Physics Letters B 759 (2016) 546–549

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

# Reheating of the Universe as holographic thermalization

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ARTICLE INFO

*Article history:*
Received 10 February 2016
Accepted 9 June 2016
Available online 14 June 2016
Editor: M. Trodden

ABSTRACT

Assuming gauge/gravity correspondence we study reheating of the Universe using its holographic dual. Inflaton decay and thermalisation of the decay products correspond to collapse of a spherical shell and formation of a blackhole in the dual anti-de Sitter (AdS) spacetime. The reheating temperature is computed as the Hawking temperature of the developed blackhole probed by a dynamical boundary, and is determined by the inflaton energy density and the AdS radius, with corrections from the dynamics of the shell collapse. For given initial energy density of the inflaton field the holographic model typically gives lower reheating temperature than the instant reheating scenario, while it is shown to be safely within phenomenological bounds.



According to the standard lore of inflationary cosmology, reheating of the Universe is caused by out-of-equilibrium decay of the inflaton field that oscillates about its potential minimum. Although this is a crucial process that determines the subsequent thermal history of the Universe, our understanding of it is still incomplete as the decay process down to the Standard Model (SM) particles is highly involved. There are several phenomenological models of reheating, providing different approaches to evaluate the reheating temperature. Among these, the most traditional one is based on perturbative Born decay of the inflaton and the reheating temperature is computed from the condition that the inflaton decay rate $\Gamma$ becomes comparable to the Hubble expansion rate $H$, as

$$T_{\rm pert} \approx \left(\frac{90}{\pi^2 g_*}\right)^{\frac{1}{4}} (M_{\rm P}\Gamma)^{\frac{1}{2}} . \tag{1}$$

Here, $g_*$ is the relativistic degrees of freedom at the time of reheating, $M_{\rm P} \equiv (8\pi G_4)^{-1/2} = 2.4 \times 10^{18}$ GeV is the reduced Planck mass and $G_4$ is the four-dimensional Newton constant. This Born decay picture is known to be too simplistic, at least in some cases, as nonperturbative resonance effects can change the decay rate drastically. In the scenario of *preheating* [1], reheating is assumed to take place in three steps: the nonperturbative resonant decay of the inflaton, followed by perturbative cascade decay of the decay products, and then eventual thermalisation. There exist proposals of other reheating mechanisms, including those based on evaporation of primordial blackholes [2], surface evaporation of Q-balls [3], and nonminimal gravitational coupling of the inflaton [4]. We discuss, in this Letter, a novel description of reheating based on gauge/gravity correspondence [5,6]. This may be considered as the limit opposite to the perturbative scenario and is supposed to take account of strongly coupled dynamics in the thermalisation process.

Following the idea of holographic thermalisation [6,7] which asserts that blackhole formation in a $(d+1)$-dimensional anti-de Sitter (AdS) spacetime is a dual description of out-of-equilibrium thermalisation in $d$-dimensional conformal field theory (CFT), we postulate that the Universe sits at the boundary of a five-dimensional asymptotically AdS spacetime. We shall consider, schematically, the boundary action of the form

$$S_{\rm bdry} = S_{\rm CFT} + \int d^4x \Phi_0(\tau)\mathcal{O}(\tau), \tag{2}$$

and regard $S_{\rm CFT}$ as the action of the Universe including (but not restricted to) the SM matter. Here we treat the inflaton as an external field that is not included in the matter of the Universe. The operator $\Phi_0(\tau)$ represents the oscillating inflaton and $\mathcal{O}(\tau)$ is the matter in the Universe that couples to the inflaton.[1] Aside from

[1] In the two-body scattering into two bosons $\phi\phi \to \chi\chi$, for example, $\Phi_0 = \phi^2$ and $\mathcal{O} = \chi^2$. In the case of Higgs inflation the Higgs field ought to be split into the massive (inflaton) part $\Phi_0$ and the nearly massless (SM) part which is in the CFT.

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http://dx.doi.org/10.1016/j.physletb.2016.06.019

the interaction with the inflaton, the matter content of the Universe is nearly massless at high energies and may be modelled as a CFT. Prior to reheating the Universe must have undergone a rapid adiabatic expansion, i.e. inflation. Therefore the CFT is at zero-temperature when reheating commences. Our use of holography is motivated by the success of holographic quantum chromodynamics (QCD) [8]; the energy scale of reheating may well be higher than that of the quark-hadron phase transition, and then the "radiation" in the Universe should consist of ultra-relativistic quark-gluon plasma. We will not, nevertheless, specify the particle content of the CFT below. Although a legitimate use of gravity dual would require e.g. a large number of colours $N$, we will take a phenomenological approach and assume the existence of the gravity dual. Our focus here is on what the gravity dual will tell us about reheating of the Universe.

The out-of-equilibrium decay of the inflaton is a process of transferring its energy to the matter in the Universe. This may be seen as disturbance of the CFT by external shock represented by the oscillating inflaton operator $\Phi_0(\tau)$ in (2). The time scale of the disturbance $\Delta\tau$ may be determined by the decay efficiency and Hubble damping. In the gravity dual, the thermalisation corresponds to formation of a blackhole in $AdS_5$, caused by collapse of a shell that destabilises the pure AdS. The thickness of the shell corresponds to the time scale of reheating $\Delta\tau$. The boundary conditions of the infalling shell should be given by the oscillating field $\Phi_0(\tau)$ of the boundary action (2), in accordance with the GKPW prescription [5,6].

