Supersymmetry Breaking in the Early Universe and the Cosmological Moduli Problem

Ioannis Dalianis

ESR

IFT-University of Warsaw

❖Outline

•Most of the beyond-the-SM theories predict plenty of gravitational interacting particles: the *dilaton*, the *moduli*, the singlet responsible for *susy breaking*, the singlet which *communicates susy breaking* to VS, the *gravitino*,…

•Their energy density in the early universe is expected to be non-negligible

•They have long lifetimes and dissipate their energy very slowly -> problematic for cosmology [*Coughlan,Fischler,Kolb,Raby,Ross '83]*

$$\boxed{\Gamma \approx \frac{m_\phi^3}{8\pi M_P^2}}$$

•There are no well-established solutions

•*Is it possible to address the problem in the very early universe?*

❖“Sources” of the Gravitational Relics

1) Thermal Scatterings in the reheated universe give an *incoherent relic density*

$$Y_\phi \equiv \frac{n_\phi}{s} \approx \alpha \frac{T_{RH}}{M_P}$$

2) Gravitational Production: During inflation quantum fluctuations of moduli of m<H exit the Hubble scale and when they re-enter behave as a homogeneous classical field of

$$\phi_0 = \sqrt{\left\langle (\delta\phi)^2 \right\rangle} \approx 5 m_I \approx 10^{-5} M_P$$

[Goncharov,Linde,Vysotsky’84]

3) Classical Moduli: Generally are expected to have a VEV of order Planck Mass.

• The inflaton finite vacuum energy breaks susy. The masses induced are of *O(H)*

• Also $\delta K = \frac{\pm C^2}{M_P^2} I^+ I \phi^+ \phi$ gives a mass term $\delta L = \pm C^2 \frac{\rho_I}{M_P^2} \phi^+ \phi$

[Dine,Randall,Thomas ’95]

•Furthermore, the form of the potential doesn’t coincide with that of zero temperature H.S. susy breaking. The minima are seperated by $O(M_P)$

To illustrate the possible behavior of the effective potential of the modulus field we can consider the simple model

$$V(\phi) = \frac{1}{2} m_\phi^2 \phi^2 + \frac{1}{2} C^2 H^2 (\phi - \phi_0)^2$$

- C<<1. Modulus mass very small, the damping is slow, quantum fluctuations are not suppressed
- C≈1. Modulus is critically damped and driven to the local minimum $O(M_P)$
- C>>1. As Hubble parameter decreases, the minimum moves and drags with it the scalar field. C>30 could reduce the amplitude of the oscillations by the factor 10^{-10}

[Linde '96]

❖ Cosmological Problems & Constraints

$$\Gamma = \frac{m_\phi^3}{M_{Pl}^2} \begin{cases} < H_0 \rightarrow m_\phi < 20MeV \\ > H_0 \rightarrow m_\phi > 20MeV \end{cases}$$

- The light moduli overclose the universe for $\frac{\delta\phi}{M_P} > 10^{-9}\left(\frac{m_\phi}{100MeV}\right)^{-1/4}$

- The heavy moduli decay causing an entropy crisis except if $Y_\phi \leq 10^{-12} - 10^{-15}$
  For 1TeV modulus this means $\delta\phi \leq 10^{-10} M_P$

So, we don't want the decaying moduli to spoil the

✓ *BBN*, then $T_{RH} > T_{BBN} \approx 6MeV \Rightarrow m_\phi > 10^2 TeV$

✓ *Thermal LSP abundance*, then $T_{RH} > T_{dec} \approx O(1)GeV \Rightarrow m_\phi > 10^5 TeV$

✓ *Baryogenesis*, then $T_{RH} > T_{BG} \approx O(M_{EW}) \Rightarrow m_\phi > \ldots$

❖ Proposed Solutions

1. Making the moduli heavy enough we have the "*moduli induced gravitino problem*"

[Endo,Hamaguchi,Takahashi & Nakamura,Yamaguchi'06]

The branching ratio to gravitini it is found to be $Br_{3/2}(\phi_{R,I} \to 2\psi_{3/2}) \cong O(1-0.01)$
which violates the bounds
a) $Y_{3/2} \leq Y_{DM}$ if gravitino is the LSP, and *b)* $Y_{3/2} < 10^{-12}$ if it isn't the LSP.

