Quantengravitation und das holographische Universum

Johannes Kepler Universität Linz, Physikkolloquium, März 2017

Daniel Grumiller

Institute for Theoretical Physics
TU Wien

http://quark.itp.tuwien.ac.at/∼grumil

grumil@hep.itp.tuwien.ac.at

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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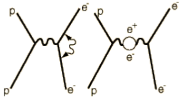

Feynman diagrams contributing to Lamb shift

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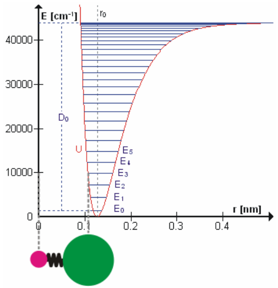
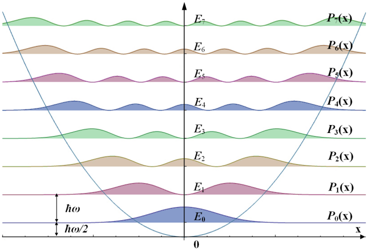
- weakly coupled phonons and electrons in condensed matter





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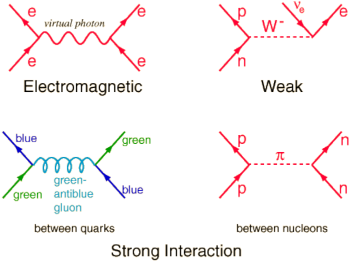

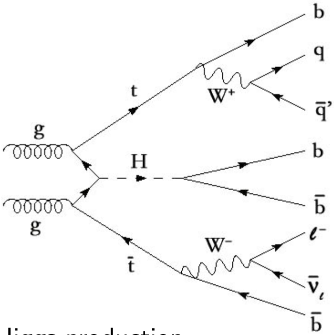

Higgs production

Simple idea:

> Harmonic oscillator: take a physical system and shake it

Amazingly successful:

- QFT corrections to Hydrogen atom
- weakly coupled phonons and electrons in condensed matter
- Standard Model of particle physics
- see also the JKU curriculum “Technische Physik”

Lectures in JKU Bachelor curriculum containing harmonic oscillator

- Grundlagen der Physik I-V
- Analysis für Physiker(innen) I-II
- Mathematische Methoden der Physik
- Theoretische Mechanik
- Theoretische Quantenmechanik I
- Theoretische Thermodynamik
- Theoretische Elektrodynamik I
- diverse Wahllehrveranstaltungen

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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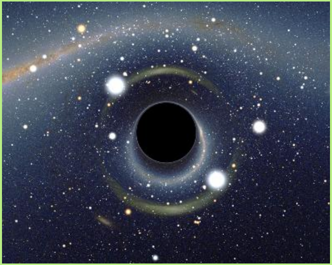
Punch-line of this talk:

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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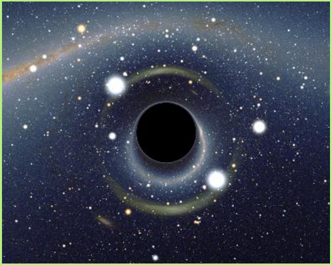

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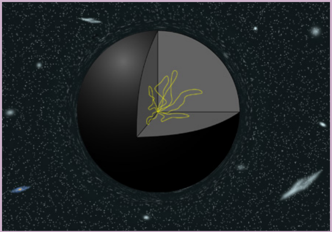
Black holes: The most complicated objects conceivable



Quantum mechanics:

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

Bekenstein–Hawking:

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

Outline

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Simulation of accretion disk around black hole
(data by K. Thorne et. al. used in movie "Interstellar")

