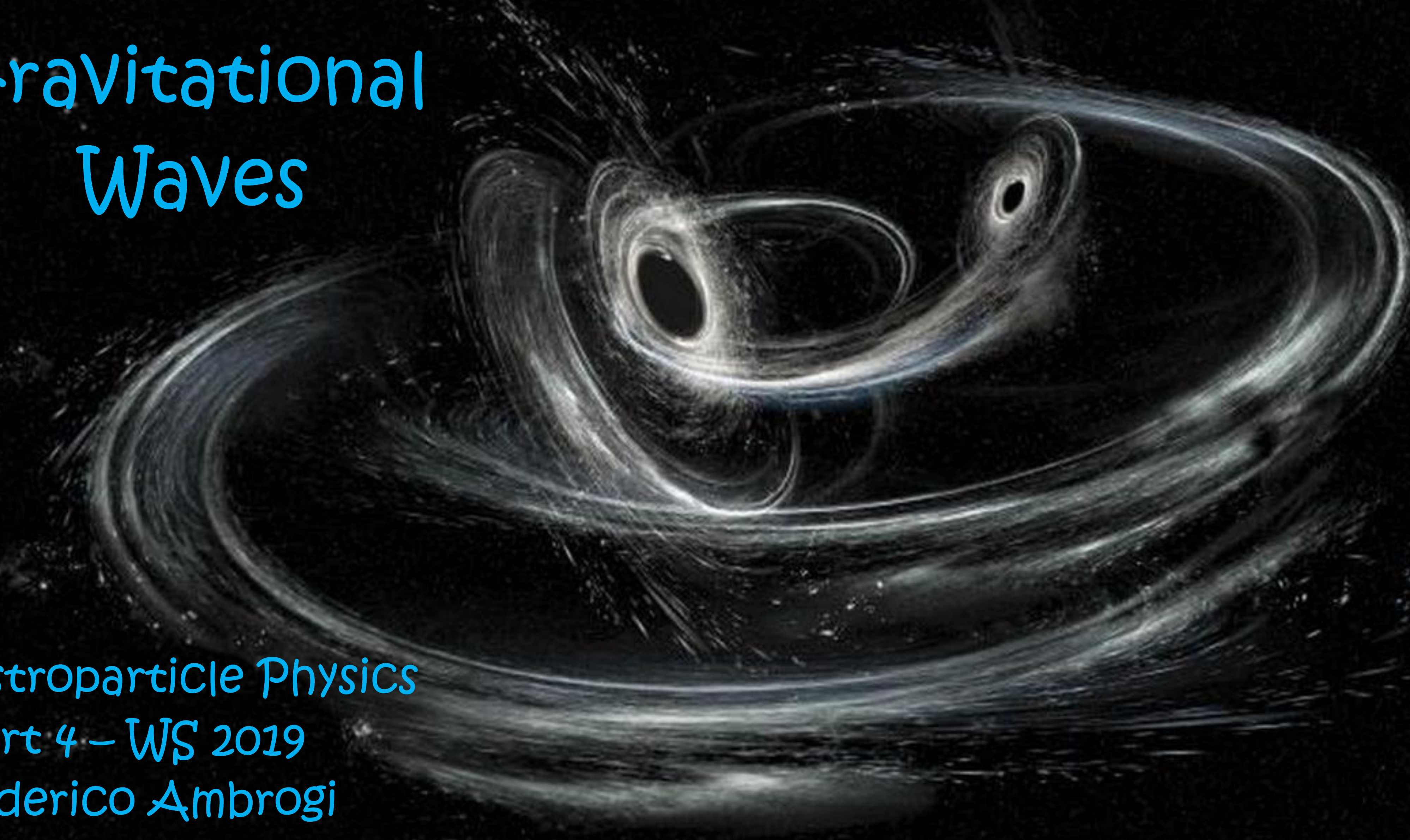
Overview

- **November 20th**
- Gravitational Waves
- Introduction to Dark Matter (history, evidences)

- **December 4th**
- Dark Matter "Theory"
    - Cosmology, History of the Universe, ΛCDM Cosmological Model
    - Dark Matter in Cosmology
    - Nucleosynthesis

- **December 11th**
- Dark Matter "Experiments"
    - → Phenomenology of Dark Matter
    - → Experimental Searches

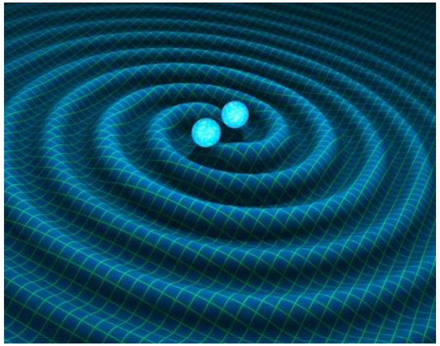
Gravitational Waves

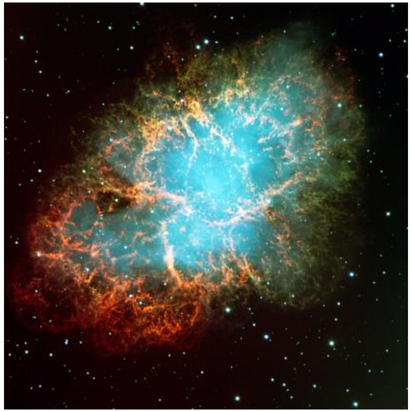


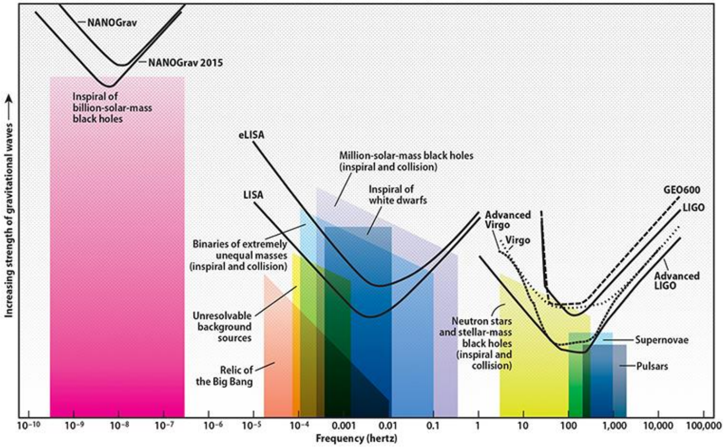
Astroparticle Physics
Part 4 – WS 2019
Federico Ambrogi

Gravitational Waves (GWs) represent one of the hot topic in current Astrophysics

- Another fundamental proof that Einstein‘s general relativity is correct
- Give complementary and independent measurements of astrophysical/cosmological parameters
- Allow to observe atrophysical objects/events that cannot be seen with electromagnetic waves or cosmic rays
- Allow to test the ΛCDM Cosmological Model and the evolution of the universe
- (...)







In this lecture:

- *Introduction to GWs*
- *Sources: Black Holes, Neutron Stars*
- *Interferometry: LIGO, VIRGO, LISA*
- *Characterization of GW events*
- *Multimessenger astronomy*

Gws: “ripples” or distortion in the space-time fabric travelling at the speed of light (c) .

- Through their propagation, they distort the space and time around massive bodies or massless particles

- In particular, GW change the distance between two fixed points

How do we detect Gws?

- The amplitudes and the frequencies of the waves depend on the sources

What produces Gws?

Supermassive black holes,
formation of black holes,
binary systems,
early universe dynamics etc.

https://arxiv.org/abs/1703.00187
https://www.tat.physik.uni-tuebingen.de/~kokkotas/Teaching/NS.BH.GW_files/GW_Physics.pdf

What are these Gravitational Waves ???

"One of the first predictions of General Relativity (GR, 1916)"

https://www.mdpi.com/2218-1997/2/3/22/pdf

- Einstein immediately started working on the solution of his field equation in the form of waves
- It took > 50 years to derive generally accepted solutions & the proper equations for the wave forms
- ~1970s: claim by Weber of the observation of GWs (not confirmed by other similar experiments)
- 1974: discovery of the binary system SR B1913+16 (and the Hulse–Taylor binary) → first *indirect* test of Gws emission

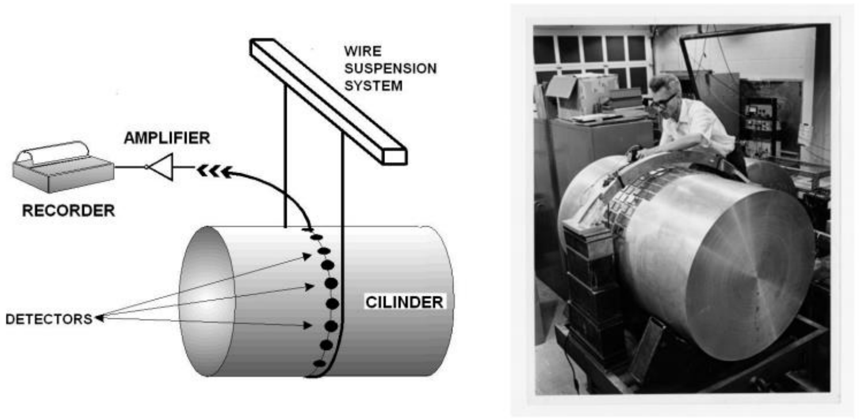


Figure 4. Sketch of Weber's cylinder detector and photo of Joseph Weber at the antenna.

Arecibo (Puerto Rico) telescope: 305-meter radio telescope, world's largest single-aperture telescope (until 2016, with the Chinese FAST telescope)

The Hulse-Taylor Binary Pulsar PSR B1913+16

https://arxiv.org/pdf/1011.0718.pdf

- Double neutron stars binary system first observed in 1974
- According to general relativity a binary star system should radiate energy in the form of gravitational waves
- Rate of change in orbital period (Peters and Matthews,1963):

$$\dot{P}_b^{\rm GR} = -\frac{192\,\pi\,G^{5/3}}{5\,c^5}\left(\frac{P_b}{2\pi}\right)^{-5/3}\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right)(1-e^2)^{-7/2}\,m_1\,m_2\,(m_1+m_2)^{-1/3}$$
$$= -1.699451(8)\times 10^{-12}\left[\frac{m_1\,m_2\,(m_1+m_2)^{-1/3}}{M_\odot^{5/3}}\right]$$

Ratio observation vs prediction accounting for galactic corrections

$$\frac{\dot{P}_b - \Delta\dot{P}_{\rm b,gal}}{\dot{P}_b^{\rm GR}} = 0.997 \pm 0.002.$$

$$m_1 = 1.4398 \pm 0.0002\ M_\odot$$
$$m_2 = 1.3886 \pm 0.0002\ M_\odot$$

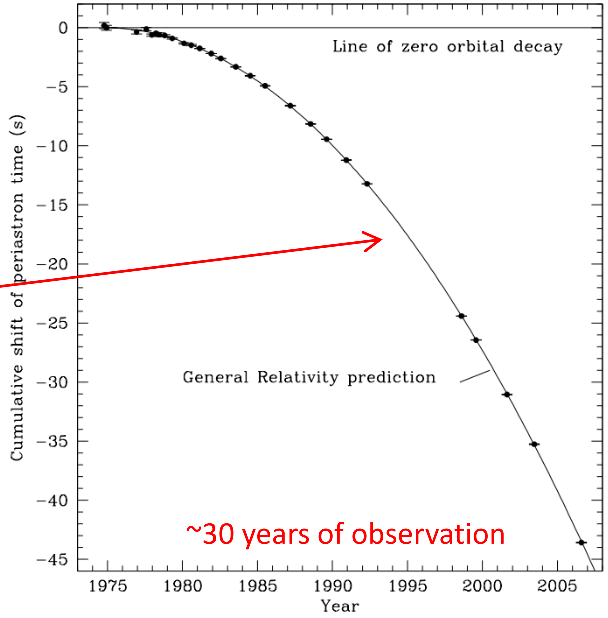


Fig. 2.— Orbital decay caused by the loss of energy by gravitational radiation. The parabola depicts the expected shift of periastron time relative to an unchanging orbit, according to general relativity. Data points represent our measurements, with error bars mostly too small to see.

"As we have shown before, this result provides conclusive evidence for the existence of gravitational radiation as predicted by Einstein's theory."

What are these Gravitational Waves ???

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[1993 Nobel prize to Hulse and Taylor]

- 14th September 2016 at 09:50:45 UTC: First observation of GW150914 (event of two black holes merger)
- 11th February 2016: announcement of the first neutron stars (NS) mergers by the Gravitational-Wave Observatory LIGO (LIGO + VIRGO)
- 1st December 2018: catalog of 11 GW events (10 BH , 1 NS) from the first two observation Runs
- Now: O3, Run 3 of observation (LIGO+VIRGO+KAGRA in December 2019)

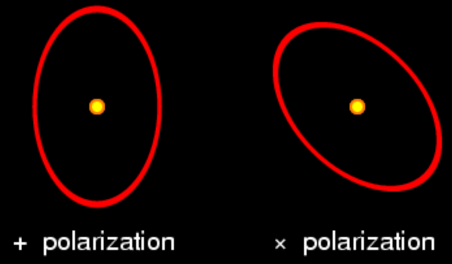
Basic Properties

- After production, GW propagate basically unaltered (no interaction with the intergalactic medium)
- Wave amplitude decrease with propagation
- Can be redshifted (cosmological, gravitation and Doppler redshift)
- Their wave form (amplitude, frequency) carries the information of their source
- More exotic effects (hard to calculate analytically, dropping linearized theory) might distort the wave from
- Produced by time variations of the mass quadrupole moment of the source

While you can have emission of EM waves from time derivative of a dipole, the derivative of a dipole of an isolated mass is zero since it equals to momentum conservation

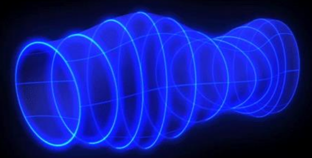
- Two polarization states
- Carry energy

http://www.tapir.caltech.edu/~teviet/Waves/gwave_details.html



The energy flux (i.e. the energy *dE* crossing an area *dA* orthogonal to the *direction of the wave* in a time *dt*) is given by

$$\frac{dE}{dA\,dt} = \frac{c^3}{32\pi G}\sum_{i,j}\dot{h}_{ij}^2 = \frac{c^3}{16\pi G}\left(\dot{h}_+^2 + \dot{h}_\times^2\right)$$

