Theoretical implications of present LHC unobservations

0) What was found
1) Finite naturalness
2) A new principle
3) Agravity
4) Landau poles

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Talk FNAL, August 22, 2014

Mobilitas
ESF programm

Euroopa Liit
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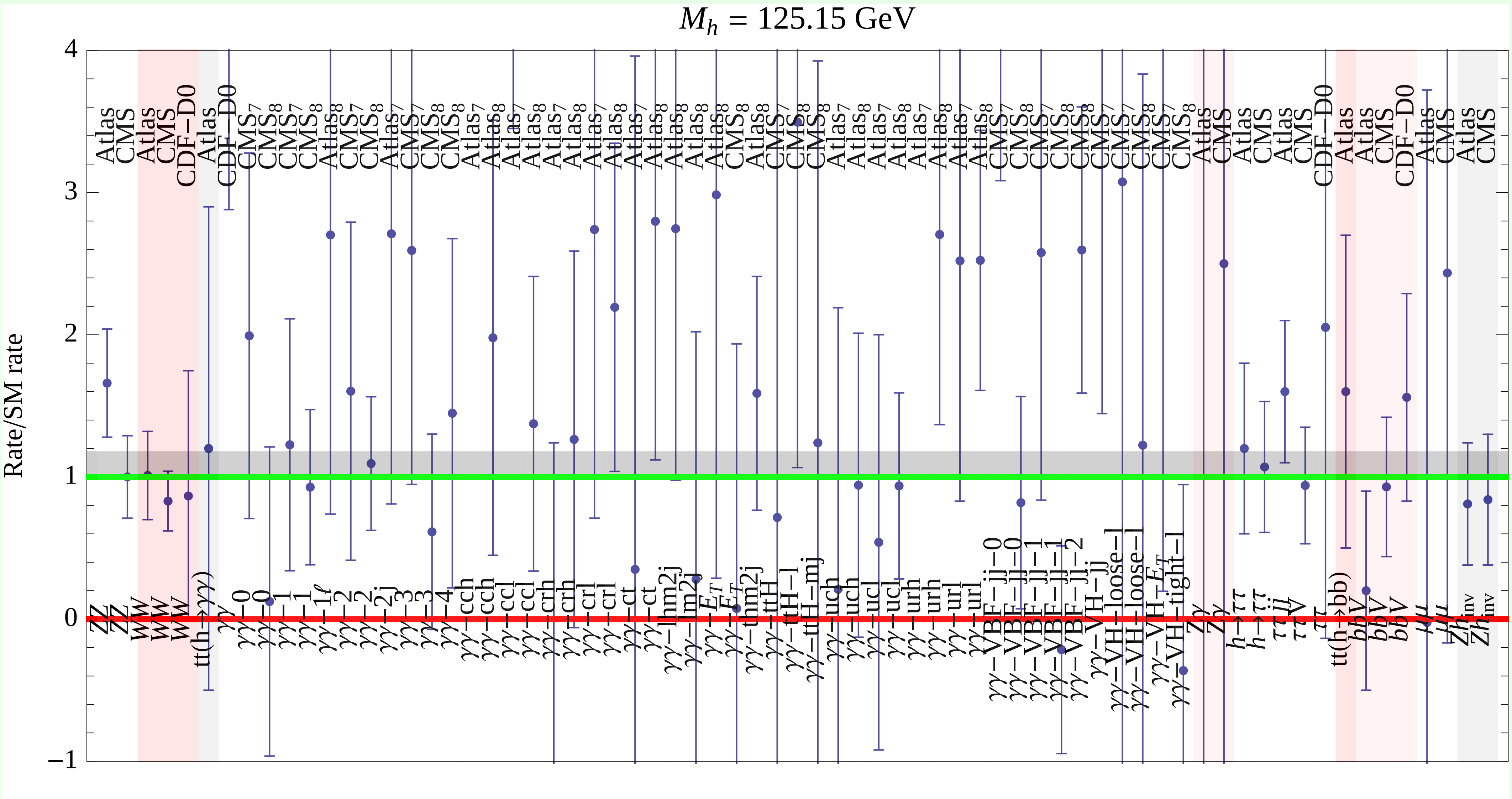
Eesti tuleviku heaks

