

Title: Fundamental Physics in 2010

Date: Feb 07, 2007 07:00 PM

URL: <http://pirsa.org/07020013>

Abstract: Will big questions be answered when the Large Hadron Collider (LHC) switches on in 2007? What will scientists find? Where might the research lead? Nima Arkani-Hamed, a noted particle theorist, is a Professor of Physics at Harvard University. He investigates a number of mysteries and interactions in nature – puzzles that are likely to have experimental consequences in the next few years via particle accelerators, like the LHC, as well as cosmological observations. <kw>fundamental physics, Nima Arkani-Hamed, 'Future of Fundamental Physics', general relativity, quantum mechanics, Large Hadron Collider, L H C, quark, quantum gravity, string theory, special relativity, standard model, Planck scale, space-time, vacuum, Higgs boson, super symmetry </kw>

The Future



of

Fundamental Physics



Nima Arkani-Hamed
Harvard University

Theoretical Physics

Thrives on

CRISES +
PARADOXES.

Many of us feel that
our current struggles are
paving the way....

Theoretical Physics

Thrives on

CRISES +
PARADOXES.

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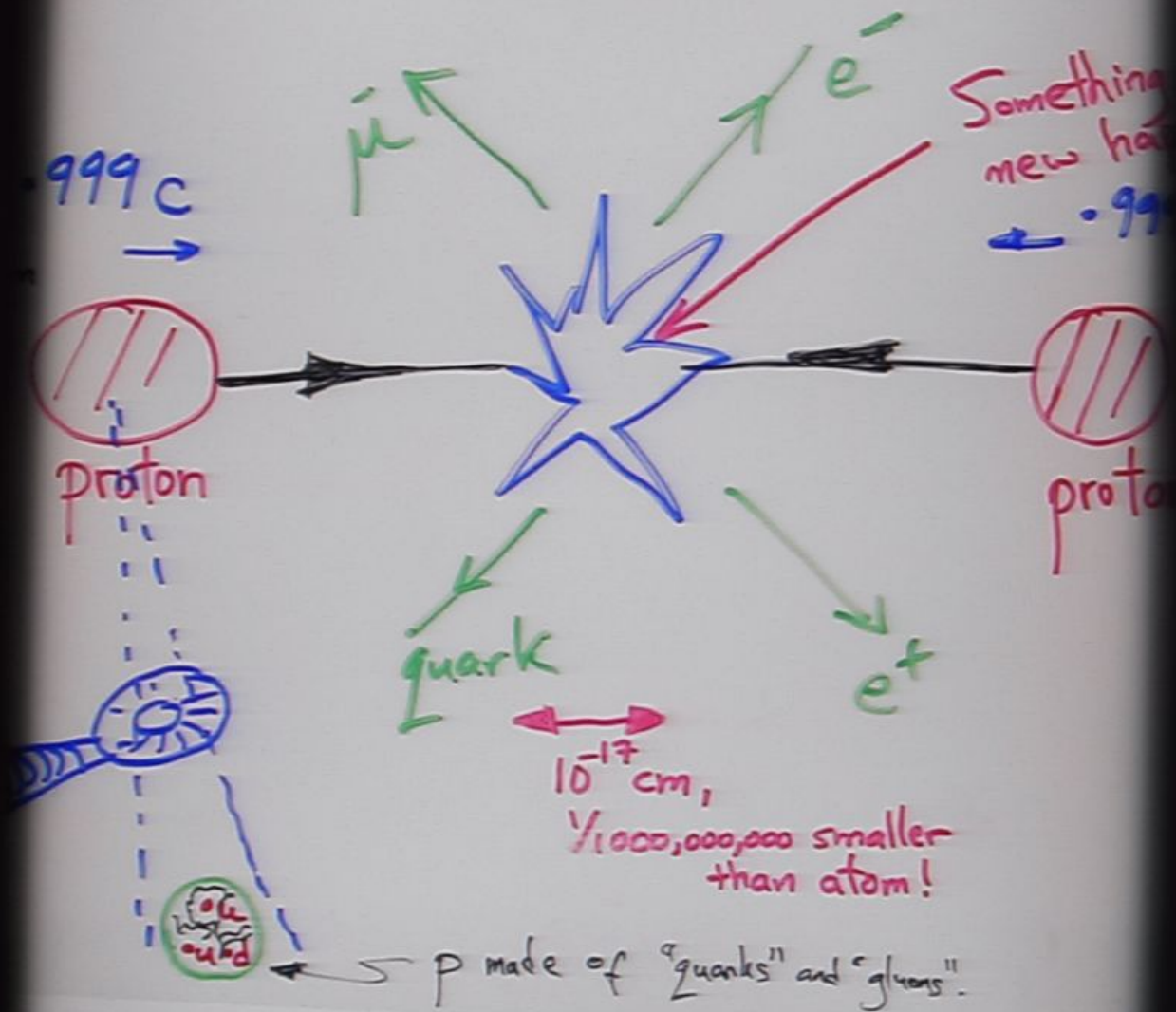
... for a Revolution
in our understanding
of physics on the same
scale as those of
Relativity + Quantum Mechanics
at the beginning of the
20th century.

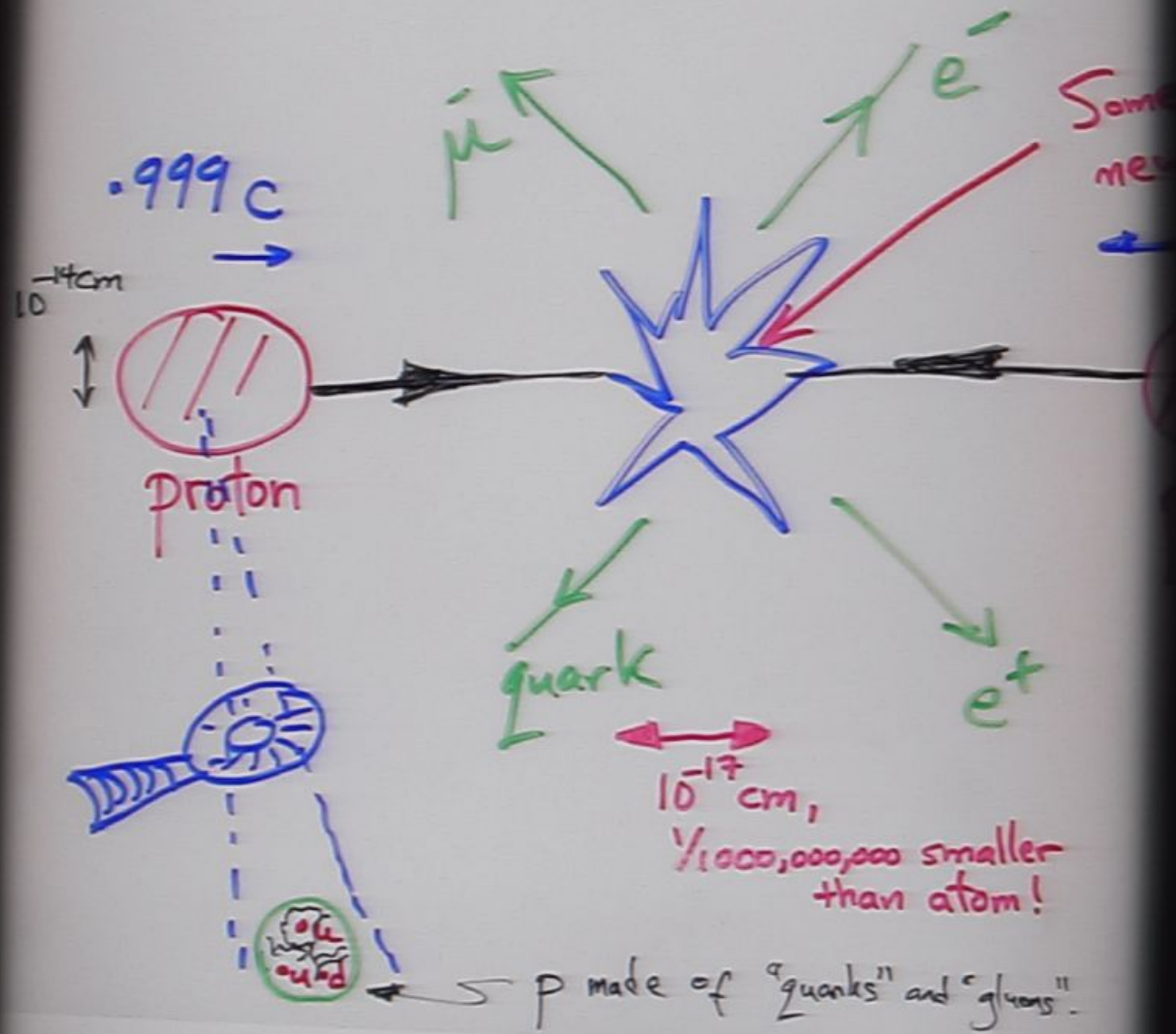
A spectacular new
EXPERIMENT -
the Large Hadron Collider -
might well usher in
the revolution.

