Status and Perspectives in String Theory

Dieter Lüst, MPP and LMU-München

MPP: 100 Year Anniversary, October 12th, 2017

Outline:

String theory in a nutshell

The string theory landscape

Some general lessons about strings and quantum gravity

Tension between different theories:

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Electromagnetism ⟷ classical mechanics

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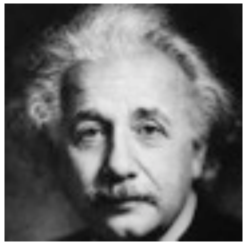
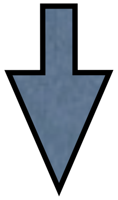
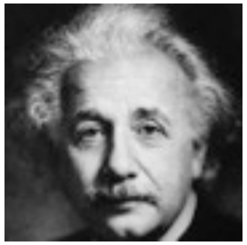




Special and General Relativity

Tension between different theories:

Electromagnetism ⟷ classical mechanics



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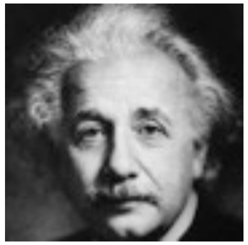

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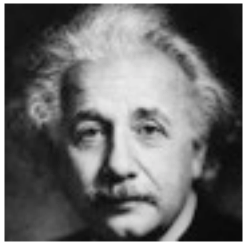

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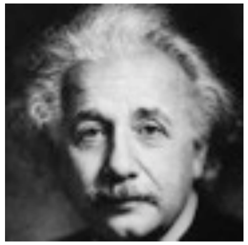

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Time dilatation,
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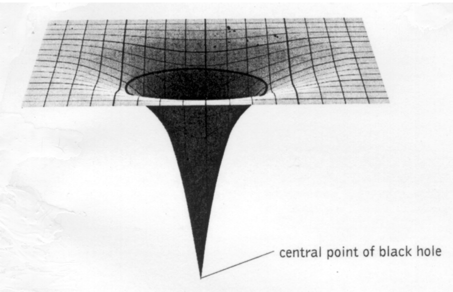

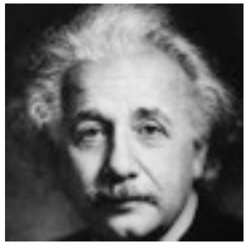

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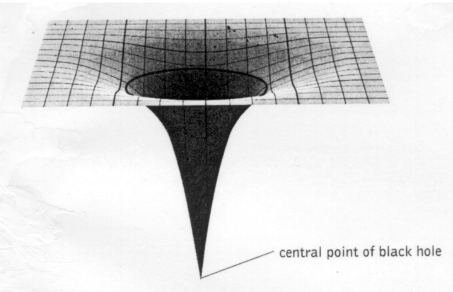

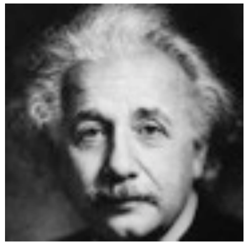

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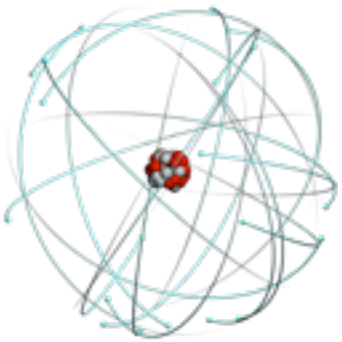

Matter waves, entanglement

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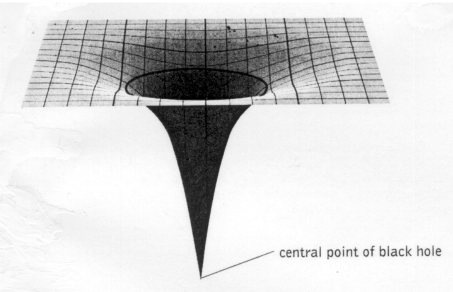

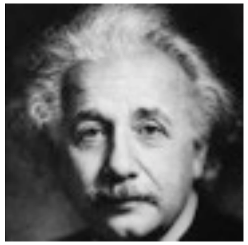

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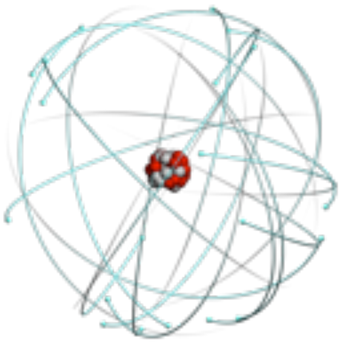

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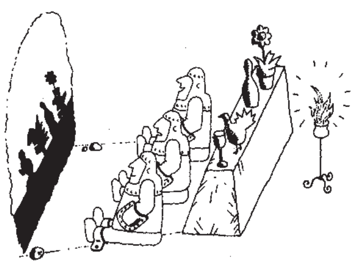

Strings,
extra dimensions
emergent space-time ?

Quantum Gravity ?

Mass scale of Quantum Gravity:

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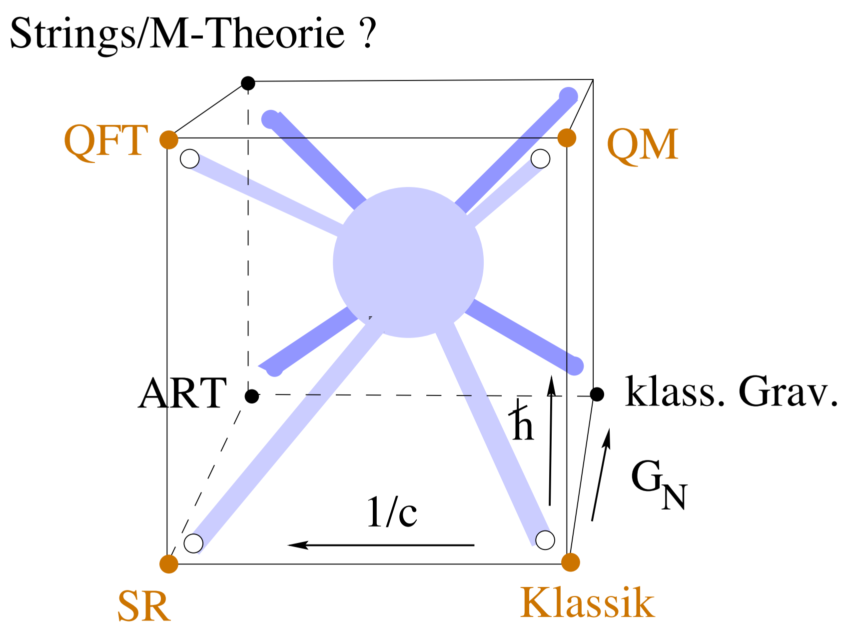

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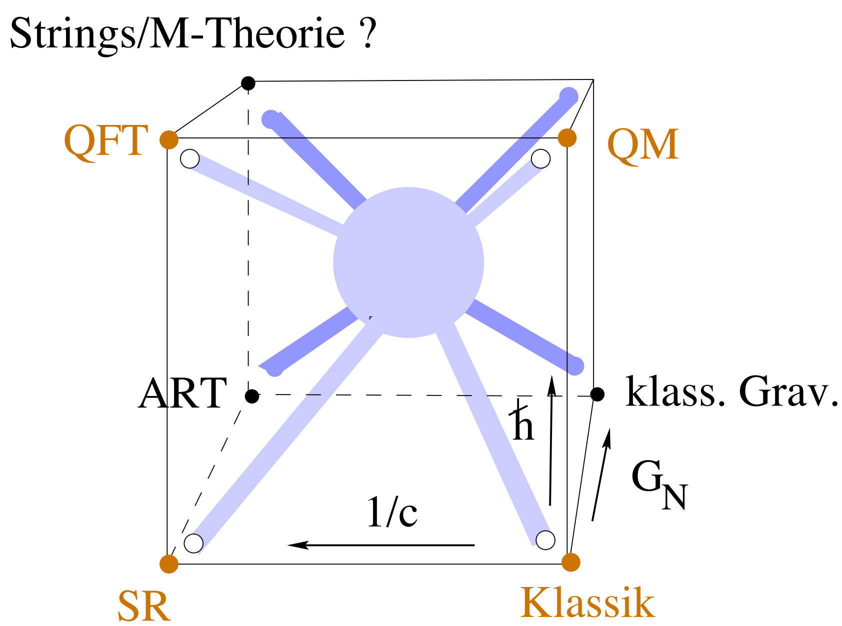

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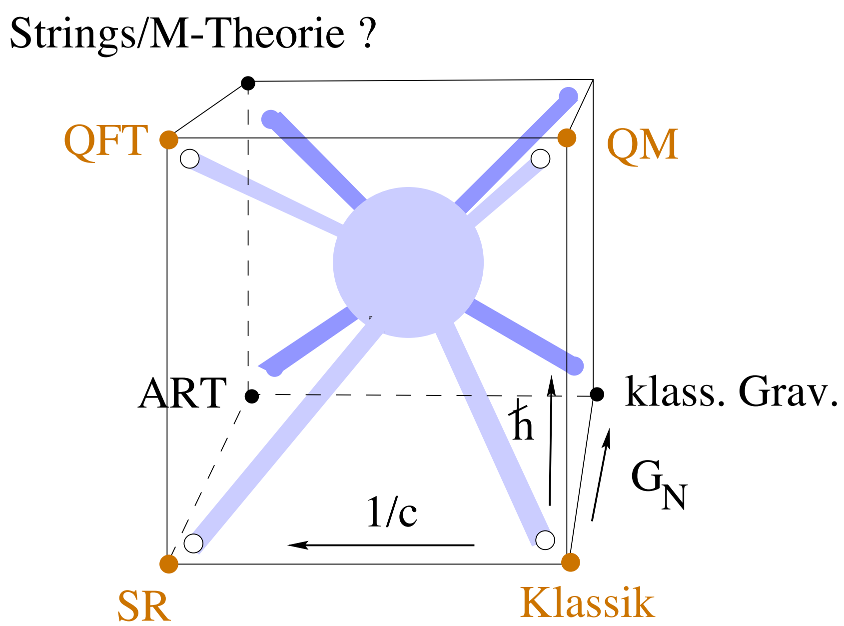

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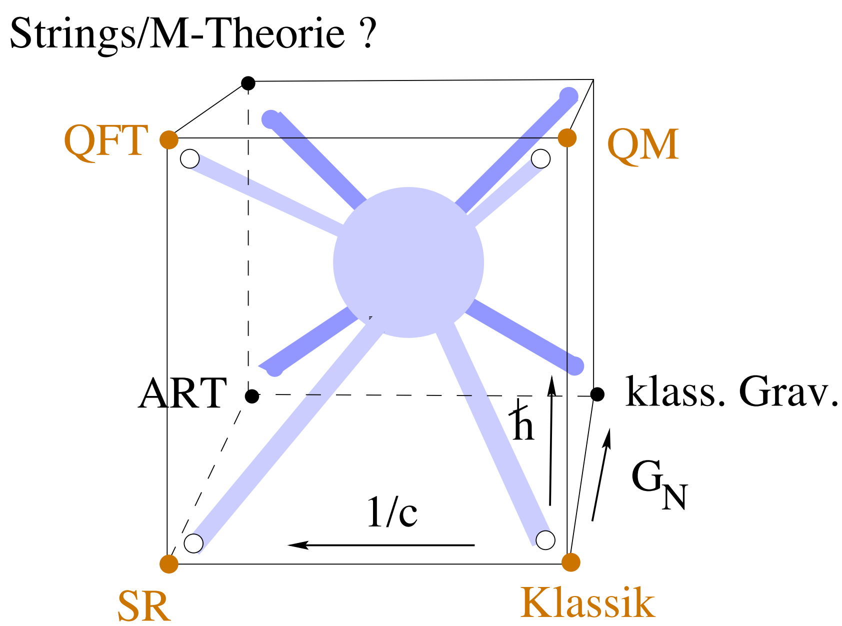

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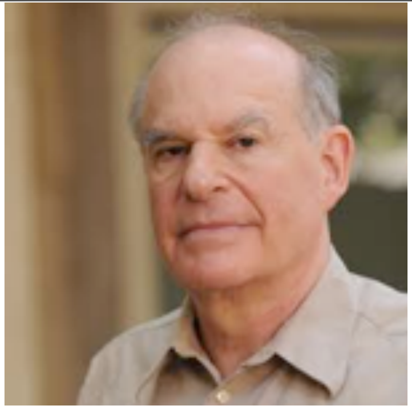
At this scale gravity becomes strong !!

