BLACK HOLE PHYSICS

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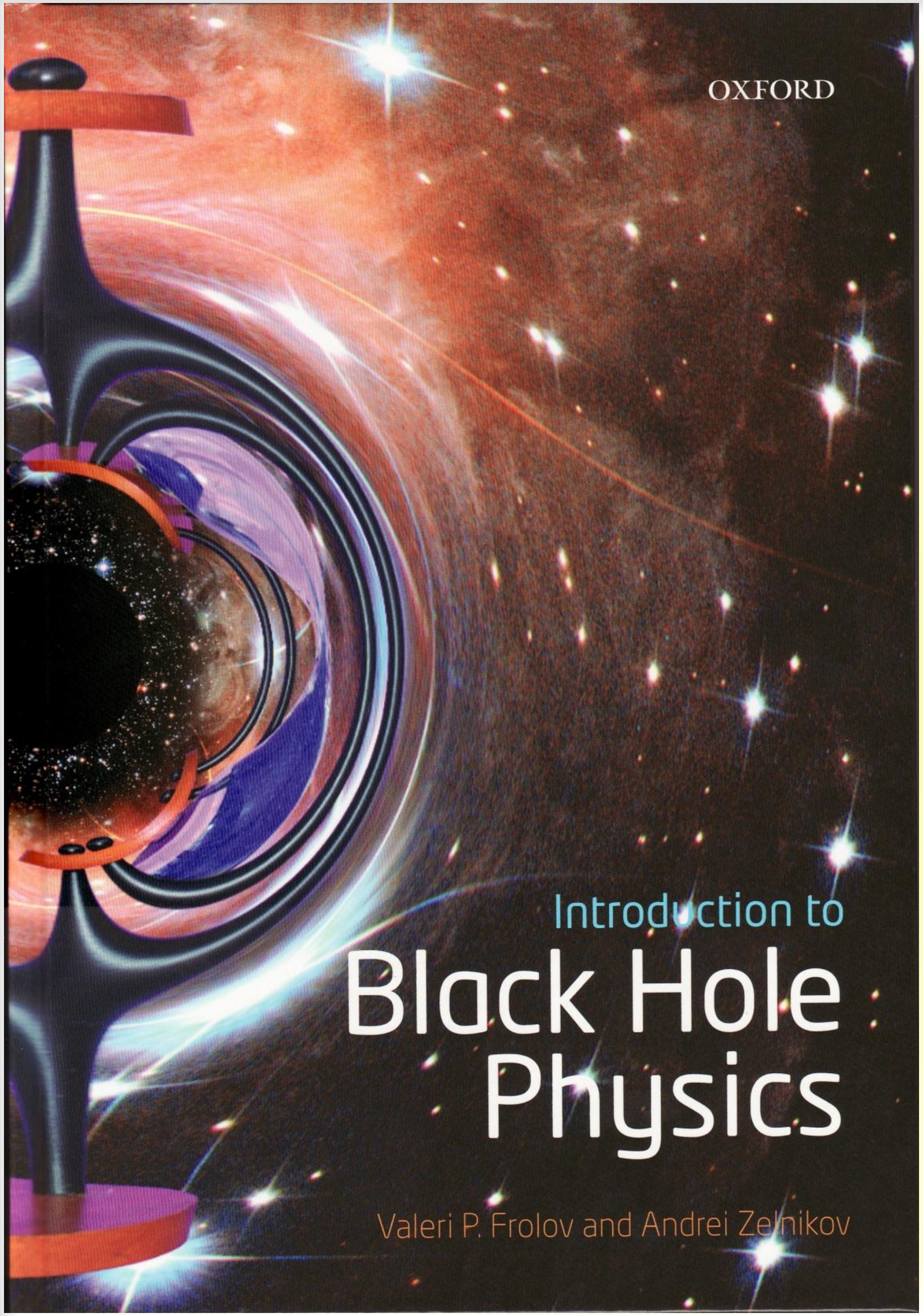
Black Holes’ Physics

