$\nu -$ *Inflaton Dark Matter*

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A. Torres Manso and J. G. Rosa JHEP 02(2019) 020 [1811.02302].

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GGI lectures on the theory of fundamental interactions

Galileo Galilei Institute for Theoretical Physics Firenze

Introduction

- Unified Model where same scalar field ϕ
  - Drives Inflation
  - Accounts for Dark Matter
- Incomplete decay   M. Bastero-Gil et al 1501.05539
  - into two right-handed neutrinos $N_1,\ N_2$
  - leads to successful reheating
  - leaves a stable remnant of ϕ
- $N_{i's}$ lead to the generation of the observed
  - light neutrino masses
  - baryon asymmetry

Model Description

- Impose a discrete symmetry $C_2 \subset \mathbb{Z}_2 \times S_2$ on the fields

$$\phi \leftrightarrow -\phi \ , \qquad N_1 \leftrightarrow N_2$$

  - Equal tree-level mass, $M_1 = M_2$, but opposite sign coupling with ϕ.

$$\mathcal{L} = \mathcal{L}_{Inf} + \mathcal{L}_{N\,Kin} + \mathcal{L}_{SM} + \mathcal{L}_{N\,Mass} + \mathcal{L}_{SM \leftrightarrow N};$$

$$\mathcal{L}_{Inf} = \frac{M^2 + \xi\phi^2}{2} R - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi);$$

$$\mathcal{L}_{N\,Mass} = -\frac{1}{2}(M_1 + h\phi)N_1 N_1^c - \frac{1}{2}(M_1 - h\phi)N_2 N_2^c - \frac{1}{2} M_3 N_3 N_3^c;$$

$$\mathcal{L}_{SM \leftrightarrow N} = y_{i\ell} N_i^c H\, L + h.c.$$

Imposing a Discrete Symmetry: Consequences

- Inflaton interacts only with N_1 & N_2

- For $\mathbf{M_1} > \frac{\mathbf{m}_\phi}{\mathbf{2}}$

$\rightarrow$ ϕ decay kinematically blocked

$\rightarrow$ stable at the minimum

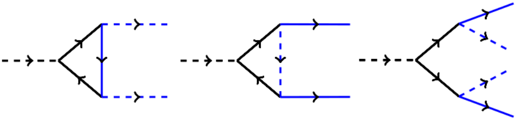

Figure 1: Symmetry's forbidden decays

- Far from the origin

$\rightarrow$ effective mass $M_\pm = |M_1 \pm h\phi|$

$\rightarrow$ breaking of the symmetry

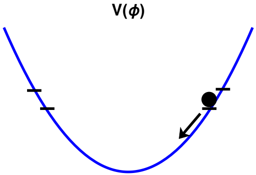

Figure 2: Allowed decay region with a decaying condition $|M_1 \pm h\phi| < \frac{m_\phi}{2} \implies |\phi| \gtrsim \frac{M_1}{h}$

Seesaw mechanism and the mass generation

- At late times, when the inflaton is lying close to the minimum, $\phi \ll M_1/h$

$$\mathcal{L}_{Mass} = -\frac{1}{2}M_1 N_1 N_1^c - \frac{1}{2}M_2 N_2 N_2^c - \frac{1}{2}M_3 N_3 N_3^c + y_{i\ell} N_i^c H\, L + h.c.$$

- As a result of the $N_1 \leftrightarrow N_2$ symmetry

$$M_R = \begin{pmatrix} M_1 & 0 & 0 \\ 0 & M_1 & 0 \\ 0 & 0 & M_3 \end{pmatrix} \quad m_D = \frac{v}{\sqrt{2}} \begin{pmatrix} y_{1e} & y_{1\mu} & y_{1\tau} \\ y_{1e} & y_{1\mu} & y_{1\tau} \\ y_{3e} & y_{3\mu} & y_{3\tau} \end{pmatrix} \qquad \begin{matrix} (y_{1\ell} = y_{2\ell}) \\ (M_1 = M_2) \end{matrix}$$

$$\mathcal{M}_\nu = -m_D^T M_R^{-1} m_D \quad \Rightarrow \quad \det \mathcal{M}_\nu = 0 \quad \Rightarrow \quad m_i = 0$$

