Warm inflation in supersymmetric models

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Overview

- Review warm inflation

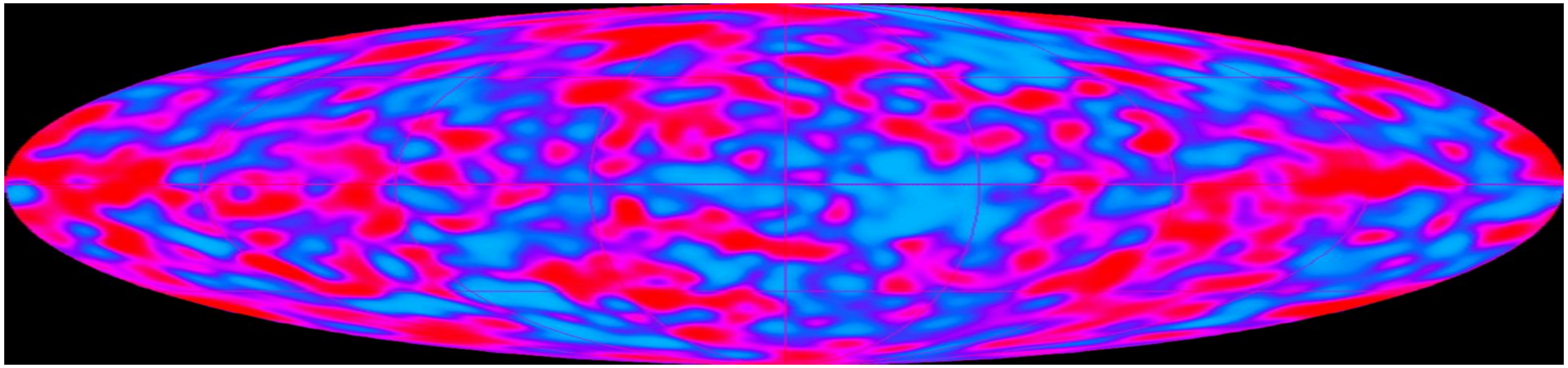
- Study of $g^2\phi^2\chi^2$, $g\phi\bar{\psi}\psi$ interactions *during* inflation

- SUSY models

- Observational implications

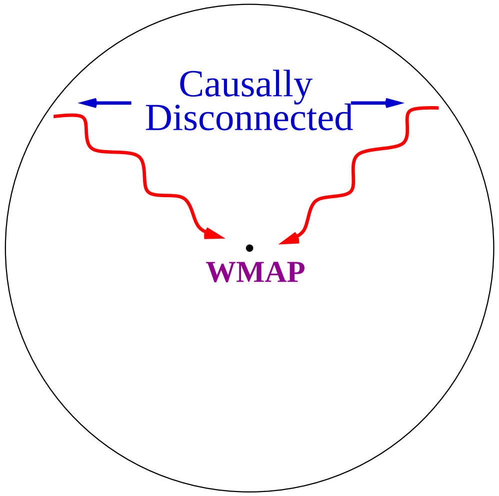
- Conclusions

Inflation

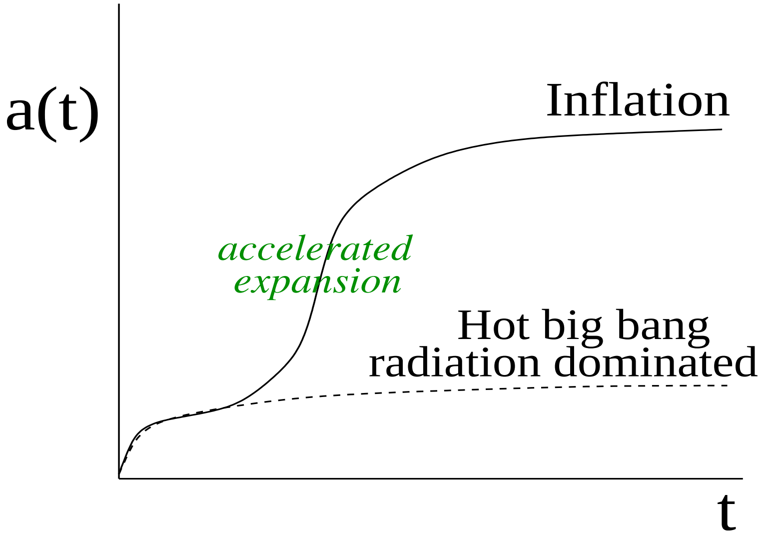


The puzzle of cosmological initial conditions:

$\frac{\Delta T}{T} < 10^{-5}$ in CMBR without causal contact



The inflation solution (1981+)

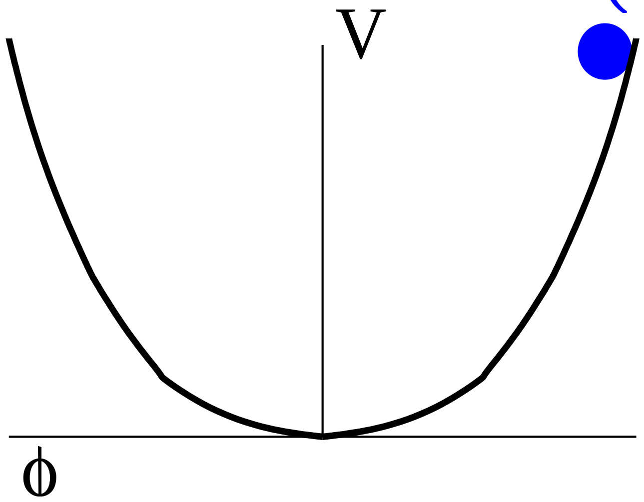


Accelerated expansion $\ddot{a}(t) > 0$

implies $\rho + 3p < 0$

How to get from high energy physics?

Scalar field ("inflaton") dynamics



$$\rho = \frac{\dot\phi}{2} + V(\phi) + \frac{(\nabla\phi)^2}{2R^2}$$

$$p = \frac{\dot\phi}{2} - V(\phi) - \frac{(\nabla\phi)^2}{6R^2}$$

- Cold inflation: Just Choose $V(\phi)$

$$\ddot\phi + 3H\dot\phi + V'(\phi) = 0$$

Potential energy dominated $3H\dot\phi \gg \ddot\phi$, "slow-roll"

