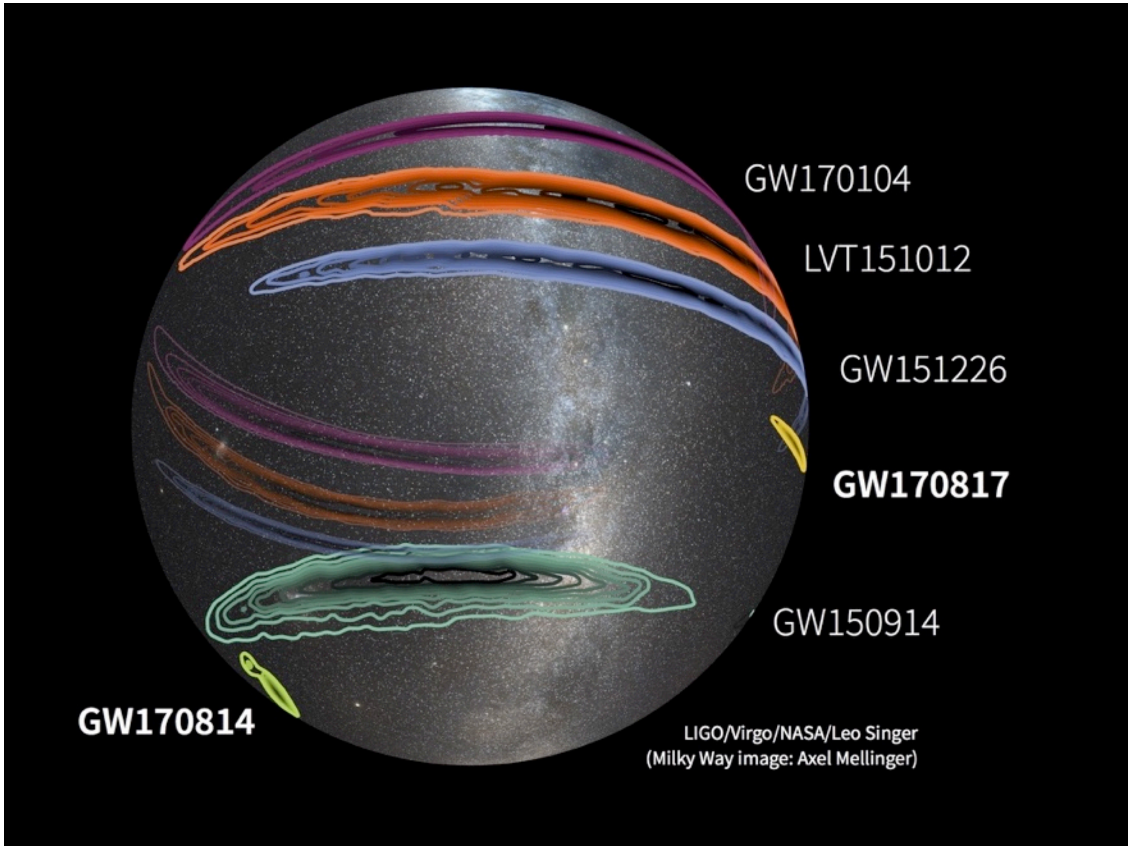
GW170814 and GW170817
the LIGO/Virgo detections of GWs from BBH and BNS



José Antonio Font (Universitat de València)
www.uv.es/virgogroup

The Gravitational Waves Hunting

1960s

Weber devised and constructed the first bar detector

1970s – 2000s

Room Temperature & Cryogenic Bar Detectors

Narrow Band Frequency detectors
(100 Hz @ 1KHz) & ($h \sim 10^{-21}$)

1970s – 2010s

Interferometers
Concept, Contruction & Operational

Broad Band Frequency detectors
(20 – 6000 Hz) & ($h \sim 10^{-23}$)

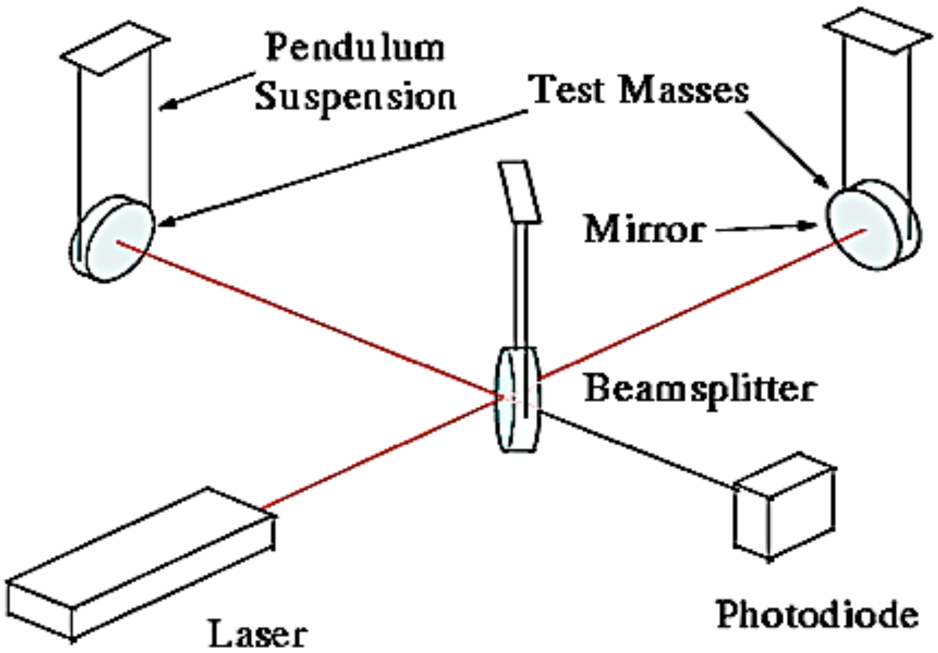
AURIGA – INFN/Padova

Virgo : Scientific Collaboration

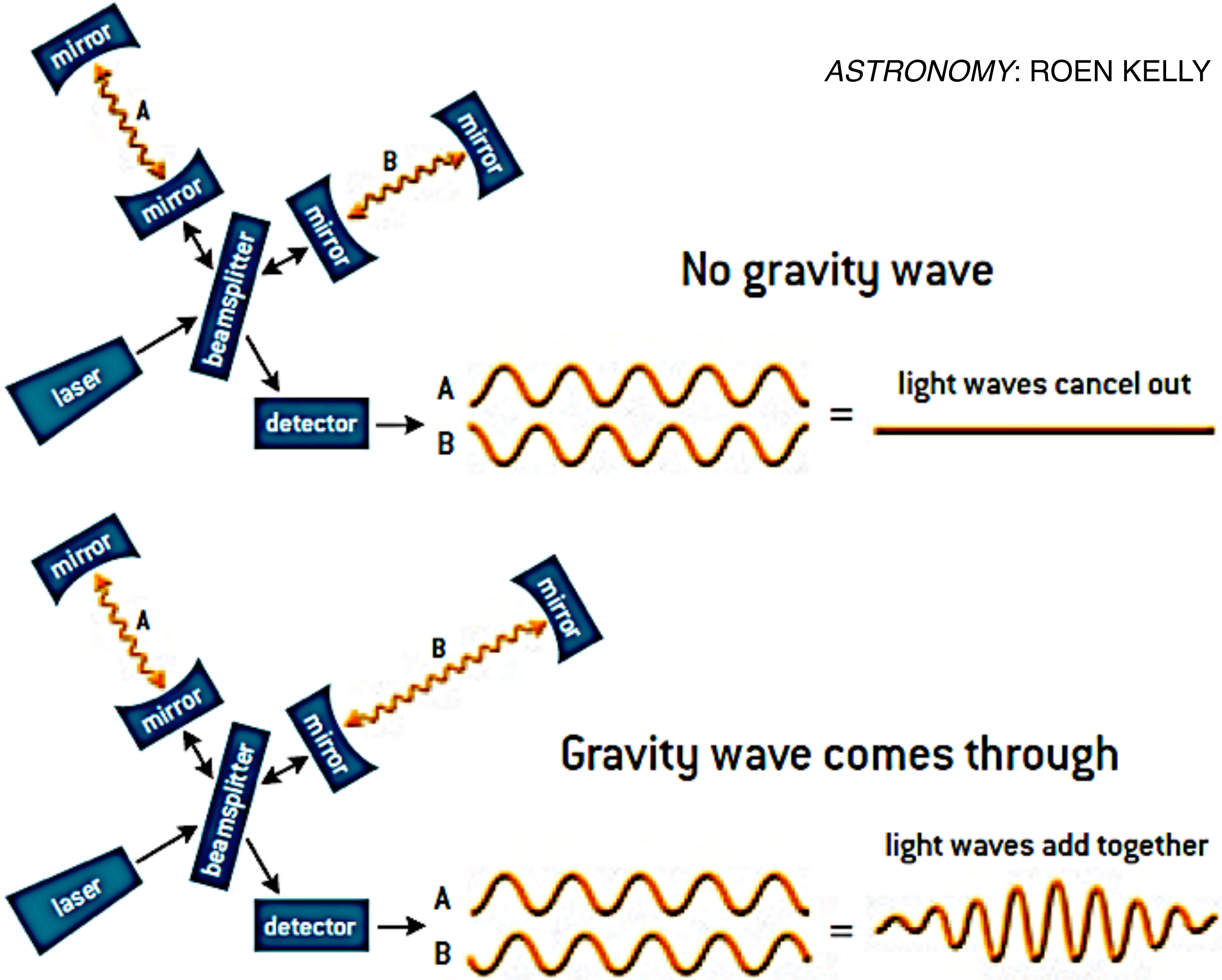
Italy, *France*, Netherlands, Poland, Hungary and Spain

Interferometer Detectors

Michelson-Morley interferometers. Test masses separated by large distances and suspended as pendulums to isolate them from seismic noise and reduce thermal noise.

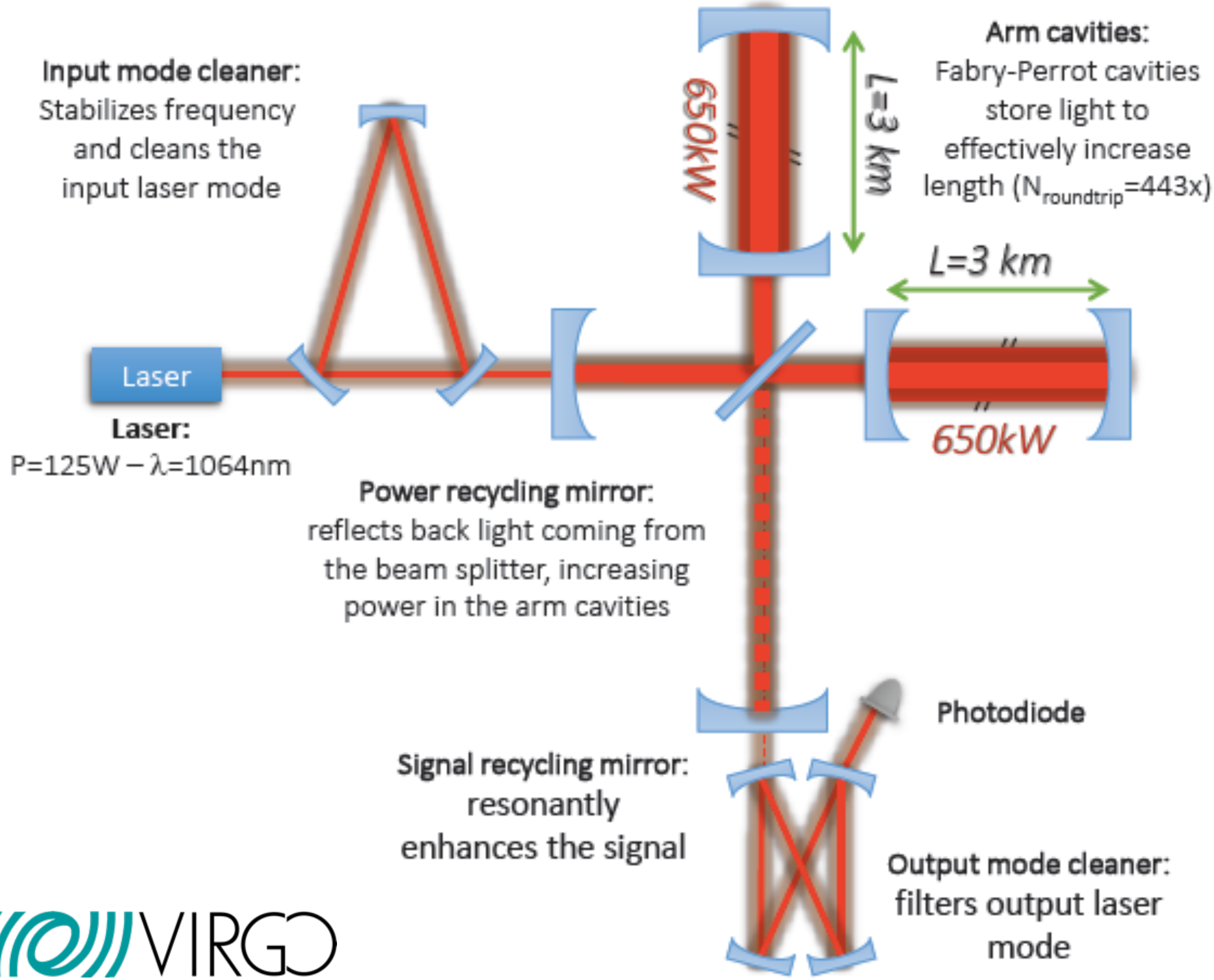


Analyzing the laser interference fringes allows to control the movement of the masses during their interaction with gravitational radiation.



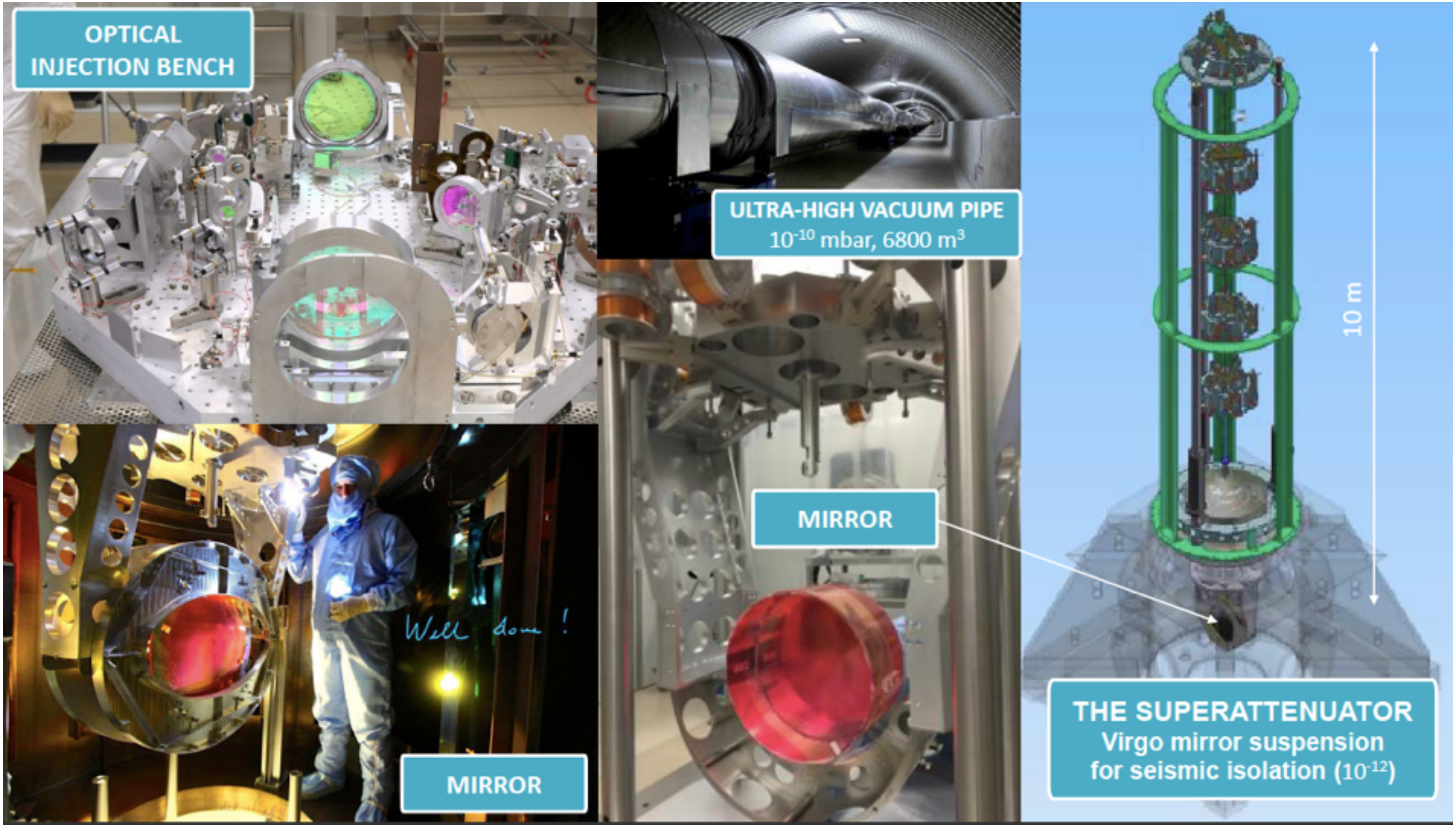
The (infinitesimal) change in the length of the arms originates a change in the intensity of the light (interference fringes) at the detector's output.

The Advanced Virgo interferometer



VIRGO

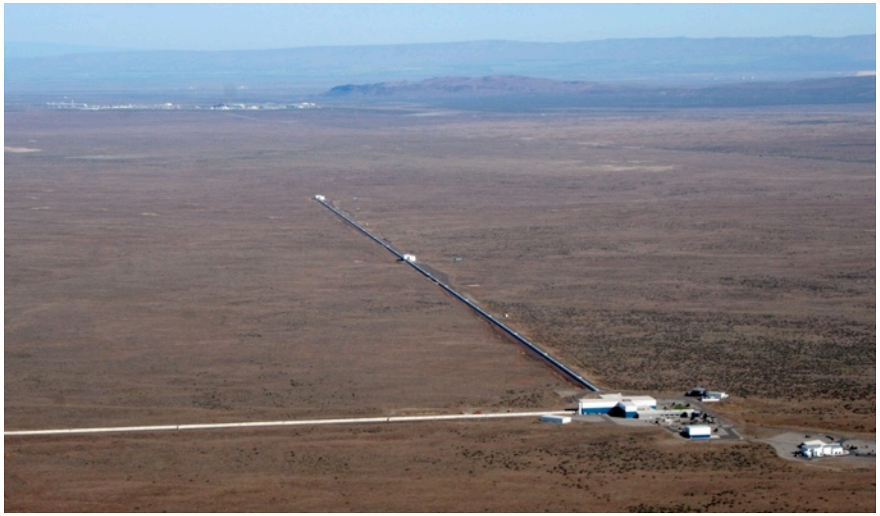
The Advanced Virgo interferometer



VIRGO

Our current network

LIGO Hanford Observatory



LIGO Livingston Observatory

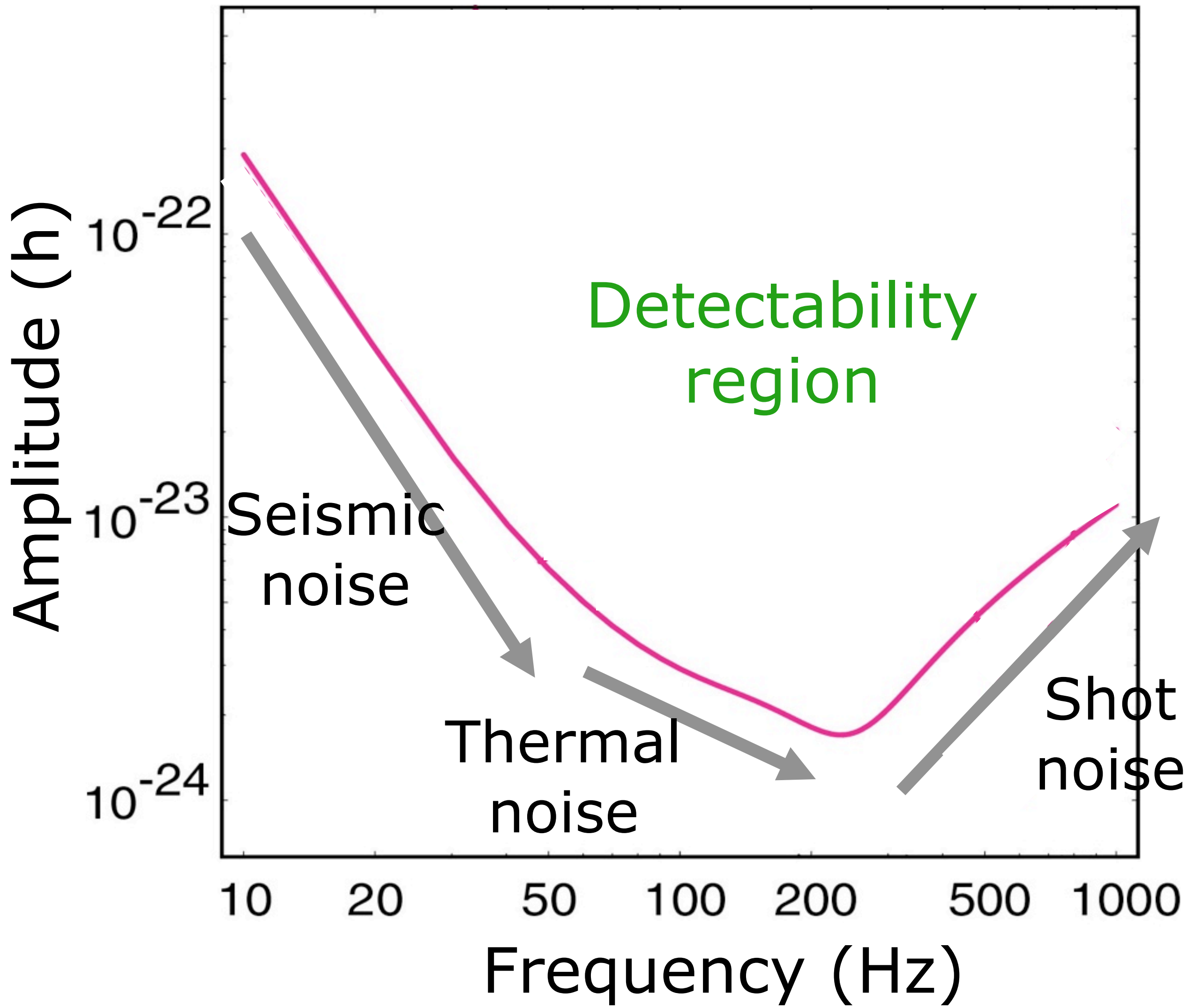
Virgo Observatory

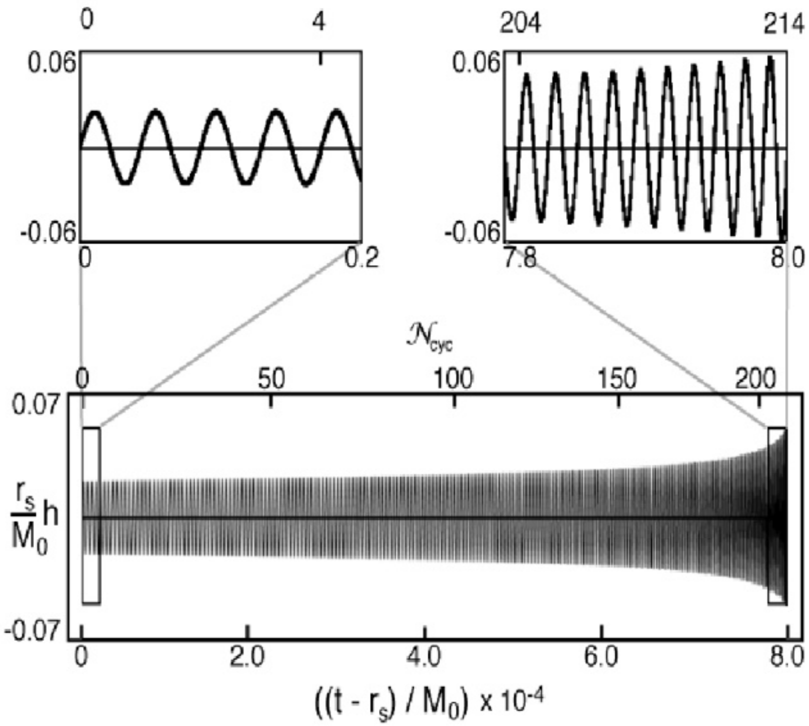
Expanded Network of Interferometers 2020+