Seesaw mechanism and the mass generation

- The mass matrix of the light neutrinos is diagonalized by U_{PMNS}

$$\mathcal{M}_\nu = U^*_{PMNS} M^d_\nu U^\dagger_{PMNS}, \quad \text{with} \quad M^d_\nu = diag\left(m_1, m_2 e^{-i\phi_1}, m_3 e^{-i\phi_2}\right)$$

- Based on neutrino oscillations results

$$U_{PMNS} \simeq U_{TBM} \quad \text{and} \quad \Delta m^2_{12} \simeq 10^{-5}\text{eV} \ll \Delta m^2_{23} \simeq 2\times 10^{-3}\text{eV} \quad \Rightarrow \quad m_1 = m_2$$

- Combining the two approaches
  - Inverted hierarchy: $m_1 \simeq m_2 = \frac{(y^2_{1e}+2y^2_{1\mu})v^2}{M_1}, \quad m_3 = 0;$
  - Normal hierarchy: $m_1 \simeq m_2 = 0, \quad m_3 = v^2\left(\frac{2y^2_{1\mu}}{M_1} + \frac{y^2_{3\mu}}{M_3}\right);$

$$M_1 \simeq 1.21\times 10^{15}\, y^2_{eff}\ GeV, \quad \text{with} \quad y^2_{eff} = \sum_\ell y^2_{1\ell}$$

Inflation

$$V(\phi) = \frac{1}{2}m_\phi^2\phi^2 + \lambda\phi^4, \text{ with } \frac{\xi\phi^2}{2}R$$

$$\hat{g}_{\mu\nu} = \Omega^2 g_{\mu\nu} \quad \Downarrow \quad \phi \to \chi$$

$$\Omega^2 = 1 + \frac{\xi\phi^2}{M_P^2} \qquad \frac{d\chi}{d\phi} = \sqrt{\ldots}$$

$$U(\chi) = V(\phi)\left(1 + \frac{\xi\phi^2}{M_P^2}\right)^{-2}$$

$$\lambda\phi^4 \gg \frac{1}{2}m_\phi^2\phi^2 \quad \Downarrow \quad \phi \gg M_P/\sqrt{\xi}$$

$$U(\chi) \simeq \lambda M_P^4/\xi^2$$

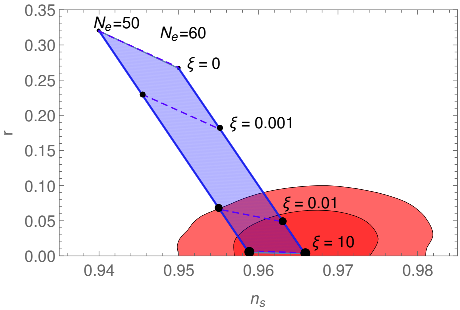

Figure 3: Observational predictions. The red contours correspond to the 68% and 95% C.L. results from *P. A. R. Ade, et al. (Planck), Planck 2015 results. XIII.*

$$\Delta_R^2 = 2.2 \times 10^{-9} \Longrightarrow \lambda \simeq 4 \times 10^{-10}\xi^2$$

- When $\epsilon \simeq 1 \longrightarrow \phi_e \simeq M_P/\sqrt{\xi}$

Reheating

$$\ddot{\phi} + 3H\dot{\phi} + \Gamma_\phi \dot{\phi} + 4\lambda\phi^3 = 0; \qquad \dot{\rho}_R + 4H\rho_R = \Gamma_\phi \dot{\phi}^2; \qquad H^2 = \frac{\frac{1}{2}\dot{\phi}^2 + \lambda\phi^4 + \rho_R}{3M_P^2};$$

$$\Gamma_\pm = \frac{h^2}{16\pi}\sqrt{12\lambda\phi^2}\left(1 - \frac{4\,(M_1 \pm h\phi)^2}{12\lambda\phi^2}\right)^{\frac{3}{2}}; \qquad m_{eff} = \sqrt{12\lambda\phi^2}$$

