Where in the World

are

SUSY + WIMPS?

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

Is 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 dimless #'s arise "from nowhere".

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

... $\int_0^\infty dx\ \mathrm{sinc}\,x\,\mathrm{sinc}\frac{x}{3}\cdots\mathrm{sinc}\frac{x}{13} = \frac{\pi}{2}$ but $\int_0^\infty dx\ \mathrm{sinc}\,x\cdots\mathrm{sinc}\frac{x}{15} = \frac{\pi}{2} - 2.1\times10^{-11}$!

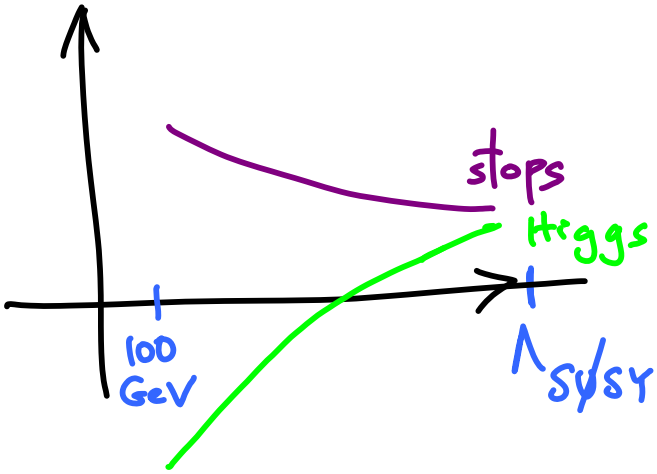
But we've never encountered this sort of things in theories where Higgs mass becomes calculable!

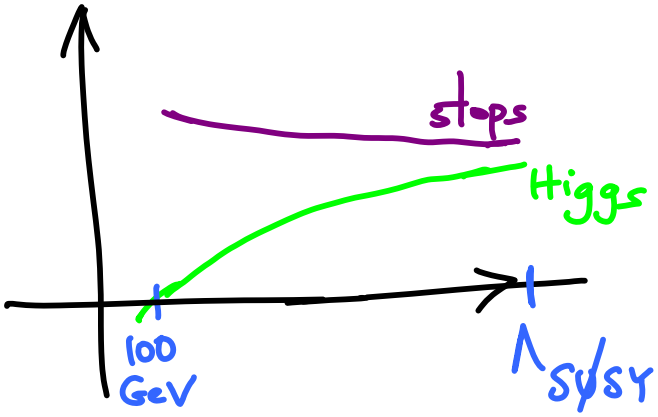
My Own Best Bet

(Since ~ 2004/2005)

Minimal Split SUSY

Why No SUSY @ LEP?





—— $Z, h, \tilde{t}, \tilde{g}$...

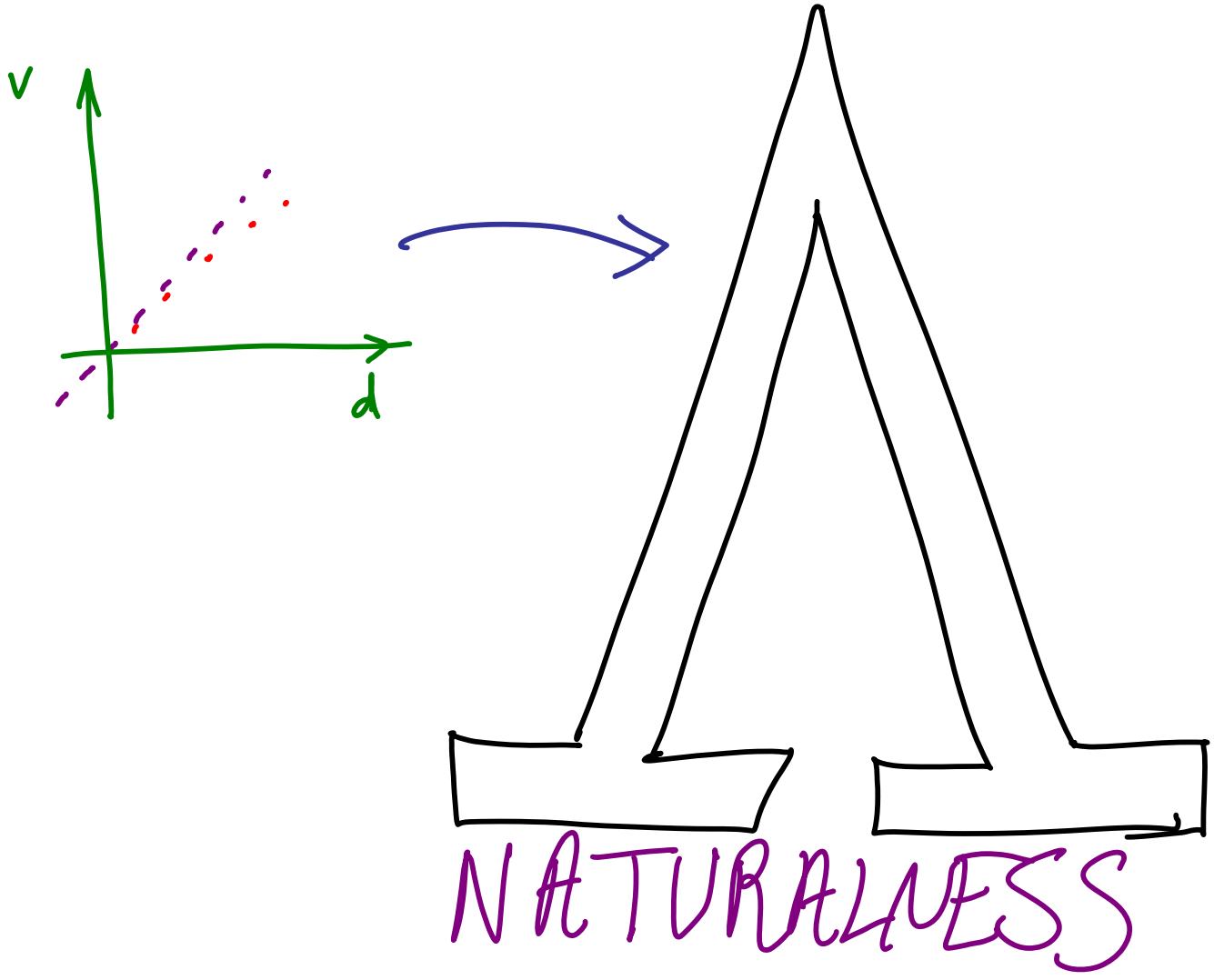
—— $\tilde{\ell}$, EWKinos

"Natural" Spectrum

?

