Deciphering the violent universe through gravitational waves

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AEI Hannover
on behalf of LIGO Scientific Collaboration

Monitoring the non-thermal Universe
19 September 2018

INFRARED

Infrared

OPTICAL

Infrared shows smaller cool red stars that make up most of the galaxy.

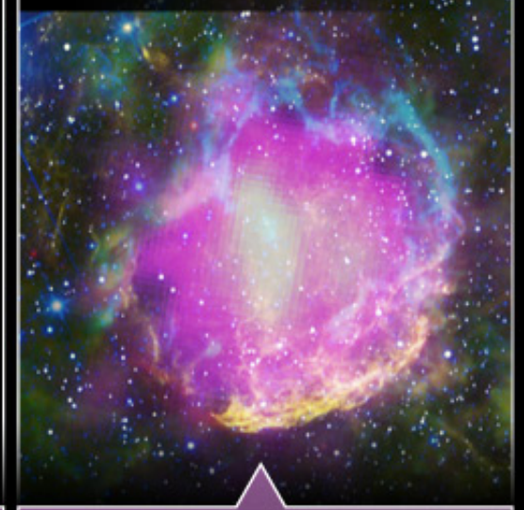
ULTRAVIOLET

Type O and B stars have surface temperatures around 30,000K

X-RAY

Ultraviolet shows the larger hot blue stars that are less frequent in galaxies.

GAMMA RAYS



X-rays are emitted from the hottest regions of gas where atoms are ionized.

Thermal Radiation

Heat is motion. As molecules, atoms, and ions are heated up in plasma, electrons are accelerated near protons creating photons of increasing energies.

Non-Thermal Radiation

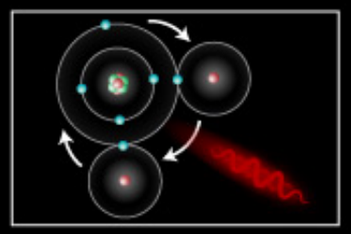
Strong magnetic fields can accerlate electrons faster than thermal processes alone, emtting extremely high energy photons.

▼ Molecules break down (100 K)

▼ Hydrogen is ionized (10,000 K)

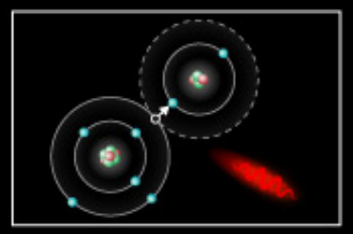
▼ Limit of Thermal Radiation (1,000,000 K)

100 K — 10,000 K — 10,000,000 K — 100,000,000,000 K



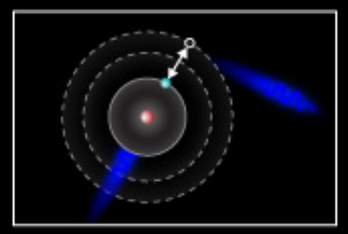
Molecular Motion

Low energy photons are created from molecules twisting and spinning.



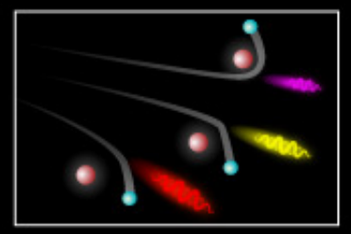
Atoms Colliding

Low to high energy photons are created when atoms exchange electrons in collisions.



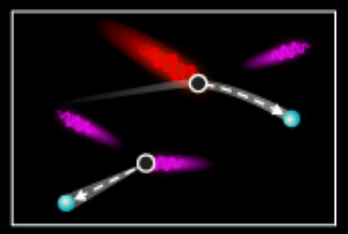
Photon Absorbtion

Atoms can absorb the energy of a photon, which excites an electron to release another photon.



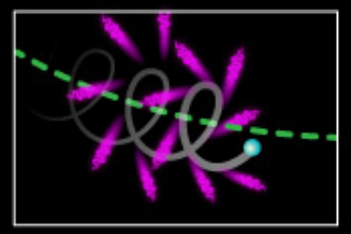
Free Electrons

In an ionized gas, electrons fly past nuclei creating photons in a continuum of energy levels.



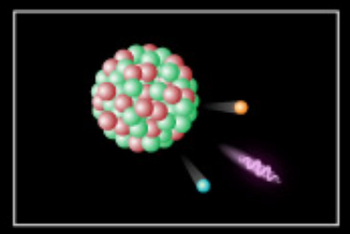
Compton Scattering

Photons can collide with electrons, causing the electron to gain or lose energy releasing a photon.



Synchrotron Radiation

Strong magnetic feilds can accelerate electrons to release extremely high energy photons.

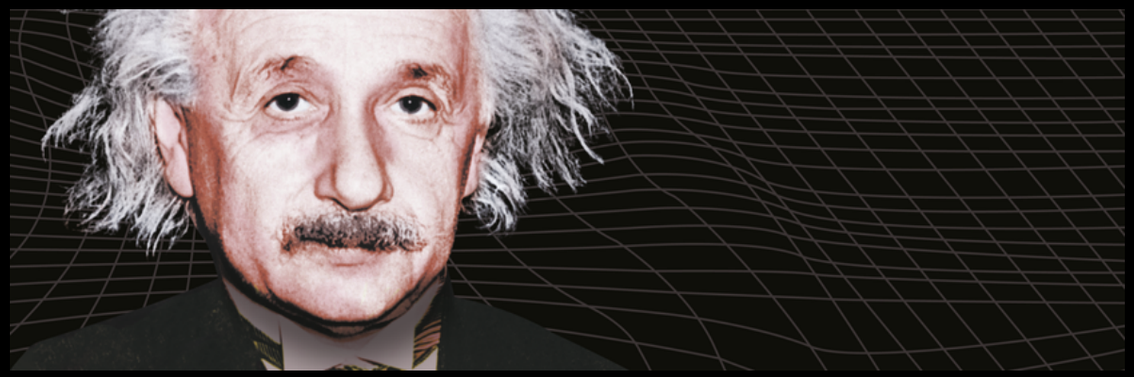


Nuclear Emission

High energy gamma rays and subatomic particles are emited from the nuclei of radioactive atoms.

A new window of the universe

Einstein's *space-time waves*



LIGO Livingston

LIGO Hanford

Virgo

GEO600

The Gravitational Wave Spectrum

Sources

Quantum fluctuations in early universe

Binary Supermassive Black Holes in galactic nuclei

Compact Binaries in our Galaxy & beyond

Compact objects captured by Supermassive Black Holes

Rotating NS, Supernovae

wave period

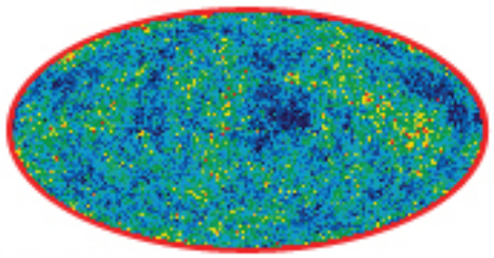
age of universe | years | hours | sec | ms

log(f)