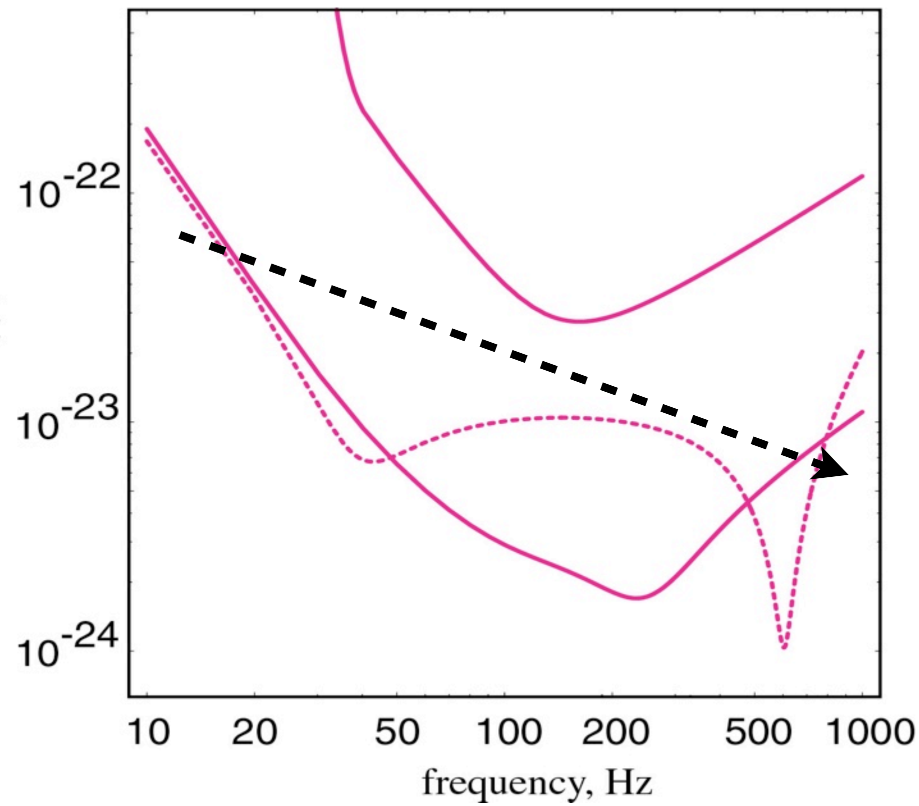
Towards a global GW research infrastructure

Noise-dominated observations

The small amplitude of gravitational waves calls for an extreme reduction of the sources of noise



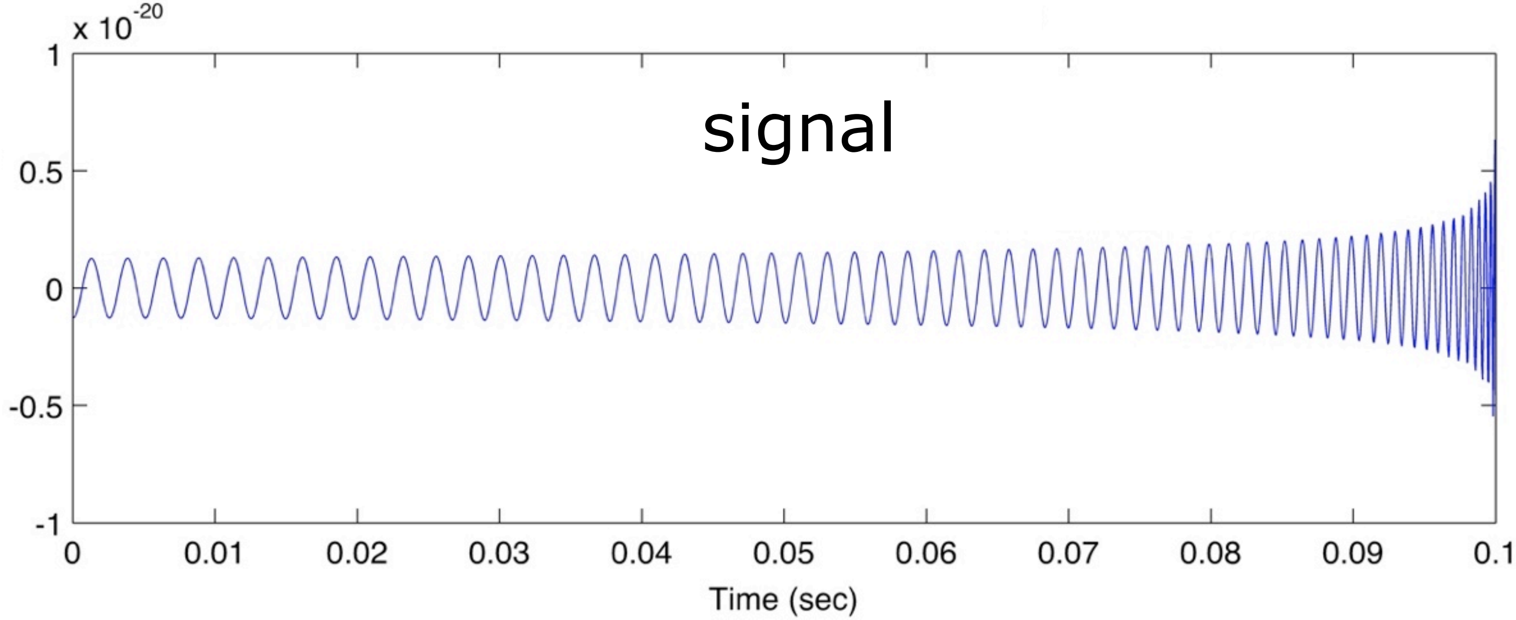


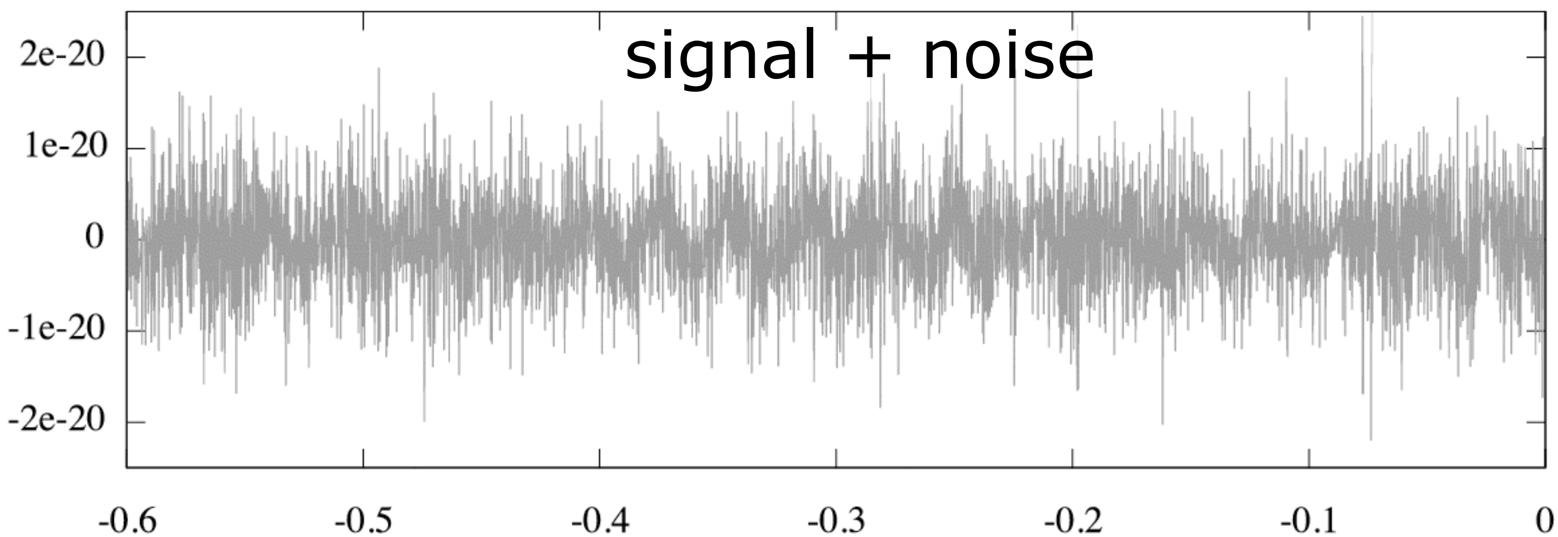


If sufficient mergers were detected we could average orbital parameters and use mergers as standard sirens.

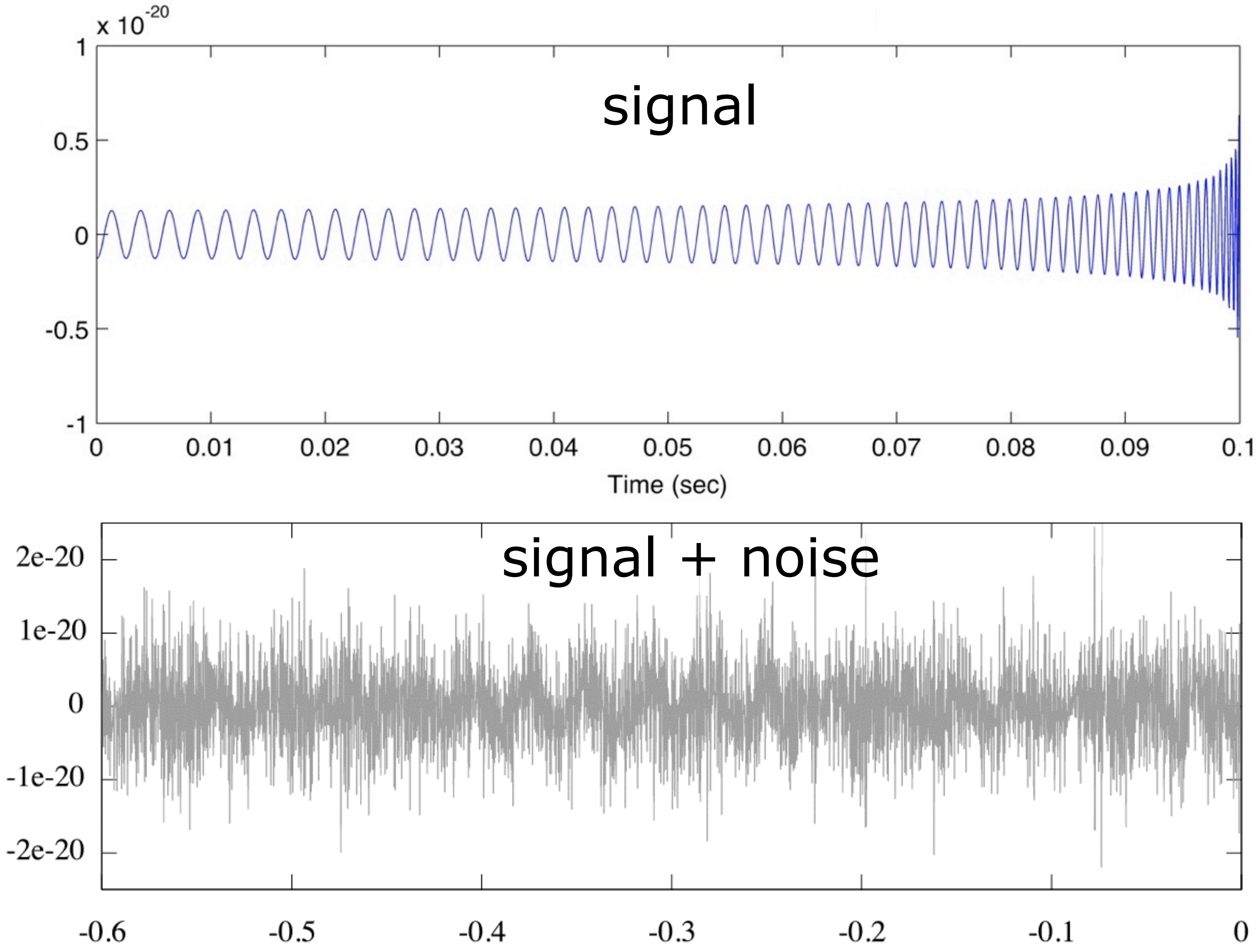
Numerical relativity simulations needed to extract accurate gravitational waveforms.

A “chirp” gravitational waveform

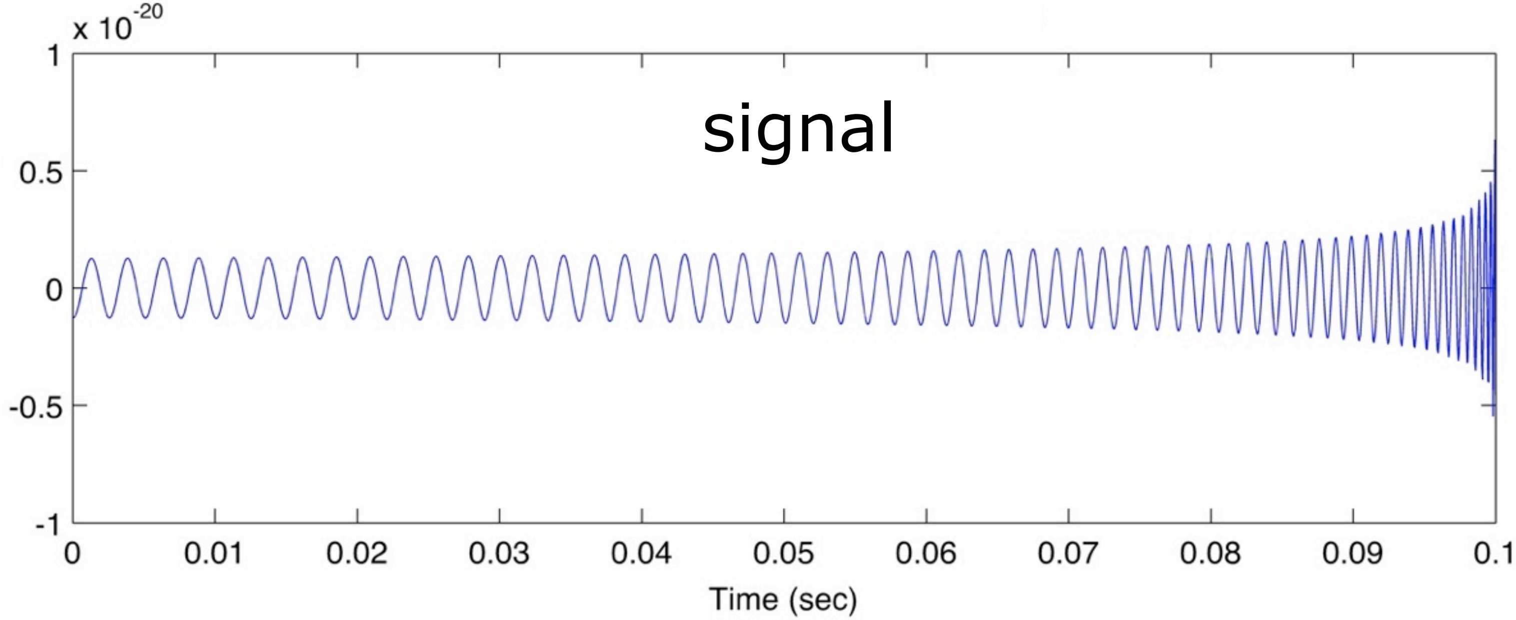


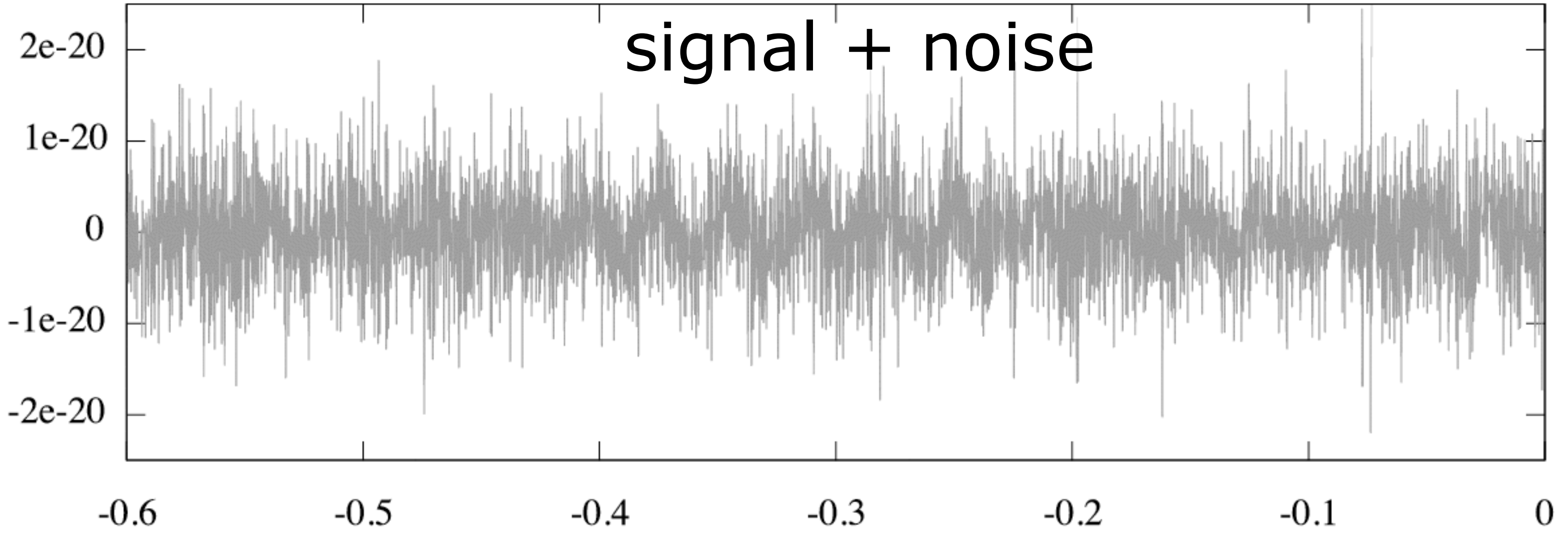


A “chirp” gravitational waveform



A "chirp" gravitational waveform





Advanced technology

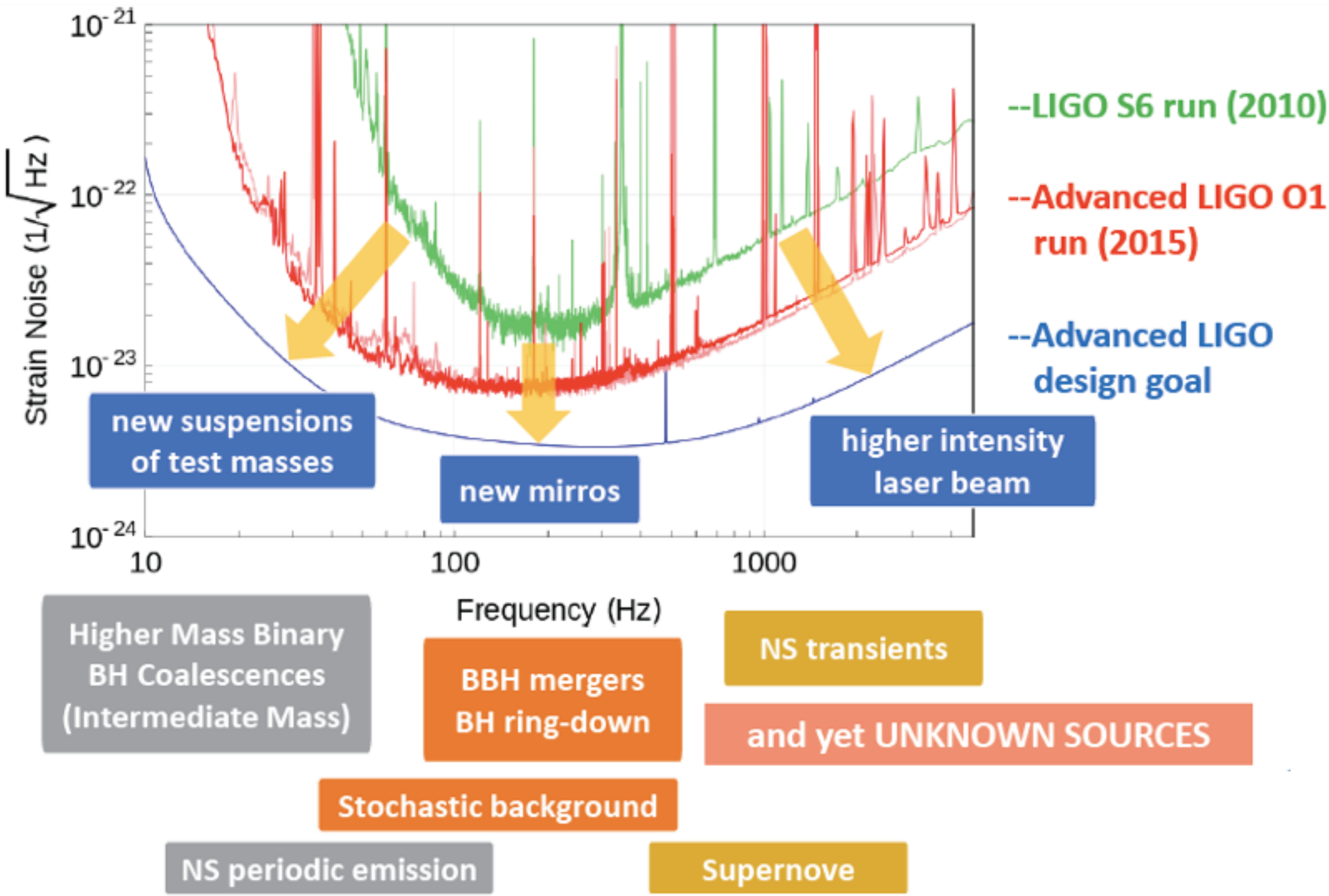
- ultra-vacuum arms ($p \sim 10^{-9}$ mbar). Movements (vibration) of test mases (40 kg) and suspensions induced by thermal effects.

