BARYOGENESIS AND DARK MATTER IN MULTIPLE HIDDEN SECTORS

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Department of Physics

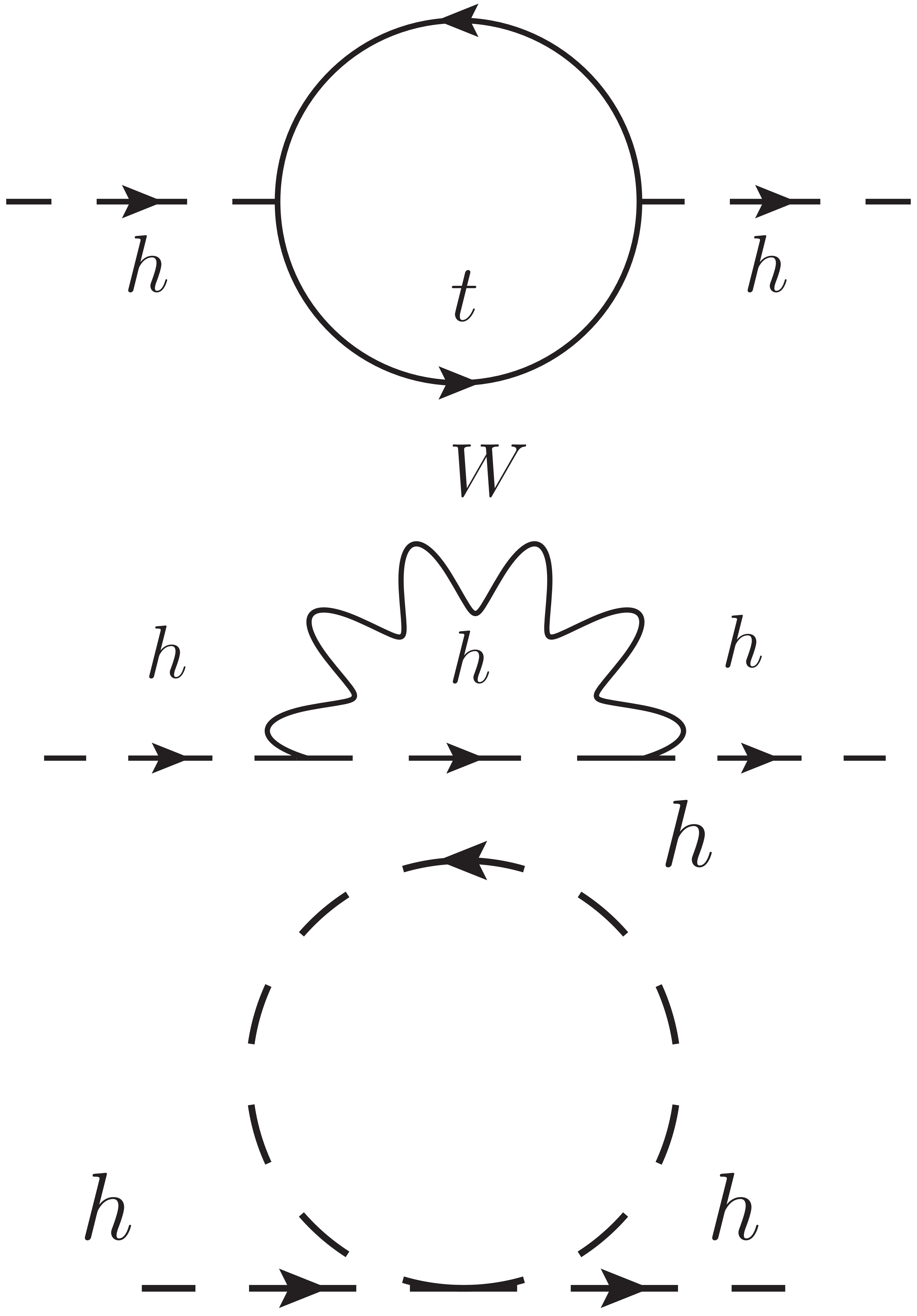
arXiv:2206.11314, submitted to JHEP. With Hassan Easa, Thomas Gregoire and Catarina Cosme.

DANIEL STOLARSKI

PASCOS 2023 June 28, 2023

THE HIERARCHY PROBLEM

Why is the Higgs so much lighter than other mass scales (neutrino, GUT, Planck)?

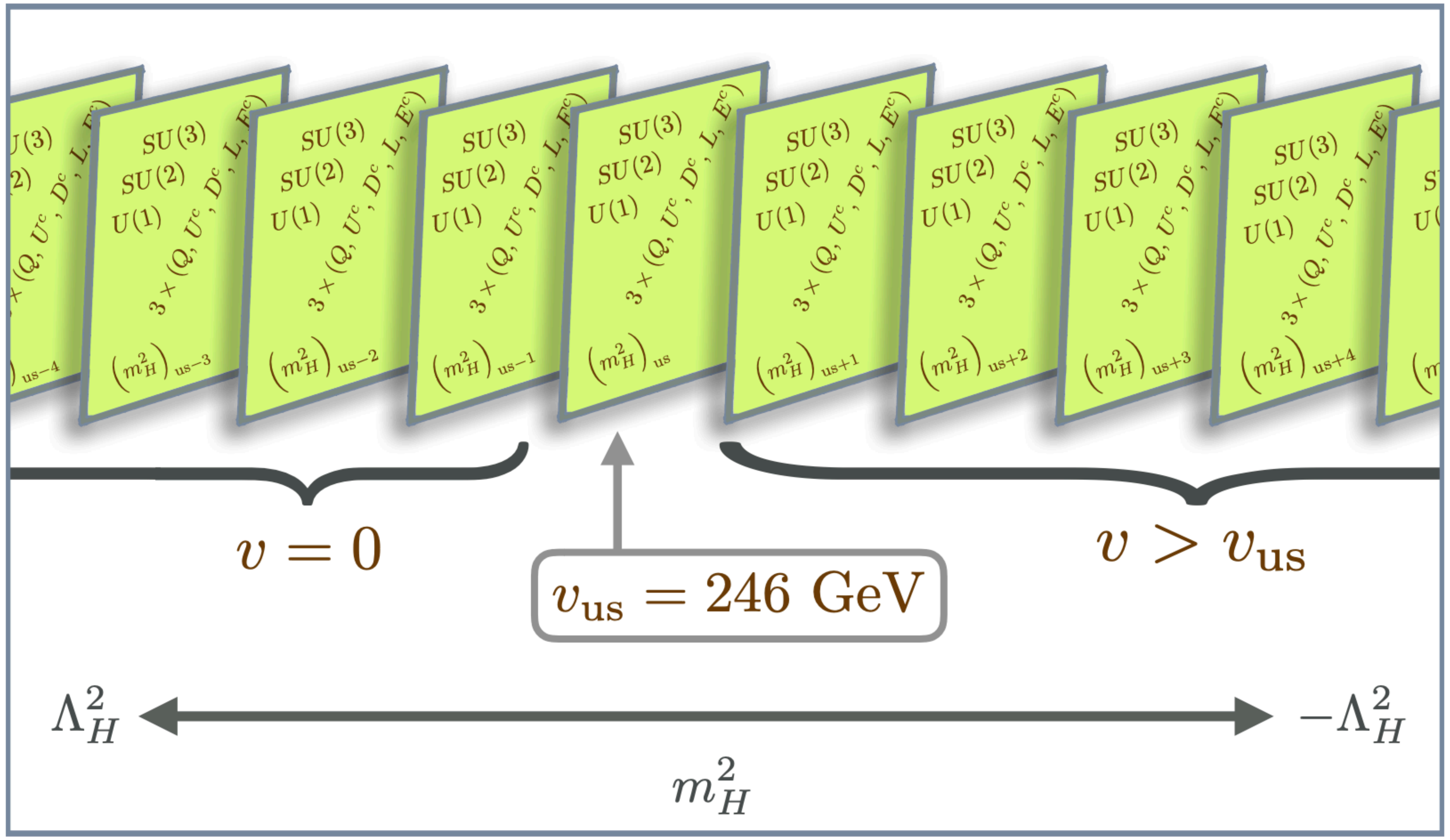


$$\delta m_H^2 \sim \frac{\Lambda^2}{16\pi^2} \gg m_H^2$$

NNATURALNESS SOLUTION

Nnaturalness hep-ph > arXiv:1607.06821

Nima Arkani-Hamed, Timothy Cohen, Raffaele Tito D'Agnolo, Anson Hook, Hyung Do Kim, David Pinner



