BLACK HOLE CONCEPT

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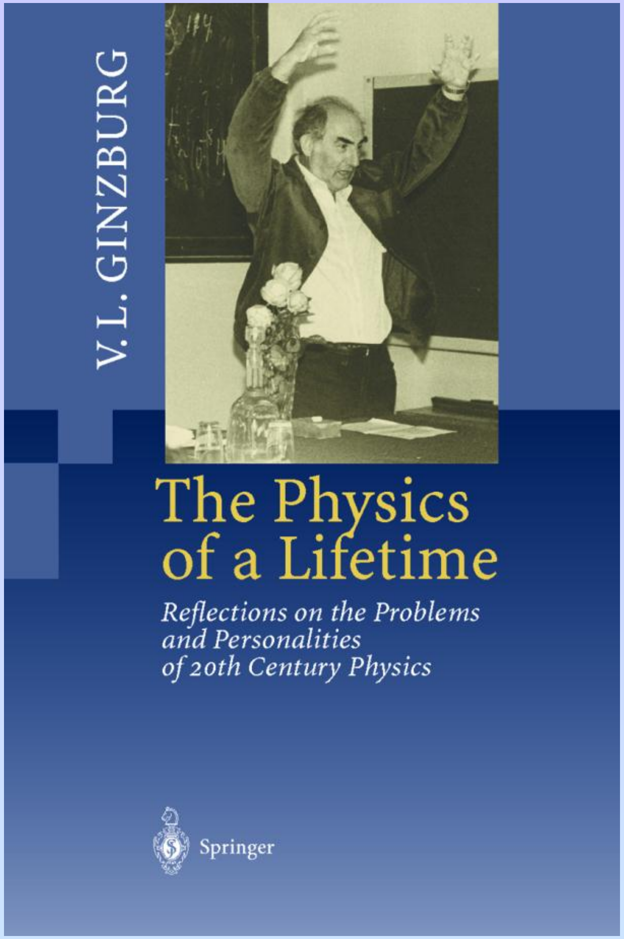
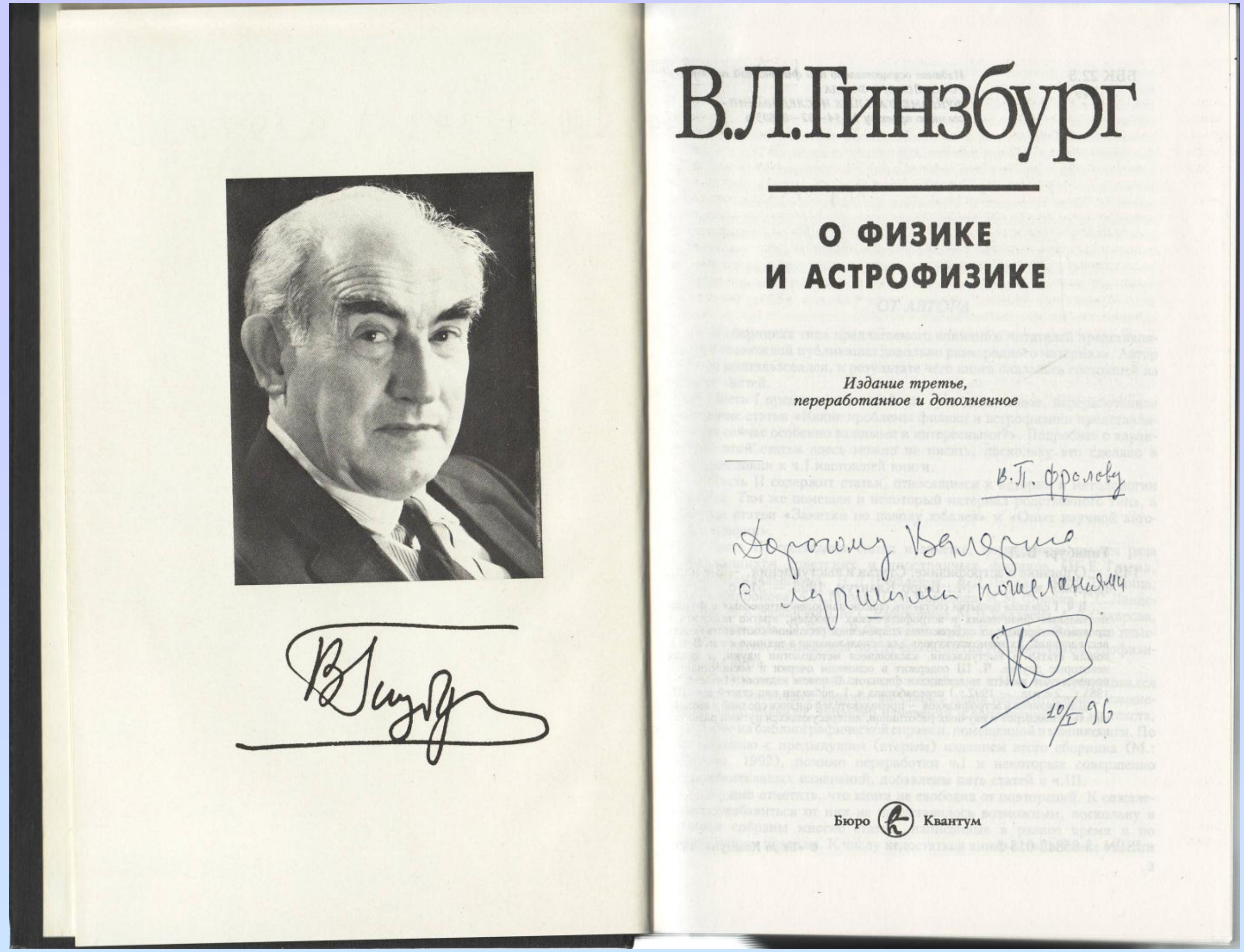
Ginzburg Conference on Physics
May 28 - June 2, 2012 in Moscow

V.L.





1995: #21. “Black holes” of total 24 problems

Black hole concept, its evolution, modern status of BHs, and open problems

BLACK HOLES - BIG PICTURE

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.

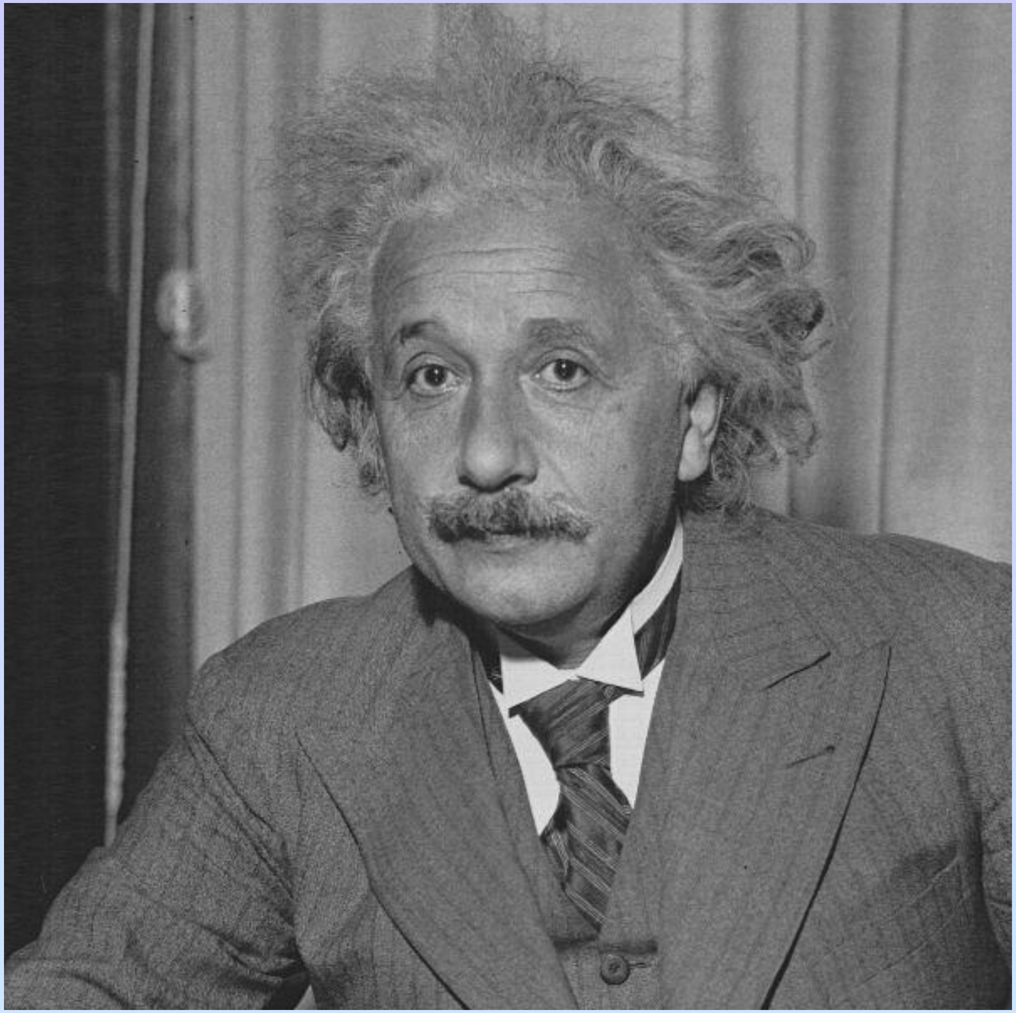
The boundary of the black hole, called the event horizon, is a surface at which the escape velocity is equal to the velocity of light.

