Crunching Naturalness

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Naturalness Problem

- Naturalness - potential problem in the UV completions of the SM.
- Direct UV completions of the SM will only be compatible with observations if unnatural connections between different parameters exist.
- The UV completions are necessary - GUT, Planck.
- This property gets worse as the departure from SM occurs at higher energy scales.

Natural Models

- Models where the Higgs mass is predicted to be small at the ground state of the theory - SUSY, Composite Higgs. **Ground state naturalness**

- Models where the Higgs mass is large at the ground state, but small at the current metastable state - Anthropics, relaxion. **Metastable naturalness**

Current Status

- No top partners at the LHC - in tension with ground state naturalness
- Anthropics - no bulletproof argument for the Higgs (unlike the CC)
- Many new ideas for metastable naturalness:
  - Relaxion (Graham, Kaplan, Rajendran 15')
  - Inflating to the Weak Scale (Hochberg,Geller,Kuflik 19')
  - Self Organized Localization (Giudice, McCullough,You 21' , see also Gian's talk!)
  - Selfish Higgs (Giudice, Kehagias, Riotto, 19')

Our Idea

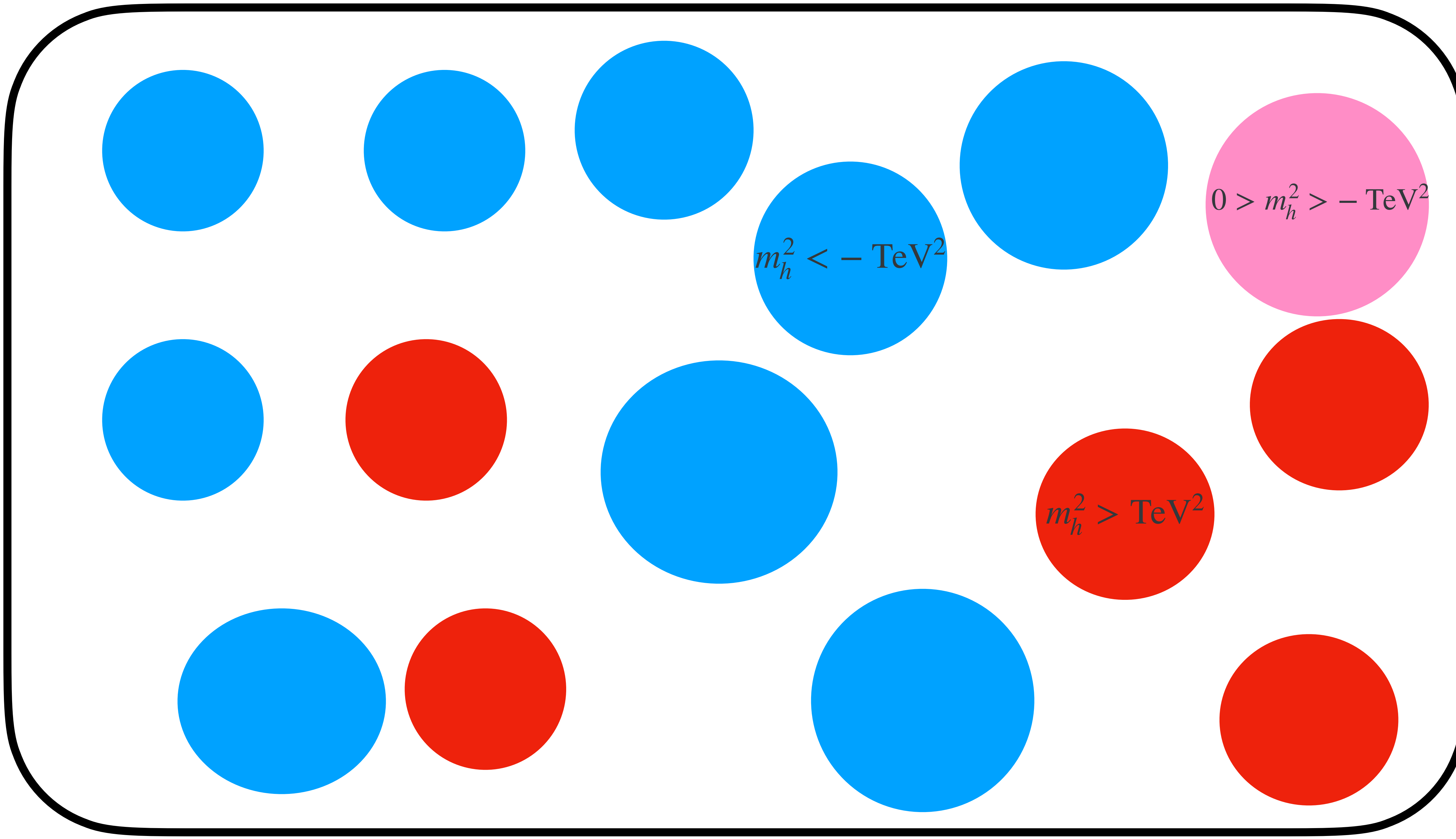
- The Higgs mass is multivalued in the landscape

- Having a Higgs mass above EW will destabilize and destroy the local patch very early on.

