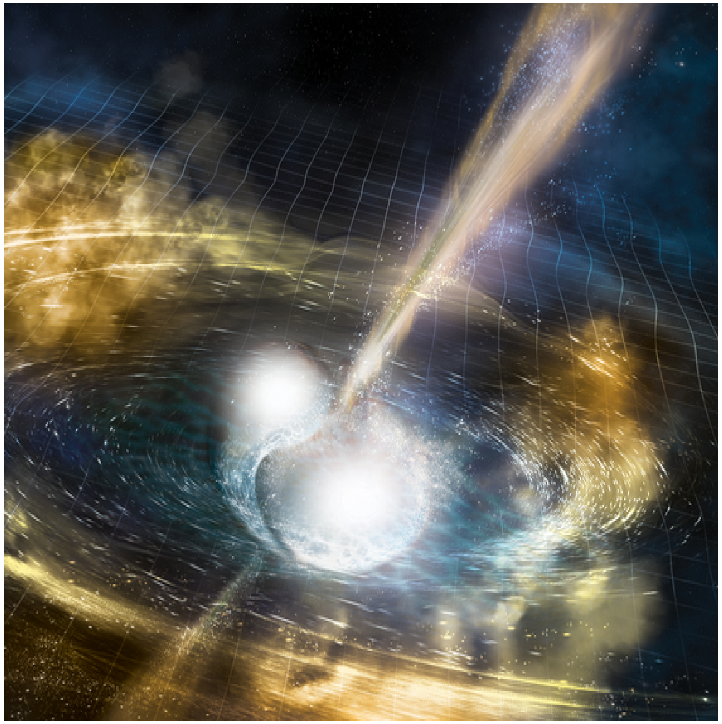
# – Results from O2 run –
# Multi-messenger observations of a binary neutron star merger
## GW170817

Loïc Rolland
for the Virgo and LIGO collaborations



Séminaire au LAPP
10 novembre 2017

Virgo web site: http://public.virgo-gw.eu/
LIGO web site: http://www.ligo.org/

# What is a gravitational wave?

## GW origin

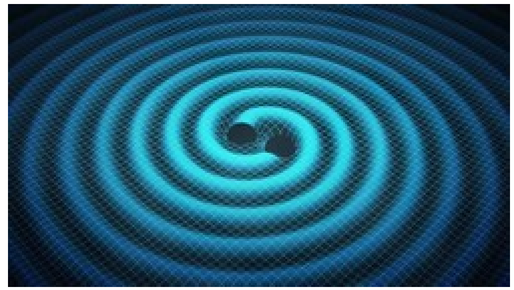
Masses in motion

↓

Space-time deformation

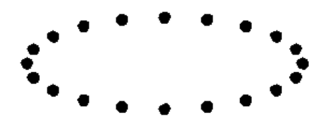
↓

Gravitational wave



- transversal plane wave
- propagation at the light speed c
- two polarisation states (+ and x)

## Detectable effect on free fall masses



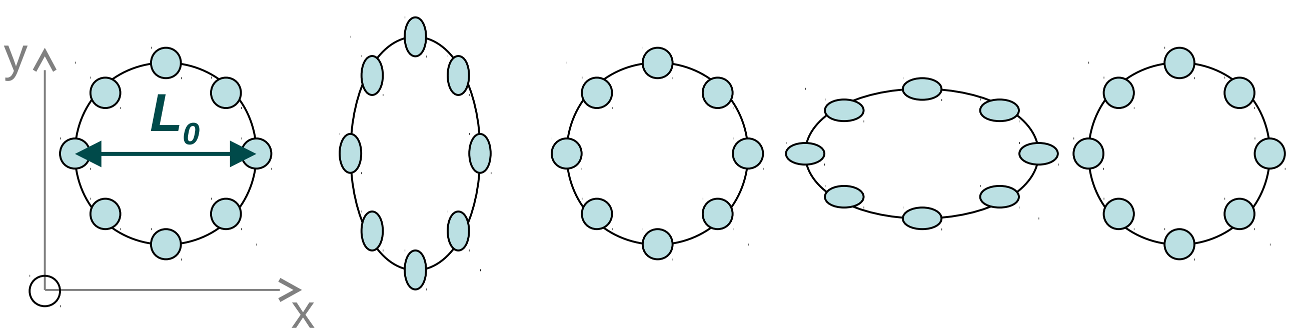


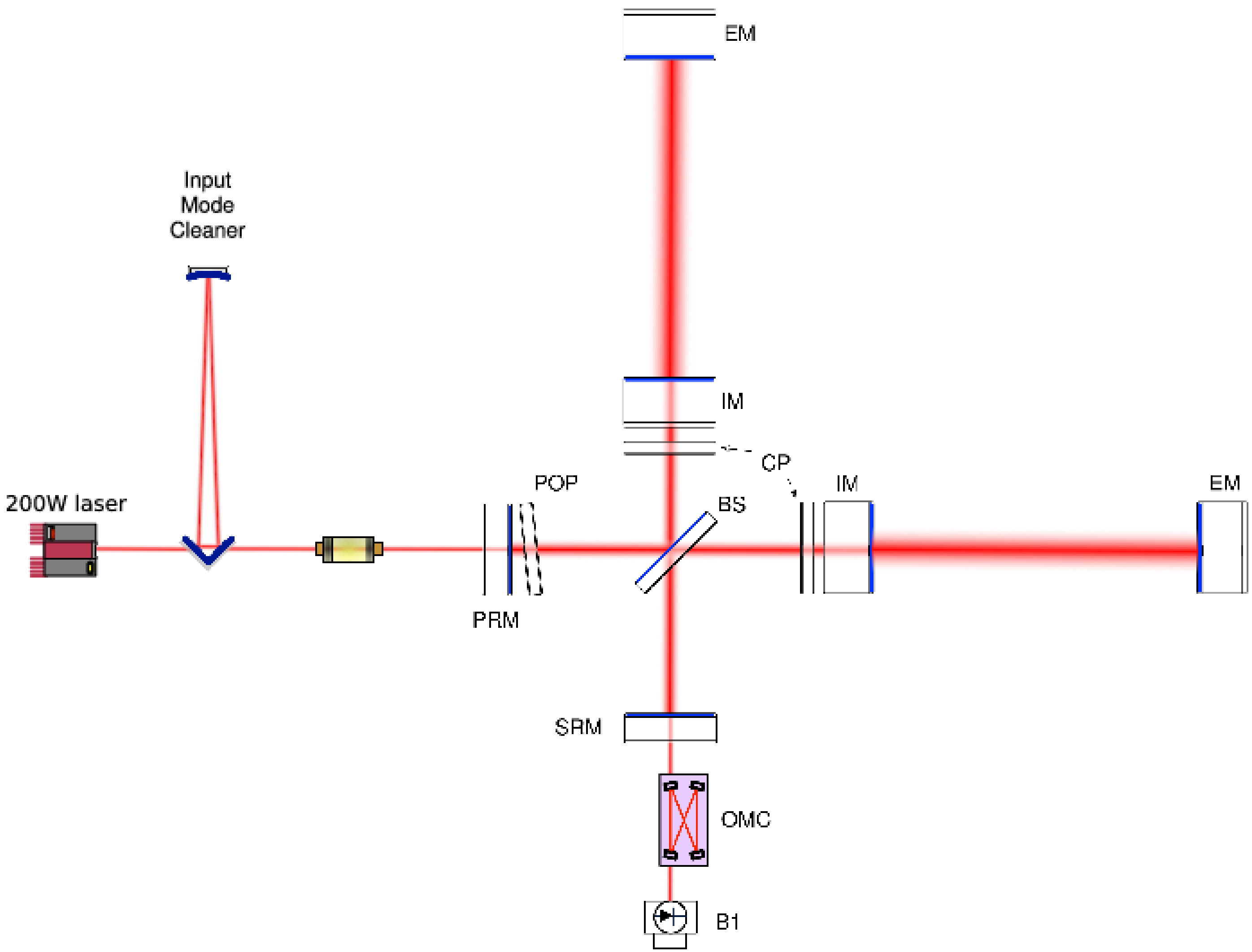

*Illustration of the metric variation with free fall masses initially located along a circle, for a + polarised GW propagating along z*

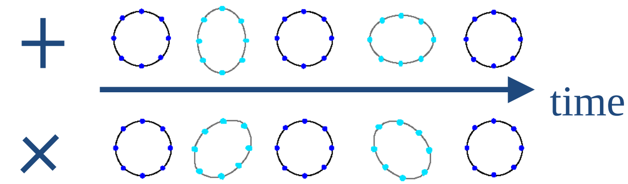
$$\delta L_x(t) = \frac{1}{2}\, h(t)\, L_0$$

*h(t)*: amplitude of the GW

(*h* has no dimension)

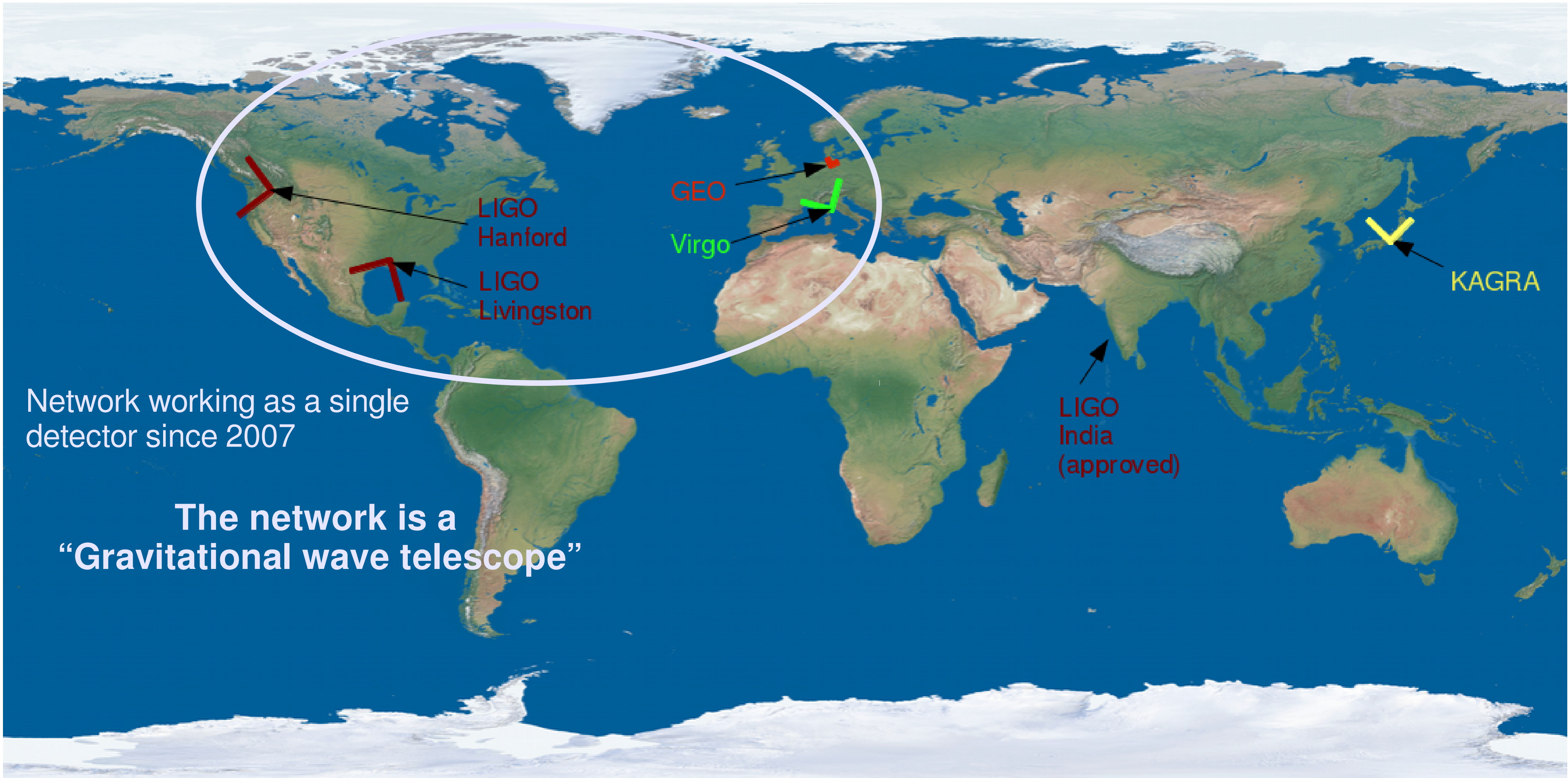
# A gravitational wave interferometer



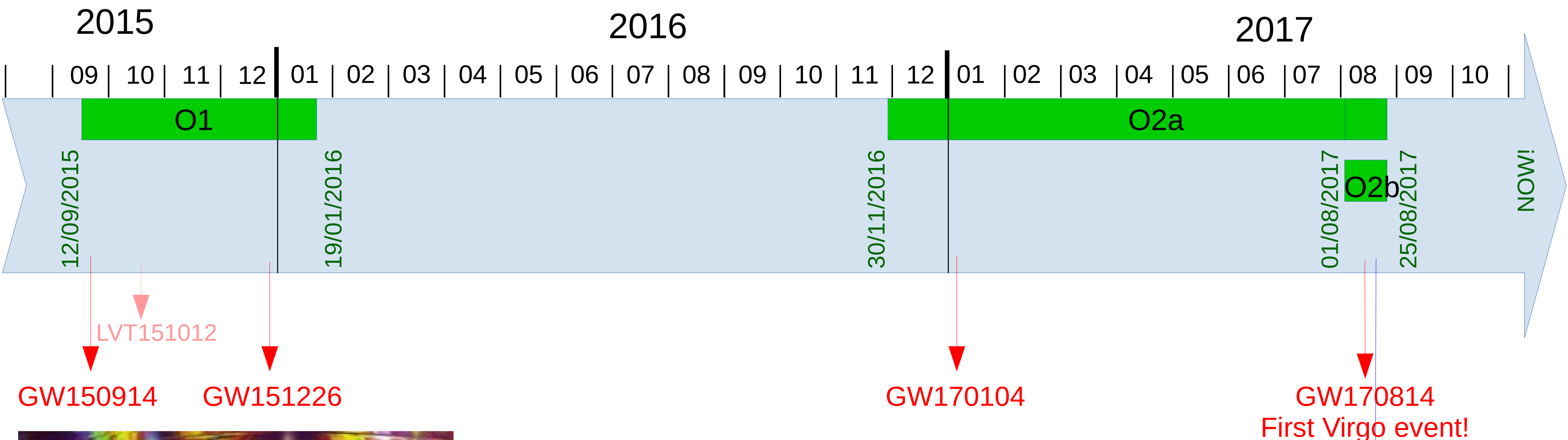

For GW170814, first Virgo detected event:
$h = 5\times10^{-22}$ → $\delta L = \pm\, 0.8 \times 10^{-18}$ m

