WHAT STRING THEORY HAS TAUGHT US ABOUT QUANTUM GRAVITY AND UNIFICATION OF FORCES.

HIROSI OOGURI

(CALTECH)

SCALES IN PARTICLE PHYSICS

c = SPEED OF LIGHT = $\frac{[\text{LENGTH}]}{[\text{TIME}]}$

$\hbar$ = PLANCK CONSTANT = [ENERGY] × [TIME]

IN THE NATURAL UNITS,

$$\text{LENGTH} = \text{TIME} = \frac{1}{\text{ENERGY}} = \frac{1}{\text{MASS}}$$

$$1\,m = 3 \times 10^{-9}\,s = \frac{1}{2 \times 10^{-16}\,GeV}$$

GeV : UNIT OF ENERGY

- STANDARD MODEL OF PARTICLE PHYSICS
  HAS BEEN TESTED FOR $\lesssim 10^2\,GeV \sim \frac{1}{10^{-18}\,m}$

- FERMILAB (CHICAGO SUBURB) $\sim 10^3\,GeV$
  CERN LHC (SWITZERLAND) $\sim 10^4\,GeV$
  ··· OUR BEST MICROSCOPES

- ELECTRON MASS $\sim 5 \times 10^{-4}\,GeV$

  PLANCK MASS $\sim 1.2 \times 10^{19}\,GeV$

ELECTRON MASS

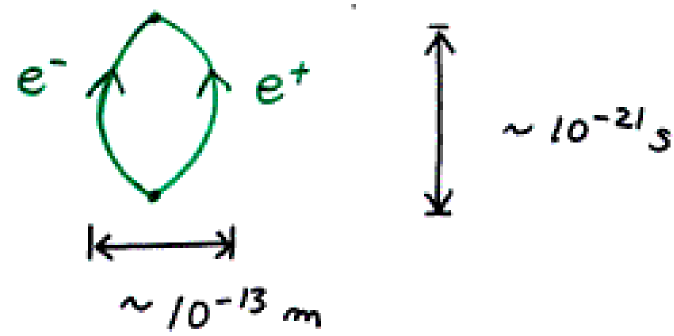
$$= 9 \times 10^{-31}\ \mathrm{kg}$$

$$= 5 \times 10^{-4}\ \mathrm{GeV} \qquad E = mc^2$$

$$= \frac{1}{3.8 \times 10^{-13}\ \mathrm{m}}$$

$$= \frac{1}{1.3 \times 10^{-21}\ \mathrm{s}}$$

VACUUM FLUCTUATION



NEWTON CONSTANT

$$F = G_{\mathrm{NEWTON}} \frac{m_1 m_2}{r^2}$$

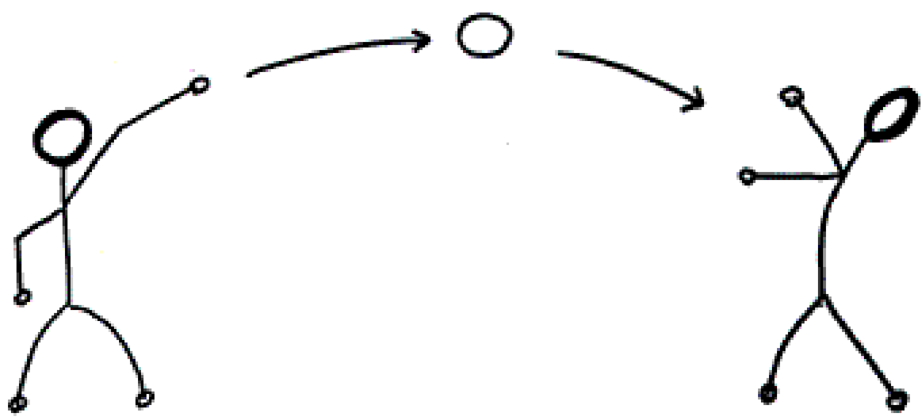
$$G_{\mathrm{NEWTON}} = 6.67\ \mathrm{m^3\,kg^{-1}\,s^{-2}} = \left[\frac{1}{1.2 \times 10^{19}\ \mathrm{GeV}}\right]^2$$

PLANCK MASS $= G_{\mathrm{NEWTON}}^{-1/2}$

$$= 1.2 \times 10^{19}\ \mathrm{GeV}$$

$$= 2.2 \times 10^{-8}\ \mathrm{kg}$$

WORLD ACCORDING TO CLASSICAL PHYSICS.



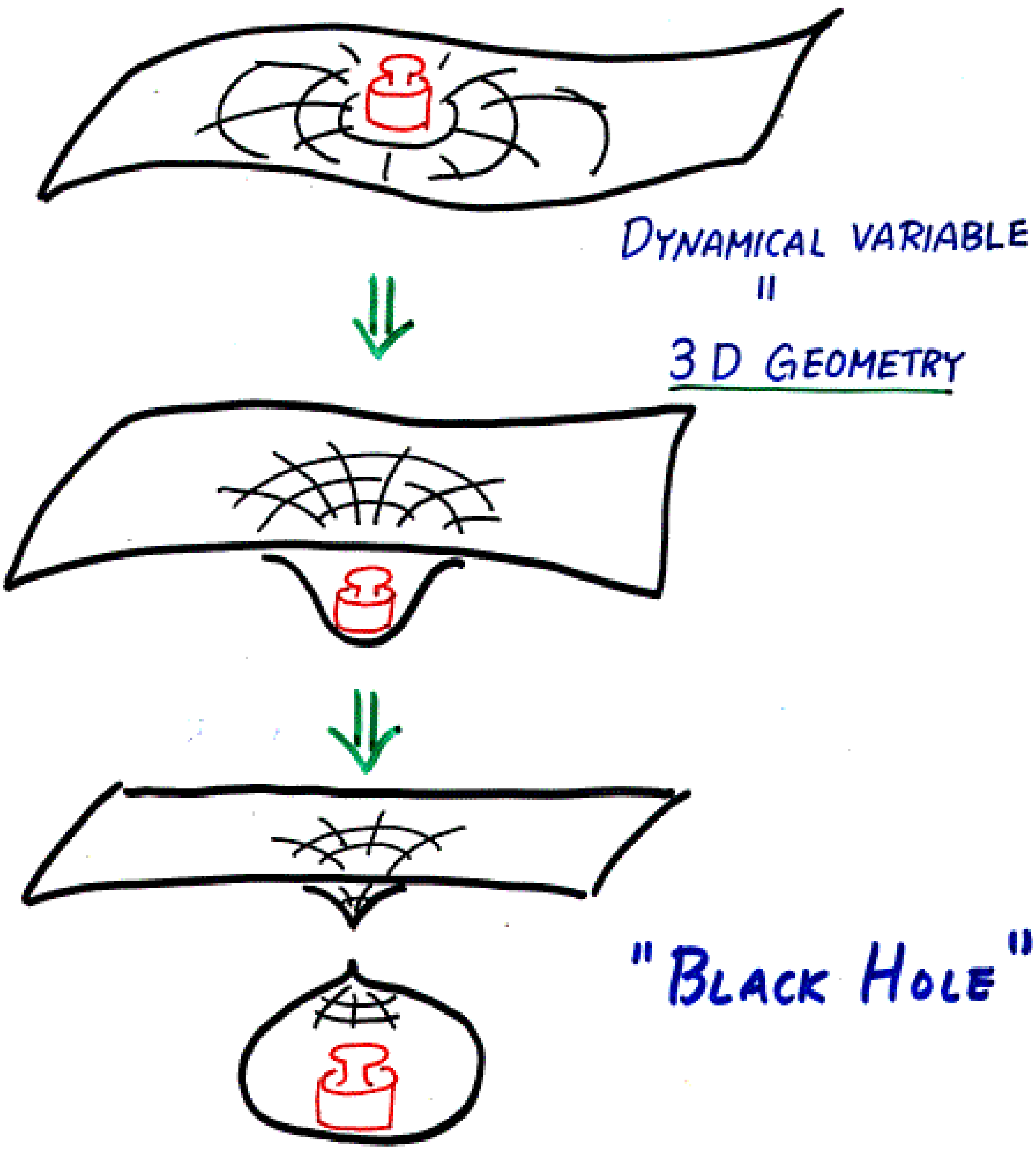
DYNAMICAL VARIABLE :