—— Z, h

"Nature-al" spectrum


v
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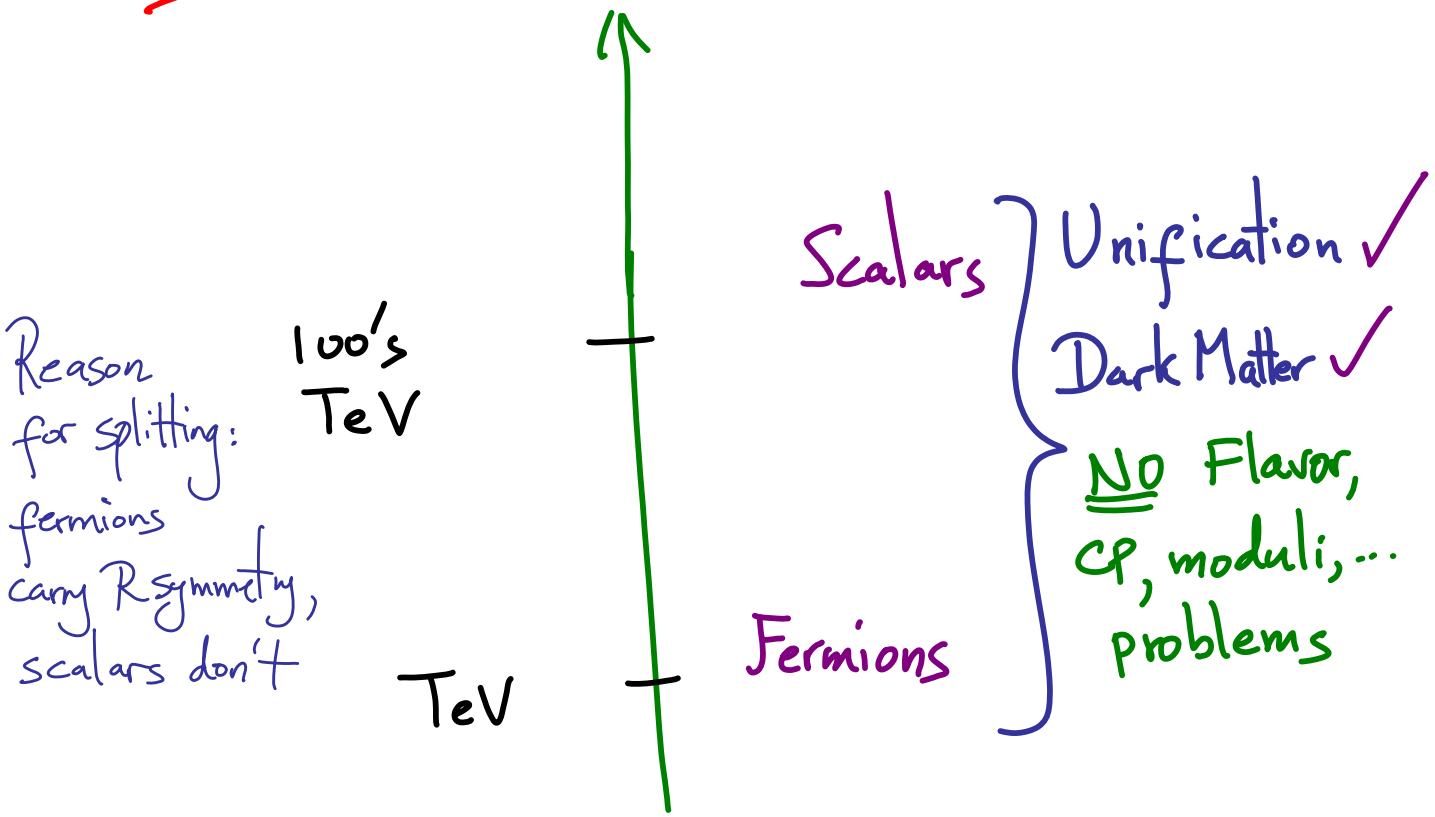
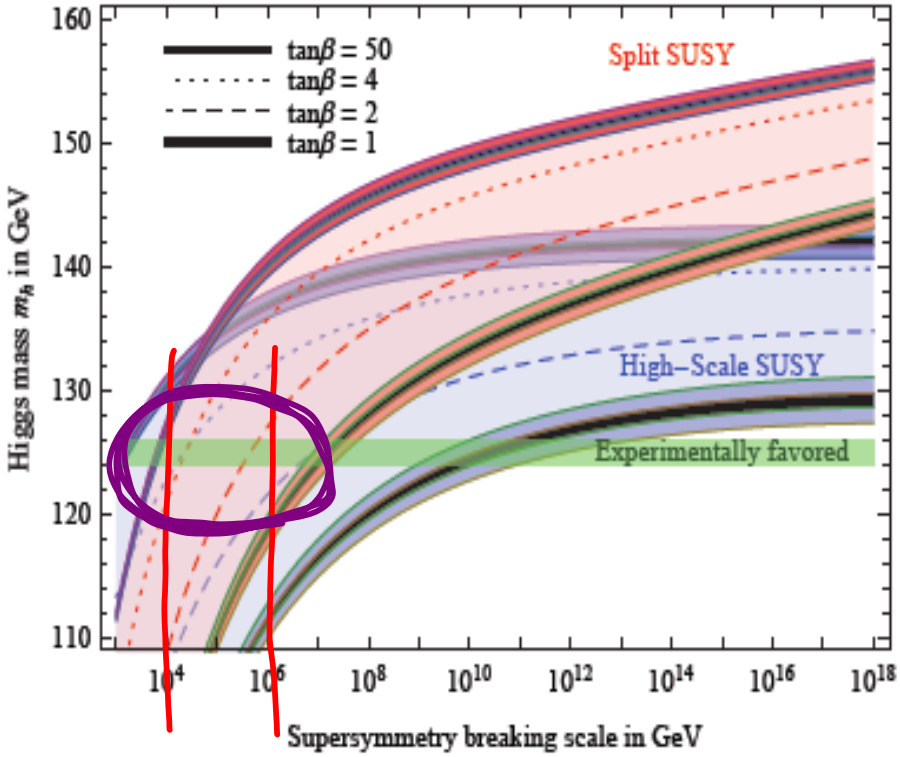
NATURALNESS