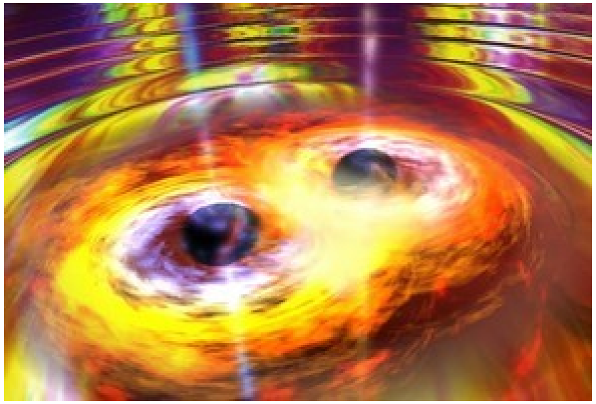
# An international network of detectors




- ✔ Rejection of spurious local noise (coincidence) → better sensitivity
- ✔ Source localisation (triangulation) → astronomy
- ✔ Wave polarization

# Summary of O1 and O2 runs



O2 run duty cycles:

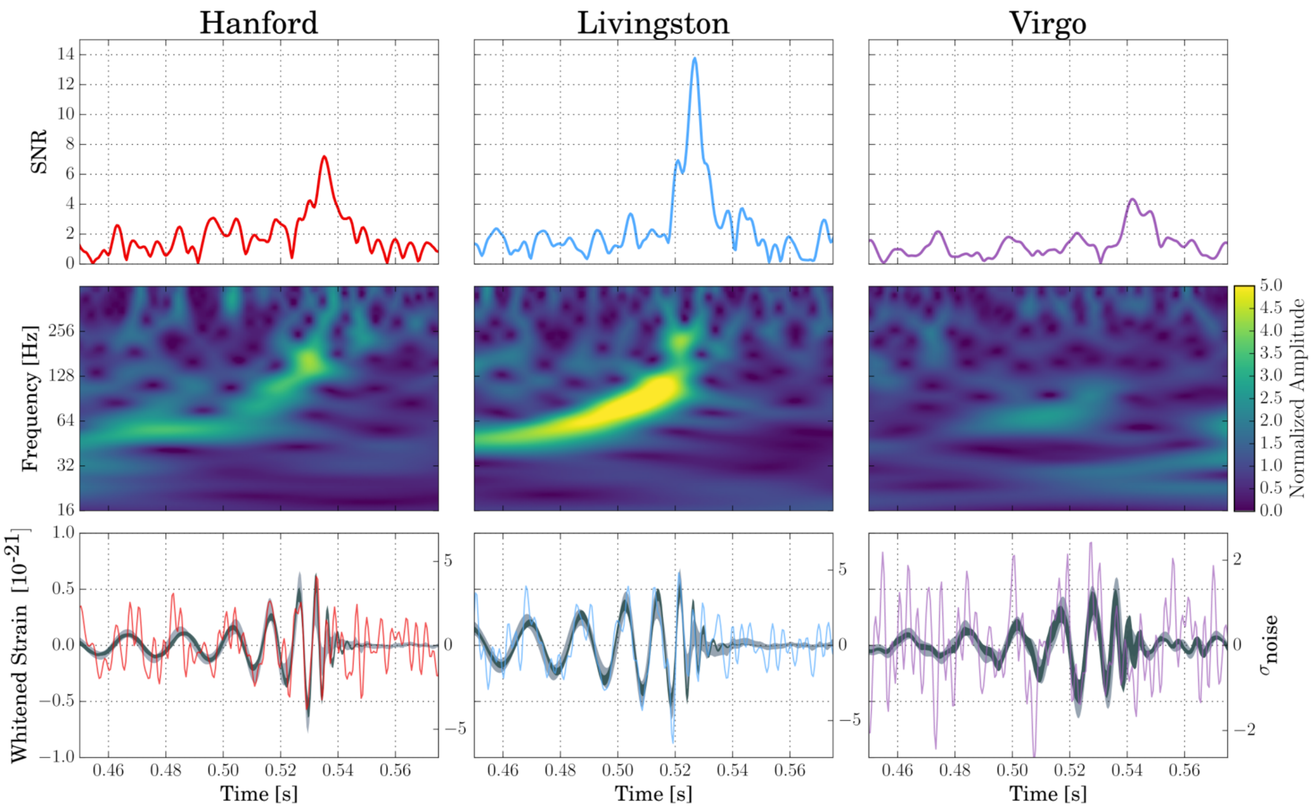
- LIGO H1: ~60%
- LIGO L1: ~60%
- Virgo V1: ~80% (O2b)

GW170817
+ multi-messenger detections!

Binary black holes
Binary neutron stars

# GW170814: the first Virgo event!

**August 14, 2017 at 10h30m43s UTC**
Combined SNR = 18
False alarm rate < 1 per 27000 years



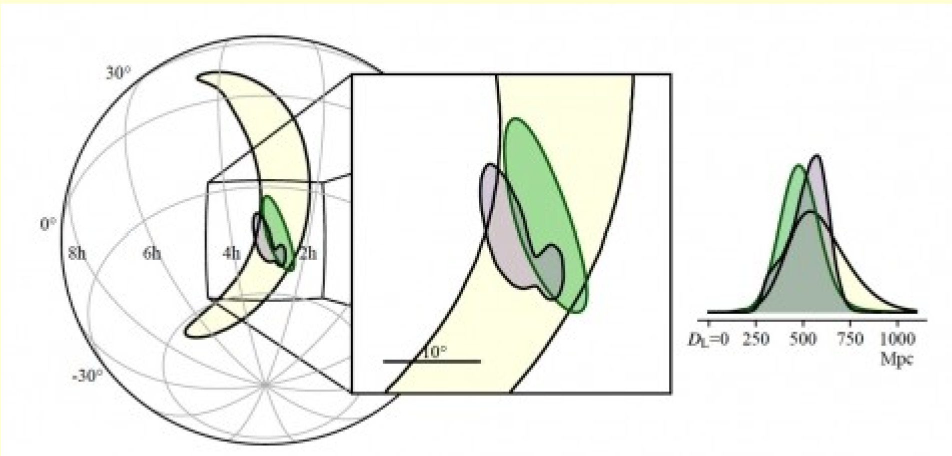

False alarm rate:

| | |
|---|---|
| Primary black hole mass $m_1$ | $30.5^{+5.7}_{-3.0}\,\mathrm{M}_\odot$ |
| Secondary black hole mass $m_2$ | $25.3^{+2.8}_{-4.2}\,\mathrm{M}_\odot$ |
| Chirp mass $\mathcal{M}$ | $24.1^{+1.4}_{-1.1}\,\mathrm{M}_\odot$ |
| Total mass $M$ | $55.9^{+3.4}_{-2.7}\,\mathrm{M}_\odot$ |
| Final black hole mass $M_\mathrm{f}$ | $53.2^{+3.2}_{-2.5}\,\mathrm{M}_\odot$ |
| Radiated energy $E_\mathrm{rad}$ | $2.7^{+0.4}_{-0.3}\,\mathrm{M}_\odot c^2$ |
| Peak luminosity $\ell_\mathrm{peak}$ | $3.7^{+0.5}_{-0.5} \times 10^{56}\,\mathrm{erg\,s^{-1}}$ |
| Effective inspiral spin parameter $\chi_\mathrm{eff}$ | $0.06^{+0.12}_{-0.12}$ |
| Final black hole spin $a_\mathrm{f}$ | $0.70^{+0.07}_{-0.05}$ |
| Luminosity distance $D_\mathrm{L}$ | $540^{+130}_{-210}$ Mpc |
| Source redshift $z$ | $0.11^{+0.03}_{-0.04}$ |

→ a binary black hole merer,
similar to the first ever detected event GW150914

# Improvements with Virgo data

## Better sky source localisation




Using only two LIGO detectors: 700 deg$^2$

↓

Including Virgo detector: 80 deg$^2$

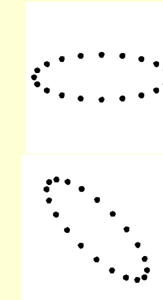
2D localisation

→ sky area reduced by factor ~10

3D localisation

→ sky volume reduced by factor ~20

## First tests of GW polarisation

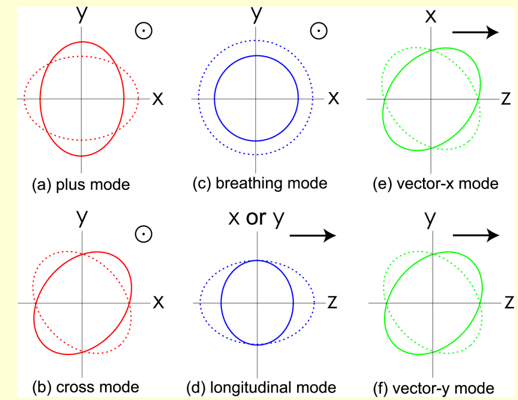


**General Relativity**

→ 2 polarization modes for GW

**Generic metric theories of gravity**

→ 6 modes allowed

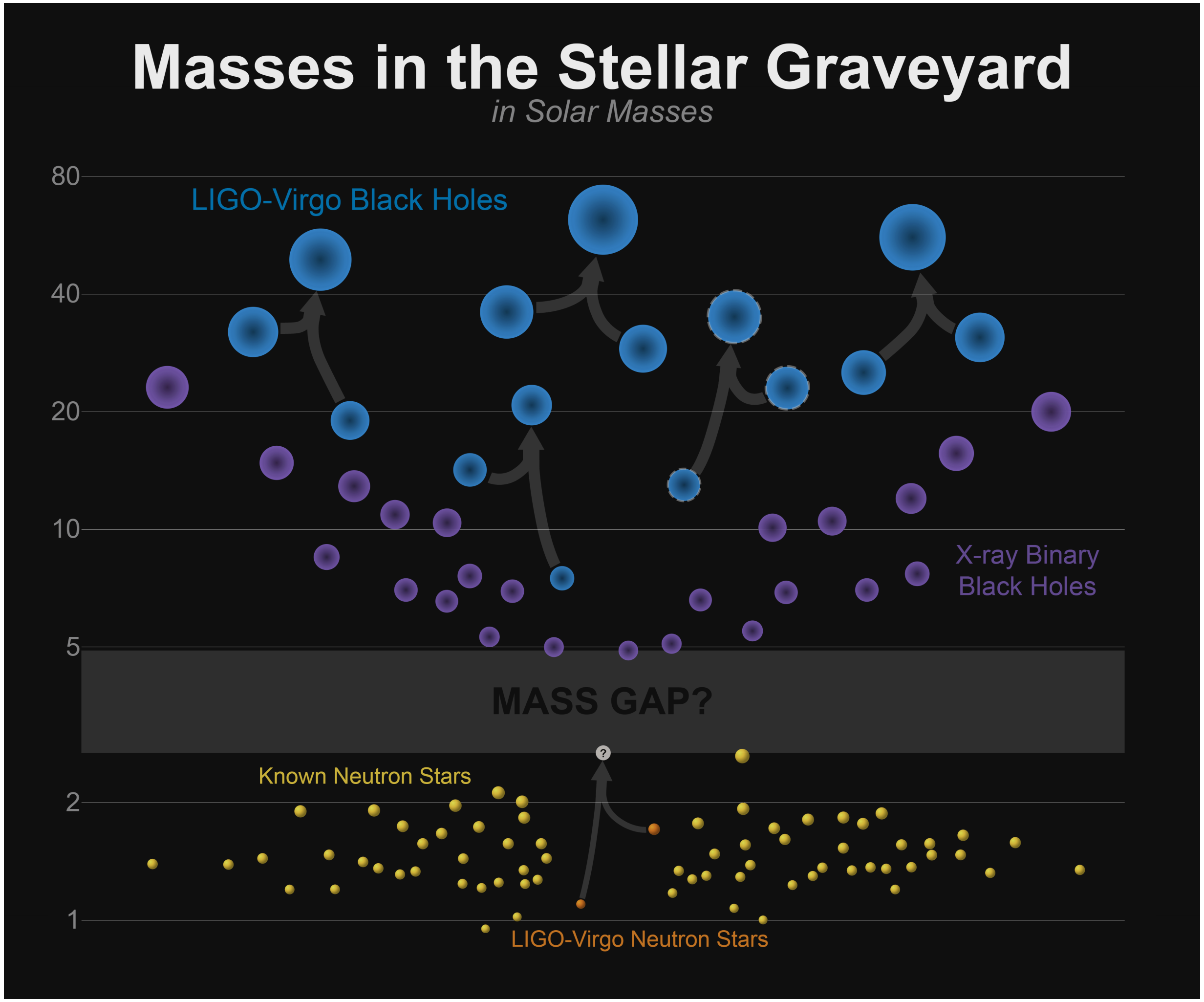



**New tests with GW170814**

Interferometer sensitive to GW projected onto the detector local + mode
Can study GW polarization modes using multiple detectors with different orientations

→ pure + and x modes favoured
wrt pure scalar of vector polarizations
(polarization mixtures no tested yet)

# Binary compact objects masses




Binary black holes

Binary neutron stars

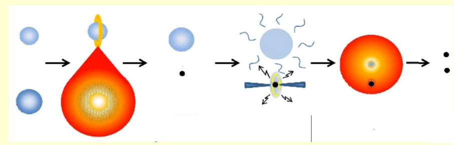
# In brief: physics w/ binary black holes

**Astrophysical implications**

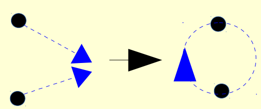
Formation of massive stars?

Formation of BBH

From binary stars (disfavoured?)



