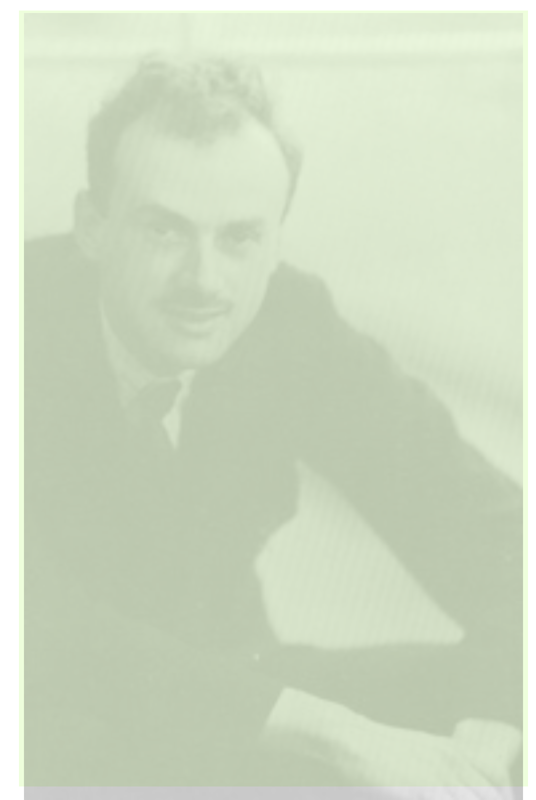
What is String Theory ?

- present status from a historical perspective -

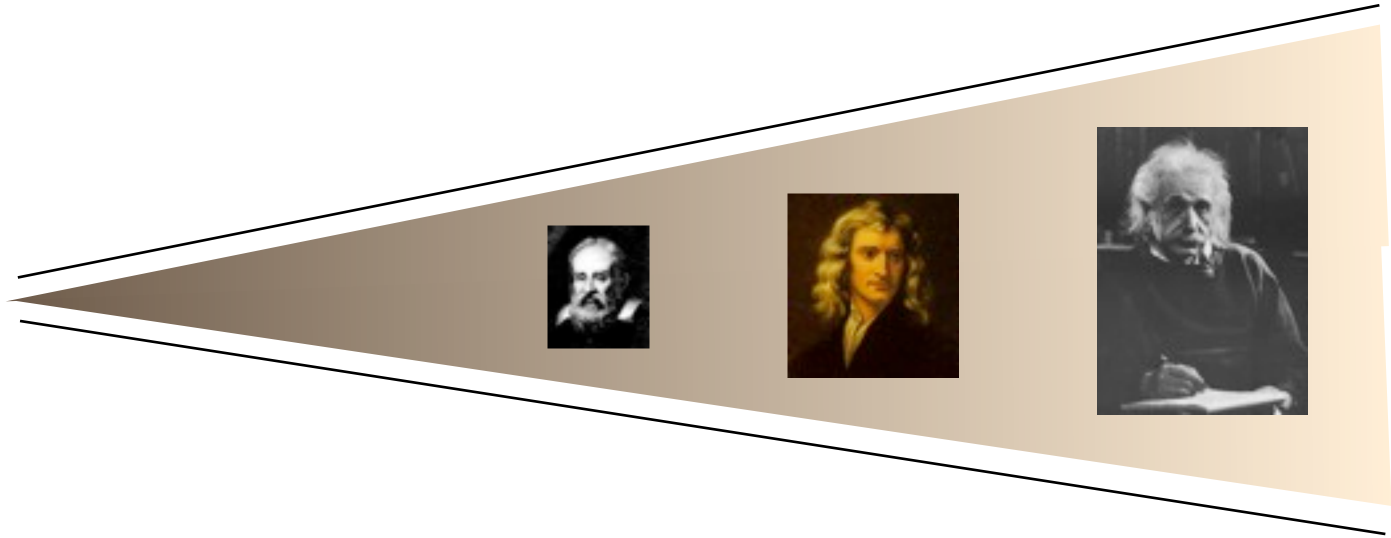


NTU, 2011

Prologue：What is physics?

“*The endeavor of exploring,*
on the basis of empirical facts,
the most fundamental laws
which exist behind all kinds
of phenomena surrounding us.”

from *What is physics ?,* Shin-ichiro Tomonaga, 1979



As the understanding of basic physical laws were developed deeper, our horizons have been broadened, both in macroscopic and microscopic directions.

"More is different"

(P. W. Anderson, 1972)

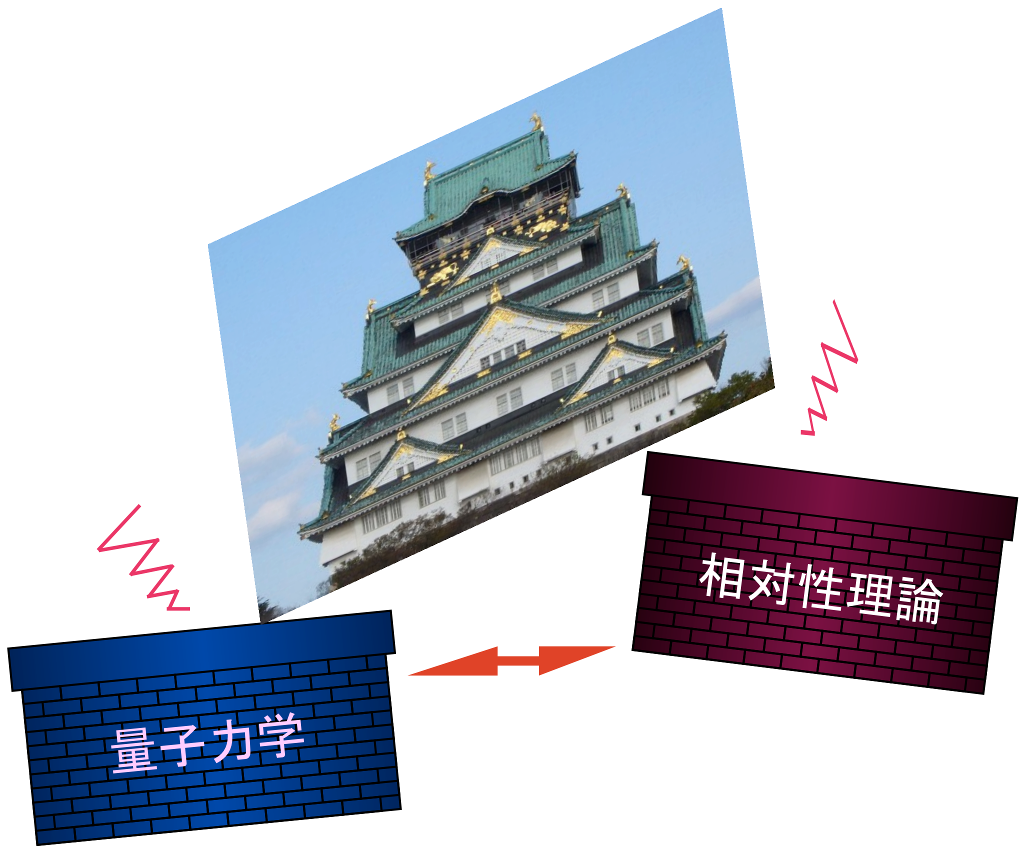
and

Deeper is more !

What is the most fundamental problem remaining unsolved in the 20th century physics?

- Conflict between two central pillars of modern physics,

quantum theory
and
general relativity



General Relativity

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = -\kappa^2 T_{\mu\nu}$$

LHS: *'made of marble'* — *Geometry of space-time*

RH: *'made of mere wood'* — *Quantum theory of matter*

according to Einstein himself.

The principles of general relativity are governed entirely by classical concepts of particles and fields.

No uncertainties, and no fluctuations at all.

"The real goal of my research has always been the simplification and unification of the system of theoretical physics.

I attained this goal satisfactorily for macroscopic phenomena, but not for the phenomena of quanta and atomic structure.

....

I believe that despite considerable success, the modern quantum theory is still far from a satisfactory solution of the latter group of problems."

