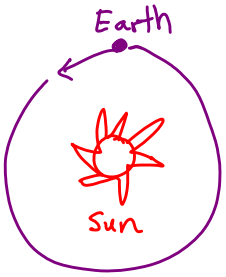
Space-Time, Quantum Mechanics

+

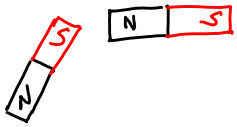
The Large Hadron Collider

4 Basic Interactions

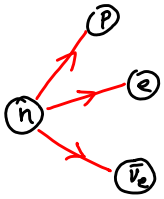
Gravity

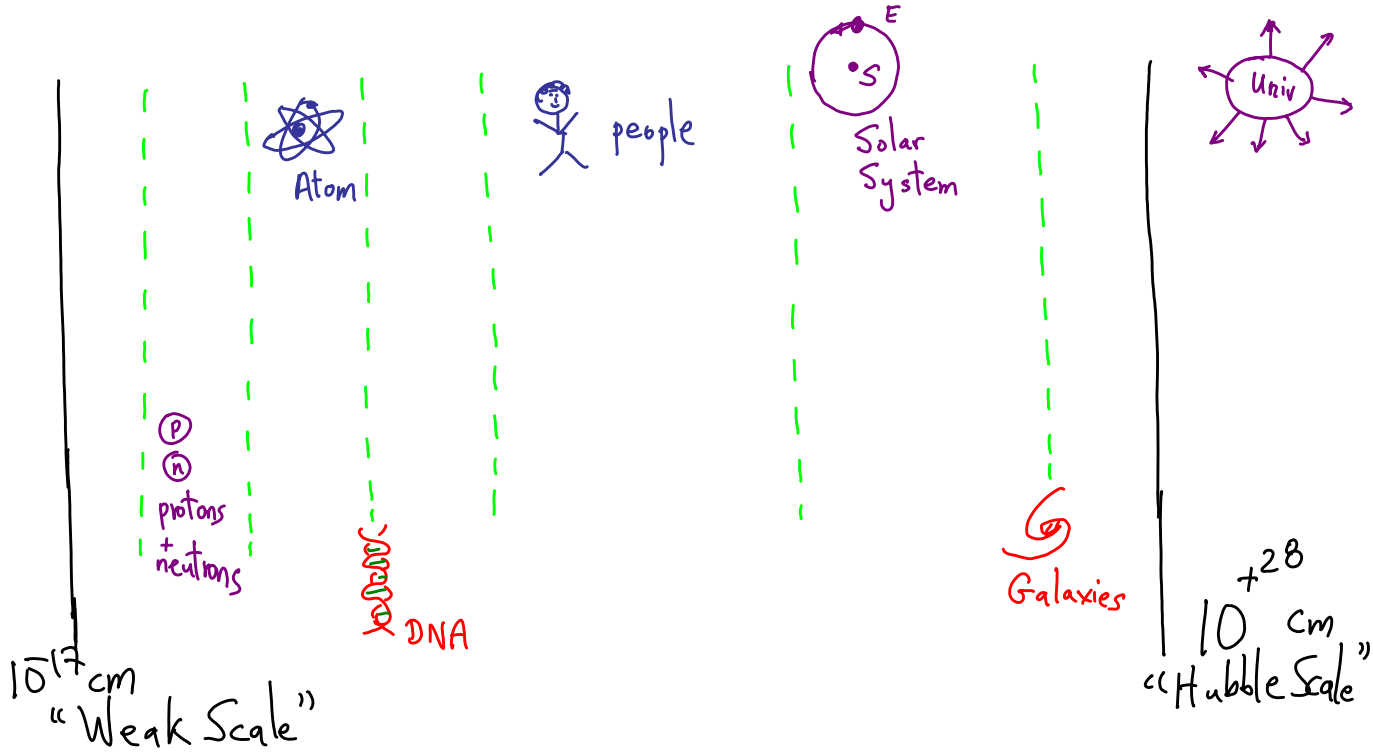


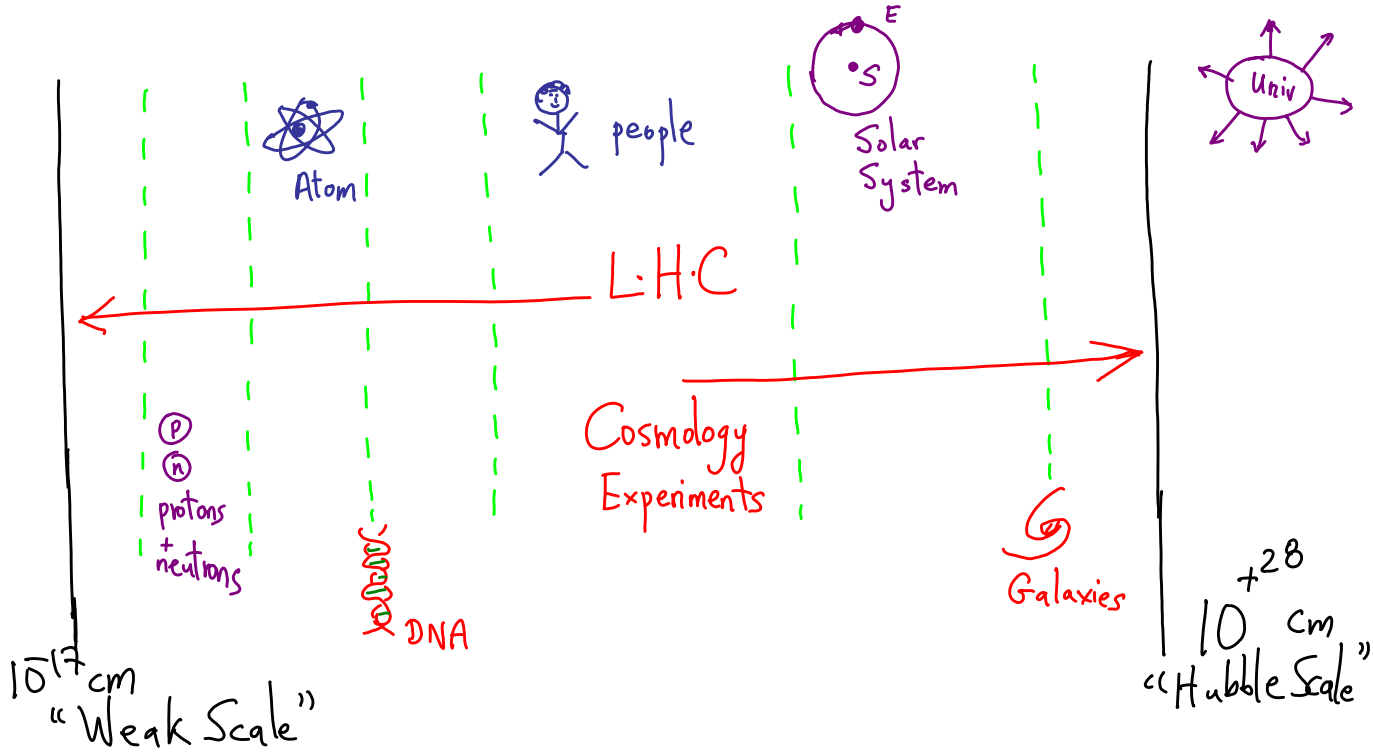
Electromagnetism



Weak + Strong




Atom
people
E
S
Solar System
Univ
p
n
protons + neutrons
DNA
Galaxies
10^{-17} cm
"Weak Scale"
10^{+28} cm
"Hubble Scale"


E
S
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Cosmology Experiments
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Galaxies
10^{-17} cm
"Weak Scale"
10^{+28} cm
"Hubble Scale"

10^{-33} cm

"Planck Length"

10^{-17} cm

"Weak Scale"

10^{+28} cm

"Hubble Scale"

A note on Units

$$\text{time} = \frac{\text{distance}}{c}$$

$$\text{Energy} = \frac{\hbar}{\text{time}}$$

Put $\hbar = c = 1$

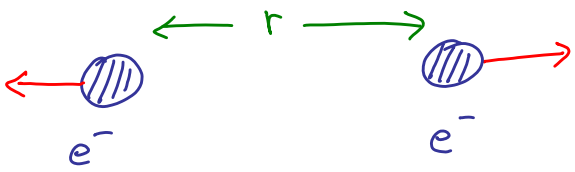
$10^{16}\ \text{GeV}^{-1}$

Mass $\sim 10^{29}$ GeV

Lecture time $\sim 10^{27}\ \text{GeV}^{-1}$

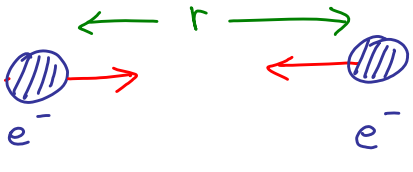
$(m_p c^2) = 1$ GeV

(p) $\updownarrow 10^{-14}$ cm $\sim \text{GeV}^{-1}$



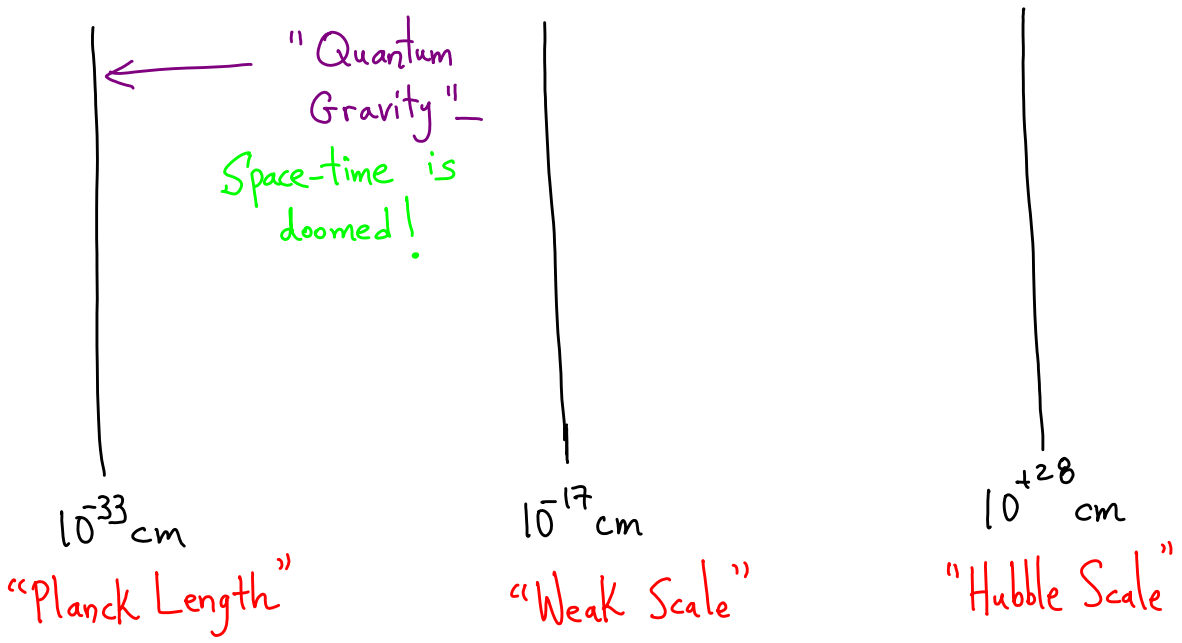
$$E^{electric} \sim \left(\frac{e^2}{4\pi}\right)\frac{1}{r}$$

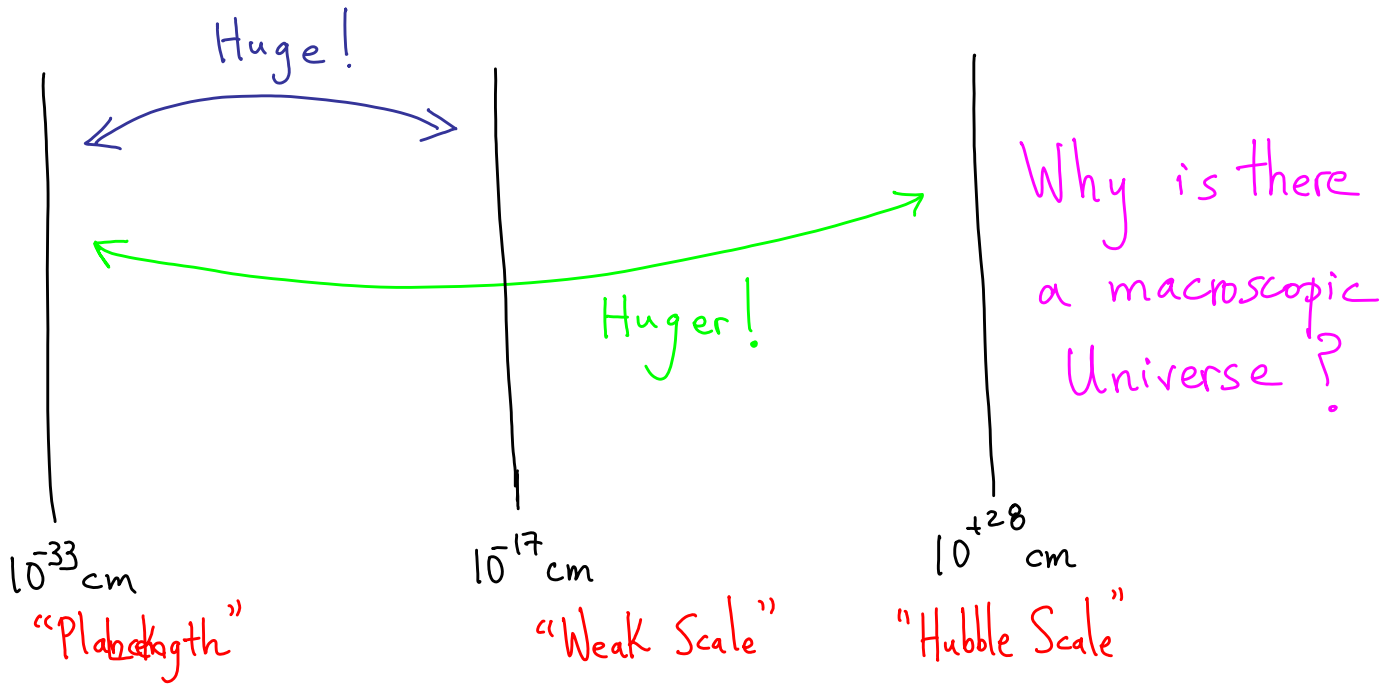
strength $\sim \frac{1}{137}$ (a pure number!)