블랙 홀 '물리학

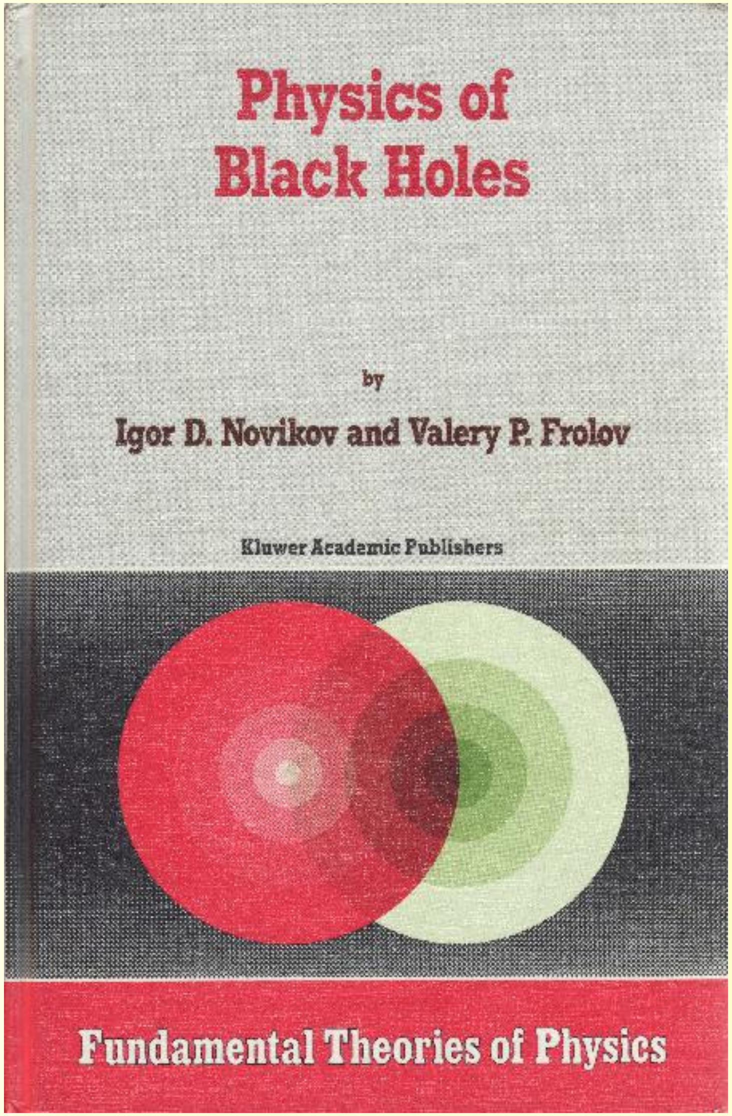
ブラックホール'物理学

黑洞'物理

физика черных дыр



http://www.amazon.ca/Introduction-Black-Physics-Valeri-Frolov/dp/0199692297



PDF file of the book can be found at http://libgen.org/ (search for "frolov novikov")

Outline of the Lectures

1. Black Holes: Big picture
2. Brief history of black holes
3. Black holes in astrophysics
4. Search for black holes
5. Highlights of BH astrophysics
6. Physics in accelerated frames
7. Einstein equations
8. Spherically symmetric black holes
9. Rotating black holes
10. Higher dimensional black holes
11. Classical and quantum fields near BHs
12. Problems and puzzles of black holes

Everything should be made as simple as possible, but not simpler.

— Albert Einstein

1. Black Holes: Big Picture

We are living in “Black Hole Land”

- **Black holes in science**
- **Black holes in science fiction**
- **Black holes in movies**
- **Black holes in art**
- **Back holes in economy**
- **Black holes in philosophy**