A. Einstein, 1936

Quantum Theory :

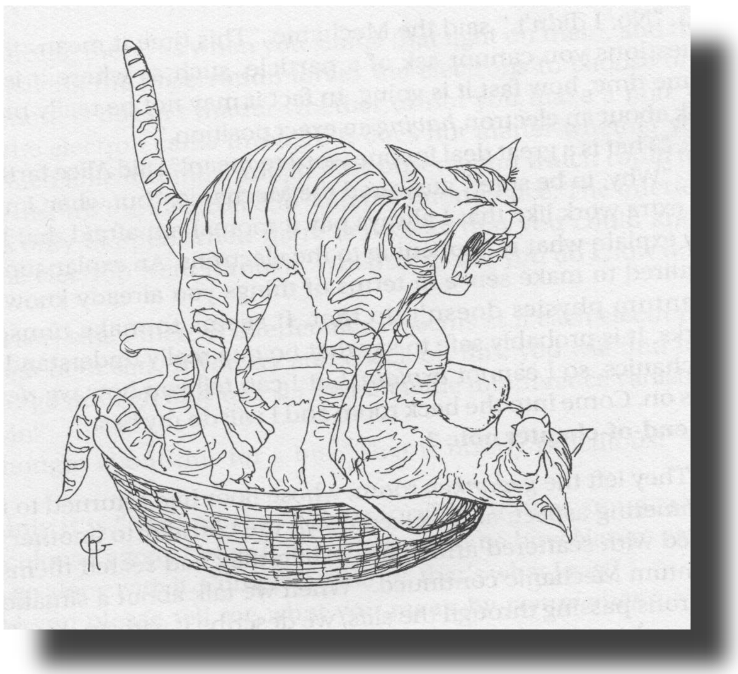
characterized by fluctuations of physical states

$$\psi = \sum c_n \psi_n$$

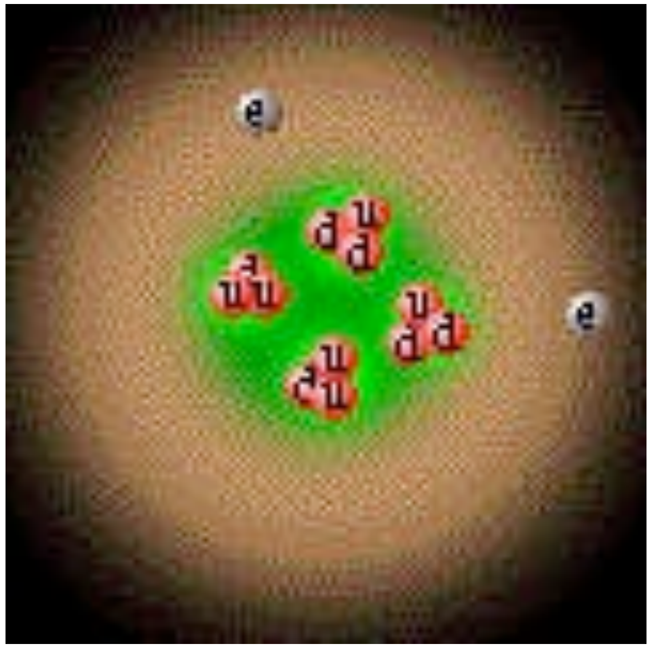
superposition principle

$$\Delta x \Delta p \geq h$$

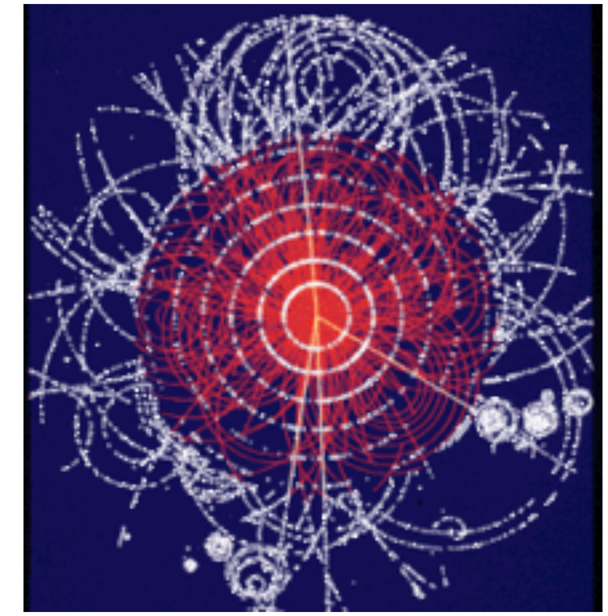
uncertain relation

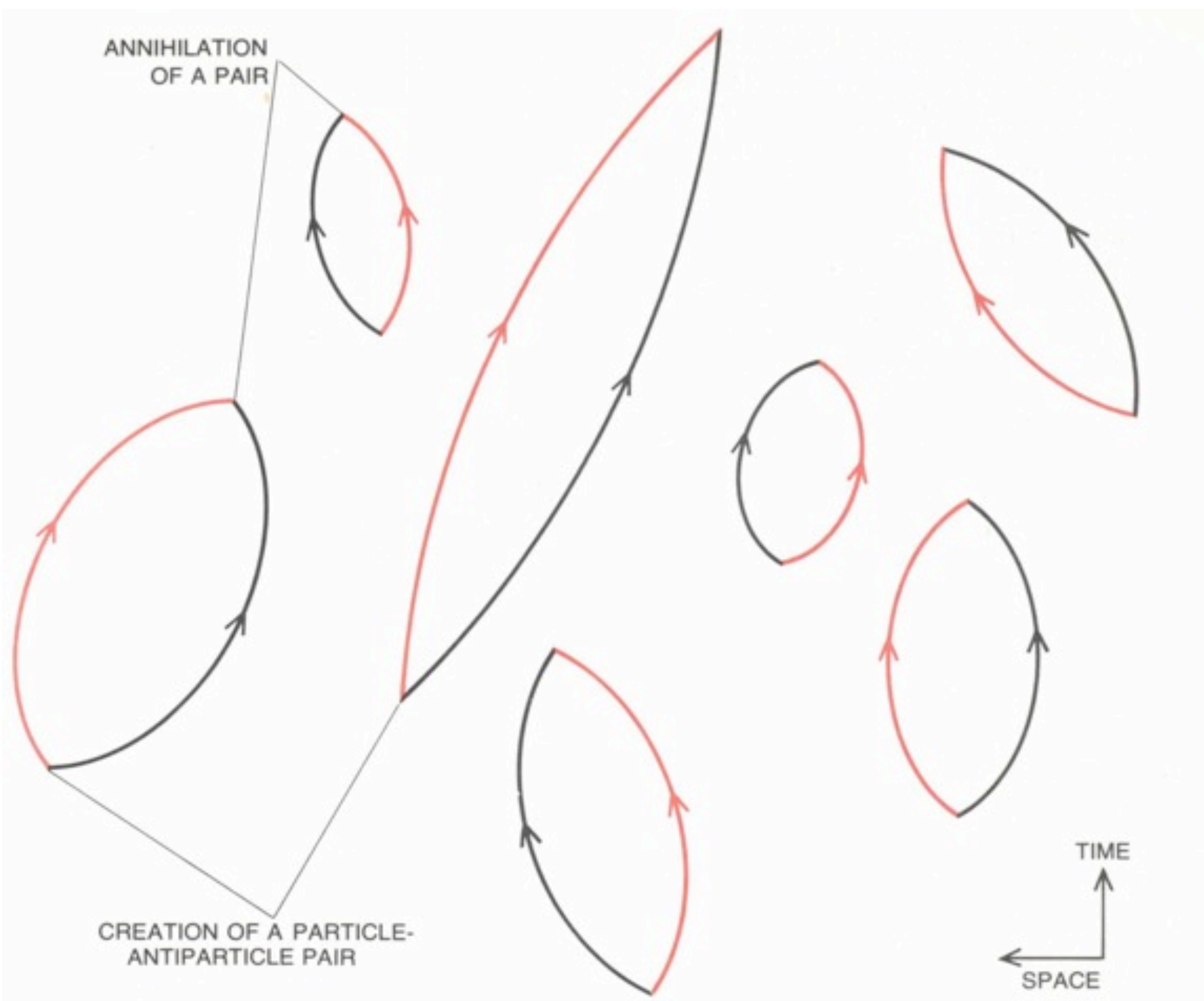


The constitution and the stability of matter can never be explained without quantum theory.



Even the vacuum and the geometry
of space-time itself are microscopically
fluctuating and superposing
among themselves,
by pair creation/annihilation
of all sorts of elementary particles.





Quantum Gravity:

quantum theory of
space-time geometry

creation/annihilation
of gravitons

If general relativity is combined naively to the ordinary rules of quantization, we encounter serious difficulties.

