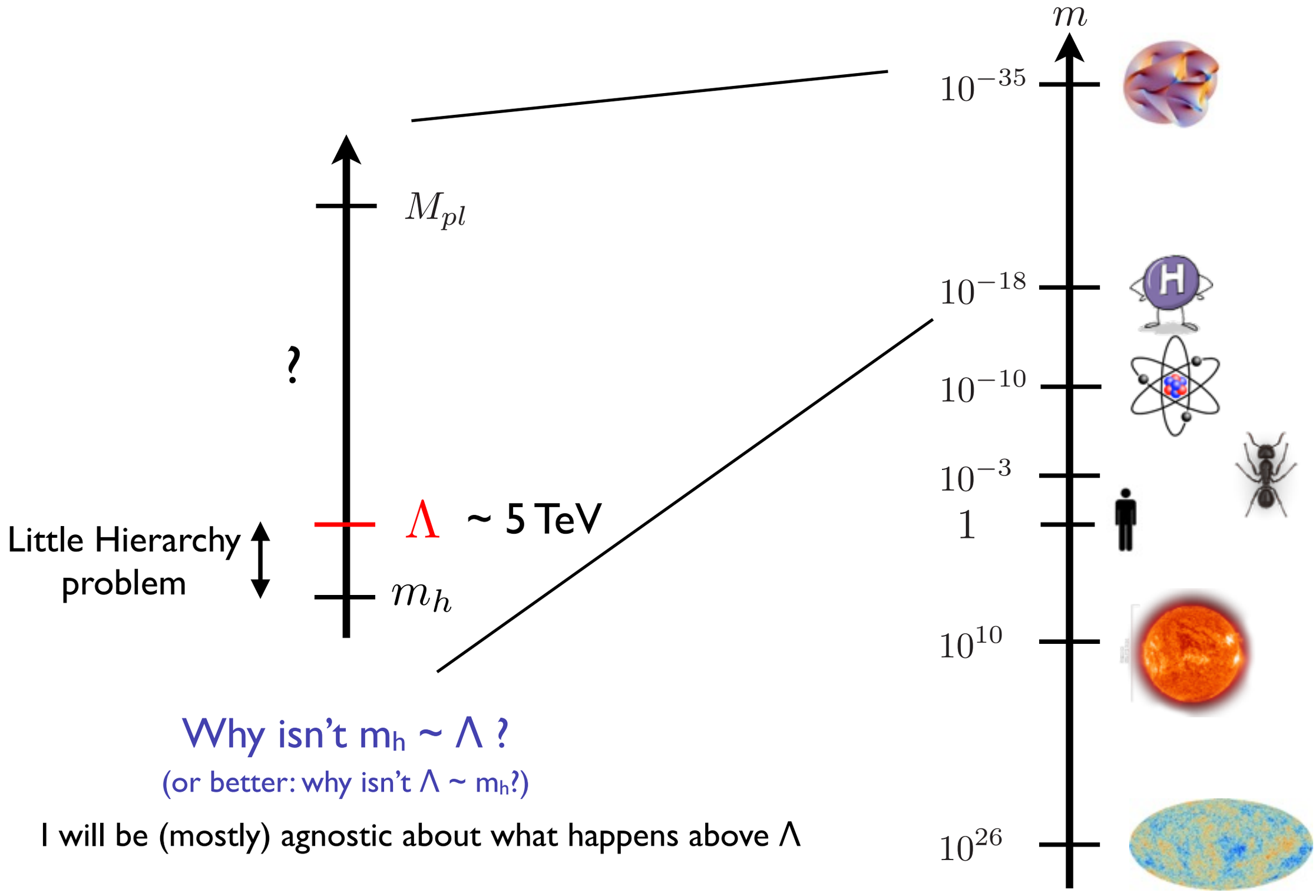
Models and signatures of Neutral Naturalness

Simon Knapen
UC Berkeley & LBL

@ UC Davis 10 / 19 / 15

1411.7393: N. Craig, SK, P. Longhi
1410.6808: N. Craig, SK, P. Longhi
N. Craig, SK, P. Longhi, M. Strassler: in progress
M. Freytsis, SK, D. Robinson, Y. Tsai: in progress

Little Hierarchy problem



Why isn't $m_h \sim \Lambda$?

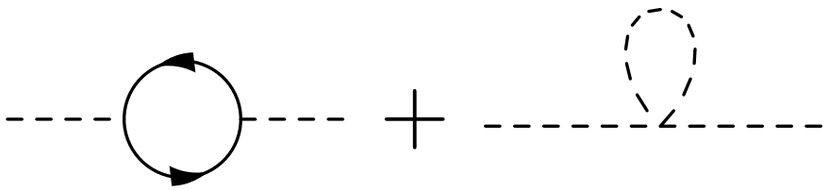
(or better: why isn't $\Lambda \sim m_h$?)

I will be (mostly) agnostic about what happens above Λ

Top partner 'theorem'

- Symmetry based solutions require a top partner
- The usual suspects: SUSY or global symmetry

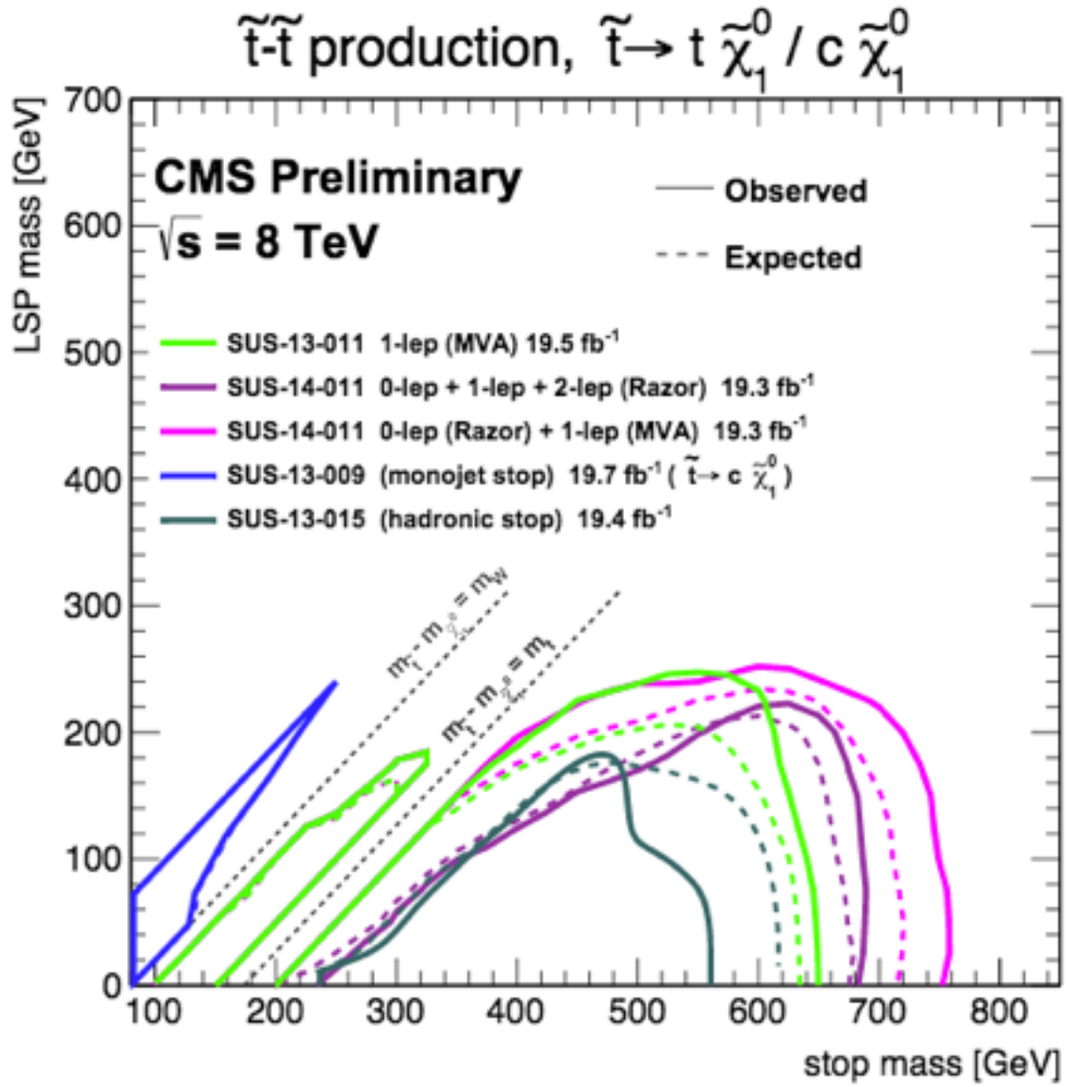
supersymmetry



➡ Commute with QCD

➡ Top partner must be colored

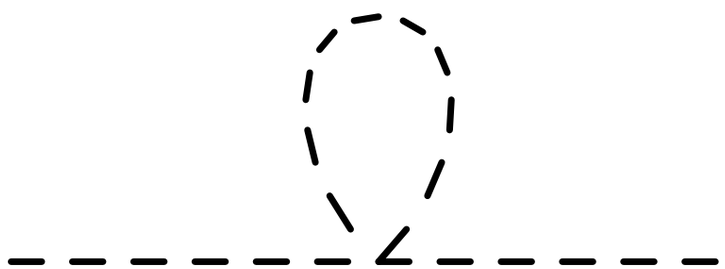
Can we relax this assumption?



Canceling the divergence

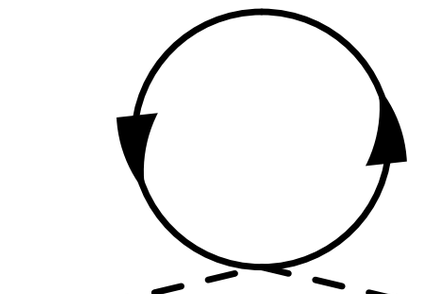
Bottom-up

supersymmetry



$$\sim \frac{N_c}{16\pi^2} y_t^2 \Lambda^2$$

global symmetry



$$\sim \frac{N_c}{16\pi^2} y_t^2 \Lambda^2$$

At 1 loop, only the number of colors enters

Top-down

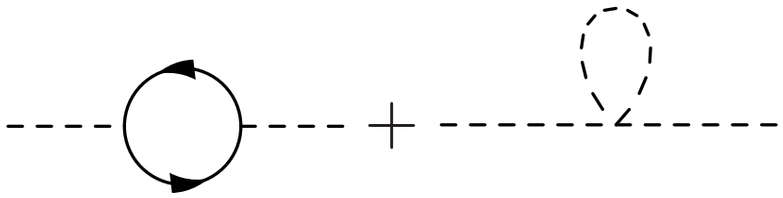
Charge the top under a symmetry that does not commute with QCD

'Accidental' symmetry

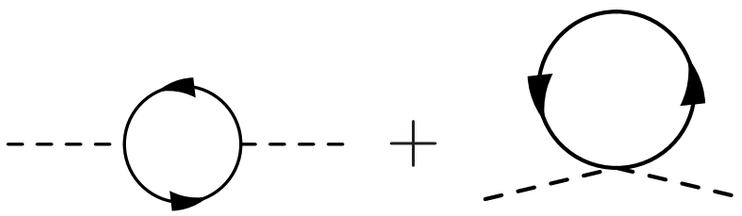
What are the rules?

Exact symmetries

softly broken SUSY



SB global symmetry



Very well studied

Accidental symmetries

Accidental SUSY

- Folded susy
- …

Orbifolds provide a roadmap

This talk

Accidental global symmetry

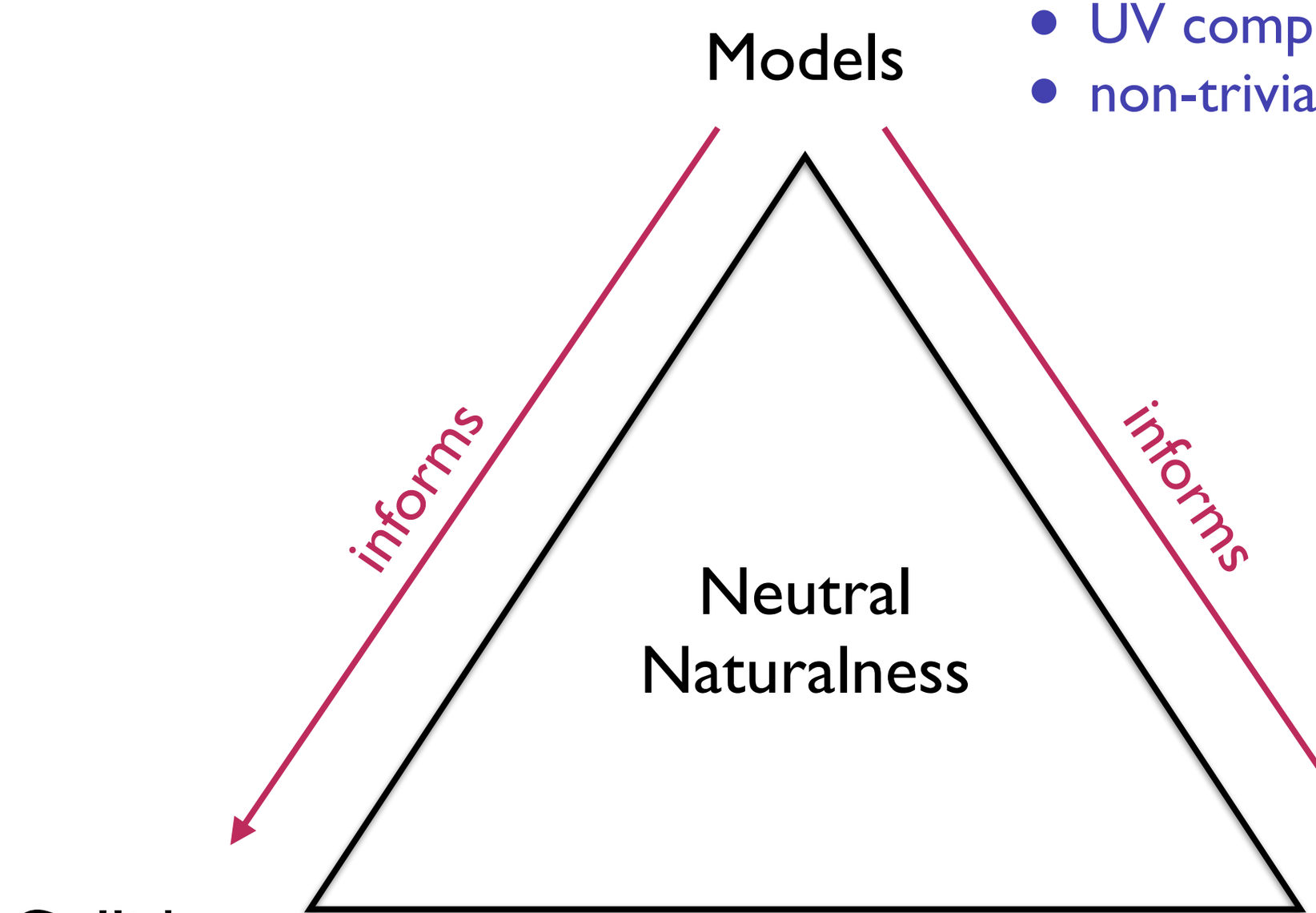
- Twin Higgs
- Quirky Little Higgs
- …

What sits here?

