The birth, life and death of astrophysical black holes

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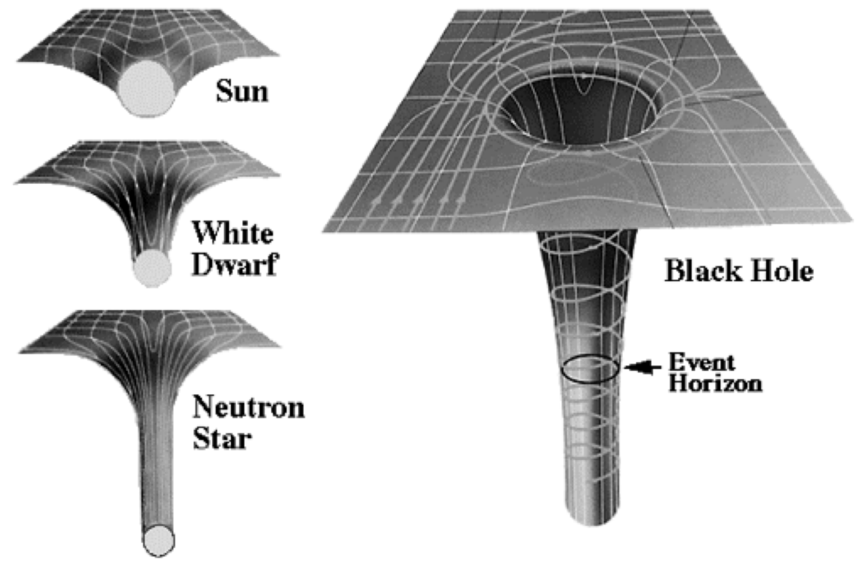
Today's topics

1. What are black holes?
2. What types of black holes exist in the Universe and how did they form?
3. How can black holes be observed ?
4. How do black holes evolve and how can we model their dynamical evolution?
5. What is the future of black holes and how do they die ?
6. What have we learned today?

1. What are black holes?

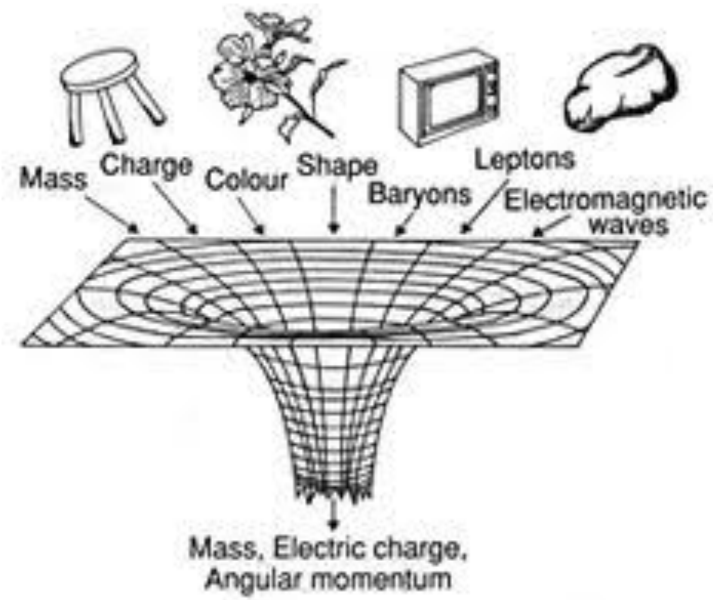
- The first idea for black holes was put forward by the geologist John Michell in 1784, who based on the Newton's law of gravity speculated about the existence of "a body so massive that even light could not escape from it".
- According to Einstein's (1915) Theory of General relativity the observed gravitational effect between different masses results from their warping of spacetime.



- A **black hole** is a region of spacetime exhibiting such strong gravitational effects that nothing, not particles or even electromagnetic radiation, such as light, can escape from inside it.

The properties of black holes

- Black holes were just mathematical curiosities for a long time, until people started to realised in the 1960s that black holes are real physical objects that exist in the Universe.
- The physicist Robert Dicke came up with the name black hole, when he reportedly compared the phenomenon to the “Black Hole of Calcutta”, a notorious prison, where people entered but never left alive.
- Black holes are in fact incredibly simple objects. According to the ”No hair theorem” they can only have three global properties:



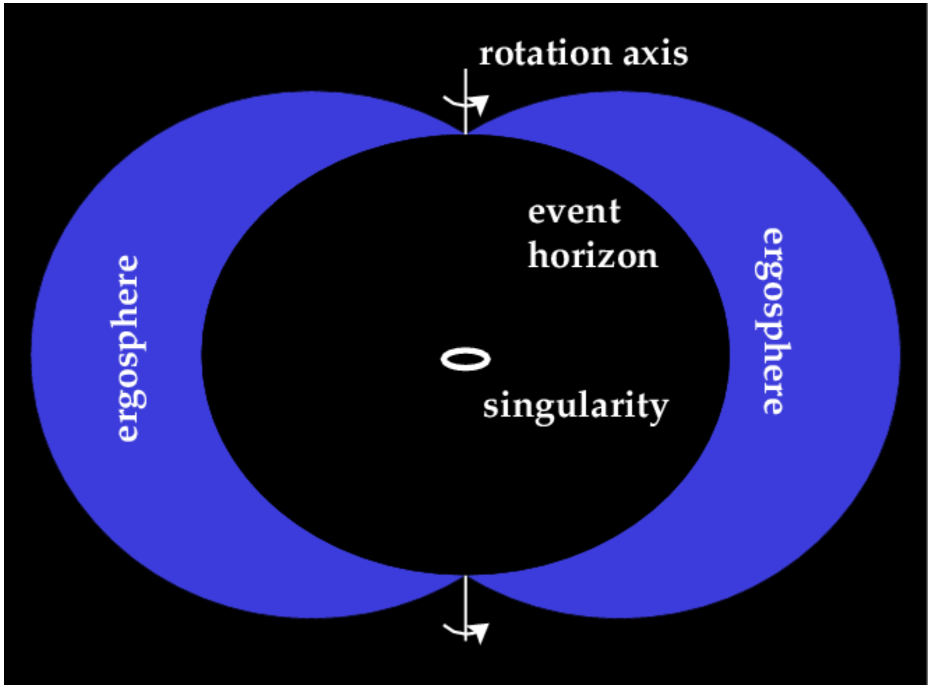
Mass: $M>0$
Angular momentum: $L>0$
Electric charge: $Q \sim 0$

The structure of black holes

- The Event horizon: A boundary in spacetime, the inside from which nothing, not even light, can escape. For a stationary non-rotating black hole the Schwarzschild radius is:

$$R_{\mathrm{Sch}} = \frac{2GM}{c^2} = 2.95\ \mathrm{km} \times \frac{\mathrm{M}}{\mathrm{M}_\odot}$$

- Singularity: Point-like structure, where the curvature of spacetime become infinite. Has a zero volume and contains all the mass of the black hole, thus resulting in infinite density.
- Rotating black holes are surrounded by a region of spacetime in which it is impossible to stand still, called the ergosphere. This is the result of a process known as frame-dragging.



What would happen to the Earth if the Sun suddenly turned into a black hole?

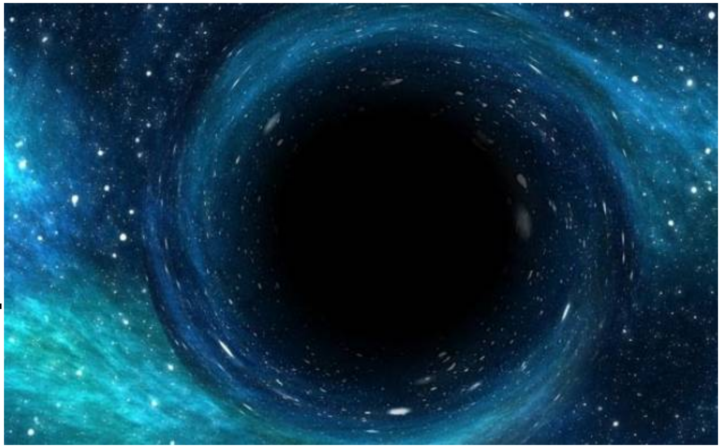
- If all the matter in the Sun would be compressed inside a radius of 3 kilometres, the Sun would turn into a black hole (this is only possible in theory).
- What would happen to the Earth?

A. Nothing, everything would continue as before.

B. The Earth and all the planets would fall into the black hole.

C. The closest planets would fall into the black hole, but the Earth would remain in its orbit.

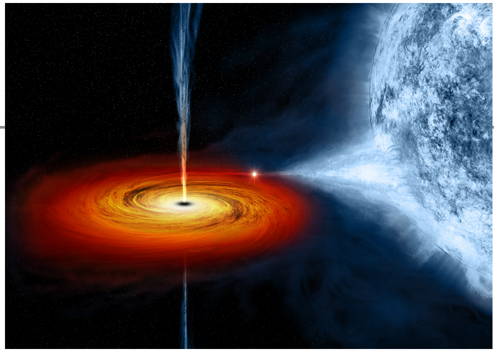
D. The sky would turn dark, but the Earth and the other planets would continue in their orbits.



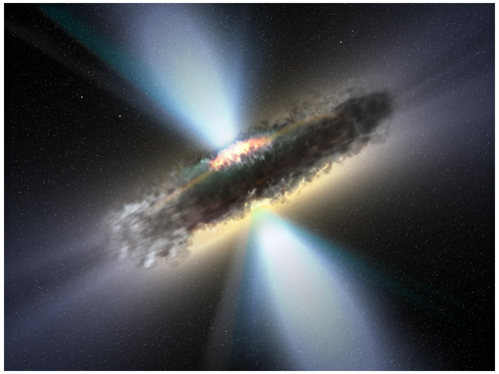
Answer D is correct, **but why?**

Black holes are **not** ”cosmic vacuum cleaners”.

2. What types of black holes exist?



1. **Stellar-mass black holes:**
   How large?: about 3-100 times the mass of the Sun. The event horizons are about ~9-300 km.
   Where?: Throughout the galaxy and the Universe. Everywhere where massive stars are formed.



