A framework for the next generation of stationary cosmological models

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Abstract

According to a generic tired-light hypothesis found consistent with H(z) data, the density number of galaxies has been nearly constant over the last 10 Gyr at least, the density number of star-forming galaxies, as probed by sources of gamma-ray bursts, being constant as well, meaning that, as far as galaxies are concerned, the Universe has been stationary. On the other hand, an analysis of the luminosity distances of quasars and supernovae Ia shows that the Universe is far from being as transparent as assumed nowadays, the photon lifetime along the line-of-sight being one third of the Hubble time.

Keywords: Alternative cosmologies, Tired-light model, Luminosity distance, Cosmic opacity, Distance duality, Galaxy counts, Gamma-ray bursts.

Introduction

The family of cosmologies initiated by Georges Lemaitre [1] proved able to make challenging predictions. Among them: luminosity distances are larger than angular ones by a factor of $(1+z)^2$ [2]; *all* remote events look slower than local ones by a factor of $(1+z)$ [3]; there is an isotropic radiation with the spectrum of a blackbody at a temperature of $T_0(1+z)$, T_0 being its local temperature [4].

Such predictions have been backed by numerous observations. For instance, the expected time-dilation of remote events has been found in the light curves of supernovae Ia [5, 6, 7, 8], a thermal radiation at a temperature of $T_0 = 2.7°$K has been observed [9, 10] and its redshift dependence has been confirmed [11, 12, 13].

However, several clouds are still obscuring the brilliance of ΛCDM [14, 15, 16, 17], the so-called "concordance cosmology" [18]. In particular, ΛCDM is based on a "cosmic trinity" [19] of three essential ingredients with weird properties and for which there is still no direct evidence, namely, an early stage of accelerated expansion [20, 21], a dark matter and an energy components of unknown nature [16, 22, 23], both accounting for ≈ 95% of the matter-energy content of the Universe [24].

In other words, according to ΛCDM, the dominant forms of matter-energy are of a different nature on Earth and far away. Though such an hypothesis was taken for granted in the ancient times, it is the opposite hypothesis that has proven fruitful since the Renaissance, namely, that what is observed on Earth is representative of what is found in the rest of Universe. Given the numerous successes of the later hypothesis, it seems reasonable to push it forward once more.

However, it is not obvious to build from scratch a new cosmology able to compete with the result of the work of several generations of brilliant scientists. On the other hand, given the huge time and distance scales involved in cosmological problems, key physical ingredients may still be missing, like a tiny variation of quantities nowadays assumed to be constant [25, 26, 27].

So, as a preliminary step, it may prove useful to identify a set of ingredients that may serve as a basis for the development of such a new cosmology. This is the main goal of the present work.

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Main hypothesis

The tired-light model

As proposed previously [28, 29], let us assume that photons can not fly away for ever. However, instead of interpreting electromagnetic radiation as an interaction between a source and an absorber, let us posit that photons have *all* the same maximum range, d_V, due to a loss of their energy such that:

$$h\nu_{obs} = h\nu_0 - f_\nu d_T \qquad (1)$$

where ν_0 is the frequency of the photon when it is emitted, ν_{obs}, its frequency when it is observed, d_T, the distance between its source and the observer, h being the Planck constant. So, $\nu_{obs} = 0$ when $d_T = d_V$ and $f_\nu = \frac{h\nu_0}{d_V}$. Thus, eqn 1 can also be written as follows:

$$\nu_{obs} = \nu_0(1 - \frac{d_T}{d_V})$$

That is:

$$\frac{z}{1+z} = \frac{d_T}{d_V} \qquad (2)$$

while, when $z \ll 1$:

$$z \approx \frac{d_T}{d_V}$$

So, assuming that:

$$d_V = \frac{c_0}{H_0} \qquad (3)$$

yields:

$$z \approx \frac{H_0}{c_0} d_T$$

which is the relationship anticipated by Lemaitre [1] and further confirmed by Hubble [30], H_0 being the Hubble constant, c_0, the speed of light.

Though the idea that the Lemaitre-Hubble law is the result of some tired-light mechanism has already been proposed a number of times (*e.g.* [31, 32, 33, 34, 35, 36, 37]), note that the hypothesis that photons may *all* have the same range has been, to my knowledge, little considered so far.

Consistency with H(z) data

Let us now assume that, as checked in various contexts, the speed of light is constant (e.g. [38, 39, 40, 41, 42, 43, 44]) and that the delay due to the Shapiro effect [45] can be neglected, in such a way that:

$$d_T \approx c_0 \Delta t \qquad (4)$$

where Δt is the photon time-of-flight. With eqn 3, eqn 2 becomes:

$$\frac{z}{1+z} = \frac{H_0}{c_0} d_T \qquad (5)$$

That is, with eqn 4:

$$\frac{z}{1+z} = H_0 \Delta t \qquad (6)$$

As a consequence:

$$\frac{\partial z}{\partial t} = -H_0(1+z)^2 \qquad (7)$$

Measures of $\frac{\partial z}{\partial t}$ obtained with the cosmic chronometer method, that is, through studies of the age of passively evolving galaxies, are usually provided through $H(z)$ [46, 47], which is defined as follows [48]:

$$H(z) = -\frac{1}{1+z}\frac{\partial z}{\partial t}$$

Thus, with eqn 7:

$$H(z) = H_0(1+z) \qquad (8)$$

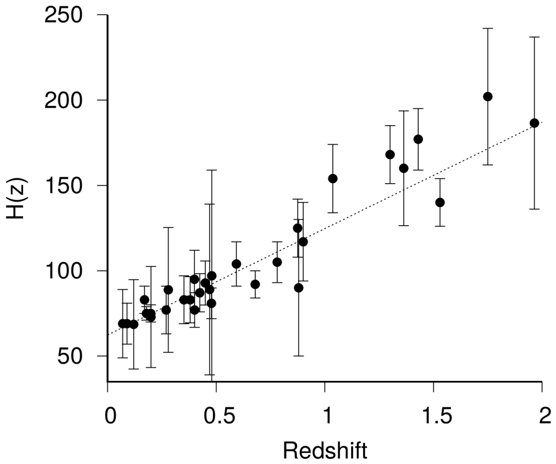

Figure 1: H(z) as a function of redshift, as obtained with the cosmic chronometer method. Dotted line: $H(z) = H_0(1+z)$, with $H_0 = 65$ km/s/Mpc.