Only a few data points

0609152: G. Burdman, Z. Chacko, H. Goh, R. Harnik
0506256: Z. Chacko, H. Goh, R. Harnik
0812.0843: H. Cai, H. Cheng, J. Terning

Outline

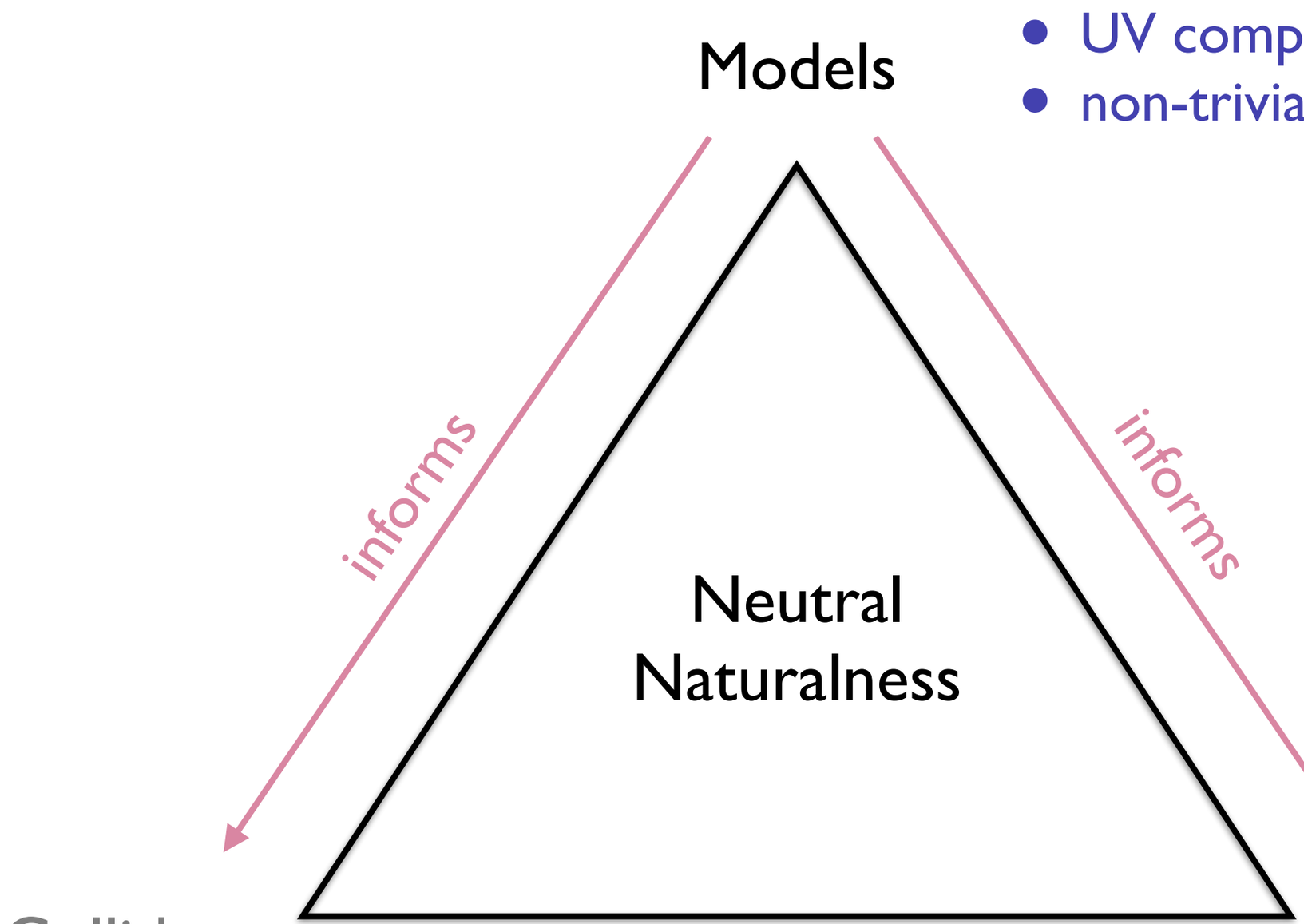


- UV completions?
- non-trivial cancellations?

- LHC
- future colliders
- Intensity frontier

- Dark matter?
- Constraints from BBN, CMB?

Outline



- UV completions?
- non-trivial cancellations?

Colliders

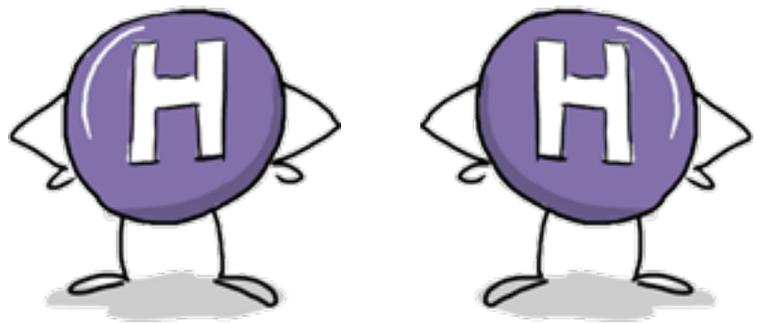
- LHC
- future colliders
- Intensity frontier

Cosmology

- Dark matter?
- Constraints from BBN, CMB?

Z. Chacko, H, Goh, R. Harnik, '05
...

The Twin Higgs



Take H in the fundamental of a global SU(4)

$$V(H) = -m^2|H|^2 + \lambda|H|^4$$

Spontaneously breaks SU(4) → SU(3): 7 goldstones

Now gauge $SU(2)_A \times SU(2)_B \subset SU(4)$ (eat 6 goldstones) $H = \begin{pmatrix} h_A \\ h_B \end{pmatrix}$

$$V(H) \supset \frac{1}{16\pi^2}\frac{9}{4}\Lambda^2\left(g_A^2 h_A^2 + g_B^2 h_B^2\right)$$ Spoils the SU(4) symmetry

Extra ingredient: Z_2 symmetry A ↔ B such that $g = g_A = g_B$

$$V(H) \supset \frac{1}{16\pi^2}\frac{9}{4}g^2\Lambda^2\left(h_A^2 + h_B^2\right) = \frac{1}{16\pi^2}\frac{9}{4}g^2\Lambda^2|H|^2$$

Accidental SU(4) symmetry preserved in the 1 loop effective potential

(quadratic piece only)

The Twin Standard Model

$$[SU(3)_c \times SU(2)_w \times U(1)_Y]^2 \times Z_2$$

$$V(H) \supset -m^2|H|^2 + \lambda|H|^4 + \underbrace{y_t h_A q_A u_A}_{\text{SM top}} + \underbrace{y_t h_B q_B u_B}_{\text{Twin top}}$$

Spontaneously breaks SU(4) → SU(3): 7 goldstones

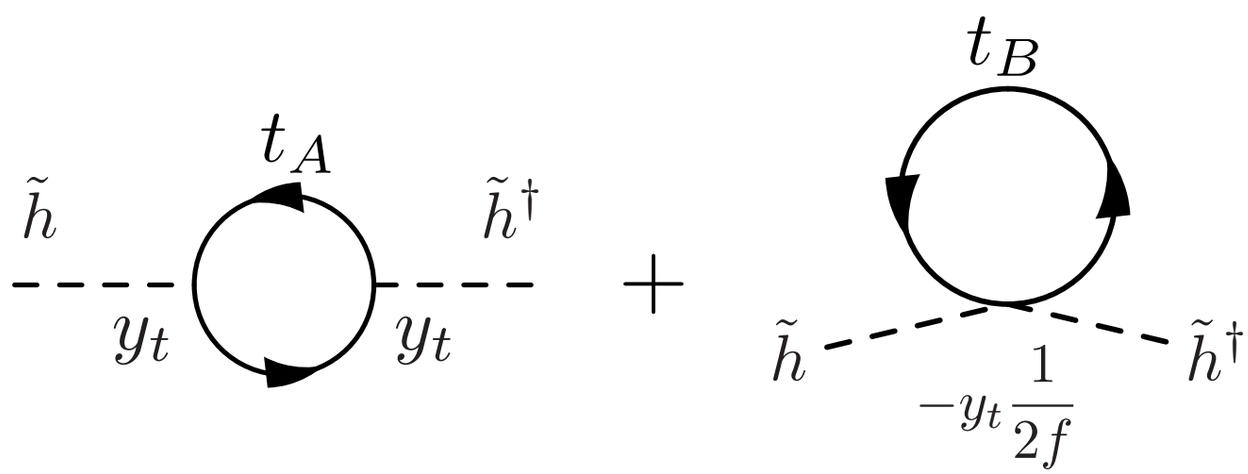
$$H = \begin{pmatrix} h_A \\ h_B \end{pmatrix} = \exp(\frac{i}{f}\Pi) \begin{pmatrix} 0 \\ 0 \\ 0 \\ f \end{pmatrix}$$

$$\Pi = \left(\begin{array}{ccc|c} 0 & 0 & 0 & \tilde{h}_1 \\ 0 & 0 & 0 & \tilde{h}_2 \\ 0 & 0 & 0 & 0 \\ \hline \tilde{h}_1^* & \tilde{h}_2^* & 0 & 0 \end{array}\right) + \cdots$$

$$h_A = i\tilde{h} + \cdots$$

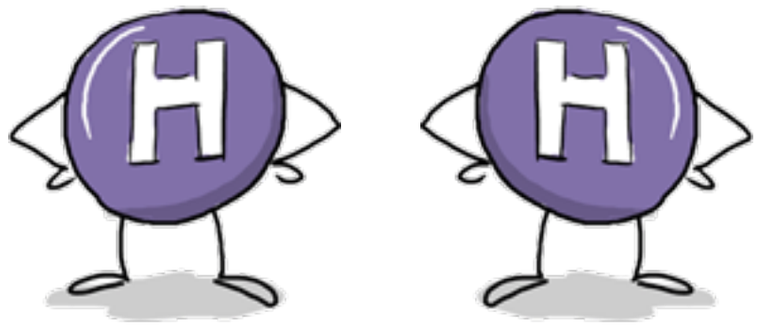
$$h_B = f - \frac{1}{2f}\tilde{h}^\dagger\tilde{h} + \cdots$$

QCD singlet!



Z. Chacko, H, Goh, R. Harnik, '05
...

The general idea



The Higgs is a pseudo goldstone boson of an accidental global symmetry of 1 loop effective potential

The Twin Higgs desperately needs a UV completion around 5 TeV

UV completions

(Or how to stabilize Λ)

Composite Higgs	✓ Natural home of Twin Higgs ✗ Mild tension with EWPT	0811.0394: P. Batra, Z. Chacko 1411.2974: M. Geller, O. Telem 1501.07803: R. Barbieri, et. al. 1501.07890: M. Low, A. Tesi, L. Wang
Supersymmetry	✓ Fully perturbative ✓ m_h ✗ a bit more tuned	0604076: S. Chang, L. Hall, and N. Weiner 0604066: A. Falkowski, S. Pokorski, M. Schmaltz 1312.1341: N. Craig, K. Howe
Orbifolds	✓ SM - Twin unification ✓ Easy to generalize ✗ hard to go above 10 TeV	1411.7393: N. Craig, SK, P. Longhi 1410.6808: N. Craig, SK, P. Longhi

Orbifolds

Orbifolds in field theory

Map between two field theories: "Mother" → "Daughter"
(Mother does not necessarily flow to the daughter)

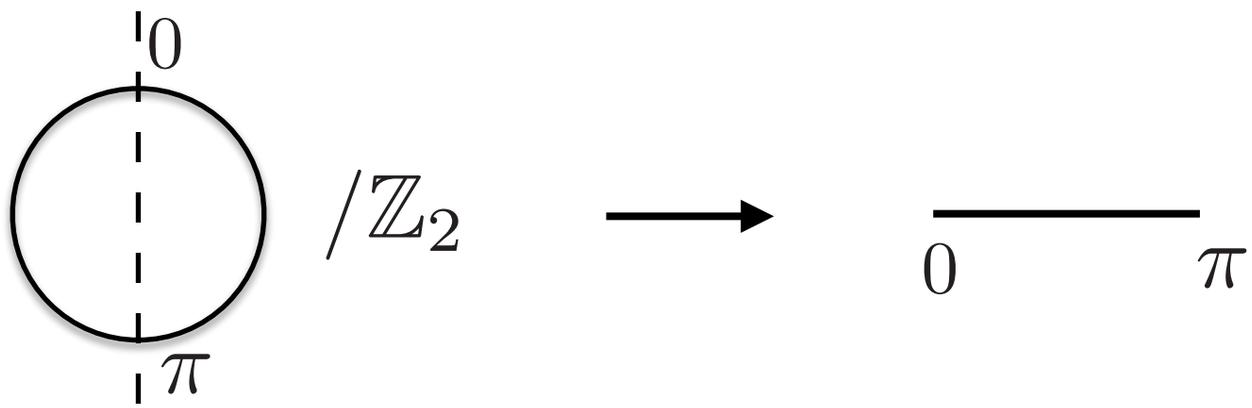
Geometric interpretation

Quotient space of manifold modded out by a discrete group $\mathcal{G}$

$$\mathcal{G}: \quad \phi^i[y] \quad \rightarrow \quad R(g)_{ij}\ \phi^j[g(y)]$$

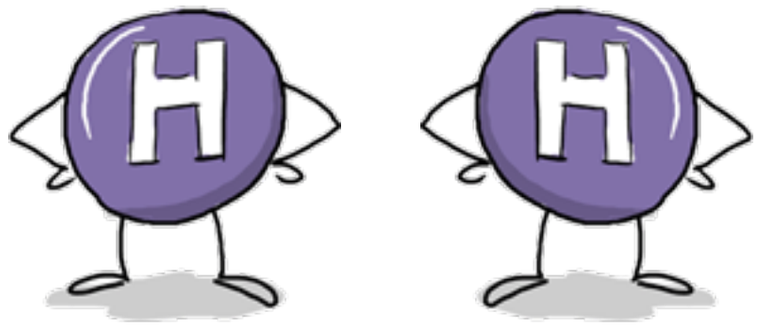
Need a space time fixed point: $g(y_0) = y_0$

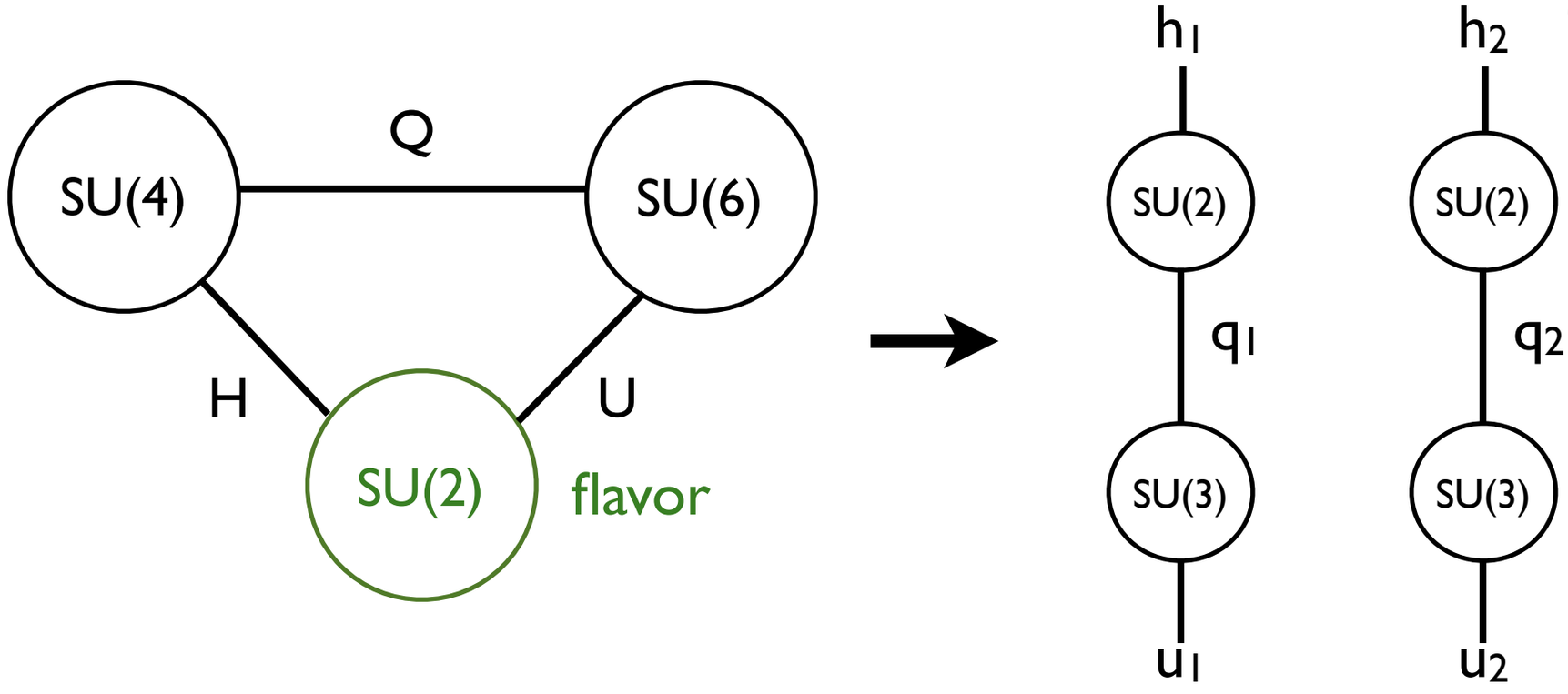
Example: $S^1/\mathbb{Z}_2$



Twin Higgs as an orbifold

$$V(H) = -m^2 \mathrm{Tr}\ H^\dagger H + \lambda \left[\mathrm{Tr}\ H^\dagger H\right]^2$$



