SuperSoft Stops

Israel Joint Seminar

At Home

April 22nd 2020

Matthew McCullough

Based on: Cohen, Craig, Giudice, MM 2019

Cohen, Craig, Koren, MM, Tooby-Smith 2020

Prologue:

The Hierarchy Problem…

Higgs Mechanism

- The Higgs sector of the Standard Model involves the Higgs field and the gauge fields

$$H \qquad\qquad W_\mu^a$$

- The Lagrangian for this theory is

$$\mathcal{L} = \left|(\partial_\mu + ig\sigma^a W_\mu^a)H\right|^2$$
$$+m^2(T)|H|^2 - \lambda(T)|H|^4 + \ldots$$

Higgs Mechanism

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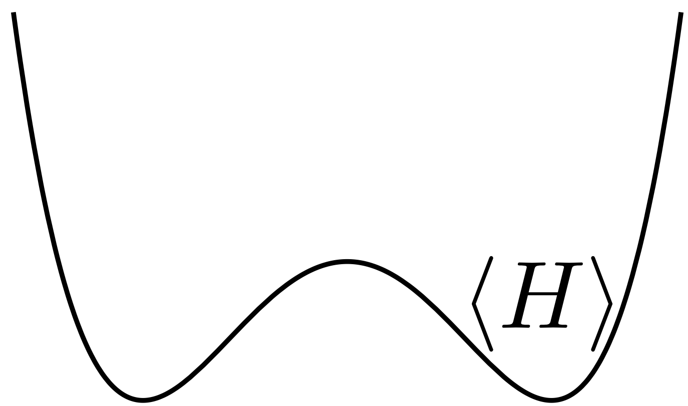
$$+m^2(T)|H|^2 - \lambda(T)|H|^4 + \ldots$$

- Below the critical temperature the mass-squared is negative:



- Gauge bosons become massive: $M_W \sim g\langle H\rangle$

Ginzburg-Landau

- The G-L Theory of superconductivity involves a complex scalar field and the photon (magnetic vector potential)

$$\Phi \qquad\qquad A$$

- The Free energy for this theory is

$$F = |(\nabla + 2ieA)\Phi|^2$$

$$+m^2(T)|\Phi|^2 + \lambda|\Phi|^4 + \ldots$$

- Where the mass depends on the temperature.

Ginzburg-Landau

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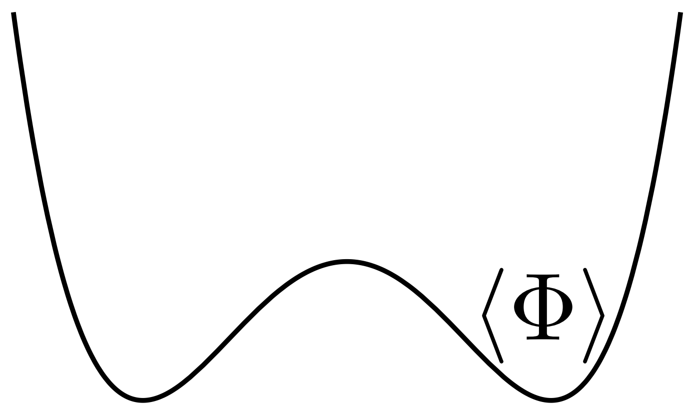


- Photon has become massive: $m_A \sim e\langle\Phi\rangle$

The Elephant in the Room

Ginzburg-Landau is just a phenomenological model, with no explanation of parameters. The macroscopic parameters follow from the detailed microscopic BCS theory (Gor'kov) and there are no surprises.

The order parameter at zero temperature is of the typical scale associated with underlying microscopic parameters.

The Elephant in the Room

Ginzburg-Landau is just a phenomenological model, with no explanation of parameters. The ma... copic parameters follow from the de... in BCS theory (Gor'kov) and th...

Phenomenological model parameters, such as the order parameter $\langle ee \rangle$ predicted by microscopic theory.

Φ

The order parameter at zero temperature is of the typical scale associated with underlying microscopic parameters.

The Elephant in the Room

Performing the same exercise with the Higgs field.

We can look to see if the symmetry breaking is like Ginzburg-Landau

- Direct analogy, would have no light Higgs boson: Experimentally excluded.
- Perhaps not directly analogous, but similar composite story: Study the Higgs…

The Elephant in the Room

We expect the Higgs model is phenomenological, just like G-L. But something totally different seems to be going on.

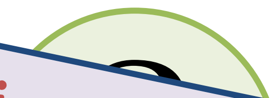
There is a hierarchy between the phenomenological model parameters and the microscopic parameters (Planck, GUT, RHN, PQ,...).

Furthermore, this hierarchy is not protected by any symmetry: Quantum corrections do not respect such a hierarchy.

The Elephant in the Room

We expect the Higgs model is phenomenological, just like G-L. But something totally different seems to b

If the phenomenological model parameters, such as $\langle H \rangle$, predicted by microscopic theory, then why the hierarchy?



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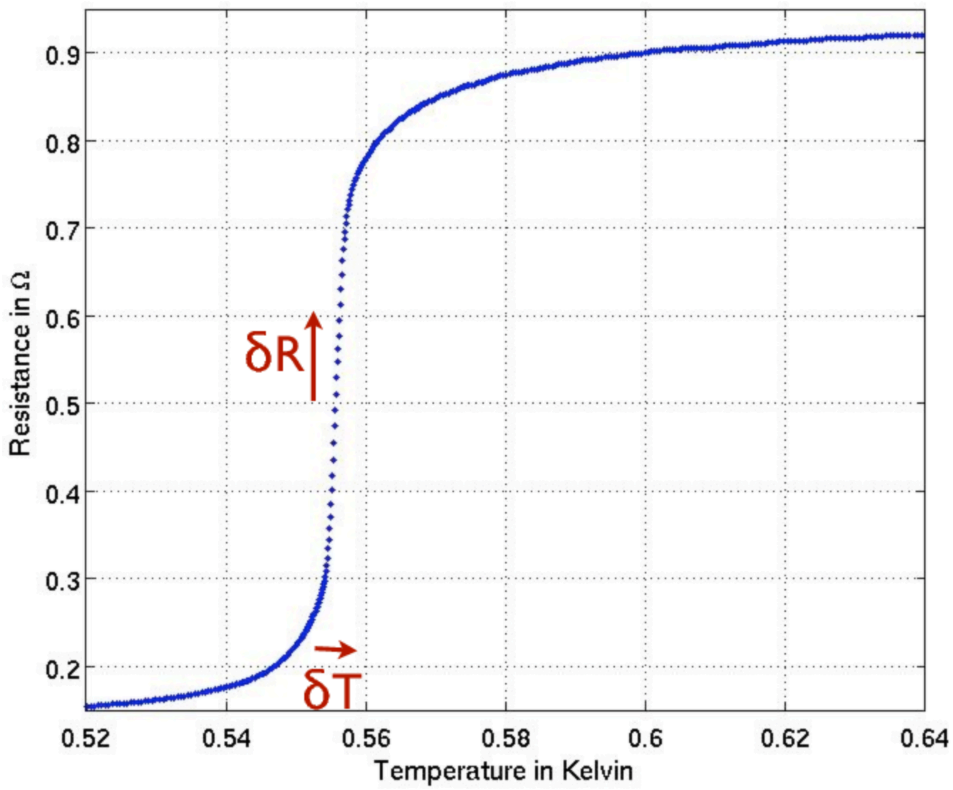
Fine-Tuning?

Essentially, it seems like the Universe is just like a Transition Edge Sensor:



- Taken from 1309.5383

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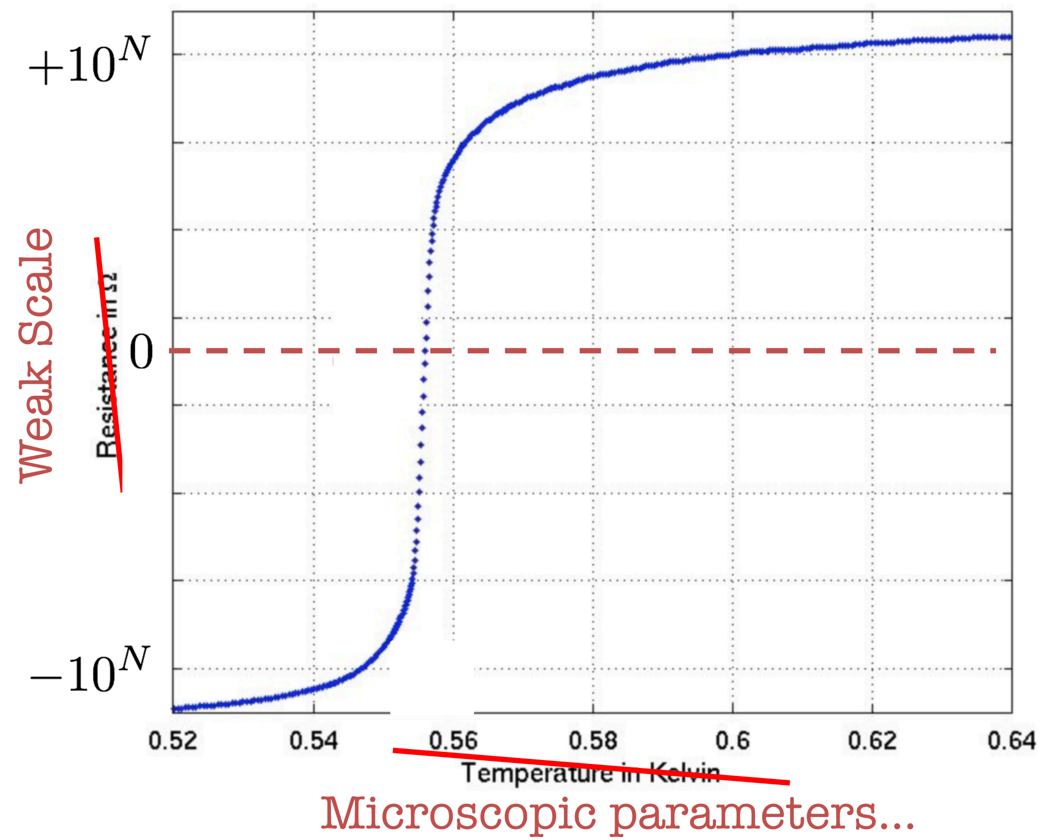

