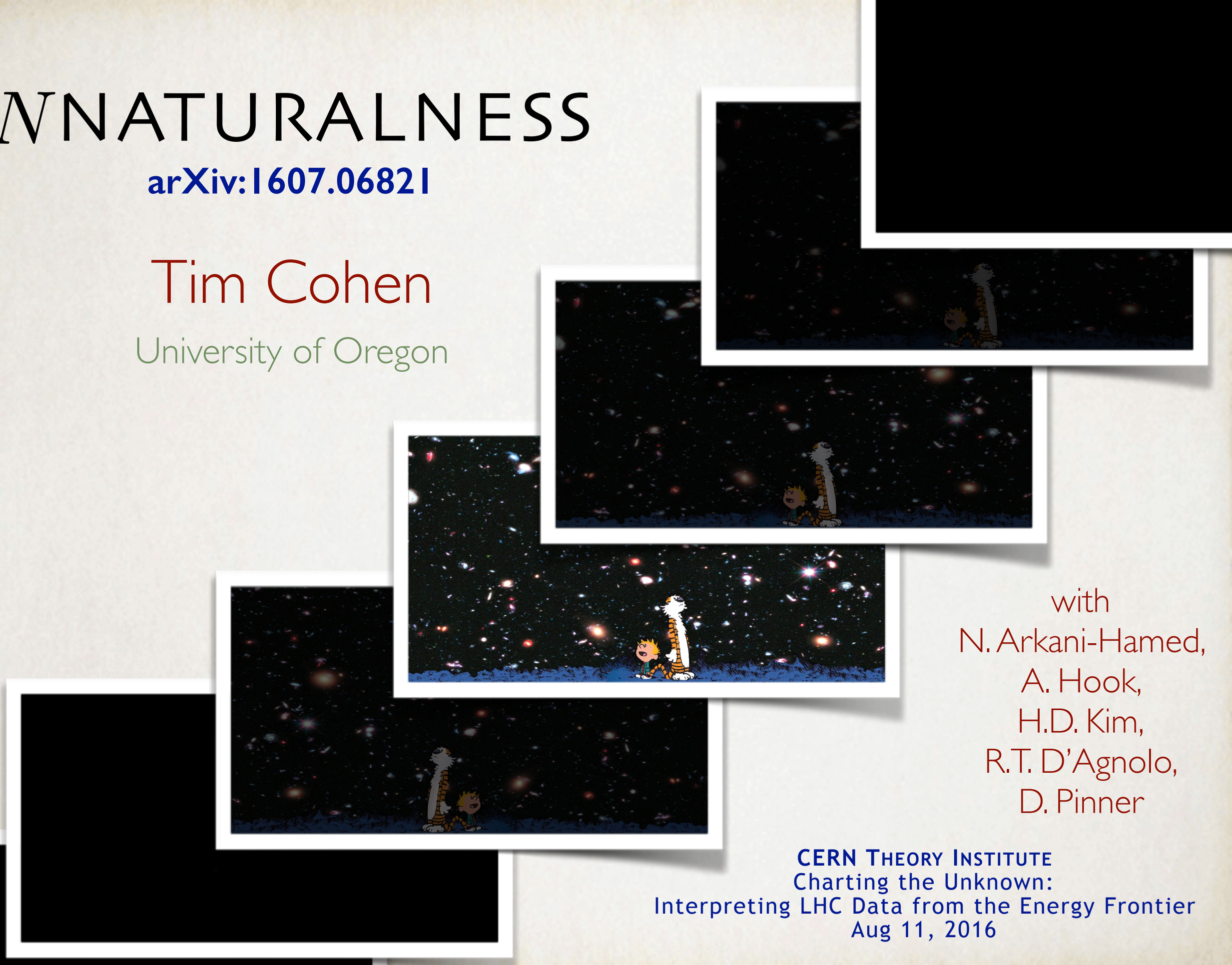
$\mathcal{N}$NATURALNESS

arXiv:1607.06821

Tim Cohen

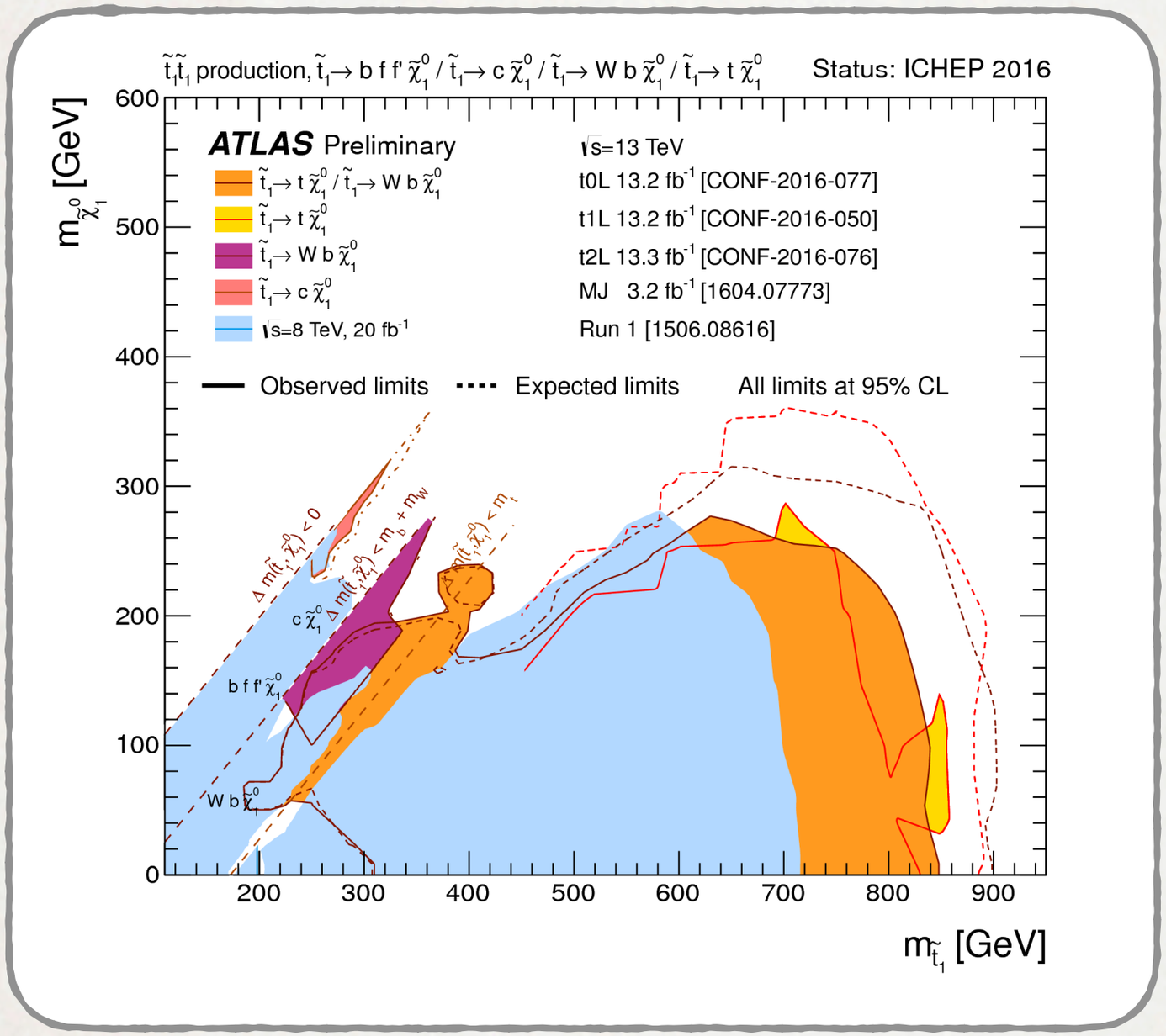
University of Oregon



with
N. Arkani-Hamed,
A. Hook,
H.D. Kim,
R.T. D'Agnolo,
D. Pinner

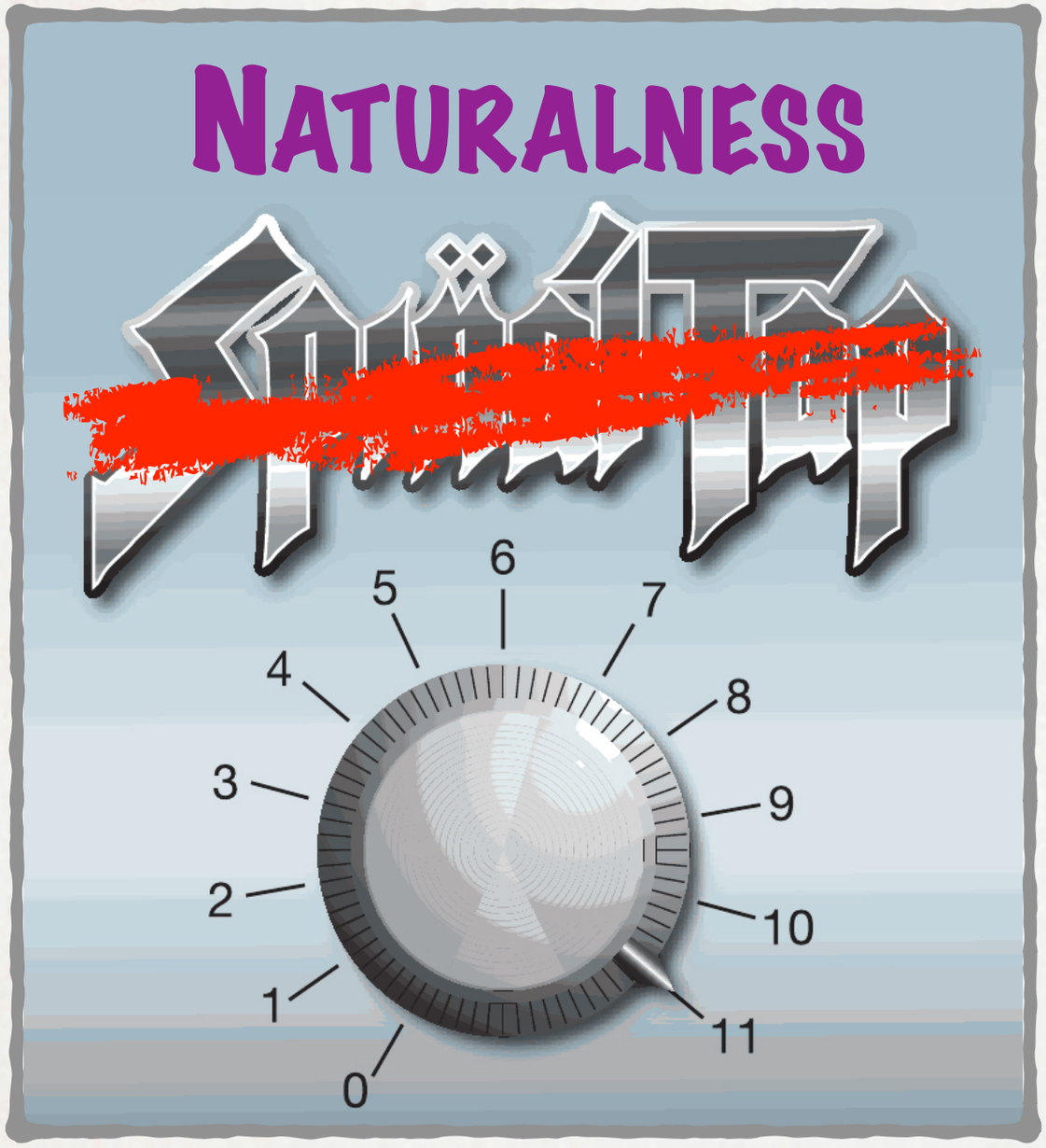
CERN Theory Institute
Charting the Unknown:
Interpreting LHC Data from the Energy Frontier
Aug 11, 2016

