Black Holes: Theory, Observations & Applications

Habilitandenkolloquium November 2010

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Appetizer, Part I

Physics of the 20^{th} century: harmonic oscillator

Simple idea:

Harmonic oscillator: take a physical system and shake it

Amazingly successful:

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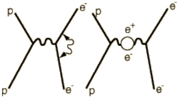

Feynman diagrams contributing to Lamb shift

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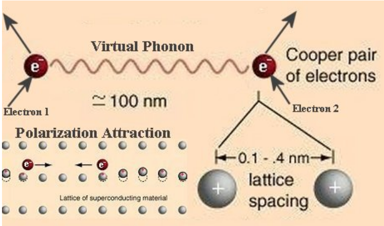

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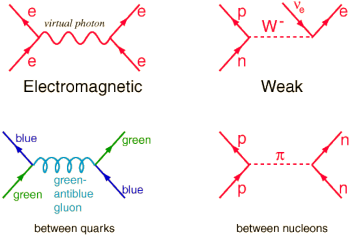


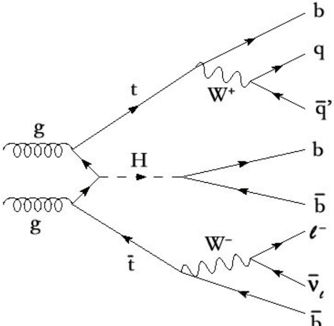
Electromagnetic

Weak

between quarks

between nucleons

Strong Interaction



Higgs production

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- see also the TU Wien curriculum "Technische Physik"

Lectures in Bachelor curriculum containing harmonic oscillator

- Grundlagen Physik
- Praktische Mathematik
- Analysis
- Mechanik
- Mathematische Meth.
- Quantenmechanik
- Elektrodynamik
- Festkörperphysik
- Elektronik
- Atom,Kern,Teilchenph.
- Laborübungen
- div. Spezialvorlesungen

Appetizer, Part II

Physics of the 21^{st} century: black holes? [see colloquium by Strominger at Harvard]

Application of harmonic oscillator limited to perturbative phenomena

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Application of harmonic oscillator limited to perturbative phenomena

Many physical systems require non-perturbative physics:

- QCD at low energies
- High T_c superconductors
- Graphene
- Cold atoms
- Gravity at high curvature

Generally speaking:

Strongly coupled systems require new techniques

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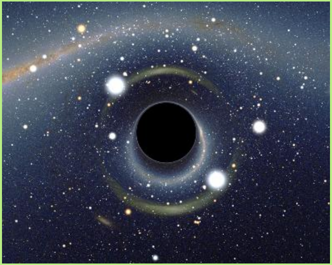
Punch-line of this talk:

Black hole holography can provide such a technique

Appetizer, Part III

Black holes have apparently paradoxical properties

Black holes: The simplest macroscopic objects in the Universe



Properties determined by:

- Mass M
- Angular momentum J
- Charge(s) Q

Black hole $\sim$ elementary particle!

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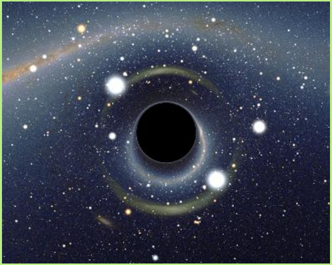

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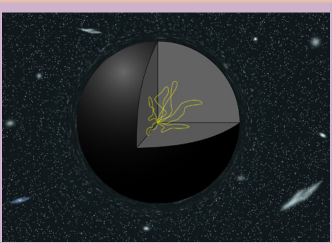
Black holes: The most complicated objects conceivable



Quantum mechanics:

- Black holes radiate
- Black holes have entropy
- Black holes are holographic

Bekenstein–Hawking:

$$S_{BH} \sim A_{\text{hor}}/4$$

Outline

Brief history of black holes and observations

Theory and applications

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Theory and applications

Milestones in Pre-History

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- S. Chandrasekhar (1931): Gravitational collapse of Fermi gas
- M. Kruskal; G. Szekeres (1960): Global structure of Schwarzschild

What is a black hole?

