Why 'String Theory' ?

Costas Bachas (LPENS)

November 2019

What do string theorists do ?

A search of the web might confuse you.

In addition to the main annual Strings Conference, there are many spring-offs that have a semi-independent life

STRINGS 2019 - BRUSSELS, BELGIUM

9-13 juillet 2019
Brussels
Fuseau horaire Europe/Brussels

UPPSALA UNIVERSITET

STRING MATH 2019

01-05 JULY 2019, UPPSALA, SWEDEN

Knut och Alice Wallenbergs Stiftelse

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The videos can be found here.

The series of String-Math conferences has developed into a central event on the interface between mathematics and physics related to string theory, quantum field theory and neighboring subjects. The conference will take place July 1-5

2019 STRING PHENOMENOLOGY

LOCAL ORGANIZERS:

DAVID ANDRIOT
ALESSANDRA GNECCHI
SEUNG-JOO LEE
WOLFGANG LERCHE
FABIAN RUEHLE
KONSTANTINOS SIAMPOS
TIMO WEIGAND

24-28 JUNE 2019

CERN

https://indico.cern.ch/e/sp2019

CERN

SwissMAP
The Mathematics of Physics
National Centre of Competence in Research

Integrability in Gauge and String Theories 2019

15-19 July 2019 **Kräftriket, Stockholm**

- List of registrants
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- Conference Poster
- **Practical Information**
  - What is Nordita?
  - Directions to BizApartments Hotel
  - Accommodation
  - Nordita Contact Information
  - Restaurants
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  - Stockholm Tourist Info
  - Stockholm Public Transport

Venue

Wallenbergsalen, Business School of Stockholm University, Kräftriket campus (Kräftriket 3A).

Scope

The conference will cover cutting-edge non-perturbative methods in quantum field theory, as well as mathematical aspects of integrability and its more traditional applications in condensed-matter physics and statistical mechanics. Solvable models play crucial role in theoretical physics, as they illustrate general concepts in a simpler setting and provide insights into the qualitative features of more complex phenomena. Key to the fundamental constituents of matter, gauge fields proved difficult to understand beyond perturbation theory, in the regime without a small parameter. Integrable models of gauge interactions provide an insight into genuine non-perturbative phenomena at any coupling strength. Their intimate connection to string theory and holographic duality makes these models invaluable tools in studying gauge interactions in the non-perturbative domain and in exploring their links to quantum gravity and string theory.

The conference is succeeded by a related event, **Holographic QCD**.

Download poster (PDF)

Trinity College Dublin, July 1st-5th 2019

Scattering amplitudes in quantum field theory describe the interactions of fundamental particles and fields, both known and undiscovered. Their calculation is vital to discovery experiments at the high-energy frontier and to precision studies of elusive particles, such as the Higgs boson. In recent years, techniques developed for the computation of scattering amplitudes have pointed to deep new

Short summary:

1

Effort to go **beyond the Standard Model** of fundamental interactions, unify them with **quantum gravity,** and address the puzzles of **cosmology.**

2

Replaced **Quantum Field Theory** as `theoretical laboratory' for new **(strong-coupling) tools**/techniques with possible applications in:

Condensed matter, quantum chaos/info, QCD, mathematics

1 BSM, Quantum Gravity, Cosmology

Fundamental Interactions + Cosmology

described by two pillars :