- Non-renormalizable ultra-violet divergences, due to space-time fluctuations:

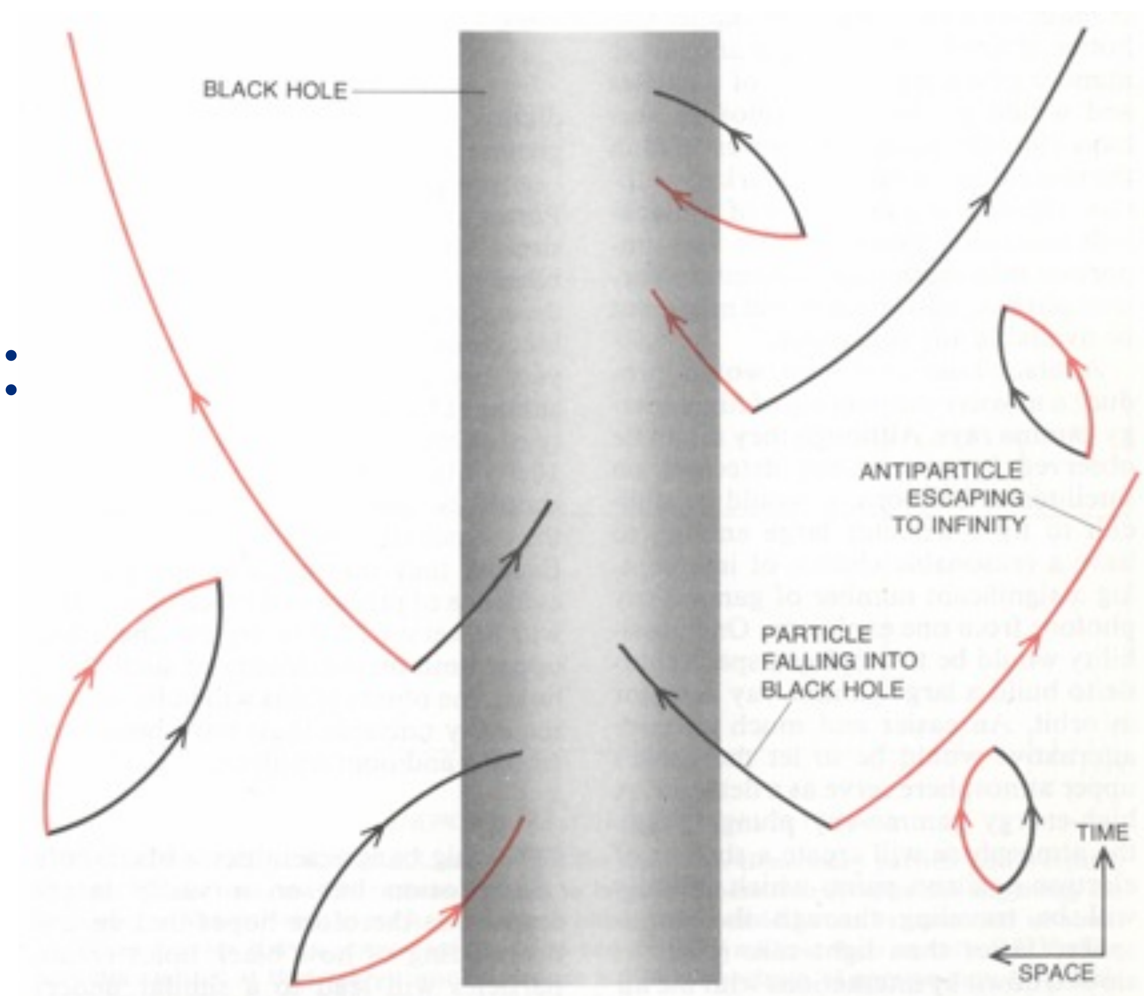
$$\sum_n \left(\frac{\kappa}{a^{(D-2)/2}} \right)^{2n} f_n$$

$$a \longrightarrow 0$$

cut-off length scale at small distances

- Information puzzle in (approximate) quantum mechanics around black-holes:

This is related to the ultraviolet difficulty, since the **wave lengths** of signals reaching infinity must be **infinitely short** at the space-time horizon. (Time lapse becomes infinitely slow as seen from an outside observer.)



This conflict indicates that

General Relativity is **not** a fundamental theory, but is

- a low-energy **effective theory**

  which is valid **only** at sufficiently long distances,
  but breaks down microscopically.

historical analogy of low-energy effective theory:

- four-fermi theory of weak interactions

  $\longrightarrow$ Weinberg-Salam theory

- sigma model for low-lying hadrons

  $\longrightarrow$ QCD

Quantum theory and general relativistic theory of gravity must be truly unified, by replacing general relativity by a more fundamental microscopic theory of gravity

But, the conceptual framework of these theories are quite different :

- the concept of “states” in quantum theory is defined globally on the basis of linear superposition principle.

- space-time and states in general relativity are defined on the basis of patching works of local events .

Unfortunately, we do know any valid direct approaches, so far, to the unification of these two different conceptual frameworks in the framework of (quantum) **local** field theory.

And also, old attempts towards **non-local** field theories suffered from either violation of quantum mechanical unitarity and or Lorentz invariance.

String Theory

- suggests new intrinsic mechanisms
  for a complete ***elimination*** of ultraviolet infinities
  and
  for ***unifying all fundamental interactions including gravity,***

within the **general** framework of quantum theory
(*at least in the perturbation theory*).

- But, unfortunately, is still immature and is **in the "making" stage.**

What is string ?

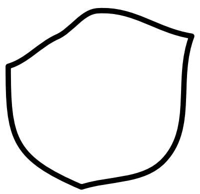
fundamental string (‘ F1’)

- only has 1 dimensional extension
- mass density : $1/2\pi\alpha'$

strictly constant $\longrightarrow$ the unique fundamental constant of string theory

$$\sqrt{\alpha'} \equiv \ell_s$$ string length constant

closed string : generate gravitational field



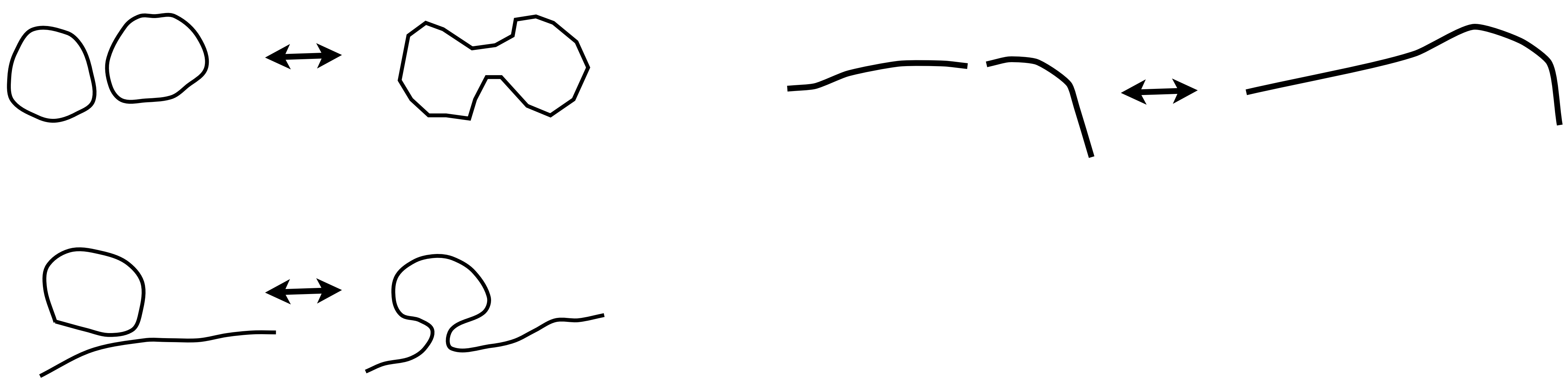
open string : generate gauge fields

- **closed string** interacts with all kinds of strings

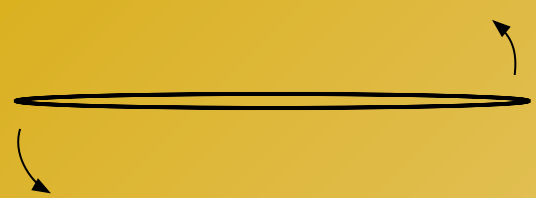
  in a universal manner which is consistent with general relativity at long distances.

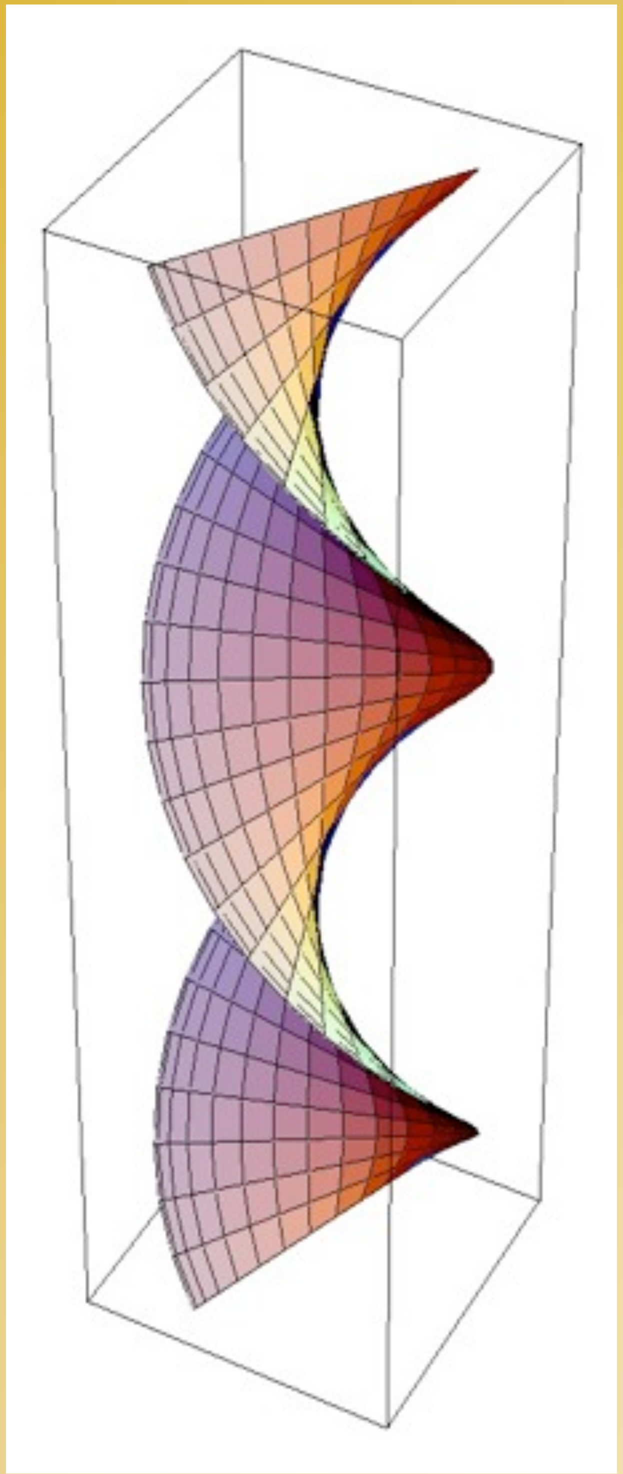
- **open strings** interacts among themselves

