NATURALNESS

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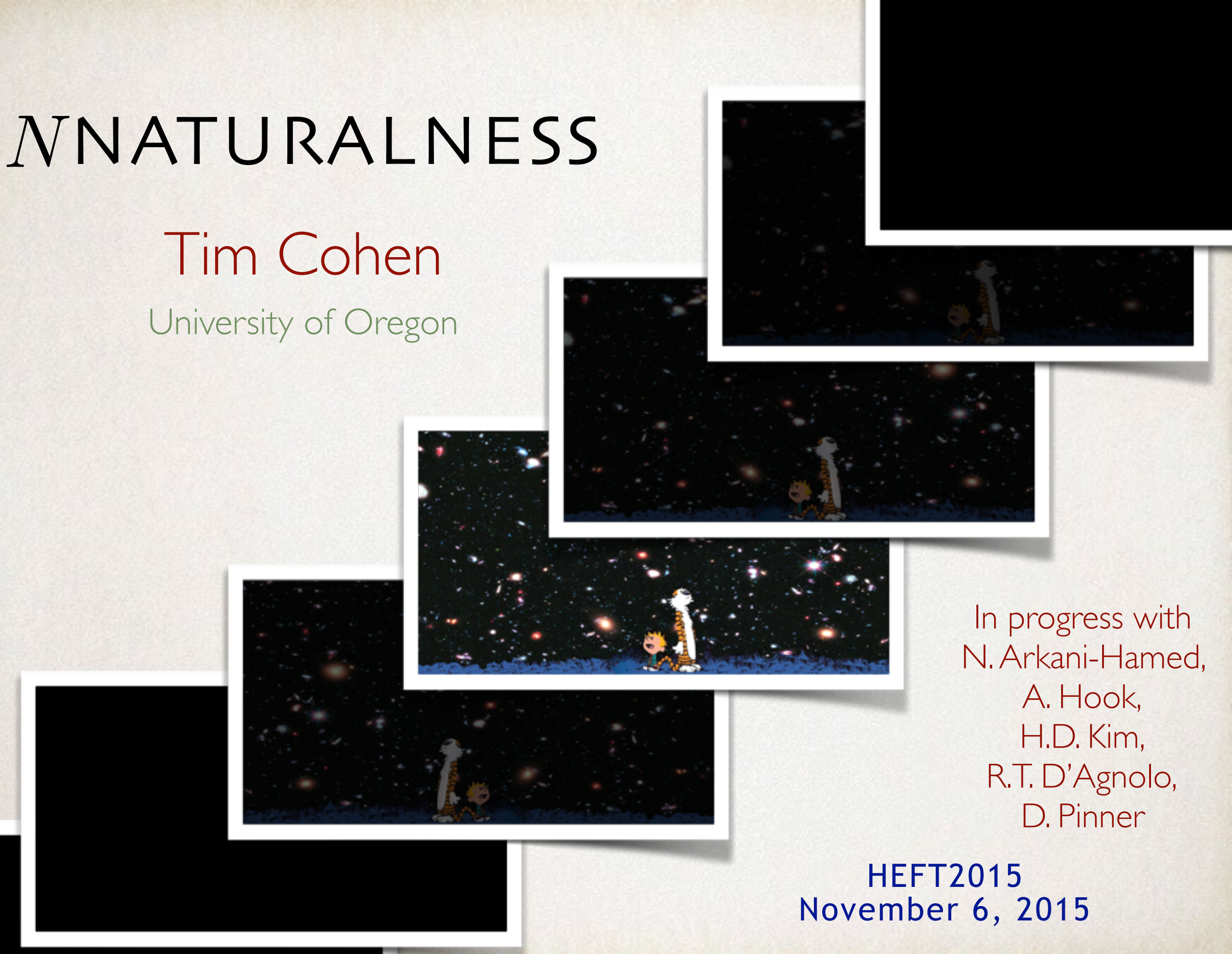
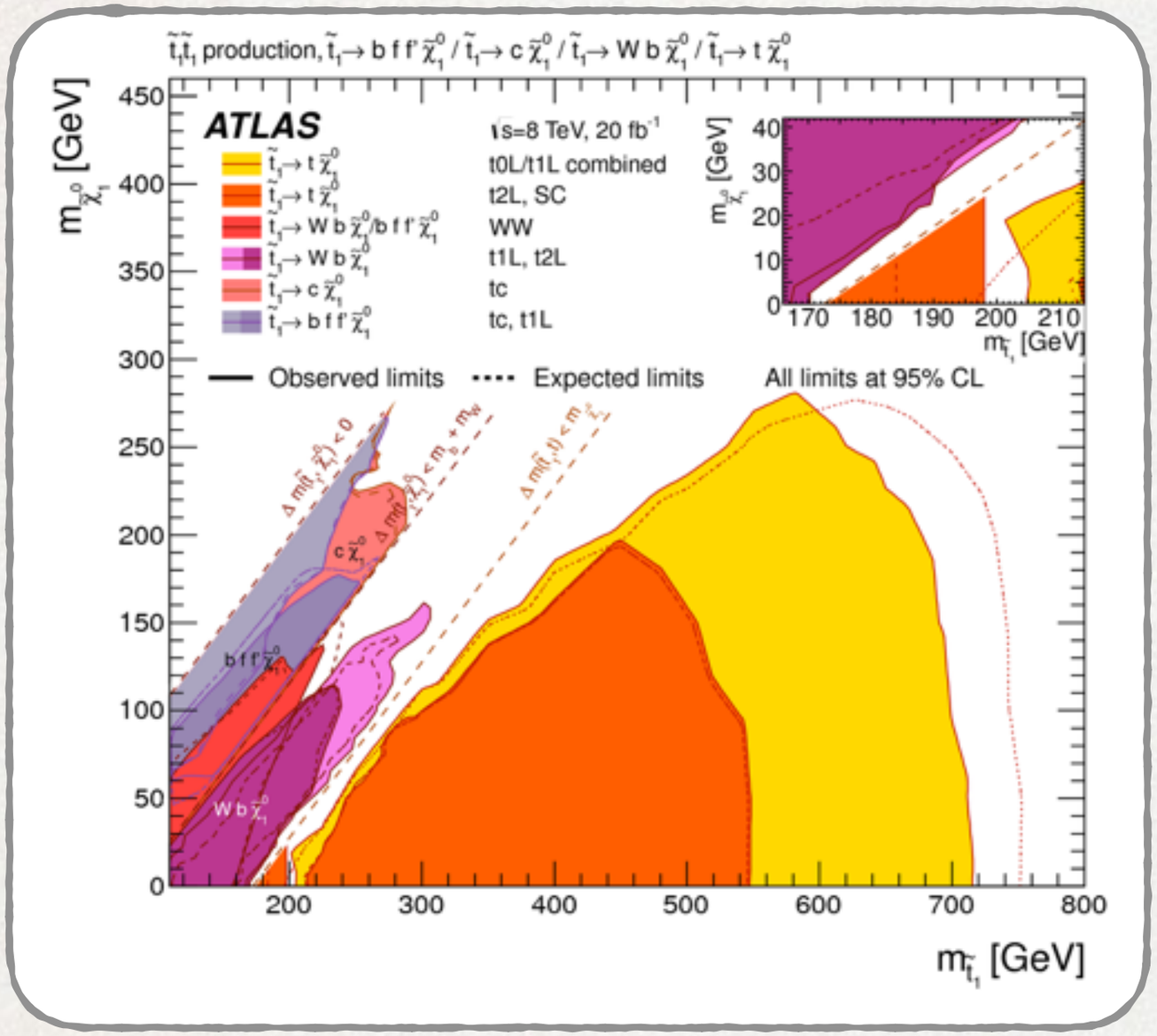
University of Oregon



