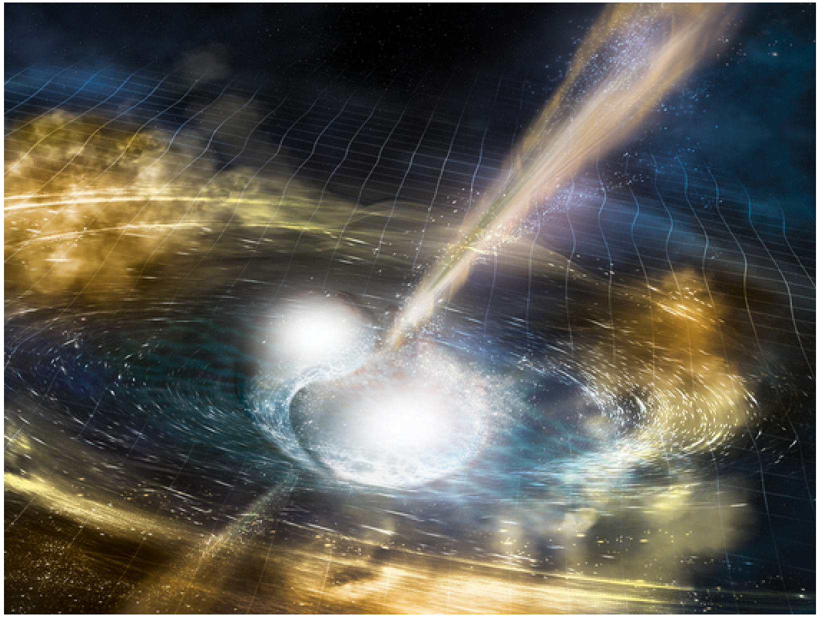
# Implications of LIGO/Virgo gravitational wave detections

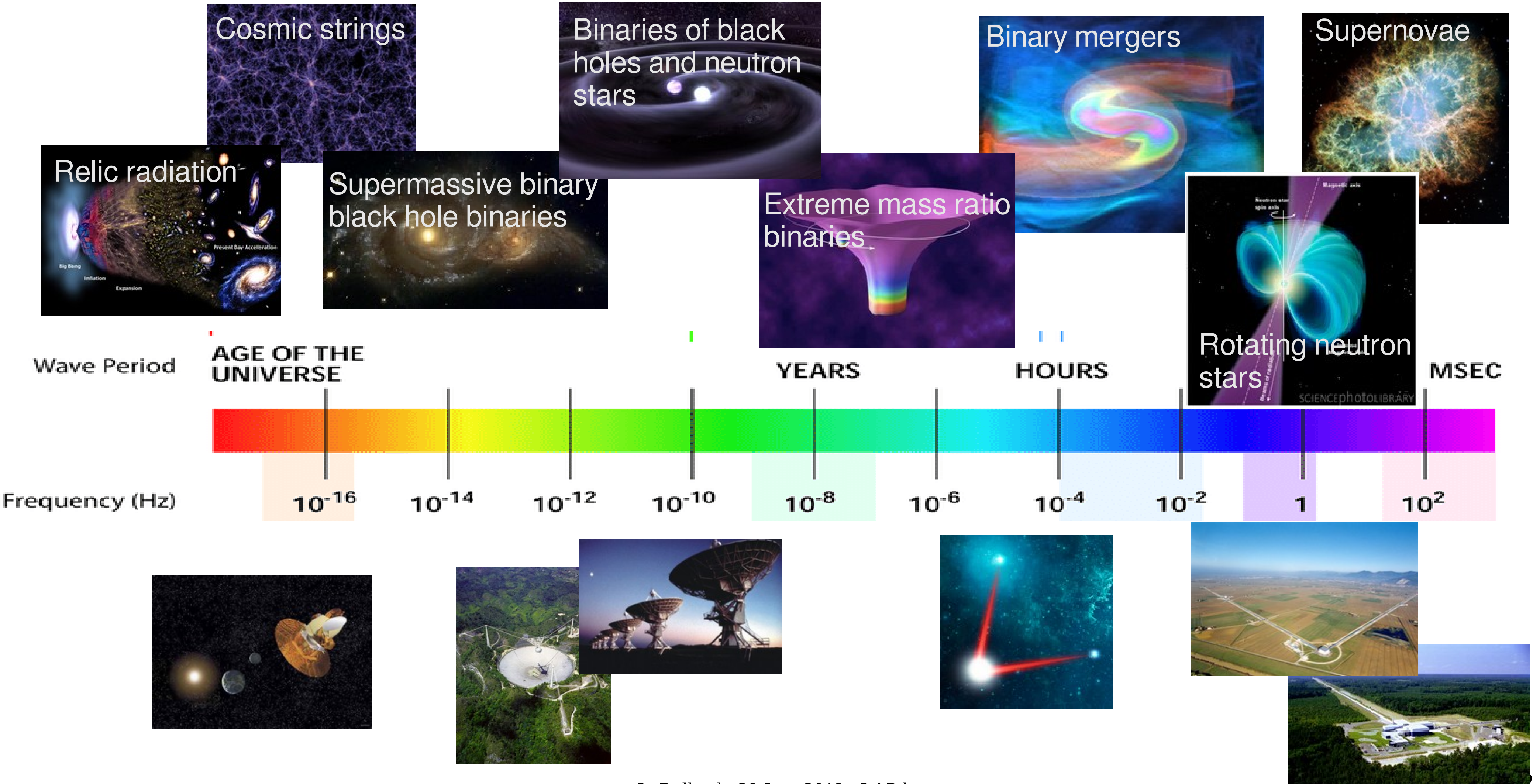
Loïc Rolland

for the Virgo Collaboration and the LIGO Scientific Collaboration

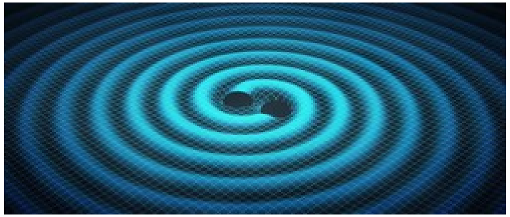


The 14th International Workshop Dark Side of the Universe
Annecy, 29th June 2019

# The gravitational wave spectrum



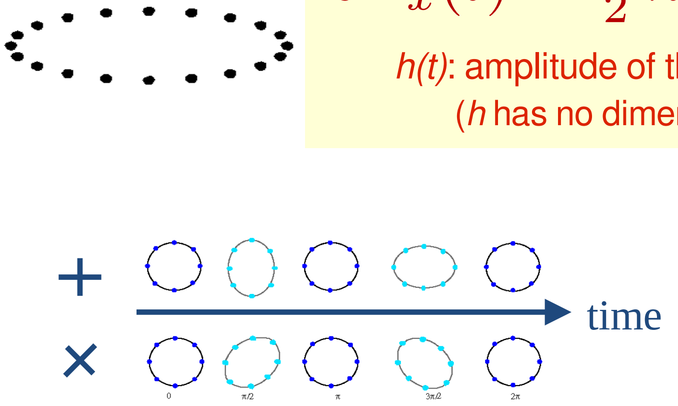
# Detecting gravitational waves with ground-based interferometers

