Physics for everyone:

How to explain gravitational waves to a lay audience

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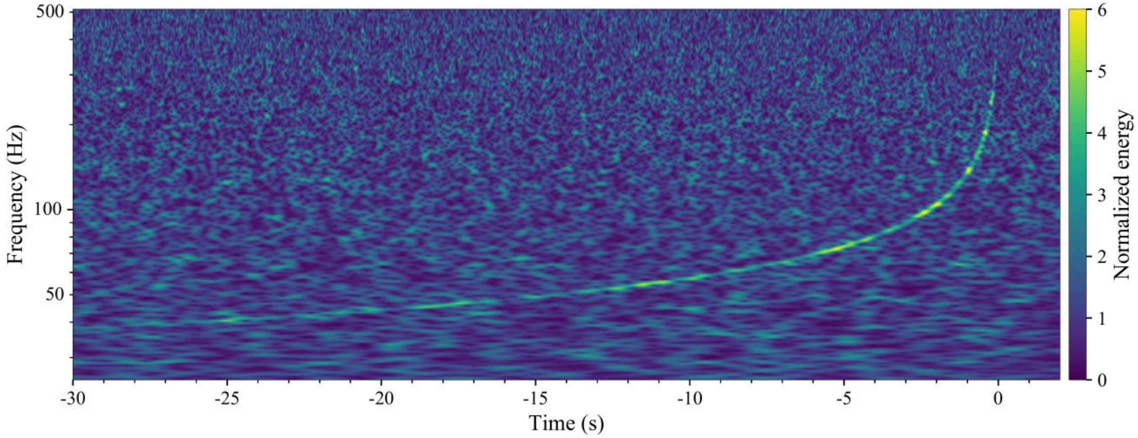
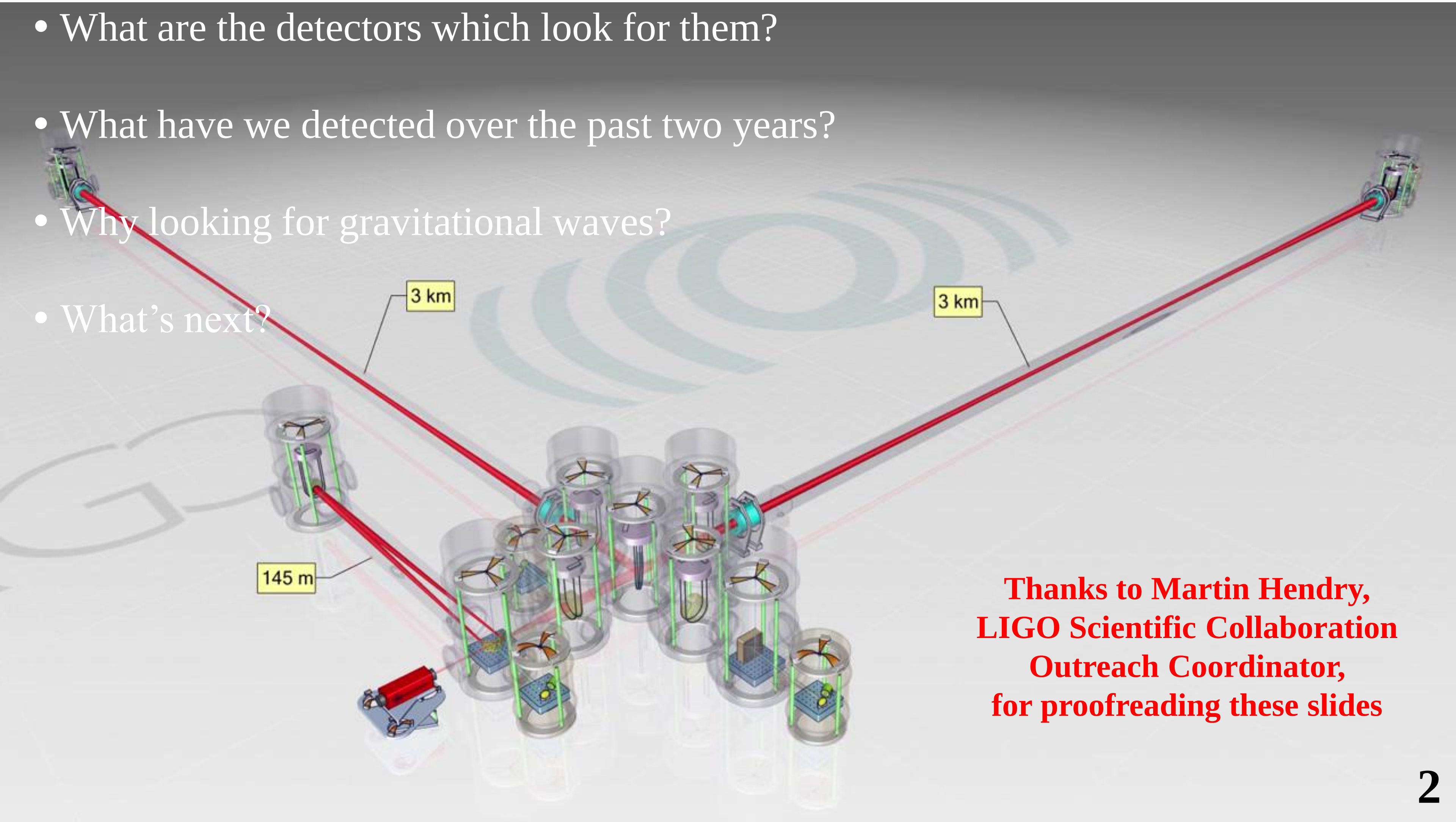


Answering the following questions

- What are gravitational waves?
- What are the detectors which look for them?
- What have we detected over the past two years?
- Why looking for gravitational waves?
- What's next?

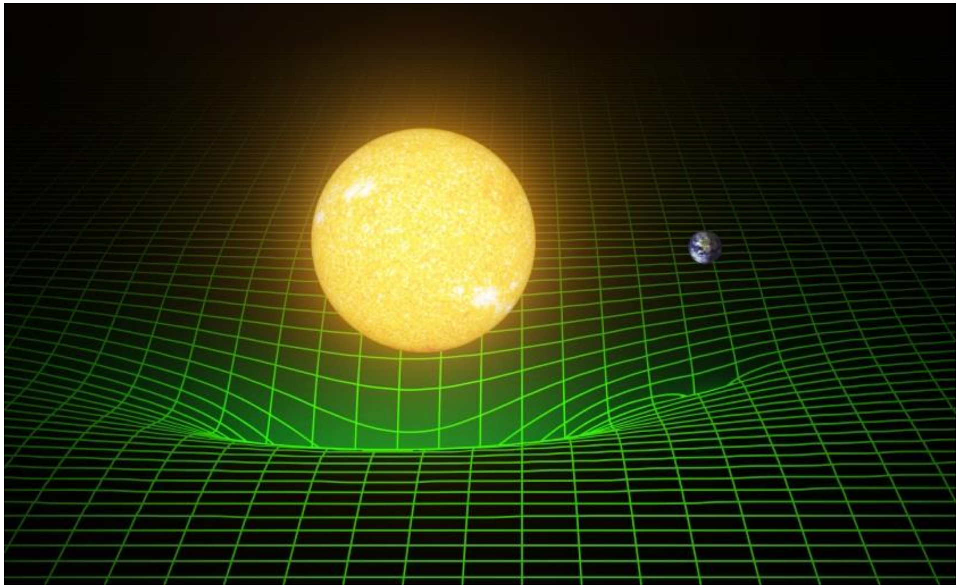


Thanks to Martin Hendry, LIGO Scientific Collaboration Outreach Coordinator, for proofreading these slides

Gravitational waves

- "Space-time tells matter how to move; matter tells space-time how to curve"

  John Archibald Wheeler (1990)
  - A massive body warps the space-time fabric
  - Objects (including light) move along paths determined by the space-time geometry



Two-dimensional illustration of how mass in the Universe distorts space-time

- Gravitational waves: one of the first predictions of general relativity (1916)
  - Accelerated masses induce perturbations of the space-time, which propagate at the speed of light

Gravitational waves

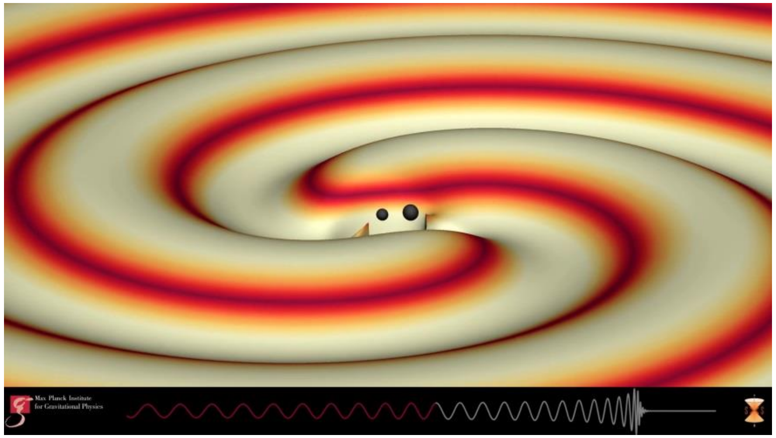
- Einstein’s equations
  - Curvature [m] = 0.000000000000000000000000000000000000000002 [m/J] × Energy [J]