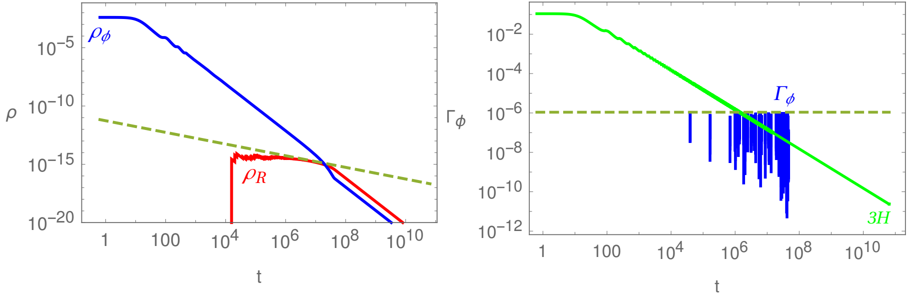

Figure 4: Numerical integration of the inflaton-radiation dynamical system of equations.

Decaying condition $\Rightarrow \quad |M_1 \pm h\phi| < \frac{m_\phi}{2} \implies |\phi| \gtrsim \frac{M_1}{h}$

Reheating

- We are able to estimate:
  - Reheating temperature

$$T_R = 4 \left(\frac{100}{g_{\star R}}\right)^{-1/4} \left(\frac{M_1}{\mathrm{TeV}}\right)^{2/3} \xi^{5/6} h^{-1/3}\,\mathrm{TeV}$$

  - Obtain an upper bound on

$$M_1 < \frac{3\sqrt{3}\lambda^{1/2} h^2 M_P}{4\pi^2} \simeq 6.6 \times 10^{12} \xi\, h^2\,\mathrm{GeV}$$

- Ensure the production of SM particles before BBN

$$\left.\frac{\Gamma_{N_i \to SM}}{H}\right|_{T=100\,\mathrm{MeV}} > 1$$

Evaporation of the Condensate: WIMPlaton dark matter

- Right-handed neutrinos and decay products, may scatter off the inflaton particles
- Depending or T_R we may still have N_1 and N_2 in the thermal bath

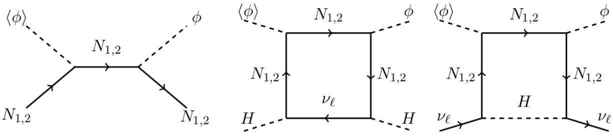

Figure 5: Dominant Feynman diagrams for evaporation processes

$$\left.\frac{\Gamma^{(N)}_{evap}}{H}\right|_{T=M_1} \gtrsim 1$$

$$\left.\frac{\Gamma^{(h)}_{evap}}{H}\right|_{T=0.1\,\mathrm{TeV}} \gtrsim 1$$

- The scalar particles may thermalize, destroying the condensate;
- When such processes become inefficient, inflaton decouples from the thermal bath.

$$m_\phi \simeq 1.4 h^2 \left(\frac{\Omega_{\phi 0} h_0^2}{0.1}\right)^{1/2} \mathrm{TeV}$$

WIMPlaton scenario

$$\frac{m_\phi}{2} < M_1 < \frac{3\sqrt{3}\lambda^{1/2} M_P m_\phi}{4\pi^2 \mathrm{TeV}}$$

- If $M_1 > T_R$

$$m_\phi \gtrsim 4.9 \times 10^{-5} \left(\frac{M_1}{\mathrm{GeV}}\right)^{1/2} \mathrm{GeV}$$

- If $M_1 < T_R$

$$m_\phi \gtrsim 1.7 \times 10^{8} \left(\frac{\mathrm{GeV}}{M_1}\right) \mathrm{GeV}$$

