ELTE EÖTVÖS LORÁND UNIVERSITY

Thermal Leptogenesis

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Zimányi School, 6th of December 2024.

The Standard Models

Particle physics

- Quantum Field Theory (QFT)
- $\mathbf{G_{SM}} = \mathrm{SU(3)_c \times SU(2)_L \times U(1)_Y}$
- Particle content:
  - Quarks
  - Charged leptons
  - Neutrinos
  - Higgs boson
  - Gauge bosons

Cosmology

- **ΛCDM**: FLRW + SM + BSM
- General relativity (background)
- QFT (particle processes)

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- Energy content of Universe (Ω_i):
  - Relativistic matter ($\gamma + \nu$)
  - Non-relativistic matter (Baryonic matter + DM)
  - Dark energy (~~vacuum,~~ ???)

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Why is this not vanishing?

Matter-antimatter asymmetry – Sakharov conditions

- Assumption: Baryon asymmetry generated and not pre-inflation relic

Through some B -violating processes

Inflation: Exponential dilution

Matter-antimatter asymmetry – Sakharov conditions

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- Sakharov conditions: requirements for successful generation of asymmetry [A.D. Sakharov, 1967]

    1. Baryon number violation
    2. C and CP violation
    3. Deviation from equilibrium

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1. Baryon number violation: sphaleron process
2. C and CP violation: CP violation in the CKM matrix
3. Deviation from equilibrium: Phase transitions

Electroweak baryogenesis possible?

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1. Baryon number violation: sphaleron process — This is OK
2. ~~C and CP violation: CP violation in the CKM matrix~~ — Not enough
3. ~~Deviation from equilibrium: Phase transitions~~ — Not strong

~~Electroweak baryogenesis possible?~~

* *(It can still be fixed with a bit of tinkering...)*

Matter-antimatter asymmetry – Leptogenesis

- Idea: Generate ΔL instead of ΔB → Use sphaleron processes to convert

Through lepton number violating decays of HNLs

Sphalerons violate $\Delta B + \Delta L$ but they conserve $\Delta B - \Delta L$

Matter-antimatter asymmetry – Leptogenesis

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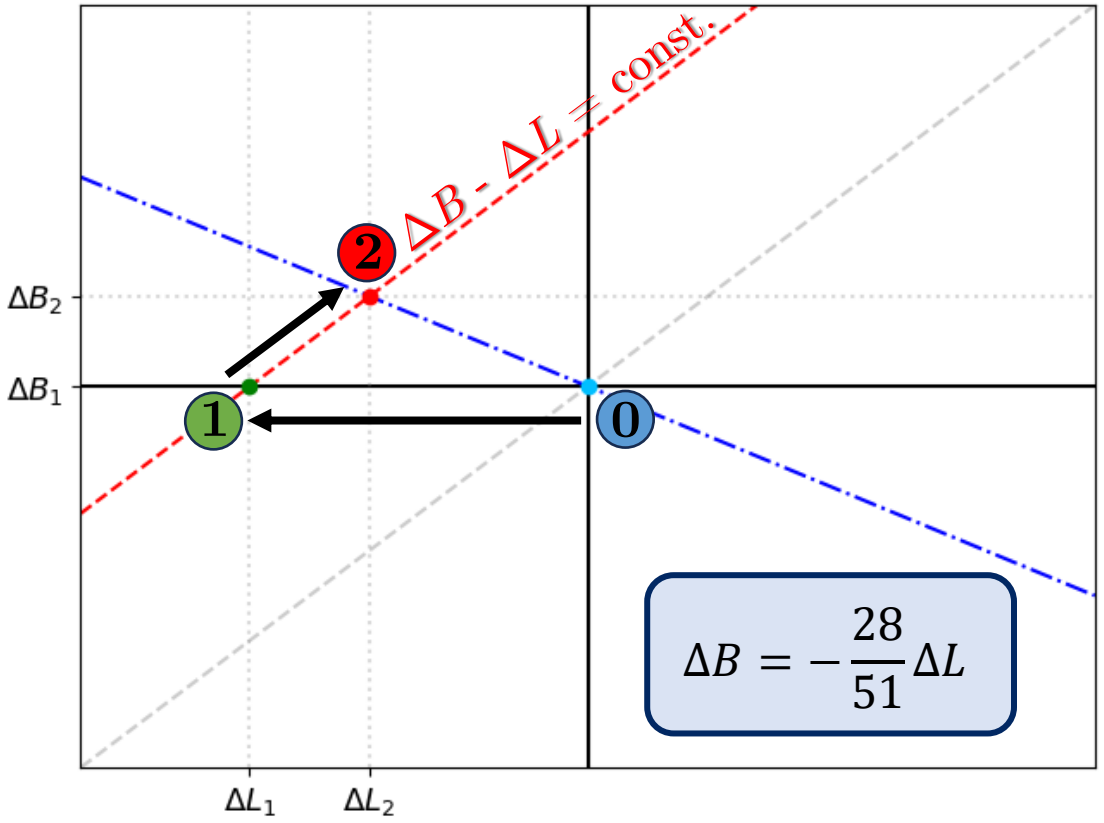

