

Quantum Mechanics

+

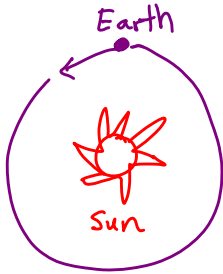
Space - Time

in the

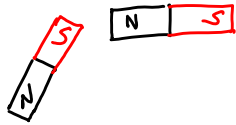
21st Century

4 Basic Interactions

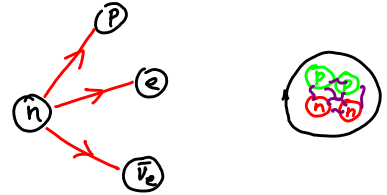
Gravity

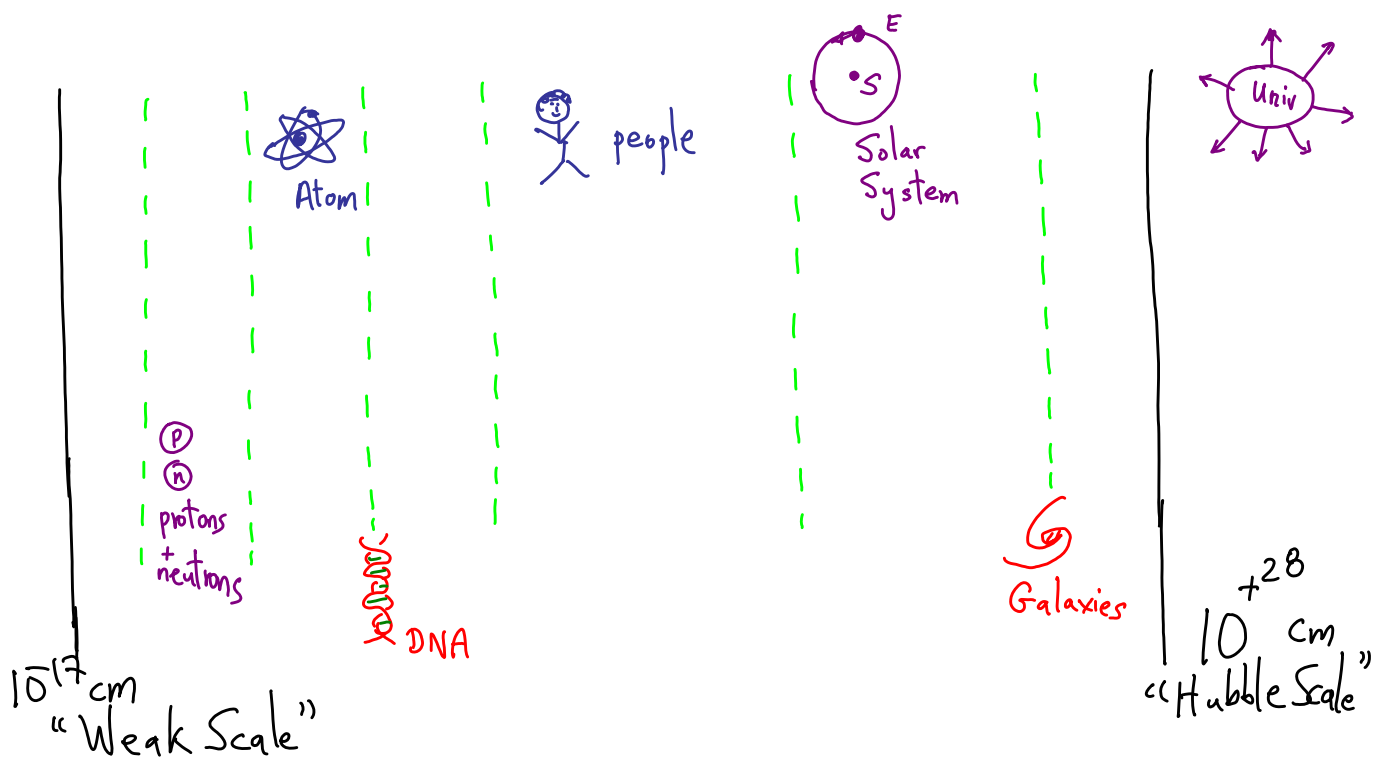


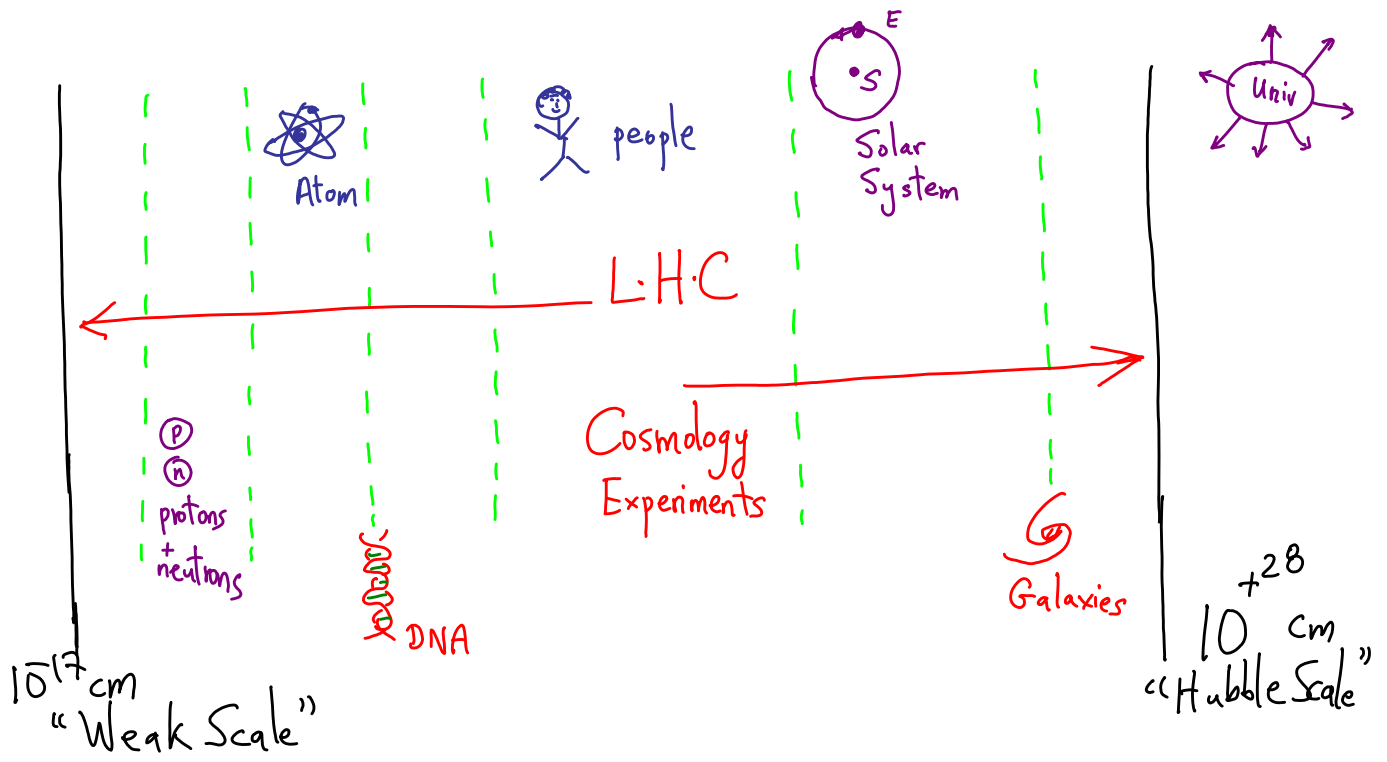
Electromagnetism



Weak + Strong







10^{-33} cm

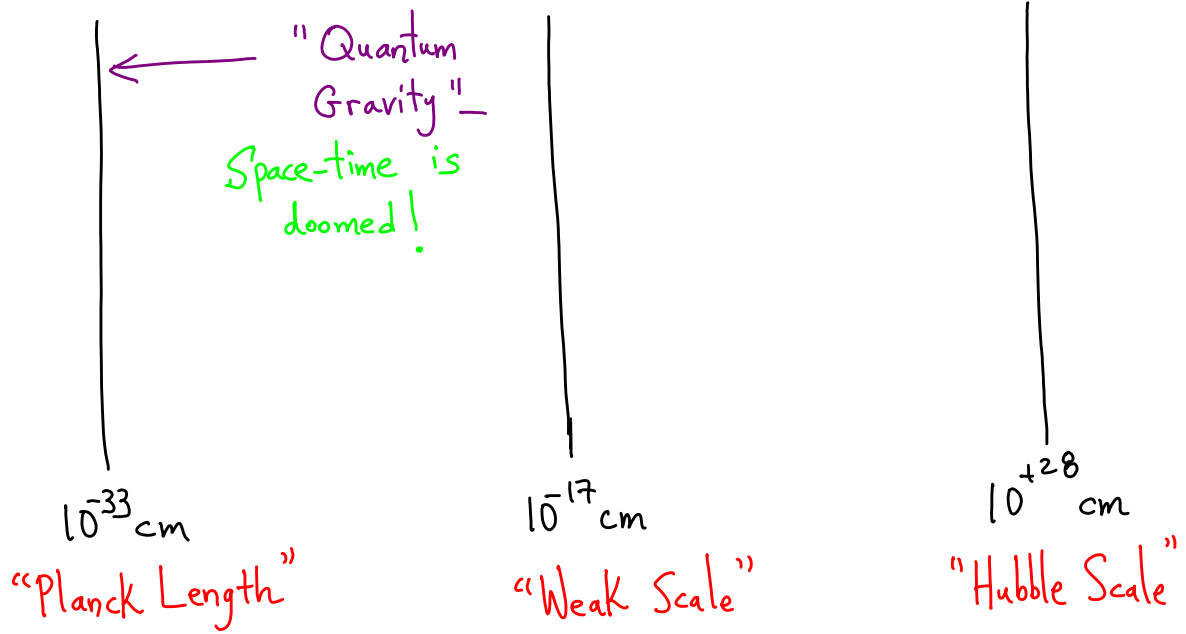
"Planck Length"

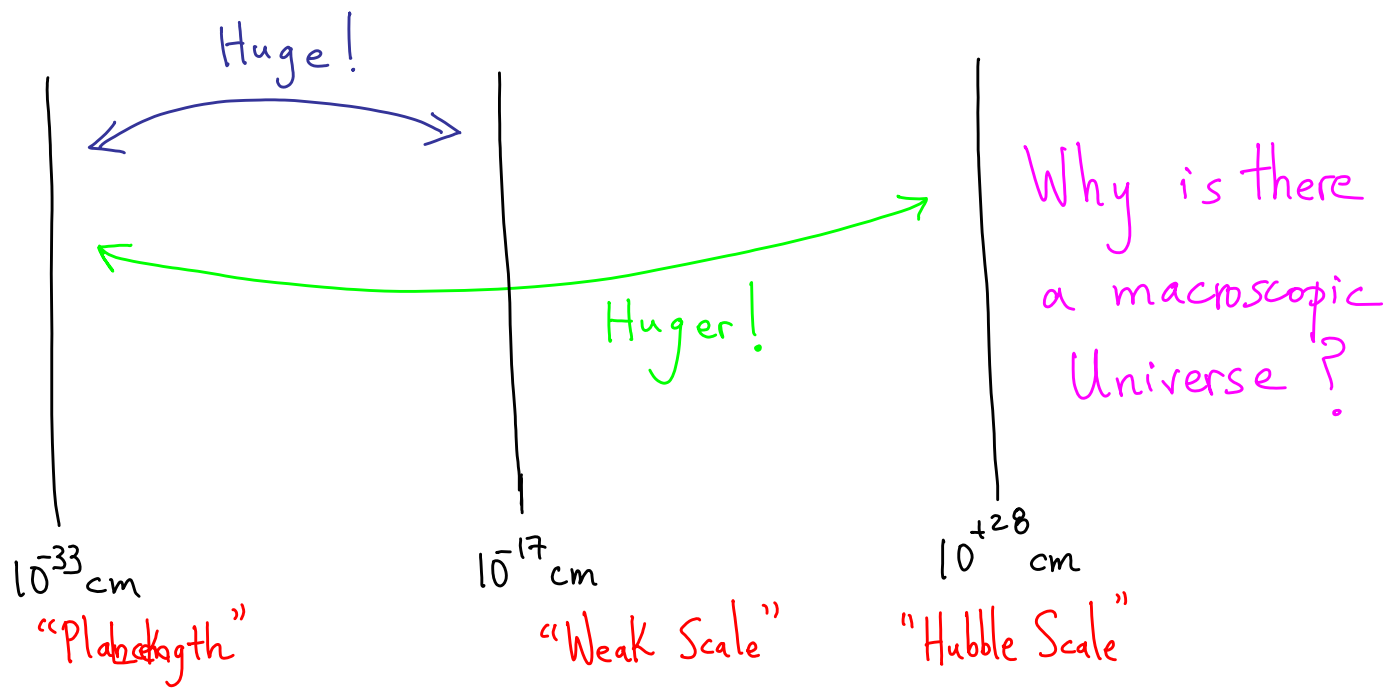
10^{-17} cm

"Weak Scale"

10^{+28} cm

"Hubble Scale"





A note on Units

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

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

$$\text{Put } \hbar = c = 1$$



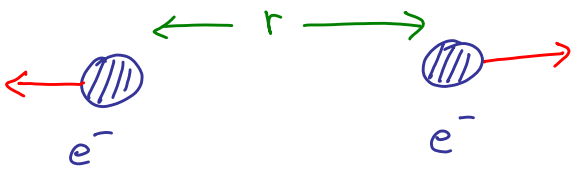
10^{16} GeV^{-1}

Mass $\sim 10^{29} \text{ GeV}$

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

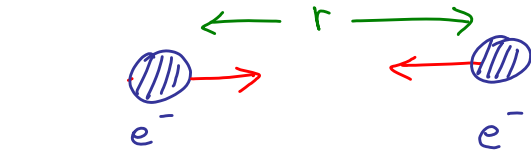
$$(m_p c^2) = 1 \text{ GeV}$$

$$\textcircled{P} \updownarrow 10^{-14} \text{ cm} \sim \text{GeV}^{-1}$$



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

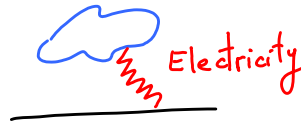
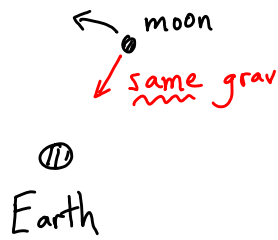
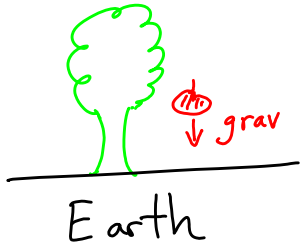
$\alpha \sim \frac{1}{137}$ (a pure number!)
 strength



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

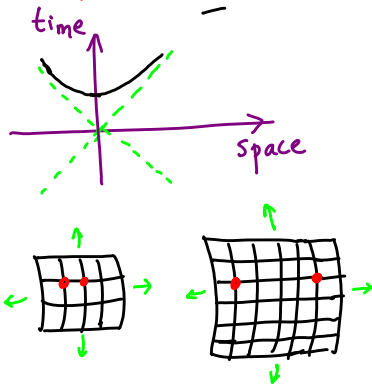
$\sim (10^{-33} \text{ cm})^2 \sim (\ell_{\text{Planck}})^2$

Unification



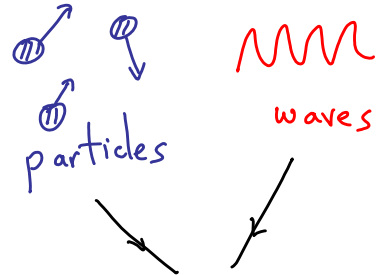
Different Aspects of Same Thing!