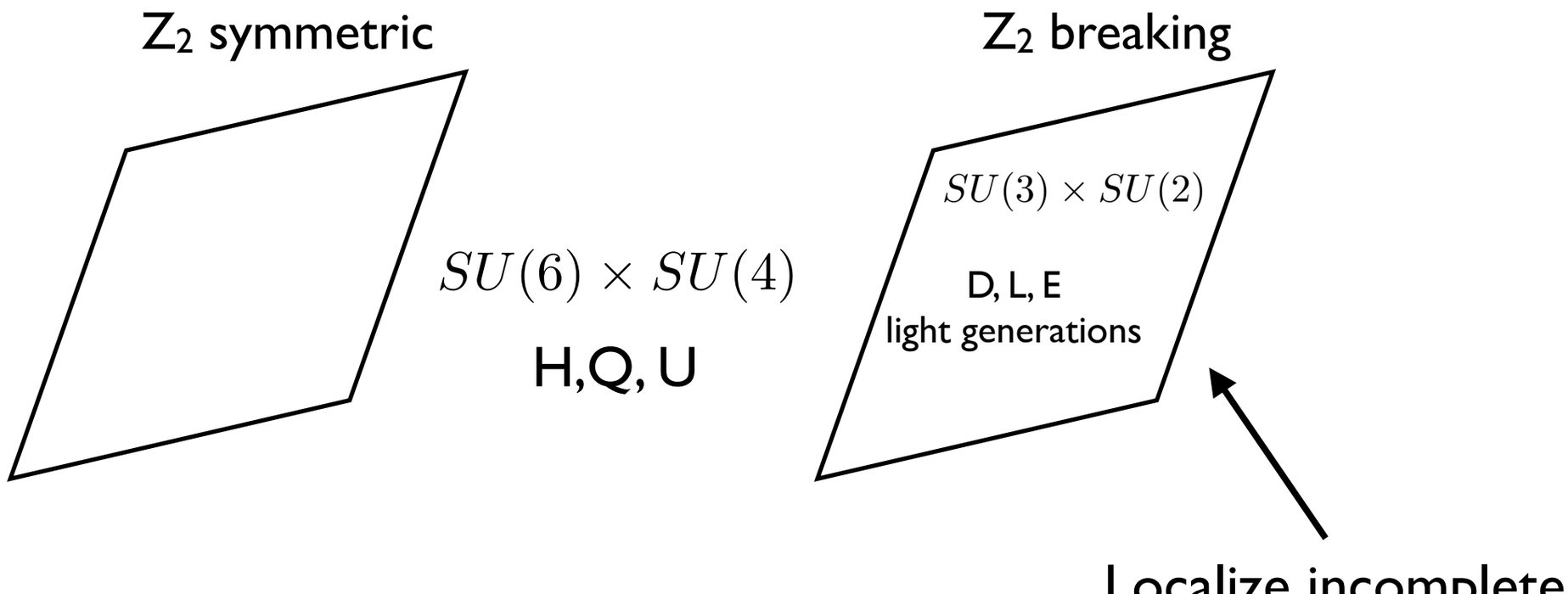


$$SU(6) \times SU(4) \times SU(2)/\mathbb{Z}_2 \quad \rightarrow \quad [SU(3) \times SU(2)]^2 \times U(1) \times U(1) \times \mathbb{Z}_2$$

Completely analogous to orbifold GUT's: $SU(5)/\mathbb{Z}_2 \rightarrow SU(3) \times SU(2) \times U(1)$

1411.7393: N. Craig, SK, P. Longhi
1410.6808: N. Craig, SK, P. Longhi

Geometry in 5D



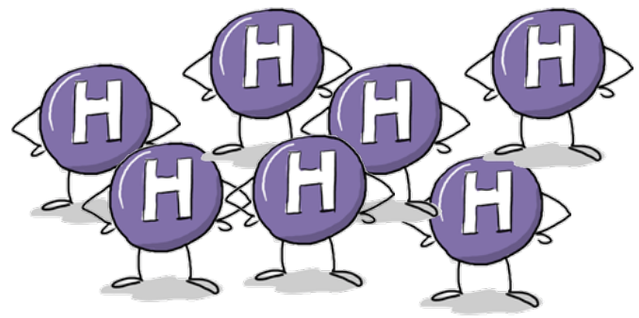
Full unification possible with Trinification or Pati-Salam

(Deconstruction also possible)

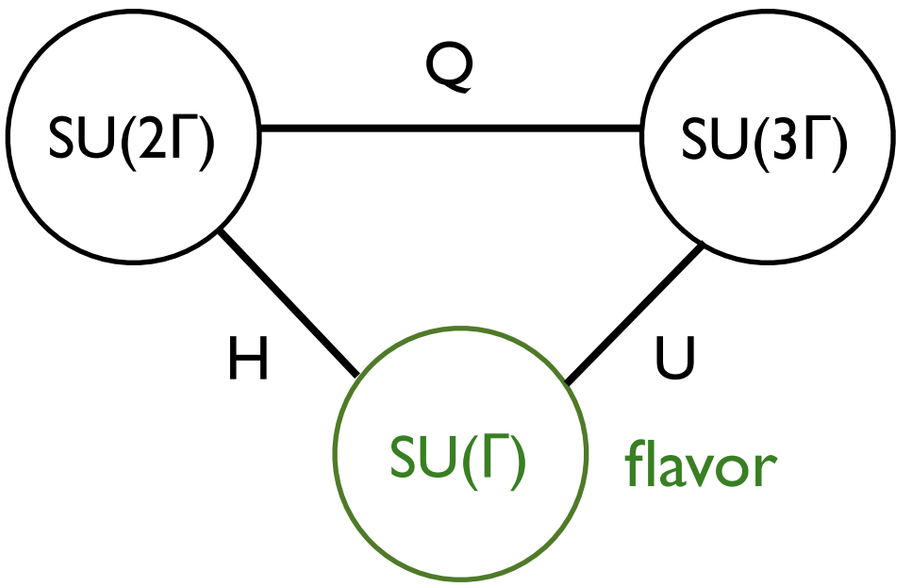
Can we generalize beyond Z_2 ?

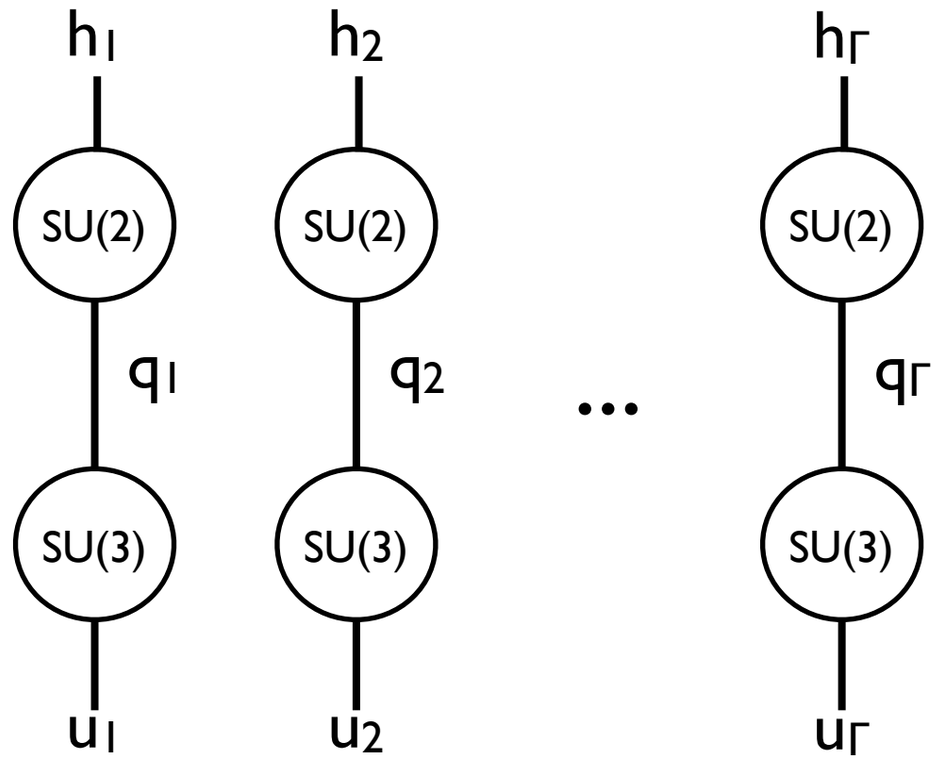
Example 1: Z_Γ orbifold

$$
\begin{aligned}
SU(2\Gamma)/\mathbb{Z}_\Gamma &\rightarrow SU(2)^\Gamma \times U(1)^{\Gamma-1} \\
SU(3\Gamma)/\mathbb{Z}_\Gamma &\rightarrow SU(3)^\Gamma \times U(1)^{\Gamma-1}
\end{aligned}
$$



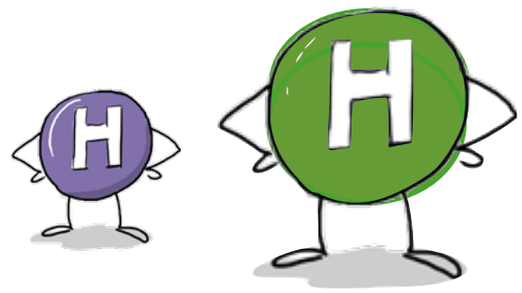
'Twin' Higgs mechanism goes through as before



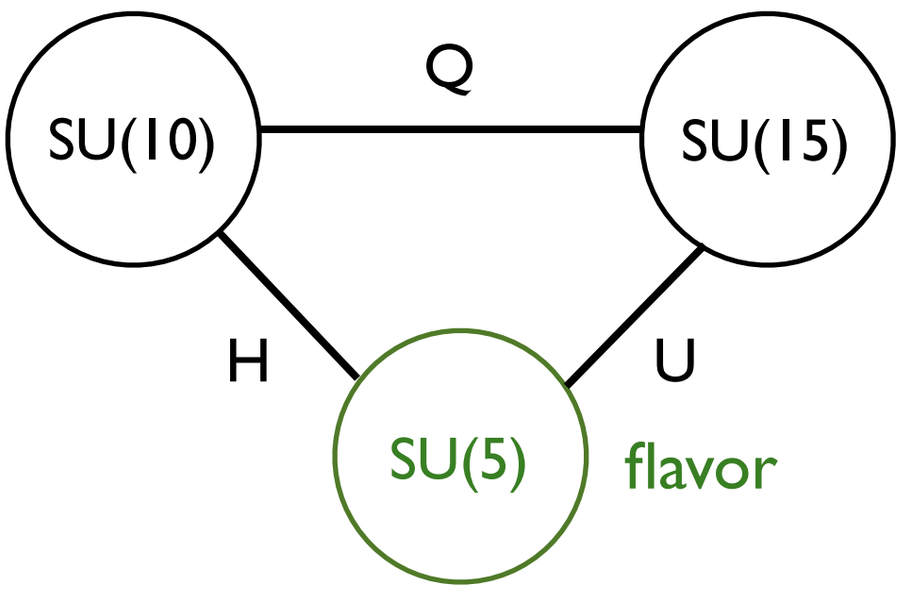


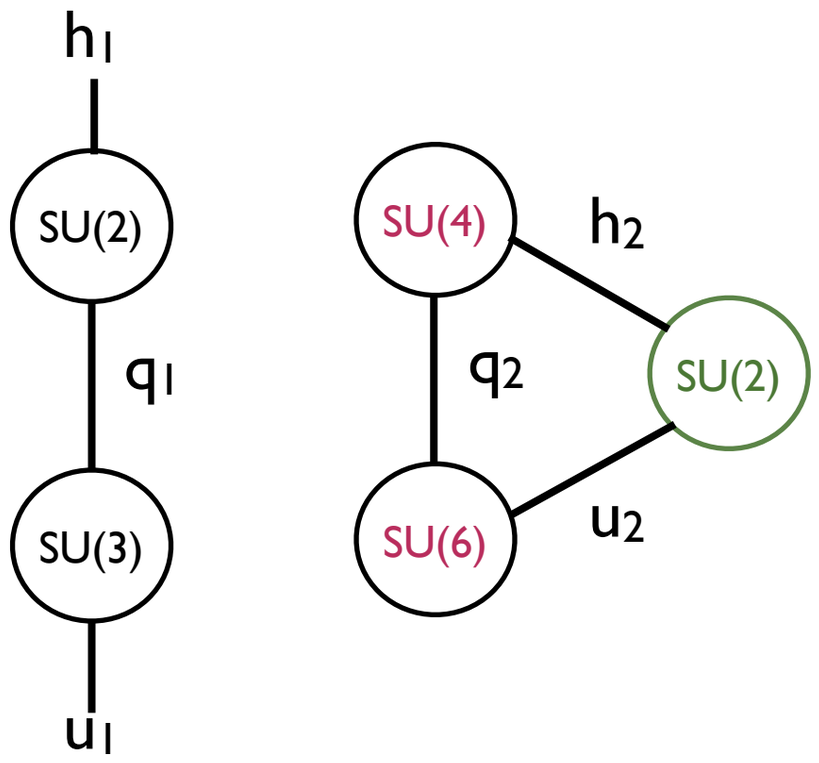
Example 2: S_3 orbifold

$$SU(10)/S_3 \quad \to SU(2) \times SU(4) \times U(1)$$
$$SU(15)/S_3 \quad \to SU(3) \times SU(6) \times U(1)$$



'Twin' Higgs mechanism goes through as before,
but non-trivially



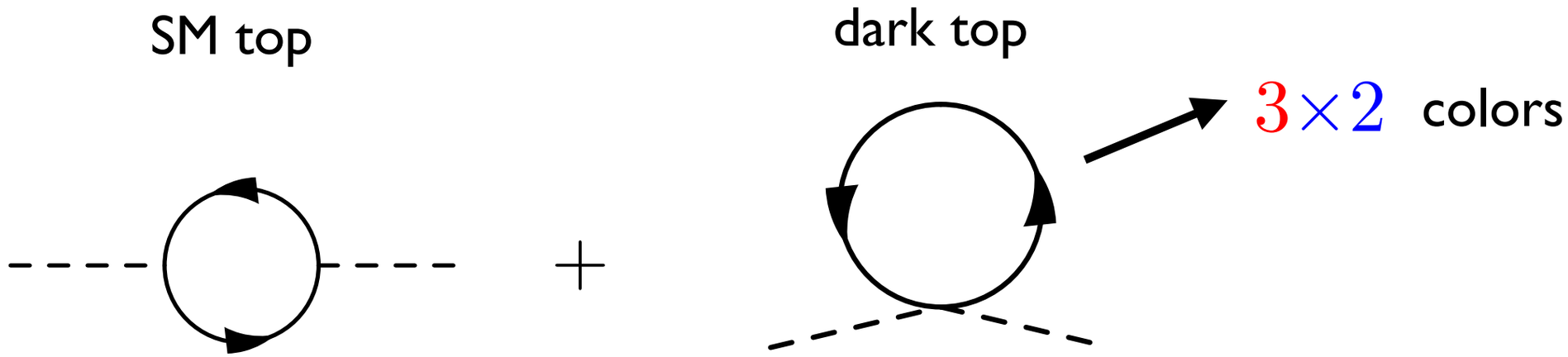


1411.7393: N. Craig, SK, P. Longhi
1410.6808: N. Craig, SK, P. Longhi

with $g^{(1)} = g^{(2)}/\sqrt{2}$

Canceling the divergence

Yukawa and gauge couplings get rescaled



$$\delta m_h^2 = -y_t^2 \frac{3}{8\pi^2}\Lambda^2 + \left(\frac{y_t}{\sqrt{2}}\right)^2 \frac{3\times2}{8\pi^2}\Lambda^2$$

$$= 0$$

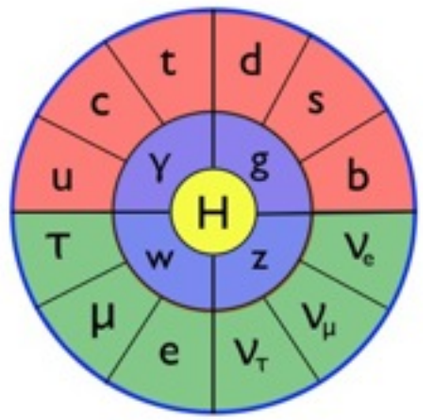
The cancellation goes through, even if the number of dark colors > 3 !

