INSTITUTO DE FÍSICA

PONTIFICIA UNIVERSIDAD CATÓLICA DE VALPARAÍSO

Black Holes and Holography

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29 August 2019

Departamento de Astronomía, Universidad de Chile

AdS/CFT correspondence

- Proposal of the Argentinean physicist Juan Maldacena 1997
- Special case of the so called Holographic principle
- In five years, the article of Maldacena had 3000 citations and it has become one of the most evident conceptual advances of theoretical physics of 90's.
- At the moment the paper has 14845 citations


dossier Newsweek

EL PODER DE LA MENTE

THE POWER OF THE MIND

El más brillante de los científicos argentinos habla sobre el origen de las ideas, la música de las matemáticas y su "viaje" a través del espacio-tiempo con lápiz y papel. / *The most brilliant Argentine scientist tells us about the origins of ideas, music and mathematics, and of the "journey" through time and space that he took with pencil and paper.*

Texto / Text: Por Matías Loewy

64 Cielos Argentinos : Octubre / October 2012

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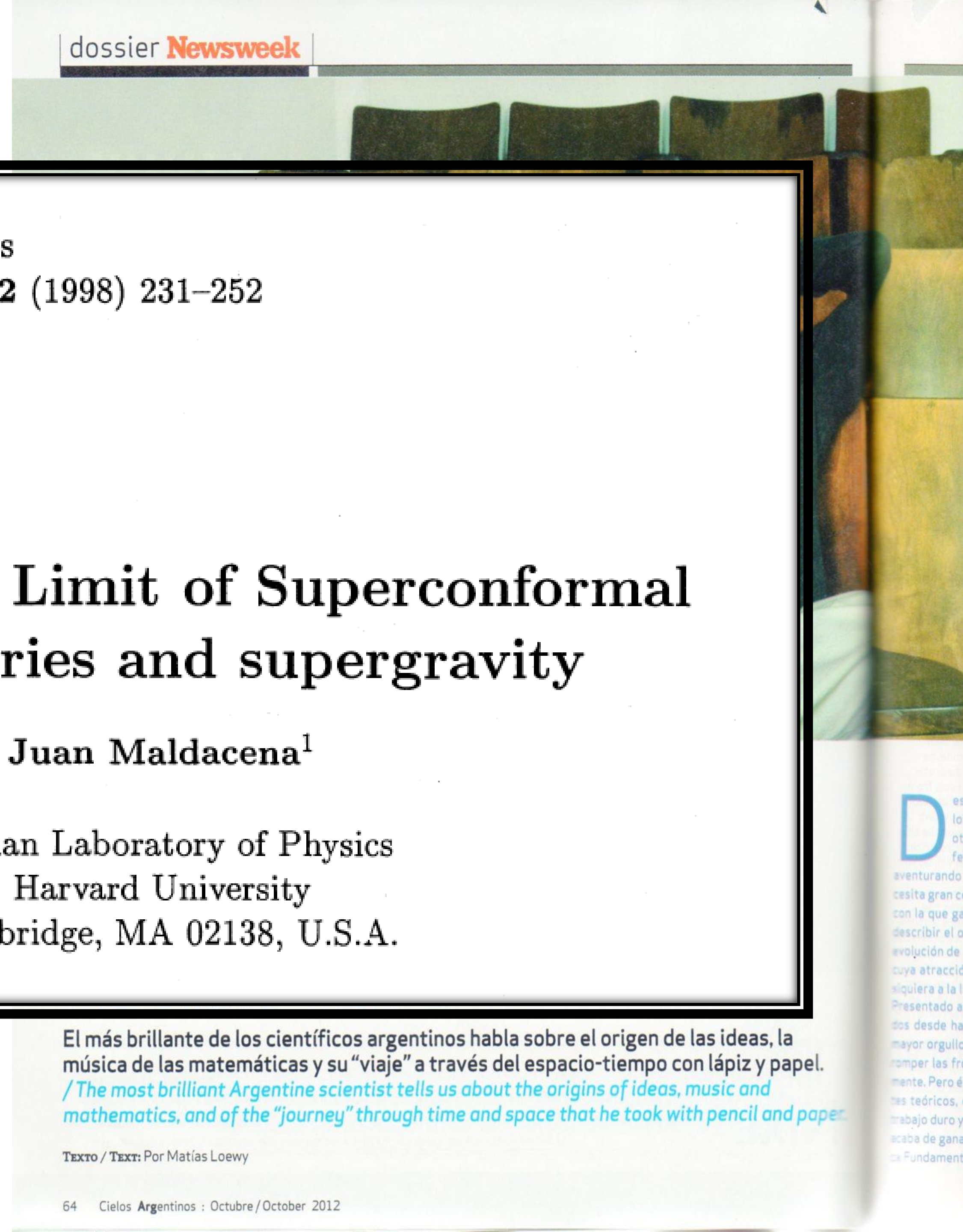


Adv. Theor. Math. Phys. **2** (1998) 231–252

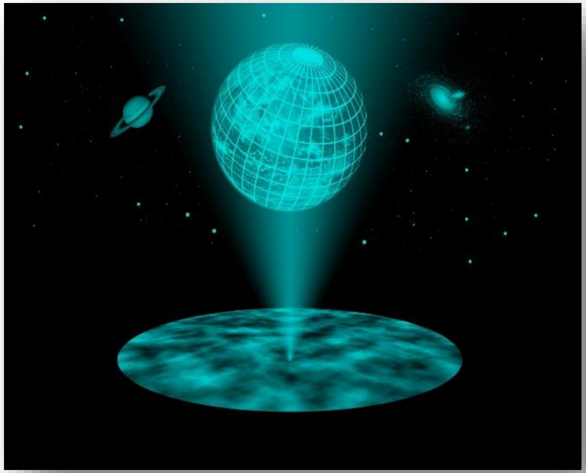
The Large N Limit of Superconformal field theories and supergravity

Juan Maldacena[1]

Lyman Laboratory of Physics
Harvard University
Cambridge, MA 02138, U.S.A.