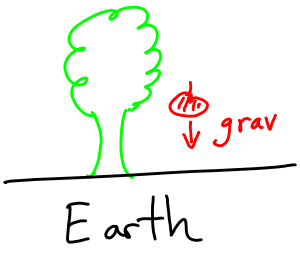
$$E^{grav} \sim -G_N \frac{m_e^2}{r}$$

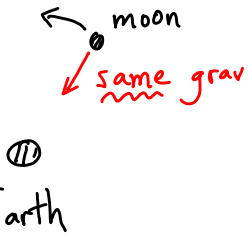
$$\sim (10^{-33}\ cm)^2 \sim (\ell_{Planck})^2$$

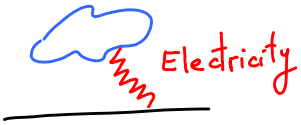

"Quantum Gravity" — Space-time is doomed!
10^{-33} cm
"Planck Length"
10^{-17} cm
"Weak Scale"
10^{+28} cm
"Hubble Scale"


Huge!
Huger!
Why is there a macroscopic Universe?
10^{-33} cm
"Planck length"
10^{-17} cm
"Weak Scale"
10^{+28} cm
"Hubble Scale"

Unification

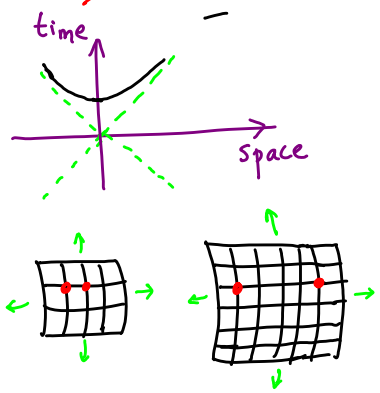






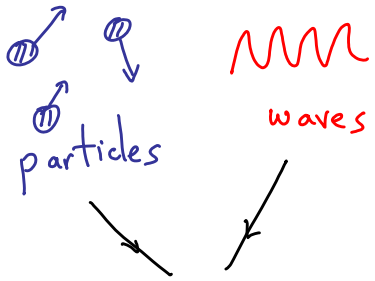
Different Aspects of Same Thing!

Relativity

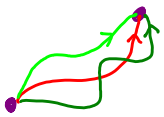


Space – Time

Quantum Mechanics



Quantum Particles



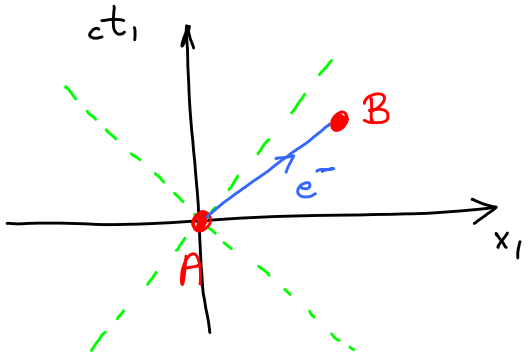
Synthesis of QM + Relativity:

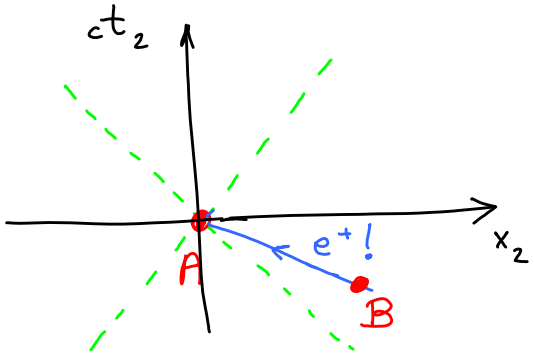
"Quantum Field Theory"

→ Forces existence of anti-particles

- e^- e^+
- p^+ p^-

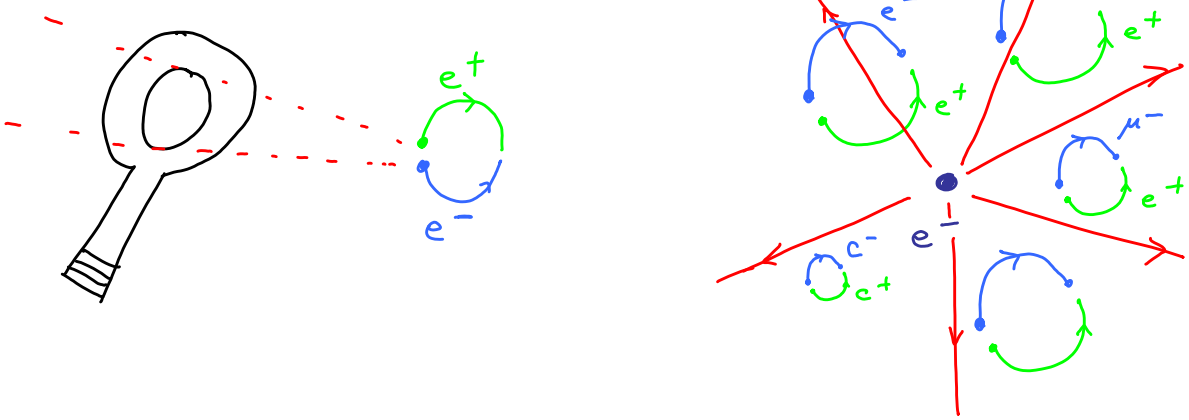
} Amazing: Unification of Space-time + Quantum Mechanics doubled the world!



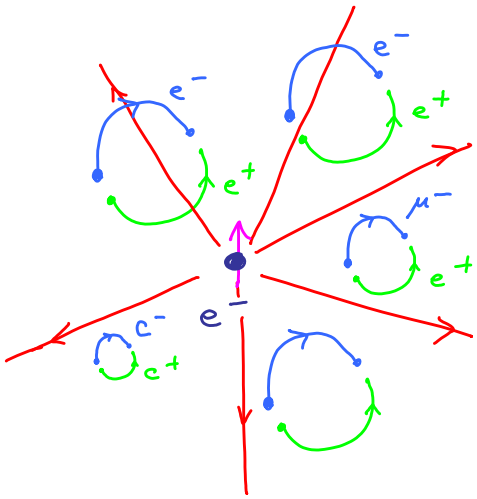


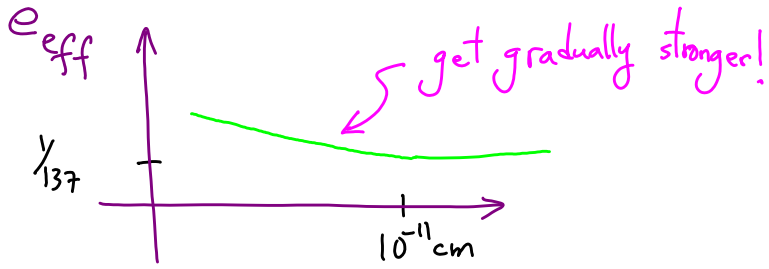
Causality ⟶ Antiparticles

"Vacuum" is Exciting!

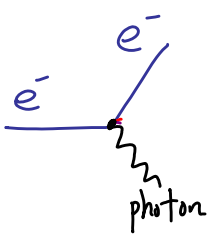


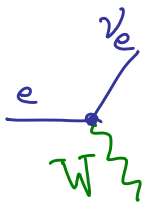
These developments culminated in the 1970's with the invention of a specific Q.F.T describing all known interactions down to at least 10^{-16} cm.... spectacularly successful!

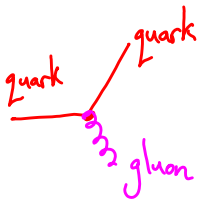


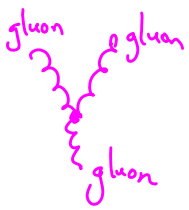


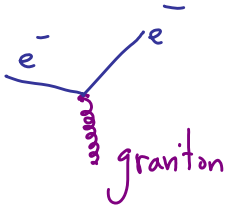
"$\frac{g-2}{2}$" = .00115 9652181 ...

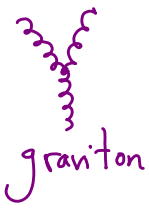

e⁻
e⁻
photon

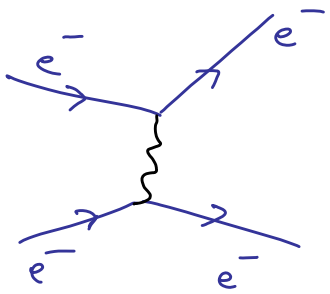

e
νe
W

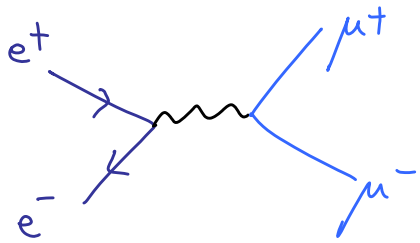

quark
quark
gluon


gluon
gluon
gluon

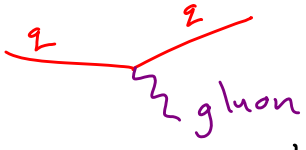

e⁻
e⁻
graviton

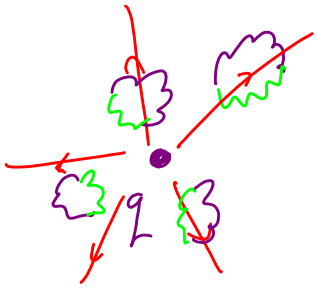

graviton

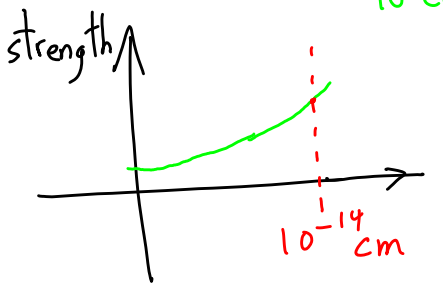

e⁻
e⁻
e⁻
e⁻

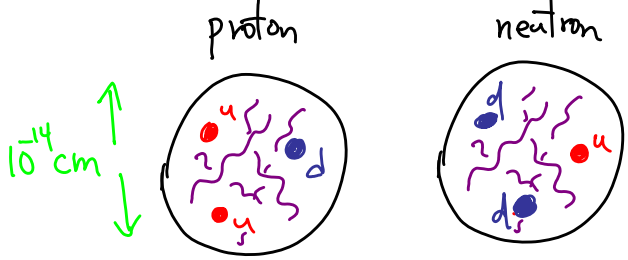

e+
μ+
e⁻
μ⁻

The apparent huge disparity between forces is a long-distance illusion:

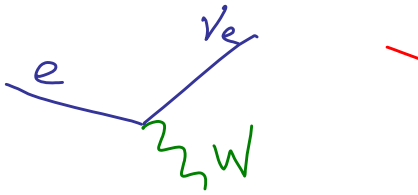


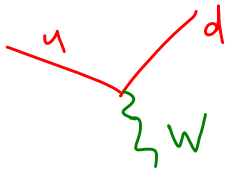


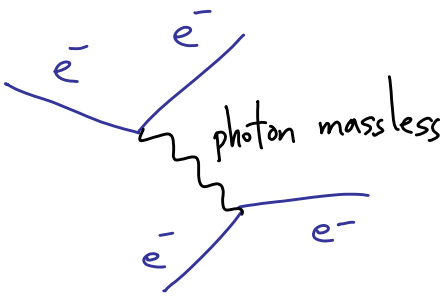




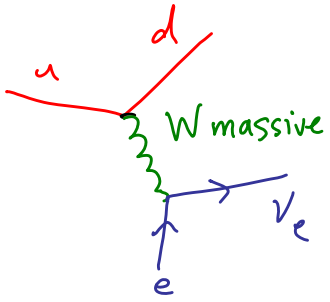
quarks + gluons
"confined"





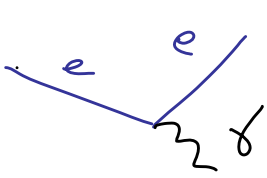


long-range force

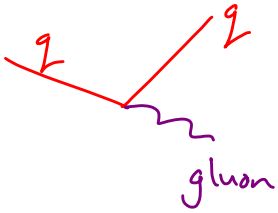


short-range!
($\sim 10^{-16}$ cm)

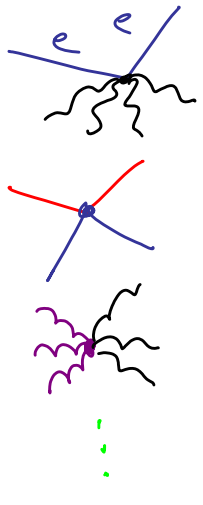
"Effective" Theories



$\sim \frac{1}{137}$



$\sim \frac{1}{10}$



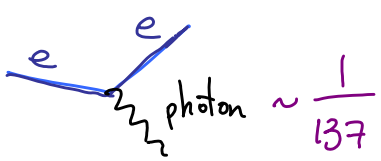
strength ~ (length)$^{1,2,3,\ldots}$

↓

Irrelevant at "long" distances!

The Menu

		Gluons	"W's"	+ Photon"
		$SU(3)_c$	$\times$ $SU(2)_L$	$\times$ $U(1)_Y$
$3\times$	Q	3	2	$+\frac{1}{6}$
	U^c	$\bar{3}$	-	$-\frac{2}{3}$
	D^c	$\bar{3}$	-	$+\frac{1}{3}$
	L	-	2	$-\frac{1}{2}$
	E^c	-	-	$+1$



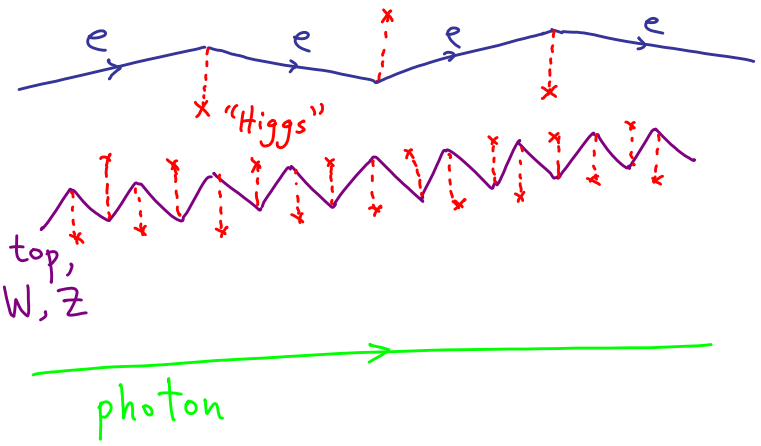
$\sim \frac{1}{137}$

$\sim \frac{1}{60}$

$\sim \frac{1}{10}$

SIMILAR!