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

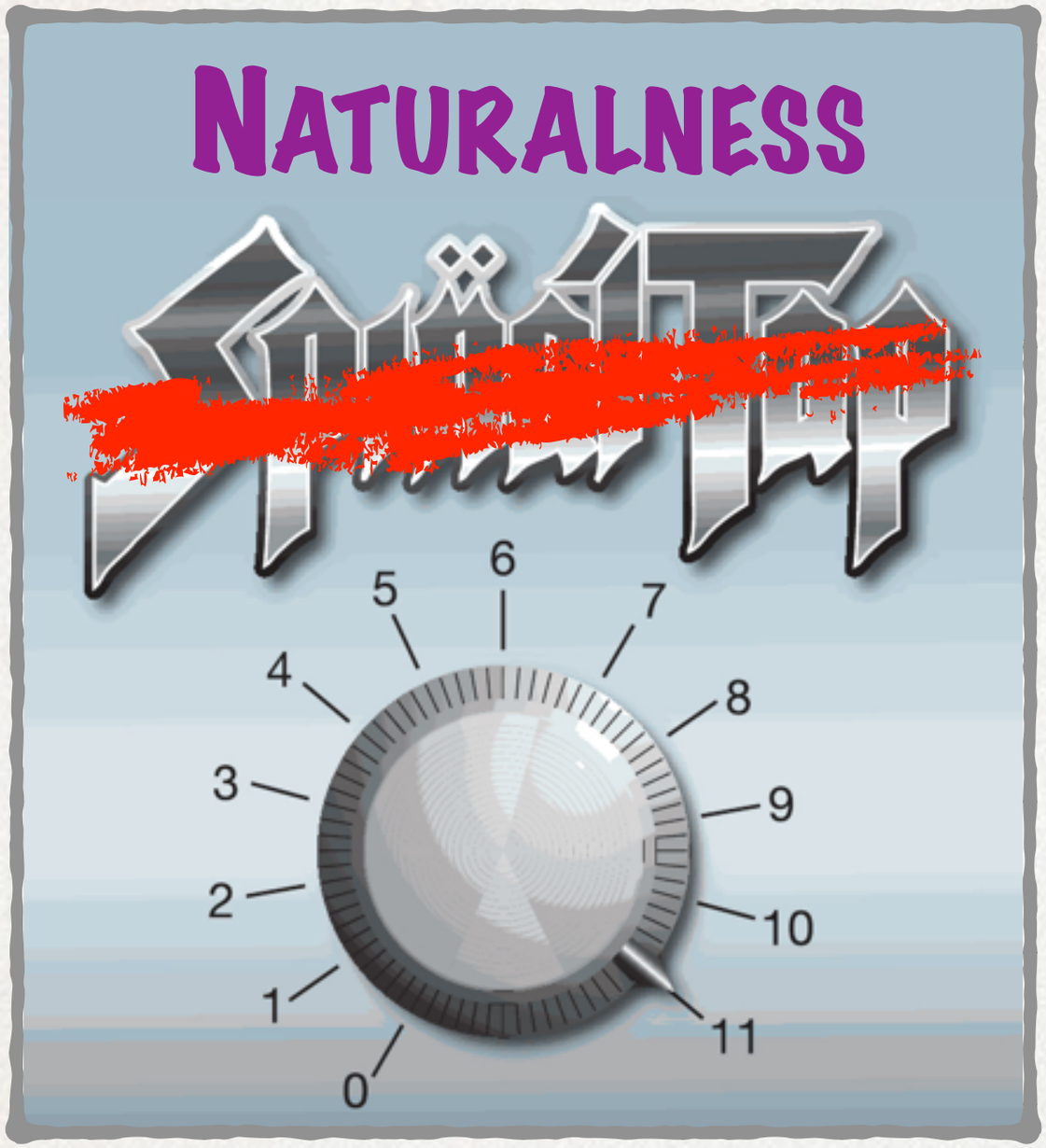
HEFT2015
November 6, 2015

NATURALNESS AND DATA



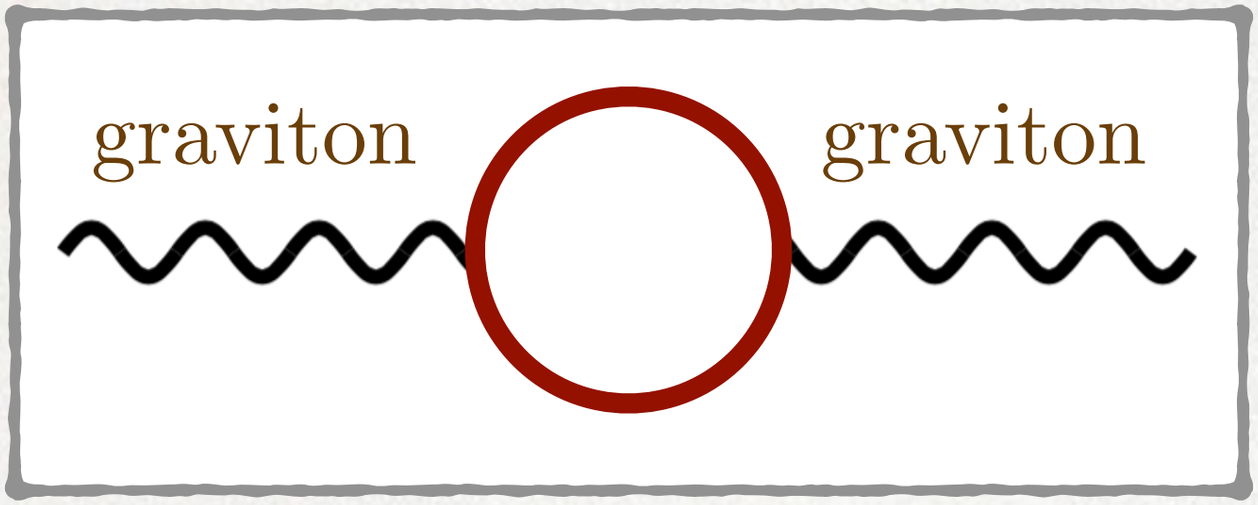
Top partner limits constrain natural scenarios.

Naturalness



BRINGING DOWN THE CUTOFF

Gravity sees all degrees of freedom.

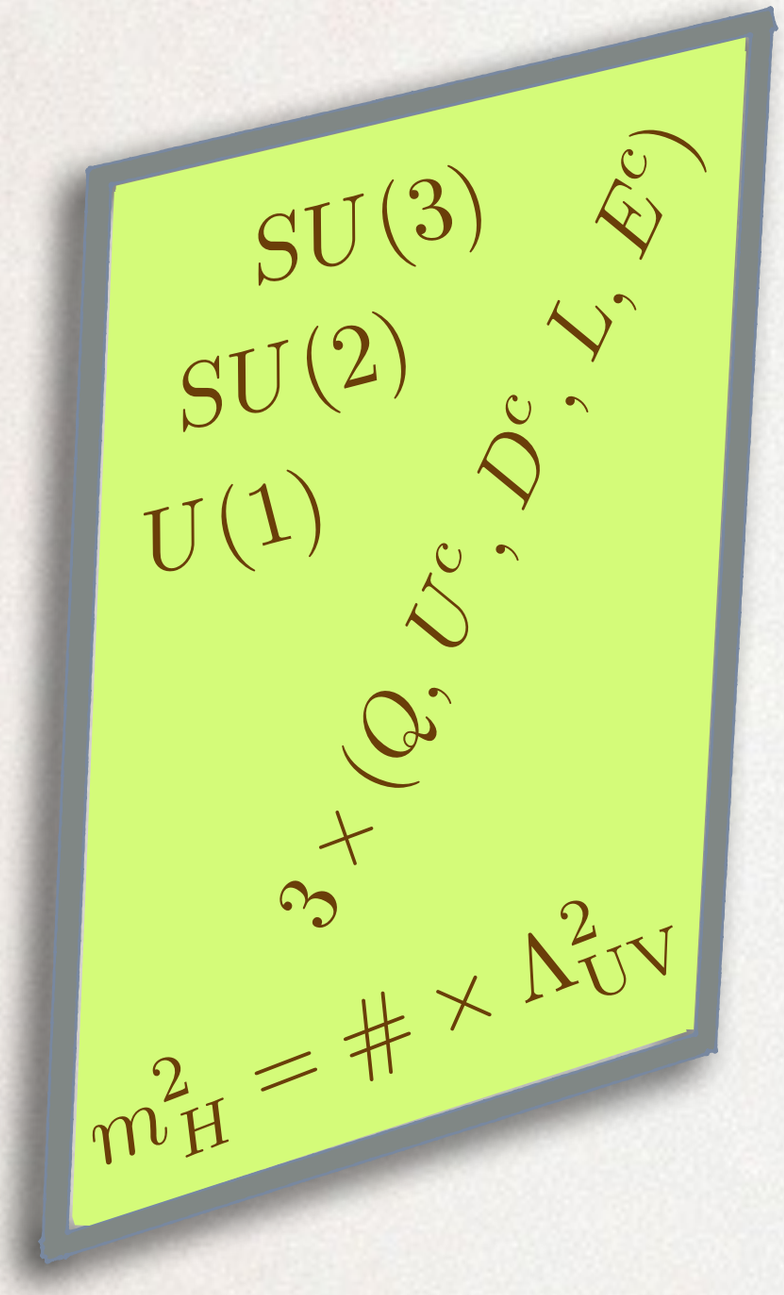


$$M_{\rm pl}^2(\mu) = M_{\rm pl}^2(0) - N\frac{\mu^2}{96\,\pi^2}$$

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

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

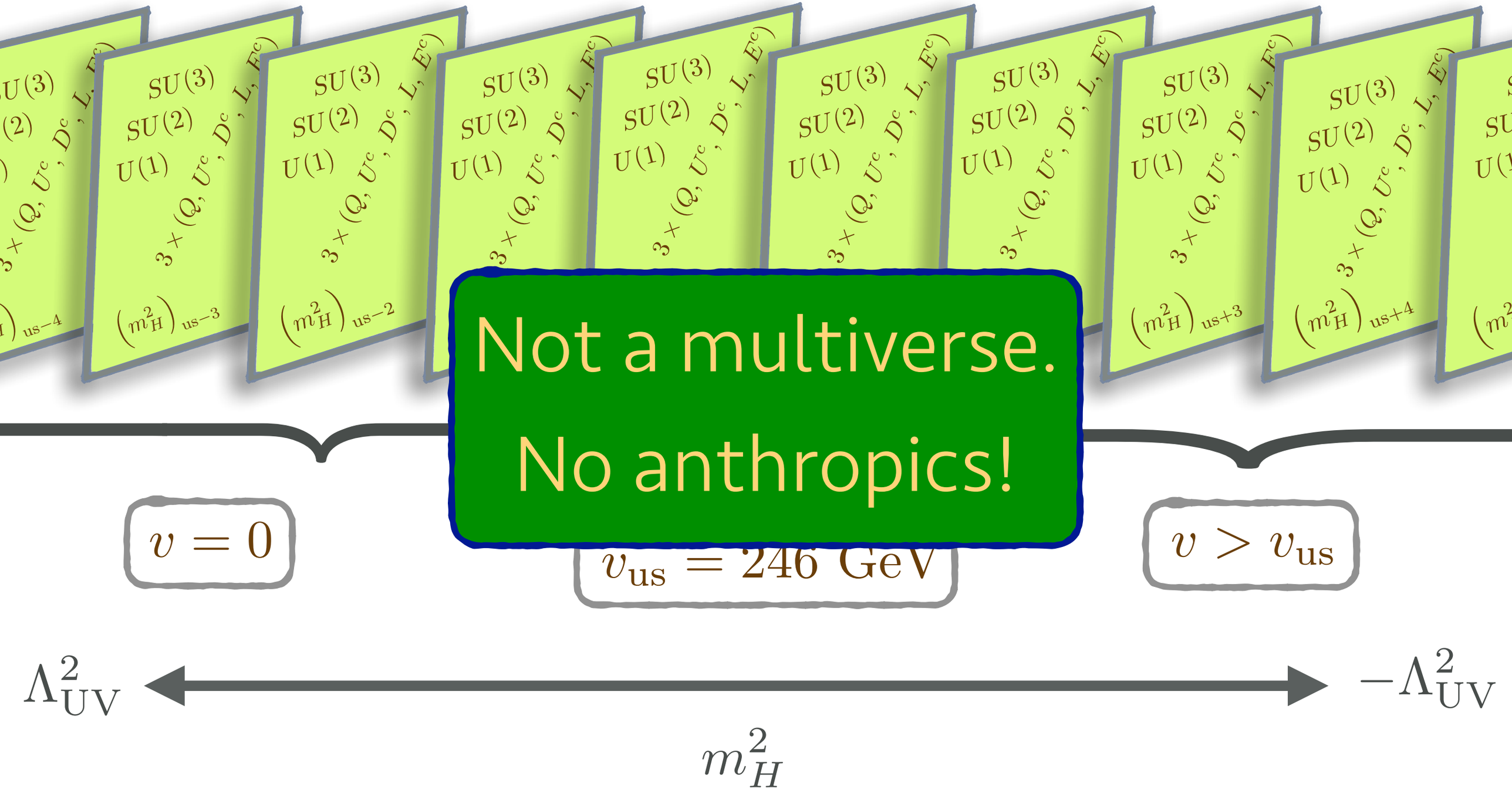
A RANDOM COPY



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

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

N COPIES


SU(3)
SU(2)
U(1)
$3_+(Q, U^c, D^c, L, E^c)$
$\left(m_H^2\right)_{us-4}$
$\left(m_H^2\right)_{us-3}$
$\left(m_H^2\right)_{us-2}$
$\left(m_H^2\right)_{us+3}$
$\left(m_H^2\right)_{us+4}$
Not a multiverse.
No anthropics!
$v = 0$
$v_{us} = 246\ \text{GeV}$
$v > v_{us}$
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

Unlikely to have time, please see slides online!