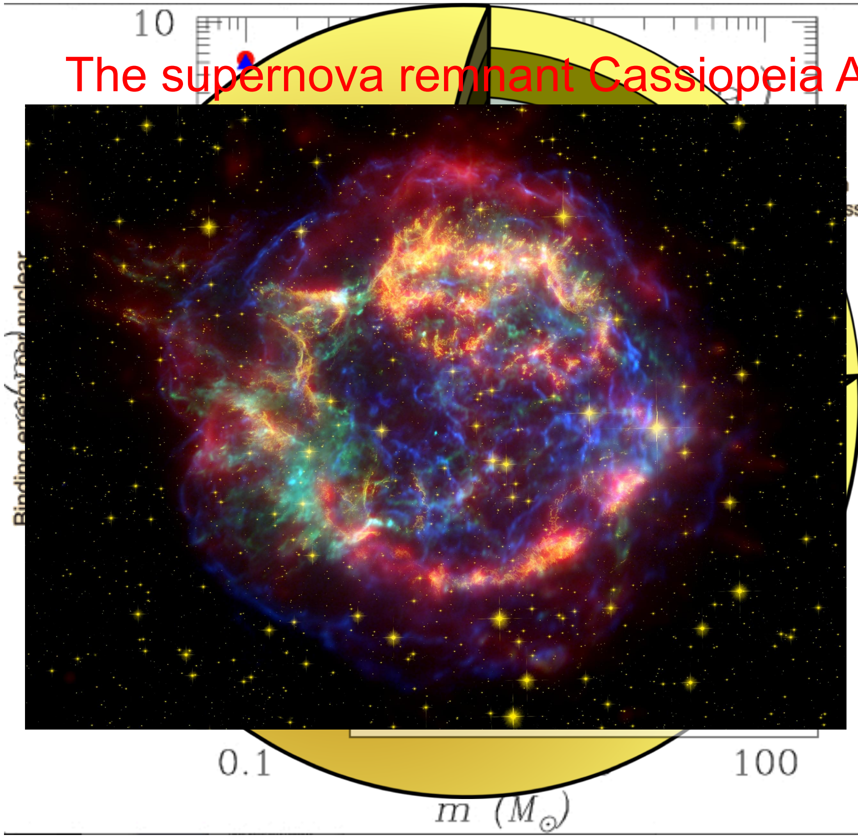
2. **Supermassive black holes :**
   How large?: about 10^5-10^{10} times the mass of the Sun. The event horizons are roughly about the size of the Solar System.
   Where?: In the centres of galaxies. For example the Milky Way contains a supermassive black hole with a mass of 4 million solar masses.

3. **Intermediate-mass black holes:**
   How large?: about 10^3-10^4 times the mass of the Sun. The event horizons are 1000s of kilometres.
   Where?: In the cores of dense stellar clusters.

The formation of stellar-mass black holes

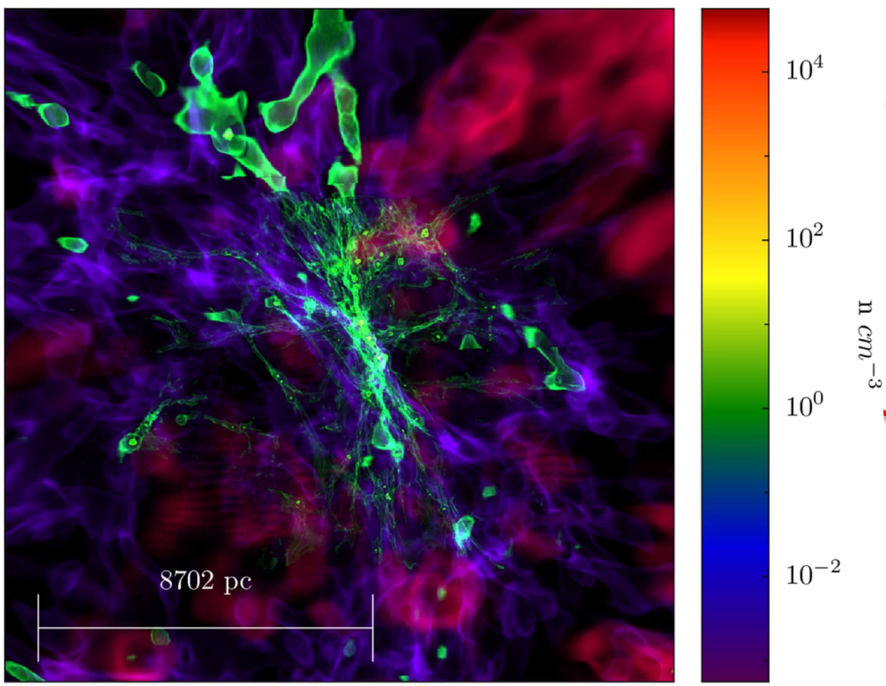
- **The number of black holes:** Only very massive stars ($M \geq 15\text{-}20\ M_\odot$) leave behind black holes, when they die. The vast majority of stars are light. Roughly only 1 out of every 1000 formed stars is massive enough to from a black hole.
- **The structure of stars**: A massive stars has a distinct onion-like structure towards the end of its life, with fusion proceeding in different shells.
- **The end of fusion:** When an iron core has formed, the fusion process cannot continue as fusing iron results in a loss of energy.
- **Supernova:** The star becomes unstable and the outer parts of the star explodes in a supernova. The core can collapse into a black hole, if its mass exceeds $\sim 3\ M_\odot$.

The supernova remnant Cassiopeia A



The formation of supermassive black holes

A numerical simulation run by our group depicting the formation of a supermassive black hole in the very early Universe.