Relativity

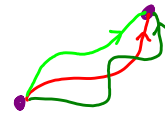


Space-Time

Quantum Mechanics



Quantum
Particles



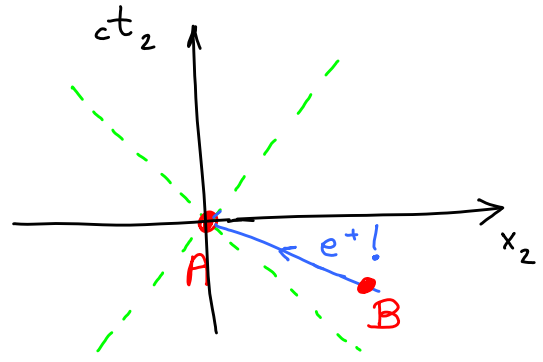
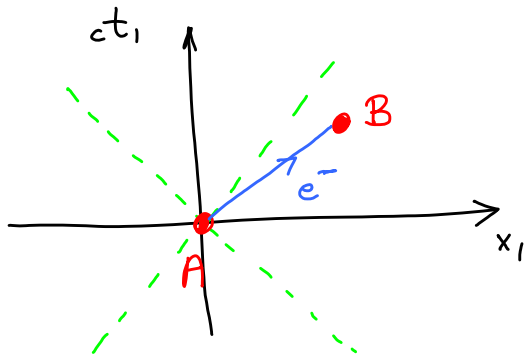
Synthesis of QM + Relativity:

"Quantum Field Theory"

→ Forces existence of anti-particles

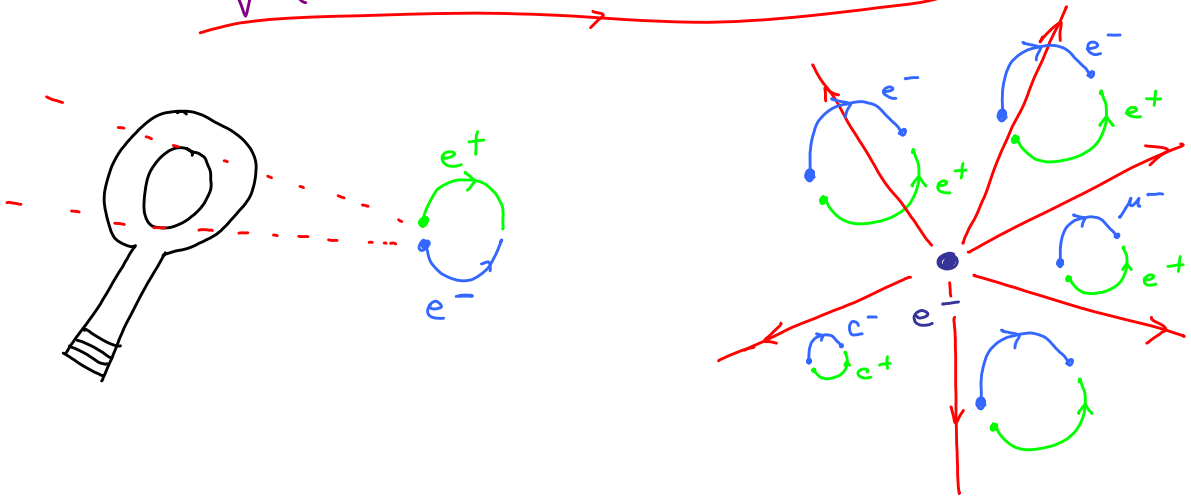
• e^- • e^+
• p^+ • p^-

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

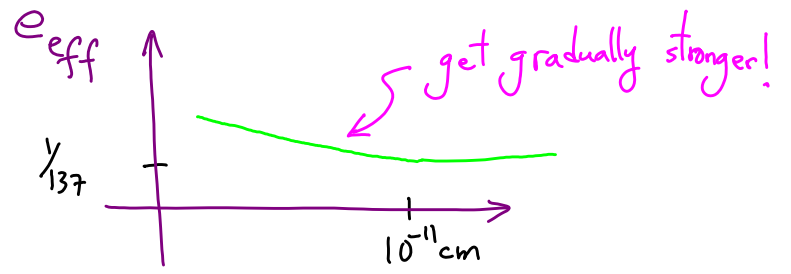
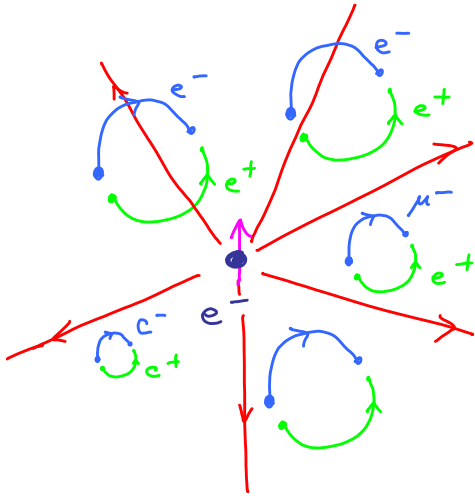


Causality \longrightarrow Antiparticles

"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!

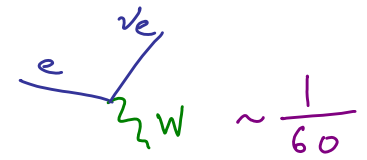
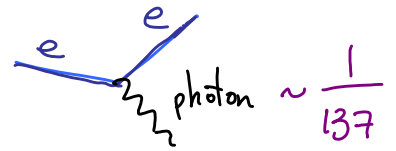


$$\frac{g-2}{2} = .001159652181 \dots$$

The Menu

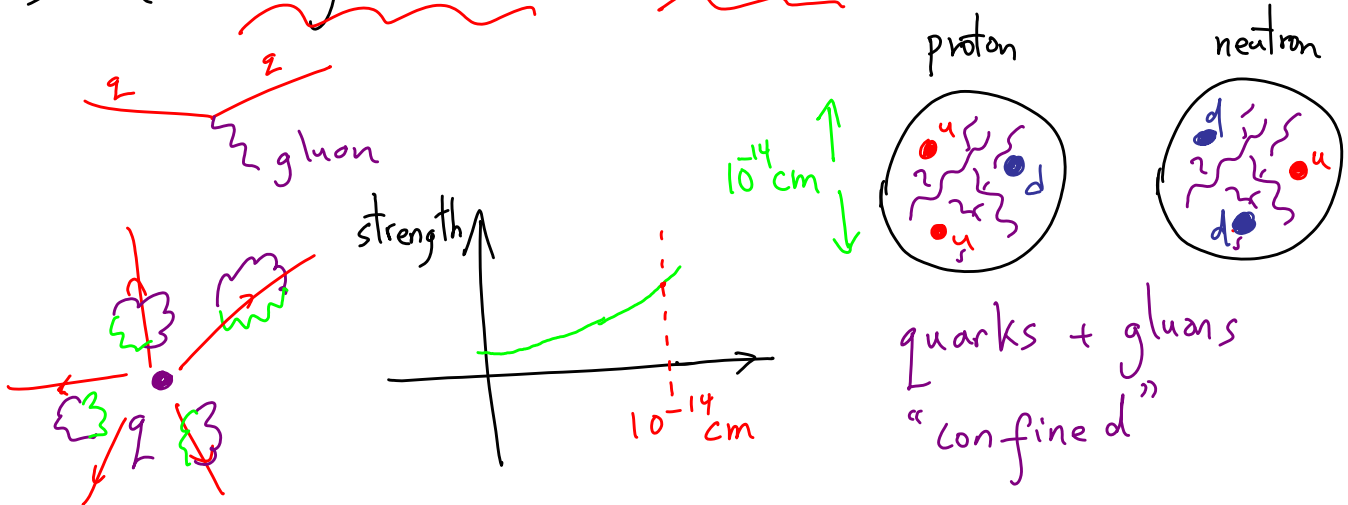
3 x
 $\begin{matrix} U_c \\ D_c \\ L \\ E_c \end{matrix}$

	Gluons	"W's"	+	Photon"	
	$SU(3)_c$	\times	$SU(2)_L$	\times	$U(1)_Y$
	3		2	$+\frac{1}{6}$	
	3		-	$-\frac{2}{3}$	
	3		-	$+\frac{1}{3}$	
	-		2	$-\frac{1}{2}$	
	-		-	+1	

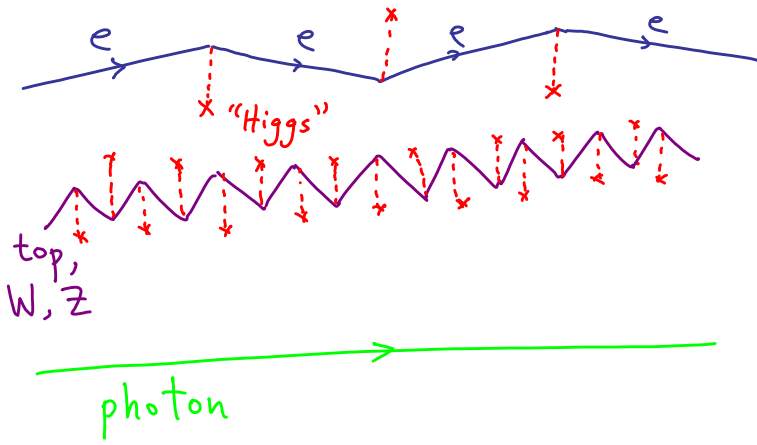


SIMILAR!

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



Origin of Mass



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

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

{ NOT ACCURATE! }

The Real Story

Amazing difference between massive + massless particles with spin:

massive

$S = 1$



3 polarizations

massless



2 polarizations

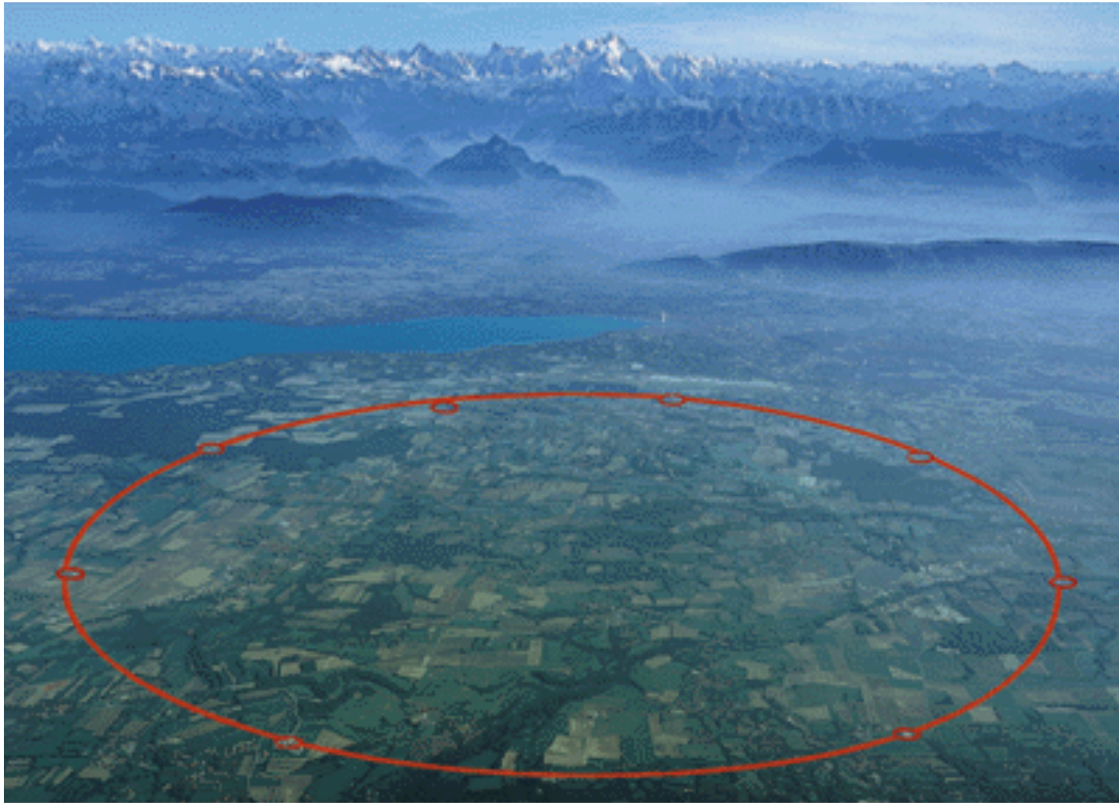
The extra degrees of freedom
for W, Z particles have to
come from somewhere!

Also: the "third" polarization behaves
very badly @ high-energy ----

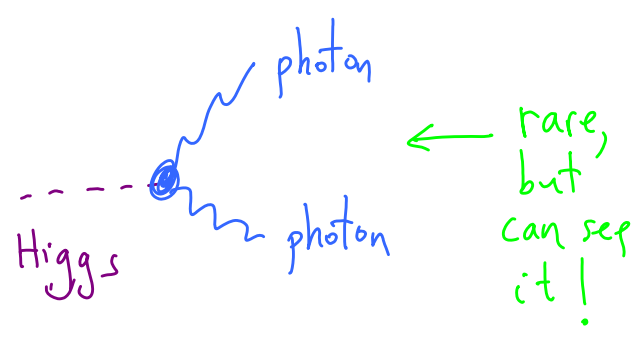
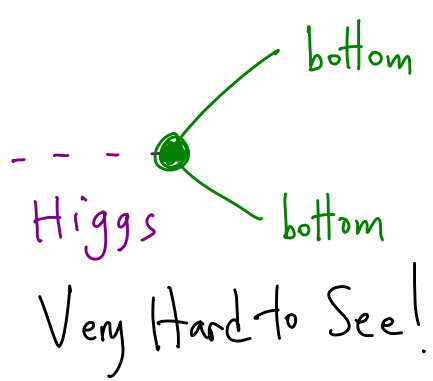
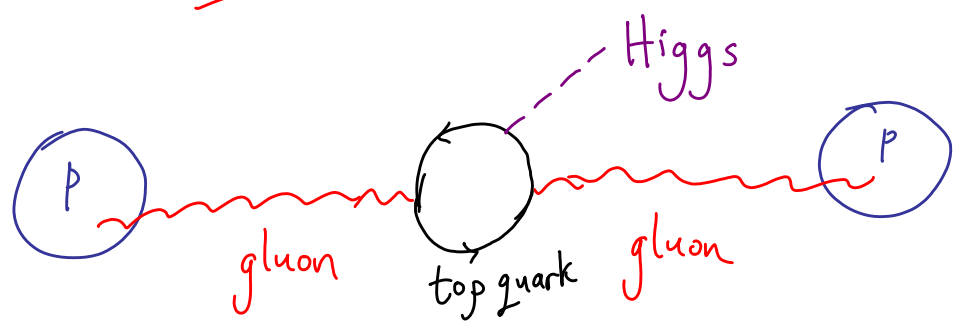
..... A theory that can be extrapolated
to higher energies, without breaking down,
needs something else!

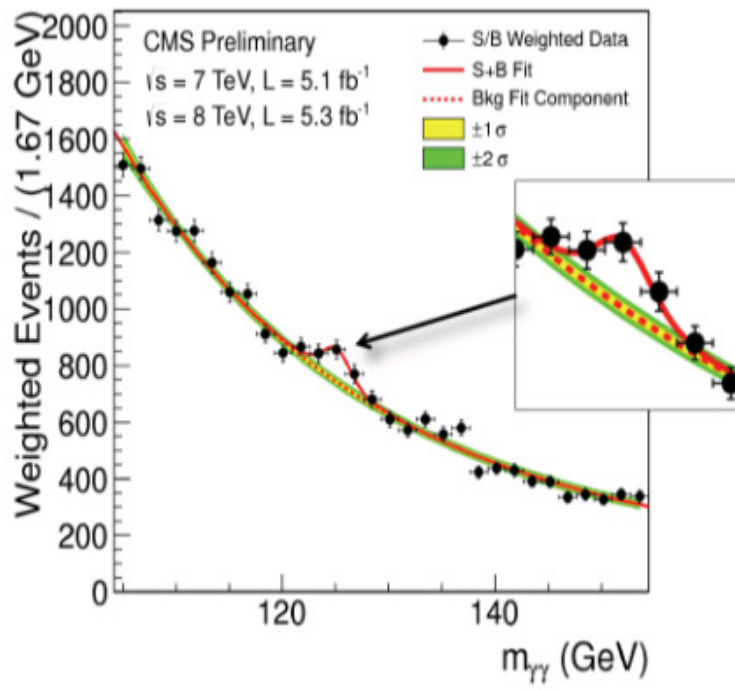
... That's the Job of the Higgs.....

