NATURALNESS

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Top partner limits constrain natural scenarios.
For simplicity:
Only variation away from our Standard Model is Higgs mass parameter.

$$-\Lambda_{\text{UV}}^2 \lesssim \left( m_H^2 \right)_i \lesssim \Lambda_{\text{UV}}^2$$
Not a multiverse.
No anthropics!

\[ \nu = 0 \]

\[ \nu_{us} = 246 \text{ GeV} \]

\[ \nu > \nu_{us} \]

\[ \Lambda_{UV}^2 \]

\[ -\Lambda_{UV}^2 \]

\[ m_H^2 \]
But why is there energy density in only our sector?!?
OUTLINE

General Mechanism

Two Simple Models

Signatures!

Completing the Story

Outlook
GENERAL MECHANISM
<table>
<thead>
<tr>
<th>$m^2_H &gt; 0$</th>
<th>$m^2_H &lt; 0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Massless photon</td>
<td>Massless photon</td>
</tr>
<tr>
<td>$W^\pm, Z^0$ masses</td>
<td>$W^\pm, Z^0$, and fermion masses</td>
</tr>
<tr>
<td>$\sim \Lambda_{QCD}$</td>
<td>$\sim \Lambda_{QCD}$</td>
</tr>
<tr>
<td>Fermion masses</td>
<td>Neutrino masses:</td>
</tr>
<tr>
<td>$\sim y_f \frac{\Lambda_{QCD}^3}{m^2_H}$</td>
<td>- Majorana mass $\sim \nu^2$</td>
</tr>
<tr>
<td>$T_{sphaleron} &lt; \Lambda_{QCD}$</td>
<td>- Dirac mass $\sim \nu$</td>
</tr>
<tr>
<td>no baryon relic density</td>
<td></td>
</tr>
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<td></td>
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</table>
$S$ reheats the Universe after inflation.

Couples universally to all copies.
The reheaton is a gauge singlet;

Parametrically lighter than the naturalness cutoff, $\Lambda_H / \sqrt{N}$;

Couplings are most relevant ones possible that involve Higgs bosons of each sector.
COUPLE $S$ TO $H + X$

<table>
<thead>
<tr>
<th>$m_H^2 &gt; 0$</th>
<th>$m_H^2 &lt; 0$</th>
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<tbody>
<tr>
<td>$S$</td>
<td>$S$</td>
</tr>
<tr>
<td>$H$</td>
<td>$X'$</td>
</tr>
<tr>
<td>$X$</td>
<td>$\langle H \rangle$</td>
</tr>
<tr>
<td>$\Gamma \sim m_S$</td>
<td>$\Gamma \sim m_S$</td>
</tr>
<tr>
<td>or</td>
<td>or</td>
</tr>
<tr>
<td>$S$</td>
<td>$S$</td>
</tr>
<tr>
<td>$X$</td>
<td>$X$</td>
</tr>
<tr>
<td>$t$</td>
<td>$t$</td>
</tr>
<tr>
<td>$\Gamma \sim \frac{m_S^5}{m_H^4}$</td>
<td>$\Gamma \sim \frac{v^2m_S^3}{v^4}$</td>
</tr>
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</table>

Increasing $m_H^2$

Increasing $v$
Even spacing for Higgs mass squared parameters:

\[
\left( m^2_H \right)_i = i \times \left( m^2_H \right)_{us}
\]

So that \( v_i \sim \sqrt{i} \).
MASSLESS DOF

Energy density in additional relativistic degrees of freedom.

\[ N_{\text{eff}} \sim \frac{\sum \rho_i}{\rho_{us}} \sim \frac{\sum \Gamma_i}{\Gamma_{us}} \sim \log N \]

Relic density of additional neutrinos.

\[ \Omega_{\nu} h^2 \sim \begin{cases} \frac{\sum v_i \rho_i^{3/4}}{v_{us} \rho_{us}^{3/4}} & \sim N^{3/4} \quad \text{Dirac} \\ \frac{\sum v_i^2 \rho_i^{3/4}}{v_{us}^2 \rho_{us}^{3/4}} & \sim N^{5/4} \quad \text{Majorana} \end{cases} \]
MASSIVE DOF

THERMAL FREEZE-OUT

Heaviest sector that thermalizes

Model dependence

\[ \Omega h^2 = \frac{s_0}{\rho_c} \sum_{i=-N_d}^{N_d} m_i Y_i^{fo} + ... = a (N_d)^p + ... \]

Naively, \( a \sim \Omega^{us} h^2 \), and \( p > 0 \).

Neglect contribution from reheaton decays (relevant at large \( N \)).

