

How old is the Universe ?

Setting new constraints on the age of the Universe

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ABSTRACT

There are three independent techniques for determining the age of the universe: via cosmochronology of long-lived radioactive nuclei, via stellar modelling and population synthesis of the oldest stellar populations, and, most recently, via the precision cosmology that has become feasible with the mapping of the acoustic peaks in the cosmic microwave background. We demonstrate that all three methods give completely consistent results, and enable us to set rigorous bounds on the maximum and minimum ages that are allowed for the universe. We present new constraints on the age of the universe by performing a multiband colour analysis of bright cluster ellipticals over a large redshift range ($0.3 < z < 0.9$), which allows us to infer the ages of their stellar populations over a wide range of possible formation redshifts and metallicities. Applying a conservative prior to Hubble’s constant of $H_0 = 70 \pm 15 \text{ km s}^{-1} \text{ Mpc}^{-1}$, we find the age of the universe to be $13.2_{-2.0}^{+3.6} \text{ Gyr}$ (1σ), in agreement both with the estimates from type Ia supernovae, as well as with the latest uranium decay estimates, which yield an age for the Milky Way of $12.5 \pm 3 \text{ Gyr}$. If we combine the results from cluster ellipticals with the analysis of the angular power spectrum of the cosmic microwave background and with the observations of type Ia supernovae at high redshift, we find a similar age: $13.4_{-1.0}^{+1.4} \text{ Gyr}$. Without the assumption of any priors, universes older than 18 Gyr are ruled out by the data at the 90% confidence level.

Key words: galaxies: elliptical and lenticular, cD — galaxies: evolution — cosmology: Cosmic Microwave Background, anisotropy, power spectrum

1 INTRODUCTION

Discrepancies between age determinations, such as for globular clusters and from the Hubble constant, have long plagued cosmology. The situation has changed dramatically in the past three years, however, as the Hubble constant proponents (Mould et al. 2000) have converged on a value which we conservatively take to be of $H_0 = 70 \pm 15 \text{ km s}^{-1} \text{ Mpc}^{-1}$, and because of several other developments. Type Ia supernova measurements have provided strong evidence for a cosmological constant (Perlmutter et al. 1999; Riess et al. 1998), and mapping of the acoustic peaks in the cosmic microwave background has fixed the cosmological parameters with unprecedented precision (Netterfield et al. 2001). Finally, detection of uranium in an old Population II star has provided a direct nuclear chronometer for the age of our galaxy (Cayrel et al. 2001). Any one of these measurements may be suspect, but the remarkable concordance that we find enables to show here by a combined likelihood analysis that combination of these constraints provides, for the first time, rigorous upper and lower bounds on the age of the universe.

Consider first stellar model determinations of the age of

the universe. The small scatter found in the absolute luminosity of the brightest cluster galaxies (BCGs) over a wide range of redshifts motivated their use as standard candles to determine cosmological parameters (Gunn & Oke 1975). However, this analysis was based on the assumption that this type of galaxy should not undergo significant evolution in luminosity with lookback time. Tinsley (1976) showed that the brightening of main sequence stars poses a major hurdle in the use of BCGs as standard candles. Predicting the luminosity evolution is a rather challenging endeavour since it strongly depends both on the star formation history as well as on the dynamical history. An analysis of bright ellipticals in a large sample of clusters observed in the near-infrared (Aragón-Salamanca, Baugh & Kauffmann 1998) concluded that the stellar mass in BCGs over a large redshift range ($0 < z < 1$) has evolved by a factor between 2 and 4 depending on the cosmology, in agreement with the predictions of hierarchical clustering scenarios of structure formation (Kauffmann & Charlot 1998). On the other hand, an analysis of the colours of bright cluster ellipticals is only dependent on their star formation history. The small scatter found in the colour-magnitude relation of cluster el-

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lpticals (Bower, Lucey & Ellis 1992; Stanford, Eisenhardt & Dickinson 1998) hints at old stellar populations, formed at redshifts $z_F \gtrsim 3$. The use of galaxy colours as a “cosmic clock” is nevertheless a challenging task especially due to the age-metallicity degeneracy, which causes age effects to be mimicked by a range of metal abundances (Worthey 1994).