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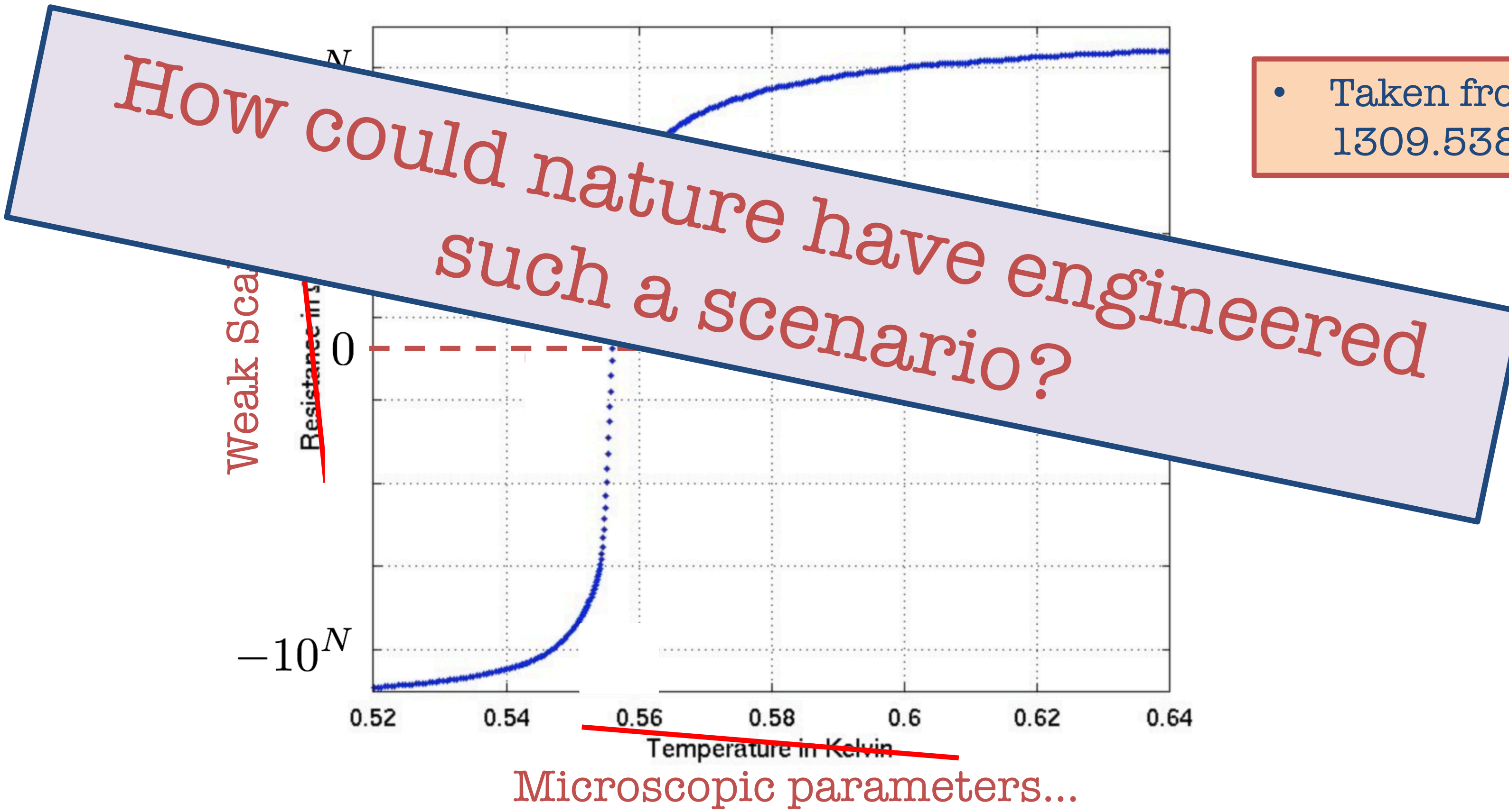


- Taken from 1309.5383

Hierarchy Problem

Many* approaches follow four basic paradigms...

Symmetry.

Locality.

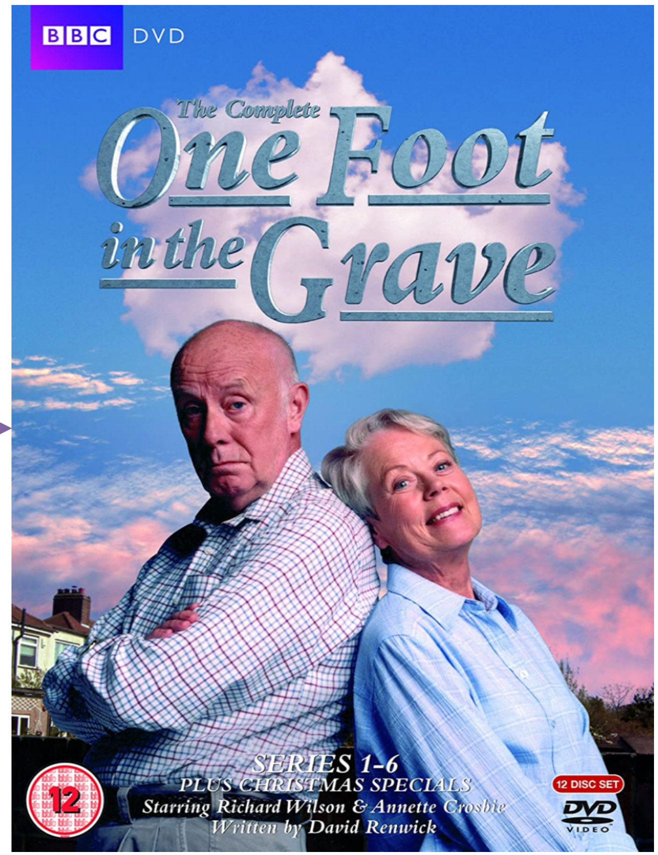
Dynamics.

Anthropics.

This talk will cover two recent variations on the symmetry theme.

Supersymmetry

We've all heard the declarations that SUSY is dead.
But is it really? Maybe one foot in the grave...

Data →  ← SUSY

but we're a long way off any definitive statements.

Supersymmetry

What is the problem, really?

$$\delta M_H^2 \propto \frac{\widetilde{m}^2}{16\pi^2} \log(\Lambda_{\rm UV}/\widetilde{m})$$

If we have small logs then it is still ok to have

$$\widetilde{m} \sim 4\pi M_H$$

Which is still about consistent with LHC constraints.

Supersymmetry

Thus the problem isn't really the soft mass scale. The problem is the logs. We need to get rid of them...

Supersymmetry

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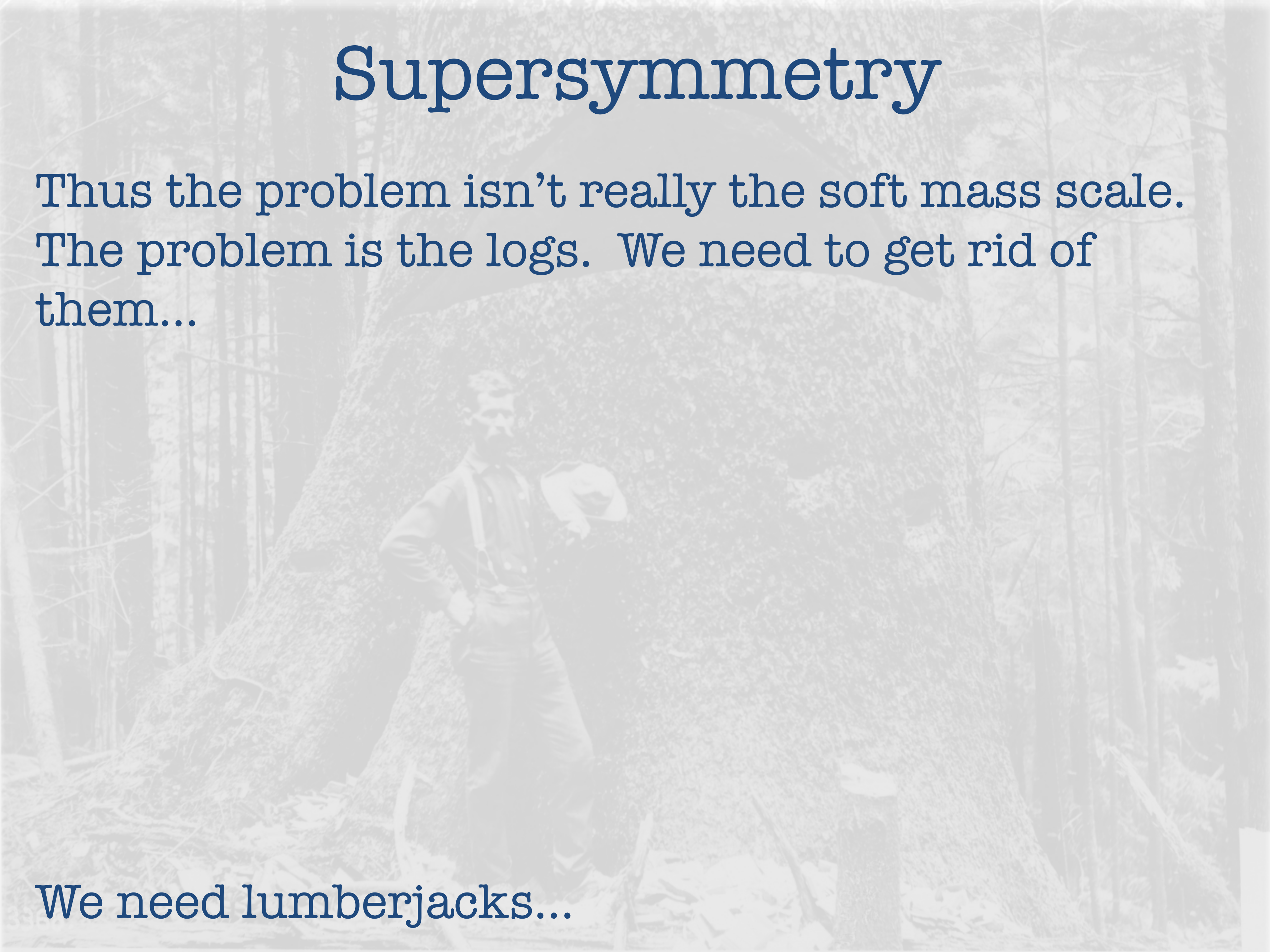
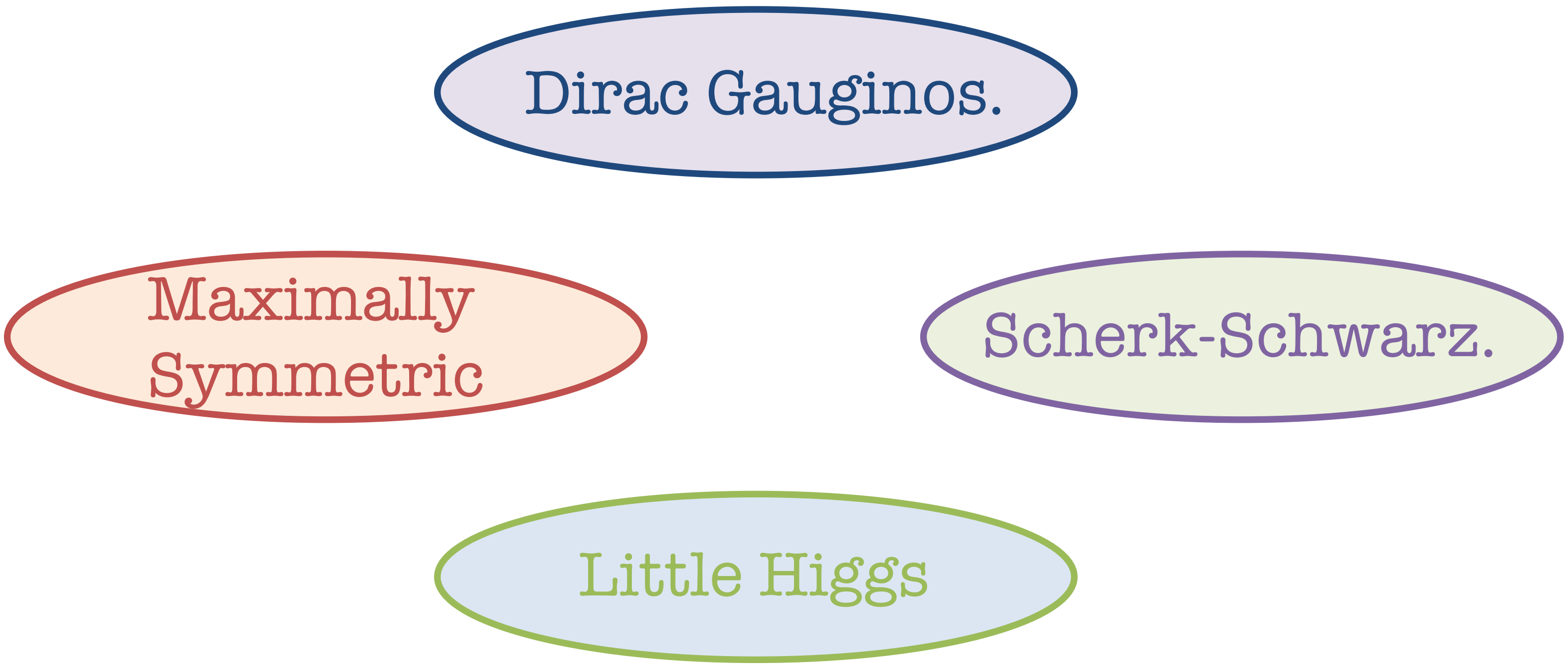
We need lumberjacks...



