The importance of being warm (during inflation)

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Contents

- Inflation: basics
- Warm inflation
- Contact with observations
- $V = \lambda\phi^4$ is alive!

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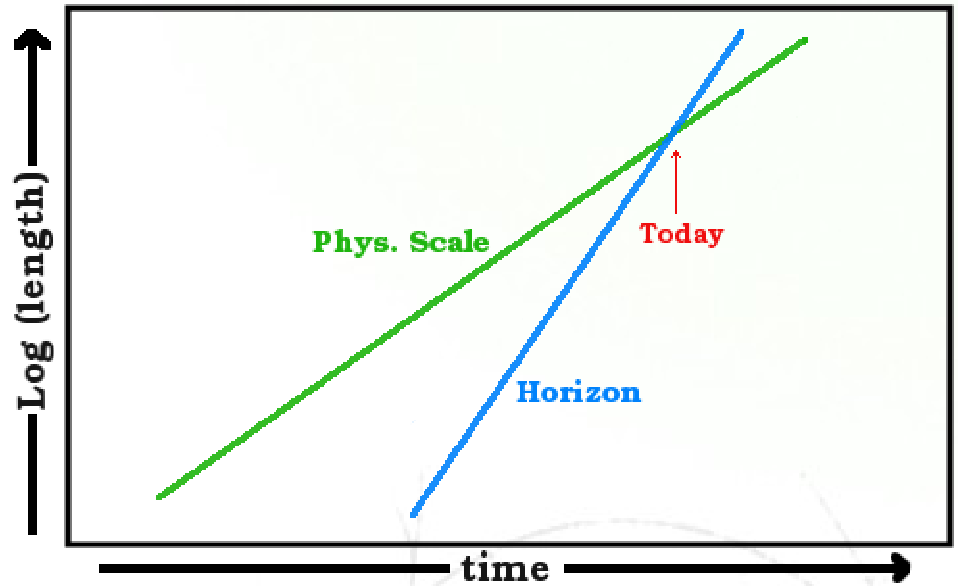
ugr Universidad de Granada

- Horizon problem
  Why the Universe is homogeneous?
- Flatness problem
  Why it is flat?
  $$|\Omega(1s) - 1| < O(10^{-16})$$
- Unwanted relics
  How to avoid them?
- Primordial density perturbation
  What's the origin of structure?



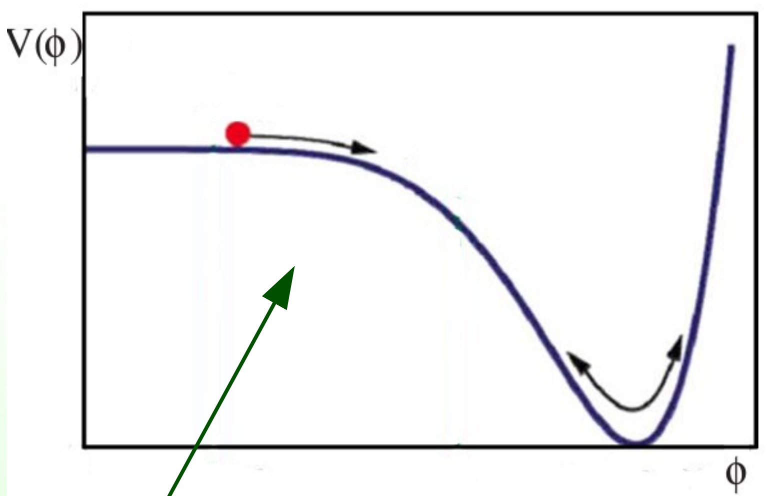
Inflation

(Cold) Inflation

$$\ddot{a} \sim -(\rho + 3p)$$

- Constant ✘
- Scalar field ✔

$$V(\phi) \gg \dot{\phi}^2$$



$$\ddot{\phi} + \underbrace{3H\dot{\phi}}_{\text{friction}} + V_\phi = 0$$

Flat potential

Inflation
interactions?