NATURALNESS AND DATA



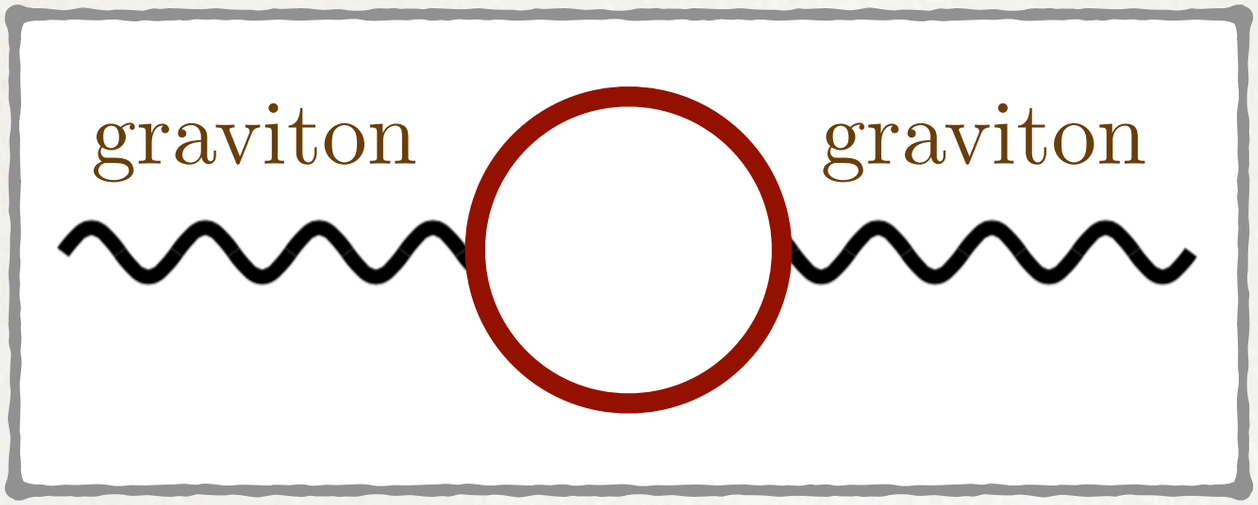
Top partner limits constrain natural scenarios.

Naturalness



BRINGING DOWN THE CUTOFF

Gravity sees all degrees of freedom.

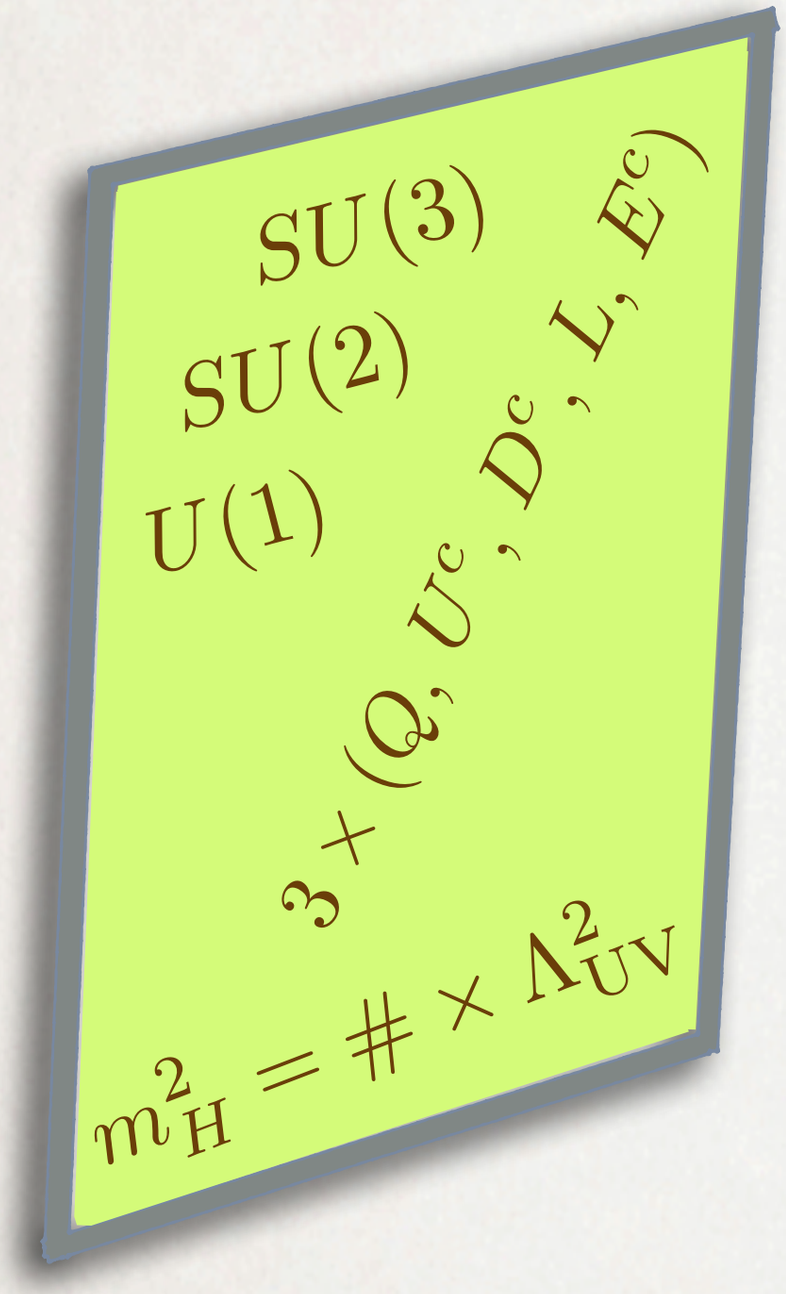


$$M_{\rm pl}^2(\mu) = M_{\rm pl}^2(0) - N\frac{\mu^2}{96\,\pi^2}$$

$$\Lambda_{\rm UV} \sim \frac{M_{\rm pl}(0)}{\sqrt{N}}$$

Larsen, Wilczek [arXiv:hep-th/9506066]; Calmet, Gong, Hsu [arXiv:0806.4605]

