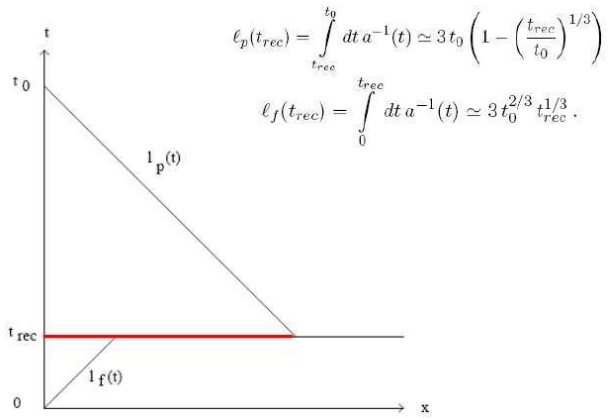

Fig. 1. The plot of the physical distance x versus time t illustrates the homogeneity problem: the past light cone $\ell_p(t)$ at the time $t_{\rm rec}$ (in red) is much larger than the forward light cone $\ell_f(t)$ at $t_{\rm rec}$. Adapted from Brandenberger (2004).

dom to gravity (Brans-Dicke theory being the paradigmatic example of this type), or by adopting an action built with higher-order invariants.

Other ways to avoid the singularity are:

- Changing the way gravity couples to matter, from minimal to non-minimal coupling;
- Using a non-perfect fluid as a source.

Finally, quantum gravitational effects also give the chance of a bounce[7]. In the next section we shall briefly discuss how a bounce can solve some of the problems that the cosmological model pre-1980 had.

2. THE BOUNCE AND THE PROBLEMS OF THE STANDARD COSMOLOGY

In addition to the initial singularity, SCM had other problems. Among them we can cite the following (Brandenberger 1999):

- The homogeneity problem: the comoving region over which the CMB is observed to be homogeneous to better than one part in 10^{-4} is much larger than the comoving forward light cone at the time of recombination (see Figure 1).
- The flatness problem: the quantity $|\Omega - 1|$ decreases with the evolution of a universe dominated by matter or radiation. Since $\Omega \approx 1$ today (Komatsu et al. 2011), Ω must have been incredibly close to 1 in the past.
- The generation of primordial perturbations: clusters of galaxies have nonrandom correlations on scales larger than 50 Mpc. This scale is comparable to the comoving horizon at $t_{\rm eq}$. If the initial density perturbations were produced much before $t_{\rm eq}$, the correlations cannot be explained by a causal mechanism[8].

[7]See Novello & Perez Bergliaffa (2008) for details about all these items.

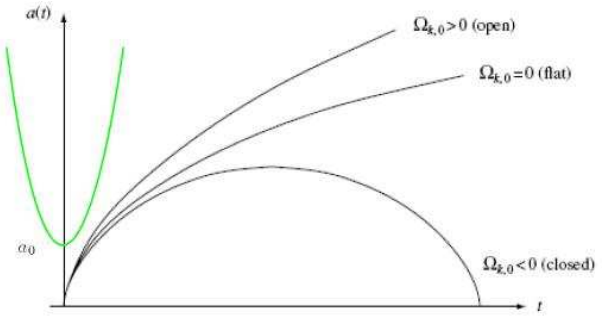

Fig. 2. Typical evolution of the scale factor in a nonsingular cosmological model (in green), as opposed to the singular big bang model.

Except for the inital singularity, these problems were addressed by inflation (which has problems of its own as we mentioned before)[9]. We shall see next that a model with a bounce may also face these issues succesfully. Let us state that by a nonsingular model with a LFRW geometry we mean a model in which the scale factor attains a minimum value (Figure 2).

Consequently, a model with a bounce solves the problem of the initial singularity by construction. Regarding the homogeneity problem, the future light cone is given by

$$\ell_f(t) = a(t) \int_{t_i}^{t} \frac{dt}{a(t)}.$$

Assuming the equation of state $p = \omega\rho$ it follows that $a(t) \propto (-t)^{\frac{2}{3(1+\omega)}}$. Hence,

$$\ell_f(t) \propto (-t_i)^{\frac{1+3\omega}{3(1+\omega)}} (-t)^{\frac{2}{3(1+\omega)}} + t.$$

If there is a contracting phase led by a perfect fluid with $\omega > -1/3$, then $\ell_f(t)$ diverges for $t_i \to \infty$, thus solving the horizon problem. The flatness problem, is encoded in the equation

$$\frac{d}{dt}|\Omega - 1| = -2\frac{\ddot{a}}{\dot{a}^3}.$$

Since the standard evolution drives Ω to 1, an era during which the evolution of the universe forces $|\Omega - 1|$ away of zero is needed. This can achieved by an

[8]Actually, standard cosmology cannot explain how primordial density perturbations are generated.

[9]For a review of inflation, see for instance Bauman (2009).