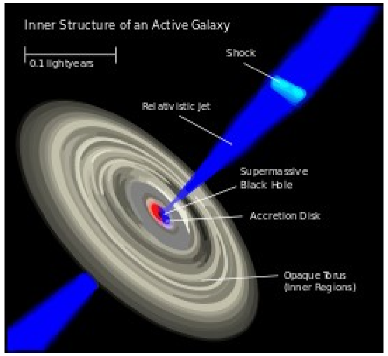

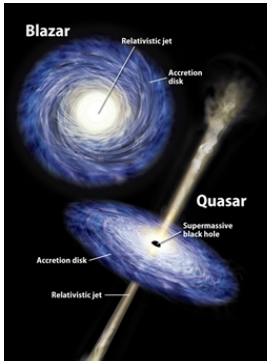

Revising "standard model" of black holes (SMBH)

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and
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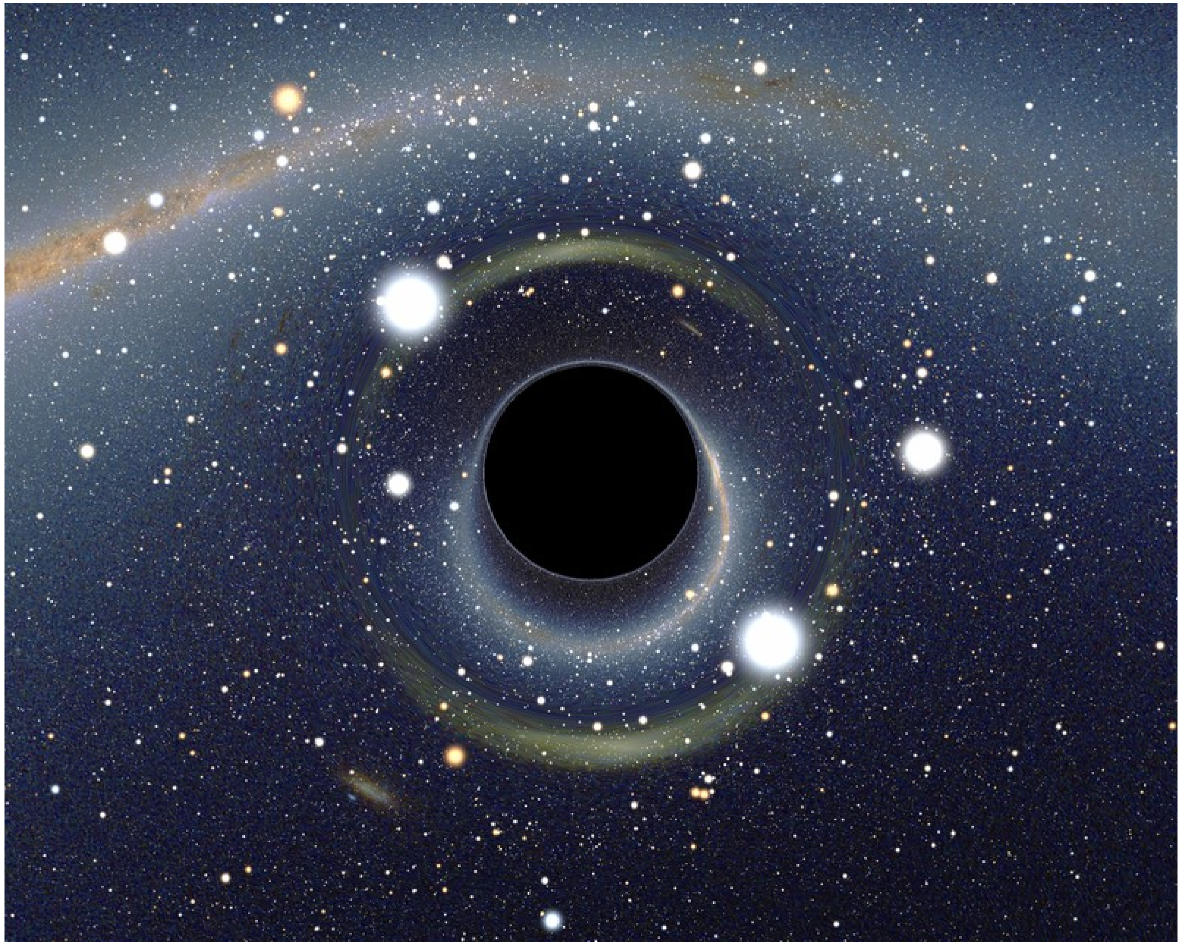
GRACOS 16, Kazan, 5-7 November 2016