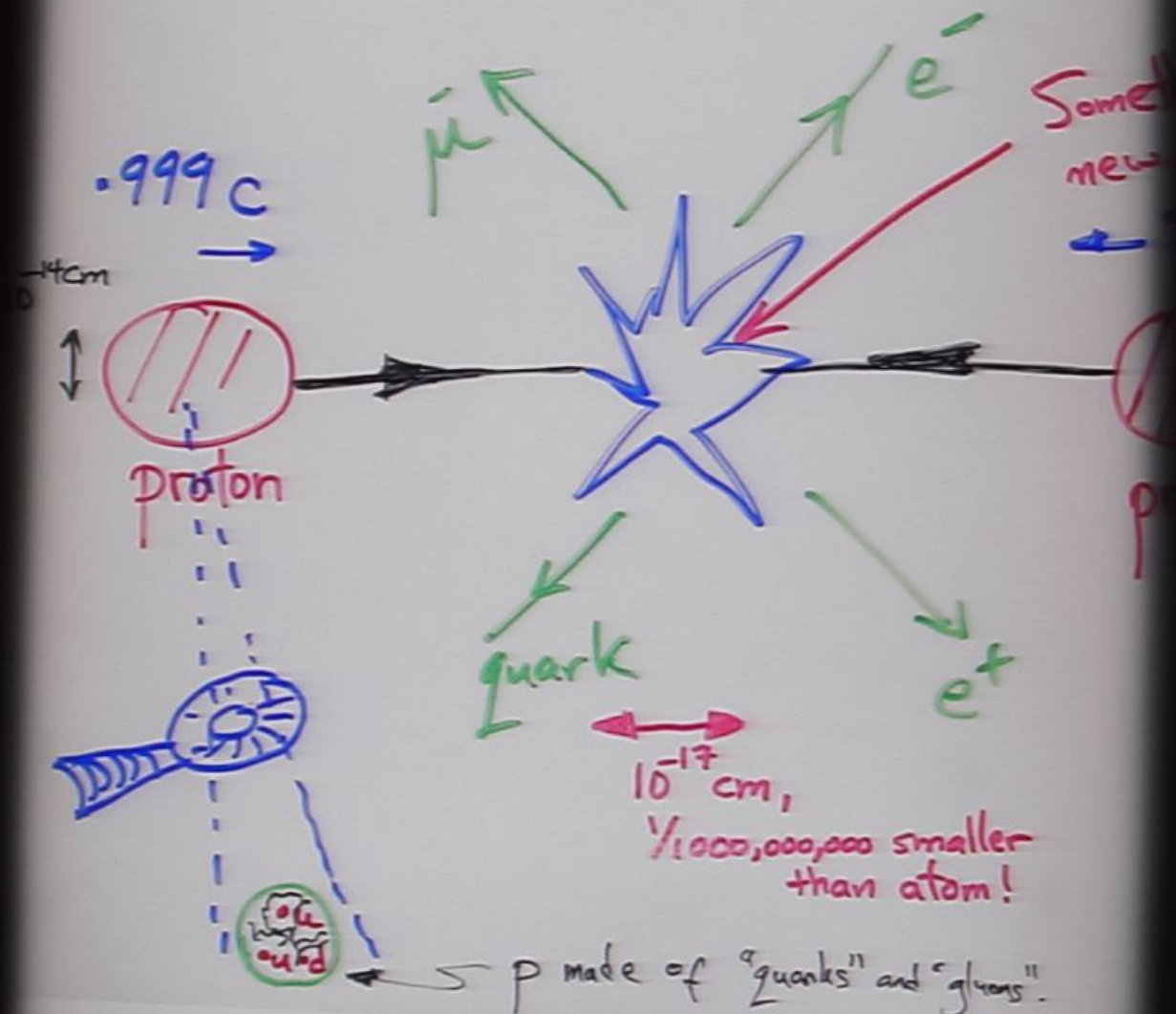
Begin operation

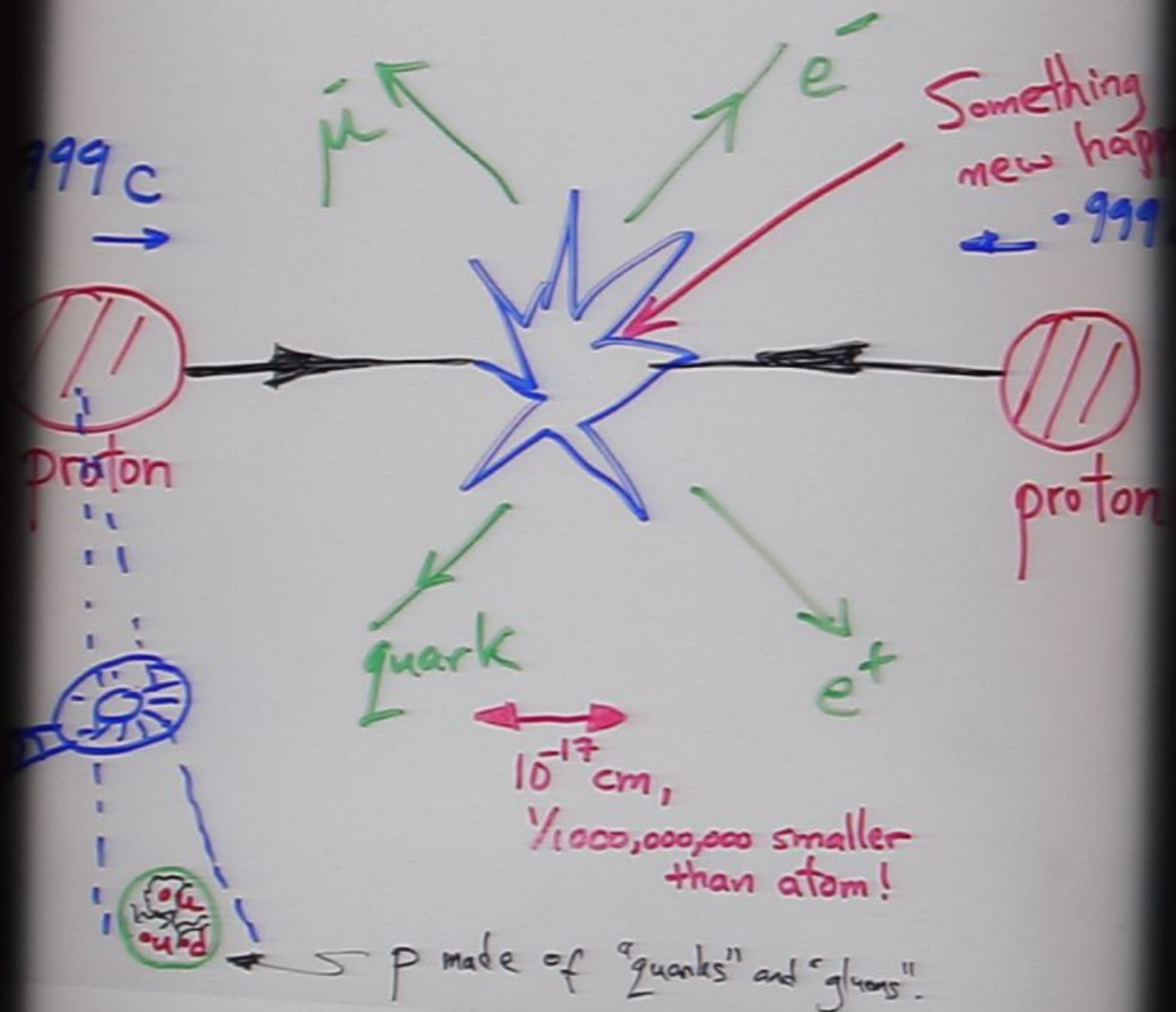
THIS FALL!







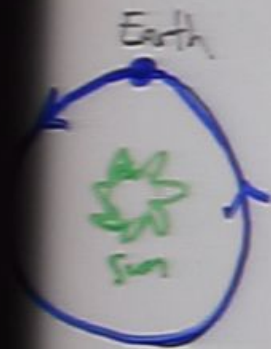






4 Basic Interactions

Gravity



Electromagnetism

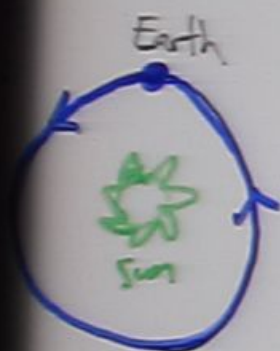


Weak



4 Basic Interactions

Gravity



Electromagnetism



Weak



+ Basic Interactions

Electromagnetism



Weak + Strong



Atom

people

Solar system

Univ.

DNA

Galaxies

10^{28} cm
Size of Universe

Atom

people

Solar system



Galaxies

DNA

Galaxies

Universe



10^{-17} cm
"Weak"
length

protons
+ neutrons



Atom



people

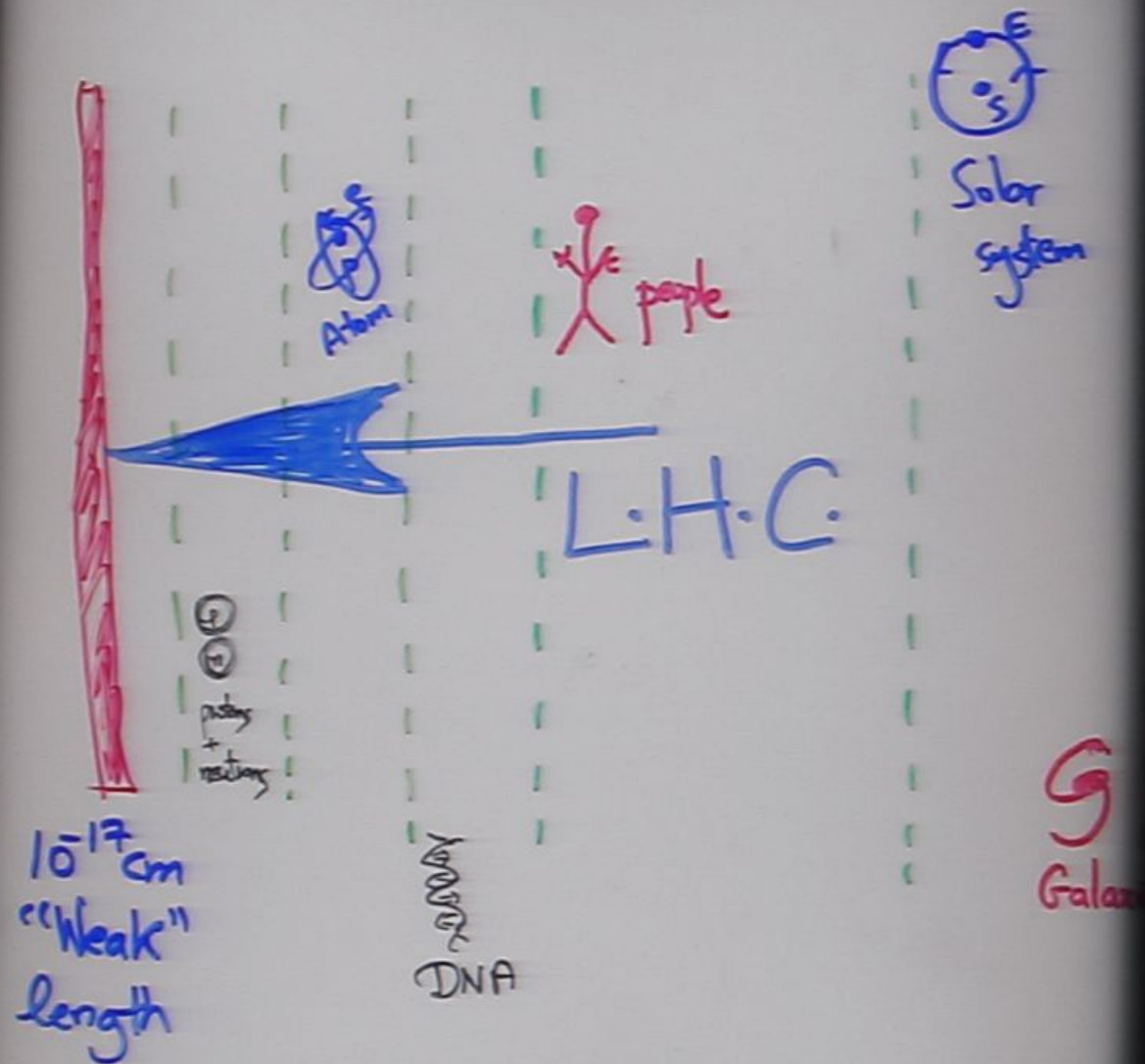
DNA



Solar
system



Galaxy





10^{-17} cm
"Weak"
length

3 cm
"Weak"
length"



10^{-17} cm
"Weak"
length"



10^{-33} cm
"Planck
Length"



10^{-17} cm
"Weak"
length



10^{+28} cm
Size
of Univ.

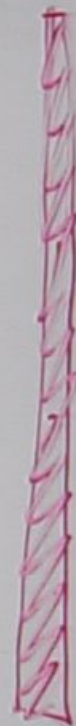


10^{-33} cm
"Planck
Length"

• Quantum
Gravity
• EMERGENT
SPACETIME
• String Theory
+ BEYOND



10^{-17} cm
"Weak"
length



10^{+28} cm
Size
of Univ.



10^{-33} cm
"Planck
Length"