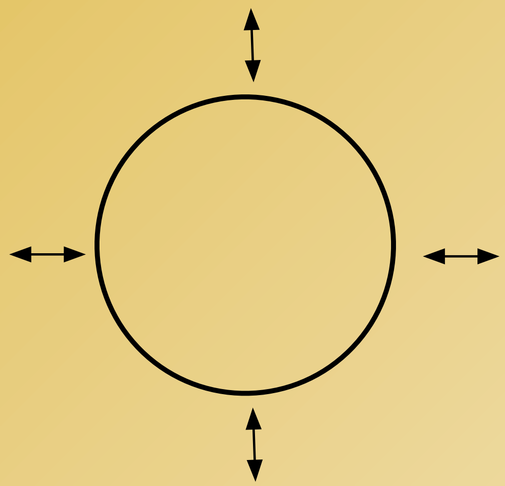
  in a universal manner which is consistent with gauge theory at long distances.

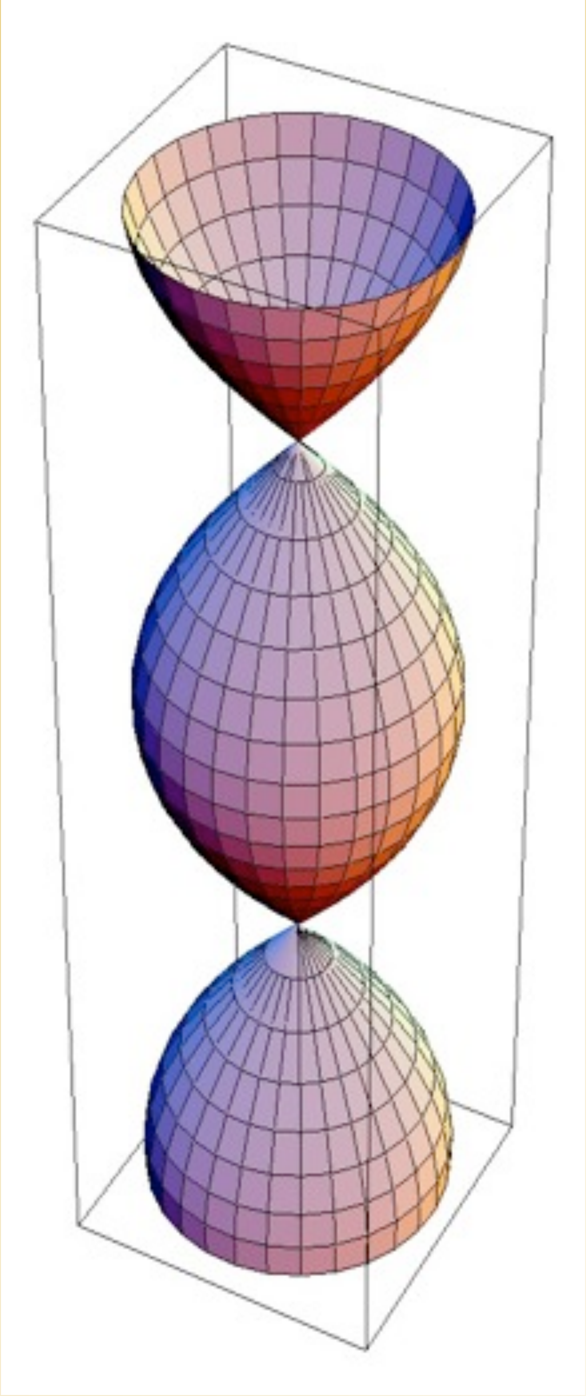


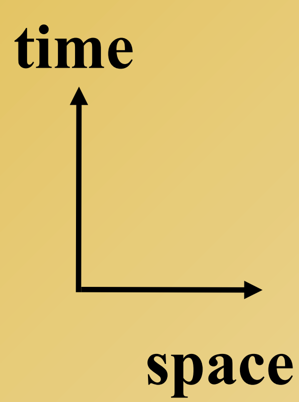
classical images of strings in motion











graviton

dilaton

In string theory, **gravity and gauge interactions are “emergent” phenomena** arising from a single dynamical framework of quantum mechanics of relativistic strings :

quantum fluctuations of strings

$\updownarrow$

quantum fluctuations of space-time and gauge fields

and

the condensation of various modes of strings induces space-time curvatures, coupling constant, and ***all*** allowed `external` fields:

the structure to be expected for a background-independent theory.

Furthermore, closed strings can also be regarded as being induced from quantum fluctuations (or loop effects) of open strings.

related to gauge/gravity correspondence, later

"String theory is, at a new level, the realization of old ideas concerning induced gravitation! I cannot refrain from feeling proud on this point!"

A. D. Sakharov (1921-89), 1985

Nobel peace prize 1975

Vacuum Quantum Fluctuations in Curved Space and the Theory of Gravitation†

Academician A. D. Sakharov

Translated from Doklady Akademii Nauk SSSR, vol. **177**, *No. 1, pp. 70–71, November 1967. Original article submitted August 28, 1967.*

In Einstein's theory of gravitation one postulates that the action of space-time depends on the curvature (R is the invariant of the Ricci tensor):

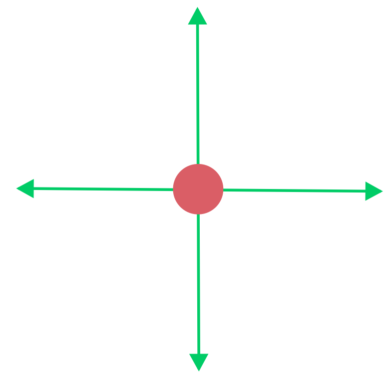
$$S(R) = -\frac{1}{16\pi G}\int (dx)\sqrt{-g}\,R. \qquad (1)$$

If we neglect dilation of violin strings,
the degrees of freedom of vibration at each point are 2.

$\mathbf{2}=3+1-(1+1)$

space dimensions

time



The fundamental string live in (**critical**) 10 (=1+9) dimensional space-time, and the vibrational degrees of freedom are only from transverse directions

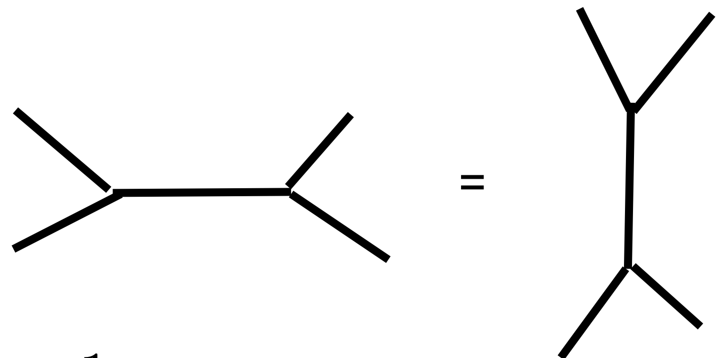
$\mathbf{8}=9+1-(1+1)$

This is why graviton and gauge fields can emerge.

Potentially, the critical dimension suggests that string theory might be able to explain why our space-time is 4 dimensional, provided that we find appropriate dynamical mechanisms of reducing 10 dimensions to 4.