Supersymmetry

We have seen examples of theories with suppressed logs for decades…



Have we exhausted the model space of such supersoft theories?

Supersymmetry

We have seen examples of theories with suppressed logs for decades...

Dirac Gauginos.

Models with Dirac gauginos do a great job. However, this only suppresses logs in the gaugino contribution to scalar masses. Not in the contributions of scalar masses to scalar masses. So only partially supersoft.

Supersymmetry

We have seen examples of theories with suppressed logs for decades...

Scherk-Schwarz.

Scherk-Schwarz models tend to have large Wilson coefficients, which can be interpreted as a finite scale in the log, and also a lowish cutoff as compared to, e.g. the GUT scale.

Supersymmetry

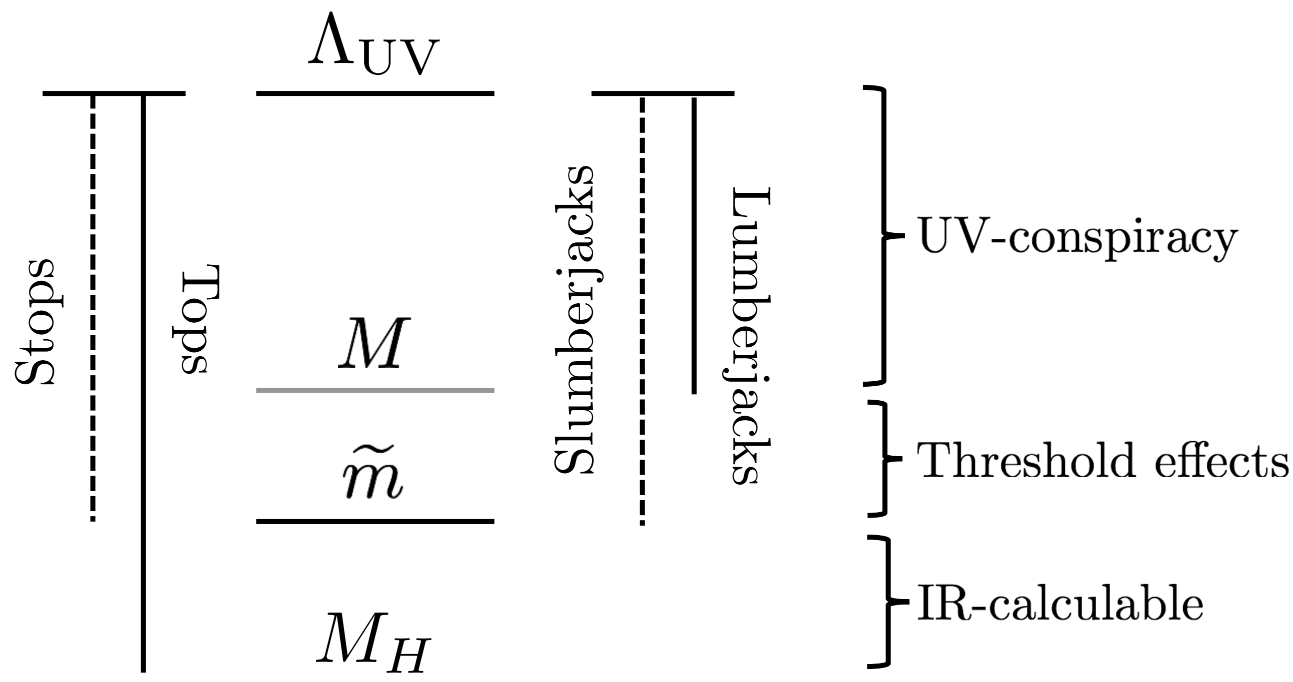
We have seen examples of theories with suppressed logs for decades...

Low-Scale SUSY.

Models with low-scale SUSY breaking have small logs, by construction, but not that small, since the cutoff is around 30 TeV. Also, from a model-building perspective, challenging to construct. Low cutoff again.

Supersoft Stops

If we could design a supersoft stop sector, what would it look like, from top down?



Require equal-and-opposite RG contributions from some new sector to cancel top-stop logs.

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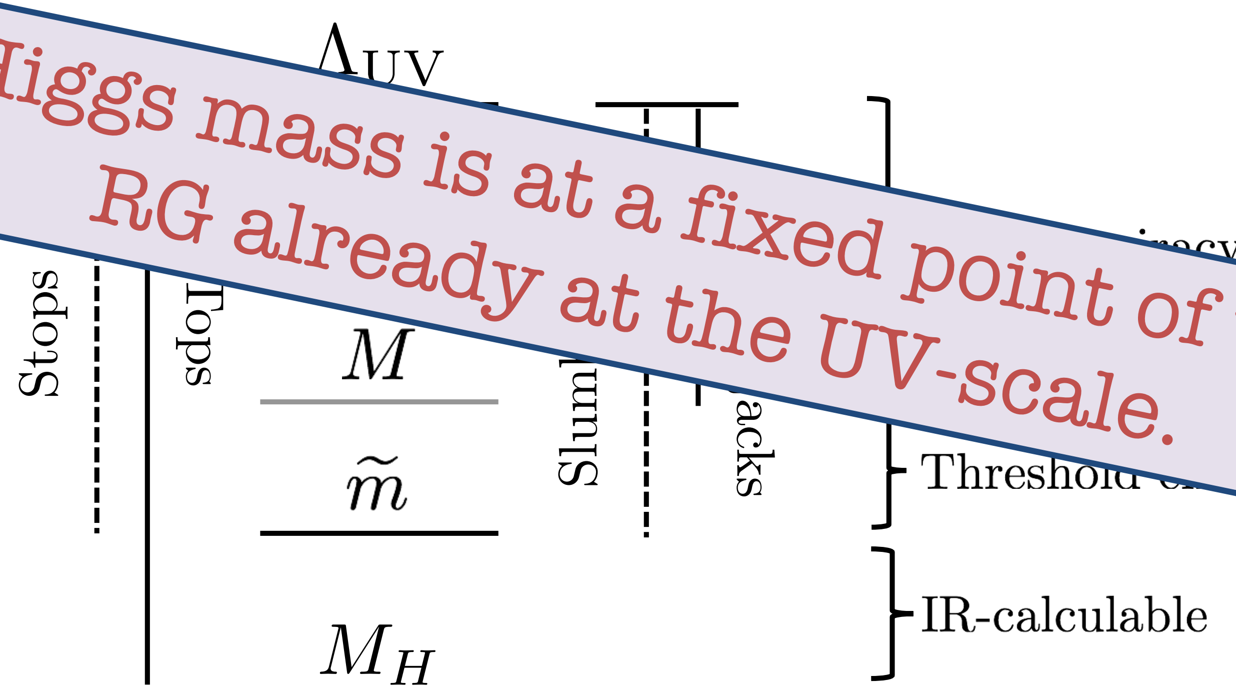

Higgs mass is at a fixed point of the RG already at the UV-scale.

Require equal-and-opposite RG contributions from some new sector to cancel top-stop logs.

Supersoft Stops

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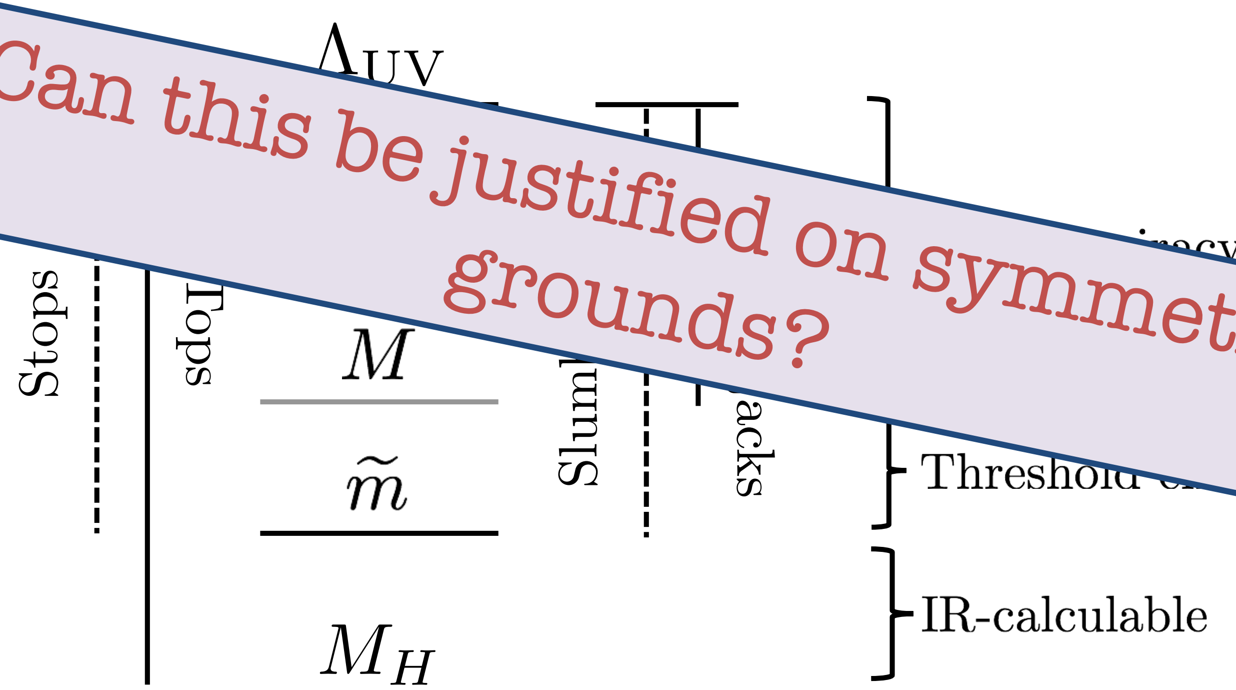

Can this be justified on symmetry grounds?

Require equal-and-opposite RG contributions from some new sector to cancel top-stop logs.

Supersoft Stops

The recipe requires ingredients which are becoming painfully familiar now...

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Step 1. Add a copy of something. In this case, let's just do top-stops.

Supersoft Stops

The recipe requires ingredients which are becoming painfully familiar now…

Step 1. Add a copy of something. In this case, let's just do top-stops.

Step 2. Endow theory with an exchange symmetry.

$$\boldsymbol{W_{\lambda}} = \lambda_t\, \boldsymbol{H_u}\, \boldsymbol{Q}\, \boldsymbol{U^c} + \lambda_t\, \boldsymbol{H_u}\, \boldsymbol{Q'}\, \boldsymbol{U'^c}$$

Swap

Supersoft Stops

Step 3. Break exchange symmetry and SUSY with the same spurion.

$$V_{\text{Soft}} \simeq \widetilde{m}^2 \left(|\widetilde{Q}|^2 + |\widetilde{U}^c|^2 - |\widetilde{Q}'|^2 - |\widetilde{U}'^c|^2 \right)$$

Swap and flip

Note that at this stage the desired RG evolution is guaranteed. No logs! Only problem is that our new fields are tachyons and break QCD.

Supersoft Stops

Step 4. Introduce SUSY-preserving source of exchange breaking:

$$\boldsymbol{W_M} = M\left(\boldsymbol{Q}'\,\overline{\boldsymbol{Q}}' + \boldsymbol{U}'^{\boldsymbol{c}}\,\overline{\boldsymbol{U}}'^{\boldsymbol{c}}\right)$$

The nice story with RG cancellation is preserved far above the scale M, but breaks down at this scale. Thus expect M to replace the UV-scale

$$\delta M_{H_u}^2 \simeq -\frac{3\,\lambda_t^2}{8\pi^2}\,\widetilde{m}^2\left[\frac{3}{2} + \log\left(\frac{M^2}{\widetilde{m}^2}\right)\right]$$

Indeed this happens.