Outlook

GENERAL MECHANISM

JUST A SIGN

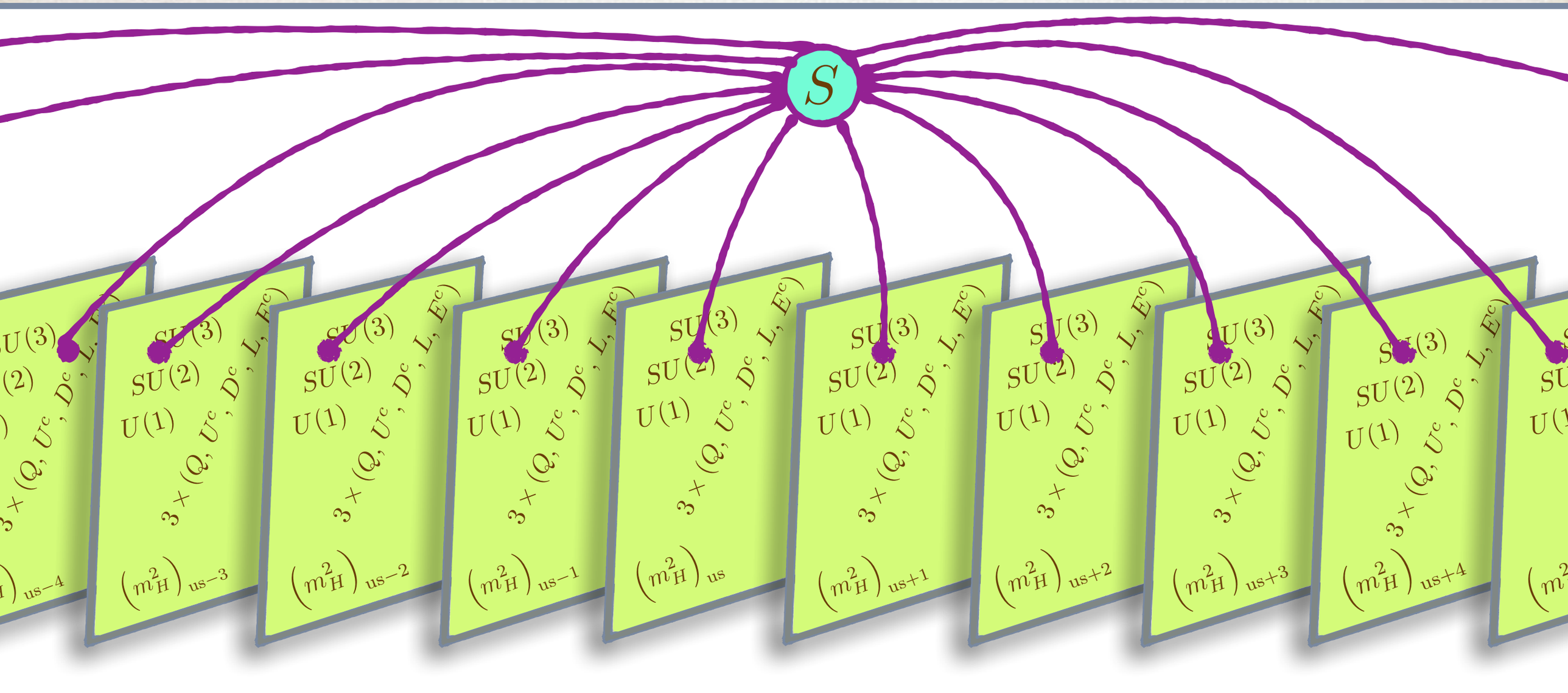
$m_H^2 > 0$	$m_H^2 < 0$

• Massless photon
• $W^\pm$, Z^0 masses $\sim \Lambda_{\rm QCD}$
• Fermion masses $\sim y_f \frac{\Lambda_{\rm QCD}^3}{m_H^2}$
• $T_{\rm sphaleron} < \Lambda_{\rm QCD}$: 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.

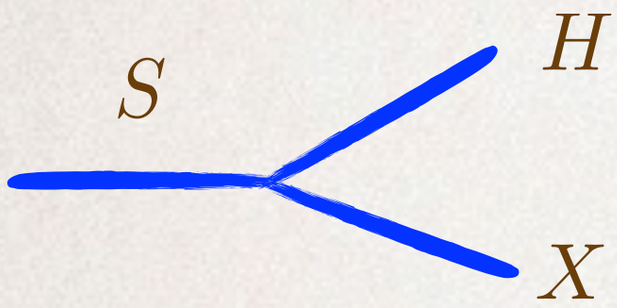
Couples universally to all copies.



COUPLE S TO $H + X$

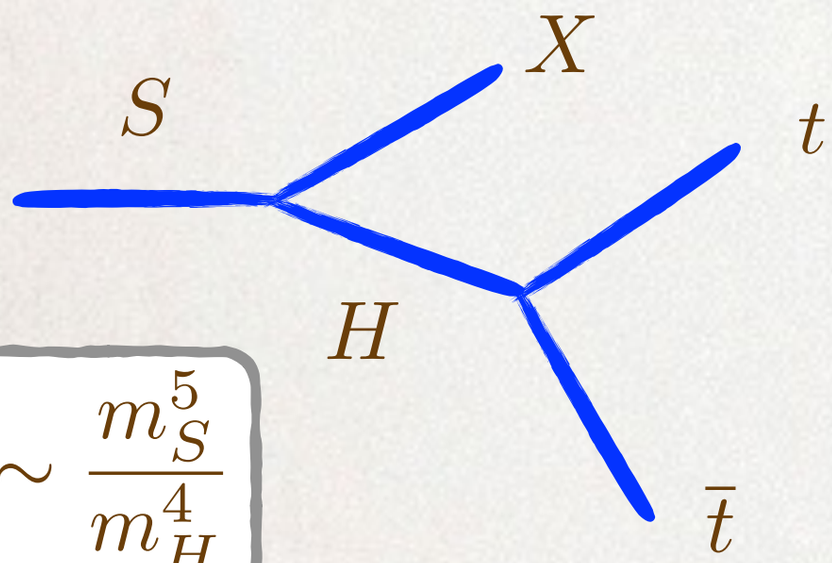
$m_H^2 > 0$ | $m_H^2 < 0$

Increasing m_H^2

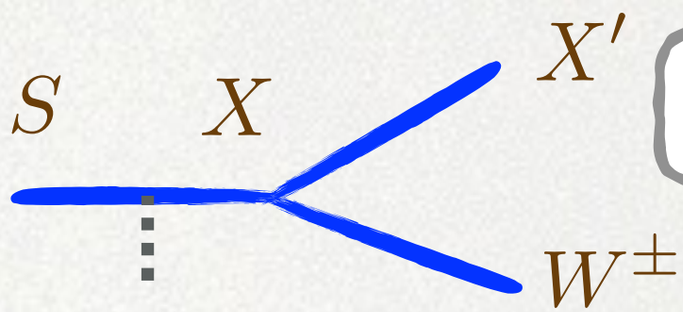


$\Gamma \sim m_S$

or

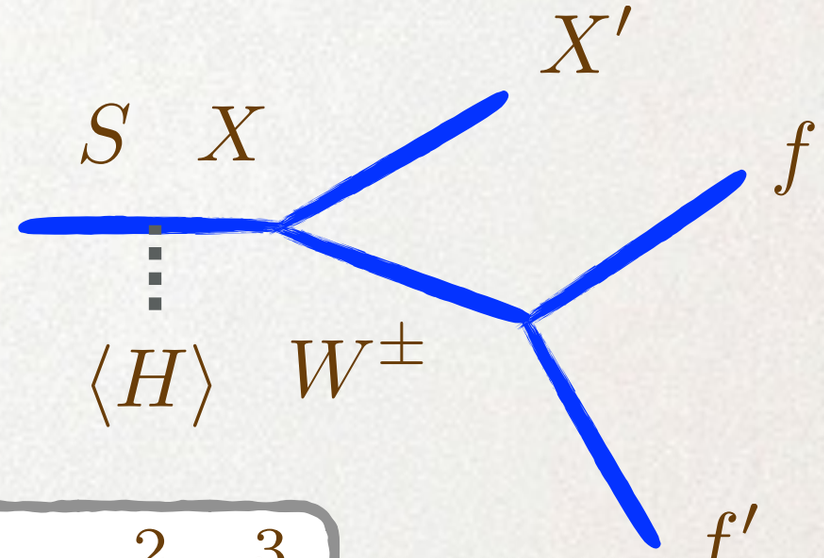


$$\Gamma \sim \frac{m_S^5}{m_H^4}$$



$\Gamma \sim m_S$

or



$$\Gamma \sim \frac{v^2 m_S^3}{v^4}$$

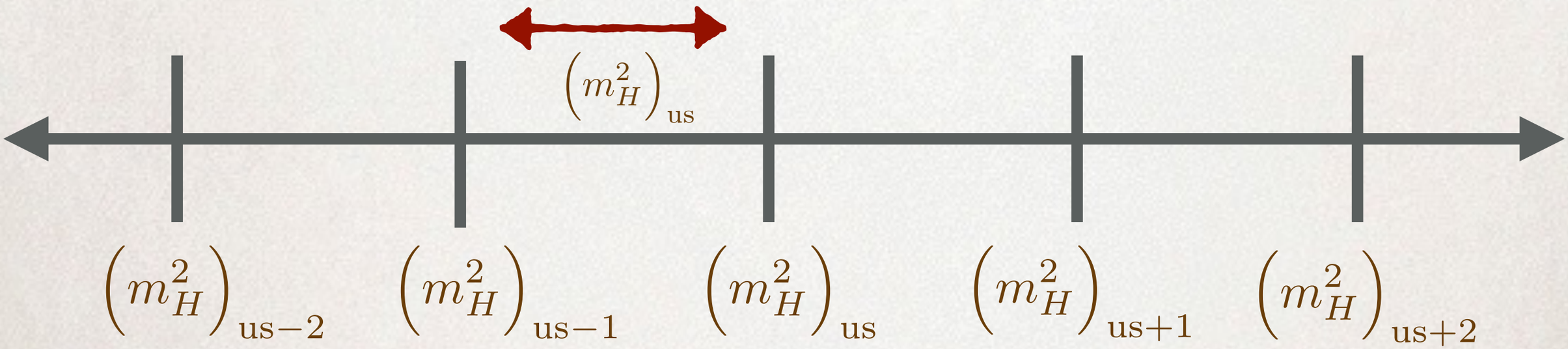
Increasing v

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 $v_i \sim \sqrt{i}$.



DOMINANT SIGNATURES

Energy density in additional relativistic degrees of freedom.

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

Relic density of additional neutrinos.

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

HOW MANY COPIES?

Full hierarchy problem

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

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

and

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

HOW MANY COPIES?

Little hierarchy problem

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

$$+$$

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

$$N \sim 10^4$$

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

Tons of signatures at future colliders!