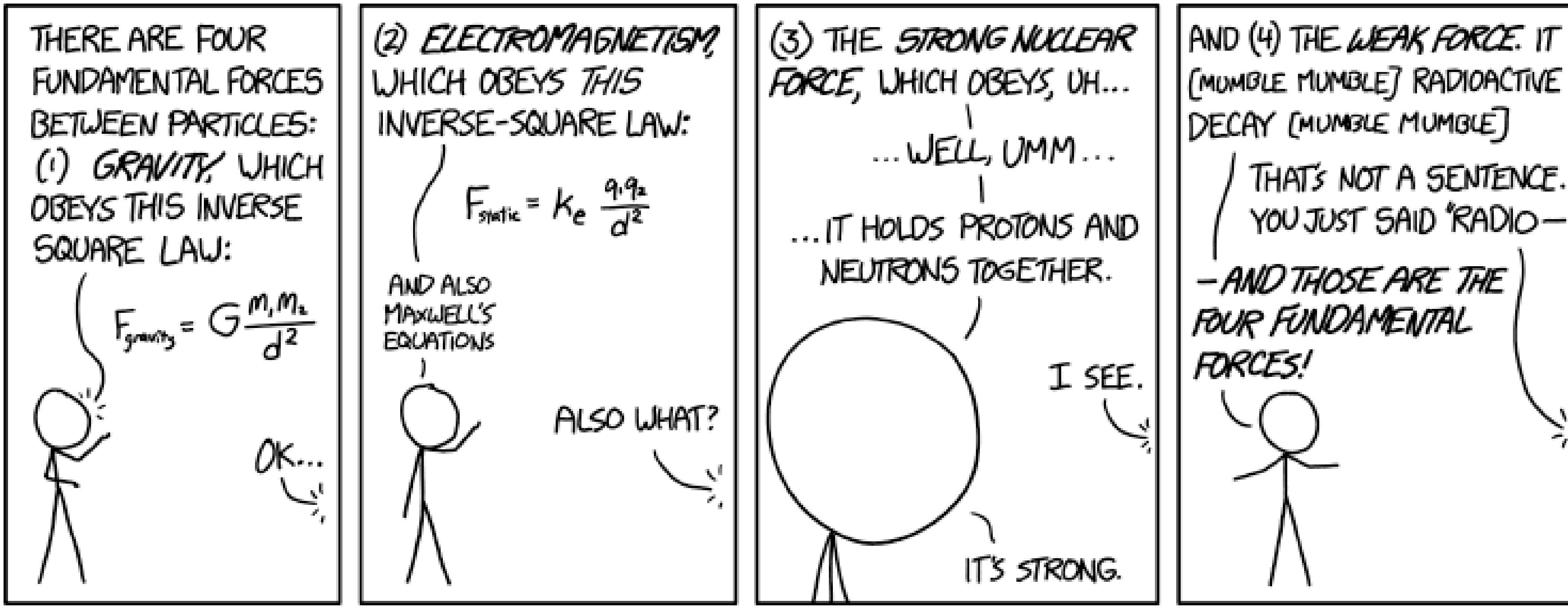
This presentation is about…

- From where the inspiration of holography in gravity comes from
- Why this idea is so successful
- What is a holographic projection of a black hole
- Our contribution to the subject
- Challenges



There is no good quantum theory of everything

Even though the dynamics of the particles has been subjected to only four fundamental forces



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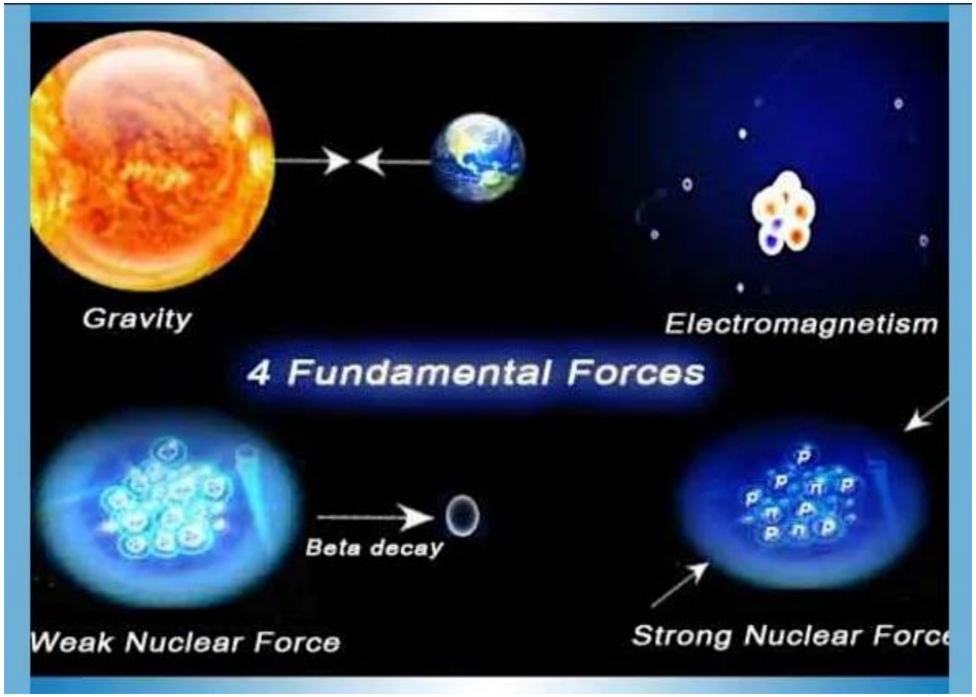


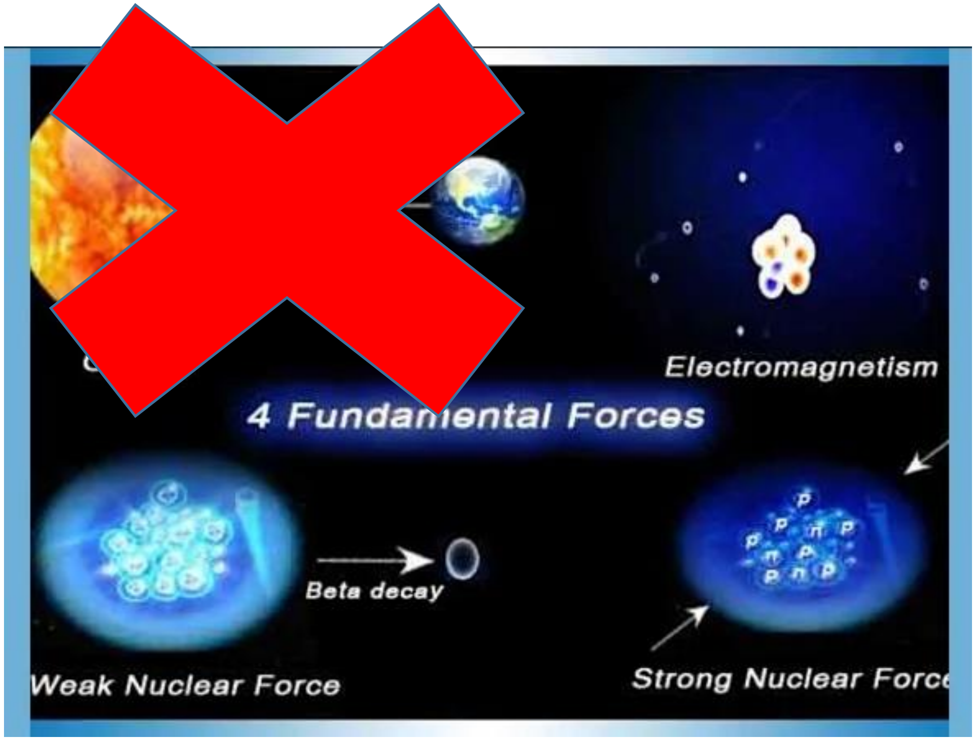
Grand Unified Theory (GUT)
Unifies only three fundamental forces (without gravitation)

Theory of Everything
Unifies all four fundamental forces

There is no good quantum theory of everything

Even though the dynamics of the particles has been subjected to only ~~four~~ **3** fundamental forces

If we forget about the gravitational force, the world is FLAT, described by a Quantum Field Theory