Isolated black hole (simulation)



Black hole theory beyond the “Standard model”

Prior to the beginning of the 21st century, stationary black holes were understood to be remarkably simple objects. A number of black hole theorems, including topology, rigidity, nohair, and stability theorems established that black holes are spherical in topology, uniquely specied by asymptotic charges, and stable. Since the corresponding exact and general solutions was already known, (Schwarzchild for vacuum non-rotating, Kerr for rotating, Kerr-Newman for rotating BH with charges) there was little motivation to search for new stationary solutions.

But more recently, anticipation of detection of gravitational waves and imaging of the center of Galaxy, motivations from higher dimensions, development of string theory, holography, or simply a desire to understand general relativity more broadly, have lead to considerations that violate many of the assumptions of these black hole theorems. Consequently, the theory of black holes is now far fuller and richer than previously believed.

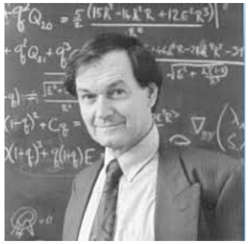
This new development was partly due to development of numerical methods to solve Einstein equations both for stationary, and dynamical situation, including full four-dimensional integration. It was also related to theoretical progress in understanding some long-standing problems such as non-controversial introduction of the graviton mass.

Basic features of SMBH

Cosmic censorsphip (CC) : singularities must be hidden by event horizons

- **No hair, other than monopole gravitational and electromagnetic fields, dipole gravitational field (rotation), with EM multipole structure only that induced by rotation**
- **Event horizon of stationary black hole has spherical topology**
- **Final stationary state of collapsing body is described by Kerr metric**

Kerr BH



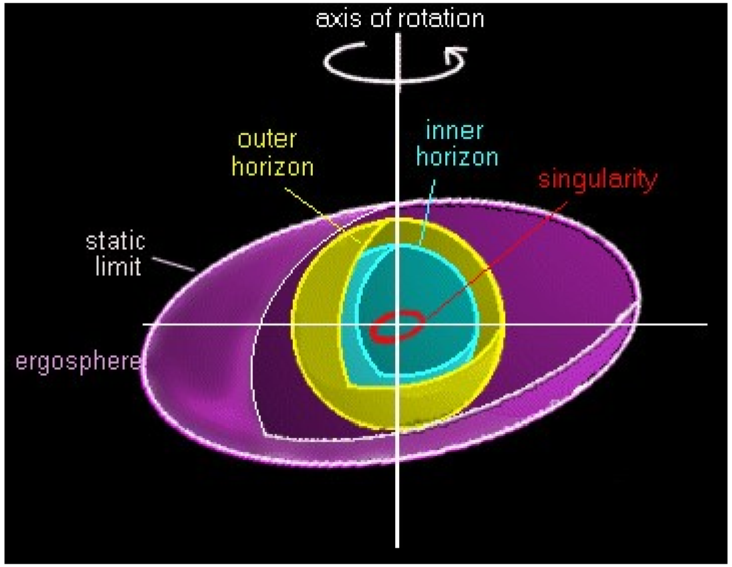
- The pink surface bounds ergosphere:

$$r_{\rm ergo} = M + \sqrt{M^2 - a^2\cos^2\vartheta}$$

- The yellow sphere – the event horizon

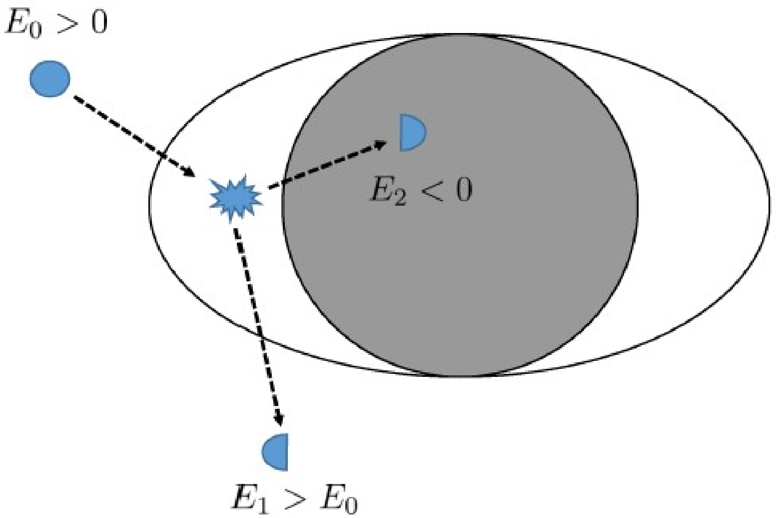
$$r_+ = M + \sqrt{M^2 - a^2}$$

inside of which there is an inner horizon, unstable against matter perturbations. In the ergosphere all bodies must rotate (dragging of inertial frames). Such bodies may enter and leave this region, but they can't leave interior inside yellow surface