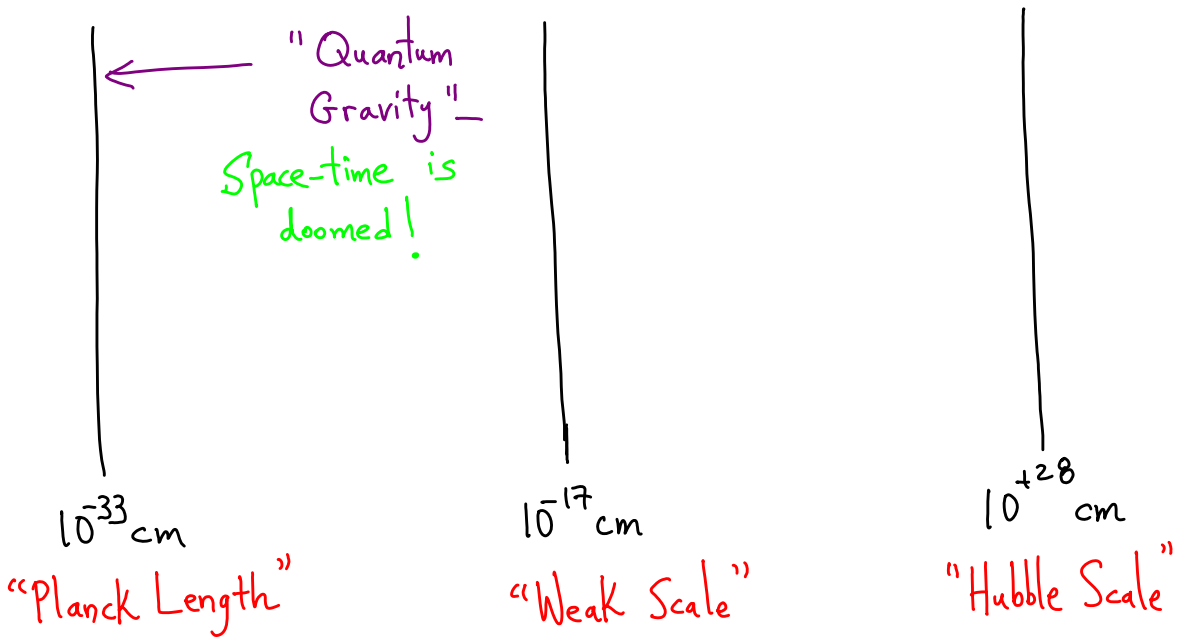
Origin of Mass



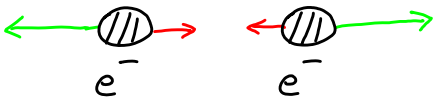
Typical length between collisions $\sim 10^{-17}$ cm.

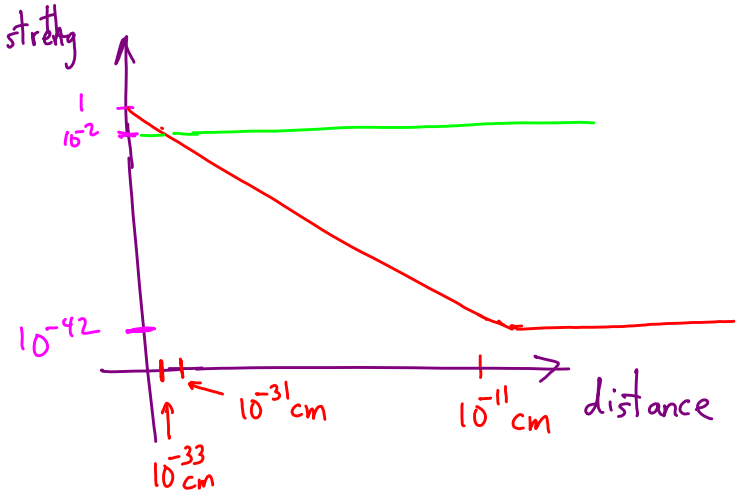
L.H.C. must excite "Higgs Particle"!

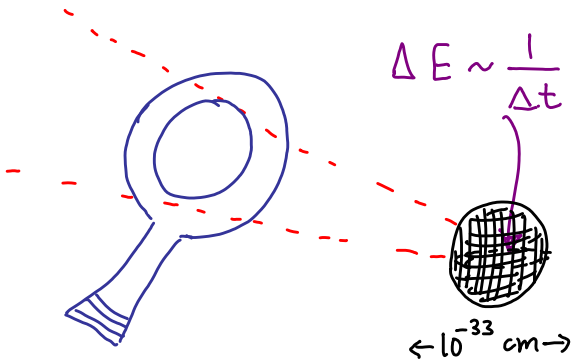
Space-Time is Doomed — What Replaces It?


"Quantum Gravity" — Space-time is doomed!
10^{-33} cm
"Planck Length"
10^{-17} cm
"Weak Scale"
10^{+28} cm
"Hubble Scale"

Gravity is strong at the Planck Scale



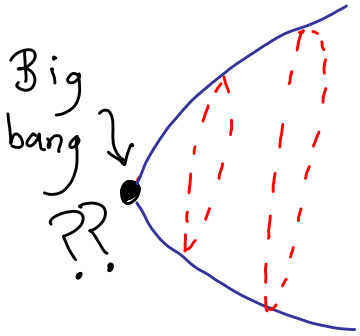


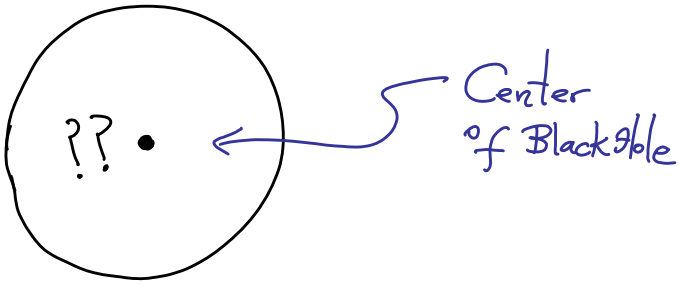


$\rightarrow$ eventually make Black Hole!

No Operational meaning to distance $< 10^{-33}$ cm, times $< 10^{-43}$ s, ...

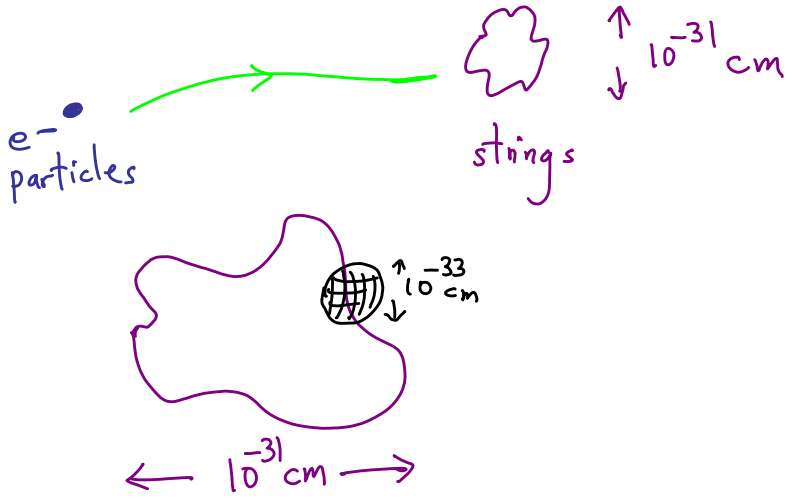
End of Space-Time





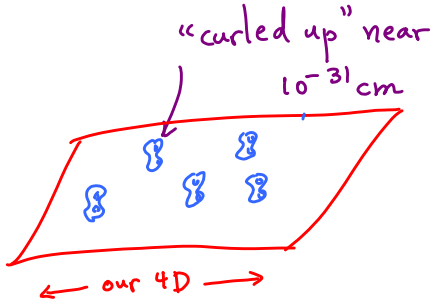
Our theories just break down when gravity is strong and quantum gravity effects are dominant.

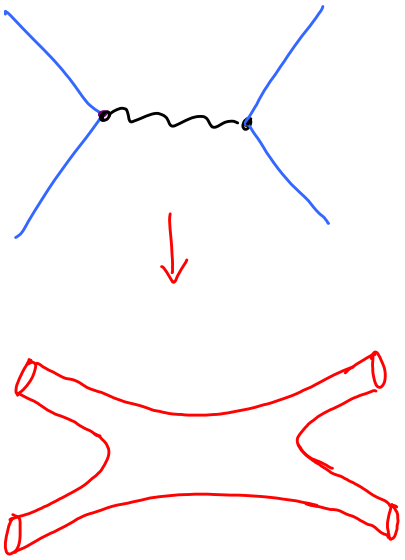
String Theory Pre 1995



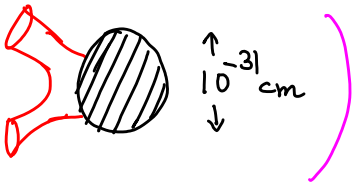
+ Supersymmetry

+ extra dimensions





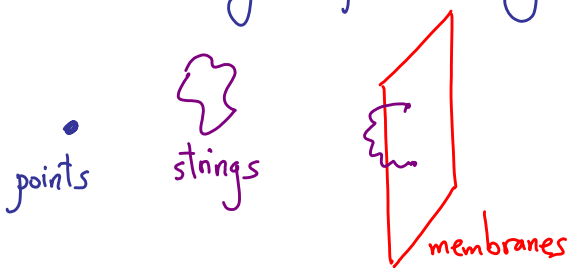
(Still, at high enough energies,



)

Strings Post 95

- Not a theory of strings!



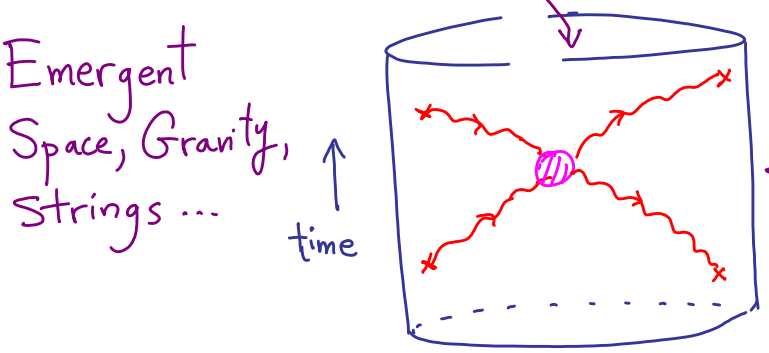
- Strings / extra dimensions can have any size

One Quantum Theory

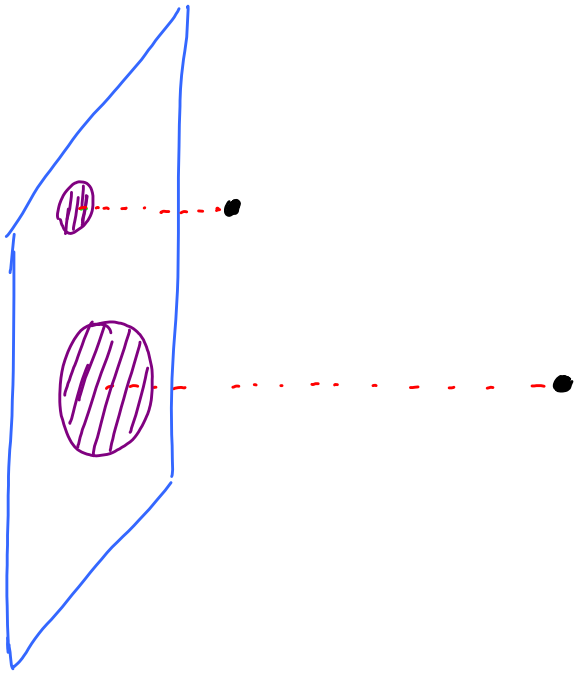
Many Solutions

Many Classical Limits

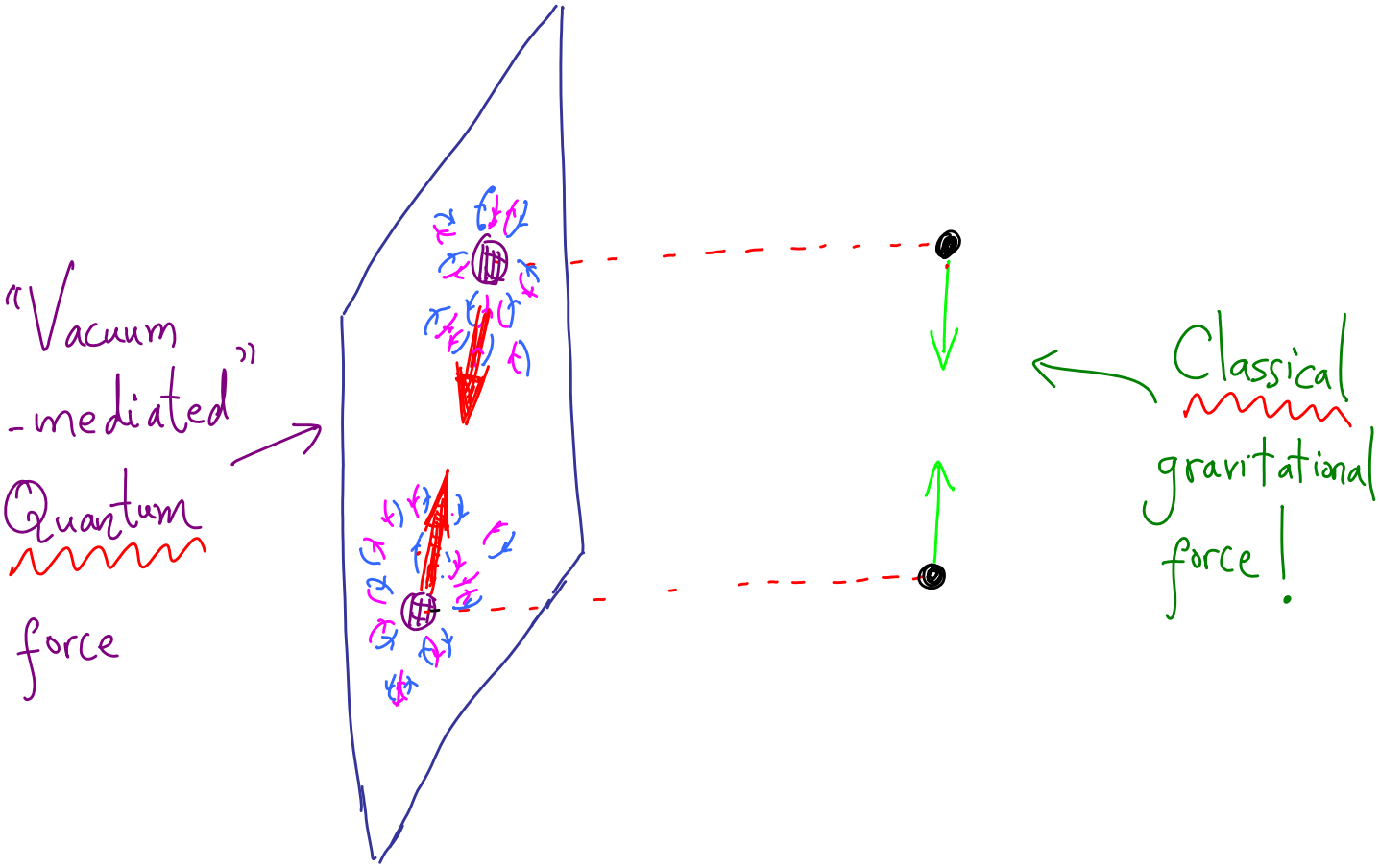
(Quantum Gravity)$_{D+1}$ = (Quantum Field Theory)$_D$ (!)