Minimal Split SUSY

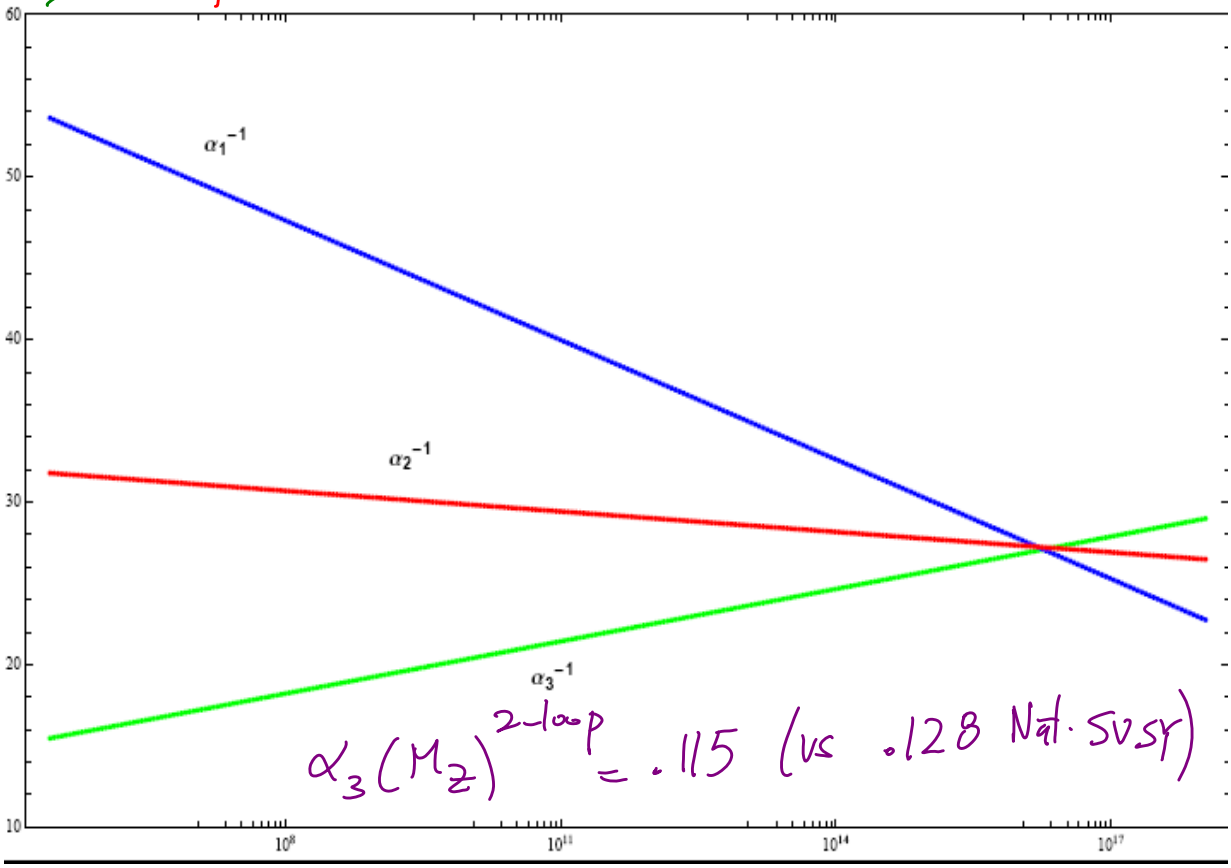


Predicted range for the Higgs mass



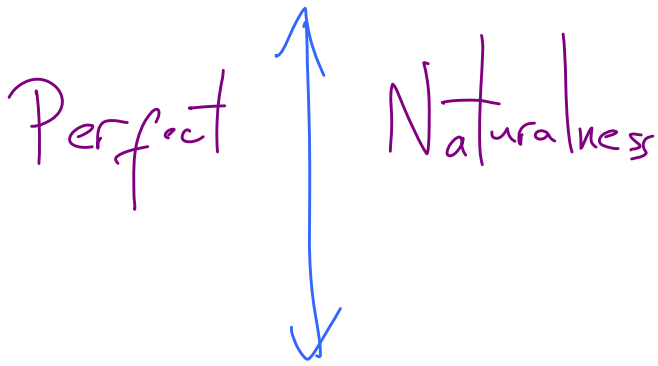
120 GeV $\lesssim m_{Higgs} \lesssim$ 135 GeV

Unification a Bit Better than Natural SUSY



$\alpha_3(M_Z)^{2\text{-loop}} = .115$ (vs .128 Nat. SUSY)

WIMPS

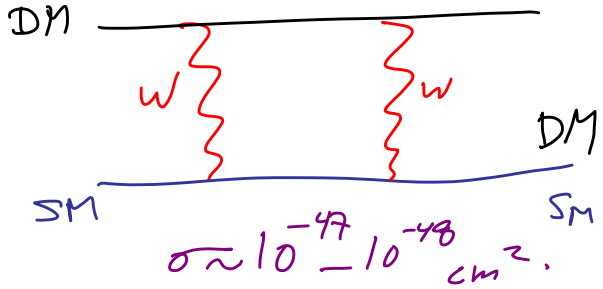


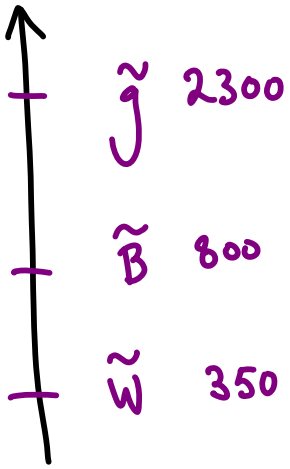
100's of GeV, Accessible to LHC
+ Direct Detection

... But absolute simplest, least "clever" WIMPS — e.g. Electroweak doublets, triplets ("Higgsinos", "Winos") — weigh 1–3 TeV.

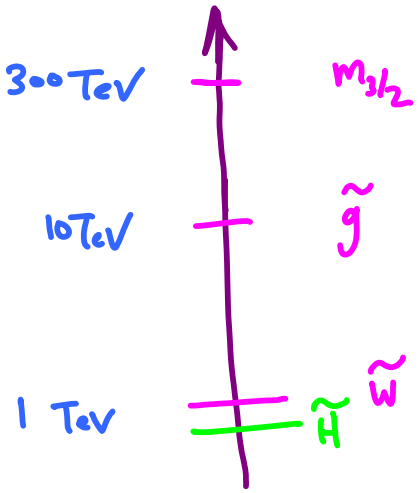
LHC : inaccessible.

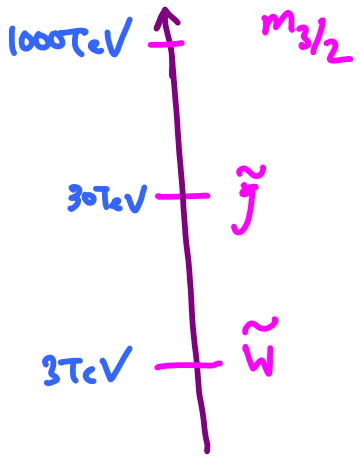
Direct Detection : invisible (so far! close to ν-floor..)





