BLACK HOLES

OBSERVATORIO
ASTRONÓMICO
NACIONAL

Classical Black Holes

00. Introduction. Black Holes

Edward Larrañaga

Outline for Part 1

General Information

Graduate Course

MSc. in Astronomy

PhD. in Astronomy

Tuesday 16:00 - 18:00

Thursday 16:00 - 18:00

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Evaluation

- 2 Exams: 20% each
- Exercises: 60%

Evaluation

- Exams:
  - Middle term: 20%
  - Final: 20%
- Exercises: 60%
  - Individual
  - Weekly exercises.
  - Handwritten or $\TeX$?

Tutoring Hours

- Monday 18:00 - 19:00
- Wednesday 18:00 - 19:00

References I

[1] D. Raine and E. Thomas *Black Holes. An Introduction*. Second Edition. Imperial College Press. 2010

[2] V. P. Frolov, and I. D. Novikov *Black Hole Physics: Basic Concepts and New Developments*. Dordrecht: Kluwer 1998

[3] V. P. Frolov and A. Zelnikov *Introduction to Black Hole Physics*. Oxford University Press. 2011

[4] G. E. Romero and G. S. Vila. *Introduction to Black Hole Astrophysics*. Lecture Notes in Physics 876. Springer 2014

[5] C. Bambi. *Black Holes: A Laboratory for Testing Strong Gravity*. Springer 2017

[6] P. K. Townsend. *Black Holes. Lecture Notes*. Cambridge University. U.K. 1997

References II

[7] D. L. Meier. *Black Hole Astrophysics. The Engine Paradigm*. Springer 2012

[8] M. Camenzind. *Compact Objects in Astrophysics. White Dwarfs, Neutron stars and Black Holes*. Springer 2007

Outline for Part 2

Dark Stars. XVIII Century

Dark Stars. XVIII Century

- **John Michell** (1783). Introduces the term *Dark Stars* to describe an object so massive that light can not escape from its surface.
- **Pierre-Simon Laplace** (1796). Independently proposes the same idea of Michell. Points that the *'largest luminous bodies in the Universe may be invisible'*.

Newton's Law of Gravity

$$\vec{F} = -\frac{GMm}{r^2}\hat{r}$$

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$$G = 6.67 \times 10^{-11} \frac{\mathrm{N \cdot m^2}}{\mathrm{kg^2}}$$

Poisson's Equation

$$\nabla^2 \Phi = 4\pi G \rho$$

Escape Velocity

$$v_{esc} = \sqrt{\frac{2GM}{r}}$$

Schwarzschild's Radius

$$r_S = \frac{2GM}{c^2}$$

Schwarzschild's Radius

Object	**Mass** ($M_\odot$)	**Schwarzschild's Radius** (km)
Earth	3×10^{-6}	8.9×10^{-6}
Sun	1	2.95

Critical Density for the formation of a Black Hole

$$\rho_c = \frac{M}{\frac{4\pi r_s^3}{3}}$$

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$$\rho_c \sim 10^{19} kg/m^3 \sim 10^{16} g/cm^3$$

Important Advances in the XX Century

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- General Relativity (Relativistic Theory of Gravity). Einstein (1916)
- Schwarzschild's Solution (1916)
- Gravitational Collapse of stellar objects description (1920's)
- Discovery of matter with densities in the range $10^9 - 10^{17} kgm^3$. White Dwarfs and Neutron Stars (1930's - 1950's)
- Rotating black hole solution. Kerr (1963)
- 'Black Hole' name is coined by J. A. Wheeler (1967)

Important Advances in the XX Century

- First evidence of supermassive (and superdense) objects in AGN's (1960's - 1970's).
- Y. Zel'dovich and E. Salpeter proposed that quasars were powered by a supermassive black hole (1964).
- T. Bolton - L. Webster and P. Murdin. Identification of the first stellar black hole candidate: Cygnus X-1 (1971)
- S. Hawking shows that black holes may not be black after all (1974)
- Sagittarius A* is discovered. B. Balick and R. Brown (1974)
- Evidence of a supermassive black hole in M87 (1978)

Black Holes description in GR

- The first solution of Einstein field equations describing a black hole is *Schwarzschild's geometry* (1916).
- H. Reissner y G. Nordström found a non-rotating spacetime describing an electrically charged black hole (1916-1918)
- R. Kerr found the solution describing a rotating black hole (1963)
- E. Newman and collaborators found the solution describing a rotating and electrically charged black hole (1965)

The No-Hair Theorem

W. Israel, B. Carter and D. Robinson show that, under certain assumptions, black holes in GR can be fully characterized by three parameters:

- Mass M
- Spin angular momentum J
- Electric charge Q

* This theorem is valid **only** in GR.