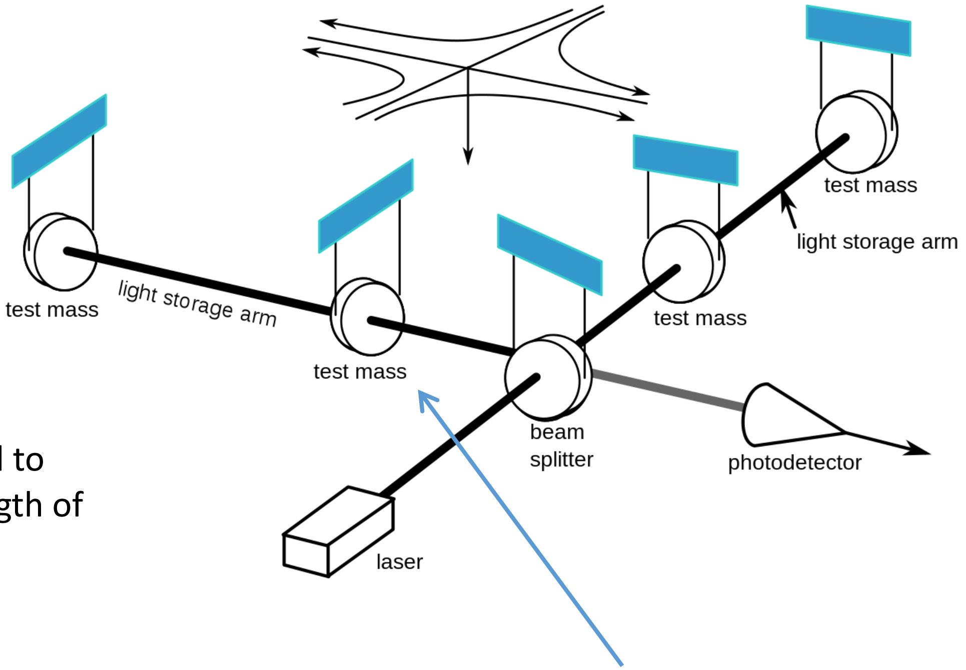


The Interferometers

LIGO: the Laser Interferometer Gravitational-Wave Observatory (LIGO)
Handford (Washington) and Livingstone (Louisiana)

VIRGO: Pisa (Italy)

https://www.ligo.caltech.edu/page/what-is-interferometer



Test masses = mirrors
Their relative position is affected by the passage of the GW

Principles of Michelson's Interferometers

- The passage of gravitational waves, with strain amplitude h (related to the actual amplitude of the GW) causes the modification of the length of the orthogonal arms Lx and Ly (=4 Km) of the interferometer:

$$\Delta L(t) = \delta L_x - \delta L_y = h(t)L$$

- An interference pattern will then appear in the photodetector
- The optical signal is proportional to the GW strain
- Nd:YAH laser, 1064 nm; 20kW at source, amplified to 100kW circulating in the arms
- 2nd best vacuum created on Earth (1st: LHC), Pressure < 1 micro Pascal

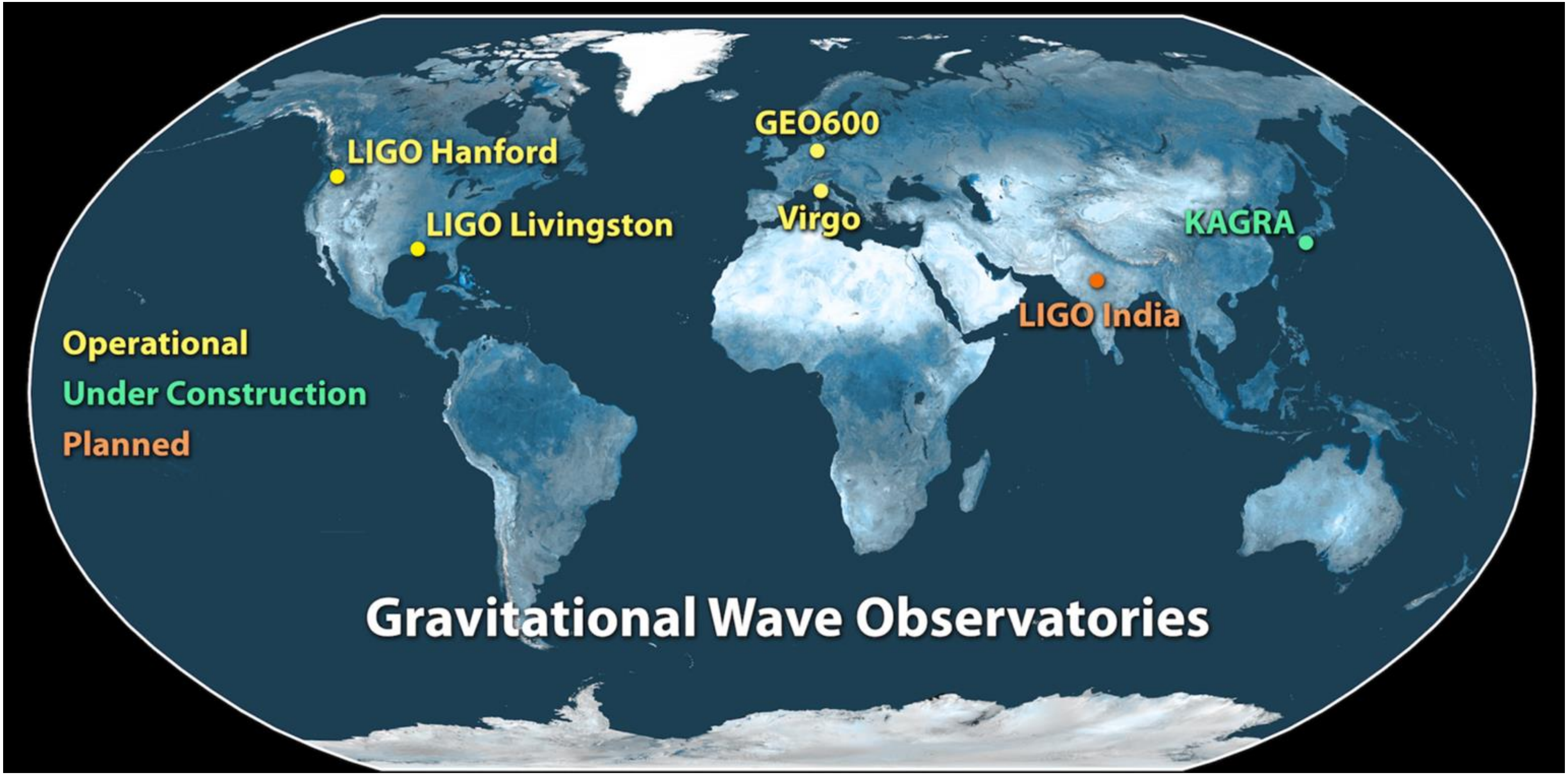
The Interferometers


Virgo (Pisa,Italy)

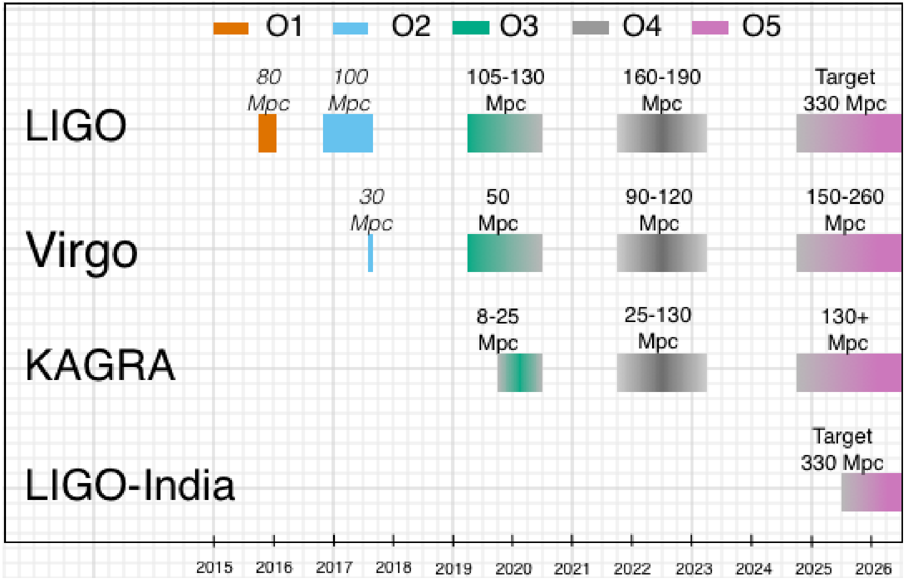

LIGO (Livingstone, USA)


LIGO (Handford, USA)

+ KAGRA (Japan): “KAGRA to Join LIGO and Virgo in Hunt for Gravitational Waves news from 4th October 2019 ” , observation run from Dec. 2019
+ LIGO India (~2025)


LIGO Hanford
LIGO Livingston
GEO600
Virgo
KAGRA
LIGO India
Operational
Under Construction
Planned
Gravitational Wave Observatories

https://www.gw-openscience.org/alerts/



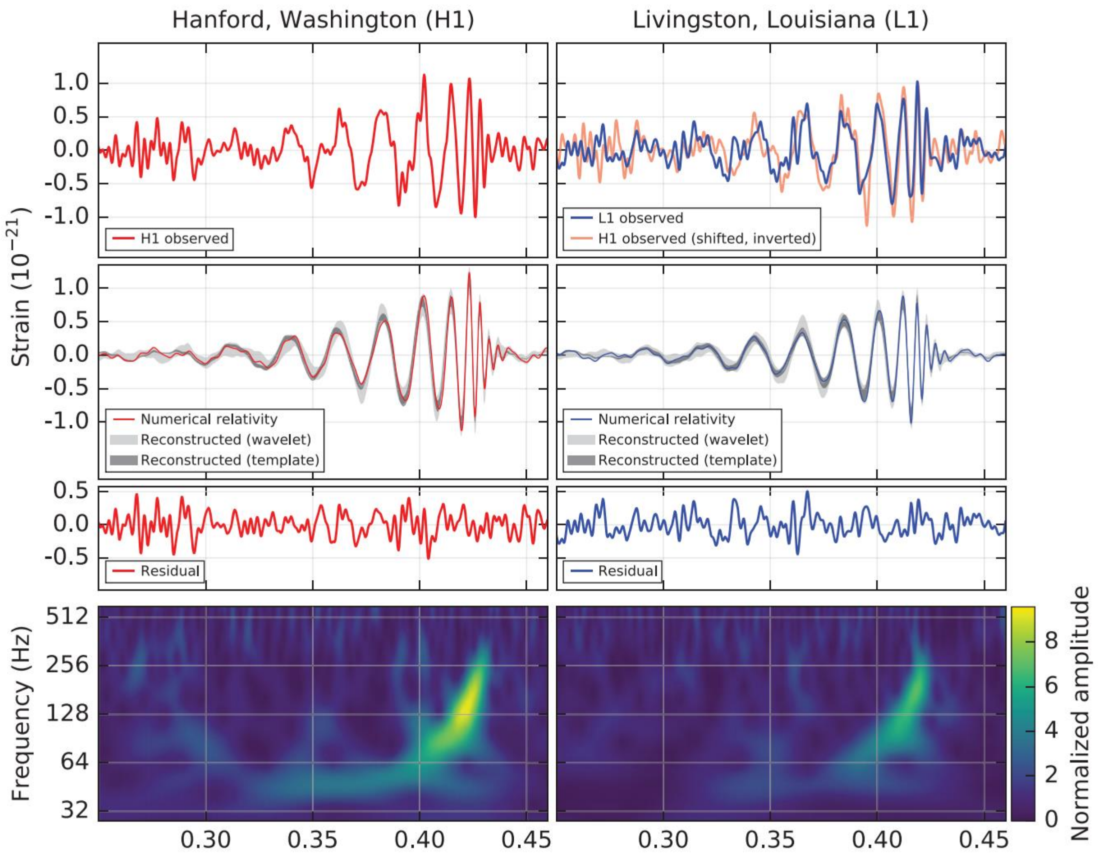
- LIGO Run O3 just restarted after ~1 month break
- KAGRA should be online by December 2019

From GCN Circular 24045:
Our third observing run ("O3") began as scheduled on 2019 April 1 at 15:00 UTC.
[...]
As of April 2 20:00 UTC, we have configured our low-latency analysis pipeline to ***send public alerts for significant gravitational-wave transient candidates that are detected in coincidence across two or more gravitational-wave detectors.***
Automated Preliminary GCN Notices will be sent immediately without any human intervention. Shortly afterward, they will be vetted by an LSC/Virgo rapid response team and either confirmed with an Initial GCN Notice and Circular, or withdrawn with a Retraction.
Retraction notices may be issued more frequently over the next few weeks as our understanding of the instrumental background improves.
[...]
This marks the beginning of the era of public alerts for the field of gravitational-wave astronomy.

+ Multimessenger Astronomy

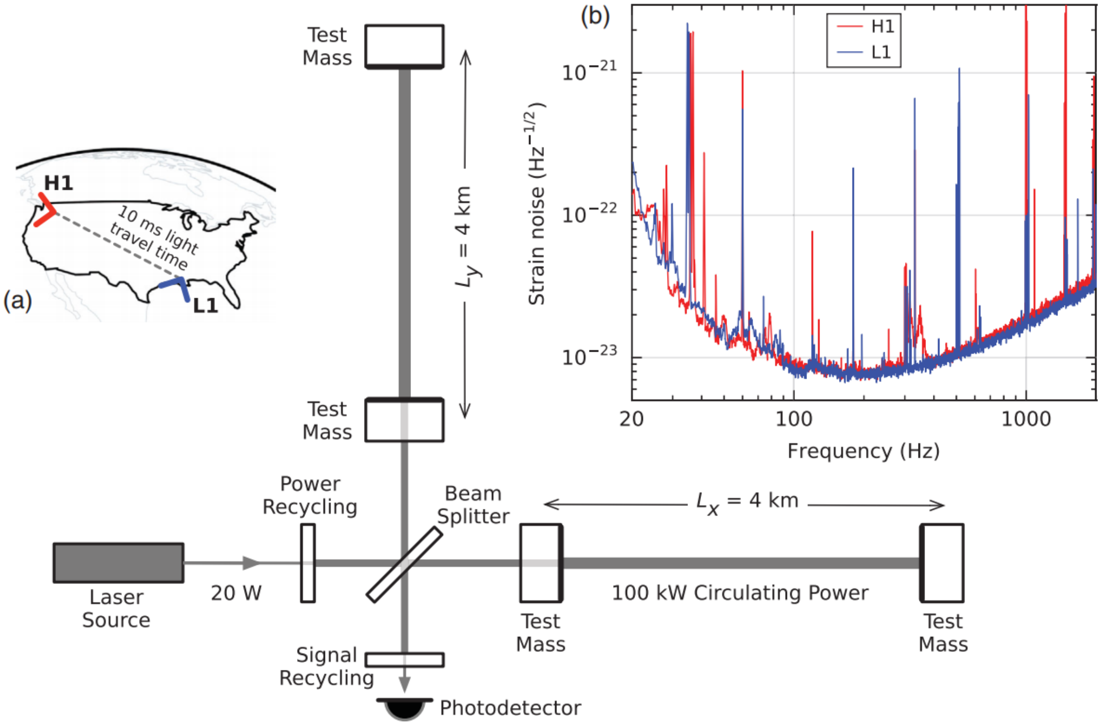
The first event: GW150914 (BBH, Binary Black Holes)

- Simultaneous observation of a transient gravitation wave signal by the two LIGO observatories on September 14, 2015
- First direct detection of gravitational waves
- First observation of a binary black hole merger
- Probability of fake signal: 1/203.000 years
- Over 0.2 s, the frequency increases from 35->150 Hz and the amplitude reaches a peak



