Baryogenesis from Flavon Decays

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Based on work done in collaboration with Seyda Ipek, Michael Ratz
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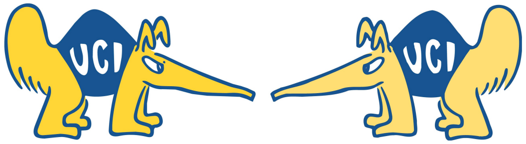
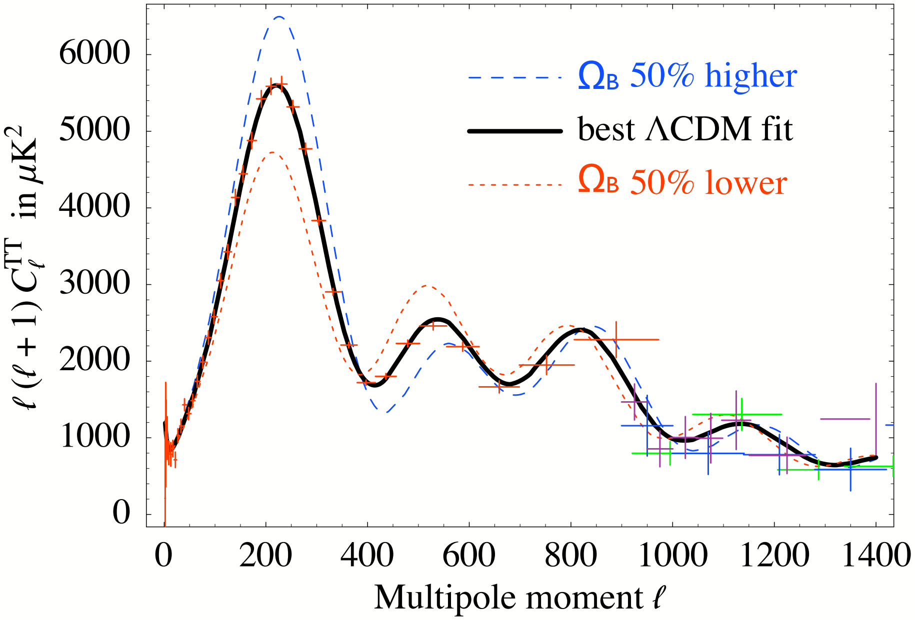


FLASY2019, USTC, Hefei, China, July 26, 2019

Evidence of Matter-Antimatter Asymmetry

- CMB anisotropy

$$\frac{\Delta T}{T} = \sum_{l,m} a_{lm} Y_{lm}(\theta, \phi) \qquad C_l = \langle |a_{lm}|^2 \rangle$$

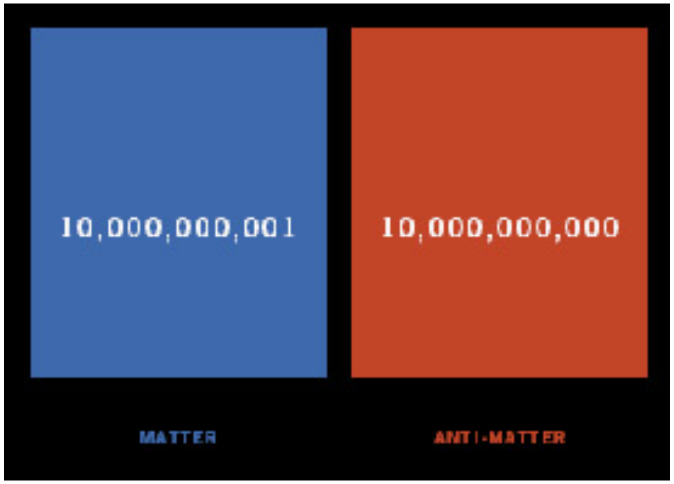


- Big Bang Nucleosynthesis
  - primordial deuterium abundance agree with WMAP $\Longleftrightarrow$
  - ^{4}He & ^{7}Li $\Longleftrightarrow$ discrepancies

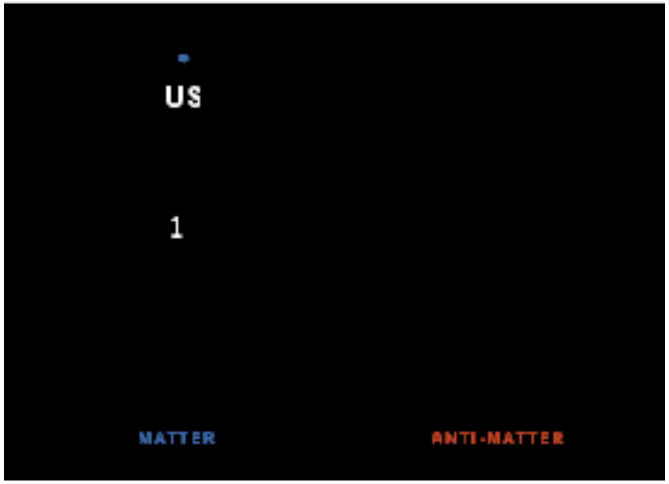
- WMAP + Deuterium Abundance

$$\frac{n_B}{n_\gamma} \equiv \eta_B = (6.1 \pm 0.3) \times 10^{-10}$$

Three Sakharov Conditions



Early Universe



Universe Now

[Picture credit: H. Murayama]

- **Baryon number can be generated dynamically, if**
  - violation of baryon number
  - violation of Charge (C) and Charge Parity (CP)
  - departure from thermal equilibrium

Baryon Number Asymmetry beyond SM

- Within the SM:
  - CP violation in quark sector not sufficient to explain the observed matter-antimatter asymmetry of the Universe

- **neutrino oscillation ⇒ non-zero neutrino masses**

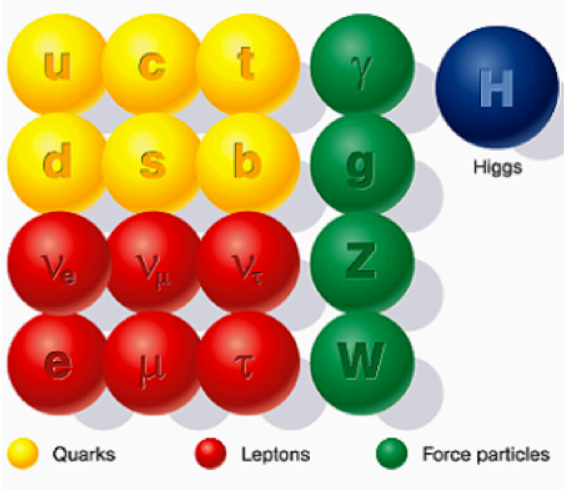
- neutrino masses open up a new possibility for baryogenesis: Fukugita, Yanagida, 1986

Leptogenesis

- connect to neutrino properties
- $T < M_R$: out-of-equilibrium decays of N → ΔL
- sphaleron processes: $\Delta L \rightarrow \Delta B$

Reasons to go Beyond the Standard Model

- **Observational:**
  - **neutrino masses**
  - cold dark matter
  - **baryon asymmetry** of the Universe
- **Theoretical:**
  - in the language of the SM, Quantum Field Theory, it is hard to describe gravitation
- **Aesthetical:** the structure of the SM is very peculiar