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

$$-\frac{N}{2} \leq i \leq \frac{N}{2}$$

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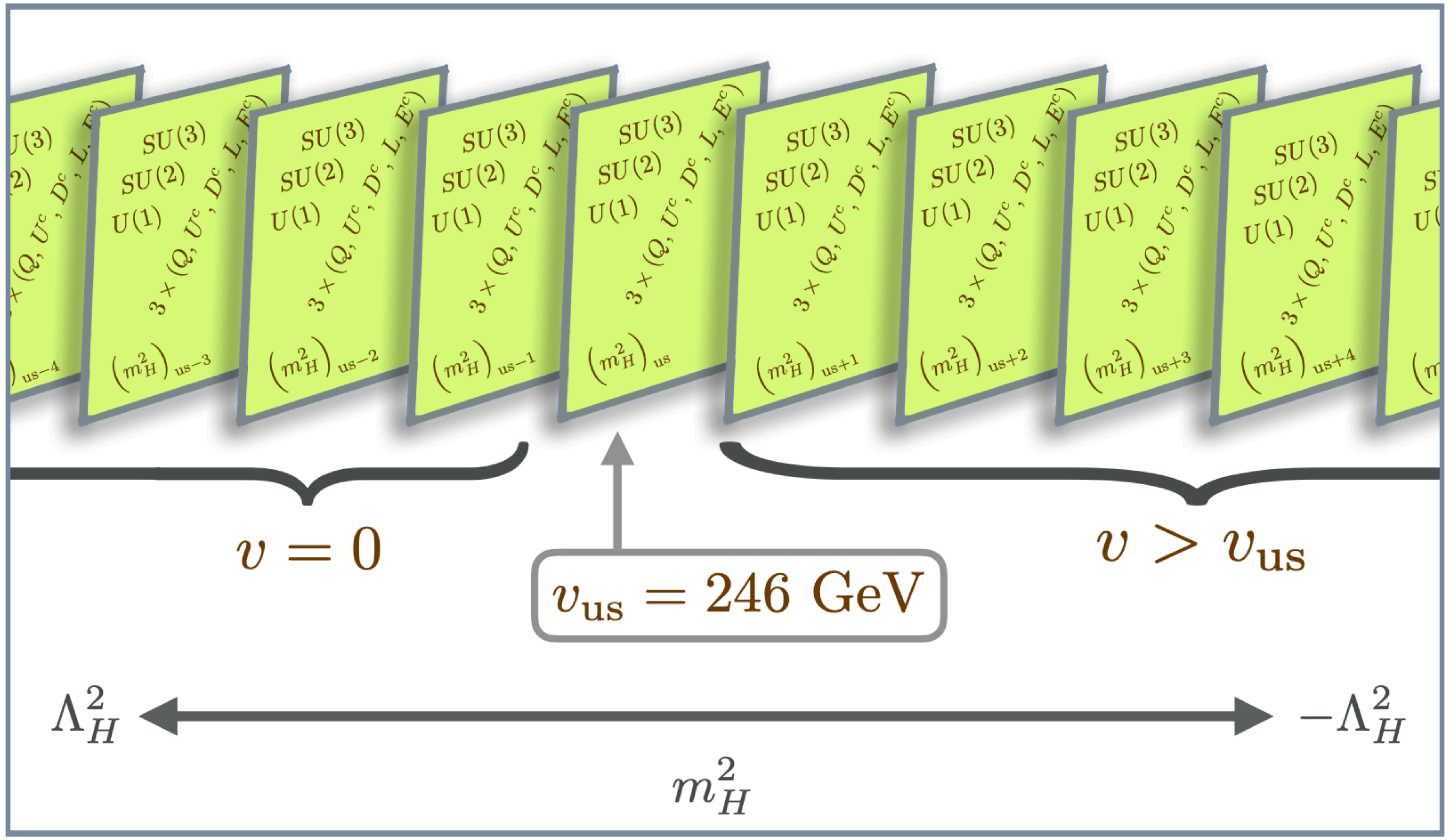

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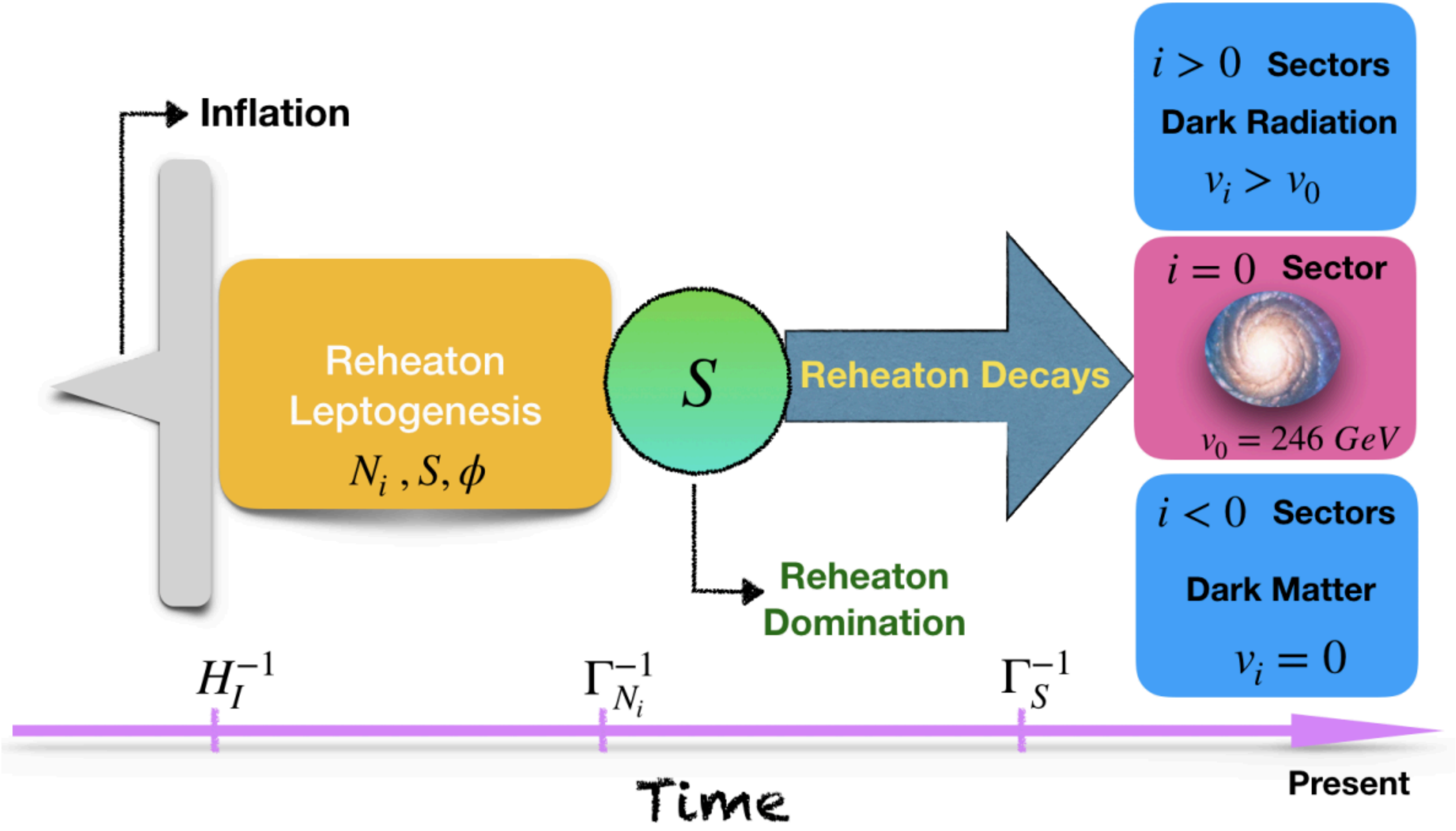
$$-\frac{N}{2} \leq i \leq \frac{N}{2}$$

The SM is the sector with the lowest negative Higgs mass squared.

How do we explain our universe?