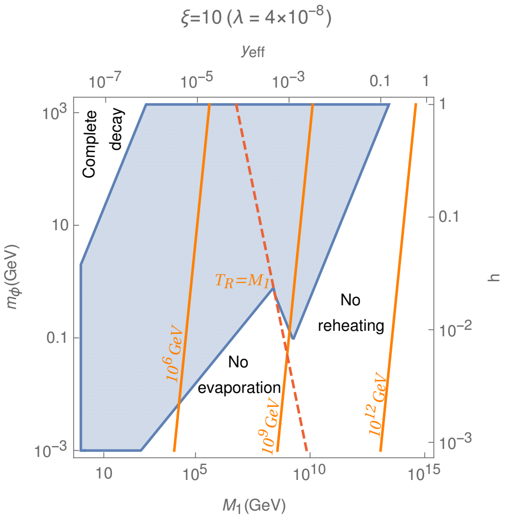

Figure 6: Orange lines represent different values for the reheating temperatures and the dashed line, $M_1 = T_R$, limits the evaporation conditions.

$$\frac{m_\phi}{2} < M_1 < \frac{3\sqrt{3}\lambda^{1/2} M_P m_\phi}{4\pi^2 \mathrm{TeV}}$$

- If $M_1 > T_R$

$$m_\phi \gtrsim 4.9 \times 10^{-5} \left(\frac{M_1}{\mathrm{GeV}}\right)^{1/2} \mathrm{GeV}$$

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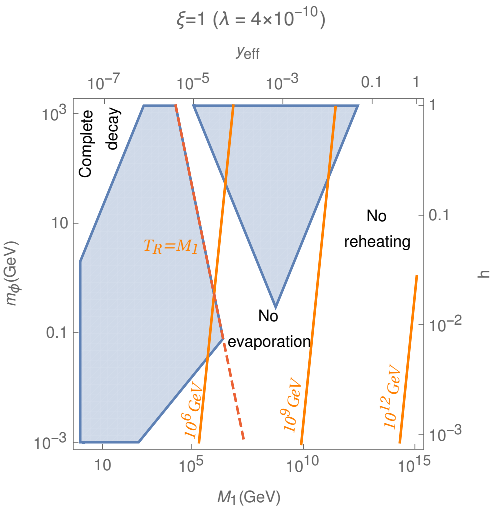

Figure 7: Orange lines represent different values for the reheating temperatures and the dashed line, $M_1 = T_R$, limits the evaporation conditions.

WIMPlaton scenario

$$\frac{m_\phi}{2} < M_1 < \frac{3\sqrt{3}\lambda^{1/2} M_P m_\phi}{4\pi^2 \mathrm{TeV}}$$

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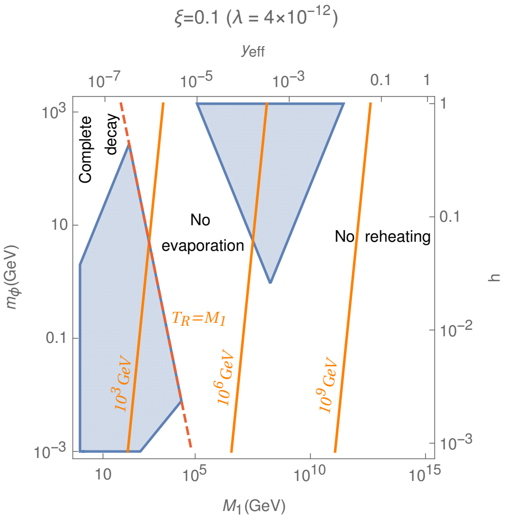

Figure 8: Orange lines represent different values for the reheating temperatures and the dashed line, $M_1 = T_R$, limits the evaporation conditions.

Oscillating scalar field dark matter scenario

- As we have seen the inflaton decays until its amplitude falls bellow

$$\phi_{DR} = \frac{M_1}{h}$$

- If at this stage evaporation processes are inefficient, while the $\lambda\phi^4$ dominates, the condensate behaves as dark radiation (DR)

- When $\frac{1}{2}m_\phi^2\phi^2$ becomes dominant, ϕ behaves as CDM, and $\frac{n_\phi}{s} = \kappa$

$$\phi_{CDM} = \sqrt{\frac{1}{2}\frac{m_\phi^2}{\lambda}}.$$

- We can relate it to the measured dark matter density

$$m_\phi \simeq 3.2\, h^2 \xi^{3/2} \left(\frac{\Omega_{\phi 0} h_0^2}{0.1}\right)\left(\frac{\mathrm{GeV}}{M_1}\right)\ \mathrm{GeV}.$$