-16 -14 -12 -10 -8 -6 -4 -2 0 +2

Detectors

Cosmic Microwave Background Polarization

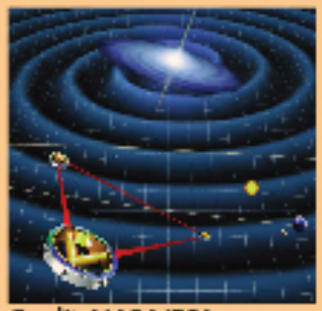


Credit: NASA / WMAP Science Team

Pulsar Timing

Credit: NRAO/AUI/NSF

Space Interferometers



Credit: NASA/ESA

Terrestrial Interferometers

Credit: LIGO Laboratory

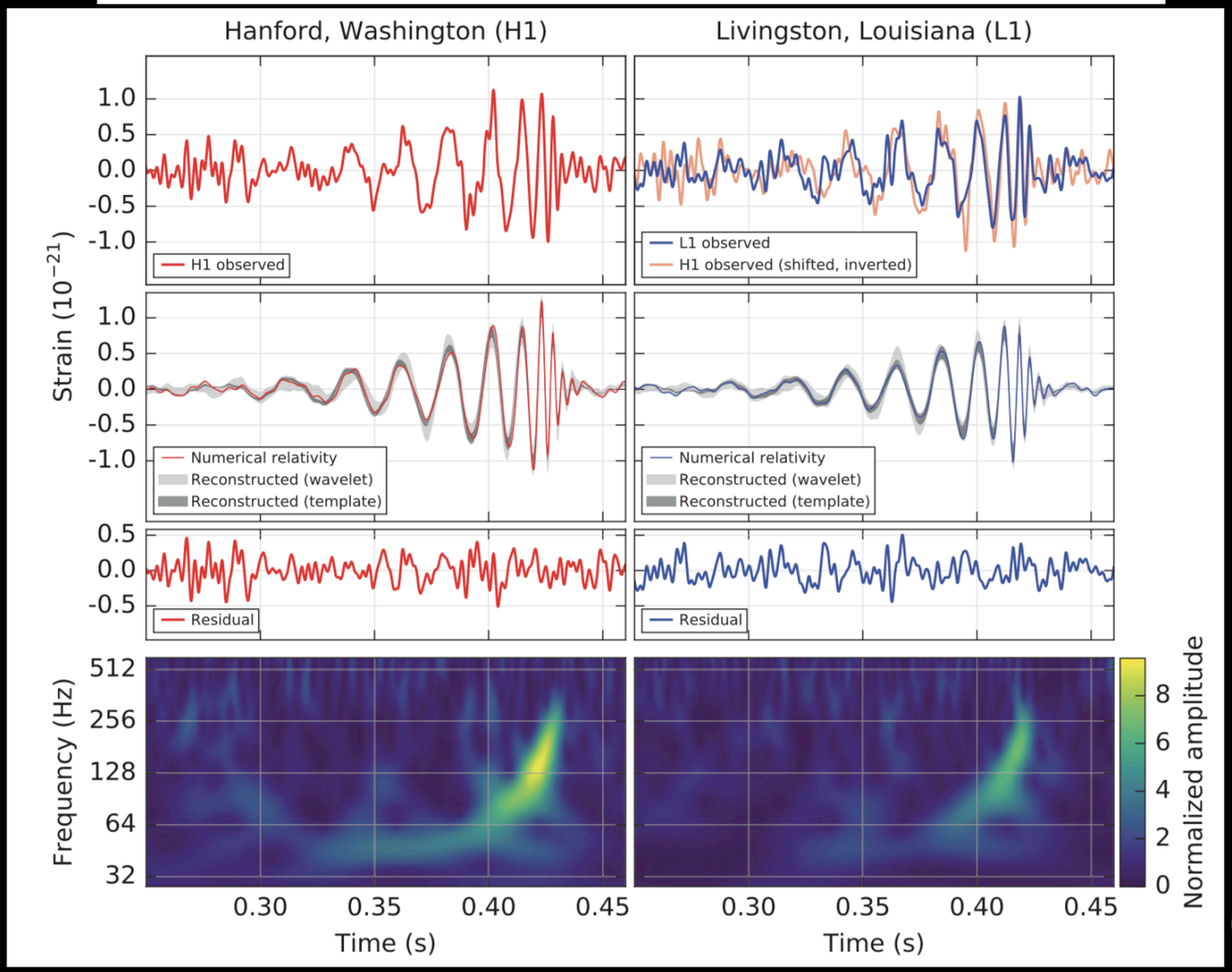
Credit: NASA

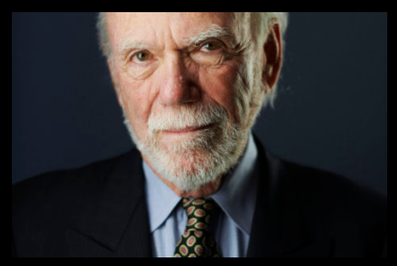
The birth of gravitational waves era

PRL 116, 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

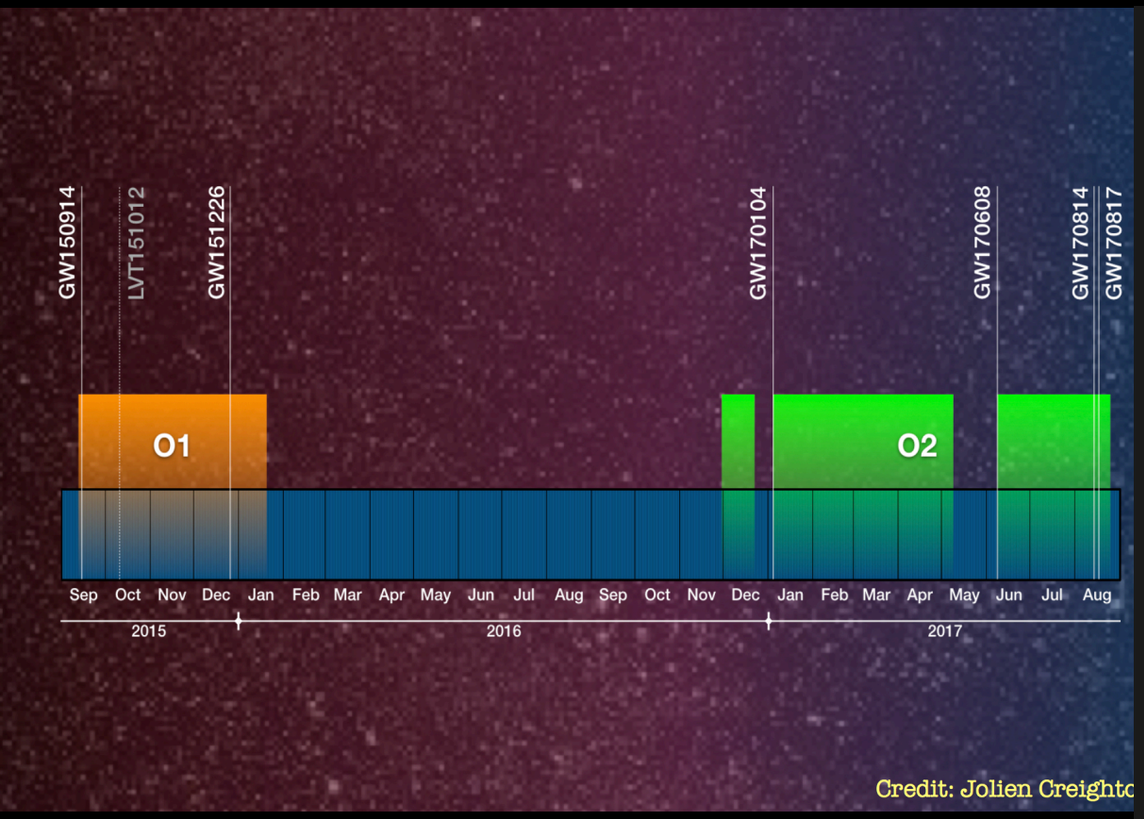
B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

