Theoretical implications of present LHC unobservations

0) What was found
1) What was not found
2) Finite naturalness
3) The adimensional principle
4) Agravity
5) Landau poles

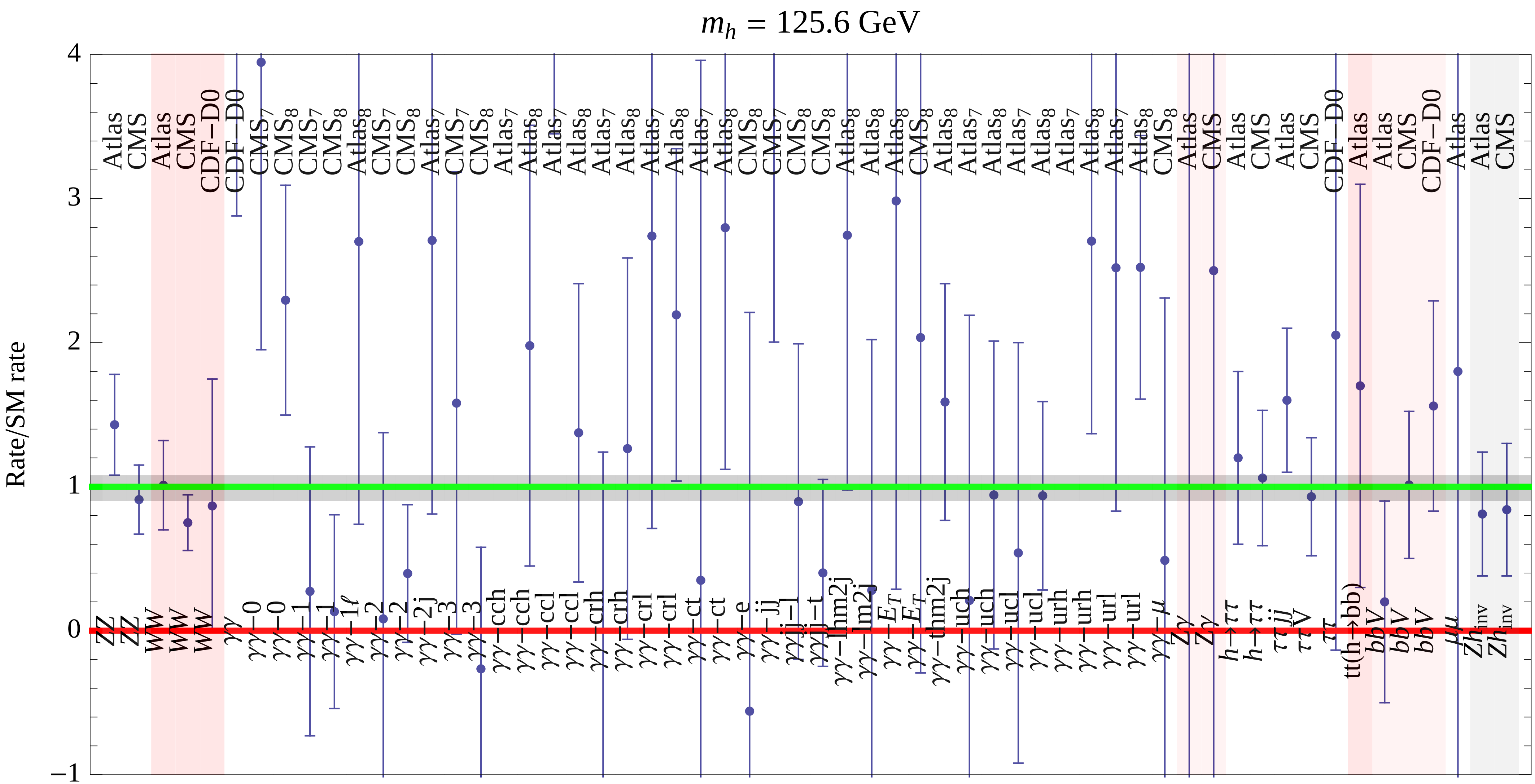
Alessandro Strumia

Talk at Cortona 2014

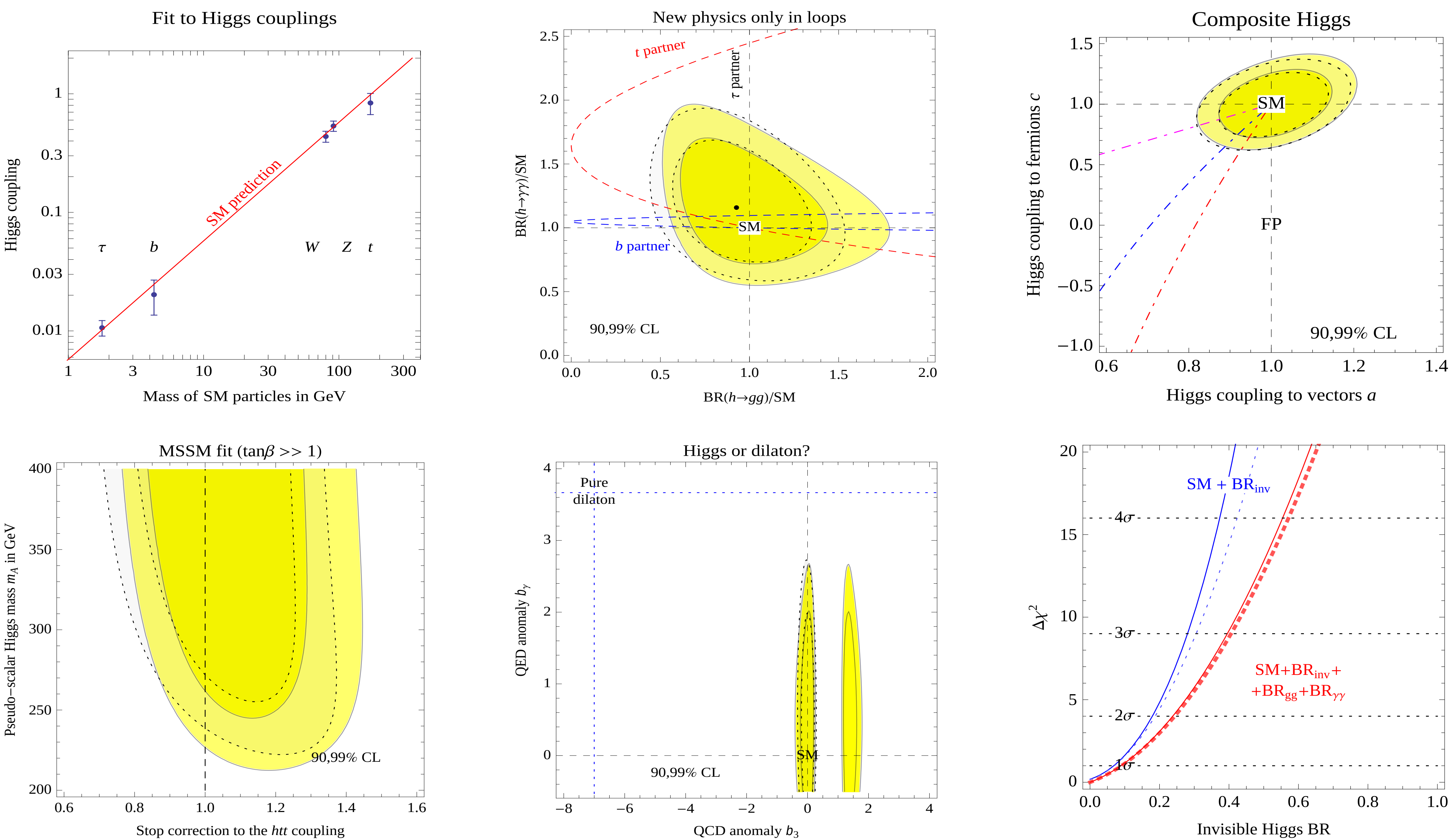
0) What was found

But should not have been found

Only the Higgs



The SM Higgs

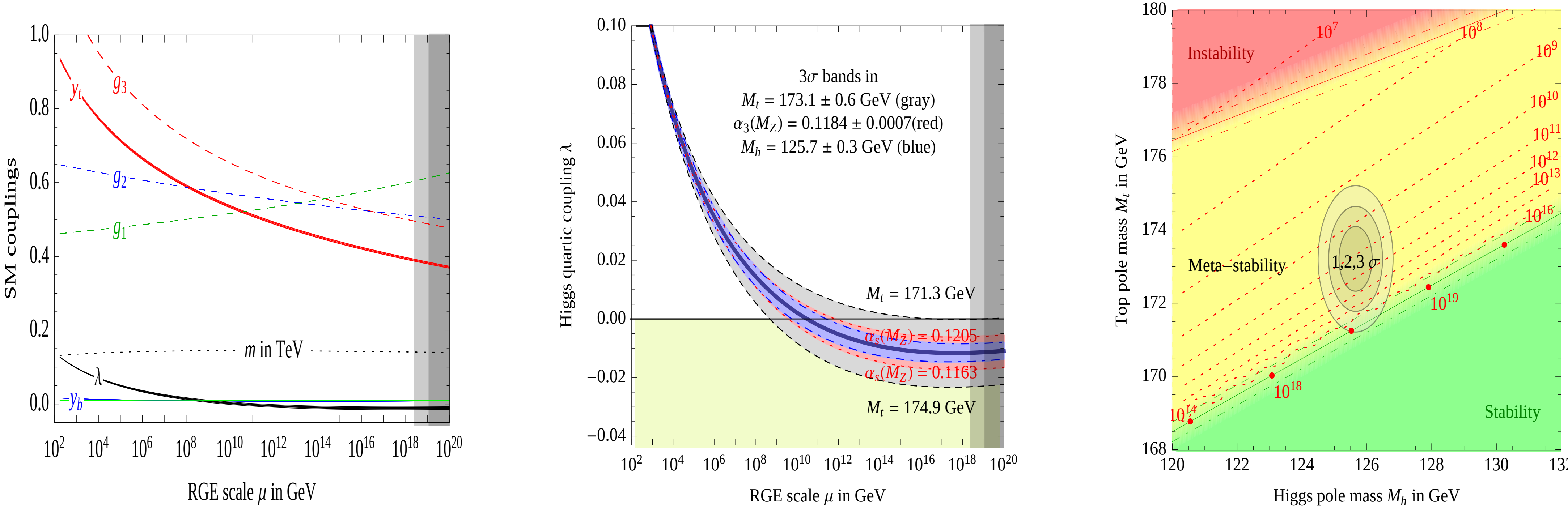


[Giardino, Kannike, Masina, Raidal Strumia, 1403.4226]

And nothing else

Maybe up to the Planck scale

For the measured M_h, M_t the SM can be extrapolated up to $M_{\rm Pl}$.
And is close to vacuum meta-stability.



For the measured masses even the β-function of λ ~vanishes around $M_{\rm Pl}$

$$\lambda \approx \beta_\lambda \approx 0 \quad \text{at } M_{\rm Pl}$$

2) What was not found

But it should have been found

A solution to the hierarchy problem

"Obviously" the loop correction to the Higgs mass is quadratically divergent

$$\delta M^2_{\text{Higgs}} \sim g^2 \Lambda^2$$

new physics at the weak scale "must" cut-off it before it gets unnaturally big:

$$M \lesssim \sqrt{\text{Fine Tuning}} \times \begin{cases} 50\,\text{GeV} & \textbf{if } \ln\Lambda \textbf{ remains e.g. SUSY} \\ 400\,\text{GeV} & \textbf{if finite e.g. technicolor} \end{cases}$$