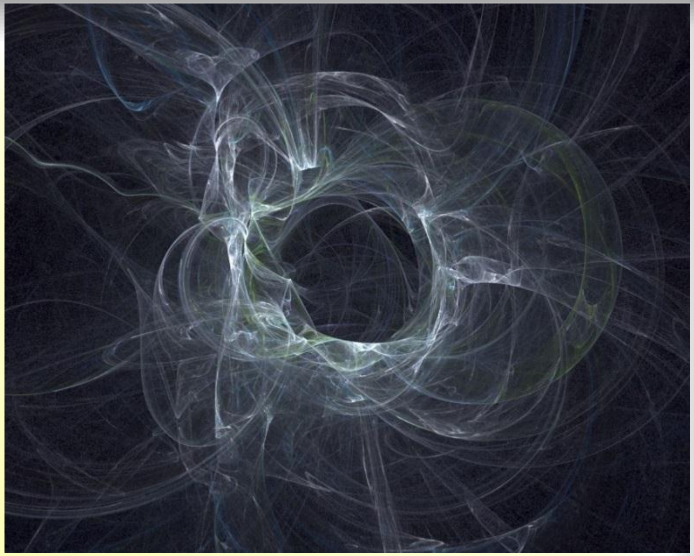
At: http://www.google.ca

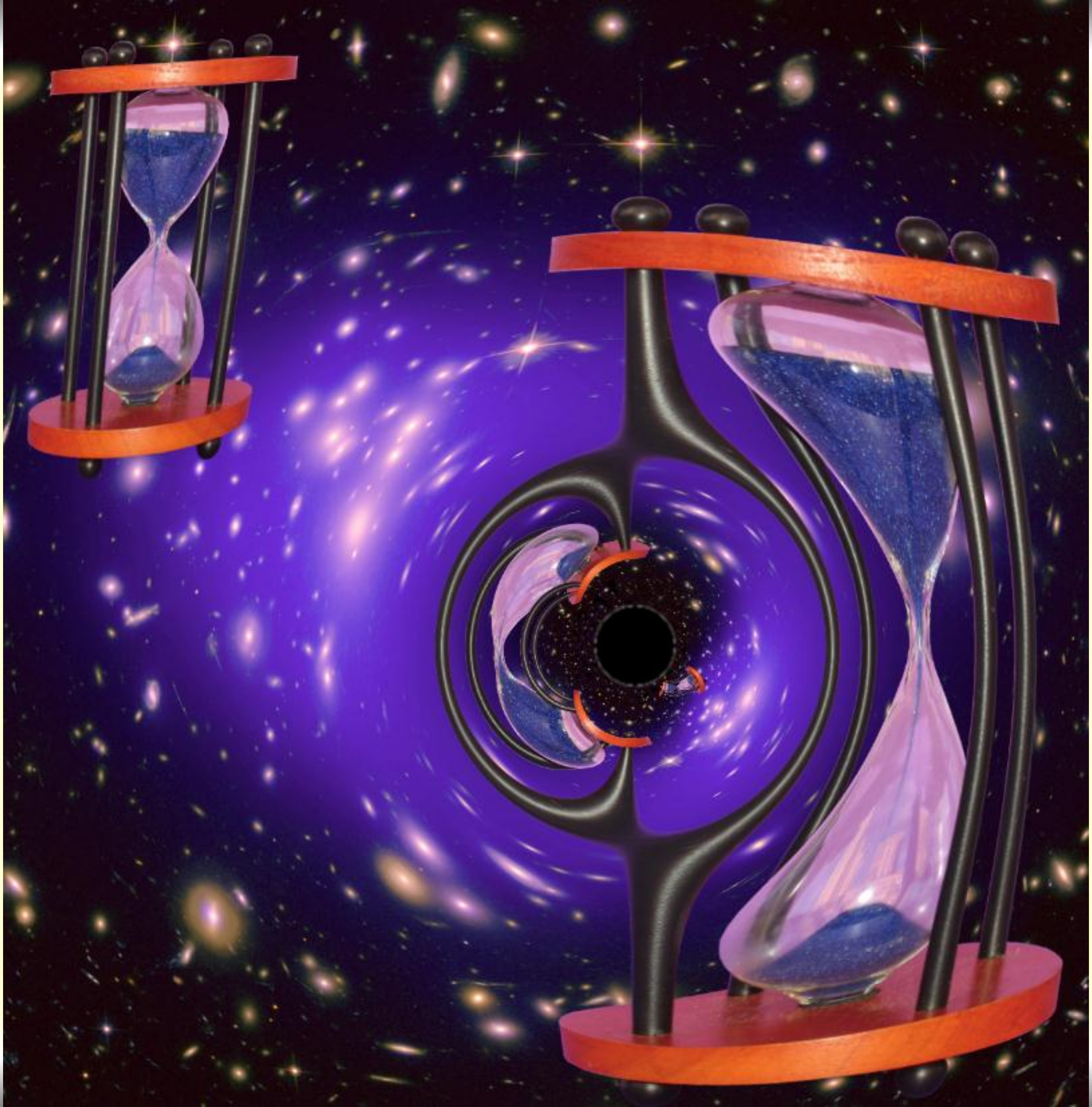
BLACK HOLE 278,000,000

NEUTRON STAR 4,640,000

In virtual reality black hole are more `real' than neutron stars.

Artistic Vision of BHs



A black hole is a compact massive object, the gravitational field of which is so strong that nothing (even the light) can escape from it.

The boundary of the black hole, called the event horizon, is a surface at which the escape velocity is equal to the velocity of light.

$$\tfrac{1}{2}mv^2 = \frac{GMm}{R} \quad \Rightarrow \quad R_g = \frac{2GM}{c^2}$$

Newtonian gravity and Dark Stars

A dark star is an object escape velocity of which is greater than speed of light.

John Michell in 1783 introduced the notion "dark star". In his 1783 paper to the Royal Society Michell wrote:

$1.23\times10^{8}\,M_{\odot}$

If the semi-diameter of a sphere of the same density as the Sun in the proportion of five hundred to one, and by supposing light to be attracted by the same force in proportion to its [mass] with other bodies, all light emitted from such a body would be made to return towards it, by its own proper gravity.

Later, in 1796, Pierre-Simon Laplace independently had come to a similar notion.

$$\frac{1}{2} m v_{\text{escape}}^2 = G \frac{mM}{r}$$

Escape velocity of which is greater than speed of light.

$$v_{\text{escape}} \sim \left(\frac{2GM}{r} \right)^{1/2} \geq c \qquad r_S = \frac{2GM}{c^2} \qquad r \leq r_S$$

Formally "Dark Stars" are not black holes, since in the Newtonian gravity one can extract information from an internal region of the "Dark Star". In the Einstein theory of gravity this information extraction process is impossible.

