Black Holes I (136.028)

Daniel Grumiller

Institute for Theoretical Physics
TU Wien

http://quark.itp.tuwien.ac.at/∼grumil/teaching.shtml

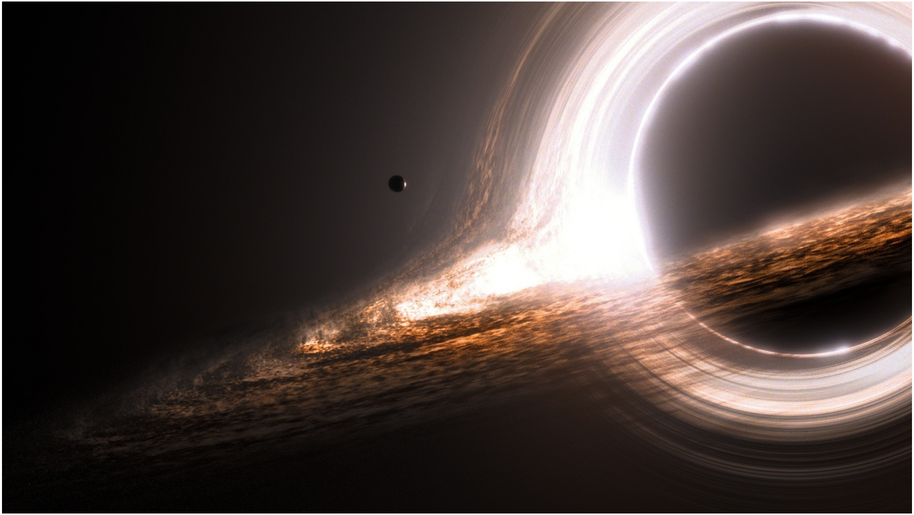
FWF

grumil@hep.itp.tuwien.ac.at

Outline

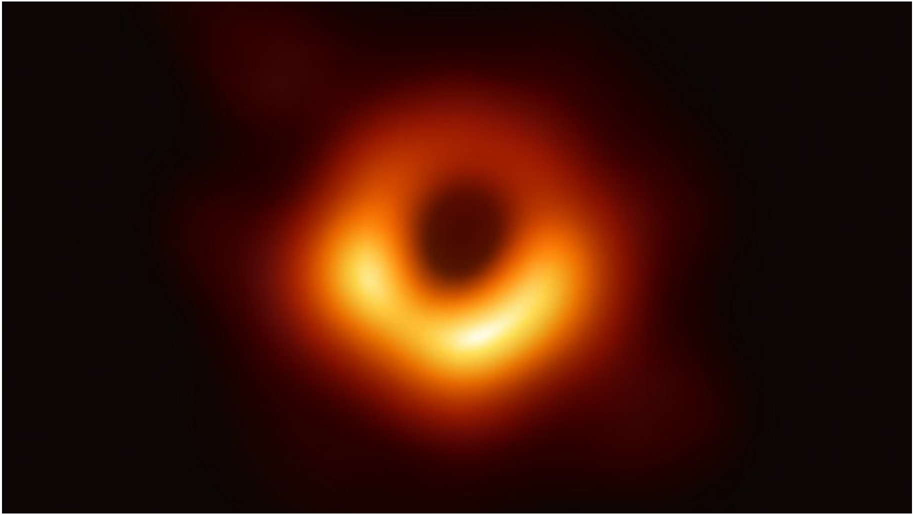
Titelbild 2009-2014 (random webpage)

Titelbild 2015-2018 (James, von Tunzelmann, Franklin and Thorne)



1502.03808 "Gravitational Lensing by Spinning Black Holes in Astrophysics, and in the Movie Interstellar"
1502.03809 "Visualizing Interstellar's Wormhole"

Titelbild seit 2019 (EHT collaboration)



1906.11238 "First M87 Event Horizon Telescope Results. I. The Shadow of the Supermassive Black Hole"

Outline

Overview and goal of lectures

Modus and organizational issues

Literature

History of black holes

Exercises

Why Study Black Holes?

Depending whom you ask you'll hear:

- General Relativist: because they are unavoidable
- Mathematician: because they are interesting
- Science Fiction Writer: because they are cool
- Astrophysicist: because they explain the data
- String Theoretician: because they hold the key to quantum gravity
- Particle Physicist: because they might be produced at LHC
- Cosmologist: because they exist
- Numerical Relativist: because they present challenge for coding skills
- Nuclear Physicist: because they are dual to a strongly coupled plasma
- Condensed Matter Physicist: because we can produce them in the lab
- Gravitational Wave Experimentalist: because we need to understand black holes to provide templates for gravitational wave detection

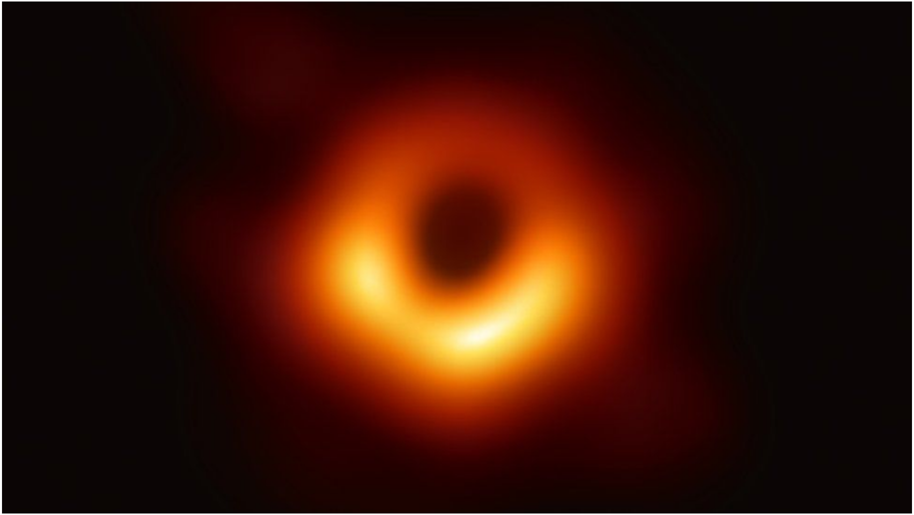
Why Study Black Holes?

