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Emergent Spacetime

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Emergent Spacetime

1 Quantum Gravity

- Four kinds force in Nature:
  - Gravity;Newton, Einstein
  - Electromagnetic force;Maxwell
  - Strong interaction force;
  - Weak force;

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- Two revolutionary discoveries in 20th century:
  - General relativity Einstein 1915:A theory of gravitation.
    Spacetime is dynamical: the interaction between spacetime and matter is nonlinear;
    Black Hole, Cosmology, GPS, ...;
  - Quantum principle: uncertainty principle, wave-function, ...
    High energy physics: QED, QCD, SM, GUT, SUSY ....
    Condensed matter physics, ...

- **Unification:** Einstein's dream
  - Gravity with EM: Kaluza-Klein;
  - Electro-Weak plus Strong interaction: unified in Standard model;
    - ⋆ In the framework of Quantum Field Theory;(SR+QM)
    - ⋆ Gauge principle play the central role;
    - ⋆ Gauge group: $SU(3) \times SU(2) \times U(1)$;
    - ⋆ Gauge bosons as the mediators of forces:
      Gluon, $W^{\pm}$, Z, Photon;
    - ⋆ The best theory we have; (Higgs in LHC?)
    - ⋆ The background geometry is Minkowski spacetime;

- Three questions:
  - How to quantize gravity?
  - How to unify gravity with other forces?
  - Why quantum gravity?
- Answers:
  - Graviton is massless spin-2 particle; (Gravitational wave?LIGO, LISA, ...)
  - Gravity is non-renormalizable; ($\mathcal{N} = 8$ supergravity finite?)
  - Gravity is special: nonlinear, background and dynamical; (Background independence essential?)
  - Canonical quantum gravity, loop quantum gravity, spin foam, ...;
  - String theory: unify the gravity with others in a natural way. The most promising candidate of quantum gravity;
  - Quantum black hole, cosmological singularity and various questions in particle physics and cosmology; (A better understanding of QM?)

2 Spacetime in String theory

- Spacetime near Planck scale l_p
  - ⋆ $l_p \sim 10^{-33} cm$;
  - ⋆ Important question: physics near the cosmological singularity. Singularity resolved? Initial condition for inflation? DE?...
  - ⋆ Quantum effect of gravity important;
  - ⋆ Usual concept of spacetime by metric make sense?

- Quantum foam? John Wheeler 1960's
  - ⋆ Spacetime subject to the kinds of uncertainty required by QM;
  - ⋆ Spacetime has foaminess: geometry has complex shapes and textures.
  - ⋆ Quantum BH appear at l_p and then evaporate in 10^{-43} seconds;
  - ⋆ Wormhole would form and dissolve;
  - ⋆ Baby universe?

- Noncommutative Geometry(NCG)
  - Operator algebra in QM;
  - Quantum spacetime as operator algebra;
  - Noncommutative geometry;A. Connes 1994
  - In string theory, NCG has natural realization:
    - Open String Field Theory; E. Witten 1986
    - D-brane with B_2 field; Seiberg & Witten 1999, ...

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- String theory:
  - The elementary particles are not really point-like. They are "TINY" strings;
  - There are two kinds of strings: open and closed;
  - Unify the gravity with the other forces in a natural way;
  - The string has constant tension $T = \frac{1}{2\pi\alpha'}$;
  - There exists an intrinsic length scale:

$$l_s^2 = \alpha' \tag{1}$$

  - α' as Planck constant in the string worldsheet action;
  - String coupling constant g_s govern the string interaction;

- **T-duality**: The closed string on a circle with radius R is equivalent to the one on a circle with radius α'/R;
  - ⋆ Momentum $\leftrightarrow$ Winding;
  - ⋆ Winding conservation is a stringy symmetry;
  - ⋆ Background geometry is ambiguous: what is the background metric?
  - ⋆ Due to the extensive nature of the string;
  - ⋆ String probe cannot detect the features in the geometry which are smaller than l_s;
  - ⋆ Generalized to "Mirror symmetry" in Calabi-Yau manifolds;

- S-duality
  - ⋆ Quantum nature: D-brane ...;
  - ⋆ D-brane probe: Nonperturbative. Matrix model;
  - ⋆ Strong/Weak duality: highly quantum/semiclassical backgrounds;
  - ⋆ Breakdown of small distance/high energy connection: as we try to increase the energy of a probe, it becomes bigger;

- Locality in String theory:
  - ⋆ QFT: local, keep causality, S-matrix analytic;
  - ⋆ String theory: causal, S-matrix is analytic, but might not be local;
  - ⋆ Dualities suggest non-locality;

- Spacetime in String theory:
  - ⋆ Ambiguity in geometry;(Stringy geometry in mathematics)
  - ⋆ Ambiguity in topology: topology transition;
  - ⋆ Fuzziness: locality lost;
  - ⋆ Matrix cosmology? Matrix degrees of freedom to describe the physics near the cosmological singularity;

3 Emergent Spacetime

- Space and time are not fundamental, they are emergent concepts;
- The concept of locality cannot be fundamental;
- General covariance is a derived and useful concept at long distances;
- A fundamental theory should not have an underlying spacetime;

- Examples of emergent Space:
  1. Myers effect: fuzzy space;R. Myers 1999
  2. Matrix QM: 2D noncritical string theory;M. Douglas 1991, ...
  3. Emergent space in BFSS matrix model;BFSS 1997
  4. AdS/CFT correspondence.

- AdS/CFT correspondence:
  - String theory in Anti-de-Sitter spacetime and a CFT at its boundary;
  - A definition of string theory;
  - The best studied one: IIB superstring in $AdS_5 \times S^5$ is dual to the $\mathcal{N} = 4$ Super-Yang-Mills in the large N limit; (AdS_5/CFT_4 correspondence)Maldacena 1997
  - Gravity/Gauge correspondence;
  - String states/operators;(Beyond gravity/gauge correspondence)
  - Strong/Weak duality;

- The ideas behind AdS_5/CFT_4:
  - Large N_c gauge theory is a string theory;'t Hooft 1974, A. Polyakov, ...
  - Holographic principle; 't Hooft 1992, L. Susskind 1993
  - Open/Closed string duality;

- Physical implications
  - String theory side:
    - Black hole physics: entropy, quasi-normal mode, unitary evolution;
    - Background independence and emergent space: LLM 2004 Half-BPS states in SYM correspond to various supergravity configurations, which are asym. to $AdS_5 \times S^5$;
  - Gauge theory side:
    - AdS/QCD: strong coupling, meson spectrum, ...;
    - RHIC (Relativistic Heavy Ions Collider) physics: QGP,...;

- Emergent time:
  - If space emerges, why not time?
  - No example;
  - Locality in time? Violation of causality?
  - What does it mean to have a theory without fundamental time?"Dynamics"?
  - Wavefunction?Unitarity? ....
  - Implications: the physics of space-like and null singularities (BH singularity and the cosmological singularity), the wave-function of the Universe, initial conditions for the Universe,...;