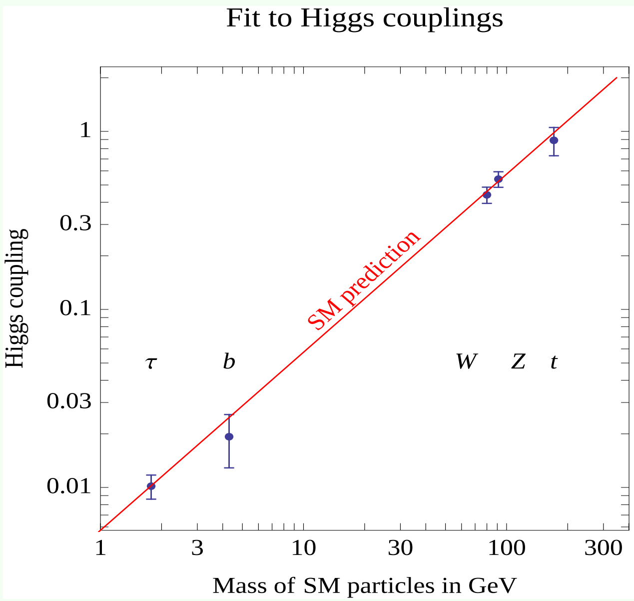
0) What was found

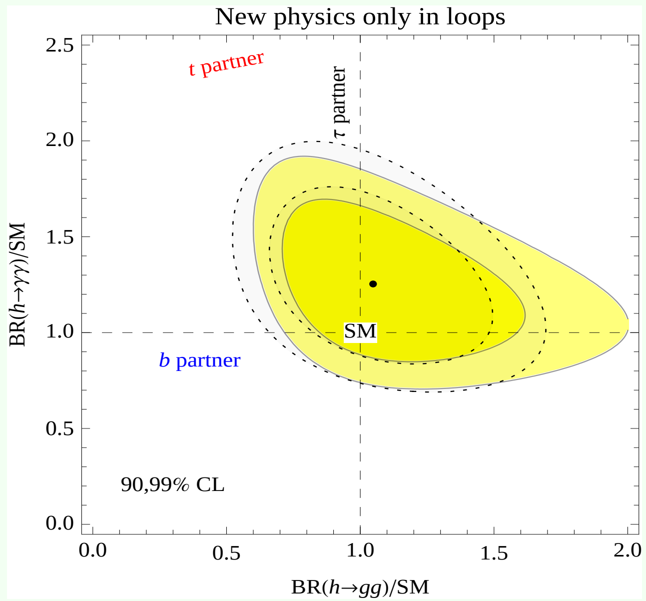
But should not have been found

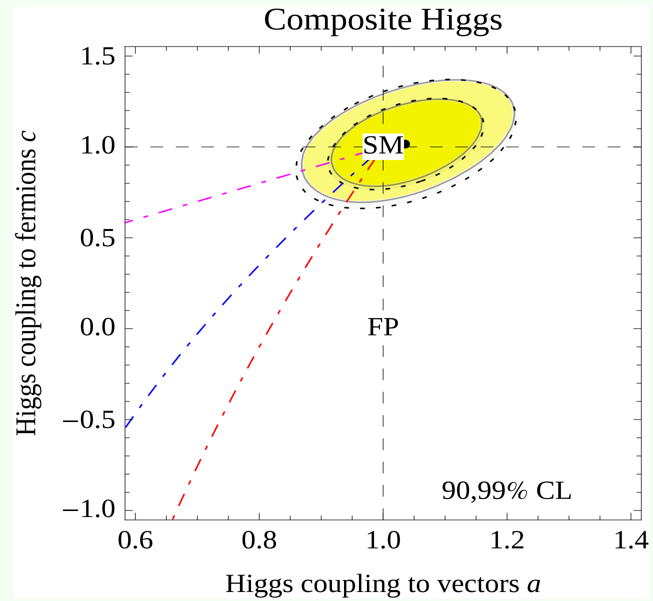
Only the Higgs

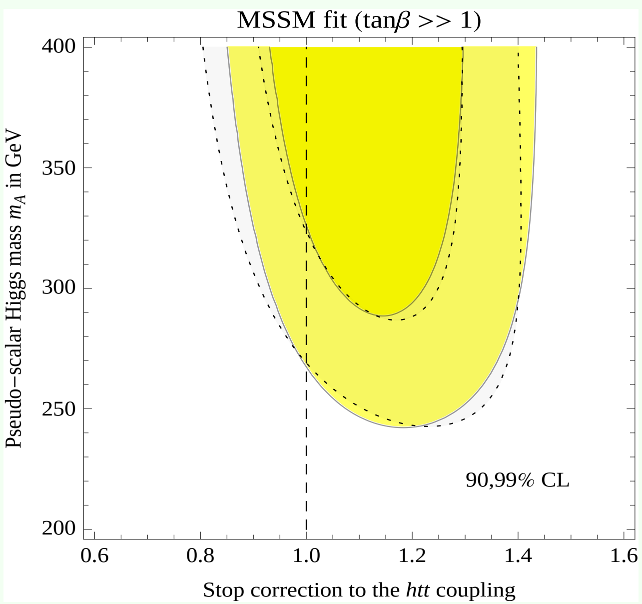


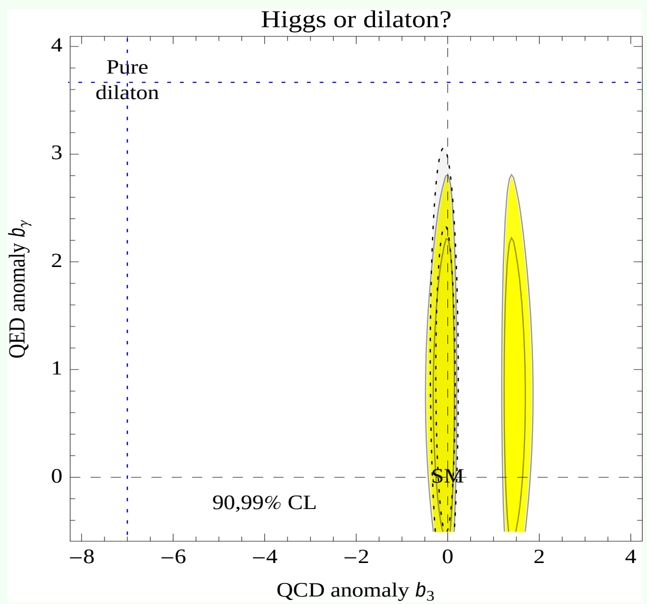
The SM Higgs

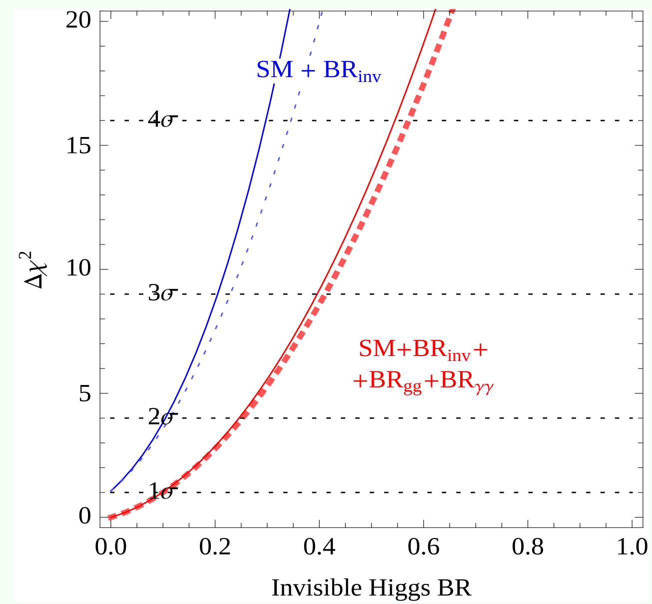










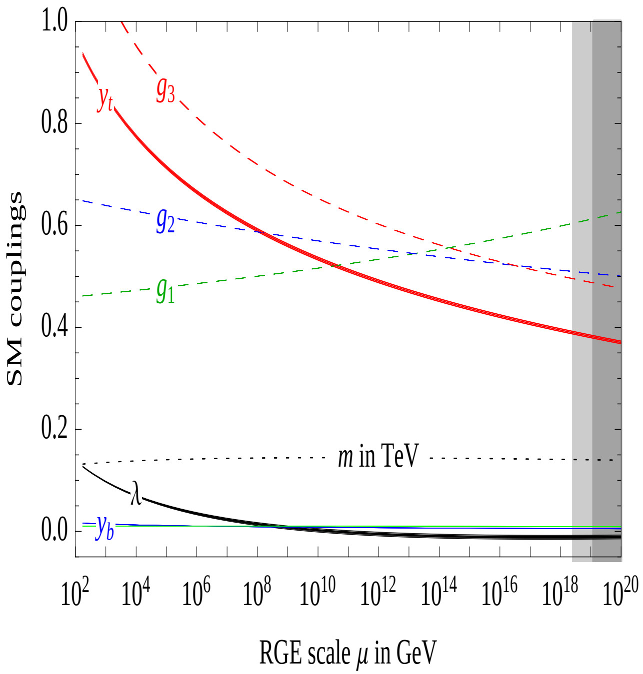


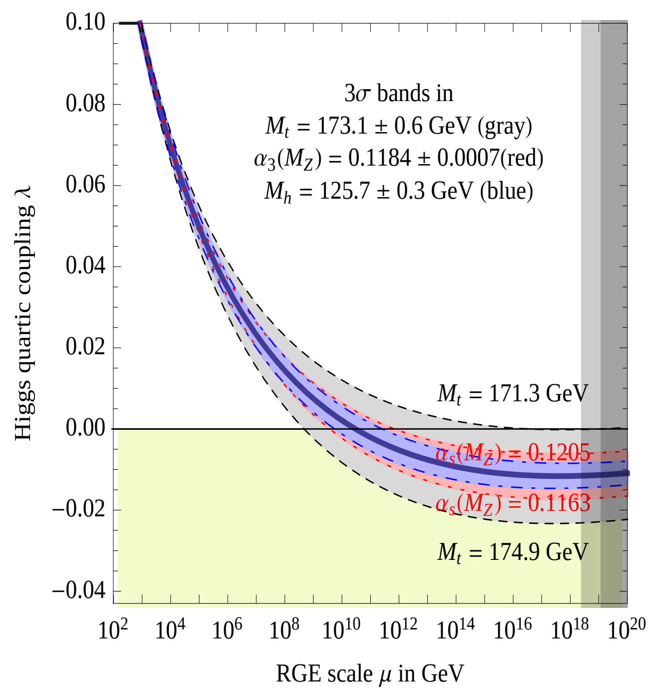
[Giardino, Kannike, Masina, Raidal Strumia, 1303.3570 + updates]