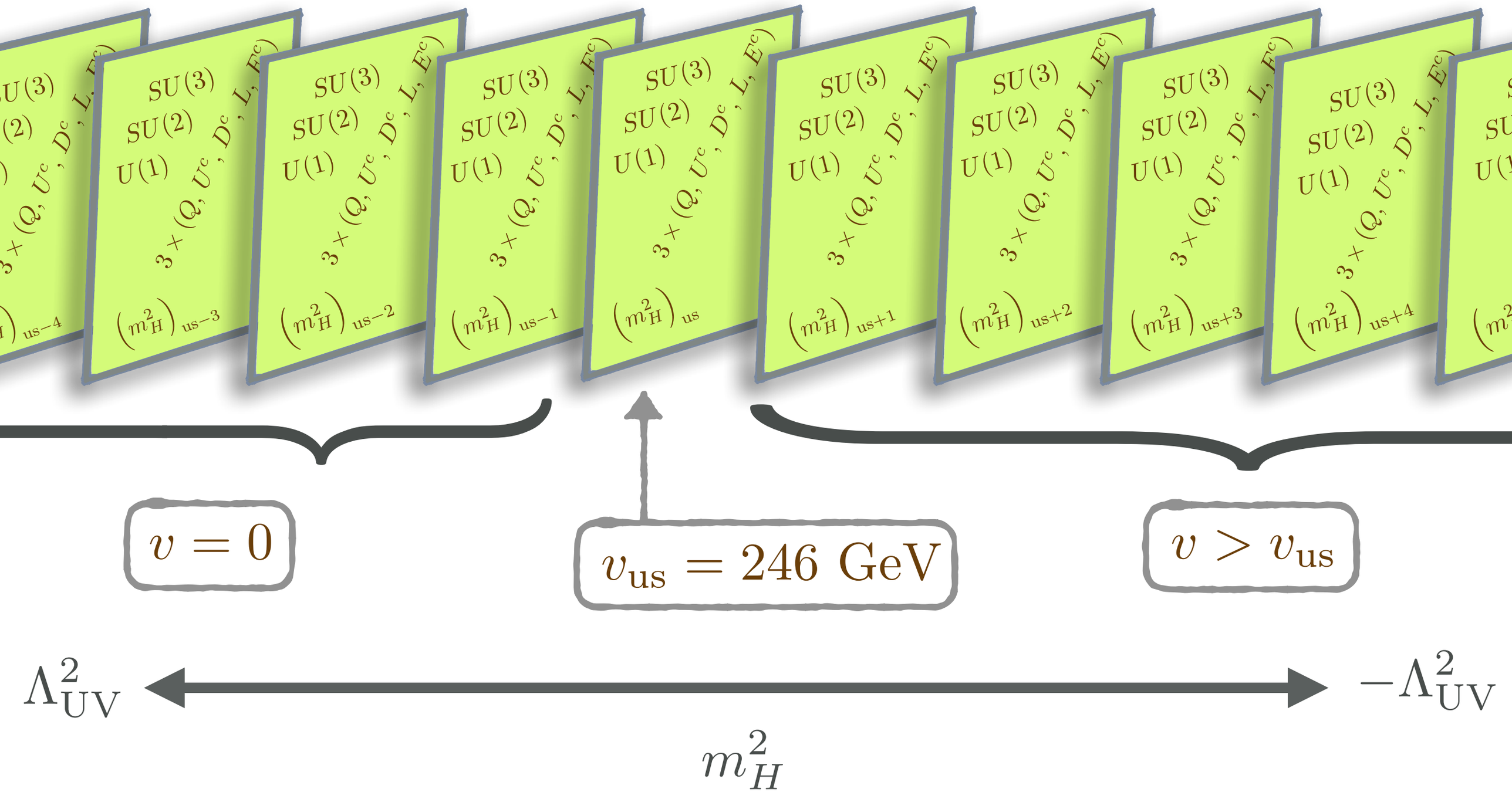
A RANDOM COPY



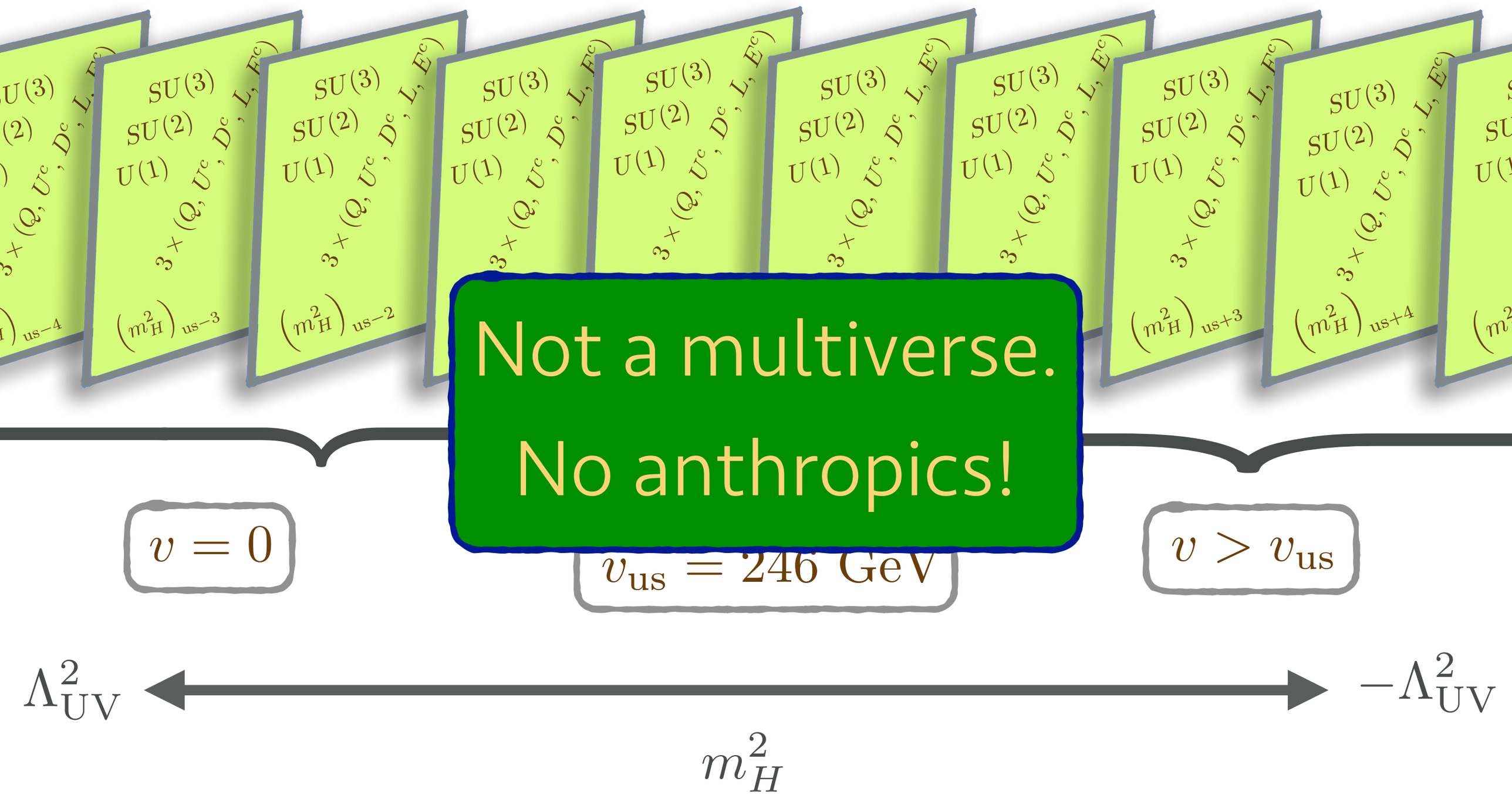
For simplicity:
Only variation away from our Standard Model is Higgs mass parameter.

$$-\Lambda_{\rm UV}^2 \lesssim \left(m_H^2\right)_i \lesssim \Lambda_{\rm UV}^2$$

N COPIES


SU(3)
SU(2)
U(1)
$3\times(Q, U^c, D^c, L, E^c)$
$(m_H^2)_{us-4}$
$(m_H^2)_{us-3}$
$(m_H^2)_{us-2}$
$(m_H^2)_{us-1}$
$(m_H^2)_{us}$
$(m_H^2)_{us+1}$
$(m_H^2)_{us+2}$
$(m_H^2)_{us+3}$
$(m_H^2)_{us+4}$
$v = 0$
$v_{us} = 246$ GeV
$v > v_{us}$
Λ_{UV}^2
$-\Lambda_{UV}^2$
m_H^2

N COPIES


SU(3)
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$3\times(Q, U^c, D^c, L, E^c)$
$(m_H^2)_{us-4}$
$(m_H^2)_{us-3}$
$(m_H^2)_{us-2}$
$(m_H^2)_{us+3}$
$(m_H^2)_{us+4}$
Not a multiverse.
No anthropics!
$v = 0$
$v_{us} = 246$ GeV
$v > v_{us}$
Λ_{UV}^2
$-\Lambda_{UV}^2$
m_H^2

Hierarchy problem: ✓

But why is there energy density in only our sector?!?

OUTLINE

General Mechanism

Two Simple Models

Signatures!

Completing the Story

Outlook

GENERAL MECHANISM

JUST A SIGN

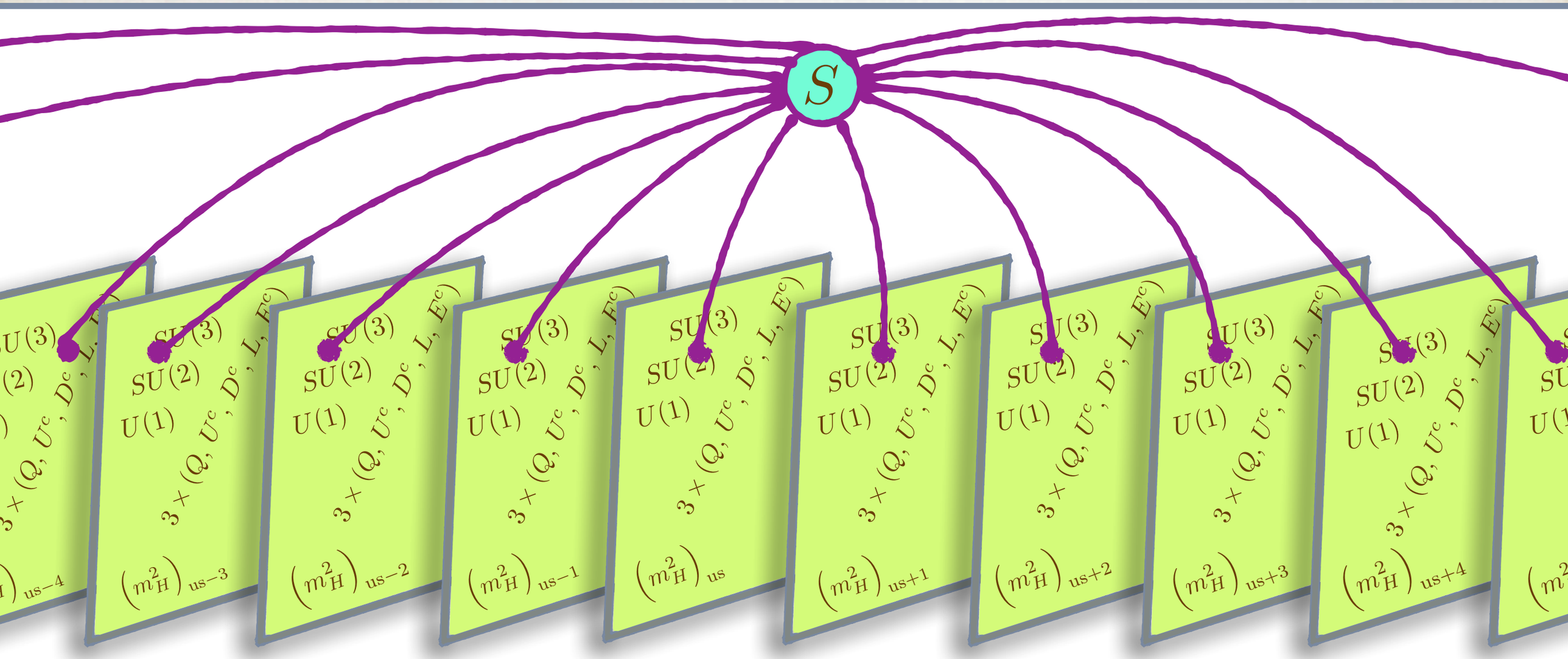
$m_H^2 > 0$	$m_H^2 < 0$

• Massless photon
• $W^\pm,\ Z^0$ masses $\sim \Lambda_{\rm QCD}$
• Fermion masses $\sim y_f \dfrac{\Lambda_{\rm QCD}^3}{m_H^2}$
• $T_{\rm sphaleron} < \Lambda_{\rm QCD}$: no baryon relic density
• No baryon relic density
	• Massless photon
	• $W^\pm,\ Z^0$, and fermion masses $\sim v$
	• Neutrino masses:
	  • Majorana mass $\sim v^2$
	  • Dirac mass $\sim v$

THE REHEATON

S reheats the Universe after inflation.

Couples universally to all copies.



MODEL REQUIREMENTS

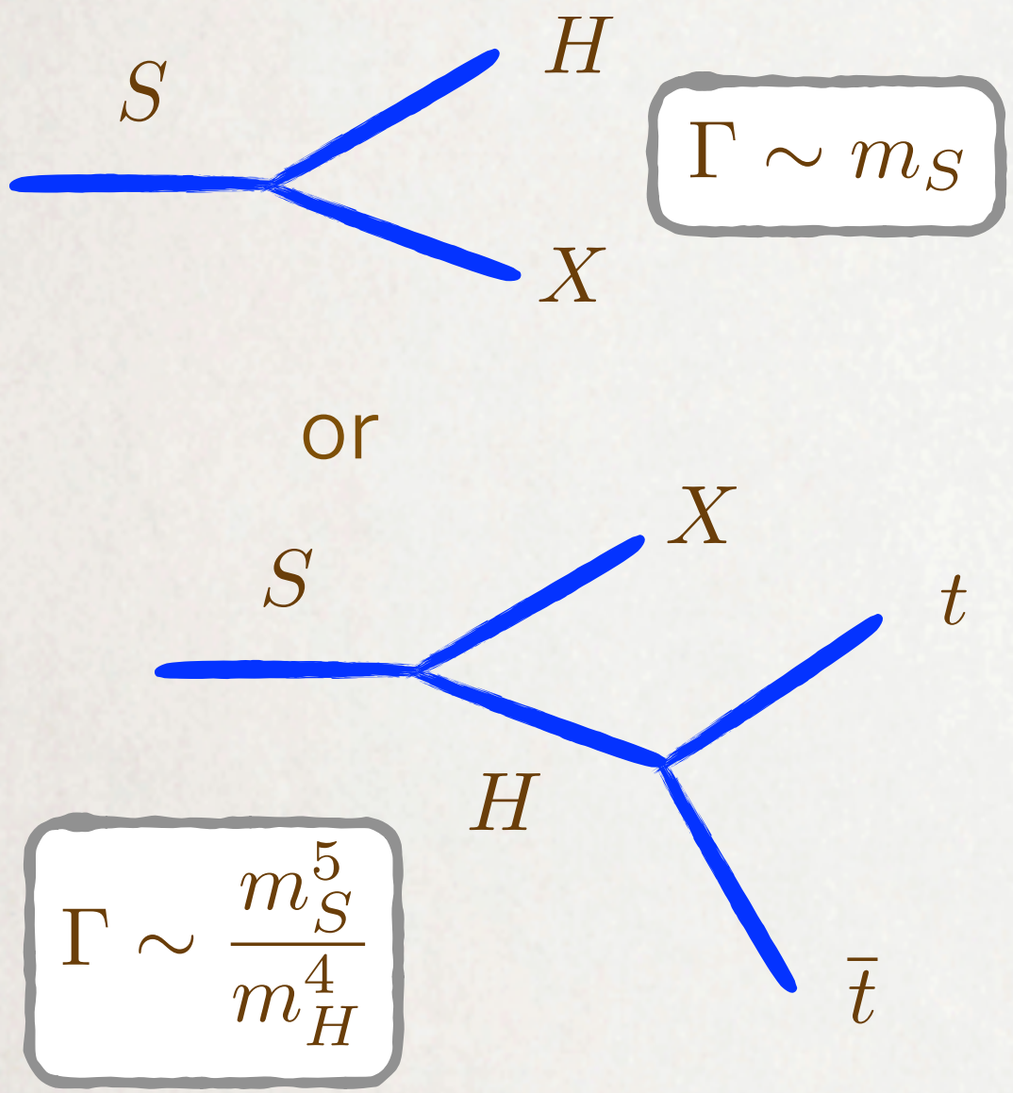
i) The reheaton is a gauge singlet;

