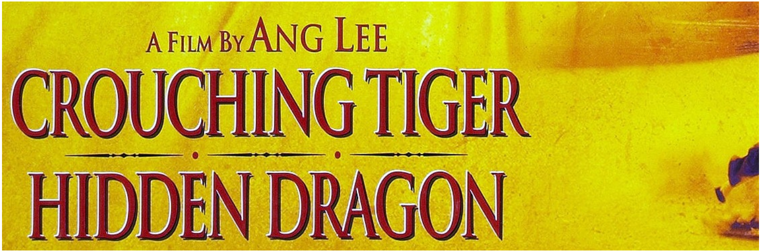


FPF2 Meeting
28 May 2021

A talk By ~~Ang Lee~~ Ameen Ismail

CRUNCHING DILATON HIDDEN NATURALNESS

(a new approach to the hierarchy problem)

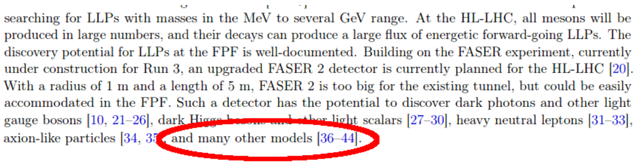
PRL **126**, 091801 (2021) [arXiv:2007.14396]

in collaboration with C. Csáki, R. T. D'Agnolo, and M. Geller

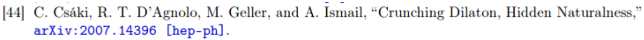
FPF2 Meeting

28 May 2021

Snowmass 2021 LOI



searching for LLPs with masses in the MeV to several GeV range. At the HL-LHC, all mesons will be produced in large numbers, and their decays can produce a large flux of energetic forward-going LLPs. The discovery potential for LLPs at the FPF is well-documented. Building on the FASER experiment, currently under construction for Run 3, an upgraded FASER 2 detector is currently planned for the HL-LHC [20]. With a radius of 1 m and a length of 5 m, FASER 2 is too big for the existing tunnel, but could be easily accommodated in the FPF. Such a detector has the potential to discover dark photons and other light gauge bosons [10, 21–26], dark Higgs bosons and other light scalars [27–30], heavy neutral leptons [31–33], axion-like particles [34, 35], and many other models [36–44].



[44] C. Csáki, R. T. D'Agnolo, M. Geller, and A. Ismail, "Crunching Dilaton, Hidden Naturalness," `arXiv:2007.14396 [hep-ph]`.

