New Models of Elementary & Composite Higgs Bosons

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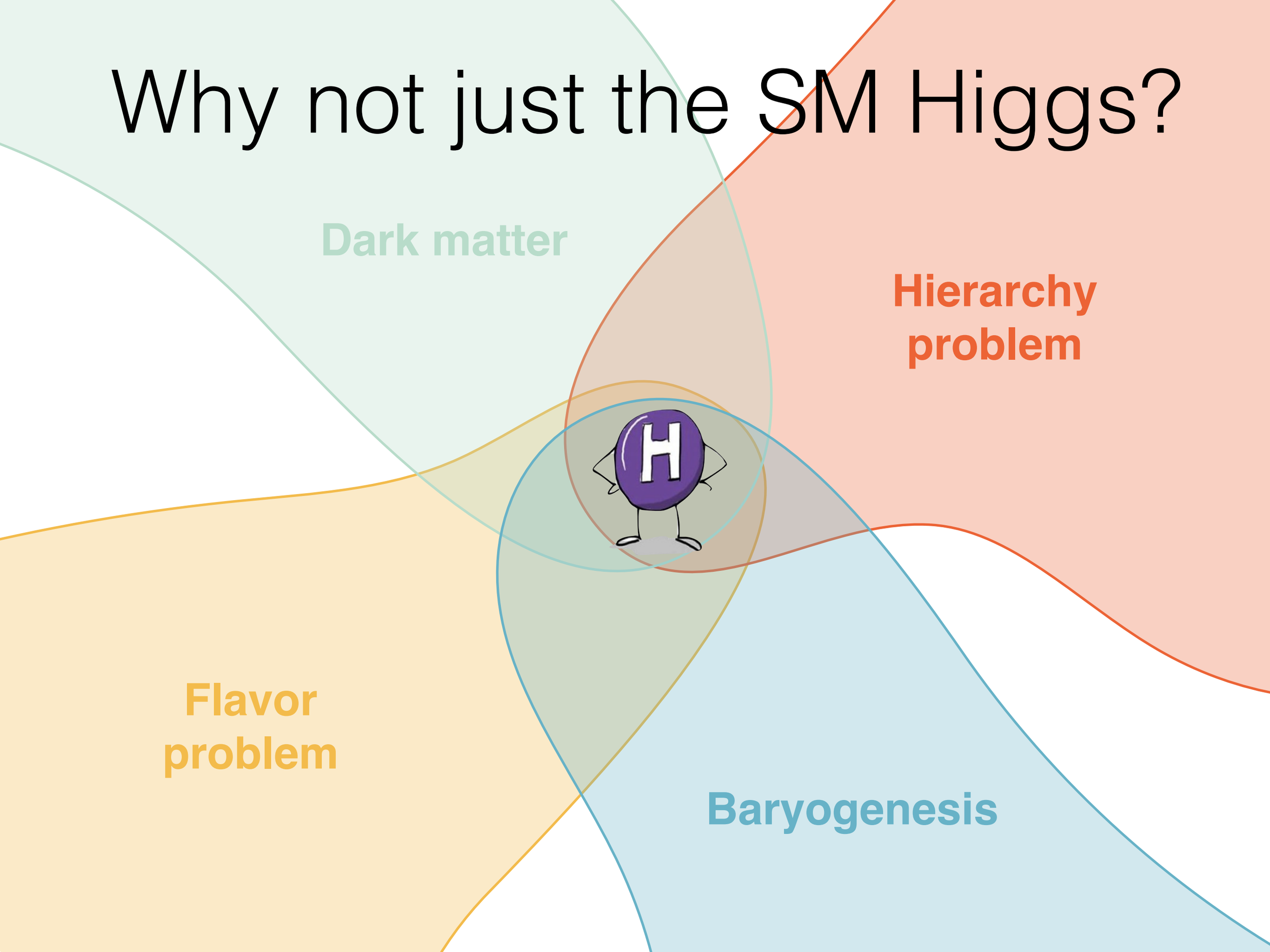
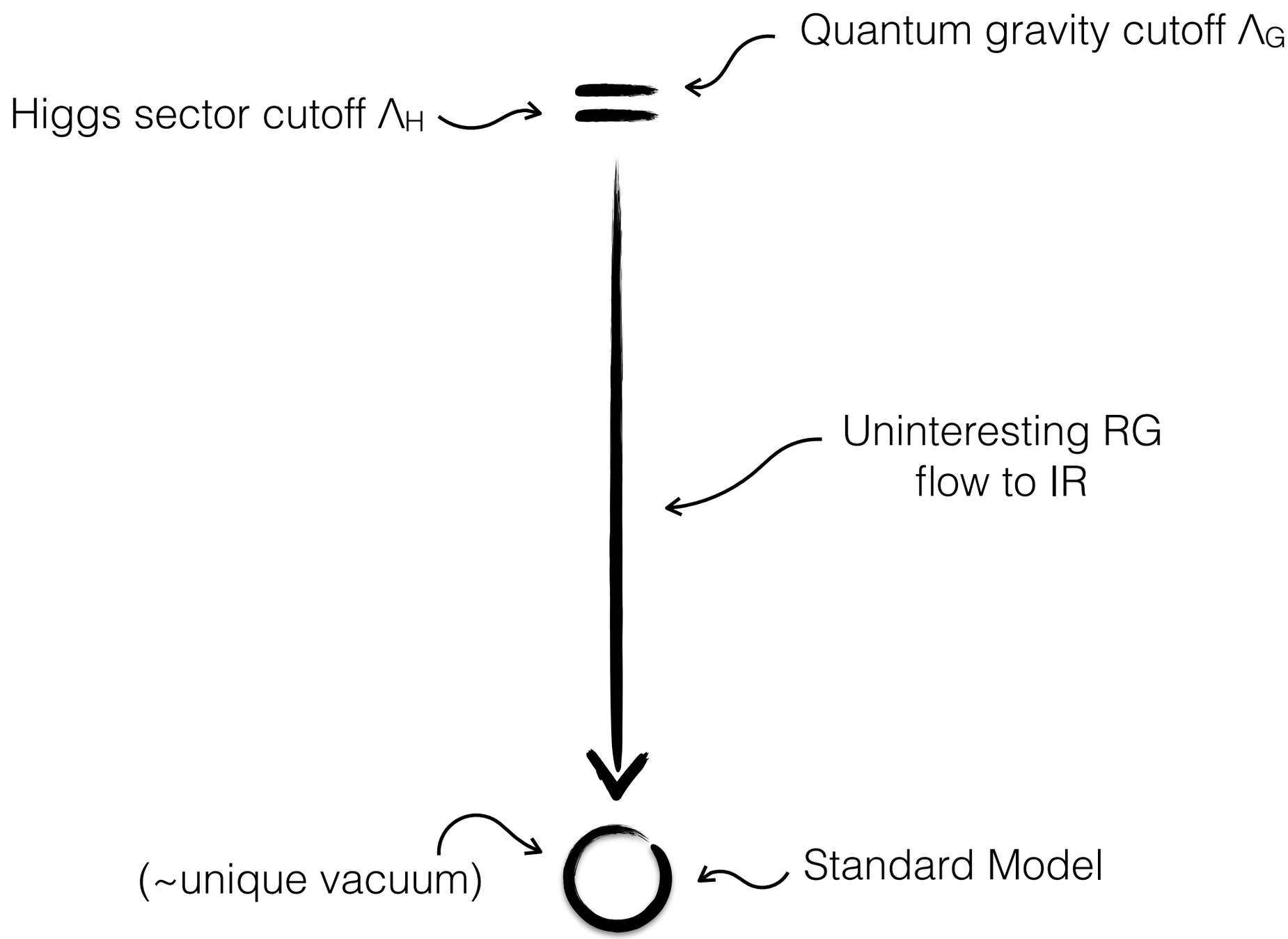
Why not just the SM Higgs?



The Hierarchy Problem



m_H is not technically natural $\Rightarrow$ Hierarchy problem

Low Cutoff

For example:

- Technicolor
- Large extra dimensions
- Randall-Sundrum
- Little string theory
- …

But…

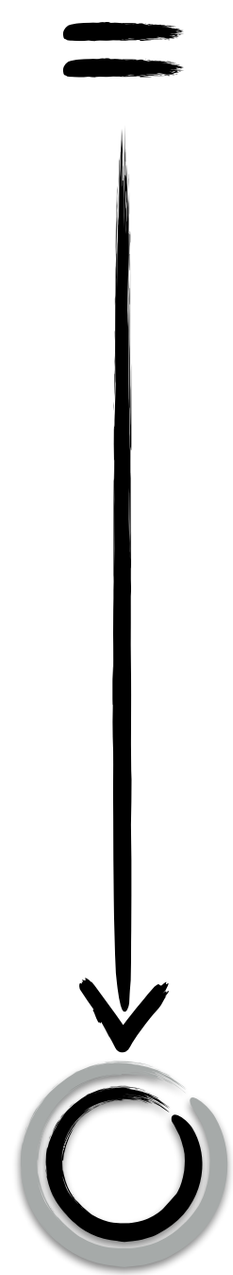
No separation between Higgs, cutoff

- Thus far, Higgs looks elementary
- No evidence for additional light states
- No evidence for higher-dim operators

Symmetries

For example:

