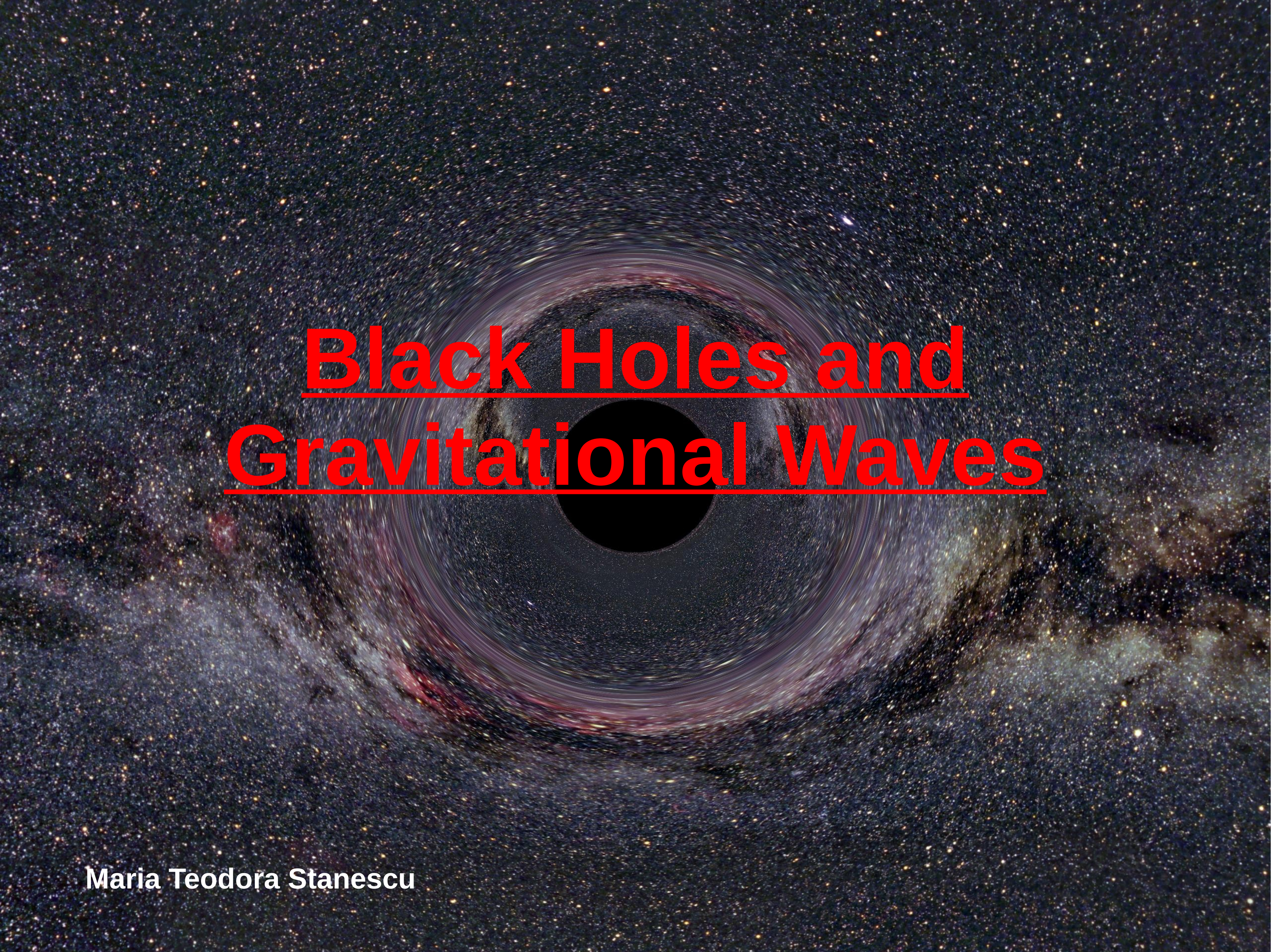

Black Holes and Gravitational Waves

Maria Teodora Stanescu

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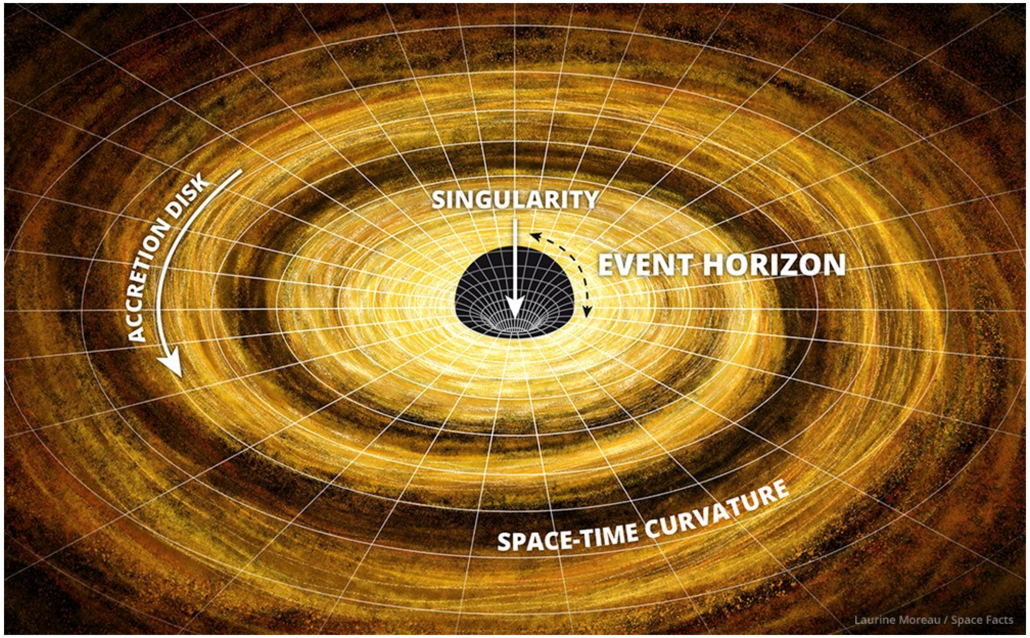
1. What are black holes?