We focus on the brightest cluster ellipticals — which are assumed to have a simple star formation history as explained below — and use stellar population synthesis models (Bruzual & Charlot, in preparation, hereafter B&C) in order to infer the age of the stars in these galaxies. We have compared this technique both with the analysis of the latest measurements of the angular power spectrum of the cosmic microwave background radiation (CMBR) observed by the BOOMERanG collaboration (de Bernardis et al. 2000, 2001) as well as with the observations of high redshift type Ia supernovae (Perlmutter et al. 1999; Riess et al. 1998) in order to estimate the age of the universe. We also compare these ages with the ages derived for globular clusters (Salaris & Weiss 1998) and the oldest halo stars (Cayrel et al. 2001), to which one has to add an age for the Milky Way that must correspond to the time elapsed between the Big Bang and formation at a redshift of at least 2, and more conservatively 5 or even 10.

We find that four completely independent age determinations — namely CMBR, galaxy colours for clusters at $z \lesssim 1$, stellar evolution applied to old globular clusters, and radioactive isotope dating of old stars — lead to a consistent result. These age probes represent different combinations of Big Bang parameters (H_0 , Ω_m , Ω_Λ), galaxy evolution parameters (star formation rate history, initial stellar mass function), stellar evolution parameters (stellar mass, composition and mixing length), and nucleochronology (half-life of ^{238}U), respectively. In this paper we add the spectrophotometric study of bright cluster ellipticals to the growing list of cosmological probes used to determine the age of the Universe (Lineweaver 1999; Primack 2000).

2 USING BRIGHT CLUSTER ELLIPTICALS AS COSMIC CLOCKS

We use the sample of Stanford, Eisenhardt & Dickinson (1998), which comprises 17 clusters over a large redshift range ($0.3 < z < 0.9$). The sample was extracted on the basis of available imaging with the Wide Field and Planetary Camera 2 on board the Hubble Space Telescope — for morphological classification purposes — from a larger sample of 46 clusters drawn from a variety of optical, X-ray and radio-selected clusters. Each cluster was imaged in near-infrared J , H and K bands as well as two optical passbands, which were chosen as a function of redshift to straddle the 4000\AA break in the galaxy rest-frame (i.e. roughly mapping rest-frame U and V bands). For each cluster we select the three brightest early-type systems which fall on the colour-magnitude relation and choose the reddest one, always taking care not to select an outlier. For each galaxy we compared the observed colours with the predictions of a grid of simple stellar populations with different ages and metallicities, from the latest models of B&C. The comparison was performed using a χ^2 test applied between the four observed colours for each

of the 17 clusters ($c_{n,i}$; $n = \{1 \dots 17\}$, $i = \{1 \dots 4\}$), and the predictions from the population synthesis models ($\mathcal{C}_{n,i}$), namely:

$$\chi_{SSP}^2 = \sum_{n=1}^{17} \sum_{i=1}^4 (c_{n,i} - \mathcal{C}_{n,i})^2 / \sigma_i^2 + (\text{Model}(U - V)_{z=0} - 1.6)^2 / \sigma_0^2. \quad (1)$$

The colour scatter σ_i is chosen to be ± 0.2 magnitudes for all four colours, and comprises the effect of photometric error bars, uncertainties in the modelling of stellar populations as well as colour scatter in bright ellipticals. In order to further tighten the allowed region of parameter space, we have applied a constraint at zero redshift, using high precision photometry of the Coma and Virgo clusters (Bower et al. 1992), adding the second term shown in equation (1). Hence, for a given age-metallicity point, we evolve the system to zero redshift (with a given cosmology) and then compare its $U - V$ colour with the observed $(U - V)_{z=0} = 1.6$ with a scatter $\sigma_0 = 0.1$ mag.

