EFFECT of PRIMORDIAL MAGNETIC FIELDS on the INFLATON DECAY PROCESS

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PRIMORDIAL MAGNETIC FIELDS

Magnetic fields have a widespread presence in the universe, at all scales.

Their origin is currently unknown, they can be either primordial or associated to structure formation

They have been observed up to galaxy clusters and superclusters and there is indirect evidence, from gamma-ray observations of blazars, of an intergalactic magnetic field with a lower bound

$$B \approx 10^{-16} - 10^{-15}\,\mathrm{Gauss}$$

WARM INFLATION

A model for inflation where (quasi) thermal equilibrium is maintained, with no need of a large scale reheating. It requires a dissipative component of sufficient size (Berera & Fang, 1995; Berera, 1995).

$$\ddot{\phi} + \left(3H + \Upsilon\right)\dot{\phi} + V_{T,\phi} = 0$$

Starting from the finite temperature one-loop Coleman-Weinberg potential for SU(5), they find a slow-roll solution for unexceptional values of the coupling constant.

WARM INFLATION

Particle models with global SUSY, with dissipative effects of particle production

In a two stage "reheating" process:

$$\phi \to \chi \to \tilde{y}\ \tilde{y}$$

heavy boson (χ) — light fermions ($\tilde{y}$)

the radiative corrections to the inflaton potential are small due to fermion-boson cancellation and thermal contribution to the inflaton mass from heavy sector loops are Boltzmann suppressed

The flatness of the (new inflation type) potential is not spoiled

(Hall and Moss, 2004)

WARM INFLATION

Assumptions

- One superfield is coupled to the inflaton (becomes very heavy) and the other one has a vanishing coupling (light sector)
- Soft SUSY breaking in the heavy sector
- Light radiation thermalises

WARM INFLATION

$$\mathcal{L}_S = g^2 \left| \Lambda^2 - |\chi|^2 \right|^2 + 4g^2 |\varphi|^2 |\chi|^2 + 4h^2 |y|^2 |\chi|^2 + h^2 |y|^4 + 2gh\left(y^2 \varphi^\dagger \chi^\dagger + y^{\dagger 2} \varphi\chi\right)$$

with $\phi = \sqrt{2}\,\mathrm{Re}\,\varphi$

$$\mathcal{L}_f = \mathrm{g}\left(\varphi\,\overline{\psi}_\chi\, \mathrm{P_L}\, \psi_\chi + \varphi^\dagger\, \overline{\psi}_\chi\, \mathrm{P_R}\, \psi_\chi\right) + \mathrm{h}\left(\chi\, \overline{\psi}_y\, \mathrm{P_L}\, \psi_y + \chi^\dagger\, \overline{\psi}_y\, \mathrm{P_R}\, \psi_y\right) + 2\mathrm{g}\left(\chi\, \overline{\psi}_\chi\, \mathrm{P_L}\, \psi_\varphi + \chi^\dagger\, \overline{\psi}_\chi\, \mathrm{P_R}\, \psi_\varphi\right) + 2\mathrm{h}\left(y\, \overline{\psi}_y\, \mathrm{P_L}\, \psi_\chi + y^\dagger\, \overline{\psi}_y\, \mathrm{P_R}\, \psi_\chi\right)$$

Feynman diagrams.

