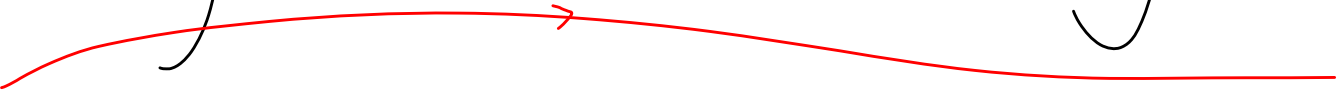



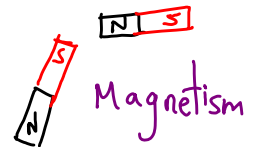
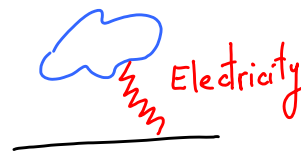
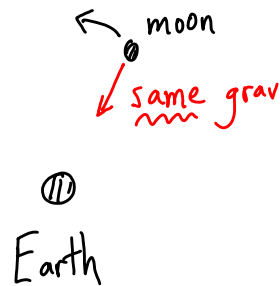
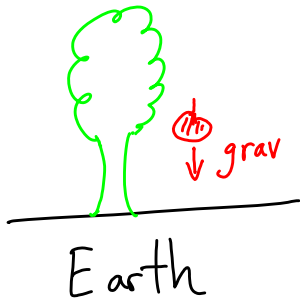
Unification + Fundamental Physics:



A Status Report

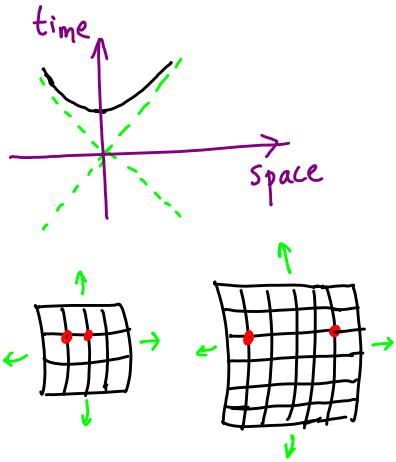


Unification



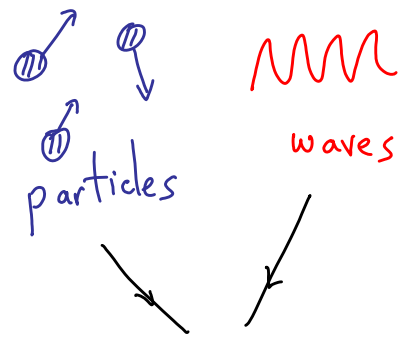
Different Aspects of Same Thing!

Relativity

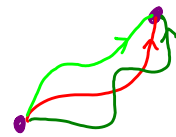


Space-Time

Quantum Mechanics

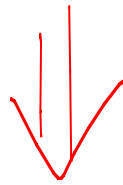


Quantum
Particles

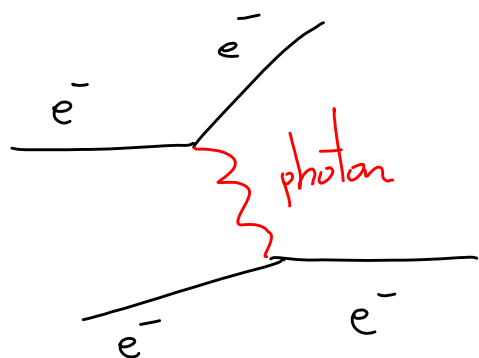
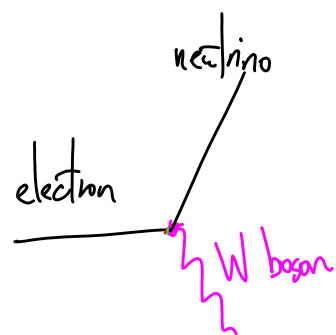
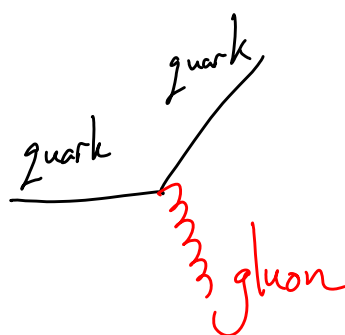
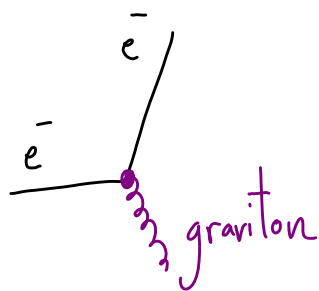
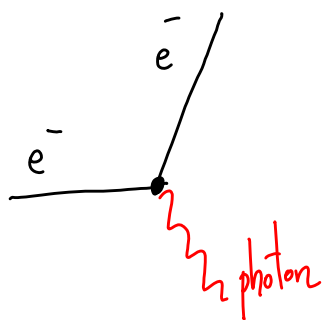


Triumph of 20th Century

Relativity + Quantum Mechanics



Universe is Inevitable



The Menu

Gluons

"W's + Photon"

$SU(3)_c \times SU(2)_L \times U(1)_Y$

3 x $\begin{matrix} Q \\ U^c \\ D^c \\ L \\ E^c \end{matrix}$

3

2

$+\frac{1}{6}$

$\bar{3}$

-

$-\frac{2}{3}$

$\bar{3}$

-

$+\frac{1}{3}$

-

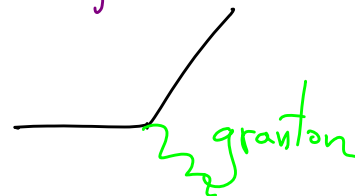
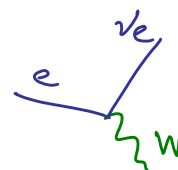
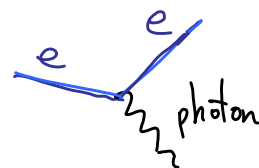
2


$-\frac{1}{2}$

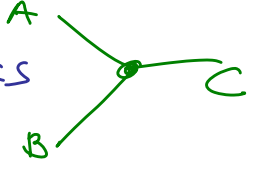

-

-

+1



Whatever the Ultimate Theory
Relativity  Quantum Mechanics

At "Long" distances, particles interacting as 
with spins $0, \frac{1}{2}, 1, \frac{3}{2}, 2$.  unique,
"gravity"

Already: Profound sort of Unification
in Language + Structure of Laws!

Important difference between massive +
massless particles with spin:

Massive $\uparrow S=1$

3
m spin

massless



2 helicities
m

One extra guy!