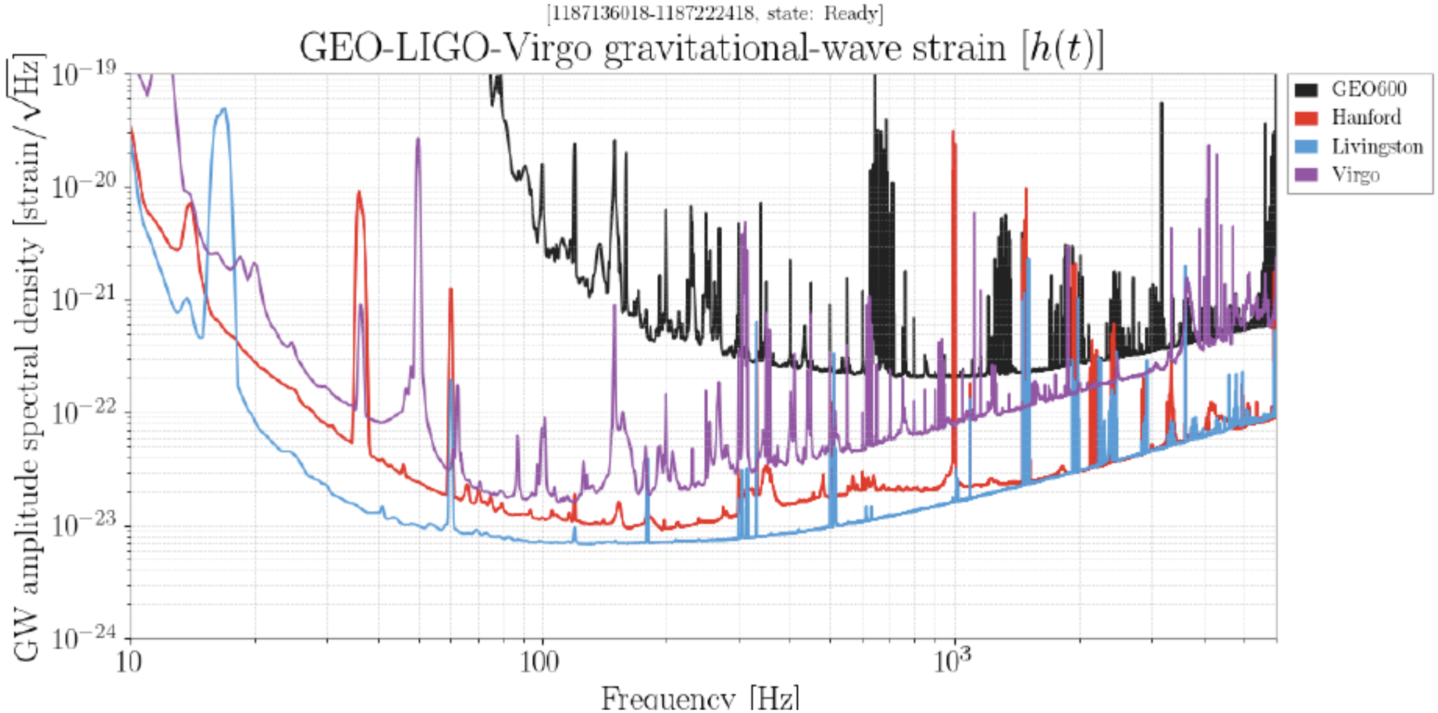
- high power lasers (Nd:YAG 1064 nm wavelength laser). Shot noise: fluctuations in the number of photons in the laser produce fluctuations in the signal.

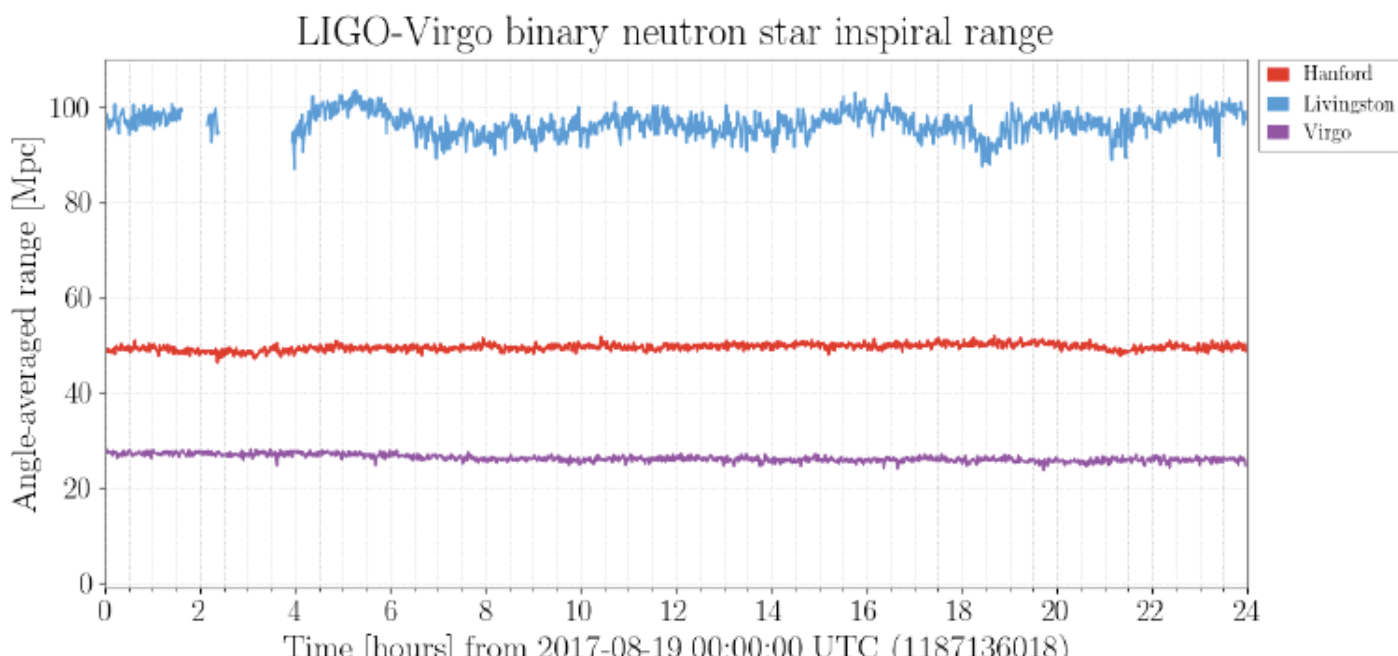
- highly reflective mirrors (SiO_2).

- monolythic suspension systems to isolate the detectors from vibrations. Reduce seismic noise.

Spectral sensitivity enhancement

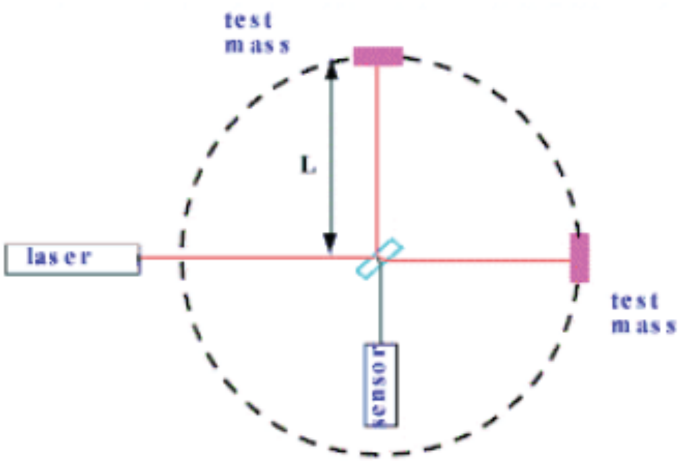



[1187136018-1187222418, state: Ready]
GEO-LIGO-Virgo gravitational-wave strain [$h(t)$]
GW amplitude spectral density [strain/$\sqrt{\text{Hz}}$]
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10
100
10^{3}
Frequency [Hz]
GEO600
Hanford
Livingston
Virgo


LIGO-Virgo binary neutron star inspiral range
Angle-averaged range [Mpc]
100
80
60
40
20
0
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

Directional sensitivity of detectors

Each interferometer senses only one of the two GW polarizations:



- measures the linear combination

$$h_{det} = F_+ h_+ + F_\times h_\times$$

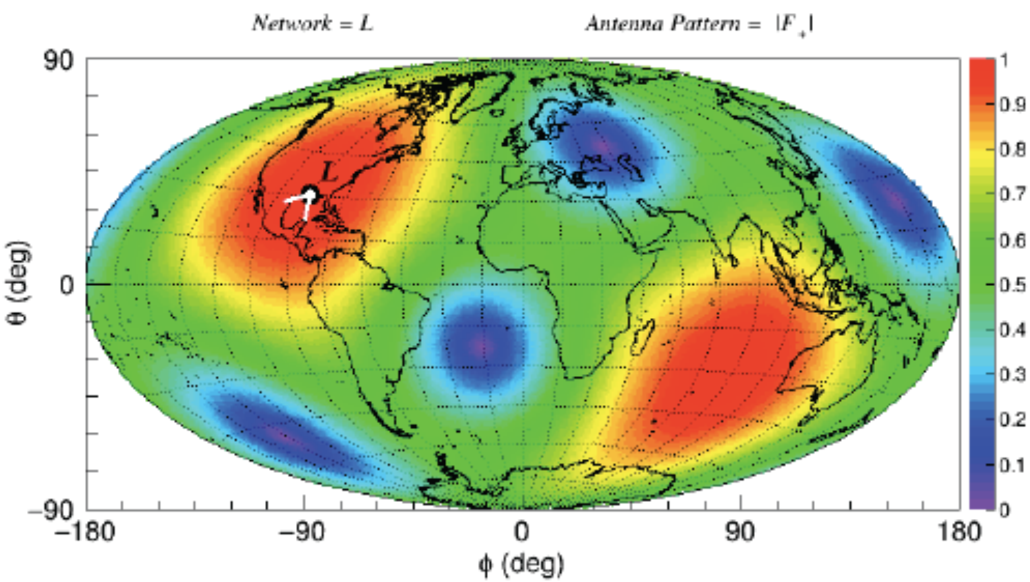
$$F_{+,\times}(\text{sky direction})$$

antenna patterns for + and x

- misses the orthogonal combination

Broad directional sensitivity:

LIGO Livingston



The LIGO network of two detectors

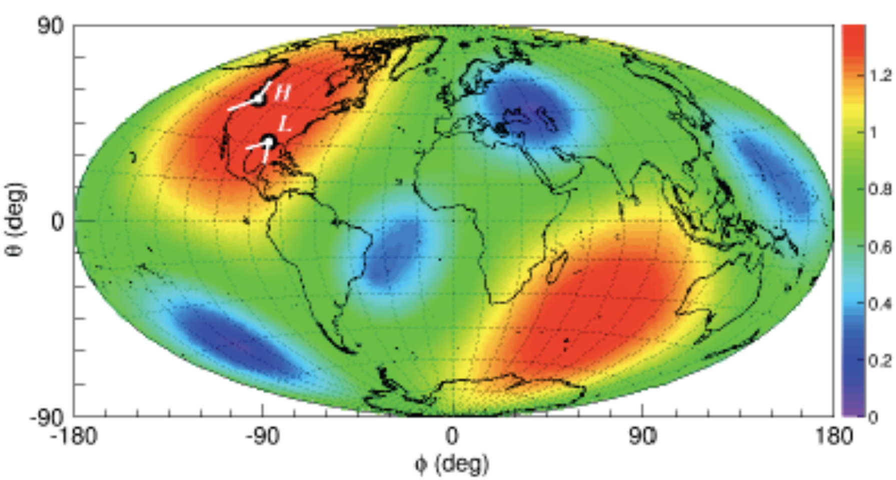
- **Detection confidence: discriminate GW candidates from noise fluctuations**
  - ✓ **At least two detectors in coincidence observation are required**
    unless for searches of persistent and well parametrized signals, e.g. periodic GWs
  - ✓ multimessenger searches with other detectors can help

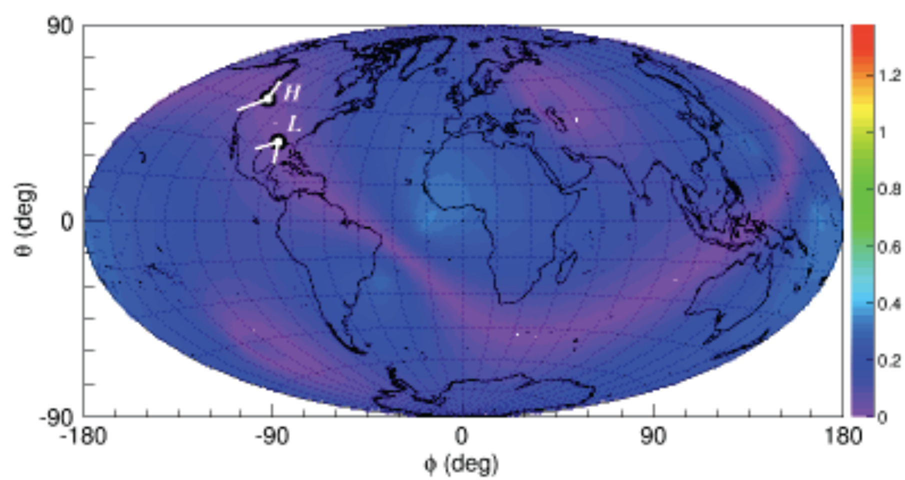
LIGOs arms are almost aligned

- **Sky coverage of LIGOs is very similar to that of a single detector**

  $\Rightarrow$ **almost blind to one GW polarization per each direction:**

$|\vec{F}_+|$ **LIGO Hanford + LIGO Livingston** $|\vec{F}_\times|$



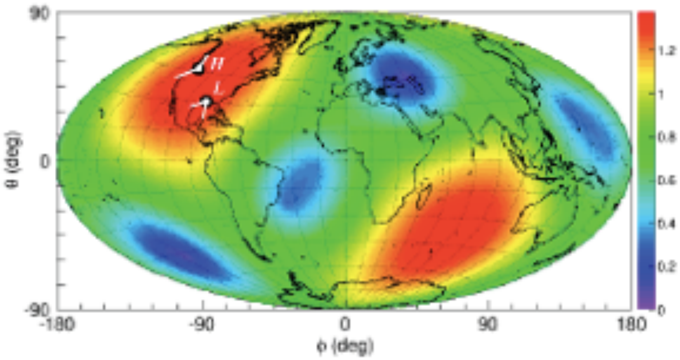


Benefit of adding Virgo detector

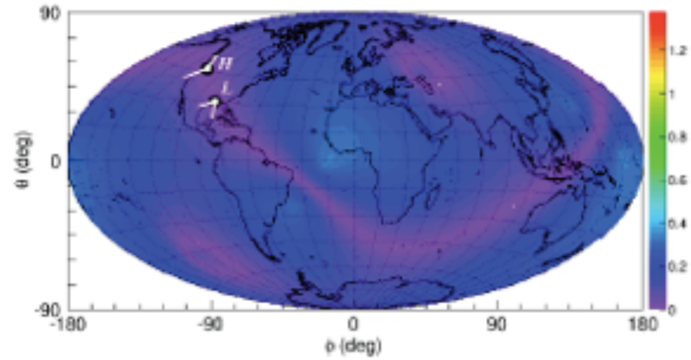
- **Detection confidence**: lower background and higher Signal-to-Noise Ratio
- Increased **time coverage of the survey** by detector pairs
- **coverage of sky and both GW polarizations**: better waveform reconstruction

LIGO Hanford + LIGO Livingston

$|\vec{F}_{+}|$

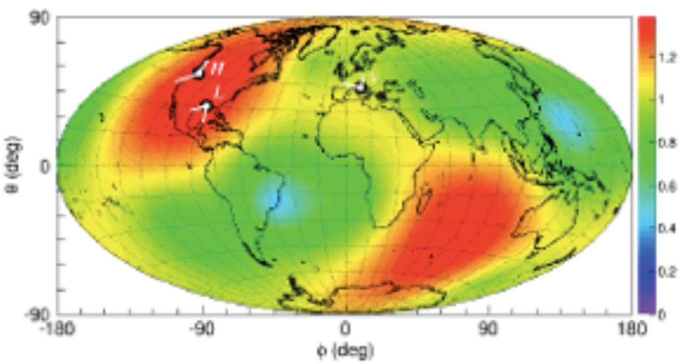


$|\vec{F}_{\times}|$



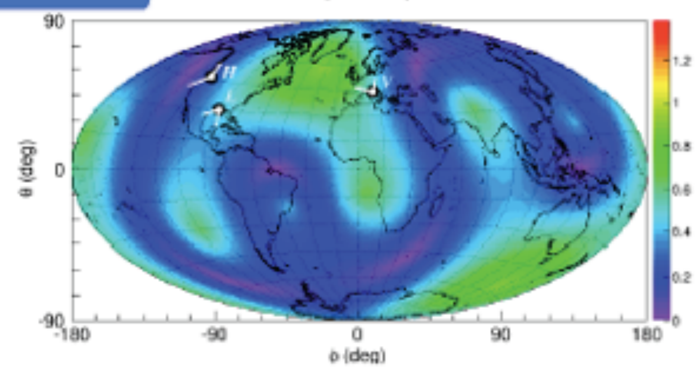
LIGO Hanford + LIGO Livingston and Virgo

$|\vec{F}_{+}|$

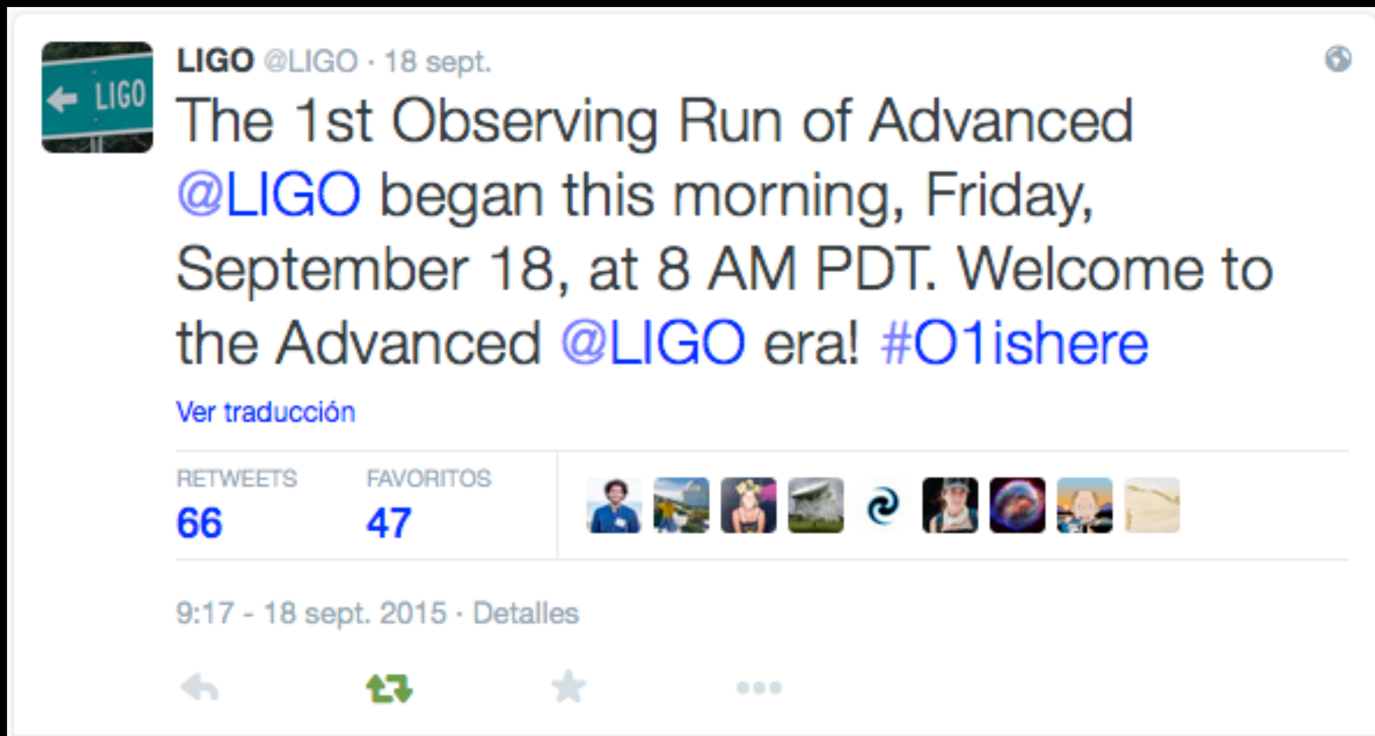


assuming same spectral sensitivity

$|\vec{F}_{\times}|$



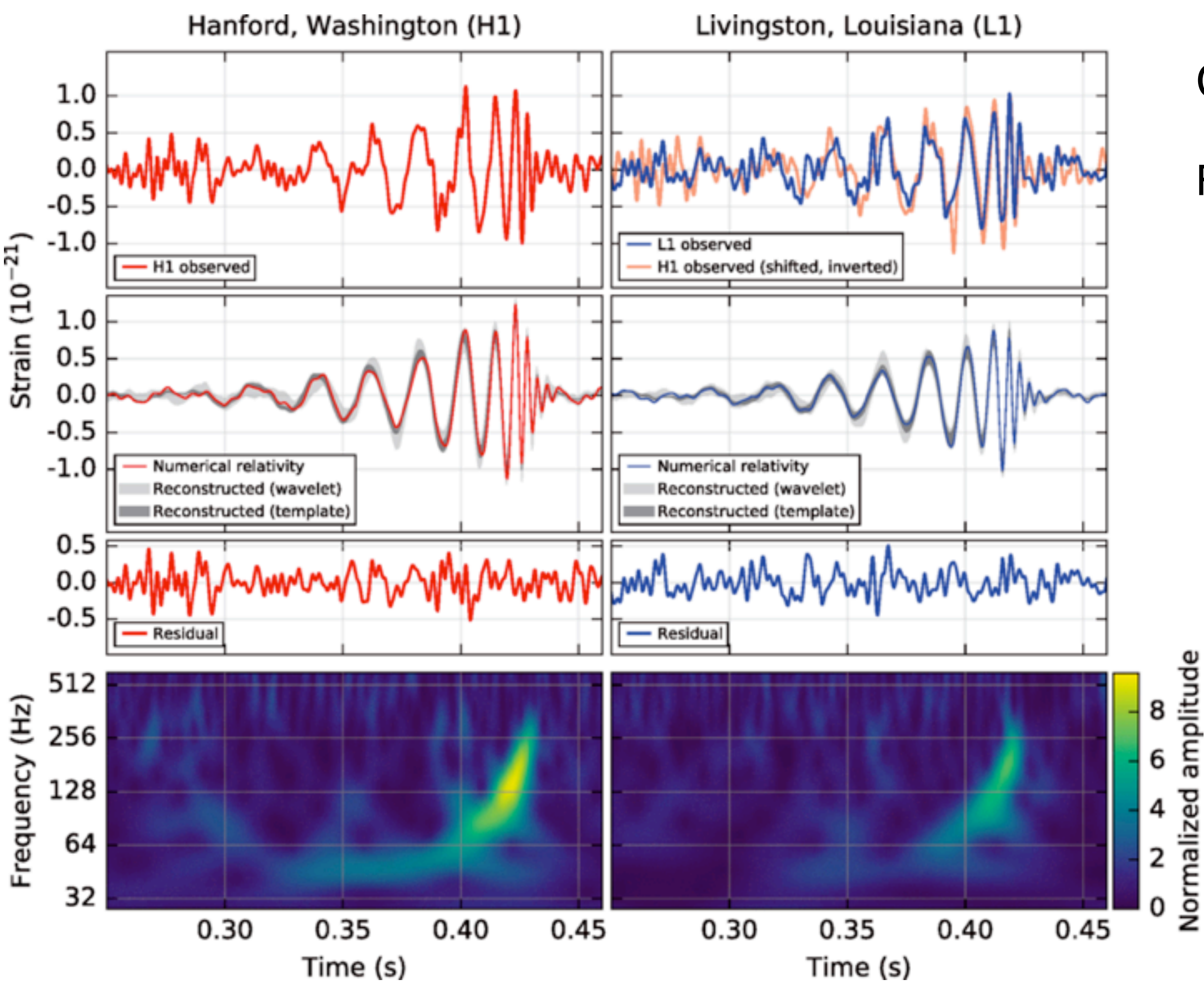
Advanced LIGO commissioned in 2014
Advanced Virgo in 2017



“We are there, we are in the ballpark now. It’s clear that this is going to be pulled off.”

(**Kip Thorne**, The Documentary, BBC World Service, 18/9/2015)

GW150914: the first GW observation



Abbott et al., PRL, 116, 061102 (2016)

Combined SNR: 24

FAR: 1 event per 203 000 years

significance > 5.1 σ

$$D_L = 410^{+160}_{-180}\,\mathrm{Mpc}$$

$$m_1 = 36^{+5}_{-4}\,M_\odot$$

$$m_2 = 29^{+4}_{-4}\,M_\odot$$

Final BH mass:

$$m_{\mathrm{BH}} = 62^{+4}_{-4}\,M_\odot$$

Distance: **1300 million light years**

Duration detected signal: **200 ms**

Testing GR in the strong-gravity regime

- **Black holes have no hair.** In GR, the outcome of a BBH merger is a Kerr black hole, completely described by its mass (M) and its spin (a). For quasi-circular orbits, GR allows to compute M and a from the masses and spins of the individual black holes.