Standard Model



Quantum (gauge) Field Theory

Einstein's General Relativity

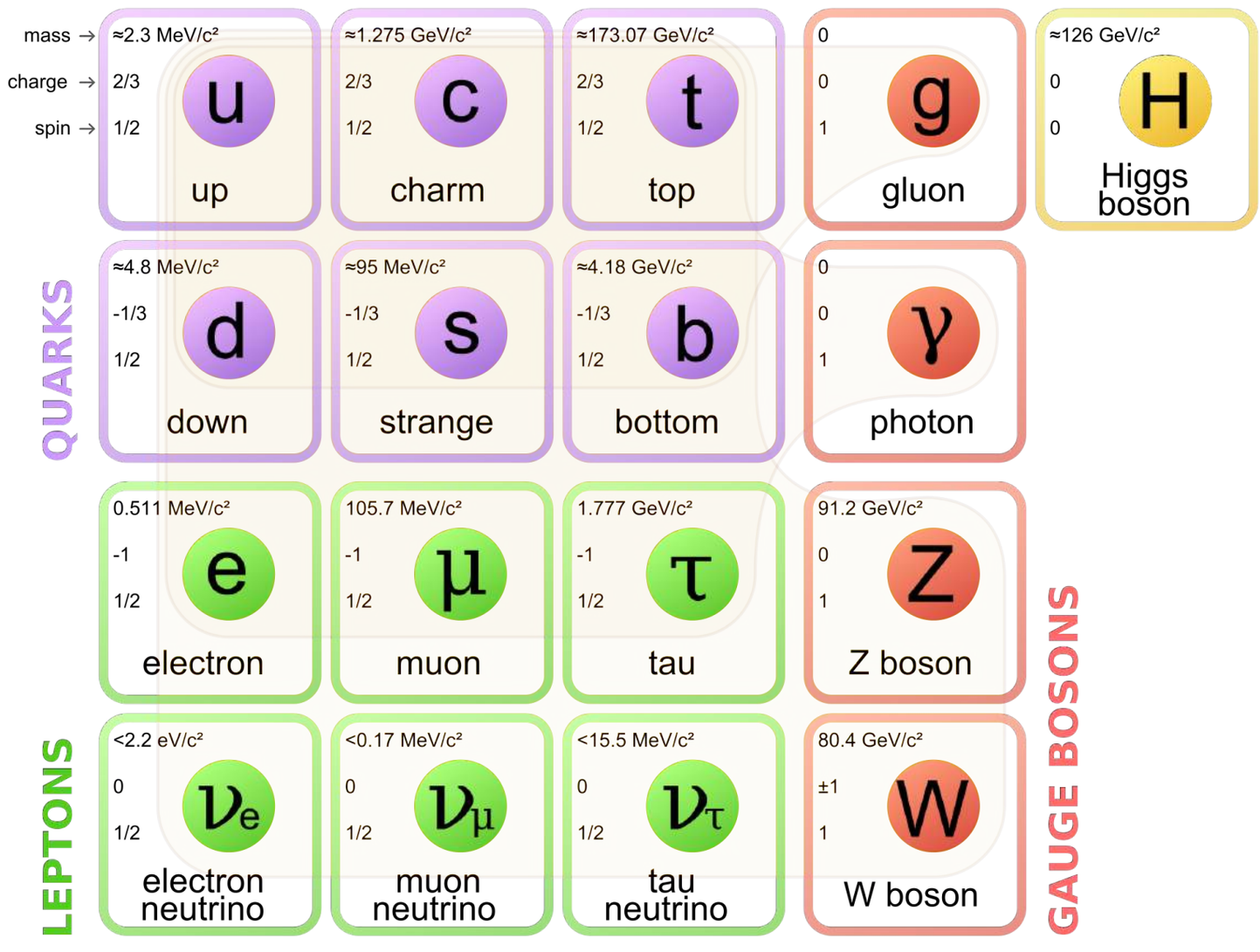
Classical geometry

The Standard Model

matter, spin 1/2

why 3 ?

radiation, spin 1

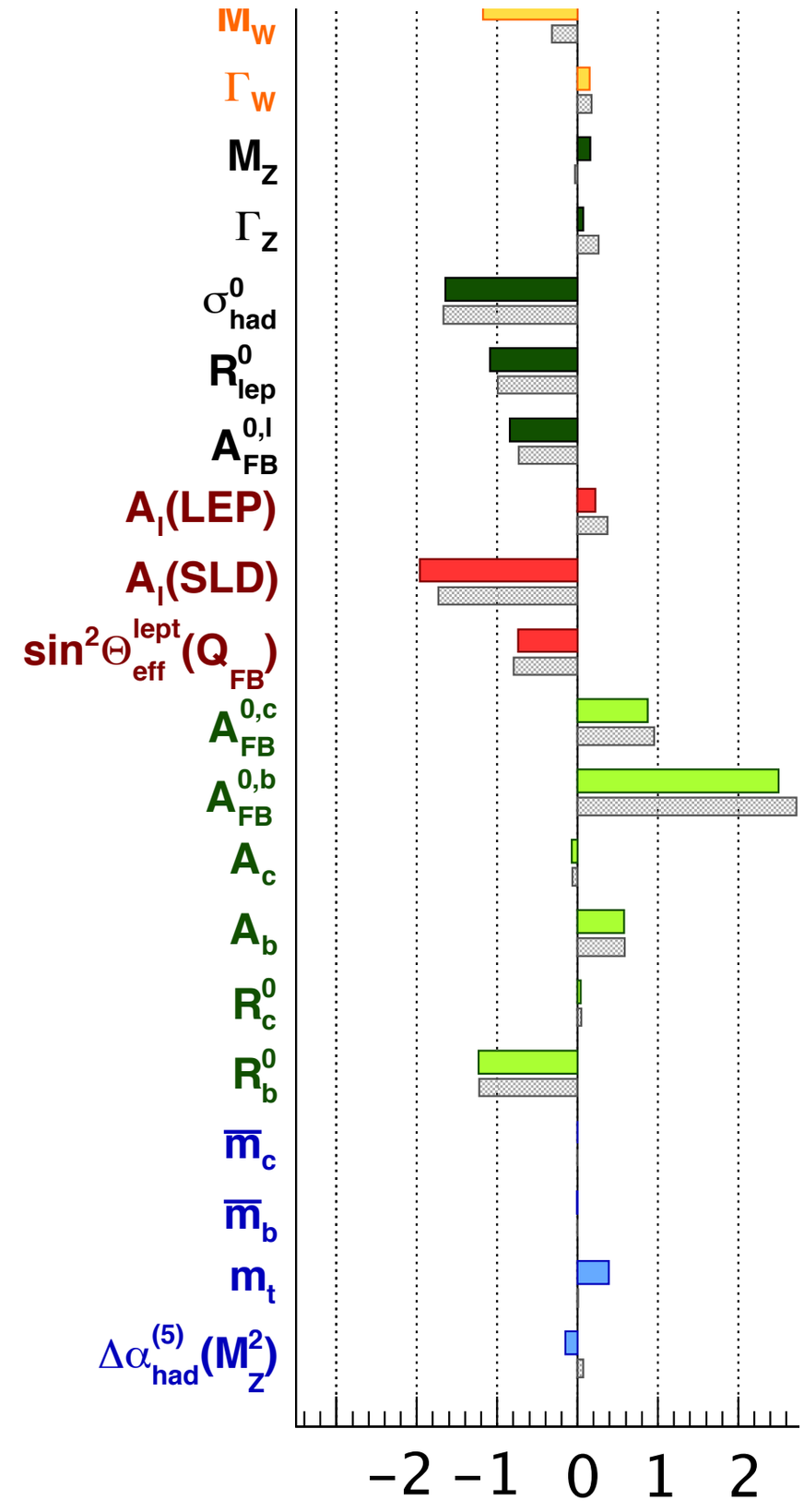


no evidence for BSM in HE data

Global SM fit (all data)