Belief in Principles Paid Off

0, $\frac{1}{2}$, 1, $\frac{3}{2}$, 2

"Supersymmetry"

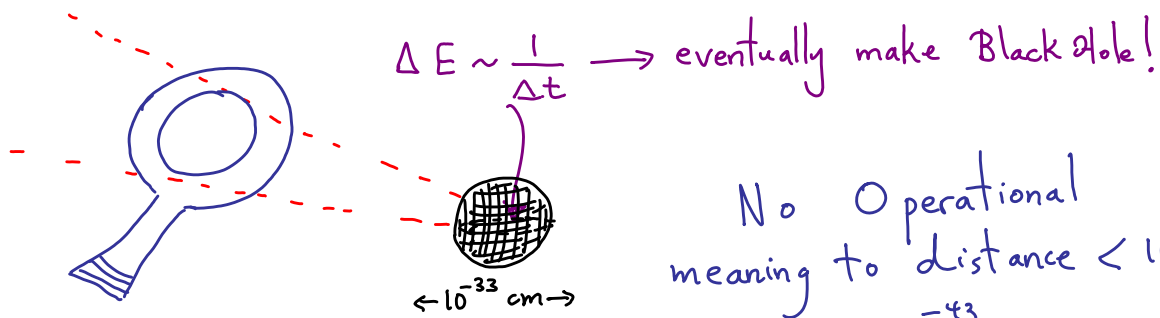
Higgs is First Really New Particle We've Seen

Central / Dramas

of
21st Century

★ End of Space-time [Gravity]
Limitations of QM [Cosmology]

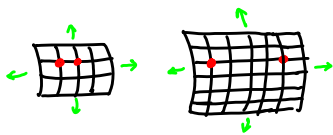
★ Why is the Universe
BIG, with BIG
THINGS in it?



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

Doom of Spacetime) Why is Universe Big?

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



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

Outline

- * "Ming Vase" Unification
- * End of Reductionism + UV/IR
- * Gauge/Gravity
- * Spacetime + QM
- * System + Observer
- * Prospects for Clues from Experiment

"Ming Vase" Unification



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

3 coupling strengths

"Grand Unification"

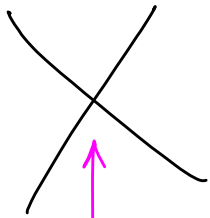
$\bar{5} + 10$ of $SU(5)$!

16 of $SO(10)$! $[-++-+]$

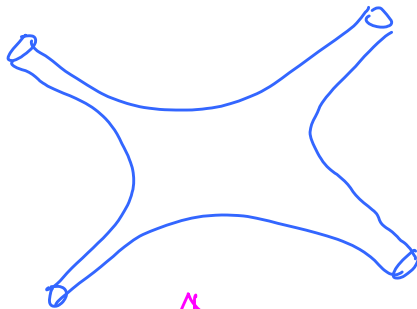
} 1 coupling strength!

String Theory

• $\rightarrow \int, 0 \uparrow 10^{-31} \text{ cm}$



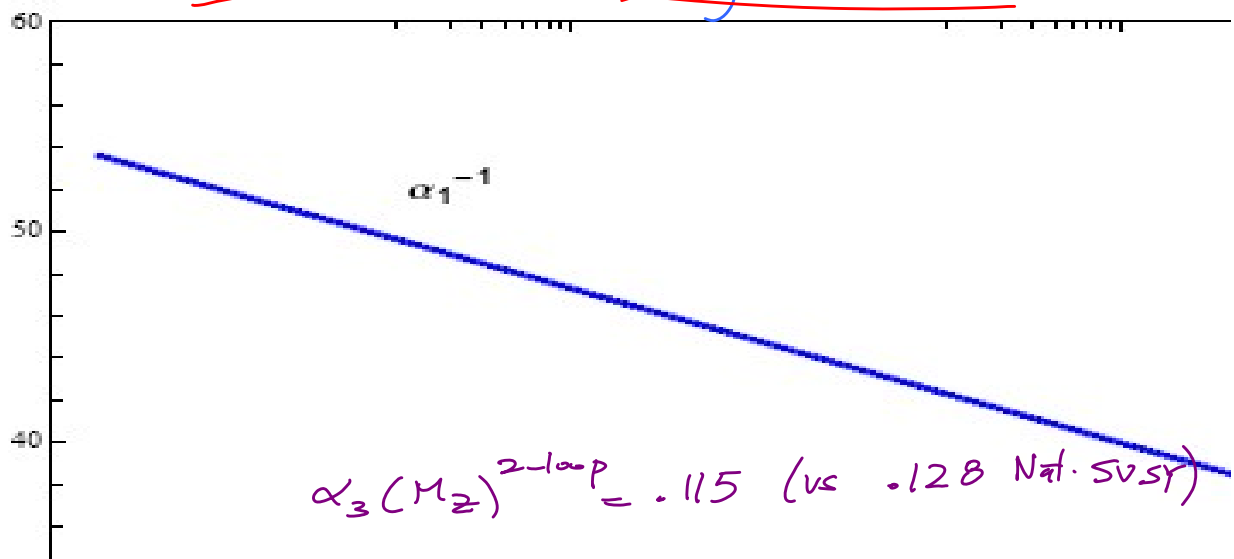
singular, arbitrary
int strength



smooth: No Adjustable Parameters!

Gravity
Inevitable!
Most striking
+ deep indic.
for Unif.


SUSY Unification



Unified forces close to String Scale!

BUT WHERE ARE THE SUPERGUYS?

M_g O_{wn} $B_{es} + B_{et}$



(Since $\sim 2004/2005$)