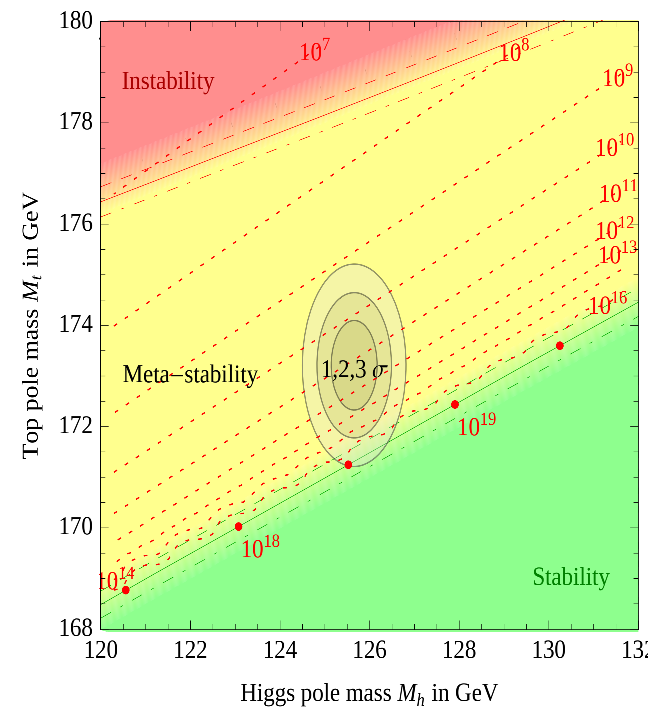
And nothing else

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 $M_{\rm Pl}$

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

The SM parameters at NNLO

SM parameters extracted with data at 2 loop accuracy: at $\bar{\mu} = M_t$

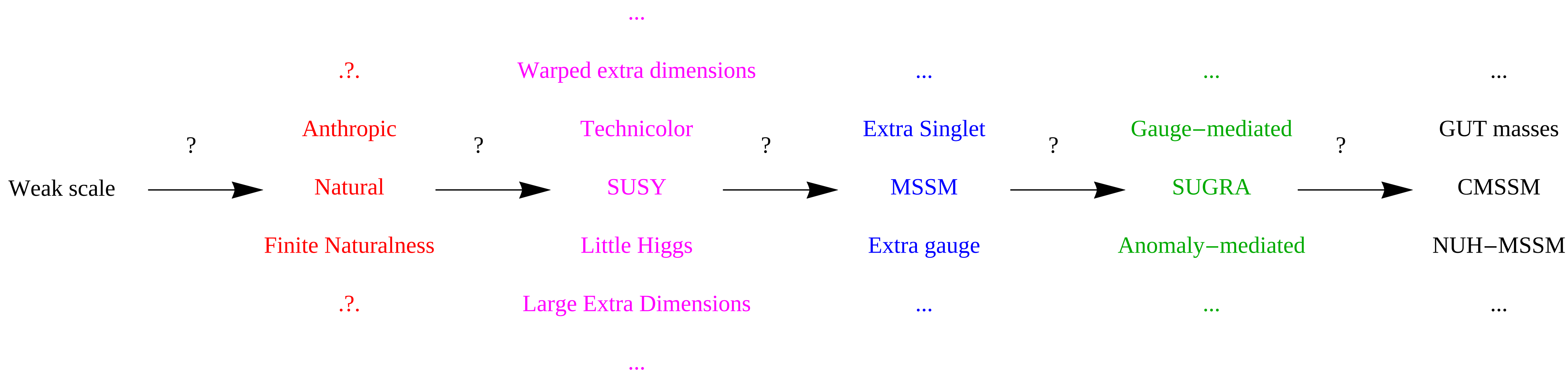
$$
\begin{aligned}
g_2 &= 0.64822 + 0.00004\left(\frac{M_t}{\text{GeV}} - 173.10\right) + 0.00011\frac{M_W - 80.384\,\text{GeV}}{0.014\,\text{GeV}}\\
g_Y &= 0.35761 + 0.00011\left(\frac{M_t}{\text{GeV}} - 173.10\right) - 0.00021\frac{M_W - 80.384\,\text{GeV}}{0.014\,\text{GeV}}\\
y_t &= 0.9356 + 0.0055\left(\frac{M_t}{\text{GeV}} - 173.10\right) - 0.0004\,\frac{\alpha_3(M_Z) - 0.1184}{0.0007} \pm 0.0005_{\text{th}}\\
\lambda &= 0.1271 + 0.0021\left(\frac{M_h}{\text{GeV}} - 125.66\right) - 0.00004\left(\frac{M_t}{\text{GeV}} - 173.10\right) \pm 0.0003_{\text{th}}\\
\frac{m}{\text{GeV}} &= 132.03 + 0.94\left(\frac{M_h}{\text{GeV}} - 125.66\right) + 0.17\left(\frac{M_t}{\text{GeV}} - 173.10\right) \pm 0.15_{\text{th}}.
\end{aligned}
$$

Renormalization to large energies is done with 3 loop RGE.

[Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia, 1307.3536]

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 a beautiful plausible scenario with beautiful LHC signals:



But LHC 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.

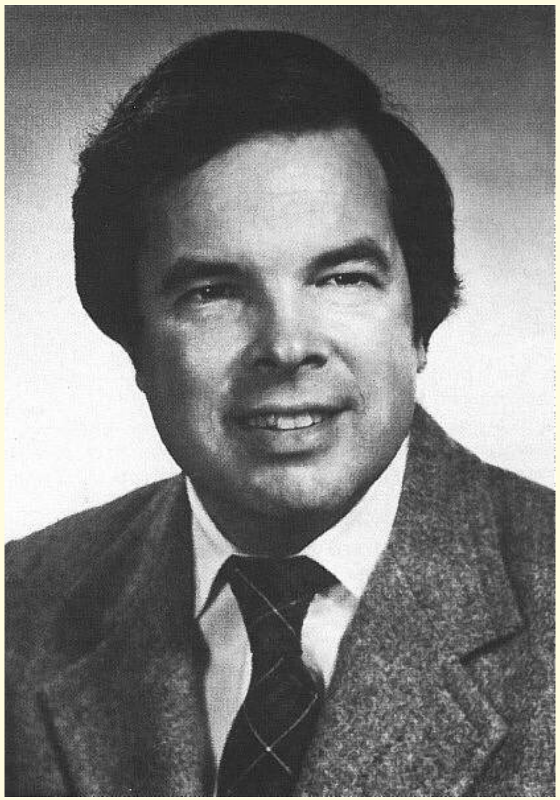
The **ugly possibility** is that
quadratic divergences vanish and a modified Finite Naturalness applies.

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.

[Caution: this is when rotten tomatoes start to fly]

Ipse undixt

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



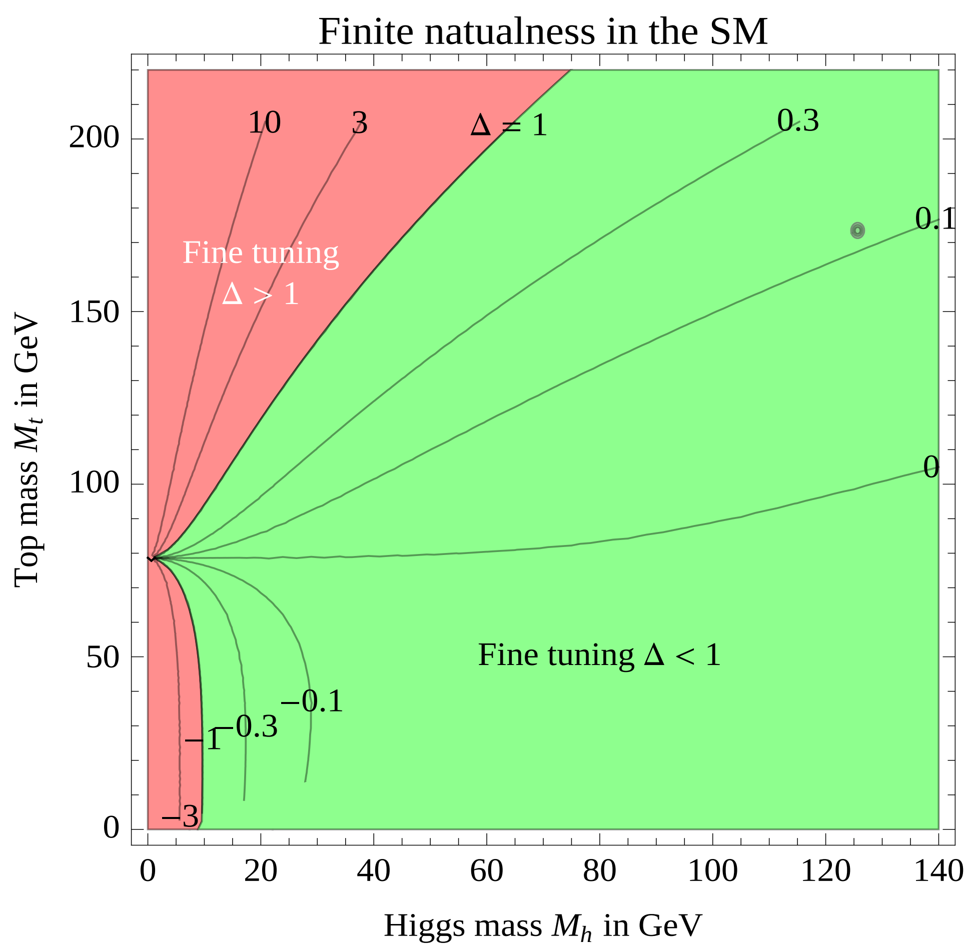
“The final blunder was a claim that scalar elementary particles were unlikely to occur in elementary particle physics at currently measurable energies unless they were associated with some kind of broken symmetry. The claim was that, otherwise, their masses were likely to be far higher than could be 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

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

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

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

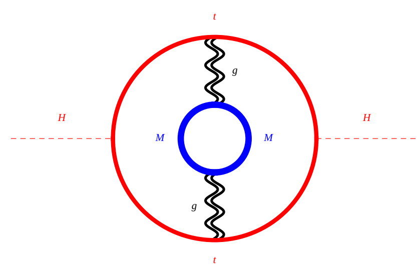
$$M \lesssim \begin{cases} 0.7\ 10^7\,\text{GeV} \times \sqrt[3]{\Delta} & \text{type I see-saw model,} \\ 200\,\text{GeV} \times \sqrt{\Delta} & \text{type II see-saw model,} \\ 940\,\text{GeV} \times \sqrt{\Delta} & \text{type III see-saw model.} \end{cases}$$

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. Einstein gravity gives an upper bound on H_I and on any mass [Arvinataki, Dimopoulos..]

