# Gauge-gravity duality and aspects of strongly coupled systems

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# Outline

Holography: gauge-gravity duality

the concept

Where string theory enters

AdS/CFT correspondence: specific realizations and a strong-weak duality

AdS/CFT and strongly coupled physic at RHIC

what we are learning

Applications to other strongly coupled systems

top-down vs bottom-up approaches

Taking stock & Conclusions

where we stand, where to go

# Black holes: the "harmonic oscillator" a la mode

Conceived by Laplace a long time back ~ 18th century

Picture taken from Wikipedia image

Solutions of Einstein's equations of motion
*They exist!*

Characterized by an event-horizon: nothing inside it can ever come out

Perfect tool to play with various theoretical concepts

# Holography: gauge-gravity duality

## Apply quantum mechanics to black holes: the black hole ain't so black!

The event-horizon gives Hawking radiation
black hole has a temperature and an entropy
the entropy goes as the area of the event-horizon

$$S = \frac{A}{4G}\left(\frac{k_B c^3}{\hbar}\right)$$

(Bekenstein, Hawking '70s)

## Quantum gravity in (d+1)-dim spacetime = theory living on the d-dim boundary

Quantum field theory in d-spacetime dimensions is described by quantum gravity in (d+1)-dimensions & vice versa

('t Hooft, Susskind '90s)

# Where strings enter: AdS/CFT

Large N gauge theories are secretly string theory

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Large N gauge theories are secretly string theory

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**Concrete examples of the holographic principle can be realized**

generally known as the AdS/CFT correspondence

classical gravity in (d+1)-dim anti de-Sitter = strongly coupled conformal field theory in d-dim

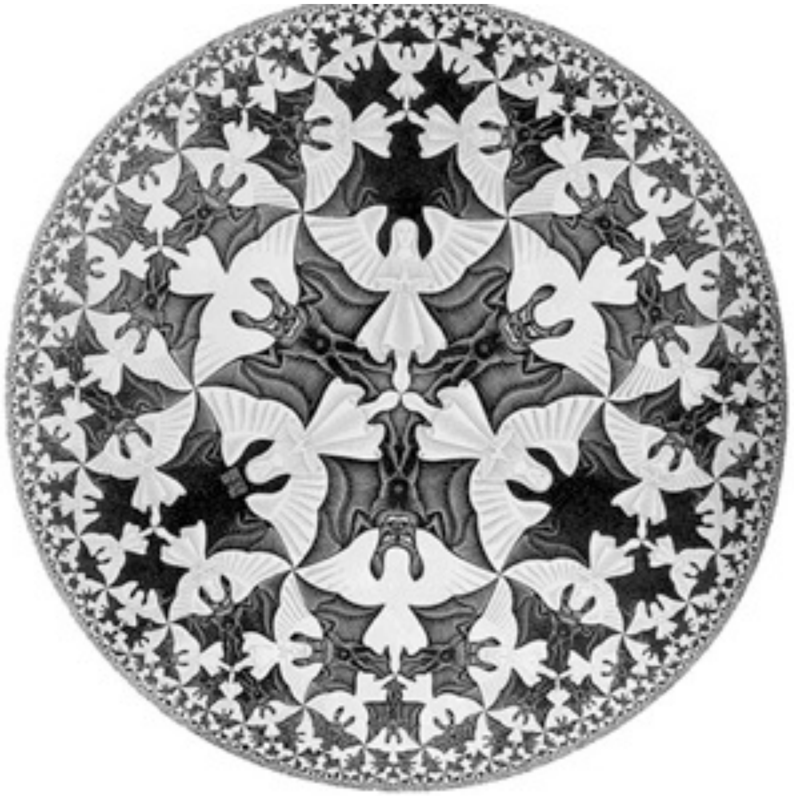
a family of such examples, both conformal and non-conformal

*and the list keeps growing ...*

(Maldacena '98)