LHC Accessible

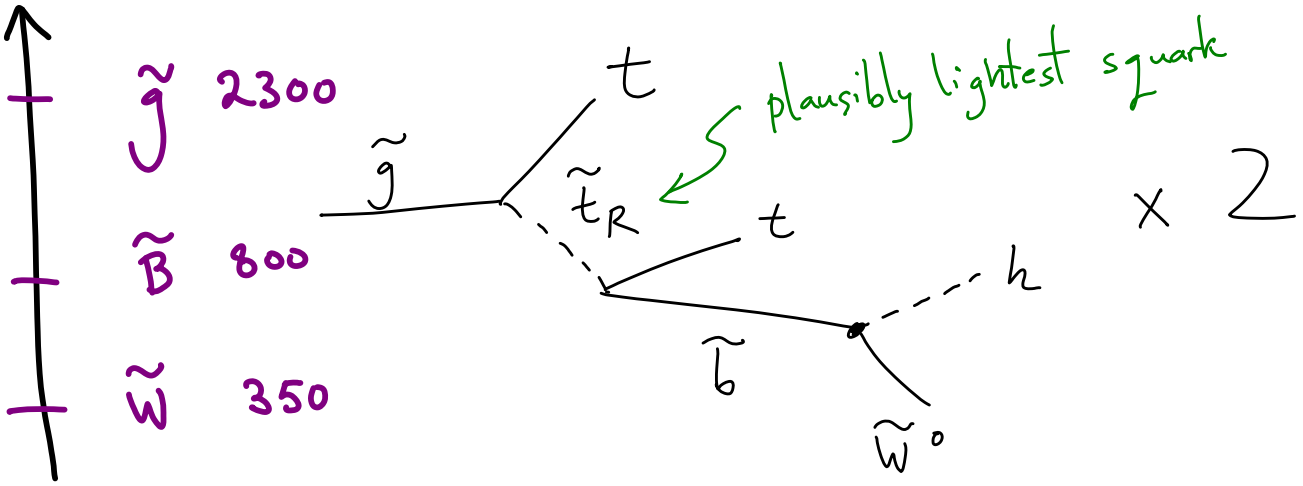




LHC Inaccessible

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).

hep-ph/0601041



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

Only need $O(1)$ events for discovery

Some New Lines of Attack

(1) Numerological Clues

(2) Cosmological Dynamics

(3) Analyticity, Causality + the Higgs

(4) Hidden Symmetries in (B)SM ?

(5) UV / IR

Clue to linking $\Lambda \longleftrightarrow m_h^2$?

$$\Lambda^{1/4} \sim \frac{m_W^2}{M_{Pl}} \Rightarrow \Lambda^{1/4} \sim m_\nu$$

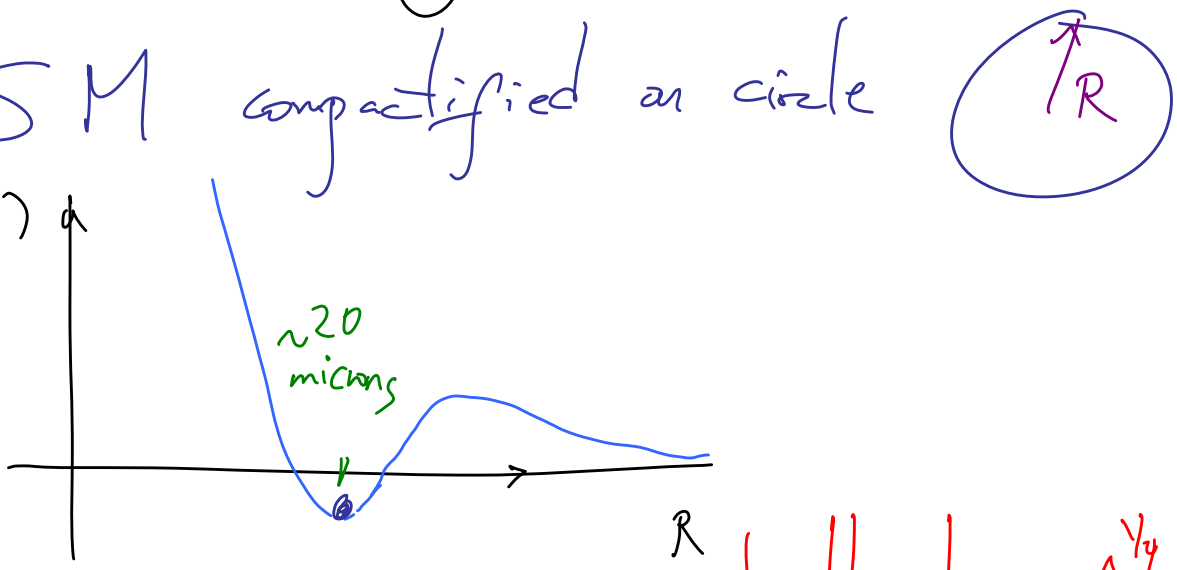
See-Saw

If DM = WIMP, Weinbergs anthropic argument predicts

$$\Lambda^{1/4} \sim T_{MR} \sim \frac{1}{\sigma_{ann} M_{Pl}} \sim \frac{m_{DM}^2}{M_{Pl}} \sim \frac{m_W^2}{M_{Pl}} !$$

Clue linking $\Lambda^{1/4} \sim m_\nu$

SM compactified on circle



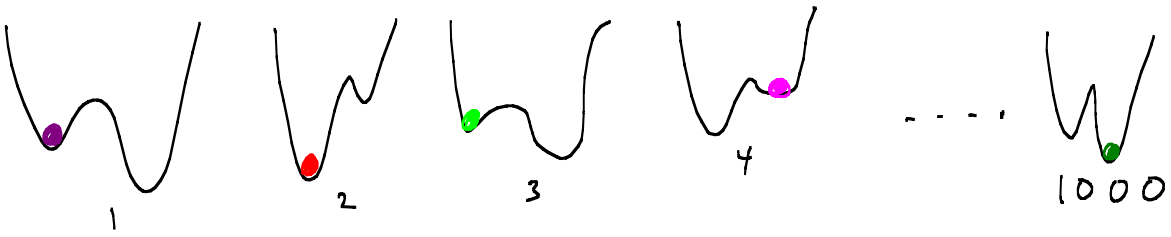
$AdS_3 \times S_1$ minimum — Delicately relies on $\Lambda^{1/4} \sim m_\nu$ to factor of 2!