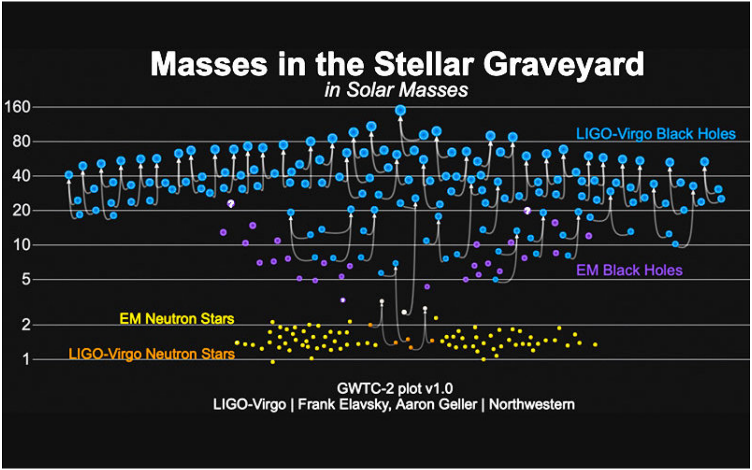
The Cosmic Censorship Conjecture

The works of R. Penrose and S. Hawking in the 1960s show that the creation of *singularities* is inevitable in a gravitational collapse described by GR.
Penrose proposed the *cosmic censorship conjecture*, which states that singularities produced by gravitational collapse must be (always) hidden behind an event horizon.

Discoveries in the XXI Century

Discoveries in the XXI Century

- First images of the Event Horizon Telescope show Sagittarius A* (2008)
- LIGO confirms the observation of gravitational waves produced by the merge of two black holes (2016)
- The Event Horizon Telescope reports the first picture of a black hole in M87 (2019)


Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

Black Holes in Astrophysics

Black Holes in Astrophysics

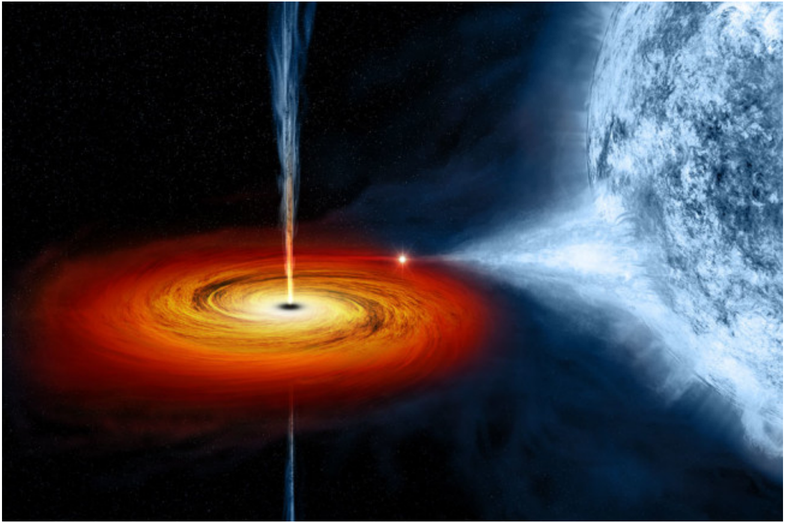
Today, there is observational evidence of three classes of black holes:

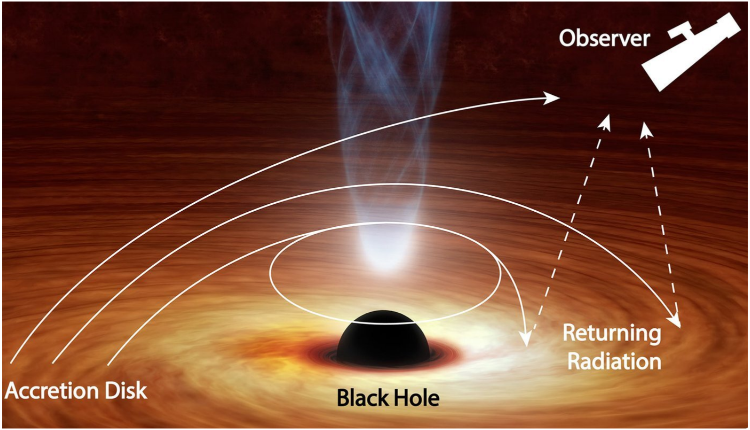
- Stellar-mass BH: $M \sim 5 - 100 M_{\odot}$
- Supermassive BH: $M \sim 10^5 - 10^{10} M_{\odot}$
- Intermediate-mass BH: Filling the mass gap between stellar and supermassive BH.

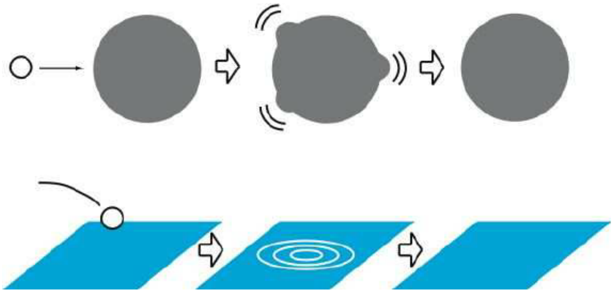
Methods to probe spacetime geometry around a BH

There are currently three possible techniques to experimentally probe the spacetime geometry around a black hole:

- Continuum-fitting method
- Analysis of X-ray reflection spectrum (Iron-line method)
- Gravitational wave emission by black hole perturbations.




Observer
Returning
Radiation
Accretion Disk
Black Hole



Top Reasons to Study Black Holes

Top Reasons to Study Black Holes

- To understand strong gravitational fields.
- To understand the final stages of stellar evolution.
- Potential insight of the connection between quantum physics and gravity.
- Potential insight of the connection between thermodynamics and gravity.

Next Lecture

01. General Relativity Review