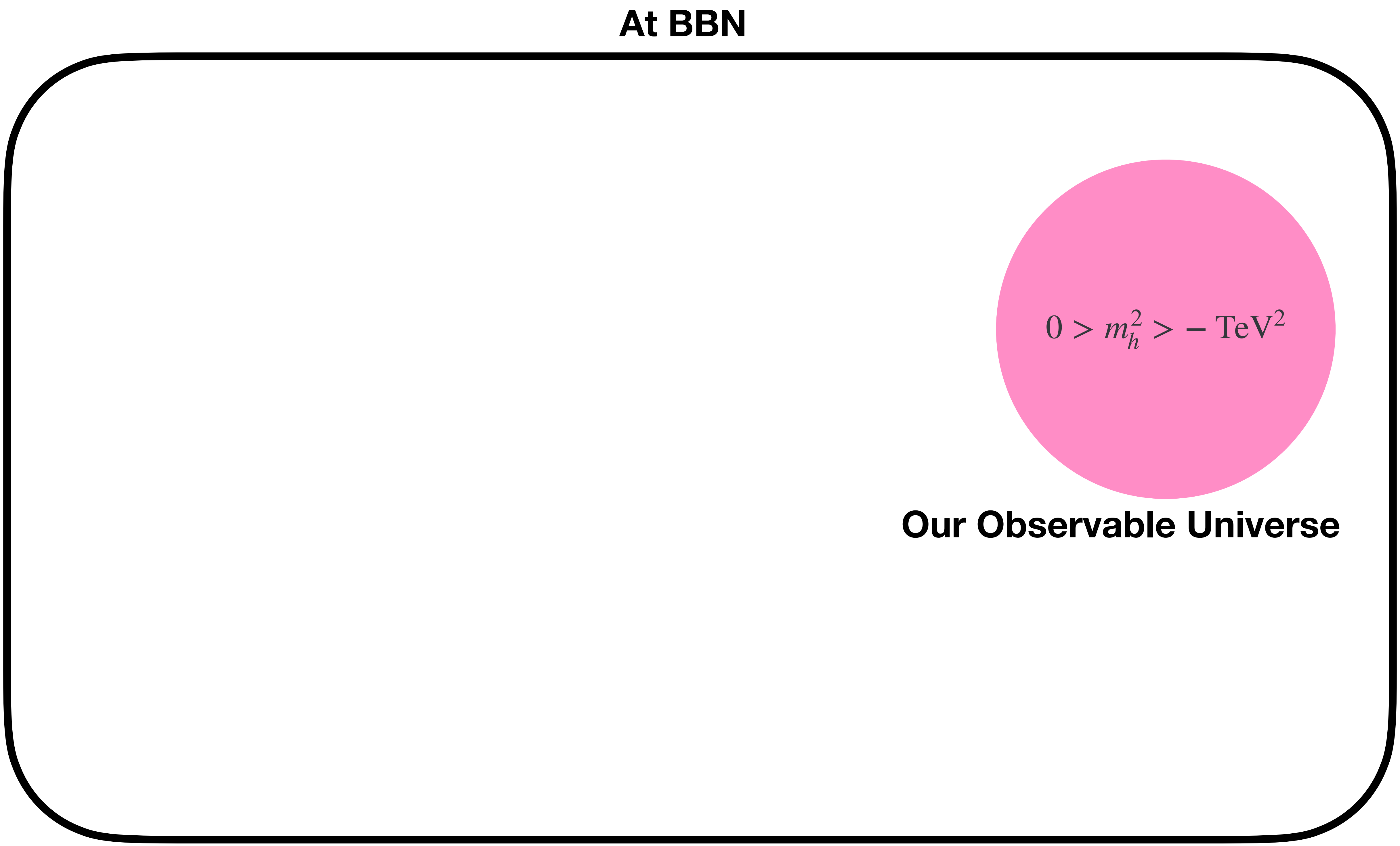
- The universe is expanding (and not crunching) only when the Higgs mass is EW or less

See also D'Agnolo, Teresi 21'