String theory as candidate for Quantum Gravity and Unification:



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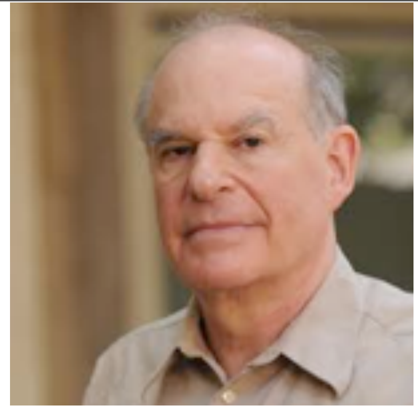

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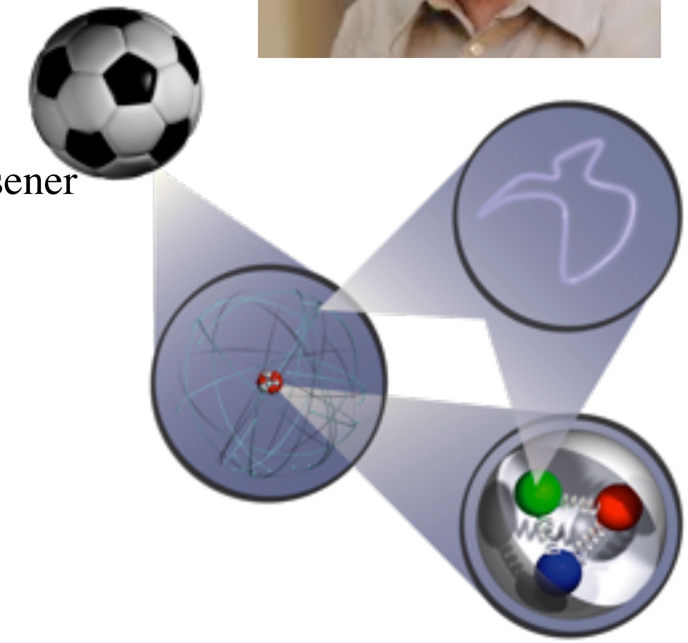
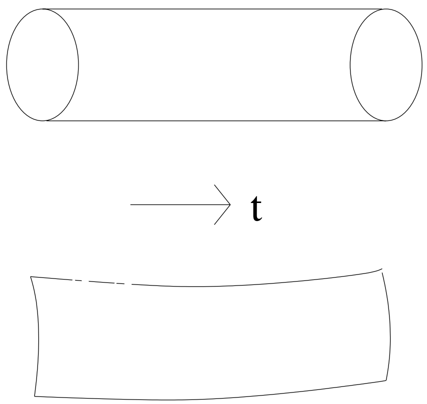
Theory of (1-dim) extended objects:



Closed strings:

geschlossener String



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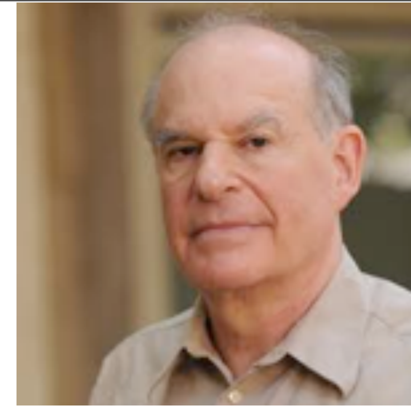

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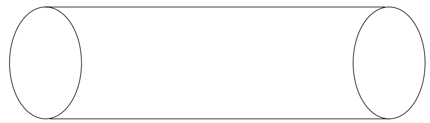

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→ t

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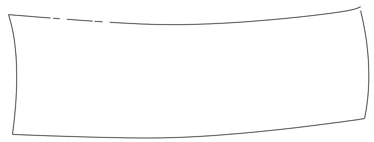

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Quantum gravity and gauge interactions arise not as an input but rather as a consequence of string interactions!

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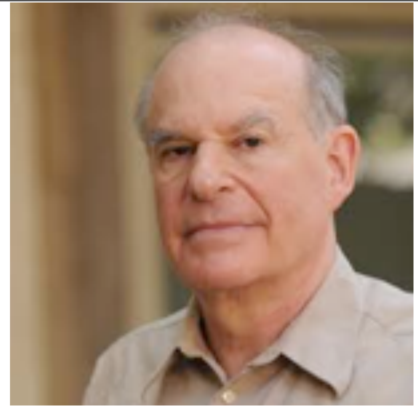

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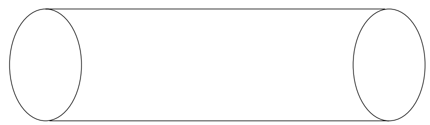

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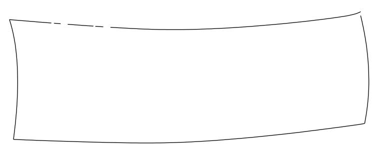

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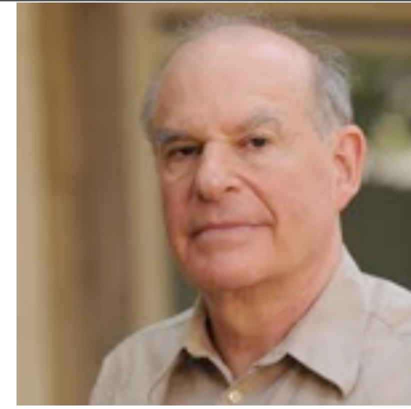

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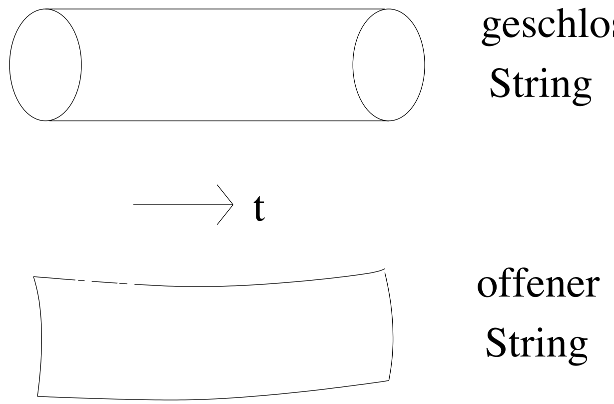

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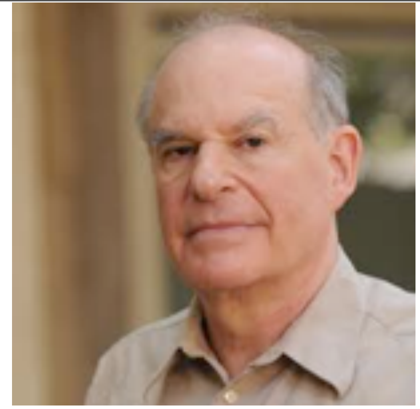

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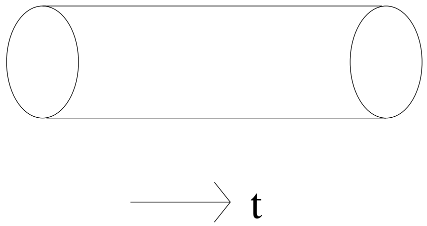

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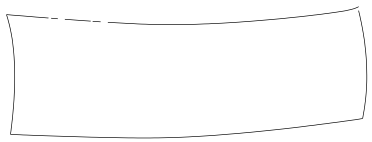

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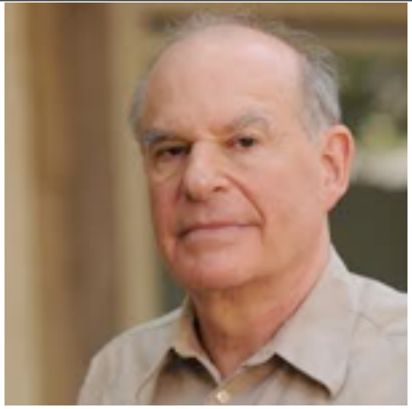

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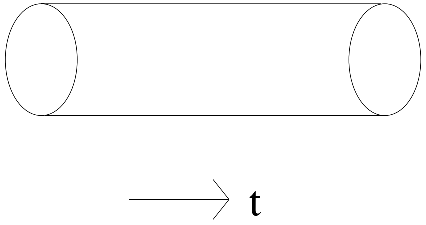

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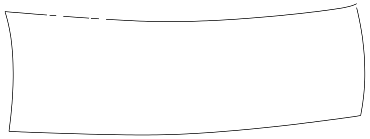

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- No UV divergences: consistent theory of quantum gravity (S. Mandelstam, 1992)

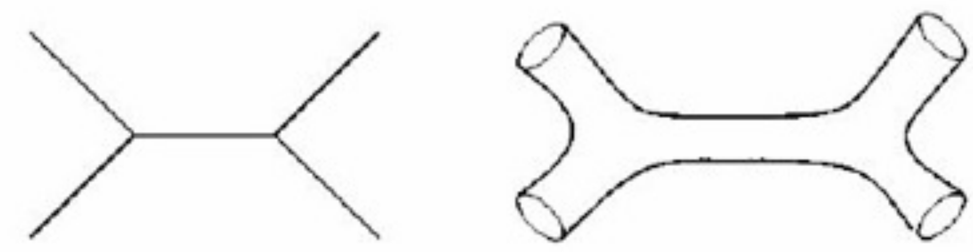

Fig.3: Particle scattering processes (left), string scattering processes (right).