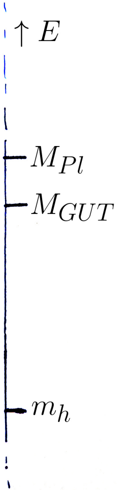
The hierarchy problem

Sensitivity of m_H^2 to the scale of new physics

Symmetry-based approaches typically predict new particles at the TeV scale

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

See also: anthropic solutions

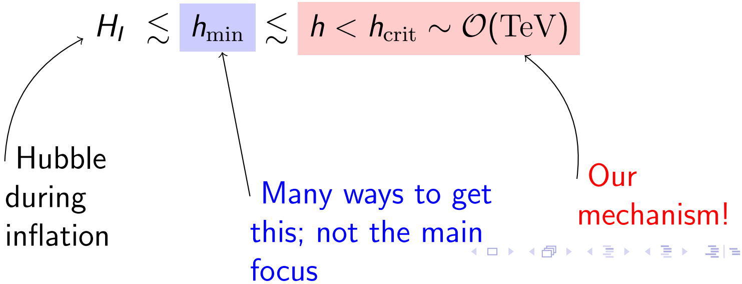


Our approach

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



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

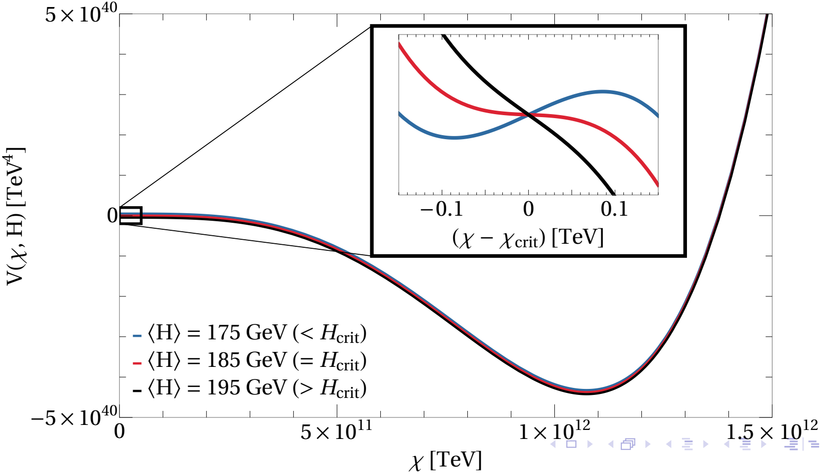
Hubble during inflation

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

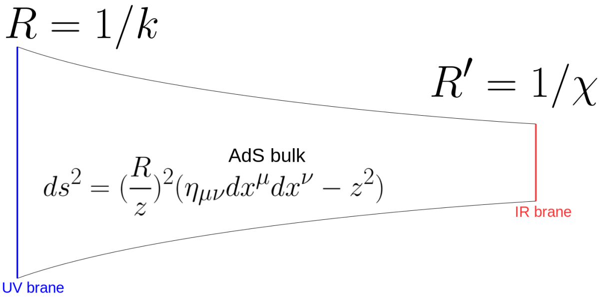
*which have NOTHING to do with resolving the hierarchy problem

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



The potential

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

Usual GW stabilization generates true vacuum:

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

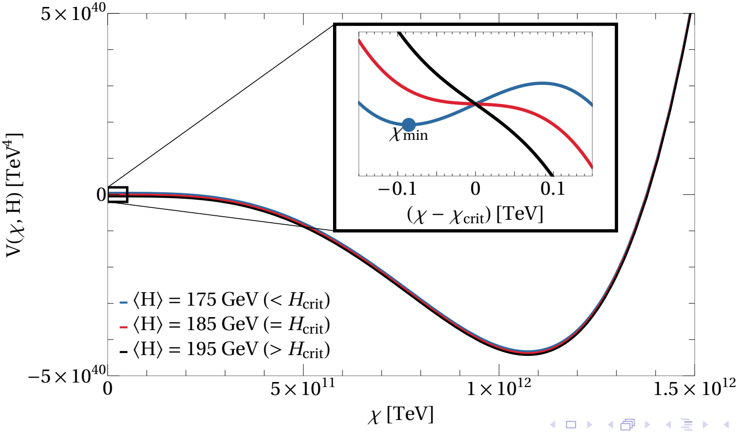
IR brane-localized terms generate false vacuum:

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

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 $\sin\theta$

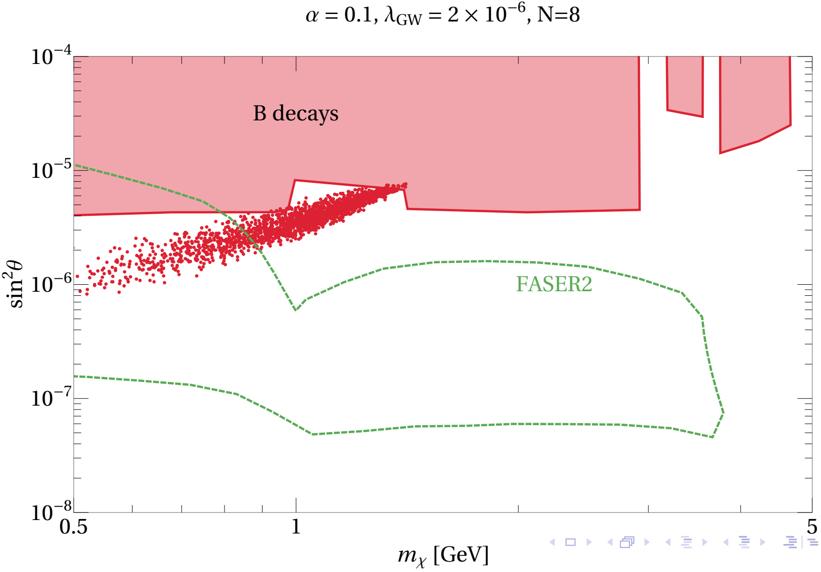
Additional direct coupling to EW gauge bosons:

$$\frac{\chi}{2\chi_{\min}\log\frac{R'}{R}}\left(\colorbox{pink}{$F_{\mu\nu}^2$} + \colorbox{lavender}{$Z_{\mu\nu}^2 + 2W_{\mu\nu}^2$}\right)$$