- Warm Inflation: Υ dominates

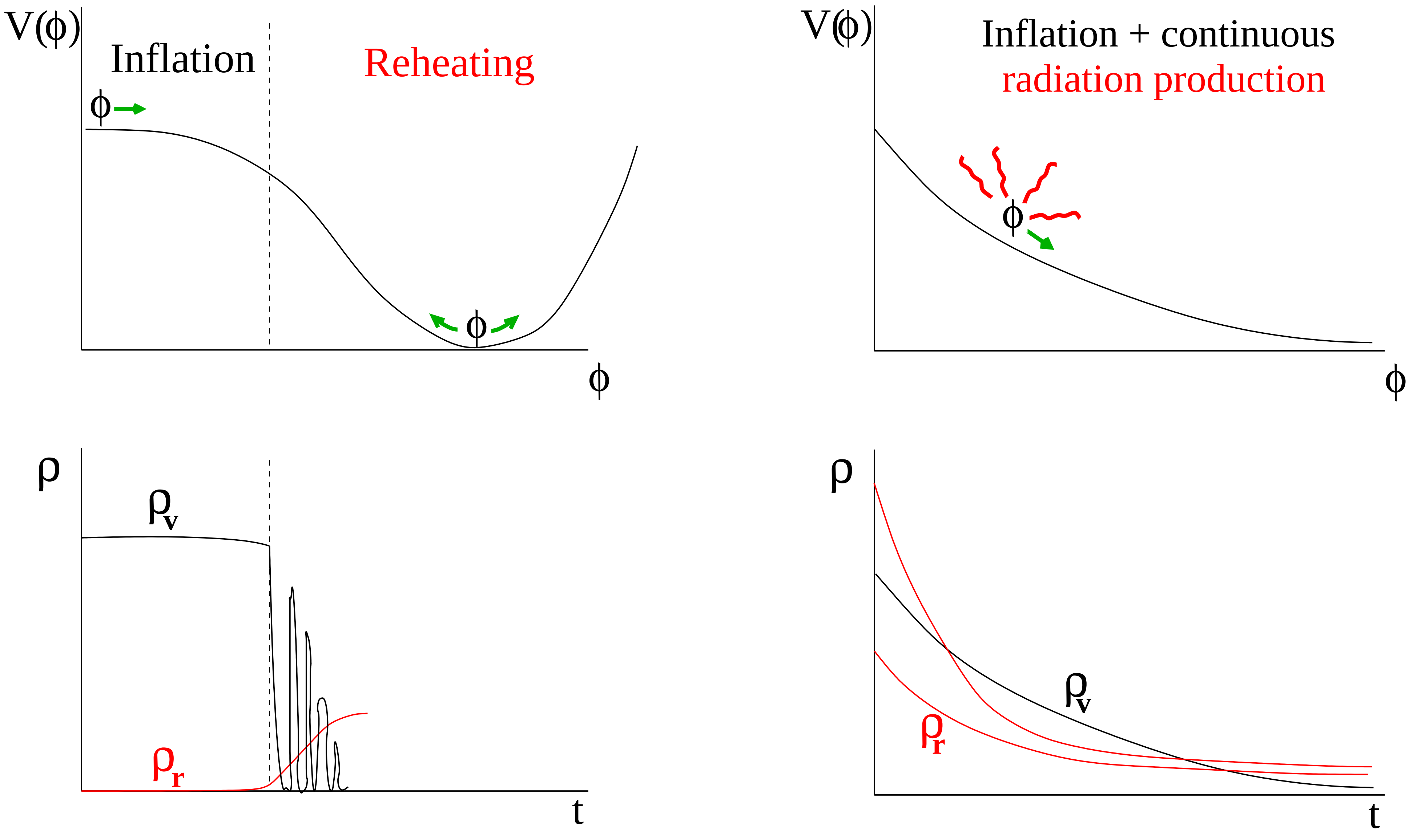
$$\ddot\phi + 3H\dot\phi + \Upsilon\dot\phi + V'(\phi) = 0$$

Slow-roll now means $\Upsilon\dot\phi \gg 3H\dot\phi, \ddot\phi$, overdamped

Two basic inflation pictures

Cold Inflation

Warm Inflation



Road to Prediction

(Ingredients to build theory of the early universe)

- Particle physics model

- Nonequilibrium (dissipative) dynamics

- Further issues

- Observational tests

Nature of the fluctuations

Thermal/quantum fluctuations leave "ripples" in early universe

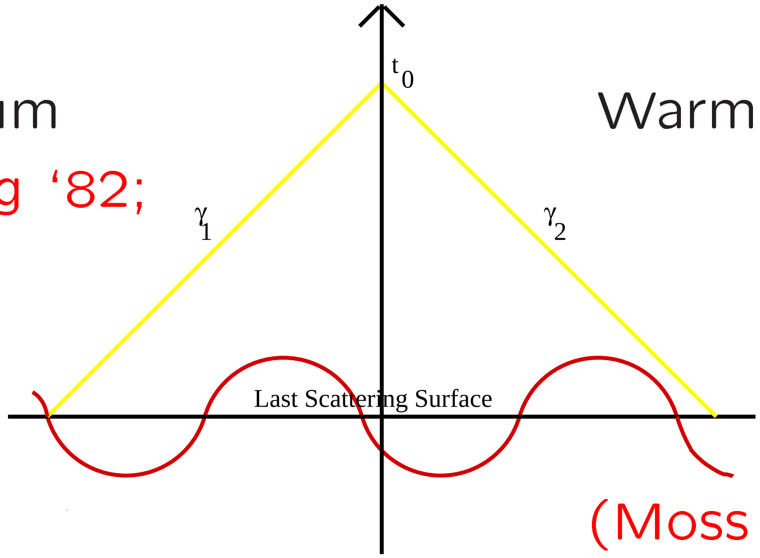
- imprinted on CMBR at Last Scattering
- amplified by gravity to make structure

Cold inflation: Quantum

(Guth, Pi '82; Hawking '82;

Starobinsky '82;

Bardeen *et. al.* '83)



Warm Inflation: Thermal

$$\delta\phi = \frac{k_F^{1/2} T^{1/2}}{2\pi}$$

$$\Upsilon < 3H : k_F = H$$

(Moss '85, AB,Fang '95)

$$\delta\phi = \frac{H}{2\pi}$$

$$\Upsilon > 3H : k_F = \sqrt{\Upsilon H}$$

(AB '99)

$$\frac{\delta\rho}{\rho} = \frac{H\delta\phi}{\dot{\phi}}\Bigg|_{\text{HORIZON EXIT}}$$

Role of particle physics

Feature	Particle Physics	Cosmology
Spontaneous symmetry breaking	mass generation	scalar fields (inflaton)
Standard model	explains collider experiments	particle spectrum (visible + dark)
Supersymmetry	solves hierarchy problem	explains flat potentials
Strings/Planck scale physics	explains gravity	solves cosmological constant problem

Energetics

- Consider GUT scale inflation: $M \sim 10^{15}$GeV

$$\Rightarrow \qquad \rho_v \sim M^4 \sim 10^{60}\text{GeV}^4 \quad \Rightarrow \quad \text{H} \sim 10^{10}\text{GeV}$$

  $\text{T} > \text{H}$ requires > 1 part in $\sim 10^{20}$ of $\rho_v \rightarrow \rho_r$
  (influences structure formation)
  $\text{T} > 1\text{GeV}$ requires > 1 part in $\sim 10^{60}$ of $\rho_v \rightarrow \rho_r$
  (makes reheating unnecessary)

- Inflation pictures
  1. Cold inflation: basic assumption is no dissipation
  2. Warm inflation: radiation production inherent (AB, PRL **75**, 3218 (1995))

- Theoretical consideration
  Equipartition Hypothesis of Statistical Mechanics: *Scalar field should distribute its energy evenly amongst all degrees of freedom.*

  Dynamical Question: *Will relevant time scales during inflation prohibit the minute' radiation production given above?*

Scalar Field (Φ) Dynamics

$$\mathcal{L}_\Phi = \frac{1}{2}(\partial_\mu \Phi)^2 - \frac{m_\phi^2}{2}\Phi^2 - \frac{\lambda}{4!}\Phi^4$$

$$\mathcal{L}_I = -\Phi \sum_{j=1}^{N_\psi} h_j \bar{\psi}_j \psi_j, \; -\frac{1}{2}\sum_{j=1}^{N_\chi} g_j^2 \Phi^2 \chi_j^2 + \cdots$$

- Decompose into background φ and fluctuations ϕ: $\Phi = \varphi + \phi$
- Effective equation of motion (EOM) for $\varphi(t)$:

$$\ddot{\varphi}(t) + 3H\dot{\varphi}(t) + \xi R \varphi(t) + m_\phi^2 \varphi(t) + \frac{\lambda}{6}\varphi^3(t) + \varphi(t)\sum_{j=1}^{N_\chi} g_j^2 \langle \chi_j^2 \rangle + \cdots = 0$$

with $\langle \phi^2 \rangle$, $\langle \phi^3 \rangle$ and $\langle \chi_j^2 \rangle$ etc... evaluated perturbatively

Closed Time Path approach - Goal

Compute Observable

$$\langle \hat{O}(t) \rangle \equiv \frac{\mathrm{Tr}(\hat{\rho}(t)\hat{O})}{\mathrm{Tr}(\hat{\rho}(t))}$$

Thermal initial state at $T^<$:

$$\rho(T^<) = \exp(-\beta H) = U(T^< - i\beta, T^<)$$

($U(t,t') \equiv \exp[-iH(t-t')]$, time evolution operator)