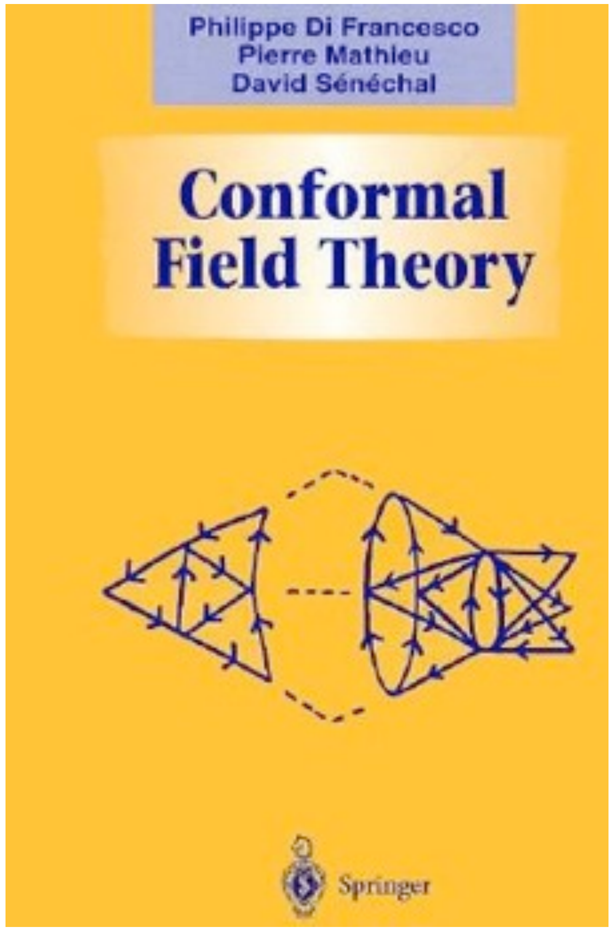
**A strong-weak duality, controllable at large N**

# Introducing the characters



Courtesy: M. C. Escher

AdS = solution of Einstein gravity with a -ve cosmological constant




CFT = describes scale-invariant systems

# Ingredients from string theory

Dp-branes: (p+1)-dim extended object where a string ends

*(e.g., D3-branes)*

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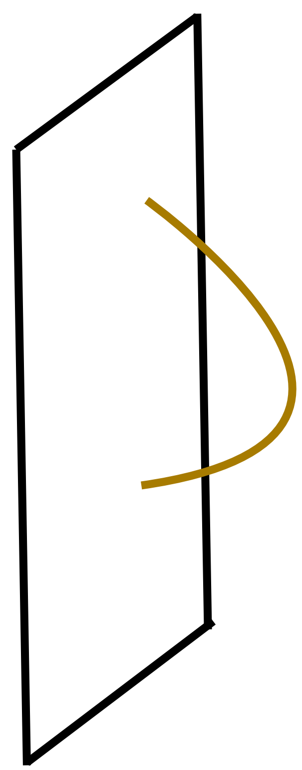

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susy gauge theory

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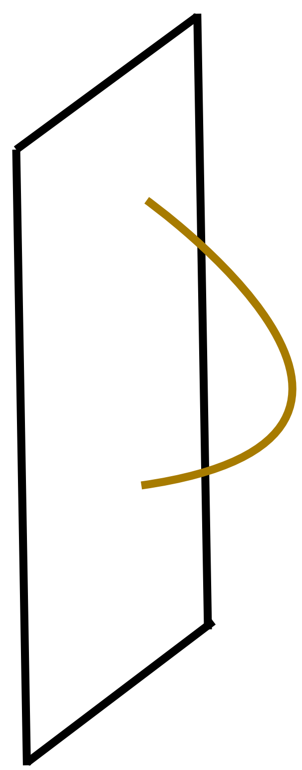

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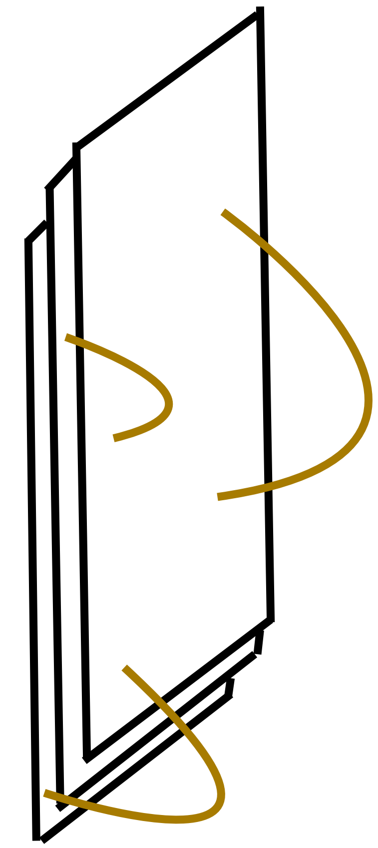


