OBSERVATION OF GRAVITATIONAL WAVES FROM A BINARY NEUTRON STAR MERGER

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Mini-Workshop on Multi-messenger Astronomy, LNF, 16-01-2018

ADVANCED VIRGO

6 European countries
23 labs, ~280 authors

Advanced Virgo (AdV): upgrade of the Virgo interferometric detector

Participated by France and Italy (former founders of Virgo), The Netherlands, Poland, Hungary, Spain

Funding approved in Dec 2009
(21.8 ME + Nikhef in kind contribution)

Project formally completed with the start of the O2 run (1 Aug 2017)

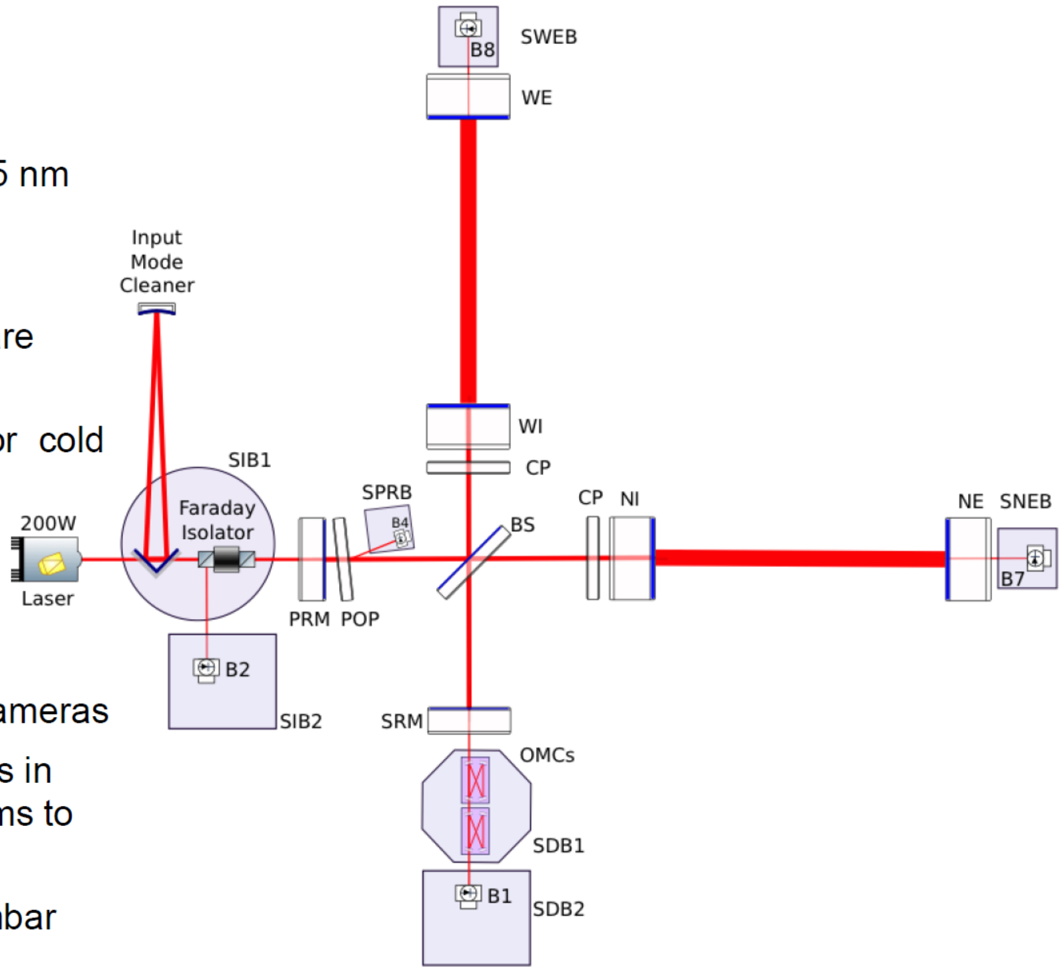
APC Paris
ARTEMIS Nice
EGO Cascina
INFN Firenze-Urbino
INFN Genova
INFN MiB-Parma-Torino
INFN Napoli
INFN Perugia
INFN Pisa
INFN Roma La Sapienza
INFN Roma Tor Vergata
INFN Padova
INFN Salerno/Uni Sannio
INFN TIFPA Trento
LAL Orsay – ESPCI Paris
LAPP Annecy
LKB Paris
LMA Lyon
NIKHEF Amsterdam
POLGRAW
RADBOUD Uni. Nijmegen
RMKI Budapest
University of Valencia

ADVANCED VIRGO DESIGN

Advanced Virgo started operation on August 1, 2017. It features many improvements with respect to Virgo and Virgo+

For 2017

- Larger beam: 2.5x larger at ITMs
- Heavier mirrors: 2x heavier
- Higher quality optics: residual roughness < 0.5 nm
- Improved coatings for lower losses: absorption < 0.5 ppm, scattering < 10 ppm
- Reducing shot noise: arm finesse of cavities are 3 x larger than in Virgo+
- Thermal control of aberrations: compensate for cold and hot defects on the core optics:
  - ring heaters
  - double axicon CO_2 actuators
  - CO_2 central heating
  - diagnostics: Hartmann sensors & phase cameras
- Stray light control: suspended optical benches in vacuum, and new set of baffles and diaphragms to catch diffuse light
- Improved vacuum: 10^{-9} mbar instead of 10^{-7} mbar



THE O2 RUN - FACTS

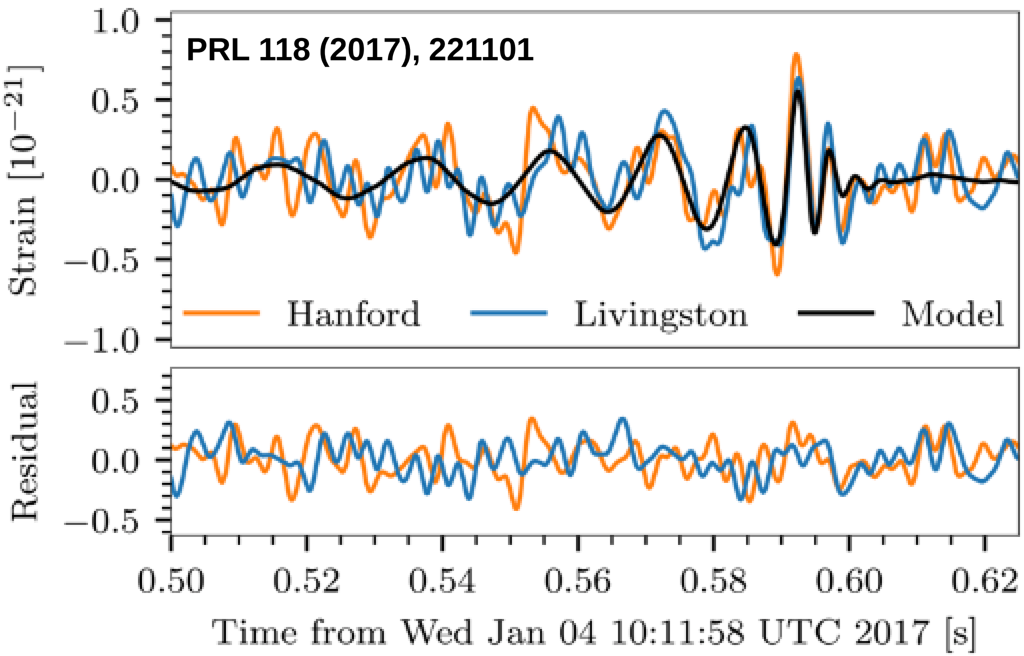
Started on November 30, 2016

VIRGO joined on August 1st, 2017

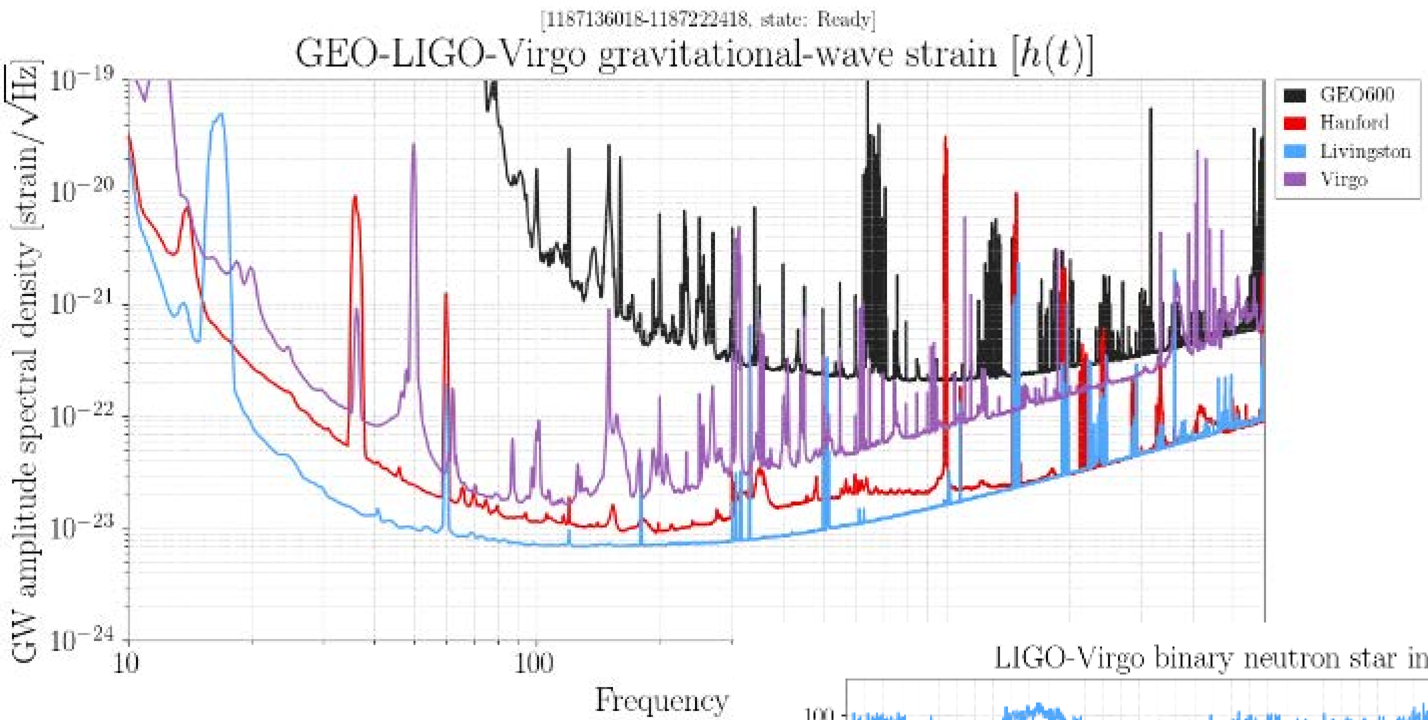
The run was stopped on Aug 25th, as previously planned by LIGO

From Aug 1st to 25th: 14.9 days of triple coincidence observation

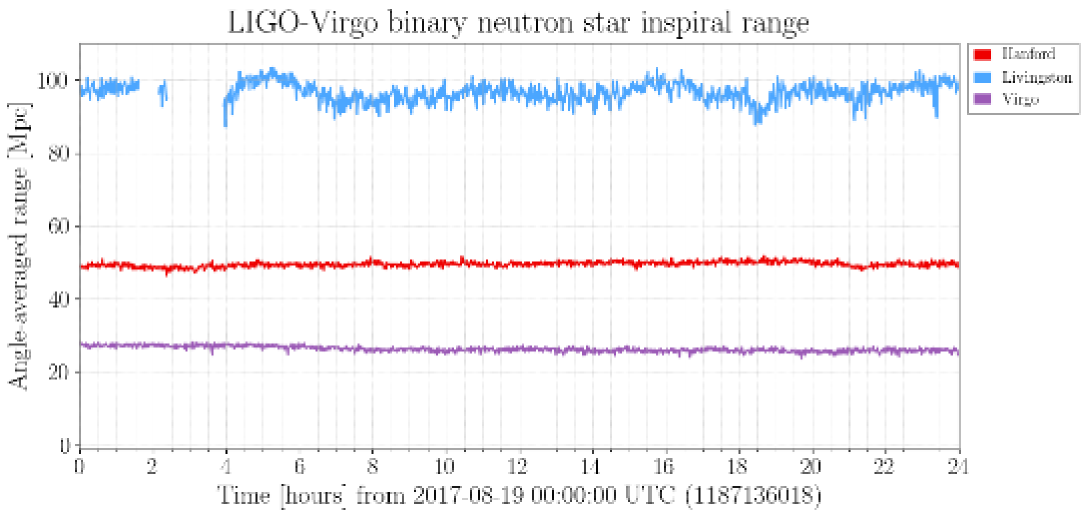
One event published before Aug 1st (GW170104)



