Physics beyond the standard model
Part III: String Theory

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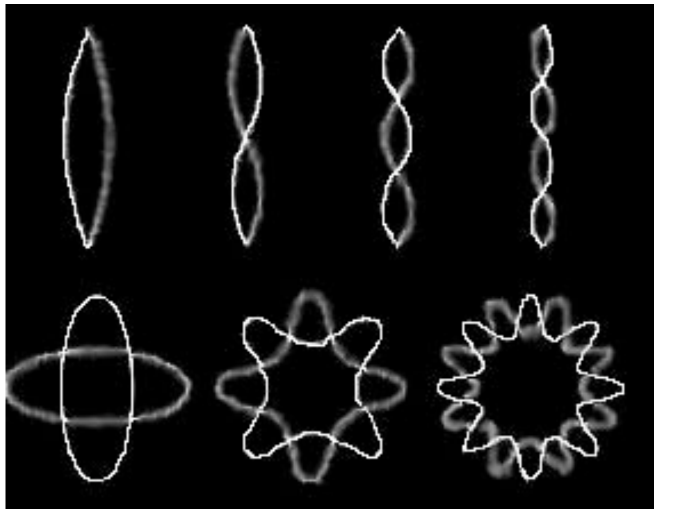

Outline

1. String Theory - The basic ideas
2. The concept of extra dimensions
3. The loss of uniqueness: living in a multiverse
4. Experimental tests - where does science end?

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String theory as TOE

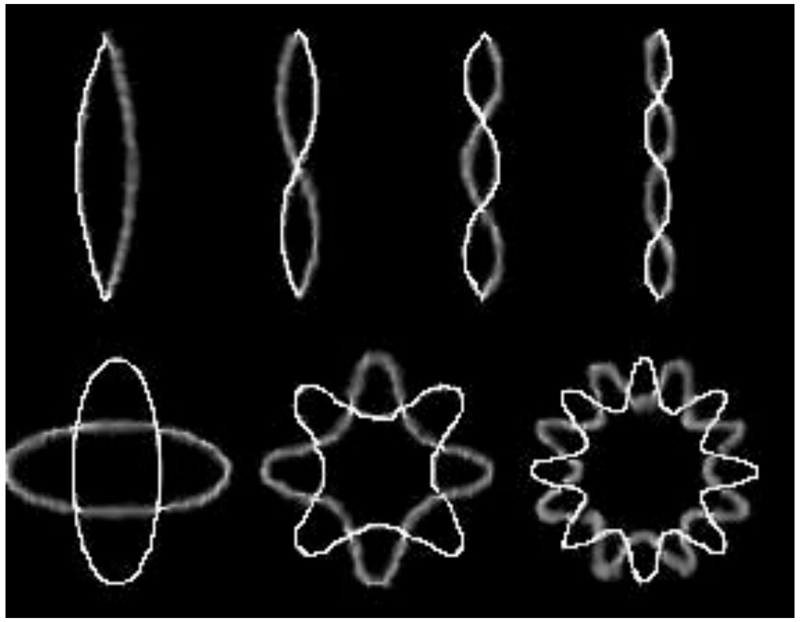
gravitation with quantum properties:
introduce graviton with spin 2

What do we expect from quantum gravity?

goal:

- Explain why there is a graviton and how it looks like
- Unification of gravity with microscopic gauge interactions

Idea:



- Elementary particles are 1-dimensional, extended objects

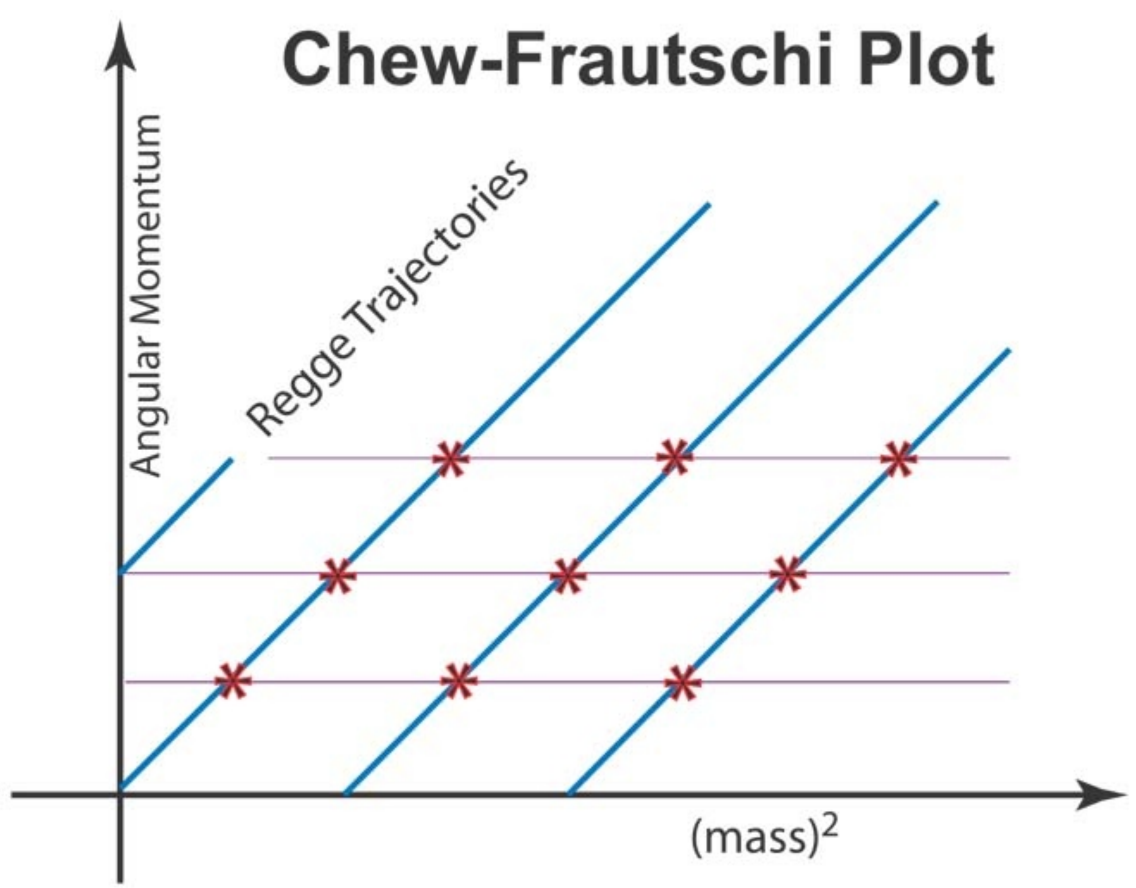
- Two different variants: open and closed strings

- Strings can perform rotation and oscillation, excitation energy is quantised

- Quantisation unit depends on the inner string tension, excitation energy is in multiples of a characteristic string energy E_{string}

- Different states of oscillation correspond to different elementary particles with different rest masses

- String-rotation creates different spins
- String spectrum corresponds to Regge trajectories: angular momentum is proportional to (quantised mass)^2
- Closed string spectrum: massless spin 2 excitations, has properties of the graviton
- Open string spectrum: massless spin 1 excitation corresponds to the photon



- 1968: Gabriele Veneziano from Florence is working on an explanation for different hadrons like proton or neutron
- Veneziano finds one formula for all string vibrations and rotations: poles of the Veneziano-function yield different hadronic particles and the corresponding S-matrices

