BLACK HOLES

OBSERVATORIO
ASTRONÓMICO
NACIONAL

Classical Black Holes

00. Introduction. Black Holes

Edward Larrañaga

Outline for Part 1

1. Introduction
   1.1 General Information
   1.2 Contents
   1.3 Evaluation
   1.4 Tutoring
   1.5 References

2. Black Holes Introduction
   2.1 Dark Stars. XVIII Century
   2.2 Important Advances in the XX Century
   2.3 Discoveries in the XXI Century
   2.4 Black Holes in Astrophysics
   2.5 Top Reasons to Study Black Holes

General Information

Graduate Course

MSc. in Astronomy

PhD. in Astronomy

Monday 16:00 - 18:00 Wednesday 16:00 - 18:00

Google Meet

Contents

Subject	Week
Introduction. General Relativity review. Black Holes in Physics. Spherically Symmetric Geometry	1
Schwarzschild's Solution. Properties. Coordinates. Geometry. Penrose Diagrams. Horizons. Definition of a Black Hole	2
Gravitational Collapse. No-Hair Theorem. Black Holes beyond GR.	3
Rotating Black Hole. Properties. Geometry	4
Motion of Massive Particles in a curved spacetime	5
Motion of Massless Particles in a curved spacetime	6
Shadow of a Black Hole	7

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Subject	Lecture
Astrophysical Black Holes. Stellar Black Holes. Supermassive Black Holes.Intermediate Black Holes. Sagittarius A*.	8
Spectral States. Observation of Black Holes. X-Ray Observatories.	9
Accretion. Spherical and Cylindrical accretion	10
Binary Systems. Roche lobe accretion. Formation of an accretion disk. Wind accretion.	11
Accretion Disks. Spectra. Thin Accretions Disks. Novikov-Thorne model.	12

Contents

Subject	Lecture
The Continuum-Fitting method. X-Ray Reflection Spectroscopy.	14
Gravitational Waves and Black Hole Evidence.	15
** Final Week	16

Evaluation

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

Evaluation

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

Tutoring Hours

- Tuesday 09:00 - 11:00
- Friday 11:00 - 13:00

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

1. Introduction
    1.1 General Information
    1.2 Contents
    1.3 Evaluation
    1.4 Tutoring
    1.5 References

2. Black Holes Introduction
    2.1 Dark Stars. XVIII Century
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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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$$G = 6.67 \times 10^{-11}\,\frac{\mathrm{N}\cdot\mathrm{m}^2}{\mathrm{kg}^2}$$

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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$$\rho_c \sim 10^{19} kgm^3 \sim 10^{16} gcm^3$$

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

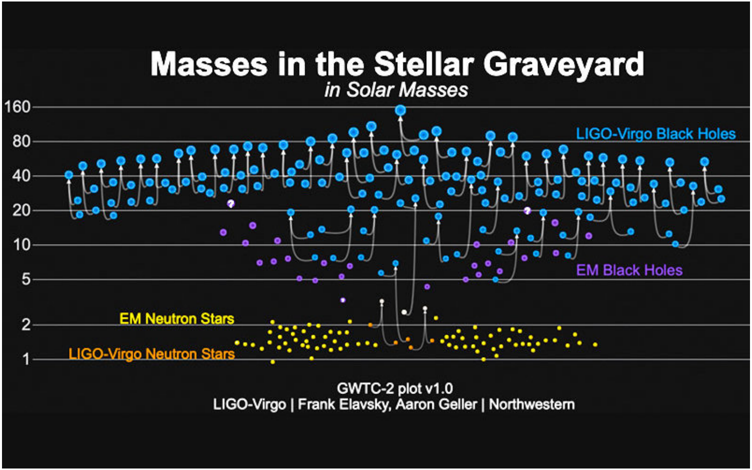
The works of R. Penrose and S. Hawking in the 1960s show that the creation of *singularities* is inevitable in a gravitational collapse described by GR.

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

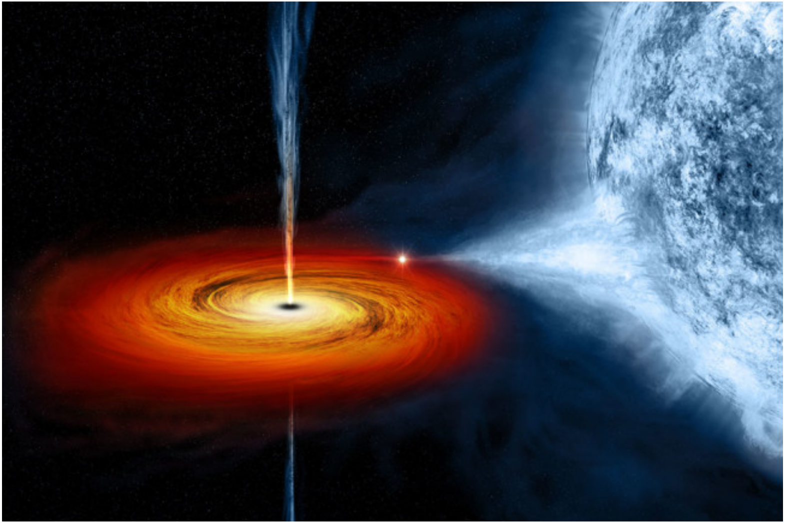
Today, there is observational evidence of three classes of black holes:

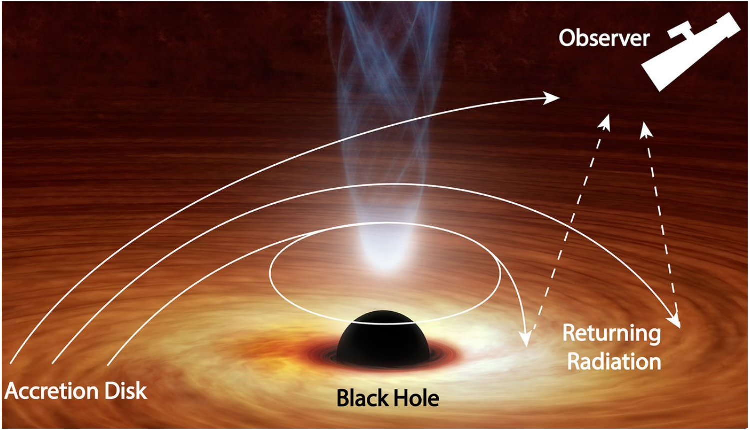
- Stellar-mass BH: $M \sim 5 - 100 M_\odot$
- Supermassive BH: $M \sim 10^5 - 10^{10} M_\odot$
- Intermediate-mass BH: Filling the mass gap between stellar and supermassive BH.

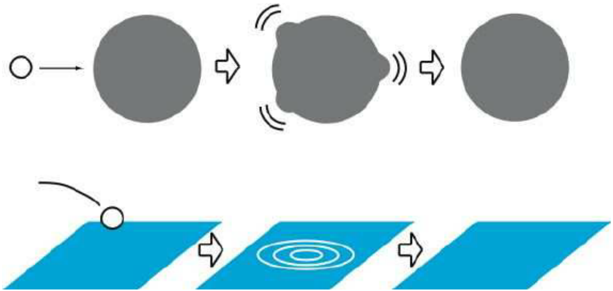
Methods to probe spacetime geometry around a BH

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