Cosmology without Inflaton

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References

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Friedmann-Lemaître-Robertson-Walker Universe

homogeneous and isotropic, cosmic microwave background reference frame

$$ds^2 = -dt^2 + a^2(t)\,d\mathbf{x}^2, \quad a(t) - \text{scale factor}$$

Hubble parameter $h \equiv \frac{\dot{a}}{a}$

Einstein equations $\Rightarrow$ **Friedmann equations** (in Planck units)

$$h^2 = \frac{8\pi\rho}{3}, \quad \dot{h} = -\frac{3}{2}h^2 - 4\pi p,$$

$\rho(t)$ - energy density, $p(t)$ - pressure of "cosmic fluid"

Probing vacuum in expanding space

One can show analytically that localized quantum thermometer (e.g. 2-level system or harmonic oscillator) at rest in the cosmic reference frame of de Sitter space and weakly coupled to massless bosonic quantum field in vacuum state relaxes to Gibbs state with relaxation rates equal to those of bosonic heat bath characterized by Gibbons-Hawking temperature[1])

$$T_{\mathrm{dS}} = \frac{h}{2\pi}$$

Thermal Vacuum Hypothesis

Vacuum in expanding de Sitter space (in cosmic reference frame), with Hubble parameter h, can be modelled by heat bath at Gibbons-Hawking temperature and chemical potentials equal to particle masses

[1] G.W. Gibbons and S.W. Hawking, Phys. Rev. D **15**, 2378 (1977)

Energy density and pressure for expanding Universe

$$\rho = \rho_{\rm dS} + \rho_r = \sigma h^4 + \rho_r, \quad \sigma \geq 0$$

$\rho_r(t) \geq 0$ – energy density of "regular matter",
$\rho_{\rm dS}(t)$ – Thermal Vacuum (TV) energy density ("TV dark energy")

Cosmological pressure p ($\rho_{\rm dS}$ does not dilute, replenished by gravity)

$$p = p_{\rm dS} + p_r = -\sigma h^4 + w_r \rho_r,$$

$w_r = p_r/\rho_r \geq 0$ - equation of state for regular matter

$w_r = 0$ - non-relativistic matter, $w_r = \frac{1}{3}$ - "radiation",

Friedmann eqs. for TV cosmology

$$\rho_r + \sigma h^4 - \frac{3}{8\pi}h^2 = 0, \quad \dot{h} = -\frac{3}{2}(1+w_r)h^2\left(1 - \frac{8\pi}{3}\sigma h^2\right).$$

Early Universe ($T_{\rm dS} = \frac{h}{2\pi} \gg \text{all masses}$)

$$\rho_{\rm dS} = \bar{\sigma} h^4 \sim T_{\rm dS}^4 \quad \text{(Stefan-Boltzmann)}, \quad \bar{\sigma} \equiv \frac{g_f}{480\pi^2}, \quad w_r = 1/3$$

$$\dot{h} = -2h^2\left[1 - \left(\frac{h}{h_0}\right)^2\right], \quad h_0 = 6\sqrt{5\pi/g_f} = \mathcal{O}(1)$$

g_f - number of "polarizations" ($\sim 10^2$),
$h(t) = h_0$ - metastable solution (empty de Sitter space).