$\delta m^2 \sim$ 

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

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

DM with EW gauge interactions

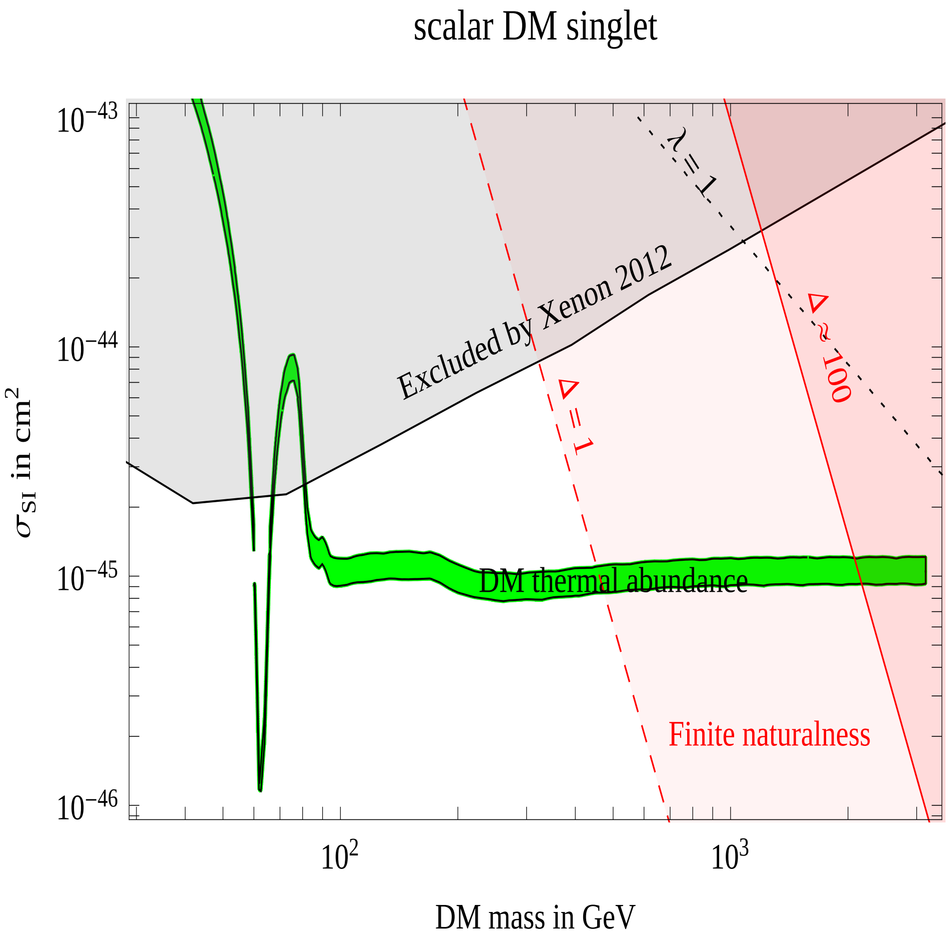
Consider a Minimal Dark Matter n-plet. 2-loop quantum corrections to M_h^2:

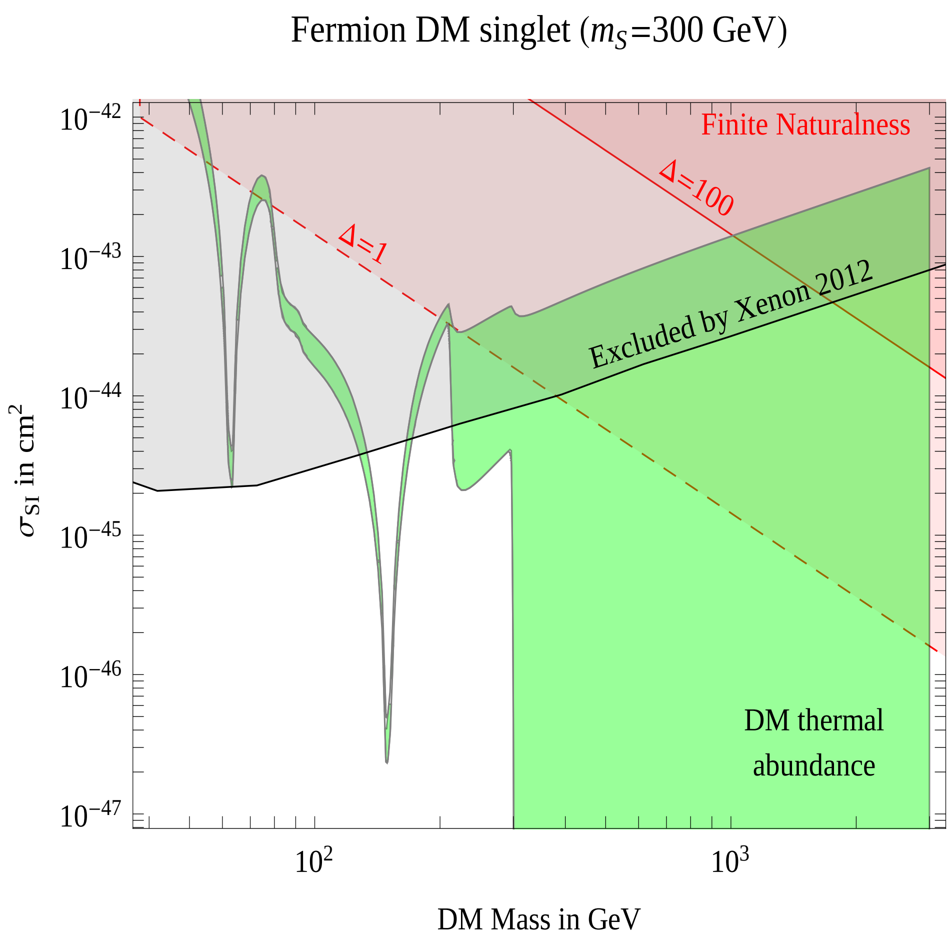
$$\delta m^2 = \frac{cnM^2}{(4\pi)^4}\left(\frac{n^2-1}{4}g_2^4 + Y^2 g_Y^4\right) \times \begin{cases} 6\ln\frac{M^2}{\Lambda^2} - 1 & \text{for a fermion} \\ \frac{3}{2}\ln^2\frac{M^2}{\Lambda\mu^2} + 2\ln\frac{M^2}{\Lambda^2} + \frac{7}{2} & \text{for a scalar} \end{cases}$$

Quantum numbers $\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	Spin	DM could decay into	DM mass in TeV	$m_{\mathrm{DM}^\pm} - m_{\mathrm{DM}}$ in MeV	Finite naturalness bound in TeV, $\Lambda \sim M_{\mathrm{Pl}}$	σ_{SI} in $10^{-46}\,\mathrm{cm}^2$
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 ≈ 1 TeV

Theory?

Using OPE techniques, Skiba et al. [1308.0025] find a divergent correction to m^2 coming from the quantum breaking of scale invariance and claim: "theories with coupling constants which approach free fixed points in the UV cannot protect the Higgs mass from fine tuning".

This claim is unjustified.
Their divergent correction is just the infinite RGE running of m^2.
This is not unnatural.

The infinite running of the ratio of two masses is physical and demands that naturally they are comparable.

Anyhow, the issue of the infinite running of masses can be bypassed by...

2) 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. [Other authors assume scale or conformal invariance as quantum symmetries and argue that the regulator must respect them. I assume that scale invariance is just an accidental symmetry, like baryon number].

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

Can this happen? I apply this principle first to matter and later to gravity.

What is the weak scale?

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

- Could be generated from nothing by heavier particles.
  - See-saw, axions, gravity...

- Could be generated from nothing by weak-scale dynamics.
  - Another gauge group might become strong around 1 TeV.
  - The quartic of another scalar might run negative around 1 TeV.

Strongly coupled models

Techni-Color can dynamically generate a mass scale for an elementary Higgs

$\star$ Hur-Ko and Raidal et al. proposed models where a scalar S interacts with the Higgs and techni-quarks such that $\lambda_{HS}|S|^2|H|^2$ becomes a Higgs mass.

$\star\star$ Lindner et al.: models where a TC scalar S developes a condensate $\langle S^* S\rangle$. (Kubo, Lim, Lindner observe that even QCD alone could do the job, if S in a big SU(3)$_c$ representation. A 15$'$ condenses around 1 TeV, when $\frac{28}{3}\alpha_3 \sim 1$).

$\star\star\star$ Antipin, Redi, Villadoro, Strumia [to appear]: the scalar S is not necessary. The TC scale is then fixed and its natural value is $f \sim M_h/\alpha_2 \sim$ few TeV, $m_\rho \sim 10\,$TeV, Techni-baryons at $\sim$30 TeV: correct DM abundance.