Definition and characteristics

- Black holes are so dense and compact objects that not even light can escape their gravitational field

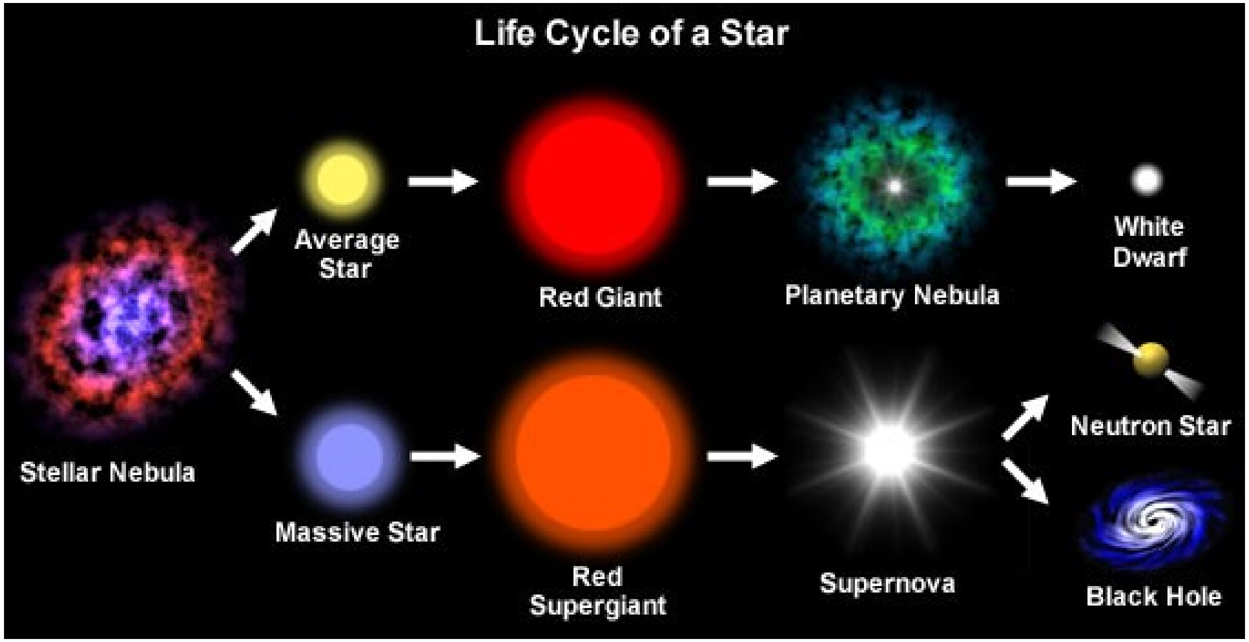
- Every black hole has a gravitational singularity (a compact center that is constantly collapsing toward 0 volume) and an event horizon (an invisible limit surrounding the singularity where the escape velocity is equal to the speed of light) → according to general relativity

- If there is matter around, the object is surrounded by an accretion disc (a disc shaped zone consisting in gas, dust and other material that orbits around the black hole)



How do they form?

- It is believed that a black hole is an ending stage of a star's life cycle



- A star starts "dying" when it uses up most of it's fuel. At that point, nothing can balance the gravitational pull and the core collapses
- Depending on the star's mass, it can turn into a white dwarf ($m \leq 1{,}4M_\odot$), a neutron star ($1{,}4M_\odot < m < 3\ M_\odot$) or a stellar mass black hole ($m > 3M_\odot$)