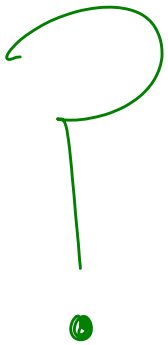
String Theory = Particle Physics



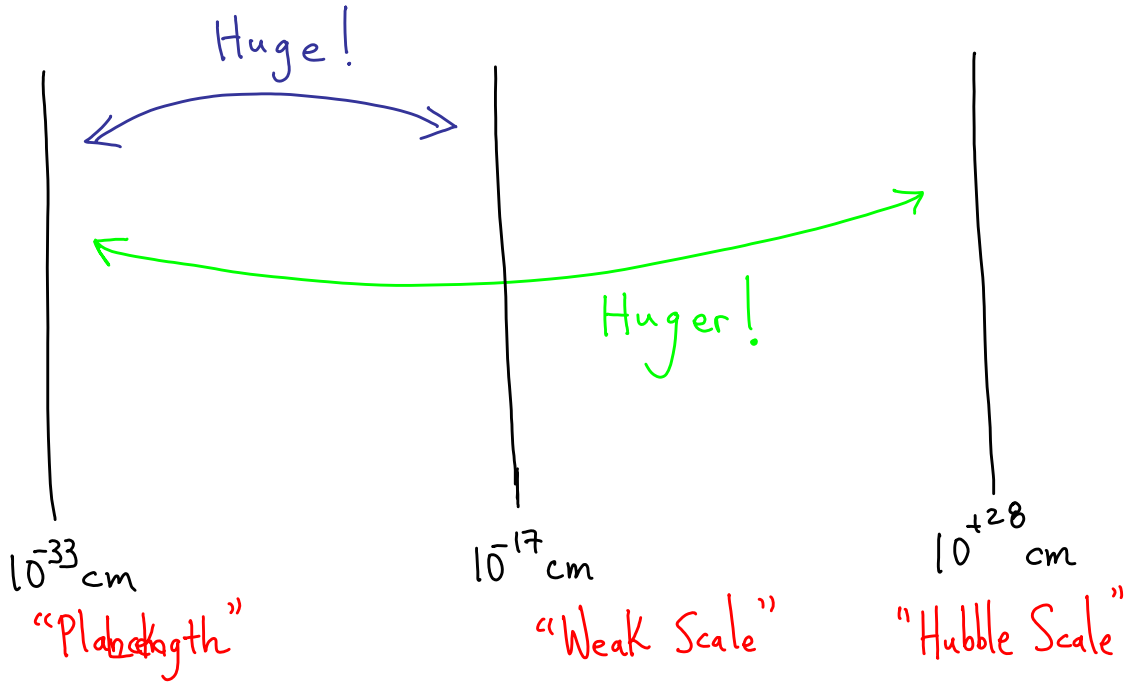
Position ↔ Scale size


"Vacuum
-mediated"
Quantum
force
Classical
gravitational
force!

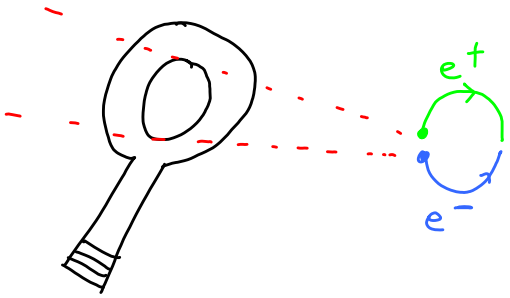
More generally, we must come to grips with Emergent Time.

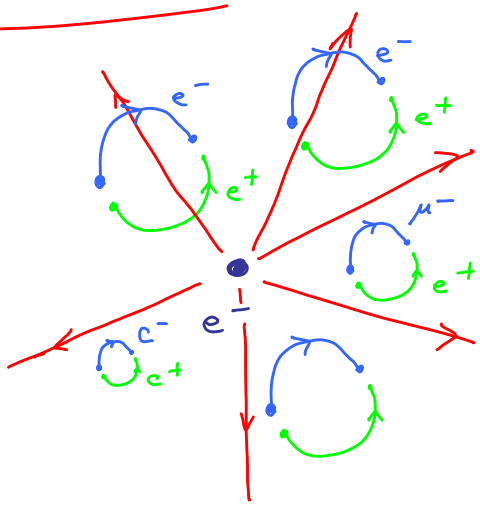


Why is there a Macroscopic Universe?


Huge!
Huger!
10^{-33} cm
"Planck length"
10^{-17} cm
"Weak Scale"
10^{+28} cm
"Hubble Scale"

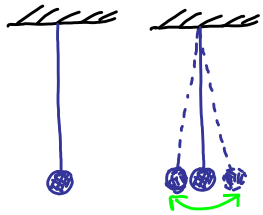
"Vacuum" is Exciting!





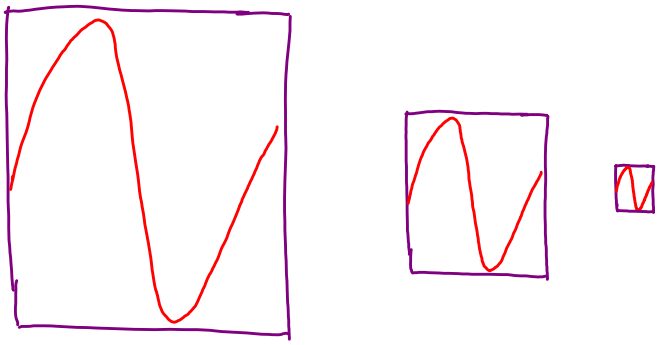
Too Exciting!

Even Vacuum has energy!



$E_{min} = 0$
classical

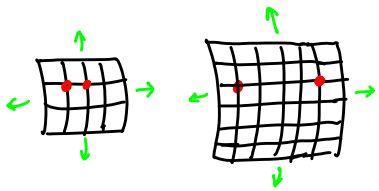
$E_{min} \sim h \times freq.$
Quantum



Bigger Fluctuations at Shorter Distances

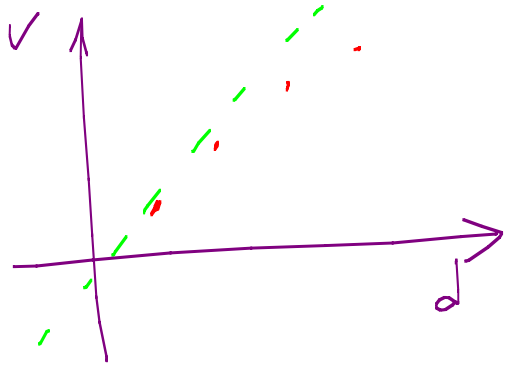
Estimating Λ

"Vacuum Energy Density" $\sim \frac{\text{Energy}}{\text{Volume}} \sim \left[\frac{\text{Planck}}{\text{Planck Volume}}\right]$



Explosive Acceleration –
Doubling size every 10^{-43} s !

Universe is Accelerating



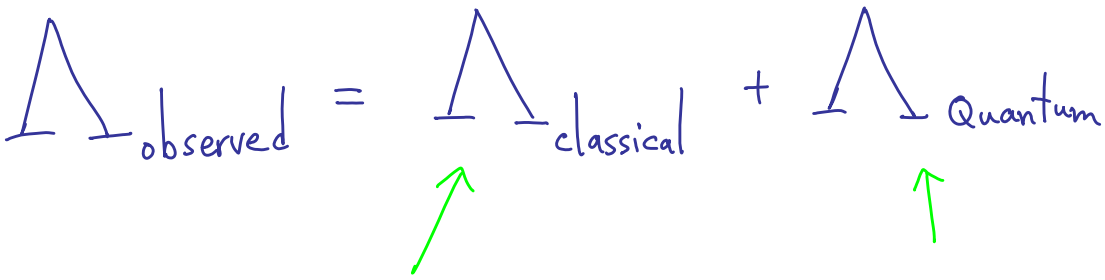
but doubles in size every 10^{10} yrs!

$\Lambda_{observed} \sim 10^{-120} \Lambda_{estimate}$

Biggest Error in History of Physics

Science

What We Do

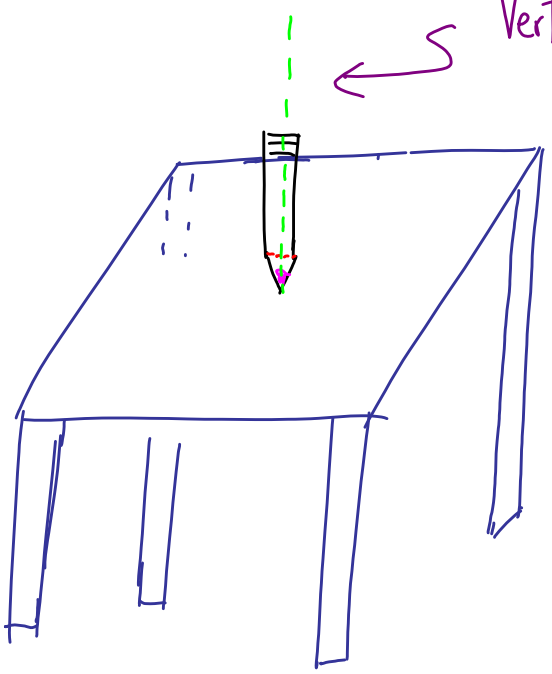


$-2.6493781\ldots.526\ldots$ (120 decimals)

$+2.6493781\ldots.534\ldots$ (120 decimals)

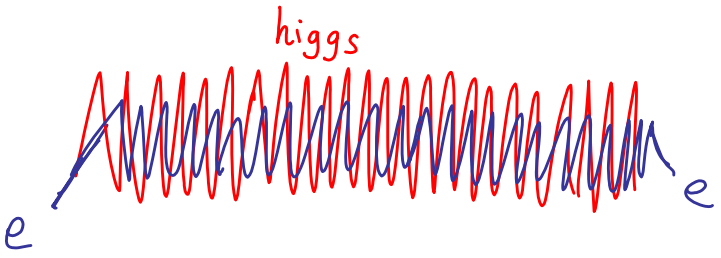
LUDICROUS!

"Fine Tuning"

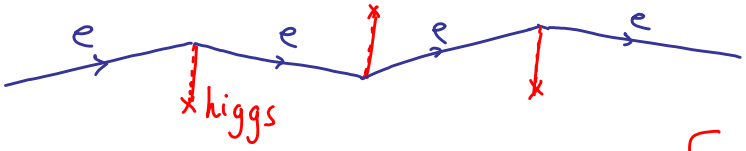


Vertical to accuracy 10^{-120} degrees!

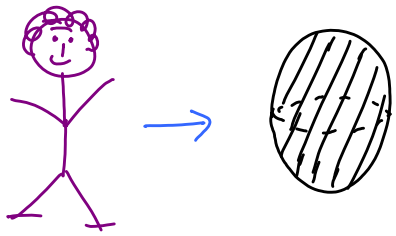
[Why is the Universe Big?]



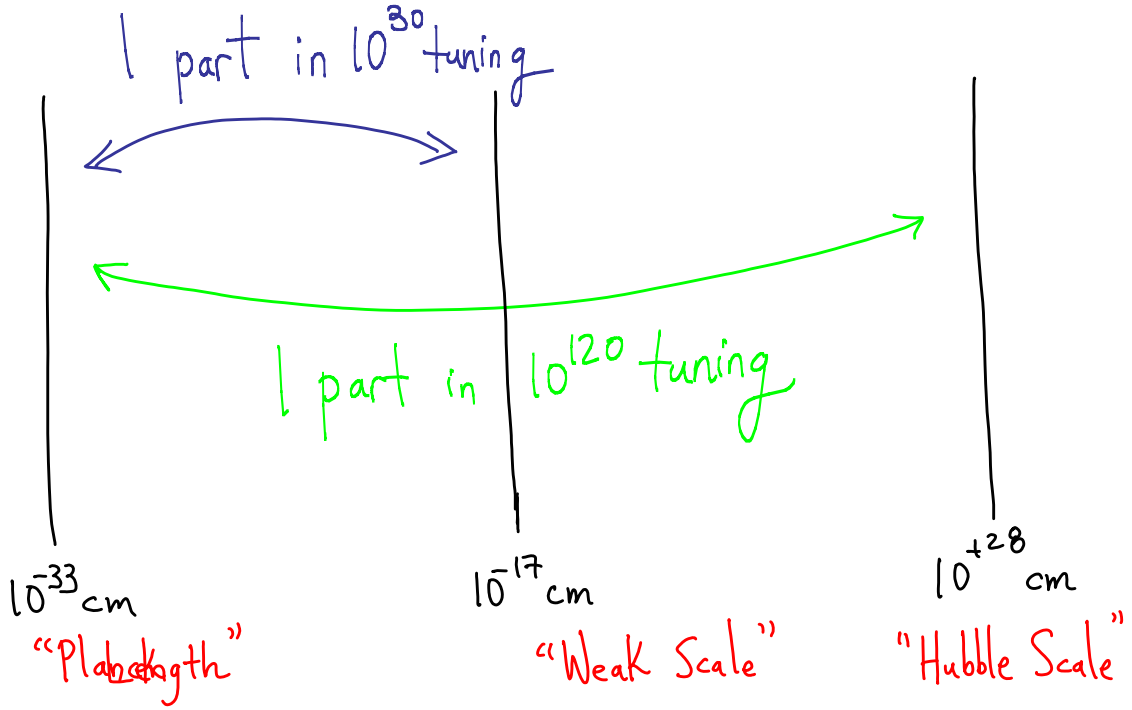
← Estimated distance between collisions $\sim 10^{-33}$ cm, vs

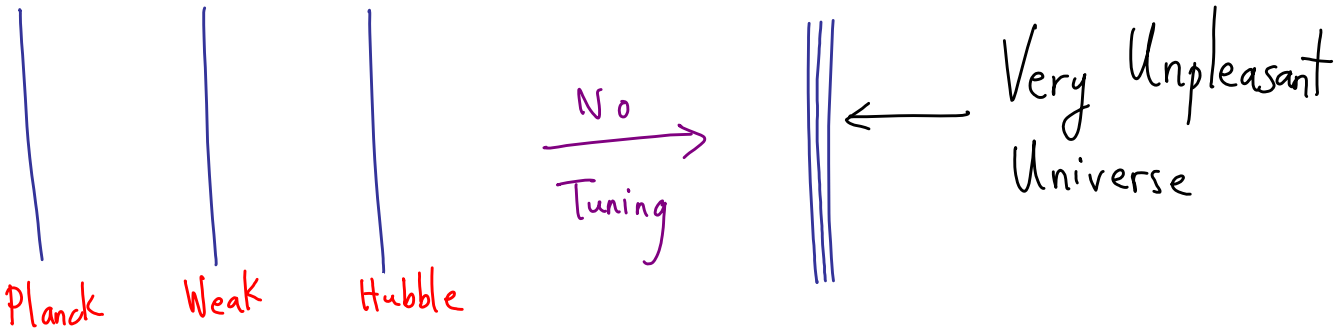


← Observed 10^{-17} cm



[Why is Gravity Weak?]