NETWORK

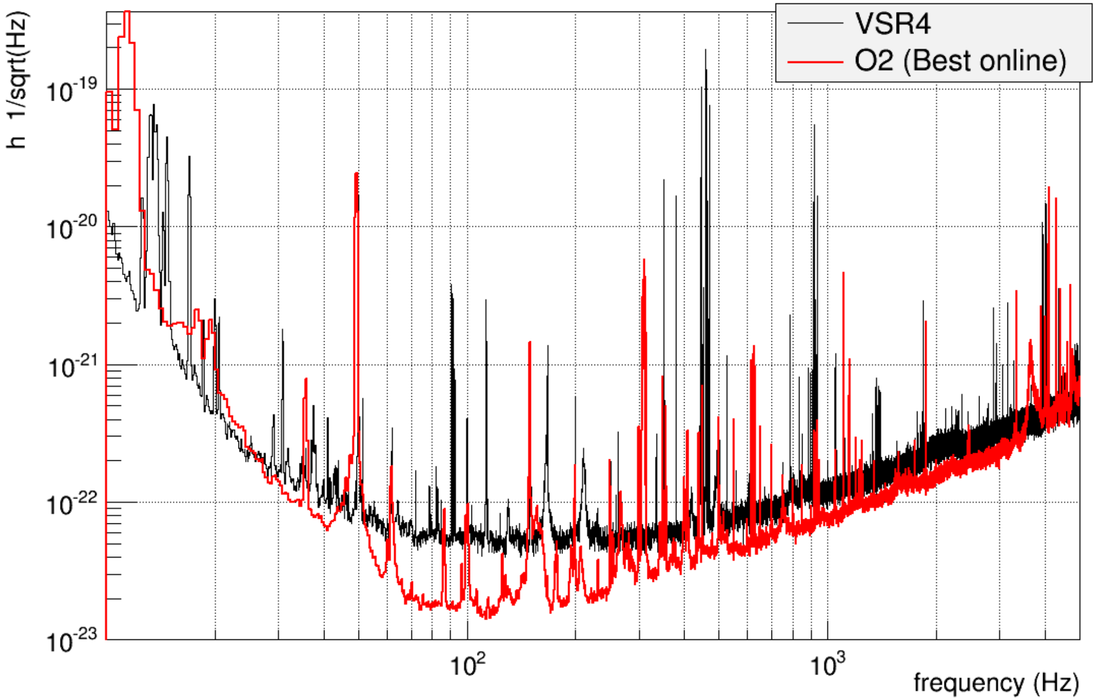


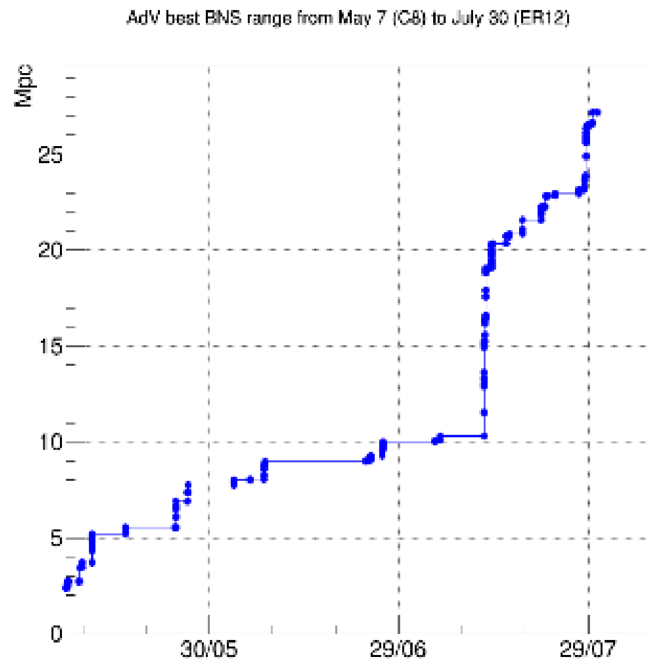
[1187136018-1187222418, state: Ready]
GEO-LIGO-Virgo gravitational-wave strain [h(t)]
GW amplitude spectral density [strain/√Hz]
10^-19
10^-20
10^-21
10^-22
10^-23
10^-24
10
100
Frequency
GEO600
Hanford
Livingston
Virgo



LIGO-Virgo binary neutron star inspiral range
Angle-averaged range [Mpc]
0
20
40
60
80
100
0
2
4
6
8
10
12
14
16
18
20
22
24
Time [hours] from 2017-08-19 00:00:00 UTC (1187136018)
Hanford
Livingston
Virgo

SENSITIVITY



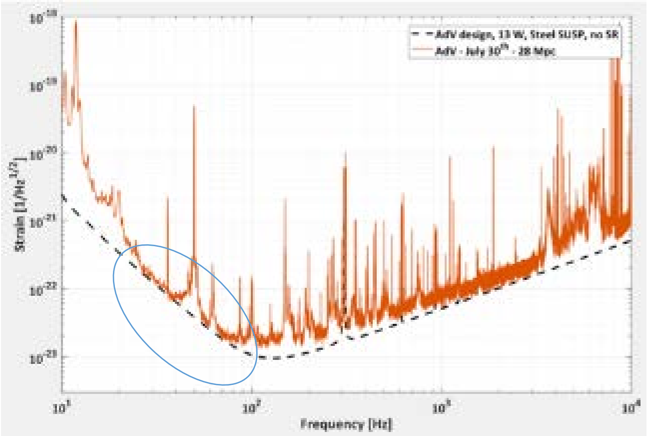


VIRGO+ (2011): BNS range of 12 Mpc

AdV (O2): 28 Mpc, ~12x larger volume of universe reached

now further improved: >30 Mpc

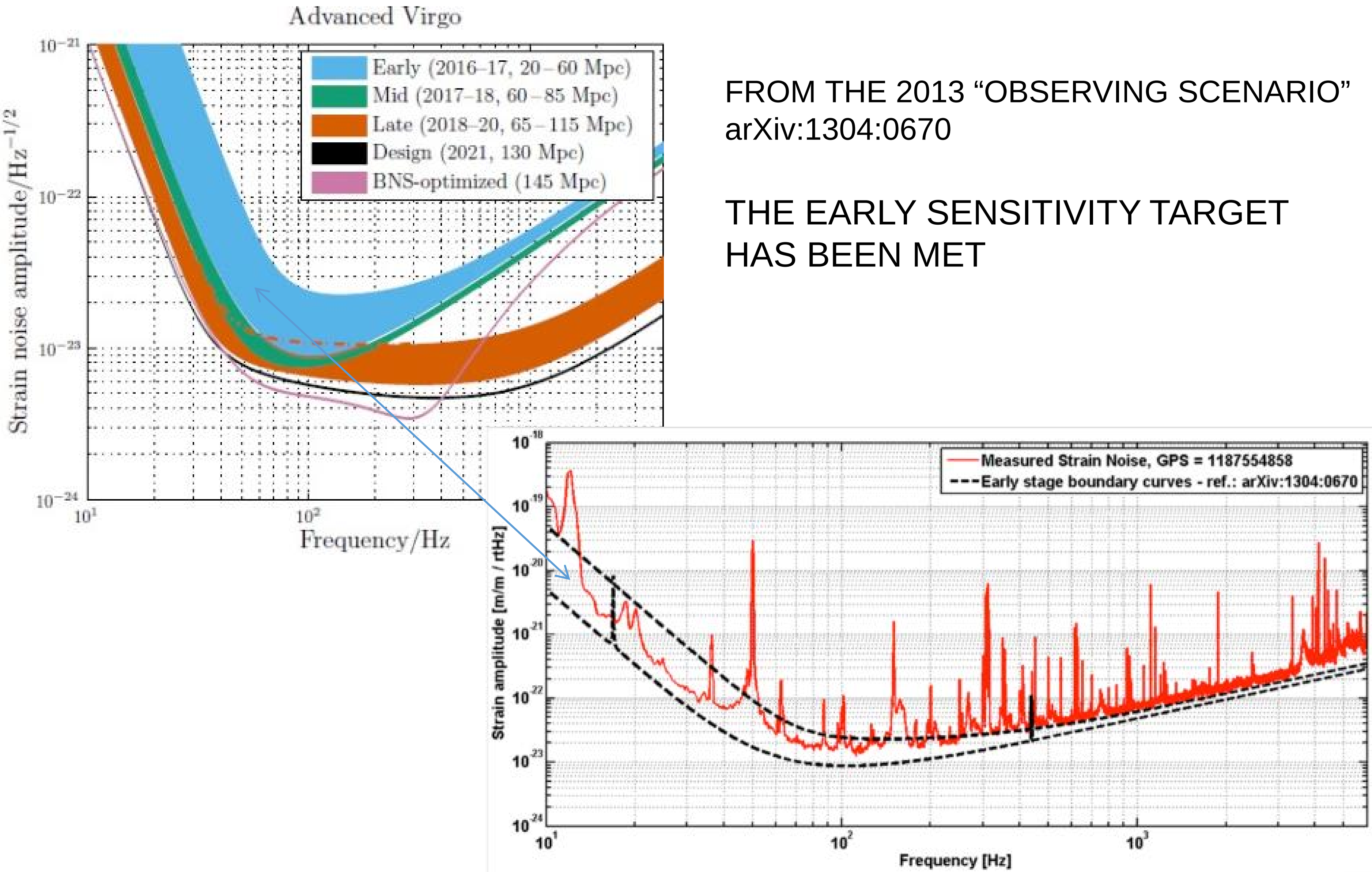
Limited by steel wires thermal noise in the low frequency range



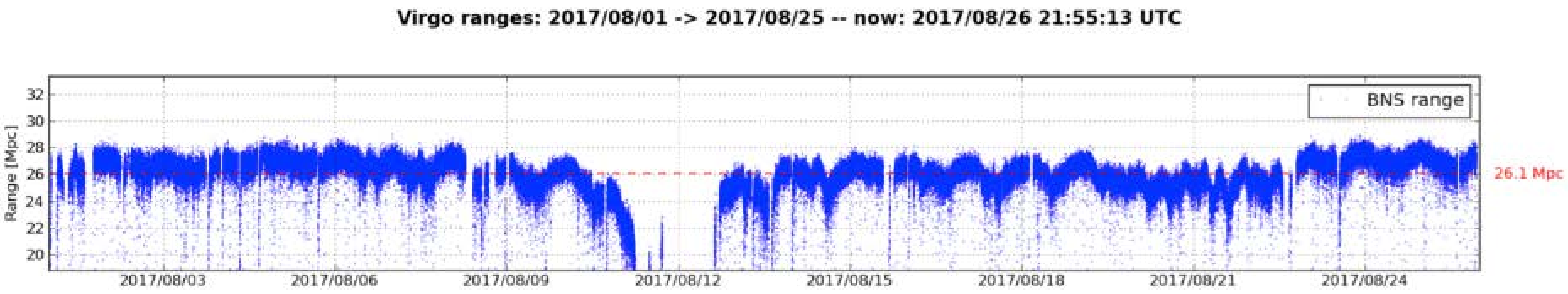
SENSITIVITY

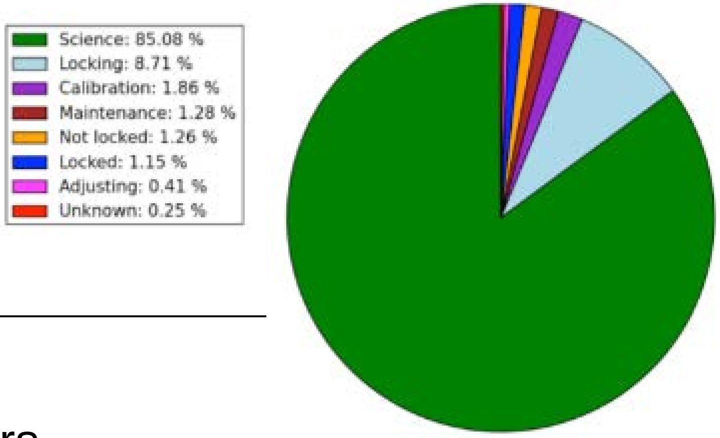
FROM THE 2013 “OBSERVING SCENARIO” arXiv:1304:0670

THE EARLY SENSITIVITY TARGET HAS BEEN MET



VIRGO IN O2





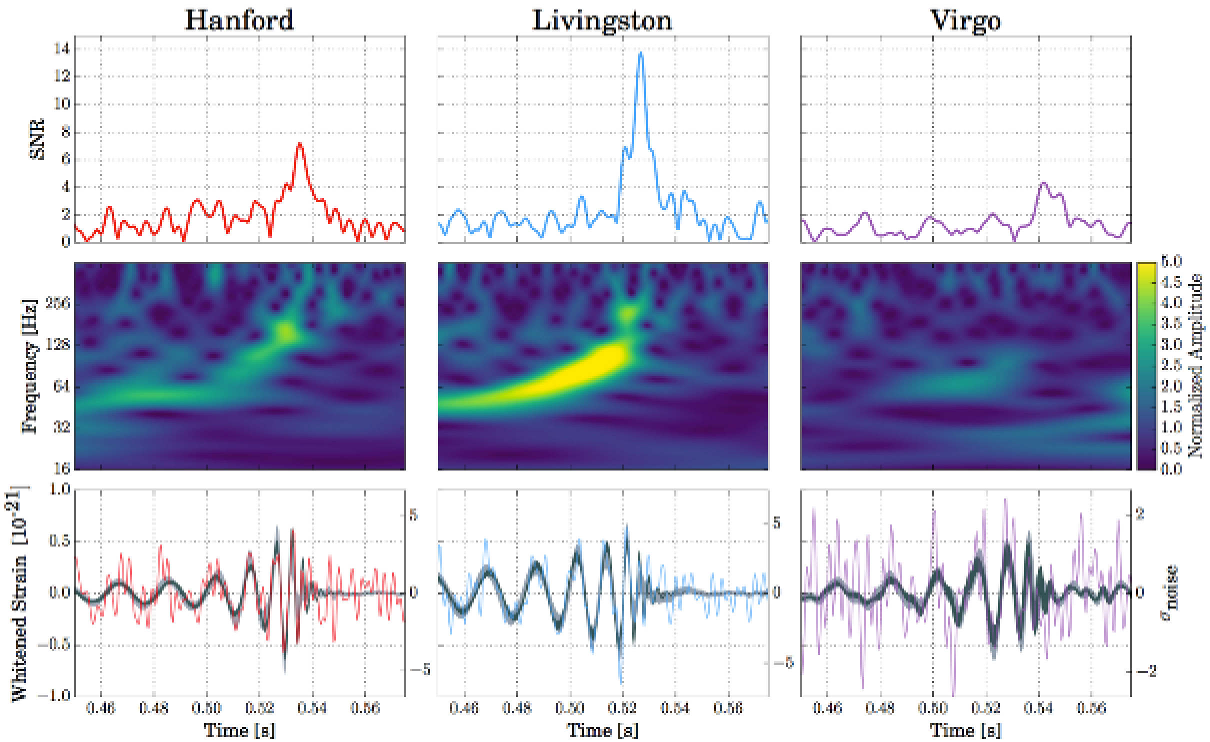
DUTY CYCLE: 85% (!!)