Early Universe(s) History

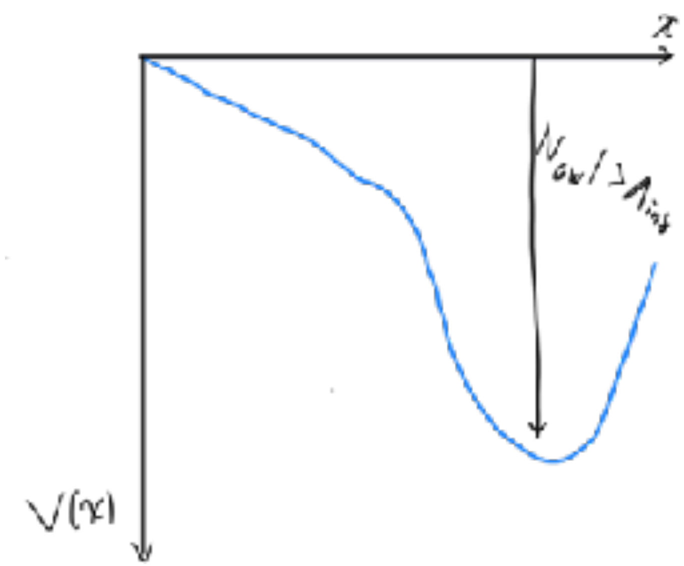


Early Universe(s) History



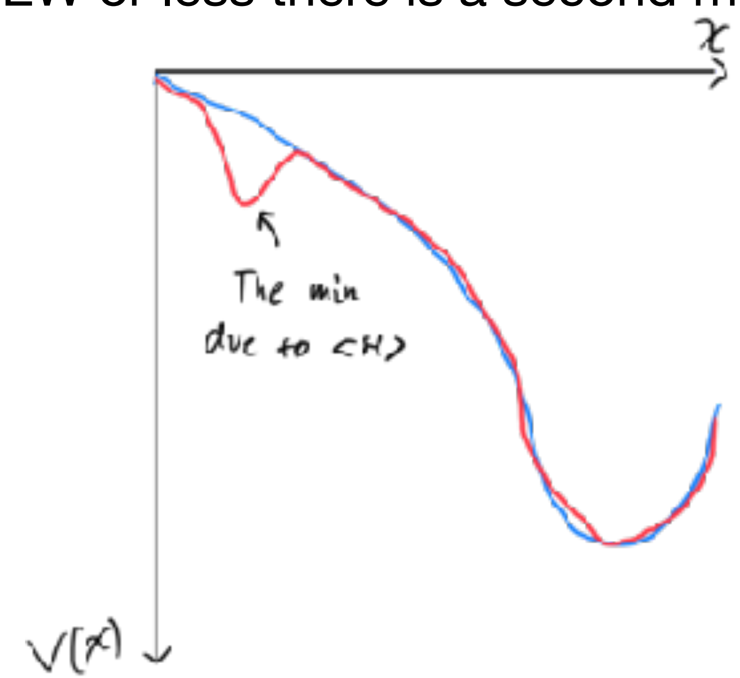
The Mechanism

- The Higgs is coupled to a CFT whose “techni-quarks” carry SU(2) charges. The dilaton has a deep and negative minimum.



- If the Higgs VEV is zero or too large, this is the only minimum.

- If the Higgs VEV is EW or less there is a second minimum very close to the origin



Reminder: Goldberger-Wise

- GW scalar in the bulk

$z = R$

$z = R'$

The position of the IR brane: dilaton

$$ds^2 = \frac{R^2}{z^2}\left(dx^\mu dx_\mu - dz^2\right)$$

$$\varphi_{GW}$$

$$\chi \sim \frac{1}{R'}$$

$$\frac{m_\varphi^2}{k^2} = \delta$$

$k = 1/R$ **(AdS radius)**

Integrating out the bulk we get terms:

$$\chi^4, \chi^{4+\delta}$$

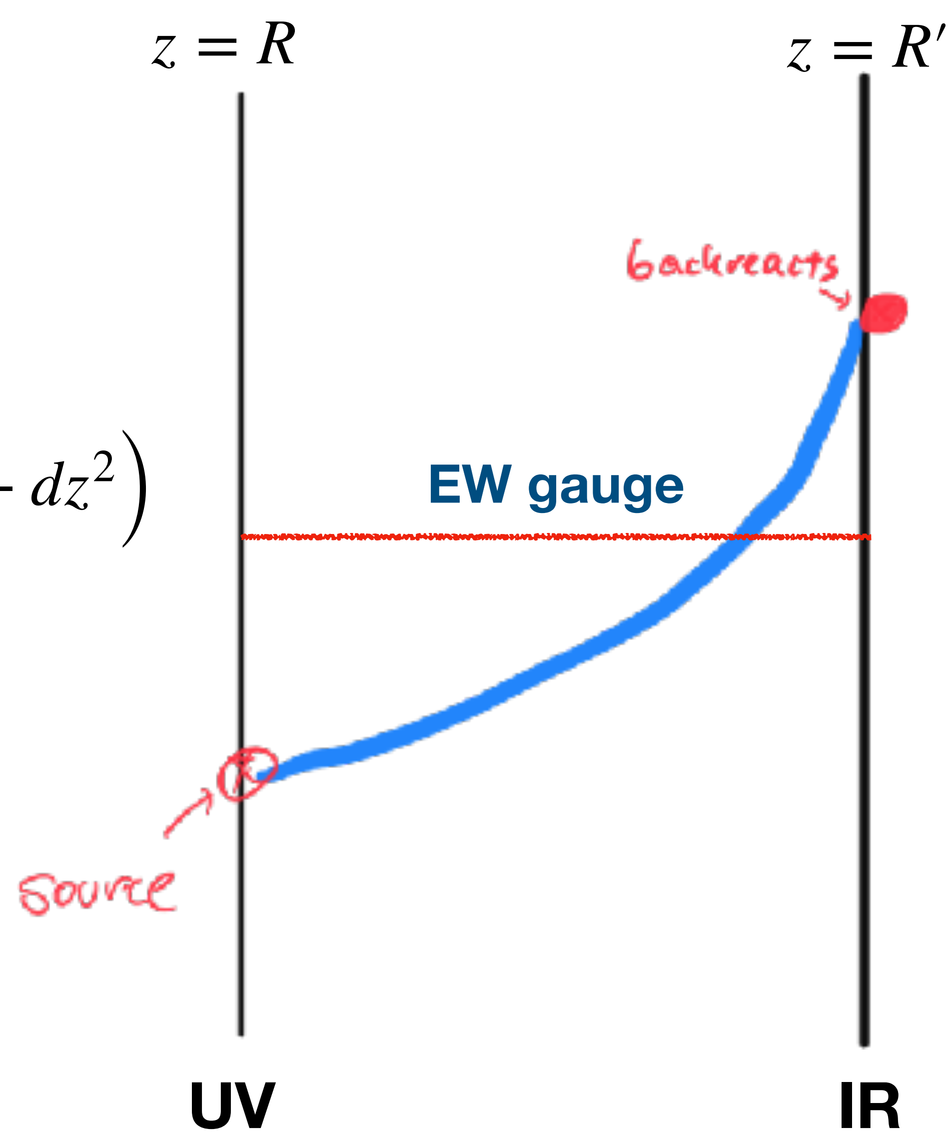
UV

IR

The CFT/RS model

- In our RS model the Higgs and the EW gauge bosons are also in the bulk.