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

Black hole gravity is strong:

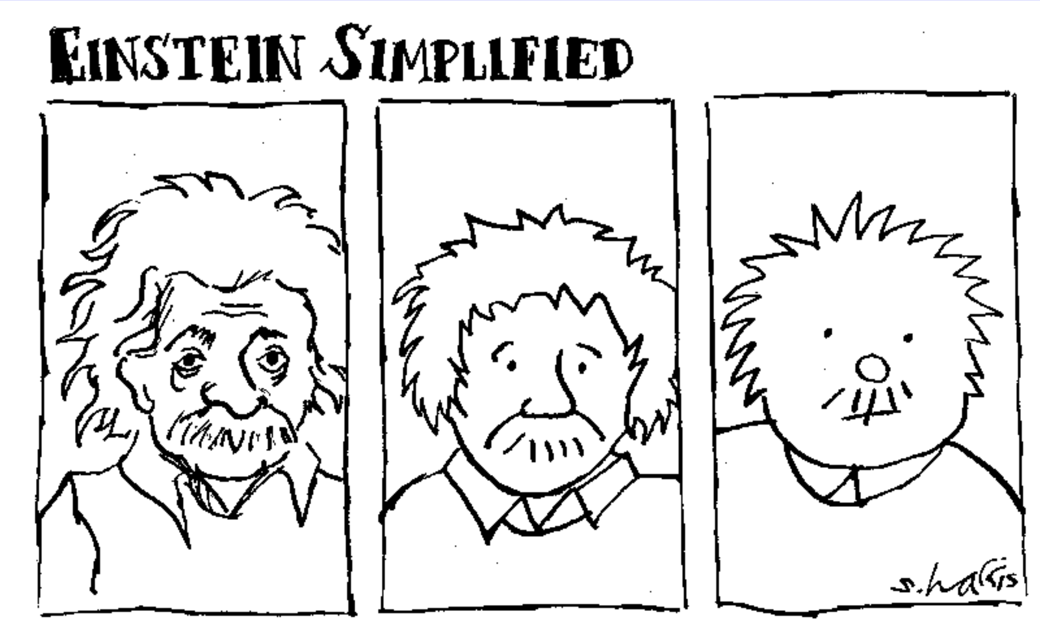
$$\frac{2\Phi}{c^2} = \frac{2GM}{c^2 R_g} = 1$$

The Einstein's theory of general relativity is required for its description



Albert Einstein
(1879--1955)

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



GRAVITY ⇔ MATTER

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

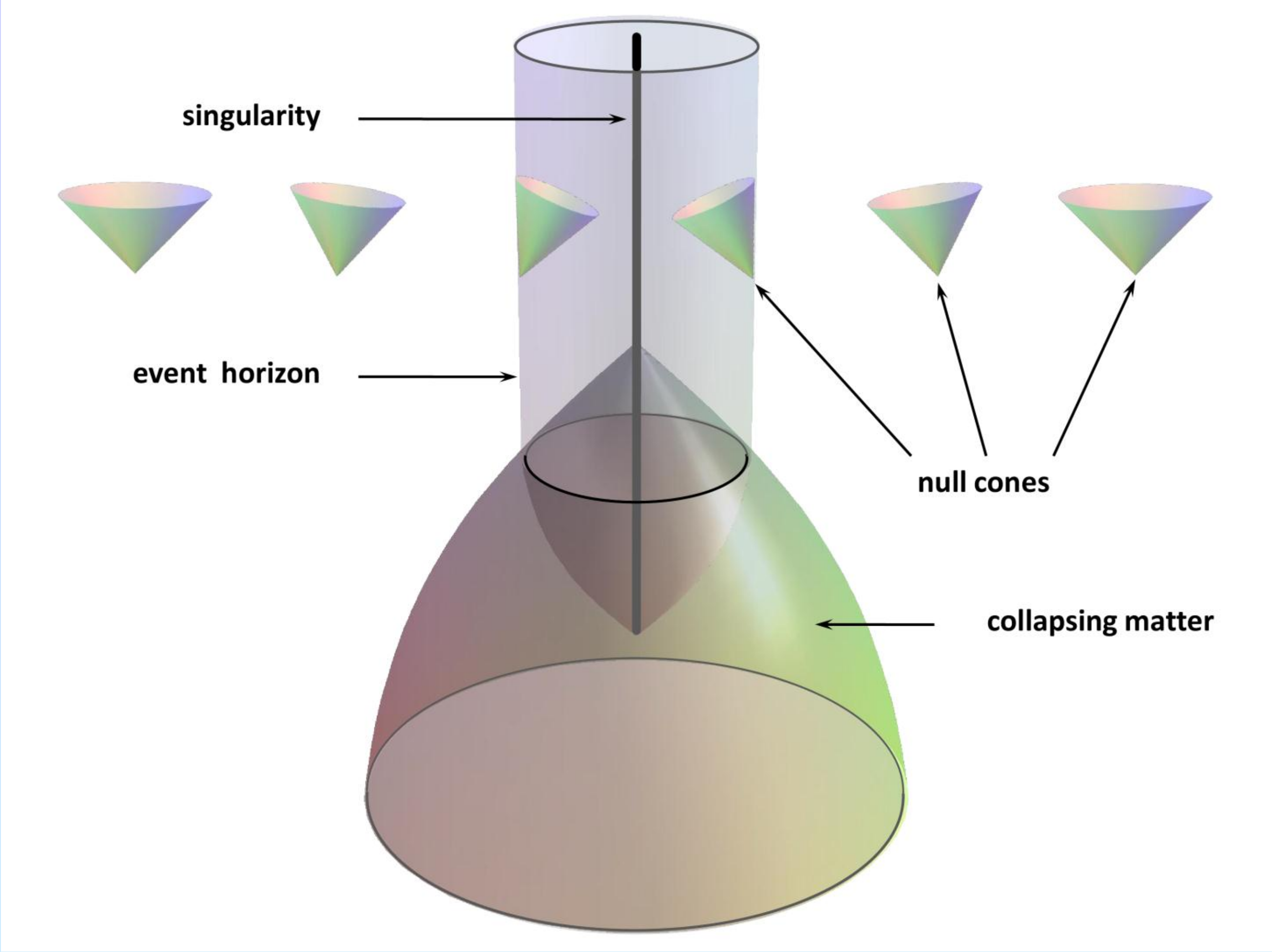
MATTER ⇒ GEOMETRY

⇒ CAUSALITY

Karl Schwarzschild
(1873--1916)

In 1916 Karl Schwarzschild, an astronomer, obtained a solution of vacuum Einstein equation, describing a spherically symmetrical static black hole. He died soon after this.