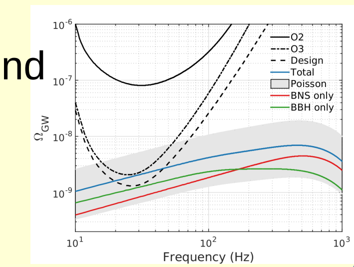
From isolated BHs



Inference of BBH population distribution and merger rate

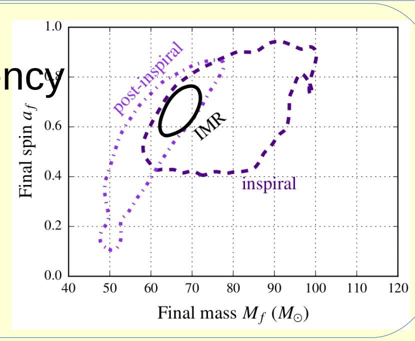
$$R = 12 - 213 \quad \mathrm{Gpc}^{-3}.\mathrm{yr}^{-1}$$

Estimation of GW stochastic background from BBH mergers



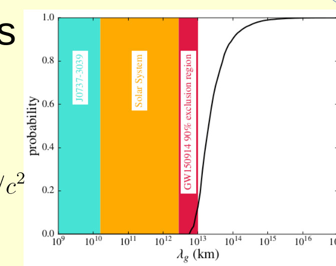

**Tests of General Relativity**

Check waveform internal consistency

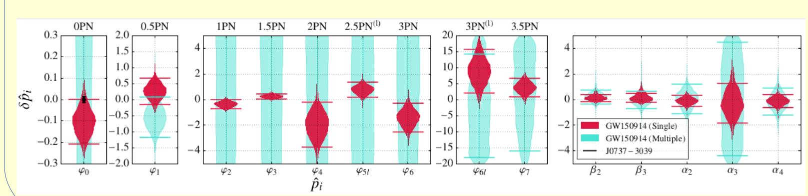



Bound on graviton mass and Lorentz violation

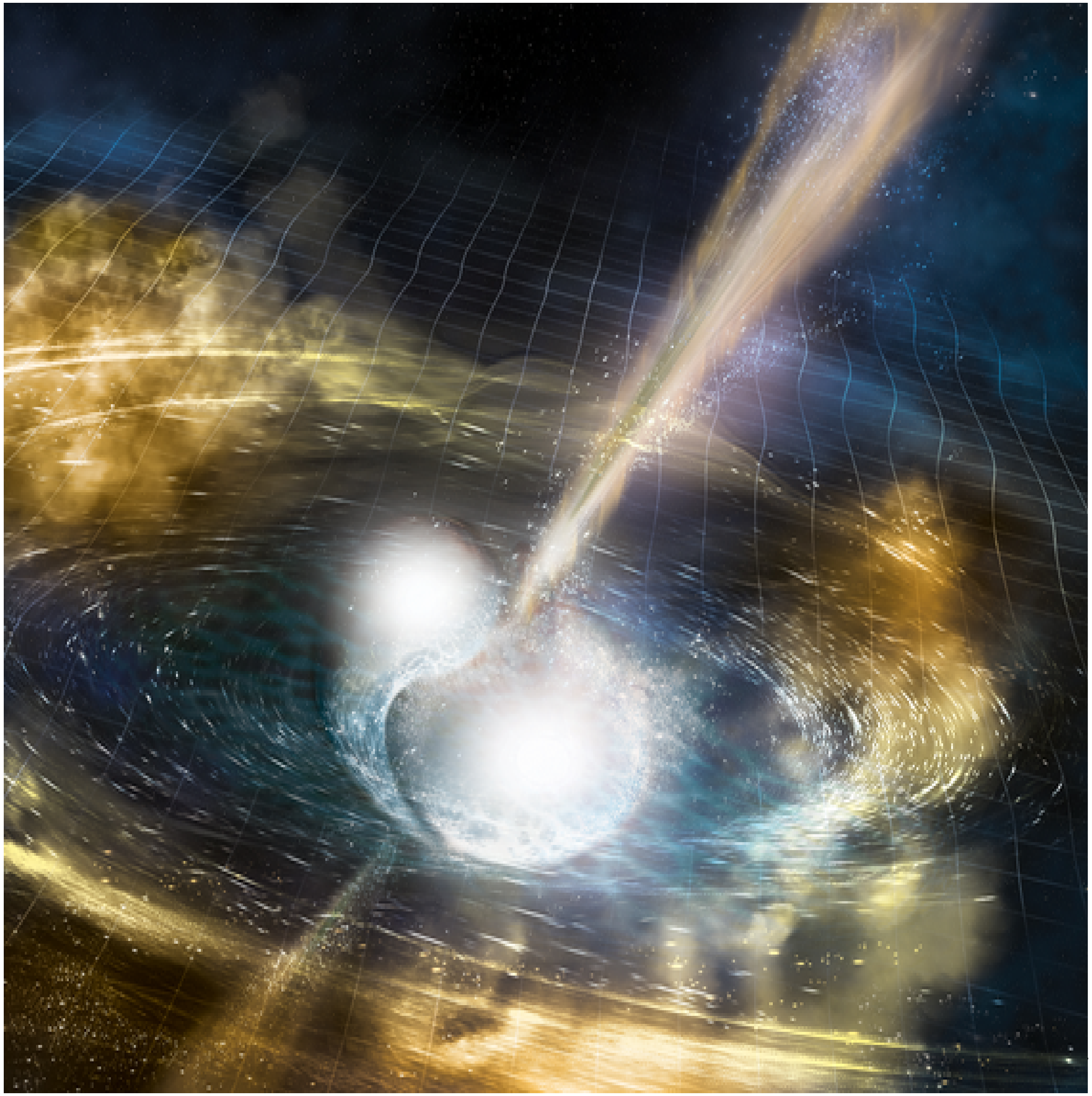
$$m_g < 1.2 \times 10^{-22}\ eV/c^2$$




Search for deviations from GR in waveform



# The first multi-messenger detection of a binary neutron star merger: GW170817



- GW data alone
- GRB association
- Electro-magnetic follow-up and kilonova
- Measurement of the Hubble constant
- Searching for neutrinos

- **GW data alone**
- GRB association
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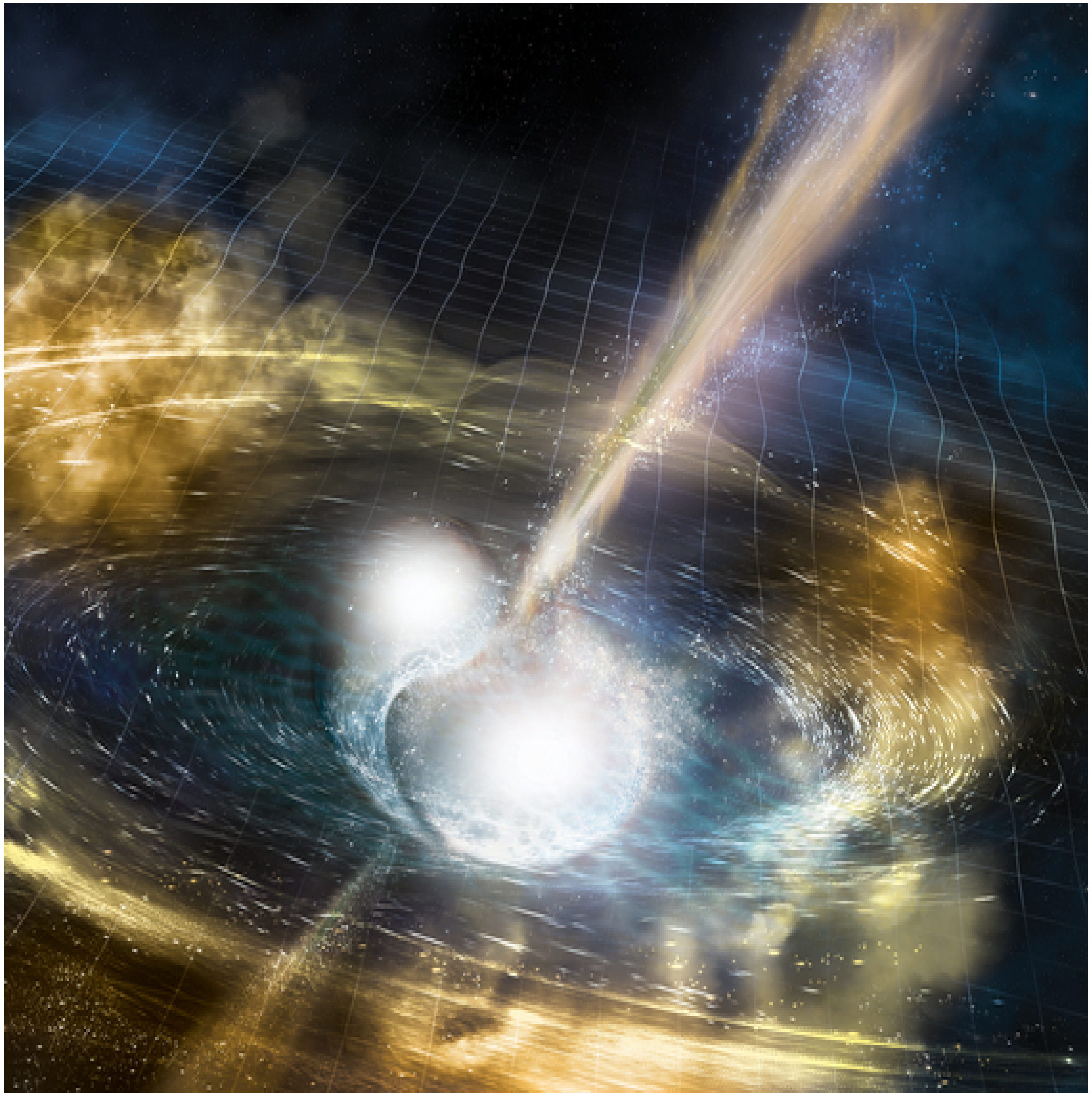
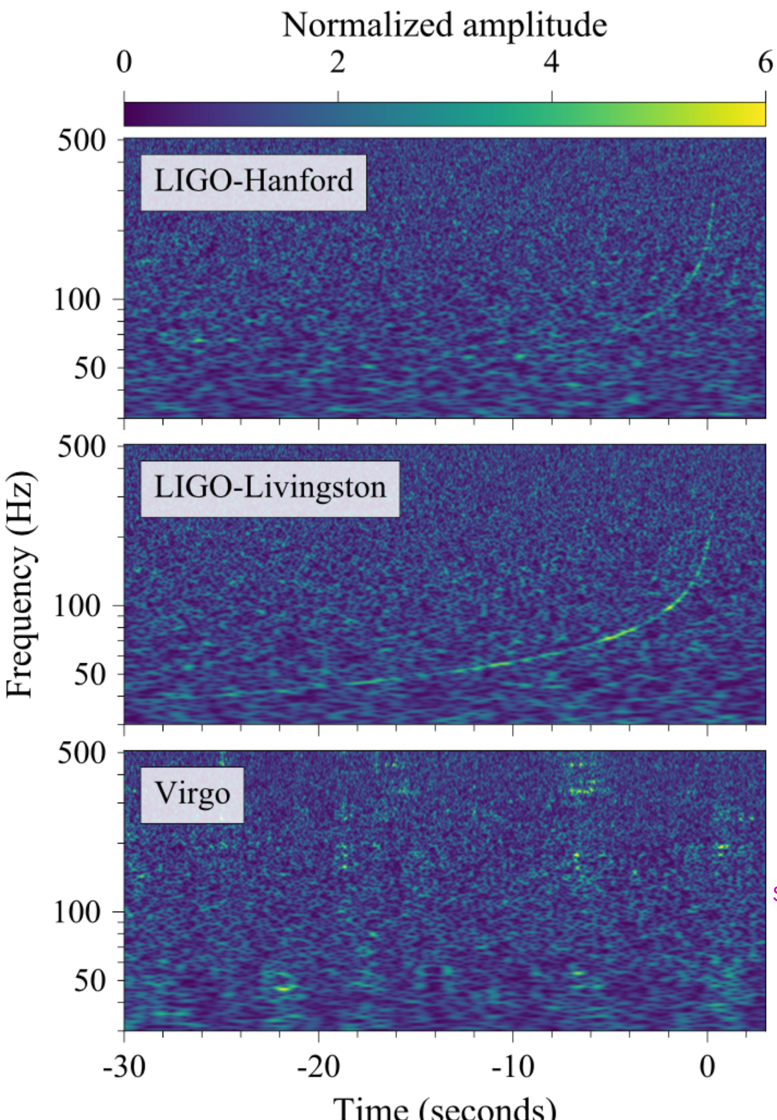


# The BNS merger in LIGO-Virgo data

**August 17, 2017 at 12h41m04.4s UTC**
Combined SNR = 32.4
False alarm rate < 1 per $8 \times 10^4$ years




SNR = 18.8

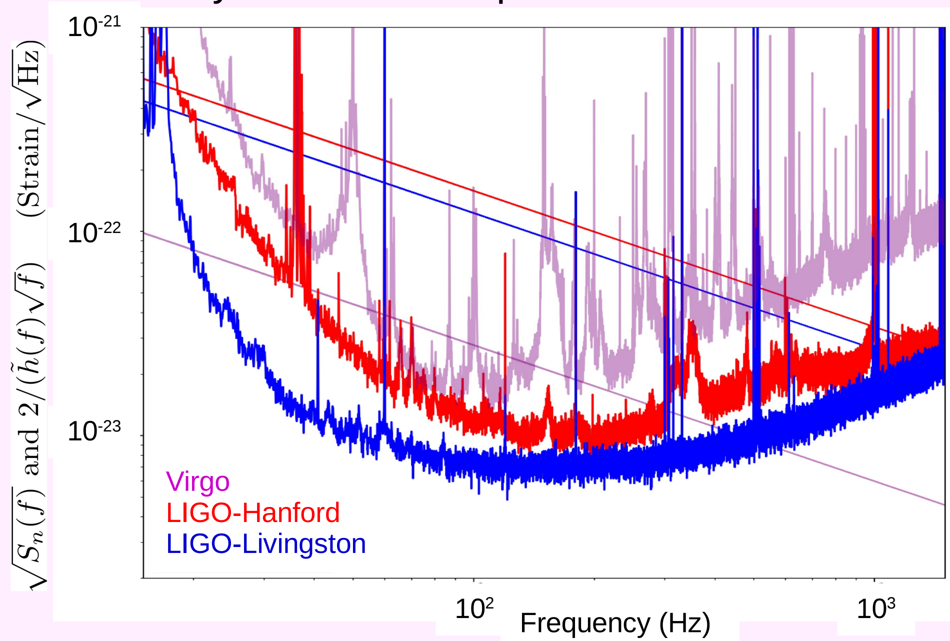
SNR = 26.4

SNR = 2.0

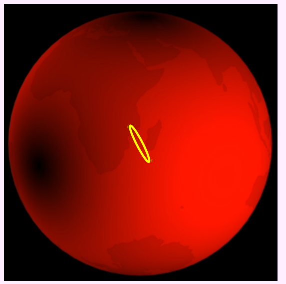
Signal duration: 100 s (from 24 Hz)