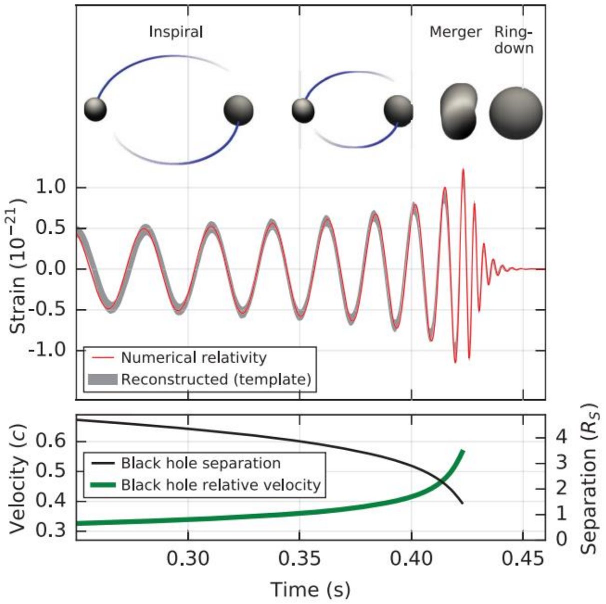
Time (s) from 09:50:45 UTC

The first event: GW150914 (BBH, Binary Black Holes)



- Instrumental noise converted to strain amplitude of the instrument close to the time of detection
- Peaks correspond to calibration lines, vibration modes of suspension fibers, power grid harmonics
- No environmental disturbances measured by surrounding instruments (seismometers, accelerometers, microphones, magnetometers, radio receivers, weather sensors, ac-power lines monitors, cosmic-rays detectors), fluctuations estimated below 6% of total GW strain
- GWs are searched in the data of the two detectors were the events are compatible with the GW propagation time H1<->L1
- (Note that GW themselves constitute a background for the measurements)

The first event: GW150914 (BBH, Binary Black Holes)



Rs = Schwarzschild radius

- Possible explanation: coalescence of black holes, i.e. their orbital inspiral and merger and final BH ringdown
- Source distance: 410+160 −180 Mpc (redshift z $=0.09^{+0.03}_{-0.04}$).
- Initial black hole masses $36^{+5}_{-4}\,M_\odot$ and $29^{+4}_{-4}\,M_\odot$, and the
- Final BH mass is $62^{+4}_{-4}\,M_\odot$
- Energy of $3.0^{+0.5}_{-0.5}M_\odot c^2$ radiated in gravitational waves

- Also possible to estimate the mass (upper limit) of the associated graviton:

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

TABLE I. Source parameters for GW150914. We report median values with 90% credible intervals that include statistical errors, and systematic errors from averaging the results of different waveform models. Masses are given in the source frame; to convert to the detector frame multiply by $(1+z)$ [90]. The source redshift assumes standard cosmology [91].

Primary black hole mass	$36^{+5}_{-4}M_\odot$
Secondary black hole mass	$29^{+4}_{-4}M_\odot$
Final black hole mass	$62^{+4}_{-4}M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$

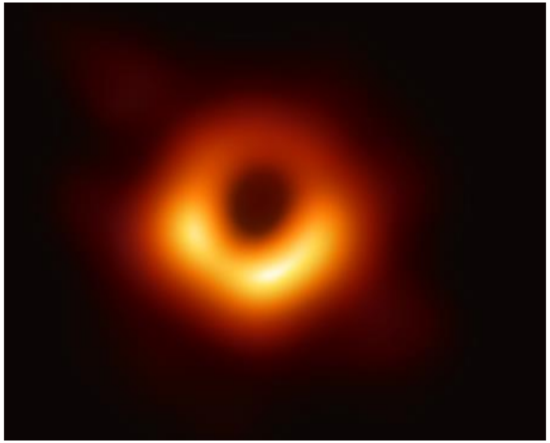
Note: extensive searches for EM follow up of the GW events were performed
EM emission is expected when neutron stars are involved in the merging
See e.g. http://www.esa.int/Science_Exploration/Space_Science/Integral_sets_limits_on_gamma_rays_from_merging_black_holes

2018 Catalog: 10 GWs events from BBHs

Since April 10th 2019 : we „see“ them! *Event Horizon Telescope Collaboration*

https://eventhorizontelescope.org/blog/first-ever-image-black-hole-published-event-horizon-telescope-collaboration

https://eventhorizontelescope.org/press-release-april-10-2019-astronomers-capture-first-image-black-hole



*Scientists have obtained the first image of a black hole, using Event Horizon Telescope observations of the center of the galaxy M87. The image shows a bright ring formed as light bends in the intense gravity around a black hole that is 6.5 billion times more massive than the Sun. This long-sought image provides the **strongest evidence to date for the existence of supermassive black holes** and opens a new window onto the study of black holes, their event horizons, and gravity.*

Note: $\mathbf{6.5 \times 10^9\ M_\odot}$ >> than the typical mass of BH detected by gravitational waves $M_{BH,gw} \approx 40\ M_\odot$
i.e. two different types of BHs

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.)

THE ASTROPHYSICAL JOURNAL LETTERS, 848:L12 (59pp), 2017 October 20 https://doi.org/10.3847/2041-8213/aa91c9

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Multi-messenger Observations of a Binary Neutron Star Merger

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(See the end matter for the full list of authors.)

(953 authors)

[Higgs boson discovery paper, ATLAS+CMS Collaborations: 5,154 Authors]

GW170817 Binary Neutron Stars Merger and Multi-Messenger Astronomy with GWs

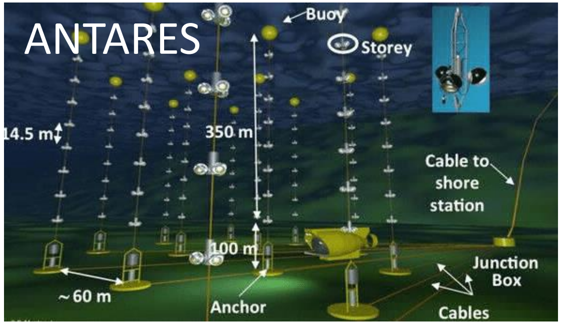
Fermi

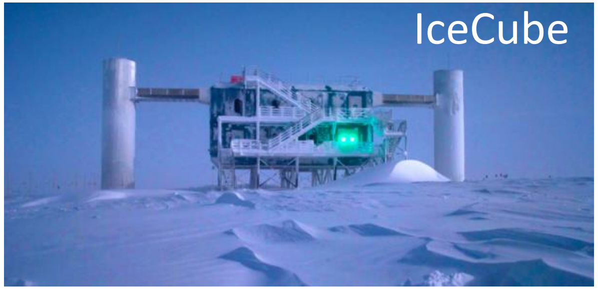
Pierre Auger

Integral

Chandra

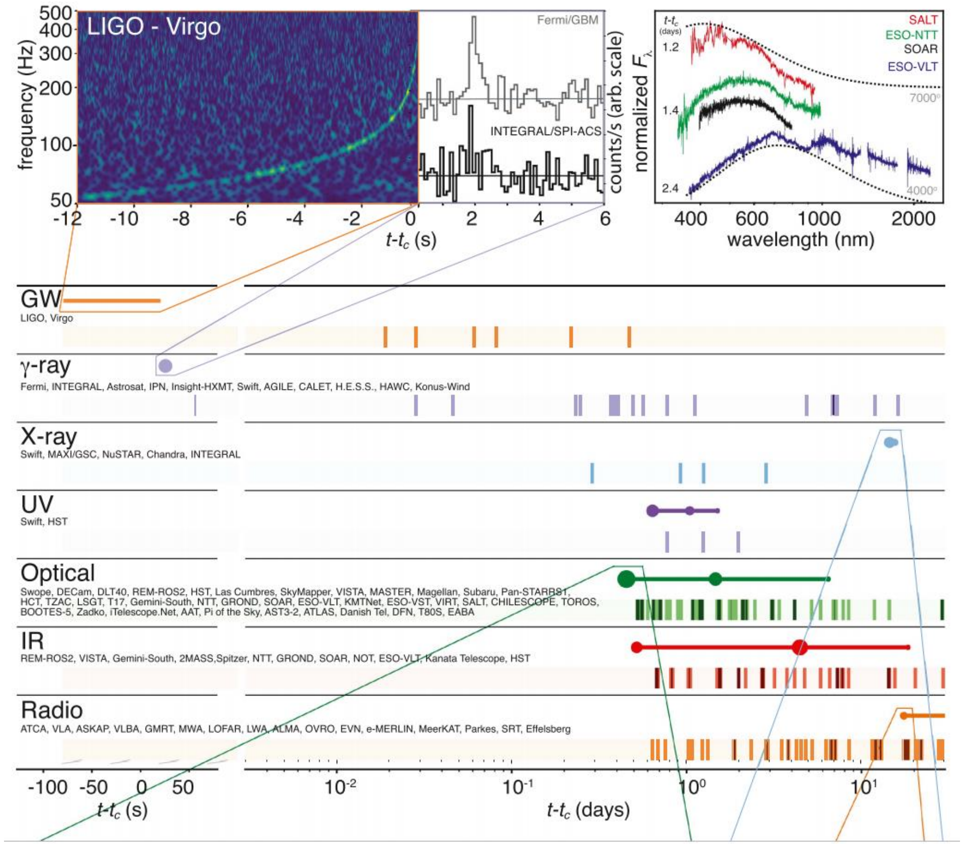
LIGO/VIRGO





- ***First joint detection of gravitational and electromagnetic radiation from a single source***
- ~ 100 s long gravitational-wave signal (GW170817)
- followed by a short Gamma Ray Burst (sGRB, GRB 170817A)
- and an optical transient (SSS17a/AT 2017gfo) found in the host galaxy NGC 4993

- Data compatible with Binary Neutron Stars merger (BNSs), followed by sGRB and a kilonova



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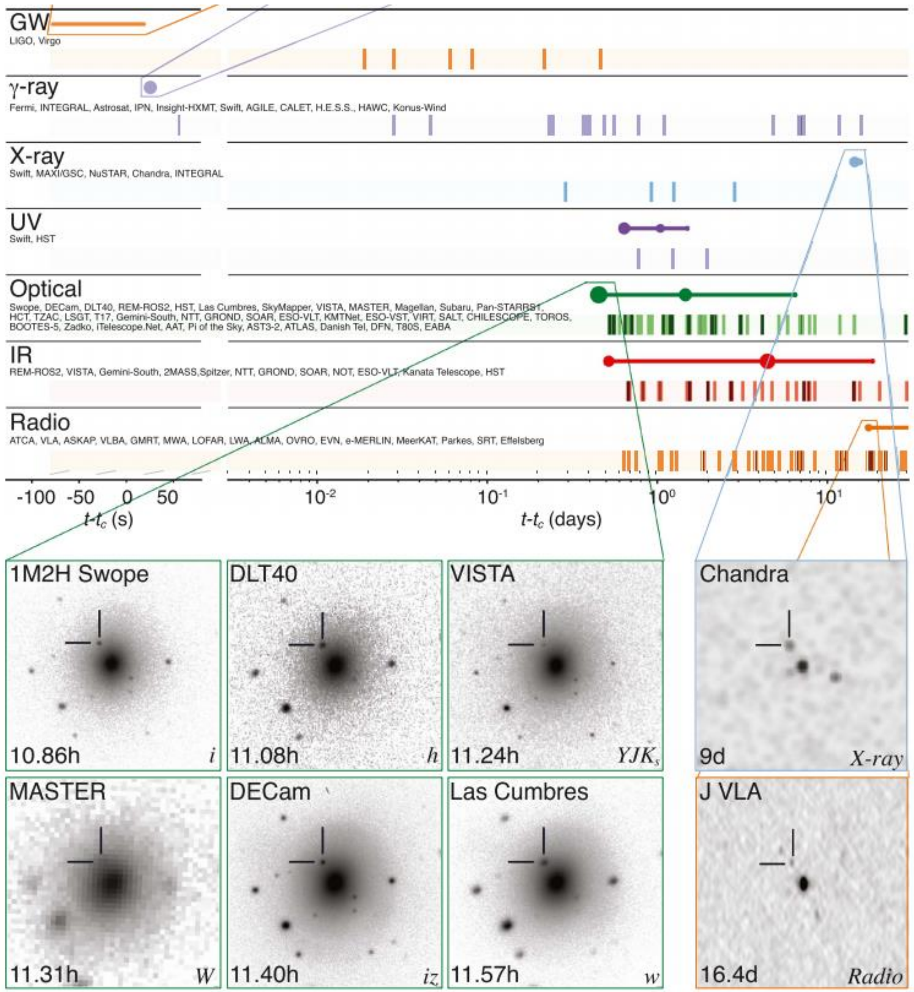


Chronology

- On **2017 August 17 12:41:06 UTC** the Fermi GBM onboard flight software triggered on, classified, and localized a GRB. A Gamma-ray Coordinates Network Notice (Fermi-GBM 2017) was issued at **12:41:20 UTC** announcing the detection of the GRB 170817A

- **~ 6 minutes** later, a GW candidate (GW170817) was registered based on a single-detector analysis of the LIGO Hanford data, consistent with a BNS coalescence, with merger time, tc, **12:41:04 UTC**, less than 2 s before GRB 170817A.

- A GCN Notice was issued at **13:08:16 UTC**. Single-detector gravitational-wave triggers had never been disseminated before in low latency. Given the temporal coincidence with the Fermi-GBM GRB, however, a GCN Circular was issued at **13:21:42 UTC** (LIGO Scientific Collaboration & Virgo Collaboration et al. 2017a) reporting that a highly significant candidate event consistent with a BNS coalescence was associated with the time of the GRB959.