In fact, it is very surprising
that something as simple as the
Higgs should be @ work here.....
but detailed calculations + precise measurements
in early 90's \rightarrow Higgs between
 $\sim 90 \rightarrow 150$ GeV.

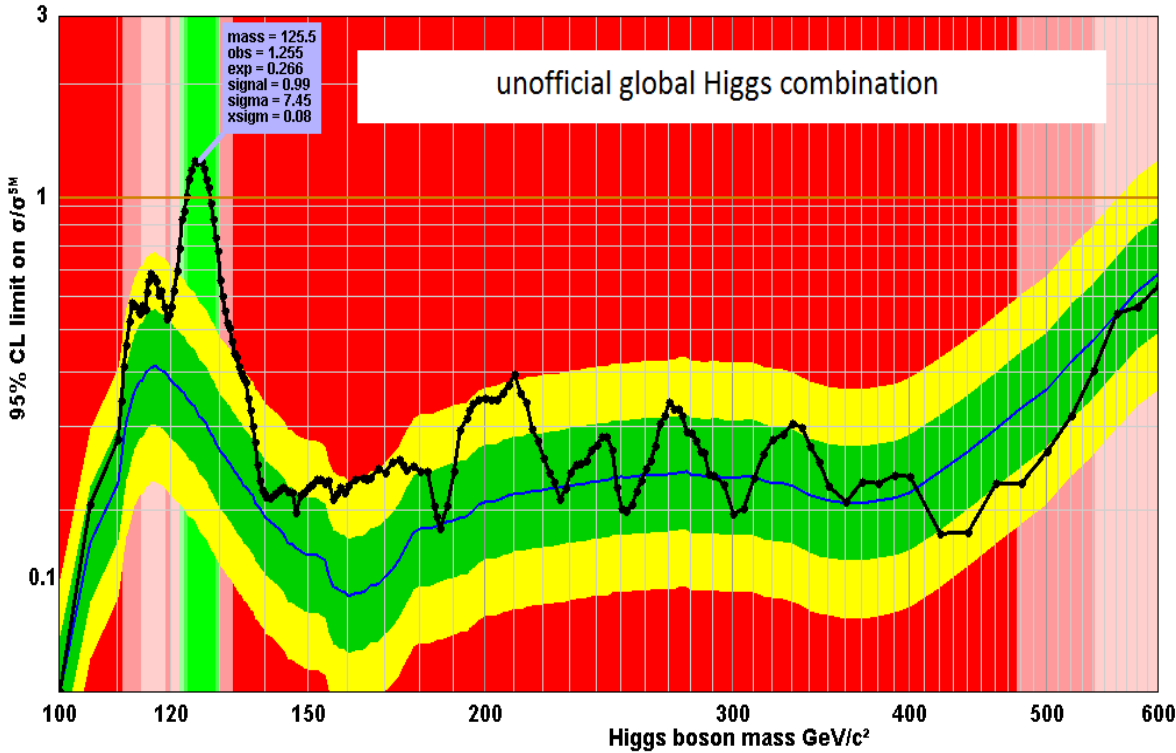


Higgs at the LHC





There
it
is!



YES!

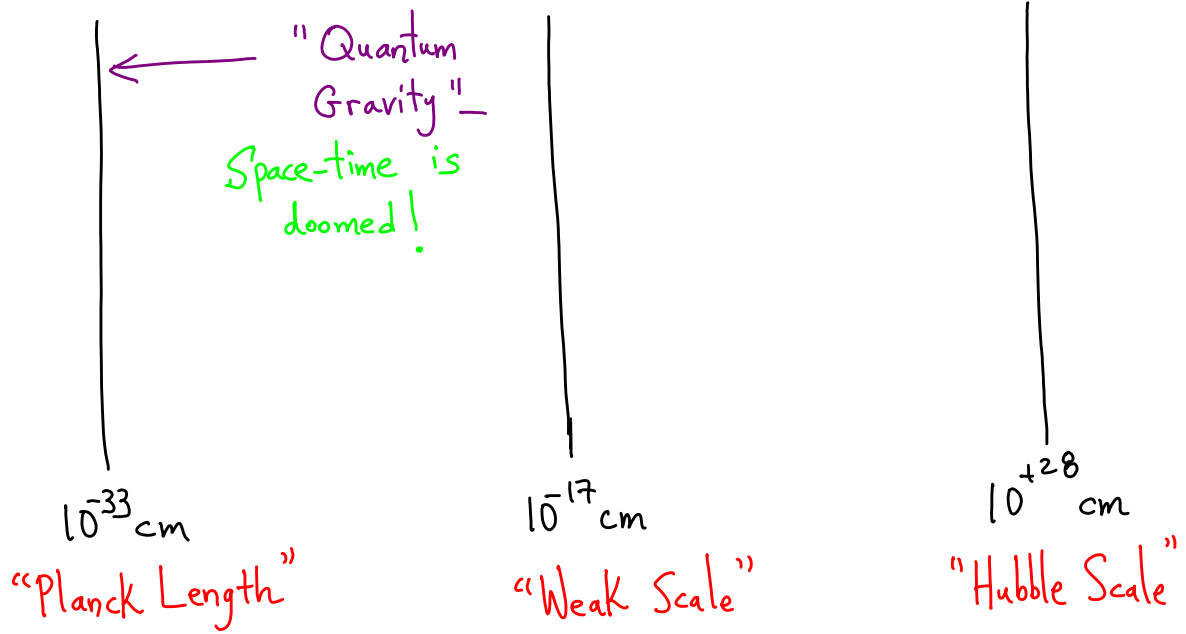
This is a TRIUMPH

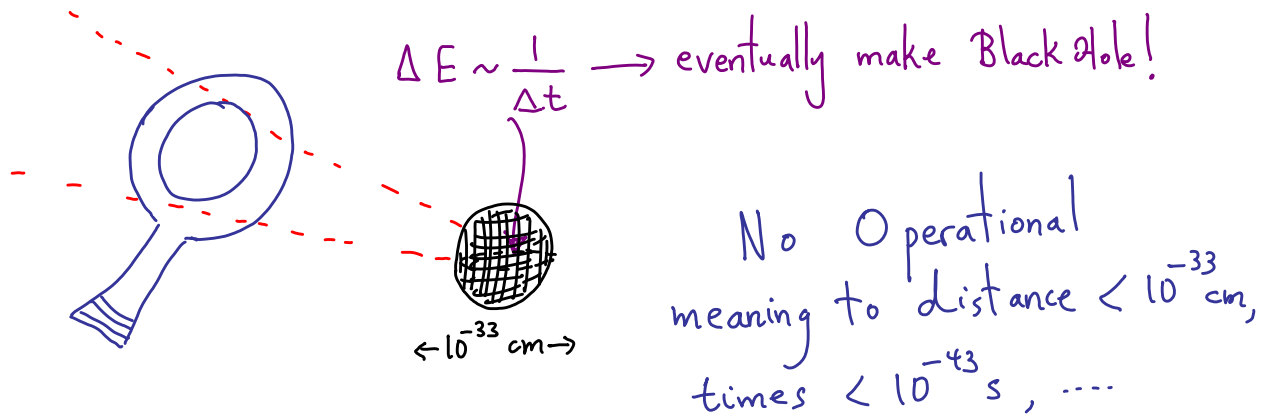
For Fundamental Physics -

PHYSICS WORKS!

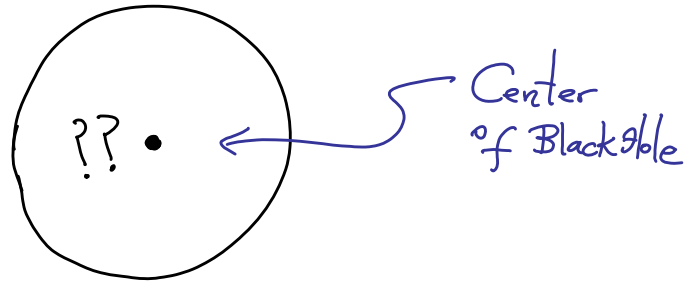
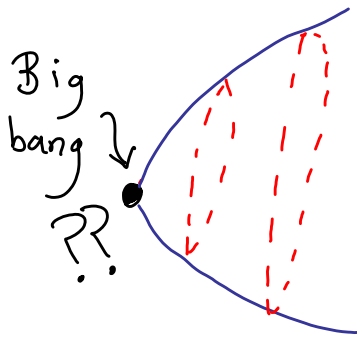
Space-Time is Doomed -

What Replaces It?



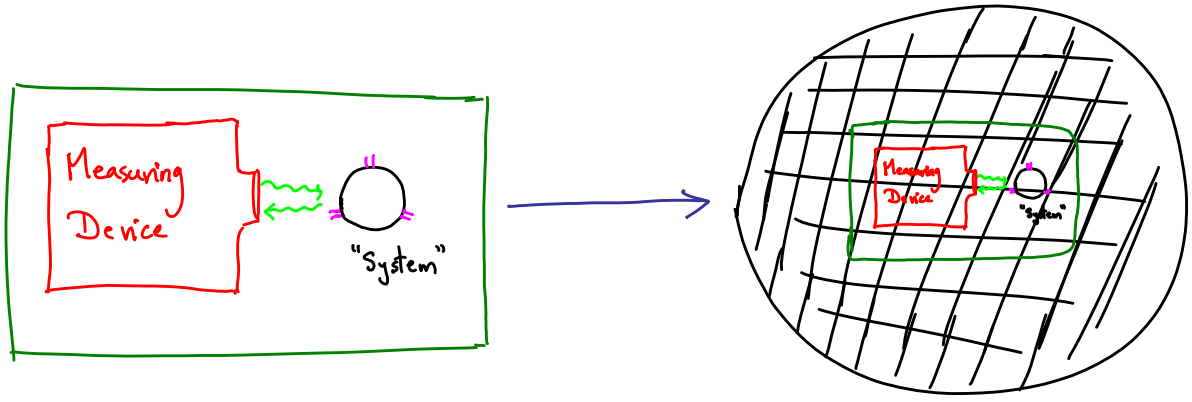


End of Space-Time



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

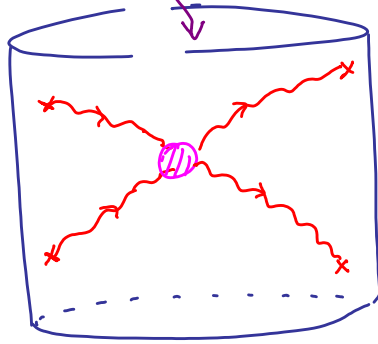
No Local Observables!



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

Emergent
Space, Gravity,
Strings ...

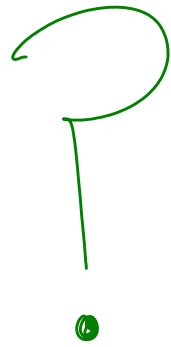
↑
time



“Anti-de Sitter
Space”

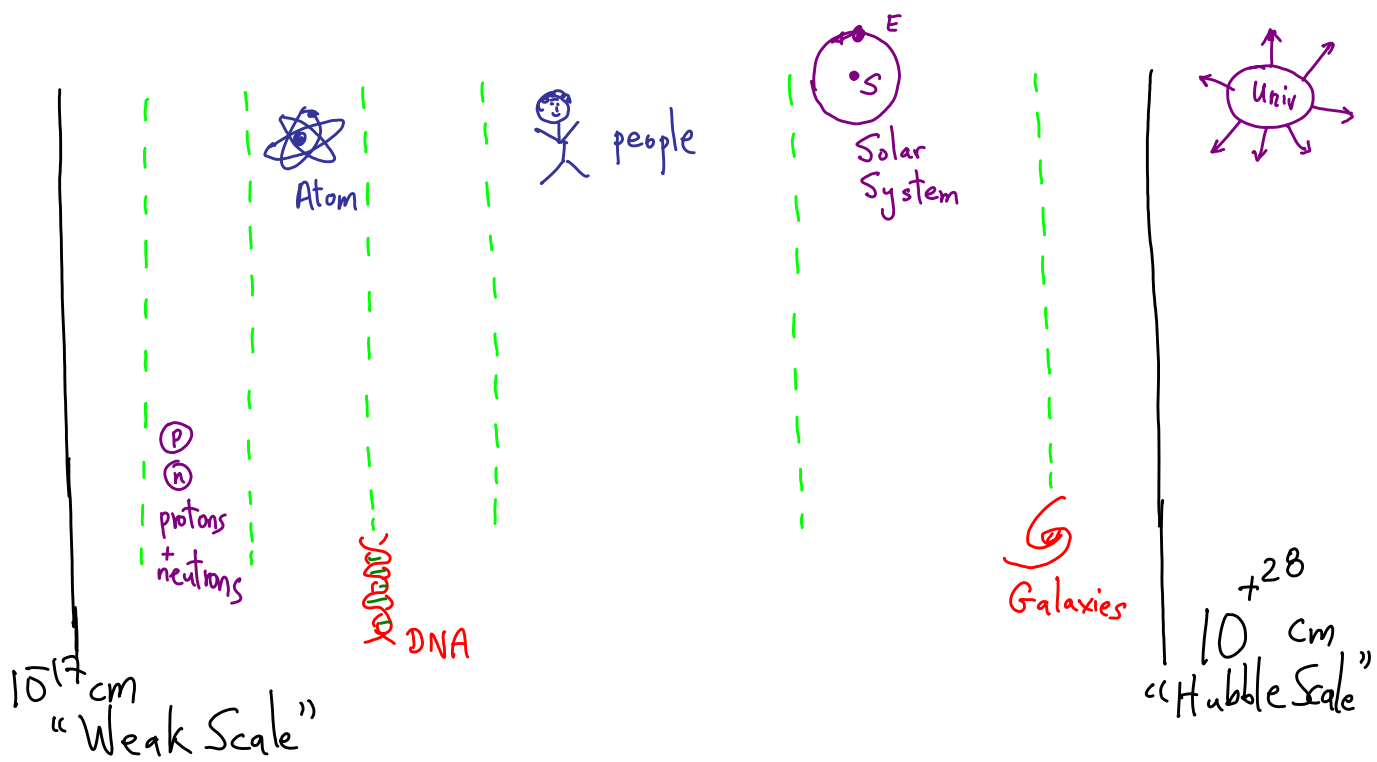
$$\text{String Theory (weak)} = \text{Particle Physics (strong)}$$

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



Why is there a

Macroscopic Universe?