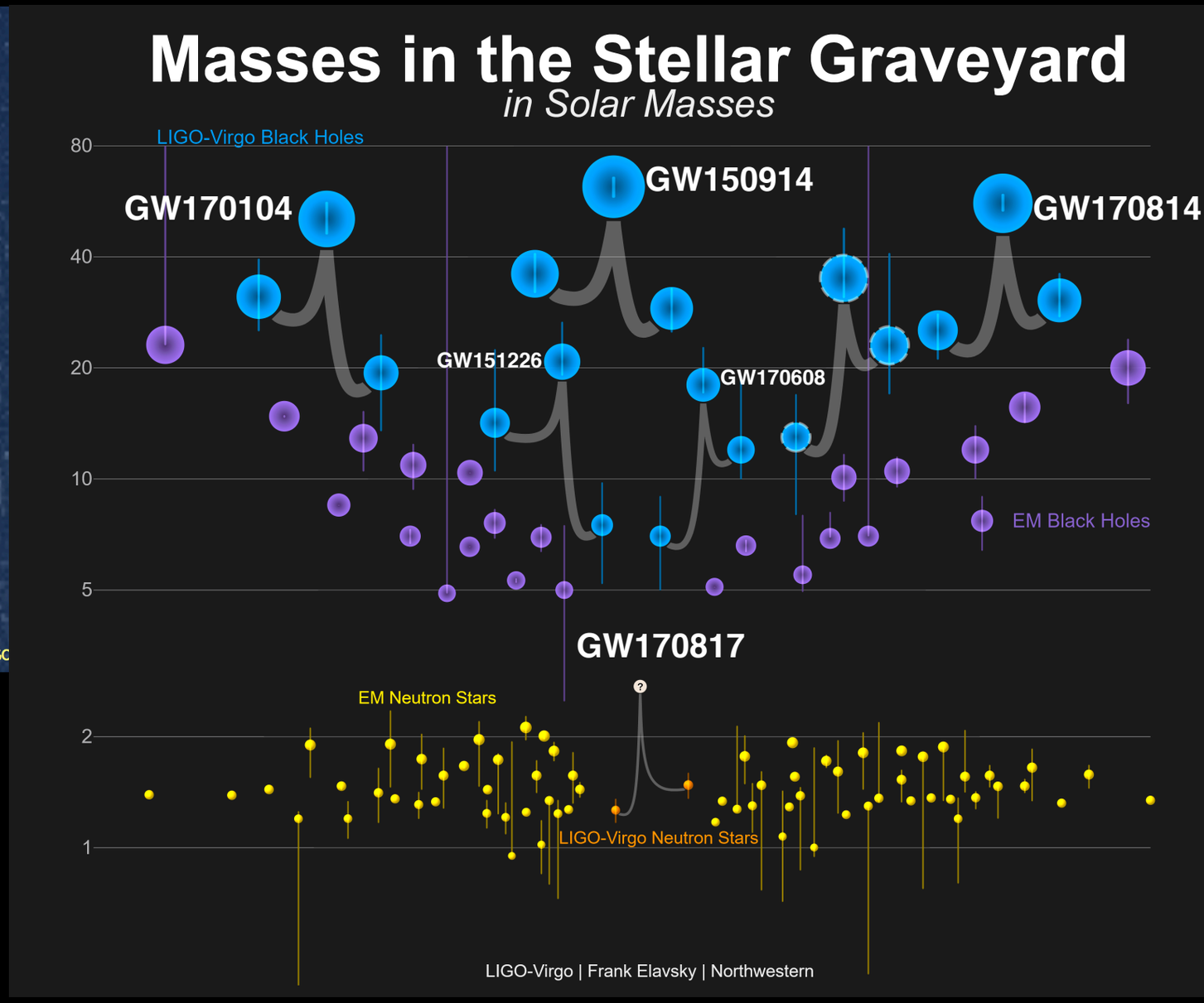




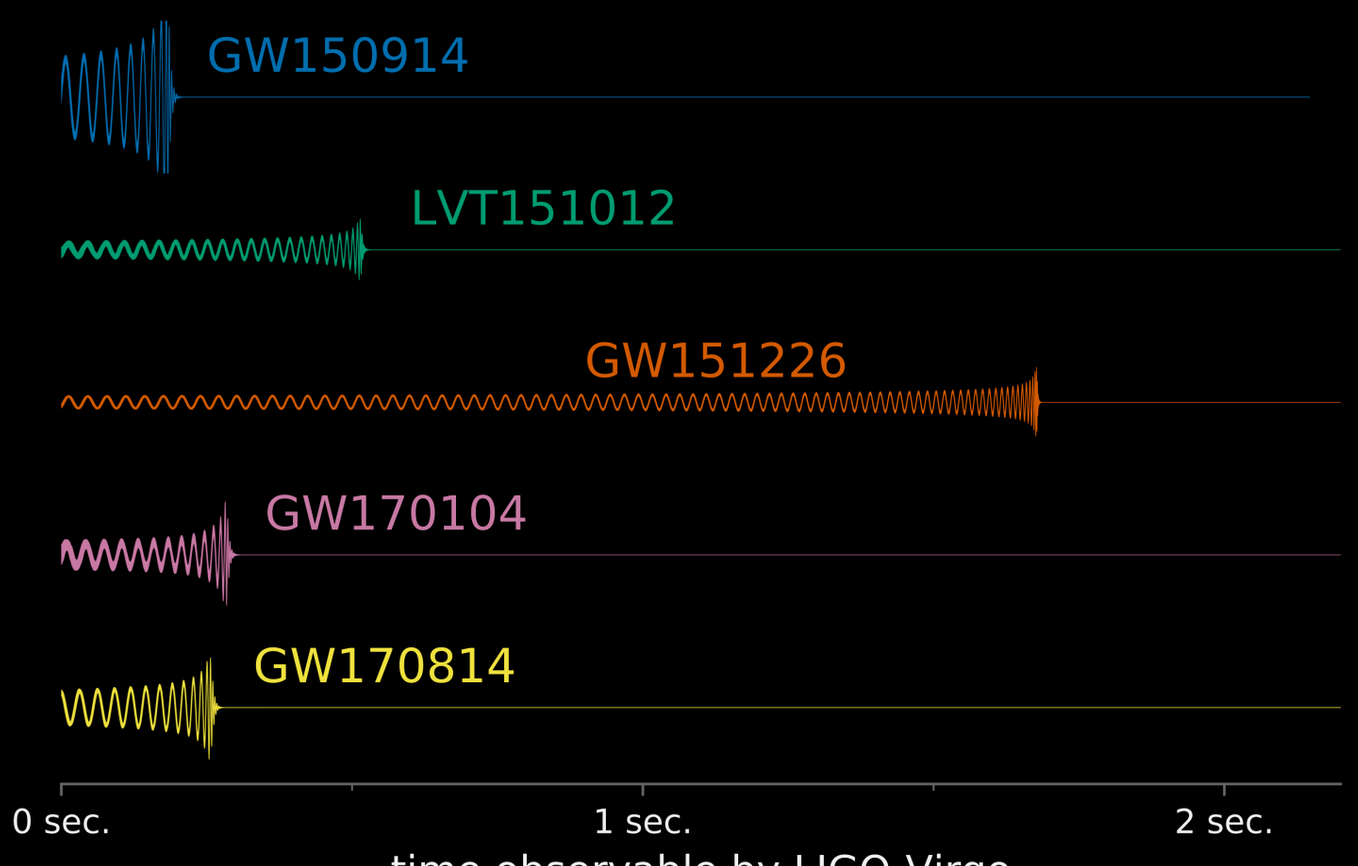
GW150914

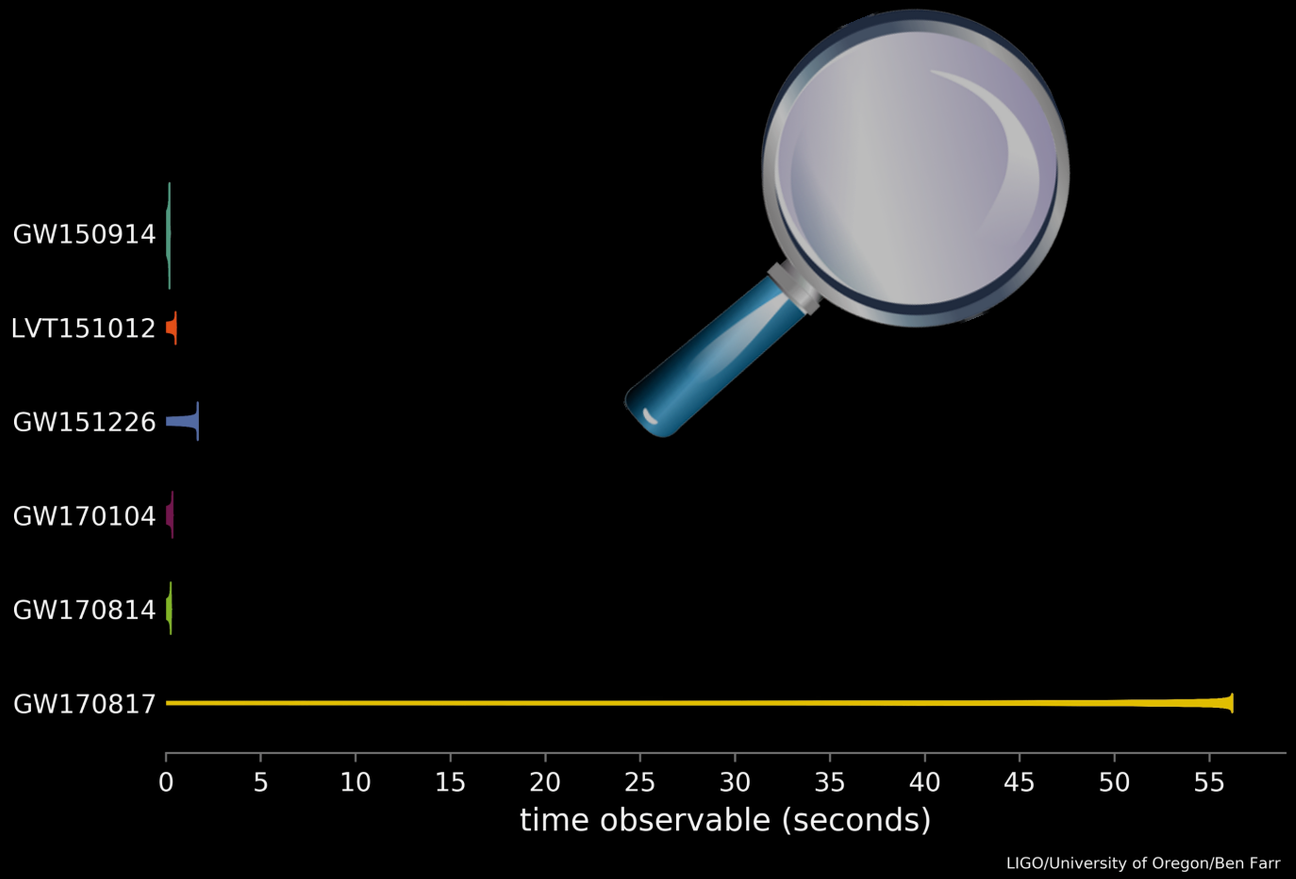
Gravitational waves detections



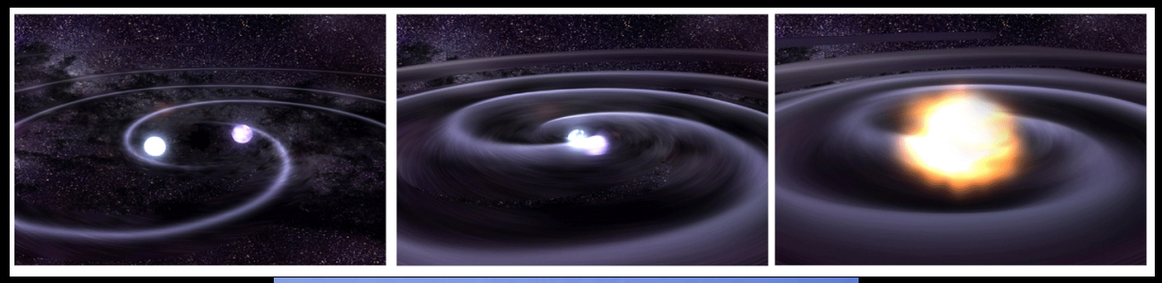


5 binary black-holes
1 binary neutron-star

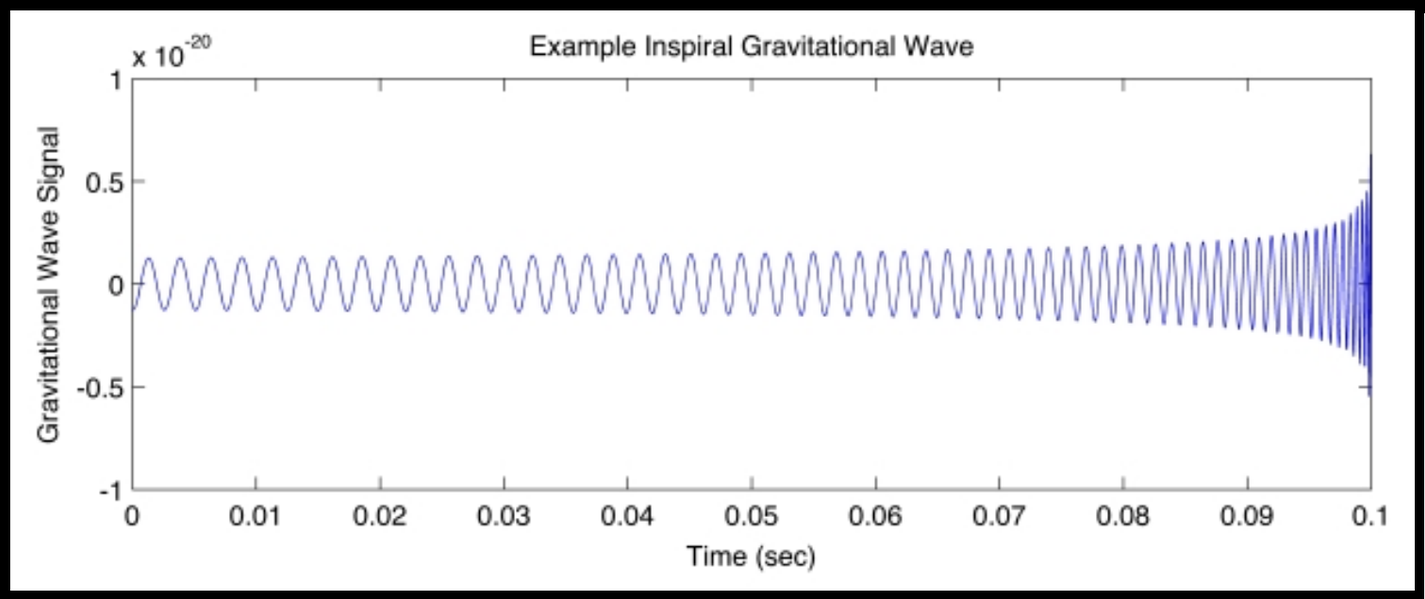

GW150914
LVT151012
GW151226
GW170104
GW170814
0 sec.
1 sec.
2 sec.
time observable by LIGO-Virgo


GW150914
LVT151012
GW151226
GW170104
GW170814
GW170817
0
5
10
15
20
25
30
35
40
45
50
55
time observable (seconds)
LIGO/University of Oregon/Ben Farr