- **Penrose process**

Due to rotation, inside the ergosphere particles may have negative energy. If some external particle enters the ergosphere and decays into two particles one of which, carrying negative energy, is absorbed by the black hole, the outgoing particle will have an increased energy. Similarly, certain waves may beam amplified under scattering on Kerr black hole



What can be wrong

- **The uniqueness theorems can be doubted is CC is waved**
- **The no hair statements are violated by expanding assumptions about matter and weakening symmetry assumptions**
- **Topological censorship is violated once asymptotic conditions are modified. In non-stationary situation non-spherical topology is possible**
- **CC remains a hypothesis which is violated in some analytical an numerical collapse models**

GW150914 (simulation)

Binary black holes

- A binary black hole (BBH) is a system consisting of two black holes in close orbit around each other.
- For many years proving the existence of BBHs was made difficult because of the nature of black holes themselves, and the limited means of detection available. However, in the event that a pair of black holes were to merge, an immense amount of energy should be given off as gravitational waves, with distinctive waveforms that were calculated using general relativity.

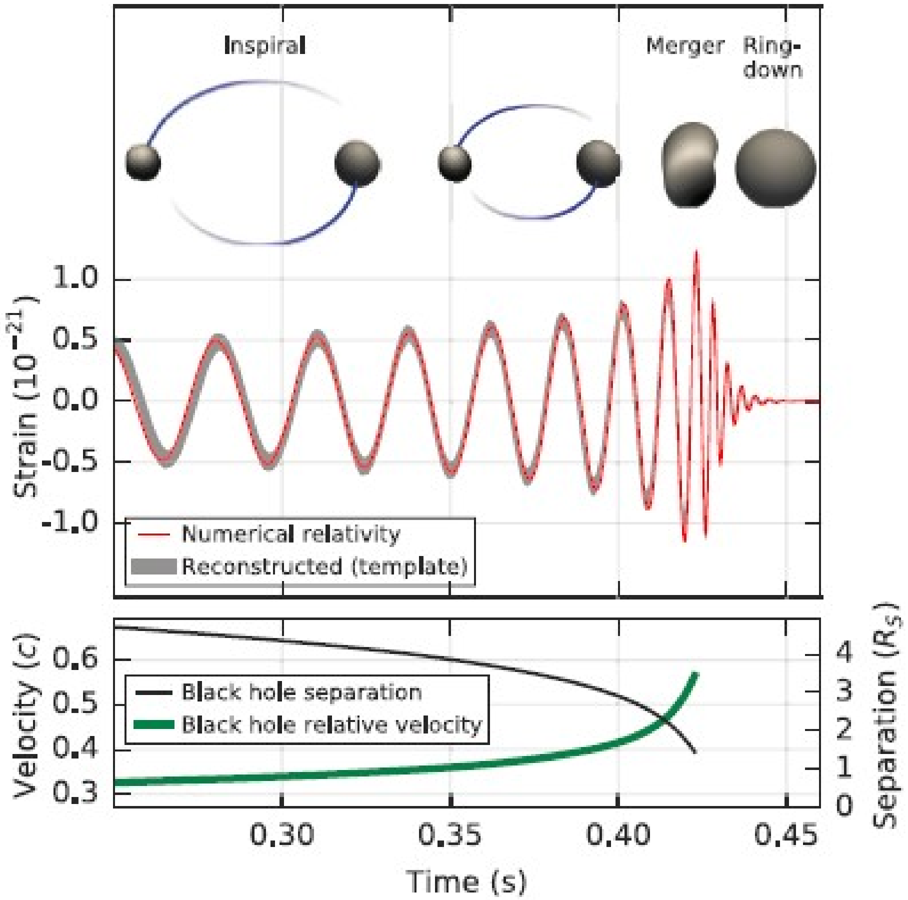
- The existence of stellar-mass binary black holes (and gravitational waves themselves) were finally confirmed when LIGO detected GW150914 (September 2015, announced February 2016), a distinctive gravitational wave signature of two merging black holes of around 30 SM each, occurring about 1.3 billion light years away. In its final moments of spiraling inward and merging, GW150914 released around 3 solar masses as gravitational energy, peaking at a rate of 3.6×10^{49} watts — more than the combined power of all light radiated by all the stars in the observable universe put together

