String Theory: The Quest for Phenomenological Predictions

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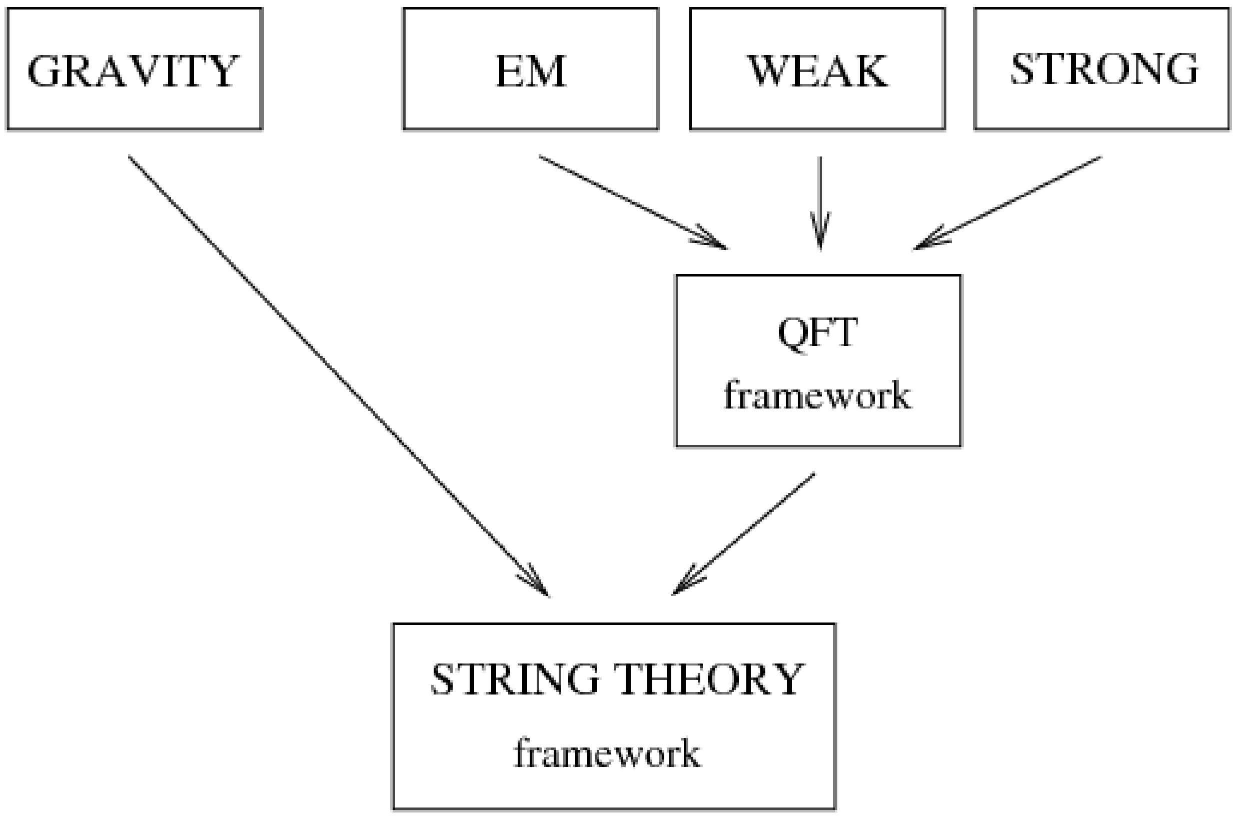
The Big Picture



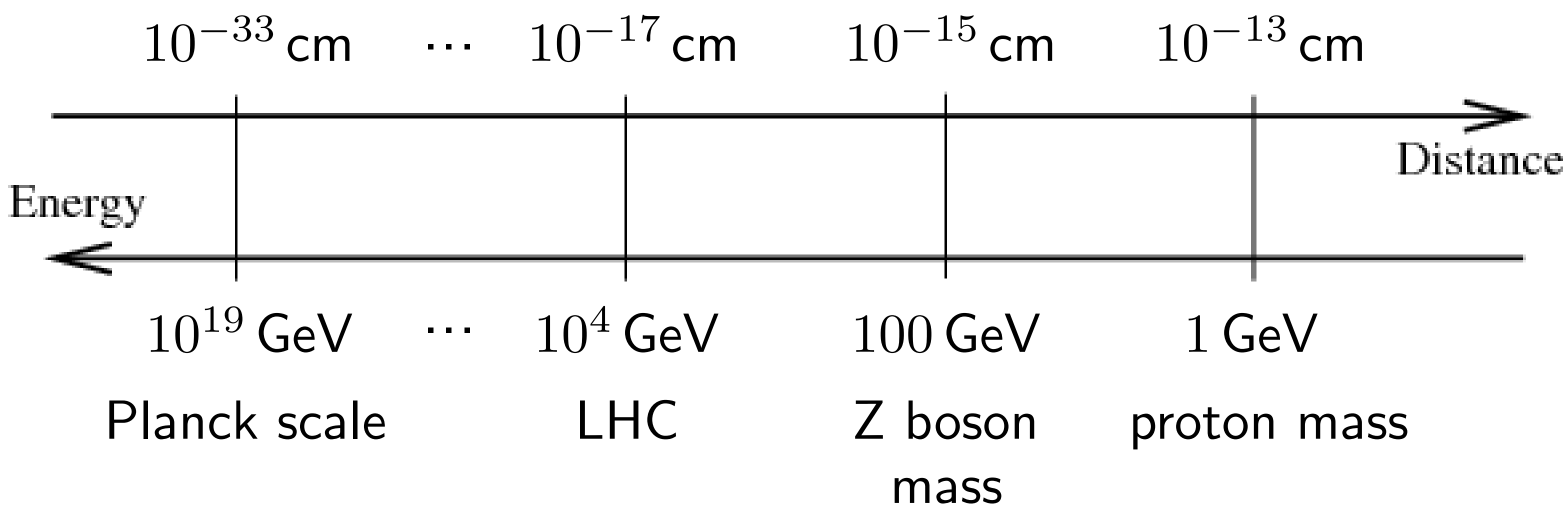
In recent years:

Gauge/Gravity Duality:	powerful tool for studying
[AdS/CFT]	strongly coupled gauge theories

Planck (quantum gravity) scale:

Planck length: $l_p = \left(\frac{hG}{c^3}\right)^{1/2} \approx 10^{-33}$ cm

Planck energy: $E_p = \frac{hc}{l_p} \approx 10^{19}$ GeV



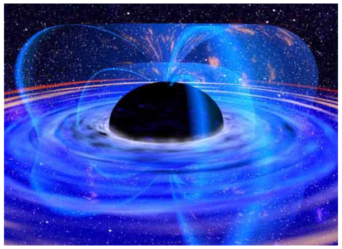
1 Joule $\approx 10^{10}$ GeV

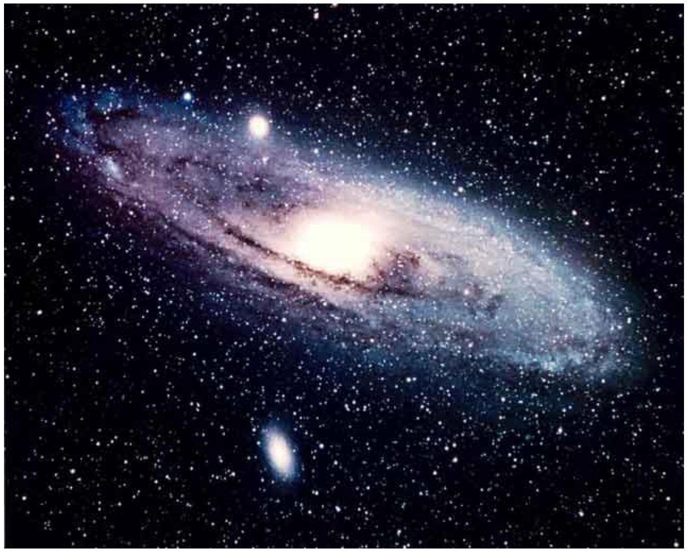
Most of the time: Can neglect gravity in studies of elementary particle physics

(So we don't see the contradiction.)

BUT: There are places in the Universe, where that's not possible (where gravity is strong)!

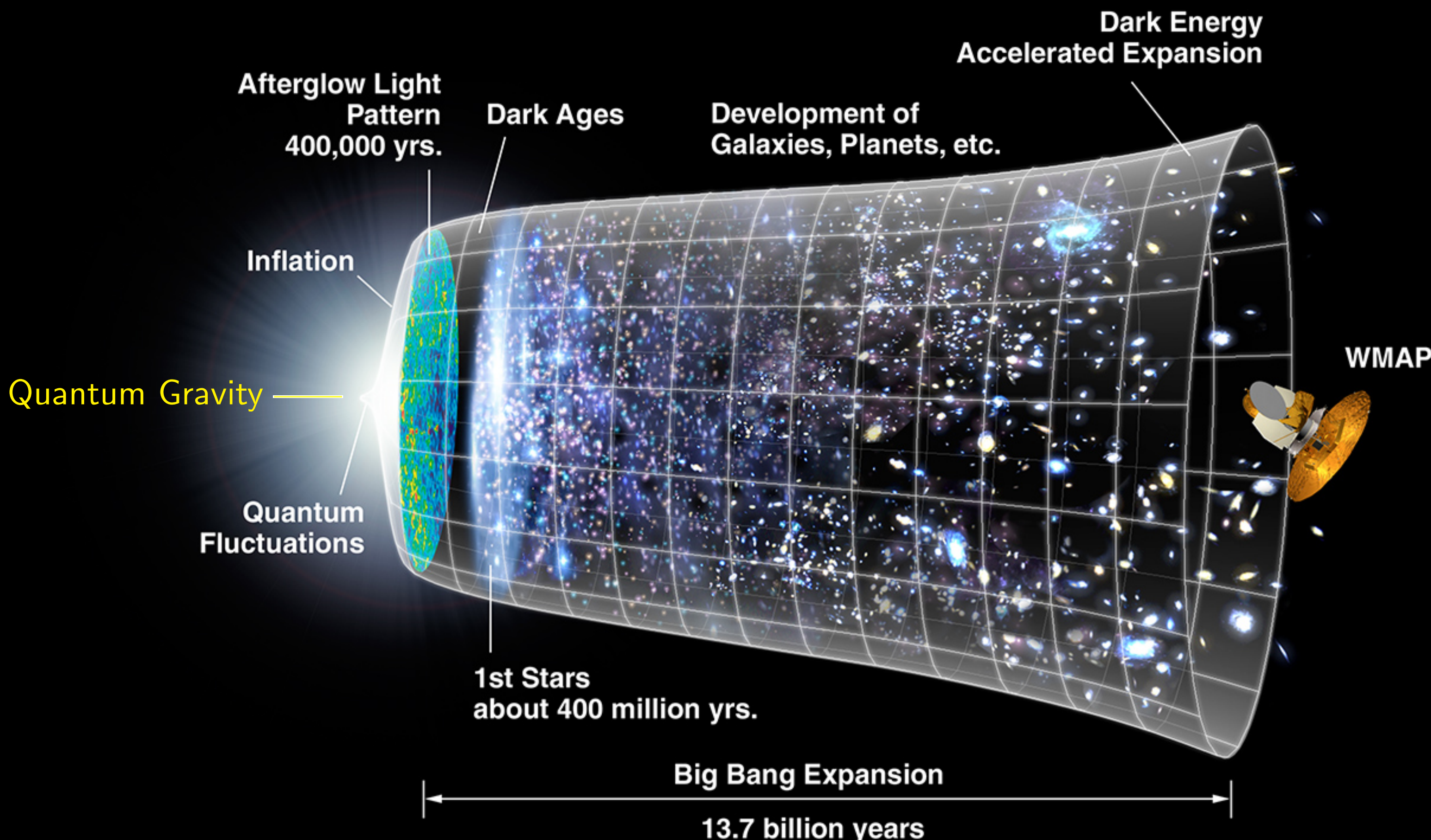
Black Holes:





Black Holes are not rare:
One at center of every galaxy!

Also, a time when Quantum Gravity crucial:



(Shortly after) Big Bang: Origin of all structure we see today!

NASA/WMAP Science Team

Why String Theory:

General Relativity - incompatible with Quantum Field Theory

(Quantum Mechanics)

More precisely: Gravity - not renormalizable

Nonrenormalizable theories:

Do not make sense within the framework of QFT!

String Theory: larger theoretical framework,

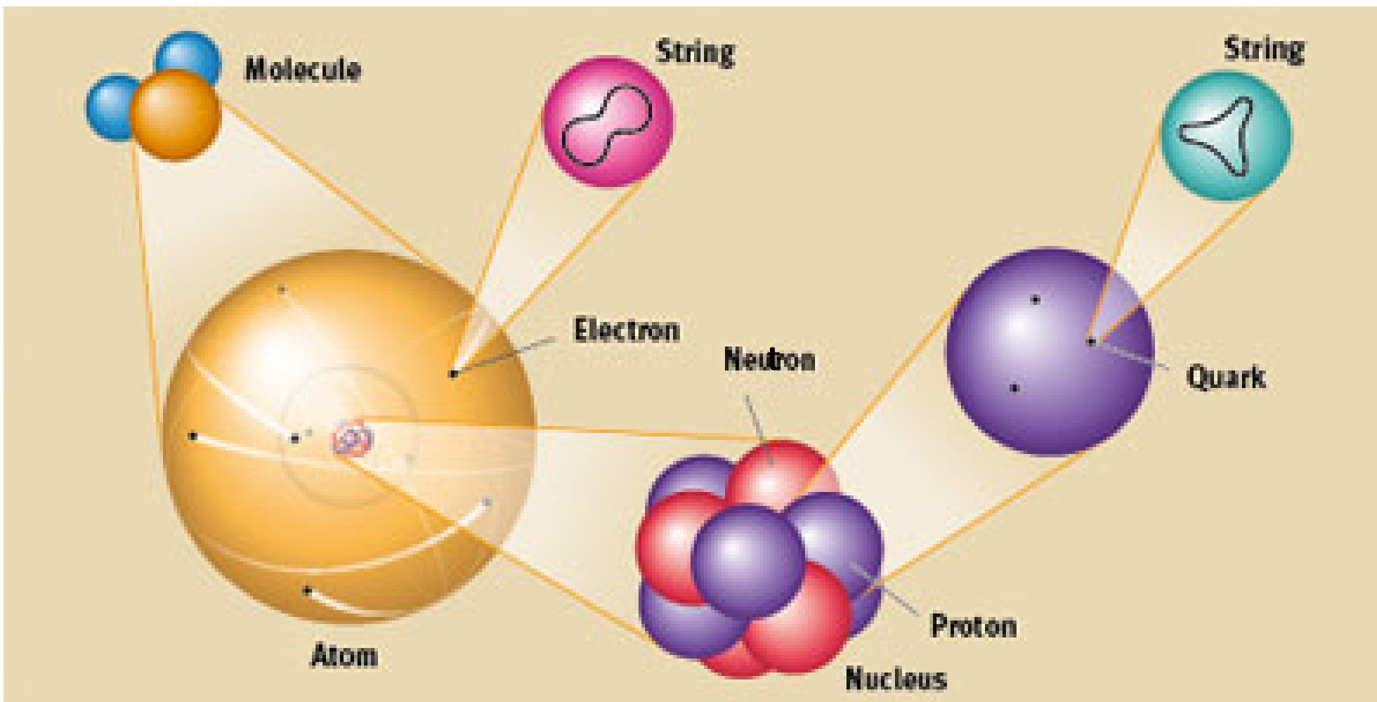
which enables the study of nonrenormalizable theories