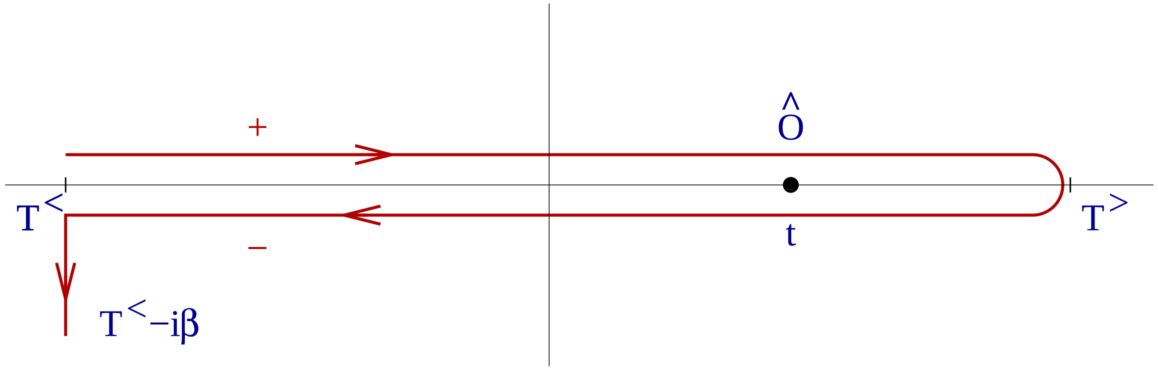
Thus

$$\langle \hat{O}(t) \rangle = \frac{\mathrm{Tr}[U(T^< - i\beta, T^<)\, U(T^<, t)\, \hat{O}\, U(t, T^<)]}{\mathrm{Tr}[U(T^< - i\beta, T^<)]}$$

Also add large positive time $T^>$

$$\langle \hat{O}(t) \rangle = \frac{\mathrm{Tr}[U(T^< - i\beta, T^<)\, U(T^<, T^>)\, U(T^>, t)\, \hat{O}\, U(t, T^<)]}{\mathrm{Tr}[U(T^< - i\beta, T^<)]}$$

Closed Time Path approach - Method



Can express as a path integral

recall $$U(t,t') \equiv \int \mathcal{D}\Phi \,\mathsf{exp}\left(i\int_{t'}^{t} d^4x\mathcal{L}[\Phi]\right)$$

$$\begin{aligned} Z[J^+,J^-,J^\beta] &= \mathsf{Tr}[U(T^< - i\beta, T^<; J^\beta)U(T^<,T^>;J^-)U(T^>,T^<;J^+)] \\ &= \int \mathcal{D}\Phi^+\mathcal{D}\Phi^-\mathcal{D}\Phi^\beta \,\mathsf{exp}\left(i\int_{T^<}^{T^>} d^4x[\mathcal{L}^{J^+}[\Phi^+] - \mathcal{L}^{J^-}[\Phi^-]] + i\int_{T^<}^{T^<-i\beta} d^4x\mathcal{L}^{J^\beta}[\Phi^\beta]\right) \end{aligned}$$

e.g. scalar field theory:

$$\mathcal{L}^J[\Phi] = \frac{1}{2}[\partial_\mu\Phi\partial^\mu\Phi - m^2\Phi^2] - \frac{\lambda}{4!}\Phi^4 + J\Phi$$

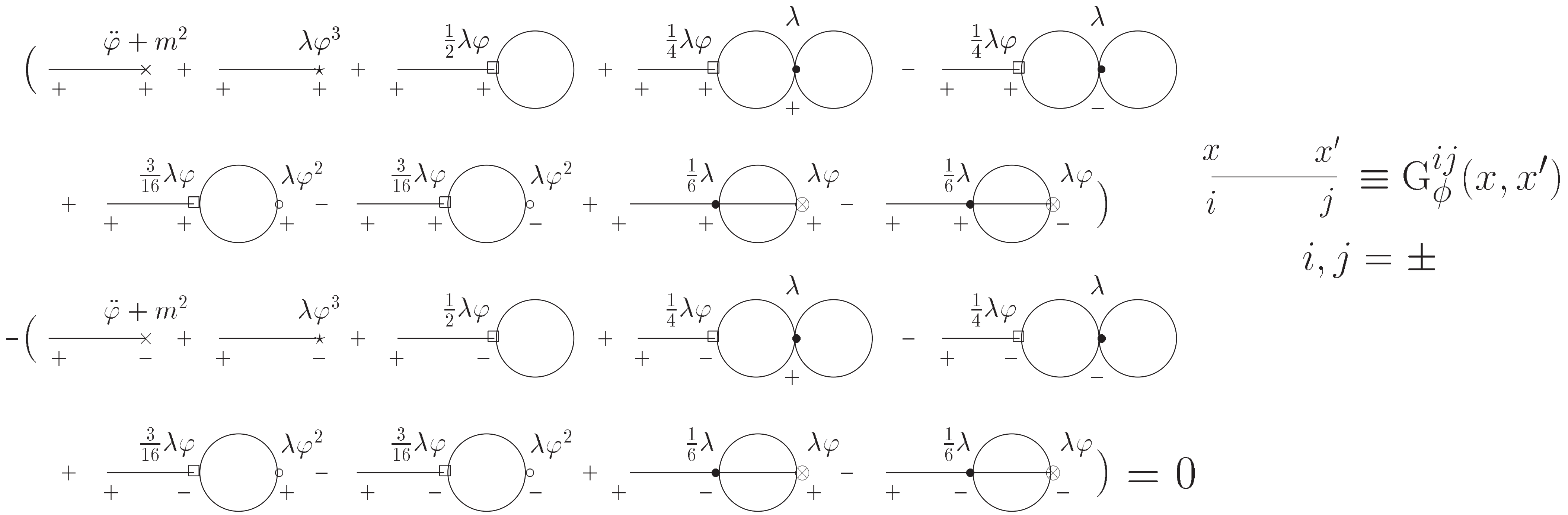
How to obtain the φ-effective EOM

Tadpole Method: demand $\langle\phi\rangle = 0$ and compute

Example: $S = \int d^4x \left[\frac{1}{2}\partial_\mu\Phi\partial^\mu\Phi - \frac{m^2}{2}\Phi^2 - \frac{\lambda}{4!}\Phi^4\right]$, $\quad \Phi = \varphi + \phi \Longrightarrow$

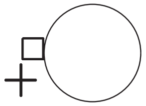
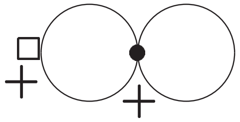
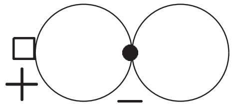
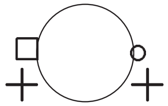
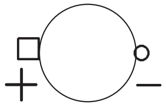
$$S = \int d^4x[-\varphi\frac{1}{2}[\Box + m^2]\varphi - \phi\frac{1}{2}[\Box + m^2]\phi - \phi[\Box + m^2]\varphi - \frac{\lambda}{4!}(\varphi^4 + 4\varphi^3\phi + 6\varphi^2\phi^2 + 4\varphi\phi^3 + \phi^4)]$$

$\langle\phi\rangle = 0$ at lowest nontrivial order $\Longrightarrow$

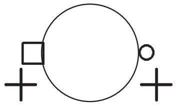
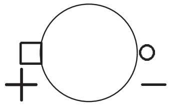


Tadpole Method (cont.) - Explicit EOM

( ) =0 $\Longrightarrow$

$0 = \int d^4x' G_\phi^{++}(x,x')$ [$\times$ + $\star$ +  +  −  +  −  + ...]