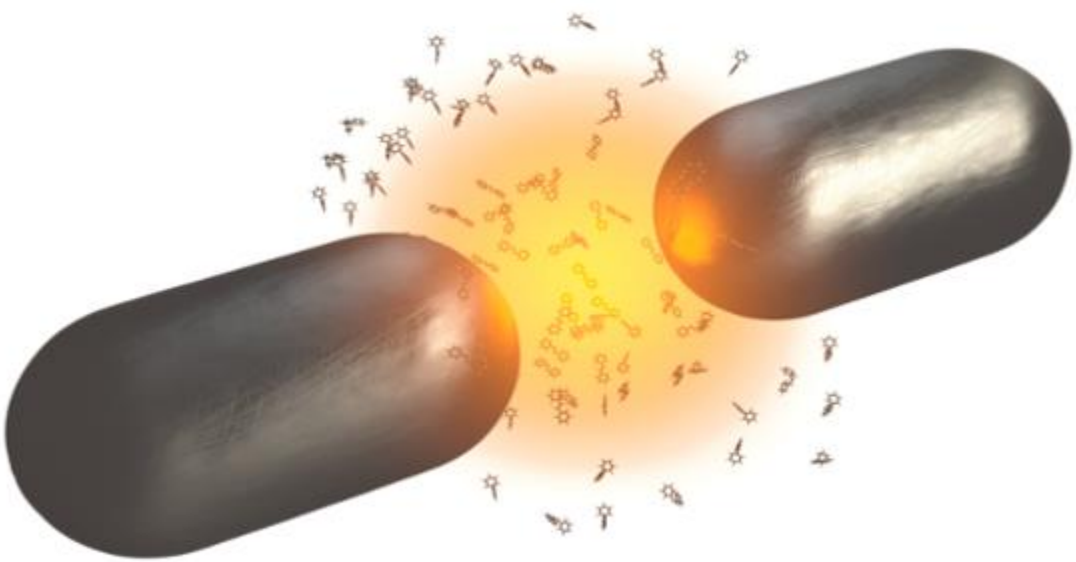


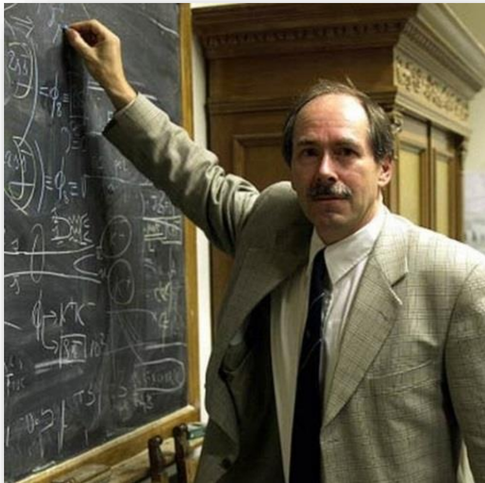
Grand Unified Theory (GUT)
Unifies only three fundamental forces (without gravitation)

Theor[illegible]ything
Unifies [illegible]r fundamental forces

Still there is a big problem of how to treat **the strong coupling** in the quantum field theory

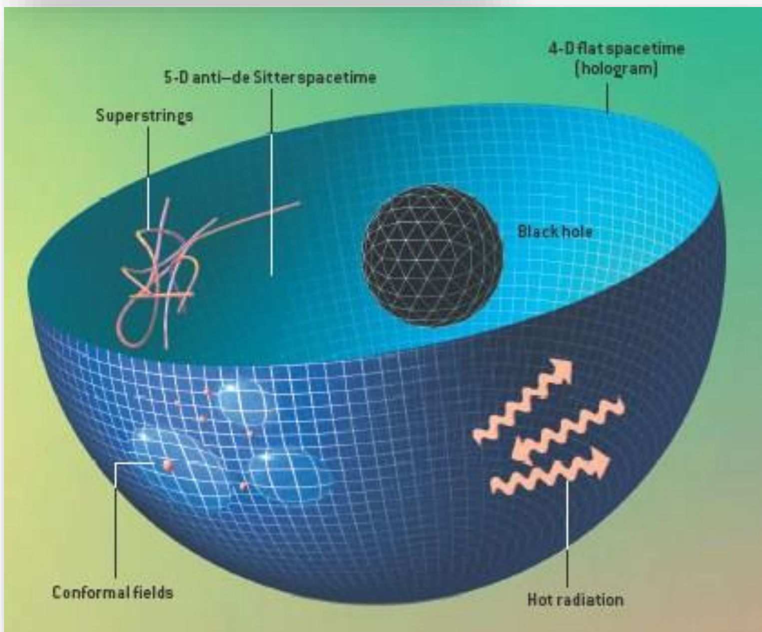
Strong coupling problem appears in Condensed Matter, High Energy Physics, Hydrodynamics, Plasma Physics, Quantum Chromodynamics (QCD), Theory of Complexity, Information Theory, Entanglement Entropy, …





Holographic principle

- Proposed by Gerard ‘t Hooft in 1993
- Developed by Leonard Susskind in 1997



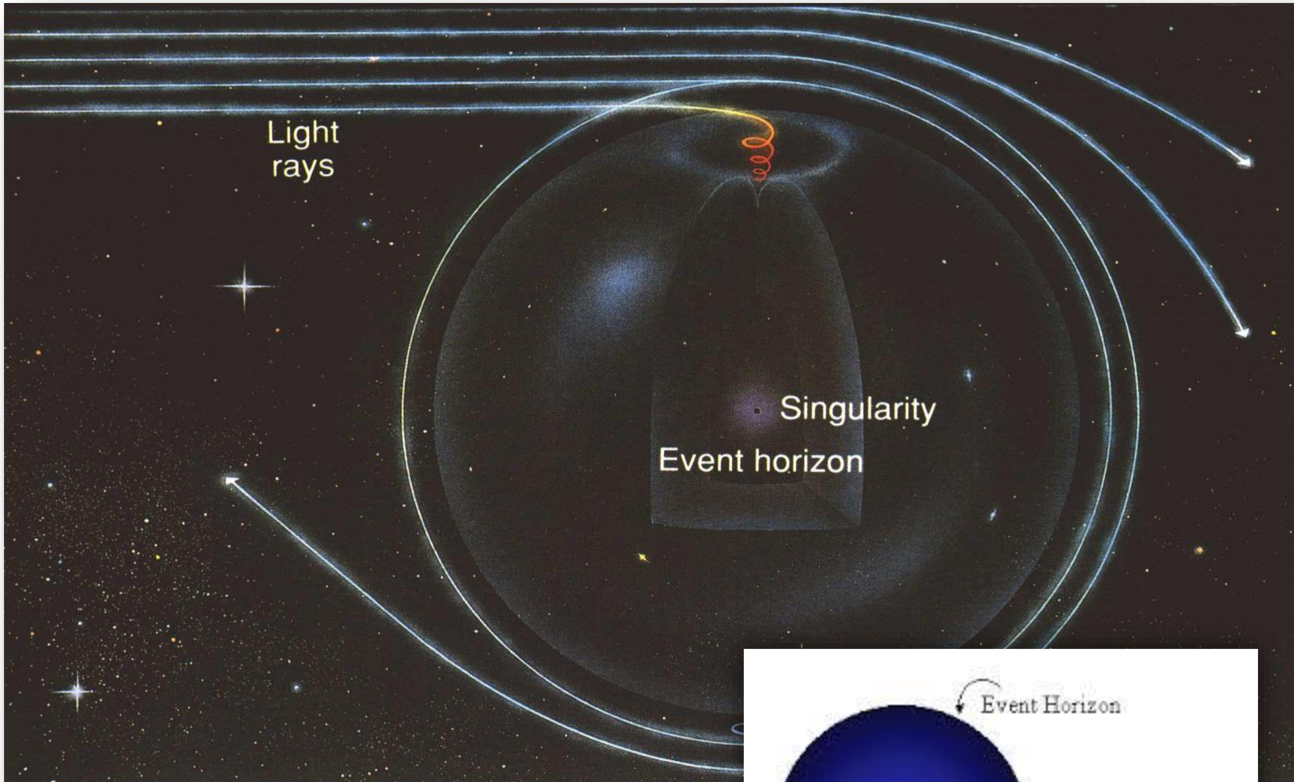
Conjecture

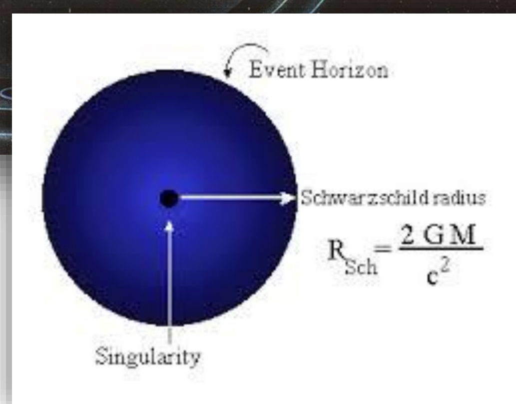
All information contained in a region of a space-time can be fully described through the degrees of freedom contained on its **boundary**. (**‘Holographic projection’**)