Fishy analogy (Bill Unruh '81):

The real stuff:

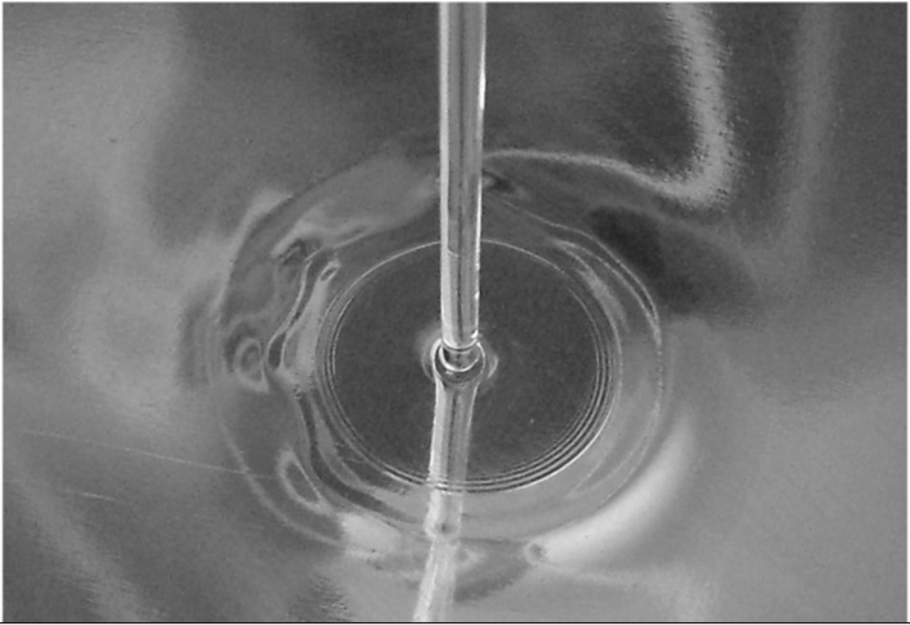
Above: black hole
(NASA picture)
Left: Waterfall

Analogy:
Infinity ↔ Lake

Horizon ↔ Point of no return

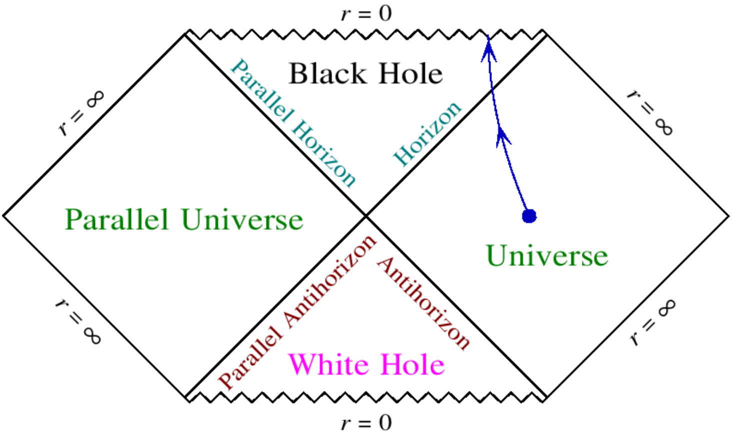
Singularity ↔ Waterfall

Hydraulic jump as black hole analog [Jannes et al, PRL (2010)]



Schwarzschild black hole

Experimental evidence: perihelion shifts, light-bending, GPS, ...



Schwarzschild line-element (horizon at $r = 2M$):

$$\mathrm{d}s^2 = -\Big(1 - \frac{2M}{r}\Big)\,\mathrm{d}t^2 + \frac{\mathrm{d}r^2}{1 - \frac{2M}{r}} + r^2\,\mathrm{d}\theta^2 + r^2\sin^2\theta\,\mathrm{d}\phi^2$$

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- 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)
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- W. Unruh (1981): Black hole analogs in condensed matter physics
- R. Jackiw, S. Deser, C. Teitelboim et al. (1982): Gravity in lower dimensions

Black holes (relatively) simple to observe in binary systems:

Black hole observations

Confirmed stellar black holes in X-ray binaries

Objects whose mass is clearly beyond TOV limit $M > 3M_\odot$:

System	$P_{\rm orb}$ [days]	$f(M)$ [$M_\odot$]	Donor Spect. Type	Classification	$M_{\rm x}$ † [$M_\odot$]
GRS 1915+105[a]	33.5	9.5 ± 3.0	K/M III	LMXB/Transient	14 ± 4
V404 Cyg	6.471	6.09 ± 0.04	K0 IV	,,	12 ± 2
Cyg X-1	5.600	0.244 ± 0.005	09.7 Iab	HMXB/Persistent	10 ± 3
LMC X-1	4.229	0.14 ± 0.05	07 III	,,	> 4
XTE J1819-254	2.816	3.13 ± 0.13	B9 III	IMXB/Transient	7.1 ± 0.3
GRO J1655-40	2.620	2.73 ± 0.09	F3/5 IV	,,	6.3 ± 0.3
BW Cir[b]	2.545	5.74 ± 0.29	G5 IV	LMXB/Transient	> 7.8
GX 339-4	1.754	5.8 ± 0.5	–	,,	
LMC X-3	1.704	2.3 ± 0.3	B3 V	HMXB/Persistent	7.6 ± 1.3
XTE J1550-564	1.542	6.86 ± 0.71	G8/K8 IV	LMXB/Transient	9.6 ± 1.2
4U 1543-475	1.125	0.25 ± 0.01	A2 V	IMXB/Transient	9.4 ± 1.0
H1705-250	0.520	4.86 ± 0.13	K3/7 V	LMXB/Transient	6 ± 2
GS 1124-684	0.433	3.01 ± 0.15	K3/5 V	,,	7.0 ± 0.6
XTE J1859+226[c]	0.382	7.4 ± 1.1	–	,,	
GS2000+250	0.345	5.01 ± 0.12	K3/7 V	,,	7.5 ± 0.3
A0620-003	0.325	2.72 ± 0.06	K4 V	,,	11 ± 2
XTE J1650-500	0.321	2.73 ± 0.56	K4 V	,,	
GRS 1009-45	0.283	3.17 ± 0.12	K7/M0 V	,,	5.2 ± 0.6
GRO J0422+32	0.212	1.19 ± 0.02	M2 V	,,	4 ± 1
XTE J1118+480	0.171	6.3 ± 0.2	K5/M0 V	,,	6.8 ± 0.4

Source: J. Casares, `astro-ph/0612312`

Black holes in X-ray binaries particularly "simple" to detect

Thermodynamics and black holes — black hole thermodynamics?

Thermodynamics

Zeroth law:

$T =$ const. in equilibrium

T: temperature

Black hole mechanics

Zeroth law:

$\kappa =$ const. f. stationary black holes

κ: surface gravity

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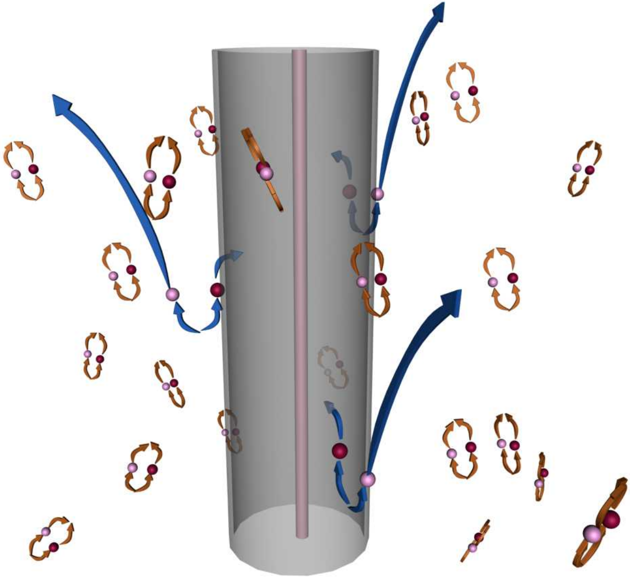
Formal analogy or actual physics?

Hawking effect

Black holes evaporate due to quantum effects!



Natural units:

$$T_H = \frac{\kappa}{2\pi}$$

$$S_{BH} = \frac{A}{4}$$

Schwarzschild (SI units):

$$T_H = \frac{\hbar c^3}{8\pi G_N k_B M}$$

$$S_{BH} = \frac{c^3 A}{4 G_N \hbar}$$

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
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- 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

Recent Milestones

- S. Hawking (2004): concedes bet on information paradox — end of "black hole wars"
- 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 binary problem
- C. Barcelo, S. Liberati, and M. Visser (2005): "Analogue gravity"
- J.E. McClintock et al. (2006): Measuring of spin of GRS1915+105 — nearly extremal Kerr black hole!
- E. Witten (2007) and W. Li, W. Song and A. Strominger (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
- O. Lahav, A. Itah, A. Blumkin, C. Gordon, and J. Steinhauer (2009): Sonic black hole in Bose-Einstein condensate