U(N) for N coincident branes

low energy physics described by a (p+1)-dim gauge theory

*(e.g., $\mathcal{N}$=4 SYM)*

# Ingredients from string theory

*(e.g., D3-branes)*

Branes also have gravitational footprint

Decoupling of the gauge theory from the rest of the "stringy" physics gives a "near-horizon" geometry

$$AdS_5 \times X^5$$

The anti de-Sitter part → $AdS_5$

some compact manifold → $X^5$

$N$ large

$\lambda = g_{\rm YM}^2 N$ large

*controllable geometry*

# A summary: an example

Classical (super)-gravity in

$AdS_5 \times S^5$

(only closed string modes)

Strongly coupled $\mathcal{N} = 4$

super Yang-Mills (SYM)

(only adjoint d.o.f.)

Isometry group:

$SO(4,2) \times SO(6)$

AdS-part ↗ sphere-part ↖

Global symmetry group:

$SO(4,2) \times SO(6)$

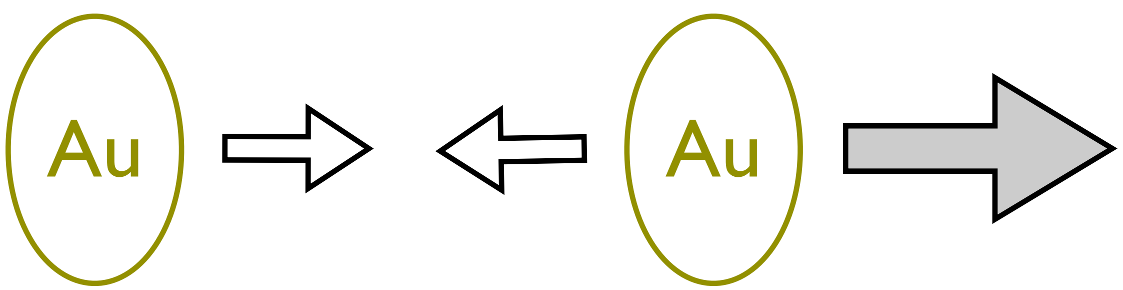
conformal group ↗ R-symmetry group ↖

AdS-black hole geometry

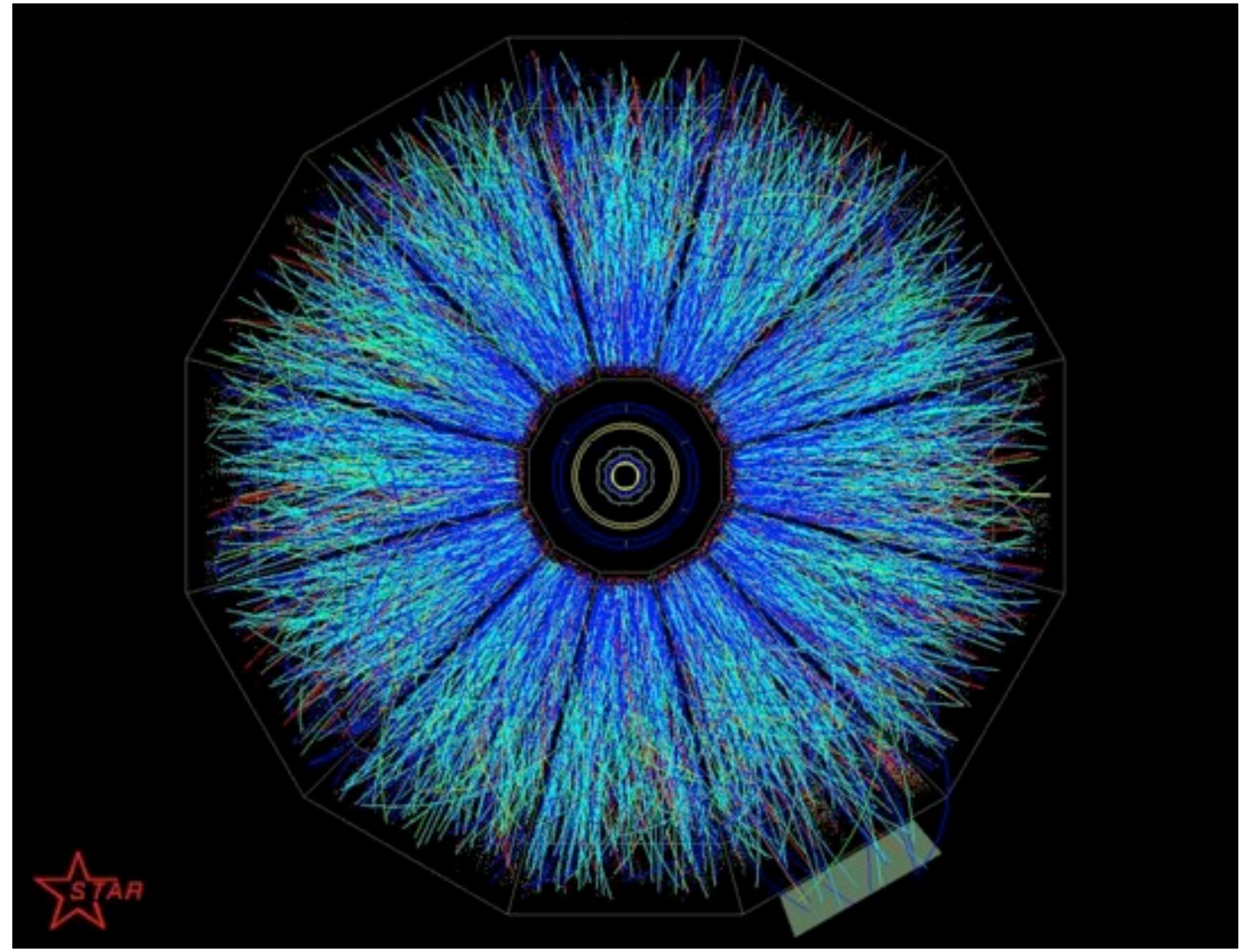
finite T physics

*classical gravity calculations teach us about strongly coupled gauge theory*

# QGP at RHIC




~ 200 GeV/nucleon




Courtesy: Wikipedia image

The physics is described by strongly coupled Quantum chromodynamics

*This is a hard deal!!*

# AdS/CFT: can it be useful?

QCD & large N gauge theory: So many differences!!

Perhaps strong coupling and finite T governs the physics ...

