Physics for everyone:
How to explain gravitational waves to a lay audience

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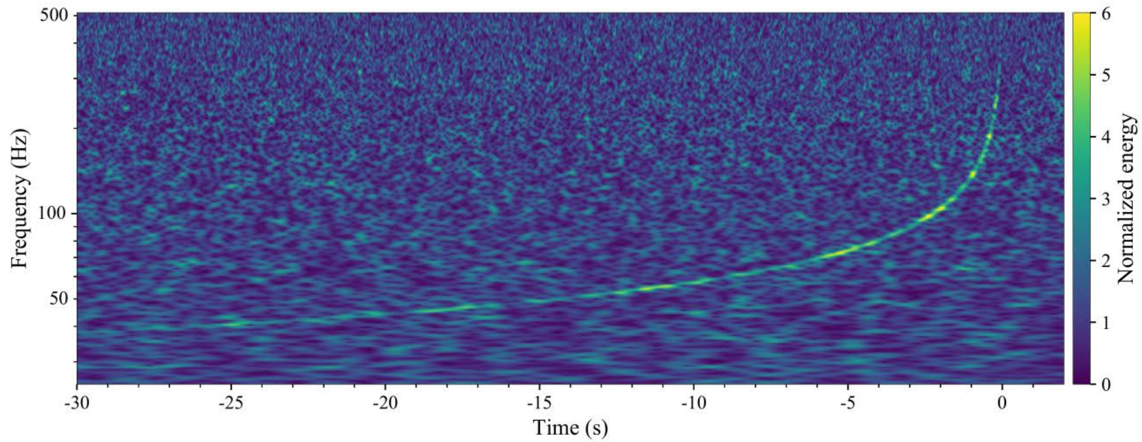

EGO EUROPEAN GRAVITATIONAL OBSERVATORY

LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

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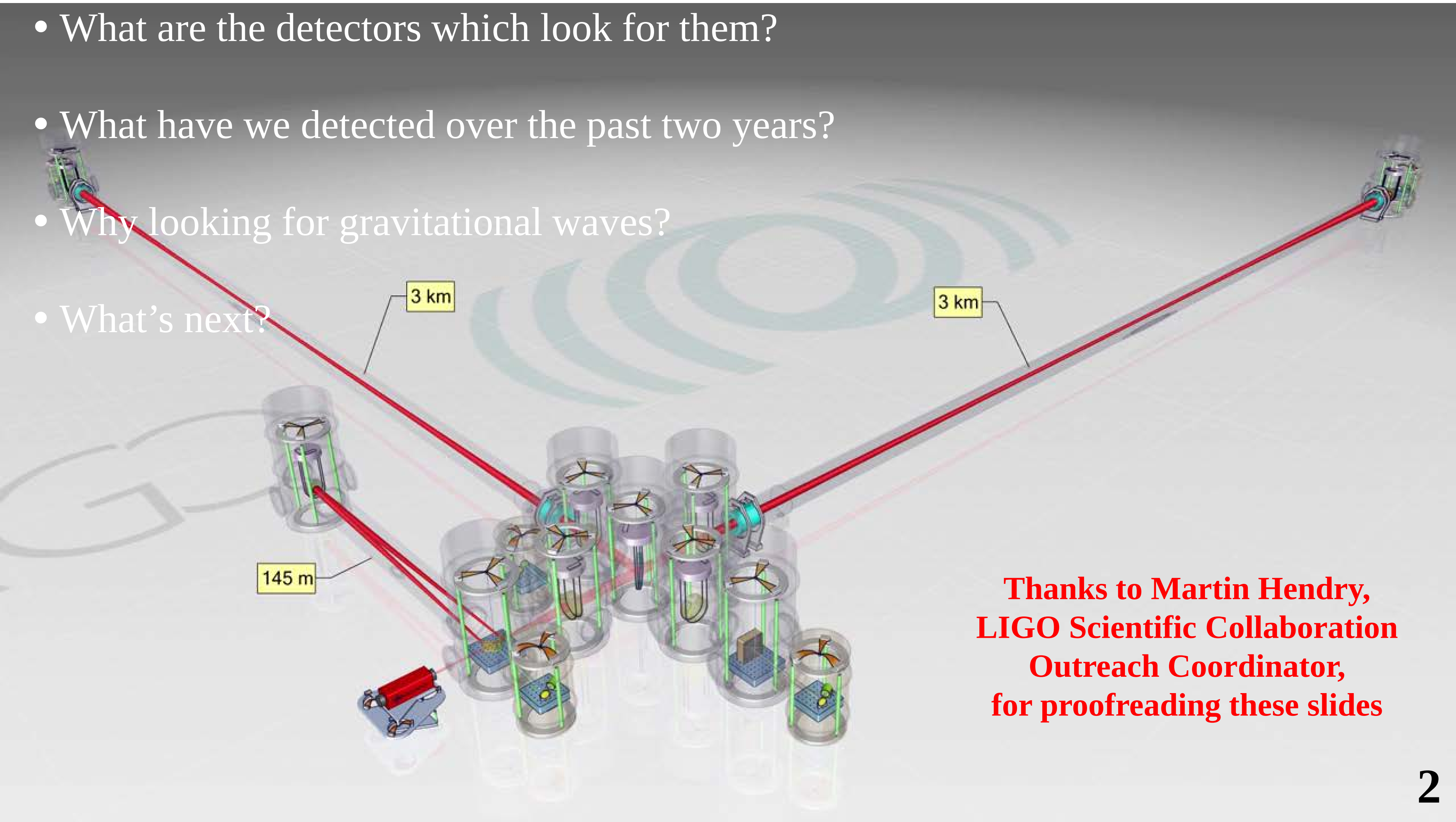
Answering the following questions

- 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,
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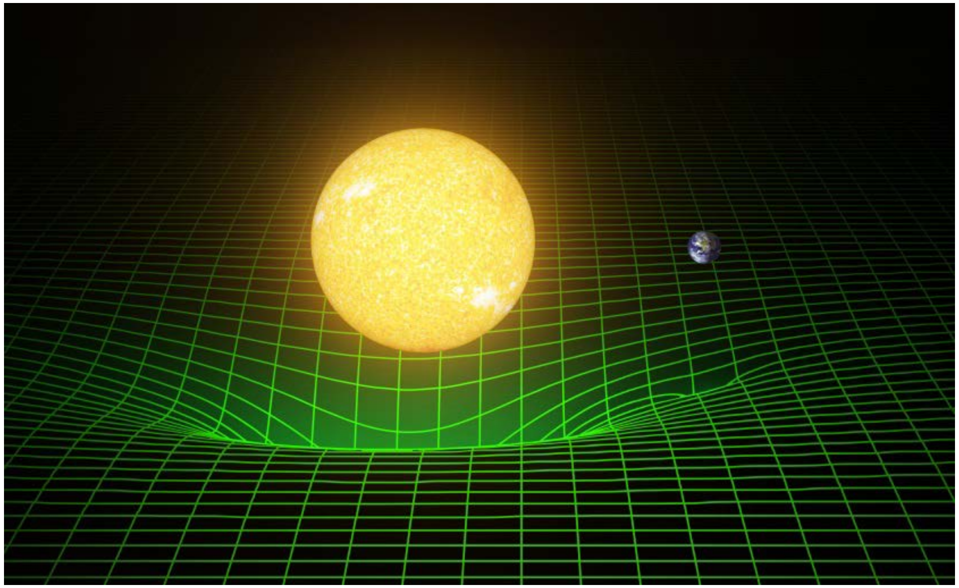
Gravitational waves