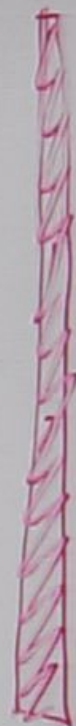


. Quantum
Gravity
. EMERGENT
SPACETIME

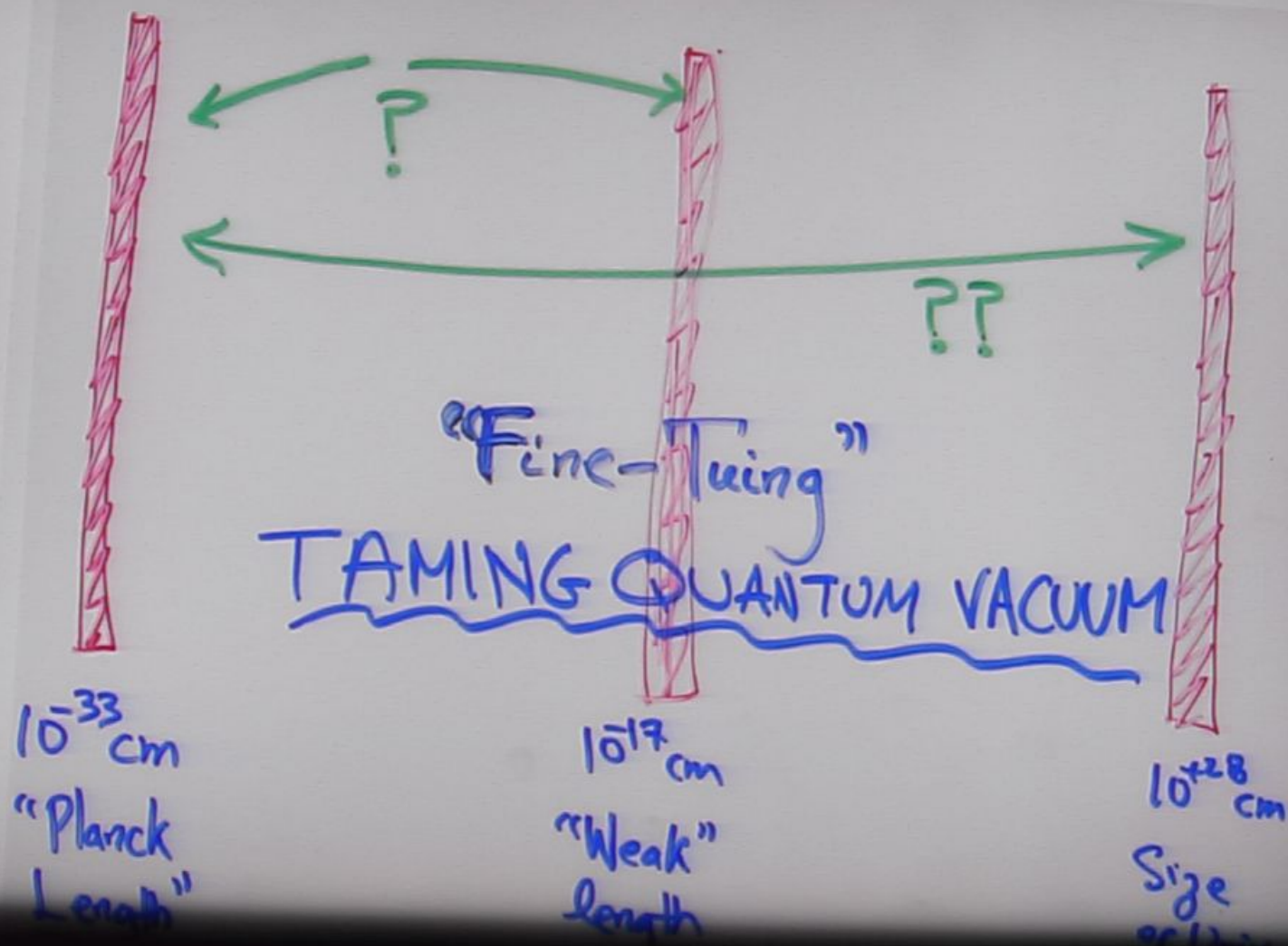
. String Theory
+ BEYOND

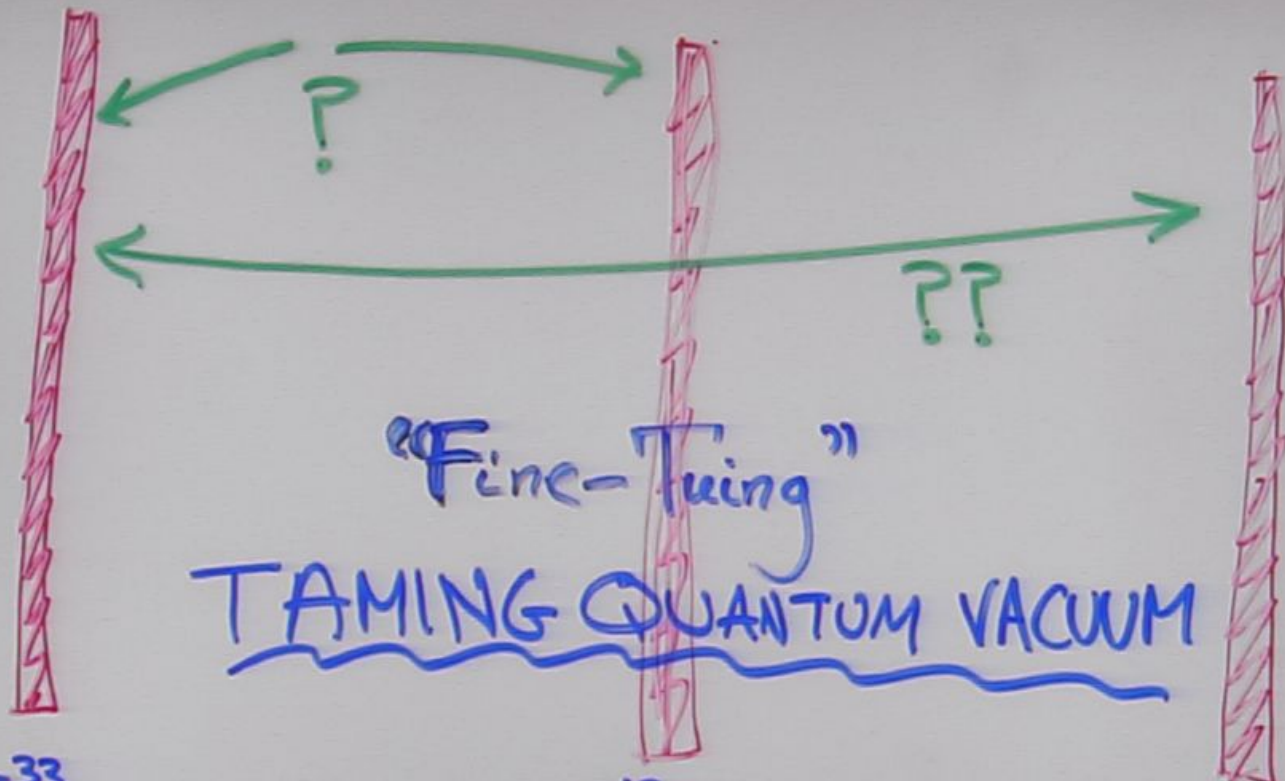


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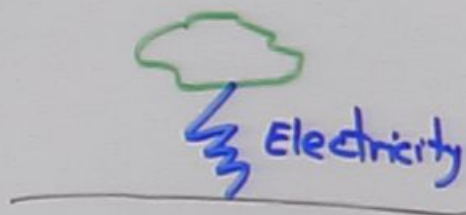
- How did we get here?
- Where might we go?
- What could the L.H.C. teach us?

Unification



moon
same grav!

Earth



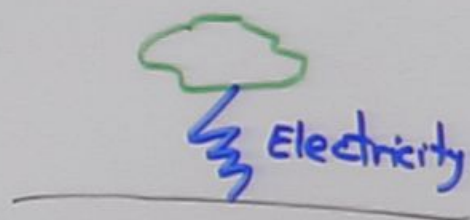
different aspects of same
thing!

Unification



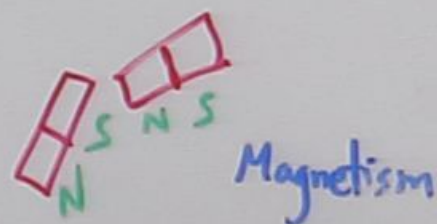
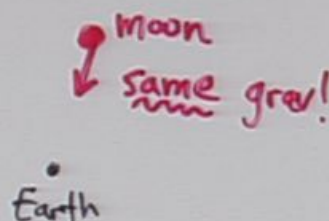
moon
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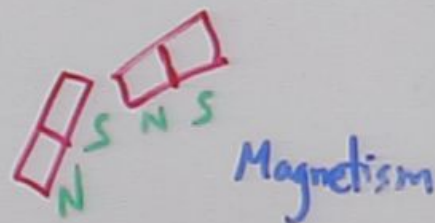
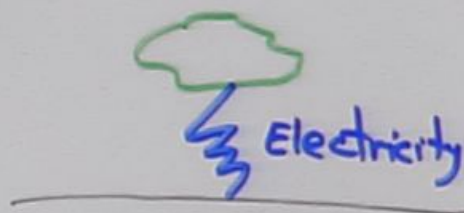
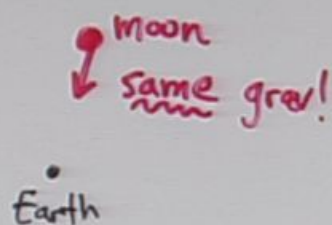
different aspects of same
thing!

Unification



different aspects of same

Unification



different aspects of same
thing!

1900 - 1930 brought more
profound insights:

Special + General Relativity

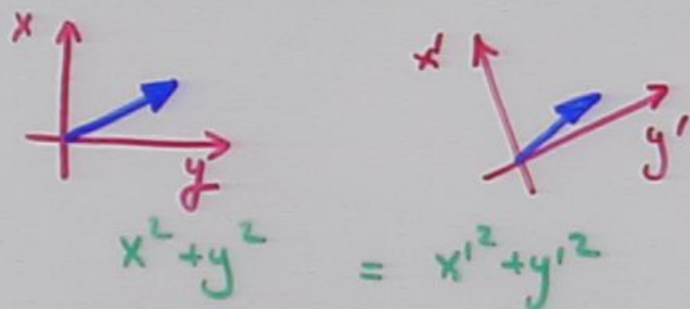
and the even more
radical

Quantum Mechanics

S. R.

Space + Time Unified

... Just as spatial directions can be rotated into each other ...

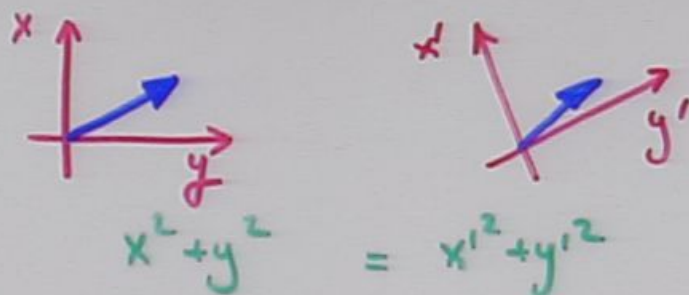


... So can time + space be "rotated" into each other

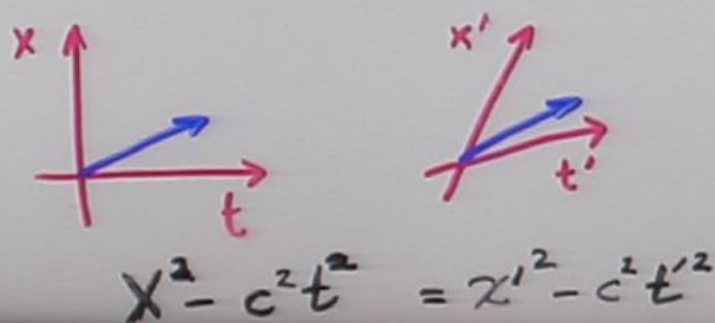


Space + time Unified

... Just as spatial directions can be rotated into each other ...



... So can time + space be "rotated" into each other

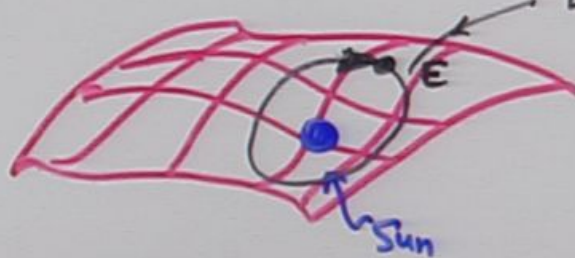


Energy + Mass Unified

$$E = M c^2$$

G.R.

Earth follows "shortest" path!



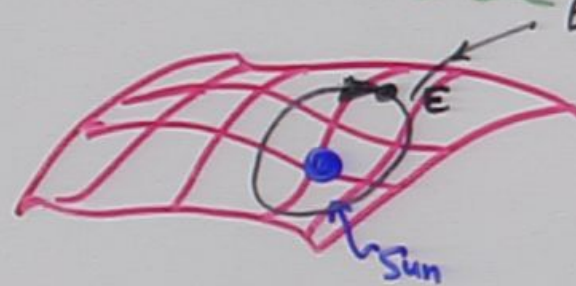
Spacetime
becomes curved,
= gravity



Energy + Mass Unified

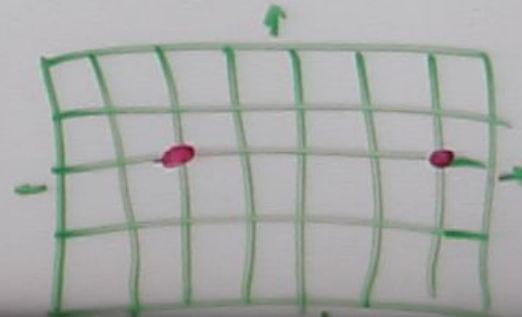
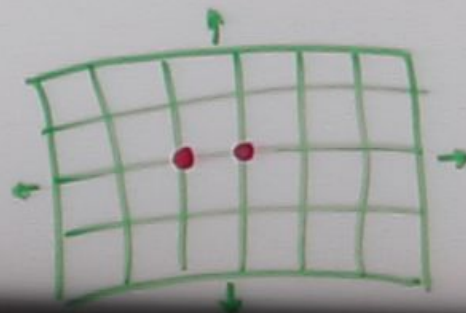
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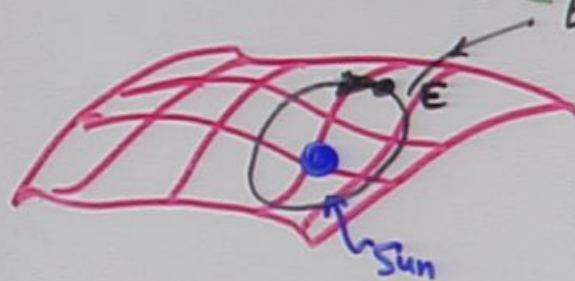
Spacetime
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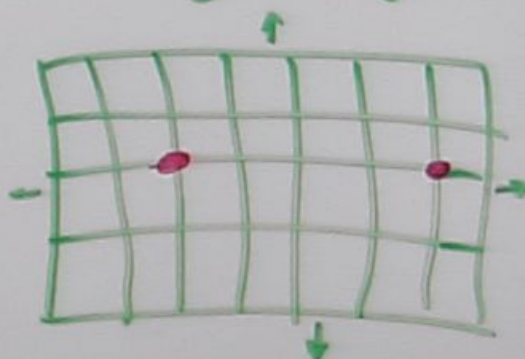
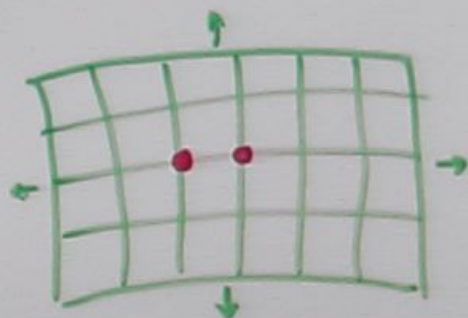
$$E = M c^2$$

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Spacetime
becomes curved,
= gravity



Expanding Universe

Quantum Mechanics

Waves $\leftrightarrow$ Particles

In fact no waves, but

Quantum Particles

Sometimes
behave as
classical
waves

Failure of
Classical Determinism

Sometimes
like
classical
particles

Uncertainty Principles

$\Delta x \Delta p \geq \hbar$

$\rightarrow \Delta p$

Quantum Mechanics

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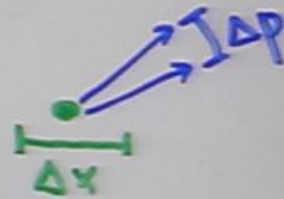
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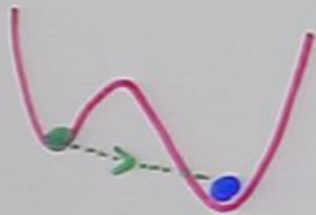
$$\Delta X \Delta p \sim h$$

$$\Delta E \Delta t \sim h$$

Planck's Constant



- Allows bizarre new phenomena
e.g. "tunneling"



[Basis for much
of our technology
today!!!!]

- Ironically, uncertainty $\Rightarrow$
stability of atoms + matter:



e^- can't
"fall" into
nucleus
due to
uncert. principle!

Synthesis of Special Rel.