Interestingly, from the holographic point of view, our world is located **on the boundary, in the flat space**, and gravity exists only in the curved spacetime volume.

Our real (*d*-dimensional) world without gravity is an *effective theory* which is a hologram of another world that has gravity (and it is *d*+1 dimensional).

Inspiration – Black hole entropy





- **Black hole**:
A region of space-time with gravitational force so strong that nothing (not even light) can escape from it.

Black hole is enclosed in the volume within its **event horizon.**

Inspiration – Black hole entropy

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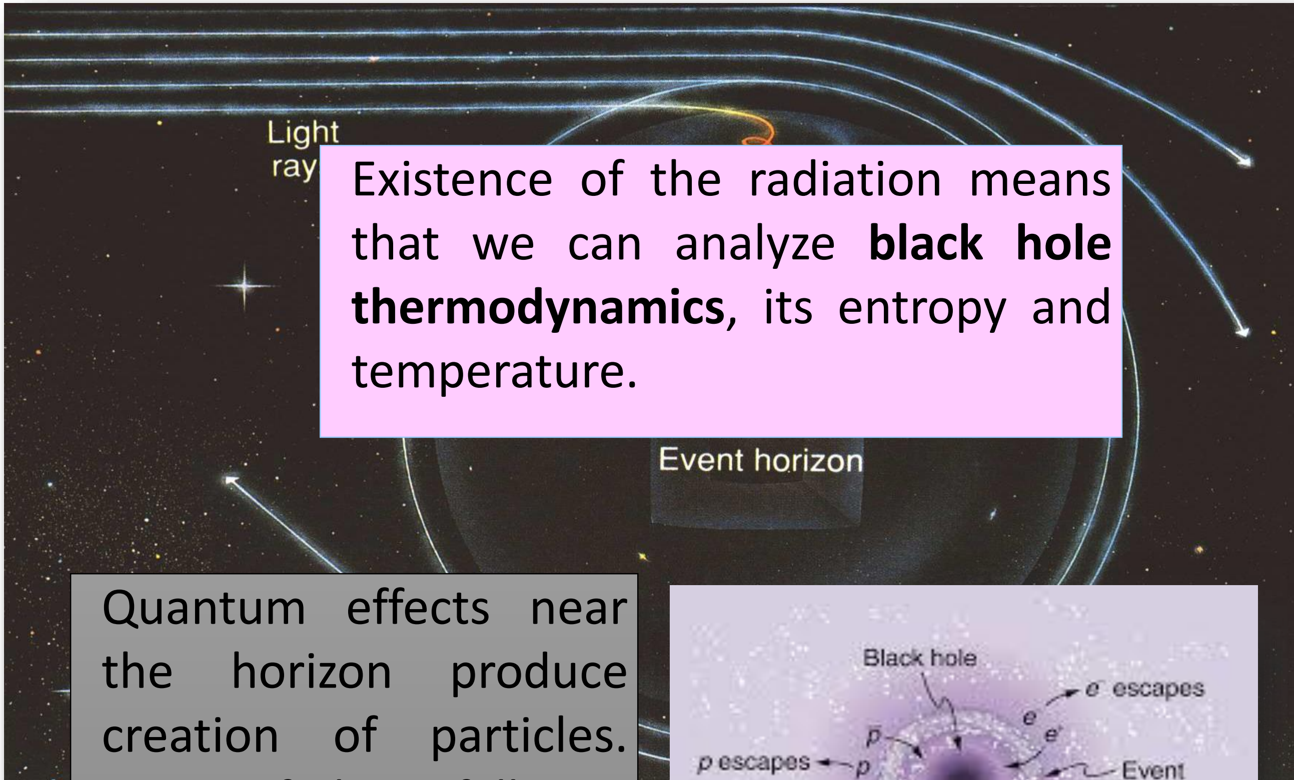
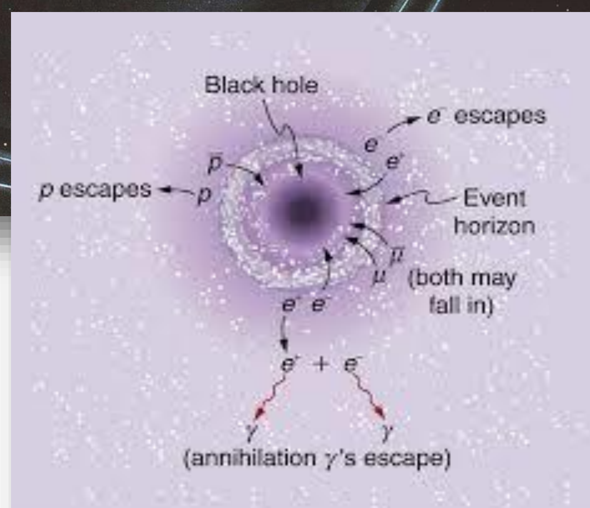
A region of space-time with gravitational force so strong that nothing (not even light) can escape from it.



Existence of the radiation means that we can analyze **black hole thermodynamics**, its entropy and temperature.

Quantum effects near the horizon produce creation of particles. Some of them fall into the black hole, other not, what can be observed as **black hole radiation**.
(Hawking radiation)



Black hole is enclosed in the volume within its **event horizon.**

Black hole thermodynamics

- Study of the black hole horizon from the point of view of the thermodynamic laws

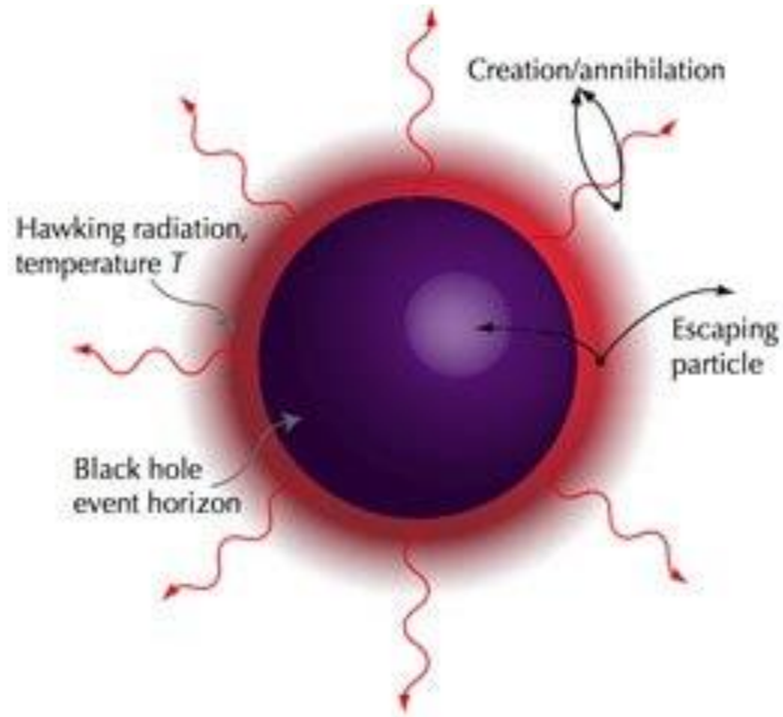
- It shows the aspects of the underlying **quantum gravity**.