For GW150914: $M = 62 \pm 4 M_\odot,\ a = 0.67^{+0.05}_{-0.07}$

Agreement between the Numerical Relativity results (fitting formulae) and GR predictions.

- GW150914 demonstrates the existence of stellar-origin black holes more massive than $\sim 25 M_\odot$ and establishes that binary black hole systems exist in Nature and can merge within a Hubble time.

• **Upper bound for the graviton mass** (mediating particle of the gravitational interaction).

In GR the graviton has zero mass and moves at the speed of light:

$$m_g = 0, \; v_g = c$$

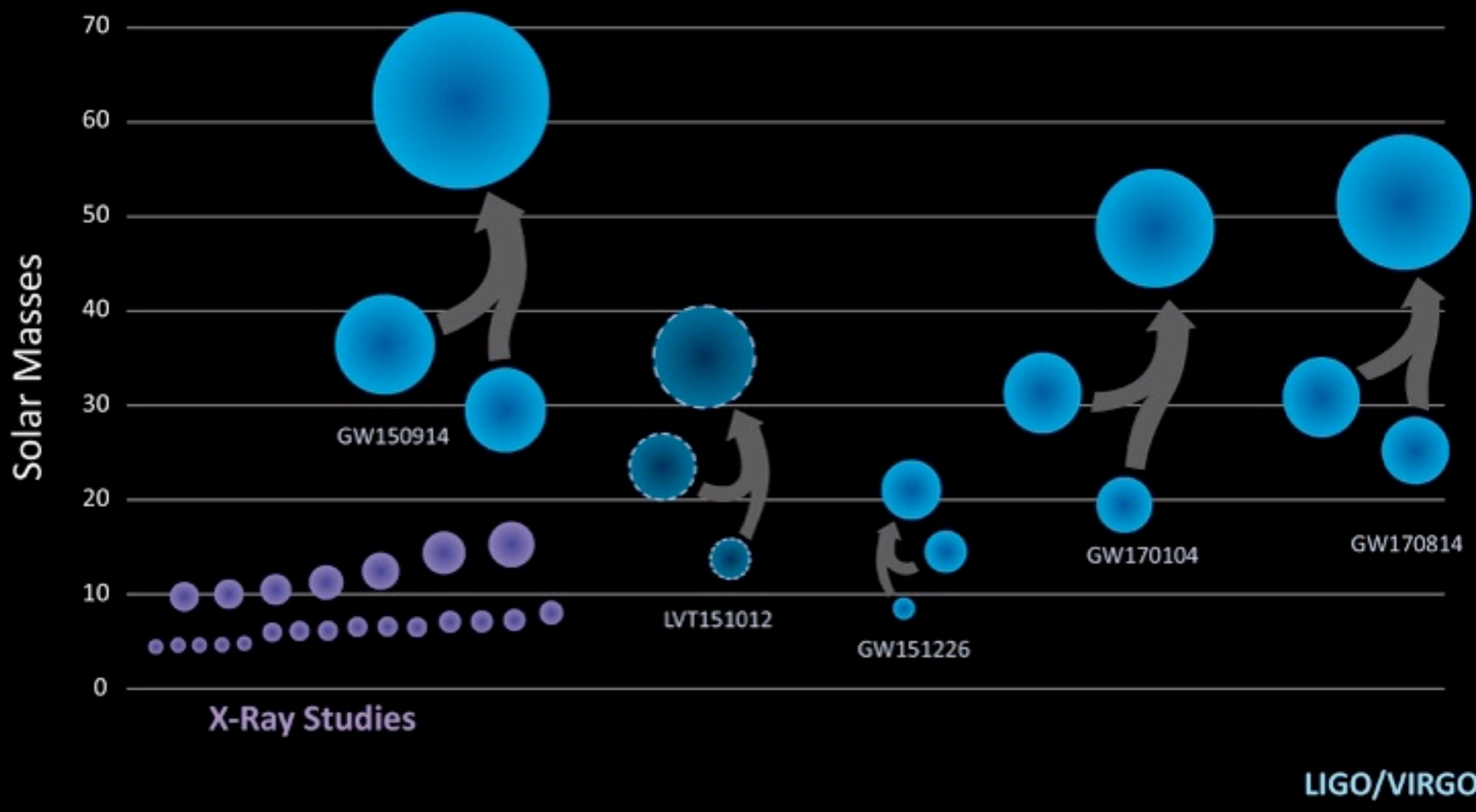
If $m_g \neq 0 \Rightarrow E^2 = p^2c^2 + m_g^2c^4$ (dispersion relation)

$$\frac{v_g^2}{c^2} := \frac{c^2p^2}{E^2} = 1 - \frac{h^2c^2}{E^2\lambda_g^2} \quad \text{with} \quad \lambda_g = \frac{h}{m_g c}$$

If λ_g is finite, low frequencies propagate slower than high frequencies. Such dispersion can be incorporated in the analysis of the phase of the signal of the binary. For the GW150914 data there is no evidence of a finite value of λ_g .

Lower bound: $\lambda_g > 10^{13}\,\mathrm{km} \Rightarrow m_g < 1.2 \times 10^{-22}\,\mathrm{eV}/c^2$

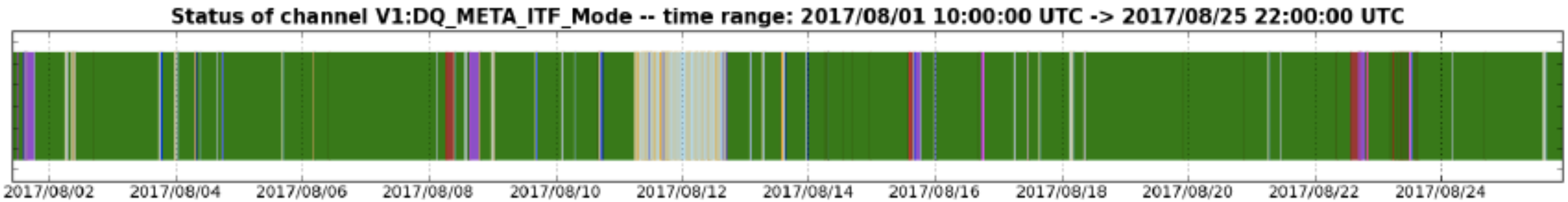
Black holes of known mass

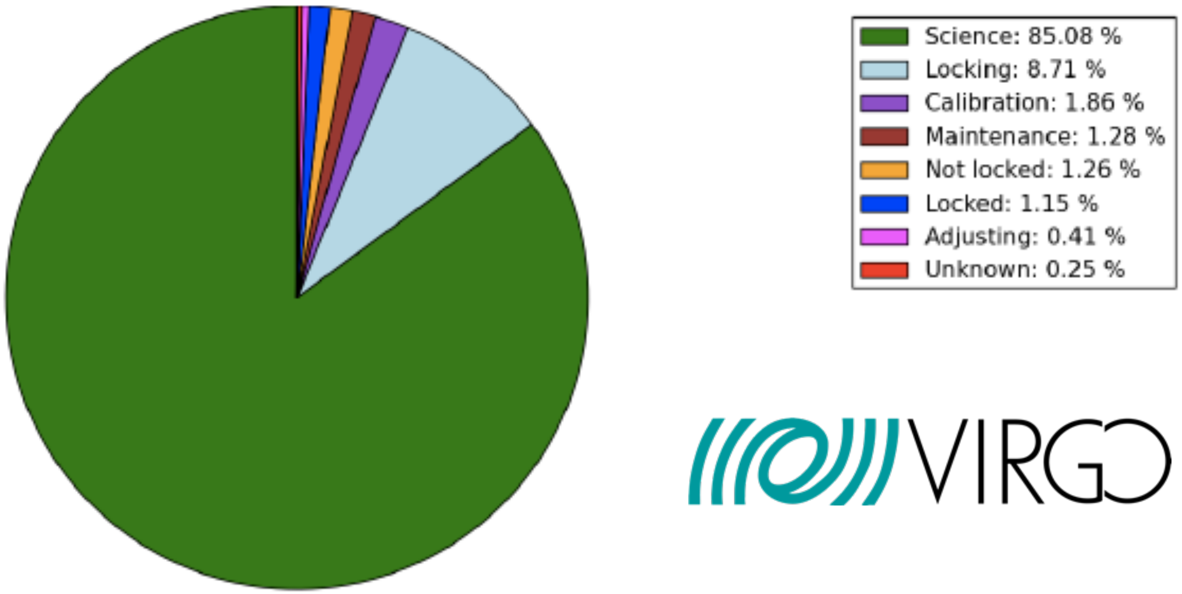


Advanced Virgo

Advanced Virgo joined Advanced LIGO for O2 run on Aug 1st. 2017

Advanced Virgo: Performance during O2

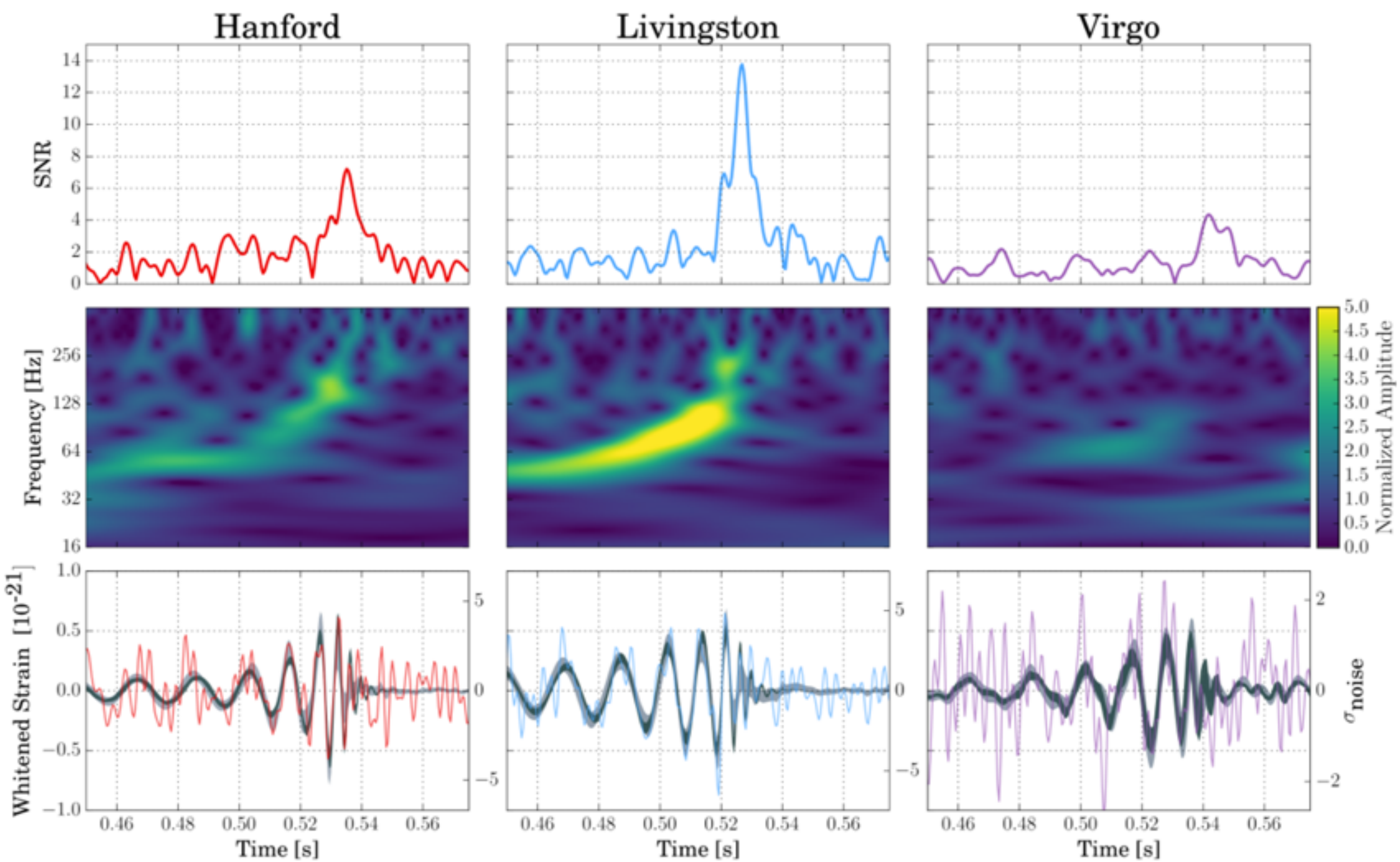




The duty cycle of the detector in science mode was **85%** during the 4 weeks of data taking in O2.

Two detections! **GW170814** and **GW170817**

GW170814: first three-detector observation



Abbott et al., PRL, 119, 141101 (2017)

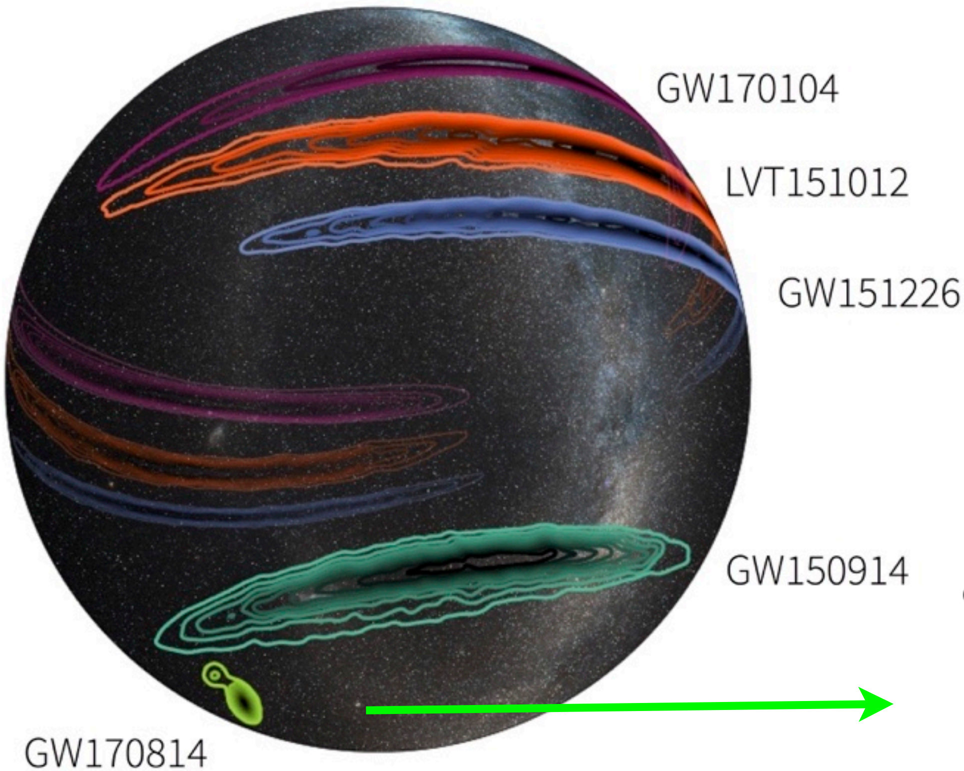
Combined SNR: 18
FAR: less than 1 event per 27000 yrs

$$m_1 = 30.5^{+5.7}_{-3.0}\,\mathrm{M}_\odot$$

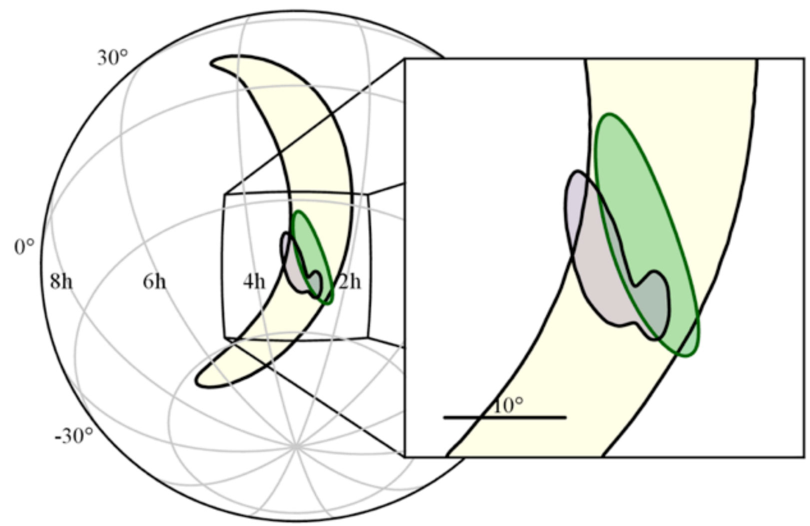
$$m_2 = 25.3^{+2.8}_{-4.2}\,\mathrm{M}_\odot$$

$$m_{\mathrm{BH}} = 53.2^{+3.2}_{-2.5}\,\mathrm{M}_\odot$$

Sky localization of the GW events



Virgo significantly improved sky localization!



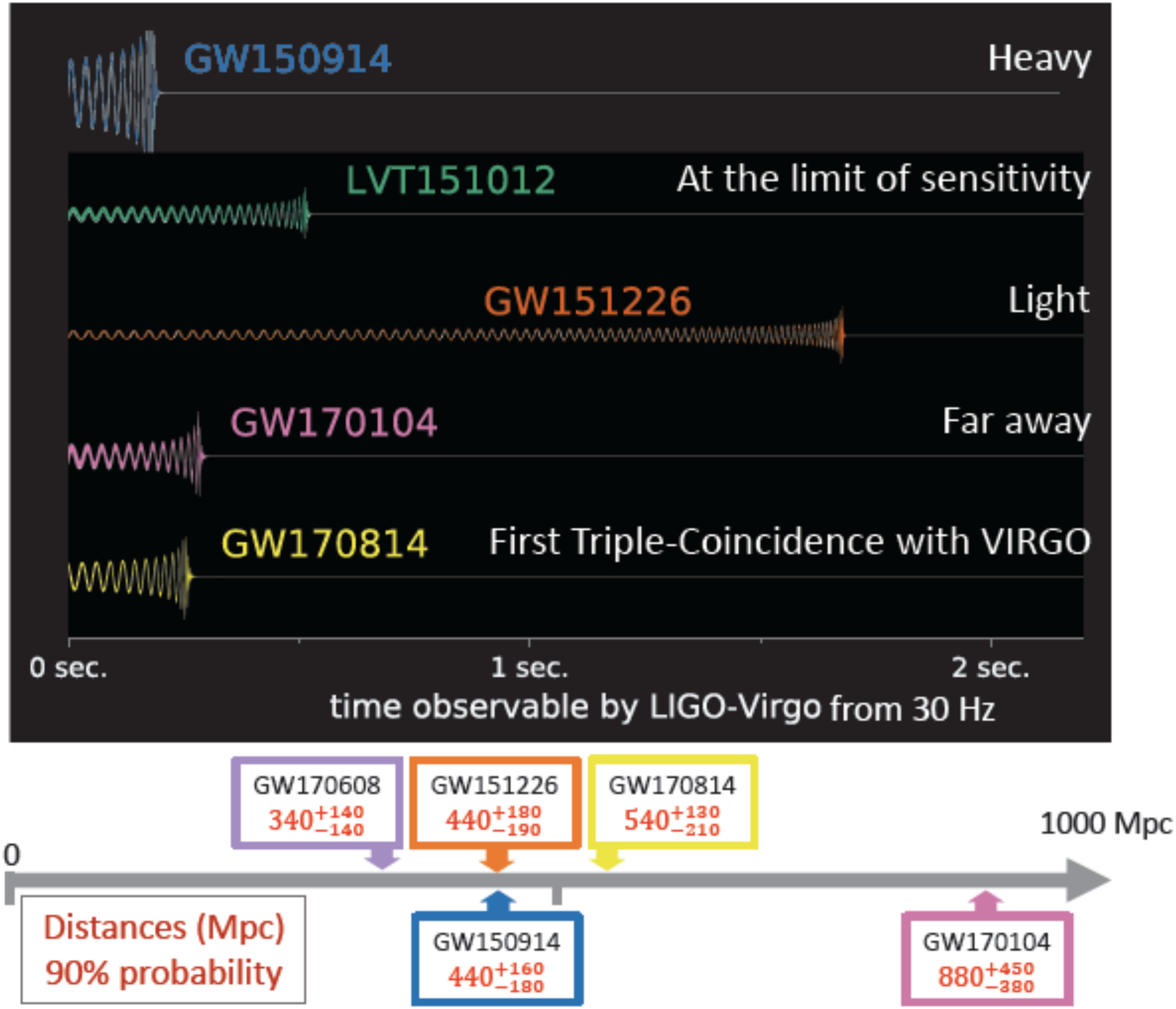
Credit:
LIGO/Virgo/NASA/Leo Singer
Milky Way image: Axel Mellinger

Abbott et al., PRL, 119, 141101 (2017)

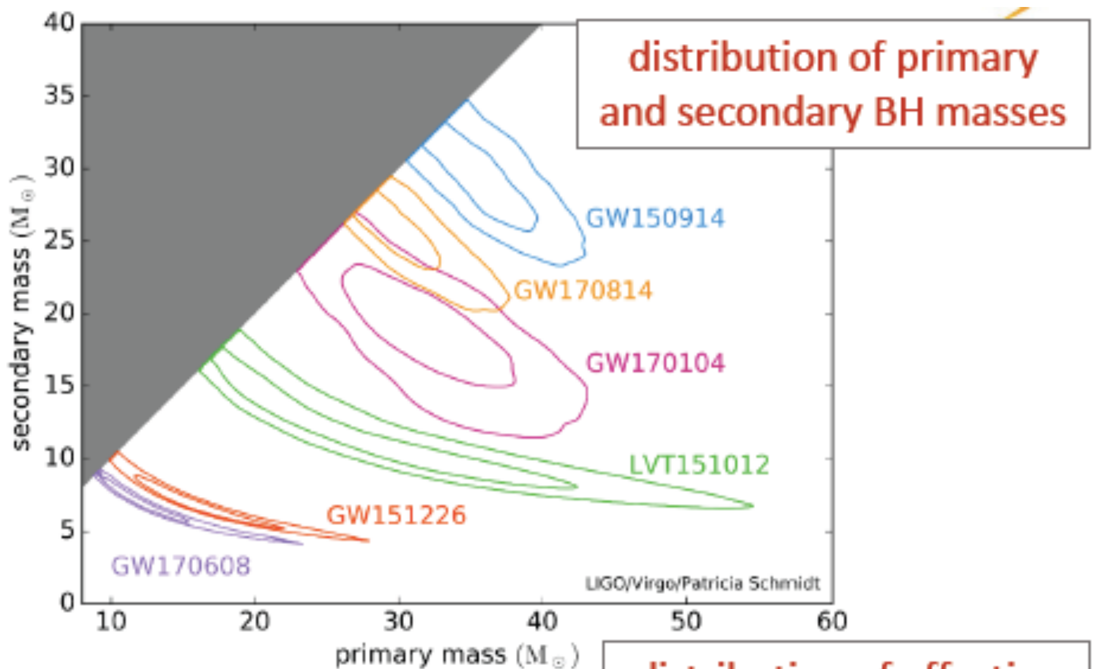
Rapid localization HL: 1160 deg^2
Rapid localization HLV: 100 deg^2

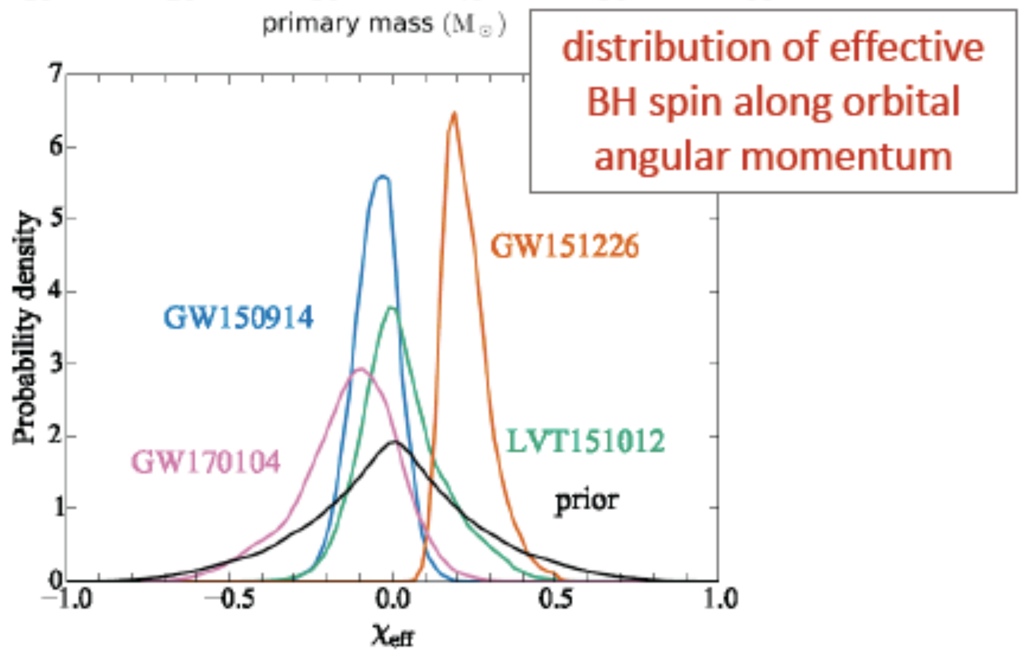
Final localization HLV: **60 deg^2**

LIGO/Virgo black holes: how diverse are they?