Weakly coupled models

The Coleman-Weinberg mechanism can dynamically generate the weak scale

In the SM it predicts a too light M_h. Add an extra scalar S with a gauge interaction (U(1), SU(2), SU(2)$\otimes$U(1)...) such that the quartic $\lambda_S|S|^4$ runs negative. Then S develops a vev and $\lambda_{HS}|S|^2|H|^2$ becomes a Higgs mass.

Hambye, Strumia, 1306.2329 proposed a model that:

1) **Dynamically generates** the weak scale and weak scale DM
2) **Preserves** the successful automatic features of the SM: B, L...
3) **Gets 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

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

Weakly coupled SU(2) model

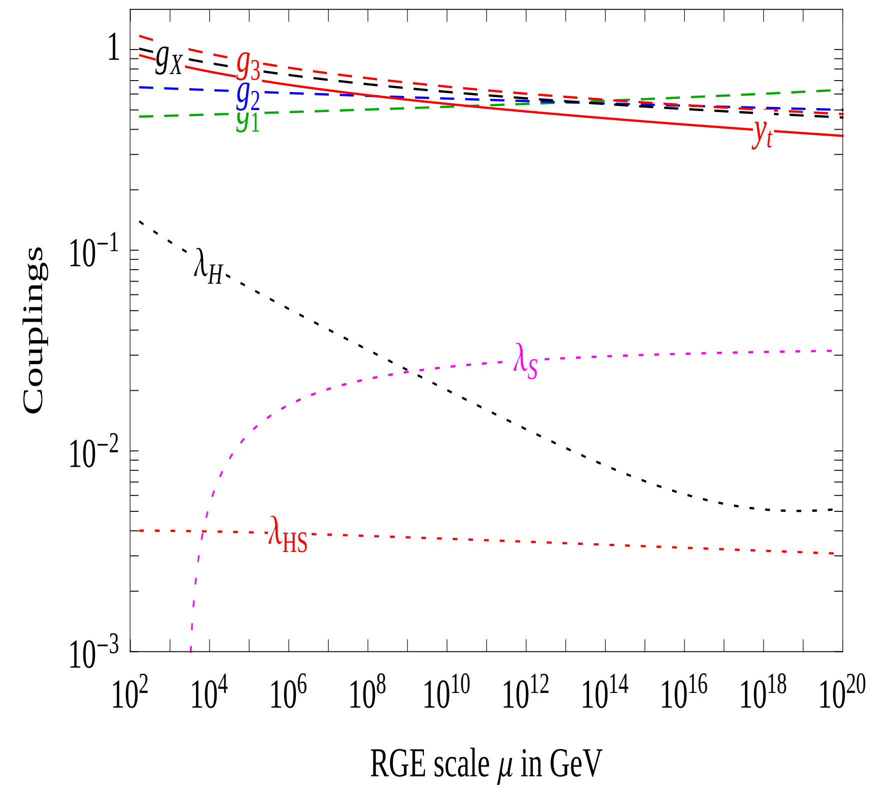
1) λ_S runs negative at low energy:

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

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

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

Problem: vacuum energy must be negative???



2) No new Yukawas.

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

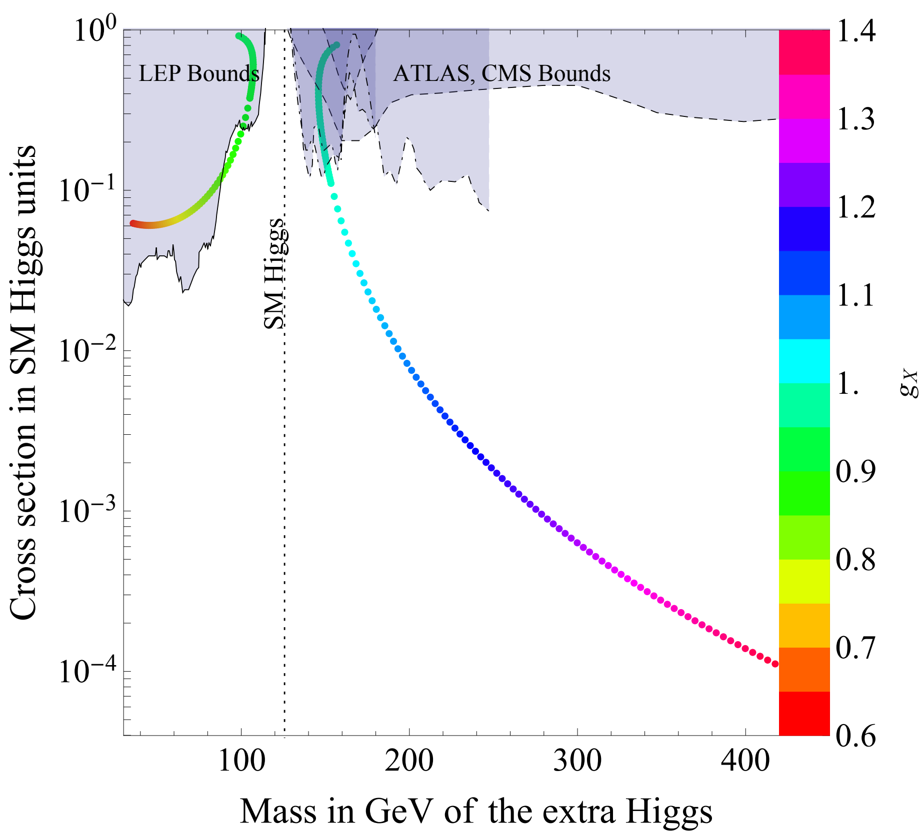
4) Bonus: threshold effect stabilises $\lambda_H = \lambda + \lambda_{HS}^2 / \beta_{\lambda_S}$.