Inflation and its graceful exit

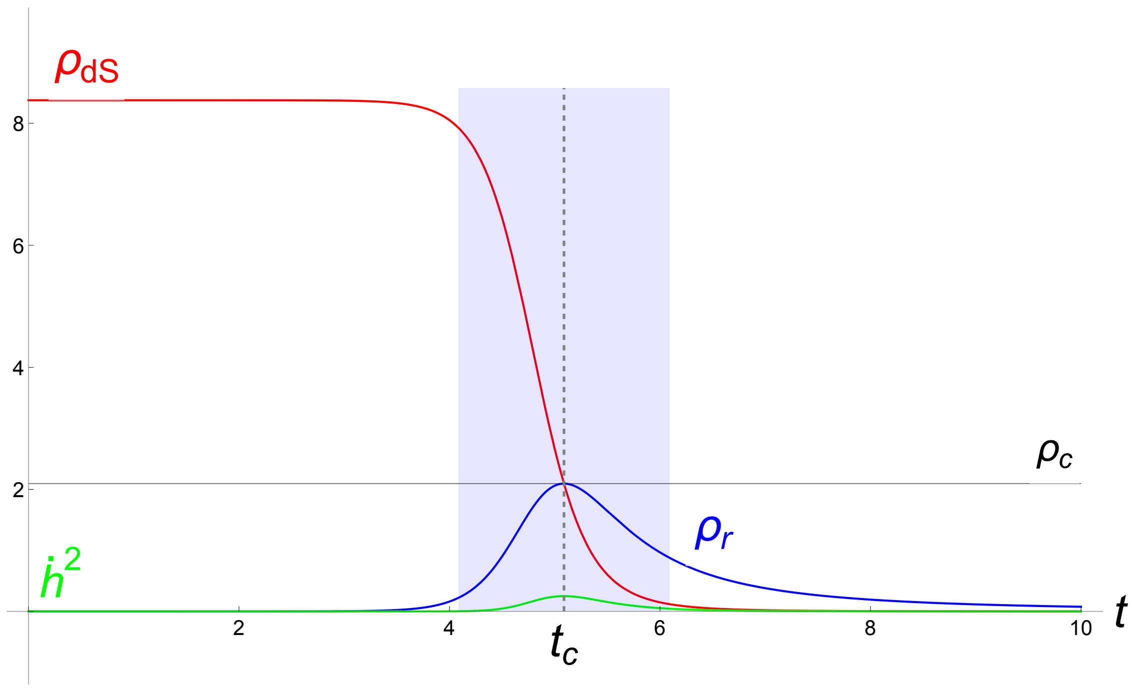

Figure 1: Evolution of $\rho_{\rm dS}$ and ρ_r for $h(0) = h_0 - 10^{-9}$;
t_c - begining of Big Bang, TV and matter in thermal equilibrium;
particle production from TV ("boiling of superheated fluid" or "superfluorescence")

Late Universe ($T_{\rm dS} = \frac{h}{2\pi} \ll \text{lowest mass} > 0$)

Energy density for quantum non-relativistic gas implies

$$\rho_{\rm dS} \simeq \sum_j g_j m_j^{5/2} h^{3/2}, \quad \sigma \simeq \frac{\sum_j g_j m_j^{5/2}}{(2\pi)^3} h^{-5/2}, \quad w_r = 0,$$

Acceleration of expansion ($\ddot{a} > 0$, but $\dot{h} < 0$)

$$\frac{\ddot{a}}{a} = \dot{h} + h^2 = \frac{h^2}{2}\left(\sqrt{\frac{9h_\infty}{h}} - 1\right), \quad h_\infty = \left[\frac{\sum_j g_j m_j^{5/2}}{3\pi^3}\right]^2$$

Accelerated expansion starts at (Universe age - 10^{18} s)

$$h = 9h_\infty, \quad h_\infty \simeq 10^{-18}\ \mathrm{s}^{-1}\,(\equiv 10^{-42}\ \mathrm{GeV}), \quad T_\gamma = 2.7K \sim 10^{-12}\ \mathrm{GeV}$$

Further consequences of TV model

1. Non-existence of particles with masses larger than $\bar{m} \sim 10^7$ GeV, but at least one particle must possess the mass of such an order of magnitude.

2. TV model can be combined with gravitational baryogenesis driven by an effective anomalous action with a cut-off scale $M_* \sim 10^7 M_{\rm Planck}$.

3. Similar "anomalous" interaction mechanism can couple Standard Model particles with dark matter sector.

Concluding remarks

1. Vacuum of de Sitter space (TV) can be treated as a metastable heat bath ("superheated fluid") at Gibbons-Hawking temperature.

2. Particle production initiated by small fluctuations ("boiling" or "superfluorescence") cools the bath terminating inflation .