$\Longrightarrow$ [ ] = 0, now convert to analytic expression

e.g.  − 

$$= \frac{3}{16}\lambda^2\varphi(t')\int d^4y[G_\phi^{++}(x',y)G_\phi^{++}(x',y) - G_\phi^{+-}(x',y)G_\phi^{+-}(x',y)]\varphi^2(t_y)$$

$$= \frac{3}{8}\lambda^2\varphi(t')\int d^4y Im[G_\phi^{++}(x',y)G_\phi^{++}(x',y)]\varphi^2(t_y), \quad \text{etc} \ldots$$

Final Expression:

$$\ddot{\varphi} + 3H\dot{\varphi} + m^2\varphi + \frac{\lambda}{6}\varphi^3 + \overset{local\ 1-loop\ V_{eff}}{terms} + \frac{3}{8}\lambda^2\varphi(t')\int d^4y Im[G_\phi^{++}(x',y)G_\phi^{++}(x',y)]\varphi^2(t_y)$$

$$+ \frac{1}{3}\lambda^2\int d^4y Im[G_\phi^{++}(x',y)G_\phi^{++}(x',y)G_\phi^{++}(x',y)]\varphi(t_y) = 0$$

Green's function $G_\phi^{ij}(x,x')$ - Basic Properties

$$G_\phi(x,x') = \begin{pmatrix} G_\phi^{++}(x,x') & G_\phi^{+-}(x,x') \\ G_\phi^{-+}(x,x') & G_\phi^{--}(x,x') \end{pmatrix} = \begin{pmatrix} i\langle T_+\phi(x)\phi(x')\rangle & i\langle\phi(x')\phi(x)\rangle \\ i\langle\phi(x)\phi(x')\rangle & i\langle T_-\phi(x)\phi(x')\rangle \end{pmatrix}$$

Fourier space: $G_\phi(x,x') = i\int \frac{d^3q}{(2\pi)^3} e^{i\mathbf{q}.(\mathbf{x}-\mathbf{x}')}\tilde{G}_\phi(\mathbf{q},t-t')$

$$\begin{aligned}
\tilde{G}_\phi^{++}(\mathbf{q},t-t') &= \tilde{G}_\phi^{>}(\mathbf{q},t-t')\theta(t-t') + G_\phi^{<}(\mathbf{q},t-t')\theta(t'-t), \\
\tilde{G}_\phi^{--}(\mathbf{q},t-t') &= \tilde{G}_\phi^{>}(\mathbf{q},t-t')\theta(t'-t) + G_\phi^{<}(\mathbf{q},t-t')\theta(t-t'), \\
\tilde{G}_\phi^{+-}(\mathbf{q},t-t') &= \tilde{G}_\phi^{<}(\mathbf{q},t-t'), \\
\tilde{G}_\phi^{-+}(\mathbf{q},t-t') &= \tilde{G}_\phi^{>}(\mathbf{q},t-t')\ .
\end{aligned}$$

Hermiticity: $\tilde{G}_\phi^{>*}(\mathbf{q},t-t') = \tilde{G}_\phi^{>}(\mathbf{q},t'-t)$

Continuity: $\frac{d}{dt}\left[\tilde{G}^{>}(\mathbf{q},t-t') - \tilde{G}_\phi^{>}(\mathbf{q},t'-t)\right]|_{t=t'} = i\delta(t-t')$

Green's Function $G_\phi(x, x')$ - Resummed Expression

Solve by Schwinger-Dyson equations

$$\left[\Box + m_\phi^2 + \frac{\lambda}{2}\varphi^2\right] G_\phi(x, x') + \int d^4z \Sigma_\phi(x, z) G_\phi(z, x') = i\delta(x, x')$$

Solution, $G_\phi^>(\mathbf{q}, t - t') =$

$$\frac{1}{2\omega_\phi}\left\{[1 + n_\phi(\omega_\phi - i\Gamma_\phi)]e^{-i(\omega_\phi - i\Gamma_\phi)(t-t')} + n_\phi(\omega_\phi + i\Gamma_\phi)e^{i(\omega_\phi + i\Gamma_\phi)(t-t')}\right\}\theta(t - t')$$
$$+\frac{1}{2\omega_\phi}\left\{[1 + n_\phi(\omega_\phi + i\Gamma_\phi)]e^{-i(\omega_\phi + i\Gamma_\phi)(t-t')} + n_\phi(\omega_\phi - i\Gamma_\phi)e^{i(\omega_\phi - i\Gamma_\phi)(t-t')}\right\}\theta(t' - t),$$

$$G_\phi^<(\mathbf{q}, t - t') = G_\phi^>(\mathbf{q}, t' - t)$$

n_ϕ - Bose distribution function, $\omega_\phi \equiv \omega_\phi(\mathbf{q})$ and $\Gamma_\phi(q) = \frac{\mathrm{Im}\Sigma_\phi(\mathbf{q}, \omega_\phi)}{2\omega_\phi}$

Robust dissipative mechanism

(AB and R. Ramos, PRD **63**, 103509 (2001) & PRD **71**, 023513 (2005))

Lagrangian (encompasses reheating/hybrid inflation models):

$$\mathcal{L}_I = -\frac{1}{2}g^2\phi^2\chi^2 - g'\phi\bar{\psi}_\chi\psi_\chi - h\chi\bar{\psi}_d\psi_d,$$

Regime $m_\chi > 2m_\psi > m_\phi$: $\Longrightarrow$ $\phi \to \chi \to \psi_d$:
copious radiation production

e.g. GUT scale $V^{1/4}(\varphi) \sim 10^{15}\text{GeV} \Longrightarrow T \sim 10^{14}\text{GeV}$

Physical Picture

- The evolution of $\varphi(t)$ changes χ-mass $\Longrightarrow$ χ-particle production from mixing $+/-$ frequency modes
(If left intact, quantum correlations of χ-field persist)
- Coupling χ to lighter ψ_d-field $\Longrightarrow$ χ-particles decay to ψ_d-particles, decohere χ-field
- Entire process backreacts on φ $\Longrightarrow$ dissipative effects

φ-effective equation of motion

$$\ddot{\varphi}(t) \;+\; 3H(t)\dot{\varphi}(t) + \xi \mathsf{R}(t)\varphi(t) + \frac{dV_{\mathrm{eff}}(\varphi(t))}{d\varphi(t)}$$
$$+\; g^4\varphi(t)\int_{t_0}^{t} dt'\varphi(t')\dot{\varphi}(t')K(t,t') = 0,$$

where

$$K(t,t') = \int_{-\infty}^{t'} dt'' \int \frac{d^3q}{(2\pi)^3}\,\mathrm{sin}\left[2\int_{t''}^{t} d\tau\omega_\chi(\tau)\right] \times \frac{\exp\left[-2m_\chi\Gamma_\chi\int_{t''}^{t} d\tau/\omega_\chi(\tau)\right]}{4\omega_\chi(t)\omega_\chi(t'')},$$

$$\omega_\chi(\tau) = \left[\mathbf{q}^2\frac{a(t)}{a(\tau)} + m_\chi^2(\tau) + 2(6\xi-1)H\right]^{1/2},$$

$$m_\chi = g\varphi \qquad \Gamma_\chi \approx \frac{h^2 m_\chi}{8\pi} \qquad H = \sqrt{\frac{8\pi V_{\mathrm{eff}}}{3m_p^2}} \qquad a(t) \approx \exp(Ht)$$

Adiabatic-Markovian Approximation

For $\frac{\dot{\varphi}}{\varphi} < H, \Gamma_\chi$; $H < \Gamma_\chi, m_\chi$; φ-effective EOM becomes:

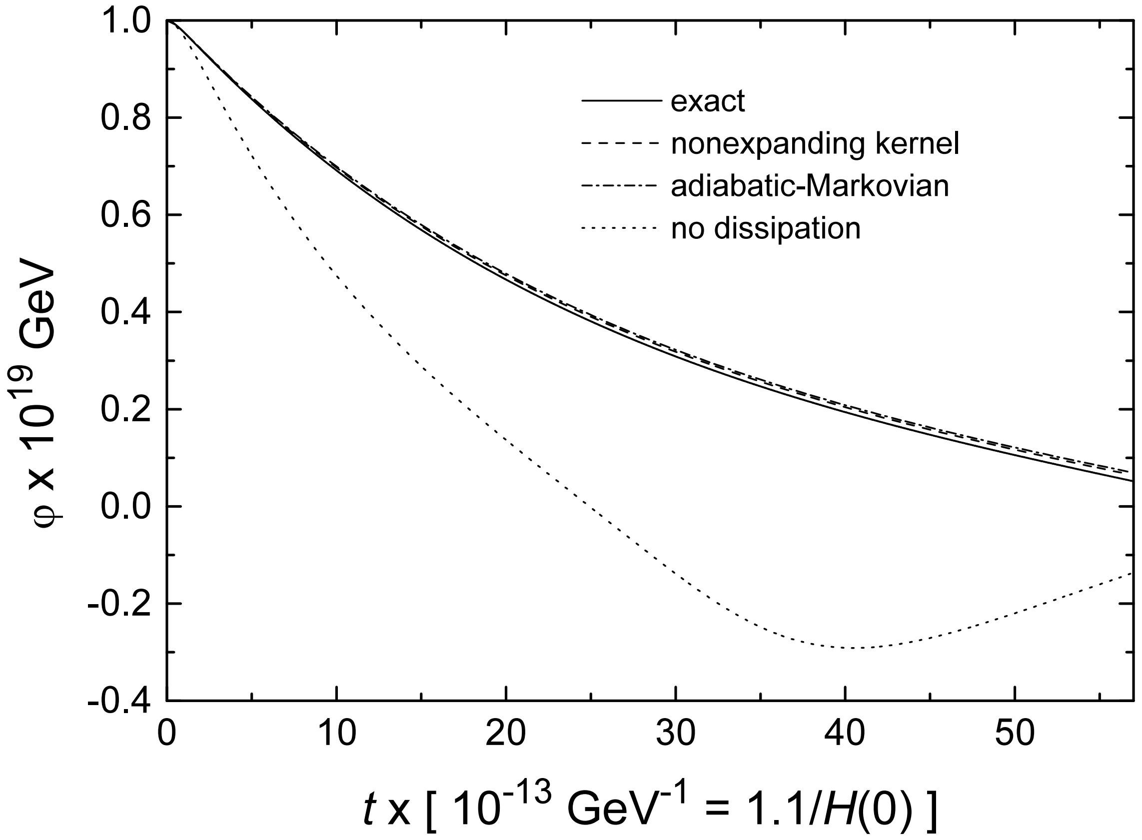
$$\ddot{\varphi} + [3H + \Upsilon(\varphi)]\dot{\varphi} + \xi R \varphi + \frac{dV_{\text{eff}}(\varphi)}{d\varphi} = 0,$$

where

$$\Upsilon(\varphi) = \frac{g^4 \varphi^2(t) \Gamma_\chi}{32\pi \sqrt{m_\chi^2 + \Gamma_\chi^2} \sqrt{2m_\chi \sqrt{m_\chi^2 + \Gamma_\chi^2} + 2m_\chi^2}}.$$

Results - comparing approximations

Evolution of $\varphi(t)$ for $V = \frac{\lambda}{4}\varphi^4$, $\lambda = 10^{-13}$, $g = h = 0.37$, $\xi = 0$, $\varphi(0) = m_p$, $\dot{\varphi}(0) = 0$.



$T > H$ during inflation (so affects $\delta\varphi$) for e.g., $g = h > 10^{-2}$ or $h = 0.1, g > 10^{-3}$

Interaction generic in inflation models

- $g^2\phi^2\chi^2$ generic to inflation models (for reheating)
- for $g \gtrsim 10^{-3}$ require SUSY for flat potential
- Minimal SUSY model with this interaction $W = \sqrt{\lambda}\Phi^3 + g\Phi X^2$

  $(\Phi = \phi + \theta\psi + \theta^2 F,\ X = \chi + \theta\psi_\chi + \theta^2 F_\chi)$

  $$\Longrightarrow \mathcal{L}_{int} \sim \frac{1}{4}g^2|\phi|^2|\chi|^2 + \frac{1}{4}g\phi\psi_\chi\psi \cdots$$

- For $\langle\phi\rangle \equiv \varphi \neq 0$ SUSY is broken with $m_{\chi_1} \gg m_{\psi_\chi} \gg m_{\chi_2}$

  $(V_{1-loop} \sim g\lambda\varphi^4 < V_{tree} \sim \lambda\varphi^4$, so flatness preserved)
- $\Longrightarrow$ dissipative mechanism through $\phi \to \chi_1 \to \psi + \psi_\chi$

  just like our toy model, so all results follow

Worked example - no η-problem

Model: $V = \frac{m^2}{2}\varphi^2$

$$\Longrightarrow N_e \approx 2\sqrt{2}\frac{\varphi_0}{m}\frac{\Upsilon}{m_p},\ T \approx \frac{m^{3/4} m_p^{1/4} \varphi_0^{1/4}}{\Upsilon^{1/4}},\ \frac{\delta\rho}{\rho} \approx \left(\frac{\varphi_0}{m}\right)^{3/8}\left(\frac{\Upsilon}{m_p}\right)^{9/8}$$

For $N_e = 60$, $\frac{\delta\rho}{\rho} = 10^{-5} \Longrightarrow \frac{\varphi_0}{m} \approx 6 \times 10^8$, $\frac{\Upsilon}{m_p} \approx 4 \times 10^{-8}$

e.g., $m = 10^9$GeV $\Longrightarrow \frac{H}{m} \approx 0.17$, $\frac{\varphi_0}{m_p} \approx 6 \times 10^{-2}$, $T \approx 10^4 m$

- No η-problem: $\underline{m > H}$
- No φ amplitude problem: $\underline{\varphi < m_p}$
- No graceful exit problem: inflation $\rightarrow$ RD automatic
- No quantum-to-classical trans. problem: $\delta\varphi$ classical

Cosmological perturbations - Examples

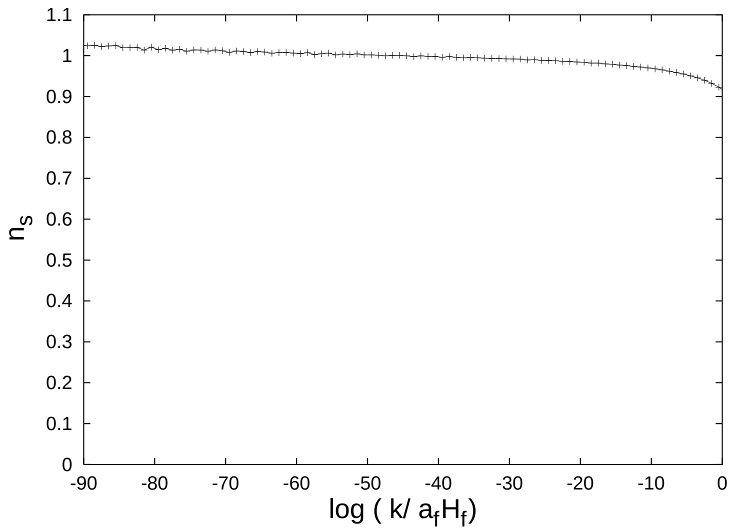
(Hall, Moss, Berera, PRD **69**, 083525 (2004), Phys. Lett. B**589**, 1 (2004))

Soft SUSY breaking:

$$V = \mu^2\phi^2\left[\log(\frac{\phi^2}{\phi_0^2}) - 1\right] + V_0$$

$$\Upsilon(\phi) = \Upsilon_0\frac{\phi}{\phi_0}, \qquad \phi_0 = 0.2m_{pl}$$

$$\mu = 6.71 \times 10^{10}\text{GeV},$$

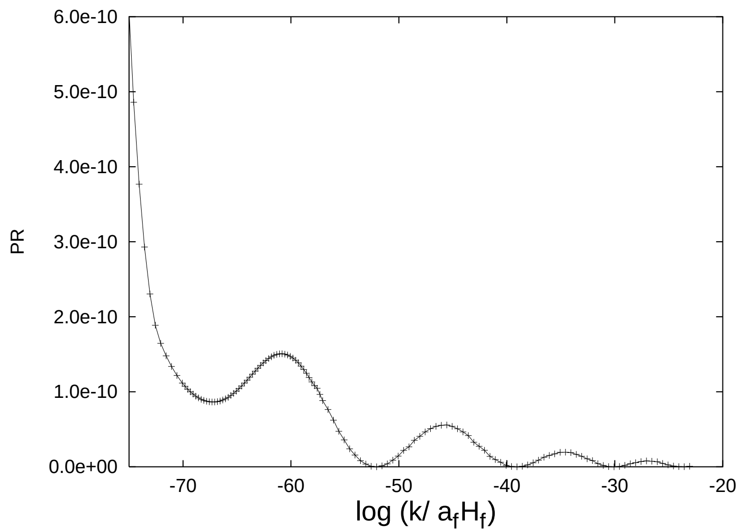


Generic symmetry breaking:

$$V = \frac{1}{4}\lambda(\phi^2 - \phi_0^2)^2$$

$$\Upsilon(\phi) = \Upsilon_0\frac{\phi^2}{T}, \qquad \phi_0 = 0.6m_{pl}$$

$$\lambda = 6.4 \times 10^{-16},$$



Supersymmetry Hybrid Inflation

(Bastero-Gil + AB, hep-ph/0411144, PRD 2005)

Basic model for inflaton sector: $W = \kappa\Phi(X_1 X_2 - \mu^2)$

$\Phi = \frac{1}{\sqrt{2}}(\phi + i\eta_\phi)$ $\qquad$ $X_i = \frac{1}{\sqrt{2}}(\chi_i + i\eta_{\chi_i})$

Has interaction structure needed for warm inflation:

$\mathcal{L}_I = -\frac{\kappa^2}{4}\phi^2\chi_i^2 - \frac{\kappa}{\sqrt{2}}\chi_i\bar{\psi}_{\chi_i}\psi$

χ-bosons can decay to heavy ψ_χ + light ψ fermion pair.