TIMELINE OF THE UNIVERSE



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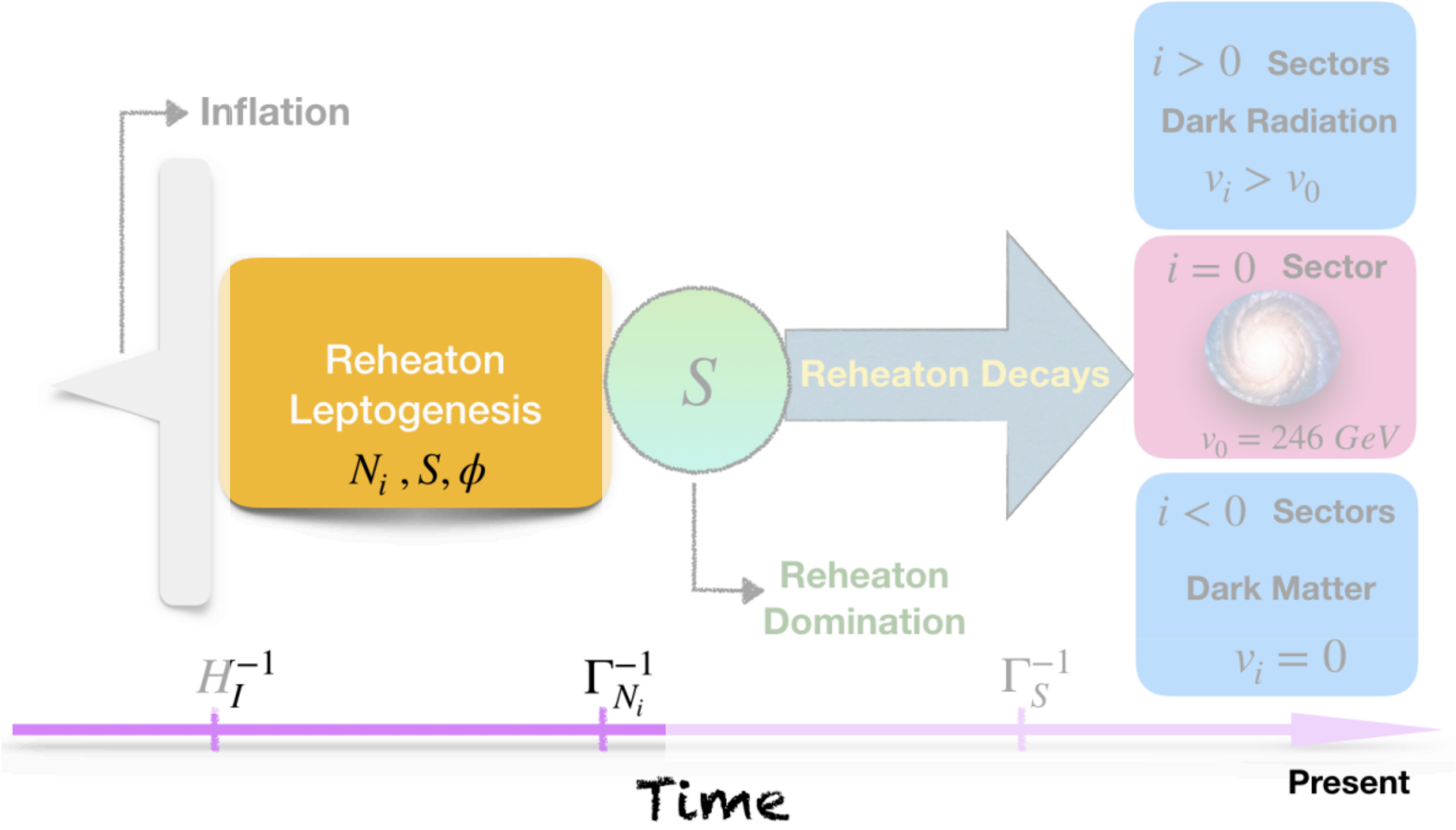


VANILLA LEPTOGENESIS

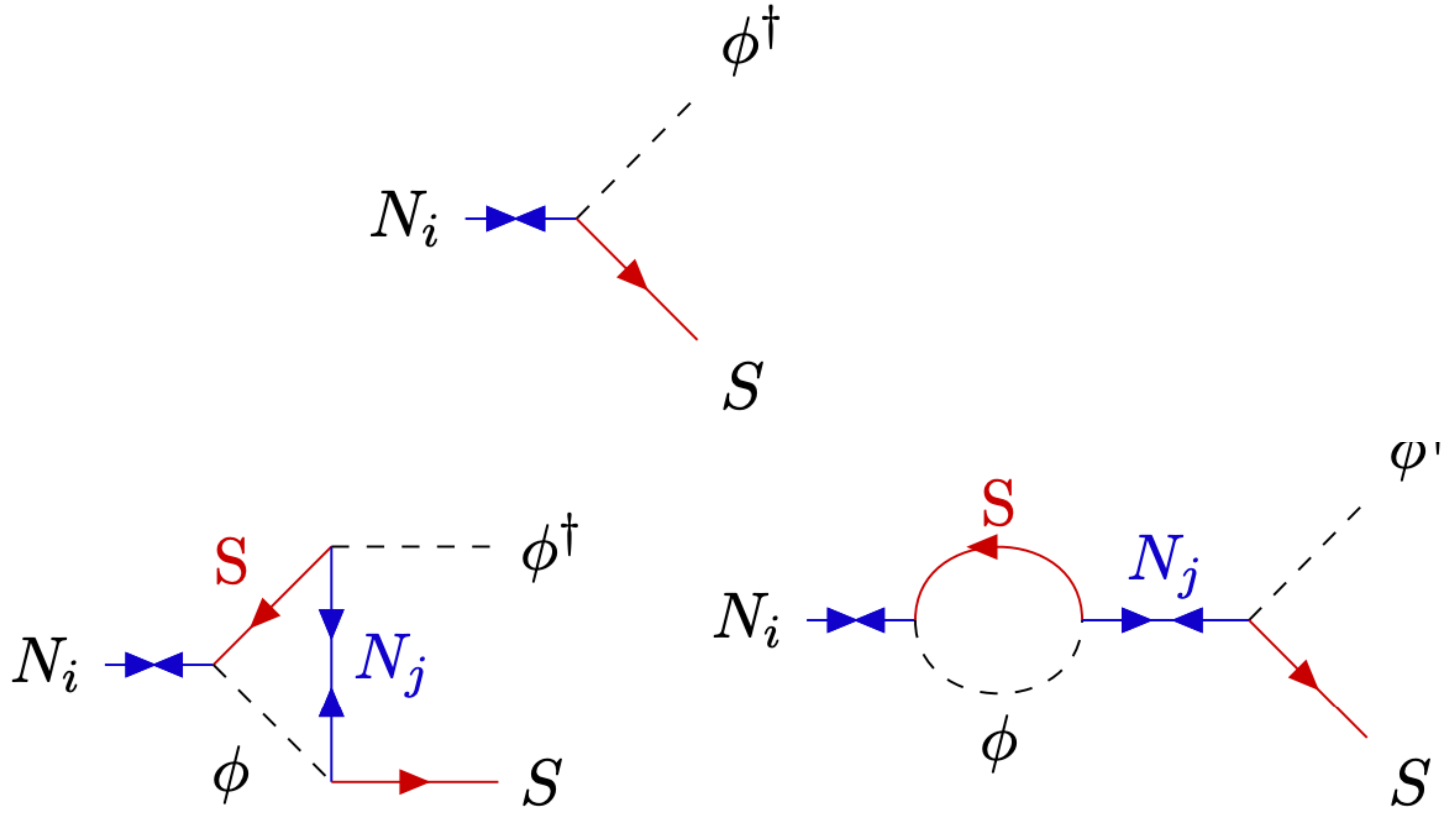
Leptogenesis sector not one of the N.

Fields are not charged under SM (or hidden) gauge groups.

Looks like original leptogenesis.

	spin	L
N_i	$1/2$	-1
S	$1/2$	-1
S^c	$1/2$	1
ϕ	0	0

Fukugita, Yanagida, PLB '86.



