

**Black holes
as a
source of information**

Juan Maldacena

12th Marcel Grossmann meeting
Paris, July 2009

20

L09914094383



L09914094383

20 EURO
ΕΥΡΩ



EURO 20
ΕΥΡΩ

gauge/gravity duality

(or AdS/CFT, holography)

Heavy Ion
collisions

Dynamical
Space-time
(General relativity)
string theory



Quantum Field
Theory

Theories of quantum
interacting particles

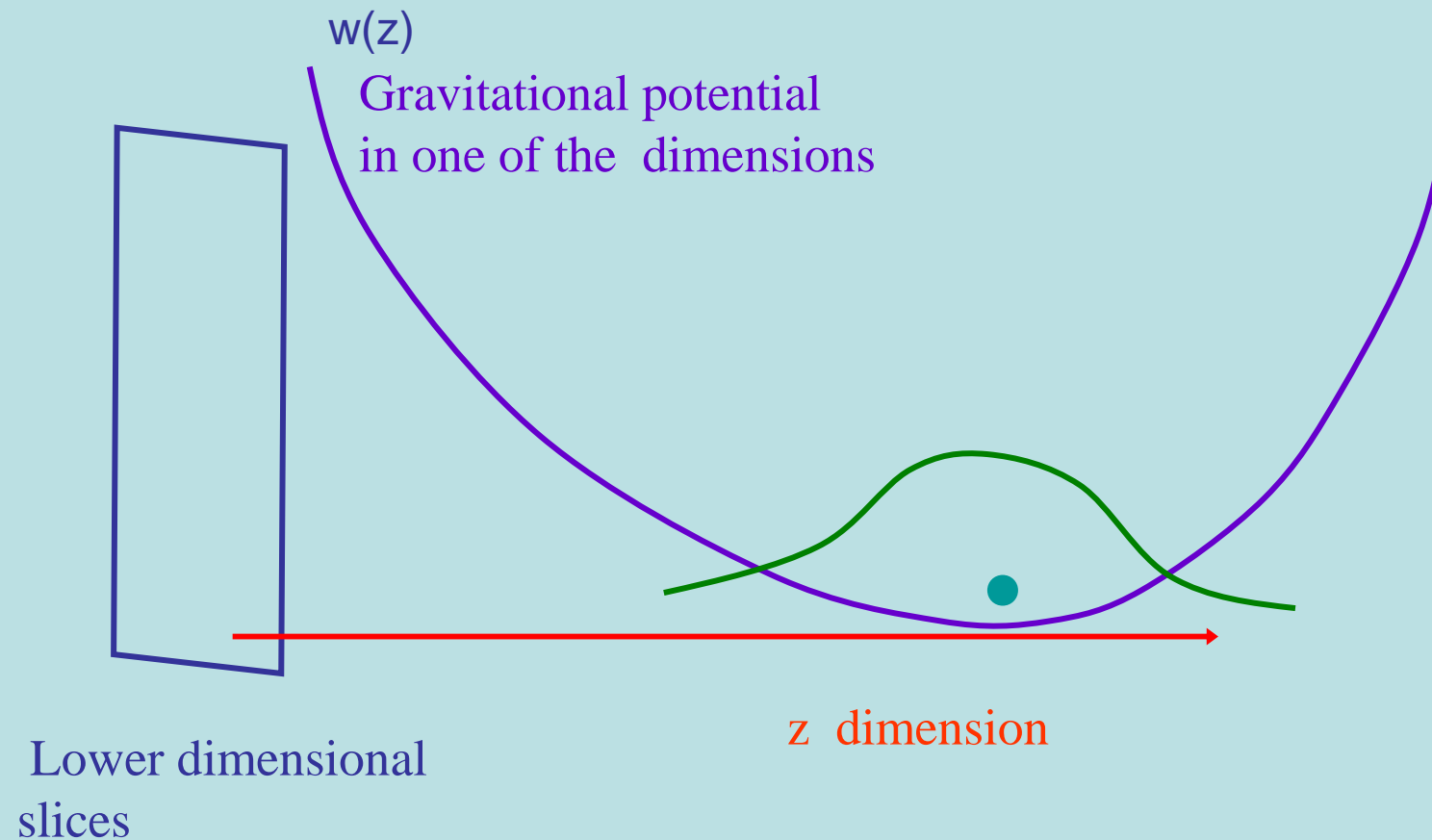
Spin chains
Integrable
systems

Condensed
matter systems

relativistic
hydrodynamics

Physics in a gravitational potential well

$$ds^2 = w(z)(-dt^2 + dx_1^2 + dx_2^2 + dz^2)$$



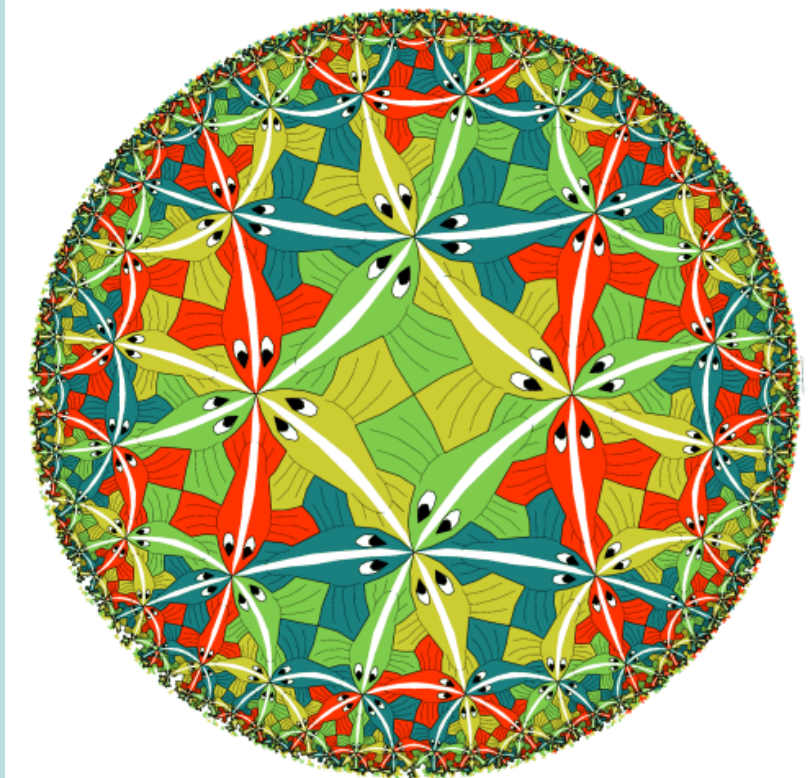
Anti-de-Sitter space

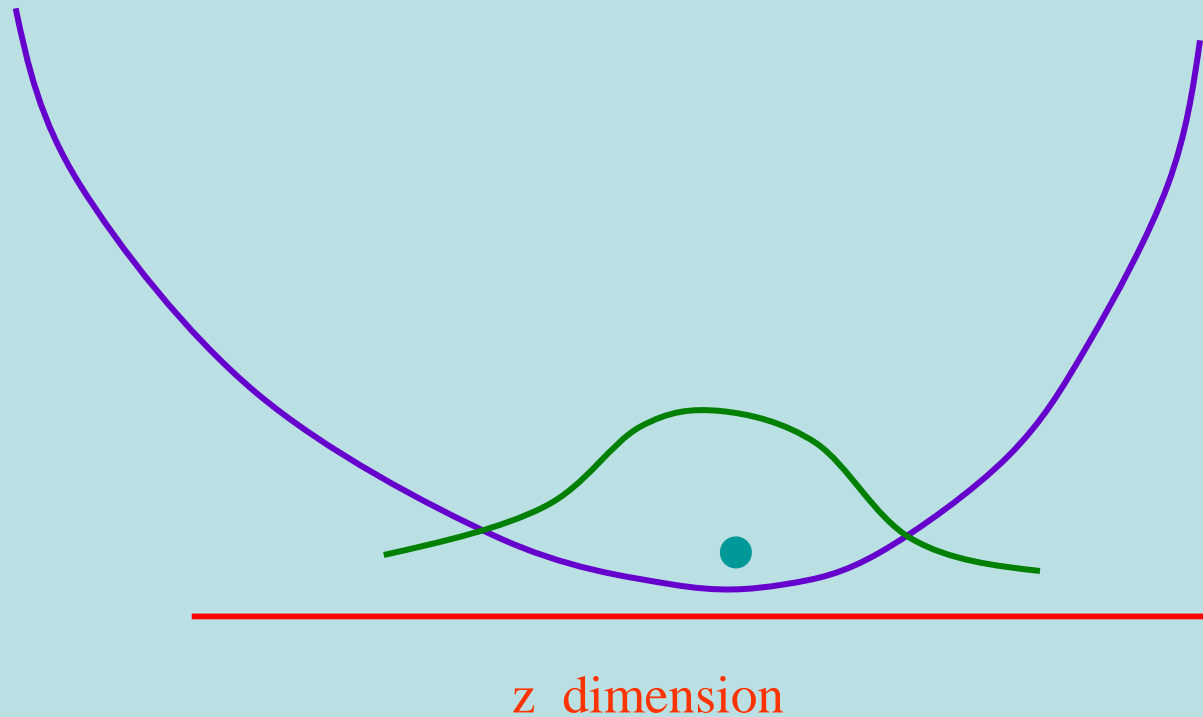
$$ds^2 = - \cosh^2 \rho dt^2 + \sinh^2 \rho d\Omega_2^2 + d\rho^2$$