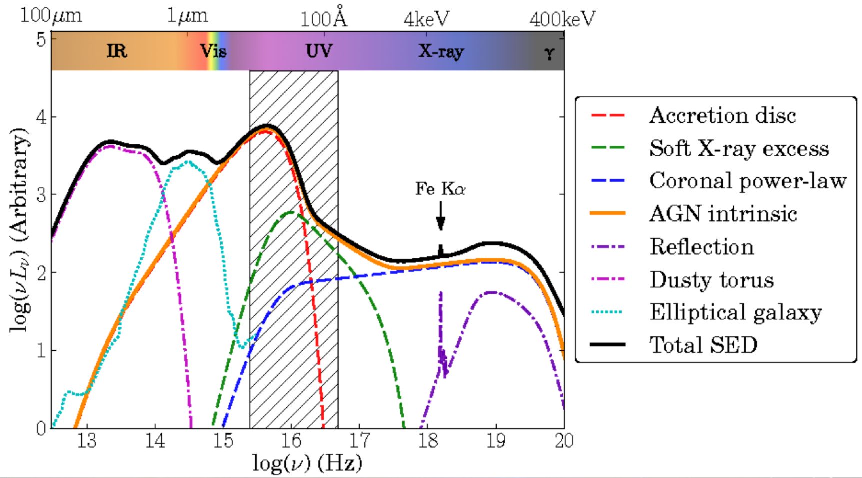


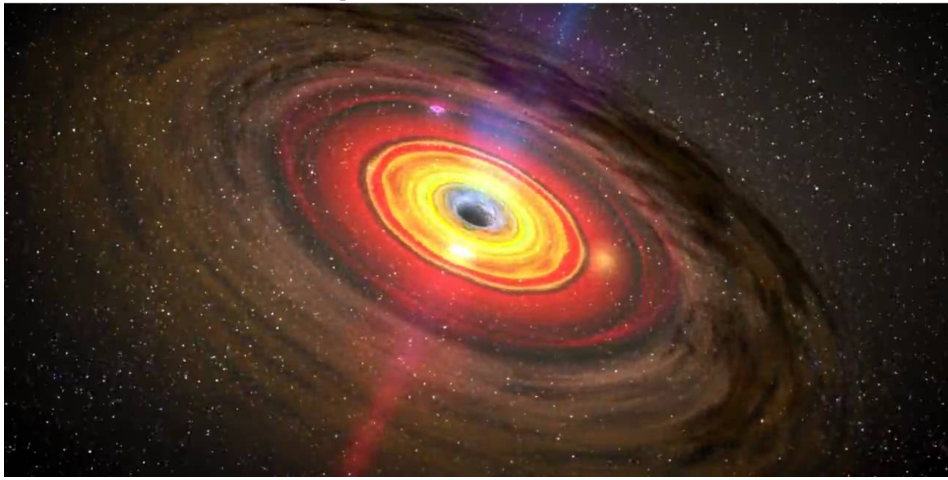
- **No metals:** In the very early Universe there was just hydrogen and helium. The lack of heavier elements made cooling inefficient.

1. **The first stars:** If molecular hydrogen (H_2) was present, the gas could still cool and form very massive stars that later evolved into black holes.
2. **Direct collapse black holes:** If no molecular hydrogen was present, gas cooling was very inefficient and this case massive gas clouds could directly collapse into black holes with masses of M_{BH}~10^4-10^5 $M_\odot$.

3. Observing black holes: Accretion discs and energy production

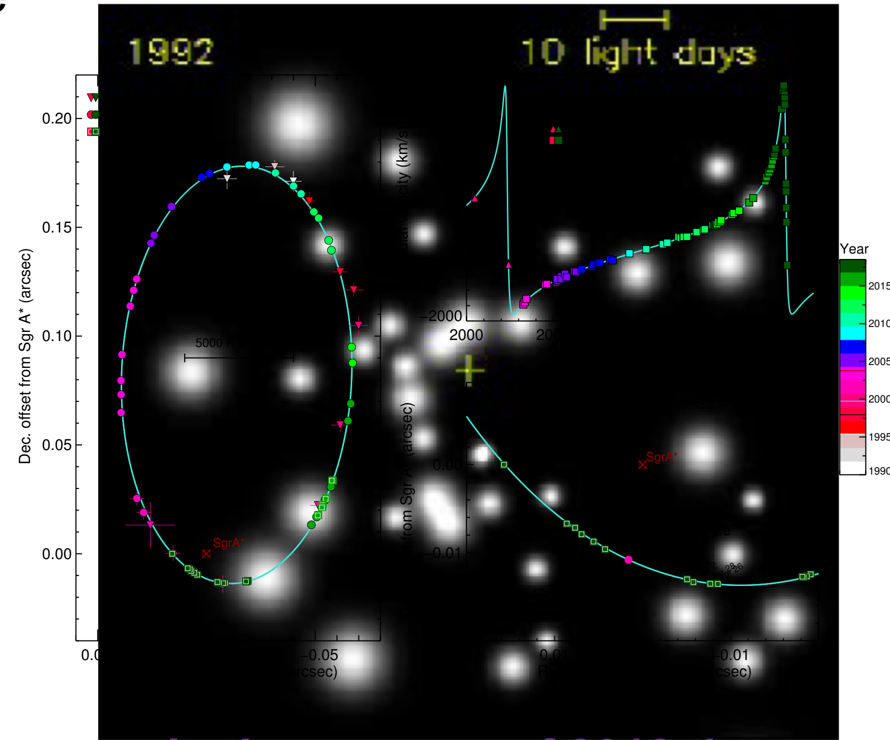
- New observations found objects that had very rapid light fluctuations and strong emissions in the X-ray and radio bands.
- When gas cools the angular momentum is generally conserved, resulting in flattened accretion discs.
- Due to the intense gravity gas is moving at very high velocities. Gravitational and frictional forces compress and raise the temperature of the material in he accretion discs, causing the emission of electromagnetic radiation.
- Typically about ~10% (max 42%) of the rest mass energy of the matter can be transformed to electromagnetic radiation (mainly X-rays). The efficiency of hydrogen fusion in stars is only 0.7 %!