Easy Gains

This model is trivial, but the gains are not. The true microscopic scale is $\Lambda_{\rm UV}$, yet the soft mass corrections are reduced from

$$\delta M_H^2 \propto \frac{\widetilde{m}^2}{16\pi^2} \log(\Lambda_{\rm UV}/\widetilde{m})$$

to

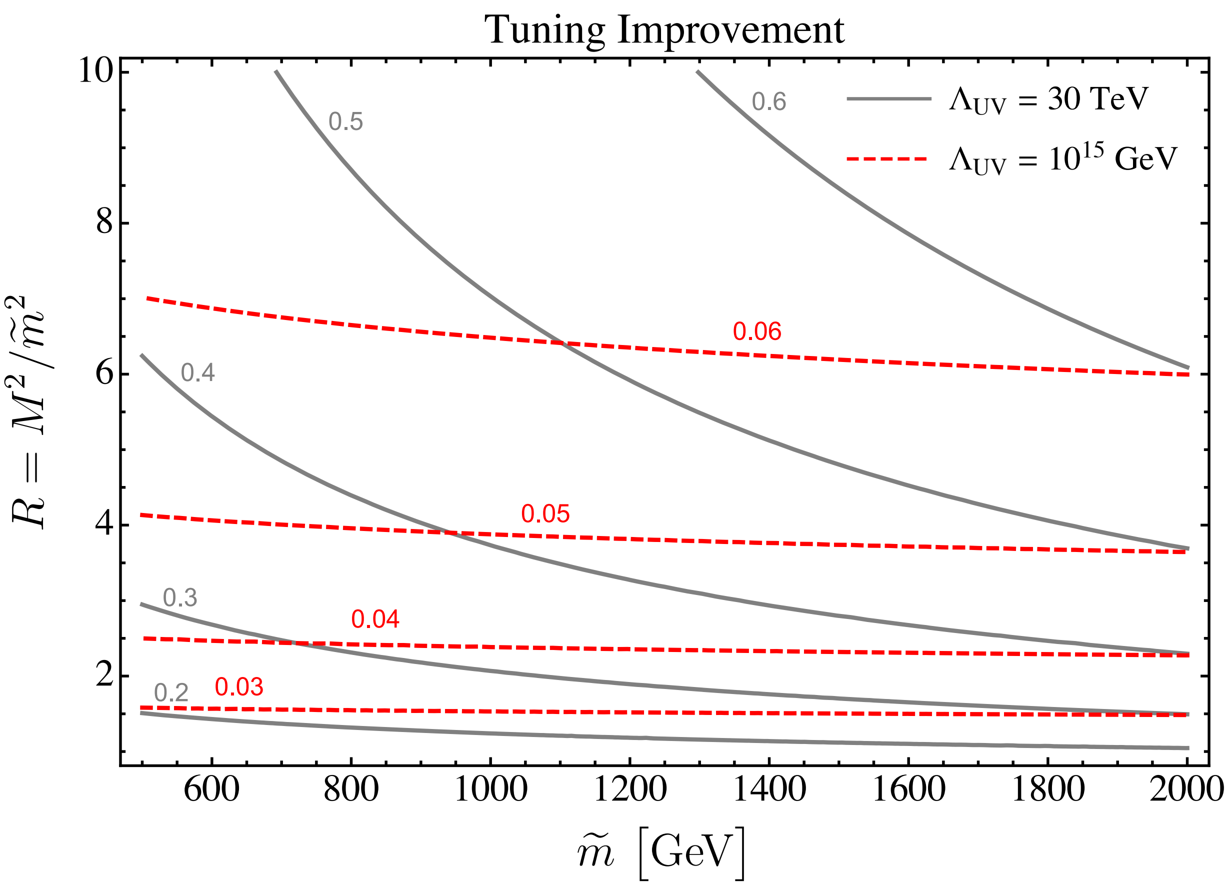
$$\delta M_{H_u}^2 \simeq -\frac{3\,\lambda_t^2}{8\pi^2}\,\widetilde{m}^2 \left[\frac{3}{2} + \log\left(\frac{M^2}{\widetilde{m}^2}\right)\right]$$

which can be much much smaller if

$$M \ll \Lambda_{\rm UV} \quad .$$

Easy Gains

Quantitatively, the improvement is:



So in this model you can have a GUT-scale cutoff, with an effective TeV-scale logarithm.

Easy Gains

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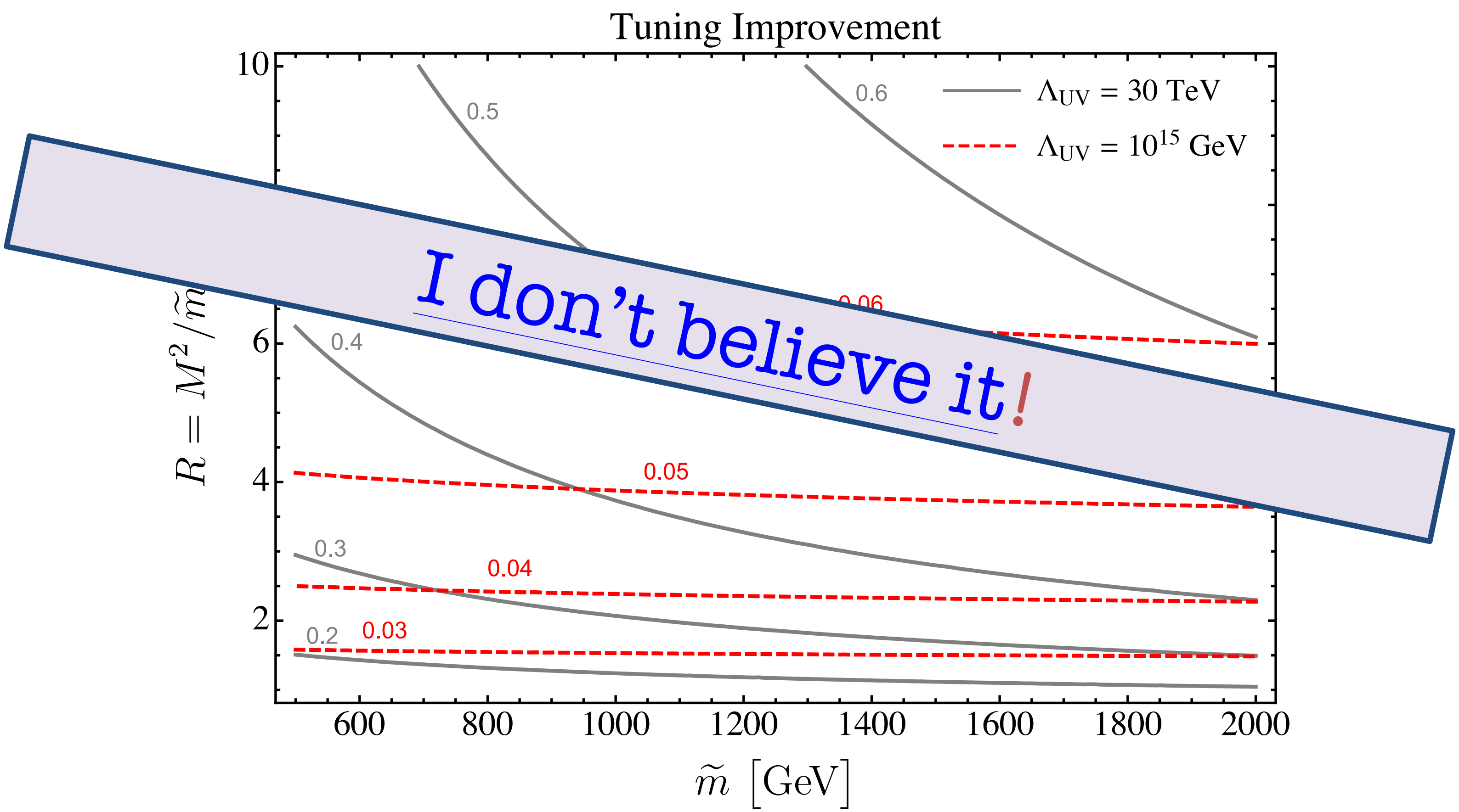


So in this model you can have a GUT-scale cutoff, with an effective TeV-scale logarithm.

UV-Completions

Superficially it appears straightforward to specify the basics of a UV-completion. Imagine all SUSY breaking originates from a superfield, odd under exchange, with a D-term:

$$\langle \mathbf{\Phi} \rangle = D_{\Phi}\, \theta^2\, \overline{\theta}^2$$

The only Kahler terms consistent with the symmetries are soft masses

$$\boldsymbol{K} = \frac{\mathbf{\Phi}}{\Lambda_{\rm UV}^2}\left(|\boldsymbol{Q}|^2 + |\boldsymbol{U^c}|^2 - |\boldsymbol{Q'}|^2 - |\boldsymbol{U'^c}|^2 \right)$$

But no Higgs coupling, no counterterm, no logs!

Skeletons

Looks easy, but UV-completion may require some non-genericity. Consider a simple model with

$$\Phi = |X|^2 - |\overline{X}|^2$$

where non-zero F-terms are different. Could also have an operator like

$$K_H = \frac{|X|^2 + |\overline{X}|^2}{\Lambda_H^2} |H|^2$$

Which would allow a Higgs mass. A model with

$$\Phi = V_{\mathrm{U}(1)}$$

may work better.

The Punchline

For sure, vanilla natural SUSY hasn't shown up as the next step in the microscopic story of the Higgs.

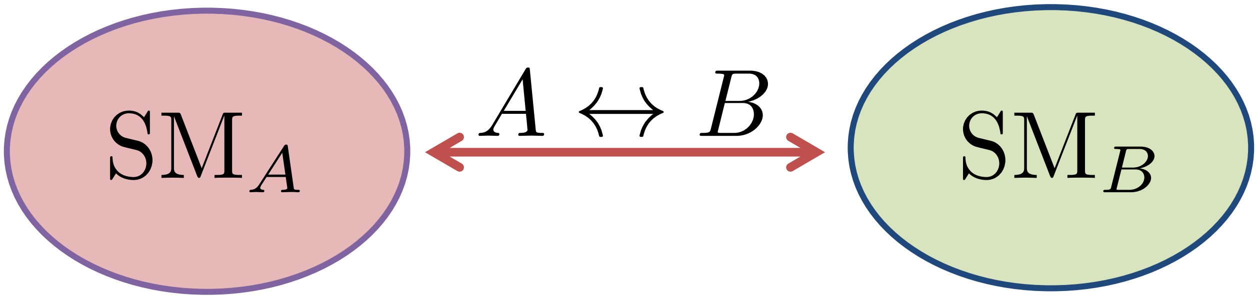
However, let's double check all theory priors before announcing the demise of natural SUSY...