M. Baak, R. Kogler, arXiv:1306.0571

Note: >3 standard deviations occurs 0.3% of the time



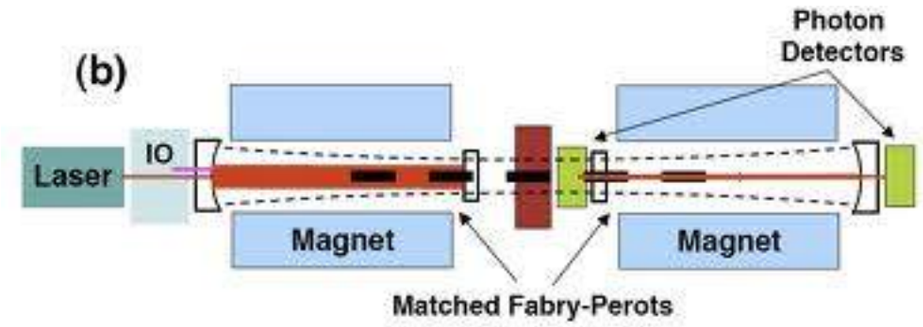
nor from

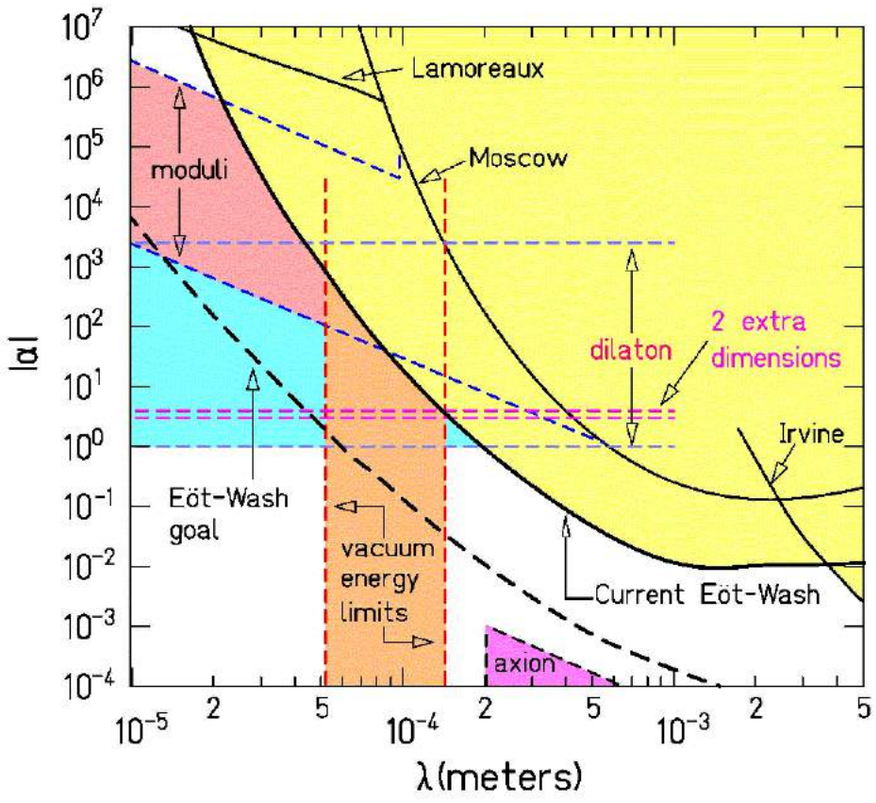
Non-accelerator experiments

(Light weakly-interacting particles)

axion searches

(Conversion to photons
in strong magnetic field)





http://www.npl.washington.edu/eotwash/

gravity modification

(Torsion-balance experiments
in sub-mm range)

Gravity is the **weakest force**:

e.g. for two electrons: $F_{\rm Coulomb} \sim 10^{42}\, F_{\rm Newton}$ $\quad G_N\, m^2 \ll q^2$

It only dominates at the extremes of (length) scale:

10^{-25} $\qquad$ 1 $\qquad$ 10^{4} $\qquad$ *Angstrom*

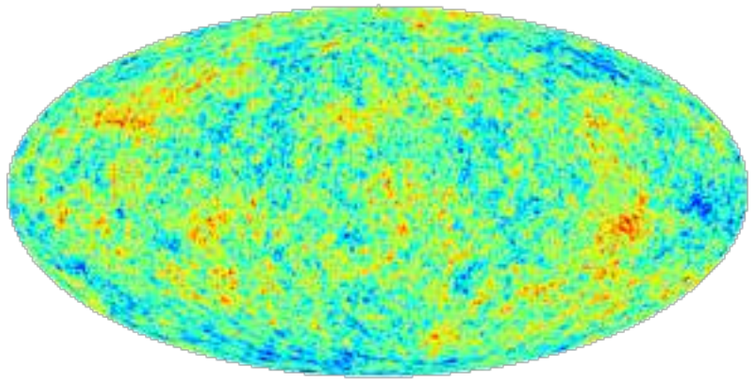
because
$E \sim \hbar c/\ell$

because matter is overall neutral
(& the strong force has finite range)

Quantum Gravity effects inaccessible to direct experiment/observation

(quantum matter/radiation in classical gravitational backgrounds is enough)