Dynamical modelling– Sgr A*

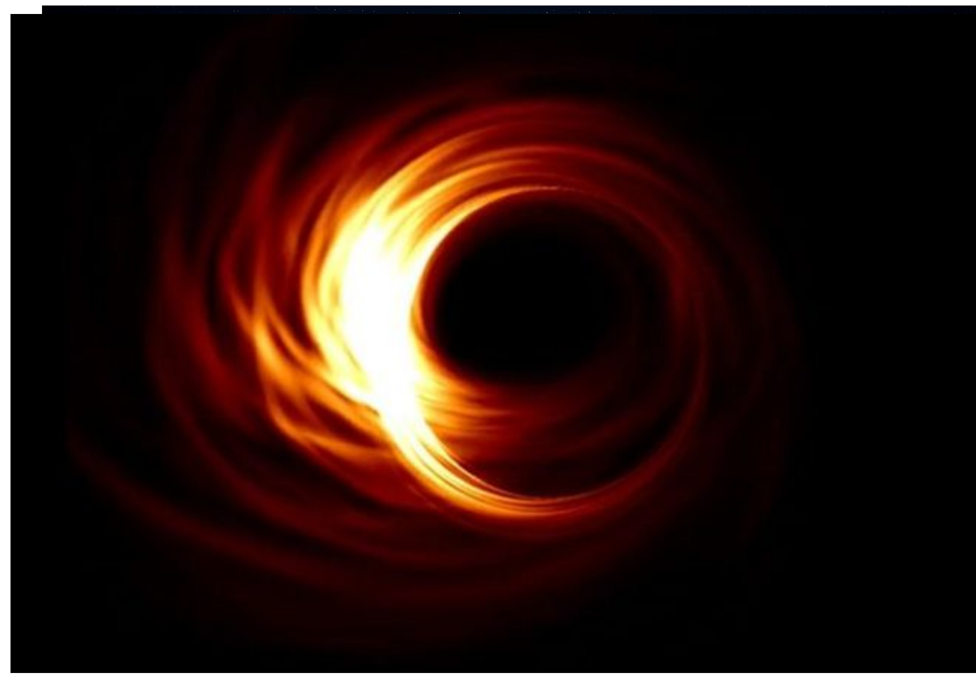
- For some black holes their masses can be derived by observing the motions of the objects around them.
- The best example of such a system is the black hole at the centre of the Milky Way, Sgr A*. Stellar orbits around this source have now been monitored for 25 years.
- One of the stars, S2, orbits that Sgr A* black hole on a orbit with a period of P=16.02 years. At its nearest approach it comes to a separation of 17 lighthours (1400 R_{Sch}) from the black hole.
- The mass of the Milky Way central black hole has been determined very accurately: $M_{BH}=4.3\times10^{6}\ M_{\odot}$.



In the summer of 2018 the next close passage of S2.

Direct observations– Event Horizon telescope

- At the moment there is an attempt under way to directly observe the shadow of the black hole at the centre of the Milky Way using the Event Horizon Telescope, which is a sub-millimetre interferometer.
- In an interferometer the signals from multiple radio telescopes around the World are combined resulting in very high spatial resolution.
- The analysis of the observations is very demanding and as of yet no results have been published.

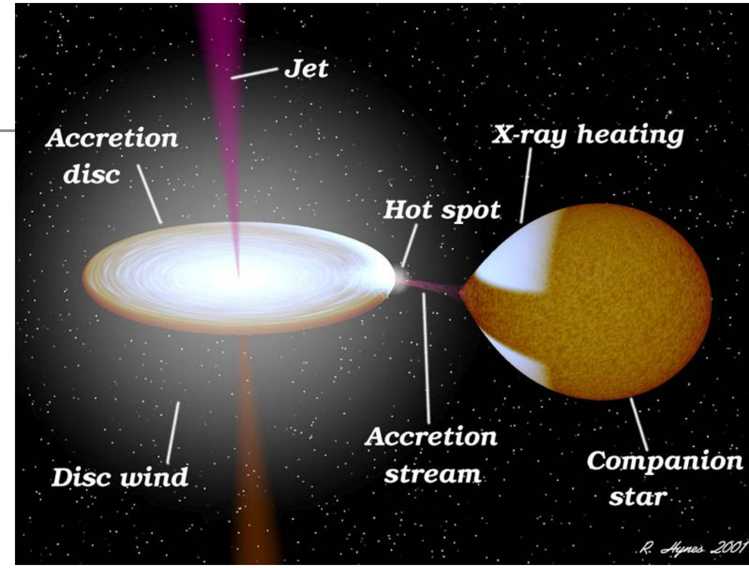


Physical simulation of the shadow of a black hole.