$$ds^2 = \frac{R^2}{z^2}\left(dx^\mu dx_\mu - dz^2\right)$$



The position of the IR brane: dilaton

$$\chi \sim \frac{1}{R'}$$

Generates Terms

$|H|^2\chi^{2+\alpha}$ $\quad |H|^4\chi^{2\alpha}$ $\quad |H|^2\chi^{2+\alpha+\epsilon}$

(from coupling to the GW or a similar marginal scalar)

The CFT interpretation

- A CFT which is charged under SU(2). Turn on two operators:
  - singlet $\mathcal{O}_\epsilon$ of dimension $4-\epsilon$
  - doublet $\mathcal{O}_H$ of dimension $3+\alpha/2$.
- We couple the doublet operator to the Higgs in the UV:

$$\tilde{\lambda}_H \mathcal{O}_H^\dagger H + \tilde{\lambda}_\epsilon \mathcal{O}_\epsilon$$

- In the IR, we get the effective potential:

$$V_{eff} = a_0\chi^4 + a_1\tilde{\lambda}_H^2 H^2\chi^{2+\alpha} + a_2\tilde{\lambda}_H^4 H^4\chi^{2\alpha} + a_3\tilde{\lambda}_\epsilon\chi^{4+\epsilon} + a_4\tilde{\lambda}_\epsilon\tilde{\lambda}_H^2 H^2\chi^{2+\alpha+\epsilon} + \ldots$$

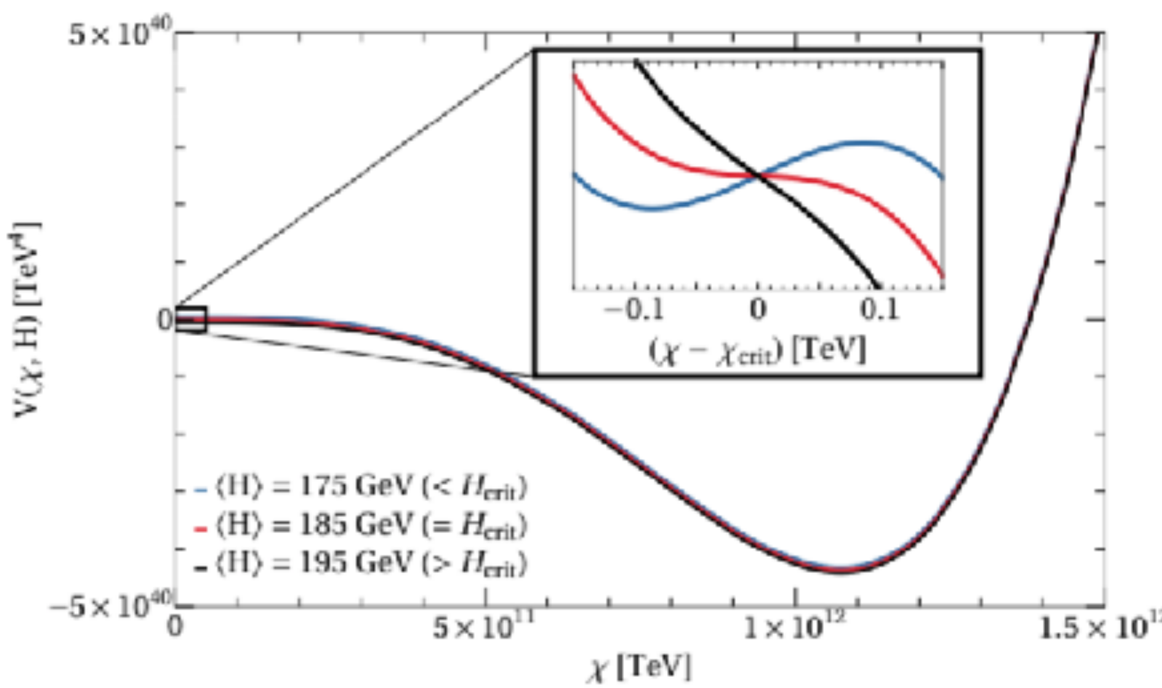
The potential

- The full potential:

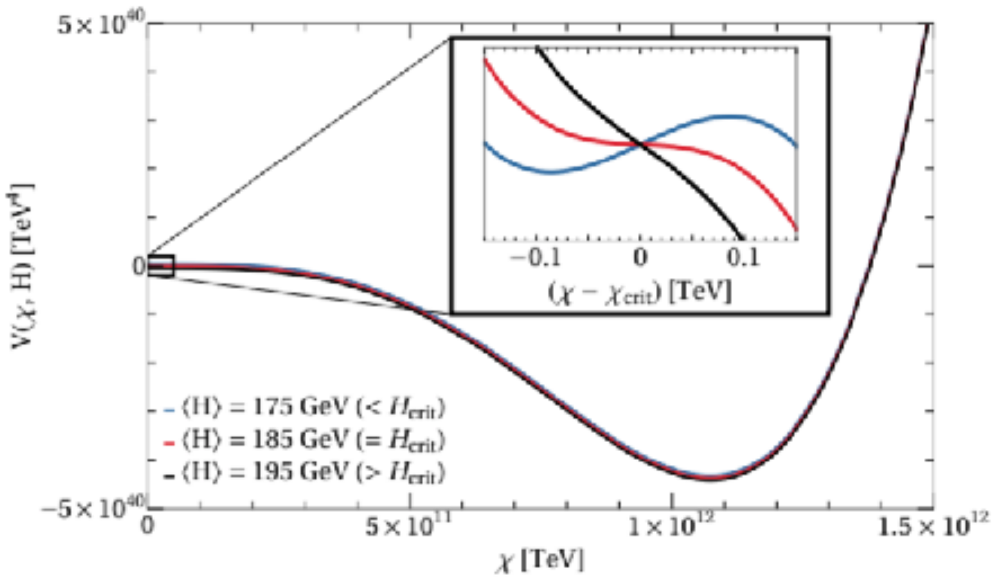
$$V(\chi, H) = V_{\rm GW}(\chi) + V_{H\chi}(\chi, H) + V_H(H)$$

