Inflationary Dynamics -

a Dissipative Quantum Field Theory Process

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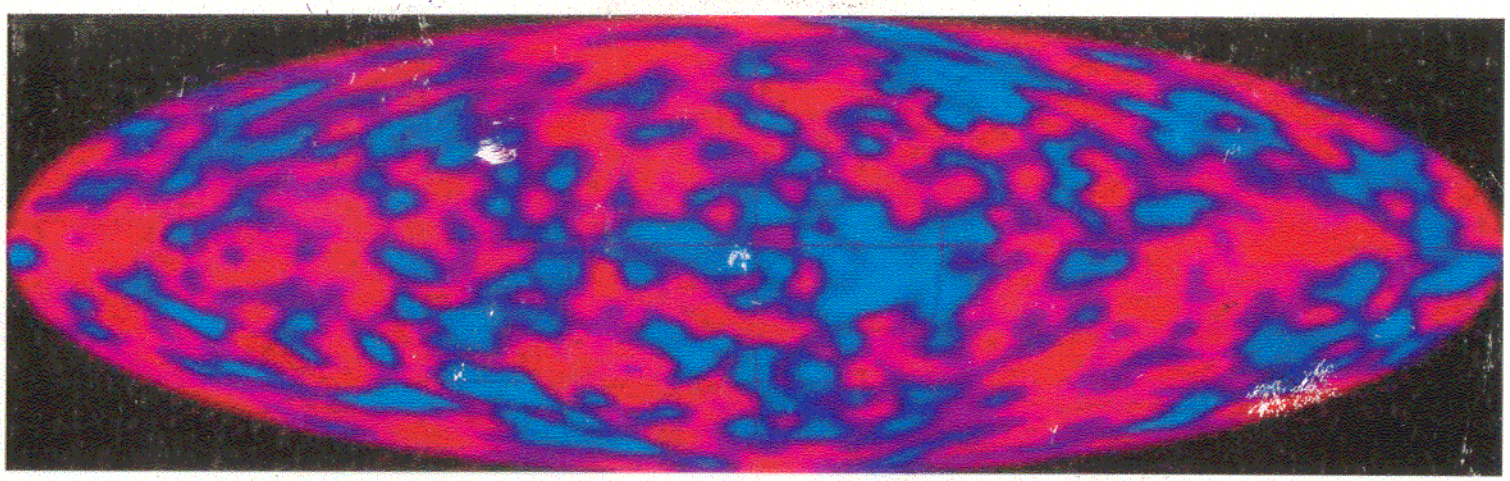
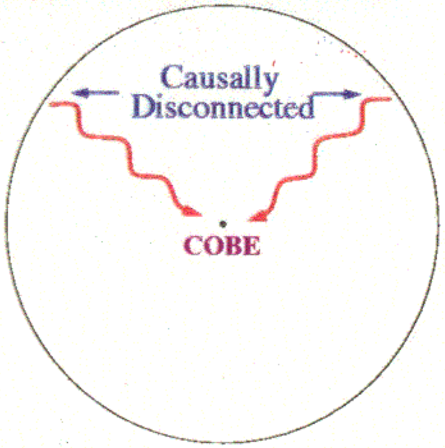
Inflation

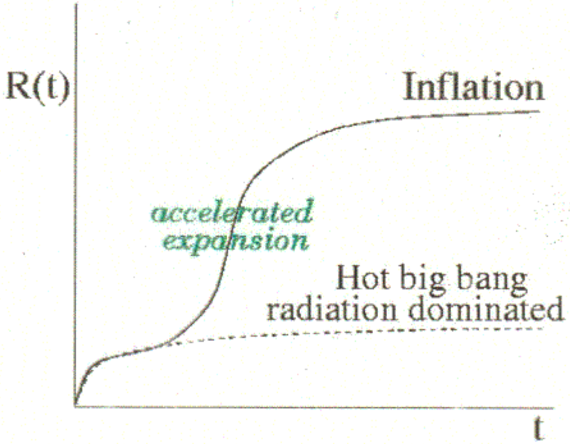


The puzzle of cosmological initial conditions:

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



The inflation solution (1981+)

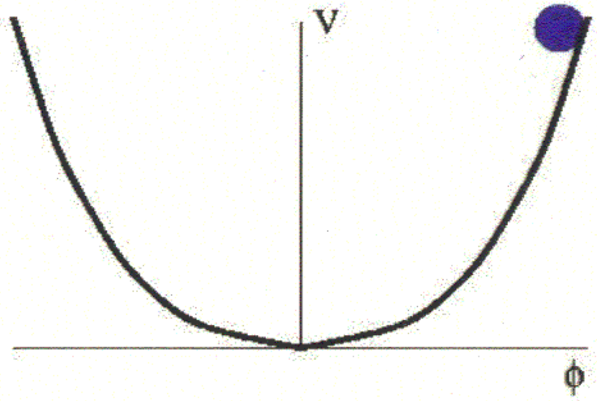


Accelerated expansion $\ddot{R}(t) > 0$

implies $\rho + 3p < 0$

How to get this from high energy physics?

Scalar field ("inflaton") dynamics



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

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

= Supercooled Inflation. Just Choose V(ϕ)

Potential energy dominated $3H\dot{\phi} \gg \ddot{\phi}$, " slow–roll"

But what about particle creation?

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

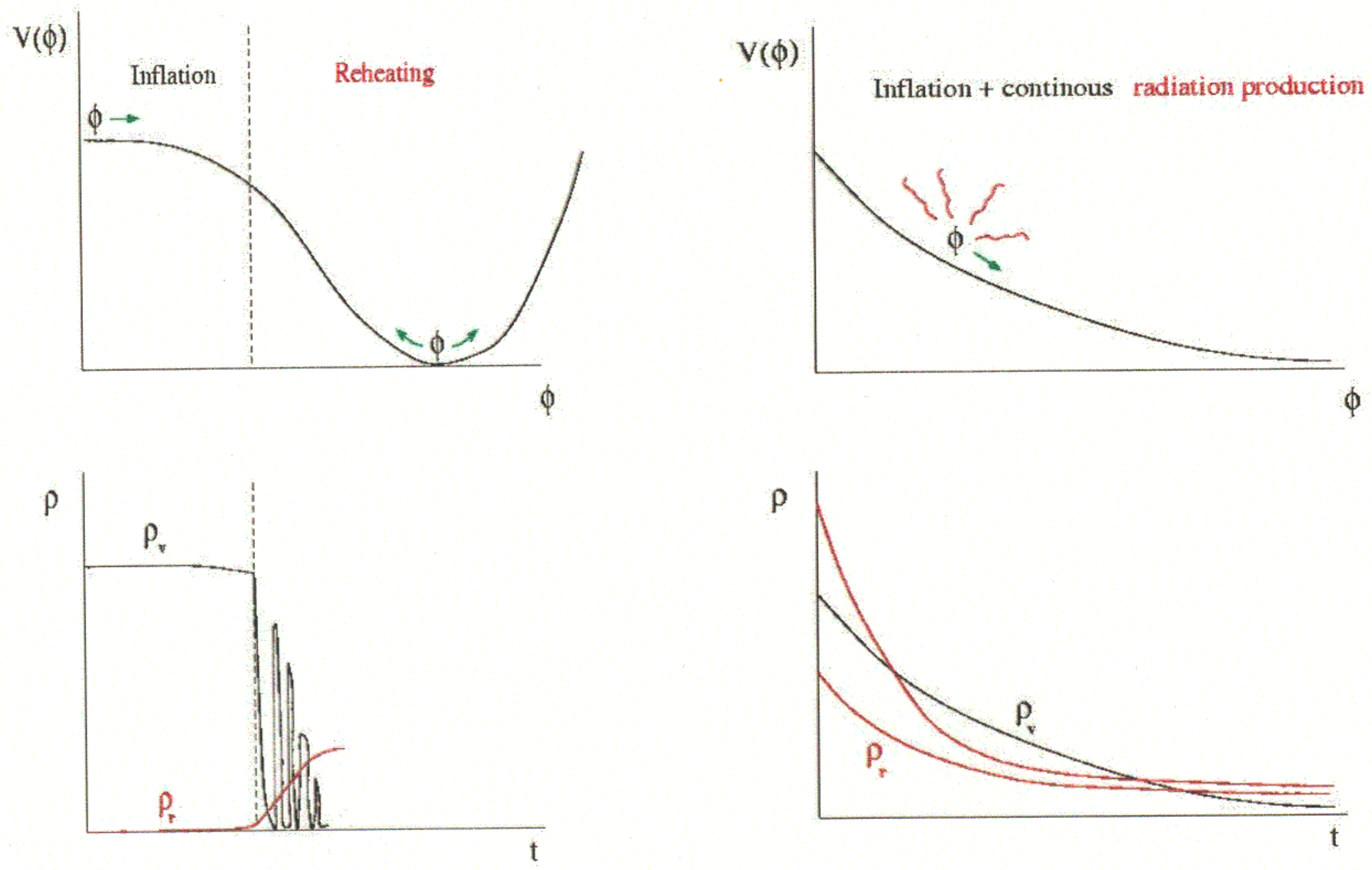
Warm inflation: η dominates

Slow–roll now means $\eta\dot{\phi} \gg 3H\dot{\phi}, \ddot{\phi}$, overdamped

The Warm Inflation Difference

Supercooled Inflation

Warm Inflation



Supercooled inflation: ϕ is isolated

– but interactions are more plausible: Warm inflation

Implies calculate

Relevant quantum mechanical process (dissipation) already studied in Condensed Matter: Caldeira–Leggett model, Fermi–Ulam–Pasta model

In Quantum Field Theory (QFT) generic couplings, $\phi^2\chi^2, \phi\bar{\psi}\psi$ yield dissipation

In restrictive cases, QFT warm inflation solutions have been obtained – confirms that warm inflation works

Considerable exploration remains

Energetics

Consider GUT scale inflation: $M \sim 10^{15}\text{GeV}$, $\rho_v \sim M^4 \sim 10^{60}\text{GeV}^4$

$\Rightarrow H \sim 10^{10}\text{GeV}$

$T > H$ requires > 1 part in $\sim 10^{20}$ of vacuum energy $\rightarrow$ radiation
(influences structure formation)

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

Supercooled inflation Basic Assumption: Scalar field isolated, will NOT dissipate the above amounts during inflation

Warm inflation: Expects above, or even more, radiation production during inflation

Equipartition Hypothesis of Statistical Mechanics: would expect the scalar field to distribute its energy evenly amongst all degrees of freedom

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

Scalar Field (Φ) Dynamics

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

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

$$\Phi = \varphi + \phi$$

Effective equation of motion (EOM) for $\varphi(t)$:

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

$\langle\phi^2\rangle$, $\langle\phi^3\rangle$ and $\langle\chi_j^2\rangle$ perturbative evaluation
2-loop order

Closed Time Path Approach - Goal

Compute

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

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)