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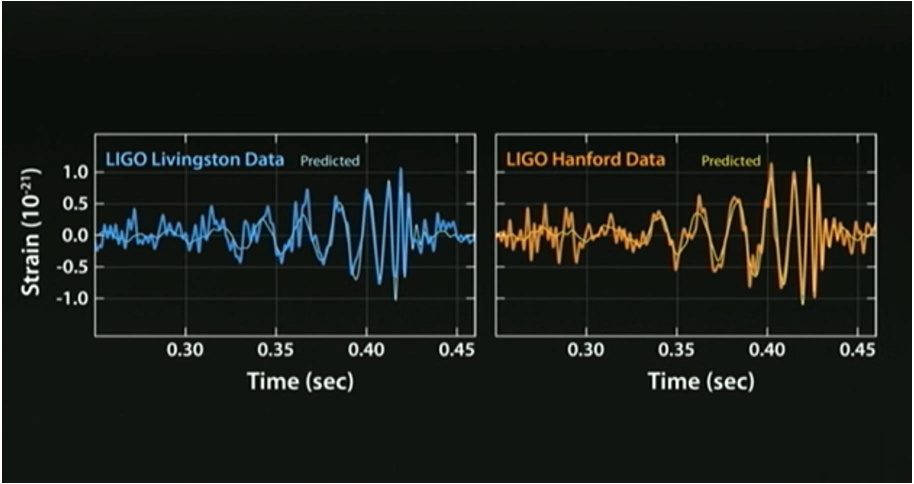
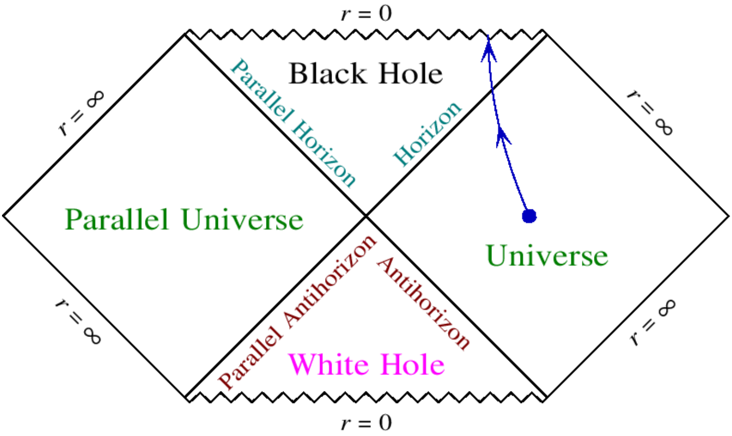


Gravitational wave signals detected by LIGO in September 2015
source was a black hole merger ($36M_\odot + 29M_\odot = 62M_\odot +$ energy)

Schwarzschild black hole

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



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

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

Outline

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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$dE \sim TdS+$ work terms

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$dS \geq 0$

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Thermodynamics	Black hole mechanics
Zeroth law: $T =$ const. in equilibrium	Zeroth law: $\kappa =$ const. f. stationary black holes
First law: $dE \sim TdS+$ work terms	First law: $dM \sim \kappa dA+$ work terms
Second law: $dS \geq 0$	Second law: $dA \geq 0$
Third law: $T \to 0$ impossible	Third law: $\kappa \to 0$ impossible

T: temperature
E: energy
S: entropy

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Formal analogy or actual physics?

Bekenstein's argument

Assume first black holes have no entropy

Simple Gedankenexperiment:

- Take empty spacetime with a black hole and a cup of tea

Total entropy in Universe:

- $S_i = S_{\text{tea cup}}$

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- Contradicts second law of thermodynamics!

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Assume now black holes have entropy proportional to area of event horizon

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Bekenstein's conclusion:

$$S_{\text{BH}} \propto A_{\text{horizon}}$$

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Total entropy in Universe:

- $S_i = S_{\text{tea cup}} + S_{\text{BH}}$
- $S = S_{\text{tea cup}} + S_{\text{BH}}$
- $S_f = 0 + S_{\text{BH}} + \Delta S_{\text{BH}}$
- ~~$S_f < S_i$~~ $S_f = S_i$

Bekenstein's conclusion:

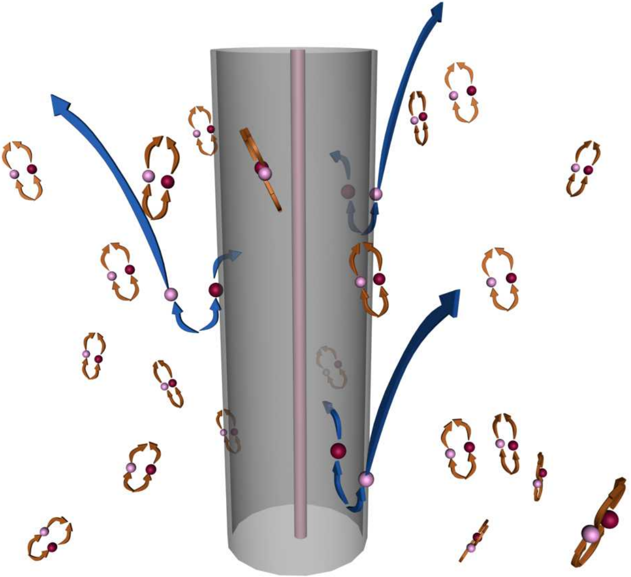
$$S_{\text{BH}} \propto A_{\text{horizon}}$$

Issue above resolved — black hole gets bigger if you throw something in it:

$$S_{\text{total}} = S_{\text{BH}} + S_{\text{tea cup}} = S_{\text{BH}} + \Delta S_{\text{BH}}$$

Hawking effect confirms Bekenstein's entropy proposal

Black holes evaporate due to quantum effects!



Natural units:

$$T_{\rm H} = \frac{\kappa}{2\pi}$$

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

Schwarzschild (SI units):

$$T_{\rm H} = \frac{\hbar c^3}{8\pi G k_B M}$$

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

Semi-classical puzzles with black holes

Black holes as the hydrogen atom of quantum gravity

ok, black holes do not violate the second law, but...

- how can smallest astro-ph black hole have huge entropy

$$S_{\mathrm{BH}} \approx 10^{77}$$

  if black holes so simple?

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> Understanding quantum behavior of black holes crucial milestone on road to quantum gravity!

Outline

Simple motivation of holographic principle

- entropy in quantum (field) theory

$$S \sim V \sim L^d$$

V: volume
L: length
d: number of spatial dimensions

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$$S \sim V \sim L^d$$

  V: volume
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  d: number of spatial dimensions

- entropy of black holes

$$S \sim A \sim L^{d-1}$$

  A: area

Simple motivation of holographic principle

- entropy in quantum (field) theory

$$S \sim V \sim L^d$$

V: volume
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d: number of spatial dimensions

- entropy of black holes

$$S \sim A \sim L^{d-1}$$

A: area

idea by 't Hooft and Susskind in 1990ies: Holographic Principle

> Quantum gravity in $d+1$ dimensions equivalent to ordinary quantum (field) theory in d dimensions

Consequences of holographic principle

If holographic principle true

- gravity can be considered as an “illusion”

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Consequences of holographic principle

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- gravity can be considered as an “illusion”
- number of dimensions is matter of perspective
- can choose to describe same physical situation in two different formulations in two different dimensions
- formulation in higher dimensions is theory with gravity
- formulation in lower dimensions is theory without gravity

Consequences of holographic principle

If holographic principle true

- gravity can be considered as an “illusion”
- number of dimensions is matter of perspective
- can choose to describe same physical situation in two different formulations in two different dimensions
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Promising idea — but is it realized in Nature?

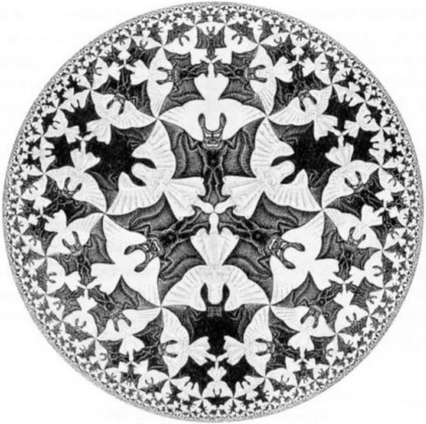
Outline

AdS/CFT [Maldacena 1997]

Motivating Anti-de Sitter/Conformal Field Theory (AdS/CFT) correspondence

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

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Idea: treat energy as the fifth coordinate

Most general line-element compatible with symmetries:

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

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

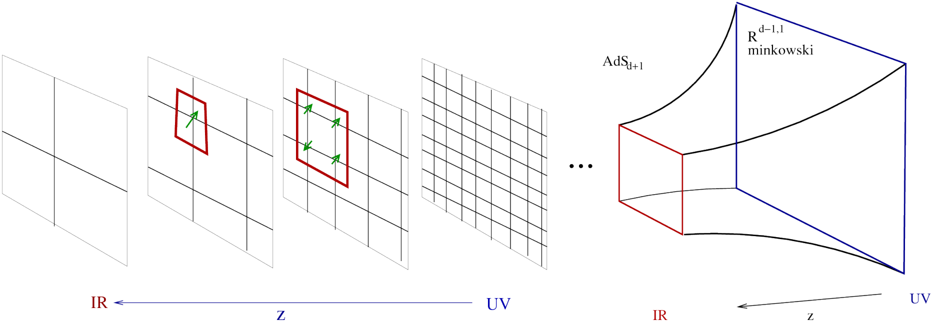
AdS/CFT

Understanding AdS/CFT as an RG flow [McGreevy 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!

AdS/CFT

AdS_3/CFT_2 as precursor [Brown, Henneaux 1986]

- gravity in three spacetime dimensions useful toy model

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- asymptotically AdS_3: physical Hilbert space falls into representations of two copies of the Virasoro algebra

  $$[L_n^\pm,\, L_m^\pm] = (n-m)\, L_{n+m}^\pm + \frac{c}{12}\,(n^3-n)\,\delta_{n+m,\,0}$$

  with Brown–Henneaux central charge (ℓ is the AdS radius, $\Lambda = -1/\ell^2$)

  $$c = \frac{3\ell}{2G}$$

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Conclusion

Any consistent theory of quantum gravity in AdS_3 (compatible with Brown–Henneaux boundary conditions) must be dual to a CFT_2!

AdS/CFT [Maldacena 1997; Gubser, Klebanov, Polyakov 1997; Witten 1998]

Precise formulation of the conjectured correspondence

Precise statement of AdS/CFT conjecture [Maldacena 1997]:

> Type IIB superstring theory on $\text{AdS}_5 \times S^5$ is equivalent to $\mathcal{N} = 4$ super-Yang–Mills theory in $3+1$ dimensions with gauge group $U(N)$

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Reformulation of conjecture as equivalence of all correlation functions:

$$\langle \exp \int \mathrm{d}^4 x \, \phi_0(x) \mathcal{O}(x) \rangle_{\mathrm{CFT}} = Z_{\mathrm{string}} \Big[\phi(x,z)\big|_{z=0} = \phi_0(x) \Big]$$

l.h.s.: generating function of correlation functions in CFT_4 for operator $\mathcal{O}$

r.h.s.: string theory partition function w. condition $\phi = \phi_0$ at AdS_5 bdry

AdS/CFT [see e.g. Aharony, Gubser, Maldacena, Ooguri, Oz 1999]

Selected checks of the AdS/CFT correspondence

- perturbative symmetries match (isometries and supersymmetries): supergroup $SU(2,2|4)$ (bosonic part: $SO(4,2) \times SU(4)$)
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simple AdS$_3$/CFT$_2$ example: all correlation functions of stress energy tensor [Bagchi, DG, Merbis 2015]

$$\langle T_{\mu_1\nu_1}(z_1) T_{\mu_2\nu_2}(z_2) \dots T_{\mu_n\nu_n}(z_n)\rangle_{\text{CFT}_2} = \frac{\delta\Gamma_{\text{AdS}_3}}{\delta g^{\mu_1\nu_1}\delta g^{\mu_2\nu_2}\dots\delta g^{\mu_n\nu_n}}\Big|_{\text{EOM}}$$

in particular ($z_{ij} := z_i - z_j$)

$$\langle T_1 T_2\rangle = \frac{c}{2z_{12}} \qquad c: \text{central charge}$$

$$\langle T_1 T_2 T_3\rangle = \frac{c}{z_{12}^2 z_{23}^2 z_{13}^2}$$

$$\langle T_1 T_2 \dots T_n T_{n+1}\rangle = \sum_{i=2}^{n}\Big(\frac{2}{z_{1i}^2} + \frac{1}{z_{1i}}\partial_{z_i}\Big)\langle T_1 T_2 \dots T_n\rangle$$