10^{-33} cm

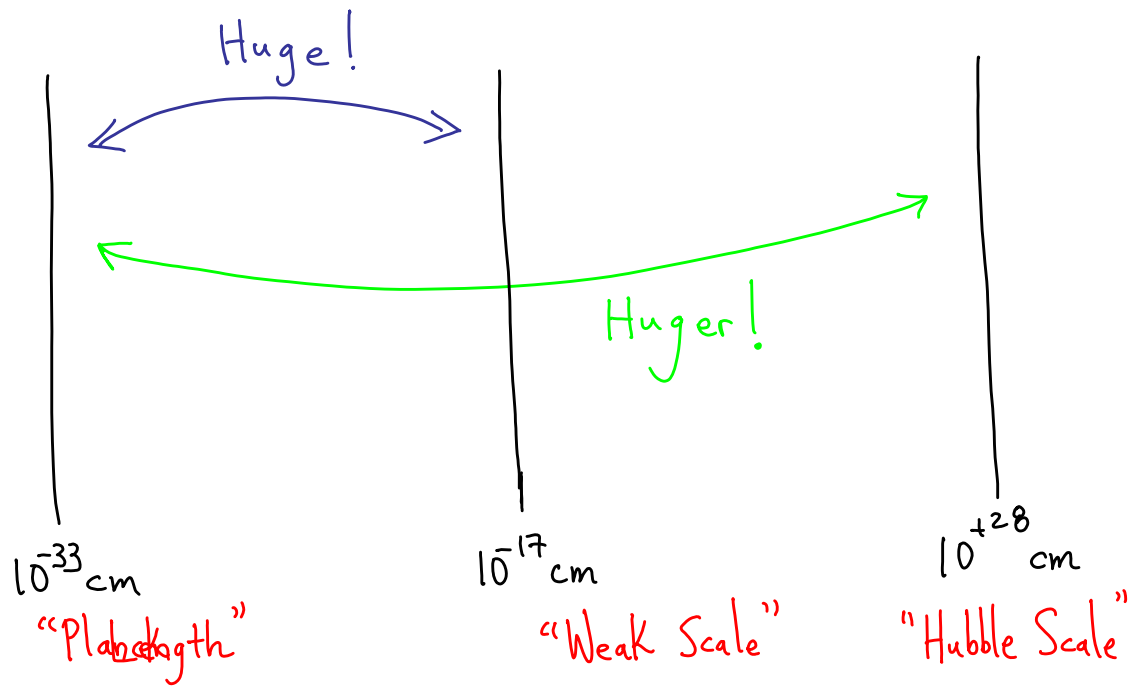
"Planck Length"

10^{-17} cm

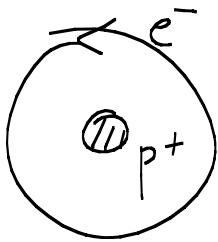
"Weak Scale"

10^{+28} cm

"Hubble Scale"



Atomic Structures



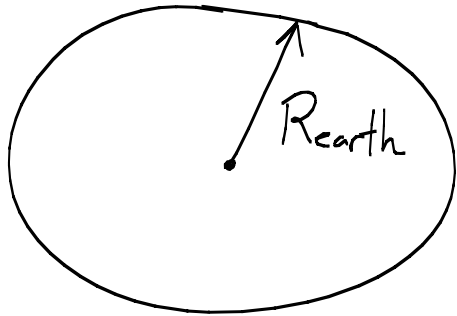
$$\frac{e^2}{4\pi r} \sim \left(\frac{1}{r}\right)^2 \frac{1}{2m} \Rightarrow r_{\text{atom}} \sim \alpha^{-1} m_e^{-1}$$
$$E_{\text{atom}} \sim \alpha^2 m_e$$

$$N_{\text{matter}} \sim \alpha^3 m_e^3, \quad \rho_{\text{matter}} \sim (\alpha^3 m_e^3) m_p$$

$$\rho_{\text{matter}} \sim \frac{E_{\text{atom}}}{V_{\text{atom}}} \sim (\alpha^5 m_e^4)$$

$$C_s^2 \text{ matter} \sim \frac{\rho_{\text{matter}}}{\rho_{\text{matter}}} \sim \left(\alpha^2 \frac{m_e}{m_p}\right)$$

Macro-Structures



$$P_{\text{grav}} \sim P_{\text{matter}}$$

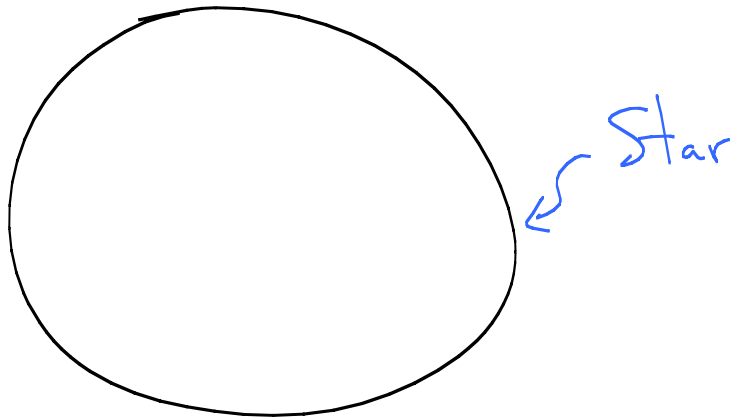
$$\frac{G(\rho R^3)^2}{R \cdot R^3}$$

$$\propto 5 m_e^4$$

$$R_{\text{earth}} \sim \underbrace{(\alpha^{-1} m_e^{-1})}_{r_{\text{atom}}}$$

$$\sqrt{\frac{\alpha}{(m_p^2 / M_{\text{pl}}^2)}}$$

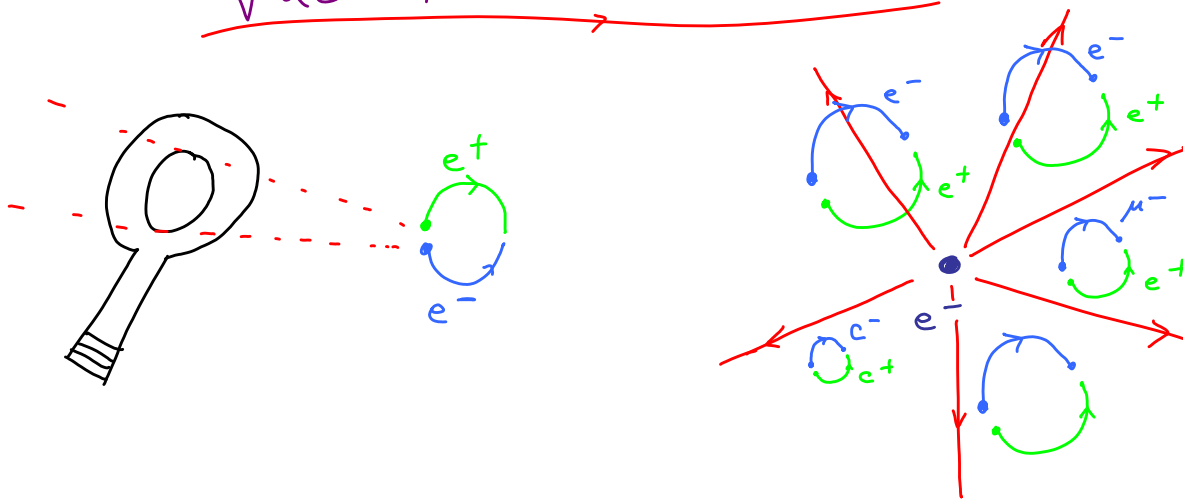
Weakness
of
Gravity!



$$N_{\text{photons}} \sim [G_N m_p^2]^{3/2} \sim 10^{57} !$$

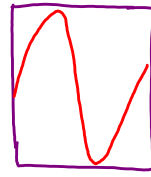
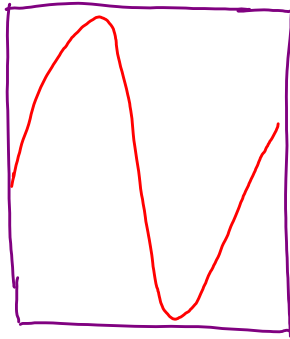
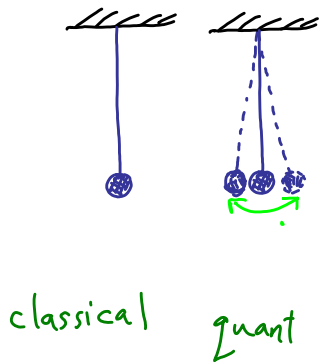
↑
Weakness of Gravity

"Vacuum" is Exciting!



Too Exciting!

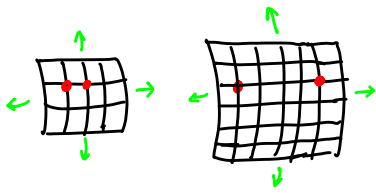
Even Vacuum has energy!



Bigger Fluctuations at Shorter Distances

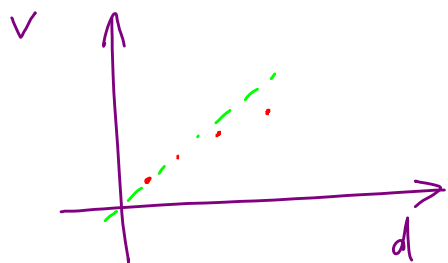
Estimating Λ

"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!

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

Biggest Error in History of Physics
Science

What We Do

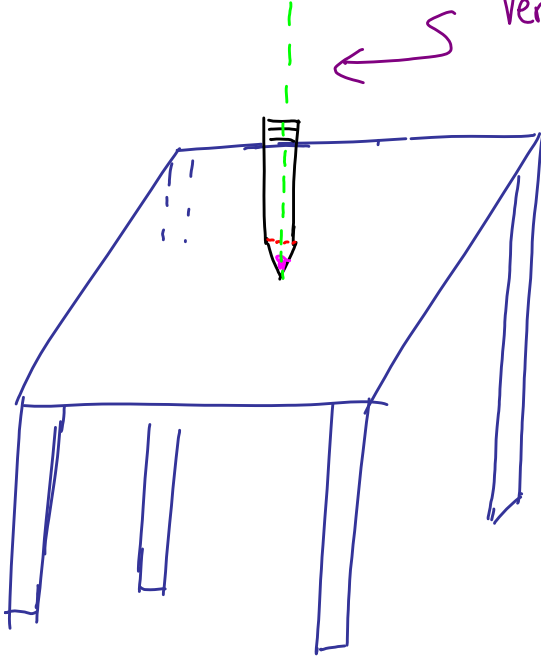
$$\Delta_{\text{observed}} = \Delta_{\text{classical}} + \Delta_{\text{Quantum}}$$

$$\begin{array}{ccc} \uparrow & & \uparrow \\ -2.6493781 \dots 526 \dots & + & 2.6493781 \dots 534 \dots \\ \underbrace{\hspace{10em}}_{120 \text{ decimals}} & & \underbrace{\hspace{10em}}_{120 \text{ decimals}} \end{array}$$

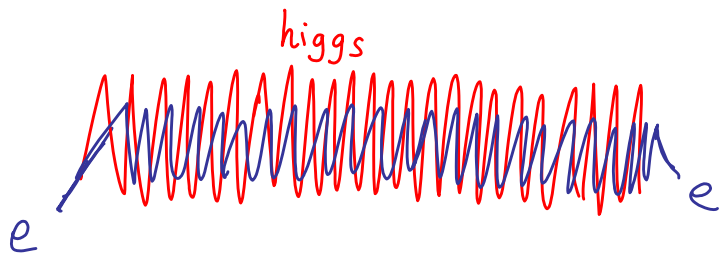
LUDICROUS!

"Fine Tuning"

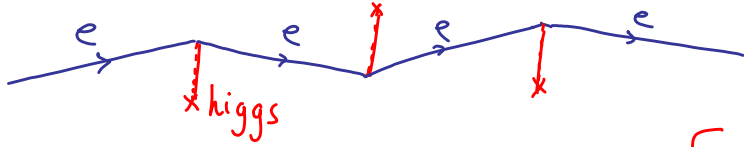
Vertical to accuracy 10^{-120} degrees!



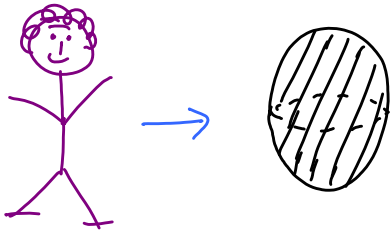
[Why is the Universe Big?]



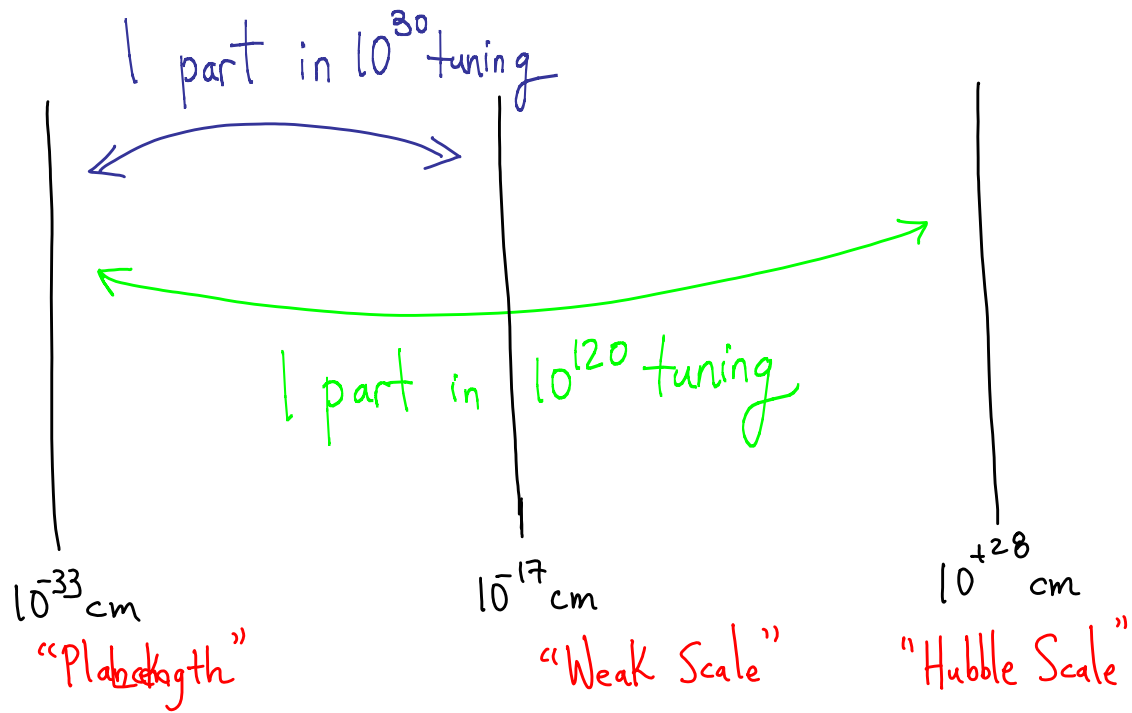
← Estimated distance between collisions $\sim 10^{-33}$ cm, vs

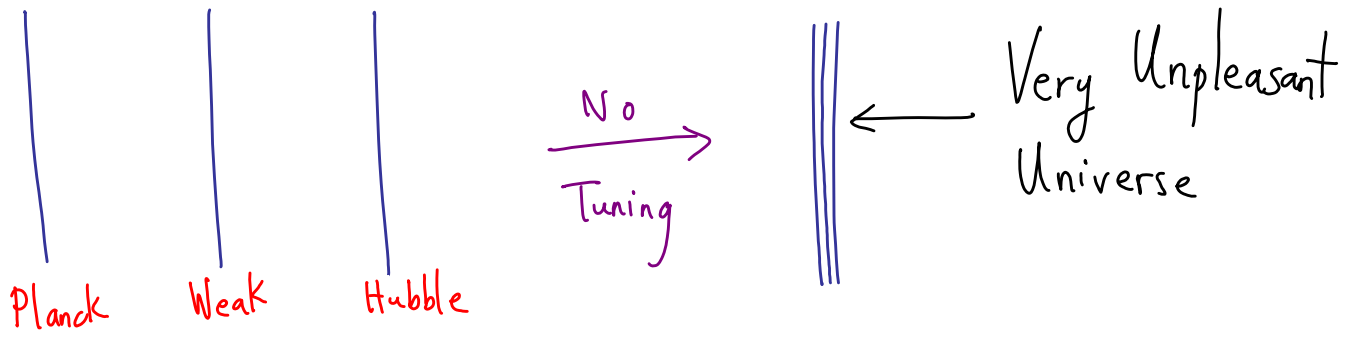


← Observed 10^{-17} cm



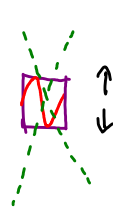
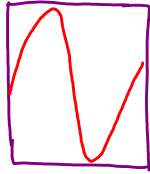
[Why is Gravity Weak?]