Universe is dominated by asymmetric population of S (reheaton).

$$\frac{n_S - n_{S^c}}{n_S + n_{S^c}} \gtrsim 10^{-6}$$

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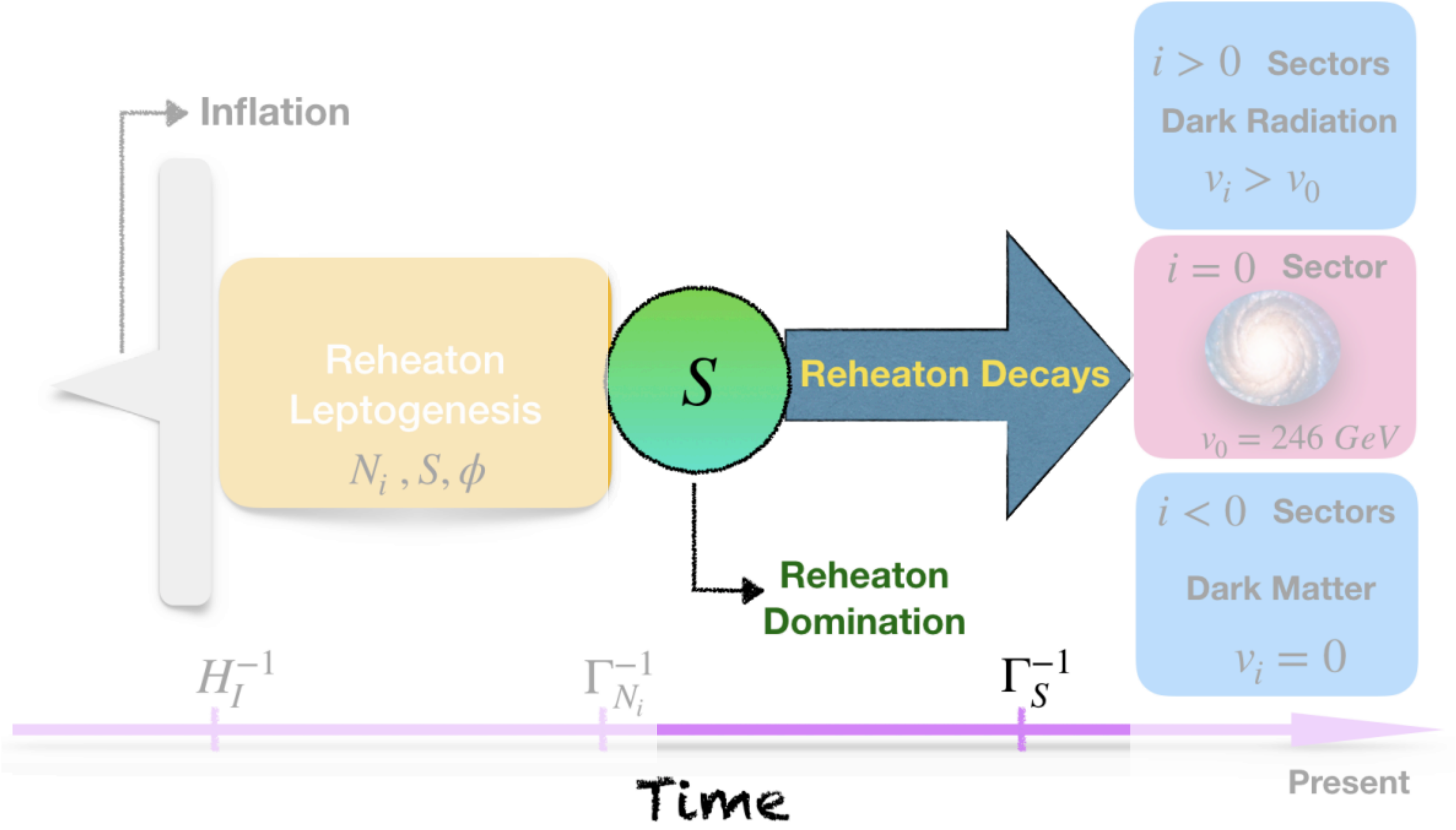
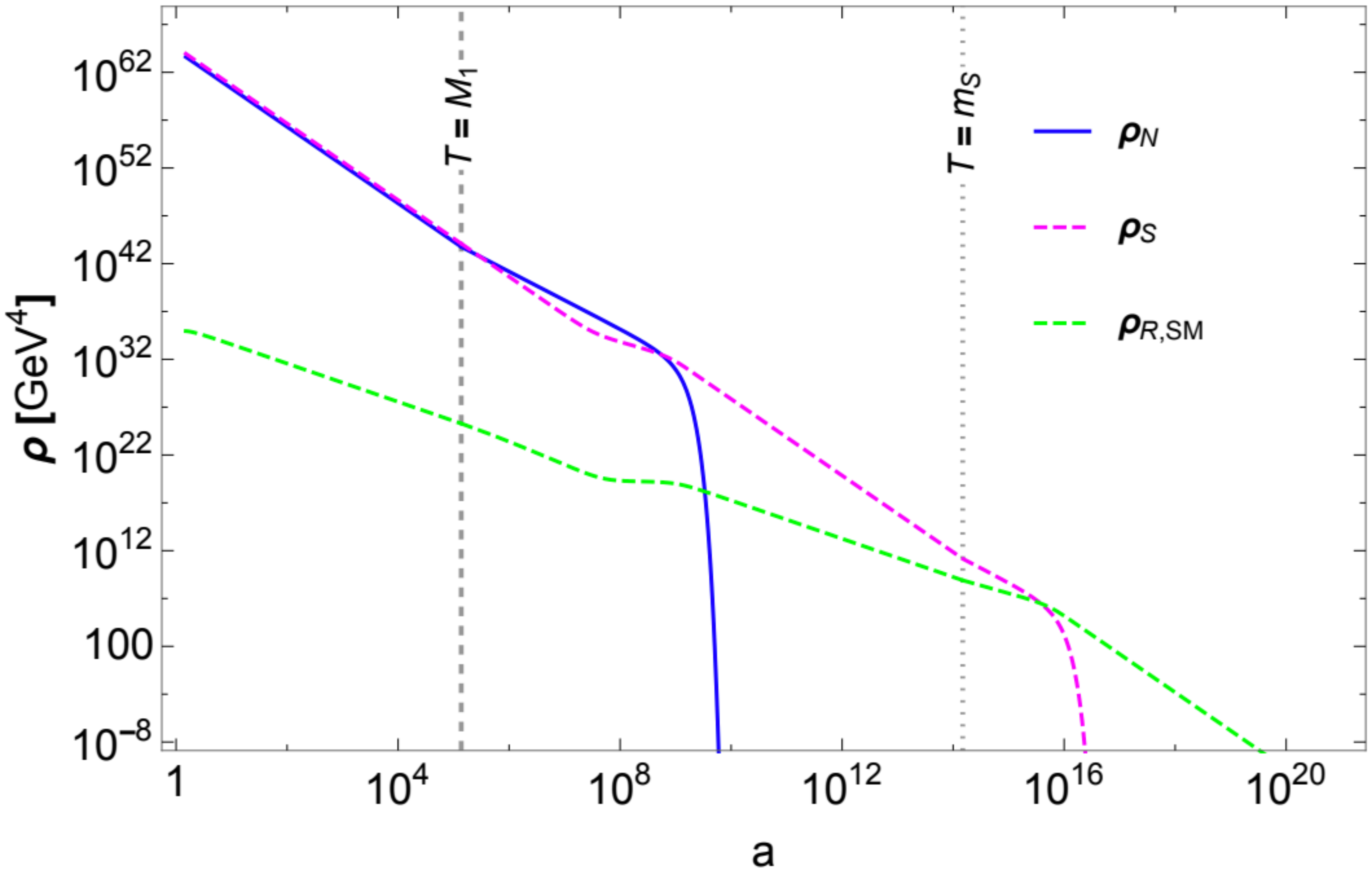


REHEATON DECAY

Reheaton has very long lifetime and becomes non-relativistic.

Reheaton decay reheats the universe up to weak scale.