**QCD**

strongly coupled plasma of gluons and fundamental matter; deconfined, screening, finite correlation length, ...

**SYM**

strongly coupled plasma of gluons and adjoint matter; deconfined, screening, finite correlation length, ...

⇨ at RHIC energy

May learn qualitatively useful lessons

# Towards a smoking gun

RHIC produces a nearly ideal fluid, with a very low viscosity/entropy ratio

$$\frac{\eta}{s} \approx \frac{1\,\mathrm{to}\,3}{4\pi}$$

$$\hbar = 1\,, \quad k_B = 1$$

Courtesy: Wikipedia image

*There is no theoretical computation to produce a similar result*

# The smoking gun

(Kovtun, Son, Starinets '05)

AdS/CFT translates this into a scattering problem in gravity

Can be performed for a large class of 10-dim backgrounds:

$$AdS_5 - \mathrm{BH} \times X^5$$

some compact manifold

Dual to large N gauge theories with various amount of susy

Universal result: $\frac{\eta}{s} = \frac{1}{4\pi}$ with $\hbar = 1$, $k_B = 1$

## Taking stock

Some universality indeed exists

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Do the details matter at all: what are the extra dimensions doing?

*is it always enough to consider some low dimensional effective gravity theory in AdS?*

If details do not always matter, can we be more adventurous?