- Supersymmetry
- Composite Higgs
- Little Higgs
- Gauge-Higgs unification
- …



But…

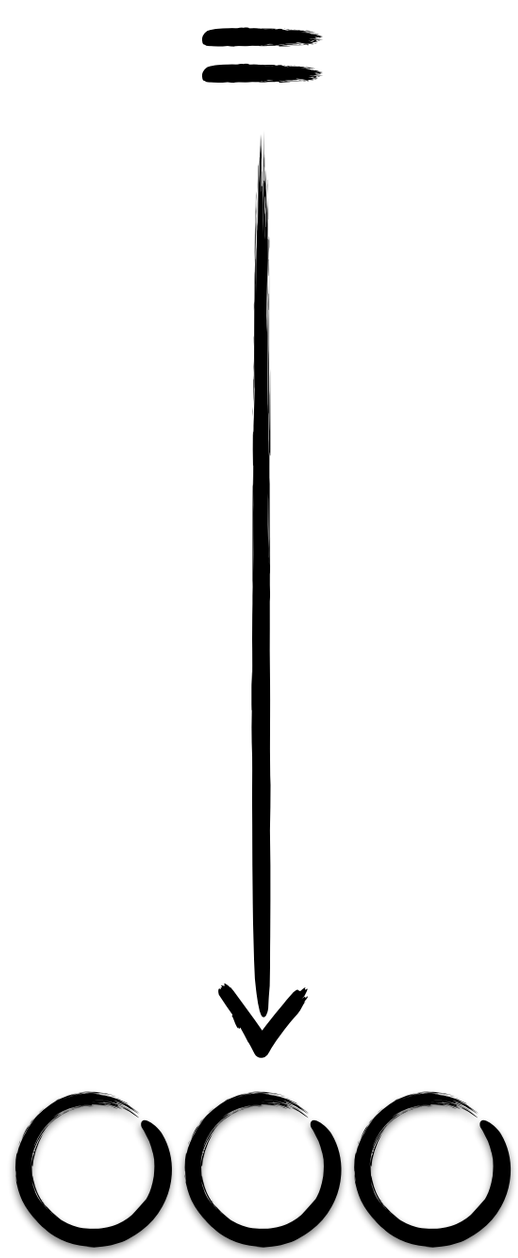
Predict partner particles w/ SM quantum #'s @ TeV scale

- No evidence for QCD-charged particles beneath ~1000 GeV
- No evidence for weakly-charged particles beneath ~ few 100 GeV

Anthropics

For example:

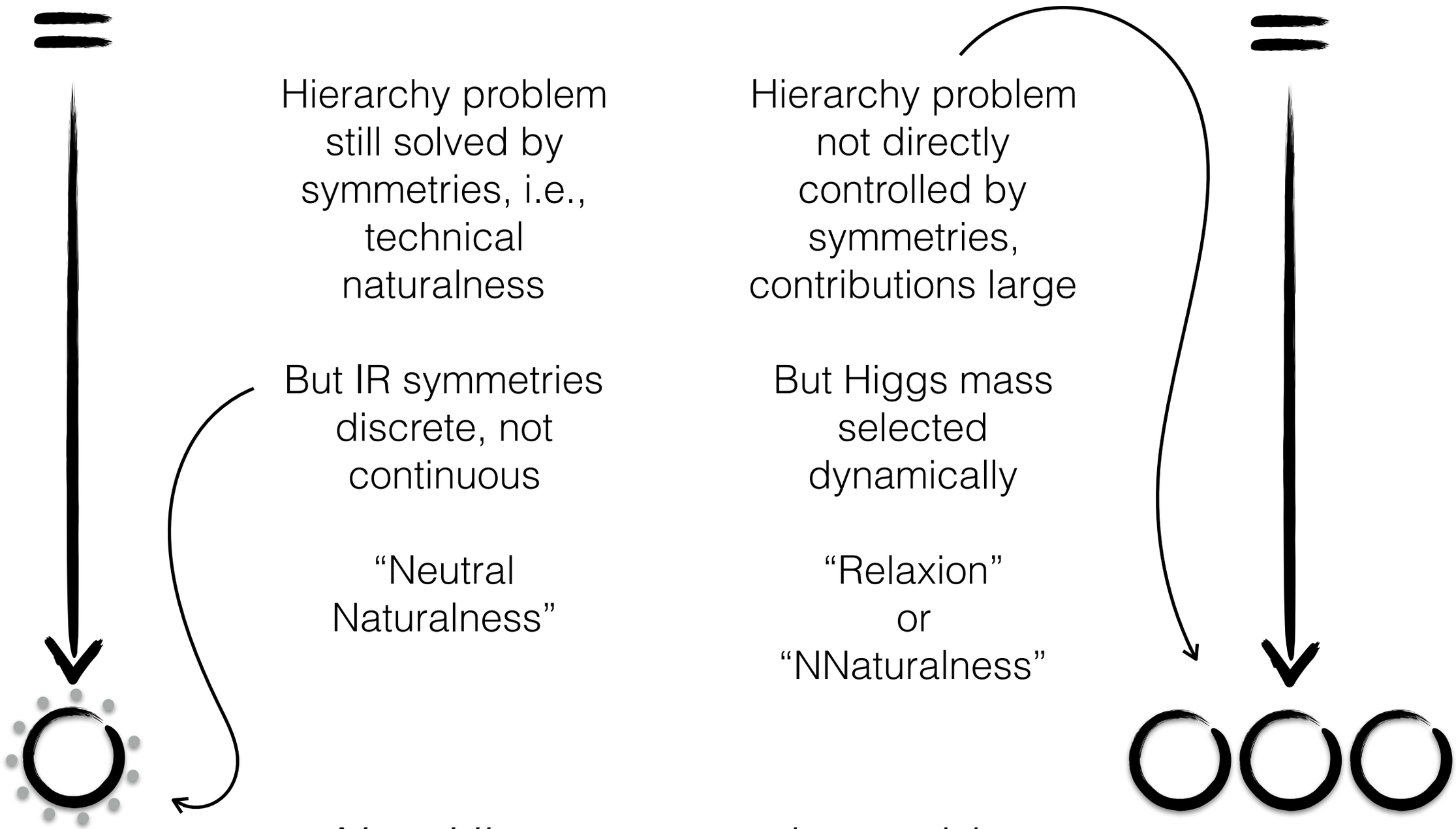
- Atomic principle (if only dim'ful parameters vary in a landscape)



But…

Not necessarily testable

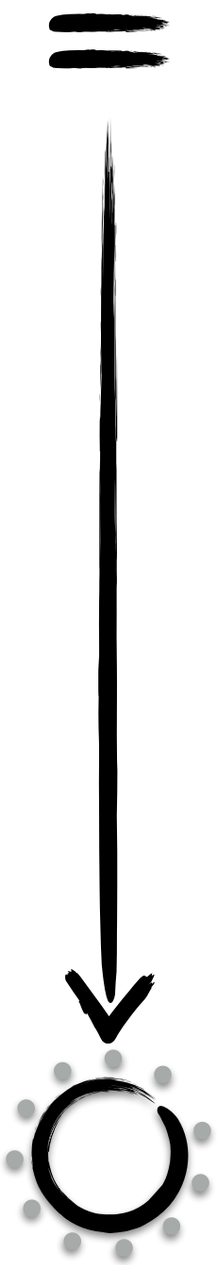
New mechanisms



New Higgses, new observables.

Neutral naturalness

The original: Twin Higgs [Chacko, Goh, Harnik '05]



Standard Model $\xleftrightarrow{Z_2}$ **Standard Model**

Radiative corrections to the Higgs mass are SU(4) symmetric thanks to Z_2:

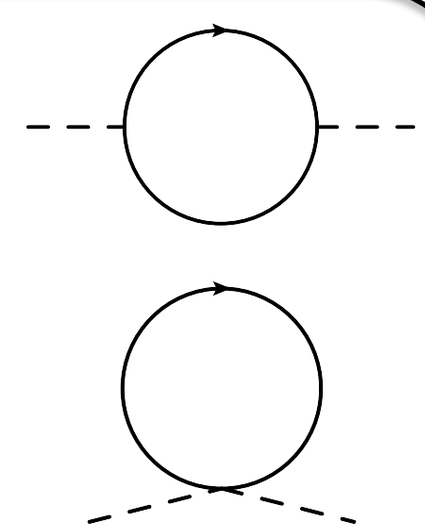
$$V(H) \supset \frac{\Lambda^2}{16\pi^2}\left(-6y_t^2 + \frac{9}{4}g^2 + \dots\right)\left(|H_A|^2 + |H_B|^2\right)$$

Higgs is a PNGB of ~SU(4), but partner states neutral under SM.