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

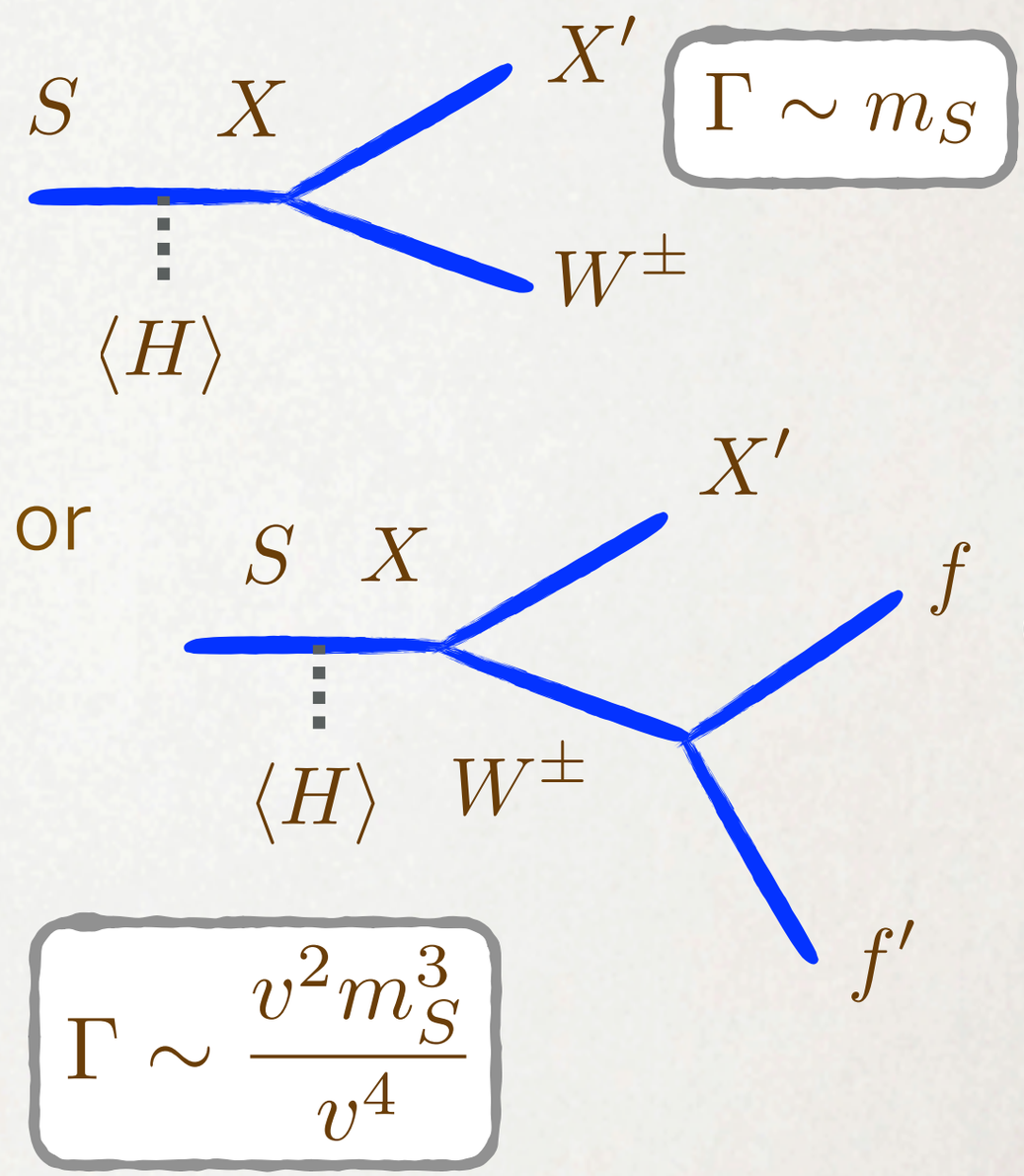
iii) Couplings are most relevant ones possible that involve Higgs bosons of each sector.

COUPLE S TO $H + X$

$m_H^2 > 0$



$m_H^2 < 0$



Increasing m_H^2

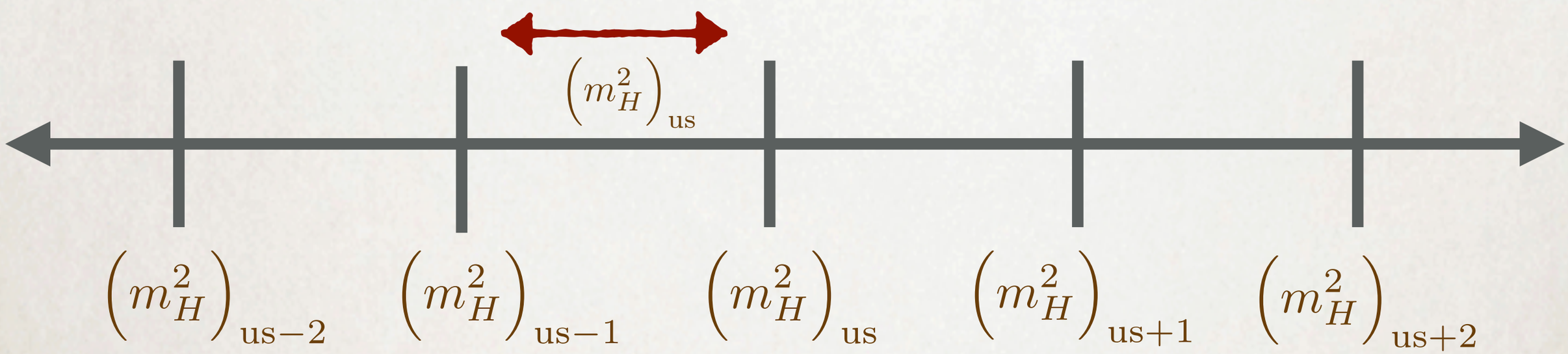
Increasing v

SIMPLEST SCENARIO

Even spacing for Higgs mass squared parameters:

$$\left(m_H^2\right)_i = i \times \left(m_H^2\right)_{\rm us}$$

So that $v_i \sim \sqrt{i}$.



MASSLESS DOF

Energy density in additional relativistic degrees of freedom.

$$N_{\rm eff} \sim \frac{\sum_{i \neq {\rm us}} \rho_i}{\rho_{\rm us}} \sim \frac{\sum_{i \neq {\rm us}} \Gamma_i}{\Gamma_{\rm us}} \sim \log N$$

Relic density of additional neutrinos.

$$\Omega_\nu h^2 \sim \begin{cases} \dfrac{\sum_{i \neq {\rm us}} v_i \, \rho_i^{3/4}}{v_{\rm us} \, \rho_{\rm us}^{3/4}} \sim N^{3/4} & \text{Dirac} \\[2ex] \dfrac{\sum_{i \neq {\rm us}} v_i^2 \, \rho_i^{3/4}}{v_{\rm us}^2 \, \rho_{\rm us}^{3/4}} \sim N^{5/4} & \text{Majorana} \end{cases}$$

MASSIVE DOF

THERMAL FREEZE-OUT

Heaviest sector that thermalizes

Model dependence

$$\Omega\, h^2 = \frac{s_0}{\rho_c^0} \sum_{i=-1}^{-N_d} m_i\, Y_i^{\rm fo} + \ldots = a\,(N_d)^p + \ldots$$

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

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

Neglect freeze-in.

HOW MANY COPIES?

Full hierarchy problem

$$\underbrace{v_{\rm us} \sim \frac{\Lambda_{\rm UV}}{\sqrt{N}} \quad \text{and} \quad \Lambda_{\rm UV} \sim \frac{M_{\rm Pl}}{\sqrt{N}}}$$

$$N \sim \frac{M_{\rm Pl}}{v_{\rm us}} \simeq 10^{16}$$

and

$$\Lambda_{\rm UV} \sim 10^{10}\ {\rm GeV}$$

HOW MANY COPIES?

Little hierarchy problem

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

$$+$$

$$\Lambda_{\rm UV} \sim M_{\rm GUT}$$

$$N \sim 10^4$$

$$\Lambda_{\rm SUSY} \sim 10 \text{ TeV}$$

HOW MANY COPIES?

Little hierarchy problem

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

$$+$$

$$\underbrace{\Lambda_{\rm UV} \sim M_{\rm GUT}}$$

$$N \sim 10^4$$

$$\Lambda_{\rm SUSY} \sim 10 \text{ TeV}$$

Tons of signatures at future colliders!

HOW MANY COPIES?

Full hierarchy problem (again)

All new degrees of freedom → $N_{\rm total}$ and $N_{\rm reheat}$ ← Couple to reheaton

$$v_{\rm us} \sim \frac{\Lambda_{\rm UV}}{\sqrt{N_{\rm reheat}}} \quad \text{and} \quad \Lambda_{\rm UV} \sim \frac{M_{\rm Pl}}{\sqrt{N_{\rm total}}}$$

with $N_{\rm total} \gg N_{\rm reheat}$

For this scenario:

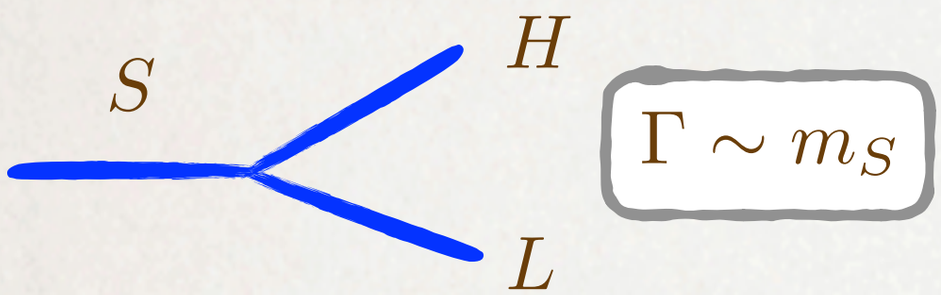
$$N \to N_{\rm reheat}$$

TWO SIMPLE MODELS

NEUTRINO REHEATON

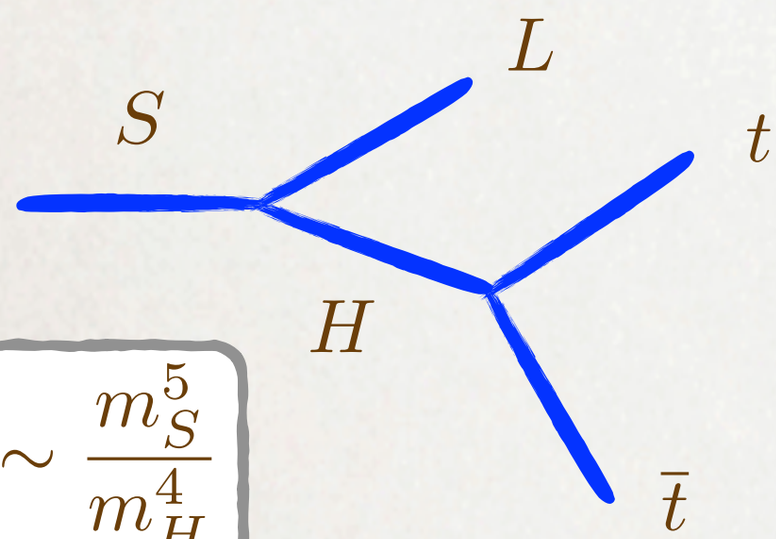
$$\mathcal{L} = m_S\, S\, S^c + \lambda \sum_i S\, H_i\, L_i$$