Oscillating Scalar Field Dark Matter Scenario

$$\frac{m_\phi}{2} < M_1 < \frac{7.7 \times 10^{10} M_1 m_\phi}{\lambda^{1/4}\mathrm{GeV}}$$

- If $M_1 > T_R$

$$m_\phi \lesssim 0.14 \left(\frac{\mathrm{GeV}}{M_1}\right)^{1/2} \lambda^{3/4}\mathrm{GeV}$$

- If $M_1 < T_R$

$$m_\phi \lesssim 4.9\times10^{11} \left(\frac{\mathrm{GeV}}{M_1}\right)^{2} \lambda^{3/4}\mathrm{GeV}$$

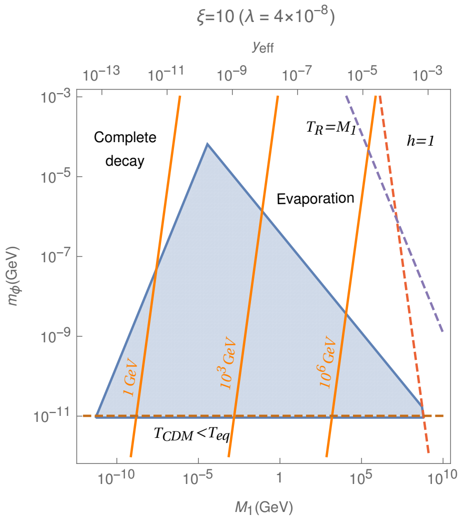

Figure 9: Orange lines represent different values for the reheating temperatures and the dashed line, $M_1 = T_R$, limits the evaporation conditions.

Oscillating Scalar Field Dark Matter Scenario

$$\frac{m_\phi}{2} < M_1 < \frac{7.7 \times 10^{10} M_1 m_\phi}{\lambda^{1/4}\mathrm{GeV}}$$

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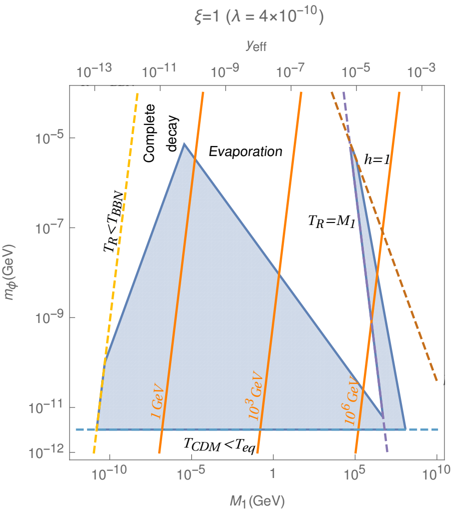

Figure 10: Orange lines represent different values for the reheating temperatures and the dashed line, $M_1 = T_R$, limits the evaporation conditions.

Oscillating Scalar Field Dark Matter Scenario

$$\frac{m_\phi}{2} < M_1 < \frac{7.7 \times 10^{10} M_1 m_\phi}{\lambda^{1/4}\mathrm{GeV}}$$

- If $M_1 > T_R$

$$m_\phi \lesssim 0.14 \left(\frac{\mathrm{GeV}}{M_1}\right)^{1/2} \lambda^{3/4}\mathrm{GeV}$$

- If $M_1 < T_R$

$$m_\phi \lesssim 4.9{\times}10^{11} \left(\frac{\mathrm{GeV}}{M_1}\right)^{2} \lambda^{3/4}\mathrm{GeV}$$

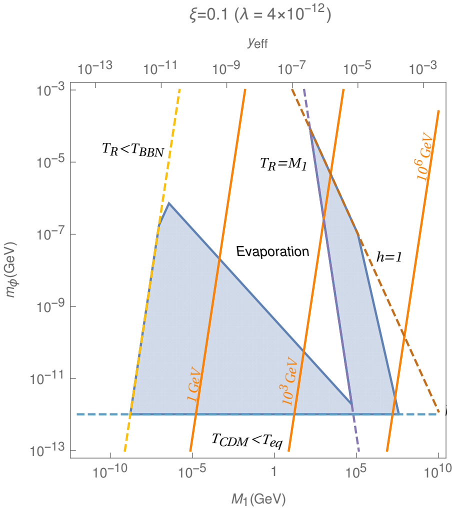

Figure 11: Orange lines represent different values for the reheating temperatures and the dashed line, $M_1 = T_R$, limits the evaporation conditions.

