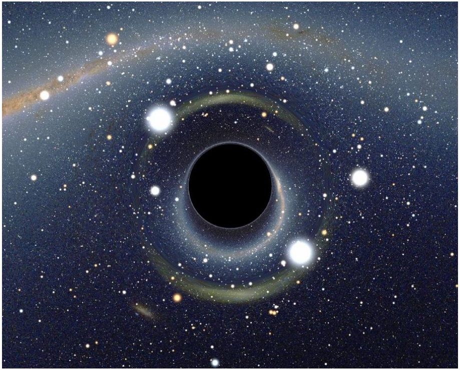
Black holes

Journées du LUX
Royaumont (France)
9-10 September 2024

What is a black hole?

A layperson definition

A **black hole** is a localized region of spacetime from which no particle, be it massive or massless (photon), can escape to an infinitely remote region.

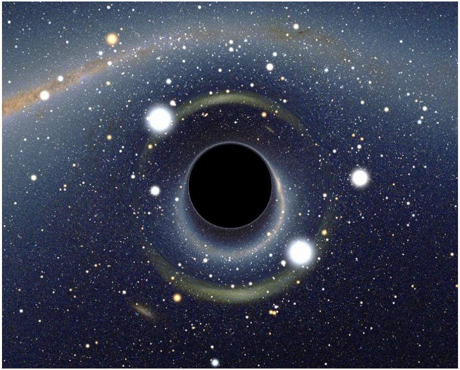


[A. Riazuelo, IJMPD **28**, 1950042 (2019)]

What is a black hole?

A layperson definition

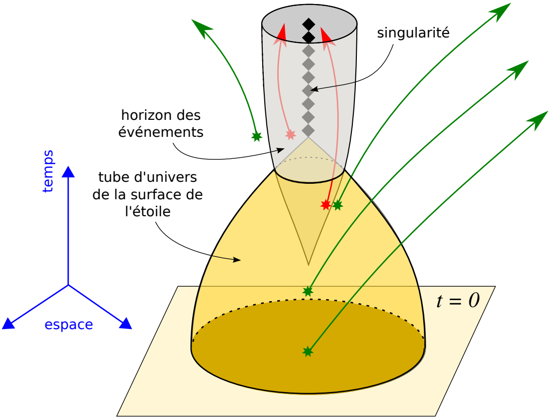
A **black hole** is a localized region of spacetime from which no particle, be it massive or massless (photon), can escape to an infinitely remote region.



[A. Riazuelo, IJMPD **28**, 1950042 (2019)]

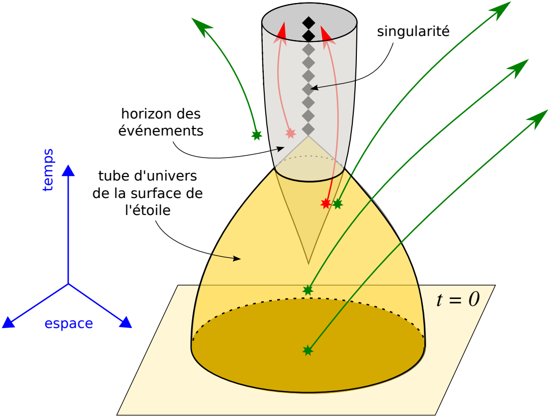
The (immaterial) boundary of the black hole region is called the **event horizon**

Black hole formation by gravitational collapse



← Spacetime diagram depicting the formation of a black hole by gravitational collapse of a stellar core

Black hole formation by gravitational collapse



← Spacetime diagram depicting the formation of a black hole by gravitational collapse of a stellar core

singularity: curvature $\longrightarrow \infty$

Penrose's theorem (1965)

Beyond a certain stage of the collapse, characterized by the appearance of **trapped surfaces**, the formation of a singularity is inevitable.

Black holes in the sky

Three kinds of black holes are observed in the Universe:

- **Stellar black holes**: remnants of massive stars:
  $M \sim 10 - 40\ M_\odot$ and $R \sim 30 - 120\ \mathrm{km}$

  examples: Cyg X-1 : $M = 15\ M_\odot$; $R = 45\ \mathrm{km}$

  GW150914: $M_1 = 36 \pm 5\ M_\odot$, $M_2 = 29 \pm 4\ M_\odot$

Black holes in the sky

Three kinds of black holes are observed in the Universe:

- **Stellar black holes**: remnants of massive stars:
  $M \sim 10 - 40\ M_\odot$ and $R \sim 30 - 120\ \mathrm{km}$

  examples: Cyg X-1 : $M = 15\ M_\odot$; $R = 45\ \mathrm{km}$

  GW150914: $M_1 = 36 \pm 5\ M_\odot$, $M_2 = 29 \pm 4\ M_\odot$

- **Intermediate mass black holes**, as ultra-luminous X-ray sources or detected via gravitational waves: $M \sim 10^2 - 10^5\ M_\odot$ and $R \sim 300\ \mathrm{km} - 3 \times 10^5\ \mathrm{km}$

  example: ESO 243-49 HLX-1 : $M \sim 10^4\ M_\odot$; $R \sim 3 \times 10^4\ \mathrm{km}$