2. Weak scale inflation , where $H = O(m_{3/2})$

[Randall,Thomas '94]

3. Thermal Inflation, where $H_{th} \approx O(1MeV - 1KeV)$

[Lyth, Stewart '95]

The low scale inflation models have drawbacks like

- There is a lower bound on the mass of the moduli that can be diluted
- The reheating temperature too low
- There is an additional misalignment with the post-inflationary minimum

The goal was to look for a way to drive moduli can be driven to the true minimum in the very early universe, e.g. during the phase of the original high scale inflation. This could provide an elegant solution to the problem.
The idea is to look for terms that could counteract the term which cause the misalignment of the low and high energy minima.

$$V(\phi) = \frac{1}{2} m_\phi^2 \phi^2 + \frac{1}{2} C^2 H^2 (\phi - \phi_0)^2$$

In the Sugra Lagrangians there are interaction terms that depend on the mass of the final state, i.e. $\delta L = -\left(\frac{m_\chi}{M_P}\right)^2 \phi^2 \chi^2$ which induces an effective mass $m^2_{\chi,eff} = \frac{m^2_\chi(0)}{1 - \phi^2 / M_P^2}$

So now the effective potential is written

$$\boxed{V_{eff}(\phi) = \frac{1}{2} m_\phi^2 \phi^2 + \frac{1}{2} C^2 H^2 (\phi - \phi_0)^2 + \frac{m^2_\chi(0)}{1 - \phi^2 / M_{|P}^2} \chi^2 \phi^2}$$

• If we want the last term to be significant, *the χ field must dominate the energy density of the universe.*

❖The χ field is the Inflaton

•The effective potential is written

$$V_{eff}(\phi) = \frac{1}{2} m_\phi^2 \phi^2 + \frac{1}{2} C^2 H^2 (\phi - \phi_0)^2 + \frac{m_{I,eff}^2}{M_P^2} I^2 \phi^2 = \frac{1}{2} m_\phi^2 \phi^2 + \frac{1}{2} C^2 H^2 (\phi - \phi_0)^2 + 6H^2 \phi^2$$

which gives an equation of motion

$$\ddot{\phi} + 3H\dot{\phi} + \left(m_\phi^2 + C^2 H^2 + 12H^2\right)\phi = C^2 H^2 \phi_0$$

The temporal minimum of the effective potential is

$$\boxed{\phi_{\min} = \frac{C^2 H^2}{m_\phi^2 + C^2 H^2 + 12H^2} \phi_0}$$

Considering initial values $\phi(t_i) = \phi_i, \quad \dot{\phi}(t_i) = 0$ the final value of the field is

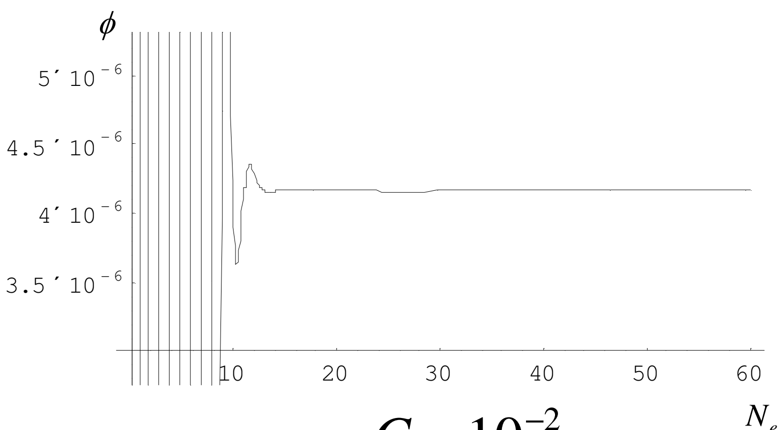
$$\phi_f \approx \phi_{\min} + \left(\phi_i - \phi_{\min}\right) \times O(e^{3N_e/2})$$

