Non-relativistic Majorana neutrinos in a thermal bath and leptogenesis

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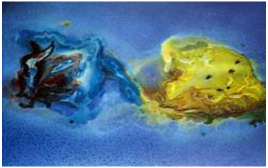


Outline

1. Motivation and introduction
2. Neutrino thermal width
3. CP asymmetry at finite temperature
4. Conclusions

Baryon asymmetry and leptogenesis

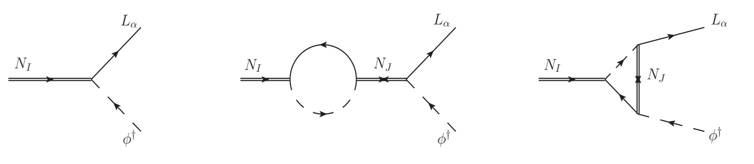
Baryon asymmetry in the Universe

- our universe is strongly matter-antimatter asymmetric

$$\eta_B = \frac{n_{\mathrm{B}} - n_{\bar{\mathrm{B}}}}{n_\gamma} = (6.20 \pm 0.15) \times 10^{-10}$$

[*WMAP collaboration (2011)*]

- within SM: $\eta_B \sim 10^{-18}$
- Baryogenesis via Leptogenesis: $\Delta L \to \Delta B$ [*M. Fukugida and T. Yanagida (1986)*]



- Three Sakarov conditions: $\Delta L \neq 0$, C and CP violation, out-of-equilibrium
- Massive Majorana neutrinos play the relevant role

Strong Wash-out

Decay parameter for the wash-out

$$K = \frac{\Gamma_1^{(T=0)}}{H(T=M_1)} = \frac{M_1 \left(F^\dagger F\right)_{11}}{8\pi 1.66 \sqrt{g^*}\frac{M_1^2}{M_{Pl}}} = \frac{\tilde{m}_1}{m_*}$$

where we may define

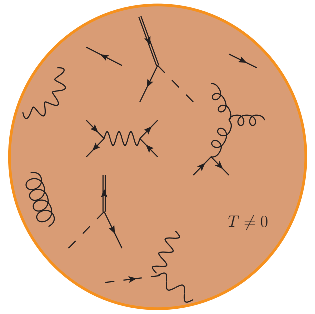
- $\tilde{m} = \left(F^\dagger F\right)_{11} \frac{v^2}{M_1}$, effective neutrino mass
- $m_* = 8\pi\, 1.66 \sqrt{g^*}\frac{v^2}{M_{Pl}} \simeq 1.1 \times 10^{-3}$ eV [*E. Nardi, Y. Nir and S. Davidson*]

- Because $\tilde{m} \simeq m_{\rm sol} = \sqrt{\Delta m^2_{\rm sol}} \simeq 9 \times 10^{-3} \Rightarrow K > 1$

1) Majorana neutrinos is coupled until $T \ll M_1$
2) The final lepton asymmetry is produced in a non-relativistic regime

Non-relativistic neutrinos in medium

Interaction at $T \neq 0$



1) Thermal production rate

A. Salvio, P. Lodone and A. Strumia (2011)
M. Laine and Y. Schroder (2012)

$$\Gamma^{(T=0)} \to \Gamma(T)$$

1) CP asymmetry at finite T

M. Garny, A. Hohenegger and A. Kartavtsev (2010)

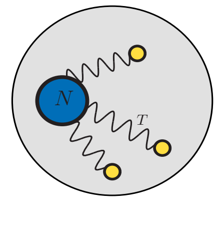
$$\epsilon = \frac{\Gamma_\ell - \Gamma_{\bar{\ell}}}{\Gamma_\ell + \Gamma_{\bar{\ell}}} \to \epsilon(T)$$

Calculations at finite temperature are difficult and tricky

However...

- the hierarchy of scales $M \gg T$ has been not fully exploited
- we want to provide an effective field theory (EFT) approach

Heavy Majorana neutrinos



$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}\bar{\psi}\left(i\partial\!\!\!/ - M\right)\psi - F_f \bar{L}_f \tilde{\phi} P_R \psi - F_f \bar{\psi} P_L \tilde{\phi}^\dagger L_f$$

- $p^\mu = M v^\mu + k^\mu$ with $|k| \sim T \ll M$
- What are the low-energy degrees of freedom? What is the $\mathcal{L}_{\rm EFT}$?