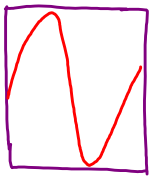

1 part in 10^{30} tuning
1 part in 10^{120} tuning
10^{-33} cm
"Planck Length"
10^{-17} cm
"Weak Scale"
10^{+28} cm
"Hubble Scale"

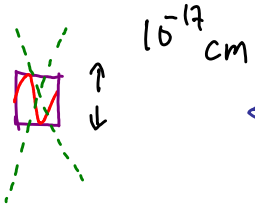


What Controls Violent Fluctuations of the Vacuum?

Why is There a Macroscopic Universe?

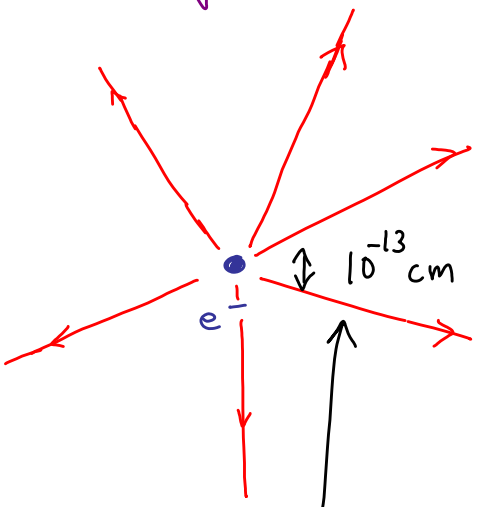
New Physics around the Corner?



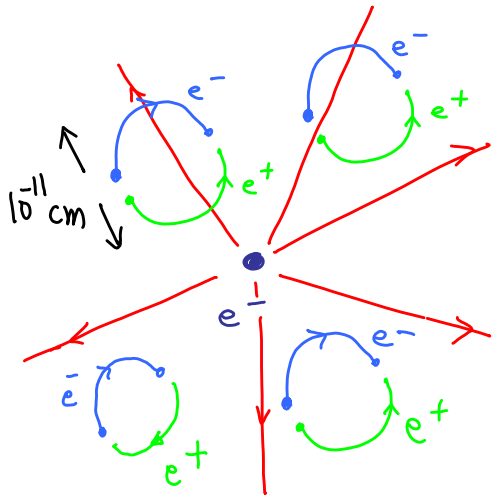


Something new needs to happen here!

Infinite Energy In Electric Field

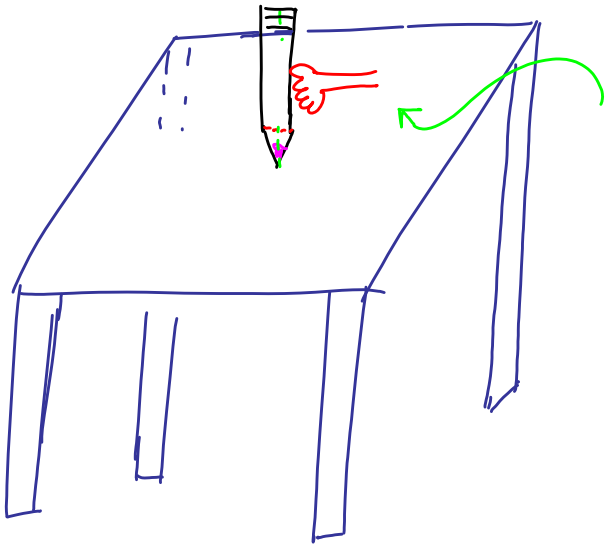


Q.M.
Rel.



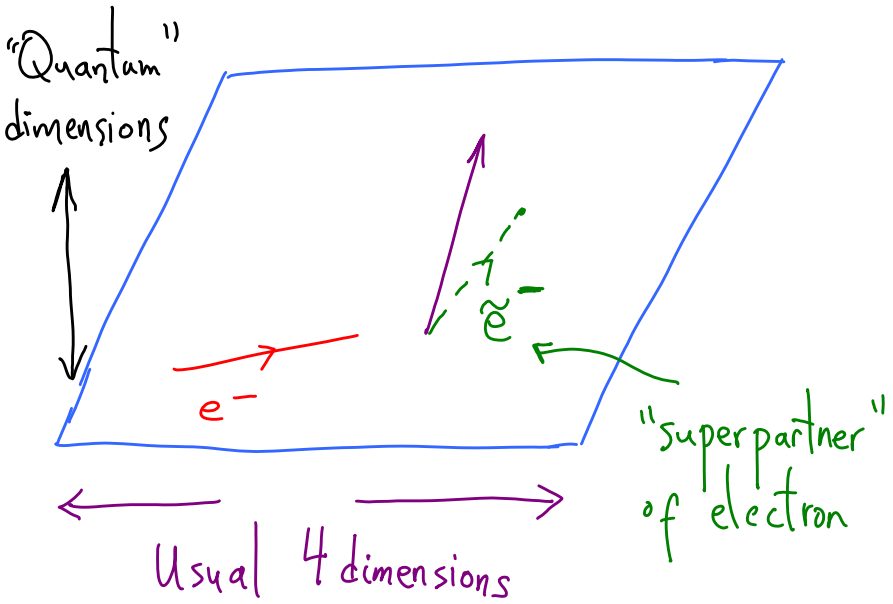
Something new by this scale

What Could It Be?



Extensions to our notion of spacetime can remove the violent quantum fluctuations

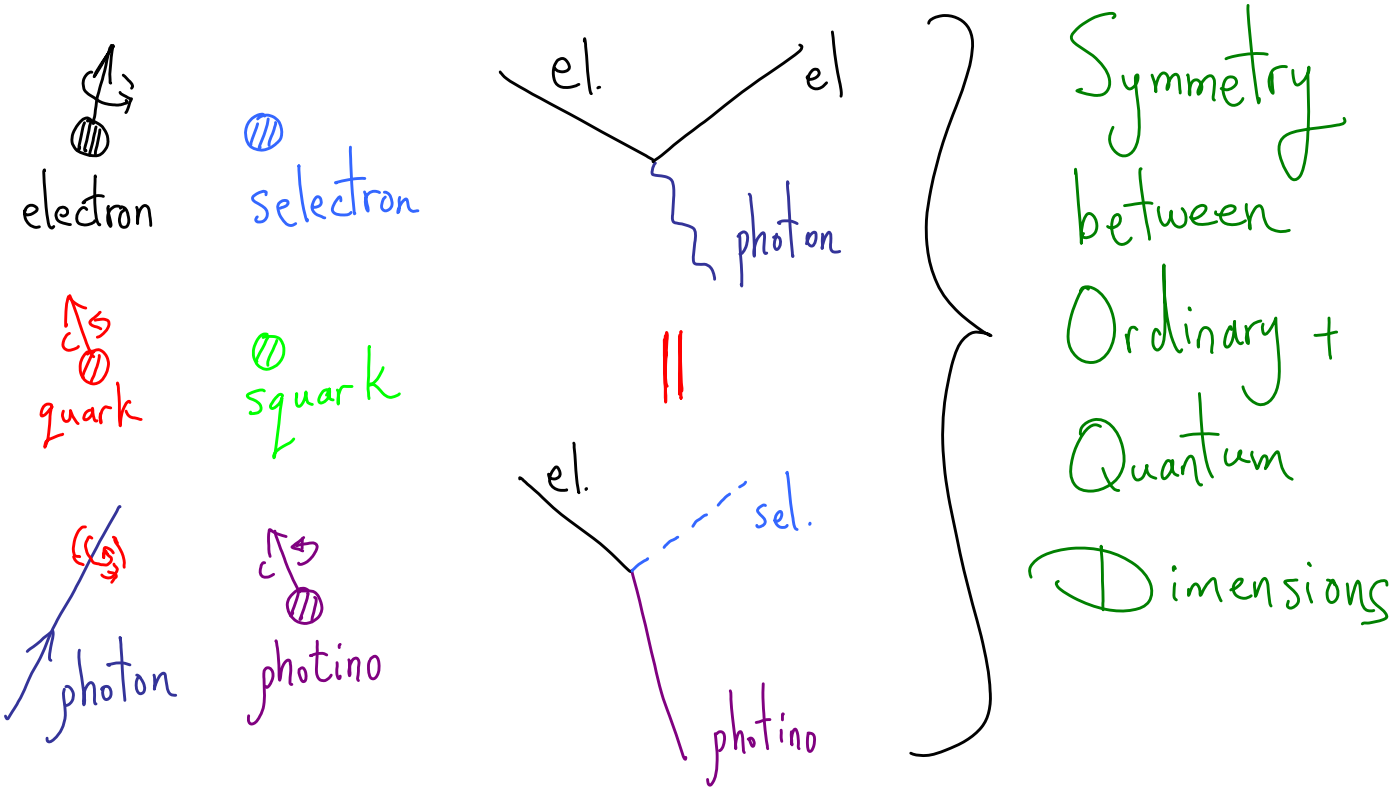
Supersymmetry



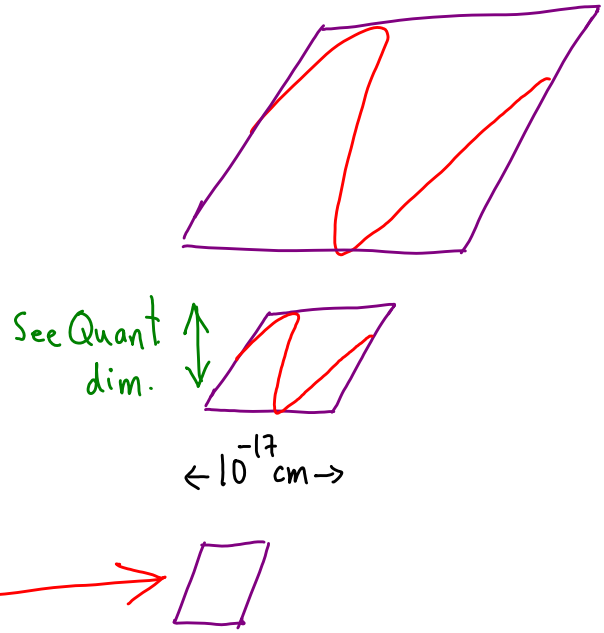
$d_x^{\text{Quantum}}, d_y^{\text{Quantum}}, \ldots$

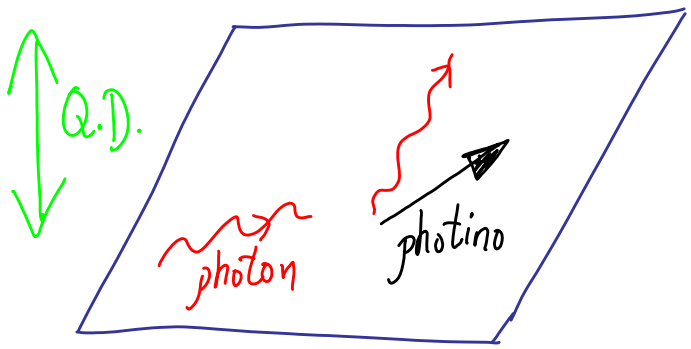
$d_x^Q d_y^Q = -d_y^Q d_x^Q$

$\left(d_{xy}^Q\right)^2 = 0$

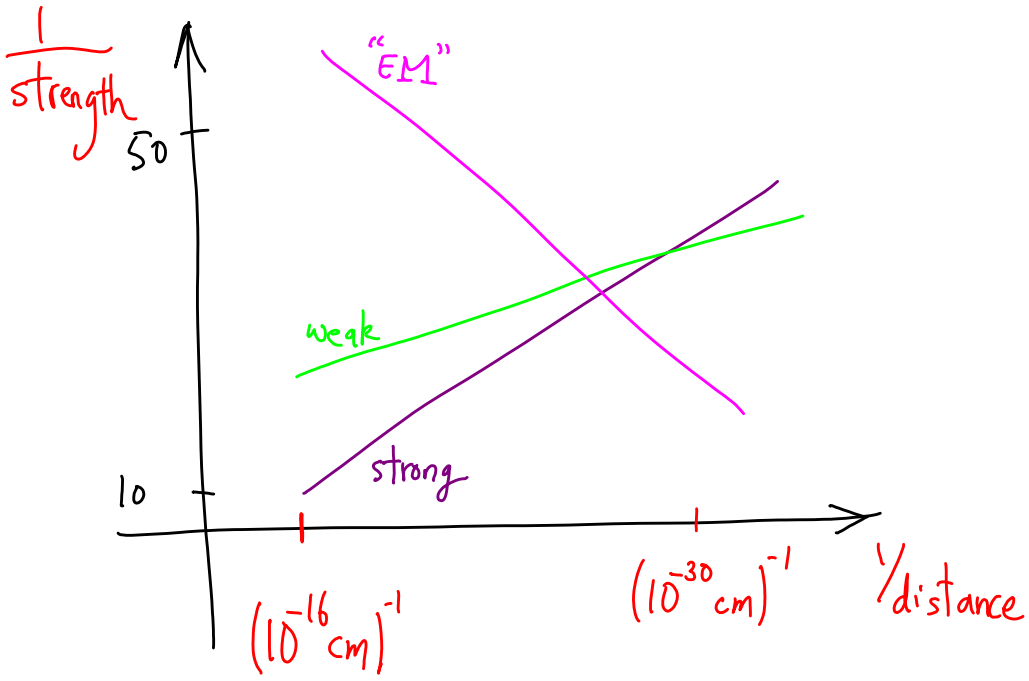

electron
selectron
quark
squark
photon
photino
el.
el
photon
el.
sel.
photino
Symmetry
between
Ordinary +
Quantum
Dimensions

