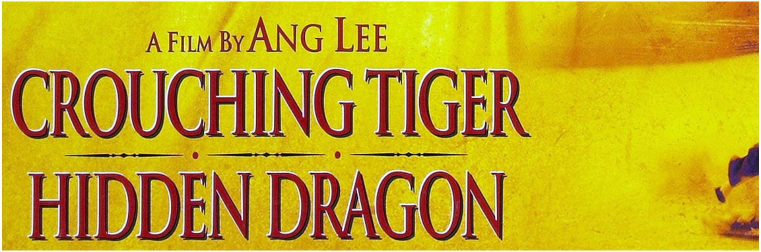

Pheno 2021 Symposium
25 May 2021

(a new approach to the hierarchy problem)

PRL **126**, 091801 (2021) [arXiv:2007.14396]
in collaboration with C. Csáki, R. T. D'Agnolo, and M. Geller
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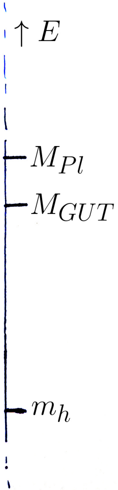
The hierarchy problem

Sensitivity of m_H^2 to the scale of new physics

Traditional approaches typically predict new particles at the TeV scale

Do we *need* top partners?



Other approaches

Cosmological dynamics can select a small Higgs VEV (relaxion, *N*naturalness, etc.)

Large corrections to m_H^2 are unsuppressed

See also: anthropic solutions

Cosmological Relaxation of the Electroweak Scale

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(Dated: June 24, 2015)

The Selfish Higgs

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***N*naturalness**

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Mass Hierarchy and Vacuum Energy

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California Institute of Technology, Pasadena, CA 91125

Inflating to the Weak Scale

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Our approach

Landscape of m_H^2 values up to a cutoff Λ:

$$V_H(H) = -m_{H,i}^2 H^\dagger H + \lambda (H^\dagger H)^2$$

Patches crunch unless $h \equiv \langle H^0 \rangle$ satisfies

$$H_I \lesssim h_{\min} \lesssim h < h_{\text{crit}} \sim \mathcal{O}(\text{TeV})$$

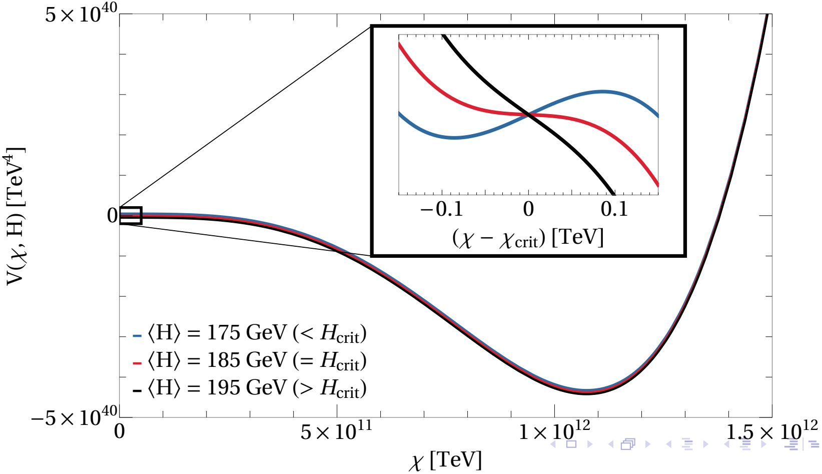
Hubble during inflation

Many ways to get this; not the main focus

Our mechanism!

Our approach

Higgs couples to dilaton of a spontaneously broken CFT sector w/ large, negative vacuum energy



The CliffsNotes

$h < h_{\rm crit}$ → long-lived metastable vacuum → standard cosmological history

$h > h_{\rm crit}$ → roll down to true vacuum → crunch!