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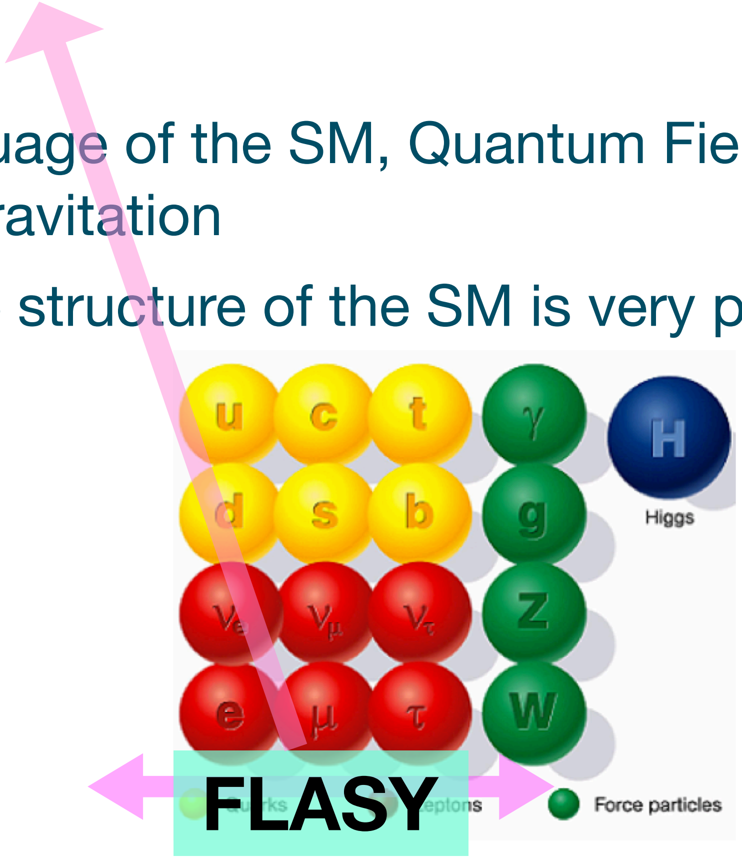


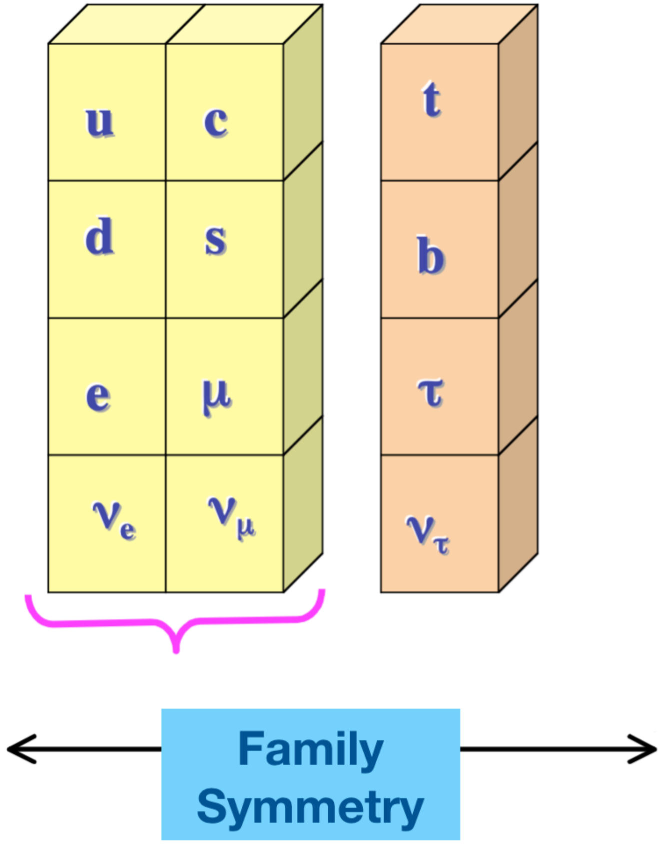
Froggatt-Nielsen Mechanism

- Popular scenario for addressing flavor hierarchies: Froggatt–Nielsen scenario

Froggatt and Nielsen [1979]

- E.g. effective Lagrangean for charged lepton masses

$$\mathscr{L} \supset y_0^{fg} \left(\frac{\widetilde{S}}{\Lambda}\right)^{n_{fg}} \overline{e}_{\mathrm{R}}^{g} \cdot \phi^* \cdot \ell_{\mathrm{L}}^{f} + \text{h.c.}$$



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Froggatt and Nielsen [1979]

$$n_{fg} = q_{\mathrm{R}}^{(f)} - q_{\mathrm{L}}^{(g)}$$

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$\mathcal{O}(1)$

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flavon

- ☞ Assume $\widetilde{S}$ acquires VEV $v_S = \varepsilon\,\Lambda$

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question:

Is that the only role of the flavon $\widetilde{S}$?

Baryogenesis through Flavon Decay

M.-C.C, S. Ipek, M. Ratz (2019)

☞ Froggatt–Nielsen Lagrangean

$$\mathscr{L} \supset y_0^{fg} \left(\frac{v_S + S}{\Lambda}\right)^{n_{fg}} \overline{e}_\mathrm{R}^g \cdot \phi^* \cdot \ell_\mathrm{L}^f + \text{h.c.}$$

➥ Flavon decays

$$S \to \overline{\ell}_\mathrm{L} + \phi + e_\mathrm{R} \quad \text{and} \quad S^* \to \ell_\mathrm{L} + \phi^* + \overline{e}_\mathrm{R}$$

- flavon decays preserve baryon and lepton number
- right–handed electrons do not couple to electroweak sphalerons
- flavon decays can produce a lepton asymmetry in the left–handed sector, i.e. $n(\ell_\mathrm{L}) \neq n(\overline{\ell}_\mathrm{L})$

Assumptions and Consequences

- ☞ Assumptions:
  - primordial flavon asymmetry (e.g. through Affleck–Dine mechanism)

    Affleck and Dine [1985]
  - flavon–number violating terms suppressed

$$\mathscr{V}_S = m^2|S|^2 + \left(\begin{array}{l} S\text{–number violating terms} \\ \text{suppressed by powers of } \Lambda \end{array}\right)$$

  - flavon decays around electroweak transition, i.e. at $T \sim 100\,\text{GeV}$
- ☞ Consequences:
  - presence of flavons prevents right–handed electrons from equilibrating
  - a realistic baryon asymmetry can be produced