Outline

Brief history of black holes and observations

Theory and applications

Black holes as the hydrogen atom of quantum gravity

Some properties of black holes (BHs):

- BHs are simple, much like elementary particles
- BHs are characterized by mass, spin and charges

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- Semi-classically BHs emit Hawking radiation
- Thermodynamically BHs have entropy proportional to horizon area:

$$S_{\mathrm{BH}} = \frac{1}{4} A_h$$

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- Thermodynamically BHs have entropy proportional to horizon area:

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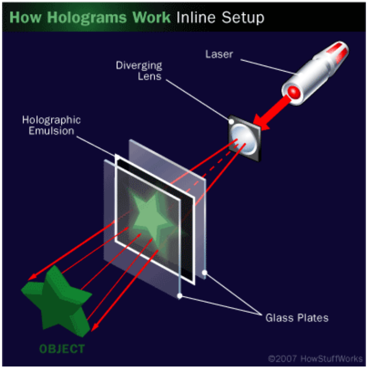
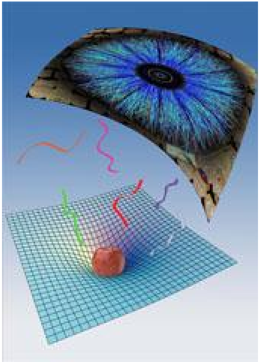
- Quantum-mechanically BH evaporation entails "information paradox"
- BHs are the simplest systems that allow to address conceptual problems of quantum gravity, for instance: unitarity of quantum gravity, microscopic understanding of BH entropy, holographic principle, modelling of BH evaporation, ...

Understanding quantum black holes and holography is milestone on road to quantum gravity!

Holography — Main idea

aka gauge/gravity duality, aka AdS/CFT correspondence





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- The number of dimensions is a matter of perspective

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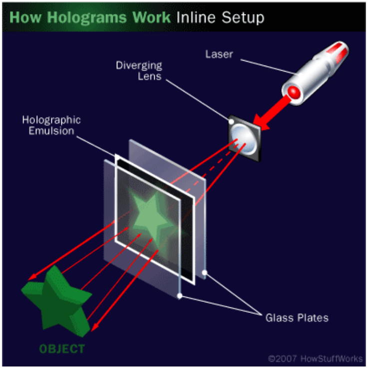

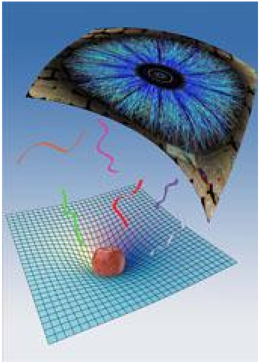

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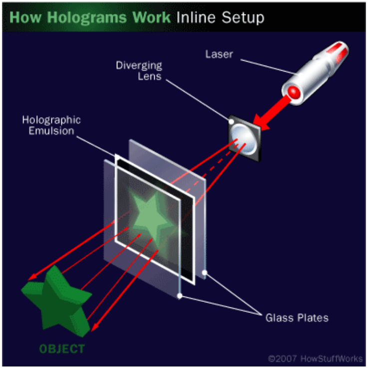

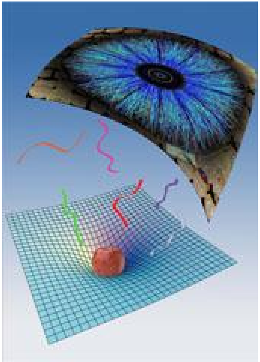

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- The number of dimensions is a matter of perspective
- We can choose to describe the same physical situation using two different formulations in two different dimensions
- The formulation in higher dimensions is a theory with gravity
- The formulation in lower dimensions is a theory without gravity

Why gravity?