- "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

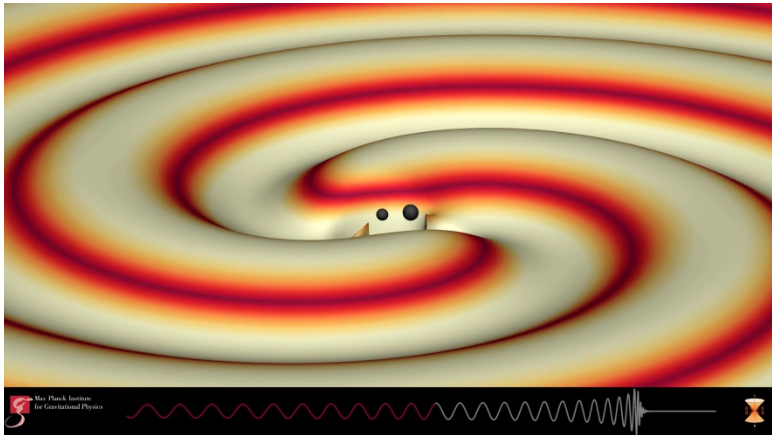
- Einstein's equations
  - Curvature [m] = 0.000000000000000000000000000000000000000002 [m/J] × Energy [J]

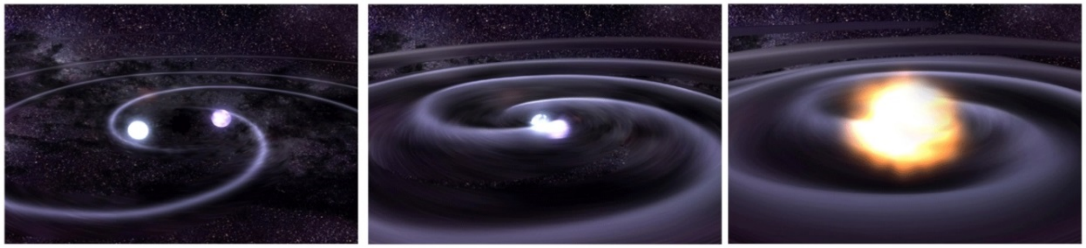
  → The space-time is incredibly stiff!

- 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 $\propto$ 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

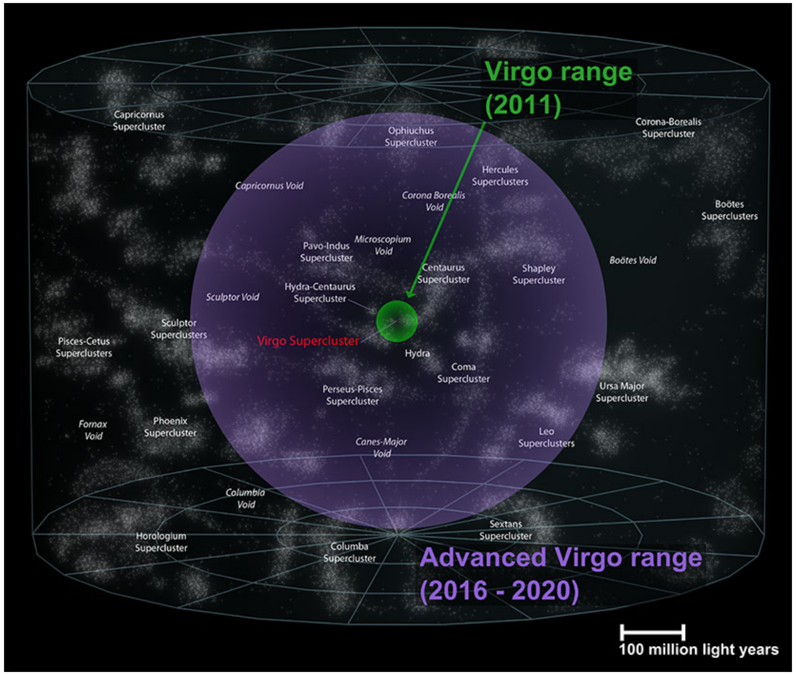
  → Rate scales as $(\text{distance})^3$

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

→ Need to probe the largest Universe volume

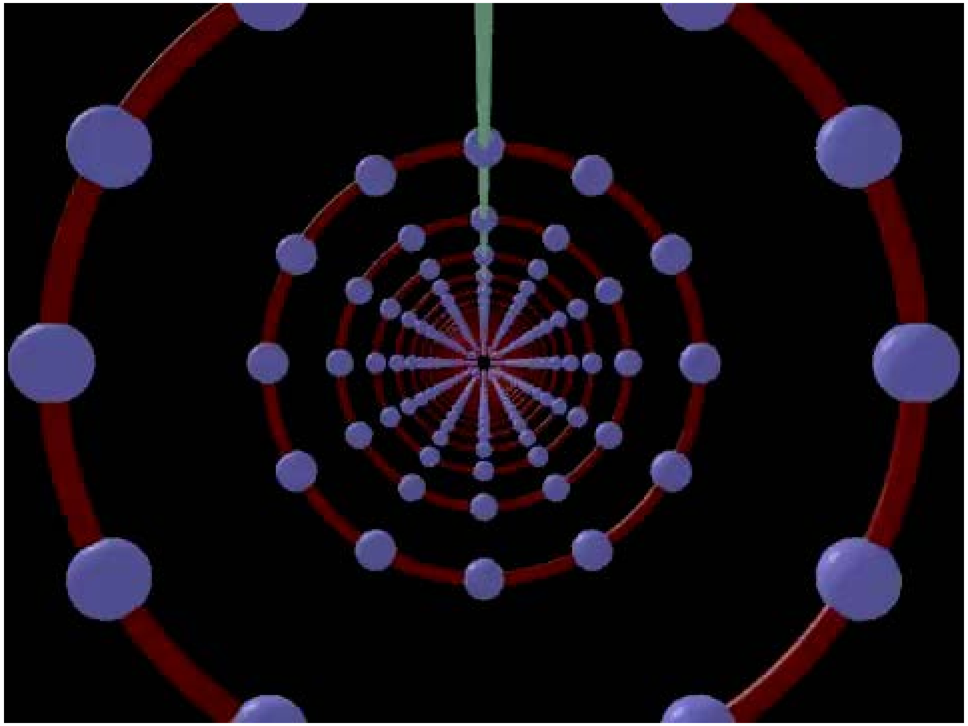
  - Pluriannual (2010-2016) upgrade of all detectors to improve their sensitivity

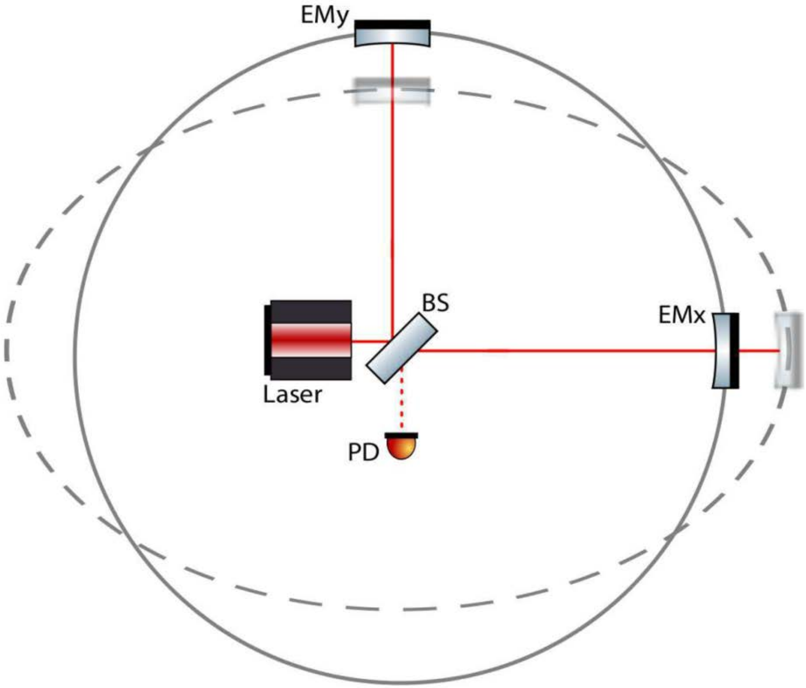
    → In return: first detections in 2015-2017!