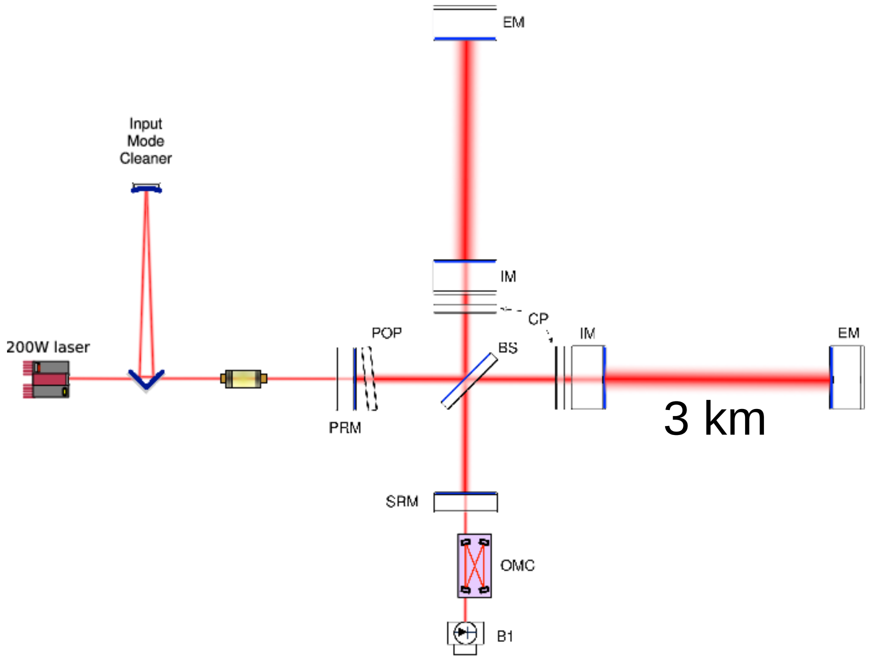


Masses in motion
↓
Space-time deformation
↓
Gravitational wave

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

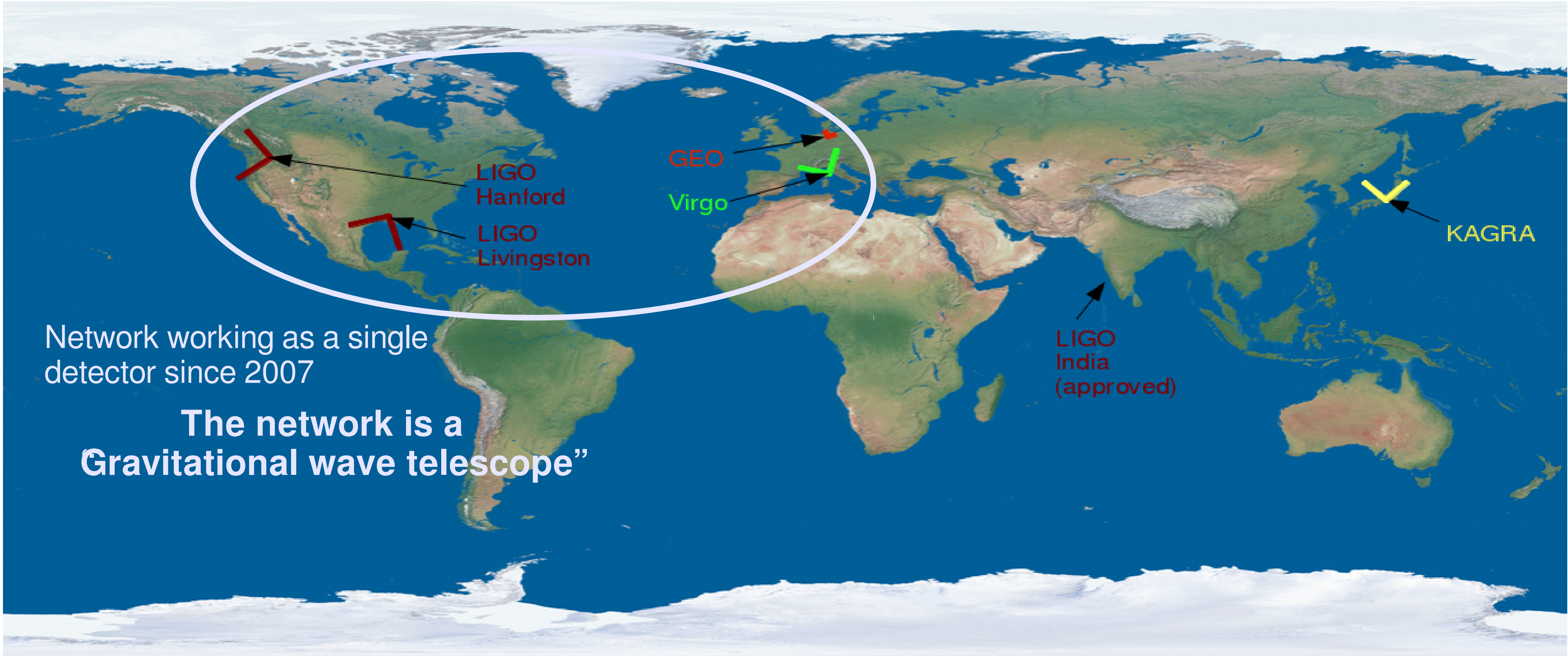
*h(t)*: amplitude of the GW
(*h* has no dimension)



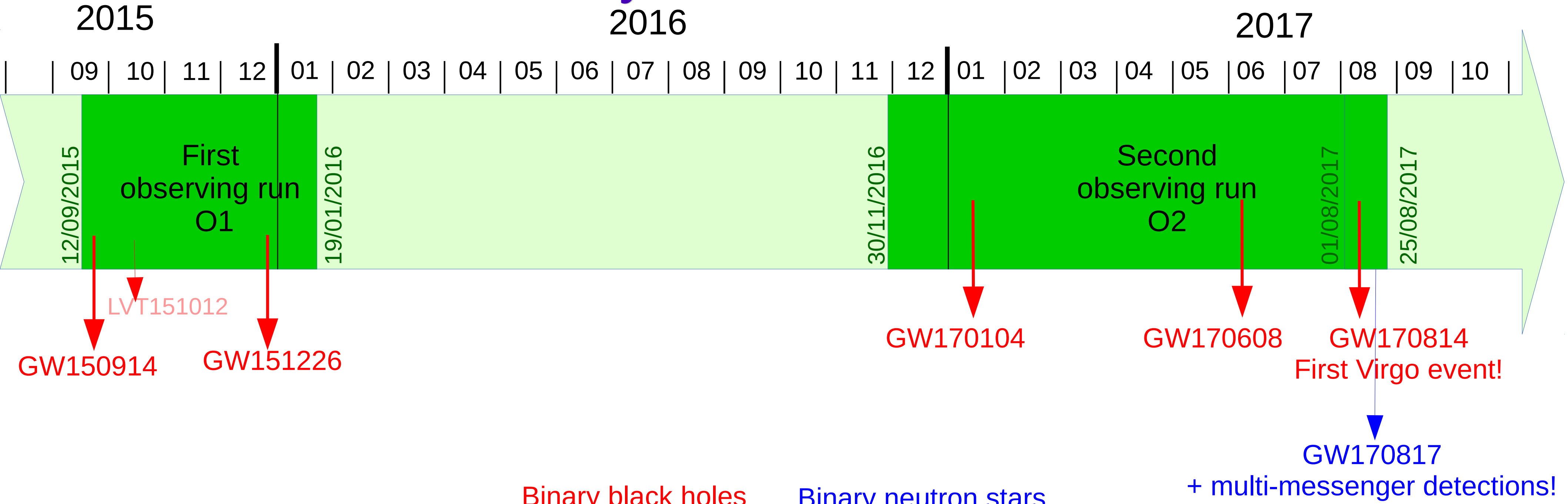

For GW170814, first Virgo detected event:
$h = 5\text{x}10^{-22} \rightarrow \delta L = \pm\, 0.8 \text{ x } 10^{-18}$ m

# An international network of detectors

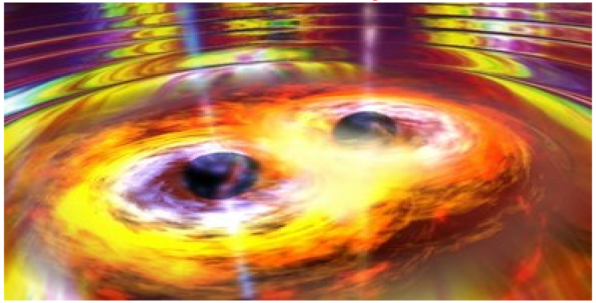



- ✔ Rejection of spurious local noise (coincidence) → better sensitivity
- ✔ Source localisation (triangulation) → astronomy
- ✔ Wave polarization