It is indeed well known that, as illustrated in Figure 1, observational data [49] are consistent with a linear relationship [50, 51]. As a matter of fact, eqn 8 is also a prediction of linear coasting cosmologies [52, 53], like the $R_h = ct$ cosmology developed by Fulvio Melia and his collaborators [54] who have claimed that, compared to ΛCDM, it is favored by several model selection criteria [55, 56].

Counts of galaxies

$n(d_T)$, the cumulative count of galaxies as a function of the light-travel distance, is such that:

$$n(d_T) = \int_0^{d_T} 4\pi N(r) r^2 dr \tag{9}$$

where $N(r)$ is the number density of galaxies at distance r.

Let us assume that $N(\Delta t)$, the number density of galaxies as a function of the photon time-of-flight, evolves slowly enough, so that:

$$N(\Delta t) \approx N_0 + \dot{N}\Delta t \tag{10}$$

where N_0 is the local number density, $\dot{N}$ being the time derivative of $N(\Delta t)$. With eqn 4 and 10, eqn 9 yields:

$$n(d_T) = \frac{4}{3}\pi d_T^3 N_0 \left(1 + \frac{3}{4}\frac{\dot{N}}{N_0}\frac{d_T}{c_0}\right) \tag{11}$$

which becomes, with eqn 3 and 5:

$$n(z) = n_{st}\frac{z^3}{(1+z)^3}\left(1 + \epsilon_N \frac{z}{1+z}\right) \tag{12}$$

where:

$$n_{st} = \frac{4}{3}\pi d_V^3 N_0$$

and:

$$\epsilon_N = \frac{3}{4H_0}\frac{\dot{N}}{N_0} \tag{13}$$

Least-square fitting, for $z \leq 3$, of the cumulative count of 52 *Swift* long Gamma-ray Bursts (GRBs) from a carefully selected sub-sample with a redshift completeness level of 90% [57] yields $\epsilon_N = 0.12 \pm 0.09$ ($n_{st} = 104 \pm 6$), confirming that the evolution of the density number of GRBs has been slow (eqn 10), with respect to the Hubble time (H_0^{-1}).

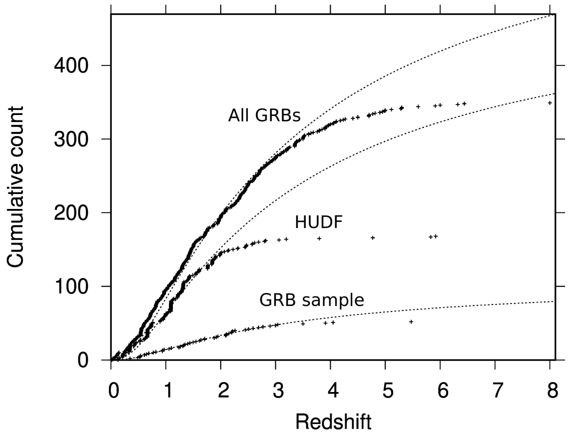

Figure 2: Cumulative counts of galaxies as a function of redshift. Top and bottom: sources of long gamma-ray bursts (GRBs) with a low (top) or high (bottom) redshift completeness level. Middle: galaxies in the Hubble Ultra Deep Field (HUDF), with robust spectroscopic redshifts. Dotted lines: single-parameter fits, when the corresponding number density of galaxies is assumed to be constant for $z \leq 2$ (HUDF) or 3 (GRBs).

As a matter of fact, when $\epsilon_N = 0$ ($\dot{N} = 0$ in eqn 13), the root-mean-square of the residuals is 0.97 ($n_{st} = 113 \pm 1$), instead of 0.96, that is, both fits are equally consistent with observational data. When the 350 *Swift* long ($t_{90} \leq 0.8$ s [58]) GRBs with a redshift known with fair accuracy are considered[1], the root-mean-square of the residuals is higher, namely 8.3 ($n_{st} = 666 \pm 2$), maybe as a consequence of a much lower redshift completeness level (redshifts are known for only 30% of the GRBs detected by *Swift* [59]).

On the other hand, fitting the cumulative count of the 169 galaxies in the Hubble Ultra Deep Field (HUDF) with robust spectroscopic redshifts[2] [60], for $z \leq 2$, yields a root-mean-square of the residuals of 5.5 ($n_{st} = 513 \pm 3$).

So, as shown in Figure 2, when the density number of galaxies is assumed to be constant ($\epsilon_N = 0$), eqn 12 allows for a fair fit of observational data, up to $z \approx 2$ at least.

Note that, since long GRBs occur in star-forming

[1] As provided on the Neil Gehrels Swift Observatory web page (https://swift.gsfc.nasa.gov/archive/grb_table), on May 2020, 12^{th}.

[2] As found in Table 4 of reference [60].

galaxies [61, 62], the fact that the number density of GRB sources does not vary significantly as a function of redshift means that the number density of star-forming galaxies does not as well, as already indicated by previous studies [63, 64]. On the other hand, the fact that the density number of galaxies is also found nearly constant in the HUDF means that the number density of quiescent galaxies follows the same trend.

So, as far as galaxy number densities are concerned, the Universe seems to have been stationary over the last ≈ 10 Gyr ($z \leq 2$), at least.

Luminosity distance

Given the kind of distance considered so far (eqn 4), observing stationarity on galactic scales could mean that, as suggested by a number of previous studies (*e.g.* [65, 66, 67, 68, 69]), the space-time metric of the Universe is static.

So, let us now assume that d_L, the luminosity distance, has the following, rather general form:

$$d_L = d_T (1+z)^{\frac{1}{2}} e^{\frac{1}{2}\tau(z)} \tag{14}$$

where $\tau(z)$ denotes the opacity between the source and the observer [70], the $(1+z)^{\frac{1}{2}}$ term corresponding to the energy loss of the photons during their travel.

On the other hand, if opacity is mostly due to a single physical phenomenon, the Universe being stationary, opacity may prove well described with a relationship as simple as:

$$\tau(z) = \frac{d_T}{c_0 \tau_p} \tag{15}$$

where τ_p is the photon lifetime along the line-of-sight. Thus, with eqn 5, eqn 14 becomes:

$$d_L = \frac{c_0}{H_0} \frac{z}{\sqrt{1+z}} e^{\frac{1}{2} \frac{1}{H_0 \tau_p} \frac{z}{1+z}} \tag{16}$$

Distance modulus

With eqn 16, μ, the distance modulus:

$$\mu = 5 \log_{10}(d_L) + 25$$

is as follows:

$$\mu = 5 \log_{10} \frac{z}{\sqrt{1+z}} + \alpha \frac{1}{H_0 \tau_p} \frac{z}{1+z} + \mu_0 \tag{17}$$

where $\mu_0 = 5 \log_{10} \frac{c_0}{H_0} + 25$, with $\alpha = 2.5 \log_{10} e$.