Brief history of string theory

1968 Veneziano model



- Channel (*s*-*t*) duality
- Regge behavior
- narrow-resonance approximation

$$V(s,t) = \int_0^1 dx\, x^{-\alpha' s - \alpha_0 - 1}(1-x)^{-\alpha' t - \alpha_0 - 1}$$

$$= \sum_{n=0}^{\infty} \frac{r_n(s)}{t - m_n^2} = \sum_{n=0}^{\infty} \frac{r_n(t)}{s - m_n^2} \longrightarrow$$

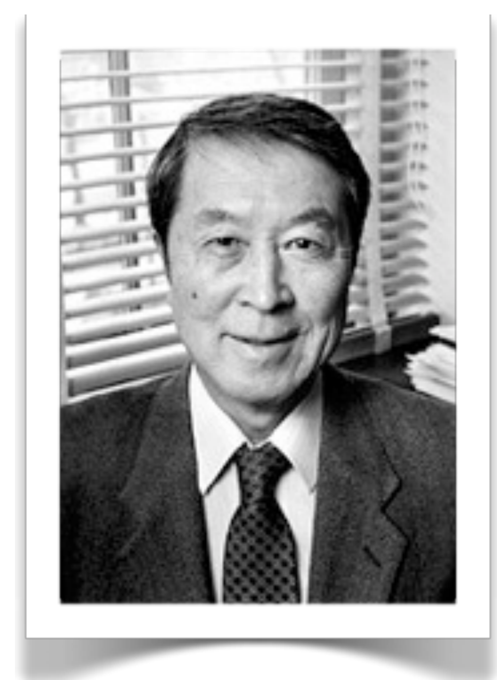
poles at

$$s \text{ or } t = m_n^2 = (n-1)/\alpha'$$

spectrum of relativistic open strings

Nambu, Susskind, Nielsen, ...

Similar formula (Virasoro, Shapiro), corresponding to closed strings



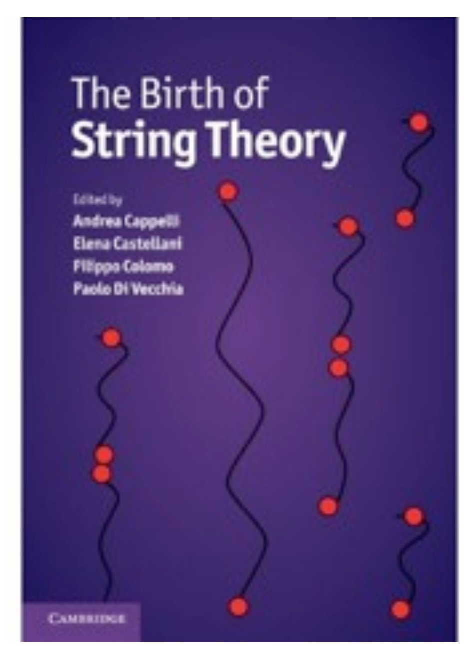
Y. Nambu (1921~)

In the 1970s, the string theory made its development from the S-matrix formula to a dynamical theory of relativistic strings. Various ideas which would become the basis for later developments was emerging from the studies of its connection to local field theory.

Gravity from strings: personal reminiscences of early developments

Tamiaki Yoneya
Institute of Physics, University of Tokyo
Komaba, Meguro-ku, Tokyo 153-8902, Japan

(arXiv:0911.1624,)
to appear in
The Birth of String Theory,
Cambridge Univ. Press.



Abstract

I discuss the early developments of string theory with respect to its connection with gauge theory and general relativity from my own perspective. The period covered is mainly from 1969 to 1974, during which I became involved in research on dual string models as a graduate student. My thinking towards the recognition of string theory as an extended quantum theory of gravity is described. Some retrospective remarks on my later works related to this subject are also given.

1970 ~ 1978 Initial developments
(*models for hadronic interactions*)

- Nambu-Goto action
- Light-cone quantization, no-ghost theorem, critical dimensions (26 or 10)
- Ultraviolet finiteness (modular invariance)
- Neveu-Schwarz-Ramond model (inclusion of "G"-partiry and fermionic degrees of freedom)
- Space-time supersymmetry

Developments related to field-theory /string connection ('70s)

- \`Fishnet' diagram interpretation, Nielsen-Olesen vortex
- Derivation of gauge theory, general relativity and supergravity from strings in the zero-slope limit $\longrightarrow$ *gravity and unification*
- Construction of various supersymmetric gauge and gravity theories
- String picture from strong-coupling lattice gauge theory
- t\` Hooft's large *N* limit

1984~1989 First revolution

- **Green-Schwarz anomaly cancelation**
- Five consistent perturbative string vacua (I, IIA, IIB, 2xHetro) in 10D
- Compactifications, new connections to mathematics
- CFT technique, renormalization group interpretation

1990~1994 Development of "old" matrix models

- Double scaling limit
- c=1 strings, 2D gravity, 'non-critical' strings
- topological field theories and strings

1995~1999 Second revolution

- discovery of D-branes
- statistical interpretation of black-hole entropy in the BPS or near-BPS limits
- conjecture of M-theory
- New matrix models, supermembranes, M(atrix) theory conjecture, ...
- AdS/CFT correspondence, ...

The most important development after 1998 :

General idea of gauge-gravity correspondence has been flourishing.

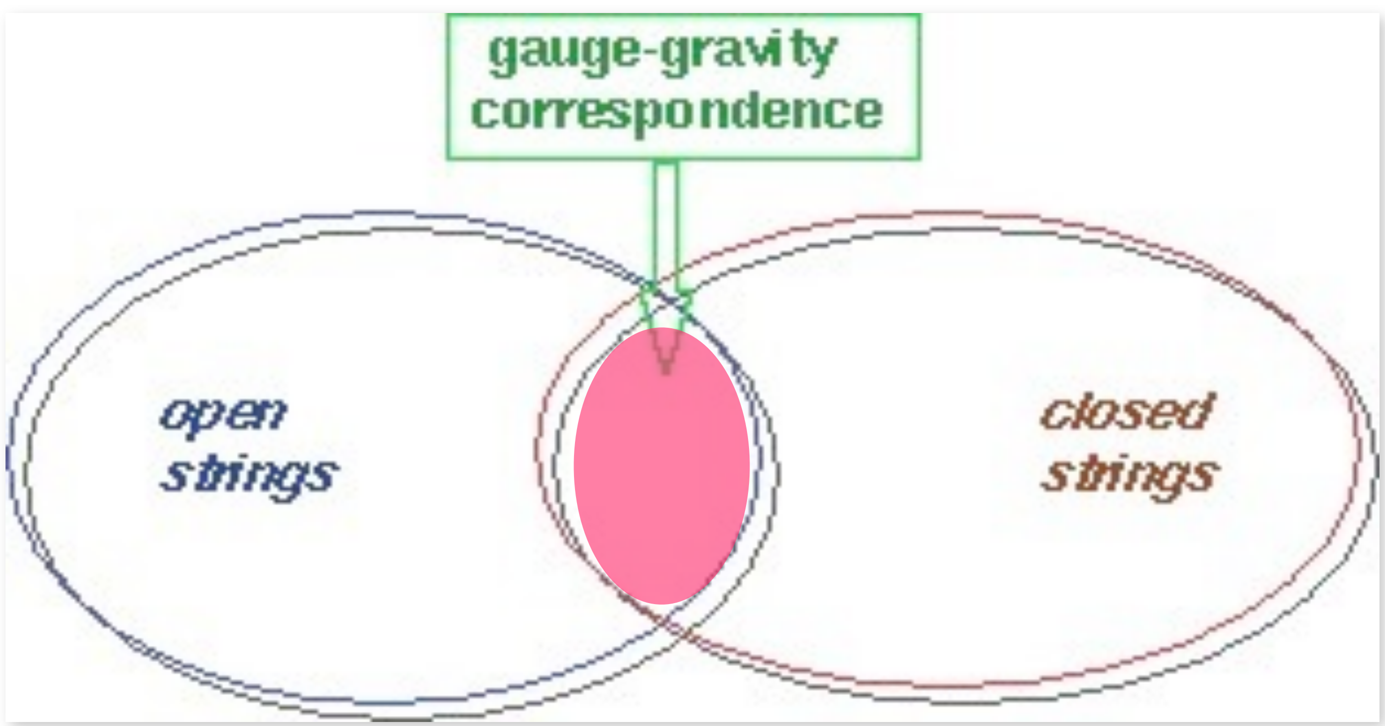
starting from Maldacena's paper in 1997

unification of two old ideas on strings from the 70s ?