Main predictions:

- light (0.1–10 GeV) dilaton
- KK electroweak gauge bosons*
- **no** top partners

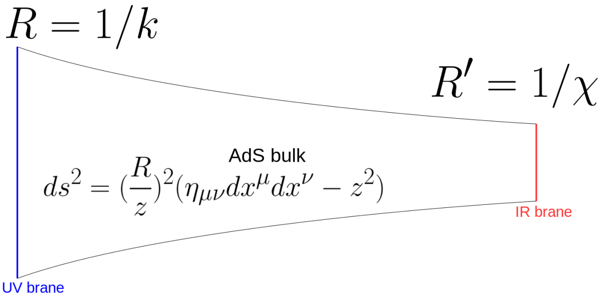
*which have NOTHING to do with resolving the hierarchy problem

RS model

Standard 5D warped description of CFT with Goldberger-Wise stabilization

Dilaton χ identified with IR brane location

Higgs in bulk, all fermions on UV brane



$$R = 1/k$$

$$R' = 1/\chi$$

AdS bulk

$$ds^2 = (\frac{R}{z})^2(\eta_{\mu\nu}dx^\mu dx^\nu - z^2)$$

IR brane

UV brane

The potential

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

Usual GW stabilization generates true vacuum:

$$V_{GW}(\chi) = -\lambda\chi^4 + \lambda_{GW}\chi^{4+\delta}$$

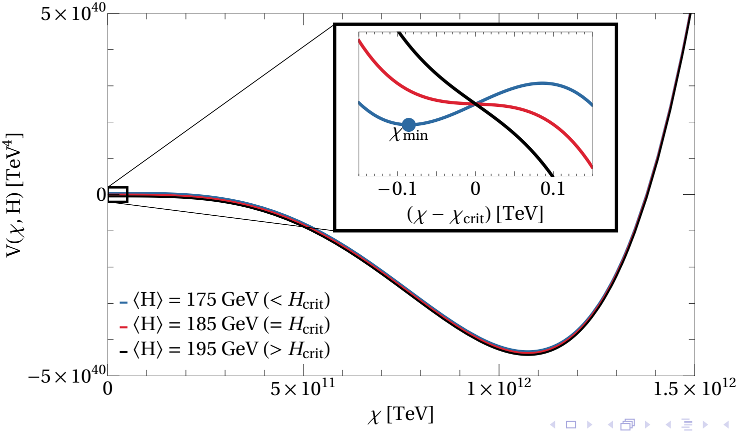
IR brane-localized terms generate false vacuum:

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

where $\alpha = 2\sqrt{4+m_b^2} - 2$; term involving marginal field (e.g. GW scalar) $\sim z^\epsilon$ gives modified quadratic

The potential

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



Phenomenology

Reminder: no top partners!

Bulk Higgs → KK electroweak gauge bosons

No KK gluons*

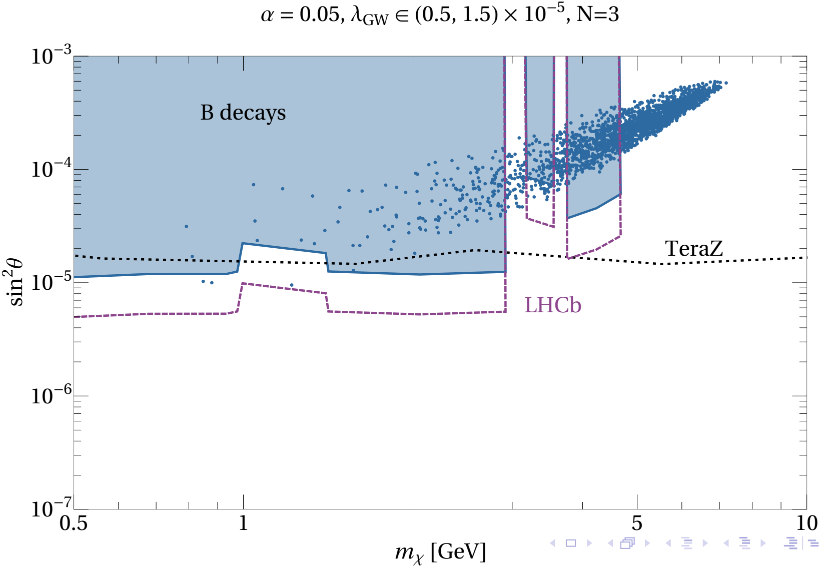
(*unless we put QCD in the bulk)