$m_H^2 > 0$



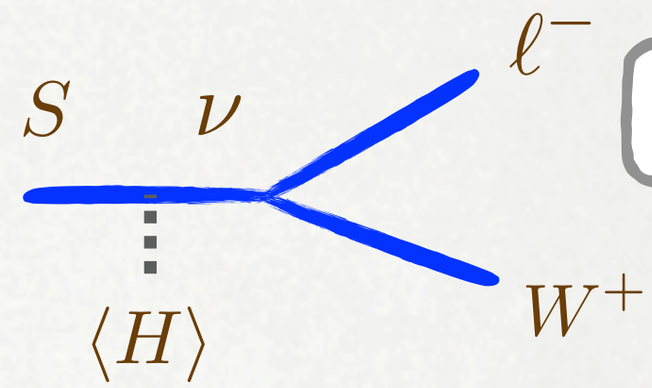
$\Gamma \sim m_S$

or



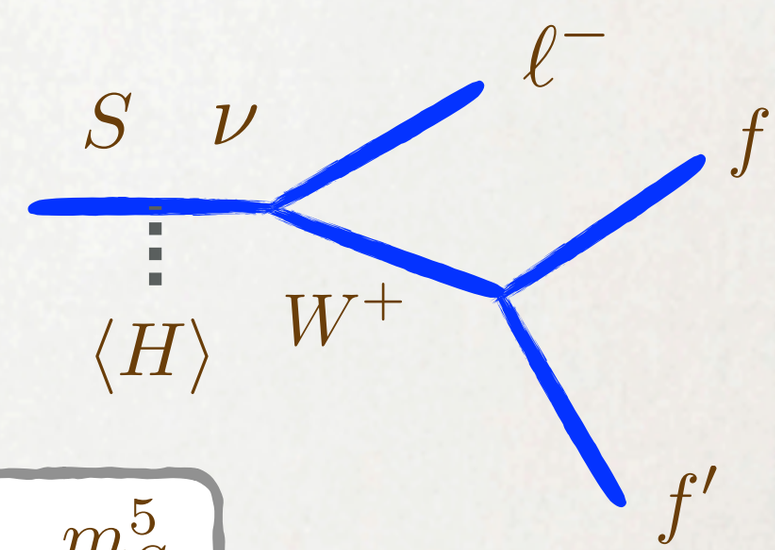
$\Gamma \sim \frac{m_S^5}{m_H^4}$

$m_H^2 < 0$



$\Gamma \sim m_S$

or

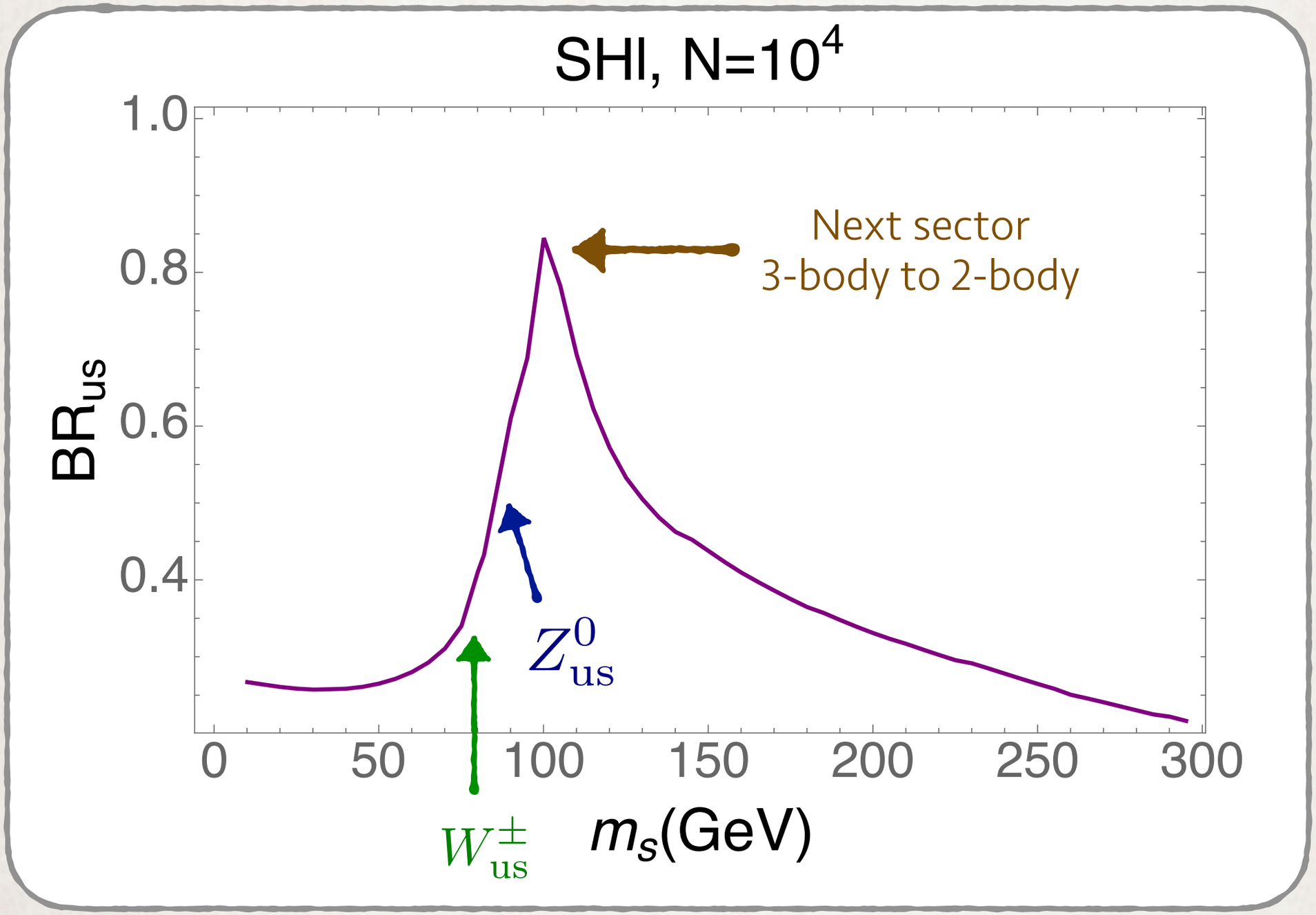


$\Gamma \sim \frac{m_S^5}{v^4}$

Increasing m_H^2

Increasing λ

NEUTRINO REHEATON



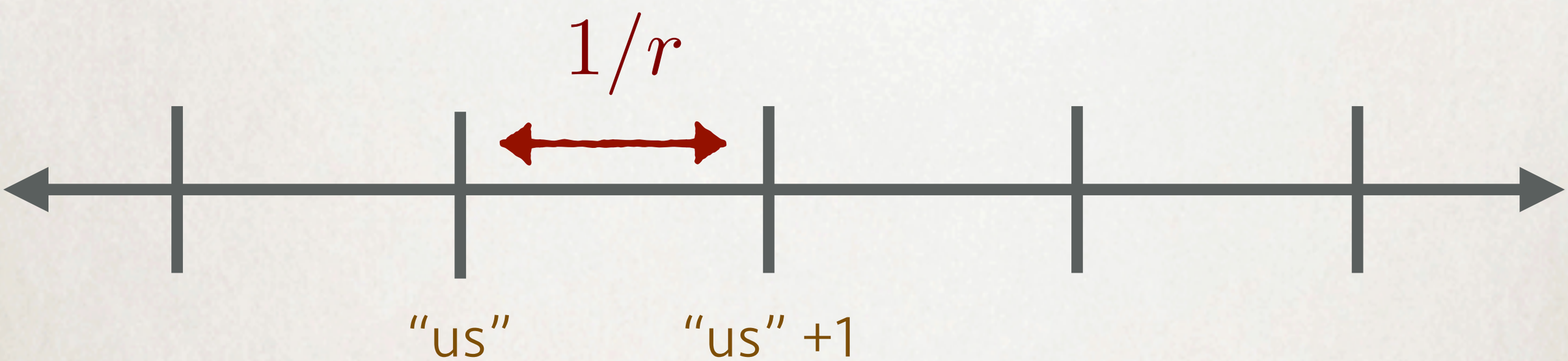
TOY SCENARIO

Parametrize distribution of Higgs masses:

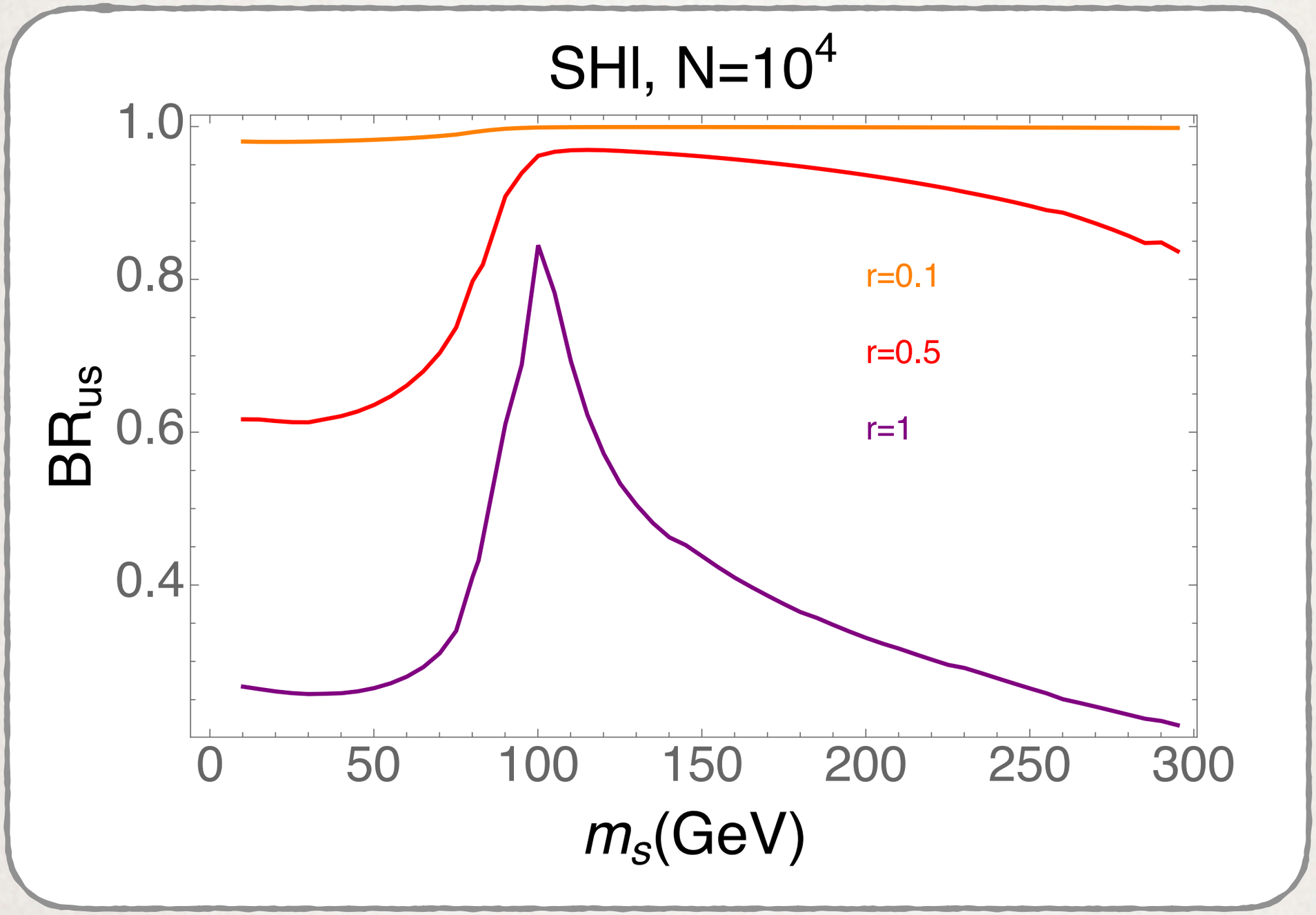
$$\left(m_H^2\right)_i = -\frac{\Lambda_H^2}{N}\left(2\,i + r\right)$$

$$\left(m_H^2\right)_{\rm us} = -r \times \frac{\Lambda_H^2}{N} \simeq -(88\ {\rm GeV})^2$$