Past performance

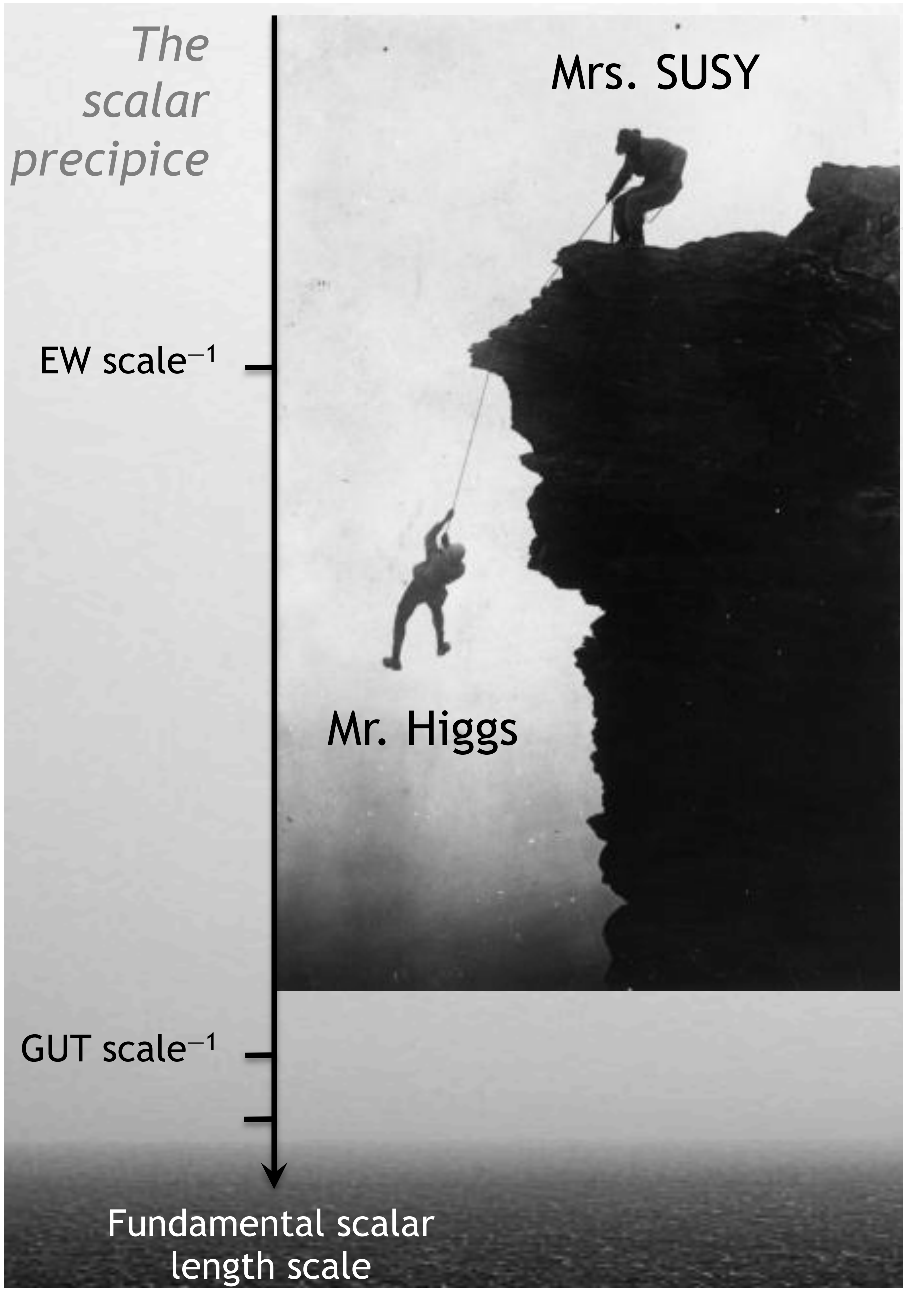
- $\surd$ The electron mass receives divergent electromagnetic corrections
  Naturalness holds thanks to new physics: chiral symmetry of $e^{\pm}$ fermions.

- $\surd$ $m^2_{\pi^\pm} - m^2_{\pi^0}$ receives power divergent electromagnetic corrections.
  Naturalness holds thanks to new physics: π are QCD composite of fermions.

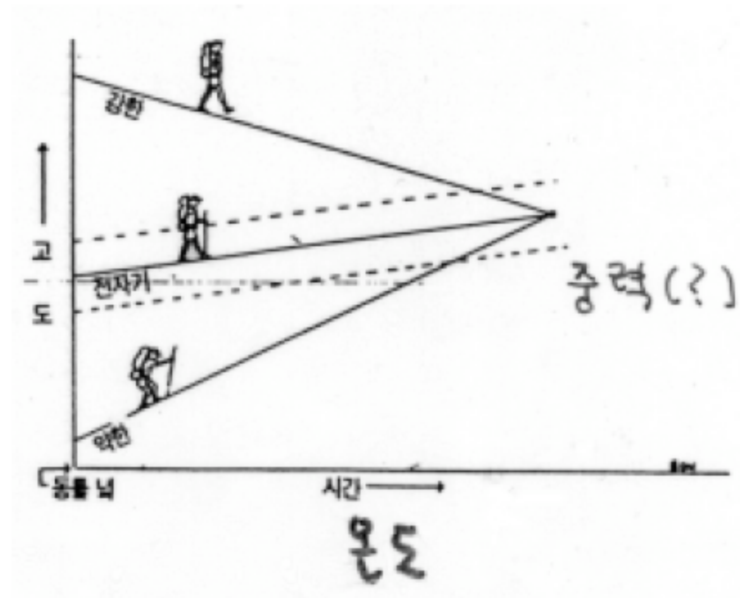
- $\surd$ K mixing receives power divergent corrections.
  Naturalness holds thanks to new physics: the charm.

- $\surd$ Higgs-like scalars present in field theories of condensed matter are not unnaturally lighter than their ultimate cut-off: the atomic lattice.

The solution to the hierarchy problem

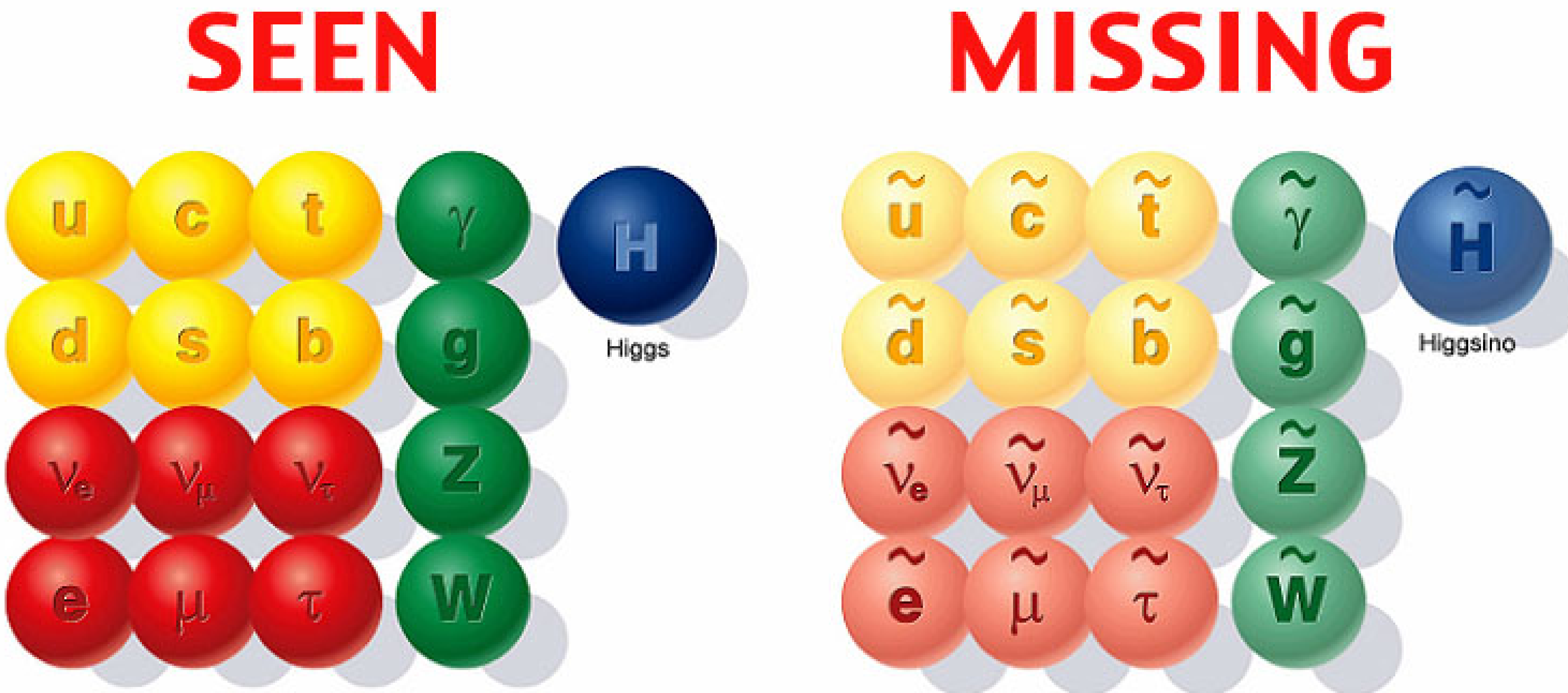


- ⋆ SUSY stabilizes Higgs: the weak scale is the scale of SUSY breaking.
- ⋆ SUSY extends Lorentz.
- ⋆ SUSY unifies fermions with bosons.
- ⋆ SUSY unifies gauge couplings.



- ⋆ SUSY gives DM aka ‘neutralino’.
- ⋆ SUSY is predicted by super-strings.
- ⋆ Worry: too many sparticles at LHC?

Half of the particles needed for supersymmetry have already been discovered



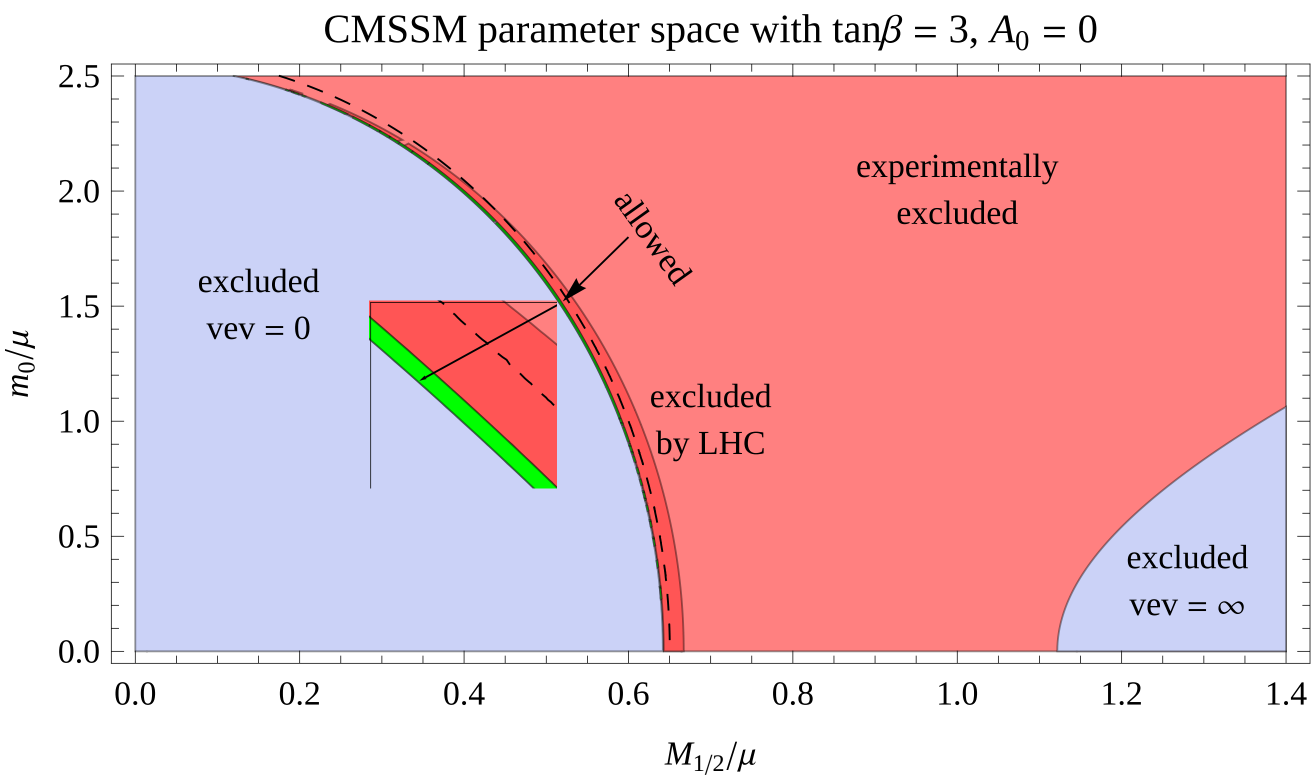
The CMSSM

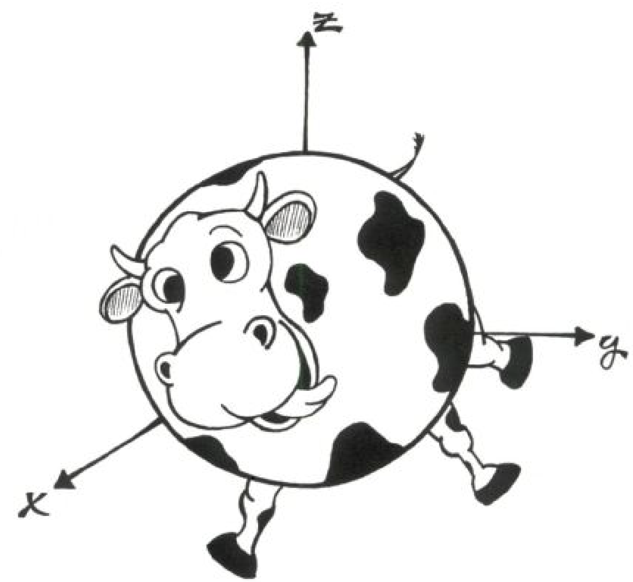
Constrained Minimal ... it is the main "spherical cow" considered by theorists