Neglect freeze-in.
Gravity sees all degrees of freedom.

\[ M_{\text{pl}}^2(\mu) = M_{\text{pl}}^2(0) - N \frac{\mu^2}{96 \, \pi^2} \]

\[ \Lambda_{\text{UV}} \sim \frac{M_{\text{pl}}(0)}{\sqrt{N}} \]

HOW MANY COPIES?

Full hierarchy problem

\[ \nu_{us} \sim \frac{\Lambda_{UV}}{\sqrt{N}} \quad \text{and} \quad \Lambda_{UV} \sim \frac{M_{Pl}}{\sqrt{N}} \]

\[ N \sim \frac{M_{Pl}}{\nu_{us}} \simeq 10^{16} \]

and

\[ \Lambda_{UV} \sim 10^{10} \text{ GeV} \]
**How Many Copies?**

Little hierarchy problem

\[ v_{us} \sim \frac{\Lambda_{SUSY}}{\sqrt{N}} \quad \text{and} \quad \Lambda_{UV} \sim \frac{M_{Pl}}{\sqrt{N}} \]

\[ \Lambda_{UV} \sim M_{GUT} \]

\[ N \sim 10^4 \]

\[ \Lambda_{SUSY} \sim 10 \text{ TeV} \]

Tons of signatures at future colliders!
HOW MANY COPIES?

Full hierarchy problem (again)

All new degrees of freedom

\[ N_{\text{total}} \quad \text{and} \quad N_{\text{reheat}} \]

Couple to reheaton

\[ \nu_{us} \sim \frac{\Lambda_{\text{UV}}}{\sqrt{N_{\text{reheat}}}} \quad \text{and} \quad \Lambda_{\text{UV}} \sim \frac{M_{\text{Pl}}}{\sqrt{N_{\text{total}}}} \]

with \[ N_{\text{total}} \gg N_{\text{reheat}} \]

For this scenario:

\[ N \rightarrow N_{\text{reheat}} \]
TWO SIMPLE MODELS
**NEUTRINO REHEATON**

\[ \mathcal{L} = m_S S S^c + \lambda \sum_i S H_i L_i \]

- \[ m_H^2 > 0 \]
  - \[ \Gamma \sim m_S \]
  - \[ \Gamma \sim \frac{m_S^5}{m_H^4} \]

- \[ m_H^2 < 0 \]
  - \[ \Gamma \sim m_S \]
  - \[ \Gamma \sim \frac{m_S^5}{\nu^4} \]

Increasing \( m_H^2 \) or Increasing \( \nu \)
SHI, $N=10^4$

$\text{BR}_{us}$

$Z_{us}^0$

$W_{us}^\pm$

Next sector
3-body to 2-body

$m_s(\text{GeV})$
TOY SCENARIO

Parametrize distribution of Higgs masses:

\[
(m^2_H)_i = -\frac{\Lambda^2_H}{N} (2i + r)
\]

\[
(m^2_H)_{us} = -r \times \frac{\Lambda^2_H}{N} \approx -(88 \text{ GeV})^2
\]

\( r \) parametrizes tuning.
SHI, N=10^4

\[ BR_{us} = \begin{cases} 
0.1 & \text{for } m_s = 0 \\
0.5 & \text{for } m_s = 50 \\
1 & \text{for } m_s = 300 
\end{cases} \]
Reheaton mass is technically natural.

Critical that reheaton mass be $O(m_{W_{us}})$.

Analogous to $\mu$-problem in the MSSM.
SCALAR REHEATON

\[ \mathcal{L} = \frac{1}{2} m_\phi \phi^2 + a \phi \sum_i |H_i|^2 \]

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<th>( m_H^2 &gt; 0 )</th>
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<td>Increasing ( m_H^2 )</td>
<td>Increasing ( \phi )</td>
</tr>
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</table>

\[ \Gamma \sim \frac{a^2}{m_\phi} \]

\[ \Gamma \sim \frac{a^2 g^4}{(16\pi^2)^2} \frac{m_\phi^3}{m_H^4} \]

\[ \Gamma \sim y_b^2 a^2 \frac{m_\phi^3}{v^4} \]

\[ \Gamma \sim y_c^2 a^2 \frac{m_\phi^3}{v^4} \]


\[ \phi, \ m_\phi = 100 \ \text{GeV} \]

\[ m^2_H < 0 \]

\[ m^2_H > 0 \]

\[ \sim i^{-1/4} \]

\[ \sim i^{-1/2} \]

\[ (\rho_i/\rho_{\text{us}})^{1/4} \]

\[ i \]

\[ 1 \quad 10^2 \quad 10^4 \quad 10^6 \quad 10^8 \quad 10^{10} \quad 10^{12} \quad 10^{14} \quad 10^{16} \]
SIGNATURES!
(AND CONSTRAINTS)
\[ \mathcal{L} = m_S S S^c + \lambda \sum_i S H_i L_i \]

Freeze-in abundance from:
\[ \nu_{us} \nu_{us} \rightarrow \nu_{us} \nu_i \]

Also, mixing with neutrino impacts their masses.