3. TV energy of the late Universe generates expansion's acceleration.

4. TV model can be combined with gravitational baryogenesis and a simple extension of the Standard Model containing dark matter.

5. No inflaton field with fine-tuned potential, reheating process and cosmological constant are needed.

Analogy to superfluorescence

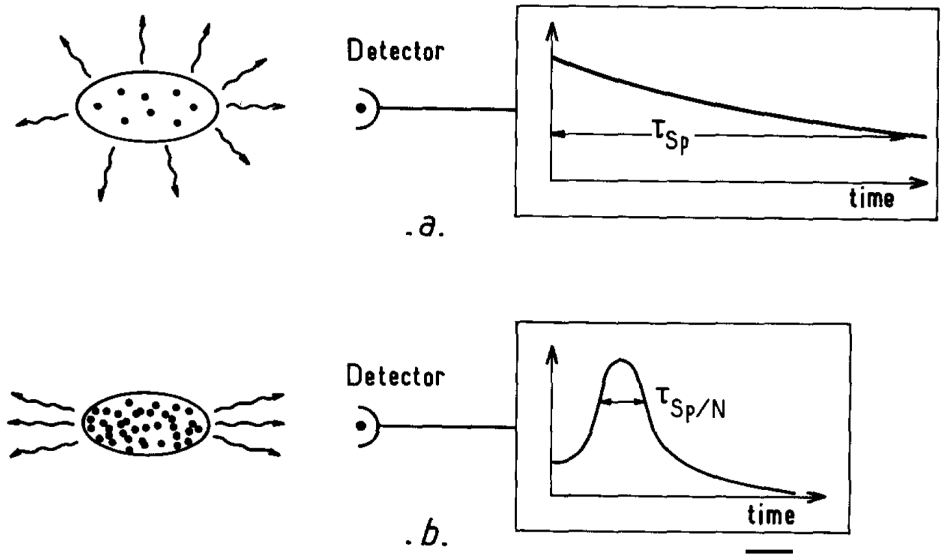

Figure 2: (a) Ordinary fluorescence. (b) Superfluorescence. Source: M. Gross & S. Haroche, Phys. Rep. **93**, 301 (1982)

Mean-field, Markovian model of superfluoresce

A sample of N 2-level identical atoms collectively interacting with a quantum electromagnetic field at the initial product state

$$\bigotimes_N |\psi\rangle \otimes |\mathrm{vac}\rangle, \quad |\psi\rangle = \begin{pmatrix} \psi_1 \\ \psi_0 \end{pmatrix}$$

After elimination of electromagnetic field, application of Markovian approximation and for large N one obtains the following non-linear Schrödinger equation for a single atom ($\langle \hat{A} \rangle_\psi \equiv \langle \psi | \hat{A} | \psi \rangle$)

$$i \frac{d}{dt}\psi = [\omega \hat{S}_z + i\frac{N\gamma_e}{2}(\langle \hat{S}_- \rangle_\psi \hat{S}_+ - \langle \hat{S}_+ \rangle_\psi \hat{S}_-)]\psi$$

$|\psi_e = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$ – metastable state relaxing to ground state $|\psi_g = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$,

γ_e - spontaneous emission rate

Nonlinear Schrödinger equation is equivalent to

$$|z|^2 = p - p^2, \quad \dot{p} = -N\gamma_e \, p\,(1-p),$$

$$z(t) = \psi_0(t)\bar{\psi}_1(t), \quad p(t) = |\psi_1(t)|^2$$

$p(t) = 1, z(t) = 0$ – metastable state

Analogical to TV model Friedmann equations for early Universe

$$p \sim h^2, \quad |z|^2 \sim \rho_r$$

Conjecture suggested by superfluorescence model

Equations of General Relativity, unlike Maxwell equations, may not be reversible dynamical equations for a classical field theory which should be then quantized (e.g. via canonical quantization or path integrals) but rather certain semiclassical, mean-field and irreversible Markovian evolution equations. They might be determined by a particular choice of the Universe initial state followed by elimination of certain degrees of freedom of an unknown fundamental quantum theory.