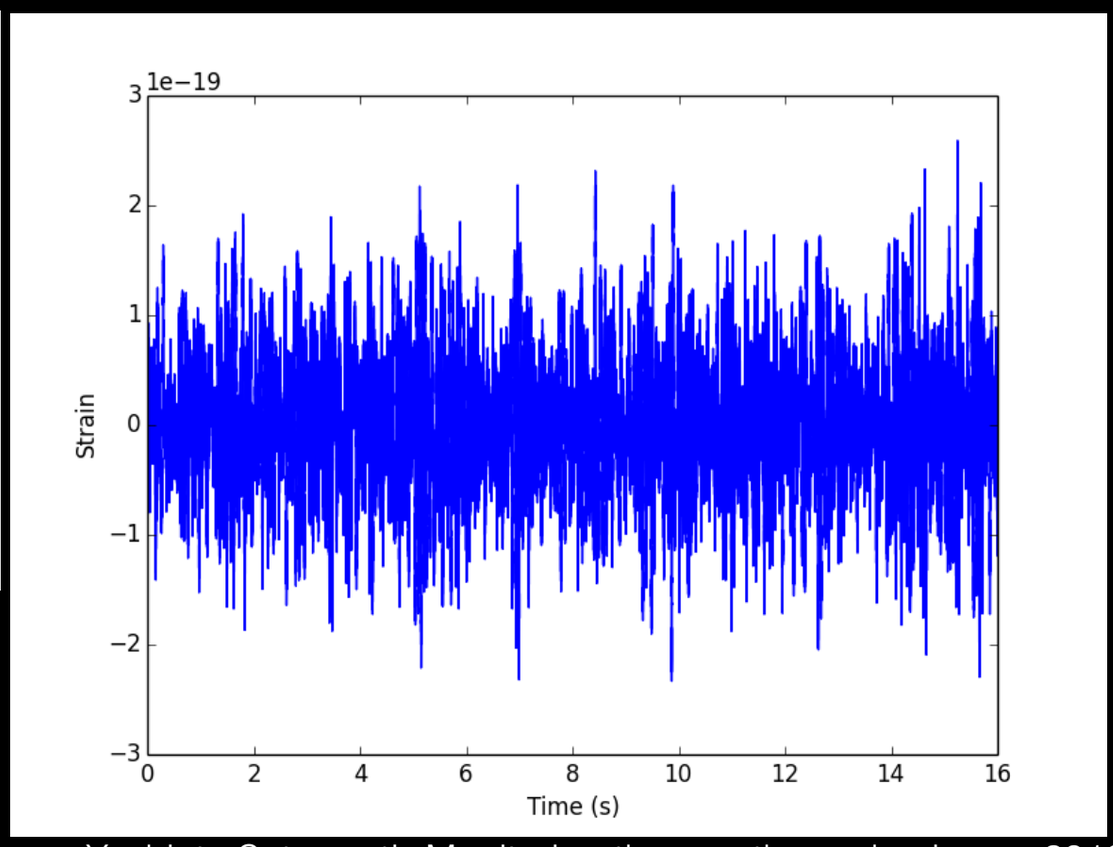
Data analysis

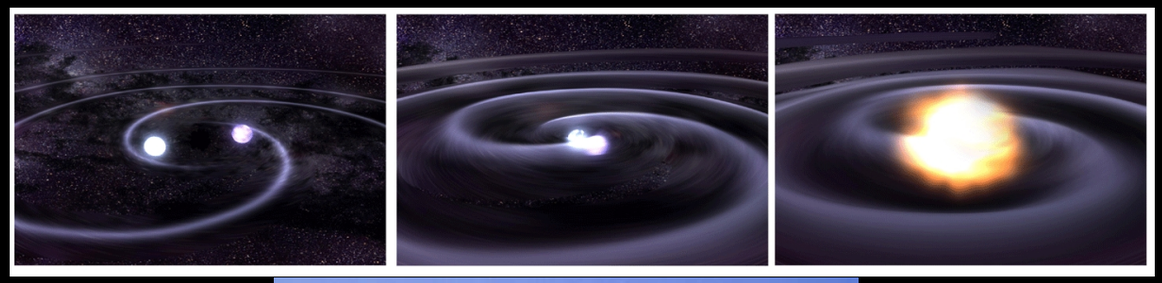


Expectation

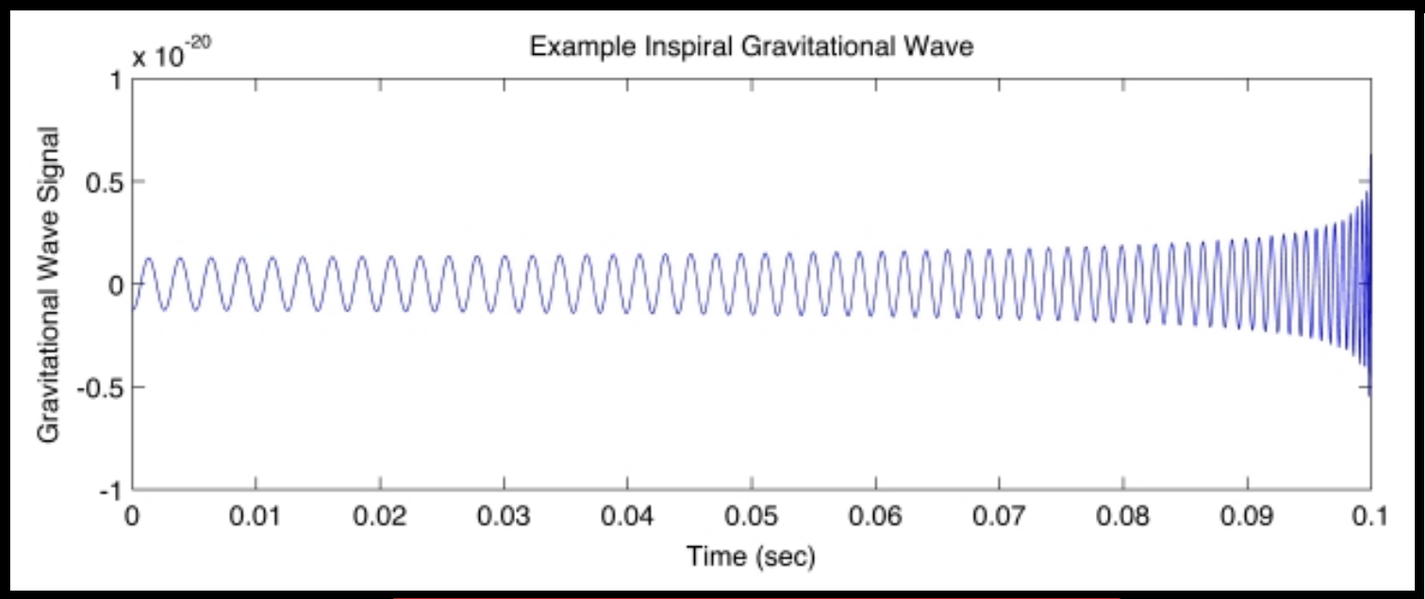


Reality



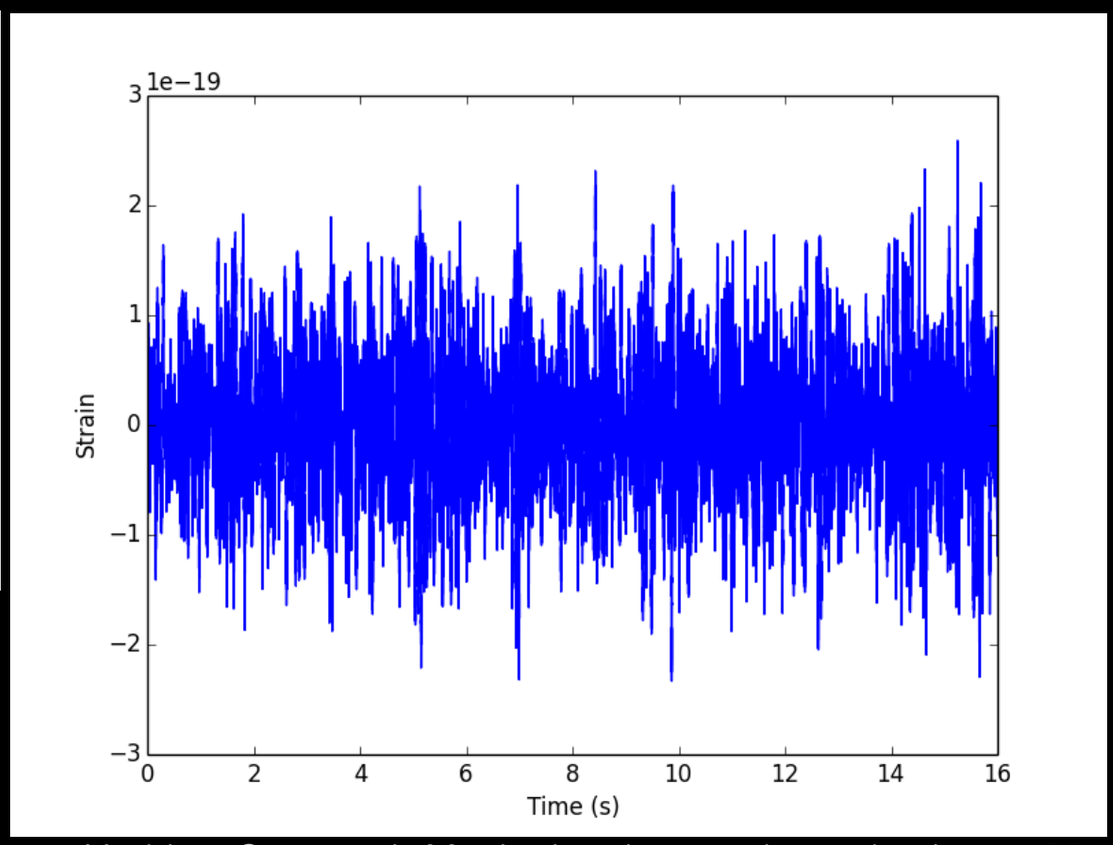


Expectation



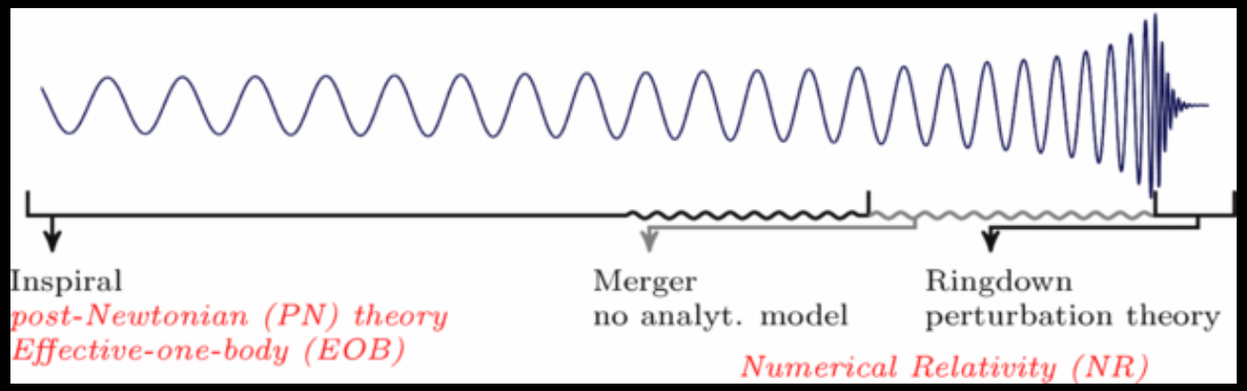
Matched filtering

Reality



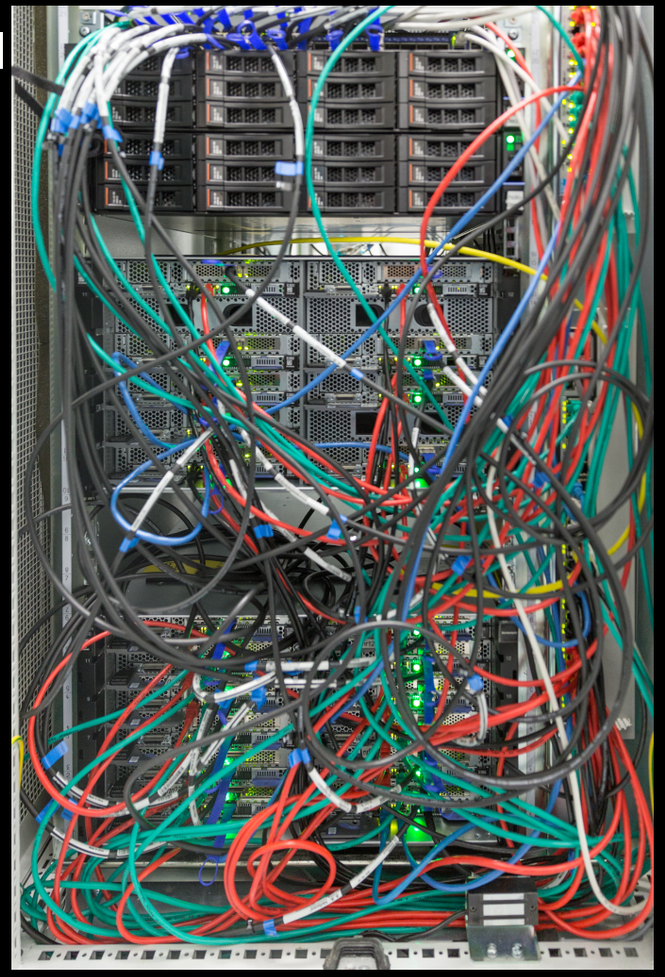
Source modelling

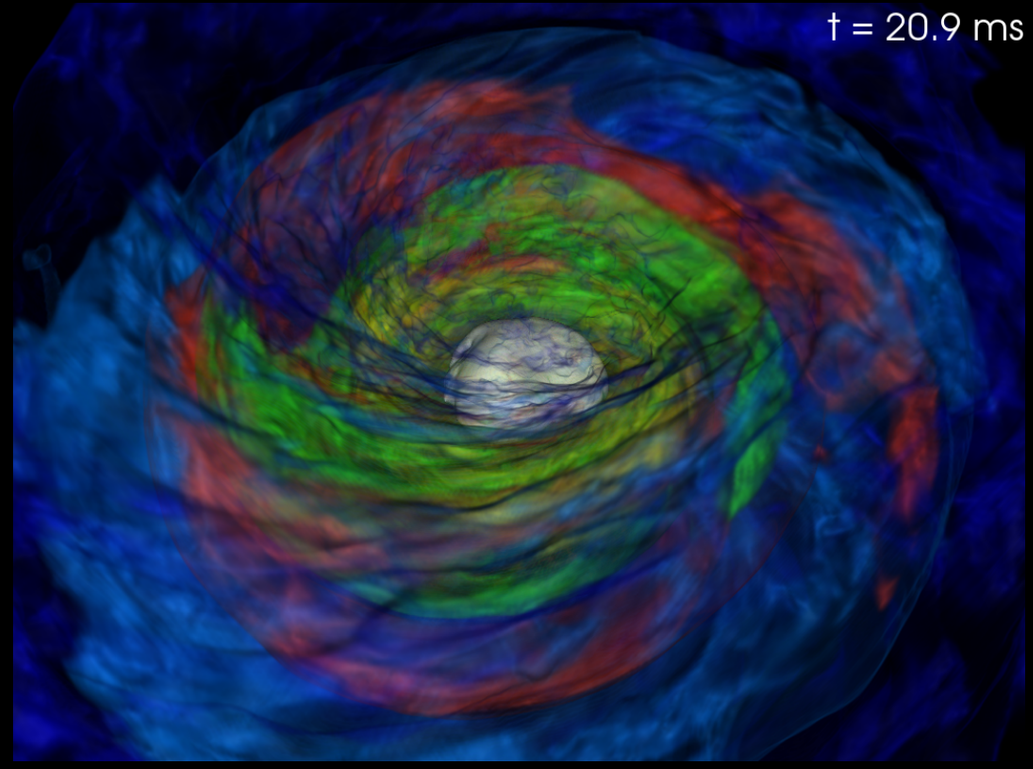
- Analytical: Post newtonian
- Simulation: Numerical relativity