1 solar mass = $1M_\odot = 2 \times 10^{30}$kg

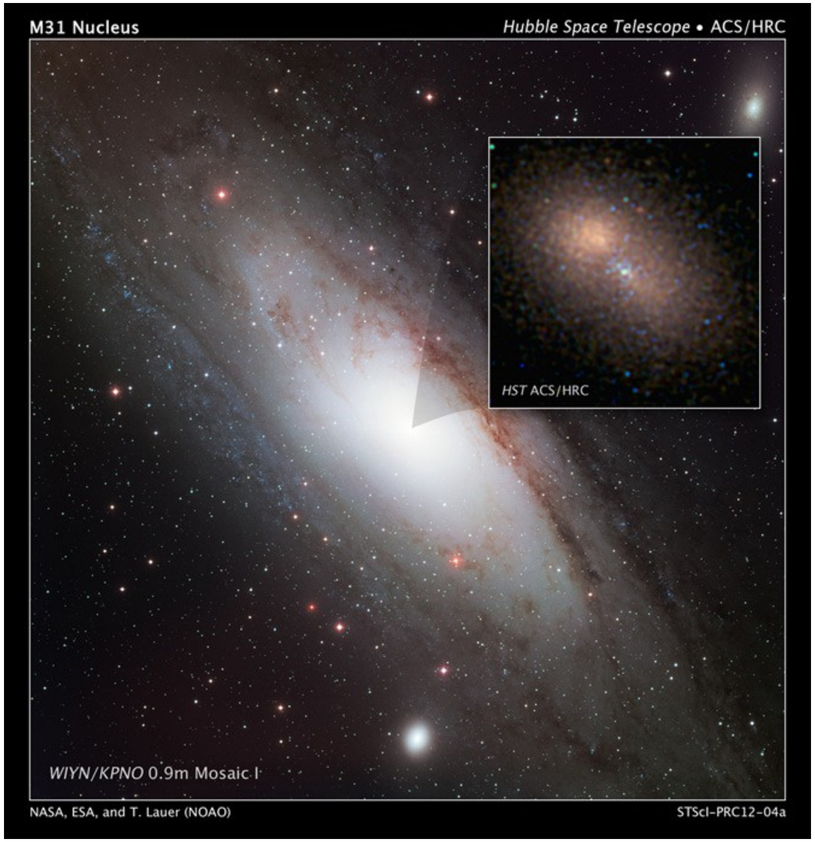
Types of black holes

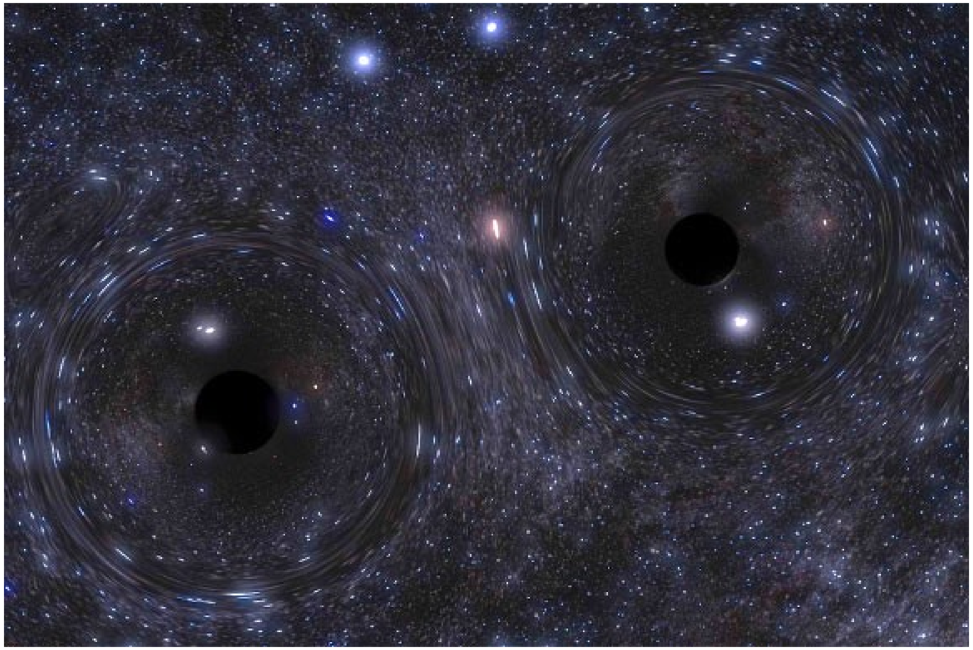
Observed

- Stellar-mass black holes
  - Have less than 20 solar masses
- Supermassive black holes
  - Have more than one million solar masses

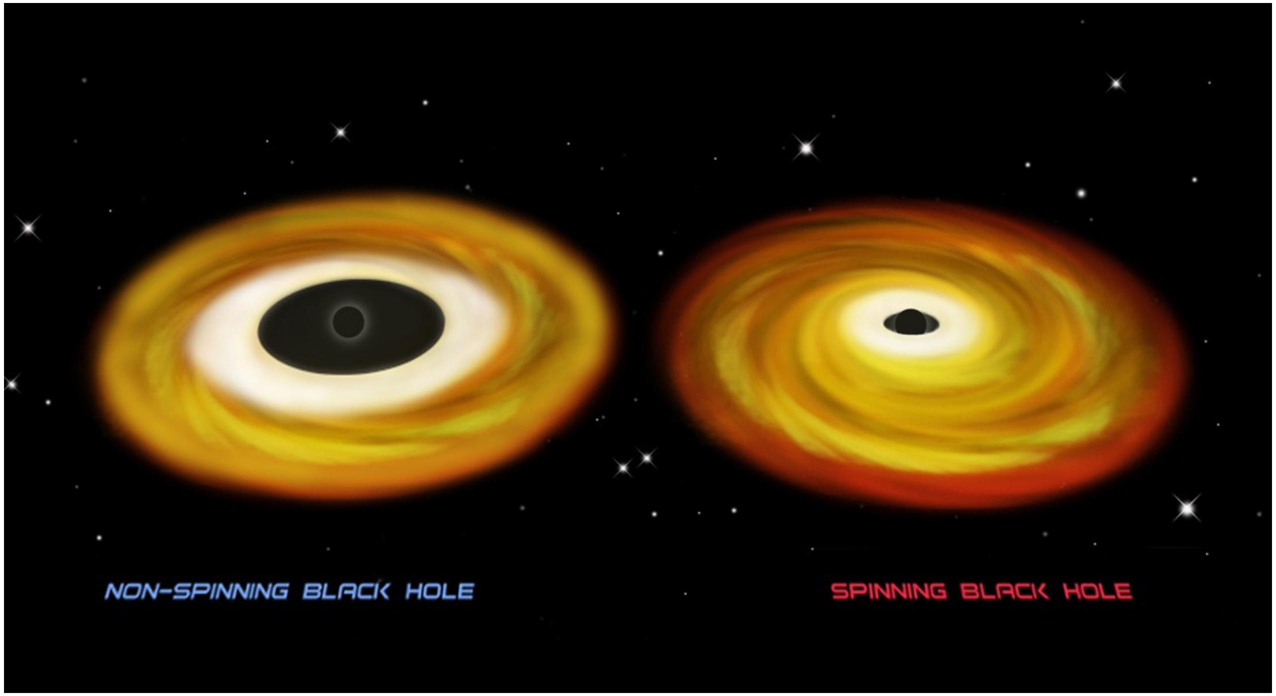
Theoretically predicted

- Intermediate-mass black holes
  - have between 20 and 1.000.000 solar masses
- Miniature black holes
  - hypothetical tiny black holes;
  - are smaller than stellar mass black holes



