

# Cosmology

## Implementation of The Benchmark Model

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### Methodology

I am using Romberg's method for the implementation of the integration with the trapezoid as its base case. I have defined a function wrt  $a$ ,  $z$ , (proper dist), and  $z$  in all three sub-parts. Then I changed the integration function input with that function. For the even sampling in the first two cases, I used log spacing (added zero separately to it for the initial condition and removed it while plotting) and in the third case, I used linear spacing respectively. Since the integration in each step is cumulative so in the next iteration of  $a$  or  $z$ , I did integration only from the previous to the current point and added the stored integral value from the previous step to it to get the current value. They are shown in the plots below and are matching with the graphs given in Ryden.

### Scale Factor as a function of time

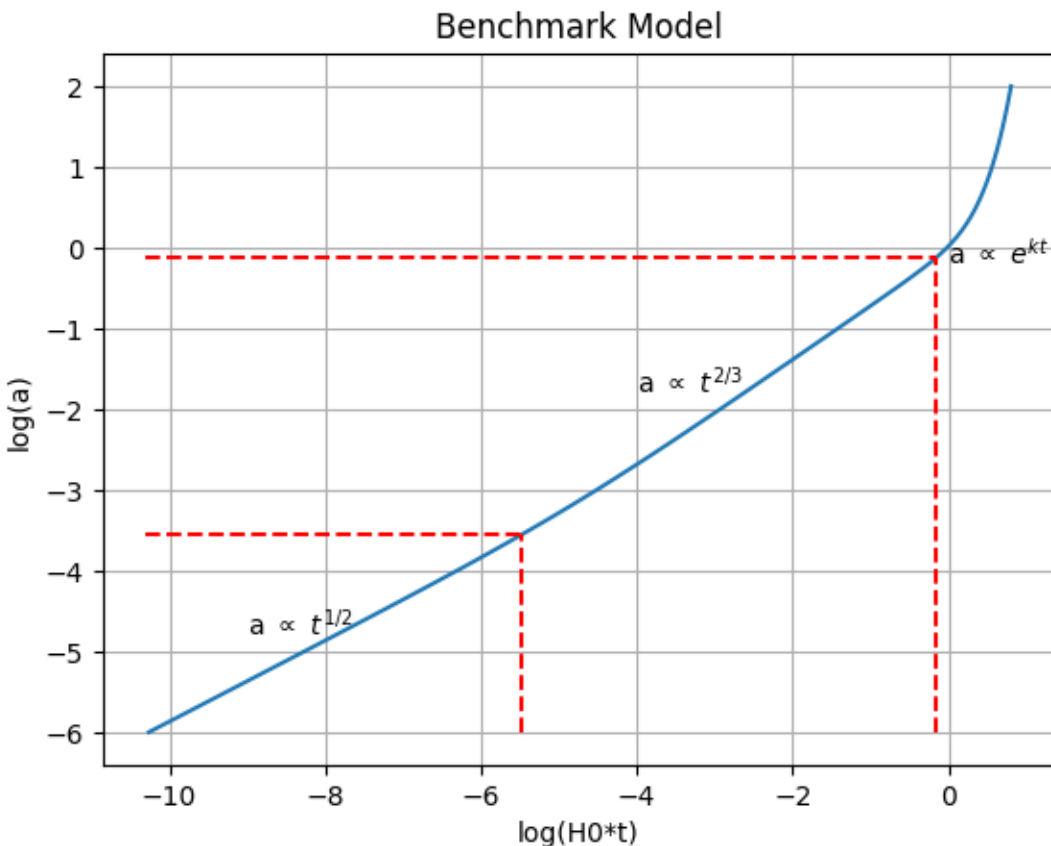


Fig. 1: The scale factor  $a(t)$  as a function of  $H_0 \cdot t$  on a log-log scale. All three regions are marked here.