Now for some hyperbole…

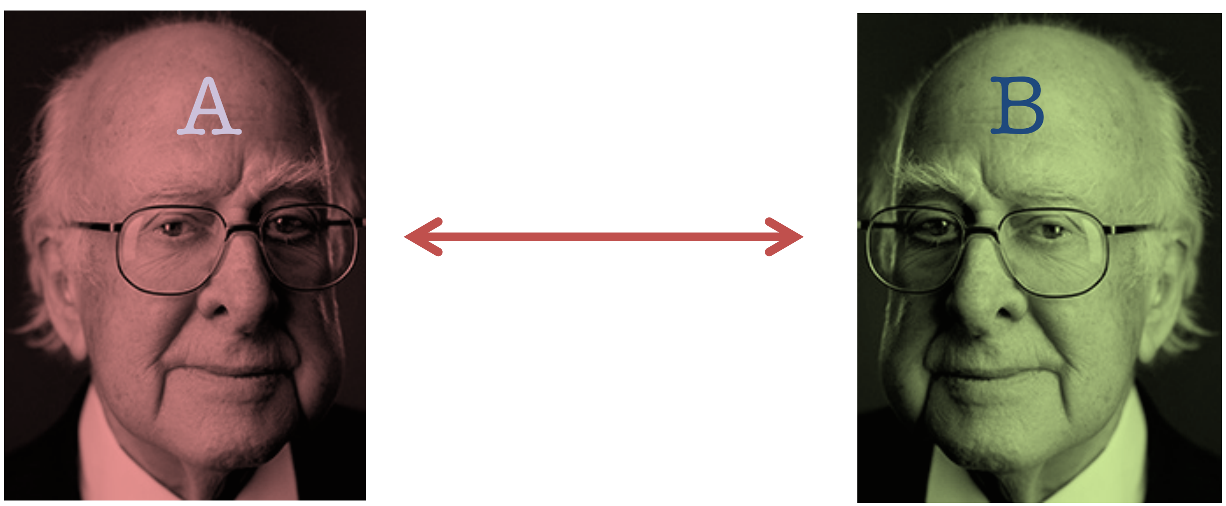
Twin Higgs

Chacko, Goh, Harnik 2005

- Take two identical copies of the Standard Model:



- Everything twinned.



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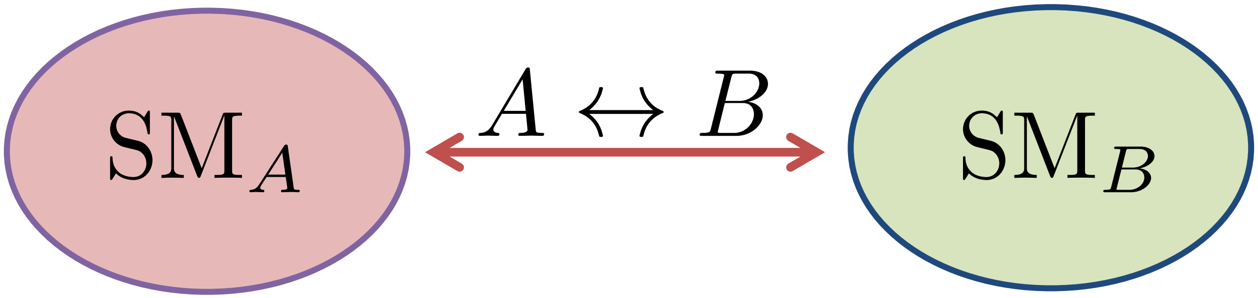


- Enhance symmetry structure to global SU(4):

Desired quartic dictated by accidental symmetry:

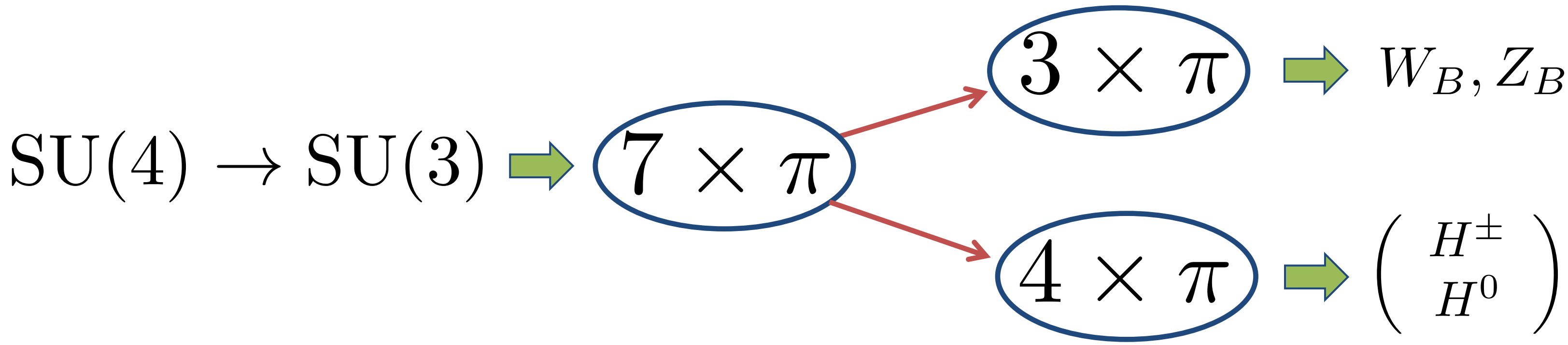
$$V_{\mathrm{Higgs}} = \lambda \left(|H_A|^2 + |H_B|^2\right)^2 - \Lambda^2 \left(|H_A|^2 + |H_B|^2\right)$$

Exchange enforces equal quadratic corrections for each Higgs. Thus masses still respect SU(4) symmetry.

Twin Higgs

Chacko, Goh, Harnik 2005

- Total symmetry-breaking pattern is: $SU(4) \to SU(3)$
- Thus 7 pseudo-Goldstone bosons:

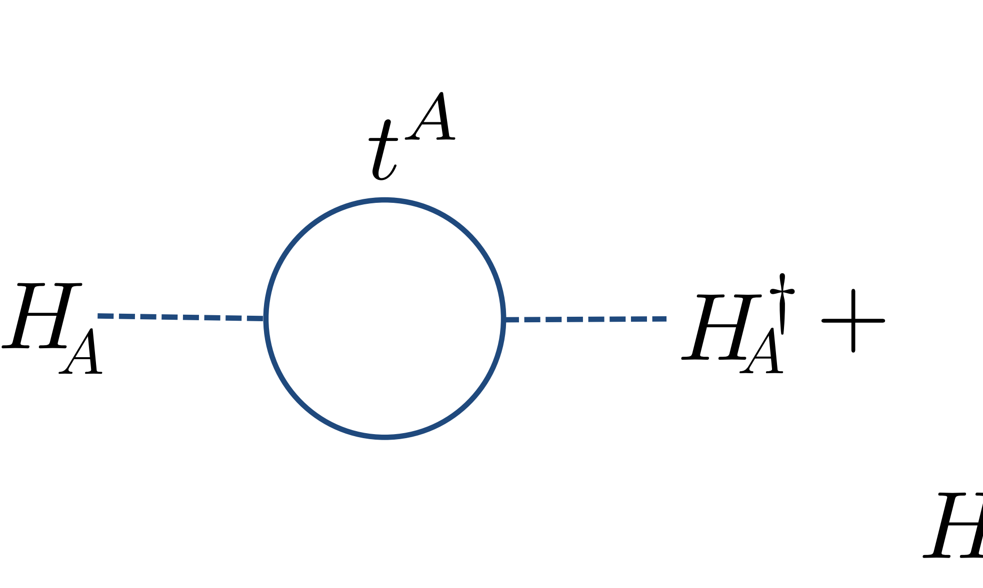


- The SM Higgs light because of the symmetry-breaking pattern!
- Hierarchy problem solved all the way up to the scale: Λ

Twin Higgs

Chacko, Goh, Harnik 2005

- In usual "quadratic divergences" parlay:



$$\sim 0 \times \Lambda^2$$

Quadratic divergences from SM top quark loops cancelled by loops of "Twin" top quarks.

- Cancellation persists for all Twin particles: Twin W-bosons, Twin gluons, etc.

Twin Higgs

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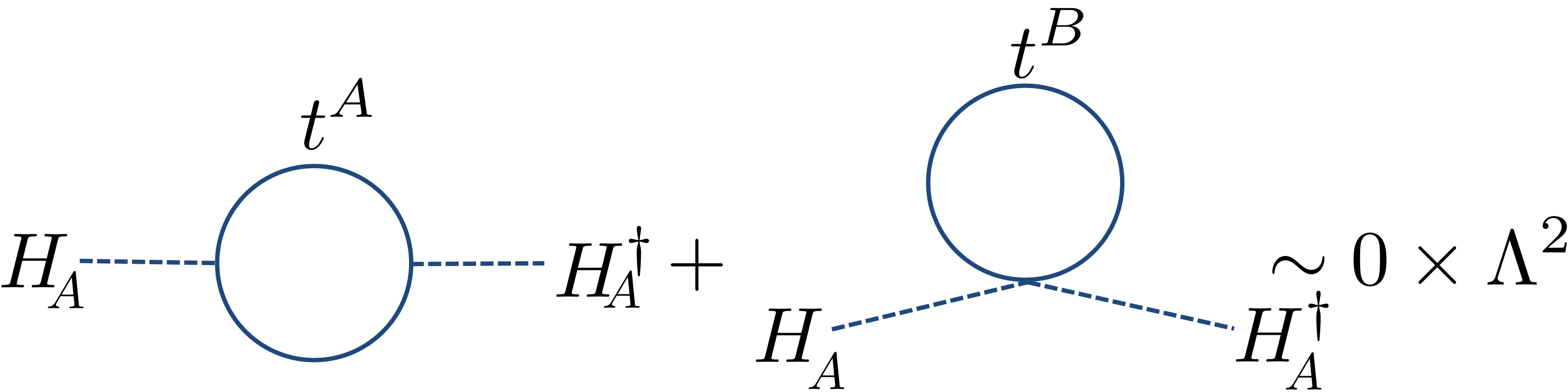

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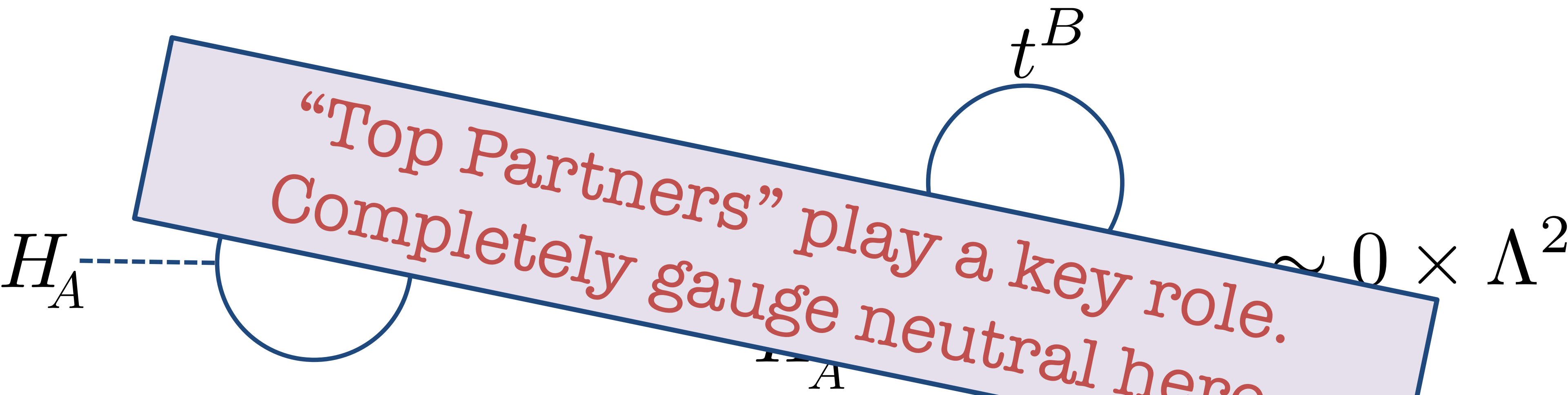

"Top Partners" play a key role.
Completely gauge neutral here.