Minimal Split SUSY

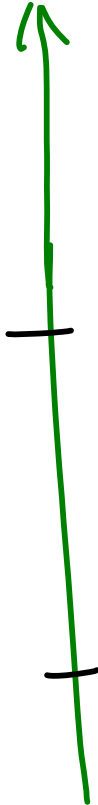


Minimal Split SUSY

Reason
for splitting:
fermions
carry R symmetry,
scalars don't

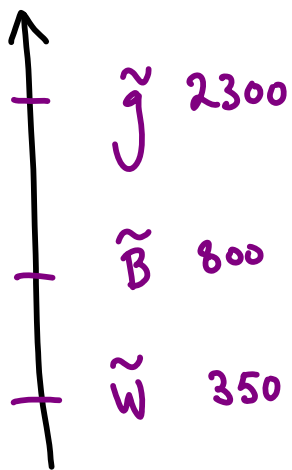
100's
TeV

TeV

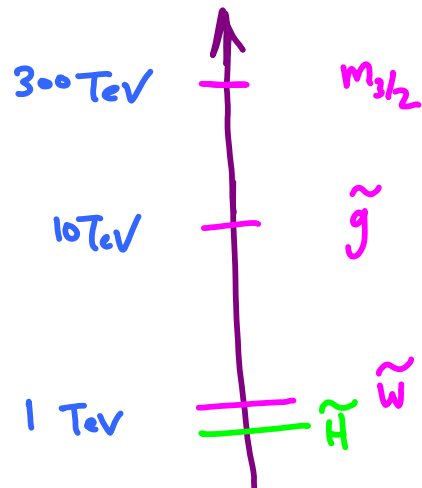


Scalars } Unification ✓
Dark Matter ✓
No Flavor,
CP, moduli, ...
problems

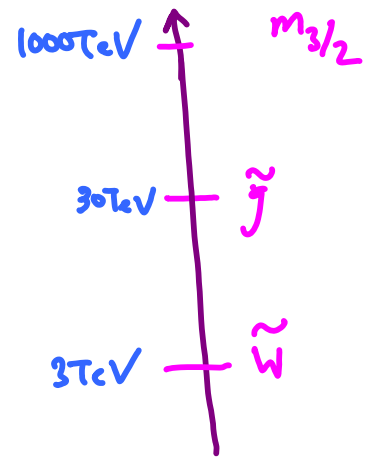
Fermions }



LHC
Accessible



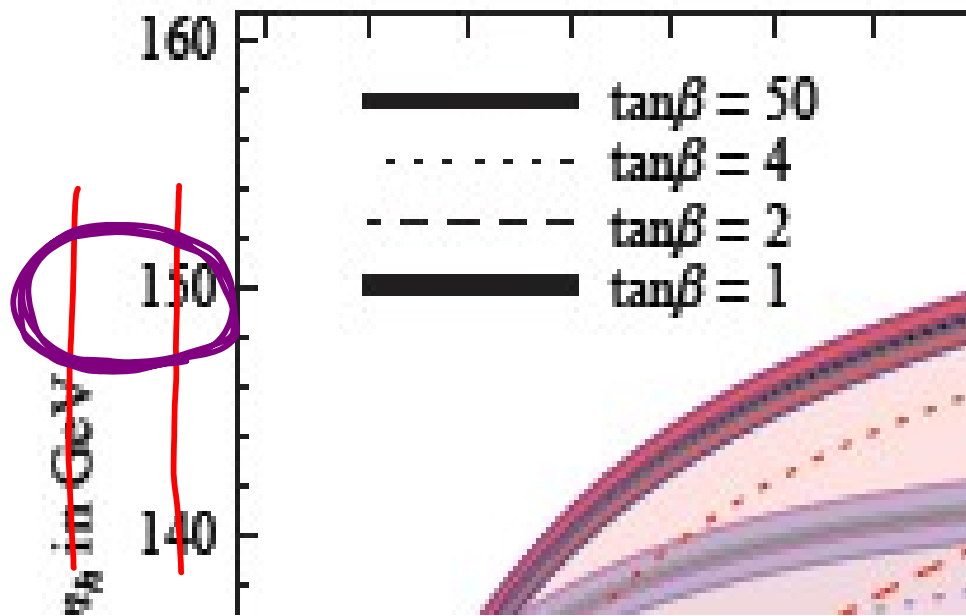
LHC
Inaccessible



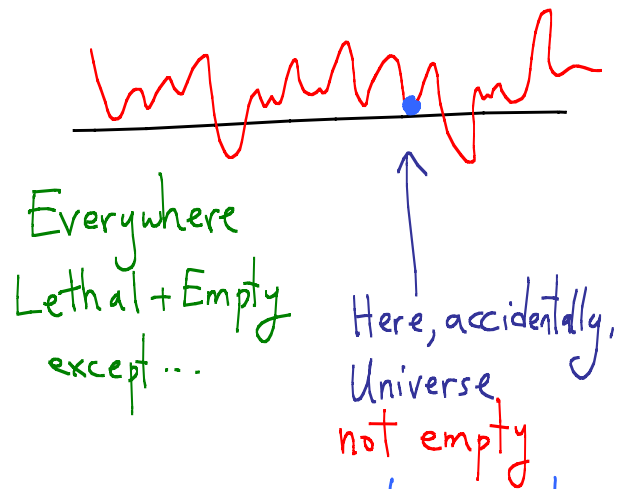
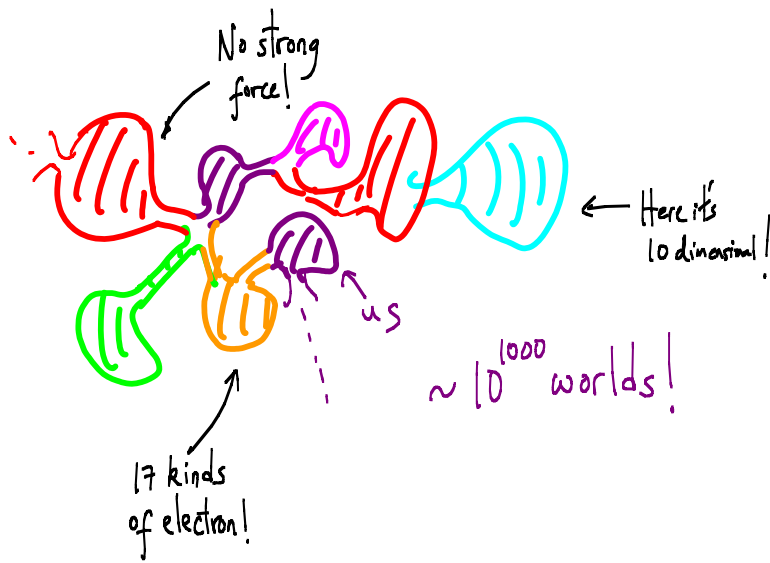
Finally, we want to remark that the supersymmetric dark-matter impasse, discussed in sect. 1, does not immediately apply to Split Supersymmetry, since values of μ of about 1 TeV or M_2 of about 2.5 TeV are perfectly acceptable, once we abandon the naturalness criterion. Why then should we expect to have an extra tuning to get well-tempered neutralinos? It is difficult to answer this question without having a more precise notion of what the physical measure of tuning actually is, but we can at least identify a competition between two factors. If we scale up the Wino to 2.5 TeV as the LSP, so there is no tuning for dark matter, we are making the scalars heavier too, which makes electroweak breaking more tuned. If we leave Winos in the hundreds of GeV range, the scalars are lighter and electroweak breaking is less tuned but there is more tuning to get the dark matter. At any rate, a 2.5 TeV Wino make Split Supersymmetry invisible at the LHC (for conventional gaugino mass relations).

(Jan 2006)

Predicted range



$$120 \text{ GeV} \lesssim m_{Higgs} \lesssim 135 \text{ GeV}$$



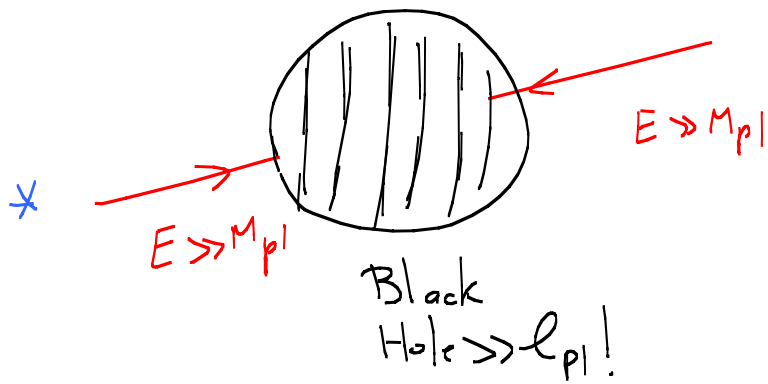
Even more extreme unification!

[But not "Ming Vase" hope—naively dead here]

End of Reductionism

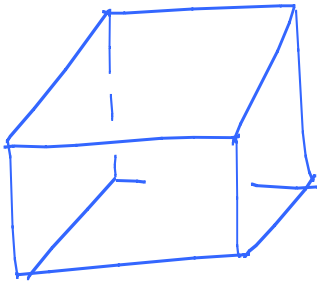


UVV/IR Fusion



High Energies
 \updownarrow
 Long distances!