Thermal Corrections to Flavon Potential

- ☞ Flavon potential

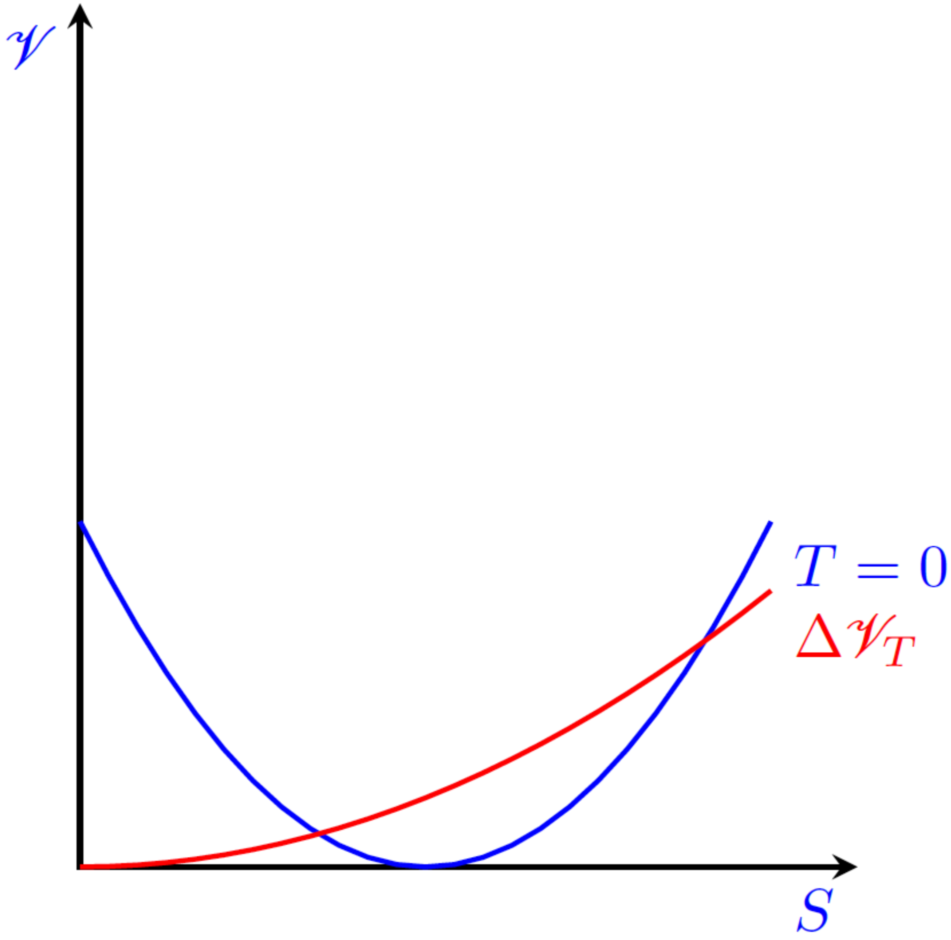
$$\mathscr{V}_{T=0} = m_S^2 |S - v_S|^2 + \dots$$

- ☞ Free energy dependens on Yukawa couplings (per Weyl fermion)

$$\Delta\mathcal{F} = \frac{5\,|y|^2}{576} T^4$$

- ➥ Thermal correction to flavon potential

Lillard, Ratz, Tait, and Trojanowski [2018]



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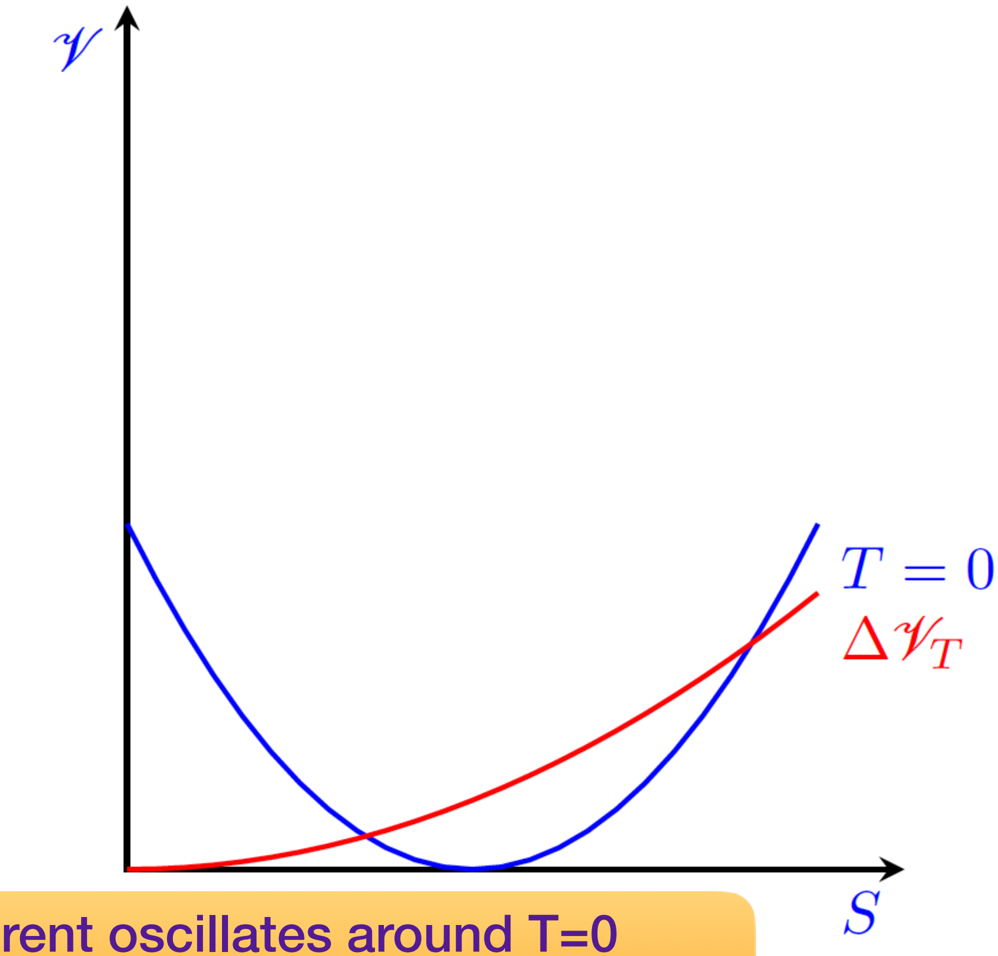


Flavon will perform coherent oscillates around T=0 minimum ⇒ energy stored in oscillations $\rho_S \sim a^{-3}$

c.f. energy density of radiation $\rho_\gamma \sim a^{-4}$

Flavon Decay and LR (non-)Equilibration

- ☞ Flavon decay rate dominated by τs

$$\Gamma_S \sim \frac{1}{\varepsilon}\,\frac{|n_\tau\, y_\tau|^2}{64\pi^3}\,\frac{m_S^3}{\Lambda^2}$$

$$y_0 \simeq 1\,, \quad \varepsilon = \frac{v_S}{\Lambda} = 0.2\,, \quad n_e = 9\,, \quad n_\tau = 3\,.$$

$$B_e \sim \left(\frac{n_e\, y_e}{n_\tau\, y_\tau}\right)^2 \sim \; 7.5 \times 10^{-7}$$

- ☞ Evolution of number densities

$$\frac{\mathrm{d}\rho_S}{\mathrm{d}t} + 3H\,\rho_S = -\Gamma_S\,\rho_S$$

$$\frac{\mathrm{d}\rho_{\mathrm{rad}}}{\mathrm{d}t} + 4H\,\rho_{\mathrm{rad}} = \Gamma_S\,\rho_S$$