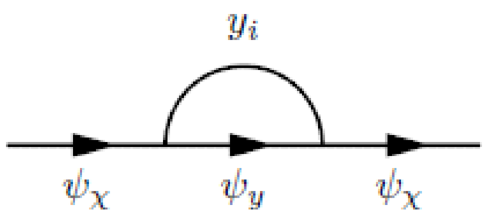
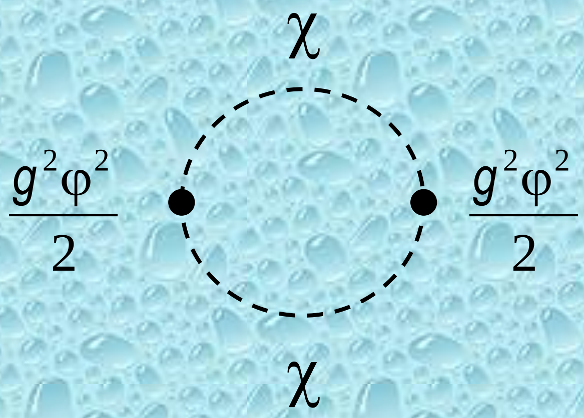
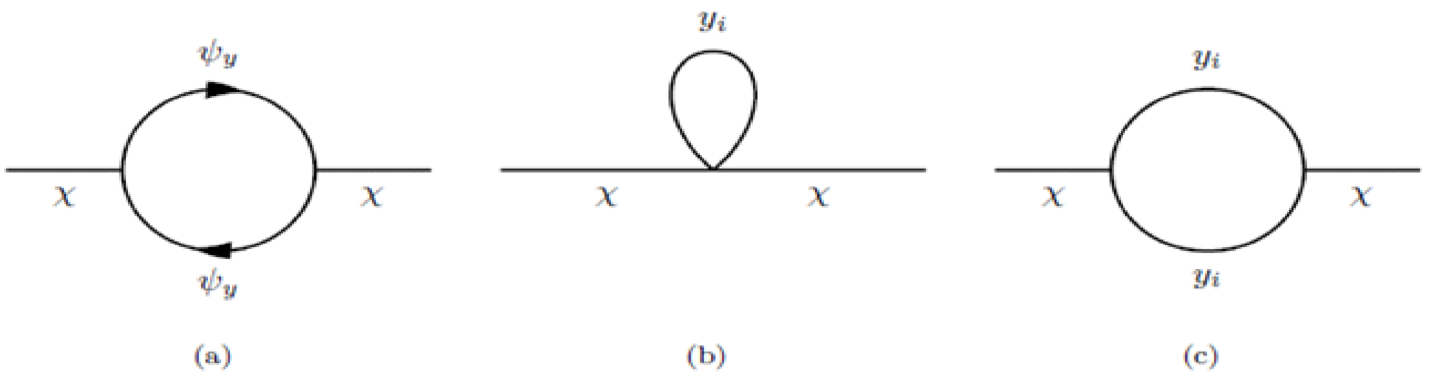


Diagram for the fermionic self energy





Diagrams for the bosonic self energy

THERMAL CONTRIBUTION

Self energies, in the HTL limit:

$$\Sigma(P) = -4h^2 T \sum_n \int \frac{d^3k}{(2\pi)^3} (\not{K} - \not{P}) \Delta(K) \tilde{\Delta}(P - K)$$

where $\Delta(K) \approx K^{-2}$, $k^0 = 2n\pi T$ for bosons and $k^0 = (2n+1)\pi T$ for fermions (denoted by a tilde)

$$m_f^2 \equiv \Sigma \approx \frac{h^2 T^2}{2}$$

$$\Pi(P)_a = h^2 T \sum_n \int \frac{d^3k}{(2\pi)^3} Tr[\not{K}(\not{K} - \not{P})] \tilde{\Delta}(K) \tilde{\Delta}(K - P)$$

$$\Pi(P)_a = -4h^2 T \sum_n \int \frac{d^3k}{(2\pi)^3} K^2 \tilde{\Delta}(K) \tilde{\Delta}(K - P) \approx \frac{1}{6} h^2 T^2$$

THERMAL CONTRIBUTION

$$\Pi\left(P\right)_b = 4h^2T\sum_n \int \frac{d^3k}{\left(2\pi\right)^3}\Delta\left(K\right) \approx \frac{1}{3}h^2T^2$$

$$\Pi\left(P\right)_c = 4g^2\phi^2T\sum_n \int \frac{d^3k}{\left(2\pi\right)^3}\Delta\left(K\right)\Delta\left(K-P\right) \approx \frac{1}{2\pi^2}g^2h^2\phi^2\log\frac{T^2}{p^2}$$

$$m_b^2 \equiv \Pi_a + \Pi_b \approx \frac{h^2T^2}{2}$$

MAGNETIC CONTRIBUTION

Propagators with magnetic fields, with
Schwinger's proper time method:

$$iD_B(\kappa) = \int_0^\infty \frac{ds}{\cos eBs} \times \exp\left\{ is\left(\kappa_\parallel^2 - \kappa_\perp^2 \frac{\tan eBs}{eBs} - m_b^2 + i\varepsilon \right)\right\}$$

$$iS_B(\kappa) = \int_0^\infty \frac{ds}{\cos eBs} \times \exp\left\{ is\left(\kappa_\parallel^2 - \kappa_\perp^2 \frac{\tan eBs}{eBs} - m_f^2 + i\varepsilon \right)\right\}$$

$$\times \left[\left(m_f + \not\kappa_\parallel \right) e^{ieBs\sigma_3} - \frac{\not\kappa_\perp}{\cos eBs} \right]$$