Example 3: The Fraternal Twin

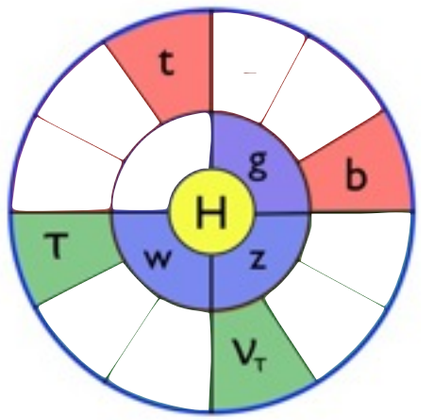
Naturalness only requires:

- Twin Higgs
- Twin top
- Twin SU(2) x SU(3)

SM



Twin



⟶ Add in full twin third generation to cancel gauge anomalies

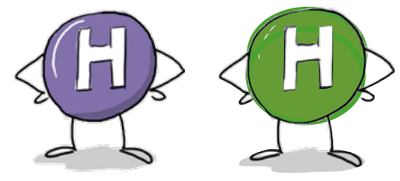
"Minimal" matter content, analogous to "Natural SUSY" framework for the MSSM

Interesting collider signatures + better cosmology

N. Craig, A. Katz, M. Strassler, R. Sundrum: 1501.05310

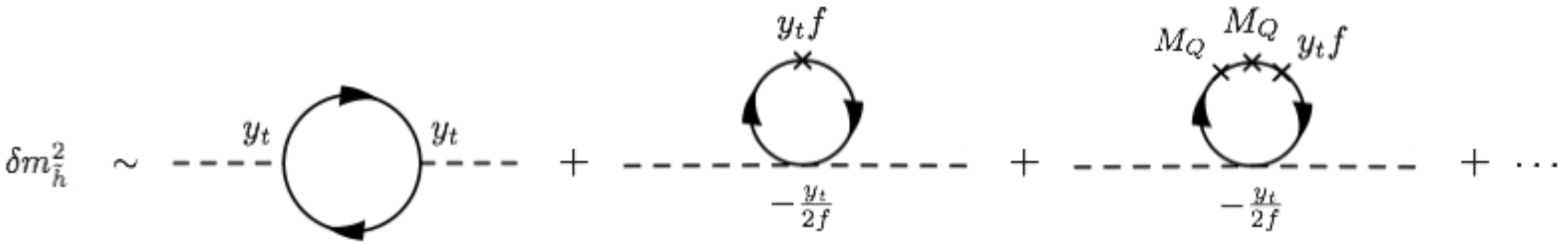
Example 4: The vector-like twin

$$\mathcal{L} \supset \underbrace{y_t H q u}_{\text{Twin Higgs…}} + \underbrace{y_t H' q' u' + M_q q' \bar{q}' + M_u u' \bar{u}'}_{\text{… but with vector-like Twin fermions!}}$$



No Twin Leptons are needed to cancel Twin gauge anomalies

Vector-like nature of twin quarks is a soft breaking:



these cancel

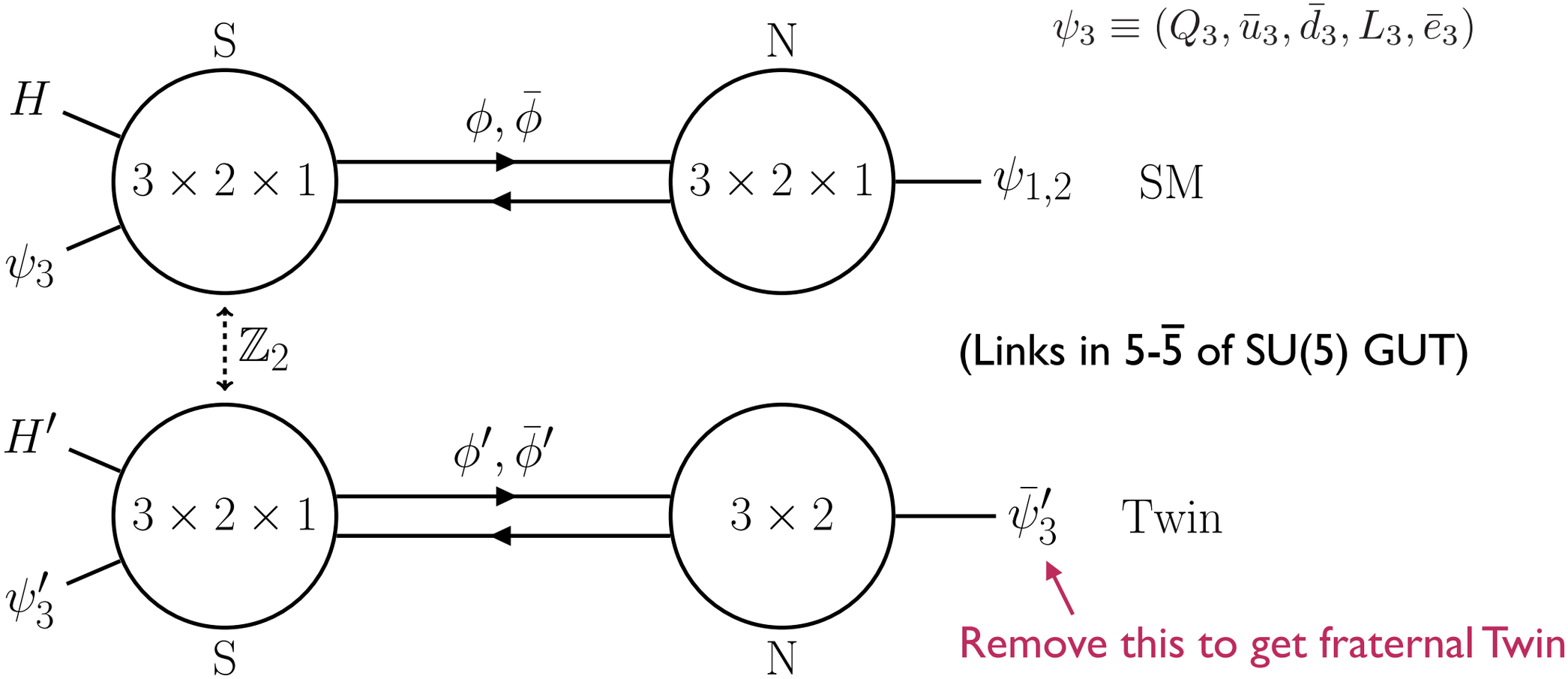
$$\sim \frac{y_t^2}{16\pi^2} M_q^2 \log \frac{M_q}{\Lambda}$$

The mechanism is preserved provided that M_q, $M_u \lesssim 500$ GeV

N. Craig, SK, P. Longhi, M. Strassler: in progress

UV completion

Use deconstruction to get an approximate Z_2 symmetry

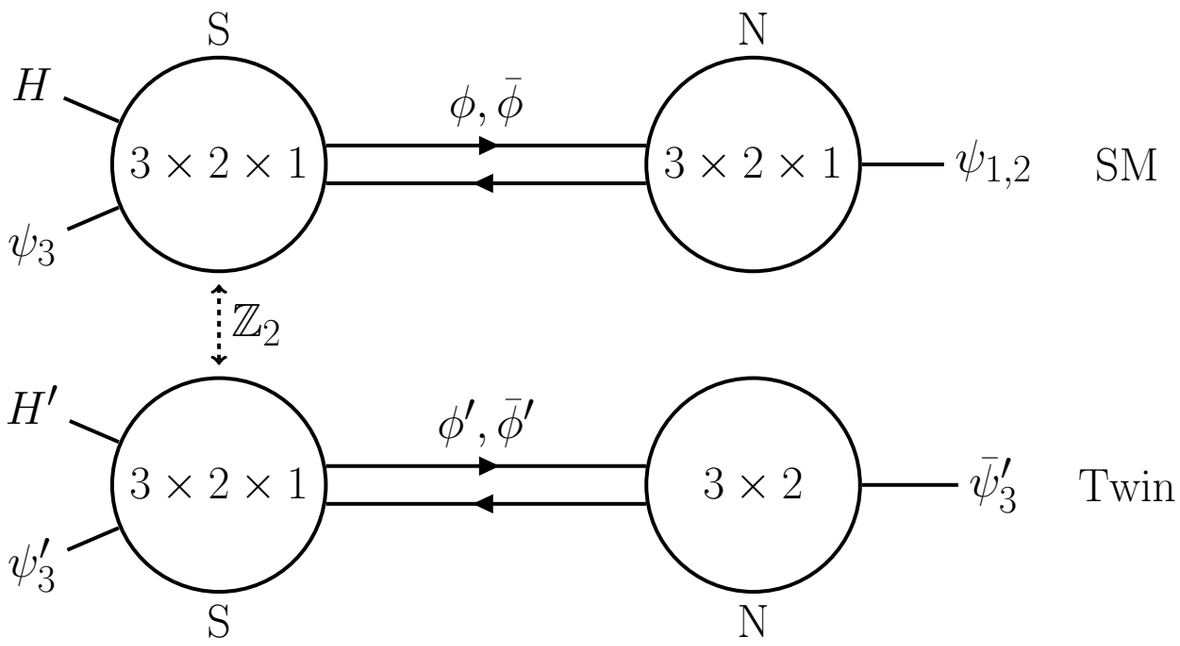


Higgsing the links leads to the vector-like twin Higgs: $\langle \phi \rangle \sim \langle \phi' \rangle \sim 5\mathrm{TeV}$

Stabilize this new scale with supersymmetry

N. Craig, SK, P. Longhi, M. Strassler: in progress

Twin Mass terms



Fields in 5 of SU(5) are lifted, fields in the 10 can remain light

$$\underbrace{d' \bar{\phi}'_T \bar{d}' + \ell' \bar{\phi}'_D \bar{\ell}'}_{5} + \underbrace{\frac{w_q}{\Lambda'} q' \phi'_T \phi'_D \bar{q}' + \frac{w_u}{\Lambda'} u' \phi'_T \phi'_T \bar{u}' + \frac{w_e}{\Lambda'} e' \phi'_D \phi'_D \bar{e}'}_{10}$$

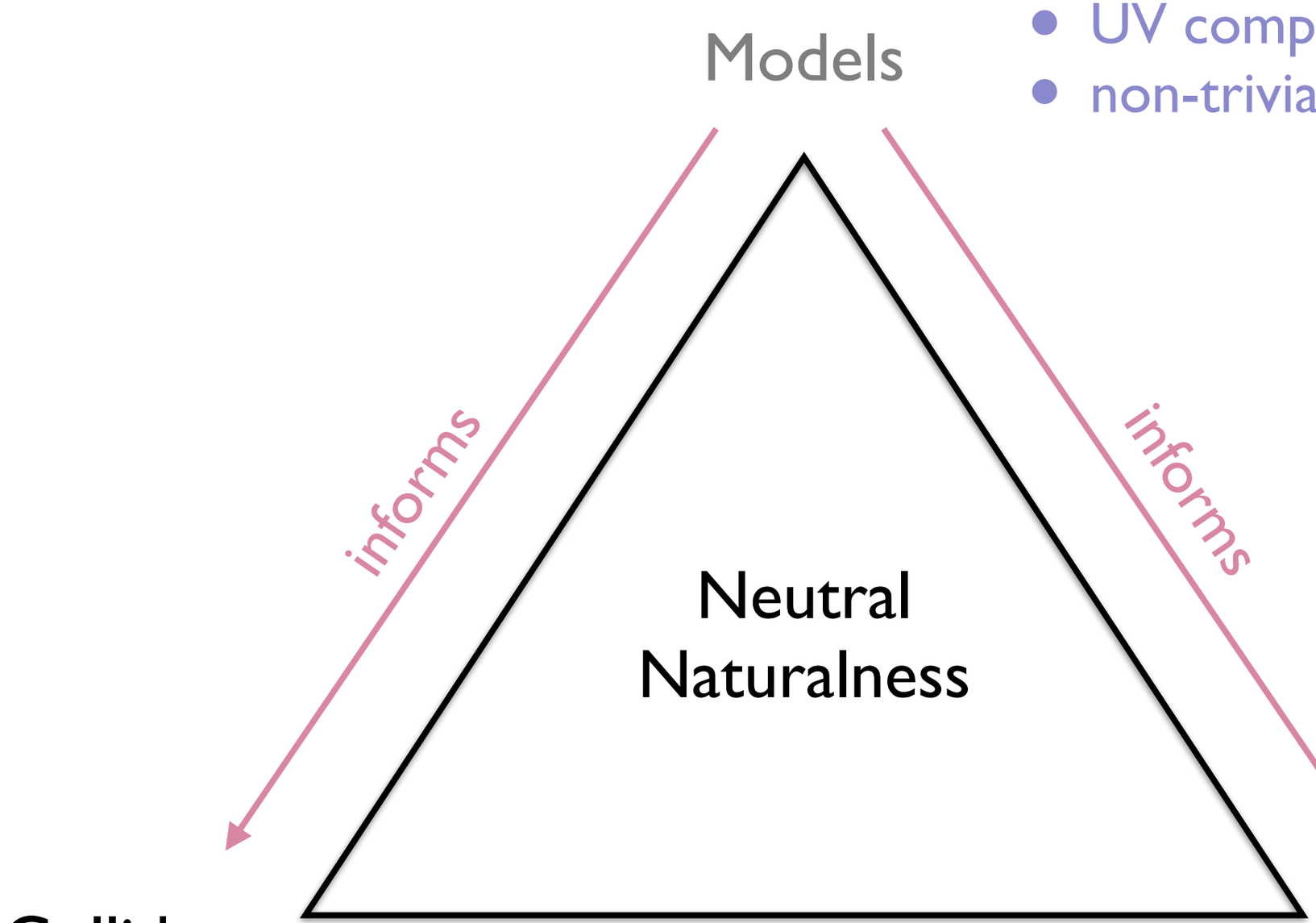
$$M_{\ell,d} \sim \Lambda \sim 5 \text{ TeV}$$

$$M_{q,u,e} \sim \Lambda^2/\Lambda' \sim 250 \text{ GeV}$$

with $\Lambda' \sim 100$ TeV

N. Craig, SK, P. Longhi, M. Strassler: in progress

Outline



- UV completions?
- non-trivial cancellations?