# Summary of O1 and O2 runs

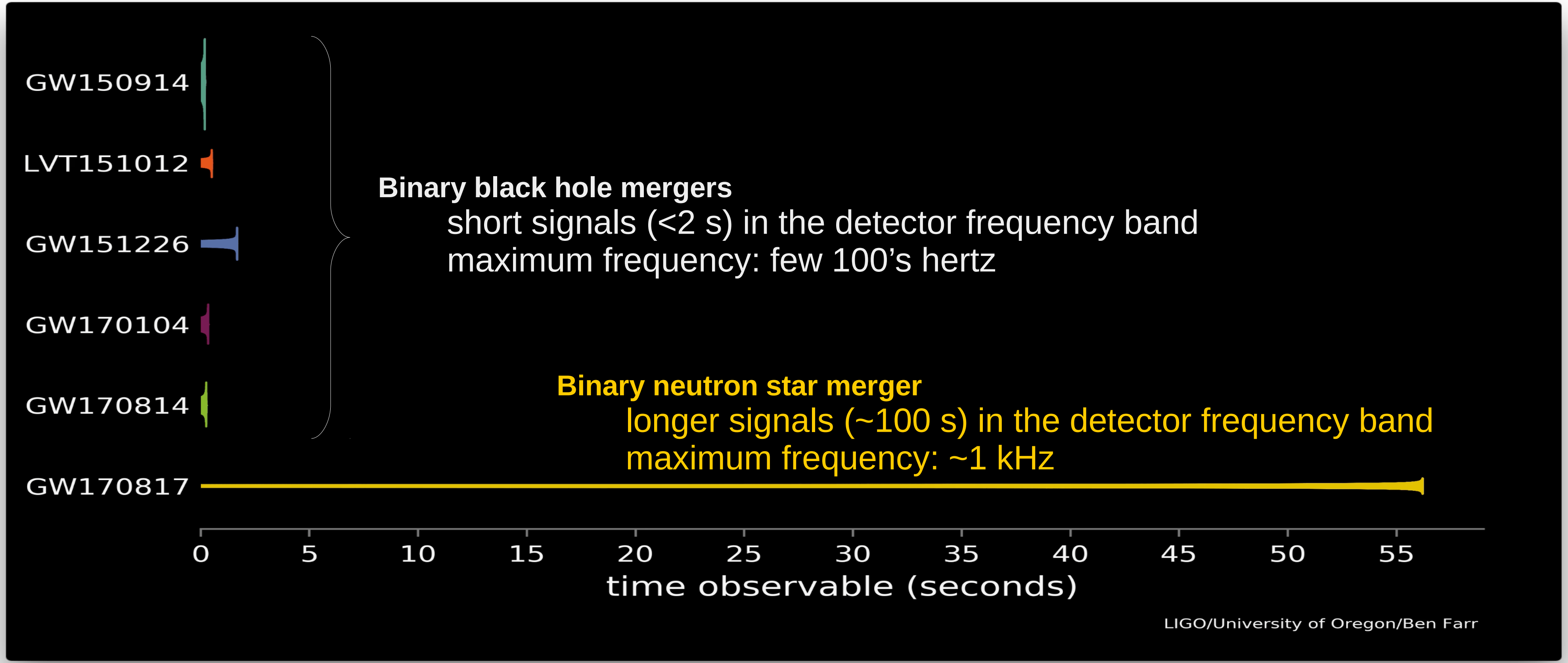



Binary black holes



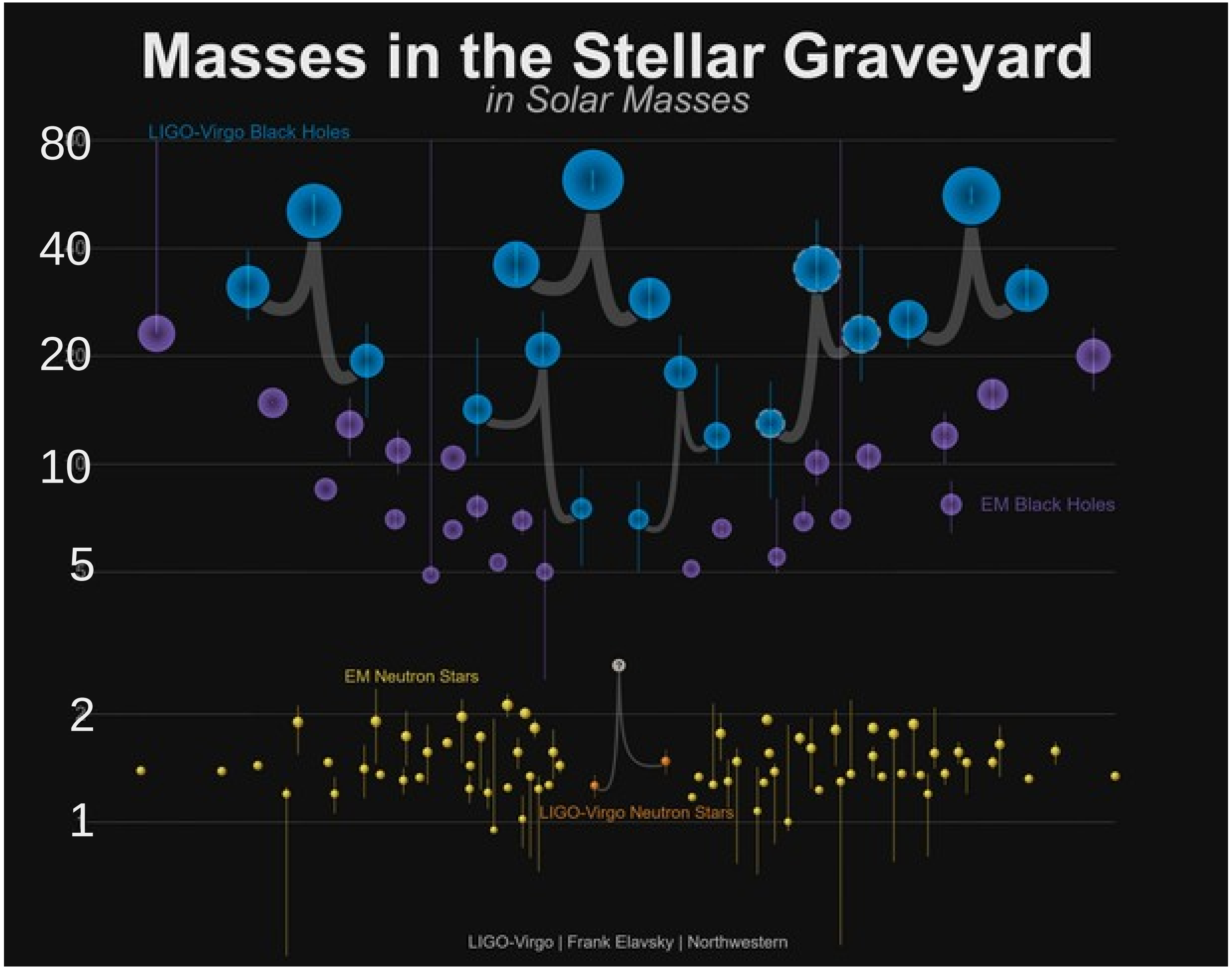
Binary neutron stars

# Comparing the detected GW signals




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

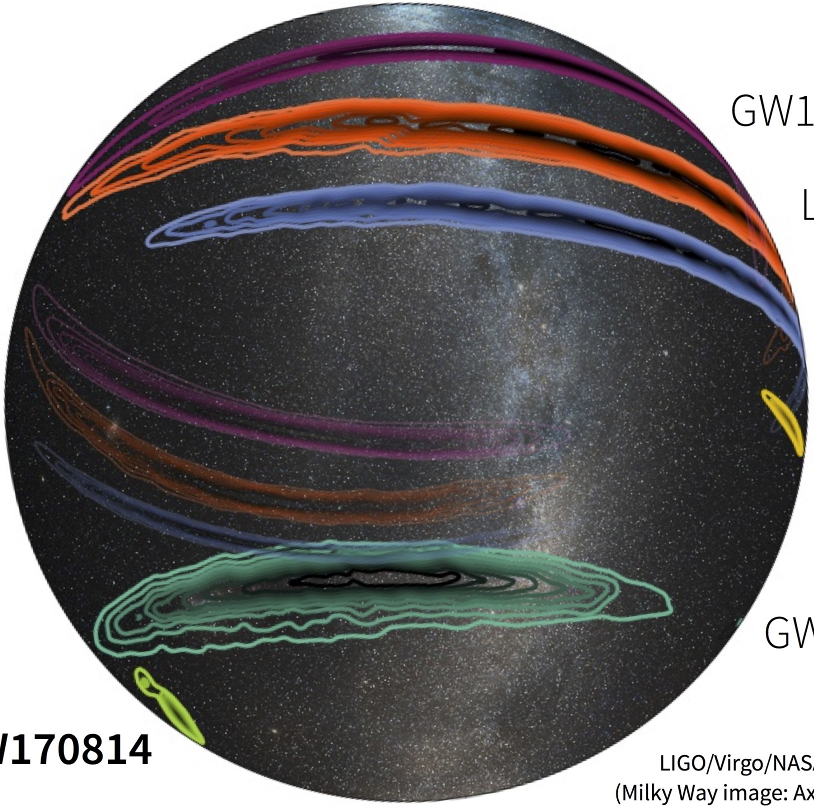
# Binary compact objects masses




Binary black holes

Binary neutron stars

# Event sky localisations

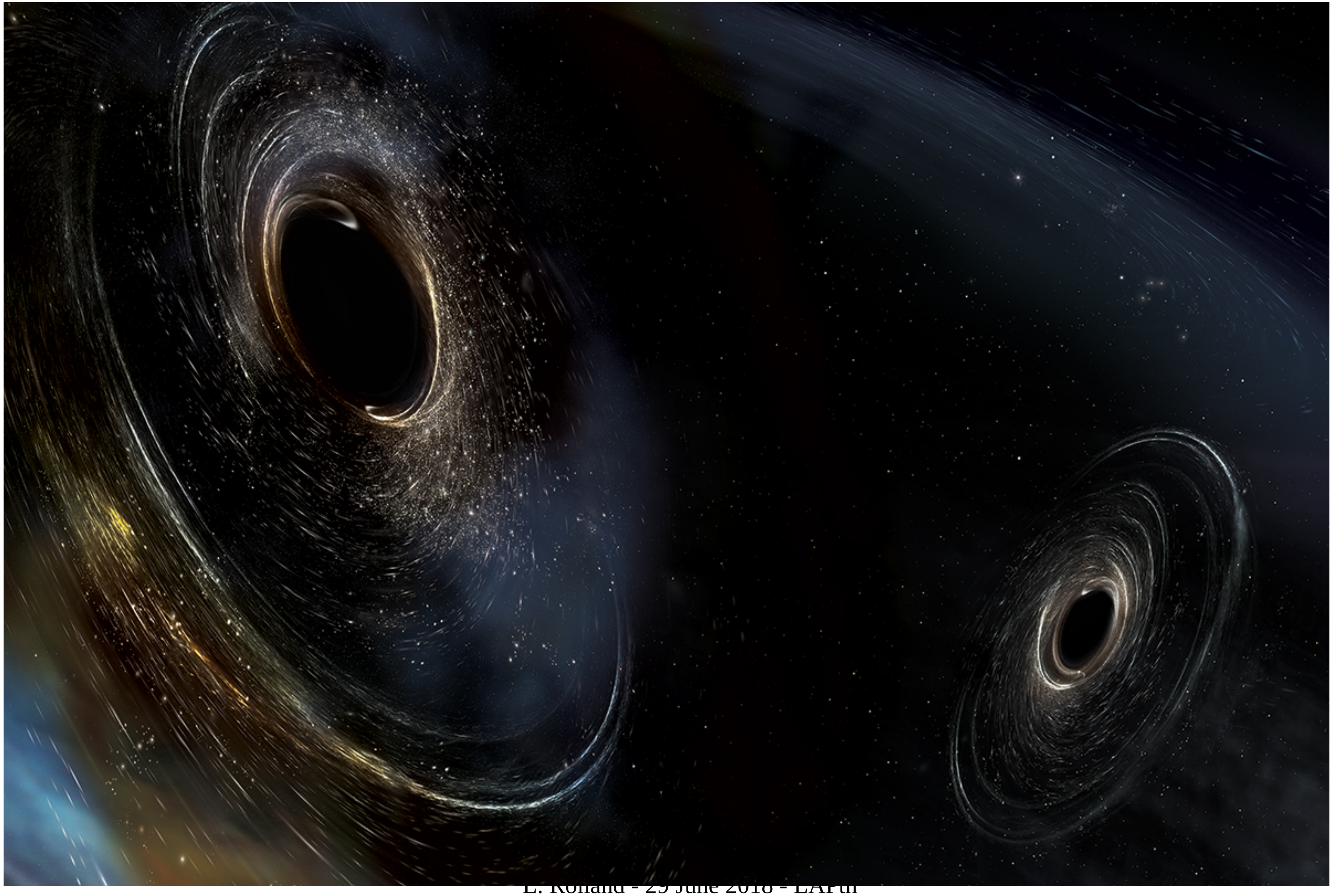



Events sky localisation areas (deg$^2$)

| | | |
|---|---|---|
| GW150914 | 600 | LIGO detections |
| GW151226 | 850 | |
| GW170104 | 1200 | |
| GW170814 | 60 | LIGO-Virgo detections |
| GW170817 | 28 | |

→ sky area reduced by factor ~10 with Virgo

# Implications of binary black hole (BBH) detections

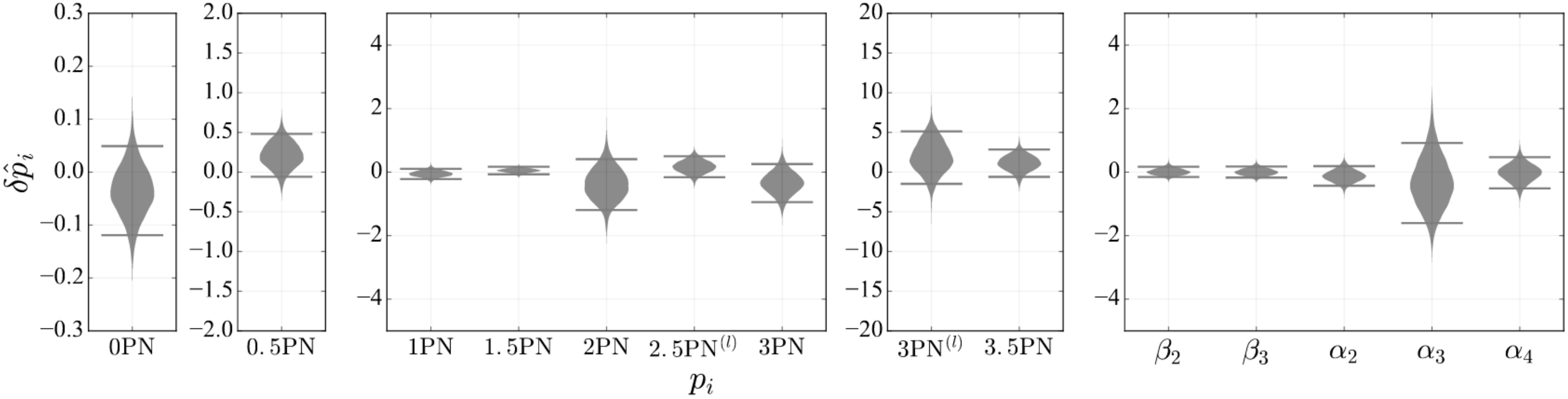


# Phenomenological tests of General Relativity

Look for phase deviations from GR at different post-Newtonian orders

$$\tilde{h}(f) = \tilde{A}(f;\overrightarrow{\theta_{GR}})\ e^{i[\Psi(f;\overrightarrow{\theta_{GR}})+\delta\Phi(f;\overrightarrow{\theta_{GR}},X_{modGR})]}$$

→ Bounds combining GW150914, GW151226 and GW170104