Embedding Leptogenesis in νIDM

- All three Sakharov conditions may be satisfied with $N_i' s$;
- Assuming Thermal production of N_3, with $M_3 < M_1$ we have S. Davidson et al. 0802.2962

$$Y_{\Delta B} \simeq \left(\frac{135\zeta(3)}{4\pi^4 g_\star} \right) C_{sphal}\, \eta\, \epsilon.$$

- The value of ϵ, the CP asymmetry, is obtained through the Davidson-Ibarra bound

S. Davidson and A. Ibarra, hep-ph/0202239

$$|\epsilon| \leq \frac{3 M_3 m_{\max}}{8\pi v^2}, \Longrightarrow M_3 \gtrsim \frac{8\pi}{3} \frac{v^2}{m_{max}} |\epsilon|$$

- Using the values for η, C_{sphal} and $Y_{\Delta B} \sim 10^{-10}$ we estimate S. Davidson et al. 0802.2962

$$|\epsilon| \gtrsim 10^{-5} - 10^{-6} \Longrightarrow M_3 \gtrsim 10^9 \text{ GeV} \Longrightarrow T_R \gtrsim 10\, M_3 \simeq 10^{10} \text{GeV}$$

Embedding Leptogenesis in νIDM

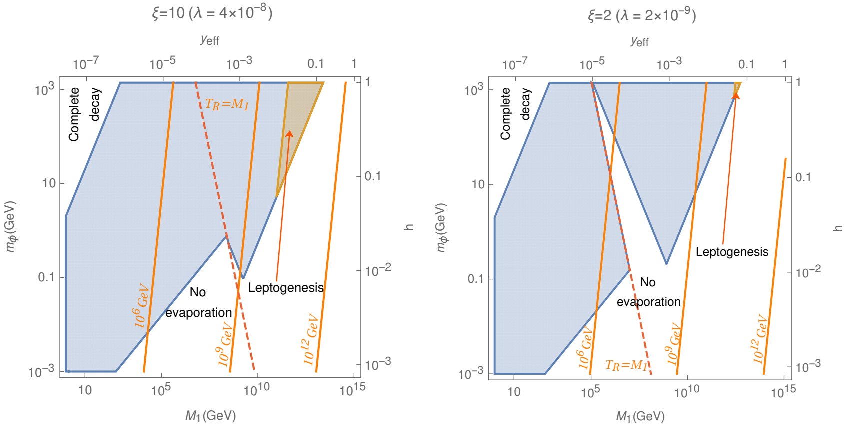

Figure 12: Constraints on model parameters in the WIMPlaton scenario. The shaded orange regions correspond to consistent scenarios for thermal leptogenesis with $T_R > 10^{10}$ GeV.

Conclusions

- Developed an economic unified model using:
  - Scalar field $\longrightarrow$ Inflation+Cold Dark Matter;
  - Right-handed neutrinos $\longrightarrow$ Neutrino masses+Baryon asymmetry.
- The chosen symmetry
  - Stable dark matter as a:
    - WIMP;
    - Oscillating scalar field condensate.
  - One massless ν_ℓ.

Back Up Slides

$$S_J = \int d^4x\sqrt{-g}\left[\frac{M^2+\xi\phi^2}{2}R - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2 - \lambda\phi^4\right]$$

$$\hat{g}_{\mu\nu} = \Omega^2 g_{\mu\nu}, \quad \Omega^2 = 1 + \frac{\xi\phi^2}{M_P^2} \Longrightarrow R = \Omega^2\left[\hat{R} - 6\left(\nabla^2\ln\Omega + (\nabla\ln\Omega)^2\right)\right]$$