I.e.: It provides a UV completion to nonrenorm. FTs

In particular: Gives description of quantum gravity

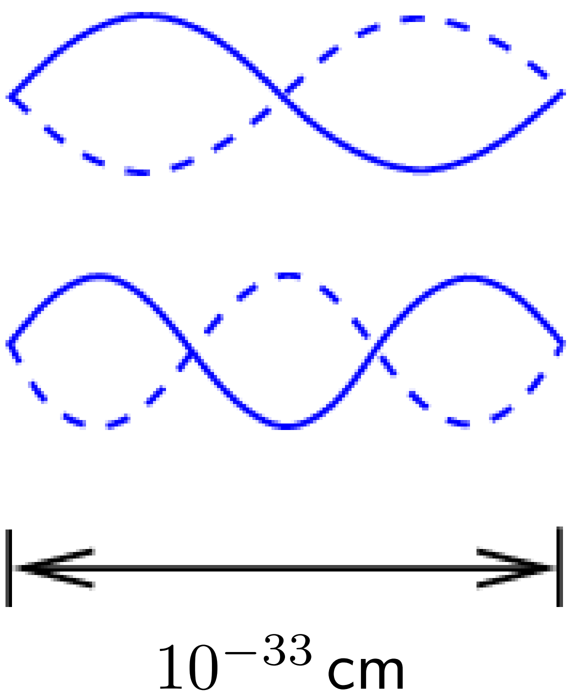
What is String Theory:

Basic idea: Replace elementary particles with strings



Each vibrational pattern gives rise to
a different elementary particle.

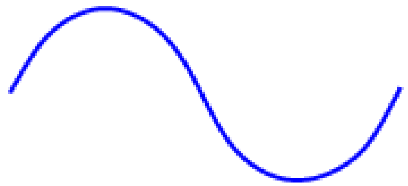
(Every mode of vibration: associated with certain mass, el. charge,
spin, other quantum numbers)



Typical string size:
of order the Planck length
[10^{-33} cm]

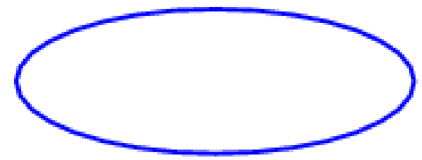
$\rightarrow$ Strings look pointlike
in present day experiments

Two kinds of strings:



open

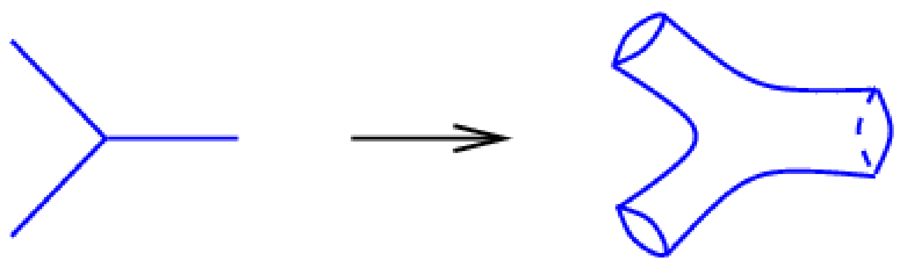
[photon, ...]



closed

[graviton, ...]

Interactions:



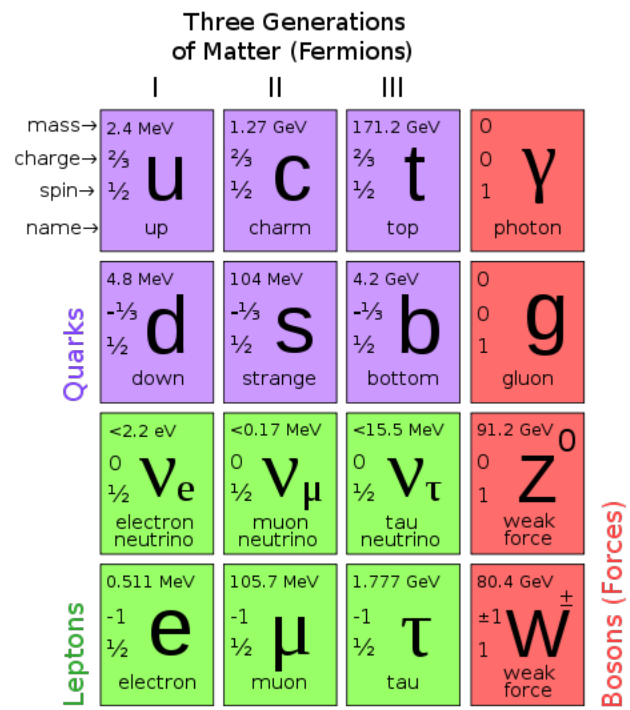
$\Rightarrow$ removes UV divergences of QFT

Supersymmetry:

Important property of string theory:

Symmetry between fermions and bosons

Standard Model
of
Particle Physics



Supersymmetry: Every particle in SM has a susy partner

Supersymmetry:

- Could be observed at the LHC
- Desirable for purely phenomenological reasons
  - Tames the quantum corrections to the masses of fundamental scalars (like Higgs boson)
  - Helps unify the gauge couplings of the EM, weak and strong interactions at high energies

$\rightarrow$ a lot of work on FT susy extensions of SM (MSSM etc.)