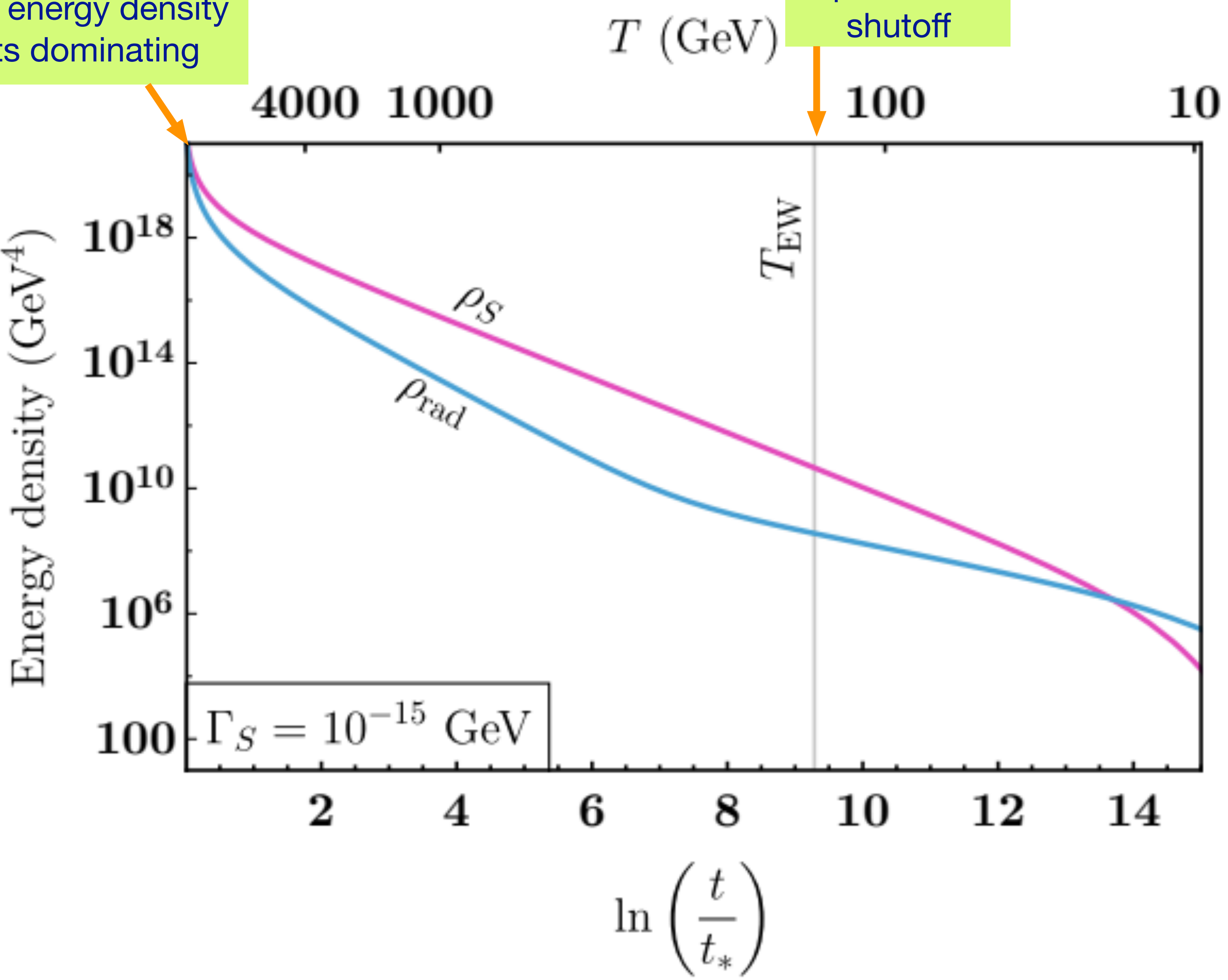
$$H^2 = \frac{8\pi}{3M_{\mathrm{Pl}}^2}(\rho_S + \rho_{\mathrm{rad}})$$

- ☞ Left–right conversion of right–handed electrons (2 → 2 scattering with Higgs)

$$\Gamma_{\mathrm{LR}} \simeq 10^{-2}\, y_e^2\, T$$

other decay products thermalized with radiation ⇒ contribute to radiation density

Energy Densities: Flavons vs Radiation



flavon energy density starts dominating

sphalerons shutoff

Energy Densities: Flavons vs Radiation

before flavor decay: $t_* < t < \tau \sim \Gamma_S^{-1}$

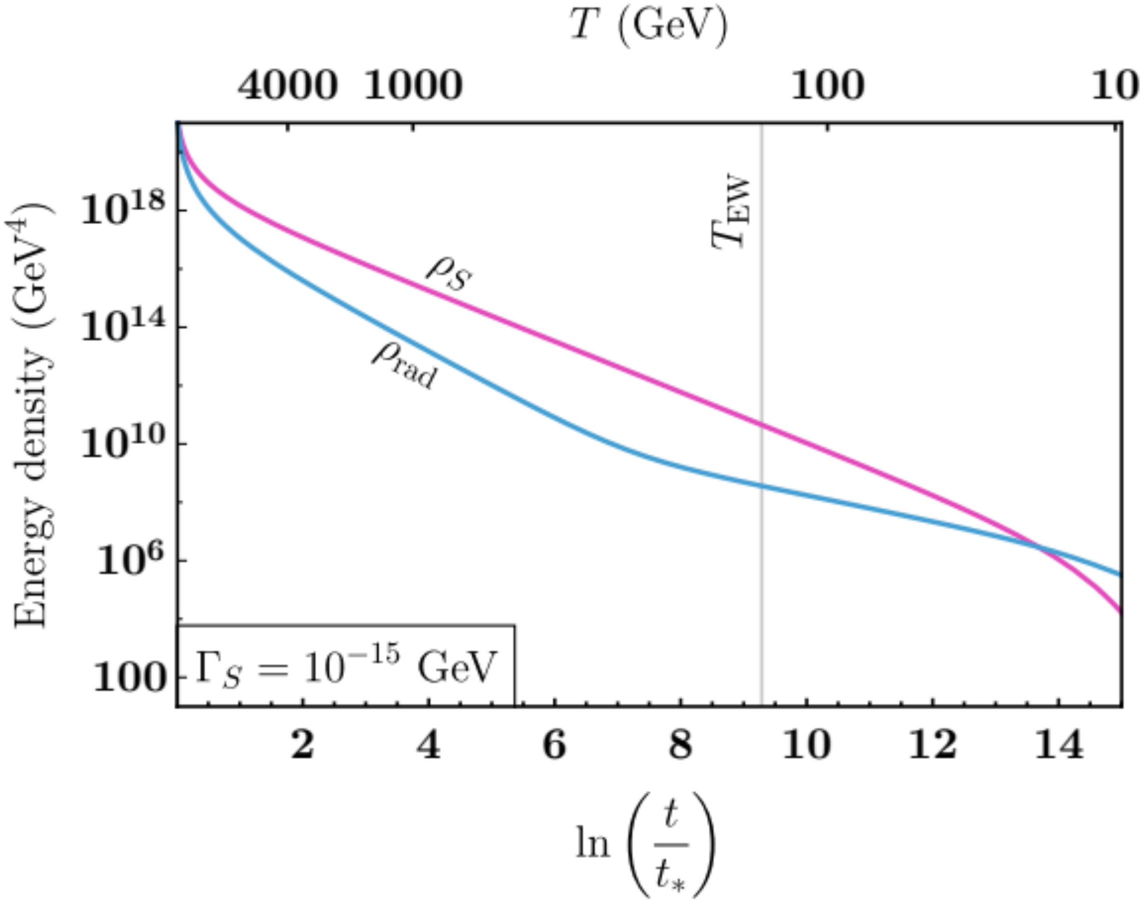
$$\rho_S(t) \simeq \frac{M_{\rm Pl}^2}{6\pi t^2}\, {\rm e}^{-\Gamma_S\, t}\ ,$$

$$\rho_{\rm rad}(t) \simeq \frac{M_{\rm Pl}^2 t_*^{2/3}}{6\pi\, t^{8/3}} + \frac{\Gamma_S\, M_{\rm Pl}^2}{10\pi\, t}$$