Light dilaton (0.1–10 GeV) inherits SM Higgs couplings, suppressed by $\sin\theta$

Additional direct coupling to EW gauge bosons:

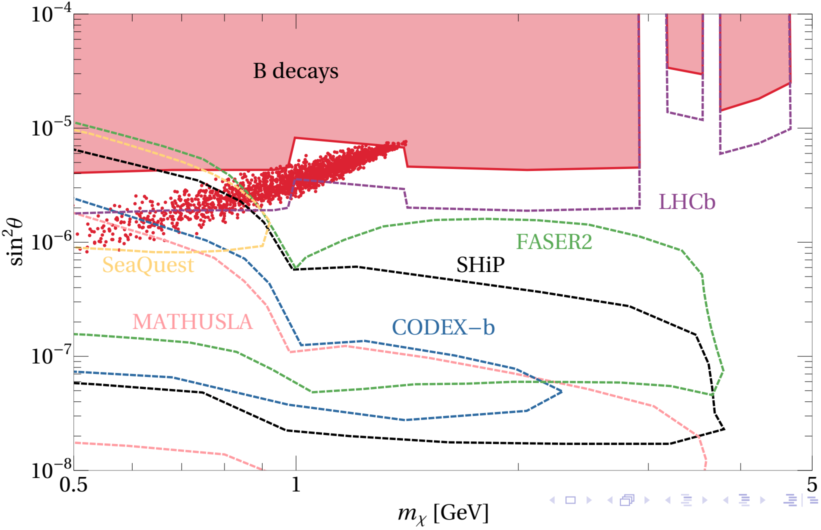
$$\frac{\chi}{2\chi_{\min}\log\frac{R'}{R}}\big(\underbrace{F^2_{\mu\nu}}_{\text{Important!}}+\underbrace{Z^2_{\mu\nu}+2W^2_{\mu\nu}}_{\text{Not important!}}\big)$$

Higher mass scan

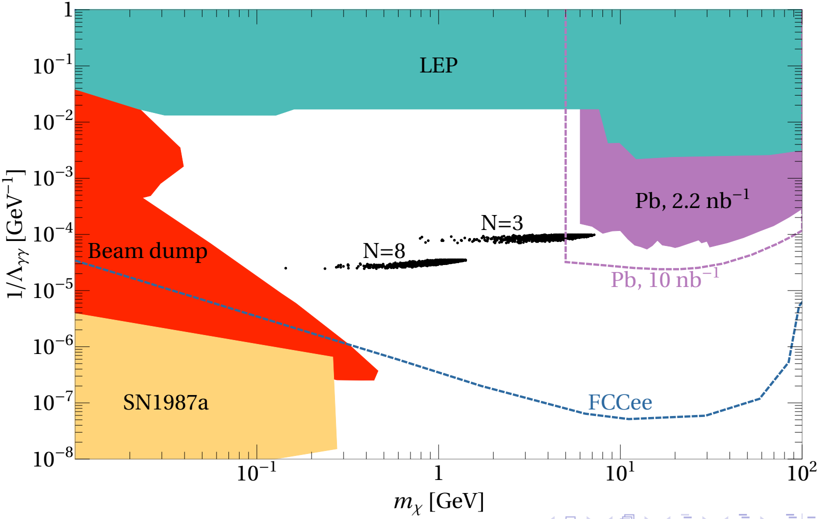


Lower mass scan

$\alpha = 0.1, \lambda_{\mathrm{GW}} = 2 \times 10^{-6}$, N=8



The photon coupling



Summary and outlook

Higgs VEV tied to cosmological stability

Parameter space mainly probed by rare B decays; see also:

- searches for weakly-coupled, light particles (FASER, SeaQuest, etc.)
- future lepton colliders (FCCee, CepC, etc.)

