One Extra Complex Singlet = Stability + DM + Inflaton

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2 Motivation

- LHC has so far discovered nothing but the Brout-Englert-Higgs boson
- No sight of SUSY or other new physics

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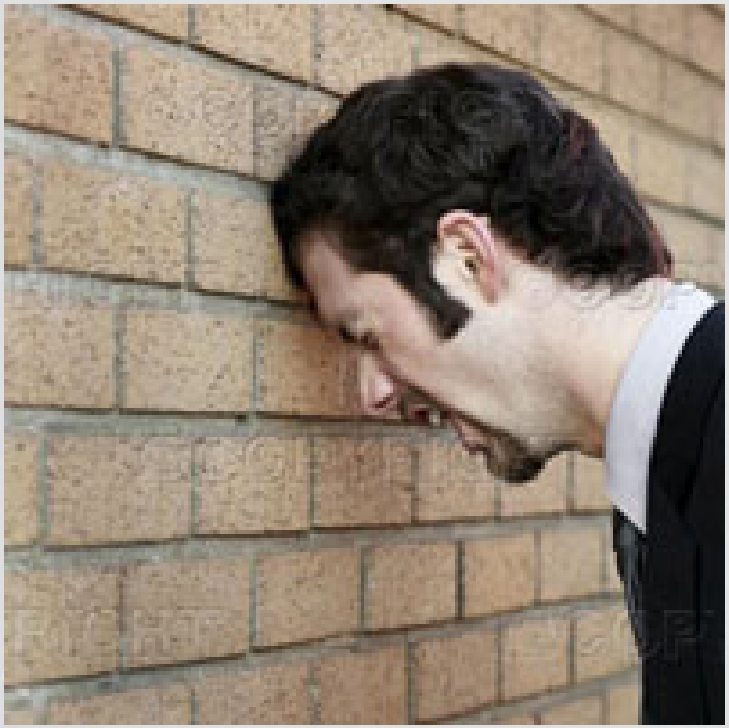
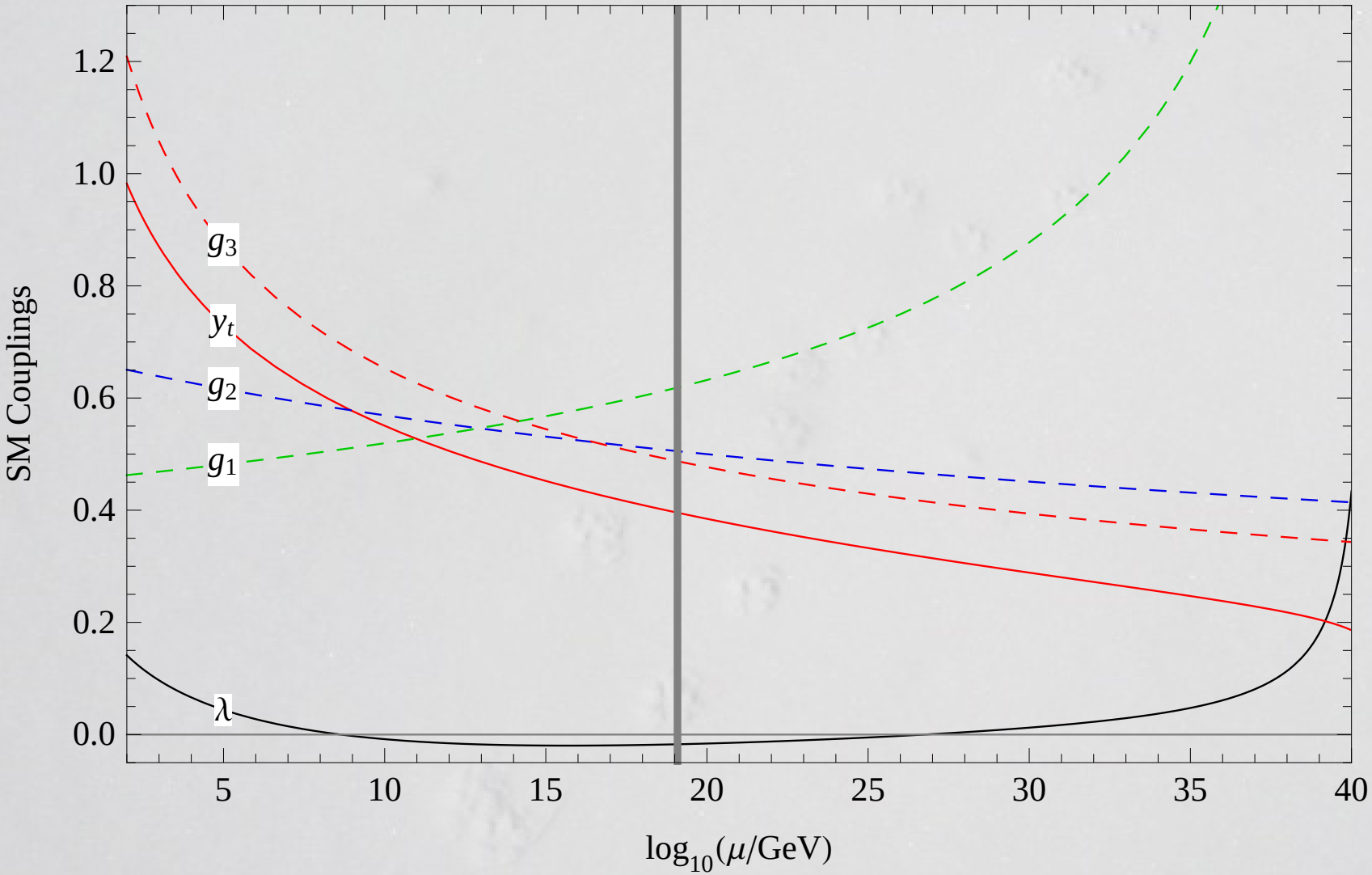