❖The Parameter C

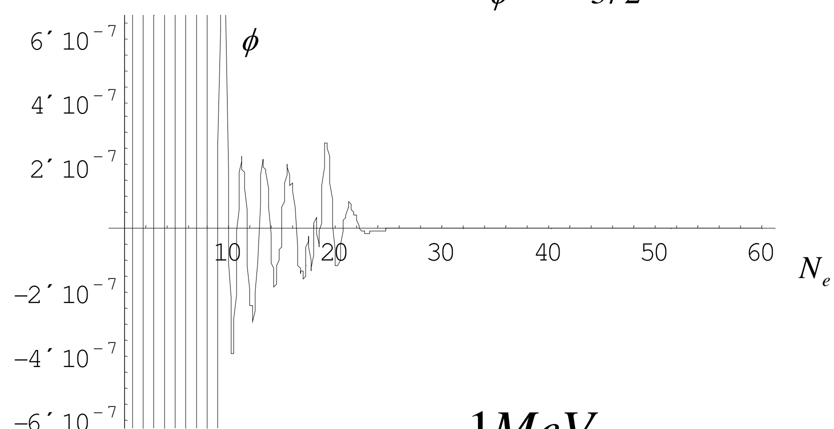
•The effective minimum is very close to the low energy minimum for $C << 1$
For $C = O(1)$ the $\phi_{\min} \approx \phi_0 \approx M_P$ and the problem remains.

•We see that for $C \leq 10^{-4}$ the modulus satisfies the cosmological bounds on the initial displacement.

•The parameter C is a coefficient of the induced mass because of the susy breaking. It is reasonable to quantify it a measure of how strongly the field couples to the susy breaking environment. *It could be expected to have a form:* $C \approx m_\phi / m_{3/2}$



$$C = 10^{-2}$$



$$C = \frac{1MeV}{20TeV} \approx 10^7$$

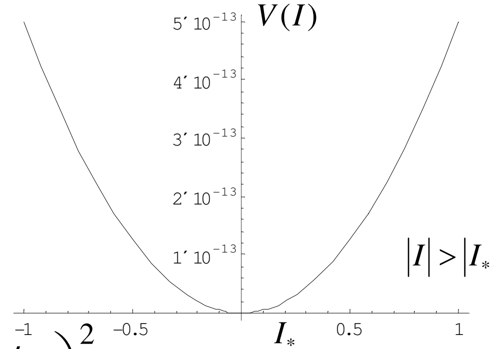
❖The χ is a resonance during Preheating (2nd stage)

•The relevant part of the Lagrangian is

$$\delta L = \frac{1}{2} m_\phi^2 \phi^2 + \frac{1}{2} C^2 H^2 (\phi - \phi_0)^2 + \frac{1}{2} m_\chi^2(0) \chi^2 + \frac{1}{2} \sigma \chi^2 I^2 + \frac{1}{2} \frac{m_{\chi,eff}^2}{M_P^2} \chi^2 \phi^2$$

Where

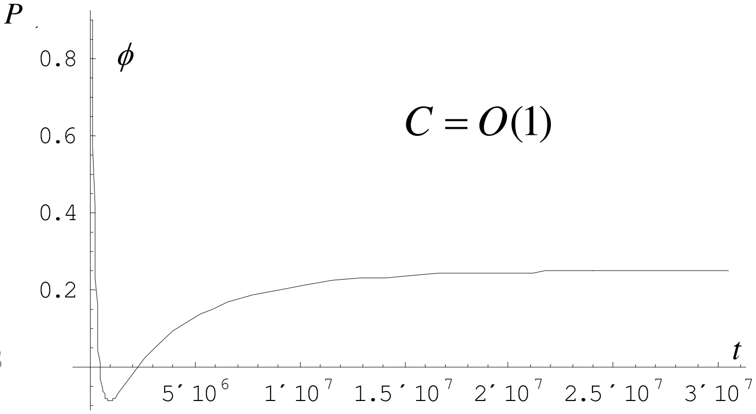
$$m_{\chi,eff}^2 = \frac{m_\chi^2(0) + \sigma^2 I^2(t)}{1 - \phi^2 / M_P^2} \quad , \quad \langle \chi^2 \rangle \approx \frac{n_\chi}{m_{\chi,eff}} \quad , \quad \boxed{\frac{\rho_\chi}{\rho_I} \approx 2\sigma^{5/2}}$$