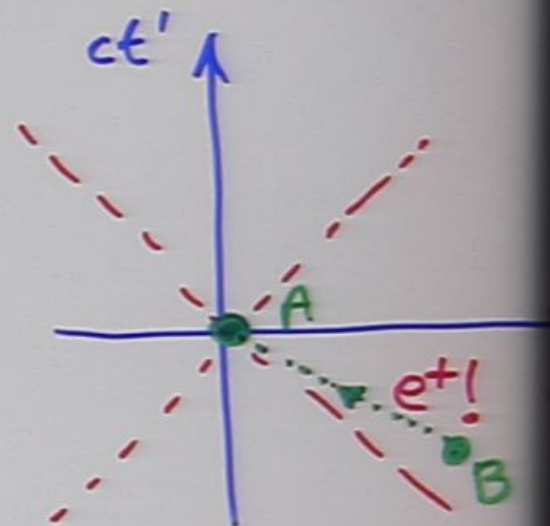
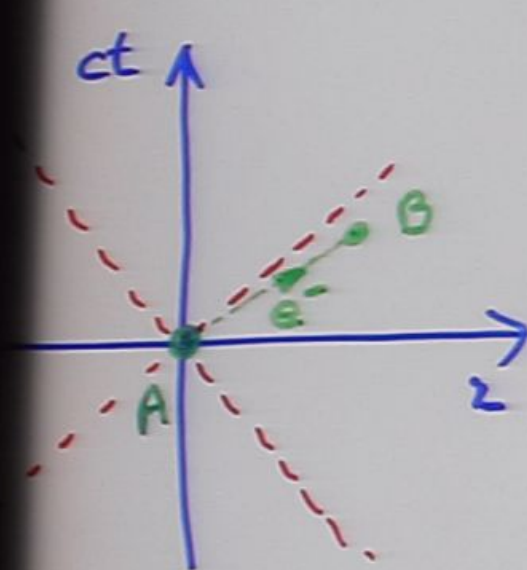
+ Quantum Mechanics

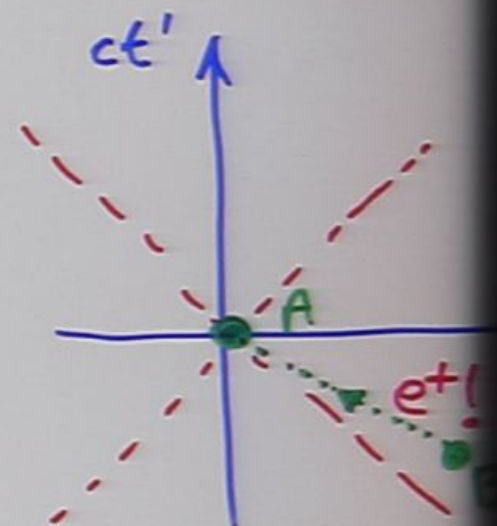
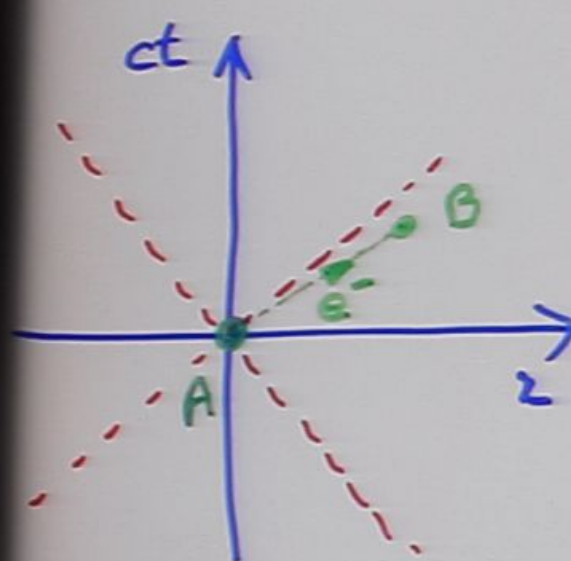
= "Quantum Field Theory"

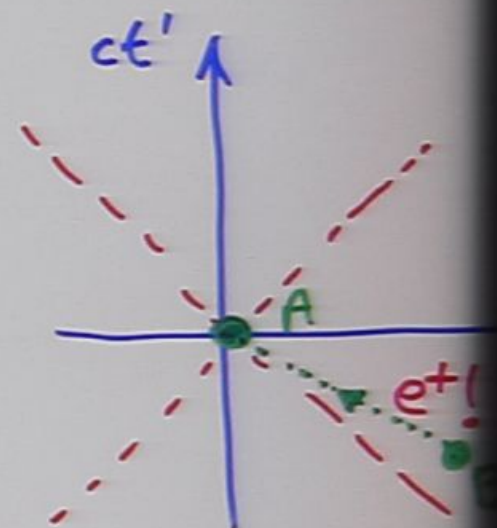
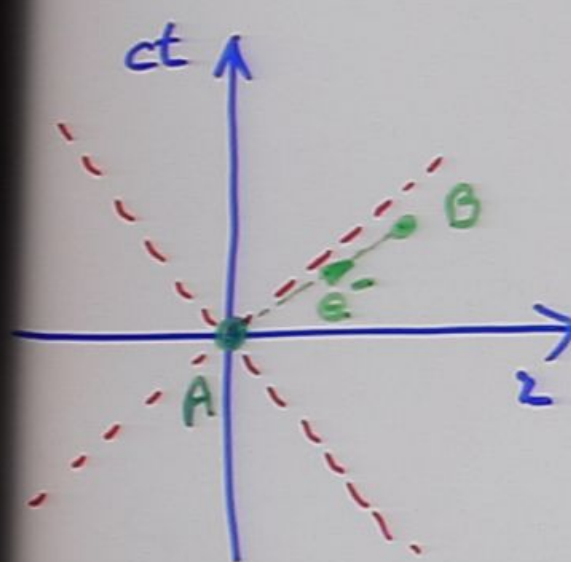
↳ Forces + predicts the
existence of antiparticles!

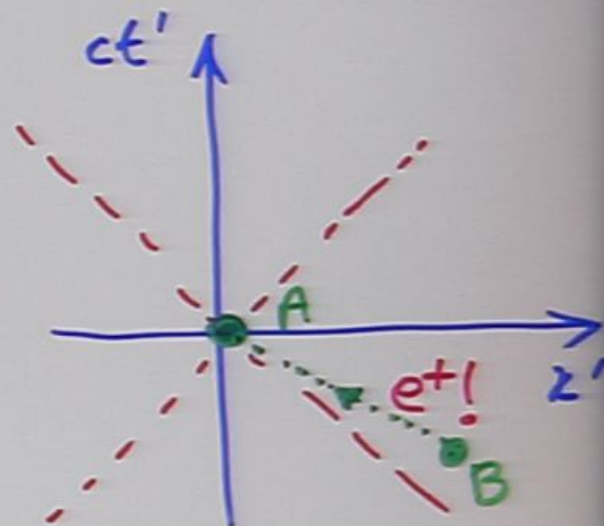
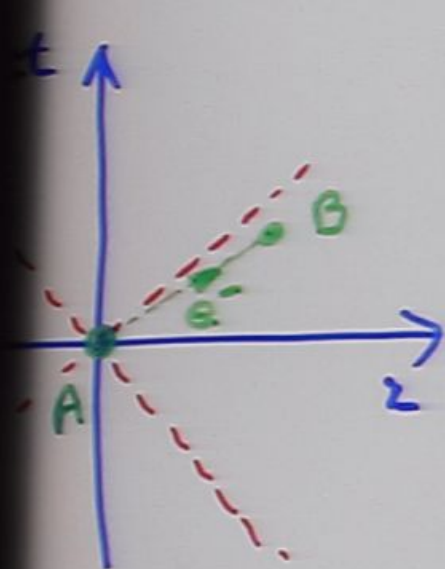
$e^- \rightarrow e^+$
 $p^+ \rightarrow p^-$

} Amazing: Unif.
of Space-time
+ QM doubled
the world!

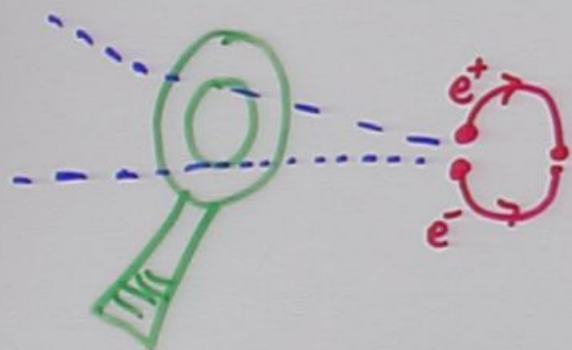








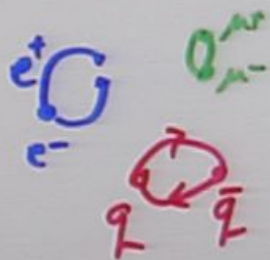
Fundamental Change to notion of "vacuum"



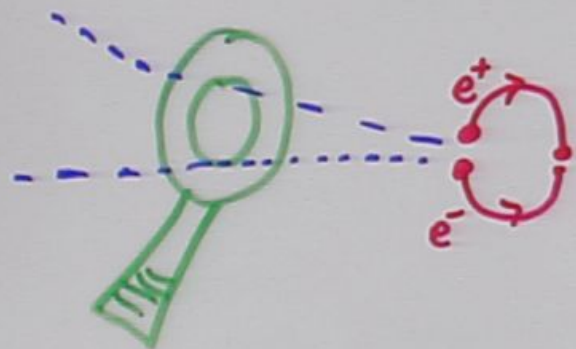
Resolving
 Δt needs ; if
 $\Delta E \sim \hbar / \Delta t$ $\Delta E > 2m_e c^2$
 "see" $e^+ e^-$ pair.

GR made spacetime
dynamical ;

QM + SR make
vacuum dynamical



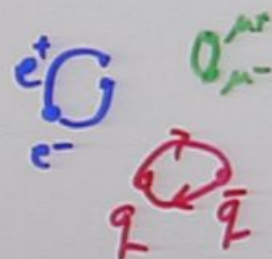
Fundamental Change to notion of "vacuum"



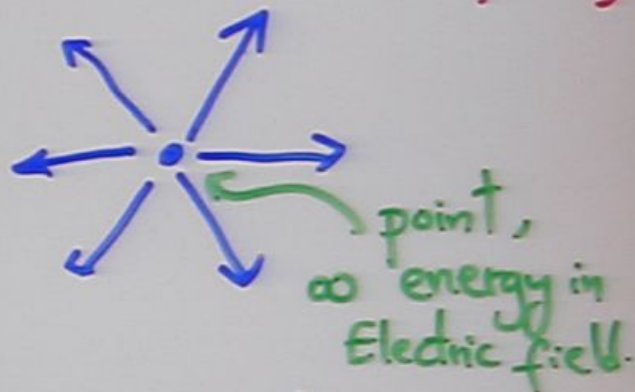
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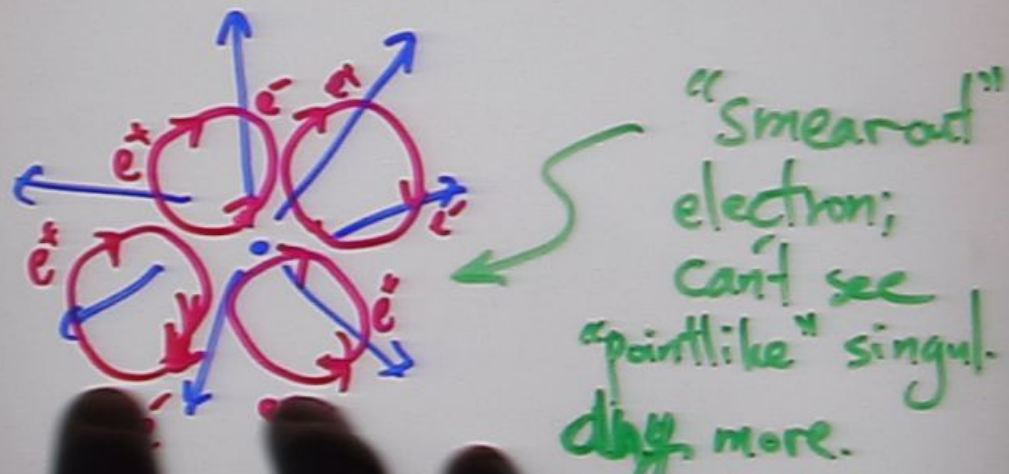
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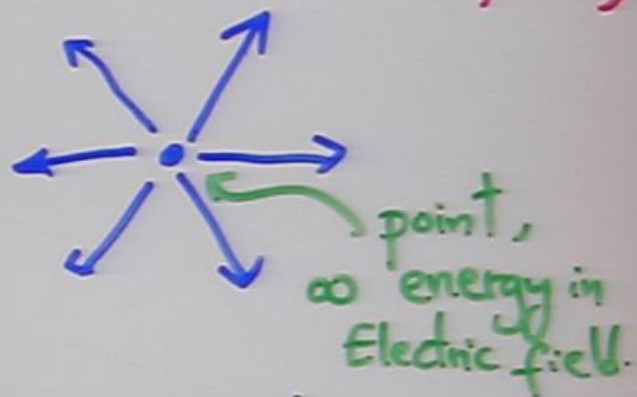
• Vacuum fluctuations solved
an old conundrum of classical
physics: "why isn't electron infinitely
heavy?"



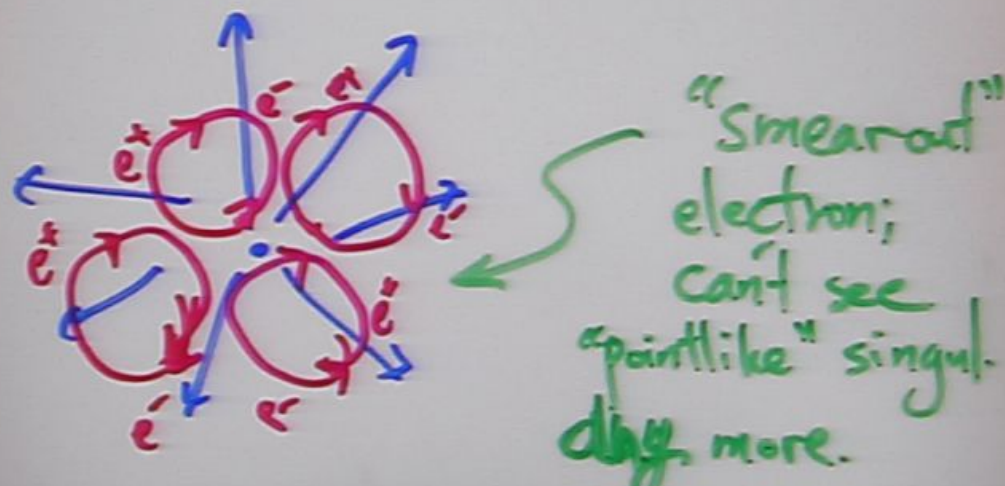
Antimatter to the rescue!