Black hole radiation

Hawking radiation

Black body radiation which is emmited by the black hole due to the quantum effects near its event horizon.

In the equilibrium, this radiation has the temperature ***T***.



Laws of the Black Hole thermodynamics

Equilibrium system, reversible process

Law 0 (Concept of the temperature)

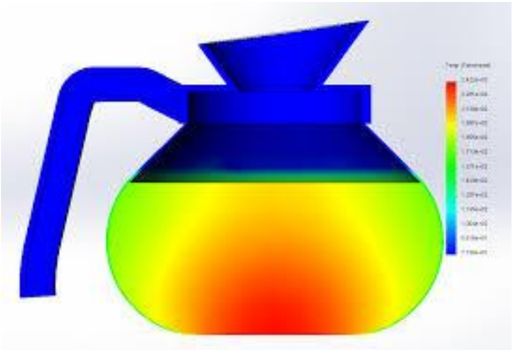
Event horizon of the stationary black hole has constant temperature.

Law 1 (Conservation of energy)

Under perturbations of a stationary black hole, the energy changes according to the conservation law:

$$\delta \mathrm{E} = T\delta S + \Omega\delta J + \Phi\delta Q + \cdots$$

Extensive variables: (E,S, J, Q, N, V, …) *global, constants*
Intensive variables: (T, Ω, Φ, μ, p, …) *local*



Laws of the Black Hole thermodynamics

Equilibrium system, reversible process

Law 2 (Entropy)

The area of the horizon is a nn decreasing function, $\delta S \geq 0$.

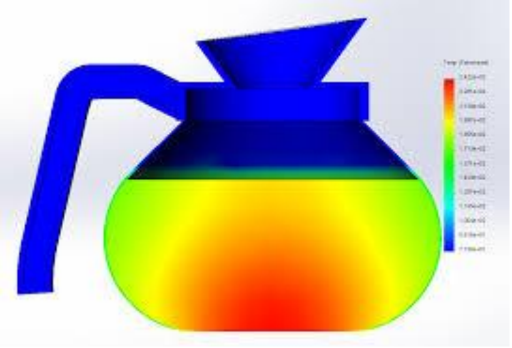
Bekenstein-Hawking entropy: $S = \frac{\text{Area of the horizon}}{4}$

Law 3 (Zero temperature)

Extremal black holes have zero temperature.

Usual thermodynamic systems:

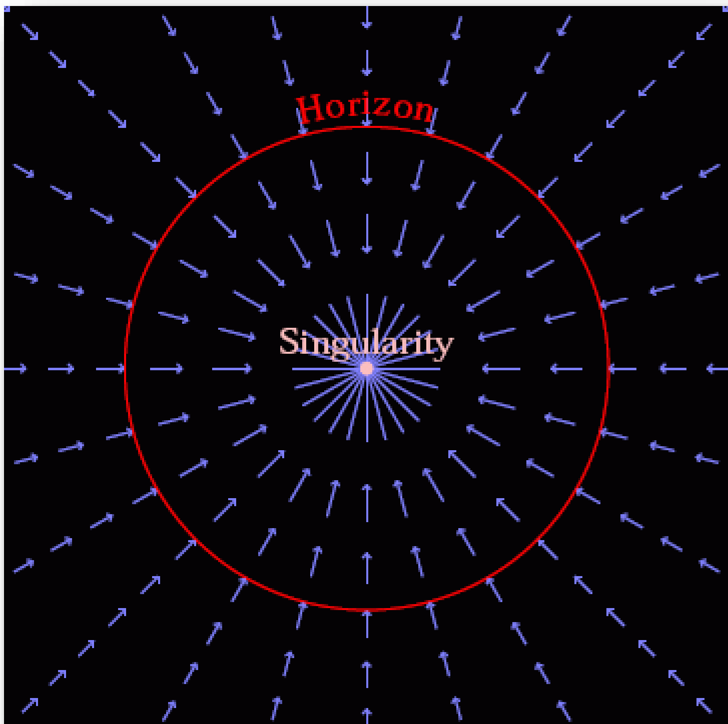
When T=0, the entropy is constant and zero.
Exceptions are non crystal solids (glass) which have constant residual entropy.



Holographic principle and entropy

Example

Even horizon of the black hole



- **Our physical intuition** says that the entropy is proportional to the volume, because it is directly proportional to the mass which is proportional to the volume.

- **Thermal gas** at high *T* has energy and entropy

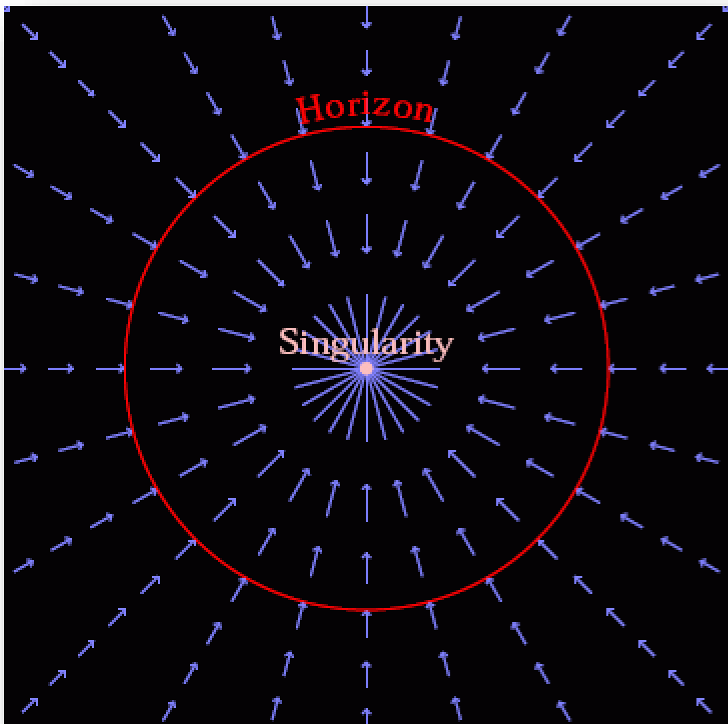
  - D=3: $\mathrm{E} \sim T^3, S \sim T^2$
  - D=4: $\mathrm{E} \sim T^4, S \sim T^3$