LIGO/Virgo black holes: how diverse are they?





Nobel Prize in Physics 2017

"for decisive contributions to the LIGO detector and the observation of gravitational waves"

Photo: Bryce Vickmark

Rainer Weiss

Prize share: 1/2

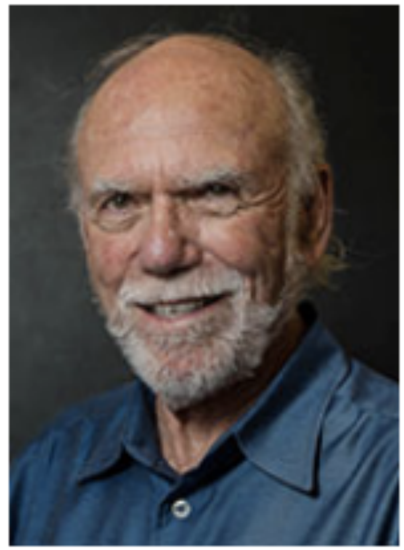


Photo: Caltech

Barry C. Barish

Prize share: 1/4

Photo: Caltech Alumni Association

Kip S. Thorne

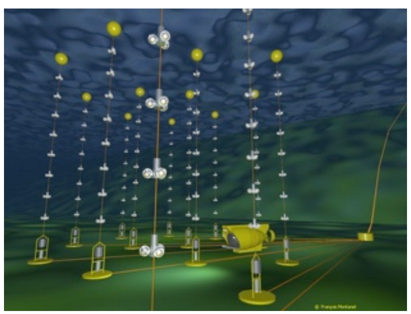
Prize share: 1/4

GW170817: first GW signal from a **binary neutron star merger!**

Multi-Messenger Astronomy

Gravitational Waves + Light + Neutrinos

gravitational
waves



cosmic rays
neutrinos

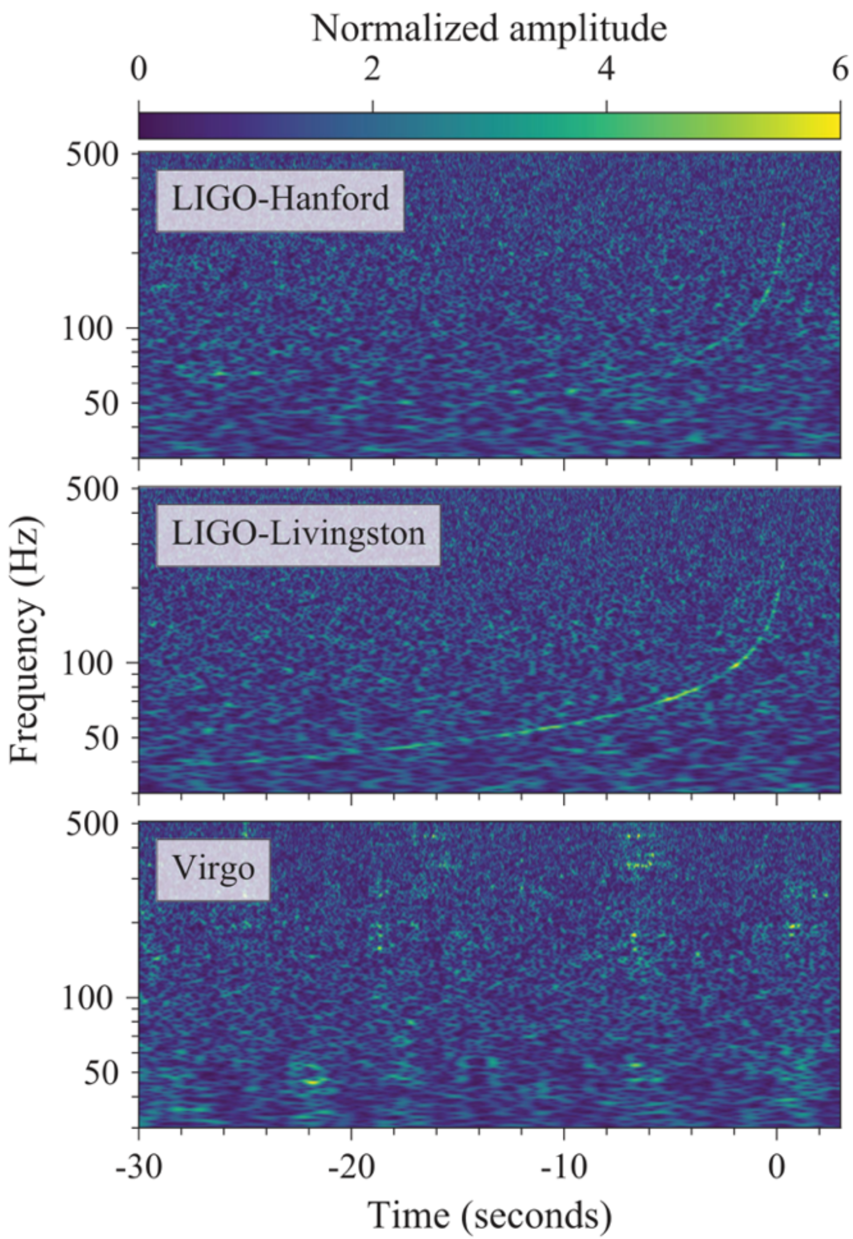
gamma rays
X rays

ultraviolet
visible / infrared

radio

LIGO/Virgo have signed **MoU** with about 92 partners from 19 countries.
200 instruments across the entire electromagnetic spectrum.

GW170817: first GW observation of a BNS merger



August 17, 2017, at 12:41:04 UTC

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

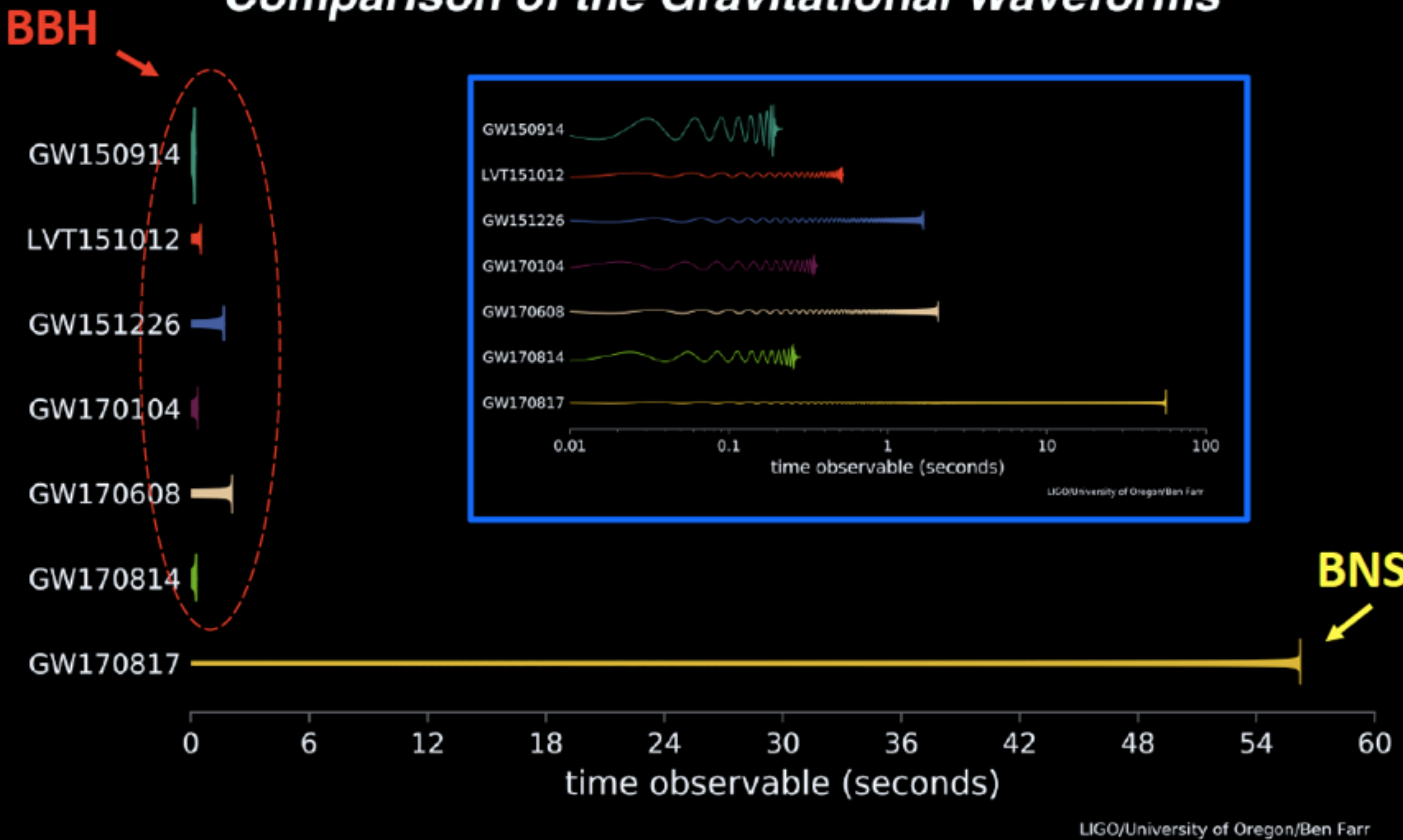
SNR is 18.8 (H), 26.4 (L) and 2.0 (V). **Combined SNR is 32.4**

Loudest signal yet observed!

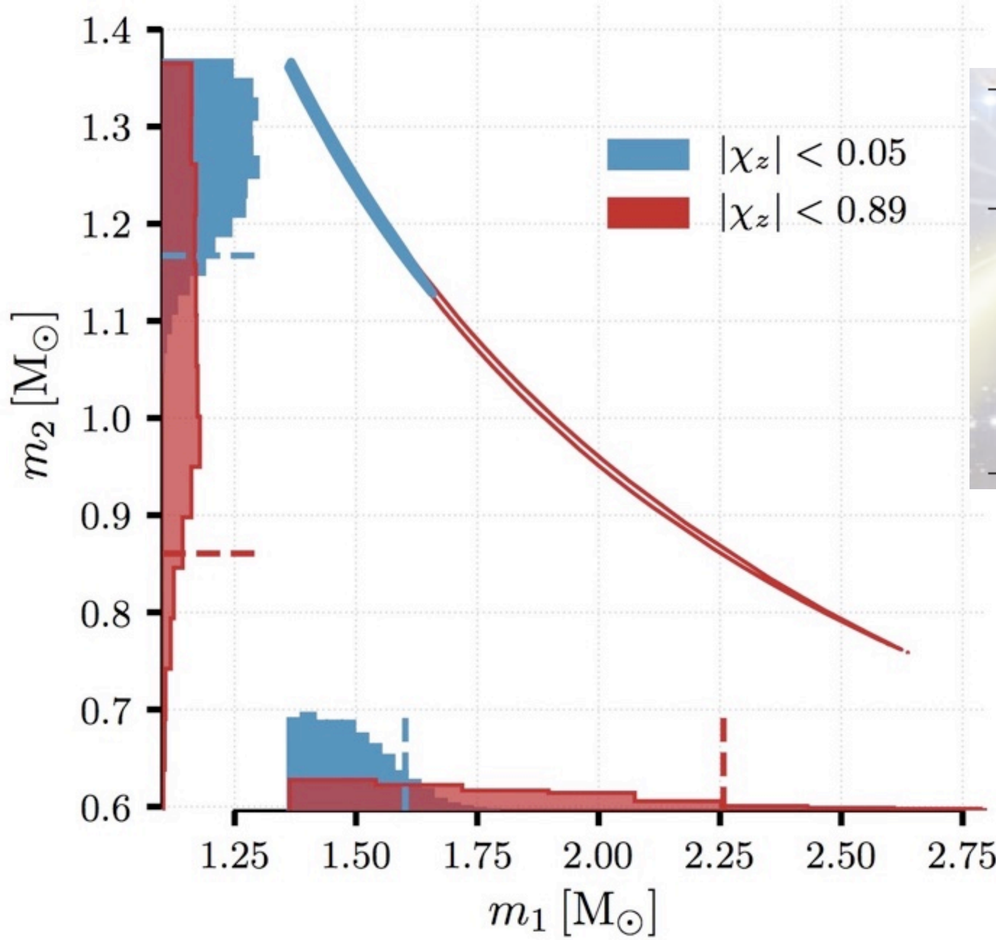
The FAR is less than one event per 80.000 years

Abbott et al., PRL, 119, 161101 (2017)

Comparison of the Gravitational Waveforms



BNS detection: component masses



	low-spin ($|\chi| \leq 0.05$)	high-spin $|\chi| \leq 0.89$
m_1	1.36 - 1.60 $M_\odot$	1.36 - 2.26 $M_\odot$
m_2	1.17- 1.36 $M_\odot$	0.86 - 1.36 $M_\odot$
M_{chirp}	$1.188^{+0.004}_{-0.002}$ $M_\odot$	$1.188^{+0.004}_{-0.002}$ $M_\odot$
M_{Tot}	$2.74^{+0.04}_{-0.01}$ $M_\odot$	$2.82^{+0.47}_{-0.09}$ $M_\odot$

Abbott et al., PRL, 119, 161101 (2017)

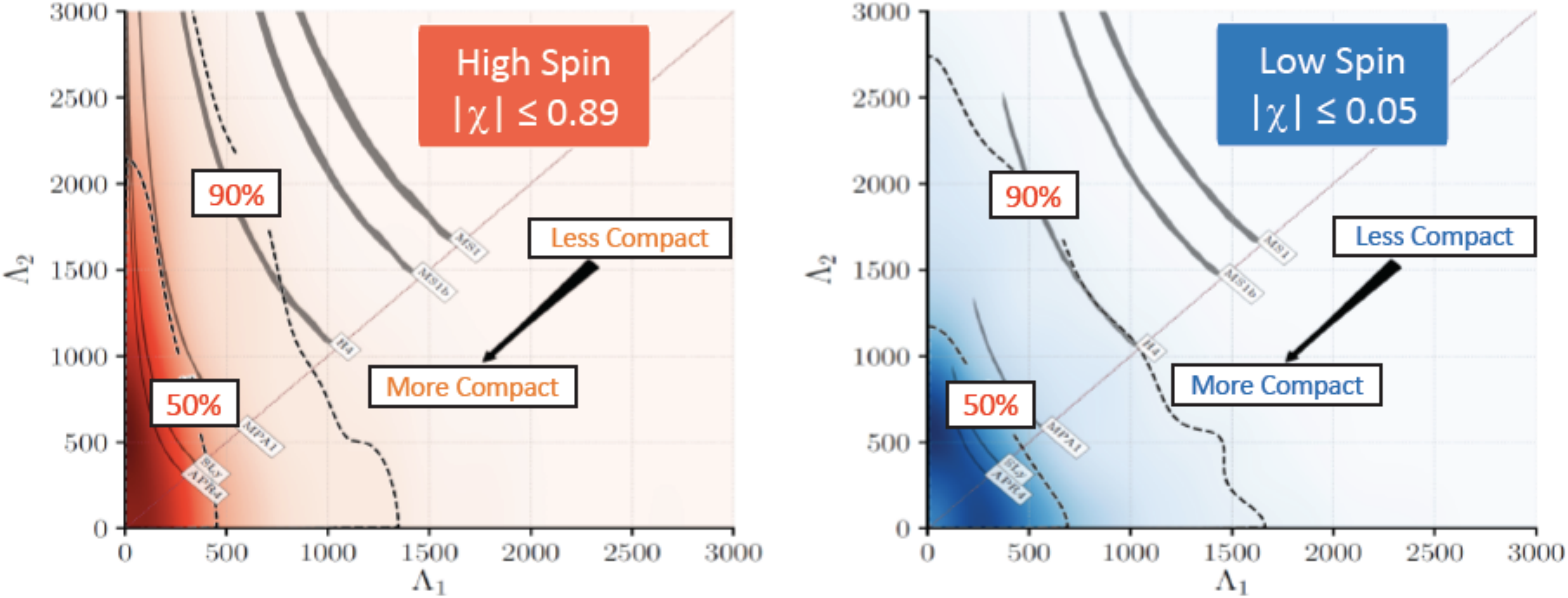
Estimated masses (m_1 and m_2) within the range of known neutron star masses and below those of known black holes.

GW170817: constraining the NS equation of state

Gravitational waves contain information about NS tidal deformations

- allows to constraint NS equation of state (EOS)
- becomes significant above $f_{\rm GW} \approx 600\,{\rm Hz}$

Probability density for the tidal deformability parameters



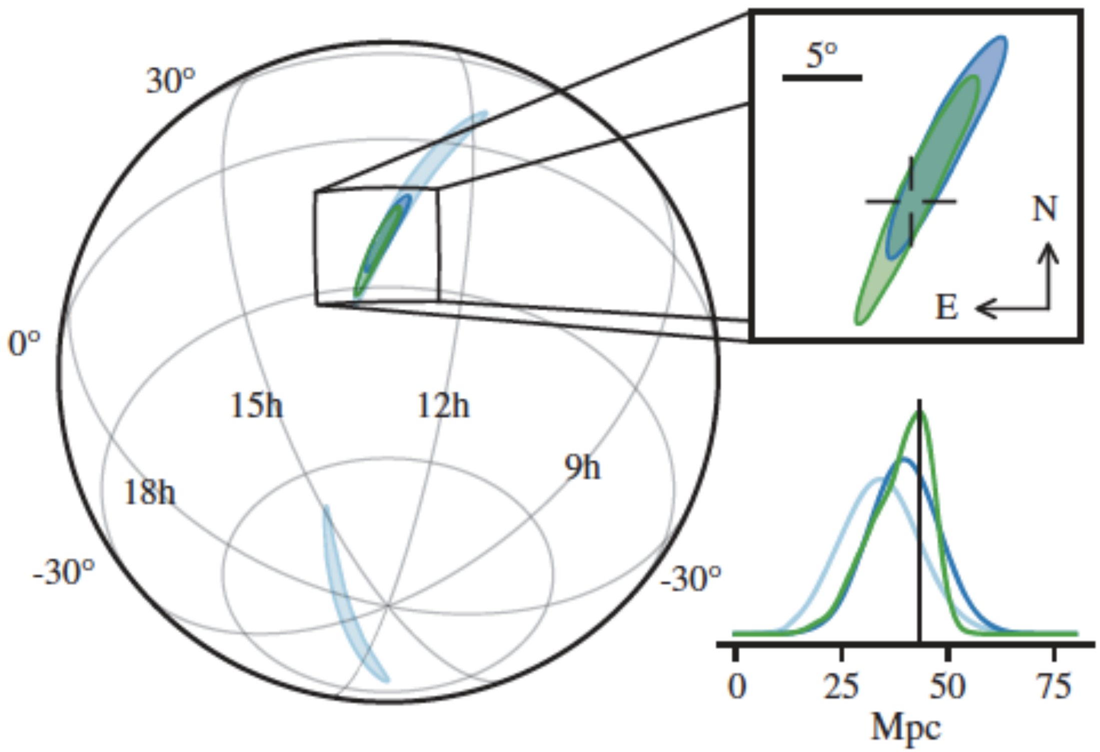
Tidal deformability parameter

$$\Lambda = \frac{2}{3} k_2 \left(\frac{R}{M} \right)^5$$

k_2
second Love number

GW170817 data consistent with more compact NS

Where did the BNS merger occur?