• Vacuum fluctuations solved
an old conundrum of classical
physics: "why isn't electron infinitely
heavy?"



Antimatter to the rescue!



These developments culminated
in the 1970's - into
a theory known as the

"Standard Model" of all
interactions. Spectacularly
successful at describing everything
at distances $\gtrsim 10^{-16}$ cm.

NO EXPERIMENT contradicts
it - even @ precisions approaching
 $\frac{1}{1000}$ (hundred measurement) and even 10^{-12}

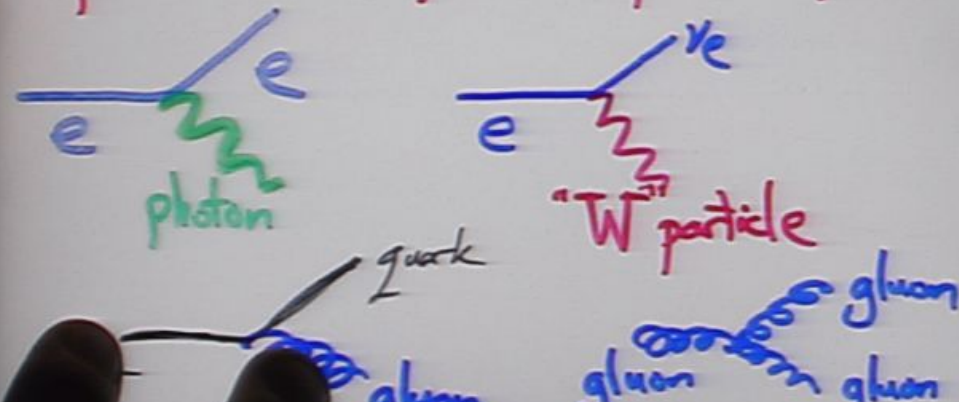


$$g_e^{\text{expt}} = 2.00231930437 \dots$$
$$\pm .000000000008$$

$$g_e^{\text{theory}} = 2.00231930431 \dots$$
$$\pm .000000000004$$

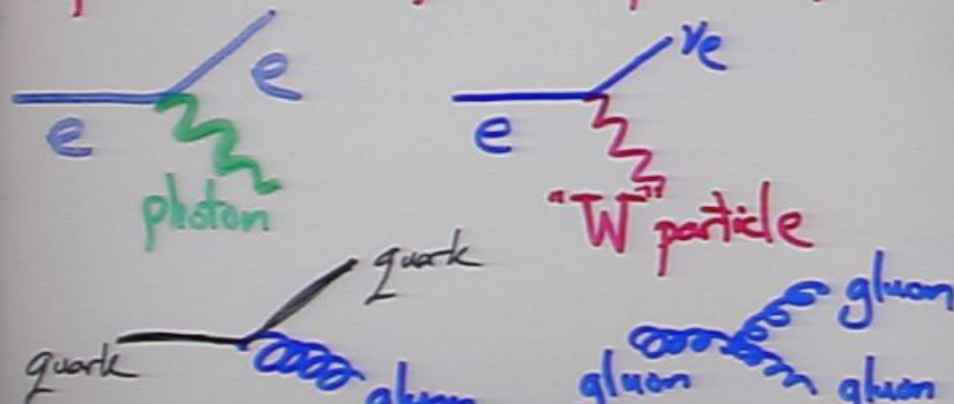
The huge apparent disparity
between electromagnetism,
strong + weak interactions is
a long-distance illusion:

around 10^{-16} cm, they are very
similar - Standard Model gives
unified description of all of them:

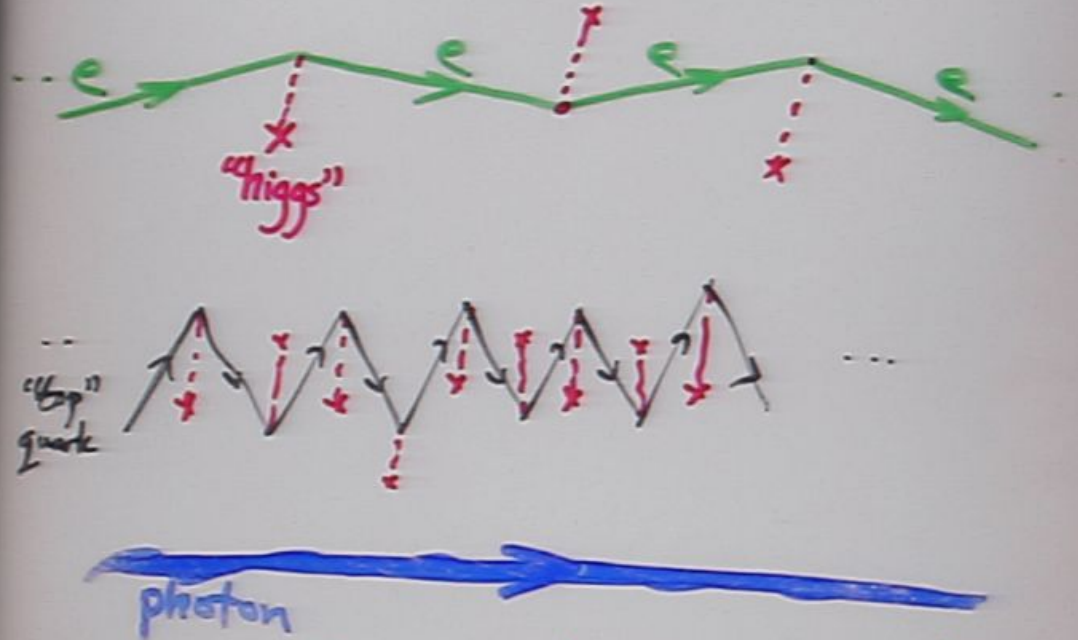


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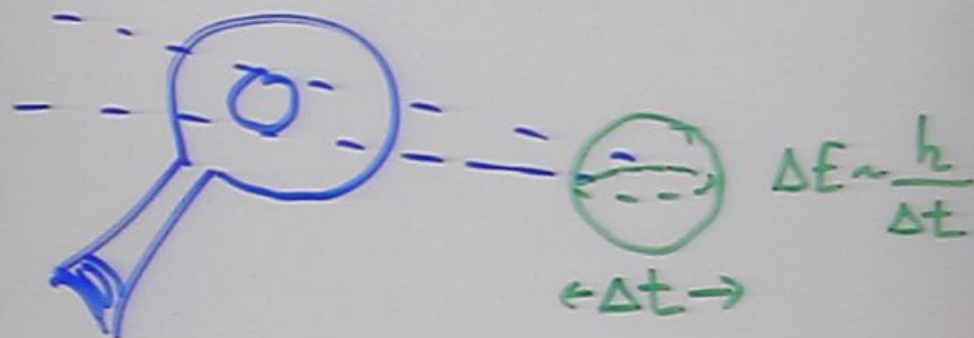
Origin of Mass



Typical length scale between int
 $\sim 10^{-17}$ cm $\Rightarrow$ L.H.C. is
guaranteed to excite
Higgs "particle". Evidence
by 2010

So What
are
the Crises?

Emergent Spacetime



Black Hole if $\frac{G \left(\frac{\Delta E}{c^2} \right)}{(c \Delta t)} \sim 1$

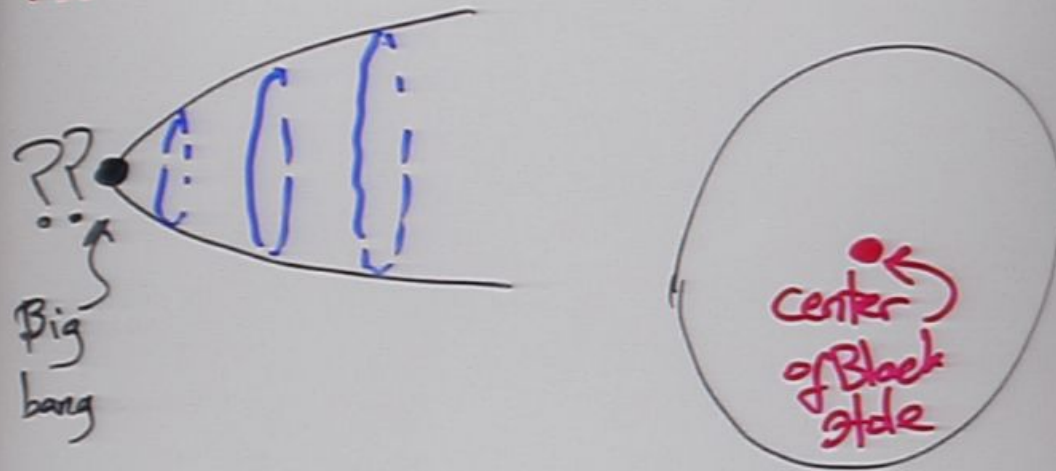
$$\Delta t \sim t_{pl} \sim 10^{-43} \text{ s}$$

$$\Delta x \sim l_{pl} \sim 10^{-33} \text{ cm}$$

SPACE-TIME DOOMED

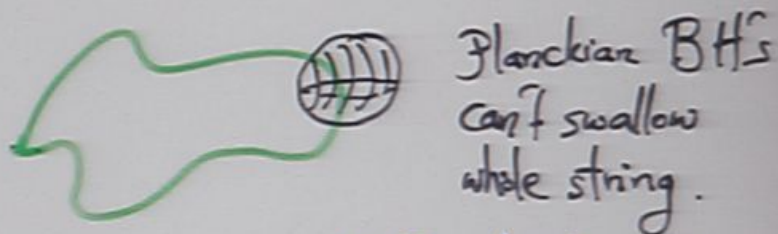
These issues also become important

...

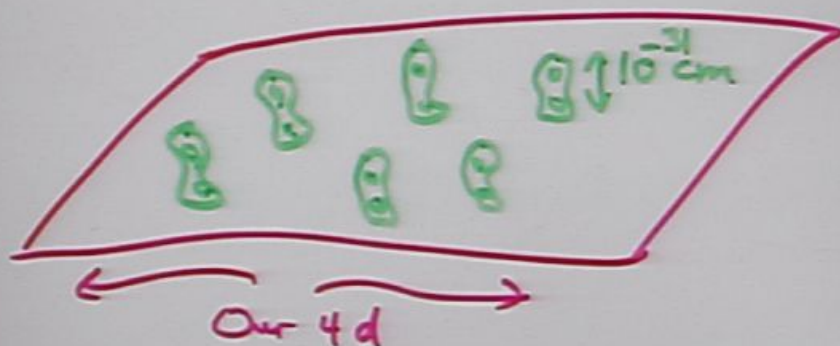


Our theories simply
break down when gravity
+ QM both become important.

String theory pre '95



10 dimensions $\rightarrow$ 6 "curled up"
to 4:



Strings post '95

- Not a theory of strings!



- Strings + extra dimensions can have any size.
- Particle $\leftrightarrow$ String unification
(best understanding of String theory is in terms of a particle theory!) via..

Strings post '95

- Not a theory of strings!



- Strings + extra dimensions can have any size.
- Particle $\longleftrightarrow$ String unification
(best understanding of String theory is in terms of a particle theory!) via..

A more disturbing realization:

string theory is "unique": no adjustable parameters. BUT, it has zillions of solutions.

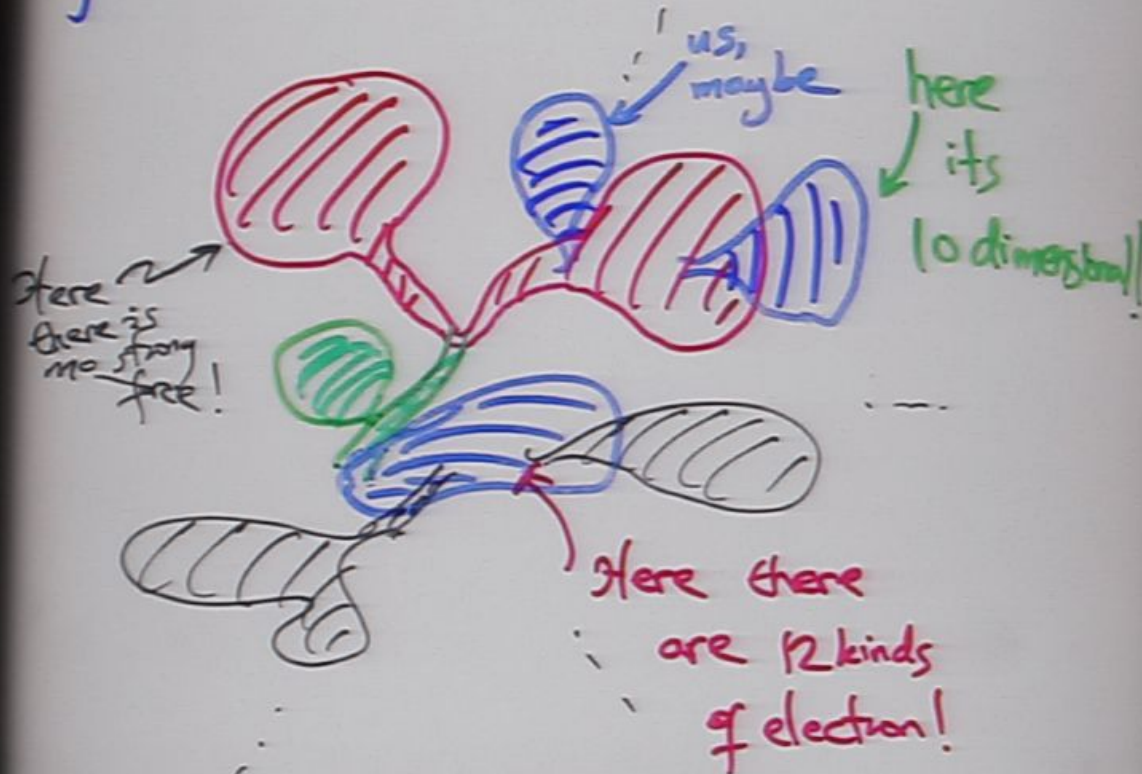
pre '95: zillions ~ millions.

post '95: zillions ~ 10^{1000} 's !