Ohme 2012

Credit: Benjamin Knispel





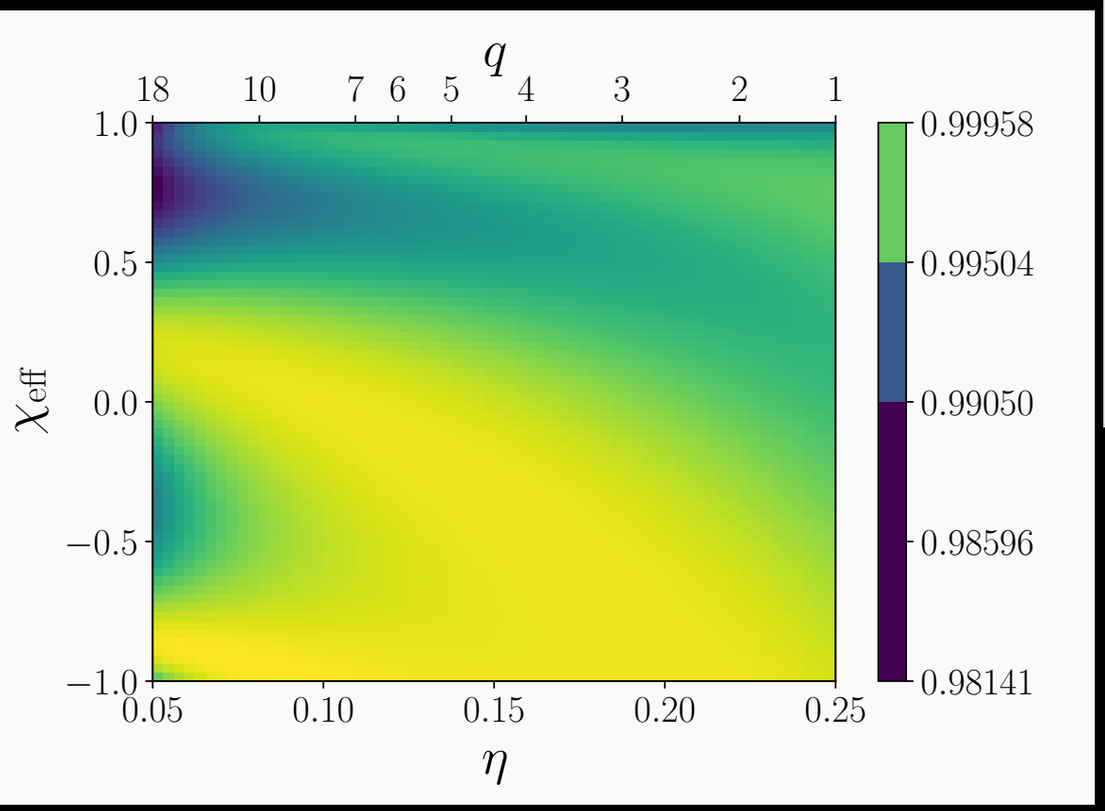
Credit: Wolfgang Kastaun

Yoshinta Setyawati. Monitoring the non-thermal universe 2018.

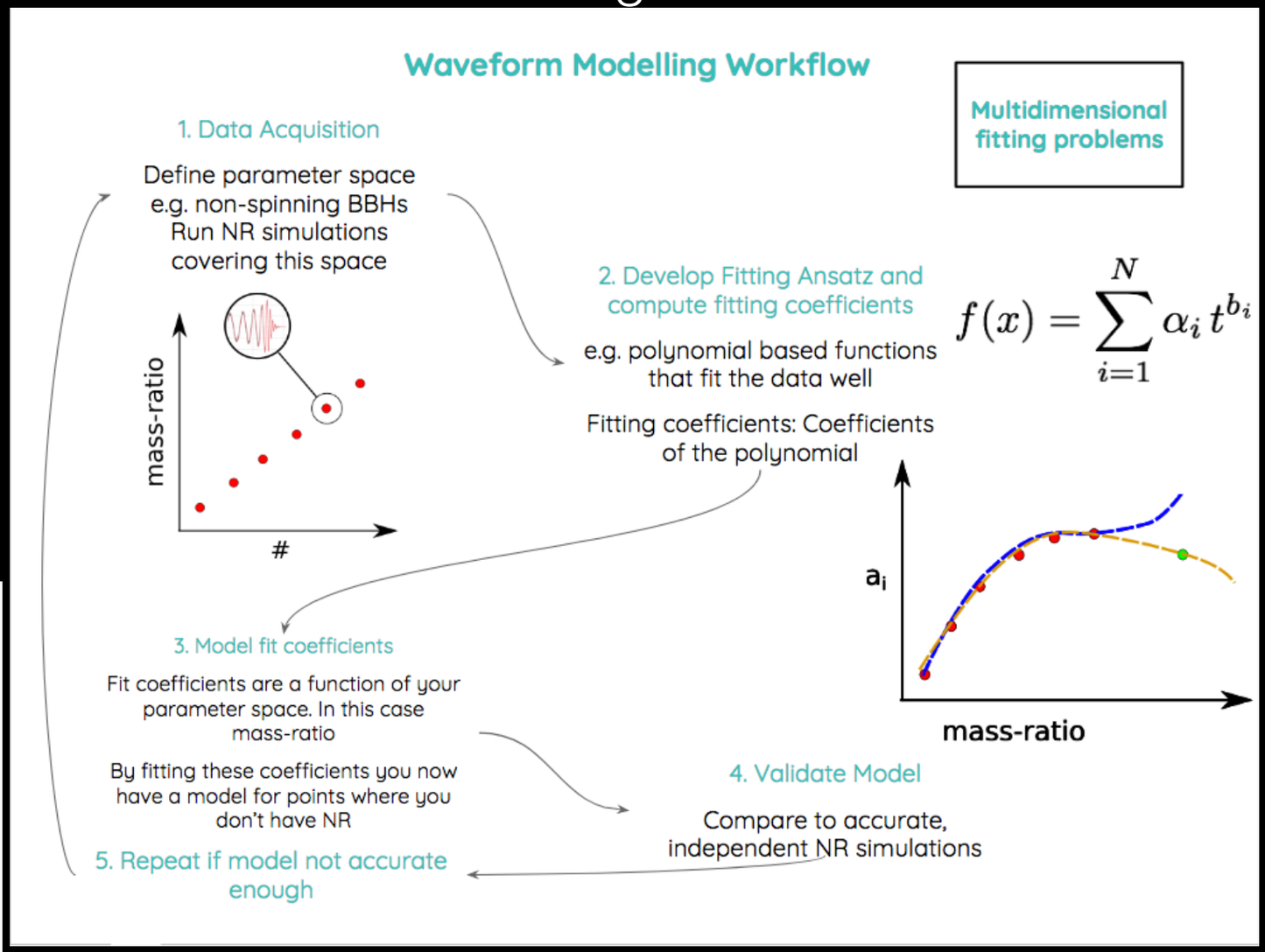
Source modelling

Other models:

- Effective-one-body
- Phenomenological
- Reduced order modelling
- Enriched basis



Phenomenological model



Credit: Sebastian Khan

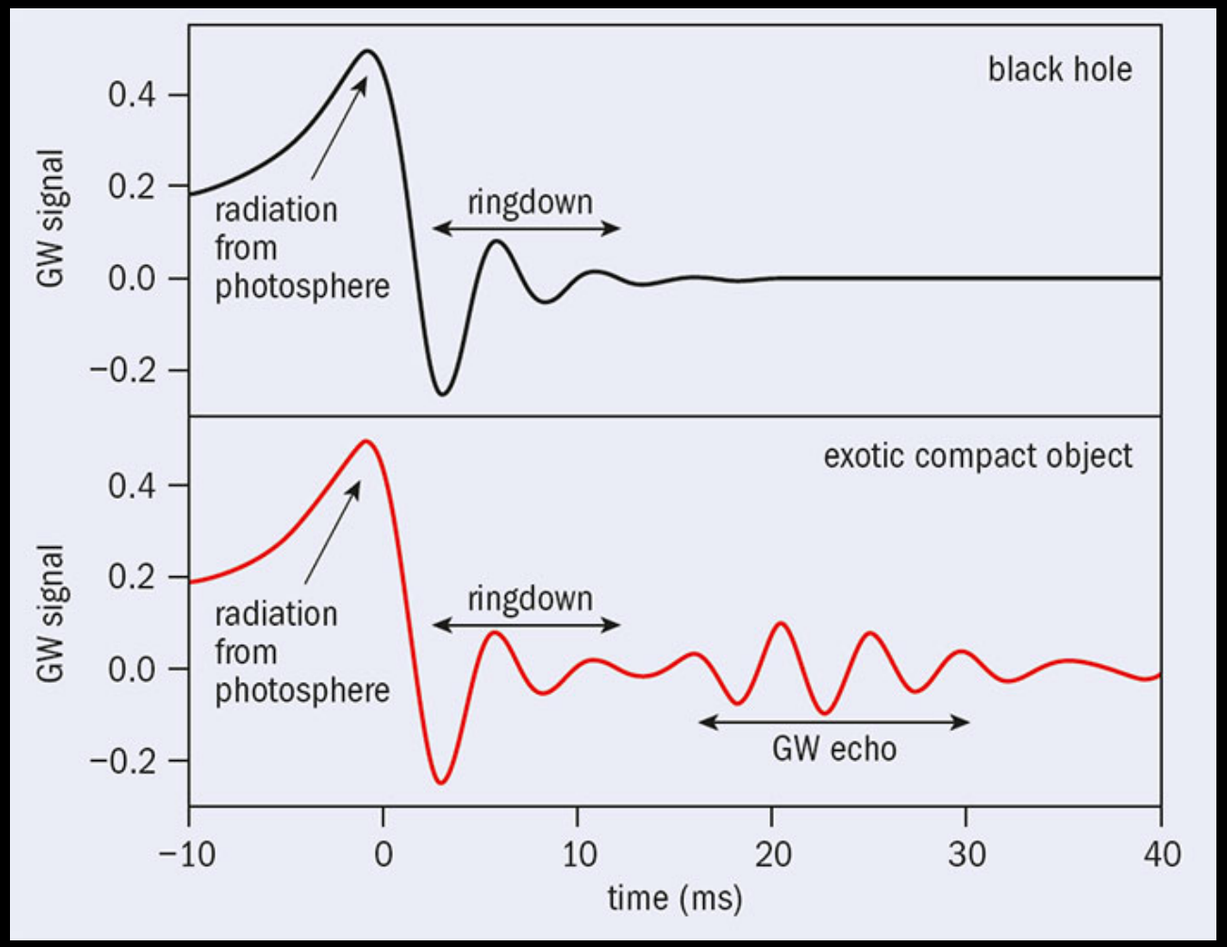
Setyawati et al in prep.