LONGEST LOCK STRETCH: 69 hours

HIGHEST BNS RANGE: 28.2 Mpc

AVERAGE RANGE: BNS 26 - BBH_{10} 134 - BBH_{30} 314 Mpc

AUGUST 14TH, 2017

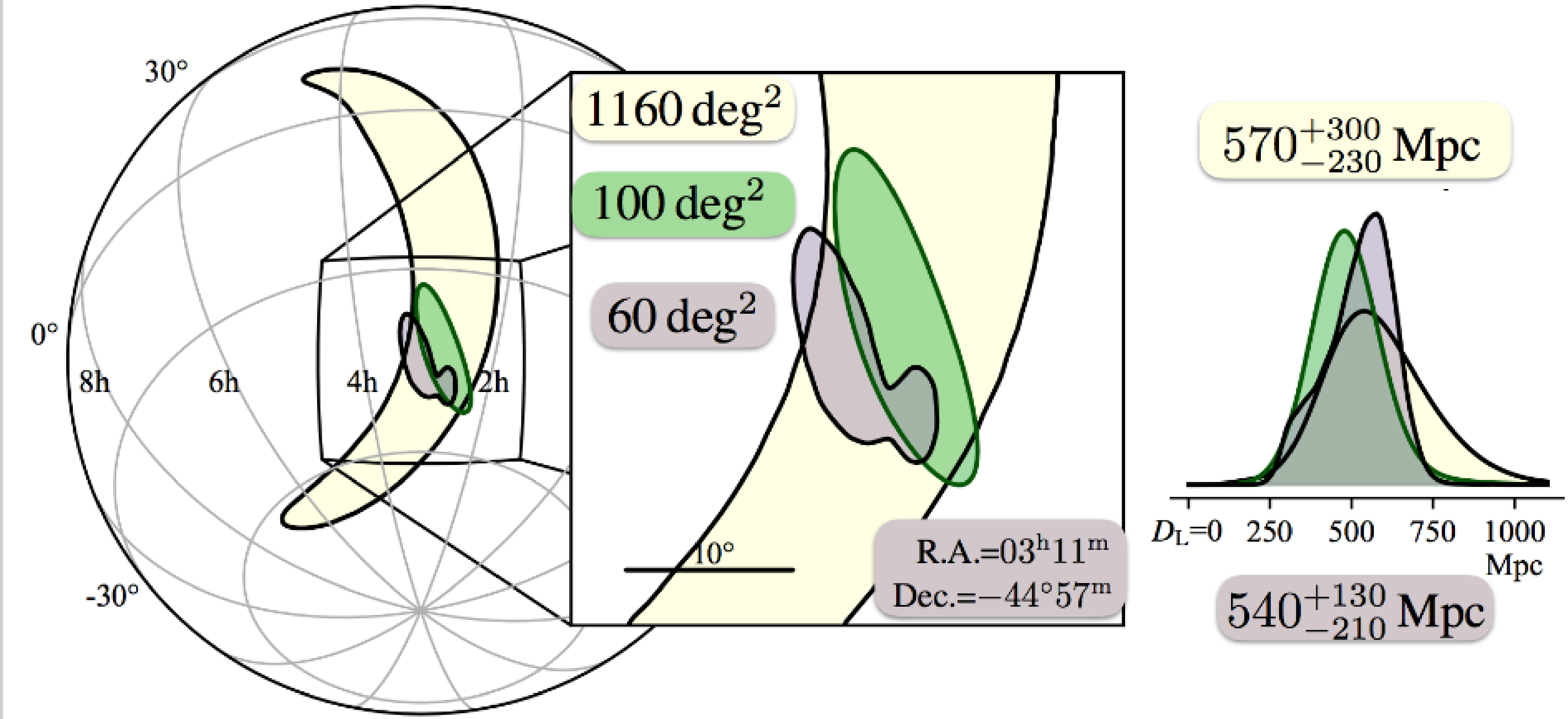


PRL, 119, 141101 (2017)

At 10:30:43 UTC, the Advanced Virgo detector and the two Advanced LIGO detectors coherently observed a transient gravitational-wave signal produced by the coalescence of two stellar mass black holes, with a false-alarm-rate of <~ 1 in 27 000 years

The GW hit Earth first at lat. 44.95˚ S, long. 72,97˚ W, Puerto Aysen, Chile.

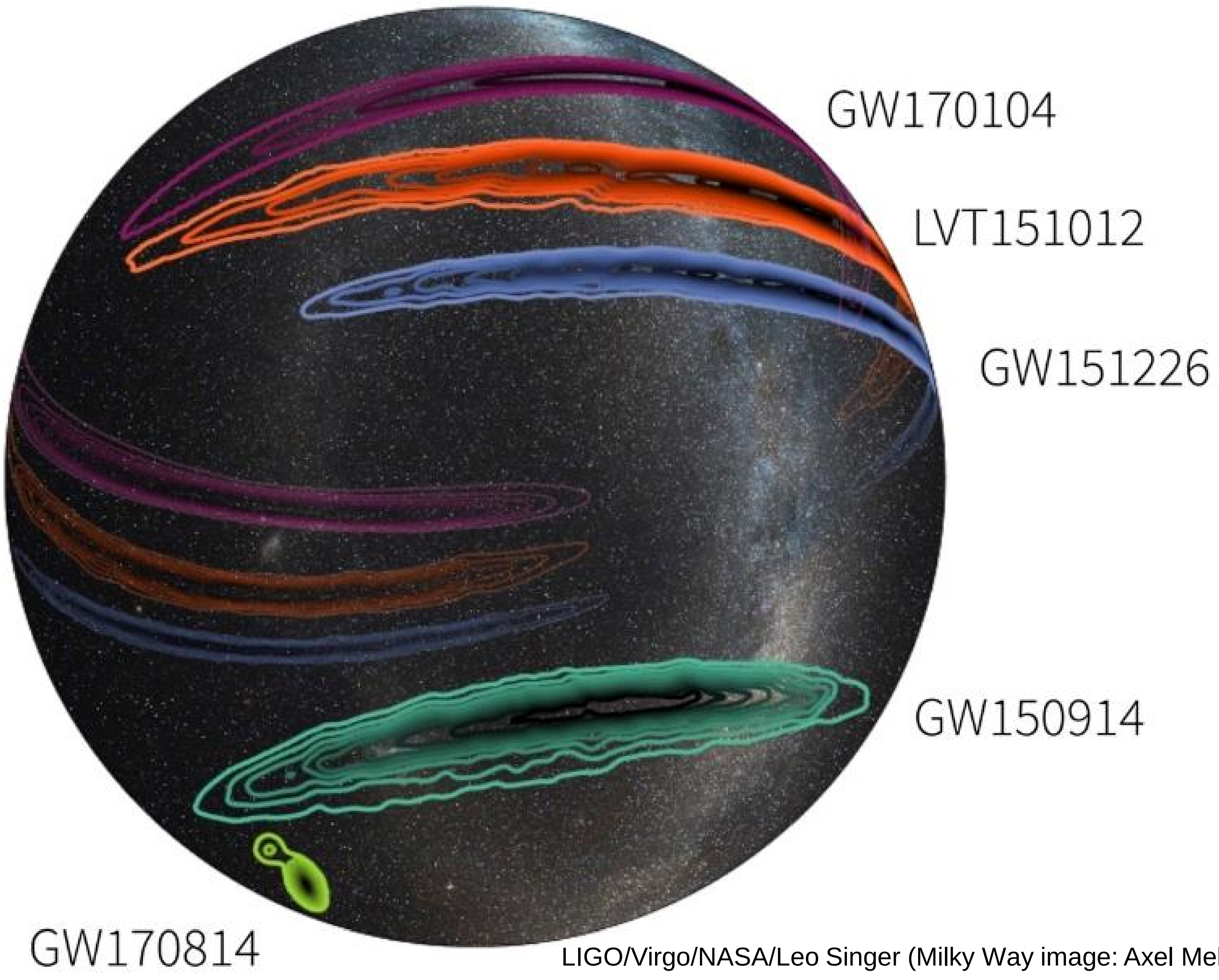
The signal was recorded at L1 first, then at H1 and Virgo with delays of ~8 and ~14 ms respectively



VIRGO HELPS REDUCING:

ERROR IN SKY AREA:	20x
ERROR IN DISTANCE:	1.5x
ERROR BOX ON THE SKY:	30x
(from 70 to 2 Mpc^3)	

THE ERA OF GW ASTRONOMY HAS FINALLY STARTED

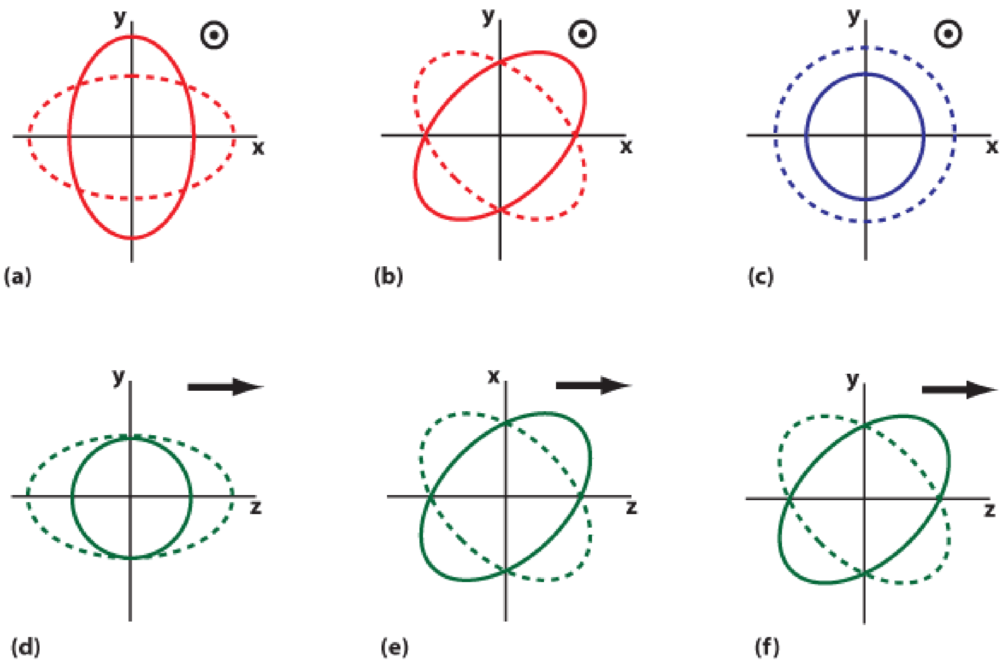


LIGO/Virgo/NASA/Leo Singer (Milky Way image: Axel Mellinger)

POLARIZATION

TENSOR (SPIN 2)
GENERAL RELATIVITY

SCALAR (SPIN 0)



VECTOR (SPIN 1)

GENERAL METRIC THEORIES OF GRAVITY ALLOW UP TO 6 POLARIZATION STATES

For the first time, thanks to the addition of a 3rd detector, one can probe the nature of the polarization states

So far a preliminary and simplified investigation has been carried out, to illustrate the potential power of this new phenomenological test of gravity

only models with “pure” polarization states (tensor, vector or scalar) have been considered

a study with “mixed” states is underway

RESULT: GR (purely tensor) is 200 and 1000 times more likely than purely vector/scalar respectively