0 Symmetric state

↓ HNL decays (CP ≠ 0)

1 $\Delta L \neq 0,\ \Delta B = 0$

↓ Sphaleron conversion

2 $\Delta L \neq 0,\ \Delta B \neq 0$

[J.A. Harvey and M.S. Turner, 1990.]

Matter-antimatter asymmetry – Sakharov conditions again

- Baryon asymmetry via leptogenesis
- Sakharov conditions:

1. Baryon number violation → sphaleron process — This is OK
2. C and CP violation → CP violation in HNL decays — This is OK
3. Deviation from equilibrium → HNL decays — This is OK

SM+HNL=leptogenesis

Matter-antimatter asymmetry – CP violation

CP violation in vacuum decays vs. in a thermal plasma

$$\epsilon_0 = \frac{\Gamma(N_i \to \phi + L) - \Gamma(N_i \to \phi^\dagger + \bar{L})}{\Gamma(N_i \to \phi + L) + \Gamma(N_i \to \phi^\dagger + \bar{L})} \longrightarrow \epsilon_T = \frac{\gamma(N_i \to \phi + L) - \gamma(N_i \to \phi^\dagger + \bar{L})}{\gamma(N_i \to \phi + L) + \gamma(N_i \to \phi^\dagger + \bar{L})}$$

Thermal decay rate

Matter-antimatter asymmetry – CP violation

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Thermal decay rate

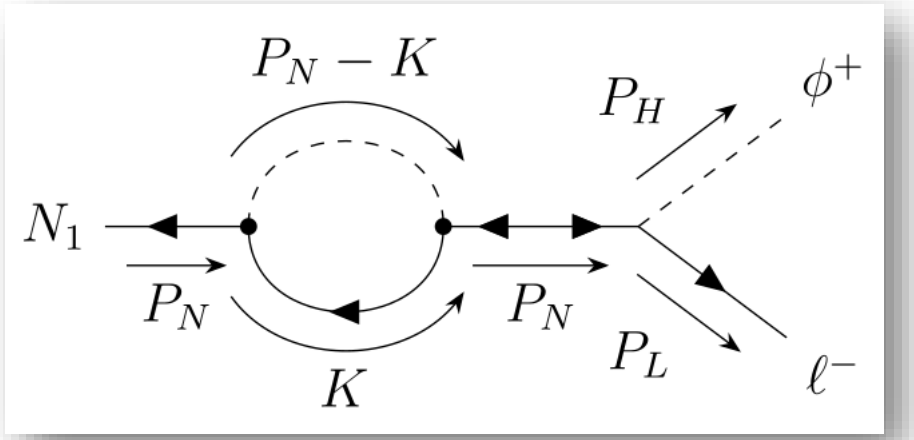
$$\epsilon_T \propto \mathrm{Im}\mathcal{M}^{T,\ (n-\mathrm{loop})}_{N_i \to \phi + L}$$