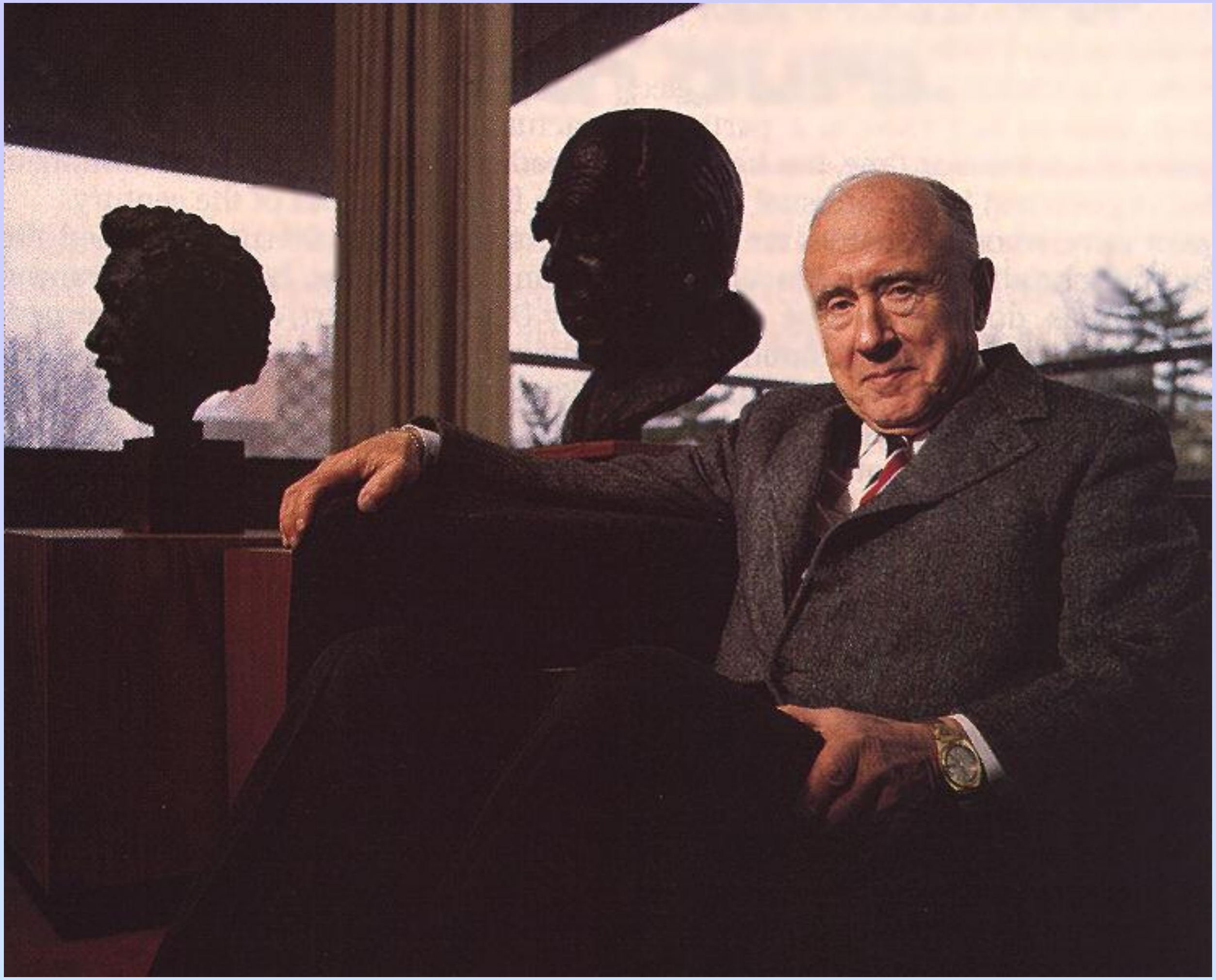
Black Holes vs Dark Starts



"Nature" of
Schw. Singularity:
Synge '50,
Finkelstein '58,
Fronsdal '59,
Szekeres '60,
Kruskal '60,
Novikov '63,64

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.



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".

Stellar mass BHs

Final state of stellar evolution:

(1) White dwarf (Chandrasekhar ('31) limit $1.44\, M_\odot$)

(2) Neutron star (pulsars, mass limit $\sim 3\, M_\odot$)

(Landau '32, Baade&Zwicky '34,

Oppenheimer&Volkoff '39)

(3) Black hole (for $M = 10 M_\odot \quad r_g = 30$ km)

(Oppenheimer&Snyder '39)

`Golden age’ of BHs

In 60’-70’th of the past century many remarkable results and exact theorems on the BH properties were proved.

SOVIET PHYSICS–DOKLADY VOL. 9, NO. 5 NOVEMBER, 1964

ASTRONOMY

THE MAGNETIC FIELDS OF COLLAPSING MASSES AND THE NATURE OF SUPERSTARS

Corresponding Member Acad. Sci. USSR V. L. Ginzburg

P. N. Lebedev Physics Institute, Academy of Sciences, USSR

Translated from Doklady Akademii Nauk SSSR, Vol. 156, No. 1, pp. 43-46, May, 1964
Original article submitted January 31, 1964

SOVIET PHYSICS JETP VOLUME 20, NUMBER 3 MARCH, 1965

ON GRAVITATIONAL COLLAPSE OF MAGNETIC STARS

V. L. GINZBURG and L. M. OZERNOĬ

P. N. Lebedev Physics Institute, Academy of Sciences, U.S.S.R.

Submitted to JETP editor March 31, 1964

J. Exptl. Theoret. Phys. (U.S.S.R.) 47, 1030-1040 (September, 1964)

Gravitational collapse of a spherically symmetric mass of gas (''star'') possessing a magnetic dipole moment is considered. The high conductivity of the medium, resulting in conservation of the magnetic field flux through a material contour, is taken into account. Some problems are discussed which may be related to the magnetic field where the collapse mechanism is used to explain the observed phenomena (radio galaxies and quasars).

Properties of 4D Black Holes

Price '72 et all

"Black holes have no hair": Mass, electric charge and angular momentum are the only 3 parameters which specify a stationary BH in Einstein-Maxwell theory (Wheeler, 1971)

Event horizon (BH boundary) is almost everywhere null surface (Penrose, ‘68)

Black hole surface topology is S^2 (Hawking, ‘72)

Its surface area never decreases (Hawking,’71,72)

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 (Israel ’67, Carter ‘71,73, Robinson ‘75)

Geodesic equations of motion in Kerr ST are completely integrable (Carter ‘68)

The Kerr metric besides the evident ST symmetries has also hidden symmetry (Killing and Killing-Yano tensors) (Penrose&Walker ‘70, Penrose&Floyd ‘73)

Massless field equations allow the separation of variables (Press ‘72, Press&Teukolsky ’72,73)

Black holes are classically stable.

Black hole concept in ‘60s

Final state of matter evolution

Exotic objects of stellar mass

Too small and dark to be observed


R.I.P.
Black Holes as Graves of Matter

40 YEARS LATER …

At: http://www.google.ca

BLACK HOLE 116,000,000

NEUTRON STAR 4,800,000

BH's `Genealogical tree'

BH mathematics

BH theorems

Higher Dim. BHs

Exact solutions

Complete integrability

Primordial BH

Grav.Rad. BH

SuperM BH

GRB

BH binaries

Stellar BH

BH astrophysics

BH models in CM

BH interior

Information loss

BH and QG
(strings, loops)

BH Stat.Phys.

BH Quantum Mech.

BH thermodynamics

BH physics

Black Holes Mathematics

Higher Dimensional BHs

Motivations :

(1) Extra-dimensions and string theory

(2) Brane-world models

(3) Black holes as probes of extra dimensions

(4) Micro BHs production in colliders?

(4) Generic and non-generic properties of BHs

Black Holes as Probes of Extra Dimensions

Higher dimensional gravity is stronger at small scales and weaker at large scales than the 4D one: $F \sim G^{(D)} M_1 M_2 / r^{(D-2)}$

If extra dimensions are compact with size L, then at the distance larger than L one has standard 4D gravity with $G = G^{(D)} / L^{(D-4)}$.

For $L \sim 0.1$ mm higher dim. gravity may be as strong as other interactions.

New fundamental (quantum gravity) scale $m_* \sim m_{Pl}(L/l_{Pl})^{-k/(k+2)}$

$r_* \sim l_{Pl}(L/l_{Pl})^{k/(k+2)}$. m_* is the lowest mass of a classical BH.

For $k=2$ and $L=0.1\text{mm}$, $m_* \sim 1\text{TeV}$ and $r_* \sim 10^{-17}\text{cm}$.

Properties of HD black holes with $r_g \leq L$ are determined by D-dim Einstein equations, so that testing their properties in our 4D experiments one probes extra dimensions (e.g. micro BH at colliders?) . At the moment there is no any indications on micro BH creation at LHC.

"To think that LHC particle collisions at high energies can lead to dangerous black holes is rubbish. Such rumors were spread by unqualified people seeking sensation or publicity.“

Academician Vitaly Ginzburg, Nobel Laureate in Physics, Lebedev Institute, Moscow, and Russian Academy of Sciences

In: **The safety of the LHC, CERN document, http://public.web.cern.ch/public/en/lhc/safety-en.html, (2003)**