$\vec{x}(t)$ = POSITION OF THE BALL AT TIME t.

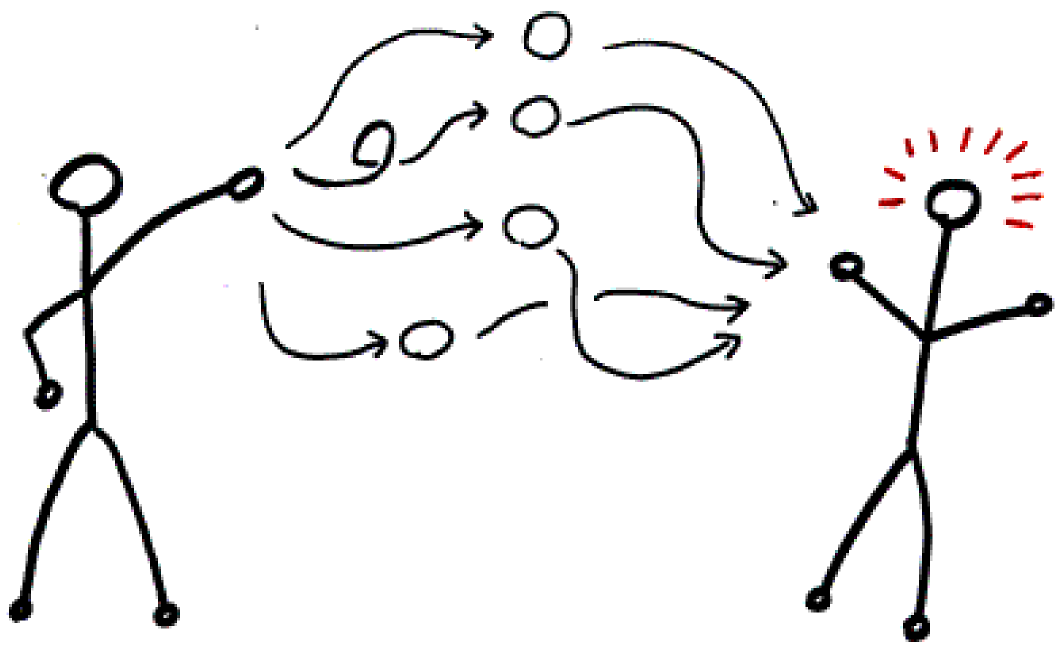
$\left(\vec{x}, \frac{d\vec{x}}{dt}\right)$ AT $t = t_0$ $\Rightarrow$ $\vec{x}(t)$ DETERMINED FOR ANY t

"INITIAL CONDITION"

EINSTEIN'S GENERAL RELATIVITY BELONGS TO CLASSICAL PHYSICS.



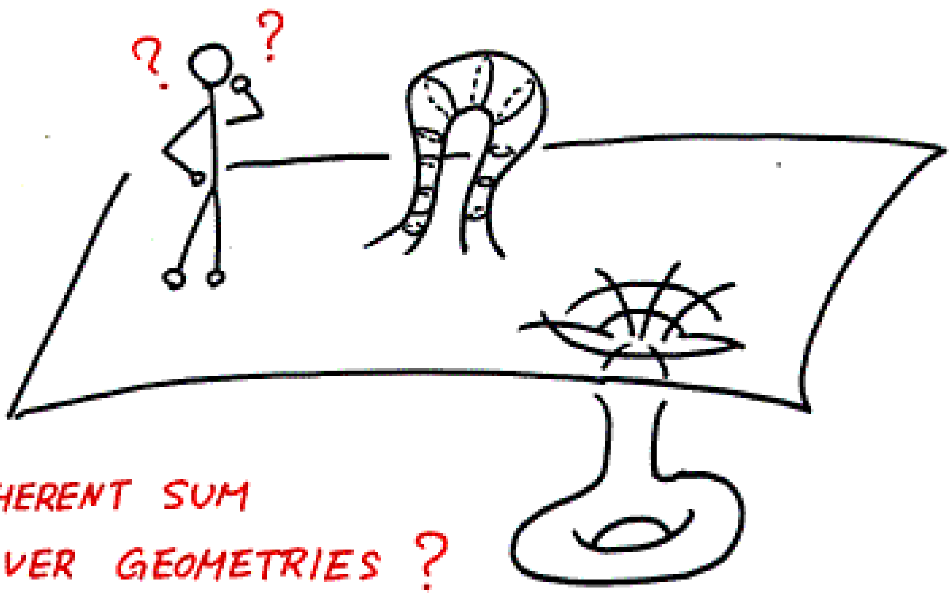
WORLD ACCORDING TO QUANTUM PHYSICS



COHERENT SUM

OVER ALL POSSIBLE TRAJECTORIES

GENERAL RELATIVITY + QUANTUM MECHANICS = ?