Depending whom you ask you'll hear:

- General Relativist: because they are unavoidable
- Mathematician: because they are interesting
- Science Fiction Writer: because they are cool
- Astrophysicist: because they explain the data
- String Theoretician: because they hold the key to quantum gravity
- Particle Physicist: because they might be produced at LHC
- Cosmologist: because they exist
- Numerical Relativist: because they present challenge for coding skills
- Nuclear Physicist: because they are dual to a strongly coupled plasma
- Condensed Matter Physicist: because we can produce them in the lab
- Gravitational Wave Experimentalist: because we need to understand black holes to provide templates for gravitational wave detection

> Perhaps you find your own motivation on this list

Down-to-earth motivation: understand the physics of this...



Black Holes I

Main goal: Introduction to black hole physics

Topics covered in this course:

1. History of black holes

Black Holes I

Main goal: Introduction to black hole physics

Topics covered in this course:

1. History of black holes
2. Phenomenology of and experiments with black holes

Black Holes I

Main goal: Introduction to black hole physics

Topics covered in this course:

1. History of black holes
2. Phenomenology of and experiments with black holes
3. Gravitational collapse and Chandrasekhar limit

Black Holes I

Main goal: Introduction to black hole physics

Topics covered in this course:

1. History of black holes
2. Phenomenology of and experiments with black holes
3. Gravitational collapse and Chandrasekhar limit
4. Metric and geodesic equation

Black Holes I

Main goal: Introduction to black hole physics

Topics covered in this course:

1. History of black holes
2. Phenomenology of and experiments with black holes
3. Gravitational collapse and Chandrasekhar limit
4. Metric and geodesic equation
5. Geodesics for Schwarzschild black holes

Black Holes I

Main goal: Introduction to black hole physics

Topics covered in this course:

1. History of black holes
2. Phenomenology of and experiments with black holes
3. Gravitational collapse and Chandrasekhar limit
4. Metric and geodesic equation
5. Geodesics for Schwarzschild black holes
6. Curvature and basics of differential geometry

Black Holes I

Main goal: Introduction to black hole physics

Topics covered in this course:

1. History of black holes
2. Phenomenology of and experiments with black holes
3. Gravitational collapse and Chandrasekhar limit
4. Metric and geodesic equation
5. Geodesics for Schwarzschild black holes
6. Curvature and basics of differential geometry
7. Hilbert action and Einstein equations

Black Holes I

Main goal: Introduction to black hole physics

Topics covered in this course:

1. History of black holes
2. Phenomenology of and experiments with black holes
3. Gravitational collapse and Chandrasekhar limit
4. Metric and geodesic equation
5. Geodesics for Schwarzschild black holes
6. Curvature and basics of differential geometry
7. Hilbert action and Einstein equations
8. Spherically symmetric black holes and Birkhoff theorem

Black Holes I

Main goal: Introduction to black hole physics

Topics covered in this course:

1. History of black holes
2. Phenomenology of and experiments with black holes
3. Gravitational collapse and Chandrasekhar limit
4. Metric and geodesic equation
5. Geodesics for Schwarzschild black holes
6. Curvature and basics of differential geometry
7. Hilbert action and Einstein equations
8. Spherically symmetric black holes and Birkhoff theorem
9. Rotating black holes: the Kerr solution

Black Holes I

Main goal: Introduction to black hole physics

Topics covered in this course:

1. History of black holes
2. Phenomenology of and experiments with black holes
3. Gravitational collapse and Chandrasekhar limit
4. Metric and geodesic equation
5. Geodesics for Schwarzschild black holes
6. Curvature and basics of differential geometry
7. Hilbert action and Einstein equations
8. Spherically symmetric black holes and Birkhoff theorem
9. Rotating black holes: the Kerr solution
10. Geodesics for Kerr black holes

Black Holes I

Main goal: Introduction to black hole physics

Topics covered in this course:

1. History of black holes
2. Phenomenology of and experiments with black holes
3. Gravitational collapse and Chandrasekhar limit
4. Metric and geodesic equation
5. Geodesics for Schwarzschild black holes
6. Curvature and basics of differential geometry
7. Hilbert action and Einstein equations
8. Spherically symmetric black holes and Birkhoff theorem
9. Rotating black holes: the Kerr solution
10. Geodesics for Kerr black holes
11. Accretion disks and black hole observations

Black Holes I

Main goal: Introduction to black hole physics

Topics covered in this course:

1. History of black holes
2. Phenomenology of and experiments with black holes
3. Gravitational collapse and Chandrasekhar limit
4. Metric and geodesic equation
5. Geodesics for Schwarzschild black holes
6. Curvature and basics of differential geometry
7. Hilbert action and Einstein equations
8. Spherically symmetric black holes and Birkhoff theorem
9. Rotating black holes: the Kerr solution
10. Geodesics for Kerr black holes
11. Accretion disks and black hole observations
12. Black hole analogs in condensed matter physics

Pre-requisites and related lectures this semester

Pre-requisites:

Special relativity!

Pre-requisites and related lectures this semester

Pre-requisites:

Special relativity!

Related lectures this semester:

- VO Einf.i.d. Allgemeine Relativitätstheorie (136.026), Herbert Balasin
- VO Einführung in die Quantenfeldtheorie I (135.817), Anton Rebhan
- VU Geometry, Topology and Physics I (136.007), Harald Skarke
- PA Projektarbeit Black Hole Physics (136.025), with Anton Rebhan
- SE ARGE fundamentale Wechselwirkungen (132.071) with Andreas Ipp and Anton Rebhan

Also: Vienna Theory Lunch Seminar, every Tuesday 12:15, alternating TU and UV (first time: October 8, TU), webpage:
http://www.univie.ac.at/lunch-seminar/
Josef Leutgeb, Susanne Wagner, Jan Lüdtke and Angelika Widl

Pre-requisites and related lectures this semester

Pre-requisites:

Special relativity!

Related lectures this semester:

- VO Einf.i.d. Allgemeine Relativitätstheorie (136.026), Herbert Balasin
- VO Einführung in die Quantenfeldtheorie I (135.817), Anton Rebhan
- VU Geometry, Topology and Physics I (136.007), Harald Skarke
- PA Projektarbeit Black Hole Physics (136.025), with Anton Rebhan
- SE ARGE fundamentale Wechselwirkungen (132.071) with Andreas Ipp and Anton Rebhan
- U. Vienna: gravity, quantum field theory, string theory, supersymmetry and cosmology lectures, seminars and projects by Piotr Chrusciel, Stefan Fredenhagen, Jan Rosseel et al.

Applications of black hole physics

- General relativity (first solution of GR: Schwarzschild!)