Some regimes of warm inflation exist ($x \equiv \phi/(\sqrt{2}\mu)$)

κ	x_e	x_R	N_R
0.1	3.4	4	0.2
0.05	1.8	2.1	0.25
0.035	1.4	1.5	0.15

Warm inflation for the last $N_R < 1$ e-folds where $x < x_R$

SUSY Hybrid Inflation + Matter

Couple inflaton sector to light fermions:

$$W = \kappa\Phi(X_1 X_2 - \mu^2) + gX_1NN$$

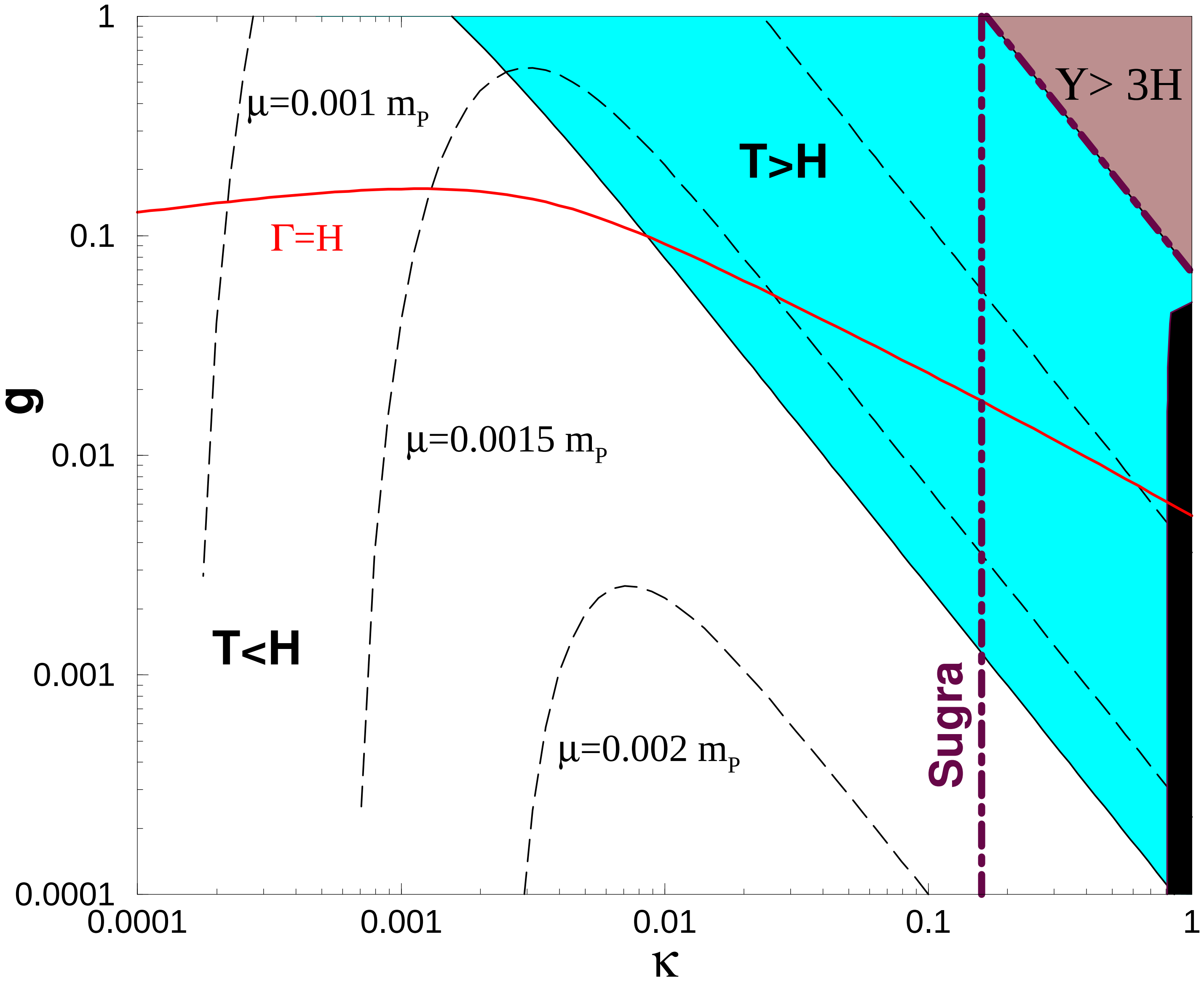
$$N = \frac{1}{\sqrt{2}}(\nu + i\psi_\nu)$$

Considered in realistic inflation models attempting to explain other particle physics (e.g. neutrinos, dark matter etc..., Kanzanas et. al. hep-ph/0403291, Jeannerot et. al. hep-ph/0002151, etc...)

χ-bosons can decay to light ψ_ν fermions - robust warm inflation

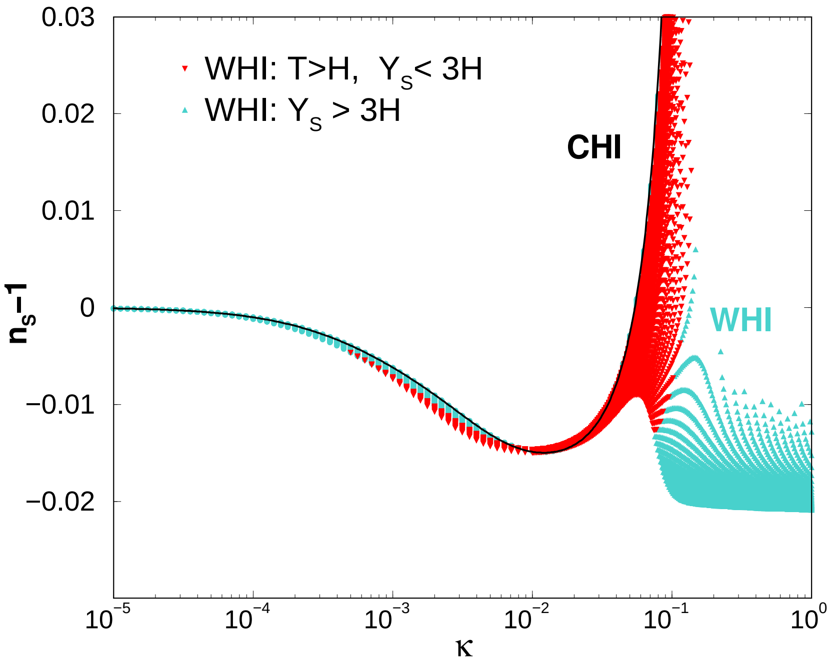
SUSY Hybrid Inflation + Matter - Results