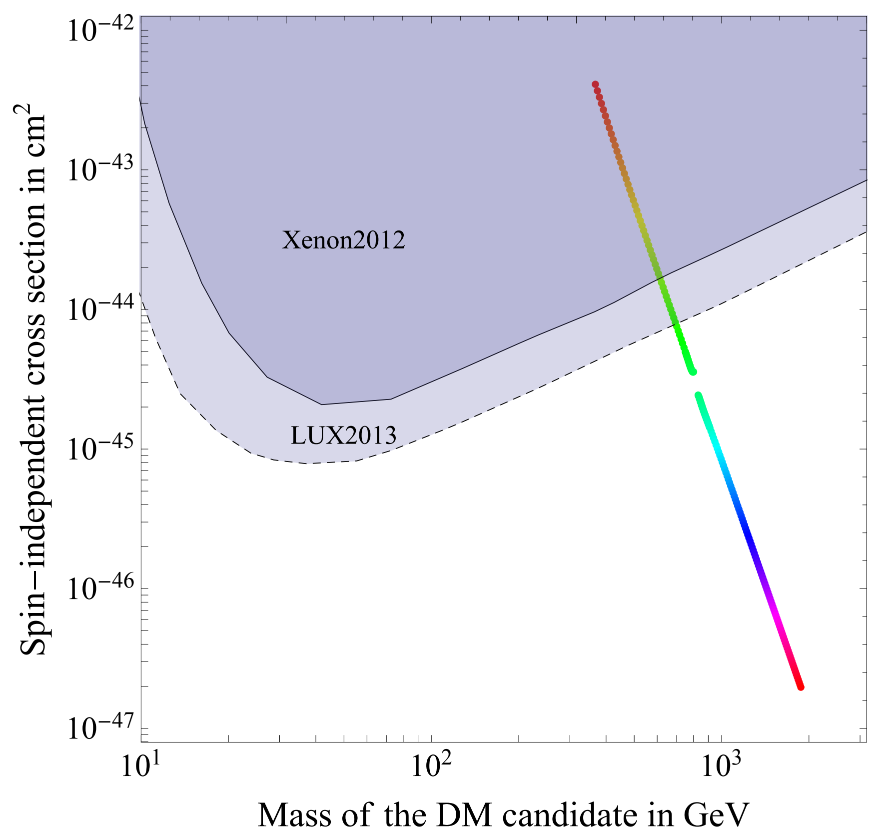
Experimental implications

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

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

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

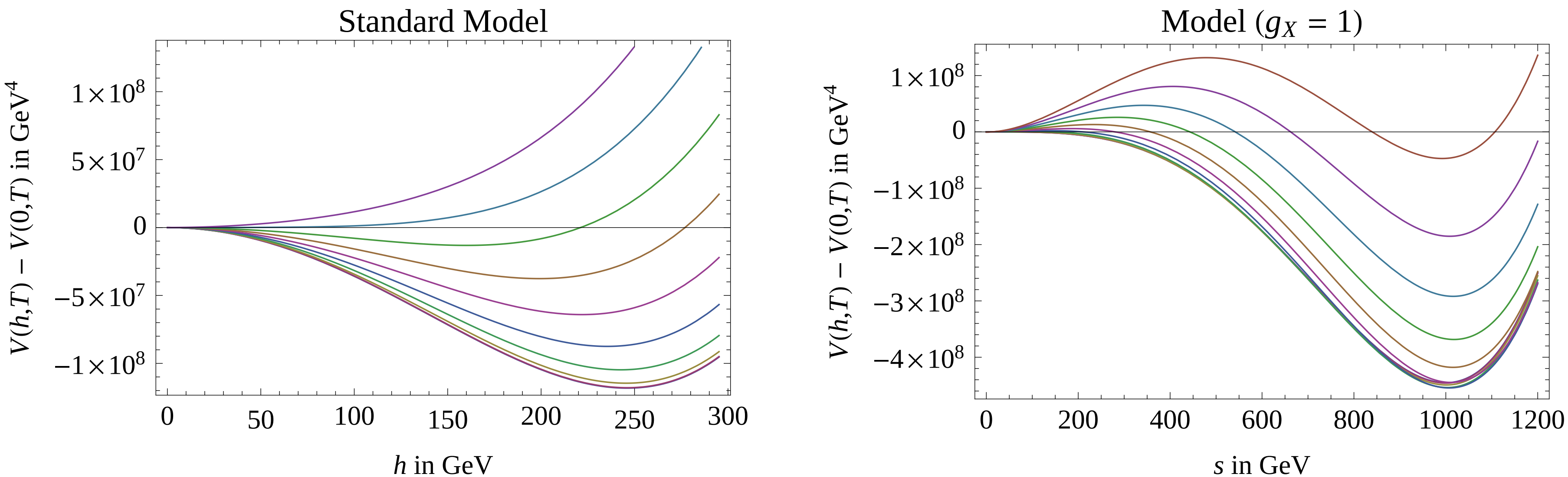




Dark/EW phase transition

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. Allows for EW baryogenesis from the QCD axion [Servant].

3) Agravity

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...

[Salvio, Strumia, 1403.4226]

Adimensional gravity

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

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

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

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:

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

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:

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

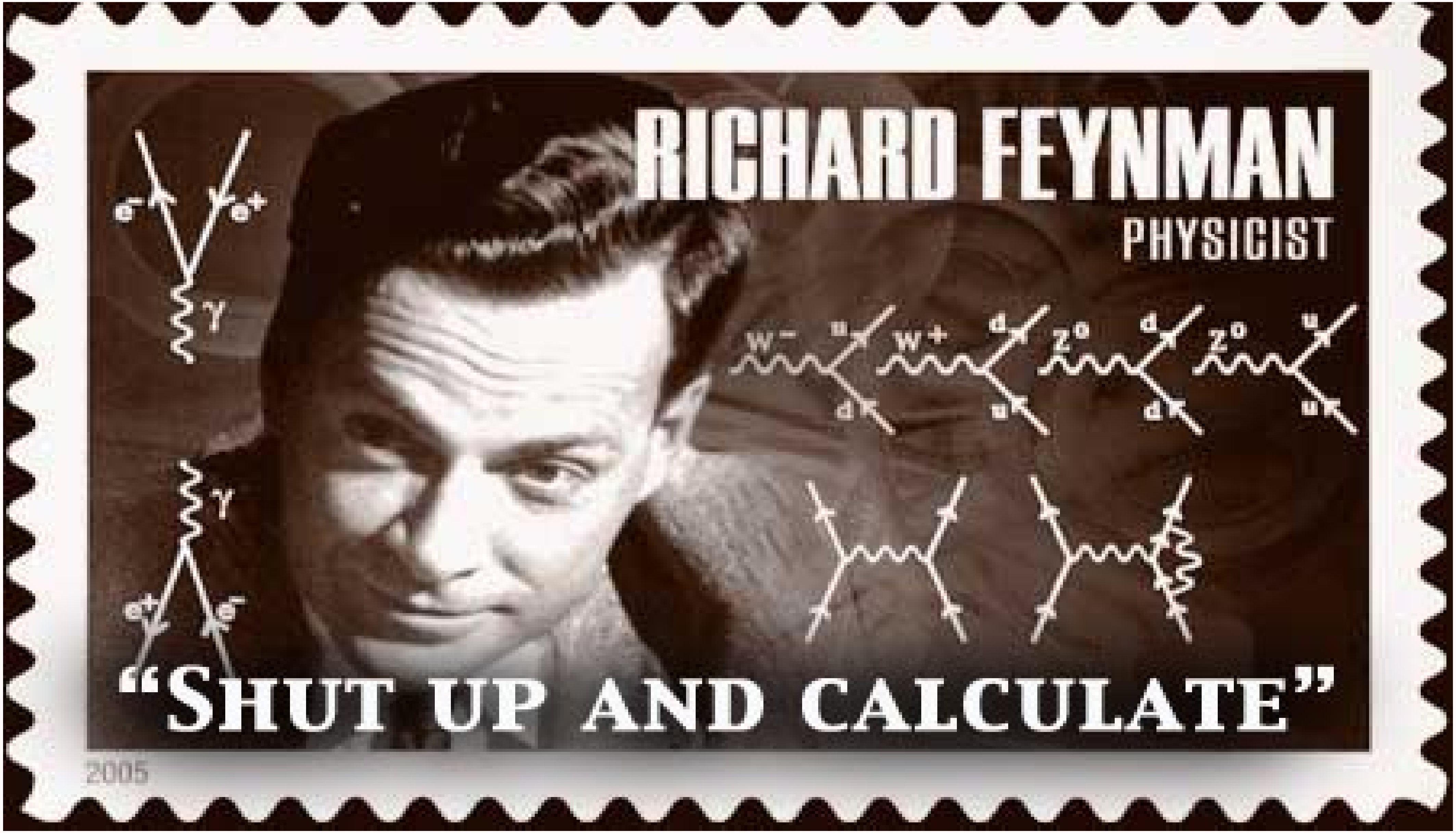
Quantistically, the state with negative kinetic term can be reinterpreted as **positive energy and negative norm** by swapping $a \leftrightarrow a^\dagger$.

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

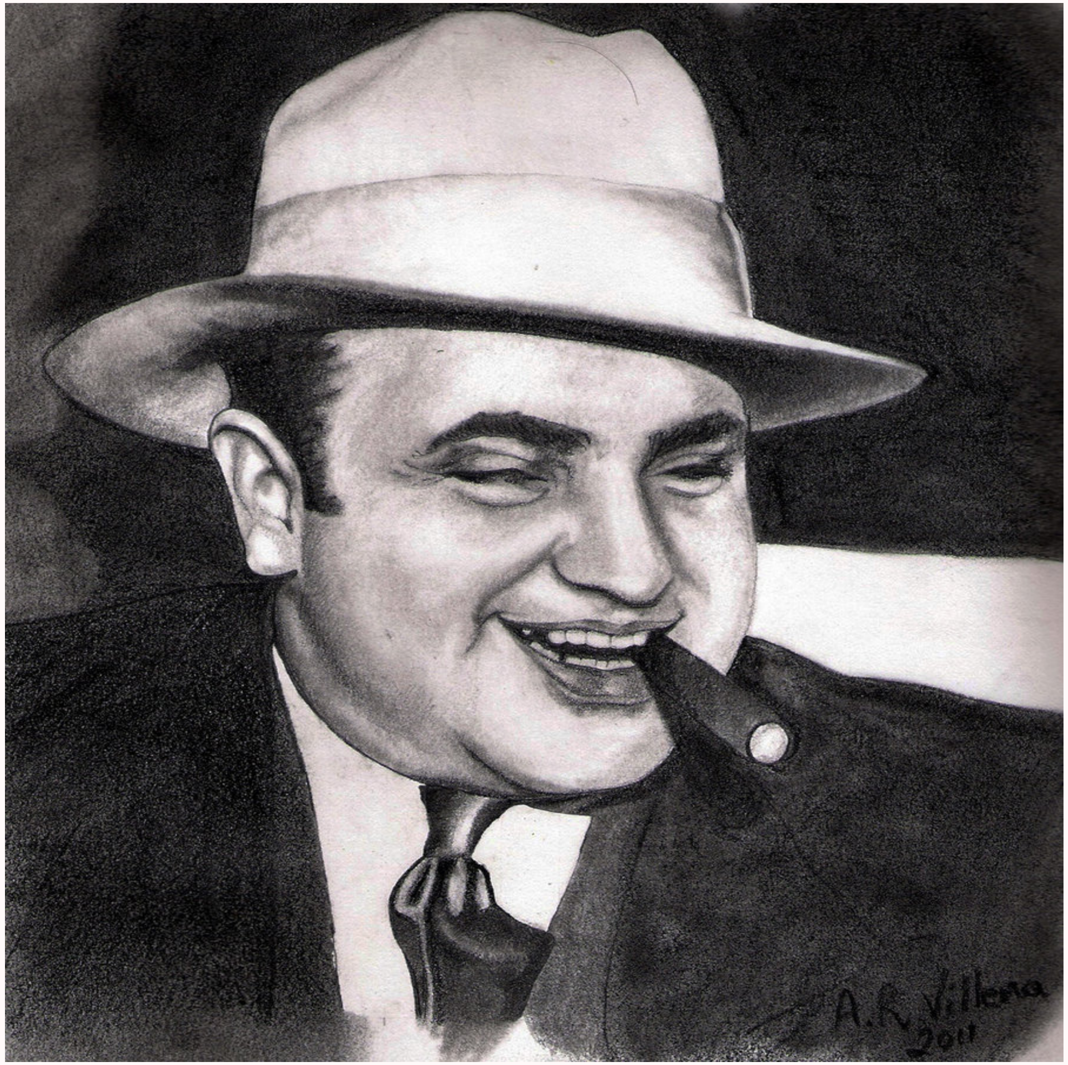
Lee, Wick, Cutkosky... claim that it gives a slightly acausal unitary S matrix.