Black Holes Definition

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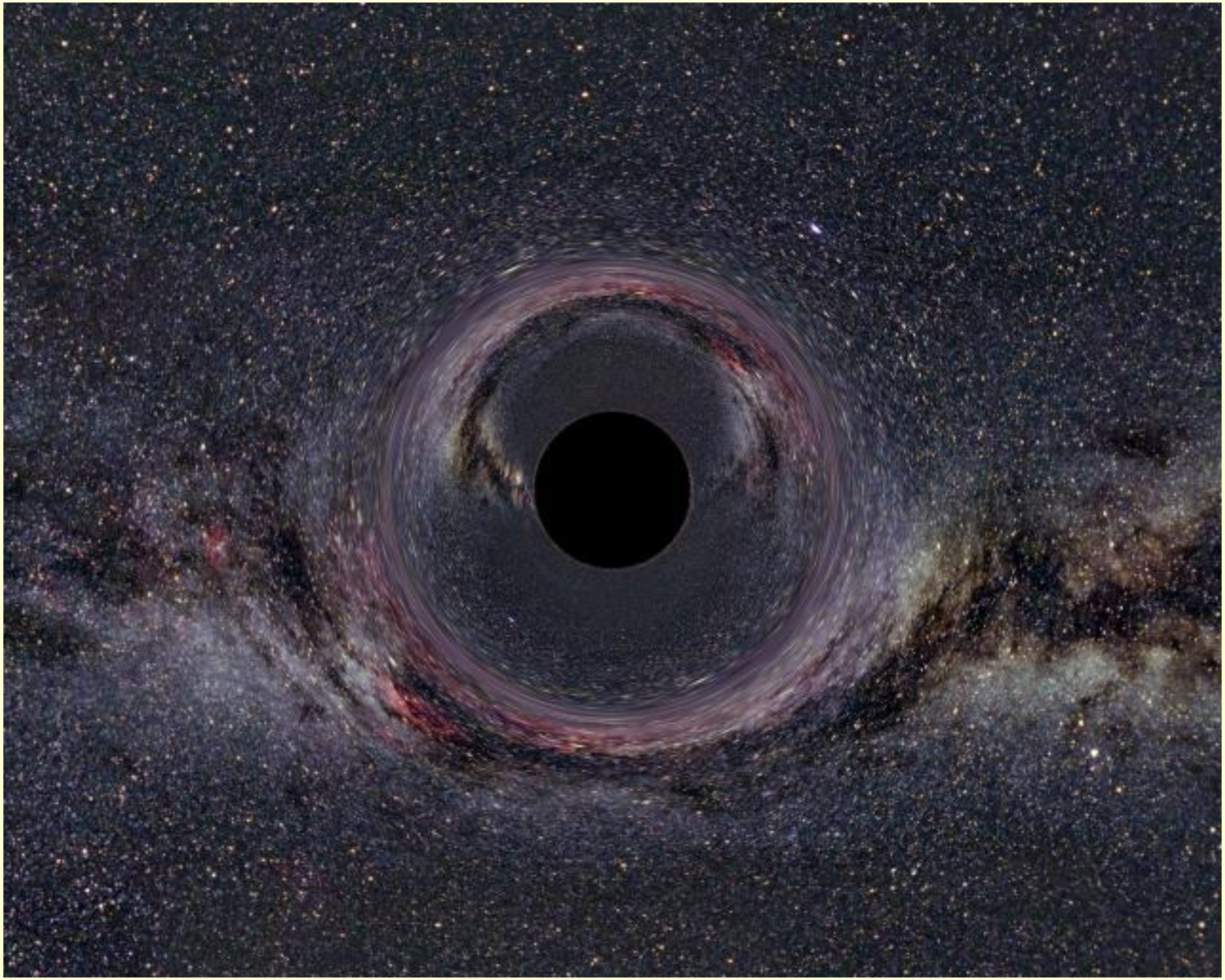


BH's `Genealogical tree'

BH mathematics

BH theorems

Exact solutions

Complete integrability

BH astrophysics

Primordial BH

Grav.Rad. BH

SuperM BH

GRB

BH binaries

Stellar BH

Einstein gravity

Newton gravity

BH physics

BH models in CM

BH interior

Information loss

Higher Dim. BHs

BH and QG (strings, loops)

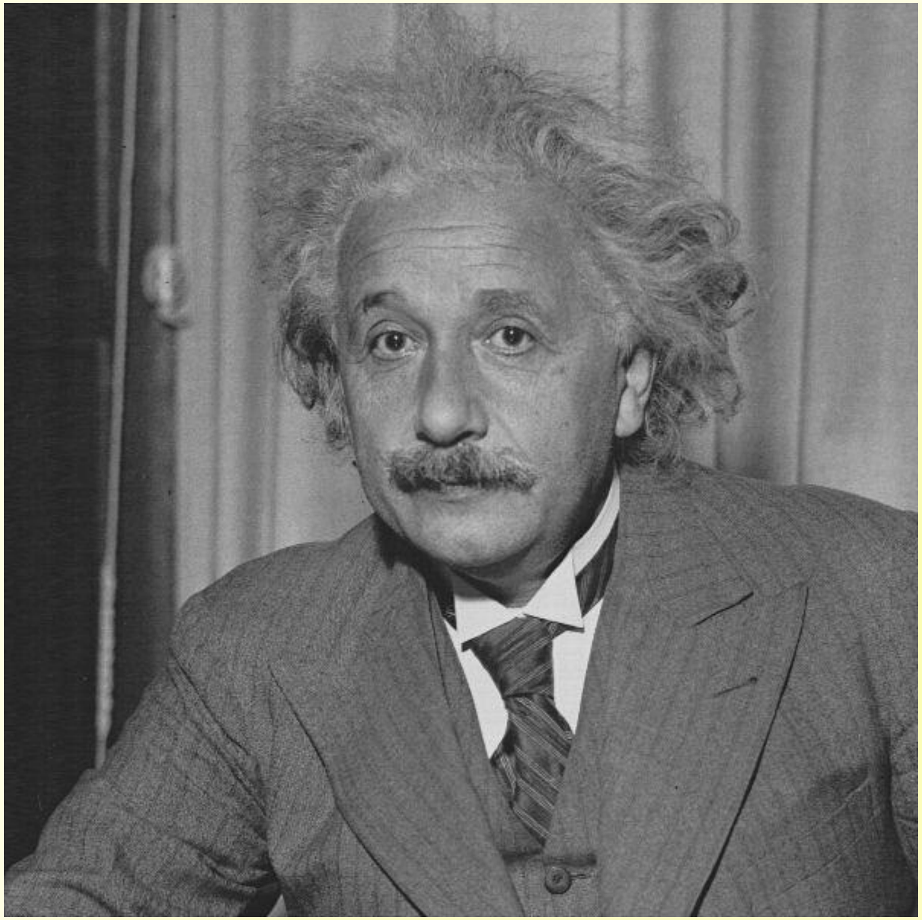
BH Stat.Phys.