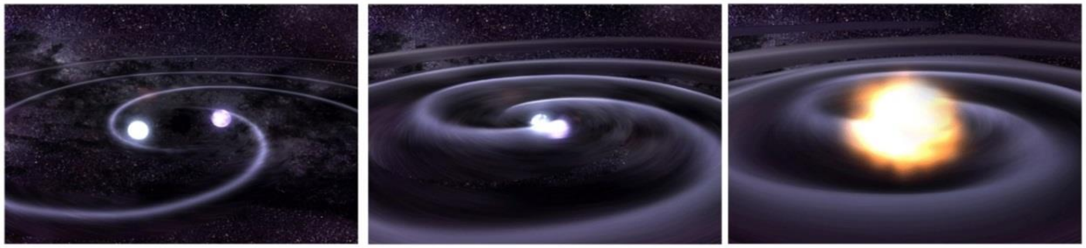
  → The space-time is incredibly stiff!

- Consequently: although most accelerated masses create gravitational waves,
  - Including you and me

  no terrestrial source can produce gravitational waves
  with an amplitude high-enough to be detected

→ Only sources from the cosmos can be searched for
  - Among which, cataclysmic events like the fusion of black holes or neutron stars





Challenges

- Such events are (very) rare in a given galaxy

- The gravitational waves they produce get diluted as they propagate into space:

  gravitational wave amplitude ∝ 1 / distance

  - Sources too far away will not be detected

→ What 'too far away' means, depends on the detector sensitivity (and on the source)

- Sensitivity twice better ⇨ a given source observable to twice the distance

- And what about the source rate?
  - Universe homogeneous and isotropic
    - Assumption true at large scale

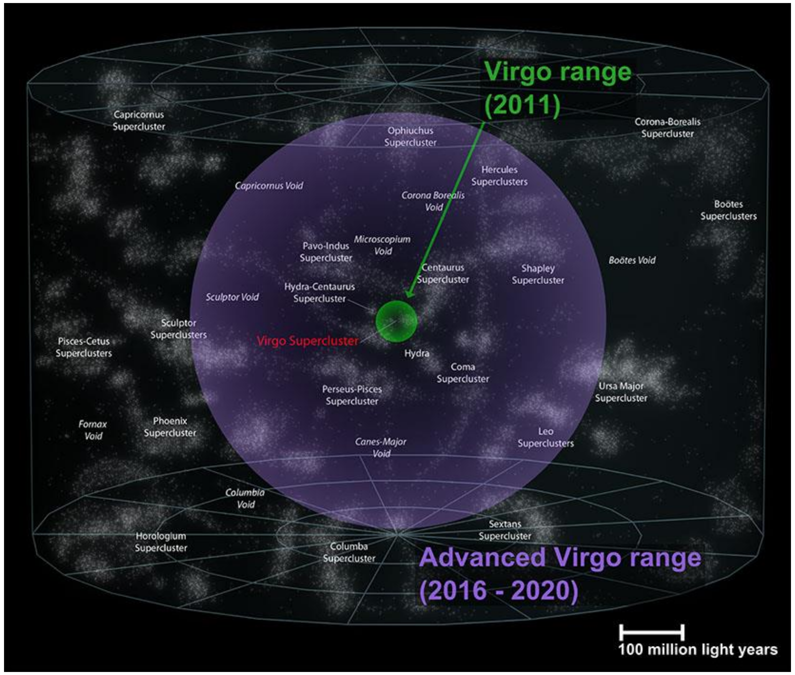
  → Rate scales as $(\text{distance})^3$

→ Sensitivity gain of a factor 2 (10) means a rate increase of a factor 8 (1000)

→ Need to probe the largest Universe volume

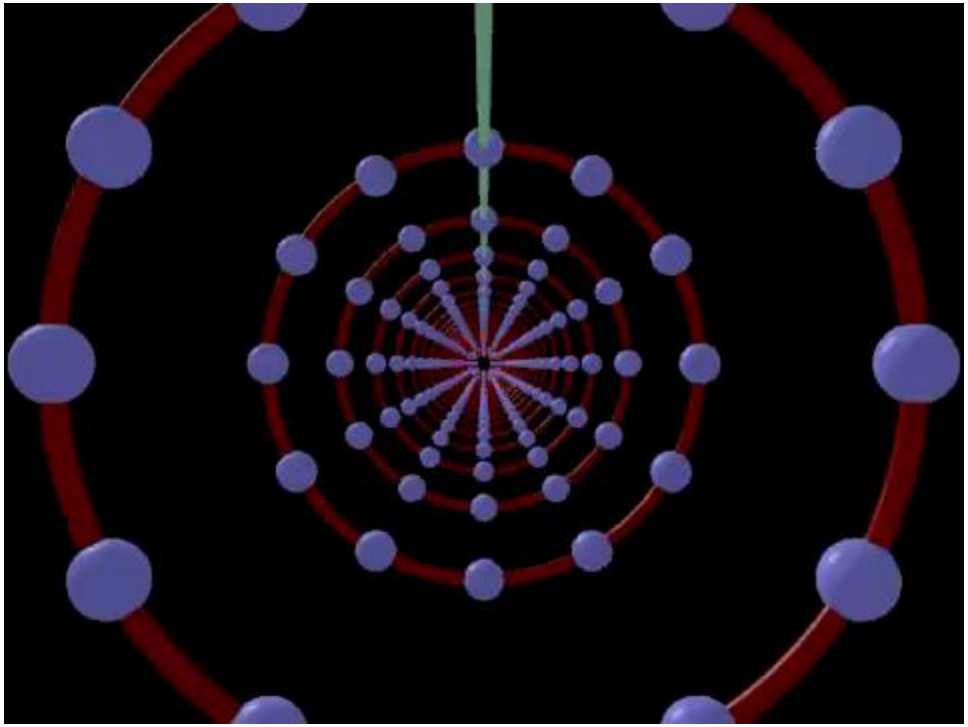
- Pluriannual (2010-2016) upgrade of all detectors to improve their sensitivity

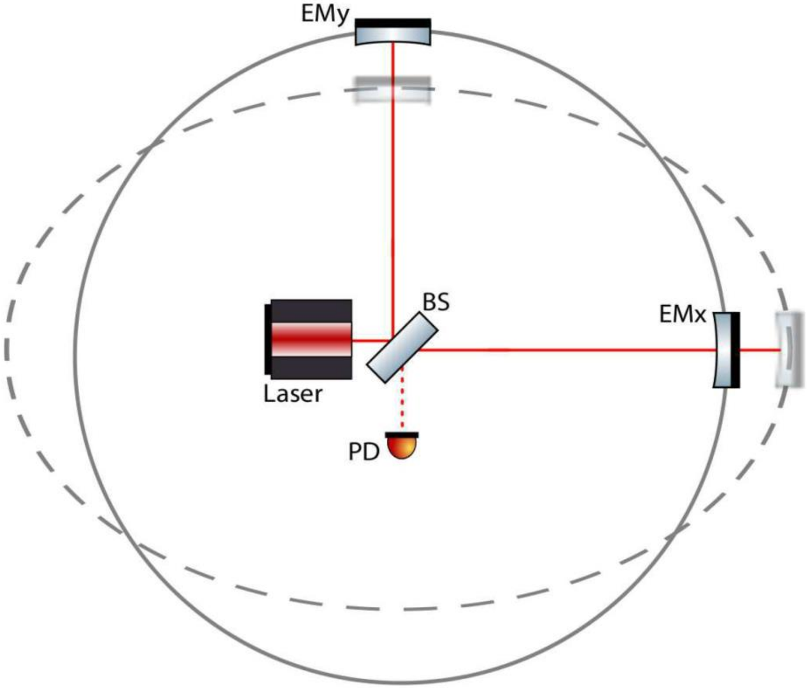
  → In return: first detections in 2015-2017!



How to detect gravitational waves?