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



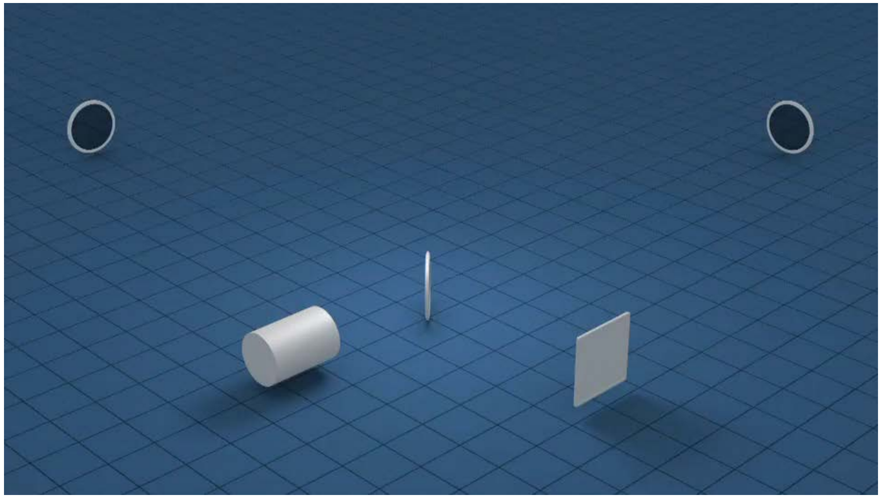


- Space-time is distorted over a length L by a quantity δL, which is proportional to L and to the gravitational-wave amplitude h

$$\delta L_{max} = \frac{hL}{2}$$

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

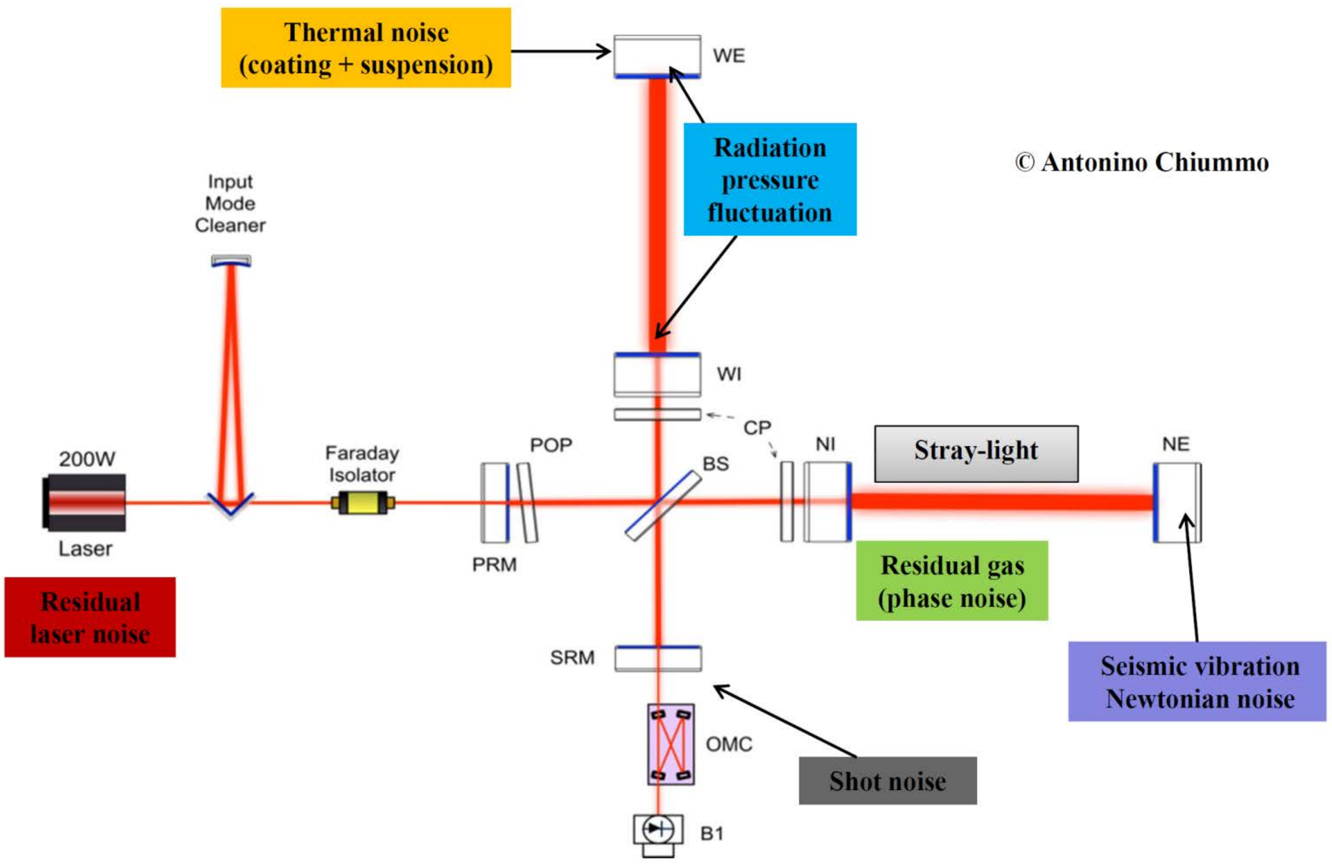
→ Beams are 'detuned' when they recombine
  - Modification of the laser beam interference pattern
    → Variation of the laser power detected at the output of the detector

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

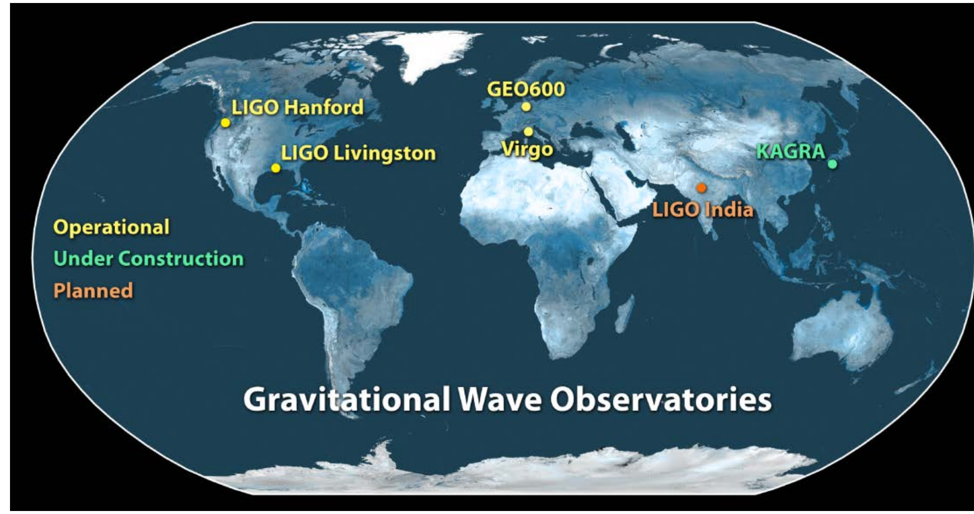
  - Design
  - Building
  - Operation
  - Maintenance
  - Upgrade



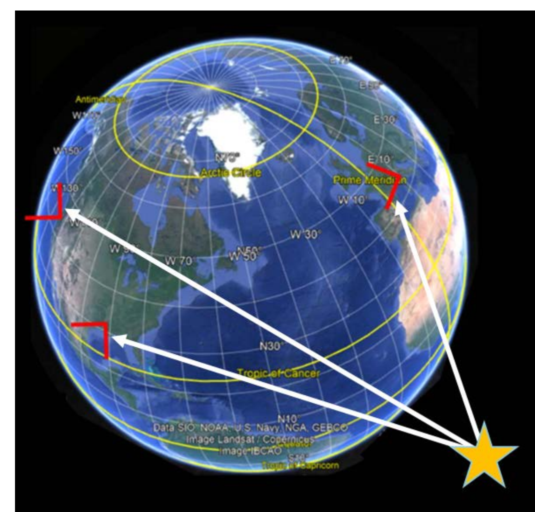
- Detector
  - Control
  - Monitoring
- Fundamental noises
  - Mitigation
- Technical noises
  - Noise hunting
- Continuous environment monitoring
  - Ground motion, weather, anthropogenic activities, etc.