* Gravitational constraints on low-energy physics





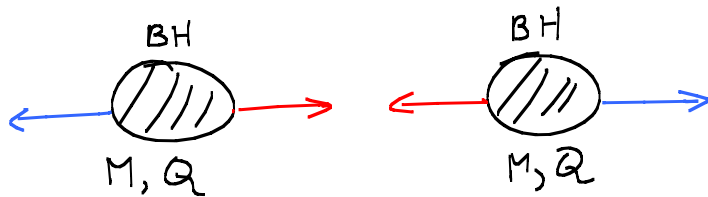
$$N_{\max} \sim e^{V_{\text{dume}}} \quad \times$$

$$\sim e^{\text{Area}/G_N} \quad \checkmark$$

"Holographic Bounds"

* More mysterious constraints enforced by BH consistency

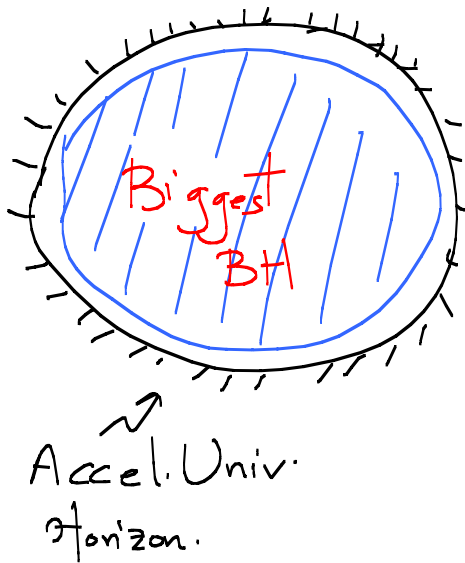
e.g.   "gravity is weakest force"



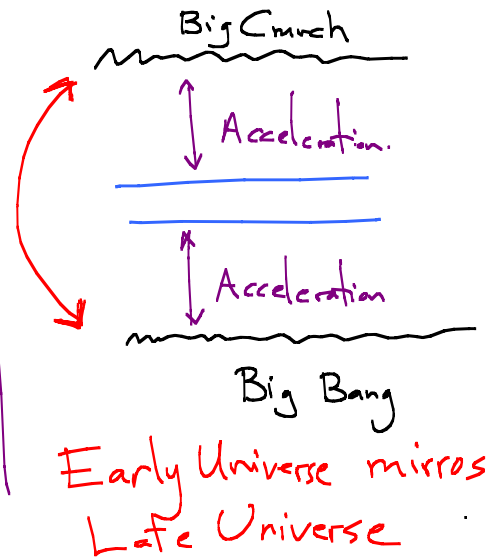
⇒ very specific signs for deviations from Einstein Gravity,
confirmed in all known examples in string theory

DEEP UNIFICATION: Gravity + other
forces can't be treated in isolation

UV/IR in Cosmology




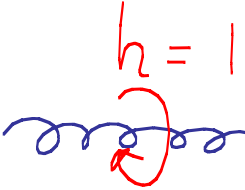
How are
D.O.F.
"Born"
in expanding
universe?

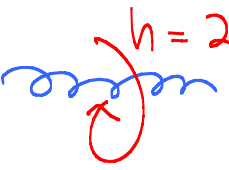


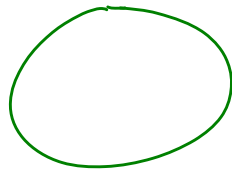
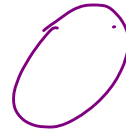
DEEP UNIFICATION : Long + Short distance
d.o.f are the same

Gauge / Gravity Unification

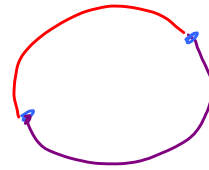


$h=1$
 gluon

$h=2$
 graviton



=



Closed

=

O_{pen}^2

Gravity

=

YM^2

Remarkable Relation Between Gravity + Gluons

$\overset{h=1}{\text{gluon}}$ $\text{Amp}[\text{3 grav}] \sim \text{Amp}[\text{3 gluon}]^2 !!$
 $\overset{h=2}{\text{graviton}}$

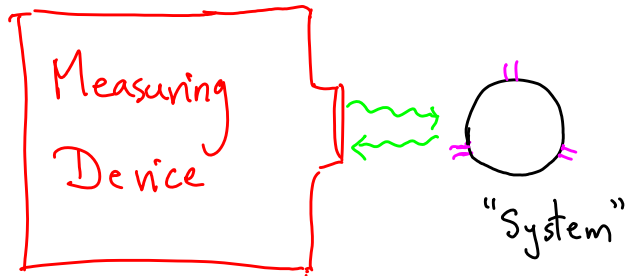
* Completely General!

* Hidden Unity which lay undiscovered for decades, right under our noses!

Big Lessons of QM

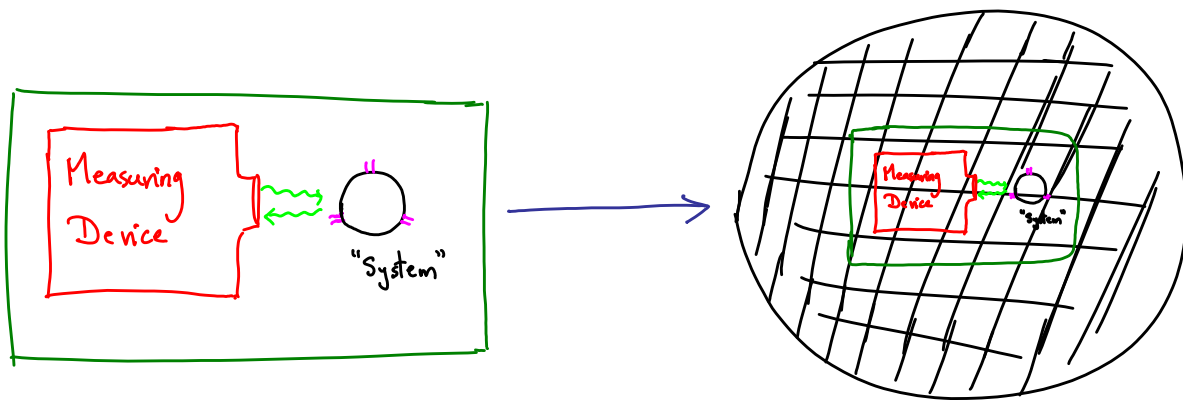
- (1) Pay careful attention to what precise observables are
- (2) Drastic loss in observables
↔ Huge gain in Unification!

Exact Quantum Observables

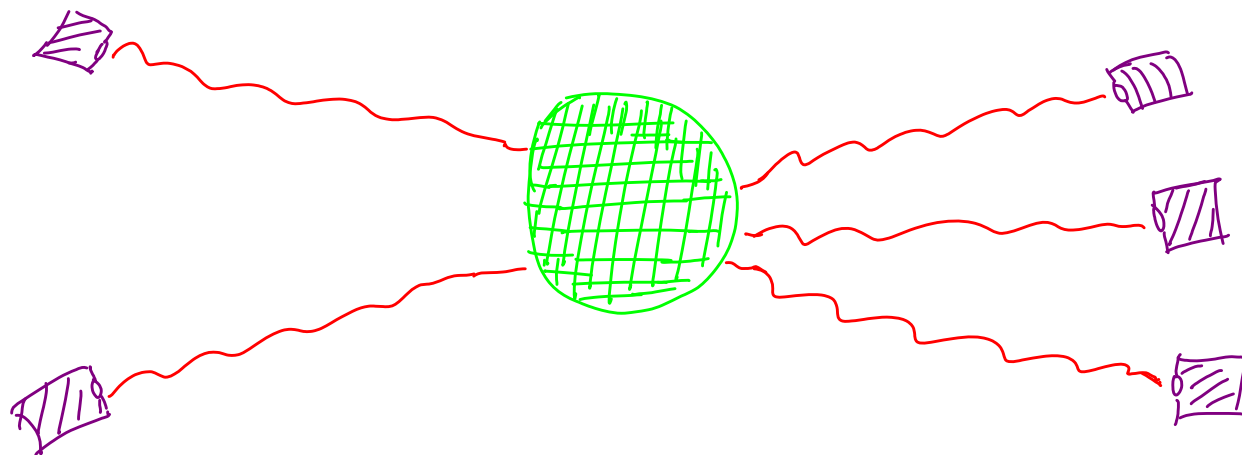


Infinitely many
measurements with
an Infinitely large
measuring apparatus!