$$V_{\rm GW}(\chi) = -\lambda\chi^4 + \lambda_{\rm GW}\frac{\chi^{4+\delta}}{k^\delta} \qquad V_{H\chi}(\chi, H) = \lambda_2|H|^2\frac{\chi^{2+\alpha}}{k^\alpha} - \lambda_{H\epsilon}|H|^2\frac{\chi^{2+\alpha+\epsilon}}{k^{\alpha+\epsilon}} - \lambda_4|H|^4\frac{\chi^{2\alpha}}{k^{2\alpha}}$$

- There is a maximal value of h for which a minimum exists



The potential



$$V_{H\chi}(\chi, H) = \lambda_2 |H|^2 \frac{\chi^{2+\alpha}}{k^{\alpha}} - \lambda_{H\epsilon} |H|^2 \frac{\chi^{2+\alpha+\epsilon}}{k^{\alpha+\epsilon}} - \lambda_4 |H|^4 \frac{\chi^{2\alpha}}{k^{2\alpha}}$$

- The critical value:

$$h_{crit} = k \left(\frac{\lambda_2}{\lambda_{H\epsilon}} \frac{4 - \alpha^2}{(2+\epsilon)^2 - \alpha^2} \right)^{\frac{1-\alpha/2}{\epsilon}} \sqrt{\frac{\lambda_2}{\lambda_4} \frac{\epsilon(2+\alpha)}{2\alpha(2-\alpha+\epsilon)}} \sim k \left(\frac{\lambda_2}{\lambda_{H\epsilon}} \right)^{1/\epsilon}$$

- The inflection point $\chi_{\rm crit} = k \left(\frac{\lambda_2}{\lambda_{H\epsilon}} \frac{4-\alpha^2}{(2+\epsilon)^2 - \alpha^2} \right)^{1/\epsilon}$

- The minimum $\chi_{\rm min} \simeq \left(\frac{h^2}{k^{\alpha}} \frac{2\alpha\lambda_4}{(2+\alpha)\lambda_2} \right)^{\frac{1}{2-\alpha}}$

Generating the hierarchy

- The critical Higgs value:

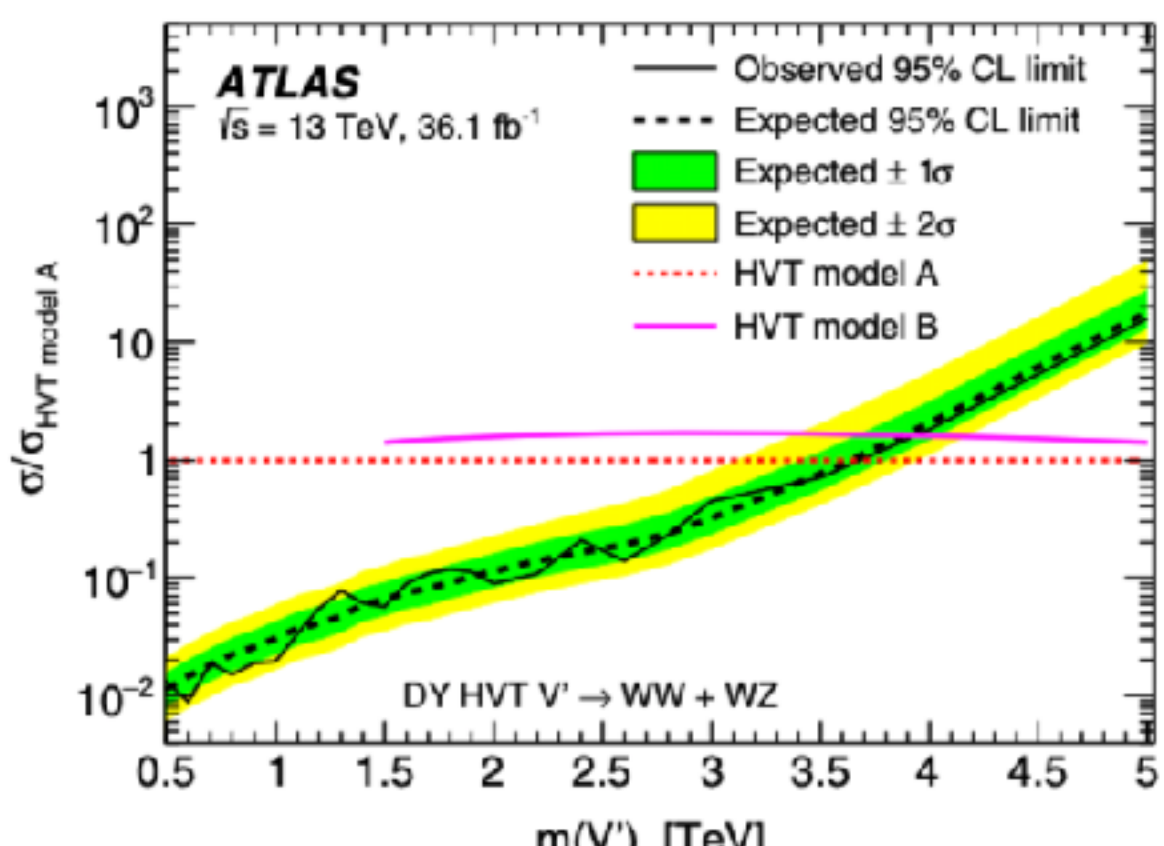
$$h_{crit} = k\left(\frac{\lambda_2}{\lambda_{H\epsilon}}\frac{4-\alpha^2}{(2+\epsilon)^2-\alpha^2}\right)^{\frac{1-\alpha/2}{\epsilon}}\sqrt{\frac{\lambda_2}{\lambda_4}\frac{\epsilon(2+\alpha)}{2\alpha(2-\alpha+\epsilon)}} \sim k\left(\frac{\lambda_2}{\lambda_{H\epsilon}}\right)^{1/\epsilon}$$