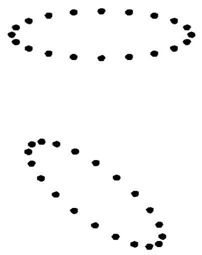



→ No evidence for deviation from GR in waveform

# First tests of GW polarization

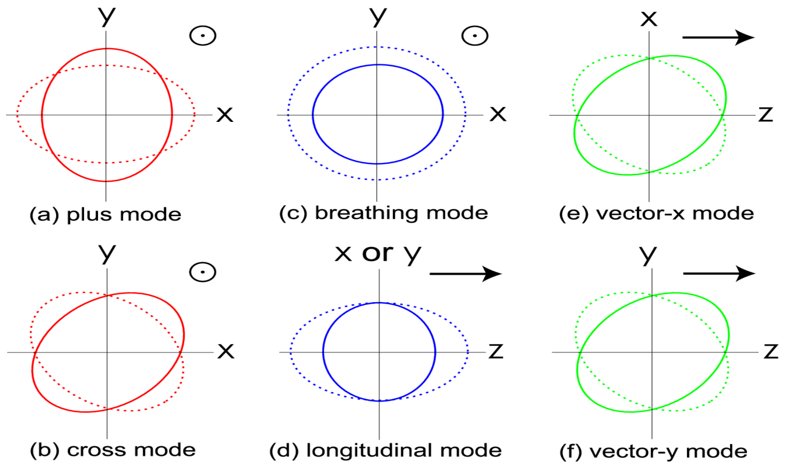
**General Relativity**

→ 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 with respect to pure scalar of vector polarizations

(polarization mixtures no tested yet)

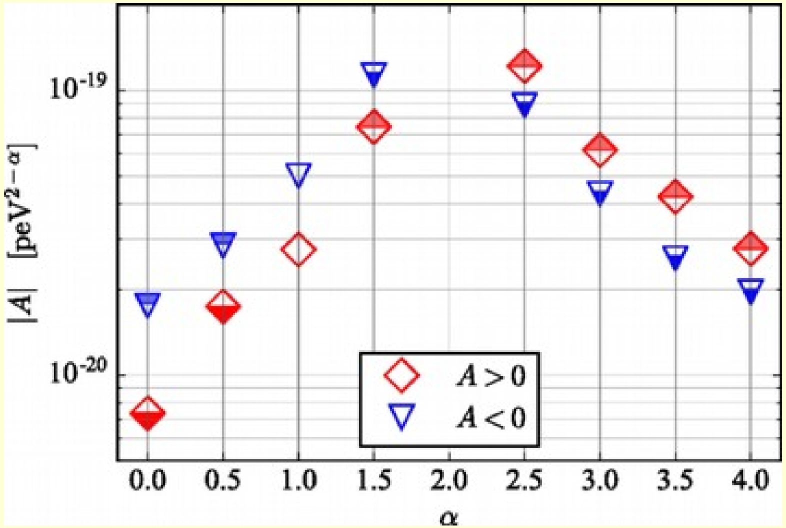
# Test of modified dispersion relation

$$E^2 = p^2c^2 + Ap^\alpha c^\alpha \quad \alpha \geq 0$$

*E*, *p*: energy and momentum of the gravitational radiation
*A*: amplitude of the dispersion

→ dephasing of GW relative to the phase evolution in GR,
with modified group velocity of GW:

$$\frac{v_g}{c} = 1 + \frac{(\alpha-1)}{2} A E^{\alpha-2}$$


First bounds derived from GW observations
First tests of superluminal propagation in the gravitational sector

90% credible upper bounds on |A|
(with GW170104, GW150914, GW151226 signals)

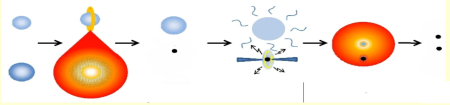
# In brief: physics with binary black holes

**Astrophysical implications**

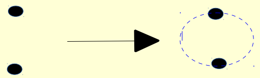
Formation of massive stars?