Colliders

- LHC
- future colliders
- Intensity frontier

Cosmology

- Dark matter?
- Constraints from BBN, CMB?

Higgs couplings

soft Z2 breaking needed:

$$V = -m^2(|h|^2 + |h'|^2) + \lambda(|h|^2 + |h'|^2)^2 + \delta(|h|^4 + |h'|^4) + \delta m^2 |h|^2$$

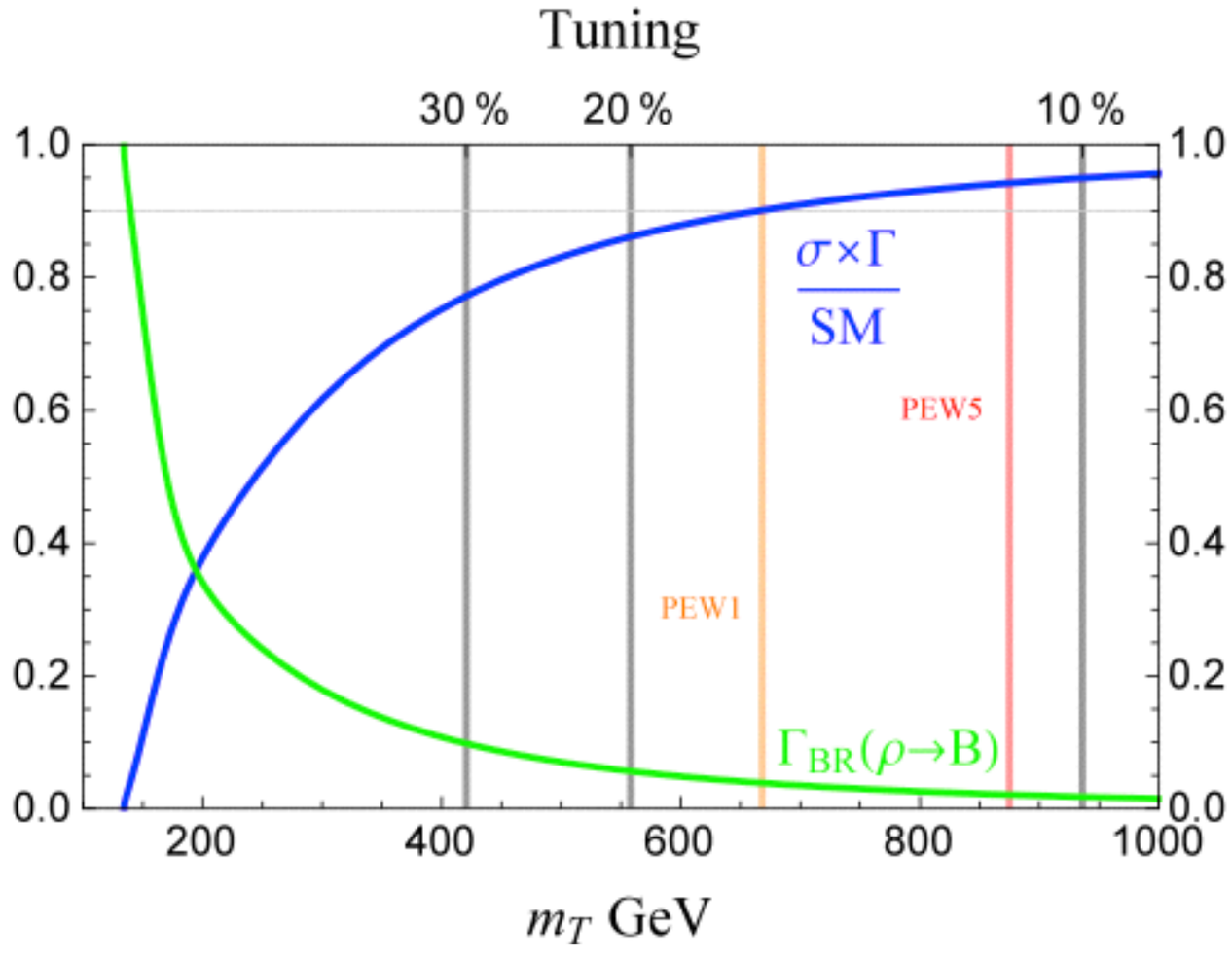
need to tune δm^2 against m^2 to achieve viable Higgs couplings

Higgs couplings measurements require irreducible tuning of order

$2\ v^2 / f^2 \sim 20\%$

with $v \equiv \langle h \rangle$, $f \equiv \langle h' \rangle$

Model independent!

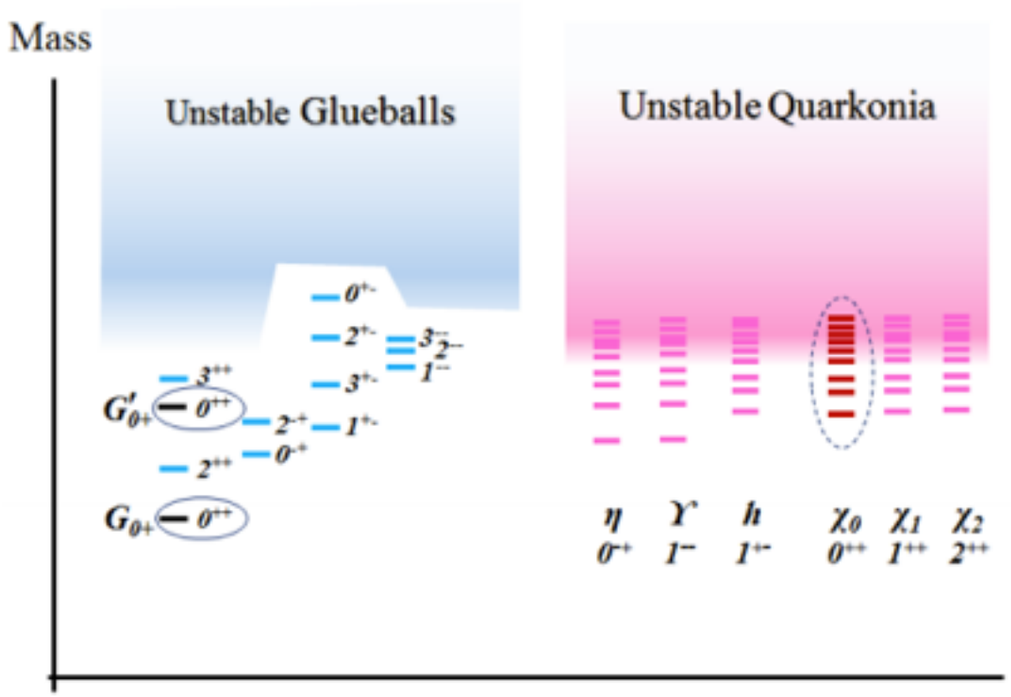


1411.3310: G. Burdman, Z. Chacko, L. de Lima, R. Harnik, C. B. Verhaaren

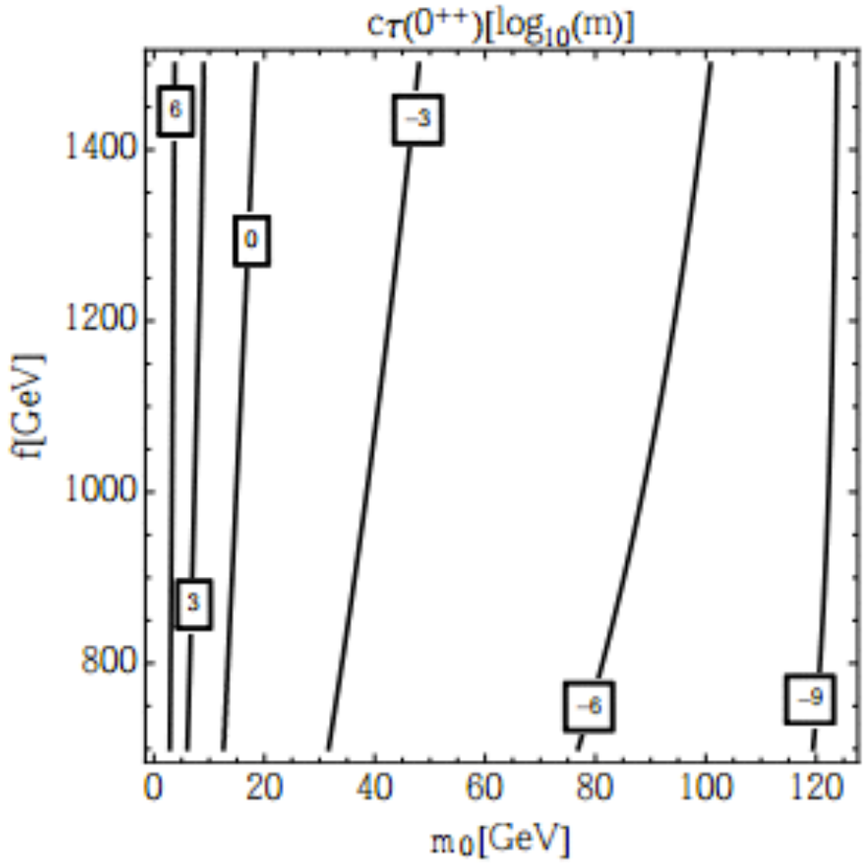
Lightest Twin Particle (LTP)

- ℓ', ν' LTP: h → invisible
- Twin hadron LTP: h → invisible + visible
  (exception: π' also invisible)

Hadron spectrum



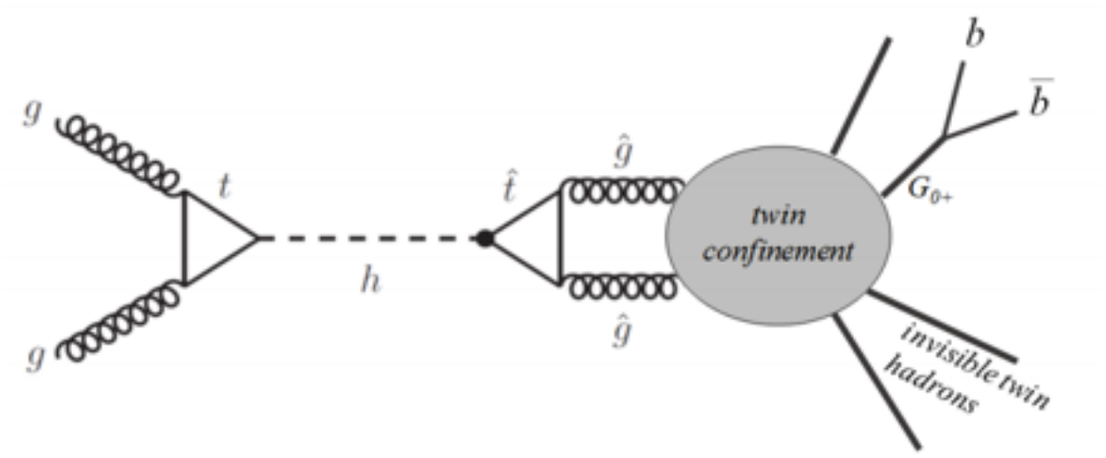
0^{++} glueball lifetime



Extra subtleties if bottomonium is the LTP

1501.05310: N. Craig, A. Katz, M. Strassler, R. Sundrum

Exotic decays

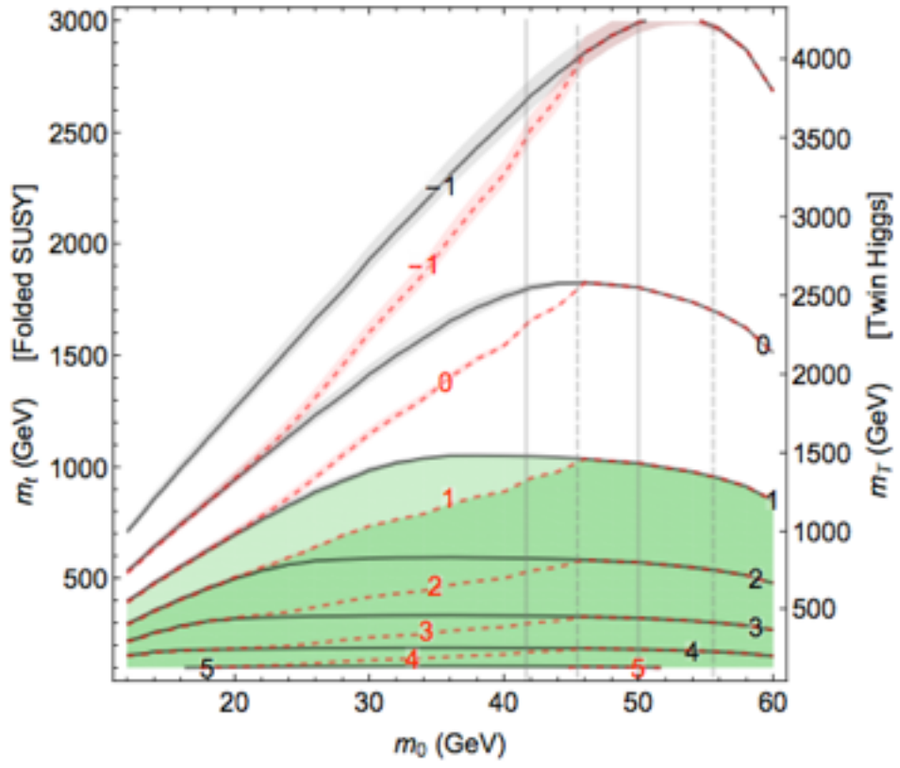


$$\mathcal{L} \supset -\frac{\hat{\alpha}_3}{6\pi}\frac{v}{f}\frac{h}{f}\hat{G}^a_{\mu\nu}\hat{G}^{\mu\nu}_a \,.$$

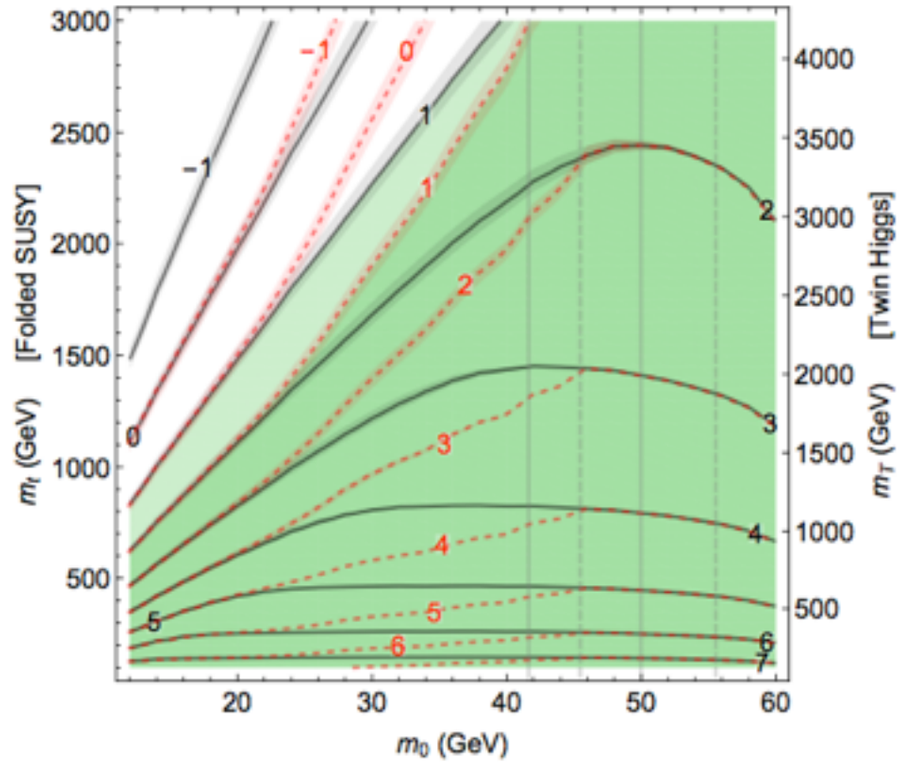
1501.05310: N. Craig, A. Katz, M. Strassler, R. Sundrum