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

Theoretical developments

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

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

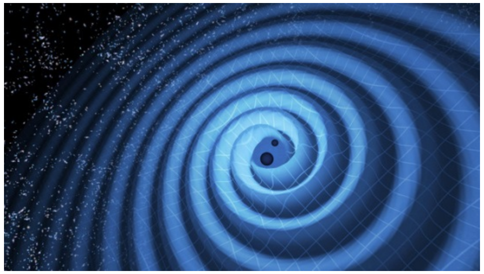
- **1963: Rotating black hole (BH) solution (Kerr)**
- **1990's: Post-Newtonian expansion (Blanchet, Damour, Deruelle, Iyer, Will, Wiseman, etc.)**
- **2000: Binary BH (BBH) effective one-body approach (Buonanno, Damour)**
- **2006: BBH merger simulation (Baker, Lousto, Pretorius, etc.)**

Experiments

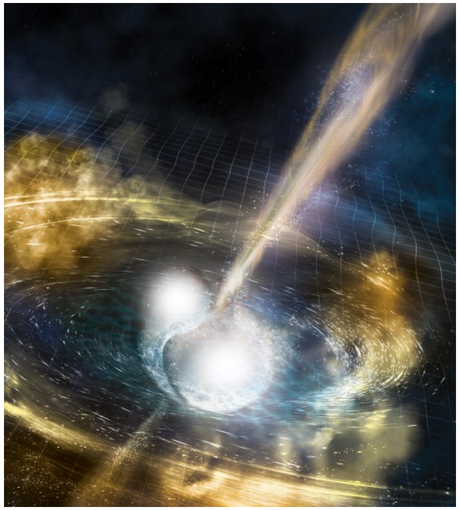
- **1960's: first Weber bars**
- **1970: first IFO prototype (Forward)**
- **1972: IFO design studies (Weiss)**
- **1974: PSRB 1913+16 (Hulse & Taylor)**
- **1980's: IFO prototypes (10m-long) (Caltech, Garching, Glasgow, Orsay)**
- **End of 1980's: Virgo and LIGO proposals**
- **1990's: LIGO and Virgo 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

