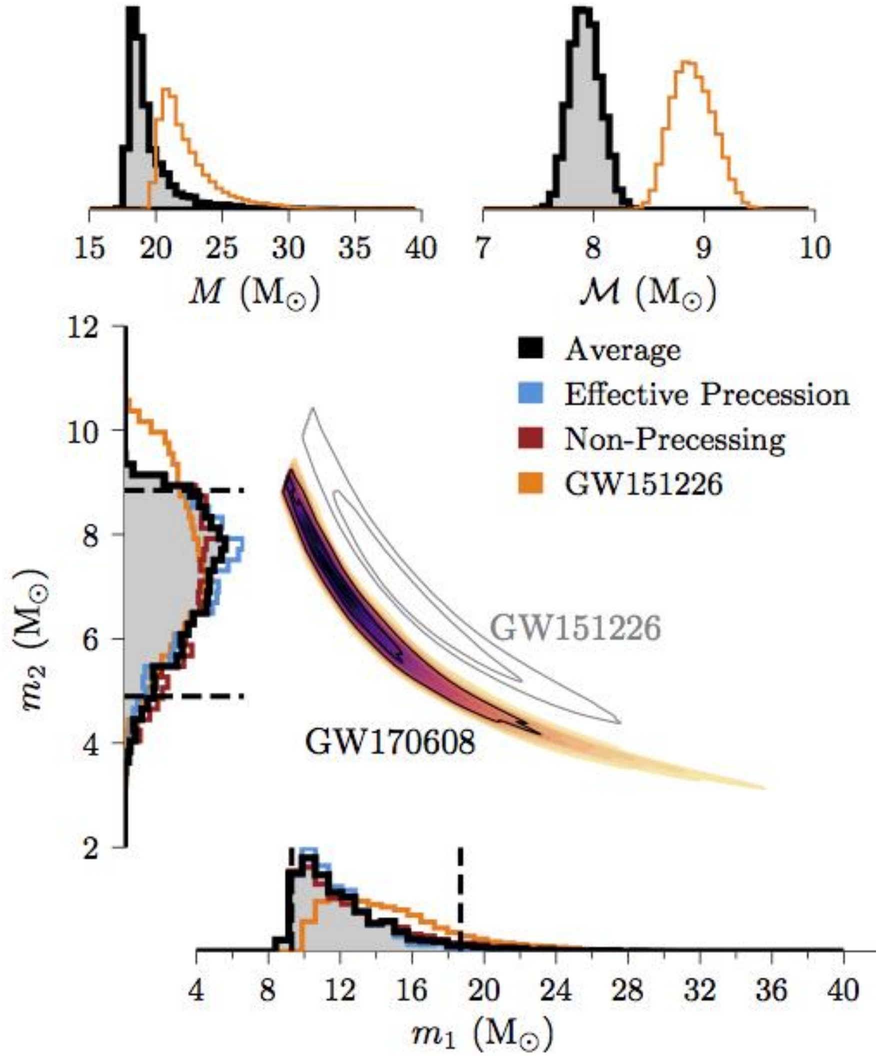
Extract information on masses, spins, energy radiated, position, distance, inclination, polarization. Population distribution may shed light on formation mechanisms

LVC reported on 6 BBH mergers

Fundamental physics, astrophysics, astronomy, and cosmology

Testing GR, waveforms (with matter)





Precision tests of GR with BBH mergers

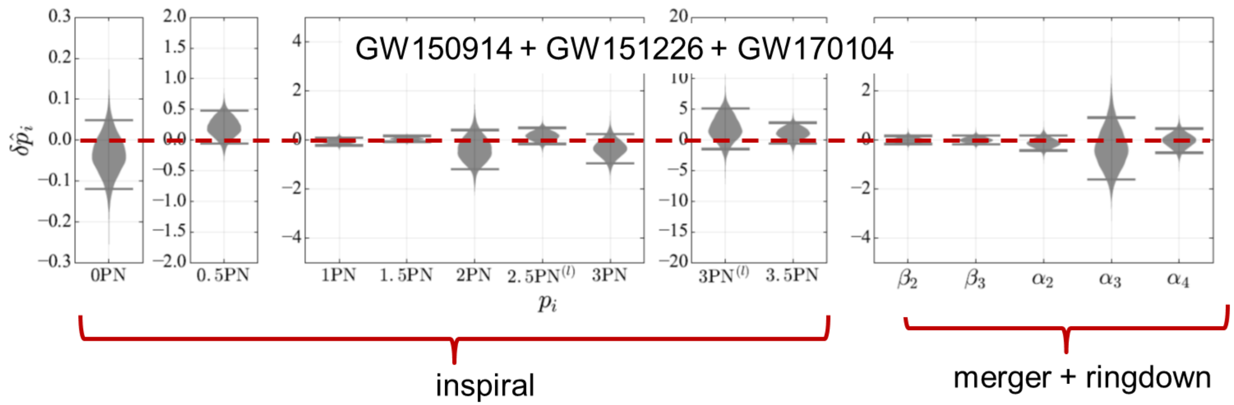
Bayesian analysis increases accuracy on parameters by combining information from multiple events

Inspiral and PN expansion

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

Merger terms: numerical GR

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



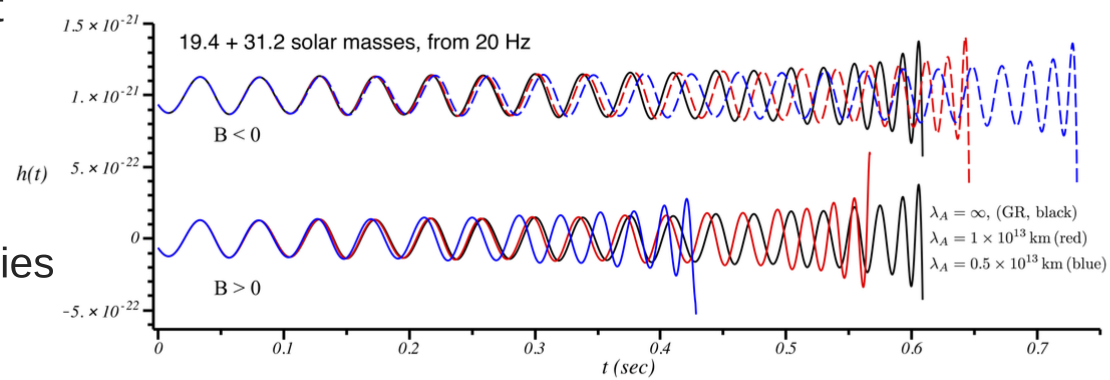
Mass of the graviton

Can be determined as $m_g \leq 10^{-22} \mathrm{eV/c^2}$

Tests of Lorentz invariance

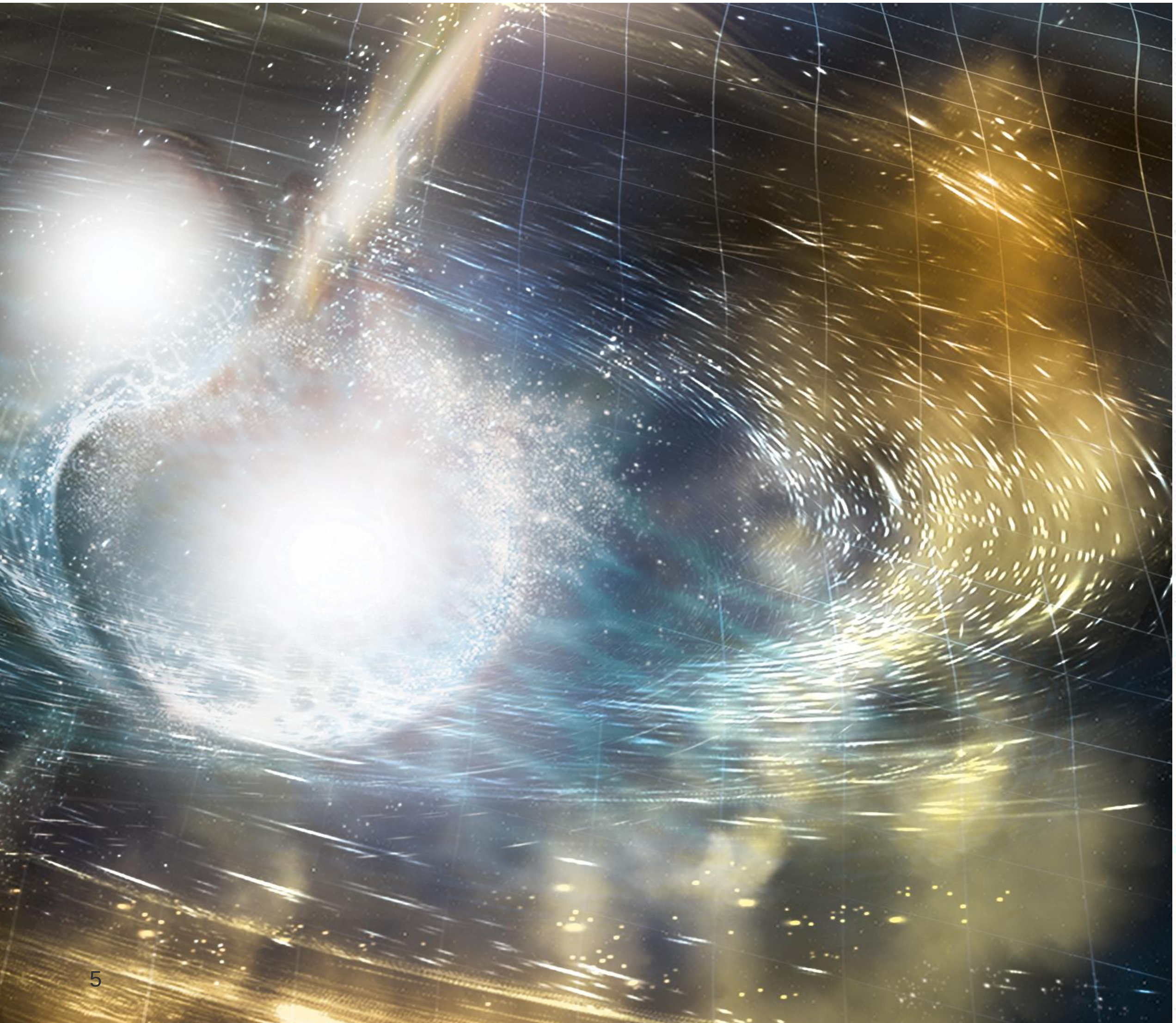
Several modified theories of gravity predict specific effects:

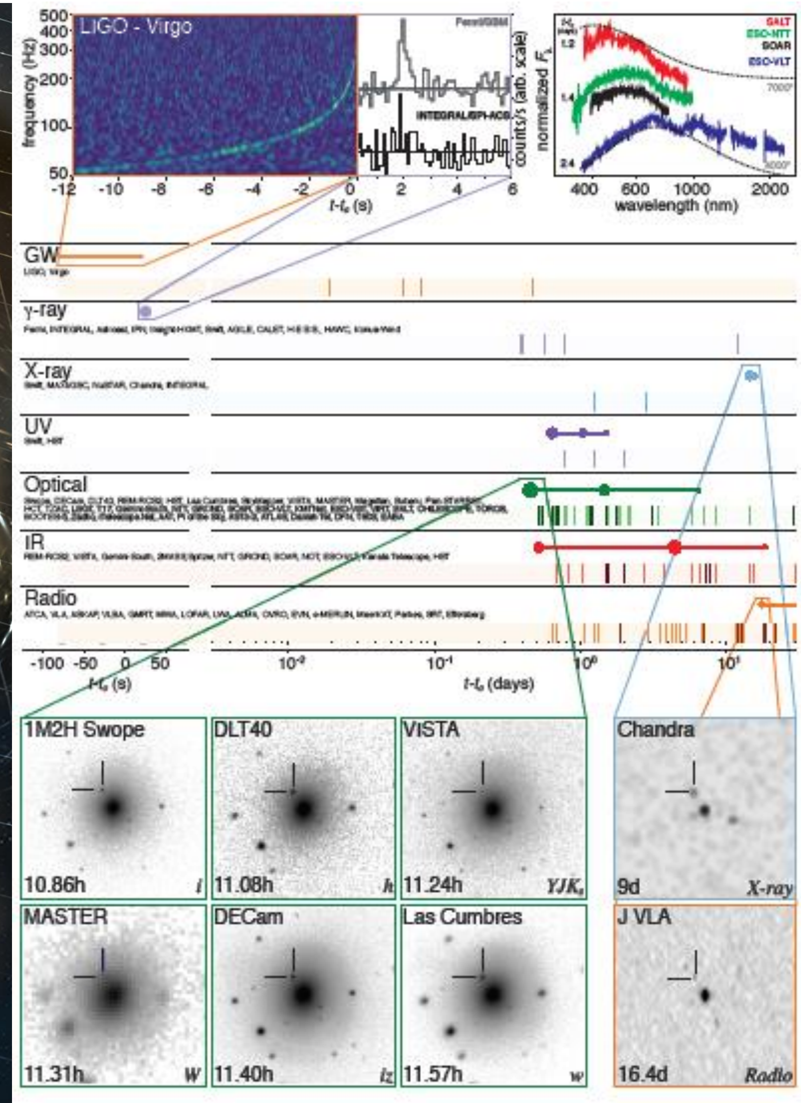
- massive-graviton theories
- multifractal spacetime
- doubly special relativity
- Horava-Lifshitz extra-dimensional theories



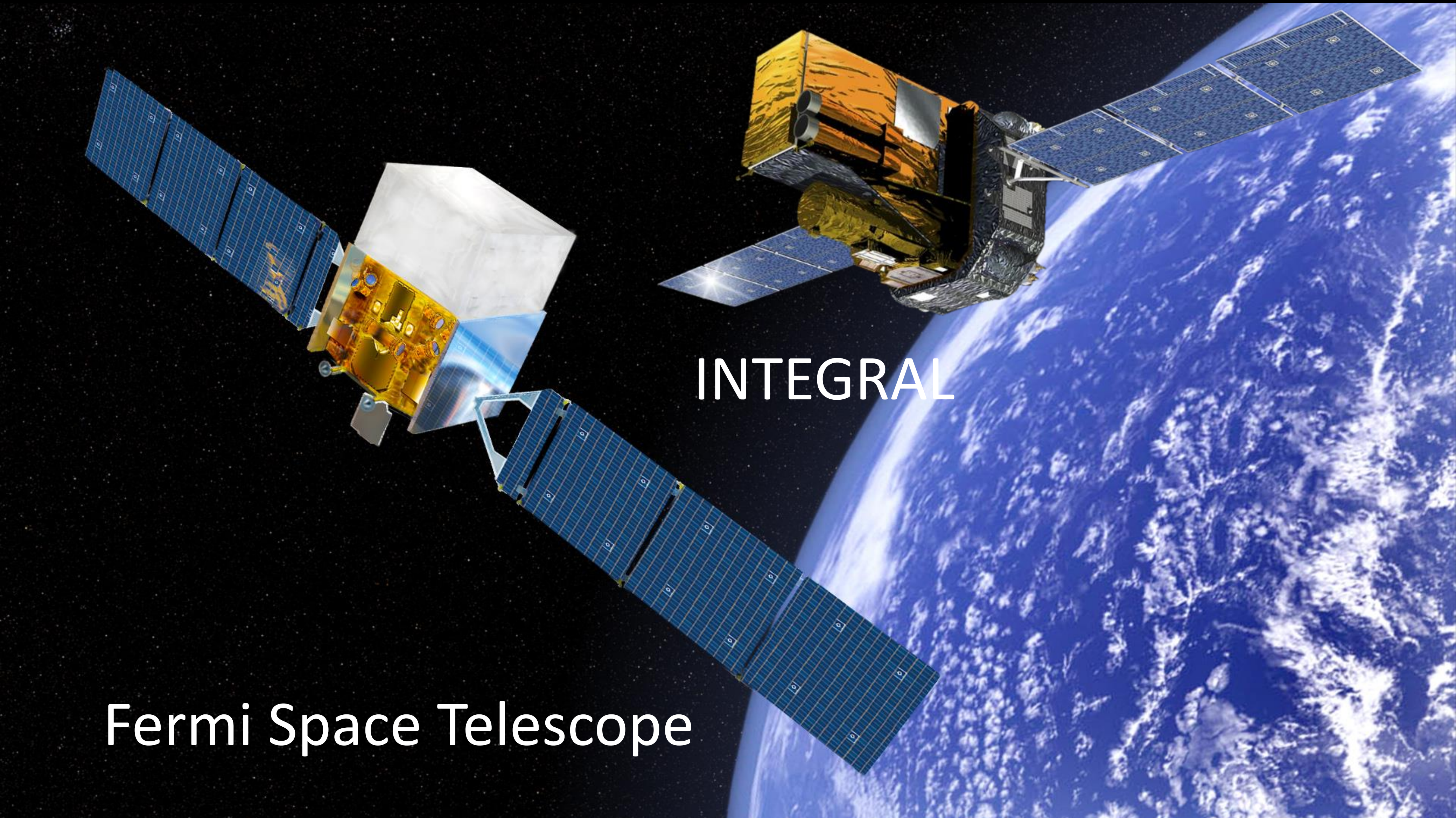
GW170817: start of multi-messenger astronomy with GW

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





Gamma rays reached Earth 1.7 seconds after GW event



Implications for fundamental physics

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

GWs and light propagation speeds

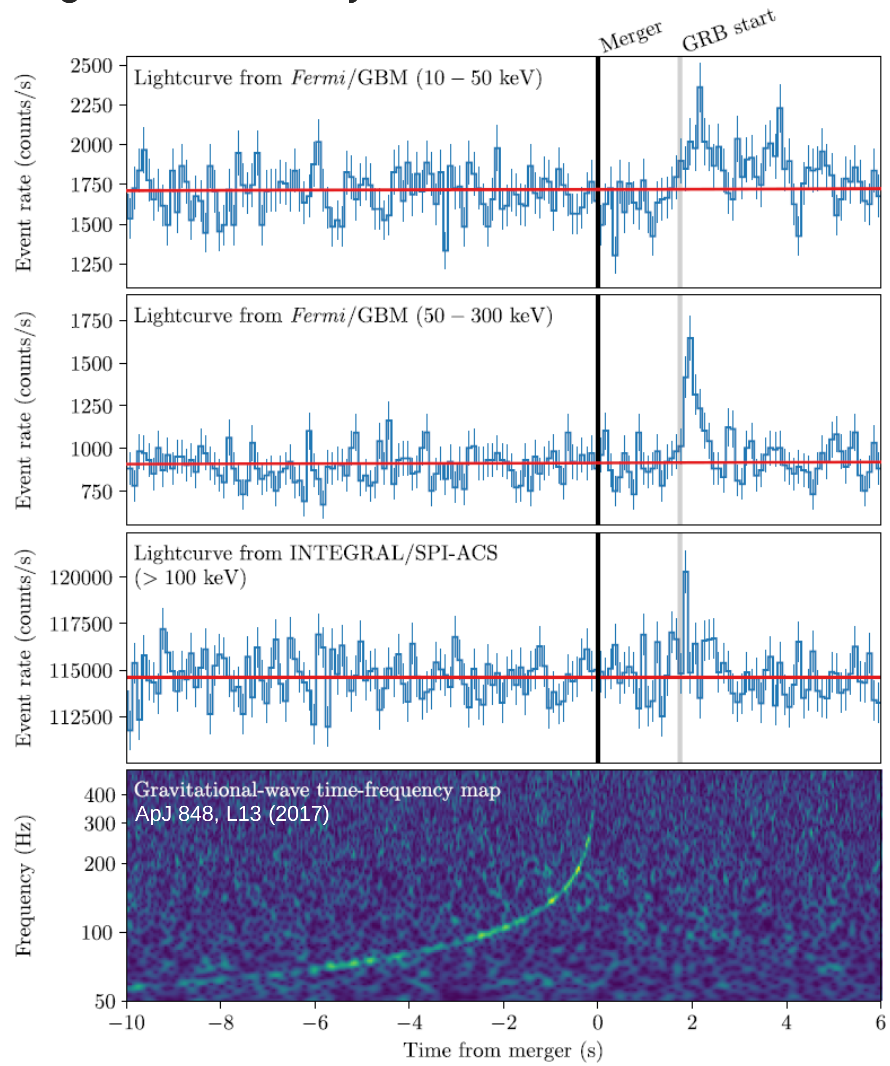
Identical speeds to about 1 part in 10^{15}