Number of events in tracker

$\sqrt{s} = 8$ TeV, $\mathcal{L} = 20$ fb^{-1}



$\sqrt{s} = 14$ TeV, $\mathcal{L} = 3000$ fb^{-1}



1506.06141: D. Curtin, C. Verhaaren

Vector-like twin pheno (one generation)

	$SU(3)$	$SU(2)$
q'	$\square$	$\overline{\square}$
$\bar{q}'$	$\overline{\square}$	$\square$
u'	$\overline{\square}$	1
$\bar{u}'$	$\square$	1

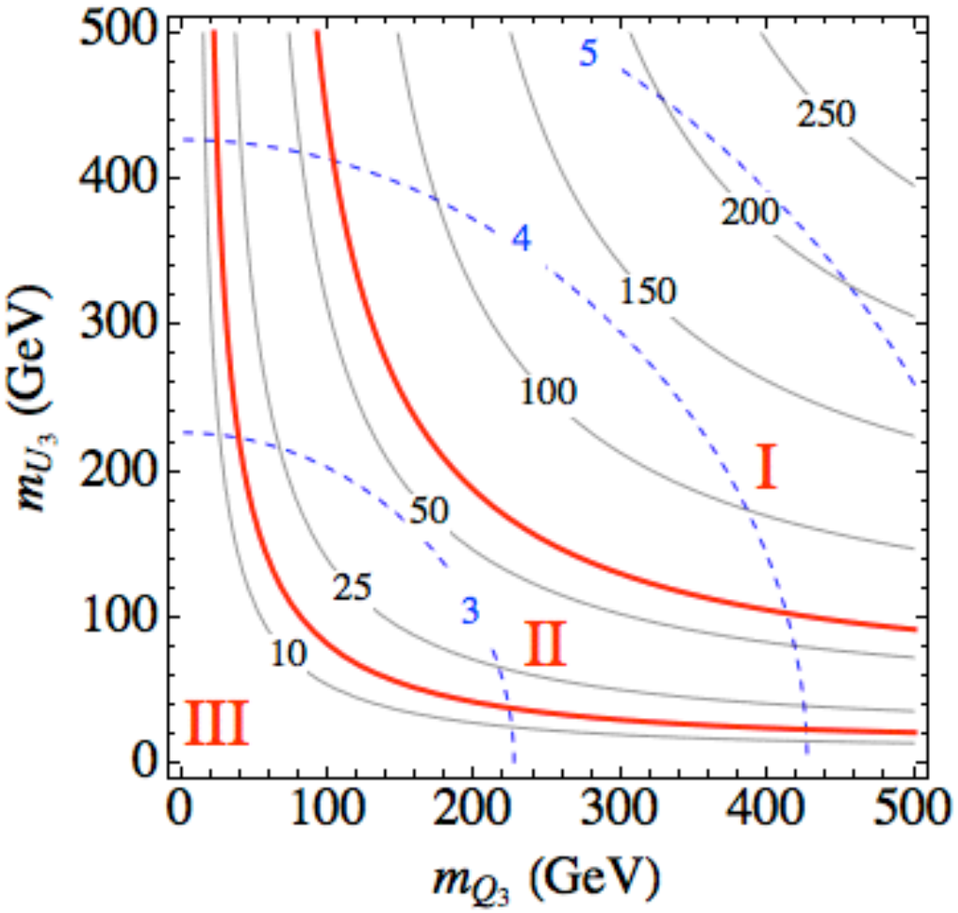
(no L′, d′ and e′)

$$\mathcal{L} \supset \begin{pmatrix} \bar{q}'_u \\ u' \end{pmatrix}^T \begin{pmatrix} M_{Q_3} & 0 \\ \frac{y_t f}{\sqrt{2}} & M_{U_3} \end{pmatrix} \begin{pmatrix} q'_u \\ \bar{u}' \end{pmatrix}$$

Mini-Seesaw

Spectrum: $m_{t_1} < m_{b_1} < m_{t_2}$

m_{t_1}



I. h → glueballs with branching ratio ~ 10^{-3}
displaced glueball decays possible

II. h → t_l t_l: excluded

III. h → t_l t_l: hadronize in glueballs and/or toponinium
displaced glueball/toponinium decays possible

N. Craig, SK, P. Longhi, M. Strassler: in progress

Vector-like twin pheno (3 generations)

	$SU(3)$	$SU(2)$	$SU(3)_Q$	$\overline{SU(3)_Q}$	$SU(3)_U$	$\overline{SU(3)_U}$
q'	$\square$	$\overline{\square}$	$\square$	1	1	1
$\bar{q}'$	$\overline{\square}$	$\square$	1	$\square$	1	1
u'	$\overline{\square}$	1	1	1	$\square$	1
$\bar{u}'$	$\square$	1	1	1	1	$\square$

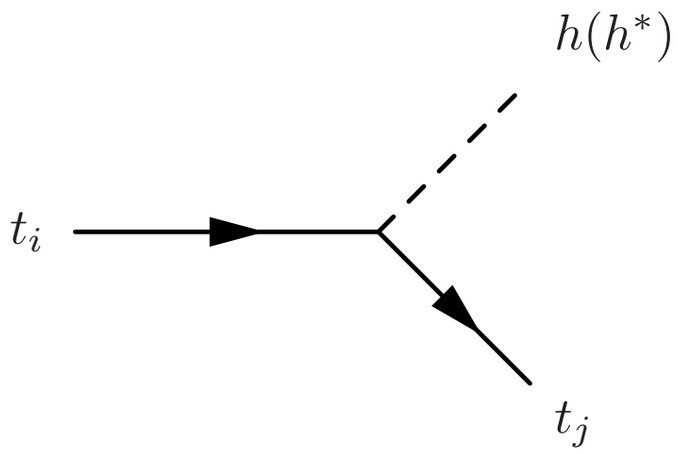
$$\mathcal{L} \supset Y_U H' q' u' + M_Q q' \bar{q}' + M_U u' \bar{u}'$$

Fully break flavor symmetries

Due to the large amount of flavors, the confinement scale is usually lower

→ glueballs decay more often outside the detector

… but twin sector generically has large flavor changing currents:

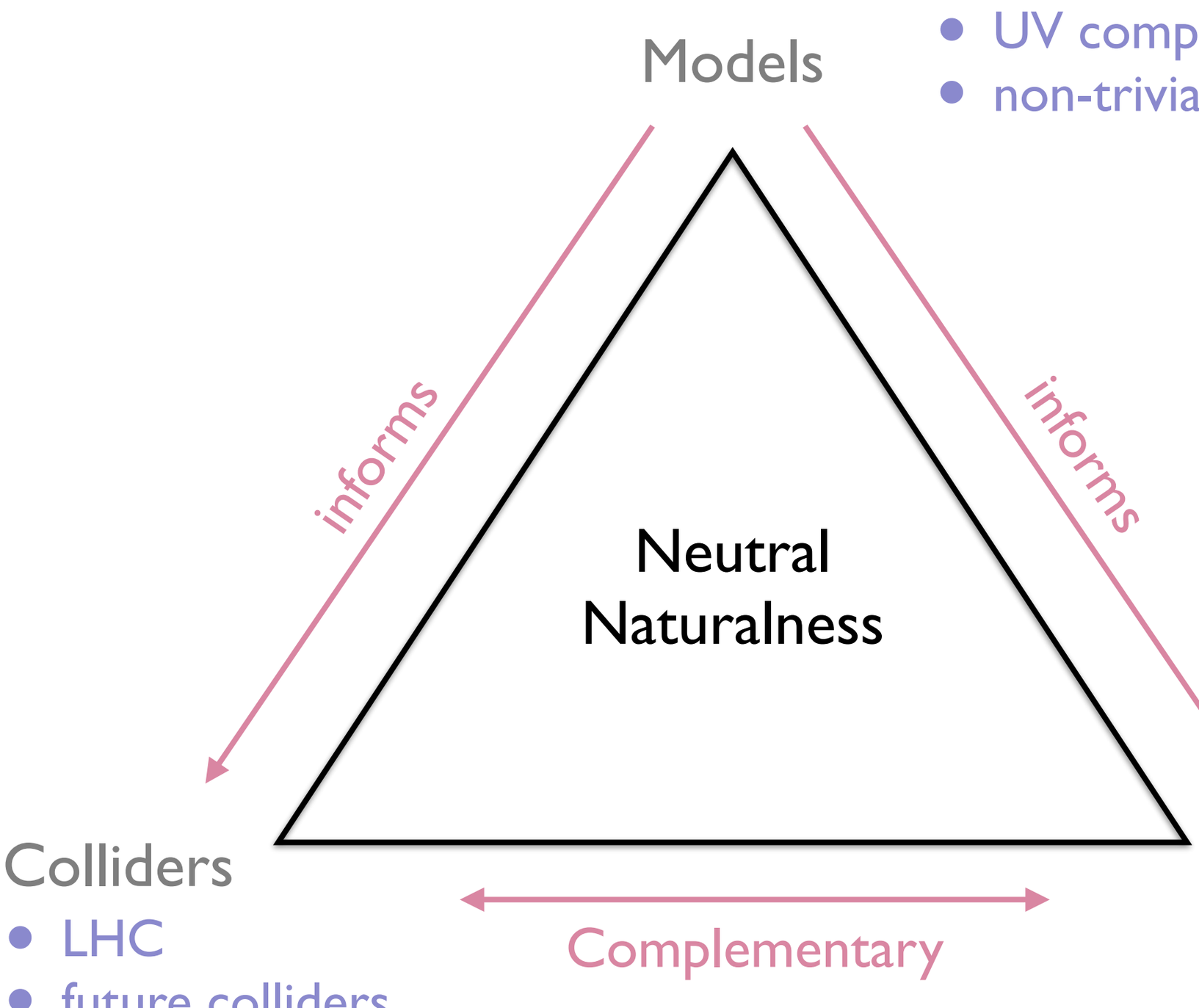


rare, but spectacular cascade decays possible!

- bb, τ τ pairs + MET
- possibly with displaced vertices

N. Craig, SK, P. Longhi, M. Strassler: in progress

Outline



- UV completions?
- non-trivial cancellations?

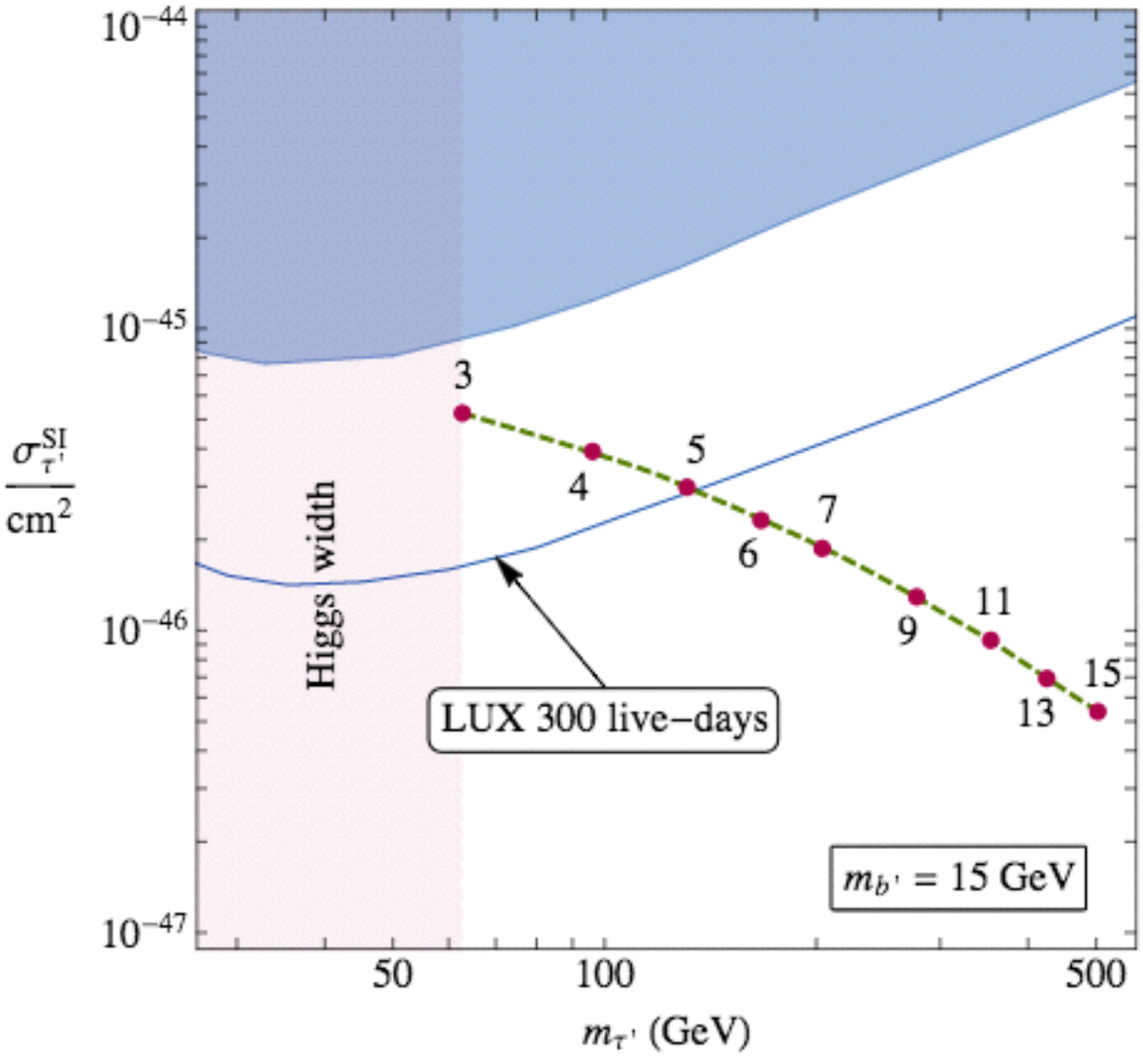
Colliders

- LHC
- future colliders
- Intensity frontier

Cosmology

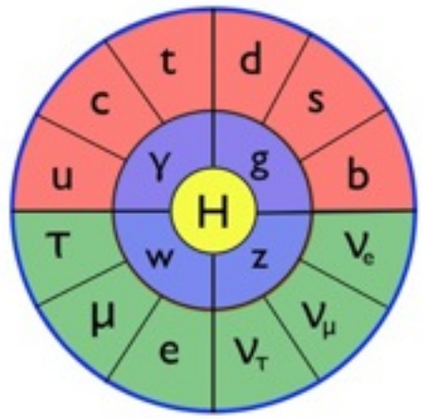
- Dark matter?
- Constraints from BBN, CMB?