Flavons decay around EW phase transition

⇒ flavon mass

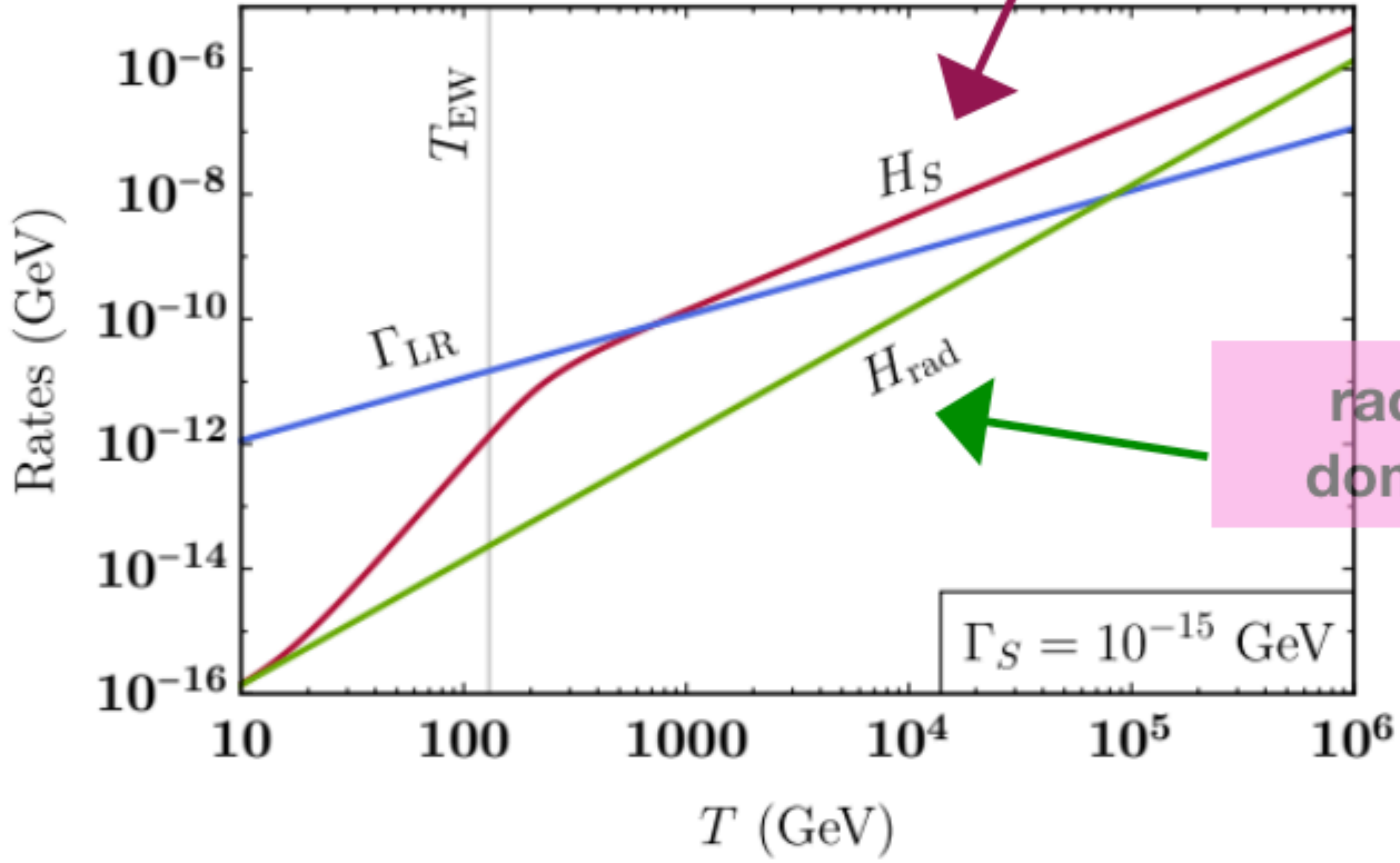
$$\frac{m_S}{\rm TeV} \sim \left(\frac{\Lambda}{10^9\,{\rm GeV}}\right)^{\frac{2}{3}} \left(\frac{\Gamma_S}{10^{-15}\,{\rm GeV}}\right)^{\frac{1}{3}}$$



Rates: Hubble vs LR Equilibration

$$H^2 = \frac{8\pi}{3M_{\rm Pl}^2}(\rho_S + \rho_{\rm rad})$$

flavon dominates



radiation dominates

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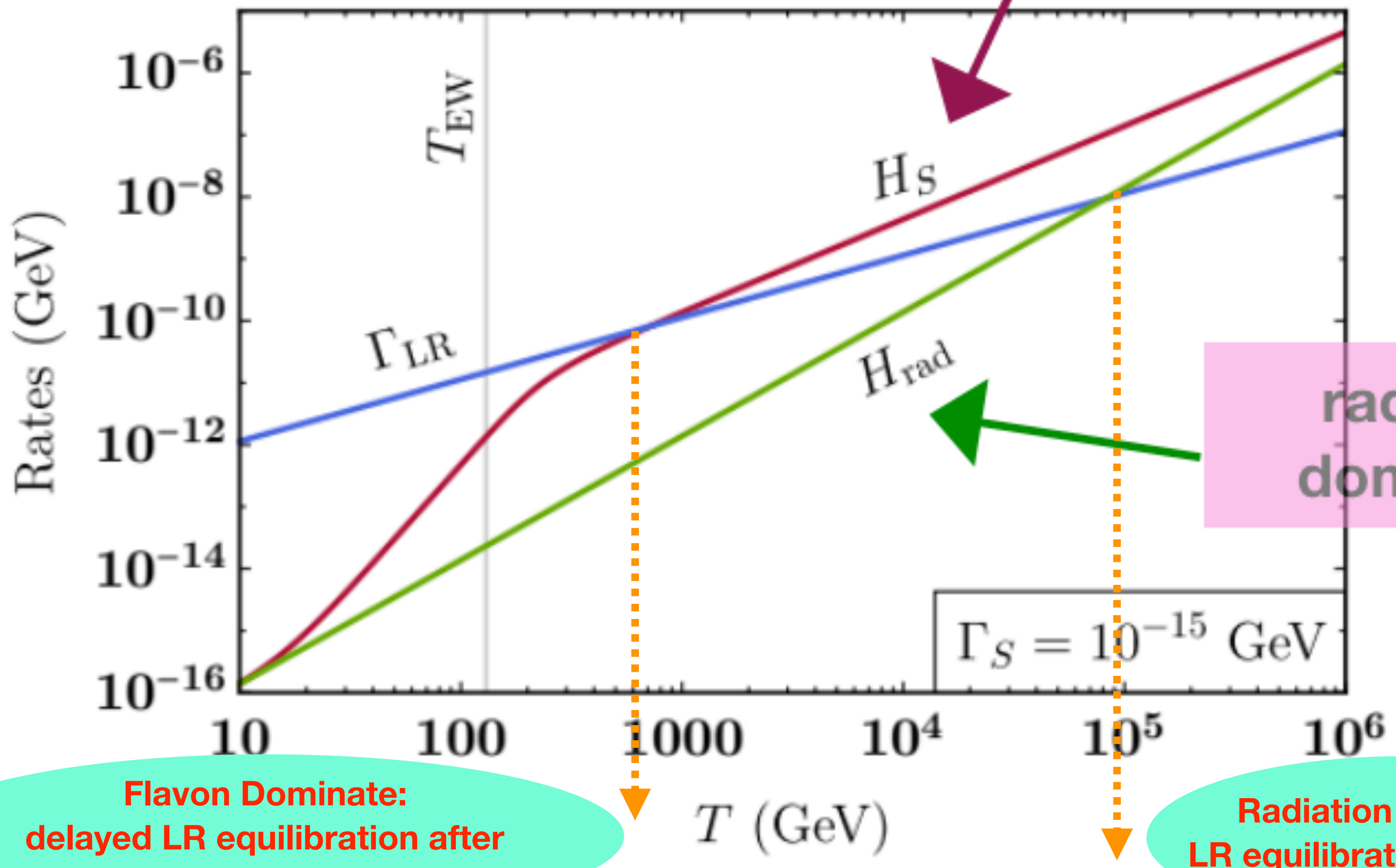