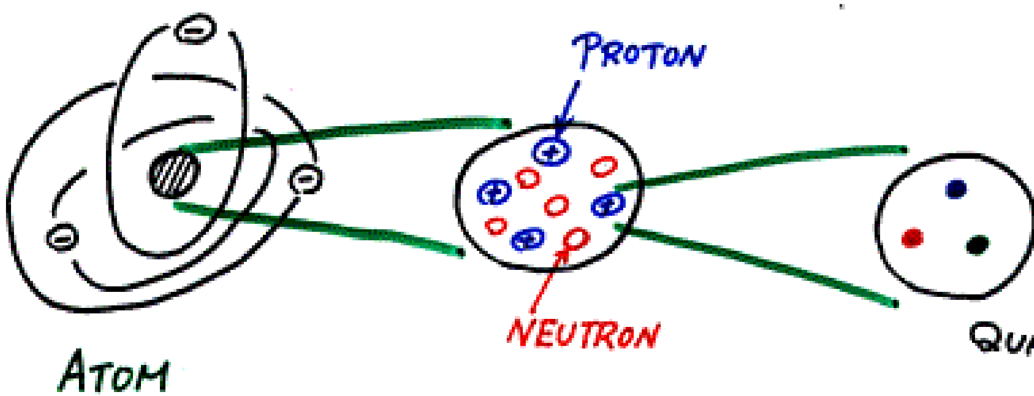
COHERENT SUM OVER GEOMETRIES ?

AT A MORE "PRACTICAL" LEVEL,

RENORMALIZATION FAILS.

RENORMALIZATION

⟸ HIERARCHY OF SCALES IN PHYSICAL WORLD



☆ TO UNDERSTAND PHENOMENA IN ATOMIC SCALE, WE DON'T HAVE TO KNOW QUARK PHYSICS IN DETAIL.

☆ QUARK PHYSICS ⟶ DETERMINE A SET OF PARAMETERS OF ATOMIC PHYSICS.

RENORMALIZATION

PROGRESS CAN BE MADE IN INCREMENTAL BASIS.

RENORMALIZATION WORKS IN PARTICLE PHYSICS.

SUPPOSE THERE IS A MYSTERIOUS PARTICLE OF VERY LARGE MASS M.

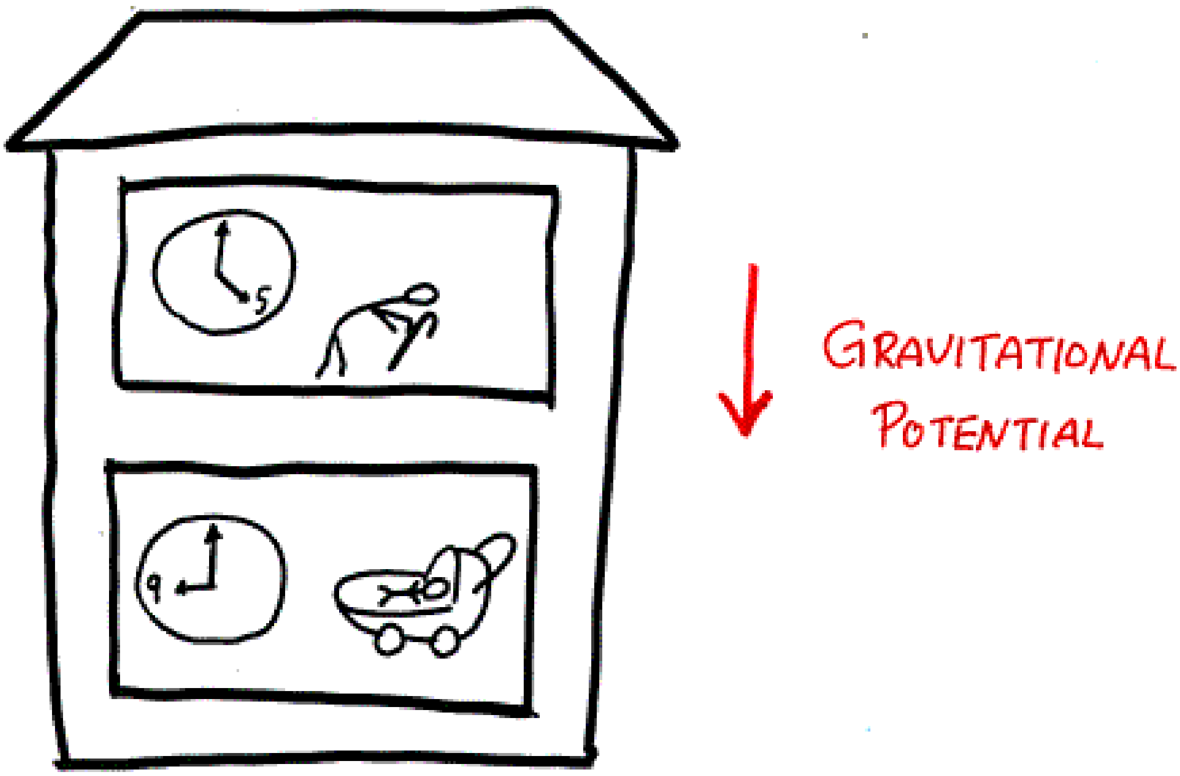
THE VIRTUAL PROCESS CAN LAST ONLY $\Delta t \sim \frac{\hbar}{Mc^2}$

- WE CANNOT SEE IT UNLESS WE LOOK IN THE TIME SCALE Δt.
- AT MOST, M CHANGES THE MASS OF THE ELECTRON.