Test of Equivalence Principle

According to General Relativity, GW and EM waves are deflected and delayed by the curvature of spacetime produced by any mass (i.e. background gravitational potential). Shapiro delays affect both waves in the same manner

Milky Way potential gives same effect to within about 1 part in a million

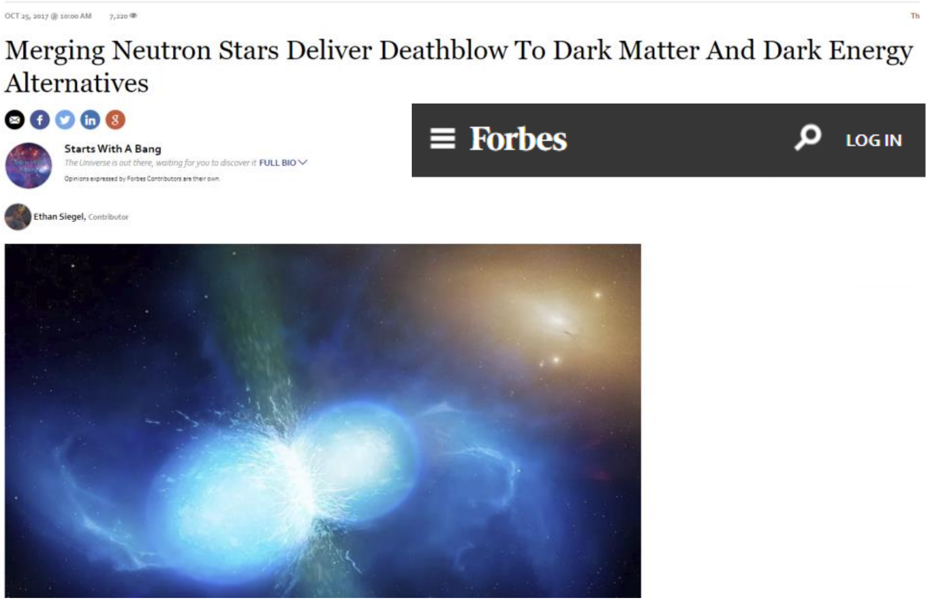
Including data on peculiar velocities to 50 Mpc: gives the same effect to within 4 parts in a billion



Advanced Virgo

Dark Energy and Dark Matter after GW170817

GW170817 had consequences for our understanding of Dark Energy and Dark Matter


OCT 25, 2017 @ 10:00 AM 7,220

Merging Neutron Stars Deliver Deathblow To Dark Matter And Dark Energy Alternatives

Forbes LOG IN

Starts With A Bang

The Universe is out there, waiting for you to discover it FULL BIO

Opinions expressed by Forbes Contributors are their own.

Ethan Siegel, Contributor

GW170817 falsifies Dark Matter Emulators

No-dark-matter modified gravity theories like TeVeS or MoG/Scalar-Tensor-Vector ideas have the property that GW propagate on different geodesics (normal matter) from those followed by photons and neutrinos (effective mass to emulate dark matter)

This would give a difference in arrival times between photons and gravitational waves by approximately 800 days, instead of the 1.7 seconds observed (arXiv:1710.06168v1)

Dark Energy after GW170817

Adding a scalar field to a tensor theory of gravity, yields two generic effects:

1. There's generally a *tensor speed excess* term, which modifies (increases) the propagation speed of GW
2. The scale of the effective Planck mass changes over cosmic times, which alters the damping of the gravitational wave signal as the Universe expands

Simultaneous detection of GW and EM signals rules out a class of modified gravity theories (arXiv:1710.05901v2)

A large class of scalar-tensor theories and DE models are highly disfavored, e.g. covariant Galileon, but also other gravity theories predicting varying cg such as Einstein-Aether, Horava gravity, Generalized Proca, TeVeS and other MOND-like gravities

	$c_g = c$	$c_g \neq c$
Horndeski	General Relativity quintessence/k-essence [46] Brans-Dicke/$f(R)$ [47, 48] Kinetic Gravity Braiding [50]	quartic/quintic Galileons [13, 14] Fab Four [15] de Sitter Horndeski [49] $G_{\mu\nu}\phi^\mu\phi^\nu$ [51], $f(\phi)$·Gauss-Bonnet [52]
beyond H.	Derivative Conformal (19) [17] Disformal Tuning (21) quadratic DHOST with $A_1 = 0$	quartic/quintic GLPV [18] quadratic DHOST [20] with $A_1 \neq 0$ cubic DHOST [23]
	Viable after GW170817	Non-viable after GW170817

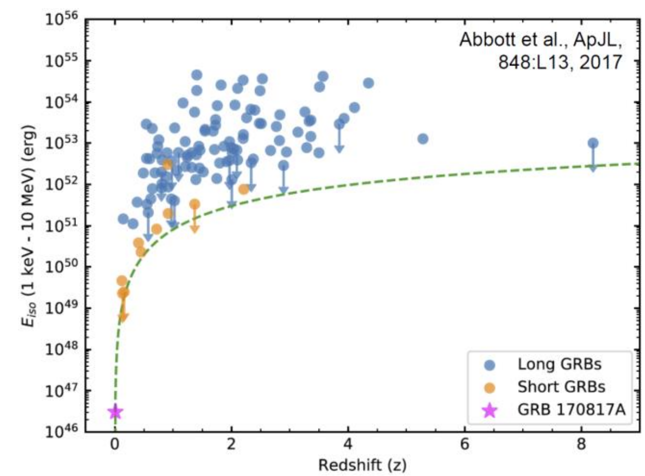
Looking into the heart of a dim nearby sGRB

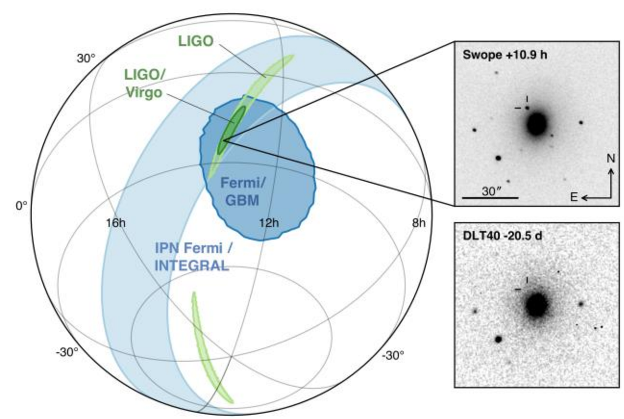
Gravitational waves identified the progenitor of the sGRB and provided both space localization and distance of the source. This triggered the EM follow-up by astronomers for the kilonova

Closest by and weakest sGRB, highest SNR GW event

LIGO/Virgo network allowed source localization of 28 (degr)^2 and distance measurement of 40 Mpc

This allowed astronomers to study for the first time a kilonova, the r-process production of elements, a rapidly fading source



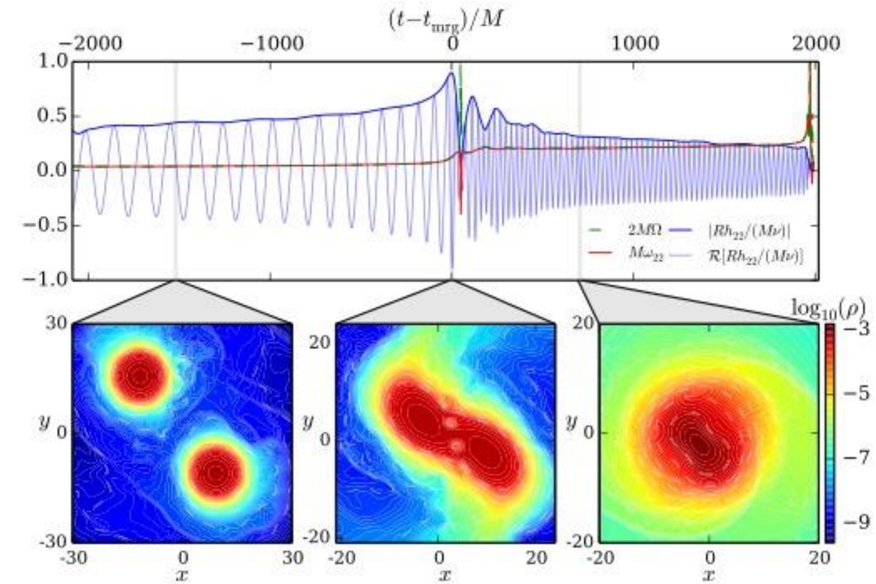


Probing the structure of neutron stars

Tidal effects leave their imprint on the gravitational wave signal from binary neutron stars. This provides information about their deformability. There is a strong need for more sensitive detectors

