

(Un) Naturalness,

Space-Time, Quantum Mechanics

+ the Vacuum

What the Hell

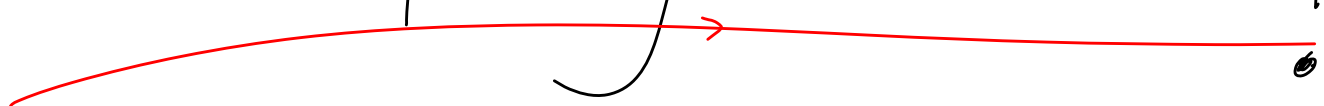


is Going On?



- \* Was Hierarchy Problem RSP?
- \* My own best bet
- \* Speculations on new lines of attack
- \* Outlook

$I \rightarrow$  Hierarchy Problem BSP



$[m_h^2$  is just a parameter —  
measure it! Who cares about this  
UV sensitivity crap?]

In every theory we have ever  
found where we can compute  
even sign of  $m_h^2$ , we see the  
real teeth of hierarchy problem


Still... pure math is filled with situations where huge dimensionless #'s arise "from nowhere".

$$\text{Ex : } \text{sinc}(x) \equiv \frac{\sin x}{x} \cdot \int_0^{\infty} dx \text{sinc} x = \frac{\pi}{2}, \int_0^{\infty} dx \text{sinc} x \text{sinc} \frac{x}{3} = \frac{\pi}{2},$$

$$\dots \int_0^{\infty} dx \text{sinc} x \text{sinc} \frac{x}{3} \dots \text{sinc} \frac{x}{13} = \frac{\pi}{2} \text{ but } \int_0^{\infty} dx \text{sinc} x \dots \text{sinc} \frac{x}{15} = \frac{\pi}{2} - 2.1 \times 10^{-11}!$$

But we've never encountered this sort of things in theories where Higgs mass becomes calculable!

$M_g$   $O_{wn}$   $B_{est}$   $B_{et}$

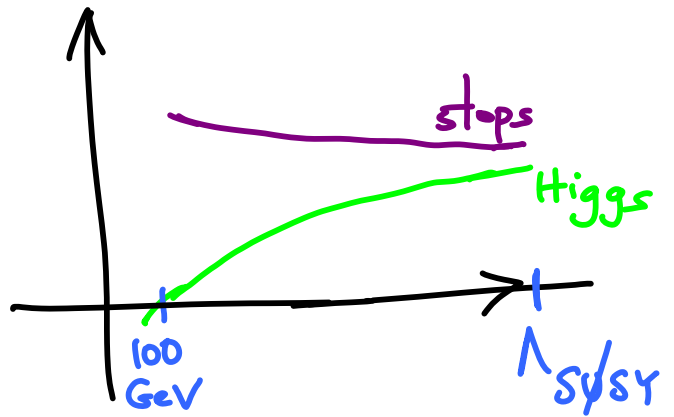
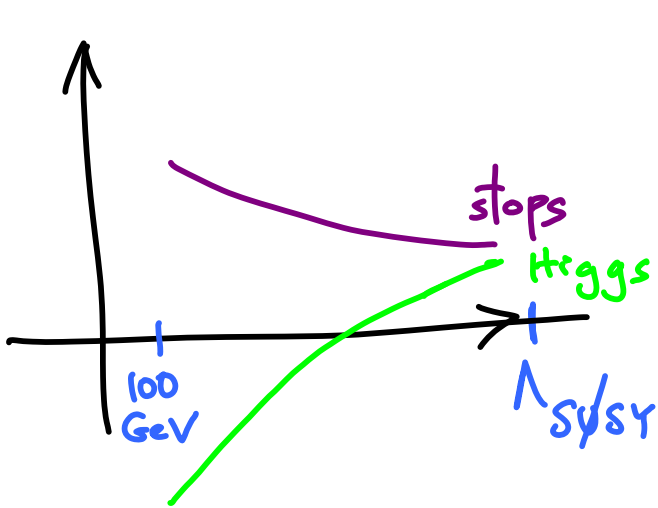


(Since  $\sim$  2004/2005)

Minimal Split SUSY



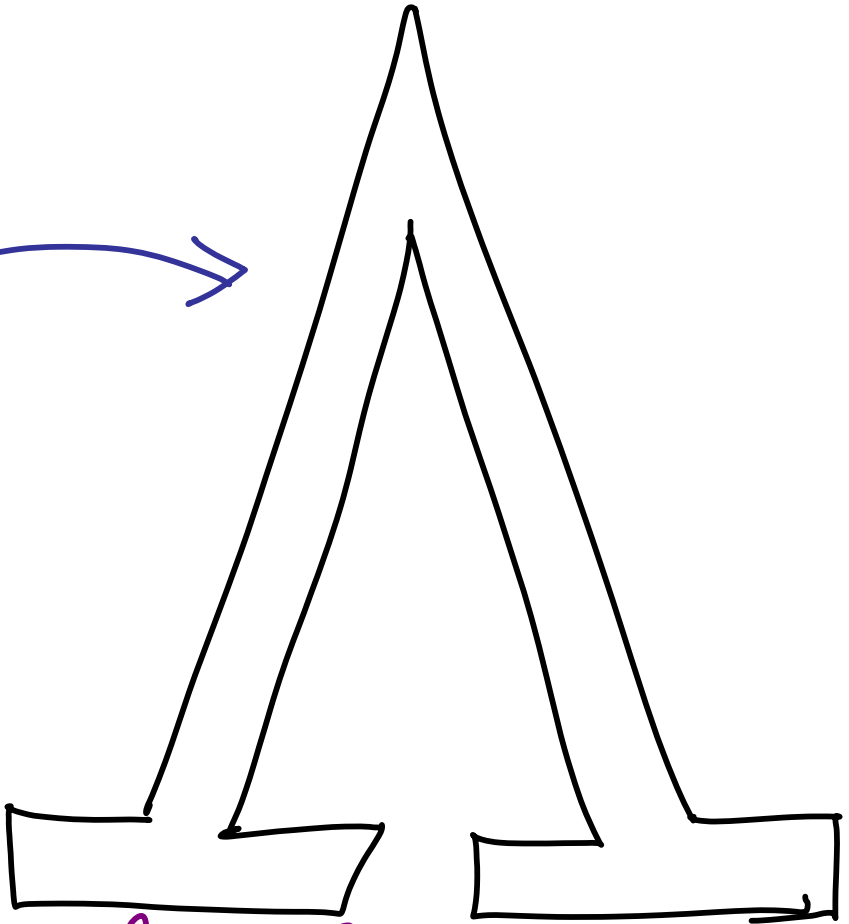
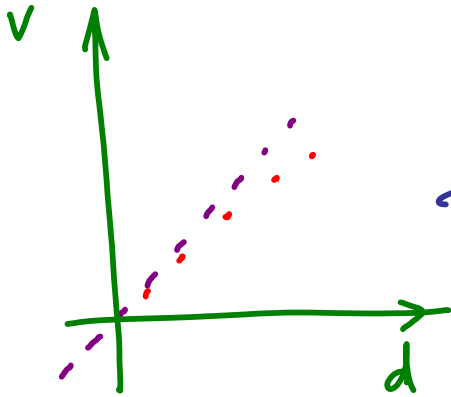
# Why No SUSY @ LEP?