Cosmological Dynamics

(A) The landscape populated by eternal inflation!

$\underbrace{W\,W}_{N}$ 2^N vacua.... can in principle be seen by experiments in our universe!

(B) The "Relaxion" Landscape



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

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

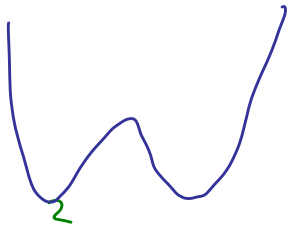
Landscape: $\sim 10^2 - 10^3$ SM singlet scalars!

* 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 unfamiliar: $S_i H^\dagger H, S_i S_j H^\dagger H$.

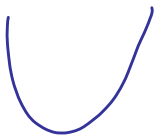
* Central "landscape" novelty: $\sim 10^2 - 10^3$ S's!

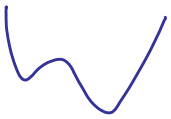
Motivation for light landscape: Correlating Hierarchy + CC



$\lambda_i\left(S_i^2 - \mu_i^2\right)^2 + a_i S_i h_u h_d$

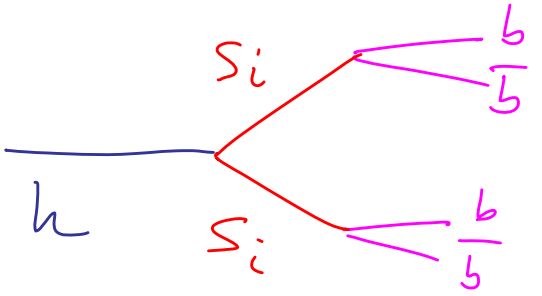
$m^2_{h_u,d} > 0$ NO scanning for CC

$|m^2_{h_u,d}| \gg \mu^2$  NO scanning for CC

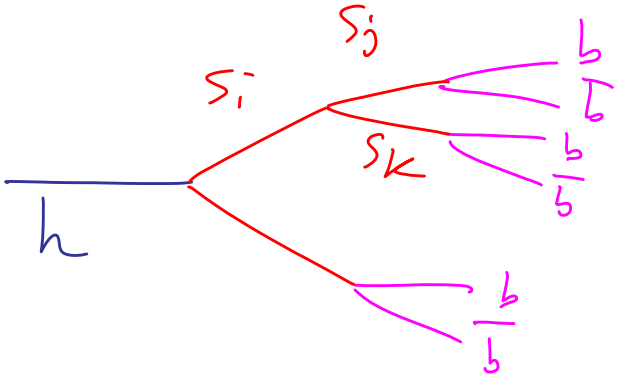
$m^2_{h_u,d} \sim \mu^2$  CAN scan for CC

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!

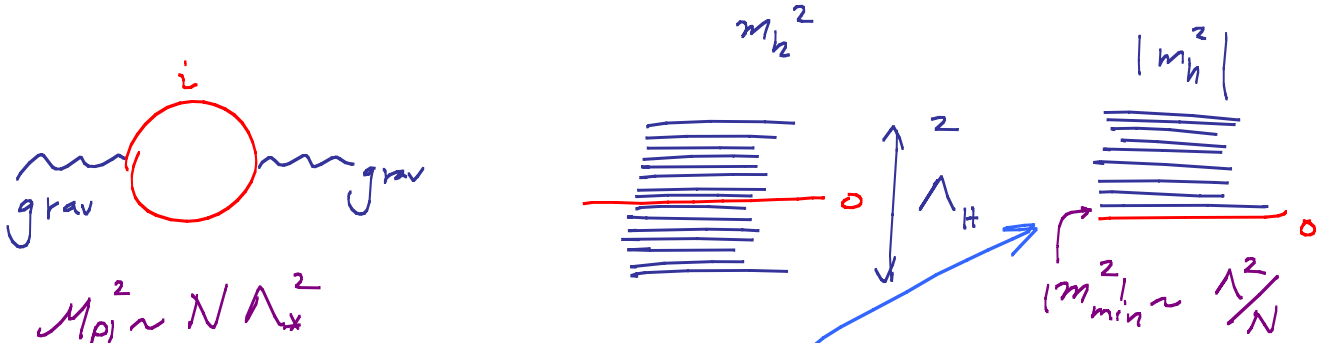


6 b events show $s_i s_j s_k$ interactions

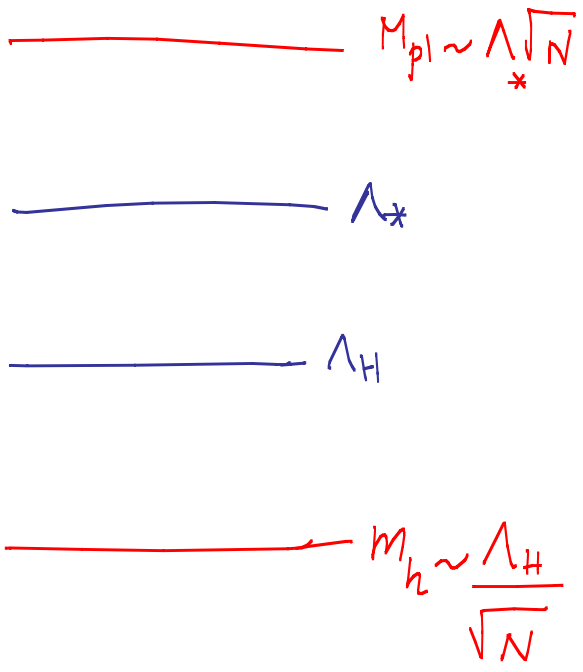
$\Rightarrow$ ~ $\Rightarrow$ direct exp. proof of exponentially many vacua!

© Reheating Dynamics: N-naturalness

N copies of (MS) SM



Cosmology Dominantly Reheats Bottom of Spectrum



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 be @ 10 TeV! [But not 1000 TeV...].

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

Complete-N-soln of hier. prob.