Rising gravitational
potential

This spacetime has a “boundary”
(conformal boundary) which is
time + sphere





We expect that at low energies the physics is approximately $2+1$ dimensional.

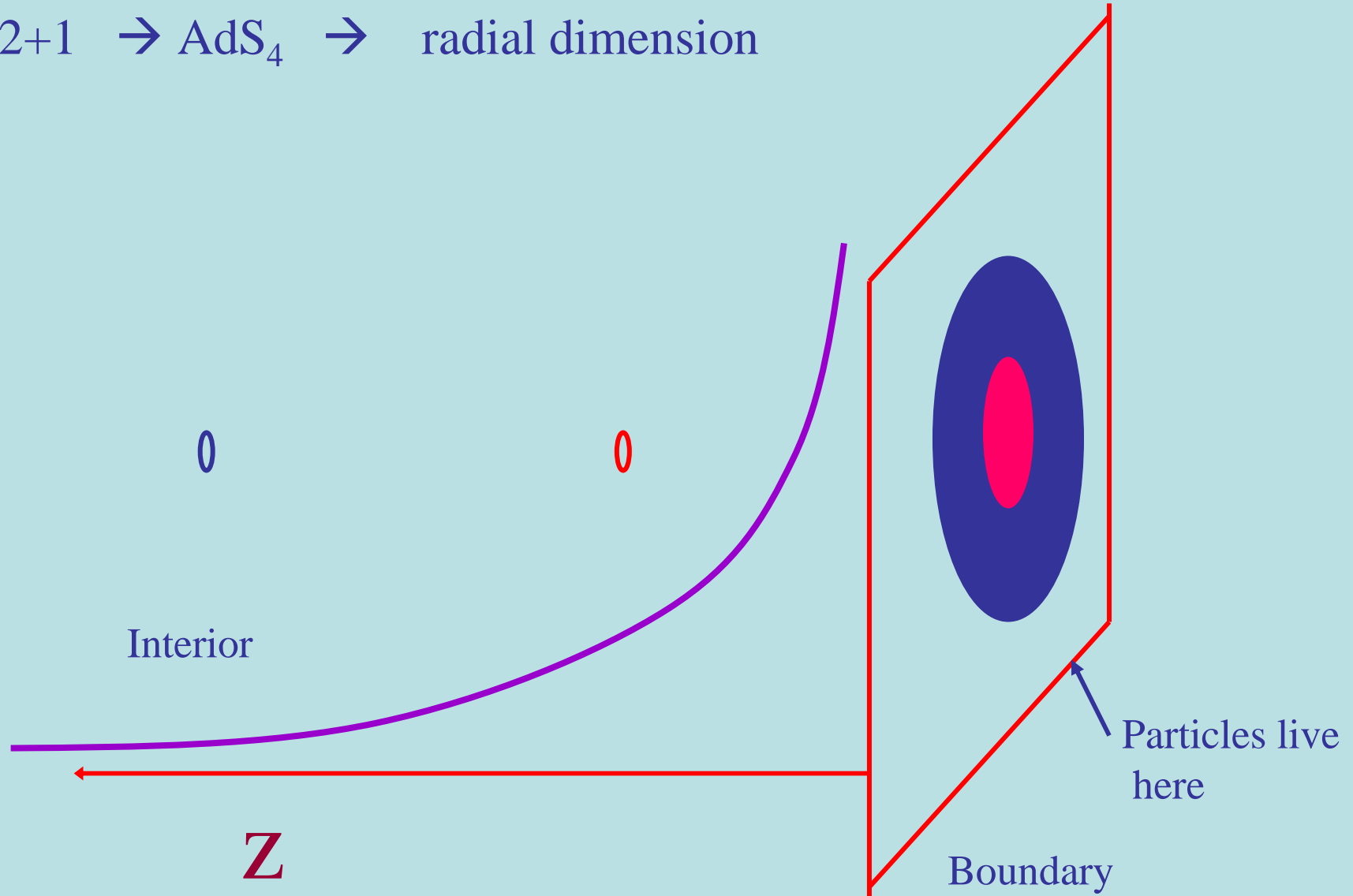
Surprise