—  $Z, h, \tilde{t}, \tilde{g} \dots$   
 —  $\tilde{L}, EW \text{ Kinus}$   
 "Natural" Spectrum

?  
 ↑  
 —  $Z, h$   
 "Nature-al" spectrum





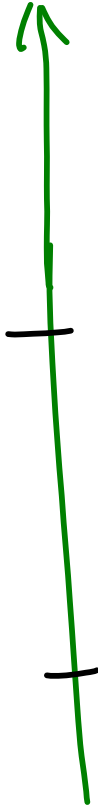
NATURALNESS

# Minimal Split SUSY

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

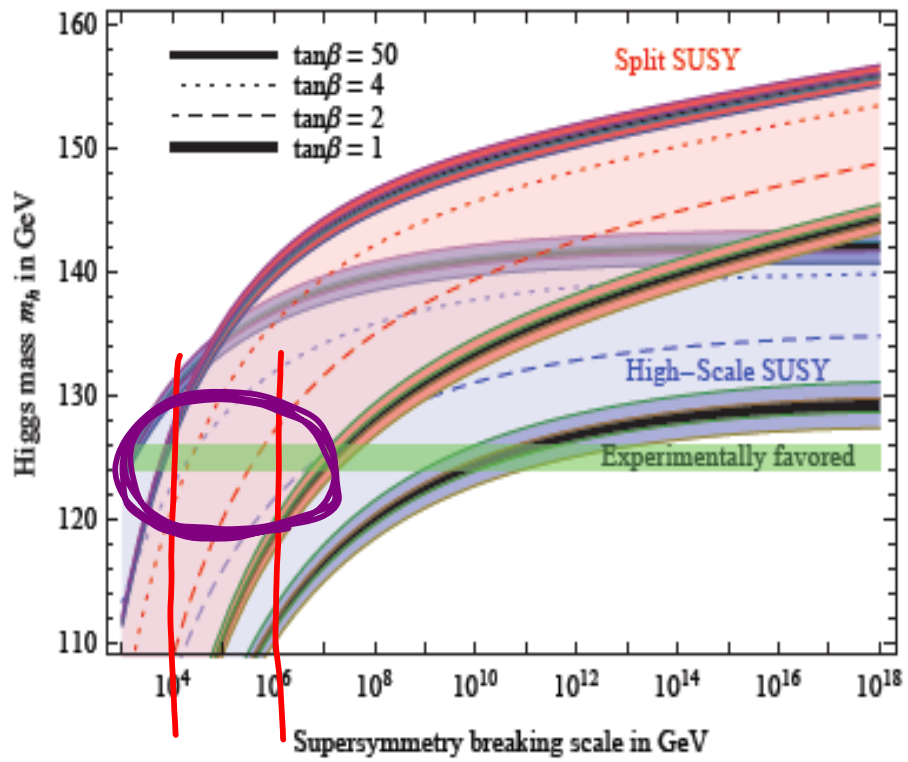
100's  
TeV

TeV



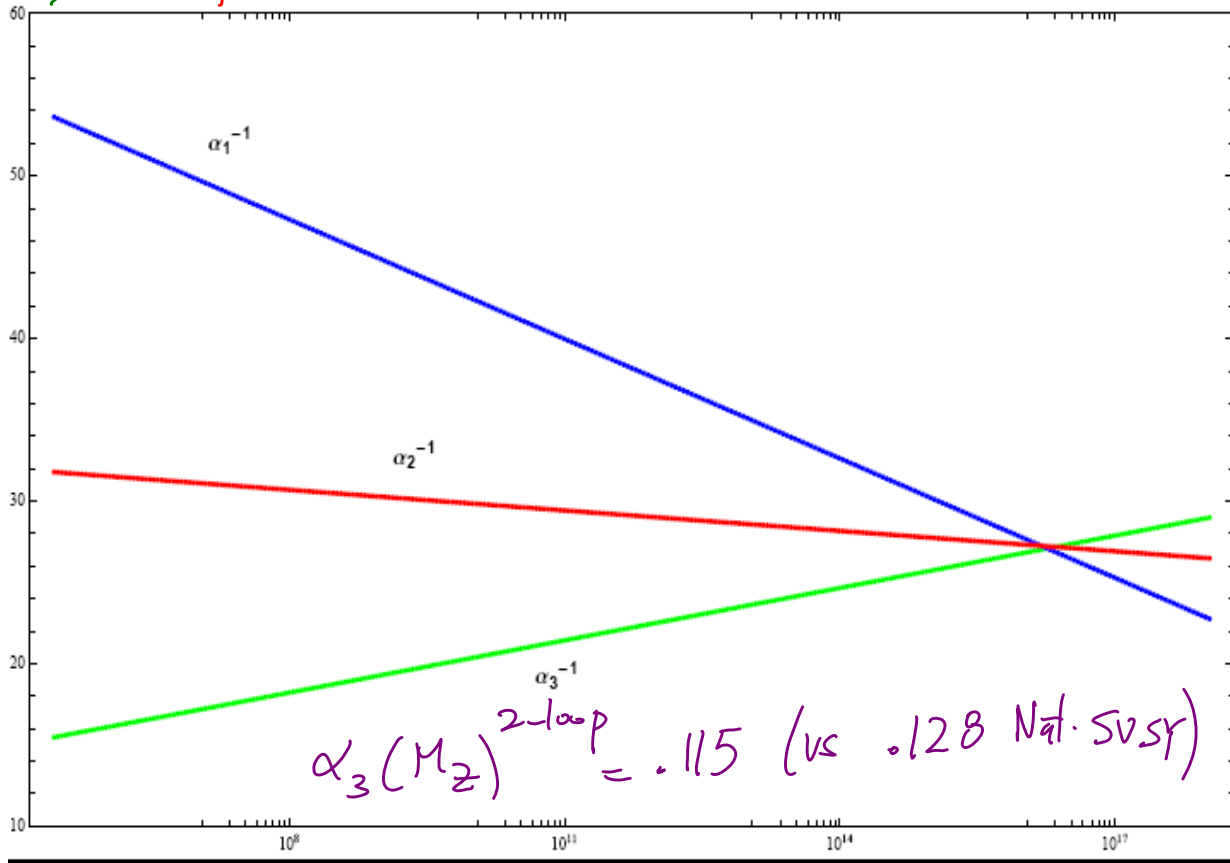
Scalars } Unification ✓  
Dark Matter ✓  
Fermions } NO Flavor,  
CP, moduli, ...  
problems

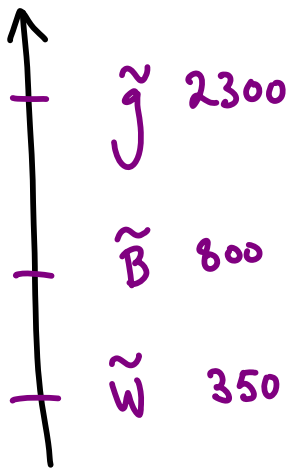