No Local Observables!



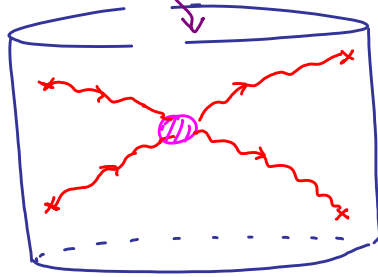
Observables on "Boundary at Infinity"



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

Emergent
Space, Gravity,
Strings ...

↑
time



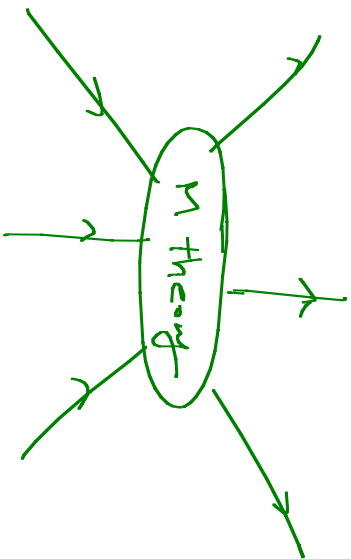
"Anti-de Sitter
Space"

"The World as a Hologram"

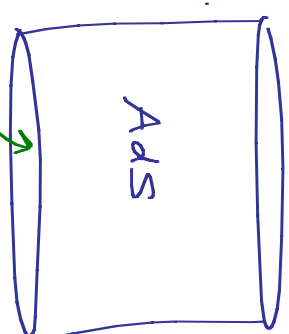
String Theory = Particle Physics

AN ASTONISHING HIDDEN UNITY

Big Tension



vs.

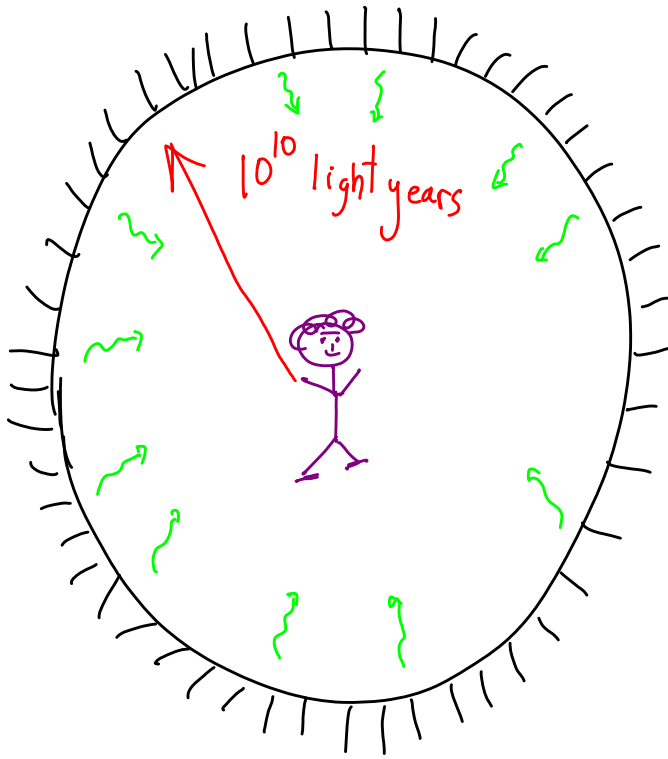


Any old
Quantum
Theory

One Unified Theory!
Landscape of connected
solutions. UNIFIED
in FLAT SPACE

It is a different
theory in Ads!

LOOKING FOR MORE UNIVERSALIFIED
"BULK" DESCRIPTION \leftrightarrow STUDY
FLAT SPACE SUMMATION, WITHOUT
SHACKLES OF MANIFEST QM, FOR
A ROAD BACK INTO THE BULK




What are
the correct
observables??

Emergent
Extension of

Space-Time
Quantum Mechanics?

Space-Time + Quantum Mechanics



QM



Emergent
Space

vs.

?



Emergent QM	Emergent Spacetime
----------------	-----------------------

Emerge together,
joined inexorably

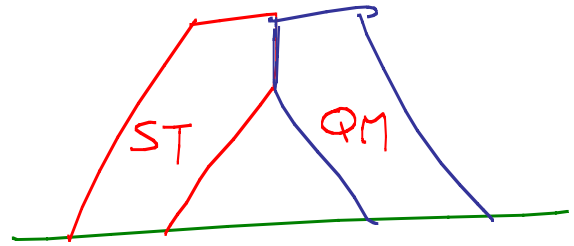
Other Circumstantial Clues

QFT
in $(3+1)$ dim

$(4+0)$ more natural

$(2+2)$ more natural

"Causal" + "Probabilistic"
intimately tied together



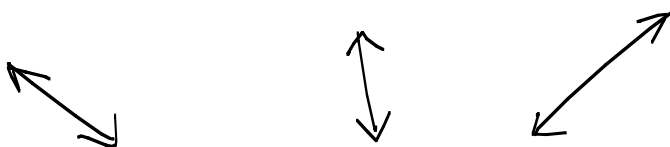
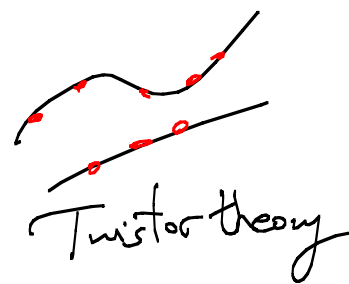
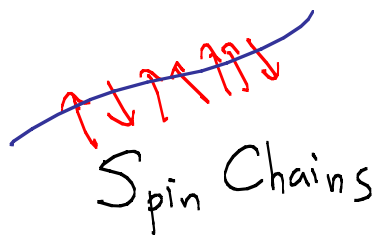
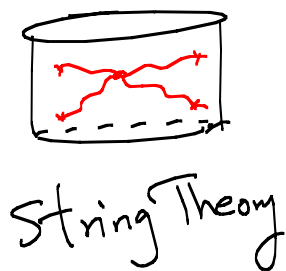
They Buttress Each
Other, making each other
more rigid + robust

Locality + Unitarity

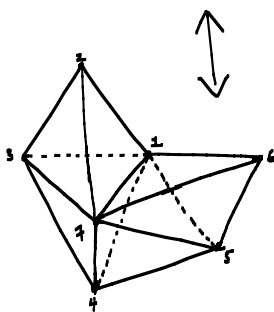
$$(1^- 2^+ 3^- 4^+ 5^+)$$

$$\frac{\langle 13 \rangle^4}{\langle 12 \rangle \langle 23 \rangle \langle 34 \rangle \langle 45 \rangle \langle 51 \rangle} \quad (!)$$

Feynman's way of doing physics makes
usual rules of spacetime + QM
manifest — but is obviously hiding
some extraordinary new structures!