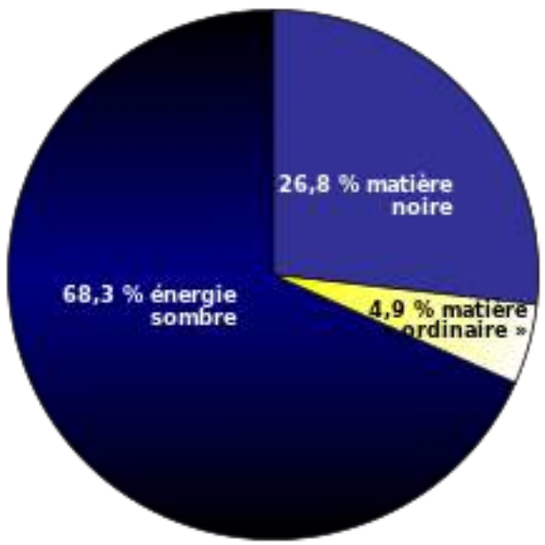
But they have played a role in the naiscant Universe



The best (only?) model for observed **C**osmic **M**icrowave **B**ackground radiation is as quantum fluctuations stretched to extragalactic scales during a period of exponential expansion of the Universe (**inflation**)

The ingredients of the presently-accepted cosmological model are a mystery

$$\Lambda_{\rm CDM}$$



$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R \;=\; T^{\rm visible}_{\mu\nu} + T^{\rm DM}_{\mu\nu} + \Lambda g_{\mu\nu}$$

What is the nature of Dark Matter and Dark energy ?

Why was Λ so much bigger during inflation than now ?

Does CMB (and galactic distribution) have a tensor component ?

Look at theory of **Quantum Gravity for answers**

More modestly, string theorists contribute at present to the search for new (beyond GR + SM) physics in two ways :

Proposing & restricting possibilities (benchmarks):

- **modified** theories of **gravity** (GW, cosmology)
- **axion**-like particles, extra **gauge bosons**, new **dimensions** (LHC, tabletop, . .)

New techniques for the calculation of **backgrounds:**

- **QCD amplitudes**
- templates for **GW** detection?

Compactification

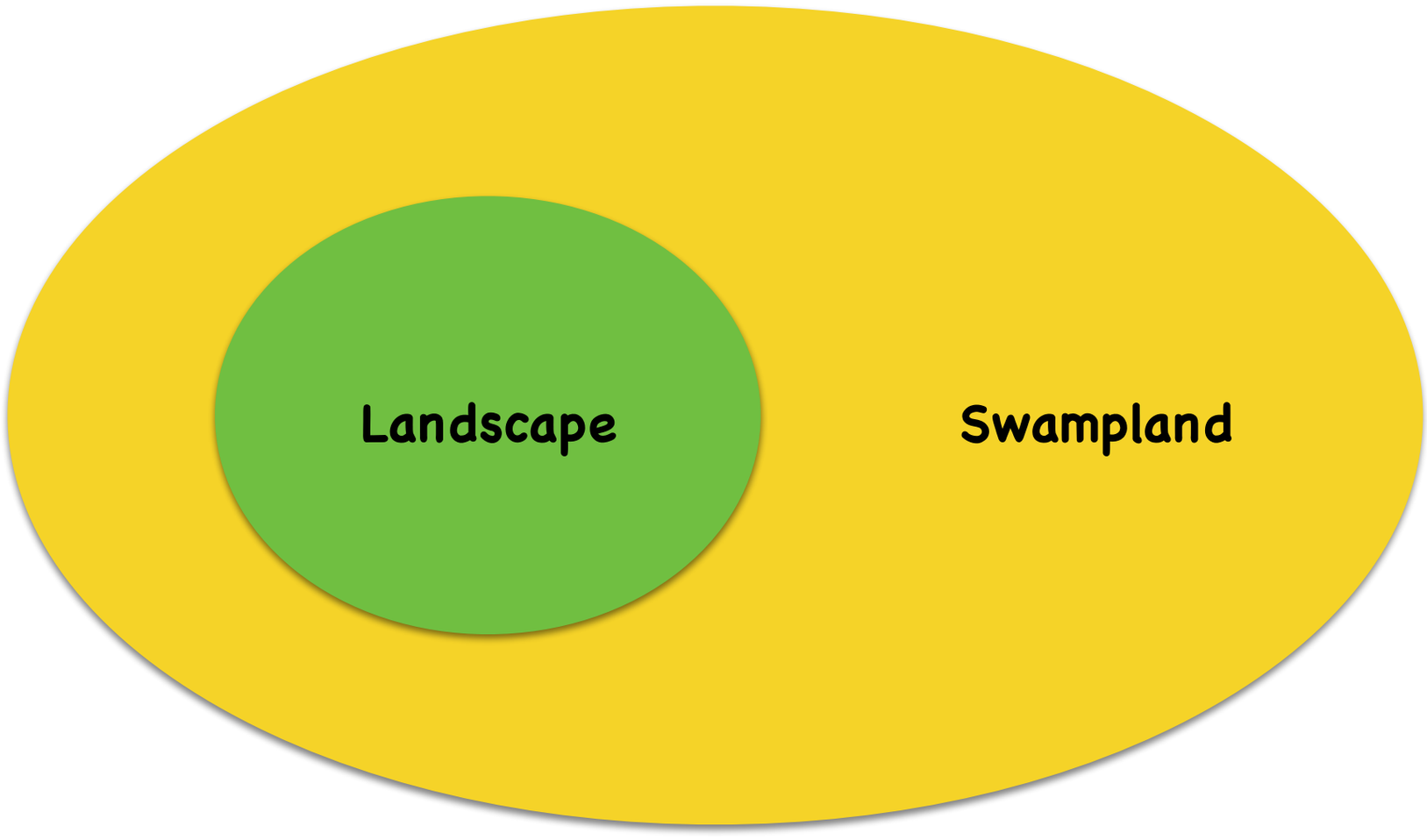
To go from 10 to 4 spacetime dimensions we must compactify string theory on a six-dimensional manifold M_6 .

determines the effective field theory;
no free parameters, all dynamical

The study of possible `string vacua' remains a very active area of research, of interest also to mathematicians:

- Calabi-Yau manifolds, mirror symmetry
- Count holomorphic cycles/brane charges
- Flux compactifications, stability, `non-geometry'

What effective field theories are consistent with quantum gravity?