⇐ <u>RENORMALIZATION.</u>

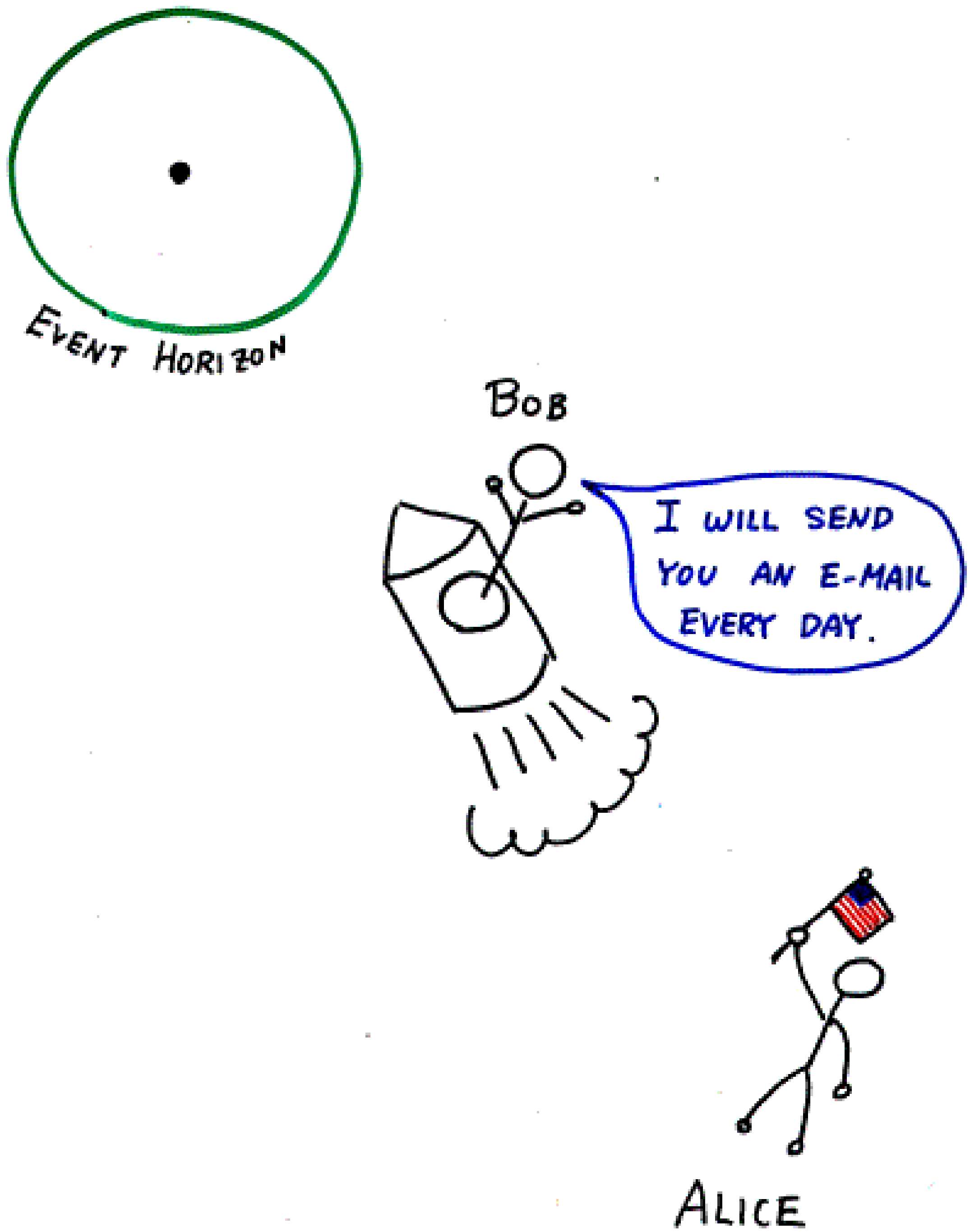
RENORMALIZATION FAILS IN GENERAL RELATIVITY.

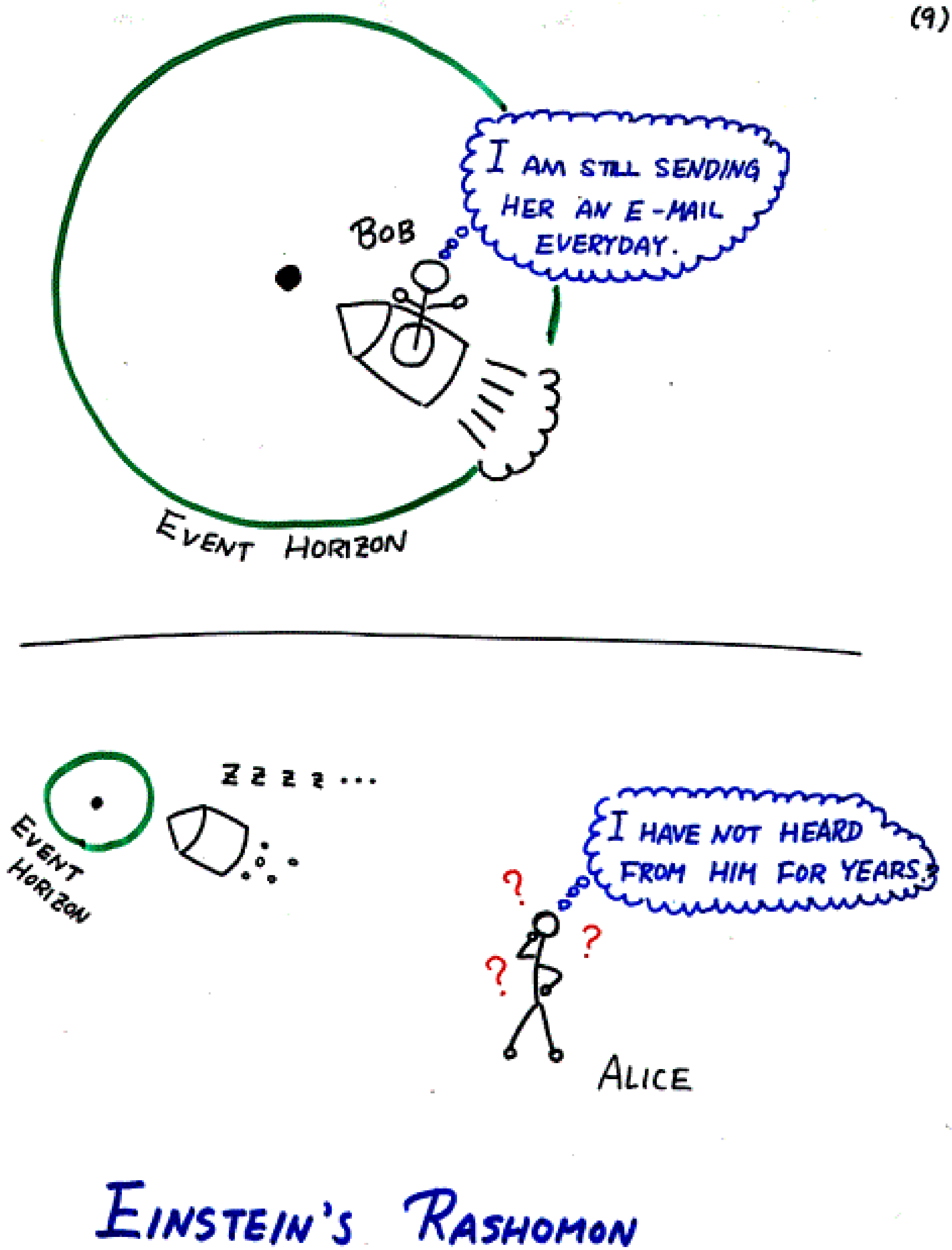
e.g. GRAVITY CAUSES TIME DELAY.