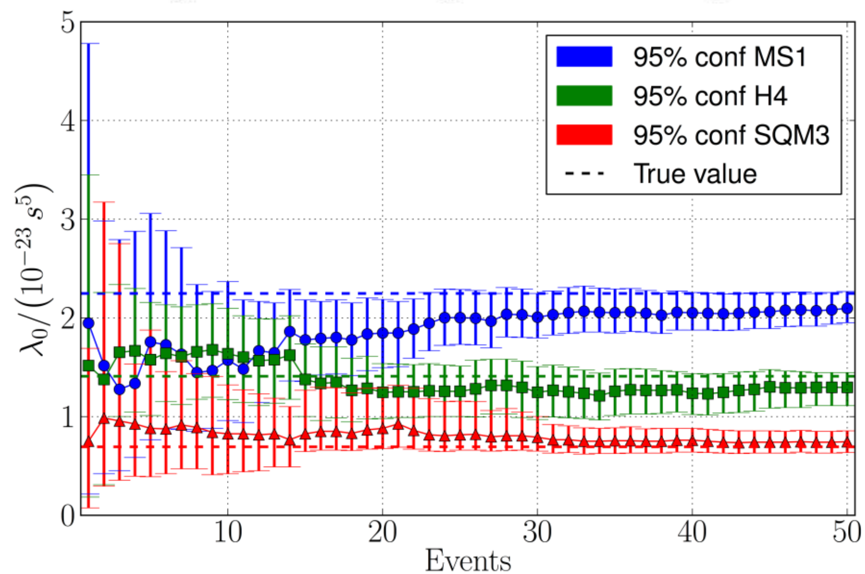
Gravitational waves from inspiraling binary neutron stars

- When close, the 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



Measurement of tidal deformations on GW170817

- More compact neutron stars favored
- “Soft” equation of state



LIGO + Virgo, PRL 119, 161101 (2017)

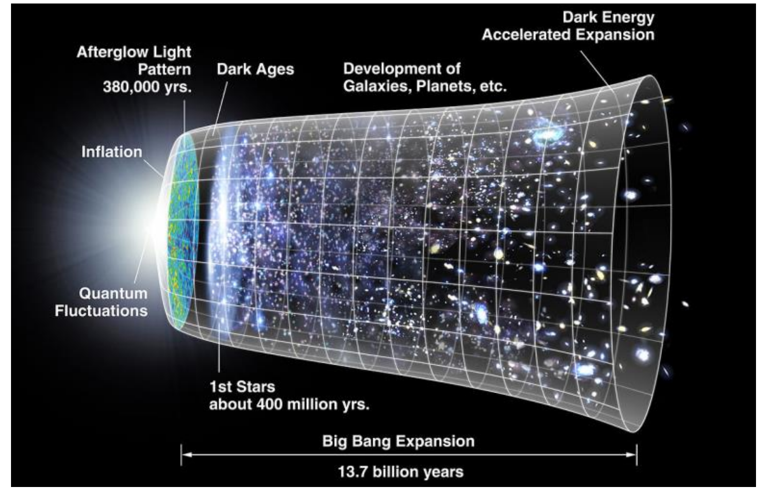
Bernuzzi, Nagar, Font, …

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

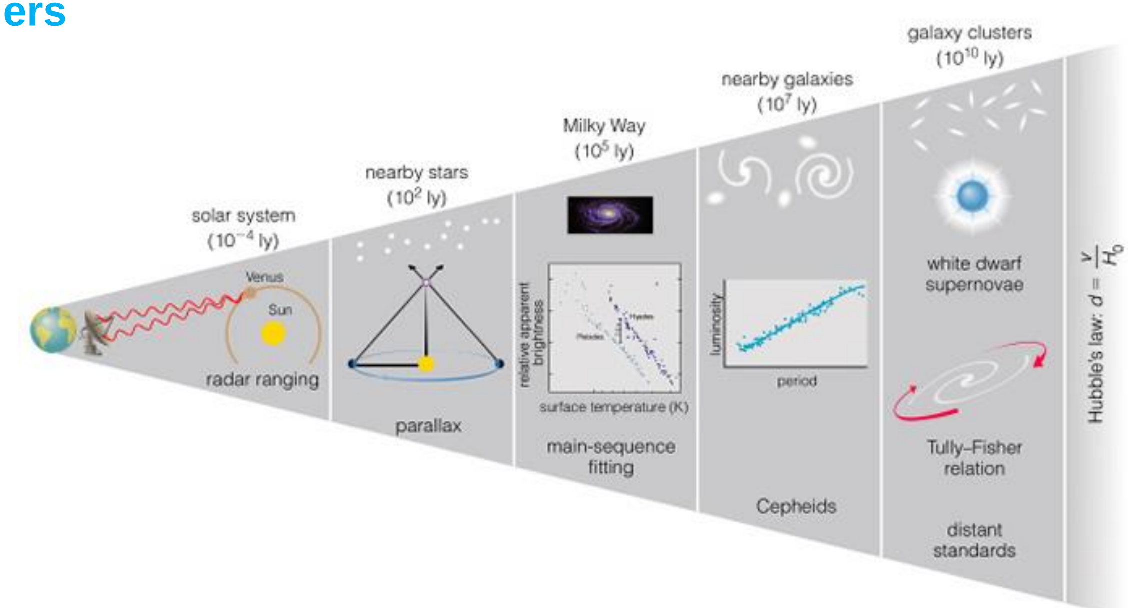
Current measurements depend on cosmic distance ladder

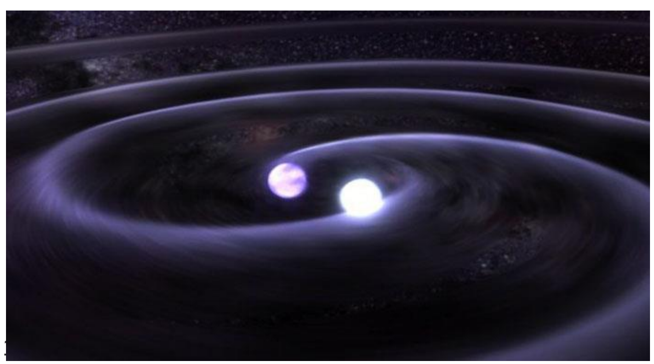
- Intrinsic brightness of *e.g.* supernovae determined by comparison with different, closer-by objects
- Possibility of systematic errors at every "rung" of the ladder



Gravitational waves from binary mergers

Distance can be measured directly from the gravitational wave signal!





A new cosmic distance marker

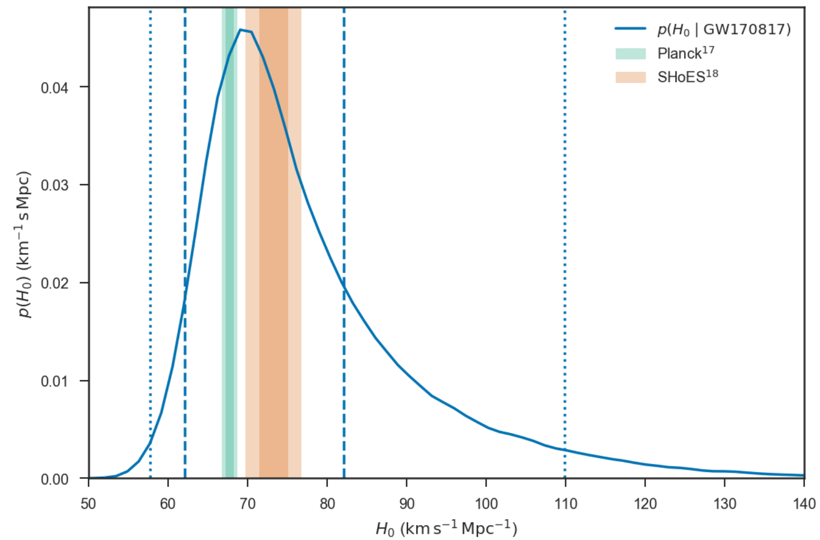
A few tens of detections of binary neutron star mergers allow determining the Hubble parameters to about 1% accuracy

Measurement of the local expansion of the Universe

The Hubble constant

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

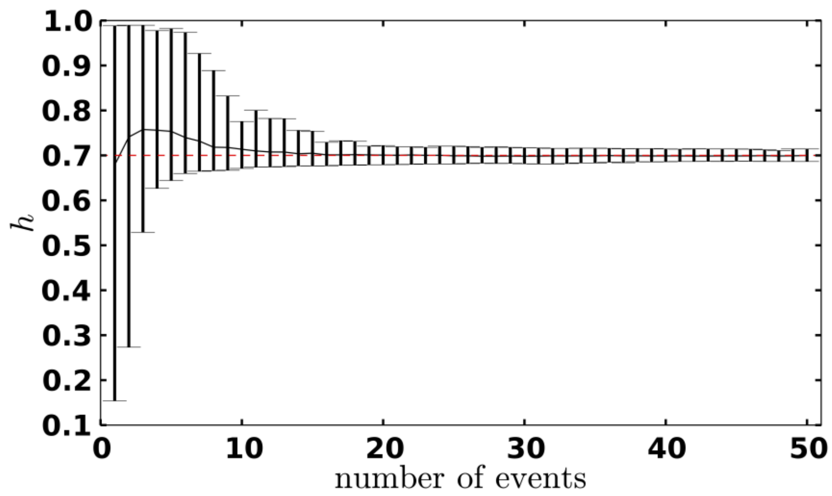
LIGO+Virgo *et al*., Nature 551, 85 (2017)