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

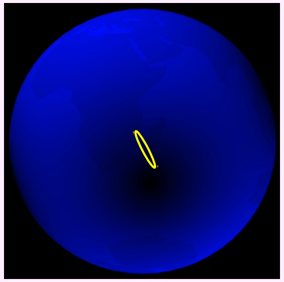
Low signal in Virgo:
Worse sensitivity + worse sky direction
→ do not participate to detection
→ significant effect on parameter estimation, sky localisation in particular




Antenna responses projected on Earth (darker → less sensitive)

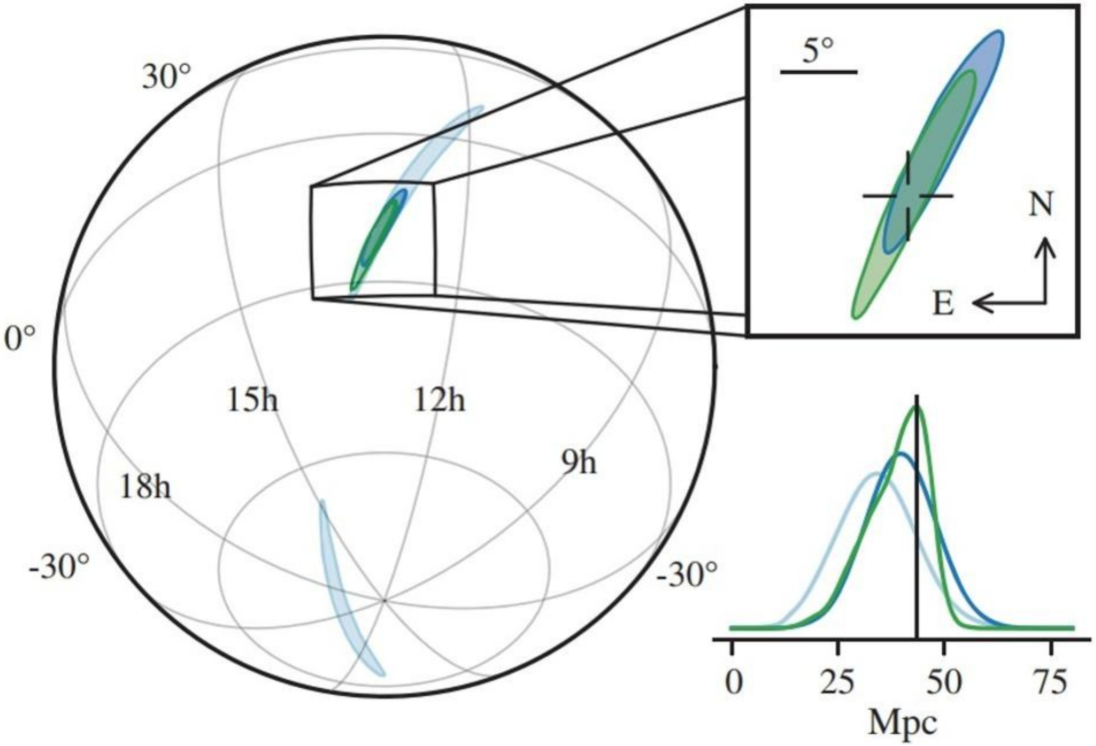


LIGO (Livingston)



Virgo

# GW170817 source localisation




- Sky location:
  - rapid loc. with HL: 190 deg$^2$
  - rapid loc. with HLV: 31 deg$^2$
  - final loc. with HLV: 28 deg$^2$

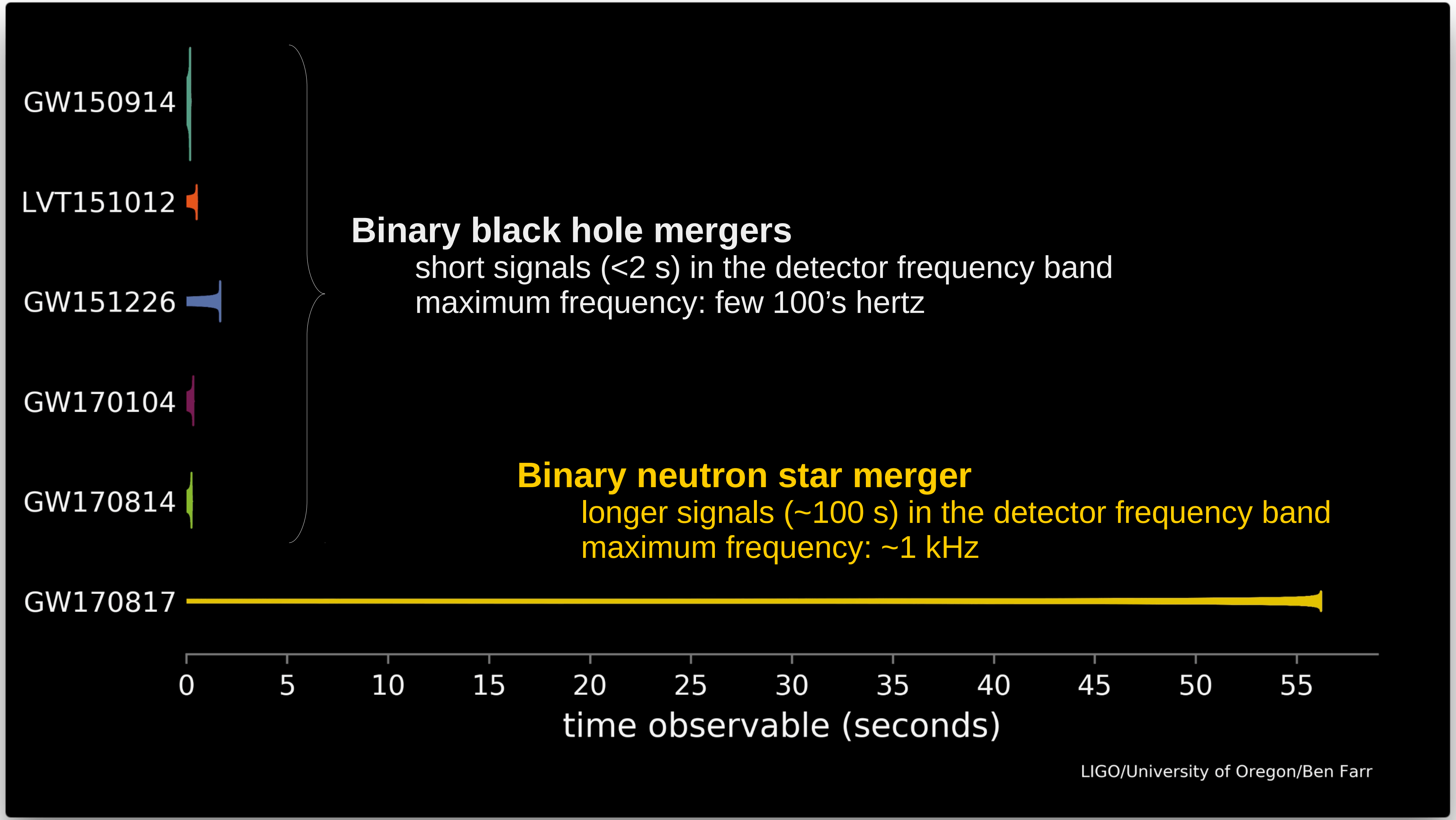
- Luminosity distance: $40^{+8}_{-14}$ Mpc
  (~120 millions of light-years)

→ 3D position: 380 Mpc$^3$

This is the closest and most precisely localized gravitational-wave signal!
→ triggered follow-up observations
→ and identification of NGC4993 as host galaxy

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

# Comparing the detected GW signals




Shape of the GW signal → information on the source type and parameters

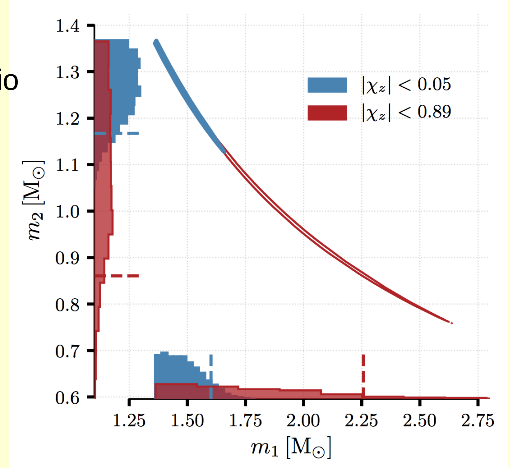
# Estimation of intrinsic parameters

## Bayesian fit of the waveform

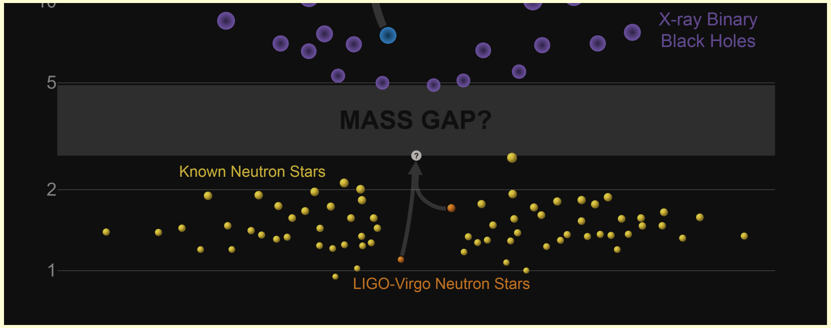
| | | Spin limit consistent with observed population | Theoretical spin limit |
|---|---|---|---|
| | | low-spin ($\|\chi\| < 0.05$) | high-spin ($\|\chi\| < 0.89$) |
| Mass parameters | $M_{chirp} (M_\odot)$ | $1.188^{+0.004}_{-0.002}$ | |
| | $m_1 \ (M_\odot)$ | 1.36–1.60 | 1.36 – 2.26 |
| | $m_2 \ (M_\odot)$ | 1.17–1.36 | 0.86 – 1.36 |
| | $m_{tot} \ (M_\odot)$ | $2.74^{+0.04}_{-0.01}$ | $2.82^{+0.47}_{-0.09}$ |
| Dimensionless tidal deformability | $\Lambda(1.4 M_\odot)$ | $< 800$ | $< 1400$ |

## Masses of the objects

Degeneracy between mass ratio and aligned spin components



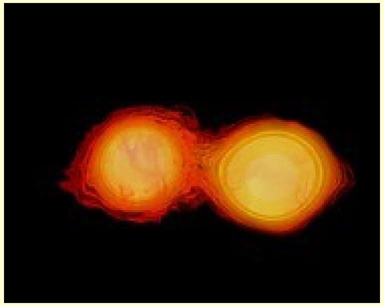

→ Masses < 2.3 $M_\odot$




→ masses consistent with two neutron stars

## Equation of state of the neutron stars

Tidal field of the companion → Deformation of the neutron star → Imprint on the shape of the gravitational wave, from f>600 Hz (→ parameter Λ)

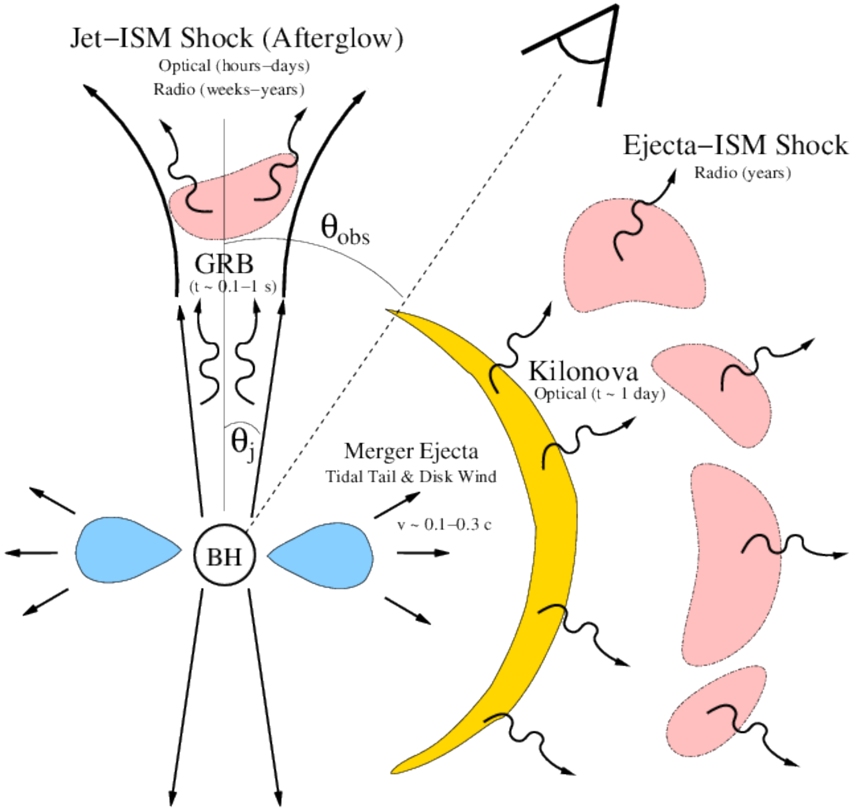


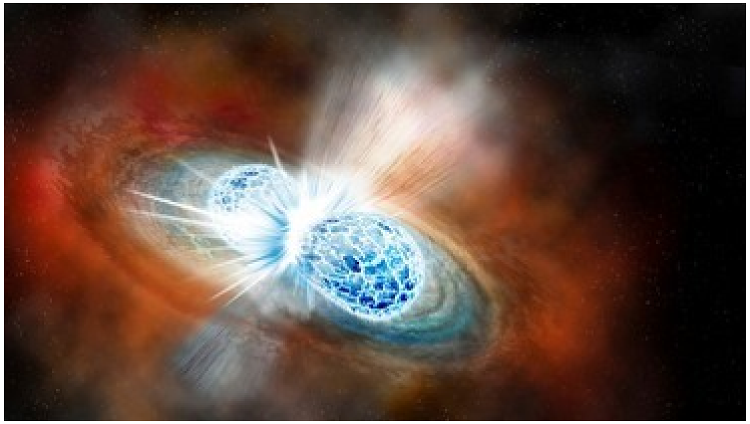
- Collision happens earlier than w/o tidal effect
- Modified final spin