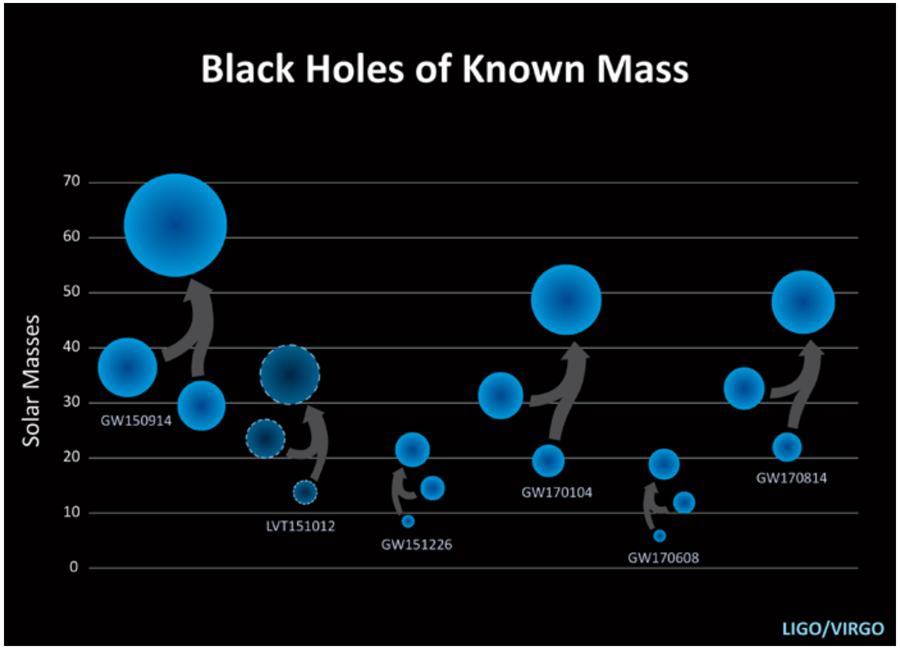
PROPERTIES OF BLACK HOLES

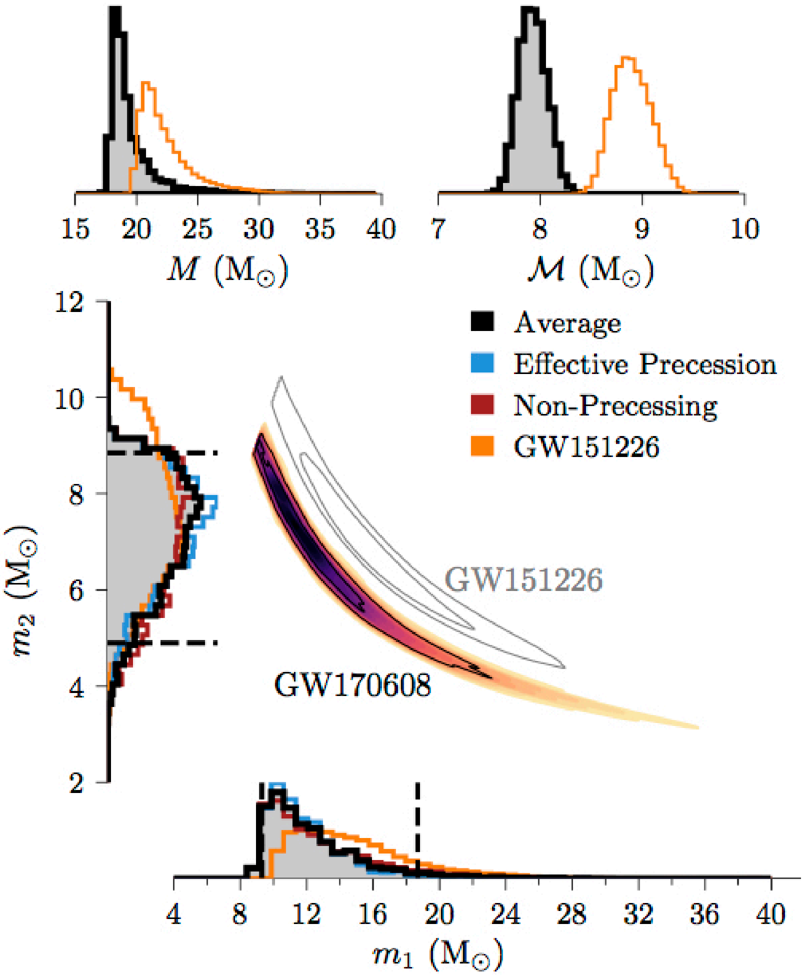
Extract information on masses, spins, energy radiated, position, distance, inclination, polarization.
Population distribution may shed light on formation mechanisms

LVC reported on 6 BBH mergers

Fundamental physics, astrophysics, astronomy, and cosmology

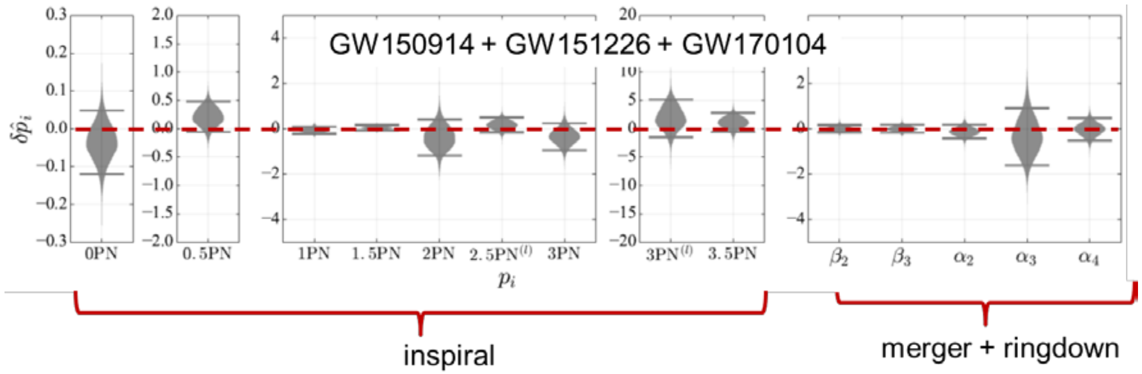
Testing GR, waveforms (with matter)





PRECISION TESTS OF GR

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?

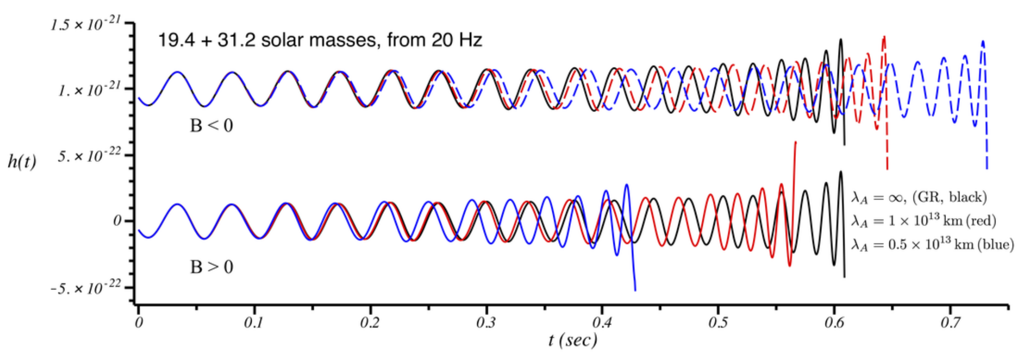
Mass of the graviton

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

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
THE LOUDEST AND CLOSEST GW SIGNAL EVER DETECTED

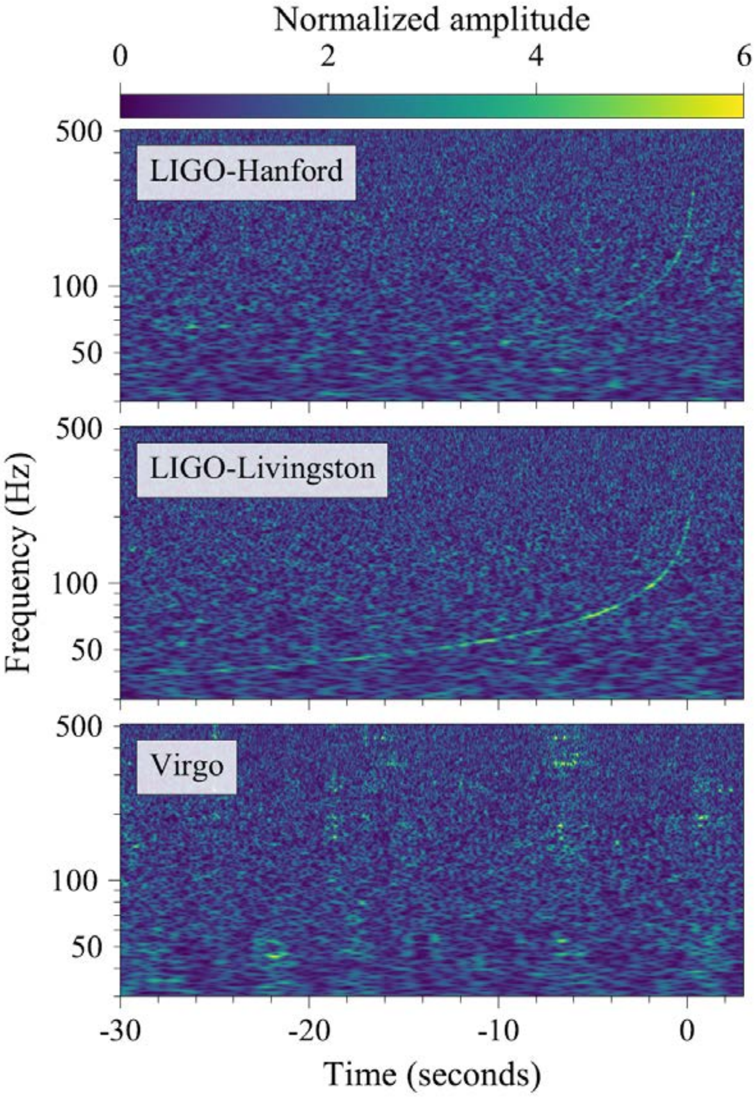
Combined SNR = 32.4
- LIGO-Livingston: 26.4
- LIGO-Hanford: 18.8
- Virgo: 2.0

GW170817 swept through the detectors' sensitive band in ~100 s (f_{start} = 24 Hz)
~3000 cycles in band

Sky localization ~28 deg^2

Identified by matched filtering the data against post-Newtonian waveform models

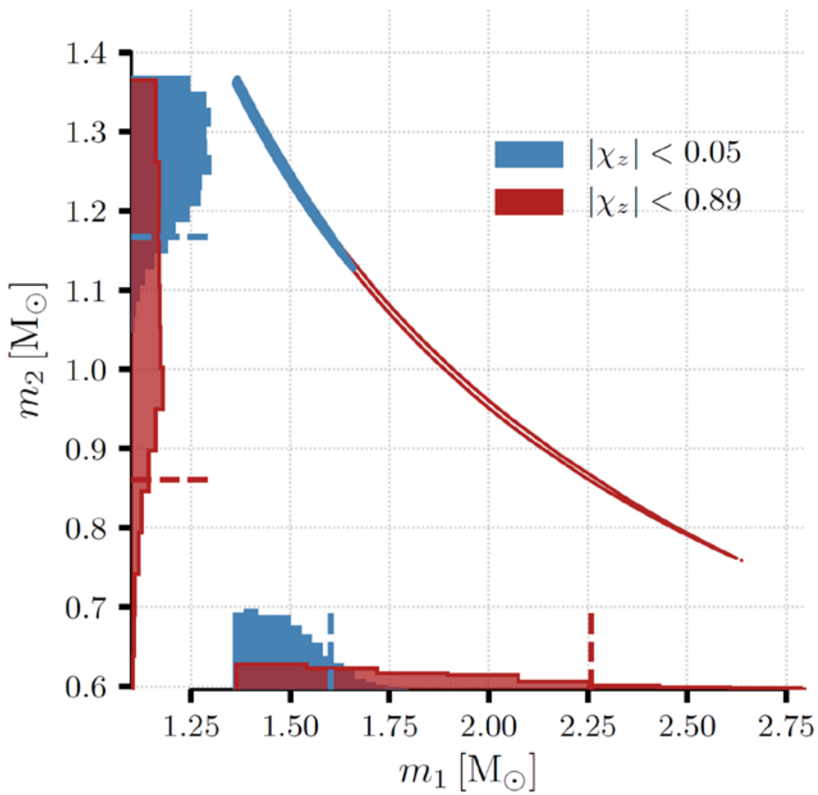
Virgo data used for sky localization and estimation of the source properties



PRL 119, 161101 (2017)

COMPONENT MASSES

Two dimensional posterior distribution for the component masses m_1 and m_2 in the rest frame of the source for the low–spin scenario ($|\chi_z|< 0{:}05$, blue) and the high–spin scenario ($|\chi_z|< 0{:}89$, red)



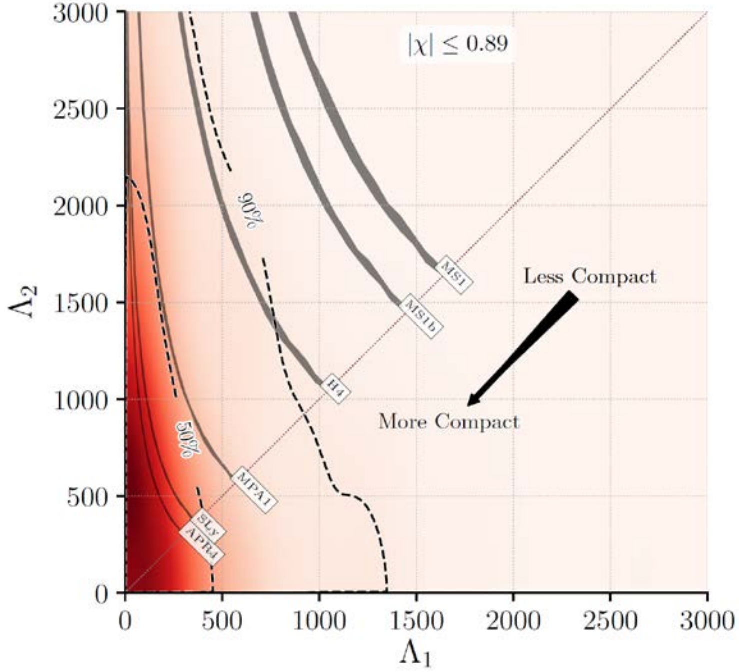
The shape of the two dimensional posterior is determined by a line of constant $\mathcal{M}$ and its width is determined by the uncertainty in $\mathcal{M}$

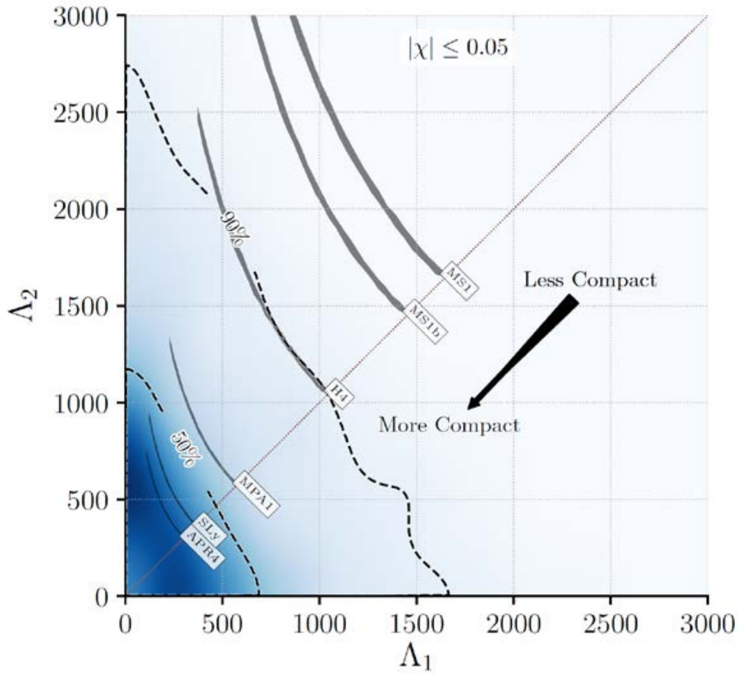
The widths of the marginal distributions is strongly affected by the choice of spin priors

The result using the low–spin prior (blue) is consistent with the masses of all known binary neutron star systems.