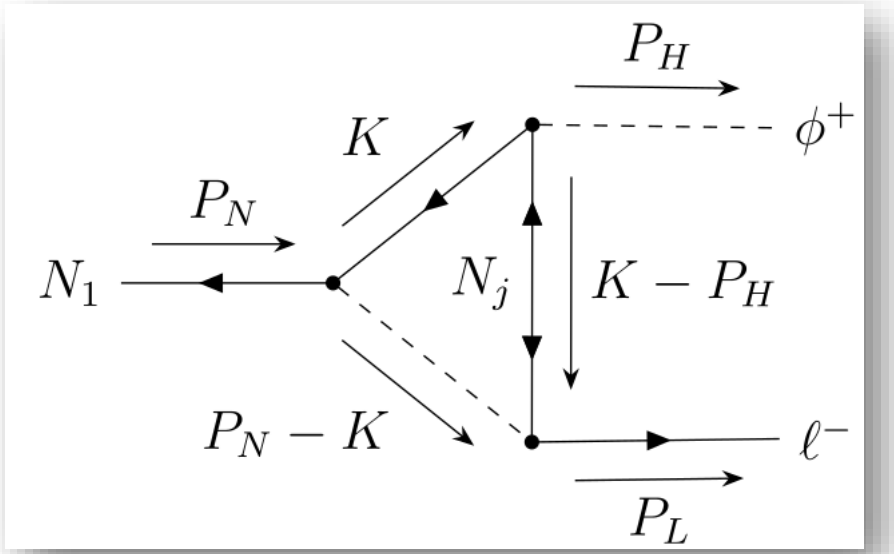
Thermal amplitude!
≠
Vacuum amplitude

Matter-antimatter asymmetry – CP violation

CP violation proportional to the imaginary part of HNL decay diagrams:

Finite temperature cutting rules!





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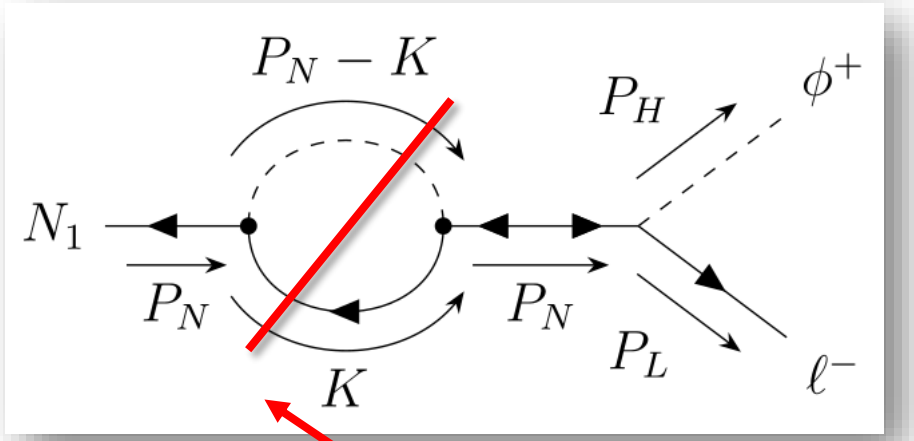

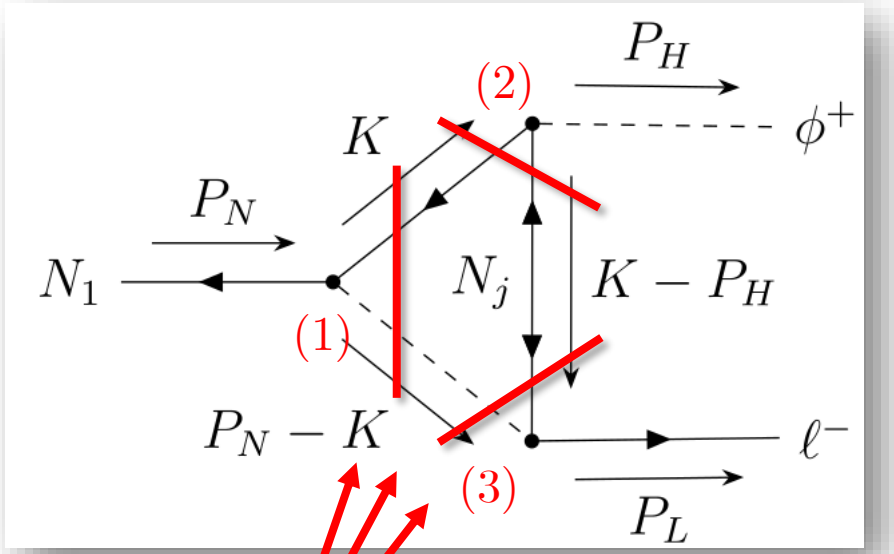

Cut propagators = On-shell

Matter-antimatter asymmetry – CP violation

[K.Seller, Zs.Szép, Z.Trócsányi, 2024.]