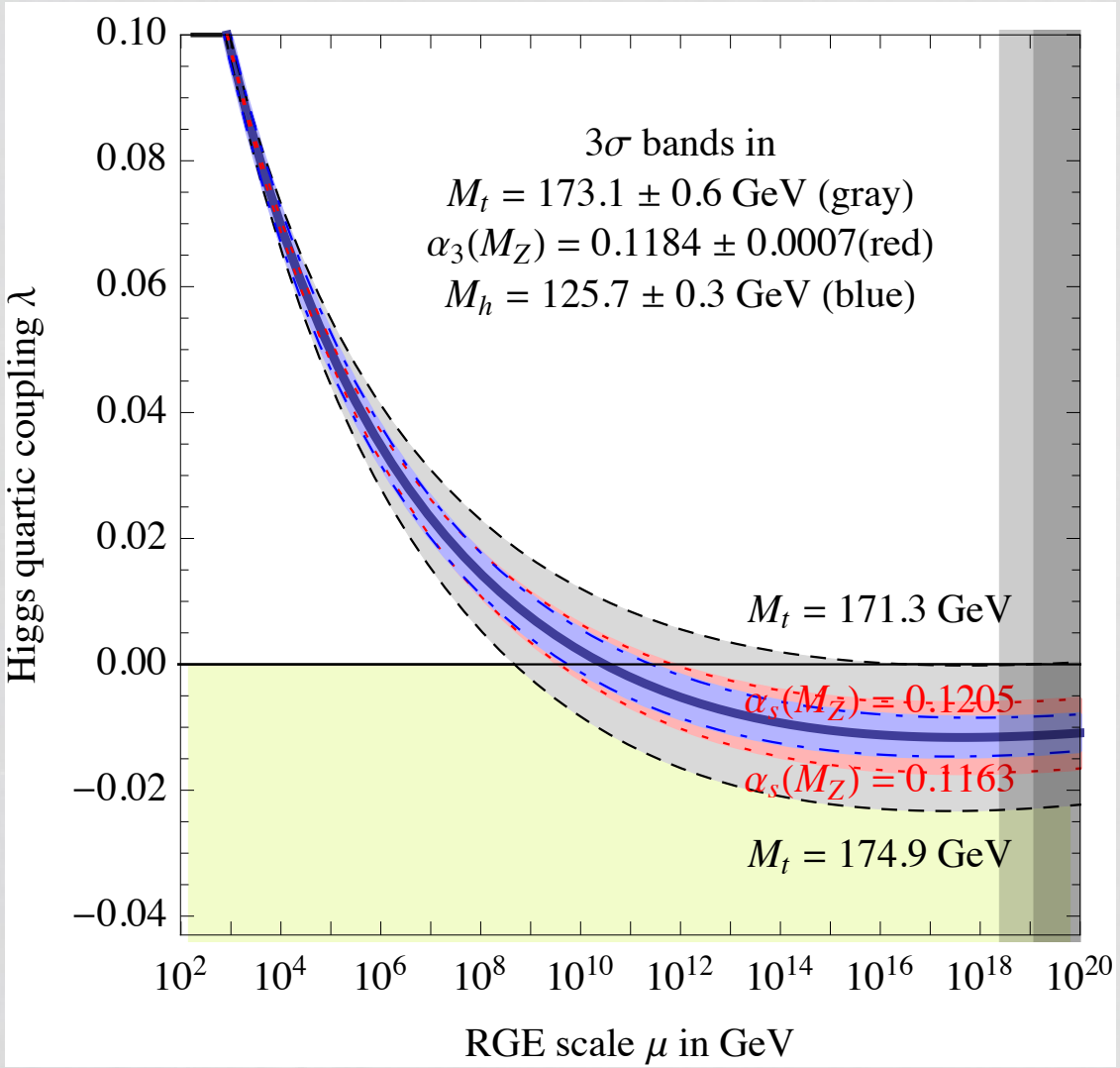
3 Motivation

- SM scalar potential is at best metastable
- Beyond the SM: dark matter & inflation, baryogenesis
- Hierarchy problem: $M_h, v \ll M_P$