problem: predicts non-existing particles

- spin 2 and zero mass: not known

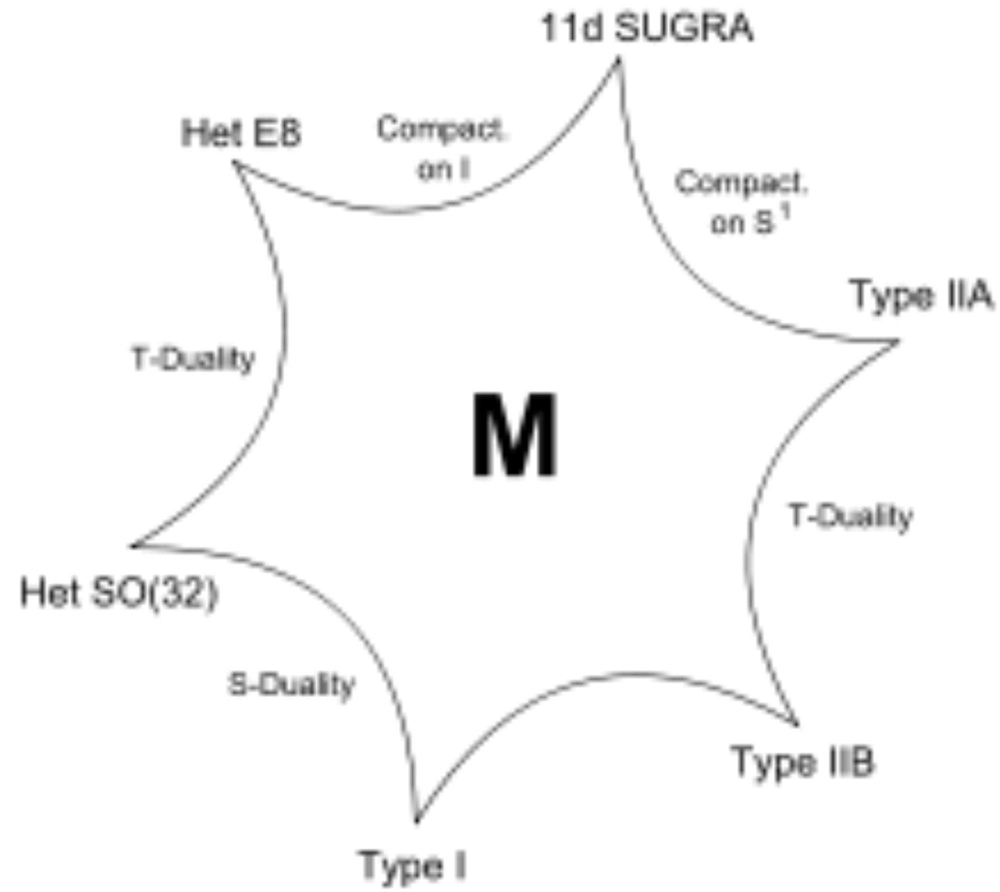
- 1974: Joel Scherk and John Schwarz suggest string theory as theory of quantum gravity
- If Planck‘s mass is set equivalent to the characteristic excitation energy m_{string} the equations of general relativity follow from the equations of closed strings

=> heavy string excitations won‘t be seen problem: how can fermions be included in the string picture?

1984: Michael Green, John Schwarz using supersymmetry: first mathematically consistent formulation

- 10 spacetime-dimensions necessary to avoid anomalies (regarding gravity and quantum motion of strings)
- 496 massless gauge bosons necessary => SO(32) gauge group, Lie group (exceptional group)

string theory type IIA and IIB: just closed string
SO(32): also open strings
E8 x E8: heterotic strings



E. Witten (1995): M-theory (mother, magic, mystery, miracle,...) in 11 dimensions:

All different types of string theories can be transformed into each other by means of dualities

Introduction of D-branes...

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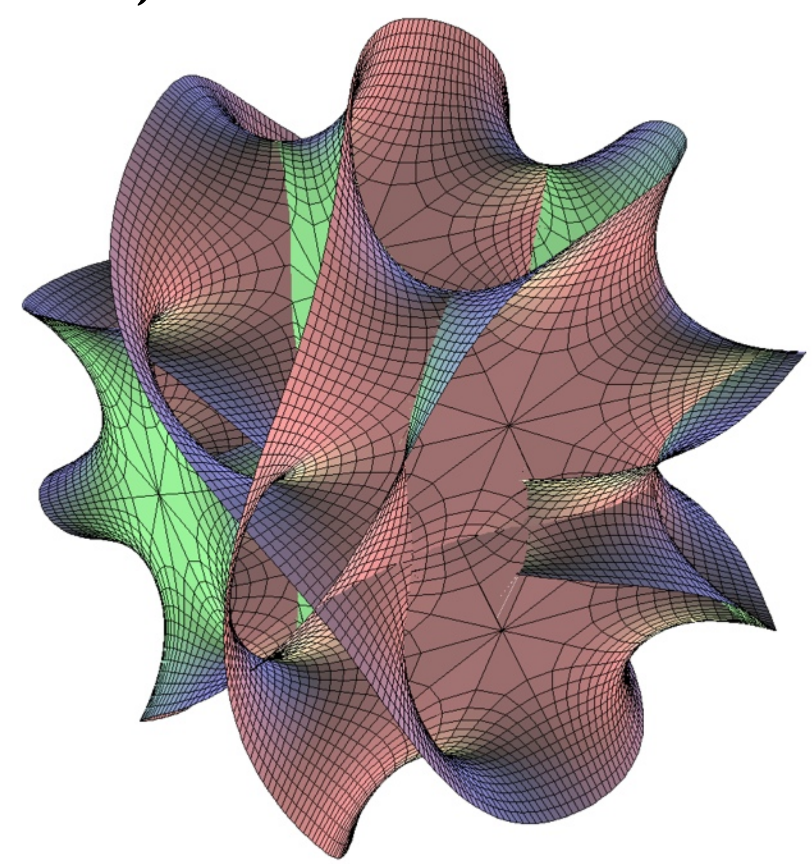
How to get back to our 3-dimensional world?