- An extensive observing campaign was launched across the electromagnetic spectrum in response to the Fermi-GBM and LIGO–Virgo detections, and especially the subsequent well-constrained, three-dimensional LIGO–Virgo localization

- A bright optical transient (SSS17a, now with the IAU identification of AT 2017gfo) was discovered in NGC 4993 (at ~40 Mpc) by the 1M2H team SWOPE (**August 18 01:05 UTC**; Coulter et al. 2017a) less than 11 hr after the merger

Gravitational-wave Observation

- single-detector trigger, GCN Notice at 13:08:16 UTC
- Three detectors reanalyses (LIGO Hanford, Livingstone, Virgo) confirmed high significance
- GW lasted for ~100 s

Virgo -> Livingstone (+22 ms) -> Hanford(+3 ms)

- Model: binary neutron stars coalescence

$$m_1 \in (1.36\text{–}2.26\ )M_\odot$$
$$m_2 \in (0.86\text{–}1.36)M_\odot$$

$\Rightarrow$ $M_{BH}= \ 2.82^{+0.47}_{-0.09} M_\odot$

"However, for this event gravitational-wave data alone cannot rule out objects more compact than neutron stars such as quark stars or black hole"

Prompt Gamma Ray Burst

- GRB detected at T0 = 12:41:06 UTC, Fermi-GBM at 12:41:20 UTC nitce (14s after detection) classified as a short GRB
- Main pulse encompassing the GRB trigger time from T0 - 0.320 s to
- T0 + 0.256 s, followed by a weak tail starting at T0 + 0.832 s and extending to T0 1.984 s

Discovery of the Optical Counterpart

https://arxiv.org/pdf/1710.05833.pdf

- Broadband observing campaign in search of electromagnetic counterparts after the announcements of Fermi and Virgo-Ligo, using using ground- and space-based telescopes
- 1M2H team was the first to discover a bright optical transient on August 17 at 23:33 UTC (tc + 10.87 hr) with the 1 m Swope telescope at Las Campanas Observatory in Chile

Broadband Follow Up

- Plethora of observations performed by many experiments covering all the EM spectrum (infrared, radio, X-Rays, late Gammas…)

Neutrinos

- Neutrinos: no highly energetic neutrinos found by the IceCube, ANTARES or Pierre Auger observatories

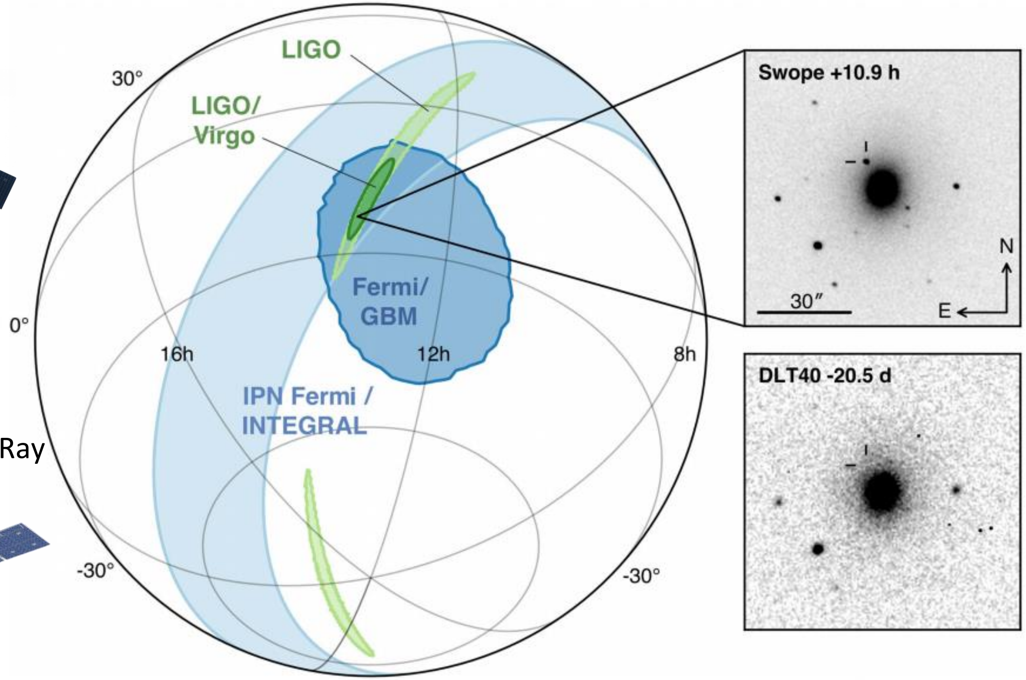
> *"[…] For the first time, gravitational and electromagnetic waves from a single source have been observed. The gravitationa lwave observation of a binary neutron star merger is the first of its kind. The electromagnetic observations further support the interpretation of the nature of the binary, and comprise three components at different wavelengths: (i) a prompt sGRB that demonstrates that BNS mergers are the progenitor of at least a fraction of such bursts; (ii) an ultraviolet, optical, and infrared transient (kilonova), which allows for the identification of the host galaxy and is associated with the aftermath of the BNS merger; and (iii) delayed X-ray and radio counterparts that provide information on the environment of the binary"*

GW170817 Binary Neutron Stars and Multi-Messenger Astronomy with GWs

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

Fermi

Host Galaxy NGC 4993



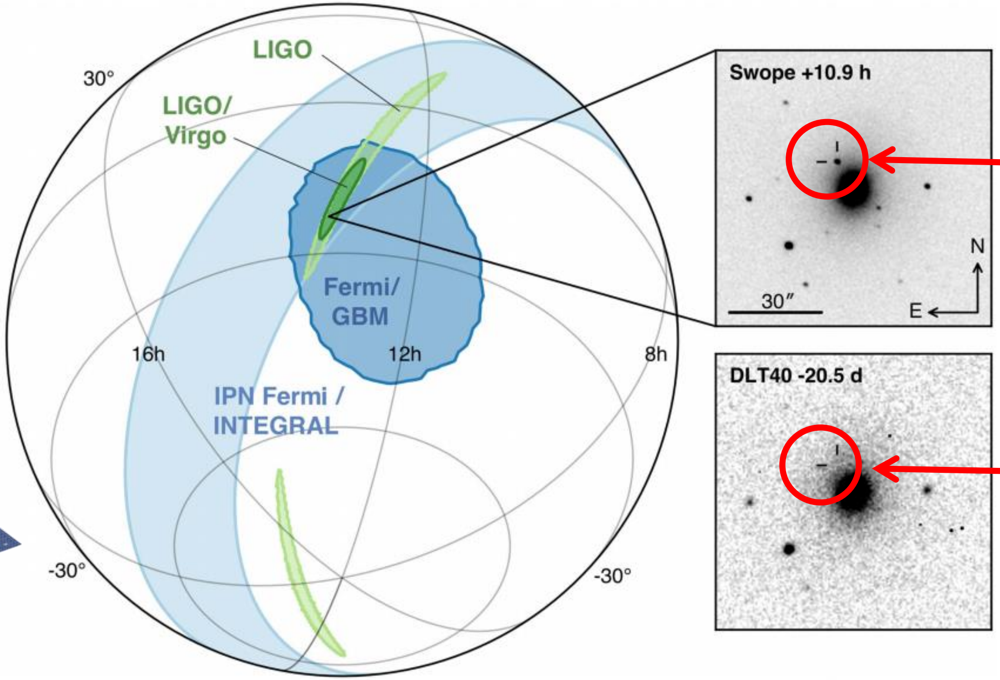
INTEGRAL
(INTErnational Gamma-Ray
Astrophysics)

Figure 1. Localization of the gravitational-wave, gamma-ray, and optical signals. The left panel shows an orthographic projection of the 90% credible regions from LIGO (190 deg^2; light green), the initial LIGO-Virgo localization (31 deg^2; dark green), IPN triangulation from the time delay between *Fermi* and *INTEGRAL* (light blue), and *Fermi*-GBM (dark blue). The inset shows the location of the apparent host galaxy NGC 4993 in the Swope optical discovery image at 10.9 hr after the merger (top right) and the DLT40 pre-discovery image from 20.5 days prior to merger (bottom right). The reticle marks the position of the transient in both images.

Besides carrying diverse information, multiple detectors/exp improve the localization of the position of the possible source

THE ASTROPHYSICAL JOURNAL LETTERS, 848:L12 (59pp), 2017 October 20 Abbott et al.

Fermi



Host Galaxy NGC 4993

! 10.9 h after the GW detection

~20 days before the GW detection

INTEGRAL

Figure 1. Localization of the gravitational-wave, gamma-ray, and optical signals. The left panel shows an orthographic projection of the 90% credible regions from LIGO (190 deg^2; light green), the initial LIGO-Virgo localization (31 deg^2; dark green), IPN triangulation from the time delay between *Fermi* and *INTEGRAL* (light blue), and *Fermi*-GBM (dark blue). The inset shows the location of the apparent host galaxy NGC 4993 in the Swope optical discovery image at 10.9 hr after the merger (top right) and the DLT40 pre-discovery image from 20.5 days prior to merger (bottom right). The reticle marks the position of the transient in both images.

Besides carrying diverse information, multiple detectors/exp improve the localization of the position of the possible source

The O1/O2 2018 Events Catalog

On December 1, 2018 the LIGO/Virgo Collaboration published a catalog of their searches for gravitational-waves from stellar-mass coalescing compact binaries:

- 10 BHBH events
- 1 NSNS event

https://www.ligo.org/science/Publication-O2BBHPop/flyer.pdf

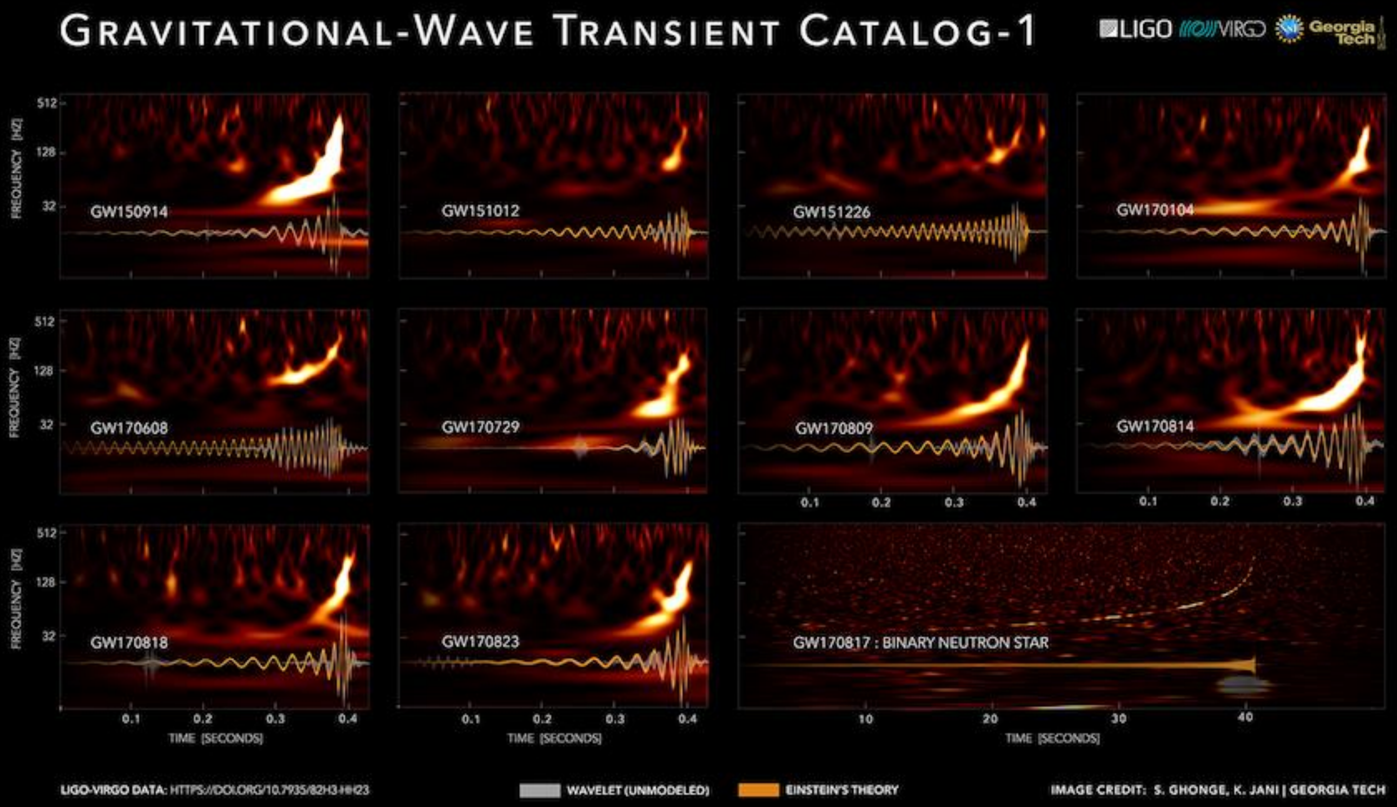
Event	$m_1/\mathrm{M}_\odot$	$m_2/\mathrm{M}_\odot$	$\mathcal{M}/\mathrm{M}_\odot$	χ_{eff}	$M_\mathrm{f}/\mathrm{M}_\odot$	a_f	$E_{\mathrm{rad}}/(\mathrm{M}_\odot c^2)$	$\ell_{\mathrm{peak}}/(\mathrm{erg\,s}^{-1})$	d_L/Mpc	z	$\Delta\Omega/\mathrm{deg}^2$
GW150914	$35.6^{+4.8}_{-3.0}$	$30.6^{+3.0}_{-4.4}$	$28.6^{+1.6}_{-1.5}$	$-0.01^{+0.12}_{-0.13}$	$63.1^{+3.3}_{-3.0}$	$0.69^{+0.05}_{-0.04}$	$3.1^{+0.4}_{-0.4}$	$3.6^{+0.4}_{-0.4}\times 10^{56}$	430^{+150}_{-170}	$0.09^{+0.03}_{-0.03}$	179
GW151012	$23.3^{+14.0}_{-5.5}$	$13.6^{+4.1}_{-4.8}$	$15.2^{+2.0}_{-1.1}$	$0.04^{+0.28}_{-0.19}$	$35.7^{+9.9}_{-3.8}$	$0.67^{+0.13}_{-0.11}$	$1.5^{+0.5}_{-0.5}$	$3.2^{+0.8}_{-1.7}\times 10^{56}$	1060^{+540}_{-480}	$0.21^{+0.09}_{-0.09}$	1555
GW151226	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.6}$	$8.9^{+0.3}_{-0.3}$	$0.18^{+0.20}_{-0.12}$	$20.5^{+6.4}_{-1.5}$	$0.74^{+0.07}_{-0.05}$	$1.0^{+0.1}_{-0.2}$	$3.4^{+0.7}_{-1.7}\times 10^{56}$	440^{+180}_{-190}	$0.09^{+0.04}_{-0.04}$	1033
GW170104	$31.0^{+7.2}_{-5.6}$	$20.1^{+4.9}_{-4.5}$	$21.5^{+2.1}_{-1.7}$	$-0.04^{+0.17}_{-0.20}$	$49.1^{+5.2}_{-3.9}$	$0.66^{+0.08}_{-0.10}$	$2.2^{+0.5}_{-0.5}$	$3.3^{+0.6}_{-0.9}\times 10^{56}$	960^{+430}_{-410}	$0.19^{+0.07}_{-0.08}$	924
GW170608	$10.9^{+5.3}_{-1.7}$	$7.6^{+1.3}_{-2.1}$	$7.9^{+0.2}_{-0.2}$	$0.03^{+0.19}_{-0.07}$	$17.8^{+3.2}_{-0.7}$	$0.69^{+0.04}_{-0.04}$	$0.9^{+0.0}_{-0.1}$	$3.5^{+0.4}_{-1.3}\times 10^{56}$	320^{+120}_{-110}	$0.07^{+0.02}_{-0.02}$	396
GW170729	$50.6^{+16.6}_{-10.2}$	$34.3^{+9.1}_{-10.1}$	$35.7^{+6.5}_{-4.7}$	$0.36^{+0.21}_{-0.25}$	$80.3^{+14.6}_{-10.2}$	$0.81^{+0.07}_{-0.13}$	$4.8^{+1.7}_{-1.7}$	$4.2^{+0.9}_{-1.5}\times 10^{56}$	2750^{+1350}_{-1320}	$0.48^{+0.19}_{-0.20}$	1033
GW170809	$35.2^{+8.3}_{-6.0}$	$23.8^{+5.2}_{-5.1}$	$25.0^{+2.1}_{-1.6}$	$0.07^{+0.16}_{-0.16}$	$56.4^{+5.2}_{-3.7}$	$0.70^{+0.08}_{-0.09}$	$2.7^{+0.6}_{-0.6}$	$3.5^{+0.6}_{-0.9}\times 10^{56}$	990^{+320}_{-380}	$0.20^{+0.05}_{-0.07}$	340
GW170814	$30.7^{+5.7}_{-3.0}$	$25.3^{+2.9}_{-4.1}$	$24.2^{+1.4}_{-1.1}$	$0.07^{+0.12}_{-0.11}$	$53.4^{+3.2}_{-2.4}$	$0.72^{+0.07}_{-0.05}$	$2.7^{+0.4}_{-0.3}$	$3.7^{+0.4}_{-0.5}\times 10^{56}$	580^{+160}_{-210}	$0.12^{+0.03}_{-0.04}$	87
GW170817	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$	$1.186^{+0.001}_{-0.001}$	$0.00^{+0.02}_{-0.01}$	≤ 2.8	≤ 0.89	≥ 0.04	$\geq 0.1\times 10^{56}$	40^{+10}_{-10}	$0.01^{+0.00}_{-0.00}$	16
GW170818	$35.5^{+7.5}_{-4.7}$	$26.8^{+4.3}_{-5.2}$	$26.7^{+2.1}_{-1.7}$	$-0.09^{+0.18}_{-0.21}$	$59.8^{+4.8}_{-3.8}$	$0.67^{+0.07}_{-0.08}$	$2.7^{+0.5}_{-0.5}$	$3.4^{+0.5}_{-0.7}\times 10^{56}$	1020^{+430}_{-360}	$0.20^{+0.07}_{-0.07}$	39
GW170823	$39.6^{+10.0}_{-6.6}$	$29.4^{+6.3}_{-7.1}$	$29.3^{+4.2}_{-3.2}$	$0.08^{+0.20}_{-0.22}$	$65.6^{+9.4}_{-6.6}$	$0.71^{+0.08}_{-0.10}$	$3.3^{+0.9}_{-0.8}$	$3.6^{+0.6}_{-0.9}\times 10^{56}$	1850^{+840}_{-840}	$0.34^{+0.13}_{-0.14}$	1651