- e.g. **Weak-Gravity** conjecture: $m^2 G_N \leq q^2 \qquad \forall$ forces

  no global symmetries

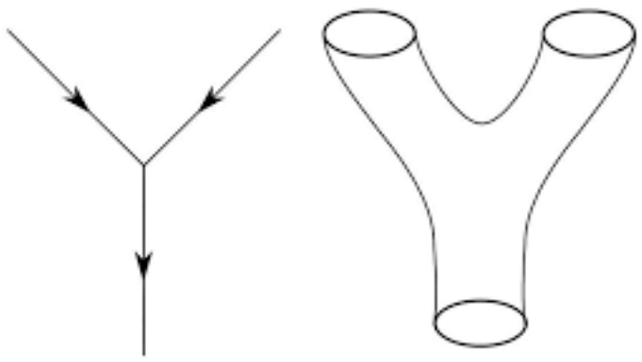
- e.g. no **eternal inflation** only quitessence ?

Reorganize Feynman-diagram expansions:

jets

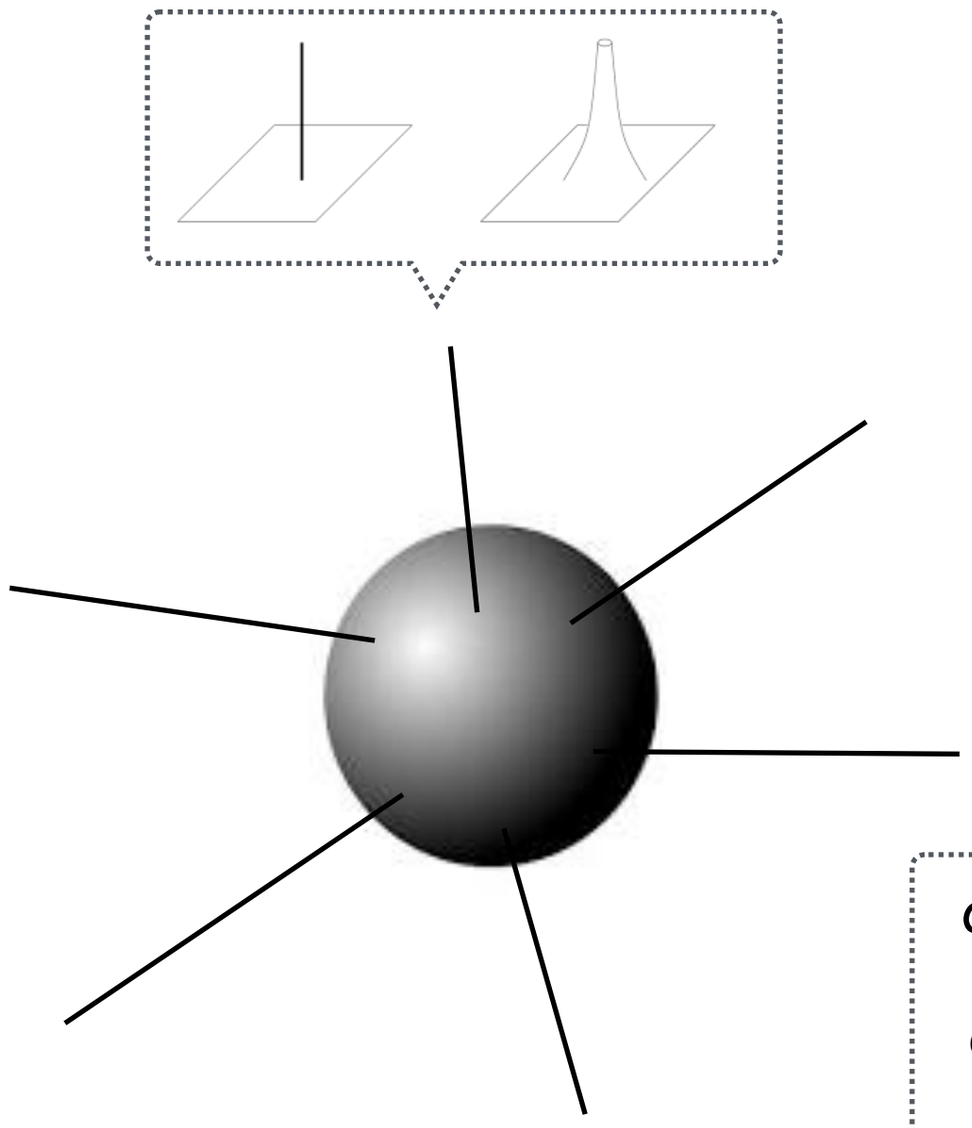
e.g. $2 \longrightarrow 4$ gluon amplitude (frequent at LHC energies)

~ 200 Feynman diagrams at tree level



string diagrams are **`fat'**

So one string diagram `rules them all'



color-flow decomposition

double copy/KLT relations

scattering eqns, reccurence relations

incorporated in codes for QCD backgrounds at LHC

2 `Modern' Quantum Field Theory

QFT is an old subject, but little could be done till recently

other than:

- weak-coupling perturbation theory (Feynman diagrams)
- numerical simulations (lattice)

Important strongly-coupled systems like **QCD**, high T_c **superconductors**, are still very partially understood.