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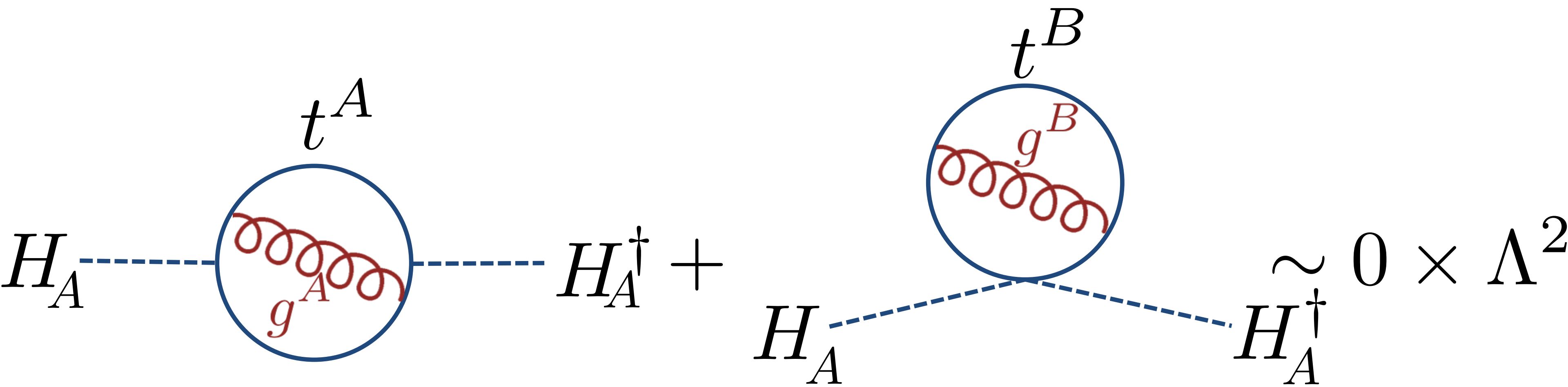

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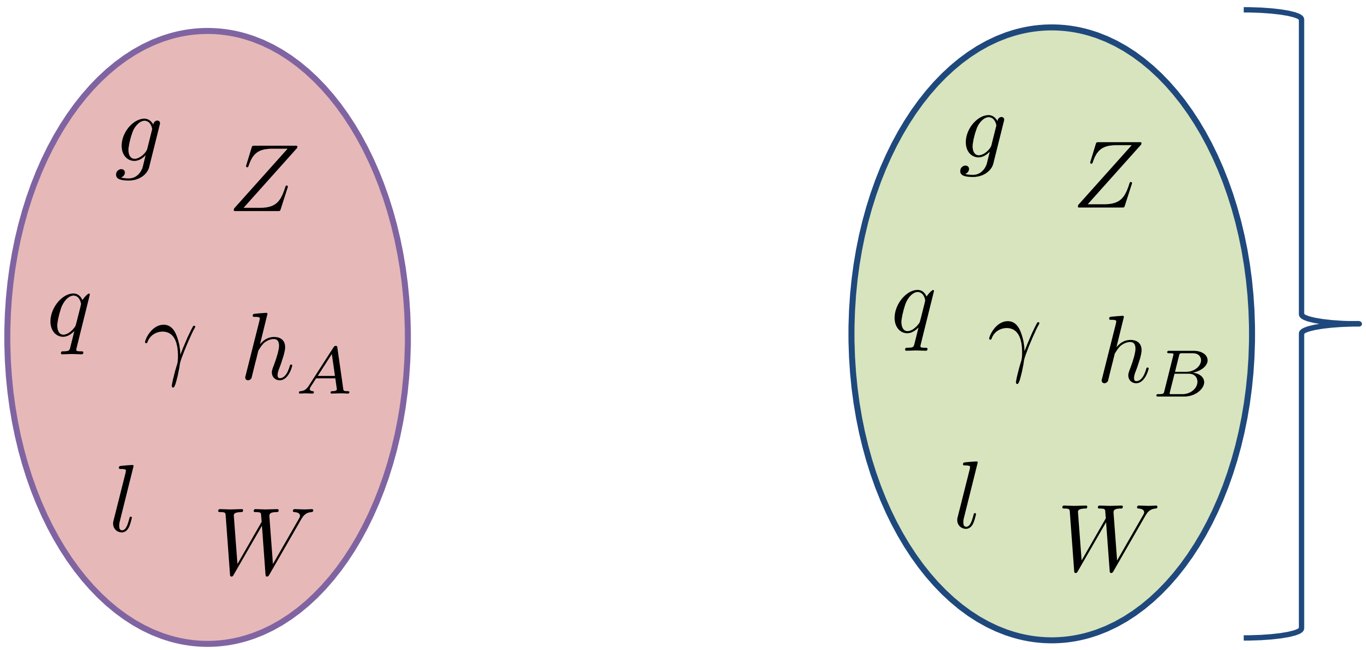
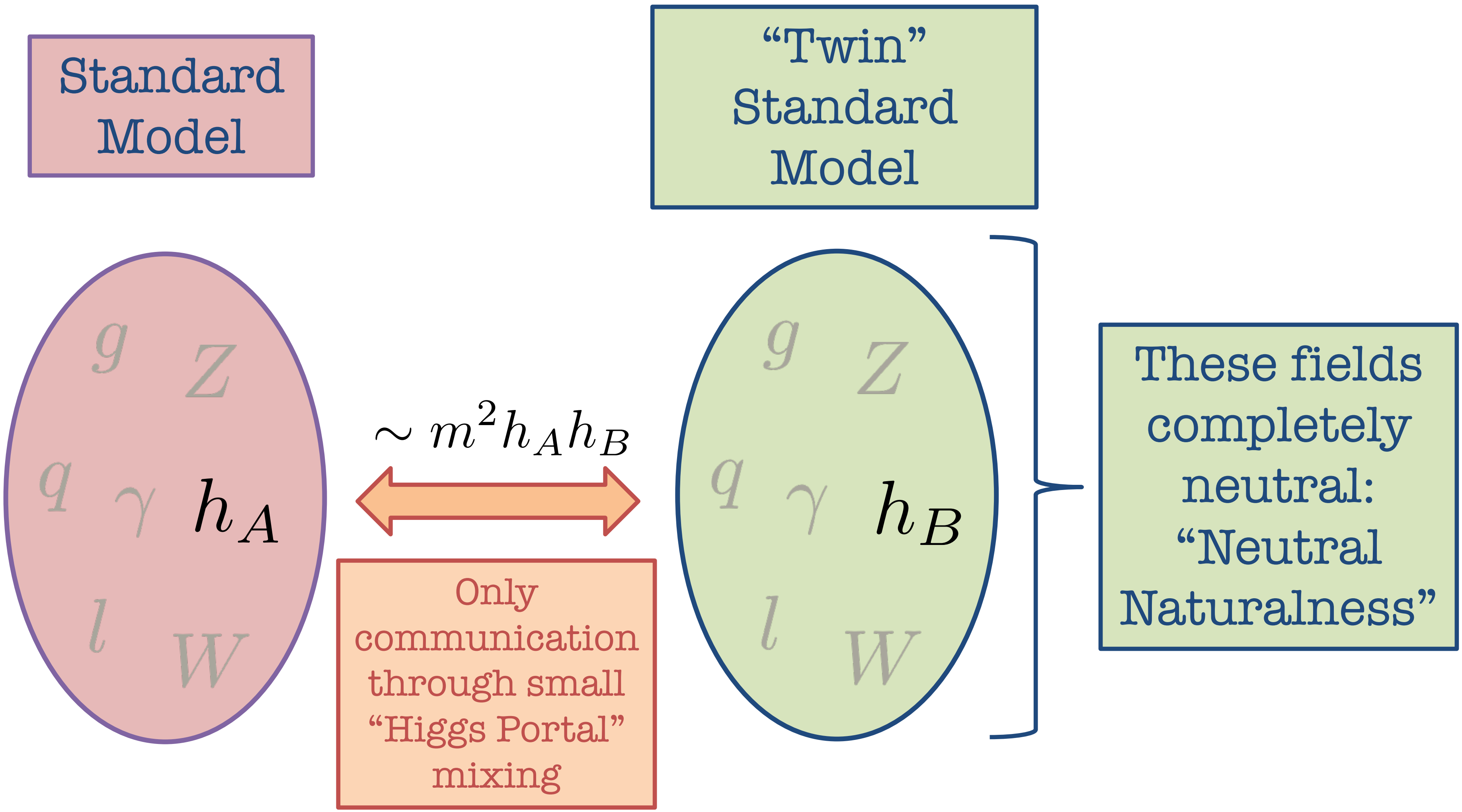
Standard Model

“Twin” Standard Model



These fields completely neutral: “Neutral Naturalness”

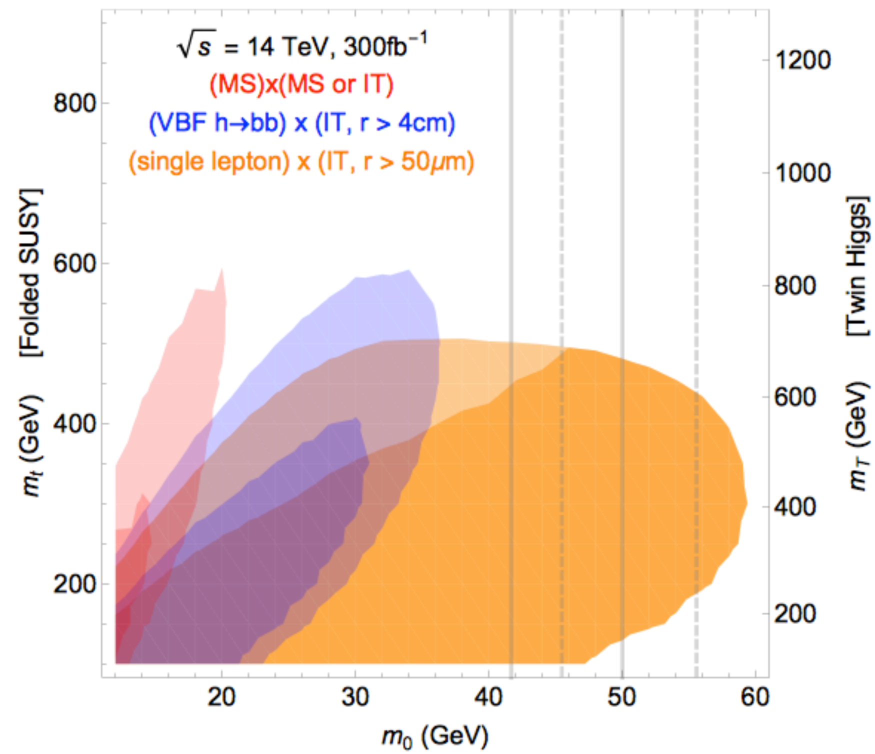
Predictions for Twin sector most robust for the Twins of the SM fields that couple most strongly to Higgs.

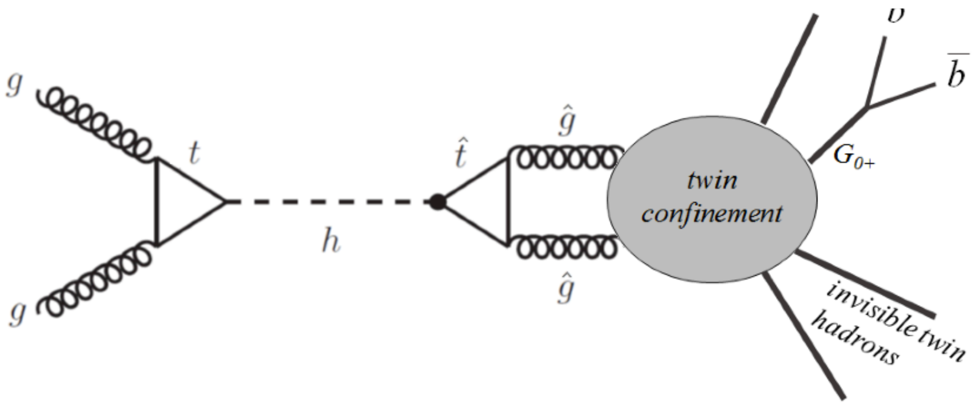

Standard Model
“Twin” Standard Model
These fields completely neutral: “Neutral Naturalness”
g Z q γ h_A l W
$\sim m^2 h_A h_B$
Only communication through small “Higgs Portal” mixing
g Z q γ h_B l W

Phenomenology

SM Higgs can decay, through the Higgs portal, to Twin gluons.