* Or $N = N_1 \times N_2 \ldots$

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

$m_h \sim \frac{\Lambda_*}{\sqrt{N_2}}$

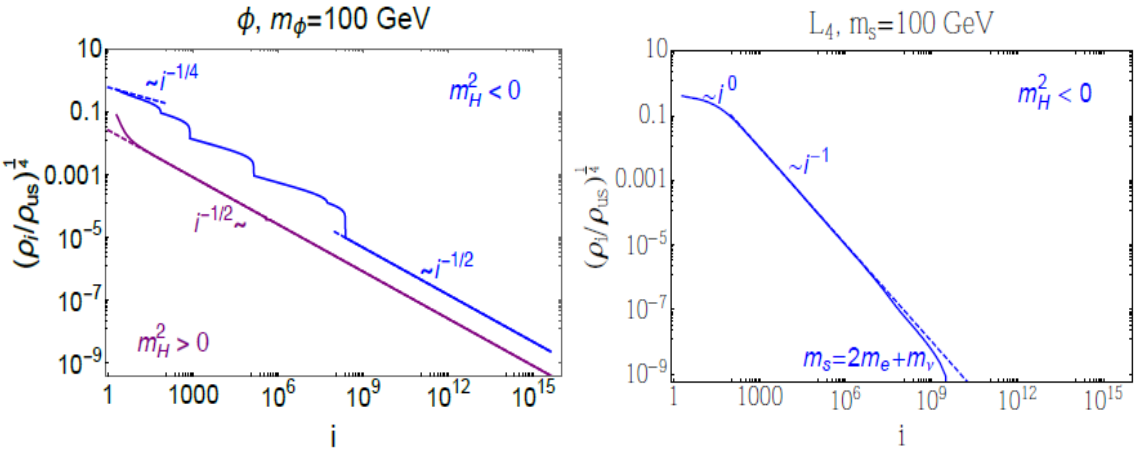


FIG. 3: Energy density deposited in each sector as a function of sector number, normalized to the energy density in our sector. The left panel is for the ϕ model with $a =$ MeV. The right panel is for the L_4 model with $\lambda \times \mu_E = 10^{-3}$ GeV, $M_L = 400$ GeV, $M_{E,N} = 500$ GeV, $Y_E = Y_N = 0.2$, and $Y_E^c = -Y_N^c = 0.5$. The solid lines are the result of a full numerical calculation. The dashed lines show the expected scalings. As discussed in the text, the steps in the ϕ model are proportional to Yukawa couplings due to the fact that ϕ decays via mixing through the Higgs.

Experimental Signals

- CMB + Large Scale Structure

* Indirect probe of large-N from axion physics

* If M_{GUT} is real, SUSY @ future colliders

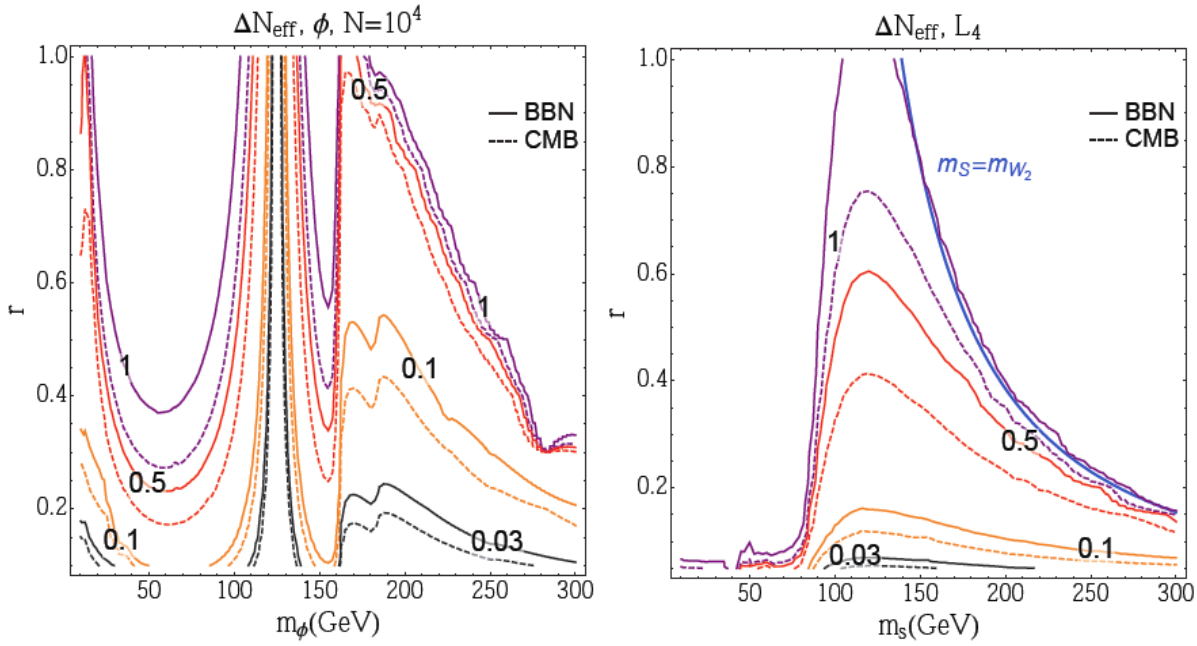
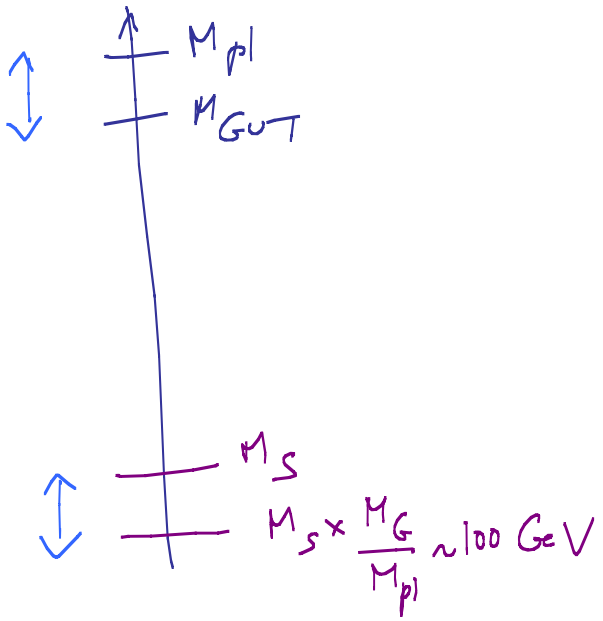


FIG. 5: $\Delta N_{\rm eff}$ contours as a function of reheaton mass and the r parameter defined in Eq. (1). $\Delta N_{\rm eff} \simeq 0.03$ corresponds to the sensitivity of CMB stage 4 experiments. The current upper bound at the CMB epoch is around 0.6. The left panel is for the ϕ model, with $a =$ MeV. The right panel is for the L_4 model, with $\lambda \times \mu_E = 10^{-3}$ GeV, $M_L = 400$ GeV, $M_{E,N} = 500$ GeV, $Y_E = Y_N = 0.2$, and $Y_E^c = -Y_N^c = 0.5$. As discussed in the text the plot is valid for a large range of N, namely $30 \lesssim N \lesssim 10^{13}$.