The dynamics of blackhole formation in the asymptotically AdS spacetime is described by the AdS–Vaidya solution [9],

$$ds^2 = -f(r,v)dv^2 + 2dvdr + r^2 d\Omega_3^2,$$
$$f(r,v) = 1 + \frac{r^2}{L^2} - \frac{r_0^2}{r^2}\theta(v), \tag{3}$$

where $L$ is the AdS radius and $r_0$ is related to the mass of the five-dimensional blackhole by

$$M_5 = \frac{3\pi r_0^2}{8G_5}. \tag{4}$$

Here, $G_5$ is the five-dimensional Newton constant. The function $\theta$ asymptotes to $\theta \to 0$ inside the shell and $\theta \to 1$ outside, and thus the AdS–Vaidya solution interpolates the pure AdS solution in the past (inside the shell) and the AdS–Schwarzschild solution in the future (outside). With the change of variables $dv = dt + f(r,v)^{-1}dr$, the metric in the static coordinates reads

$$ds^2 = -f(r)dt^2 + \frac{dr^2}{f(r)} + r^2 d\Omega_3^2, \tag{5}$$

in which the function $f(r)$ behaves as

$$f(r) \to \begin{cases} f_-(r) \equiv 1 + \frac{r^2}{L^2} & \text{(inside)}, \\ f_+(r) \equiv 1 + \frac{r^2}{L^2} - \frac{r_0^2}{r^2} & \text{(outside)}. \end{cases} \tag{6}$$

After the shock passes, the metric seen by a local observer becomes AdS–Schwarzschild, indicating that the CFT at the boundary is thermalised. The temperature of the CFT will be given by the Hawking temperature of the AdS–Schwarzschild blackhole, which may be interpreted as the reheating temperature of the Universe.

Cosmological application of holography has been actively studied since the early days of AdS/CFT correspondence. If we are to consider the Friedman–Robertson–Walker (FRW) universe as the CFT side of the correspondence, we are faced with two apparent obstacles. An expanding universe is weakly gravitating and hence the boundary theory in such a setup is not entirely decoupled from gravity. The other issue is the time dependence of the temperature; in contrast to the standard flat space CFT case in which the overall scaling of the temperature is unfixed, in cosmology the temperature has a definite value and redshifts as the inverse of the scale factor, $T \propto a^{-1}$. These features suggest that when discussing cosmology in AdS/CFT, the boundary theory should be treated dynamically [10]. The Universe is then envisaged as a hypersurface moving in the asymptotically $AdS_5$ bulk.

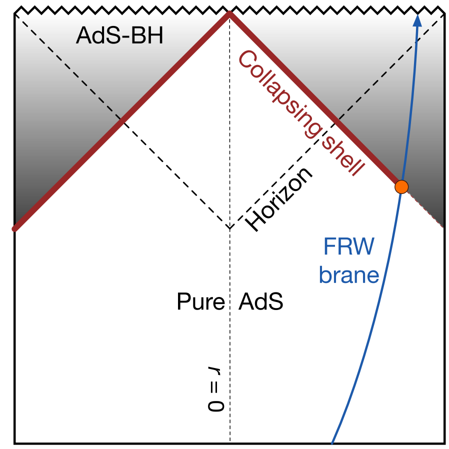


**Fig. 1.** The Penrose diagram of the AdS–Vaidya solution describing blackhole formation. The Universe is considered as a probe FRW brane, a hypersurface solving Israel's junction conditions. The collapsing shell is released form the brane during reheating, with boundary conditions given by $\Phi_0(\tau)$. The region outside the FRW brane is to be excised so that the brane represents a true boundary of the spacetime. (For interpretation of the colours in this figure, the reader is referred to the web version of this article.)

To proceed, we make use of the observation [11,12] that the Friedman equation is obtained from the induced metric on a hypersurface in the five-dimensional AdS–Schwarzschild (or AdS–Vaidya) spacetime. The emerging Friedman equation is

$$H^2 = -\frac{1}{a^2} + \frac{r_0^2}{a^4} + \cdots, \tag{7}$$

where the ellipses represent terms that come from extra matter on the brane, which are not important in our discussion of reheating and will be neglected. The second term in (7) is a radiation-like contribution proportional to the mass of the five-dimensional blackhole. In many of the brane universe literature this term is treated as an extra contribution *in addition to* the matter of the Universe, but here in holographic reheating this term is naturally interpreted as the thermal radiation resulting from thermalisation of the shock. The first term of (7) is the curvature term $-k/a^2$, indicating that we are considering the closed ($k = 1$) FRW universe.

Identification of the FRW metric and the induced metric on the hypersurface implies that the scale factor of the universe coincides with the AdS radial coordinate, $a = r$. An expanding universe is thus a brane moving away from the centre of the AdS. Fig. 1 shows embedding of the FRW universe in the AdS–Vaidya spacetime. Reheating takes place at the transition from the pure AdS to the AdS–Schwarzschild background, marked by the small orange circle. As we regard the FRW brane as a true boundary of the spacetime, the region to the right of the brane is understood to be cut away. The renormalisation scale is thus time-dependent in the global coordinates. In the unit of the boundary (FRW) time, however, the renormalisation scale is approximately constant as the warp factor is trivial. The collapsing shell is released from the brane with the boundary conditions given by $\Phi_0(\tau)$. The horizon develops as the shell collapses. Its location $r = r_+$ is found as a solution to $f_+(r) = 0$,