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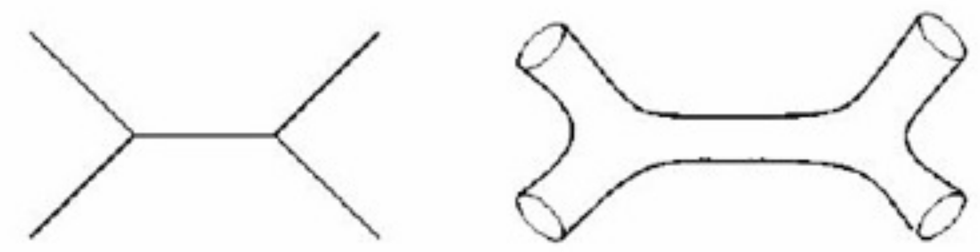

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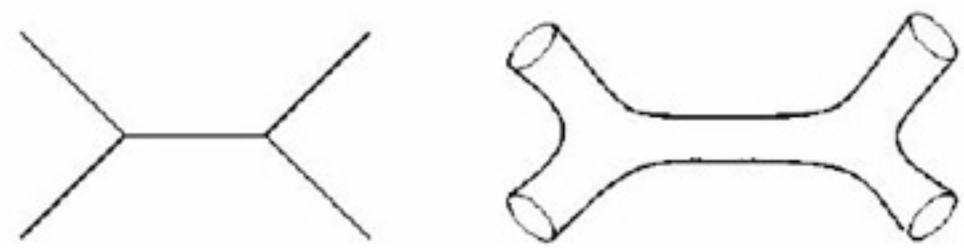

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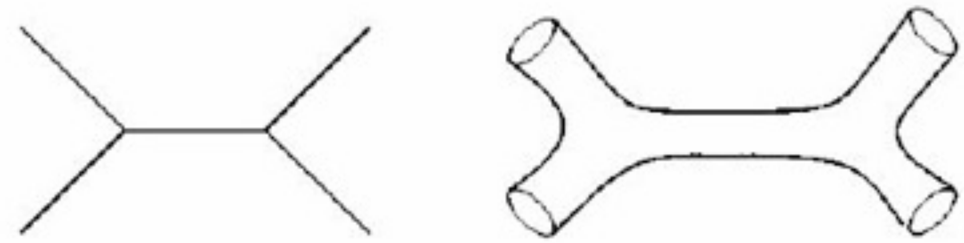

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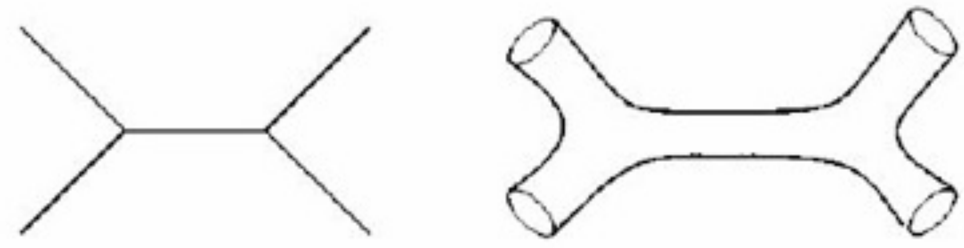
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- Higher dimensional objects ⇒ D-branes with open strings

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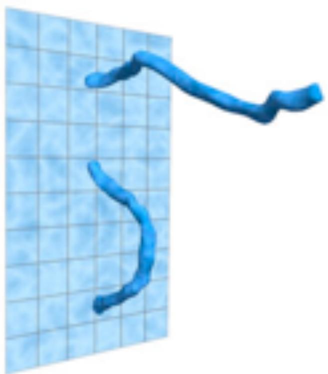

⇒ Gauge fields and gauge interactions

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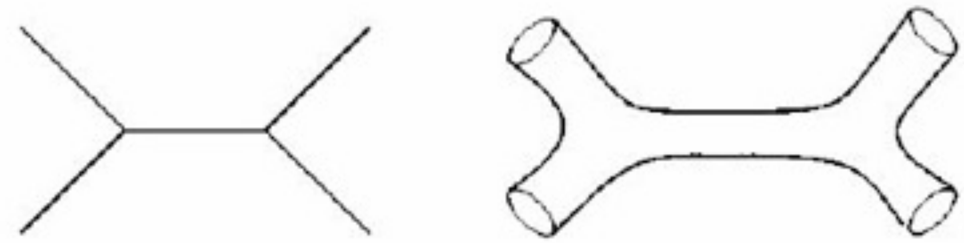

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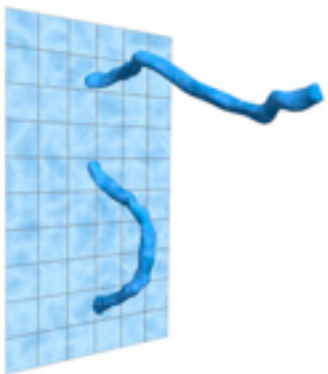

⇒ Gauge fields and gauge interactions

- Strongly coupled string theory ⇒ M-theory in D=11 (E.Witten, 1995)

Why do we observe only 4 space-time dimensions at low energies?

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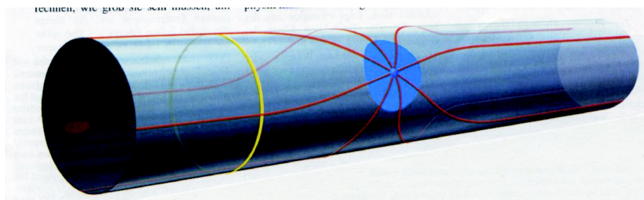
Compactification: Choose a (closed string) background geometry of the form:



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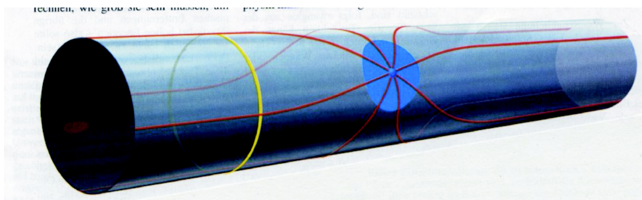

Calabi-Yau space

$$M_{10} = R^{3,1} \otimes M_6$$

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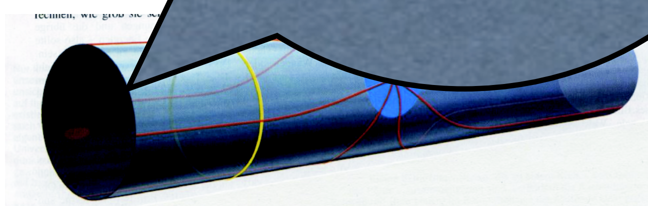

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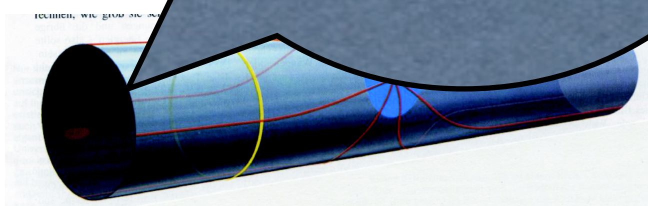

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Universal relation:

$$M^2_{\text{Planck}} \simeq \; M^{2+d^{\perp}}_{\text{string}} \; (R^{\perp})^{d^{\perp}}$$

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How many Calabi-Yau spaces exist?

How many string compactifications to four dimensions arise as consistent string solutions?

CHIRAL FOUR-DIMENSIONAL HETEROTIC STRINGS FROM SELF-DUAL LATTICES

W. LERCHE

CERN, Geneva, Switzerland

D. LÜST

Max-Planck-Institut für Physik und Astrophysik, Föhringer Ring 6, 8000 München 40, FRG

A.N. SCHELLEKENS

CERN, Geneva, Switzerland

Received 24 November 1986

It is shown how our previous work on lattice constructions of ten-dimensional heterotic strings can be applied to four dimensions. The construction is based on an extension of Narain's lattices by including the bosonized world-sheet fermions and ghosts, and uses conformal field theory as its starting point. A natural embedding of all these theories in the bosonic string is automatically provided. Large numbers of chiral string theories with and without $N = 1$ supersymmetry can be constructed. Many features of their spectra have a simple interpretation in terms of properties of even self-dual lattices. In particular we find an intriguing relation between extended supersymmetry and exceptional groups.

1. Introduction

In the early days of string theory it was considered a major embarrassment when

CHIRAL FOUR-DIMENSIONAL HETEROTIC STRINGS FROM SELF-DUAL LATTICES

W. LERCHE

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A.N. SCHELLEKENS

CERN, Geneva, Switzerland

Received 24 N

10^{1500}

4-dim. strings

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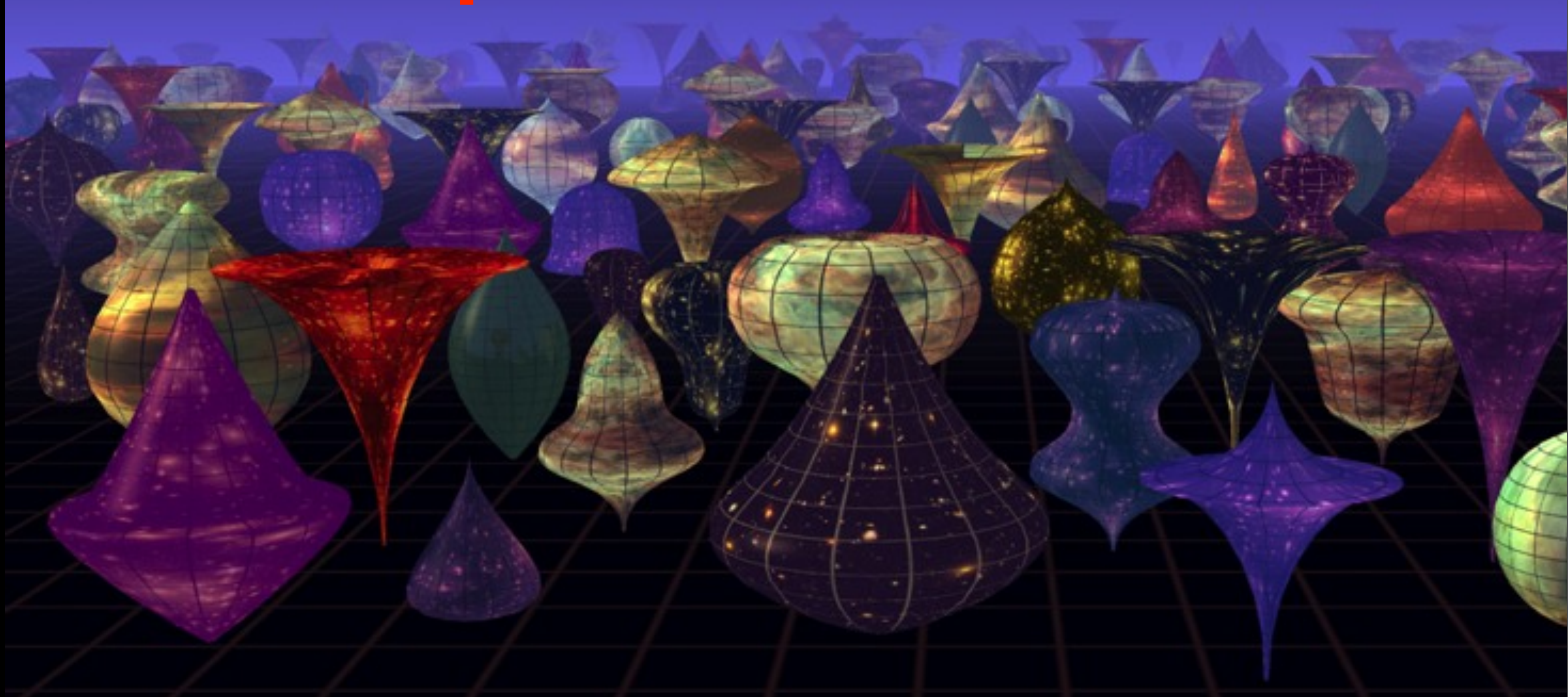