MAGNETIC CONTRIBUTION

We work with a constant magnetic field along the z axis, so $k_{||}^2=k_0^2-k_3^2$, $k_\perp^2=k_1^2+k_2^2$ and with the hierarchy of scales:

$$eB << m^2 << T^2$$

where *m* is the mass of the fields inside the loop.

MAGNETIC CONTRIBUTION

Landau levels:

$$iD_B(\kappa) = 2i\sum_{l=0}^{\infty} \frac{(-1)^l L_l\left(\frac{2\kappa_\perp^2}{eB}\right) e^{-\frac{\kappa_\perp^2}{eB}}}{\kappa_\parallel^2 - (2l+1)eB - m_b^2 + i\varepsilon}$$

$$iS_B(\kappa) = i\sum_{l=0}^{\infty} \frac{d_l\left(\frac{\kappa_\perp^2}{eB}\right) D + d_l^{'}\left(\frac{\kappa_\perp^2}{eB}\right) \overline{D}}{\kappa_\parallel^2 - 2leB - m_f^2 + i\varepsilon} + \frac{\not{\kappa}_\perp}{\kappa_\perp^2}$$

MAGNETIC CONTRIBUTION

Landau levels:

$$D = \left(m_f + \not\kappa_\parallel\right) + \not\kappa_\perp \frac{m_f^2 - \kappa_\parallel^2}{\kappa_\perp^2} \qquad \overline{D} = \gamma_5 \not u \not b \left(m_f + \not\kappa_\parallel\right)$$

$$d_l(\alpha) \equiv (-1)^n e^{-\alpha} L_l^{-1}(2\alpha), d_n' \equiv \partial d_n / \partial\alpha$$

$$D_B(k) = \frac{i}{k^2 - m_b^2} - (eB)^2 \left(\frac{i}{(k^2 - m_b^2)^2} + \frac{2ik_\perp^2}{(k^2 - m_b^2)^4} \right)$$

MAGNETIC CONTRIBUTION

Landau levels:

$$S_B(k) = \frac{\not{k} + m_f}{\not{k}^2 - m_f^2} + \frac{\gamma_5 \not{u} \not{b} \left(k_{||} + m_f\right)(eB)}{\left(k^2 - m_f^2\right)^3}$$

$$- \frac{2(eB)^2 k_\perp^2}{\left(k^2 - m_f^2\right)^4} \left(m_f + \not{k}_{||} + \not{k}_\perp \frac{m_f^2 - k_{||}^2}{k_\perp^2} \right)$$

MAGNETIC CONTRIBUTION

$$m_b^2 = \frac{h^2T^2}{2}\left(1-\frac{2m_y}{T}-\frac{1}{2\pi^2T^2}\left(\ln\left(\frac{m_y^2}{(4\pi T)^2}\right)+2\gamma_E-1\right)-\frac{(eB)^2}{12\pi m_y^3 T}\right)$$

$$m_f^2 = \frac{h^2T^2}{2}\left(1-\frac{2m_y}{T}-\frac{m_y^2}{2\pi^2T^2}\left(\ln\left(\frac{m_y^2}{(4\pi T)^2}\right)+2\gamma_E-1\right)-\frac{1}{3}\frac{r(eB)}{\pi m_y T}+\frac{11}{12\pi}\frac{(eB)^2}{m_y^3 T}\right)$$

Where r = ± 1 represents the two possible spin orientations w/r to the magnetic field