Figure 1 shows the contours at 68, 90 and 95% confidence levels in an age-metallicity diagram for the brightest ellipticals in cluster Cl0024+16 ($z = 0.39$). The degeneracy between age and metallicity is readily shown, so that old populations with low metal abundances give similar results to young stars with a higher metallicity. In the figure, we compare the result of B&C with the population synthesis models of Yi et al. (1999) who take special care in adding the contribution from core helium burning stars — horizontal branch (HB) stars — and their progeny. HB stars seem to be the most plausible candidate to explain the UV upturn ($\lambda \sim 1500\text{\AA}$) in elliptical galaxies (O’Connell 1999). However, the agreement between both models shown in Figure 1 is expected if we consider that most of the contribution of the light in the spectral range considered (i.e. between U and K bands) from elliptical galaxies comes from the main sequence and red giant branch populations, which are better understood than HB stars (Bruzual & Charlot 1993; Yi et al. 1999).

We can impose a further constraint on the metallicity for bright cluster ellipticals. In these massive systems, the deep gravitational wells prevent gas ejected from supernovae from being thrown out of the galaxy. This feedback mechanism is presumed to be more effective in low mass spheroids (Ferreras & Silk 2000a) and is the basis for the correlation between mass and metallicity (Larson 1974). A detailed analysis of metal abundances in several Fornax cluster early-type galaxies (Kuntschner 2000) shows that $[\text{Fe}/\text{H}] \gtrsim 0.0$ for ellipticals with high velocity dispersion ($\log \sigma \gtrsim 2.2$). The standard simple closed-box model is a good approximation to the chemical enrichment in bright ellipticals (Pagel 1997). In this model the evolution of the average stellar metallicity is:

$$Z = p \left[1 + \frac{\mu \ln \mu}{1 - \mu} \right], \quad (2)$$

where μ is the gas mass fraction contributing to star formation and p is the stellar yield, i.e. the mass fraction of elements other than helium generated in stars and weighted by the initial mass function (IMF). In bright ellipticals there is no significant ongoing star formation, which means $\mu \rightarrow 0$ and so $Z \sim p \lesssim 0.8Z_\odot$ (where $Z_\odot = 0.02$ is the solar metallicity). Hence, we can further constrain the upper bound to the age of the stellar populations by imposing a lower limit

to the metallicity at $[\text{Fe}/\text{H}] \gtrsim -0.1$, roughly corresponding to $Z \sim 0.8Z_\odot$, shown as a horizontal line in Figure 1.

Finally, the complete sample of 17 clusters can be combined by assuming a given cosmology ($H_0, \Omega_m, \Omega_\Lambda$) which enables us to translate redshifts into ages. A grid of models was run as follows: The cosmology was explored by choosing $0.085 \leq \Omega_m \leq 1.085$ and $0 \leq \Omega_\Lambda \leq 1.$, both in steps of 0.085; and $0.25 \leq h_0 \leq 0.95$ in steps of 0.05 (with h_0 defined as $H_0/\text{km s}^{-1}\text{Mpc}^{-1}$). The stellar populations were parametrized by the metallicity, chosen in the range $0.8 \leq Z/Z_\odot \leq 1.9$ in steps of 0.1 and the formation redshift $z_F = \{2, 2.25, 2.50, 2.75, 3, 3.25, 3.50, 3.75, 4, 6, 8, 10\}$. We ran two such models for two different initial mass functions: Salpeter (1955) and Scalo (1986), using B&C and a third one using the models of Yi et al. (1999) for a Salpeter IMF.

The metallicity is not the only factor that could modify age estimates from broadband photometry. The reddening caused by dust may also cause overestimates of stellar ages. However, dust is not expected to play a significant role in cluster ellipticals, whose gaseous component is too hot to allow significant amounts of dust to be present over large timescales. The small scatter found in the colour-magnitude relation of cluster ellipticals would require a tight conspiracy between age, metallicity and dust, in order to keep the scatter as low as observed. Furthermore, rest-frame near-ultraviolet photometry of Abell 851 ($z = 0.41$) shows that the brightest ellipticals are not redder than the dustless predictions of simple stellar populations (Ferrerias & Silk 2000b).