SUSY Beneath ~ 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

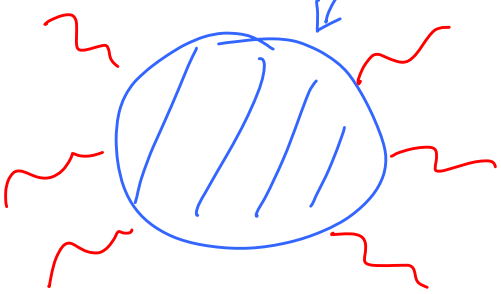
Foundations of Fund. Physics:

Lorentz Invariance } SHARP

Unitarity } SHARP

Causality

MORE MURKY....



how do we know this is "causal"?

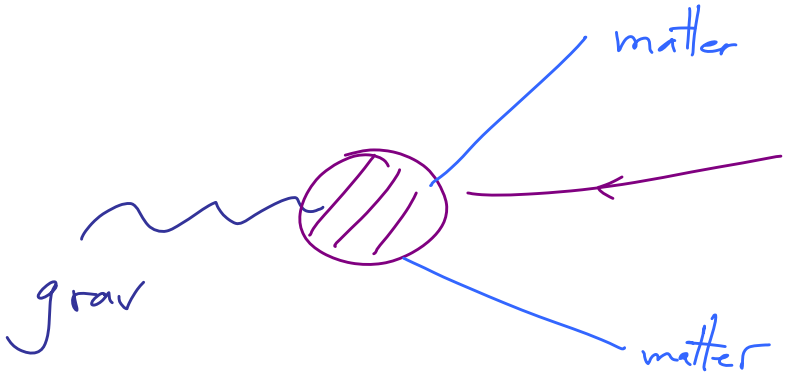
How is Causality encoded in S-matrix?

Q - from 1960's ... still don't know precise answer today!!

analyticity ... But, related to + can be checked experimentally!

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

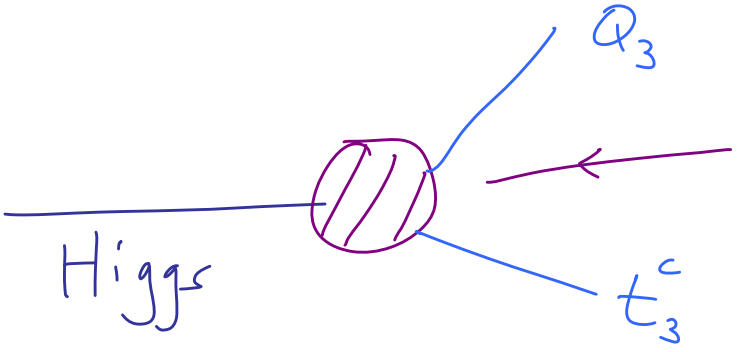
Raman's "Fat Gravity" for CC



shuts off when off-shell by more than $\sim 10^{-3}\,eV$ $\sim .\ mm^{-1}$

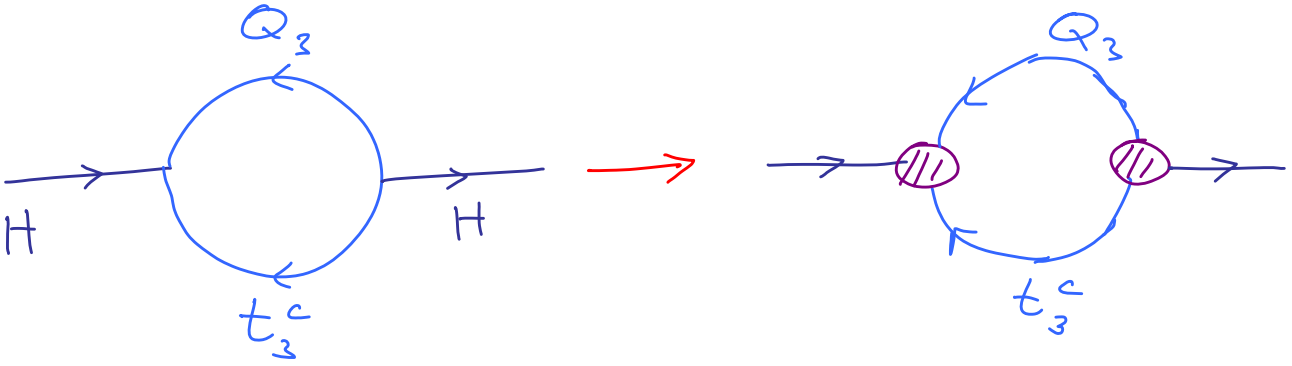
* Equivalence Principle a challenge
* On verge of being excluded by sub mm gravity exgts

"Fat Higgs" for Hierarchy



shuts off when off-shell by ~ 400 GeV

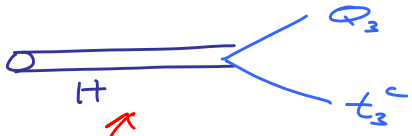
* No analog of equivalence principle challenge.
* Not close to probing @ LHC — need 100 TeV for this!



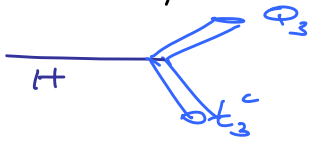
$$\frac{3}{8\pi^2}\int d^4p\ \frac{\lambda_t^2}{p^2} \longrightarrow \frac{3}{8\pi^2}\int d^4p\ \frac{\lambda_t^2}{p^2}\left(F(p^2/\Lambda^2)\right)^2$$

$$\Longrightarrow \Lambda \lesssim 400\ \text{GeV}$$

* Note: NOT standard compositeness of higgs (or both).



or of tops



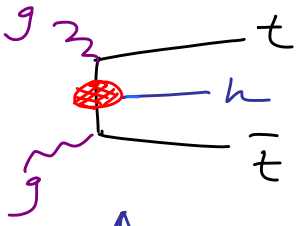
Already probing with Zh coupling @ CEPC

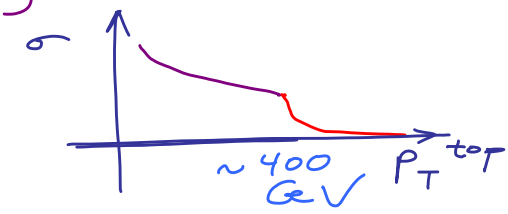
highly constrained by eg $Z \to b\bar{b}$

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

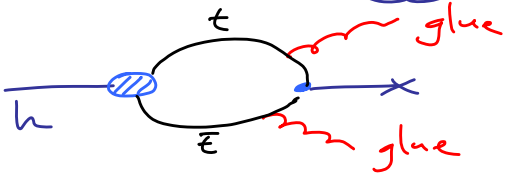
Experimentally: probe $t\bar{t}h$ vertex off-shell!