GW170817

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

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

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

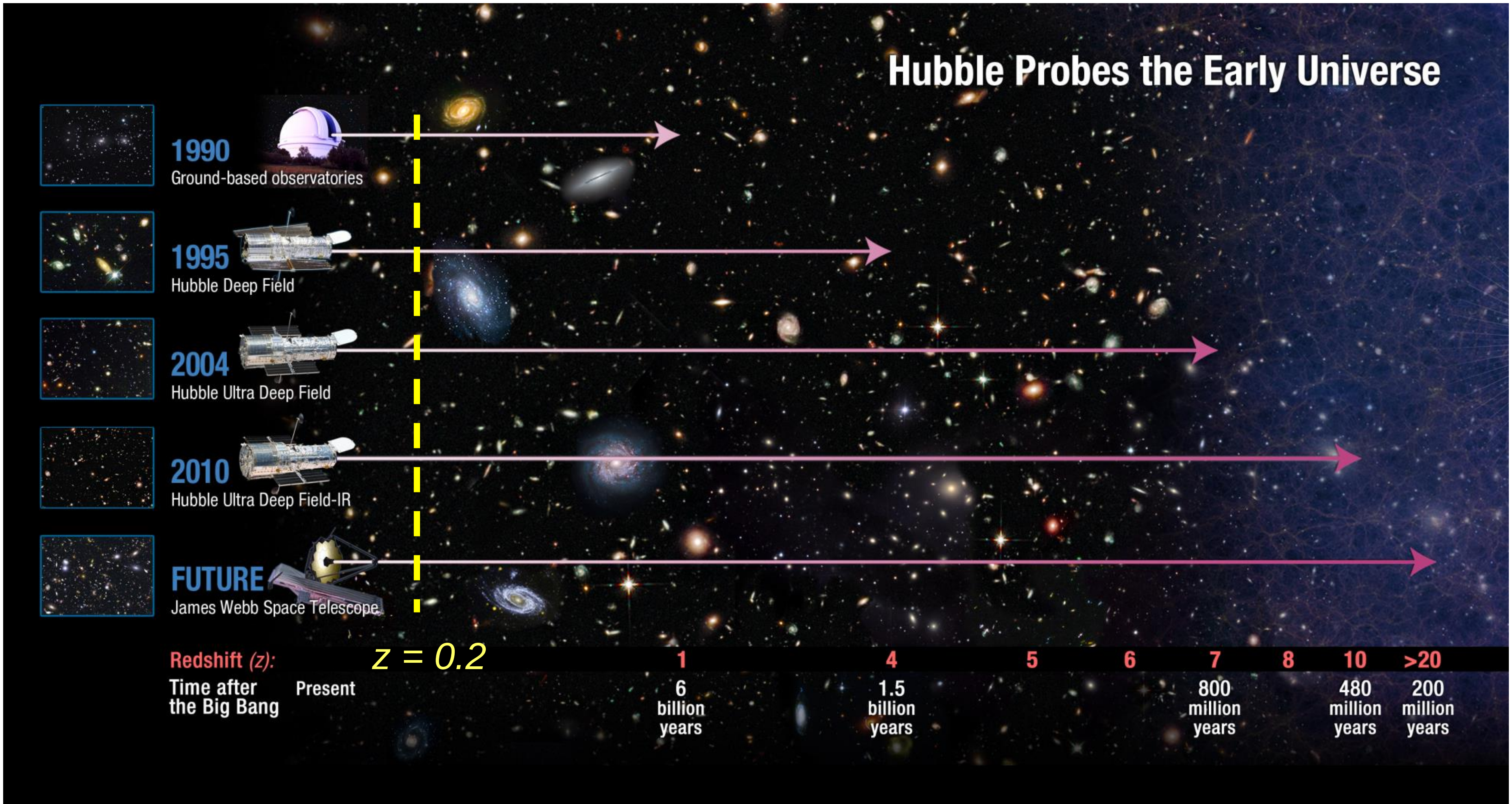
LVC will be back with improved instruments to start the next observation run (O3) in H2 this year

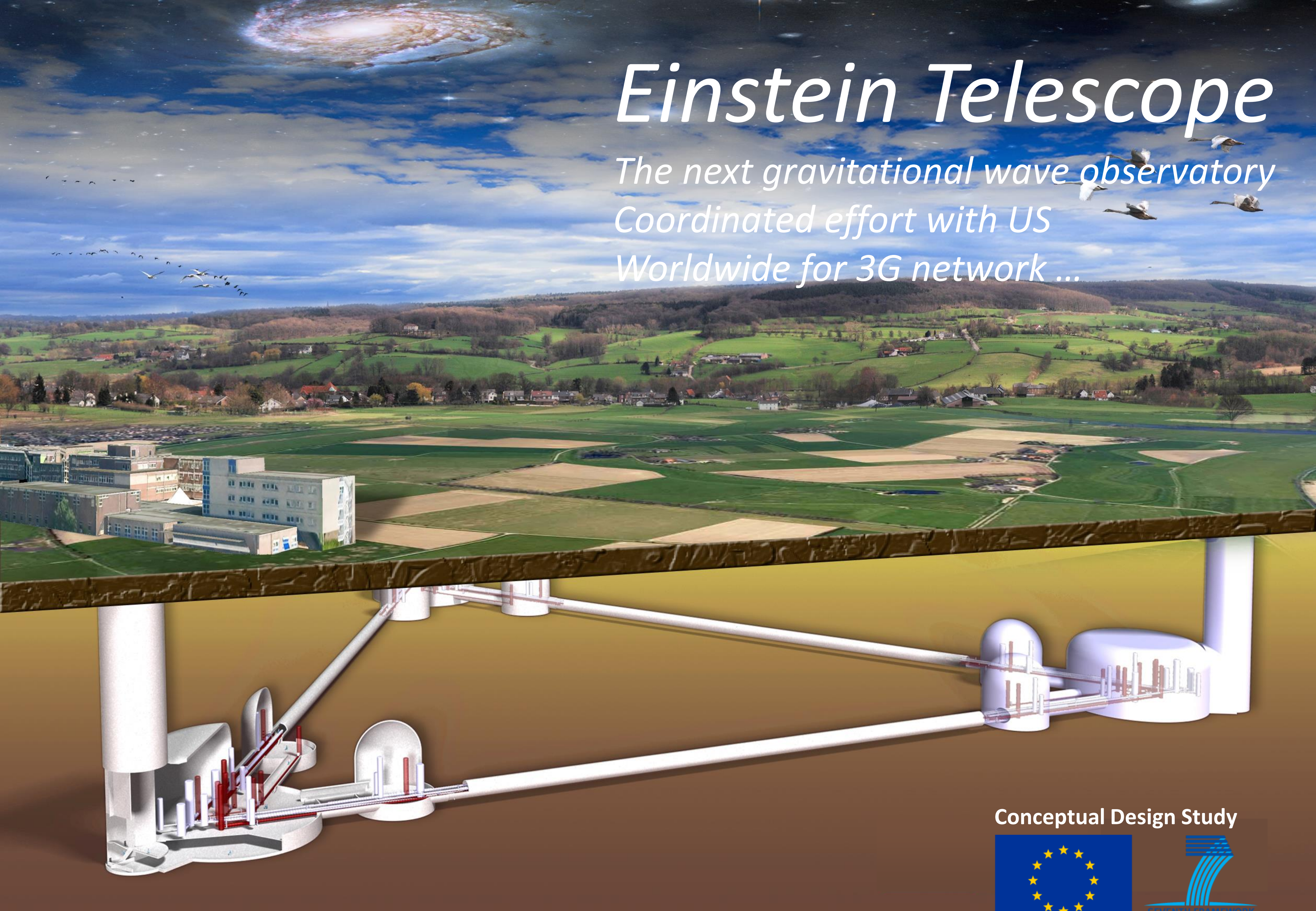
Einstein Telescope: observing all BBH mergers in Universe

This cannot be achieved with existing facilities and requires a new generation of GW observatories

We want to collect high statistics (*e.g.* millions of BBH events), high SNR, distributed over a large z-range (*z* < *20*)

This allows sorting data versus redshift, mass distributions, *etc*. Early warning, IMBH, early Universe, CW, …




Einstein Telescope
The next gravitational wave observatory
Coordinated effort with US
Worldwide for 3G network …
Conceptual Design Study

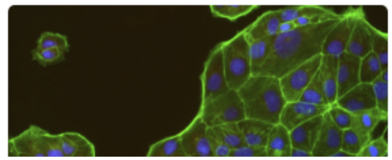
Examples of spin-off from gravitational wave research

Growing human bones using gravitational wave technology

12 September 2017

Technology originally developed to witness black holes colliding is now being used to grow human bone in a laboratory, which could revolutionise the treatment of bone injuries.

The research team used measurement technology, based on the sophisticated laser interferometer systems designed in the UK for gravitational wave detection, to turn stem cells into bone cells.

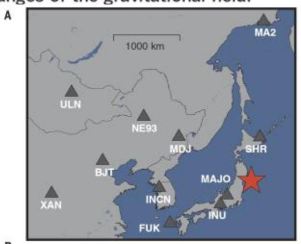


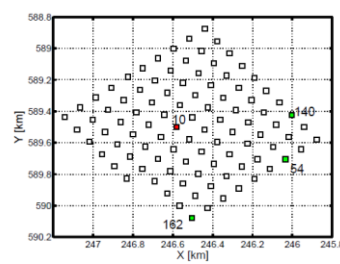
GEOPHYSICS

Observations and modeling of the elastogravity signals preceding direct seismic waves

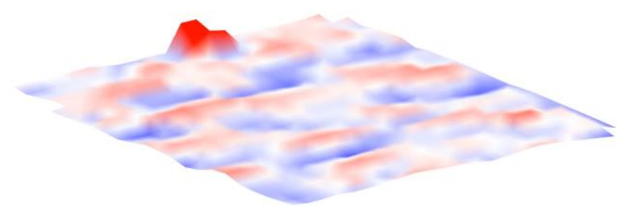
Martin Vallée,[1*] Jean Paul Ampuero,[2] Kévin Juhel,[1] Pascal Bernard,[1] Jean-Paul Montagner,[1] Matteo Barsuglia[3]

After an earthquake, the earliest deformation signals are not expected to be carried by the fastest (*P*) elastic waves but by the speed-of-light changes of the gravitational field. However, these perturbations are weak and, so far, th enough to fully understand their origins and to use th estimate of the earthquake magnitude. We show that well observed with broadband seismometers at distance from the source of the 2011, moment magnitude 9.1, Toh model them by a new formalism, taking into account bo gravity-induced motion. These prompt elastogravity s time-scale magnitude determination for great earthq





Earthquake monitoring



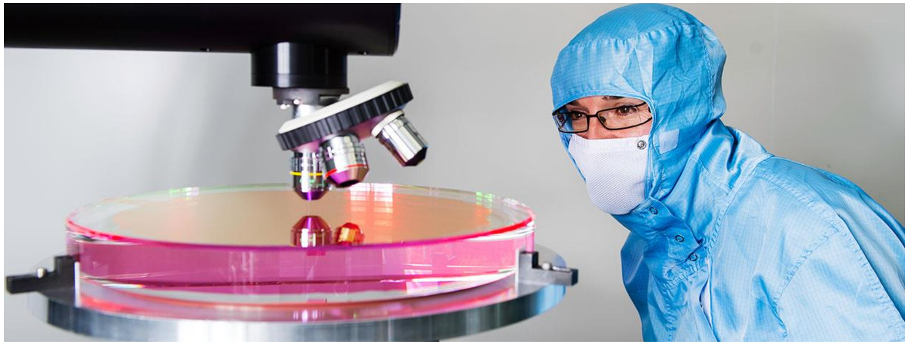
What is the added value of Einstein Telescope?