### Predicted range for the Higgs mass



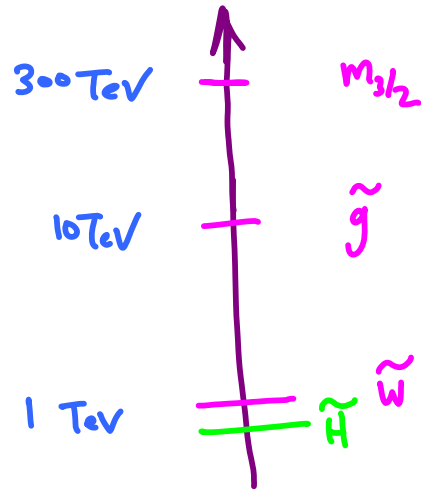
$$120 \text{ GeV} \lesssim m_{\text{Higgs}} \lesssim 135 \text{ GeV}$$

# Unification a Bit Better than Natural SUSY

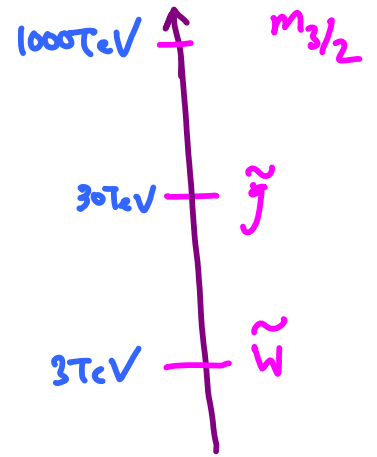




LHC  
Accessible

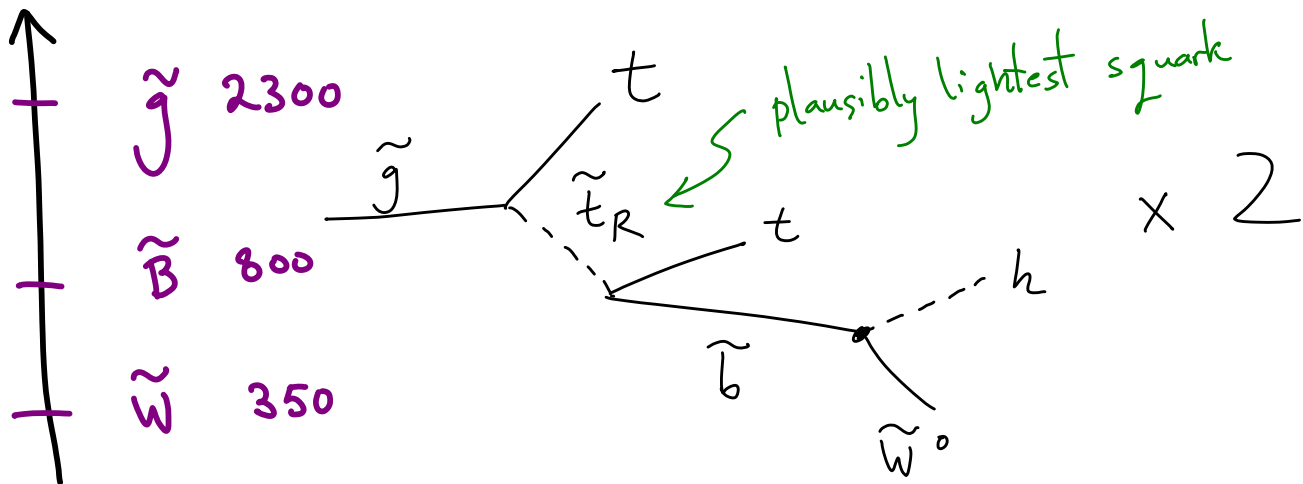


LHC  
Inaccessible



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  $\mu$  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).

hep-ph/0601041



8  $b$ 's, 4  $W$ 's [ + perhaps displacement ]  
in every event!