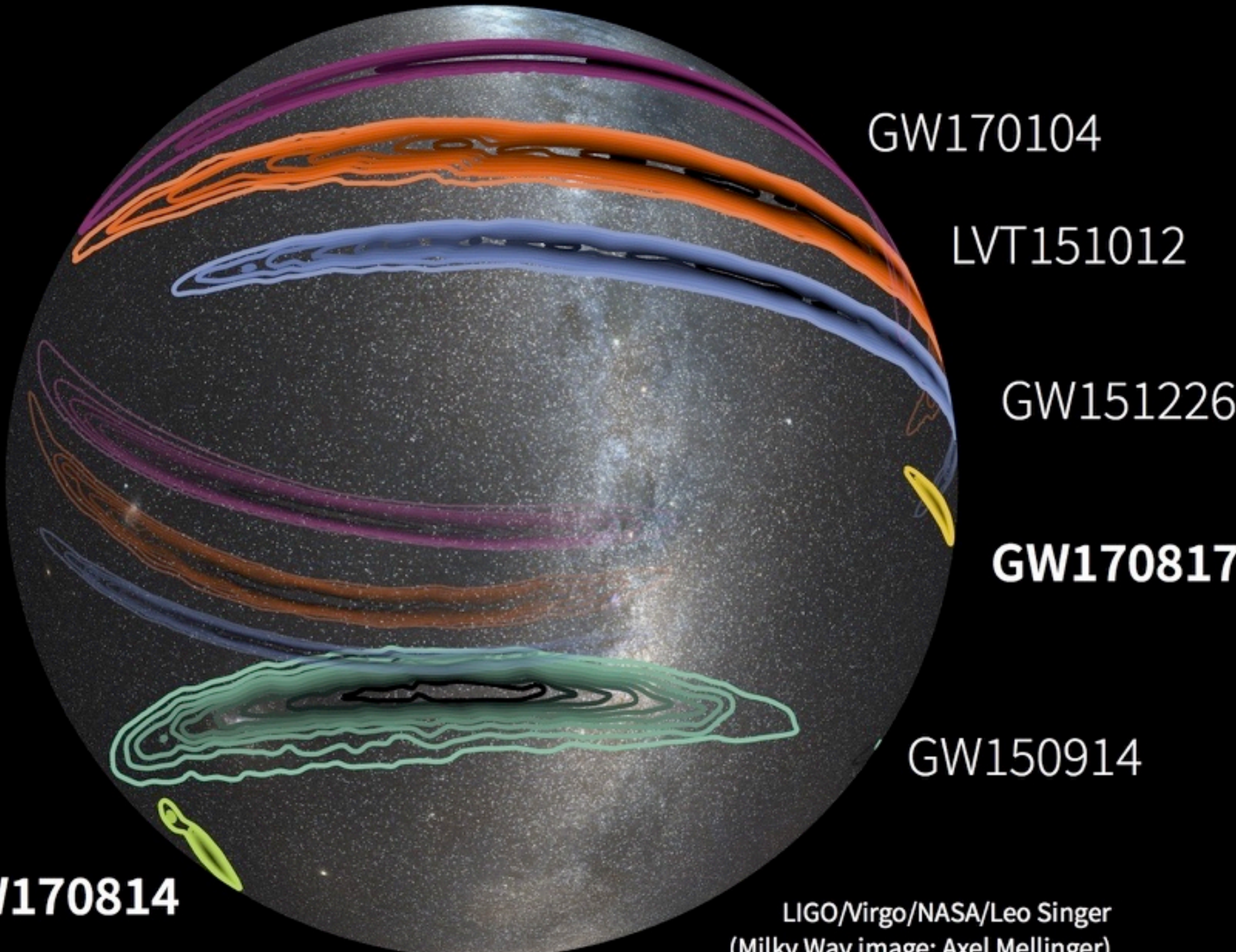


Rapid localization HL: 190 deg², HLV: 31 deg²
Final localization HLV: **28 deg²**

Luminosity distance
40^{+8}_{-14} Mpc

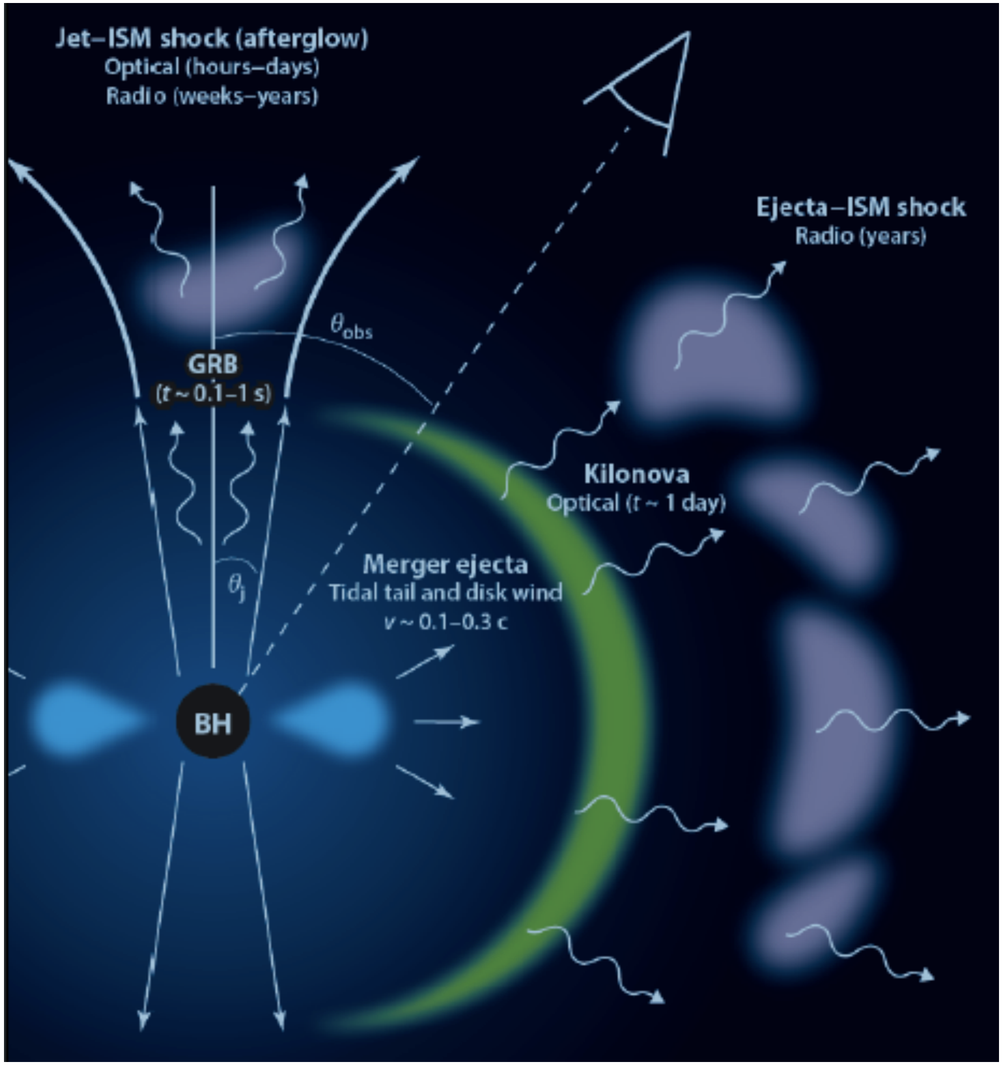
Closest and most precisely localized gravitational-wave signal.

The key role of Advanced Virgo



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

Expected EM counterparts



Metzger & Berger, ApJ, **746**, 48 (2012)

Short GRBs:

- prompt γ-ray emission (< 2 s)
- multiwavelength afterglow emission: X-ray, optical, radio (minutes, hours, days, months)

Kilonova:

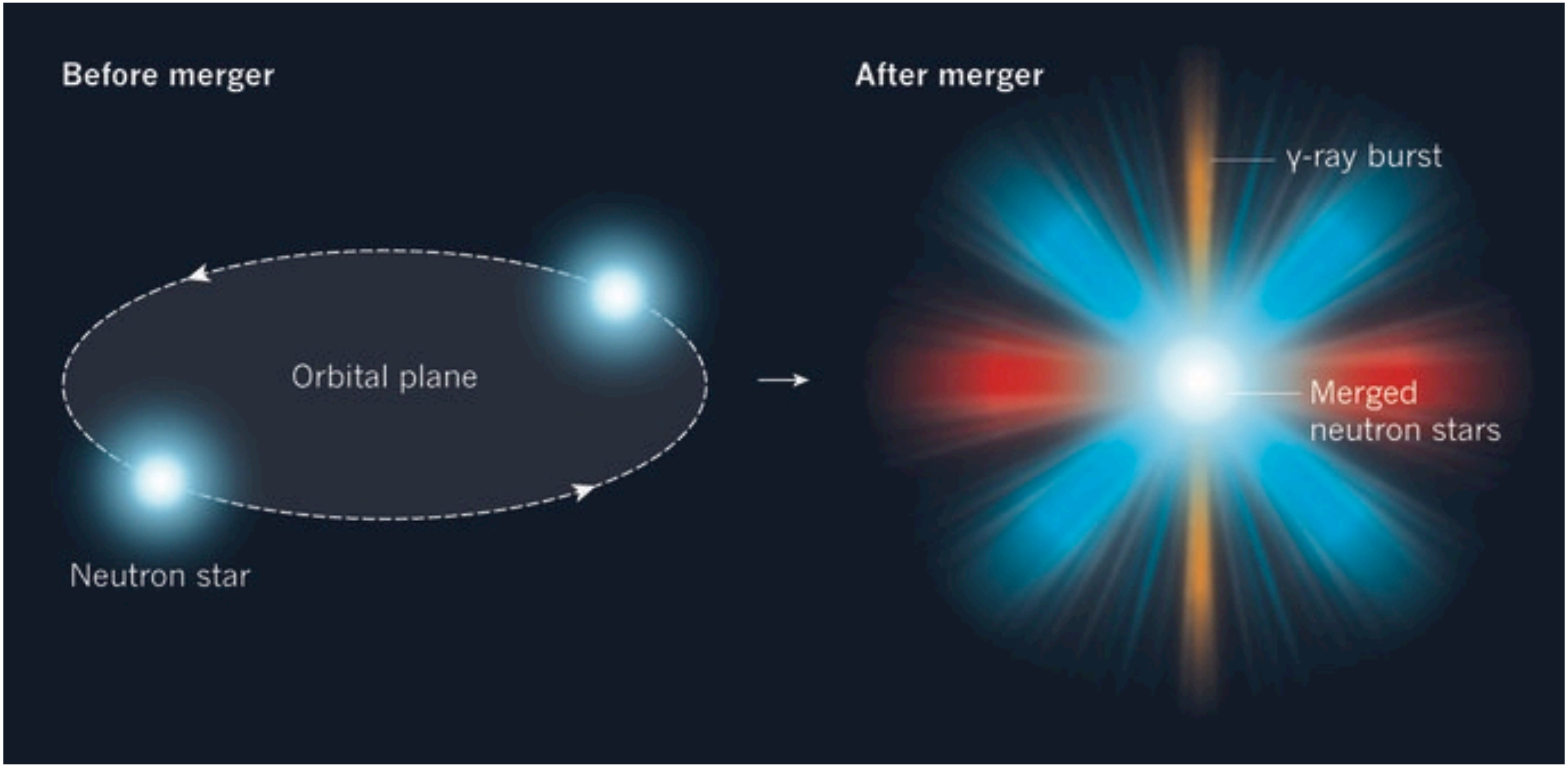
optical and near IR (days, weeks)

Late blast-wave emission:

radio (months, years)

Expected EM counterparts

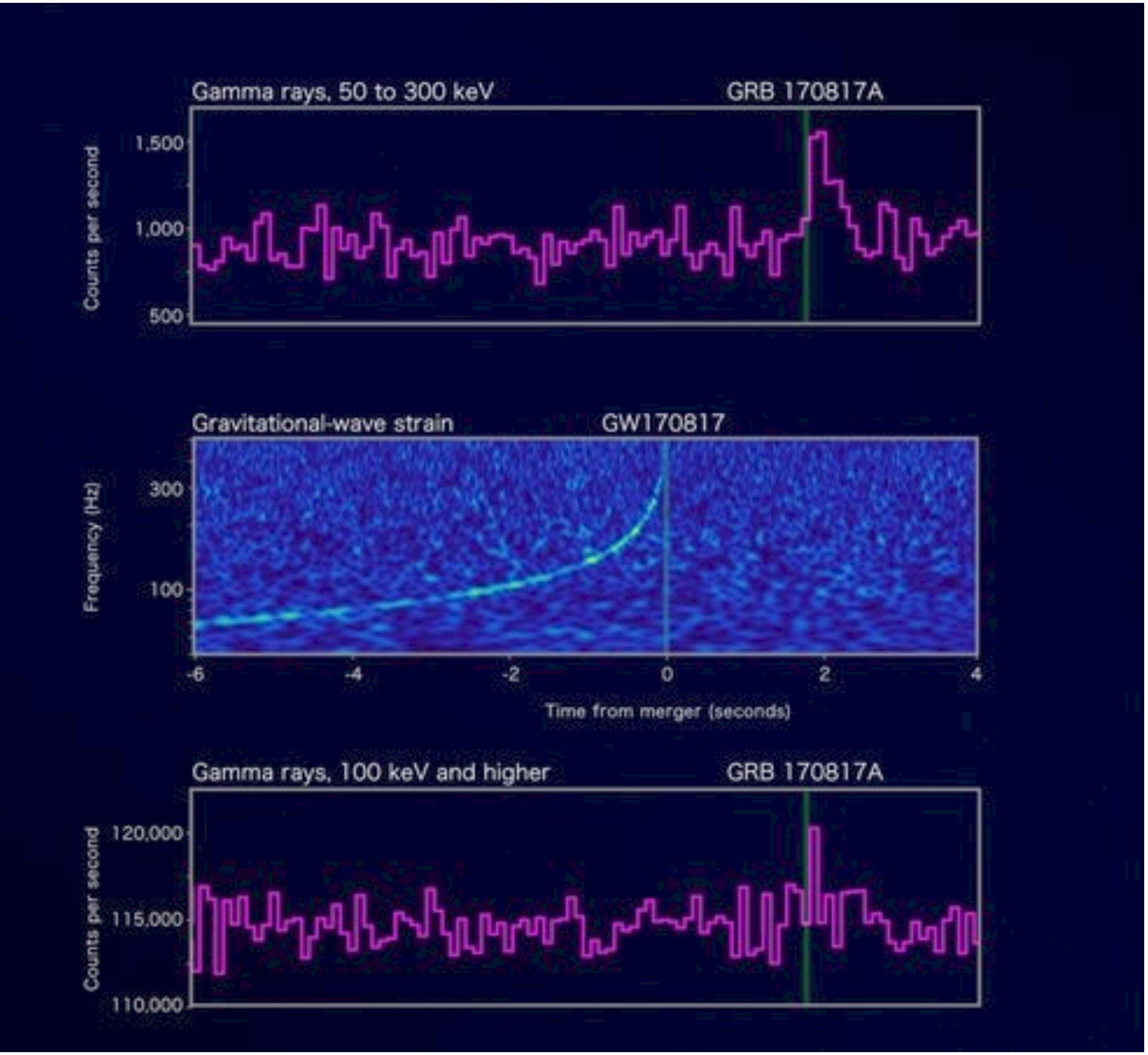
Orange: gamma-ray burst.
Blue: peak optical and X-ray emission.
Red: peak infrared emission.



M. Coleman Miller, Nature (News and Views) **551**, 36 (2017)

Gamma rays: short GRB

GRB 170817A independently detected by Fermi-GBM and INTEGRAL



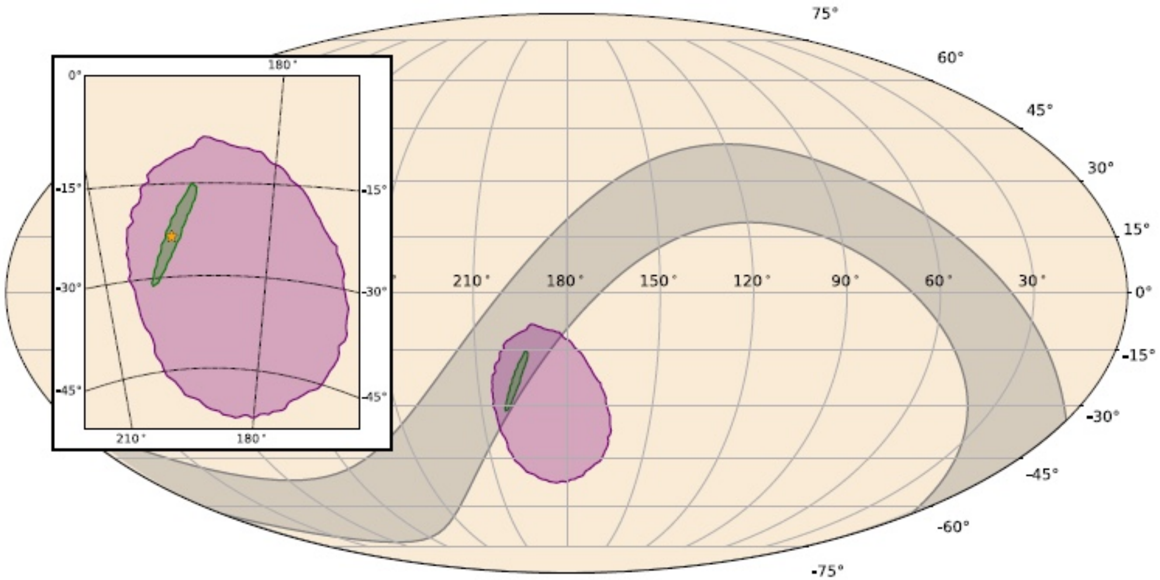
The start of the gamma-ray emission relative to the merger time is 1.7 s

$$E_{\rm iso}^{\gamma} \sim 10^{46}\,{\rm erg}$$

between 2 and 6 orders of magnitude less energetic than other observed bursts with measured redshift.

off-axis GRB?

BNS - short GRB association



Abbott et al., ApJ, 848, 13 (2017)

90 % Fermi-GBM sky localization (1100 deg^2)

90 % sky localization from Fermi and INTEGRAL timing

LIGO-Virgo 90 % credible region (28 deg^2)

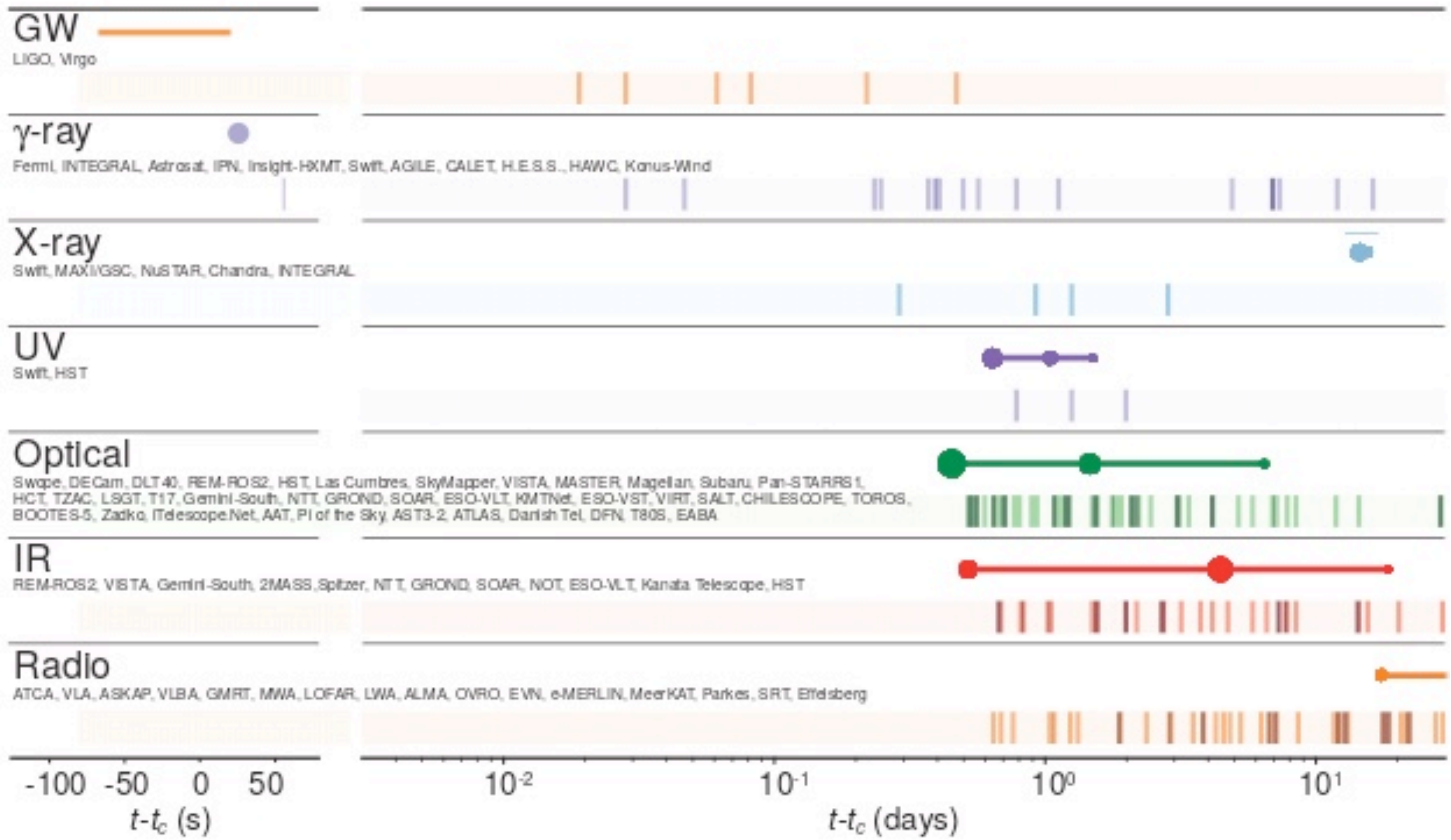
The probability that GRB 170817A and GW170817A occurred this close in time and with this level of location agreement by chance is 5.0 x 10^{-8}:

5.3 σ Gaussian-equivalent significance

First direct evidence that BNS mergers are progenitors of short GRBs

The EM follow-up campaign

A wide-range EM follow-up campaign started in the hours immediately after the observation of GW170817 and GRB 170817A



Abbott et al., ApJ, 848, L12 (2017)

The Astrophysical Journal Letters, 848:L12 (59pp), 2017 October 20 https://doi.org/10.3847/2041-8213/aa91c9

Multi-messenger Observations of a Binary Neutron Star Merger

LIGO Scientific Collaboration and Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The Insight-Hxmt Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE Team, The 1M2H Team, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, GRAWITA: GRAvitational Wave Inaf TeAm, The Fermi Large Area Telescope Collaboration, ATCA: Australia Telescope Compact Array, ASKAP: Australian SKA Pathfinder, Las Cumbres Observatory Group, OzGrav, DWF (Deeper, Wider, Faster Program), AST3, and CAASTRO Collaborations, The VINROUGE Collaboration, MASTER Collaboration, J-GEM, GROWTH, JAGWAR, Caltech-NRAO, TTU-NRAO, and NuSTAR Collaborations, Pan-STARRS, The MAXI Team, TZAC Consortium, KU Collaboration, Nordic Optical Telescope, ePESSTO, GROND, Texas Tech University, SALT Group, TOROS: Transient Robotic Observatory of the South Collaboration, The BOOTES Collaboration, MWA: Murchison Widefield Array, The CALET Collaboration, IKI-GW Follow-up Collaboration, H.E.S.S. Collaboration, LOFAR Collaboration, LWA: Long Wavelength Array, HAWC Collaboration, The Pierre Auger Collaboration, ALMA Collaboration, Euro VLBI Team, Pi of the Sky Collaboration, The Chandra Team at McGill University, DFN: Desert Fireball Network, ATLAS, High Time Resolution Universe Survey, RIMAS and RATIR, and SKA South Africa/MeerKAT
(See the end matter for the full list of authors.)

Received 2017 October 3; revised 2017 October 6; accepted 2017 October 6; published 2017 October 16

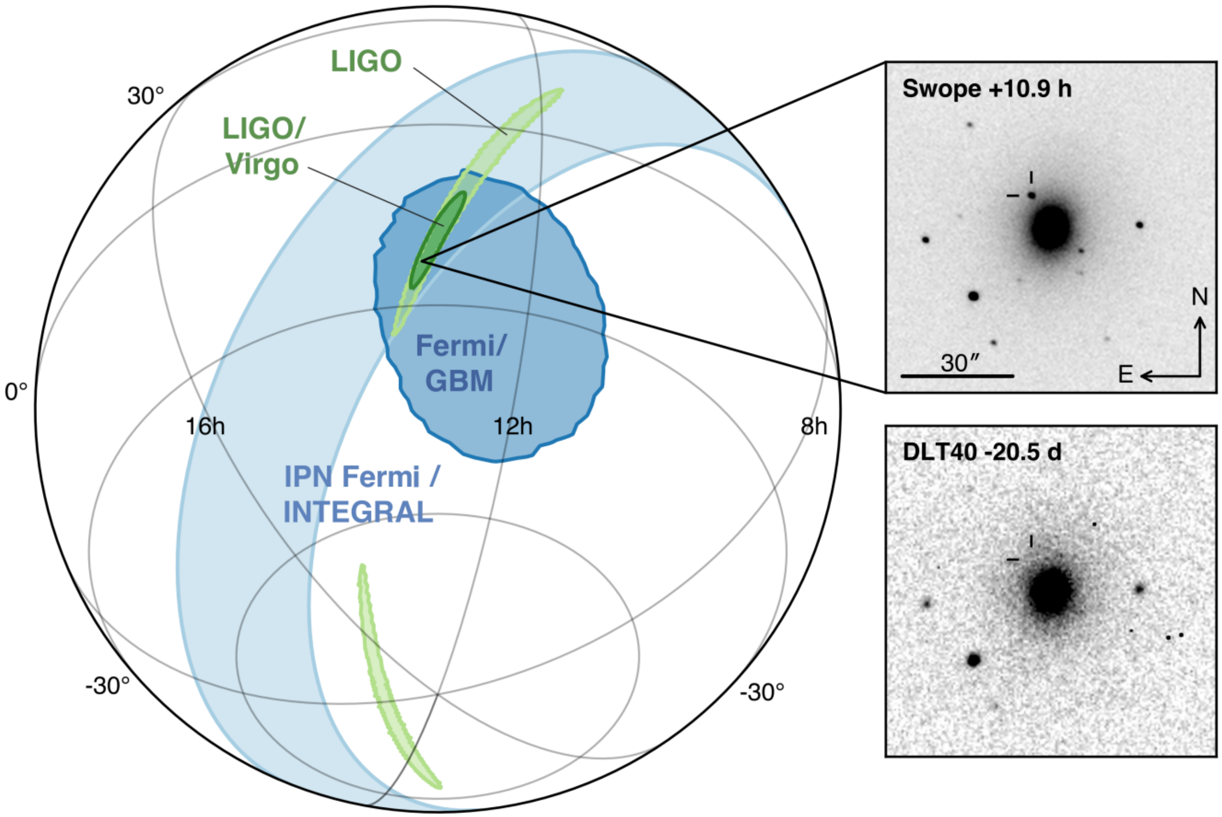
Open access paper published on October 20, 2017 in the **Astrophysical Journal Letters**, marking the beginning of Multi-Messenger Astronomy.