The arrival of ET stimulates national and regional innovation power, activity, employment and attractivity for top scientists

The facility poses extreme technical demands to equipment, that must be development specially for this application. The involvement and expertise of industry is essential

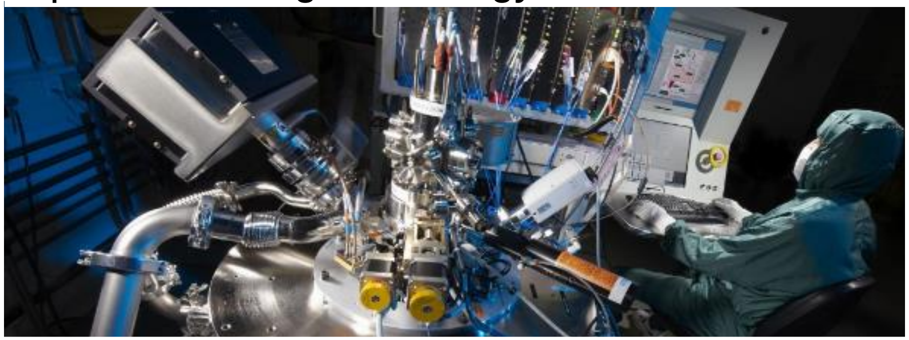
Measuring and attenuating vibrations: nano-technology, medical, defense

Optics, coatings, special materials, laser technology, semiconductor technology

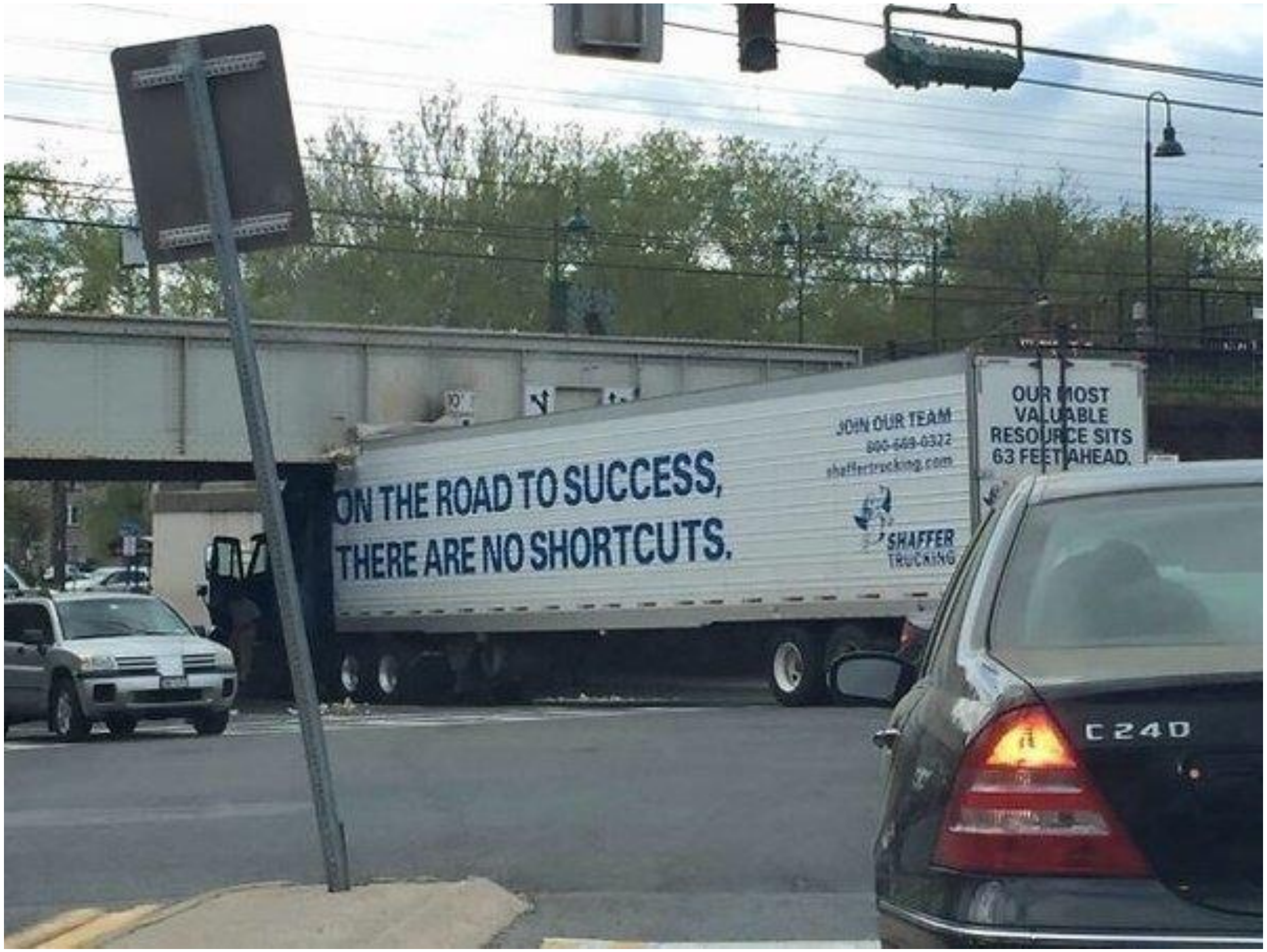


Vacuum technology: ET will be one of the biggest vacuum systems worldwide

Cryogenic systems: also applied in fusion and superconducting technology



APPEC support for strategic decisions



Adequate exploitation funds are required

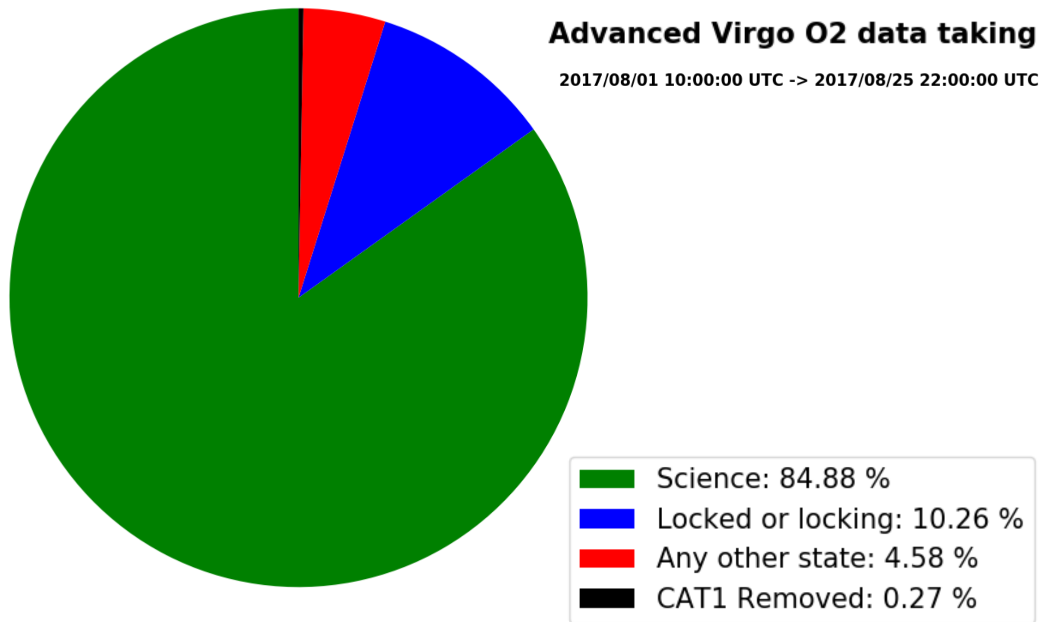
The global LIGO-Virgo network is our detector. The European Virgo detector has an obligation to carry its weight in the network of gravitational wave detectors

Virgo highlights of O2 run

- Longest stable lock stretch (# 39064) was 69 hours
- BNS range up to 28.2 Mpc
- Virgo science duty cycle was about 85%

Added scientific value of Virgo in the network

- Increased data set LH → LH **+ LV + HV + LHV**
- Increase of sky coverage
- Improvement of sky location of sources
- Measurement of GW polarization
- Improvement in distance measurement
- Three-fold coincidence for increased robustness
- Improvement in parameter estimation



Resources needed to enable

- Commissioning Virgo to design sensitivity
- Running EGO as a professional GW observatory
- Future perspective for our young and promising scientists