Only need  $\mathcal{O}(1)$  events for discovery

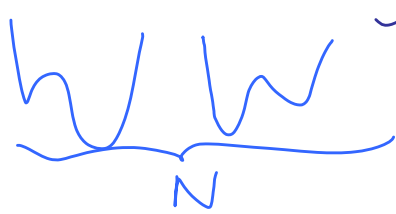
# Some New Lines of Attack

- (1) Cosmological Dynamics
- (2) Analyticity, Causality + the Higgs
- (3) Hidden Symmetries in (B)SM?
- (4) UV / IR



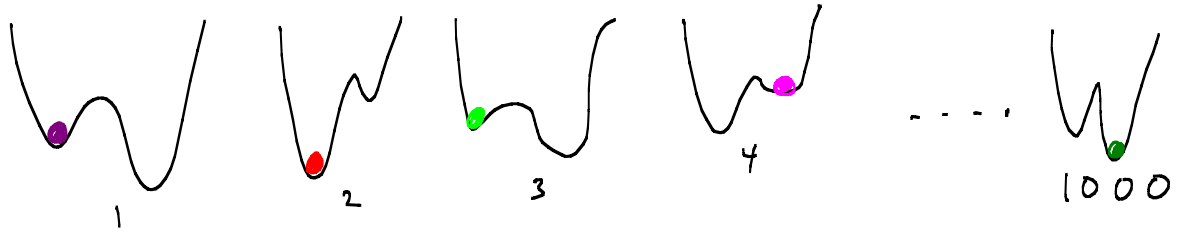
# Cosmological Dynamics

(A) The landscape populated by eternal inflation!

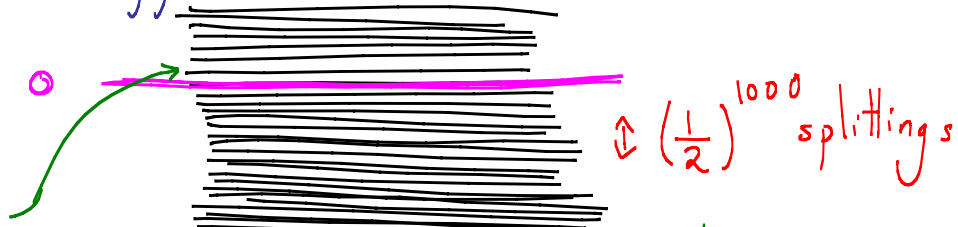


$2^N$  vacua... can in principle  
be seen by experiments  
in our universe!

{ (B) David's talk for Relaxion landscape }



$\Rightarrow 2^{1000}$  different values of energy



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

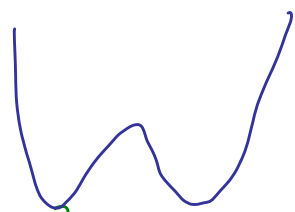
Landscape:  $\sim 10^2 - 10^3$  SM singlet scalars!

\* They could all be @ GUT/string scale....

\* But some part might be pegged to higgs mass for good reasons. Singlets  $S_i$  dominant coupling is to higgs w/ familiar:  $S_i \bar{t} h, S_j \bar{t} h$ .

\* Central "landscape" novelty:  $\sim 10^2 - 10^3$   $S$ 's!

# Motivation for light landscape: Correlating Hierarchy + CC

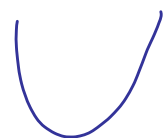


$m_{h,u,d}^2 > 0$

NO scanning for CC

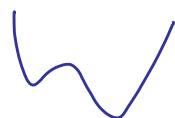
$$\lambda_i (S_i^2 - \mu_i^2)^2 + a_i S_i h_{u,d}$$

$|m_{h,u,d}^2| \gg \mu^2$



NO scanning for CC

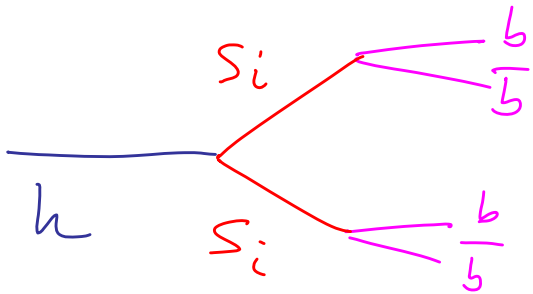
$m_{h,u,d}^2 \sim \mu^2$



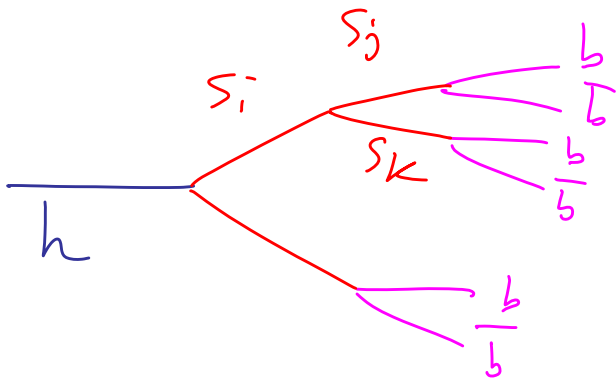
CAN scan for CC

MUST tune  $m_h^2$  in order to be able to tune the Cosmological Constant!