OBSERVED IN THE JEFFERSON LABORATORY OF PHYSICS, HARVARD UNIVERSITY, 1960.

BLACK HOLE

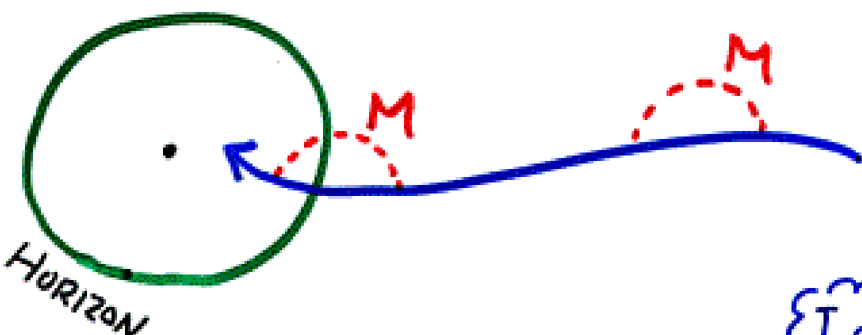



(9)
I AM STILL SENDING HER AN E-MAIL EVERYDAY.
BOB
EVENT HORIZON
Z Z Z Z ...
EVENT HORIZON
I HAVE NOT HEARD FROM HIM FOR YEARS.
ALICE
EINSTEIN'S RASHOMON

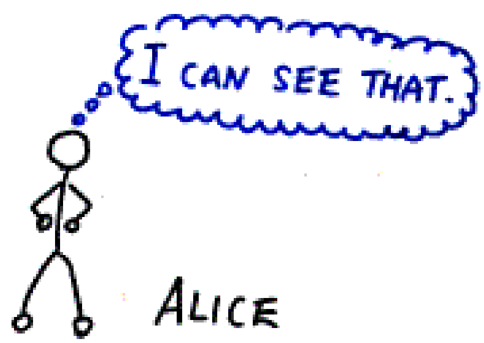
RENORMALIZATION WORKS SINCE WE CANNOT OBSERVE DIRECT EFFECTS OF HEAVY PARTICLES.

$$\Delta t \sim \frac{\hbar}{Mc^2}$$

RENORMALIZATION FAILS IN GENERAL RELATIVITY



FOR ALICE,
THE VIRTUAL PROCESS LOOKS LIKE IT TAKES MUCH LONGER TIME.



UNIFICATION OF GRAVITY

AND QUANTUM MECHANICS

WILL CLOSE

THE SHORT DISTANCE FRONTIER

OF PHYSICS

AS WE KNOW IT.

STRING THEORY

- CONTAINS ALL THE INGREDIENTS THAT ARE NECESSARY TO DESCRIBE PARTICLE PHYSICS PHENOMENA.
  - YANG - MILLS INTERACTIONS
  - CHIRAL FERMIONS
  - (SUPERSYMMETRY)

- ONLY KNOWN QUANTUM THEORY OF GRAVITY

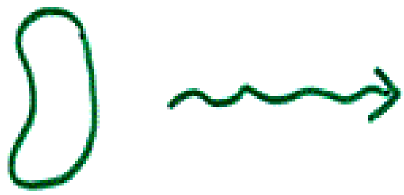
WHAT DOES STRING THEORY
TELL US ABOUT QUANTUM GRAVITY ?

WHAT DOES STRING THEORY
TELL US ABOUT THE UNIFICATION ?

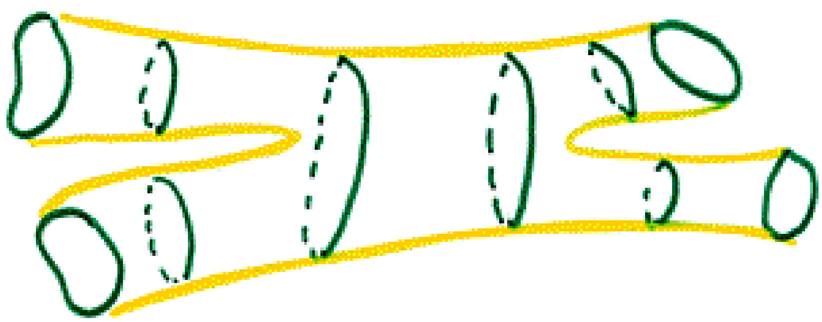
WHAT IS STRING THEORY ?

WHAT IS STRING THEORY?

BEFORE ~1995, MOST OF US THOUGHT OF IT AS DESCRIBING DYNAMICS OF



WITH INTERACTIONS AS



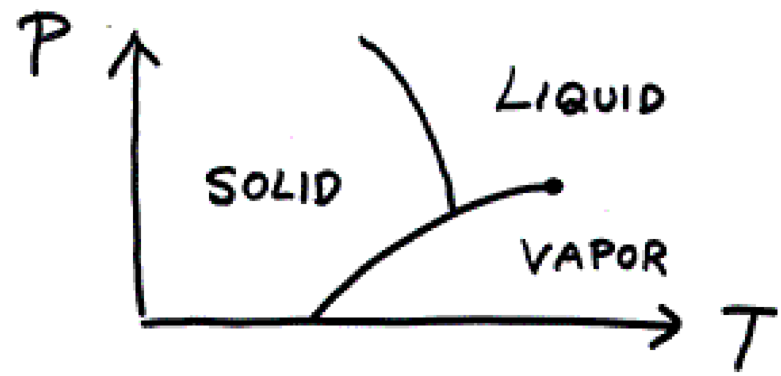
THERE WERE 5 DIFFERENT THEORIES KNOWN

- Type IIA, IIB
- HETEROTIC $E_8 \times E_8$, $SO(32)$
- Type I

~ 1995, IT BECAME CLEAR THAT STRING THEORY HAS MANY PHASES.