What Controls Violent Fluctuations of the Vacuum?
Why is There a Macroscopic Universe?

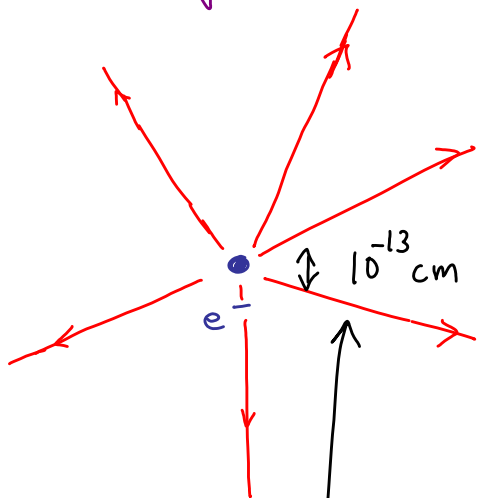
New Physics around the Corner?



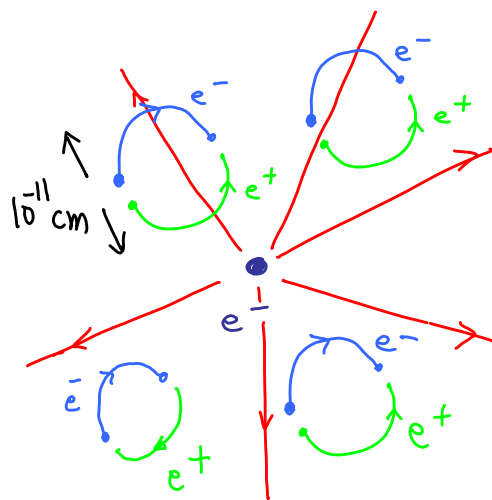
10^{-17} cm

Something new needs to happen here!

Infinite Energy In Electric Field

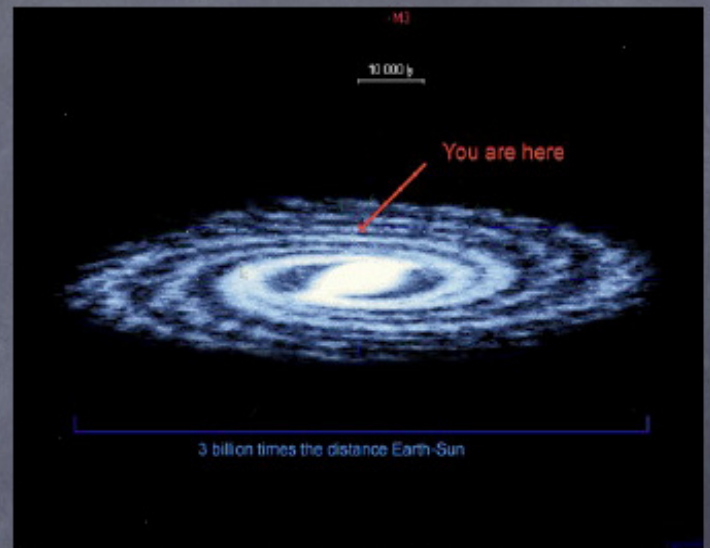
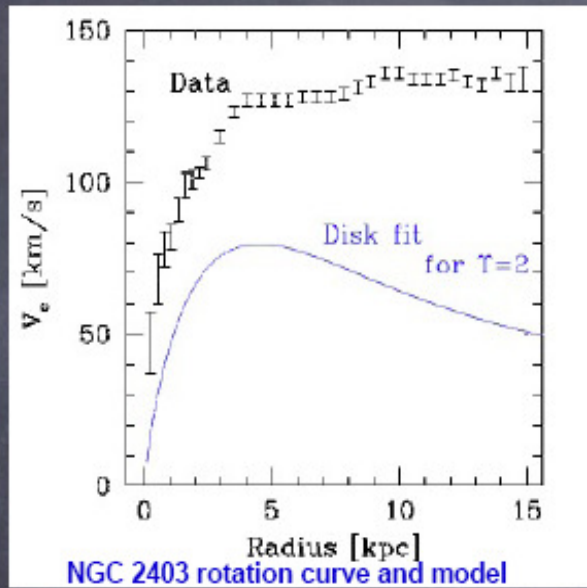


Q.M.
Rel.

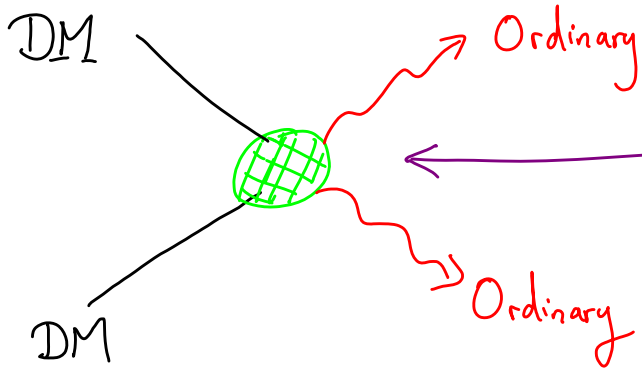


Something new by this scale

Evidence for dark matter...

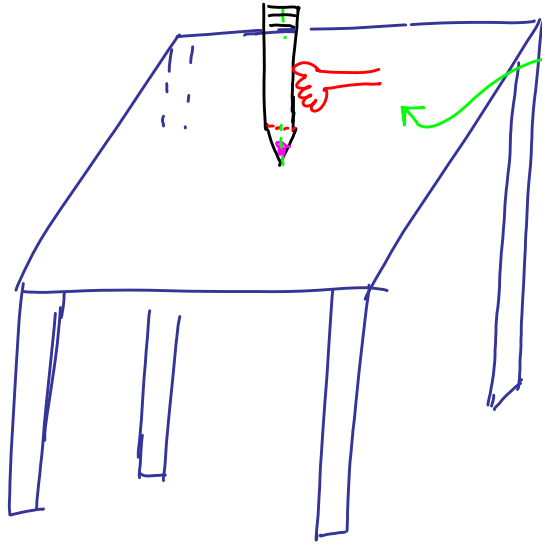


"WIMP Miracle"



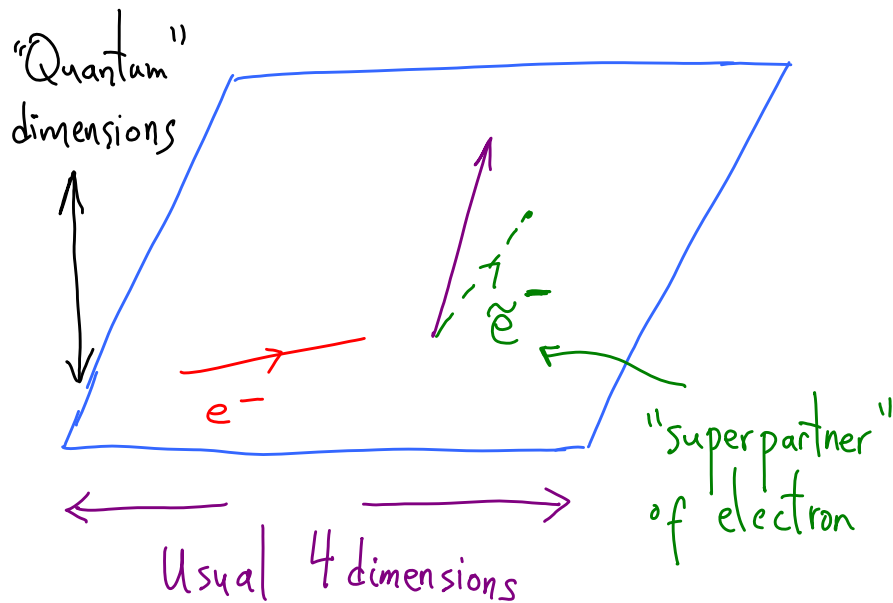
Needed range
of interaction —
weak scale ($\sim 10^{-17}$ cm)!

What Could It Be?



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

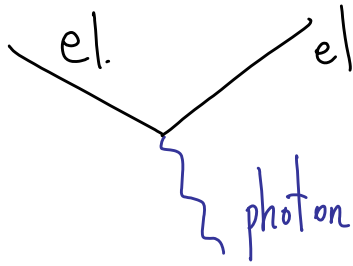
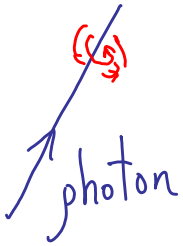
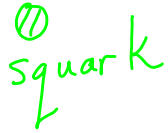
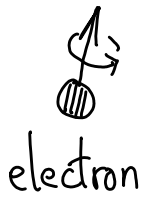
Supersymmetry



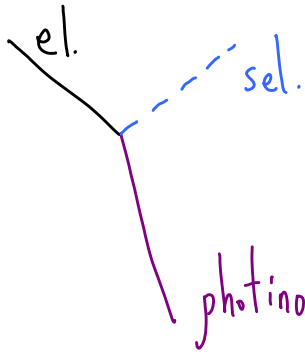
$d_x^{\text{Quantum}}, d_y^{\text{Quantum}}, \dots$

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

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



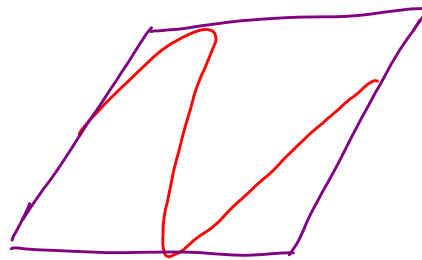
||



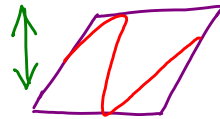
Symmetry
between
Ordinary +
Quantum
Dimensions

Violent
Quantum
Fluctuations

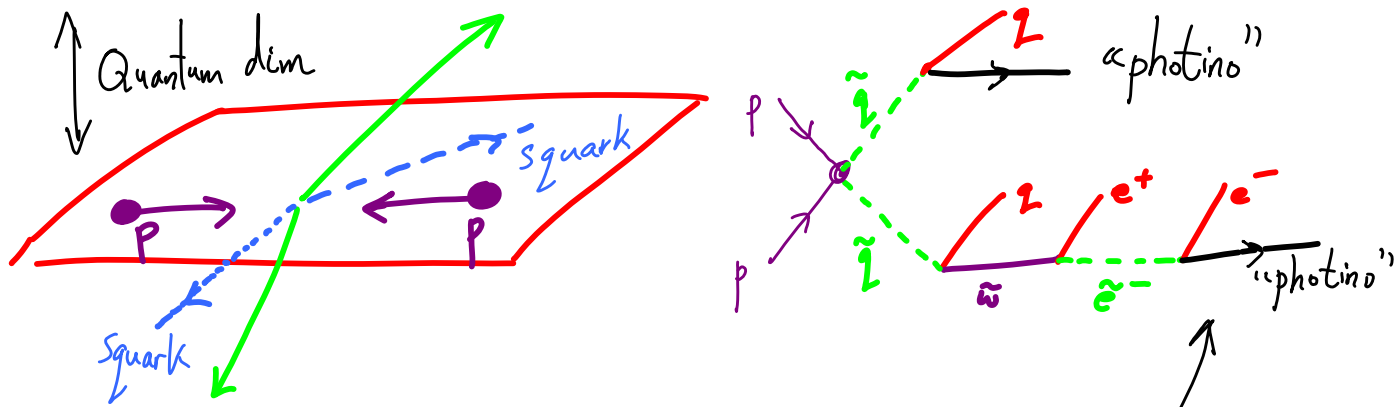
Gone
wmmm



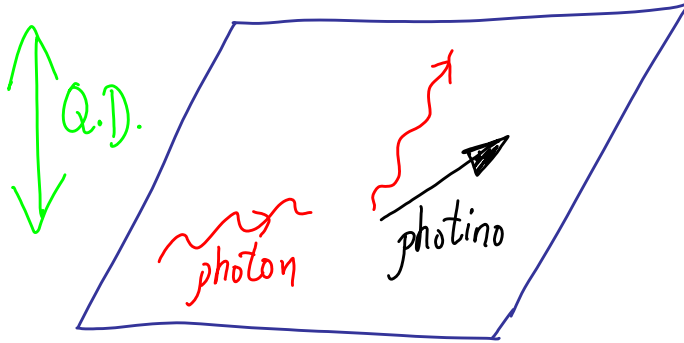
See Quant
dim.



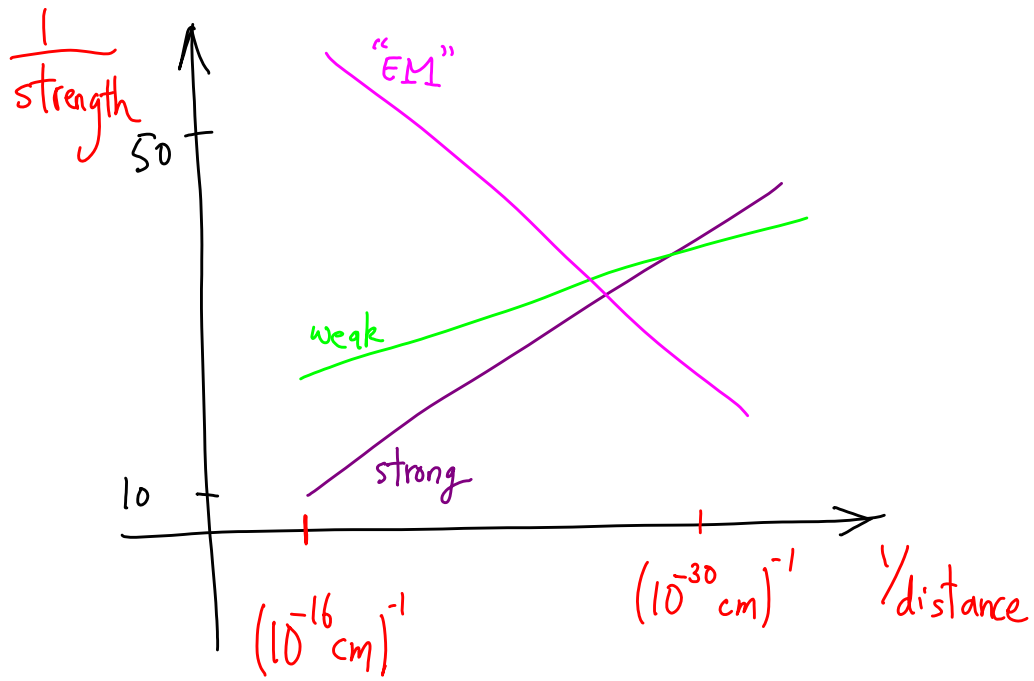
$\leftarrow 10^{-17} \text{ cm} \rightarrow$

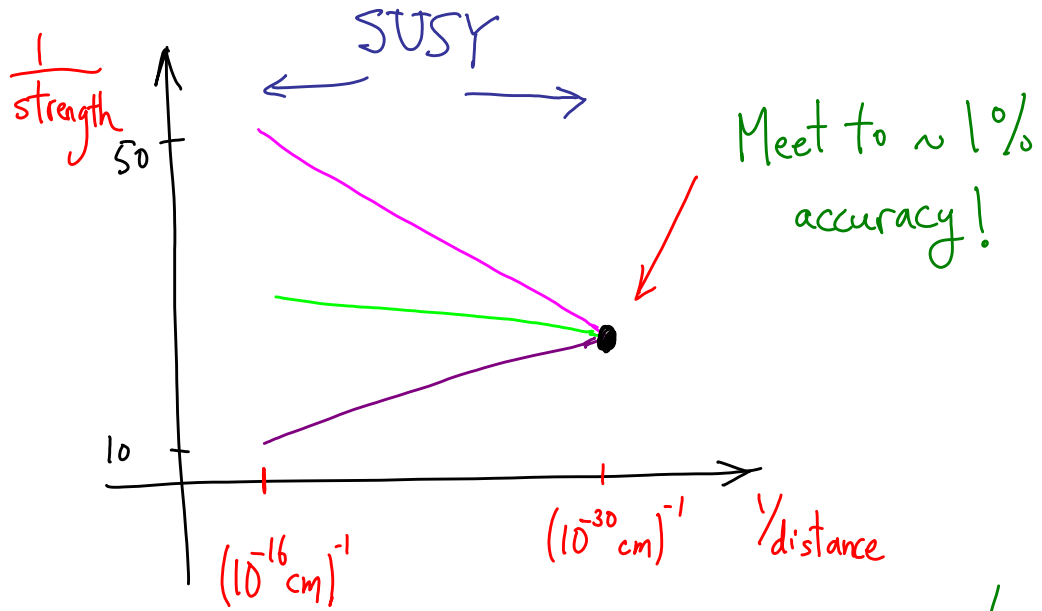


Neutral, very weakly interacting....