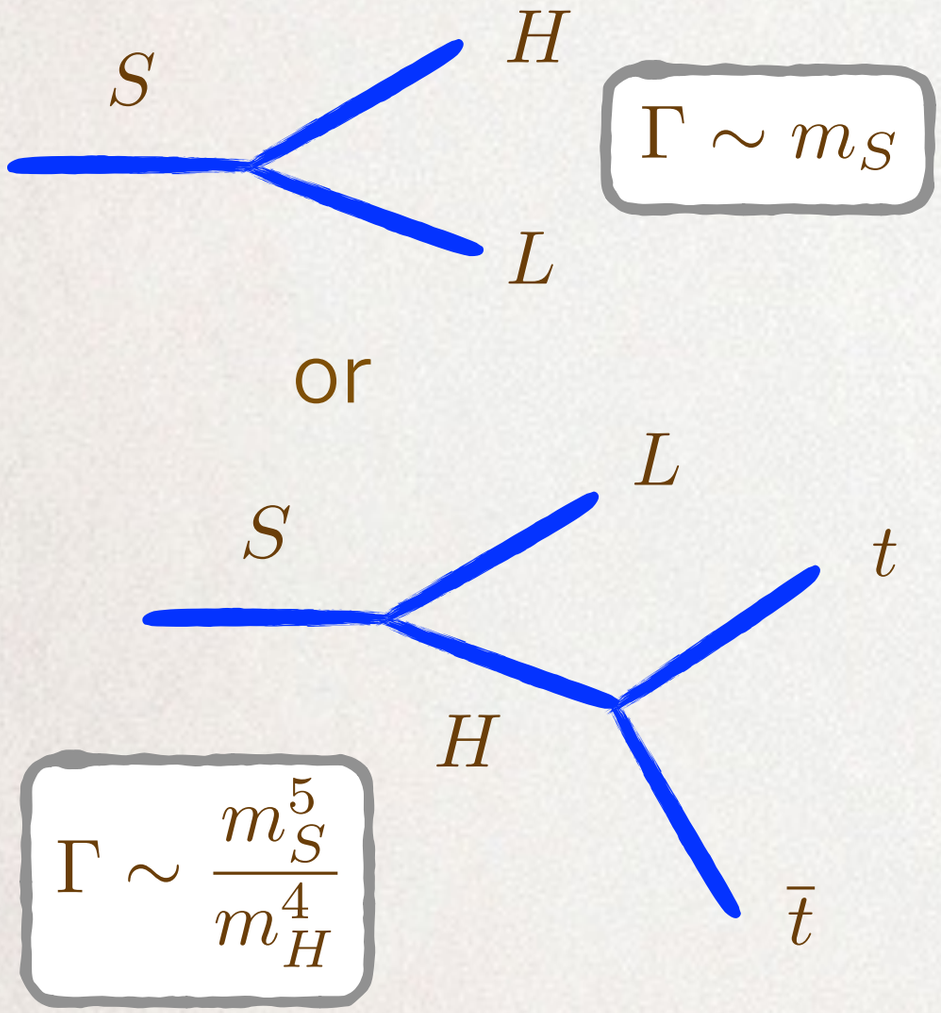
TWO SIMPLE MODELS

NEUTRINO REHEATON

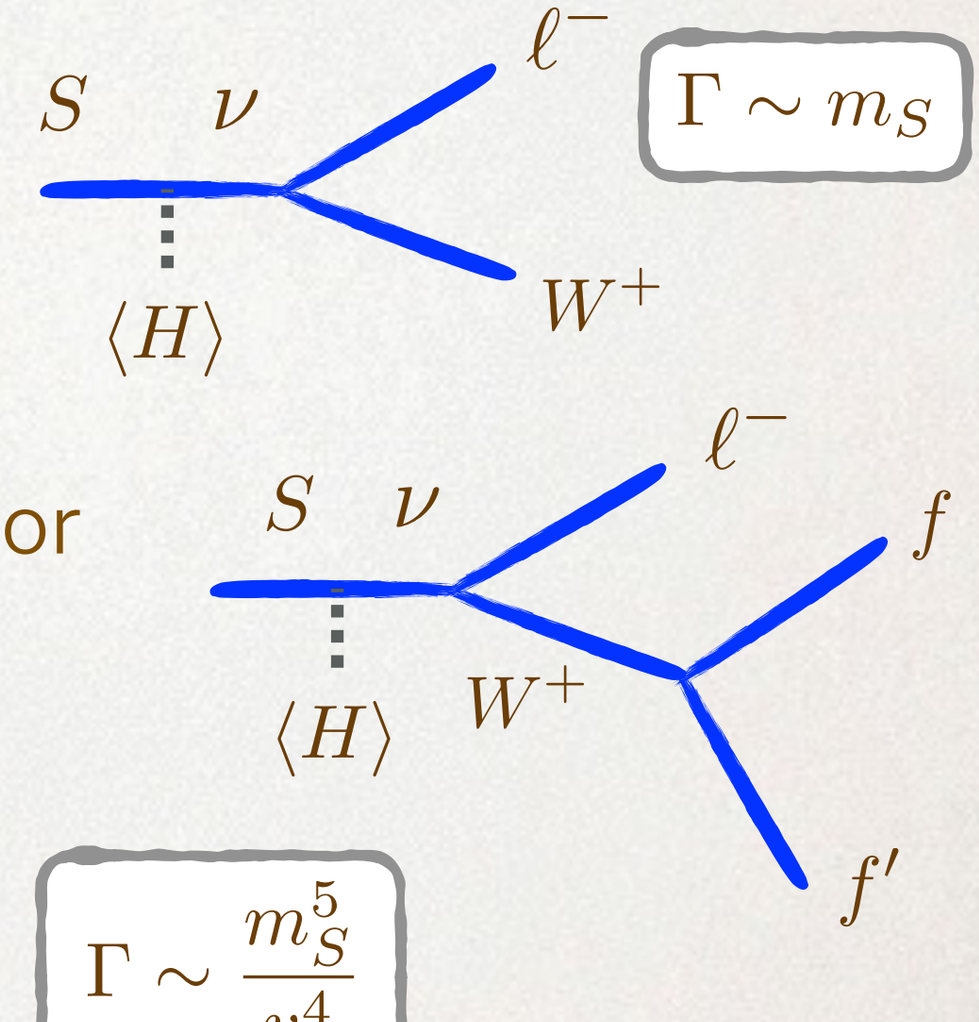
$$\mathcal{L} = m_S\, S\, S^c + \lambda \sum_i S\, H_i\, L_i$$

