The Virgo gravitational wave interferometer: status and perspectives

Francesco Fidecaro, University of Pisa and INFN
On behalf of the Virgo and LSC Collaborations
CERN, February 13, 2018

VIR-0097A-18

Outline

- Interferometers for gravitational wave detection
- The events in Observation run 2
- Plans for the future

GW detection

Gravitational waves are ripples in space time

Test masses in free fall track changes in space time By measuring separation between two test masses one can track changes in space time

Expected change, h is the deviation from flat space time:

$$\frac{\Delta L}{L} = \frac{h}{2}$$

$$h \approx 10^{-21}, L = 3km, \Delta L = 10^{-18}\text{m}$$

(Compton wavelength of a 1.2 TeV particle)

Laser wavelength:	$1.064\ 10^{-6}$ m
Ground motion over 1 s:	10^{-7} m
Thermal excitation of a 1 m pendulum	
40 kg, 300 K:	$3.2\ 10^{-12}$ m
160 kg, 20 K:	$4\ 10^{-13}$ m

This has been achieved with events GW150914, GW151226 (and candidate LVT151012) during the first observation run O1, awarding our colleagues Rainer Weiss, Barry Barish and Kip Thorne the Nobel prize 2017.

GW INTERFEROMETERS

An initial idea of Alain Brillet and Adalberto Giazotto

ADVANCEDVIRGO

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

Two 4 km interferometers separated by 3000 km

	AdV	aLIGO*
Date of approval	Dec 2009	Apr 2008
End of integration	Aug 2016	Oct 2014 (LHO)
First stable lock	Mar 2017	Feb 2015 (LHO)
Start of science run	Aug 2017	Sep 2015
Budget	23.9 ME HW	205 MUSD + in kind, HW+manpower 3 itf

~6.5 yrs

~7.5 yrs

LIGO Scientific Collaboration
900+ members 80+ institutions
16 countries

- Abilene Christian University
- Albert-Einstein-Institut
- American University
- Andrews University
- Bellevue College
- California Institute of Technology
- California State Univ., Fullerton
- California State Univ., Los Angeles
- Canadian Inst. Th. Astrophysics
- Carleton College
- Chinese University of Hong Kong
- College of William and Mary
- Colorado State University
- Columbia U. in the City of New York
- Cornell University
- Embry-Riddle Aeronautical Univ.
- Eötvös Loránd University
- Georgia Institute of Technology
- Goddard Space Flight Center
- GW-INPE, Sao Jose Brasil
- Hillsdale College
- Hobart & William Smith Colleges
- IAP – Nizhny Novogorod
- IIP-UFRN
- Kenyon College
- Korean Gravitational-Wave Group
- Louisiana State University
- Marshall Space Flight Center
- Montana State University
- Montclair State University
- Moscow State University
- National Tsing Hua University
- NCSARG – Univ. of Illinois, Urbana-Champaign

- Northwestern University
- Penn State University
- Rochester Institute of Technology
- Sonoma State University
- Southern University
- Stanford University
- Syracuse University
- Texas Tech University
- Trinity University
- Tsinghua University
- U. Montreal / Polytechnique
- Université Libre de Bruxelles
- University of Chicago
- University of Florida
- University of Maryland
- University of Michigan
- University of Minnesota
- University of Mississippi
- University of Oregon
- University of Sannio
- University of Szeged
- University of Texas Rio Grande Valley
- University of the Balearic Islands
- University of Tokyo
- University of Washington
- University of Washington Bothell
- University of Wisconsin – Milwaukee
- USC – Information Sciences Institute
- Villanova University
- Washington State University – Pullman
- West Virginia University
- Whitman College

LIGO Laboratory: California Institute of Technology; Massachusetts Institute of Technology;
LIGO Hanford Observatory; LIGO Livingston Observatory

Australian Consortium for Interferometric Gravitational Astronomy (ACIGA):
Australian National University; Charles Sturt University; Monash University; Swinburne University; University of Adelaide; University of Melbourne; University of Western Australia

German/British Collaboration for the Detection of Gravitational Waves (GEO600):
Albert-Einstein-Institut, Hannover; Cardiff University; King's College, University of London; Leibniz Universität, Hannover; University of Birmingham; University of Cambridge; University of Glasgow; University of Hamburg; University of Sheffield; University of Southampton; University of Strathclyde; University of the West of Scotland; University of Zurich

Indian Initiative in Gravitational-Wave Observations (IndIGO):
Chennai Mathematical Institute; ICTS-TIFR Bangalore; IISER Pune; IISER Kolkata; IISER-TVM Thiruvananthapuram; IIT Madras, Chennai; IIT Kanpur; IIT Gandhinagar; IPR Bhatt; IUCAA Pune; RRCAT Indore; University of Delhi

GW INTERFEROMETERS COMMUNITY

GEO 600: British-German 600 m delay line interferometer, plays an essential role in astrowatch and for the development of new ideas, part of LSC

KAGRA: Japanese project under the Kamioka Mountain, following long work on TAMA 300 and cryogeny development of LCGT

INDIGO: India joint project with LIGO (3 rd LIGO itf)

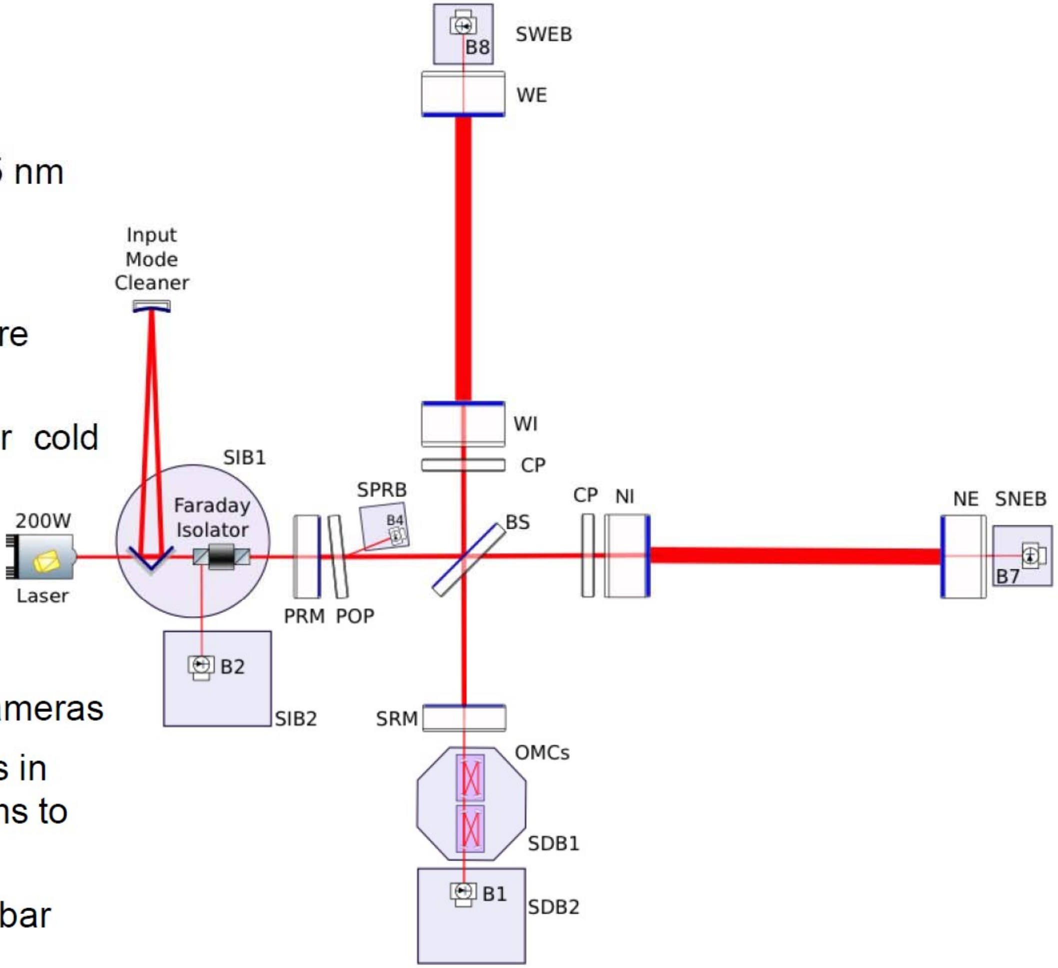
LISA: Laser Interferometer in Space Antenna, 2 million km arms

ADVANCED VIRGO DESIGN

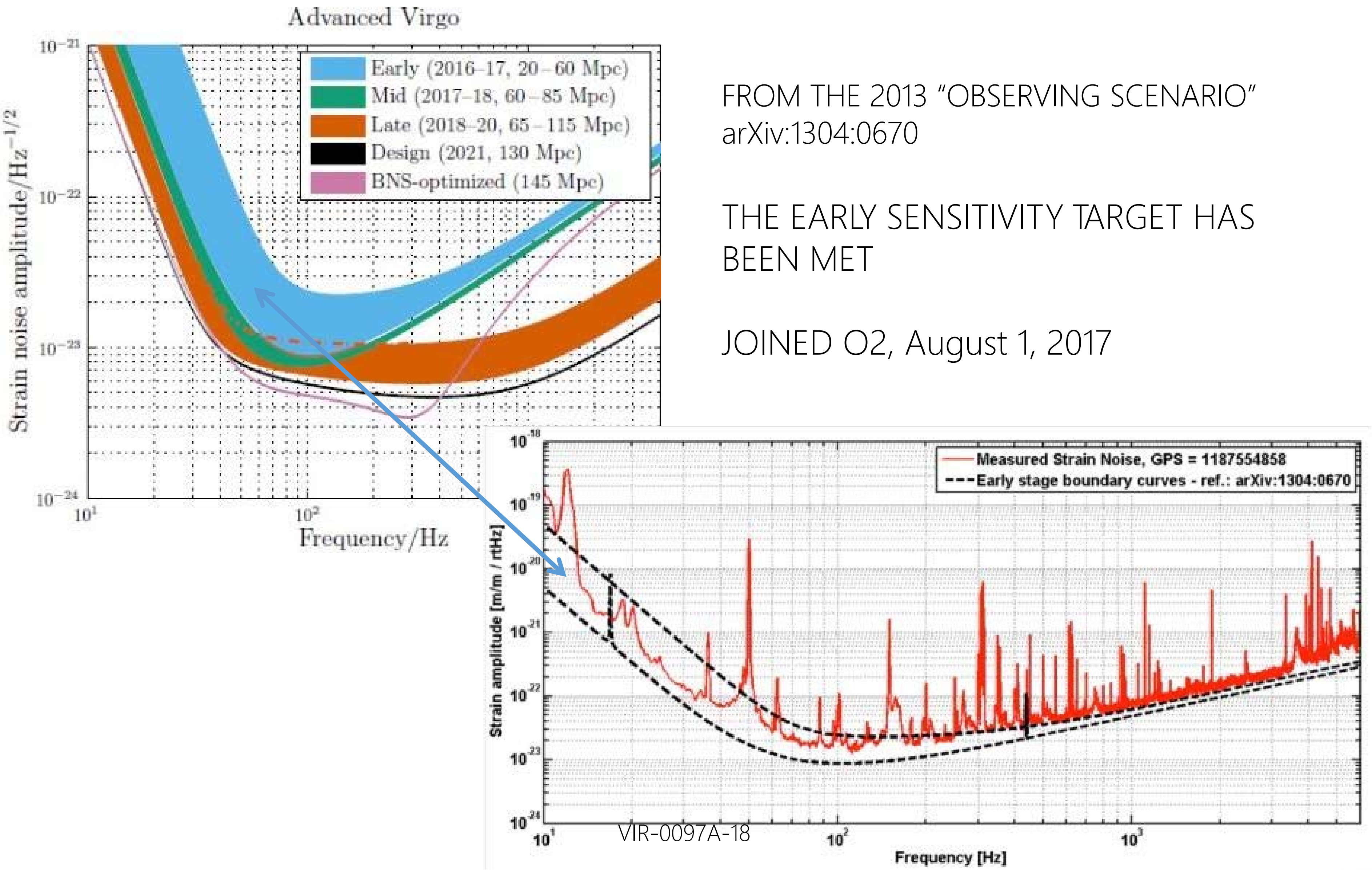
Advanced Virgo started operation on August 1, 2017. It features many improvements with respect to Virgo and Virgo+

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 CO2 actuators
  - CO2 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



SENSITIVITY FOR O2



FROM THE 2013 "OBSERVING SCENARIO"
arXiv:1304:0670

THE EARLY SENSITIVITY TARGET HAS BEEN MET

JOINED O2, August 1, 2017

THE O2 RUN - FACTS

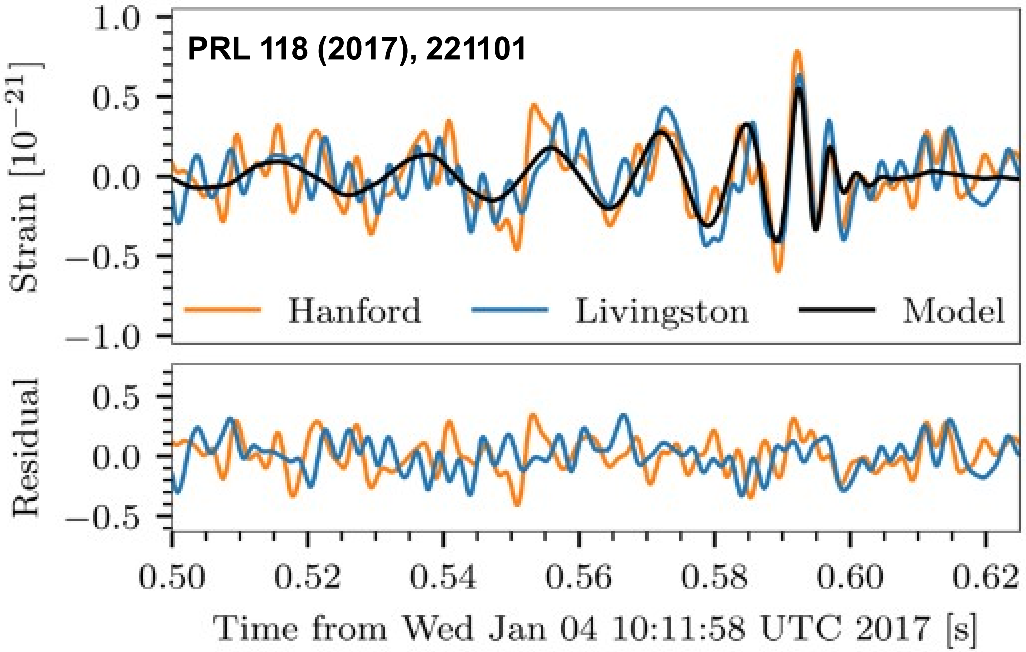
Started on November 30, 2016

Templates for waveforms, data analysis pipelines ready, together with adequate computing power

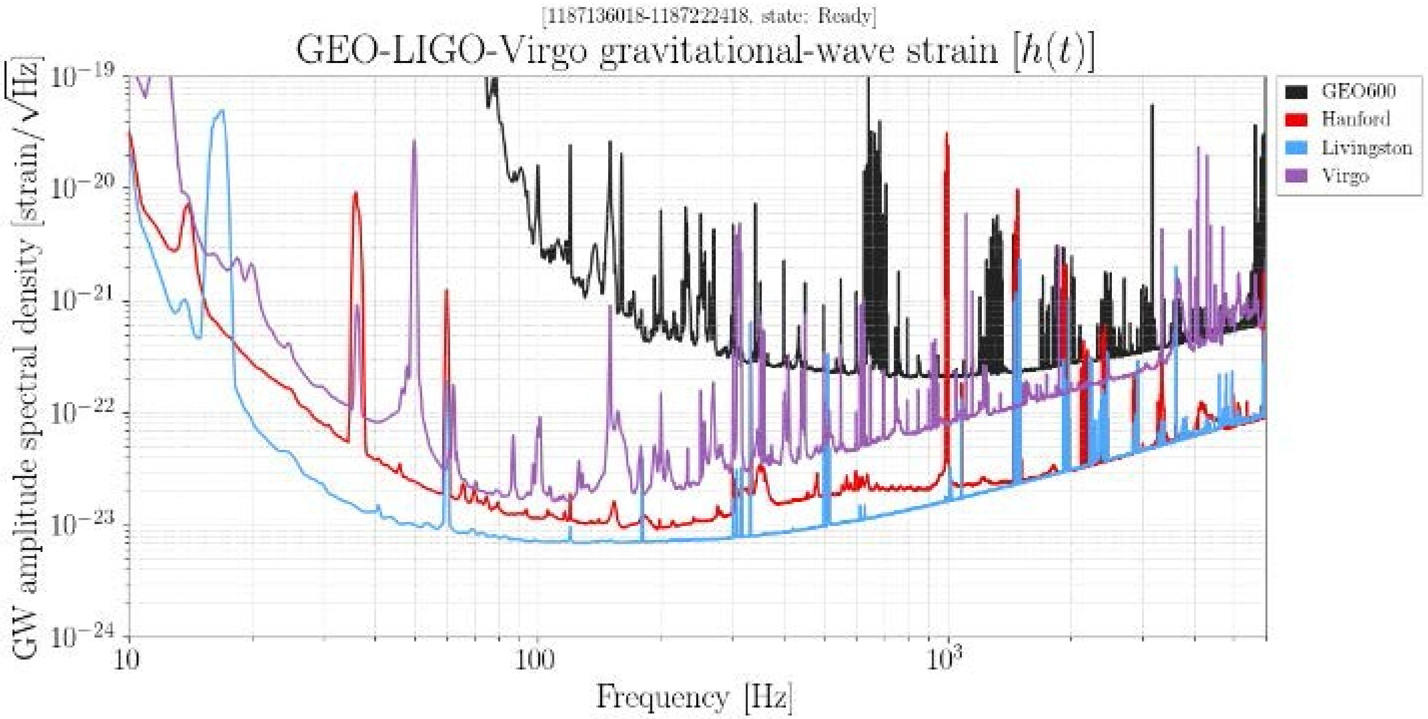
The run was stopped on Aug 25th, as previously planned by LIGO

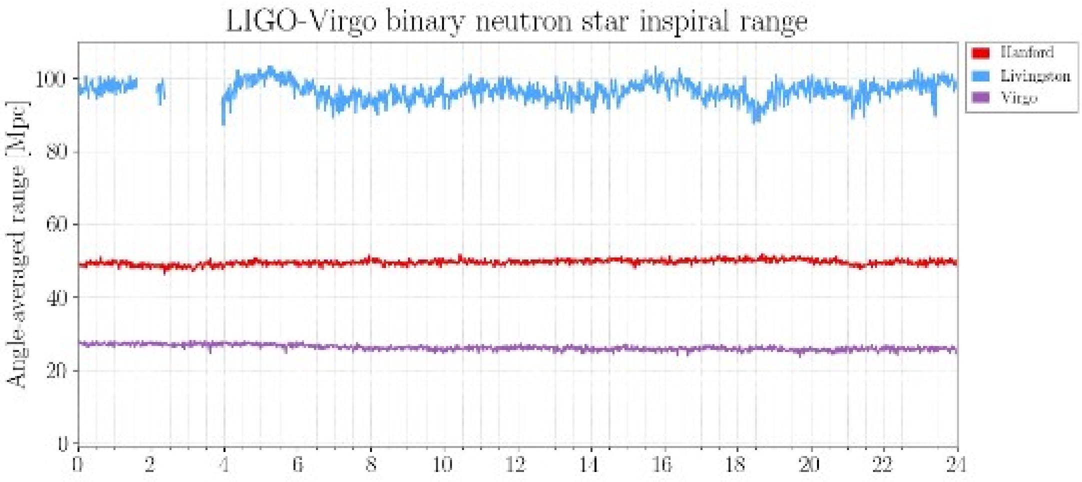
From Aug 1st to 25th: 14.9 days of triple coincidence observation

One event published before Aug 1st (GW170104)

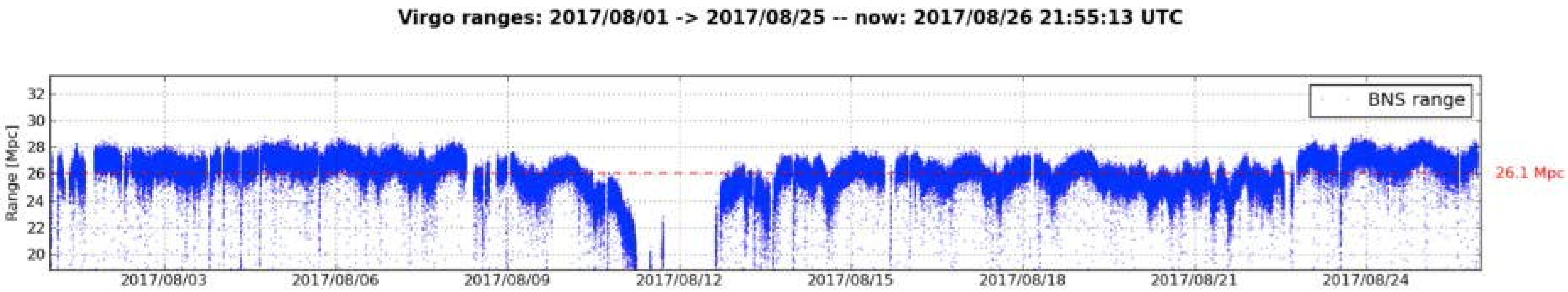


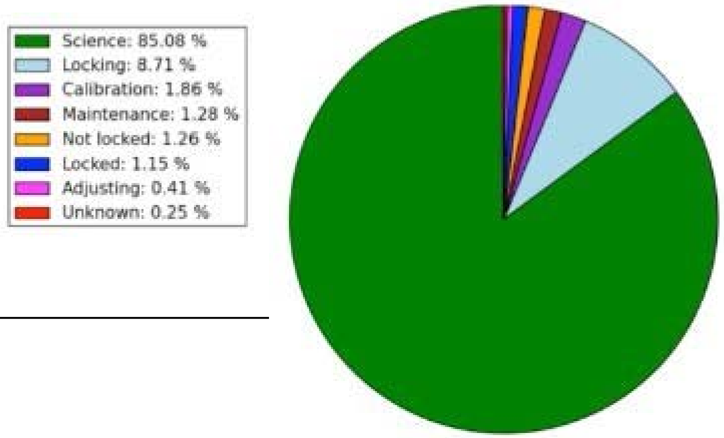
THE LV NETWORK





VIRGO IN O2


Virgo ranges: 2017/08/01 -> 2017/08/25 -- now: 2017/08/26 21:55:13 UTC



DUTY CYCLE: 85% (!!)