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





Unification of the Forces - Gravity not far behind!

Mr

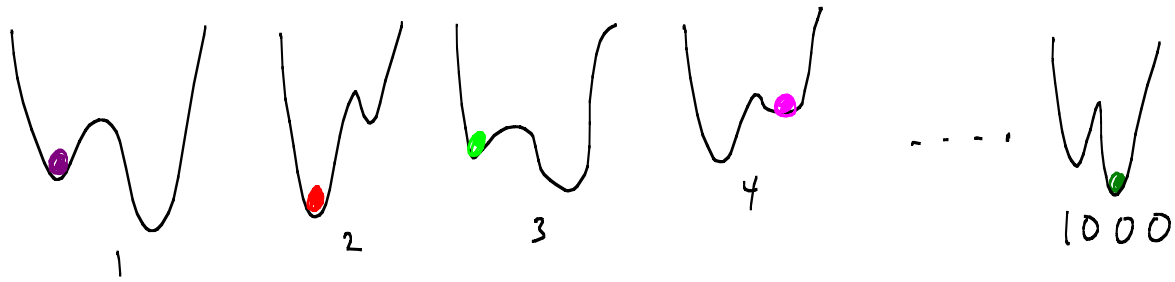
!

String Theory is "unique", **BUT**, it has
zillions of solutions.

pre-95 : zillions ~ millions
post-95 : zillions ~ $10^{1000's}$



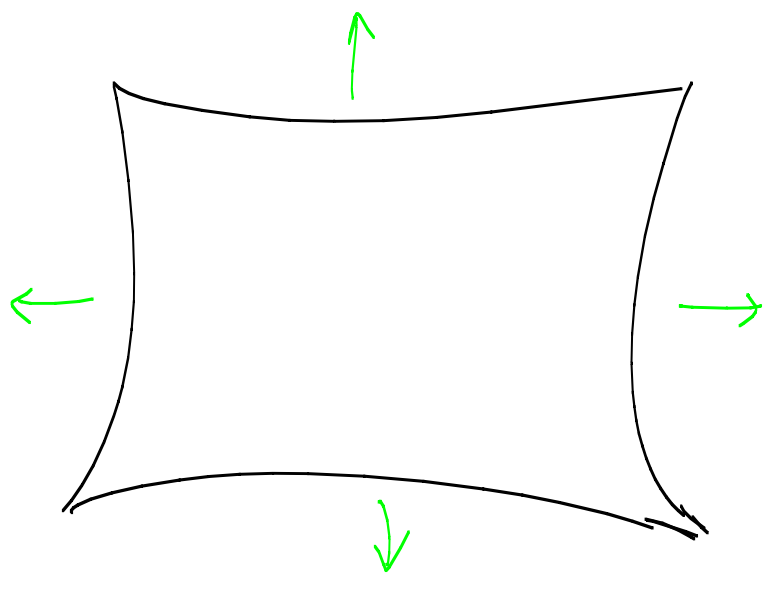
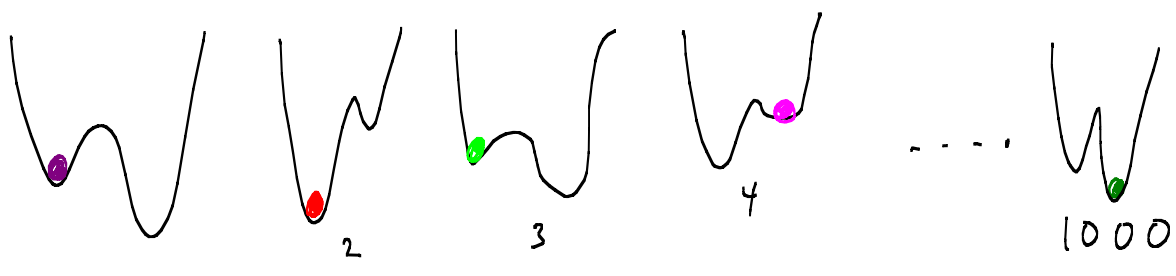
"STRING LANDSCAPE" = CONTROVERSIAL
SUBJECT



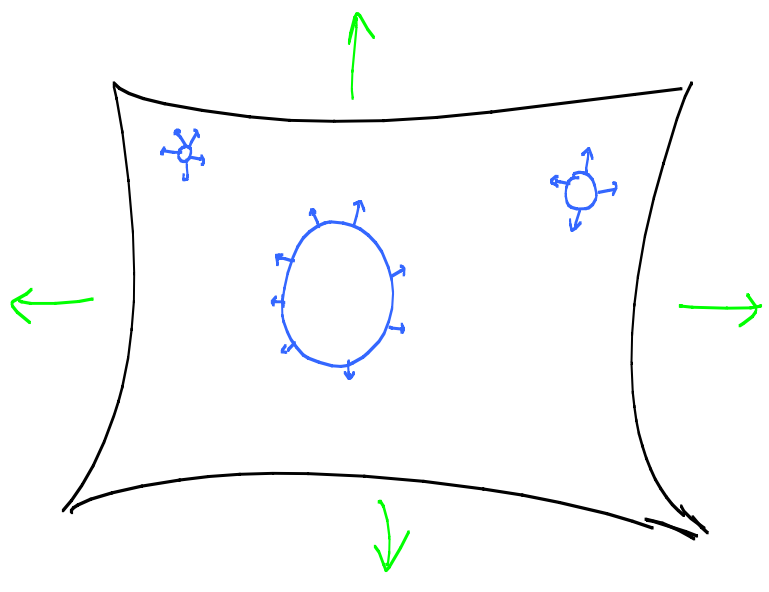
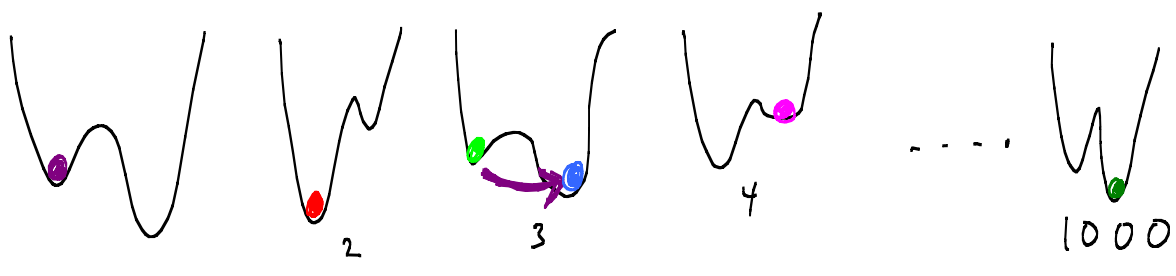
⇒ 2^{1000} different values of energy



Energy $\sim (\frac{1}{2})^{1000}$ — just statistically!

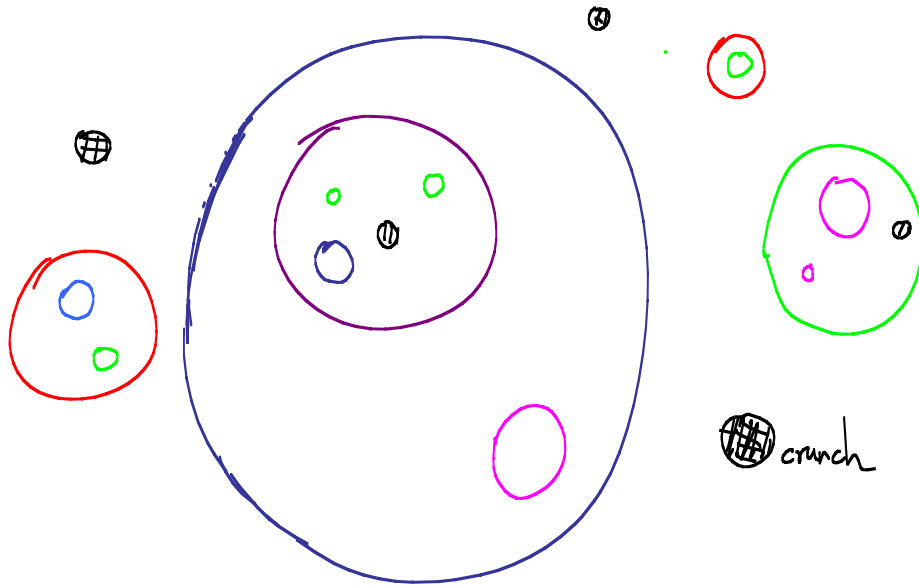


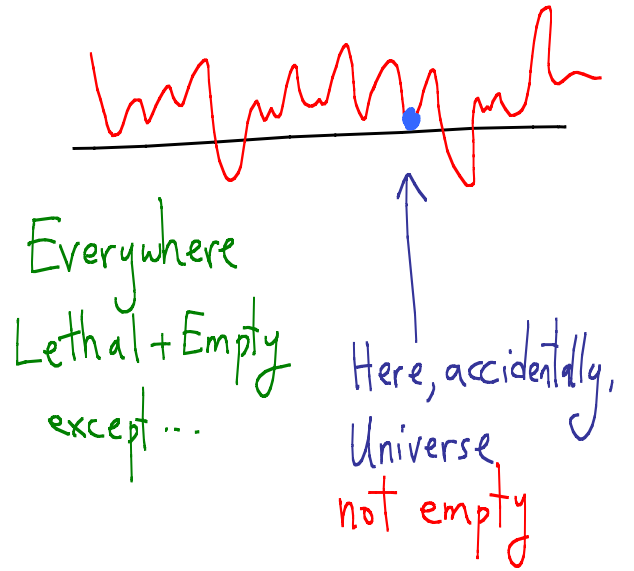
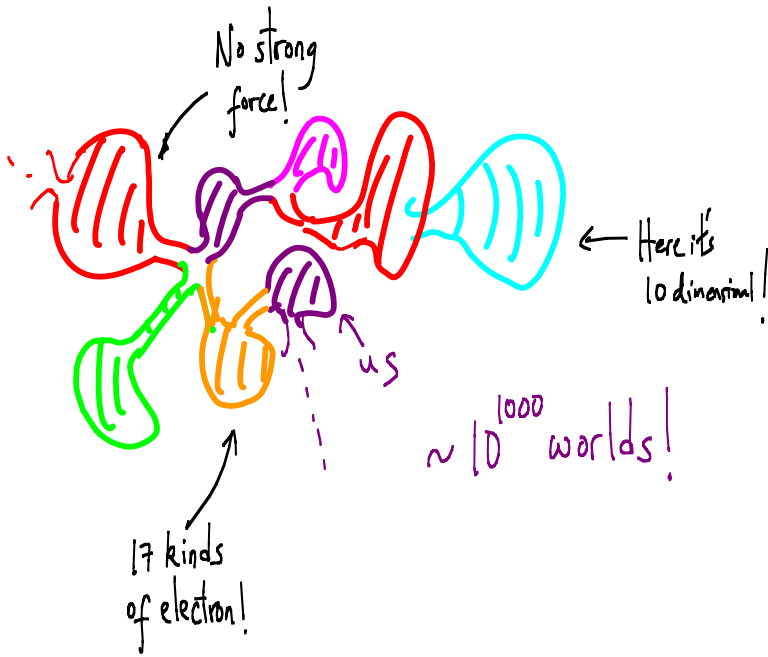
Inflating
like crazy

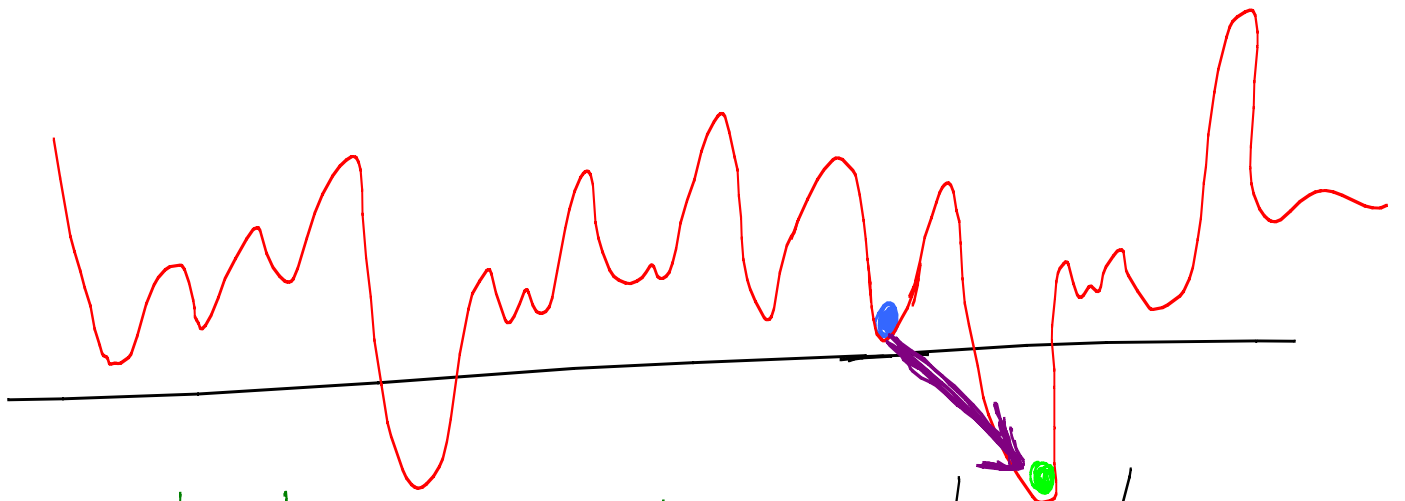


Inflating
like crazy

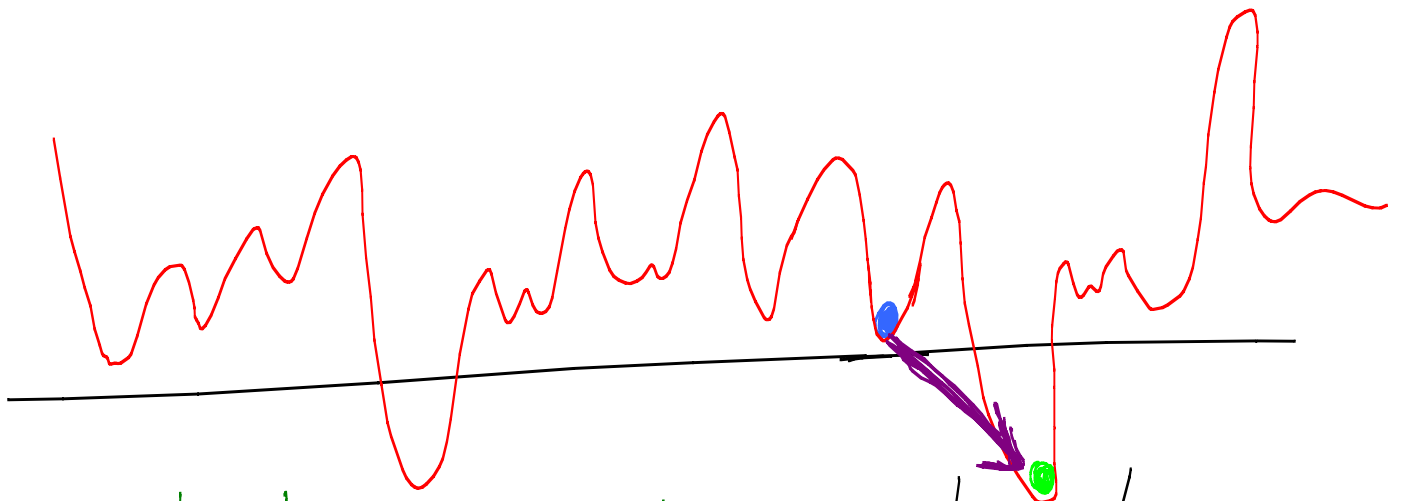
"Eternal Inflation" + The Multiverse







Catastrophic End - Tunnel into
a Big Crunch.