copy right: Kristin Riebe

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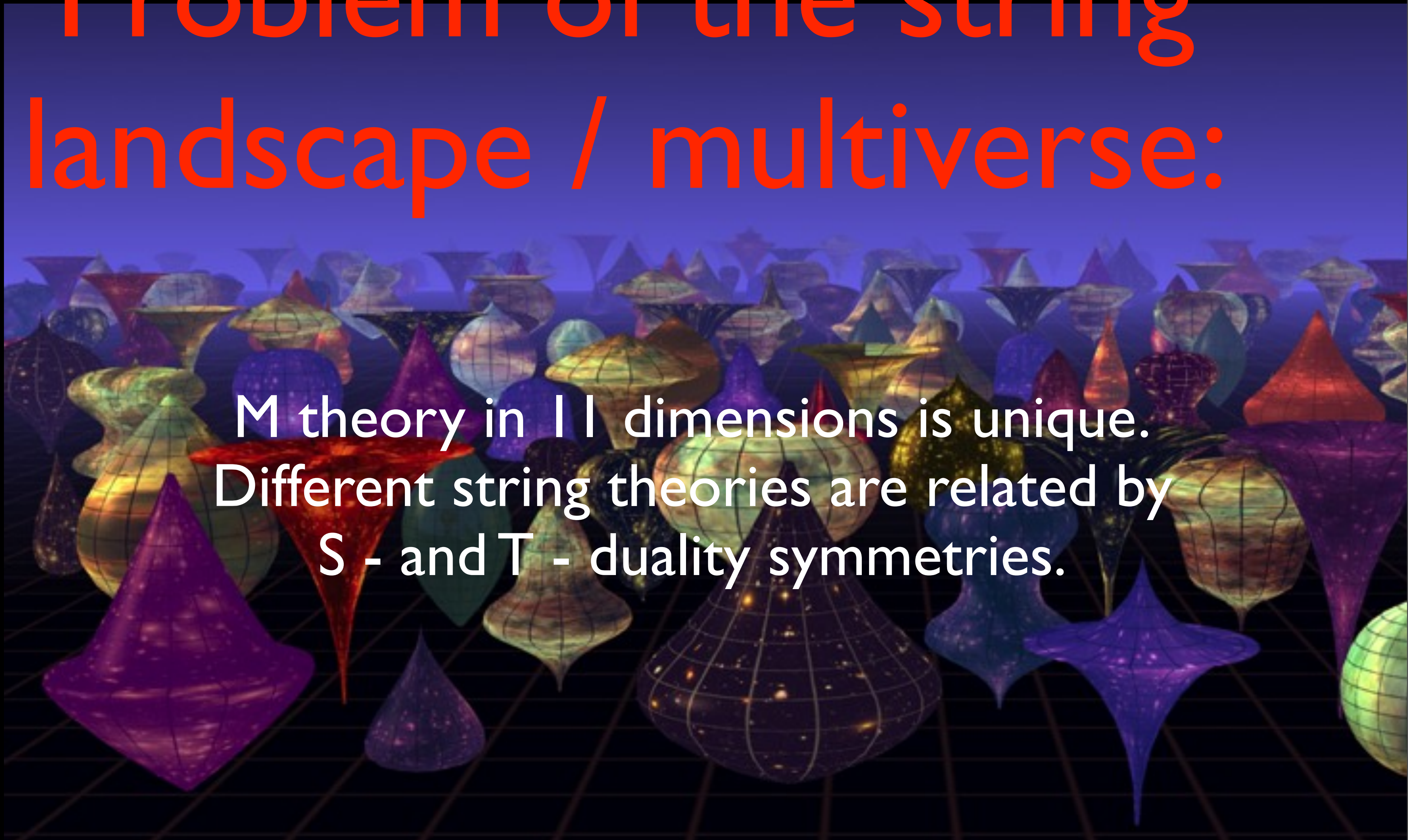

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Many $(10^{1500}\ ?)$ compactified solutions!

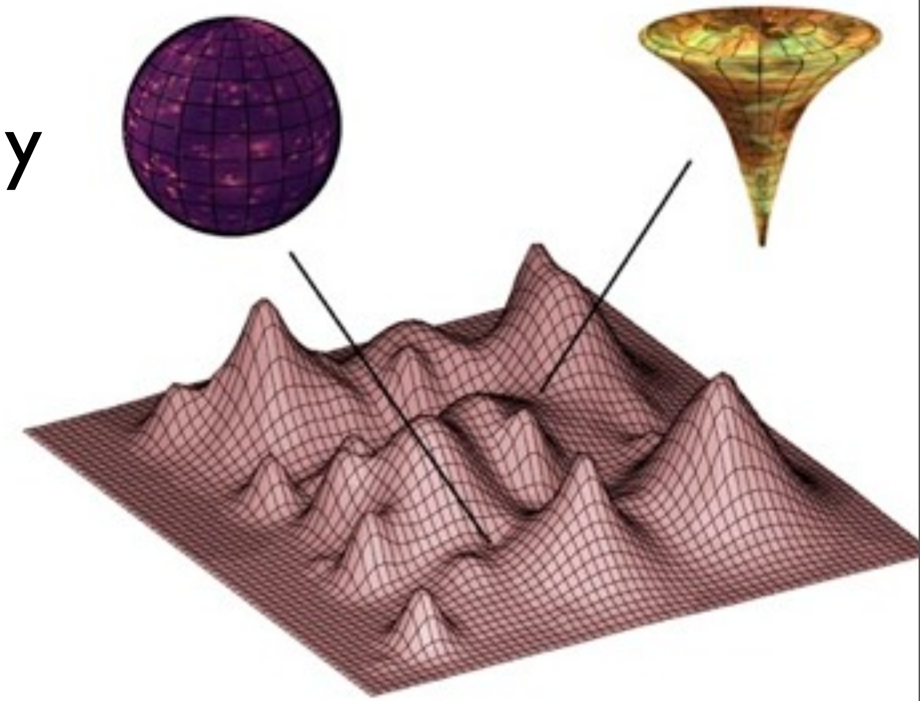
(Lerche, D.L., Schellekens, 1986; Bousso, Polchinski, 2000; Douglas, 2003: Kachru, Kallosh, Linde, Trivedi)

Landscape $\Rightarrow$ Multiverse picture:

(A. Linde, L. Susskind, ...)

- Different universes appear as different phases of an extremely complex system of solutions.

- Problem of calculability and predictability in the landscape of multiverses!



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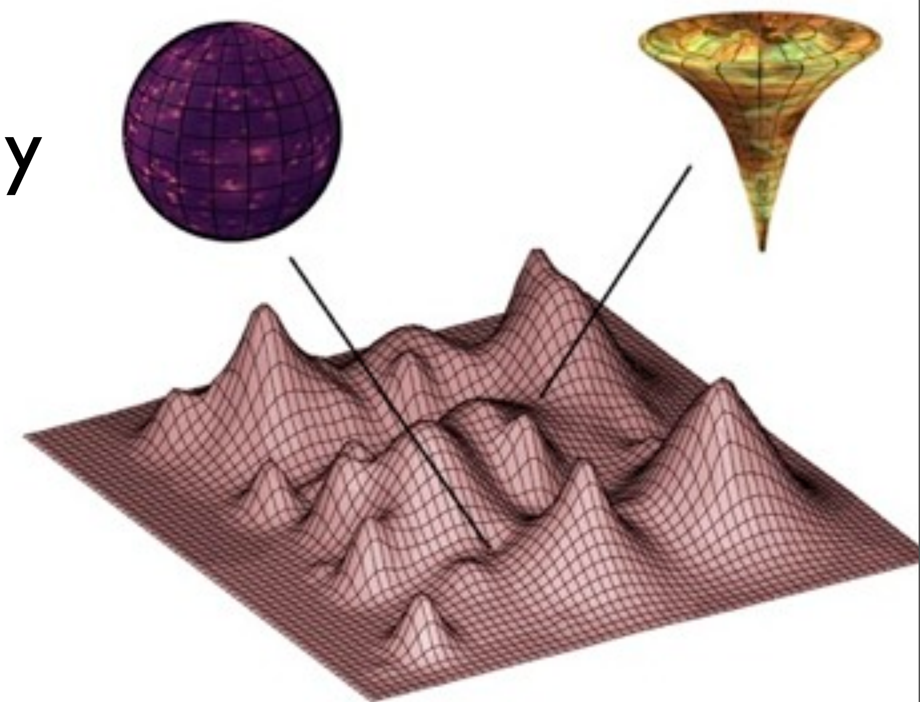

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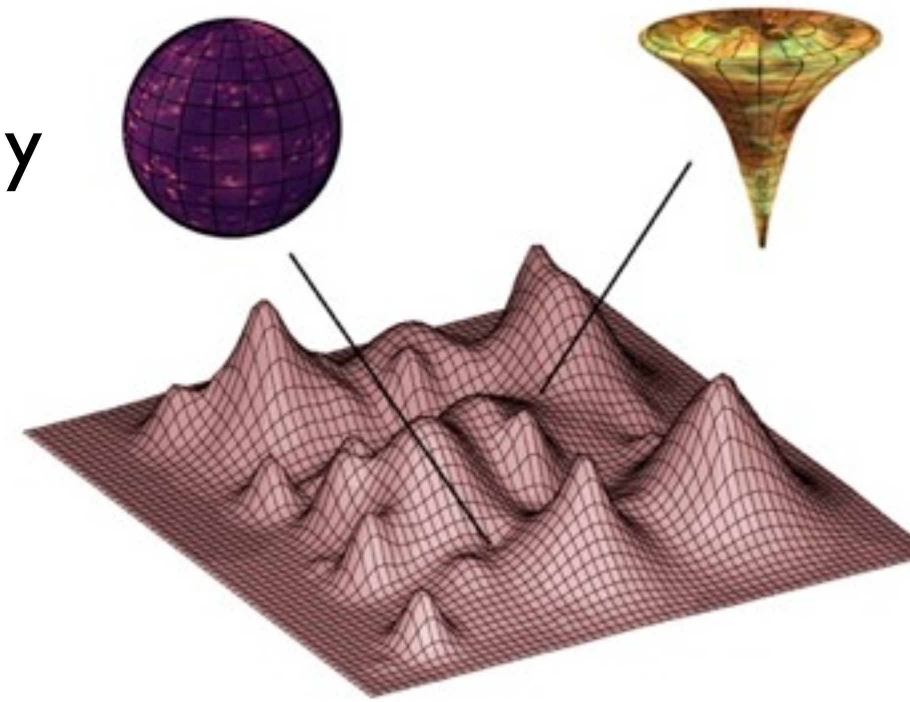

Can we explain our universe only by the anthropic principle?