- In a reference frame where the heavy particle is at rest up to to $k \ll M$

$$\mathcal{L}_{\rm EFT} = N^\dagger i\partial_0 N + \sum_i c_n\left(\frac{\mu}{M}\right)\frac{\mathcal{O}(\mu, T)_n}{M^{d_n - 4}} + \mathcal{L}_{light}$$

Observations

- In the heavy particle sector: expansion in 1/M
- Contribution of higher order operators are counted in power of T/M
- The Wilson coefficients may be computed setting T=0, in vacuum

EFT at work: matching

Matching computation at T=0

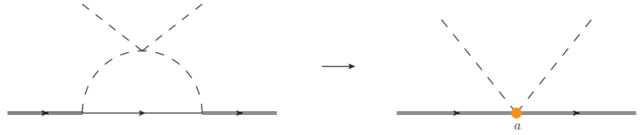
1) The low-energy Lagrangian is organized as follows:

$$\mathcal{L}_{\mathrm{EFT}} = N^{\dagger}\left(i\partial_0 - i\frac{\Gamma_0}{2}\right)N + \frac{\mathcal{L}^{(1)}}{M} + \frac{\mathcal{L}^{(2)}}{M^2} + \frac{\mathcal{L}^{(3)}}{M^3} + \mathcal{O}\left(\frac{1}{M^4}\right)$$

2) By dimensional analysis the thermal corrections scale as

$$\delta\Gamma_{(1)} \propto \frac{T^2}{M}\,, \quad \delta\Gamma_{(2)} \propto \frac{T^3}{M^2}\,, \quad \delta\Gamma_{(3)} \propto \frac{T^4}{M^3}$$

- By symmetry, the leading dimension 5 operator is: $\mathcal{L}^{(1)} = aN^{\dagger}N\phi^{\dagger}\phi$



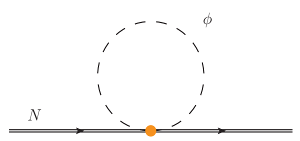
EFT at Work: thermal width

- In the $v^\mu = (1, \vec{0})$ frame, the Majorana neutrino propagator has the form

$$\left(\frac{1+\gamma_0}{2}\right)^{\alpha\beta} \frac{iZ}{k^0 - E + i\Gamma/2} = \left(\frac{1+\gamma_0}{2}\right)^{\alpha\beta} Z \left[\frac{i}{k^0 + i\epsilon} - \left(iE + \frac{\Gamma}{2}\right)\left(\frac{i}{k^0 + i\epsilon}\right)^2 + \cdots\right]$$

Thermal width in the EFT

- The self-energy diagram we can build is a tadpole in the EFT



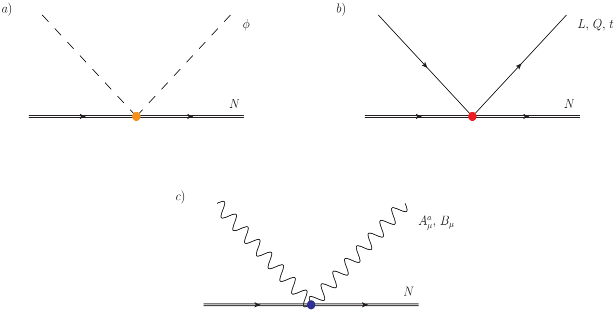
$$\Gamma_\phi = 2\frac{\mathrm{Im}\, a}{M}\langle \phi^\dagger(0)\phi(0)\rangle_T = -\frac{\lambda |F|^2 M}{8\pi}\left(\frac{T}{M}\right)^2$$

- Higgs propagator in the Real Time Formalism (RTF)

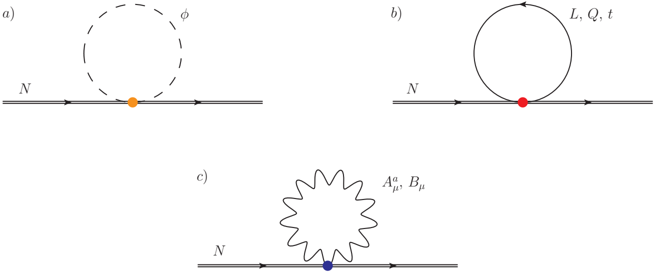
$$i\Delta_{11}(x-y) = \int \frac{d^4k}{(2\pi)^4}\left[\frac{i}{k^2 + i\epsilon} + (2\pi) n_B(|k_0|)\delta(k^2)\right] e^{-ik\cdot(x-y)}$$