These decay back through Higgs portal.





LHC has sensitivity in future.

Hyperbolic Higgs

Craig, Cohen, Giudice, MM.

The landscape of top partners in symmetry approaches:

		scalar	fermion
strong direct production	*QCD*	SUSY	Composite Higgs/ RS
DY direct production	*EW*	folded SUSY	Quirky Little Higgs
Higgs portal direct production	*singlet*	?	Twin Higgs

Mirror Glueballs

Higgs portal observables

Higgs coupling shifts $\sim$ tuning

Table from Curtin and Verhaaren.

This section: The last box.

Hyperbolic Higgs

Craig, Cohen, Giudice, MM.

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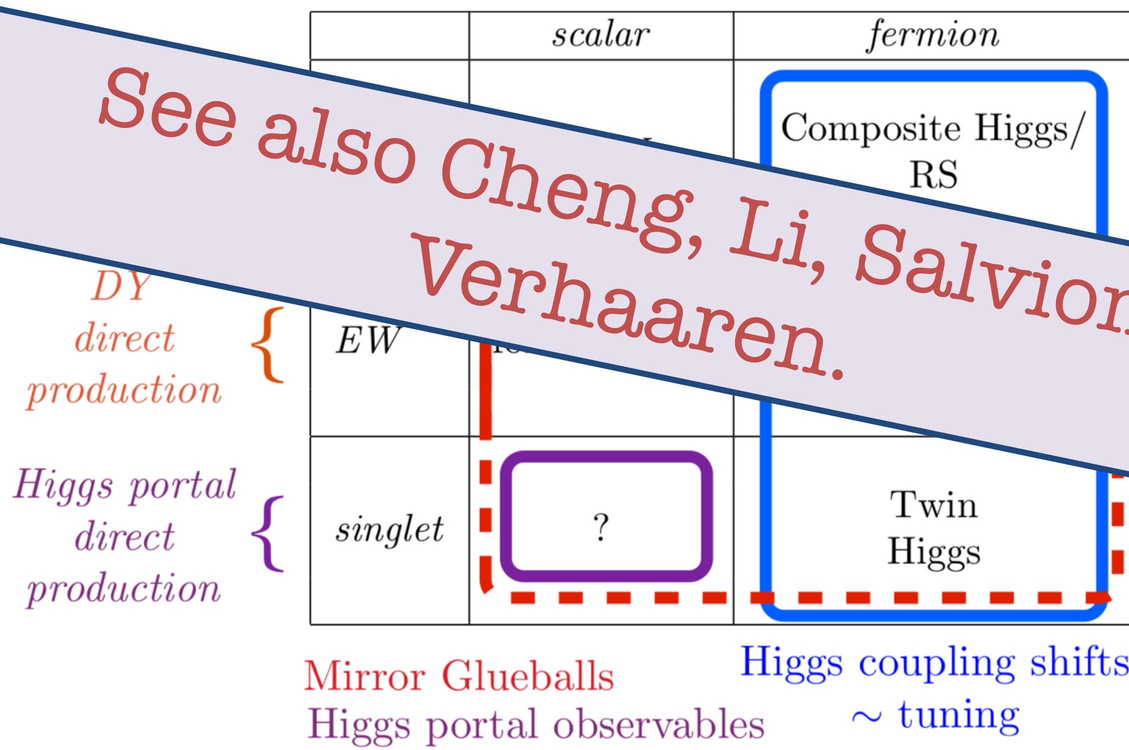

See also Cheng, Li, Salvioni, Verhaaren.

Table from Curtin and

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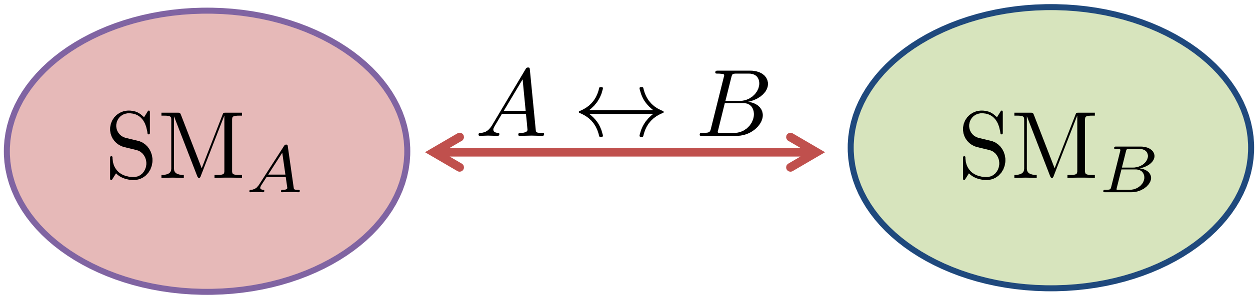
Hyperbolic Higgs

Craig, Cohen,
Giudice, MM.

Take two identical copies of the MSSM:



Take a large D-term with equal and opposite charges for Higgses:

$$V_{\mathcal{H}} = \frac{g_{\mathcal{H}}^2}{2}\left(|H|^2 - |H_{\mathcal{H}}|^2\right)^2$$

This enforces that the scalar potential respects an accidental SU(2,2) symmetry. Not symmetry of theory.

Hyperbolic Higgs

Craig, Cohen, Giudice, MM.

Remove scalar matter in A, and fermions in B:

$$\mathcal{L} = \lambda_t H \psi_Q \psi_{U^c} + \text{h.c.} + \lambda_t^2 \left(\left| H_{\mathcal{H}} \cdot \widetilde{Q}_{\mathcal{H}} \right|^2 + \left| H_{\mathcal{H}} \right|^2 \left| \widetilde{U}^c_{\mathcal{H}} \right|^2 \right)$$

Quadratic corrections respect the accidental SU(2,2) symmetry:

$$V_{\mathcal{H}} = -\Lambda^2 \left(|H|^2 - |H_{\mathcal{H}}|^2 \right) + \frac{g_{\mathcal{H}}^2}{2} \left(|H|^2 - |H_{\mathcal{H}}|^2 \right)^2$$

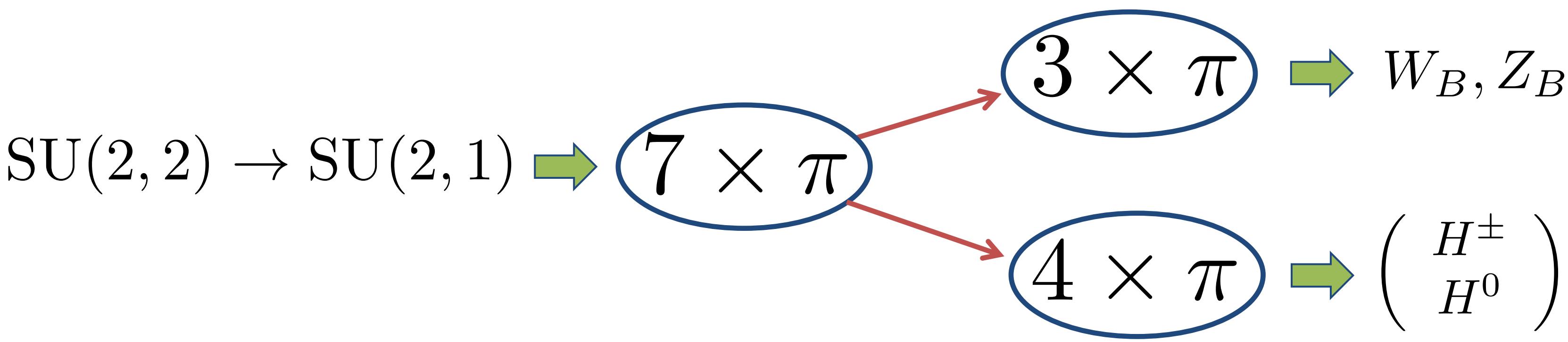
Thus, at level of one-loop corrections, scalar potential respects an accidental SU(2,2) symmetry.

Hyperbolic Higgs

Total symmetry-breaking pattern is:

$$\mathrm{SU}(2,2) \rightarrow \mathrm{SU}(2,1)$$

Thus 7 Quasi-Goldstone bosons:

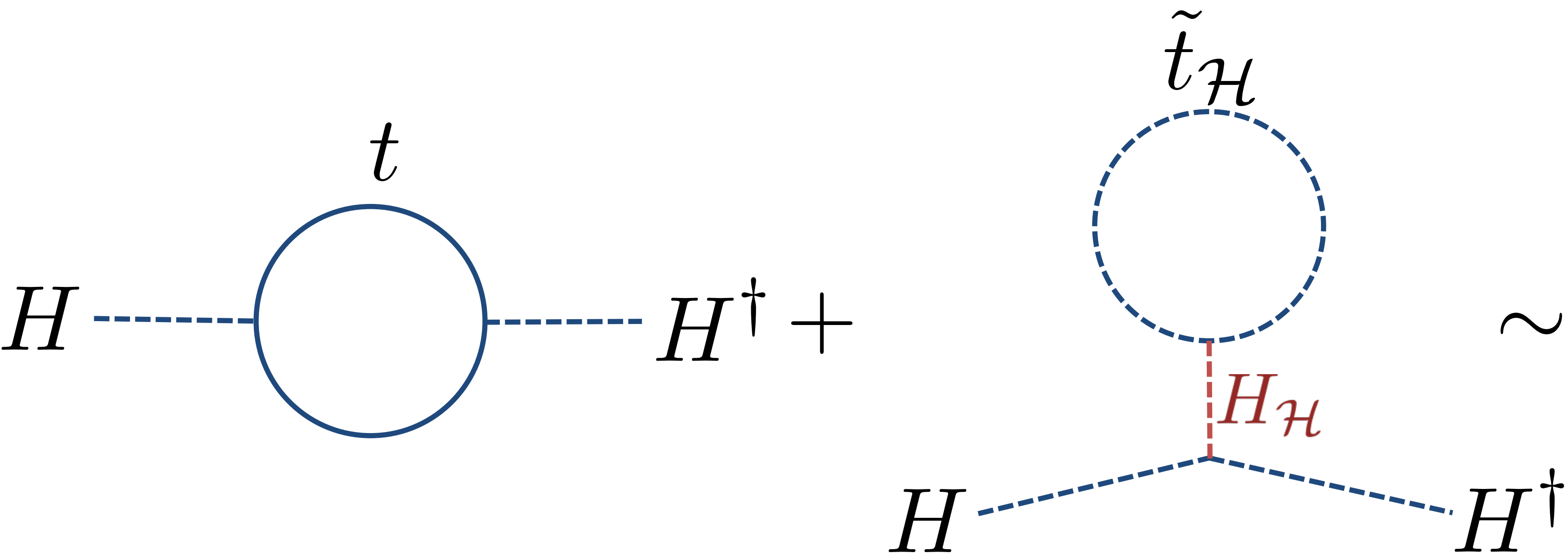


The SM Higgs light because of the symmetry-breaking pattern!

Higgs not really a Goldstone. More like an accidental flat direction…

Hyperbolic Higgs

In usual “quadratic divergences” parlay:



$$\sim 0 \times \Lambda^2$$

Quadratic divergences from SM top quark loops cancelled by loops of “Hyperbolic” stop squarks.

