Quantum Gravity and the Structure of the Universe

(A talk delivered at PIEAS, Islamabad)

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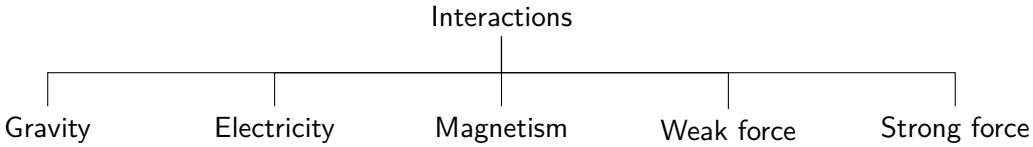
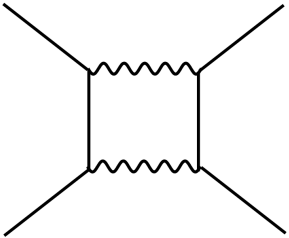
History of Unification



- There can be other unknown interactions (e.g., that affect dark matter but not normal matter)

- In 1865, Electricity + Magnetism → Electromagnetism [Maxwell]
- In 1960s, Weak force + Electromagnetism → Electroweak force [Glashow, Weinberg & Salam and many other contributors]
- Many proposals for Electroweak + Strong force → Grand Unified force [e.g. Glashow & Georgi in 1974]
- What about Gravity?

- Electroweak theory and Grand Unified models are written in the language of Quantum Field Theory (QFT)
- Can we write Gravity in QFT language? (Quantum Gravity)
- Gravitational scattering process gives divergences that can't be cured $\rightarrow$ Gravity is non-renormalizable $\rightarrow$ Need a new idea

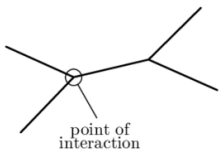


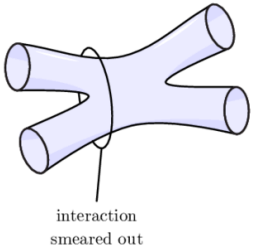
Some approaches to QG

- String theory $\rightarrow$ Fundamental entities are strings $\rightarrow$ Attempts to unify gravity with other forces
- Loop Quantum Gravity $\rightarrow$ Spacetime is replaced by a quantized, granular structure called spin networks $\rightarrow$ A theory of quantum gravity only
- Causal Dynamical Triangulations $\rightarrow$ Spacetime is replaced by a set of mathematical structures called simplices, which respects the flow of time $\rightarrow$ A theory of quantum gravity only
- Other approaches: Causal Fermionic Systems, Asymptotic safety, Causal sets

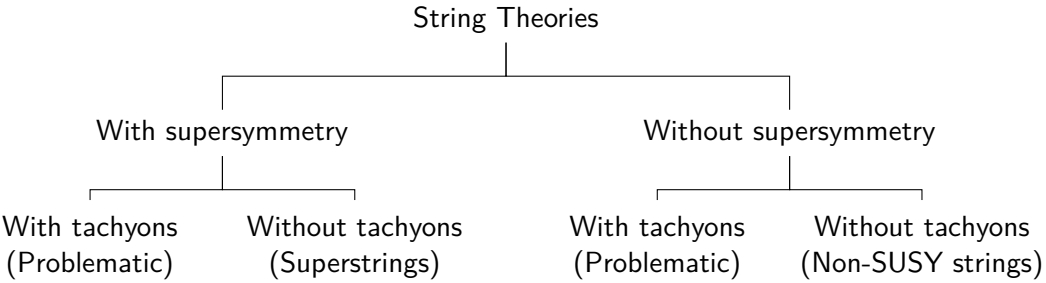
String Theory (main idea)

- The fundamental entities aren't particles but strings
- These strings can be open or closed
- The scattering processes change as follows