Progress is being made in 3 directions:

- **Susy QFTs** (integrability, dualities, 6d, localisation)
- **Conformal bootstrap** (numerical, analytical)
- **Holography** (gauge/gravity, AdS/CFT)

Many of these subjects can be studied independently

but they grew/are closely related to problems of string theory

Let me say a little more about AdS/CFT

an outgrowth of the efforts to understand

Quantum Black Holes

BHs emit radiation like **hot bodies** at

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

and carry a (Bekenstein-Hawking) **entropy**

$$S_{BH} = \frac{c^3}{G\hbar}\,\frac{1}{4}(Area_H)$$

so that $c^2 dM = T_H dS_{BH}$ 1rst law of thermodynamics

Quantum phenomena, negligible for solar BH $T_H \sim 6 \times 10^{-8} K \times \frac{M_\odot}{M}$

Theoretical puzzles:

- What is the **statistical origin** of this entropy ?

- Where is the quantum information stored after evaporation ?

  information loss ?

- What does an infalling observer see ?

  Empty space (equivalence principle) or a **firewall**

  as if travelling through a thermal bath ?

For comparison: Universe **opaque** to cosmic rays travelling with $E > 6 \times 10^{19} eV$ through the $T \simeq 2.7K$ bath of primordial photons

Greisen, **K**uz'min, **Z**atsepin Cutoff

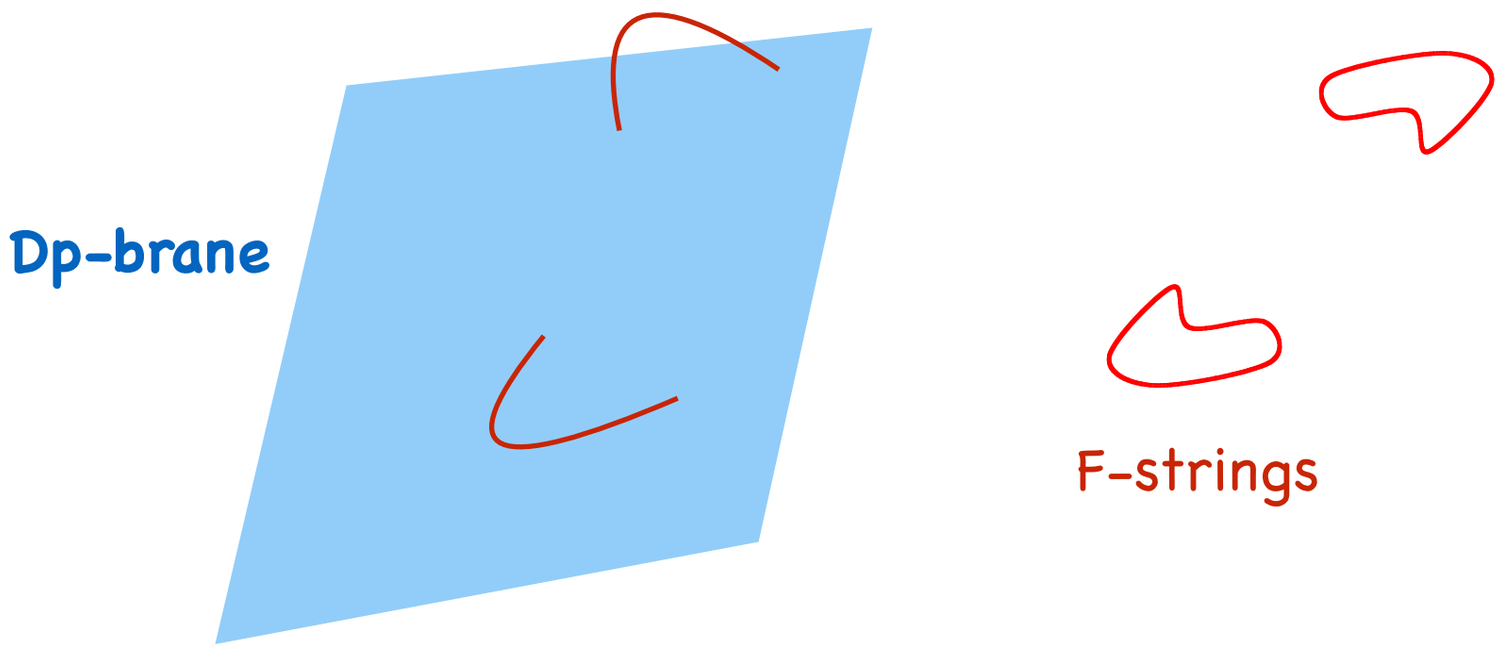
$$\gamma_{CMB} + p \to p + \pi^0$$

String theory has provided an answer to the first question

for a class of (unrealistic) charged black holes

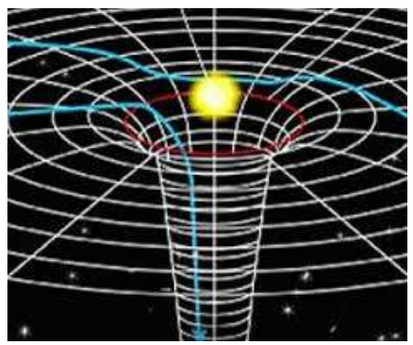
The key ingredients are **D(irichlet) branes:**