Edward Witten: compactification: description of a number of dimensions by means of a tiny, compact space

Challenge: find mathematical formulation of constraints following from string nature regarding the 6-dimensional space => Candelas, Horowitz, Strominger, Witten (1985): Calabi-Yau spaces

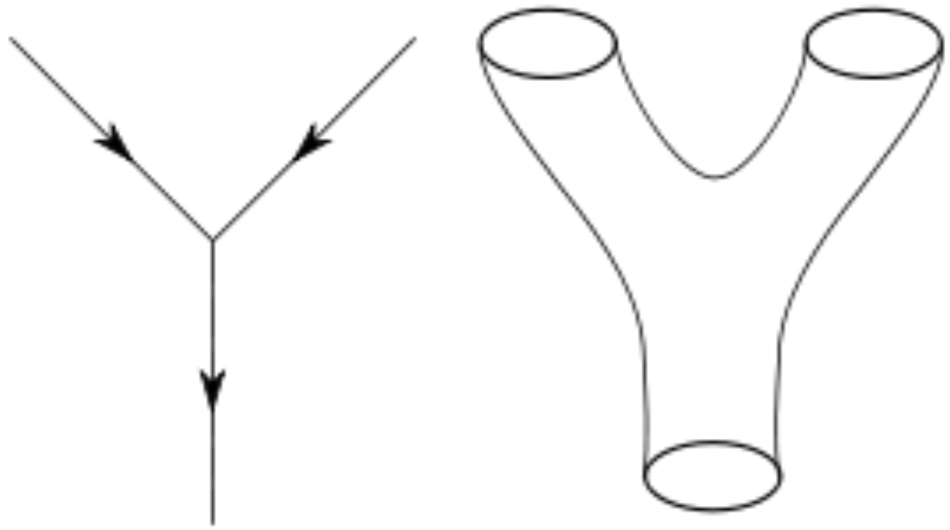
different gauge symmetry: E6 x E8: new particles, dark matter!?

explains number of quark and lepton families



Conformal field theory: Feynman diagrams for strings

Trajectory of strings in 4 space-time dimensions without Calabi-Yau compactification



- ➡ Huge number of solutions for string equation in 4 dimensions
- ➡ Interpretation of 4-dimensional stringmodels as compactifications of a 10-dimensional superstring theory possible
- ➡ Many possible compactifications on Calabi-Yau spaces