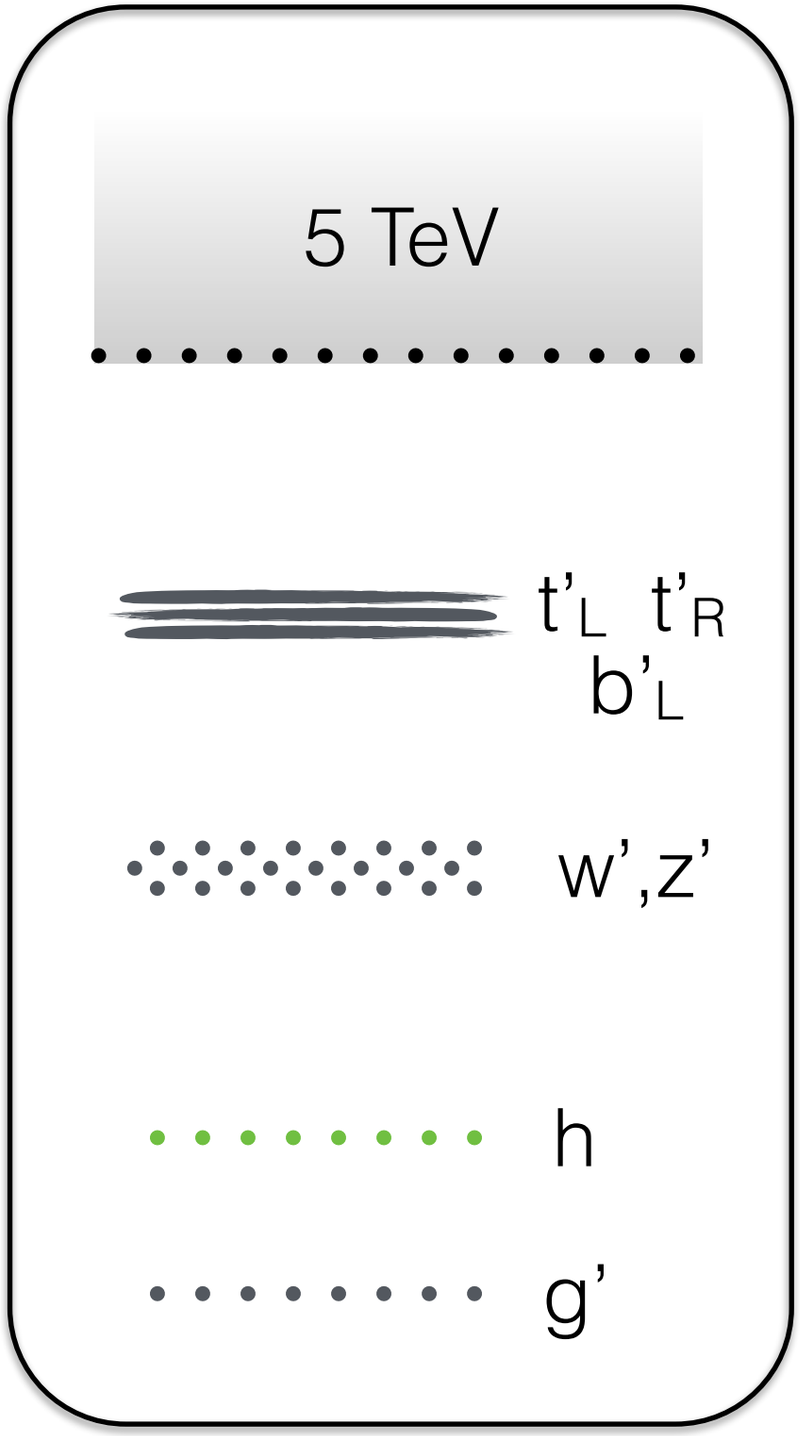
$$\mathcal{L} \supset -y_t H_A Q_3^A \bar{u}_3^A - y_t H_B Q_3^B \bar{u}_3^B$$

$$\downarrow \qquad\qquad \downarrow$$

$$h + \dots \qquad\qquad f - \frac{h^2}{2f} + \dots$$



Neutral naturalness



Simplest theory: exact mirror copy of SM

[Chacko, Goh, Harnik '05; Barbieri, Gregoire, Hall '05; Falkowski, Pokorski, Schmaltz '06; Chang, Hall, Weiner '06; NC, Howe '13]

But this is more than you need, and mirror 1st, 2nd gens lead to cosmological challenges

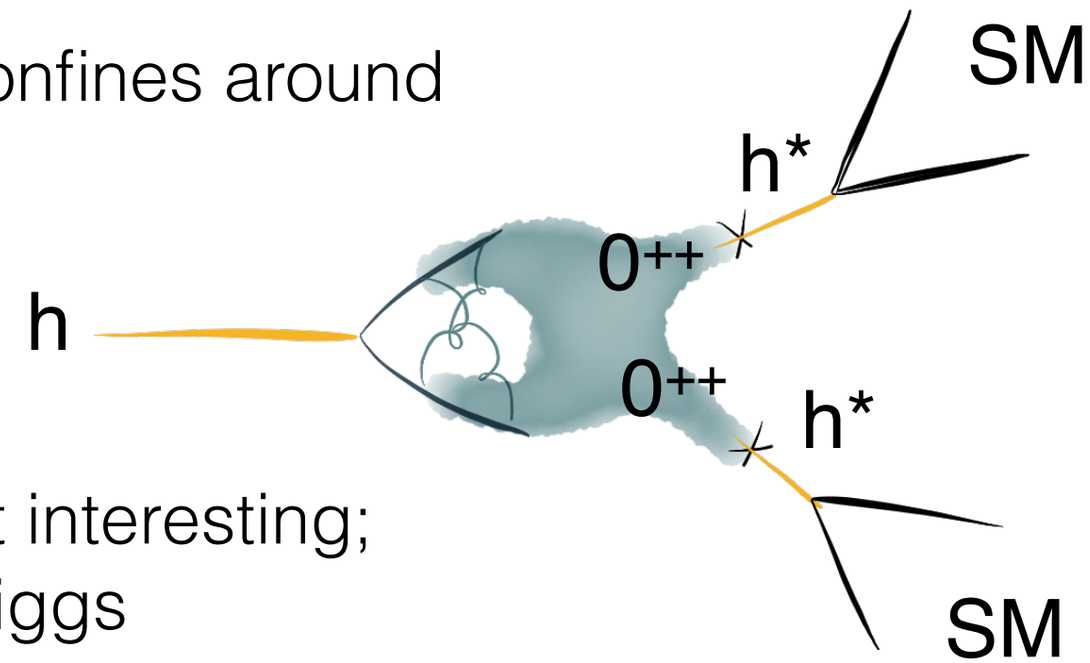
Many more options where symmetry is approximate, e.g. a good symmetry for heaviest SM particles.

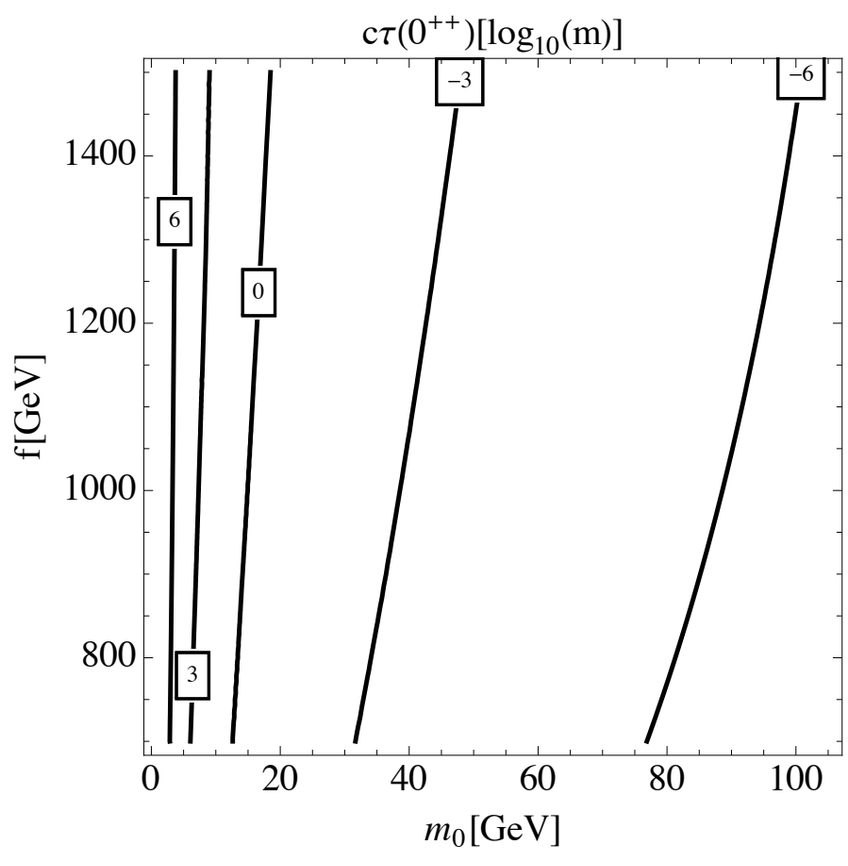
[NC, Knapen, Longhi '14; Geller, Telem '14; NC, Katz, Strassler, Sundrum '15; Barbieri, Greco, Rattazzi, Wulzer '15; Low, Tesi, Wang '15, NC, Knapen, Longhi, Strassler '16]

[NC, Katz, Strassler, Sundrum '15; Curtin, Verhaaren '15; Csaki, Kuflik, Lombardo, Slone '15]

Exotic Higgs Decays

- Twin sector must have twin QCD, confines around QCD scale
- Higgs boson couples to bound states of twin QCD
- Various possibilities. Glueballs most interesting; lightest have same quantum # as Higgs





$$\mathcal{L} \supset -\frac{\alpha_3'}{6\pi}\frac{v}{f}\frac{h}{f}G'^{a}_{\mu\nu}G'^{\mu\nu}_{a}$$