## Proper Distance at Current Time

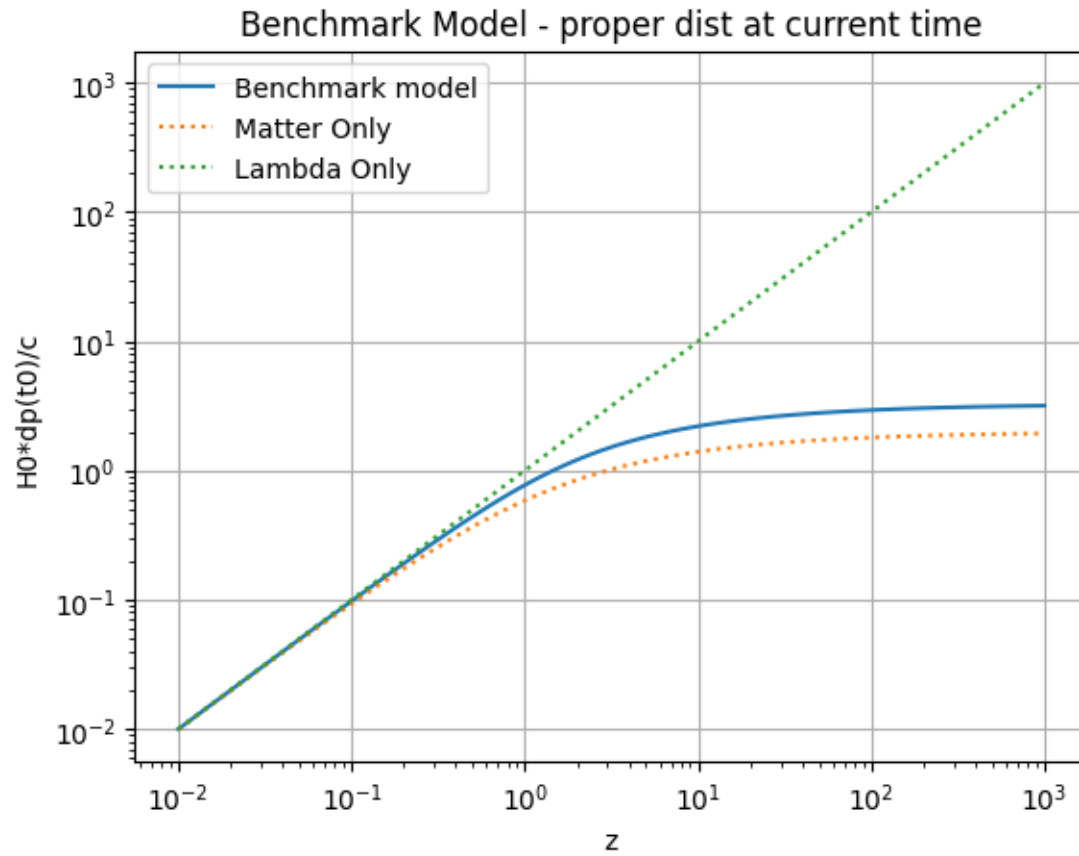
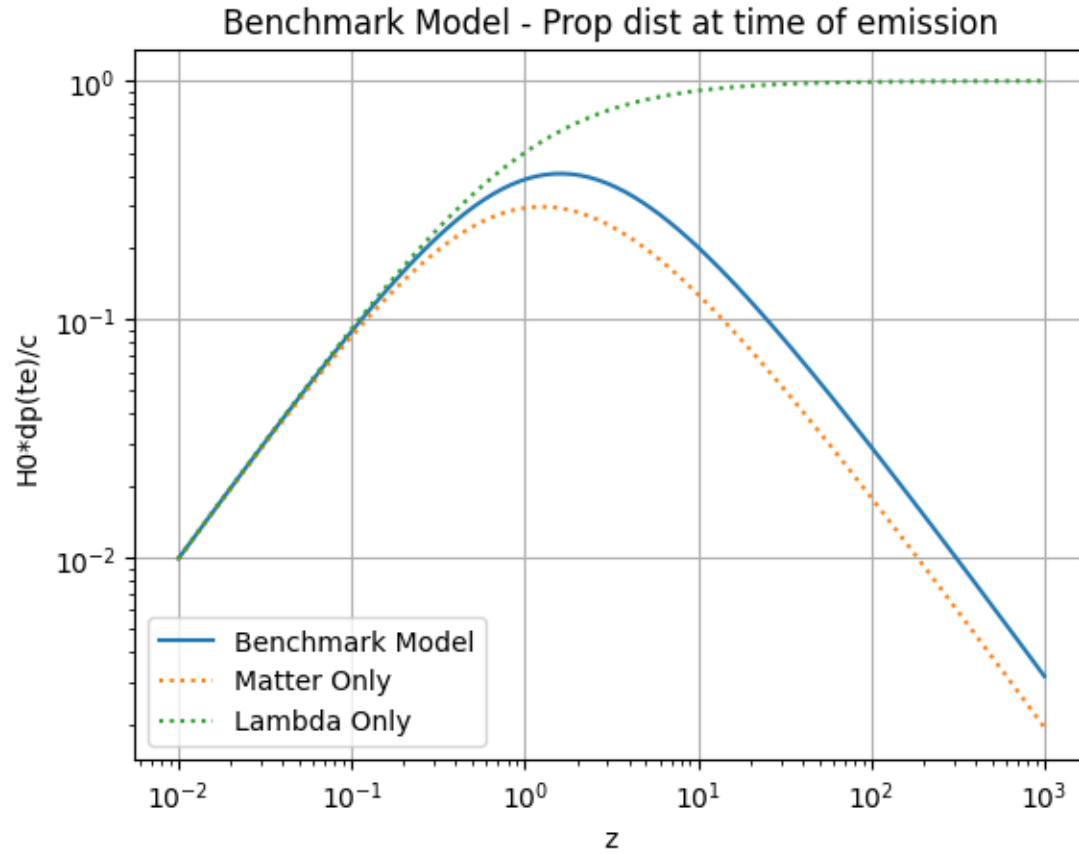