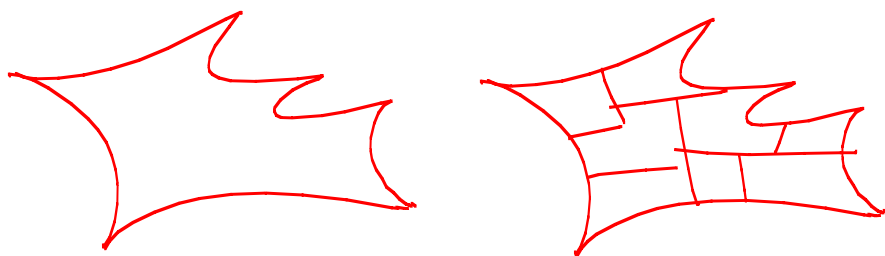


New Formulation
of Standard Physics
emergent ST + QM



Goal

Find a new picture for scatt. amps
with no space-time, Hilbert space, no
 \mathcal{L}, \mathcal{H} , no $\int \mathcal{D}\varphi e^{iS}$, no Gauge Redundancy....

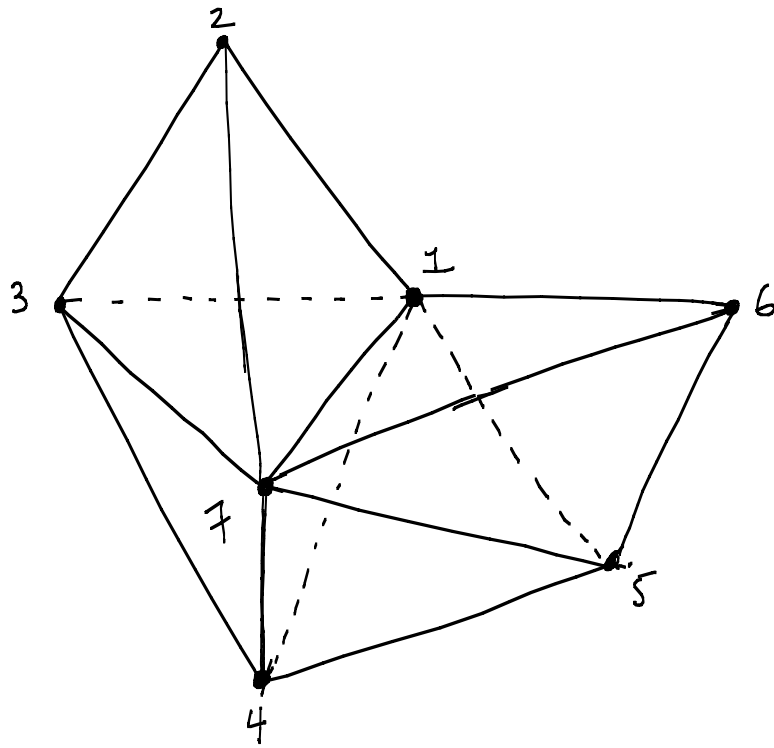


"The Volume" of "Some Region" in "Some Space"
Symmetries Manifest; Loc+Un. Derived

$$\mathcal{M}_{n,k,L}[Z] = "V_0|" [A_{n,k,L}[Z]]$$

$A_{n,k,L}[Z]$: "The Amplituhedron"

A 3D "Face"




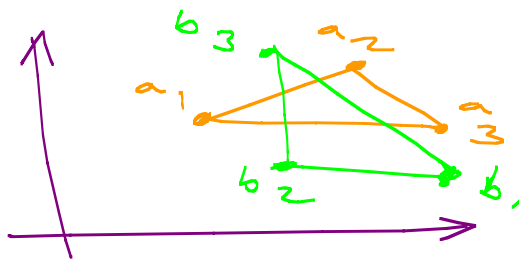
Tree Amplitude for $[1^- 2^+ 3^+ 4^+ 5^- 6^+ 7^- 8^-]$ @ LHC
{ Hundreds of Pages of Feynman Diagrams }

4 Particles to All Loops

$$(AB)_i, A_i = 1 + x_i^2 - z_i^4, B_i = 3 + y_i^2 + w_i^4$$

$$\vec{a}_i = \begin{pmatrix} x_i^+ \\ y_i^+ \end{pmatrix}, \vec{b}_i = \begin{pmatrix} w_i^+ \\ z_i^+ \end{pmatrix}, (\vec{a}_i - \vec{a}_j) \cdot (\vec{b}_i - \vec{b}_j) < 0$$


 "Triangulate"
 = 4-pt to all
 loop order!



A
highschool
geometry
problem

Textbook Unitarity
follows from geometry

$$\begin{array}{c} 2 \\ \diagup \\ \text{---} \text{L} \text{---} \\ \diagdown \\ 1 \end{array} \begin{array}{c} 3 \\ \diagup \\ \text{---} \\ \diagdown \\ 4 \end{array} = \sum_{L_1, L_2} \begin{array}{c} 2 \\ \diagup \\ \text{---} L_1 \text{---} \\ \diagdown \\ 1 \end{array} \begin{array}{c} 3 \\ \diagup \\ \text{---} L_2 \text{---} \\ \diagdown \\ 4 \end{array}$$

Emergent

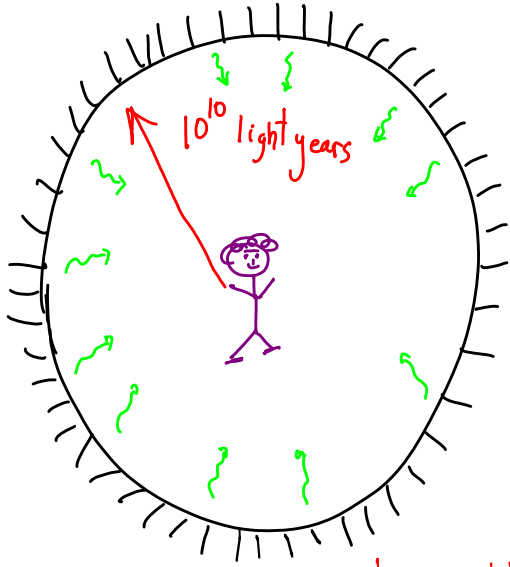
Space-Time + QM
Hand in Hand

Observer + System



QM forces us to
split world into two
parts: infinite "observers"
and finite "systems"