•The equation of motion is

$$\ddot{\phi} + 3H\dot{\phi} + C^2 H^2 (\phi - \phi_0) + \frac{3\alpha H^2}{\left(1 - \frac{\phi^2}{M_P^2}\right)^{3/2}} \phi - \frac{3\alpha H^2}{\left(1 - \frac{\phi^2}{M_P^2}\right)^{3/2}} \frac{1}{2} \left(\frac{\phi}{M_P}\right)^2 \phi = 0$$

The field generally doesn’t oscillate.



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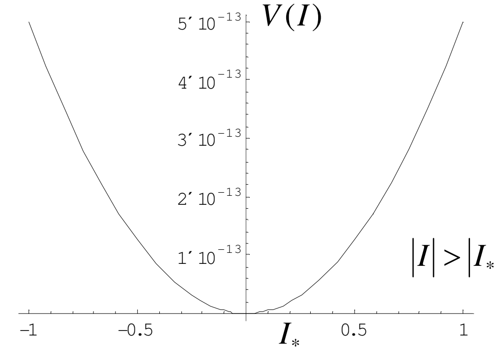

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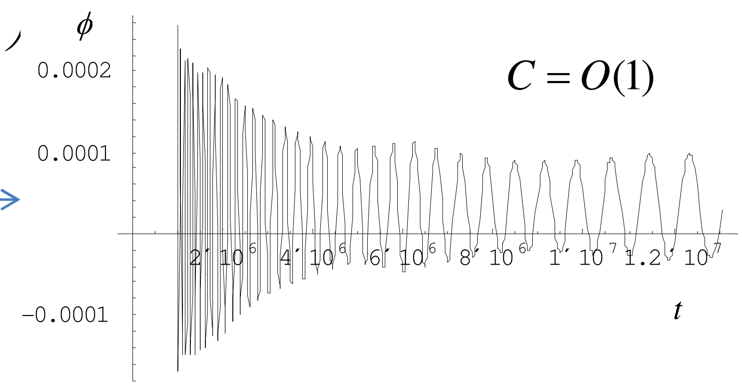
$$\ddot{\phi} + 3H\dot{\phi} + C^2 H^2 (\phi - \phi_0) + \frac{3\alpha H^2 \left(\frac{M_P}{M_S}\right)^2}{\left(1 - \frac{\phi^2}{M_P^2}\right)^{3/2}} \phi - \frac{3\alpha H^2 \left(\frac{M_P}{M_S}\right)^2}{\left(1 - \frac{\phi^2}{M_P^2}\right)^{3/2}} \frac{1}{2} \left(\frac{\phi}{M_P}\right)^2 \phi = 0$$

However, if we assume that the field ϕ has $M_S = O(0.1 - 0.01) M_P$ suppressed interactions then it oscillates vividly, and a weak trapping mechanism can take place.



❖Conclusions

•An interaction term of the form $\delta L = -(m_\chi^2 / M_P^2)\chi^2\phi^2$ can have a significant contribution to the effective potential if the χ field dominates the energy density.

•If $C < 10^{-4}$ then the $\delta L = -(m_I^2 / M_P^2) I^2 \phi^2$ term dominates and there are *no cosmological problems* even in the case that the high energy offset is $O(M_P)$
Such a small value of the parameter C could be reasonable for light moduli.

•However, if trilinear terms $\delta L = -(m_\chi^2 / M_P)\chi^2\phi$ are present in the Lagrangian, then they dominate and the effective potential induced by this coupling is not symmetric about the origin. Therefore, *the mechanism works for Lagrangians that cubic terms are absent, or have reflection symmetry.*

•*The moduli dissipates its energy efficiently only during inflation*. A preheating phase (and generally, every post-inflationary phase) can force the moduli to oscillate but its amplitude will not decay efficiently.