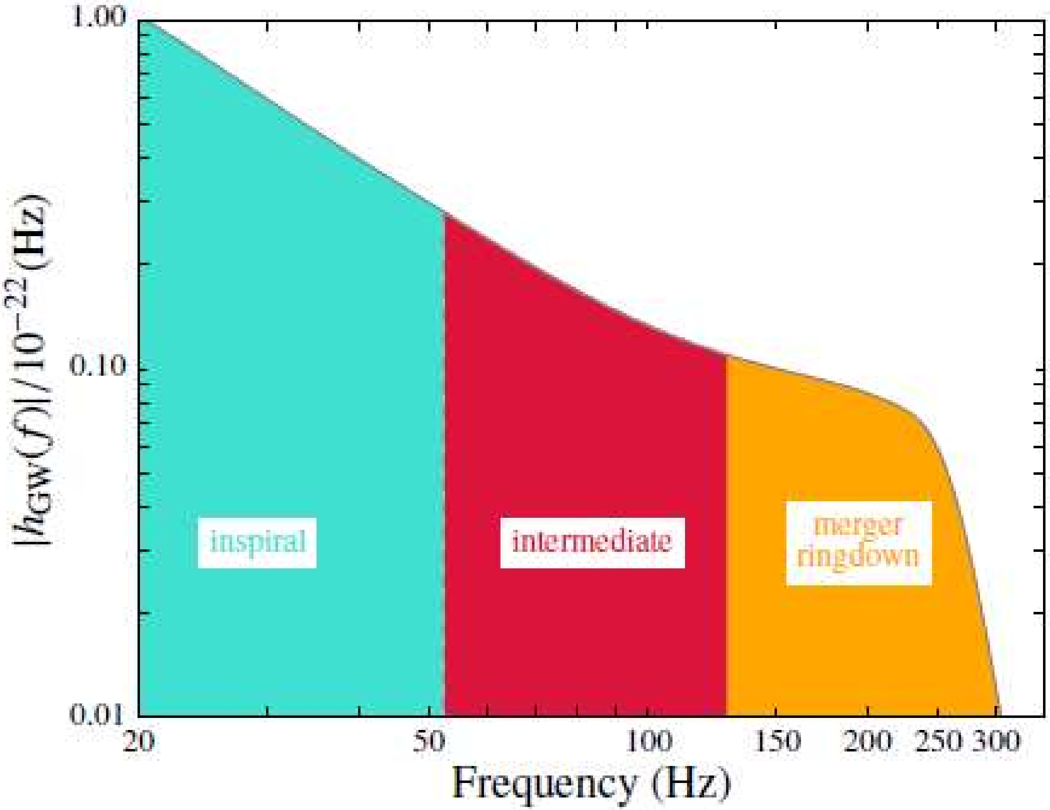
GW150914 (first detection)

Merging of two black holes with masses 36 and 29 SM with formation a of black hole of 62 SM. The distance from the Earth is about 1/30 of the size of the visible universe

The energy equivalent to three solar masses was released in the form of gravitational waves, with power 3.6 · 10^{56} erg/sec in the frequency range 25 – 350 Hz

The second detection was in December 2015: merging of 7.5 an 14 SM with 1 SM released as gravity waves




1.00
0.10
0.01
20
50
100
150
200
250
300
Frequency (Hz)
$|h_{GW}(f)|/10^{-22}$(Hz)
inspiral
intermediate
merger
ringdown