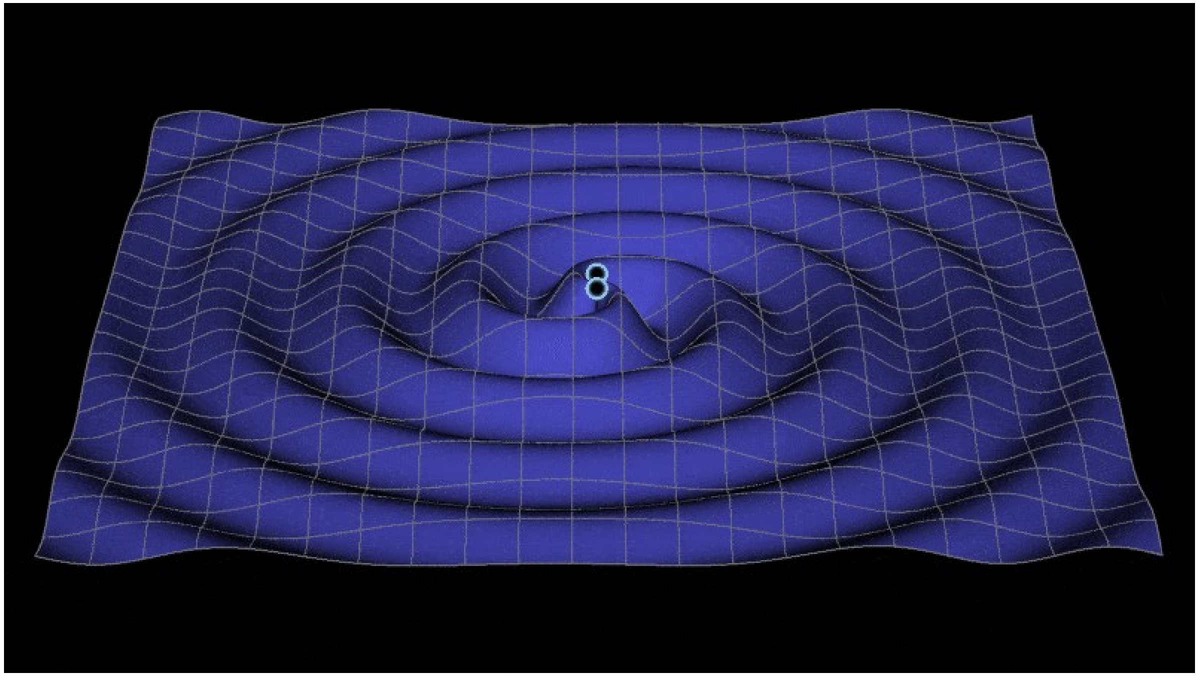


- Another classification is based on the rotation
  - Spinning black holes
    - Kerr black holes
  - Non-spinning black holes
    - Schwarzschild black holes



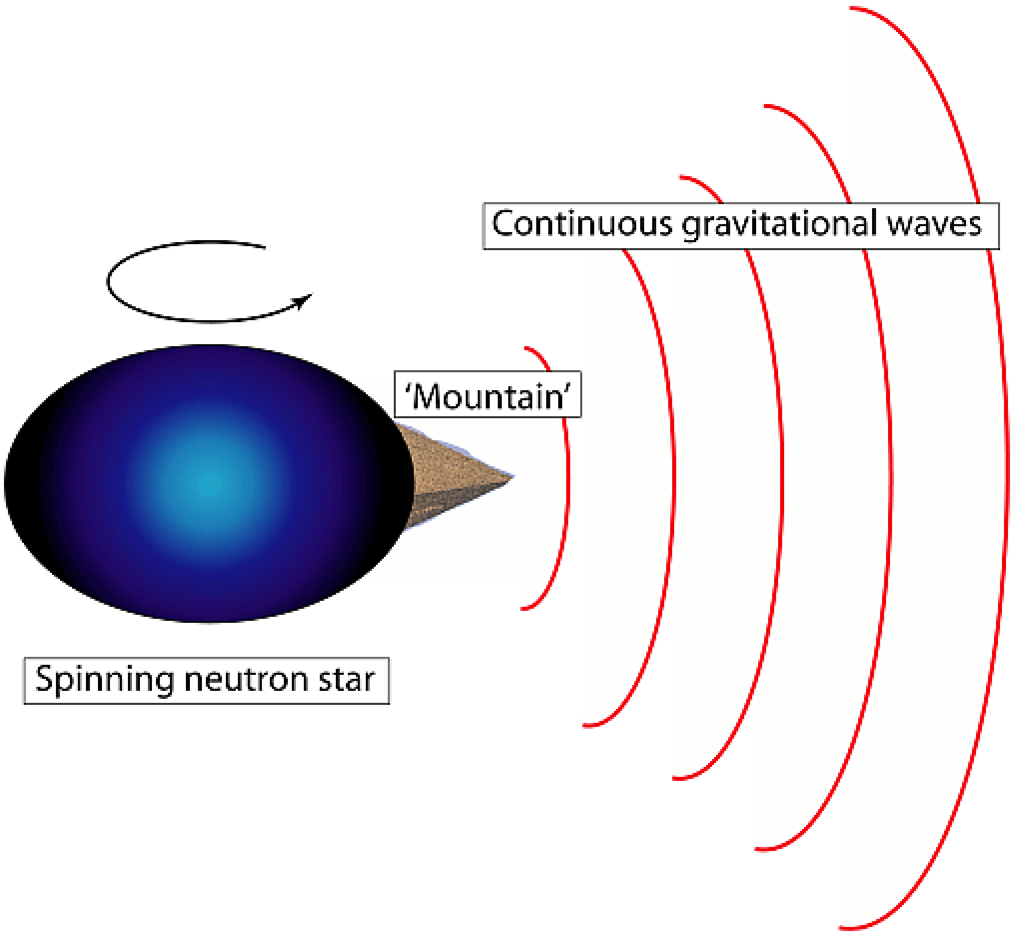
2. What are gravitational waves?