→ disfavour equations of state of neutron stars that predict less compact stars: radius < 15 km

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

# Expected electro-magnetic counterparts?



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

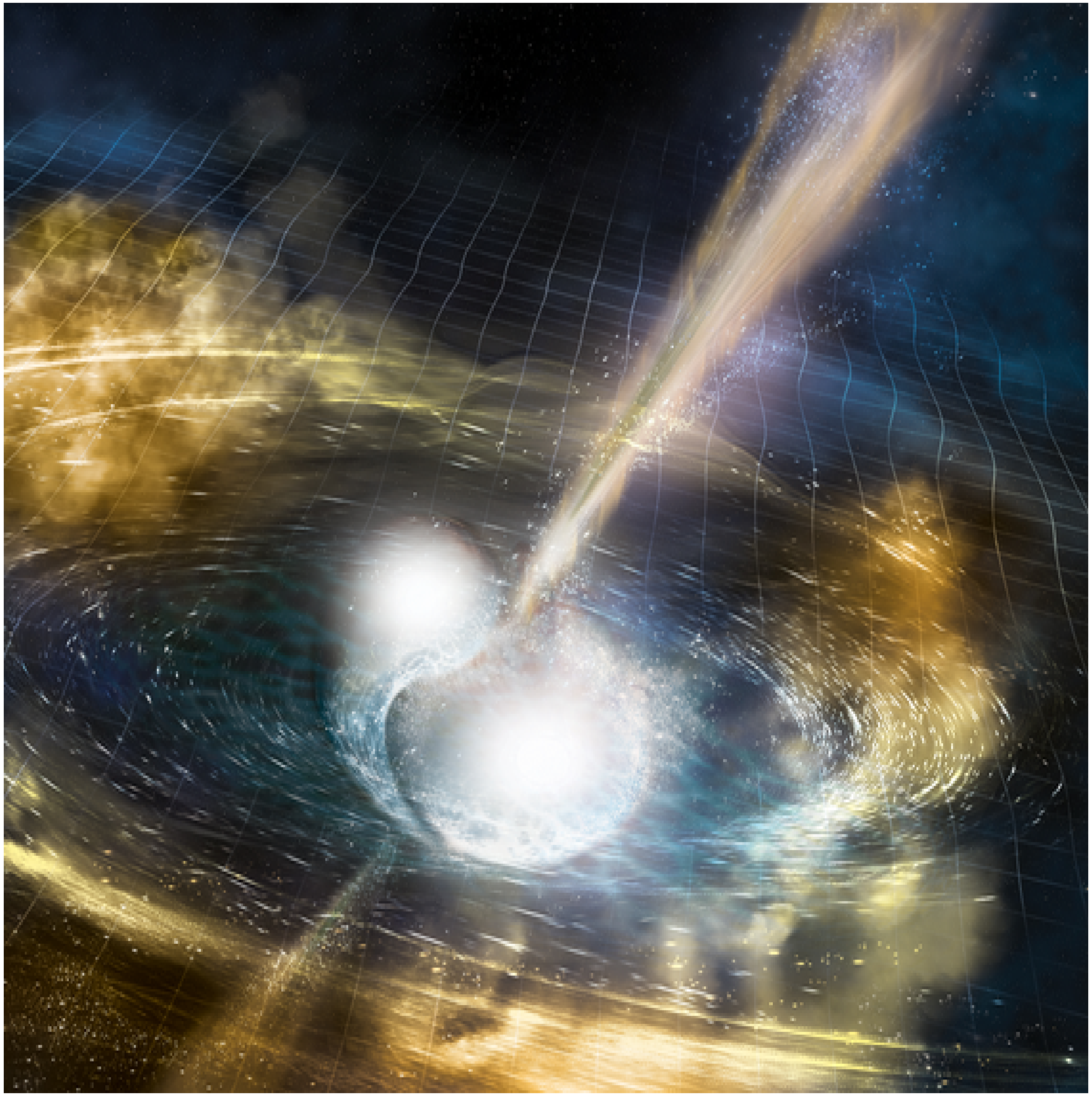
**Short gamma-ray burst (sGRB):**

- **Jet**
  → prompt γ-ray emission
  - few seconds after merger
  - last for <2 s
  - beamed
- **Interaction of jet with interstellar medium**
  → afterglow emission
  - few days after merger
  - evolves from X-ray to radio

**Kilonova**

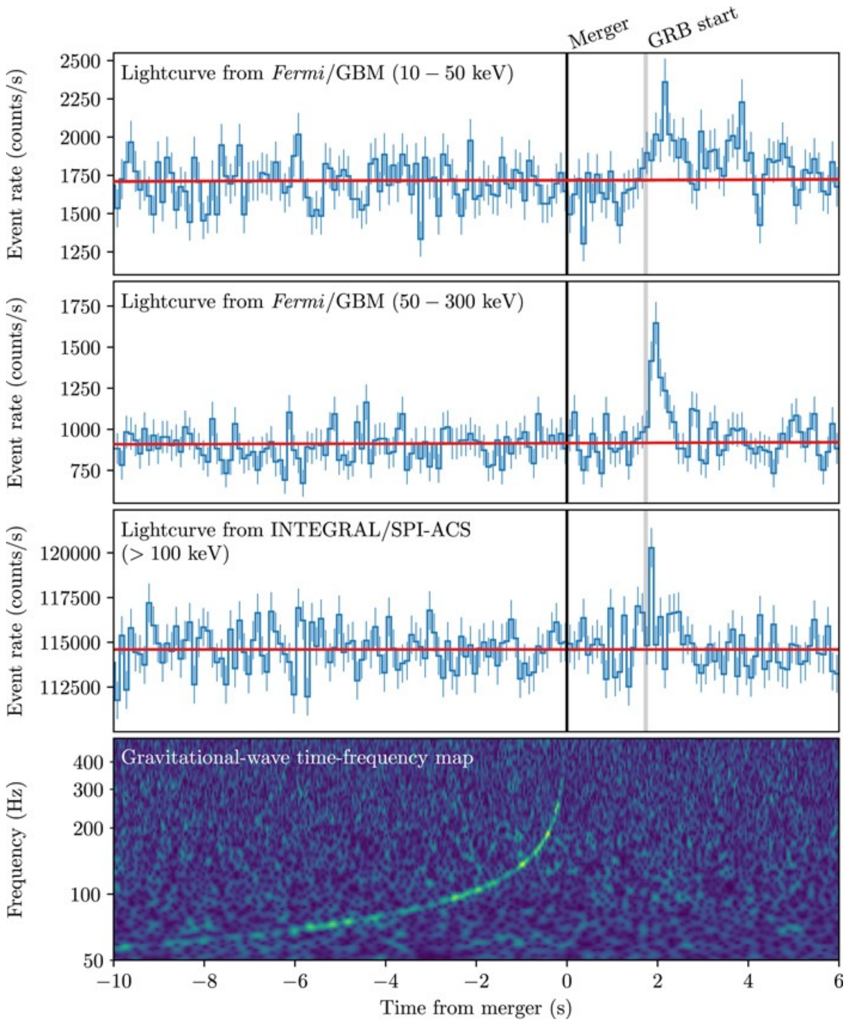
- **Conversion of hot ejected matter into r-processed elements, disintegration and thermal emission**
  → black body continuum + broad structures
  - few hours-days after merger
  - visible in UV, optical, IR
  - rapid spectral evolution

- GW data alone
- **Gamma-tray burst association**
- Electro-magnetic follow-up and kilonova
- Measurement of the Hubble constant
- Searching for neutrinos

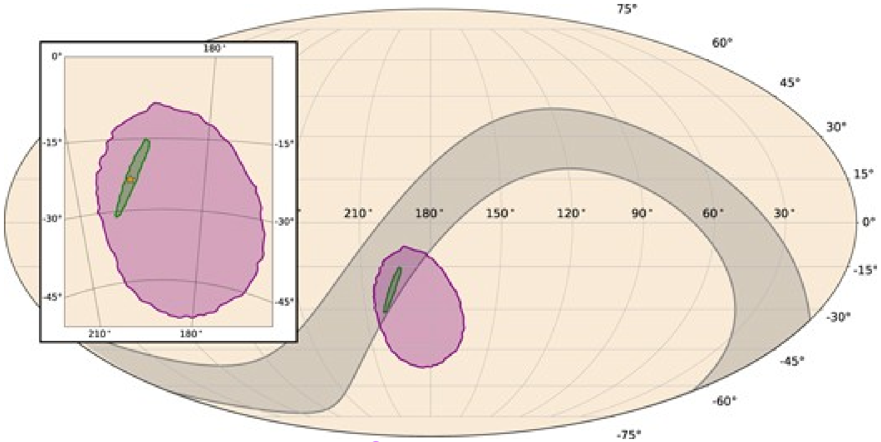


# Association with a gamma-ray burst

GRB170817A detected by Fermi and INTEGRAL
- γ-ray emission started ~1.7 s after merger time
- 3 times more likely to be a short GRB than a long GRB




GRB sky localisation (90% CL)



Fermi-GBM (1100 deg$^2$)
Fermi and INTEGRAL (deg$^2$)
LIGO-Virgo (28 deg$^2$)

Time and localisation association chance probability: 5.0 x $10^{-8}$
→ association validated within 5.3 σ

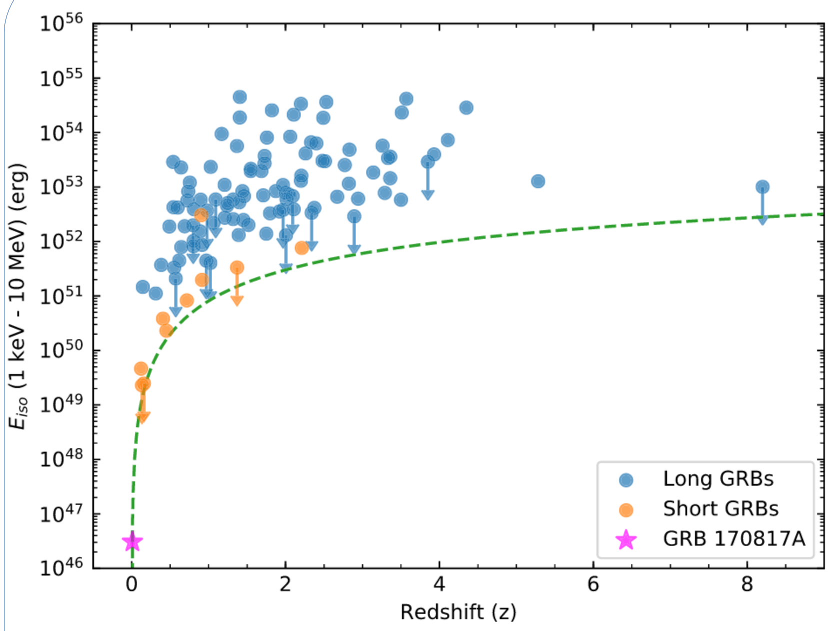
→ First direct evidence that binary neutron star mergers are progenitors of (at least some) short gamma-ray bursts!

Abbot at al., ApJ, 848, 13 (2017)

# New insight into gamma-ray bursts

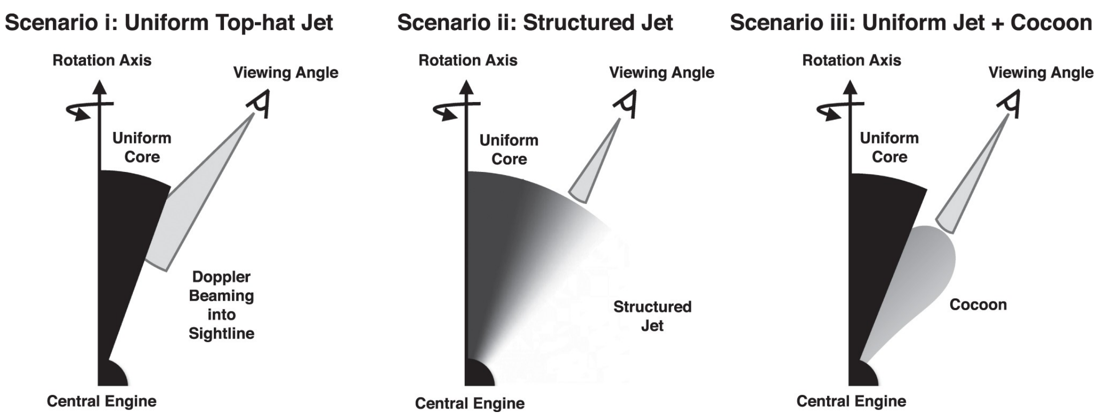
**GW170817 waveform → loose limit on BNS viewing angle**, but degeneracy with source distance
- Θ < 56°  from GW data alone
- Θ < 36°  using the known distance to the host galaxy NGC 4993

→ compatible with jet pointing towards Earth




GRB170817A:
- the **closest** short GRB with know distance (z~0.008)
  (previous closest, GRB061201: z ~0;11)
- $10^2$ to $10^6$ times **less energetic** than other bursts

→ implications/questions on the structure of the jet



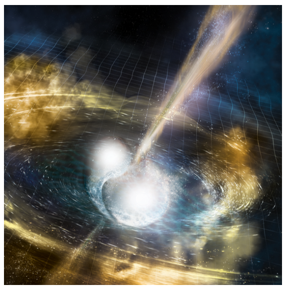

**Prediction of detection rates**
- higher rate than previously expected for sGRB to be seen in gamma-rays
- 1-50 BNS mergers expected in LIGO-Virgo during run O3 (wrt previously estimated 0.04-100)

→ 0.1 to 1.4 joint detections for GW and Fermi sGRB during run O3 (end 2018-2019)

Abbot at al., ApJ, 848, 13 (2017)