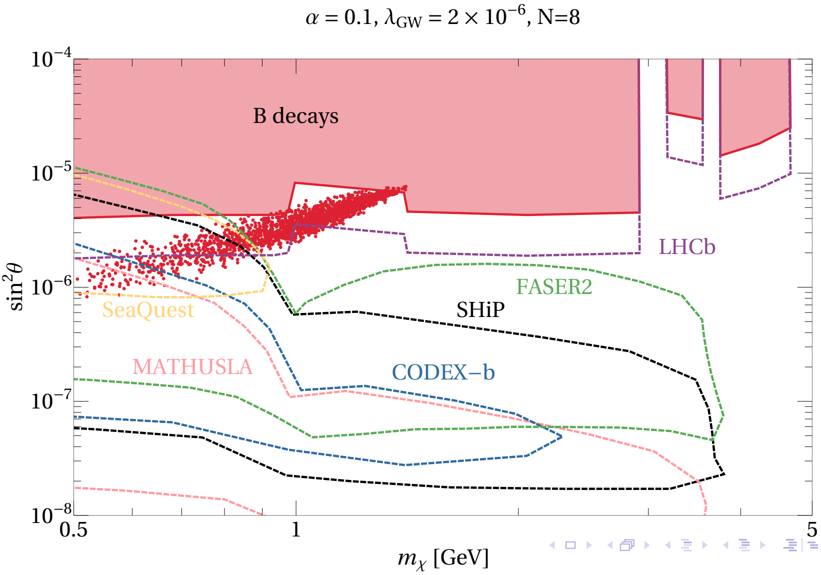
Important!

Not important!

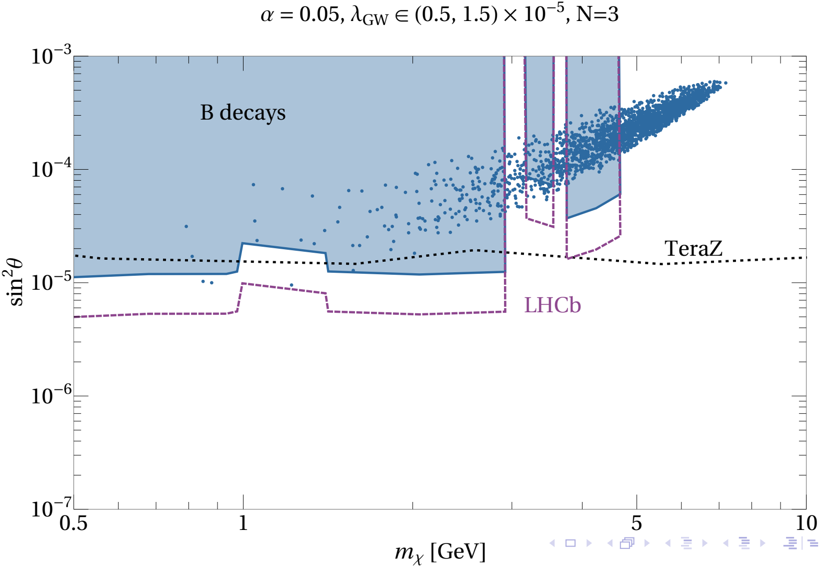
Lower mass scan



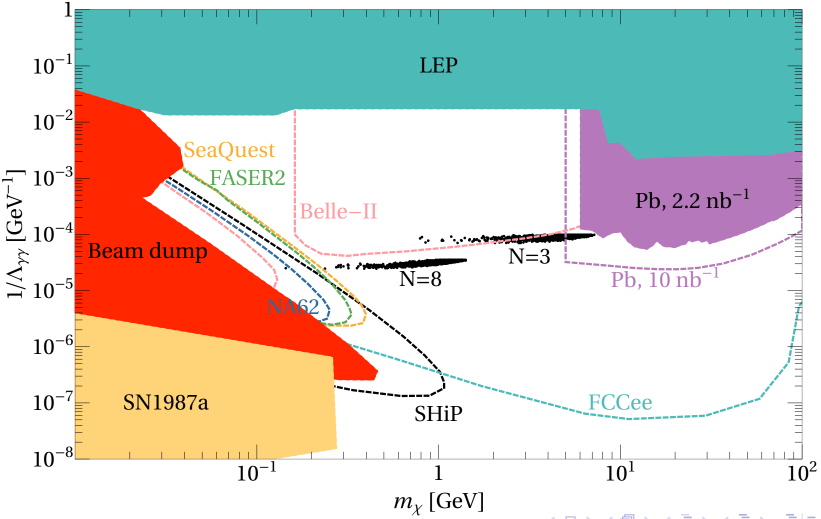
Lower mass scan



Higher mass scan



The photon coupling



Summary and outlook

Higgs VEV tied to cosmological stability

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

Opportunity to probe dilaton parameter space at the FPF!