The SUSY scale should have been the scale of EWSB breaking

$$M_Z^2 \approx 0.2 m_0^2 + 0.7 M_3^2 - 2\mu^2 = (91\,\text{GeV})^2 \times (\frac{M_3}{110\,\text{GeV}})^2 + \cdots$$

Use adimensional ratios as parameters; fix the SUSY scale from M_Z: LEP and later LHC excluded all the parameter space away from the critical line $M_Z = 0$





Beyond the CMSSM

Many models, even at the level of one-letter extensions of the MSSM

AMSSM, BMSSM, CMSSM, DMSSM, EMSSM, FMSSM, GMSSM, HMSSM, IMSSM, KMSSM, MMSSM, NMSSM, OMSSM, PMSSM, QMSSM, RMSSM, SMSSM, TMSSM, UMSSM, VMSSM, XMSSM, YMSSM, ZMSSM

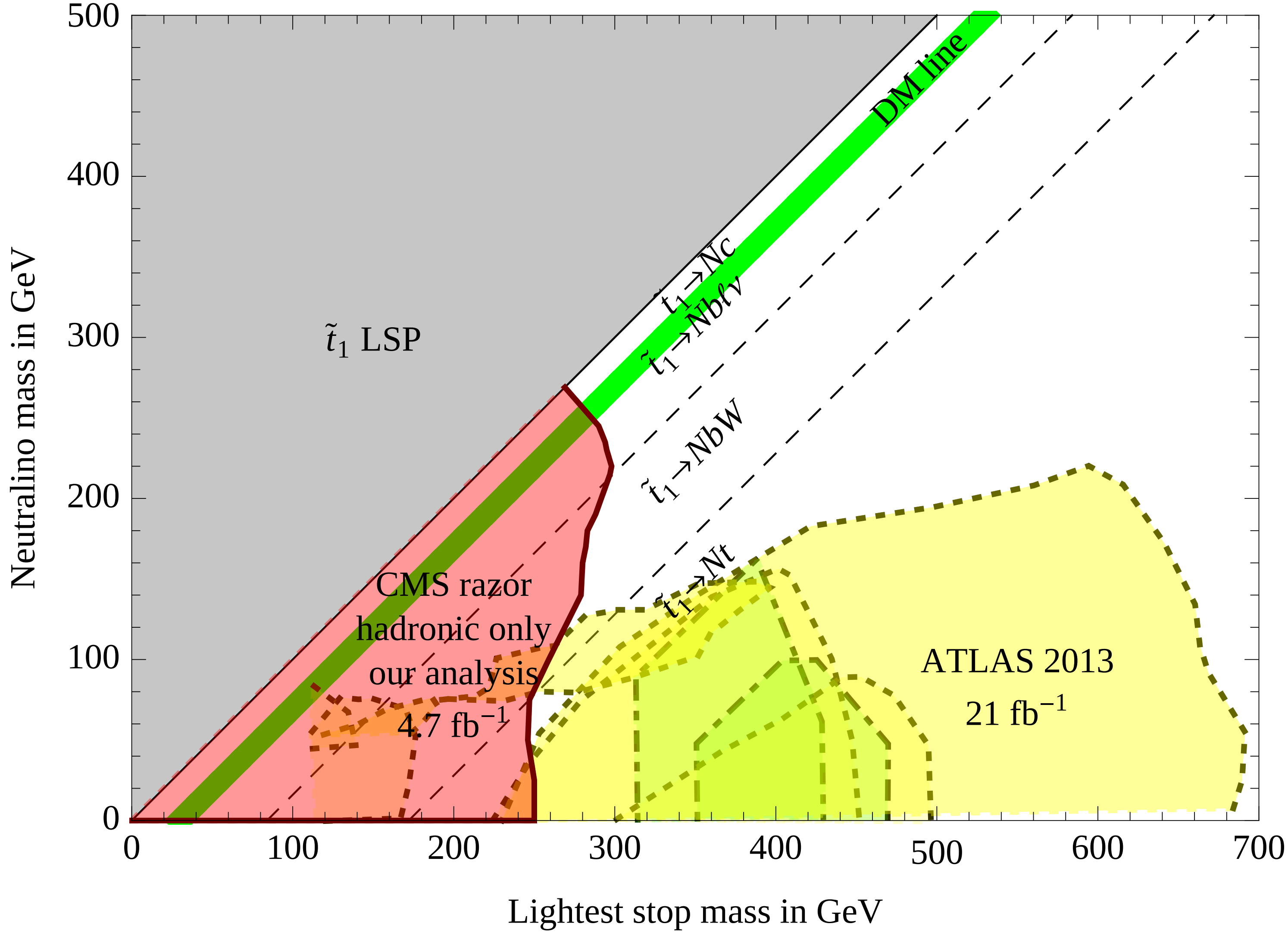
All of them have similar problems: the unit of measure is the kilo-fine-tuning.

A possibility often considered after LHC is 'natural SUSY': abandon models and maximise naturalness keeping only the sparticles more relevant for it: $\tilde{t}, \tilde{b}_L, \tilde{g}$:

$$\delta M_Z^2 \propto y_t^2 m_{\tilde{t}}^2 \qquad \delta m_{\tilde{t}}^2 \propto g_3^2 M_3^2$$

So searches for gluinos and stops are particularly important

Stop bounds



New fully model independent bound (theorist analyses of 7 TeV data) enters the main region where $\tilde{t}$ decays are ≈invisible, relying on **jet initial state radiation**. Good sensitivity at LHC thanks to big $\sigma(pp \to \tilde{t} + \tilde{t}^* + \text{jets})$ from QCD.

Natural SUSY: "not very satisfactory"

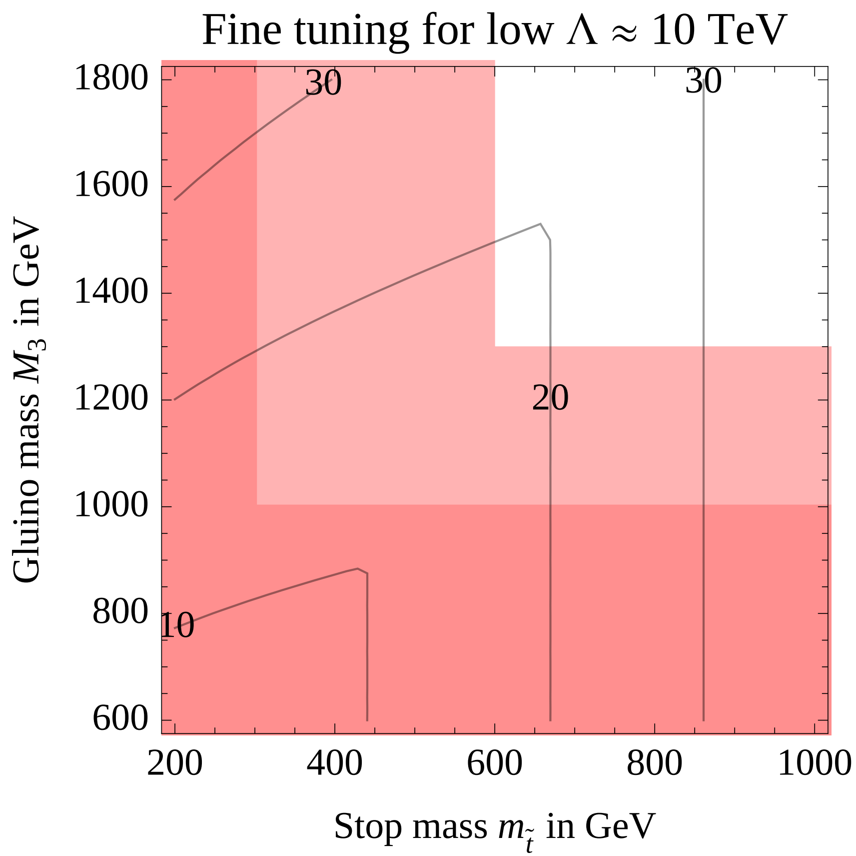
Even including quantum corrections only below a relatively low cut-off Λ,

$$\delta M_Z^2 \approx \frac{24 y_t^2}{(4\pi)^2} m_{\tilde{t}}^2 \left(1 + \frac{X_t^2}{3}\right) \ln \frac{\Lambda}{m_{\tilde{t}}}$$

for $\tan\beta \gg 1$, and

$$\delta m_{\tilde{t}}^2 \approx \frac{32 g_3^2}{3(4\pi)^2} M_3^2 \ln \frac{\Lambda}{M_3},$$

the fine-tuning now is $\Delta \sim 10 - 20$.



Reducing $\tan\beta$ does not help, worse FT to get a heavy enough Higgs:

$$M_h^2 = M_Z^2 \cos^2 2\beta + \frac{3 y_t^2 m_t^2}{4\pi^2}\left[\ln\left(\frac{m_{\tilde{t}}^2}{m_t^2}\right) + X_t^2\left(1 - \frac{X_t^2}{12}\right)\right] \qquad X_t = \frac{A_t + \mu\cot\beta}{m_{\tilde{t}}}$$

Jumping the shark

Break R-parity to try to weaken the experimental bound $M_3 \gtrsim 1.1\,\text{TeV}$:

- Leptonic RPV give leptonic gluino decays making bounds on M_3 stronger.
- Hadronic RPV is crazy and does not allow to go at $M_3 < 700\,\text{GeV}$.

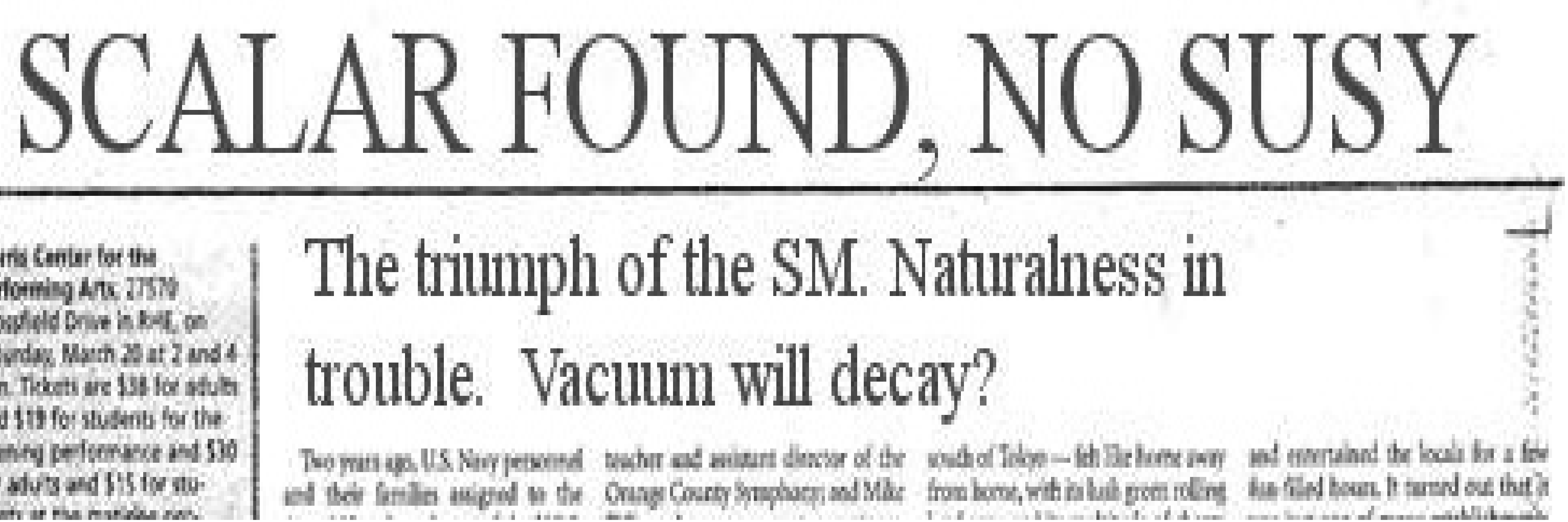
Dirac gauginos reduce $\ln \Lambda/M_3 \to \mathcal{O}(1)$ but increase the exp bound on M_3.

Compressed sparticle spectra to reduce signals, but μ should naturally be light because of $M_Z^2 = -2\mu^2 + \cdots$. And having all sparticles light is bad.

We are adding more stuff to justify why we see nothing

"We must be careful to rashly reject a new idea. Yet I dare say that this assumption ... is not very satisfactory" (Lorentz about the Stokes-Planck proposal that the aether can be compressed by gravity in the vicinity of earth).