4 Running of Standard Model Couplings

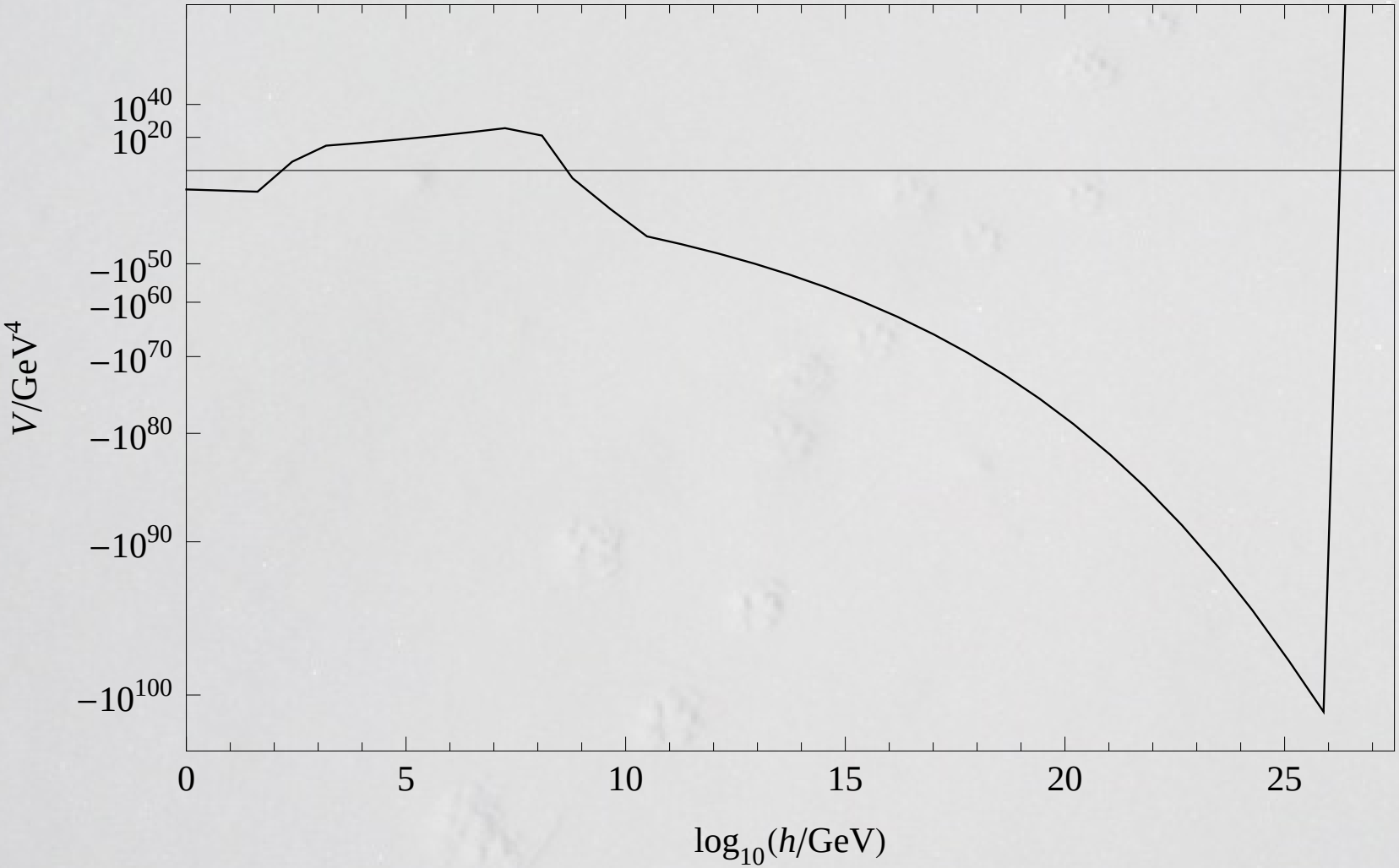


5 Running of BEH λ in SM



Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia, 2013

Standard Model Scalar Potential



7 Standard Model

- SM could be valid up to the $U(1)_Y$ Landau pole at 10^{40} GeV
- Why should we be living at the EW scale, not in the $h = 10^{26}$ GeV minimum?