Formation of BBH

From binary stars



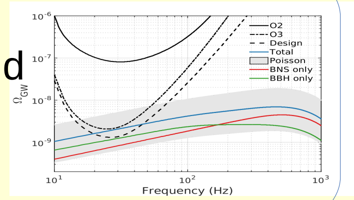
From isolated BHs



Inference of BBH population distribution and merger rate

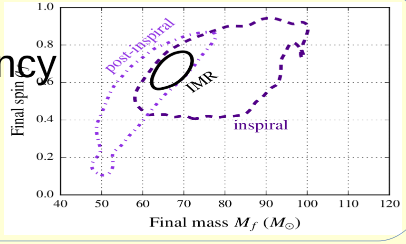
$$R = [12; 213] \quad \mathrm{Gpc}^{-3}.\mathrm{yr}^{-1}$$

Estimation of GW stochastic background from BBH mergers



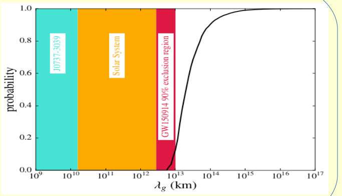

**Tests of General Relativity**

Check waveform internal consistency

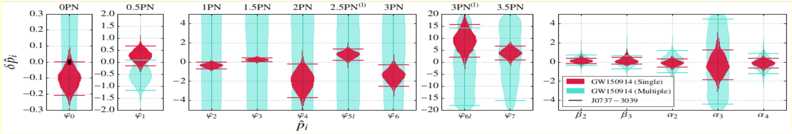



Bound on graviton mass and Lorentz violation

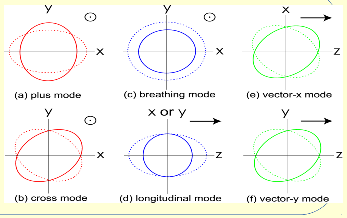
$$m_g < 1.2 \times 10^{-22} \; eV/c^2$$



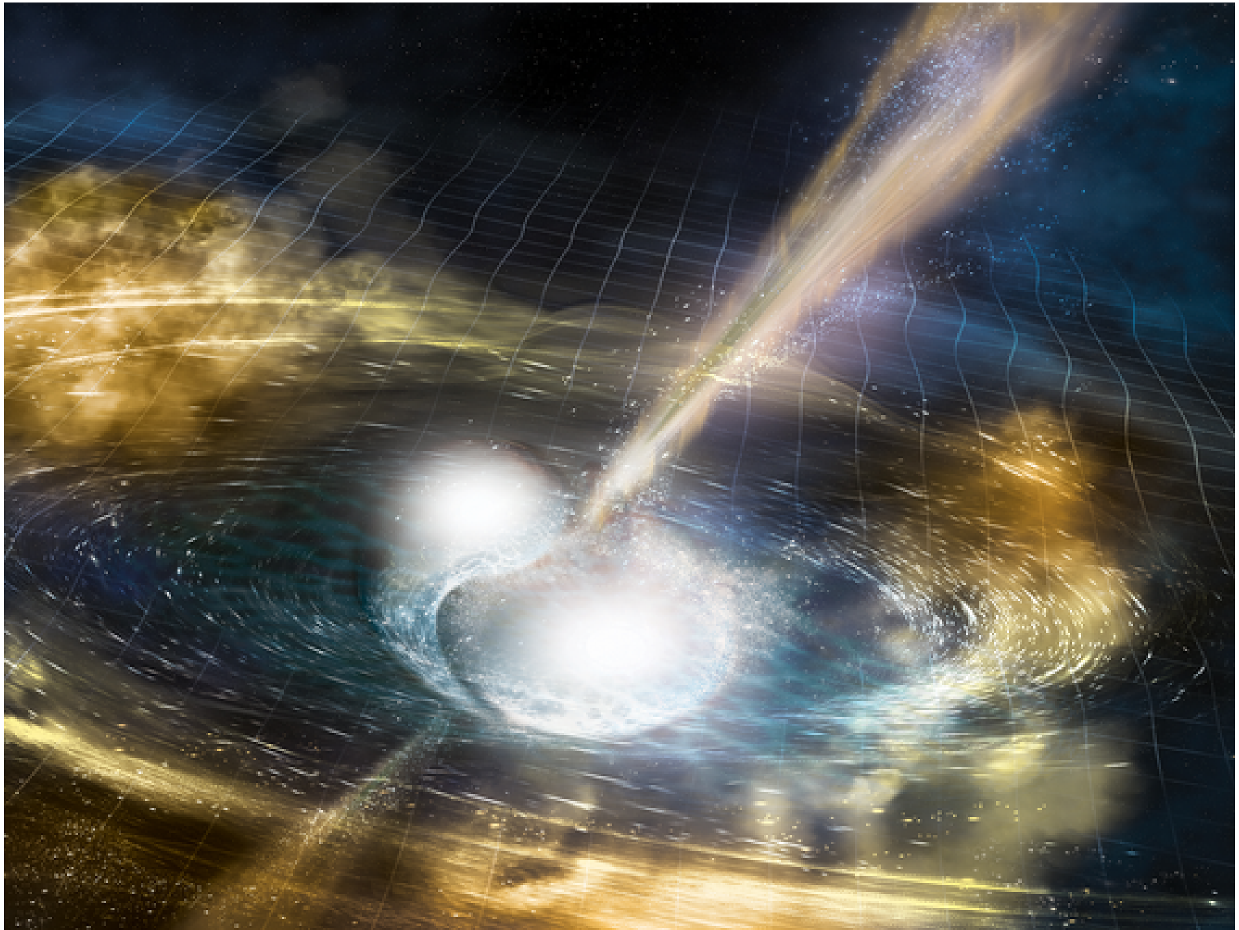

Search for deviations from GR in waveform




Tests of GW polarization



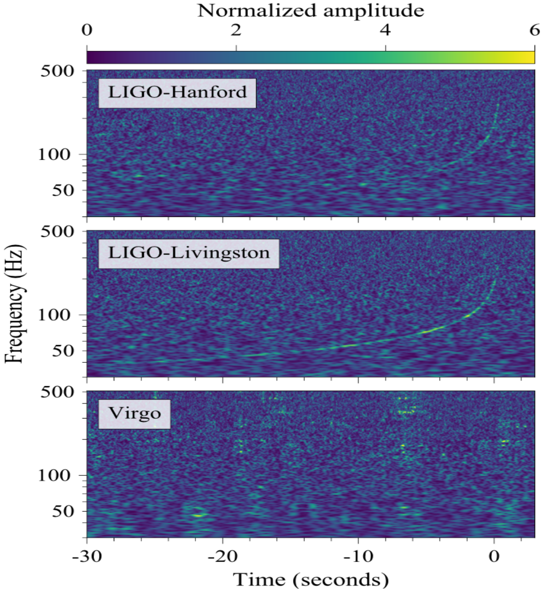
# The first multi-messenger detection of a binary neutron star (BNS) merger: GW170817

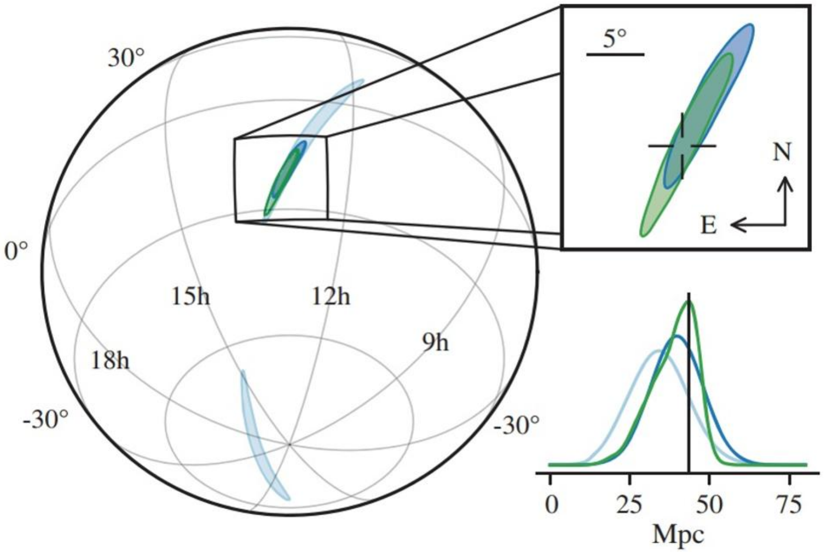


- Electro-magnetic follow-up
- GRB association
- Kilonova
- Measurement of the Hubble constant
- Searching for neutrinos

# GW170817 source localisation

**August 17, 2017 at 12h41m04.4s UTC**
Combined SNR = 32.4
False alarm rate < 1 per 8x10$^4$ years




- 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)