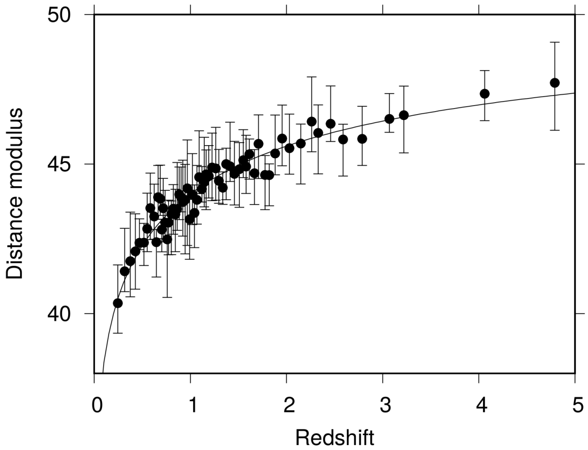

Figure 3: The distance modulus of an homogeneous sample of quasars, as a function of their redshift. Each point (filled circles) is the median of the distance moduli of 25 quasars, the error bars showing the corresponding interquartiles. Plain line: two-parameter least-square fit.

Quasars

In order to estimate τ_p, a homogeneous sample of 1598 quasars [71] with a distance modulus determined using their rest-frame X-ray and UV fluxes [72, 73] was considered. Since, with this method, individual distance moduli happen to be rather noisy, the dataset was sorted by increasing redshift values and split into 64 groups of 25 quasars with similar redshift[3], the median redshift and distance modulus of each group being used for the present analysis.

A least-square fit of these 64 median distance moduli yields $H_0 \tau_p = 0.34 \pm 0.04$, with a root-mean-square of the residuals of 0.4 ($\mu_0 = 18.1 \pm 0.2$). As shown in Figure 3, eqn 17 matches observational data over the whole redshift range, that is, up to $z \approx 5$.

The photon lifetime

Let us further assume that the lifetime of photons along the line-of-sight is for the most part due to their interaction with galaxies. Thus, since, as found with the above analysis of counts of galaxies,

[3] With 23 quasars in the highest-redshift group.

$\dot{N} \approx 0$, eqn 15 can be written as follows:

$$\tau(z) \approx \sigma_G N_0 d_T \tag{18}$$

where σ_G is the average cross section of a galaxy.

On the other hand, for $d_T = d_V$, eqn 11 yields:

$$N_0 = \frac{n(d_V)}{\frac{4}{3}\pi d_V^3}$$

So, according to eqn 3, 15 and 18:

$$\sigma_G = \frac{1}{3H_0\tau_p}\frac{4\pi d_V^2}{n(d_V)}$$

and since, as found above, $3H_0\tau_p \approx 1$:

$$\sigma_G \approx \frac{4\pi d_v^2}{n(d_V)}$$

Because there are $\approx$ 10,000 galaxies in the Hubble Extreme Deep Field (HXDF) [74], assuming that most of the galaxies in this small area have been captured, and also that the HXDF is a representative enough sample of the sky, a rough estimate can be proposed for $n(d_V)$, namely, $\approx 4\ 10^{11}$.

Thus, with $H_0 \approx 70$ km/s/Mpc [24, 75, 76, 77], $\sigma_G \approx 5\ 10^{41}$ m^2, the corresponding radius being of $\approx 2\ 10^{20}$ m, which is indeed the order of magnitude of the radius of a galaxy.

Independent checks

Supernovae Ia

Though supernovae of type Ia (SN Ia) can not be studied over a range of redshifts as wide as quasars, their luminosity distance can be determined with a much higher accuracy [78, 79]. As shown in Figure 4 for the 1048 SN Ia of the Pantheon sample with, as found above, $H_0\tau_p = 0.34$ and $\mu_0 = 18.1$, the absolute magnitude of a SN Ia being set to $M = -19.3$ [80], eqn 17 matches the data pretty well, the root-mean-square of the residuals being of 0.15 (reduced $\chi^2 = 1.1$, p-value = 0.15). Indeed, a least-square fit yields $H_0\tau_p = 0.320 \pm 0.003$ ($\mu_0 + M$ = -1.25 $\pm$ 0.01), with a root-mean-square of the residuals of 0.14 (reduced $\chi^2 = 1.0$, p-value = 0.38).

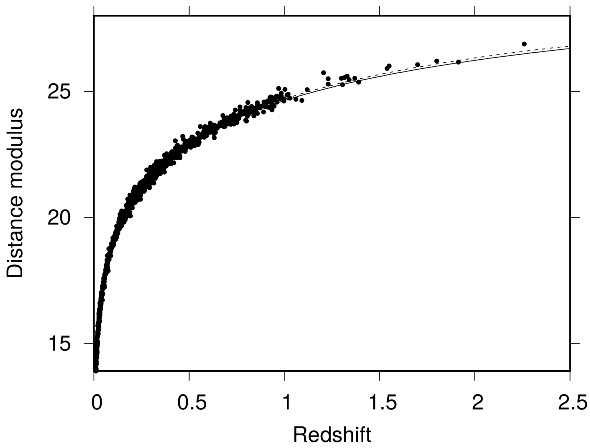

Figure 4: The distance modulus of the supernovae Ia of the Pantheon sample, as a function of their redshift (error bars not shown). Plain line: as expected with $H_0\tau_p = 0.34$; dotted line: two-parameter least-square fit.

Distance duality

Let us write the cosmic distance duality relation as follows [81]:

$$d_L = \eta(z) d_A (1+z)^2 \tag{19}$$

where d_A is the angular distance.

In the case of this relationship, metric theories of gravity, like ΛCDM, make the challenging prediction that $\eta(z) \geq 1$ [82], with $\eta(z) = 1$ if there is no loss of photon along the path between the source and the observer [2].