- They are caused by a modification in the gravitational field of one or more massive objects
- Occur when there is a change in the distribution of mass
- They travel at the speed of light; while doing this, they modify the distance between points in space
- They are small "ripples" in space and time

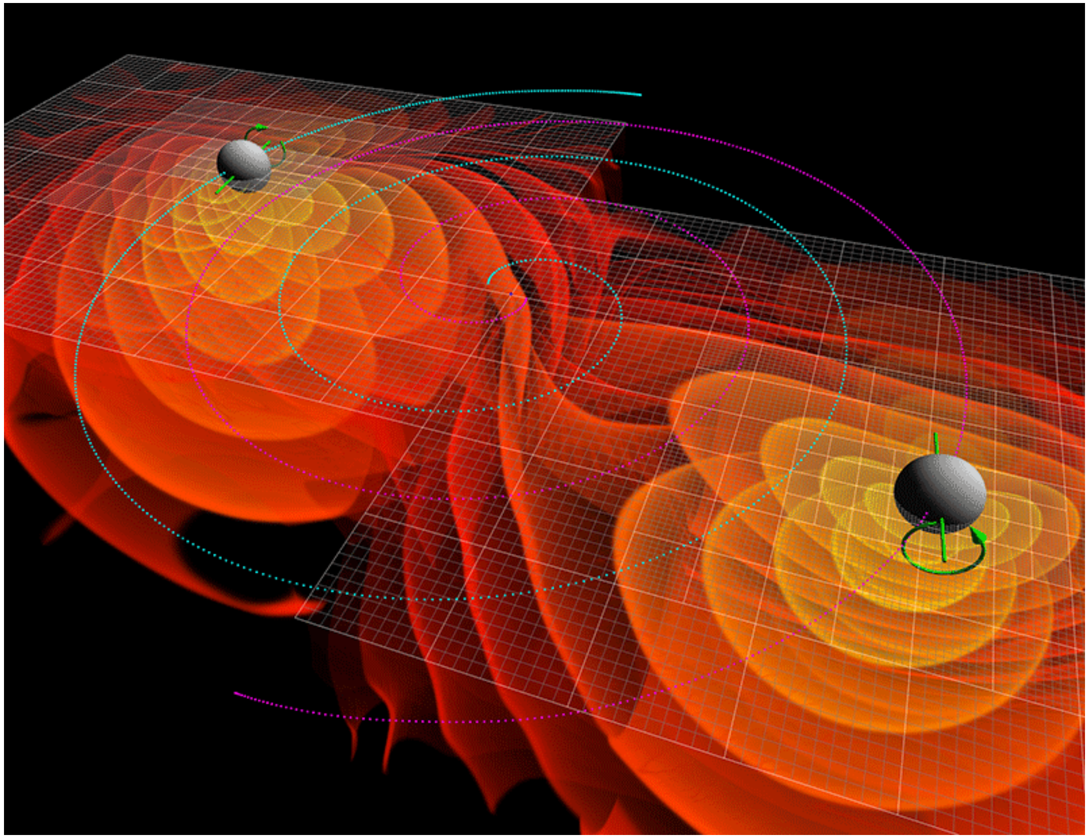


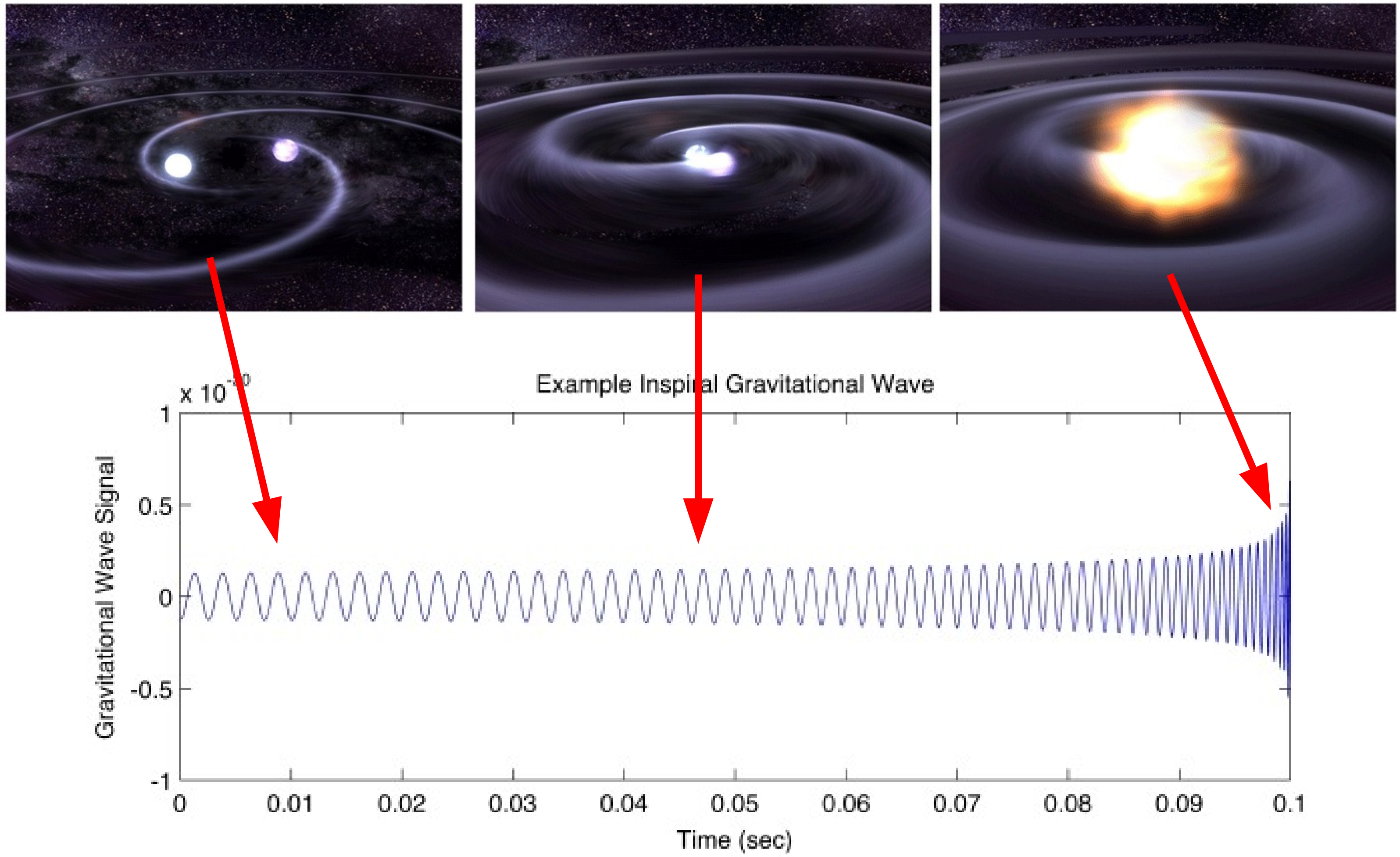
Types of gravitational waves

- **Continuous gravitational waves**
  - ➢ produced by a single spinning massive object
  - ➢ Any bump or imperfection on the surface of the object generates gravitational waves as the star spins



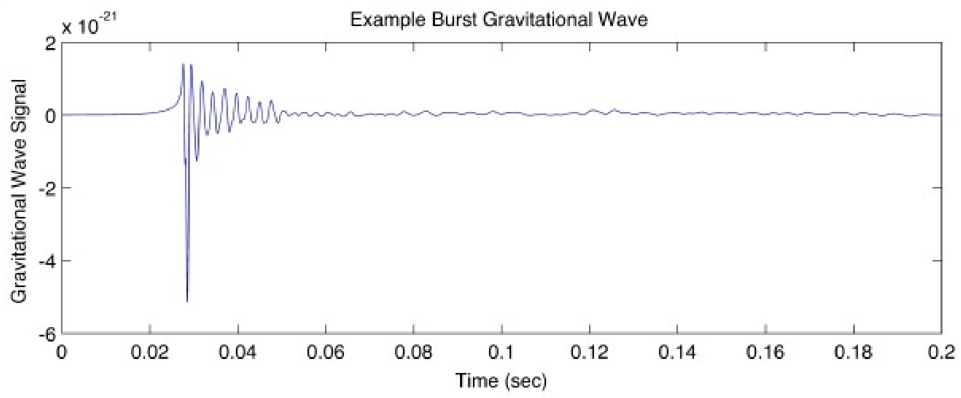
- **Compact binary inspiral gravitational waves**
  - produced by orbiting pairs of massive and dense objects like black holes or neutron stars
  - There are 3 types:
    - Binary Neutron Star (neutron star - neutron star) or NSNS
    - Binary Black Hole (black hole - black hole) or BHBH
    - Neutron Star - Black Hole Binary or NSBH

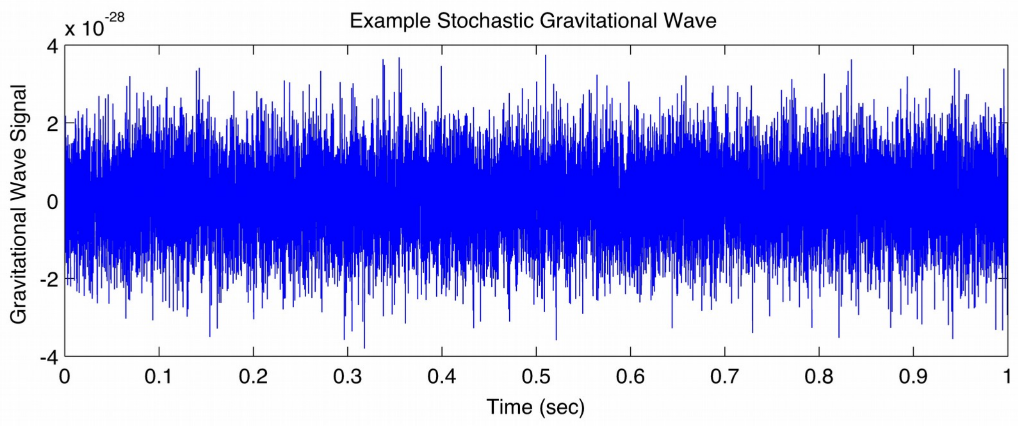




- The objects orbit around each other, they lose energy in form of gravitational waves
- By losing energy they come closer together and cause the gravitational waves to intensify
- Eventually the objects merge; this event is detected as a burst

- **Burst gravitational waves**
  - Come from short-duration, unknown or unanticipated sources
  - Recorded, for example, during the last moments of merging black holes and neutron stars supernova explosions
- **Stochastic gravitational waves**
  - Very faint signals
  - Produced by unknown events; these waves pass by Earth any time and from any direction of the Universe