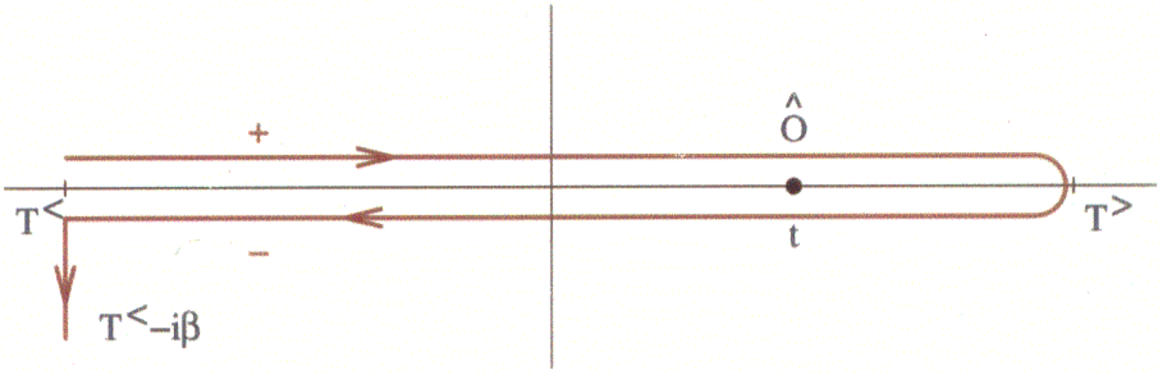
Thus

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

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

$$Z[J^+,J^-,J^\beta]$$

$$= \mathrm{Tr}[U(T^< - i\beta, T^<; J^\beta)U(T^<,T^>;J^-)U(T^>,T^<;J^+)]$$

$$= \int \mathcal{D}\Phi^+\mathcal{D}\Phi^-\mathcal{D}\Phi^\beta$$

$$\exp\left(i\int_{T^<}^{T^>} d^4x[\mathcal{L}^{J^+}[\Phi^+] - \mathcal{L}^{J^-}[\Phi^-]] + i\int_{T^<}^{T^<-i\beta} d^4x\mathcal{L}^{J^\beta}[\Phi^\beta]\right)$$

e.g. scalar field theory:

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

ROBUST DISSIPATIVE MECHANISM

(Berera and Ramos, Phys. Rev. D 63, 103509 (2001))

Focus on Lagrangian:

$$\mathcal{L}[\Phi, \chi_j, \bar{\psi}_k, \psi_k] = \frac{1}{2}(\partial_\mu \Phi)^2 - \frac{m_\phi^2}{2}\Phi^2 - \frac{\lambda}{4!}\Phi^4$$
$$+ \sum_{j=1}^{N_\chi} \left\{ \frac{1}{2}(\partial_\mu \chi_j)^2 - \frac{m_{\chi_j}^2}{2}\chi_j^2 - \frac{f_j}{4!}\chi_j^4 - \frac{g_j^2}{2}\Phi^2\chi_j^2 \right\}$$
$$+ \sum_{i=1}^{N_\psi} \bar{\psi}_i \left[i \not{\partial} - m_{\psi_i} - \sum_{j=1}^{N_\chi} h_{ij,\chi}\chi_j \right] \psi_i \,, \qquad (1)$$

Implies reaction: $\phi \to \chi \to \psi$

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

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

PHYSICAL PICTURE

(Berera, Ramos, Lawrie)

-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-field $\Longrightarrow$ χ-particles decay to ψ-particles, decohere χ-field

-Entire process backreacts on φ $\Longrightarrow$ dissipative effects

Estimates of Dissipation from Quantum Field Theory Dyanmics

R Ramos + A. B.
hep-ph/0101049
Phys. Rev. D 2001

Treat inflationary conditions: Overdamped, ultraflat potential

Direct Decay Models $\phi \to \bar{\psi}\psi, \chi\chi$ $(m_\phi > 2m_{\psi,\chi})$

$T \sim (\rho_r/g^*)^{1/4} \sim \lambda^{1/2} m_\phi/10$

$\rho_v^{1/4} \sim 10^{15-16}\mathrm{GeV}$ (GUT scale)

$\lambda \sim 10^{-(10-16)}$

$m_\phi \sim 10^{(10-13)}\mathrm{GeV}$

$\Rightarrow T \sim 10 - 10^7\mathrm{GeV}$

Sets lower bound on radiation production from generic QFT models consistent with inflation

$\Rightarrow$ Reheating redundant

No gravitino overproduction in SUSY versions

Indirect Decay Models $\phi \to \chi \to \bar{\psi}\psi$ $(m_\phi < 2m_\psi < m_\chi)$

For same parameter regime, T as large as $10^{14}\mathrm{GeV}$
- Copious radiation production

Very interesting regime, needs more study

The warm inflationary universe on a computer

A.B. with
G.Lacagnina *(lattice gauge theory)*, C.Verdozzi *(condensed matter theory)*