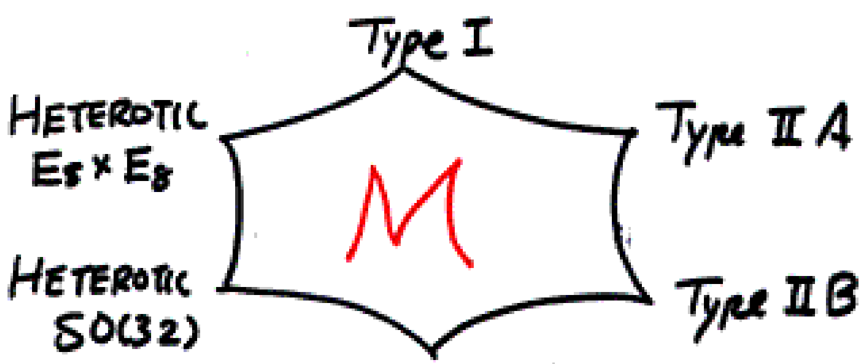
WITTEN

PHASES OF WATER



THIS COMES OUT FROM PHYSICS OF H_2O

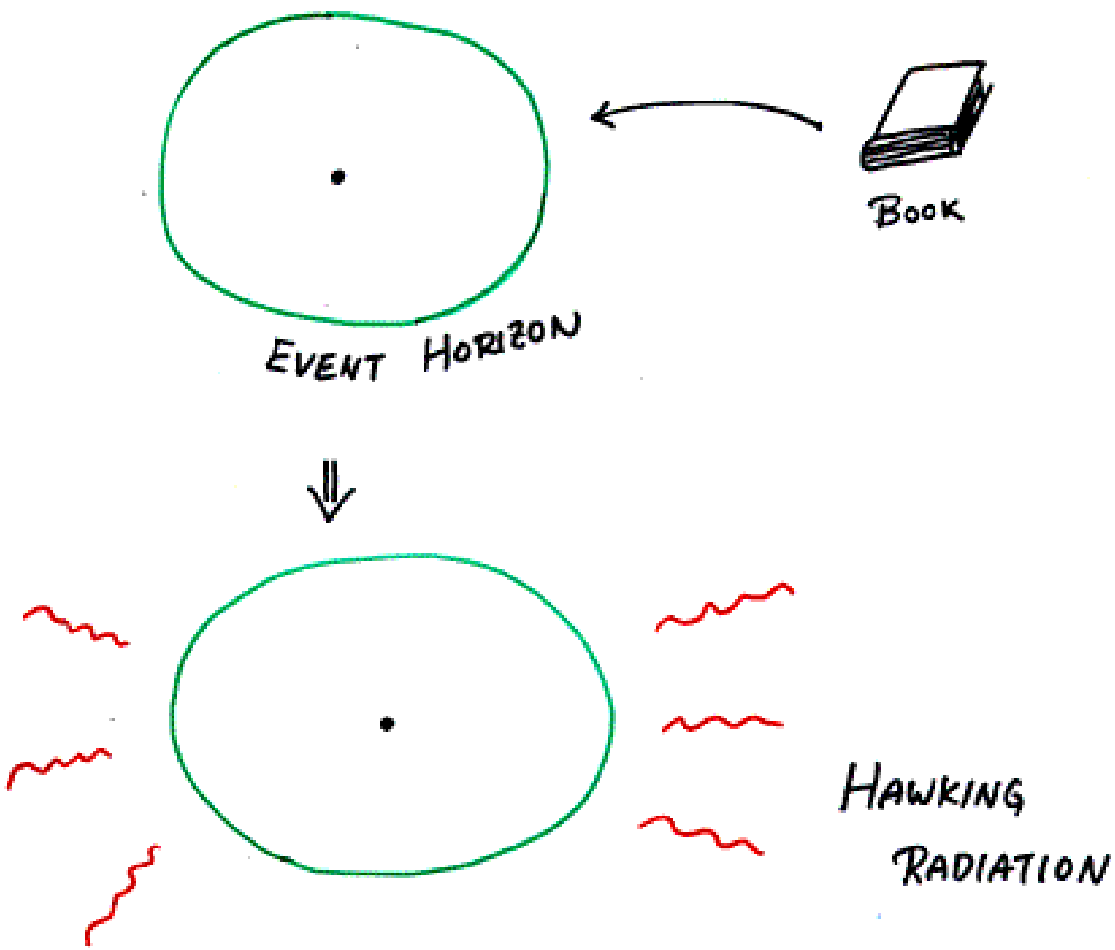
PHASES OF STRING THEORY



WHAT IS AN ANALOGUE OF H_2O?

WHAT DOES STRING THEORY TELL US ABOUT QUANTUM GRAVITY?

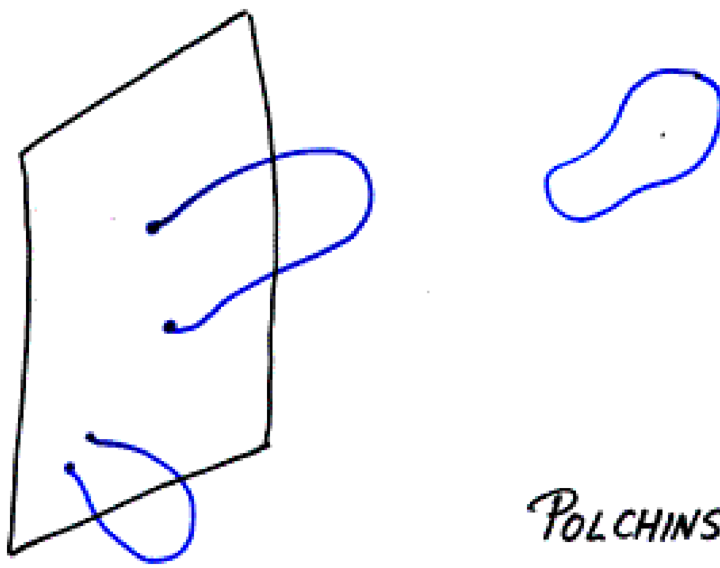
BLACK HOLE INFORMATION PARADOX



WHERE HAS THE INFORMATION GONE ?