Fine-tuning started and we do not know where it will stop: TeV? PeV? EeV?



SCALAR FOUND, NO SUSY

The triumph of the SM. Naturalness in trouble. Vacuum will decay?

...rts Center for the ...forming Arts, 27570 ...ppfield Drive in RHE, on ...turday, March 20 at 2 and 4 ...m. Tickets are $38 for adults ...d $19 for students for the ...ening performance and $30 ... adults and $15 for stu-...

Two years ago, U.S. Navy personnel and their families assigned to the ...

teacher and assistant director of the Orange County Symphony; and Mike ...

south of Tokyo — felt like home away from home, with its lush green rolling ...

and entertained the locals for a few fun-filled hours. It turned out that it ...

What is this talk about?

In the past decades, theory was driven by the naturalness principle:
"light fundamental scalars cannot exist, unless they are accompanied by new physics that protects their mass from quadratically divergent corrections".

Theorists proposed beautiful plausible scenarios with beautiful LHC signals:

Planck scale = String scale   Weak scale = SUSY scale.

But in 1998 we discovered the unnatural dark energy scale.
But in 1998 and 2002 we discovered the neutrino scales.
But in 2014 BICEP claimed the inflaton scale (or polarized dust?).
But LHC at 8 TeV found the higgs and nothing else so far.

I assume that this will be the final outcome and reconsider the basic question.

The goal of this talk is presenting an alternative: a renormalizable theory valid above $M_{\rm Pl}$ such that M_h is naturally smaller than $M_{\rm Pl}$ without new physics at the weak scale. It naturally gives inflation and an anti-graviton ghost-like.

1) Finite Naturalness

[Pappadopulo Farina, Strumia, 1303.7244]

The good, the bad, the ugly

The **good possibility** of naturalness is in trouble.

The **bad possibility** is that the Higgs is light because of ant**pic selection.

The **ugly possibility** is that
quadratic divergences vanish and a modified Finite Naturalness applies.

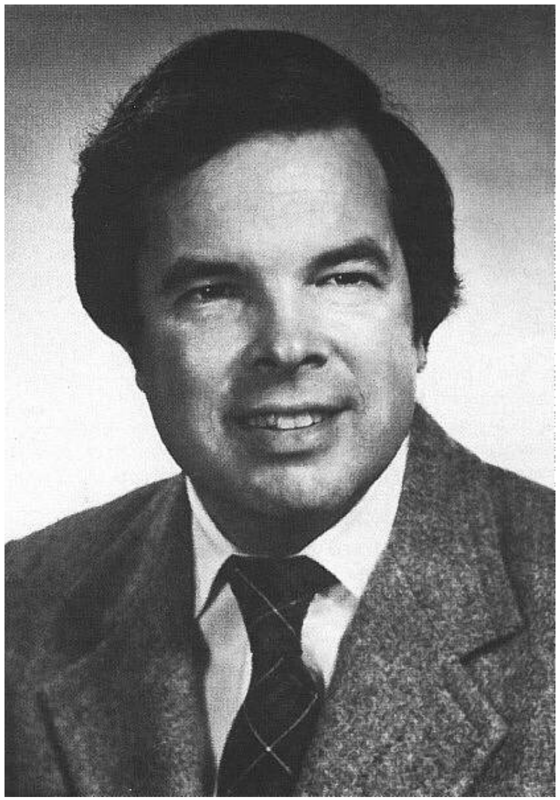
Power divergences are unphysical, nobody knows if they vanish or not. The answer is chosen by the ultimate unknown physical cut-off. Surely it is not a Lorentz-breaking lattice. Maybe it behaves like dimensional regularization.

To start, I explore if this heresy can work and find its consequences and tests.

"Finite naturalness is here considered only as a pure mathematical hypothesis without any pretence of truth"

Ipse undixt

Wilson proposed the usual naturalness attributing a physical meaning to momentum shells of power-divergent loop integrals, used in the ‘averaged action’.



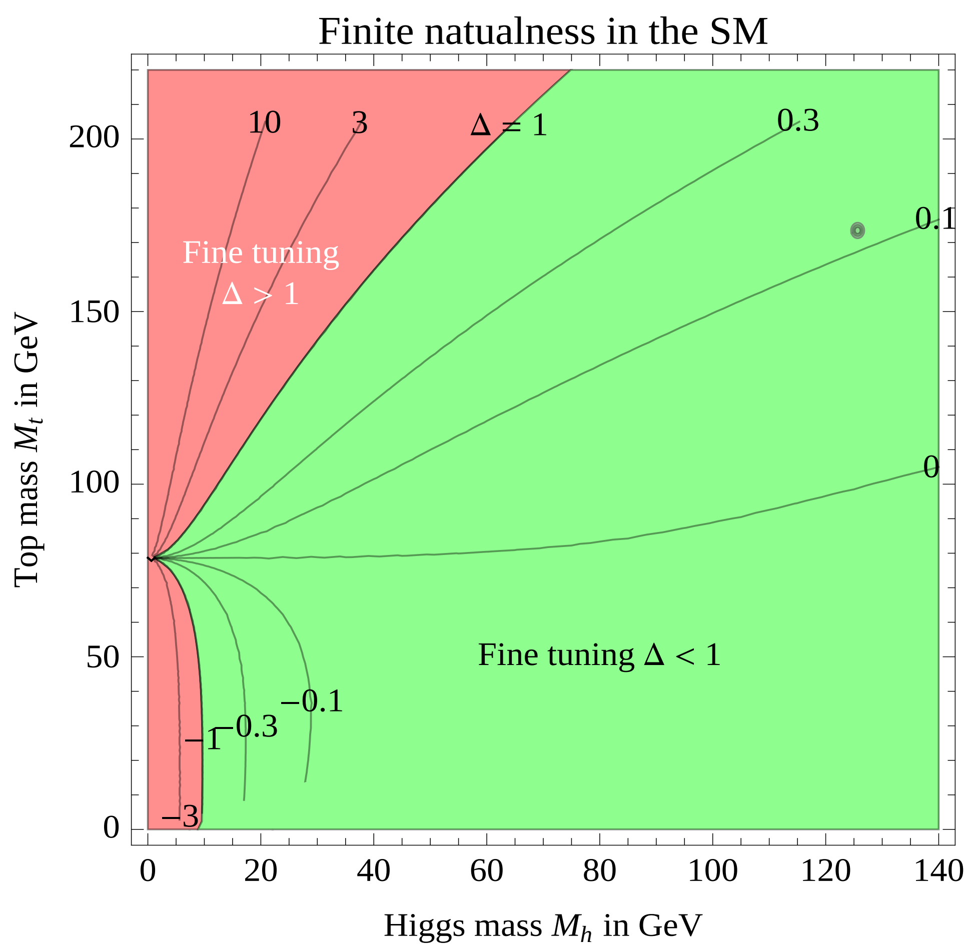
“The final blunder was a claim that scalar elementary particles were unlikely to occur in elementary particle physics at currently measurable energies unless they were associated with some kind of broken symmetry. The claim was that, otherwise, their masses were likely to be far higher than could be detected. The claim was that it would be unnatural for such particles to have masses small enough to be detectable soon.

But this claim makes no sense”

Kenneth G. Wilson — *Dec. 2004*

The SM satisfies Finite Naturalness

Quantum corrections to the dimensionful parameter $m^2 \simeq M_h^2$ in the SM Lagrangian $\frac{1}{2}m^2|H|^2 - \lambda|H|^4$ are small for the measured values of the parameters



From arXiv:1303.7244

$$M_h = 125.6\,\text{GeV} \;\Rightarrow\; m(\bar{\mu} = M_t) = 132.7\,\text{GeV} \;\Rightarrow\; m(\bar{\mu} = M_{\text{Pl}}) = 140.9\,\text{GeV}$$

Finite Naturalness and new physics

FN would be ruined by new heavy particles too coupled to the SM.
Unlike in the other scenarios, high-scale model building is very constrained.
Imagine there is no GUT. No flavour models too. Above us only sky.

FN holds if the top really is the top — if the weak scale is the highest scale.

Data demand some new physics: DM, neutrino masses, maybe axions...

FN still holds if such new physics lies not much above the weak scale.

Is this possible? If yes what are the signals?

Finite Naturalness and new physics

Neutrino mass models add extra particles with mass M

$$M \lesssim \begin{cases} 0.7\ 10^7\,\text{GeV} \times \sqrt[3]{\Delta} & \text{type I see-saw model,} \\ 200\,\text{GeV} \times \sqrt{\Delta} & \text{type II see-saw model,} \\ 940\,\text{GeV} \times \sqrt{\Delta} & \text{type III see-saw model.} \end{cases}$$

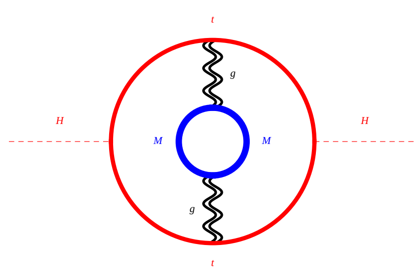
Leptogenesis is compatible with FN only in type I.

Axion and LHC usually are like fish and bicycle because $f_a \gtrsim 10^9\,\text{GeV}$. Axion models can satisfy FN, e.g. KSVZ models employ heavy quarks with mass M

$$M \lesssim \sqrt{\Delta} \times \begin{cases} 0.74\,\text{TeV} & \text{if } \Psi = Q \oplus \bar{Q} \\ 4.5\,\text{TeV} & \text{if } \Psi = U \oplus \bar{U} \\ 9.1\,\text{TeV} & \text{if } \Psi = D \oplus \bar{D} \end{cases}$$

Inflation: flatness implies small couplings. Gravity gives an upper bound on H_I and on any mass [Arvinataki, Dimopoulos..]

$\delta m^2 \sim$



$$\sim \frac{y_t^2 M^6}{M_{\text{Pl}}^4 (4\pi)^6} \qquad \text{so} \qquad M \lesssim \Delta^{1/6} \times 10^{14}\,\text{GeV}$$

Dark Matter: extra scalars/fermions with/without weak gauge interactions.

DM with EW gauge interactions

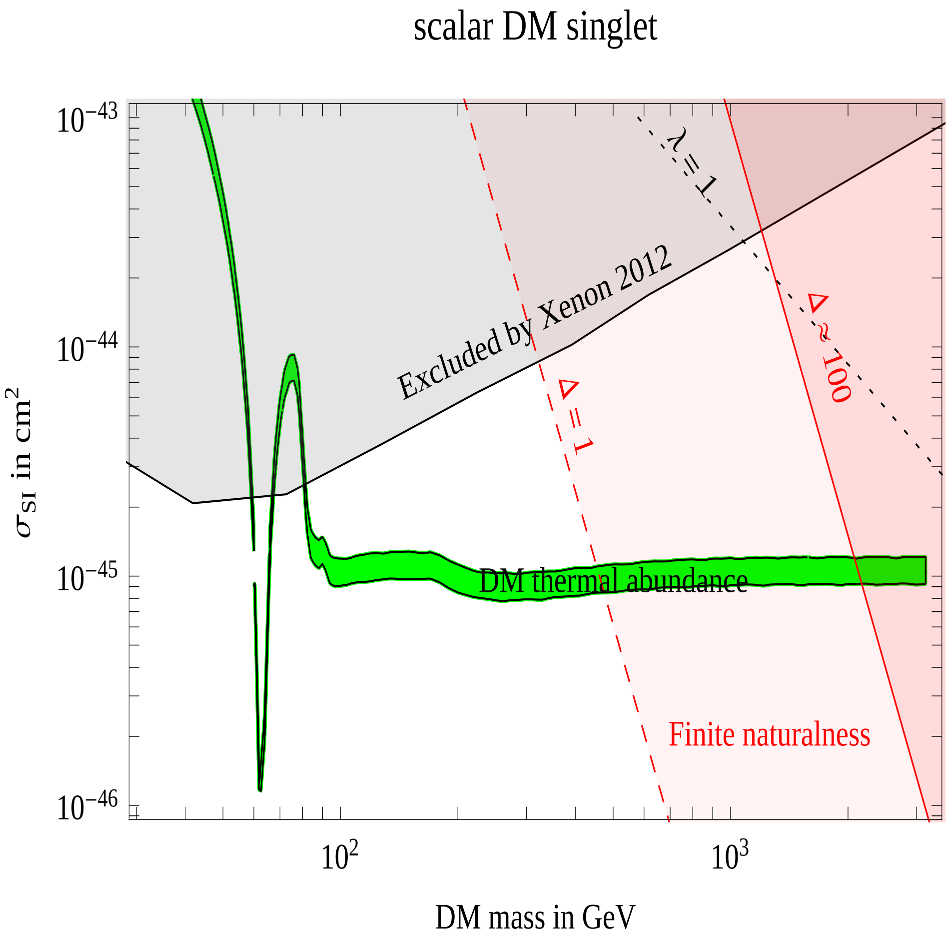
Consider a Minimal Dark Matter n-plet. 2-loop quantum corrections to M_h^2:

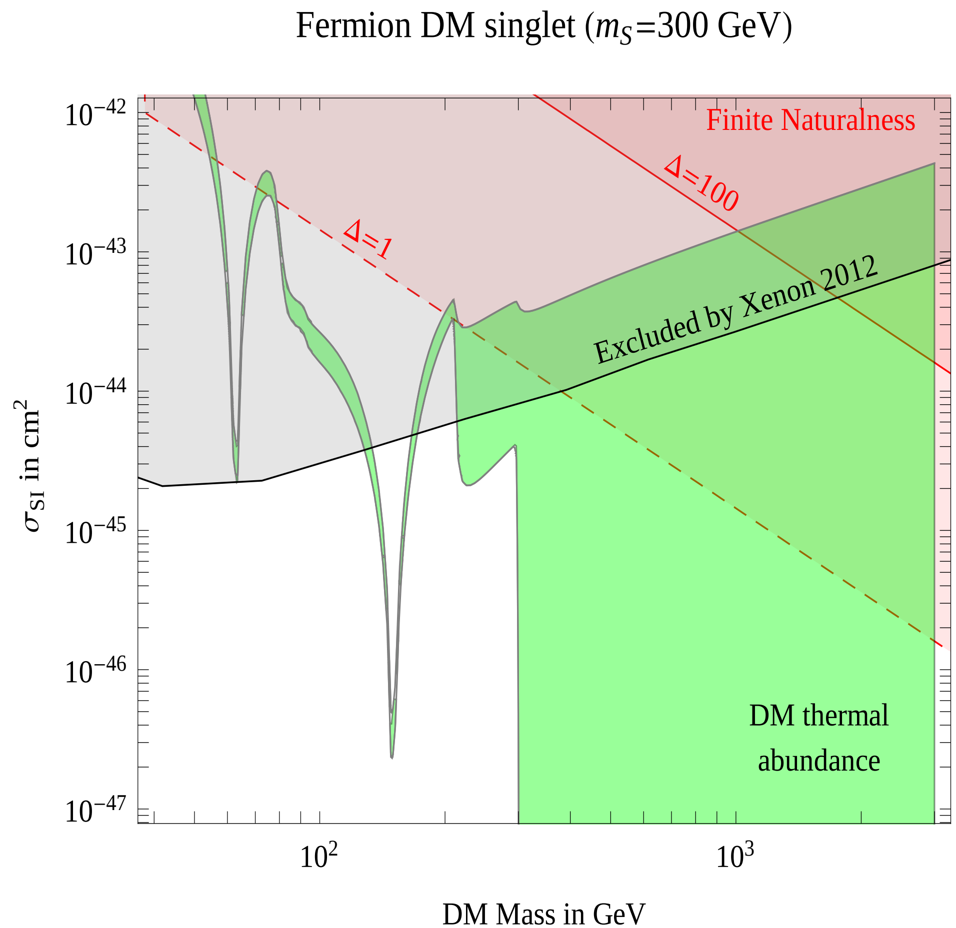
$$\delta m^2 = \frac{cnM^2}{(4\pi)^4}\left(\frac{n^2-1}{4}g_2^4 + Y^2 g_Y^4\right) \times \begin{cases} 6\ln\frac{M^2}{\Lambda^2} - 1 & \text{for a fermion} \\ \frac{3}{2}\ln^2\frac{M^2}{\Lambda\mu^2} + 2\ln\frac{M^2}{\Lambda^2} + \frac{7}{2} & \text{for a scalar} \end{cases}$$

Quantum numbers $SU(2)_L$	$U(1)_Y$	Spin	DM could decay into	DM mass in TeV	$m_{DM^\pm} - m_{DM}$ in MeV	Finite naturalness bound in TeV, $\Lambda \sim M_{Pl}$	σ_{SI} in $10^{-46}\,cm^2$
2	1/2	0	EL	0.54	350	$0.4 \times \sqrt{\Delta}$	$(2.3 \pm 0.3)\,10^{-2}$
2	1/2	1/2	EH	1.1	341	$1.9 \times \sqrt{\Delta}$	$(2.5 \pm 0.8)\,10^{-2}$
3	0	0	HH^*	2.5	166	$0.22 \times \sqrt{\Delta}$	0.60 ± 0.04
3	0	1/2	LH	2.7	166	$1.0 \times \sqrt{\Delta}$	0.60 ± 0.04
3	1	0	HH, LL	1.6+	540	$0.22 \times \sqrt{\Delta}$	0.06 ± 0.02
3	1	1/2	LH	1.9+	526	$1.0 \times \sqrt{\Delta}$	0.06 ± 0.02
4	1/2	0	HHH^*	2.4+	353	$0.14 \times \sqrt{\Delta}$	1.7 ± 0.1
4	1/2	1/2	(LHH^*)	2.4+	347	$0.6 \times \sqrt{\Delta}$	1.7 ± 0.1
4	3/2	0	HHH	2.9+	729	$0.14 \times \sqrt{\Delta}$	0.08 ± 0.04
4	3/2	1/2	(LHH)	2.6+	712	$0.6 \times \sqrt{\Delta}$	0.08 ± 0.04
5	0	0	(HHH^*H^*)	9.4	166	$0.10 \times \sqrt{\Delta}$	5.4 ± 0.4
5	0	1/2	stable	10	166	$0.4 \times \sqrt{\Delta}$	5.4 ± 0.4
7	0	0	stable	25	166	$0.06 \times \sqrt{\Delta}$	22 ± 2

DM without EW gauge interactions

DM coupling to the Higgs determines $\Omega_{\rm DM}$, $\sigma_{\rm SI}$ and Finite Naturalness δm^2





Observable DM satisfies Finite Naturalness if lighter than $\approx 1\,$TeV

3) A new principle

Nature has no scale

FN needs something different from the effective field theory ideology

$$\mathscr{L} \sim \Lambda^4 + \Lambda^2 |H|^2 + \mathscr{L}_4 + \frac{H^6}{\Lambda^2} + \cdots$$

that leads to the hierarchy problem. Nature is singling out $\mathscr{L}_4$. Why?

Principle: "**Nature has no fundamental scales Λ**".

Then, the fundamental QFT is described by $\mathscr{L}_4$: only a-dimensional couplings.

Power divergences vanish simply because they have mass dimension, and there are no masses. Scale invariance at tree level is an accidental symmetry, like baryon number. [Other authors assume scale or conformal invariance as quantum symmetries and argue that the regulator must respect them].

Quantum corrections break scale invariance and should generate $M_h, M_{\rm Pl}$

Can this happen? I apply this principle first to M_h and later to $M_{\rm Pl}$.

What is the weak scale?

- ◦ Could be the only scale of particle physics. Just so.

- Could be generated from nothing by heavier particles.

- Could be generated from nothing by weak-scale dynamics.
  - The quartic of another scalar might run negative around 1 TeV.
  - Another gauge group might become strong around 1 TeV.
  - Adding a color 15, its condensation $\frac{28}{3}\alpha_3 \sim 1$ happens around 1 TeV.

Dynamical generation of the weak scale

Goals:

1) **Dynamically generate** the weak scale and weak scale DM
2) **Preserve** the successful automatic features of the SM: B, L...
3) **Get DM stability** as one extra automatic feature.

Model:

$G_{\text{SM}} \otimes \text{SU}(2)_X$ with one extra scalar S, doublet under $\text{SU}(2)_X$ and potential

$$V = \lambda_H |H|^4 - \lambda_{HS} |HS|^2 + \lambda_S |S|^4.$$

[Hambye, Strumia, 1306.2329]

Dynamical generation of the weak scale

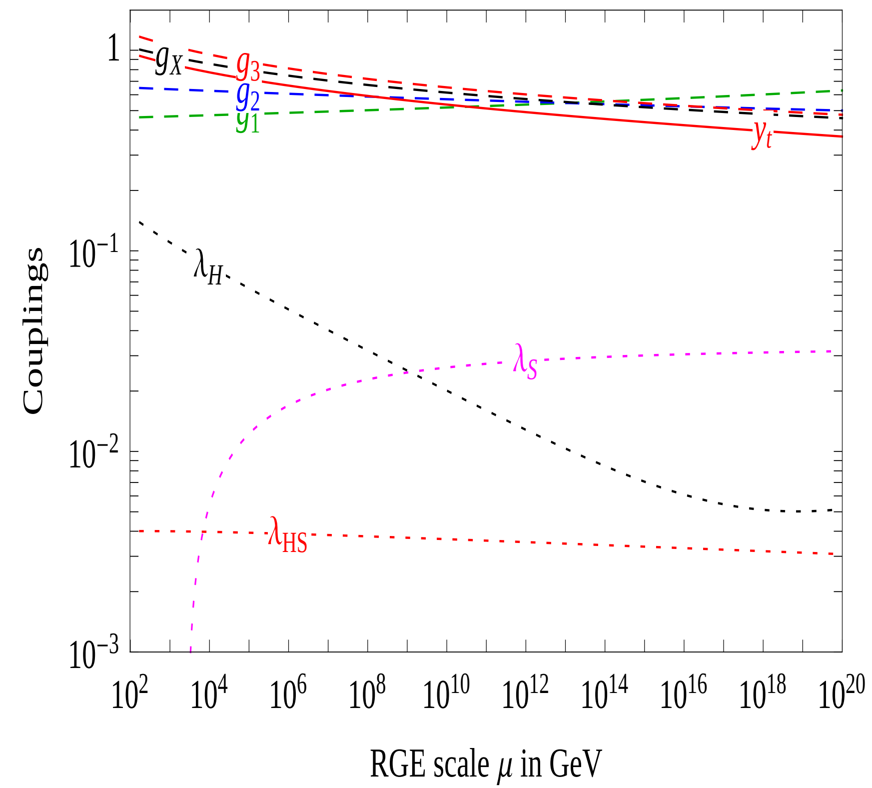
1) λ_S runs negative at low energy:

$$\lambda_S \simeq \beta_{\lambda_S} \ln \frac{s}{s_*} \qquad \text{with} \qquad \beta_{\lambda_S} \simeq \frac{9g_X^4}{8(4\pi)^2}$$

$$S(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ w + s(x) \end{pmatrix} \qquad w \simeq s_* e^{-1/4}$$

$$H(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix} \qquad v \simeq w\sqrt{\frac{\lambda_{HS}}{2\lambda_H}}$$

Problem: vacuum energy must be negative???



2) No new Yukawas.

3) $\mathrm{SU}(2)_X$ vectors get mass $M_X = \frac{1}{2} g_X w$ and are automatically stable.

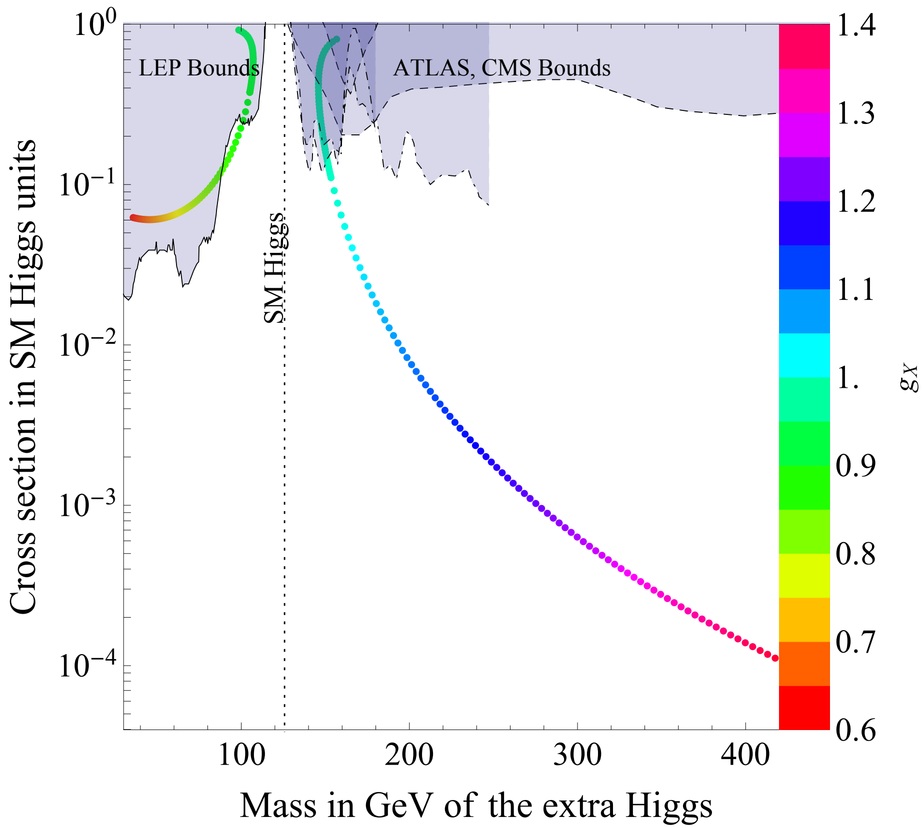
4) Bonus: threshold effect stabilises $\lambda_H = \lambda + \lambda_{HS}^2 / \beta_{\lambda_S}$.