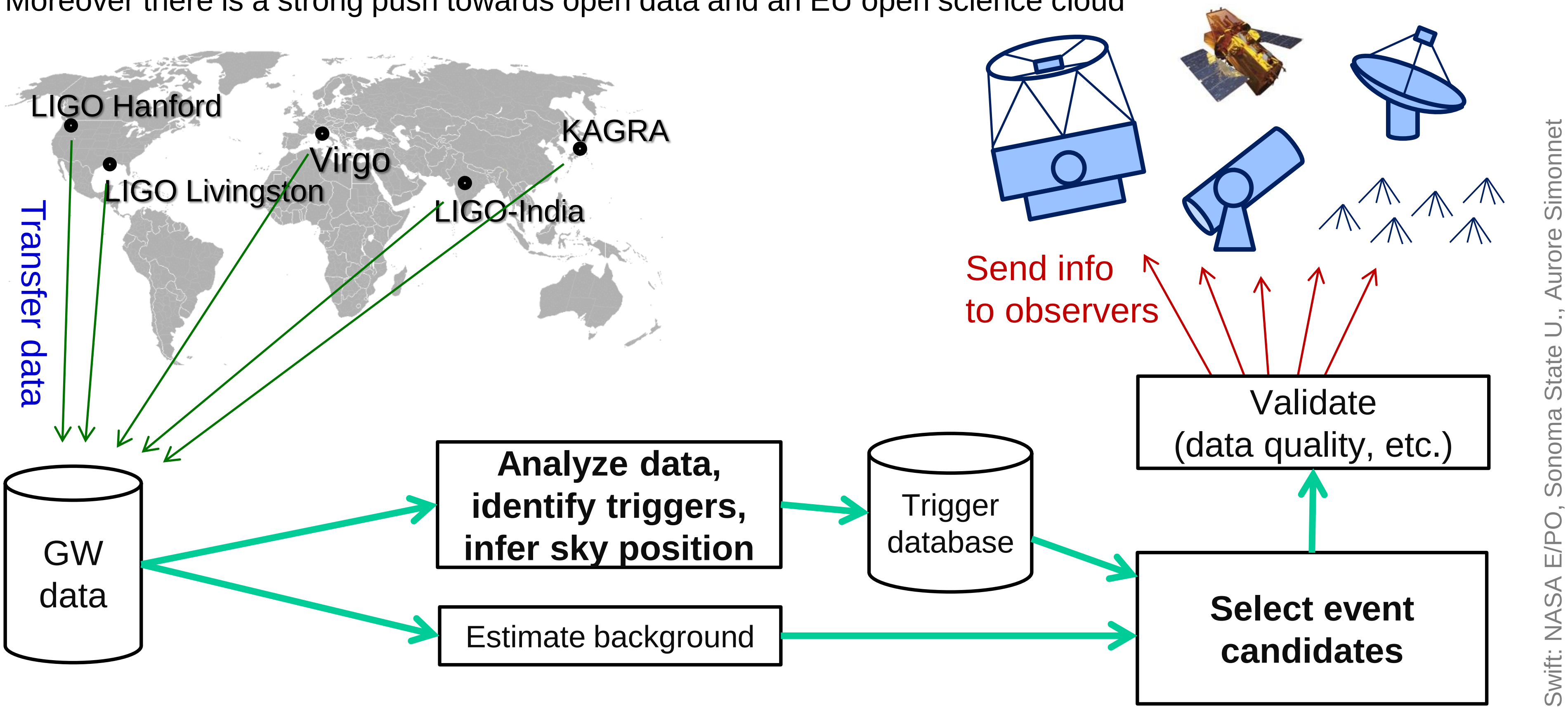
Resources should be dedicated to allow MMA computing

The LIGO-Virgo Collaboration has MOUs with 95 collaborations in astronomy and astro-particle physics. Multi-messenger astronomy requires rapid follow-up of interesting triggers and fast distribution of science data between partners distributed over the globe

Computing will become increasingly important as experiments mature

- GW event rate rapidly increases as sensitivity improves (note that GW-amplitude is measured; Rate $\sim S_{GW}^3$)
- Also computing needs grow as templates get longer

Moreover there is a strong push towards open data and an EU open science cloud

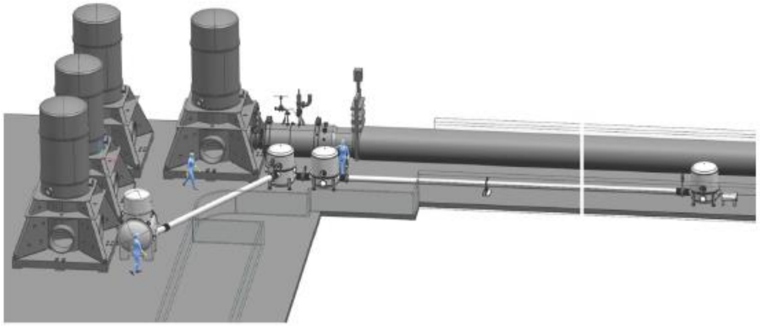


AdV+ as the next incremental step forward in sensitivity

AdV+ is the European plan to 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