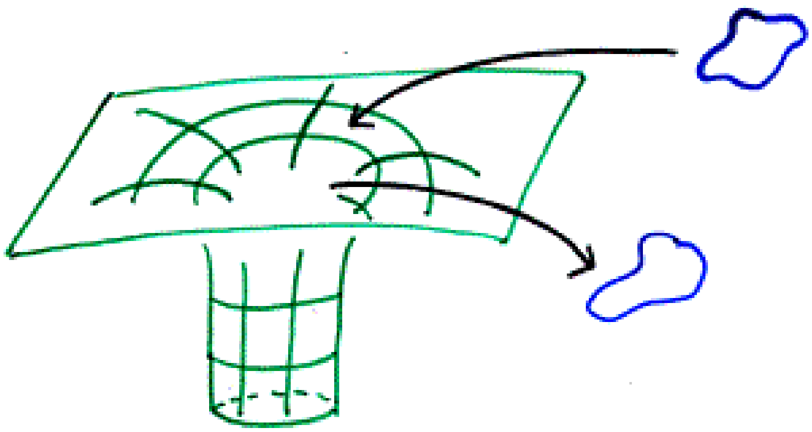
CAN STRING THEORY ANSWER THIS QUESTION ?

D - BRANES



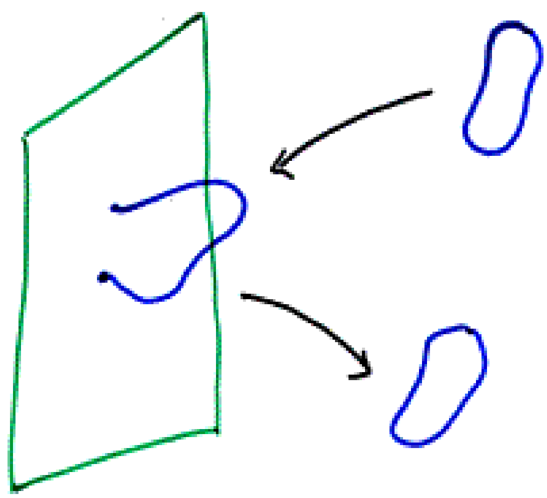
POLCHINSKI 1995

- TRADITIONAL APPROACH



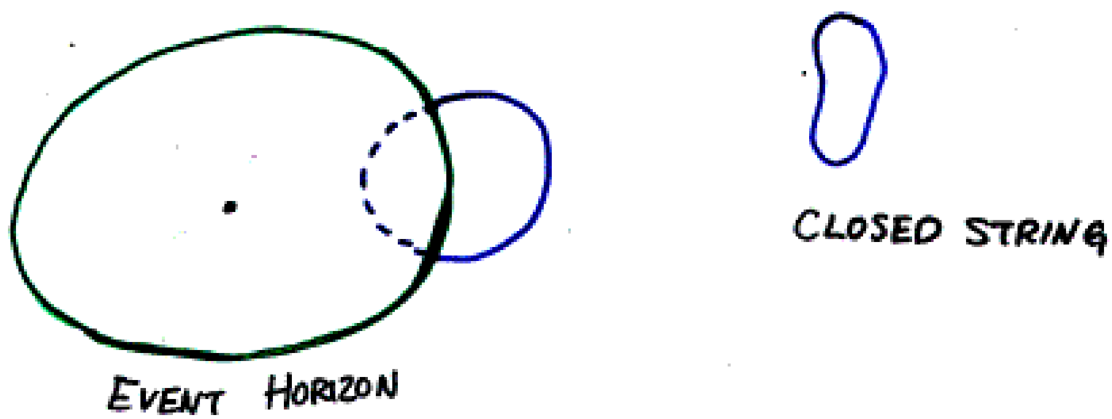
STRINGS IN THE BACKGROUND OF BLACK HOLE GEOMETRY.

- NEW APPROACH



STRINGS INTERACTING WITH D-BRANES

HEURISTIC EXPLANATION



KEY WORD IN BLACK HOLE PHYSICS

"ENTROPY"

ENTROPY IN THERMODYNAMICS

A MACROSCOPIC STATE OF IDEAL MONOATOMIC GAS, e.g. ARGON

IS CHARACTERIZED BY

VOLUME V, TEMPERATURE T, PRESSURE P

AND NUMBER OF ATOMS N

$PV = NkT$ --- EQUATION OF STATE

GIVEN (V, E, N), THERE ARE MANY

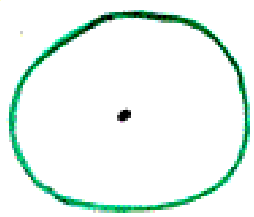
MICROSCOPIC QUANTUM STATES.

OF QUANTUM STATE

$$\sim \left(\frac{m E V^{2/3}}{\hbar^2 N^{5/3}} \right)^{\frac{2}{3}N}$$

ENTROPY $S = k \log(\text{\# QUANTUM STATES})$

BLACK HOLE IS CHARACTERIZED BY



MASS M = INTERNAL ENERGY

\+ A FEW MACROSCOPIC PARAMETERS

HAWKING HAS SHOWN THAT IT ALSO HAS TEMPERATURE T

BLACK HOLE EQUATION OF STATE

$$T \sim \frac{1}{M}$$

⇓

ENTROPY $S \sim k \left(\frac{M}{M_{PLANCK}} \right)^2$

\# QUANTUM STATE $\sim \exp\left[\text{CONST} \times \left(\frac{M}{M_{PLANCK}} \right)^2 \right]$

$M_{PLANCK} \sim 10^{-8}$ kg

ASTROPHYSICAL BLACK HOLE $M \sim 10^{31}$ kg

\# STATES $\sim \exp[10^{78}]$

D-BRANE CONSTRUCTION REPRODUCES THIS FORMULA IN SOME CASES.

QUESTIONS ABOUT THE UNIFICATION

- $M_{PLANCK} \sim 10^{19}$ GeV

  STANDARD MODEL PARAMETERS $\lesssim 10^{3}$ GeV

  WHAT CREATES SUCH A HUGE GAP ?

  ... SUPERSYMMETRY HELPS ...

- STRING THEORY IS DEFINED IN (9 + 1) DIMENSIONS.

  (9 ← SPACE; 1 ← TIME)

  (OR (10+1) DIM IN M THEORY DESCRIPTION)

  WE LIVE IN (3 + 1) DIMENSIONS.

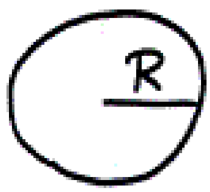
  WHAT TO DO WITH THE EXTRA 6 ?