Interestingly, measurements of $\eta(z)$ tend to provide values that are below one [83, 84, 85, 86]. For instance, by studying 34 early-type galaxies from three clusters, with redshifts between 0.72 and 0.92, Lubin & Sandage found $\eta(z) = 0.75 - 0.89$, in the I band, and $\eta(z) = 0.57 - 0.71$, in the R one [83].

Within the frame of tired-light models, $d_A = d_T$. So, with eqn 5 and 16, eqn 19 yields:

$$\eta(z) = (1+z)^{-\frac{3}{2}} e^{\frac{1}{2}\frac{1}{H_0\tau_p}\frac{z}{1+z}} \tag{20}$$

As shown in Figure 5, with $H_0\tau_p = 0.34$, $\eta(z)$ values are indeed below one, as noteworthy observed by Lubin & Sandage [83].

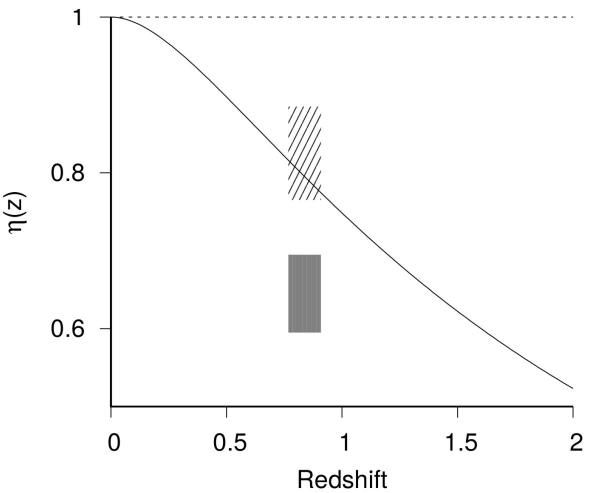

Figure 5: Compatibility with the cosmic distance duality relation, as a function of redshift. Boxes: measurements obtained by studying early-type galaxies from three clusters, in the R (grey) and I (hatched) bands. Horizontal dashed line: *minimum* value expected within the frame of metric theories of gravity like ΛCDM. Plain line: as expected with $H_0\tau_p = 0.34$.

Towards a new cosmology

Old high redshift objects

Remote objects are observed like they were at time $t = t_0 - \Delta t$, where t_0 is the observer time. On the other hand, the oldest objects in our neighborhood, like HD140283, an extremely metal- deficient subgiant star, are $\approx$ 14 Gyr old [87, 88, 89] while, for instance, the oldest object known at $z \approx 4$, namely, APM 08279+5255, an exceptionally luminous, gravitationaly lensed, quasar, seems 2 – 3 Gyr old [90, 91, 92].

Such observations suggest that, as predicted by Lemaitre cosmologies, the oldest objects known have started to emit light approximately at the same time, T_f Gyr ago. In the context of the present work, they also mean that, though the Universe happens to be stationary in terms of large structures, its content is nevertheless evolving, in the sense that there are objects that are becoming older and older.

As far as the oldest of them are concerned, $T_{obs}(z)$, their observed age at a given redshift, is expected to be:

$$T_{obs}(z) = T_f - \Delta t$$

that is, with eqn 6:

$$T_{obs}(z) = T_f - \frac{1}{H_0}\frac{z}{1+z} \tag{21}$$

as proposed previously [51]. Interestingly, according to eqn 21, if the age of HD140283 is assumed to provide a fair estimate for T_f, with $H_0 \approx 70$ km/s/Mpc [24, 75, 76, 77], the oldest objects at $z \approx 4$ are expected to have an age of $T_{obs}(4) \approx 2.8$ Gyr, in good agreement with the measured age of APM 08279+5255.

Note that it has been claimed that ΛCDM can hardly cope with the estimated age of APM 08279+5255 [90, 93, 94, 95].

The cosmic microwave background

The very existence of the Sunyaev-Zel'dovich effect in the case of remote galaxy clusters [84, 96, 97] strongly supports one of the major outcomes of Lemaitre cosmologies, namely, that the origin of the cosmic microwave background is far away.

Taken together with the fact that, as briefly recalled above, the oldest objects of the Universe seem to have started to emit light $\approx$ 14 Gyr ago, it is tempting to conclude that the history of matter formation provided by Lemaitre cosmologies is the right one, at least as far as the sequence of events is concerned.

Discussion

Are tired-light models still relevant ?

It has been claimed that theories where the Lemaitre-Hubble law is explained by a loss of energy of the photons during their travel are excluded [83], noteworthy because, as predicted by Lemaitre cosmologies [3], the SN Ia light curves seem dilated by a (1 + z) factor [5, 6, 7, 8].

However, no such time dilation was found in the light curves of quasars [98, 99] or in duration measures of GRBs [100, 101], casting doubts on a key prediction of Lemaitre cosmologies, namely, the generality of the phenomenon.

In the context of the present study, the time dilation of SN Ia light curves is instead expected to be either the signature of some evolutionary process [102], or due to cosmology-dependent assumptions made during the analyses of the light curves [55, 103].

How can the Universe be stationary ?

The hypothesis that the Universe is stationary has already been put forward, in particular within the frame of steady-state cosmologies [104, 105, 106, 107]. However, it was in a quite different context. Noteworthy, the space-time metric was *not* considered as being static.

On the other hand, herein, stationarity is observed on galactic scales, that is, when density numbers of galaxies are considered. Thus, it has to be the result of some force able to cancel the effect of gravitational attraction, when the distance between galaxies is of the order of magnitude of the average distance observed between neighboring ones. Note that stationarity can be observed only if this force has a distance dependence steeper than the gravitational one, a criterion that is not met by the force associated to the cosmological constant [108].

How are photons lost ?

$H_0\tau_p = 0.34$ means that after ≈ 3 Gyr of travel half of the photons of a quasar or of a SN Ia are missing. As suggested by the above results, their loss seems to be due to their interaction with galaxies.

So, absorption by dust in the interstellar medium, or in the halos, of galaxies could be responsible for their loss along the line-of-sight. However, since the luminosity-distances of quasars analyzed herein have been determined by comparing their X-ray and UV fluxes [71], such dust would have to be "grey" [109, 110] over a range of frequencies that wide.

On the other hand, it has been suggested that photons could have a finite lifetime [96, 111], *e.g.* by decaying into lighter particles such as massive neutrinos [112], thus reducing their flux along the line-of-sight. In this case, their interaction with the material content of galaxies could allow for momentum conservation during the pair production process.