- 4D theory has more degrees of freedom than the 3D theory

Holographic principle and entropy

Example

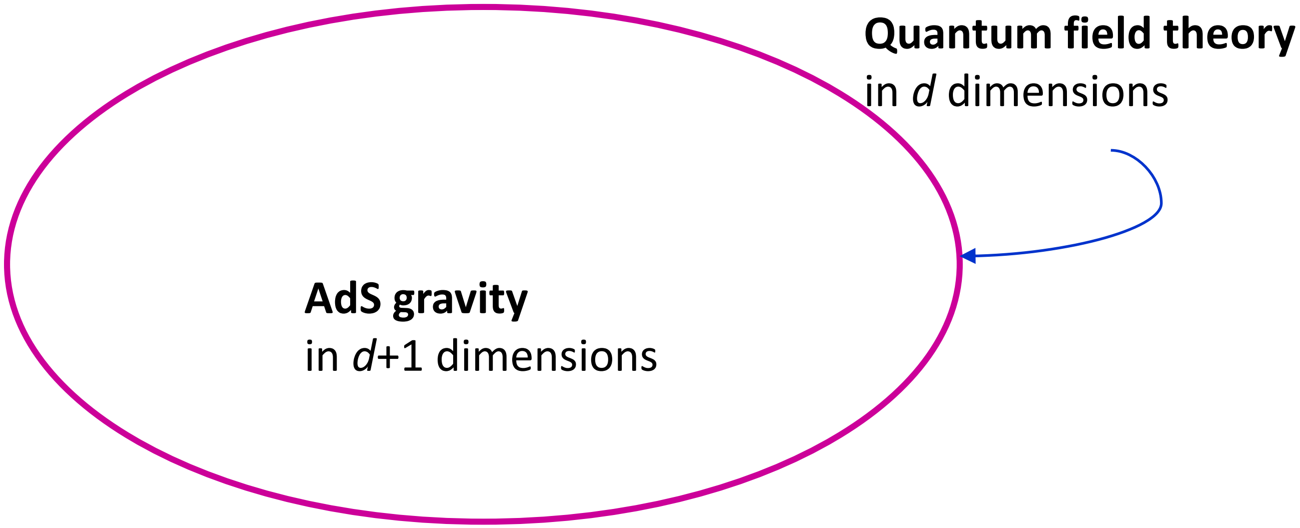
Even horizon of the black hole



- Thermal gas at high T can collapse and form a **black hole** with the event horizon r_H and the temperature $T \sim r_H$.
- Energy and entropy of a black hole in 4D coincide with a thermal gas in 3D.
- This implies that the mass occupies an **area**, and not a volume, so that the whole information about the (gravitational) universe is encoded in its boundary as a **hologram.**

AdS/CFT correspondence

This is a holographic principle applied to a (d+1)-dimensional gravity with a negative cosmological constant (i.e., **anti-de Sitter (AdS) gravity**), and a d-dimensional **conformal field theory (CFT)** living on its boundary.

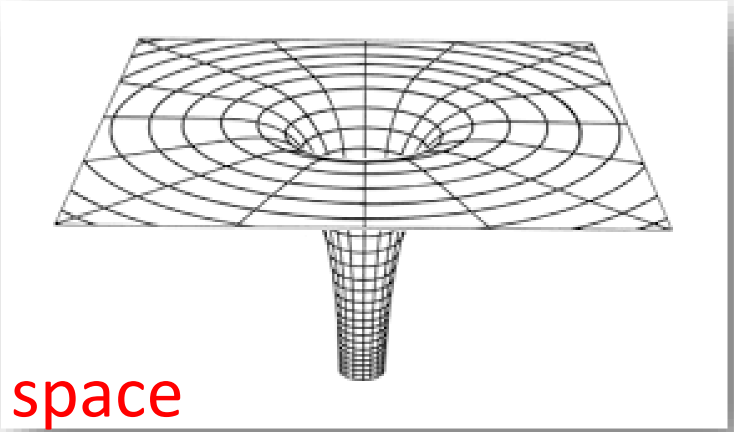


AdS/CFT correspondence

- **Conformal transformations** preserve the angles
- **Conformal symmetry** is typical in condensed matter systems close to the critical point where a phase transition occurs

- More precise mathematical statement **equals two quantum theories (AdS gravity and CFT)**, in the sense of equality of their quantum partition functions.
- In practice, we work **in classical gravity**, which corresponds to a **strongly coupled** field theory.

Why AdS space?



It is a constant curvature hyperbolic space

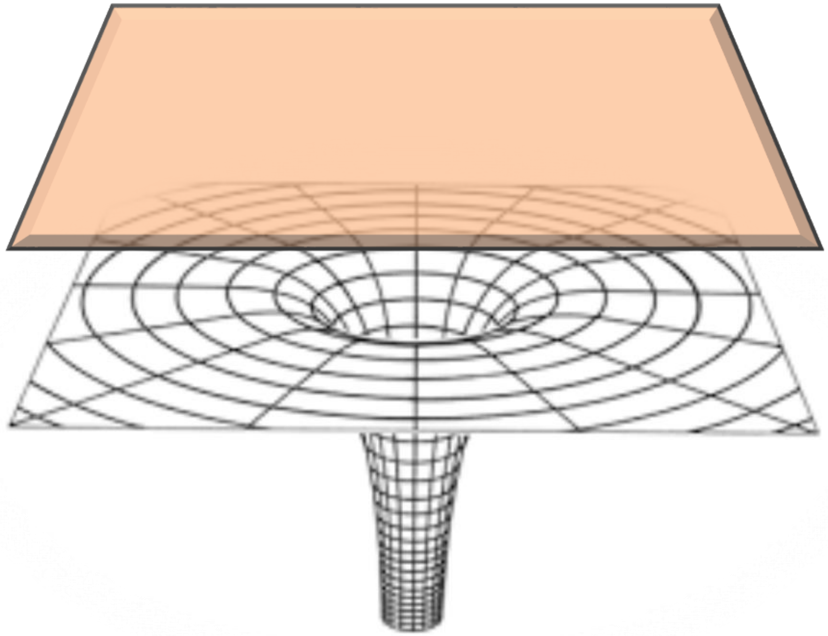
$$-t^2 + x^2 + y^2 + z^2 - u^2 = -\ell^2$$

Its boundary is a flat (Minkowski) space

- Quantum field theory lives in the Minkowski space, which is an asymptotic boundary ($r \to \infty$) of the AdS space
- Moreover, large distance in gravity corresponds to low energy in a field theory, so there is a **duality** between them
- For example, to obtain a UV finite quantum field theory (difficult), **gravity has to be IR finite (easy)**

AdS/CFT Conjecture - summary

Classical gravity in AdS space ⟷ duality ⟷ **Conformal Field Theory on the boundary**