- We want to generate a large hierarchy. We can take small ϵ and $\lambda_2 \lesssim \lambda_{H\epsilon}$.

- Generating the hierarchy with a marginal dimension - reminiscent of Goldberger-Wise.

The Little hierarchy

- Since SU(2) is in the bulk we have bounds from ATLAS and CMS at the 3-4 TeV range.
- Their production is due to the mixing of composite-elementary, and so is similar in our case to standard bulk-RS.



The little hierarchy

- This means we need a ratio:

$$\frac{h}{\chi_{\min}} \simeq \frac{h_{\text{crit}}}{\chi_{\min}} \lesssim 0.1$$

- Small couplings!

$$V_{H\chi}(\chi, H) = \lambda_2 |H|^2 \frac{\chi^{2+\alpha}}{k^{\alpha}} - \lambda_{H\epsilon} |H|^2 \frac{\chi^{2+\alpha+\epsilon}}{k^{\alpha+\epsilon}} - \lambda_4 |H|^4 \frac{\chi^{2\alpha}}{k^{2\alpha}}$$

$$\chi_{\min} \simeq \left(\frac{h^2}{k^{\alpha}} \frac{2\alpha\lambda_4}{(2+\alpha)\lambda_2} \right)^{\frac{1}{2-\alpha}} \longrightarrow$$

$$\lambda_2, \lambda_{H\epsilon} < 10^{-2} \alpha \lambda_4$$

and also

$$\lambda, \lambda_{\text{GW}} \lesssim 10^{-5}$$

We will return to this point

The light dilaton

- The little hierarchy results in a light dilaton (stabilized by the smaller Higgs VEV)

$$m_\chi \simeq m_h \sqrt{\frac{h}{\chi_{\rm min}} \frac{\pi \sin\theta}{\sqrt{6} N} - \frac{8\pi^2(\lambda - \lambda_{\rm GW})}{N^2} \frac{\chi^2_{\rm min}}{m_h^2}}$$

$$\sin\theta \sim \frac{(\lambda_2 - \lambda_{H\epsilon})}{N} \frac{h \chi_{\rm min}}{m_h^2}$$

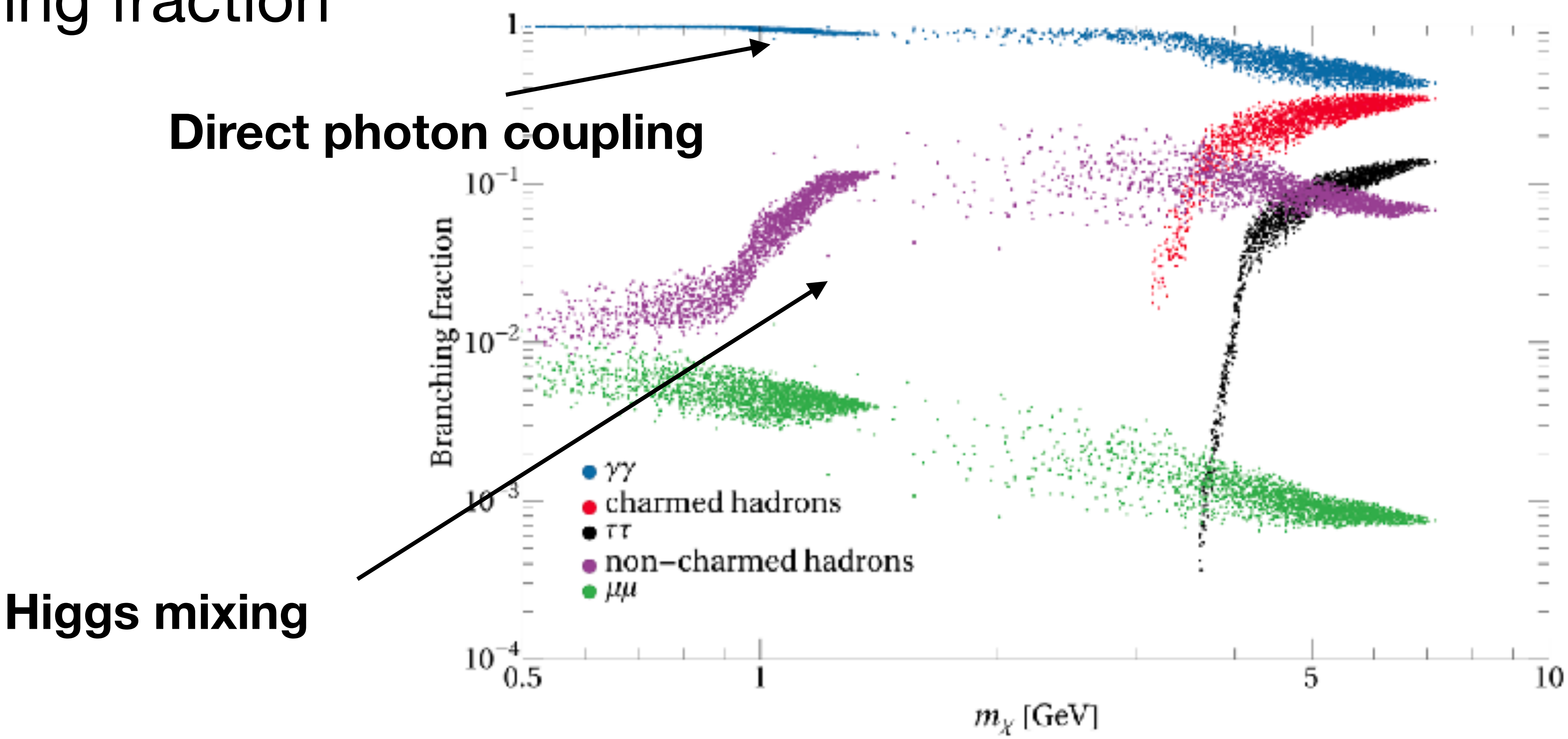
$$\lambda_2, \lambda_{H\epsilon} < 10^{-2} \alpha \lambda_4$$