Can H_0 be measured on Earth ?

Eqn 6 suggests that, like in the case of most tired-light models, the Hubble constant could, at least in principle, be measured in laboratory experiments, as a frequency drift proportional to the photon time-of-flight. Note that such measurements would be challenging ones, the expected drift being of $\approx 10^{-18}$ s^{-1}.

However, in the course of the present study, the photon lifetime along the line-of-sight has been found to be nearly one third of the Hubble time. Such a numerical coincidence may prove significant. For instance, it could mean that there is a relationship between the way photons interact with galaxies and their cosmological frequency drift, as claimed long ago by Fritz Zwicky [31, 32].

Conclusion

The present study shows that, by combining a generic tired-light model found consistent with H(z) data (Fig. 1) with the hypothesis that the Universe is far from being as transparent as assumed nowadays [70, 113], it is possible to obtain a two-parameter luminosity distance (eqn 16) able to match observations up to $z \approx 5$ (Fig. 3 and 4).

Interestingly, for $z \gg 0$, the corresponding cosmic distance duality relation (eqn 19 and 20) differs significantly from the prediction of metric theories of gravity like ΛCDM. Moreover, for $z \approx 0.8$ at least, it seems in better agreement with observations (Fig. 5).

In this context, as far as galaxy number densities are concerned, the Universe looks stationary, up to $z \approx 2$ at least (Fig. 2). However, since the oldest objects known started to emit light ≈ 14 Gyr ago, possibly as a result of the cooling of a hot medium in a state of equilibrium, the history of matter formation provided by Lemaitre cosmologies may prove to be the right one.

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References

[1] Lemaitre, G. (1927). Un Univers homogène de masse constante et de rayon croissant rendant compte de la vitesse radiale des nébuleuses extra-galactiques. *Ann. Soc. Sci. Bruxelles* **47**, 49–59.

[2] Tolman, R.C. (1930). On the estimation of distances in a curved universe with a non-static line element. *Proc. Natl. Acad. Sci. USA* **16**(7), 511.

[3] Wilson, O.C. (1939). Possible applications of supernovae to the study of the nebular red shifts. *Ap. J.* **90**, 634.

[4] Alpher, R.A. & Herman, R.C. (1949). Remarks on the evolution of the expanding universe. *Phys. Rev.* **75**(7), 1089.

[5] Kim, M., Lee, J., Matheson, T., McMahon, R., Newberg, H., Pain, R. *et al.* (1996). Cosmological time dilation using type Ia supernovae as clocks. *Nucl. Phys. B* **51**, 123–127.

[6] Leibundgut, B., Schommer, R., Phillips, M., Riess, A., Schmidt, B., Spyromilio, J., Walsh, J., Suntzeff, N., Hamuy, M., Maza, J. *et al.* (1996). Time dilation in the light curve of the distant type Ia supernova SN 1995K. *Ap. J.* **466**(1), L21–L24.

[7] Foley, R.J., Filippenko, A.V., Leonard, D.C., Riess, A.G., Nugent, P. & Perlmutter, S. (2005). A definitive measurement of time dilation in the spectral evolution of the moderate-redshift type Ia supernova 1997ex. *Ap. J. letters* **626**(1), L11.

[8] Blondin, S., Davis, T.M., Krisciunas, K., Schmidt, B., Sollerman, J., Wood-Vasey, W., Becker, A., Challis, P., Clocchiatti, A., Damke, G. *et al.* (2008). Time dilation in type Ia supernova spectra at high redshift. *Ap. J.* **682**(2), 724.

[9] Penzias, A.A. & Wilson, R.W. (1965). A measurement of excess antenna temperature at 4080 mc/s. *Ap. J.* **142**, 419–421.

[10] Dicke, R.H., Peebles, P.J.E., Roll, P.G. & Wilkinson, D.T. (1965). Cosmic black-body radiation. *Ap. J.* **142**, 414–419.

[11] Saro, A., Liu, J., Mohr, J., Aird, K., Ashby, M., Bayliss, M., Benson, B., Bleem, L., Bocquet, S., Brodwin, M. *et al.* (2014). Constraints on the CMB temperature evolution using multiband measurements of the Sunyaev–Zel'dovich effect with the South Pole Telescope. *Mon. Not. R. Astron. Soc.* **440**(3), 2610–2615.

[12] Luzzi, G., Génova-Santos, R., Martins, C., De Petris, M. & Lamagna, L. (2015). Constraining the evolution of the CMB temperature with SZ measurements from Planck data. *J. Cosmol. Astrop. Phys.* **2015**(09), 011. `https://arxiv.org/abs/1502.07858`.

[13] Baranov, I., Jesus, J.F. & Lima, J.A. (2016). Testing CCDM Cosmology with the Radiation Temperature-Redshift Relation. *arXiv* **1605**, 04857. `https://arxiv.org/abs/1605.04857`.

[14] Ostriker, J. & Steinhart, P.J. (1995). The observational case for a low-density universe with a non-zero cosmological constant. *Nature* **377**, 600–602.

[15] Krauss, L.M. & Turner, M.S. (1995). The cosmological constant is back. *Gen. Rel. Grav.* **27**(11), 1137–1144. `https://arxiv.org/abs/astro-ph/9504003`.

[16] Peebles, P.J.E. & Ratra, B. (2003). The cosmological constant and dark energy. *Rev. mod. phys.* **75**(2), 559. `https://arxiv.org/abs/astro-ph/0207347`.

[17] López-Corredoira, M. (2017). Tests and problems of the standard model in cosmology. *Found. of Phys.* **47**(6), 711–768. `https://arxiv.org/abs/1701.08720`.

[18] Tegmark, M., Zaldarriaga, M. & Hamilton, A.J. (2001). Towards a refined cosmic concordance model: Joint 11-parameter constraints from the cosmic microwave background and large-scale structure. *Phys. Rev. D* **63**(4), 043007.

[19] Di Valentino, E., Melchiorri, A. & Silk, J. (2020). Cosmic Discordance: Planck and luminosity distance data exclude LCDM.

arXiv **2003**, 04935. https://arxiv.org/abs/2003.04935.

[20] Starobinsky, A.A. (1982). Dynamics of phase transition in the new inflationary universe scenario and generation of perturbations. *Phys. Lett. B* **117**(3-4), 175–178.