*try to capture other strongly coupled systems, without worrying about microscopics*

*symmetry is the guide*

# Details matter, at least sometimes

Stringy embedding ensures the duality in a precise sense

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There is physics where the 10-dimensional details are crucial

*e.g. the "QCD" phase diagram*

Physics in the flavour sector: "quarks" in AdS/CFT

introduce branes of various dimensions as "test particles" in the 10-dim geometry

these "test particles" are aligned in the 10-dim background in a certain way

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*stability*

*what physics we want to engineer*

# The rough idea: an example

Background geometry is made of $N_c$ D3-branes

Add $N_f$ D7-branes with $N_f \ll N_c$ (Karch, Katz '02)

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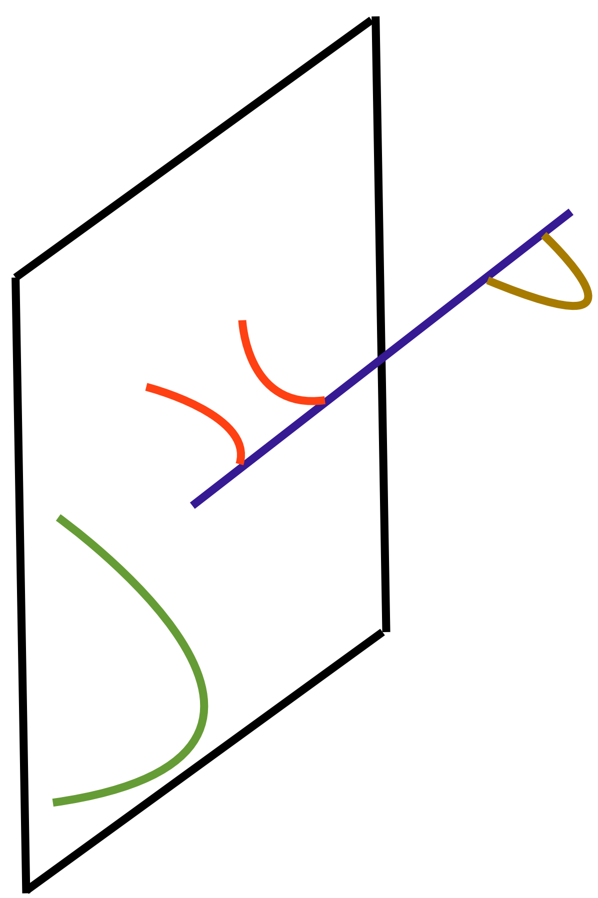

3-3 strings: adjoint sector

3-7 strings: fundamental matter

7-7 strings: global symmetry $U(N_f)$

D7-branes are simple probes of the geometry

their dynamics determine the physics in the flavour sector

# Is there a smoking gun?

A remarkably rich & varied phenomenology is obtained in the flavour sector phase structure

many features are model-dependent

complete QCD phase diagram not well-understood; the results serve as a catalogue, at least

chemical potential is particularly interesting; lattice methods inadequate

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An intriguing example:

An elegant way to realize spontaneous breaking of chiral symmetry:

$$U(N_f)_L \times U(N_f)_R \to U(N_f)_{\rm diag}$$

(Sakai-Sugimoto '04)

# Issues that we can address

*Limitations apply!*

Various phases of flavour matter, in such large N gauge theories + flavours

Phase diagram with various parameters: temperature, chemical potential, electromagnetic fields etc.

Various phase transitions and the order of the transition

Dependence of the phase structure on the number of flavours

*Lattice studies are inadequate*

# Interlude I

# When the details don't matter

## Physics far from equilibrium

*thermalization process of QGP at RHIC or LHC, no good theoretical handle on the physics*

*beyond linear response theory*

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The spherical cow approximation

Analogous problem for a strongly coupled large N gauge theory instead

*a classical gravity computation*

$\mathcal{N} = 4$ SYM

# When the black hole is forming

Thermalization process in a large N gauge theory ⟺ The formation of a black hole in AdS-space

*Need numerical GR in AdS-space*

*hard problem*

(Chesler, Lehner, Pretorius etc.)

# When the black hole is forming

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*Need numerical GR in AdS-space*

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(Chesler, Lehner, Pretorius etc.)

A simpler approach: model the black hole formation process *ab initio*

clue: an interpolation between a purely AdS to an AdS-black hole background

strategy: come up with a simple background that does the job

advantage: such a background can be probed for various kinds of physics, *easily*

(Balasubramanian et al '10, etc.)