Applications of black hole physics

- General relativity (first solution of GR: Schwarzschild!)
- Mathematical physics (causal structure of spacetime)

Applications of black hole physics

- General relativity (first solution of GR: Schwarzschild!)
- Mathematical physics (causal structure of spacetime)
- Astrophysics (the "real" black holes)

Applications of black hole physics

- General relativity (first solution of GR: Schwarzschild!)
- Mathematical physics (causal structure of spacetime)
- Astrophysics (the "real" black holes)
- Cosmology (primordial black holes; final fate)

Applications of black hole physics

- General relativity (first solution of GR: Schwarzschild!)
- Mathematical physics (causal structure of spacetime)
- Astrophysics (the "real" black holes)
- Cosmology (primordial black holes; final fate)
- Condensed matter physics (black hole analogs)

Applications of black hole physics

- General relativity (first solution of GR: Schwarzschild!)
- Mathematical physics (causal structure of spacetime)
- Astrophysics (the "real" black holes)
- Cosmology (primordial black holes; final fate)
- Condensed matter physics (black hole analogs)
- String theory (quantum gravity)

Applications of black hole physics

- General relativity (first solution of GR: Schwarzschild!)
- Mathematical physics (causal structure of spacetime)
- Astrophysics (the “real” black holes)
- Cosmology (primordial black holes; final fate)
- Condensed matter physics (black hole analogs)
- String theory (quantum gravity)
- String theory (AdS/CFT)

Applications of black hole physics

- General relativity (first solution of GR: Schwarzschild!)
- Mathematical physics (causal structure of spacetime)
- Astrophysics (the “real” black holes)
- Cosmology (primordial black holes; final fate)
- Condensed matter physics (black hole analogs)
- String theory (quantum gravity)
- String theory (AdS/CFT)
- Numerical relativity (black hole collisions, gravitational waves)

Applications of black hole physics

- General relativity (first solution of GR: Schwarzschild!)
- Mathematical physics (causal structure of spacetime)
- Astrophysics (the “real” black holes)
- Cosmology (primordial black holes; final fate)
- Condensed matter physics (black hole analogs)
- String theory (quantum gravity)
- String theory (AdS/CFT)
- Numerical relativity (black hole collisions, gravitational waves)
- Gravitational wave observations (LIGO detection of black hole mergers, future: LISA)

Applications of black hole physics

- General relativity (first solution of GR: Schwarzschild!)
- Mathematical physics (causal structure of spacetime)
- Astrophysics (the "real" black holes)
- Cosmology (primordial black holes; final fate)
- Condensed matter physics (black hole analogs)
- String theory (quantum gravity)
- String theory (AdS/CFT)
- Numerical relativity (black hole collisions, gravitational waves)
- Gravitational wave observations (LIGO detection of black hole mergers, future: LISA)
- Quantum chromodynamics? (heavy ion collisions at RHIC exploiting AdS/CFT correspondence)

Applications of black hole physics

- General relativity (first solution of GR: Schwarzschild!)
- Mathematical physics (causal structure of spacetime)
- Astrophysics (the “real” black holes)
- Cosmology (primordial black holes; final fate)
- Condensed matter physics (black hole analogs)
- String theory (quantum gravity)
- String theory (AdS/CFT)
- Numerical relativity (black hole collisions, gravitational waves)
- Gravitational wave observations (LIGO detection of black hole mergers, future: LISA)
- Quantum chromodynamics? (heavy ion collisions at RHIC exploiting AdS/CFT correspondence)
- Particle physics??? (spectacular but unlikely)

Black holes at forefront of current theoretical, experimental and numerical research

Outline

Where, when, how?

- Each Tuesday, 9:00am-12:00am (exceptions will be announced; need only 2 hours; discuss precise start), SEM 3rd floor yellow (here)

Where, when, how?

- Each Tuesday, 9:00am-12:00am (exceptions will be announced; need only 2 hours; discuss precise start), SEM 3rd floor yellow (here)
- Next three lectures: Oct. 22, Nov. 5, Nov. 12

Where, when, how?

- Each Tuesday, 9:00am-12:00am (exceptions will be announced; need only 2 hours; discuss precise start), SEM 3rd floor yellow (here)
- Next three lectures: Oct. 22, Nov. 5, Nov. 12
- about 1.5 hours lecture + time for discussion of exercises + 5 minutes break

Where, when, how?

- Each Tuesday, 9:00am-12:00am (exceptions will be announced; need only 2 hours; discuss precise start), SEM 3rd floor yellow (here)
- Next three lectures: Oct. 22, Nov. 5, Nov. 12
- about 1.5 hours lecture + time for discussion of exercises + 5 minutes break
- 3.0 ECTS, Wahlfachkataloge A (Theoretische und Mathematische Physik) & B (Atomare und Subatomare Physik)

Where, when, how?

- Each Tuesday, 9:00am-12:00am (exceptions will be announced; need only 2 hours; discuss precise start), SEM 3rd floor yellow (here)
- Next three lectures: Oct. 22, Nov. 5, Nov. 12
- about 1.5 hours lecture + time for discussion of exercises + 5 minutes break
- 3.0 ECTS, Wahlfachkataloge A (Theoretische und Mathematische Physik) & B (Atomare und Subatomare Physik)
- Credits: by completing at least 66% of the exercises or by oral exam

Where, when, how?

- Each Tuesday, 9:00am-12:00am (exceptions will be announced; need only 2 hours; discuss precise start), SEM 3rd floor yellow (here)
- Next three lectures: Oct. 22, Nov. 5, Nov. 12
- about 1.5 hours lecture + time for discussion of exercises + 5 minutes break
- 3.0 ECTS, Wahlfachkataloge A (Theoretische und Mathematische Physik) & B (Atomare und Subatomare Physik)
- Credits: by completing at least 66% of the exercises or by oral exam
- Optional: oral exam for better grade or if you have questions

Where, when, how?

- Each Tuesday, 9:00am-12:00am (exceptions will be announced; need only 2 hours; discuss precise start), SEM 3rd floor yellow (here)
- Next three lectures: Oct. 22, Nov. 5, Nov. 12
- about 1.5 hours lecture + time for discussion of exercises + 5 minutes break
- 3.0 ECTS, Wahlfachkataloge A (Theoretische und Mathematische Physik) & B (Atomare und Subatomare Physik)
- Credits: by completing at least 66% of the exercises or by oral exam
- Optional: oral exam for better grade or if you have questions
- Outlook: Black Holes II in Summer semester

Where, when, how?