$$T_{\text{RH}} \sim \sqrt{M_p \Gamma_S} \sim 100\,\text{GeV}$$



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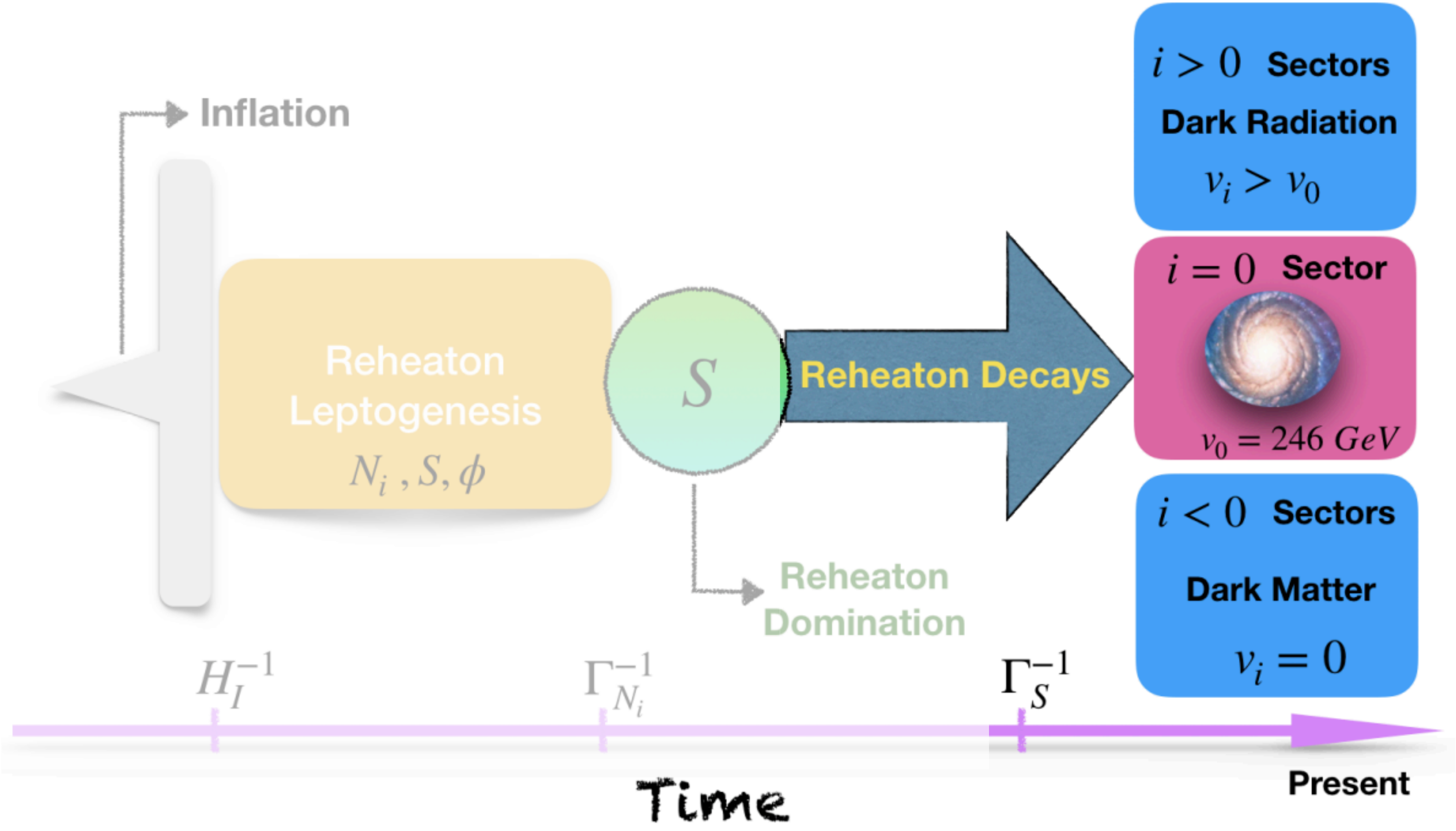

REHEATON DECAY

Reheaton energy gets divided into N sectors by branching ratios.

$$\mathscr{L} = \lambda S^c \sum_i L_i H_i - m_S S S^c$$

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

$$m_S \approx m_H(\mathrm{SM})$$

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$$\text{BR}(S \to \text{SM}) \approx 1$$

Decays to sectors with higher Higgs mass parameter become 3 body.

$$\text{BR}(S \to (i = +1)) \sim 10^{-5}$$

$$\text{BR}(S \to (i > +1)) \sim 1/i$$

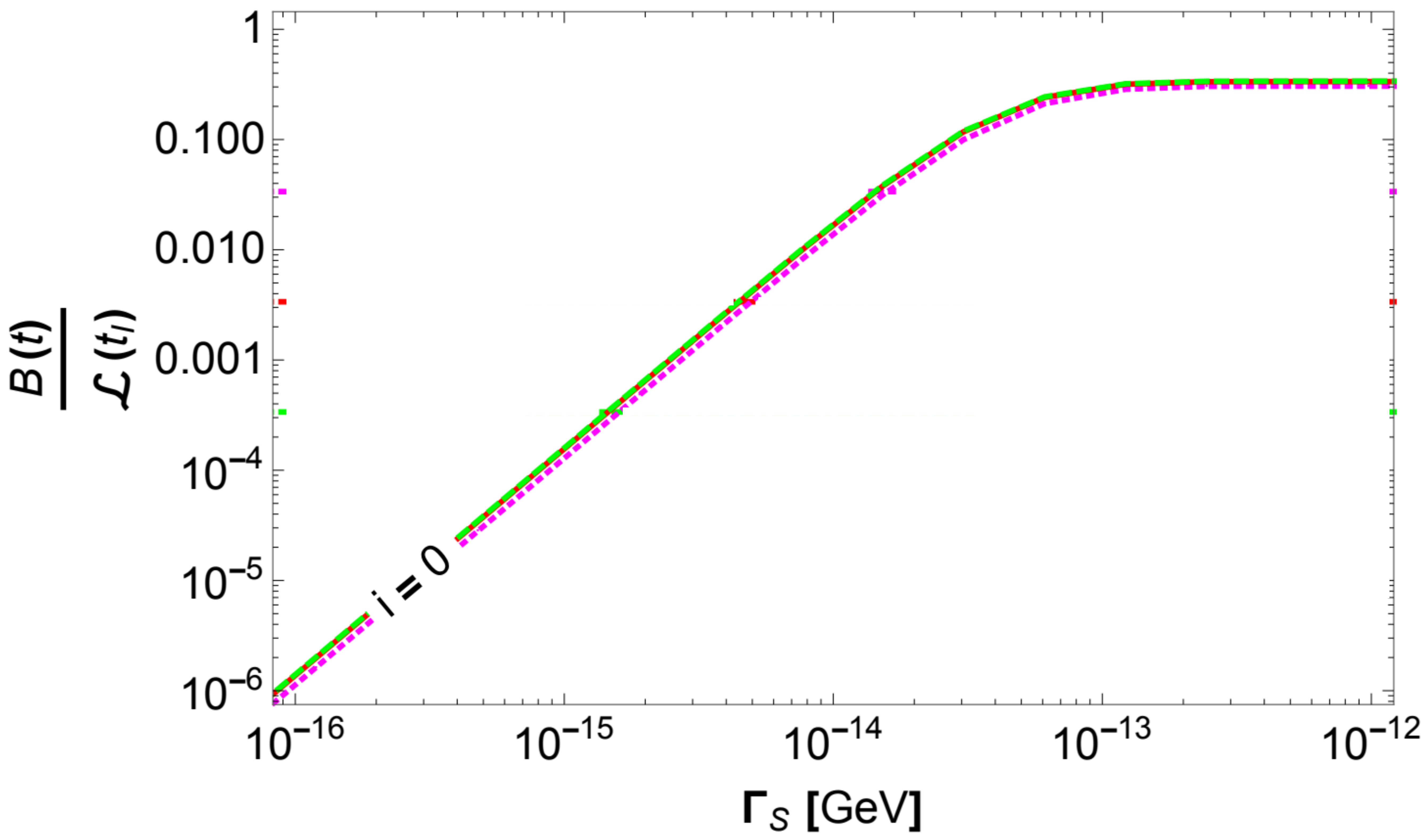
BARYOGENESIS

Lepton asymmetry also gets transferred to N sectors by branching ratios.

Electroweak sphaleron can transform lepton asymmetry into baryon asym.

Sphaleron is only active at temperatures above 130 GeV.

Kuzmin, Rubakov, Shaposhnikov, PLB '85.



$$\Delta B/\Delta L \propto \Gamma_S^2$$

EXOTIC SECTORS

What happens to SM if $m_H^2 > 0$?

Susskind PRD '79.

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Susskind PRD ’79.

$SU(2)_L \times U(1)_Y$ broken down to $U(1)_{\text{EM}}$ by colour confinement at the GeV scale.

Proton mass is roughly the same as in SM.

6 quarks much lighter than QCD scale.

Archer-Smith, Linthorne, DS, arXiv:1910.02083

REHEATON DECAY TO EXOTIC SECTORS

Lightest exotic Higgs will be similar in mass to SM Higgs.

$$\mathscr{L} = \lambda S^c \sum_i L_i H_i - m_S S S^c$$

Have mild kinematic suppression to lightest exotic sector.

$$\mathrm{BR}(S \to (i = -1)) \approx 10^{-2}$$

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DARK BARYOGENESIS

Can dark matter be the baryon in one of the hidden sectors?

$$\frac{\Delta L(\text{dark})}{\Delta L(\text{SM})} = \frac{\text{BR}(S \to \text{dark})}{\text{BR}(S \to \text{SM})} \ll 1$$

Will it be enough?

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Will it be enough?