# The AdS-Vaidya background

Gravitational collapse of a shell of null dust

The background is characterized by a mass function:

$$m(t) \to 0 \ , \quad t \to -\infty$$ pure AdS

$$m(t) \to M \ , \quad t \to +\infty$$ AdS-black hole

$m(t)$ is a simple interpolating function

We can extract the thermalization time

Study non-local operators

*2-pt function, Wilson loop, entanglement entropy = minimal area surface computation in gravity*

# Is it meaningful?

What one obtains: $\tau_{\rm therm} \approx 0.3 fm/c$

What one observes: $\tau_{\rm obs} < 1 fm/c$

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Introducing a chemical potential:

$T\ell \ll 1$ thermalization time decreases with increasing $\mu/T$

$T\ell \gg 1$ thermalization time increases with increasing $\mu/T$

$T$ : temperature

$\mu$ : chemical potential

$\ell$ : length of the operator

(Caceres & Kundu '12)

# Interlude II

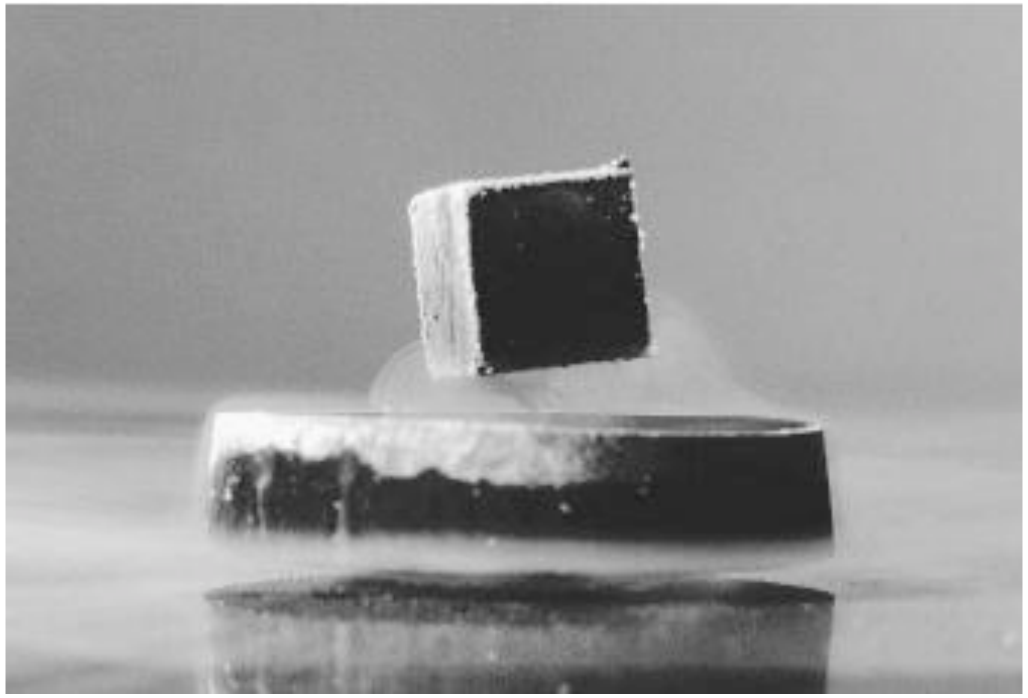
# Top-down vs bottom-up

| Top-down | Bottom-up |
| --- | --- |
| Full 10-dimensional (super)-gravity embedding | Effective low-dim gravity model |
| The duality dictionary is precise | The duality is postulated *ab initio* |
| Harder: limited number of examples exist | Simpler: more diverse phenomenology |