# Higgs Bomb Signal @ Higgs Factory



hundreds of  $b\bar{b}$  resonances!

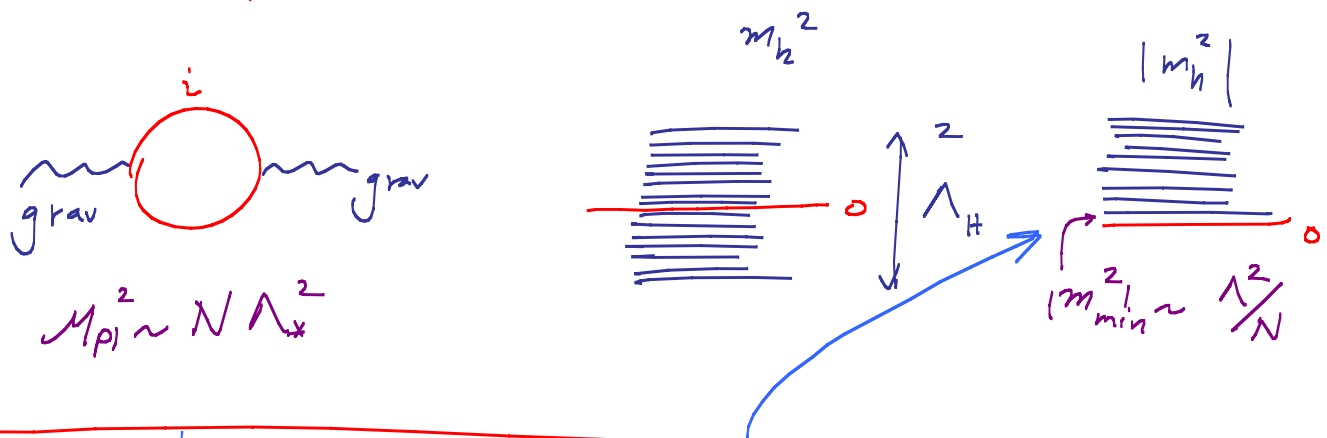


6  $b\bar{b}$  events show  $S_i S_j S_k$  interactions

⇒  ⇒ direct  
exp. proof of exponentially many vacua!

# © Reheating Dynamics: $N$ -naturalness

$N$  copies of (MS) SM



Cosmology Dominantly Reheats Bottom of Spectrum

$$M_{pl} \sim \Lambda_* \sqrt{N}$$

$$\Lambda_*$$

$$\Lambda_H$$

$$m_h \sim \frac{\Lambda_H}{\sqrt{N}}$$

## Natural Limits

$$* N \sim \frac{M_{pl}^2}{M_{GUT}^2} \sim 10^2 - 10^4$$

{  $\Lambda_* \sim M_{GUT}$  }. Modest assist to SUSY, which can naturally @ 10 TeV! [But not 1000 TeV...].

$$* N \sim \frac{M_{pl}}{m_h} \sim 10^{16}$$

Complete - N - soln of hier. prob.

$$* \text{Or } N = N_1 \times N_2 \dots$$

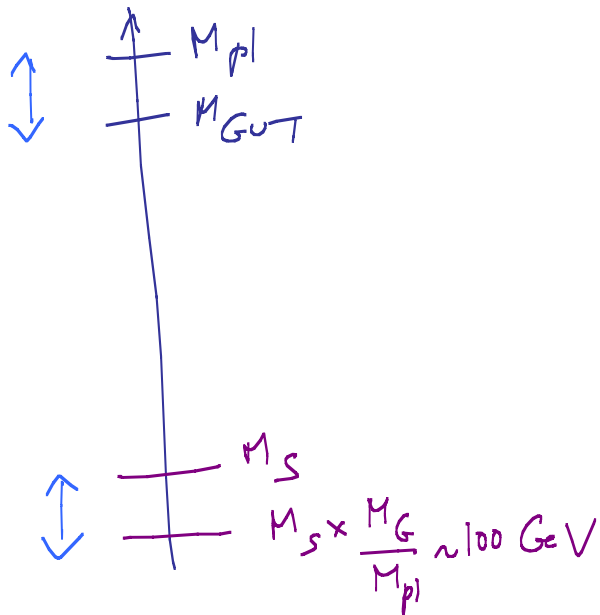
$$M_{pl} \sim \Lambda_* \sqrt{N_1 N_2} \quad m_h \sim \frac{\Lambda_*}{\sqrt{N_2}}$$

# Experimental Signals

- CMB + Large Scale Structure
- \* Indirect probe of large- $N$  from axion physics
- \* If  $M_{\text{GUT}}$  is real, SUSY @ future colliders



# SUSY Beneath $\sim 10$ TeV



- \* Unification ✓
- \* DM ✓
- \* Higgs @ 125 GeV ✓
- \* Flavor, CP safer but still constraints/signals!
- \* Not split SUSY!  
[Can't have  $10^2 - 10^3$  TeV scalars]

Analyticity, Causality + Higgs

Foundations of Fund. Physics:

Lorentz Invariance

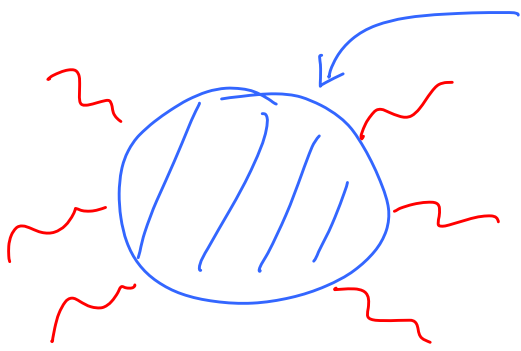
Unitarity

SHARP

Causality

MORE

MURKY....



how do we know this is "causal"?

How is Causality encoded in S-matrix?