Fig. 2: Proper distance at current time as a function of  $z$  in a log-log scale.

As  $z$  tends to infinity, the value of proper distance becomes  $3.175 (c/H_0)$ . It is near but still different from the value of  $3.24(c/H_0)$  given in Ryden.

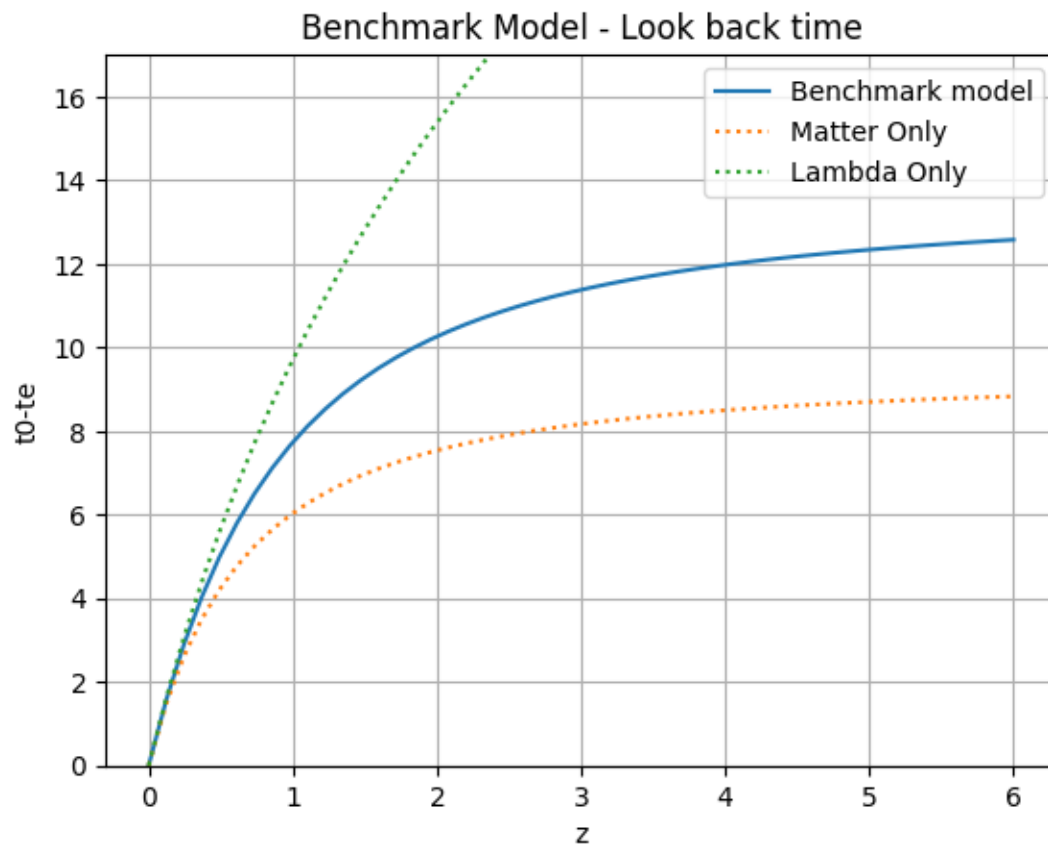
### Proper distance at Time of Emission



**Fig. 3: Proper distance at the time of emission as a function of  $z$  in a log-log scale.**

$dp(t_0)$  is divided by  $(1+z)$  to get at  $dp(te)$ . The maxima value is at 1.485 which is different from Ryden where it is 1.6 but the peak value in my case is 0.4078 which is approximately 0.41 as given in Ryden.

## Lookback Time as a function of redshift



**Fig. 4: Lookback time as a function of  $z$ .**

At  $z = 6$ , the lookback time from the benchmark model is 12.5756 which is approximately the same as 12.6 Gyr given in Ryden. The lookback time is 27.24 Gyr and 8.83 Gyr for lambda only and matter only respectively at  $z=6$ .