All part of same theory,
but different looking at long
distances. "String Landscape".

CONTROVERSIAL SUBJECT.

→ The Universe on enormously large scales is an infinite "fractal":



• How is our vacuum chosen?

[No sense in asking what
"fraction" is one or other:
 $\infty/\infty = \text{anything!}$]

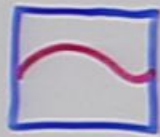
• We are clearly missing
something BIG here:
understanding QM + Cosmology
crucial to make progress.

EMERGENT TIME ? Active
Area of
Current
Research

EXPERIMENTAL
TESTS/
HELP?

Taming the Vacuum

Even vacuum has energy!
[Again: uncertainty principle]



bigger fluct
at smaller
distances

Estimate:

$$\Delta \sim \frac{\text{Energy}}{\text{Volume}} \sim \left(\frac{\text{Planck Energy}}{\text{Planck Vol.}} \right)$$

But energy curves spacetime!
curvature $\sim 10^{-33} \text{ cm!}$

Universe would double in size every
 10^{-43} s!

In fact, biggest experimental
discovery of last 20 yrs - the
universe is accelerating, but
doubles in size every 10^{10} yrs!

$$\Delta_{\text{observed}} \sim 10^{-120} \Delta_{\text{estimate}}$$

Biggest error in history of
physics.

"Why is Universe Big + Flat???"

What we do:

"Fine-tuning"

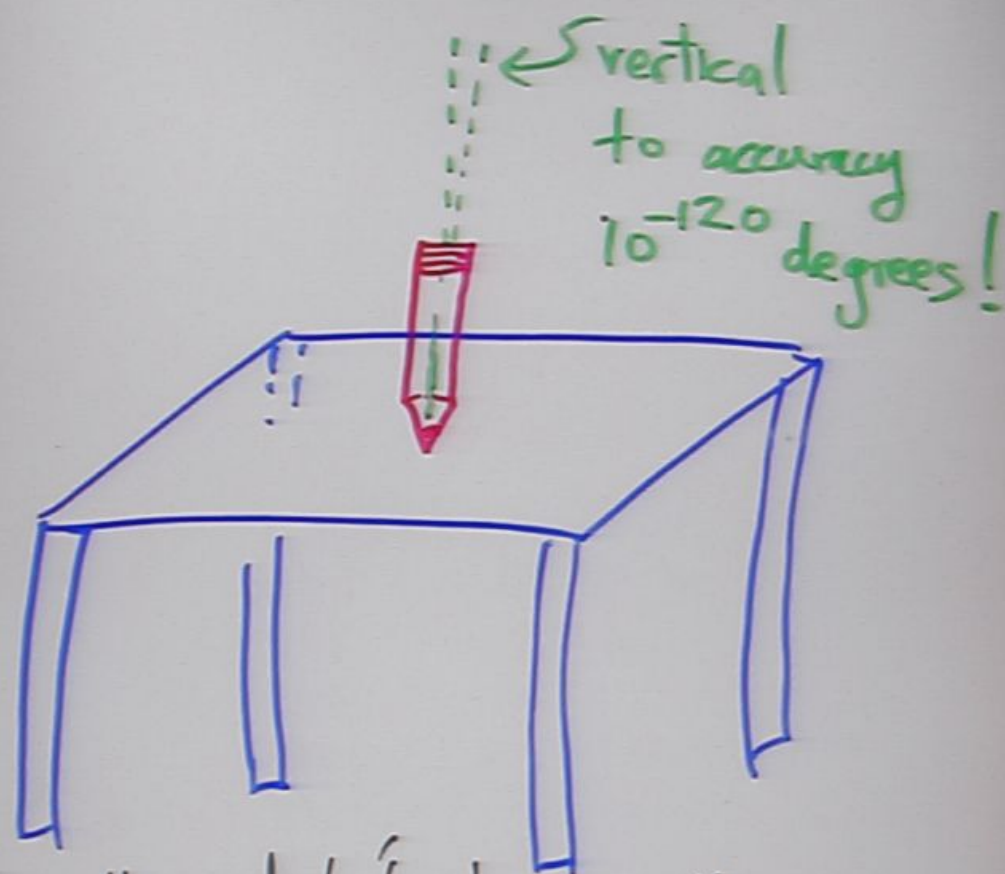
$$\Lambda_{\text{obs}} = \Lambda_{\text{classical}} + \Lambda_{\text{Quantum}}$$

-2.649370...52..

2.649378... "4 more 53..

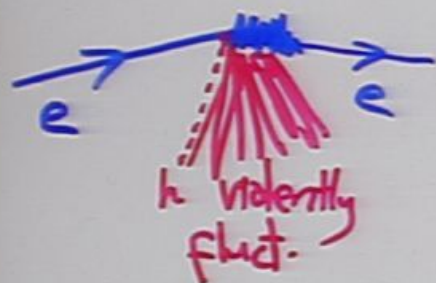
↔
Differ only in
121st decimal
place!

LUDICROUS



If this didn't happen, though,
we wouldn't exist. NOTHING
WOULD. **EMPTY UNIVERSE.**

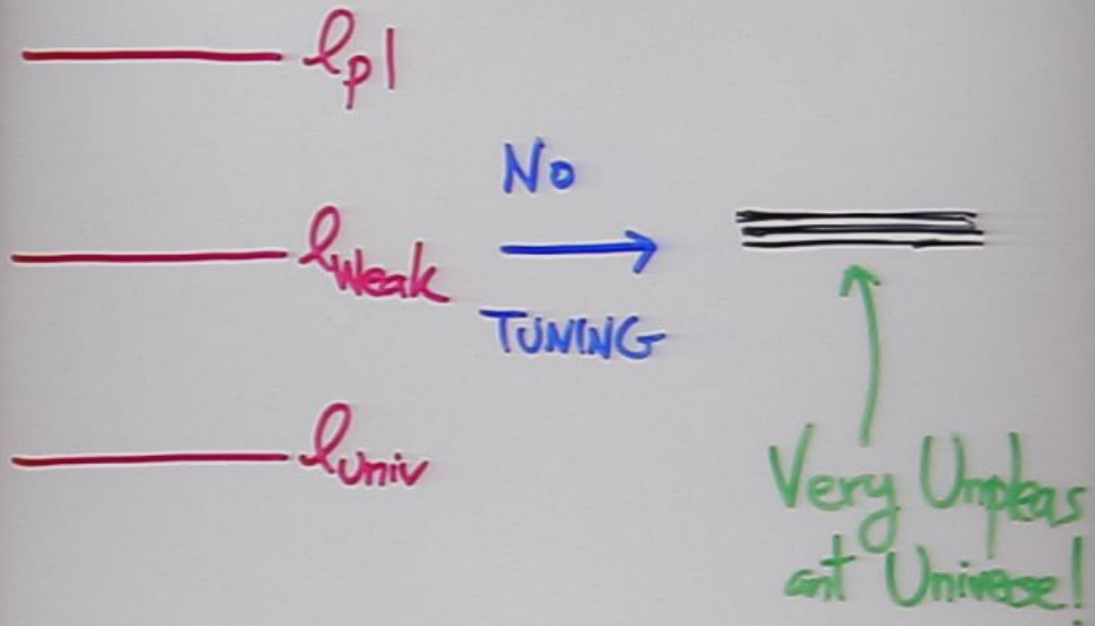
There is a virtually identical problem with the origin of mass in Standard Model!



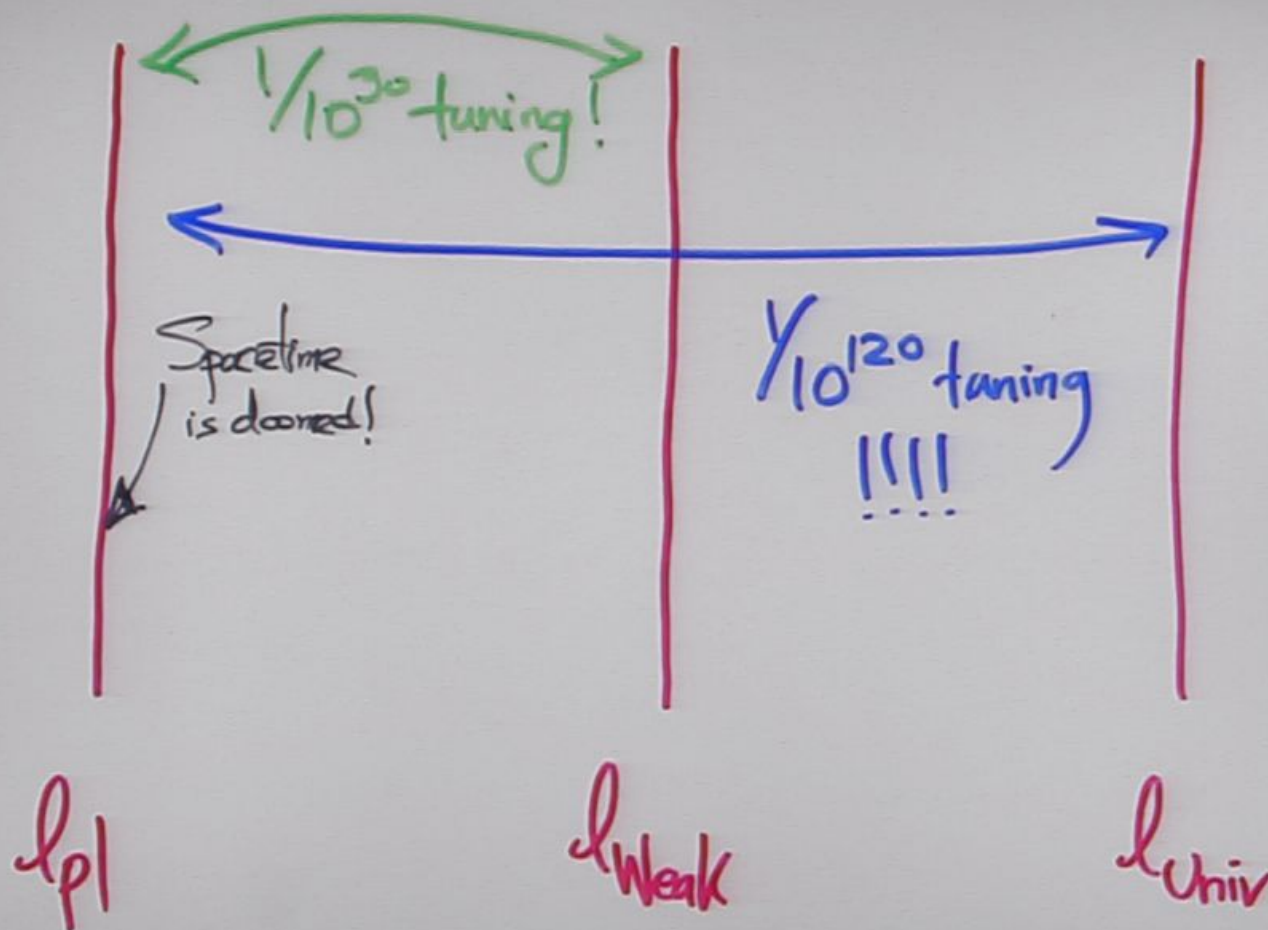
Estimate for distance between collisions is 10^{-33} cm!

Observed 10^{-17} cm value need a "tuning" of 1 in 10^{30} !
[If this didn't happen we wouldn't exist].

"Why is Gravity Weak"?



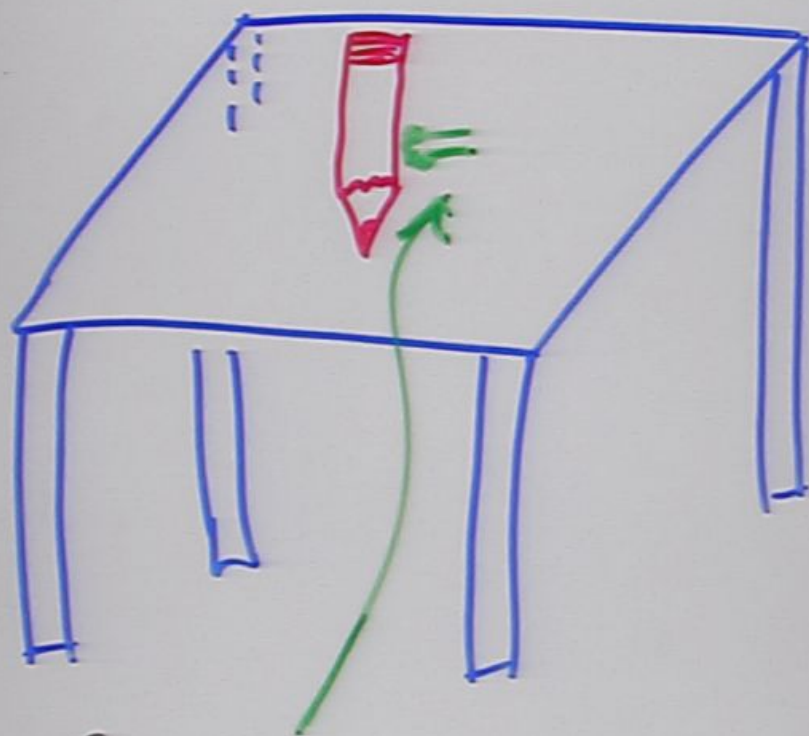
What Controls the
Violent Fluctuations
of the Vacuum?