Over 3500 authors.

Extraordinary example of international collaboration.

The identification of the host galaxy

An associated **optical transient** (SSS17a/AT 2017gfo) was discovered on August 18, 2017; the transient is located at ~10" from the center of the galaxy NGC 4993, at a distance of 40 Mpc.



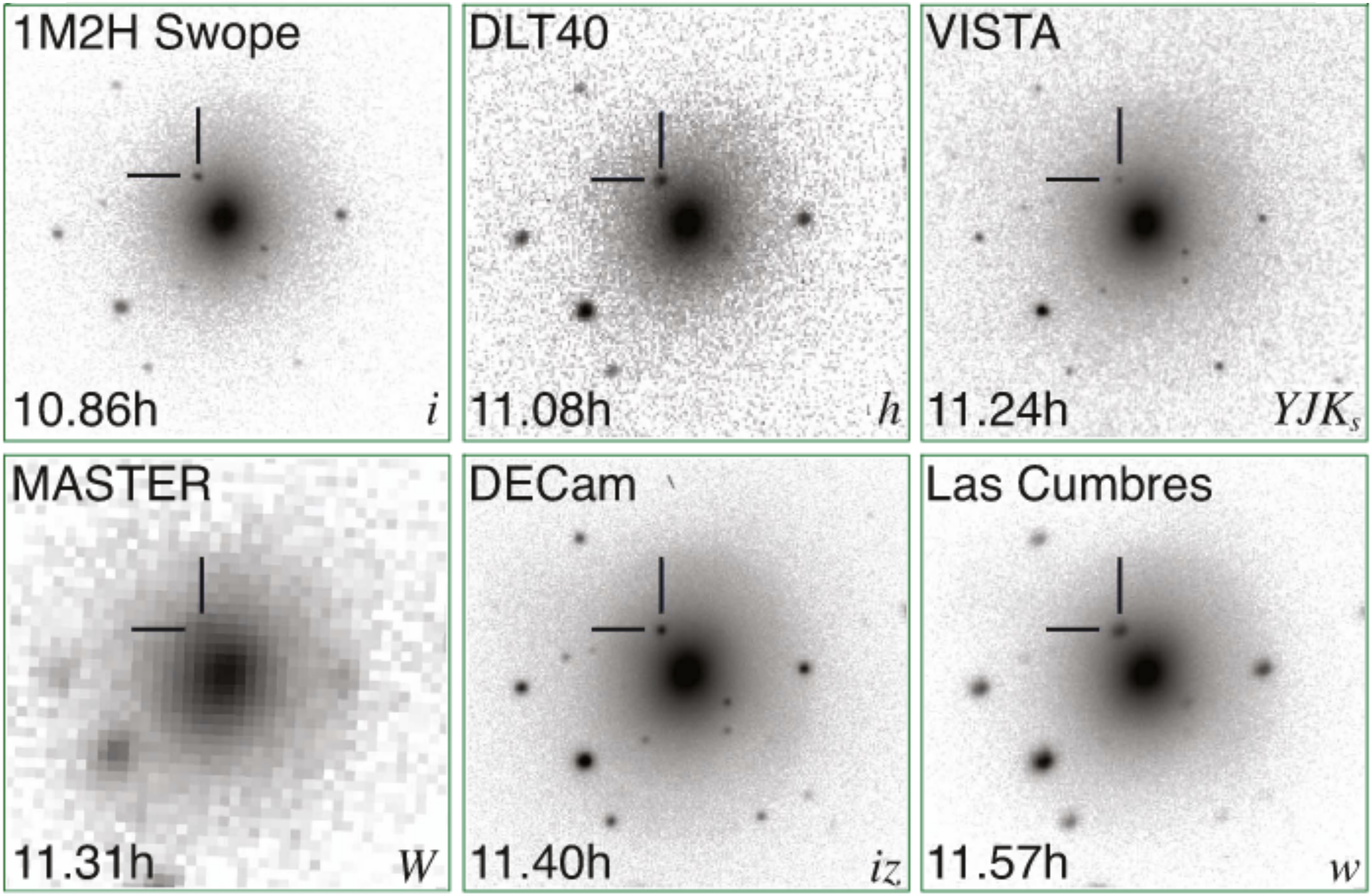
Discovery reported by 6 teams:

- SWOPE (10.86 h)
- DLT40 (11.08 h)
- VISTA (11.24 h)
- MASTER (11.31 h)
- DECam (11.40 h)
- Las Cumbres (11.57 h)

28 deg^2

Abbott et al., ApJ, 848, L12 (2017)

Optical transient (SSS17a/AT 2017gfo)



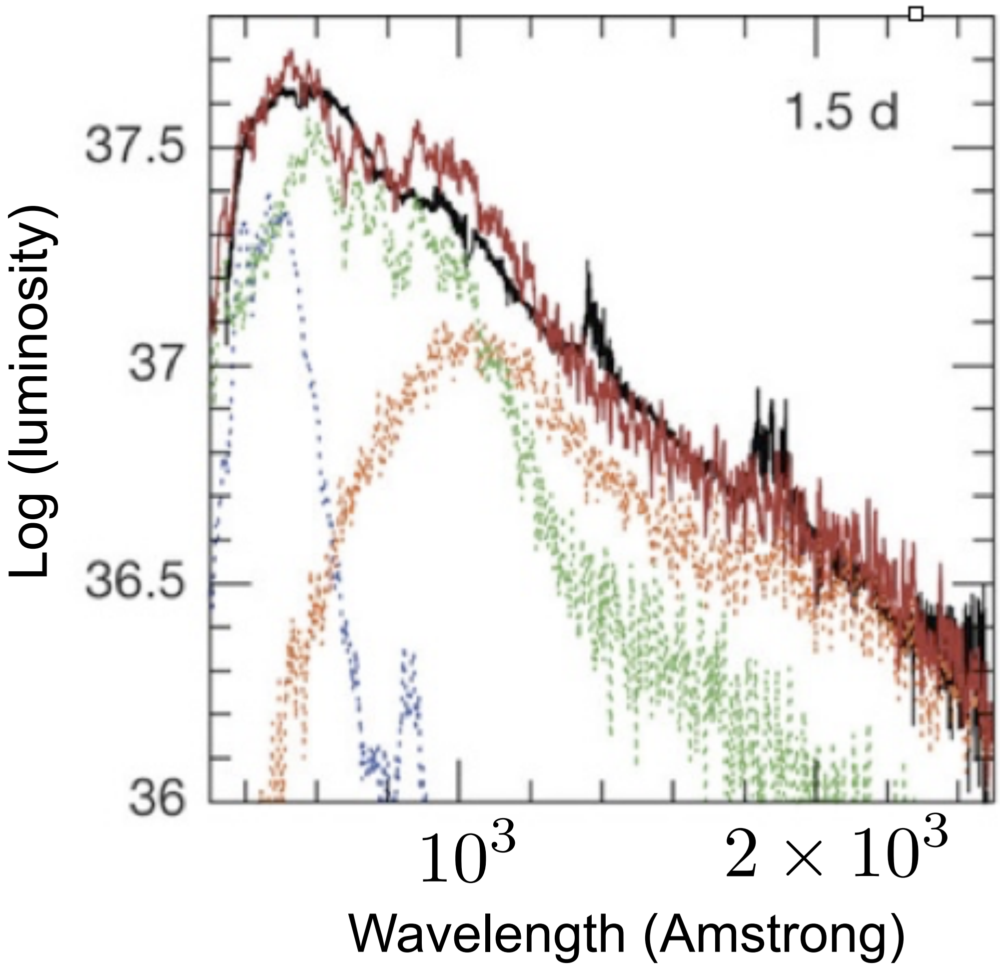
Zooming in on the source of GW170817

Credit: LIGO/Virgo

The spectroscopic identification of the **kilonova**

Spectra (black line) at the first epoch and kilonova models

Pian et al, Nature (2017)



observational data

lanthanide-rich dynamical ejecta region

wind region, lanthanide-free and lanthanide-rich, proton fraction Y_e=0.25

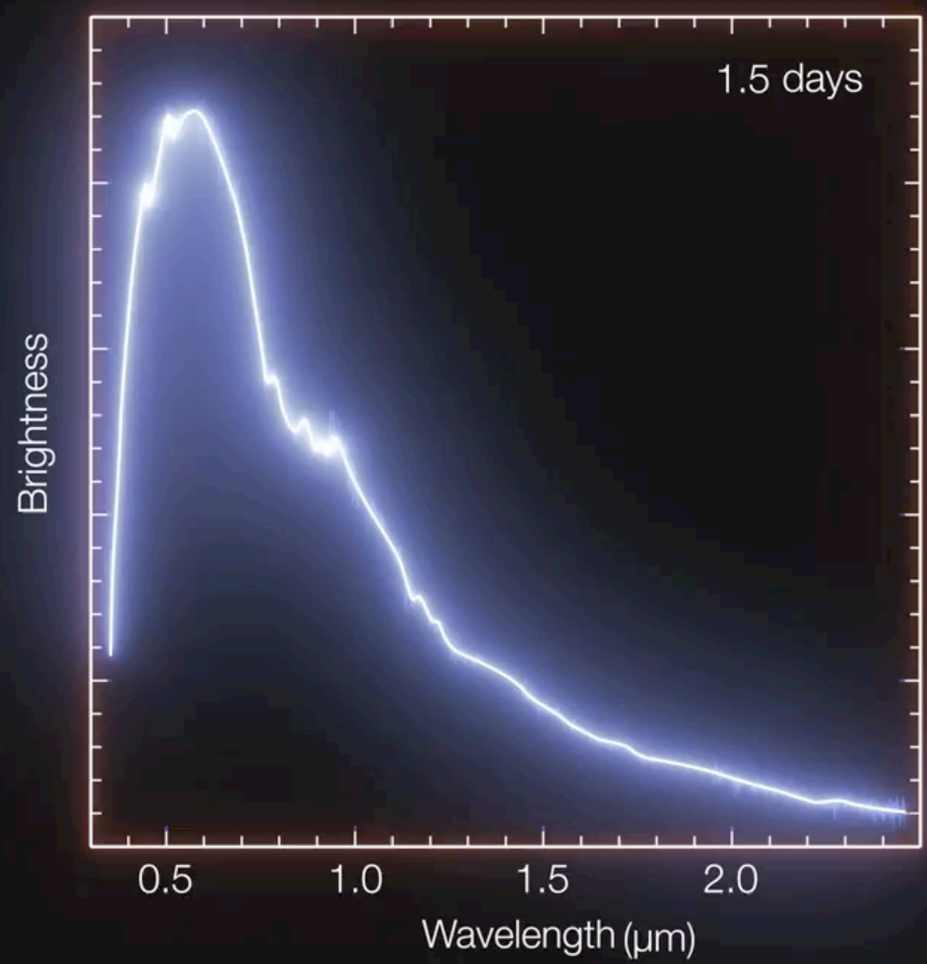
wind region, lanthanide-free, Y_e=0.3

sum of the three model components

(Models from Tanaka et al. 2017)

Evolution of observed spectrum in good match with expectations for kilonovae. **First spectroscopic identification of a kilonova!**

The spectroscopic identification of the **kilonova**



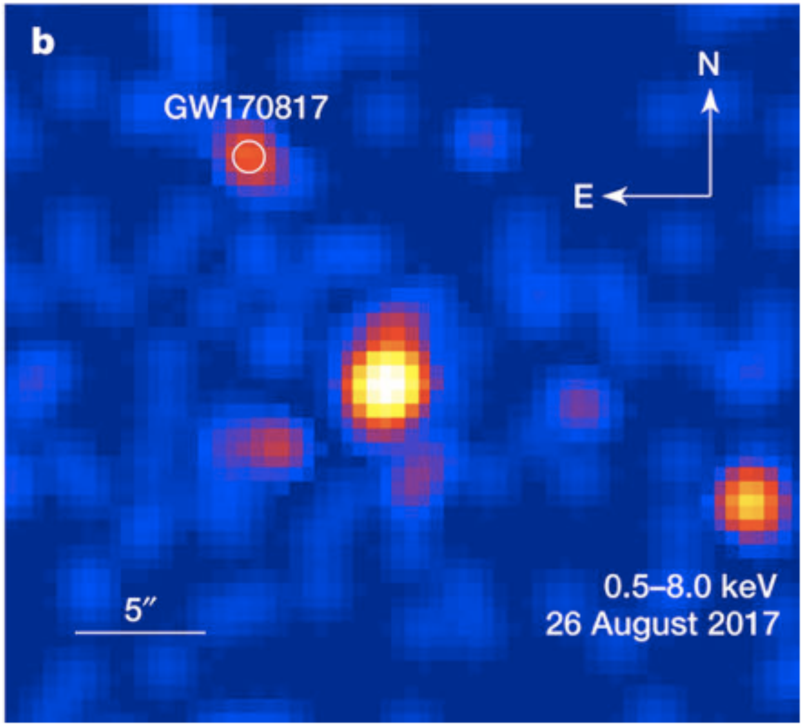
Credit: ESO/E. Pian et al./
S. Smartt & ePESSTO

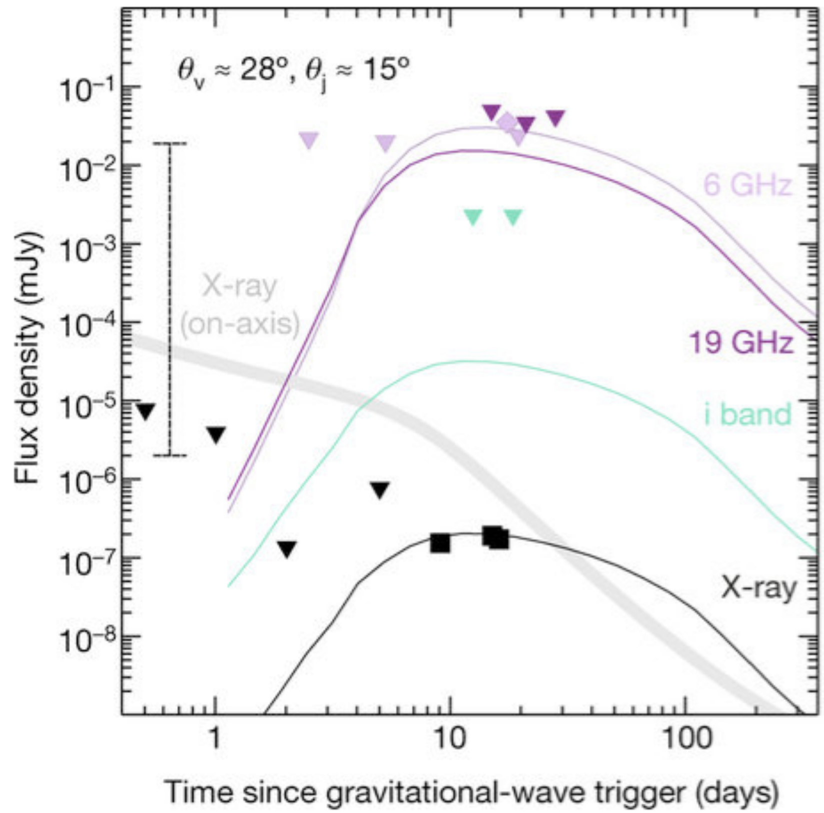
Spectra taken over 2 weeks period across all electromagnetic bands consistent with kilonova models

- "Blue" early emission dominated by Fe-group and light r-process formation; later "red" emission dominated by heavy element (lanthanide) formation

Zooming in on the kilonova in NGC 4993

X-ray observations (Chandra, 9 days after GW trigger)





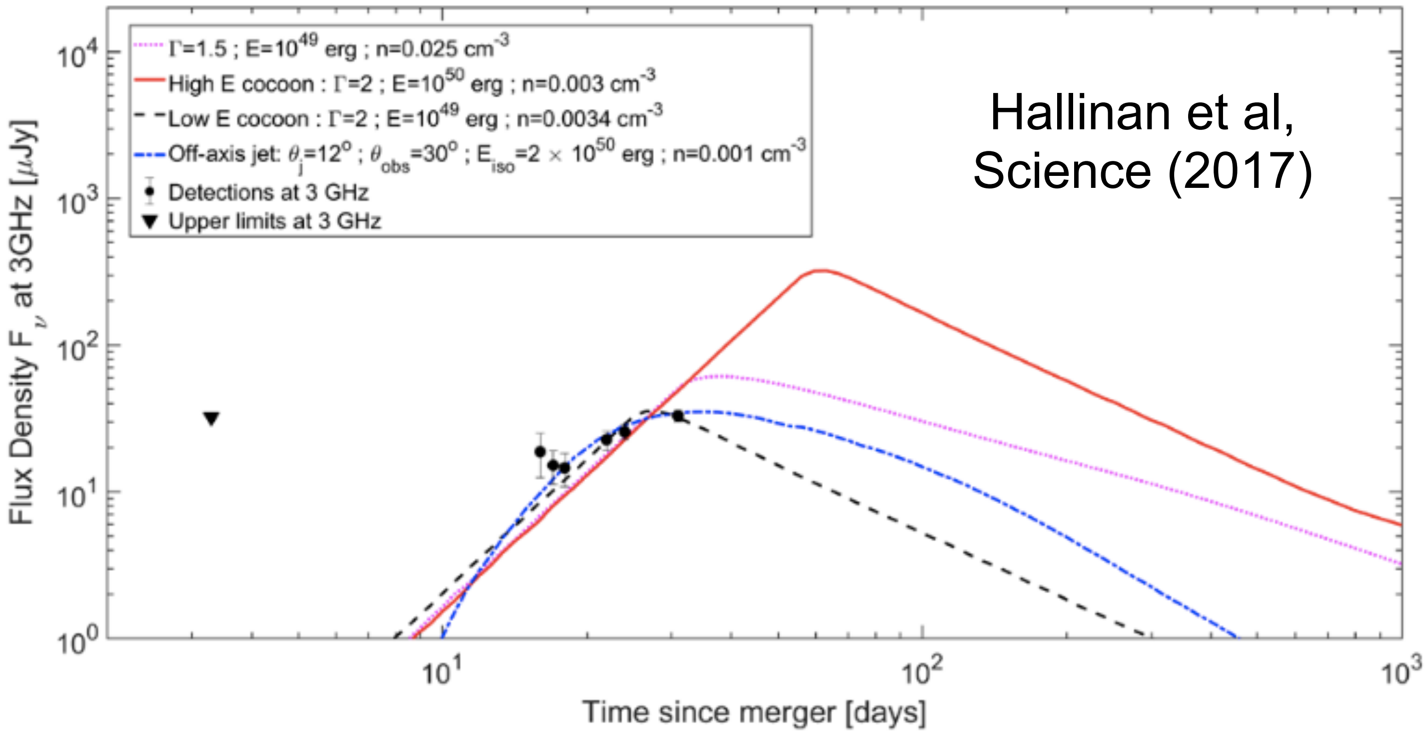
Evolution of the X-ray and radio counterparts of GW170817 compared to model predictions (thin lines) for a short GRB afterglow viewed **off-axis**.

Thick grey line shows X-ray light curve of same afterglow seen on-axis, falling in typical range of short GRBs (vertical line).

Troja et al, Nature, **551**, 71–74 (2017)

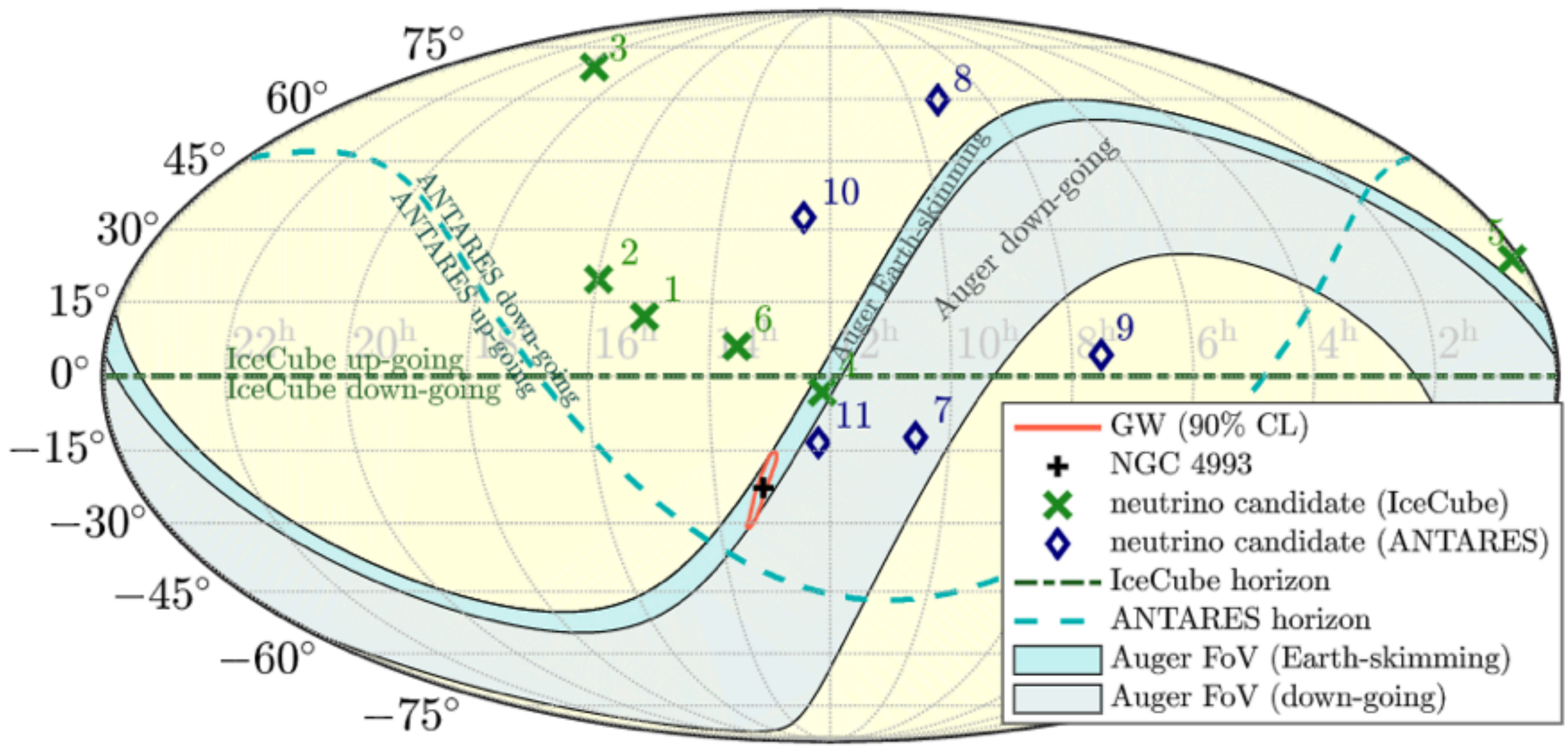
Radio observations

Radio counterpart detection consistent with the HST position of SSS17a/AT 2017gfo observed 16 days after GW170817.



Observed radio emission explained by either a collimated **ultra-relativistic jet viewed off-axis**, or a **cocoon of mildly relativistic ejecta**. Within 100 days of the merger, the radio light curves will distinguish between these models.