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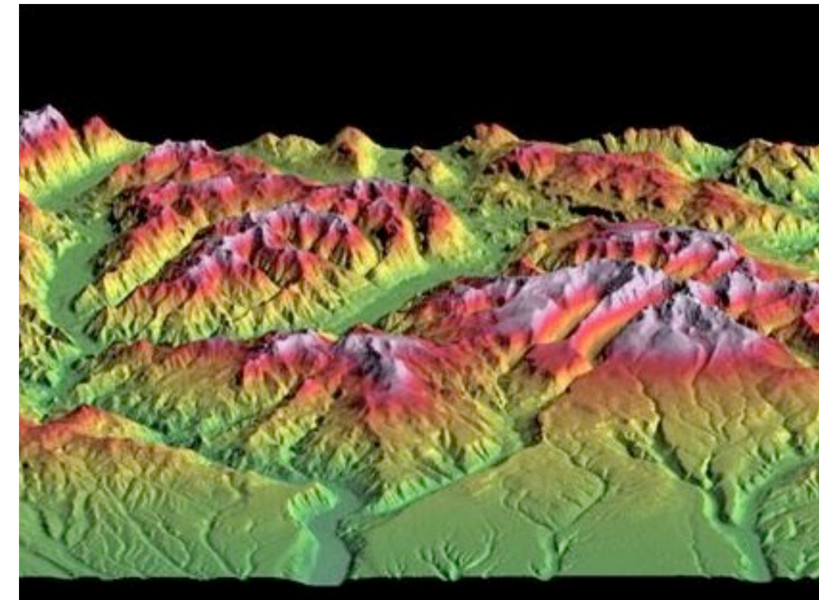
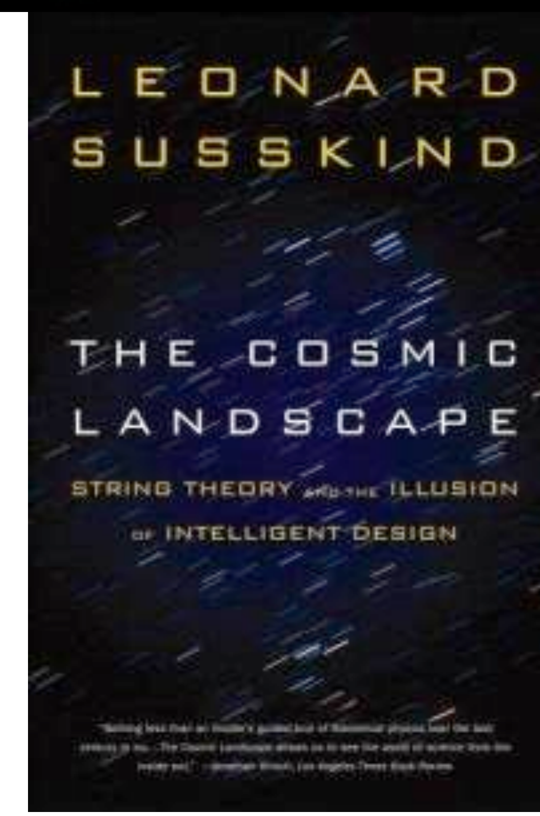
- Many different string models
- Many different string compactifications
- Many different Calabi-Yau spaces





~10^{380} solutions with a small cosmological constant!

=> Does that mean string theory has failed??

Anthropic principle:

Andrei Linde 1986:
„The huge number of possible compactifications in string theory should not be seen as difficulty, but rather as advantage of the theory, because that increases the probability of existing universes allowing for human life.“

Are the laws of particles physics unique?
Are there different laws in nature?
Did god have a choice when he created the universe?

=> String theory: laws of nature are not unique!
(but in a very precise and quantifiable way)

=> The only reason why the laws of physics seem so special and arbitrary is because they allow for our existence.

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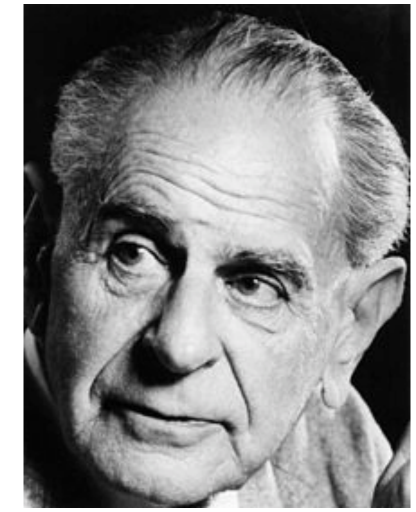
Karl Popper: A theory is scientific if it is falsifiable



General problem of quantum gravity:

String phenomena occur at extremely high energies / small distances: Planck mass ~ 10^{19} GeV

Indirect evidence:

- LHC: supersymmetry, new massive gauge bosons
- Problem: no clear predictions, always just evidence within particular string compactifications, extreme flexibility

Direct evidence:

- compactification from 10 to 4 space-time dimensions
- string excitation
- (cosmic strings?)

Two strategies of evidence:

Top-down:

- Investigate and understand all mathematical compactification solutions: very difficult due to the huge number of solutions
- E.g. idea of a string-multiverse and anthropic principle

Bottom-up:

- Start from standard model and concordance cosmology and try to find string compactifications that can reproduce our physics in four space-time dimensions

=> „Dream“: all realistic string models have one shared property to be empirically tested
=> unfortunately not the case.