The L.H.C. will ~~definitely~~
shed light on one of these
questions; if we're very lucky, it
might illuminate ~~all~~ of them.

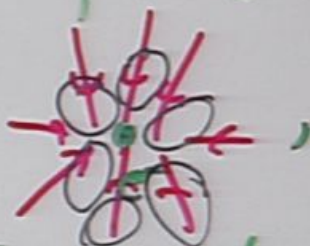
Recall L.H.C. will definitely
probe the "Higgs" - if something
tames the Higgs's violent
vacuum fluctuations - L.H.C.
must see it, revealing
a new principle of Nature.

What might it be?

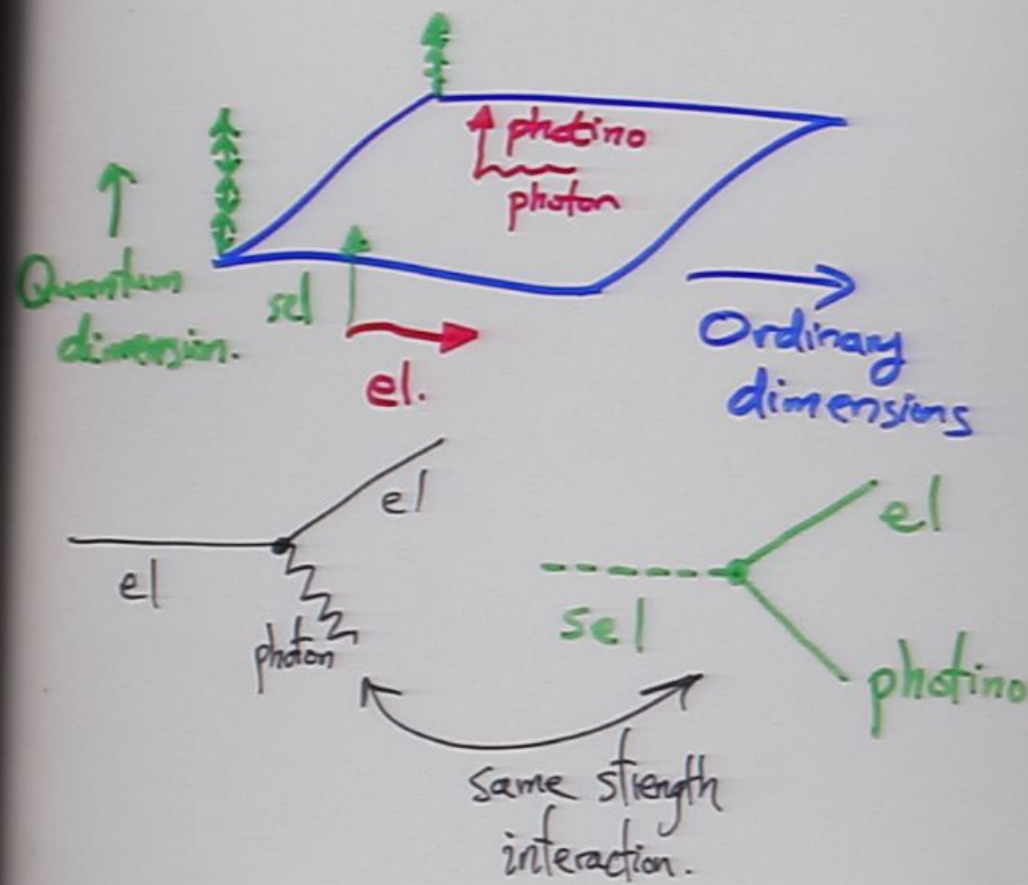


New Extensions of Spacetime
can tame these fluctuations. Again -
must be seen @ L.H.C.

• Most theoretically appealing
idea: just as QM + SR
introduced antiparticles and
solved classical infinite electron
energy problem



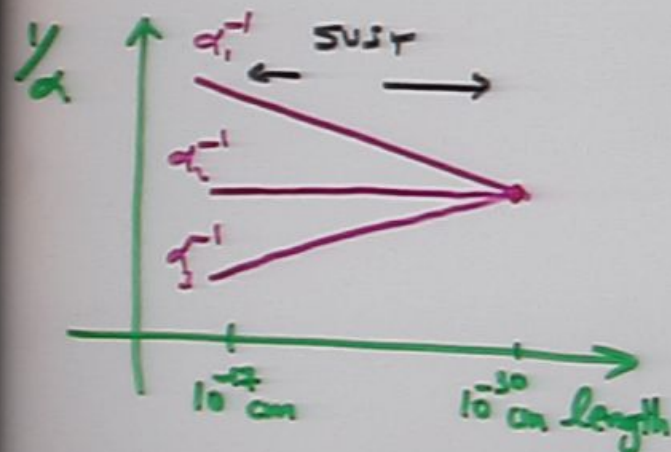
an extension of relativity,
incorporating quantum dimensions
+ known as Supersymmetry,
further doubles the world
+ amazingly solves Higgs problem!
If true: other half of world waiting at LHC



$\Rightarrow$ Superpartners must show up at the TeV scale!

e	$\longleftrightarrow$	$\tilde{e}$	spin 0
γ		$\tilde{\gamma}$	spin $\frac{1}{2}$
W		$\tilde{W}$	"
q		$\tilde{q}$	spin 0

2 Bonuses!



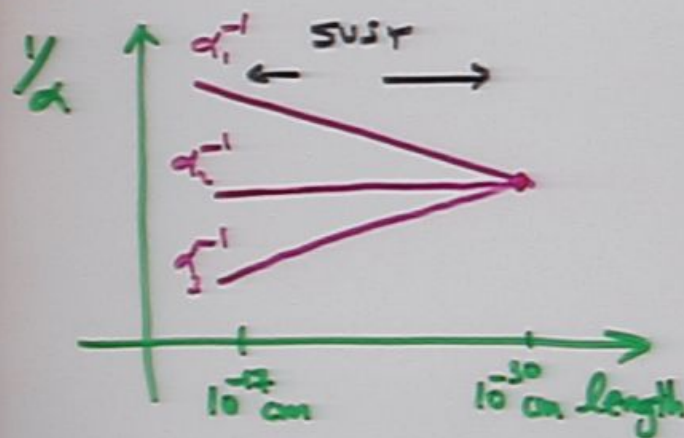
+ DARK MATTER

UNIFICATION!

⇒ Superpartners must
show up at the TeV scale!

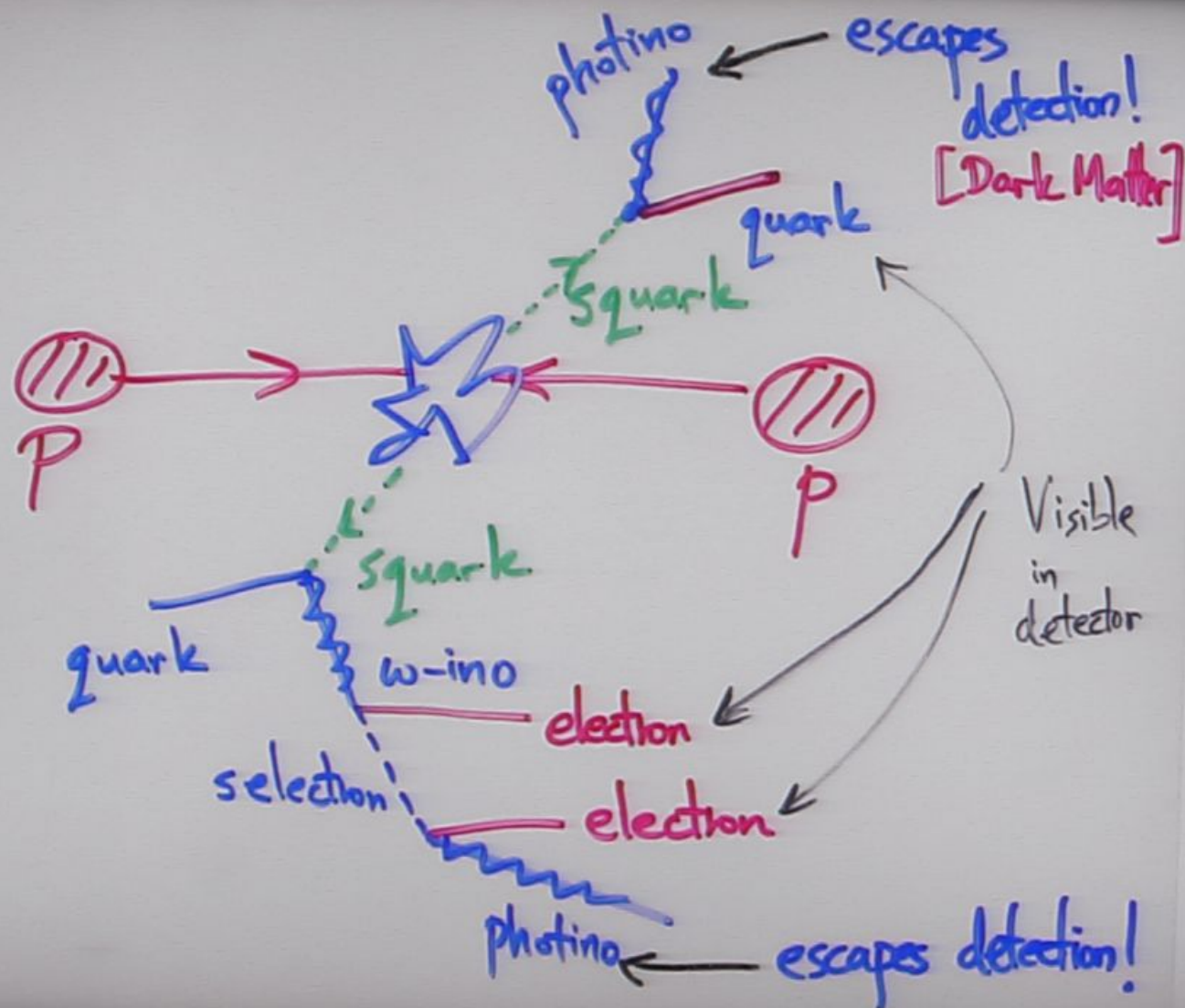
e	$\longleftrightarrow$	$\tilde{e}$	spin 0
γ		$\tilde{\gamma}$	spin $\frac{1}{2}$
W		$\tilde{W}$	"
q		$\tilde{q}$	spin 0

Σ Bonuses!

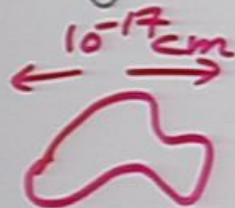


+ DARK
MATTER

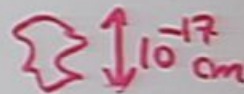
UNIFICATION!



Another possibility: Strings + Quantum Gravity at the L.H.C. (!)



Higgs + everything else.



gravity
lives
everywhere

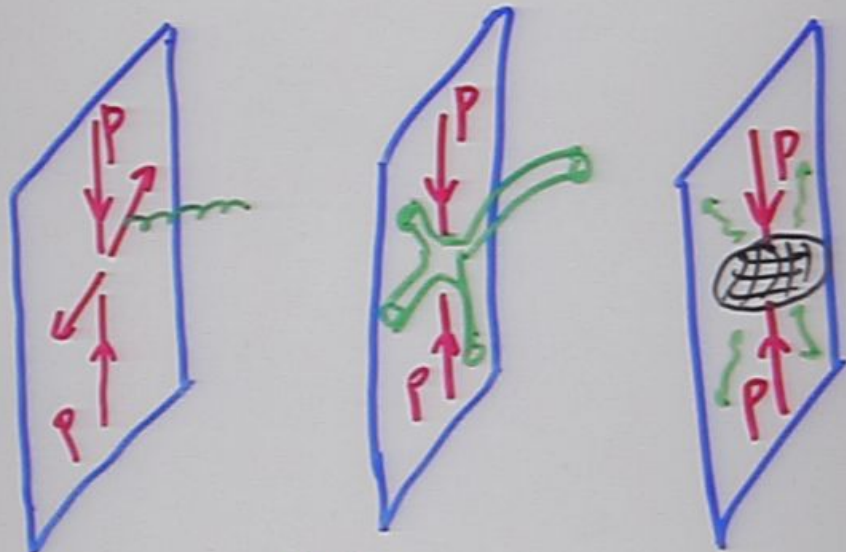
3-d Membrane
floating
in extra dimensions



Extra dim
can also be big:
from 10^{-17} cm to 1 millimeter!

--- If this Scenario
is realized in Nature ---

- L.H.C. is a Quantum Gravity
Machine



losing
energy
into
extra d

Making
Strings

Making
Black Holes

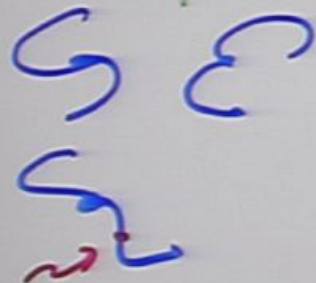
All with distinctive signatures.

Another explanation for
 tunings : enormous diversity
of environments



Just right
 distance!