flavon dominates

radiation dominates

Flavon Dominate:
delayed LR equilibration after
Sphelarons shutoff

Radiation Dominate:
LR equilibration @ 10^5 GeV

Flavon Decay and LR (non-)Equilibration

Chen, Ipek, and Ratz [2019]

☞ Right–handed electrons are *not* equilibrated because the presence of the flavon speeds up the expansion of the universe

$$\Gamma_{\mathrm{LR}} \lesssim H(\text{w/ flavon})$$

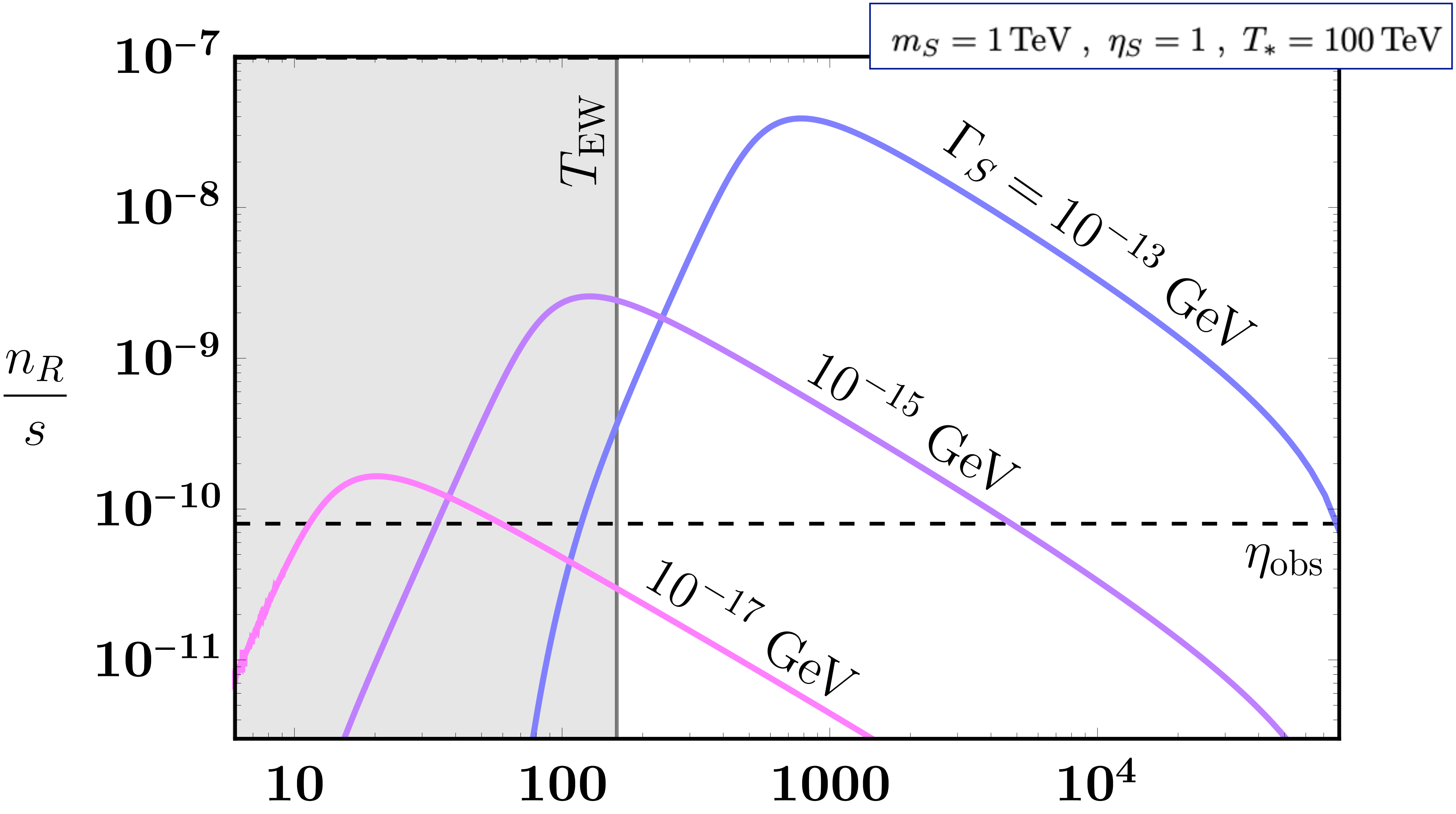
➥ A flavon asymmetry translates into an asymmetry in right–handed electrons, which is balanced by the opposite asymetry in left–handed leptons

cf. Dirac leptogenesis Dick, Lindner, Ratz, and Wright [2000]

☞ A left–handed asymmetry gets converted to a baryon asymmetry by the electroweak sphalerons