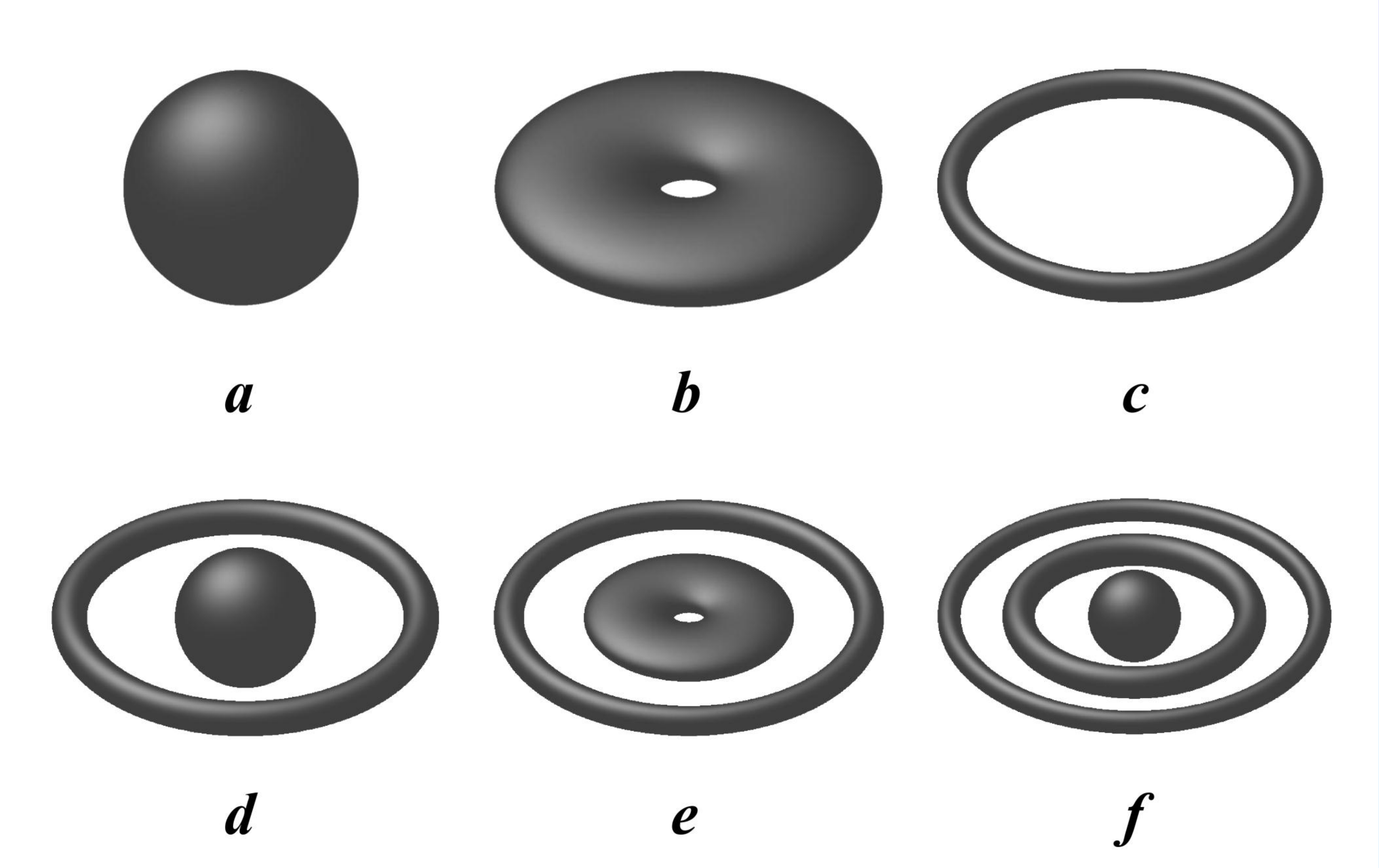
Higher Dimensional Black Hole Solutions

If in D-dimensional ST there exist $D-2$ Abelian symmetry group, the vacuum Einstein equations reduce to a nonlinear sigma model, which is a completely integrable system.

In 5D: black holes with 3 parameters (mass and 2 angular momenta).

Black rings (Emparan&Reall '08), etc...

5D vac. stationary black holes



(1) No Uniquness Theorem: For given M and J more than one BH solution

(2) Stability of HD BHs ?

Complete Integrability in Higher Dimensional Black Holes (wsth)

Complete integrability of geodesic equations and complete separation of variables in HJ and KG eqs.

Complete integrability in 5D rotating black holes (V.F.&Stojkovich ‘03)

The most general higher dimensional black hole solution (Chen, Lu, Pope ‘07) : (A)dS-Kerr-NUT

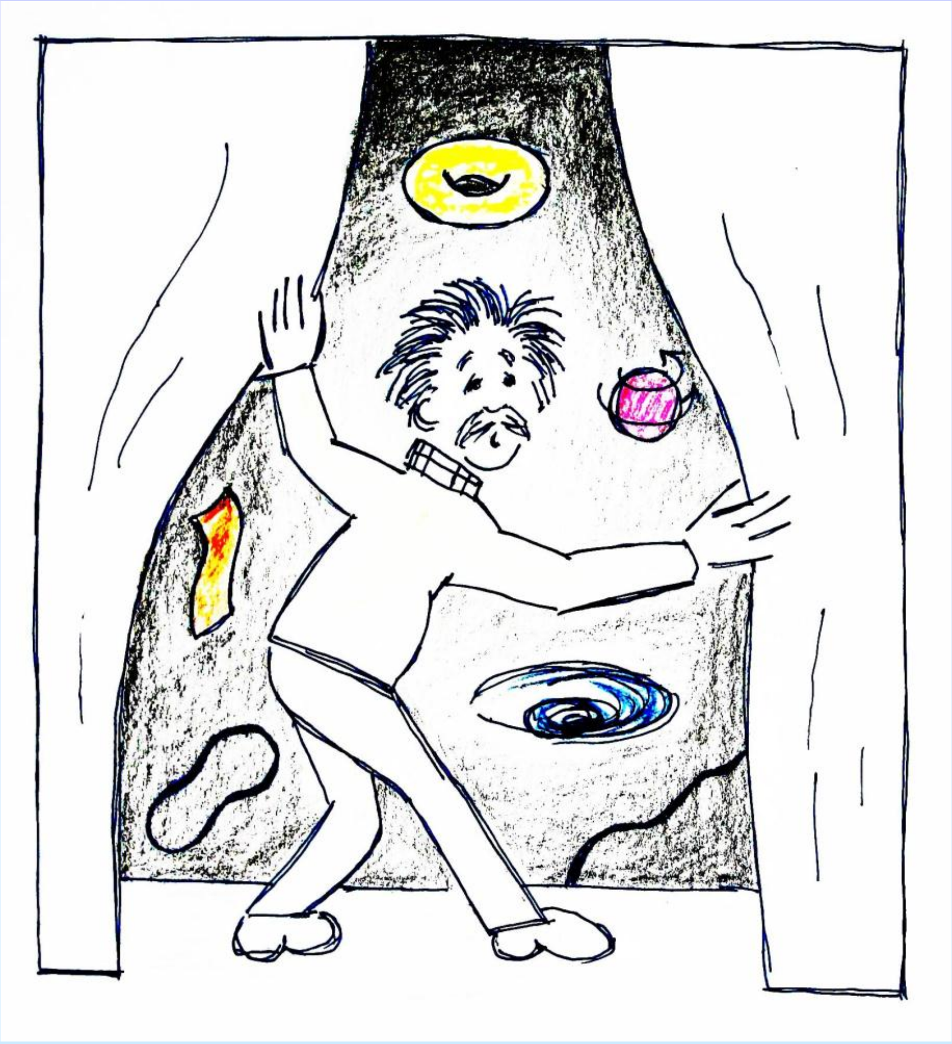
All Kerr-NUT-AdS metrics possess a generator of symmetries (Principle KY tensor, V.F.& Kubiznak ‘07).

A solution of Einstein equations which admits a PKYT is Kerr-NUT-AdS metric (Krtous,V.F.& Kubiznak ’08, Houri,Oota, Yasui ‘09)

PKYT generates enough symmetries to make geodesic equations completely integrable (Page,Krtous,Kubiznak,VF ’07)

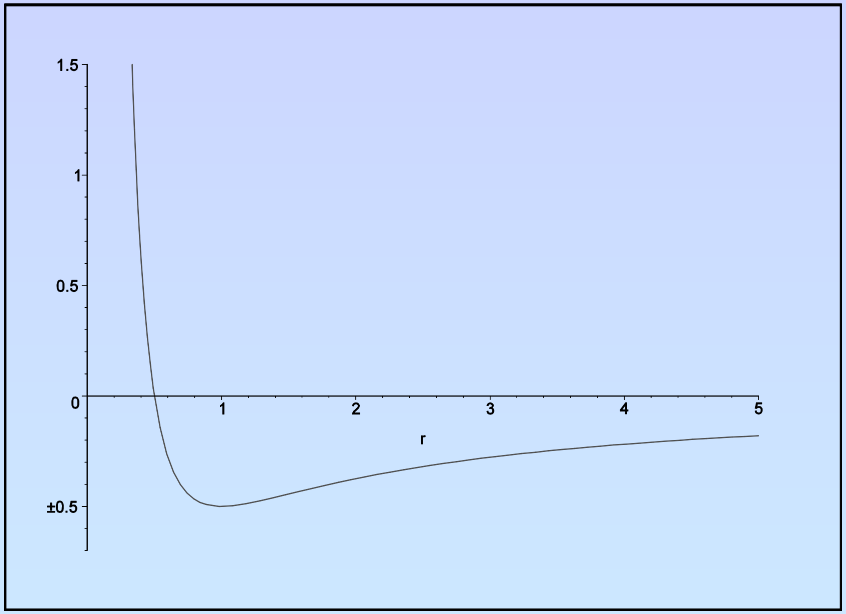
Complete separation of variables.

Black Holes Physics



Celestial Mechanics: ISCO

Existence of the innermost stable circular orbits (ISCOs) differs GR from Newtonian mechanics