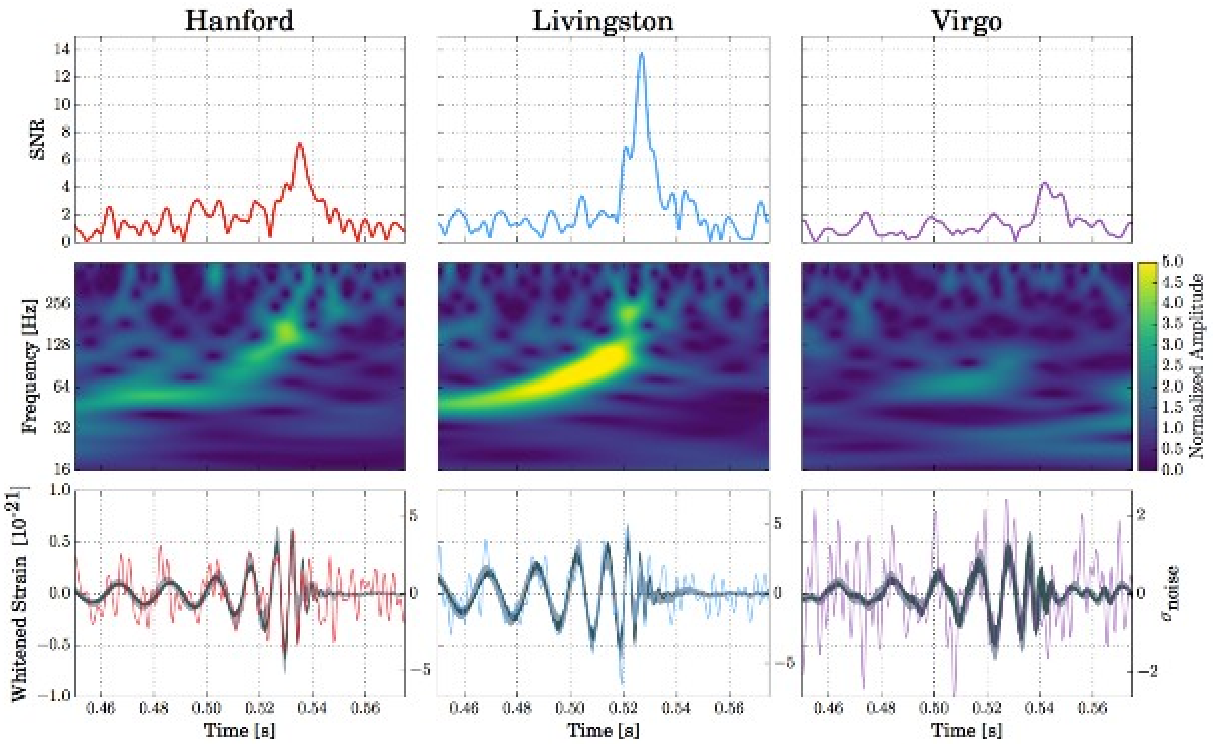
LONGEST LOCK STRETCH: 69 hours

HIGHEST BNS RANGE: 28.2 Mpc

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

GW170814: FIRST TRIPLE COHERENT SIGNAL FROM BBH

AUGUST 14TH, 2017

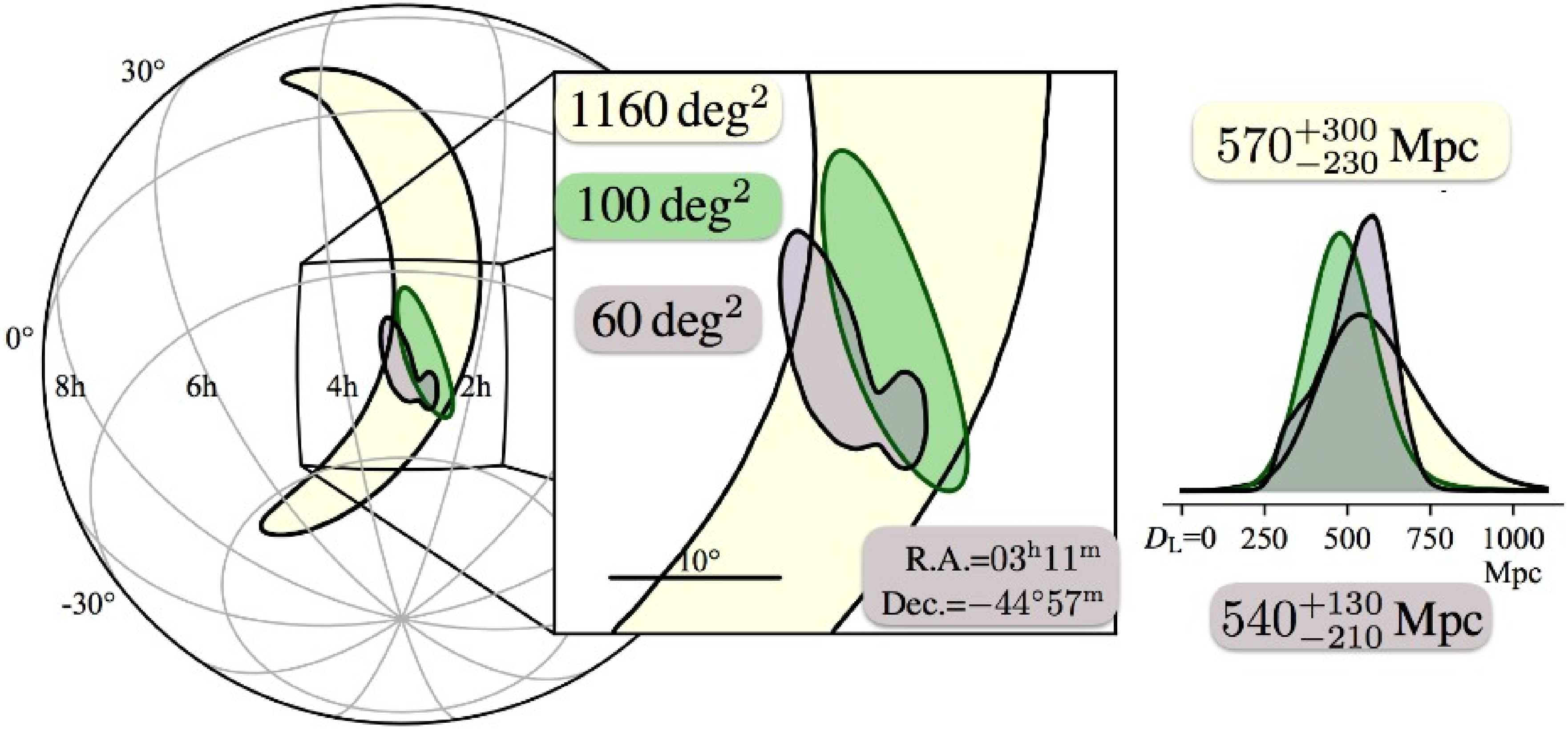


PRL, 119, 141101 (2017)

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

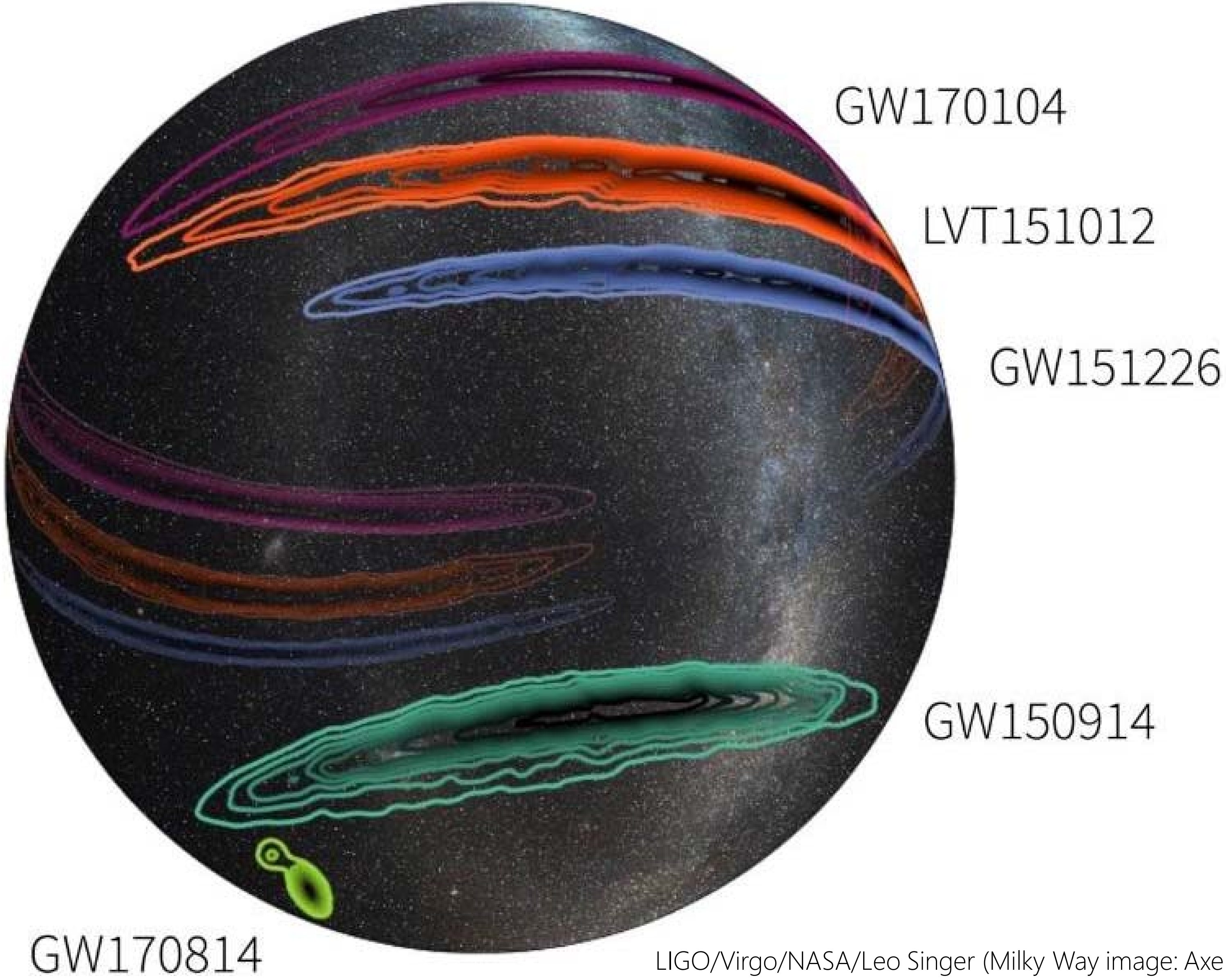


VIRGO REDUCES:

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 BEGUN

SKY AREAS

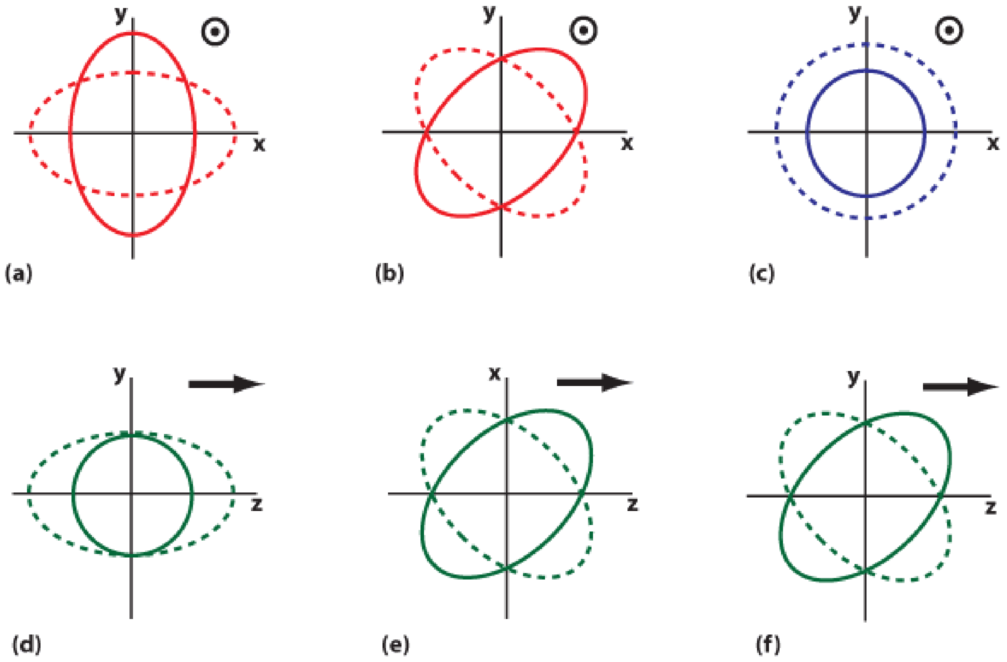


LIGO/Virgo/NASA/Leo Singer (Milky Way image: Axel Mellinger)

GW POLARIZATION STATES

TENSOR (SPIN 2)
GENERAL RELATIVITY

SCALAR (SPIN 0)



VECTOR (SPIN 1)

GENERAL METRIC THEORIES OF GRAVITY ALLOW UP TO 6 POLARIZATION STATES

LIGO and Virgo have different orientation, allowing to probe the nature of the polarization states

only models with “pure” polarization states (tensor, vector or scalar) have been considered
a study with “mixed” states is underway

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

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

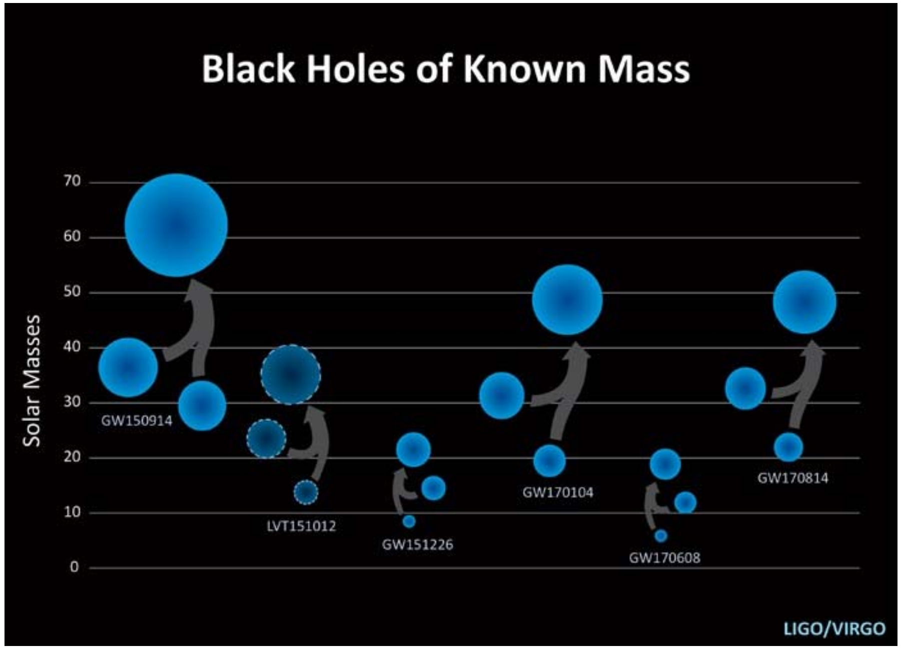
PROPERTIES OF BLACK HOLES

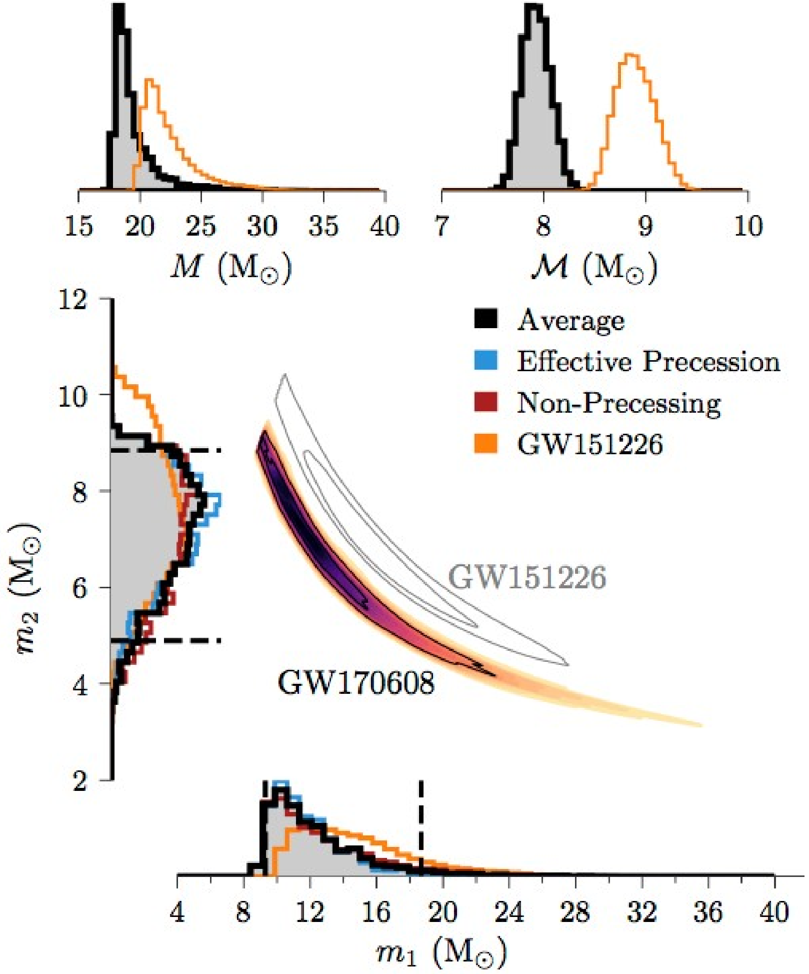
Extract information on masses, spins, energy radiated, position, distance, inclination, polarization.
Population distribution may shed light on formation mechanisms

LVC reported on 6 BBH mergers

Fundamental physics, astrophysics, astronomy, and cosmology

Testing GR, waveforms

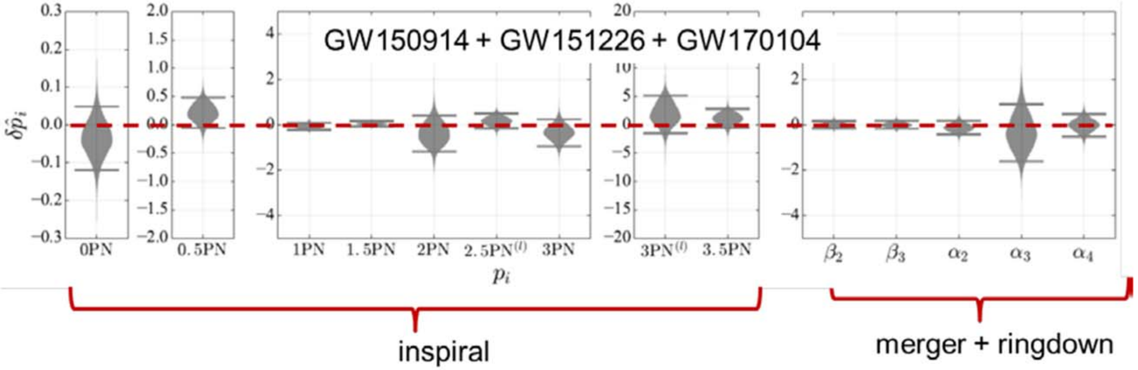




PRECISION TESTS OF GR

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?