$$\lambda, \lambda_{\rm GW} \lesssim 10^{-5}$$

- Smoking gun prediction - light dilaton mixing with the Higgs.

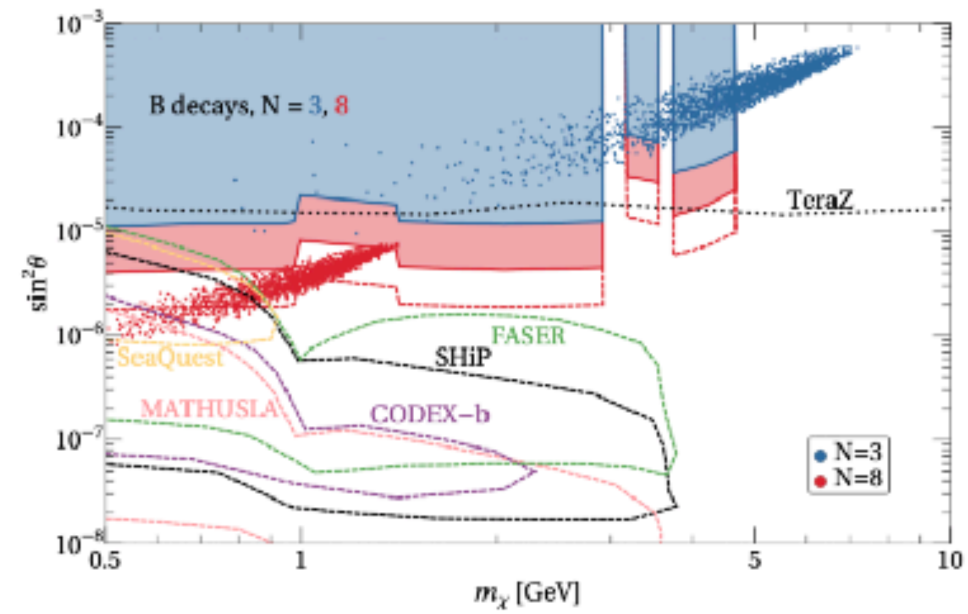
Dilaton properties

- Light Dilaton - less that 10 GeV
- Couplings - Higgs mixing, direct photon coupling
- Branching fraction

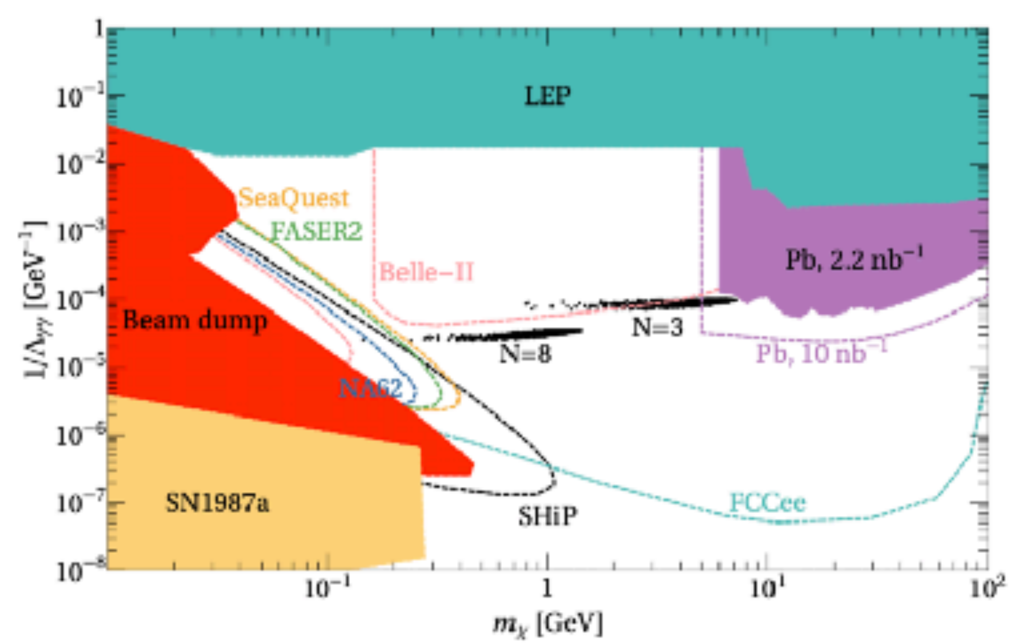


Pheno

- Constraints and projections due to Higgs mixing:



- Photon coupling



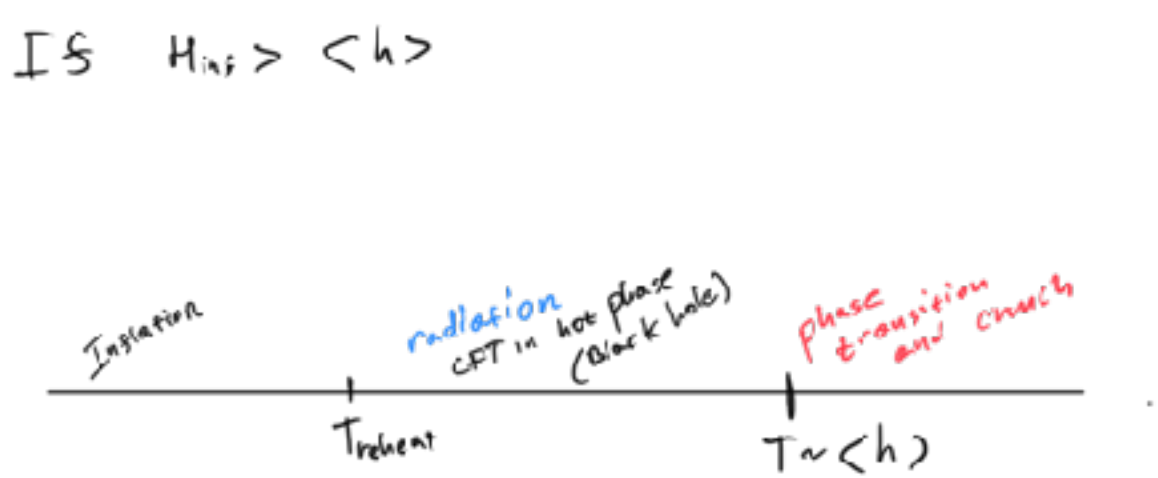
Pheno (intermediate) summary

- At a few TeV - heavy KK modes of gauge bosons and Higgs.

- At below 5 GeV - light dilaton which is produced and decays through mostly Higgs mixing and direct photons couplings.

Cosmological Dynamics

- For large Higgs VEV -



- For zero Higgs VEV - can get stuck in the hot phase and never transition.

- Need to have a limit on the supercooling of the CFT.

Breaking the supercooling

- Big departure from AdS in the IR - the BH phase disappears.

- CFT is explicitly broken - the unbroken phase is no longer a solution.

- Nucleation temperature - same order as the scale of CFT breaking.

Breaking the supercooling

- Possible solution: have QCD in the bulk. Use the contribution of QCD confinement to the potential to break CFT.
- Running coupling: $$\frac{1}{g^2(Q,\chi)} = \frac{\log\frac{k}{\chi}}{k g_5^2} - \frac{b_{\rm UV}}{8\pi^2}\log\frac{k}{Q} - \frac{b_{\rm IR}}{8\pi^2}\log\frac{\chi}{Q} + \tau$$

$$\tilde{\Lambda}(\chi) = \left(k^{b_{\rm UV}}\chi^{b_{\rm IR}} e^{-8\pi^2\tau}\left(\frac{\chi}{k}\right)^{-b_{\rm CFT}}\right)^{\frac{1}{b_{\rm UV}+b_{\rm IR}}} = \Lambda_0\left(\frac{\chi}{\chi_{\rm min}}\right)^n$$

CFT breaking scale

$$\chi_* \sim 10 - 100 \text{ MeV}$$

Von Harling, Servant 18
Baratella, Pomarol, Rompineve 19

The CC

- As long as any $H_\Lambda < \chi_*$ within the landscape - any surviving patch with any CC will have EW Higgs VEV.

- This implies a bound on the possible values of the CC - cutoff for the Higgs sector.

1. For QCD - $\Lambda < \sqrt{\chi_* M_{\rm Pl}} \lesssim 10^5\ \mathrm{TeV}$

2. Other solutions may reach $\Lambda < \sqrt{\langle h \rangle M_{\rm Pl}} \lesssim 10^7\ \mathrm{TeV}$

Tuning - the 5d cutoff

- The little hierarchy: $\lambda, \lambda_{\text{GW}} \lesssim 10^{-5}$
- What does this say about tuning? 5d contributions: $\lambda \sim \frac{1}{16\pi^2}\frac{\Lambda_5^4}{\chi^4}$.

  For natural couplings - $\Lambda_5 \lesssim \chi$.
- This can be thought of as SUSY with Λ_5 as the SUSY breaking scale:
  - Not Excluded!
  - Changes the pheno - Split SUSY (only electroweakinos), where the KK spectrum is supersymmetric.

Pheno - summary

- Light dilaton in the IR.
- EW KK spectrum - maybe supersymmetric (but high scale SUSY for everything else)
- Maybe QCD in the bulk - KK glues.
- Cosmology - CFT phase transition at below 10 GeV temperatures that involves EW physics - interesting for baryogenesis and GW.

What next?

- A full supersymmetric model.
- Study of the UV pheno.
- Study of the cosmology and predictions for baryogenesis and GW.

Summary

- What did we gain?
  - New solution to the hierarchy problem potentially up to 10^7 TeV cutoff.
  - Using landscape but conceptually different from standard anthropics.
  - New predictions for natural models - new physics (composite states) but no top partners!