- Effect of gravitational waves on space-time
  - Space is alternately stretched and squeezed in perpendicular directions, in the plane transverse to the wave propagation



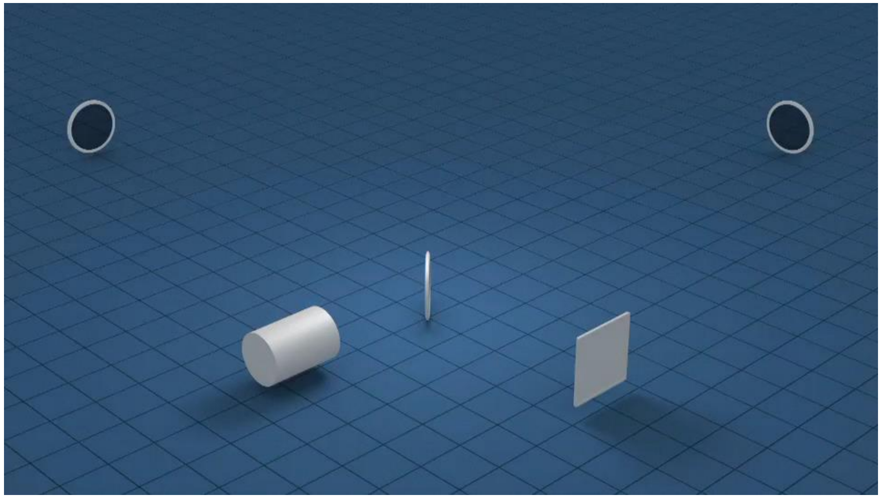


- Space-time is distorted over a length L by a quantity δL, which is proportional to L and to the gravitational-wave amplitude h

$$\delta \mathbf{L}_{\mathbf{max}} = \frac{\mathbf{hL}}{\mathbf{2}}$$

Detectors

- Michelson interferometers
  - Invented 150 years ago to test the invariance of the speed of light



- A stopwatch
  - Compares the laser beam travel times in the two perpendicular arms

- Light (laser) always propagates at the same speed: ~ 300 000 km/s in vacuum
- Incident gravitational wave distorts space-time along the arms in a differential way

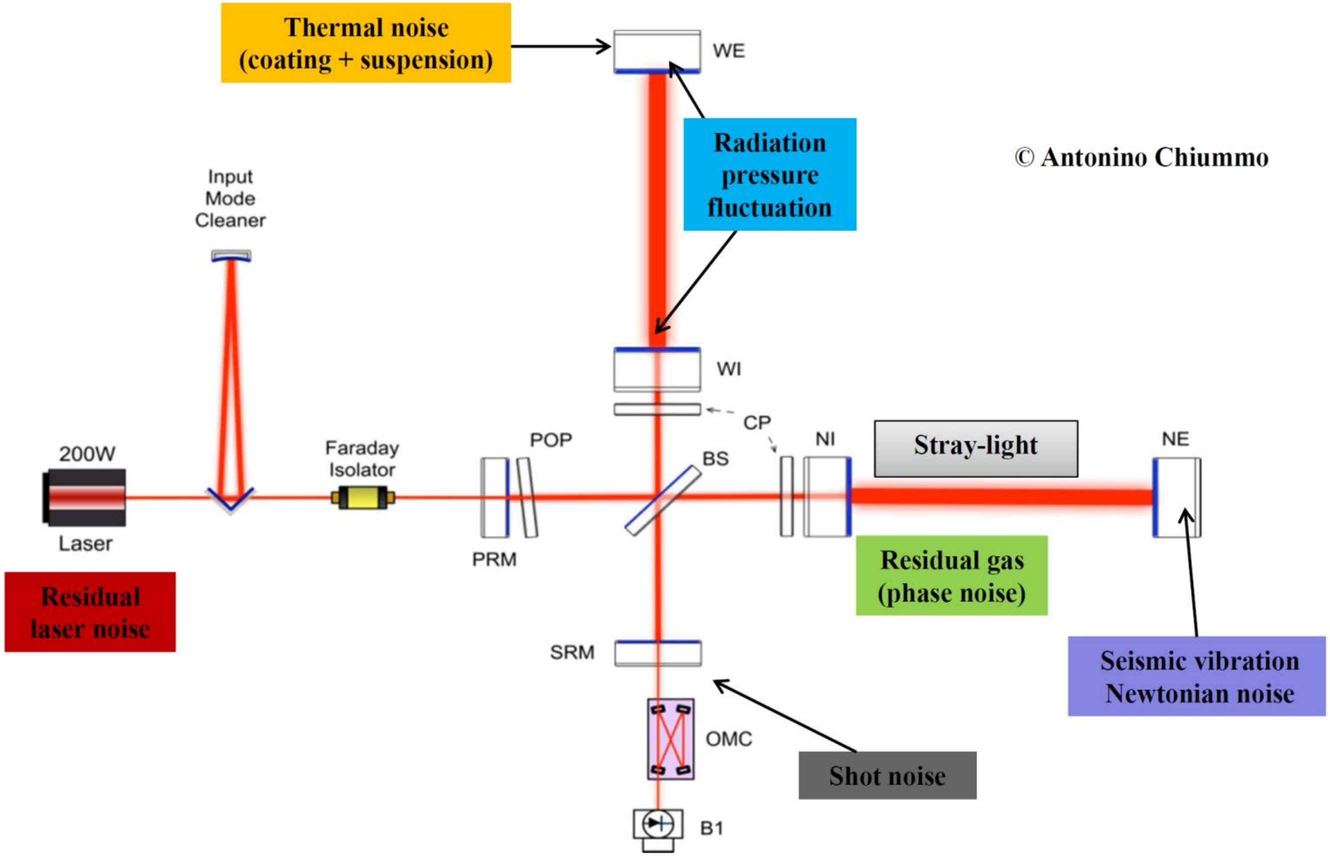
→ Beams are ‘detuned’ when they recombine
  - Modification of the laser beam interference pattern

    → Variation of the laser power detected at the output of the detector

Sensitivity

- Typical gravitational wave amplitude $h = 10^{-21} \approx \frac{\text{Size of an atom}}{\text{Earth-Sun distance}}$

→ Detecting such a tiny change requires detectors with unprecedented sensitivities
  - Design
  - Building
  - Operation
  - Maintenance
  - Upgrade



Thermal noise (coating + suspension)

Radiation pressure fluctuation

Stray-light

Residual laser noise

Residual gas (phase noise)

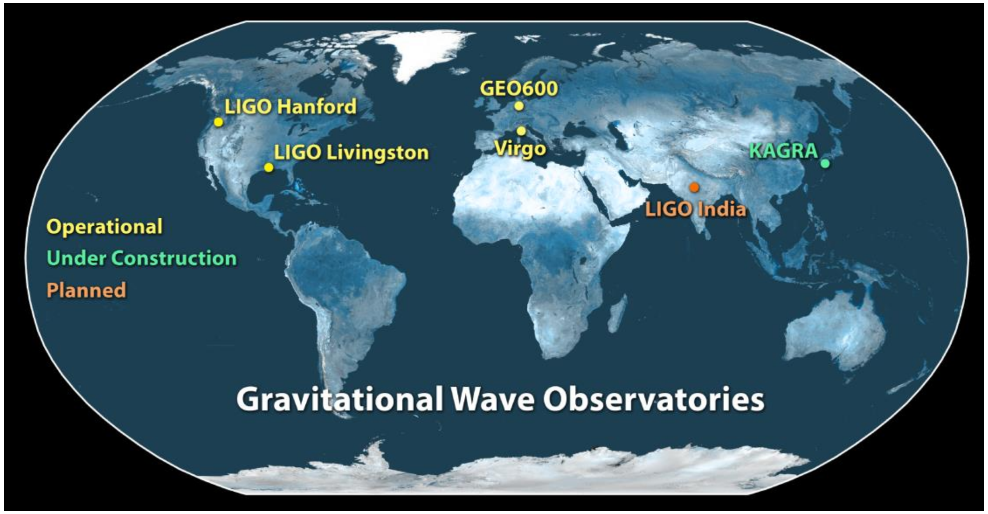
Seismic vibration Newtonian noise

Shot noise

© Antonino Chiummo

- Detector
  - Control
  - Monitoring
- Fundamental noises
  - Mitigation
- Technical noises
  - Noise hunting
- Continuous environment monitoring
  - Ground motion, weather, anthropogenic activities, etc.