- Each Tuesday, 9:00am-12:00am (exceptions will be announced; need only 2 hours; discuss precise start), SEM 3rd floor yellow (here)
- Next three lectures: Oct. 22, Nov. 5, Nov. 12
- about 1.5 hours lecture + time for discussion of exercises + 5 minutes break
- 3.0 ECTS, Wahlfachkataloge A (Theoretische und Mathematische Physik) & B (Atomare und Subatomare Physik)
- Credits: by completing at least 66% of the exercises or by oral exam
- Optional: oral exam for better grade or if you have questions
- Outlook: Black Holes II in Summer semester
- Further outlook: Projektarbeit Black Hole Physics, Master, PhD

Where, when, how?

- Each Tuesday, 9:00am-12:00am (exceptions will be announced; need only 2 hours; discuss precise start), SEM 3rd floor yellow (here)
- Next three lectures: Oct. 22, Nov. 5, Nov. 12
- about 1.5 hours lecture + time for discussion of exercises + 5 minutes break
- 3.0 ECTS, Wahlfachkataloge A (Theoretische und Mathematische Physik) & B (Atomare und Subatomare Physik)
- Credits: by completing at least 66% of the exercises or by oral exam
- Optional: oral exam for better grade or if you have questions
- Outlook: Black Holes II in Summer semester
- Further outlook: Projektarbeit Black Hole Physics, Master, PhD

Please slow me down or speed me up with questions/comments!

Outline

Webpages and popular material

- Wikipedia en.wikipedia.org/wiki/Black_hole
- Black Holes: Gravity's Relentless Pull hubblesite.org/explore_astronomy/black_holes/
- All About Black Holes www.space.com/blackholes/
- Virtual Trips to Black Holes and Neutron Stars antwrp.gsfc.nasa.gov/htmltest/rjn_bht.html
- Many artistic pictures: just google images "black holes"
- Black Holes and Time Warps: Einstein's Outrageous Legacy (K.S. Thorne, 1994, W.W. Norton, New York)
- Black Hole Physics: Basic Concepts and New Developments (V.P. Frolov and I.D. Novikov, 1998, Springer, New York)
- Gravity's Fatal Attraction: Black Holes in the Universe (M. Begelmann and M. Rees, 1995, Scientific American Library, New York)
- Was Einstein Right? Putting General Relativity to the Test (C.M. Will, 1993, BasicBooks, New York)

Textbooks and Lecture Notes

- Einstein gravity in a nutshell, (A. Zee, 2013, Princeton U. Press)
- Spacetime and Geometry: An Introduction to General Relativity, (S. Carroll, 2003, Addison Wesley)
- Notes on Relativity and Cosmology, (D. Marolf, http://www.physics.ucsb.edu/∼marolf/MasterNotes.pdf)
- Gravitation und Kosmologie, (R.U. Sexl and H.K. Urbantke, 1987, Wissenschaftsverlag, Mannheim/Wien/Zürich)
- General Relativity, (R. Wald, 1984, U. Chicago Press, Chicago)
- Gravitation, (C. Misner, K.S. Thorne and J.A. Wheeler, 1973)
- Gravitation and Cosmology: Principles and Applications of the General Theory of Relativity (S. Weinberg, 1972, John Wiley)
- The large scale structure of space-time, (S.W. Hawking and G.F.R. Ellis, 1973, Cambridge University Press, Cambridge)
- Accretion Power in Astrophysics (J. Frank, A. King and D. Raine, 2002, Cambridge University Press, Cambridge)
- Active galactic nuclei: from the central black hole to the galactic environment (J. Krolik, 1998, Princeton University Press, Princeton)

Outline

Black Holes: A Brief History of Quotes

- J. Michell (1783): "... all light emitted from such a body would be made to return towards it by its own proper gravity."

- J. Michell (1783): "... all light emitted from such a body would be made to return towards it by its own proper gravity."
- A. Eddington (1935): "I think there should be a law of Nature to prevent a star from behaving in this absurd way!"

Black Holes: A Brief History of Quotes

- J. Michell (1783): "... all light emitted from such a body would be made to return towards it by its own proper gravity."
- A. Eddington (1935): "I think there should be a law of Nature to prevent a star from behaving in this absurd way!"
- S. Hawking (1975): "If Black Holes do exist Kip (Thorne) will get one year of Penthouse."

Black Holes: A Brief History of Quotes

- J. Michell (1783): "... all light emitted from such a body would be made to return towards it by its own proper gravity."
- A. Eddington (1935): "I think there should be a law of Nature to prevent a star from behaving in this absurd way!"
- S. Hawking (1975): "If Black Holes do exist Kip (Thorne) will get one year of Penthouse."
- M. Veltman (1994): "Black holes are probably nothing else but commercially viable figments of the imagination."

Black Holes: A Brief History of Quotes

- J. Michell (1783): "... all light emitted from such a body would be made to return towards it by its own proper gravity."
- A. Eddington (1935): "I think there should be a law of Nature to prevent a star from behaving in this absurd way!"
- S. Hawking (1975): "If Black Holes do exist Kip (Thorne) will get one year of Penthouse."
- M. Veltman (1994): "Black holes are probably nothing else but commercially viable figments of the imagination."
- G. 't Hooft (2004): "It is however easy to see that such a position is untenable. *(comment on Veltman)*"

Black Holes: A Brief History of Quotes

- J. Michell (1783): "... all light emitted from such a body would be made to return towards it by its own proper gravity."
- A. Eddington (1935): "I think there should be a law of Nature to prevent a star from behaving in this absurd way!"
- S. Hawking (1975): "If Black Holes do exist Kip (Thorne) will get one year of Penthouse."
- M. Veltman (1994): "Black holes are probably nothing else but commercially viable figments of the imagination."
- G. 't Hooft (2004): "It is however easy to see that such a position is untenable. *(comment on Veltman)*"
- S. Hughes (2008): "Unambiguous observational evidence for the existence of black holes has not yet been established."

Black Holes: A Brief History of Quotes

- J. Michell (1783): "… all light emitted from such a body would be made to return towards it by its own proper gravity."
- A. Eddington (1935): "I think there should be a law of Nature to prevent a star from behaving in this absurd way!"
- S. Hawking (1975): "If Black Holes do exist Kip (Thorne) will get one year of Penthouse."
- M. Veltman (1994): "Black holes are probably nothing else but commercially viable figments of the imagination."
- G. 't Hooft (2004): "It is however easy to see that such a position is untenable. *(comment on Veltman)*"
- S. Hughes (2008): "Unambiguous observational evidence for the existence of black holes has not yet been established."
- K. Thorne (2015): "With this discovery, we humans are embarking on a marvelous new quest. … Colliding black holes and gravitational waves are our first beautiful examples."