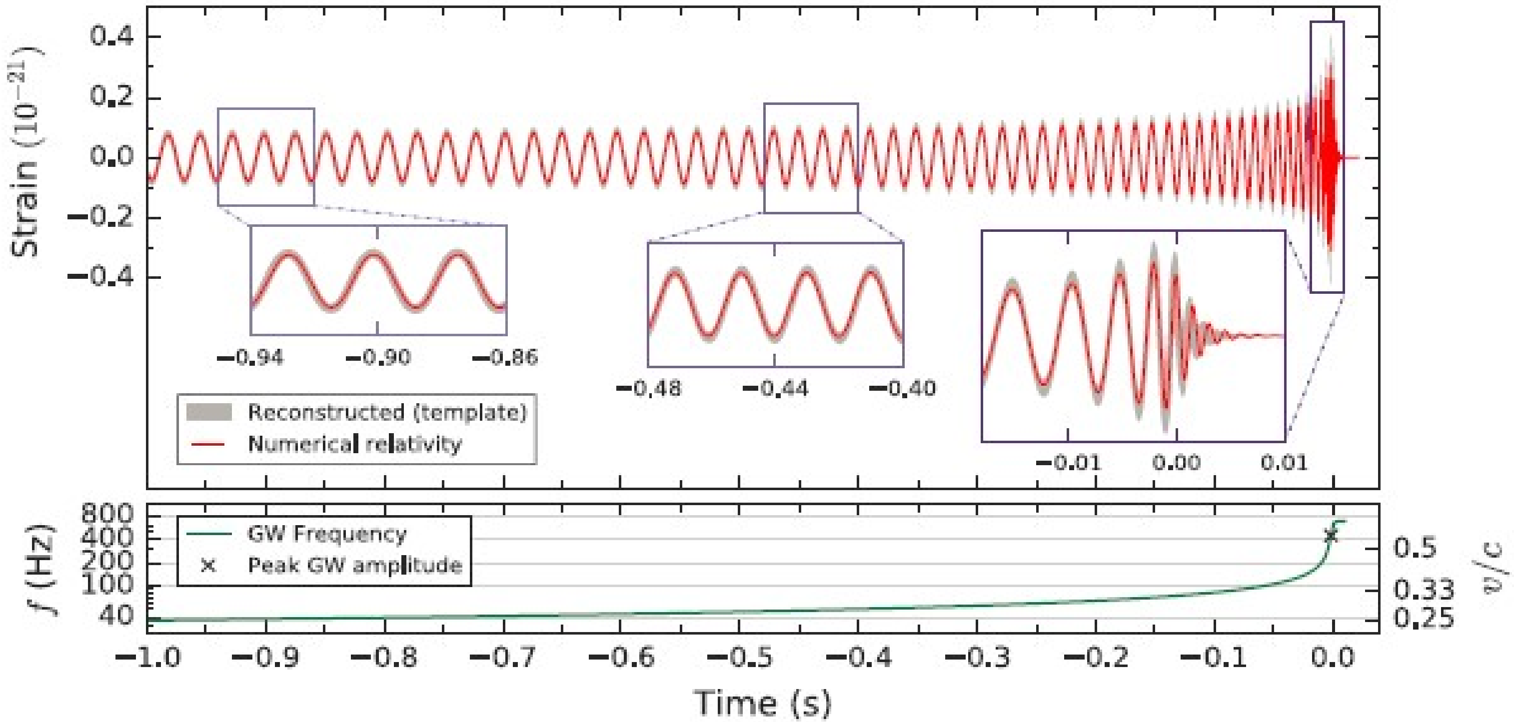
Does BH ringing proves the existence of event horizon?

Determination of parameters became possible via separate analysis of three stages of merging reflected in the frequency spectrum: Kepler rotation, damped inspiral and the final ringdown. Two first are of Newtonian and post-Newtonian nature with account for radiation reaction.

The ringdown stage is most informative about extreme gravity. It is thought to be associated with emergence of the common event horizon. Templates used by LIGO were based on the picture of quasinormal modes (QNM) which are eigenmodes of perturbations of would-be black hole disappearing at the ultimate stage of the merger.

BUT!

This analysis has certain subtleties, however. Recently it was argued (Cardoso et al, Price et al) that QNM spectrum in the high frequency region may be not related to existence of the event horizon but rather appeals to ‘light rings’ (the closed null geodesics) which can exist independently on whether or not there is a horizon. Though the initial explanation remains the most appropriate, the light rings alternative is worth to be kept in mind



Second event observed by LIGO on December 26, 2015. Coalescence of two black holes with masses 14.2 and 7.5 of solar mass, resulting in a black hole of mass 21.8 and rotation parameter 0.74. The distance is estimated as 440 Mps. About one solar mass was transformed into gravitational radiation.

Event horizon telescope

- Direct observation of the event horizon is underway (EH Telescope, BlackHoleCam pprojects)

- By measuring the shadow cast by the event horizon of the black hole in the center of the Milky Way, the project will provide the indisputable proof that black holes exist. The measurements are done by combining several radio-telescopes around the globe in a synchronised network as large as the Earth (the Event Horizon Telescope) to peer into the heart of our own Galaxy, which hosts a mysterious radio source, called Sagittarius A*, and which is considered to be the central supermassive black hole.