BH Quantum Mech.

BH thermodynamics

Black holes are now often used in theoretical physics as probes of new fundamental ideas and models such as quantum gravity, string theory, large extra dimensions, brane world models non-Einstein gravity, ets.

2. Brief History of Black Holes



Albert Einstein (1879--1955)

Spacetime is curved. Spacetime curvature is produced by the mass. Particles and light rays are geodesics.

Spacetime and Matter in GR

Differential manifold as a model of a spacetime,
its points being the events;

Metric represents the gavitational field;

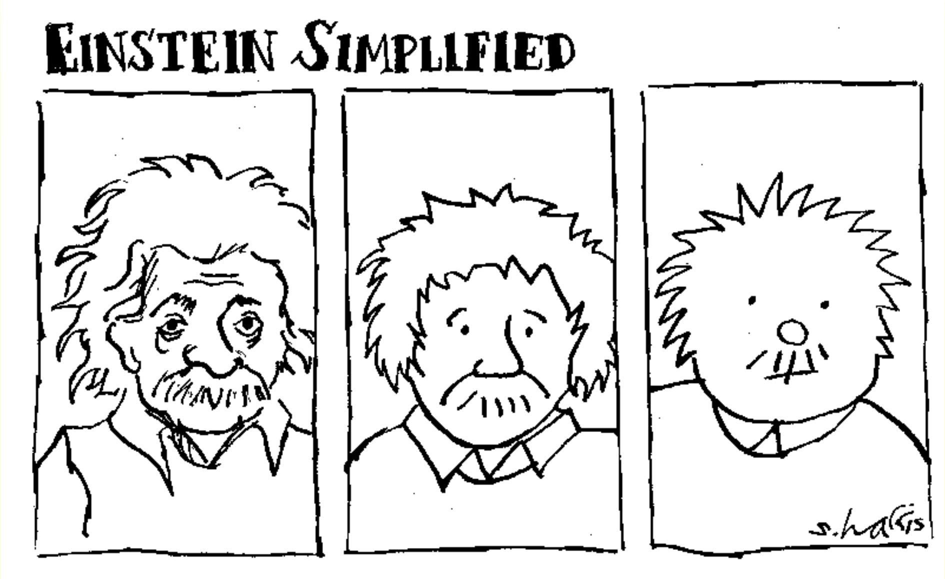
Light and particles are propagating along null and timelike geodesics;

Local null cones determine the causal structure;

Global aspects are important: non-trivial topology and causality;

Geometric formulation of asympotical flatness;

Geometric definition of a black hole in AFST.



(1915)