The Hollywood view of a black hole (Interstellar movie).

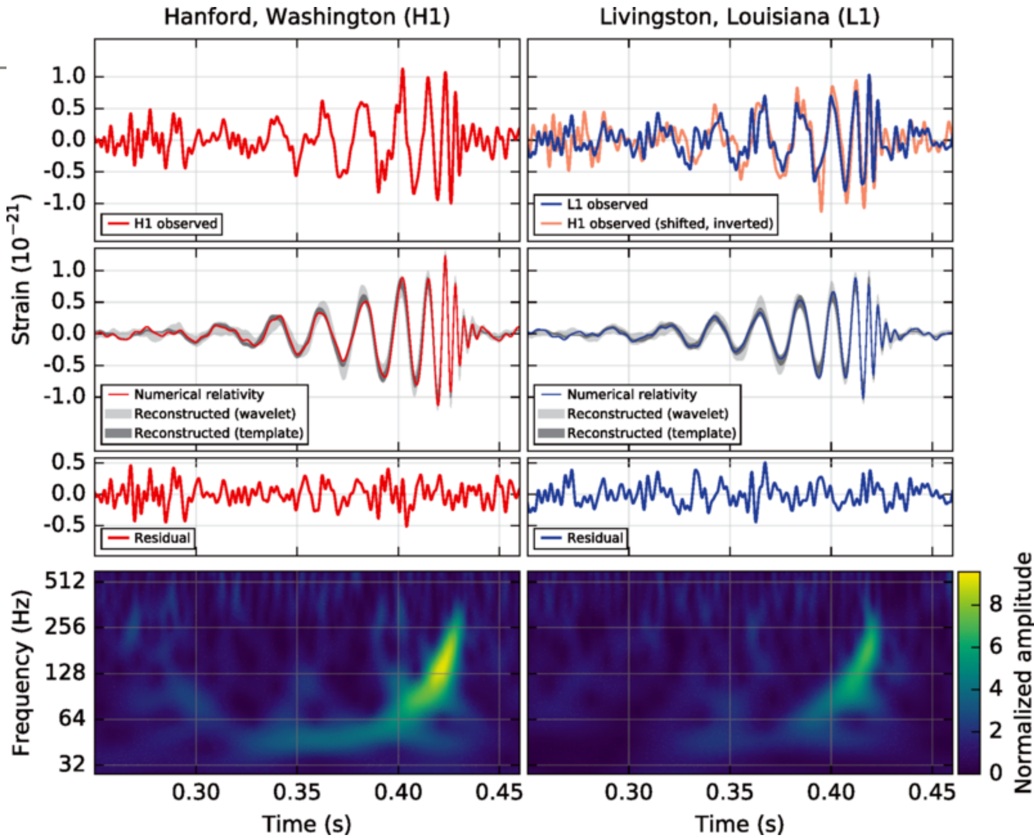
4. The evolution of black holes– Gas accretion

- The masses of black holes increase, when they accrete matter. At the same time the angular momentum typically increases, as the mass flows in typically from an accretion discs.
- For stellar-mass black holes usually the most important mass donor is a companion star in a binary system.
- Dormant supermassive black holes can be awaken by the fresh supply of gas in infalling gas clouds and stars. Galaxy mergers typically result in an increased gas flow.



Mergers of stellar-mass black holes– Gravitational waves

- In 2015 LIGO observed a GW-signal for 0.2 seconds during which the frequency rose from 35 Hz to 150 Hz.
- This was caused by the merger of two black holes with masses of M_1=36 $M_\odot$ and M_2=29 $M_\odot$.
- The mass of the new black holes was 62 $M_\odot$, with 3 $M_\odot$ emitted as gravitational waves.
- For a brief moment this merger produced 10 times more energy than the entire Universe.