Catastrophic End - Tunnel into
a Big Crunch.

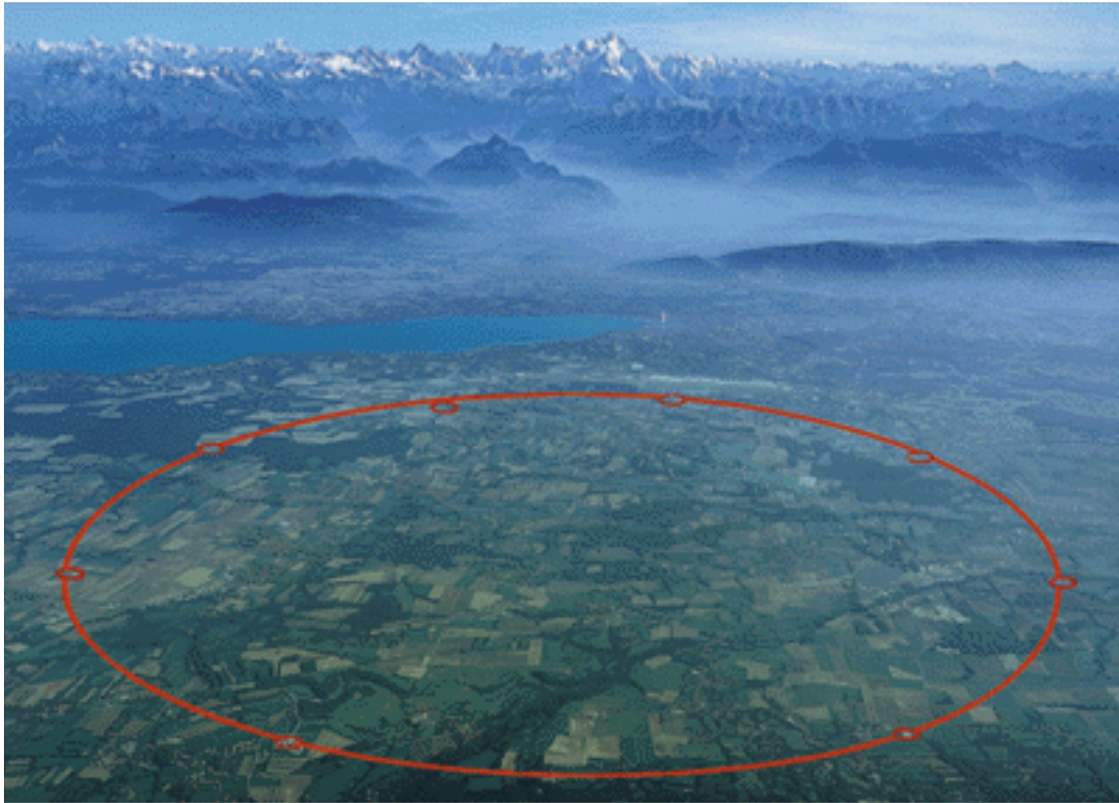
Are we tiny part of a Vast Multiverse?

• If true - modern Copernican Revolution!

• Conceptual Problem - how can we
"see" other universes - how can we
know that they're there?

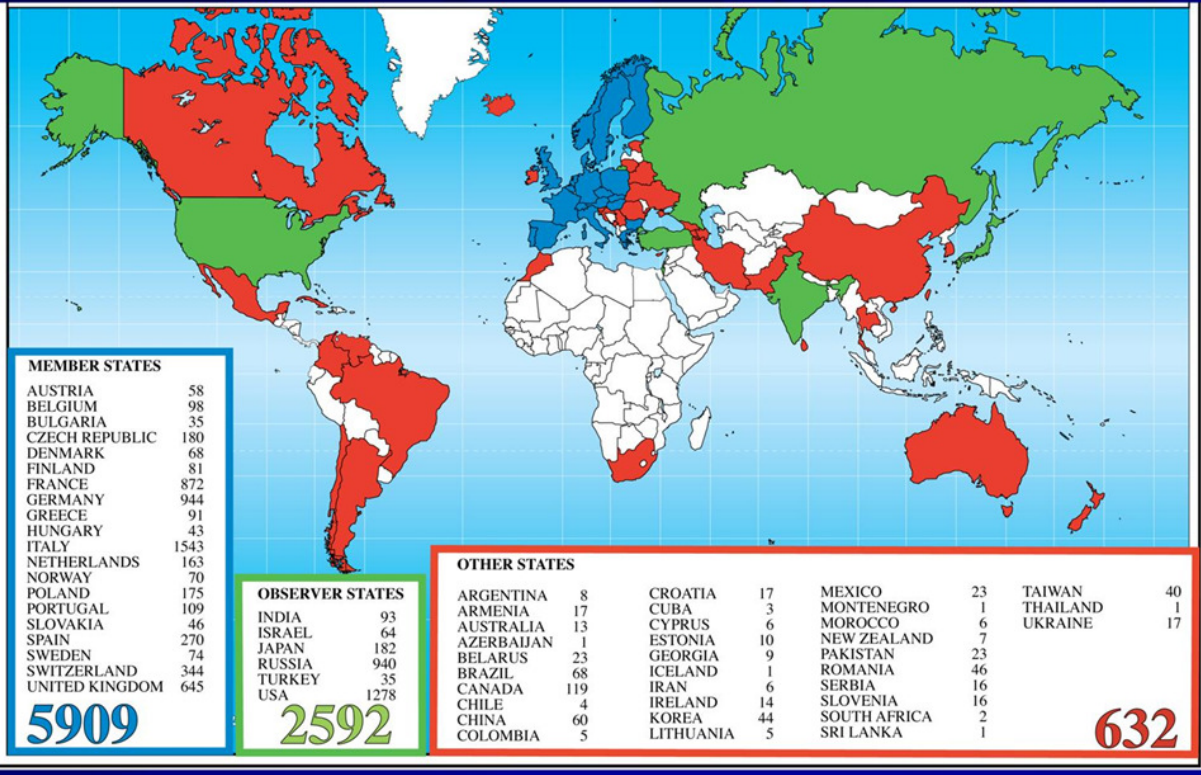
Experimental Frontier:

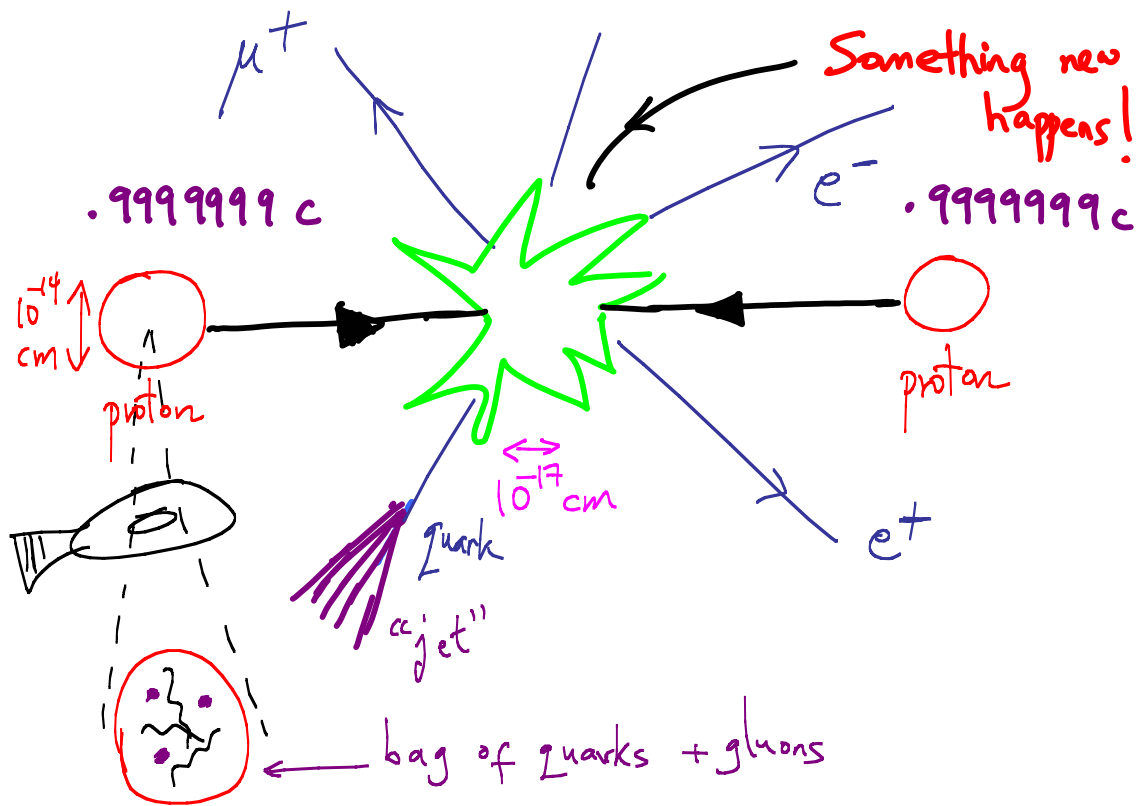
Large Hadron Collider





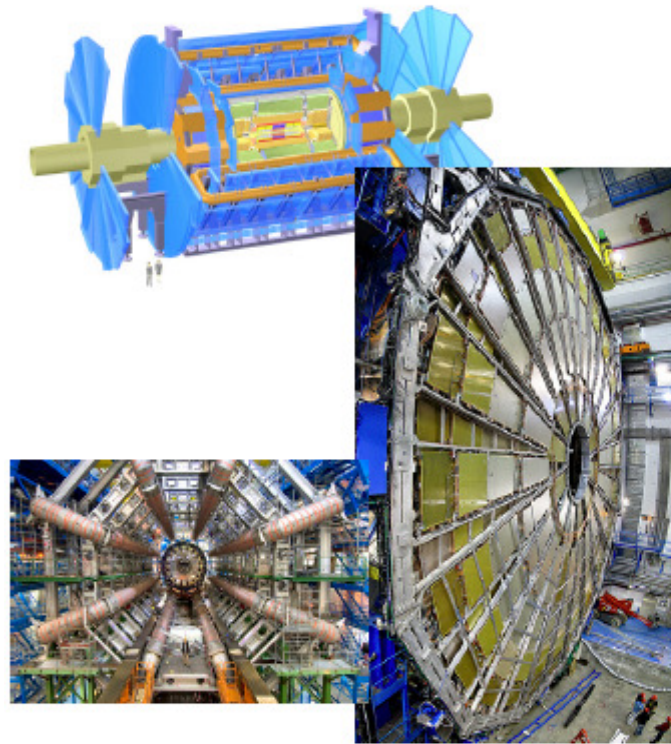
Distribution of All CERN Users by Nation of Institute on 5 February 2008