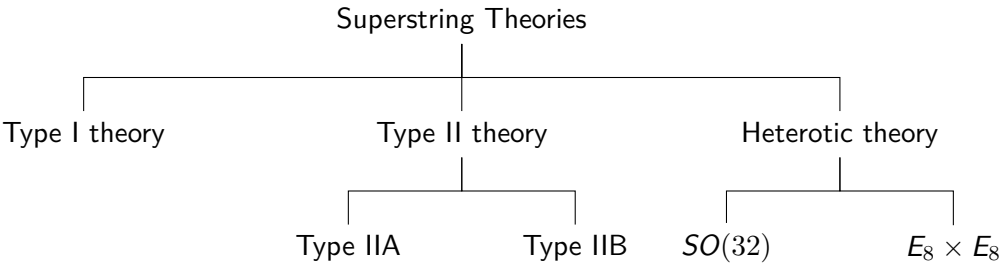


Classifications



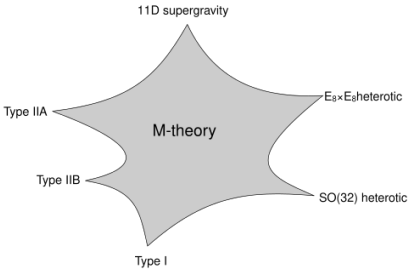
- Superstrings & Non-SUSY strings: Consistency $\rightarrow$ 10 spacetime dimensions
- 5 known superstrings and 3 known Non-SUSY strings in 10 dimensions

5 superstring theories



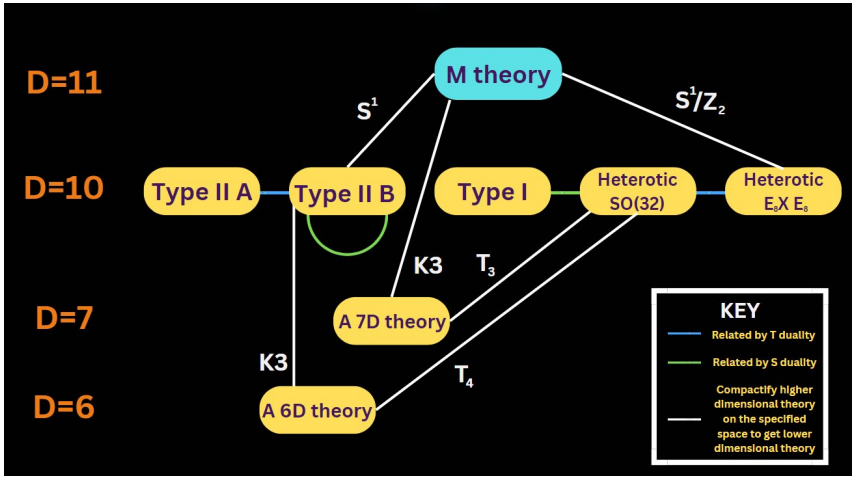
- These five theories are related to each other by **duality** transformations

M theory



- Conjecture: Five string theories are different descriptions of the same underlying theory (M-theory) in different limits [e.g. Witten, 95]
- M-theory lives in 11 dimensions (extra dimension is for the strength of force)

Structure of dualities



Compactifications

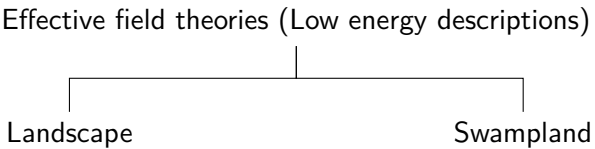
- Make the extra six dimensions smaller (compactifications)
- Information about compactifications $\rightarrow$ Physics in 4 dimensions (Standard Model + Einstein's gravity)
- Standard Model $\rightarrow$ Chiral fermions $\rightarrow$ Minimal supersymmetry $\rightarrow$Calabi-Yau manifolds (CY_3)
- **Compactifications give new relationships between different string theories**