Anti-particles teach us that sometimes we have the right equations before understanding what they mean. I ignore the ghost issue and compute.

A ghost?



Don't prosecute the ghost



Proceeding in investigations might reveal more conventional problems

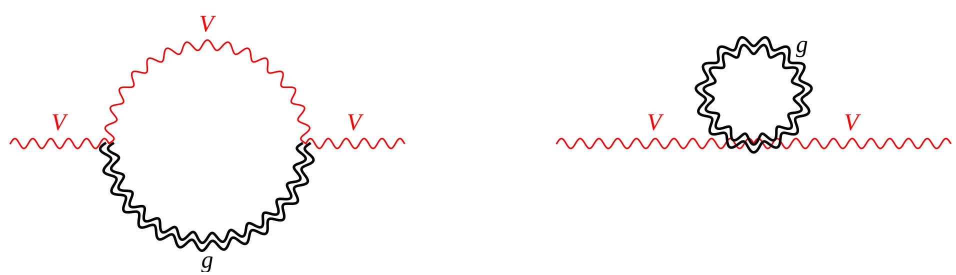
Quantum Agravity...

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.

- 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 $f_0^2 < 0$

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

...Quantum Agravity

- Yukawa couplings get an extra multiplicative RGE correction:

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

- RGE for ξ

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

- Agravity makes quartics small at low energy:

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

- Agravity creates a mixed quartic:

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

Generation of the Planck scale

Some mechanisms can generate dynamically the Planck scale

a) λ_S runs negative below $M_{\rm Pl}$ or b) f_2 or ξ_S 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:

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

The cosmological constant vanishes if

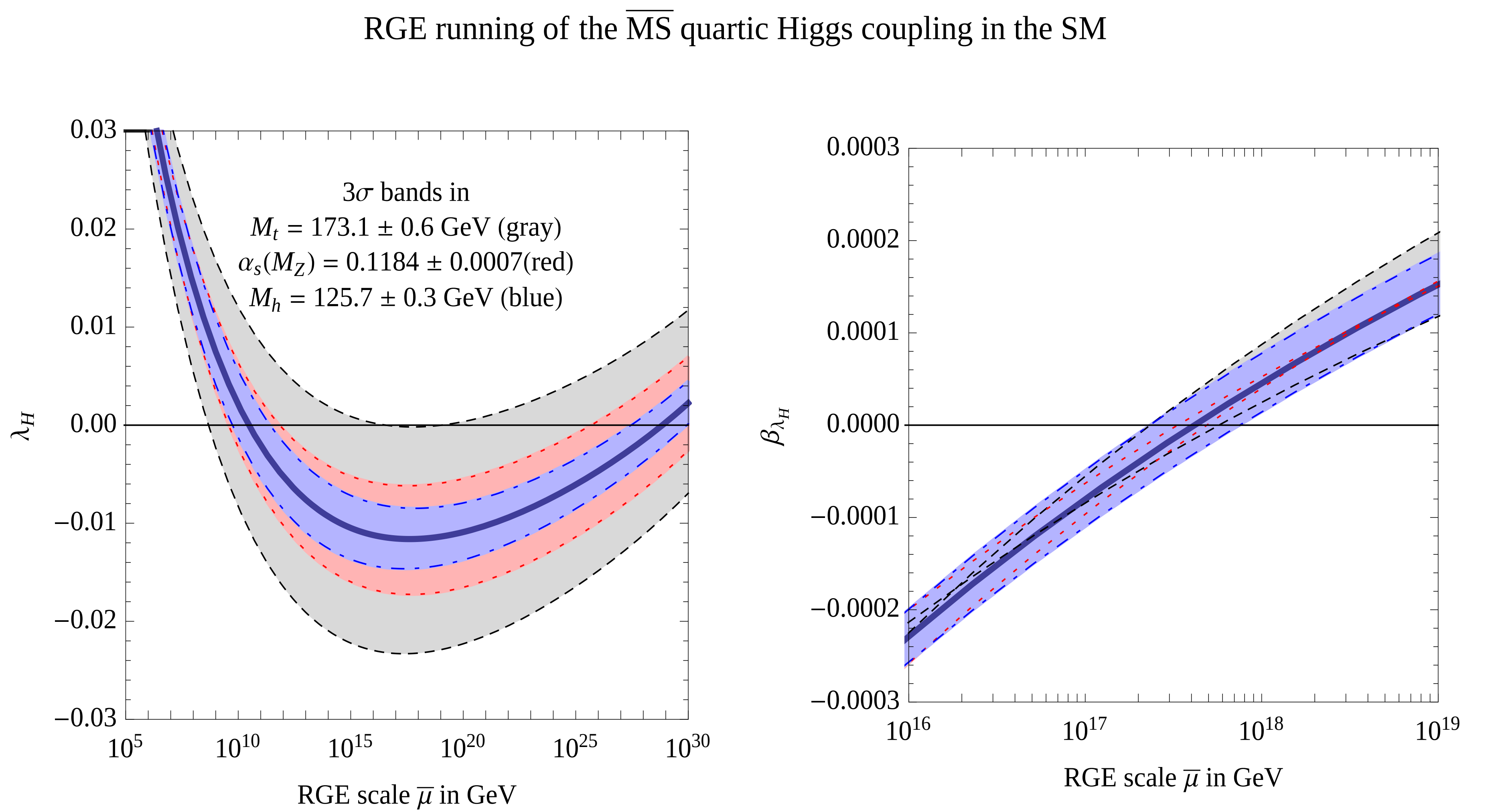
$$\lambda_S(\bar{\mu} \sim \langle S \rangle) = 0$$

Then the minimum simplifies to

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

Is this fine-tuned running possible?

This is how λ_H runs 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 very special theories. Heavy model building engineering is needed to hammer a potential until it is flat enough. BICEP calls 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

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

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 the SM-mirror model $b \approx 1.0/(4\pi)^4$ so $\xi_S \approx 230$ so $\langle s\rangle \approx 1.6\ 10^{17}$ GeV: ok.

(The full potential $V(s,h,\det g_{\mu\nu})$ prefers a different inflationary path).

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

Non-perturbative quantum gravity (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

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

Conclusion: non-perturbative QG corrections $\delta M_h^2 \propto e^{-1/f_{0,2}^2}$ can be neglected.

4) Landau poles

Landau poles

We have the RGE above M_{Pl}, can the theory reach infinite energy?
Problem: Landau poles for g_Y at 10^{43} GeV, possibly λ, y_t, y_b, y_τ?

We address this problem under two questionable assumptions:

- We assume that Landau poles give $\delta M_h^2 \sim M_{\mathrm{Landau}}^2$ and must be avoided.

  Some authors claim that Landau poles do not even exist.

- For the moment we ignore gravity.

  Agravity will change the analysis.