Detecting a gravitational wave signal

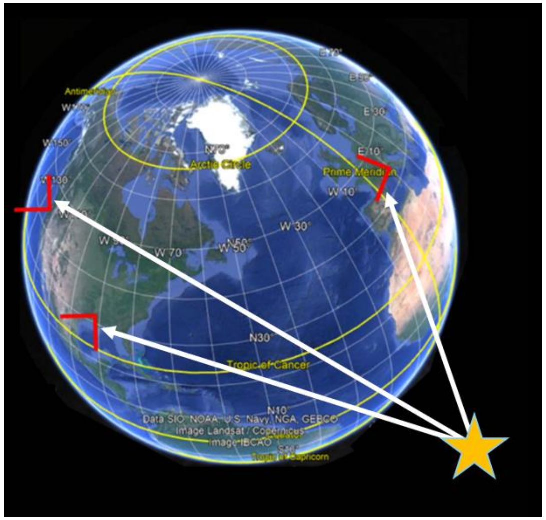


- Detector output
  - Noise fluctuations
  - Plus eventually a gravitational wave

- A single detector is not enough
  → LIGO-Virgo three-detector network
    - More instruments joining soon

- Noise fluctuations usually incoherent between distant detectors (1000's km apart)

- A real gravitational-wave interacts with all detectors on Earth
  → Should produce signals in the different instruments which are
    - Coincident in time (within a few milliseconds)
    - Coherent in shape and amplitude



- A gravitational-wave 'candidate' stands out from ordinary random variations in the noise
  - The 'stronger' the signal, the more likely it is a real event
    → The rarer the noise fluctuations which could mimic it
  - Event accurately vetted to exclude a terrestrial origin
    - Apparatus, enviroment, etc.

1916-2017: a century of progress

IFO: Interferometer

- **1916: GW prediction (Einstein)**

1957 Chapel Hill Conference (Bondi, Feynman, Pirani, etc.)

Theoretical developments

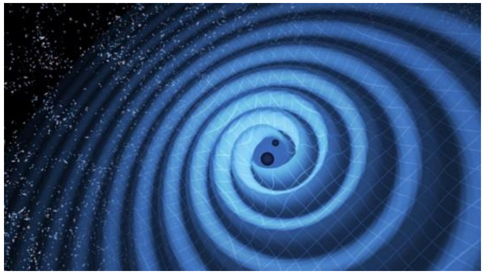
- **1963: Rotating black hole (BH) solution (Kerr)**
- **1990's: Post-Newtonian expansion (Blanchet, Damour, Deruelle, Iyer, Will, Wiseman, etc.)**
- **2000: Binary BH (BBH) effective one-body approach (Buonanno, Damour)**
- **2006: BBH merger simulation (Baker, Lousto, Pretorius, etc.)**

Experiments

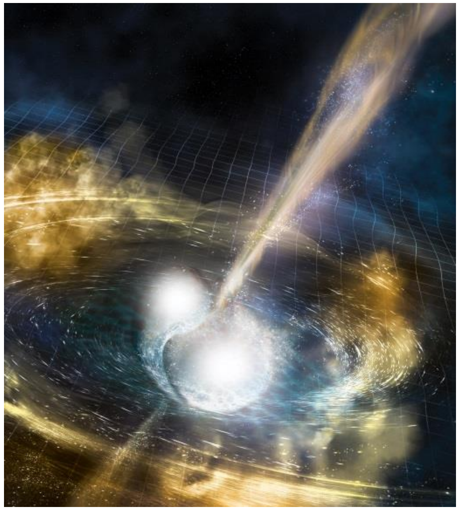
- **1960's: first Weber bars**
- **1970: first IFO prototype (Forward)**
- **1972: IFO design studies (Weiss)**
- **1974: PSRB 1913+16 (Hulse & Taylor)**
- **1980's: IFO prototypes (10m-long) (Caltech, Garching, Glasgow, Orsay)**
- **End of 1980's: Virgo and LIGO proposals**
- **1990's: LIGO and Virgo funded**
  → IFO construction
- **2005-2011: initial IFO « science » runs**
- **2007: LIGO-Virgo Memorandum of Understanding**
- **Around 2010: Advanced detectors funded**
  → Multi-year upgrades
- **2015-2017: First GW detections**

Detections

- Five published events to date – 10/2017
  - Name: GWYYMMDD for a gravitational wave (GW) detected on 20YY/MM/DD



- All events detected are compact binary coalescences
  - Compact objects: black holes or neutron stars
    - A lot of mass 'compacted' in an unusually small volume
      → Strong gravity
  - Accelerated at relativistic speeds

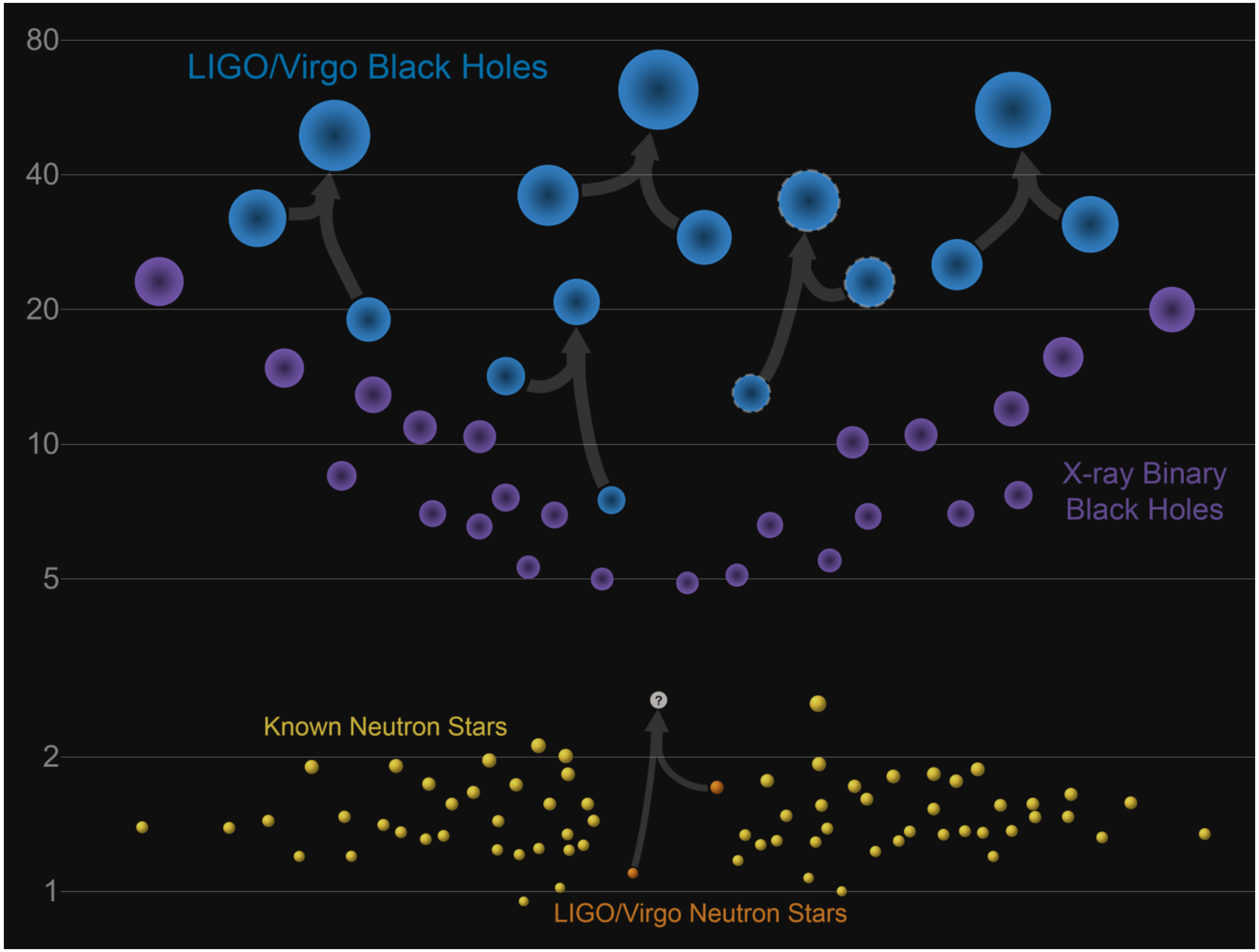


- Binary system: two compact stars orbiting around one another
  - Lose energy by emitting gravitational waves
    → Come closer, orbital motion speeds up
  - The closer they are, the more they emit gravitational waves
    → The more they come closer, the faster they travel
  - They end up merging, inducing a cataclysmic event

→ Diverging phenomenon
  - Gravitational-wave emission peaks at the merger
  - The whole process can take hundreds of million years
    - Only final moments (~seconds at most) detectable with ground-based detectors

Detections

- Four binary black hole coalescence
  - GW150914, GW151226, GW170104, GW170814
- One binary neutron star merger: GW170817