Black holes in the sky

Three kinds of black holes are observed in the Universe:

- **Stellar black holes**: remnants of massive stars:
  $M \sim 10 - 40\ M_\odot$ and $R \sim 30 - 120\ \mathrm{km}$

  examples: Cyg X-1 : $M = 15\ M_\odot$; $R = 45\ \mathrm{km}$

  GW150914: $M_1 = 36 \pm 5\ M_\odot$, $M_2 = 29 \pm 4\ M_\odot$

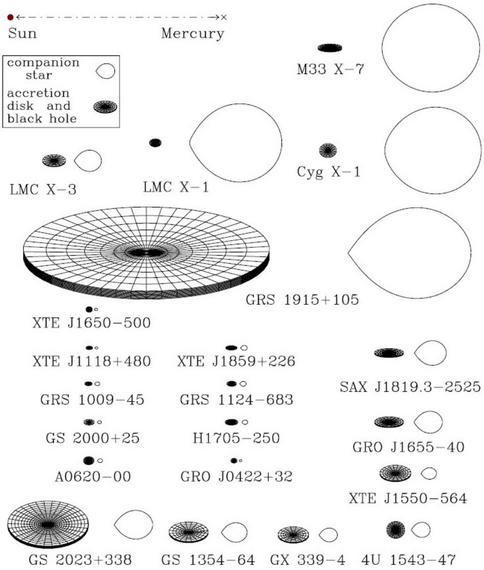
- **Intermediate mass black holes**, as ultra-luminous X-ray sources or detected via gravitational waves: $M \sim 10^2 - 10^5\ M_\odot$ and $R \sim 300\ \mathrm{km} - 3 \times 10^5\ \mathrm{km}$

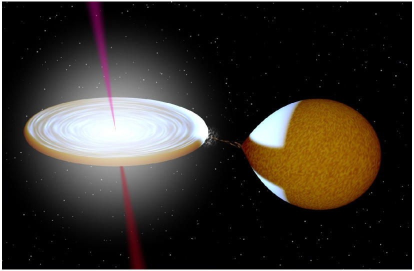
  example: ESO 243-49 HLX-1 : $M \sim 10^4\ M_\odot$; $R \sim 3 \times 10^4\ \mathrm{km}$

- **Supermassive black holes**, in galactic nuclei:
  $M \sim 10^5 - 10^{10}\ M_\odot$ and $R \sim 3 \times 10^5\ \mathrm{km} - 200\ \mathrm{UA}$

  example: Sgr A* : $M = 4.3 \times 10^6\ M_\odot$;
  $R = 13 \times 10^6\ \mathrm{km} = 18\, R_\odot = 0.09\ \mathrm{UA} = \frac{1}{4} \times$ radius of Mercury's orbit

Stellar black holes in X-ray binaries

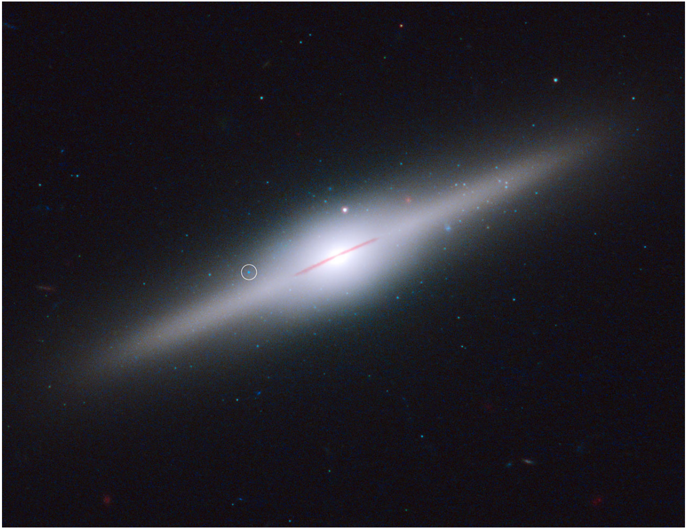




~ 20 identified black holes in our galaxy
$\Longrightarrow$ indirect detection (criterion based on the mass of the dark component)

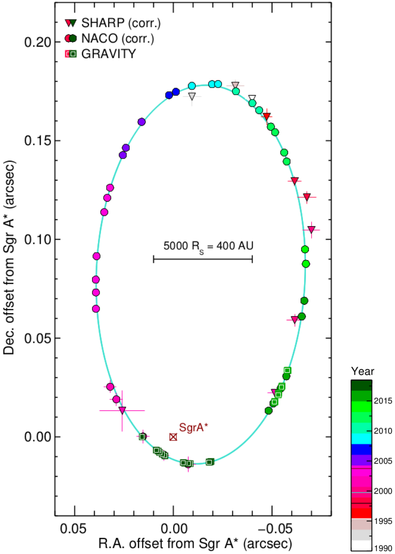
[McClintock et al. (2011)]

ESO 243-49 HLX-1: an intermediate mass black hole ?



