PHI IN THE SKY - PORTO
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SELF-SIMILAR DYNAMICS IN WARM INFLATION

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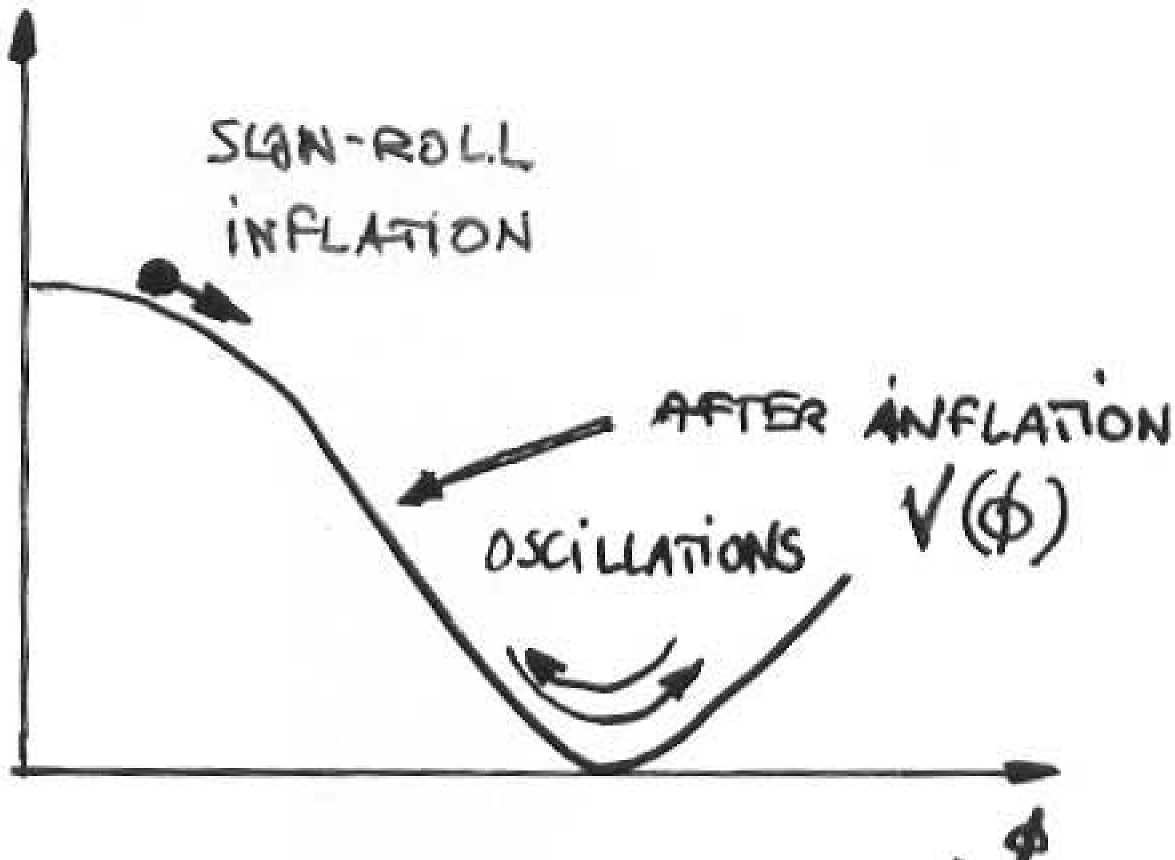
1. BASIC IDEAS OF WARM INFLATION
2. EQUATIONS / DYNAMICAL SYSTEM
3. SCALING SOLUTIONS
4. THERMODYNAMICS
5. CONCLUSION

THE ORIGINAL PROPOSALS OF INFLATION LEAD TO A SUPERCOOLED UNIVERSE AFTER THE ACCELERATED STAGE OF EXPANSION

'COOL' INFLATION



$\rho_{rad}/m \sim 0$

$T \propto \frac{1}{a}$

POST-INFLATIONARY REHEATING IS NEEDED (FOR e.g. BBN) !