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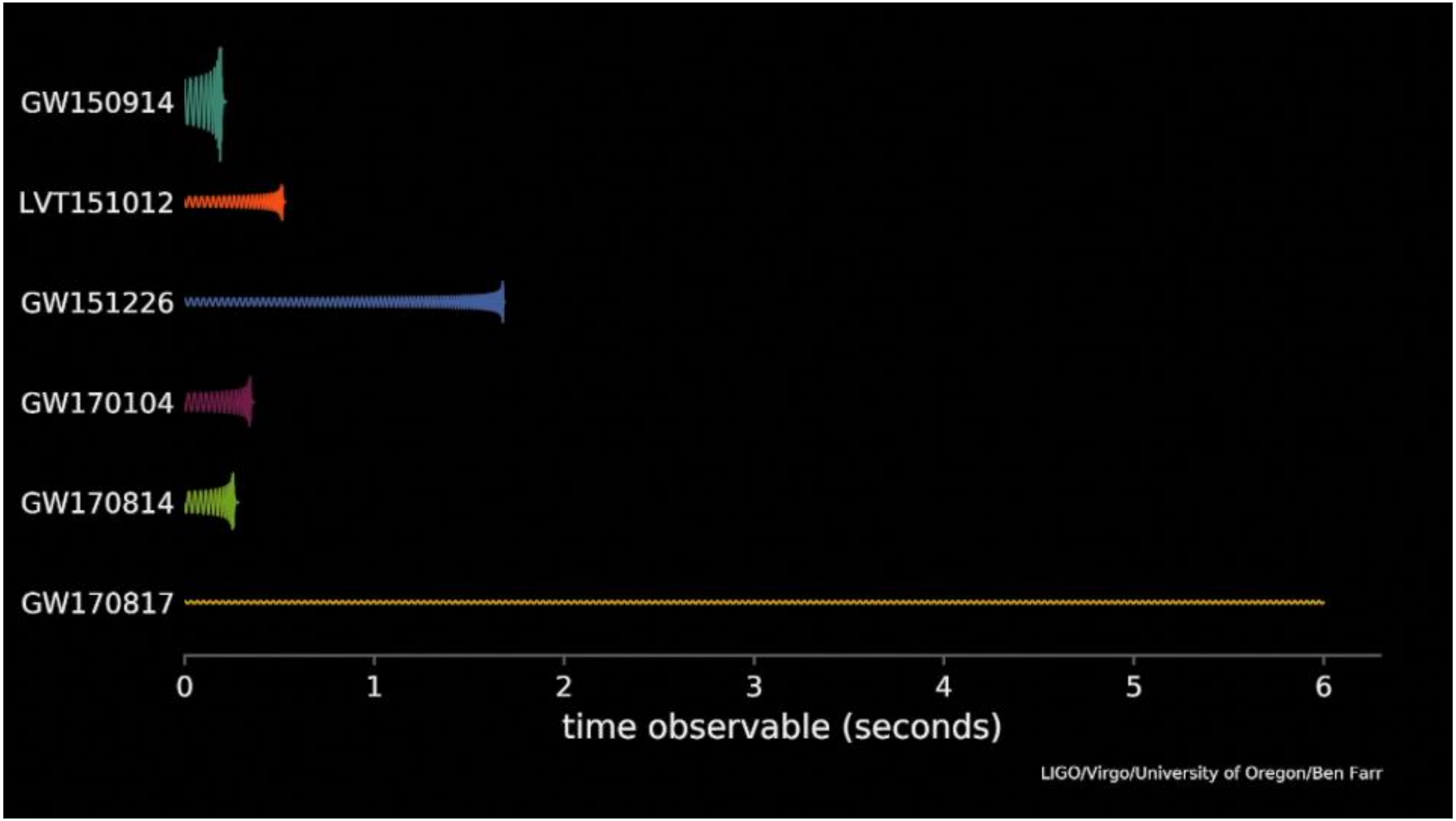
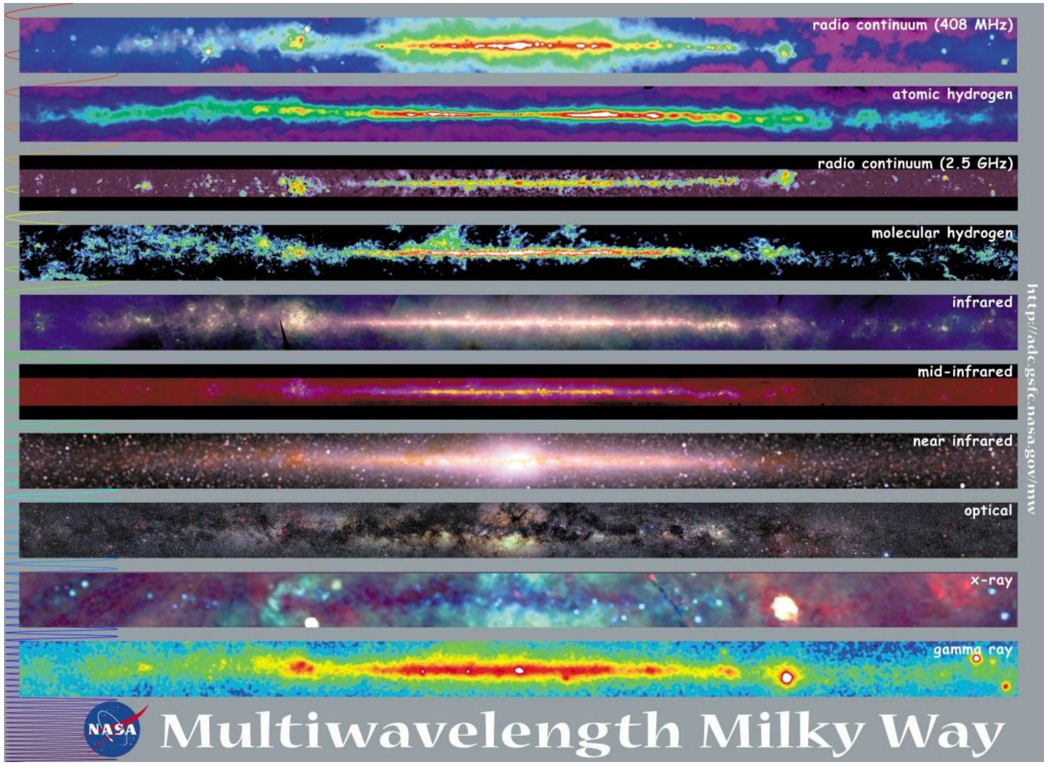


LIGO/Virgo/University of Oregon/Ben Farr

A new window onto the Universe



- Astronomy/cosmology: observation of the Universe
  - Optical light
  - Whole electromagnetic spectrum
    - Radio, microwaves, infrared, visible light, ultraviolet, X rays, gamma rays
  - Cosmic rays – charged particles
  - Neutrinos – neutral particles
  - And now: gravitational waves

→ Multi-messenger astronomy

- Two-way alert system between LIGO-Virgo and tens of partners worldwide
  - Significant gravitational-wave candidates trigger alerts for telescopes
    - Rapid response (~tens of minutes) required for transient sources
    - Sky localization map provided by the gravitational-wave detector network
  - Tailored gravitational-wave searches started when an event of interest has been observed in the sky by a telescope
    - Sky location and timing known

Santa comes in August: GW170817

- Binary neutron star fusion
  - Gravitational waves: detection and source localization
  - Gamma ray burst
  - Detection of the optical counterpart, follow-up observations over weeks