Gravity + Cosmology don't like this



No precise observables

time ↑

Our Acceleration

~~~~~  
Bigbang

Late acceleration  
makes it in principle  
impossible to learn anything  
about initial singularity!

This raises the possibility that  
we are misinterpreting string

landscape - the different regions  
aren't "out there" but are different

APPROXIMATE "System/Observer"

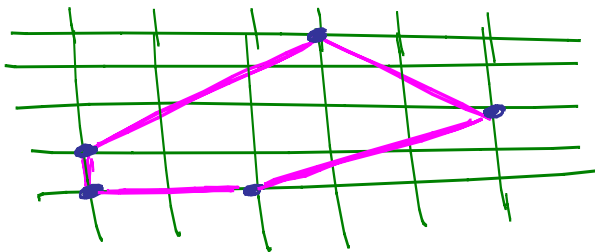
Splits of A SINGLE OBJECT

# Cosmology $\longleftrightarrow$ Number Theory

\* No need for reals in finite systems.

[\* Note: Cosmology breaks all symmetries]

Joy ex:  $A + Bx^2 + Cx^5y^2 + Dx^3y^4 + Ey = 0$   
 $A' + B'x^2 + C'x^5y^2 + D'x^3y^4 + E'y = 0$



# solution = Area of  
"Newton"  
Polygon!  
 $\{ \text{c.f. Amplitudes} = \text{Volumes} \}$

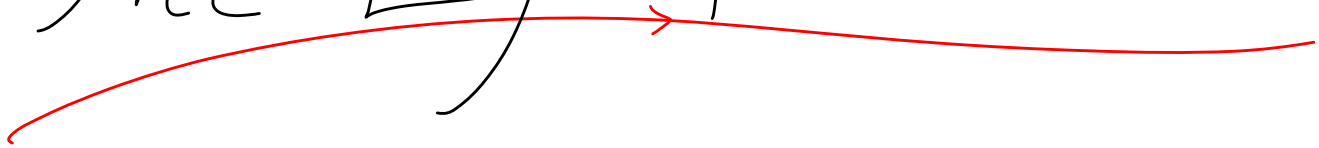
## Wild Conjecture

The most mysterious huge hierarchies in our universe will ultimately be related to enormous numbers naturally generated as a consequence of logarithmic distribution of primes [cf Riemann Hypothesis]

"Ming Vase" Returns with a Vengeance!



The Experimental Frontier

A red curved line starts below the word 'The', goes under 'Experimental' where it has a small arrow pointing right, and then continues under 'Frontier'.

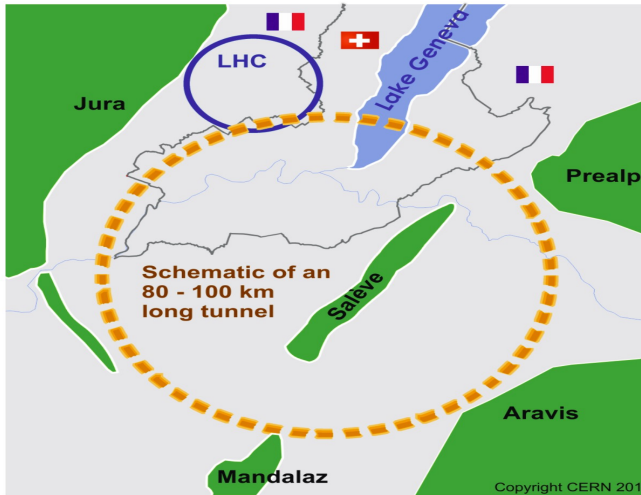
LHC



Collisions  $\sim 10,000 \text{ GeV} \sim 10,000\times$  mass of proton  
Velocity  $\sim 0.9999999\times c_{\text{light}}$   
Probing  $\sim 10^{-17} \text{ cm} \sim 1000\times$  smaller than nucleus

# Next Energy Frontier Machines: 100 TeV Collider

## Site



- Preliminary selected: Qinhuangdao (秦皇岛)
- Strong support by the local government



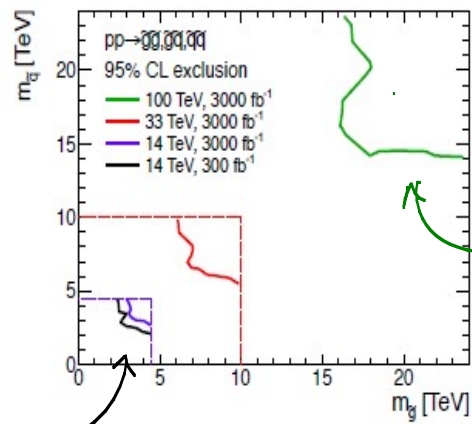
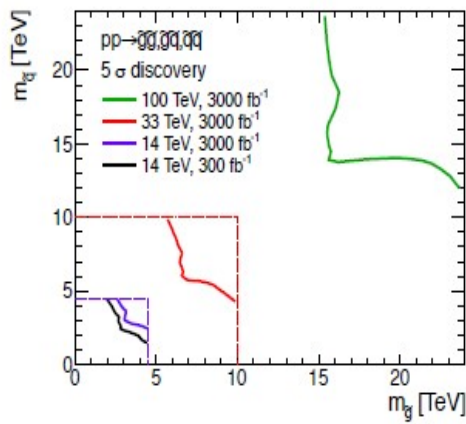
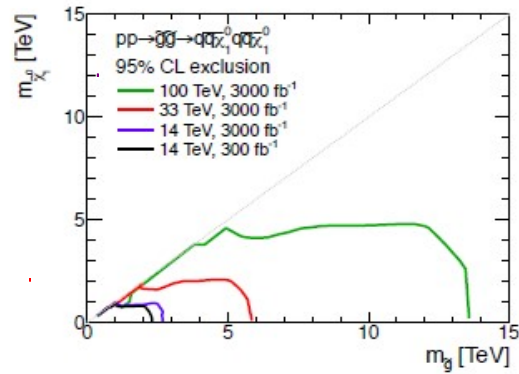