It is exactly $2+1$ dimensional at all energies.

The $2+1$ dimensional theory is a theory of strongly interacting particles moving on the boundary, without gravity.

Emergent space

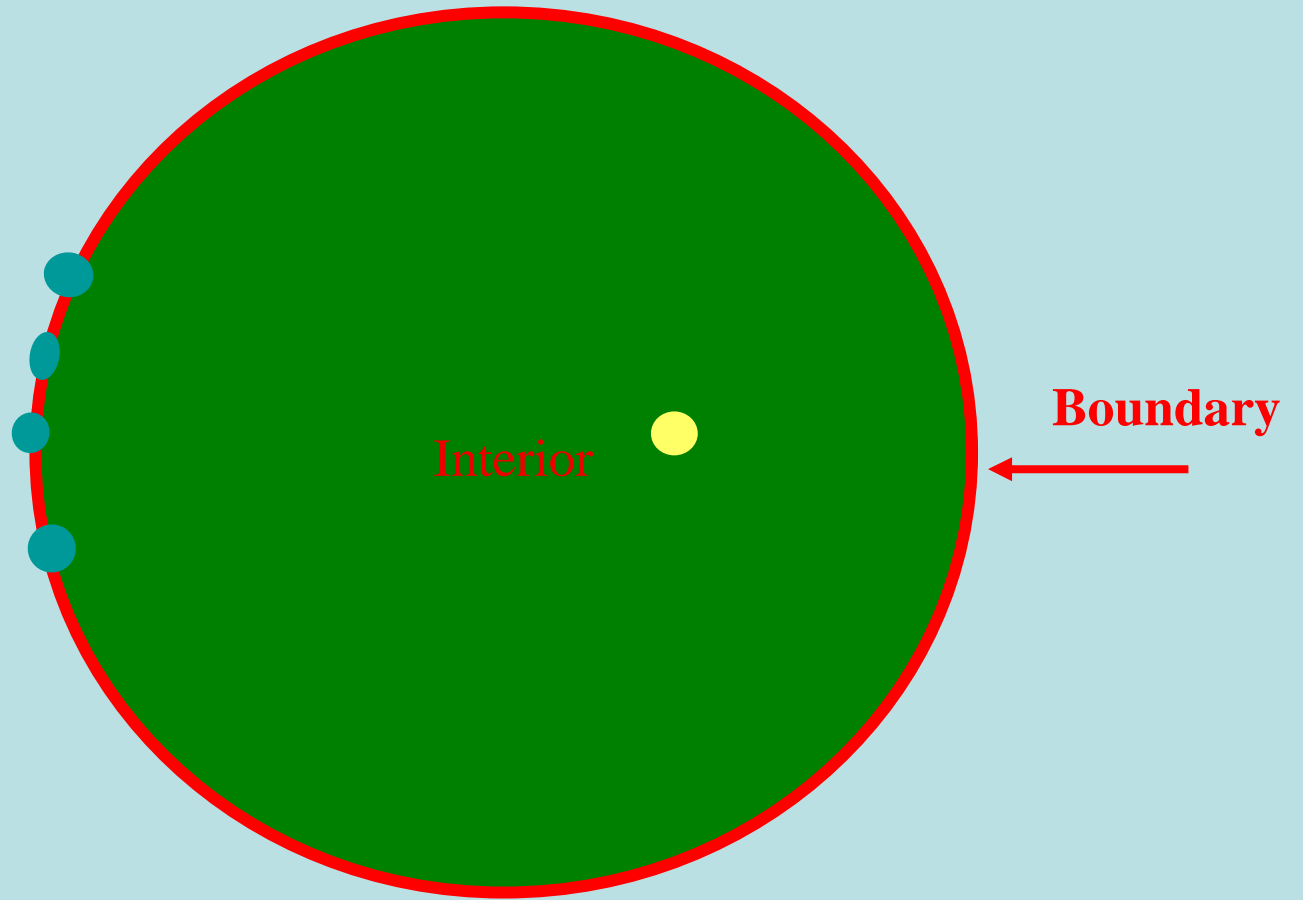
2+1 \rightarrow AdS₄ \rightarrow radial dimension