Black Holes: A Brief History of Quotes

- J. Michell (1783): "... all light emitted from such a body would be made to return towards it by its own proper gravity."
- A. Eddington (1935): "I think there should be a law of Nature to prevent a star from behaving in this absurd way!"
- S. Hawking (1975): "If Black Holes do exist Kip (Thorne) will get one year of Penthouse."
- M. Veltman (1994): "Black holes are probably nothing else but commercially viable figments of the imagination."
- G. 't Hooft (2004): "It is however easy to see that such a position is untenable. *(comment on Veltman)*"
- S. Hughes (2008): "Unambiguous observational evidence for the existence of black holes has not yet been established."
- K. Thorne (2015): "With this discovery, we humans are embarking on a marvelous new quest. ... Colliding black holes and gravitational waves are our first beautiful examples."
- S. Doeleman (2019): "We have taken the first picture of a black hole."

Milestones in Pre-History

- O.C. Rømer (1676): speed of light finite

Milestones in Pre-History

- O.C. Rømer (1676): speed of light finite
- I. Newton (1686): gravity law

$$F_r = -G_{\text{N}}\,\frac{mM}{r^2}$$

Milestones in Pre-History

- O.C. Rømer (1676): speed of light finite
- I. Newton (1686): gravity law

$$F_r = -G_{\mathrm{N}}\,\frac{mM}{r^2}$$

- J. Michell (1783): "all light emitted from such a body would be made to return towards it by its own proper gravity"

Milestones in Pre-History

- O.C. Rømer (1676): speed of light finite
- I. Newton (1686): gravity law

$$F_r = -G_{\mathrm{N}} \frac{mM}{r^2}$$

- J. Michell (1783): "all light emitted from such a body would be made to return towards it by its own proper gravity"
- P.S. Laplace (1796): Exposition du systéme du Monde ("dark stars")

Milestones in Pre-History

- O.C. Rømer (1676): speed of light finite
- I. Newton (1686): gravity law

$$F_r = -G_{\mathrm{N}}\,\frac{mM}{r^2}$$

- J. Michell (1783): "all light emitted from such a body would be made to return towards it by its own proper gravity"
- P.S. Laplace (1796): Exposition du systéme du Monde ("dark stars")
- T. Young (1801): interference experiments confirm Huygen's theory of the wave nature of light; Newton's theory of light is dead, and so are dark stars

Milestones in Pre-History

- O.C. Rømer (1676): speed of light finite
- I. Newton (1686): gravity law

$$F_r = -G_{\mathrm{N}}\,\frac{mM}{r^2}$$

- J. Michell (1783): "all light emitted from such a body would be made to return towards it by its own proper gravity"
- P.S. Laplace (1796): Exposition du systéme du Monde ("dark stars")
- T. Young (1801): interference experiments confirm Huygen's theory of the wave nature of light; Newton's theory of light is dead, and so are dark stars
- A. Einstein (1905): Special relativity

Milestones in Pre-History

- O.C. Rømer (1676): speed of light finite
- I. Newton (1686): gravity law

$$F_r = -G_{\mathrm{N}}\,\frac{mM}{r^2}$$

- J. Michell (1783): "all light emitted from such a body would be made to return towards it by its own proper gravity"
- P.S. Laplace (1796): Exposition du systéme du Monde ("dark stars")
- T. Young (1801): interference experiments confirm Huygen's theory of the wave nature of light; Newton's theory of light is dead, and so are dark stars
- A. Einstein (1905): Special relativity
- A. Einstein (1915): General relativity (GR)

Milestones in Pre-History

- O.C. Rømer (1676): speed of light finite
- I. Newton (1686): gravity law

$$F_r = -G_{\rm N}\,\frac{mM}{r^2}$$

- J. Michell (1783): "all light emitted from such a body would be made to return towards it by its own proper gravity"
- P.S. Laplace (1796): Exposition du systéme du Monde ("dark stars")
- T. Young (1801): interference experiments confirm Huygen's theory of the wave nature of light; Newton's theory of light is dead, and so are dark stars
- A. Einstein (1905): Special relativity
- A. Einstein (1915): General relativity (GR)
- K. Schwarzschild (1916): First exact solution of GR is a black hole!

Milestones in Pre-History

- O.C. Rømer (1676): speed of light finite
- I. Newton (1686): gravity law

$$F_r = -G_{\rm N}\,\frac{mM}{r^2}$$

- J. Michell (1783): "all light emitted from such a body would be made to return towards it by its own proper gravity"
- P.S. Laplace (1796): Exposition du systéme du Monde ("dark stars")
- T. Young (1801): interference experiments confirm Huygen's theory of the wave nature of light; Newton's theory of light is dead, and so are dark stars
- A. Einstein (1905): Special relativity
- A. Einstein (1915): General relativity (GR)
- K. Schwarzschild (1916): First exact solution of GR is a black hole!
- S. Chandrasekhar (1931): Gravitational collapse of Fermi gas

Milestones in Pre-History

- O.C. Rømer (1676): speed of light finite
- I. Newton (1686): gravity law

$$F_r = -G_{\mathrm{N}} \frac{mM}{r^2}$$

- J. Michell (1783): "all light emitted from such a body would be made to return towards it by its own proper gravity"
- P.S. Laplace (1796): Exposition du systéme du Monde ("dark stars")
- T. Young (1801): interference experiments confirm Huygen's theory of the wave nature of light; Newton's theory of light is dead, and so are dark stars
- A. Einstein (1905): Special relativity
- A. Einstein (1915): General relativity (GR)
- K. Schwarzschild (1916): First exact solution of GR is a black hole!
- S. Chandrasekhar (1931): Gravitational collapse of Fermi gas
- M. Kruskal; G. Szekeres (1960): Global structure of Schwarzschild

Milestones in the Classic Era

- R. Kerr (1963): Exact (and essentially unique) rotating (and charged) black hole solution sparks interest of astrophysics community

Milestones in the Classic Era

- R. Kerr (1963): Exact (and essentially unique) rotating (and charged) black hole solution sparks interest of astrophysics community
- Cygnus X-1 (1964): first detection of X-ray emission from a black hole in a binary system (though realized only in 1970ies that it might be black hole; conclusive evidence only in 1990ies)

Milestones in the Classic Era

- R. Kerr (1963): Exact (and essentially unique) rotating (and charged) black hole solution sparks interest of astrophysics community
- Cygnus X-1 (1964): first detection of X-ray emission from a black hole in a binary system (though realized only in 1970ies that it might be black hole; conclusive evidence only in 1990ies)
- J. Wheeler (December 1967): Invention of the term "Black Hole"