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e.g. anomaly associated with global $SU(4)_R$ currents

$$\big(\mathcal{D}^\mu J_\mu\big)^a = \frac{N^2-1}{384\pi^2} i\, d^a{}_{bc}\, \epsilon^{\mu\nu\kappa\lambda} F^b_{\mu\nu} F^c_{\kappa\lambda}$$

gravity computation (valid in large N limit) yields

$$\big(\mathcal{D}^\mu J_\mu\big)^a = \frac{N^2}{384\pi^2} i\, d^a{}_{bc}\, \epsilon^{\mu\nu\kappa\lambda} F^b_{\mu\nu} F^c_{\kappa\lambda}$$

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- anomalous dimension of Konishi operators matches up to seven loops

$$\begin{aligned}\Delta &= 4 + 12g^2 - 48g^4 + 336g^6 + 96\big(-26 + 6\zeta(3) - 15\zeta(5)\big)g^8 \\ &- 96\big(-158 - 72\zeta(3) + 54\zeta^2(3) + 90\zeta(5) - 315\zeta(7)\big)g^{10} \\ &- 48\big(160 + 432\zeta^2(3) - 2340\zeta(5) - 72\zeta(3)[-76 + 45\zeta(5)] - 1575\zeta(7) \\ &+ 10206\zeta(9)\big)g^{12} + 48(-44480 - 8784\zeta^2(3) + 2592\zeta^3(3) - 4776\zeta(5) \\ &- 20700\zeta^2(5) + 24\zeta(3)[4540 + 357\zeta(5) - 1680\zeta(7)] - 26145\zeta(7) \\ &- 17406\zeta(9) + 152460\zeta(11)\big)g^{14} + \mathcal{O}(g^{16})\end{aligned}$$

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  uses map to spin-chain system and techniques for integrable systems for instance, magnon-dispersion relation

$$E(p) = \sqrt{1 + \frac{\lambda}{\pi^2} \sin^2(p/2)}$$

  or cusp-anomalous dimension $\pi D_{\text{cusp}} = \sqrt{\lambda} - 3\ln 2 - \beta(2)/\sqrt{\lambda} + \dots$

  $\beta(2)$ is Catalan's constant, $\beta(2) = \sum_{n=0}^{\infty}(-1)^n/(2n+1)^2$

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- correspondence between instantons

  e.g. charge-k type IIB D-instanton action coincides with charge-k super Yang–Mills instanton action [see e.g. Bianchi 2001]

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- matching of entropy between gravity and field theory side

e.g. Bekenstein–Hawking entropy from Cardy formula for CFT_2

$$S_{\text{BH}} = \frac{A}{4} = 2\pi \sum_{\pm} \sqrt{c\Delta^{\pm}/6} = S_{\text{CFT}}$$

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  e.g. UV/IR connection [Susskind, Witten 1998]; high T behavior of entropy in string theory $S\sim T^3$, like in CFT$_4$

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- holographic entanglement entropy [Ryu, Takayanagi 2006]

  remarkable proposal: HEE $=$ area of extremal surface
  later proved [Lewkowycz, Maldacena 2013]

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- holographic entanglement entropy [Ryu, Takayanagi 2006]
- holographic checks of various inequalities (e.g. holographic entropy bound "$S \leq S_{\rm BH}$", quantum null energy condition, quantum focussing conjecture, strong subadditivity, ...)

Non-AdS holography?

... is a bit like 'non-elephant biology'!