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

FAFfing

This procedure allows to check if any QFT obeys Full Asymptotic Freedom:

1) Get 1-loop RGE, asymptotically approximate

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

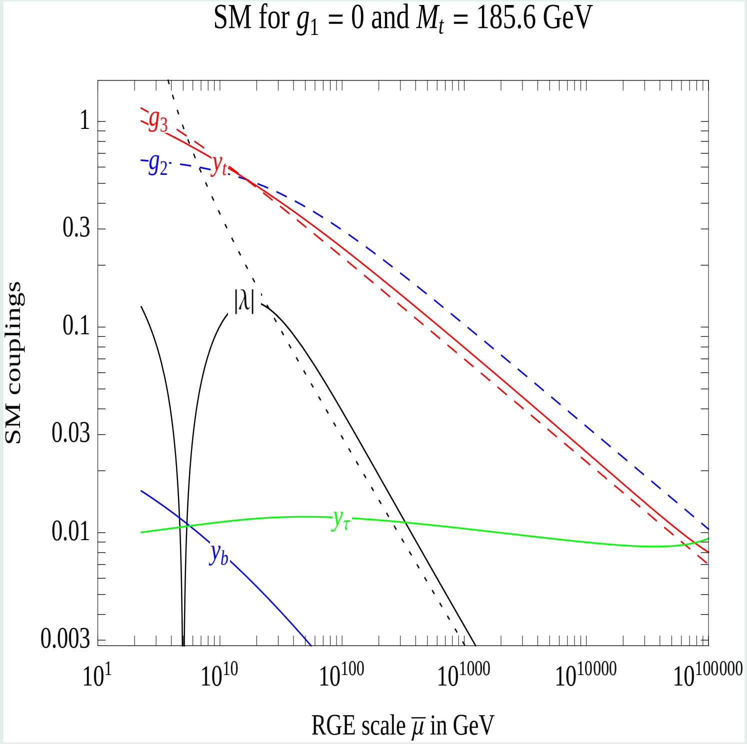
2) Get a system of ordinary equations in c_i.

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: 1) $g_Y = 0$; in this limit 2) $M_t = 185\,\text{GeV}$; 3) $y_\tau = 0$; 4) $M_h < 243\,\text{GeV}$ and $\lambda < 0$ at large energy.

FAF-SM

Can the SM be extended into a theory valid up to infinite energy?
Avoid Landau poles by making hypercharge non abelian.

We found realistic SU(5) FAF models. But GUTs are not compatible with finite naturalness, that demands extensions at the weak scale. Making sense of $Y = T_{3R} + (B-L)/2$ needs $\mathrm{SU}(2)_R$. We found 2 possibilities:

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

Common experimental signals:

- A W_R boson and a Z'_{B-L}: $M_{W_R} > 2\,\mathrm{TeV}$, $M_{Z'_{B-L}} > 1.8_{333}, 3.8_{224}\,\mathrm{TeV}$.

- Higgs $(2_L, \bar{2}_R)$ contains 2 doublets coupled to u and d: new flavour violations controlled by a right-handed CKM matrix. If its mixing angles are equal to (smaller than) the CKM angles one has $M_H > 19\,\mathrm{TeV}$ ($0.8\,\mathrm{TeV}$).

- A light higgs-like state, if G_{FAF} breaks dynamically to G_{SM} one has

$\mathrm{SU}(4)_c \otimes \mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R$

Fermions	Scalars	$\mathrm{SU}(2)_L$	$\mathrm{SU}(2)_R$	$\mathrm{SU}(4)_{\mathrm{PS}}$	$\mathrm{U}(1)_{B'}$
$\psi_L = \begin{pmatrix} \nu'_L, e'_L \\ u_L, d_L \end{pmatrix}$	ϕ_L	$\bar{2}$	1	4	$+1$
$\psi_R = \begin{pmatrix} \nu_R, u_R \\ e_R, d_R \end{pmatrix}$	ϕ_R	1	2	$\bar{4}$	-1
$\psi = \begin{pmatrix} \nu_L, \bar{e}'_L \\ e_L, \bar{\nu}'_L \end{pmatrix}$	ϕ	2	$\bar{2}$	1	0

No extra chiral fermions. Flavor can survive to lepto-quark vectors. Yukawas

$$-\mathscr{L}_Y = Y_N\,\psi_L\psi\phi_R + Y_L\,\psi\psi_R\phi_L + Y_U\psi_R\psi_L\phi + Y_D\,\psi_R\psi_L\phi^c$$

admit FAF solution, but no FAF solution for the 24 quartics. A 2 generation FAF model [Kalashnikov, 1977, CCCP] cannot be extended to 3 generations.

$\mathrm{SU}(3)_c \otimes \mathrm{SU}(3)_L \otimes \mathrm{SU}(3)_R$

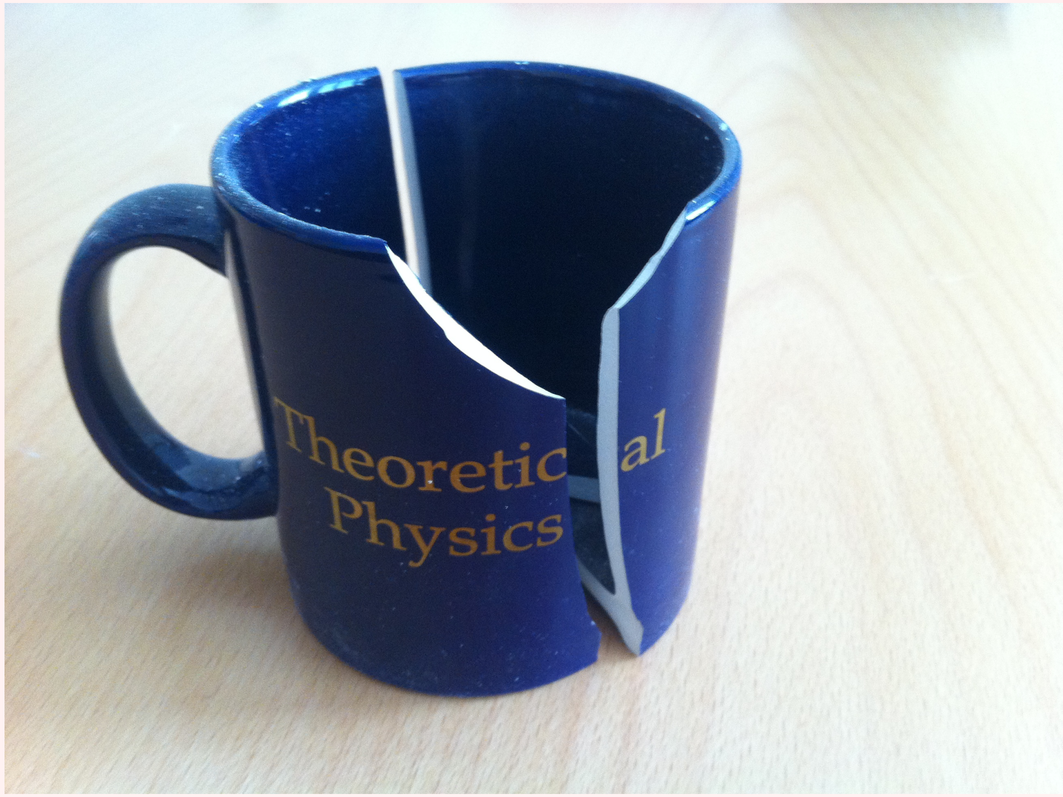
Matter fields	spin	$\mathrm{SU}(3)_L$	$\mathrm{SU}(3)_R$	$\mathrm{SU}(3)_c$
$Q_R = \begin{pmatrix} u_R^1 & u_R^2 & u_R^3 \\ d_R^1 & d_R^2 & d_R^3 \\ d'^1_R & d'^2_R & d'^3_R \end{pmatrix}$	1/2	1	3	$\bar{3}$
$Q_L = \begin{pmatrix} u_L^1 & d_L^1 & \bar{d}'^1_R \\ u_L^2 & d_L^2 & \bar{d}'^1_R \\ u_L^3 & d_L^3 & \bar{d}'^3_R \end{pmatrix}$	1/2	$\bar{3}$	1	3
$L = \begin{pmatrix} \bar{\nu}'_L & e'_L & e_L \\ \bar{e}'_L & \nu'_L & \nu_L \\ e_R & \nu_R & \nu' \end{pmatrix}$	1/2	3	$\bar{3}$	1
H_1, H_2	0	3	$\bar{3}$	1

No bad vectors, but extra fermions chiral under $\mathrm{SU}(3)^3$. Yukawas

$$-\mathscr{L}_Y = \sum_{i=1}^{2} (y_Q^i \; Q_L Q_R H_i + \frac{y_L^i}{2} L L H_i^*)$$

admit FAF solution. For $1H$: 2 quartics, FAF solutions. But $2H$ are needed: 20 quartics, no FAF solutions, FAF demands conservation of baryon number.

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 SUSY multiverse of branes wrapped on compactified 6 or 7 extra dimensions.