Binary black-hole

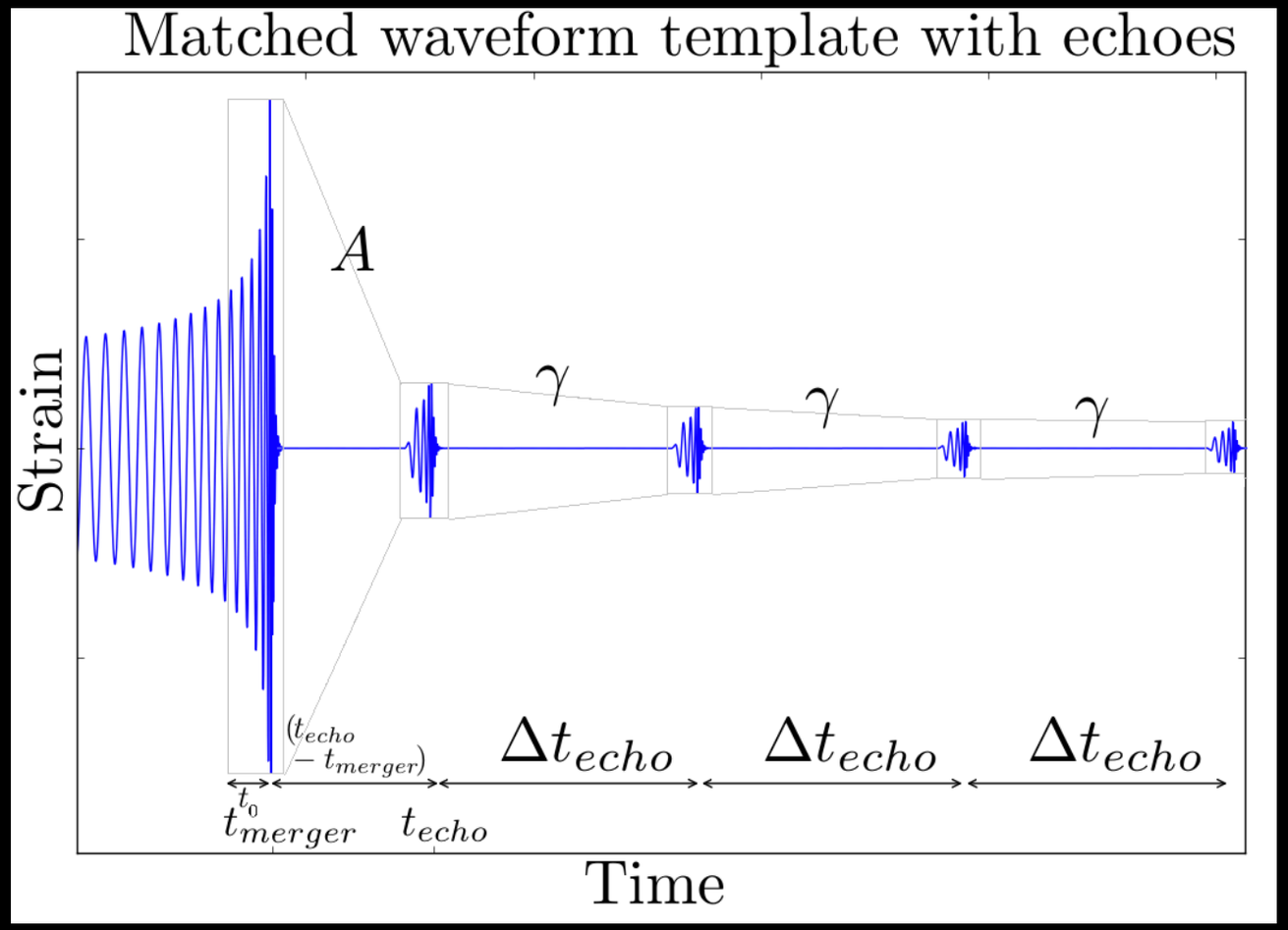
Binary black-hole

- Do they exist?
- Consistency with general relativity?
  - Echoes
  - Hawking area theorem

Echoes



https://cerncourier.com/linking-waves-to-particles/



Westerweck et al 2018

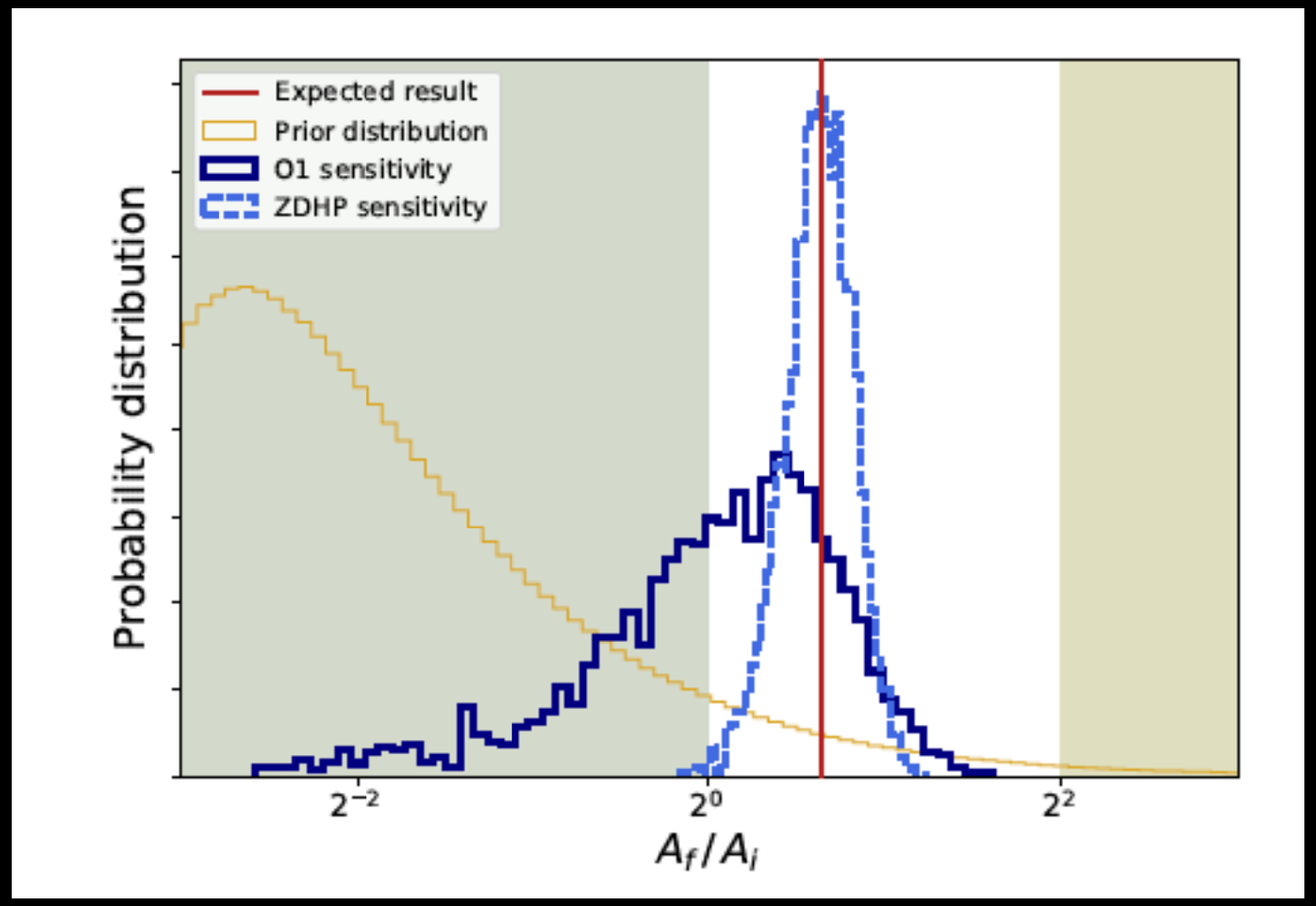
Hawking area theorem

If two black holes coalesce, the area of the final event horizon is greater than the sum of the areas of the initial horizons.

Area of Kerr black hole:

$$A = 8\pi m^2(1 + \sqrt{1 - \chi})$$

$$A_f > A_1 + A_2$$

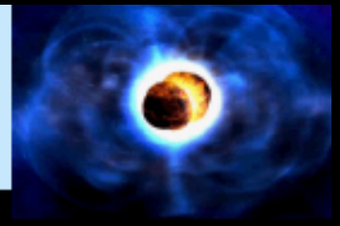


Cabero et al 2017

Binary neutron-star

The most extensive observing campaign ever….

Low-latency GW data analysis pipelines to promptly identify GW candidates and send GW alerts