EFFECTIVE POTENTIAL

$$V_\chi = \int \frac{d^4 P}{(2\pi)^4} \ln \det\left(D^{-1}\right) - \int \frac{d^4 P}{(2\pi)^4} \ln \det\left(S^{-1} S^{*-1}\right)^{-1/2}$$

$$iS^{-1} = \not{P} - m_{\Psi_\chi}^2 \qquad D^{-1} = P^2 + m_\chi^2$$

$$m_\chi^2 = 2g^2\phi^2 + m_b^2(T,B) + M_S^2$$

$$m_{\Psi_\chi}^2 = 2g^2\phi^2 + m_f^2(T,B)$$

EFFECTIVE POTENTIAL

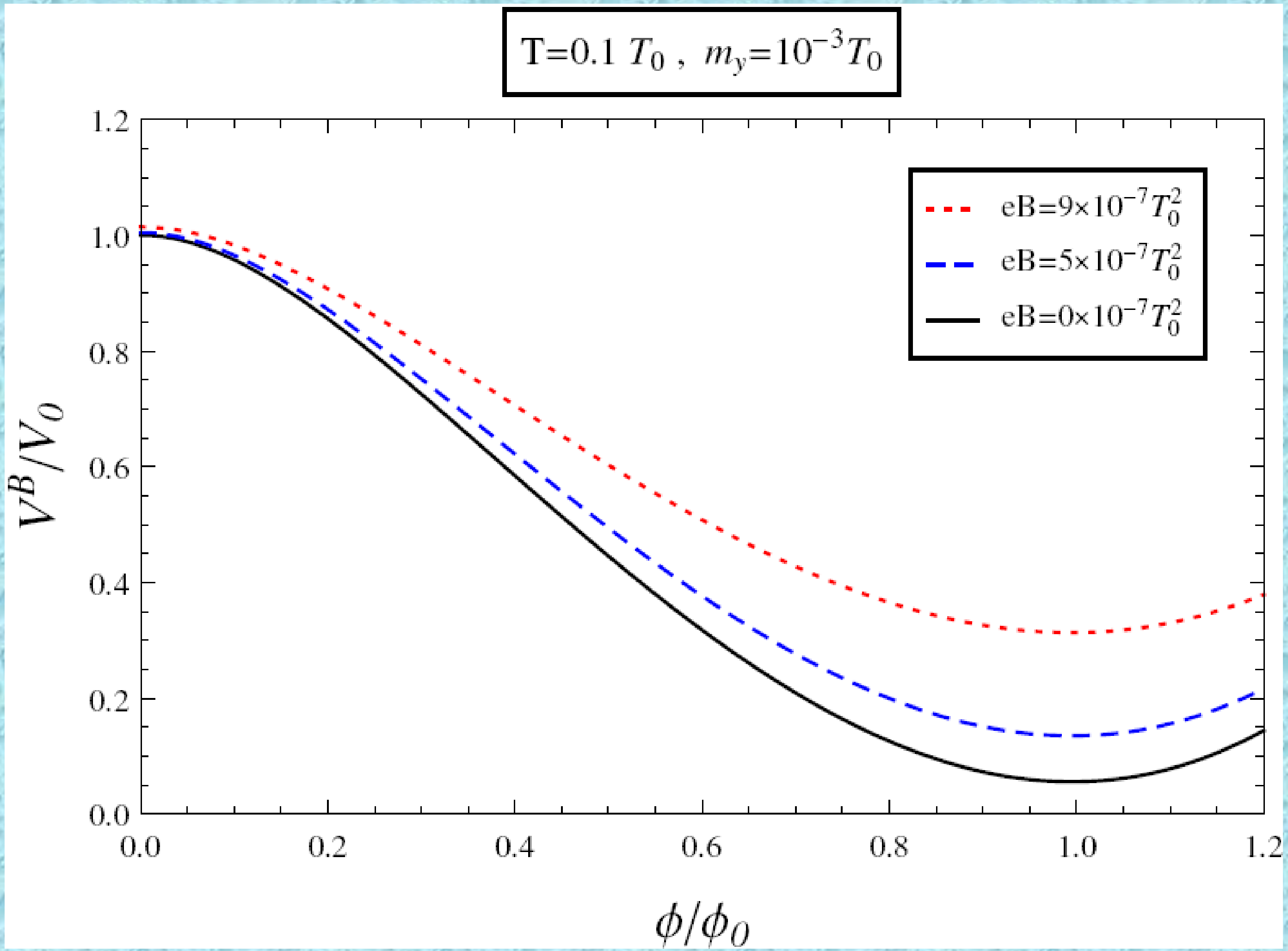
$$V_\chi = \frac{M_S^2}{16\pi^2}\left(2g^2\phi^2 + m_b^2(T,B)\right)\left[1 - \frac{m_f^2(T,B) - m_b^2(T,B)}{M_S^2}\right]\left[\ln\left(\frac{2g^2\phi^2 + m_b^2(T,B)}{2g^2\phi_0^2}\right) - 1\right] + \frac{M_S^2 g^2 \phi_0^2}{8\pi^2}$$

$$V(\phi, T, B) = -\frac{\pi^2}{90} g_* T^4 + V_\chi(\phi, T, B)$$

G.P., Á. Sánchez, A. Ayala, A. J. Mizher,

Phys. Rev. D 90, 083504 (2014)