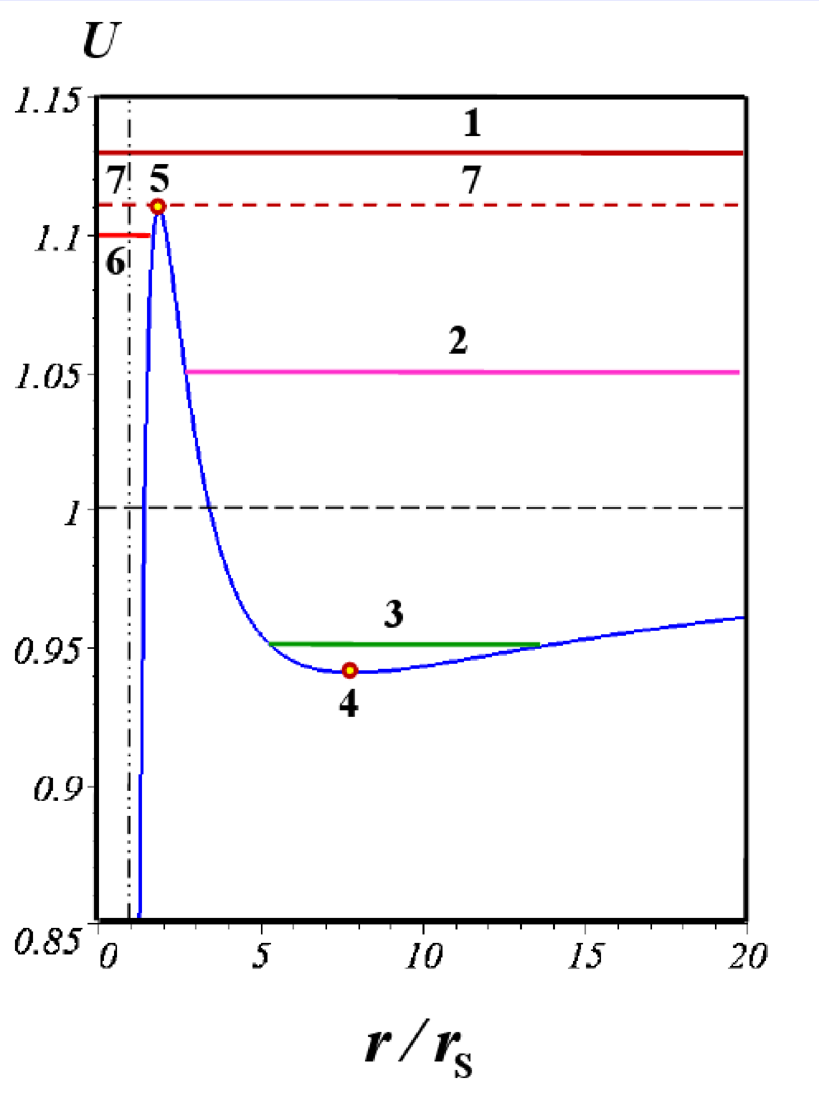


$$U = -\frac{GmM}{r} + \frac{L^2}{2mr^2};$$

$$U' = 0 \Rightarrow r = \frac{L^2}{GmM};$$

In Newtonian theory the radius of a circular orbit can be arbitrary small

(No stable bounded orbits in HD gravity !)
Anthropic principle excludes D>4 with $L_{e\,\mathrm{dim}} = \infty$



Schwarzschild BH:

$$r_{ISCO} = 3r_g = 6M$$

$$E_{ISCO} / m = \sqrt{8/9}$$

BH efficiency: 5.72%

Extremal Kerr BH ($J/M^2=1$):

$$r_{ISCO} = M$$

$$E_{ISCO} / m = \sqrt{1/3}$$

BH efficiency: 42.36%

BH Eigen Modes

Gravitational perturbations of a black hole behave like an oscillator with damping

$$\delta g \sim \exp(-i\Omega t), \quad \Omega = \omega - i\Gamma,$$

$$\omega = M^{-1} f(J/M^2), \quad \Gamma = M^{-1} F(J/M^2).$$

An excited black relaxes to its `ground' stationary state by emitting gravitational waves. They `bring' us information about M and J.

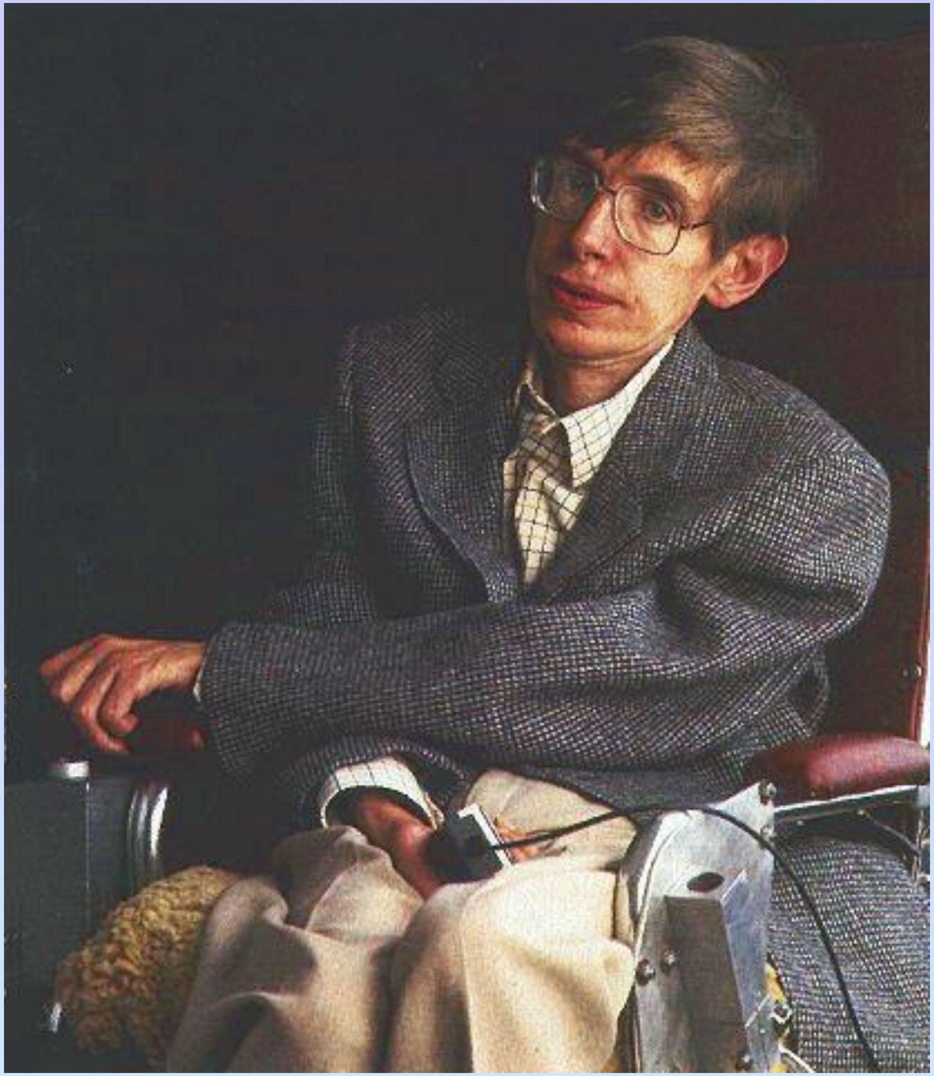
BH Thermodynamics

Bekenstein 72-73, Hawking 74-75

$$dM = T\, dS$$

$$S = \frac{A}{4\, l_{Pl}^2}, \quad A = 4\pi\, r_g^2 \sim M^2,$$

$$T = \frac{\hbar c^3}{8\pi G k M} \sim M^{-1}$$



Stephen
Hawking
(1942 --)

In 1974 British physicist Stephen Hawking proved that black holes are quantum unstable.

The vacuum near a black hole is unstable. The gravitational field is so strong that it produces particles. As a result the black hole emits as a heated black body with temperature:

$$kT = \frac{\hbar c^3}{8\pi GM} \sim 10^{-6} \frac{M_\odot}{M} K$$

Planck units: $\mu_{Pl} = \sqrt{\frac{\hbar c}{G}} \sim 10^{-5}\, g,$

$$\lambda = \sqrt{\frac{\hbar G}{c^3}} \sim 10^{-33}\, cm, \quad \tau_{Pl} = \sqrt{\frac{\hbar G}{c^5}} \sim 10^{-43}\, \mathrm{sec}$$

Life-time of a black hole:

$$t_{BH} \sim \left(\frac{M}{\mu_{Pl}}\right)^3 \tau_{Pl} \sim 10^{17}\, \mathrm{sec} \left(\frac{M}{10^{15}\, g}\right)^3$$

Hawking effect is important for mini-black-holes only

Vacuum in a homogeneous gravitational field and excitation of a uniformly accelerated detector[1)]

V. L. Ginzburg and V. P. Frolov

P. N. Lebedev Physics Institute, Academy of Sciences of the USSR

Usp. Fiz. Nauk **153**, 633–674 (December 1987)

The theory of quantum effects in uniformly accelerated frames of reference and in a homogeneous gravitational field is discussed. Ways of describing processes of excitation of, and radiation from, a uniformly accelerated detector in a uniformly accelerated and in an inertial frame of reference are compared. Particular attention is devoted to a discussion of the equivalence principle for quantum phenomena in connection with the excitation of a uniformly accelerated detector and a detector at rest in a homogeneous gravitational field.

Equivalence principle in quantum domain

Excitation and emission of a "detector" in accelerated motion in a vacuum or in uniform motion at a velocity above the velocity of light in a medium

V. L. Ginzburg and V. P. Frolov

P. N. Lebedev Physics Institute, Academy of Sciences of the USSR, Moscow

(Submitted 12 February 1986)

Pis'ma Zh. Eksp. Teor. Fiz. **43**, No. 6, 265–267 (25 March 1986)

The question of the excitation of a "detector" moving at constant acceleration in a vacuum has recently been discussed extensively. In the present letter it is noted that this excitation and the associated emission are analogous to corresponding events in the region of the anomalous Doppler effect which arises when a "detector" moves at a constant velocity above the velocity of light in a medium.

Unruh effect and Anomalous Doppler effect

Black Holes in Astrophysics

Black holes have very high efficiency of rest-mass-to-energy transformation

Black holes are now used as a natural engine model whenever it is required to explain large energy production in a small compact space region

How many black holes are in our Galaxy?