UV completion and little hierarchy problem ($\lambda, \lambda_{GW} \sim 10^{-5}$)

Thank you!

for more info:

`arxiv.org/abs/2007.14396`

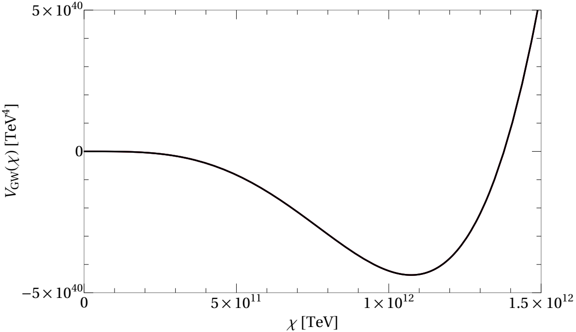
`ai279@cornell.edu`

`pages.physics.cornell.edu/~ai279/`

GW potential

GW field yields potential $V_{GW}(\chi) = -\lambda\chi^4 + \lambda_{GW}\chi^{4+\delta}$

Small explicit breaking of scale invariance (δ) by GW bulk mass



$$\chi_{GW} \sim k\left(\frac{\lambda}{\lambda_{GW}}\right)^{1/\delta}$$

Brane-localized terms

Higgs field sourced on UV brane; VEV scales as $z^{2\pm\sqrt{4+m_b^2}}$

Can show UV source scales on IR brane as $H_{\mathrm{UV}}\chi^{\sqrt{4+m_b^2}-2} \equiv H_{\mathrm{UV}}\chi^{\alpha/2-1}$; $\alpha = 2\sqrt{4+m_b^2} - 2$

Brane-localized quadratic term $\rightarrow |H|^2\,\chi^{2+\alpha}$

Brane-localized quartic term $\rightarrow |H|^4\,\chi^{2\alpha}$

Allow terms including GW scalar $\sim z^{\epsilon}$ (or any other nearly marginal field) $\rightarrow |H|^2\,\chi^{2+\alpha+\epsilon}$

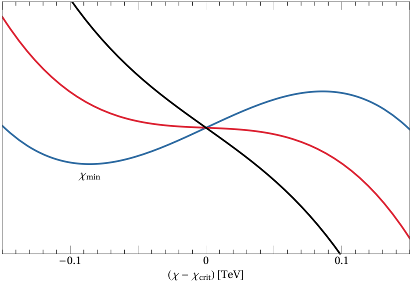
Brane-localized terms

Putting this all together:

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

For small $h < h_{\text{crit}}$, $V_{H\chi}$ has a local minimum in χ!

Minimum disappears for $h \geq h_{\text{crit}}$



Analytical estimates

Neglecting V_{GW} around metastable minimum, estimate:

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

Large separation of scales $h_{\text{crit}}, \chi_{\text{crit}}, \chi_{\text{min}} \ll k$ from small ϵ

Analytical estimates

Neglecting V_{GW}—is this okay?

Require V_{GW} to be dominated by $V_{H\chi}$ around χ_{crit}

$$\to \lambda \sim \lambda_{GW} \lesssim \frac{\lambda_2^2}{\lambda_4}$$

Larger λ, λ_{GW} washes out the metastable minimum

The little hierarchy

Little hierarchy: $\dfrac{h}{\chi_{\rm min}} \lesssim 0.1$

Implies $\lambda_2 \lesssim 10^{-2}$; $\lambda, \lambda_{GW} \lesssim 10^{-5}$

And a light dilaton:

Dilaton mass and mixing

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

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

Parameter scans

Take $k = 10^8$ TeV, $h \simeq 174 = 246/\sqrt{2}$ GeV

	Parameter	Scan 1 range	Scan 2 range
	λ	$1.1\lambda_{GW}$	$1.1\lambda_{GW}$
V_{GW}	λ_{GW}	$(0.5, 1.5) \times 10^{-5}$	$\mathbf{2 \times 10^{-6}}$
	δ	0.01	0.01
	λ_2	$(0.5, 1.5) \times 10^{-2}$	$\mathbf{(0.5, 1) \times 10^{-2}}$
	$\lambda_{H\epsilon}$	$(2, 4) \times \lambda_2$	$(2, 4) \times \lambda_2$
$V_{H\chi}$	λ_4	$(2, 3)$	$(2, 3)$
	α	0.05	$\mathbf{0.1}$
	ϵ	$(0.03, 0.1)$	$\mathbf{(0.05, 0.01)}$
	N	3	$\mathbf{8}$