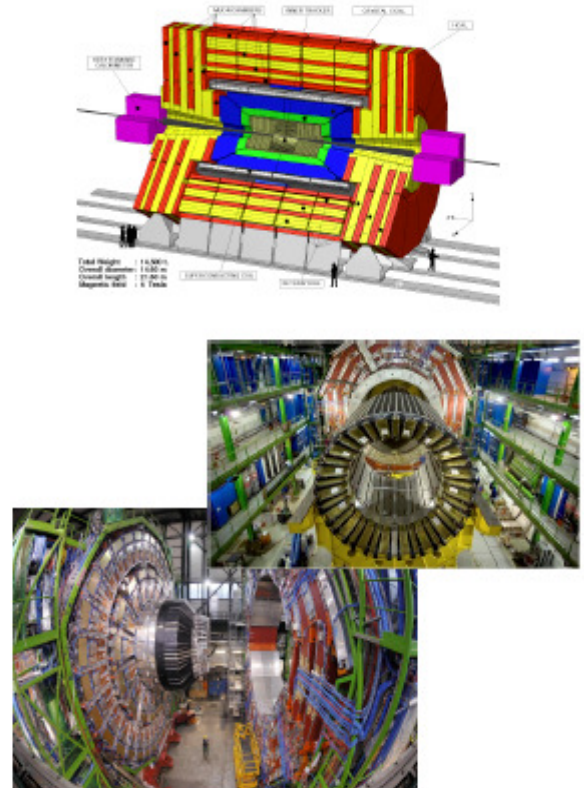


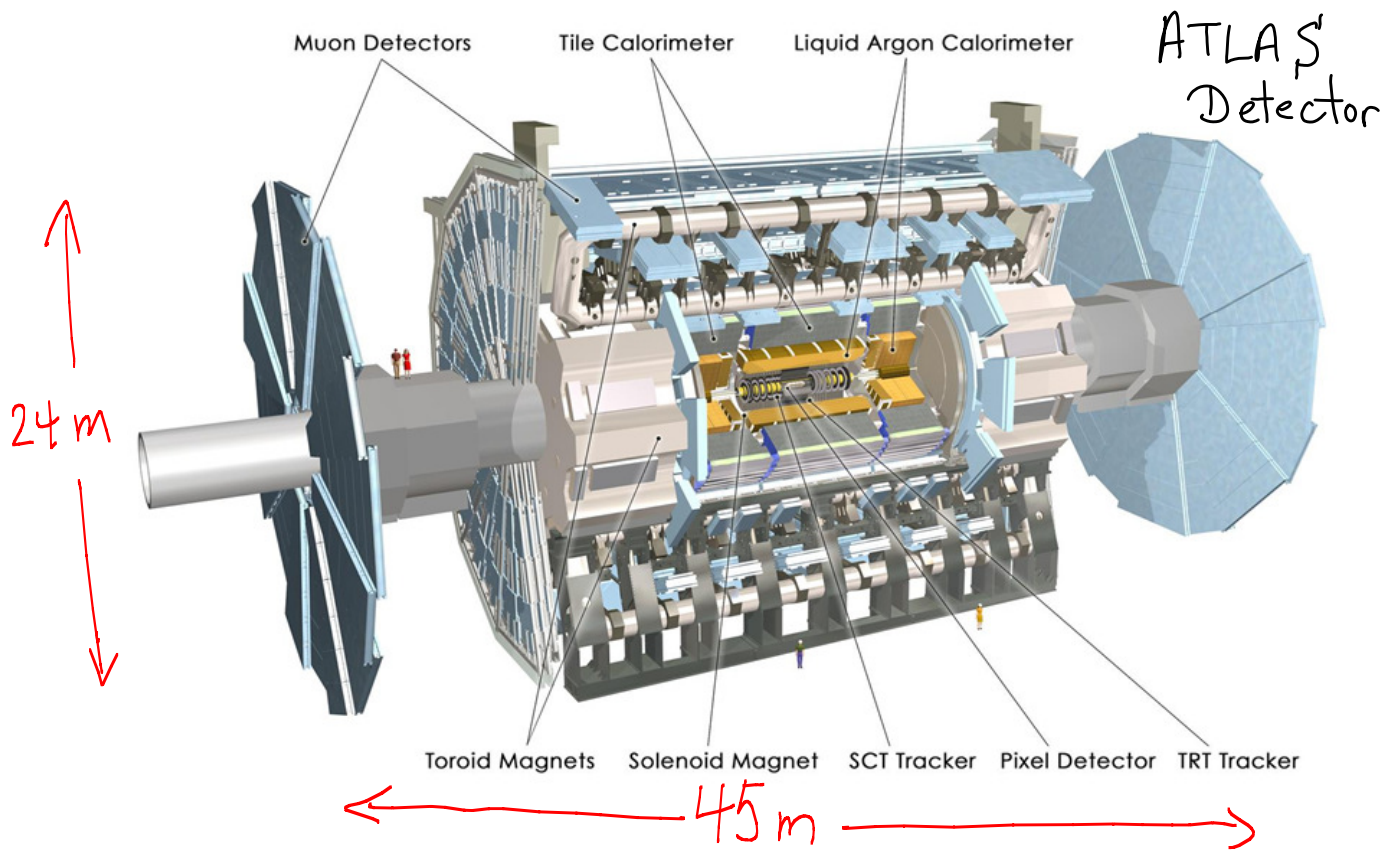
Particle Detectors

ATLAS



CMS





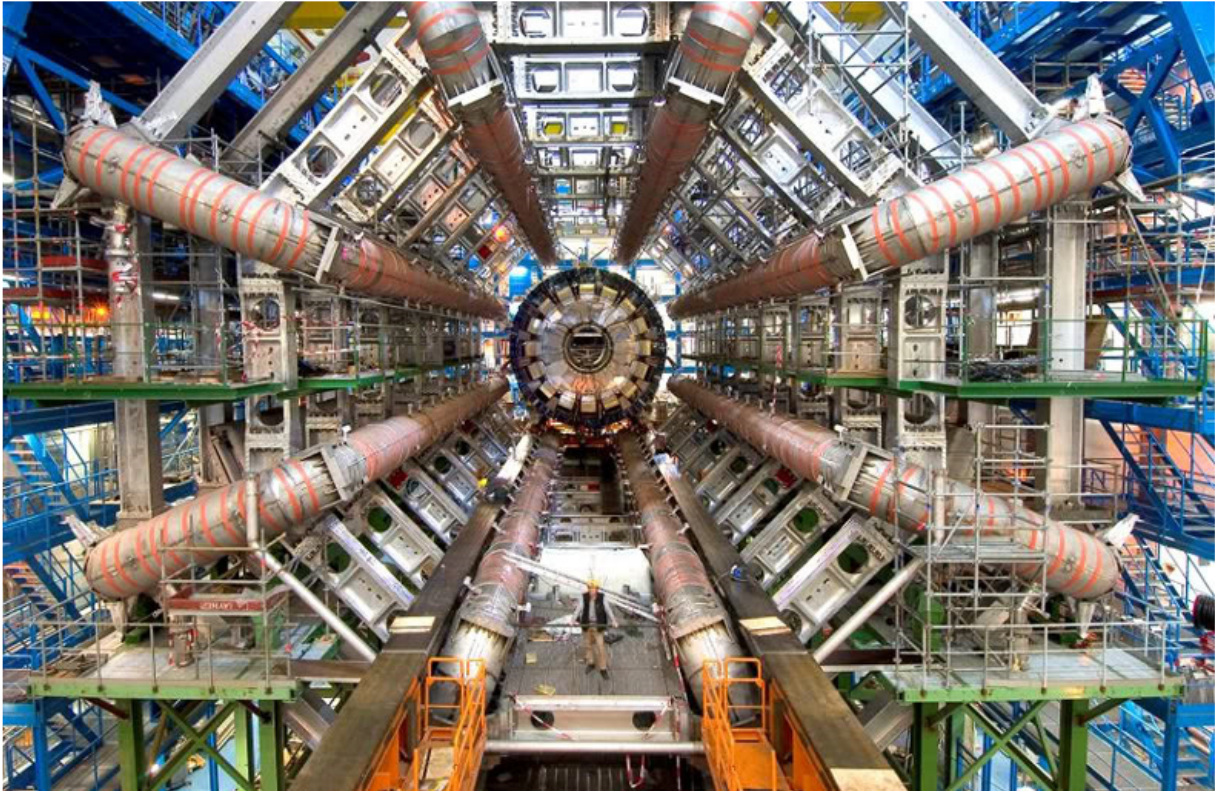
Collision Event at 7 TeV

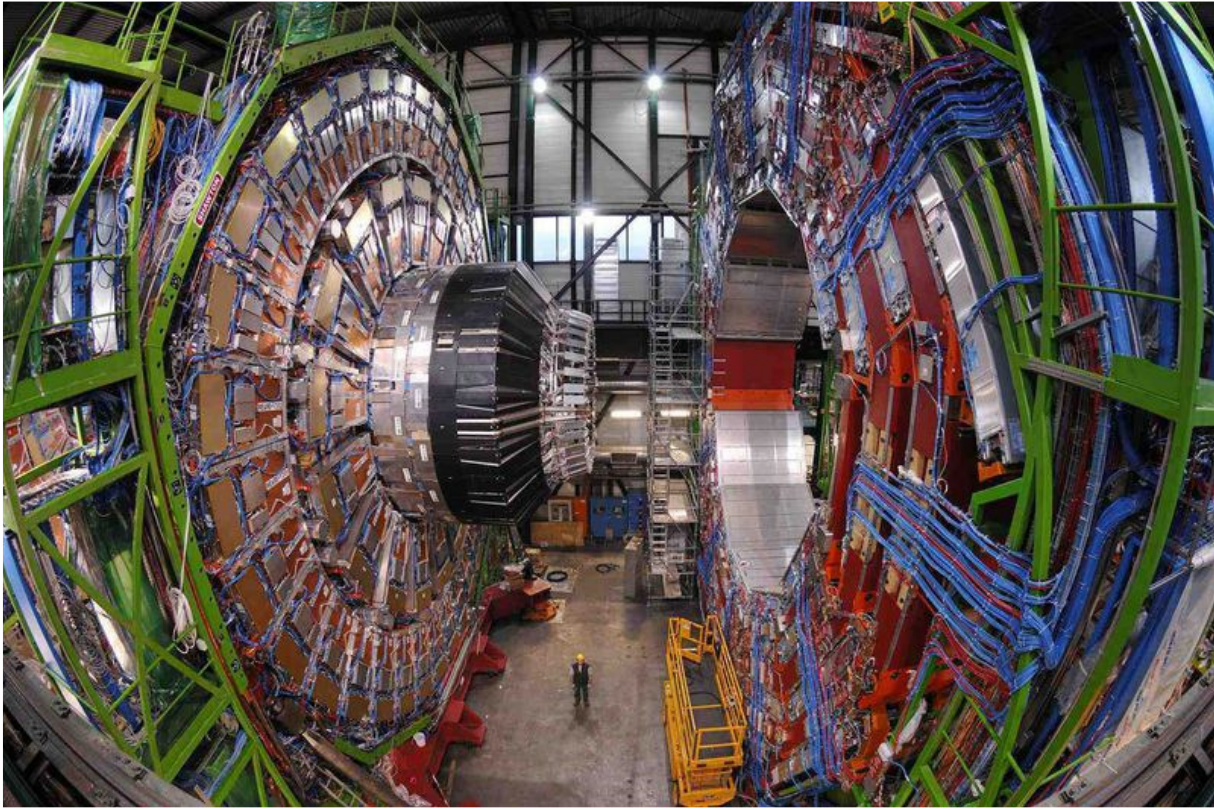


 **ATLAS**
EXPERIMENT

2010-03-30, 12:58 CEST
Run 152166, Event 316199

<http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html>





CMS
Detector

Underground Experiment Cavern

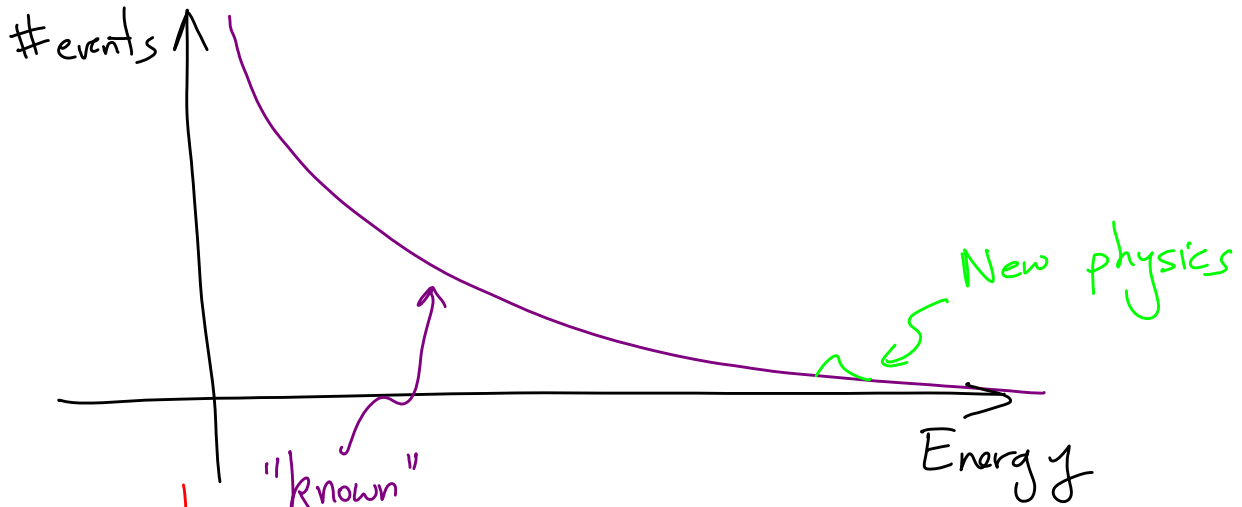


L.H.C. operations are now in
full swing - machine + detector
performance is spectacular!

Massive amount of information:

\sim Tbyte/s \rightarrow 10^{10} Zetabytes/yr!

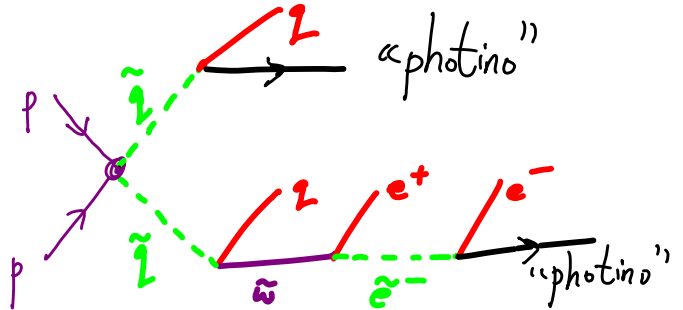
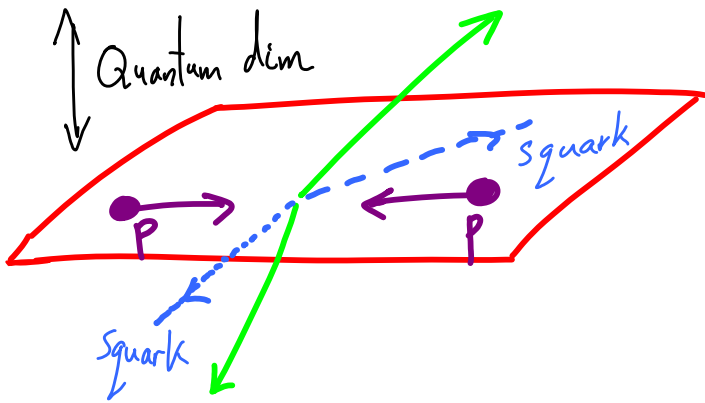
[Total other info on the planet ~ 10 Zb/yr].



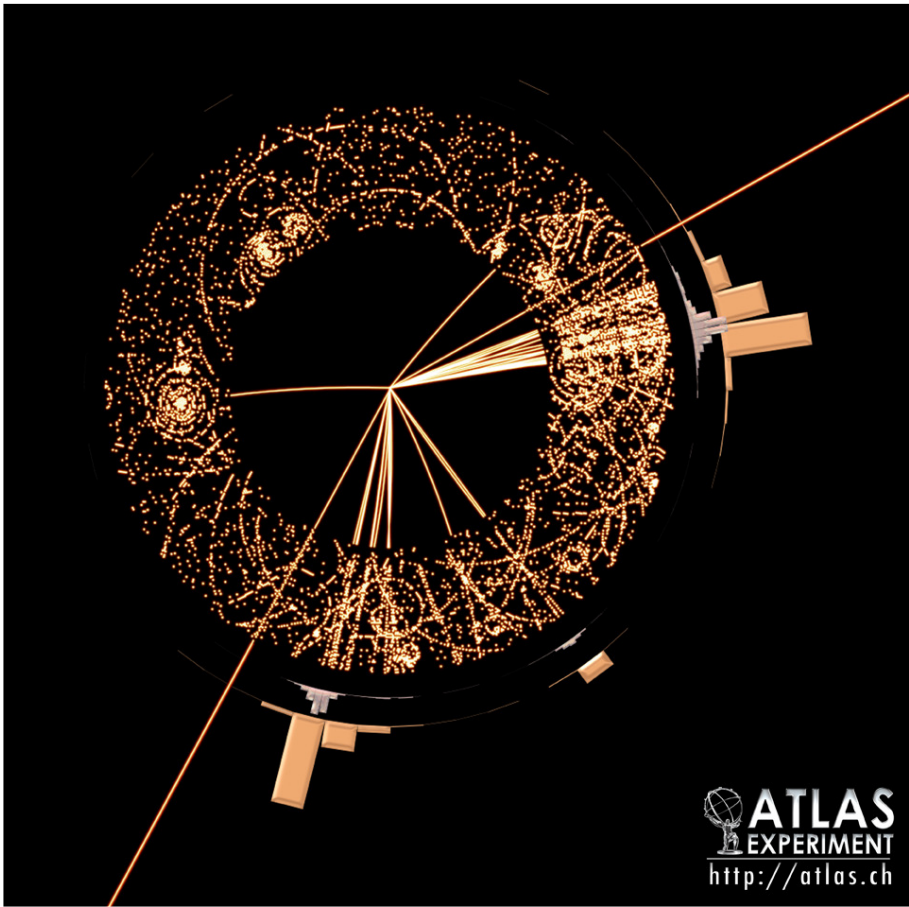
Rates:

- ~ 1 billion collisions/sec
- ~ 10 top quarks/sec
- ~ 1 squark minute.

SUSY at the LHC



«Missing» Energy



 **ATLAS**
EXPERIMENT
<http://atlas.ch>

What Might We Know By



2020?

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

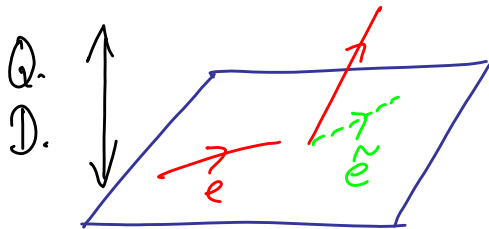
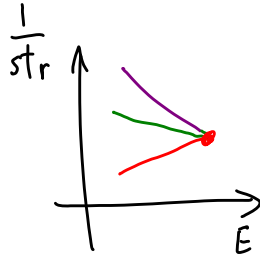
No "fine-tuning" for "why is gravity weak"?

[What about Λ ?]

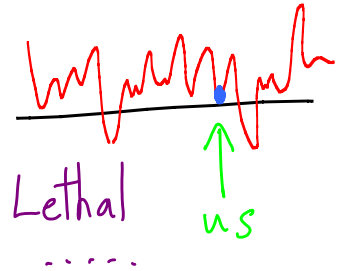
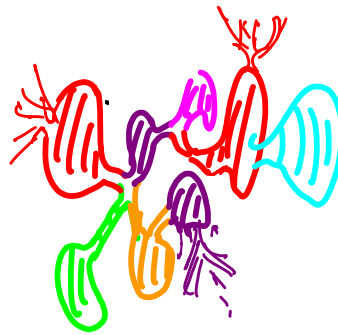
• Only Higgs + nothing else?

Very ~~confusing~~ Confusing. Evidence for
fine-tuning → just like  

Order



Chaos



Λ + weakness of gravity?