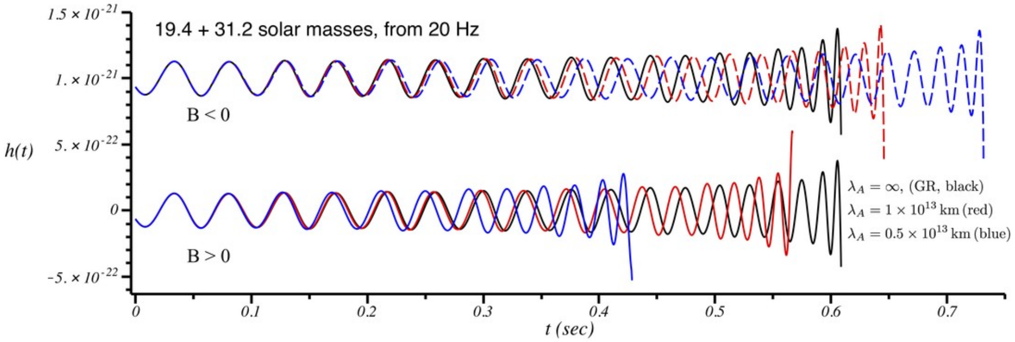
Mass of the graviton

Can be determined as $m_g \le 10^{-22}$ 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: FIRST BINARY NEUTRON STAR SIGNAL

GW170817: THE LOUDEST AND CLOSEST GW SIGNAL EVER DETECTED

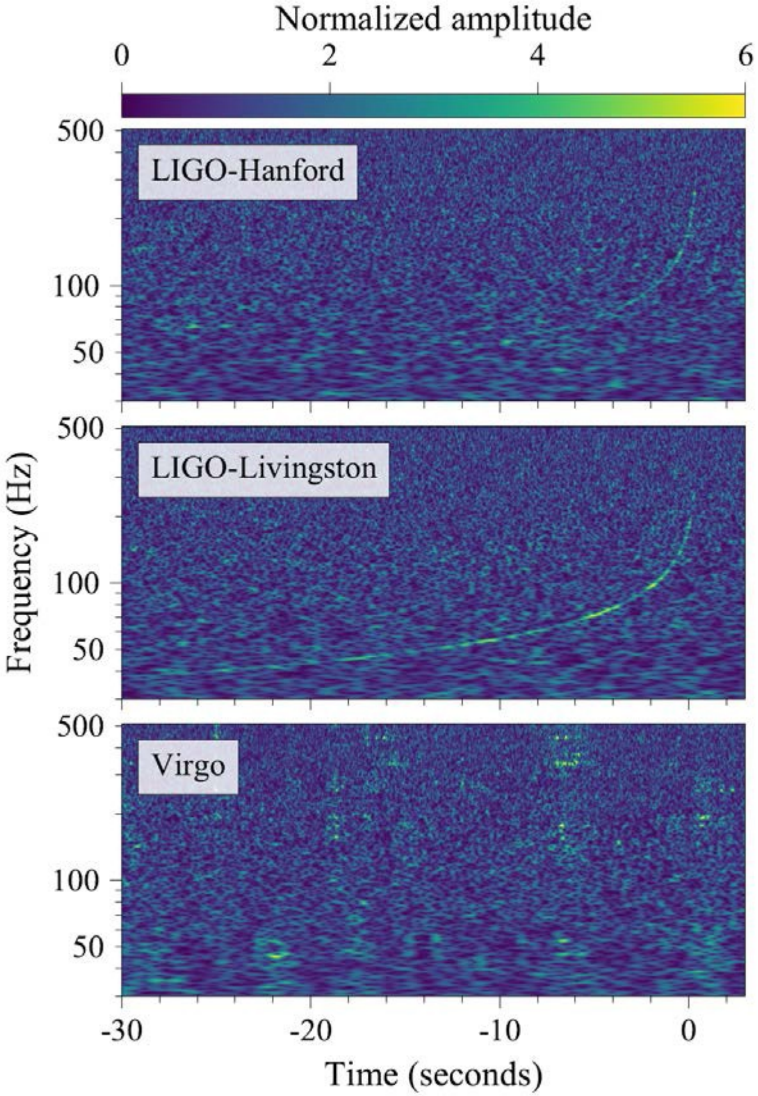
Combined SNR = 32.4
LIGO-Livingston: 26.4
LIGO-Hanford: 18.8
Virgo: 2.0

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)

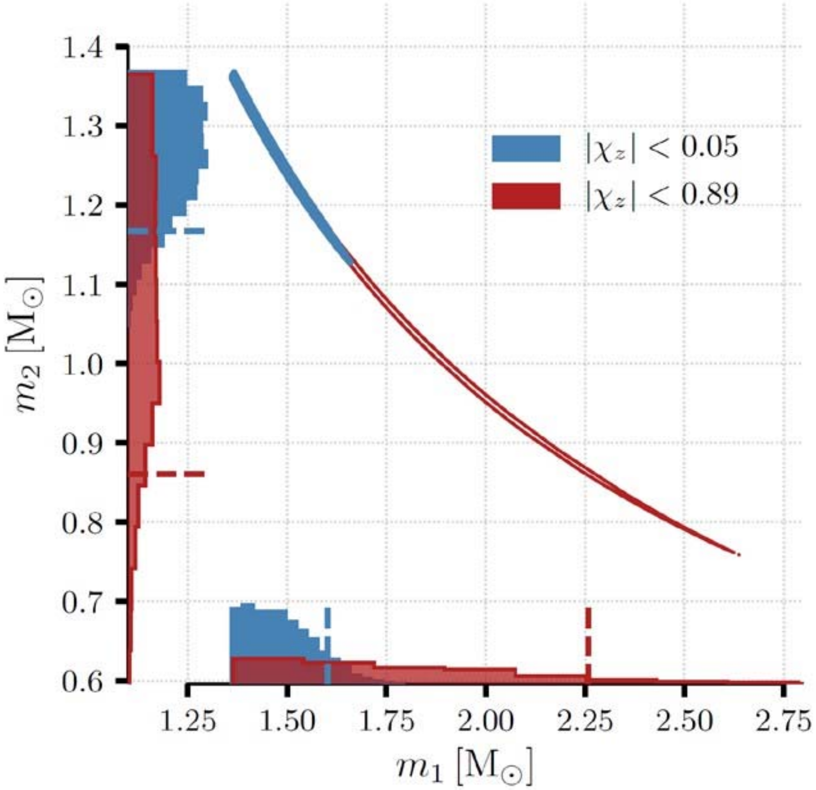
COMPONENT MASSES

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

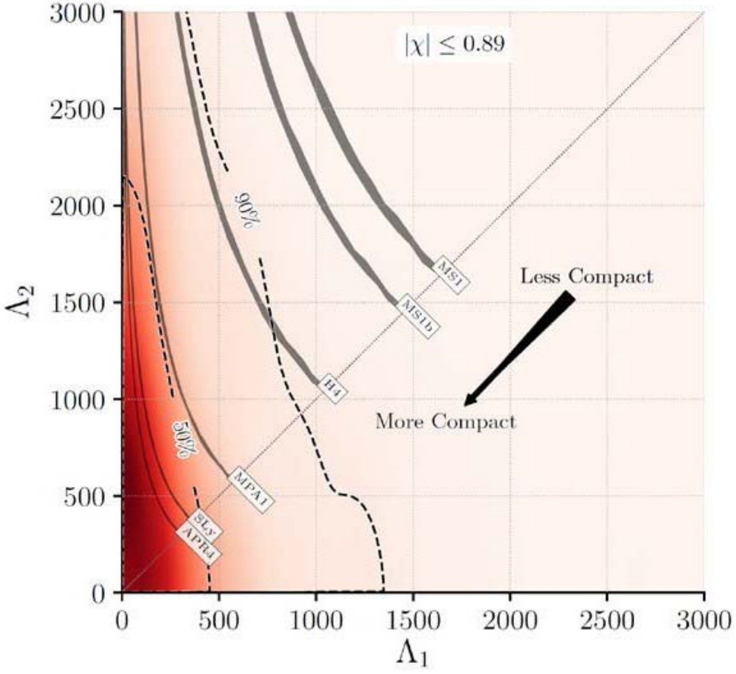
The result using the low–spin prior (blue) is consistent with the masses of all known binary neutron star systems.

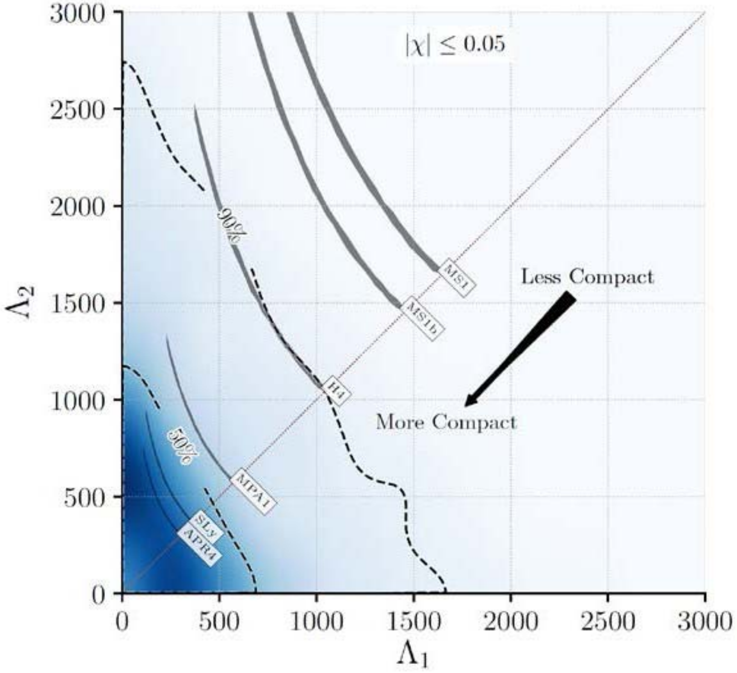


$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}} = \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3} \dot{f}\right]^{3/5}$$

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

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

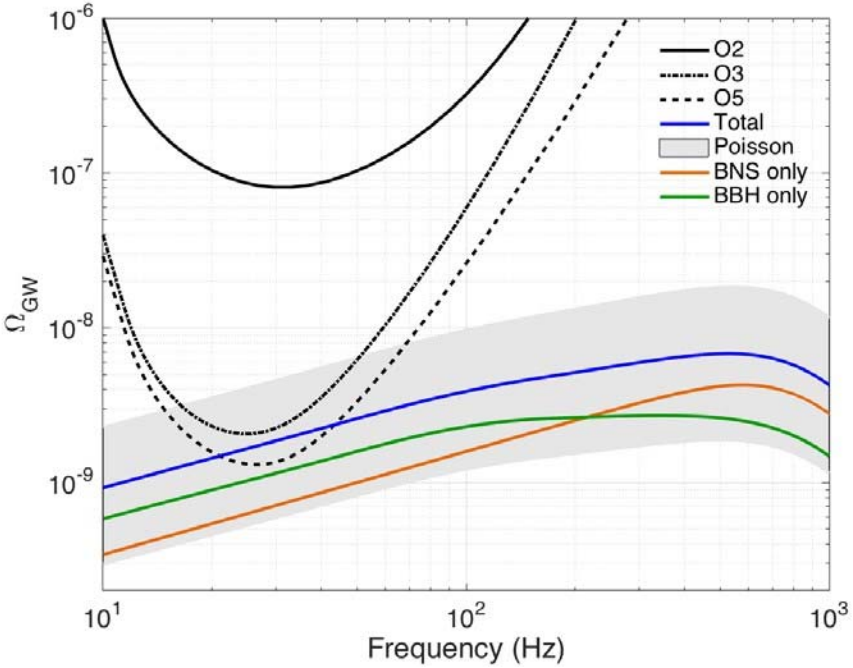
$$\Lambda = (2/3)k_2[(c^2/G)(R/m)]^5.$$

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

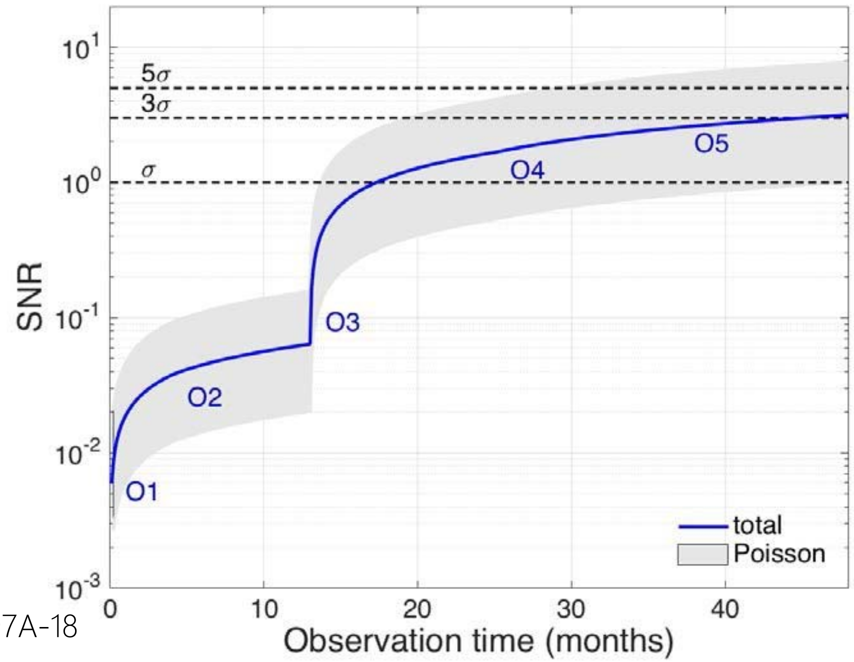
EOS that produce less compact stars, such as MS1 and MS1b, are ruled out

ASTROPHYSICAL STOCHASTIC BACKGROUND

GW170817 allows to estimate the contribution of BNS to the astrophysical stochastic background



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



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)

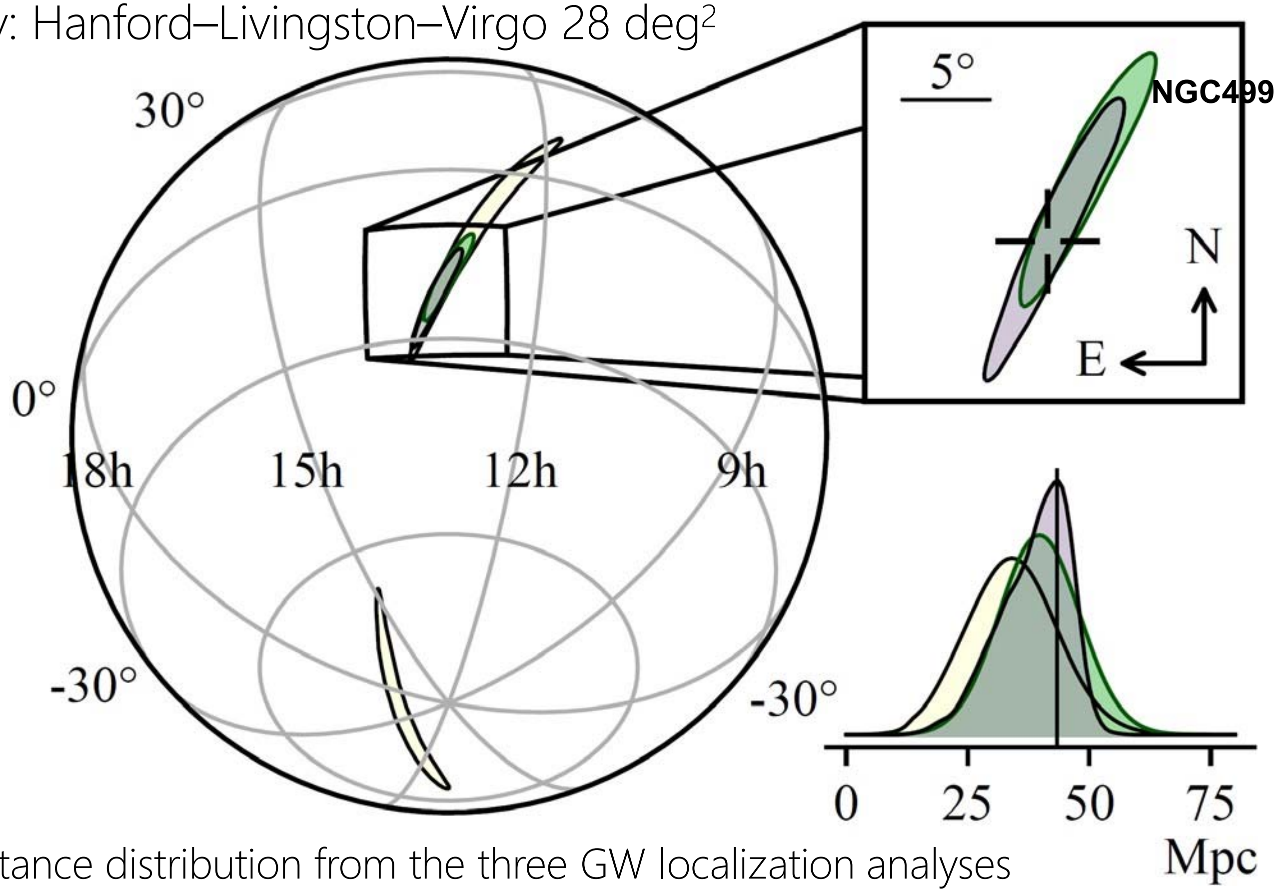
Searches for short (<1 s) and medium (< 500 s) duration transients have not found any signals

Searches for long-duration transients are currently ongoing

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

POSITION IN THE SKY

Low-latency:
Hanford–Livingston (190 deg^2)
Hanford–Livingston–Virgo (31 deg^2)
Higher latency: Hanford–Livingston–Virgo 28 deg^2



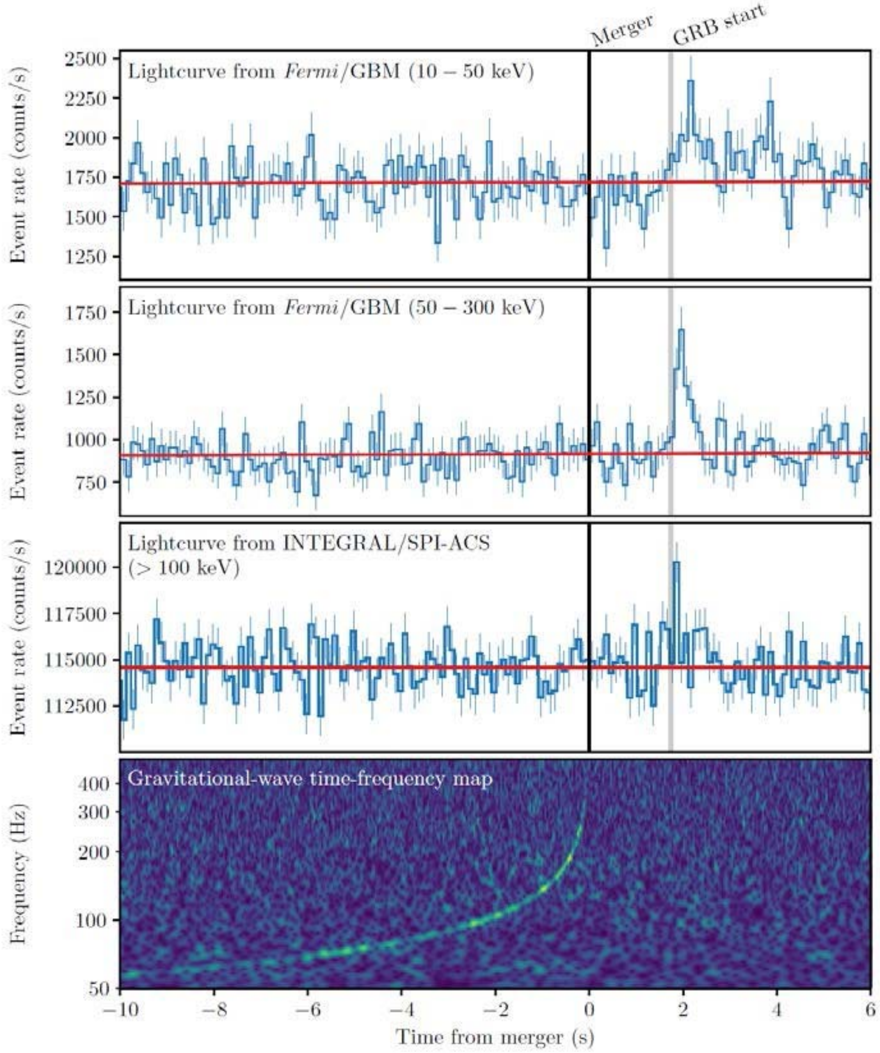
Luminosity distance distribution from the three GW localization analyses
The distance of NGC 4993, assuming the redshift from the NASA/IPAC Extragalactic Database and standard cosmological parameters is shown with a vertical line