EFFECTIVE POTENTIAL



$$\frac{V^B}{V_0} = \frac{V(\phi, T, B) - V(0, T, 0)}{V(0,0,0)} + 1$$

$$W_{eff}\left[\varphi\right]=\int d^{4}x\left[\frac{1}{2}\left(\partial\varphi\right)^{2}-V_{eff}\left(\varphi\right)\right] \qquad (4)$$

$$+\frac{1}{2}\int d^{4}x_{1}d^{4}x_{2}\left[\varphi\left(x_{1}\right)M\left(x_{1}-x_{2}\right)\varphi\left(x_{2}\right)\right]$$

$$M\left(p_{0},\mathbf{p}\right)=Re\left(M\left(p_{0},\mathbf{p}\right)\right)+iIm\left(M\left(p_{0},\mathbf{p}\right)\right) \qquad (5)$$

DISSIPATION COEFFICIENT

$$Im\left(M\left(p_0,\mathbf{p}\right)\right) = \lim_{\varepsilon\to 0} \frac{M\left(p_0 + i\varepsilon,\mathbf{p}\right) - M\left(p_0 - i\varepsilon,\mathbf{p}\right)}{2i\varepsilon} \qquad (6)$$

$$\varphi Im\left(M\left(p_0,0\right)\right)\varphi \rightarrow \varphi Im\left(M\left(\partial_t^2,0\right)\right)\varphi \qquad (7)$$

$$\begin{aligned}\varphi Im\left(M\left(\partial_t^2,0\right)\right)\varphi &\sim \Upsilon\, \varphi\,\partial_t^2\varphi \\ &= \Upsilon\, \dot{\varphi}^2\end{aligned} \qquad (8)$$

DISSIPATION COEFFICIENT

$$\mathcal{L}_{eff} = p = \frac{1}{2}(\partial\varphi)^2 - V_{eff} + \frac{\Upsilon}{2}\dot{\varphi}^2 \qquad (9)$$

$$\mathcal{H}_{eff} = \rho = \frac{1}{2}(\partial\varphi)^2 + V_{eff} + \frac{\Upsilon}{2}\dot{\varphi}^2 \qquad (10)$$

$$\dot{\rho} = -3(\rho + p)H \qquad (12)$$

$$3H(1+\Upsilon)\dot{\varphi} + \frac{dV(\varphi)}{d\varphi} \approx 0 \qquad (13)$$

DISSIPATION COEFFICIENT

$$\Upsilon = \frac{4}{T}\left(\frac{g^2}{2}\right)^2 \varphi^2 \int \frac{d^4p}{(2\pi)^4}\, \rho_\chi^2 n_B (1 + n_B) \qquad (1)$$

The dissipation coefficient Υ is related to the decay width Γ_χ for the different processes envolved in the decay.

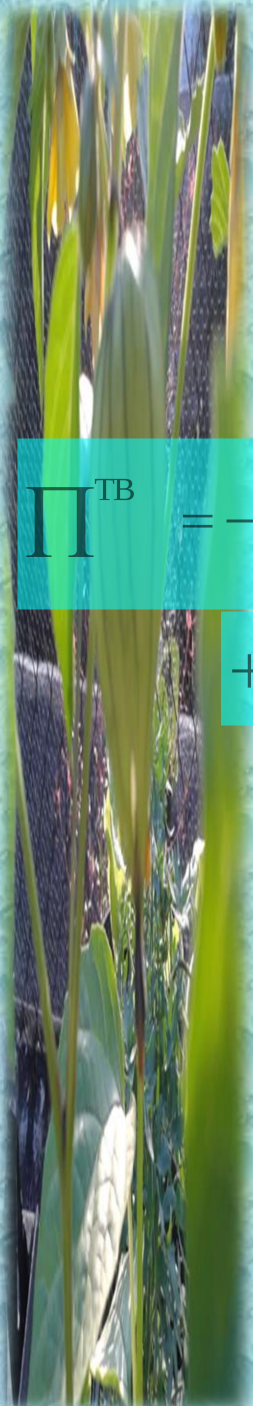
$$\rho_\chi(p_0, p) = \frac{4\omega_p \Gamma_\chi}{\left(p_0^2 - \omega_p^2\right)^2 + 4\omega_p^2 \Gamma_\chi^2} \qquad (3)$$