Not surprising given
 Zillions of Galaxies



we are
 here

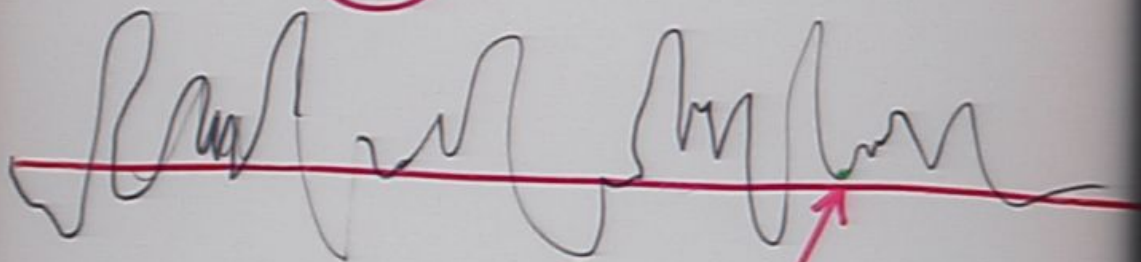
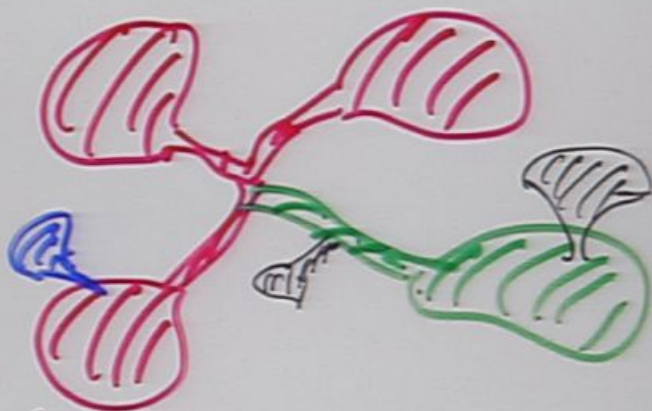


$$\frac{V_{\text{Earth}}}{V_{\text{Univ}}} \approx \frac{1}{10^{60}}!$$

Again obvious -
 we can't live
 anywhere else!

Could we be a tiny part
of a vast multiverse?

More
than
 10^{1000}
worlds!



Univ.
Everywhere
Lethal + EMPTY
except
...

here, accidentally,
 $\Lambda_{\text{classical}}$, Λ_{quantum}
cancel accurately
enough so Univ
L + EMPTY

If this picture is true,
Modern Copernican Revolution -
biggest discovery of our time.

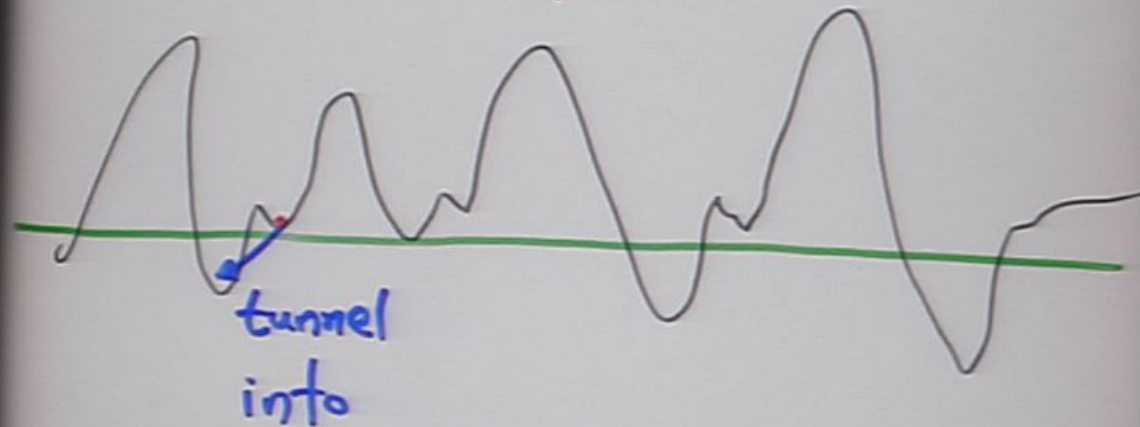
Conceptual problem: can't (yet)
"see" other universes - how
can we know they are there?

• Could the L.H.C. weigh in
on this? **YES!**

• **NOTHING** beyond usual Higgs, or,
in some well-motivated theories

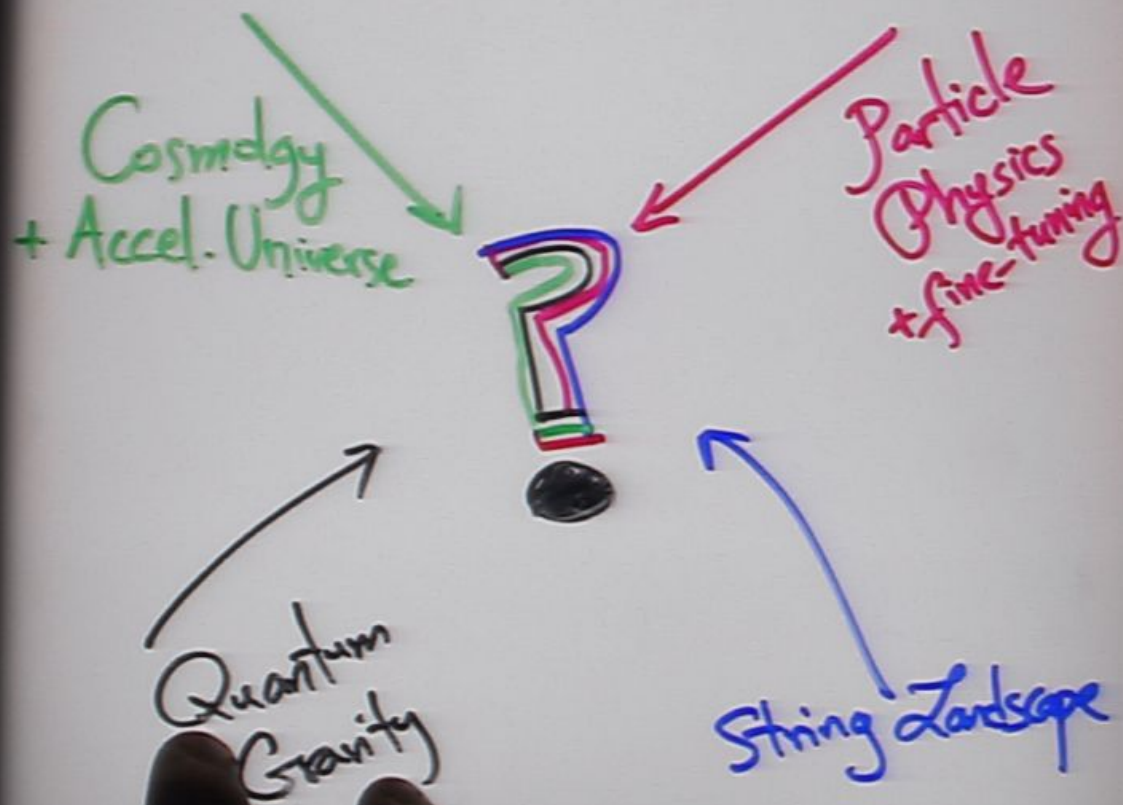
• The detection of peculiarly long-lived
particles

Our "Vacuum" will have
a catastrophic end

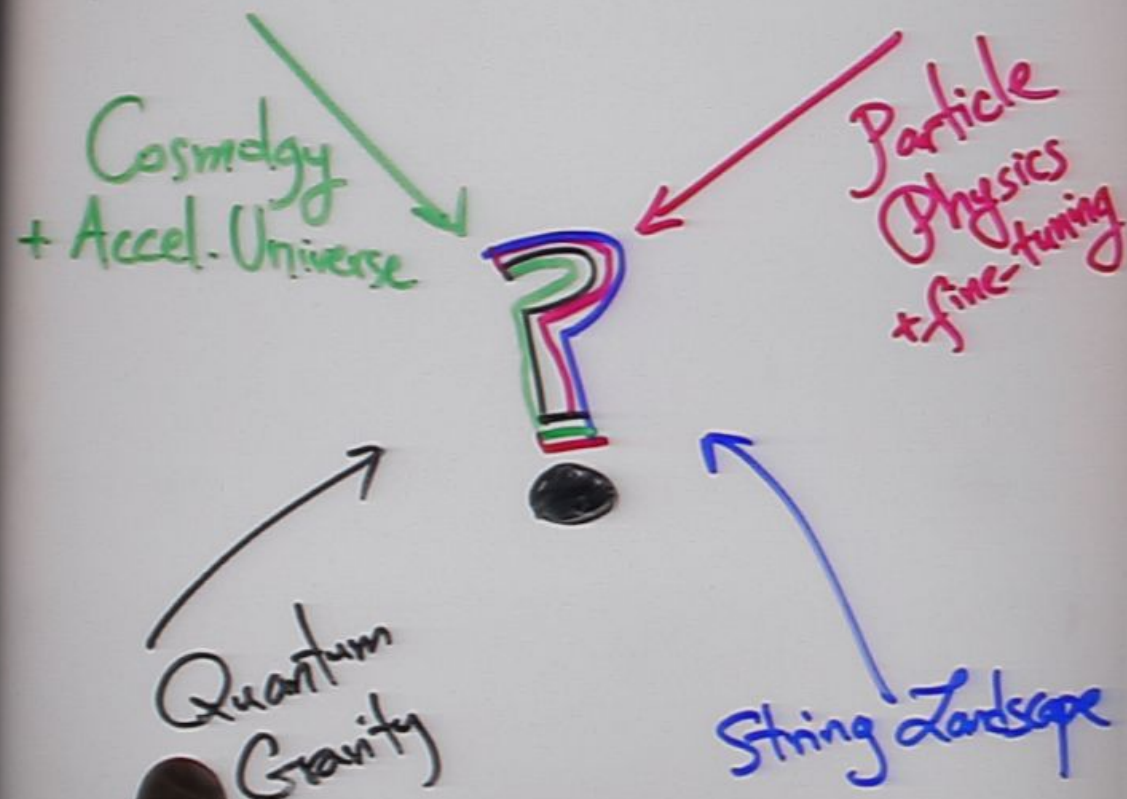


tunnel
into
a BIG CRUNCH
in our future

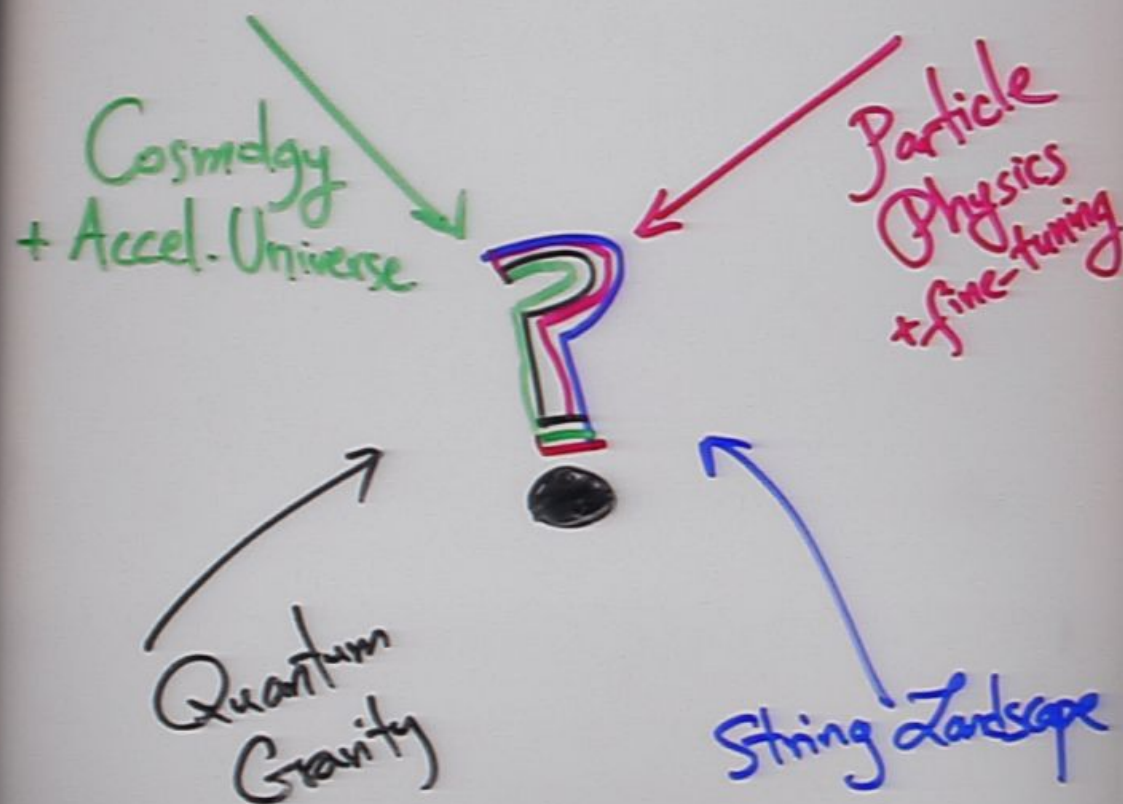
We have seen many modern ideas of theoretical physics, on a collision course with each other + experiments:



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The last time tensions
about fundamental ideas was
so high was the ~~er~~ of
the twin revolutions of
relativity + quantum mechanics.

STAKES ARE HIGH

What will L.H.C
tell us?

New Spacetime?

Quantum Gravity?

Multiverse ??



STAY TUNED

We'll have something
solid to say

by 2010.