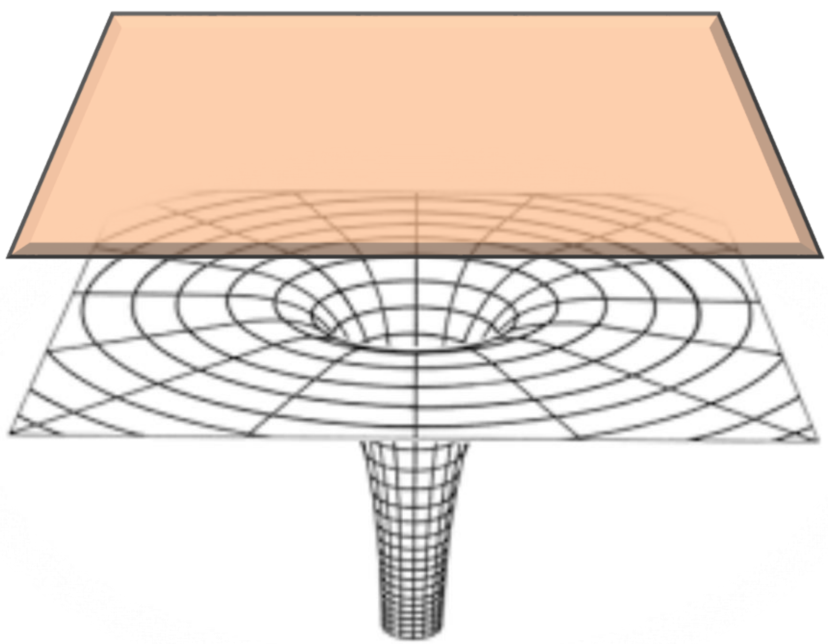


High energy

Low energy

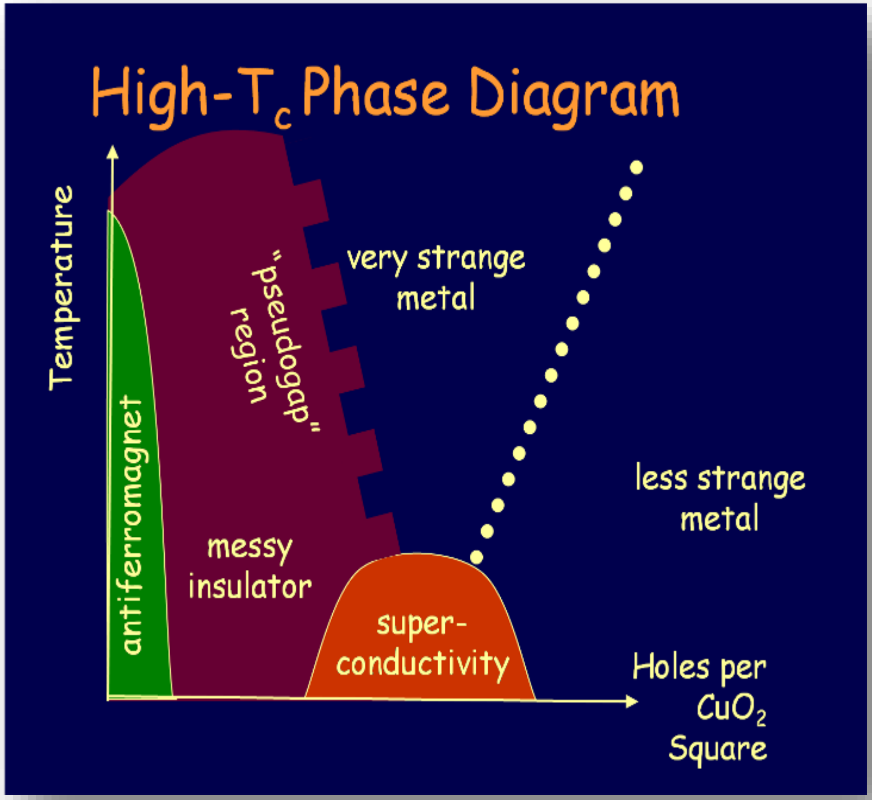
AdS/CFT Conjecture - summary

Holographic calculations are so important because they are a powerful **analitical mathematical tool** **to obtain non-perturbative results** about strongly coupled systems in the flat space .



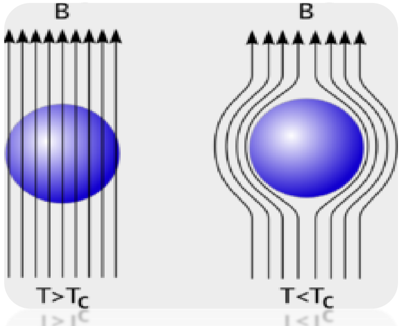
Application: Holographic superconductors

Properties of superconductors below some critical temperature T_c



Electric :
They conduct electric current without resistance and energy loss

Magnetic:
Meissner effect, magnetic field cannot penetrate into the material

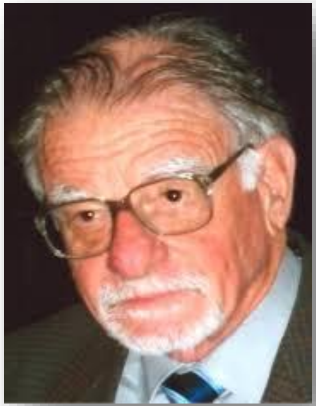


Holographic Superconductors

High Tc superconductors

- **Discovered in 1986, received Nobel Price in Physics in 1987**

Johannes Georg Bednorz



Karl Alexander Müller

- **There is no good microscopic theory to explain them**
- **BCS theory (1957) fails for T_c >30K.**

Holographic Superconductors

Gauge/Gravity duality is the only analytic method to calculate properties of high *T* superconductors.

How to model a physical theory of a Holographic Superconductor

Minimal field content in AdS gravity necessary to describe a superconductor in a quantum field theory

Superconductor	Gravity	Field
Has constant T	Has Hawking *T*, we need a black hole	Metric, $g_{\mu\nu}(x)$
Satisfiedsthe Ohm Law $J = \sigma E$	Charged black hole	Electromagnetic field, $A_\mu(x)$
Possess an order parameter, O	Hairy black hole	Scalar field, $\psi(x)$

Holographic Superconductors

- **Superconductor is holographically dual to a hairy black hole**
- When a black hole develops hair, it corresponds to a phase transition of a superconductor from a normal state to a superconducting state

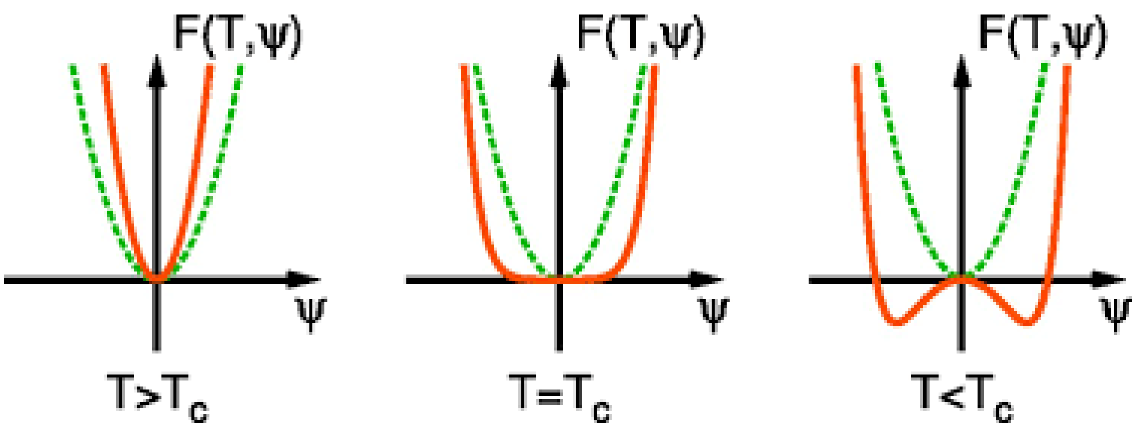
What is black hole hair?