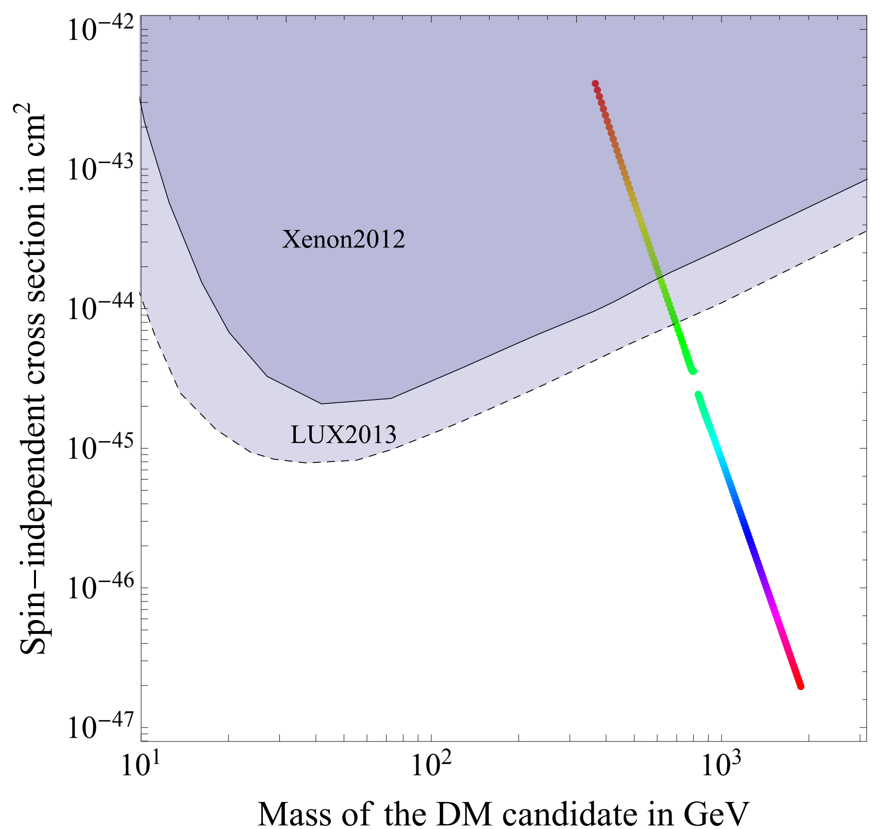
Experimental implications

1) New scalar s: like another h with suppressed couplings; $s \to hh$ if $M_s > 2M_h$.
2) Dark Matter coupled to s, h. Assuming that DM is a thermal relict

$$\sigma v_{\text{ann}} + \frac{1}{2}\sigma v_{\text{semi-ann}} = \frac{11 g_X^2}{1728\pi w^2} + \frac{g_X^2}{64\pi w^2} \approx 2.2 \times 10^{26}\,\frac{\text{cm}^3}{\text{s}}$$

fixes $w = g_X \times 2\,\text{TeV}$, so all is predicted in terms of one parameter g_X:



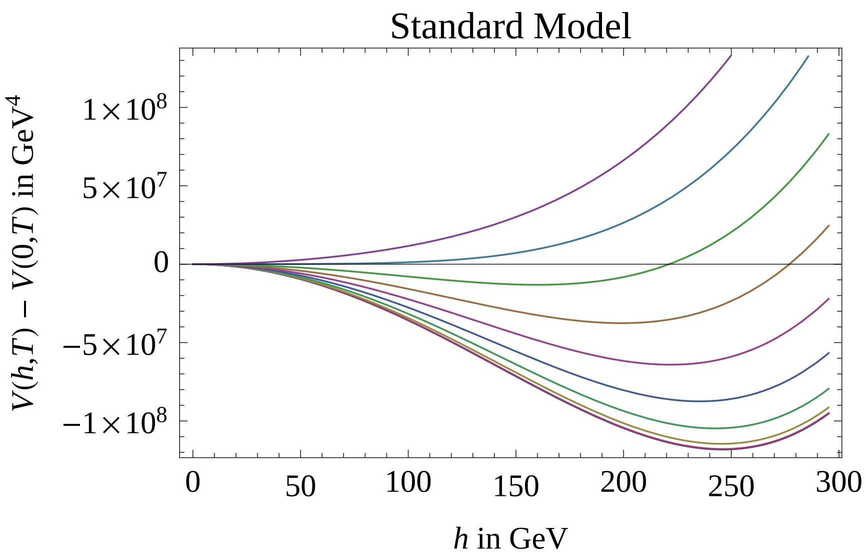


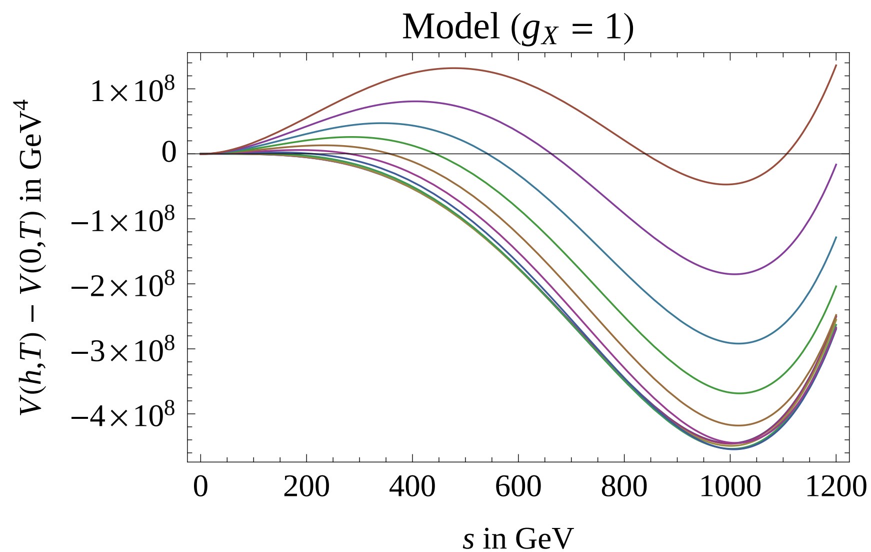
(Insignificant hint in ZZ and $\gamma\gamma$ data around 143 GeV)

Dark/EW phase transition

The model predicts a first order phase transition for s

The universe remains trapped at $s = 0$ until the potential energy ΔV is violently released via thermal tunnelling: $\Gamma \sim T^4 e^{-S/T}$ with $S \propto g_X^4$.





- For the critical value $g_X \approx 1.2$ one has $\Delta V \approx \rho$ such that

$$f_{\text{peak}} \approx 0.3\,\text{mHz} \qquad \Omega_{\text{peak}} h^2 \approx 2\ 10^{-11} \qquad \text{detectable at LISA}$$

- For $g_X > 1.2$ gravitational waves become weaker.
- For $g_X < 1.2$ the universe gets trapped in a (too long?) inflationary phase.

4) Agravity

[Salvio, Strumia, 1403.4226]

What about gravity?

Does quantum gravity give $\delta M_h^2 \sim M_{\rm Pl}^2$ ruining Finite Naturalness?

Maybe $M_{\rm Pl}^{-1}$ is just a small coupling and there are no new particles around $M_{\rm Pl}$.

Quantum gravity would be very different from what strings suggest...

Adimensional gravity

Applying the adimensional principle to the SM plus gravity and a scalar S gives:

$$\mathscr{S} = \int d^4x \, \sqrt{|\det g|} \, \mathscr{L}$$

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \frac{R^2}{3f_0^2} + \frac{R^2 - 3R_{\mu\nu}^2}{3f_2^2} - \xi_H |H|^2 R + |D_\mu S|^2 - \xi_S |S|^2 R - \lambda_S |S|^4 + \lambda_{HS} |HS|^2$$

where f_0, f_2 are the adimensional 'gauge couplings' of gravity and $R \sim \partial_\mu \partial_\nu g_{\mu\nu}$.

Of course the theory is renormalizable, and indeed the graviton propagator is:

$$\frac{-i}{k^4}\left[2f_2^2 P_{\mu\nu\rho\sigma}^{(\text{spin }2)} - f_0^2 P_{\mu\nu\rho\sigma}^{(\text{spin }0)} + \text{gauge-fixing}\right].$$

The Planck scale should be generated dynamically as $\xi_S \langle S \rangle^2 = \bar{M}_{\rm Pl}^2/2$.

Then, the spin-0 part of $g_{\mu\nu}$ gets a mass $M_0 \sim f_0 M_{\rm Pl}$ and the spin 2 part splits into the usual graviton and an anti-graviton with mass $M_2 = f_2 \bar{M}_{\rm Pl}/\sqrt{2}$ that acts as a Pauli-Villars in view its negative kinetic term [Stelle, 1977].

A ghost?

Classically, higher derivatives are bad [Ostrogradski, 1850]:

$$\partial^4 \Rightarrow \text{unbounded negative kinetic energy} \Rightarrow \text{the theory is dead.}$$

The dispersion relation $P^4 = m^4$ has 4 solutions: $E = \pm m$ and $E = \pm im$.

In presence of masses, ∂^4 can be decomposed as 2 fields with 2 derivatives:

$$\frac{1}{k^4} \to \frac{1}{k^4 - M_2^2 k^2} = \frac{1}{M_2^2}\left[\frac{1}{k^2} - \frac{1}{k^2 - M_2^2}\right]$$

Quantistically, the state with negative kinetic term can be reinterpreted as **positive energy and negative norm** by swapping $a \leftrightarrow a^\dagger$.

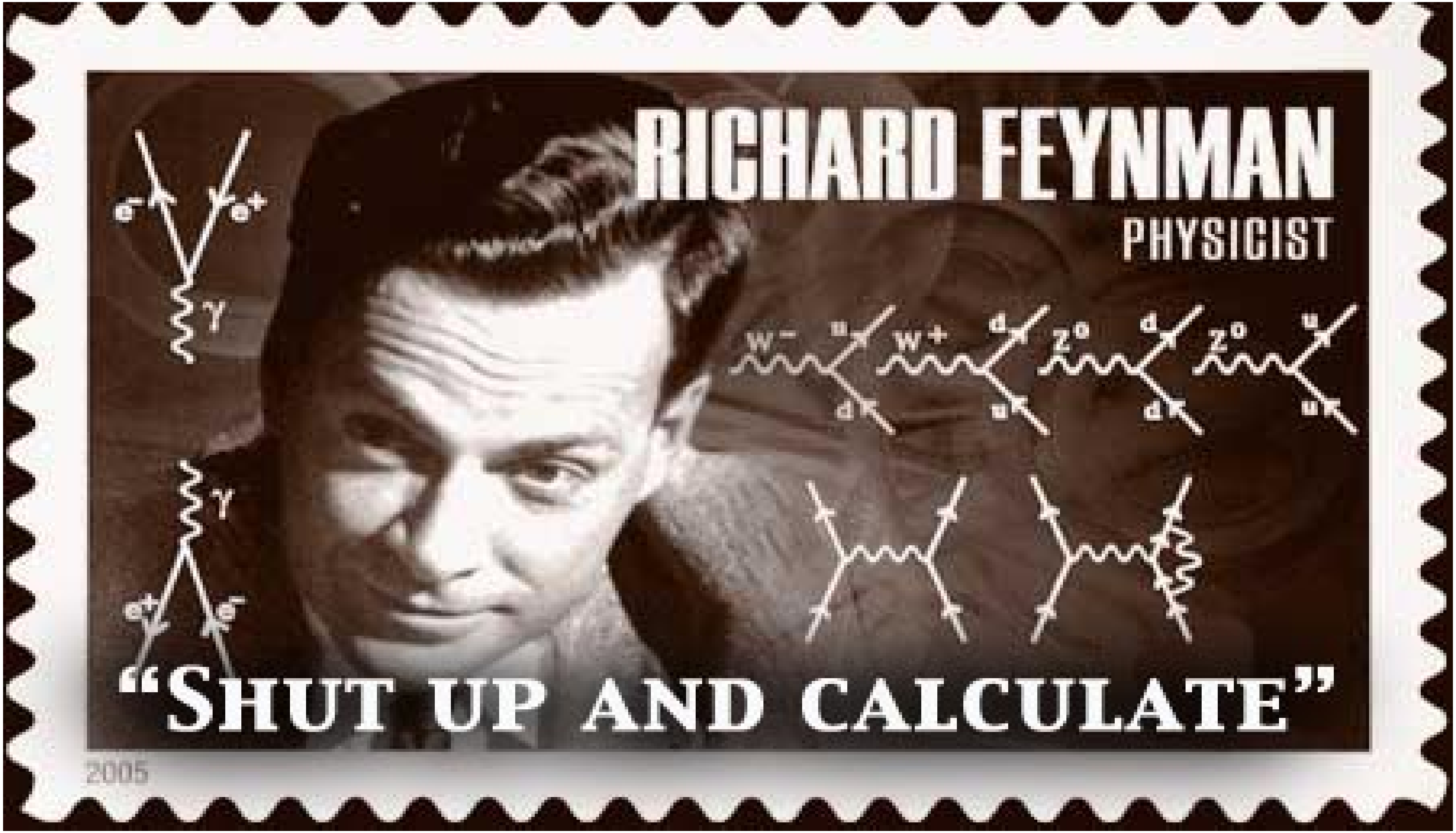
This is the $i\epsilon$ choice that makes the theory renormalizable.