TABLE III. Selected source parameters of the eleven confident detections. We report median values with 90% credible intervals that include statistical errors, and systematic errors from averaging the results of two waveform models for BBHs. For GW170817 credible intervals and statistical errors are shown for IMRPhenomPv2NRT with low spin prior, while the sky area was computed from TaylorF2 samples. The redshift for NGC 4993 from [87] and its associated uncertainties were used to calculate source frame masses for GW170817. For BBH events the redshift was calculated from the luminosity distance and assumed cosmology as discussed in Appendix B. The columns show source frame component masses m_i and chirp mass $\mathcal{M}$, dimensionless effective aligned spin χ_{eff}, final source frame mass M_f, final spin a_f, radiated energy E_{rad}, peak luminosity l_{peak}, luminosity distance d_L, redshift z and sky localization $\Delta\Omega$. The sky localization is the area of the 90% credible region. For GW170817 we give conservative bounds on parameters of the final remnant discussed in Sec. V E.

Spectrograms and waveforms for the gravitational-wave transient catalog

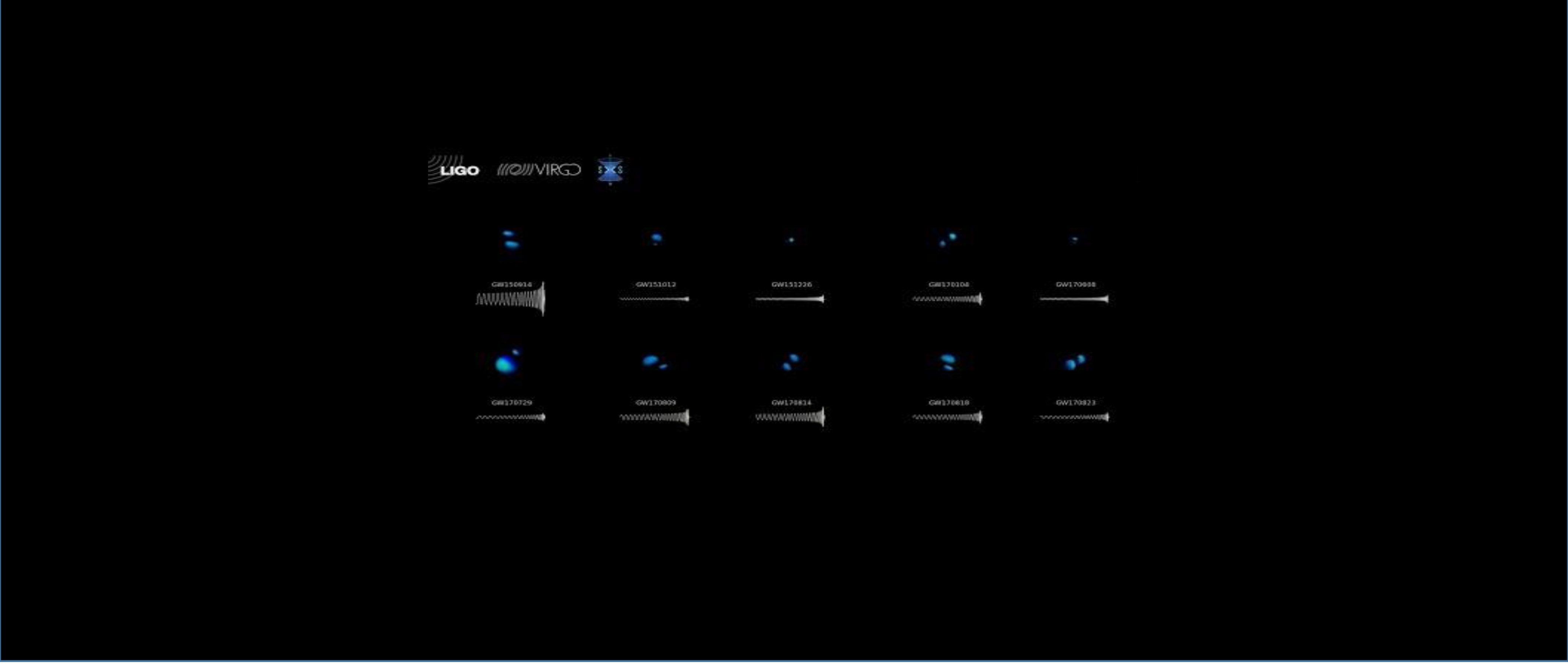
The spectrogram color indicates a measure of signal strength; the increase of signal frequency with time clearly shows the characteristic "chirp" signature of a binary inspiral.

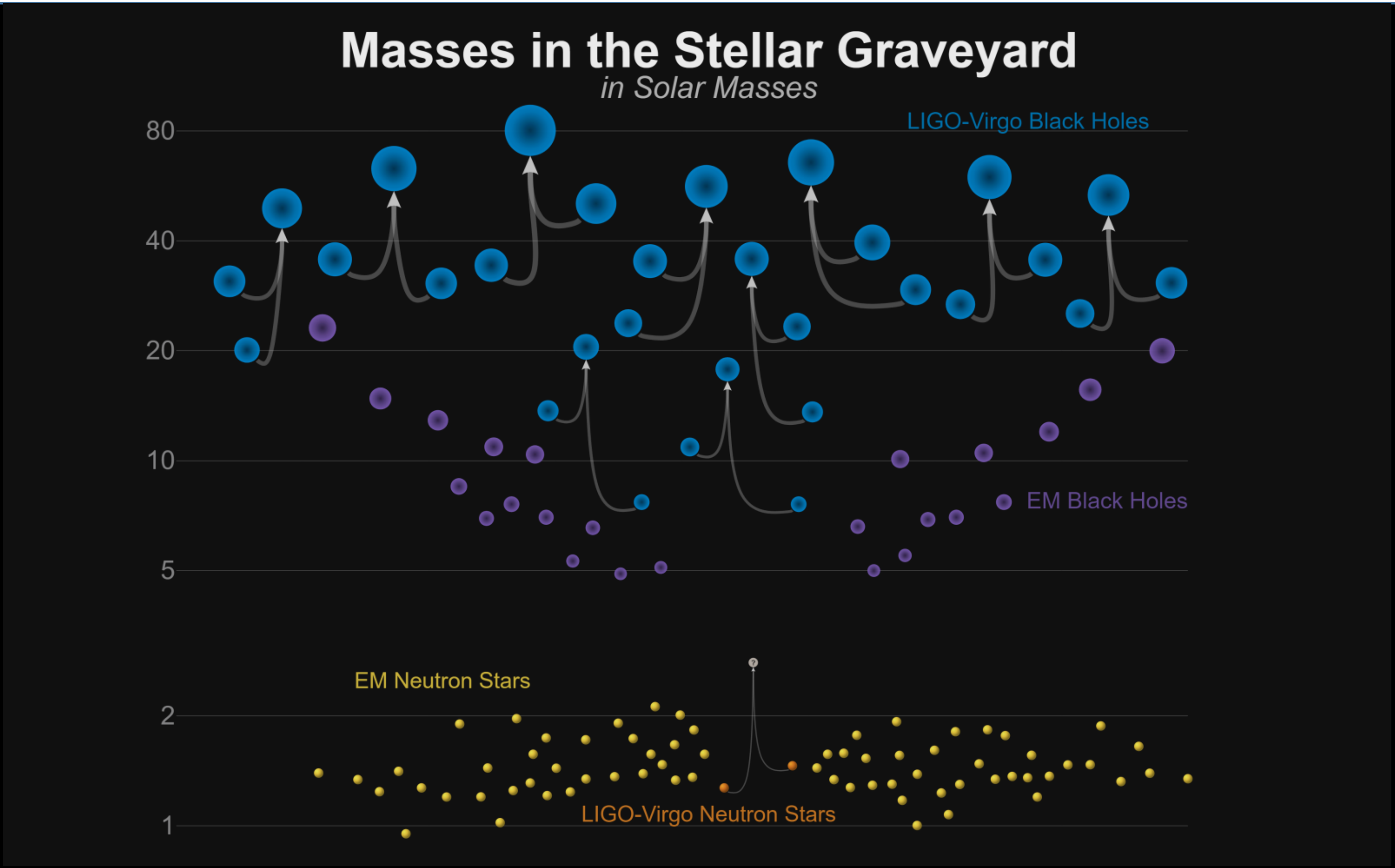
The waveforms shown at the bottom of each panel are produced from either a range of models based on Einstein's theory (orange) or a wavelet decomposition of the observed signal (gray).



The O1/O2 2018 Events Catalog

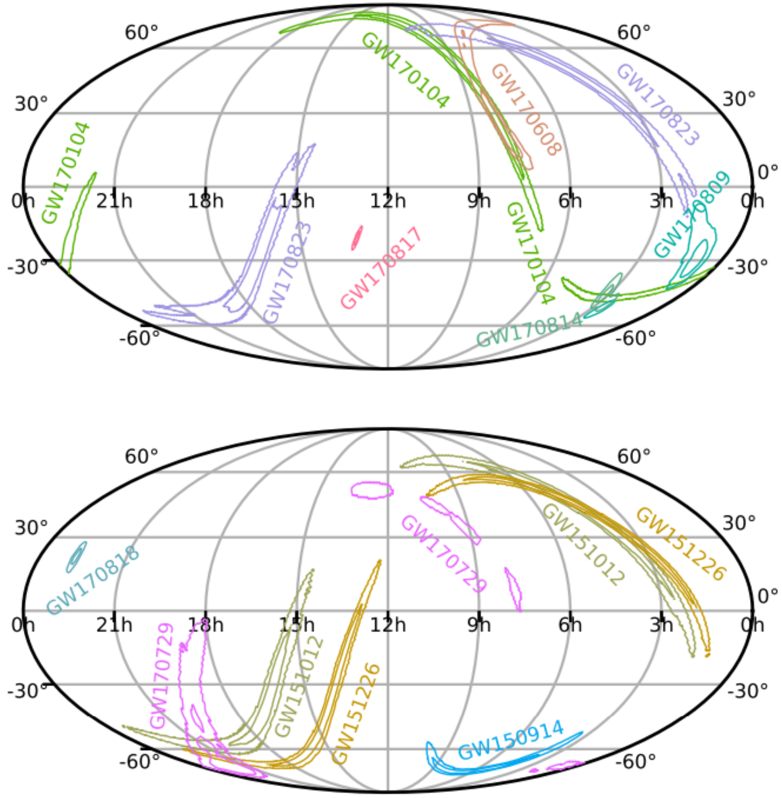
https://www.youtube.com/watch?v=9xY53UyQjQs





Masses in the Stellar Graveyard
in Solar Masses
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
?

Projections in the Sky



Distributions of Masses

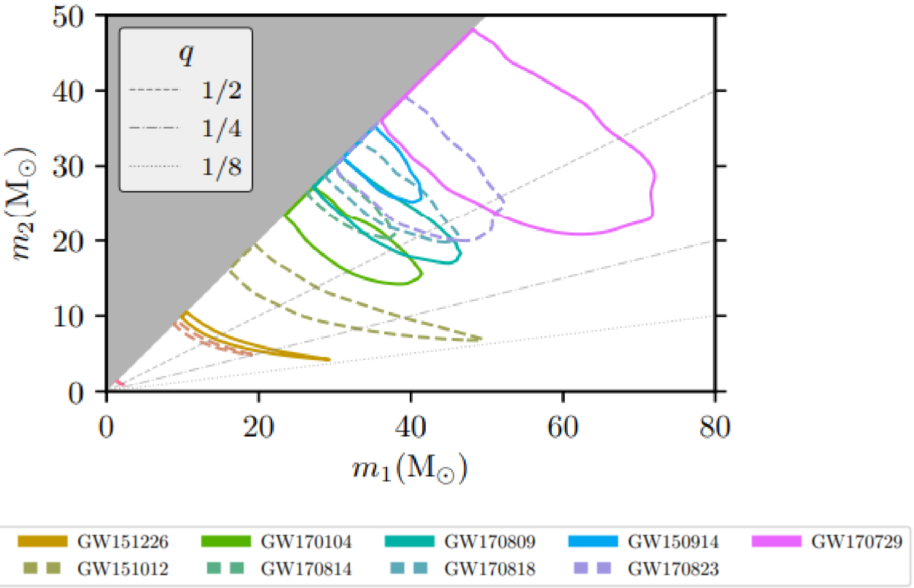


FIG. 4. Parameter estimation summary plots I. Posterior probability densities of the masses, spins, and SNR of the GW events. For the two-dimensional distributions, the contours show 90% credible regions. *Left panel:* Source frame component masses m_1 and m_2. We use the convention that $m_1 \geq m_2$, which produces the sharp cut in the two-dimensional distribution. Lines of constant mass ratio $q = m_2/m_1$ are shown for $1/q = 2, 4, 8$. For low-mass events, the contours follow lines of constant chirp mass. *Right panel:* The mass M_f and dimensionless spin magnitude a_f of the final black holes. The colored event labels are ordered by source frame chirp mass. The same color code and ordering (where appropriate) apply to Figs. 5 to 8.