# GW/GRB association and speed of gravity

**Emission**
at the binary neutron star merger
→ GW and γ-rays



Assumption:
γ-rays emitted between
0 and 10 s after GW

**Propagation**
Along at least 26 Mpc
($85 \times 10^6$ light-years)

GW →

γ-rays →

**Detection** on Earth
→ GW and γ-ray signals

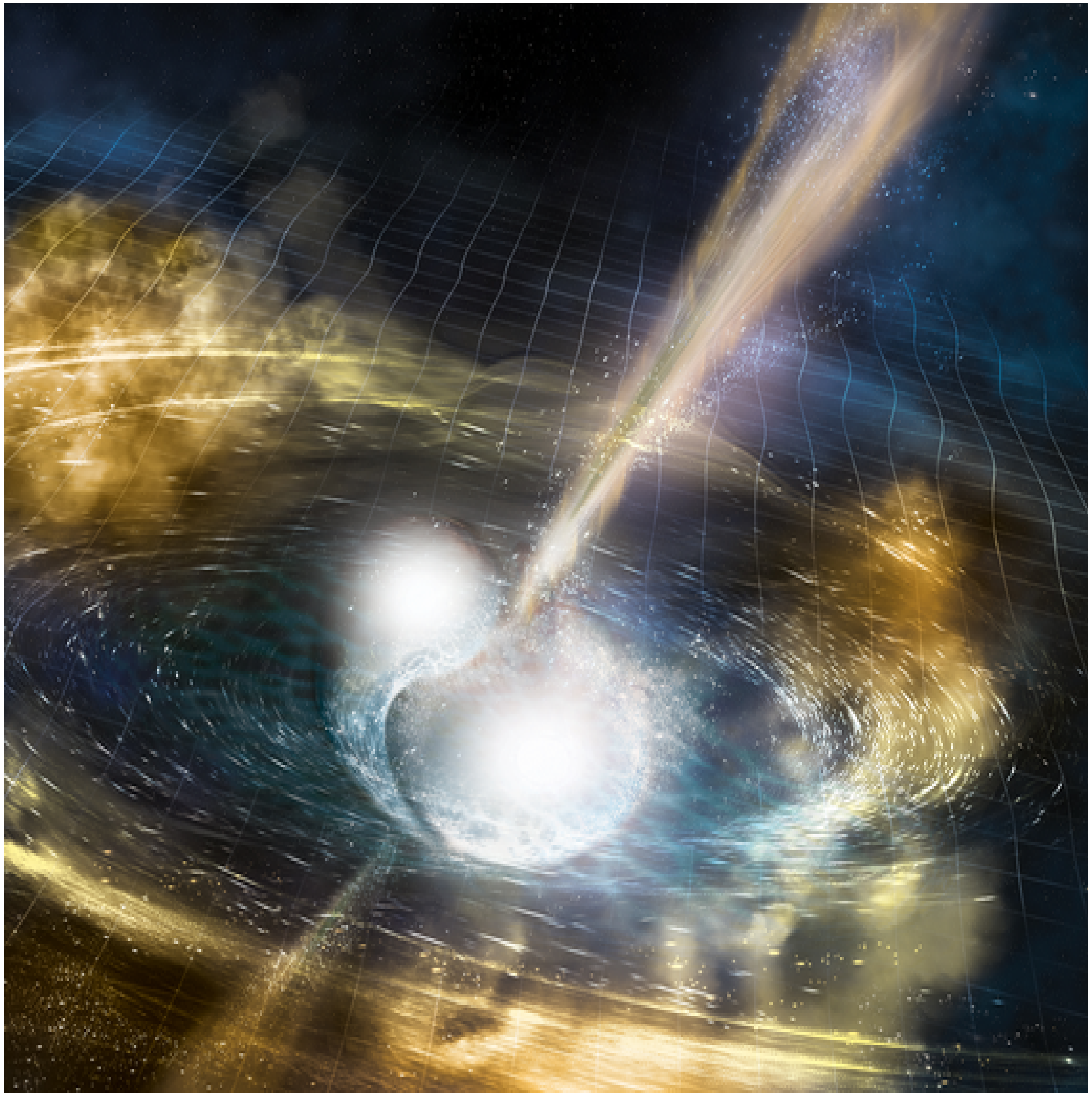
γ-rays detected
1.74 ± 0.05 s
after GW
merger

Previous constraints
were allowing a time
difference of 1000 years!

Difference between speed of gravity and speed of light:
$[-3 \times 10^{-15} ; +7 \times 10^{-16}] \times c$

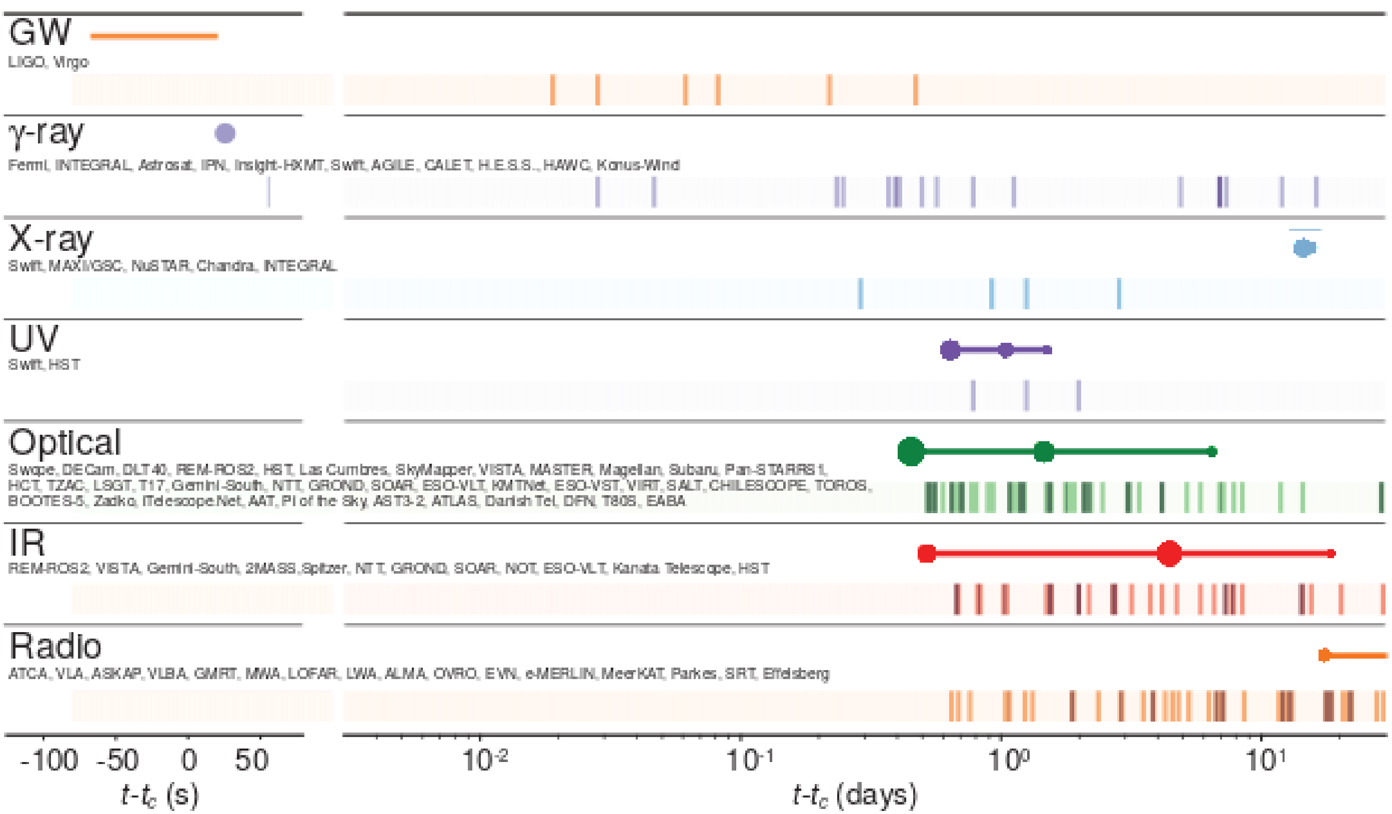
Abbot at al., ApJ, 848, 13 (2017)

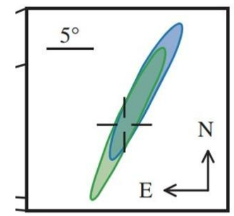
- GW data alone
- GRB association
- **Electro-magnetic follow-up and kilonova**
- Measurement of the Hubble constant
- Searching for neutrinos



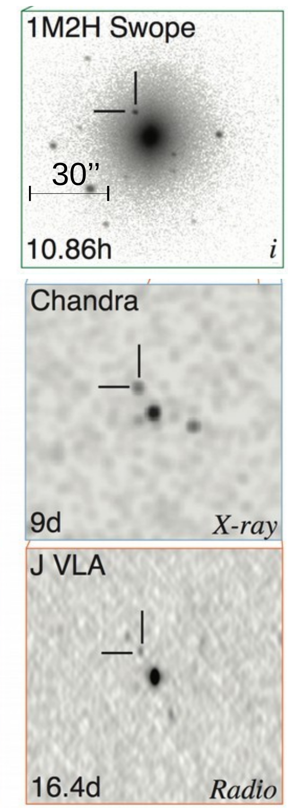
# The electro-magnetic follow-up campaign

| T0 | T0 + 1,7 s | T0 + 5 h | T0 + 11 h | T0 + 11 h | T0 + 9 d | T0 + 16 d |
|---|---|---|---|---|---|---|
| GW detection → | GRB detection → | GW localisation → | Optical counterpart → | Host galaxy NGC4993 → | X-ray counterpart → | radio-ray counterpart |




+ distance: 40 $^{+8}_{-14}$ Mpc

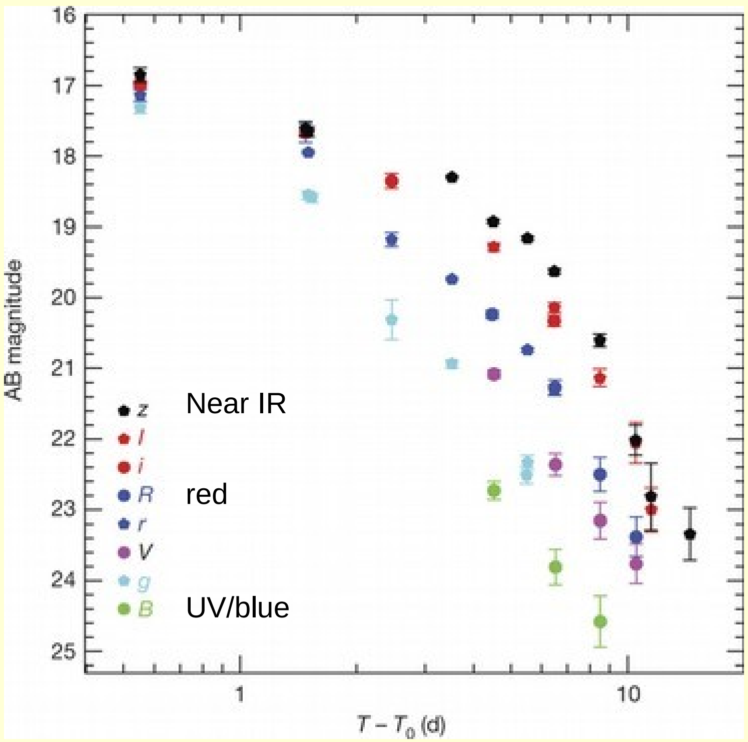



Identification of the host galaxy: NGC4993, at ~40 Mpc

*Abbott et al., The Astrophysical Journal Letters, 848:L12 (2017)*

# Following the optical transient

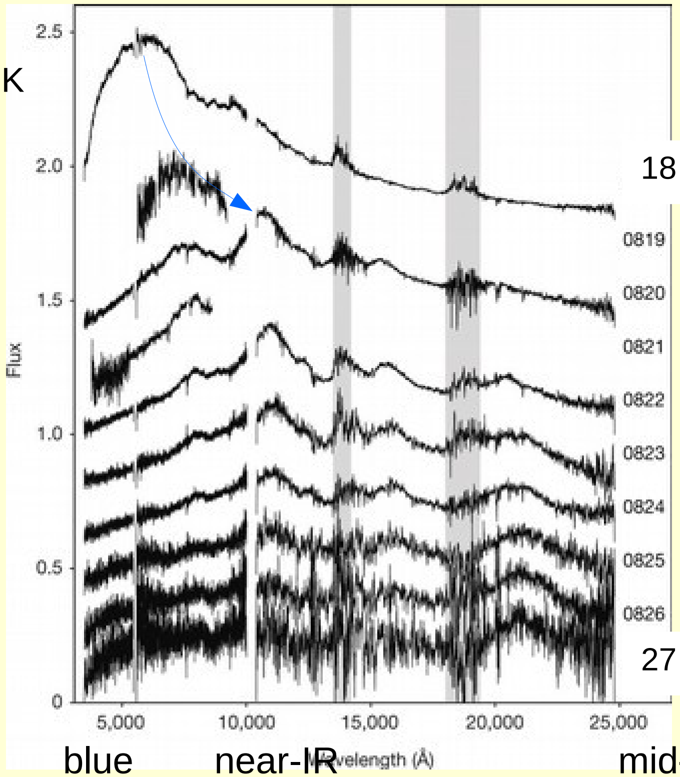
## Light curves in different bands
(blue to near-infrared)