Q - from 1960's ... answer to day !!

analyticity ...

still don't know precise

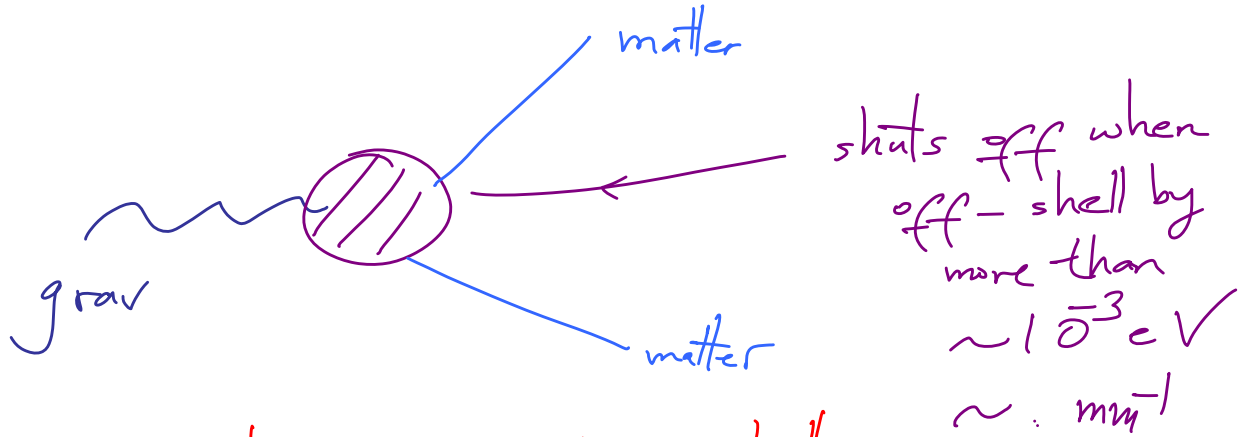
But, related to

+ can be checked experimentally!

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Important to Check these for the Higgs now! As w/ strong int. in 1960's

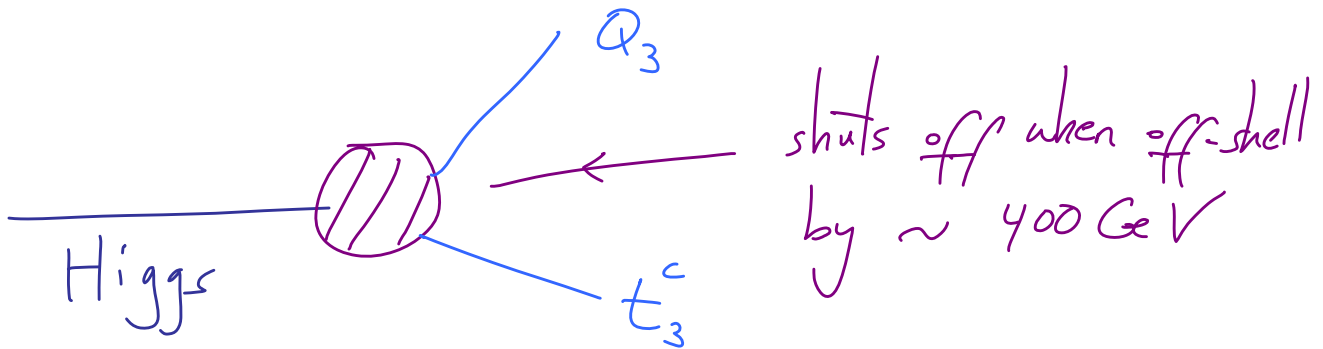
# Raman's "Fat Gravity" for CC



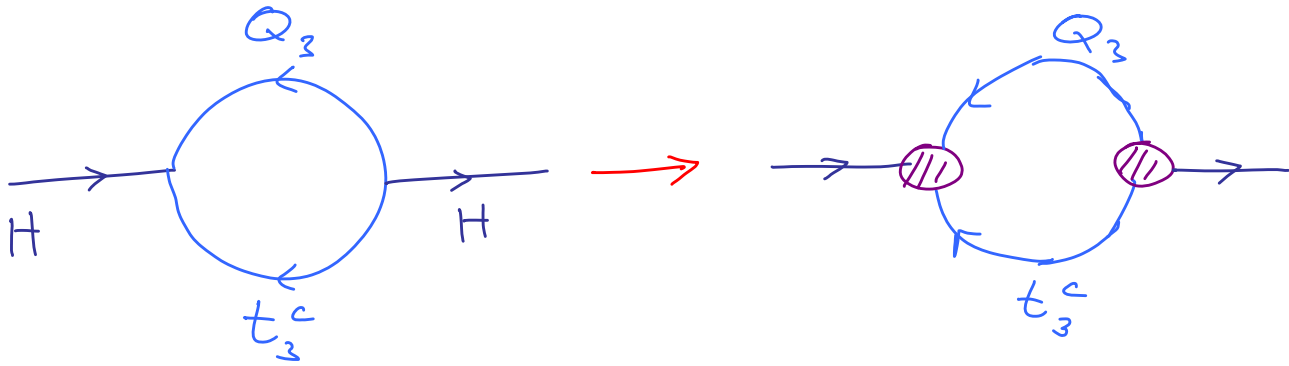
\* Equivalence Principle a challenge

\* On verge of being excluded by submm gravity expts

# "Fat Higgs" for Hierarchy



- \* No analog of equivalence principle challenge.
- \* Not close to probing @ LHC — need 100 TeV for this!