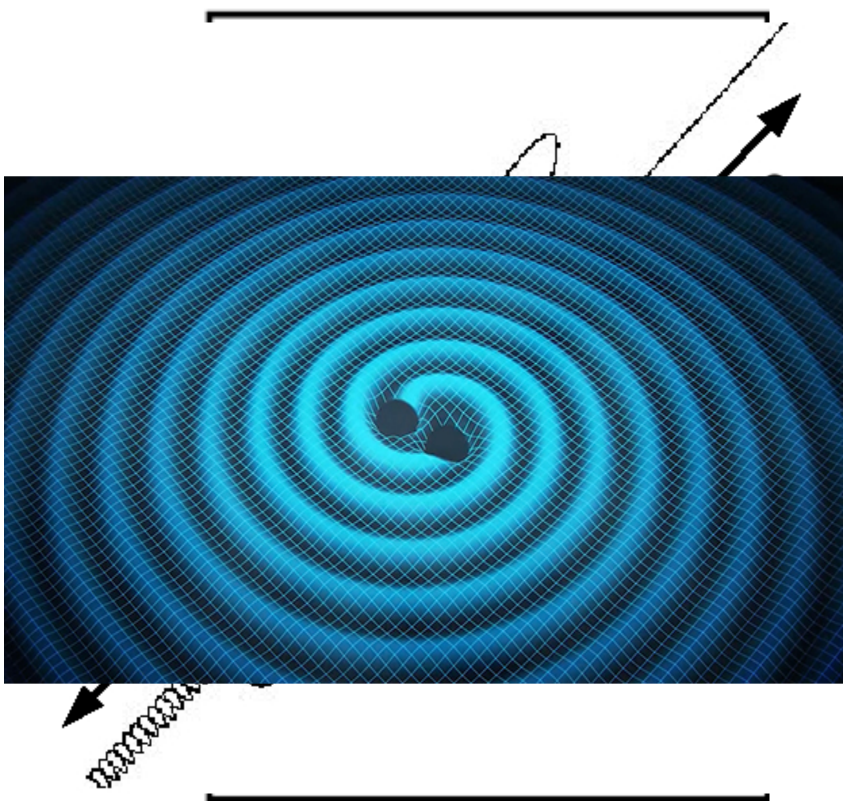


The observed displacement of h=10^{-21} corresponds to a relative change of length, which is a 1/10000 times the width of proton.

Mergers of supermassive black holes

- When galaxies merges, their supermassive black holes will also eventually merge. This happens through three distinct phases.

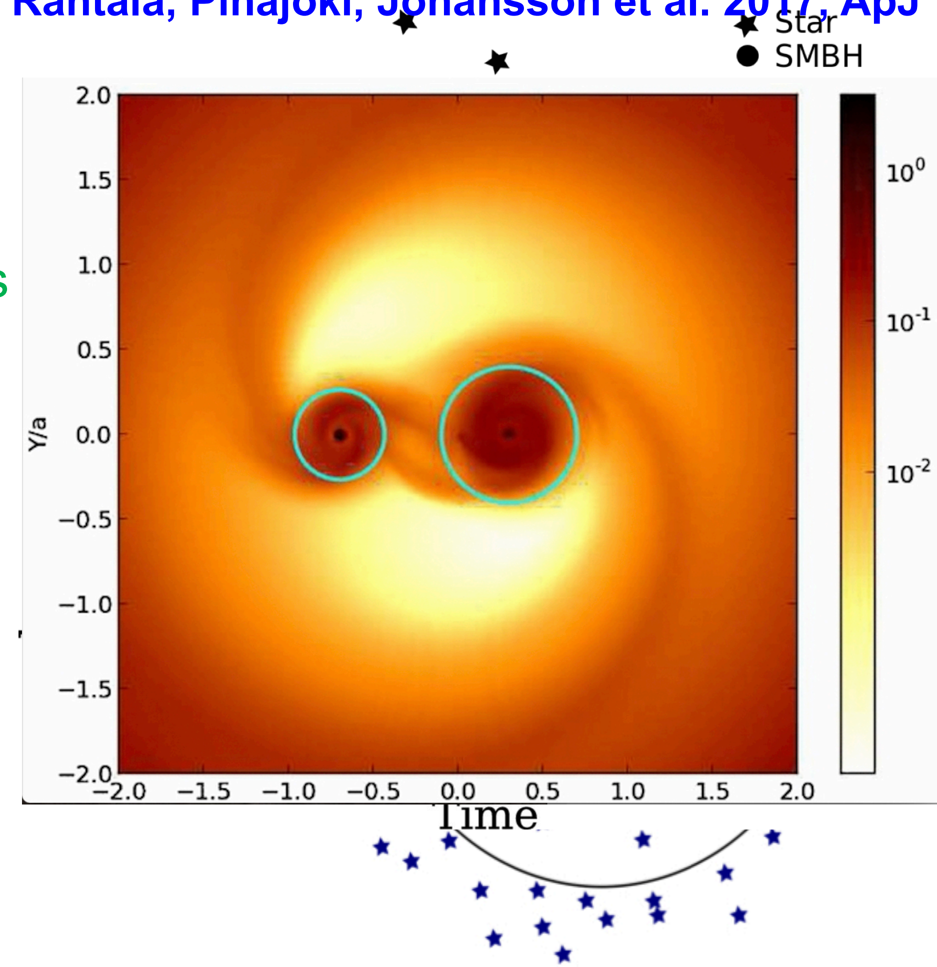
1. Firstly, dynamical friction from stars and gas reduces the semi-major axis of the BH binary to few tens of lightyears.
2. Next, the semi-major axis of the binary will shrink by kicking out stars in complex three-body interactions.
3. The emission of gravitational waves will eventually dominate the loss of orbital energy at very small (<0.01 lyrs) binary separations.