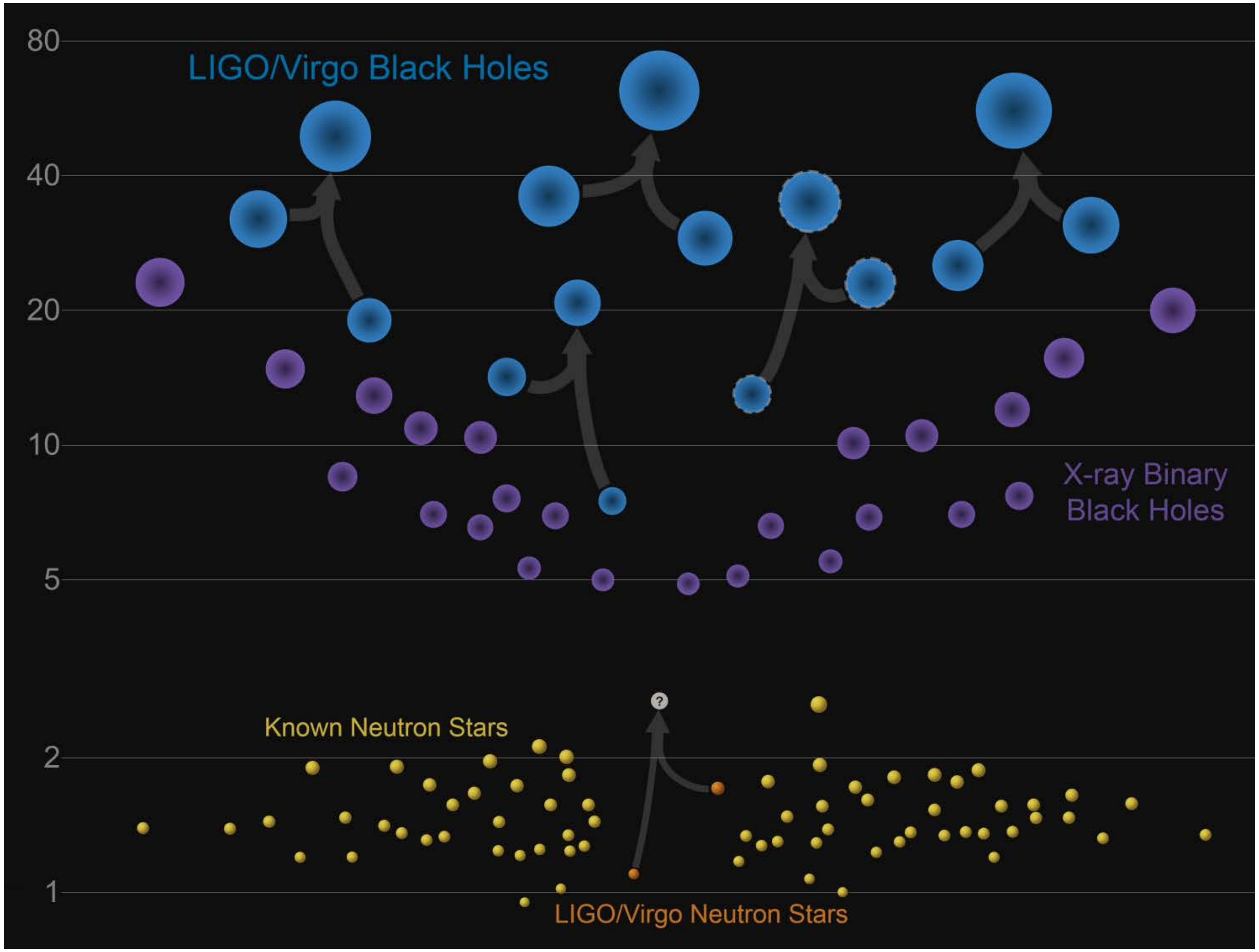


- Binary system: two compact stars orbiting around one another
  - Lose energy by emitting gravitational waves
    → Come closer, orbital motion speeds up
  - The closer they are, the more they emit gravitational waves
    → The more they come closer, the faster they travel
  - They end up merging, inducing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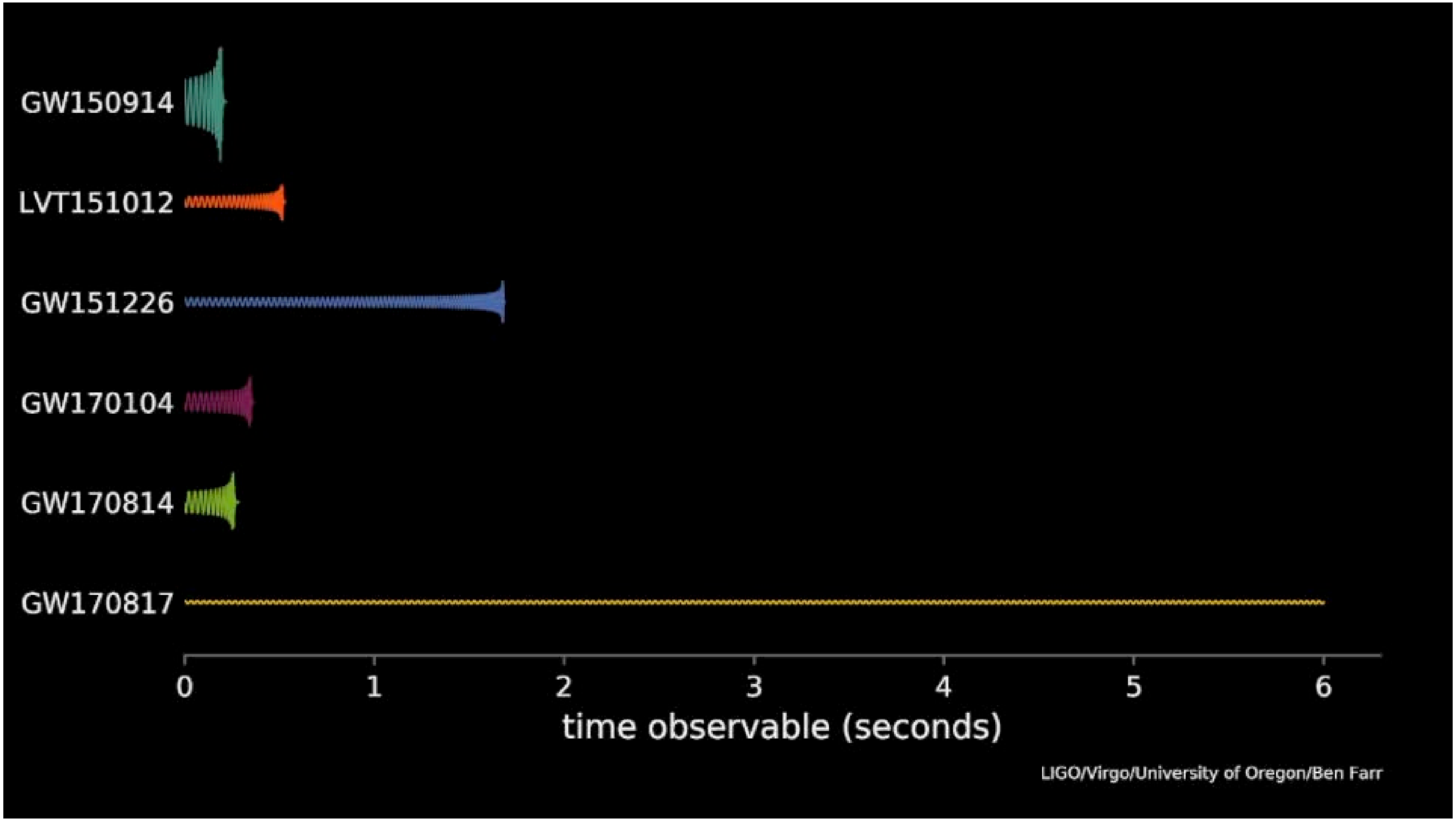
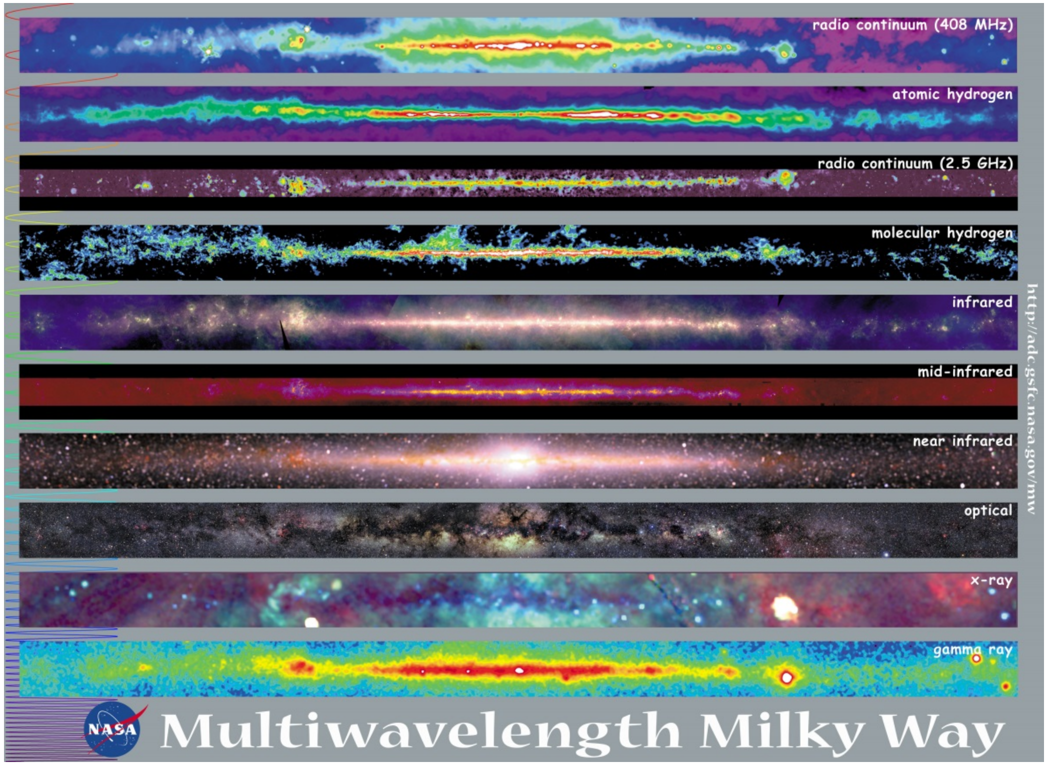