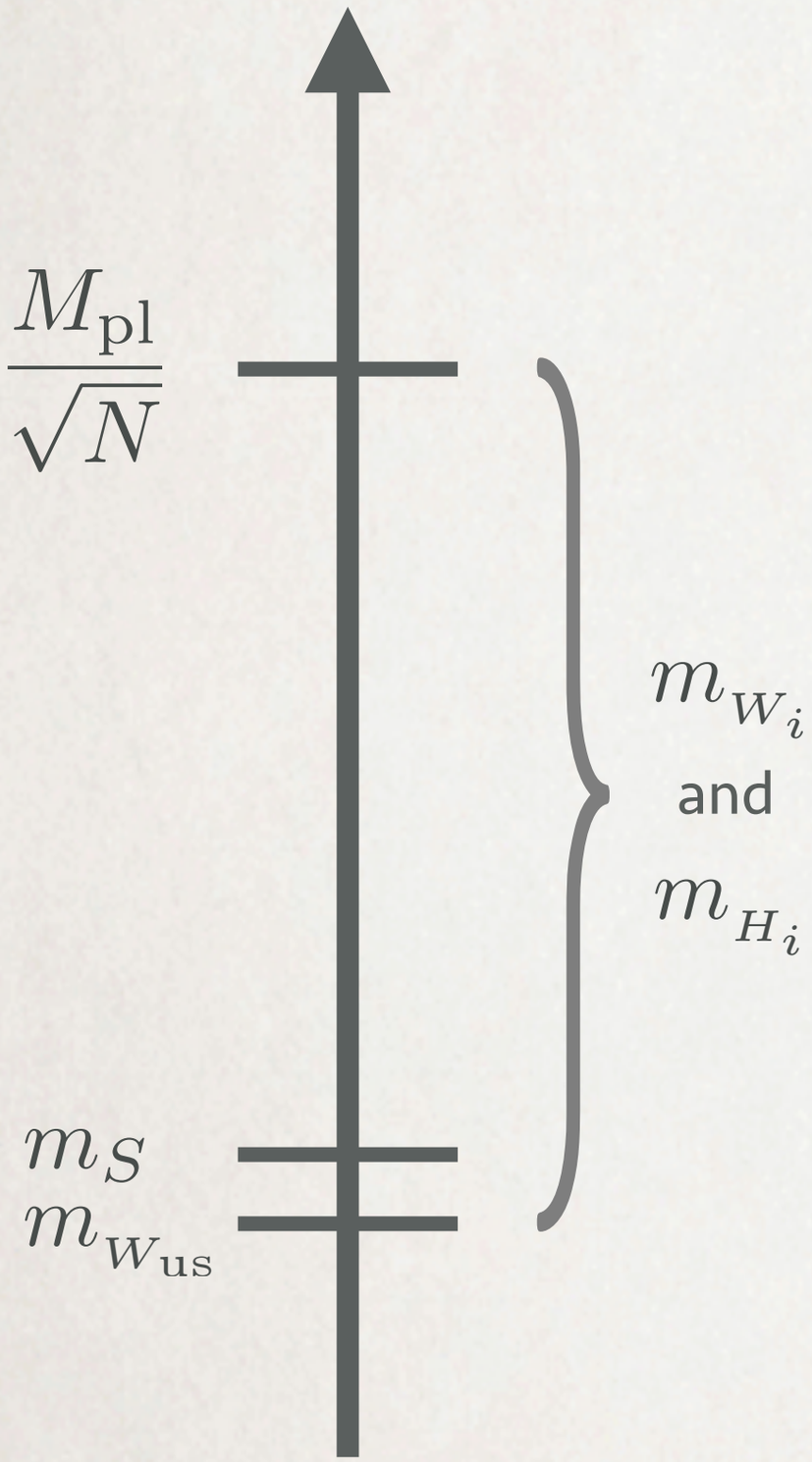
r parametrizes tuning.



NEUTRINO REHEATON



μ-PROBLEM



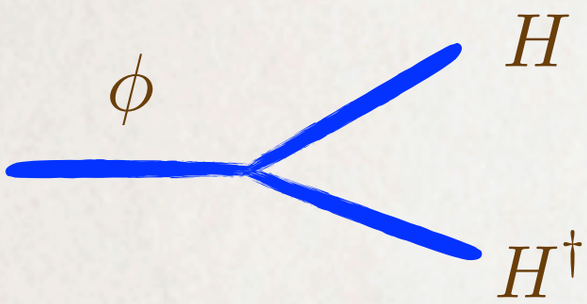
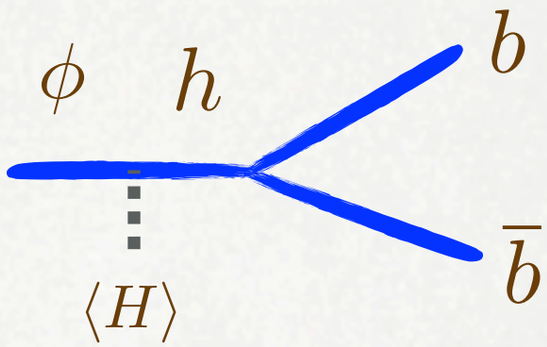
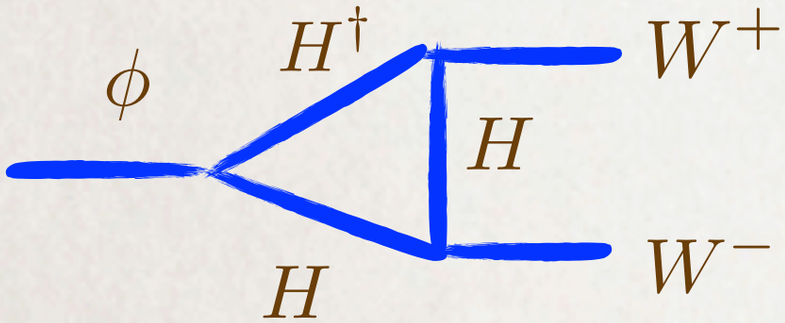
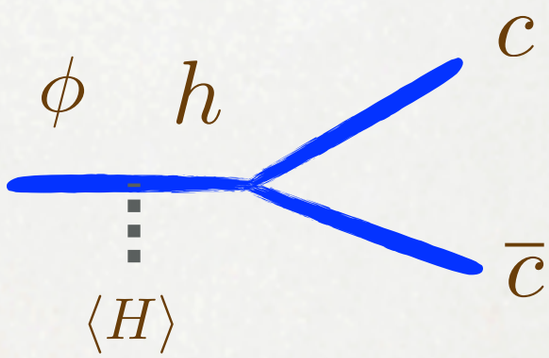
Reheaton mass is technically natural.

Critical that reheaton mass be $\mathcal{O}\left(m_{W_{\rm us}}\right)$.

Analogous to μ-problem in the MSSM.

SCALAR REHEATON

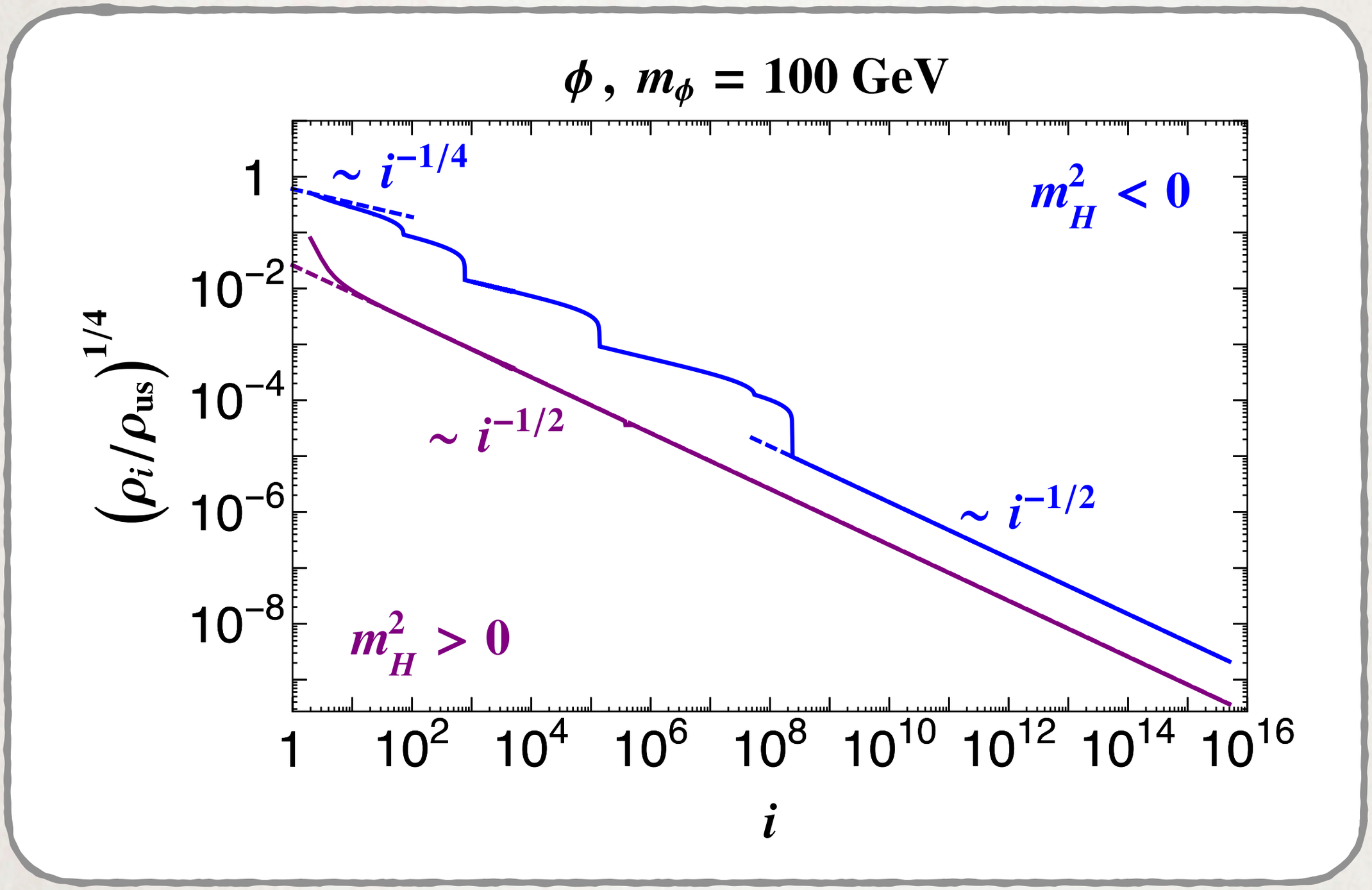
$$\mathcal{L} = \frac{1}{2} m_\phi \phi^2 + a\,\phi \sum_i \left|H_i\right|^2$$