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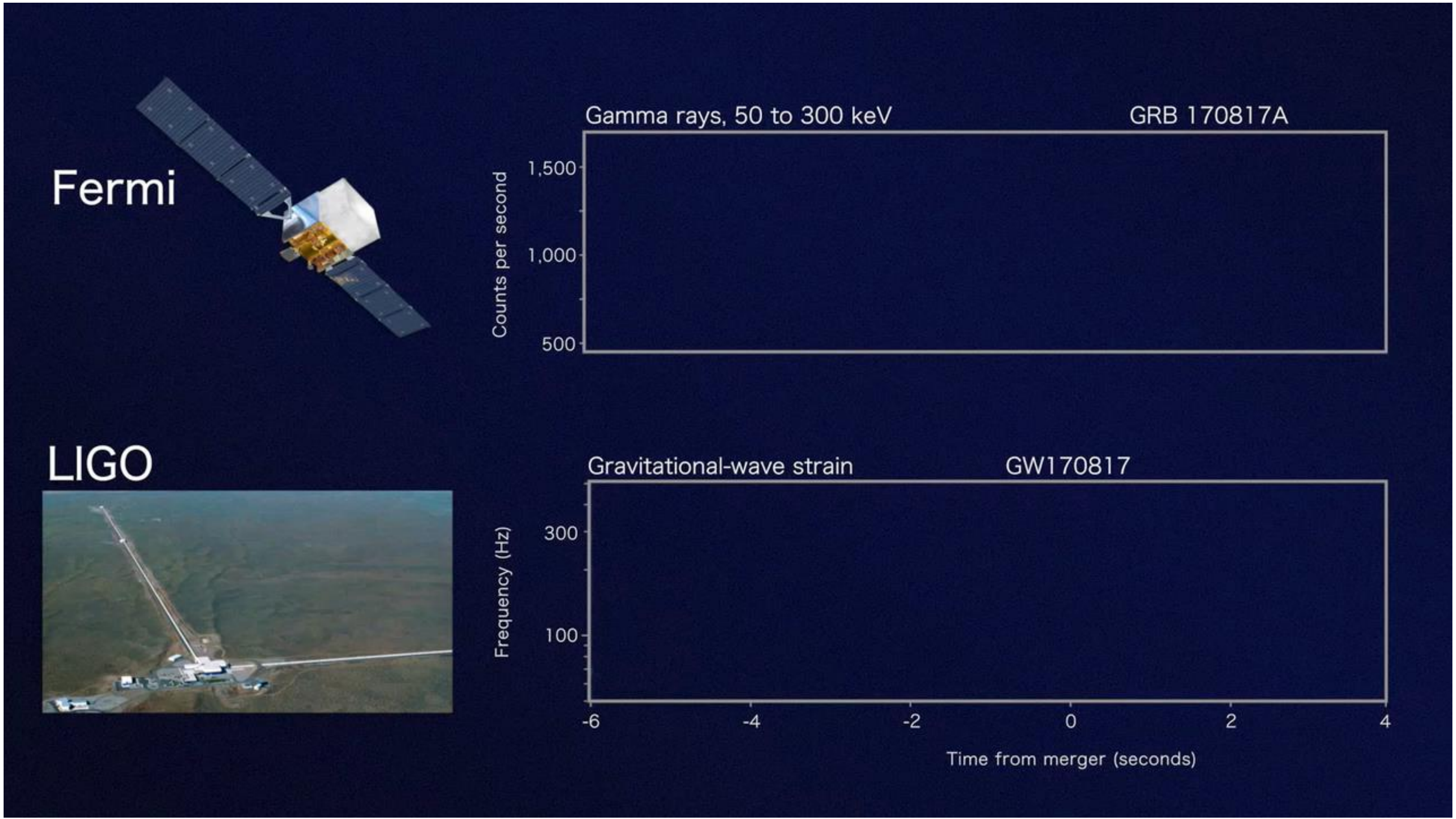

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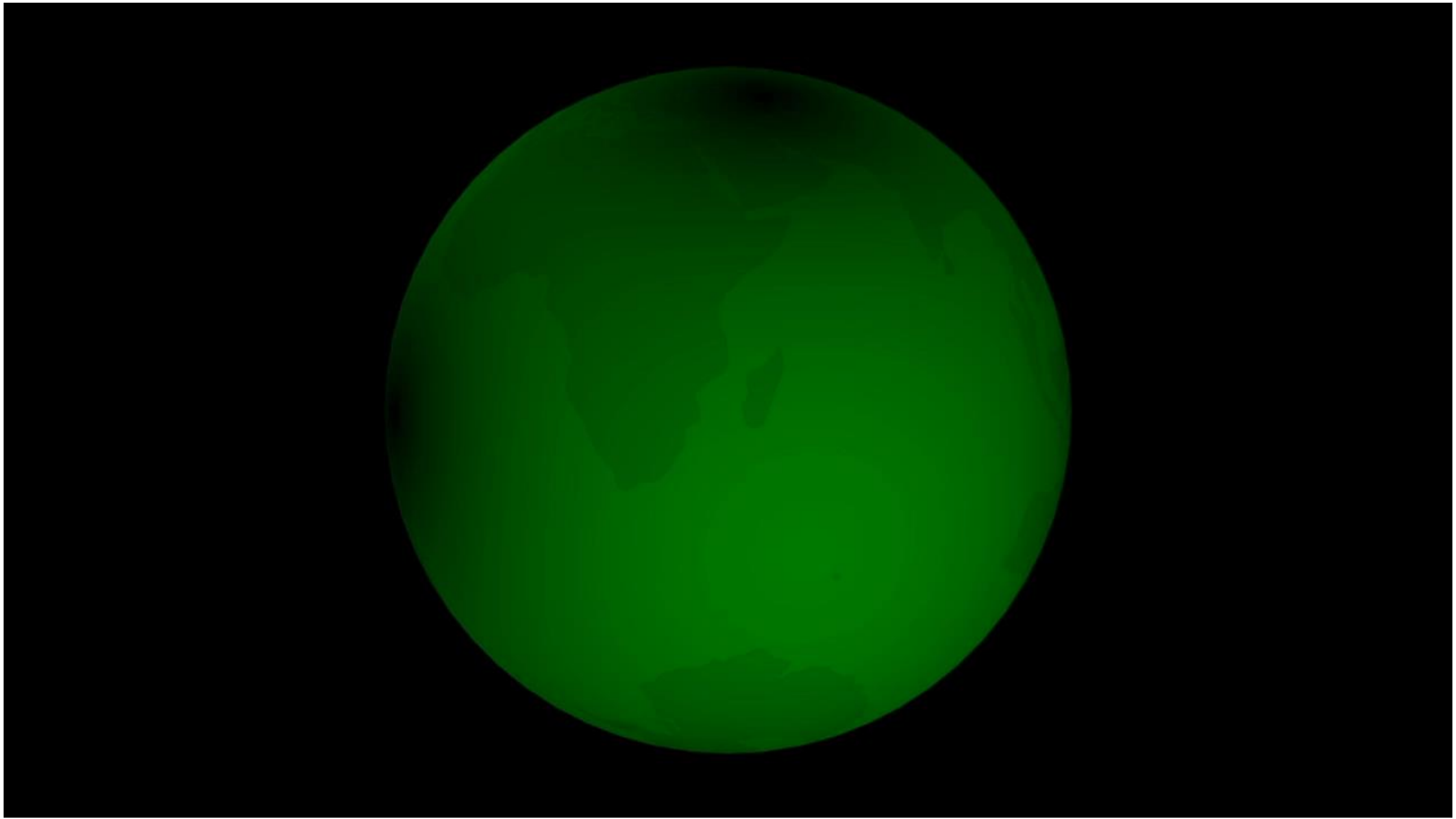

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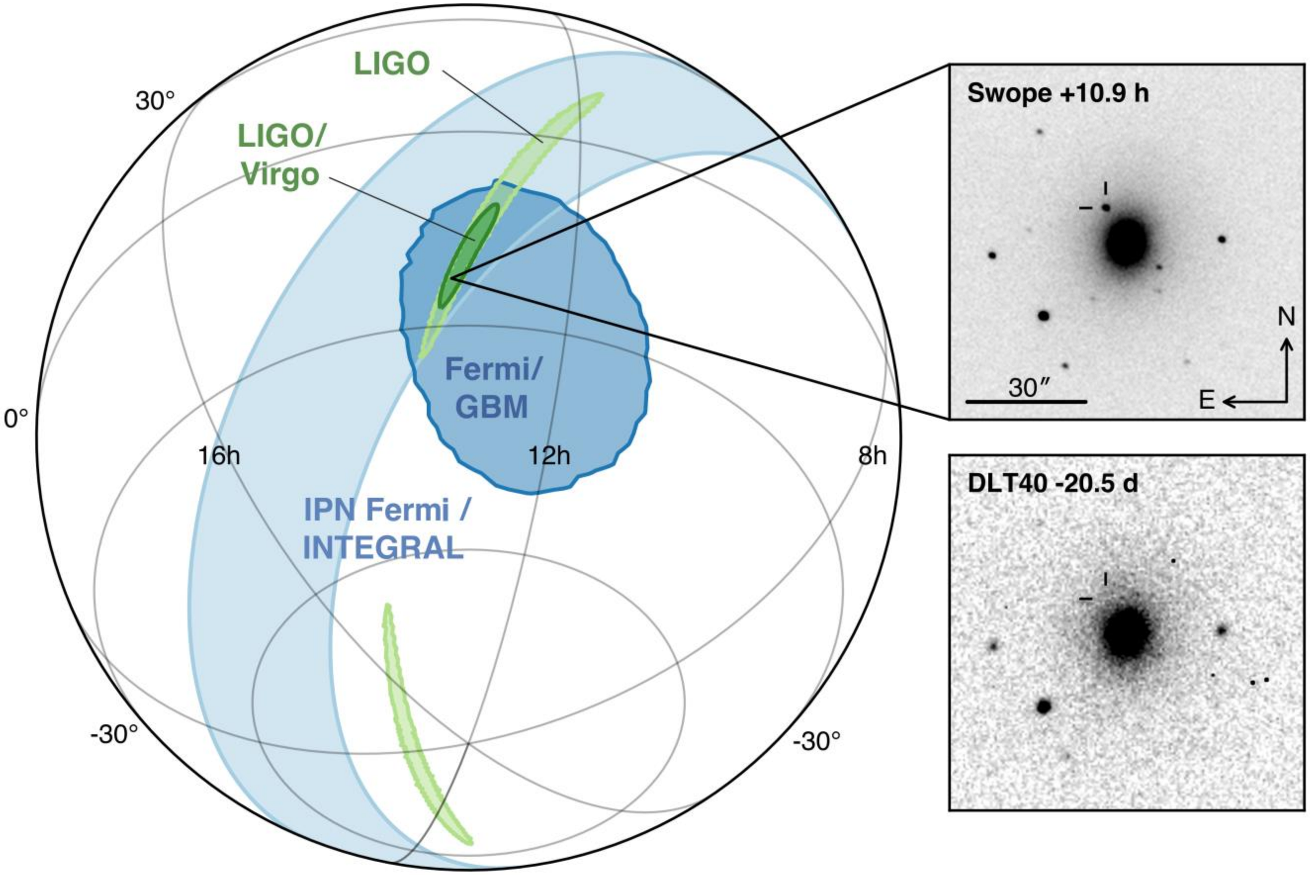