DISSIPATION COEFFICIENT

Γ_χ is defined by: $\Gamma_\chi = \mathrm{Im}\Pi / 2\omega(\mathbf{p})$

with $\omega(\mathbf{p})^2 = \mathbf{p}^2 + m_R^2$

$$\mathrm{Disc}\Pi = -2i\,\mathrm{Im}\,\Pi = -ig^2 \int \frac{d^3p}{(2\pi)^3} \frac{2\pi}{2E_1 2E_2} \{\delta(p_0 - E_1 - E_2)(1 + n_1 + n_2)\}$$



DISSIPATION COEFFICIENT

$$\prod^{TB} = -g_{\chi}^{2}\sum\int\frac{d^4k}{(2\pi)^4}\Big\{\Delta_{x_1}(p-k)\Delta_{x_2}(k)-(eB)\Big(\Delta_{x_1}(p-k)\Delta^{3}_{x_2}(k)+\Delta_{x_2}(k)\Delta^{3}_{x_1}(p-k)\Big)$$
$$+(eB)^2\Big(2k_{\perp}^{2}\Delta_{x_1}(p-k)\Delta^{4}_{x_2}(k)+2(p-k)_{\perp}^{2}\Delta_{x_2}(k)\Delta^{4}_{x_1}(p-k)\Big)\Big\} \quad (14)$$

$$I_{nm}\equiv\sum\int\frac{d^4k}{(2\pi)^4}\Delta^{n+1}_{x_1}(p-k)\Delta^{m+1}_{x_2}(k) \quad (15)$$

DISSIPATION COEFFICIENT

$$\mathrm{Im}\left(\Pi^{T}\right) \equiv -\frac{g_\chi^2 \pi}{4(2\pi)^2 p}\left\{\int_{E_1^-}^{E_1^+} dE_1 \left(\frac{1}{2} + n_\beta(E_1)\right) + \int_{E_2^-}^{E_2^+} dE_2 \left(\frac{1}{2} + n_\beta(E_2)\right)\right\}$$

$$= -\frac{g_\chi^2 \pi}{4(2\pi)^2 p}\left\{\frac{1}{2}\left(E_1^+ - E_1^-\right) + \frac{1}{\beta}\ln\left(\frac{1-e^{-\beta E_1^+}}{1-e^{-\beta E_1^-}}\right)\right.$$

$$\left. + \frac{1}{2}\left(E_2^+ - E_2^-\right) + \frac{1}{\beta}\ln\left(\frac{1-e^{-\beta E_2^+}}{1-e^{-\beta E_2^-}}\right)\right\} \qquad (16)$$

M. Bastero-Gil, A. Berera, R. Ramos, JCPA 1109 (2011) 033

DISSIPATION COEFFICIENT

$$E_1^{\pm} = \frac{p_0\left(p_0^2 - p^2 + m_1^2 - m_2^2\right)}{2\left(p_0^2 - p^2\right)}$$

$$\pm \frac{|\vec{p}|}{2\left(p_0^2 - p^2\right)}\sqrt{\left[\left(p_0^2 - p^2\right) - (m_1 - m_2)^2\right]\left[\left(p_0^2 - p^2\right) - (m_1 + m_2)\right]}$$