GWs as a test for Cosmology and the Evolution of the Universe

- It is possible to use the use the properties of the sources of the GWs observed to constrain Cosmology and evolution models
- Neutron Star – Black Hole merger (NSBH) not seen yet

- It is possible to set upper limits, with a certain confidence level (here 90%) on the number of events per volume of universe per unit of time
- GW170817 used as a *Standard Sirene (see next)*

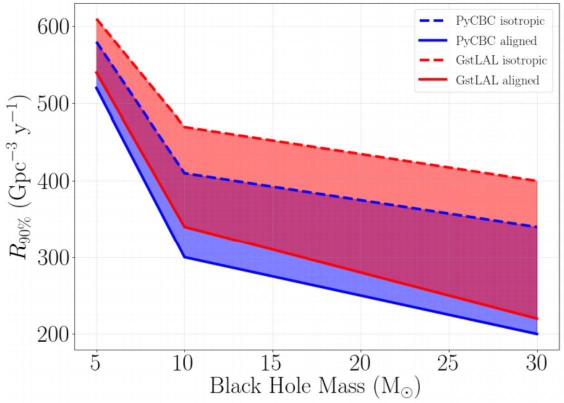


FIG. 14. This figure shows the 90% rate upper limit for the NSBH category, measured at a set of three discrete BH masses (5, 10, 30 $M_\odot$) with the fiducial NS mass fixed to 1.4 $M_\odot$. The upper limit is evaluated for both matched-filter search pipelines, with GstLAL corresponding to red curves and PyCBC to blue. We also show two choices of spin distributions: isotropic (dashed lines) and aligned spin (solid lines).

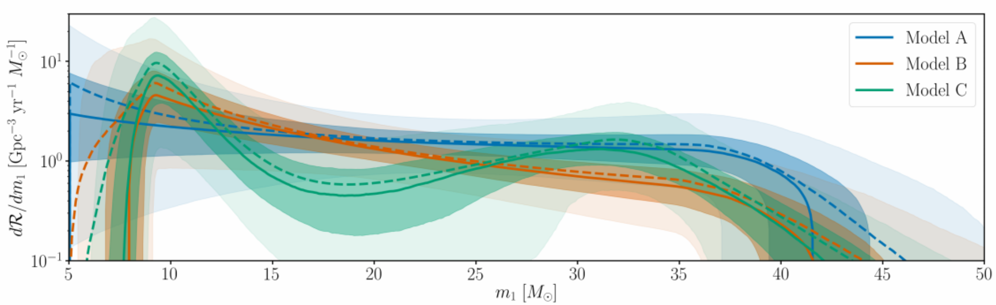


Figure 2: *The number of black holes of a given mass which participate in mergers over a given volume of space, for a few different model assumptions. Model A has the least amount of complexity and Model C is the most complex. The solid lines, dark shades, and light shades show the median, 50%, and 90% credible intervals, and the dashed line shows the 'posterior population distribution', or best prediction for what mass a typical population member might have. Adapted from Figure 1 in the paper.*

https://www.ligo.org/science/Publication-O2BBHPop/index.php

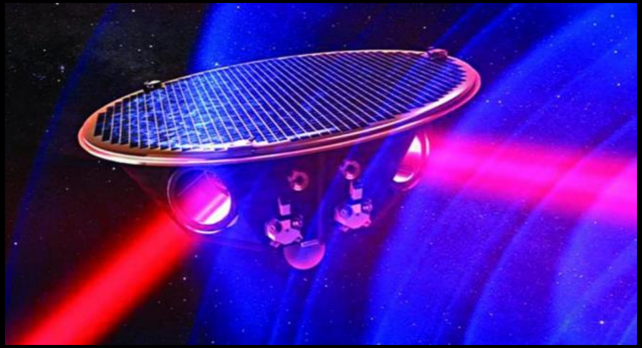
"GW measurements of black holes have already had profound implications for stellar astrophysics. Most black holes are heavier than the previously known population of stellar-mass black holes from EM obs. of X-ray binary systems; this told us something about how and where heavy BBHs might have formed. "

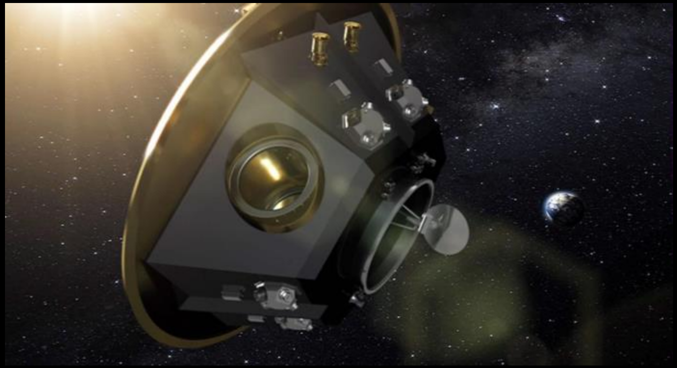
The Future: Space Interferometers

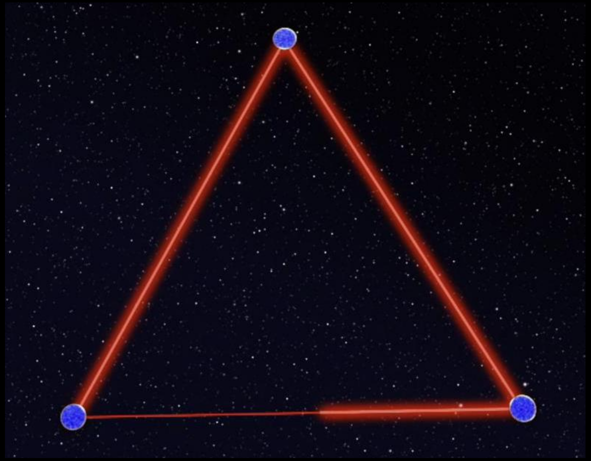
Laser Interferometer Space Antenna (LISA) mission of the European Space Agency

http://www.esa.int/Science_Exploration/Space_Science/A_unique_experiment_to_explore_black_holes

https://www.elisascience.org/files/publications/LISA_L3_20170120.pdf







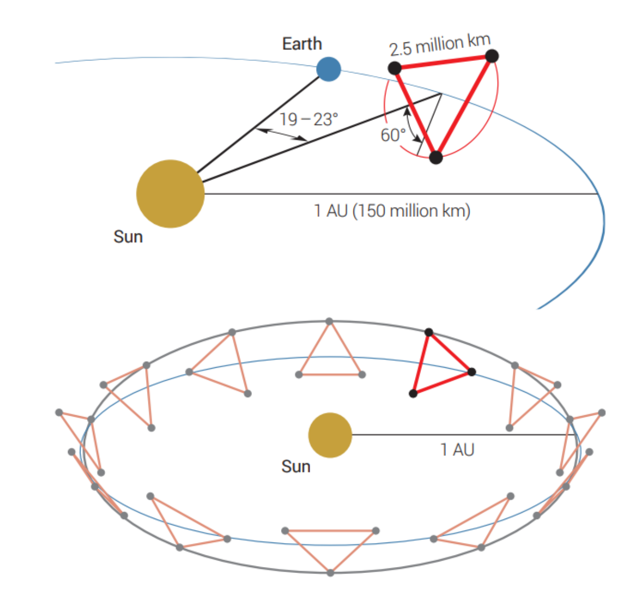


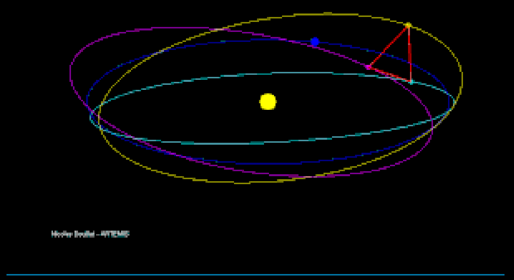
Figure 4: Depiction of the LISA Orbit.

Laser Interferometer Space Antenna (LISA) mission of the European Space Agency

http://www.esa.int/Science_Exploration/Space_Science/A_unique_experiment_to_explore_black_holes

https://www.elisascience.org/files/publications/LISA_L3_20170120.pdf

- First dedicated space-based gravitational wave detector
- Three spacecraft arranged in an equilateral triangle with sides 2.5 million km long, flying along an Earth-like heliocentric orbit



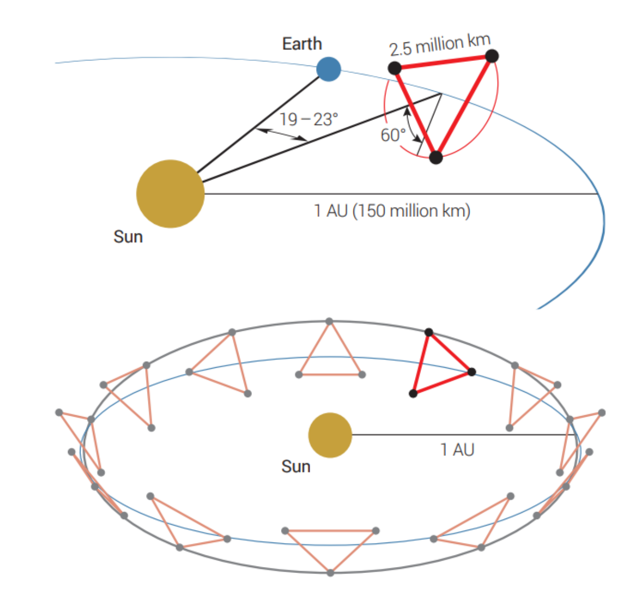
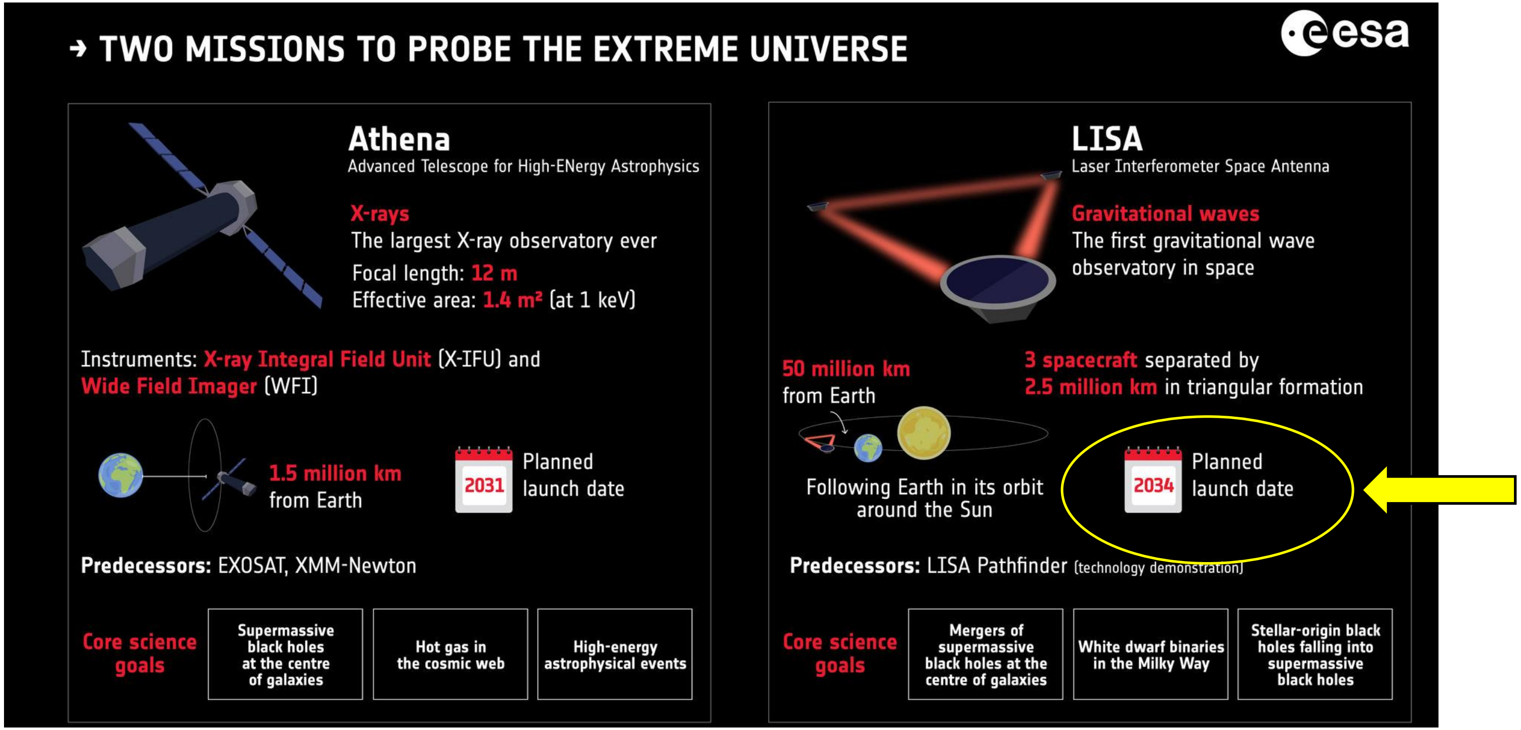


Figure 4: Depiction of the LISA Orbit.