3 AGE FROM COSMOLOGY: METHOD

In the *standard* inflationary framework, the cosmic microwave background power spectrum depends essentially on 3 cosmological parameters (Efstathiou & Bond 1999): the physical matter density in baryons ($\omega_b = \Omega_b h^2$), the overall physical matter density ($\omega_m = \Omega_m h^2$) and the parameter $R = \sqrt{\omega_m/\omega_k} f(y)$ where $f(y)$ is $\sinh(y)$, y , $\sin(y)$ for open, flat and closed models respectively and where

$$y = \omega_k^{1/2} \int_{a_r}^1 \frac{da}{[\omega_m a + \omega_k a^2 + \omega_\Lambda a^4]^{1/2}}, \quad (3)$$

with $\omega_k = h^2(1 - \Omega_m - \Omega_\Lambda)$. Cosmological models with the same values of the parameters ω_m , ω_b and R will have nearly-identical power spectra on degree and subdegree angular scales. Furthermore, the age of the universe is given by

$$t_0 = 9.8\text{Gyr} \int_0^1 \frac{ada}{[\omega_m a + \omega_k a^2 + \omega_\Lambda a^4]^{1/2}}. \quad (4)$$

Under the assumption of a flat universe (i.e. $\omega_k = 0$ and $R \sim \text{const}$) as the recent CMBR measurements seem to suggest, it is easy to show that nearly degenerate models with the same ω_Λ , ω_m and ω_b will have also similar ages. Thus, in principle, a measurement of the CMBR spectrum can be extremely helpful in the determination of the age of the universe in flat cosmologies. The curvature itself, however, due to the dependence of R from Ω_Λ and Ω_m , cannot be constrained by CMBR measurements alone better than 10 – 20%.

This introduces a limitation in the use of the CMBR spectrum for producing independent strong constraints on the age. However, the integrated Sachs-Wolfe effect on large angular scales and the assumption of mild external priors on the various cosmological parameters can break the above degeneracies and reduce the error in the age estimation from CMBR. In what follows we will put constraints on the age of the universe by comparing the recent CMBR data obtained from the BOOMERanG experiment with a database of models with cosmological parameters sampled as described in the previous section. We also vary the spectral index of the primordial density perturbations within the range $n_s = 0.50, \dots, 1.50$, the optical depth $\tau_c = 0.0, \dots, 0.3$, and we rescale the fluctuation amplitude by a pre-factor taken as a free parameter.

The theoretical models are computed using the publicly available CMBFAST program (Seljak & Zaldarriaga 1996) and are compared with the BOOMERanG-98 and COBE results. We include the COBE data using Lloyd Knox's RADPack packages. The power spectra from these experiments are estimated in 19 and 24 bins respectively, spanning the range $2 \leq \ell \leq 1050$. For the BOOMERanG-98 the spectrum we assign a flat shape, $\ell(\ell + 1)C_\ell/2\pi = C_B$.

Following de Bernardis et al. we approximate the signal C_B inside the bin as a Gaussian variable. The likelihood for a given cosmological model is then defined by $L = e^{-\chi_{\text{CMBR}}^2/2}$ with

$$\chi_{\text{CMBR}}^2 = \sum_B (C_B^{\text{th}} - C_B^{\text{ex}})^2 / \sigma_B^2, \quad (5)$$

where C_B^{th} (C_B^{ex}) is the theoretical (experimental) band power, and σ_B is the quoted error bar. We consider a 10% calibration error for the BOOMERanG-98 experiment by adding a gaussian term $\chi_{\text{cal}}^2 = (1.0 - A_{\text{cal}})^2 / (0.24)^2$ and by finding the value of A_{cal} that for a given cosmological models maximizes the likelihood. We also marginalize over the beam uncertainty (1.4') and we found that the removal of systematics — does not change the results of our analysis. We multiply L by our chosen priors and attribute a likelihood to each age in the 1 – 30 Gyr range by finding the 'nuisance' parameters that maximise it. We then define our central values and 1σ for the age from the 16%, 50% and 84% integrals of L over age.