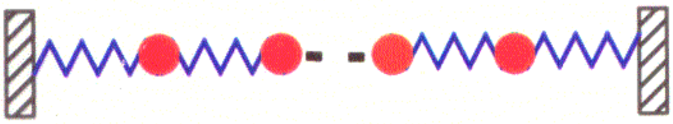
- study of **overdamped motion** and its universal features;
- study of how **equipartition** is achieved

Conceptually / practically important and FEASIBLE

Goals:

1) Numerical simulations of **quantum/classical** models from condensed matter: **Fermi-Pasta-Ulam, Caldeira-Leggett**

FPU



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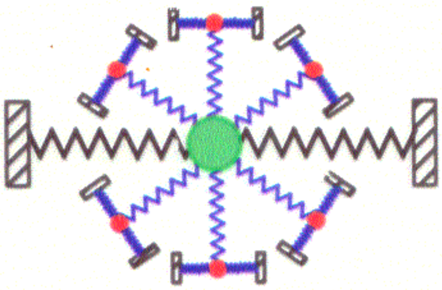
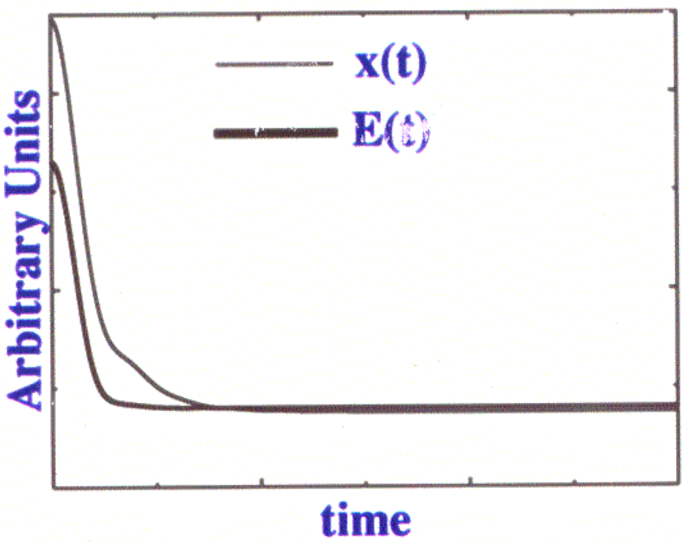
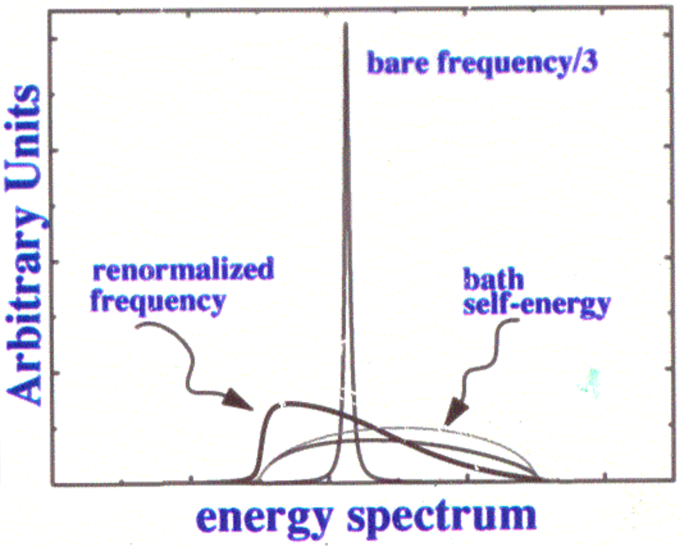