- AdS/CFT most likely true
- holography appears to work in Anti-de Sitter space

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- Success of AdS/CFT motivates to take holography seriously and test it in more generality
- Study non-AdS holography to test generality of holographic principle (and also for potential new applications)

Flat space holography

Ongoing collaboration with Bagchi et al since 2012 on Flat Space_3/Galilean CFT_2

Brief summary:

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Brief summary: it may work

- concrete proposal for holographic correspondence in 3 dimensions

  Flat space chiral gravity Bagchi, DG, Detournay 2012

  $$I = \frac{k}{4\pi} \int \big(\Gamma \wedge \mathrm{d}\Gamma + \tfrac{2}{3}\,\Gamma \wedge \Gamma \wedge \Gamma\big)$$

  conjectured to be dual to chiral CFT$_2$ with $c = 24k$
  (for $k = 1$ conjecturally dual to monster CFT, see Witten 2007)

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Brown–Henneaux-like pre-cursor Barnich, Compère 2006

$$[L_n,\, L_m] = (n-m)\, L_{n+m} + \frac{c_L}{12}\, \delta_{n+m,\,0}$$
$$[L_n,\, M_m] = (n-m)\, M_{n+m} + \frac{c_M}{12}\, \delta_{n+m,\,0}$$
$$[M_n,\, M_m] = 0$$

algebra known as BMS_3 or GCA_2 [Bagchi 2010]

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  analogue of S-transformation works on both sides
  Barnich 2012; Bagchi, Detournay, Fareghbal, Simon 2012

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  e.g. gravitational anomaly $c - \bar{c} = \frac{3}{\mu G}$ Bagchi, DG, Detournay 2012

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- anomalies match
- all stress-tensor correlation functions match

  analogous to AdS$_3$/CFT$_2$ calculation [Bagchi, DG, Merbis 2015]

$$\langle M^1\, N^2\rangle = \frac{c_M}{2s_{12}^4}$$

$$\langle N^1\, N^2\rangle = \frac{c_L - 2c_M\tau_{12}}{2s_{12}^4}$$

$$\langle M^1\, N^2 \dots N^n\rangle = \sum_{i=2}^{n}\Big(\frac{2}{s_{1i}^2} + \frac{c_{1i}}{2}\partial_{\varphi_i}\Big)\langle M^2\, N^3 \dots N^n\rangle$$

$$\langle N^1 N^2 \dots N^n\rangle = \frac{c_L}{c_M}\langle M^1 N^2 \dots N^n\rangle + \sum_{i=1}^{n} u_i \partial_{\varphi_i}\langle M^1 N^2 \dots N^n\rangle$$

N, M: Galilean/Carrollian conformal analogue of stress-tensor components

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- proposal for holographic entanglement entropy matches

Bagchi, Basu, DG, Riegler 2015; Basu, Riegler 2016

$$S_{\text{HEE}} = \frac{c_L}{6}\,\ln\frac{\ell_\varphi}{a} + \frac{c_M}{6}\,\frac{\ell_u}{\ell_\varphi}$$

$c_{L,M}$: central charges in BMS$_3$

a: cut-off

$\ell_{\varphi,u}$: define size and orientation of entangling region

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- First tests of flat space holography work
- Encouraging to pursue flat space holography
- Numerous further tests possible/desired
- Numerous conceptual issues (harder than AdS/CFT!)

Rindler holography/Near horizon holography

Soft Heisenberg hair [Afshar, Detournay, DG, Merbis, Perez, Tempo, Troncoso 2016]

Main idea

Impose boundary conditions that ensure existence of regular horizon

Conclusions so far: it is possible (at least in 3 dimensions)!

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- Surprise 1: near horizon symmetry algebra = Heisenberg algebra

$$[X_n, P_m] = i\delta_{n,m} \,\text{if}\, n \neq 0 \qquad [X_0, \bullet] = [P_0, \bullet] = 0$$

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- Surprise 2: entropy formula ridiculously simple and universal

$$S = 2\pi P_0$$

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Conclusions so far: it is possible (at least in 3 dimensions)!