Increasing m_H^2

$m_H^2 > 0$

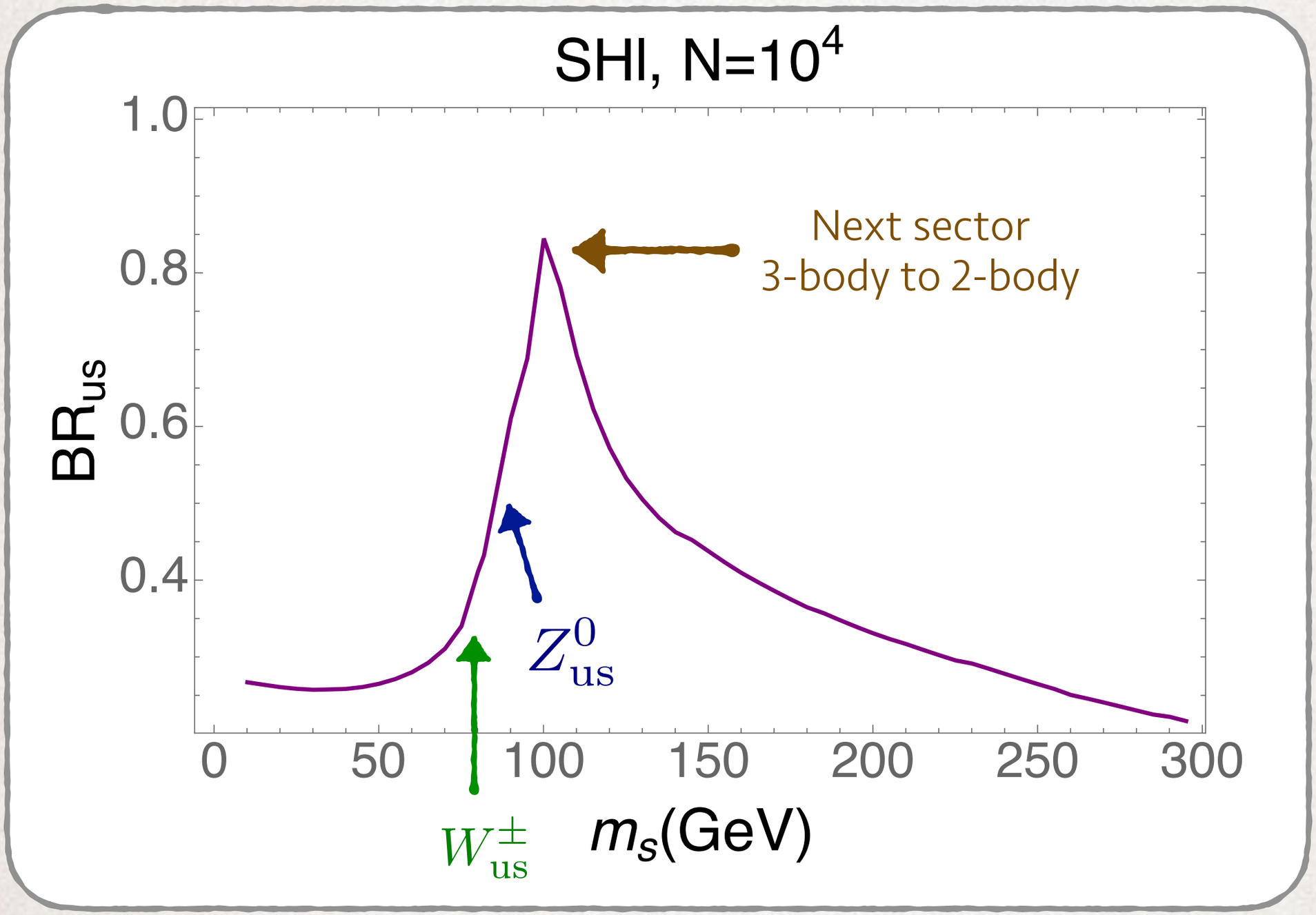


$m_H^2 < 0$



Increasing v

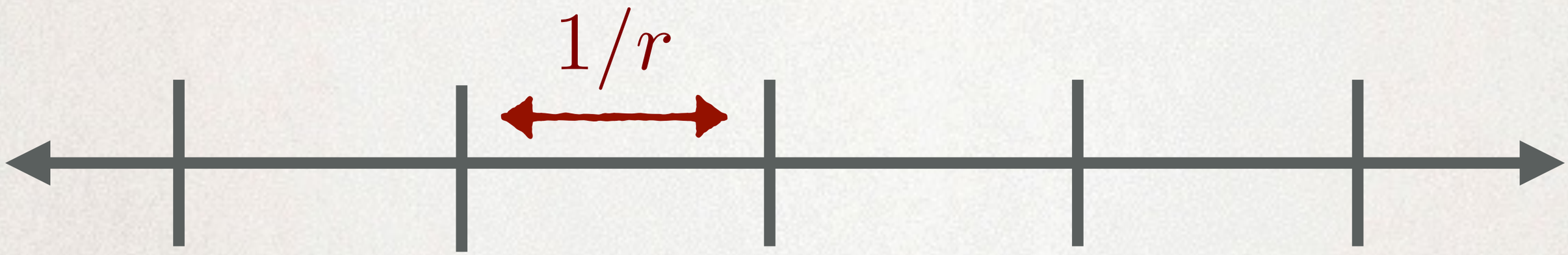
NEUTRINO REHEATON



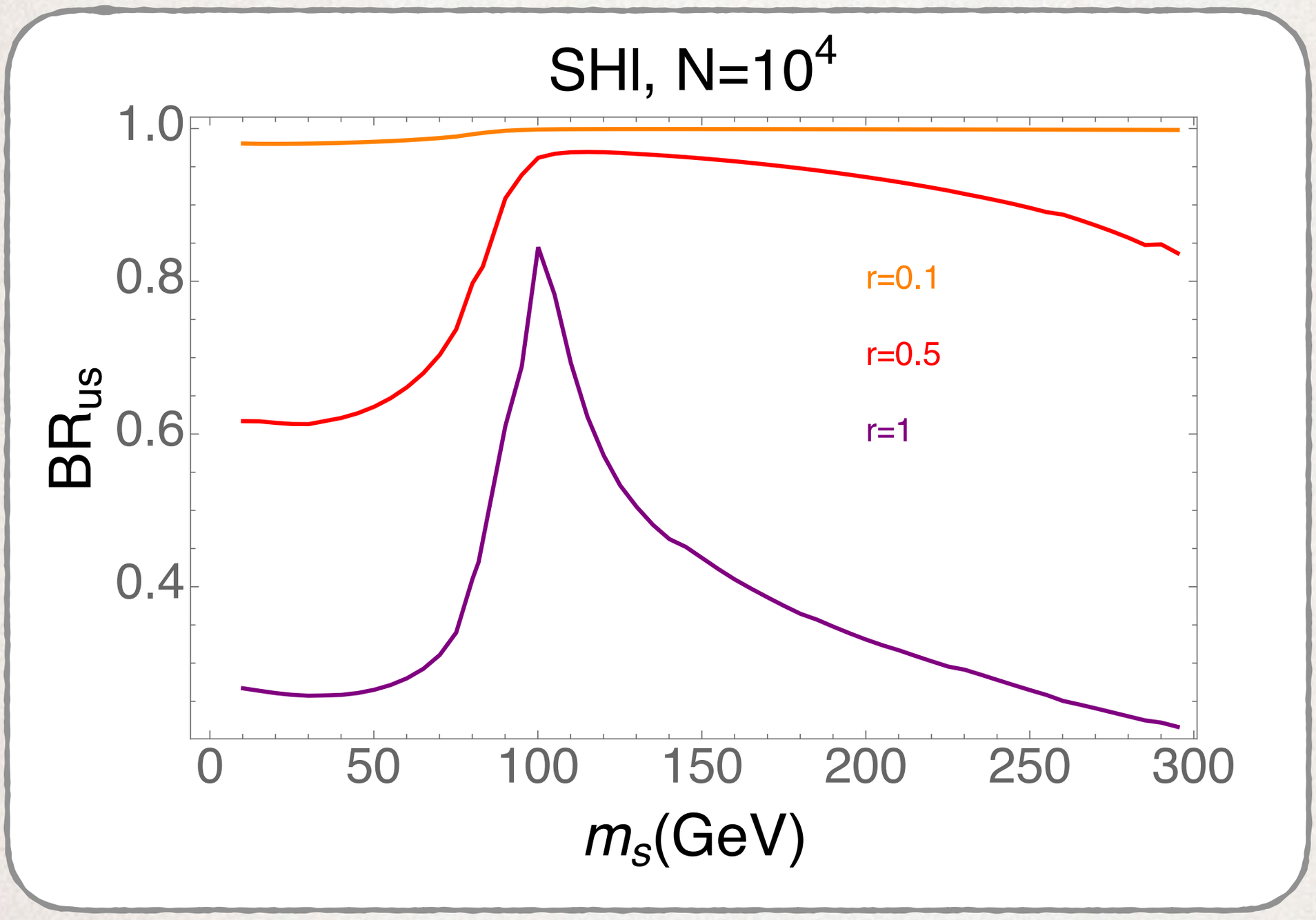
TOY SCENARIO

Parametrize distribution of Higgs masses:

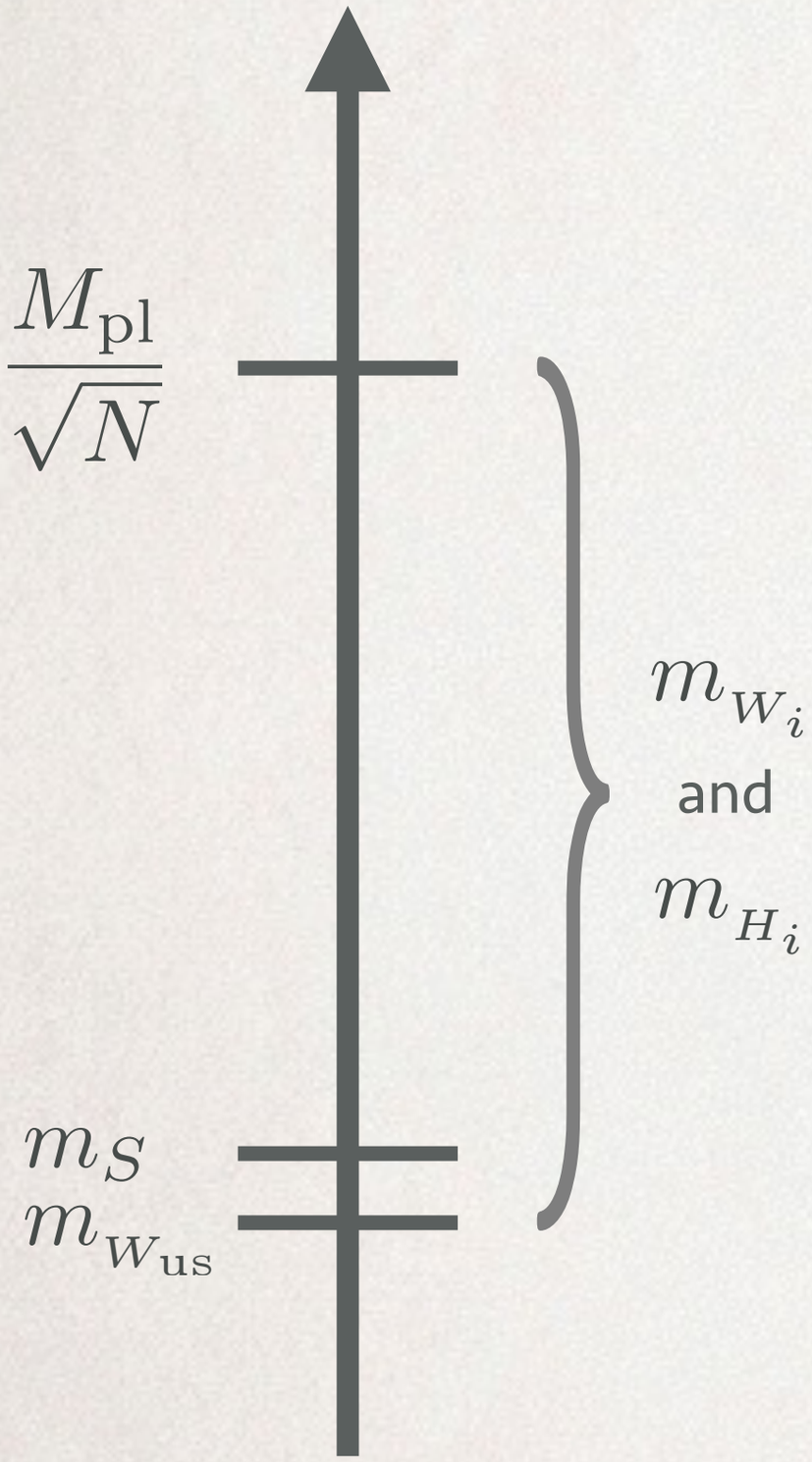
$$\left(m_H^2\right)_i = \frac{1}{r} \times i \times \left(m_H^2\right)_{\rm us}$$



NEUTRINO REHEATON



μ-PROBLEM



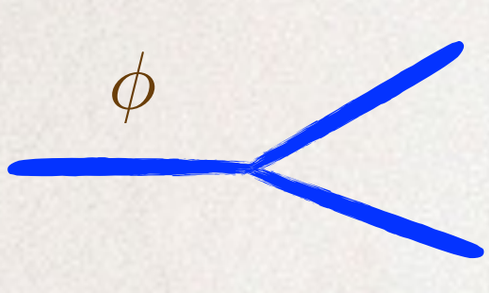
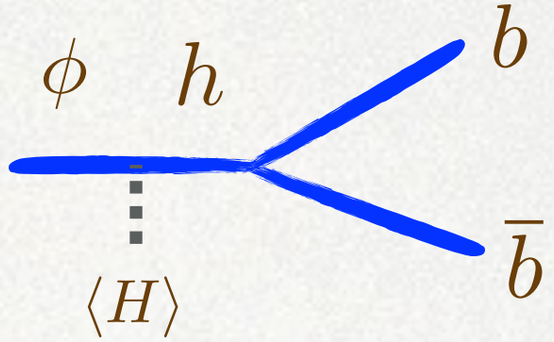
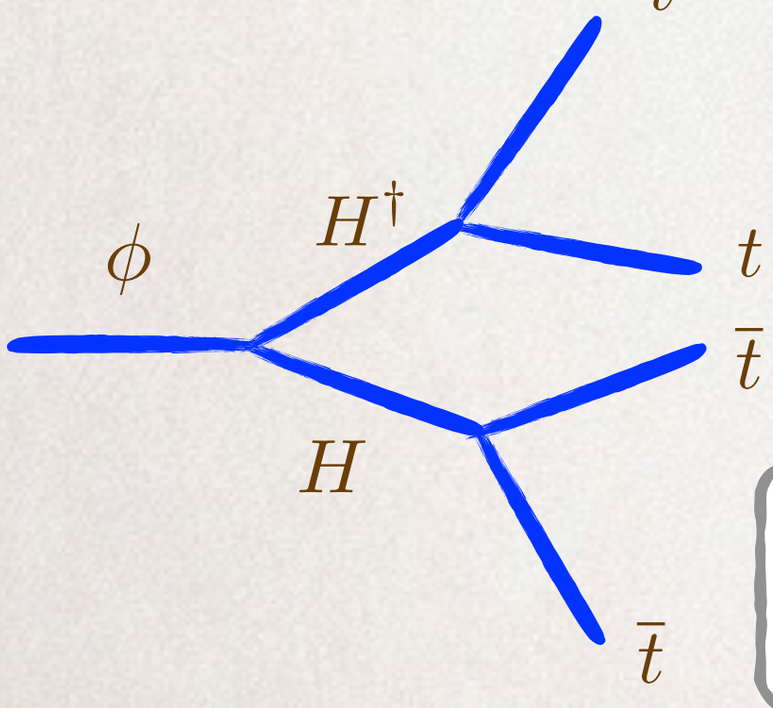
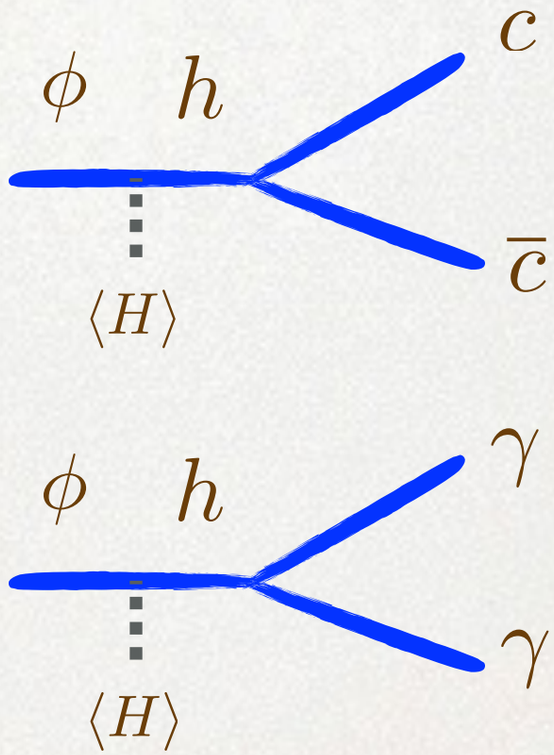
Reheaton mass is technically natural.