- The project aims also at finding new radio pulsars near this black hole, which will allow to measure its physical properties with high accuracy. By combining these measurements with advanced computer simulations of the behaviour of light and matter around black holes, BlackHoleCam will test predictions of different theories of gravity, including Einstein's theory of General Relativity, with unprecedented precision

Singularity theorems by Hawking and Penrose

for a recent review see

M. M. Senovilla and D. Garfinkle, The 1965 Penrose singularity theorem, Class. Quant.Grav. 32 (2015), no. 12, 124008, [arXiv:1410.5226].

these ultimately led to formulation of the Cosmic Censorship conjecture (CCS)

R. Penrose, Gravitational collapse: The role of general relativity, Riv. Nuovo Cim. 1 (1969) 252{276. [Gen. Rel. Grav.34,1141(2002)
S. Hawking and G. Ellis, The Large Scale Structure of Space-Time. Cambridge University Press, Cambridge, 1973.

One of the best books on the black hole theory:

1973, in Black Holes, Les Houches, ed. De Witt and De Witt, Gordon and Breach, New-York.

One of the best papers, which opened many perspectives:

Carter B., 1968, Phys. Rev., 174, 1559.

Black Hole Uniqueness Theorems

This is a broad term that encompasses many theorems about spacetime topology, their symmetries and their asymptotic quantities. Ultimately, these theorems strive to prove the uniqueness of a solution in a given theory.
Naturally, these theorems were first formulated in asymptotically at 4-dimensional Einstein-Maxwell theory.They were subsequently generalized to a number of supergravity
and superstring theory inspired field systems if four and higher dimensions.
Reviews on the four-dimensional uniqueness theorems can be found in

M. Heusler, Black hole uniqueness theorems. Cambridge University Press, 1996.
P. T. Chrusciel, J. L. Costa, and M. Heusler, Stationary Black Holes: Uniqueness and Beyond, Living Rev. Rel. 15 (2012) 7, [arXiv:1205.6112].
D. Robinson, Four decades of black holes uniqueness theorems, in: The Kerr Spacetime: Rotating Black Holes in General Relativity." (Editors: D. L. Wiltshire, M. Visser, S. M. Scott (Cambridge University Press, 2009).).
A. Ionescu and S. Klainerman, Rigidity Results in General Relativity: a Review, arXiv:1501.0158.

These theorems apply to `stationary' solutions, meaning they have a Killing vector field that is timelike everywhere in the asymptotic region. In this case dimensional reduction leads to three-dimensional gravity coupled sigma-model which is simpler for analysis and open different ways to construct exact solution and to prove uniqueness.

Static asymptotically flat black hole with regular horizon must be spherically symmetric and is given by Schwarzschild metric (Israel). It is therefore satisfies Cosmic Censorship conjecture. It is fully characterized by the only parameter –mass Thjs result belongs to Israel, who also generalized it to Reissner-Nordstrom solution of the Einstein-Maxwell system, in which case CCS holds if charge is less than mass in appropriate units

Stationary asymptotically flat regular black hole must be axisymmetric (Hawking’s rigidity theorem) The rigidity theorem guarantees that the black hole is time independent, axisymmetric, and must rotate along an isometry, and hence emits no gravitational radiation.

Hawking's topological theorem constrains the topological properties of black It states that 4-dimensional asymptotically flat stationary black holes obeying the dominant energy condition, must have horizons with spherical topology.

The topological and rigidity theorems are fundamental ingredients for the uniqueness Theorem of Carter-Robinson-Mazur: all regular stationary, asymptotically at (non-) degenerated black holes of the Einstein-Maxwell equations in d = 4 dimensions are uniquely specied by their mass, angular momentum, and electric charge, and have horizon topology S2. The most general solution is the Kerr-Newman family which includes the Kerr Reissner-Nordstrom and Schwarzschild as special cases. This unique spefication is an indication that black holes are featureless, and hence `have no hair'.