Problems to deal with

- We require a hierarchy between 'big' and 'small' dimensions (scale-separation) $\rightarrow$ Hard to achieve (DGKT is an example)
- We require solutions with a positive cosmological constant that live long enough (metastable deSitter problem) $\rightarrow$ Very hard to achieve (KKLT scenario, excited deSitter are some attempts)
- We require extra particles (moduli) to be heavy (moduli stabilization) $\rightarrow$ Requires a number of techniques to achieve

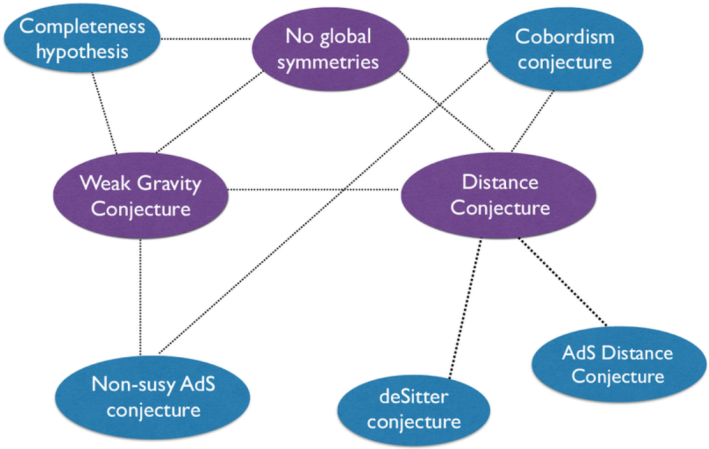
Swampland Program

- What does quantum gravity look like at low energies?



- Landscape → Consistent with gravity at high energies
- Swampland → Inconsistent with gravity at high energies
- How to identify swampland EFTs at low energies? → **Swampland conjectures**

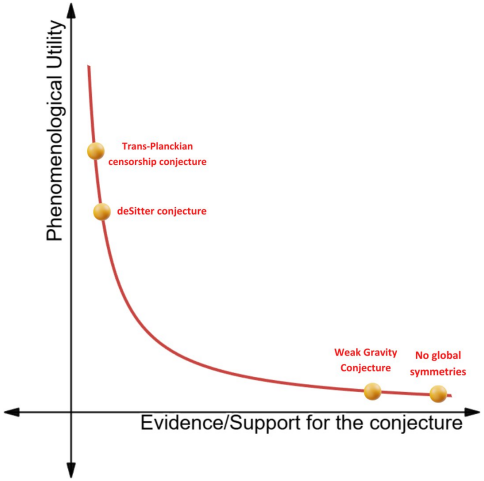
Swampland conjectures



Swampland conjectures

- No global symmetries: *"Quantum gravity can't have any global symmetries"*
  $\rightarrow$ Predicts new objects
- Weak gravity conjecture (WGC): *"Gravity is the weakest force for quantum gravity with electromagnetism"*
  $\rightarrow$ Implications for cosmology
- Distance conjecture: *"Effective theory breaks down in some limits"*
  $\rightarrow$ Implications for scale separation and cosmology

Swampland conjectures



String Universality

- Do all EFTs that aren't in swampland come from string theory?

  If they do $\rightarrow$ All quantum gravity theories should be equivalent to string theory (String Universality)

  If they don't $\rightarrow$ There can be distinct quantum gravity theories

- String Universality is shown to hold in 10, 9, and 8 dimensions (may be 6 dimensions as well)

Unsolved issues

- Proof and extension of the distance conjecture: Can you derive it from first principles? How to extend it to the space of solutions?
- Which version of WGC is the correct and complete version?
- Which new objects are required for no global symmetries conjecture (for example, the R_7 brane)? How to understand them?
- Is any non-SUSY AdS solution stable?
- How to understand the swampland conjectures in holographic language?
- What is the structure of the relationships between swampland conjectures?

Thanks for listening

Questions?