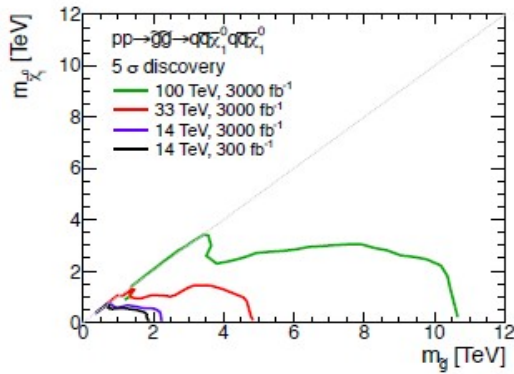
↑  
CERN

~100 km, ~10x LHC Energy

20 - 40 yr Future

↑  
CHINA

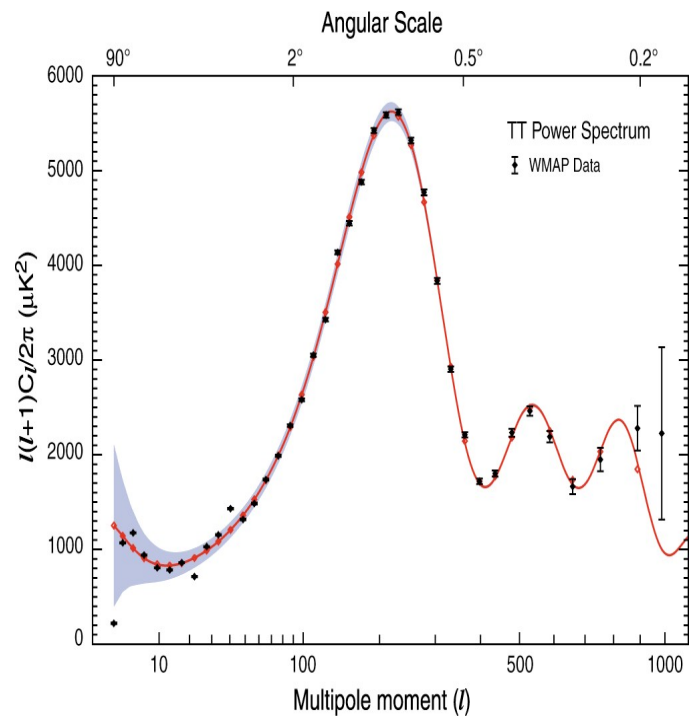
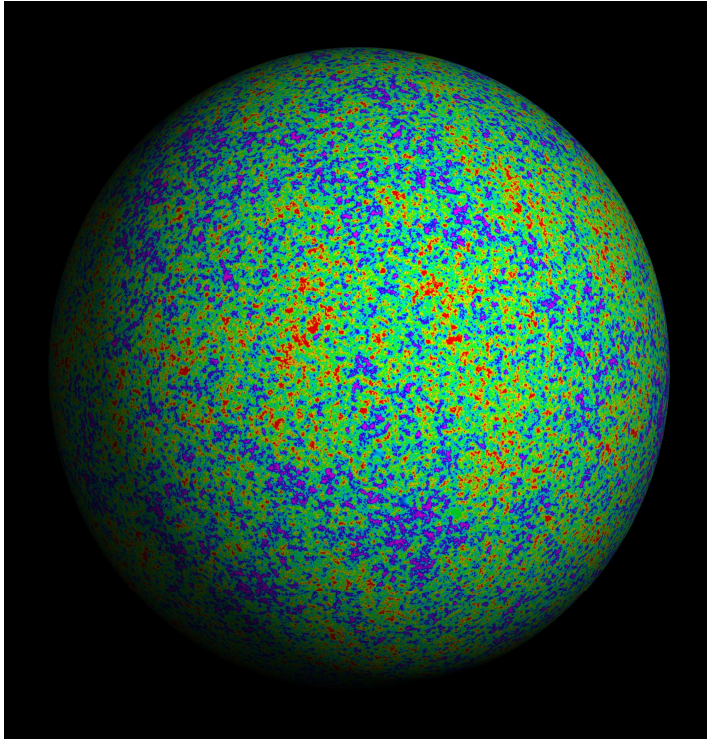
# 30 yr Anticipated Version of SUSY Can't Hide



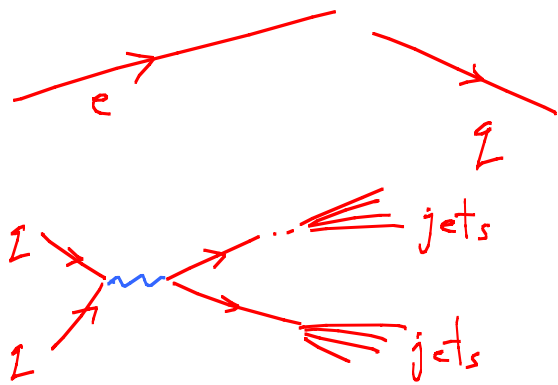
LHC

100 TeV  
Collider

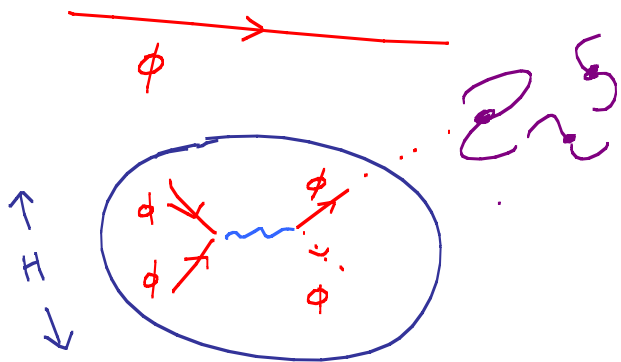
# Cosmic Microwave Background



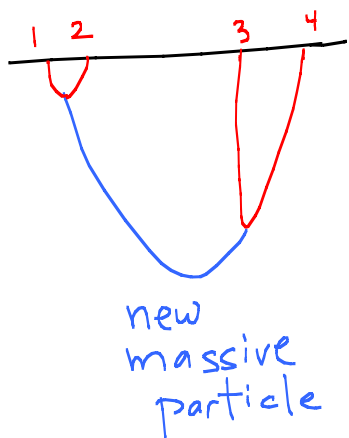
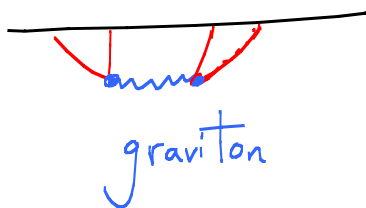
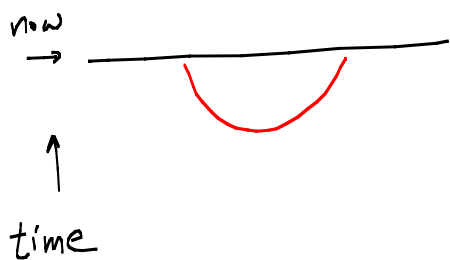
# "Cosmological Collider Physic"



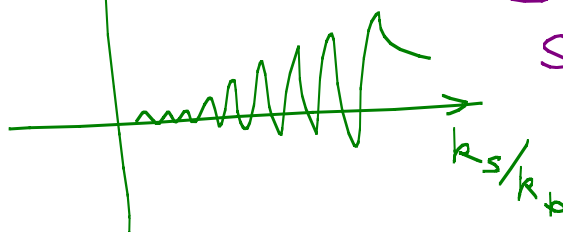
New Particles in  
accelerators from  
features in cross-sections



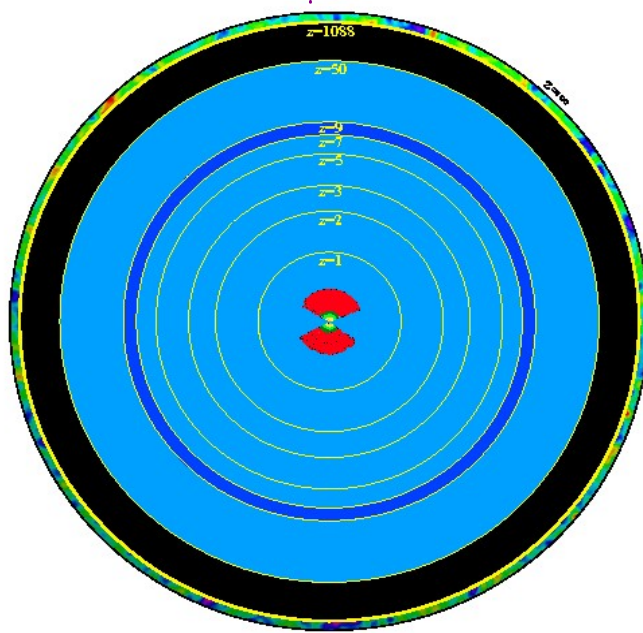
New Particles from  
patterns in non-Gaussianities



non-G



"Cosmological  
Double  
Slit  
Expt."



20 - 40 yr Future

A Volumes  
worth of  
Universe to  
Uncover!

Can Probe  
some new physics  
 $10^{10} \times$  higher  
than any terrestrial  
accelerator!



# Extremely Weakly Interacting Frontiers

- \* Gravity Waves !!
- \* Cosmic neutrino background
- \* Dipole moments
- \* Axions
- \* "Dark" photons
- \* Dark matter

Many New  
Ideas Exploit  
Advances in  
Quantum-Coherent  
Atomic Physics!

This is a singular  
time in the development  
of Fundamental Physics

The questions on the  
Table are the deepest  
ones — underpinnings of  
space + time, origins +  
fate of our large Universe

Increasingly deep +  
unexpected notions of  
Unification are being  
uncovered in our theoretical  
exploration of Field/String theory

And we await **and need** more  
input from experiment: from LHC  
of course, Cosmological observations  
+ the new frontier of small-scale experiments

Exhilarating Time To  
Be Doing Physics

"Next Steps" needed  
will likely be Revolutionary

IDEAL TIME TO  
BE 25!