- Surprise 1: near horizon symmetry algebra = Heisenberg algebra

$$[X_n, P_m] = i\delta_{n,m} \,\text{if}\, n \neq 0 \qquad [X_0, \bullet] = [P_0, \bullet] = 0$$

- Surprise 2: entropy formula ridiculously simple and universal

$$S = 2\pi P_0$$

- Surprise 3: algebra can be used to construct all black hole microstates

$$\big|\mathrm{BTZ} - \mathrm{micro}\big\rangle \sim \prod_{0<n_i^\pm<N^\pm} J^\pm_{-n_i^\pm}\big|0\big\rangle$$

$J^\pm_n$: linear combinations of X_n, P_n; $N^\pm$: mass/angular momentum

Soft Heisenberg hair microstates [Afshar, DG, Sheikh-Jabbari, (Yavartanoo) 2016]

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- Boltzmann's formula yields Bekenstein–Hawking entropy!

$$S = \ln p(N^+) + \ln p(N^-) = 2\pi\sum_\pm \sqrt{c\Delta^\pm/6} + \dots = \frac{A}{4} + \dots$$

  ... denote subleading (log-) corrections

Outline

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We can expect many new applications in the next decade(s)!

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Observable of interest is shear viscosity over entropy density, η/s

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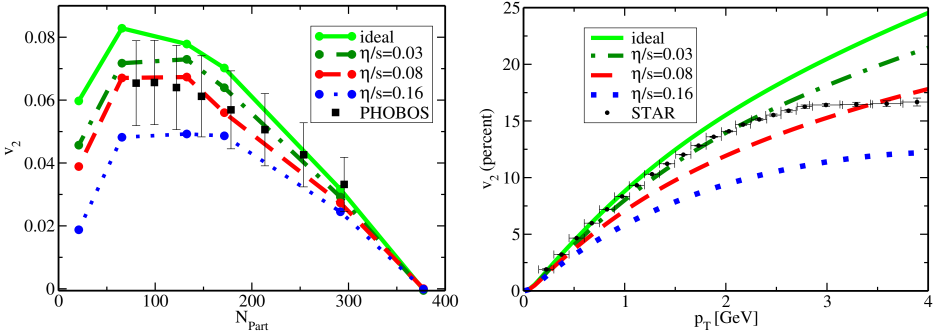
Simple and sharp prediction from holography for η/s in strongly coupled non-Abelian plasma

Experimental results [see e.g. Romatschke, Romatschke 2007]



Best fit of data [Luzum, Romatschke 2008]

$$\frac{\eta}{s} = 0.10 \pm 0.10(\text{theory}) \pm 0.08(\text{experiment})$$

Compare with holographic prediction

$$\frac{\eta}{s} = \frac{1}{4\pi} \approx 0.08$$

Summary

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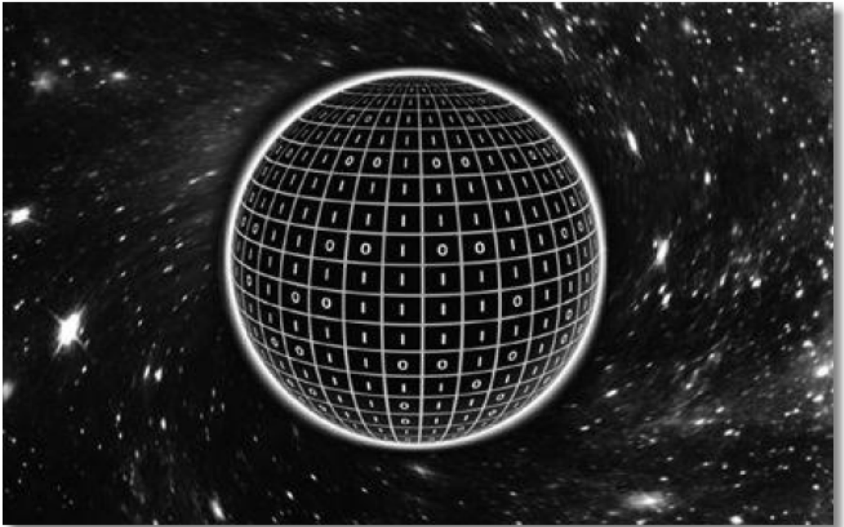