Milestones in the Classic Era

- R. Kerr (1963): Exact (and essentially unique) rotating (and charged) black hole solution sparks interest of astrophysics community
- Cygnus X-1 (1964): first detection of X-ray emission from a black hole in a binary system (though realized only in 1970ies that it might be black hole; conclusive evidence only in 1990ies)
- J. Wheeler (December 1967): Invention of the term "Black Hole"
- S. Hawking and R. Penrose (1970): Black holes contain singularities

Milestones in the Classic Era

- R. Kerr (1963): Exact (and essentially unique) rotating (and charged) black hole solution sparks interest of astrophysics community
- Cygnus X-1 (1964): first detection of X-ray emission from a black hole in a binary system (though realized only in 1970ies that it might be black hole; conclusive evidence only in 1990ies)
- J. Wheeler (December 1967): Invention of the term “Black Hole”
- S. Hawking and R. Penrose (1970): Black holes contain singularities
- J. Bekenstein (1972): Speculation that black holes might have entropy

Milestones in the Classic Era

- R. Kerr (1963): Exact (and essentially unique) rotating (and charged) black hole solution sparks interest of astrophysics community
- Cygnus X-1 (1964): first detection of X-ray emission from a black hole in a binary system (though realized only in 1970ies that it might be black hole; conclusive evidence only in 1990ies)
- J. Wheeler (December 1967): Invention of the term "Black Hole"
- S. Hawking and R. Penrose (1970): Black holes contain singularities
- J. Bekenstein (1972): Speculation that black holes might have entropy
- N.I. Shakura and R.A. Sunyaev (1972): First accretion disk model

Milestones in the Classic Era

- R. Kerr (1963): Exact (and essentially unique) rotating (and charged) black hole solution sparks interest of astrophysics community
- Cygnus X-1 (1964): first detection of X-ray emission from a black hole in a binary system (though realized only in 1970ies that it might be black hole; conclusive evidence only in 1990ies)
- J. Wheeler (December 1967): Invention of the term "Black Hole"
- S. Hawking and R. Penrose (1970): Black holes contain singularities
- J. Bekenstein (1972): Speculation that black holes might have entropy
- N.I. Shakura and R.A. Sunyaev (1972): First accretion disk model
- J. Bardeen, B. Carter and S. Hawking (1973): Four laws of black hole mechanics

Milestones in the Classic Era

- R. Kerr (1963): Exact (and essentially unique) rotating (and charged) black hole solution sparks interest of astrophysics community
- Cygnus X-1 (1964): first detection of X-ray emission from a black hole in a binary system (though realized only in 1970ies that it might be black hole; conclusive evidence only in 1990ies)
- J. Wheeler (December 1967): Invention of the term "Black Hole"
- S. Hawking and R. Penrose (1970): Black holes contain singularities
- J. Bekenstein (1972): Speculation that black holes might have entropy
- N.I. Shakura and R.A. Sunyaev (1972): First accretion disk model
- J. Bardeen, B. Carter and S. Hawking (1973): Four laws of black hole mechanics
- S. Hawking (1974): Black holes evaporate due to quantum effects

Milestones in the Classic Era

- R. Kerr (1963): Exact (and essentially unique) rotating (and charged) black hole solution sparks interest of astrophysics community
- Cygnus X-1 (1964): first detection of X-ray emission from a black hole in a binary system (though realized only in 1970ies that it might be black hole; conclusive evidence only in 1990ies)
- J. Wheeler (December 1967): Invention of the term "Black Hole"
- S. Hawking and R. Penrose (1970): Black holes contain singularities
- J. Bekenstein (1972): Speculation that black holes might have entropy
- N.I. Shakura and R.A. Sunyaev (1972): First accretion disk model
- J. Bardeen, B. Carter and S. Hawking (1973): Four laws of black hole mechanics
- S. Hawking (1974): Black holes evaporate due to quantum effects
- W. Unruh (1981): Black hole analogs in condensed matter physics

Milestones in the Classic Era

- R. Kerr (1963): Exact (and essentially unique) rotating (and charged) black hole solution sparks interest of astrophysics community
- Cygnus X-1 (1964): first detection of X-ray emission from a black hole in a binary system (though realized only in 1970ies that it might be black hole; conclusive evidence only in 1990ies)
- J. Wheeler (December 1967): Invention of the term "Black Hole"
- S. Hawking and R. Penrose (1970): Black holes contain singularities
- J. Bekenstein (1972): Speculation that black holes might have entropy
- N.I. Shakura and R.A. Sunyaev (1972): First accretion disk model
- J. Bardeen, B. Carter and S. Hawking (1973): Four laws of black hole mechanics
- S. Hawking (1974): Black holes evaporate due to quantum effects
- W. Unruh (1981): Black hole analogs in condensed matter physics
- R. Jackiw, S. Deser, C. Teitelboim et al. (1982): Gravity in lower dimensions

Milestones in the Modern Era

- E. Witten et al. (1984): First superstring revolution

Milestones in the Modern Era

- E. Witten et al. (1984): First superstring revolution
- M. Bañados, C. Teitelboim and J. Zanelli (1992): Black holes in three dimensions

Milestones in the Modern Era

- E. Witten et al. (1984): First superstring revolution
- M. Bañados, C. Teitelboim and J. Zanelli (1992): Black holes in three dimensions
- M. Choptuik (1993): Critical collapse in numerical relativity

Milestones in the Modern Era

- E. Witten et al. (1984): First superstring revolution
- M. Bañados, C. Teitelboim and J. Zanelli (1992): Black holes in three dimensions
- M. Choptuik (1993): Critical collapse in numerical relativity
- G. 't Hooft and L. Susskind (1993): Holographic principle

Milestones in the Modern Era

- E. Witten et al. (1984): First superstring revolution
- M. Bañados, C. Teitelboim and J. Zanelli (1992): Black holes in three dimensions
- M. Choptuik (1993): Critical collapse in numerical relativity
- G. 't Hooft and L. Susskind (1993): Holographic principle
- H.-P. Nollert; N. Andersson (1992): Quasinormal modes of a "ringing" Schwarzschild black hole

Milestones in the Modern Era

- E. Witten et al. (1984): First superstring revolution
- M. Bañados, C. Teitelboim and J. Zanelli (1992): Black holes in three dimensions
- M. Choptuik (1993): Critical collapse in numerical relativity
- G. 't Hooft and L. Susskind (1993): Holographic principle
- H.-P. Nollert; N. Andersson (1992): Quasinormal modes of a "ringing" Schwarzschild black hole
- J. Polchinski (1995): p-branes and second superstring revolution