Murray Gell-Mann:

``If we really live in a multiverse, Physics will have been reduced to an environmental science like Botany.''

(from M. Duff, 1987)

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  - Supersymmetry breaking is still a big problem.

- Explore all mathematically consistent possibilities.

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In total $3.4 \cdot 10^{28}$ susy D-brane models.

$5.7 \cdot 10^{6}$ of them possess MSSM like spectra!

Only one in 10^{-22} models gives rise to a MSSM like vacuum!

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New strategies to handle big data: Machine and deep learning

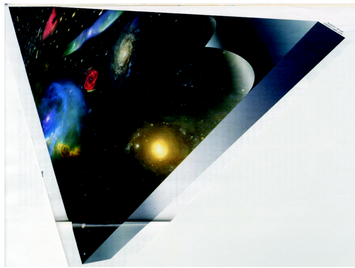
(Y. He, 2017)

- Look for generic features in the landscape in some classes of models:

Low string scale and large extra dimensions:

(N. Arkani-Hamed, S. Dimopoulos, G. Dvali, 1998)

- Gauge and matter fields are living on lower dimensional branes:



- Gravity lives in an higher-dimensional bulk

$$M_{\mathrm{Planck}}^2 \simeq M_{\mathrm{string}}^{2+d^\perp} \, (R^\perp)^{d^\perp}$$

If $R^\perp$ is very large, M_{string} can be very low.

Generic feature of low string/gravity scale models:

Production of universal string Regge excitations at the LHC.

String Hunters‘ Companion: Model independent calculation of production cross sections:

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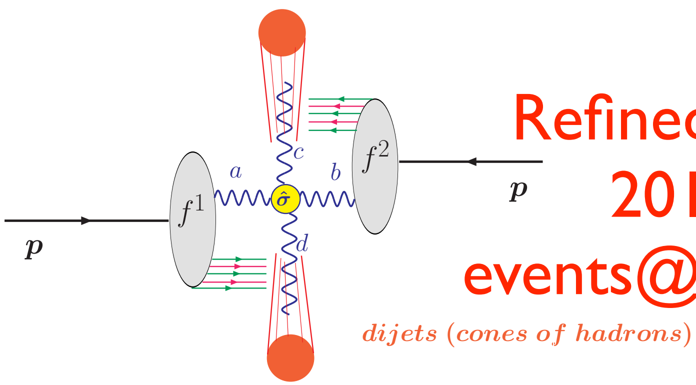

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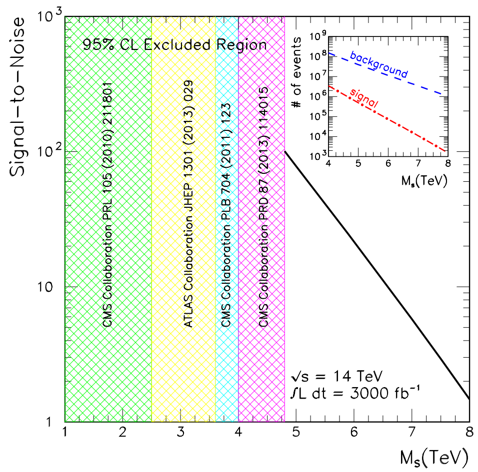

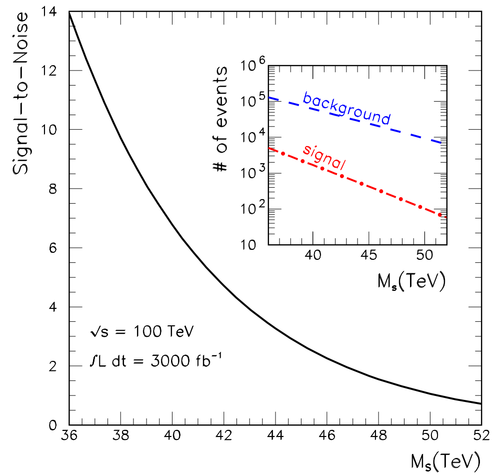

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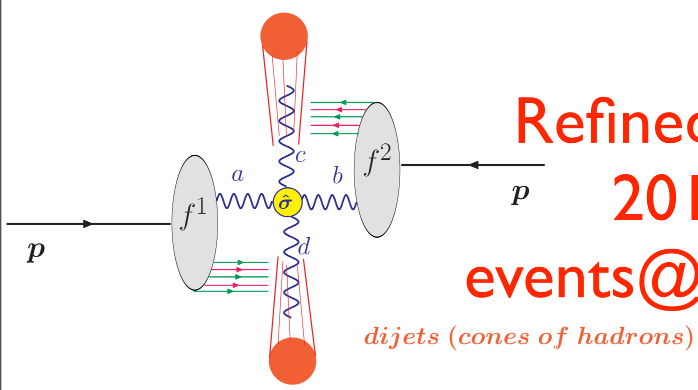

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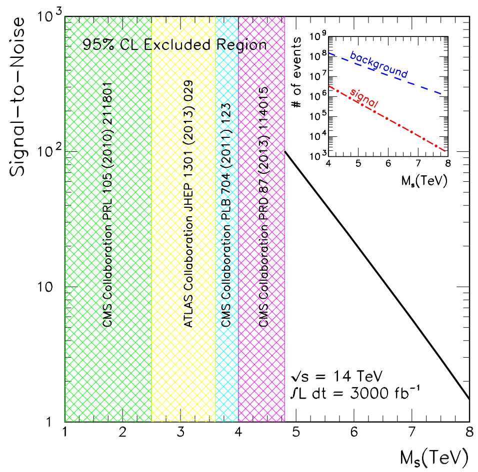

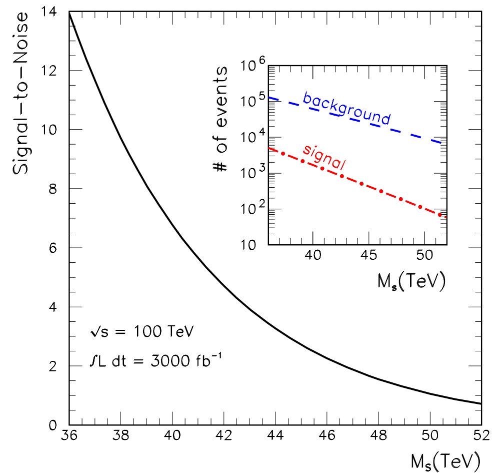

LHC(13) (ATLAS/CMS): $M_{\text{string}} \geq 7\ \text{TeV}$

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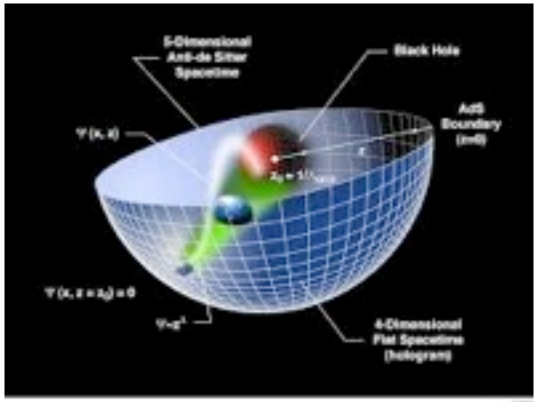
- Structure of perturbative gravitational (and also gauge theory) scattering amplitudes
- Holography and the AdS/CFT correspondence
- Quantum properties of black holes
- The swamp land approach and the weak gravity conjecture

(i) Holography and the AdS/CFT correspondence:

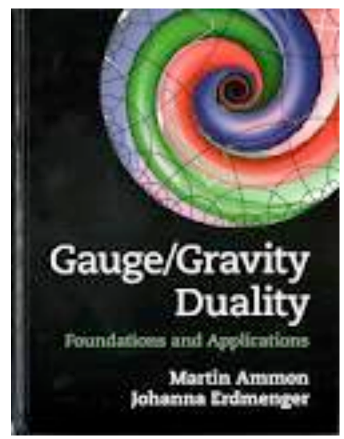
(J. Maldacena, 1997; E. Witten, 1998)

(Quantum) gravity in the D+1 bulk theory $\Leftarrow$ Duality $\Rightarrow$ Quantum field theory on the D-dimensional holographic boundary theory



Many applications for condensed matter physics: AdS/CMT:

Compute correlation functions in strongly coupled systems via dual quantities in classical gravity theory.



Reverse strategy:

Some new important insights for quantum gravity from the dual field theory side.

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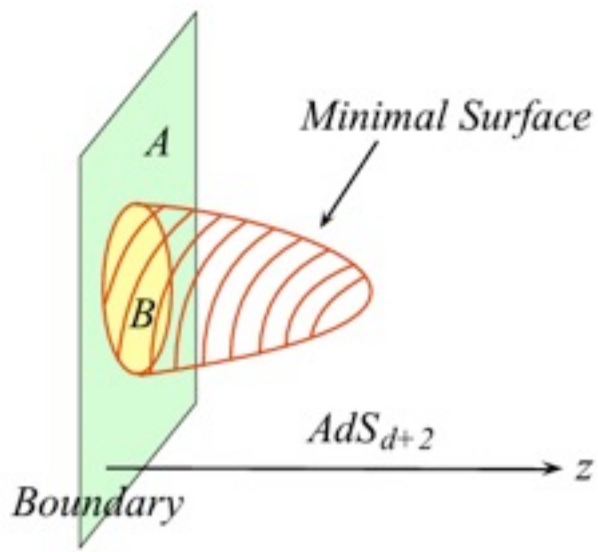
Some new important insights for quantum gravity from the dual field theory side.