GRAVITY ⇔ MATTER

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$

MATTER ⇒ GEOMETRY

⇒ CAUSALITY

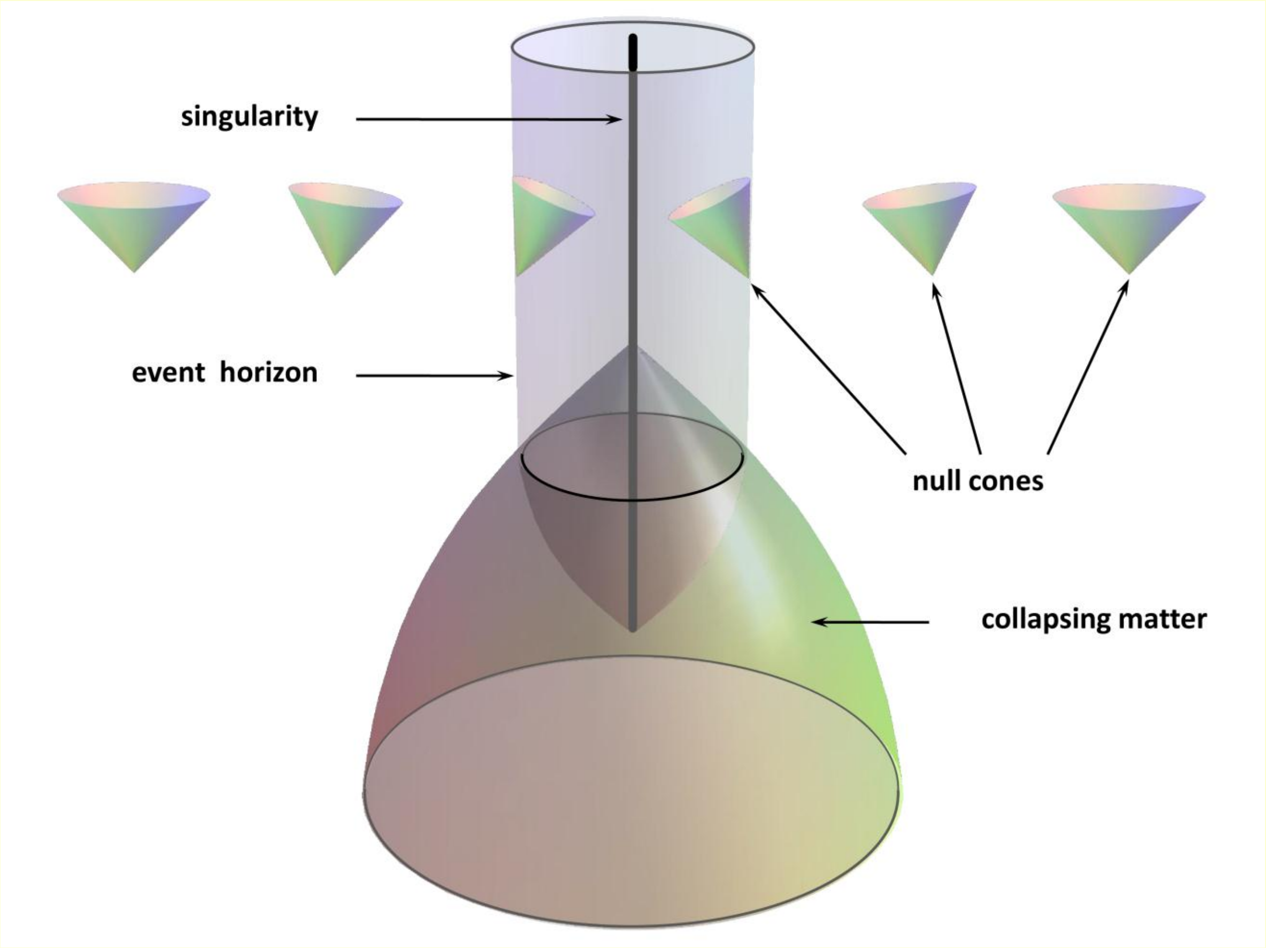
Black Holes in the Einstein Gravity

Karl Schwarzschild
(1873--1916)

Karl Schwarzschild in 1915 found the solution of the Einstein equations, that had been published earlier the same year, describing the gravitational field of a massive spherical object. He wrote this paper while being in the German army during World War I. He served on both the western and eastern fronts, rising to the rank of lieutenant in the artillery.

The properties of black holes are so unusual that even Einstein himself couldn't accept the idea that these weird objects may exist in reality in spite of the fact that they were the solutions of his relativity theory.

Black Holes vs Dark Starts



What is the fate of stars?

The first theoretical prediction of the existence of astrophysical black holes was made for the stellar mass black holes. Indeed, if one asks what might be a good candidate for a black hole, the natural place to look is the world of `dead stars'.

The theory predicts three types of final configurations of the star evolution:

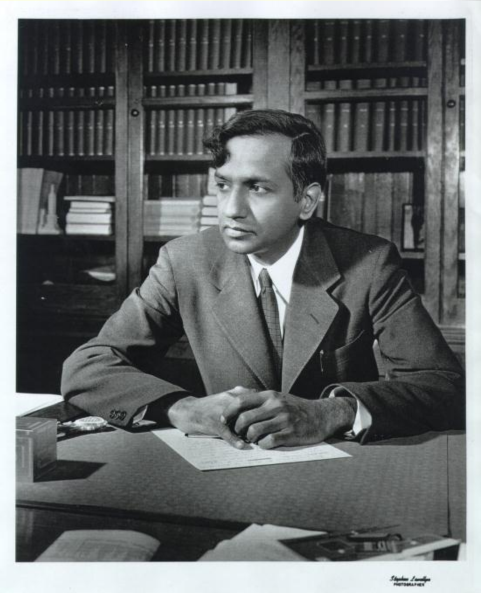
(i) white dwarfs,
(ii) neutron stars,
(iii) black holes.

White dwarfs and neutron stars are formed when the mass of a collapsing star core is less than some critical values. For the higher mass of the collapsing star core a black hole is formed.

White dwarfs can not be too big!

In 1930 during his trip from India to England the Indian physicist Subrahmanyan Chandrasekhar started to work on the calculation of the statistics of a degenerate Fermi gas in application to white dwarfs.

$$M_{\text{Chandrasekhar limit}} = 1.44\, M_{\odot} = 2.864 \cdot 10^{33}\ g$$



After a talk by Chandrasekhar on the mass limit for white dwarfs, Arthur Stanley Eddington replied:
The star has to go on radiating and radiating and contracting and contracting until, I suppose, it gets down to a few km radius, when gravity becomes strong enough to hold in the radiation, and the star can at last find peace. I think there should be a law of Nature to prevent a star from behaving in this absurd way!

Mechanism of instability of gravitating stars

`Cold' gas of fermions: $p_F \sim n^{1/3}$. Pressure $P \sim n^{\gamma} \sim M^{\gamma} R^{-3\gamma}$,

Non-relativistic gas γ=5/3, relativistic gas γ=4/3.

$$\frac{GM\rho}{R^2} \sim \nabla P \Rightarrow GM^2 \sim PR^4 \sim M^{\gamma} R^{4-3\gamma}$$

For γ=5/3 $\Rightarrow$ R $\sim M^{-1/3}$; For γ=4/3 $\Rightarrow M = M_* = \frac{m_{Pl}^3}{\mu^2}$

μ is a mass per unit Fermi particle

Degenerate gas of electrons -> WD

Masses of typical stable *white dwarfs* lie between $0.5\,M_{\odot}$ and $0.7\,M_{\odot}$ solar mass, their radius as about the radius of the Earth, and density of the order of $10^{6}\ g/cm^{3}$. There are no known white dwarfs with the mass more than $1.33\,M_{\odot}$. Over 97% of the stars in our Galaxy are or will become white dwarfs.