Theory at the boundary

- Large N $SU(N)$ gauge theory with scalars and fermions.
- Large N limit \rightarrow strings \rightarrow gravity, if R/l_{string} and R/l_{Planck} are both large. (strong coupling)

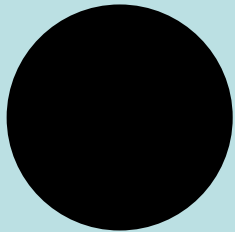




Gravitational physics in the interior \leftrightarrow Particles on the boundary

Black Holes

$$ds^2 = -dt^2 \left(1 - \frac{r_h}{r}\right) + \frac{dr^2}{\left(1 - \frac{r_h}{r}\right)} + r^2 d\Omega_2^2$$
$$ds^2 = -dt^2 \left(1 - \frac{r_h}{r} + r^2\right) + \frac{dr^2}{\left(1 - \frac{r_h}{r} + r^2\right)} + r^2 d\Omega_2^2$$



We can consider black holes in a gravitational potential

Or black holes in Anti-de-Sitter space.

Quantum Mechanics and black holes

- Black holes emit thermal radiation
- This is a quantum effect

Hawking 1974

$$T \sim \frac{\hbar}{r_h}, \quad \lambda_T \sim r_h, \quad \hbar \sim \frac{1}{N^2}$$

- Very small and unimportant for ordinary astrophysical black holes.
- Important consequences for this talk.

Black Hole Thermodynamics

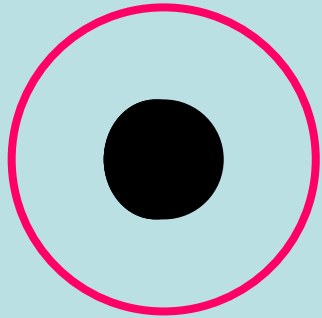
Black holes are thermal objects
(\rightarrow even white black holes!)

Temperature \rightarrow Entropy (1st law)

$$S = \frac{(\text{Area of the horizon})}{4G_N \hbar}$$

Falling into a black hole \sim thermalizing

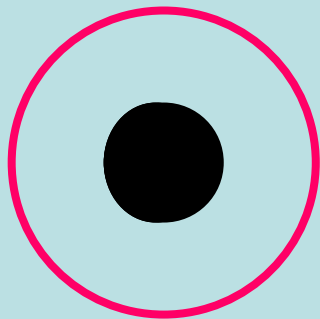
Information Lost ?



Do black holes destroy quantum information ?

No if they are described by a boundary theory

Information found!



Use black holes to learn about quantum field theory.