Twin Wimp Miracle (fraternal Twin)

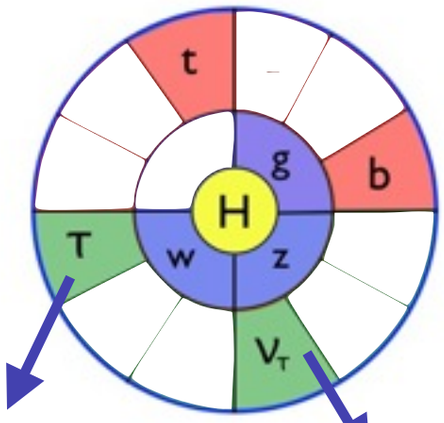


$$\Delta N_{eff} \gtrsim 0.075$$

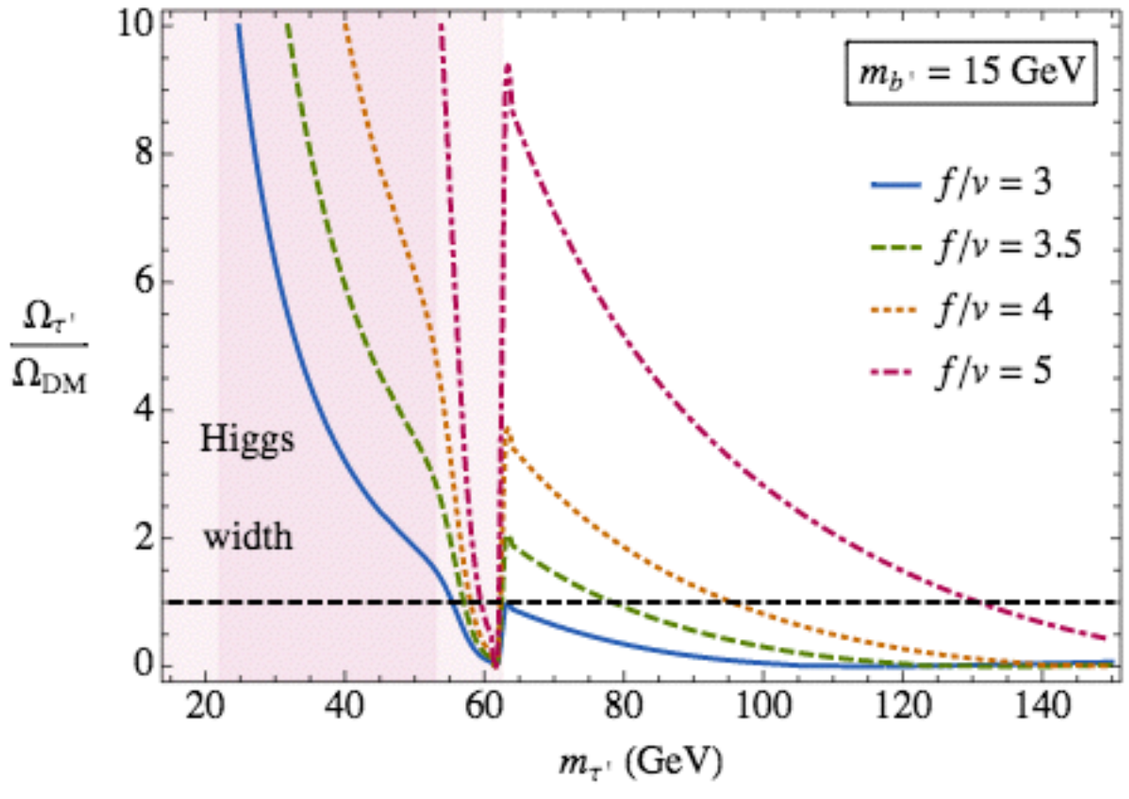
SM



Twin



Dark Matter Dark Radiation

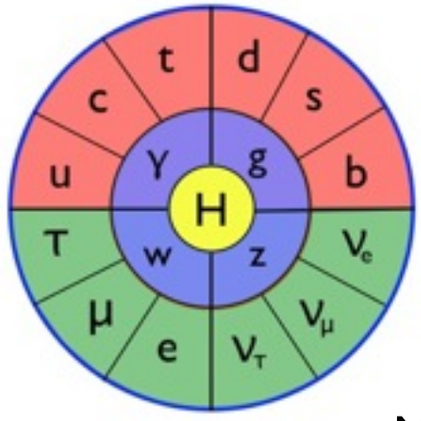


1505.07109: I. Garcia Garcia, R. Lasenby, J. March-Russell
1505.07113: N. Craig, A. Katz

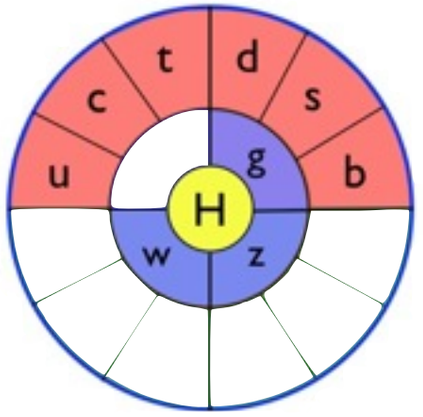
Twin Wimp Miracle (with light quarks)

- No Twin Leptons ⟶ $\Delta N_{eff} = 0$
- 2 Light flavors
- Dark Matter: Twin electroweak Doublet

SM

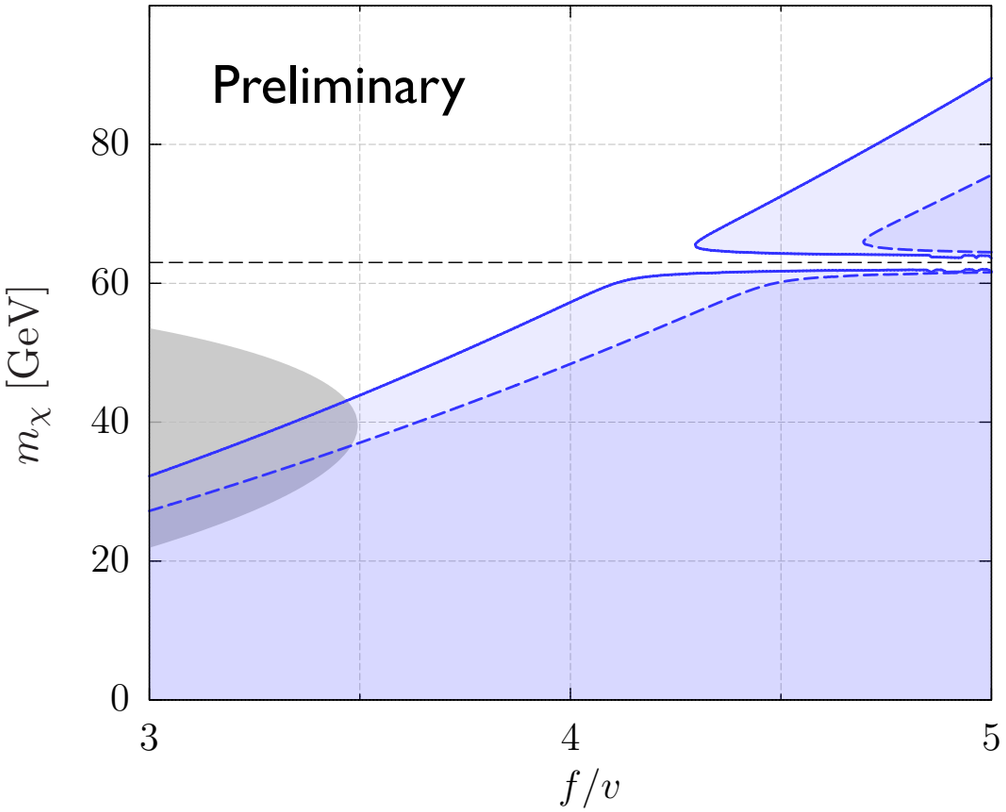


Twin

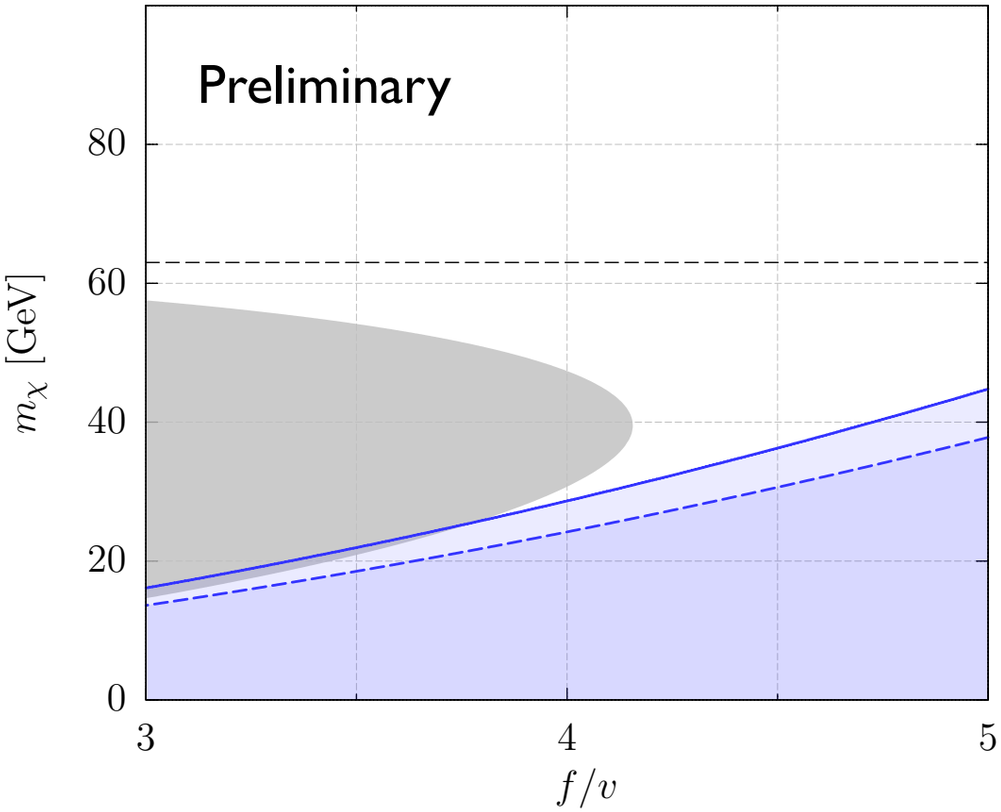


$+ \chi$

Dirac

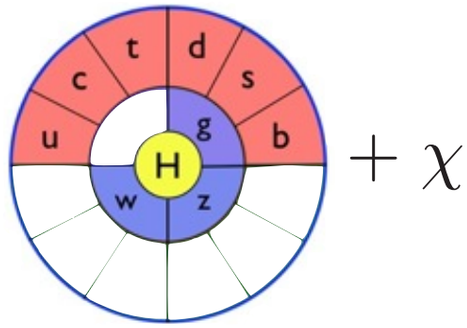


Majorana



M. Freytsis, SK, D. Robinson, Y. Tsai: in progress

BBN



$+\ \chi$

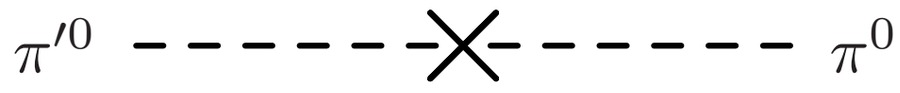
- Pions are lightest twin particles

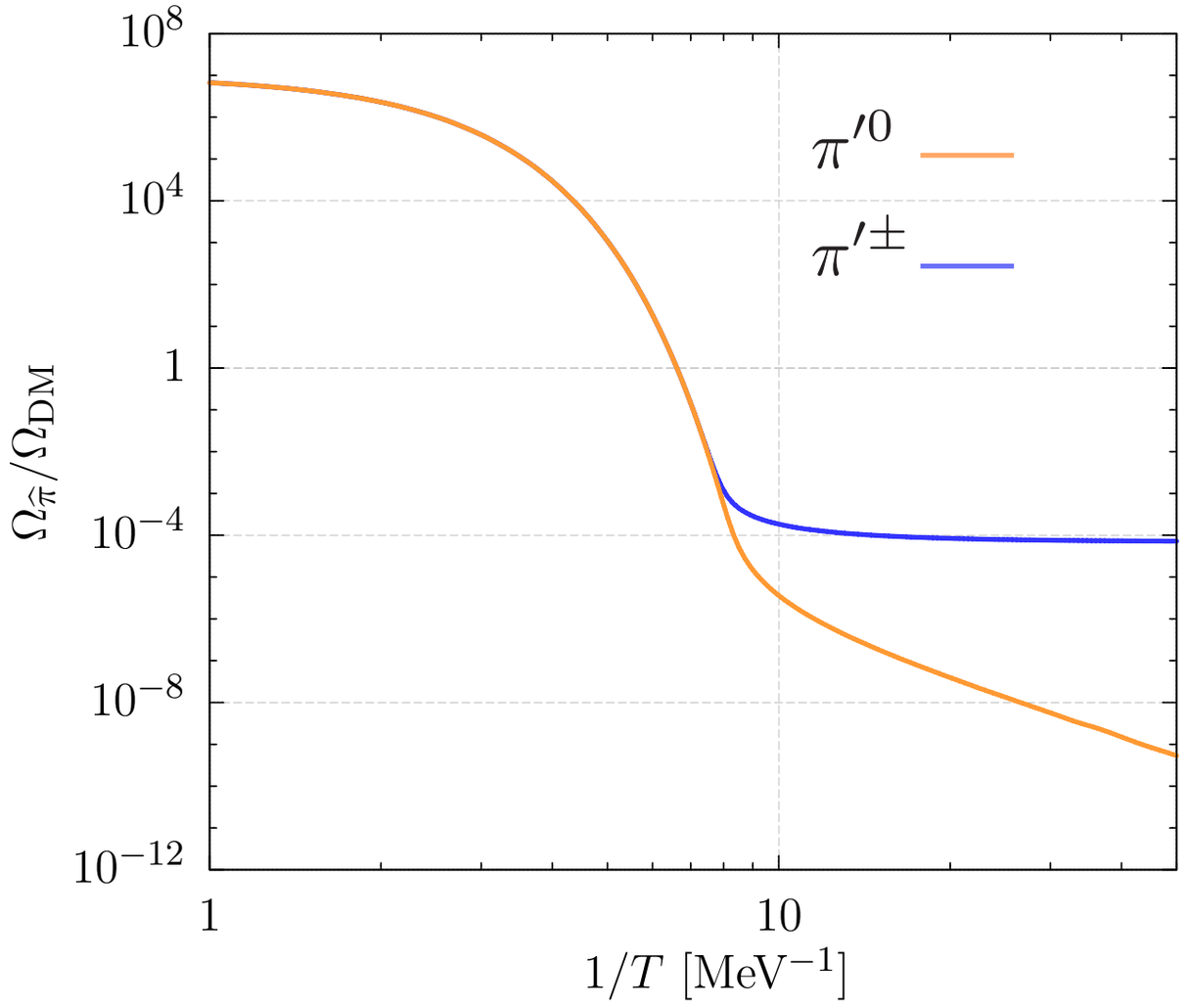
$$m_{\pi'} \sim \sqrt{\frac{f}{v}} m_\pi \lesssim 1\ \mathrm{GeV}$$

- $\pi'^{\pm}$ is stable, π'^{0} very long-lived

- If not depleted, pions dominate universe at BBN

Decay twin π'^{0} through mixing with SM π^0





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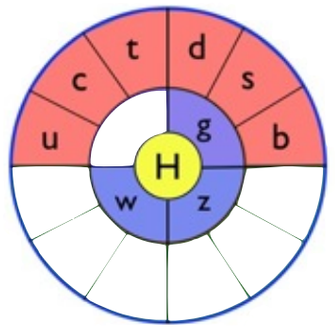
Pion decay