$$\int_{K_1} \mathfrak{Im}\tilde{V}_{\mathrm{R;RR}}\big(\{P_N, P_L\}, K_1\big) = -2\pi^2 \int \frac{\mathrm{d}^4 K_1}{(2\pi)^4} \Bigg\{$$

$$\mathrm{sgn}(k_1^0)\mathrm{sgn}(k_2^0)\mathcal{P}\frac{1}{K_3^2 - \overline{m}_{N_j}^2}\delta(K_1^2 - \overline{m}_L^2)\delta(K_2^2 - \overline{m}_\phi^2)\big[f_{\mathrm{F}}(k_1^0) + f_{\mathrm{B}}(k_2^0)\big] \qquad (1)$$

$$+\mathrm{sgn}(k_1^0)\mathrm{sgn}(k_3^0)\mathcal{P}\frac{1}{K_2^2 - \overline{m}_\phi^2}\delta(K_1^2 - \overline{m}_L^2)\delta(K_3^2 - \overline{m}_{N_j}^2)\big[f_{\mathrm{F}}(k_1^0) - f_{\mathrm{F}}(k_3^0)\big] \qquad (2)$$

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Something like this...

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Finite at T=0

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Something like this...

Vanishing at T=0

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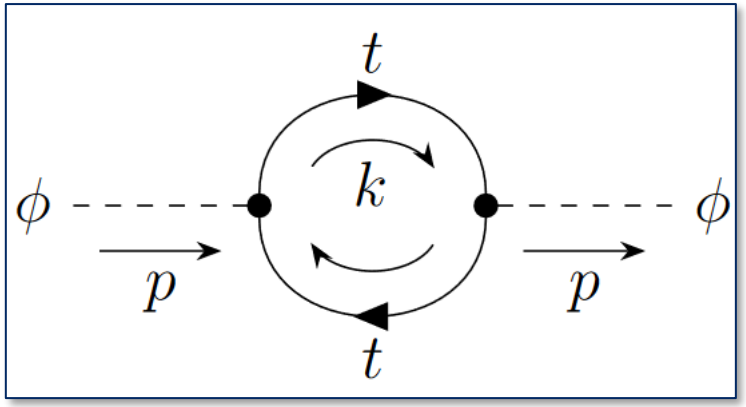
Something like this...

Lorentz invariance violation!

Matter-antimatter asymmetry – Thermal masses

- Universe filled with hot and rapidly interacting plasma
- Particles traversing the plasma get screened due to interactions
  - Particles gain an effective "thermal mass"
- Thermal mass proportional to coupling and temperature $M_{\mathrm{T}} \propto gT$
- Calculated from self energy diagrams in finite T field theory, *e.g.* :