A new window onto the Universe

- 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

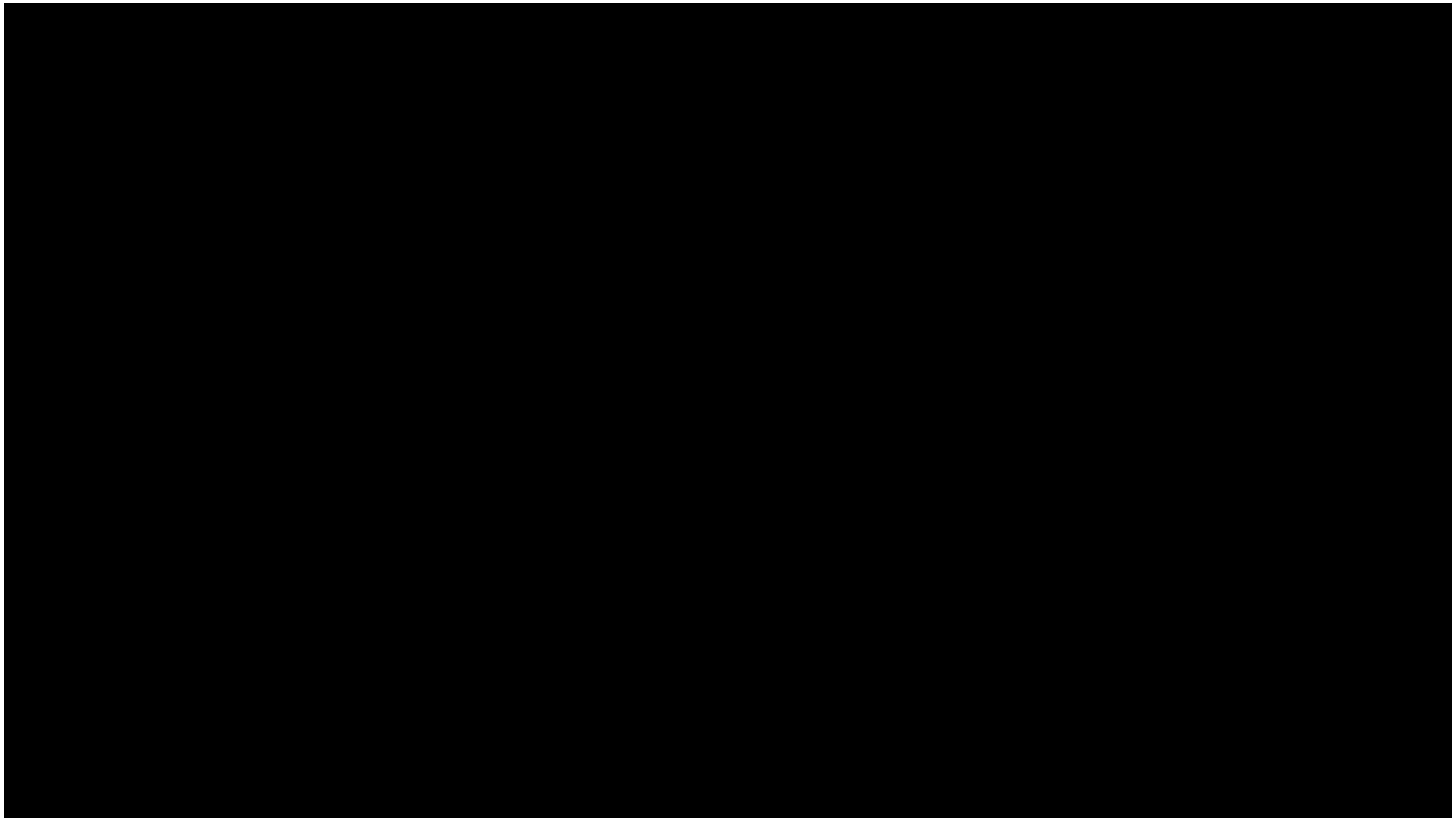
→ Multi-messenger astronomy



- 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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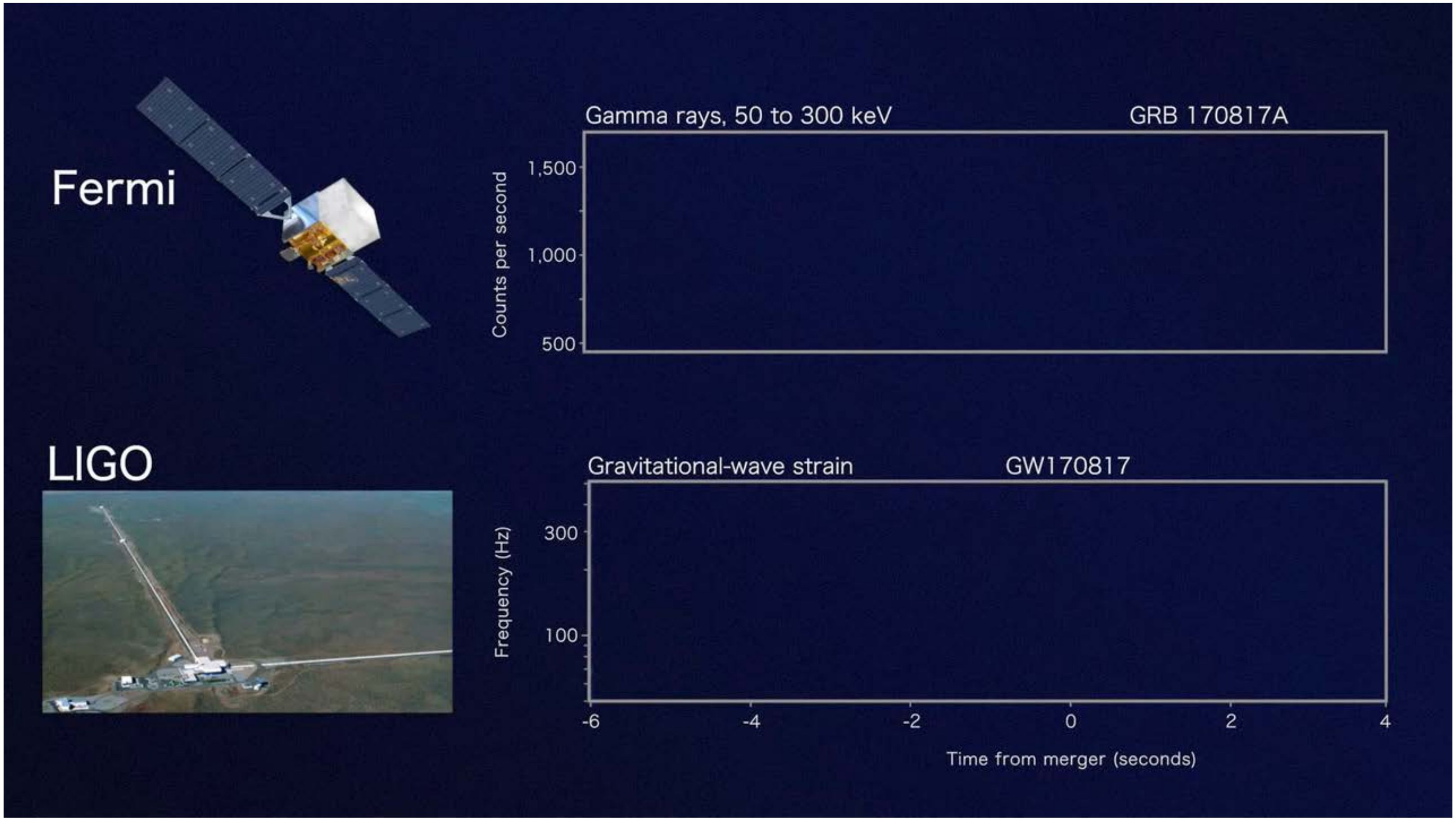

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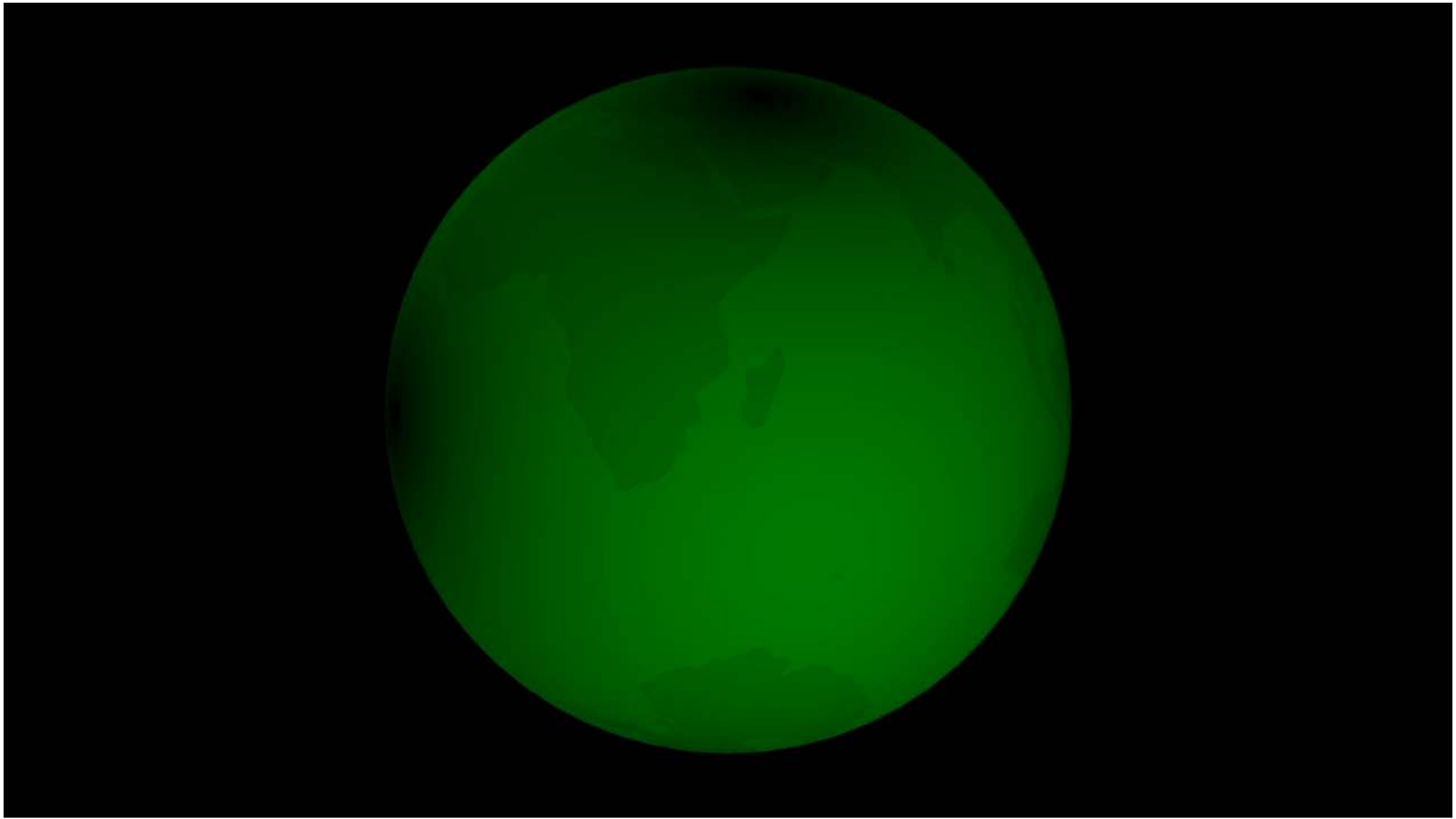