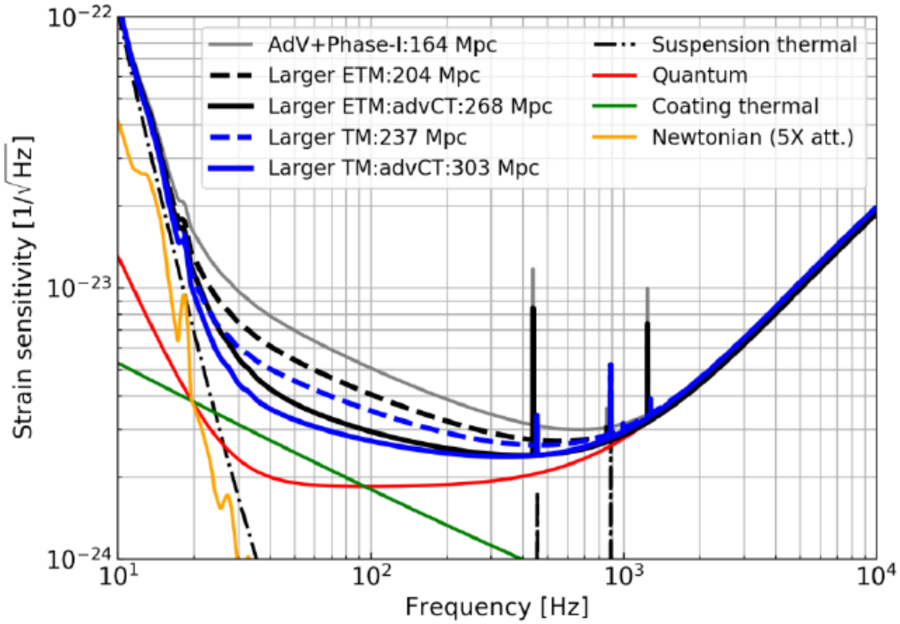
AdV+ features

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



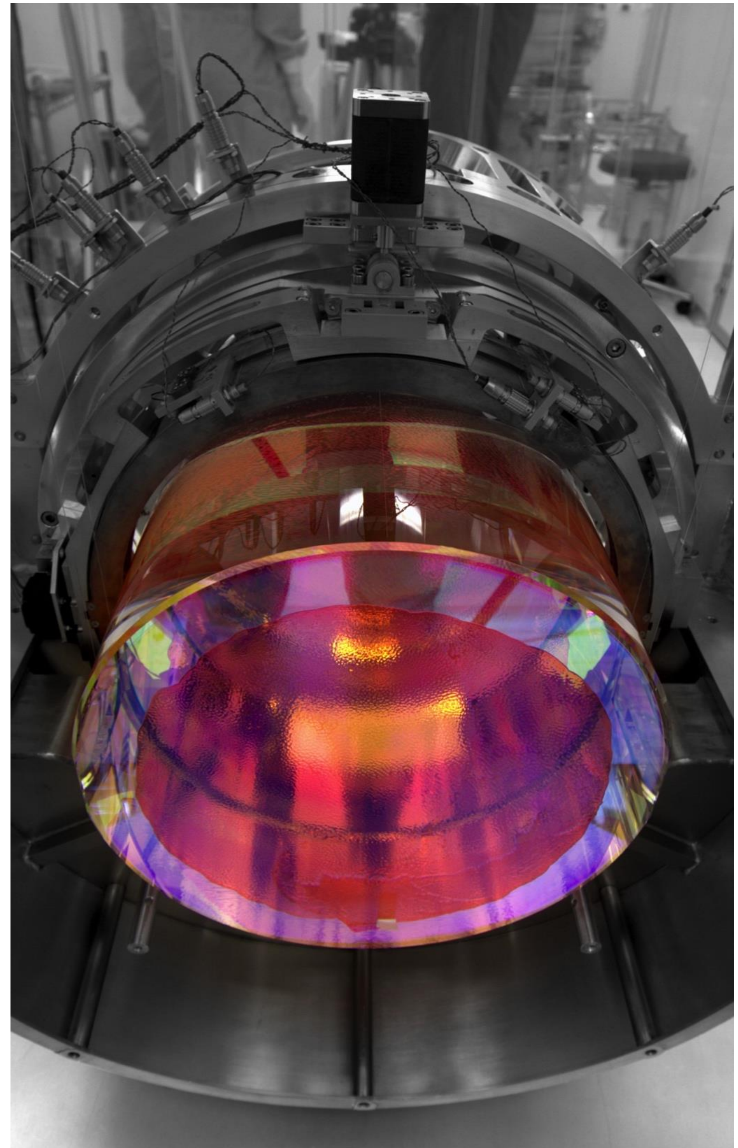
Upgrade activities

- 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



AdV+ 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

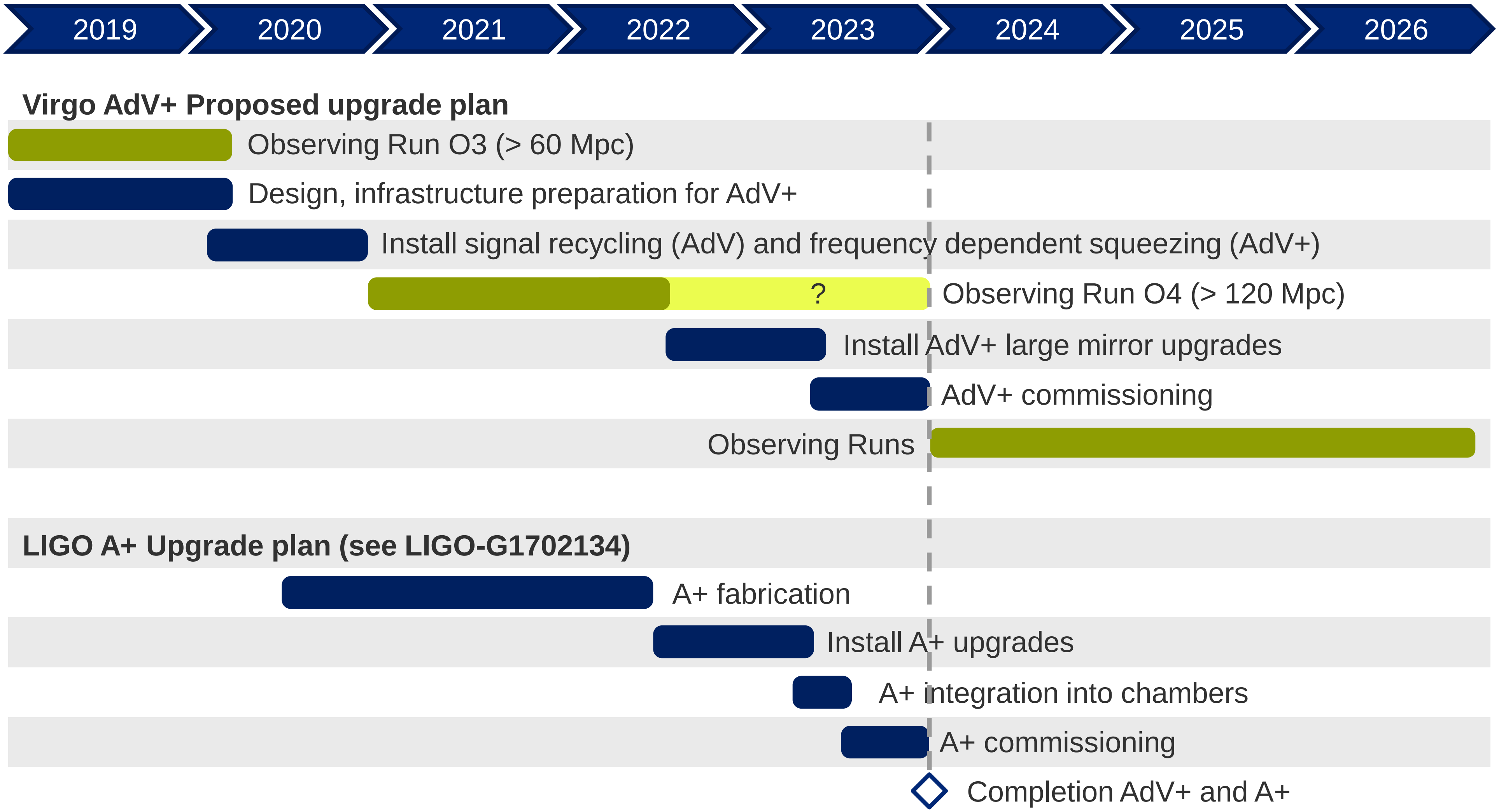
- Flatness < 0.5 nm rms over central 160 mm of mirrors by using ion beam polishing (robotic silica deposition was investigated)
- Ti:Ta_2O_5 and SiO_2 stacks with optical absorption about 0.3 ppm

Expand LMA capabilities for next generation

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

AdV+ to be carried out in parallel with LIGO's A+ upgrade

Five year plan for observational runs, commissioning and upgrades



Note: duration of O4 has not been decided at this moment

AdV+ is part of a strategy to go from 2nd generation to Einstein Telescope

Einstein Telescope and CERN

How can APPEC help in supporting a CERN role in our quest for Einstein Telescope? There is strong scientific overlap, and we should take advantage of existing expertise and resources

Science

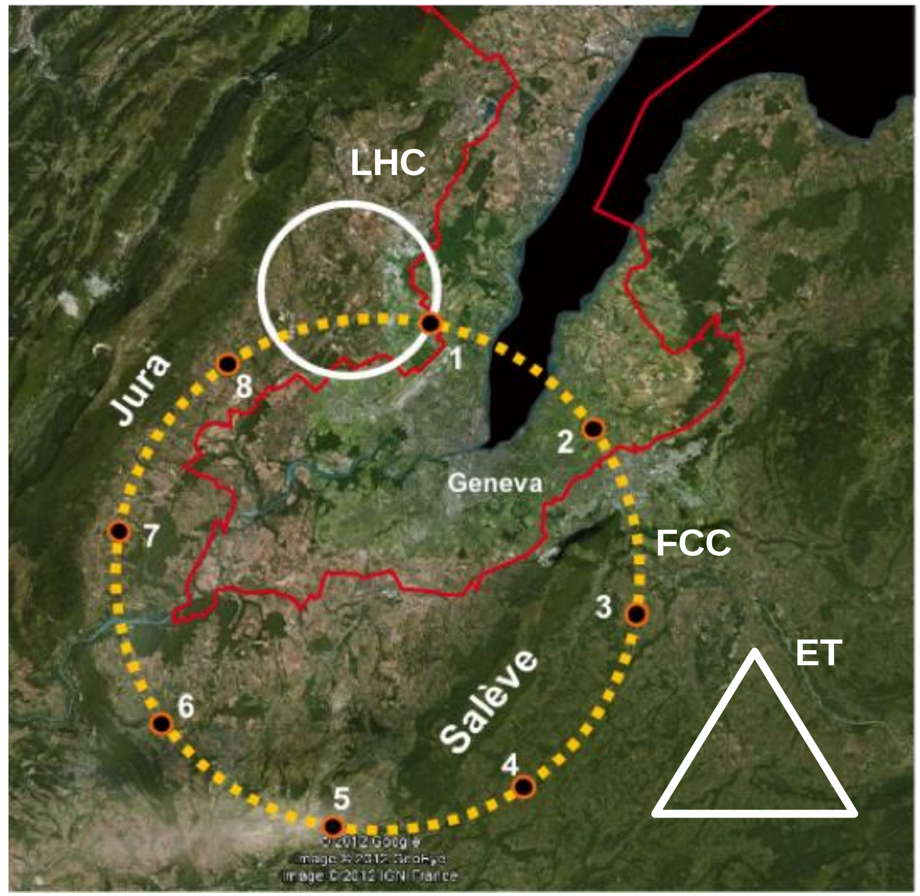
- Gravity is a fundamental interaction with most important open scientific issues
- GWs are the dynamical part of gravity
- Strong scientific interest from HEP
- Involve GW scientists in upcoming EU HEP Strategy discussion

Governance

- Financial and project management
- Excellent, robust and proven organization

Technical

- Vacuum infrastructure, underground construction
- Cryogenics, controls



Gravitational Wave International Committee

GWIC seeks to facilitate international collaboration and cooperation in use of GW facilities

What is GWIC?

Working Group (GW11) of the International Union of Pure and Applied Physics (IUPAP)

Links to the International Astronomical Union (IAU) and the International Society for General Relativity and Gravitation (ISGRG)

GWIC membership represents the world's active gravitational wave projects, as well as other relevant communities, covering gravitational wave frequencies from nanohertz to kilohertz

https://gwic.ligo.org/

GWIC strongly supports and is working to coordinate upgrades of future detectors

GWIC on Exploitation of LIGO and Virgo

APPEC has a crucial role in providing support for European contributions to the global Advanced detector network

GWIC on 3G GW observatories

APPEC has a critical role in supporting European scientists (via appropriate instruments) to participate in the 3G activities: global network science case studies, networking, R&D, etc

APPEC could interface to GWAC to provide a collective perspective on European work in the global context

Gravitational Wave Agency Correspondents

GWAC's primary purpose is to enable international co-sponsoring activities in GW Astrophysics

GWAC is a GW "funding" agencies committee promoted by NSF, involving

- Australian Research Council (ARC)
- Canada Foundation for Innovation (CFI)
- Centre National de la Recherche Scientifique (CNRS)
- Consejo Nacional de Ciencia y Tecnología (CONACYT)
- Deutsche Forschungsgemeinschaft (DFG)
- Istituto Nazionale di Fisica Nucleare (INFN)
- National Aeronautics and Space Administration (NASA)
- Science & Technology Facilities Council (STFC)
- Netherlands Science Organization (NWO)

GWAC is a tool for the GW community. Type of activities

- Large scale: developing new GW observatories
- Medium scale: support of GW R&D of any kind (risk mitigation, characterization, DA, etc.)
- Small scale: training of junior scientists, investigator exchange programs, etc.

Slide info: from Pedro Maronetti, NSF
"Dawn 2" Meeting
Atlanta, GA – July, 2016

What is needed now?

A strategy to transition from 2nd generation to Einstein Telescope. This requires that industry, politics and science are acting in consort so that we together can investigate this unique chance on an iconic European project

How can APPEC help us? By facilitating:

- An innovative upgrade (AdV+) and R&D programs should be defined together with industry
- MOU with the most important scientific parties should be established
- Scientists will develop the international science/governance case for ET: GWIC (Summer 2018)
- European research organizations will develop a common strategy that will lead to an ESFRI request backed by various ministries (2019)

A unique chance for Europe, but support from the ministries of various partner countries is of essential importance

European Strategy Forum
on Research Infrastructures

ESFRI