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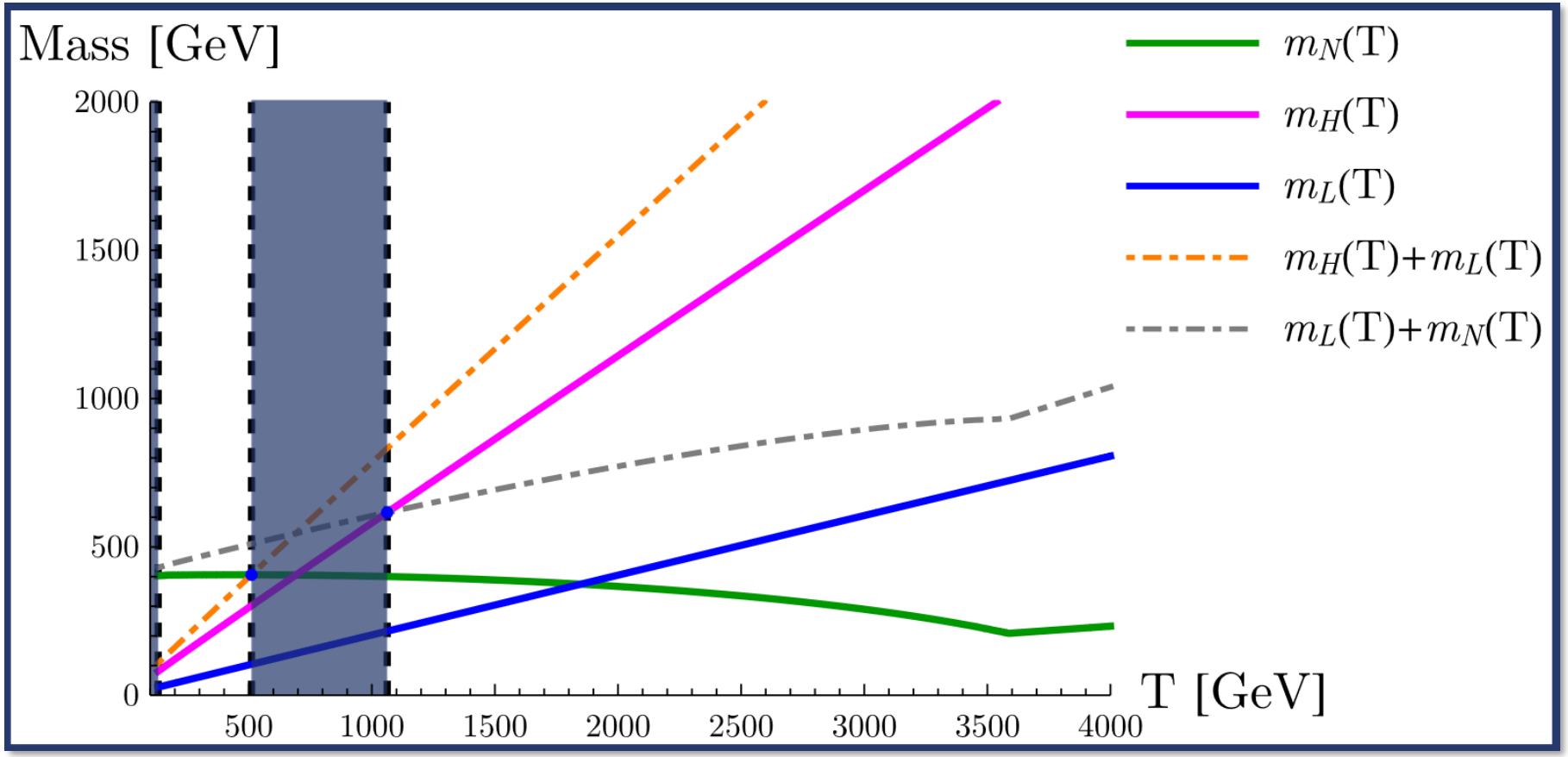

