Toward a Quantum Theory of Gravity

**Quantum Field Theory**

1. Particles (i.e., quantized field excitations) propagate through spacetime (flat) and interact via coupled fields.
   - Black Holes (Hawking radiation, Singularity)
   - Dark Matter
   - Dark Energy
   - GUT era & Planck era

2. Flexible on number of dimensions,

3. Various interactions, strengths

**Gravity**

1. Particles move through spacetime following curvature of spacetime itself.
   - Stress Energy tensor (matter, radiation)

2. Metric tensor (spacetime geometry)

3. 4 Dimensions (3 space, 1 time)

4. Gravity $10^{40}$ times weaker than others

**Math:** Based on gauge symmetry, start with "Lagrangian" that describes energies/particles:

\[ L = (\text{quarks} + \text{gluons}) + (\text{electro} + \text{magnetism}) + (\text{weak interactions}) + (\text{Higgs mechanism}) + \cdots \]

Includes free fields, fermion-fields, boson interactions, Higgs.

Math can convert $L$ into relevant equations of motion.

VERY DIFFICULT to add some gravity interaction, doesn't fit format.

**String Theory, AdS/CFT duality**

**Very Difficult** to include more complex interactions or particles.

Einstein field equations relate stress-energy tensor to metric:

\[ G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \]

Includes spacetime curvature and mass/energy (cosmological constant optional).
String Theory

Attempt to reconcile QFT and gravity by replacing concept of a point particle with a tiny loop of string. Just as a string can vibrate in modes of half-integer wavelength, the loop of string can take on vibrational modes.

**REAL STRING**

**STRING THEORY**

- Diameter ~ Planck length $1.6 \times 10^{-35}$ m

The different vibrational modes = different particles. All particles "made of" vibrating strings.

In order to describe all particles & their characteristics, the strings vibrate in extra dimensions. These "compactified dimensions" are like the surface of a long wire; up close there are traversable dimensions but from afar the wire is 1D. Treating particles as strings simplifies the treatment of interactions, as in Feynman diagrams:

QFT Feynman diagram

- Time

String Model

- Time
- Interactions fully determined by shape/topology

Consider multiple possible paths