For SM-like sectors, sphaleron is less efficient than SM.

$$\frac{\Omega_{\text{DM}}}{\Omega_{\text{B}}} \approx \frac{\Delta B(\text{dark})}{\Delta B(\text{SM})} < \frac{\Delta L(\text{dark})}{\Delta L(\text{SM})} \lesssim 10^{-5}$$

Not even close (need ~ 5).

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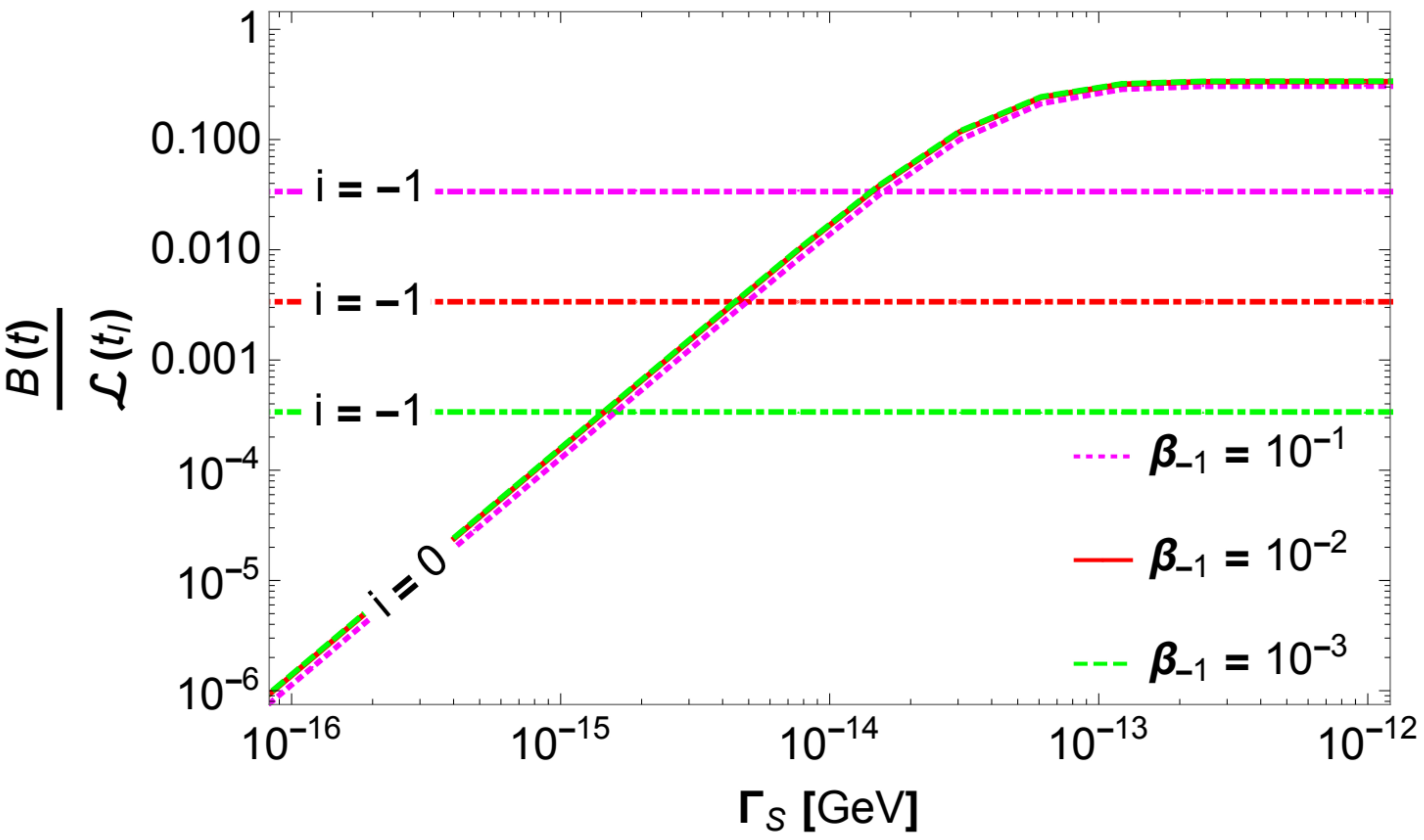
For exotic sectors sphaleron is active down to QCD scale so its much more efficient!



Dark asymmetry depends only on

$$\beta_{-1} = \text{BR}(S \to (i = -1)).$$

DISAGREEMENT

hep-th > arXiv:hep-th/0501082

Predictive Landscapes and New Physics at a TeV

Nima Arkani-Hamed, Savas Dimopoulos, Shamit Kachru

A No Baryons for $m_h^2 > 0$

Phase transition temperature $T_c < m_p$.

Sphaleron process is biased towards erasing any baryon asymmetry.

Estimate tiny final baryon asymmetry $n_B/s \sim \Lambda_{QCD}/M_{Pl} \sim 10^{-18}$.

SPHALERON RATE

Is the sphaleron fast enough to wash out asymmetry?