Produce in rare Higgs decays (BR~10^{-3}-10^{-4})
(Also produced via heavy twin Higgs)

$$gg \to h \to 0^{++} + 0^{++} + \ldots$$

Decay to SM via Higgs: $0^{++} \to h^* \to f\bar{f}$

Long-lived, length scale ~ LHC detectors

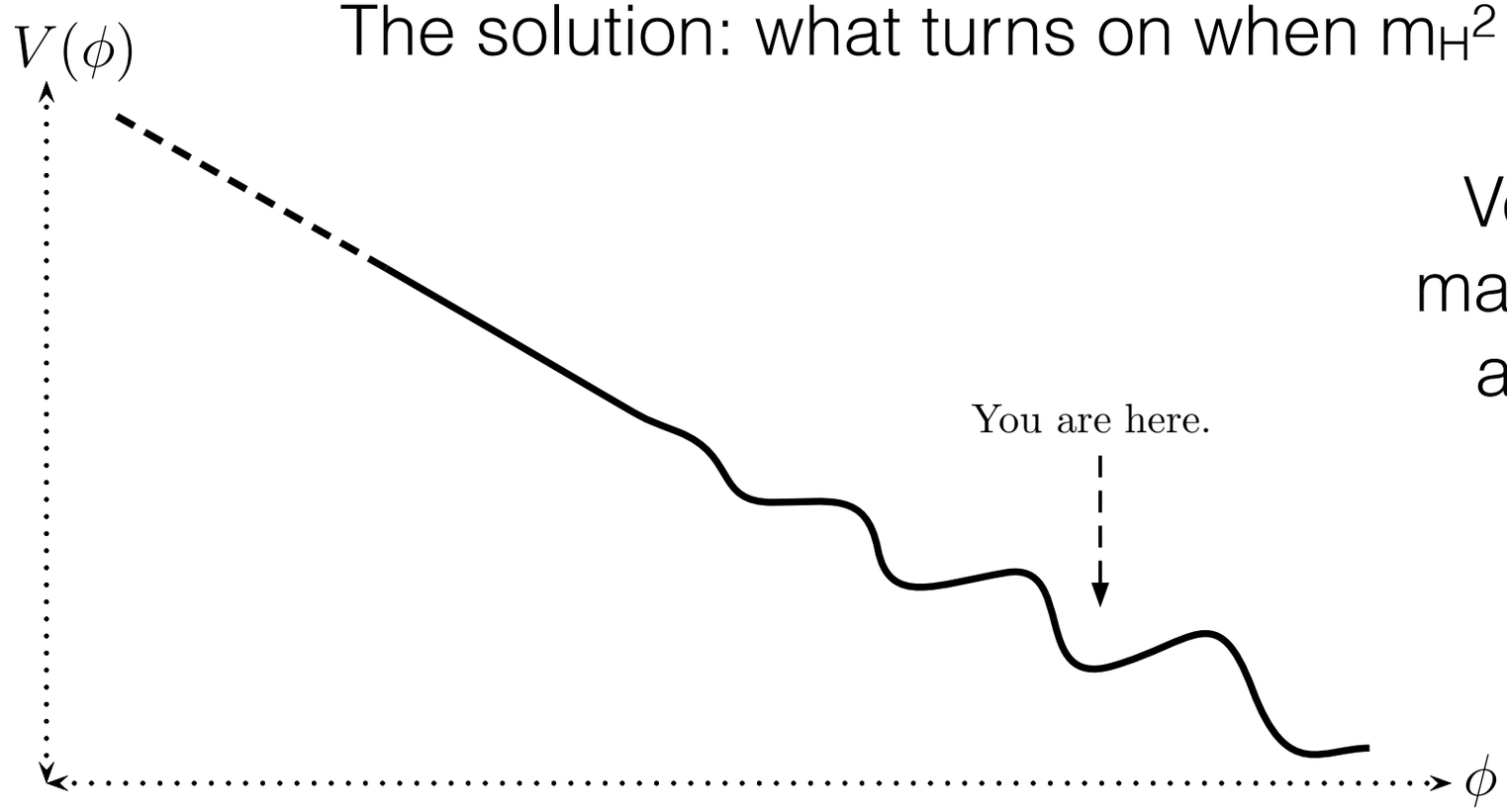
See e.g. talks by G. Watts, T. Adams, P. Ilten

Relaxion

What if the weak scale is selected by dynamics, not symmetries?

The idea: couple Higgs to field whose minimum sets $m_H=0$
The problem: How to make $m_H=0$ a special point of potential?

The solution: what turns on when m_H^2 goes negative?



Vev gives quark masses which give axion potential.

"Relaxion"

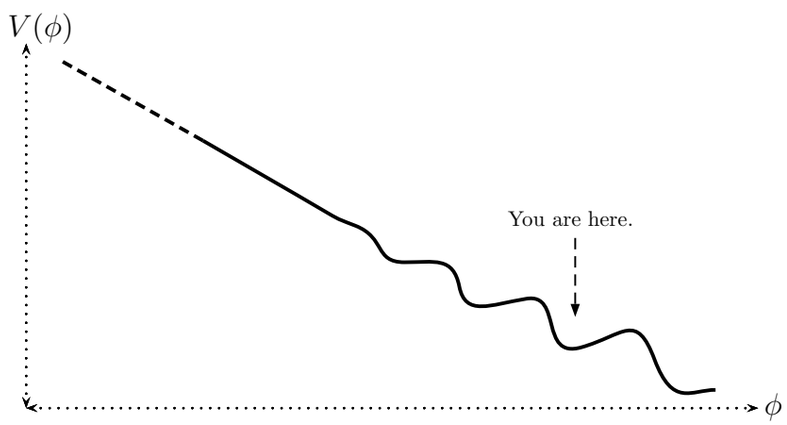
[Graham, Kaplan, Rajendran '15]

But: immense energy stored in evolving field, need dissipation.

[Graham, Kaplan, Rajendran '15]

Relaxion

Simplest version: use an axion coupled to QCD during inflation.



$$(-M^2 + g\phi)|H|^2 + V(g\phi) + \frac{1}{32\pi^2}\frac{\phi}{f}\tilde{G}^{\mu\nu}G_{\mu\nu}$$

$$\Rightarrow \left(-M^2 + g\phi\right)|H|^2 + V(g\phi) + \Lambda^4(H)\cos\left(\phi/f\right)$$

Viable for Higgs + non-compact axion + inflation w/

- Very low Hubble scale ($\ll \Lambda_{QCD}$)
- 10 Giga-years of inflation

Various other subtleties regarding technical naturalness, CC, avoidance of fine-tuning to inflationary sector; need to solve strong CP problem

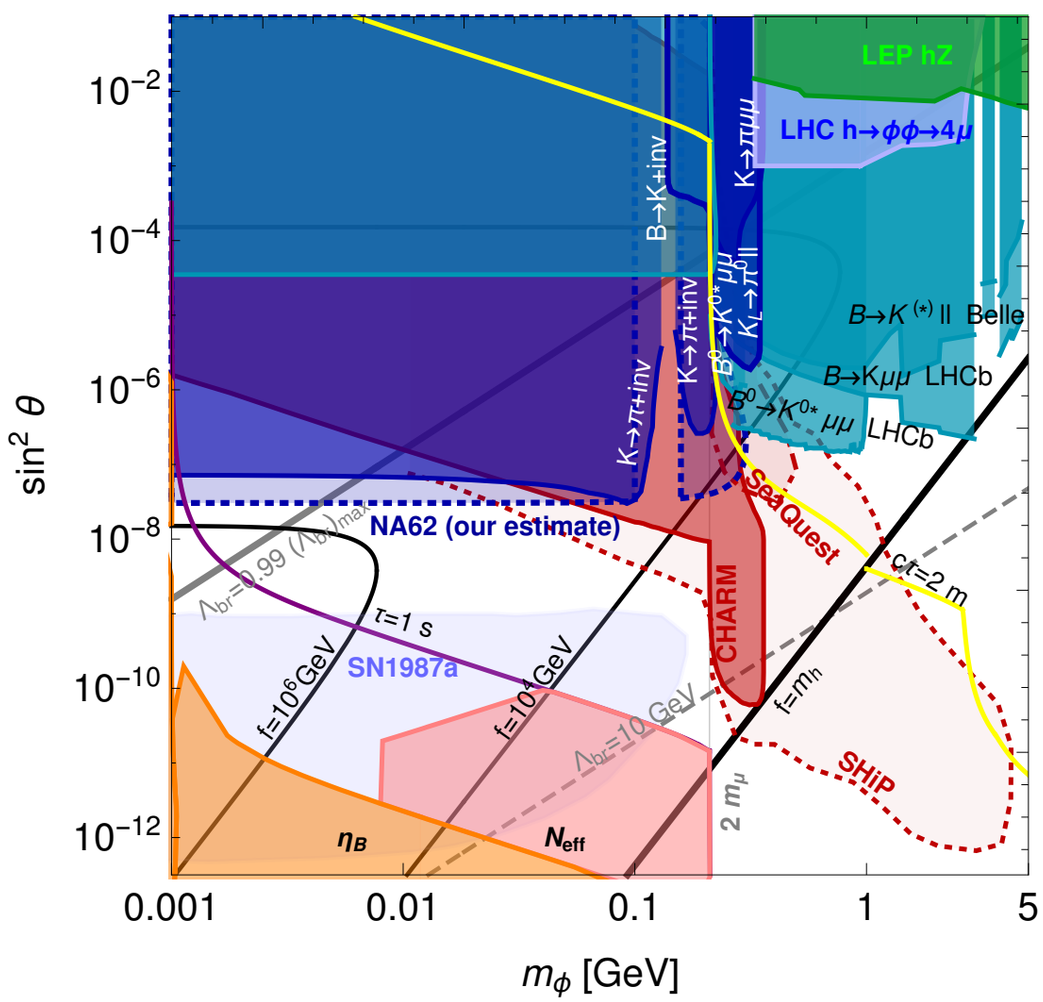
Higgs is SM-like, but there is a new singlet Higgs coupled via $g\phi|H|^2$ and $\Lambda^4(H)\cos\left(\phi/f\right)$