Black hole

=

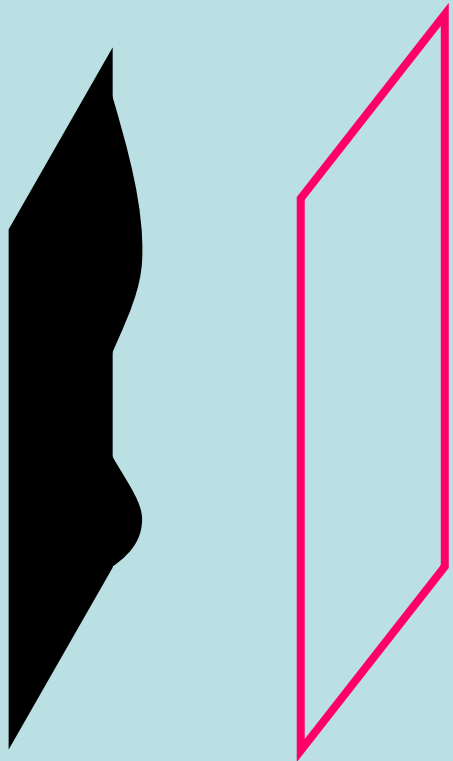
Easy solution to a hard problem

- Strongly coupled system of particles → simple problems of waves in a black hole background.
- We get “information” from a black hole.
- Applied general relativity

Boundary particles are
a microscopic description
of the black hole

The black hole gives a
macroscopic description of
the strongly interacting theory
of particles on the boundary

- Field theory at finite temperature = black brane in Anti-de-Sitter space



Entropy = Area of the black hole

Ripples on the black brane = hydrodynamic modes

Absorption in to the black hole = dissipation, viscosity.

Transport coefficients \rightarrow Solving wave equations in this background.

Einstein equations \rightarrow hydrodynamics

Instructions for Use



- 1-Start from the physical system you are interested in.
- 2-Look for a theory which is vaguely similar (has similar symmetries) but has a gravity dual.
- 3-Do computations in the gravity dual
- 4-Extract some lessons or gain intuition which might (or might not) apply to your system.

Properties of the quark gluon “liquid”

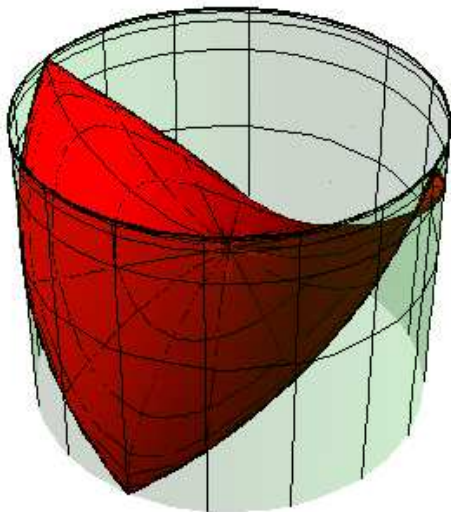
- Heavy ion collisions \rightarrow new phase of matter
- Dual to forming a black hole in AdS.
- In this case we have a 3+1 theory on the boundary and a 4+1 theory in the interior.
- Low value of $\eta/s \sim 1/(4\pi) \rightarrow$ almost perfect fluid

Damour,
Policastro, Son, Starinets

Hubeny, Rangamani, Minwalla,
Van Raamsdonk, Bhattacharyya, Wadia,
Longanayagam, Trivedi, Fouxon, Oz.....

Strings and minimal surfaces

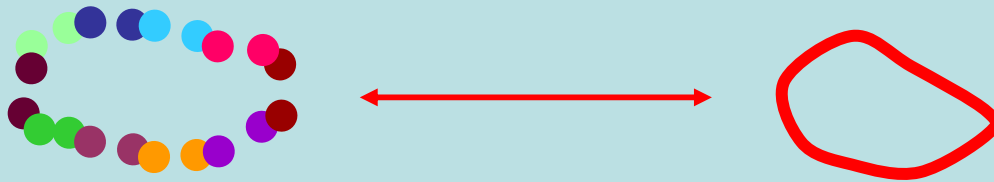
- Strings?
- Wilson loops and scattering amplitudes at strong coupling \rightarrow area of minimal surfaces in AdS.
- Geometrization of many questions.



Gave some insights about properties of scattering amplitudes in maximally supersymmetric Yang Mills theory