BUT: supersymmetry + gravity = supergravity,
SUGRA - low energy effective action of string theory

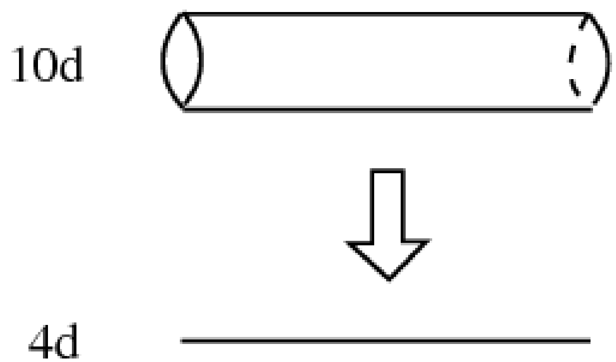
- Indirect indication for string theory

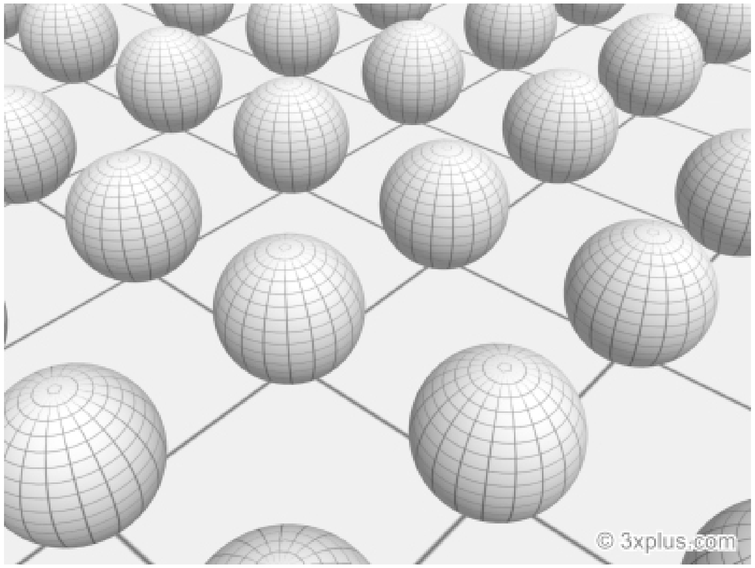
Compactification:

Supersymmetric string theory: consistent only in 10 dimensions!

[i.e., strings propagate in 10-dimensional space-time]

$\Rightarrow$ Need to compactify 6 dimensions:





$\rightarrow$ Effective 4-dimensional description

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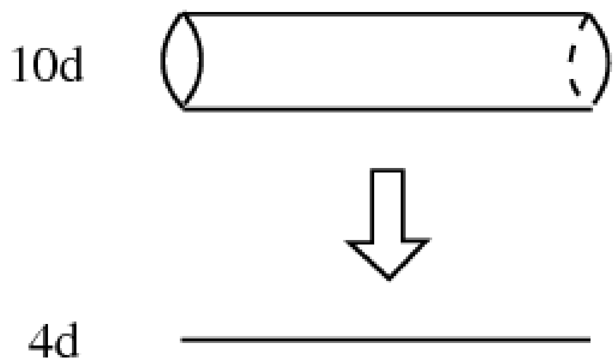
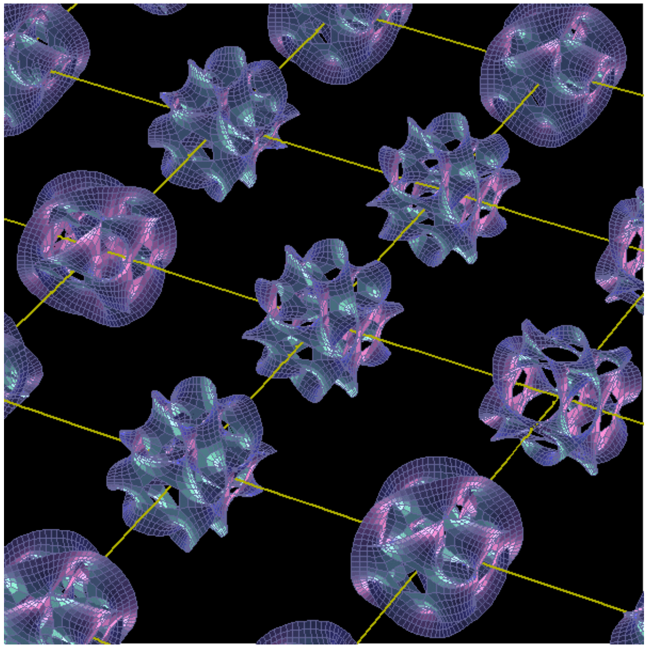




$\rightarrow$ Effective 4-dimensional description

Compactification:

Parity violation $\Rightarrow$ fermions in Standard Model are chiral

So want chiral fermions in 4d susy EFT after compactification

[technical term: $N = 1$ susy in 4d]

$\Rightarrow$ restriction on internal 6d space [has to be Calabi-Yau]

6d manifold: many allowed deformations with no energy cost,

allowed deformations: preserve equations of motion and supersymmetry conditions

In 4d effective theory:

Defs give rise to massless scalars without potential (moduli)

Simpler example:

Kaluza-Klein theory: 5d gravity on $M_4 \times S^1$

$$g^{(5)}_{mn} = \begin{bmatrix} g^{(4)}_{\mu\nu} & A_\mu \\ A_\nu & \phi \end{bmatrix}$$

Radius of S^1: modulus

In 4d: S^1 size manifests itself as scalar ϕ

In general:

Moduli vevs determine 4d properties (couplings, masses etc.)

As long as moduli arbitrary: no predictivity

$\rightarrow$ Need to generate potentials for the moduli!

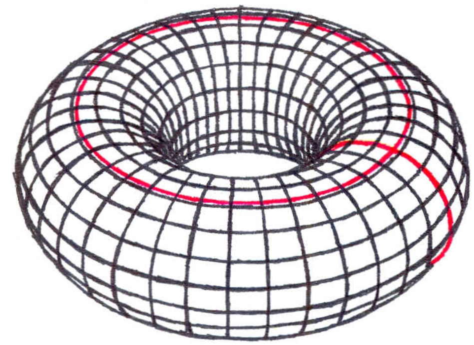
[then moduli would be fixed at minima]

Moduli

Torus:

Topologically non-trivial 1-cycles

[non-contractible curves]



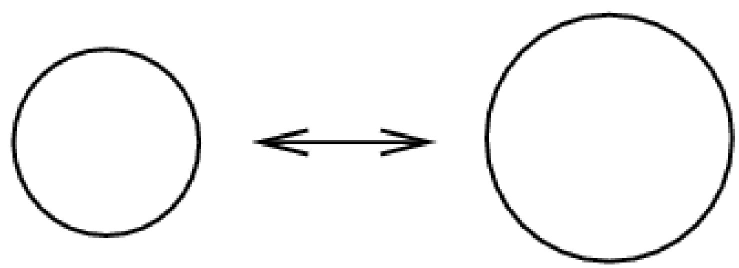
Calabi-Yau 3-fold:

Topologically non-trivial 2-, 3- and 4-cycles [n-cycle: n-dim.]

Moduli: deformations of these cycles

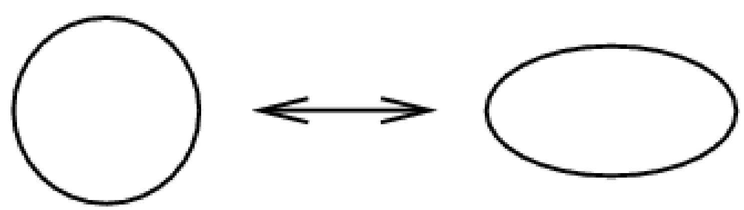
Size moduli:

[Kähler moduli]



Shape moduli:

[complex structure moduli]

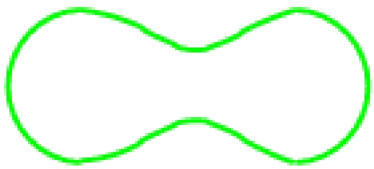


Generating Moduli Potentials

(Moduli Stabilization)

Classical level:

Turn on background fluxes:



g_{mn}, B_{mn}, A_{mnp}, ...

B_{mn}, A_{mnp}: antisymmetric tensor field potentials

[generalize EM potential A_μ]

Flux: $\langle B_{mn} \rangle \neq 0 \; , \; \langle A_{mnp} \rangle \neq 0$

$\rightarrow$ Complicates eqs. of motion and susy conditions;

In 4d: looks like a potential

More formally:

Background fluxes are due to higher-dimensional analogues of EM field

[EM field strength: 2-form $F_2 = \frac{1}{2} F_{\mu_1 \mu_2} dx^{\mu_1} \wedge dx^{\mu_2}$]

In string theory:

$\exists$ p-form field strengths $F_p = \frac{1}{p!} F_{\mu_1 \ldots \mu_p} dy^{\mu_1} \wedge \ldots \wedge dy^{\mu_p}$

[Ex.: Type IIA: F_2, H_3, F_4, F_6]

Background flux: $F_p \neq dA_{p-1}$ globally

[i.e. topologically nontrivial configuration; cannot be gauged away]

BUT: Fluxes backreact on the geometry

$\Rightarrow$ 6d manifold cannot be same as in fluxless case

[cannot be Calabi-Yau anymore]

$\rightarrow$ Need to consider generalized compactifications !