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} = \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3} \dot{f}\right]^{3/5}$$

$$\mathcal{M} = 1.188^{+0.004}_{-0.002} M_\odot$$





PROBING THE STRUCTURE OF NEUTRON STARS

Tidal effects leave their imprint of the gw signal from BNS. This provides infos about their deformability

To leading order the gw phase is determined by the parameter

$$\tilde{\Lambda} = \frac{16}{13} \frac{(m_1 + 12m_2)m_1^4\Lambda_1 + (m_2 + 12m_1)m_2^4\Lambda_2}{(m_1 + m_2)^5}$$

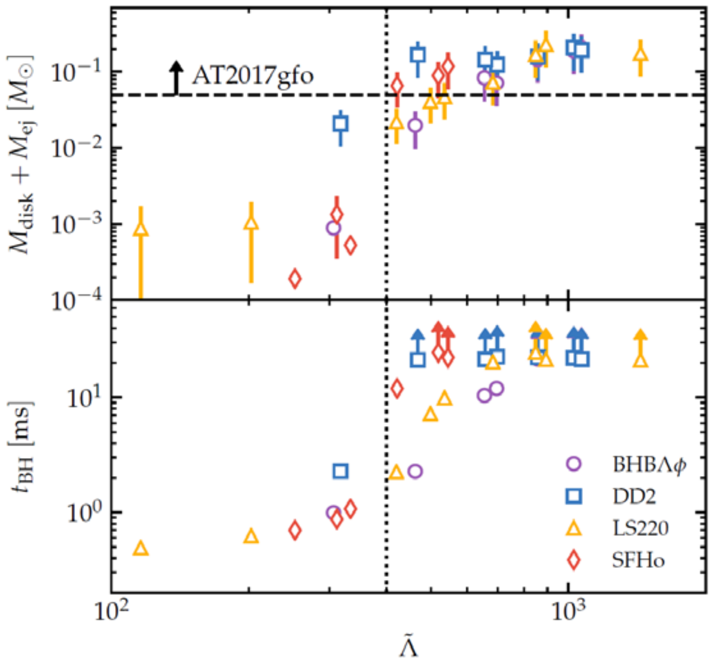
Λ_i: tidal deformability parameter

$$\Lambda = (2/3)k_2[(c^2/G)(R/m)]^5.$$

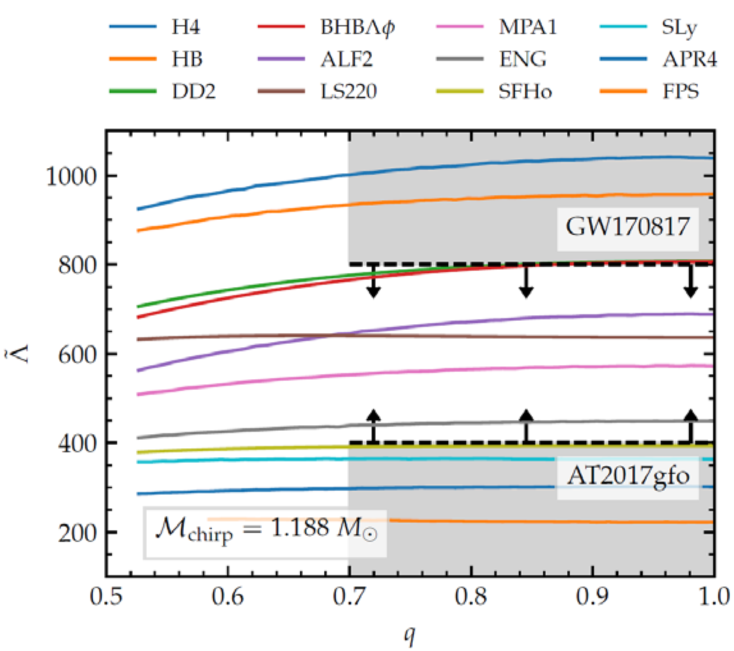
k_2 = second Love number
NS response to an applied gravitational field

EOS that produce less compact stars, such as MS1 and MS1b, are ruled out

PROBING THE STRUCTURE OF NEUTRON STARS



The interpretation of the UV/optical/infrared counterpart of GW170817 with kilonova models, combined with new numerical relativity results, imply a complementary lower bound on the tidal deformability parameter

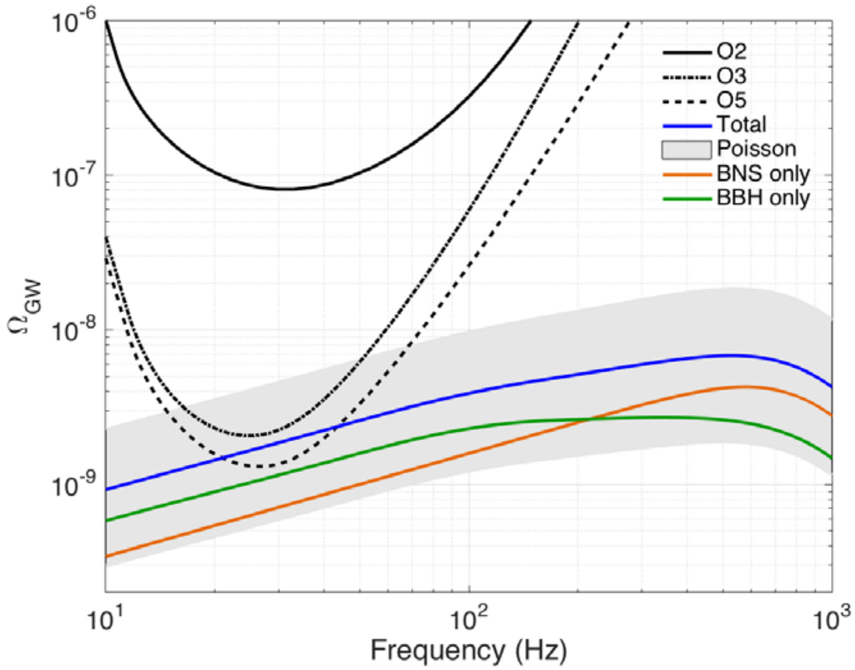


The joint constraints tentatively rule out both extremely stiff and soft NS equations of state

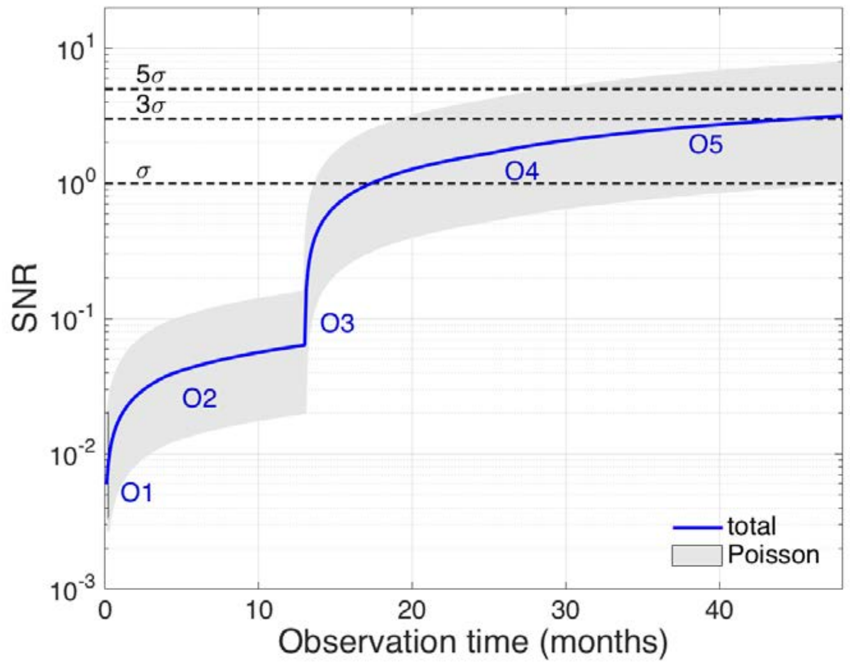
Astrophys. J. Lett. 852:L29 (2018)

ASTROPHYSICAL STOCHASTIC BACKGROUND

GW170817 allows to estimate the level at which binary NSs contribute to the stochastic background



$$R = 1540^{+3200}_{-1220} \text{ Gpc}^{-3} \text{ yr}^{-1}$$



arXiv:1710.05837

GW170817 REMNANT

EM observations have not been able, so far, to give an answer

The outcome of the BNS coalescence can be:

- **BH prompt formation** (high frequency quasi-normal modes)
- **Hypermassive NS** collapsing to a BH in < 1s (burst-like signal)
- **Supramassive NS** collapsing to a BH in 10 - 10^4 s (long-transient signal)
- **Stable NS** (continuous-wave signal)

Searches for short (<1 s) and medium (< 500 s) duration transients have not found any signals

Searches for long-duration transients are currently ongoing

Astrophys. J. Lett. 851, L16 (2017)

Low-latency:

Hanford–Livingston (190 deg^2)

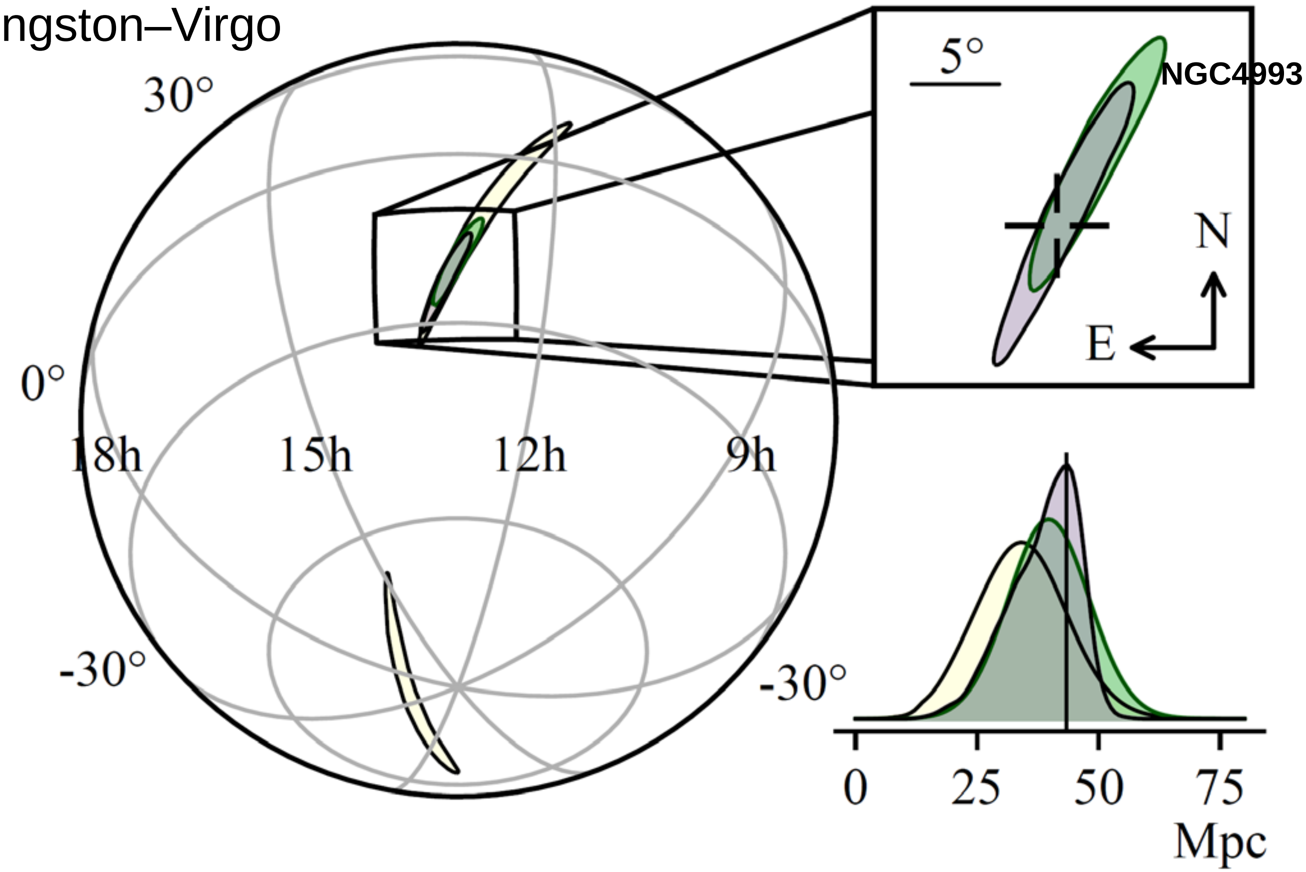
Hanford–Livingston–Virgo (31 deg^2)

LOCALIZATION

Higher latency:

Hanford–Livingston–Virgo

28 deg^2



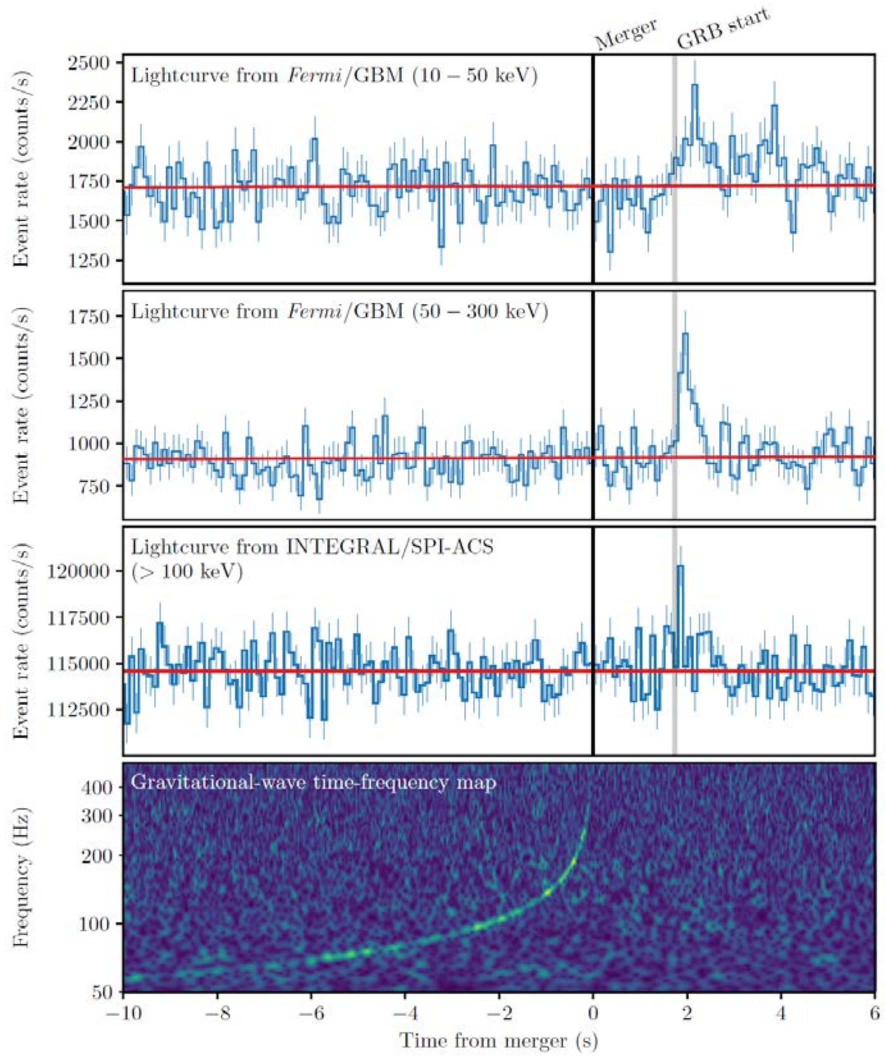
Luminosity distance distribution from the three GW localization analyses The distance of NGC 4993, assuming the redshift from the NASA/IPAC Extragalactic Database and standard cosmological parameters is shown with a vertical line

GRB 170817A

The Fermi Gamma-ray Burst Monitor Independently detected a gamma-ray burst (GRB170817A) with a time-delay of
1.734 ± 0.054 s with respect to the merger time

The probability of a chance temporal and spatial association of GW170817 and GRB 170817A is
5.0×10^{-8}

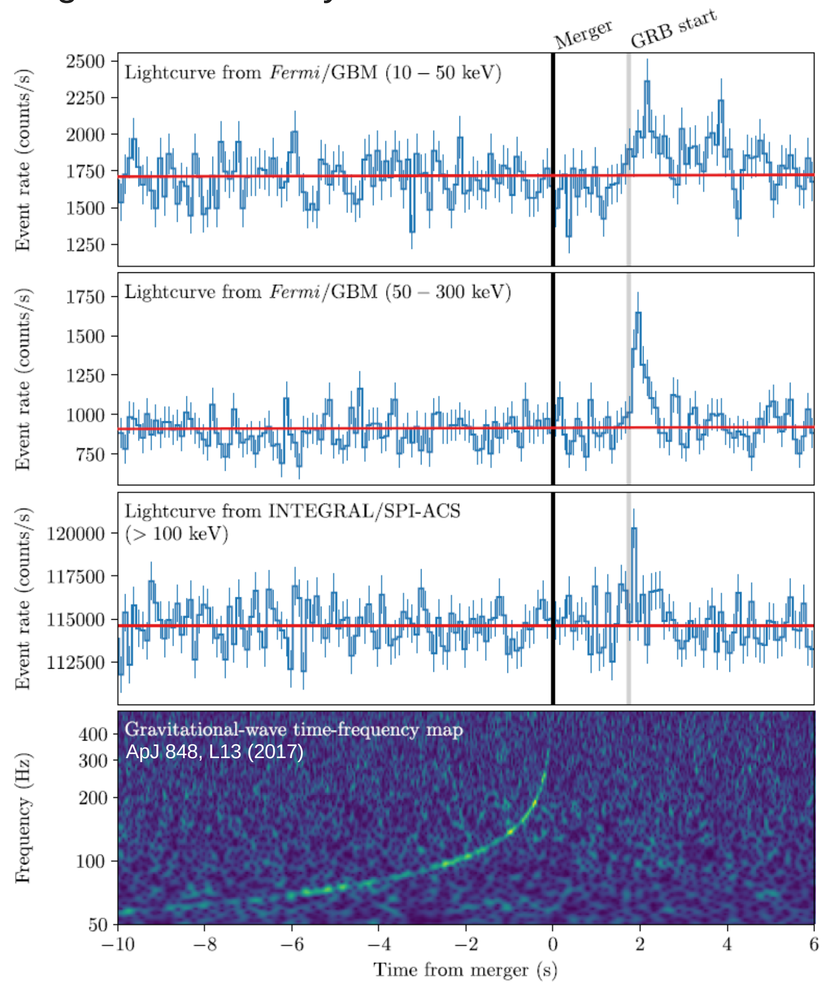
Binary neutron star (BNS) mergers are progenitors of (at least some) SGRBs



Astrophys. J. Lett. 848, L13 (2017)

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

$$\delta t_{\rm S} = -\frac{1+\gamma}{c^3}\int_{\mathbf{r}_e}^{\mathbf{r}_o} U(\mathbf{r}(l))dl.$$

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

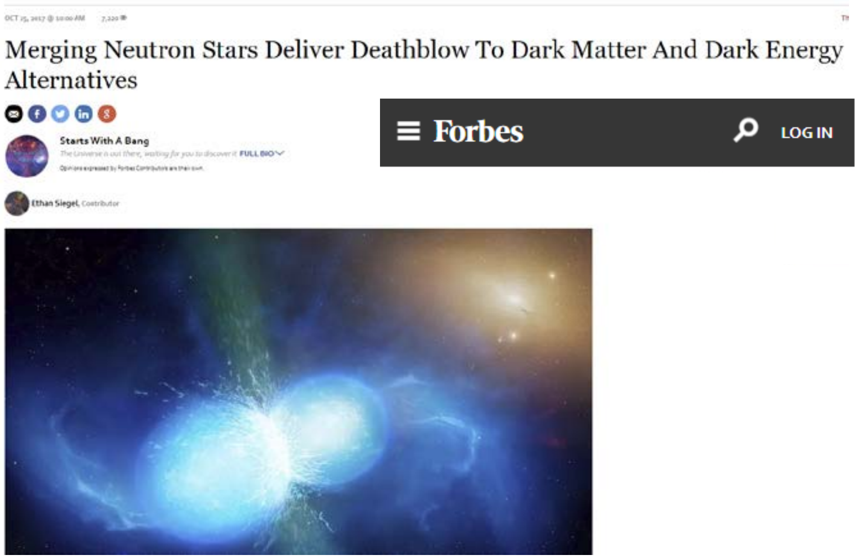
$$-1.2\times10^{-6} \leq \gamma_{\rm GW} - \gamma_{\rm EM} \leq 2.6\times10^{-7}$$

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

$$\Delta\gamma \leq 4\times10^{-9}.$$

DARK ENERGY AND DARK MATTER AFTER GW170817

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


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

Forbes

LOG IN

Starts With A Bang

Ethan Siegel

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:1710.06168

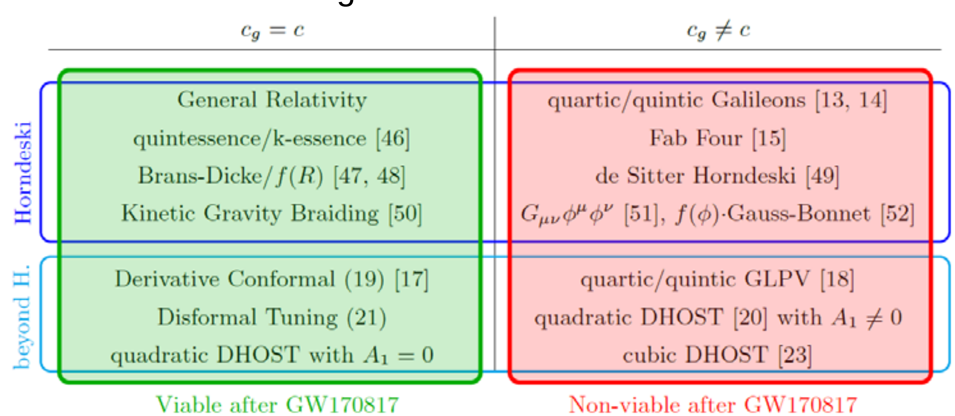
Dark Energy after GW170817

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

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



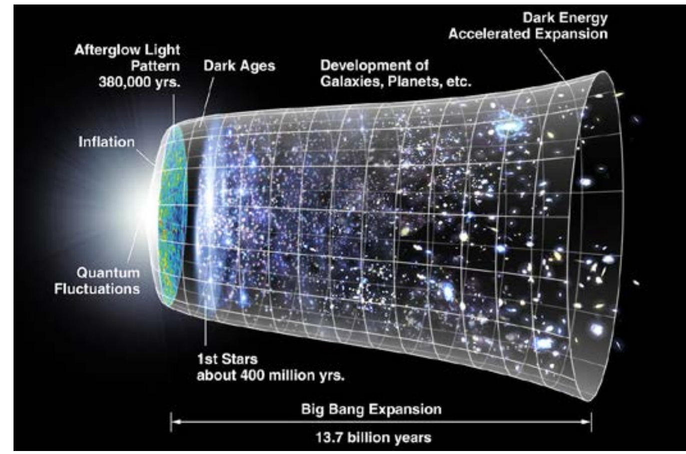
PRL 119, 251304 (2017)

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

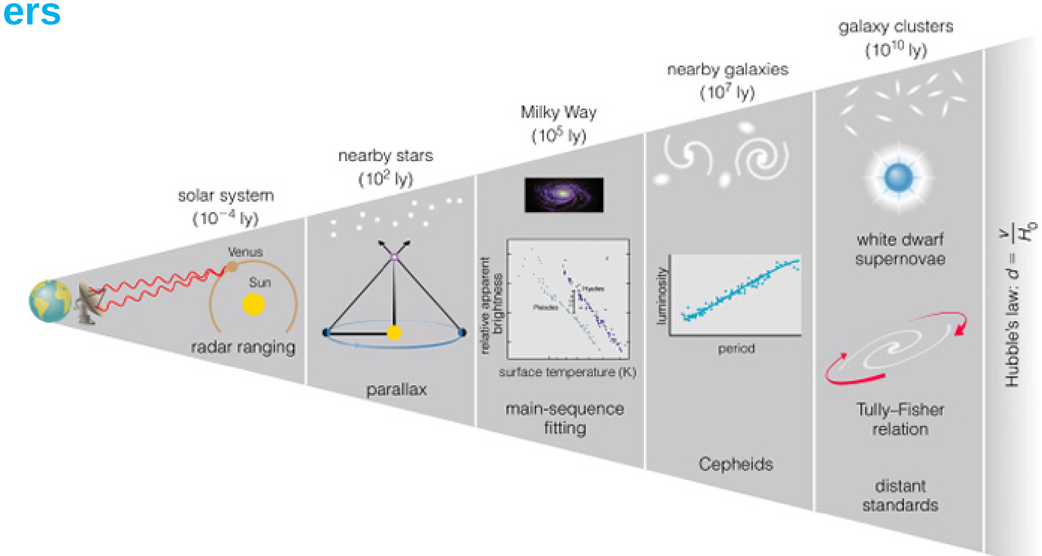
Current measurements depend on cosmic distance ladder

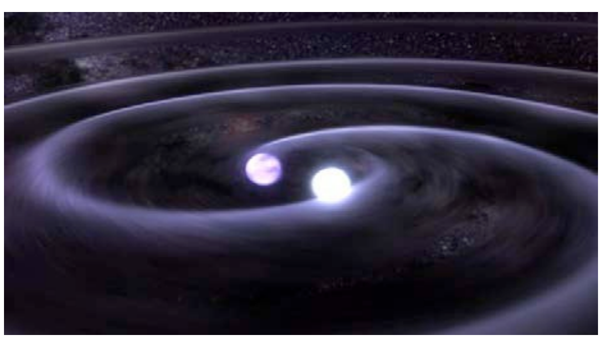
- Intrinsic brightness of *e.g.* supernovae determined by comparison with different, closer-by objects
- Possibility of systematic errors at every “rung” of the ladder



Gravitational waves from binary mergers

Distance can be measured directly from the gravitational wave signal!