- **No hair theorem**: All black holes in Einstein-Maxwell gravity in asymptotically flat space in 4D can be characterized by only three classical observables from the outside: (M,Q,J). All other information disappears on the horizon.
- **Hair** can appear in D>4, non-flat space, no Einstein gravity, etc.…

A role of the scalar field ψ (order parameter)

$\psi = 0,$ Black hole without hair, $T \geq T_c$
Normal phase of the superconductor, free energy F_0

$\psi \neq 0,$ hairy black hole, $T \leq T_c$
Superconducting phase, free energy $F \leq F_0$



Temperature fluctuation **T** produces a change in the thermodynamic potential **F** and the scalar field ψ ‘detects’ a change in the minimum of the potential because it acquires $\psi \neq 0$

A role of the scalar field ψ (order parameter)

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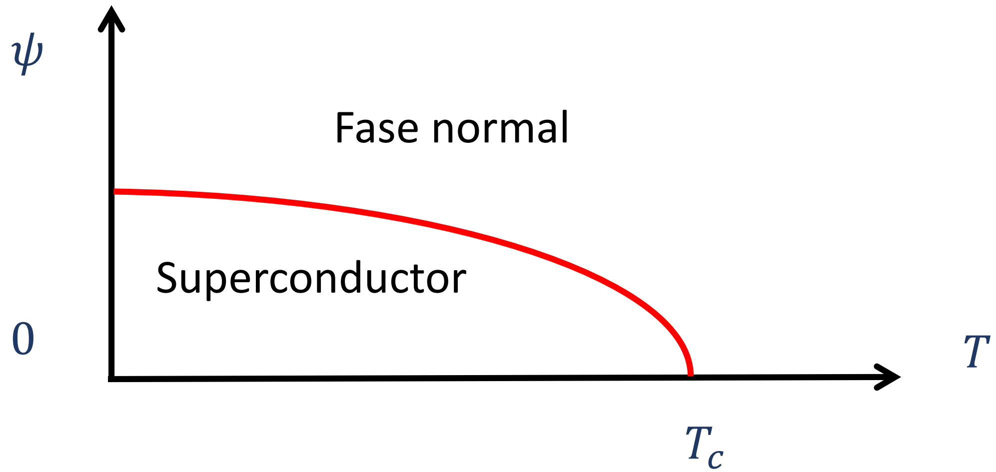
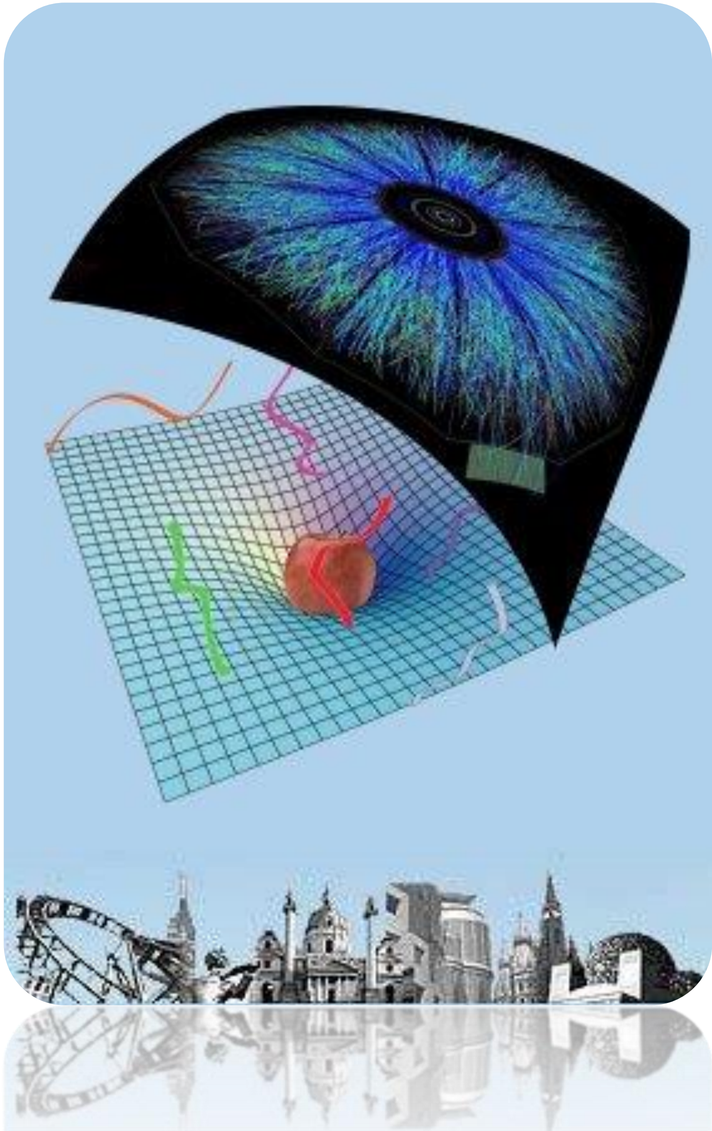


Typical form of the order parameter **which describes a phase transition of the second order**, where the free energy has **discontinuous second derivative in the critical point.**

Holographic superconductor



Goal: to have an unstable black hole

Black hole fluctuations can be rewritten as the **Ohm law** $J_i = \sigma E_i$ where the conductivity coefficient σ presents a linear response of the system to the electric field.

Gravitational equations on the boundary are scale-invariant, what is typical for phase transitions.

The duality between the supercondutor and AdS gravity ensures that the Einstein equation coupled to the EM field and a scalar field contains all the quantum information about the superconductor!

Holographic superconductors

First results

2008—2010, Franco, Hartnoll, Herzog, Gubser, Garcia-Garcia, Horowitz, …

- **Free enrgy** of the superconductor
- Coefficient – **conductivity** (inverse resistance)
- **Critical exponent** (β=1/2), describes $\psi \propto |T_C - T|^\beta$
- **Order of the phase transition**
- **Energy gap** and **energy pseudo-gap**
- Specific heat
- Meissner effect (magnetic field)

Etc.

Holographic superconductors

Some of our contributions to the subject

2018, JHEP, Marrani, OM, Quezada León, Case T=0
2017, PRD, Cvetkovic, OM, Simic, Theories Lovelock-Chern-Simons
2017, PRD; 2016 PRD, Aranguiz, Kuang, OM , Phase transitions of black holes
2016, PRD, Araneda, Aros, OM, Olea , Duality of the Weyl tensor, Magnetic mass in gravity
....
2013, JHEP, Blagojevic, Cvetkovic, OM, Olea , Holography with torsion
…
2009, PRD, OM, Olea; 2007, JHEP, OM, Olea , IR renormalization of AdS gravity
…
2006 JHEP, Bañados, OM, Theisen , Holography in first order formalism

Challenge: T=0 case

Geometry of the extremal black hole, $T = 0$, cannot be obtained in a continuous way from the non-extreme black hole with $T \neq 0$ by taking $T \to 0$.

There is no much information about its holography in the literautre

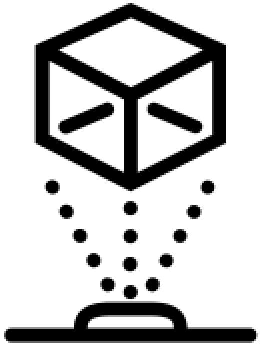
Properties of the extremal black hole

- It has at least two event horizons that coincide
- It has minimal mass
- Does not radiate (T=0)
- It is the most stable in the family (M,Q,J)
- Its entropy is not zero
- It is stable in suprgravity (BPS state)
- All discovered black holes are near-extremal with M=J y Q=0
- **Method of Euclidean action to find free energy fails**

Other applications of Gauge/Gravity Duality

- Holographic hydrodynamics
- Quantum anomalies
- Non relativistic field theories
- Anisotropic field theories
- Condensed matter applications
- QCD applications
- Entanglement entropy

…




Thank you for your attention!
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