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

Analogous to μ-problem in the MSSM.

SCALAR REHEATON

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

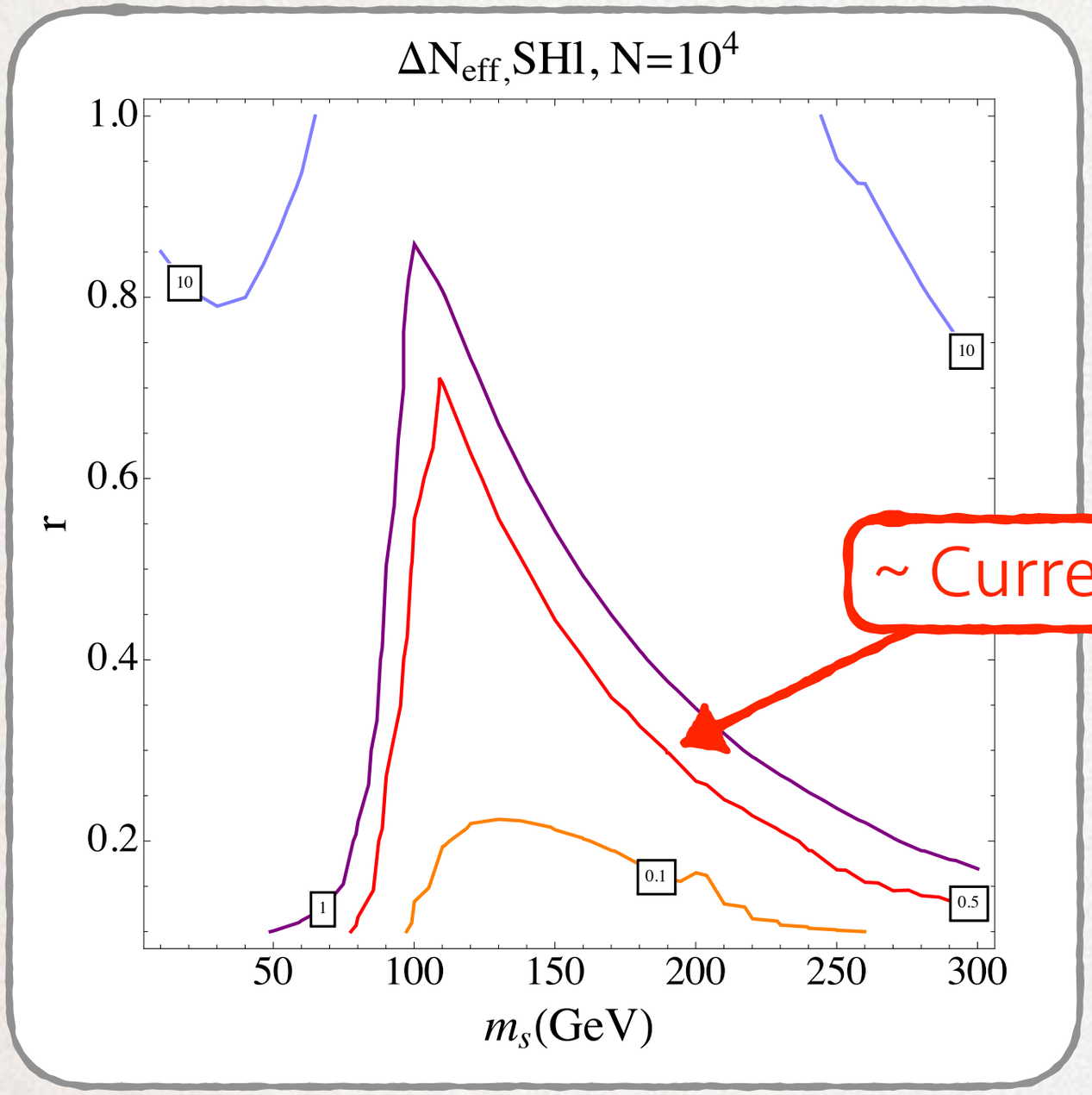
$m_H^2 > 0$	$m_H^2 < 0$
 $\Gamma \sim \frac{a^2}{m_\phi}$	 $\Gamma \sim y_b^2\, a^2 \frac{m_\phi^3}{v^4}$
 $\Gamma \sim a^2 \frac{m_\phi^7}{m_H^8}$	 $\Gamma \sim y_c^2\, a^2 \frac{m_\phi^3}{v^4}$ $\Gamma \sim \frac{e^4\, a^2}{16\pi^2} \frac{m_\phi^3}{v^4}$

Increasing m_H^2 ↓

Increasing v ↓

SIGNATURES!