Motivation

We want to build a minimal extension of SM that takes care of vacuum stability, known new physics *&* can alleviate the hierarchy problem

Classical Scale Invariance

- Only dimensionless couplings in the Lagrangian
- Quartic couplings in the scalar potential
- Broken by *logarithmically* running couplings
- Use a renormalisation scheme that respects classical scale invariance: dimensional reduction Bardeen, 1995

Standard Model

- The only dimensional term in the SM is the Higgs mass term:

$$V_H = \mu^2 |H|^2 + \lambda |H|^4$$

Recipe for Dimensionful Terms

- Introduce a scalar S with $\lambda_{SH}|S|^2|H|^2$
- λ_S runs negative and generates $\langle S \rangle$ at a scale $\langle S \rangle \ll M_P$ since $V(S) = \lambda_S(\mu \approx S)|S|^4$
- Mass term for H is generated as

$$\mu^2 = \lambda_{SH}|\langle S \rangle|^2$$

Coleman & Weinberg, 1973; Hempfling, 1996; Meissner & Nicolai, 2007; Hambye & Strumia, 2013; Khoze, 2013, and others

Hierarchy problem?

- No new high scales, no new particles
- Gravity is different: M_P does not matter!(?)

Asymptotic safety: Weinberg, 1979, Niedermaier & Reuter, 2006; Niedermaier, 2007; Percacci, 2009; Litim, 2008

Agravity: Salvio & Strumia, 2014

Extending the SM

- Add a complex singlet $S = s_R + i s_I$

Most general classically scale invariant potential invariant under $S \to S^\dagger$,

$$V = \lambda_H |H|^4 + \lambda_S |S|^4 + \frac{\lambda'_S}{2}\left[S^4 + (S^\dagger)^4\right] + \frac{\lambda''_S}{2}|S|^2\left[S^2 + (S^\dagger)^2\right]$$
$$+ \lambda_{SH}|S|^2|H|^2 + \frac{\lambda'_{SH}}{2}|H|^2\left[S^2 + (S^\dagger)^2\right]$$

13 Extending the SM

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In the basis of real fields,

$$V = \frac{1}{4}\lambda_H h^4 + \frac{1}{4}\lambda_I s_I^4 + \frac{1}{4}\lambda_{RI} s_I^2 s_R^2 + \frac{1}{4}\lambda_R s_R^4 + \frac{1}{4}\lambda_{RH} h^2 s_R^2 + \frac{1}{4}\lambda_{IH} h^2 s_I^2$$

Extending the SM

- The VEV of s_R induces EWSB

$$\lambda_R = \beta_{\lambda_R} \ln \frac{|s_R|}{s_0} \qquad \text{Hambye \& Strumia, 2013}$$

$$v = v_R \sqrt{\frac{|\lambda_{RH}|}{2\lambda_H}}, \qquad v_R \simeq s_0 e^{-1/4}$$

for tiny $\lambda_{RH} < 0$

$$m_h^2 \simeq v^2 \left(2\lambda_H - \frac{\lambda_{RH}^2}{\beta_{\lambda_R}} \right)$$

$$m_s^2 \simeq v^2 \left(\frac{2\beta_{\lambda_R}\lambda_H}{|\lambda_{RH}|} + \frac{\lambda_{RH}^2}{\beta_{\lambda_R}} \right)$$

$$m_A^2 \simeq v^2 \left(\frac{\lambda_H \lambda_{RI}}{|\lambda_{RH}|} + \frac{\lambda_{IH}}{2} \right)$$