WARM INFLATION $\longrightarrow$ DISSIPATIVE EFFECTS DURING INFLATION (FRICTION TERM)

$\Longrightarrow$ TRANSFER OF ENERGY TO THE RADIATION MATTER COMPONENT WHILE INFLATING [A. BERERA, PRL 75, 3218 (19

$\Longrightarrow$ "WARM" UNIVERSE AFTER INFLATION ENDS

BARE WARM INFLATION MODEL

COUPLING

$$\begin{cases} \ddot{\phi} + 3H\dot{\phi} + \Gamma_\phi \dot{\phi} + \partial V / \partial \phi = 0 \\ \dot{\rho} + 4H\rho = + \Gamma_\phi \dot{\phi}^2 \end{cases}$$

FRICTION

[HOSOYA & SAKAGAMI PRD29(84)]

(...) $\longrightarrow$ REHEATING

$$3H^2 = \frac{8\pi}{m_p^2}\left[\rho + \frac{\dot{\phi}^2}{2} + V(\phi)\right]$$

$\Rightarrow$ 'SLOW ROLL' $\rightsquigarrow \ddot{\phi} \simeq 0 \Rightarrow \dot{\phi} \simeq - \dfrac{V'(\phi)}{3H(1+r)}$

HAPPENS FOR STEEPER POTENTIALS $r \gg 1$

$r \equiv \Gamma_\phi / 3H$

QUESTIONS:

[YOKOYAMA & LINDE (1999)] $\Gamma\dot{\phi}^2$ NOT SUFFICIENTLY STRONG ...

QUANTUM STATISTICS (NON-EQUILIBRIUM FORMALISM) ...

[BERERA & RAMOS; 2003, PLB]

EVOLUTION OF PERTURBATIONS (THERMAL) VERSUS CMB

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[L. HALL, I. MOSS, A. BERERA: astro-ph/0402299, astro-ph/0305015]

OUR (PHENOMENOLOGICAL) MODELS

$$\boxed{\begin{aligned} &\Gamma_\phi = \tilde{\Gamma}(\phi)\, H^\delta , \quad \delta = \text{CONST.} \\ &p = (\gamma - 1)\rho + \Pi \end{aligned}}$$

FRW, $k=0$

$1 < \gamma < 2$

$\Pi \equiv$ VISCOUS PRESSURE

$= -3\xi \rho^\alpha H^{2(1-\alpha)}$

$\xi, \alpha =$ CONSTS.

USE EXPANSION NORMALIZED VARIABLES:

$$x = \frac{\dot{\phi}}{\sqrt{6}H} , \quad y = \frac{\sqrt{V}}{\sqrt{3}H}$$

$$W(\phi) = \sqrt{\tfrac{3}{2}}\left(\frac{V'(\phi)}{V(\phi)}\right)$$

$$r = \Gamma_\phi / 3H , \quad \chi = \Pi / 3H^2$$

$$\Rightarrow \boxed{\begin{aligned} x' &= x\left(Q - 3(1+r)\right) - W(\phi)\, y^2 \\ y' &= (Q + W(\phi)x)\, y \\ r' &= r\left[\sqrt{6}\,\frac{\partial_\phi \tilde{\Gamma}}{\tilde{\Gamma}}\, x + Q(1-\delta)\right] \\ \phi' &= \sqrt{6}\, x \end{aligned}}$$

! →

[Nunes & Mimoso PLB 488 (2000)]

$$Q = \frac{3}{2}\left[2x^2 + \gamma(1 - x^2 - y^2) - 3^\alpha \xi (1 - x^2 - y^2)^\alpha\right]$$

NB: $q = Q - 1$

TWO TYPES OF FIXED POINTS:

- $x = 0 \Rightarrow [\dot{\phi} = 0] \Rightarrow$ EXTREMA OF POTENTIAL $V(\phi)$
- $\psi = 1/\phi \to 0$, AS $\phi \to \infty \Rightarrow$

$$\psi' = -\sqrt{6}\, x\, \psi^2$$

$\Rightarrow$ CRITICAL POINTS DEPEND ON THE ASYMPTOTIC BEHAVIOUR OF $V(\phi)$ AND OF $\tilde{\Gamma}(\phi)$

SELF-SIMILAR (SCALING) BEHAVIOUR ARISES IF

$V(\phi)$ ASYMPTOTES TO EXP. BEHAVIOUR: $V \sim e^{-\lambda\phi}$

$\tilde{\Gamma}(\phi_\infty) \propto [V(\phi_\infty)]^{\frac{1-\delta}{2}}$ (IF $\delta = 1 \Rightarrow \Gamma_\phi \propto H$)