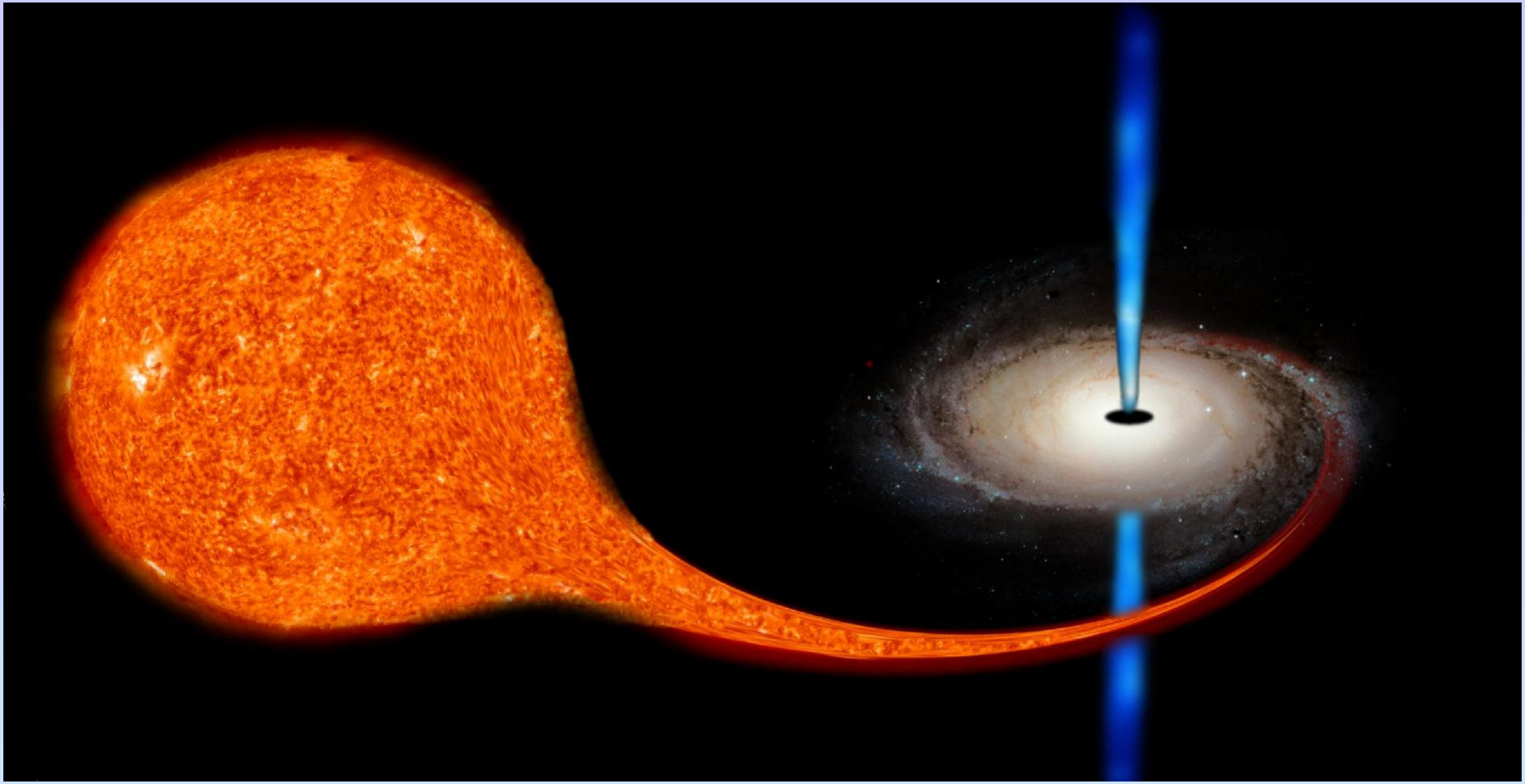
Total number of stars in our Galaxy is about 10^{11}. Estimated number of black holes in it is about $10^8 - 10^9$. The number of neutron stars is up to 10 times larger .

Stellar mass Black Holes now

More than 20 stellar mass BHs observed

All of them are X-ray sources in binaries

All except 4 are in our Galaxy



Persistent BHs ($Syg\ X-1,\ LMC\ X-1, LMC\ X-3$)

Transient BHs

Newtonian mechanics is used to determine the mass of the BH candidates.

GR is required to obtain confirmations

Matter, falling onto BH, forms an accretion disk. ISCO radius determines its inner edge, as well as temperature and luminosity of the disk and shortest period of fluctuations of its radiation

- Measuring of BH spin
- Iron X-ray line broadening
- Microquasars

Gamma-ray bursts

Gamma-ray bursts (GRB) are the brightest objects in the Universe. They are observed once or twice a day, as highly energetic explosions. They are registered as a lower energy gamma-ray bursts, which last typically a few seconds. The distribution of GRBs over the sky is homogeneous. The sources of most GRBs are billions of light years away from the Earth. The energy released during a burst is about 10^51 erg within a few seconds.

It is believed that the central engine of the (long) gamma-ray bursts is a black hole formed by a collapse of a massive rapidly rotating star.

BH Classification

BH as a classical object: $M > 10^{-5}\,g$

Primordial BHs: $M < M_{\odot} = 2\times 10^{33}\,g$

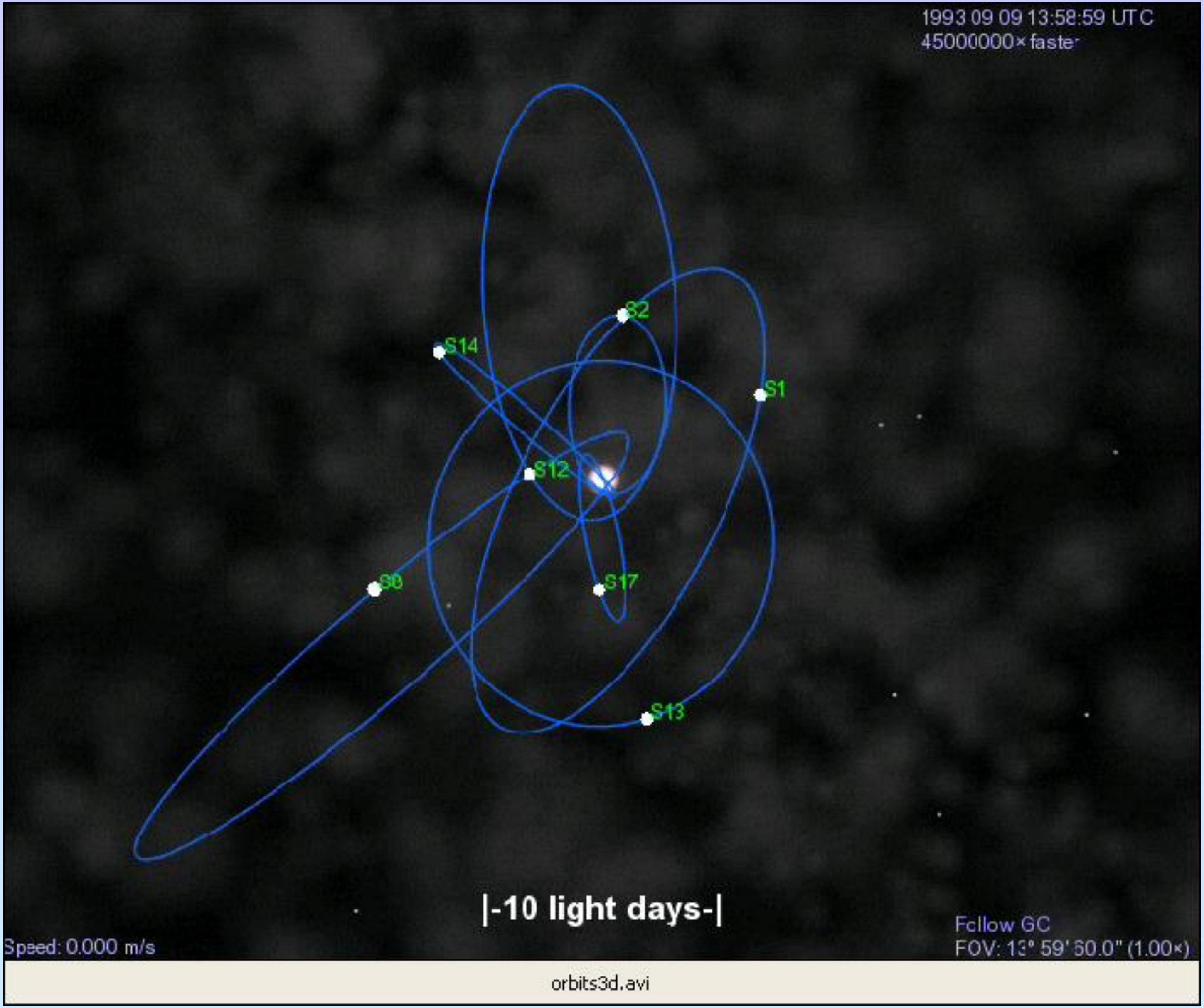
Stellar mass BHs: $M \sim 3M_{\odot} - 100M_{\odot}$

Supermassive BHs: $M \sim 10^{6} - 10^{10}\,M_{\odot}$

Black Hole in Milky Way

The galactic center harbours a compact object of very large mass (named Sagittarius A*), strongly suspected to be a supermassive black hole.