→ Decrease of light flux,
faster at UV/blue than at NIR wavelengths

## Time evolution of light spectrum

Black body 5000 K
r ~ $8 \times 10^{14}$ cm
v ~ 0.2 c
rapid cooling

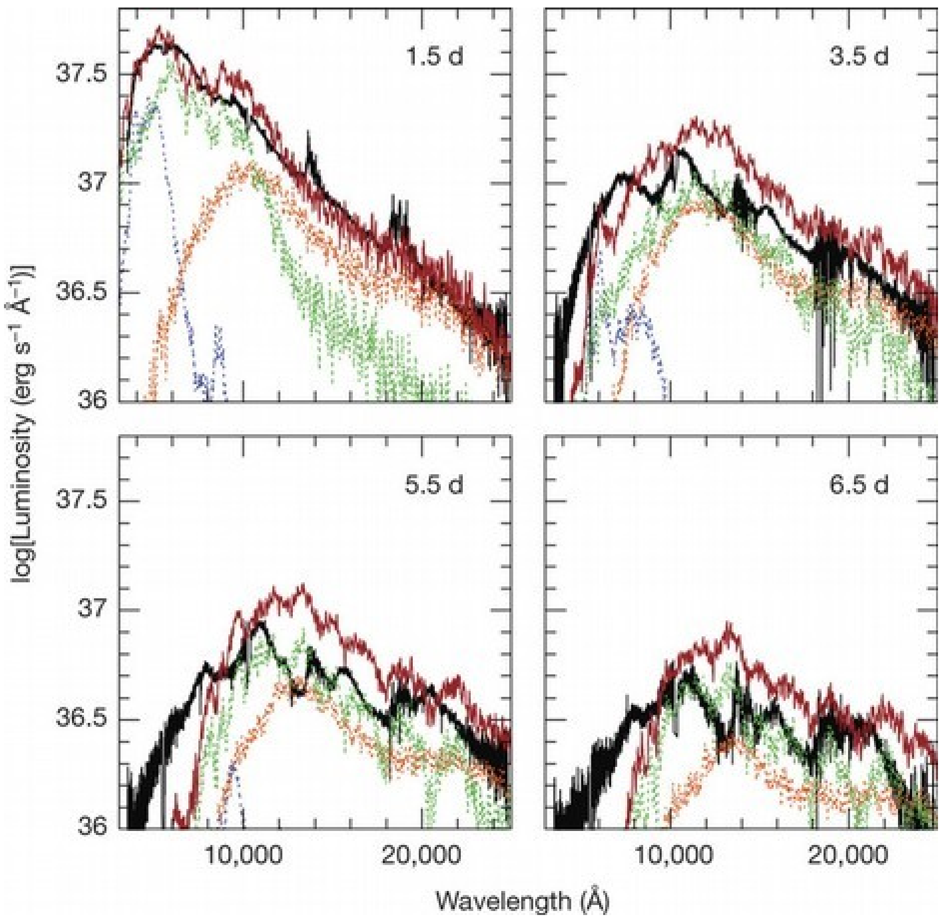



→ and spectral evolution
- colour changed from blue to red black body
- with apparition of lines

→ rapid cooling of ejecta (0.01 to 0.05 $M_\odot$ )


Abbot et al., Astrophys. J. Lett. (2017)
E.. Pian et al., Nature 551, 67 (2017)

# Data vs kilonova (pre-existing) models




Good agreement between **data** (black) and kilonova models behaviour (red):

- temporal spectral evolution
- apparition of broad spectral features

→ first spectroscopic identification of a kilonova

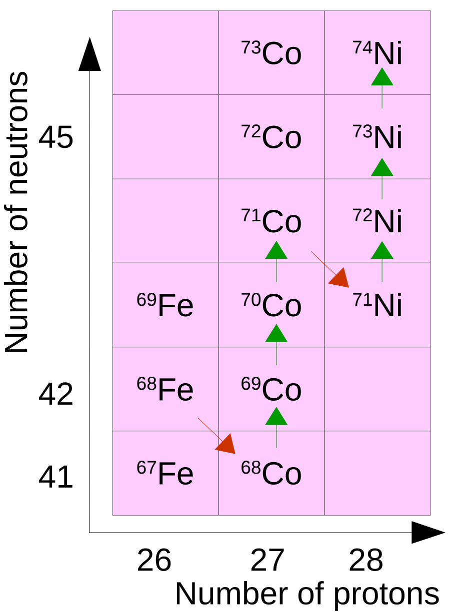
Models with different components and parameters:

- mass, spin and EOS of the neutron stars
- thermal effects, neutrino/radiation hydrodynamics, magnetic fields

- matter ejected in dynamic ejecta and winds
- matter composition: with or without lanthanides


Abbot et al., Astrophys. J. Lett. (2017)
E.. Pian et al., Nature 551, 67 (2017)

# Kilonova and nucleosynthesis of heavy nuclei




β⁻ disintegrations
Neutron capture

Tidal effects before merger

↓

Ejection of high speed matter rich in neutrons

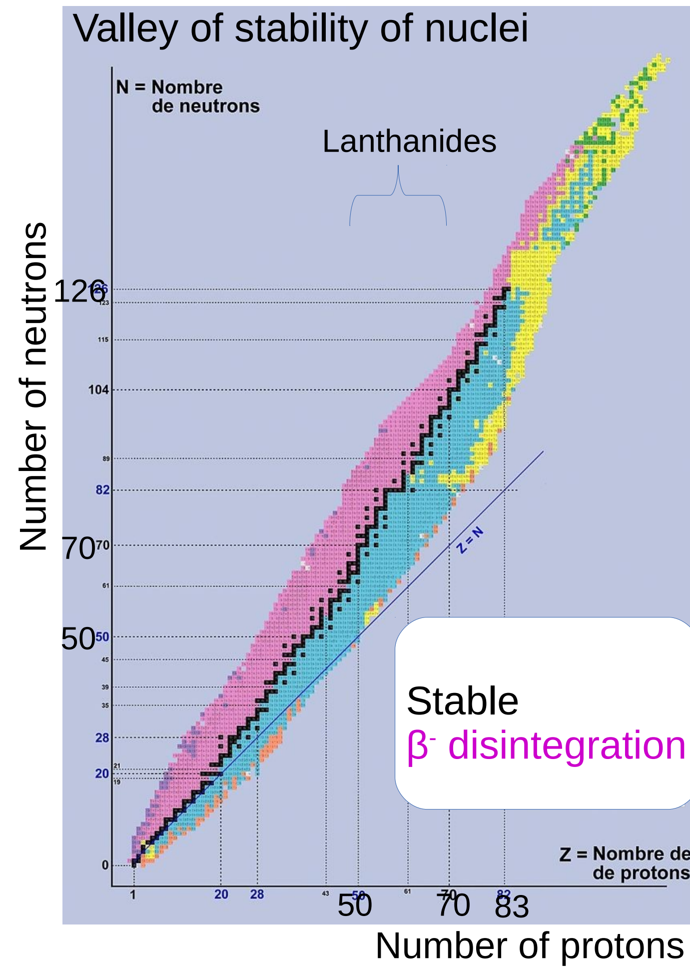
↓

Rapid fusion of heavy unstable elements, rich in neutrons (r-process)

β⁻ disintegrations

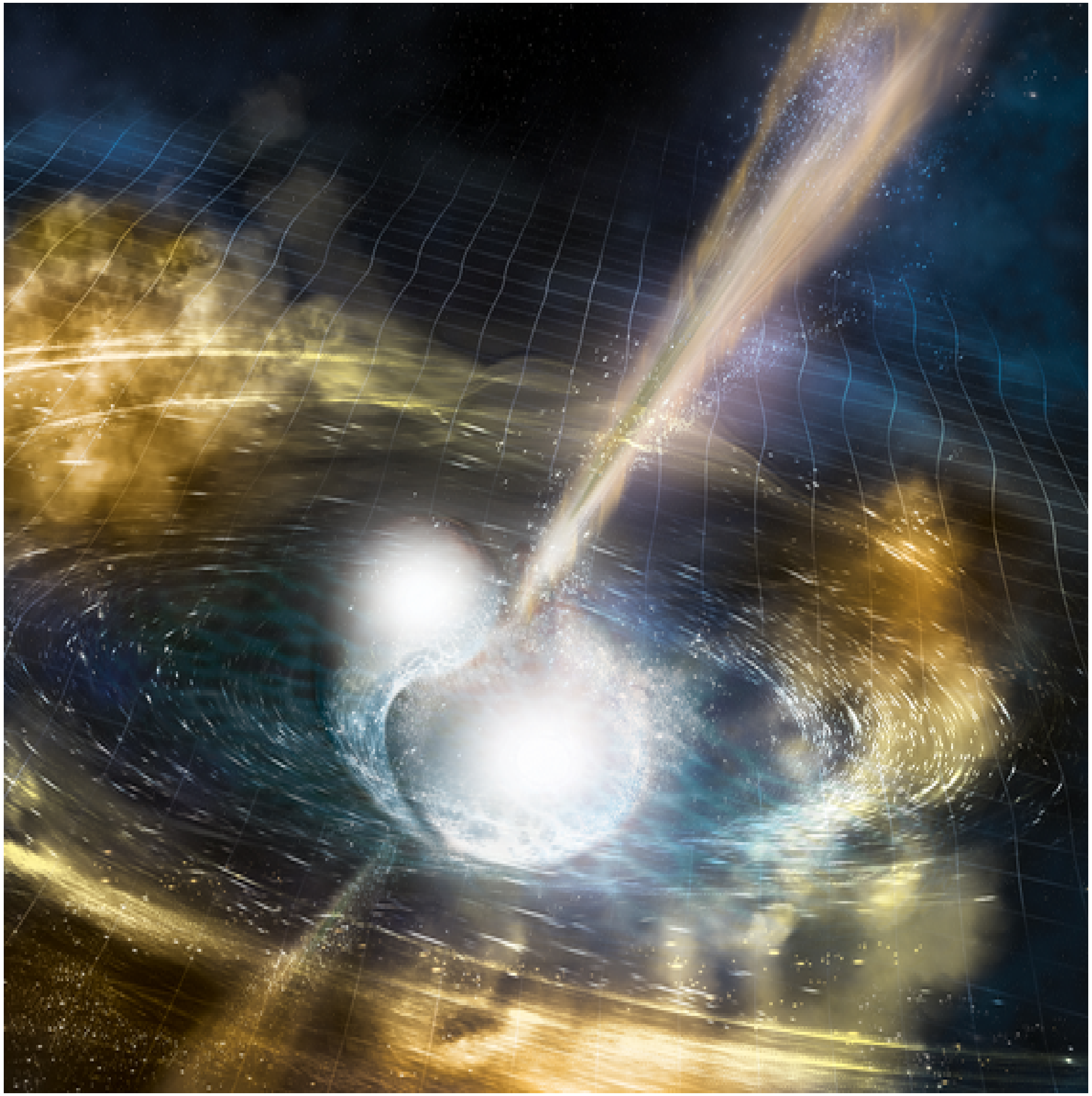
↓

Heavy stable elements
→ up to Pb, Bi, including Au, Pt



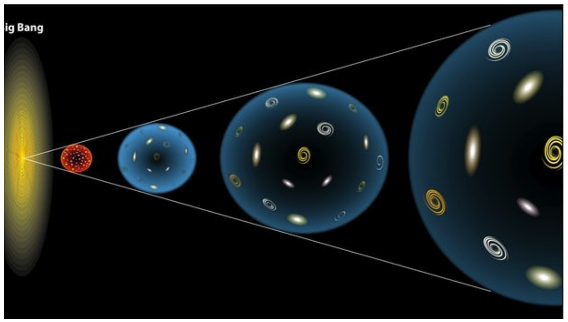

→ Binary neutron star mergers are probably the main sources of heavy elements in the Universe

- GW data alone
- GRB association
- Electro-magnetic follow-up and kilonova
- **Measurement of the Hubble constant**
- Searching for neutrinos