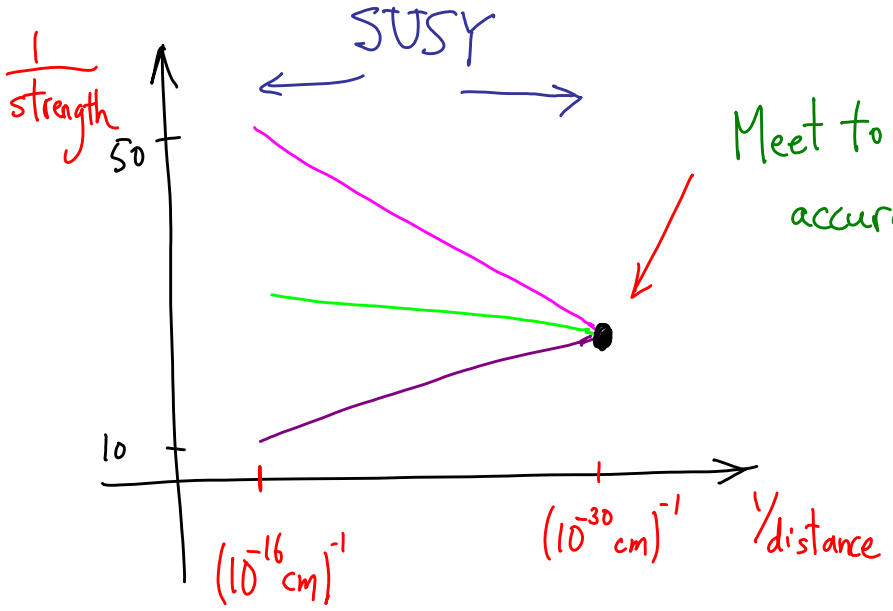
Violent
Quantum
Fluctuations
Gone



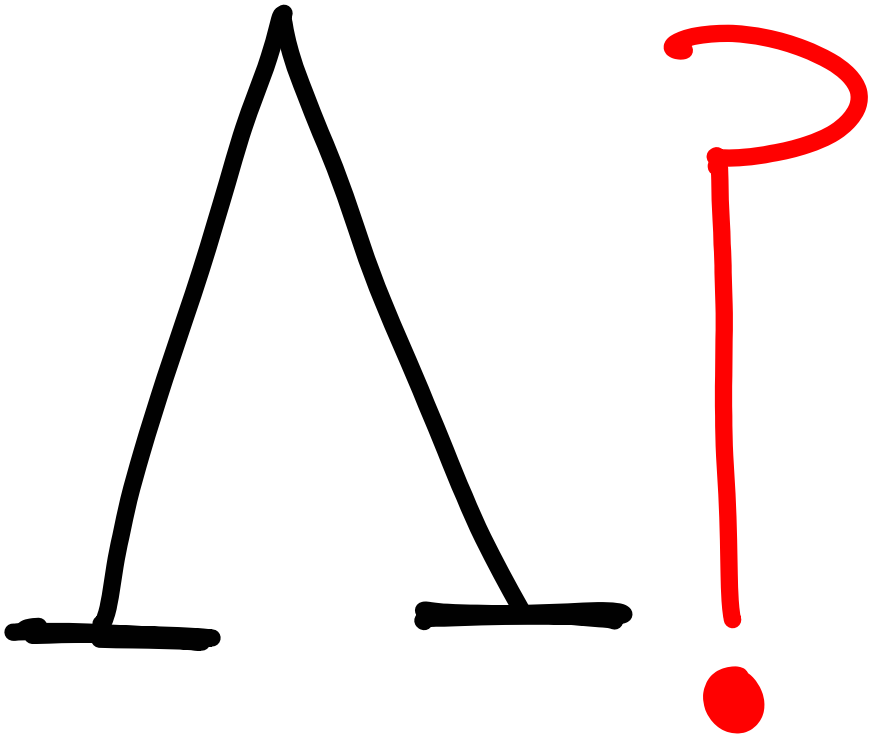


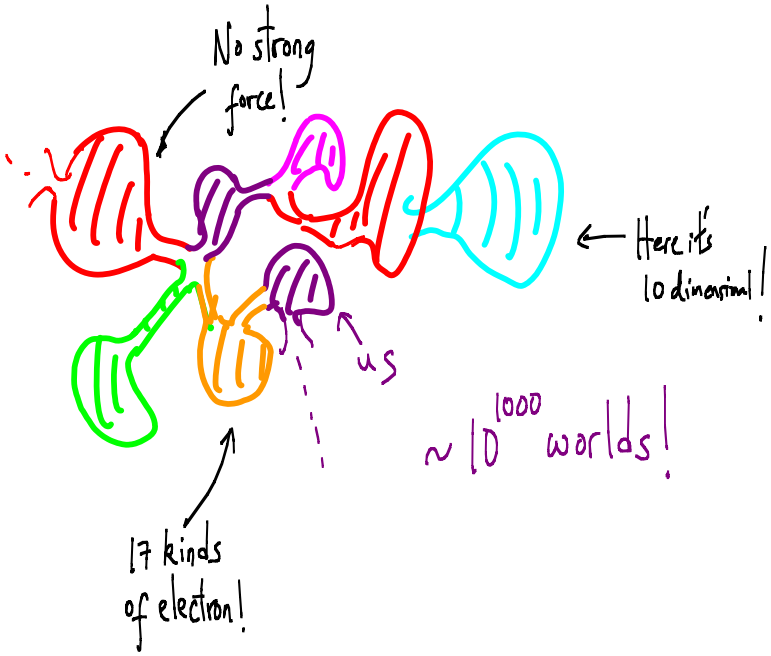
Dark Matter
Might be Light,
Moving in the new
Quantum Dimensions!


1/strength
50
10
"EM"
weak
strong
$(10^{-16}\,cm)^{-1}$
$(10^{-30}\,cm)^{-1}$
1/distance

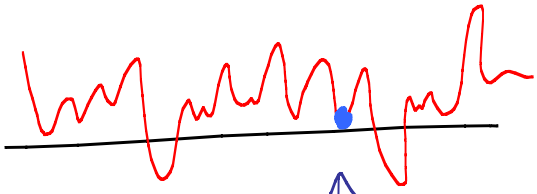


Unification of the Forces – Gravity not far behind!





$\sim 10^{1000}$ worlds!



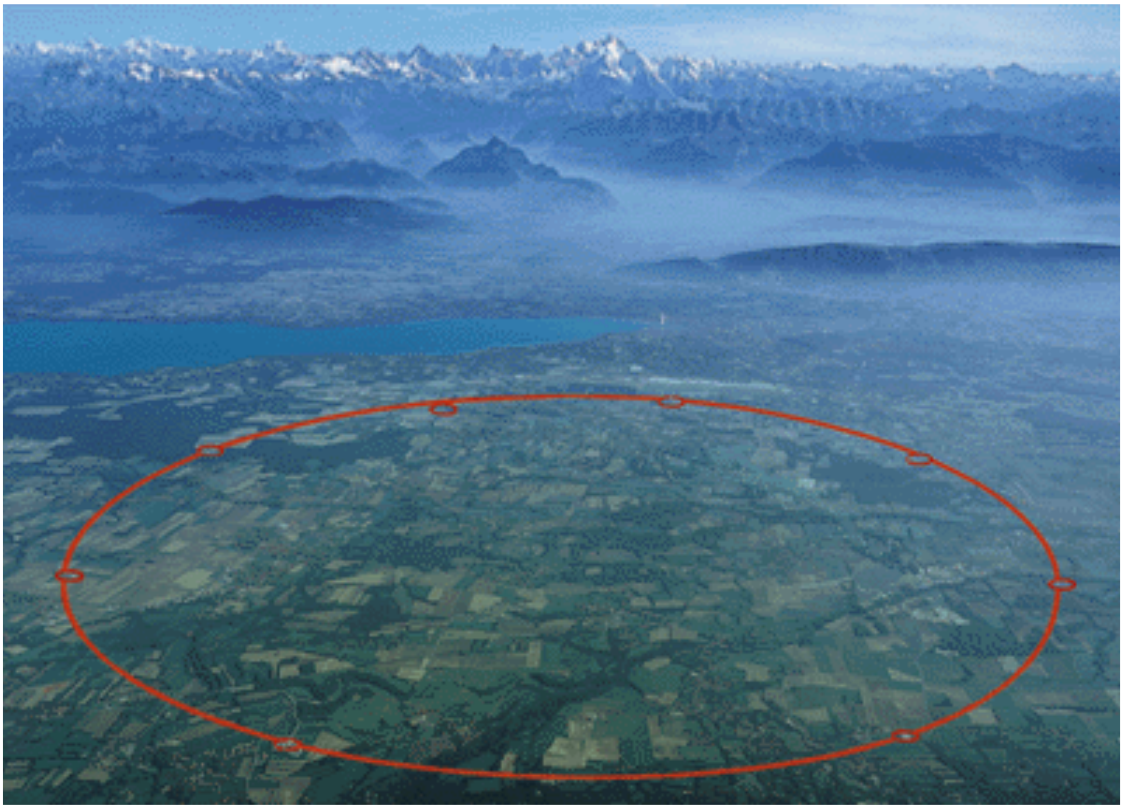
Everywhere Lethal + Empty except ...

Here, accidentally, Universe not empty

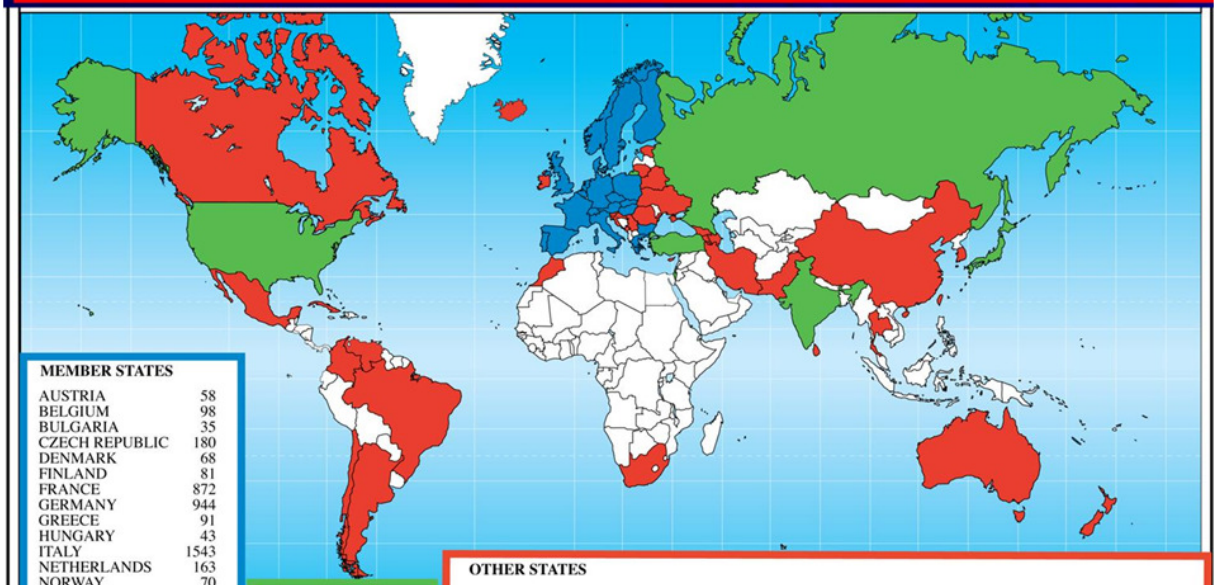
Are we tiny part of a Vast Multiverse?

- If true — modern Copernican Revolution!
- Conceptual Problem — how can we "see" other universes — how can we know that they're there?

Large Hadron Collider



Distribution of All CERN Users by Nation of Institute on 5 February 2008



MEMBER STATES

AUSTRIA	58
BELGIUM	98
BULGARIA	35
CZECH REPUBLIC	180
DENMARK	68
FINLAND	81
FRANCE	872
GERMANY	944
GREECE	91
HUNGARY	43
ITALY	1543
NETHERLANDS	163
NORWAY	70
POLAND	175
PORTUGAL	109
SLOVAKIA	46
SPAIN	270
SWEDEN	74
SWITZERLAND	344
UNITED KINGDOM	645

5909

OBSERVER STATES

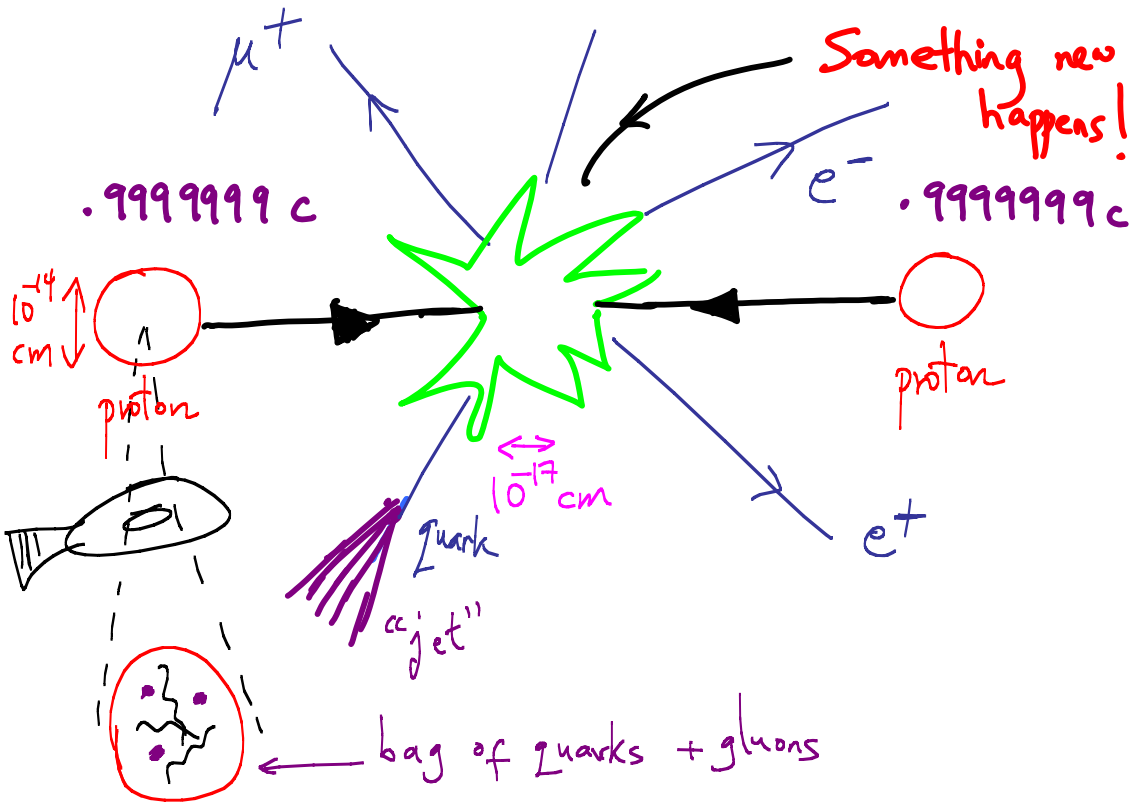
INDIA	93
ISRAEL	64
JAPAN	182
RUSSIA	940
TURKEY	35
USA	1278