Neutrinos



Within ±500 s of GW170817:

ANTARES neutrino candidates: 5
IceCube neutrino candidates: 6
Pierre Auger neutrino candidates: 0

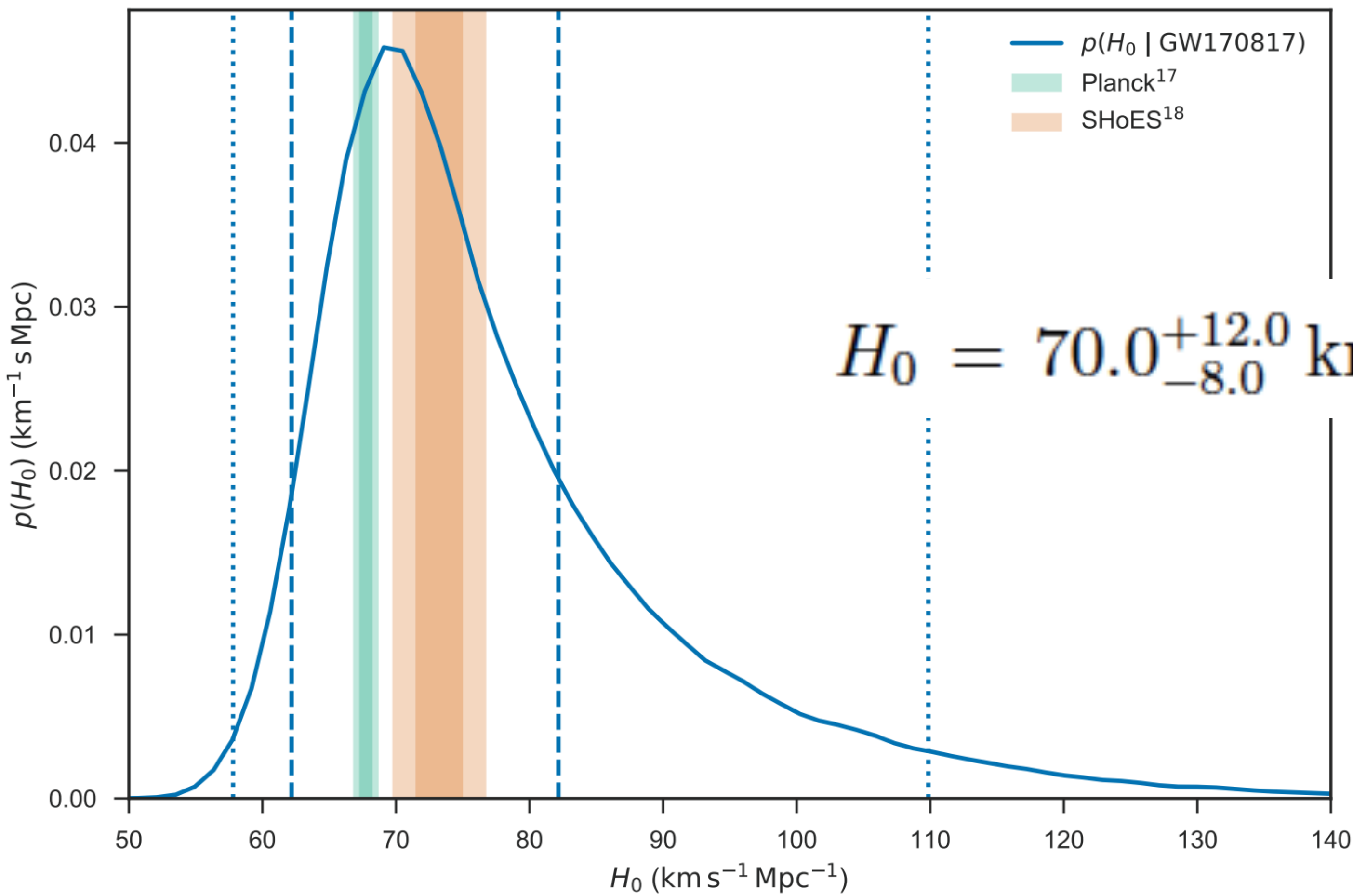
No one directionally coincident with GW170817

Non-detection of neutrinos consistent with model predictions of short GRBs observed off-axis.

Albert et al. ApJ, 2017

GW170817: implications for **cosmology**

GW170817 can be used as a **"standard siren"**: combining the **distance** (inferred from the inspiral GW signal) with the recession **velocity** of the source (redshift; inferred from EM signal) the **Hubble constant** can be measured.

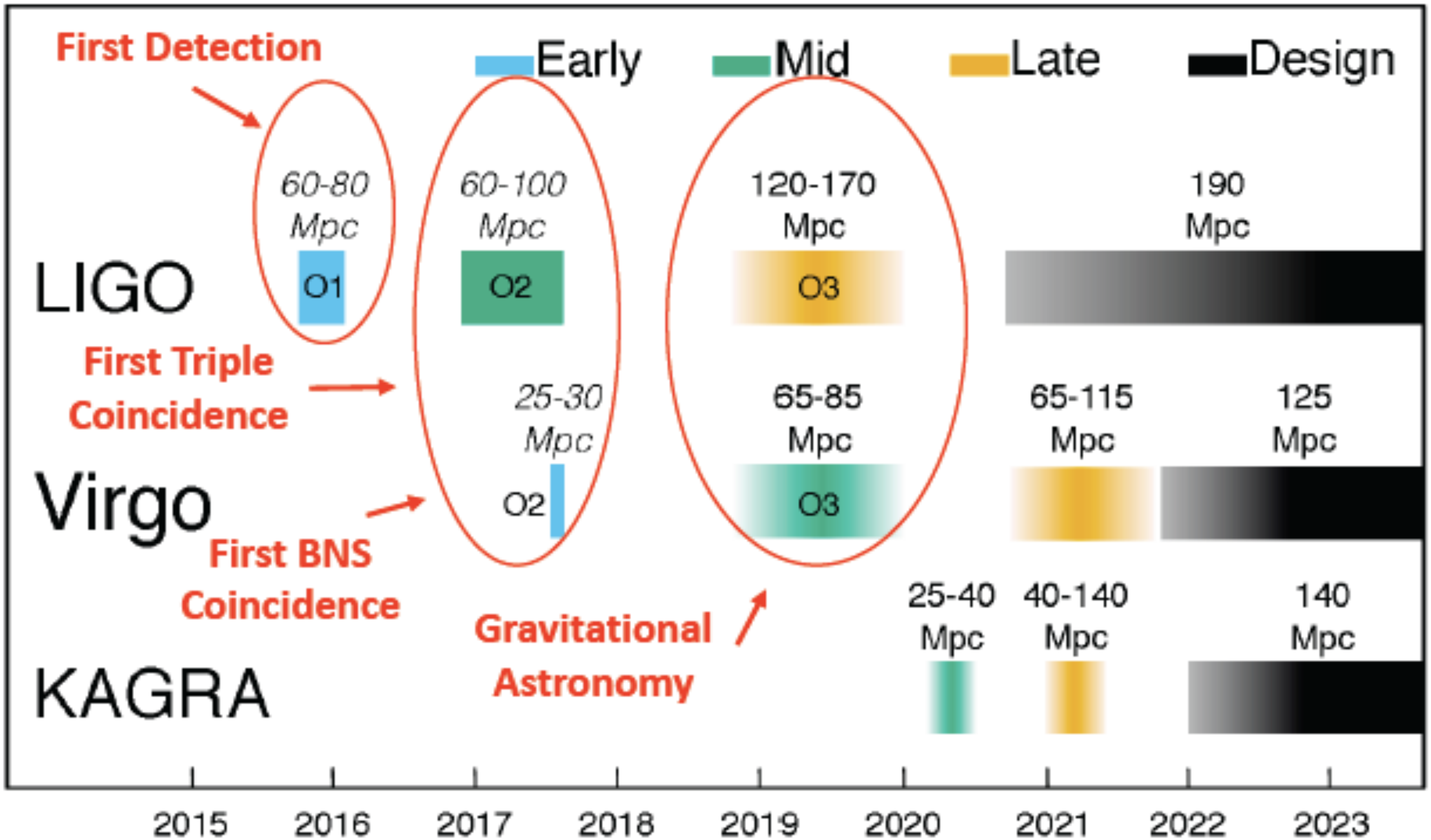


$$v_H = H_0\, d$$

$$H_0 = 70.0^{+12.0}_{-8.0}\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$$

Abbot et al, Nature, **551**, 85–88 (2017)

Plans for LIGO-Virgo-KAGRA surveys



arXiv:1304.0670v4

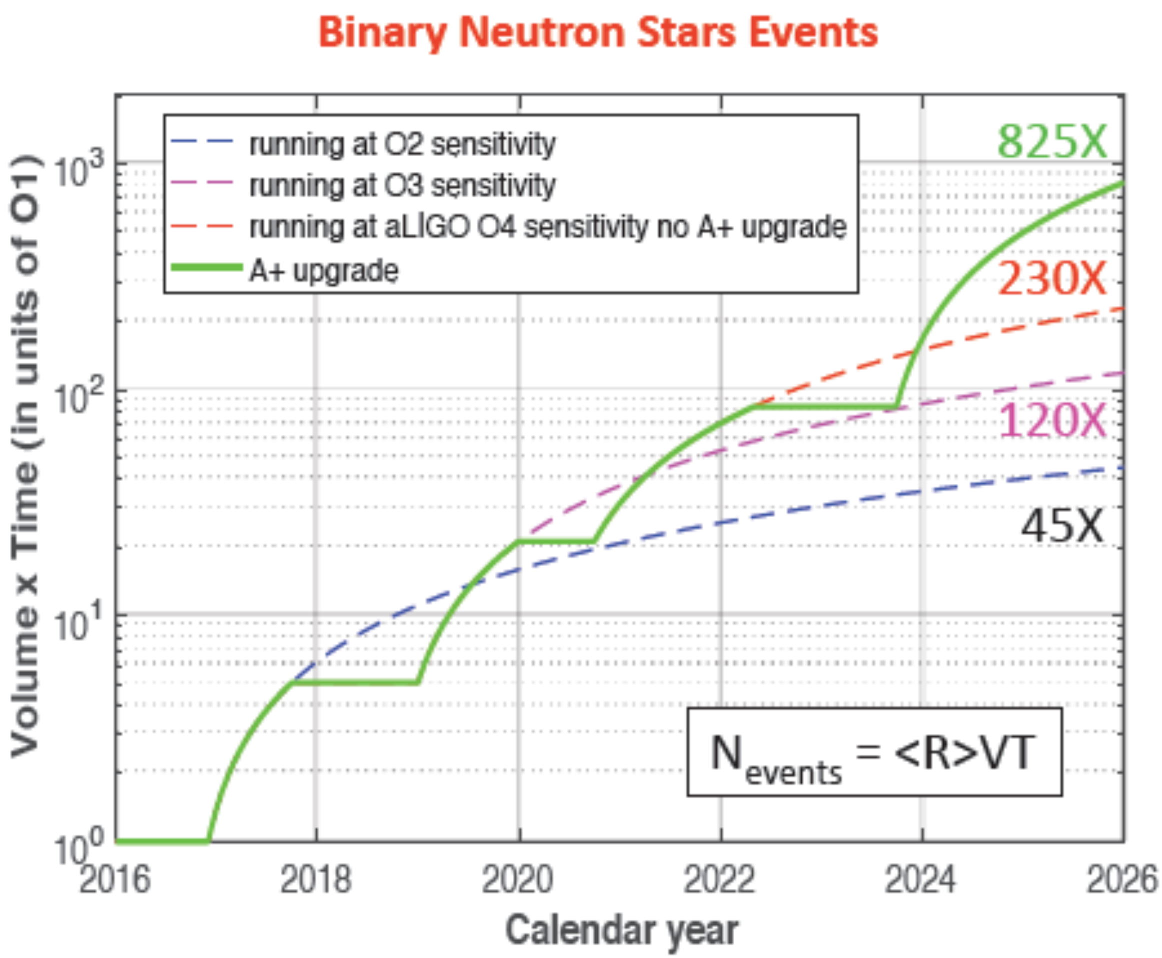
At design sensitivity:

1000x gain in surveyed volume of Universe w.r.t. first generation detectors

BBH detection rate: 50-500 / year

BNS detection rate: 10-300 / year

Plans for LIGO-Virgo-KAGRA surveys

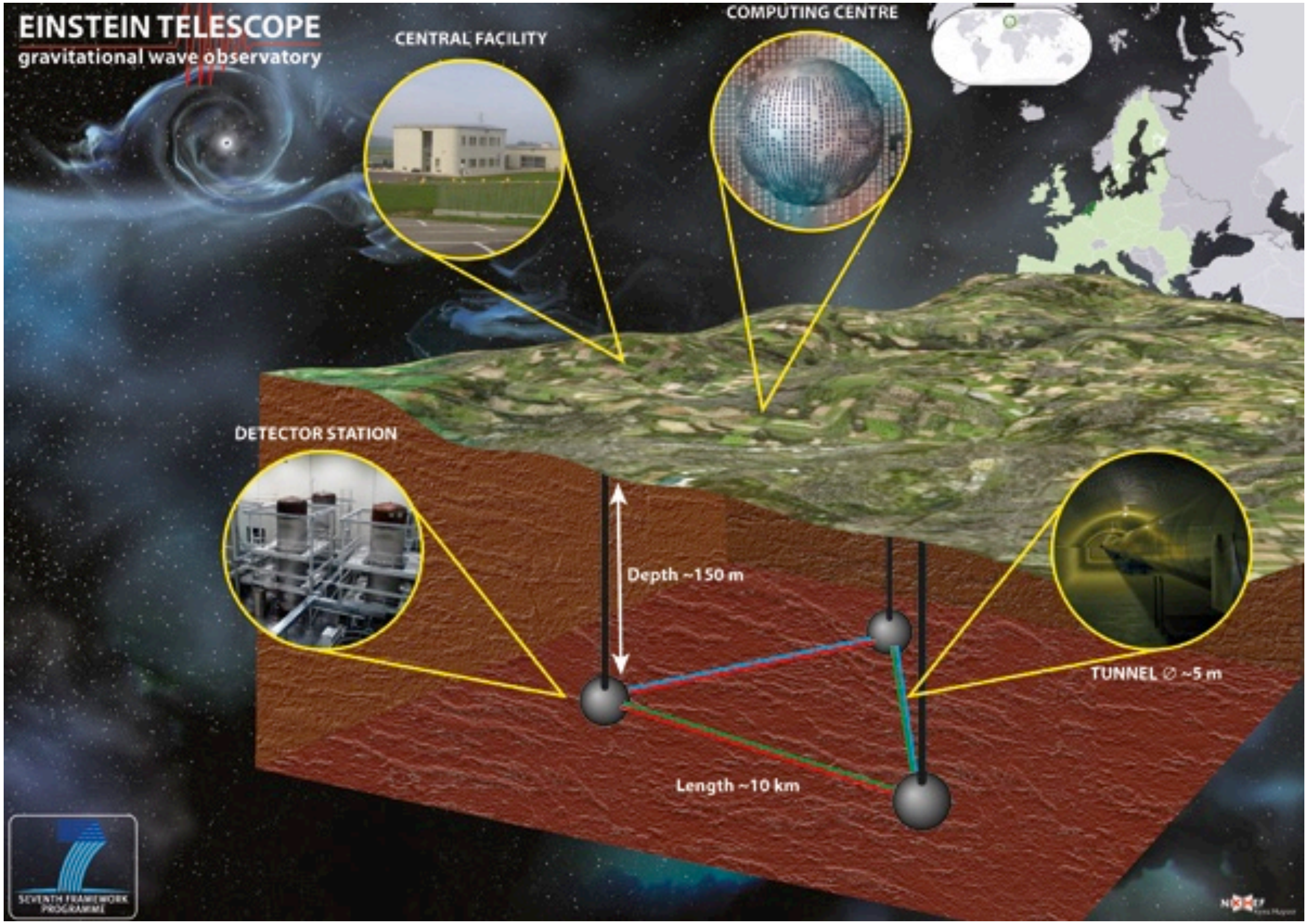


<R> average astrophysical rate

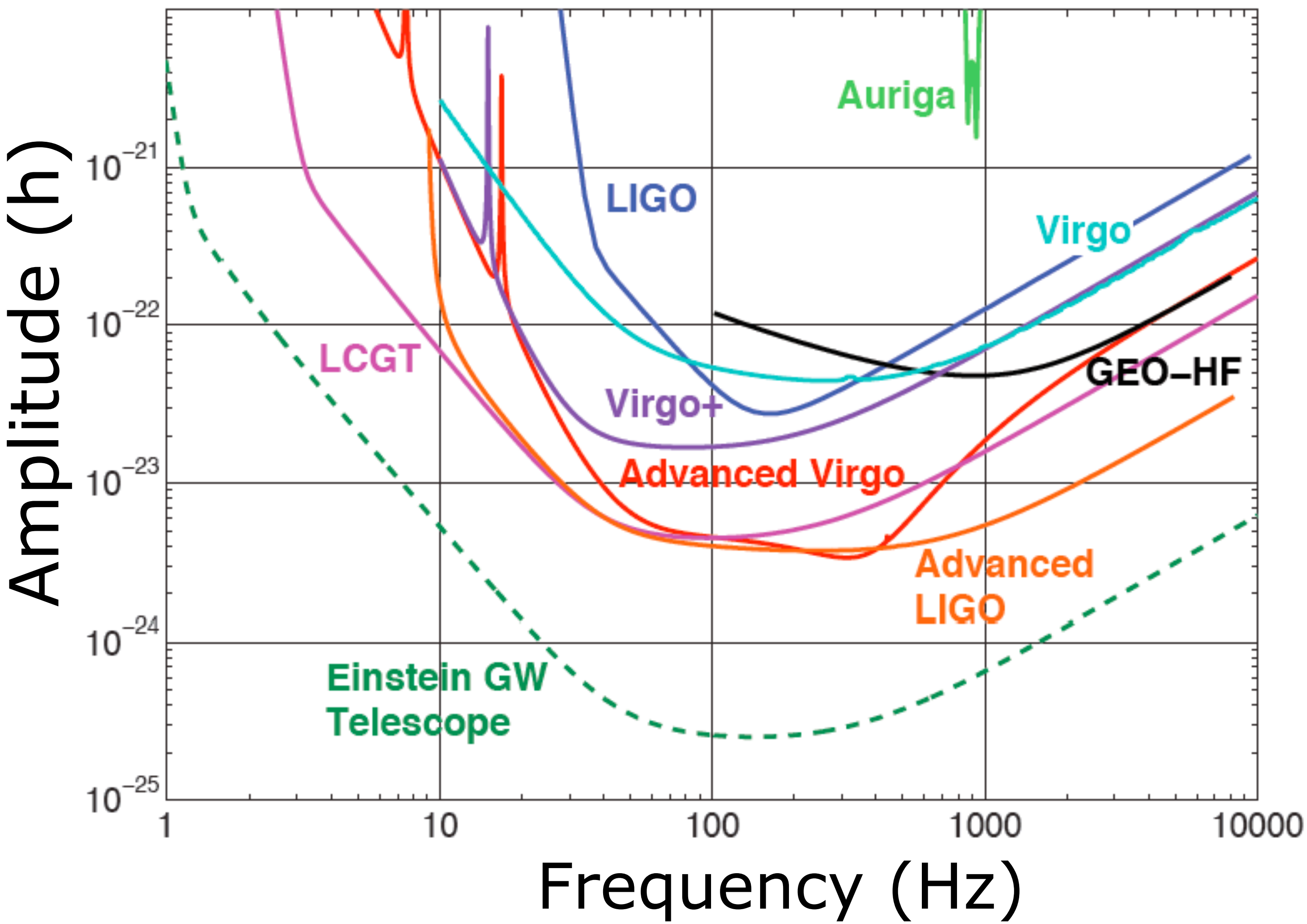
V volume of the universe probed → $(\text{Range})^3$

T coincident observing time

Einstein Telescope (2025+)

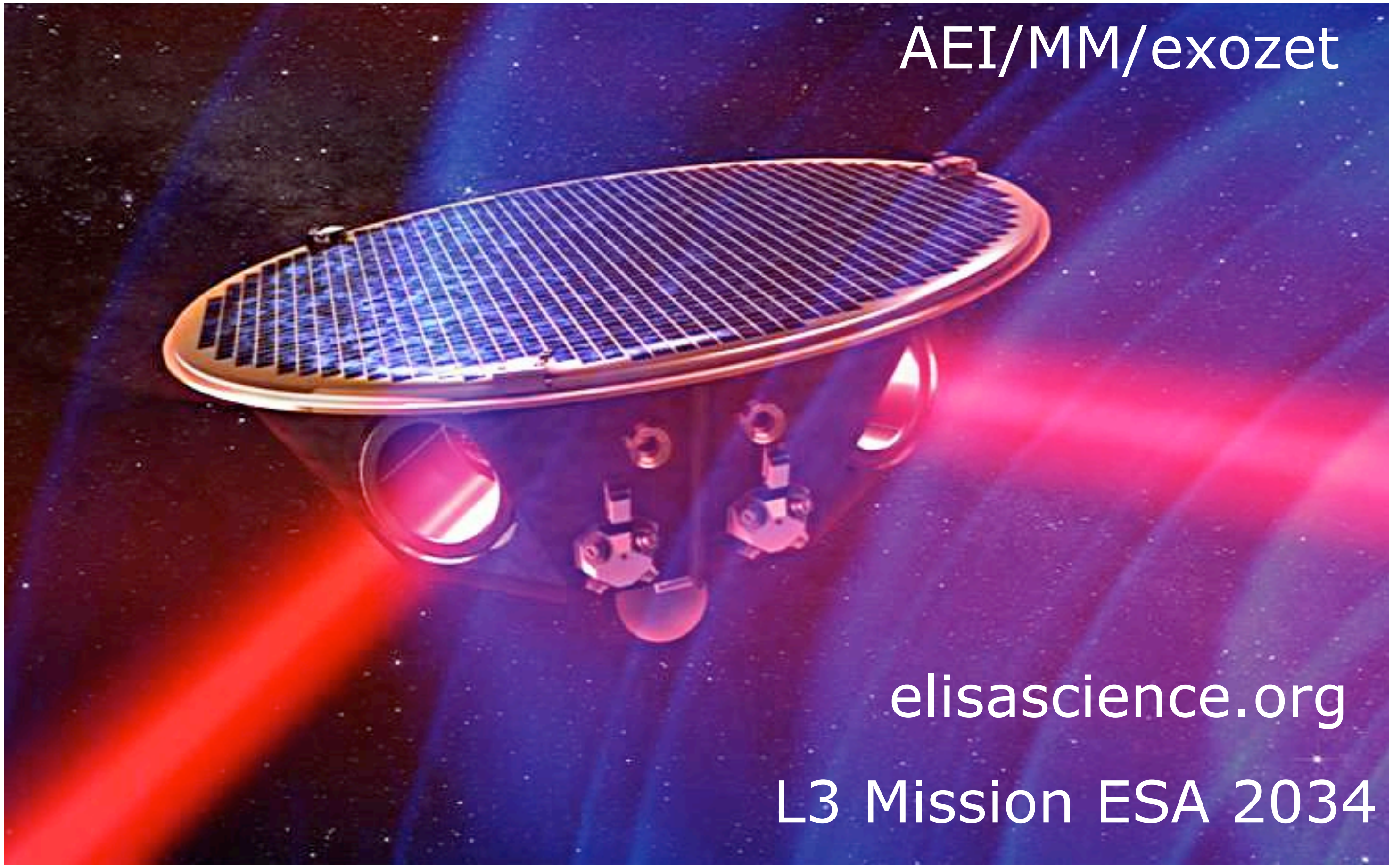


Third-generation GW detector (post aLIGO, aVirgo and KAGRA). Conceptual design study financed by EU.



Events / year	BNS	BH/NS	BBH
aLIGO	0.4-400	0.2-300	2-4000
ET	10^3-10^7	10^3-10^7	10^4-10^8

LISA: Space Interferometer (2034)



Three spacecraft constellation, arranged in an equilateral triangle with sides 1 million km long, flying along an Earth-like heliocentric orbit.

Focused on the 10^{-4}-10^{-1} Hz frequency range.

Where are we now?

- Advanced LIGO O1: Sept 12 2015 - Jan 19 2016.
- Advanced LIGO O2: Nov 30 2016 - Aug 25 2017.
- Advanced Virgo joined O2: Aug 1 - Aug 25 2017.

1 year break until O3. Major upgrades

Spain is currently represented in:

- LIGO Scientific Collaboration, UIB group
- Virgo Collaboration, Valencia University group.

Conclusions

(Einstein was again right)

- LIGO/Virgo have accomplished a several-decade long effort with the historical first detections of gravitational waves.

- Merging BBH and BNS observed for the first time.

- Two brand new fields of research: Gravitational-wave astronomy and Multi-messenger astronomy.

- Plans underway to improve detectors sensitivity for O3 and beyond.

Stay tuned for exciting new discoveries!