# An "application": holographic superconductors

An interesting state of matter with zero electrical resistivity

BCS theory does explain a class of these



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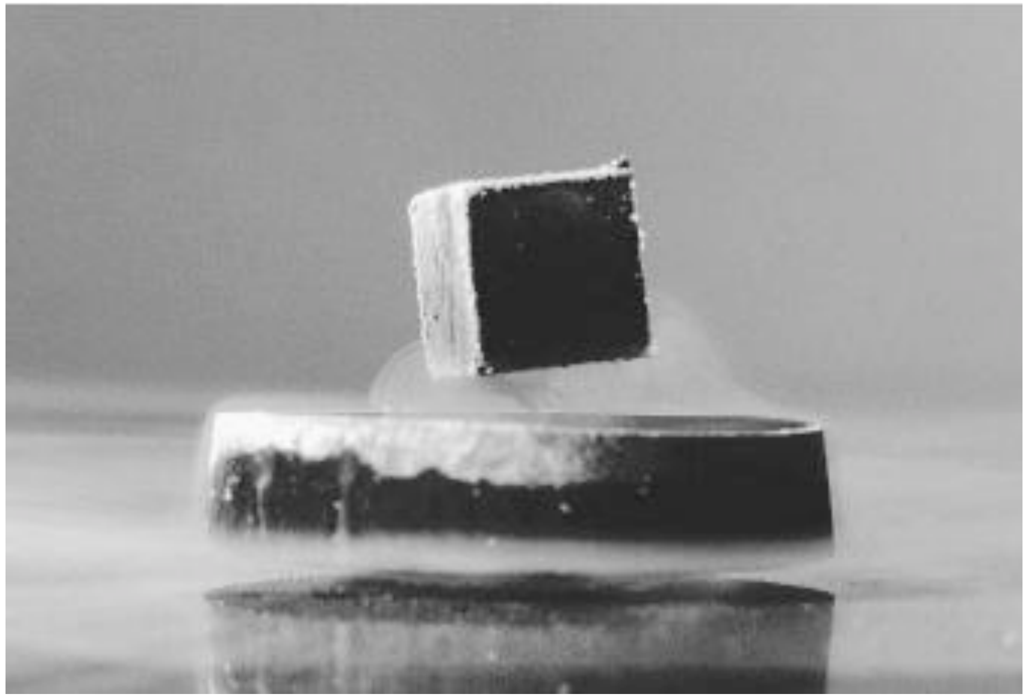

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We will appeal to:

Weinberg: “Superconductivity for particular theorists”

For our purposes, superconductivity = spontaneous breaking of global U(1)

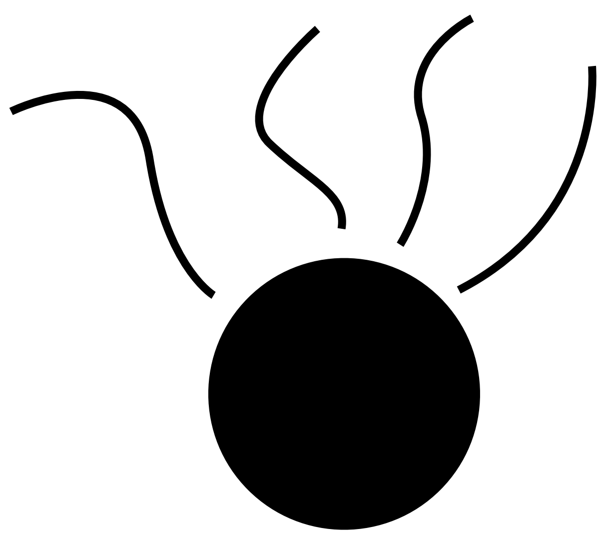
# Holographic superconductors: ingredients

Abelian Higgs model coupled to Einstein gravity with -ve cosmological constant

*(Bottom-up model)* (Gubser; Hartnoll, Herzog, Horowitz '08)

$$\mathcal{L} = \frac{1}{2}R - \frac{1}{4}F^2 - |\partial\phi - iqA\phi|^2 - V(|\phi|)$$

*tunable* ($q$) *choose at will* ($V$)

Ground state:  black hole with scalar hair!

hair = condensate, hence symmetry breaking

# Holographic SC: stringy embedding

The effective model can be embedded in 10 and 11-dim sugra

*(Top-down model, freedom to tune is constrained)*

(Gauntlett, Sonner, Wiseman '09)

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(Most of the) above embeddings are unstable, the fate of the rest is unclear!

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There is an embedding without any known pathology

*it's subtle!*

(Bobev, Kundu, Pilch, Warner '11)

Behaves like a superconductor, but has an explicit breaking of the U(1)

Universal: hairy black holes are always favoured, a superconducting phase transition with T

*can also be a 1st order phase transition*

# Taking stock: concluding remarks

Stringy embeddings are important

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What are we learning? Why do this?

at least a catalogue of possibilities: phases of matter described by such theories

*various phases have been realized: non-Fermi liquids, non-relativistic scale-invariant systems, etc, etc..*

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if not about condensed-matter physics, we learn about gravity

*the existence and constructions of hairy black holes, numerical GR in AdS etc.*

Exciting times are ahead!

# Thank You