Lee-Wick particle spectrum in the early universe

References:

- Phys. Rev. D **77**, 025012 (2008)
- Phys. Lett. B **674**, 330 (2009)
- arXiv:1007.1537 [hep-ph] , (2010)

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- The important point is in this kind of theories there are some unusual kind of fields which arise as partners of the normal Standard model fields.

- The partner fields are unusual in many respects, as these fields may have a negative Lagrangian density, or imaginary coupling constants etc. etc..

  But the most unusual nature, as far as this talk is concerned, is about their thermal properties.

The thermodynamic properties of ultra-relativistic fields

- If a normal bosonic field have one unusual partner then:
- the combined energy density of these ultra-relativistic field and its partner is

$$\rho_b = \frac{gM^2T^2}{24} \, . \qquad \left[\text{Previously} \, , \;\; \rho_b = \frac{g\pi^2 T^4}{30}\right]$$

where g internal degrees of freedom and M is the mass of the partner field.

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- The entropy density

$$s_b = \frac{gM^2T}{12}\,. \quad \left[\text{Previously}\,,\ \ s_b = \frac{4g\pi^2T^4}{30}\right]$$

The thermodynamic properties of ultra-relativistic fields

- If a normal fermionic field have more than one unusual partner then the total energy density becomes negative, a feature still not well understood in Chiral theories. But if there are precisely one Lee-Wick partner then:
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$$\rho_f = \frac{gM^2T^2}{48} \, . \qquad \left[\text{Previously} \, , \;\; \rho_f = \frac{7}{8}\frac{g\pi^2T^4}{30}\right]$$

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$$s_f = \frac{gM^2T}{24} . \quad \left[\text{Previously} , \ \ s_f = \frac{7g\pi^2 T^3}{180} \right]$$

The overall thermodynamic properties

The net energy density and entropy density of a system of ultrarelativistic normal bosons and their partners with mass M_i are:

- Overall Energy Density:

$$\rho = \frac{T^2}{24}\left[\sum_i g_i M_i^2 \left(\frac{T_i}{T}\right)^2 + \frac{1}{2}\sum_i g_i M_i^2 \left(\frac{T_i}{T}\right)^2\right]$$

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- Overall Entropy density:

$$s = \frac{\tilde{M}^2}{12}\tilde{g}_{*s} T \quad \left[\text{Previously}\,, \;\; s = \frac{2\pi^2}{45} g_{*s} T^3\right]$$

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The effective degrees of freedom

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$$\tilde{g}_* = \sum_{i=\text{relv. bosons}} g_i \left(\frac{M_i}{\tilde{M}}\right)^2 \left(\frac{T_i}{T}\right)^2 + \frac{1}{2} \sum_{i=\text{relv. fermions}} g_i \left(\frac{M_i}{\tilde{M}}\right)^2 \left(\frac{T_i}{T}\right)^2$$

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- The values of $\tilde{g}_*$ and $\tilde{g}_{*s}$ are smaller than the corresponding values of g_* and g_{*s} in conventional cosmology.

Temperature time relation during radiation domination

- As in the presence of the regulator fields

$$s = \frac{\tilde{M}^2}{12} \tilde{g}_{*s} T$$

for an isentropic process

$$T(t) = \frac{T_0}{a^3(t)} \qquad \left[\text{Usually} \, , \;\; T(t) = \frac{T_0}{a(t)} \right]$$

$a(t)$ being the FRW scale-factor, T_0 a constant.

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- The last equation yields

$$\left(\frac{\dot{T}}{T}\right) = -3H$$

where

$$H^2 = \frac{8\pi}{3m_{\rm Pl}^2}\rho$$

is the square of the Hubble parameter, $m_{\rm Pl}$ is the Plank mass.

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- As

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- Solving

$$\left(\frac{\dot{T}}{T}\right) = -3H$$

we get

$$t \sim 10^{-24}(\pi\tilde{g}_*)^{1/2}\left(\frac{m_{\mathrm{Pl}}}{\tilde{M}}\right)\left(\frac{1\mathrm{GeV}}{T}\right)\mathrm{sec}\, .$$

Conclusion

- The relation

$$t \sim 10^{-24} (\pi \tilde{g}_*)^{-1/2} \left(\frac{m_{\rm Pl}}{\tilde{M}} \right) \left(\frac{1 {\rm GeV}}{T} \right) {\rm sec}$$

  is different from the temperature-time relation in standard cosmology, where

$$t \sim 10^{-6} g_*^{-1/2} \left(\frac{1 {\rm GeV}}{T} \right)^2 {\rm sec} \, .$$

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- In the very early universe lets assume $g_* \sim 100$ and $\tilde{g}_* \sim 80$ as $\tilde{g}_* < g_*$ and let $\tilde{M} \sim 10^3\,\rm GeV$

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- Then, the GUT scale $T_{\rm GUT} \sim 10^{15}\,{\rm GeV}$ corresponding to $t_{\rm GUT} \sim 10^{-24}\,{\rm sec}$. Where conventional cosmology gives $t_{\rm GUT} \sim 10^{-35}\,{\rm sec}$.

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is different from the temperature-time relation in standard cosmology, where

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- Then, the GUT scale $T_{\rm GUT} \sim 10^{15}\,\rm GeV$ corresponding to $t_{\rm GUT} \sim 10^{-24}\,\rm sec$. Where conventional cosmology gives $t_{\rm GUT} \sim 10^{-35}\,\rm sec$.
- Consequently, the thermodynamics of the regulator fields can slowdown the pace of development of the early universe.

  The regulator fields or the Lee-Wick partners can decay in the early universe giving rise to the conventional thermal history, later.