2592

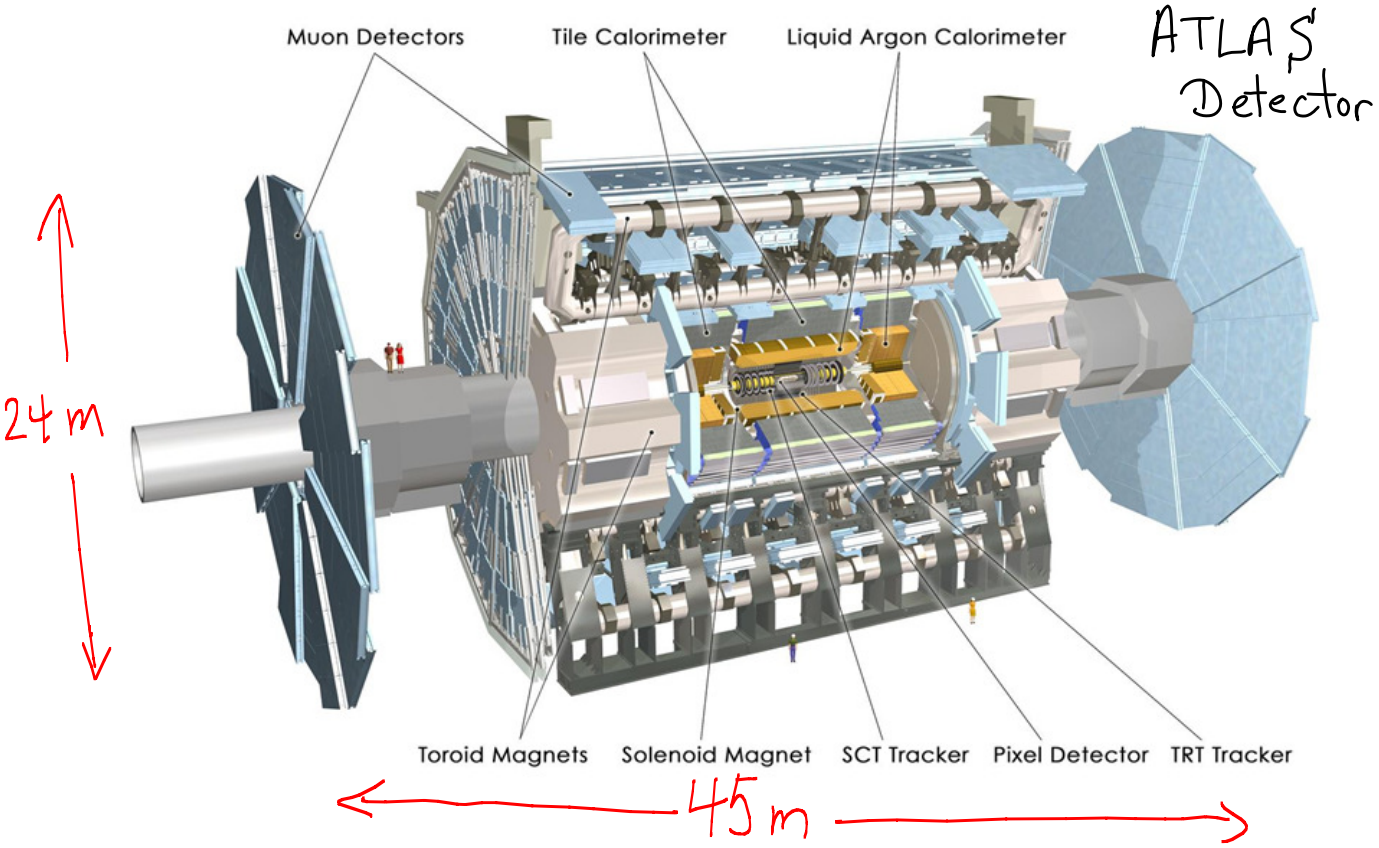
OTHER STATES

ARGENTINA	8	CROATIA	17	MEXICO	23	TAIWAN	40
ARMENIA	17	CUBA	3	MONTENEGRO	1	THAILAND	1
AUSTRALIA	13	CYPRUS	6	MOROCCO	6	UKRAINE	17
AZERBAIJAN	1	ESTONIA	10	NEW ZEALAND	7		
BELARUS	23	GEORGIA	9	PAKISTAN	23		
BRAZIL	68	ICELAND	1	ROMANIA	46		
CANADA	119	IRAN	6	SERBIA	16		
CHILE	4	IRELAND	14	SLOVENIA	16		
CHINA	60	KOREA	44	SOUTH AFRICA	2		
COLOMBIA	5	LITHUANIA	5	SRI LANKA	1		

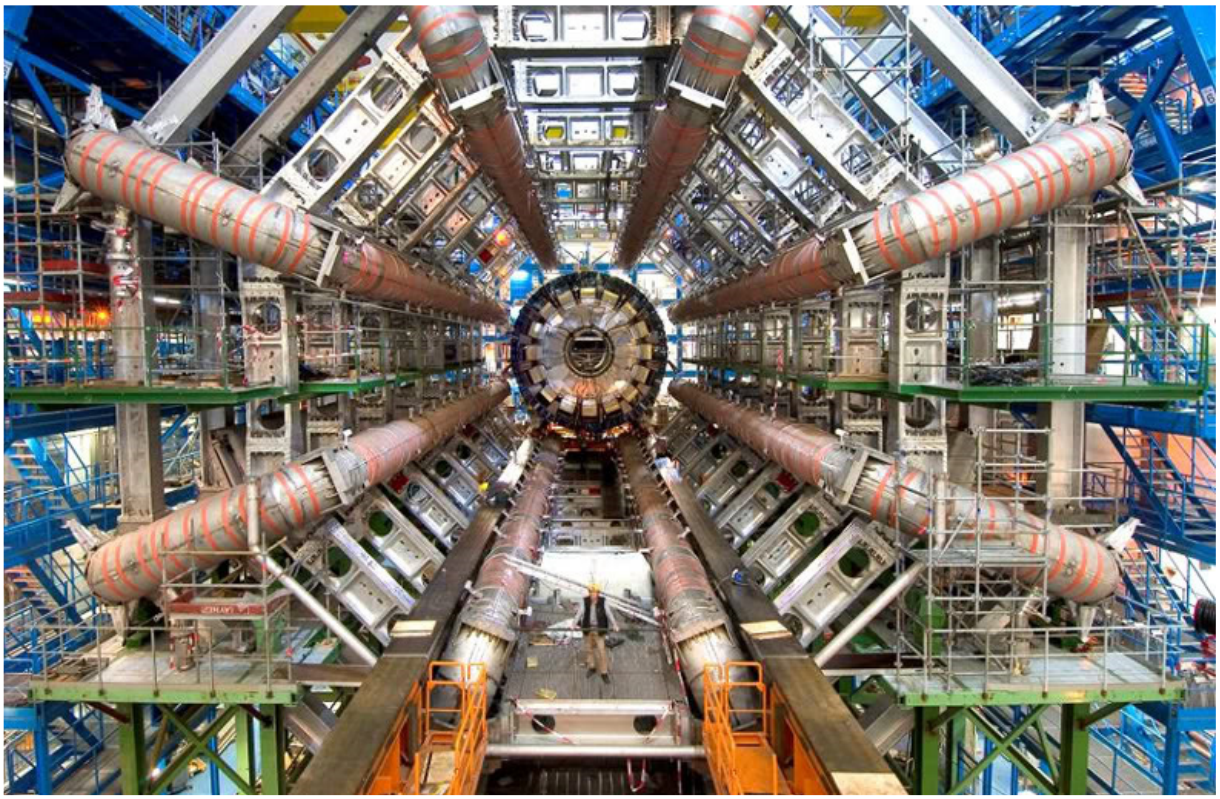
632

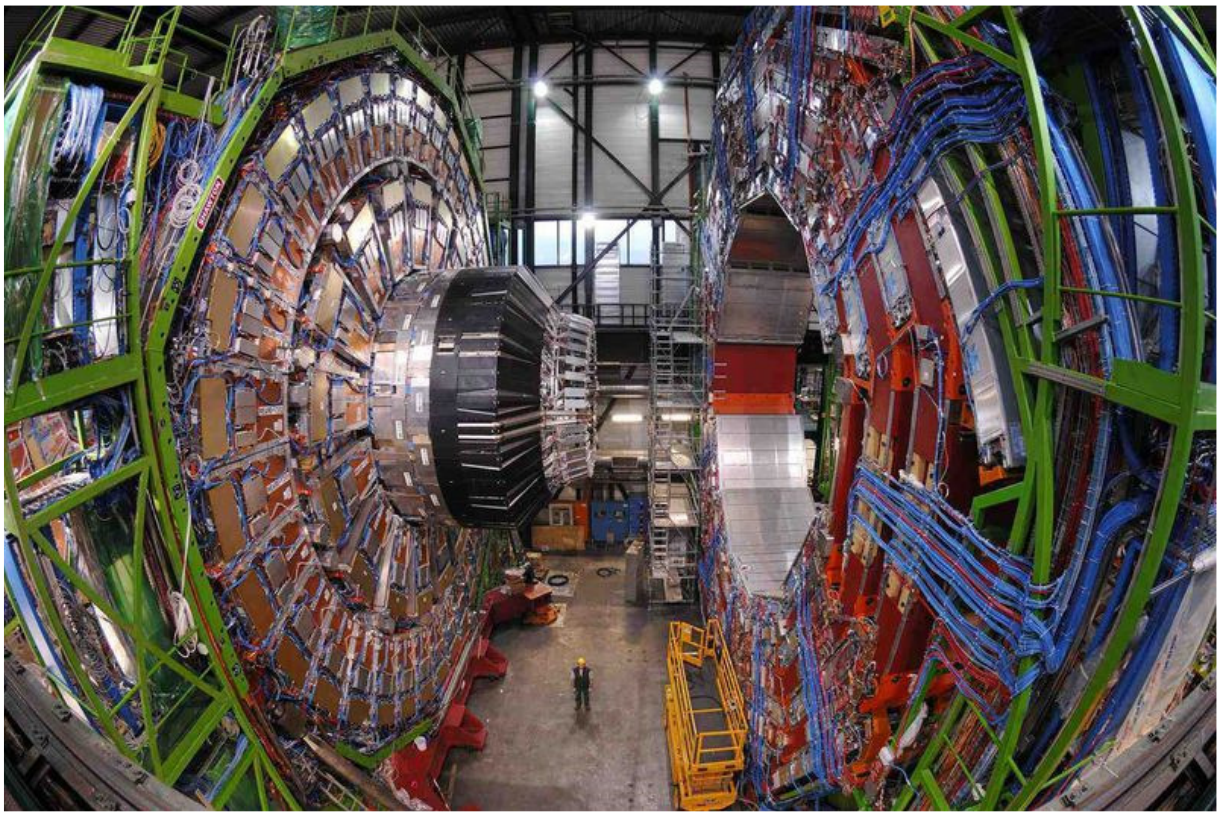

μ^+
Something new happens!
e^-
.9999999 c
.9999999 c
10^{-14} cm
proton
proton
$\leftrightarrow$
10^{-17} cm
quark
"jet"
e^+
bag of quarks + gluons

ATLAS Detector



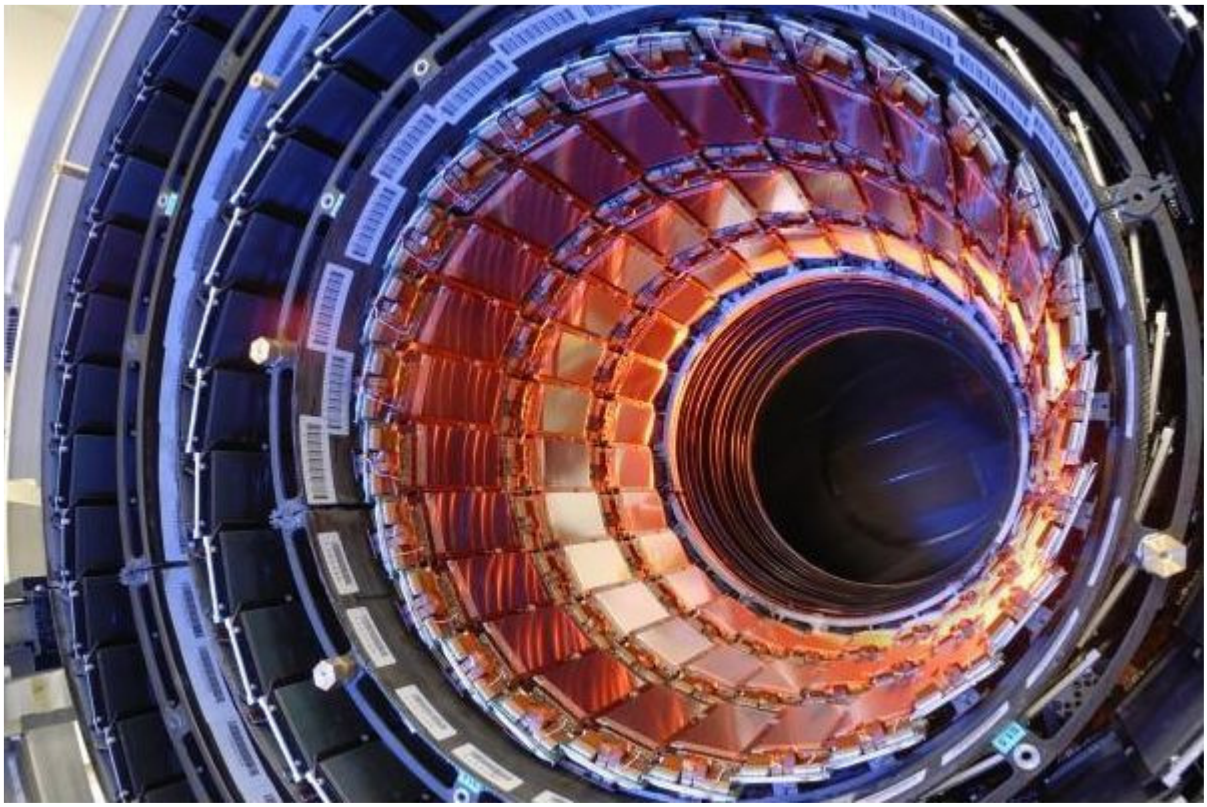

Collision Event at
7 TeV
ATLAS
EXPERIMENT
2010-03-30, 12:58 CEST
Run 152166, Event 316199
http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html





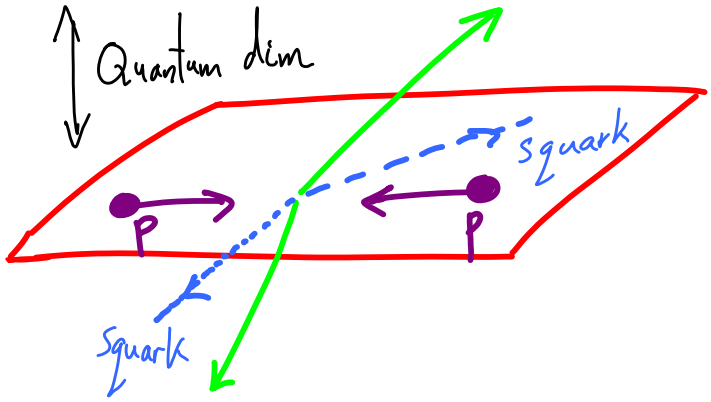
CMS Detector

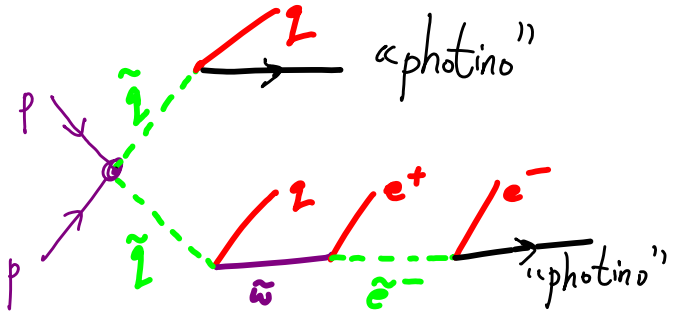
VERY FANCY DIGITAL CAMERA!