A NEW COSMIC DISTANCE MARKER

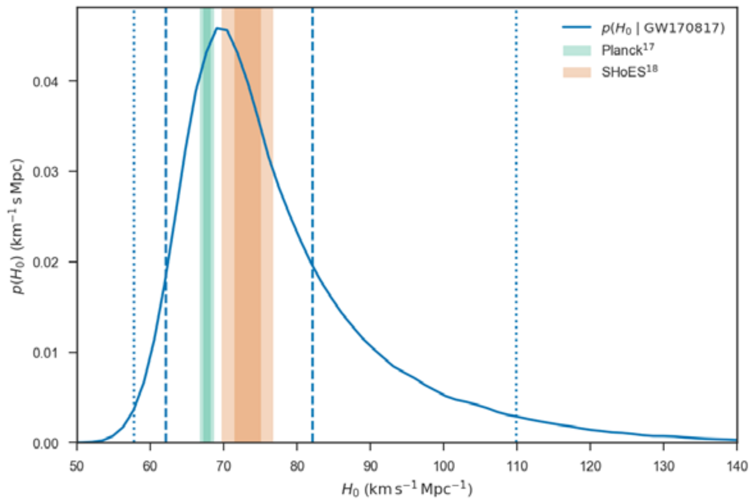
A few tens of detections of binary neutron star mergers allow determining the Hubble parameters to about 1% accuracy

Measurement of the local expansion of the Universe

The Hubble constant

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

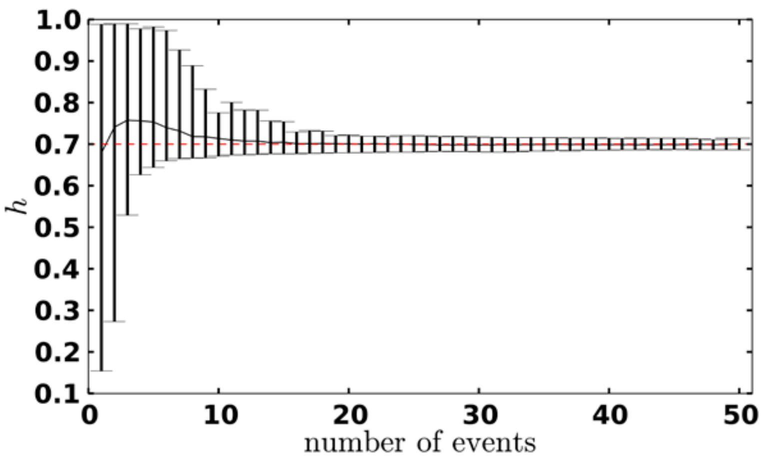
LVC, Nature 551, 85 (2017)



GW170817

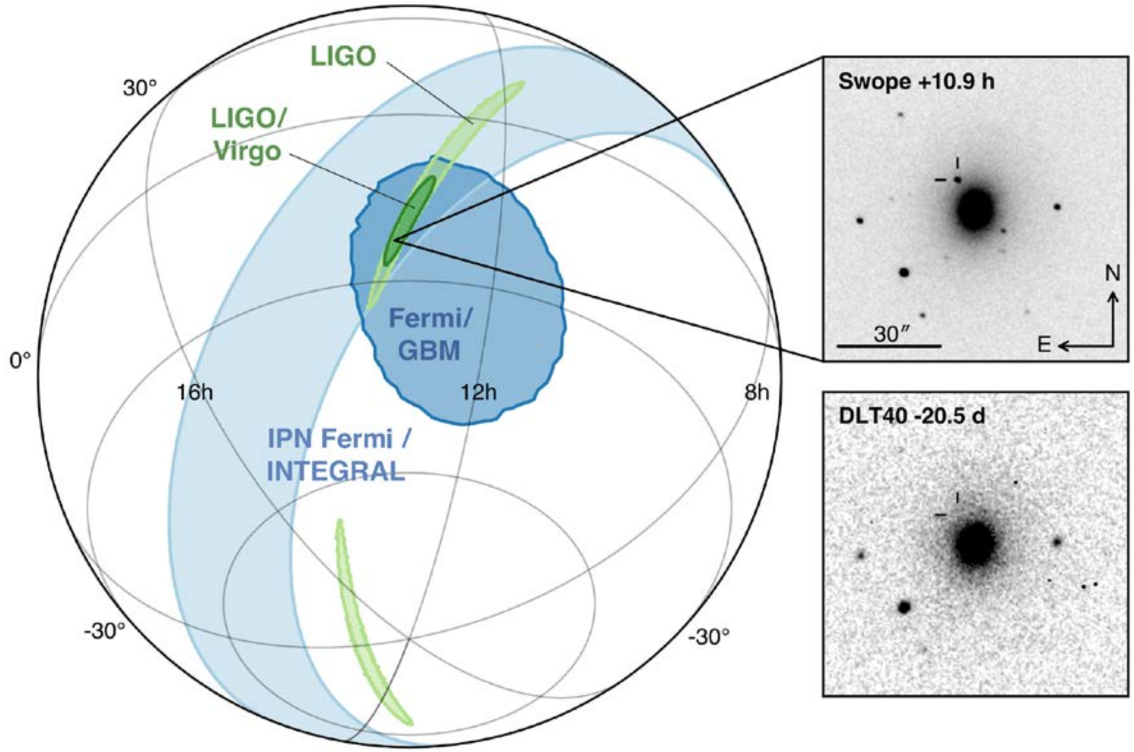
- One detection: limited accuracy
- Few tens of detections with LIGO/Virgo will be needed to obtain O(1%) accuracy

Del Pozzo, PRD 86, 043011 (2012)



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

GW170817: START OF MULTIMESSENGER ASTRONOMY

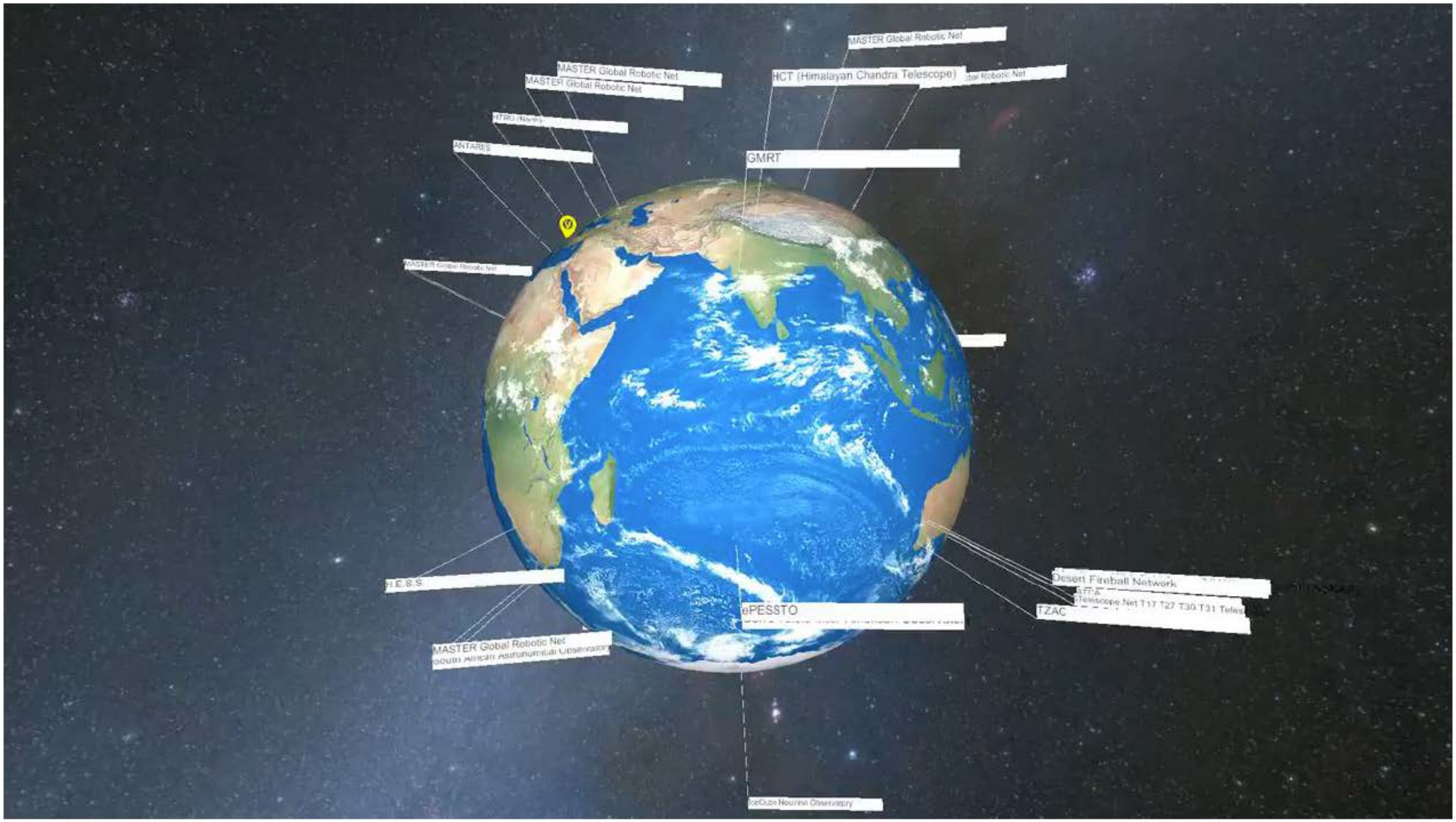


Location of the apparent host galaxy **NGC 4993** in the Swope optical discovery image 10.9 hrs after the merger

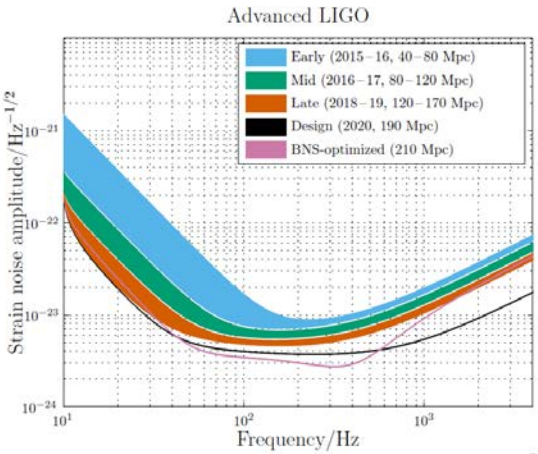
Astrophys. J. Lett. 848, L12 (2017)

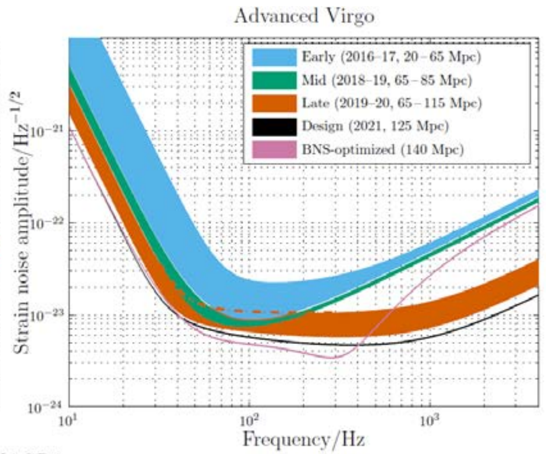
WORLDWIDE EFFORT TO OBSERVE GW170817

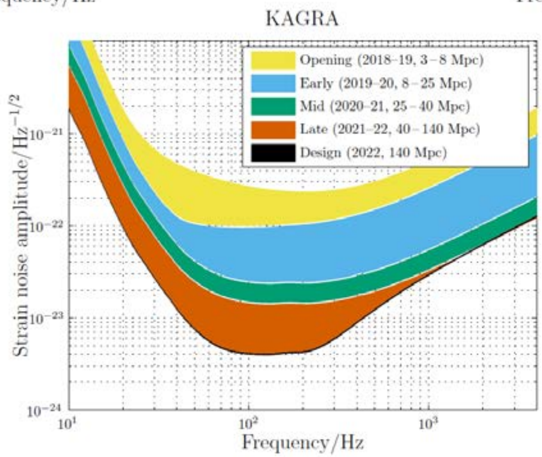
GW170817 was observed by about 70 observatories all over Earth (including Antarctica) and in space