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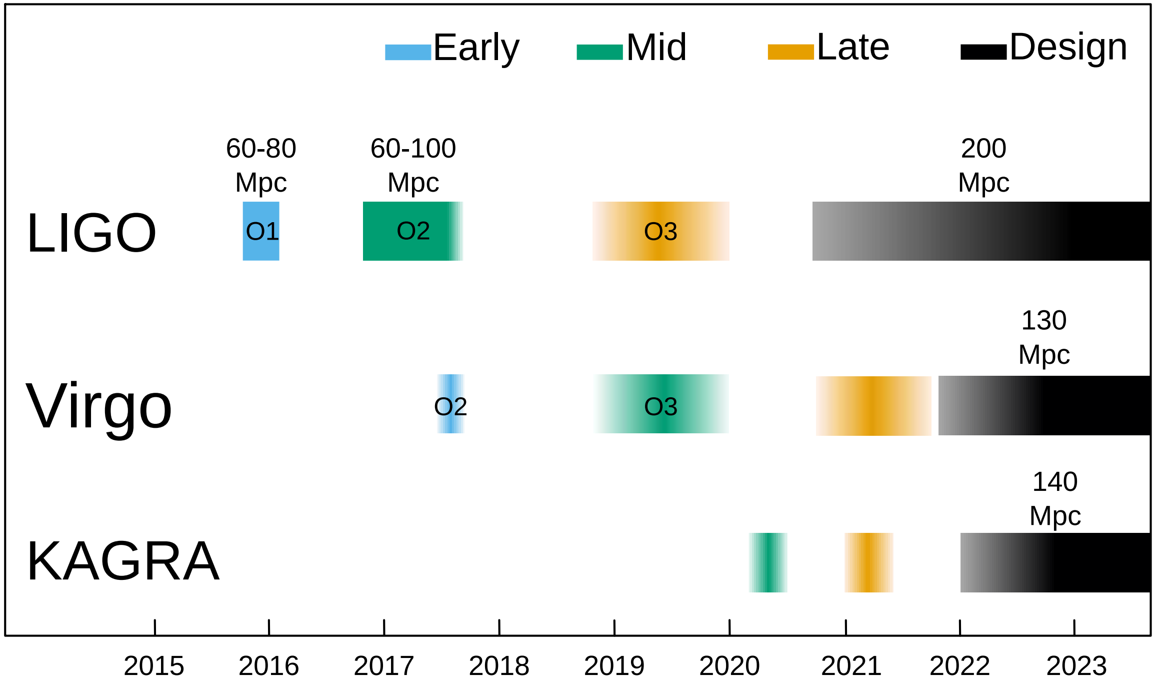
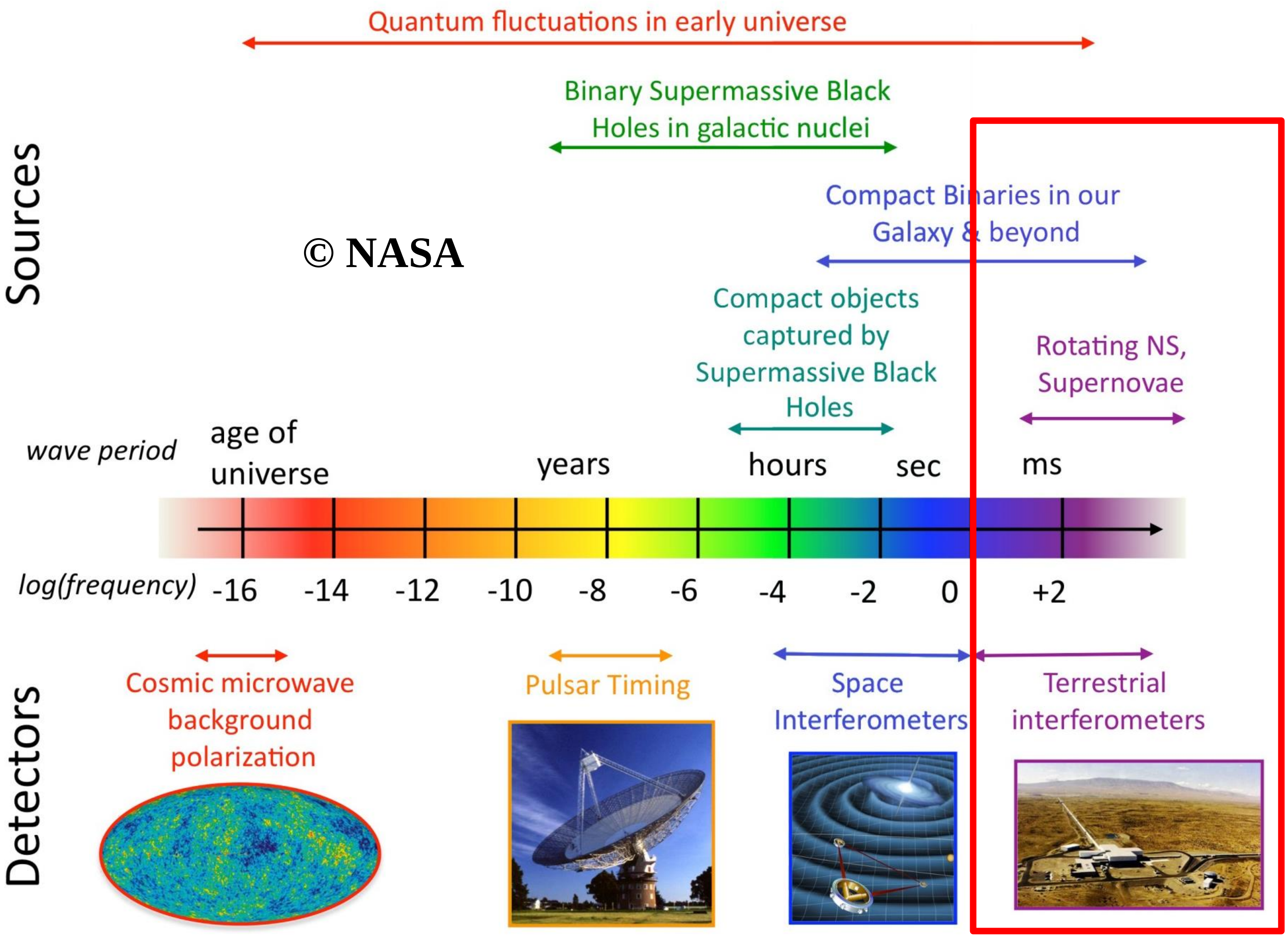
What’s next?

- « Observation 2 » (O2) data taking period ended on August 25, 2017
- One year of upgrade for the three detectors: LIGO & Virgo
- O3 run to start in Fall 2018
  - For about a year
- Sensitivy improvement
- Higher duty cycle
- Larger network
  - KAGRA (Japan) will join by 2020
  - Followed by LIGO-India some years later



Gravitational wave spectrum



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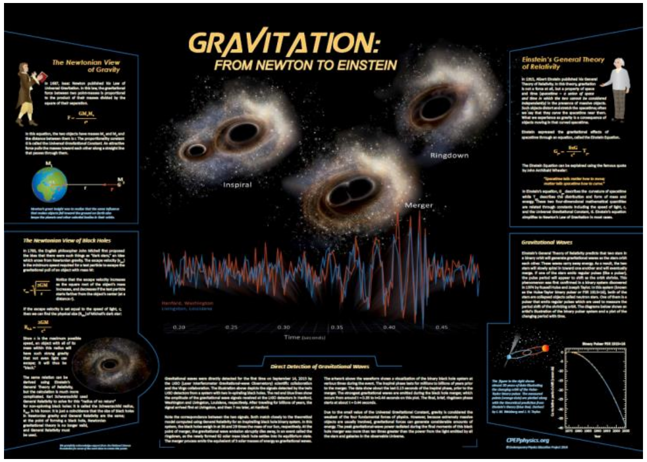
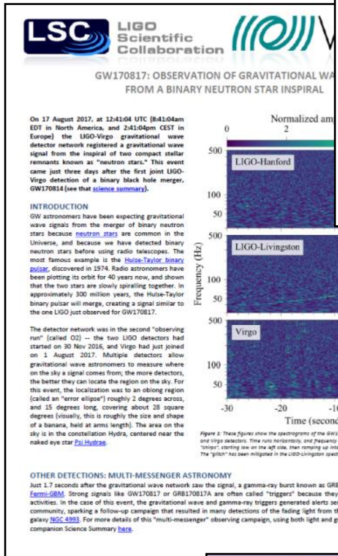
LIGO, Virgo, etc.