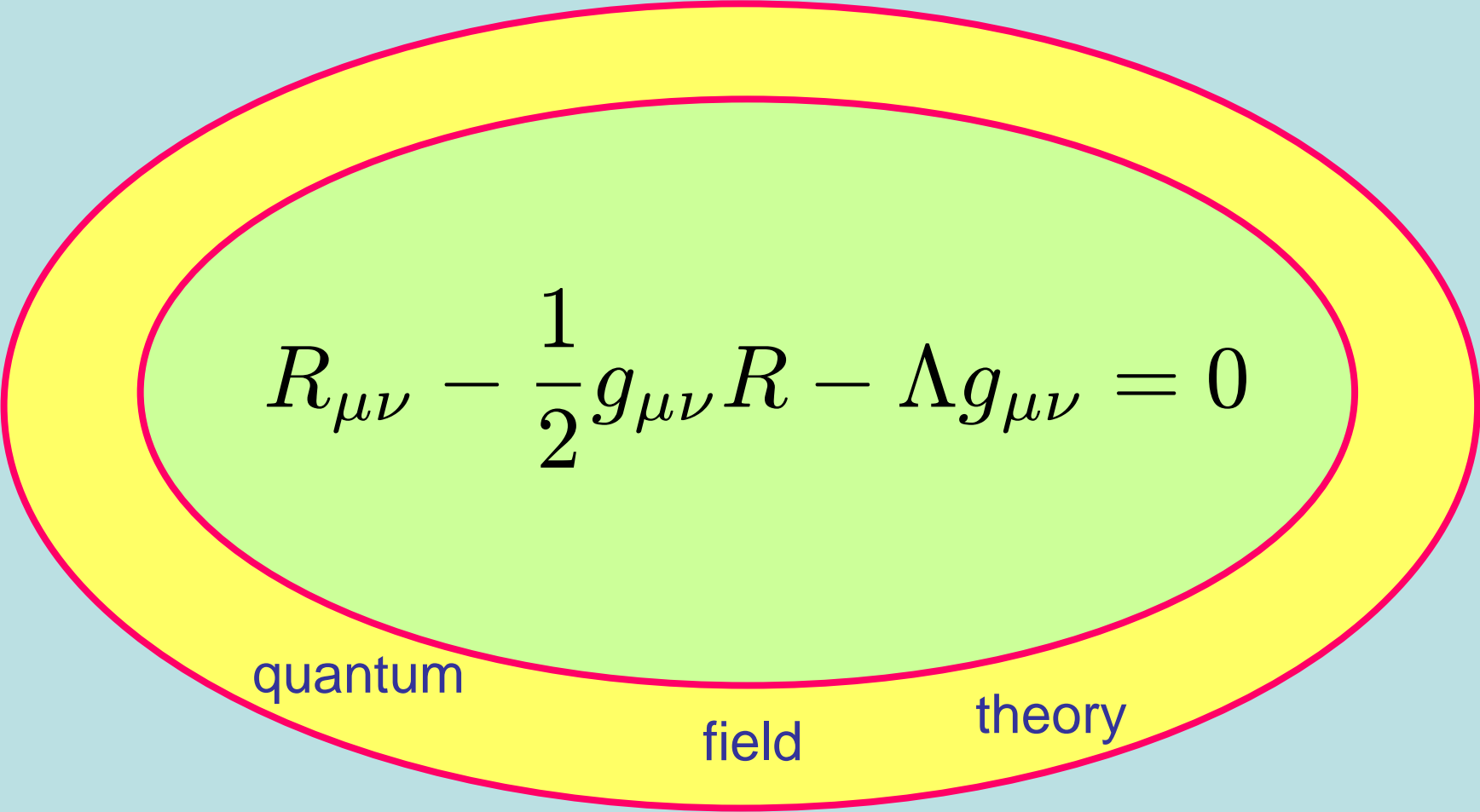
Some symmetries are easier to see at strong coupling \rightarrow implications for weak coupling.

Spin chains and integrability



- Color entanglement \rightarrow 1+1 problem
- Like a spin chain \rightarrow Integrability
- Use methods similar to those of condensed matter physics.
- Solve the problem for all values of the coupling constant
- Interpolate between weakly coupled Yang Mills theory and strings in $AdS_5 \times S^5$

Beisert
Staudacher
Eden
Janik
Frolov
Arutyunov
Kazakov
Gromov
Vieira...


$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R - \Lambda g_{\mu\nu} = 0$$

quantum

field

theory

Spacetime and gravity emerge together from
a theory without gravity

Conclusions

- Black hole thermodynamics is an interesting and fundamental problem in theoretical physics
- The gauge-gravity duality connects black holes with thermal states in relatively ordinary particle theories
- We can use black holes to learn about certain strongly interacting systems.
- We can use geometrical concepts to solve some strongly interacting systems.