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 x 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

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

Neutrino ok (1987 a) 1-6 month delay
Using Milky Way potential: 2.5 10^{11} $M_\odot$ in 100 kpc: order of 1 year

$$-1.2 \times 10^{-6} \leq \gamma_{\mathrm{GW}} - \gamma_{\mathrm{EM}} \leq 2.6 \times 10^{-7}$$

Also: dark matter emulators, see eg S. Boran et al., 1710.06168

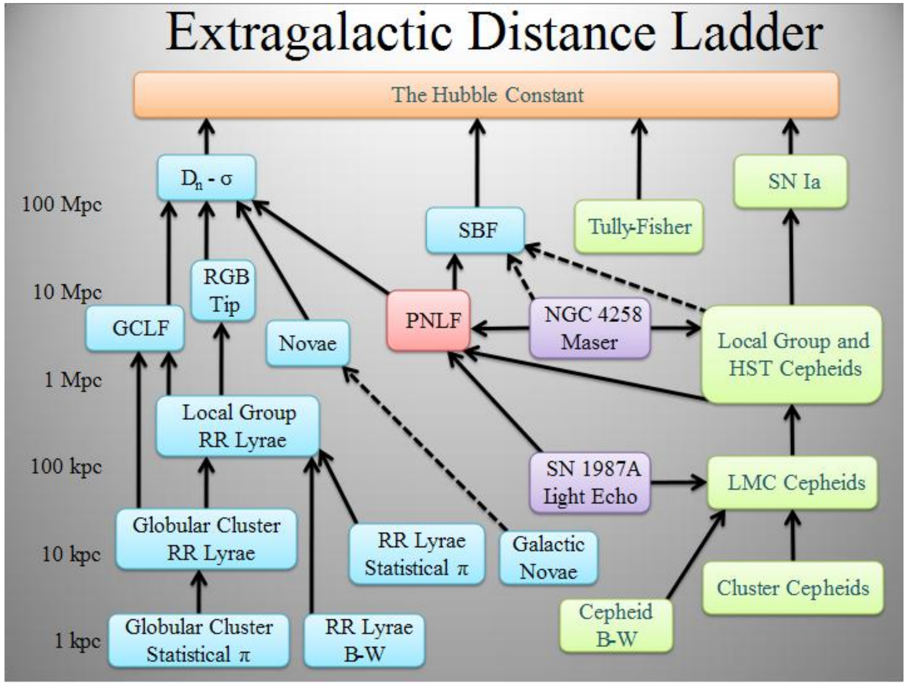
B. P. Abbott et al. Astrophys. J. Lett. 848, L13 (2017)

THE COSMIC DISTANCE LADDER

BNS: Direct distance measurement
If associated with an optical counterpart, a red shift can be measured:
completely new measurement of the Hubble constant (Schutz, 1986)

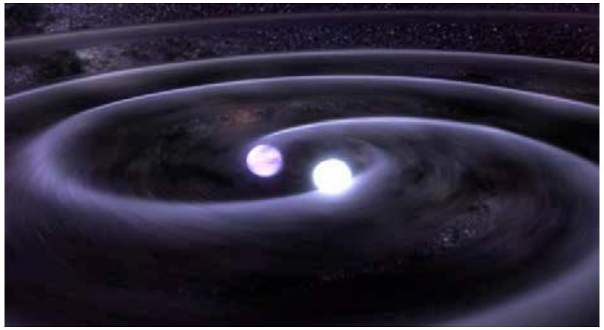
Beyond parallax method, distance is inferred from apparent luminosity, having the intrinsic brightness empirically correlated with other observables of the source

Once the parameters of the binary system are measured,
the amplitude of gravitational waves can be predicted



wikipedia.org/wiki/Cosmic_distance_ladder

Luminosity distance from 1/R



$$h_{ij}(t) = \frac{2G}{c^4 R} \frac{d^2 Q_{ij}(t)}{dt^2}$$

A NEW STANDARD CANDLE

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)

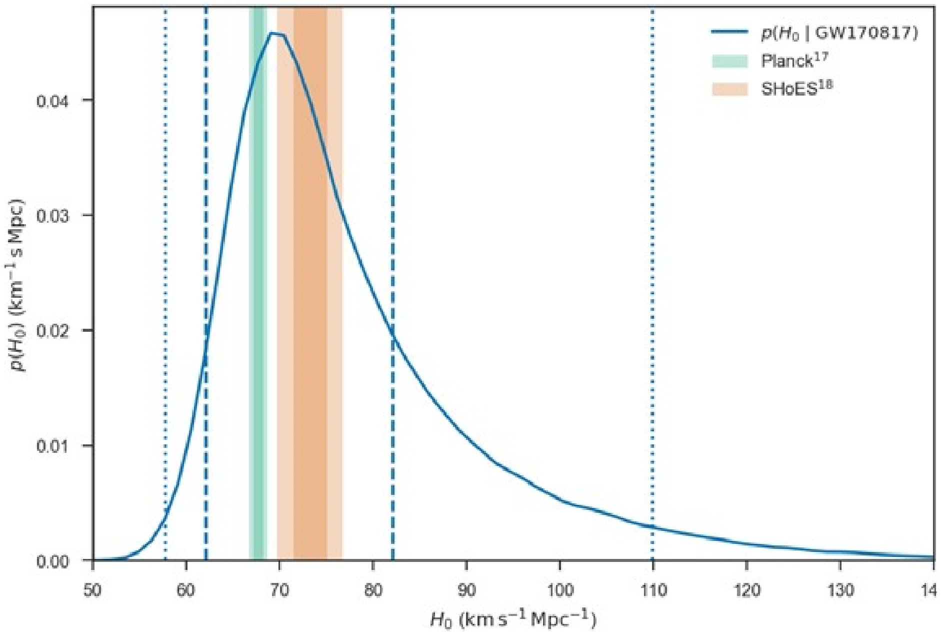
LVC, Nature 551, 85 (2017)

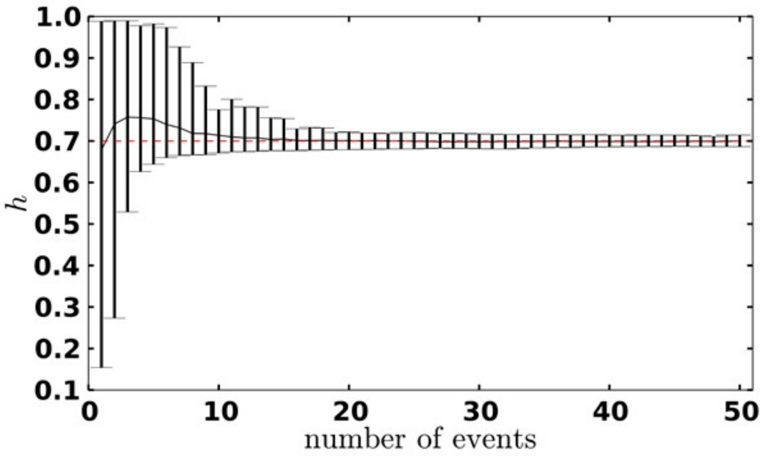
GW170817

- 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)

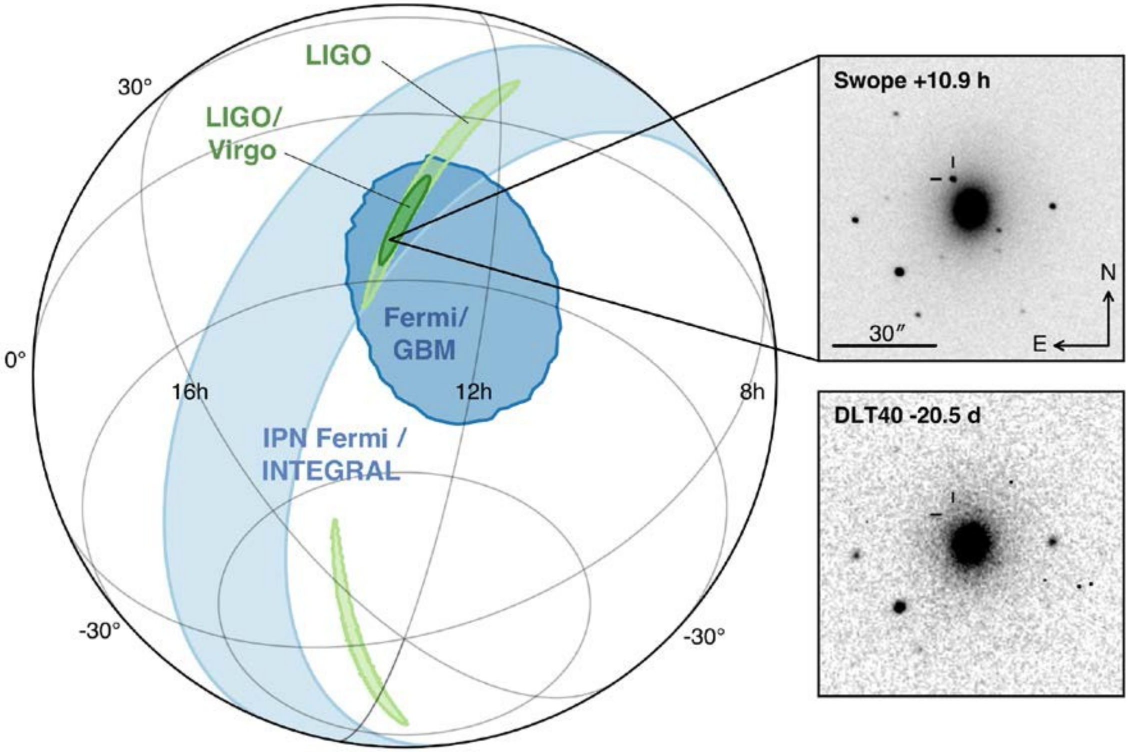
With the capability of detecting sources further away one can extend the Hubble relation and study expansion acceleration of the Universe





GW170817: BEGIN OF MULTIMESSENGER ASTRONOMY

GW170817 was localized in the Southern sky, setting for Northern observatories and becoming visible in Chile about 10 h later

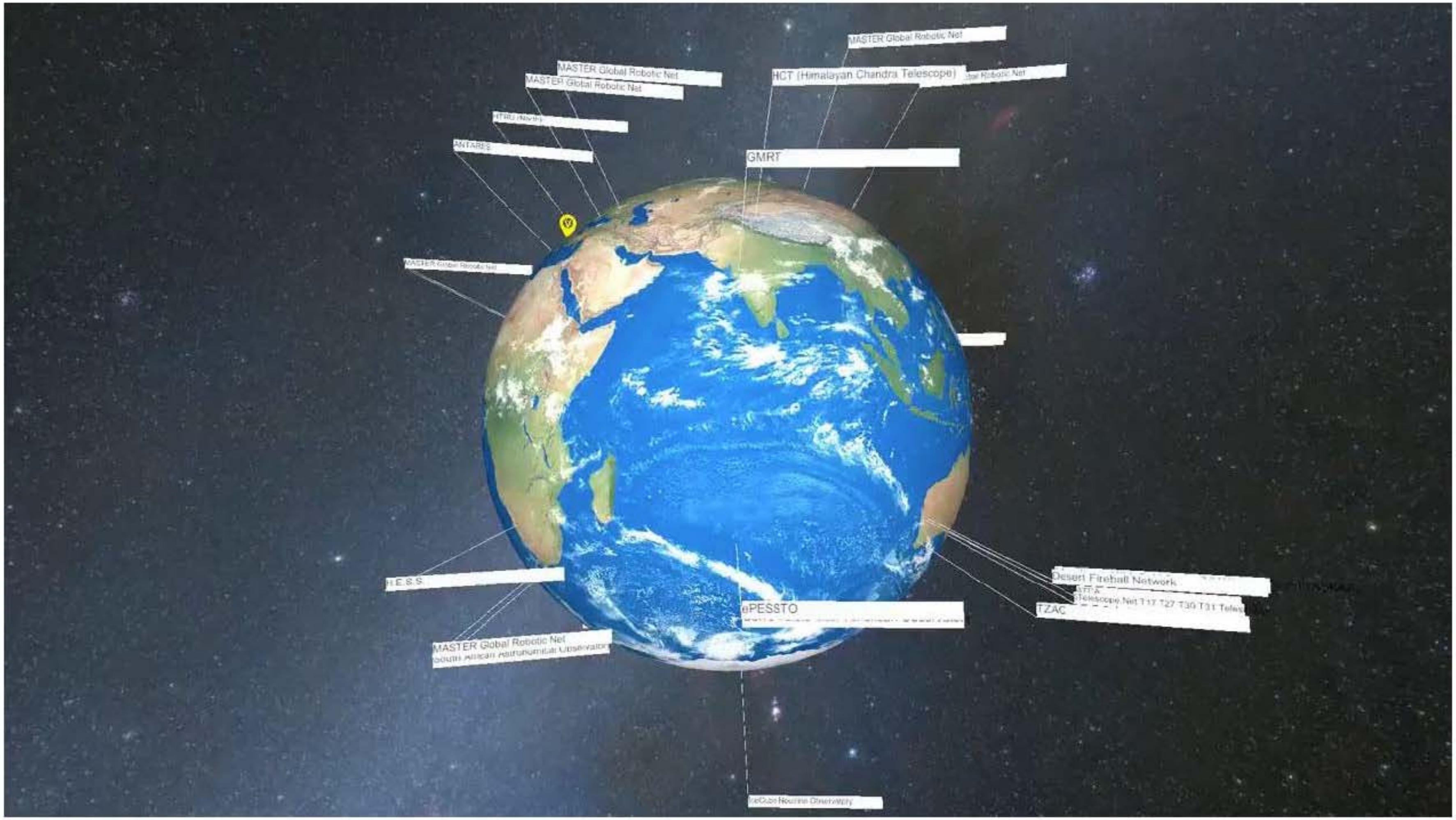


Location of the apparent host galaxy **NGC 4993** in the Swope optical discovery image 10.9 hrs after the merger

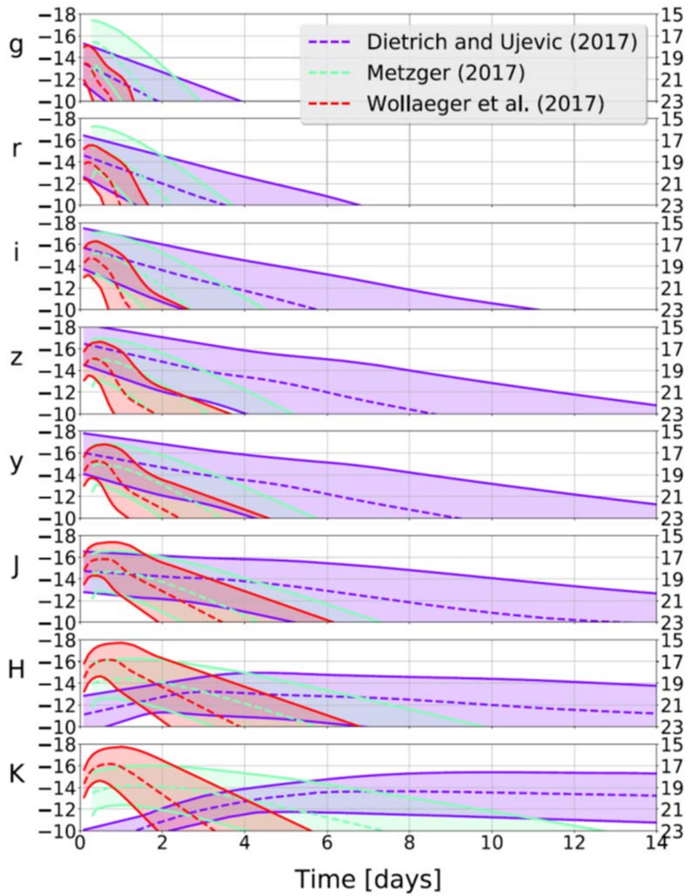
Astrophys. J. Lett. 848, L12 (2017)

WORLDWIDE EFFORT TO OBSERVE GW170817

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



THE FULL STORY

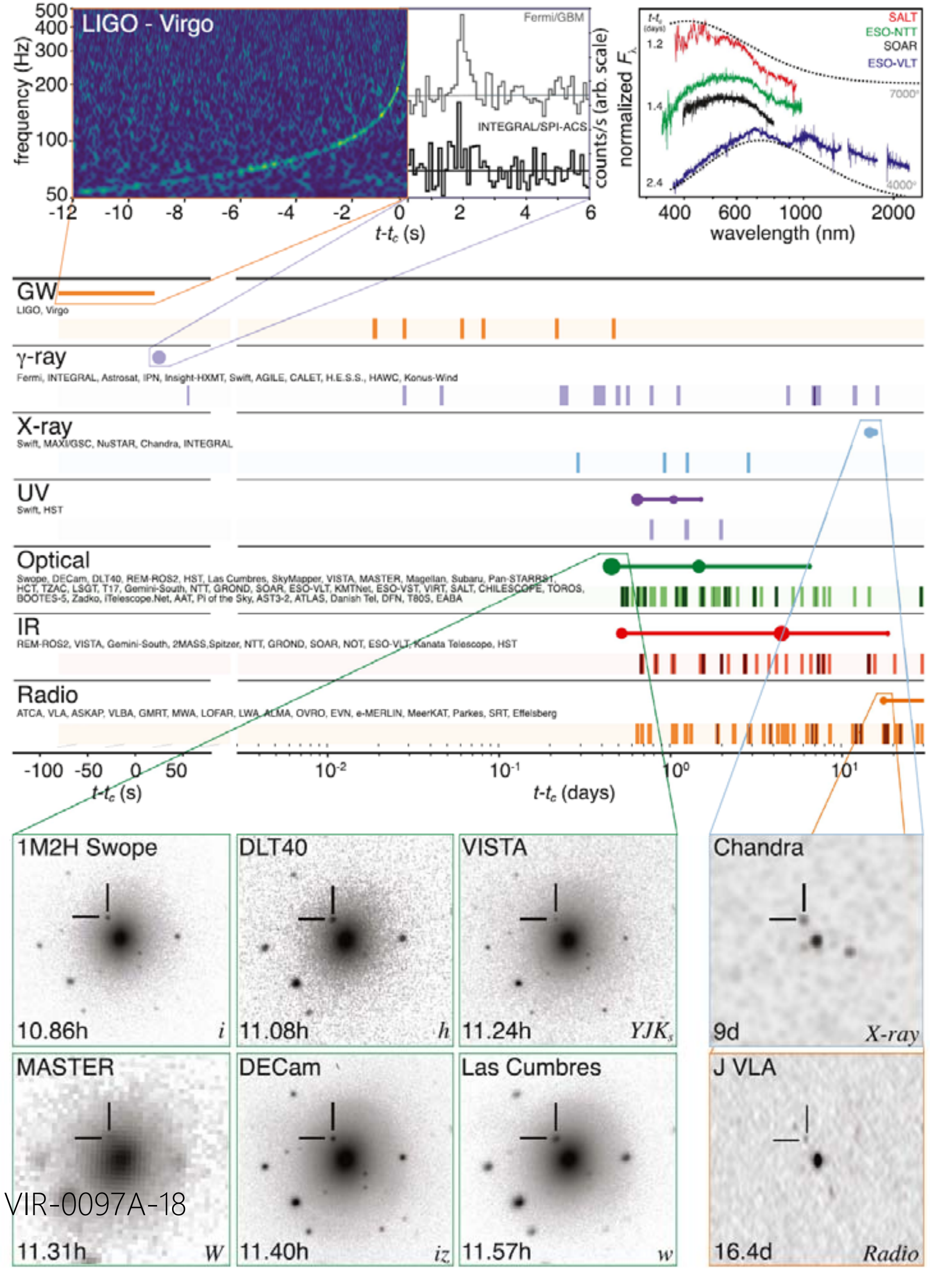


From GW parameters: Abbott et al.,ApJl, 850:L39

ESO animation X-Shooter kilonova spectra

https://vimeo.com/238427785

The Astrophysical Journal Letters, 848:L12 (59pp), 2017 October 20 Abbott et al.



VIR-0097A-18

OPTICAL COUNTERPART

Nature

Optical emission from a kilonova following a gravitational-wave-detected neutron-star merger, Iair Arcavi, Griffin Hosseinzadeh, D. Andrew Howell, Curtis McCully, Dovi Poznanski+ et al.

> Optical to near-infrared observations of a transient coincident with the detection of the gravitational-wave signature of a binary neutron-star merger and a low-luminosity short-duration γ-ray burst are presented and modelled.

Spectroscopic identification of r-process nucleosynthesis in a double neutron-star merger E. Pian, P. D'Avanzo, S. Benetti, M. Branchesi, E. Brocato+ et al.