- Holographic entanglement entropy (S. Ryu, T. Takayanagi, 2006)

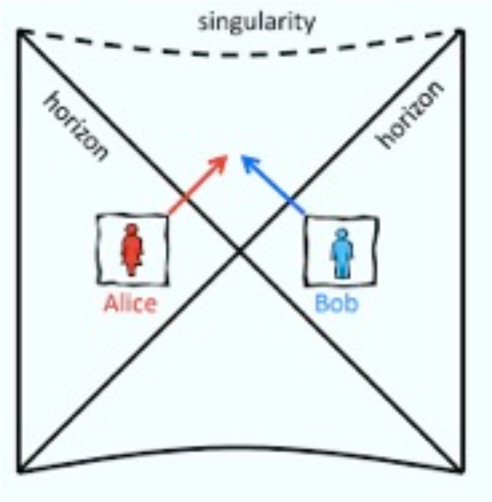
von Neumann entropy

$$S(\rho_A) = \frac{Area(\gamma_A)}{4G_N}$$



- Gravity and quantum information - emergent geometry

Bulk space-time can be described by entangled states in boundary quantum mechanics



Worm hole is an entangled state: (J. Maldacena, L. Susskind, 2013)

$$|\Psi\rangle = \sum_n e^{-\beta E_n/2} |\bar{E}_n\rangle_L \times |E_n\rangle_R$$

(thermal field double)

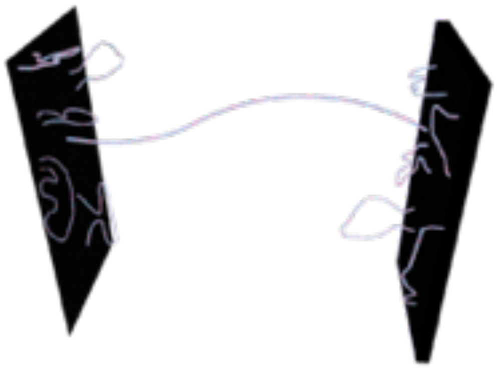
(ii) Quantum properties of black holes

One of the most celebrated results of string theory as quantum gravity theory:

Microscopic derivation of black hole entropy (in 5D):

(A. Strominger, C. Vafa, 1996)

Black holes can be viewed as bound states of 3x N D-branes.



$$S_{BH} = \frac{\text{Area}}{4} = 2\pi\sqrt{\frac{N^3}{2}}$$

Entropy is due to open string degeneracy.

Complementary proposal for a quantum black hole picture:

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- Formation of a black hole $\Leftrightarrow$ graviton condensate at quantum critical point = Bose-Einstein condensate
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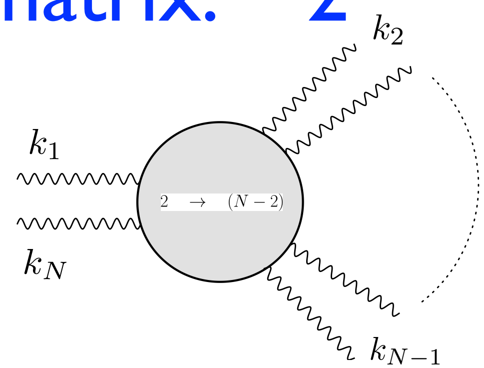

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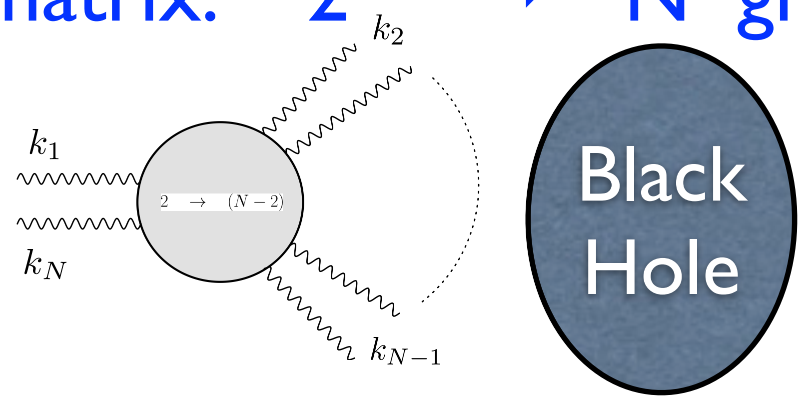

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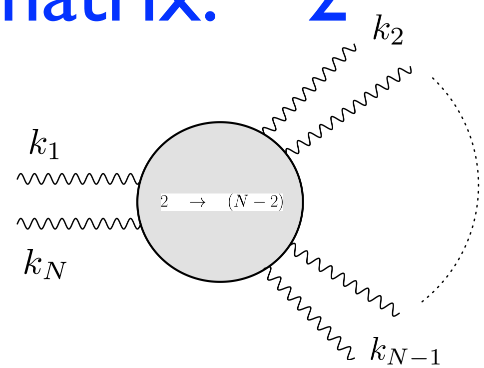

Strings at very high energies

G. Dvali, C. Gomez, R. mann, D.L., S.. Stieberger 2014)

(iii) The swamp land approach (H. Ooguri, C. Vafa, 2006)

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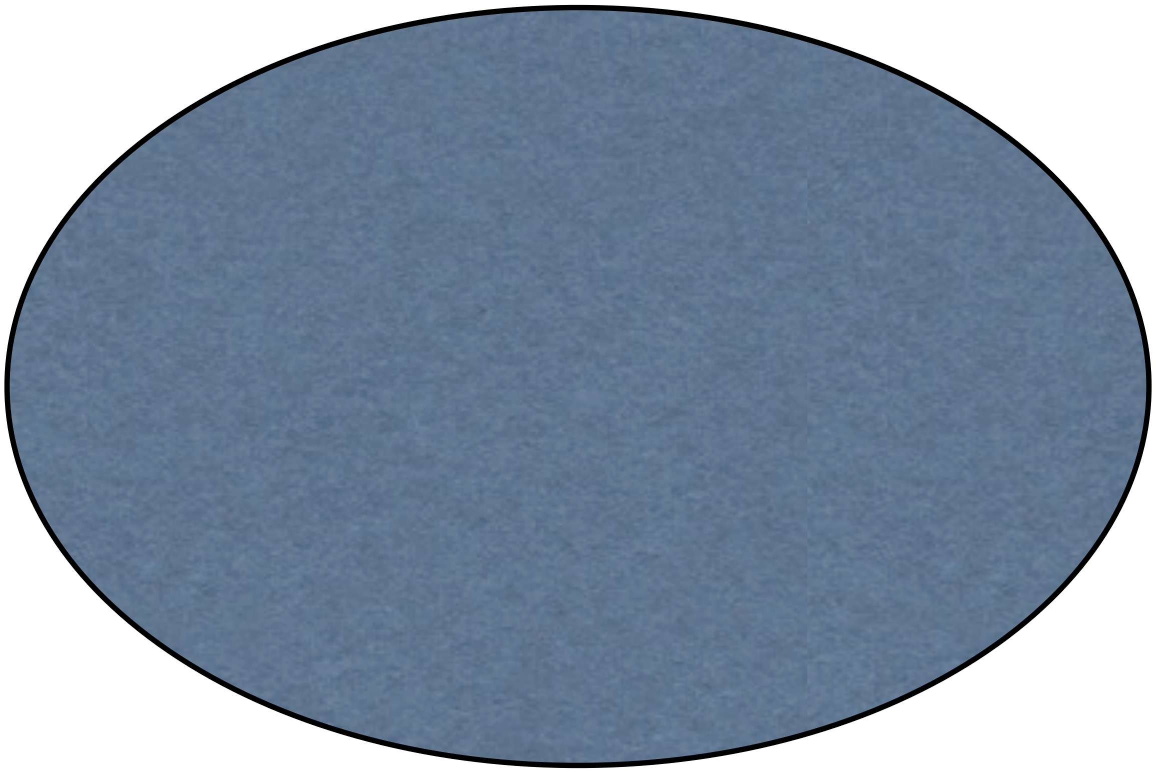

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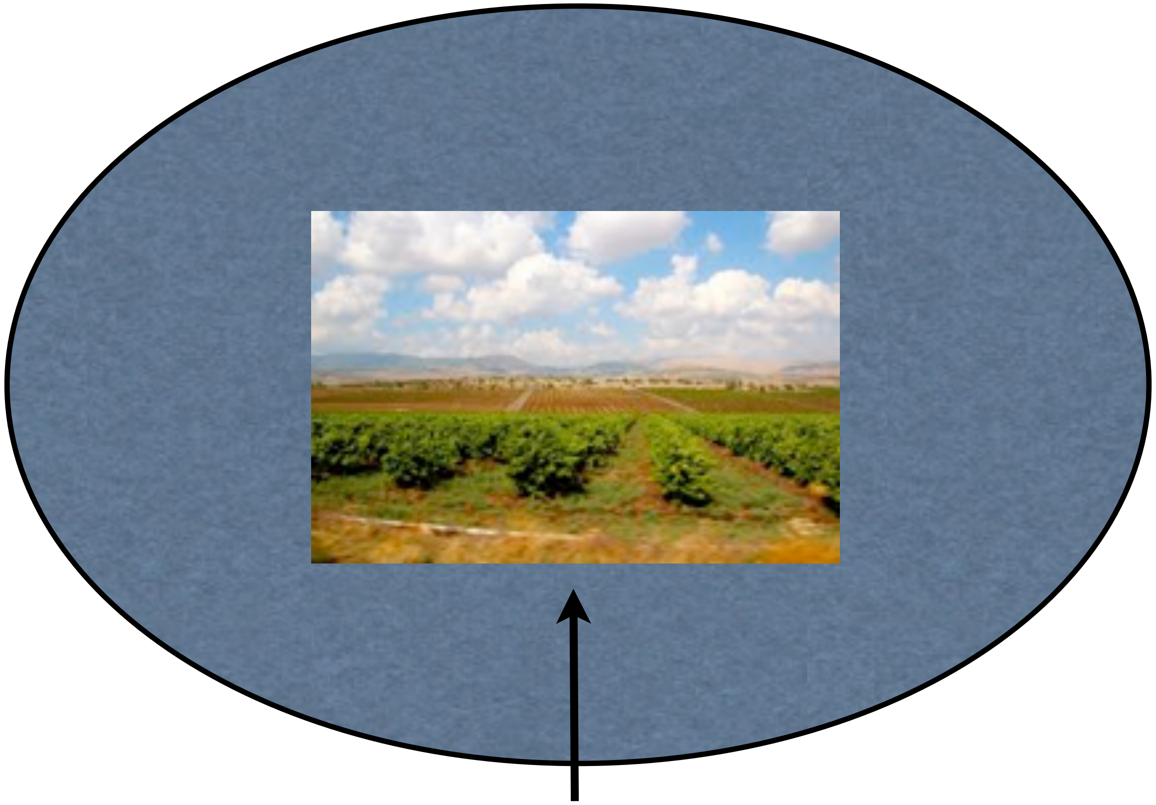

Fruitful quantum field theories that can be consistently embedded in quantum gravity/string theory in the UV.