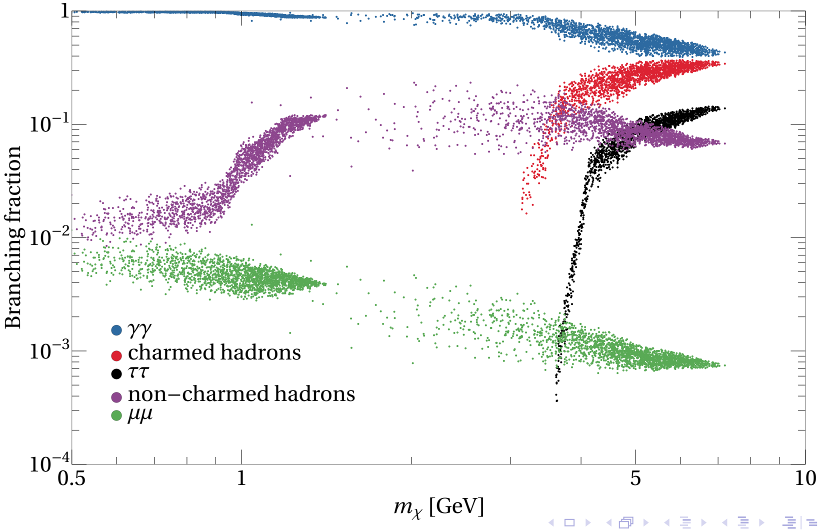
Scan 2 probes lower masses (differences in **bold**)

Selection criteria

Randomly generate 10^5 points, retain those that satisfy:

- Existence of second potential minimum at $\chi_{\rm min} > 1$ TeV
- $h_{\rm crit} \leq 2$ TeV for naturalness
- Minimum of 2D potential, reproduces SM Higgs mass
- Metastable vacuum cosmologically long-lived ($S_4 \gtrsim 200$)

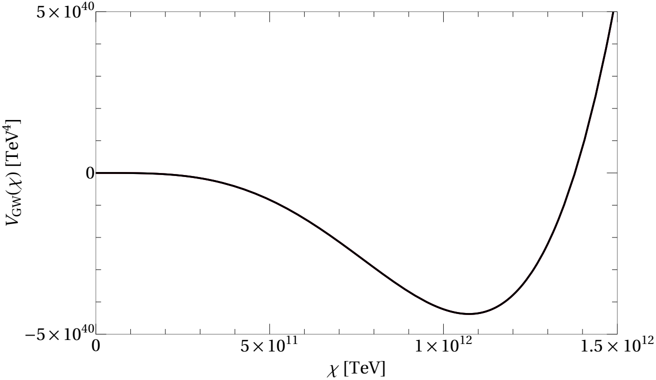
χ decays mainly to photons



Small Higgs VEVs

As $h \to 0$ we worry about eternal inflation

Nearly flat potential near $\chi = 0$



A solution

von Harling & Servant 1711.11554

Baratella, Pomarol, Rompineve 1812.06996

Add to potential $\lambda_\gamma \chi^\gamma \tilde{\Lambda}^{4-\gamma}$, with $\tilde{\Lambda} \ll k$

Defines scale $\chi_* = \tilde{\Lambda} \lambda_\gamma^{\frac{1}{4-\gamma}}$

In the IR $\chi \lesssim \chi_*$:

- Explicit breaking of scale invariance dominates
- Description in terms of dilaton breaks down
- Effectively generates $\mathcal{O}(\chi_*^2)$ mass term

Bulk gauge group

Generate new term by any relevant operator with a coupling that grows in the IR

How about bulk QCD? Can show

$$\chi_* \sim \tilde{\Lambda} \sim \Lambda_{\rm QCD}$$

for $\chi_{\rm min} \sim 1$ TeV, $h = 0$

Dark gauge group also works!

Need highest Hubble constant in landscape $< \chi_*$ for no eternal inflation

Yields minimal Higgs VEV $h_{\rm min} \sim 0.1\chi_*$