The Relaxion Higgs

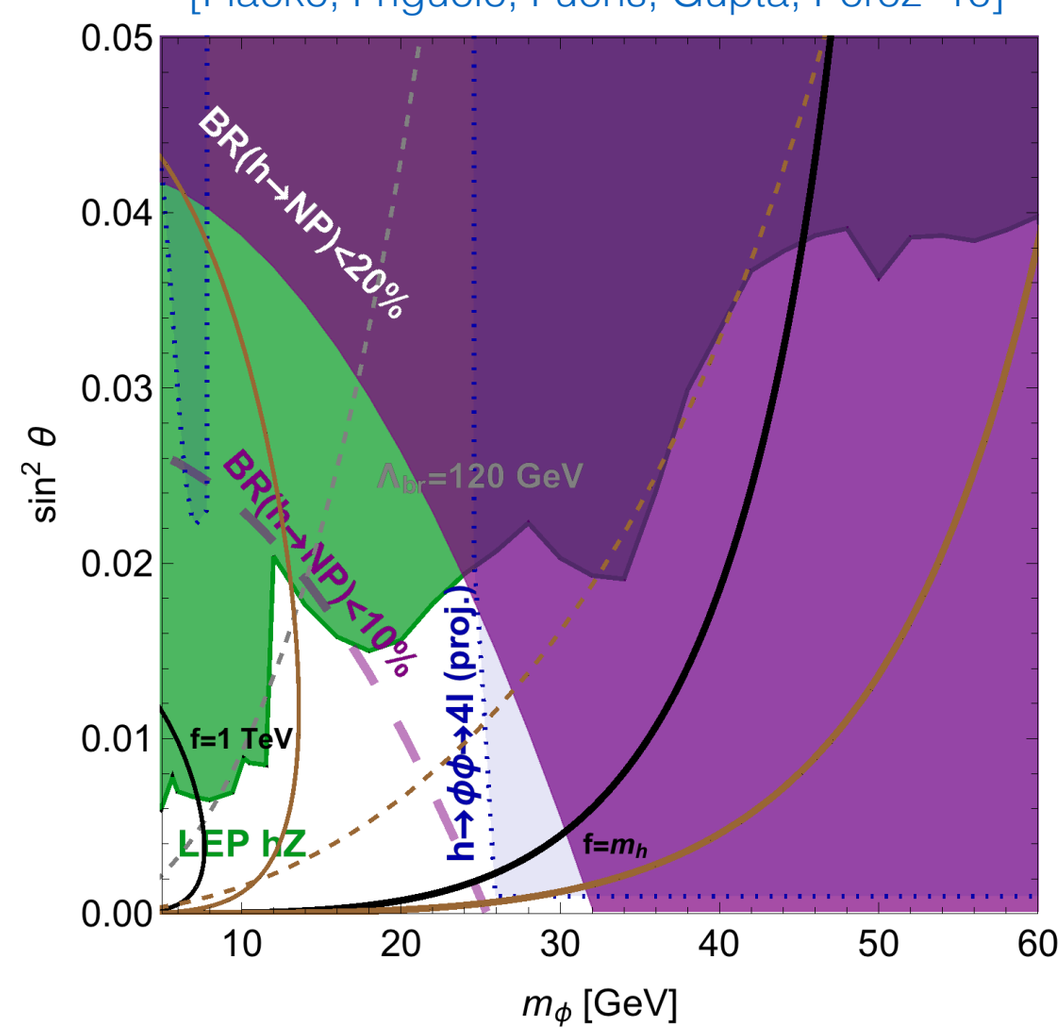
$\Lambda^4(H)\cos(\phi/f)$ gives ϕ - H mixing* w/ $\sin\theta \simeq \frac{y_u f_\pi^3}{m_h^2 f}\sin\left(\frac{\langle\phi\rangle}{f}\right)$

Signatures: very light, weakly coupled singlet Higgs

[Flacke, Friguele, Fuchs, Gupta, Perez '16]



[Flacke, Friguele, Fuchs, Gupta, Perez '16]

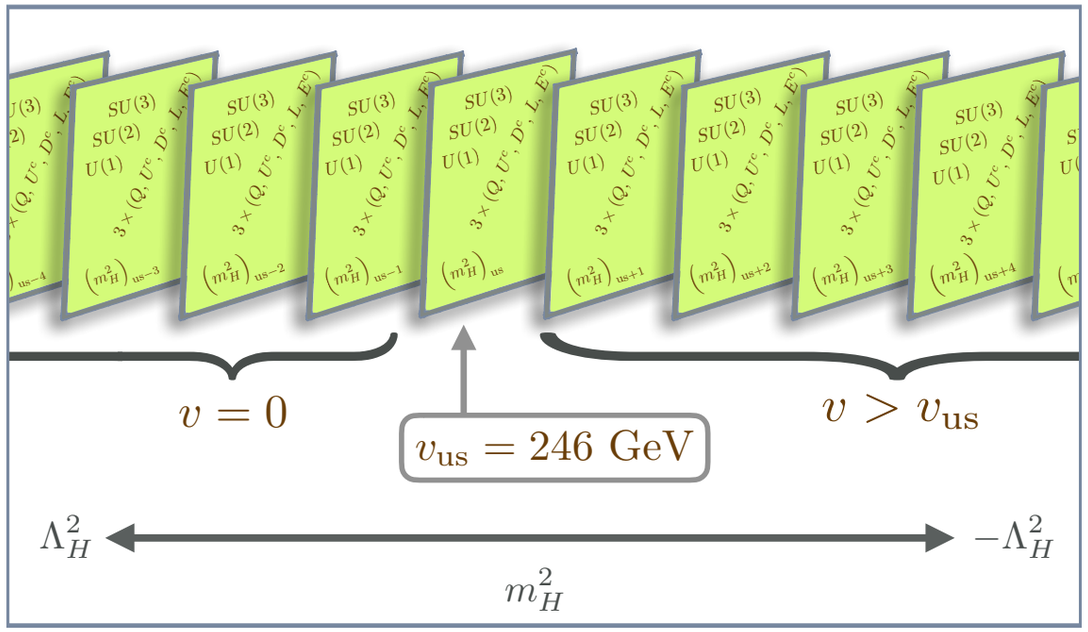


+5th force for m_ϕ < eV & cosmology for eV < m_ϕ < MeV

**assuming ⟨ϕ⟩ breaks CP*

[Arkani-Hamed, Cohen, D'Agnolo, Hook, Kim, Pinner '16]

NNaturalness

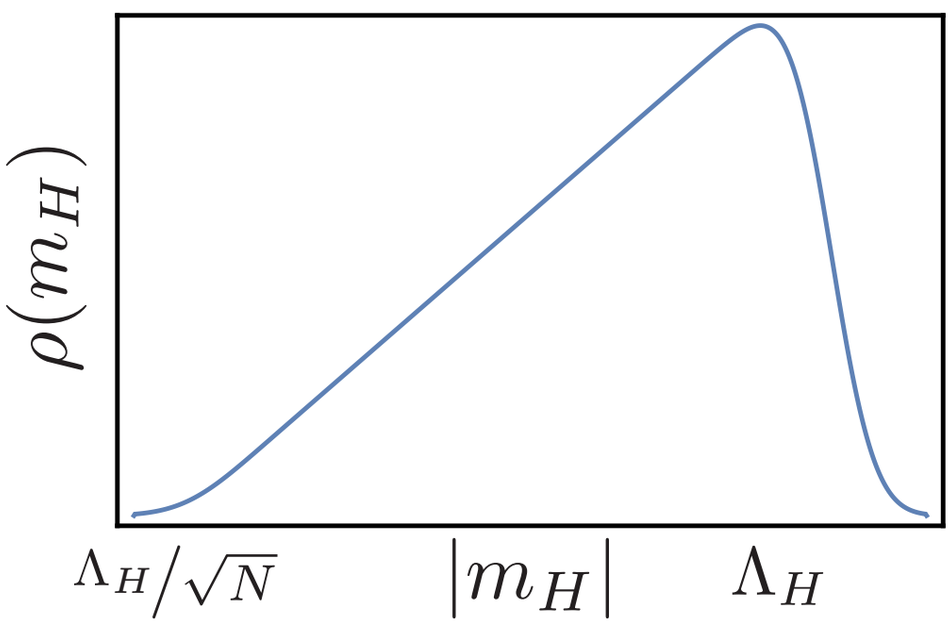


N copies of the SM

High Higgs cutoff Λ_H, high gravity cutoff Λ_G

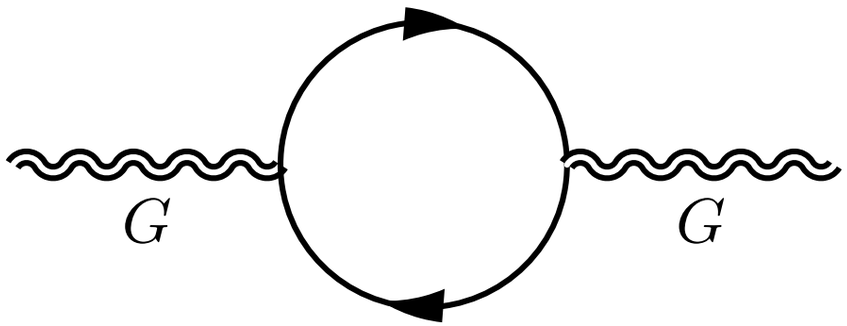
Two effects:

1. Random UV contributions → flat distribution of m_H^2 between $\pm\Lambda_H^2$



At least 1 copy w/ $|m_H| \sim \Lambda_H/\sqrt{N}$

2. Large number of species renormalizes Planck scale (e.g. graviton wavefunction renorm.)



Gravitational strong coupling scale Λ_G below M_{Pl}

$$M_{Pl}^2 \sim N\Lambda_G^2$$

NNaturalness

Scale separation from large N:

M_{Pl}

$\uparrow$

$\sqrt{N}$

$\downarrow$

Λ_G

Λ_H

$\uparrow$

$\sqrt{N}$

$\downarrow$

$|m_H|_0$

For example:
One copy w/ weak-scale Higgs for

N=10^{16}:
$\Lambda_H = 10^{10}$ GeV
$\Lambda_G = 10^{10}$ GeV
(That's it.)

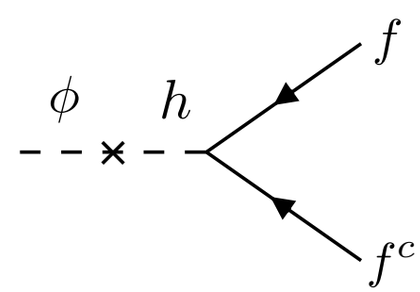
N=10^4:
$\Lambda_H = 10^4$ GeV
$\Lambda_G = 10^{16}$ GeV
(SUSY or compositeness at Λ_H)

Now…why does the copy with the smallest m_H dominate?
Cosmology.