Reheating
interactions required!

Warm inflation

[Berera'95]

Inflaton coupled to other fields $\mathcal{L} \sim g^2\phi^2\chi^2$

Equation of motion for the quantum effective action

$$\frac{\delta\Gamma}{\delta\phi(x)} = \ddot{\phi} + 3H\dot{\phi} + \frac{\partial V}{\partial\phi} + \int dx'^4 \Sigma_R(x-x')\delta\phi(x) = 0$$

Adiabatic evolution

$$\ddot{\phi} + 3H\dot{\phi} + V_\phi = -\Upsilon(t)\dot{\phi}$$

$$\dot{\rho}_r + 4H\rho_r = +\Upsilon(t)\dot{\phi}^2$$

Dissipation!

- Extra friction
- Smooth graceful exit
- Observational effects

$T > H$

Which interactions?

Thermal corrections to the inflaton mass

$$\mathcal{L} \sim g^2\phi^2\chi^2 \longrightarrow m_\phi^2 \sim \begin{cases} g^2T^2 & m_\chi \ll T \ ✘ \\ g^2 e^{-m_\chi/T} & m_\chi \gg T \end{cases}$$

[Berera,Gleiser&Ramos'98; Yokoyama&Linde'98]

Pattern of interactions
[Berera&Ramos'02]

$$\mathcal{L} \sim g^2\phi^2\chi^2 + hM\chi\sigma^2 \quad \begin{cases} m_\chi \gg T & \text{heavy catalyst field} \\ m_\sigma \ll T & \text{radiation} \end{cases}$$

Supersymmetric version

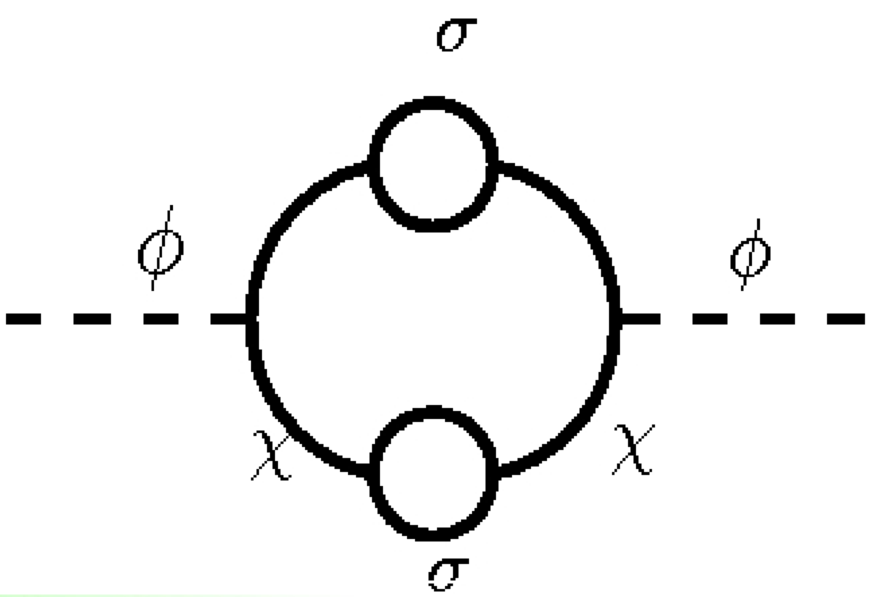
$$W = f(\phi) + \frac{g}{2}\Phi X^2 + \frac{h}{2} X Y^2$$

small radiative corrections

$$g^2 N_X, h^2 N_Y \lesssim 1$$

One loop correction to the inflaton self-energy

$$\Upsilon = \frac{4}{T} g^4 \phi^2 \int \frac{d^4 p}{(2\pi)^4} \rho_\chi^2 n_B (1 + n_B)$$



$$\rho_\chi = \frac{4 w_p \Gamma_\chi}{(p_0^2 - w_p^2)^2 + 4 w_p^2 \Gamma_\chi^2}$$