3. History

Black holes

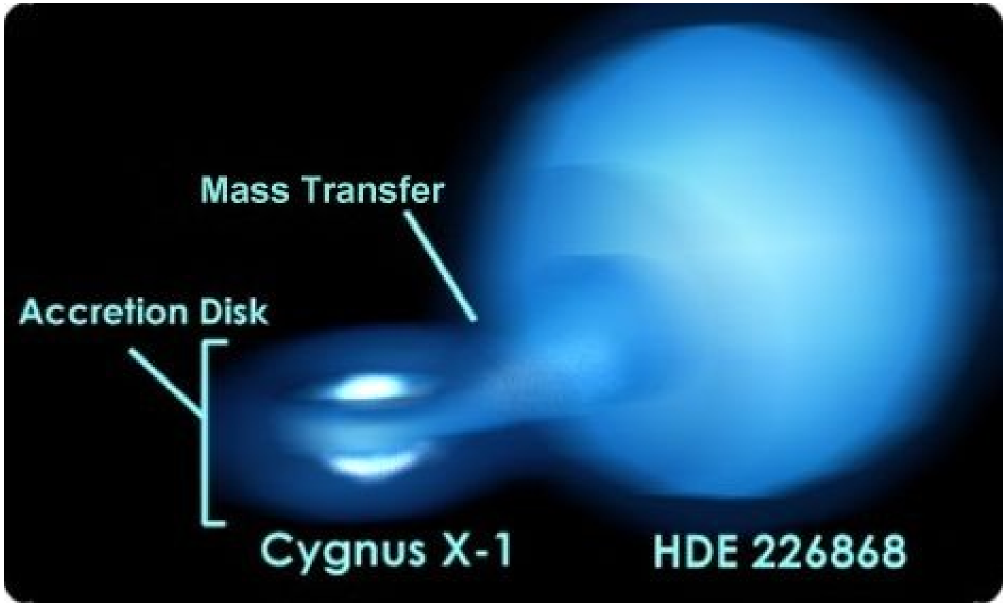
- 1783 **John Mitchell**
  - Suggests that the gravity of some stars could be so strong that not even light could escape from them; he named them dark stars

Gravitational waves

- 1905 **Henri Poincaré**
  - The first to propose the existence of gravitational waves, emanating from a body and propagating at the speed of light

- 1915 **Albert Einstein**
  - General Relativity shows that gravity is a ‘warp’ in spacetime caused by matter. The more massive an object, the greater it warps the space around it
  - Predicted the existence of gravitational waves

- 1915 **Karl Schwarzschild**
  - Shows that enough matter packed into a small-enough space would have such a powerful gravitational field that nothing could escape from it, including light
- 1971
  - First direct observation of a stellar-mass black hole: Cygnus X-1

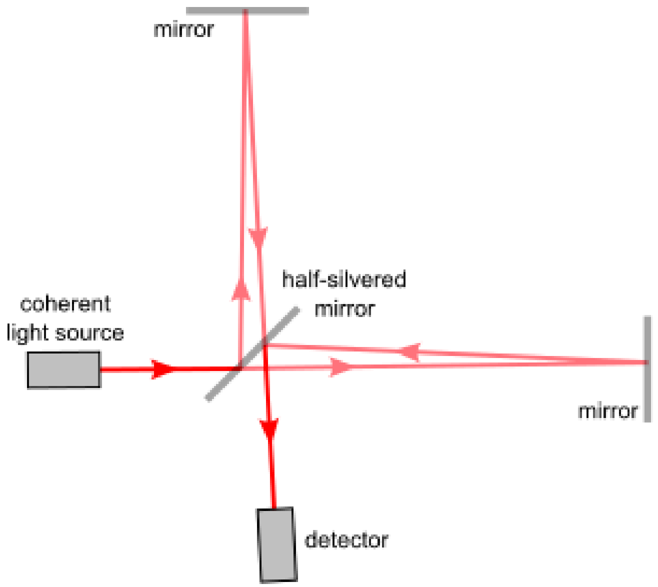


- 1974 **Russell Alan Hulse and Joseph Hooton Taylor, Jr.**
  - Firs indirect observation of gravitational waves
  - They analysed the gradual decay of the orbital period of the Hulse-Taylor pulsar, which fitted precisely with the loss of energy and angular momentum in gravitational radiation predicted by general relativity.
- 2015 **GW150914**
  - First direct observation of gravitational waves by the Laser Interferometer Gravitational-Wave Observatory (LIGO)
  - They were produced by two merging black holes with ca. 29 $M_\odot$ and 36 $M_\odot$

4. how can we detect gravitational waves?