Reheaton ϕ starts universe via $\phi\,|H_i|^2$ couplings

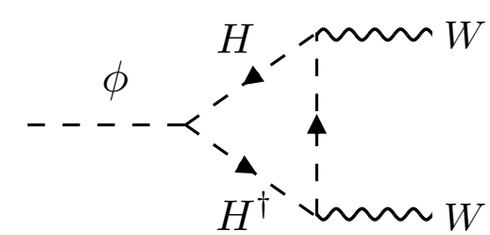
Decays (provided $m_\phi < |m_{H_i}|$)

$m^2_{H,i} < 0$



$$\Gamma \propto \frac{1}{m^2_{H,i}}$$

$m^2_{H,i} \geq 0$



$$\Gamma \propto \frac{1}{m^4_{H,i}}$$

Preferentially reheats copy w/ smallest $|m_H|$ & $m_H^2<0$

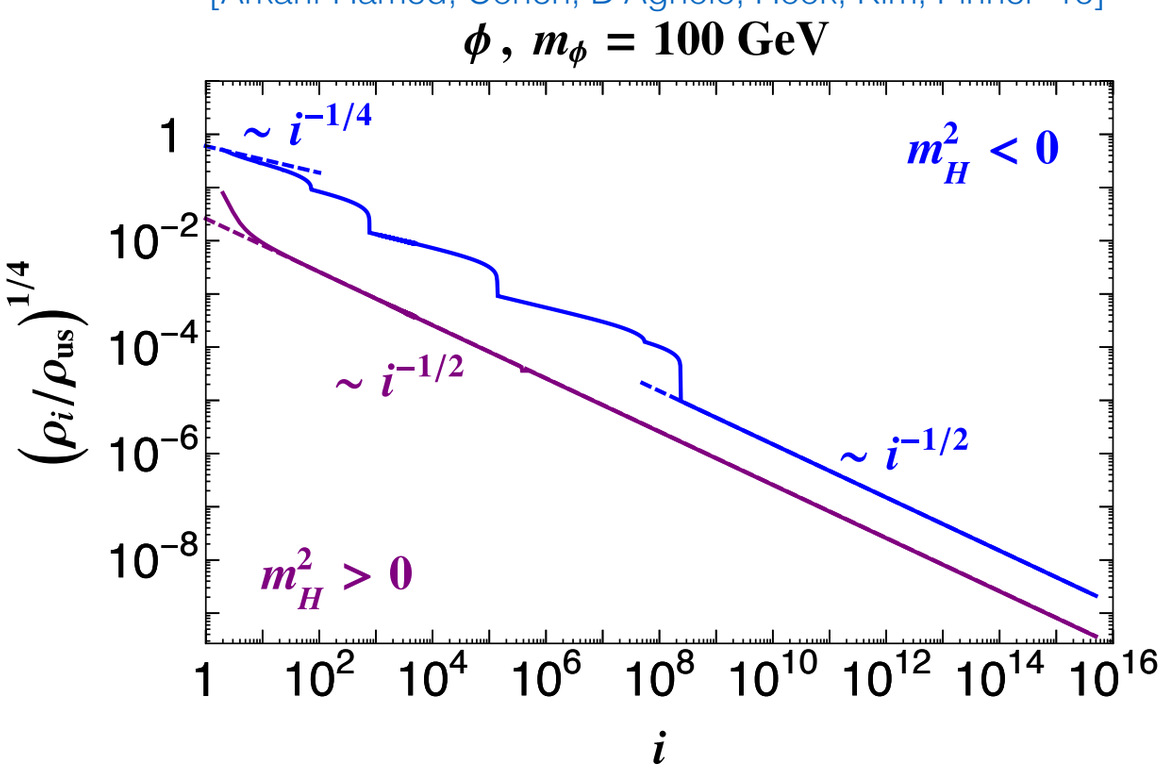
N Higgses…in the sky

All sectors reheated by some amount ⇒ dark radiation

$$\frac{\rho_i}{\rho_{\rm us}} = \frac{\Gamma_i}{\Gamma_{\rm us}}$$

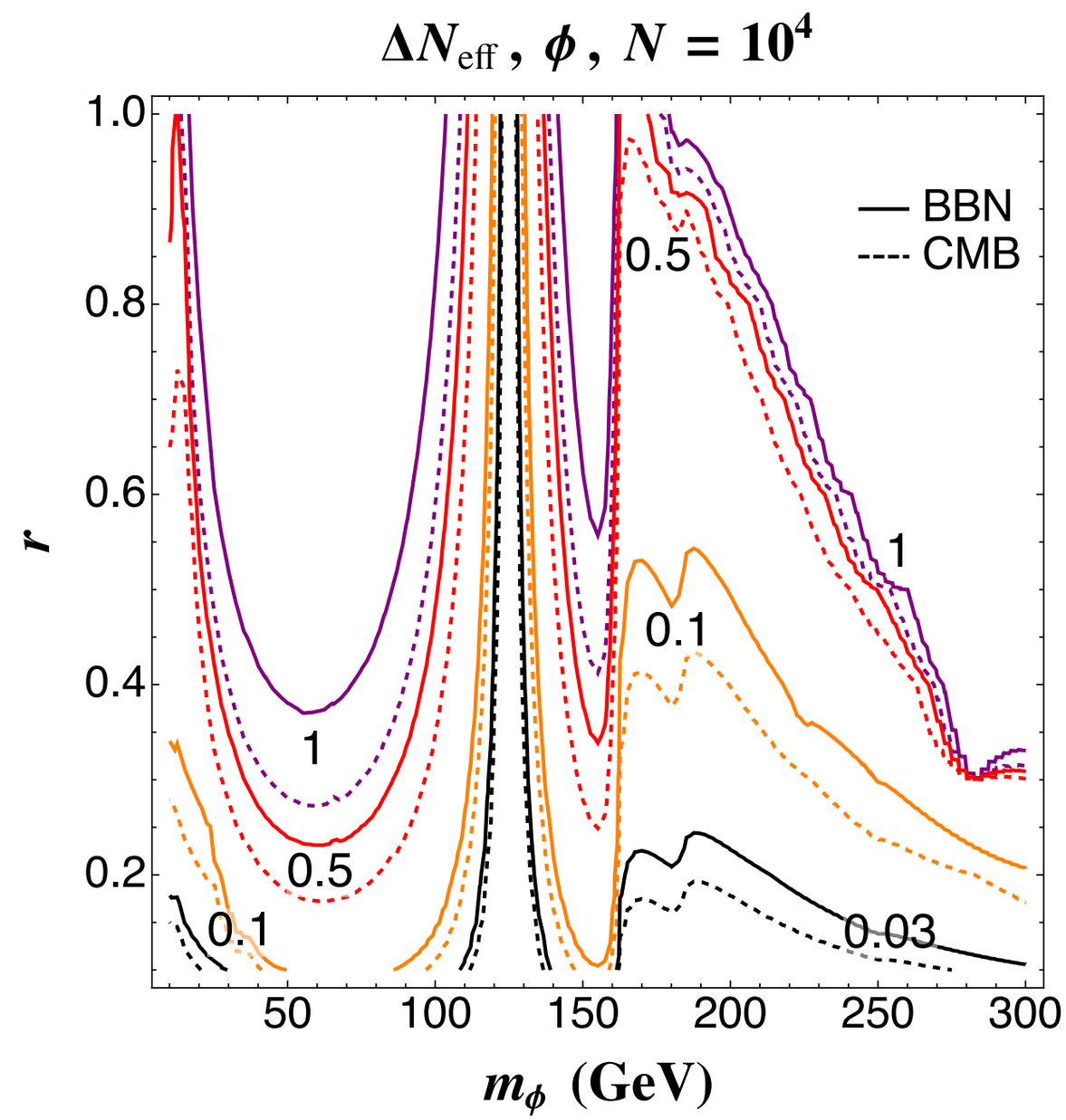
Dominated by sectors with similar scales

[Arkani-Hamed, Cohen, D'Agnolo, Hook, Kim, Pinner '16]