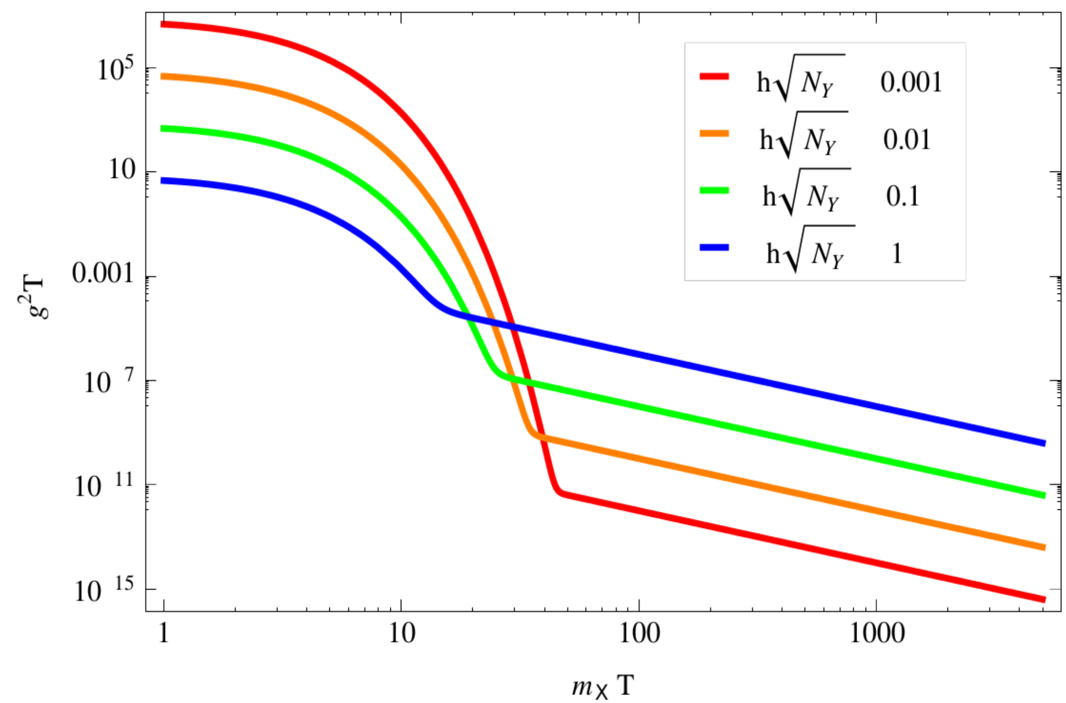
$$w_p^2 = p^2 + m_\chi^2$$

[Moss&Xiong'08; BasteroGil,Berera&Ramos'11]
[BasteroGil,Berera,Ramos&Rosa'12]

- Virtual modes (low-momentum)

$$\Upsilon = C_\phi \frac{T^3}{\phi^2}$$

$$C_\phi = 0.02 h^2 N_X N_Y$$



- On-shell modes (pole)

[BasteroGil,Berera,Ramos&Rosa'12]

$$\Upsilon = \frac{32}{\sqrt{2\pi}} \frac{g^2 N_X}{h^2 N_Y} \sqrt{m_\chi T} e^{-m_\chi/T}$$

Interactions ⟶ Energy transfer

$$\ddot{\phi} + 3H\dot{\phi} + V_\phi = -\Upsilon\dot{\phi}$$
$$\dot{\rho}_r + 4H\rho_r = +\Upsilon\dot{\phi}^2$$

Conditions

- $V(\phi) \gg \dot{\phi}^2$
- $\rho_\phi > \rho_r$
- $T > H$

$$\rho_r = \frac{\pi^2}{30} g_* T^4$$

Strong dissipation

- Smaller scales
- No η-problem
- Steeper potentials

⟶ inflection point inflation

$$V(\phi) \simeq V_0 \left[1 + 3\beta^2 \left(\frac{\phi - \phi_0}{\phi_0}\right) + 4\left(\frac{\phi - \phi_0}{\phi_0}\right)^3\right]$$

Warm inflection ⟶ no fine tunning

[RC&Rosa'12]

For low-momentum dissipation

strong dissipation ⟶ $N_\chi \gtrsim 10^5 - 10^6$

- Larger GUTs, Branes, extra dimensions?