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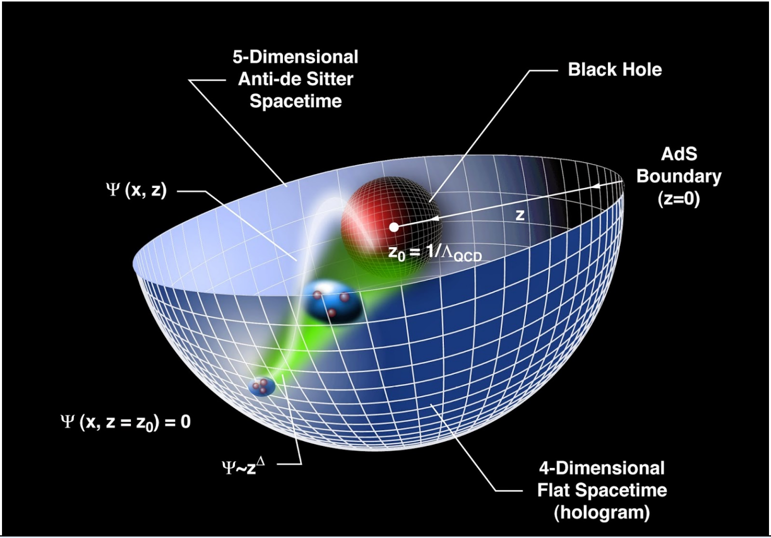

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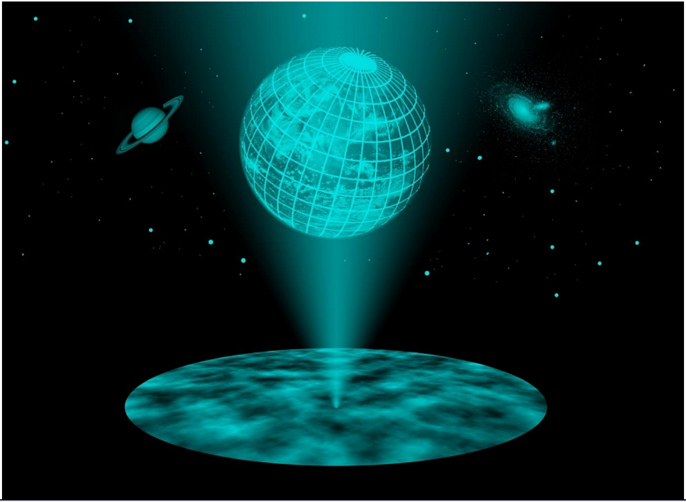

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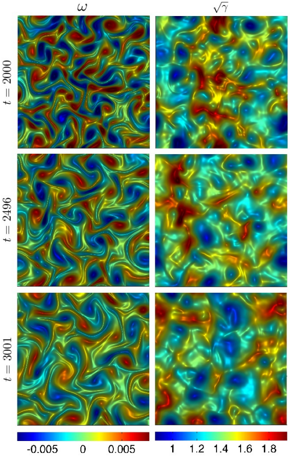
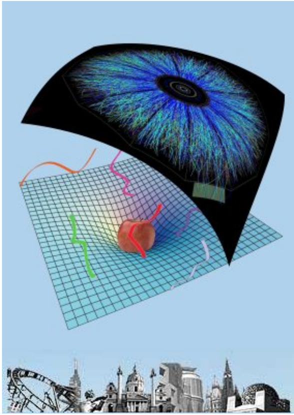
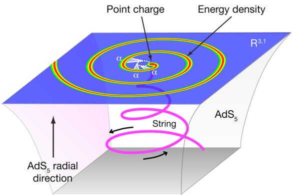
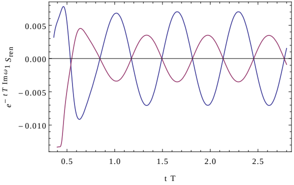
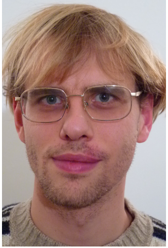








My black holes & holography group at TU Wien (postdocs & PhDs)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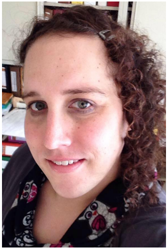
Mirah Gary


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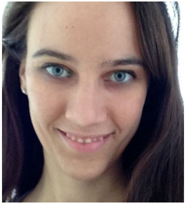
Iva Lovrekovic


Stefan Prohazka


Jakob Salzer


Friedrich Schöller


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Thank you for your attention!