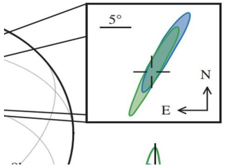
→ 3D position: 380 Mpc$^3$

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

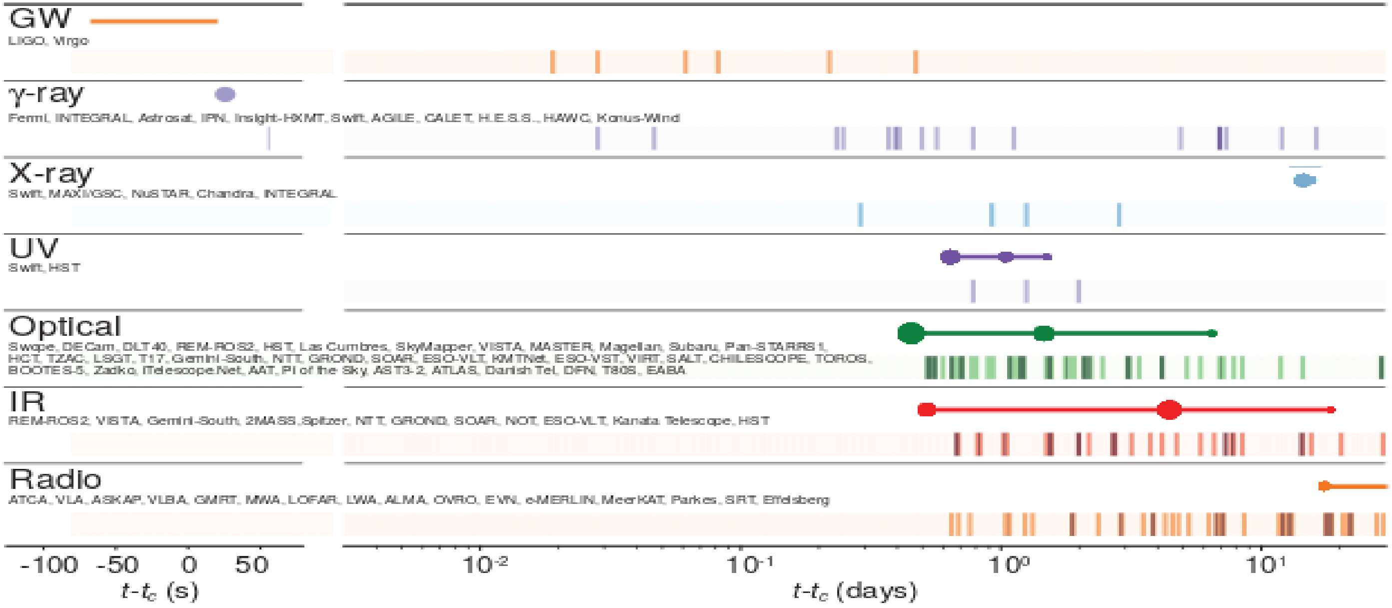
*Abbott et al., PRL, 119, 161101 (2017)*

# The electro-magnetic follow-up campaign

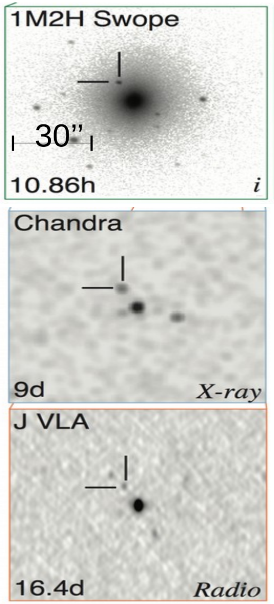
T0 — GW detection → T0 + 1,7 s — γ-ray burst detection → T0 + 5 h — Localisation GW → T0 + 11 h — Optical counterpart : Identification of host galaxy → T0 + 9 days — X-ray counterpart → T0 + 16 days — Radio counterpart




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




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

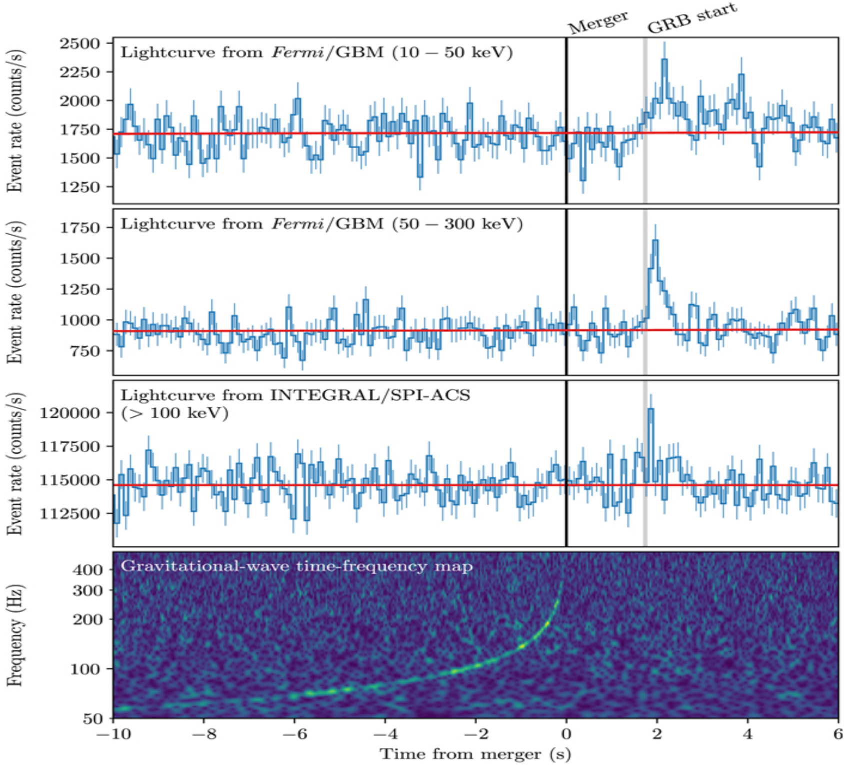



Identification of the host galaxy: NGC4993, at ~40 Mpc

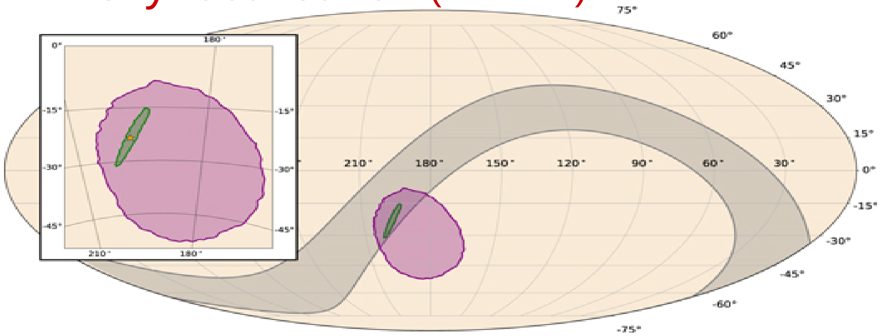
# Association with a gamma-ray burst

## 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 $10^{-8}$

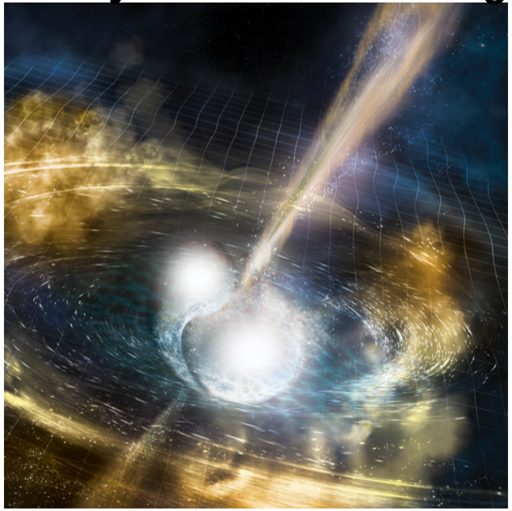
→ association validated within 5.3 σ

→ 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)

# GW/GRB association and speed of gravity

**Binary neutron star merger**

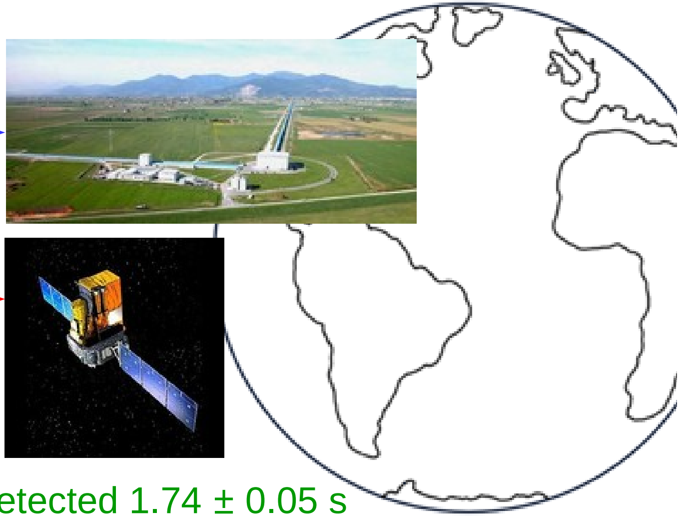


**Propagation**
along at least 26 Mpc

**Gravitational wave**

**γ-rays**

**Detection** on Earth



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

γ-rays detected 1.74 ± 0.05 s
after merger seen by GW

Previous constraints
were allowing a time
difference of 1000 years!