- Each of the spacecraft contains two telescopes, two lasers and two test masses (each a 46 mm, 2 kg, gold-coated cube of gold/platinum)
- 2.5 million km corresponds to 8.3 seconds or 0.12 Hz

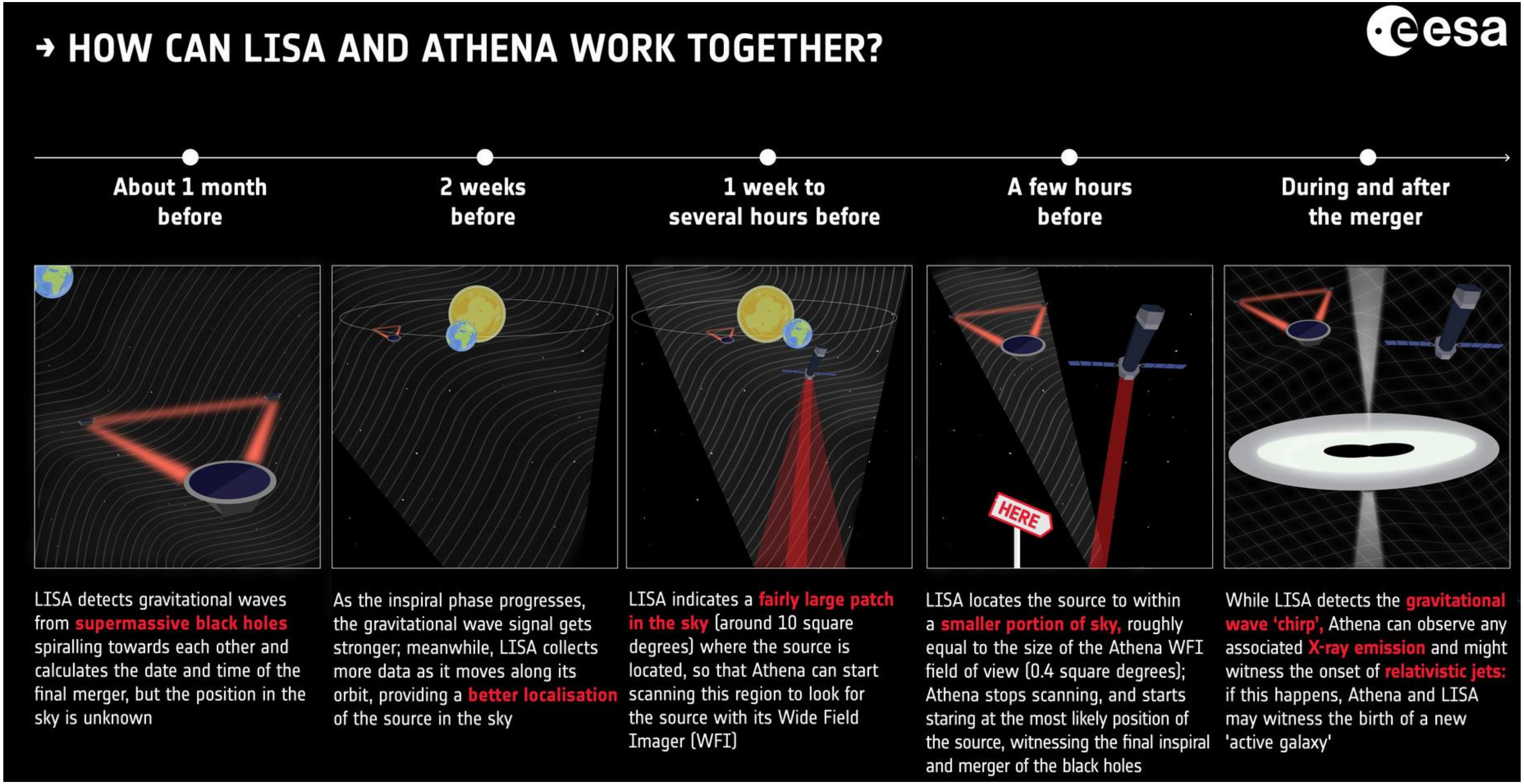
Laser Interferometer Space Antenna (LISA) mission of the European Space Agency

http://www.esa.int/Science_Exploration/Space_Science/A_unique_experiment_to_explore_black_holes



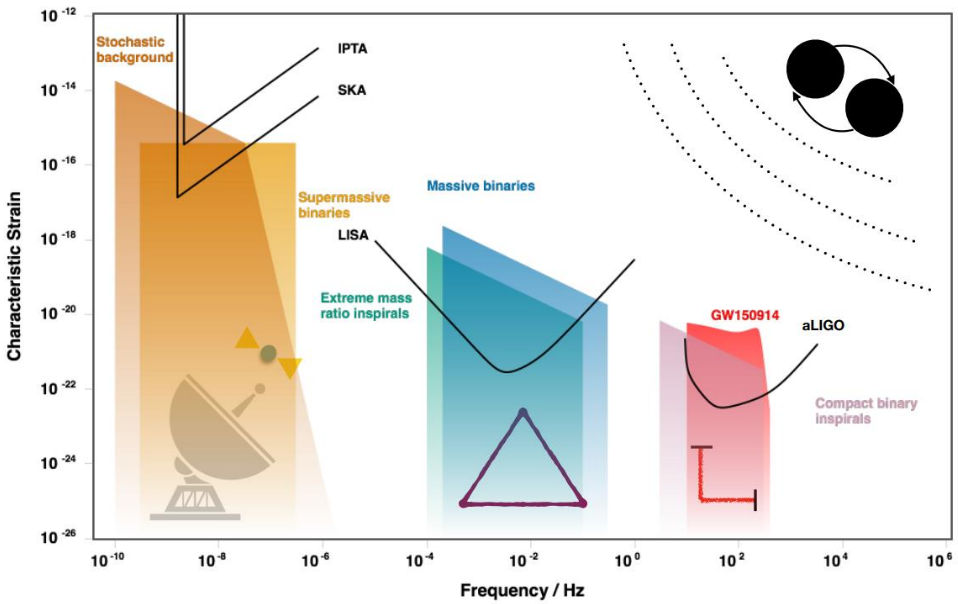
"[…] But there is one extremely exciting experiment that we could only perform if both missions are operational at the same time for at least a few years: bringing sound to the 'cosmic movies' by observing the merger of supermassive black holes both in X-rays and gravitational waves"

The Future: Space Interferometers



The Future: Space Interferometers

https://arxiv.org/pdf/1806.06979.pdf



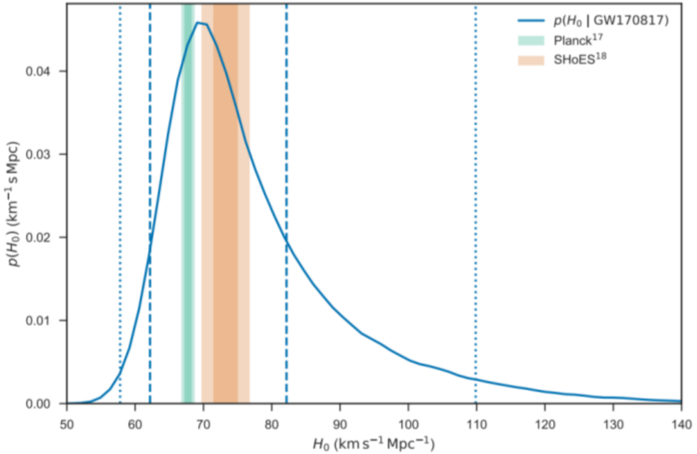
- With LISA it will be possible to observe e.g. BBHs months to week before the actual merger with great accuracy in determining the position in the sky
- The actual merger could be then detected by aLIGO
- This makes it possible to follow the merging events in time

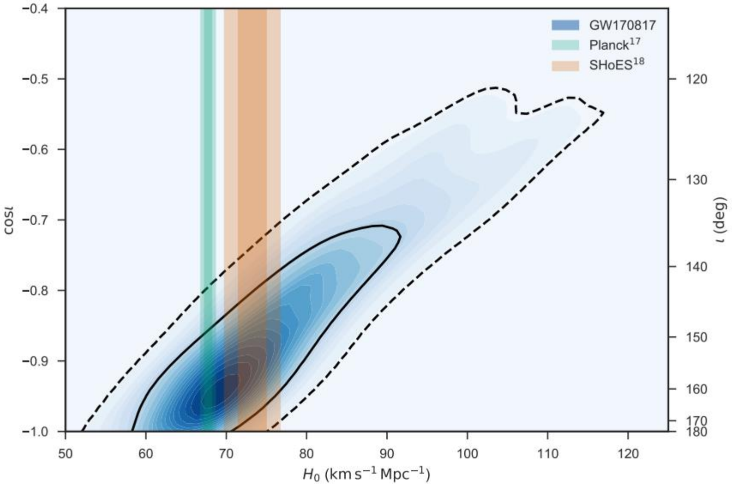
- EMRI (extreme mass ratio inspirals): e.g. BH of ~50 $M_\odot$ inspiraling around a massive BH (~10^6 $M_\odot$) that should be common in the galactic centres
- Stochastic gravitational waves background (e.g. from Inflation, phase transitions, spontaneous symmetry breaking)
- […]

GW170817 Measurement of H_0 – *GWs as Standard Sirene*

*A GRAVITATIONAL-WAVE **STANDARD SIREN** MEASUREMENT OF THE HUBBLE CONSTANT*

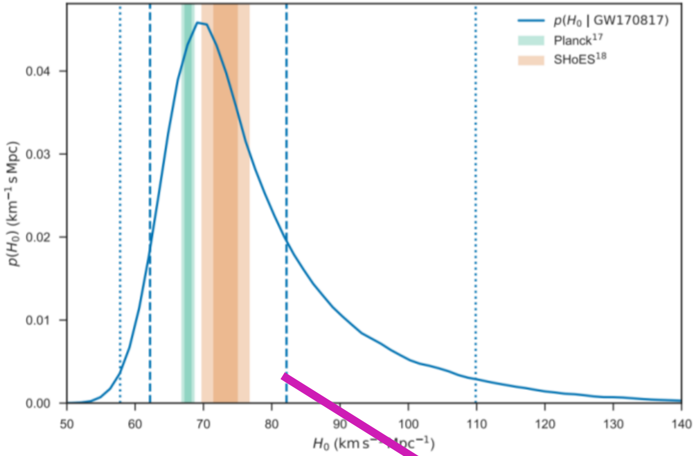
https://arxiv.org/pdf/1710.05835.pdf
SHoES: https://arxiv.org/pdf/1903.07603.pdf



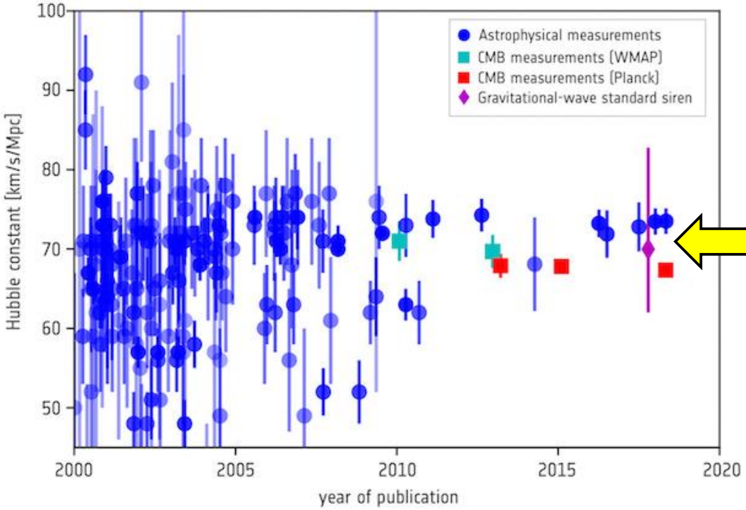


A GRAVITATIONAL-WAVE ***STANDARD SIREN*** *MEASUREMENT OF THE HUBBLE CONSTANT*

https://arxiv.org/pdf/1710.05835.pdf
SHoES: https://arxiv.org/pdf/1903.07603.pdf

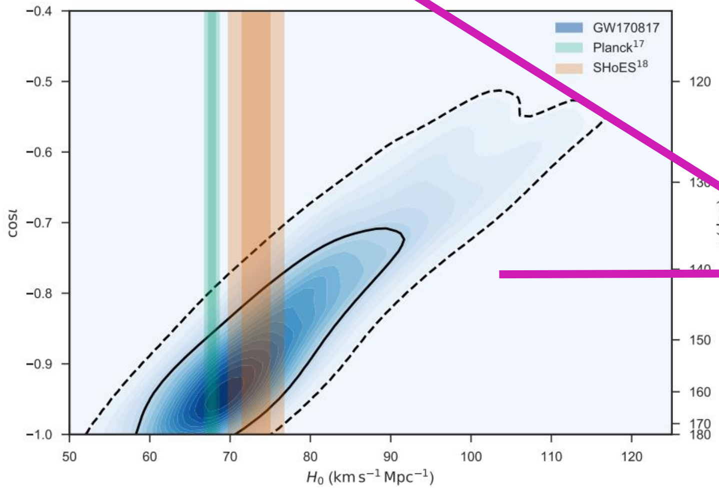


https://www.theguardian.com/science/2019/nov/02/hubble-constant-mystery-that-keeps-getting-bigger-estimate-rate-expansion-universe-cosmology-cepheid



??? Maybe New Physics needed in the ΛCDM ???

[Next Lecture]



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

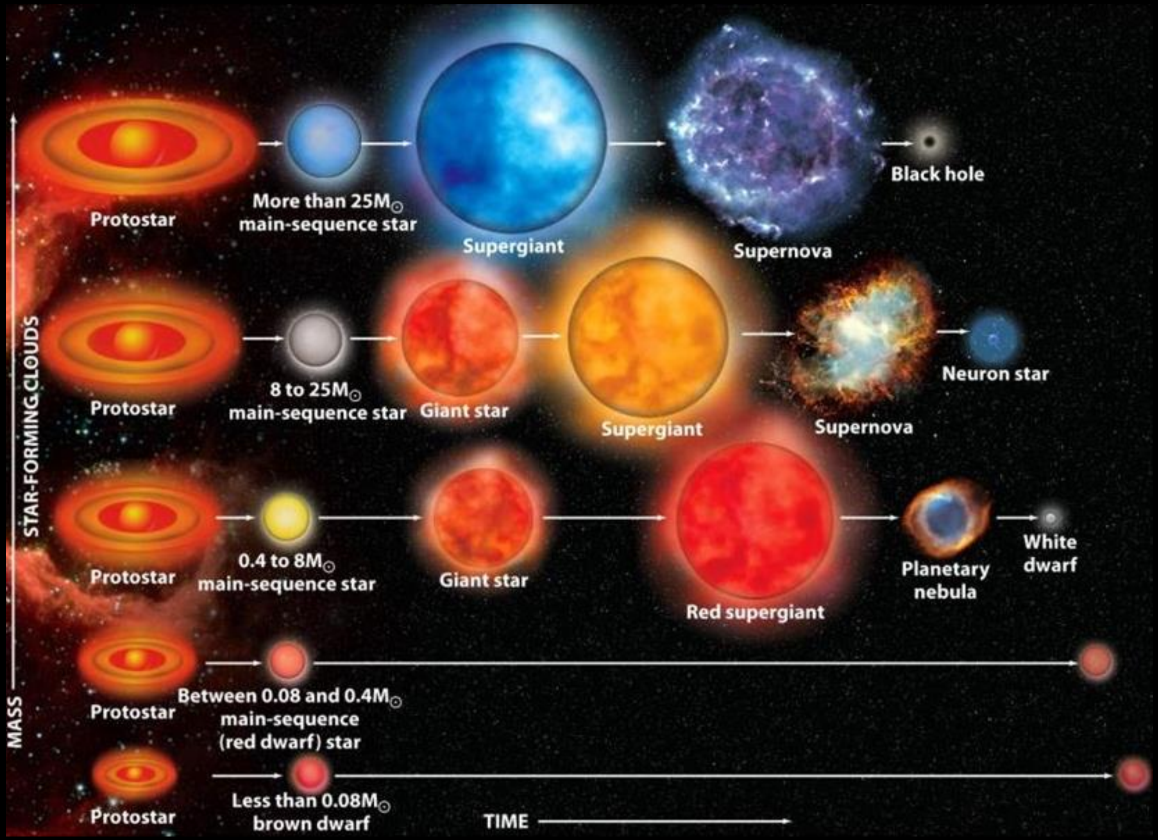
[Hubble's constant in SI units is 1.62×10^{-18} / s]
1 Pc = 3.26 light years