$$\phi\mapsto\chi; \quad \frac{d\chi}{d\phi} = \sqrt{\frac{\Omega^2+6\xi^2\phi^2/M_P^2}{\Omega^4}} \Longrightarrow S_E = \int d^4x\sqrt{-\hat{g}}\left[\frac{M_P^2}{2}\hat{R} - \frac{1}{2}\partial_\mu\chi\partial^\mu\chi - U(\chi)\right]$$

$$\epsilon = \frac{1}{2}M_p^2\left(\frac{U'(\chi)}{U(\chi)}\right)^2, \qquad \eta = M_p^2\frac{U''(\chi)}{U(\chi)}, \qquad N_e = \frac{1}{M_P^2}\int_{\chi_e}^{\chi_*}\frac{U(\chi)}{U'(\chi)}d\chi\,.$$

$$r = 16\epsilon \simeq \frac{12}{N_e^2}; \qquad n_s = 1-6\epsilon+2\eta \simeq 1-\frac{2}{N_e}.$$

$$\begin{array}{c}\Delta^2_{\mathcal{R}\ obs} = 2.2\times10^{-9} \\ \Delta^2_{\mathcal{R}} = \frac{1}{24\pi^2}\frac{V}{M_P^4}\frac{1}{\epsilon_\phi}\end{array} \Longrightarrow U/\epsilon_\chi = (0.0269M_P)^4 \Longrightarrow \lambda \simeq 4\times10^{-10}\xi^2$$

$$\dot{\rho}_R + 4H\rho_R = \Gamma_\phi \dot{\phi}^2$$

$$\ddot{\phi} + 3H\dot{\phi} + \omega^2\phi = 0; \quad \omega \simeq \sqrt{3\lambda\Phi^2} \Rightarrow \phi(t) \simeq \Phi(t)\sin(\omega t + \alpha); \quad \Phi(t) = \left(\frac{3}{\lambda}\right)^{1/4}\left(\frac{M_p}{2t}\right)^{1/2}$$

$$\Gamma_\phi \dot{\phi}^2 = \left(2\,\frac{\Gamma_{\max}}{2}\,2\,\Delta t\,\frac{\omega}{2\pi}\right)\dot{\phi}^2; \qquad 4H\,\rho_R = \frac{2}{t}\rho_R$$

$$\rho_R = \frac{3\sqrt{3}\lambda^{3/2}M_1^2 M_p}{4\pi^2 h}\Phi \implies \rho_\phi = \rho_R \Leftrightarrow \lambda\Phi^4 = \frac{3\sqrt{3}\lambda^{3/2}M_1^2 M_p}{4\pi^2 h}\Phi$$

$$M_1 \text{ bound} \Rightarrow \Phi > M_1/h$$

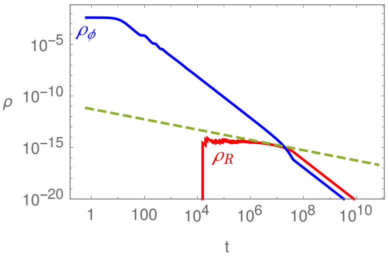

Figure 13: Numerical integration of the inflaton-radiation dynamical system of equations.

Back up slides: Evaporation

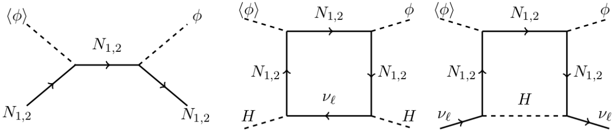

Figure 14: Dominant Feynman diagrams for evaporation processes

$$\Gamma^{(N)}_{evap} \simeq \frac{h^4}{12\pi^3}\left(1+\log\left(\frac{T}{m_\phi}\right)\right) T \quad \Longrightarrow \quad \left.\frac{\Gamma^{(N)}_{evap}}{H}\right|_{T=M_1} \simeq 10^{13} h^4 g_\star^{-1/2}\left(\frac{1\ \mathrm{TeV}}{M_1}\right) \gtrsim 1$$