$m_H^2 > 0$	$m_H^2 < 0$
 $\Gamma \sim \frac{a^2}{m_\phi}$	 $\Gamma \sim y_b^2\, a^2 \frac{m_\phi^3}{v^4}$
 $\Gamma \sim \frac{a^2\, g^4}{(16\pi^2)^2} \frac{m_\phi^3}{m_H^4}$	 $\Gamma \sim y_c^2\, a^2 \frac{m_\phi^3}{v^4}$
	⋮

Increasing m_H^2

Increasing v

SCALAR REHEATON



SIGNATURES!
(AND CONSTRAINTS)

NEUTRINO OVERCLOSURE

$$\mathcal{L} = m_S \, S \, S^c + \lambda \sum_i S \, H_i \, L_i$$

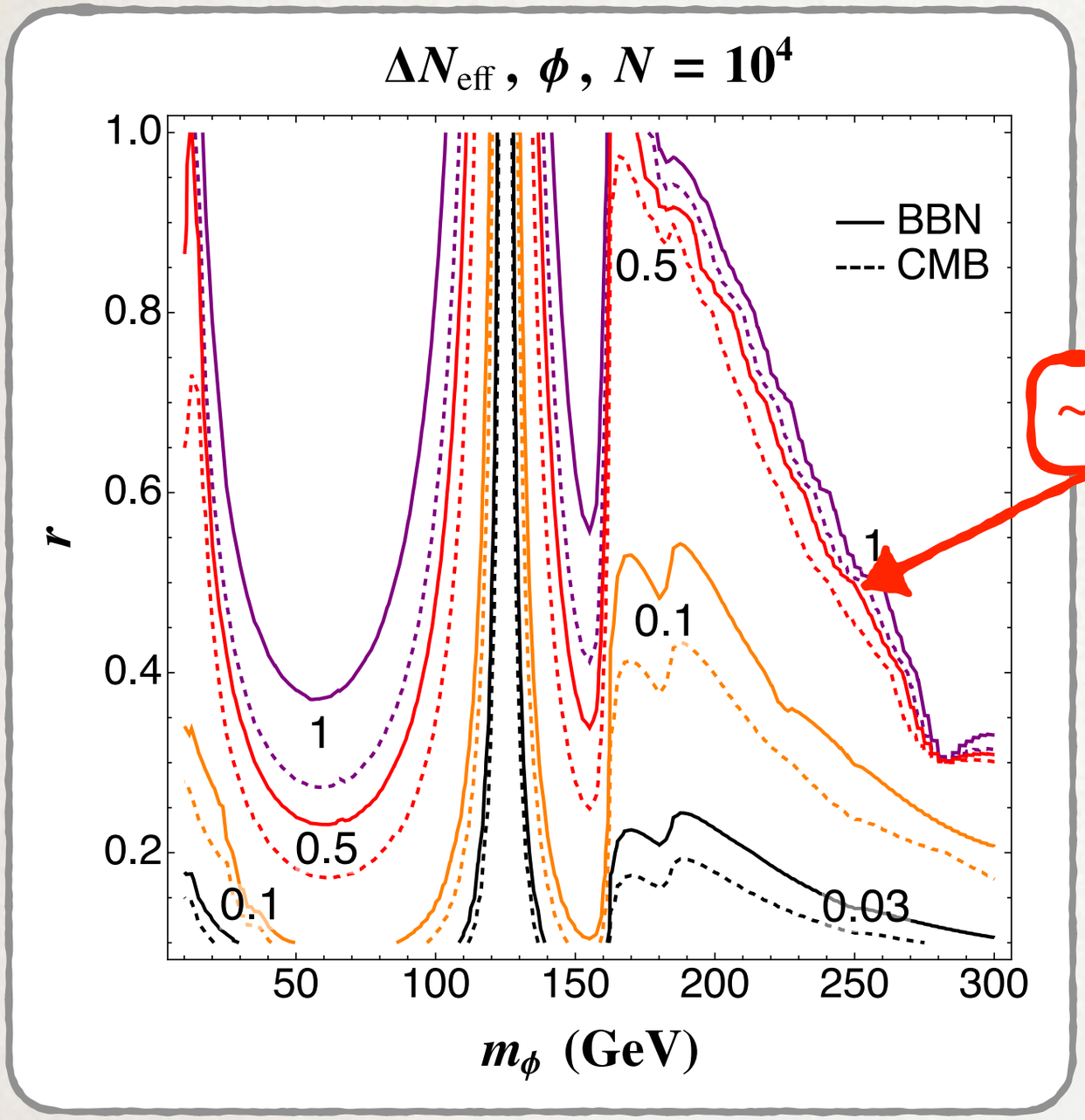
Freeze-in abundance from:

$$\nu_{\rm us} \nu_{\rm us} \to \nu_{\rm us} \nu_i$$

Also, mixing with neutrino impacts their masses.

Hard to go beyond $N \sim 10^3$.

$N_{\rm eff}$



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

~ Current constraint

CMB Stage IV: future constraint on $N_{\rm eff} \lesssim 0.02$.

Also constrain $\sum m_{\nu_i}$ to SM value.

Wu, et al. [arXiv:1402.4108]

ELECTRON (AND PROTON) OVERCLOSURE

Scalar model: $\mathcal{L} = \frac{1}{2} m_\phi \phi^2 + a\,\phi \sum_i \left|H_i\right|^2$

Estimate thermal electron density.

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

Requiring

$$\Omega_e^\phi\, h^2 \lesssim 0.1 \times \Omega_{\rm DM}\, h^2 \quad \Longrightarrow \quad N_\phi \lesssim 10^5$$

Proton (symmetric) abundance subdominant.

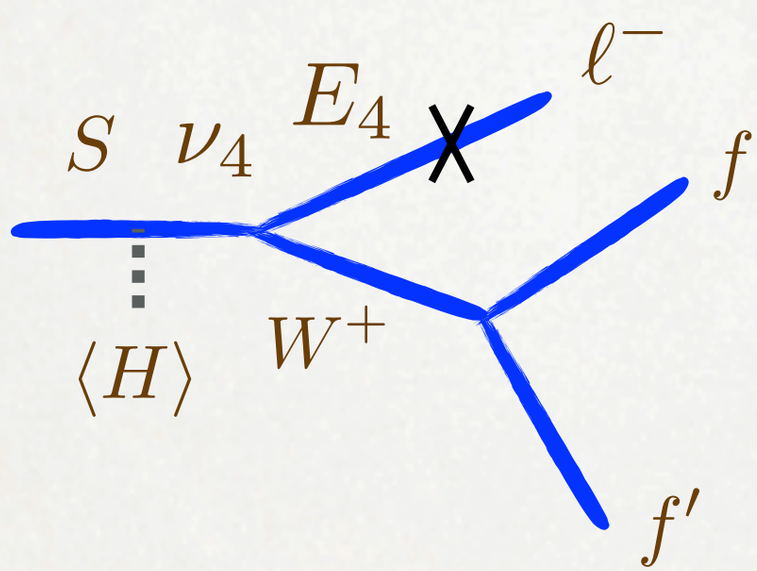
GETTING TO $N = 10^{16}$

Ultra-safe model: add vector like-lepton.

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

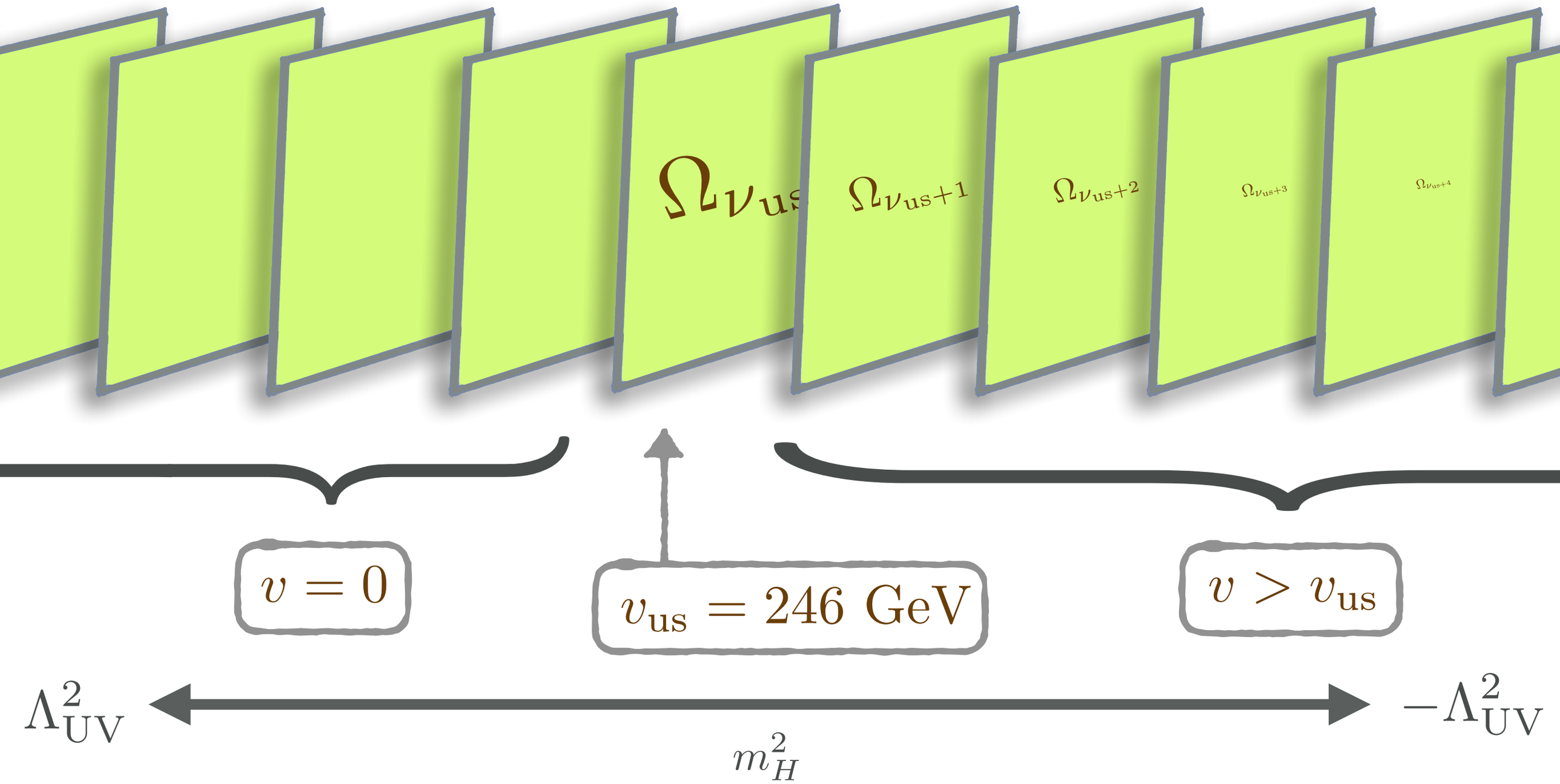
with

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



$$\Gamma \sim \frac{m_S^9}{v^8}$$

POWER AT SMALL SCALES



Potentially observable imprint on small scale power spectrum of cosmological perturbations.