Milestones in the Modern Era

- E. Witten et al. (1984): First superstring revolution
- M. Bañados, C. Teitelboim and J. Zanelli (1992): Black holes in three dimensions
- M. Choptuik (1993): Critical collapse in numerical relativity
- G. 't Hooft and L. Susskind (1993): Holographic principle
- H.-P. Nollert; N. Andersson (1992): Quasinormal modes of a "ringing" Schwarzschild black hole
- J. Polchinski (1995): p-branes and second superstring revolution
- A. Strominger and C. Vafa (1996): Microscopic origin of black hole entropy

Milestones in the Modern Era

- E. Witten et al. (1984): First superstring revolution
- M. Bañados, C. Teitelboim and J. Zanelli (1992): Black holes in three dimensions
- M. Choptuik (1993): Critical collapse in numerical relativity
- G. 't Hooft and L. Susskind (1993): Holographic principle
- H.-P. Nollert; N. Andersson (1992): Quasinormal modes of a "ringing" Schwarzschild black hole
- J. Polchinski (1995): p-branes and second superstring revolution
- A. Strominger and C. Vafa (1996): Microscopic origin of black hole entropy
- J. Maldacena (1997): AdS/CFT correspondence

Milestones in the Modern Era

- E. Witten et al. (1984): First superstring revolution
- M. Bañados, C. Teitelboim and J. Zanelli (1992): Black holes in three dimensions
- M. Choptuik (1993): Critical collapse in numerical relativity
- G. 't Hooft and L. Susskind (1993): Holographic principle
- H.-P. Nollert; N. Andersson (1992): Quasinormal modes of a "ringing" Schwarzschild black hole
- J. Polchinski (1995): p-branes and second superstring revolution
- A. Strominger and C. Vafa (1996): Microscopic origin of black hole entropy
- J. Maldacena (1997): AdS/CFT correspondence
- S. Dimopoulos and G.L. Landsberg; S.B. Giddings and S. Thomas (2001): Black holes at the LHC?

Milestones in the Modern Era

- E. Witten et al. (1984): First superstring revolution
- M. Bañados, C. Teitelboim and J. Zanelli (1992): Black holes in three dimensions
- M. Choptuik (1993): Critical collapse in numerical relativity
- G. 't Hooft and L. Susskind (1993): Holographic principle
- H.-P. Nollert; N. Andersson (1992): Quasinormal modes of a "ringing" Schwarzschild black hole
- J. Polchinski (1995): p-branes and second superstring revolution
- A. Strominger and C. Vafa (1996): Microscopic origin of black hole entropy
- J. Maldacena (1997): AdS/CFT correspondence
- S. Dimopoulos and G.L. Landsberg; S.B. Giddings and S. Thomas (2001): Black holes at the LHC?
- Saggitarius A* (2002): Supermassive black hole in center of Milky Way

Milestones in the Modern Era

- E. Witten et al. (1984): First superstring revolution
- M. Bañados, C. Teitelboim and J. Zanelli (1992): Black holes in three dimensions
- M. Choptuik (1993): Critical collapse in numerical relativity
- G. 't Hooft and L. Susskind (1993): Holographic principle
- H.-P. Nollert; N. Andersson (1992): Quasinormal modes of a "ringing" Schwarzschild black hole
- J. Polchinski (1995): p-branes and second superstring revolution
- A. Strominger and C. Vafa (1996): Microscopic origin of black hole entropy
- J. Maldacena (1997): AdS/CFT correspondence
- S. Dimopoulos and G.L. Landsberg; S.B. Giddings and S. Thomas (2001): Black holes at the LHC?
- Saggitarius A* (2002): Supermassive black hole in center of Milky Way
- R. Emparan and H. Reall (2002): Black rings in five dimensions

Milestones in the Modern Era

- E. Witten et al. (1984): First superstring revolution
- M. Bañados, C. Teitelboim and J. Zanelli (1992): Black holes in three dimensions
- M. Choptuik (1993): Critical collapse in numerical relativity
- G. 't Hooft and L. Susskind (1993): Holographic principle
- H.-P. Nollert; N. Andersson (1992): Quasinormal modes of a "ringing" Schwarzschild black hole
- J. Polchinski (1995): p-branes and second superstring revolution
- A. Strominger and C. Vafa (1996): Microscopic origin of black hole entropy
- J. Maldacena (1997): AdS/CFT correspondence
- S. Dimopoulos and G.L. Landsberg; S.B. Giddings and S. Thomas (2001): Black holes at the LHC?
- Saggitarius A* (2002): Supermassive black hole in center of Milky Way
- R. Emparan and H. Reall (2002): Black rings in five dimensions
- S. Hawking (2004): concedes bet on information paradox

Recent Milestones

- P. Kovtun, D. Son and A. Starinets (2004): Viscosity in strongly interacting Quantum Field Theories from black hole physics

Recent Milestones

- P. Kovtun, D. Son and A. Starinets (2004): Viscosity in strongly interacting Quantum Field Theories from black hole physics
- F. Pretorius (2005): Breakthrough in numerical treatment of binaries

Recent Milestones

- P. Kovtun, D. Son and A. Starinets (2004): Viscosity in strongly interacting Quantum Field Theories from black hole physics
- F. Pretorius (2005): Breakthrough in numerical treatment of binaries
- J.E. McClintock et al. (2006): Measuring of spin of GRS1915+105

Recent Milestones

- P. Kovtun, D. Son and A. Starinets (2004): Viscosity in strongly interacting Quantum Field Theories from black hole physics
- F. Pretorius (2005): Breakthrough in numerical treatment of binaries
- J.E. McClintock et al. (2006): Measuring of spin of GRS1915+105
- E. Witten (2007), W. Li, W. Song and A. Strominger; D. Grumiller and N. Johansson (2008): Quantum gravity in three dimensions?