Extending the SM

- The VEV of s_R induces EWSB
- s_I as DM remains stable due to CP

Curing the Potential Instability

- Threshold correction from integrating out a scalar

  Elias-Miró, Espinosa, Giudice, Lee, Strumia, 2012; Lebedev, 2012

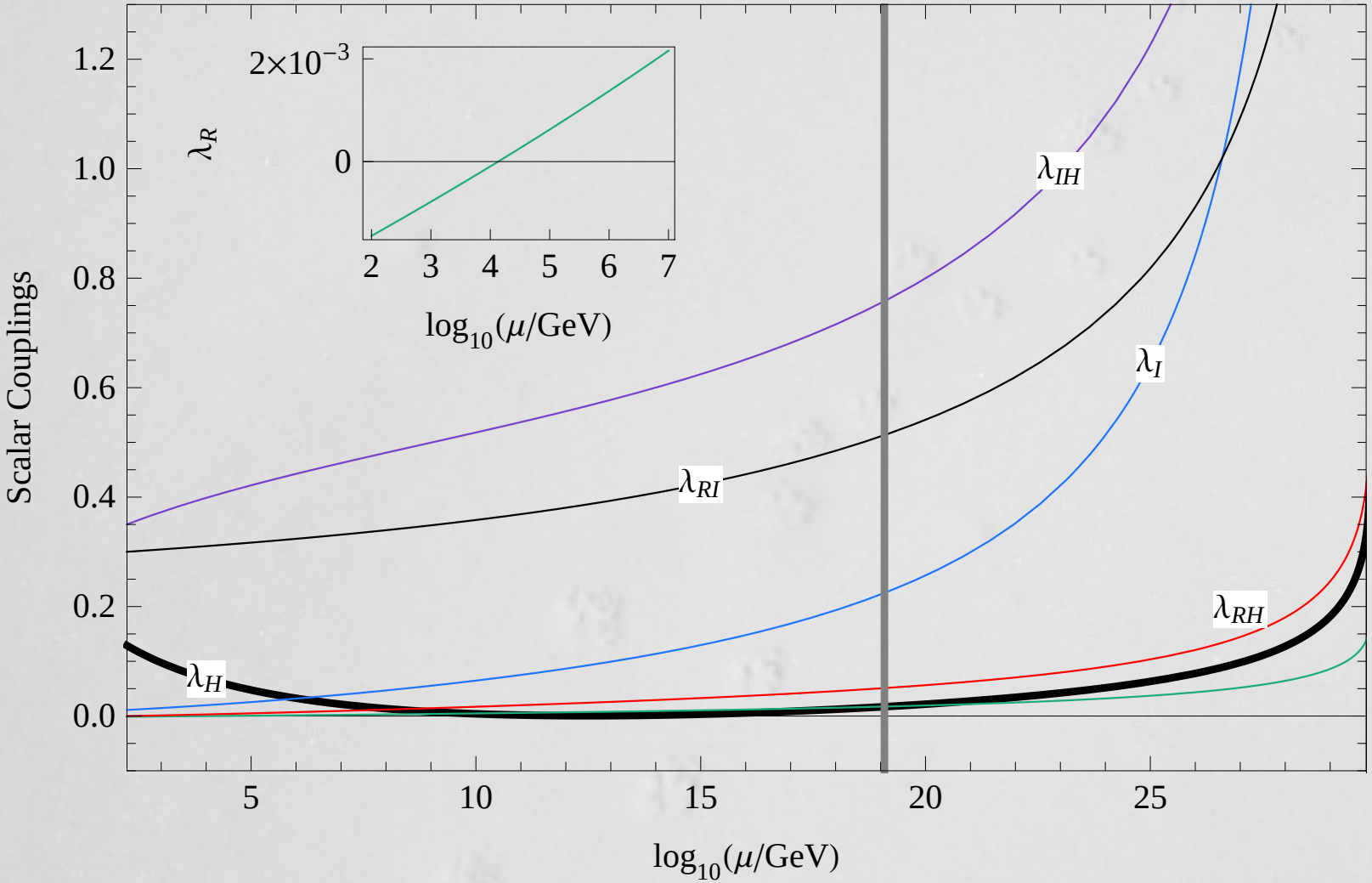
- Higgs portal contribution to running of λ:

$$\Delta\beta_\lambda \propto \lambda_{HS}^2$$

Extended SM Running Couplings

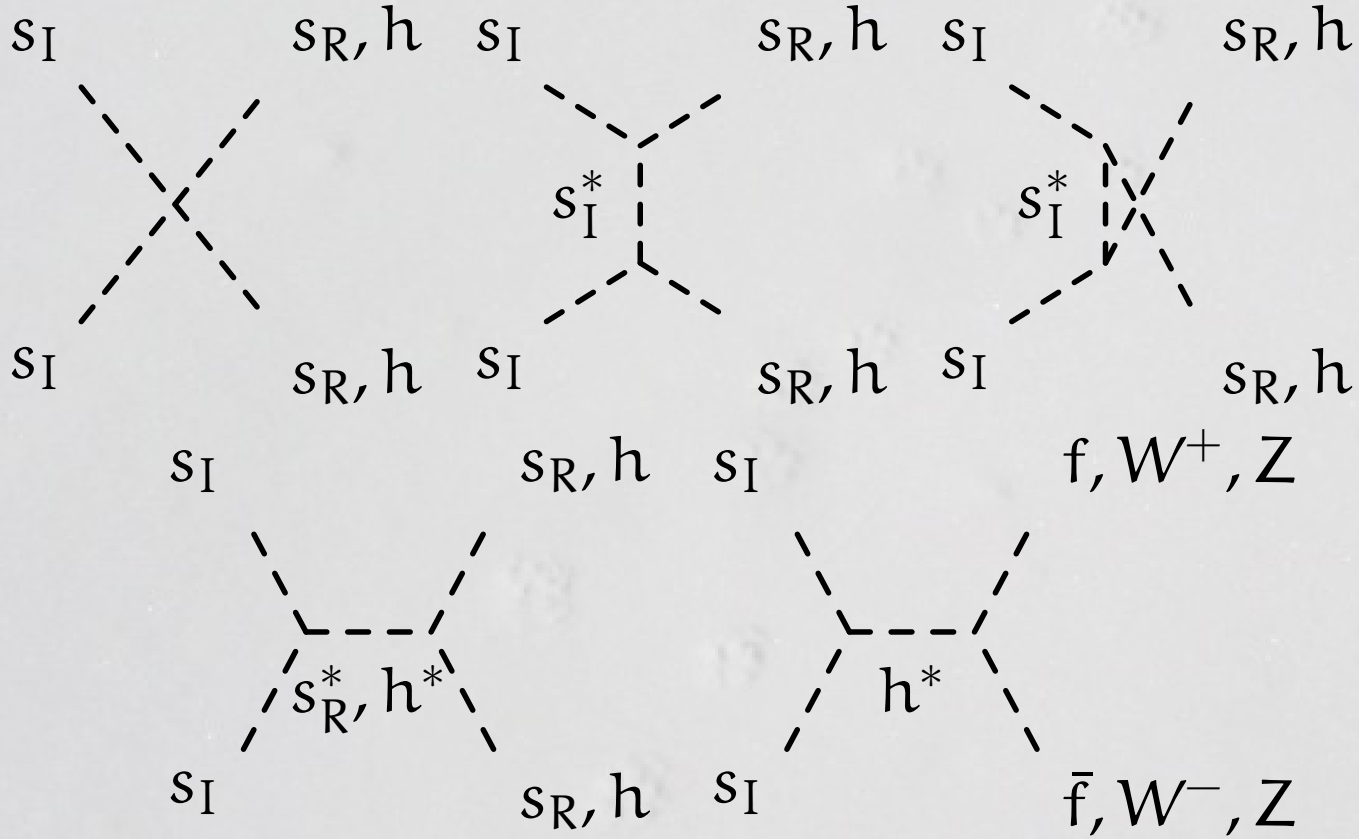
- Need $\lambda_{IH} > 0.35$ to cure the instability
- If $\lambda_{IH} > 0.60$, the Landau pole is below M_P
- To obtain s_0 in the range $s_0 \lesssim 10^5$ GeV, $\lambda_{RI} \gtrsim 0.3$ if $\lambda_R \sim -10^{-3}$ at the EW scale
- Another reason why a *complex* singlet is needed: $16\pi^2 \beta_{\lambda_R} \approx \frac{1}{2}\lambda_{RI}^2$