$N_{\rm eff}$



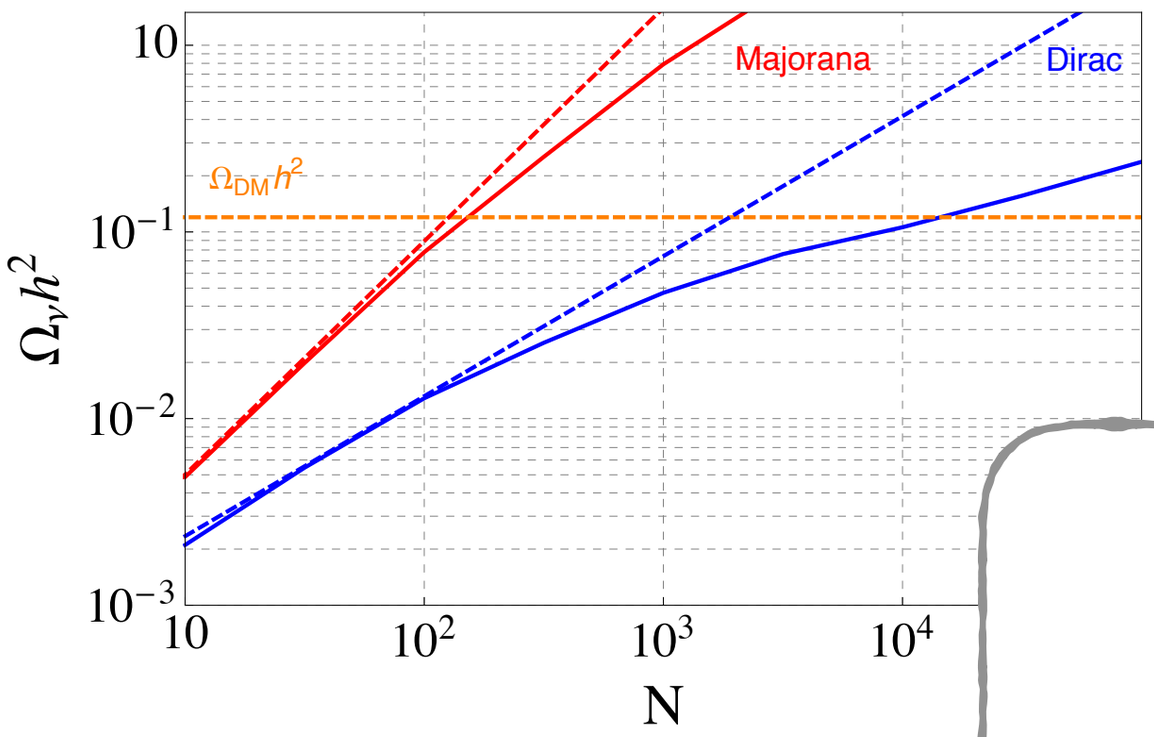
~ Current constraint

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

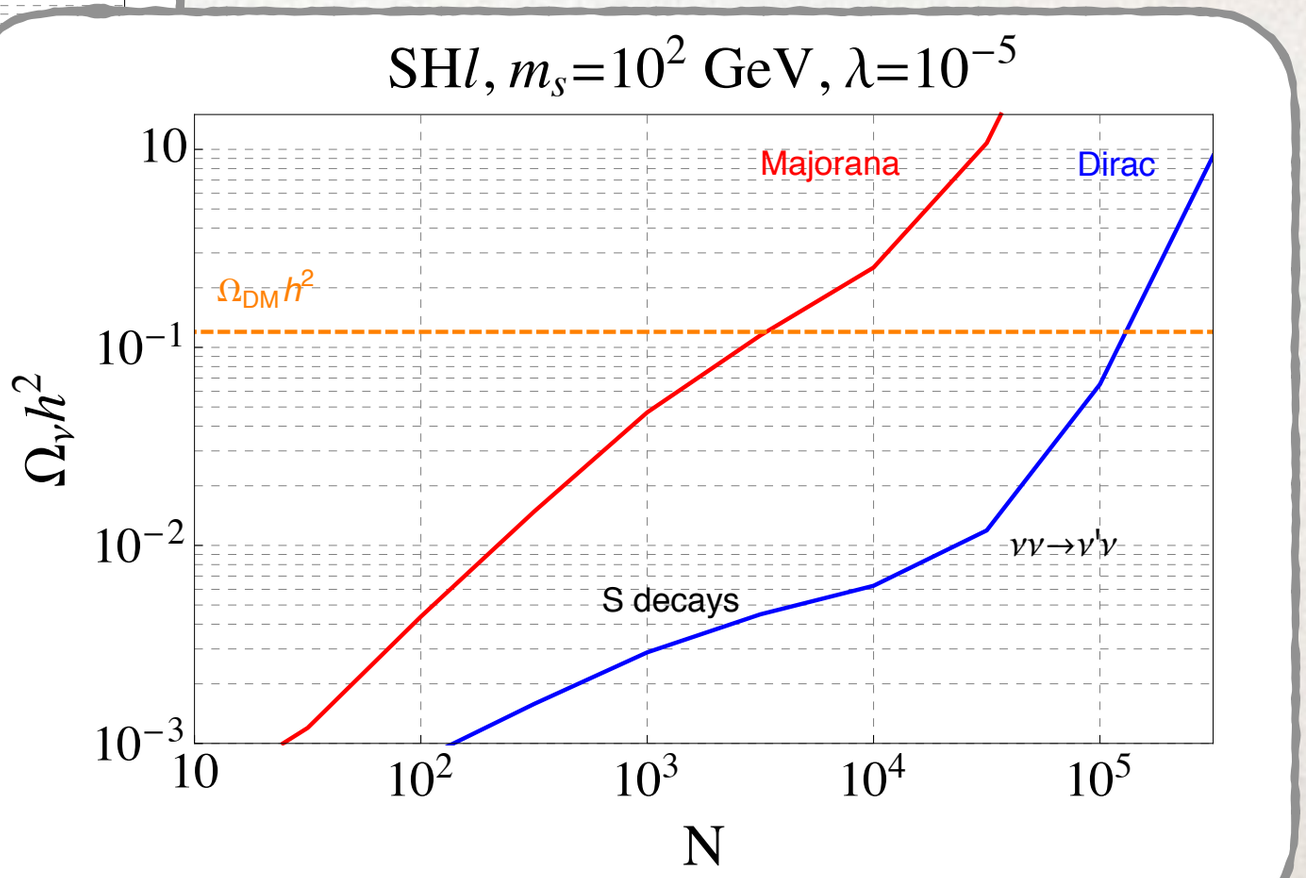
Also constrain $\sum m_{\nu_i}$ to SM value.

Wu, et al. [arXiv:1402.4108]

NEUTRINO OVERCLOSURE

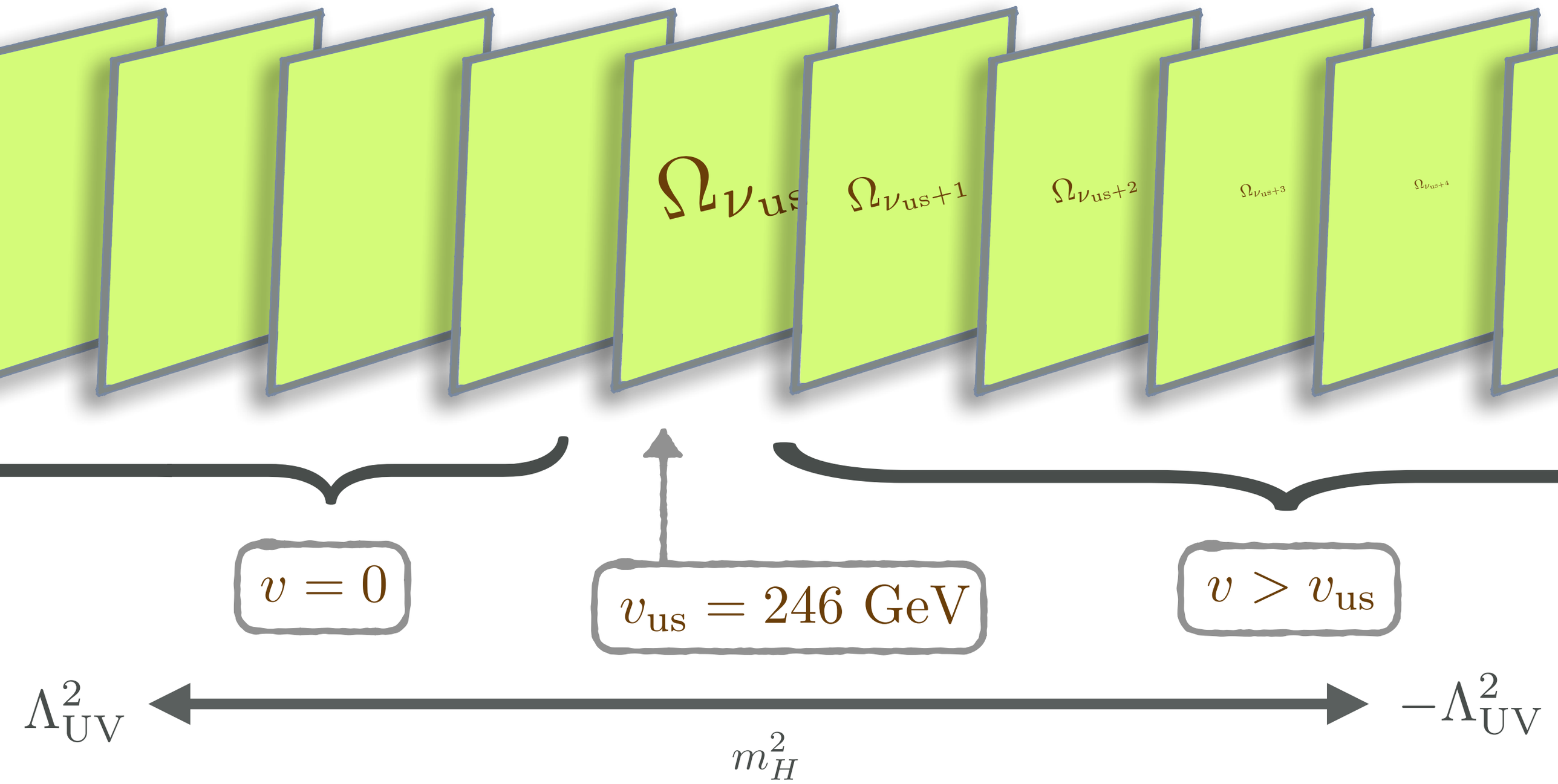


$$\mathcal{L} = m_S\, S\, S^c + \lambda \sum_i S\, H_i\, L_i$$



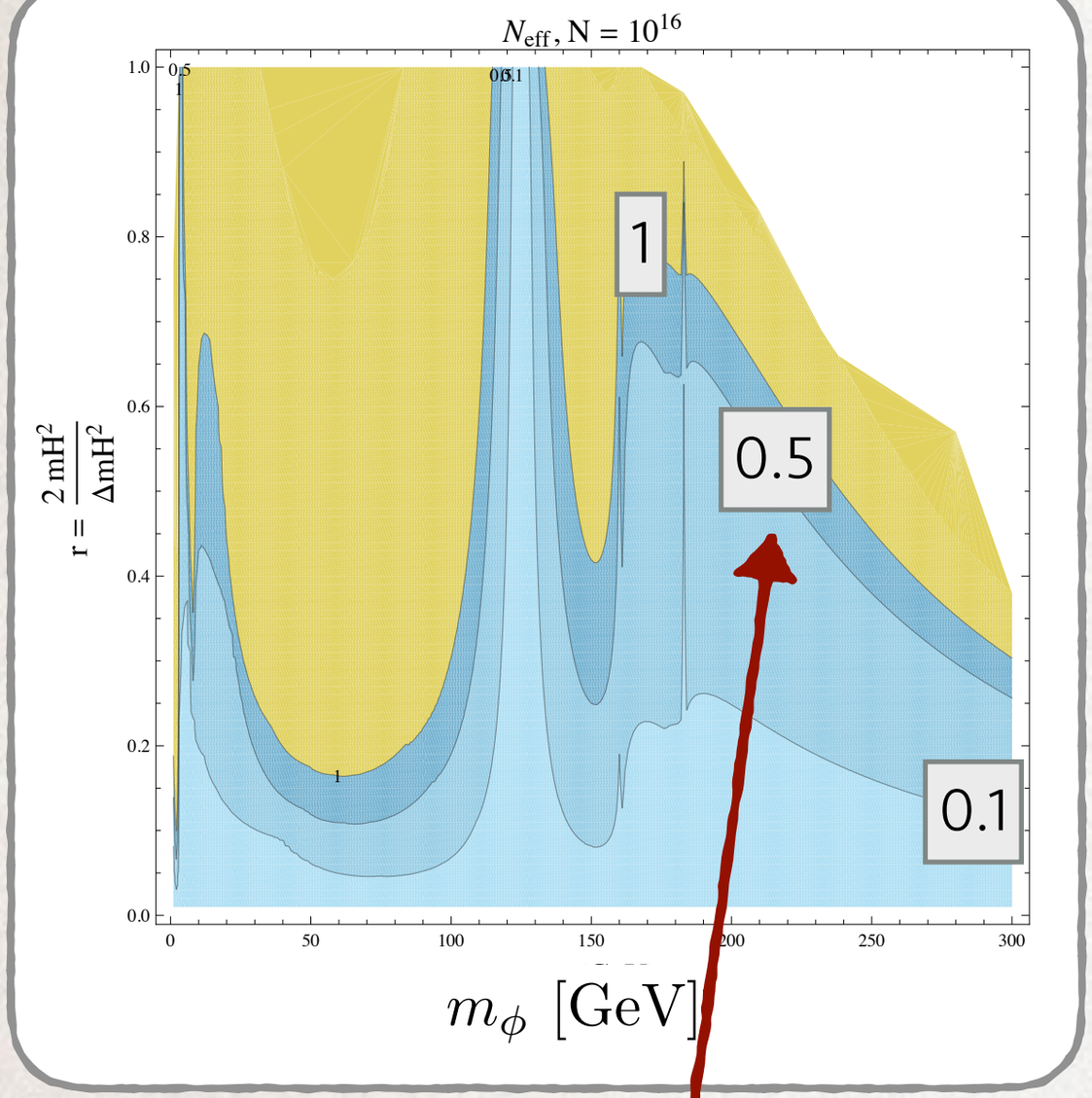
From decays, thermal abundances, production from our Z^0 boson.