LSC VIRGO

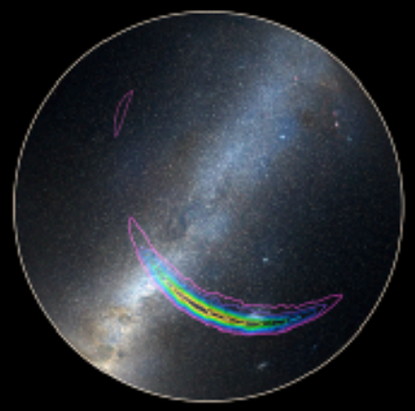
GW candidates

Sky Localization

EM facilities

LIGO-H LIGO-L

Virgo



Event validation

a few min

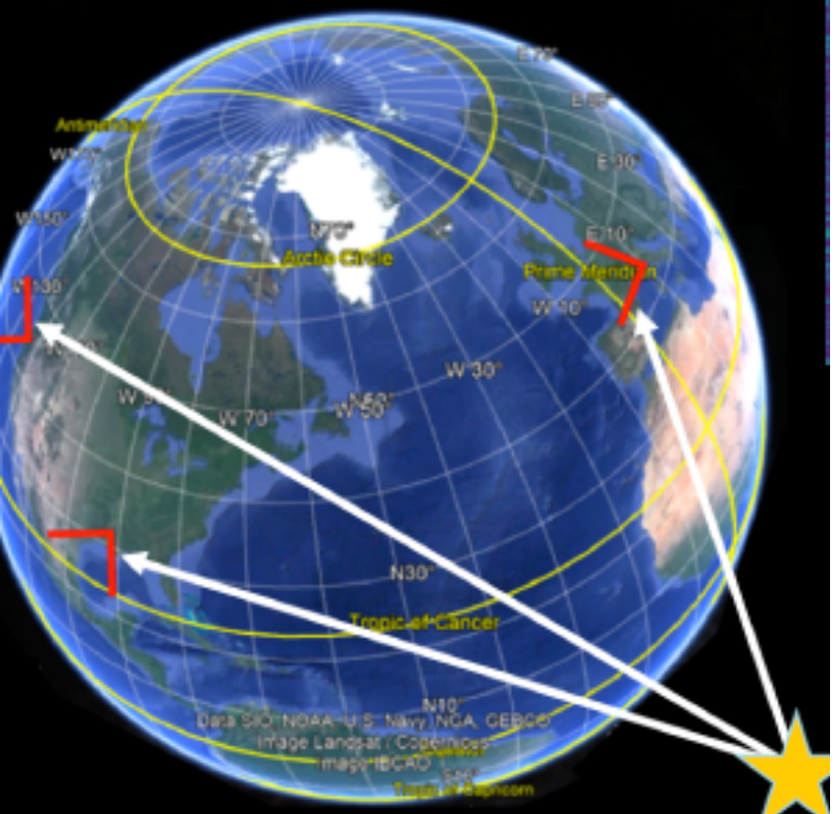
30 min

Parameter estimation codes

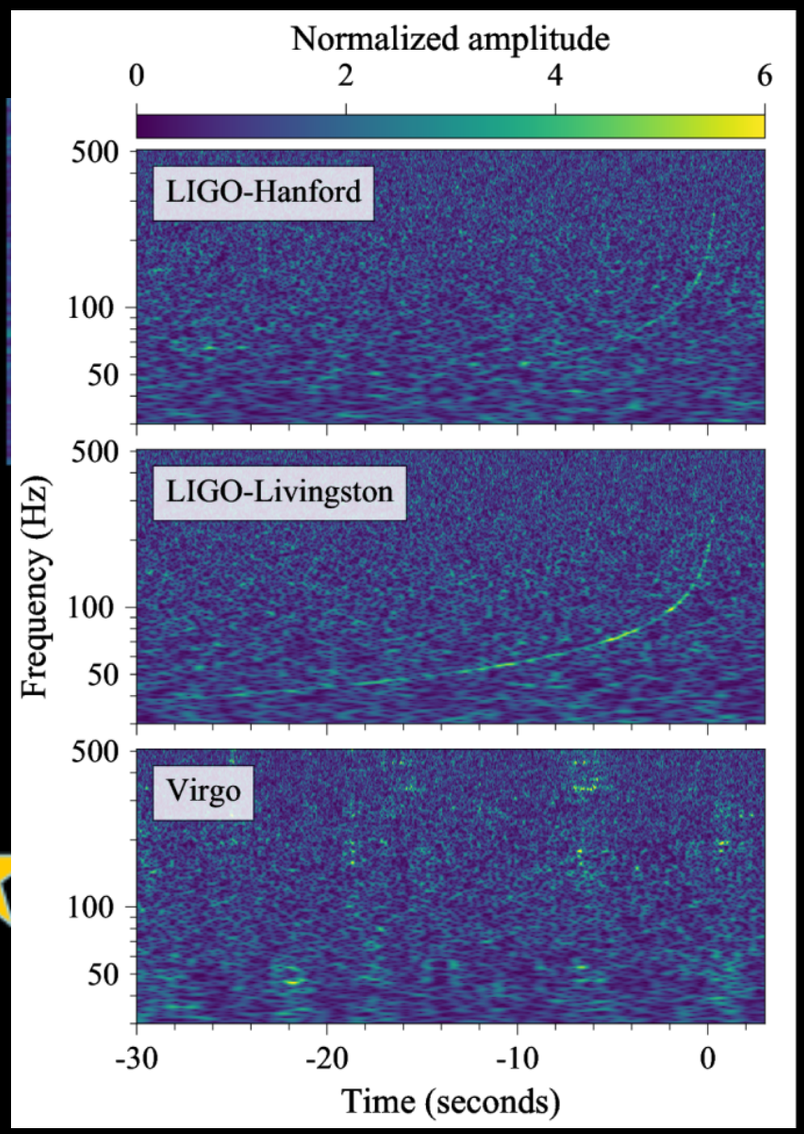
Hours,days, weeks

GW candidate updates

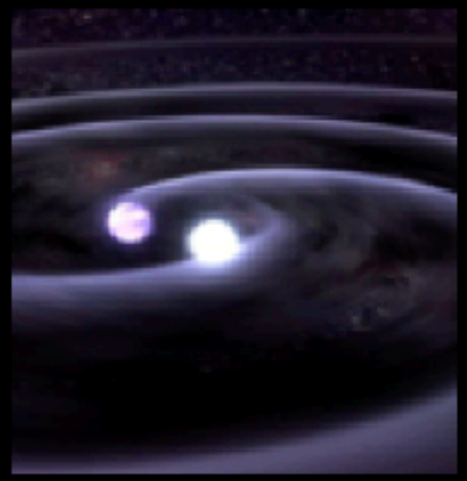
Binary neutron star: GW170817



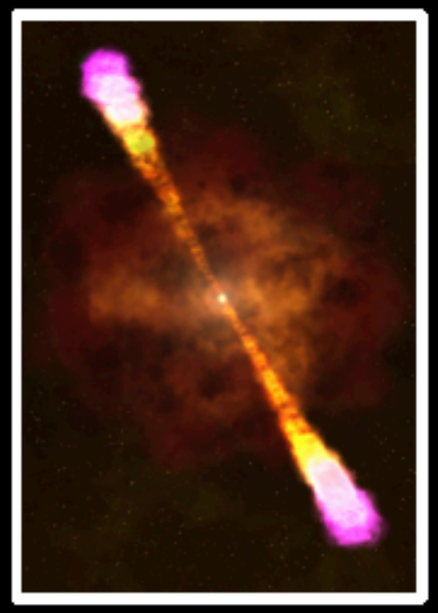
Sky localisation 31 deg²
Distance 40±8 Mpc