The estimated mass of the central BH is about 4 million solar masses within a volume with radius no larger than 6.25 light-hours (45 AU).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orbits3d.avi

Stars in Keplerian orbits around central black hole

$\Rightarrow$ high-precision measurement of BH mass: $4\times10^6\ M_\odot$

Periastron of closest encounter: $\sim 2000\ r_g$

(star $S2$ has period about 15.2 yrs)

Getting even closer: X-ray & IR flares, some with

periodicity $\sim$ 17min $\Rightarrow$ hot spot in inner disk, at $\sim 10\ r_g$

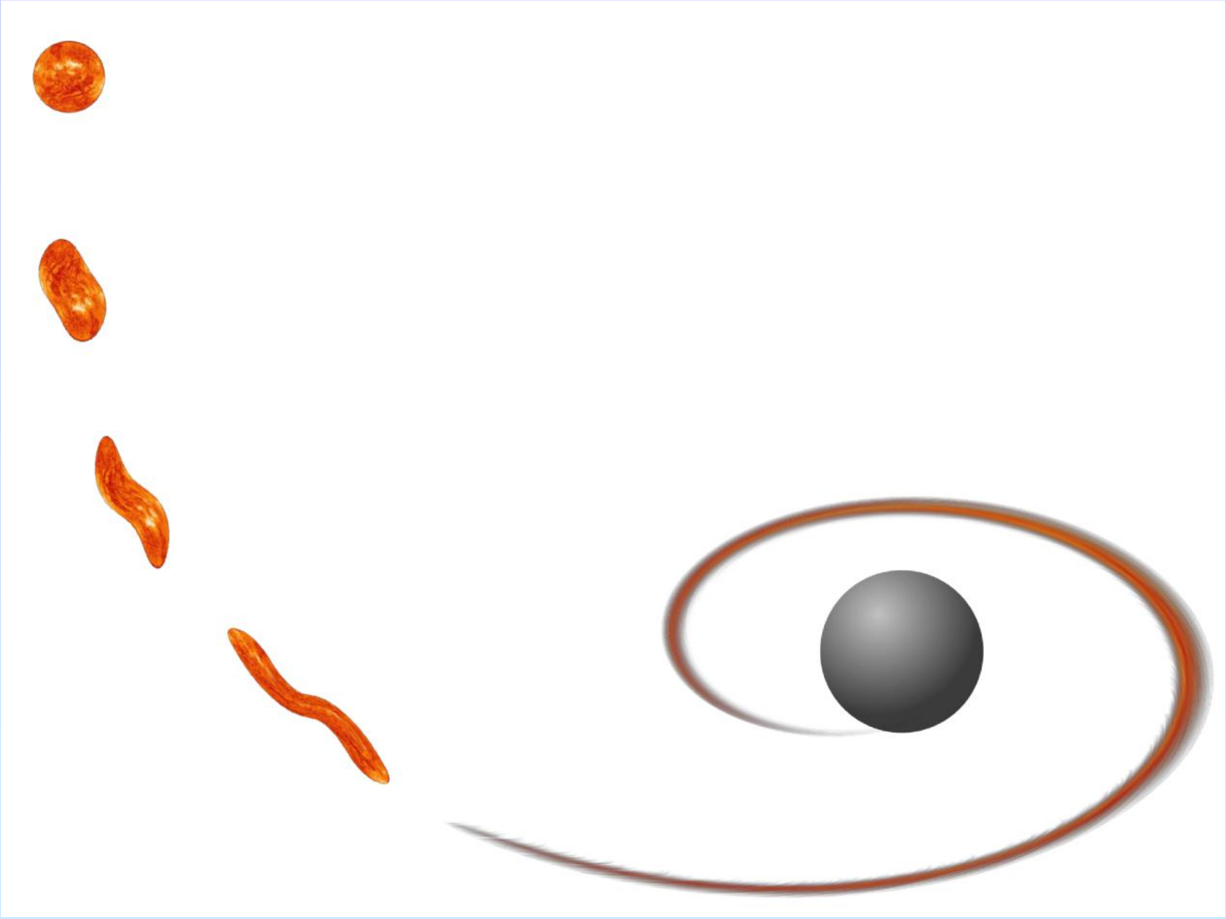
Supermassive Black Holes

"It is likely that a BH exists at the center of every massive galaxy."

From the Summary of the talk by Stefanie Komossa (MPE Garching) at the Black Holes VI meeting at Nova Scotia, Canada, May 2007

However the mechanism of SMBM formation and their role in the galaxies evolution are not clear.

Tidal disruption of a star at close encounter of BH



$$\frac{GMb}{R^3} \sim \frac{Gm}{b^2}$$

$$R \sim \left(\frac{M}{m}\right)^{1/3} b$$

Primordial Black Holes

Many different mechanisms of PBH production in the Early Universe have been discussed:

(i) Initial density fluctuations;
(ii) Soft equation of state during phase transitions;
(iii) Collapse of cosmic strings;
(iv) Bubble collisions.

No evidence of existence of PBHs was found

Black Hole Puzzles

Information Loss Puzzle

$$\begin{pmatrix}\text{Pure}\\ \text{state}\end{pmatrix} \overset{\text{Collapse}}{\Longrightarrow} \begin{pmatrix}\text{Black}\\ \text{hole}\end{pmatrix} \overset{\text{Evaporation}}{\Longrightarrow} \begin{pmatrix}\text{Thermal}\\ \text{radiation}\end{pmatrix}$$

Microscopic Origin of Black Hole Entropy

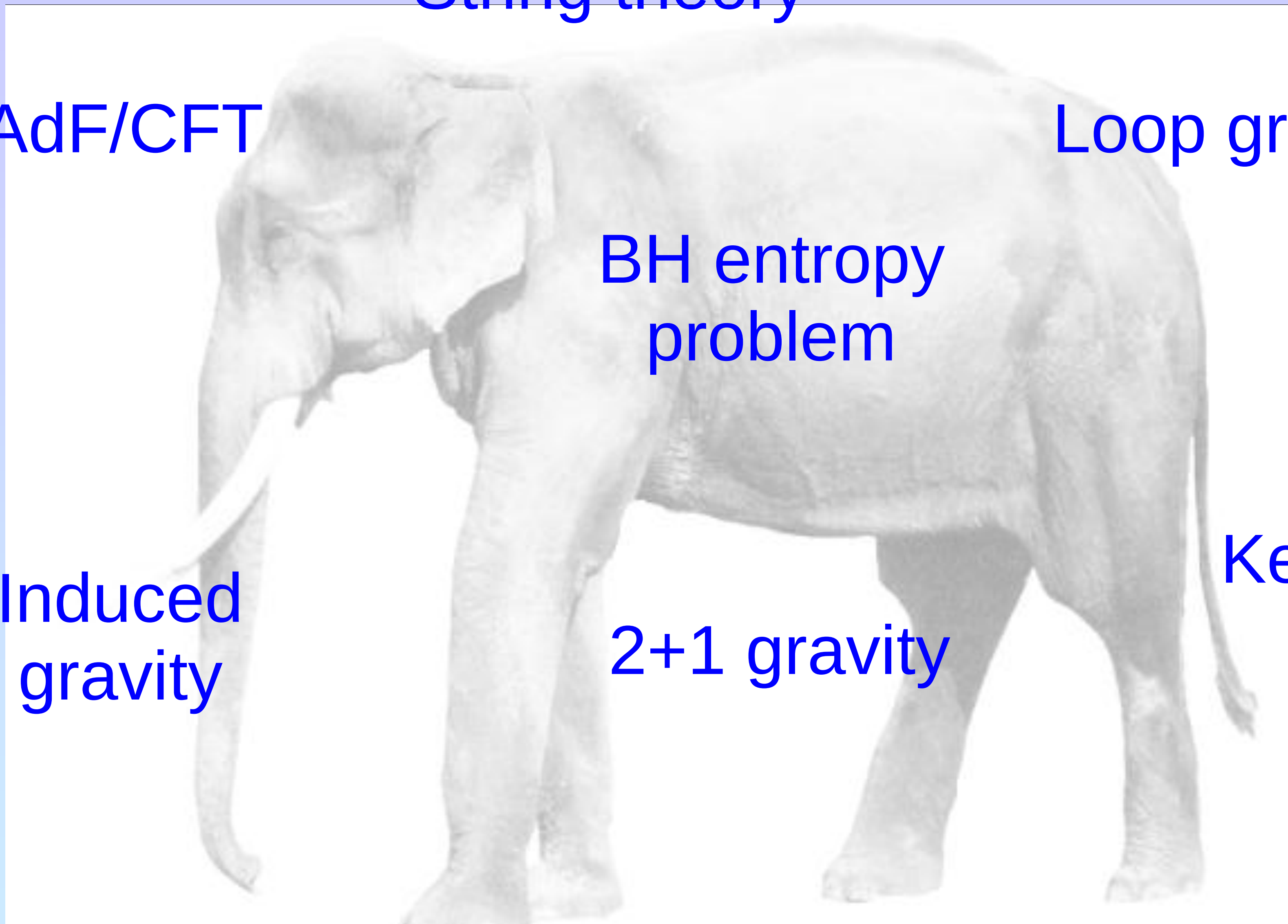
What are microscopical degrees of freedom

responcible for BH entropy $S = \dfrac{A}{4\, l_{Pl}^2}$?