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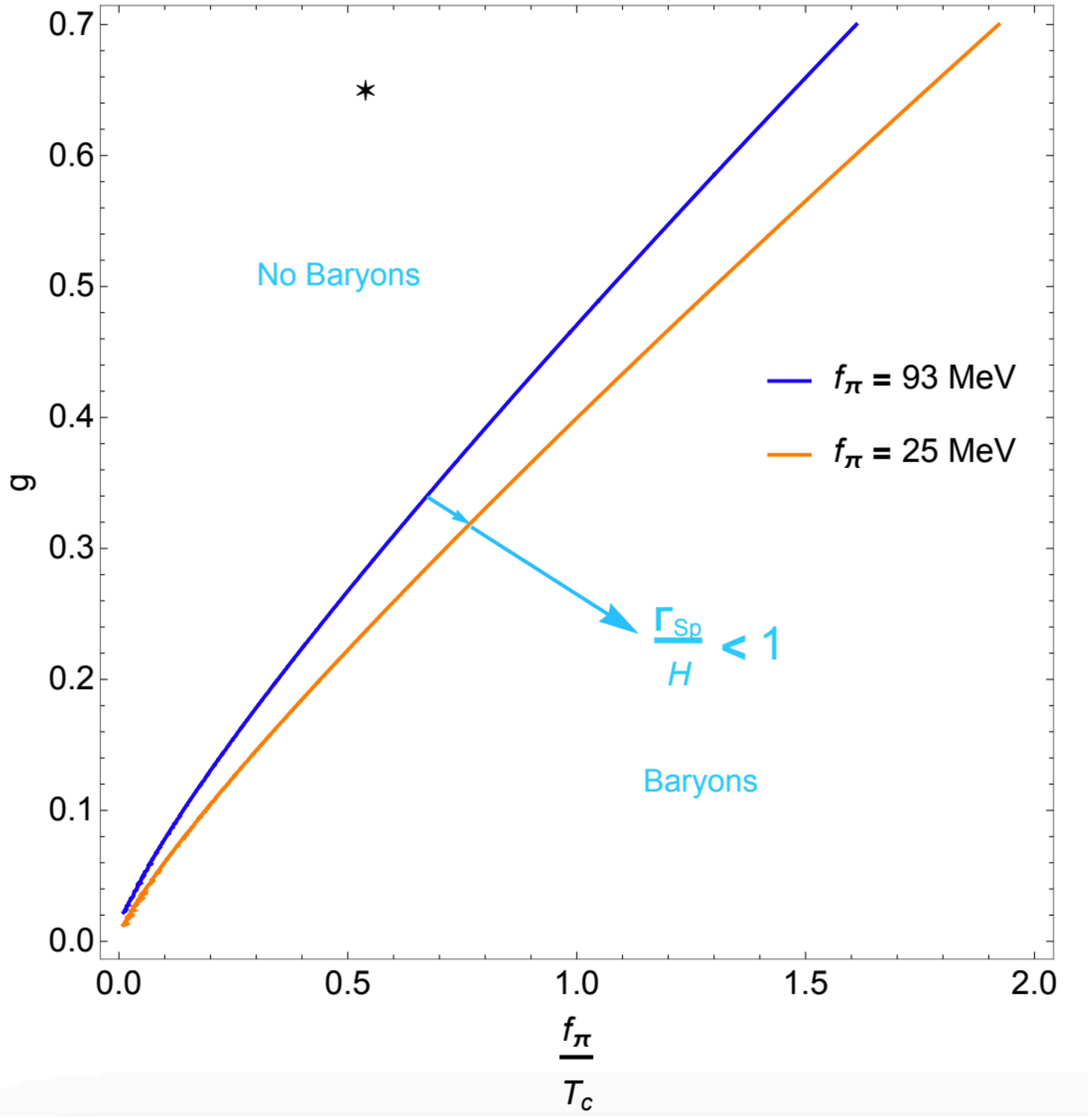
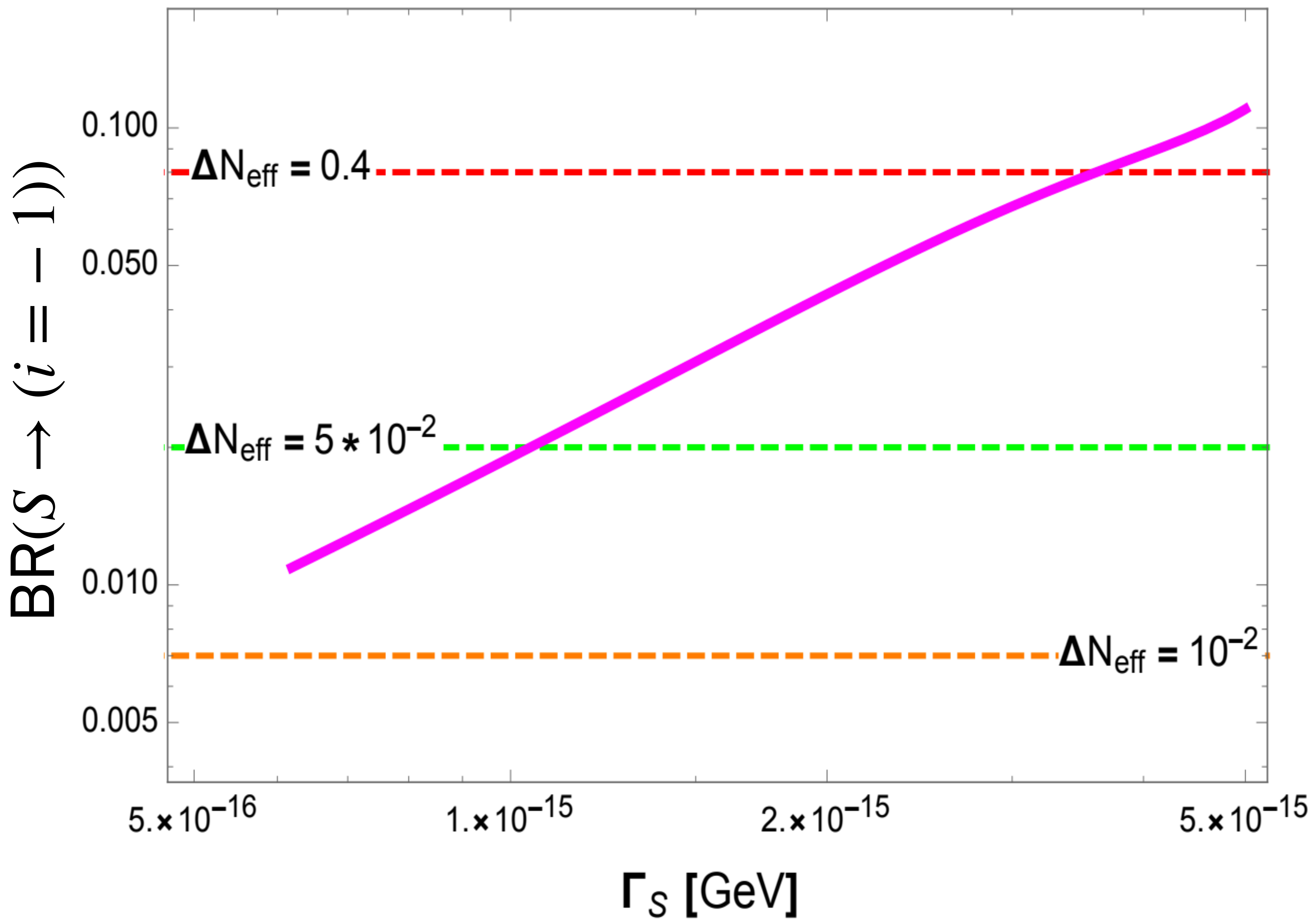


CONCLUSIONS



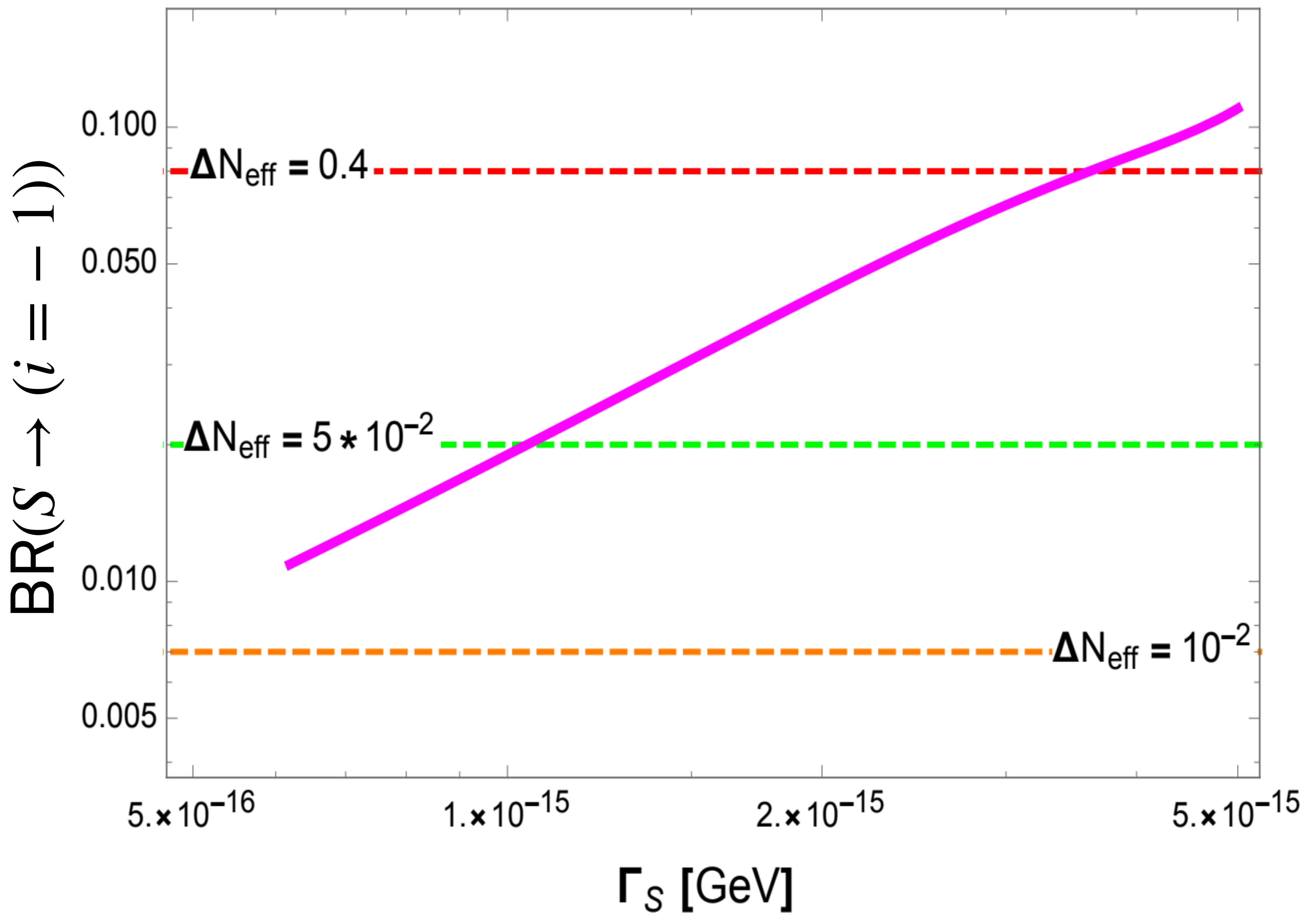
CONCLUSIONS

Built a model which gives a baryon asymmetry and dark matter in NNaturalness framework.

Dark matter is neutron in sector without Higgs vev.

Predict $\Delta N_{\rm eff} \gtrsim 0.01$.

Interesting dark matter pheno.