Hard to go beyond \( N \sim 10^3 \).
CMB Stage IV: future constraint on $N_{\text{eff}} \lesssim 0.02$.
Also constrain $\sum m_{\nu_i}$ to SM value.

Wu, et al. [arXiv:1402.4108]
ELECTRON (AND PROTON) OVERCLOSURE

Scalar model: \( \mathcal{L} = \frac{1}{2} m_\phi \phi^2 + a \phi \sum_i |H_i|^2 \)

Estimate thermal electron density.

\[
\Omega_e^\phi h^2 = \sum_{i=1}^{N_{th}} \frac{m_e^i n_e^i}{\rho_c^0} \approx \left( \frac{m_e^{\text{us}} T_0^{\text{us}}}{\rho_c^0} \right)^3 \frac{N_{th}^{5/2}}{M_{\text{pl}} v_{\text{us}} \alpha^2}
\]

Requiring

\[
\Omega_e^\phi h^2 \lesssim 0.1 \times \Omega_{\text{DM}} h^2 \quad \implies \quad N_\phi \lesssim 10^5
\]

Proton (symmetric) abundance subdominant.
GETTING TO $N = 10^{16}$

**Ultra-safe model:** add vector like-lepton.

$$\left( L, L^c, E, E^c, N, N^c \right)$$

with

$$\mathcal{L} \supset \text{mass terms} + \text{Yukawa terms} + \lambda HLS + \mu_E E e^c$$

\[ \Gamma \sim \frac{m_S^9}{v^8} \]
Potentially observable imprint on small scale power spectrum of cosmological perturbations.
MIXING BETWEEN SECTORS

**Kinetic mixing:** $\epsilon_i F_{\mu \nu} F^{\mu \nu}_i$.

Energy loss in stars $\implies \sqrt{\sum_i \epsilon_i^2} \lesssim 10^{-14}$

**Neutral state mixing:** $\epsilon_i^n \nu_i^\dagger \bar{\sigma}^\mu D_{\mu \nu}$.

Neutrino production rate from neutral current bremsstrahlung $\implies \sqrt{\sum_i (\epsilon_i^n)^2} \lesssim 10^{-4}$

**Charged state mixing:** $\epsilon_i^c G_F \left( \nu_i^\dagger \bar{\sigma}^\mu e^c \right) (p^\dagger \bar{\sigma}_\mu n)$.

SN1987a charged current neutrino production $\implies \sqrt{\sum_i (\epsilon_i^c)^2} \lesssim 10^{-5}$
COMPLETING THE STORY
REHEAT TEMPERATURE

\[ T_{\text{rh}} \sim \sqrt{\Gamma_{\text{reheaton}} \, M_{\text{pl}}} \]

Set by size of reheaton - Higgs coupling.

Constrained to be \( \lesssim m_{W_{\text{us}}} \).

\[ T \sim |m_H| \] in other sectors changes predictions.

Leads to larger reheaton branching ratios into \( i \neq \text{us} \).

[Tension can be alleviated by preheating.]
Low reheat temperature: not all standard mechanisms work.

One option
Primordial lepton asymmetry.
Only converted to baryons for sectors with $T > T_{\text{sphaleron}} \sim m_W$. 
STRONG CP

Assume only breaking of $\mathbb{Z}_2$ is from $m_H^2$, common axion to all sectors.

Same effective $\theta_{CP}$ for all sectors.

Axion gets contribution to mass from every $\Lambda_{QCD}$. Larger $m_\alpha$ as function of $f$. 
DARK MATTER

MANY OPTIONS

Thermal relic
(neutralino in SUSY scenario?)

Relics from other sectors

Axion

Superpartner of reheaton

...
Observable in HL-LHC, tera-Z, 100 TeV pp??

Very challenging.

Observability in tension with low reheat temp.

Likely only possible for small $N$.

Potentially see rate change by sending more energy through propagator to access more sectors!
OUTLOOK
Dynamically realizing $N$

\[ \langle \mathbf{h}_i \rangle \neq 0 \quad \Rightarrow \quad \text{Extra dimension (deconstruction)} \]

\[ \langle \mathbf{h}_i \rangle = 0 \quad \Rightarrow \quad \text{Large number of DOF's} \]
CONCLUSIONS

Novel solution to big/little hierarchy problem.

Many simple models exist.

Success relies on cosmology.

Constrained by $N_{\text{eff}}$, neutrino, electron, and proton over closure.

If strong CP solved by axion, expect it to be heavier.

If $N \lesssim 10^4$, spectacular signatures at LHC or future colliders.

Observe “steps” in primordial power spectrum.