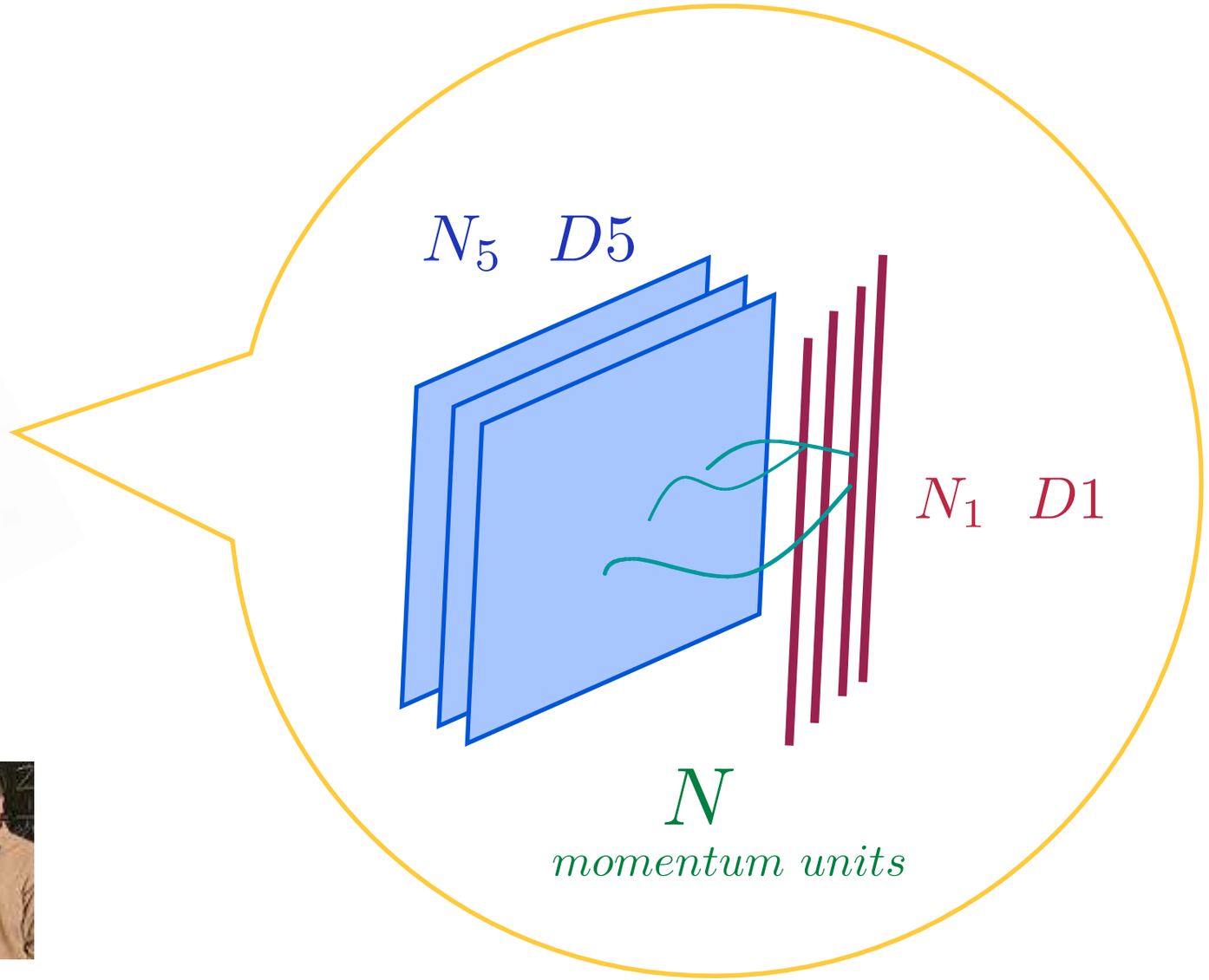
spacetime defects on which **open** strings can end



D-branes are **solitons** of string theory, and collections of them make up Black Holes with smooth large semiclassical horizons

A 3-charge BH



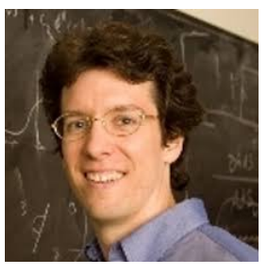


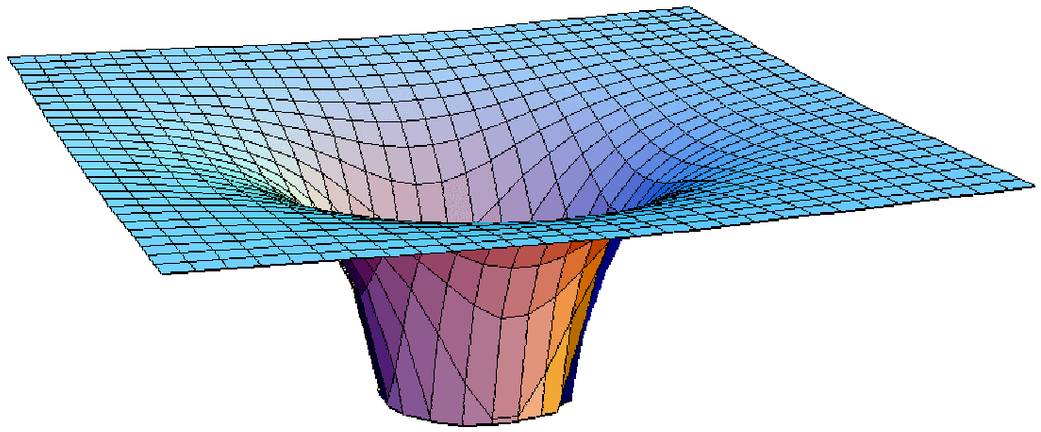
Counting quantum states gives:

$$S \simeq 2\pi\sqrt{NN_1N_5} = \frac{Area_H}{4G}$$

But to address the other two questions we need a detailed description of the dynamics of these degrees of freedom