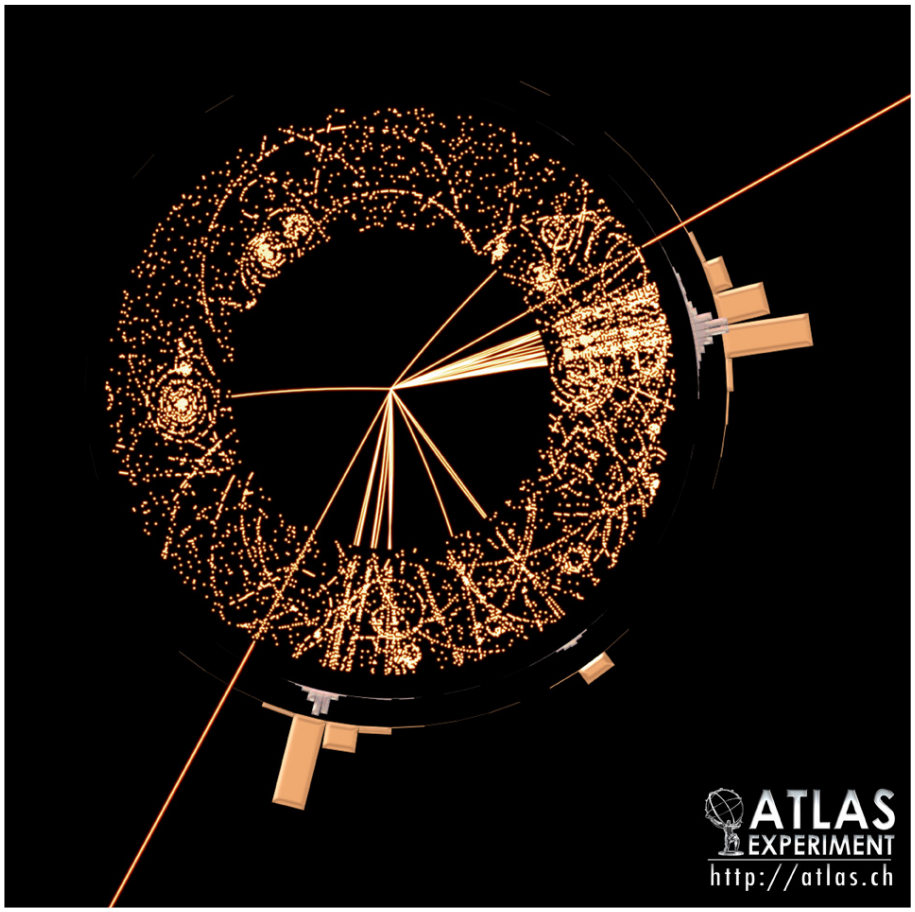
Underground Experiment Cavern

SUSY at the LHC

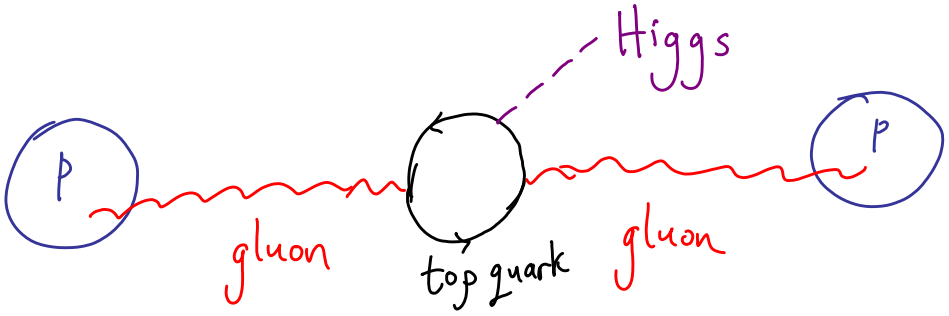


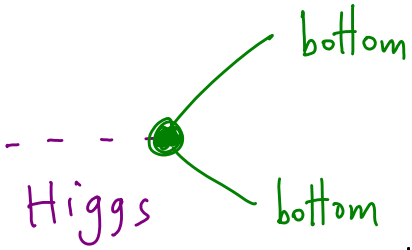


"Missing" Energy

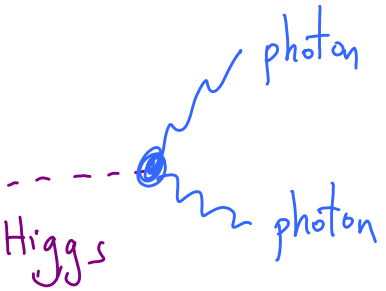

ATLAS
EXPERIMENT
http://atlas.ch

Higgs at the L·H·C

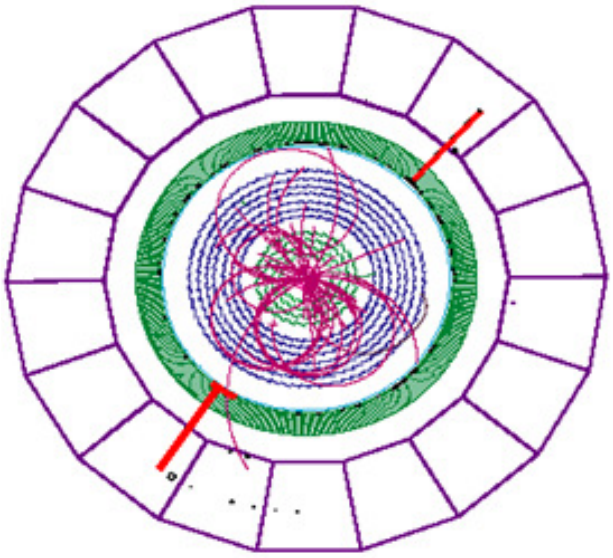


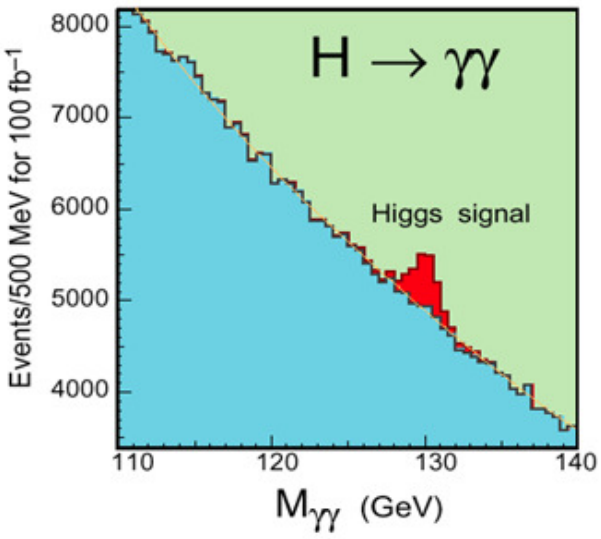


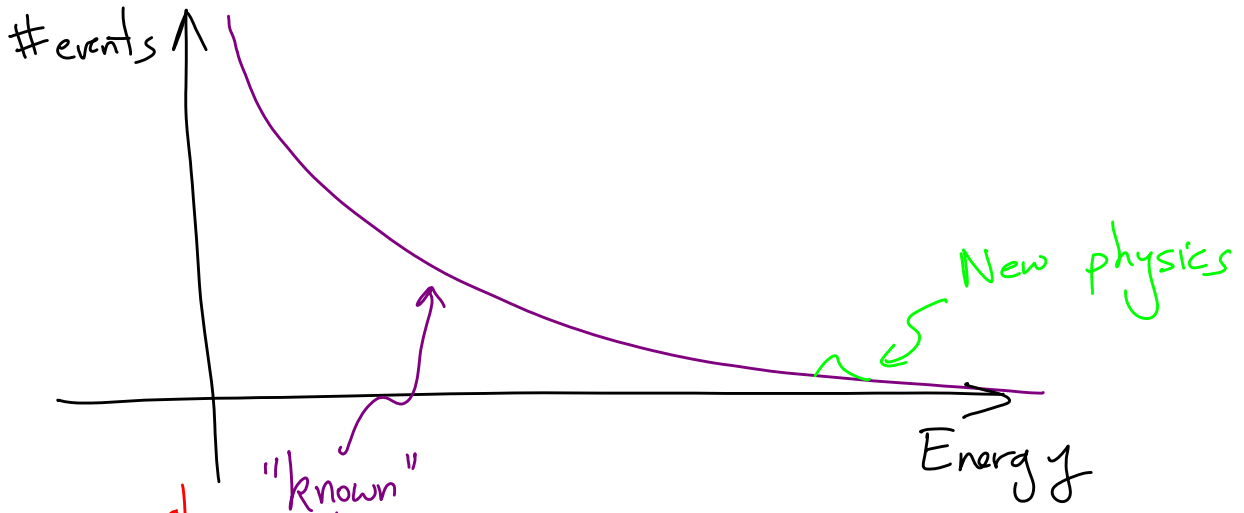
Very Hard to See!



← rare, but can see it!




H → γγ
Higgs signal
Events/500 MeV for 100 fb⁻¹
8000
7000
6000
5000
4000
110
120
130
140
M_γγ (GeV)



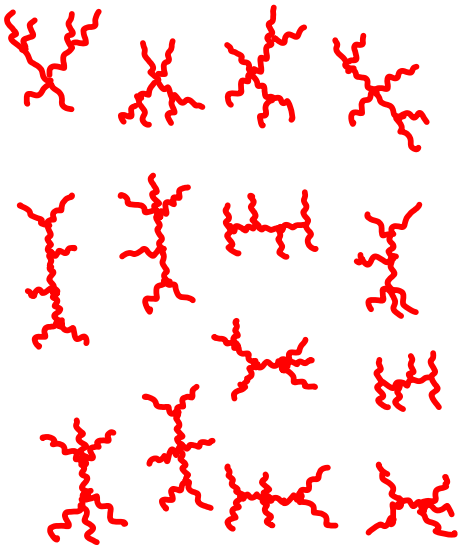
Rates:

~ 1 billion collisions/sec

~ 10 top quarks/sec

~ 1 squark minute.

Feynman Gets Hard

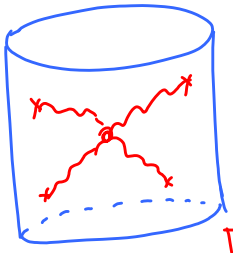


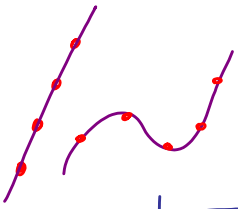
+ ...

220 Diagrams

10's of thousands of terms ...

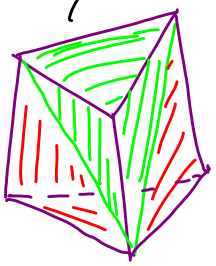
Sitting Under our Noses for 60 yrs





Twistor Theory

Scattering Without Spacetime?



Algebraic Geometry

What Might We Know By 2020?

See "Nothing"?

"Impossible"!

See SUSY - Euphoria! First extension of spacetime since Einstein.

No "fine-tuning" for "why is gravity weak"?

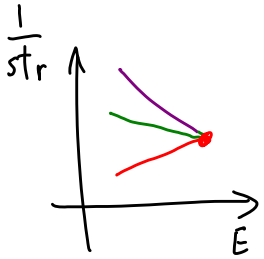
[What about Λ?]

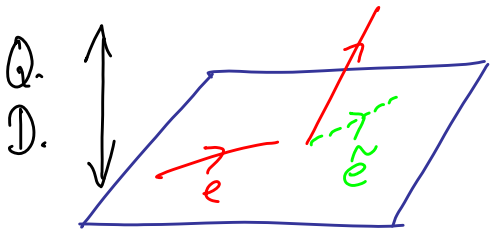
- We might have a "Dark Matter Factory" by 2020 – could well produce ~ millions of DM particles by then.

- Only Higgs + nothing else?

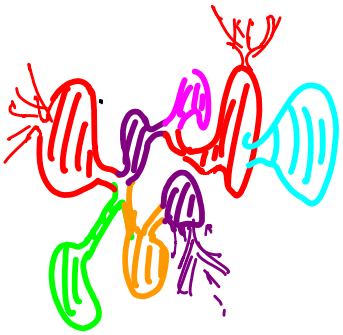
Very Confusing. Evidence for fine-tuning → just like Λ ???

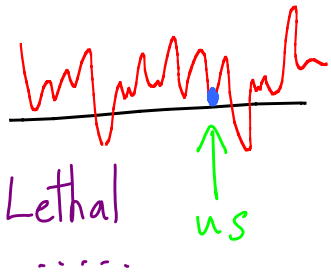
"Order"





"Chaos"





Λ + weakness of gravity?

STAY TUNED

The Best Is Yet To Come!