[21] Linde, A.D. (1982). A new inflationary universe scenario: a possible solution of the horizon, flatness, homogeneity, isotropy and primordial monopole problems. *Phys. Lett. B* **108**(6), 389–393.

[22] Bergström, L. (2000). Non-baryonic dark matter: observational evidence and detection methods. *Rep. Progr. Phys.* **63**(5), 793.

[23] Bartelmann, M. (2010). The dark universe. *Rev. Mod. Phys.* **82**(1), 331–382.

[24] Aghanim, N., Akrami, Y., Ashdown, M., Aumont, J., Baccigalupi, C., Ballardini, M., Banday, A., Barreiro, R., Bartolo, N., Basak, S. *et al.* (2018). Planck 2018 results. VI. Cosmological parameters. *arXiv* **1807**, 06209. https://arxiv.org/abs/1807.06209.

[25] Dirac, P.A. (1937). The cosmological constants. *Nature* **139**(3512), 323–323.

[26] Webb, J.K., Flambaum, V.V., Churchill, C.W., Drinkwater, M.J. & Barrow, J.D. (1999). Search for time variation of the fine structure constant. *Phys. Rev. Lett.* **82**(5), 884–887.

[27] Sanejouand, Y.H. (2009). About some possible empirical evidences in favor of a cosmological time variation of the speed of light. *EPL (Europhys. Lett.)* **88**(5), 59002. https://arxiv.org/abs/0908.0249.

[28] Tetrode, H. (1922). Über den wirkungszusammenhang der welt. eine erweiterung der klassischen dynamik. *Zeitschrift für Physik* **10**(1), 317–328.

[29] Wheeler, J.A. & Feynman, R.P. (1945). Interaction with the absorber as the mechanism of radiation. *Rev. Mod. Phys.* **17**(2-3), 157.

[30] Hubble, E. (1929). A relation between distance and radial velocity among extragalactic nebulae. *Proc. Natl. Acad. Sc. USA* **15**(3), 168–173.

[31] Zwicky, F. (1929). On the redshift of spectral lines through interstellar space. *Proc. Nat. Acad. Sc. USA* **15**(10), 773–779.

[32] Zwicky, F. (1933). The redshift of extragalactic nebulae. *Helv. Phys. Acta* **6**(110), 138.

[33] Finlay-Freundlich, E. (1954). Red-shifts in the spectra of celestial bodies. *Proc. Phys. Soc. A* **67**(2), 192.

[34] de Broglie, L. (1966). Sur le déplacement des raies émises par un objet astronomique lointain. *Comptes Rendus Acad. Sci. Paris* **263**, 589–592.

[35] Pecker, J.C. & Vigier, J.P. (1988). A possible tired-light mechanism. *Apeiron* **2**, 13–15.

[36] Marmet, L. (2018). On the interpretation of spectral red-shift in astrophysics: A survey of red-shift mechanisms-II. *arXiv* **1801**, 07582.

[37] North, J.D. (1965). *The measure of the universe. A History of modern cosmology.* Oxford University Press.

[38] Krisher, T.P., Maleki, L., Lutes, G.F., Primas, L.E., Logan, R.T., Anderson, J.D. & Will, C.M. (1990). Test of the isotropy of the one-way speed of light using hydrogen-maser frequency standards. *Phys. Rev. D* **42**(2), 731.

[39] Schaefer, B.E. (1999). Severe limits on variations of the speed of light with frequency. *Phys. Rev. Letters* **82**(25), 4964. https://arxiv.org/abs/astro-ph/9810479.

[40] Antonini, P., Okhapkin, M., Göklü, E. & Schiller, S. (2005). Test of constancy of speed of light with rotating cryogenic optical resonators. *Phys. Rev. A* **71**(5), 050101. https://arxiv.org/abs/gr-qc/0504109.

[41] Tu, L.C., Luo, J. & Gillies, G.T. (2004). The mass of the photon. *Rep. Prog. Phys.* **68**(1), 77.

[42] Eisele, C., Nevsky, A.Y. & Schiller, S. (2009). Laboratory test of the isotropy of light propagation at the 10^{-17} level. *Phys. Rev. Letters* **103**(9), 090401.

[43] Nemiroff, R.J., Connolly, R., Holmes, J. & Kostinski, A.B. (2012). Bounds on spectral dispersion from fermi-detected gamma ray bursts. *Phys. Rev. Lett.* **108**(23), 231103. https://arxiv.org/abs/1109.5191.

[44] Williams, J.G., Turyshev, S.G. & Boggs, D.H. (2014). The past and present earth-moon system: the speed of light stays steady as tides evolve. *Planetary science* **3**(1), 1–9.

[45] Reasenberg, R., Shapiro, I., MacNeil, P., Goldstein, R., Breidenthal, J., Brenkle, J., Cain, D., Kaufman, T., Komarek, T. & Zygielbaum, A. (1979). Viking relativity experiment-verification of signal retardation by solar gravity. *Ap. J.* **234**, L219–L221.

[46] Stern, D., Jimenez, R., Verde, L., Kamionkowski, M. & Stanford, S.A. (2010). Cosmic chronometers: constraining the equation of state of dark energy. I: H(z) measurements. *J. Cosmol. Astrop. Phys.* **2010**(02), 008.

[47] Moresco, M., Verde, L., Pozzetti, L., Jimenez, R. & Cimatti, A. (2012). New constraints on cosmological parameters and neutrino properties using the expansion rate of the universe to z $\approx$ 1.75. *J. Cosmol. Astrop. Phys.* **2012**(07), 053.

[48] Jimenez, R. & Loeb, A. (2002). Constraining cosmological parameters based on relative galaxy ages. *Ap. J.* **573**(1), 37–42.

[49] Yu, H., Ratra, B. & Wang, F.Y. (2018). Hubble parameter and Baryon Acoustic Oscillation measurement constraints on the Hubble constant, the deviation from the spatially flat ΛCDM model, the deceleration–acceleration transition redshift, and spatial curvature. *Ap. J.* **856**(1), 3.

[50] Kumar, S. (2012). Observational constraints on hubble constant and deceleration parameter in power-law cosmology. *Mon. Not. R. Astron. Soc.* **422**(3), 2532–2538.

[51] Sanejouand, Y.H. (2014). A simple Hubble-like law in lieu of dark energy. *arXiv* **1401**, 2919. https://arxiv.org/abs/1401.2919.