Holography postulates that quantum horizons are described by ordinary gauge QFT in one lower dimension





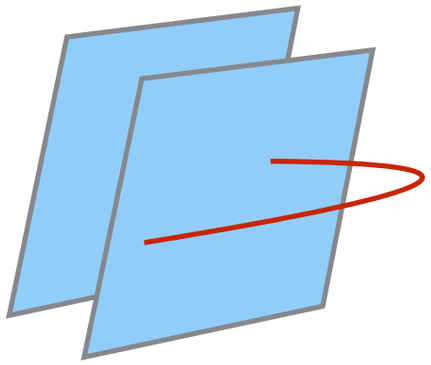
free gravity waves

⊕

light because of
huge redshift

Closed-string theory in AdS5xS5

for Black 3-branes



free gravity waves

⊕

SU(N) Yang-Mills

The mathematical equivalence between a theory of gravity (in a AdS trap) and ordinary gauge theories has since:

- been verified in detail using **integrability**
- been extended to other examples
- used to model the quark-gluon plasma, non-Fermi liquids etc

Its many repurcussions are at the core of much of the current research in string theory

Most applications use the classical Einstein equations to derive properties of strongly-coupled QFT systems:

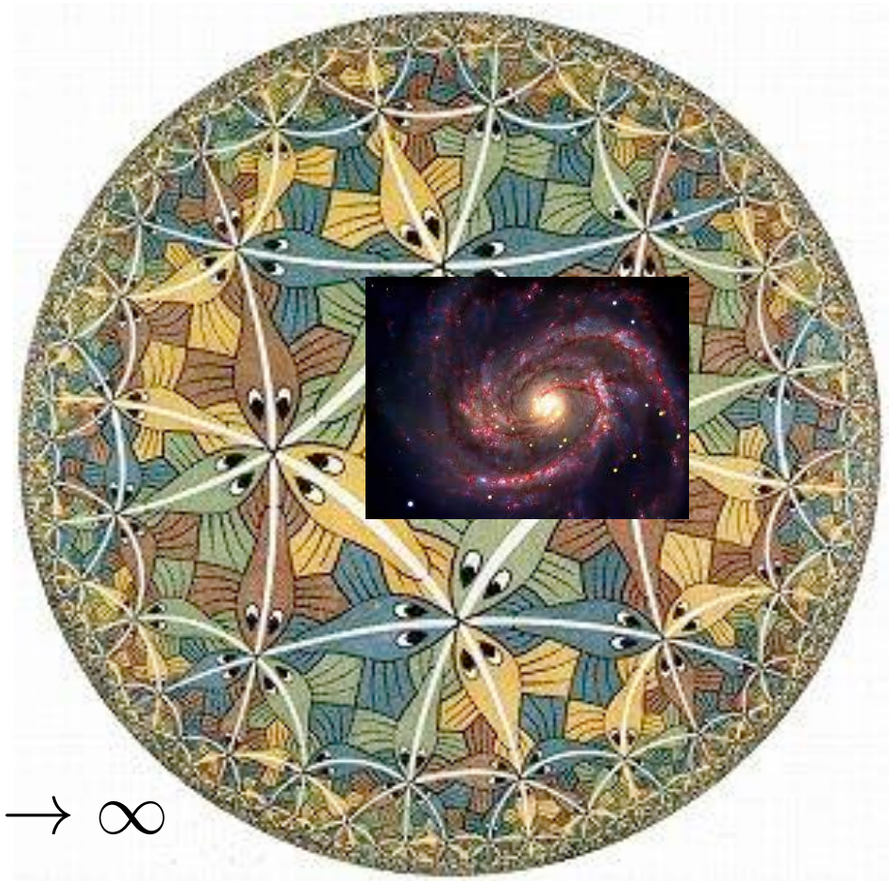
eg. **viscocity/entropy** of 'holographic' fluids $\frac{\eta}{s} \leq \frac{\hbar}{4\pi k_B}$

much closer to exptl number than perturbative QCD

Less success till now in using the duality in the opposite way:

Information paradox ? **de Sitter/CFT ?**

M.C. Escher, *Circle Limit III*, 1959.
strictly-speaking this is EAdS2



$\rho \to \infty$

AdS is a **gravitational trap**

in global coordinates

$$ds^2 = d\rho^2 + e^{2\rho}(-dt^2 + d\vec{x}d\vec{x})$$

infinite **blueshift** repels
from boundary

But in interior anything goes :

(Small) **black holes** form and evaporate, **singularities** appear etc
All this is described by YM theory !

Hard to believe that YM has information loss.

But precisely how is the paradox resolved?

need dynamics at strong coupling

Between Causality-Locality, Equivalence Principle & QM

something must give, but what ?

Simpler models in lower dimensions: near AdS_2/CFT_1

Their study has lead to some surprising relations between gravity and **quantum chaos** (universal bounds, . . .)

Most of these subjects and many others

(exceptional symmetries, topological strings,
string field theory, string-inspired cosmology . . .)

are studied somewhere in the Paris area.

A regular bi-monthly double seminar brings people together
on thursday mornings in IHP

There are also strong groups outside Paris

String Theory in France

APC - Paris Diderot
LPENS, Paris
LPTHE - Jussieu, Paris

CPHT - Polytechnique
IHES, Bures-sur-Yvette
IPhT, Saclay
LPT, Orsay

String Theory in Greater Paris

Théorie des cordes en région parisienne

LPENS, Lyon
IPNL-Claude Bernard, Lyon
LAPTh, Annecy
LMPT, Tours
LCC, Montpellier 2

Dont hesitate to go out, meet the people, ask them questions . . .