Hyperbolic Higgs

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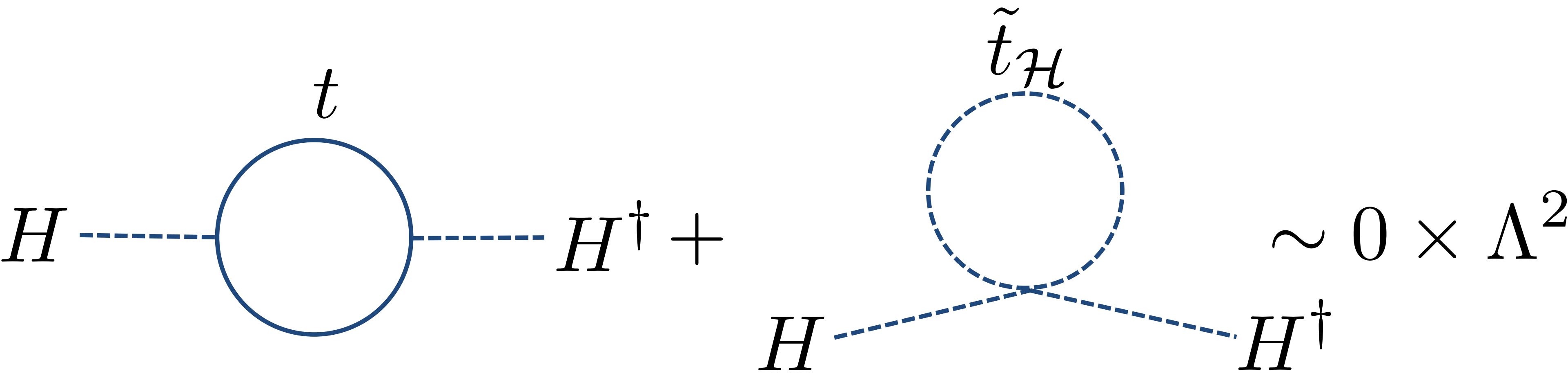

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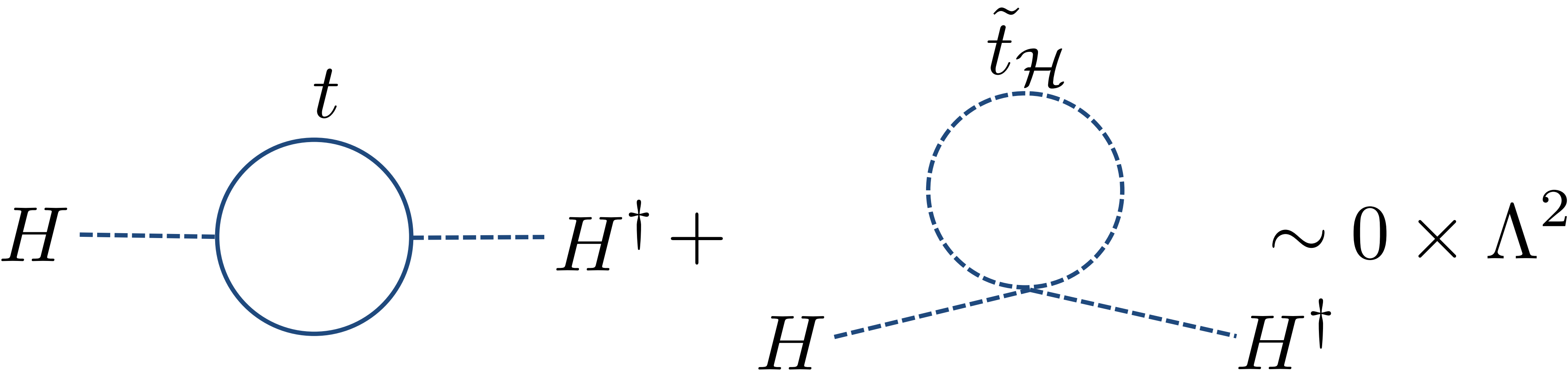
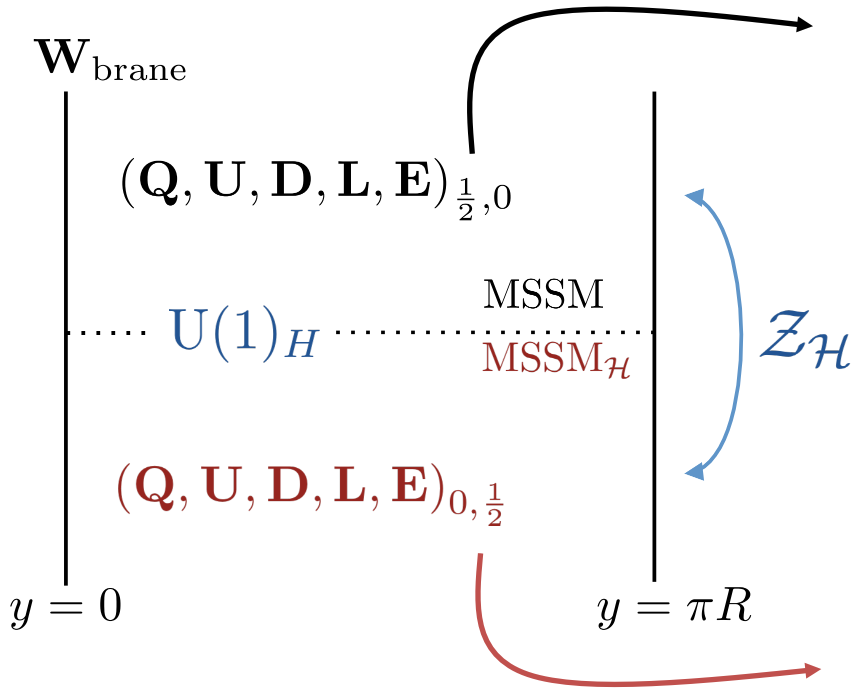


Quadratic divergences from SM top quark loops cancelled by loops of "Hyperbolic" stop squarks.

$$\mathcal{L} \sim \lambda_t \, H \, \psi_Q \, \psi_{U^c} + \text{h.c.} + \lambda_t^2 \, |H|^2 \left(\left| \tilde{t}^L_{\mathcal{H}} \right|^2 + \left| \tilde{t}^R_{\mathcal{H}} \right|^2 \right)$$

UV-Completion

Scherk-Schwarz provides a natural home for the top sector. Take a flat extra dimension:



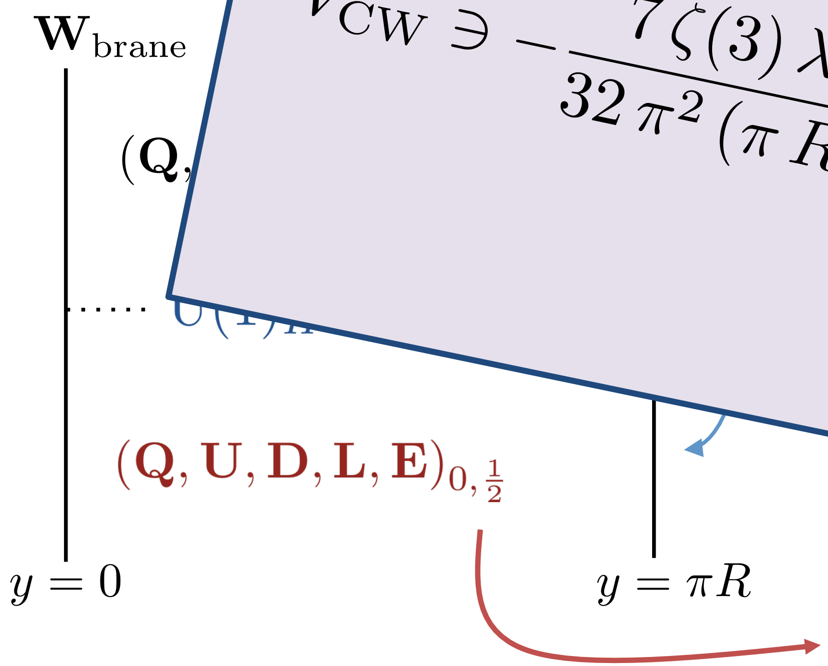
$$V_{\mathrm{CW}}(H) = \frac{1}{2}\,\mathrm{Tr}\sum_{n=-\infty}^{\infty}\int\frac{\mathrm{d}^4p}{(2\,\pi)^4} \times \log\frac{p^2+(n+q_B)^2/R^2+M^2(H)}{p^2+(n+q_F)^2/R^2+M^2(H)}$$

$$V_{\mathrm{CW}}(H_{\mathcal{H}}) = \frac{1}{2}\,\mathrm{Tr}\sum_{n=-\infty}^{\infty}\int\frac{\mathrm{d}^4p}{(2\,\pi)^4} \times \log\frac{p^2+(n+q_F)^2/R^2+M^2(H_{\mathcal{H}})}{p^2+(n+q_B)^2/R^2+M^2(H_{\mathcal{H}})}$$

- Scherk-Schwarz: “project out” modes and automatically give opposite sign corrections!

UV-Completion

Scherk-… hwarz provides a natural home for the top sector. … dimension:



∞ … $\mathrm{d}^4 p$ … $\frac{M^2(H)}{M^2(H)}$

$V_{\mathrm{CW}}(H_{\mathcal{H}}) = \frac{}{2}$ … $\sum_{n=-\infty}$ …

$$\times \log \frac{p^2 + (n+q_F)^2/R^2 + M^2(H_{\mathcal{H}})}{p^2 + (n+q_B)^2/R^2 + M^2(H_{\mathcal{H}})}$$

One-loop corrections:

$$V_{\mathrm{CW}} \ni -\frac{7\,\zeta(3)\,\lambda_t^2}{32\,\pi^2\,(\pi\,R)^2}\left\{3\,|H|^2 - 3\,|H_{\mathcal{H}}|^2 - |Q_{\mathcal{H}}|^2 - 2\,|U^c_{\mathcal{H}}|^2\right\}$$

Scherk-Schwarz: “project out” modes and automatically give opposite sign corrections.

A Shallow Grave.

We also need the Hyperbolic quartic. Use gauge D-term, but haven't seen a new gauge force...

$$V_{\mathrm{U}(1)_{\mathcal{H}}} \ni \frac{g_{\mathcal{H}}^2}{2}\, \xi \left(|H_{\mathcal{H}}|^2 - |H|^2 - f_{\mathcal{H}}^2 \right)^2$$

Supersymmetric breaking: D-term vanishes. Must have SUSY breaking, parameterised by

$$\xi = \left(1 - \frac{M_V^2}{M_S^2} \right)$$

But this feeds into U(2,2) violating soft masses!

$$V_{\mathrm{U}(1)_{\mathcal{H}}} \ni -\frac{g_{\mathcal{H}}^2\, M_V^2}{16\,\pi^2} \log\left(1 - \xi\right) \left(|H_{\mathcal{H}}|^2 + |H|^2 \right)$$

A Shallow Grave.

We also need the Hyperbolic quartic. Use gauge D-term, bu[…] a new gauge force...

$$V \ldots {}^2 \ldots f^2 \Big)^2$$

Super[…] Must

have […]

No free lunch....

Internal tension between LEP, SUSY-breaking, and desired U(2,2) symmetry.

Fine-tuning? May not be much better than a standard SUSY Twin Higgs story.

But this feeds into U(2,2) violating so[…]es..

$$V_{\mathrm{U}(1)_{\mathcal{H}}} \ni -\frac{g_{\mathcal{H}}^2 \, M_V^2}{16\,\pi^2} \log\left(1-\xi\right) \left(|H_{\mathcal{H}}|^2 + |H|^2\right)$$

Phenomenology

Phenomenology has not been studied, however one aspect could be radically different to Twin. If...

$$\langle \tilde{t}_{\mathcal{H}} \rangle \neq 0$$

Then:

- Hyperbolic QCD is broken, so no glueball signatures, no hidden sector hadronisation.
- Longitudinal modes of Hyperbolic Gluons are Top Partners!
- Radial modes of Hyperbolic Stops mix with Higgs, so Higgs becomes, partially, its own top partner!

Summary

Theorists are Bayesian creatures and in many cases our priors are peaked around a sense of minimality or simplicity which is not necessarily justified.

The status naturalness in symmetry-based approaches to the hierarchy problem is clear for models with peaked theory priors.

However, to fully understand the status of naturalness itself, we must understand the theory landscape, even where we may have had low priors.