Direct: 100 TeV





Indirect: Higgs Factory



$$K_g \sim \left(\frac{m_t^2}{\Lambda^2}\right) \sim 10\%$$

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

} Trivial @ Higgsfact.

↑ + Mutually non-analytic!!

Higgs probe of Foundations: Causal, Relativistic QM

Hidden Symmetries in (B)SM?

Witten '95: Maybe world SUSY, 3d $\not\Longrightarrow$ Bose-Fermi deg. (tiny, grav.)

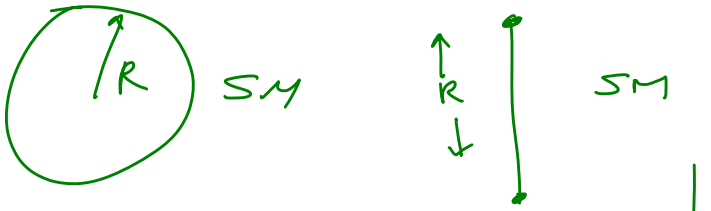
strong coupling → Big Bose/Fermi Splitting, but grow 4th dim!

4D Picture ⟷ (Duality) ⟷ 3D Picture

4D Picture: Weakly Coupled, but $\Lambda = 0$ mysterious!

3D Picture: Strongly Coupled, but $\Lambda = 0$ obvious!

Prediction:



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

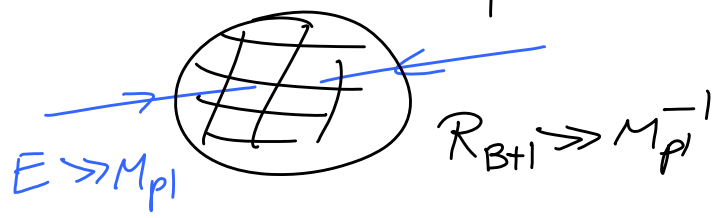
False for SM

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

In past decade — we have seen that consistency of UV with BH horizon thermodynamics + causality — has teeth.

Surprising constraints on EFT

* Positive Signs for (∞ # of !) higher-dim ops

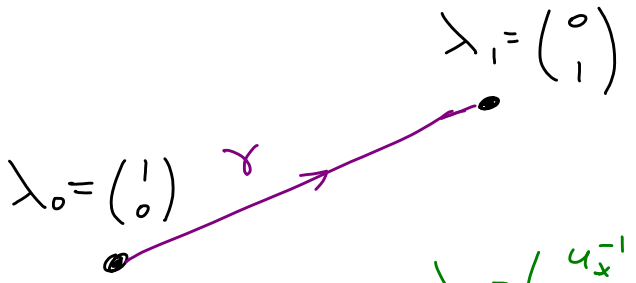
* "Weak Gravity" Conjecture

Might these extend to surprises for Relevant Ops like Λ, m_h^2 ?

UV/IR Toy Model I

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

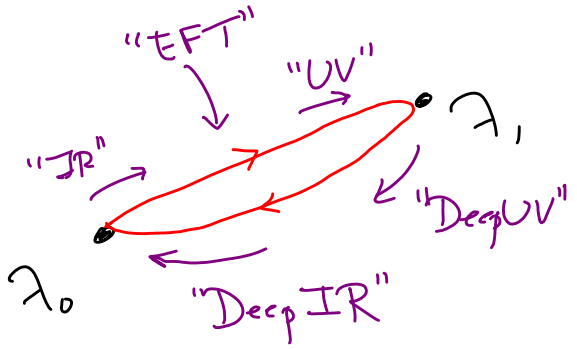
$$\int_0^\infty \frac{du\,\left(1-\epsilon u^2\right)}{\left(1+\frac{u}{u_*}+\epsilon u^2\right)^2} = 0 \text{ for any } \epsilon > 0 !$$



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

$\cdot \lambda_* = \begin{pmatrix} u_*^{-1} \\ 0 \end{pmatrix}$

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

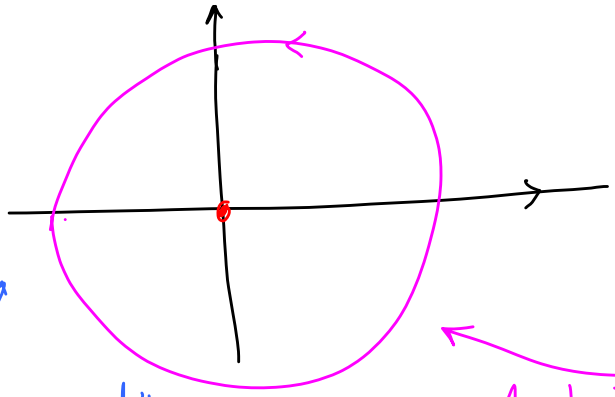


$$\lambda = \lambda_0 + u\lambda_1 + \varepsilon u^2 \lambda_0$$

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

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

UV/IR Toy Model II



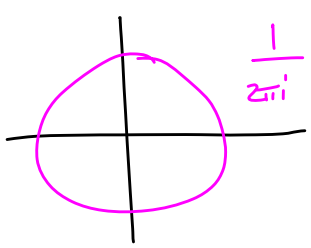
$$\frac{1}{2\pi i}\oint_{\gamma}\frac{d\tau}{\tau} = 1$$

"measured" on real axis

Analytic continued

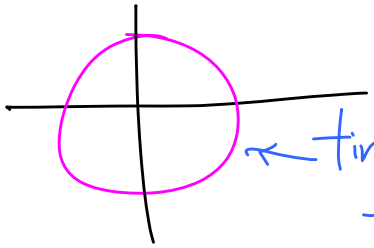
$$\frac{1}{\tau} = -i\int_0^{\infty} dE\ e^{iE\tau}.$$

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

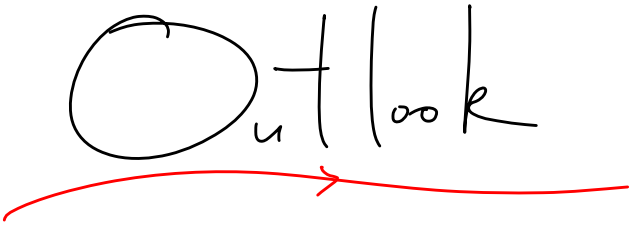


$$\frac{1}{2\pi i} \oint_\gamma d\tau f \sim 1$$

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



$$\frac{1}{2\pi i} \oint_\gamma d\tau f = 0 !$$


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 ⇝ 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!