Four laws of black hole mechanics

(Bardeen, Carter and Hawking 1972)

Zeroth: **The horizon has constant surface gravity for a stationary black hole. This quantity is analogous to free fall acceleration on the horizon**

First: **The change of the BH mass, angular momentum and area of the horizon are related by** $\delta M = \frac{k}{8\pi}\delta A_H + \Omega_{\rm H}\delta J$ **, where** $\Omega_{\rm H} = a/(2Mr_+)$ **is angular velocity of the horizon**

Second: **The area of the horizon in all interaction of BH with surrounding matter can only increase**

Third: **The state of extremal (M=a) BH can not be reached in a finite sequence of operations**

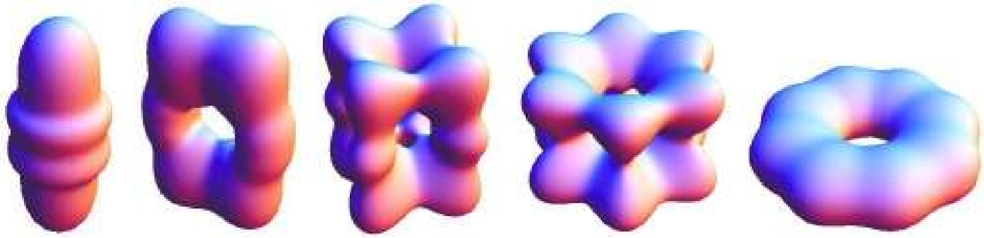
Thermodynamical interpretation: **dE=T dS**

Evading rigidity and topological censorship

Stationary asymptotically AdS black holes with flat and hyperbolic topology of the horizon in the models with negative cosmological constant

In dynamical picture the evolving horizon in d=4 may temporarily exhibit toroidal topology

'Candy' black holes of Einstein-Maxwell-AdS theory (Herdeiro and Radu) with no continuous isometries



Black rings and their decendants in D=5 and higher dimensions

Black holes on the branes in extradimensional scenarios

Yes-hair and non-uniqueness

The original no-hair theorem proves that all black hole solutions of the Einstein-Maxwell equations of gravitation and electromagnetism can be completely characterized by only three externally observable classical parameters: mass, angular momentum and electric charge. All other information (for which "hair" is a metaphor) about the matter which formed a black hole or is falling into it, "disappears" behind the black-hole event horizon and is therefore permanently inaccessible to external observers.

- **However later on it was discovered that in more complicated field theories than Maxwell, black hole with some hair are possible: Einstein-Yang-Mills (**Volkov and Gal'tsov, Gravitating nonAbelian solitons and black holes with Yang-Mills fields, Phys. Rept. 319 (1999) 1 **Einstein-Skyrme** (Bizon…), **more recently – Einstein-complex scalar** (Herdeiro and Radu). **It becomes clear that 'hairy' BH are generic. But unstable! This is so in D=4: in higher dimensions a variety of stable BHs violating uniqueness are found**

- **Moreover, two years ago it was discovered that black holes may carry so-called Bondi-Metzner-Sachs quantum hair, associated with infinite symmetries of the asymptotical metrics. These may be relevant for resolution of the information paradox raised by Hawking: information is lost when matter falls into black hole and is not restored in the thermal evaporation process**

Many other hairy black holes have been constructed with a condensed matter dual interpretation. This area of research is quite broad see reviews :

G. T. Horowitz, Introduction to Holographic Superconductors, Lect. Notes Phys. 828 (2011)

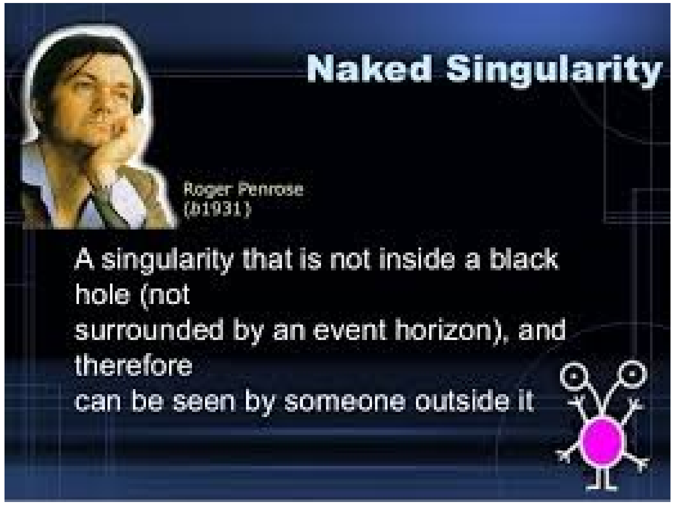
S. A. Hartnoll, Horizons, holography and condensed matter, arXiv:1106.4324