- hadronic strings for quark confinement from gauge theory
- string theory for ultimate unification as an extension of general relativity

Gauge/Gravity correspondence

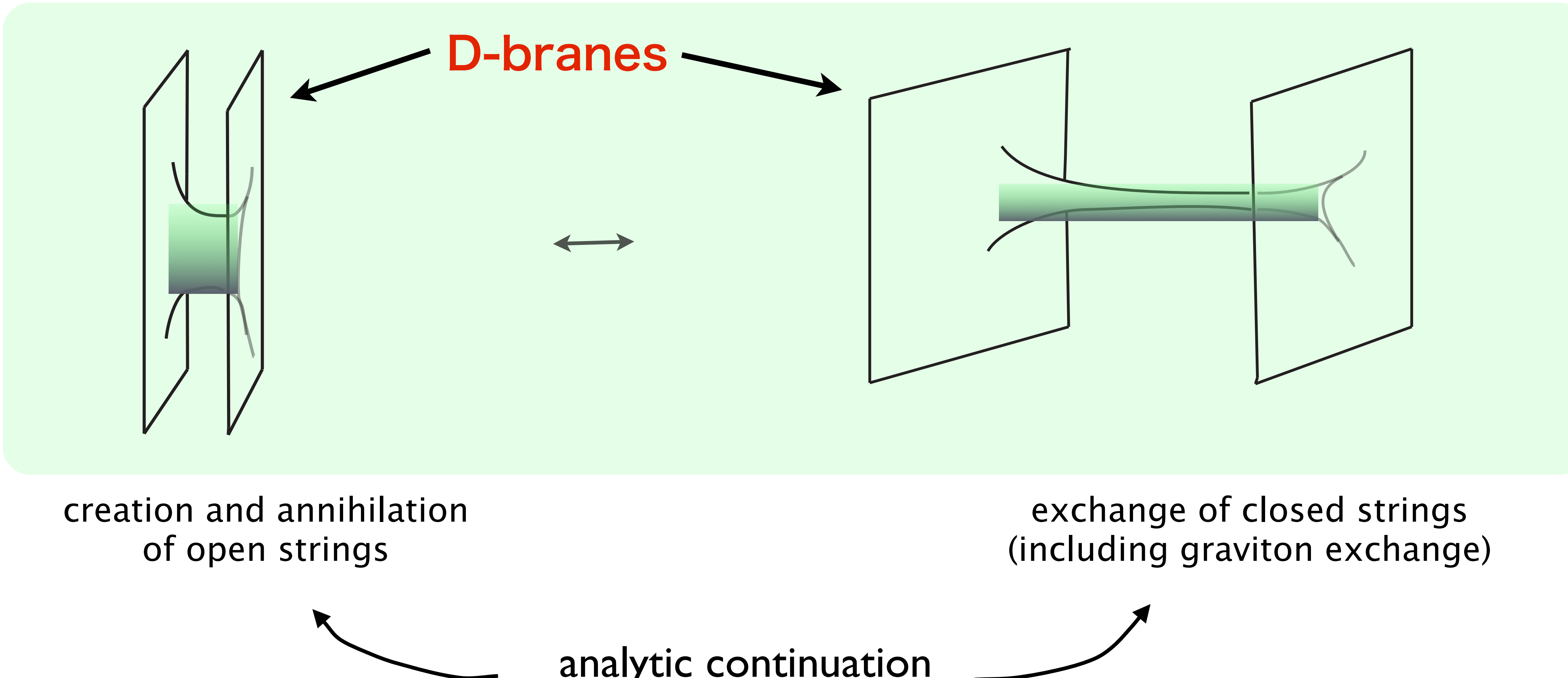
- The fact that gravity (general relativity) and gauge theory are united in a single framework leads to an entirely new connection between them,
  giving nontrivial predictions to the gauge-theory side from gravity side (and *vice versa*)



a realization of
`**holography**':

quantum gravity in the bulk
must be formulated using only
the degrees of freedom
on the boundary.
('t Hooft, Susskind, ...)

- open-closed string duality in string perturbation theory (simplest one-loop case)



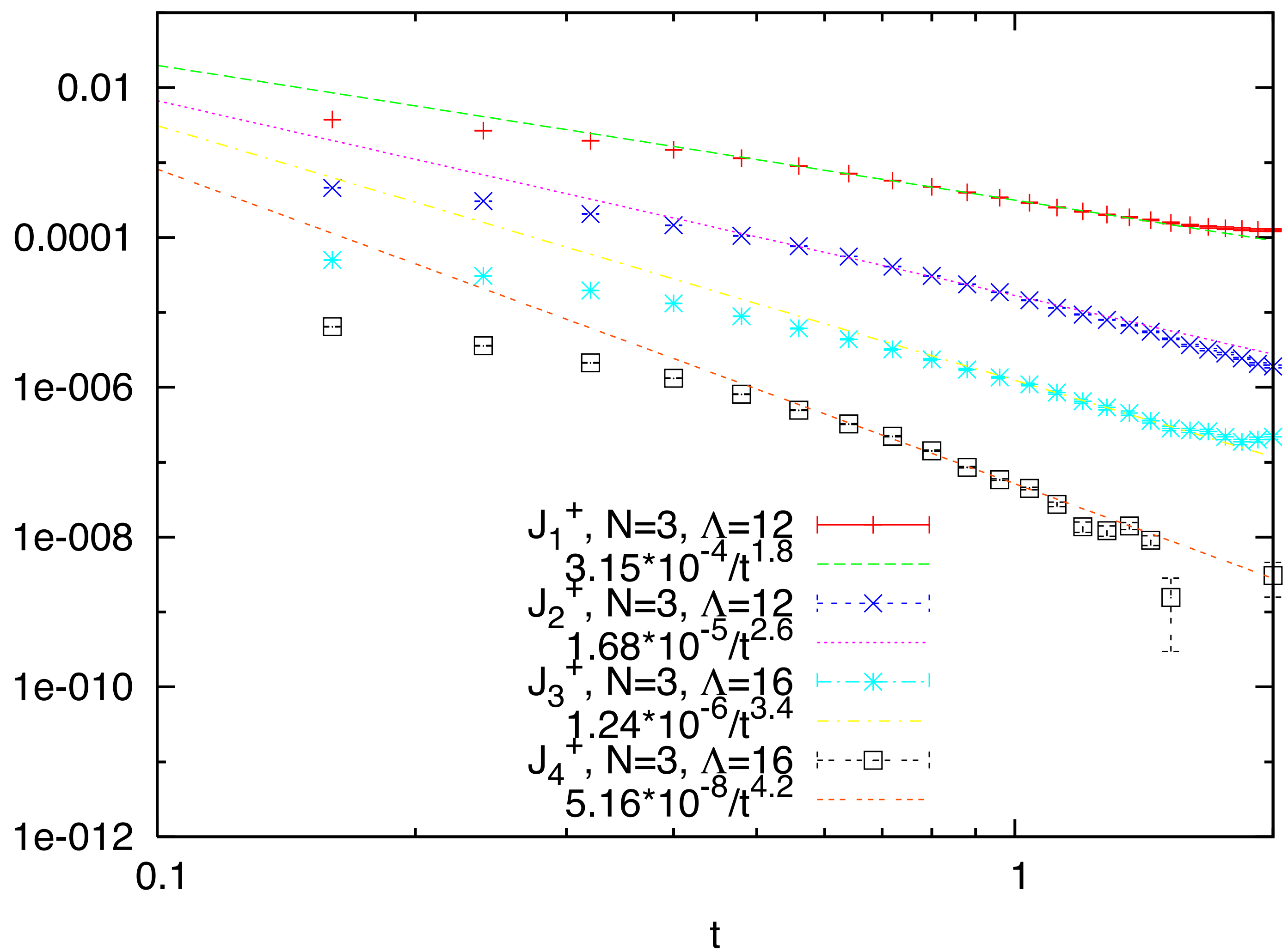
effective theory
=gauge theory

description on
the boundary

effective theory
=gravity

description
in the bulk

Example: **Predictions** (Sekino-T.Y. 1999) on the correlation functions for a strong-coupling gauge theory (0+1 dimensional super Yang-Mills theory, the so-called `Matrix theory') has recently been **checked through Monte Carlo simulations**



$$J^{+ij}_{l,i_1,\cdots,i_l} \equiv \frac{1}{N}\mathrm{Str}\left(F_{ij}X_{i_1}\cdots X_{i_l}\right)$$

$$\langle O(t)O(t')\rangle \sim \left(|t-t'|^{-\eta}\right)$$

$$\eta = 1 + 4\ell/5$$

Hanada-Nishimura-Sekino-T.Y.. Phys. Rev. Lett. 104 (2010)151601
see also arXiv:1108.5153[hep-th]

The meaning of string theory

- encompasses almost all relevant ideas and/or methods devised in the past towards unification

- provides an entirely new scheme of unifying all interactions including gravity

  (motion or spectra and interaction are completely unified)

- provides a microscopic explanation of black hole entropy in terms of quantum statistical language using D-branes

  (albeit in some special cases)

- resolves non-renormalizable divergences in terms of intrinsic non-locality in a way which is consistent with unitarity

- The characterization of short distance structure of space-time embodied in string theory relates to one of most fundamental questions of quantum gravity.