(1) Each $(2l_{Pl})^2$ element of BH surface has 1 bit of entropy $\Rightarrow$ Quantum gravity is required

(2) Universality problem: BH is determined by low energy physics parameters

(3) BH is a ground (vacuum) state of classical gravitational field $\Rightarrow$ gravity should be an emergent phenomenon

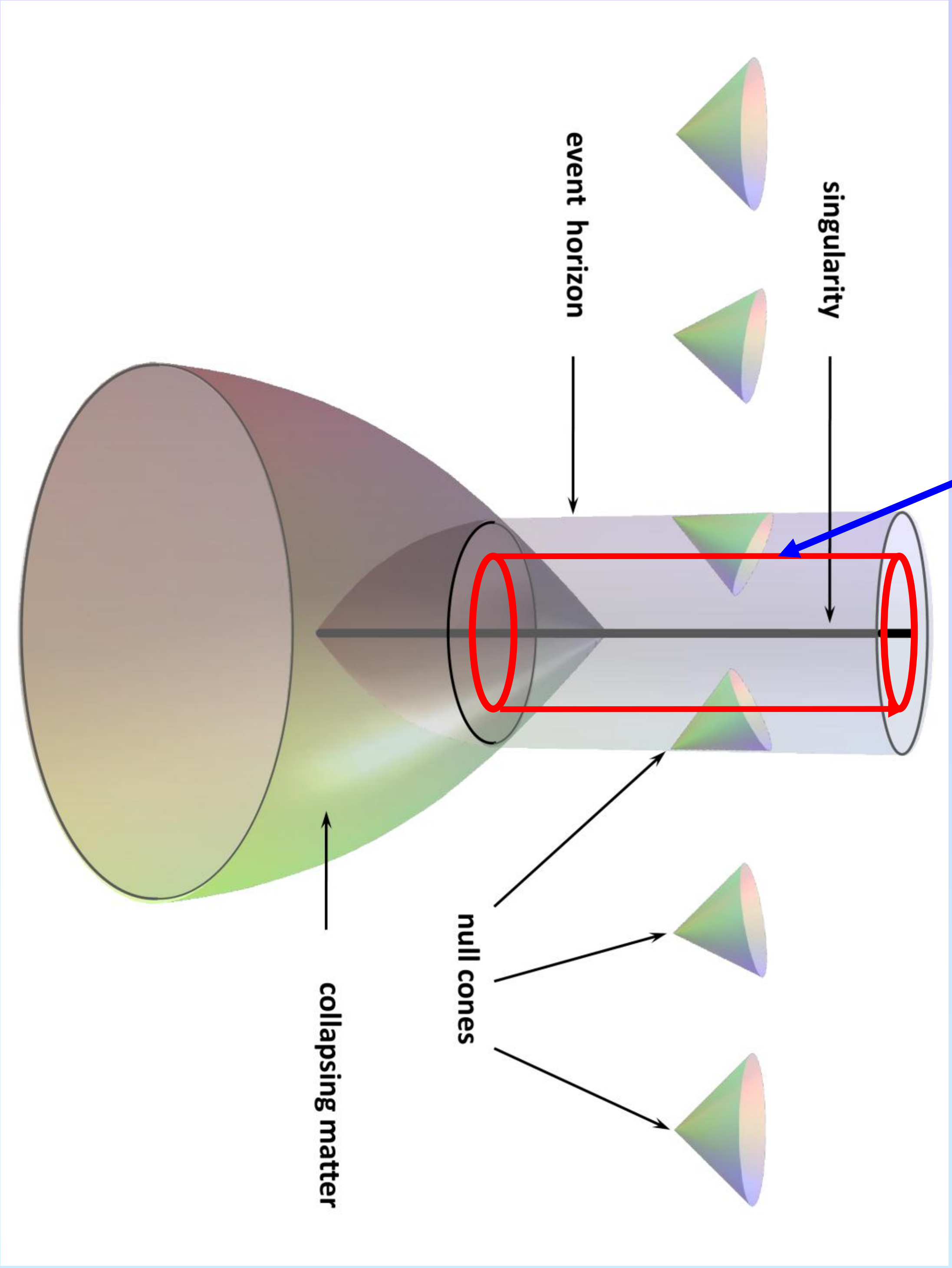

String theory
AdF/CFT
Loop gravity
BH entropy problem
Kerr/CFT
Induced gravity
2+1 gravity

Black Hole Interior Puzzle

Gravitational radius $r_g = \dfrac{2GM}{c^2}$

"The spatial volume inside the black hole is $\sim r_g^3$".

Is this right? No, this is completely wrong!



r plays the role of time inside BH

Slice $r = \text{const}$ has topology $S^2 \times R$

Spatial volume $\sim r_g^2 \times (t/c) >>> r_g^3$

Contracting anisotropic universe

“Through A Black Hole Into A New Universe?”
V.F., Markov, Mukhanov, **Phys.Lett. B216 (1989) 272;**
“Black Holes As Possible Sources Of Closed and Semiclosed Worlds” ,V. F., Markov, Mukhanov, IC/88/91. May 1988. **Phys.Rev. D41 (1990) 383;**
“How many new worlds are inside a black hole?”
Barrabes and V. F. **Phys.Rev. D53 (1996) 3215**

Buonanno, Damour, Veneziano ‘99: “Gravitational instability, leading to the possible formation of many black holes” … each of which becomes the place of “birth of a baby Friedmann universe after a period of dilaton-driven inflation”.

Smolin, ***The Life of the Cosmos*** ‘97: “A collapsing black hole causes the emergence of a new universe on the "other side", whose fundamental constant parameters (speed of light, Planck length and so forth) may differ slightly from those of the universe where the black hole collapsed. Each universe therefore gives rise to as many new universes as it has black holes.”

INSTEAD OF SUMMARY

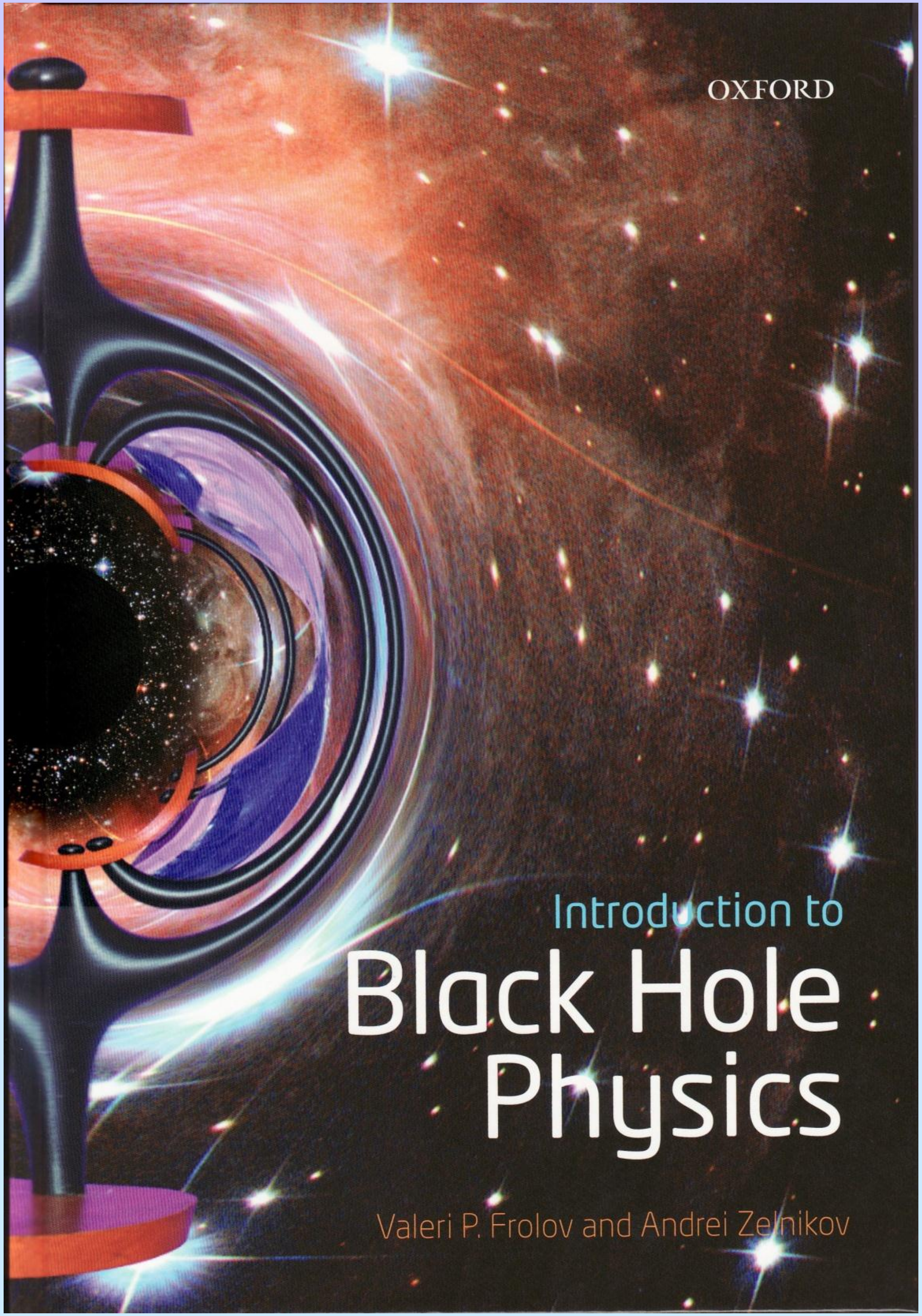
`VERY BIG' PICTURE

Birth: Matter is generated during the inflation. Its large scale structure in our world is a result **vacuum** fluctuations amplification in the early inflating Universe

Life: Supernova explosions -> heavy elements -> planets and life

Death: Black holes are `matter graves' in our Universe

Reincarnation: Black holes as origin of new universes: `Life after death' ????????????



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