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Swampland of theories that are inconsistent as quantum gravity theory

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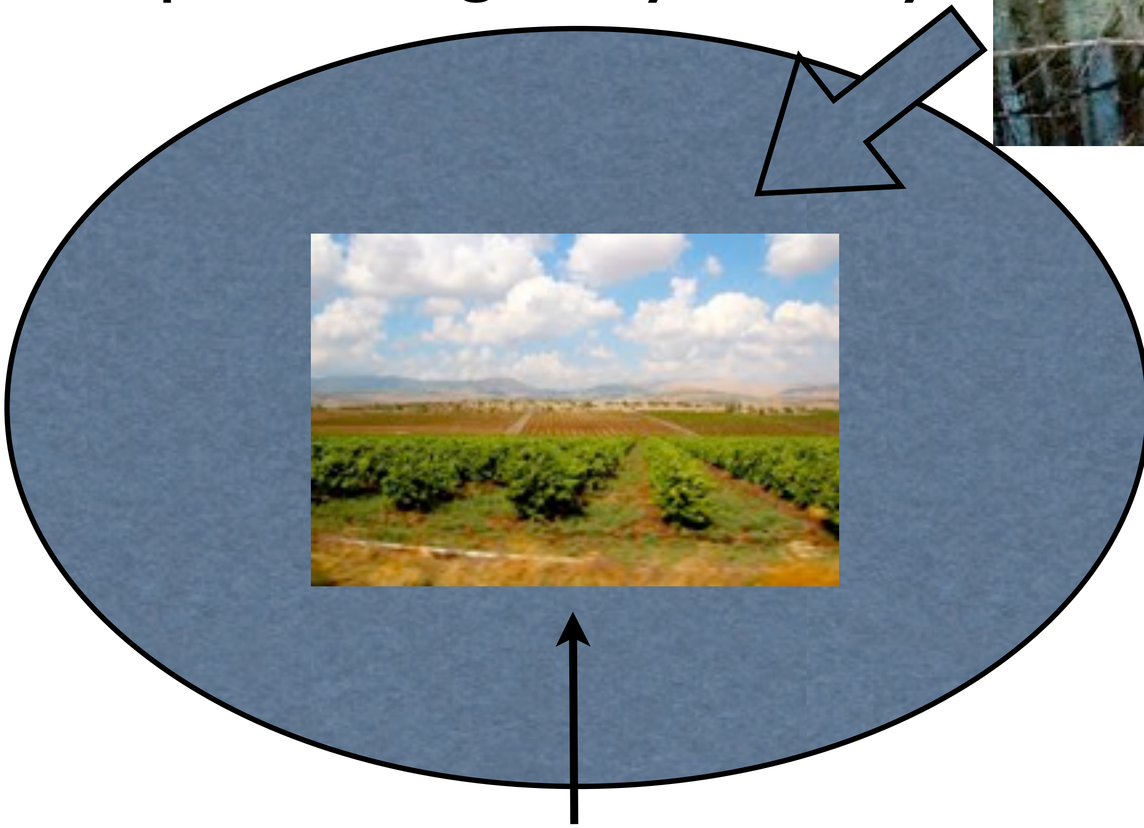

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Axion WGC ⇒ Large field inflation: $\Phi_{\rm inflaton} \leq M_{\rm Planck}$

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What is happening if one crosses the UV cut-off scale ?

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New feature of quantum gravity: UV/IR mixing.

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- T-duality (a small compact space is equivalent to a large compact space)
- Duality invariant generalization of Einstein gravity

$\Rightarrow$ Double Field Theory, Exceptional Field Theory

(D. Berman, H. Godazgar, O. Hohm, C. Hull, E. Malek, H. Nicolai, M. Perry, F. Rudolph, H. Samtleben, B. Zwiebach, ...)

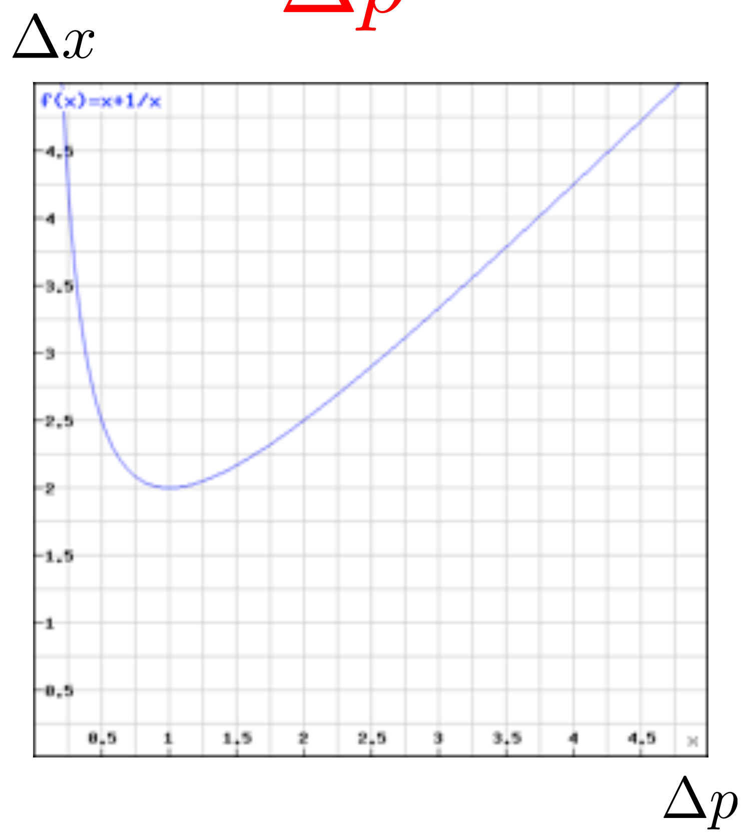
String scattering at super-string scale energies:

Refinement of Heisenberg relation: $\Delta x \geq \frac{\hbar}{\Delta p} + \alpha' \Delta p$

(A. Amati, M. Ciafaloni, G.Veneziano, 1987)

$\Rightarrow$ Smallest possible distance:

$$\Rightarrow \quad \Delta x \geq \Delta x_{min} \simeq L_{\rm string}$$



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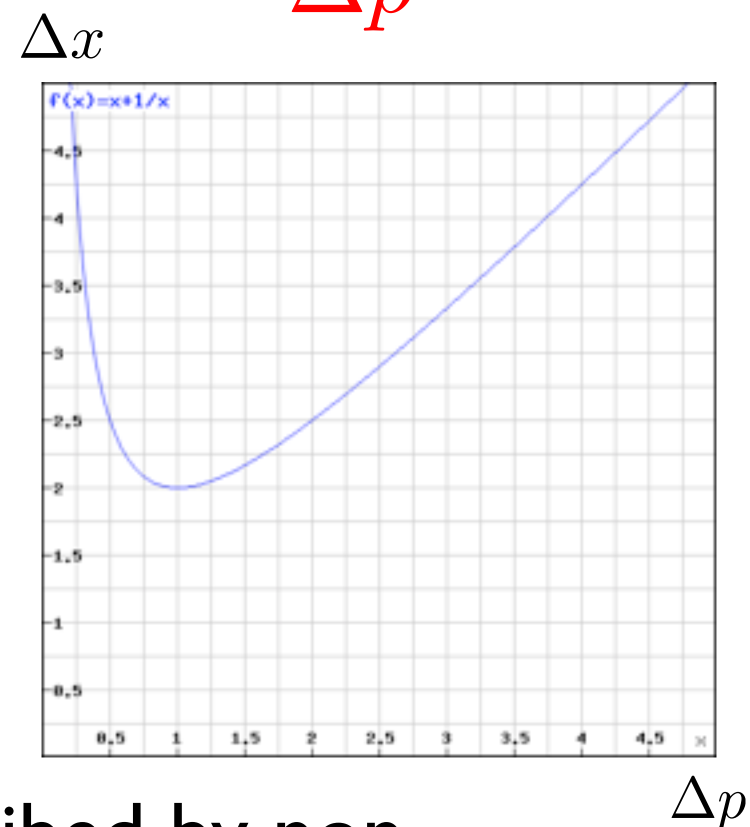

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Mathematically this can be described by non-commutative and non-associative geometry.

(D.L., A. Blumenhagen, E. Plauschinn, 2010)

Volume uncertainty: $\Delta V = \Delta X^1 \, \Delta X^2 \, \Delta X^3 \geq L^3_{\mathrm{string}}$

(D. Mylonas, P. Schupp, R. Szabo, 2013; Chamseddine, Connes, Mukhanov, 2014)

Another problem in (quantum) gravity:

Hierarchy problem:

Why is the scale of gravity apparently so much higher that the mass scale of the Standard Model?

$$M_{\rm Planck} \simeq 10^{19}\ \text{GeV} \;\; >> M_{\rm Higgs} \simeq 126\ \text{GeV} \;\; ?$$

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$$M_{\text{Planck}} \simeq 10^{19} \text{ GeV} \quad >> M_{\text{Higgs}} \simeq 126 \text{ GeV} \quad ?$$

Newton (1680), Planck (~ 1900)

ATLAS, CMS (2012)

Another problem in (quantum) gravity:

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Cosmological constant problem:

$$\Lambda_{\text{cosm}} \simeq 10^{-120}\ M_{\text{Planck}}^4$$

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Lowering the UV cut-off: New physics at the weak scale.

- Supersymmetry: $M_{\mathrm{SUSY}} \simeq 1 - 10\ \mathrm{TeV}$

(J. Wess, B. Zumino, 1974)

- String theory with a low fundamental scale of gravity:

$$M_{\mathrm{string}} \simeq 1 - 10\ \mathrm{TeV}$$

String resonances (excited quarks) at a few TeV

Possible new solution of the hierarchy problem based on quantum gravity and UV / IR mixing:

The IR weak scale at low energies is a consequence of UV gravity at high energies.

No new physics/particles will emerge at the weak scale.

Concrete proposal: Refined weak gravity conjecture:

(E. Palti, 2017)

Consider gravity plus U(1) plus a neutral scalar field ϕ , which is coupled to a charged particle h:

$$\mathcal{L} = \frac{M_p^2}{2} R - \frac{1}{4g^2} F^2 - |Dh|^2 - (\partial\phi)^2 - m^2 h^* h - m_\phi^2 \phi^2 - 2m\mu\phi h^* h + \ldots$$

gauge coupling g

scalar field coupling μ

UV cut off scale of the theory is still given as:

$$\Lambda_{UV} \leq g M_{\text{Planck}}$$

But UV quantum gravity now implies an IR mass scale :

(D.L., E. Palti, 2017)

$$m_h \leq \sqrt{g^2 - \mu^2} M_{\text{Planck}} \equiv \beta M_{\text{Planck}}$$

This particle could be e.g. the Higgs or a light fermion and its mass can be arbitrarily far from the UV cut-off scale.