[52] Kolb, E.W. (1989). A coasting cosmology. *Ap. J.* **344**, 543–550.

[53] Benoit-Lévy, A. & Chardin, G. (2008). Observational constraints of a Milne Universe. *arXiv* **0811**, 2149. https://arxiv.org/abs/0811.2149.

[54] Melia, F. & Shevchuk, A.S.H. (2012). The $R_h = ct$ universe. *Month. Not. Roy. Astron. Soc.* **419**(3), 2579–2586. https://arxiv.org/abs/1109.5189.

[55] Melia, F. & Maier, R.S. (2013). Cosmic chronometers in the $R_h = ct$ Universe. *Month. Not. Roy. Astron. Soc.* **432**(4), 2669–2675. https://arxiv.org/abs/1304.1802.

[56] Melia, F. & Yennapureddy, M.K. (2018). Model selection using cosmic chronometers with gaussian processes. *J. Cosmol. Astrop. Phys.* **2018**(02), 034. https://arxiv.org/abs/1802.02255.

[57] Salvaterra, R., Campana, S., Vergani, S.D., Covino, S., D'Avanzo, P., Fugazza, D., Ghirlanda, G., Ghisellini, G., Melandri, A., Nava, L. *et al.* (2012). A complete sample of bright Swift long gamma-ray bursts. I. Sample presentation, luminosity function and evolution. *Ap. J.* **749**(1), 68. https://arxiv.org/abs/1112.1700.

[58] Bromberg, O., Nakar, E., Piran, T. & Sari, R. (2013). Short versus long and collapsars versus non-collapsars: A quantitative classification of gamma-ray bursts. *Ap. J.* **764**, 179. https://arxiv.org/abs/1210.0068.

[59] Gehrels, N., Chincarini, G., Giommi, P., Mason, K.O., Nousek, J.A. *et al.* (2004). The Swift gamma-ray burst mission. *Ap. J.* **611**(2), 1005. https://arxiv.org/abs/astro-ph/0405233.

[60] Rafelski, M., Teplitz, H.I., Gardner, J.P., Coe, D., Bond, N.A., Koekemoer, A.M., Grogin, N., Kurczynski, P., McGrath, E.J.,

Bourque, M. *et al.* (2015). UVUDF: Ultraviolet Through Near-infrared Catalog and Photometric Redshifts of Galaxies in the Hubble Ultra Deep Field. *A. J.* **150**(1), 31. https://arxiv.org/abs/1505.01160.

[61] Michałowski, M.J., Kamble, A., Hjorth, J., Malesani, D., Reinfrank, R., Bonavera, L., Cerón, J.C., Ibar, E., Dunlop, J., Fynbo, J. *et al.* (2012). The optically unbiased GRB host (TOUGH) survey. VI. Radio observations at z < 1 and consistency with typical star-forming galaxies. *Ap. J.* **755**(2), 85. https://arxiv.org/abs/1205.4239.

[62] Japelj, J., Vergani, S., Salvaterra, R., D'Avanzo, P., Mannucci, F., Fernandez-Soto, A., Boissier, S., Hunt, L., Atek, H., Rodríguez-Muñoz, L. *et al.* (2016). Are long gamma-ray bursts biased tracers of star formation? Clues from the host galaxies of the Swift/BAT6 complete sample of bright LGRBs-II. Star formation rates and metallicities at z < 1. *A&A* **590**, A129. https://arxiv.org/abs/1604.01034.

[63] Borch, A., Meisenheimer, K., Bell, E.F., Rix, H.W., Wolf, C., Dye, S., Kleinheinrich, M., Kovacs, Z. & Wisotzki, L. (2006). The stellar masses of 25000 galaxies at 0.2 < z < 1.0 estimated by the COMBO-17 survey. *A&A* **453**(3), 869–881.

[64] Brammer, G.B., Whitaker, K.E., van Dokkum, P.G., Marchesini, D., Franx, M., Kriek, M., Labbe, I., Lee, K.S., Muzzin, A., Quadri, R.F. *et al.* (2011). The number density and mass density of star-forming and quiescent galaxies at 0.4 < z < 2.2. *Ap. J.* **739**(1), 24. https://arxiv.org/abs/1104.2595.

[65] Einstein, A. (1917). Kosmologische betrachtungen zur allgemeinen Relativitatstheorie. *Sitz. Preuss. Akad. Wiss.* **1**, l42–l52.

[66] LaViolette, P.A. (1986). Is the universe really expanding? *Ap. J.* **301**, 544–553.

[67] Crawford, D.F. (1993). A static stable universe. *Ap. J.* **410**, 488–492.

[68] Lerner, E.J., Falomo, R. & Scarpa, R. (2014). UV surface brightness of galaxies from the local Universe to z ≈ 5. *Int. J. Mod. Phys. D* **23**, 1450058.

[69] Lerner, E.J. (2018). Observations contradict galaxy size and surface brightness predictions that are based on the expanding universe hypothesis. *Mon. Not. R. Astron. Soc.* **477**(3), 3185–3196.

[70] Holanda, R. & Busti, V. (2014). Probing cosmic opacity at high redshifts with gamma-ray bursts. *Phys. Rev. D* **89**(10), 103517. https://arxiv.org/abs/1402.2161.

[71] Risaliti, G. & Lusso, E. (2019). Cosmological constraints from the Hubble diagram of quasars at high redshifts. *Nat. Astr.* **3**(3), 272. https://arxiv.org/abs/1811.02590.

[72] Risaliti, G. & Lusso, E. (2015). A hubble diagram for quasars. *Ap. J.* **815**(1), 33. https://arxiv.org/abs/1505.07118.

[73] Lusso, E. & Risaliti, G. (2016). The tight relation between X-ray and ultraviolet luminosity of quasars. *Ap. J.* **819**(2), 154. https://arxiv.org/abs/1602.01090.

[74] Illingworth, G., Magee, D., Oesch, P., Bouwens, R.J., Labbé, I., Stiavelli, M., Van Dokkum, P., Franx, M., Trenti, M., Carollo, C.M. *et al.* (2013). The HST eXtreme deep field (XDF): combining all ACS and WFC3/IR data on the HUDF region into the deepest field ever. *Ap. J. Supplement Series* **209**(1), 6.