POWER AT SMALL SCALES



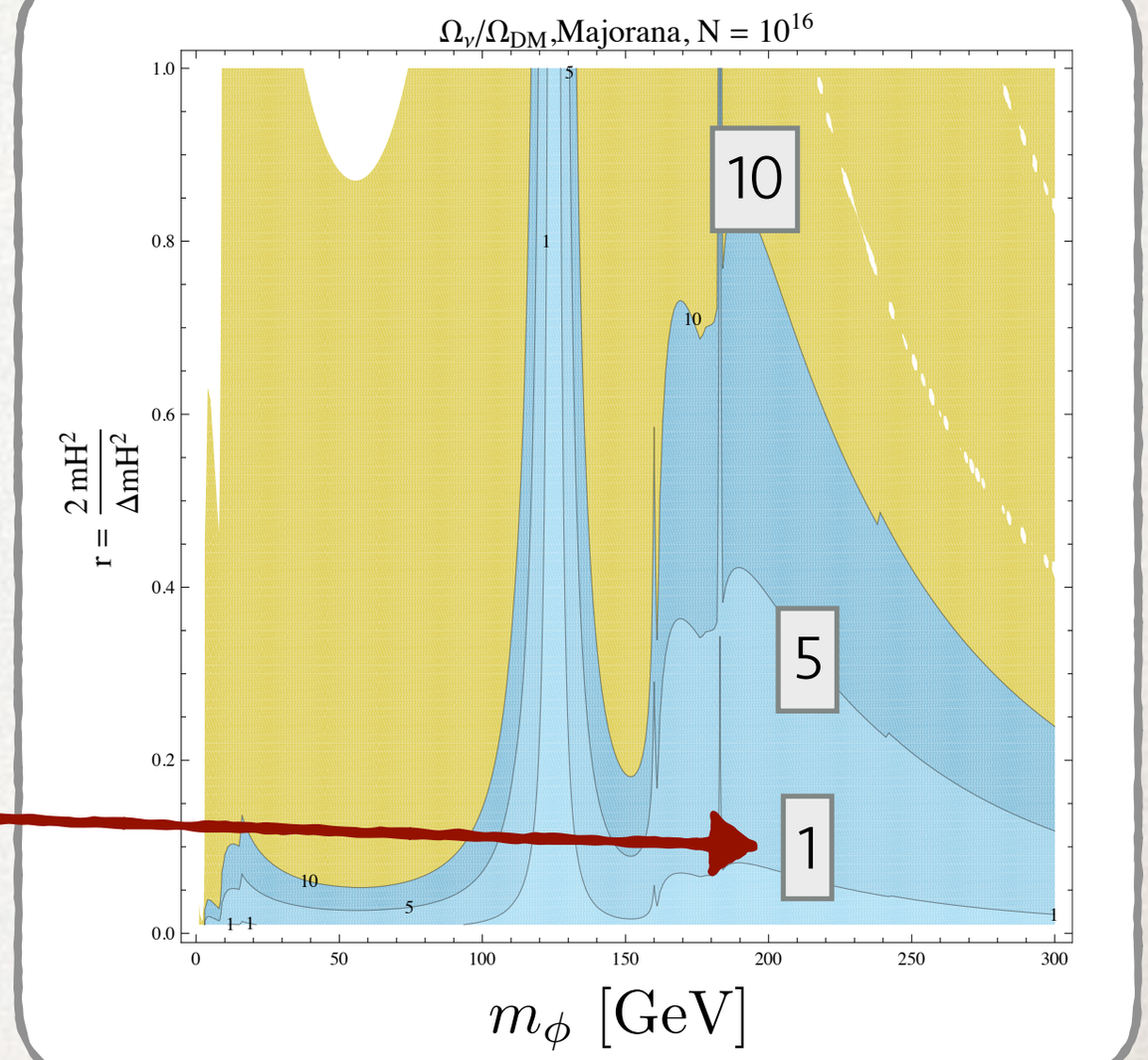
Potentially observable imprint on small scale power spectrum of cosmological perturbations.

GETTING TO $N = 10^{16}$

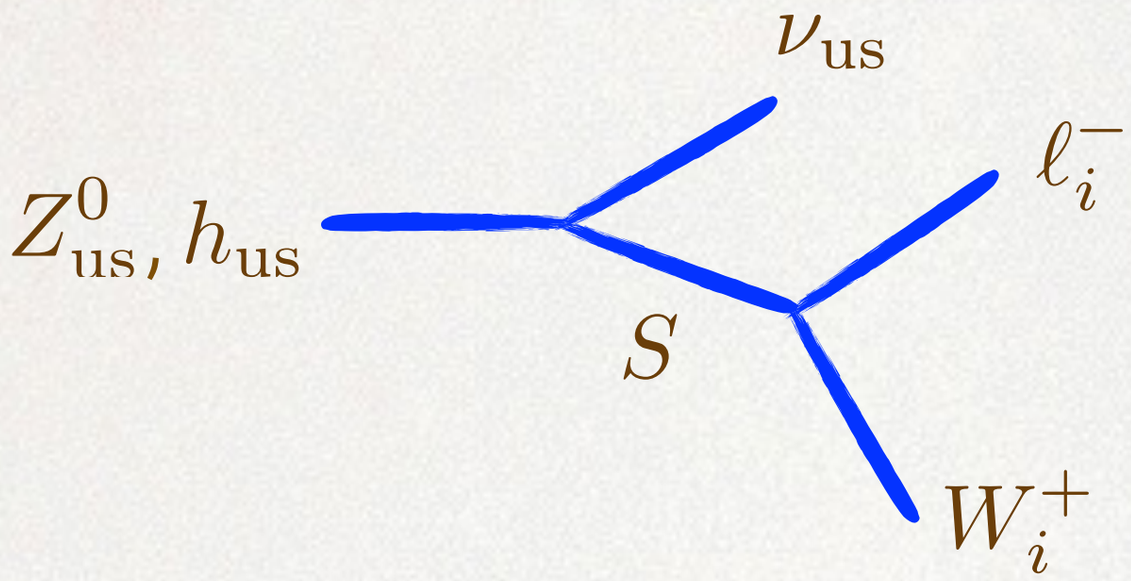


$$\mathcal{L} = \frac{1}{2} m_\phi \phi^2 + a\,\phi \sum_i \left| H_i \right|^2$$

Constraint



RARE DECAYS



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

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

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.

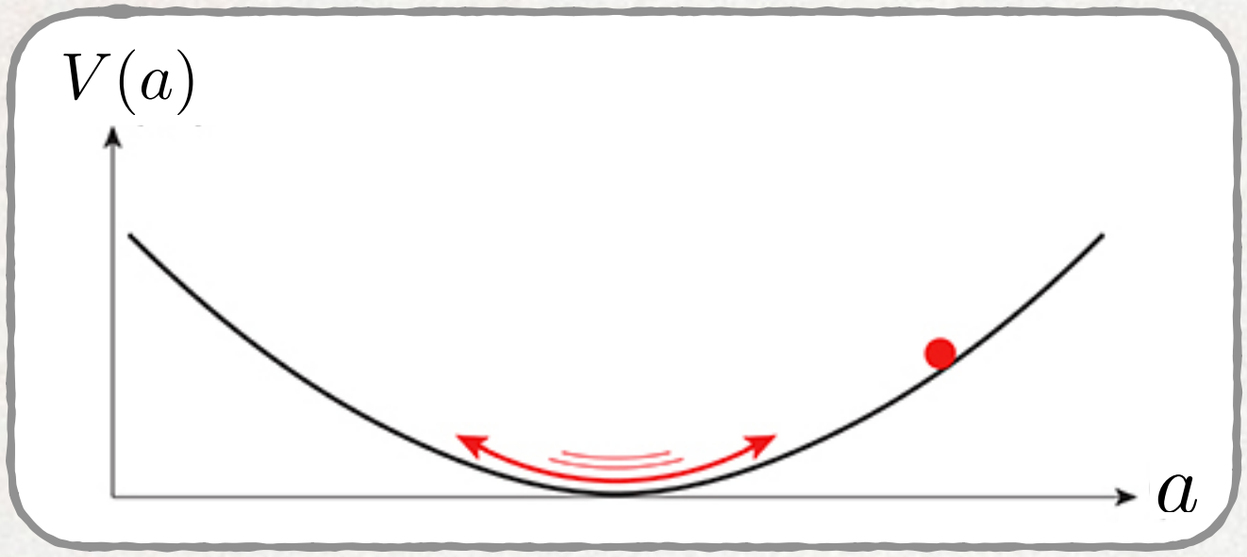
One option

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?)

Neutrinos from other sectors

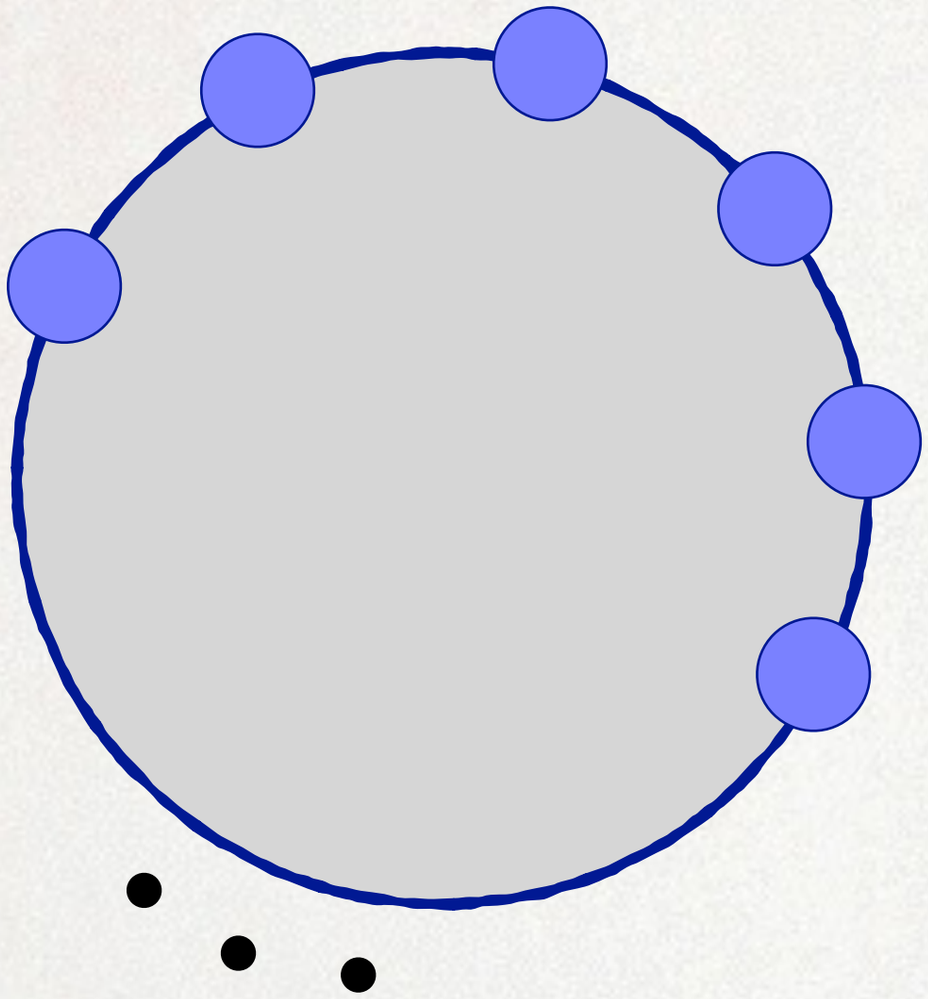
Axion

Superpartner of reheaton

…

OUTLOOK

DYNAMICALLY REALIZING N



"Link fields"

$\langle \bigcirc_i \rangle \neq 0$ ⇨ 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 $N_{\rm eff}$ and neutrino over closure.

Rare Z^0 and h decays.

Observe "steps" in primordial power spectrum.