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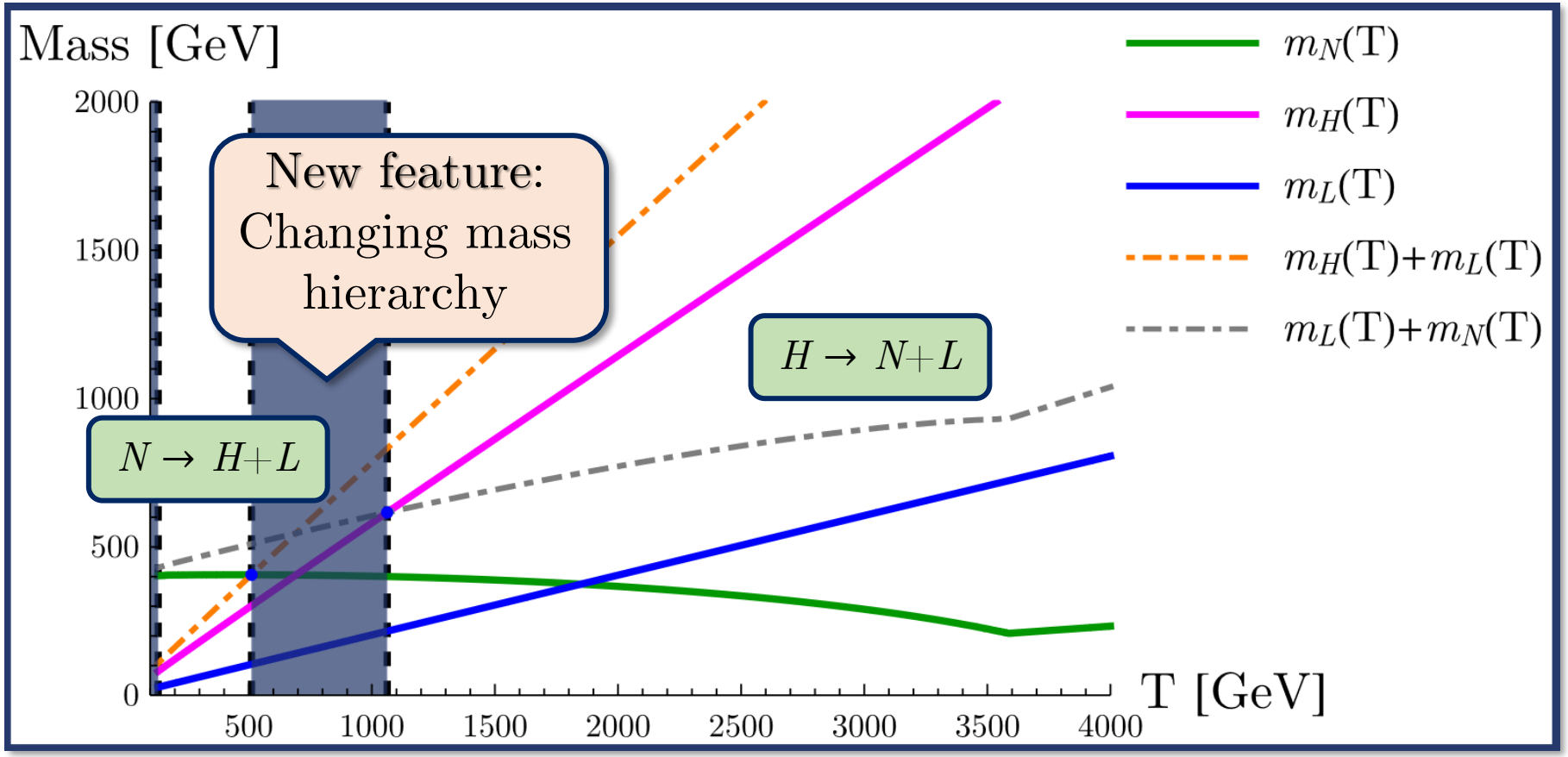