~~BRAIN~~ BRANE WORLD --- NEW APPROACH TO THE UNIFICATION

☆ TRADITIONAL IDEA

--- KALUZA-KLEIN COMPACTIFICATION

THE EXTRA 6 DIMENSIONS ARE SMALL



HOW SMALL SHOULD IT BE?

CONSTRAINT :

WE HAVE NOT SEEN IT

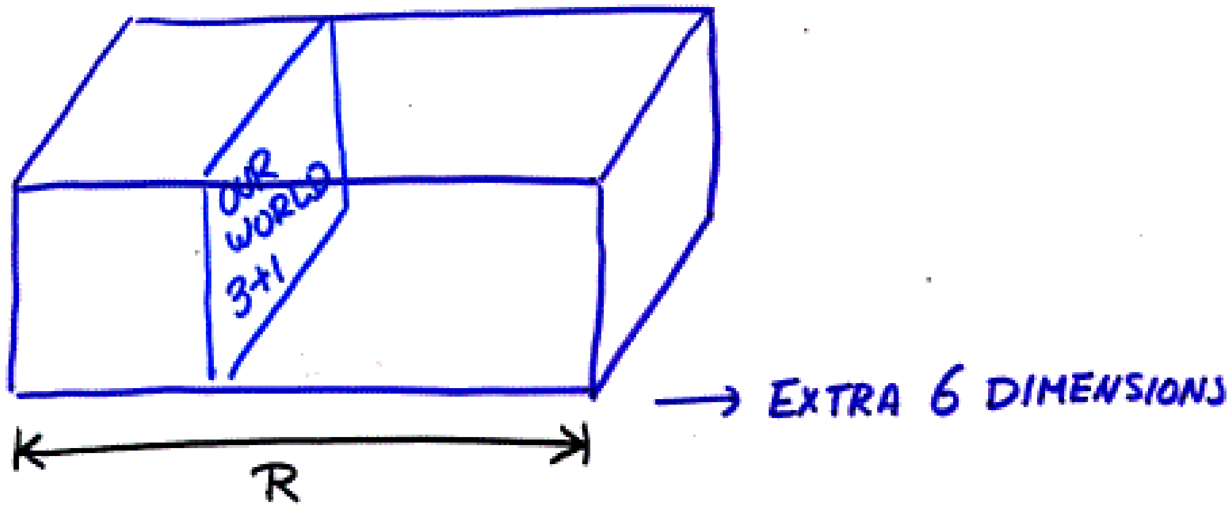
⇓

$R < \lambda$. λ : RESOLUTION OF OUR BEST MICROSCOPE = ACCELERATOR

$$R \lesssim 10^{-18} m = \frac{1}{100 GeV}$$

($R < \frac{1}{10^{16} GeV}$ IF YOU WANT TO PRESERVE GUT.)

☆ BRANE WORLD ··· ALTERNATIVE SENARIO



WE ARE CONFINED IN (3+1) DIMENSIONAL SUBSPACE

⇒ THE ACCELERATOR DOES NOT DIRECTLY PROBE THE EXTRA DIMENSIONS.

GRAVITATIONAL FIELD CAN PROBE IT

--- OBSERVATIONS ARE LIMITED.

$$R < 10^{-3}\,m = \frac{1}{10^{-13}\,GeV}$$ *

* NEXT TRANS PARENCY

STRING THEORY MAY ALLOW SUCH A CONSTRUCTION. (IN PROGRESS).

WHY IS IT INTERESTING ?

MORE PRECISE BOUND

☆ CAVENDISH-TYPE EXPERIMENT

EXTRA-DIMENSIONS WOULD MODIFY THE NEWTON LAW.

$\Rightarrow \quad R < 10^{-3}\, m$

☆ SUPERNOVA 1987A NEUTRINO BURST

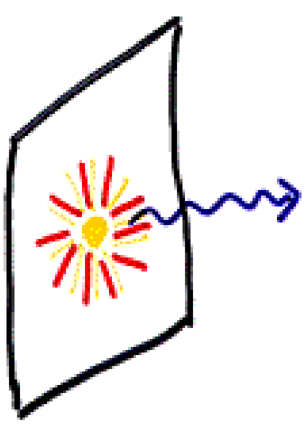
THE ENERGY OF THE SUPERNOVA EXPLOSION COULD HAVE ESCAPED INTO THE EXTRA DIMENSIONS, REDUCING THE NEUTRINO SIGNAL.

$\Rightarrow \quad R < 10^{-7}\, m$

FOR 2 EXTRA DIM

$10^{-8}\, m$

FOR 3 EXTRA DIM



CAN WE OBSERVE QUANTUM GRAVITY EFFECTS IN NATURE.

$M_{PLANCK} \sim 10^{19}\, GeV$

OUR TECHNOLOGY (AND $) ALLOWS US TO PROBE $\sim 10^{4}\, GeV$

BUT

M_{PLANCK} MAY NOT BE THE FUNDAMENTAL QUANTUM GRAVITY SCALE.

$M_{FUND.}$: THE FUNDAMENTAL SCALE IN HIGHER DIMENSIONS

⇓ COMPACTIFY n DIMENSIONS SIZE R

$$M_{PLANCK} = \sqrt{M_{FUND}^{\,n+2}\, R^{n}}$$

M_{FUND} CAN BE MUCH LOWER THAN M_{PLANCK} IF R IS LARGE.

$$M_{PLANCK} = 10^{19}\,GeV = \sqrt{M_{FUND}^{n+2} R^n}$$

- KALUZA - KLEIN COMPACTIFICATION

$$R < 10^{-18}\,m = \frac{1}{100\,GeV}$$

$$\Downarrow$$

$$M_{FUND} > 10^{13}\,GeV \qquad n = 1$$

$$\vdots \qquad\qquad \vdots$$

$$10^{6}\,GeV \qquad n = 6$$

- BRANE WORLD

$$R < 10^{-3}\,m = \frac{1}{10^{-13}\,GeV}$$

(TIGHTER CONSTRAINT FROM SUPERNOVA)

$$\Downarrow$$

$$M_{FUND} > 10^{8}\,GeV \qquad n = 1$$

$$300\,GeV \qquad n = 2$$

(100000 GeV)

$$1\,GeV \qquad n = 3$$

(1000 GeV)

QUANTUM GRAVITY

MAY BE JUST AROUND

THE CORNER.