"With two years of observation LISA can measure the Hubble constant more accurately than any present method, and with a comparable accuracy to that expected from other future space missions."

https://sci.esa.int/web/planck/-/60504-measurements-of-the-hubble-constant

Some Extras

Stellar Evolution (i.e. Where BHs and NSs come from)



Take home

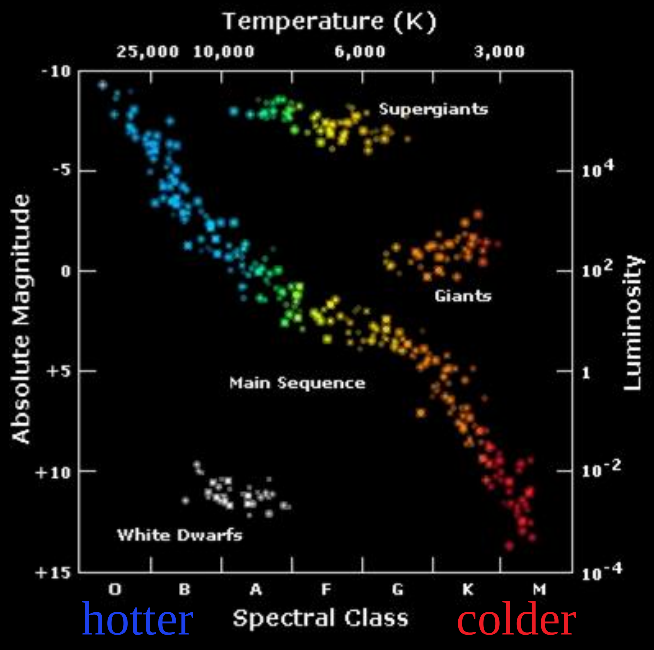
- Star evolution mostly depends on the mass of the original gas cloud
- Metallicity i.e. chemical composition impacts fusion processes
- For initial mass Mi > 0.08 $M_\odot$ -> white dwarfs
- For Mi > 8 $M_\odot$ -> Supernova (SN) explosion and NS remnant

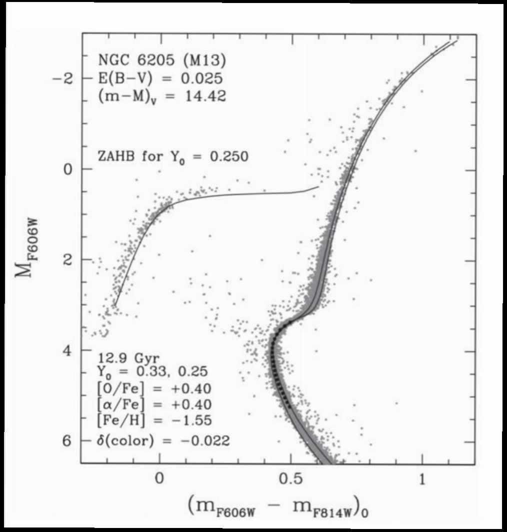
- For Mi > 8 $M_\odot$ -> SN explosion and formation of BHs (fallback or direct)

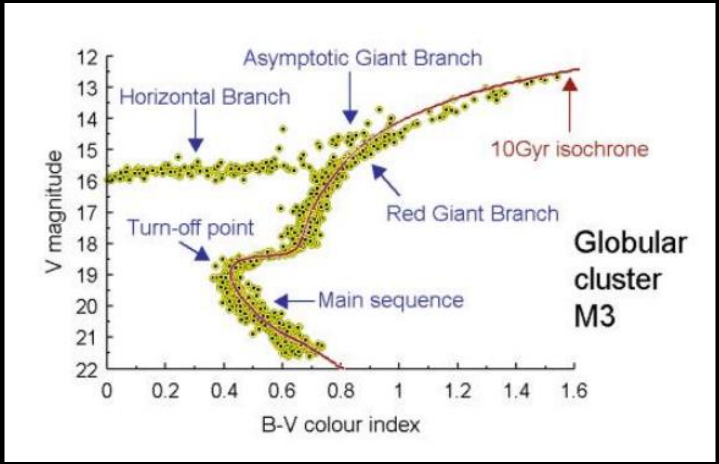
Stellar evolution end with the creation of White Dwarfs, SNe, Neutron Satrs, Black Holes which are sources of gravitationl waves!

[Typical numbers of neutron star:
Mass ~ 1.4 $M_\odot$
radius ~ 10 Km
magnetic field 10^{12} Gauss (LHC: 4 T = 40k Gauss, average in Milky way ~ microGauss, Earth surface~0.2 Gauss)]

Stellar Evolution (i.e. Where BHs and NSs come from)







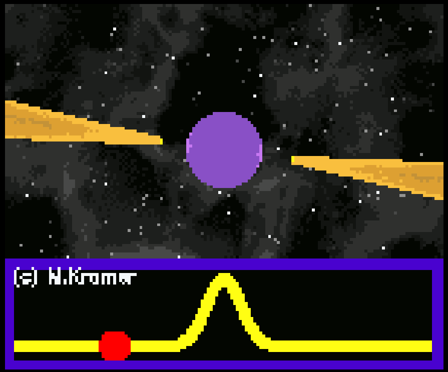
- Isochrone: curve on the HR diagram representing a population of stars of ~ same age (like e.g. globular clusters)
- By fitting the stellar population with a model isochrone, it is possible to estimate the population age
- Each feature (e.g. turning points, branches,…) of the isochrone can be explained by models of stellar evolution (type/size/region of nuclear fusion processes)

Pulsars

http://www.jb.man.ac.uk/distance/frontiers/pulsars/section1.html

- Pulsars (Pulsating Radio Source) are rapidly spinning neutron stars
- Their rotation period span from the order of milliseconds to the order of ~8 seconds
- Pulse: collection of radio waves of different frequencies
- Rotation period extremely stable, although the rotation speed slows down with time
- „Lighthouse“ effect

Composite optical/X-ray image of the Crab Nebula, showing synchrotron emission in the surrounding pulsar wind nebula, powered by injection of magnetic fields and particles from the central pulsar.



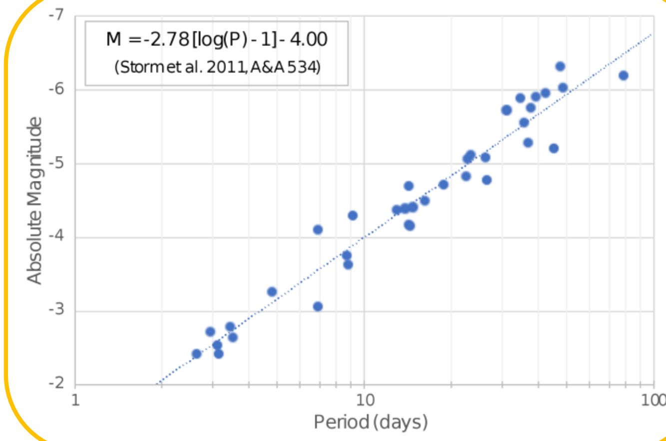
Optical image of the Crab nebula (NOAO).
The arrow marks the position of the pulsar.

Standard Candle and Standard Sirens

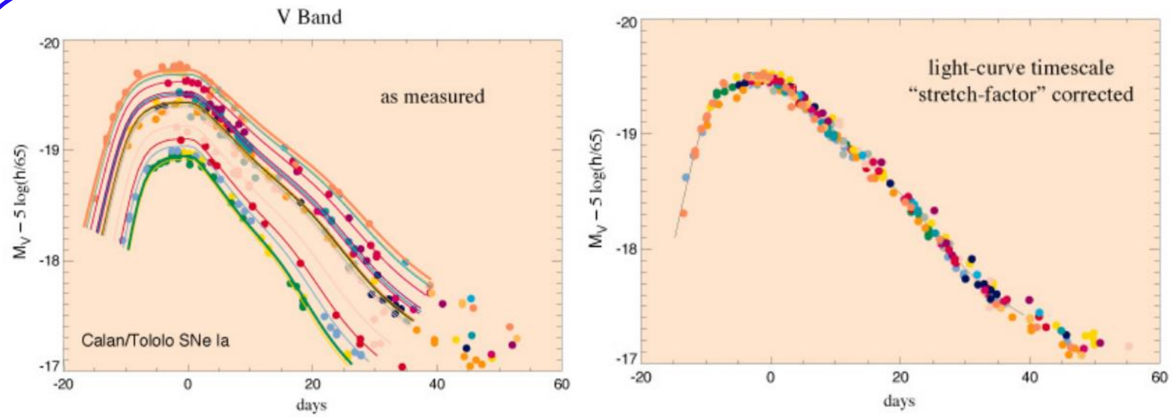
- Determining accurate astrophsical object distances is extremely important and typically challenging
- Standard candles (def. By Henrietta Leavitt) are astronomical objects used as physical distance indicators
- SNe Ia are also standard candles since the total luminosity is known from models
- They are caused by the mass accretion of a Carbon-Oxygen white dwarf from a stellar companion, eventually exceeding the Chandrasekhar limit for degenerate electron (1.44 $M_{\odot}$)
  (they were crucial for the discovery of the accelerated expansion of the universe due to Dark Energy)

Atrophysical objects / events with known properties and defined, calculable brightness → ***From observed luminosity one can extract the distance***

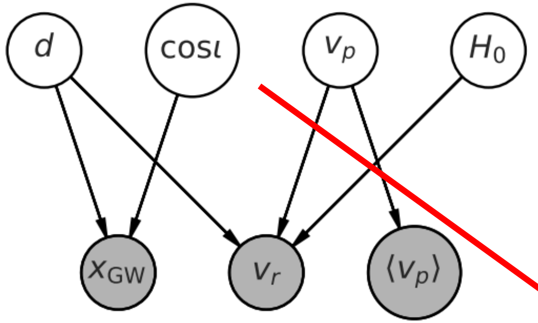
Cepheides stars



Supernovae Ia



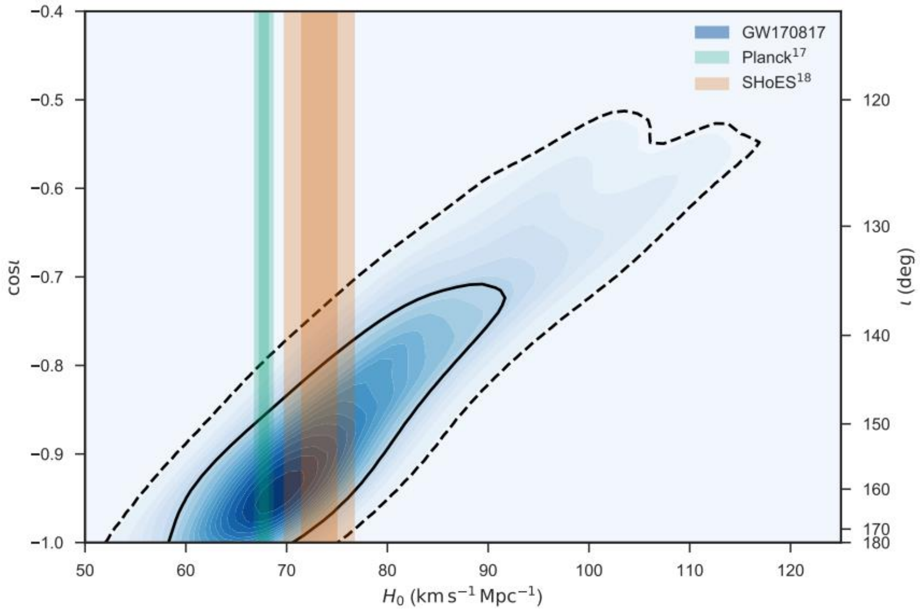
Standard Candle and Standard Sirens

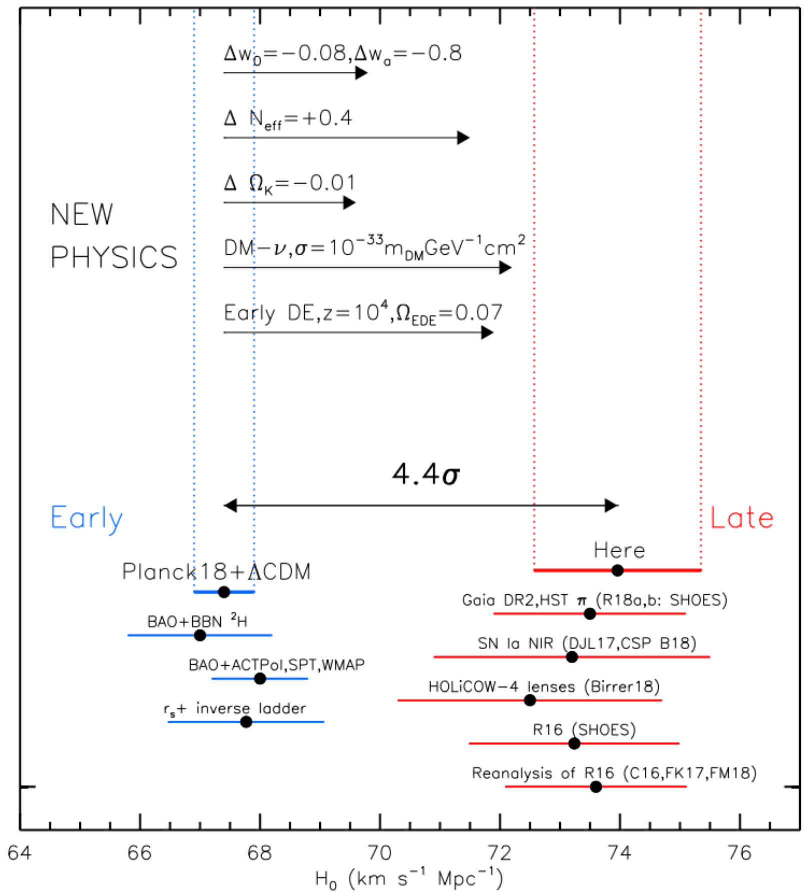


Parameters

Observed Data

Extended Data Figure 1. Graphical model illustrating the statistical relationships between the data and parameters. Open circles indicate parameters which require a prior; filled circles described measured data, which are conditioned on in the analysis. Here we assume we have measurements of the GW data, x_{GW}, a recessional velocity (i.e. redshift), v_r, and the mean peculiar velocity in the neighborhood of NGC 4993, $\langle v_p \rangle$. Arrows flowing into a node indicate that the conditional probability density for the node depends on the source parameters; for example, the conditional distribution for the observed GW data, $p\left(x_{\mathrm{GW}} \mid d, \cos\iota\right)$, discussed in the text, depends on the distance and inclination of the source (and additional parameters, here marginalized out).





" Large Magellanic Cloud Cepheid Standards Provide a 1% Foundation for the Determination of the Hubble Constant and Stronger Evidence for Physics Beyond ΛCDM"

https://arxiv.org/abs/1903.07603

http://users.math.cas.cz/~krizek/cosmol/pdf/E21.pdf

-> critic on the estimation of the Masses of the BHs due to simplification in the treatment of GW (*neglect total redshift* !)