The holographic principle in black hole physics

`Boltzmann/Planck`: entropy of photon gas in d spatial dimensions

$$S_{\text{gauge}} \propto \text{volume} \propto L^d$$

`Bekenstein/Hawking`: entropy of black hole in d spatial dimensions

$$S_{\text{gravity}} \propto \text{area} \propto L^{d-1}$$

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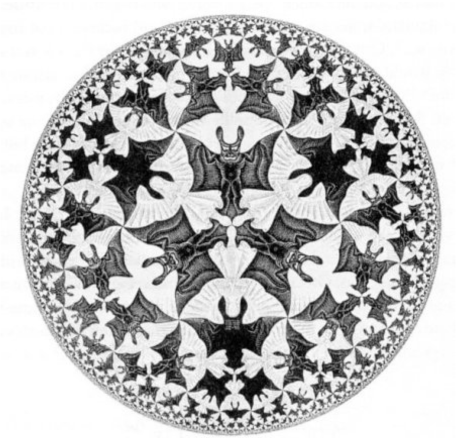
$$\text{e.g.} \quad \langle T_{\mu\nu}\rangle_{\text{gauge}} = T^{BY}_{\mu\nu} \qquad \delta(\text{gravity action}) = \int \mathrm{d}^d x \sqrt{|h|}\, T^{BY}_{\mu\nu}\, \delta h^{\mu\nu}$$

Motivating AdS/CFT

The AdS line element

Best studied realization of holography is AdS/CFT correspondence:

- AdS is a negatively curved spacetime (maximally symmetric)



Open Universe Looking from inside, boundary at infinity
Limit Circle IV, by M. C. Escher

Motivating AdS/CFT

The AdS line element

Best studied realization of holography is AdS/CFT correspondence:

- AdS is a negatively curved spacetime (maximally symmetric)
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$$\mathrm{d}s^2 = (E/L)^2 \eta_{\mu\nu}\,\mathrm{d}x^\mu\,\mathrm{d}x^\nu + (L/E)^2\,\mathrm{d}E^2$$

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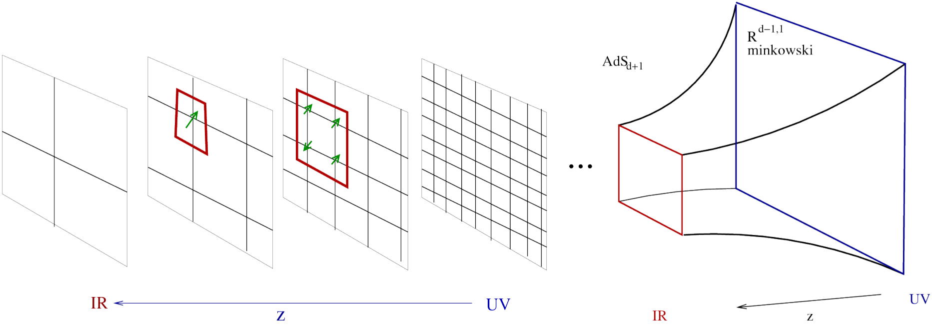
This is precisely the line element of AdS in 1 dimension higher!

Understanding AdS/CFT as an RG flow [McGreevy, AHEP (2009)]

Convenient coordinate trafo: $z = L^2/E$

$$\mathrm{d}s^2 = (L/z)^2\big(\eta_{\mu\nu}\,\mathrm{d}x^\mu\,\mathrm{d}x^\nu + \mathrm{d}z^2\big)$$

Field theoretic interpretation: RG-flow!



Left: series of block-spin transformations

Right: cartoon of AdS spacetime

UV in field theory $\sim$ IR in gravity theory!

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We can expect many new applications in the next decade!

Black holes in the lab: realistic scenarios

Creation of dual black holes – basic logic

- Gauge/gravity duality states that certain black hole configurations are equivalent to certain field theory configurations
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Ultra-relativistic heavy ion collisions at RHIC and LHC

$$\text{Theory}: \frac{\eta}{s} = \frac{1}{4\pi} \qquad \text{Experiment}: \frac{\eta}{s} \approx 0.1 \pm \text{a lot}$$

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Future possibilities for creation of dual black holes

- Cold atoms (warped AdS/non-relativistic CFT correspondence)
- Holographic superfluids/superconductors (gauge/gravity duality)
- Quenched disorder (AdS/logarithmic CFT correspondence)

Black holes group at TU Wien

Current members (in alphabetical order) and MISTI exchange students (third row)

Hamid Afshar

Max Attems

Branislav Cvetkovic

Sabine Ertl

Niklas Johansson

Thomas Zojer

Amy Cottle

Ana-Maria Piso

Zijie Zhou

Thank you for your attention!