Degenerate gas of neutrons -> NS

***Neutron stars* are remnants of massive stars after their gravitational collapse. Neutron stars are created during supernova events. They are composed almost entirely of neutrons. A typical mass of a neutron star is between 1.35 and about 2.0 solar masses. Their corresponding radii are between 15 and 8 km. The heaviest known neutron star has the mass about 2 solar mass. Neutron stars have an average density on order of $8.4\times10^{13}-1\times10^{15}$ g/cm^{3}.**

An escape velocity from a surface of a neutron star is around 150,000 km/s, about 50% of the speed of light.

The critical mass of the neutron stars, a so called Tolman-Oppenheimer-Volkov limit, is approximately 2-3 solar masses.

Roy Kerr (1934 --)

The most general stationary solution of vacuum Einstein equations describing an isolated black hole was found in 1963 by Roy Kerr. It is axisymmetric and uniquely specified by 2 parameters: mass M and angular momentum J. This solution was presented at the First Texas Symposium.

Ezra T. Newman and Roger Penrose (1962). "An Approach to Gravitational Radiation by a Method of Spin Coefficients". *Journal of Mathematical Physics* **3** (3): 566–768. *Errata (1963)*

Kerr was a referee of this paper. He found a mistake in sign of one term. Based on the equations with a wrong sign term Newmann and Goldberg arrived to conclusion that there is no (algebrailally special) solutions for rotating analogue of the Schwarzschild metric. Kerr found and corrected a mistake and obtained his famous solution.

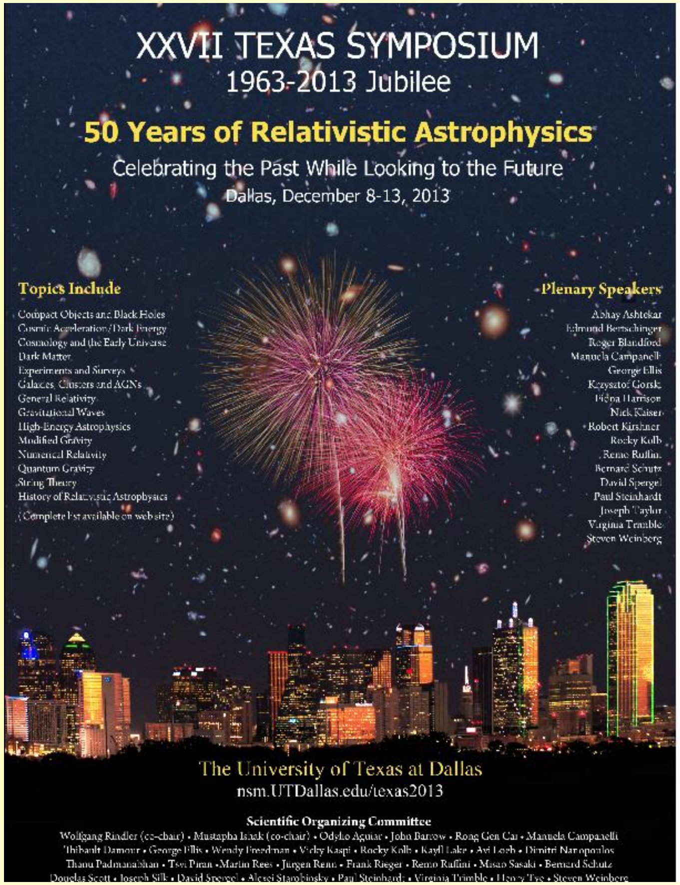
First results on observations of quasars were also reported at the First Texas symposium. The first quasars (3C 48 and 3C 273) were discovered by Allan Sandage. The **Third Cambridge Catalogue of Radio Sources** (**3C**) is an astronomical catalogue of celestial radio sources . The radio source 3C 48 was finally tied to an optical object. In 1962 another radio source, 3C 273, was predicted to undergo five occultations by the moon. It was identified with the optically observed source. Its optical spectrum was obtained. At the end of 1964 more than 30 quasars were discovered. (Wiki)