Lee, Wick, Cutkosky... claim that ghosts give a slightly acausal unitary S matrix.

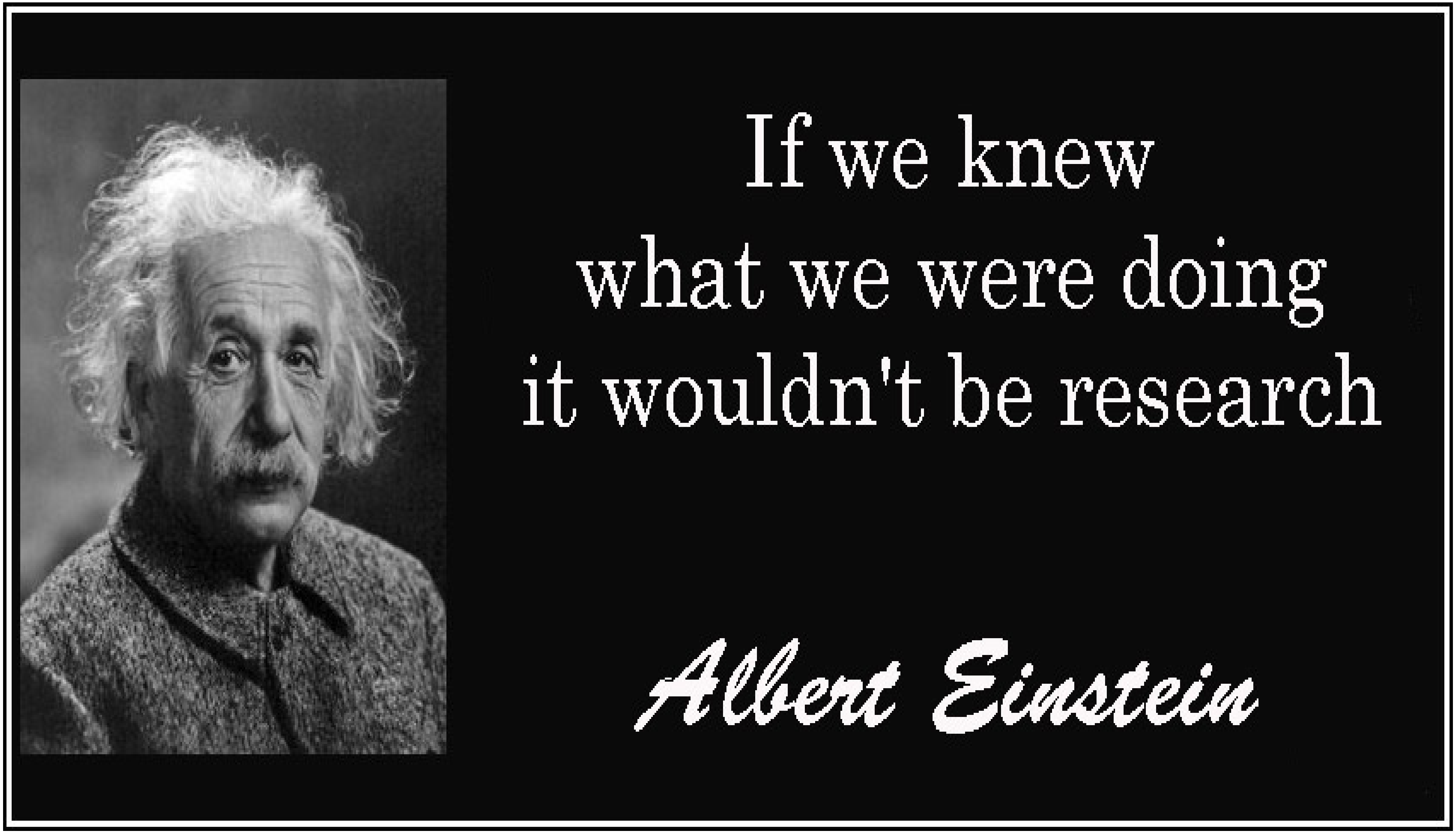
Without masses, ∂^4 cannot be decomposed. Such crackpotton field has its own quantisation rules, I do not yet understand what they mean.

This is what happened with anti-particles: sometimes we have the right equations before understanding what they mean. I ignore the issue and compute.

A ghost?



A ghost?


If we knew
what we were doing
it wouldn't be research
Albert Einstein

A ghost?

Quantum Agravity...

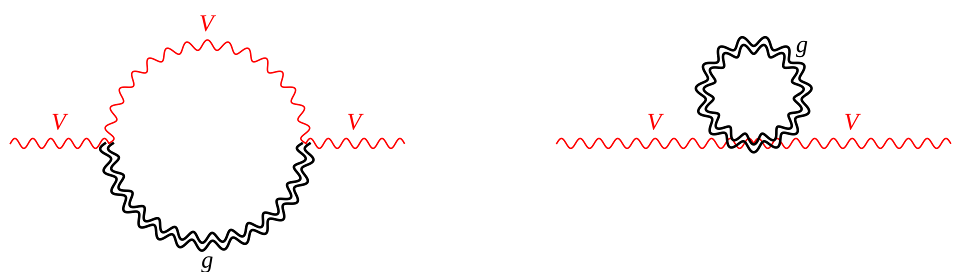
The quantum behaviour of a renormalizable theory is encoded in its RGE.
The unusual $1/k^4$ makes easy to get signs wrong. Literature is contradictory.

Preliminary results at one loop:

- f_2 is asymptotically free:

$$(4\pi)^2 \frac{df_2^2}{d\ln\mu} = -f_2^4 \left[\frac{133}{10} + \frac{N_V}{5} + \frac{N_f}{20} + \frac{N_s}{60}\right]$$

- Gravity does not affect running of gauge couplings: these two diagrams cancel



presumably because abelian g is undefined without charged particles.

- f_0 is not asymptotically free unless $f_0^2 < 0$

$$(4\pi)^2 \frac{df_0^2}{d\ln\mu} = \frac{5}{3} f_2^4 + 5 f_2^2 f_0^2 + \frac{5}{6} f_0^4 + \frac{f_0^4}{12} \sum_s (1 + 6\xi_s)^2$$

...Quantum Agravity

- Yukawa couplings get an extra multiplicative RGE correction:

$$(4\pi)^2 \frac{dy_t}{d\ln\mu} = \frac{9}{2} y_t^3 - y_t (8 g_3^2 - \frac{15}{8} f_2^2)$$

- The RGE for ξ is perturbative up to $\xi_H \lesssim 1/f_0$

$$(4\pi)^2 \frac{d\xi_H}{d\ln\mu} = -\frac{5}{3}\frac{f_2^4}{f_0^2}\xi_H + f_0^2 \xi_H (6\xi_H + 1)(\xi_H + \frac{2}{3}) + (6\xi_H + 1)\left[2y_t^2 - \frac{3}{4} g_2^2 + \cdots\right]$$

- Agravity makes quartics small at low energy:

$$(4\pi)^2 \frac{d\lambda_H}{d\ln\mu} = \xi_H^2 [5 f_2^4 + f_0^4 (1 + 6\xi_H)^2] - 6 y_t^4 + \frac{9}{8} g_2^4 + \cdots$$

- Agravity creates a mixed quartic:

$$(4\pi)^2 \frac{d\lambda_{HS}}{d\ln\mu} = \frac{\xi_H \xi_S}{2} [5 f_2^4 + f_0^4 (6\xi_S + 1)(6\xi_H + 1)] + \text{multiplicative}$$

Generation of the Planck scale

Some mechanisms can generate dynamically the Planck scale

$\boxed{\text{a) } \lambda_S \text{ runs negative below } M_{\rm Pl}}$ or $\boxed{\text{b) } f_2 \text{ or } \xi_S \text{ run non-perturbative.}}$

Focus on a): scalar Planckion. ξ_S makes the vacuum equations non-standard:

$$\frac{\partial V}{\partial S} - \frac{4V}{S} = 0 \qquad \text{i.e.} \qquad \frac{\partial V_E}{\partial S} = 0$$

where $V_E = V/(\xi S^2)^2 \sim \lambda_S(S)/\xi_S^2(S)$ is the Einstein-frame potential. The vev

$$\langle S \rangle = \bar{M}_{\rm Pl}/\sqrt{2\xi_S}$$

needs a condition different from the usual Coleman-Weinberg:

$$\frac{\beta_{\lambda_S}(\bar{\mu} \sim \langle S \rangle)}{\lambda_S(\bar{\mu} \sim \langle S \rangle)} - 2\frac{\beta_{\xi_S}(\bar{\mu} \sim \langle S \rangle)}{\xi_S(\bar{\mu} \sim \langle S \rangle)} = 0$$

Furthermore, the cosmological constant is fine-tuned to zero by imposing

$$\lambda_S(\bar{\mu} \sim \langle S \rangle) = 0$$

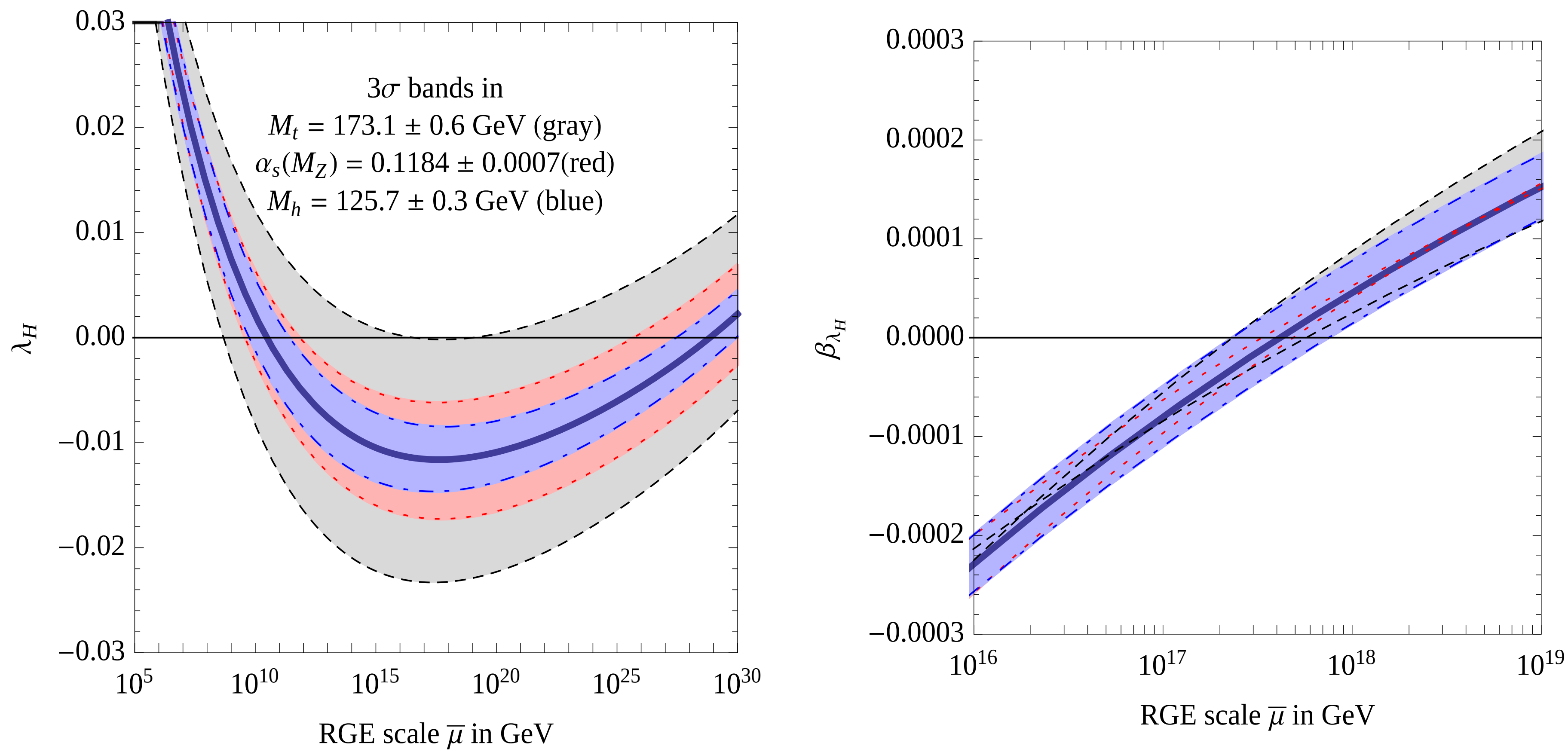
So the minimum equation simplifies to

$$\beta_{\lambda_S}(\bar{\mu} \sim \langle S \rangle) = 0$$

$\lambda_S = \beta_{\lambda_S} = 0$ around $M_{\rm Pl}$: is this running possible?