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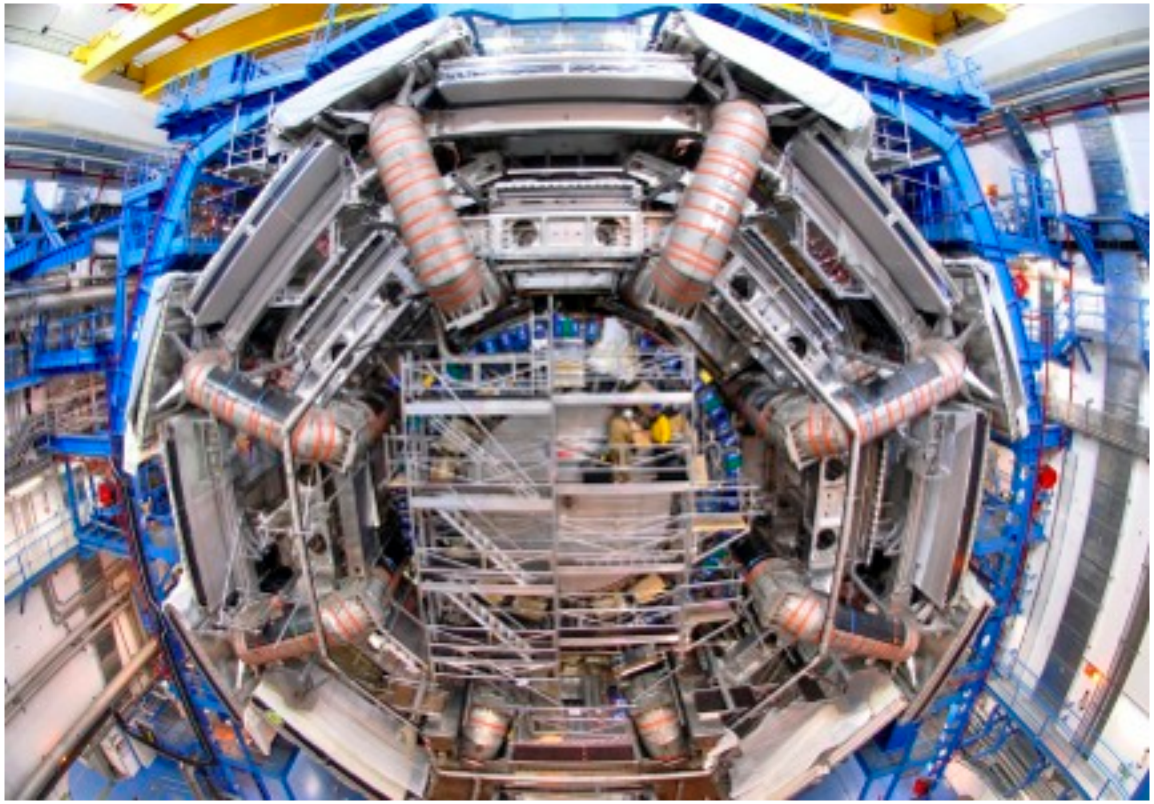
Particle physics:



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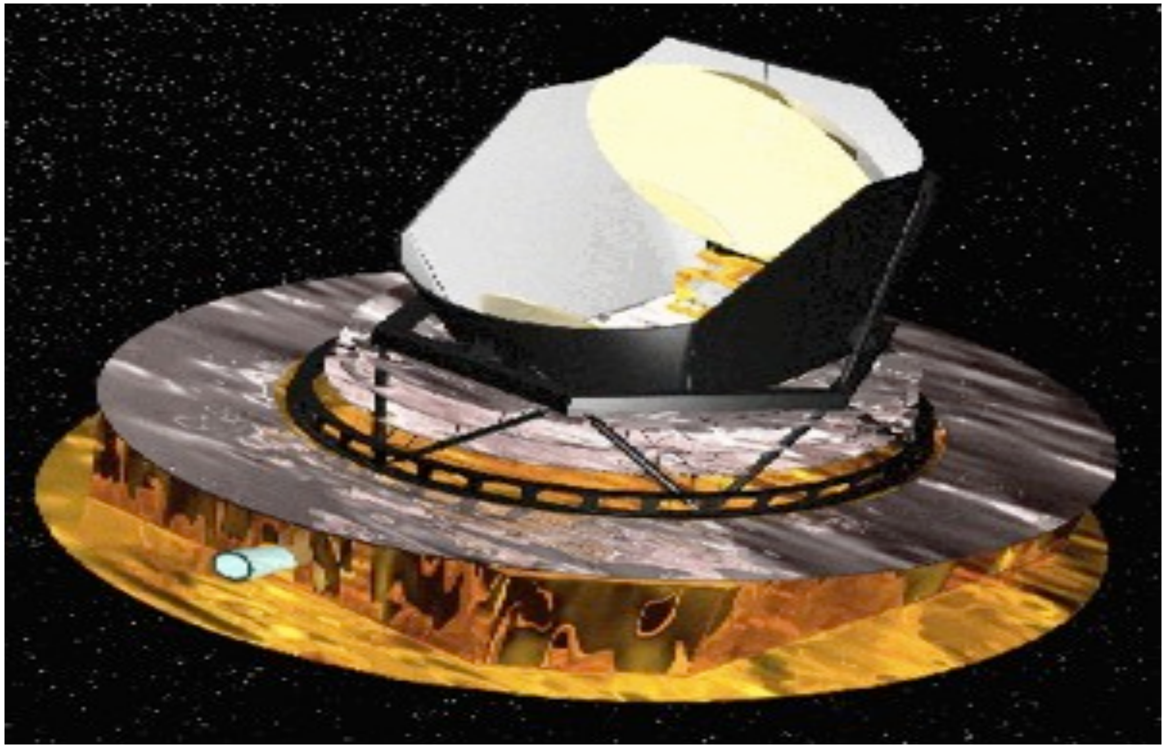
Astrophysics/cosmology



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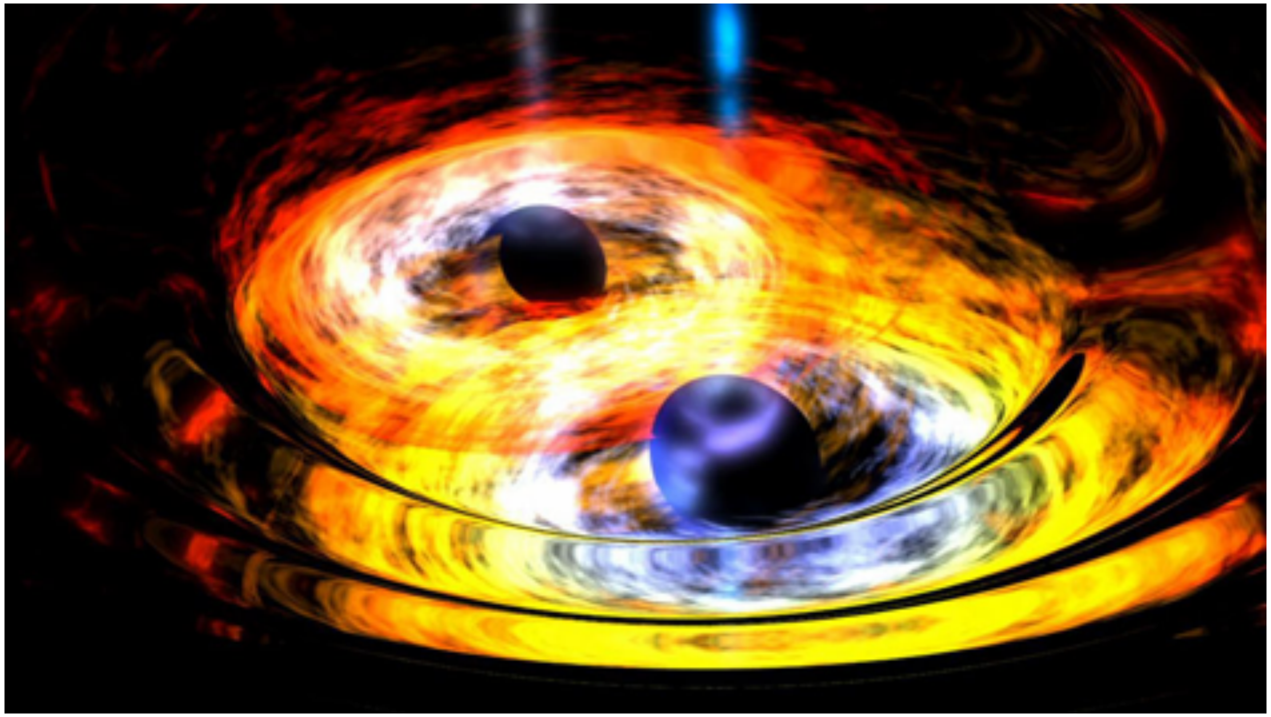
Gravitational waves/black holes



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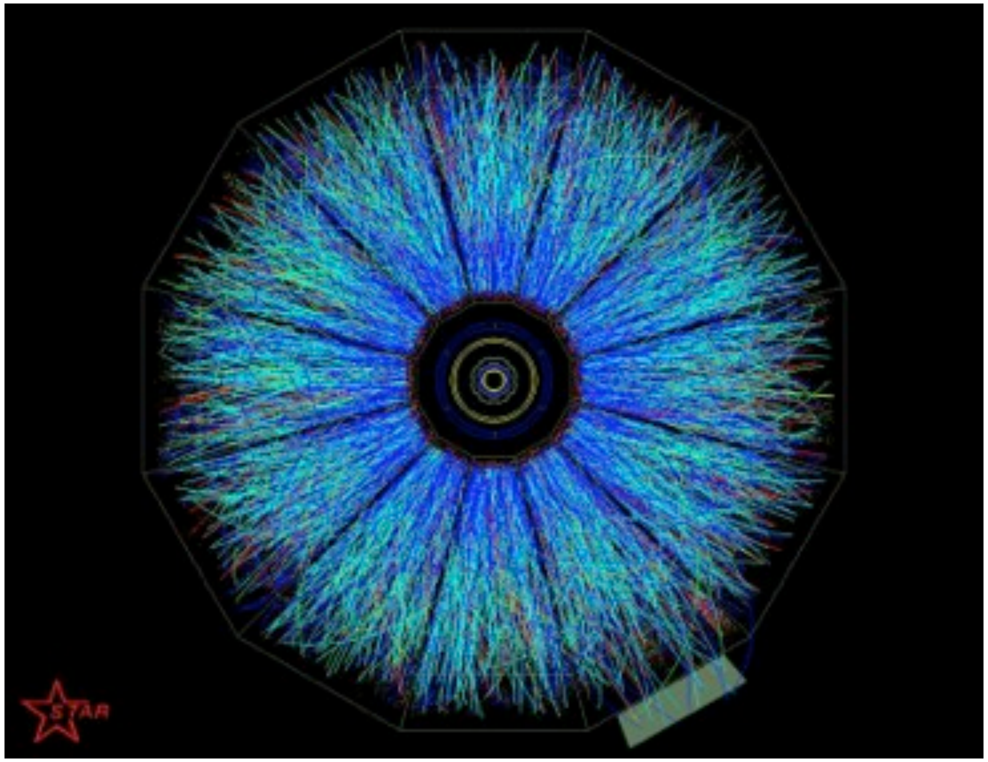
Strongly coupled system (QCD, condensed matter)



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Thank you!