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

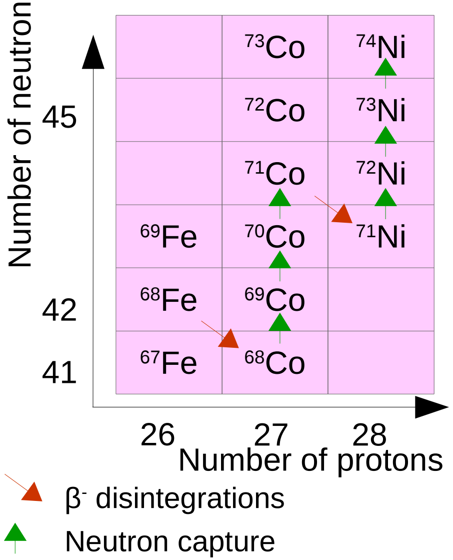
Abbot at al., ApJ, 848, 13 (2017)

# Implications on gravitation models

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

From Ezquiaga & Zumalacarregui, arxiv 1710.05901
+ 1710.06394, 1710.05893, 1710.05877....

# Kilonova and nucleosynthesis of heavy nuclei




Tidal effects before merger

↓

Ejection of high speed matter rich in neutrons

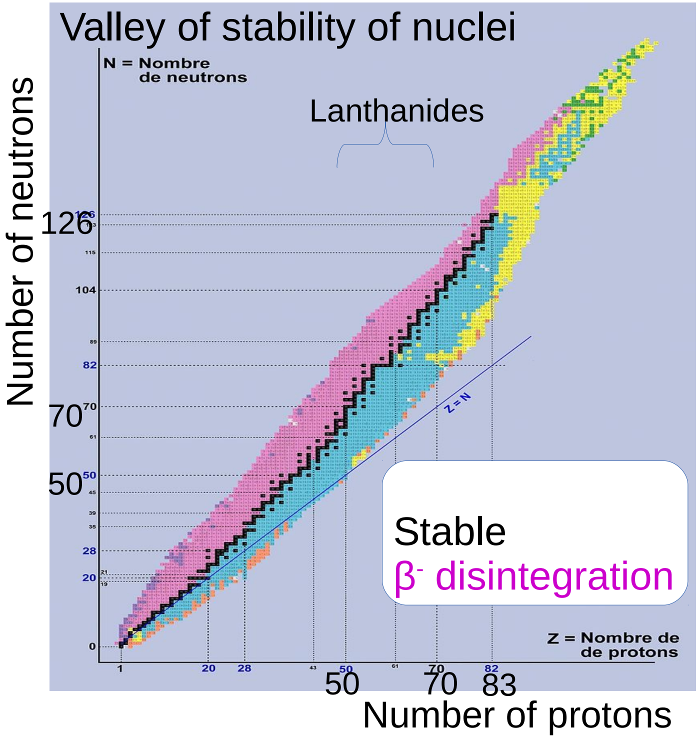
↓

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

# What is the merger remnant?

**Estimation of intrinsic parameters:**
Bayesian fit of the waveform

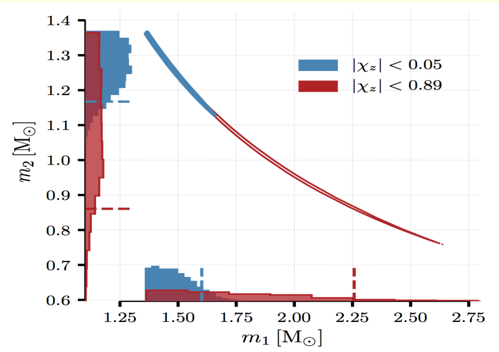
Mass parameters

| | Spin limit consistent with observed population: low-spin ($\lvert\chi\rvert < 0.05$) | Theoretical spin limit: high-spin ($\lvert\chi\rvert < 0.89$) |
|---|---|---|
| $M_{chirp} (M_\odot)$ | $1.188^{+0.004}_{-0.002}$ | |
| $m_1 \ (M_\odot)$ | 1.36–1.60 | $1.36 - 2.26$ |
| $m_2 \ (M_\odot)$ | 1.17–1.36 | $0.86 - 1.36$ |
| $m_{tot} \ (M_\odot)$ | $2.74^{+0.04}_{-0.01}$ | $2.82^{+0.47}_{-0.09}$ |

## Masses of the initial objects

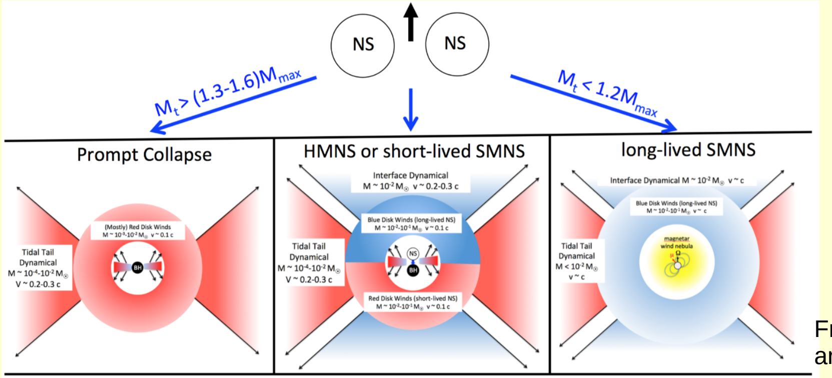
Degeneracy between mass ratio and aligned spin components

→ Masses < 2.3 $M_\odot$




→ masses consistent with two neutron stars

## About the remnant




From Margalit & Metzger, arxiv 1710.05938

Imprint in both GW and EM signals, but lack of sensitivity and difficult to interpret

→ unknown nature of the remnant:
- black hole
- hypermassive neutron star
- long-lived supramassive neutron star

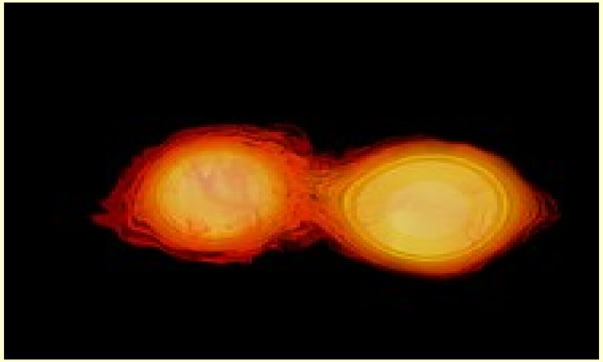
*Abbott et al., PRL, 119, 161101 (2017)*

# What is the equation of state of neutron stars?

**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 | $\Lambda(1.4 M_\odot)$ | $< 800$ | $< 1400$ |

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



- Collision happens earlier than without tidal effect
- Modified final spin

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

# New measurement of the Hubble constant

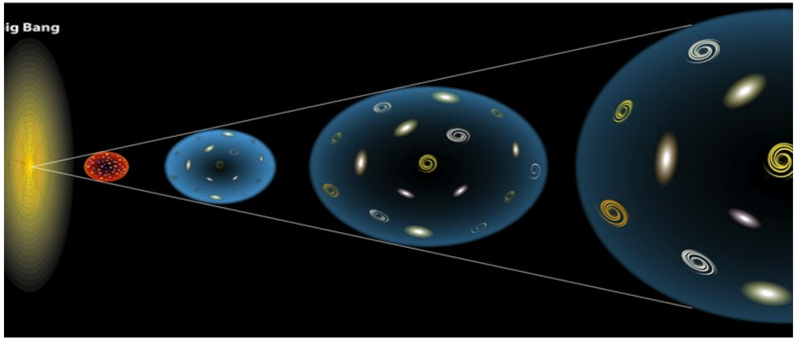
**GW170817 can be used as a standard siren**

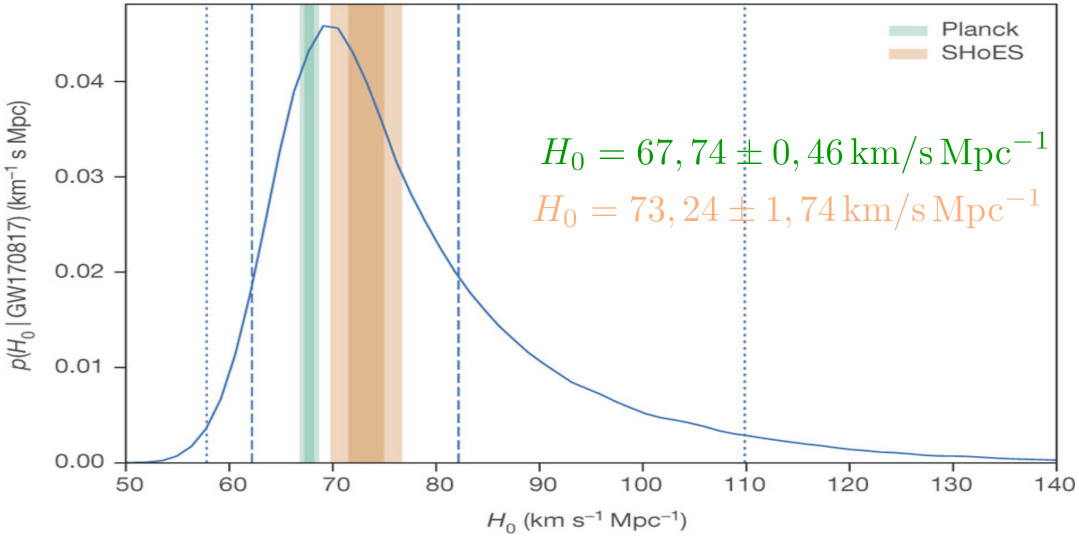
$$v_r = H_0 \times D_{luminosity}$$

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

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

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



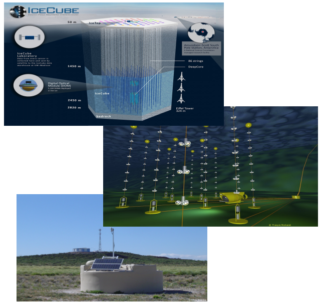

$H_0 = 67,74 \pm 0,46\,\mathrm{km/s\,Mpc^{-1}}$

$H_0 = 73,24 \pm 1,74\,\mathrm{km/s\,Mpc^{-1}}$

Completely new independent measurement of $H_0$
→ will help in understanding current 'tension'...