HST image [NASA/ESA/S. Farrel (2012)]

Sgr A*: the supermassive black hole at the Galactic Center



- distance: $d = 26,000$ light-years
- mass: $M = 4.10 \times 10^6\, M_\odot$
- spin $J = aM$ unkown yet...

$\Longrightarrow$ shadow size $\Theta \sim 53\ \mu\mathrm{as}$

$\longleftarrow$ Orbit of S2 star around Sgr A*

S2: type B star

orbital period: $P = 16.05\ \mathrm{yr}$

periastron (May 2018):

- $r_{\rm per} = 120\ \mathrm{au} = 3 \times 10^3 M$
- $v_{\rm per} = 7650\ \mathrm{km\,s^{-1}} = 0.025\, c$

[GRAVITY team, A&A **615**, L15 (2018)]

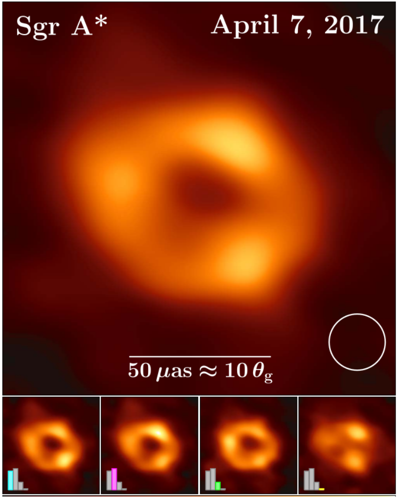


Image of Sgr A*'s close surroundings (*Event Horizon Telescope*)

[EHT Collaboration, ApJ **930**, L12 (2022)]

The no-hair theorem

— One of the most beautiful results in general relativity

Uniqueness theorem ("no-hair")

Dorochkevitch, Novikov & Zeldovitch (1965), Israel (1967), Carter (1971), Hawking (1972), Robinson (1975)

Within 4-dimensional general relativity, a stationary black hole is entirely described by only two numbers[a]:

- its *mass* M
- its *angular momentum* J

The corresponding solution of Einstein's equation is the Kerr solution (1963). For $J = 0$, it reduces to the Schwarzschild solution (1916).

[a] three if a nonzero electric charge is allowed, which is not relevant from an astrophysical point of view.

The no-hair theorem

— One of the most beautiful results in general relativity

Uniqueness theorem ("no-hair")

Dorochkevitch, Novikov & Zeldovitch (1965), Israel (1967), Carter (1971), Hawking (1972), Robinson (1975)

Within 4-dimensional general relativity, a stationary black hole is entirely described by only two numbers[a]:

- its *mass* M
- its *angular momentum* J

The corresponding solution of Einstein's equation is the Kerr solution (1963). For $J = 0$, it reduces to the Schwarzschild solution (1916).

[a] three if a nonzero electric charge is allowed, which is not relevant from an astrophysical point of view.

$\Longrightarrow$ *"A black hole has no hair"* (John A. Wheeler)

Hot topics and open questions in black hole physics

- Testing general relativity via black hole observations (LIGO-Virgo-KAGRA, LISA, EHT, GRAVITY), notably by checking the no-hair theorem
- Finding black hole solutions and assessing their stability in modified gravity and/or in dimension higher than 4
- Determining the origin of supermassive black holes
- Searching for primordial black holes
- Computing the fate of matter/observers below the horizon in a *rotating* gravitational collapse (formation of a Cauchy horizon?)
- Finding a microscopic (quantum) origin to the black hole entropy

Theoretical studies of black holes at LUTH/LUX

- Gravitational radiation from binary black holes in general relativity and in scalar-tensor theories (Laura Bernard[1], Alexandre Le Tiec, Stavros Mougiakakos, Sashwat Tanay, Tom Colin, Eve Dones)
- Numerical solutions for rotating black holes in alternative theories of gravity (Philippe Grandclément, Hugo Candan)
- Perturbative studies of Kerr black holes; applications to Sgr A* (Alexandre Le Tiec, Éric Gourgoulhon)
- 5-dimensional black holes for holographic study of the quark-gluon plasma (Éric Gourgoulhon)

Main collaborations:

- *Observatoire:* GRAVITY team (LESIA/LIRA)
- *Paris area:* GRACES (ENS), theory team (IJCLab), GReCO (IAP)
- *Farther away:* AEI Potsdam, Perimeter Institute (Canada), etc.

[1]Color code: CNRS staff, post-docs, doctoral students