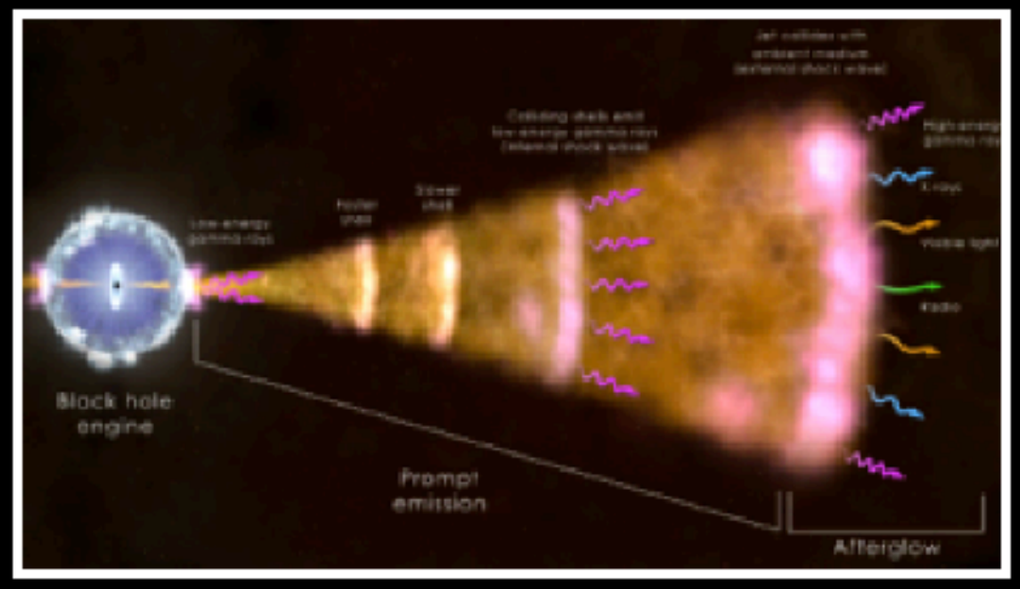
LIGO/NASA/Leo Singer



NS merger



Short GRB

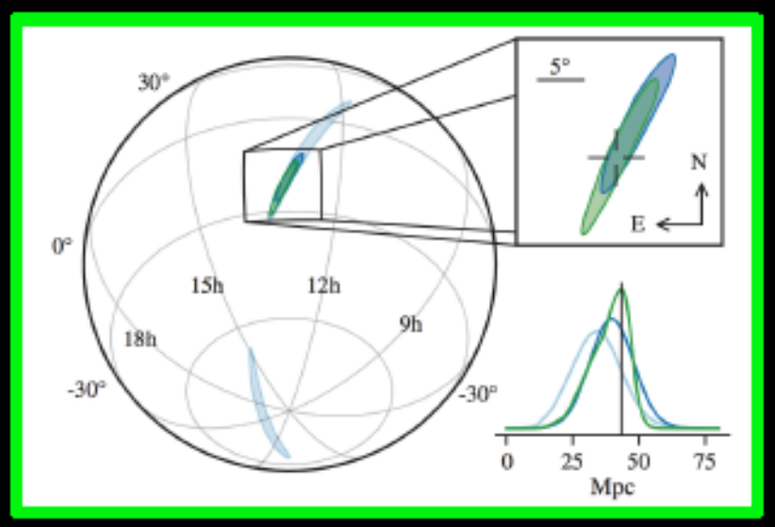


X-ray

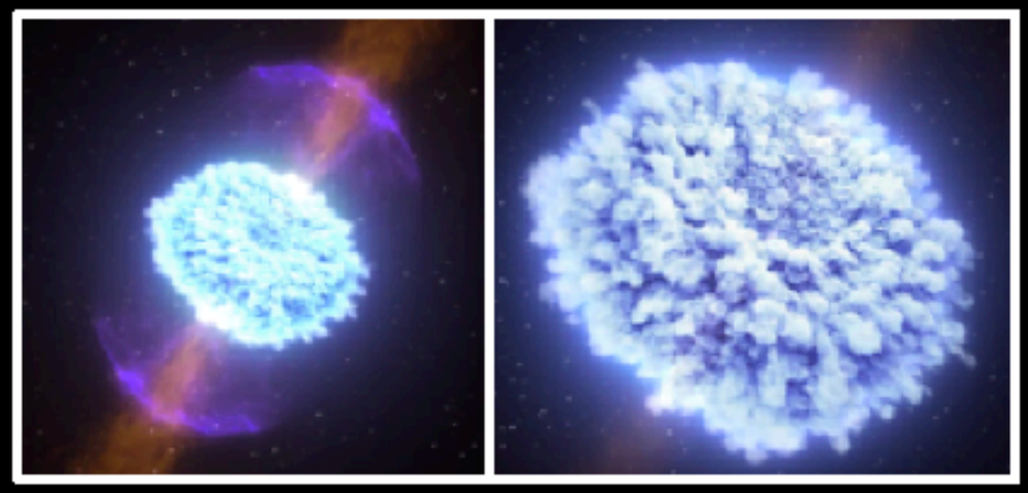
Radio afterglow

t0 1.7s +5.23hrs +10.87 hrs +9 days +16 days

GW sky localization

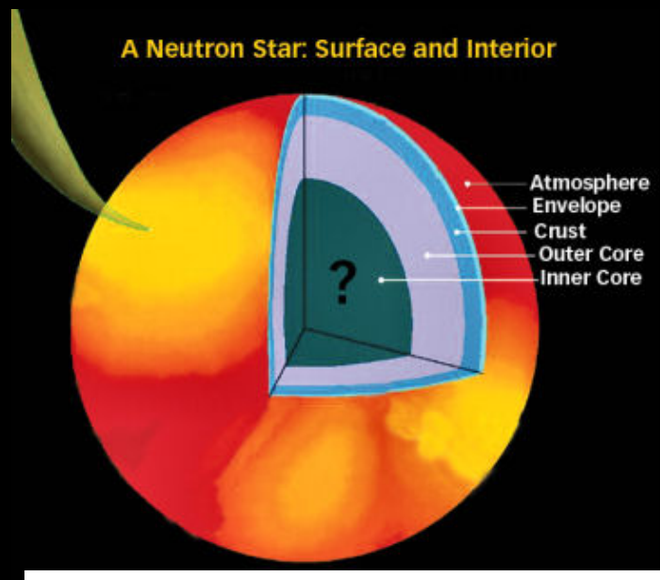


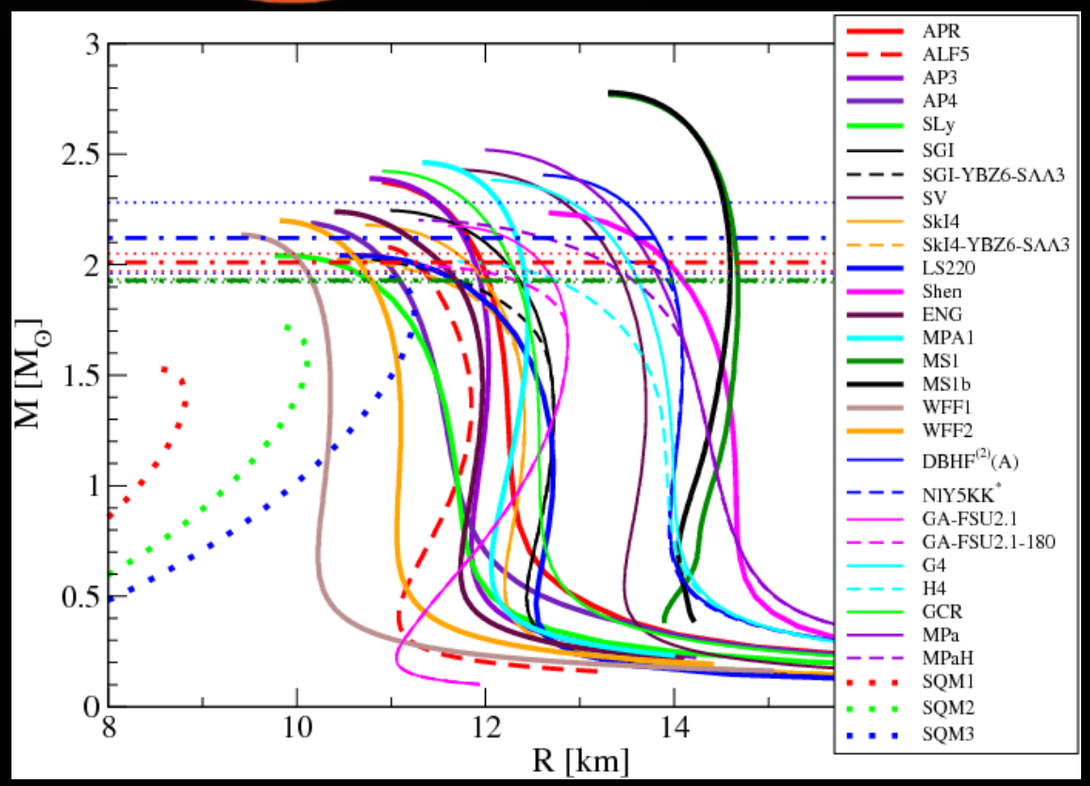
UV/Optical/NIR Kilonova



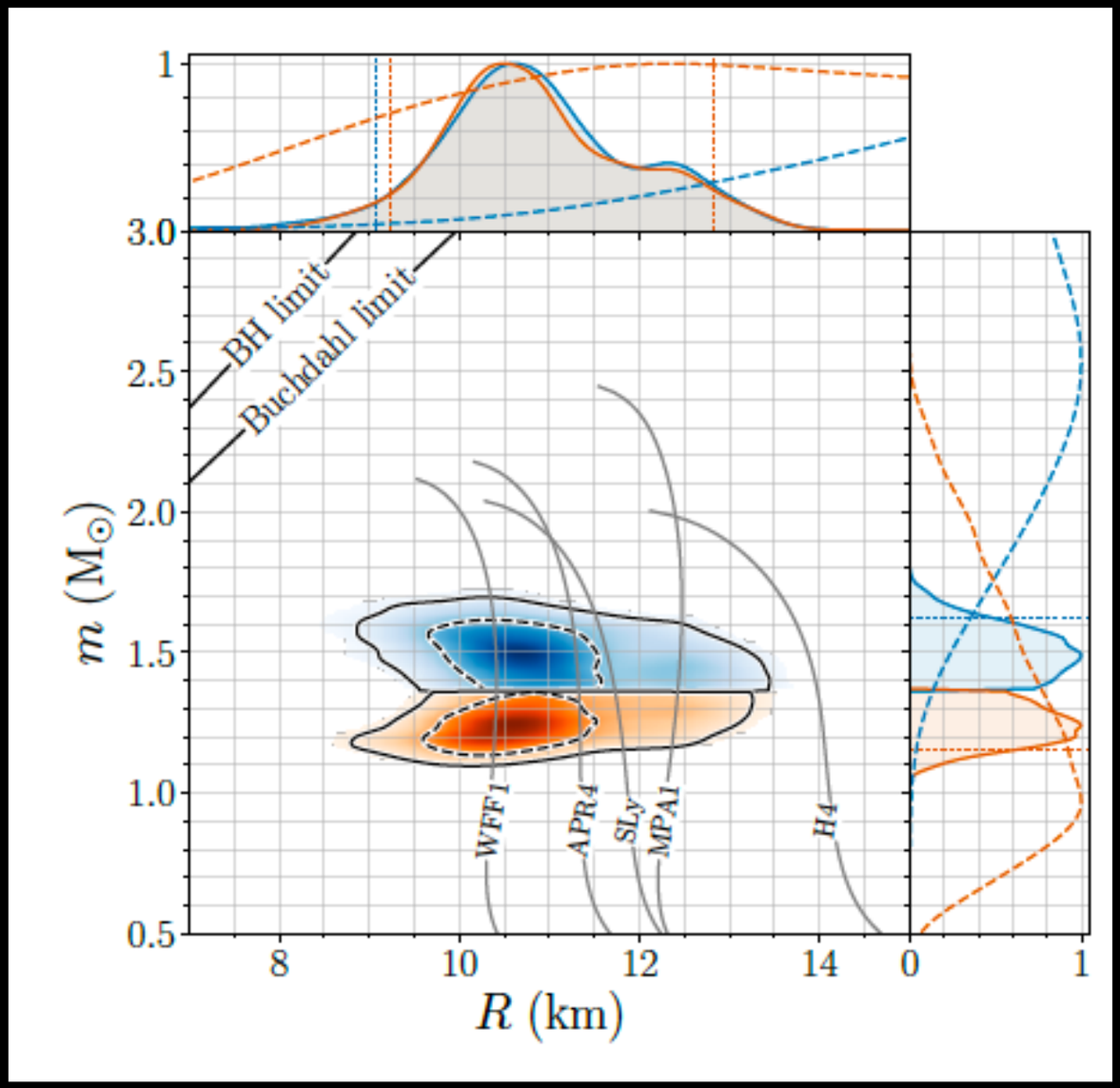
LVC + astronomers, ApJL, 848, L12

Constraining the neutron star equation of state



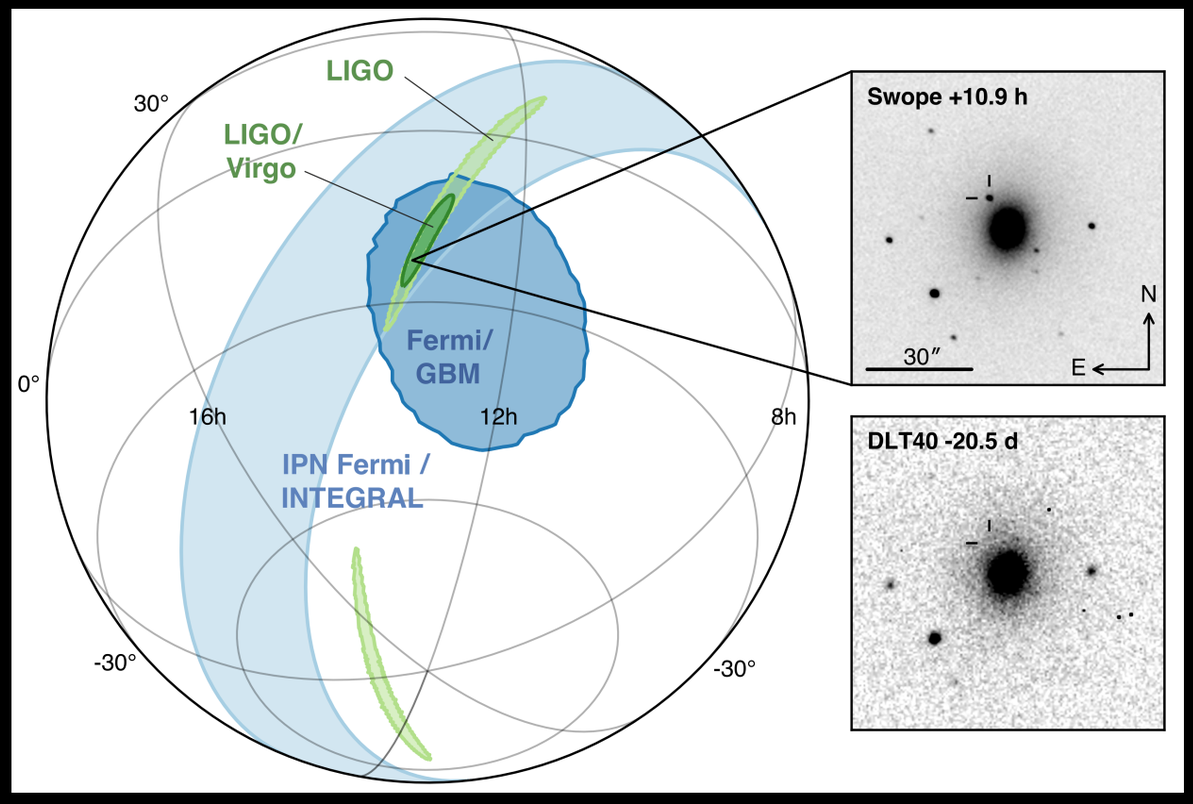


Yagi & Yunes 2016



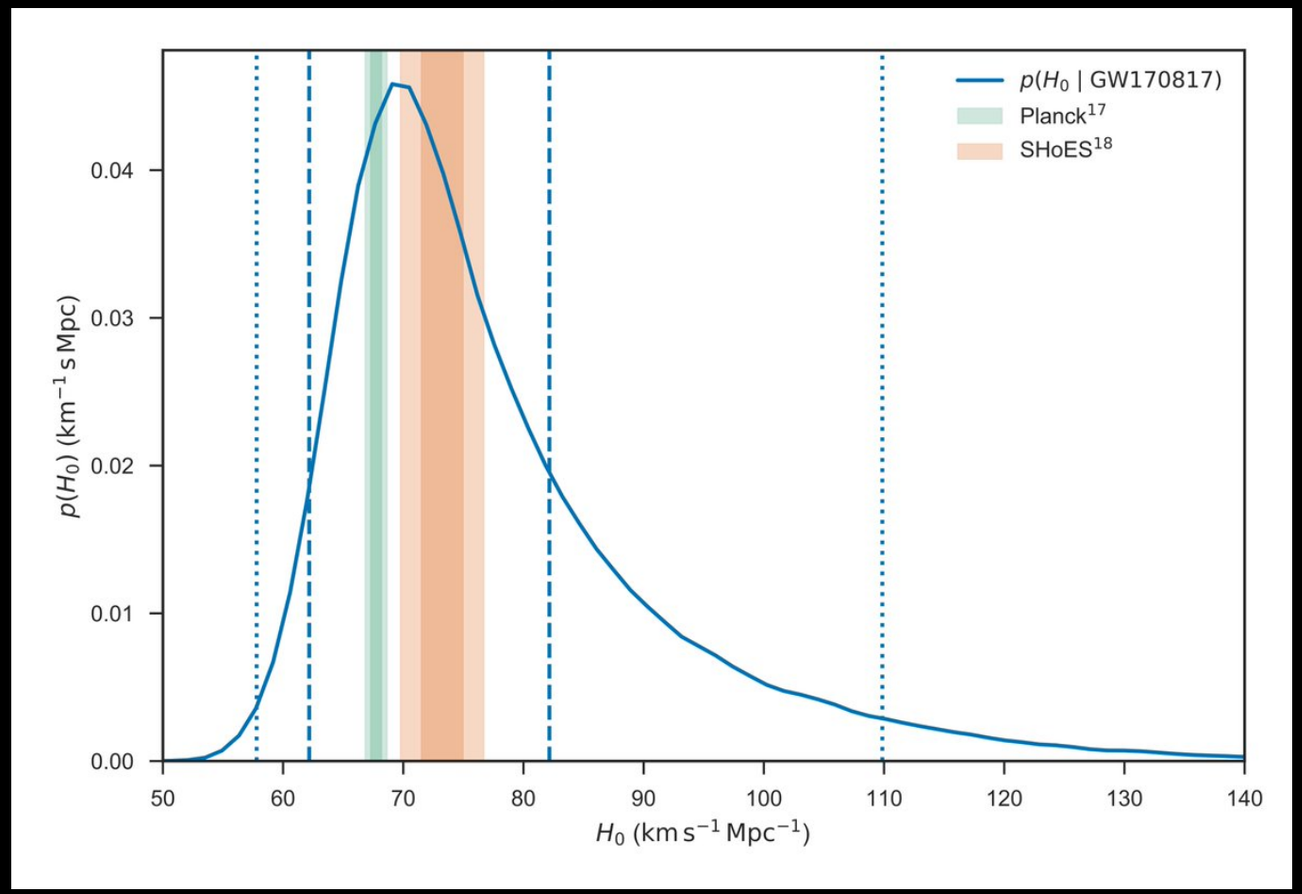
Abbott et al (LVC) 2018

Hubble constant



Combining the distance measured from gravitational waves and NGC4993 recession velocity.

Abbott et al (LVC), Nature 2017



$$v_H = H_0 d$$

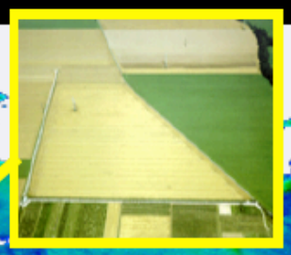
$$H_0 = 70^{+12}_{-8} \mathrm{km\ s^{-1} Mpc^{-1}}$$

Other sources

- Compact binary coalescences:
    - Neutron star-black hole binary?
    - Intermediate mass black hole binary?
- Spinning neutron star (continuous waves)?
- Core collapse supernovae?
- Other exotic objects?

Upcoming network

LIGO-Hanford
(4 km)



GEO (600 m)

KAGRA
(2019+)

indigo

LIGO-India
(2022+)

Virgo (3 km)

LIGO-Livingston
(4 km)

indigo

LIGO detector in India
(4 km)

KAGRA

Underground detector in
Kamioka mine (3km)

Thank you!

From electromagnetic waves we see the universe, through gravitational waves we hear the universe, and with neutrinos we taste the universe.

Cochem, 19 September 2018