> Observations of the transient associated with the gravitational-wave event GW170817 and γ-ray burst GRB 170817A reveal a bright kilonova with fast-moving ejecta, including lanthanides synthesized by rapid neutron capture.

The X-ray counterpart to the gravitational-wave event GW170817 E. Troja, L. Piro, H. van Eerten, R. T. Wollaeger, M. Im+ et al.

> Detection of X-ray emission at a location coincident with the kilonova transient of the gravitational-wave event GW170817 provides the missing observational link between short γ-ray bursts and gravitational waves from neutron-star mergers

A kilonova as the electromagnetic counterpart to a gravitational-wave source S. J. Smartt, T.-W. Chen, A. Jerkstrand, M. Coughlin, E. Kankare+ et al.

> Observations and modelling of an optical transient counterpart to a gravitational-wave event and γ-ray burst reveal that neutron-star mergers produce gravitational waves and radioactively powered kilonovae, and are a source of heavy elements.

Origin of the heavy elements in binary neutron-star mergers from a gravitational-wave event Daniel Kasen, Brian Metzger, Jennifer Barnes, Eliot Quataert & Enrico Ramirez-Ruiz

> Modelling the electromagnetic emission of kilonovae enables the mass, velocity and composition (with some heavy elements) of the ejecta from a neutron-star merger to be derived from the observations.

A gravitational-wave standard siren measurement of the Hubble constant The LIGO Scientific Collaboration and The Virgo Collaboration, The 1M2H Collaboration, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, The Las Cumbres Observatory Collaboration+ et al.

> The astronomical event GW170817, detected in gravitational and electromagnetic waves, is used to determine the expansion rate of the Universe, which is consistent with and independent of existing measurements.

PLANS FOR THE FUTURE OF GW PHYSICS

SOURCE FREQUENCY SPECTRUM

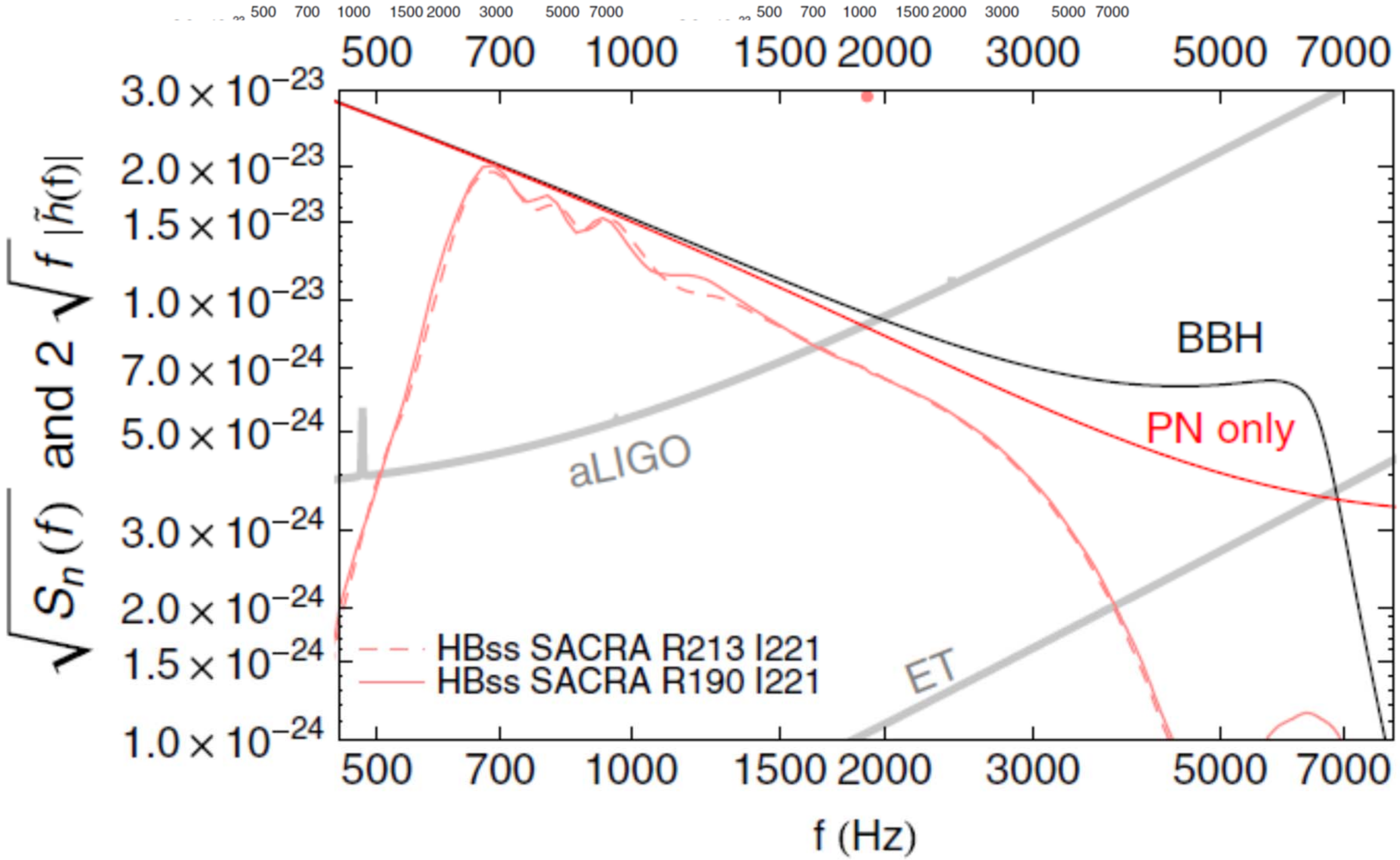
Frequency band	Cosmological 10^{-16} Hz	Nanohertz band $10^{-9} - 10^{-7}$ Hz	Millihertz band $10{-}4\ \ - 10{-}3$ Hz	Audio band $10 - 10^{4}$ Hz
Signal source	frozen relic waves from the big bang at ultralow frequency	Waves from supermassive black holes at a frequency 1 cycle per 3 years waves from massive black hole	binaries at 1 cycle per minute partially masked by galactic binary star systems	audio frequency waves, from coalescence of stellar mass neutron stars and black holes
Detection technique	B-mode polarisation of the cosmic microwave background	correlated pulse arrival time variations of millisecond pulsar signals	drag free space interferometers of 10^{6} km baseline	High power ground based multi-kilometer baseline interferometers

Binary systems: the lower the frequency, the higher the mass, the higher the signal, the farther detected: seek low frequency

Cosmological stochastic background could be more accessible at low frequency

Table by D. Blair et al. 1602.02872

FEATURES OF BNS SPECTRUM



Featureless spectrum for BBH (solid black curve)

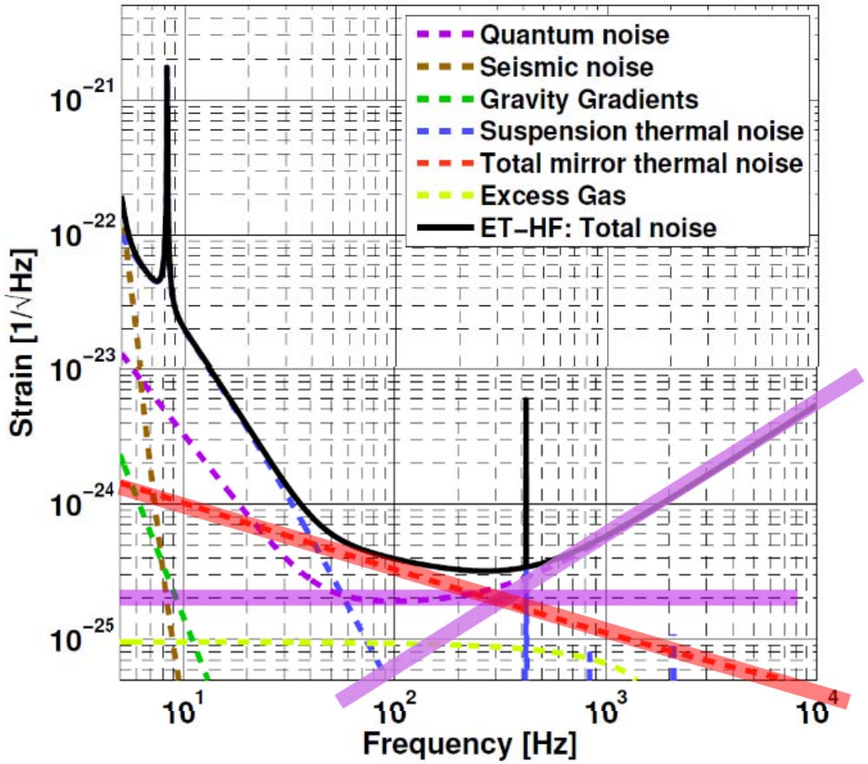
High frequency: higher resolution inside the system (SN)

GW spectroscopy of BNS: lines up to 7 kHz depending on the EOS,

Read et al PRD 88 (2013) 044042

EINSTEIN TELESCOPE NOISE SOURCES

ET-HF



Quantum noise: shot noise, radiation pressure, Heisenberg uncertainty principle

Thermal noise: contact with a thermal bath, mirrors are part of a system that undergoes thermodynamic fluctuations, i.e. resistor Johnson noise

Seismic noise: test mass isolation from supports

Gravity gradients: local gravity fluctuations, main source is displacement of ground air interface

Quantum noise high f: 5 10^{-25} (f / 1 kHz) $\mathrm{Hz}^{-1/2}$

$$h_n = \frac{\lambda f_{GW}}{c}\sqrt{\frac{hc}{\lambda}\frac{1}{\eta R_C P_{in}}}\,\xi$$

Quantum noise level flat: 2 10^{-25} $\mathrm{Hz}^{-1/2}$

$$h_n = \frac{\lambda}{4\mathcal{F}L}\sqrt{\frac{hc}{\lambda}\frac{1}{\eta R_C P_{in}}}\,\xi$$

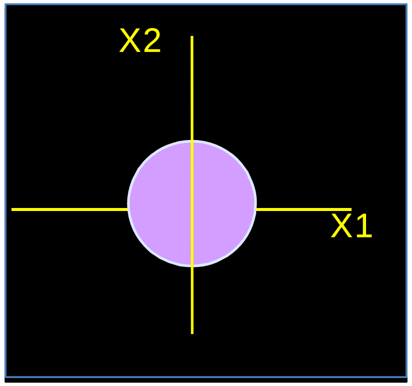
Mirror thermal noise: 10^{-25} (f / 1 kHz) $^{-1/2}$ $\mathrm{Hz}^{-1/2}$ room temperature

What is quantum noise?

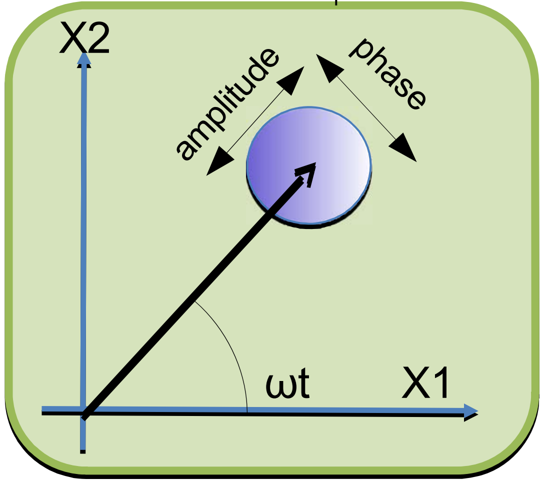
$$\hat{X}_1 = \frac{\hat{a} + \hat{a}^+}{2} \qquad \hat{X}_2 = \frac{\hat{a} - \hat{a}^+}{2i}$$

$$\hat{E} = \hat{X}_1 \cos \omega t + i\hat{X}_2 \sin \omega t$$

$$\Delta X_1 \, \Delta X_2 \geq 1$$



“Ball on a stick” picture



After Eric Oelker’s & Lisa Barsotti’s slides

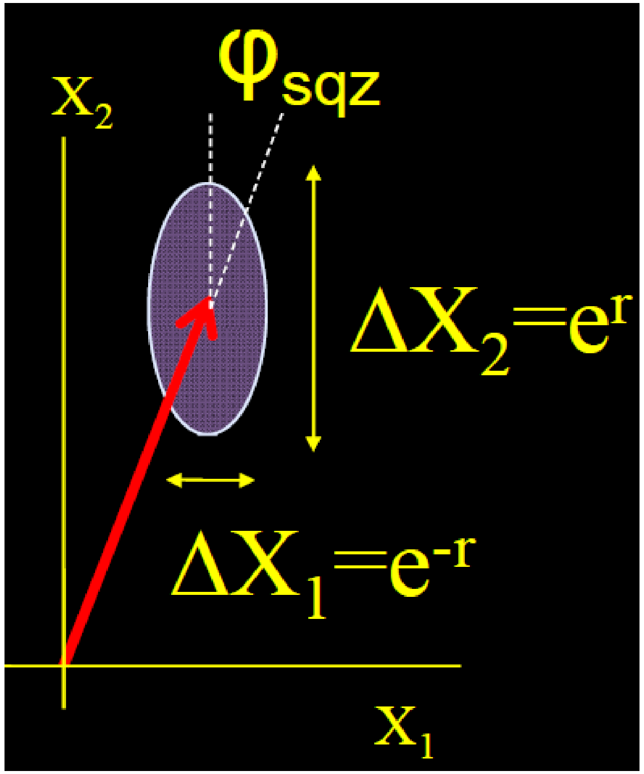
- Electromagnetic field is quantized
- Quadrature operators don't commute
- The two quadratures satisfy an uncertainty principle.
- Implies that there are zero-point fluctuations on the electromagnetic field.

Squeezed states of light

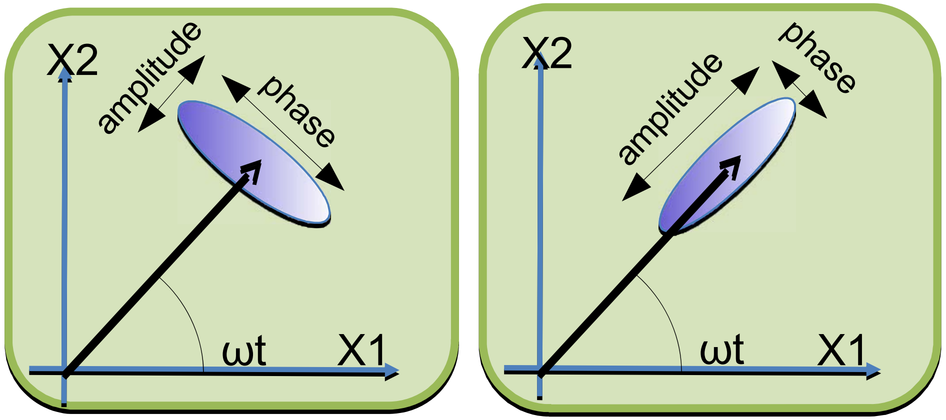
Still satisfy uncertainty principle:

$\Delta X_1 \, \Delta X_2 \geq 1$

But noise has been redistributed:

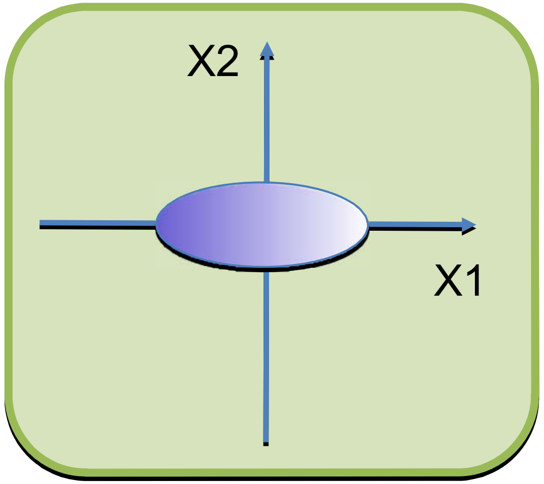


Squeezed Coherent States



We use squeezed vacuum:

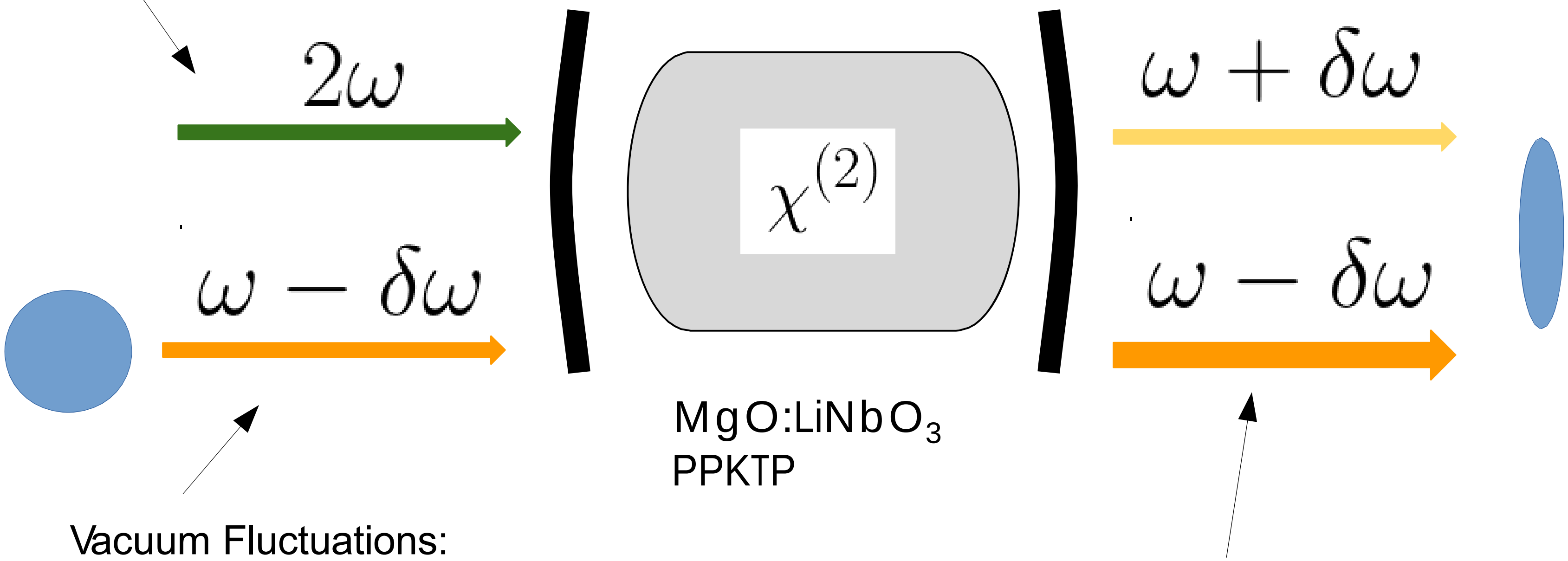
No Coherent amplitude



Generating Squeezing: Optical Parametric Oscillation

$$P(\omega_1 - \omega_2) = 2\epsilon_0 \chi^{(2)} E_1 E_2^*$$

Pump Field



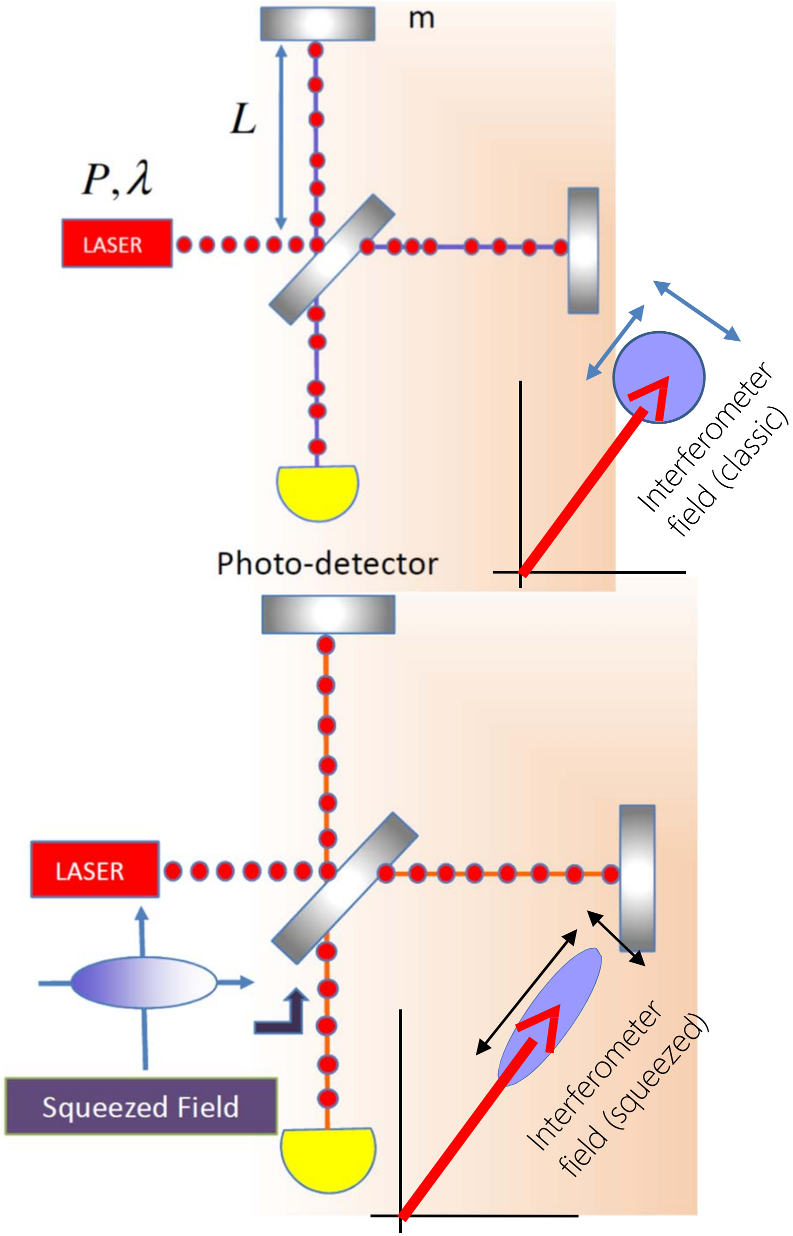
$MgO{:}LiNbO_3$
PPKTP

Vacuum Fluctuations:
Uncorrelated

Produces photon pairs with a well defined phase relationship

They are correlated.