[technical term: $SU(3)$ structure manifolds]

Generalized compactifications:

Can be studied due to math developments from last decade

My work:

L.A. [JHEP 0901 (2009) 017 , arXiv:0806.3820]; L.A. [Fortsch. Phys. 57 (2009) 492 , arXiv:0901.4148];
L.A., F. Larsen, R. O'Connell [JHEP 1011 (2010) 010 , arXiv:1006.4981]:

– New method for systematic study of moduli stabilization:

Reformulated minimization of moduli potential

into solving simplified set of algebraic equations

Quantum contributions:

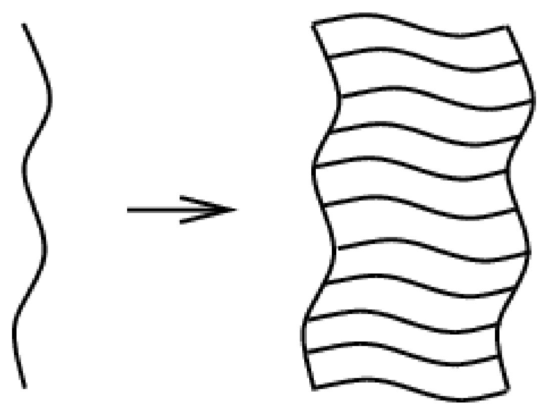
Qualitatively important:

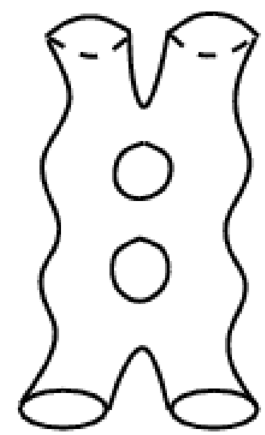
In many interesting cases: Fluxes not enough!

I.e., for some moduli no potential even in generalized comp.

For such moduli: quantum corrections are leading effect

- perturbative corrections:



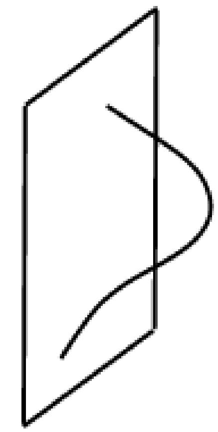


α' - extended nature of the string

g_s - string loops

- non-perturbative effects:

D-branes:



Boundary conditions for open strings
[dynamical hypersurfaces carrying charge]

Brane instantons:

Euclidean branes with p-dimensional worldvolume
wrapping a p-dimensional internal submanifold

	0	1	2	3	4	5	6	7	8	9
Mink. D3-brane:	$\times$	$\times$	$\times$	$\times$						
Eucl. D3-brane:					$\times$	$\times$	$\times$	$\times$		

L.A., C. Quigley, S. Sethi [JHEP 1010 (2010) 065, arXiv:1007.4793];
L.A., D. Vaman [Nucl. Phys. B733 (2006) 132, arXiv:hep-th/0506191]:

– Leading perturbative corrections to 4d moduli potential

L.A., P. de Medeiros, A. Sinkovics [Adv. Theor. Math. Phys. 10 (2006) 713, arXiv:hep-th/0507089];
L.A., K. Zoubos [JHEP (0610) (2006) 071, arXiv:hep-th/0606271]:

– Membrane and five-brane instanton contributions

L.A., K. Zoubos [Phys. Rev. D74 (2006) 026005, arXiv:hep-th/0602039]:
L.A., C. Quigley [JHEP 1102 (2011) 113, arXiv:1007.5047];

– Moduli stab. via comb. of classical and quantum effects
– Existence of heterotic large volume minima

L.A., R. Ricci, S. Thomas [Phys. Rev. D77 (2008) 025036, arXiv:hep-th/0702168];
L.A., V. Calo [Nucl. Phys. B801 (2008) 45, arXiv:0708.4159];
L.A., V. Calo, M. Cicoli [JCAP 0910 (2009) 025, arXiv:0904.0051]:

– Finite temperature corrections

More formally: **4d $N = 1$ Potential**

Low energy effective description: Supergravity

$N = 1$ SUGRA in 4d:

$$V = e^K (K^{i\bar{j}} D_i W D_{\bar{j}} \bar{W} - 3|W|^2) \ ,$$

$$D_i = \partial_i + K_i \ , \quad K_i = \partial_i K \ , \quad K_{i\bar{j}} = \partial_i \partial_{\bar{j}} K \ , \quad K^{i\bar{j}} K_{\bar{j}\ell} = \delta^i_\ell$$

K - Kähler potential , $K_{i\bar{j}}$ - Kähler metric

W - superpotential

Different compactifications $\rightarrow$ different K, W

Minima of V: $D_i W = 0$ - supersymmetric

$D_i W \neq 0$ - spontaneously broken susy

Classical and quantum contributions:

$$K(\Phi^i) = K_{cl} + K_{pert} + K_{non-pert} \quad , \quad \Phi^i \text{ - moduli}$$

$$W(\Phi^i) = W_{cl} + W_{non-pert} \quad , \quad W_{pert} \equiv 0$$

Standard CY(3) compactifications $\Rightarrow$ $V \equiv 0$

$\rightarrow$ Need to consider additional effects !