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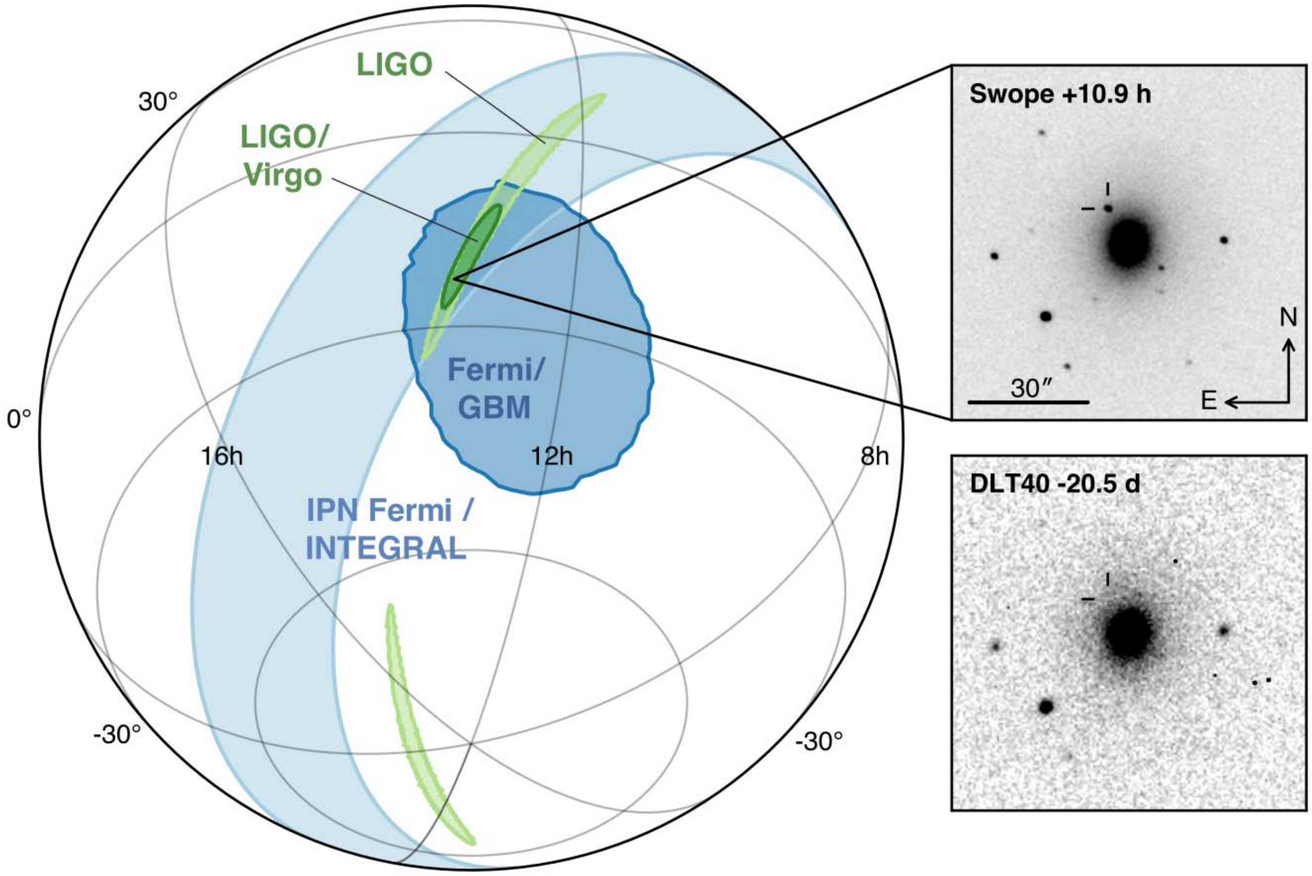