4 DISCUSSION

The results are summarized in Table 1 using external priors based on theoretical restrictions as well as on recent astronomical observations. The finite volume of parameter space sampled imposes further implicit constraints on the age of the universe. However, the large range of parameters explored implies this implicit constraint is rather weak, as can be seen from the last entry in Table 1 (constant likelihood across the parameter space without any priors), for which the estimated age of the universe at a 68% confidence level is 19.8 ± 9 Gyr. The constraint imposed by stellar populations in bright cluster ellipticals (Salpeter IMF) yields an age between 12 and 13 Gyr regardless of the prior on h_0 or on the population synthesis model chosen, although imposing a prior on h_0 results in smaller error bars, roughly

around $13.2_{-2.0}^{+3.6}$ Gyr. This is in agreement with estimates of the age of the universe from Type Ia supernovae at high redshift (Perlmutter et al. 1999; Riess et al. 1998). Using a Scalo IMF does not change the age estimates significantly: the best fit gives ages less than 5% compared to a Salpeter IMF, i.e. well below the error bars.

The latest measurement of the age of the oldest stars in the Milky Way through the decay of ^{238}U gives a value of 12.5 ± 3 Gyr (Cayrel et al. 2001), which is consistent with the above ages if we assume the process of star formation started in our galaxy 1 – 3 Gyrs after the Big Bang, corresponding to a formation redshift $z_F \gtrsim 2$ for a reasonable range of cosmologies. Another technique which allows for a reasonably accurate estimate of the age of our galaxy involves globular clusters. The ages of globular clusters can be inferred in a distance-independent way by analyzing several features in the stellar colour-magnitude diagram such as the luminosity gap between the main sequence turnoff and the base of the zero age horizontal branch, or the colour gap between the turnoff point and the tip of the red giant branch. Salaris & Weiss (1998) explored a sample of halo and disk globular clusters, finding the age of the oldest cluster (NGC 6366) to be 12.2 ± 1.1 Gyr. However, Pont et al. (1998) estimate an age of 14 Gyr for M92 with a more standard distance-dependent technique, involving a fit to the main-sequence in a colour-magnitude diagram. M92 is estimated by Salaris & Weiss (1998) to be 11.0 ± 1.1 Gyr old.

The estimates from CMBR data give values that are perfectly consistent with the analysis using stellar populations. Since the new BOOMERanG data is perfectly consistent with present estimates of the baryon content from Big Bang Nucleosynthesis (Burles et al. 1999) the prior $\Omega_b h^2 = 0.02 \pm 0.002$ has little effect on the results as we can see in the fifth row of Table 1. We note that our CMBR analysis is restricted to a specific class of models based on *adiabatic* primordial perturbations and with a limited number of parameters. Assuming different mechanisms of structure formation than those predicted by inflation such as topological defects and/or isocurvature fluctuations would drastically change our conclusions. Furthermore, restricting our analysis to purely baryonic universes would yield higher values for the age of the universe, namely around ~ 22 Gyr (Griffiths, Melchiorri & Silk 2001). Thus, the consistency between the age values inferred from CMBR and those obtained by stellar populations can be considered as a further confirmation of the standard inflationary scenario.

As an interesting check of the models, we decided to invert the analysis presented here so that the formation redshift and the average metallicity of stellar populations in bright ellipticals could be inferred from estimates to the age of the universe. With a conservative prior on Hubble's constant ($H_0 = 70 \pm 15 \text{ km s}^{-1} \text{ Mpc}^{-1}$), we find the average metallicity to be $Z/Z_\odot = 1.10 \pm 0.18$ and 1.17 ± 0.31 for a Salpeter and a Scalo IMF, respectively, using the population synthesis models of Bruzual & Charlot. Adding the age constraint from CMBR data does not significantly change the result, giving $Z/Z_\odot = 1.14 \pm 0.18$ (Salpeter) and 1.14 ± 0.28 (Scalo). On the other hand, all formation redshifts explored in this paper ($2 < z_F < 10$) are allowed, and only the latest formation epochs ($z_F \sim 2$) are mildly ruled out at the 68% confidence level, which is compatible with the latest esti-

mates from morphological and spectroscopic studies of high redshift clusters (Van Dokkum & Franx 2001).

Hence, we have presented the study of the colours of bright cluster ellipticals as an additional analysis to be incorporated in the medley of cosmological probes. With a set of reasonable assumptions for the stellar populations in this type of galaxies, we infer an age of the universe of $13.2_{-2.0}^{+3.6}$ Gyr and a final result — combining the results from stellar populations in cluster ellipticals, the angular power spectrum of the CMBR and type Ia supernovae — of $13.4_{-1.0}^{+1.4}$ Gyr. Without the assumption of any priors, the combined analysis rules out universes older than 18 Gyr at a 90% confidence level.