$$\Gamma^{(h)}_{evap} \simeq \frac{\zeta(3)}{128\pi^5} h^2 y_{eff}^2 T \quad \Longrightarrow \quad \left.\frac{\Gamma^{(h)}_{evap}}{H}\right|_{T=100\ \mathrm{GeV}} \simeq 10^{11} h^2 g_\star^{-1/2} y_{eff}^2 \gtrsim 1\ .$$

$$\Gamma^{(\nu)}_{evap} \propto T^3/M_1^2$$

Back up slides: Condensate

$$\Omega_{\phi 0} = \frac{\rho_{\phi 0}}{\rho_{c0}} = \frac{m_\phi n_{\phi 0}}{3H_0^2 M_P^2} = \frac{m_\phi s_0}{3H_0^2 M_P^2} \left(\frac{n_\phi}{s}\right)_{CDM}$$

$$T_{DR} \simeq T_R \Rightarrow \frac{\phi_{DR}}{\phi_{CDM}} \simeq \frac{T_R}{T_{CDM}}$$

$$\left(\frac{n_\phi}{s}\right)_{CDM} = \left(\frac{\rho_\phi}{m_\phi s}\right)_{CDM} = \frac{\frac{1}{2} m_\phi \phi_{CDM}^2}{\frac{2\pi^2}{45} g_{\star CDM} T_{CDM}^3}; \qquad s_0 = \frac{2\pi^2}{45} g_{\star 0} T_0^3$$

$$\Omega_{\phi 0} h_0^2 \simeq 3 \times 10^{-9} \left(\frac{g_{\star R}^{3/4}}{g_{\star CDM}}\right) \frac{1}{\lambda^{3/4} h^2} \left(\frac{m_\phi M_1}{\mathrm{GeV}^2}\right)$$

$$m_\phi \simeq 3.2 g_{\star CDM} g_{\star R}^{-3/4} h^2 \xi^{3/2} \left(\frac{\Omega_{\phi 0} h_0^2}{0.1}\right) \left(\frac{\mathrm{GeV}}{M_1}\right) \ \mathrm{GeV}$$

Back up slides: Leptogenesis

- $Y_{\Delta B} \simeq \left(\frac{n_{N_3}}{s_{T \gg M_3}}\right) C_{sphal}\eta\epsilon = \left(\frac{135\zeta(3)}{4\pi^4 g_\star}\right) C_{sphal}\eta\epsilon$
- $\epsilon \equiv \frac{\Gamma(N_3\to HL)-\Gamma\left(N_3\to \bar{H}\bar{L}\right)}{\Gamma(N_3\to HL)+\Gamma\left(N_3\to \bar{H}\bar{L}\right)}; \qquad |\epsilon| \leq \frac{3M_3 m_{\rm max}}{8\pi v^2}$
- $\Gamma^{N_3}_{prod} \sim \sum_\ell \frac{y_t^2 |y_{3\ell}|^2}{4\pi} T \qquad \Gamma^{N_3}_D = \left[y_\nu y_\nu^\dagger\right]_{33} \frac{M_3}{8\pi} \qquad \Gamma^{N_3}_{prod} > \Gamma^{N_3}_D$

$$\frac{\Gamma_D}{H} \simeq 0.2\, g_\star^{-1/2}\, y^2_{3\ eff}\, \frac{M_P}{T} \Longrightarrow \frac{\Gamma_D}{H} > 1 \Longrightarrow y^2_{3\ eff} = \sum_\ell |y_{3\ell}|^2 \gtrsim 1.7\times 10^{-16}\, \frac{M_3}{\rm GeV}$$

$$\Gamma_{ID}(HL \to N_3) \simeq \Gamma_D e^{-M_3/T_*} < H$$

- $\Gamma_{B+L\ violation} \simeq 250\alpha_W^5 T; \qquad Y_{\Delta B} \simeq \frac{12}{37} Y_{\Delta(B-L)}$

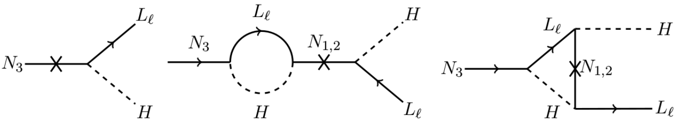

Figure 15: Feynman diagrams contributing to the CP asymmetry ϵ