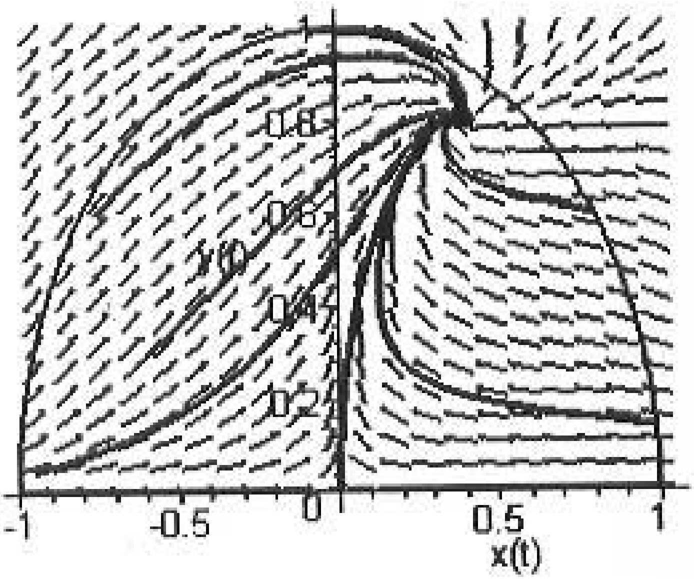
$\Rightarrow$ POWER LAW BEHAVIOUR OF $a(t) \sim t^A$

$$(3\gamma A - 2)\left[A - \frac{2}{\lambda^2}\left(1 + \tilde{r} A^{\delta-1}\right)\right] =$$

$$= \frac{4}{\lambda^2}\tilde{r} A^{\delta-1} + 3^{1+\alpha}\xi A^{2-\alpha}\left[A - \frac{2}{\lambda^2}(1 + \tilde{r} A^{\delta-1})\right]$$

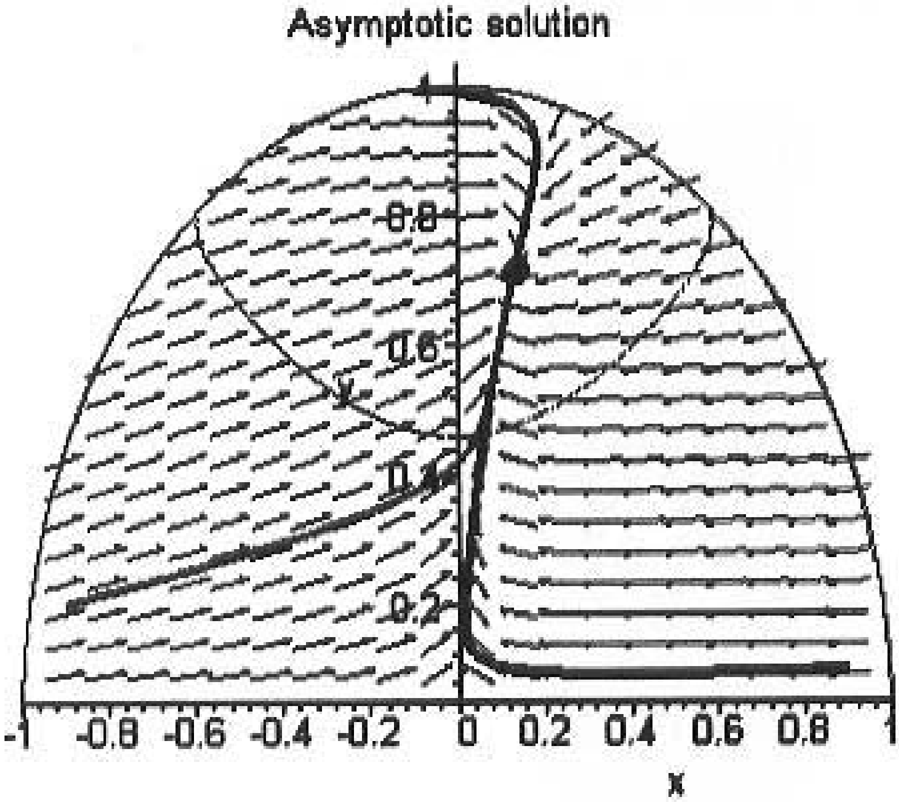
Model without Viscous Pressure

Asymptotic behaviour of the model when r=0.5, γ=1, e λ=2√(2/3).