Running of Couplings in SM + S

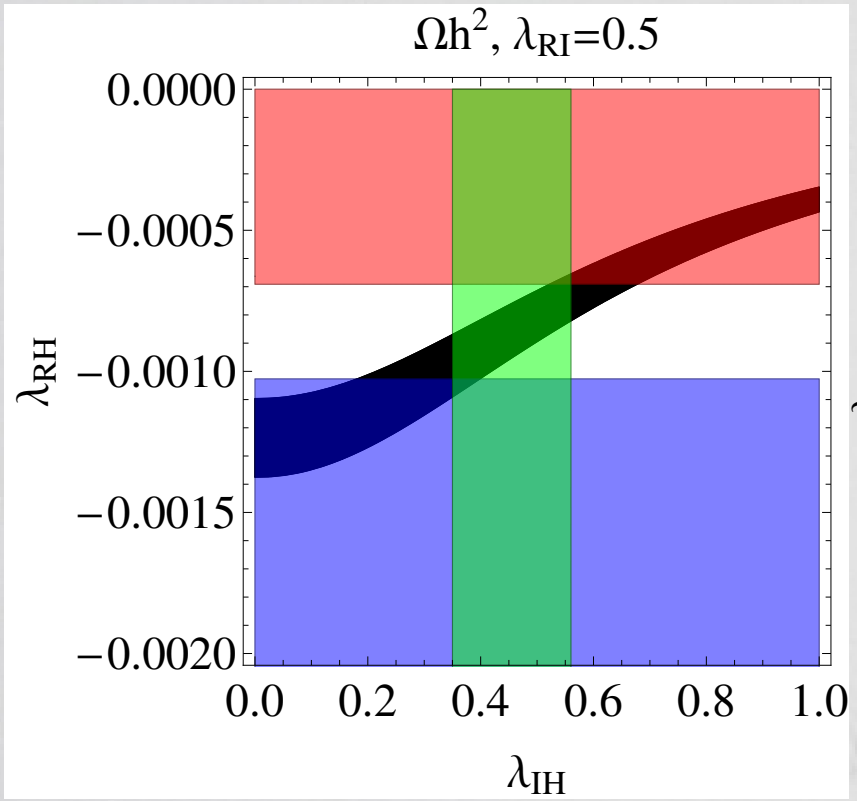


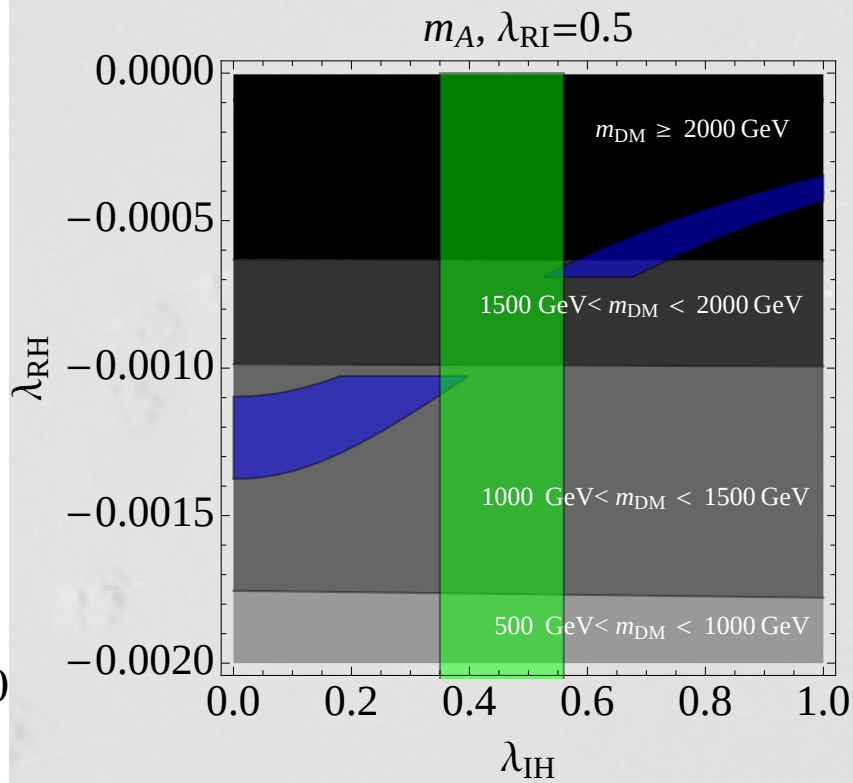
$$\text{At } m_t = 173.1 \text{ GeV}, \lambda_{RI} = 0.3, \lambda_R = -1.2 \times 10^{-3},$$
$$\lambda_{IH} = 0.35, \lambda_I = 0.01, \lambda_{RH} = -10^{-4}, \lambda_H = 0.12879$$