2) Simulations of lattice quantum field theory models: **Caldeira-Leggett**, ϕ^4

An example of overdamping in the classical regime



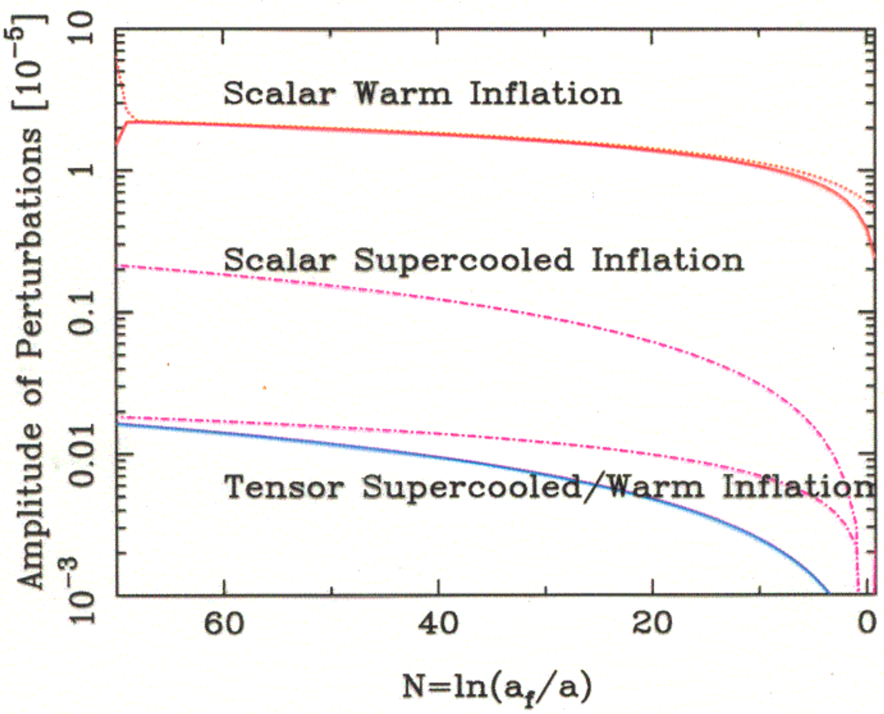


Signatures of Warm Inflation

(Taylor & Berera, 2000, Phys Rev D)

- **Standard inflation has no interactions so universe is supercooled.**
- **Warm inflation includes interactions**

Amplitude of perturbations: $V = \frac{1}{2}m^2\varphi^2$



- **Warm inflation predicts different tensor-to-scalar ratio than supercooled inflation.**
- **No consistency relation in warm inflation**
- **Mechanism for isocurvature modes - which may be detectable by Planck.**

Non–Gaussianity in the CMB from Warm Inflation

(astro–ph/0205152, in press Phys. Rev. D)

A Gaussian distribution of gravitational field perturbations will have bispectrum

$$B \sim \langle \Phi(\mathbf{k}_1)\Phi(\mathbf{k}_2)\Phi(\mathbf{k}_3)\rangle \quad \text{equal to zero.}$$

Expanding the scalar field fluctuations to second order leads to the expression

$$\langle \Phi(\mathbf{k}_1)\Phi(\mathbf{k}_2)\Phi(\mathbf{k}_3)\rangle = A_{\rm inf}(2\pi)^3\delta^3(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3)\left[P_\Phi(\mathbf{k}_1)P_\Phi(\mathbf{k}_2) + \text{perms}\right],$$

where A_{infl} is not zero due to the self–interaction of the scalar field.

We find for warm inflation

$$A_{\rm inf}^{\rm warm} = 7\times10^{-2} \qquad \text{compares to} \qquad A_{\rm inf}^{\rm supercooled} = 5\times10^{-2}\ .$$

These contributions to the bispectrum are over–ridden by other physical effects, and will be undetectable in the CMB for the MAP and Planck Surveyor satellites.

Conclusion

Inflationary cosmology lacks thorough treatment of interaction dynamcis - could solve the problems it confronts

—Inflation in general can occur concurrent with radiation production, warm inflation (PRL 75, 3218 (1995))

—Observational tests for radiation during inflation

- tensor/scalar ratio (PRD 62, 083517 (2000))
- nongaussian
- isocurvature

— Quantum field theory robust mechanism for warm inflation (PRD 63, 103509 (2001))