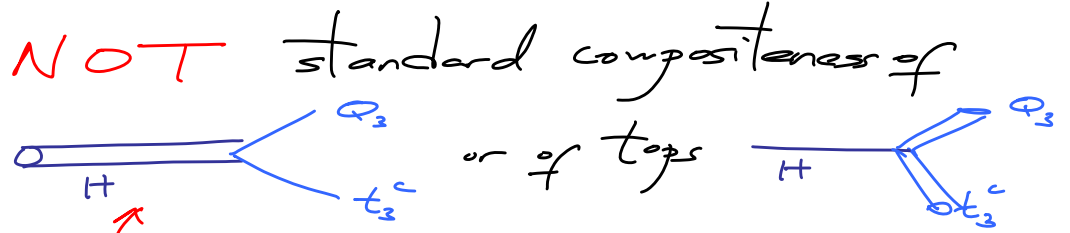
$$\frac{3}{8\pi^2} \int d^4 p \frac{\lambda_t^2}{p^2}$$



$$\frac{3}{8\pi^2} \int d^4 p \frac{\lambda_t^2}{p^2} \left( F\left(\frac{p^2}{\Lambda^2}\right) \right)^2$$

$$\Rightarrow \Lambda \simeq 400 \text{ GeV}$$

\* Notes:  
 higgs  
 (or both) .



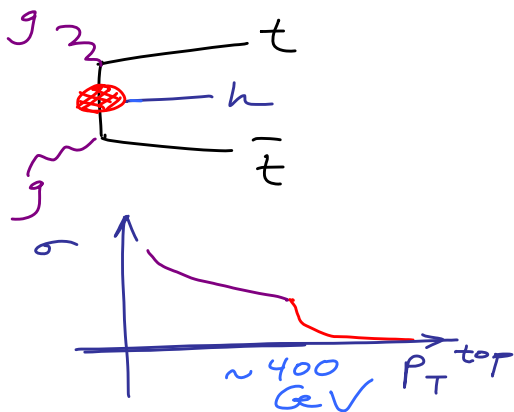
Already probing with Zh  
 coupling @ CEPC

highly constrained  
 by eg Z → bb

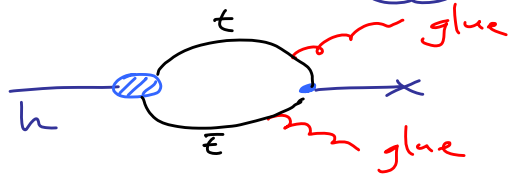
\* A more minimal (+ more loony!) idea. Higgs,  
 tops are pointlike to themselves, but mutually nonlocal  
 @ short scales

Experimentally: probe  $t\bar{t}h$  vertex off-shell!

Direct: 100 TeV



Indirect: Higgs Factory



$$K_g \sim \left( \frac{m_t^2}{\Lambda^2} \right) \sim 10\% \quad \left. \begin{array}{l} \text{Trivial} \\ \text{@} \\ \text{Higgsfact.} \end{array} \right\}$$

$$K_\gamma \sim \text{few \%}$$

+ Brutally non-analytic!!

Higgs probe of Foundations: Causal, Relativistic QM



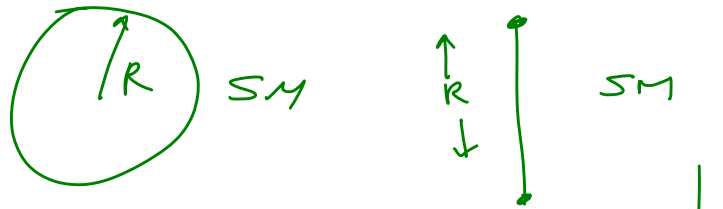
# Hidden Symmetries in (B)SMP

Witten '95: Maybe world SUSY, 3d  
 $\Rightarrow$  Bose-Fermi deg. (tiny, grav.)

$\xrightarrow{\text{strong coupling}}$  Big Bose/Fermi Splitting, but  
grow 4th dim!

4D Picture  $\xleftrightarrow{\text{Duality}}$  3D Picture  
Weakly Coupled,  
but  $\Lambda = 0$  mysterious!  
Strongly Coupled,  
but  $\Lambda = 0$   
obvious!

Prediction:



$E_{\text{Casimir}}[R] = 0!$

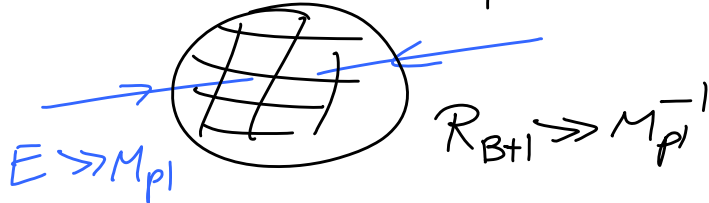
False for SM

Q: Is it possible to add particles/interactions, with any tunings you like, to make this happen?

Either Impossible, Or Ridiculously Predictive!

# UV/IR

\* Because of Gravity,



Deep UV =  
Deep IR

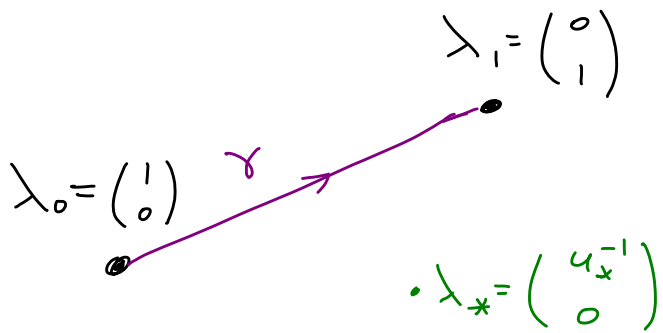
Reductionism / Wilsonian Paradigm **False**