[BasteroGil,Berera&Rosa'12]
[Matsuda'13; Bhattacharjee&Deshamukhya'13]

- Bulk viscosity effects

[DelCampo,Herrera,Pavón,Villanueva'10]
[BasteroGil,RCB,Ramos&Vicente'12]

- Pole dominated dissipation

$$h^2 N_Y < g^2 N_X \lesssim 1$$

[BasteroGil,Berera,Ramos&Rosa'12]

Predictions

[Berera&Fang'95; Berera'95;Berera'00;Moss&Berera'04]

$$\delta\ddot{\phi}_k + 3H(1+Q)\delta\dot{\phi}_k + \frac{k^2}{a^2}\delta\phi_k \simeq \sqrt{2\Upsilon T}a^{-3/2}\xi_k$$

$$Q = \frac{\Upsilon}{3H}$$

Weak dissipation

$$\Delta^2_{\mathcal{R}} \simeq \left(\frac{H_*}{\phi_*}\right)^2 \left(\frac{H}{2\pi}\right)^2 [1 + 2n_* + \kappa_*]$$

$$r \simeq \frac{16\epsilon_\phi}{1 + 2n_* + \kappa_*}$$

dissipation

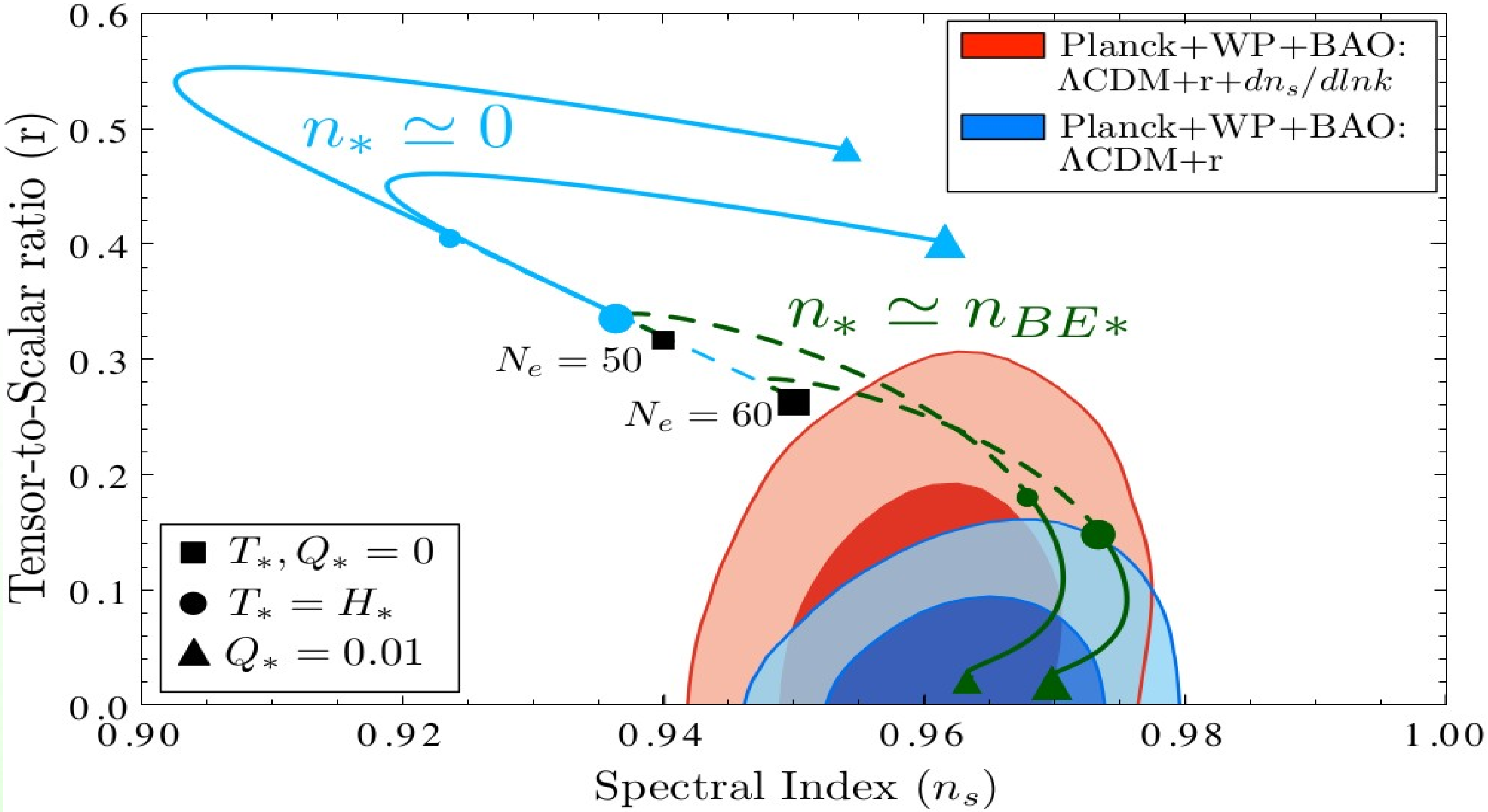
$$\kappa = 2\pi Q \frac{T}{H}$$

inflaton state

$$n_* \begin{cases} \ll 1 & \text{vacuum} \\ (e^{k/aT} - 1)^{-1} & \text{thermal} \end{cases}$$

[Bartrum,BasteroGil,Berera,RC,Ramos&Rosa'13]

Example: quartic potential



$$V = \frac{\lambda}{4}\phi^4$$

$g_* = 228, 75$

- $T \ll H$ ill-defined thermal equilibrium
- $n_*, \kappa_* \ll 1$ larger field values than CI
- $n_* \simeq n_{BE}$ strong suppression

[Bartrum,BasteroGil,Berera,RC,Ramos&Rosa'13]