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TABLE 1: Constraints on the Age of the Universe

Prior	B&C	Yi	CMBR	CMBR+B&C	CMBR+B&C+SN-Ia	Database
$h = 0.70 \pm 0.15, \omega_b = 0.025 \pm 0.01$	$13.2^{+3.6}_{-2.0}$	$13.4^{+4.4}_{-2.8}$	$13.8^{+1.8}_{-1.4}$	$13.6^{+1.6}_{-1.0}$	$13.4^{+1.4}_{-1.0}$	$16.0^{+6.4}_{-6.0}$
$h = 0.72 \pm 0.08, \omega_b = 0.025 \pm 0.01$	$13.0^{+3.0}_{-2.0}$	$13.2^{+4.4}_{-2.4}$	$13.2^{+1.2}_{-1.0}$	$13.2^{+1.0}_{-0.8}$	$13.2^{+1.2}_{-0.8}$	$14.2^{+4.4}_{-4.4}$
$h = 0.70 \pm 0.15, \omega_b = 0.025 \pm 0.01, \Omega = 1$	$13.2^{+3.4}_{-2.2}$	$13.6^{+4.0}_{-3.0}$	$13.4^{+1.2}_{-1.0}$	$13.4^{+1.0}_{-0.8}$	$13.4^{+1.0}_{-1.0}$	$15.2^{+6.8}_{-5.4}$
$h = 0.70 \pm 0.15, \omega_b = 0.02 \pm 0.002$	$13.0^{+3.4}_{-2.0}$	$13.4^{+4.4}_{-2.8}$	$14.0^{+1.6}_{-1.4}$	$13.6^{+1.6}_{-1.0}$	$13.4^{+1.8}_{-0.8}$	$15.8^{+6.2}_{-5.4}$
No prior	$13.6^{+5.0}_{-2.4}$	$12.4^{+4.8}_{-2.6}$	$14.6^{+1.8}_{-2.2}$	$14.2^{+1.6}_{-1.6}$	$13.6^{+1.6}_{-1.2}$	$19.8^{+8.8}_{-9.0}$