Outreach & education resources

- LIGO and Virgo: committed to produce such materials
    - In various languages
- For each detection
    - Science summaries, factsheet, infographics, etc.
- Educational resources
    - CPEP poster
- Teacher training
- Site visits
- Open data
  https://losc.ligo.org
- Visit our websites
    - http://www.virgo-gw.eu/#news http://public.virgo-gw.eu
    - https://www.ligo.caltech.edu http://www.ligo.org
- Contact us
    - outreach@ego-gw.it (Virgo) & lsc-epo@ligo.org (LIGO)




LSC LIGO Scientific Collaboration

GW170817: OBSERVATION OF GRAVITATIONAL WA
FROM A BINARY NEUTRON STAR INSPIRAL

On 17 August 2017, at 12:41:04 UTC (8:41:04am EDT in North America, and 2:41:04pm CEST in Europe) the LIGO-Virgo gravitational wave detector network registered a gravitational wave signal from the inspiral of two compact stellar remnants known as "neutron stars." This event came just three days after the first joint LIGO-Virgo detection of a binary black hole merger, GW170814 (see that science summary).

INTRODUCTION

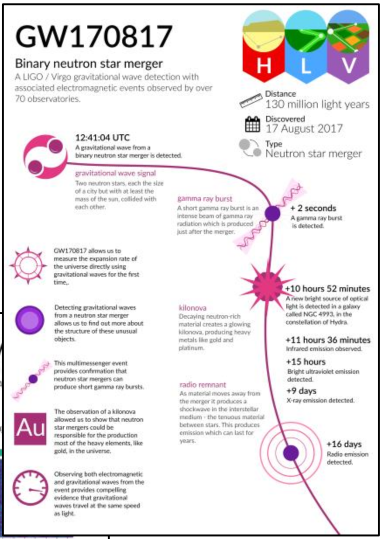
GW astronomers have been expecting gravitational wave signals from the merger of binary neutron stars because neutron stars are common in the Universe, and because we have detected binary neutron stars before using radio telescopes. The most famous example is the Hulse-Taylor binary pulsar, discovered in 1974. Radio astronomers have been plotting its orbit for 40 years now, and shown that the two stars are slowly spiralling together. In approximately 300 million years, the Hulse-Taylor binary pulsar will merge, creating a signal similar to the one LIGO just observed for GW170817.

The detector network was in the second "observing run" (called O2) -- the two LIGO detectors had started on 30 Nov 2016, and Virgo had just joined on 1 August 2017. Multiple detectors allow gravitational wave astronomers to measure where on the sky a signal comes from; the more detectors, the better they can locate the region on the sky. For this event, the localization was to an oblong region (called an "error ellipse") roughly 2 degrees across, and 15 degrees long, covering about 28 square degrees (visually, this is roughly the size and shape of a banana, held at arms length). The area on the sky is in the constellation Hydra, centered near the naked eye star Psi Hydrae.

Figure 1: These figures show the spectrograms of the GW170817 signal in each of the LIGO and Virgo detectors. Time runs horizontally, and frequency runs vertically. The binary signal "chirps", starting low on the left side, then ramping up into a steep curve on the right side. The "glitch" has been mitigated in the LIGO-Livingston spectrogram and is not seen here.

OTHER DETECTIONS: MULTI-MESSENGER ASTRONOMY

Just 1.7 seconds after the gravitational wave network saw the signal, a gamma-ray burst known as GRB170817A was detected by Fermi-GBM. Strong signals like GW170817 or GRB170817A are often called "triggers" because they initiate other astronomy activities. In the case of this event, the gravitational wave and gamma-ray triggers generated alerts sent out to the astronomical community, sparking a follow-up campaign that resulted in many detections of the fading light from the event, located near the galaxy NGC 4993. For more details of this "multi-messenger" observing campaign, using both light and gravitational waves, see the companion Science Summary here.


GW170817

Binary neutron star merger

A LIGO / Virgo gravitational wave detection with associated electromagnetic events observed by over 70 observatories.

Distance
130 million light years

Discovered
17 August 2017

Type
Neutron star merger

12:41:04 UTC
A gravitational wave from a binary neutron star merger is detected.

gravitational wave signal
Two neutron stars, each the size of a city but with at least the mass of the sun, collided with each other.

gamma ray burst
A short gamma ray burst is an intense beam of gamma ray radiation which is produced just after the merger.

+ 2 seconds
A gamma ray burst is detected.

GW170817 allows us to measure the expansion rate of the universe directly using gravitational waves for the first time,.

+10 hours 52 minutes
A new bright source of optical light is detected in a galaxy called NGC 4993, in the constellation of Hydra.

Detecting gravitational waves from a neutron star merger allows us to find out more about the structure of these unusual objects.

kilonova
Decaying neutron-rich material creates a glowing kilonova, producing heavy metals like gold and platinum.

+11 hours 36 minutes
Infrared emission observed.

+15 hours
Bright ultraviolet emission detected.

This multimessenger event provides confirmation that neutron star mergers can produce short gamma ray bursts.

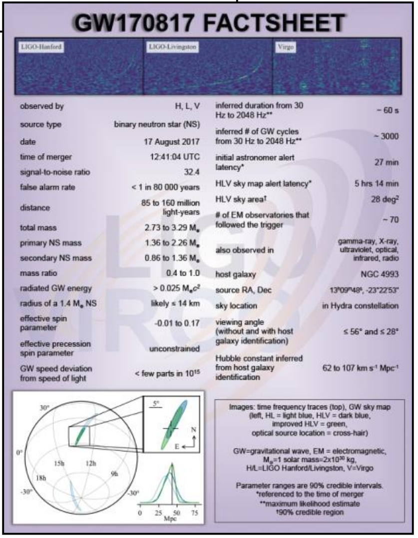
radio remnant
As material moves away from the merger it produces a shockwave in the interstellar medium - the tenuous material between stars. This produces emission which can last for years.

+9 days
X-ray emission detected.

Au
The observation of a kilonova allowed us to show that neutron star mergers could be responsible for the production most of the heavy elements, like gold, in the universe.

+16 days
Radio emission detected.

Observing both electromagnetic and gravitational waves from the event provides compelling evidence that gravitational waves travel at the same speed as light.


GW170817 FACTSHEET

observed by	H, L, V
source type	binary neutron star (NS)
date	17 August 2017
time of merger	12:41:04 UTC
signal-to-noise ratio	32.4
false alarm rate	< 1 in 80 000 years
distance	85 to 160 million light-years
total mass	2.73 to 3.29 $M_\odot$
primary NS mass	1.36 to 2.26 $M_\odot$
secondary NS mass	0.86 to 1.36 $M_\odot$
mass ratio	0.4 to 1.0
radiated GW energy	> 0.025 $M_\odot c^2$
radius of a 1.4 $M_\odot$ NS	likely ≤ 14 km
effective spin parameter	-0.01 to 0.17
effective precession spin parameter	unconstrained
GW speed deviation from speed of light	< few parts in 10^{15}

inferred duration from 30 Hz to 2048 Hz**	~ 60 s
inferred # of GW cycles from 30 Hz to 2048 Hz**	~ 3000
initial astronomer alert latency*	27 min
HLV sky map alert latency*	5 hrs 14 min
HLV sky area†	28 deg^2
# of EM observatories that followed the trigger	~ 70
also observed in	gamma-ray, X-ray, ultraviolet, optical, infrared, radio
host galaxy	NGC 4993
source RA, Dec	$13^h09^m48^s$, -23°22'53"
sky location	in Hydra constellation
viewing angle (without and with host galaxy identification)	≤ 56° and ≤ 28°
Hubble constant inferred from host galaxy identification	62 to 107 km s^{-1} Mpc^{-1}

Images: time frequency traces (top), GW sky map (left, HL = light blue, HLV = dark blue, improved HLV = green, optical source location = cross-hair)

GW=gravitational wave, EM = electromagnetic, $M_\odot$=1 solar mass=2×10^{30} kg, H/L=LIGO Hanford/Livingston, V=Virgo

Parameter ranges are 90% credible intervals.
*referenced to the time of merger
**maximum likelihood estimate
†90% credible region