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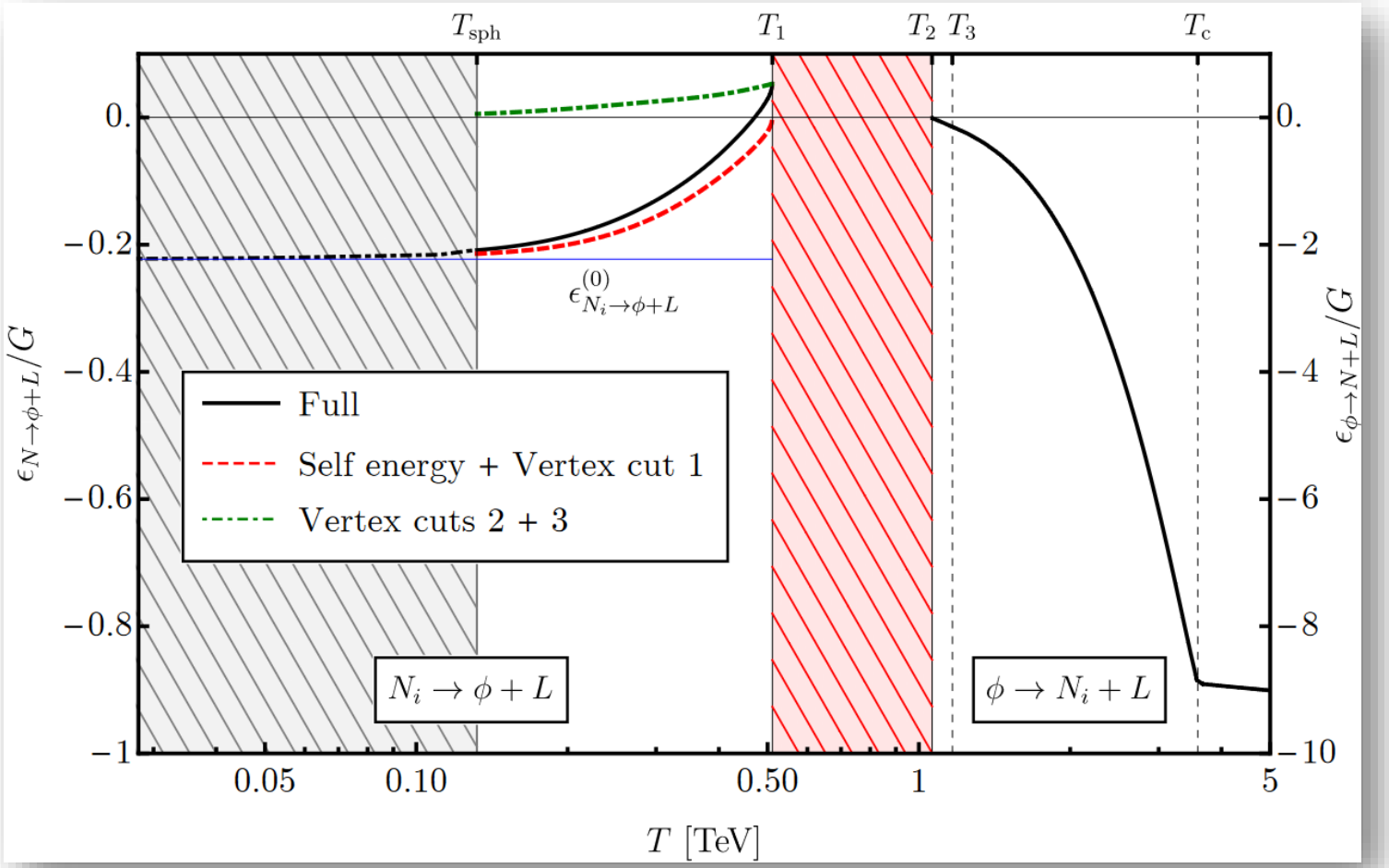

Matter-antimatter asymmetry – Boltzmann equations

Calculate the particle abundance in the expanding Universe in the presence of number changing particle interactions

1. HNLs out of equilibrium (Sakharov III.)
2. ΔL generated by out of equilibrium decays of HNLs

1. ∂_t(HNL abundance) = (HNL producing reactions)
2. $\partial_t(\Delta L$ abundance) = ε (HNL decay rate) – (ΔL washout by scatterings)

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$$sHz\frac{\mathrm{d}\mathcal{Y}_{\Delta\mathrm{L}}}{\mathrm{d}z} \simeq \gamma_{\mathrm{D}}\left[\epsilon\left(\frac{\mathcal{Y}_N}{\mathcal{Y}_N^{\mathrm{eq}}}-1\right)-\frac{\mathcal{Y}_{\Delta\mathrm{L}}}{\mathcal{Y}_\ell^{\mathrm{eq}}}\right]-\frac{\mathcal{Y}_{\Delta\mathrm{L}}}{\mathcal{Y}_\ell^{\mathrm{eq}}}\left[2\gamma_{N,s}^{\mathrm{sub.}}+4\gamma_{N,t}+\gamma_{\phi,s}\frac{\mathcal{Y}_N}{\mathcal{Y}_N^{\mathrm{eq}}}+2\gamma_{\phi,t}\right]$$

washout

$$sHz\frac{\mathrm{d}\mathcal{Y}_N}{\mathrm{d}z} \simeq \left(1-\frac{\mathcal{Y}_N}{\mathcal{Y}_N^{\mathrm{eq}}}\right)\left(\gamma_\chi+\gamma_{\mathrm{D}}+2\gamma_{\phi,s}+4\gamma_{\phi,t}\right)$$

Summary

- Cosmology necessarily involves BSM physics
- Particle physics sees (almost?) nothing while cosmology needs vast quantities of unknown matter/energy
- Advancements in experimental techniques allow us to probe the Universe closer and closer to the very beginning
- Leptogenesis easily/naturally solvable by particle physics
    - Adding RHNs to SM can basically solve everything (neutrino mass/DM/B)

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