THANK YOU

REHEATON DECAY

$$\mathscr{L} = \sum_i \left[S^c(L_4H)_i + \mu_L(\ell L_4^c)_i + M_L(L_4L_4^c)_i\right]$$

Integrate out vectrolike doublet:

$$\mathscr{L}_{\langle H\rangle\neq 0} \sim v_i W^+ \ell_i S^c$$

$$\mathscr{L}_{\langle H\rangle = 0} \sim \ell_i H_i S^c$$

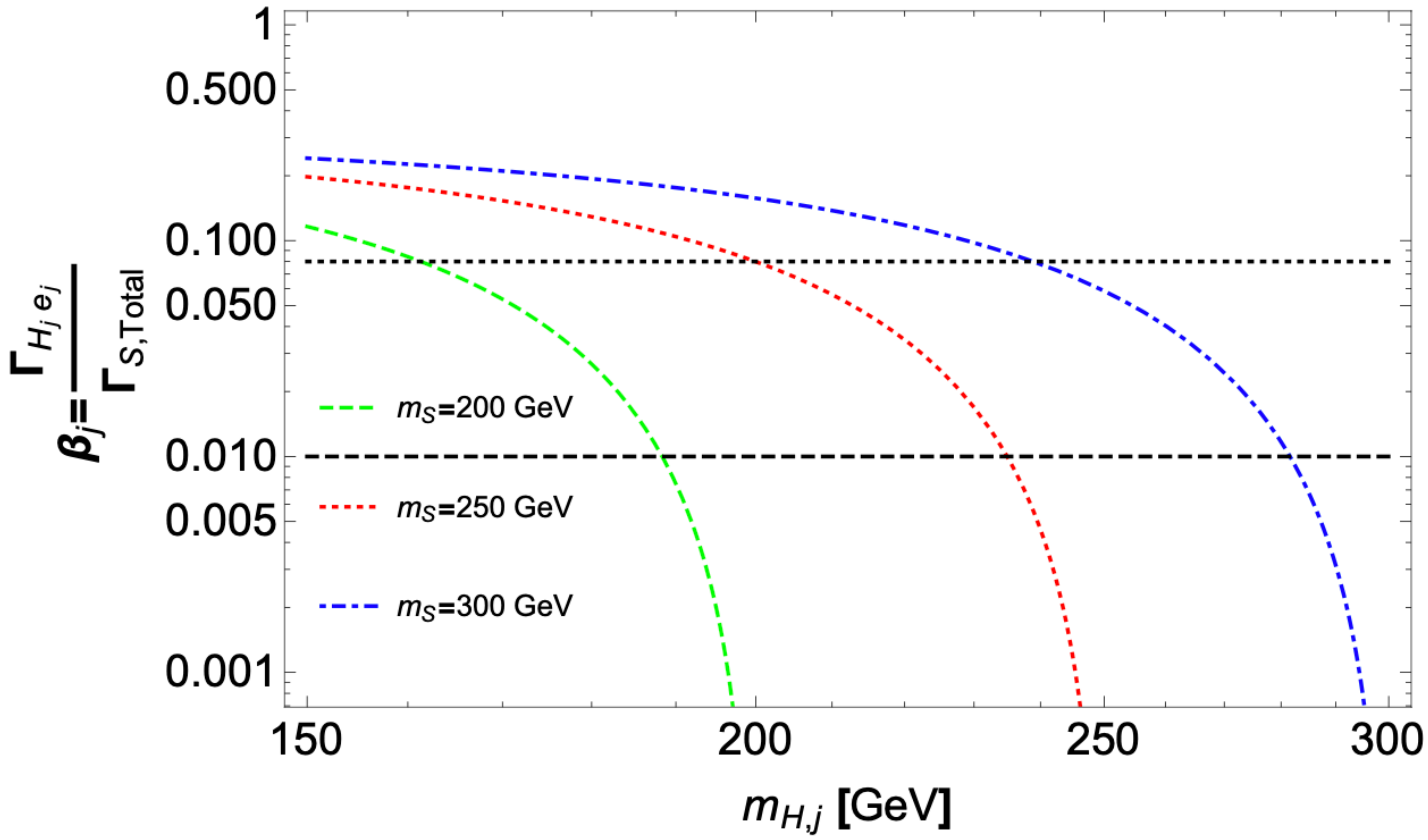
$$\Gamma_{\text{2-body}} \sim \lambda^2$$

Three body decays:

$$\Gamma_{\langle H\rangle\neq 0} \sim \frac{\lambda^2}{m_W^2} \sim \frac{1}{i}$$

$$\Gamma_{\langle H\rangle = 0} \sim \frac{\lambda^2}{m_H^4} \sim \frac{1}{i^2}$$

REHEATON BRANCHING RATIOS



(a) $i = -1$ sector

LIMITS

$$\Delta N_{\rm eff} = \frac{4}{7}\left(\frac{11}{4}\right)^{4/3} g_\star^h(T^h_{\rm Dec}) \left[\frac{g_\star^h(T^h_{\rm RH})}{g_\star^{\rm SM}(T^{\rm SM}_{\rm RH})}\right]^{1/3} \left[\frac{g_\star^{\rm SM}(T^{\rm SM}_{\rm Dec})}{g_\star^h(T^h_{\rm Dec})}\right]^{4/3} \frac{\Gamma(S\to {\rm Hidden})}{\Gamma(S\to{\rm SM})}.$$

$\langle H\rangle \neq 0$ sectors:

$$\Delta N_{\rm eff}^{\rm Decay} \simeq 1.0\times 10^{-4} \left[\frac{g_\star^{k=1}(T^{k=1}_{\rm RH})}{g_\star^{\rm SM}(T^{\rm SM}_{\rm RH})}\right]^{1/3} \left(\frac{\gamma_1}{10^{-5}}\right) \ln(k_{\rm max})$$

$\langle H\rangle = 0$ leading sector:

$$\Delta N_{{\rm eff},j}^{\rm Decay} \simeq 7.4 \left[\frac{g_\star^{j}(T^{j}_{\rm RH})}{g_\star^{\rm SM}(T^{\rm SM}_{\rm RH})}\right]^{1/3} \left(\frac{\beta_j}{1-\beta-\gamma}\right)$$

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$$\sum_i \frac{\Omega_{\nu,i}}{\Omega_{\rm DM}} \sim 2.4 \times 10^{-2} \left(\frac{m_0}{0.06\,\text{eV}}\right) \left(\frac{\gamma_1}{10^{-5}}\right)^{3/4} \left(\frac{N_{\rm max}}{250}\right)^{5/4}$$

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Too much hot dark matter if there are more than 250 sectors.

DIRAC NEUTRINOS

Take neutrinos to be Dirac: $m_i \propto v_i$.

Neutrinos only thermalize up to

$N_{\text{max}} \simeq 2{,}500$.

$$\sum_i \frac{\Omega_{\nu,i}}{\Omega_{\text{DM}}} \sim 5 \times 10^{-3} \left(\frac{m_0}{0.06\,\text{eV}}\right) \left(\frac{\gamma_1}{10^{-5}}\right)^{3/4} \left(\frac{N_{\text{max}}}{2{,}500}\right)^{3/4}$$

No bounds from these sectors.

NON THERMAL NEUTRINOS

For larger vevs, neutrinos produced via direct reheaton decay: $S \to 3\nu\bar{\nu}\nu$.

Neutrinos have energy $\sim m_s/3$ and do not interact.

$$\frac{\Omega_{\nu,i}}{\Omega_{\text{DM}}} \sim 2.4 \times 10^{-2} \left(\frac{m_0}{0.06\,\text{eV}}\right)\left(\frac{\gamma_1}{10^{-5}}\right)\left(\frac{N_{\text{max}}}{10^5}\right)^{1/2}$$

Can compute free-streaming, these neutrinos are not hot.

Could be all of dark matter for $N_{\text{max}} \simeq 3 \times 10^8$.

DARK MATTER

Lightest baryon in exotic sector is the neutron.

Neutrons have large self interactions:

$$\sigma_{nn} \sim 10^{-22}\ \text{cm}^2 > 2 \times 10^{-24}\ \text{cm}^2$$

Tension with bullet cluster bounds.

DARK NUCLEI

Neutrons will generically bind into nuclei.

Nuclei can get quite large (no Coulomb barrier!).

Dark nuclei can get very large $A_{\text{max}} \sim 10^{24}$.

Hardy, Lasenby, March-Russel, West, 1411.3739.

No problem with bullet cluster. Could be strange pheno.

WITTEN NUGGETS

QCD phase transition is first order. Will there be pockets in the quark phase?

Witten PRD '84.

Yes, but nuggets rapidly evaporate via emission of $\pi + \ell$.

Process conserves all gauge quantum numbers but violates B-L.

Electroweak sphaleron active inside nuggets, will destroy baryons.