Primary signals in dark radiation, extensive coverage by CMB-S4

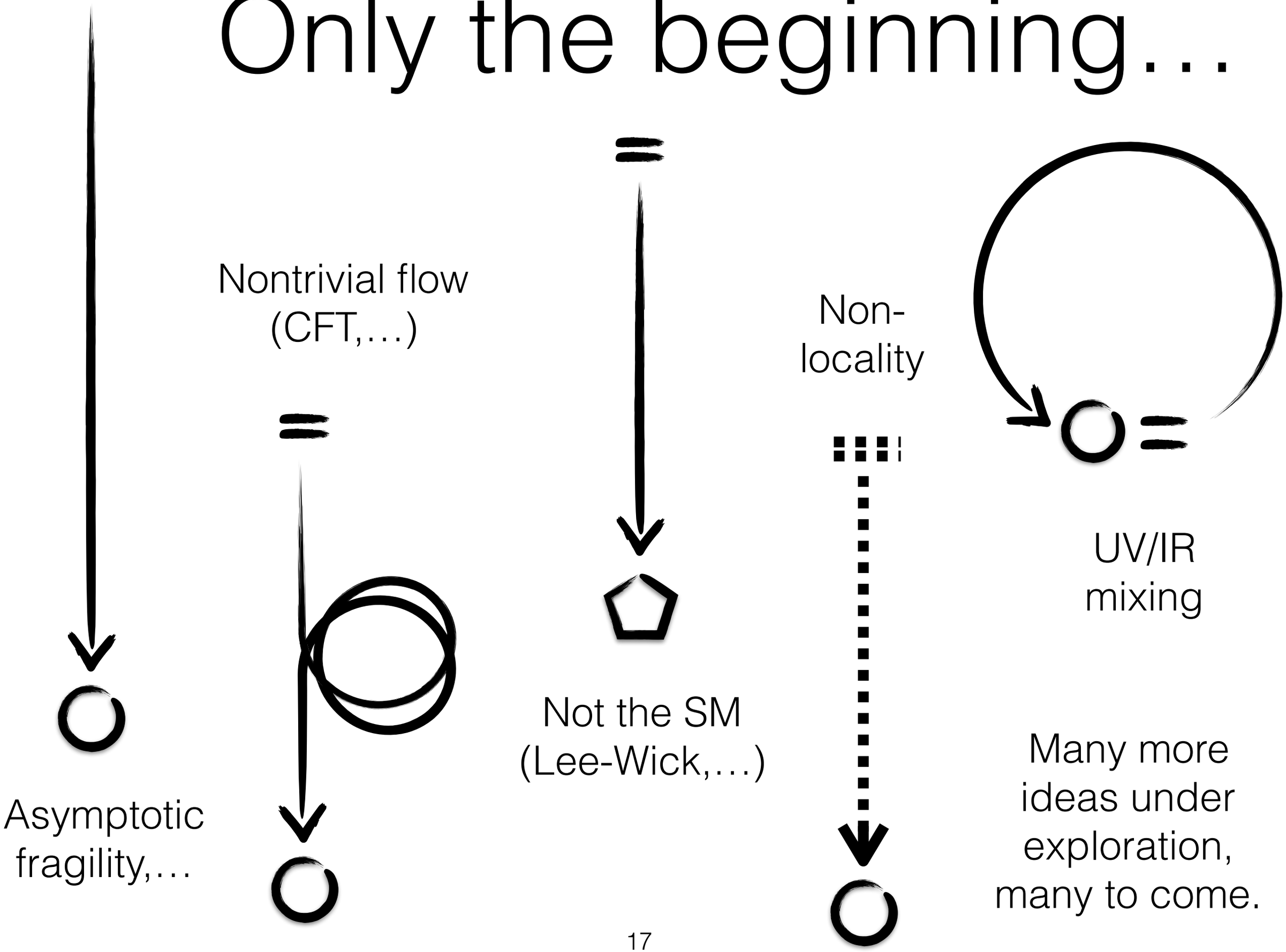
[Arkani-Hamed, Cohen, D'Agnolo, Hook, Kim, Pinner '16]



(r=1 ↔ flat m_H^2; r<1 ↔ larger splitting)

NB, similar mechanism for Twin Higgs cosmology
[NC, Koren, Trott '16; Chacko, NC, Fox, Harnik '16]

Only the beginning…



Conclusions

- Many reasons to expect something beyond the SM Higgs, but many “older” models of elementary & composite Higgs bosons under strain from null results.

- Worthwhile to continue exploring as much as possible, but also motivates qualitatively new mechanisms and models.

- Beginning of an era of theory exploration beyond established paradigms: neutral naturalness, relaxion, NNaturalness, …

- New solutions to the hierarchy problem leading to new signals *across the energy, intensity, and cosmic frontiers*.

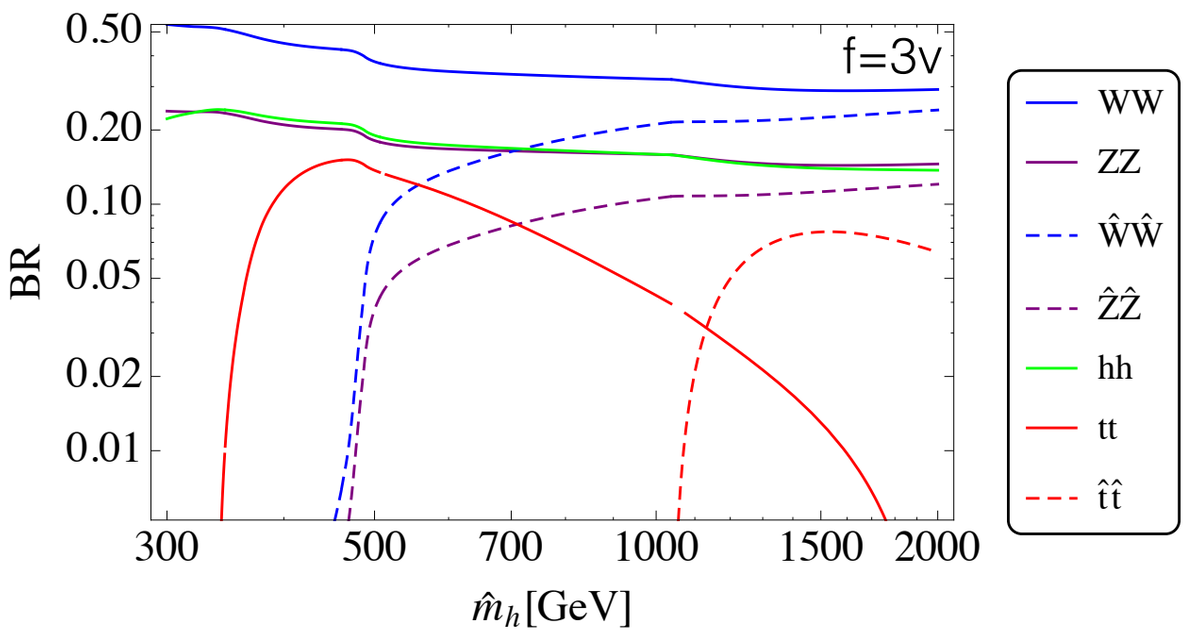
- Thus far we have only scratched the surface…

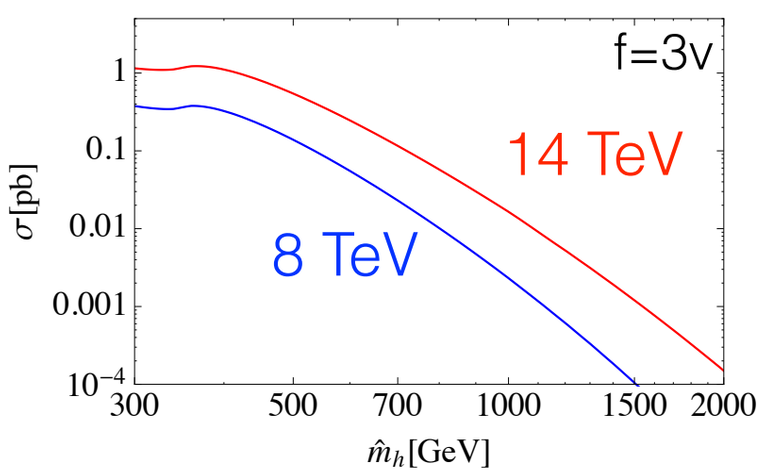
Thank you!

Bonus material

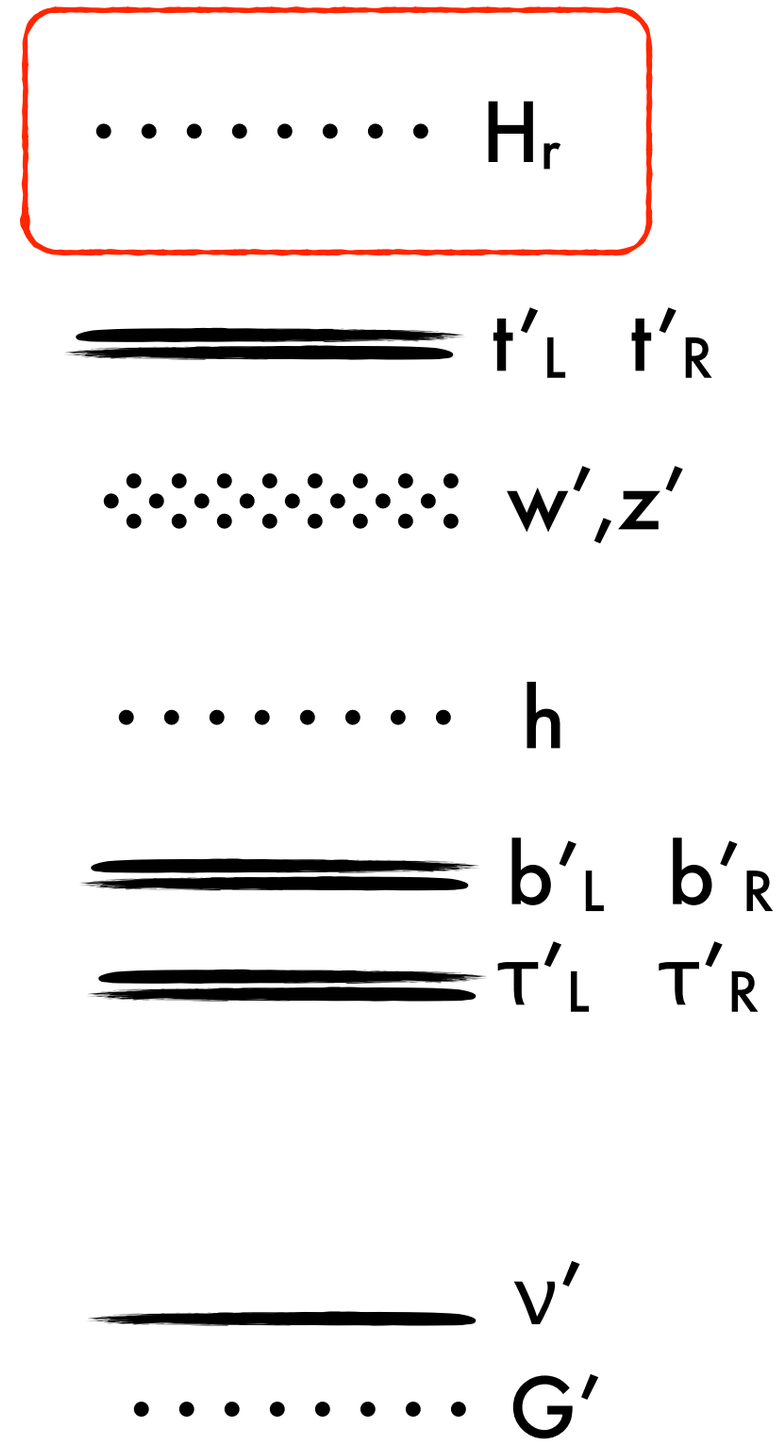
Heavy Twin Higgs

- Heavy radial mode may be accessible. ~TeV scale state strongly preferred by naturalness, precision electroweak.
- At 0th order, *singlet Higgs* w/ 1:3:3 hh:SM:Invisible