LIGO

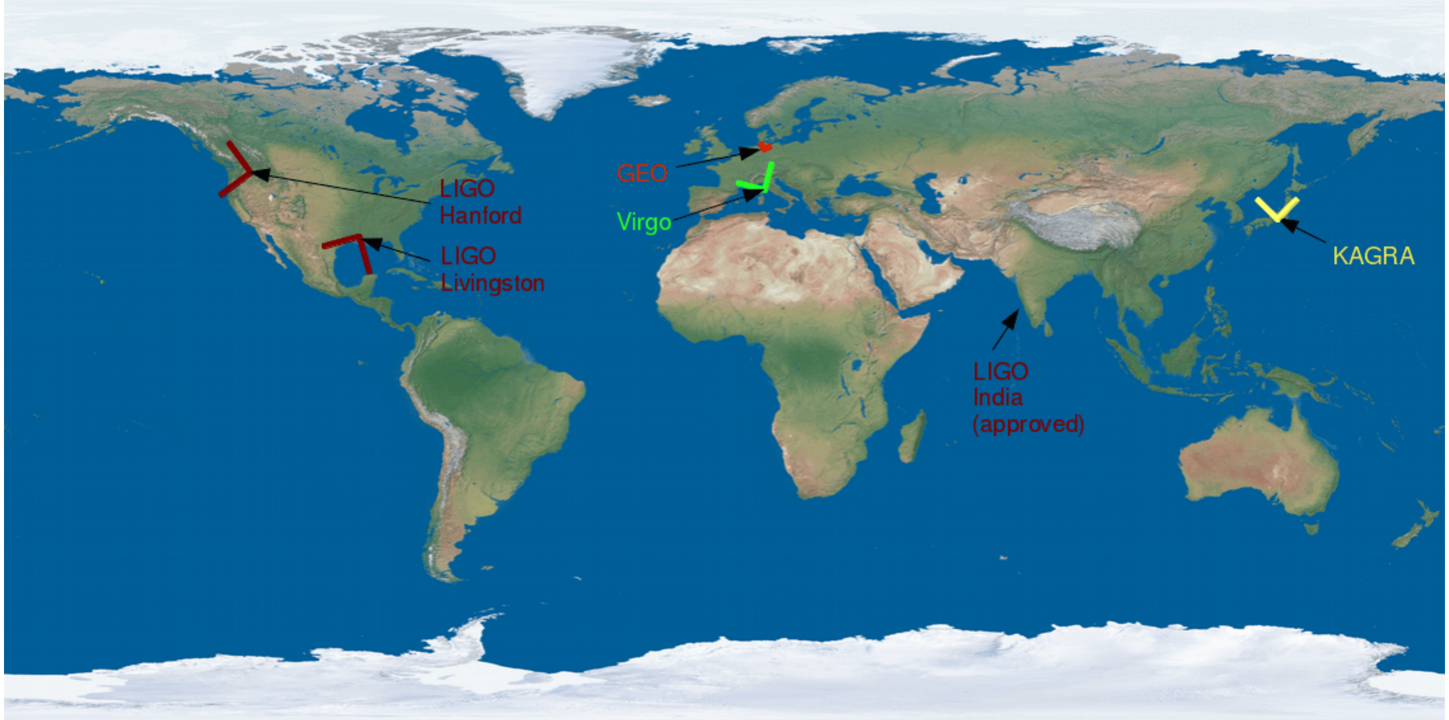
- light from a single source is emitted and split in 2 by a beam splitter
- The 2 light beams travel the same distance through different tubes positioned perpendicularly to each other
- The beams are reflected back by mirrors and redirected towards a light detector



- Normally, the light waves are set completely out of phase so that there is no signal detected
- When gravitational waves pass by the interferometer, they change the length of the tubes
- The speed of light is constant and therefore the light beams would have to travel different distances
- Because of this, they will not be out of phase anymore and the light detector receives a signal

Gravitational waves observatories

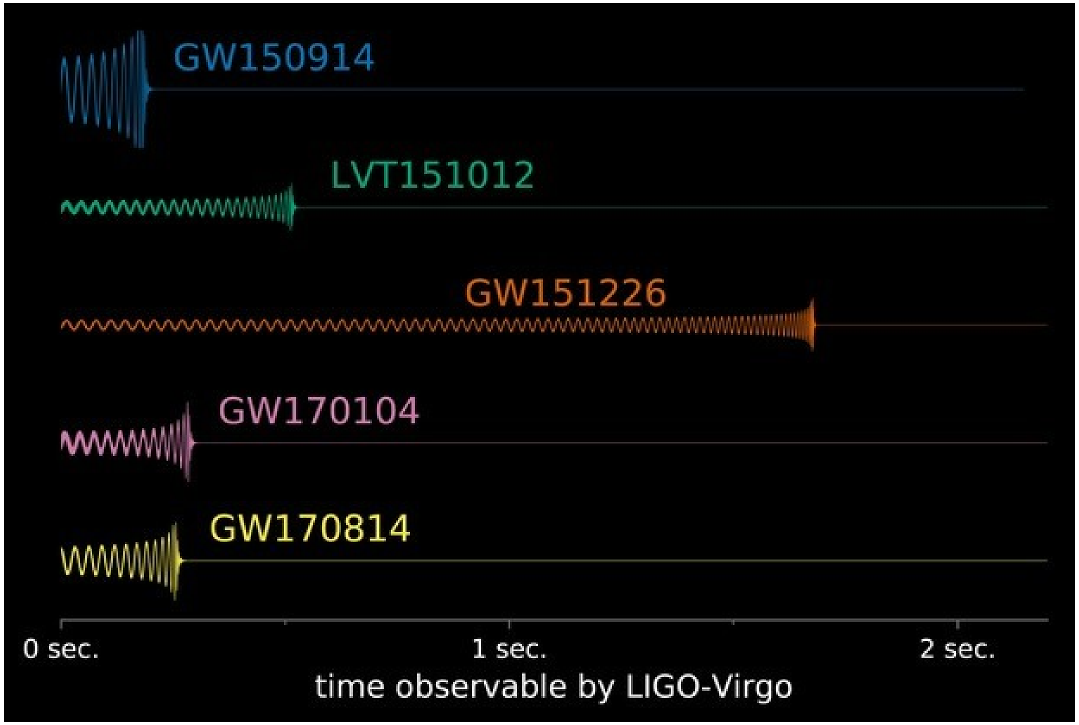
- The Laser Interferometer Gravitational-Wave Observatory (LIGO) is located in the USA; there are 2 identical devices:
  - one in Hanford, Washington
  - one in Livingston, Louisiana
- Virgo is located near Pisa, Italy
- KAGRA is located in Japan
- GEO600 is located near Hanover, Germany



Results

- Since the first detection in 2015, there have been other 6 recordings made of gravitational waves
- 5 of them were caused by the merger of two black holes

  - LVT151012
  - GW151226
  - GW170104
  - GW170104
  - GW170608



5. Conclusions

- **With the help of gravitational waves astronomy, we have been able to directly observe gravitational waves for the first time, in 2015**
- **These waves were produced by the merger of stellar black holes with masses of 29 M☉ and 36 M☉**
- **The estimated mass of the newly created black hole is of 62 M☉, an intermediate-mass black hole**
- **The equivalent energy of 3 M☉ was emitted in form of gravitational waves**

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