Test compactification of 10 spacetime dimensions:

- Kaluza-Klein excitations of elementary particles that are able to penetrate into additional dimensions
  - small radius of extra-dimensions => very massive particles
- New particles, which just interact gravitationally living in extra dimensions => dark matter?
- Spectrum of SUSY particles depends on form of additional space dimensions
- Energy stored in extra dimensions => dark energy?
- Information on geometry of extra space dimensions in CMB and in gravitational waves?
- Free parameters from standard model can be deduced from details of extra space dimensions

Test strings as 1-dimensional objects: string excitations

- Every elementary particle has excitation modes with identical properties but higher spin

➡ Problem: characteristic string excitation energy not known, (does not depend on geometric details of extra dimensions)

➡ If it is of the order of Planck energy it is not accessible to us

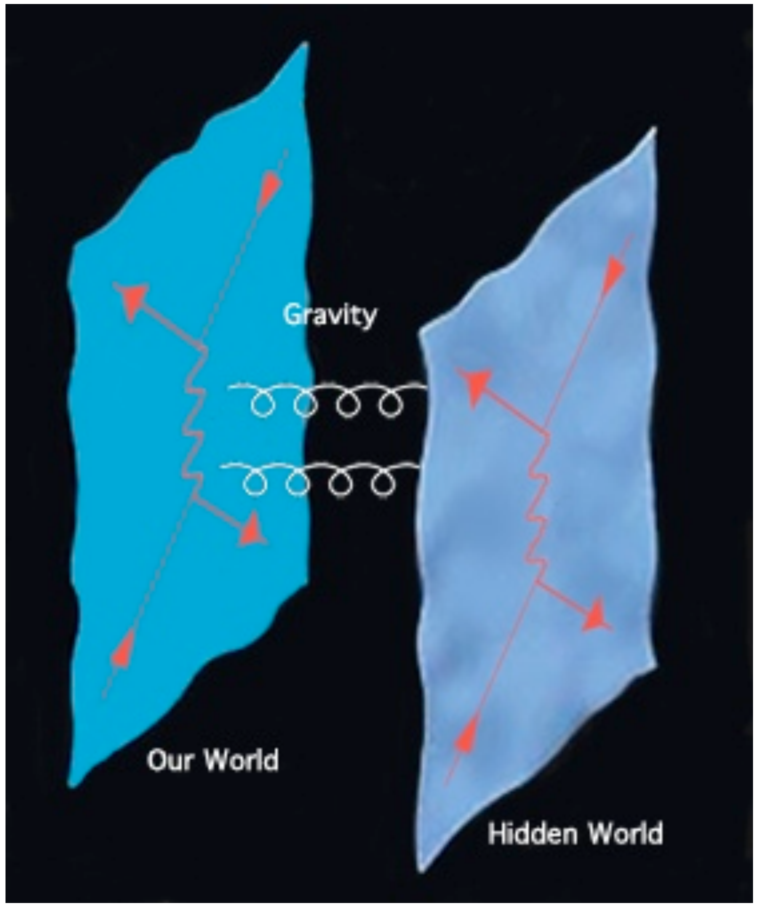
ISB models - Brane worlds: 4-dimensional membrane embedded in a (large) higher dimensional space

Elementary particles of the standard model can't enter extra dimensions, only gravitation can

➡ Gravitation is so relatively weak because it can ‚escape' in extra dimensions, gravitational constant is originally higher, depending on volume of extra-space

➡ There are different Planck masses: one in our 4 dimensions, one in 10 dimensions, depending on the volume of the extra-space

➡ Supported by the hierarchy problem (why are the energy scales of the standard model and of quantum gravity so different?)



Effects of quantum gravity / brane scenario:

- Microscopic black holes in the LHC, Hawking radiation
- Change of the $1/r^2$- behavior of the gravitational force on small scales

Which size of extended extra dimensions would be necessary to make this measurable (planck mass is ~1Tev)?

- 1 extra dimension: 10^8 km
- 2 extra dimensions: ~10^{-4} m: is being tested, rather not
- 3 extra dimensions: 10^{-9} m, too small to measure
- 6 extra dimensions: 10^{-14} m, too small to measure

- string excitations would be measurable: first Regge modes „LHC-String-Hunters'-Companion-Project"

So: is string theory an empirical science

?