Yes, this is how λ_H can run in the SM!

RGE running of the $\overline{\text{MS}}$ quartic Higgs coupling in the SM



H cannot get a Planck-scale vev. Model: add a mirror copy of the SM, broken by the fact that S, the Higgs mirror, lies in the Planck minimum: $\xi_S \sim 10^{1\div 2}$.

Inflation = perturbative agravity

Inflation needs special theories with flat potential and/or super-Planckian vevs.

A successful class of models is ξ-inflation: a scalar S with $-\frac{1}{2}f(S)R+V(S)$.
Redefine $g_{\mu\nu}=g^E_{\mu\nu}\times\bar M^2_{\rm Pl}/f$ to the Einstein frame to make the graviton canonical

$$\sqrt{\det g}\left[-\frac{f}{2}R+\frac{(\partial_\mu s)^2}{2}-V\right]=\sqrt{\det g_E}\left[-\frac{\bar M^2_{\rm Pl}}{2}R_E+\bar M^2_{\rm Pl}(\frac{1}{f}+\frac{3f'^2}{2f^2})\frac{(\partial_\mu s)^2}{2}-V_E\right]$$

where $V_E=\bar M^4_{\rm Pl}V/f^2$ is flat (good for inflation) if $V(S)\propto f^2(S)$ **above** $M_{\rm Pl}$.

In general, this restriction is unmotivated and uncontrollable.

In quantum agravity $f(S)=\xi_S(\bar\mu\sim S)|S|^2$ and $V(S)=\lambda_S(\bar\mu\sim S)|S|^4$!

Inflation is a typical phenomenon in agravity: the slow-roll parameters are the β-functions, which are small if the theory is perturbative. In the Einstein frame

$$\epsilon \equiv \frac{\bar M^2_{\rm Pl}}{2}\left(\frac{1}{V_E}\frac{\partial V_E}{\partial s_E}\right)^2=\frac{1}{2}\frac{\xi_S}{1+6\xi_S}\left[\frac{\beta_{\lambda_S}}{\lambda_S}-2\frac{\beta_{\xi_S}}{\xi_S}\right]^2,$$

$$\eta \equiv \frac{\bar M^2_{\rm Pl}}{V_E}\frac{\partial^2 V_E}{\partial s_E^2}=\frac{\xi_S}{1+6\xi_S}\left[\frac{\beta(\beta_{\lambda_S})}{\lambda_S}-2\frac{\beta(\beta_{\xi_S})}{\xi_S}+\frac{5+36\xi_S}{1+6\xi_S}\frac{\beta^2_{\xi_S}}{\xi^2_S}-\frac{7+48\xi_S}{1+6\xi_S}\frac{\beta_{\lambda_S}\beta_{\xi_S}}{2\lambda_S\xi_S}\right].$$

Approximating agravity inflation

If the inflaton is the Planckion s, its potential is approximately logarithmic

$$\lambda_S(\bar\mu \approx s) \approx 0 + 0 \ln s + \frac{g^4}{2(4\pi)^4} \ln^2 \frac{s}{\langle s\rangle}, \qquad \xi_S(\bar\mu) \approx \xi_S$$

The canonical Einstein-frame field is

$$s_E = \bar M_{\rm Pl} \sqrt{\frac{1+6\xi_S}{\xi_S}} \ln \frac{s}{\langle s\rangle}$$

and its potential is:

$$V_E = \frac{\bar M_{\rm Pl}^4}{4} \frac{\lambda_S}{\xi_S^2} \approx \frac{M_s^2}{2} s_E^2 \qquad \text{with} \qquad M_s = \frac{g^2 \bar M_{\rm Pl}}{2(4\pi)^2} \frac{1}{\sqrt{\xi_S(1+6\xi_S)}}$$

Inflation occurs at $s_E \approx 2\sqrt{N}\bar M_{\rm Pl}$ for $N \approx 60$: above the Planck scale:

$$A_s \approx \frac{g^4 N^2}{24\pi^2 \xi_S(1+6\xi_S)} \qquad n_s \approx 1 - \frac{2}{N} \approx 0.967, \qquad r = \frac{A_t}{A_s} \approx \frac{8}{N} \approx 0.13,$$

In general: (3 predictions) $-$ (2 parameters ξ_S and g) $=$ (1 prediction).

In the SM-mirror model $g \approx 1.0$ so $\xi_S \approx 230$ i.e. $\langle s\rangle \approx 1.6\ 10^{17}$ GeV: ok.

Generation of the Weak scale

RGE running generates M_h from $M_{\rm Pl}$. 3 regimes:

1) below $M_{0,2}$: ignore agravity, M_h runs logarithmically as in the SM

$$(4\pi)^2 \frac{dM_h^2}{d\ln\bar\mu} = \beta_{\rm SM} M_h^2 \qquad \beta_{\rm SM} = 12\lambda_H + 6y_t^2 - \frac{9g_2^2}{2} - \frac{9g_1^2}{10}$$

2) between $M_{0,2}$ and $M_{\rm Pl}$: the apparent masses run:

$$(4\pi)^2 \frac{dM_h^2}{d\ln\bar\mu} = \left[\beta_{\rm SM} + 5f_2^2 + \frac{5}{3}\frac{f_2^4}{f_0^2} + \cdots\right] M_h^2 - \xi_H \left[5f_2^4 + f_0^4(1+6\xi_H)\right] \bar M_{\rm Pl}^2$$

3) above $M_{\rm Pl}$ couplings are adimensional: $\lambda_{HS}|H|^2|S|^2$ leads to $M_h^2 = \lambda_{HS}\langle s\rangle^2$:

$$(4\pi)^2 \frac{d\lambda_{HS}}{d\ln\bar\mu} = -\xi_H\xi_S[5f_2^4 + f_0^4(6\xi_S+1)(6\xi_H+1)] + \cdots$$

The weak scale arises if $f_{0,2} \sim \sqrt{M_h/M_{\rm Pl}} \sim 10^{-8}$ i.e. $M_{0,2} \sim 10^{11}$ GeV

All small parameters such as $f_{0,2}$ and $\lambda_{HS} \sim f_{0,2}^4$ are naturally small

The Planckion s can have any mass between M_h and $M_{\rm Pl}$

Black holes

Perturbative Quantum Gravity cannot convert a small coupling $1/M_{\rm Pl}$ into a big mass. Non-perturbative QG, a black hole with mass $M_{\rm BH}$, could give

$$\delta M_h^2 \sim M_{\rm BH}^2 e^{-M_{\rm BH}^2/M_{\rm Pl}^2}.$$

The black holes possibly dangerous for FN have mass $M_{\rm BH} \sim M_{\rm Pl}$.

Such black holes do not exist if the fundamental coupling of gravity is small. The minimal mass of a black hole is $M_{\rm BH} > M_{\rm Pl}/f_{0,2}$ because of

$$V_{\rm Newton} = -\frac{Gm}{r}\left[1 - \frac{4}{3}e^{-M_2 r} + \frac{1}{3}e^{-M_0 r}\right]$$

Non-perturbative QG corrections $\delta M_h^2 \propto e^{-1/f_{0,2}^2}$ can be neglected for $f_{0,2} \ll 1$

5) Landau poles

[Giudice, Isidori, Salvio, Strumia, to appear]

Landau poles

We have the RGE above $M_{\rm Pl}$, can the theory reach infinite energy?

Problem: Landau poles for g_Y, possibly λ, y_t, y_b, y_τ? To analyse any QFT:

1) Get 1-loop RGE, asymptotically approximate

$$g_i = c_i / \ln \bar\mu \ll 1$$

2) Get a system of ordinary equations in c_i.

3) Find multiple sets of solutions $c_i^1, c_i^2, \ldots$.

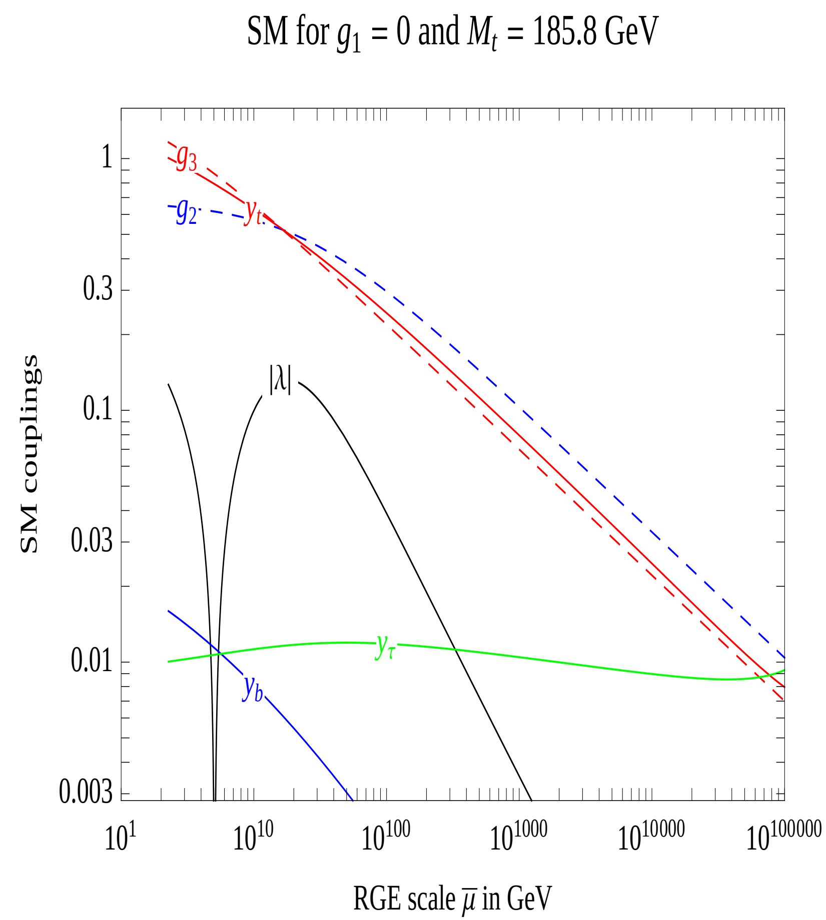
4) Check if at least one physical solution exists, such that all couplings are real.

5) If yes, extrapolate down to low energy.

6) Perturb: UV fixed points admit deformations; IR fixed points are predicted.

In the SM there is one acceptable solution and it predicts $g_Y, y_\tau = 0$ and, in this limit, y_t ($M_t \approx 185.8\,\text{GeV}$) and an acceptable range for M_h.

But $g_Y \neq 0$ gives a Landau pole at $10^{43}\,\text{GeV}$.



Landau poles

Can the SM be extended into a theory valid up to infinite energy?

Idea: **avoid Landau poles by making hypercharge non abelian**. The best possibilities — SU(5)-like GUTs — are not compatible with finite naturalness.

FN demands extensions at the weak scale. There are two possibilities:

$$\text{SU}(4)_c \otimes \text{SU}(2)_L \otimes \text{SU}(2)_R \qquad \text{and} \qquad \text{SU}(3)_c \otimes \text{SU}(3)_L \otimes \text{SU}(3)_R$$

Flavor, precision data, LHC... imply multi-TeV bounds on some particles (H', Z', W'...). Difficult attempt to reconcile bounds with naturalness is underway.

Conclusions

The exploration is still in progress.

The truth can be somewhere along this set of ideas.

Of course, going from Higgs and no SUSY to modified naturalness to an anti-graviton ghost at 10^{11} GeV is risky.

Of course, it is much more reasonable to imagine ant***pic selection within a multiverse of branes wrapped on 6 or 7 extra dimensions compactified on...