SQUEEZED VACUUM



Injecting a squeezed vacuum state inside the interferometer instead of having classical vacuum entering the output port (Caves 1981)

However at low frequency you want to decrease amplitude fluctuations or radiation pressure

Need for a frequency dependent squeezed vacuum

QUANTUM NOISE

Review Articles:

S. S. Y. Chua, B. J. J. Slagmolen, D. A. Shaddock and D. E. McClelland, Quantum squeezed light in gravitational-wave detectors," Class. Quantum Grav. **31**, 183001 (2014).

D.E. McClelland, N. Mavalvala, Y. Chen, and R. Schnabel, Advanced Interferometry, quantum optics and optomechanics in gravitational wave detectors", Laser and Photonics Rev. 5, 667 (2011). Roman Schnabel, Nergis

Mavalvala, David E. McClelland & Ping K. Lam, Quantum metrology for gravitational wave astronomy, Nature Communications **1**, 121 (2010).

Lisa Barsotti, Jan Harms, Roman Schnabel, Squeezed vacuum states of light for gravitational wave detectors, ROP

The context of Coatings Development

G. Cagnoli et al., LMA, Genova, Urbino, Roma 2, Salerno Sannio

- Materials

Pragmatic

Selection and Optimization

- ♦ Advanced detectors upgrade
- ♦ 3rd generation

Fundamental Physics

- ♦ **Origin of losses and relaxations in amorphous materials**

Collaborations

- ♦ ViSIONs: origin of relaxations
- ♦ Virgo Coating R&D +Jena U.+PTB
- ♦ GAST: FR, D, UK, IT, crystalline coatings on sapphire

- Coaters and metrology

Ongoing

- ♦ Uniformity
- ♦ In-situ optical metrology for real time thickness control
- ♦ Spectrophotometric bench for large optics

Planned

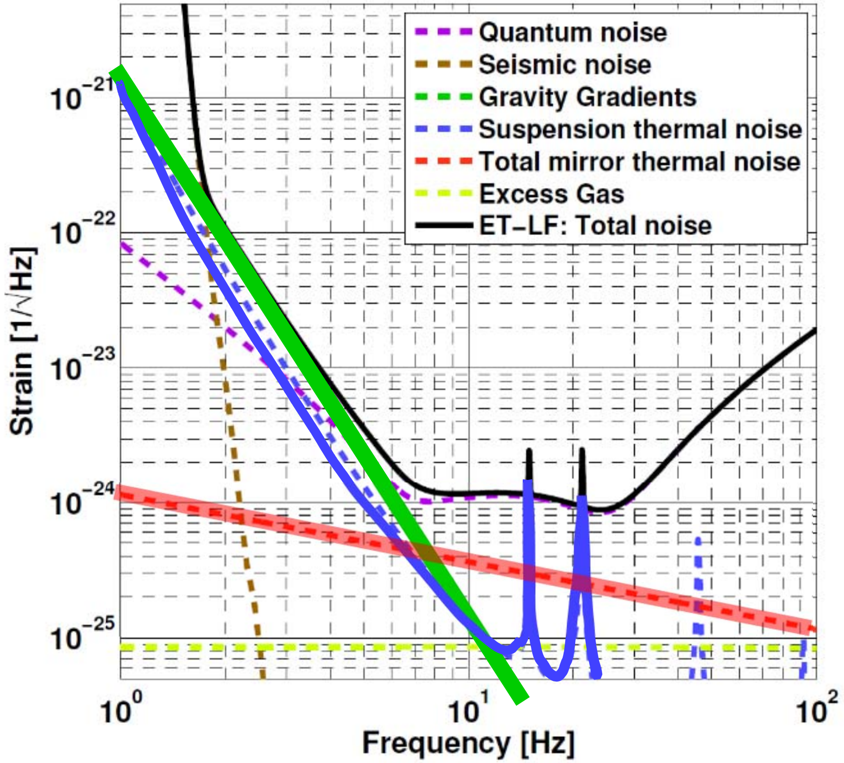
- ♦ High T deposition
- ♦ Point like defects
- ♦ Post deposition coating correction

The international context

- Advanced Virgo +
  - φ↓ w↑
- LIGO Scientific Collaboration
  - Centre of Coating Research φ↓
    - Labs: 9, 3 coaters
    - Funding: 3M$ (postdocs)
    - Projects: aLIGO+
      Voyager
  - ♦ Caltech φ↓
    - Labs: 1
    - Funding: ?
    - Projects:
      aLIGO+
      Voyager
  - ♦ Glasgow φ↓
    - Labs: 2, 2 coaters
    - Funding: ?
    - Projects: aLIGO+
      Voyager
      ET
- KAGRA
  - Cryogenic, there will be an upgrade

EINSTEIN TELESCOPE NOISE SOURCES

ET-LF Cryogenic

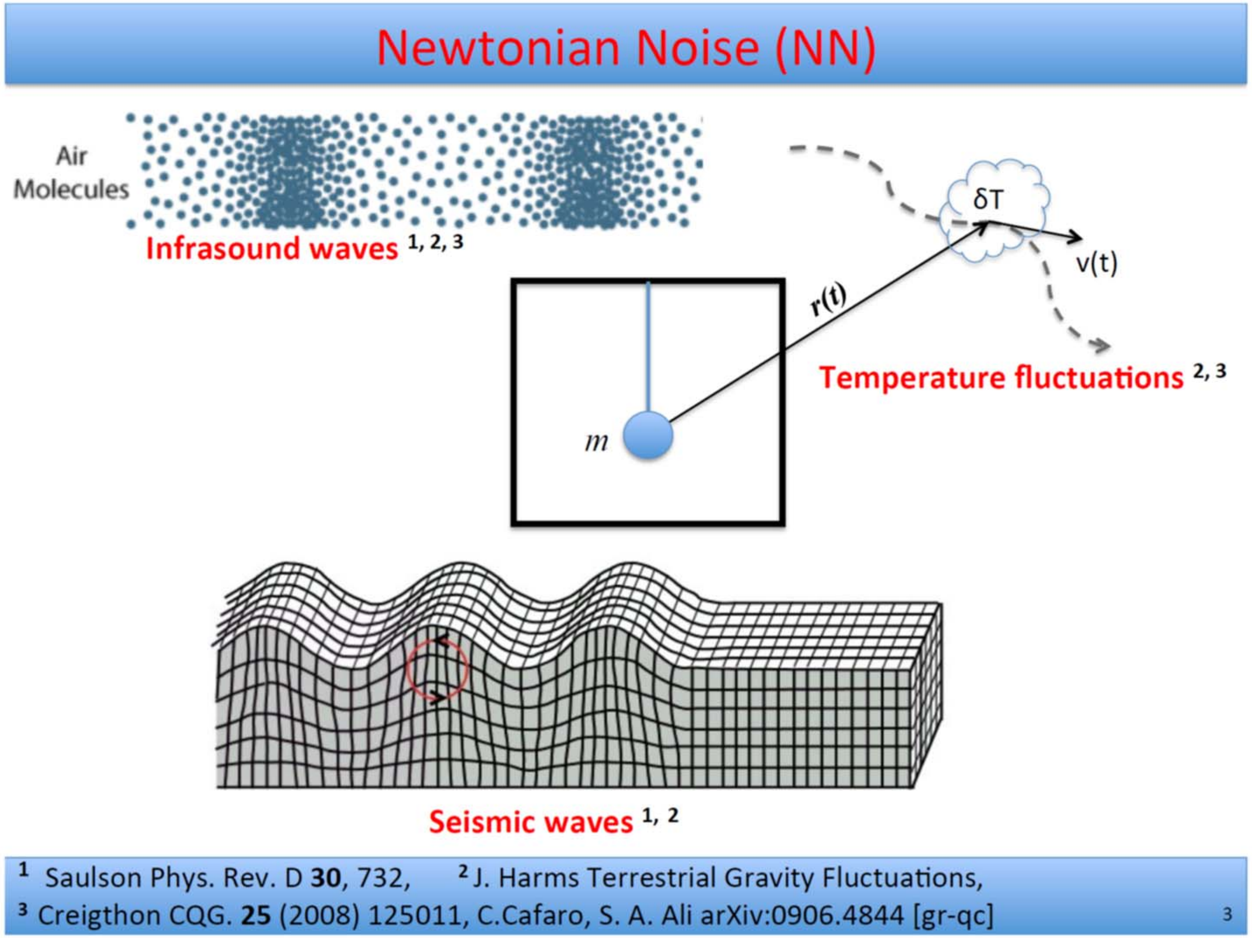


Mirror thermal noise: 10^{-25} (f / 100 Hz) $^{-1/2}$ Hz$^{-1/2}$ cryogenic

Pendulum thermal noise: 10^{-25} (f / 10 Hz) $^{-5/2}$ Hz$^{-1/2}$ cryogenic

Gravity gradients: 2 10^{-21} (f / 1 Hz) $^{-4}$ Hz$^{-1/2}$

GRAVITY GRADIENTS



Newtonian Noise (NN)

[1] Saulson Phys. Rev. D **30**, 732, [2] J. Harms Terrestrial Gravity Fluctuations,
[3] Creigthon CQG. **25** (2008) 125011, C.Cafaro, S. A. Ali arXiv:0906.4844 [gr-qc]

Beccaria et al., CQG, 1999

UNDERGROUND CRYOGENIC INTERFEROMETER

Pioneering work by KAGRA under the Kamioka Mountain

Gravity gradients are strongly reduced going underground

Microseism is also much lower, but this may be spoiled by ventilation and pumping systems!

NEAR TERM FUTURE

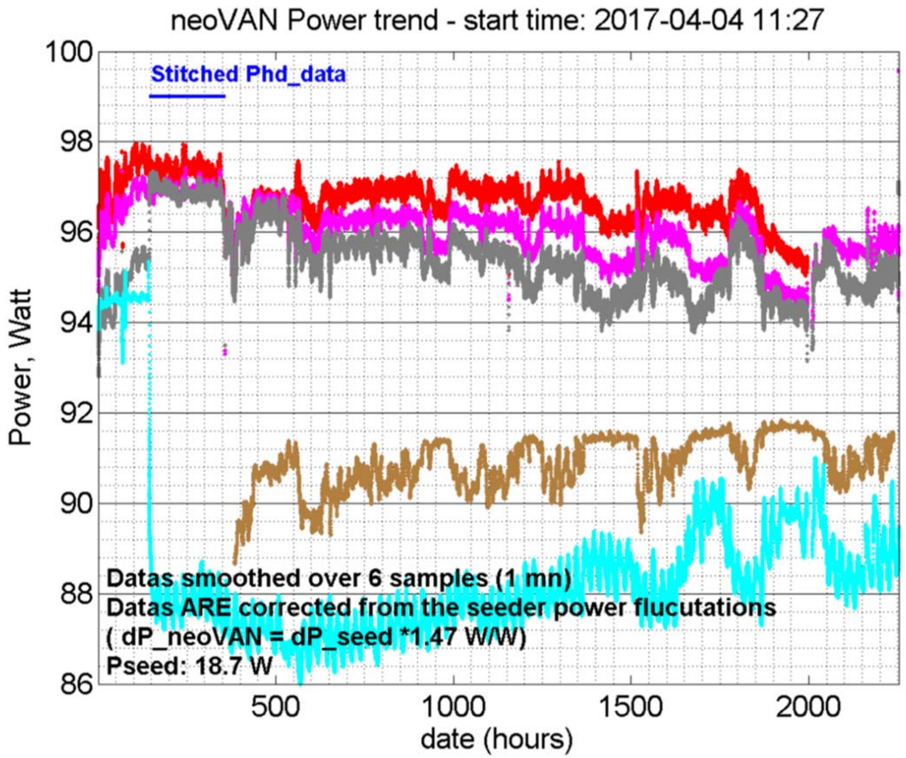
Solid state laser tests in Nice

Long-term power trend OK

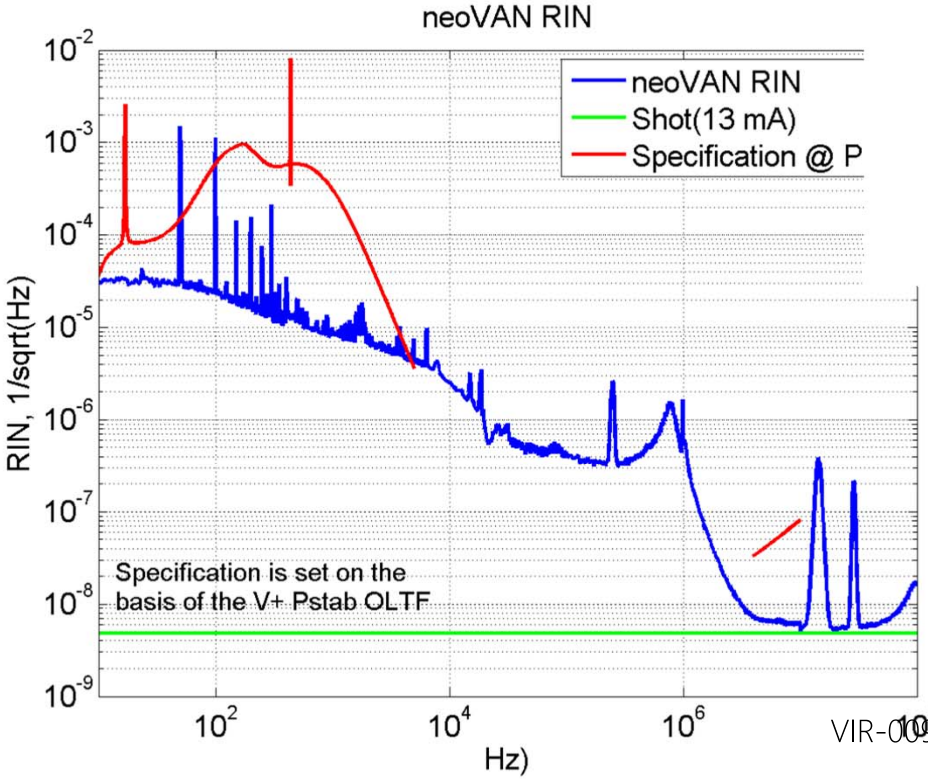
Problems:

- TEM$_{oo}$: only 84% instead of 89% (AEI)
- Power deficit (8%)

- In contact with LSC experts
- Comparing with LIGO 70W laser experience



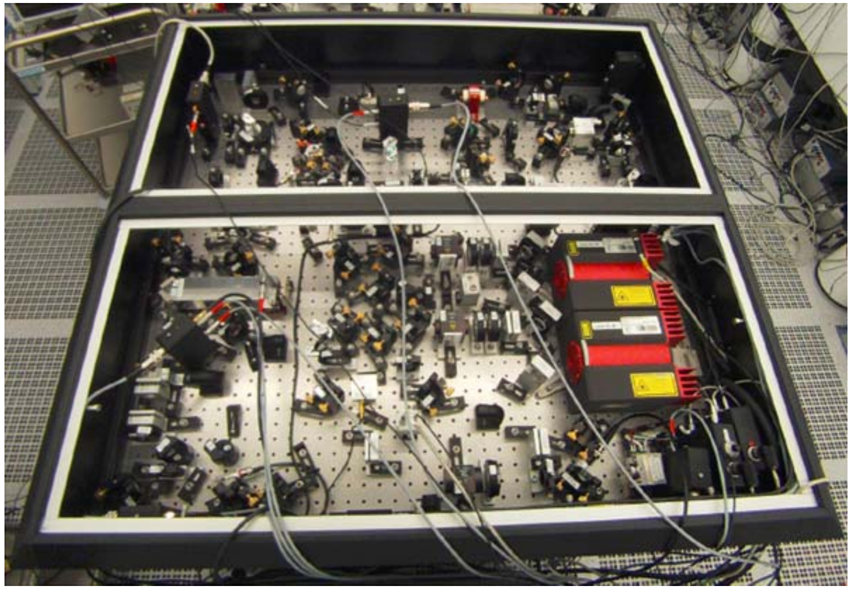
Datas smoothed over 6 samples (1 mn)
Datas ARE corrected from the seeder power flucutations
(dP_neoVAN = dP_seed *1.47 W/W)
Pseed: 18.7 W



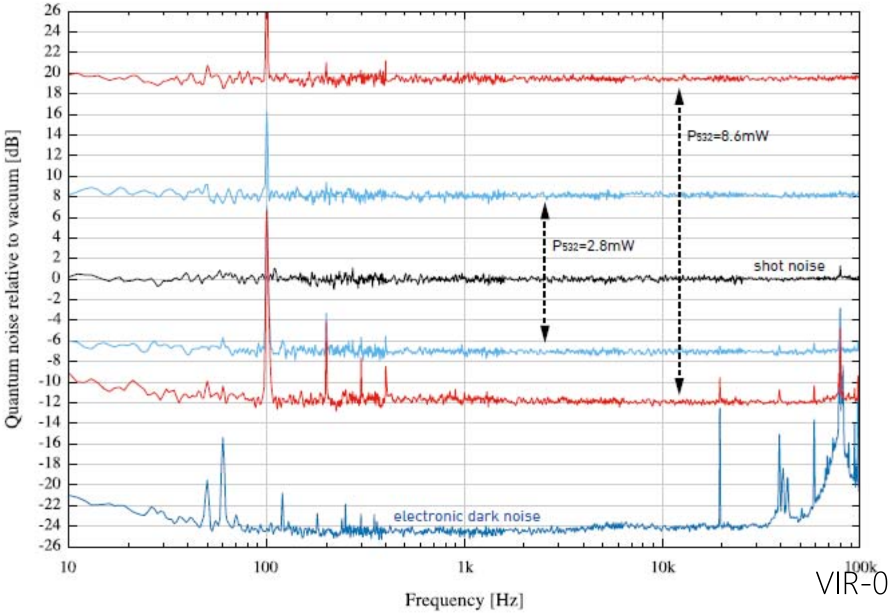
Specification is set on the basis of the V+ Pstab OLTF

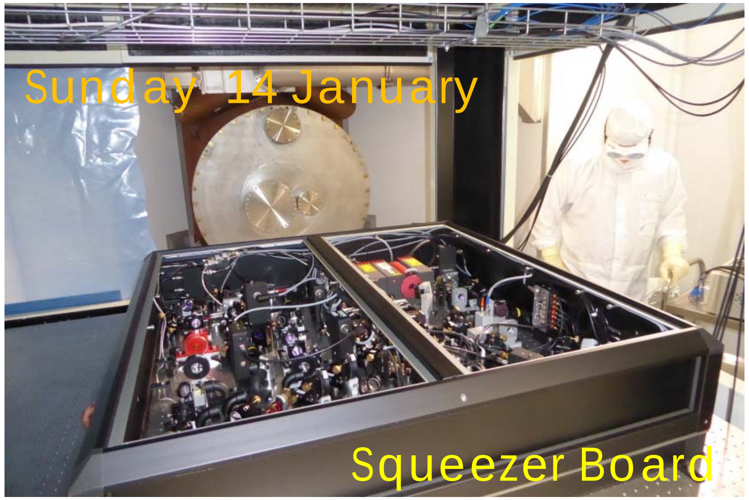
Intensity noise within specs

THE AEI SQUEEZER STATUS



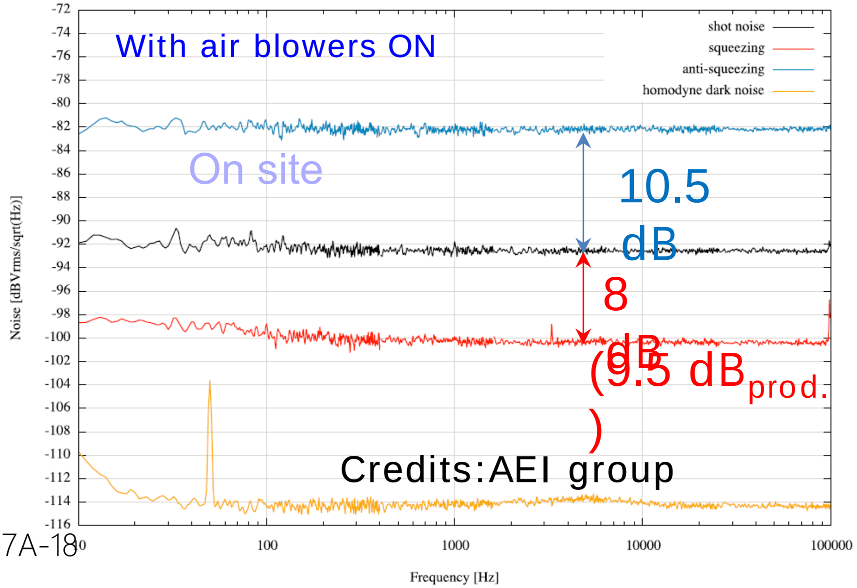
Up to 12 dB of squeezing degree demonstrated in the audio band