Sub-leading operators

- Higher order operators in the effective Lagrangian
- Higgs, fermions (quarks and leptons) and gauge bosons effective vertices



- Thermal tadpoles induced by the sub-leading operators



EFT for Majorana fermions works:

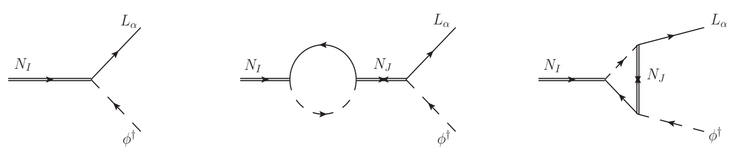
$$\Gamma_T = \frac{|F|^2 M}{8\pi}\left\{-\lambda\left(\frac{T}{M}\right)^2 - \frac{\pi^2}{80}\left(\frac{T}{M}\right)^4 (3g^2+g'^2) - \frac{7\pi^2}{60}\left(\frac{T}{M}\right)^4 |\lambda_t|^2 + \mathcal{O}\left(\frac{T}{M}\right)^6\right\}$$

M. Laine and Y. Schroeder (2012)

CP asymmetry

- Thermal corrections to the CP asymmetry defined as follows

$$\epsilon = \sum_{I,f} \frac{\Gamma(N_I \to \ell_f) - \Gamma(N_I \to \bar{\ell}_f)}{\Gamma(N_I \to \ell_f) + \Gamma(N_I \to \bar{\ell}_f)} \Rightarrow \boxed{\eta_B \sim \epsilon}$$



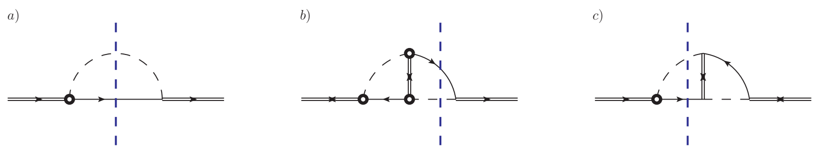
1) We consider two Majorana neutrinos N_1 and N_2, $\epsilon \sim \mathrm{Im}\left[(\mathrm{F}_1 \mathrm{F}_2^*)^2\right]$

$$M_1 \ll M_2$$

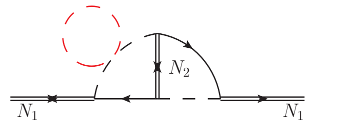
2) We focus on the direct CP asymmetry (vertex diagram)

At T=0, in vacuum already two loops

- Diagrams relevant for the direct asymmetry: $\epsilon_0 = -\frac{\mathrm{Im}\left[(F_1 F_2^*)^2\right]}{16\pi |F_1|^2} \left(\frac{M_1}{M_2}\right) + \cdots$



In medium thermal particles enter the game



- three loops at finite temperature

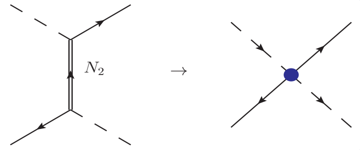
  $\rightarrow$ **very hard task**

- there are hierarchies of scales!

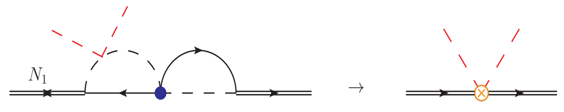
  $M_2 \gg M_1 \gg T$

We can use the EFT approach

1) Integrate out the energy modes of order M_2



2) Integrate out the energy modes of order M_1



Result:

$$\epsilon_T = -\frac{\mathrm{Im}\left[(F_1F_2^*)^2\right]}{16\pi|F_1|^2}\frac{3\,\lambda}{2}\left(\frac{M_1}{M_2}\right)\left(\frac{T}{M_1}\right)^2 + \cdots$$

Conclusions

- Non-relativistic regime may be relevant for leptogenesis
- Interactions occur in medium

- Formulation of an EFT to deal with Majorana neutrinos in medium
- Test the EFT: neutrino thermal width up to $\mathcal{O}\left(\frac{T}{M}\right)^4$

  2-loops ($T \neq 0$) $\rightarrow$ 1-loop (T=0) + 1-loop (thermal tadpoles)

- Address the CP asymmetry in the EFT formalism
- Matching calculation (cutting rules at $T = 0$) and thermal tadpoles ($T \neq 0$)
- In the non-relativistic regime thermal corrections are under control
- To do list: self-energy diagram, resonant case $M_1 \simeq M_2$