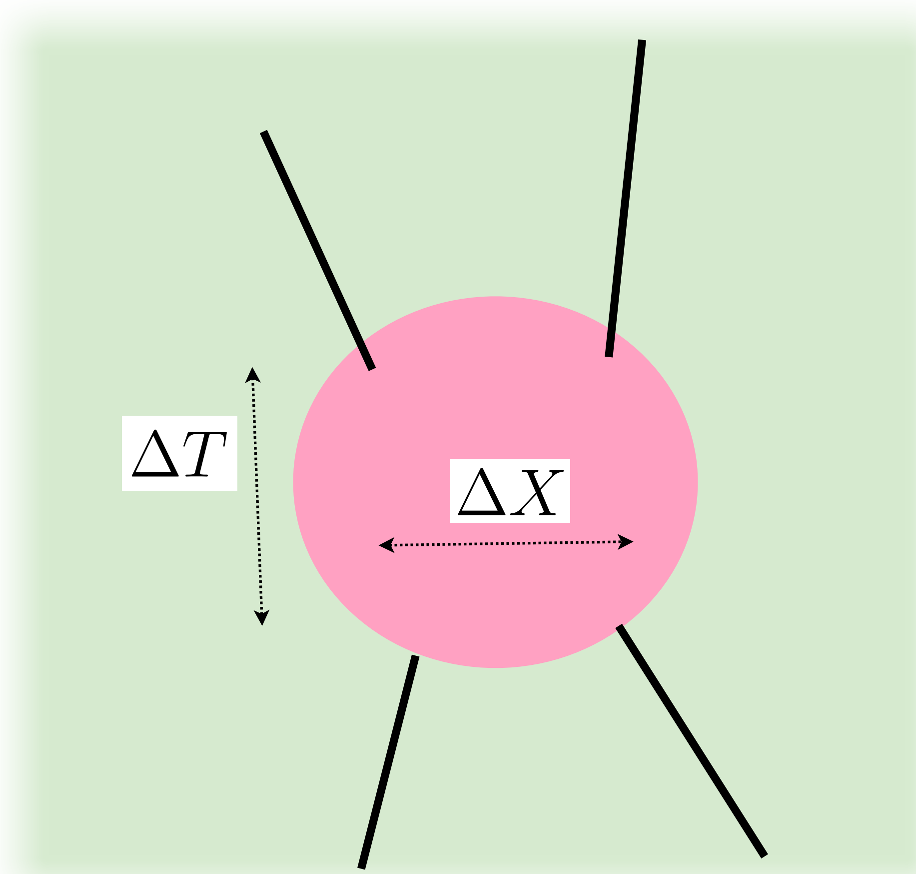
a possible expression :

uncertainty relation of space and time

$$\Delta E \Delta t \gtrsim h \longrightarrow \Delta X \Delta T \gtrsim \ell_s^2$$

$$\Delta E \sim \Delta X \frac{h}{\ell_s^2} \qquad \Delta t = \Delta T$$

・This can be interpreted as the space-time representation of the world-sheet **conformal symmetry** which governs the quantum dynamics of strings and is responsible for the reduction of degrees of freedom both in UV and IR regions.



To summarize:

string theory enables us to derive general relativity and gauge interaction naturally from quantum mechanics of fundamental strings. In this sense, string theory provides the **ingredients** which are necessary for achieving the final unification. (This is already a grand **prediction**!)

At the ***present stage*** *of development,* ***however, it is still an immature 'theory'***.

- we only have a perturbative definition for constructing scattering amplitudes.
- we do not know the primordial principles behind it.
- we cannot yet make any definite predictions to the real world.

The present immaturity of string theory does ***not*** mean that the theory cannot make any predictions in principle.
There is no other competing theory, exhibiting such a tight structure of self-consistency and hence in principle of highest predictability at least ***potentially***.

The present status of string theory is *somewhat* similar to that of early quantum theory before 1924.
We do not yet have true languages for describing string theory.

It is unclear to what extent various recent ideas (say, the "string landscape", "world-brane scenarios", ...) for model building survive when we would finally find such true languages.

We need non-perturbative definition of string theory
such that its whole apparatus could be put on computers
(remember how lattice gauge theory has been benefitting QCD).

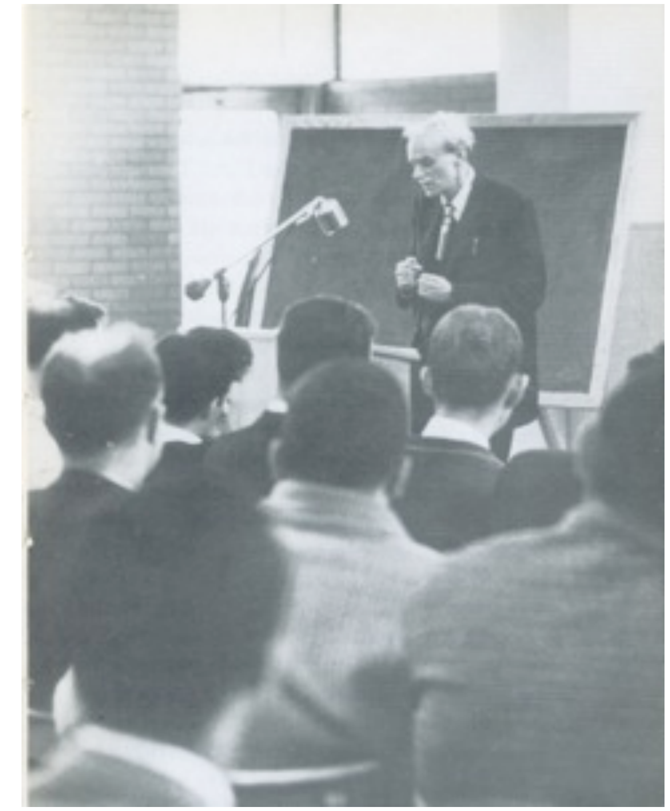
We have to be patient and to learn more,
in view of such a grandiose synthesis we are looking for !

On the experimental side, hopefully, various increasingly
precise data from cosmological observations
(background fluctuations, dark matter, dark energy, etc)
would provide us key basis for the future development.

Epilogue: Historical remarks

- Dirac's anticipation of strings in 1955

"The lines would then be the elementary concept in terms of which the whole theory of electrons and the electromagnetic field would have to be built up. ***Closed lines would be interpreted as photons and open lines would have their ends interpreted as electrons or positrons***. ..."



P. A. M. Dirac
(1902-1984)

GAUGE-INVARIANT FORMULATION OF
QUANTUM ELECTRODYNAMICS[1]

By P. A. M. Dirac

ABSTRACT

Electrodynamics is formulated so as to be manifestly invariant under general gauge transformations, through being built up entirely in terms of gauge-invariant dynamical variables. The quantization of the theory can be carried out by the usual rules and meets with the usual difficulties.

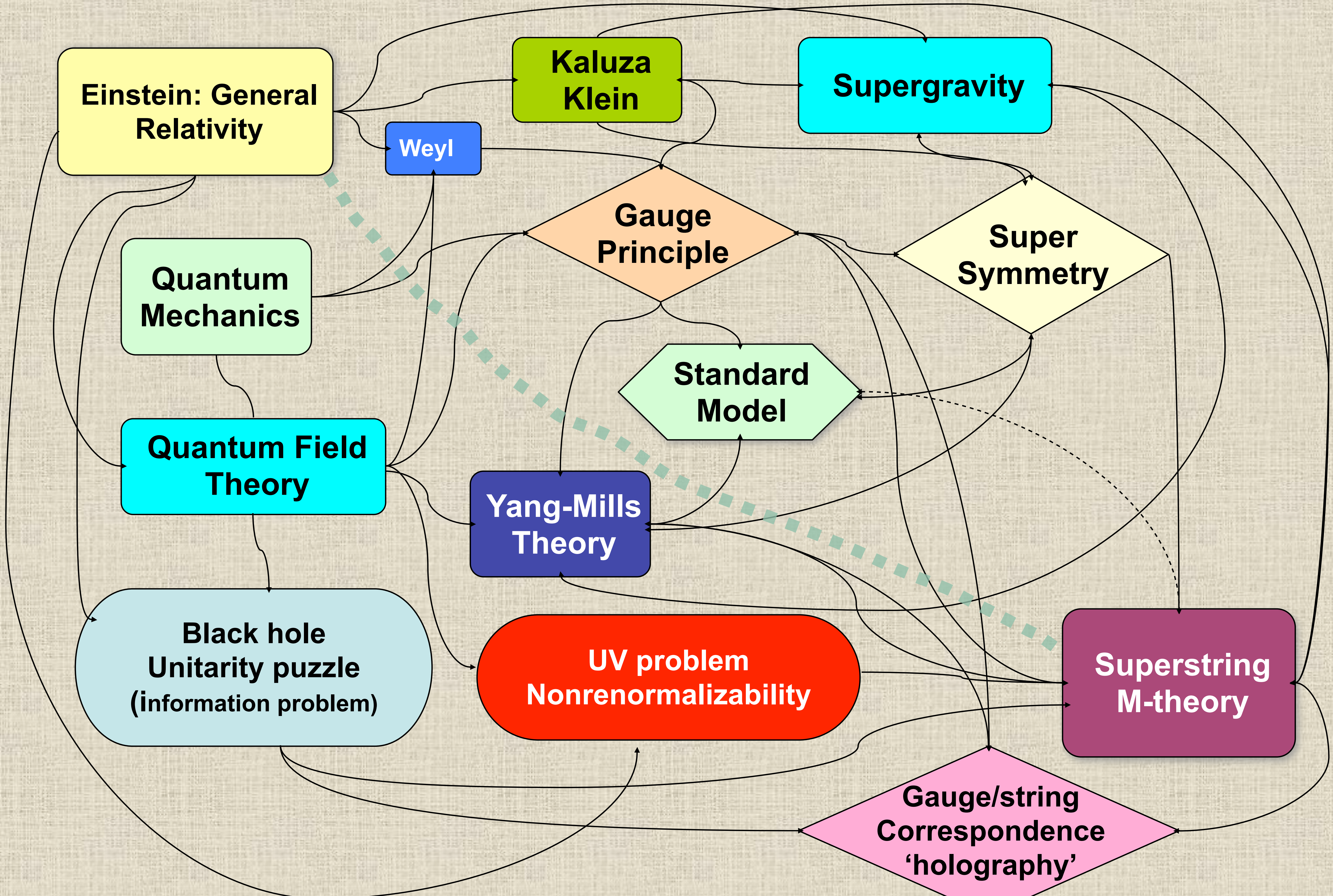
It is found that the gauge-invariant operation of creation of an electron involves the simultaneous creation of an electron and of the Coulomb field around it. The requirement of manifest gauge invariance prevents one from using the concept of an electron separated from its Coulomb field.