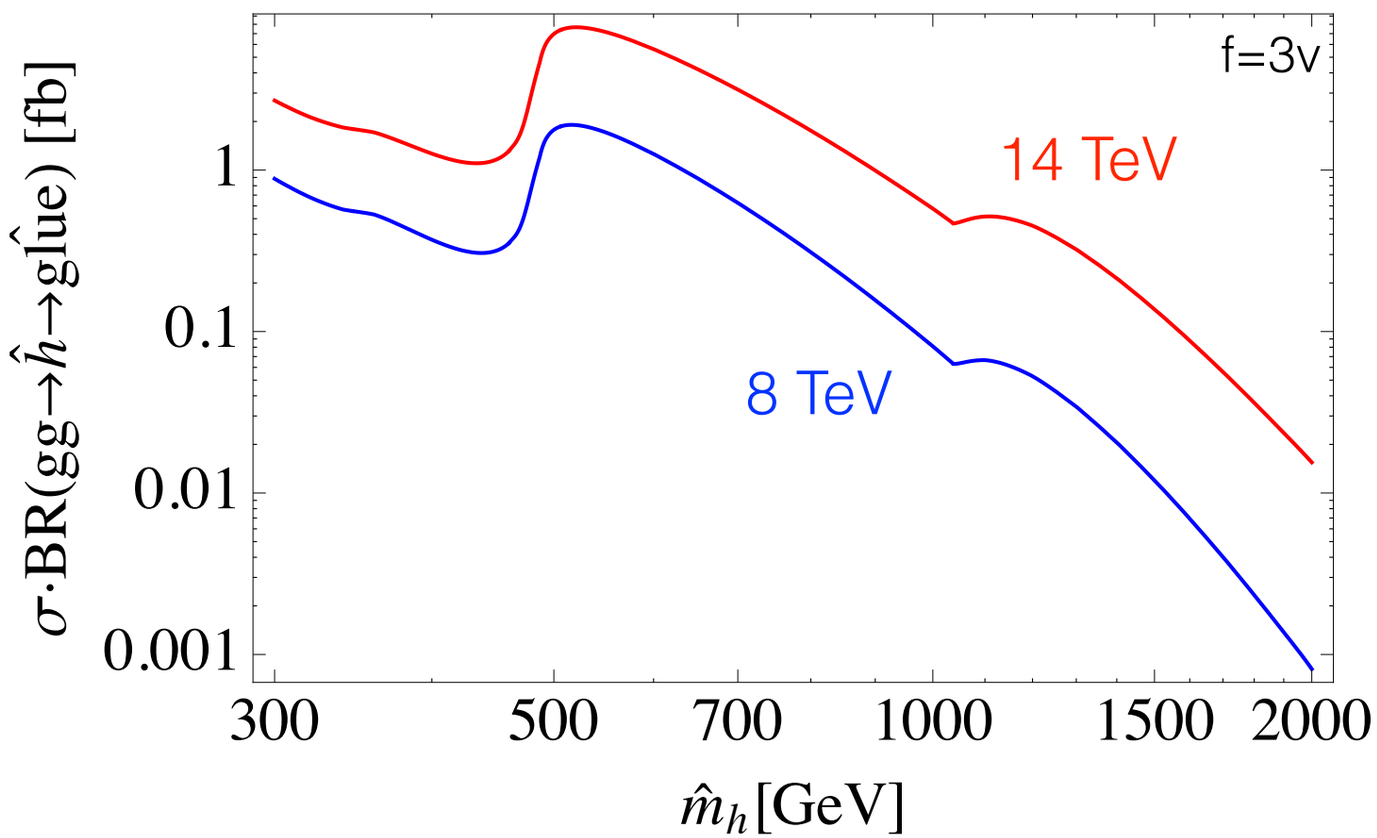


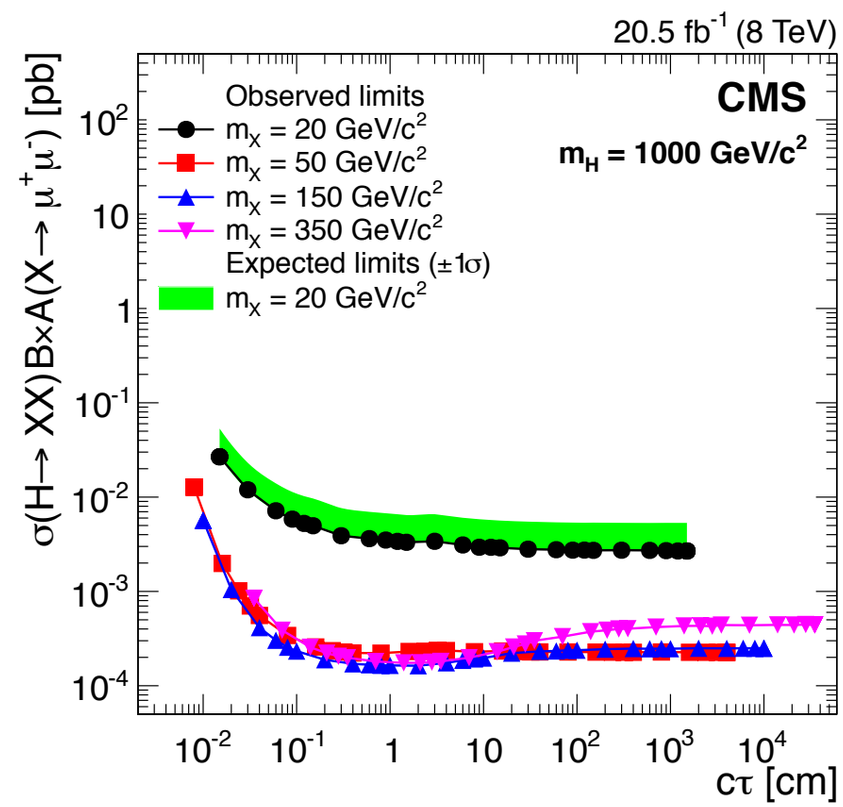
Current searches not yet constraining; very interesting for 13/14 TeV LHC



Exotic Decays of a Twin Higgs

Most effort has focused on production via h(125).
But glueballs also produced in decays of heavy twin Higgs:





Rate comparable to h(125), but more striking kinematics.
Also an open mode for higher glueball masses.

Study of discovery potential in progress [NC, Gori, Redigolo]

[Graham, Kaplan, Rajendran '15]

QCD' Relaxion

Viable alternative: dark QCD + axion

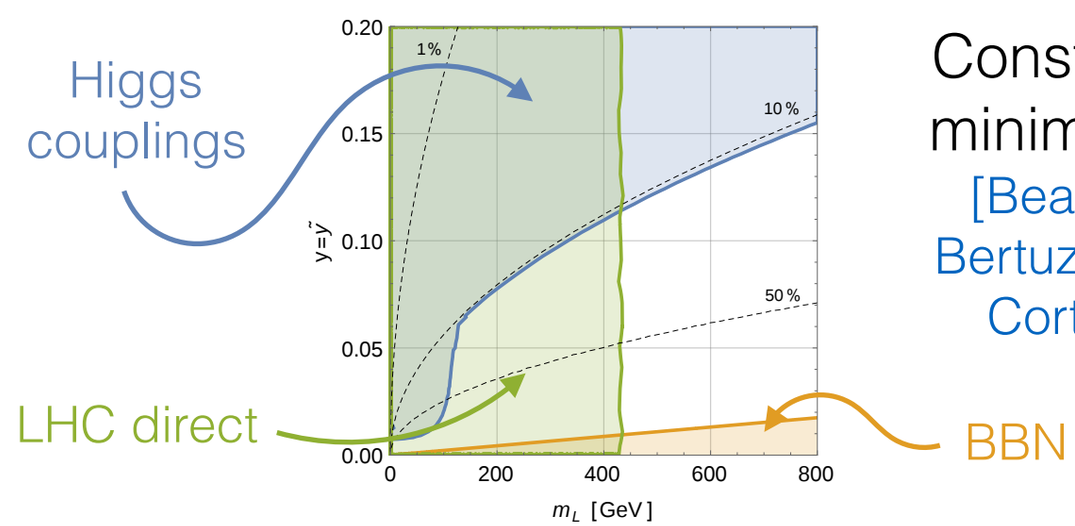
Field	$SU(3)_N$	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
L	$\square$	$-$	$\square$	$-1/2$
L^c	$\overline{\square}$	$-$	$\square$	$+1/2$
N	$\square$	$-$	$-$	0
N^c	$\overline{\square}$	$-$	$-$	0

I.e. axion of a different SU(3); need to tie in Higgs vev

Bounds on mechanism imply $$f_{\pi'} < v \;\text{ and }\; m_L < \frac{4\pi v}{\sqrt{\log(M/m_L)}}$$

New confining physics near weak scale!

Couples to Higgs, electroweak bosons; hidden valley signatures. Various possibilities.



Constraints on minimal model [Beauchesne, Bertuzzo, Grilli di Cortona '17]

Rich hidden valley physics [Strassler, Zurek '06], many signatures to explore