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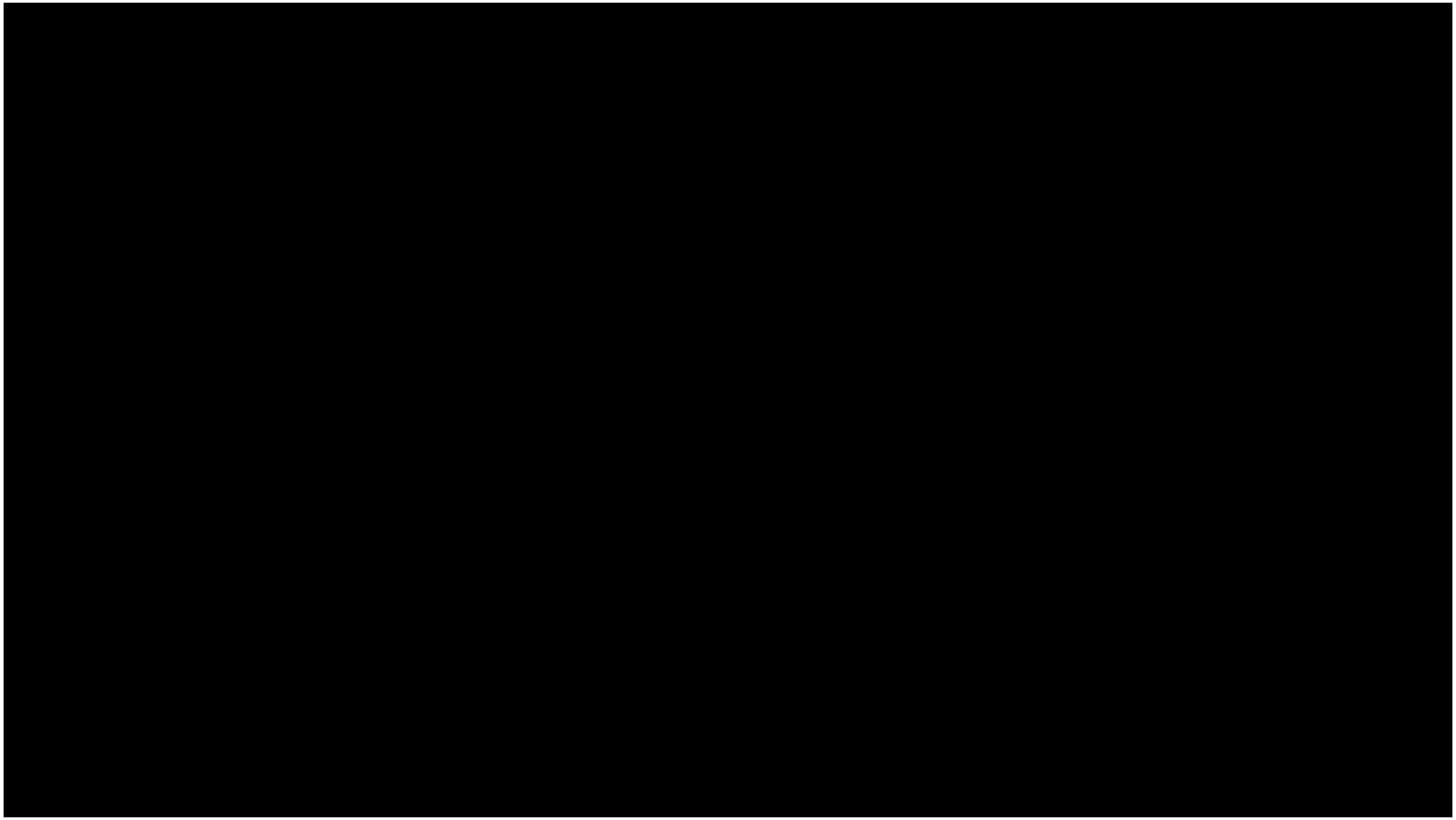
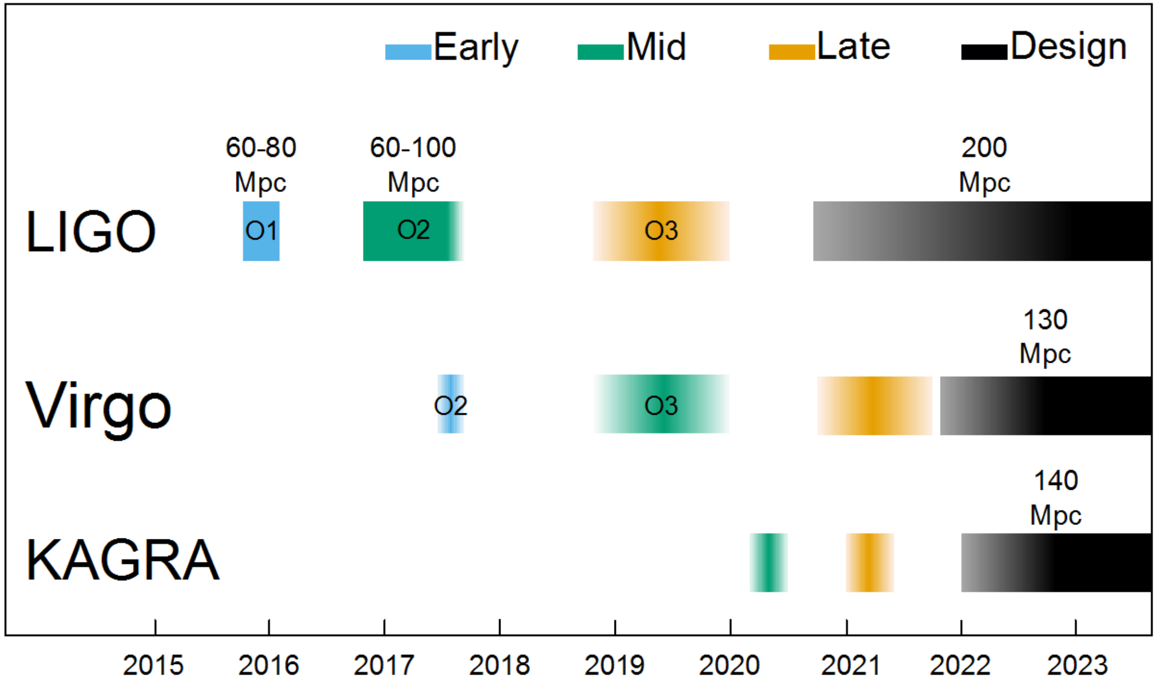
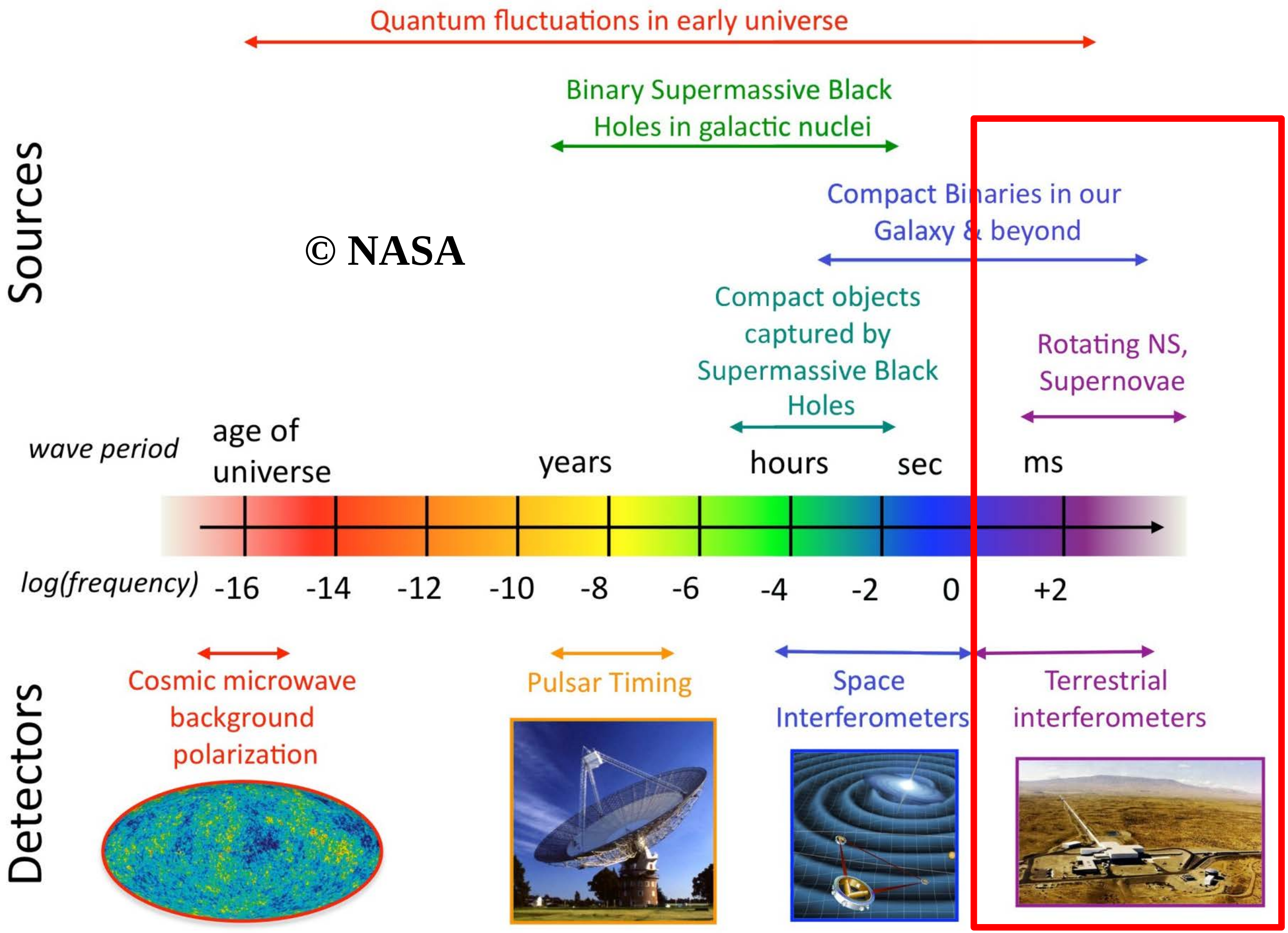


What's next?

- « 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



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
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