Thank you!

for more info:

`arxiv.org/abs/2007.14396`

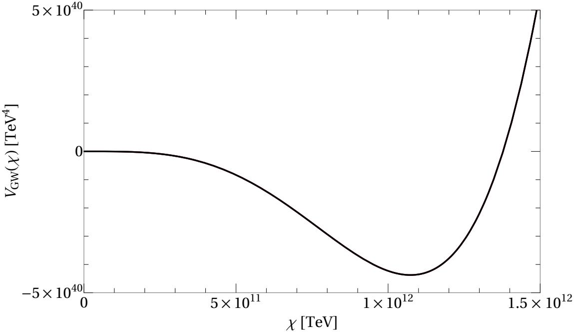
`ai279@cornell.edu`

`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) $\rightarrow |H|^2\,\chi^{2+\alpha+\epsilon}$

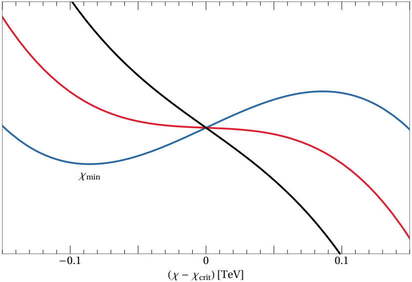
Brane-localized terms

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

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



Analytical estimates

Neglecting V_{GW} around metastable minimum, estimate:

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

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

Analytical estimates

Neglecting V_{GW}—is this okay?

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

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

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

The little hierarchy

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

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

And a light dilaton:

Dilaton mass and mixing

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

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

Parameter scans

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

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

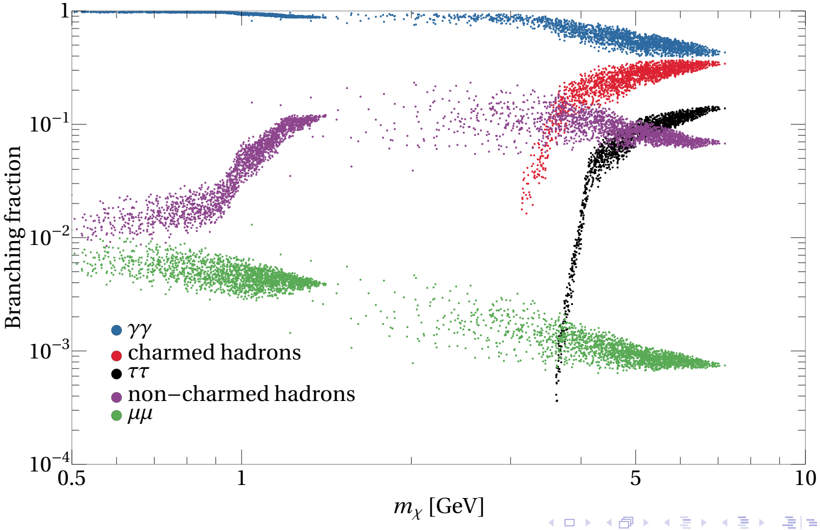
Scan 2 probes lower masses (differences in **bold**)

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 ($S_4 \gtrsim 200$)

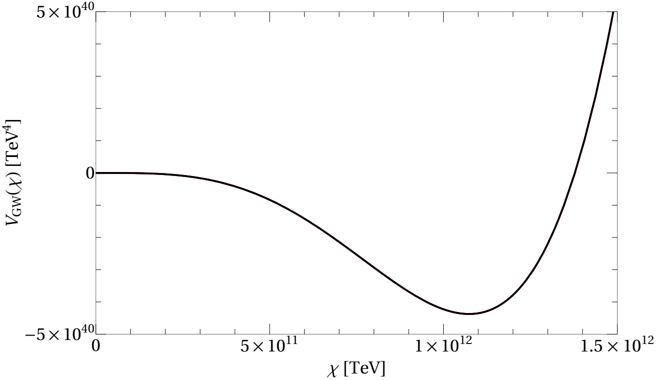
χ decays mainly to photons



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

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

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

Dark gauge group also works!

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

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