Canadian Journal of Physics, 33(1955) 650

H. Yukawa (1907-1981) was also one of main advocates of non-local field theory from the late 1940s.

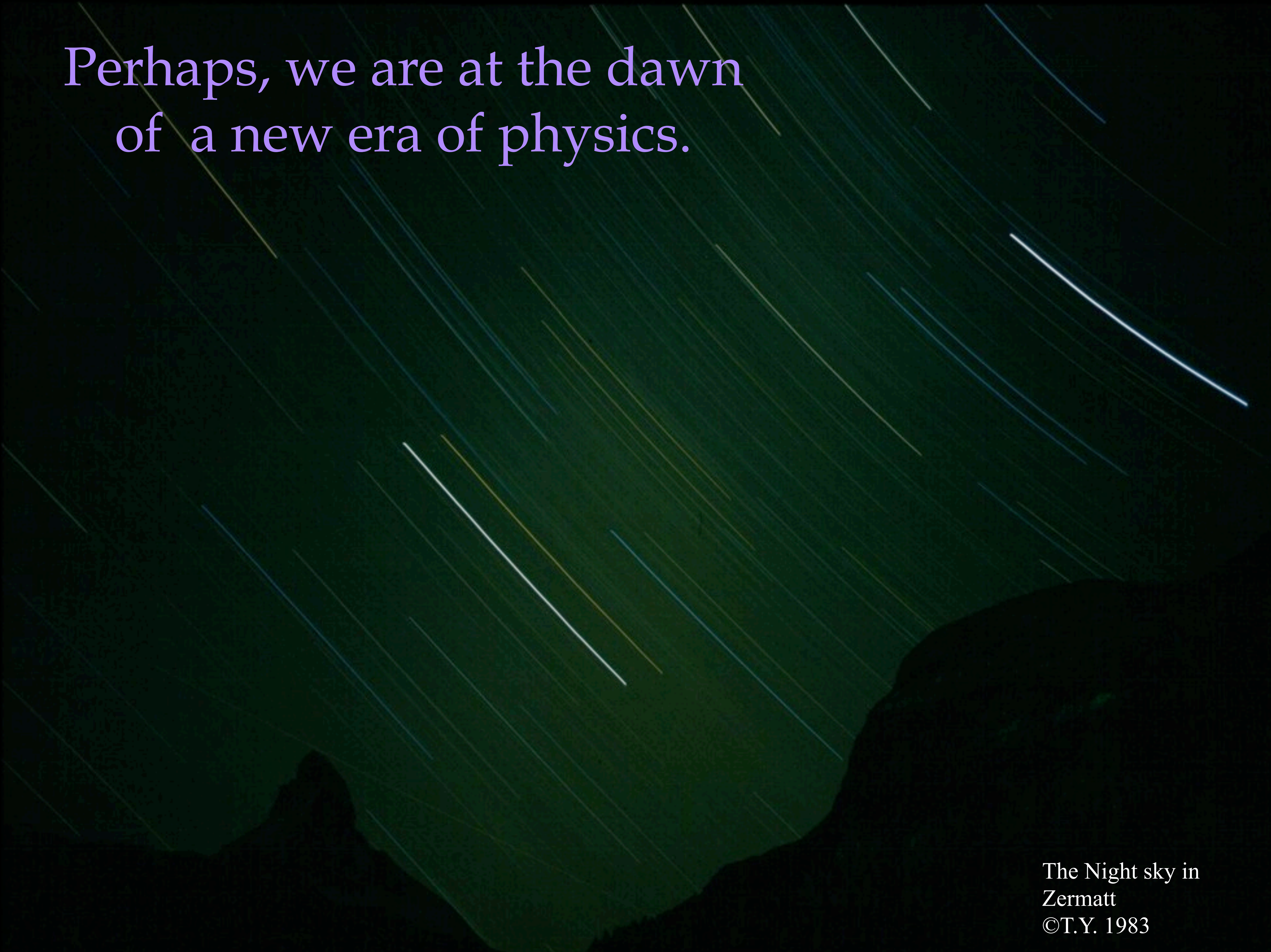
「素粒子を点と思っていたのでは、’てん’で話にならない」

"It is pointless to conceive elementary particles as mere points."

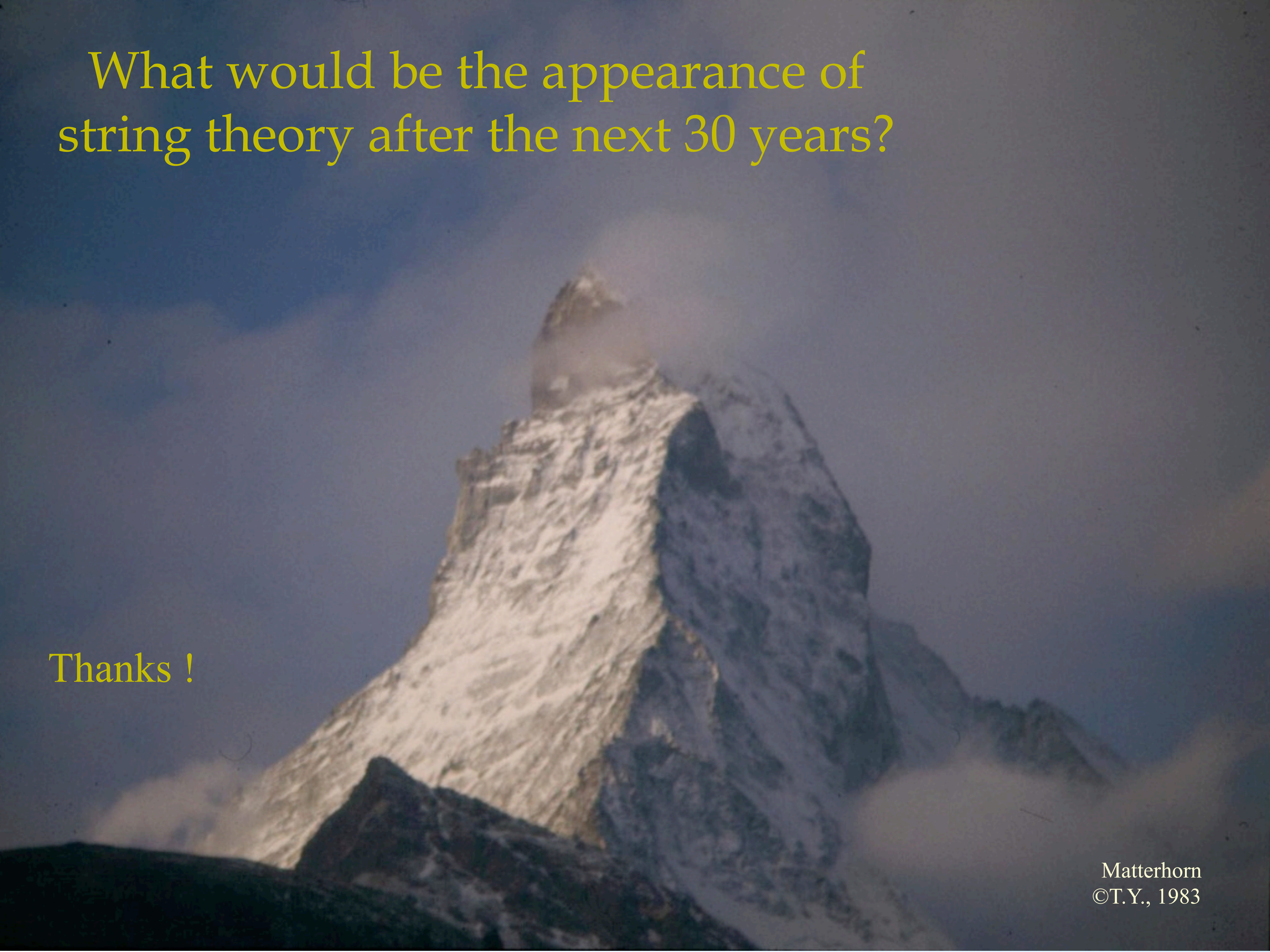


Web of Unification

Perhaps, we are at the dawn
of a new era of physics.



The Night sky in
Zermatt
©T.Y. 1983


What would be the appearance of
string theory after the next 30 years?
Thanks !
Matterhorn
©T.Y., 1983