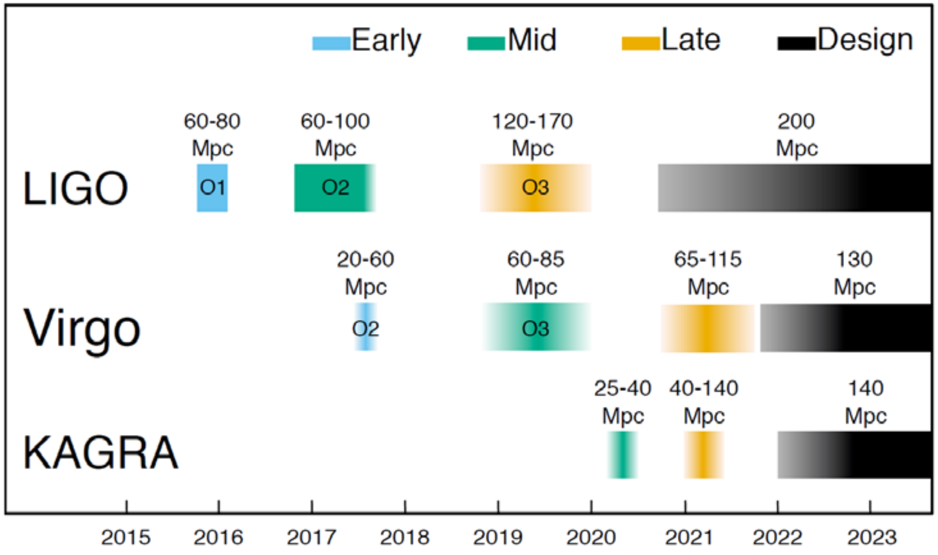


LIGO-VIRGO-KAGRA OBSERVING SCENARIO



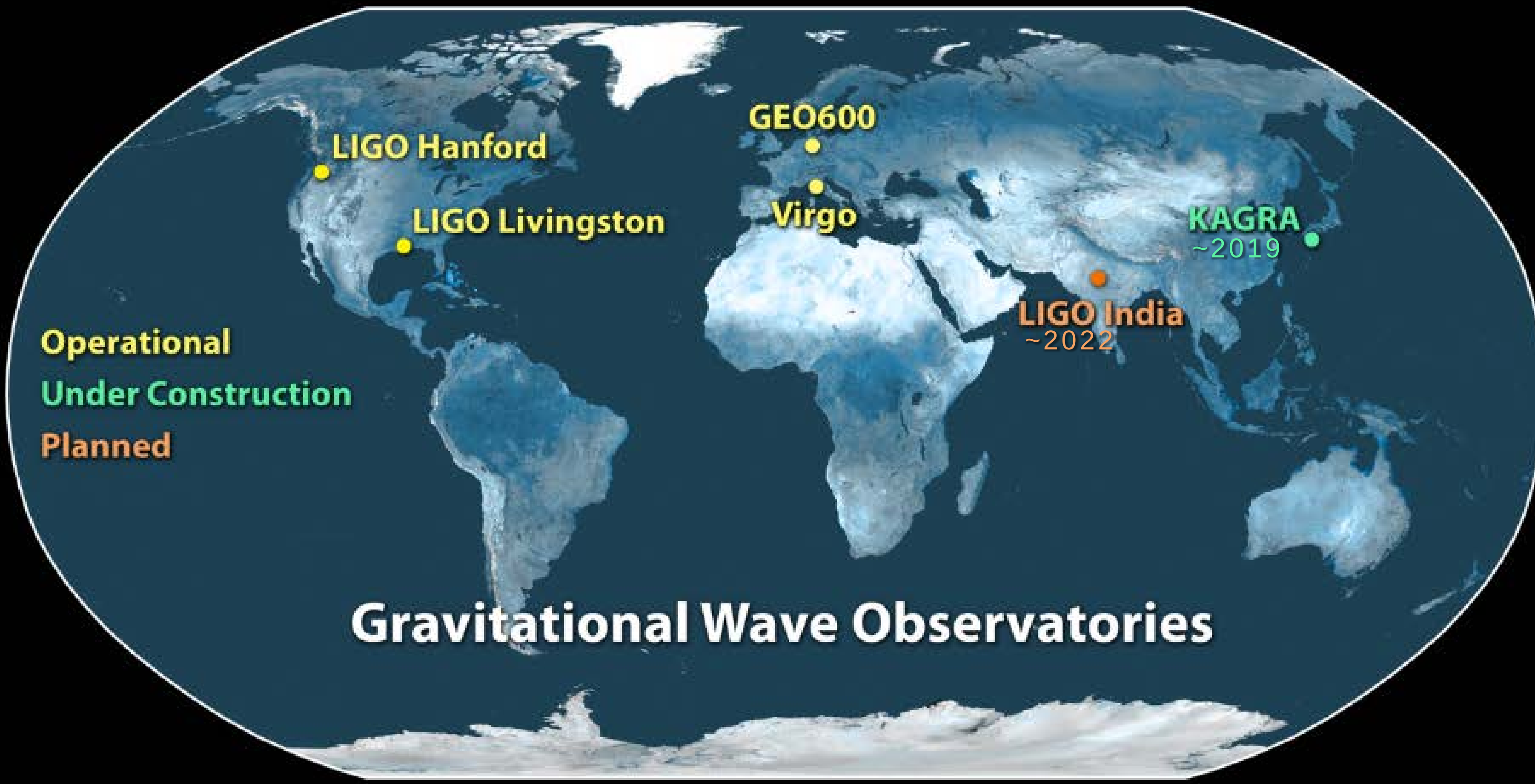






arXiv:1304.0670
Living Rev Relativ (2016) 19

TOWARDS A GLOBAL GW RESEARCH INFRASTRUCTURE



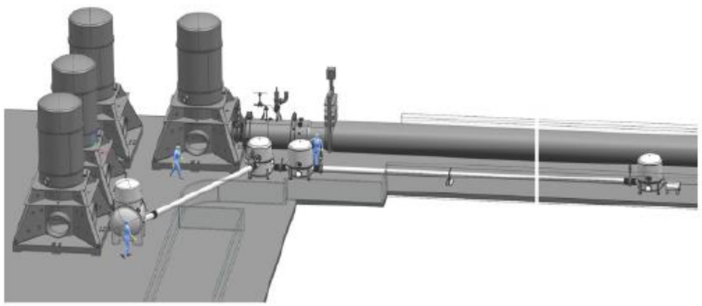
THE NETWORK IS THE DETECTOR

ADVANCED VIRGO+

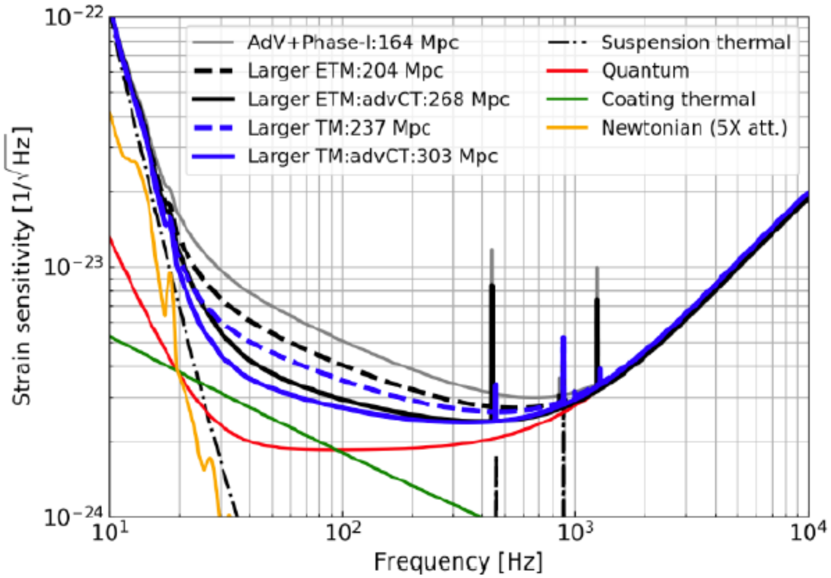
Quantum noise will be tackled and thermal noise reduced. The optical design of the Fabry-Perot arms will be modified to accommodate larger beams and heavier test masses

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

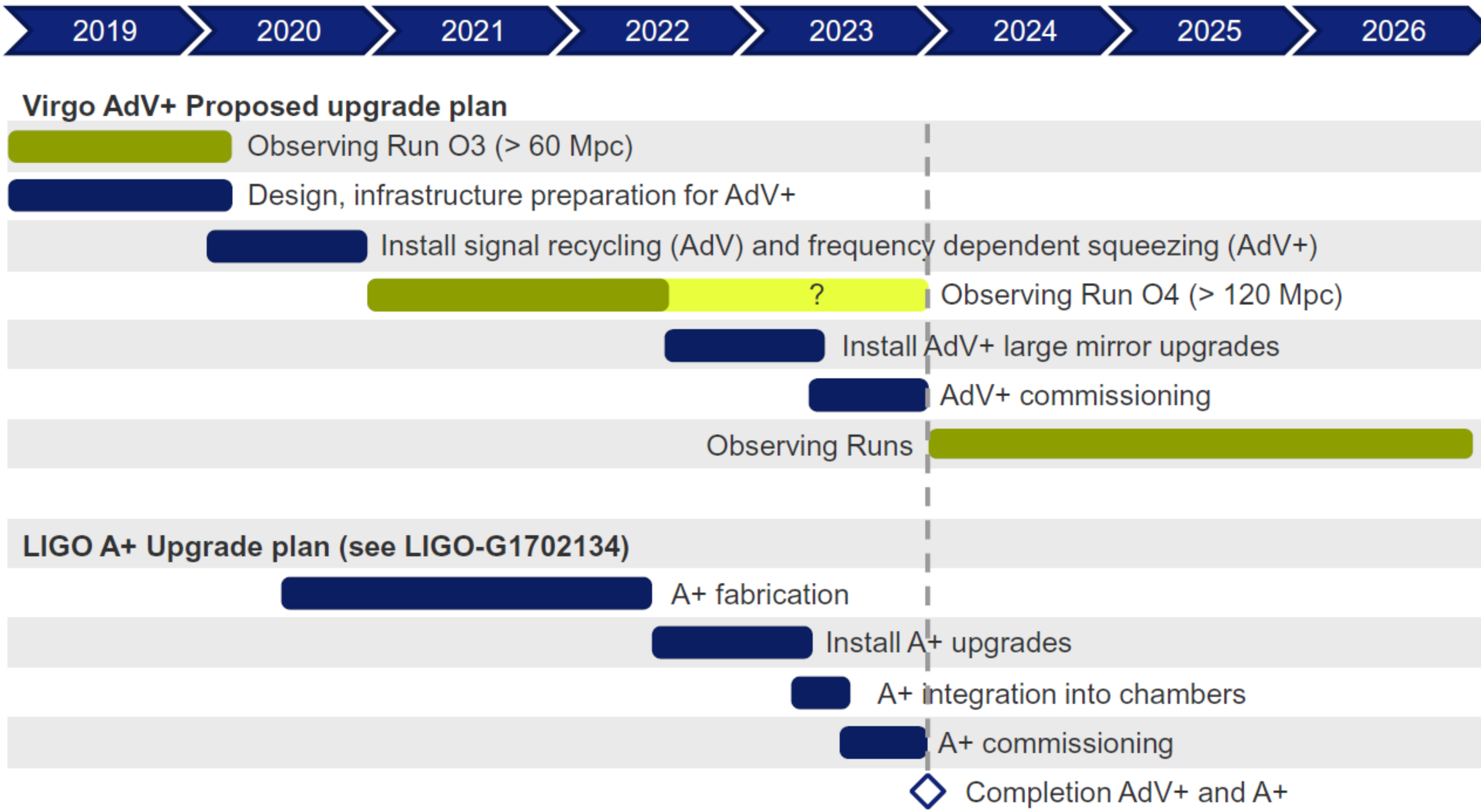


- Secure Virgo's scientific relevance
- Safeguard investments by scientists and funding agencies
- Implement new innovative technologies
- De-risk technologies needed for third generation observatories
- Attract new groups wanting to enter the field

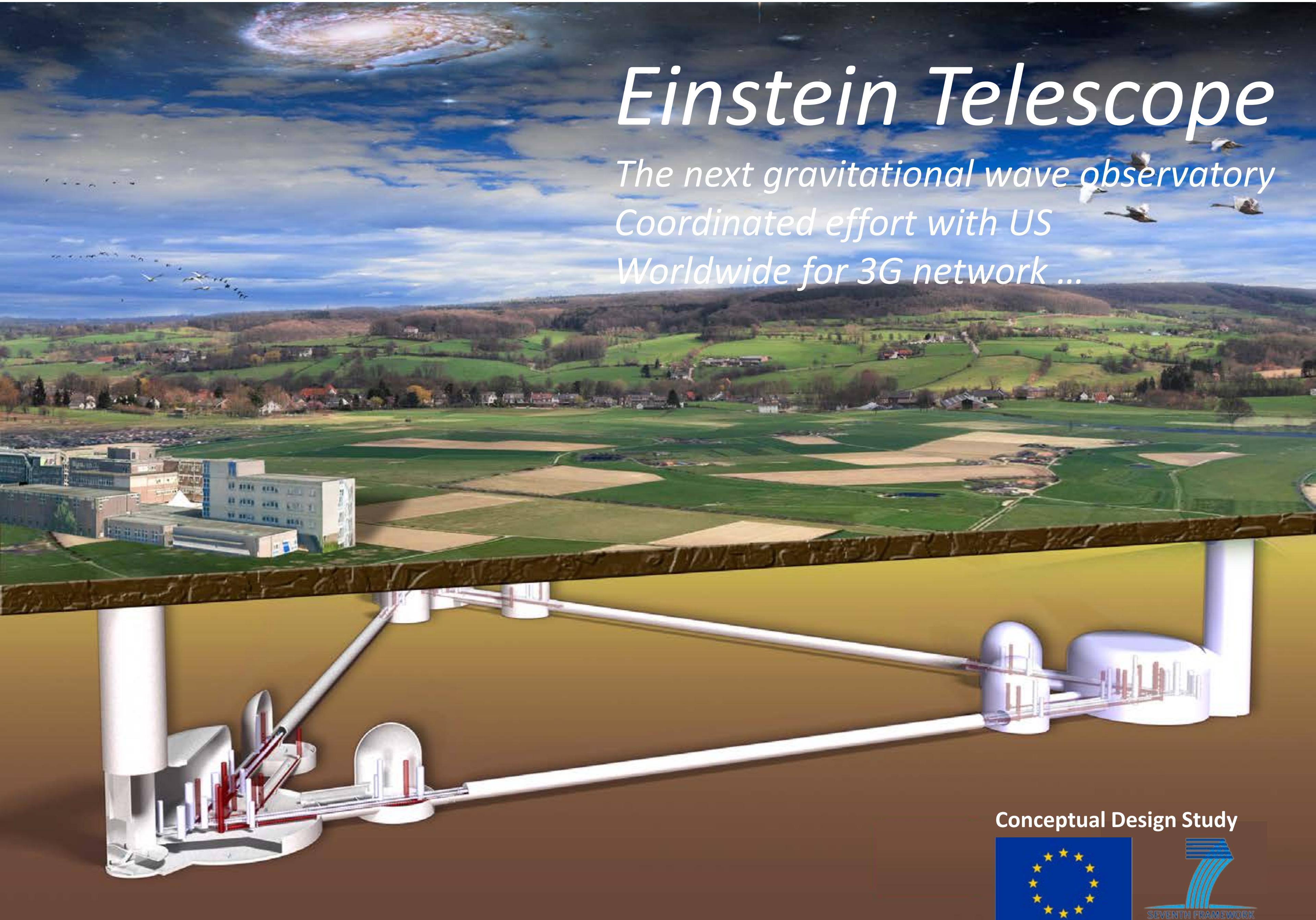


TENTATIVE TIMELINE

Five year plan for observational runs, commissioning and upgrades



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


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

SCIENTIFIC IMPACT OF GW 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 fall this year

OUTLOOK

Upgrade of VIRGO, to guarantee that it will maintain its leading position at the frontier of European science and technology in the next 15-20 years

Kick-off of an R&D program, to provide a strategic advantage to the national scientific community in key technologies that will enable the realization of the next generation of ground-based detectors at the end of the next decade

Involvement of a wide community of Italian scientists in support of the design, requirement and architecture definition of the experiment, to create a critical mass of scientists that will drive the design and scientific exploitation of the present and of the next generation detectors, on Earth and in space