(49)

$$
\mathrm{Im}\left(\Pi^{\mathrm{TB}}\right)^{\mathrm{decay}} = -\frac{g_\chi^2 \pi}{4(2\pi)^2 \mathrm{p}} \sum_{\substack{i=1,2 \\ \sigma=\pm 1}} \sigma \Bigg\{ \frac{1}{2}\mathrm{E}_i^\sigma + \frac{1}{\beta}\ln\left(1-\mathrm{e}^{-\beta \mathrm{E}_i^\sigma}\right)
$$

$$
+\frac{(\mathrm{eB})^2}{12}\left[-\frac{1}{12\left(\mathrm{E}_i^\sigma\right)^3} + \frac{m_i^2\left(\frac{1}{2}+n\left(\mathrm{E}_i^\sigma\right)\right)}{\left(\mathrm{E}_i^\sigma\right)^5} + \frac{1}{2}\frac{n_{\mathrm{B}}\left(\mathrm{E}_i^\sigma\right)}{\left(\mathrm{E}_i^\sigma\right)^3} - \frac{1}{2}\frac{1}{\mathrm{E}_i^2}\frac{\mathrm{d}n_{\mathrm{B}}\left(\mathrm{E}_i\right)}{\mathrm{dE}_i}\bigg|_{\mathrm{E}_i^\sigma} \right.
$$

$$
\left. + m_i^2 \frac{\mathrm{d}}{\mathrm{dE}_i}\frac{n\left(\mathrm{E}_i\right)}{\mathrm{E}_i^4}\bigg|_{\mathrm{E}_i^\sigma} - \frac{1}{3}\frac{\mathrm{d}^2}{\mathrm{dE}_i^2}\frac{\left(\mathrm{E}_i^2 - m_i^2\right)n\left(\mathrm{E}_i\right)}{\mathrm{E}_i^4}\bigg|_{\mathrm{E}_i^\sigma} \right]\Bigg\}
$$

$$
\times \theta\left(\mathrm{p}_0^2 - \mathrm{p}^2 + \left(m_1 + m_2\right)^2\right)
$$

Where the θ function has been

introduced to guarantee that $E^{\pm}$ has real values

$$\mathrm{Im}\left(\Pi^{\mathrm{TB}}\right)^{\mathrm{decay}} = -\frac{g_\chi^2 \pi}{4(2\pi)^2 \mathrm{p}} \sum_{\substack{i=1,2 \\ \sigma=\pm 1}} \sigma \left\{ \frac{1}{2} \mathrm{E}_i^\sigma + \frac{1}{\beta} \ln\left(1 - e^{-\beta \mathrm{E}_i^\sigma}\right) \right.$$

$$+ \frac{(eB)^2}{12} \left[-\frac{1}{12\left(\mathrm{E}_i^\sigma\right)^3} + \frac{m_i^2\left(\frac{1}{2} + n\left(\mathrm{E}_i^\sigma\right)\right)}{\left(\mathrm{E}_i^\sigma\right)^5} + \frac{1}{2}\frac{n_{\mathrm{B}}\left(\mathrm{E}_i^\sigma\right)}{\left(\mathrm{E}_i^\sigma\right)^3} - \frac{1}{2}\frac{1}{\mathrm{E}_i^2}\frac{d n_{\mathrm{B}}\left(\mathrm{E}_i\right)}{d\mathrm{E}_i}\Bigg|_{\mathrm{E}_i^\sigma} \right.$$

$$\left.\left. + m_i^2 \frac{d}{d\mathrm{E}_i}\frac{n\left(\mathrm{E}_i\right)}{\mathrm{E}_i^4}\Bigg|_{\mathrm{E}_i^\sigma} - \frac{1}{3}\frac{d^2}{d\mathrm{E}_i^2}\frac{\left(\mathrm{E}_i^2 - m_i^2\right) n\left(\mathrm{E}_i\right)}{\mathrm{E}_i^4}\Bigg|_{\mathrm{E}_i^\sigma} \right] \right\}$$

$$\times \theta\left(\mathrm{p}_0^2 - \mathrm{p}^2 + \left(m_1 + m_2\right)^2\right)$$

M. Bastero-Gil, G.P., Á. Sánchez, work in progress

CONCLUSIONS

We have calculated magnetic contributions to the effective potential and to the dissipation coefficient of a warm inflation model, based on global supersymmetry and a two-stage reheating process.

For the employed hierarchy of scales, corrections are small and the flatness of the potential is not spoiled. In fact, magnetic terms work in the direction of making the potential less steep.

PRESENT and FUTURE WORK

- Analysis of the effect of the magnetic field on the decay process(through the dissipation coefficients)

- Effect on density fluctuations