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

# Search for high-energy neutrinos from GW170817



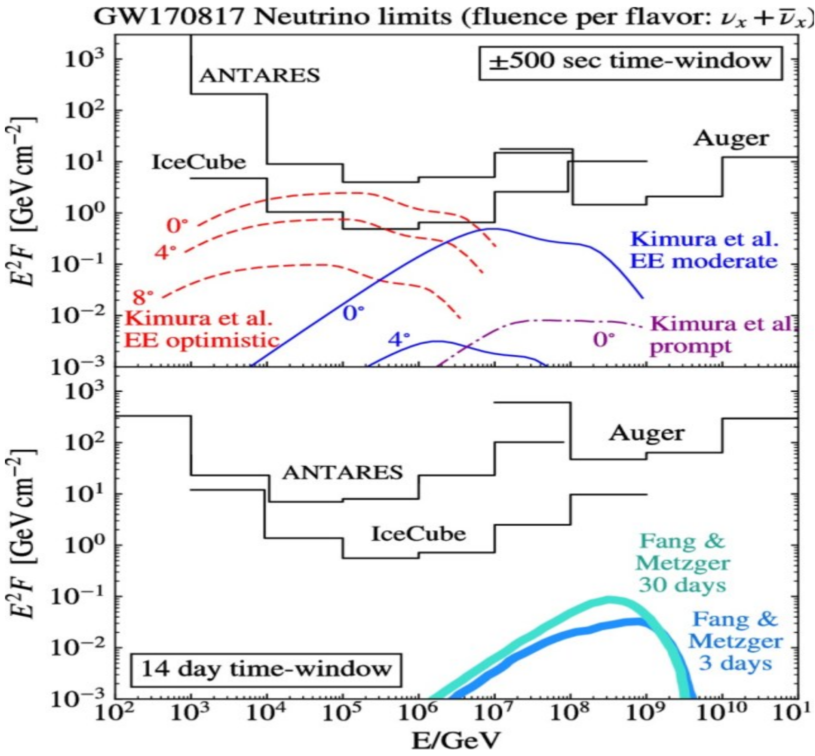
IceCube

ANTARES

Pierre Auger Observatory

Thermal MeV neutrinos

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



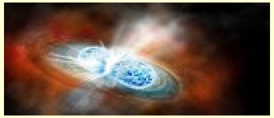

→ no signficant neutrino counterpart within 500 s around GW170817, nor in the subsequent 14 days

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

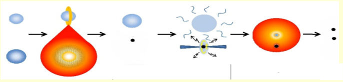
Will continue rapid search for neutrino candidates from GW sources
→ could improve fast localisation of GW events down to ~1 $deg^2$

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

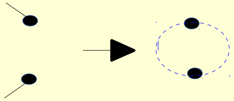
## Astrophysical implications



Formation of BNS



From binary stars?



From isolated NS?

Inference of BNS population distribution and merger rate

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

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

Origin of GRB, jet beaming

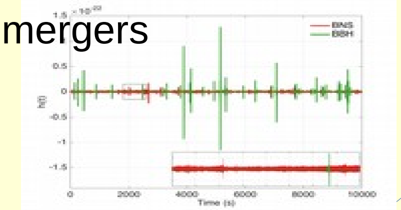
Kilonova modelling

Equation of state of NS (r<15 km)

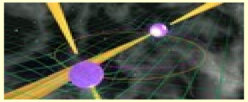
Short- or long-lived post-merger remnant neutron star?

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: [$-3\times10^{-15}$ ; $+7\times10^{-16}$] x c

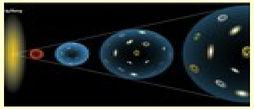
Search for deviations from GR in waveform

Study of GW polarisation

New bounds on Lorentz violation

New test of the equivalence principle

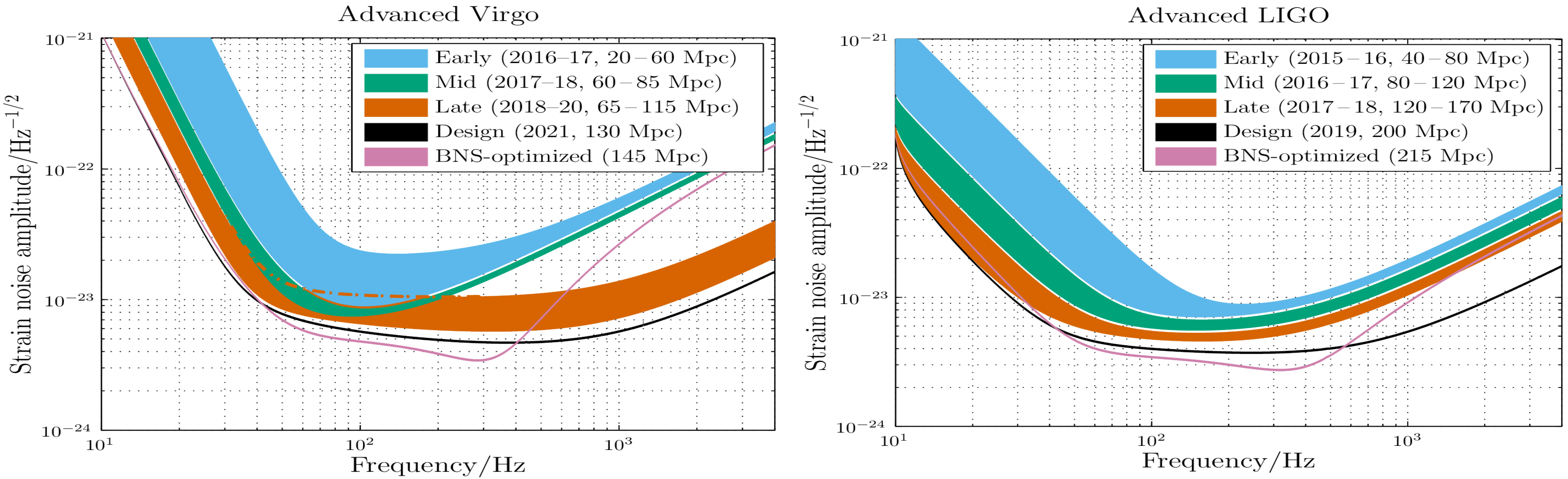
## Cosmology



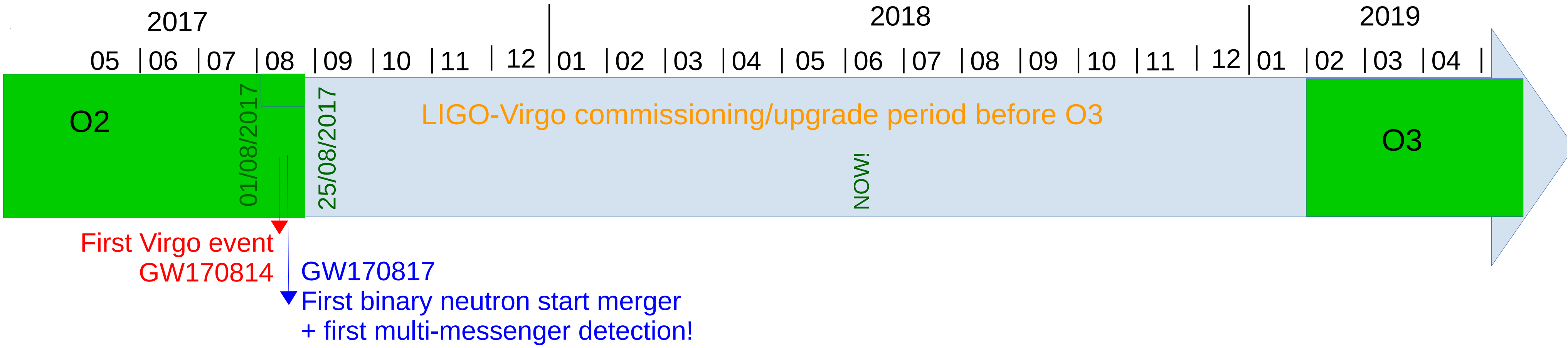
Independent measurement of Hubble constant

# Towards observation run O3 in 2019

LIGO-Virgo commissioning/upgrade period before O3



# Summary




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!