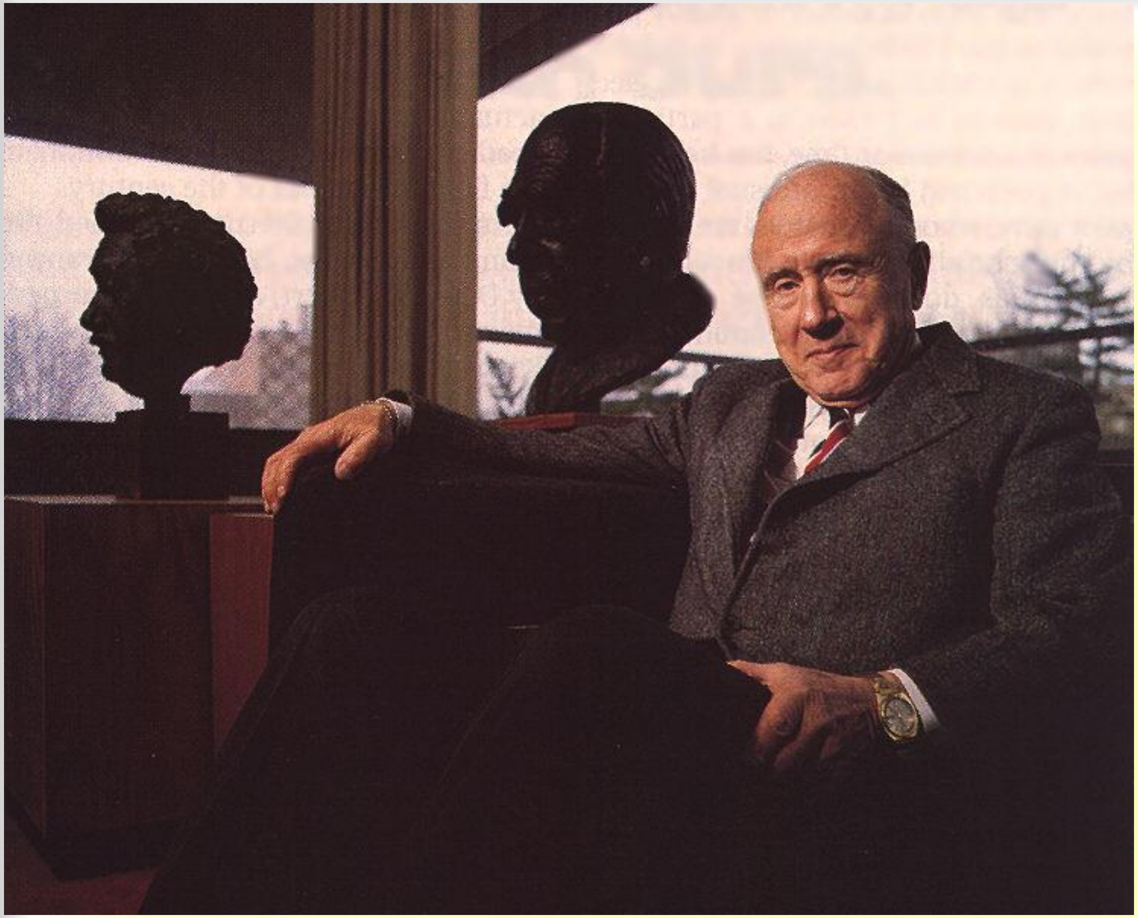
Main properties:

1. Large red-shift (37% for 3C 48)
2. Large distance
3. Very high luminocity
4. Short time fluctuations
5. Very small size

Black hole model was proposed to explain the power production in quasars.

First Texas Symposium
On Relativistic Astrophysics
December, 1963, Texas





John Archibald Wheeler (1911--2008)

The name "black hole" was invented in December 1967 by John Archibald Wheeler. Before Wheeler, these objects were often referred to as "black stars“ or "frozen stars".

For bibliography then — after use — for Big. folder

AAAS INVITED LECTURES

Sigma Xi–Phi Beta Kappa Lecture

FRIDAY, DECEMBER 29 1967
West Ballroom, New York Hilton

8:30 p.m. Chairlady: MINA REES (*Dean of Graduate Studies, City University of New York*)

Speaker: JOHN A. WHEELER (*Professor of Physics, Princeton University*)

Our Universe: The Known and the Unknown.

The formation of new stars and the explosion of old stars and the greatest variety of events, gigantic in scale and in energy, make the universe incomparably more interesting than any fireworks display that anyone could imagine in his wildest dreams. However, in all this wealth of events not one single effect has been discovered which has led to a new law of physics, and not one single finding has ever been obtained which is generally recognized to be incompatible with existing law. On the contrary, Einstein's relativity and the quantum principle and the lesser laws together predict astonishing events—some of them like the expansion of the universe already observed and others on "the most wanted list" of many present-day investigators. Among these are the "missing matter" predicted to be present by Einstein's theory and the "black holes" predicted to result from the "continued gravitational collapse" of an over-compact mass. No prediction of standard well-established theory is more revolutionary than "superspace," the dynamical arena of Einstein's general relativity, and none seems more likely to have consequences for all of physics, from elementary particle physics to the dynamics of the universe.

The first public use of the term "black hole": Lecture appears in the Phi Beta Kappa journal "The American Scholar" and in the Sigma Xi Journal, "American Scientist" Vol. 56 No. 1 Spring 1968, pp 1-20. pp (E), (F)

pp (A), (B), (C), (D)

The first pulsar was observed on November 28, 1967, by Burnell and Hewish.

Cygnus X-1 is a galactic X-ray source and first stellar mass black hole candidate. It was discovered in 1964 during a rocket flight . It is one of the strongest X-ray sources seen from Earth. It is now estimated to have a mass about 14.8 solar mass. Uhuru X-ray satellite discovered fluctuations in the X-ray emission that occurs several times a second. This means that the energy is generated within a small region of roughly 10^5 km size.

Mathematical Aspects

`Golden age' of BH theory

In 60'-70'th of the past century many remarkable results and exact theorems on the BH properties were proved.
(Israel, Penrose, Hawking, Carter, Price, Teukolsky, …)

Properties of 4D Black Holes

Event horizon (BH boundary) is almost everywhere null surface

Black hole surface topology is S^2.

Its surface area never decreases (EC)

Soon after their formation black holes become stationary (the `balding phase' $T \sim r_g / c$) .

Stationary black holes are either static (Schwarzschild) or axially symmetric (Kerr).

Uniqueness theorem: Stationary isolated BHs are uniquely specified by their mass and angular momentum and are described by the Kerr metric.

The Kerr metric besides the evident ST symmetries has also hidden symmetry.

Geodesic equation of motion are completely integrable. Massless field equations allow the separation of variables.

Black holes are classically stable.