$+ \chi$

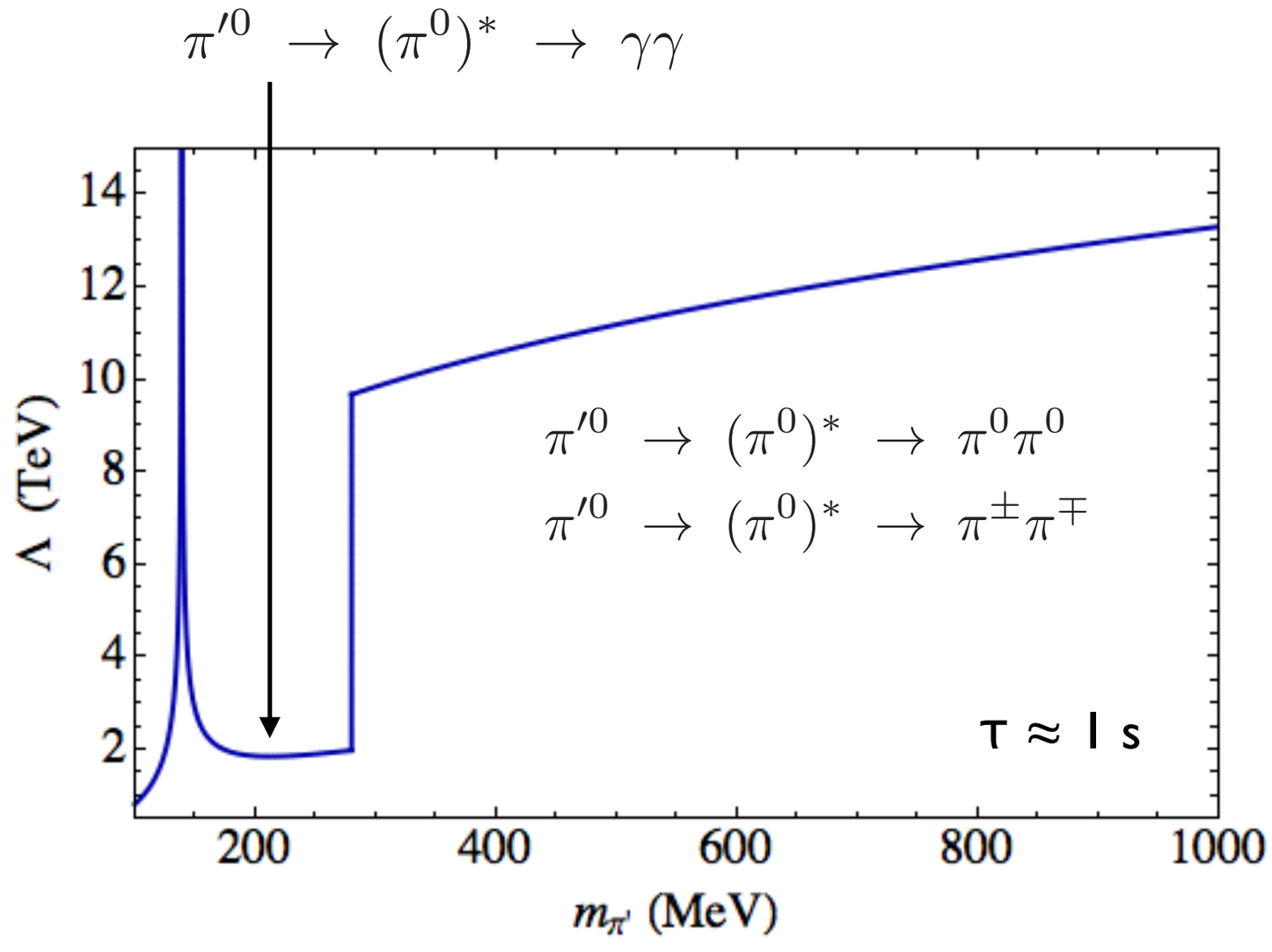
Extra portal needed to decay the twin pions before BBN

For example:

$$\frac{1}{\Lambda^2} \quad q'^{\dagger}\gamma_\mu\gamma_5 q' \quad q^{\dagger}\gamma^\mu\gamma_5 q$$

$$\downarrow$$

$$\frac{f_\pi f_{\pi'}}{\Lambda^2} \quad \partial^\mu \pi'^0 \partial_\mu \pi^0$$



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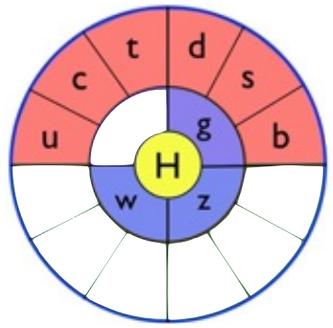
A UV completion

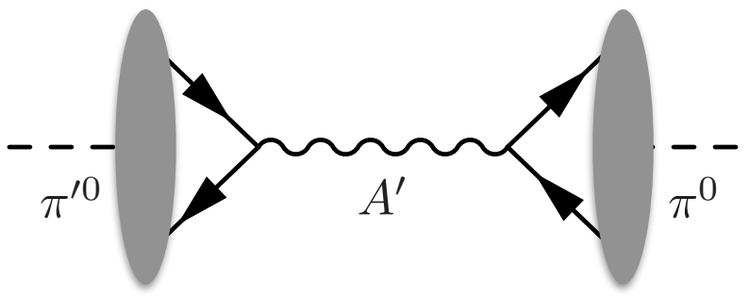


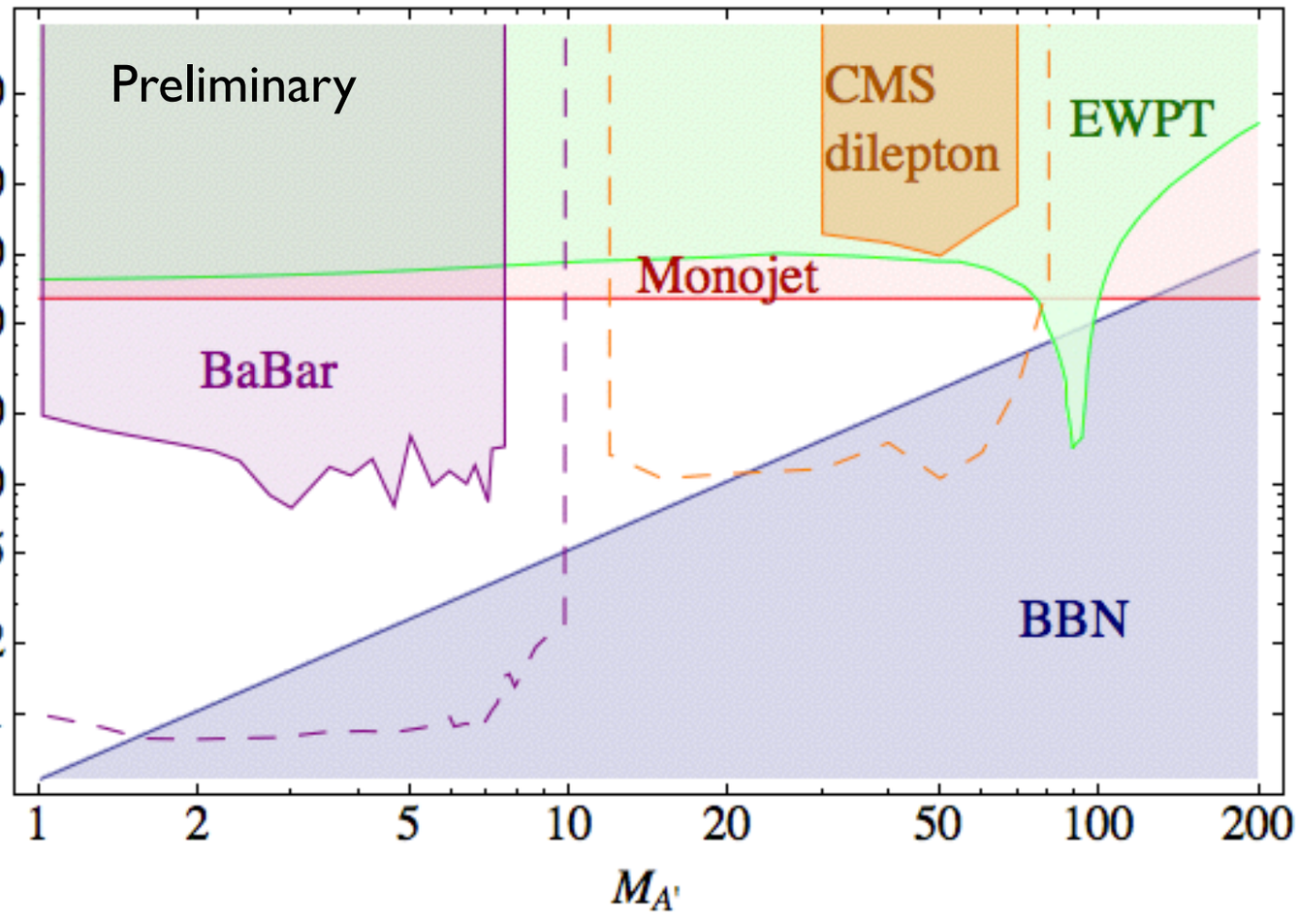
$+ \chi$

Leptophobic U(1) portal:

$$\mathcal{L} = g' A'_\mu \left(\bar{u}_R^\dagger \sigma^\mu \bar{u}_R + \bar{u}_R'^\dagger \sigma^\mu \bar{u}'_R \right) - g' A'_\mu \left(\bar{d}_R^\dagger \sigma^\mu \bar{d}_R + \bar{d}_R'^\dagger \sigma^\mu \bar{d}'_R \right)$$

Avoid isospin singlet!





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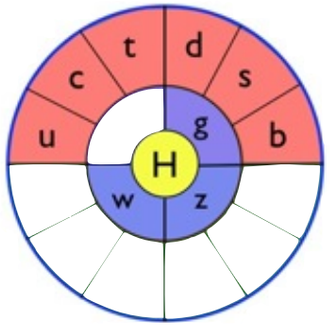
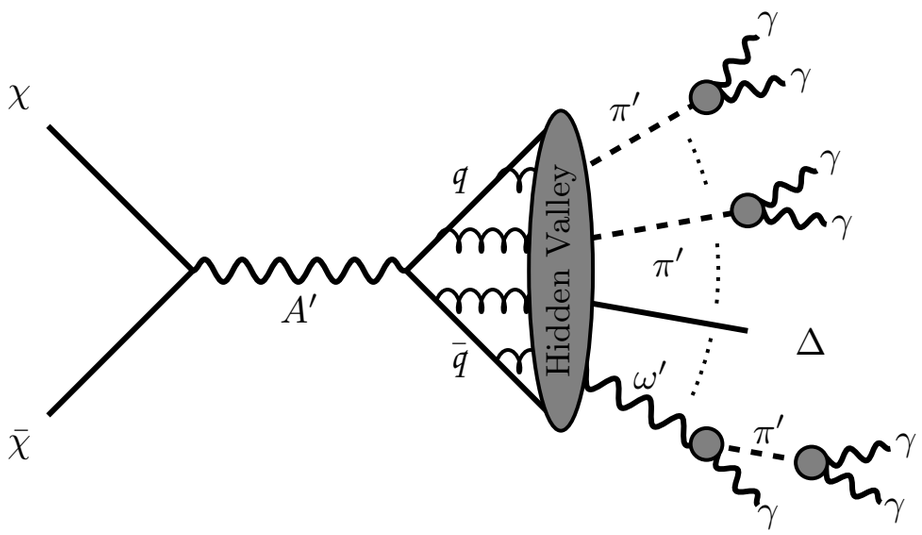
Indirect detection



$+ \chi$



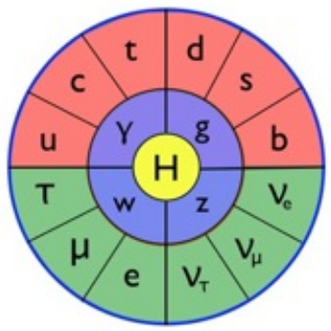
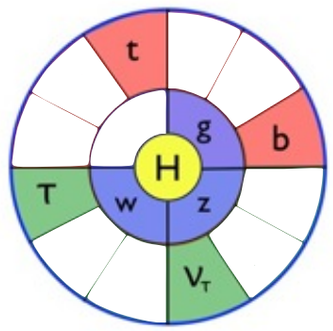
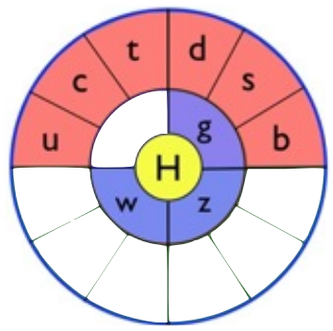
Galactic center, dwarf spheroidals, …

$$m_{\pi'} < 2m_\pi \longrightarrow \text{photons}$$

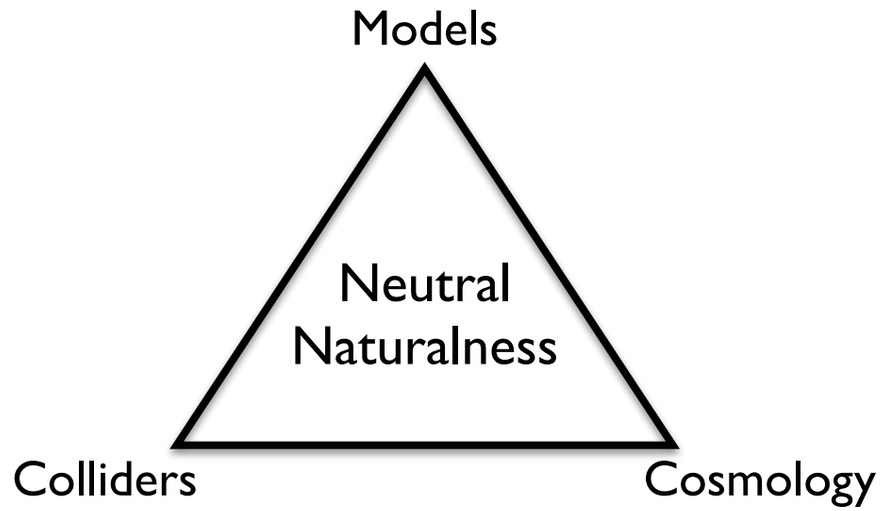
$$m_{\pi'} > 2m_\pi \longrightarrow \text{soft leptons + photons}$$

1410.3818: M. Freytsis, D. Robinson, Y. Tsai.
M. Freytsis, SK, D. Robinson, Y. Tsai: in progress

Summary

Twin sector / Observable			 $+\ \chi$
Higgs couplings	$f/v \gtrsim 3$	$f/v \gtrsim 3$	$f/v \gtrsim 3$
CMB	$\Delta N_{eff} \gtrsim 7$	$\Delta N_{eff} \gtrsim 0.075$	$\Delta N_{eff} = 0$
BBN	No bound	Depends on spectrum	Always decay pions
LHC	Maybe resonances	Higgs portal + maybe resonances	Maybe resonances
Intensity frontier	No signal	No signal	Dark photon searches
Direct detection	No WIMP	Higgs portal	Higgs portal
Indirect detection	No WIMP	$b\bar{b},\ \tau^+\tau^-$	$\gamma\gamma,\ \ell^+\ell^-$ (soft)

Conclusions and outlook



Models:

- non-trivial examples: S_3, fraternal, vector-like twins
- (better?) UV completions are essential
- We need more models, especially bottom-up, as surprising signatures may emerge

Colliders:

- Look for displaced and Higgs-rich events at the LHC (Hidden sector pheno can be wild!)
- Look for the resonances / KK-states

Probes heavy LTP

Cosmology:

- Complementary with LHC
- Other opportunities: Asymmetric DM, dark atoms, twin W dark matter, etc

Probes light LTP