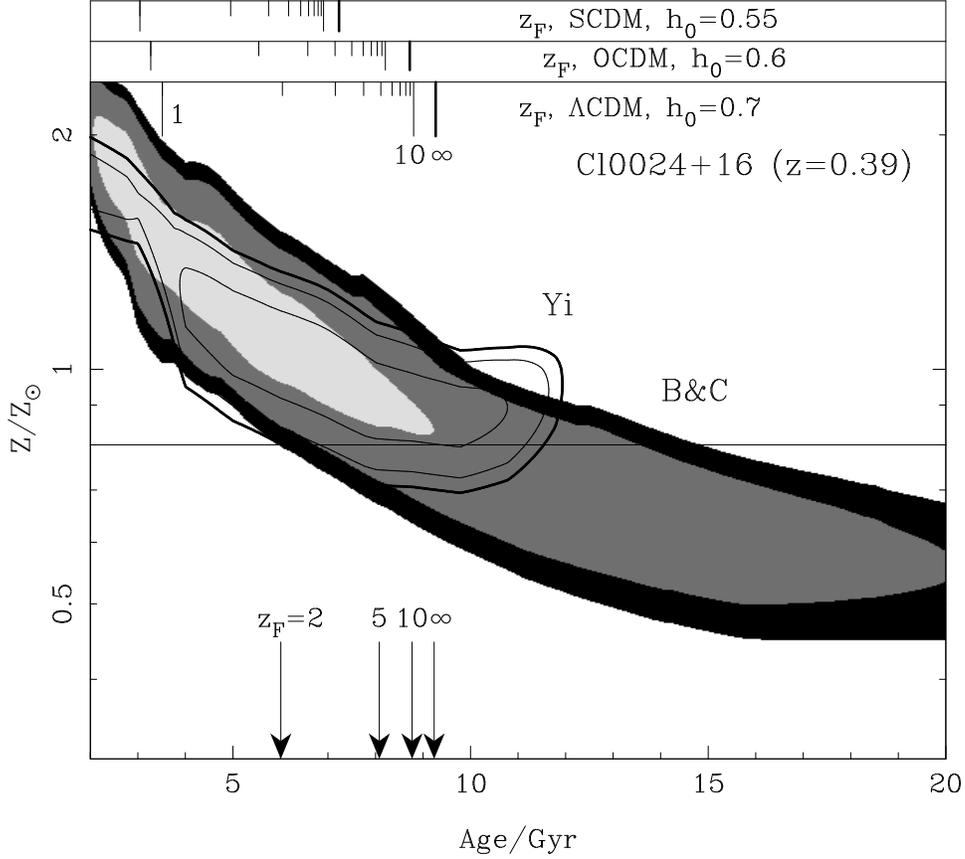


Figure 1: Age-metallicity diagram for cluster Cl0024+16 ($z = 0.39$) using the photometry from Stanford, Eisenhardt & Dickinson (1998). The contours are at the 68, 90 and 95% (thick line) confidence levels of the χ^2 defined in the text. Solid (dotted) lines correspond to the population synthesis models of Bruzual & Charlot (2001) and Yi et al. (1999), respectively. Both assume a Salpeter initial mass function. The arrows and one of the top axes give the stellar ages for three different formation redshifts assuming a Λ -dominated flat cosmology (Λ CDM, $\Omega_m = 0.3$; $h_0 = 0.7$). The other axes on top give formation redshifts for other popular cosmologies: OCDM ($\Omega_m = 0.3$; $\Omega_{\Lambda} = 0$; $h_0 = 0.6$); and SCDM ($\Omega_m = 1$; $\Omega_{\Lambda} = 0$; $h_0 = 0.55$). The horizontal line shows the lower limit to the metallicity expected for bright cluster ellipticals.