Recent Milestones

- P. Kovtun, D. Son and A. Starinets (2004): Viscosity in strongly interacting Quantum Field Theories from black hole physics
- F. Pretorius (2005): Breakthrough in numerical treatment of binaries
- J.E. McClintock et al. (2006): Measuring of spin of GRS1915+105
- E. Witten (2007), W. Li, W. Song and A. Strominger; D. Grumiller and N. Johansson (2008): Quantum gravity in three dimensions?
- S. Gubser; S. Hartnoll, C. Herzog and G. Horowitz (2008): "Holographic superconductors"; D. Son; K. Balasubramanian and J. McGreevy (2008): Black hole duals for cold atoms proposed

Recent Milestones

- P. Kovtun, D. Son and A. Starinets (2004): Viscosity in strongly interacting Quantum Field Theories from black hole physics
- F. Pretorius (2005): Breakthrough in numerical treatment of binaries
- J.E. McClintock et al. (2006): Measuring of spin of GRS1915+105
- E. Witten (2007), W. Li, W. Song and A. Strominger; D. Grumiller and N. Johansson (2008): Quantum gravity in three dimensions?
- S. Gubser; S. Hartnoll, C. Herzog and G. Horowitz (2008): "Holographic superconductors"; D. Son; K. Balasubramanian and J. McGreevy (2008): Black hole duals for cold atoms proposed
- M. Henneaux, S.-J. Rey; A. Campoleoni et al.; M. Gutperle, P. Kraus (2011): Higher spin black holes

Recent Milestones

- P. Kovtun, D. Son and A. Starinets (2004): Viscosity in strongly interacting Quantum Field Theories from black hole physics
- F. Pretorius (2005): Breakthrough in numerical treatment of binaries
- J.E. McClintock et al. (2006): Measuring of spin of GRS1915+105
- E. Witten (2007), W. Li, W. Song and A. Strominger; D. Grumiller and N. Johansson (2008): Quantum gravity in three dimensions?
- S. Gubser; S. Hartnoll, C. Herzog and G. Horowitz (2008): "Holographic superconductors"; D. Son; K. Balasubramanian and J. McGreevy (2008): Black hole duals for cold atoms proposed
- M. Henneaux, S.-J. Rey; A. Campoleoni et al.; M. Gutperle, P. Kraus (2011): Higher spin black holes
- A. Almheiri, D. Marolf, J. Polchinski, J. Sully (2012): Firewalls?

Recent Milestones

- P. Kovtun, D. Son and A. Starinets (2004): Viscosity in strongly interacting Quantum Field Theories from black hole physics
- F. Pretorius (2005): Breakthrough in numerical treatment of binaries
- J.E. McClintock et al. (2006): Measuring of spin of GRS1915+105
- E. Witten (2007), W. Li, W. Song and A. Strominger; D. Grumiller and N. Johansson (2008): Quantum gravity in three dimensions?
- S. Gubser; S. Hartnoll, C. Herzog and G. Horowitz (2008): "Holographic superconductors"; D. Son; K. Balasubramanian and J. McGreevy (2008): Black hole duals for cold atoms proposed
- M. Henneaux, S.-J. Rey; A. Campoleoni et al.; M. Gutperle, P. Kraus (2011): Higher spin black holes
- A. Almheiri, D. Marolf, J. Polchinski, J. Sully (2012): Firewalls?
- A. Bagchi, D. Grumiller et al, G. Barnich et al, A. Strominger et al (2012-2017): flat space holography?

Recent Milestones

- P. Kovtun, D. Son and A. Starinets (2004): Viscosity in strongly interacting Quantum Field Theories from black hole physics
- F. Pretorius (2005): Breakthrough in numerical treatment of binaries
- J.E. McClintock et al. (2006): Measuring of spin of GRS1915+105
- E. Witten (2007), W. Li, W. Song and A. Strominger; D. Grumiller and N. Johansson (2008): Quantum gravity in three dimensions?
- S. Gubser; S. Hartnoll, C. Herzog and G. Horowitz (2008): "Holographic superconductors"; D. Son; K. Balasubramanian and J. McGreevy (2008): Black hole duals for cold atoms proposed
- M. Henneaux, S.-J. Rey; A. Campoleoni et al.; M. Gutperle, P. Kraus (2011): Higher spin black holes
- A. Almheiri, D. Marolf, J. Polchinski, J. Sully (2012): Firewalls?
- A. Bagchi, D. Grumiller et al, G. Barnich et al, A. Strominger et al (2012-2017): flat space holography?
- S. Hawking et al, L. Donnay et al, H. Afshar et al (2016): soft hair

Recent Milestones

- P. Kovtun, D. Son and A. Starinets (2004): Viscosity in strongly interacting Quantum Field Theories from black hole physics
- F. Pretorius (2005): Breakthrough in numerical treatment of binaries
- J.E. McClintock et al. (2006): Measuring of spin of GRS1915+105
- E. Witten (2007), W. Li, W. Song and A. Strominger; D. Grumiller and N. Johansson (2008): Quantum gravity in three dimensions?
- S. Gubser; S. Hartnoll, C. Herzog and G. Horowitz (2008): "Holographic superconductors"; D. Son; K. Balasubramanian and J. McGreevy (2008): Black hole duals for cold atoms proposed
- M. Henneaux, S.-J. Rey; A. Campoleoni et al.; M. Gutperle, P. Kraus (2011): Higher spin black holes
- A. Almheiri, D. Marolf, J. Polchinski, J. Sully (2012): Firewalls?
- A. Bagchi, D. Grumiller et al, G. Barnich et al, A. Strominger et al (2012-2017): flat space holography?
- S. Hawking et al, L. Donnay et al, H. Afshar et al (2016): soft hair
- LIGO collaboration (2016): first detection of gravitational waves

Recent Milestones

- P. Kovtun, D. Son and A. Starinets (2004): Viscosity in strongly interacting Quantum Field Theories from black hole physics
- F. Pretorius (2005): Breakthrough in numerical treatment of binaries
- J.E. McClintock et al. (2006): Measuring of spin of GRS1915+105
- E. Witten (2007), W. Li, W. Song and A. Strominger; D. Grumiller and N. Johansson (2008): Quantum gravity in three dimensions?
- S. Gubser; S. Hartnoll, C. Herzog and G. Horowitz (2008): "Holographic superconductors"; D. Son; K. Balasubramanian and J. McGreevy (2008): Black hole duals for cold atoms proposed
- M. Henneaux, S.-J. Rey; A. Campoleoni et al.; M. Gutperle, P. Kraus (2011): Higher spin black holes
- A. Almheiri, D. Marolf, J. Polchinski, J. Sully (2012): Firewalls?
- A. Bagchi, D. Grumiller et al, G. Barnich et al, A. Strominger et al (2012-2017): flat space holography?
- S. Hawking et al, L. Donnay et al, H. Afshar et al (2016): soft hair
- LIGO collaboration (2016): first detection of gravitational waves
- EHT collaboration (2019): first picture of black hole (in galaxy M87)

Outline

Get copies at the end of lecture (essentially now) or download PDF from
http://quark.itp.tuwien.ac.at/∼grumil/teaching.shtml

Get copies at the end of lecture (essentially now) or download PDF from
http://quark.itp.tuwien.ac.at/∼grumil/teaching.shtml

Next week we try to understand how these two pictures are related...