J. McGreevy, Holographic duality with a view toward many-body physics, Adv. High Energy Phys. 2010 (2010) 723105

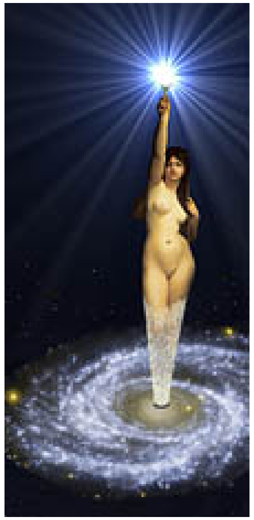
A more subtle way of evading the no-hair theorems is by breaking assumption that the scalar field has the same symmetries as the gravitational field. Indeed, the gravitational field only needs to have the same symmetries as the stress tensor coupled through the Einstein equation, not necessarily the matter fields themselves. A simple example of this is a complex scalar which is neither axisymmetric nor time-independent, but its combination in the stress tensor is. C. Herdeiro, E. Radu Construction and physical properties of Kerr black holes with scalar hair, Class.Quant.Grav. 32 (2015) no.14, 144001

For review of higher D hairy BH see

Ó. J.C. Dias J. E. Santos, B. Way, Numerical Methods for Finding Stationary Gravitational Solutions Class.Quant.Grav. 33 (2016) no.13, 133001



Naked singularities liberated?



Overspinning and overcharged Kerr- Newman --- time-like NC

Fisher-Janis-Newman-Winicour (scalar field) --- null NC (rotating version wrong!)

Gamma-metrics (Zipoy-Voorhees, Tomimatsu-Sato…) --- attractive by simplicity, not confirmed by collapse modeling

Scalar field collapse (Christodoulou '94) --- NC arise for non-generic initial data (unstable ?)

Gravastars and firewalls --- unfavored by LIGO: no afterglows
Imaging of naked singularities is underway

NUT WORMHOLES G.Clement and DG '15

Wormholes are another alternative to BHs. Usually it is associated with exotic matter (quantum). But invoking metric with Newman-Unti-Tambution (NUT) parameter one can construct WHs supprted by Maxwell field. The simplest example is given by supercritically charged black holes with NUT provide a new setting for traversable wormholes. This does not require exotic matter, a price being the Misner string singularities. Without assuming time periodicity to make Misner strings unobservable, one can show that, contrary to expectations, geodesics do not stop there. Moreover, since there is no central singularity the space-time turns out to be geodesically complete.

An unpleasant feature of spacetimes with NUTs is the presence of regions where the azimuthal angle ' becomes timelike, signalling the appearance of closed timelike curves (CTCs). But one can show that among them there are no closed timelike or null geodesics, so the freely falling observers should not encounter causality violations. Considering worldlines of charged particles, we find that, although these can become closed in the vicinity of the wormhole throat for large enough charge-to-mass ratio, the non-causal orbits are still disconnected from the distant zones.

$$ds^2 = -f(dt - 2n(\cos\theta + C)\,d\varphi)^2 + f^{-1}dr^2 + (r^2+n^2)(d\theta^2 + \sin^2\theta d\varphi^2)$$

$$A = \Phi(dt - 2n(\cos\theta + C)\,d\varphi)\,,$$

$$f = \frac{(r-m)^2 + b^2}{r^2+n^2}\,, \quad \Phi = \frac{qr + p(r^2-n^2)/2n}{r^2+n^2}$$

$$(b^2 = q^2 + p^2 - m^2 - n^2)\,.$$

Conclusions and outlook

- **In XX century black holes were thought to be universal physical objects described by restricted class of metrics and having much symmetries. This view was based on certain physical assumptions and particular matter choices, (linear fields) which sometimes were too restrictive.**

- **During past two decades it became clear that relaxing some of these assumptions (non-linear matter fields, adding negative cosmological constant, allowing non-trivially realized symmetries, or no symmetries), one arrives at substantially wider classes of black hole solutions. This is especially true for solutions motivated by holographic applications and higher-dimensional solutions. Various new solutions were found using new numerical codes.**

- **At the same time, it became clear that observations may be compatible with wider classes of metric, non necessarily black holes, so imaging such objects as wormholes and naked singularities became demanded, especially in anticipation of data from the Event Horizon Telescope and new events on gravitational wave detection.**

  Extending classes of admissible metrics for astrophysical modeling appeals to revision of quasinormal modes, accretion disks and other crucial problems of “old” black hole theory to be ready to confront it with future observations.