Model with Viscous Presure.

Asymptotic behaviour of the model when
r=5, γ=4/3, e λ=4 √(2/3), ζ=1/4, α= 1/2 e α=1/2.



- Fixed Point at (0.13,076)

(x_*, y_*)

COSMOLOGICAL TWO-FLUID THERMODYNAMICS:

$$T^{ik} = T^{ik}_{(1)} + T^{ik}_{(2)}$$

cf [W. ZIMDAHL & D. PAVÓN, GRG 33: 791 (2001)]

$$T^{ik}_{(A)} = \rho_{(A)} u^i u^k + p_{(A)} h^{ik}$$

$$N^i_{(A)} = n_{(A)} u^i \qquad (A = 1, 2)$$

$$\nabla_k T^{ik}_{(A)} = - t^i_{(A)}$$

$$\nabla_i N^i_{(A)} = \dot{n}_{(A)} + 3H\, n_{(A)} = n_{(A)} \Gamma_{(A)}$$

EACH COMPONENT IS GOVERNED BY ITS GIBBS EQ.

$$\Rightarrow \quad n_{(A)} T_{(A)} \dot{s}_{(A)} = u_a t^a_{(A)} - (\rho_{(A)} + p_{(A)}) \Gamma_{(A)}$$

$$! \Longrightarrow \quad \frac{\dot{T}_{(A)}}{T_{(A)}} = -3H \left(1 - \frac{\Gamma_{(A)}}{3H}\right) \frac{\partial p_{(A)}}{\partial \rho_{(A)}} + \frac{n_{(A)} \dot{s}_{(A)}}{\partial \rho_{(A)} / \partial T_{(A)}}$$

CONSTANT ENTROPY PER PARTICLE $\Longrightarrow$ $\dot{s}_{(A)} = 0$

$$\Rightarrow \quad \frac{\dot{T}_{(A)}}{T_{(A)}} = -3H \left(1 - \frac{\Gamma_{(A)}}{3H}\right)(\gamma_{(A)} - 1)$$

AND $\quad (\rho_{(1)} + p_{(1)}) \Gamma_{(1)} = -(\rho_2 + p_2) \Gamma_2$

APPLYING THIS TO (1) = RAD
(2) = ϕ $\Rightarrow$

$$\frac{\dot{T}_{RAD}}{T_{RAD}} = -3H\left(1 - \frac{\Gamma_{RAD}}{3H}\right) \times \frac{1}{3}$$

$$= -H\left(1 - \frac{\dot{\phi}^2}{4\rho}\frac{\Gamma_\phi}{H}\right)$$

SO THAT FOR SCALING SOLS IT IS POSSIBLE TO HAVE

$$\frac{\Gamma_{RAD}}{3H} \equiv \lambda \simeq 1 \Rightarrow \boxed{\Gamma_\phi \propto H}$$

$$\Rightarrow \dot{T}_{RAD} \simeq 0$$

WITHOUT THE NEED TO RESORT TO THE EXTREME CASE $r >> 1$.

$\Rightarrow$ THIS AVOIDS THE CRITICISM OF [YOKOYAMA & LINDE, PRD 60:083509 (1999)]

CONCLUSION

SELF-SIMILAR, SCALING SOLUTIONS REQUIRE VARYING Γ_ϕ.

VARIATION OF Γ_ϕ HAS TO BE PROPORTIONAL TO A POWER OF $V(\phi)$ (EXPONENTIAL/ASYMPTO

WHEN THE EXIST, THE SCALING SOLUTIONS OCCUR FOR ANY CHOICE OF ADMISSIBLE PARAMETERS

$$\left(\text{e.g. } V_{\phi} \sim e^{-\lambda \phi_{\infty}} \longrightarrow \lambda^2 \gtrsim 3\gamma \right)$$

INFLATIONARY SCALING SOLUTIONS EMERGE FOR SMALL VALUES OF THE SCALAR FIELD DECAY RATE.

$$\left(r = \frac{\Gamma}{3H} \lesssim 1 \right)$$

THERMODYNAMIC ARGUMENTS JUSTIFY/MOT IMPORTANCE OF SCALING SOLUTIONS FOR THE WARM INFLATION SCENARIO (?! EXIT ?!)

PROBLEM