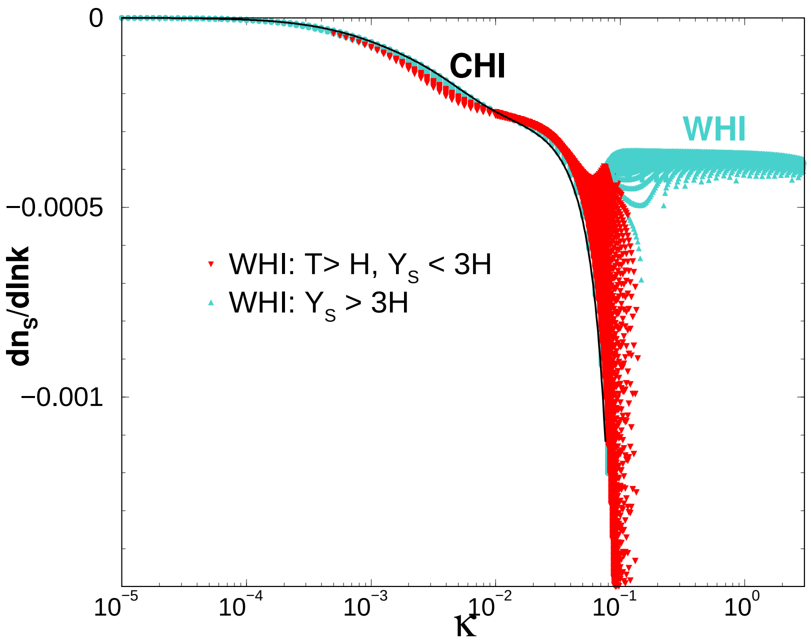
Regimes of warm and cold inflation



SUSY Hybrid Inflation + Matter - Results

Differences in spectral index warm vs. cold inflation





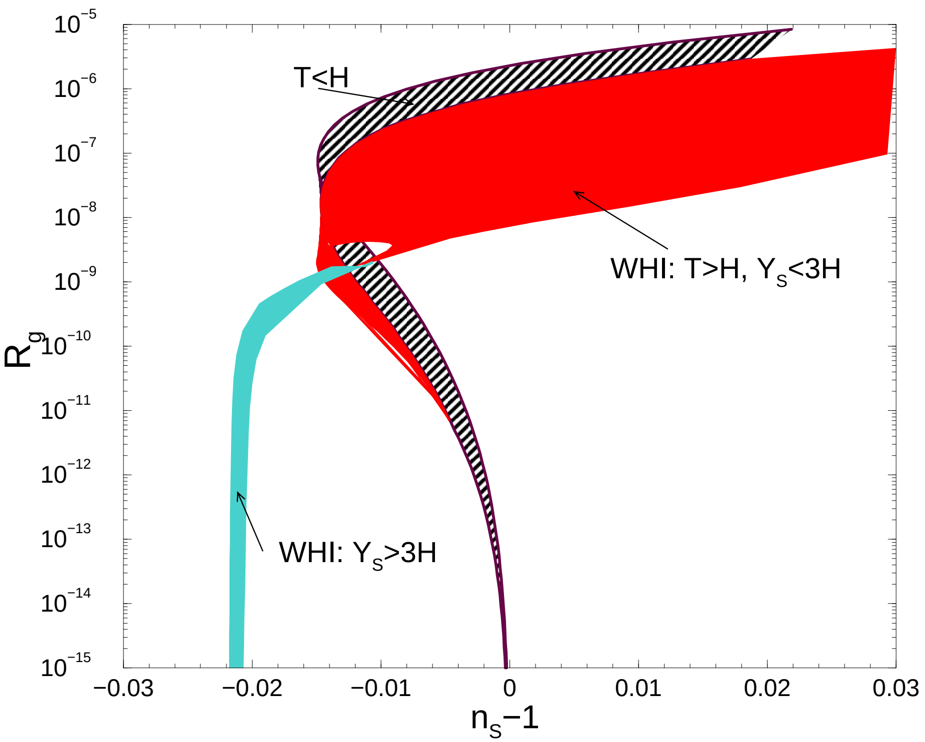
$-6\epsilon + 2\eta$ cold inflation

$n_s - 1 =$ $\left(-\frac{17}{4}\epsilon + \frac{3}{2}\eta - \frac{1}{4}\beta\right)$ warm inflation $\Upsilon < 3H$ $\left(\beta \equiv \frac{1}{8\pi G}\frac{\Upsilon_{,\phi} V_{,\phi}}{\Upsilon V}\right)$

$\frac{1}{r}\left(-\frac{9}{4}\epsilon + \frac{3}{2}\eta - \frac{9}{4}\beta\right)$ warm inflation $\Upsilon > 3H$ $\left(\frac{1}{r} \equiv \frac{\Upsilon}{3H}\right)$

SUSY Hybrid Inflation - tensor/scalar ratio

$$R_g \equiv \frac{P_{tensor}}{P_{\mathcal{R}}}$$



Clear prediction: For strong dissipative warm inflation expect

Sneutrino warm inflation

(Bastero-Gil + AB, hep-ph/0507124)

MSSM + ν_{RH}:

$W = \frac{M_i}{2} N_i N_i + (h_N)_{ij} H_u L_i N_j + h_t H_u Q_3 U_3^c + \cdots$

$\Longrightarrow$ inflaton potential $\sim M_N^2 \phi_N^2$

Dissipative channel: N_i couple H_u which decay to tops

$$\frac{\Upsilon}{3H} \approx \frac{\sqrt{6\pi}}{120} \left(\frac{h_N^2}{4\pi} \right)^{3/2} \left(\frac{h_t^2}{4\pi} \right) \left(\frac{m_p}{M_N} \right)$$

$$(Y_t = h_t^2/(4\pi) \approx 1)$$

Cold inflation: $|h_N| < 10^{-3}$, $\phi_N > m_p$, $M_N \approx 2 \times 10^{13}\text{GeV}$

(Murayama, *et al.*, PRL **70**, 1912 ‘93; Ellis, *et al.*, PLB **581**, 9 ‘04)

Sneutrino warm inflation - solutions

Strong dissipative regime:

$$|h_N| > 0.1$$

$$\frac{\Upsilon}{3H} > O(100) \Rightarrow \phi_N < m_p$$

$$|h_N| \approx 0.1 \left(\frac{10^{10}\text{GeV}}{M_N}\right)^{1/3} \quad \text{(COBE)}$$

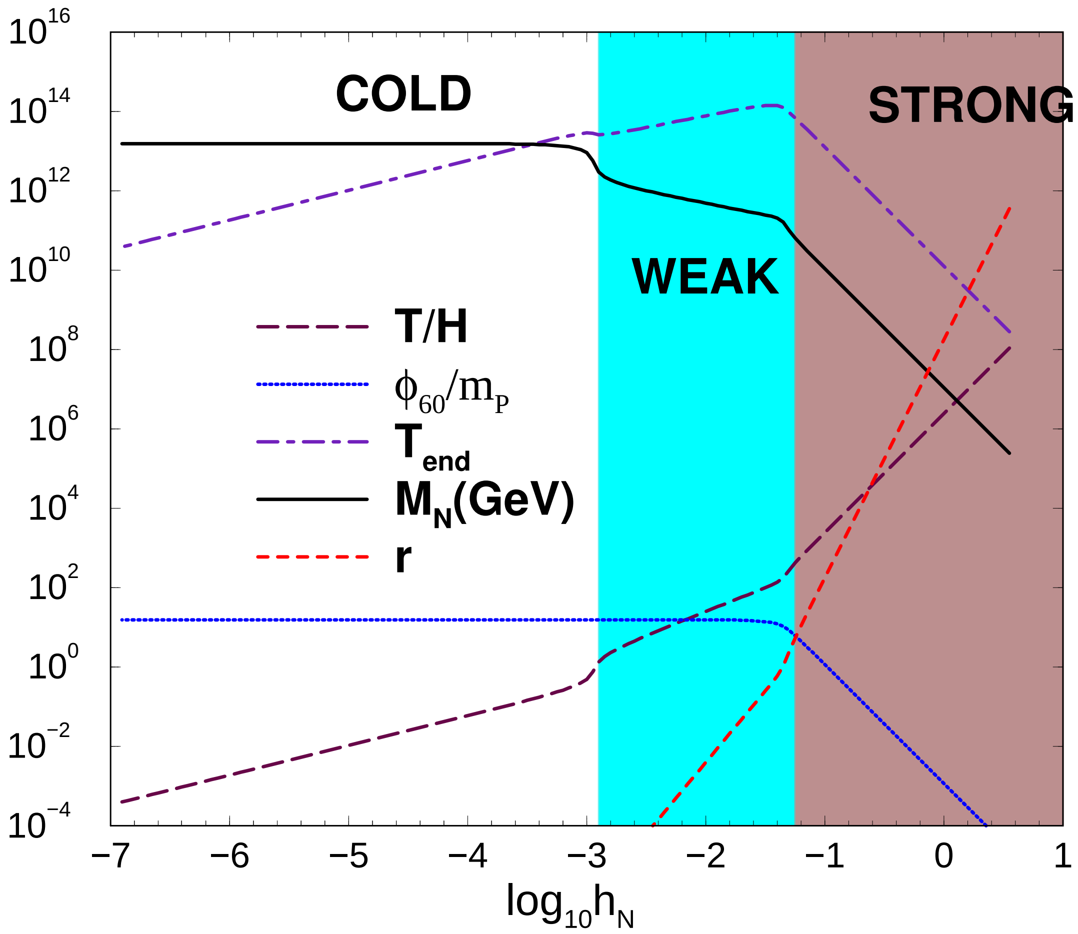
$$n_s - 1 \approx -0.025$$

$$dn_s/d\ln k \approx -O(10^{-4})$$

$$10^8\text{GeV} \leq T_{end} \leq 10^{13}\text{GeV}$$

problems with gravitinos?