THE WORLD IS NOT LIKE  
SOME CRAPPY METAL

# UV/IR Toy Model I

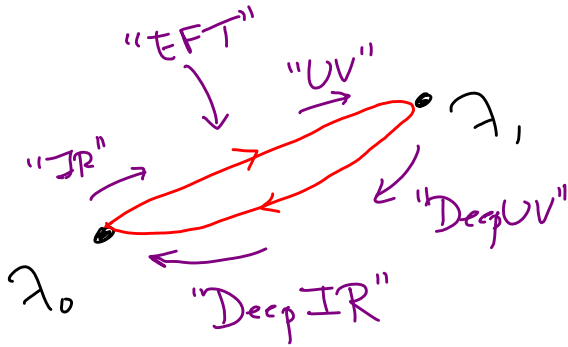
$$\int_0^{\infty} \frac{du}{\left(1 + \frac{u}{u_*}\right)^2} = u_*$$

$$\int_0^{\infty} \frac{du (1 - \epsilon u^2)}{\left(1 + \frac{u}{u_*} + \epsilon u^2\right)^2} = 0 \text{ for any } \epsilon > 0!$$



$$\int_{\gamma} \frac{\langle \lambda d\lambda \rangle}{\langle \lambda \lambda_* \rangle^2} = u_*$$

$$\lambda = \lambda_0 + u \lambda_1$$

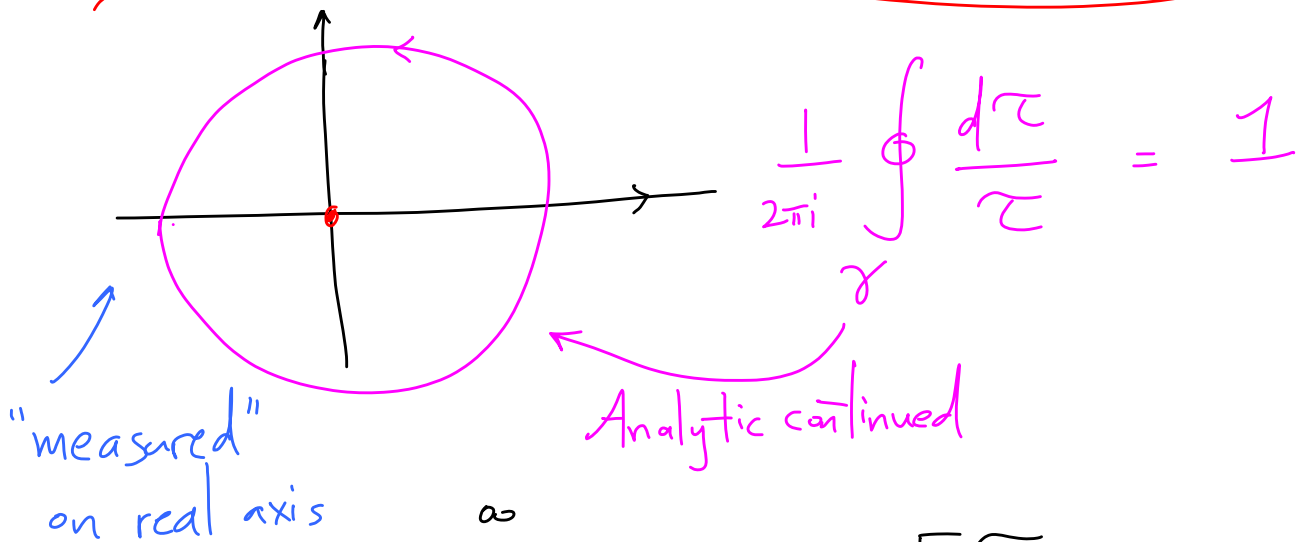


$$\lambda = \lambda_0 + u \lambda_1 + \epsilon u^2 \lambda_0$$

$$\int_{\gamma} \frac{\langle \lambda d\lambda \rangle}{\langle \lambda \lambda_* \rangle^2} = 0!$$

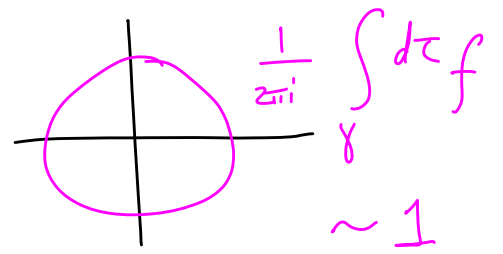
"Deep UV" cancels "Deep IR" for  
 trivial topological reason

# UV/IR Toy Model II

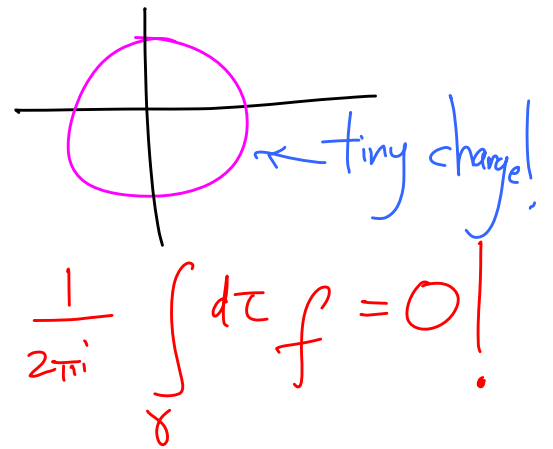


$$\frac{1}{\tau} = -i \int_0^{\infty} dE e^{iE\tau}$$

$$f(\tau) = -i \int_0^{\infty} \frac{dE}{(1 + E/\Lambda)^P} e^{iE\tau}$$



$$f(\tau) = -i \int_0^{\infty} dE e^{-E^2/\Lambda^2} e^{iE\tau}$$



Outlook





Explaining Parameters

vs

Understanding Dynamics

“Why are planetary  
distances what  
they are”

vs

“What is  
Motion?”

“What is QFT?”

{ + Note: NOT EUCLIDEAN  
QFT! Look at Questions  
where TIME  $\rightsquigarrow$  COSMOLOGY  
are crucial }

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

Nature is teaching us deep,  
surprising, (disquieting to some!)  
lessons via the L.H.C

We are being forced to rethink  
+ reformulate the foundations

IDEAL TIME TO BE 25!