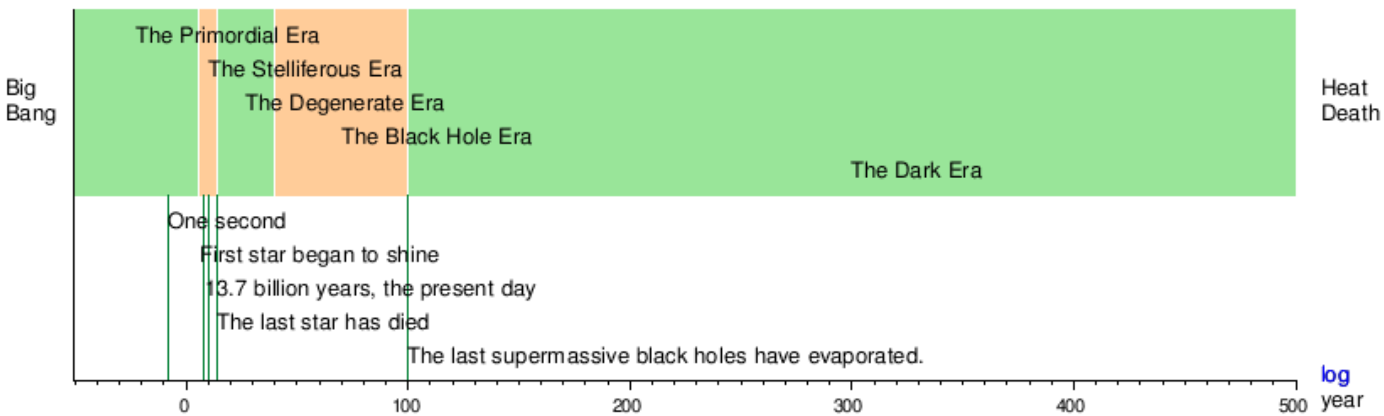
KETJU: Hybrid Nbody +hydrodynamics code

1. KETJU **(chain in Finnish)**: Built on the GADGET-3 code. Includes algorithmically regularised chain regions around every black hole.
2. The dynamics close to the black holes is accurately resolved. GADGET is used for the long distance force.
3. Includes Post-Newtonian corrections up to order 3.5 PN, valid down to ~10 Schwarzschild radii
4. **The main novelty is that KETJU enables accurate dynamics simultaneously with gas physics.**

Rantala, Pihajoki, Johansson et al. 2017, ApJ



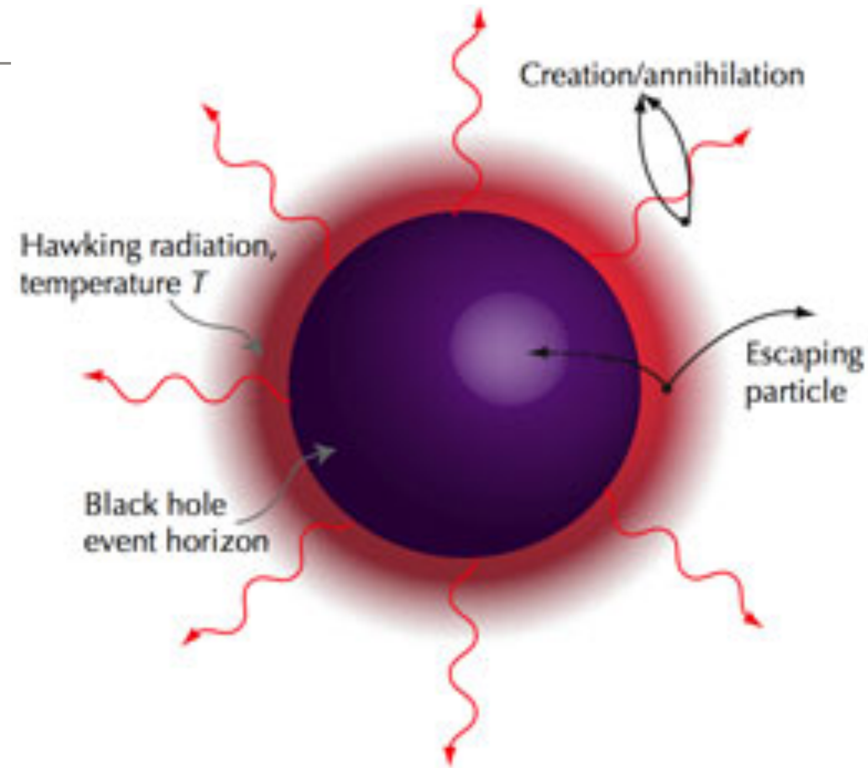
5. The future of black holes– The epoch of black holes



- In the very distant future when the Universe if about 10^{40}-10^{100} years (present-day age ~10^{10} years) all stars have long ago died and there are only black holes left in the Universe.
- An accurate prediction is difficult, since we do not yet know what exactly is going to happen with the accelerating expansion of the Universe.

Hawking radiation and the death of black holes

- Even black holes do not live forever. Stephen Hawking showed in 1974 that due to quantum effects black holes emit radiation close from their Event horizons.
- This Hawking-radiation has never been observed, as it is extremely weak. The temperature of black hole with a mass of a few solar masses is only about one millionth of a degree above absolute zero.



- A one solar mass black hole would evaporate due to the emission of Hawking radiation in about 10^{64} years.

What have we learned today?

1. Black holes are extremely dense concentrations of mass in space-time and their properties can be fully described by their mass, angular momentum and electric charge.
2. There are stellar-mass, supermassive and intermediate-mass black holes in the Universe. Black holes are formed when matter is compressed to extreme densities.
3. The accretion discs surrounding black holes produce huge amounts of energy. In addition black holes can be observed through the dynamics of surrounding stars and also directly through gravitational waves.
4. The masses of black holes increase through gas accretion. Using powerful new simulation codes, the dynamical evolution of black holes from large-scales all the way to the gravitational-wave driven coalescence can be modelled.
5. Not even black holes will live forever. Instead they will eventually evaporate through Hawking radiation. But for this to happen, you have to wait almost an eternity.