Freeze-Out: Annihilation Diagrams

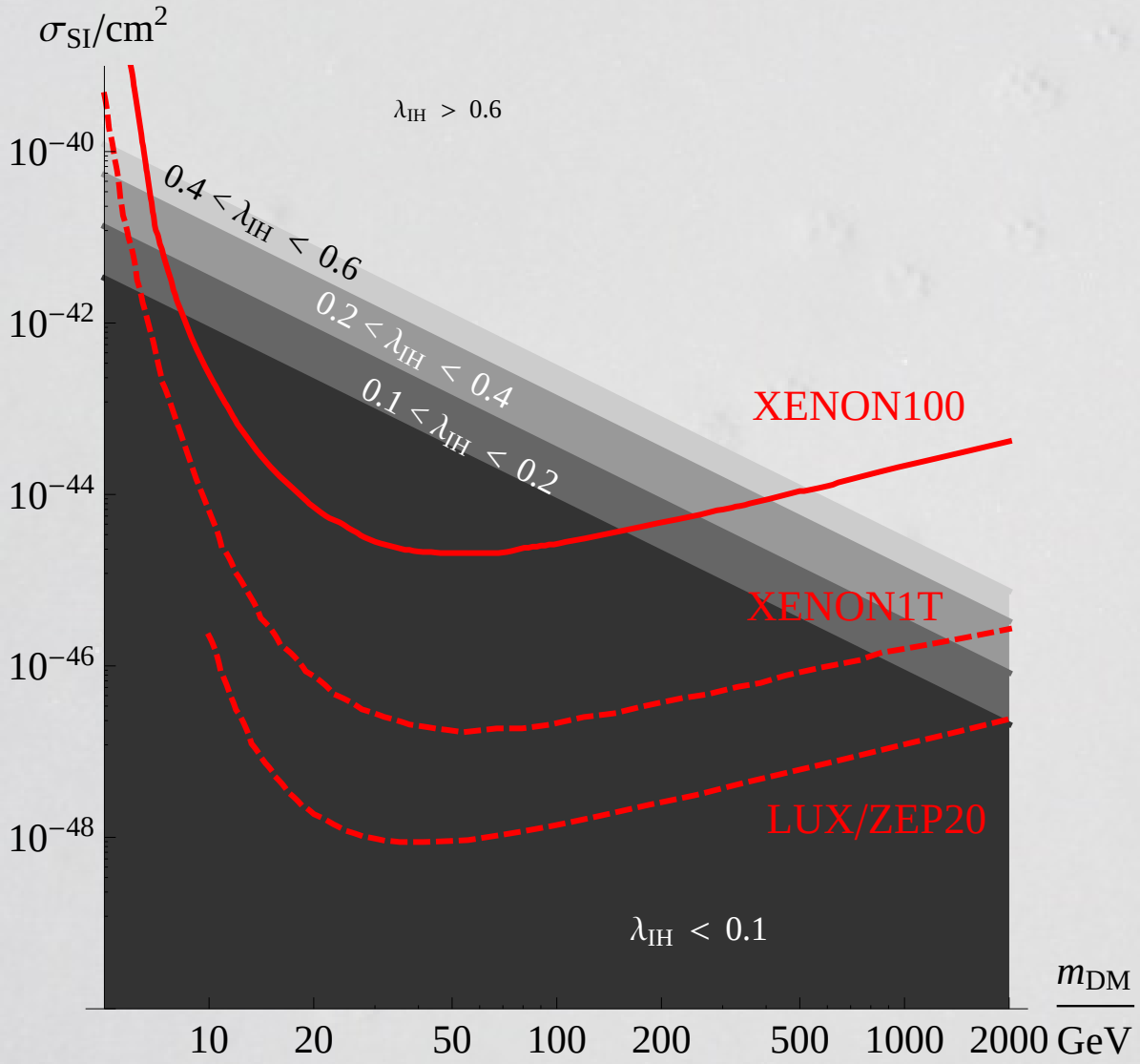


Relic Density





Direct Detection



Inflation

- Chaotic ϕ^4 inflation
- Possible with fine-tuned couplings, $\lambda_R \lesssim 10^{-13}$
- Fixed point at $\lambda_R = \lambda_{RH} = \lambda_{RI} = 0$

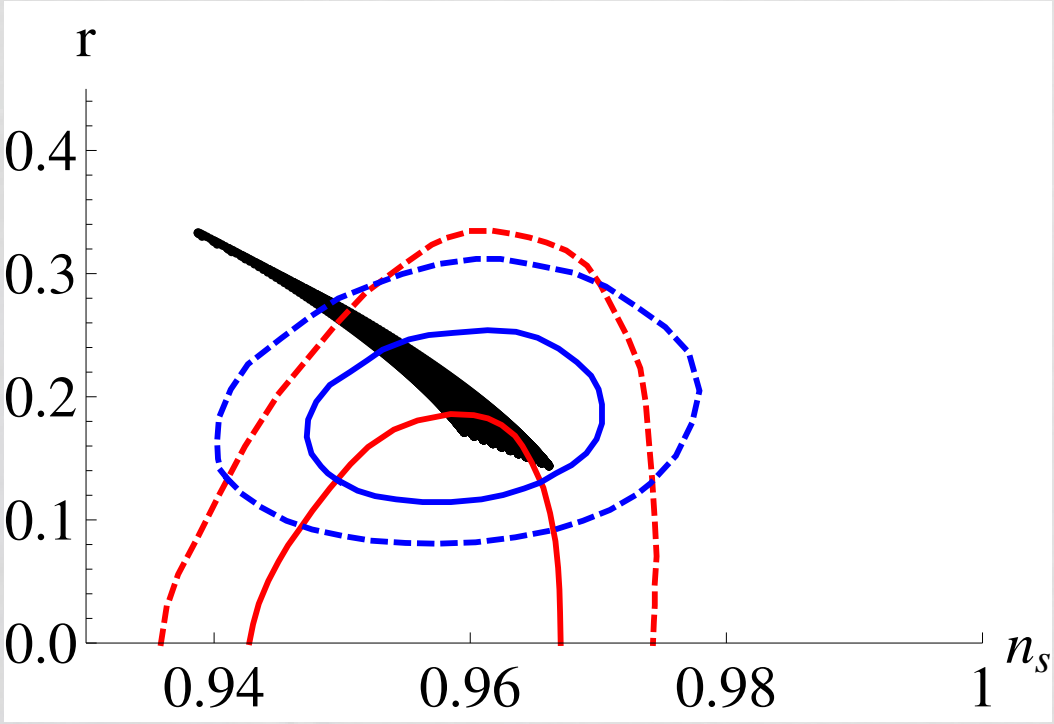


Figure courtesy A. Racioppi

Conclusions

- Classically scale-invariant models may alleviate the hierarchy problem
- SM + S could be valid on *all* scales
- Higgs portal to new physics

A complex singlet can:

- dynamically induce EWSB
- provide a DM candidate
- provide the inflaton

- Loose ends: quantum gravity & Planck scale, Landau poles