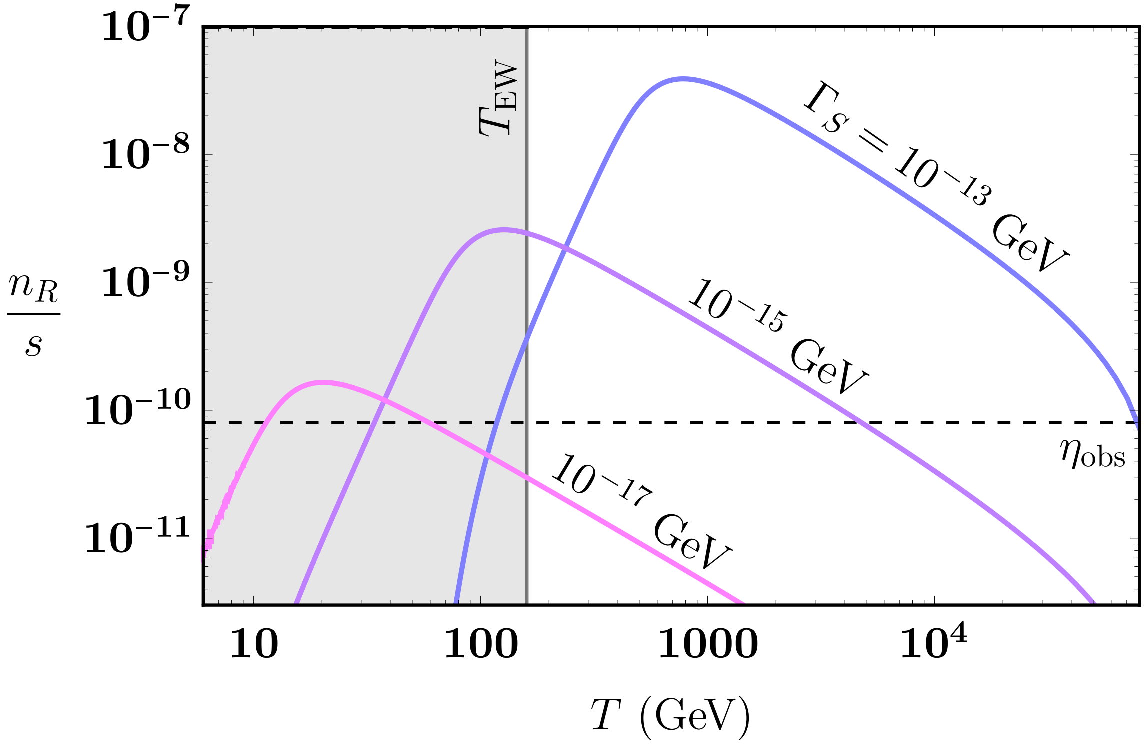
Kuzmin, Rubakov, and Shaposhnikov [1985]

Rates: Hubble vs LR Equilibration



$$n_{\mathrm{R}} = n_{e_{\mathrm{R}}} - n_{\bar{e}_{\mathrm{R}}}$$

Rates: Hubble vs LR Equilibration



Small Γ_S :

delaying equilibration

⇳

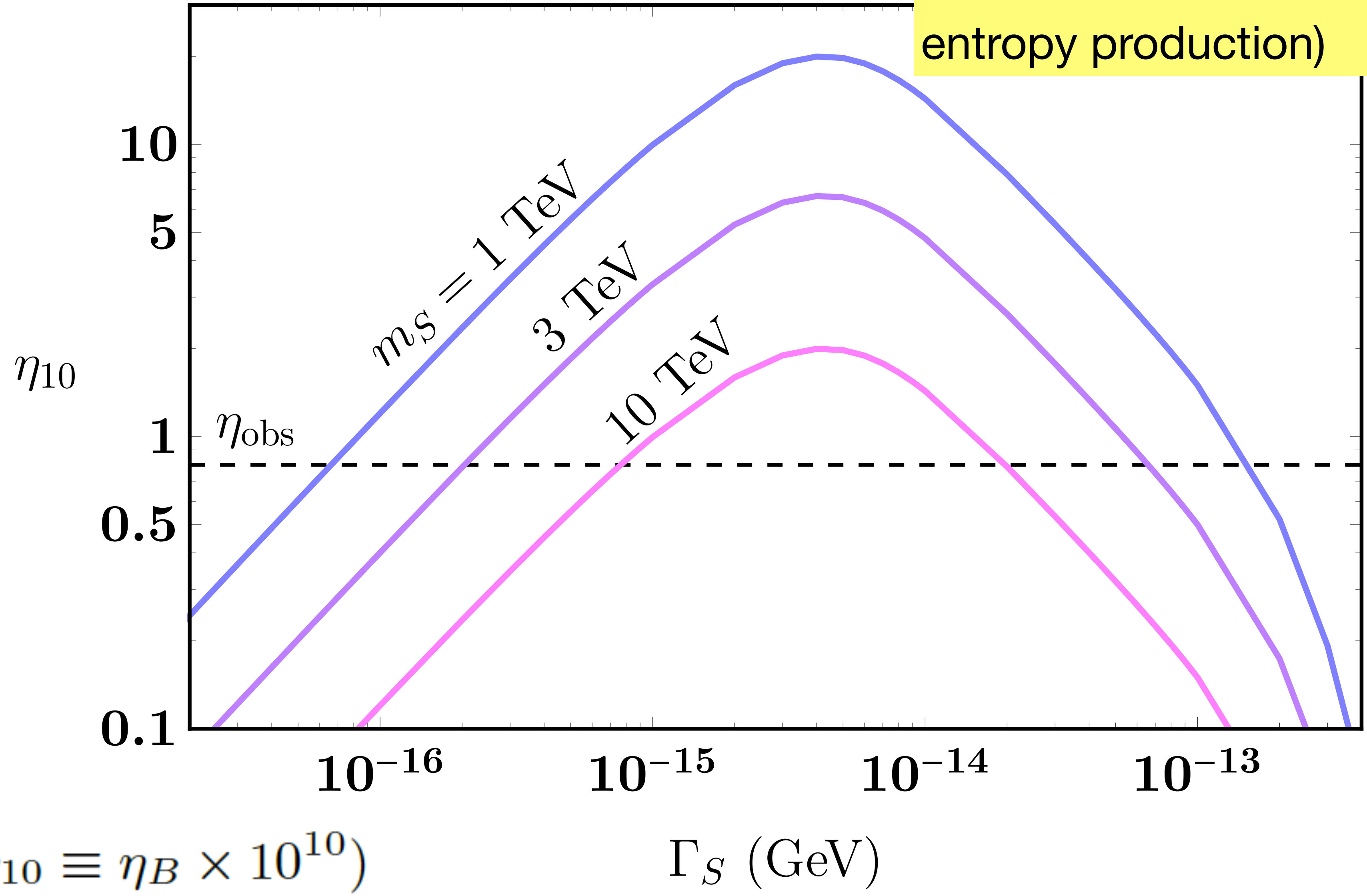
smaller number of
flavons decay

- e_R asymmetry produced by flavon decay
- LR equilibration washout asymmetry
- smaller decay rate → later LR equilibration

Baryon Number Asymmetry

Primordial flavon asymmetry $\eta_s = 1$

m_s ↑ ⇒ η ↓ (dilution due to entropy production)