MIXING BETWEEN SECTORS

KINETIC MIXING: $\epsilon_i \, F_{\mu\nu} \, F_i^{\mu\nu}$.

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

NEUTRAL STATE MIXING: $\epsilon_i^n \, \nu_i^\dagger \bar{\sigma}^\mu D_\mu \nu$.

Neutrino production rate from neutral current bremsstrahlung

$$\Longrightarrow \quad \sqrt{\sum_i (\epsilon_i^n)^2} \lesssim 10^{-4}$$

CHARGED STATE MIXING: $\epsilon_i^c \, G_F \left(\nu_i^\dagger \, \bar{\sigma}^\mu \, e^c \right) \left(p^\dagger \bar{\sigma}_\mu \, n \right)$.

SN1987a charged current neutrino production

$$\Longrightarrow \quad \sqrt{\sum_i (\epsilon_i^c)^2} \lesssim 10^{-5}$$

COMPLETING THE STORY

REHEAT TEMPERATURE

$$T_{\rm rh} \sim \sqrt{\Gamma_{\rm reheaton}\, M_{\rm pl}}$$

Set by size of reheaton - Higgs coupling.

Constrained to be $\lesssim m_{W_{\rm us}}$.

$T \sim |m_H|$ in other sectors changes predictions.
Leads to larger reheaton branching ratios into $i \neq {\rm us}$.

[Tension can be alleviated by preheating.]

BARYOGENESIS

Low reheat temperature:

not all standard mechanisms work.

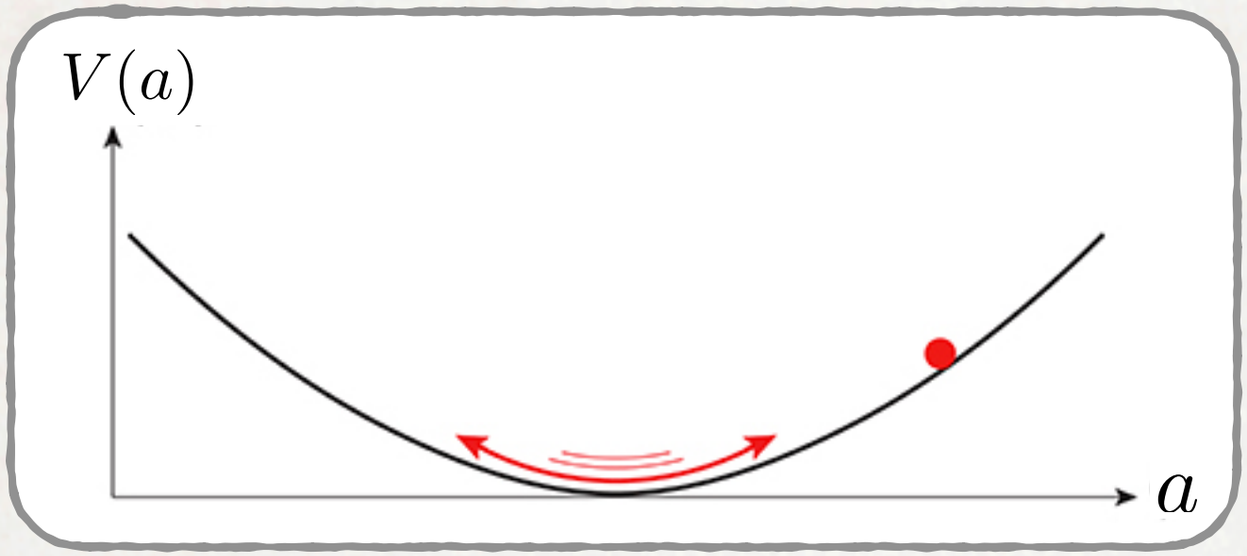
ONE OPTION

Primordial lepton asymmetry.

Only converted to baryons for sectors

with $T > T_{\rm sphaleron} \sim m_W$.

STRONG CP



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

Same effective $\theta_{\rm CP}$ for all sectors.
Axion gets contribution to mass from every $\Lambda_{\rm QCD}$.
Larger m_a as function of f.

DARK MATTER

MANY OPTIONS

Thermal relic
(neutralino in SUSY scenario?)

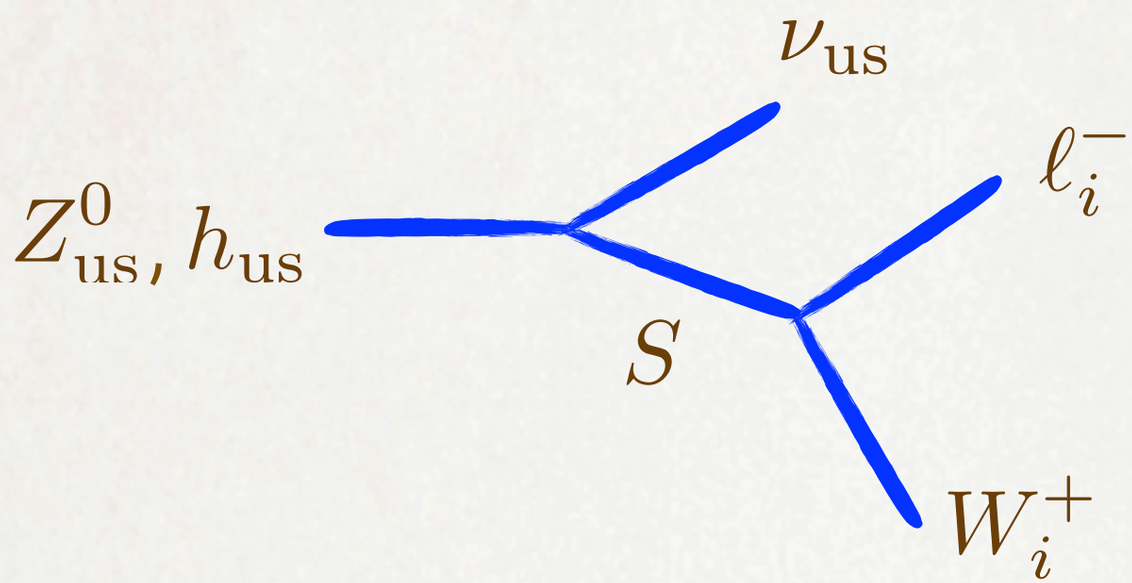
Relics from other sectors

Axion

Superpartner of reheaton

...

RARE DECAYS



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

Very challenging.

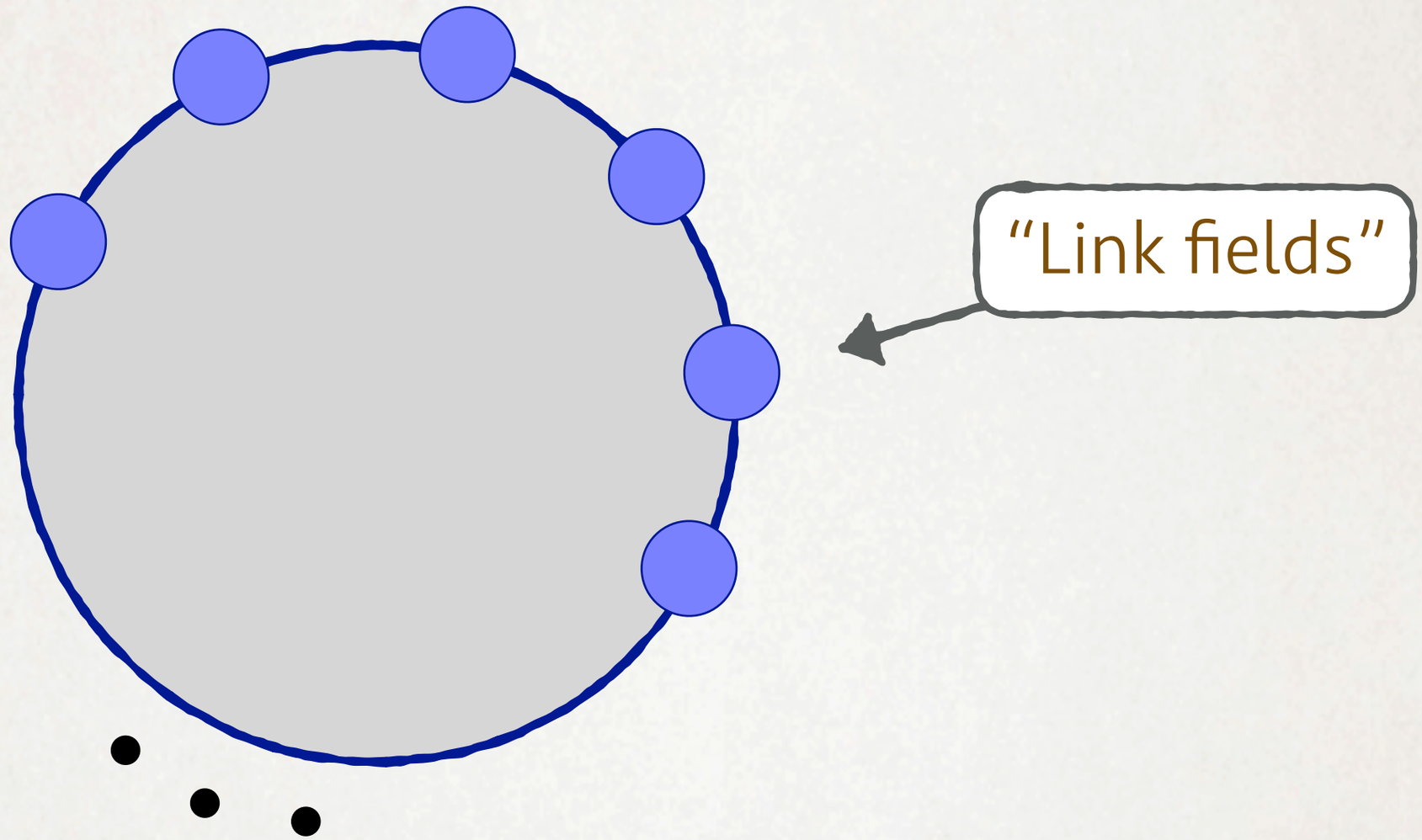
Observability in tension with low reheat temp.

Likely only possible for small N.

Potentially see rate change by sending more energy through propagator to access more sectors!

OUTLOOK

DYNAMICALLY REALIZING N



$\langle \bigcirc_i \rangle \neq 0$ ⇨ Extra dimension (deconstruction)

$\langle \bigcirc_i \rangle = 0$ ⇨ Large number of DOF's

CONCLUSIONS

Novel solution to big/little hierarchy problem.

Many simple models exist.

Success relies on cosmology.

Constrained by $N_{\rm eff}$, 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.