# New measurement of the Hubble constant

$H_0$ describes the expansion rate of the (present) Universe



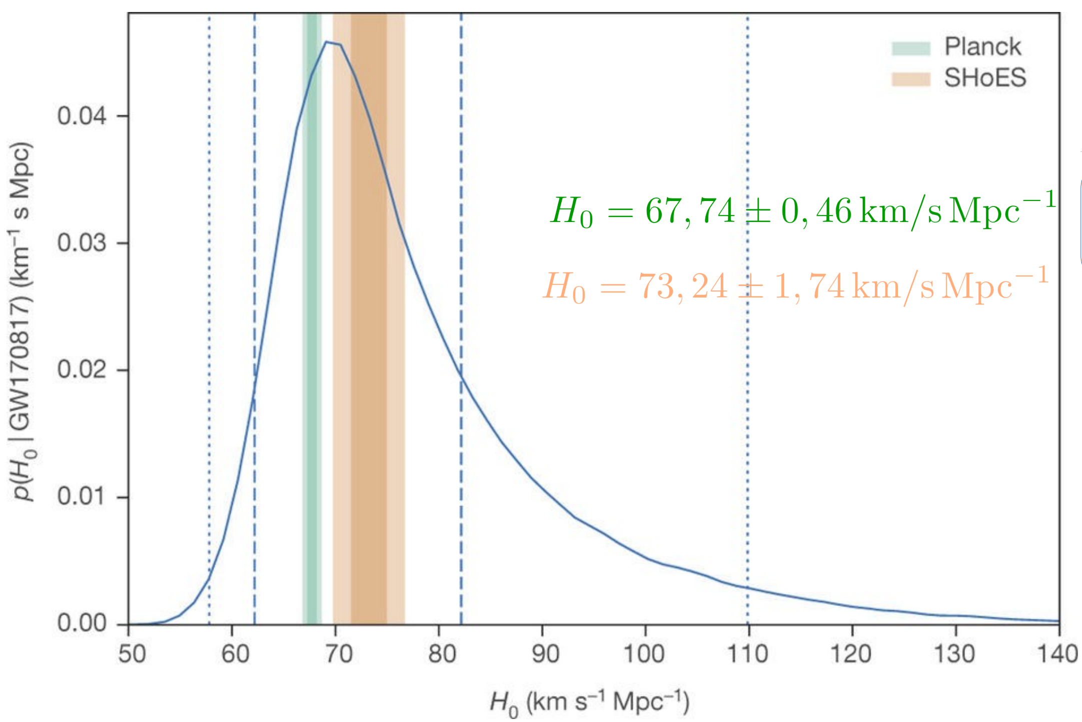

**GW170817 can be used as a standard siren**

$$D_{luminosity} = H_0 \times v_r$$

Estimated directly from GW signal $(43.8^{+2.9}_{-6.9}\,\mathrm{Mpc})$

Determined from host galaxy NGC4993 $(3017 \pm 166\,\mathrm{km/s})$

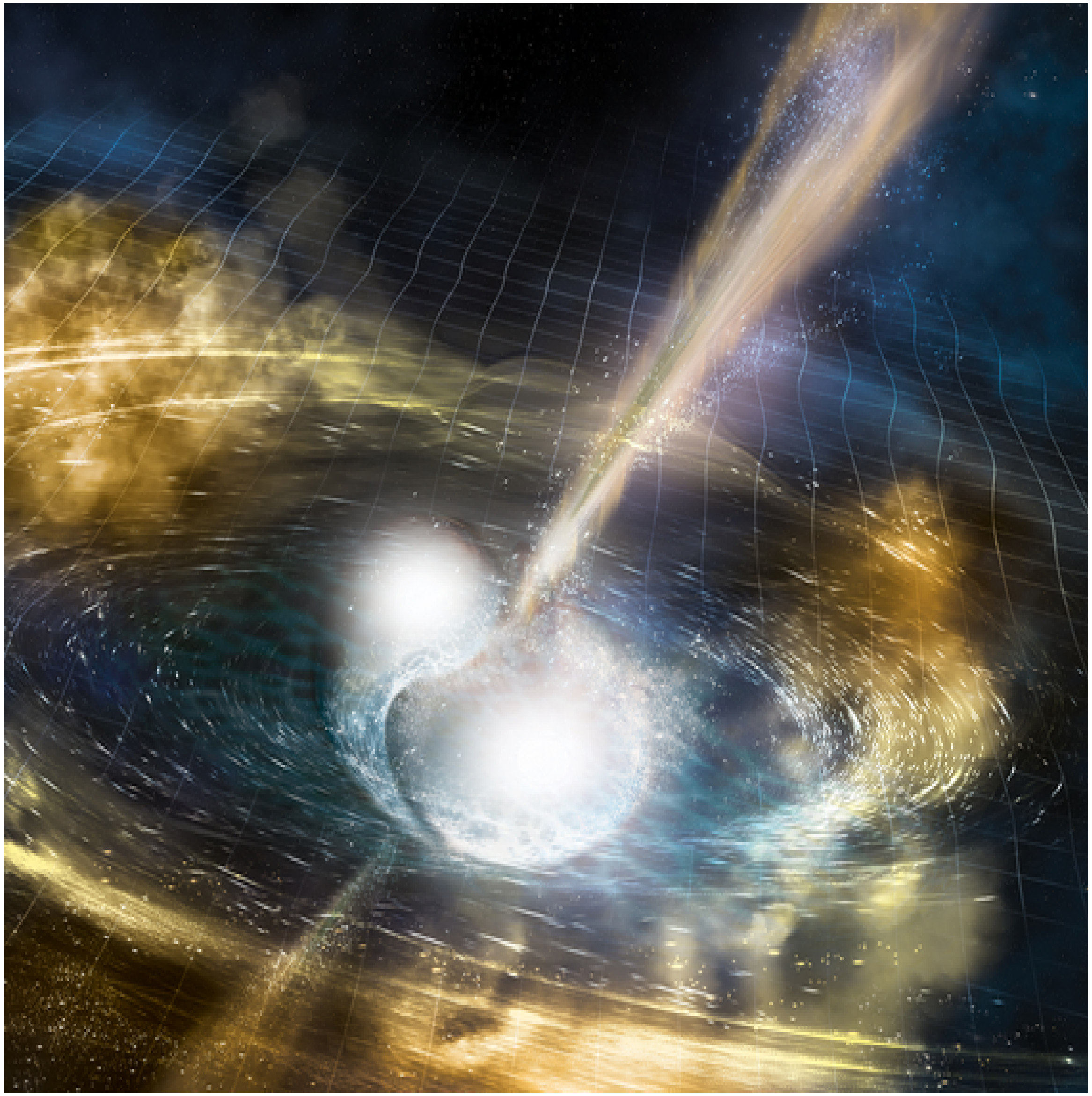
→ inferred Hubble constant: $H_0 = 70^{+12}_{-8}\,\mathrm{km/s\ Mpc^{-1}}$



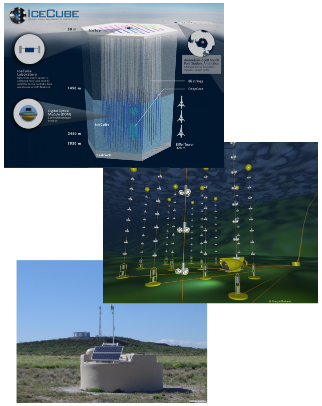

Completely new independent measurement of $H_0$
→ will help in understanding curent ‘tension’...

Abbot et al., Nature, vol. 551, 7678 (2017)

- GW data alone
- GRB association
- Electro-magnetic follow-up and kilonova
- Measurementsn of the Hubble constant
- Searching for neutrinos



# Search for high-energy neutrinos from GW170817




IceCube

ANTARES

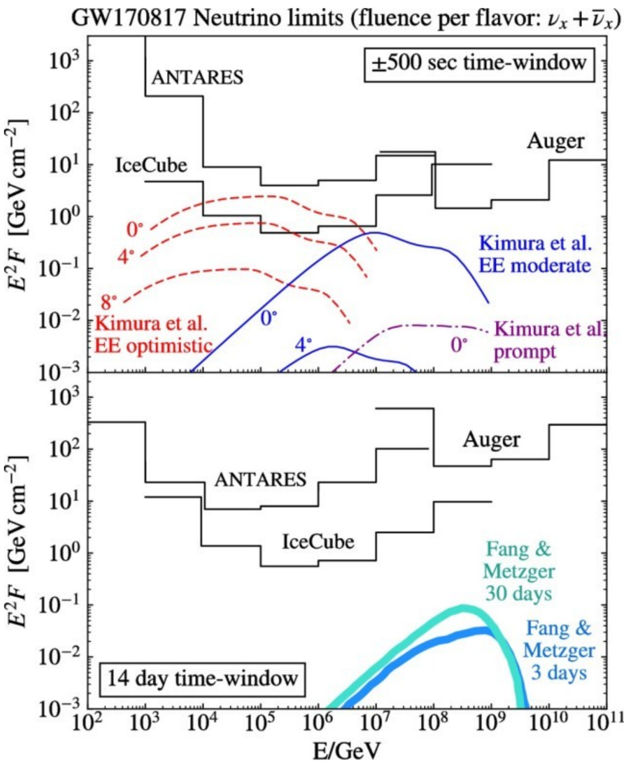
Pierre Auger Observatory

Thermal MeV neutrinos

High energy neutrinos ($10^2$ to $10^{11}$ GeV)

→ no signficant neutrino counterpart within 500 s around GW170817, nor in the subsequent 14 days

Consistent with typical GRB observed off-axis, or with low luminosity GRB

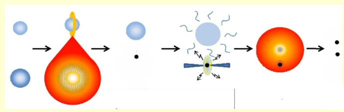



Will continue rapid search for neutrino candidates from GW sources
→ could improve fast localisation of GW events down to ~1 deg²

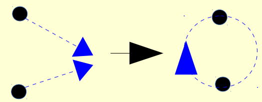
# A long non-exhaustive list of new data and tests

## Astrophysical implications

Formation of BNS



From binary stars? (favoured?)



From isolated NS?

Origin of GRB, jet beaming

Kilonova modelling

Equation of state of NS (r<15 km)

Short- or long-lived post-merger remnant neutron star?

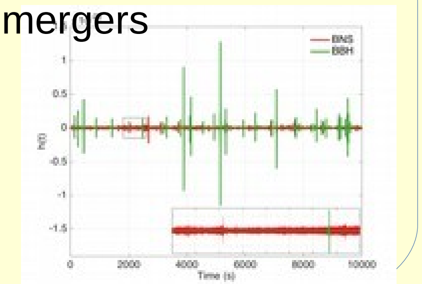
Inference of BNS population distribution and merger rate

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

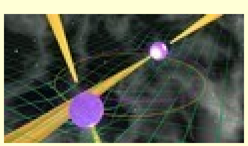
$$(R < 12600\,\mathrm{Gpc}^{-3}.\mathrm{yr}^{-1} \quad \mathrm{from} \;\; 01)$$

Estimation of GW stochastic background from BNS mergers

→ will be detected in the coming years



## Tests of General Relativity



Difference between speeds of gravity and light: $[-3\times10^{-15}\ ;\ +7\times10^{-16}]\times c$

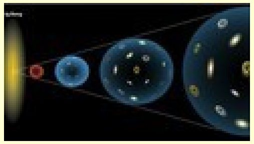
Search for deviations from GR in waveform

Study of GW polarisation

New bounds on Lorentz violation

New test of the equivalence principle

## Cosmology



Independent measurement of Hubble constant

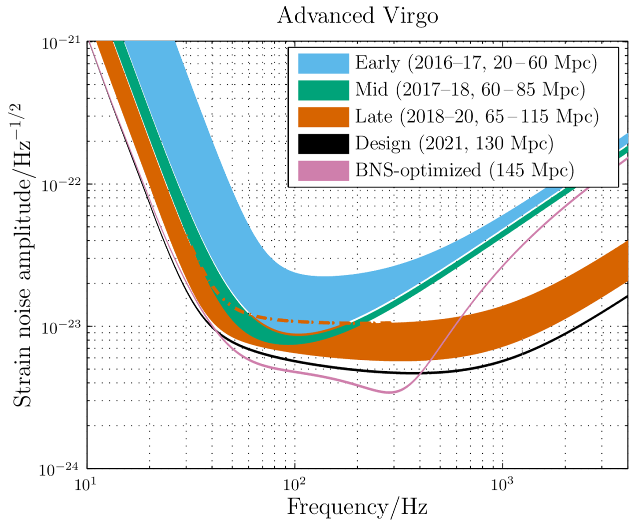
# Improving the LIGO-Virgo sensitivity

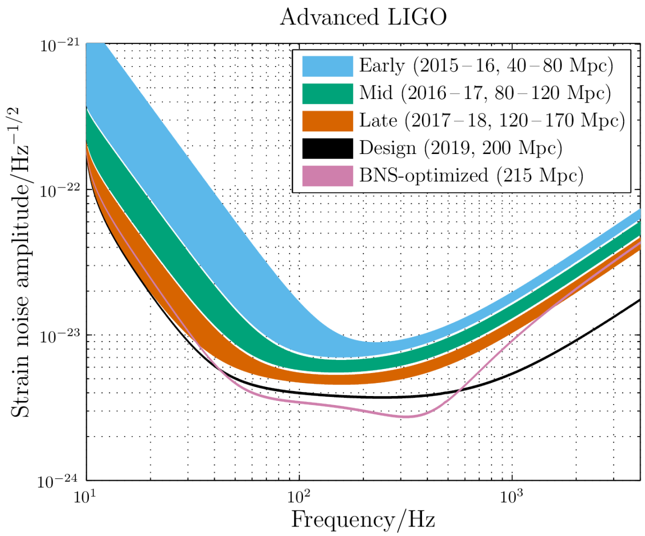
**Virgo upgrades in 2018, before O3:**

- Re-installation of monolithic suspensions
- Installation of frequency independent squeezer bench
  - Modifications of parts of optical benches to reduce optical losses
  - More digital alectronics and channels to be collected
- Increase of laser power
  - Adapt the photodiodes
- Test of Newtonian noise sensors
- Installation of MuxDemux electronics
- Reduce calibration/reconstruction uncertainties
  - Installation of photon calibrator and tests of Newtonian calibrator
- Improve/automatize data quality and data analysis for faster alerts

**Virgo upgrades in 2020, after O3:**

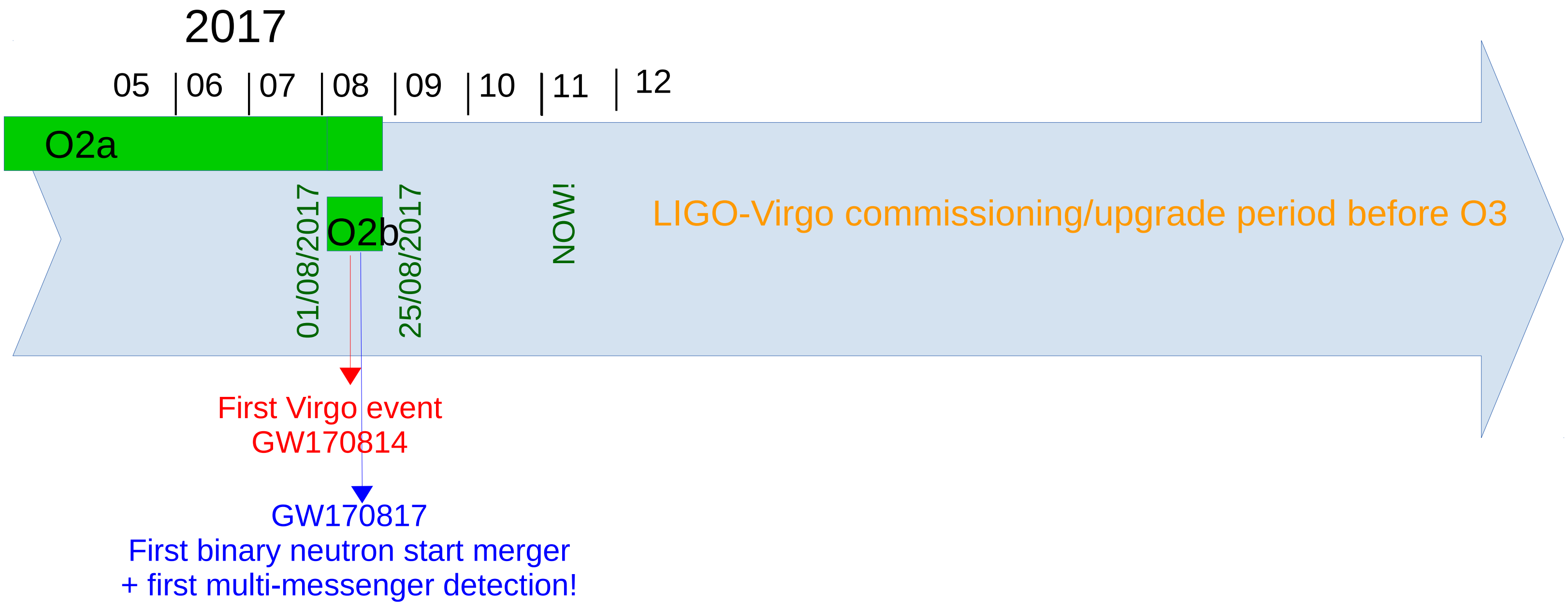
- Installation of SR mirror
- Installation of high power laser
- Installation of frequency dependent squeezer bench
  - New optical benches and new vacuum tanks
  - Low loss optics
  - New optics and more electronics



# Summary

Virgo has successfully joined the gravitational wave detector network!




First tests
of GW polarization

First observation
of a binary neutron star merger

First BNS-short GRB
association

First photometric observation
of a kilonova

First GW measurement
of Hubble constant

Looking forward to detect
NS-BH,
BNS and BBH stochastic backgrounds,
Supernova, …

and to have other
multi-messenger detections!