$$T_{end} \approx T_{RH} > 10^9 - 10^7\text{GeV}$$



Lowering post-inflation temperature

Two slow-roll sneutrino fields

Heavy field ϕ_{N_3} dominates inflation

M_{N_3}, $|h_{N_3}| \geq 0.1 \Rightarrow$ Inflaton

Lighter field ϕ_{N_1}, $M_{N_1} \ll M_{N_3}$

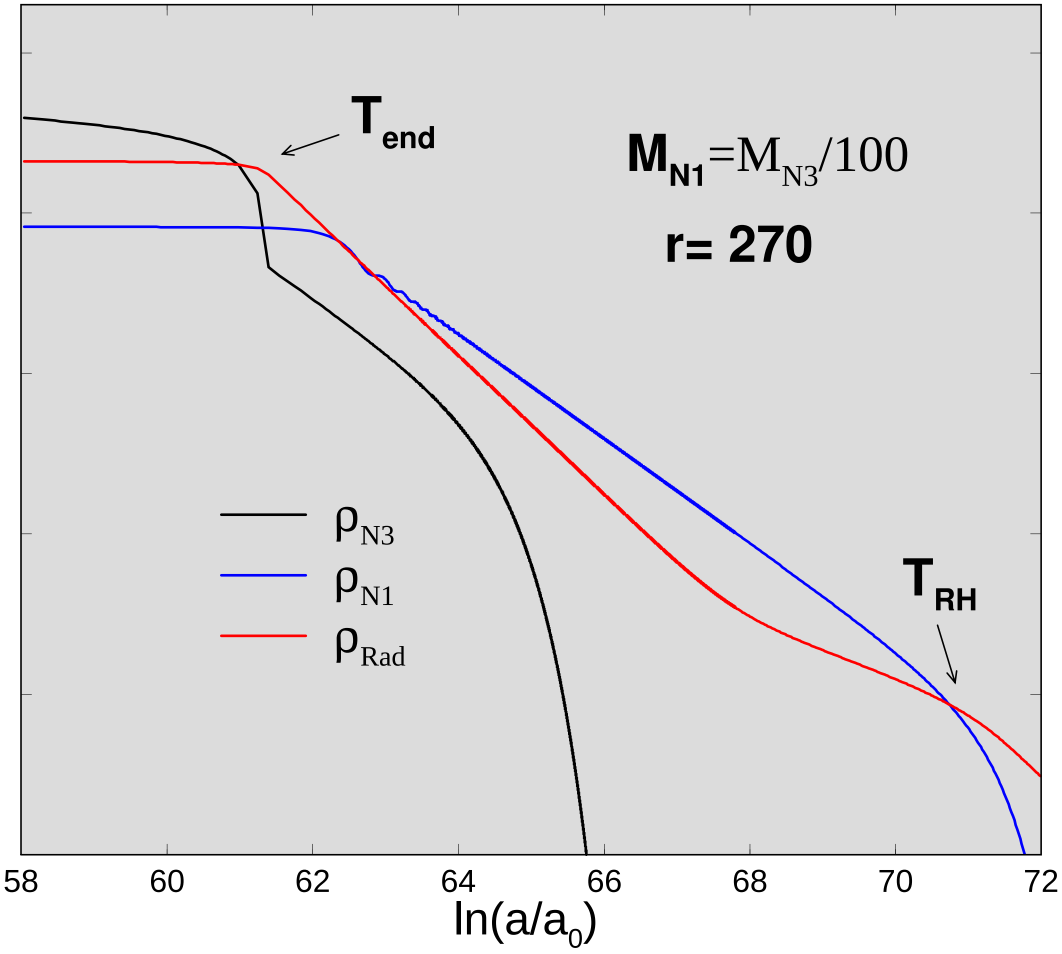
Weakly coupled $|h_{N_1}| \ll 1$

Oscillations after warm inflation

Weak coupling $\Longrightarrow$ low reheat T

$T_{RH} \approx 0.4\sqrt{\Gamma_{N_1} m_p} \quad \Longrightarrow$

$|h_{N_1}| \approx 10^{-6} \left(\frac{T_{RH}}{10^6\mathrm{GeV}}\right) \left(\frac{10^8\mathrm{GeV}}{M_{N_1}}\right)$



Non-thermal Leptogenesis

Out-of-equilibrium ($M_{N_1} < T_{RH}$) decay during "reheating":

$\frac{n_L}{s}|_{RH} \approx |\epsilon_1| \frac{3T_{RH}}{4M_{N_1}}$ (ϵ_1 = CP asymmetry parameter)

$$|\epsilon_1| \approx \frac{3}{8\pi (h_N^\dagger h_N)_{11}} \sum_{i\neq 1} Im[(h_N^\dagger h_N)_{1i}]^2 \frac{M_{N_1}}{M_{N_i}}$$

$$\leq \frac{3}{8\pi} \sqrt{\Delta m_A^2} \frac{M_{N_1}}{v_u^2} \approx 2 \times 10^{-8} \left(\frac{M_{N_1}}{10^8 \mathrm{GeV}} \right)$$

$\sqrt{\Delta m_A^2} \approx 0.05\mathrm{eV}$, atmospheric neutrino mass

$\hookrightarrow$ $$\boxed{\left.\frac{n_B}{s}\right|_{RH} \lesssim 5 \times 10^{-11} \frac{T_{RH}}{10^6\, GeV}}$$

$(n_B/s \simeq (8.7 \pm 0.4) \times 10^{-11})$

$\hookrightarrow$ Non-thermal lept. + $T_{RH} < 10^7 - 10^6 \mathrm{GeV} \Rightarrow \boxed{|h_{N3}| \leq 0.24}$

$\hookrightarrow$ Other possibilities? Larger ϵ_1? non-thermal?..-

(Murayama, *et al.*; Ellis, *et al.*; Raidal, *et al.*, hep-ph/0408015)

Inflation in the NMSSM

NMSSM: $W = \lambda \Phi H_u H_d - \kappa \Phi^3 + h_t Q_3 U_3^c H_u + \cdots$

$\Longrightarrow$ inflaton potential $\sim \kappa^2 \phi^4$

(same field solves "μ-problem")

Cold inflation: Chaotic inflation potential,

$\Longrightarrow \phi > m_{planck} \Longrightarrow$ infinite number of unsuppressed nonrenormalizable operators $a_n (\frac{\phi}{m_{planck}})^n \phi^4$

Warm inflation: inflation for $\phi < m_{planck}$,
opens up modeling building prospect

Perhaps the minimal model consistent with Standard Model and particle cosmology (work in progress)

Conclusion

- Generic interactions in all inflation models ($g^2\phi^2\chi^2$, $g\phi\bar{\psi}\psi$) yield dissipative effects DURING inflation (warm inflation)
  - $\Longrightarrow$ inflaton fluctuations generally not zero-point quantum fluctuations
  - $\Longrightarrow$ Affects background ($\langle\phi\rangle$) inflaton evolution (friction term $\Upsilon\dot{\varphi}$ etc...)

- For strong dissipation $\Upsilon > 3H$
  - NO eta-problem $m_\phi > H$
  - NO φ amplitude problem $\varphi < m_{planck}$