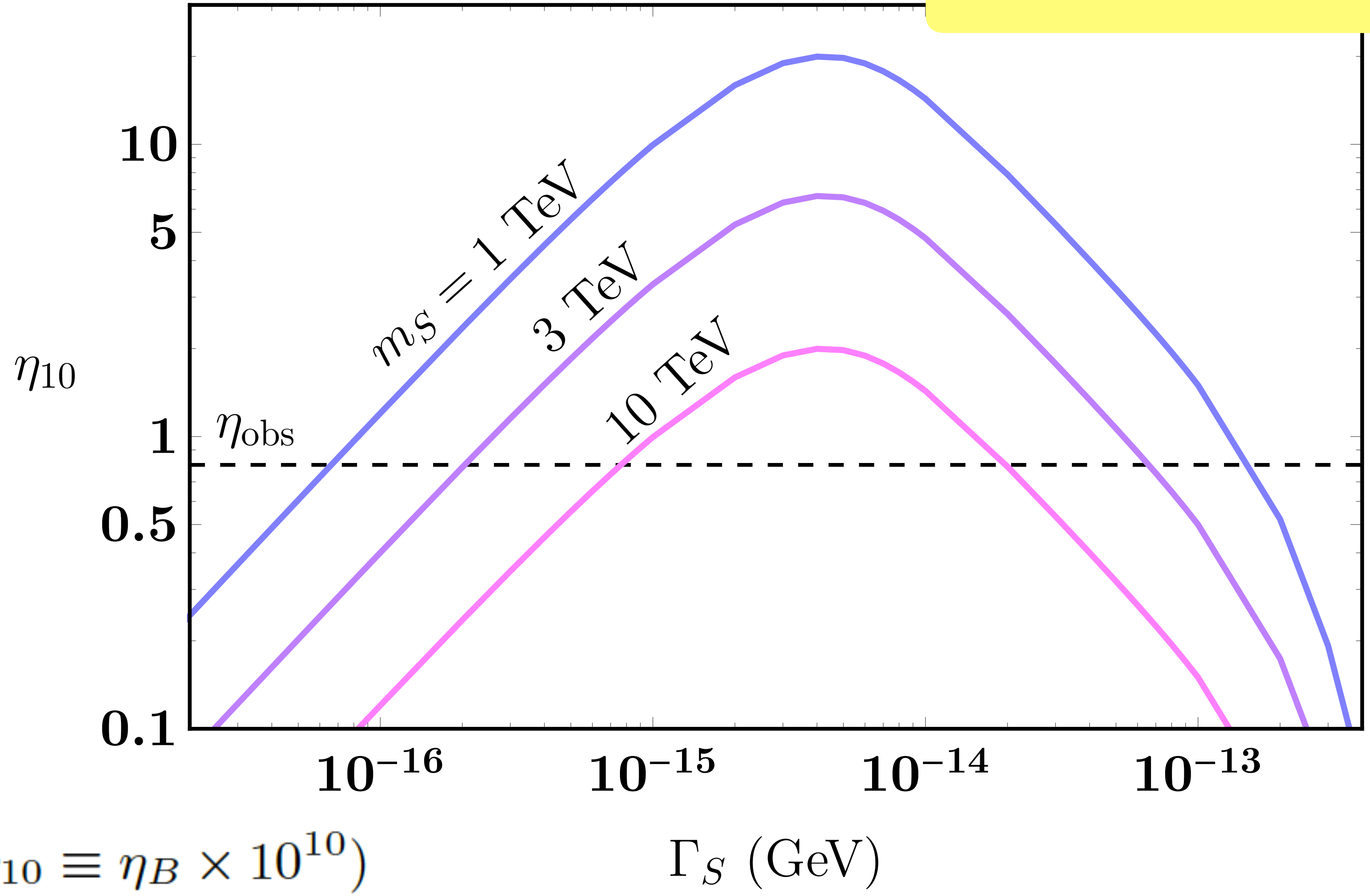


$(\eta_{10} \equiv \eta_B \times 10^{10})$

Baryon Number Asymmetry

$$\frac{m_S}{\mathrm{TeV}} \sim \left(\frac{\Lambda}{10^9\,\mathrm{GeV}}\right)^{\frac{2}{3}} \left(\frac{\Gamma_S}{10^{-15}\,\mathrm{GeV}}\right)^{\frac{1}{3}}$$

O(TeV) flavon mass can produce successful BAU: $\Lambda \sim O(10^9)$ GeV



$(\eta_{10} \equiv \eta_B \times 10^{10})$

Baryogenesis through Flavon Decay

Chen, Ipek, and Ratz [2019]

☞ Decays of a flavon, which is introduced in order to explain fermion mass hierarchies, can explain the observed baryon asymmetry if:

- there is a primordial flavon asymmetry
- flavon number is approximately conserved
- the flavon decays around $T \sim 100\,\text{GeV}$

☞ The observed smallness of the electron Yukawa coupling is instrumental for that scenario

Flavon decay too early ($T_d \gg T_{ew}$): right-handed electron equilibrate
⇒ no baryon asymmetry generated

Flavon decay too late ($T_d \ll T_{ew}$): sphalerons not active
⇒ no baryon asymmetry generated

Allowed parameter space: $m_s \sim O(\text{TeV})$, $\Gamma_s \sim (10^{-16} - 10^{-13})$ GeV

Outlook

Summary

- **Baryogenesis through Flavon Decay:**
  - Flavons: ingredient exists already in flavor models a la Froggatt-Nielsen
  - Flavons in early Universe:
    - decay produces left-right asymmetry in lepton sector
      - sphalerons convert left-handed part of the asymmetry
    - dominate Universe before the EW scale
      - increasing Hubble rate
      - preventing right-handed electron equilibration
    - can work for both Dirac and Majorana neutrinos (c.f. Dirac leptogenesis)
    - possible gravity wave background F. d'Eramo, K. Schmitz (2019)

Backup Slides

Dirac Leptogenesis

Dick, Lindner, Ratz, Wright, 2000;
Murayama, Pierce, 2002; ...

- Leptogenesis possible when neutrinos are Dirac particles
- small Dirac mass through suppressed Yukawa coupling
- Characteristics of Sphaleron effects:
  - only left-handed fields couple to sphalerons
  - sphalerons change (B+L) but not (B-L)
  - sphaleron effects in equilibrium for T > Tew
- If L stored in RH fermions can survive below EW phase transition, net lepton number can be generated even with L=0 initially
- for SM quarks and leptons: rapid left-right equilibration through large Yukawa
  - LH: (B+L) ← RH: (B+L)

no net asymmetry
if B = L = 0 initially

Dirac Leptogenesis

- LR equilibration for neutrinos:
  - neutrino Yukawa coupling $\lambda \bar{\ell}_L H \nu_R$
  - rate for conversion $\Gamma_{LR} \sim \lambda^2 T$
  - for LR conversion not to be in equilibrium

$$\Gamma_{LR} \lesssim H \ , \quad \text{for} \quad T > T_{eq} \qquad\qquad H \sim \frac{T^2}{M_{\rm Pl}}$$

  - Thus LR equilibration can occur at much later time

$$T \ \lesssim \ T_{eq} \ll T_{EW} \qquad \Rightarrow \qquad \lambda^2 \lesssim \frac{T_{eq}}{M_{\rm Pl}} \ll \frac{T_{EW}}{M_{\rm Pl}}$$

$$M_{\rm Pl} \sim 10^{19} \ \text{GeV} \qquad T_{EW} \sim 10^2 \ \text{GeV} \qquad \lambda < 10^{-(8\sim9)}$$

$$m_D < 10 \ \text{keV}$$

Dirac Leptogenesis

Dick, Lindner, Ratz, Wright, 2000