Classical: background fluxes $\rightarrow$ W_{cl}

Perturbative: α', g_s corrections $\rightarrow$ K_{pert}

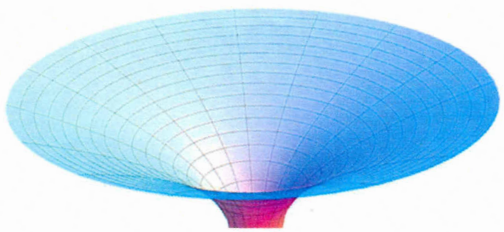
Non-perturbative: brane instantons $\rightarrow$ K_{np}, W_{np}

Type IIB: W_{cl} (complex) , W_{np} (Kähler)

Gauge/Gravity Duality

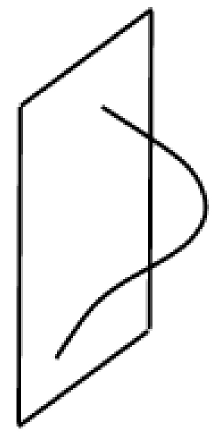
(AdS/CFT correspondence)

Two different perspectives on D-branes in string theory:



gravity background
[SUGRA solution]

$\longleftrightarrow$



open strings BCs
[gauge theory]

A stack of large number of D-branes:

Two sides of duality encode same degrees of freedom

[The two sides have equal partition functions!]

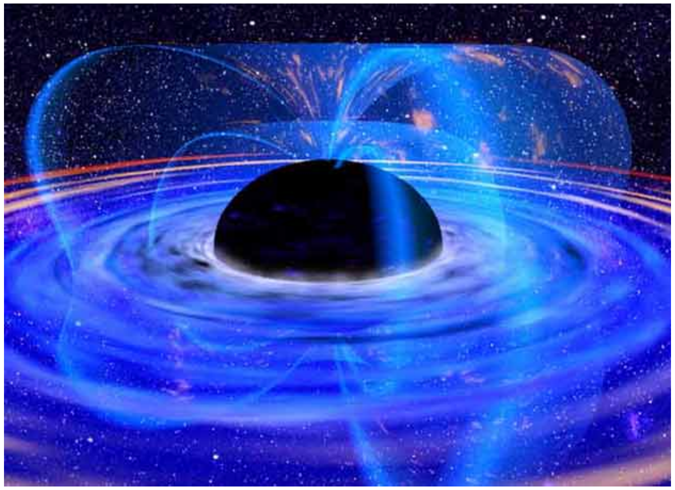
Gauge/gravity duality:

strong coupling $\longleftrightarrow$ weak coupling

$\Rightarrow$ Can use classical supergravity to learn about strongly coupled gauge theories

Aside:

In principle: Could use gauge theory to learn about:



In practice: At present ???...

Gauge theory from gravity dual:

Possible applications:

- high T_c superconductivity
- quark-gluon plasma [viscosity/entropy density]
- dynamical electroweak symmetry breaking

Electroweak symmetry breaking:

Mass generation:

Fundamental scalar or strongly coupled gauge dynamics?

[Higgs boson] [technicolor]

Fund. scalar masses: destabilized by quantum corrections

$\rightarrow$ need supersymmetry; still have fine-tuning

Gauge theory with two dynamical scales:

L.A. [Nucl. Phys. B843 (2011) 429 , arXiv:1006.3570]:

– Gravity dual of chiral symmetry breaking

L.A., P. Suranyi, L.C.R. Wijewardhana [Nucl. Phys. B852 (2011) 39 , arXiv:1105.4185];
L.A., P. Suranyi, L.C.R. Wijewardhana [Nucl. Phys. B862 (2012) 671 , arXiv:1203.1968];
L.A., P. Suranyi, L.C.R. Wijewardhana [JHEP 1305 (2013) 003 , arXiv:1212.1176];
L.A., P. Suranyi, L.C.R. Wijewardhana [arXiv:1306.1981]:

– S-parameter in dynamical electroweak SB

– Vector and scalar meson spectra

– No (techni-)dilaton

Another application of same gravitational background:
Slow-walking Cosmological Inflation...

New method for verifying stability:

L.A., P. Suranyi, L.C.R. Wijewardhana [arXiv:1309.6678]:

In gauge/gravity duality: often need non-supersymmetric probe branes

[for constructing duals of interesting gauge theories]

$\Rightarrow$ no guarantee that there is no $m^2 < 0$ perturbation

$\rightarrow$ have to compute fluct. spectrum explicitly to verify that

[requires numerical methods]

Our (analytical!) method:

– Look only at $m = 0$ states. Their radial profile contains all necessary info about stability.

– Furthermore, $m = 0$ fluct. profile can be obtained from classical solution, whose stability we are investigating.

Summary and Outlook

The picture so far:

String/M-theory compactifications: many moduli

$\rightarrow$ Need to stabilize them for phenomenology

Moduli stabilization:

Via combination of classical and quantum effects

$\Rightarrow$ Theory becomes predictive!

For the future:

- Concrete "(MS) Standard Model" compactification?...
- Early Universe cosmology (Inflation)?...
- Strongly coupled gauge theories?...

Common problem for both topics:

[Gauge/Gravity Duality and Moduli Stabilization]

String backgrounds with nonvanishing fluxes

$\rightarrow$ many open issues ...

Generalized complex geometry: metric + NS flux

Proposed exceptional generalized geometry:

metric + NS + RR flux ... (?)

A more natural unified description of metric and all fluxes:

? Generalized holonomy on an appropriate bundle ...

Thank you!