Sunday 14 January

Squeezer Board



With air blowers ON

On site

10.5 dB

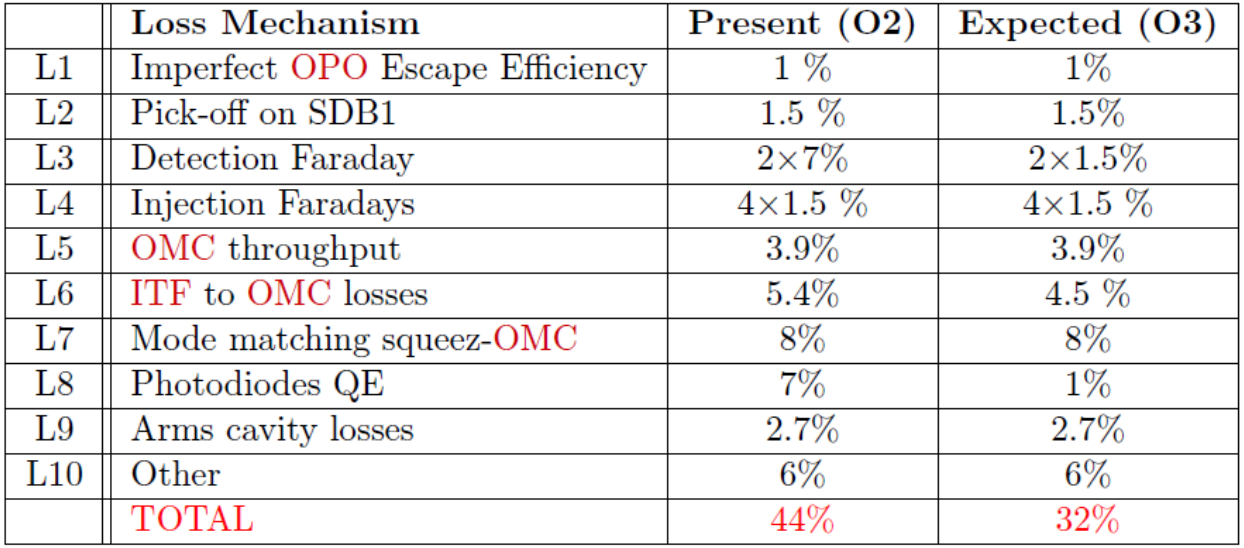
8 dB

(9.5 $\text{dB}_{\text{prod.}}$)

Credits:AEI group

Expected sensitivity

- ☐ **Optical Losses** Maximum expected HF gain: **4.7 dB**



	Loss Mechanism	Present (O2)	Expected (O3)
L1	Imperfect OPO Escape Efficiency	1 %	1%
L2	Pick-off on SDB1	1.5 %	1.5%
L3	Detection Faraday	2×7%	2×1.5%
L4	Injection Faradays	4×1.5 %	4×1.5 %
L5	OMC throughput	3.9%	3.9%
L6	ITF to OMC losses	5.4%	4.5 %
L7	Mode matching squeez-OMC	8%	8%
L8	Photodiodes QE	7%	1%
L9	Arms cavity losses	2.7%	2.7%
L10	Other	6%	6%
	TOTAL	44%	32%

← New in vacuum faraday

← New high QE Photodiode

- ☐ **Effect of technical noise** (not included in GWINC !)

O2

Shot noise @1kHz 5.4×10^{-23} $\text{Hz}^{-1/2}$

Dark noise @1kHz 2.3×10^{-23} $\text{Hz}^{-1/2}$

Residual SSFS@ 1kHz 1.7×10^{-23} $\text{Hz}^{-1/2}$

→ Maximum **O2** HF gain: **3.1 dB**

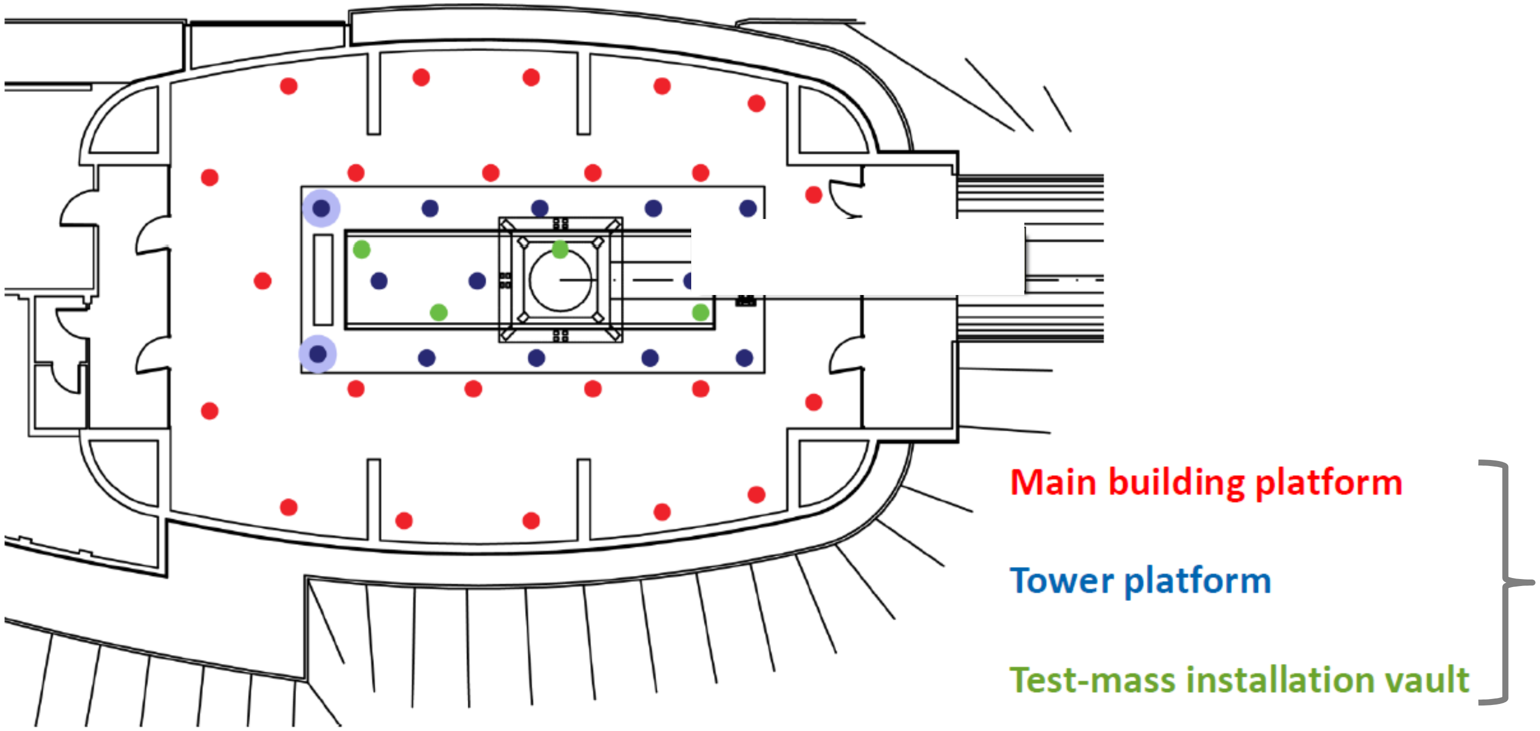
O3 Electronic noise optimization → Maximum **O3** HF gain: **4.0 dB**

Newtonian Noise sensor test installation

An array of NN sensors will temporarily be installed in each terminal building

- Characterize seismic noise
- Refine simulations
- Develop optimized sensor array layout for post-O3 NN subtraction system

North End Building sensor layout

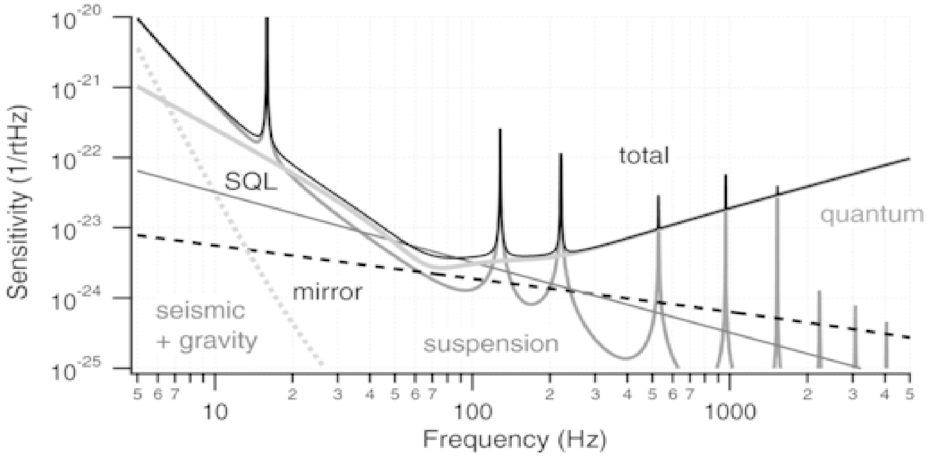


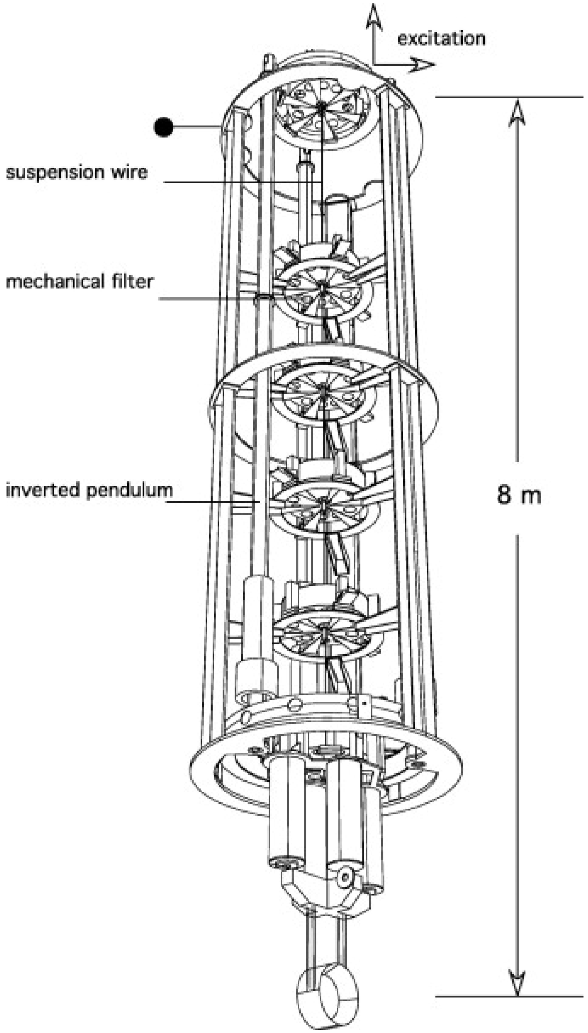
Seismic noise

Isolation systems by Virgo and LIGO performing well
KAGRA coming up

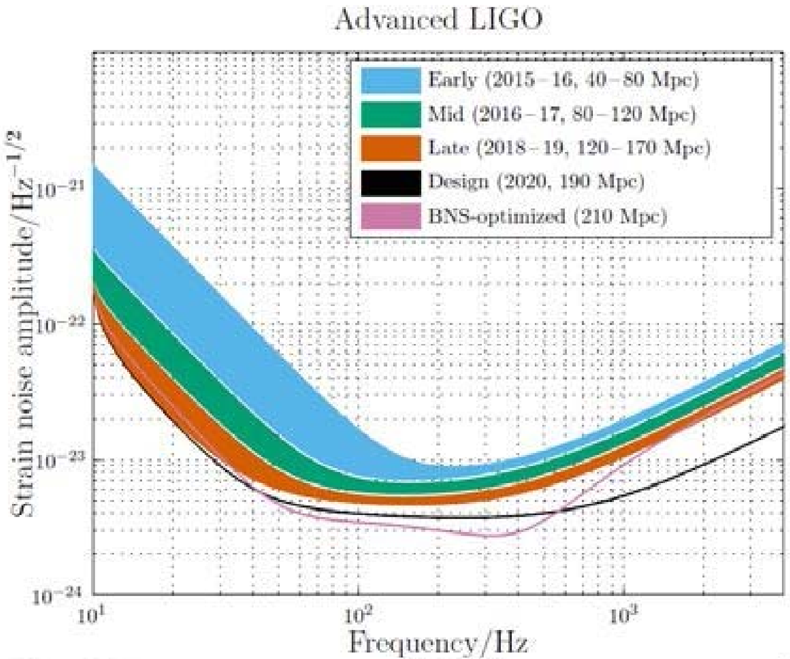
Virgo superattenuator suits third generation requirements for longitudinal noise down to 4 Hz
KAGRA has suspensions similar to Virgo but

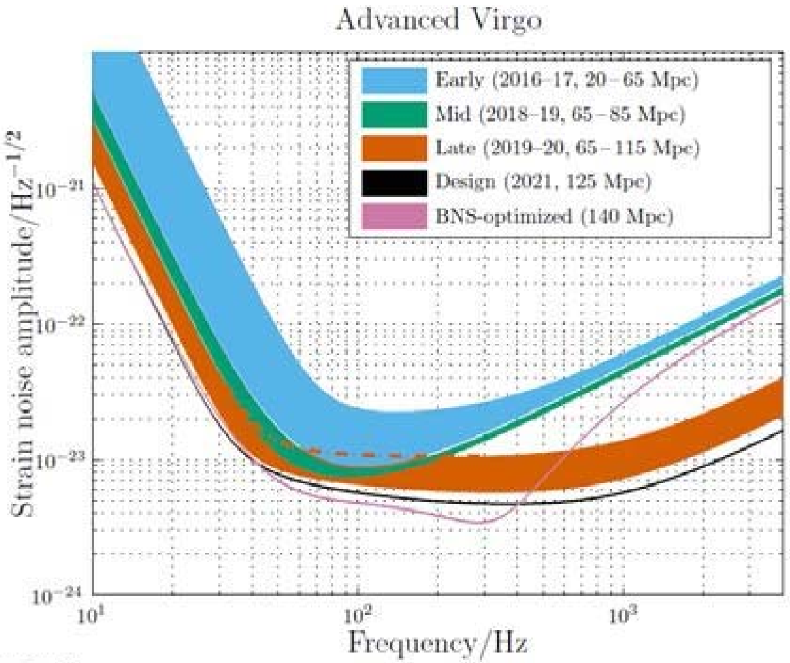
Work on:
Rotational dofs: better sensing and control is needed
Robustness against rough weather
Immunity with respect to small earthquakes