Thermalization

$$\chi \to \sigma\sigma\phi$$

Thermalization
- decays
- inverse decays
- thermal scatterings

[Anisimov,Buchmuller,Drewes,Mendizabal'09]

$$\frac{\Gamma_{\phi *}}{H_*} \simeq 9(\alpha_h \alpha_g)^{3/2} \left(\frac{1-n_s}{0.04}\right) \left(\frac{0.01}{r}\right)^{3/2} \left(\frac{0.005}{Q_*}\right)^{1/2}$$

$$\alpha_h = \frac{h^2 N_Y}{4\pi} \qquad \alpha_g = \frac{g^2 N_X}{4\pi}$$

not too small

Warm baryogenesis

Out-of-equilibrium dissipation + B,C,CP violation

↓

baryon asymmetry

[BasteroGil,Berera,Ramos&Rosa'12]

- Baryon-to-entropy ratio depends on inflaton

  (no GUT relics or gravitinos) [Bartrum,Berera,&Rosa'12]

- Baryon isocurvature and adiabatic modes anticorrelated

$$B_B \simeq 3(n_s - 1) \simeq -0.12 \qquad n_{iso} \simeq (3 - n_s)/2 \simeq 1.02$$

- Relative matter isocurvature spectrum

$$\beta_{iso} \simeq (\Omega_b/\Omega_c)^2 B_B^2 \simeq 4.8 \times 10^{-4} < 0.0087 \qquad \text{(Planck)}$$

Summary

First principles paradigm:

- significant progress in model building
- interesting implications: dynamics and observations
- $V = \frac{\lambda}{4}\phi^4$ in perfect agreement with Planck
- Prospects: viscosities, BSM, model building...

Thank you!