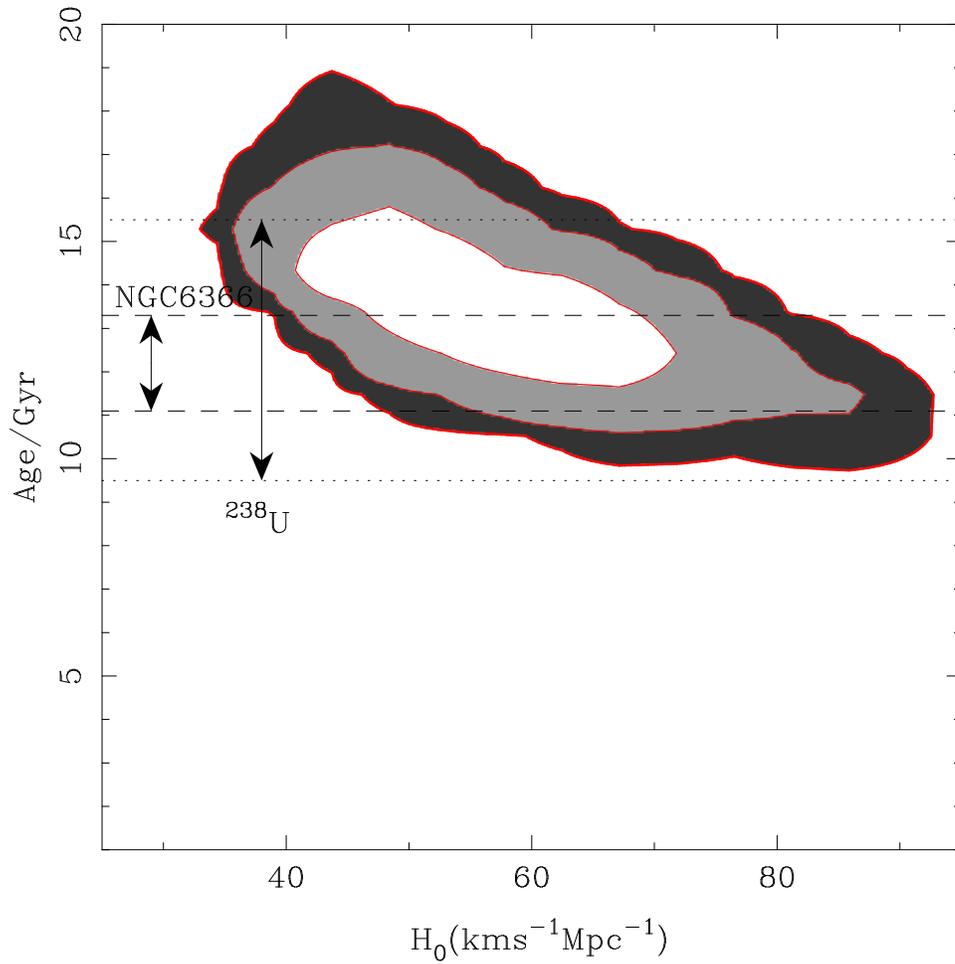


Figure 2: Estimate of the age of the universe as a function of H_0 preferred by a joint analysis combining the stellar populations in bright ellipticals for a Salpeter initial mass function and the observed angular power spectrum of the CMBR. The ^{238}U age-measurement of an old halo star in our galaxy of Cayrel et al. (2001) is also shown as dashed lines, however one should shift this age upwards by an amount corresponding to the lapse between $t = 0$ and the first processes of star formation in our galaxy. The age of the oldest halo globular cluster in the sample of Salaris & Weiss (1998) is also shown.

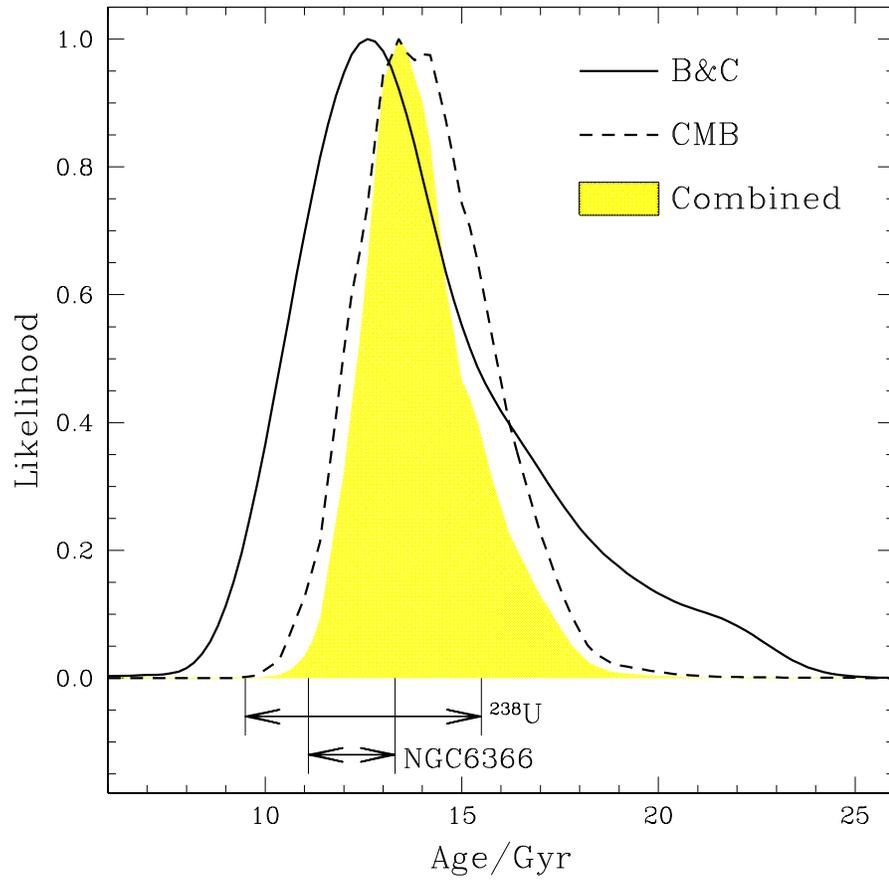


Figure 3: Likelihood curves for the estimates of the age of the universe using a comparison between the colours of bright cluster ellipticals and the latest population synthesis models of Bruzual & Charlot (B&C; solid line); and the angular power spectrum of the CMBR (dashed). The shaded area gives the likelihood of the combined analysis. Universes older than 18 Gyr are ruled out at a 90% confidence level.