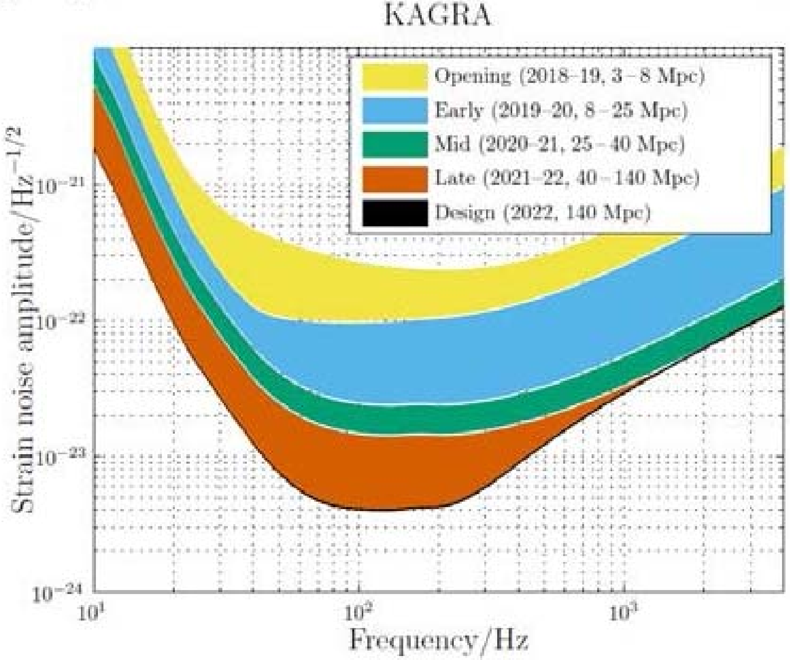


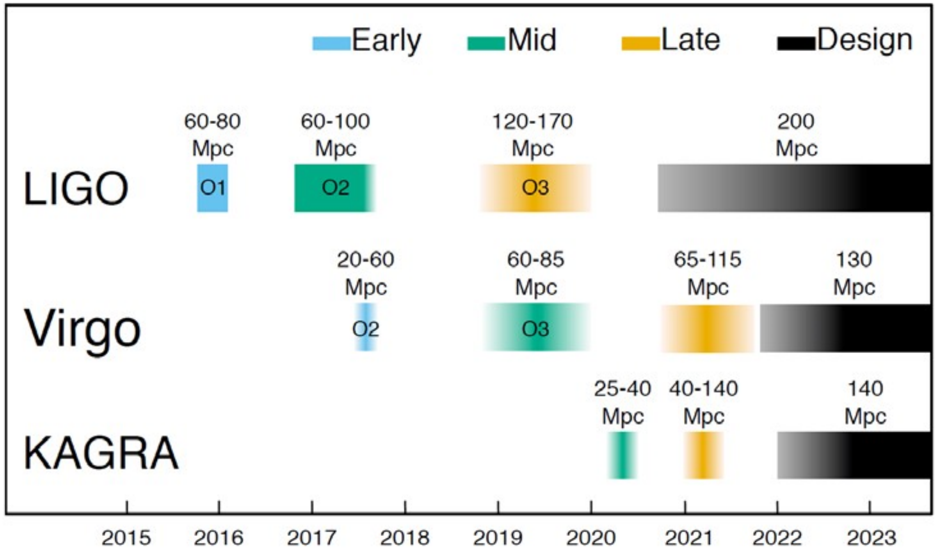
LIGO-VIRGO-KAGRA OBSERVING SCENARIO





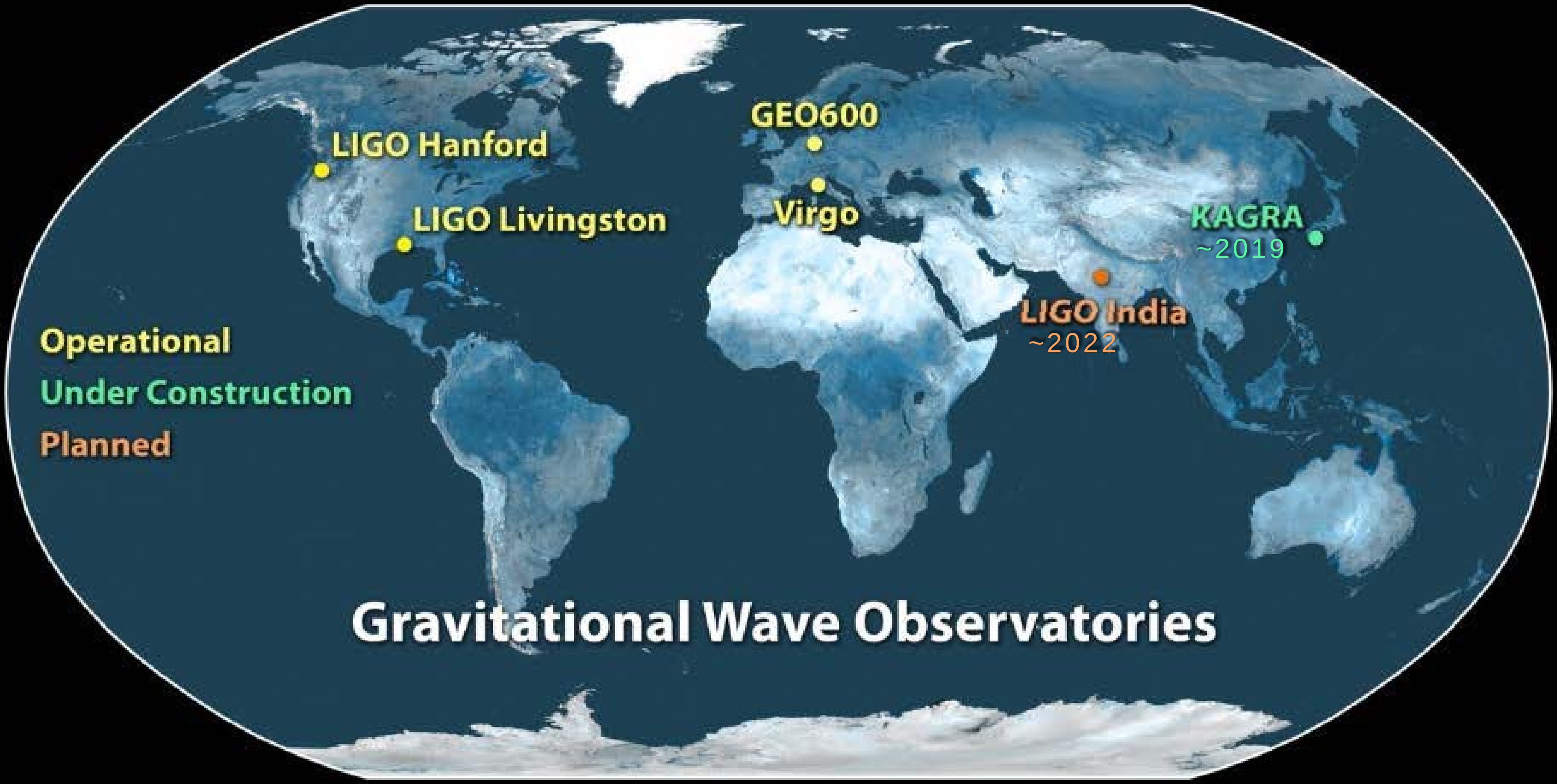
3x range
27x rate





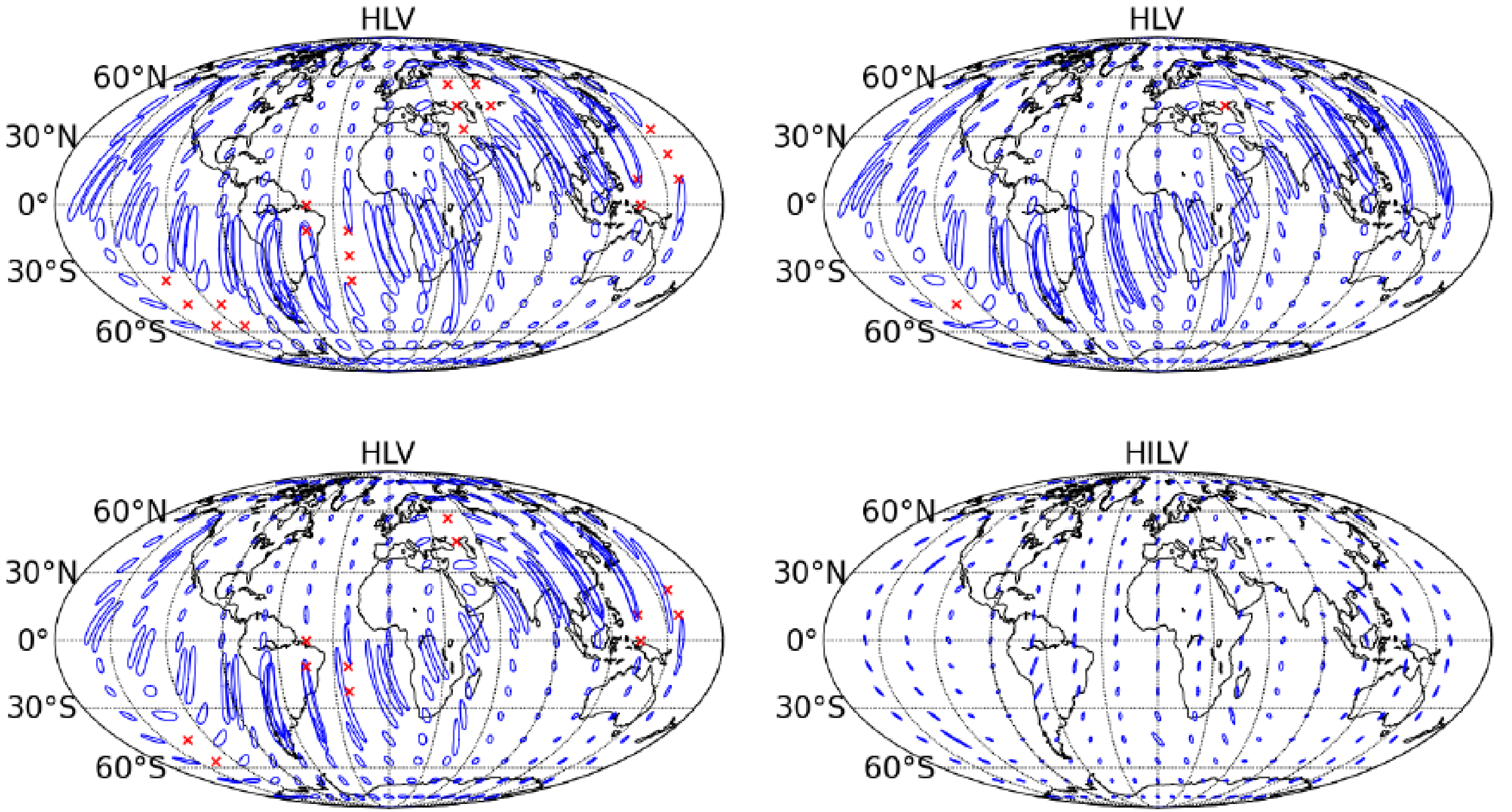
arXiv:1304.0670 Living Rev Relativ (2016) 19

TOWARDS A GLOBAL GW RESEARCH INFRASTRUCTURE



THE NETWORK IS THE DETECTOR

ANGULAR RESOLUTION WITH LIGO-INDIA



Top: localization for a BNS at 80 Mpc by HLV O2 (*left*) and O3 (*right*)
Bottom: localization for a BNS at 160 Mpc by HLV design (*left*) and HLVI, similar for KAGRA
Abbott, B.P., Living Rev Relativ (2016) 19: 1. https://doi.org/10.1007/lrr-2016-1

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

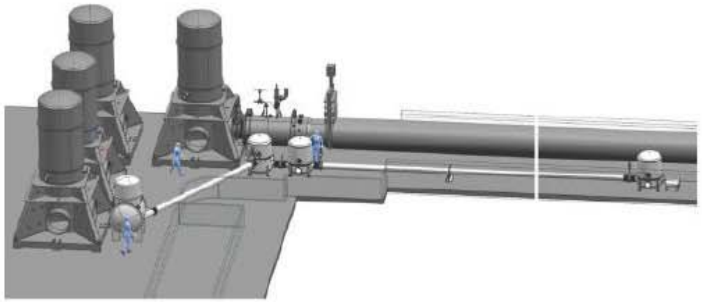
Tuned signal recycling and HPL: 120 Mpc

Frequency dependent squeezing: 150 Mpc

Newtonian noise cancellation: 160 Mpc

Larger mirrors (105 kg): 200-230 Mpc

Improved coatings: 260-300 Mpc



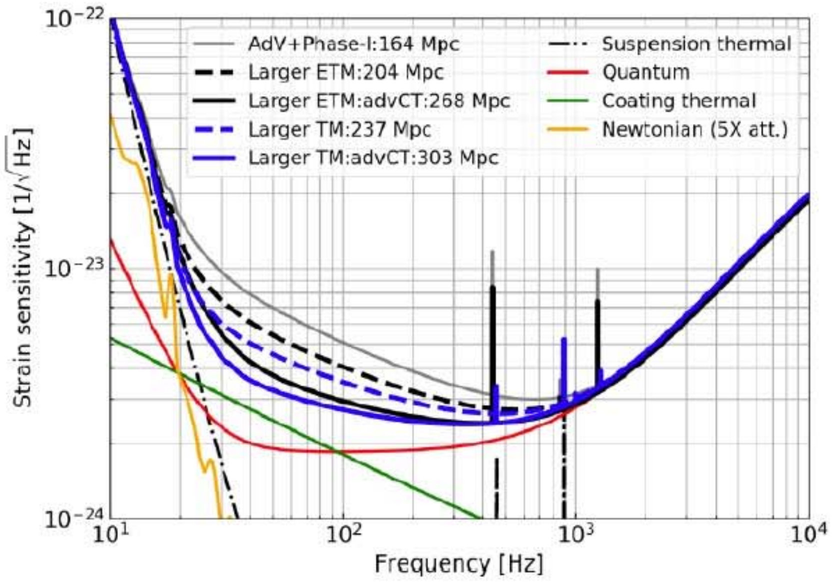
Secure Virgo's scientific relevance

Safeguard investments by scientists and funding agencies

Implement new innovative technologies

De-risk technologies needed for third generation observatories

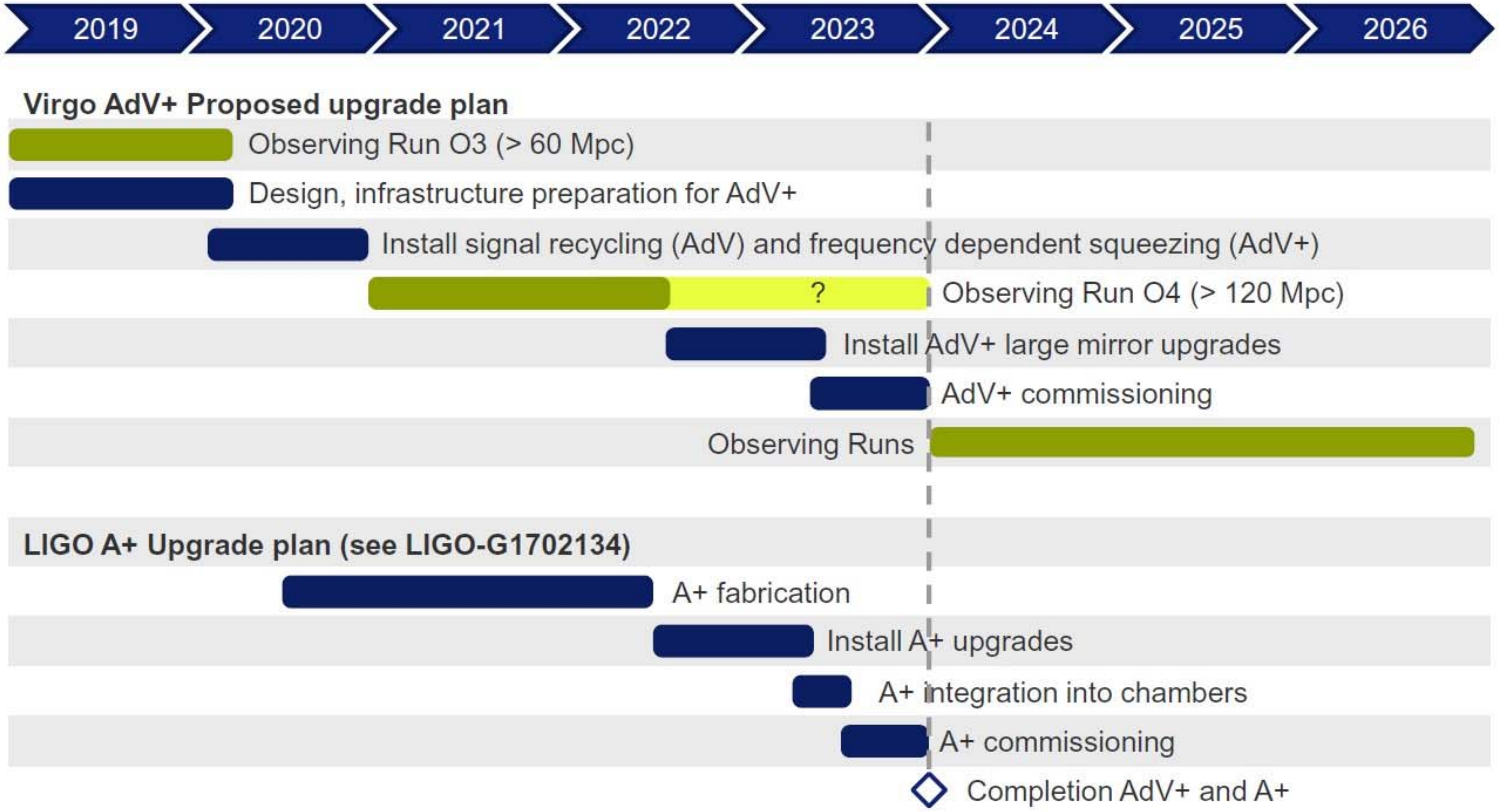
Attract new groups wanting to enter the field



A+ is the LIGO initiative

TENTATIVE TIMELINE

Five year plan for observational runs, commissioning and upgrades



2019 2020 2021 2022 2023 2024 2025 2026

Virgo AdV+ Proposed upgrade plan

Observing Run O3 (> 60 Mpc)

Design, infrastructure preparation for AdV+

Install signal recycling (AdV) and frequency dependent squeezing (AdV+)

? Observing Run O4 (> 120 Mpc)

Install AdV+ large mirror upgrades

AdV+ commissioning

Observing Runs

LIGO A+ Upgrade plan (see LIGO-G1702134)

A+ fabrication

Install A+ upgrades

A+ integration into chambers

A+ commissioning

◇ Completion AdV+ and A+

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

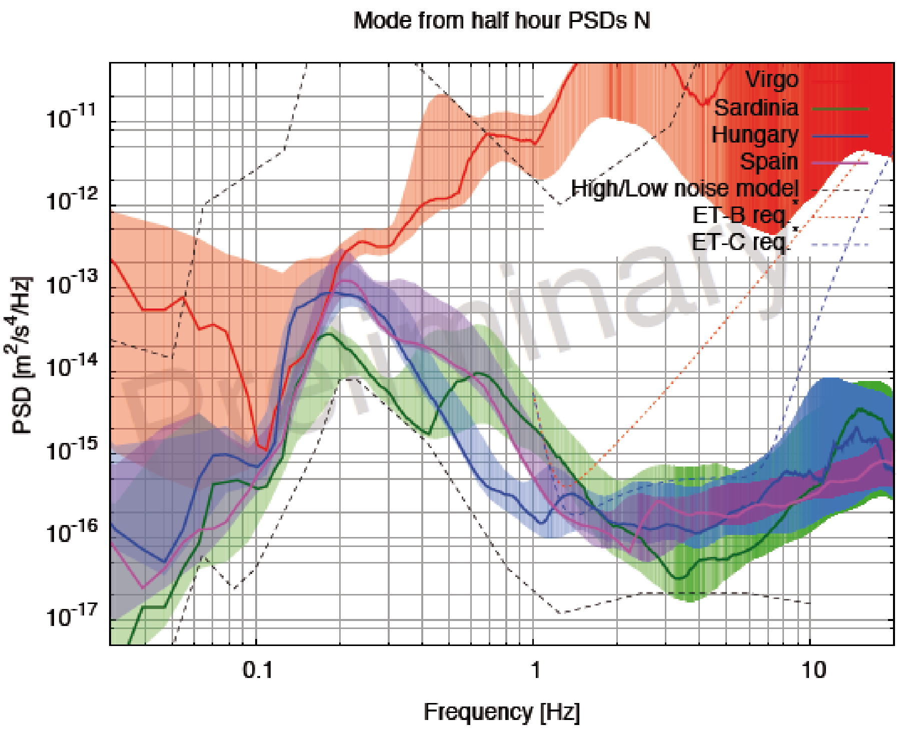
Gravity gradients

Final remedy for gravity gradients is going underground

European Third generation GW Observatory

Einstein Telescope: triangle configuration hosting 3 interferometers possibly dual low- and high-frequency

Several sites identified, detailed underground seismic characterization in progress

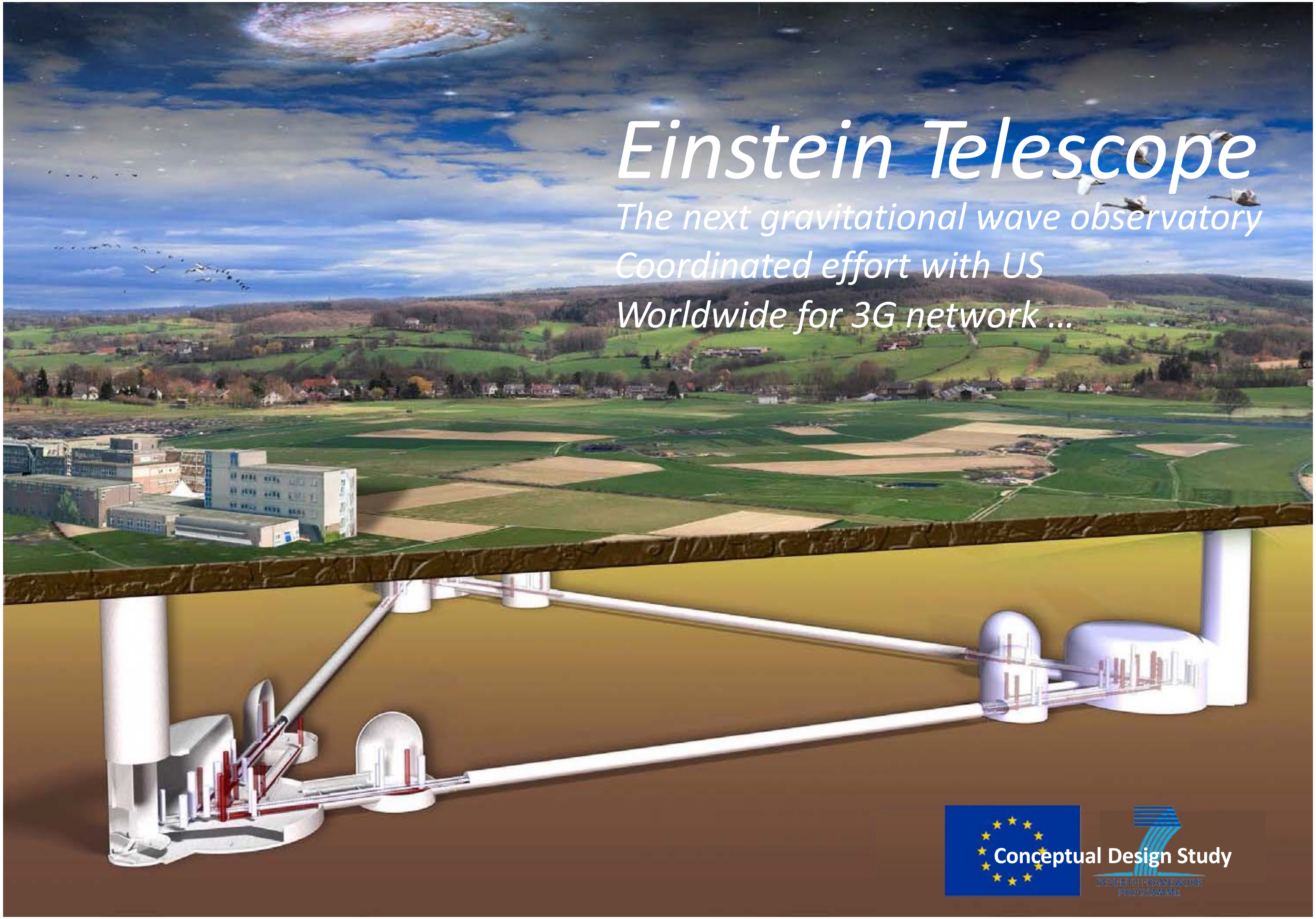


Virgo, 0 m

Sardinia, 185 m Sos Enattos

Hungary, 400 m

LSC, Spain, 800 m



Einstein Telescope

The next gravitational wave observatory

Coordinated effort with US

Worldwide for 3G network …

Conceptual Design Study

SEVENTH FRAMEWORK PROGRAMME

SUMMARY

Observation Run O2 has been generous:

- First triple coherent signal from BBH;
  - GR is working fine, first look at polarization states
- First BNS signal and electromagnetic follow up:
  - BNS produce short GRBs
  - Remnant evolution follows kilonova model
  - EM observation shows that r-processes occur, producing heavy elements

Improvements are coming for O3

Plan for full use of infrastructure and 3rd generation

The physics of gravitational waves has just begun!

SCIENTIFIC IMPACT OF GW PHYSICS

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