[75] Riess, A.G., Macri, L.M., Hoffmann, S.L., Scolnic, D., Casertano, S., Filippenko, A.V., Tucker, B.E., Reid, M.J., Jones, D.O., Silverman, J.M. *et al.* (2016). A 2.4% determination of the local value of the Hubble constant. *Ap. J.* **826**(1), 56. https://arxiv.org/abs/1604.01424.

[76] Paturel, G., Teerikorpi, P. & Baryshev, Y. (2017). Hubble law: measure and interpretation. *Found. Phys.* **47**(9), 1208–1228. https://arxiv.org/abs/1801.00128.

[77] Riess, A.G., Casertano, S., Yuan, W., Macri, L., Anderson, J., MacKenty, J.W., Bowers, J.B., Clubb, K.I., Filippenko, A.V., Jones, D.O. *et al.* (2018). New parallaxes of galactic cepheids from spatially scanning the hubble space telescope: Implications for the hubble constant. *Ap. J.* **855**(2), 136. https://arxiv.org/abs/1801.01120.

[78] Riess, A.G., Filippenko, A.V., Challis, P., Clocchiatti, A., Diercks, A., Garnavich, P.M., Gilliland, R.L., Hogan, C.J., Jha, S., Kirshner, R.P. *et al.* (1998). Observational evidence from supernovae for an accelerating universe and a cosmological constant. *A. J.* **116**(3), 1009–1038. https://arxiv.org/abs/astro-ph/9805201.

[79] Perlmutter, S., Aldering, G., Goldhaber, G., Knop, R.A., Nugent, P. *et al.* (1999). Ω and Λ from 42 high-redshift supernovae. *Ap. J.* **517**(2), 565–586. https://arxiv.org/abs/astro-ph/9812133.

[80] Suzuki, N., Rubin, D., Lidman, C., Aldering, G., Amanullah, R. *et al.* (2012). The Hubble Space Telescope Cluster Supernova Survey. V. Improving the Dark-energy Constraints above z > 1 and Building an Early-type-hosted Supernova Sample. *Ap. J.* **746**(1), 85. https://arxiv.org/abs/1105.3470.

[81] Holanda, R.F.L., Lima, J.A.S. & Ribeiro, M.B. (2010). Testing the Distance–Duality Relation with Galaxy Clusters and Type Ia Supernovae. *Ap. J. letters* **722**(2), L233. https://arxiv.org/abs/1005.4458.

[82] Bassett, B.A. & Kunz, M. (2004). Cosmic distance-duality as a probe of exotic physics and acceleration. *Phys. Rev. D* **69**(10), 101305. https://arxiv.org/abs/astro-ph/0312443.

[83] Lubin, L.M. & Sandage, A. (2001). The Tolman surface brightness test for the reality of the expansion. IV. A measurement of the Tolman signal and the luminosity evolution of early-type galaxies. *The Astron. J.* **122**(3), 1084.

[84] Uzan, J.P., Aghanim, N. & Mellier, Y. (2004). Distance duality relation from x-ray and Sunyaev-Zel'dovich observations of clusters. *Phys. Rev. D* **70**(8), 083533. https://arxiv.org/abs/astro-ph/0405620.

[85] Holanda, R., Goncalves, R. & Alcaniz, J. (2012). A test for cosmic distance duality. *J. Cosmol. Astroph. Phys.* **2012**(06), 022.

[86] Holanda, R., Busti, V. & Alcaniz, J. (2016). Probing the cosmic distance duality with strong gravitational lensing and supernovae Ia data. *J. Cosmol. Astrop. Phys.* **2016**(02), 054.

[87] Bond, H.E., Nelan, E.P., VandenBerg, D.A., Schaefer, G.H. & Harmer, D. (2013). HD 140283: A star in the solar neighborhood that formed shortly after the big bang. *Ap. J. letters* **765**(1), L12. https://arxiv.org/abs/1302.3180.

[88] VandenBerg, D.A., Bond, H.E., Nelan, E.P., Nissen, P., Schaefer, G.H. & Harmer, D. (2014). Three ancient halo subgiants: precise parallaxes, compositions, ages, and implications for globular clusters. *Ap. J.* **792**(2), 110. https://arxiv.org/abs/1407.7591.

[89] Creevey, O., Thévenin, F., Berio, P., Heiter, U., von Braun, K., Mourard, D., Bigot, L., Boyajian, T., Kervella, P., Morel, P. *et al.* (2015). Benchmark stars for Gaia Fundamental properties of the Population II star HD 140283 from interferometric, spectroscopic, and photometric data. *A&A* **575**, A26. https://arxiv.org/abs/1410.4780.

[90] Friaça, A., Alcaniz, J. & Lima, J. (2005). An old quasar in a young dark energy-dominated universe ? *Month. Not. R. Astron. Soc.* **362**(4), 1295–1300. https://arxiv.org/abs/astro-ph/0504031.

[91] Hasinger, G., Schartel, N. & Komossa, S. (2002). Discovery of an ionized Fe K edge in the z= 3.91 broad absorption line quasar APM 08279+ 5255 with XMM-Newton. *Ap. J. letters* **573**(2), L77. https://arxiv.org/pdf/astro-ph/0207005.

[92] Komossa, S. & Hasinger, G. (2002). The X-ray evolving universe: (ionized) absorption and dust, from nearby Seyfert galaxies to high-redshift quasars. *arXiv* **0207**,

321. https://arxiv.org/pdf/astro-ph/0207321.

[93] Sethi, G., Dev, A. & Jain, D. (2005). Cosmological constraints on a power law universe. *Phys. Lett. B* **624**(3-4), 135–140. http://arxiv.org/abs/astro-ph/0506255.

[94] Jain, D. & Dev, A. (2006). Age of high redshift objects – a litmus test for the dark energy models. *Phys. Lett. B* **633**(4-5), 436–440. https://arxiv.org/abs/astro-ph/0509212.

[95] Yang, R.J. & Zhang, S.N. (2010). The age problem in the ΛCDM model. *Month. Not. Roy. Astron. Soc.* **407**(3), 1835–1841. https://arxiv.org/abs/0905.2683.

[96] Colafrancesco, S. & Marchegiani, P. (2014). Probing photon decay with the Sunyaev-Zeldovich effect. *A & A* **562**, L2.

[97] Hughes, J.P. & Birkinshaw, M. (1998). A measurement of the hubble constant from the X-ray properties and the sunyaev-zeldovich effect of cl 0016+16. *Ap. J.* **501**(1), 1.

[98] Hawkins, M. (2001). Time dilation and quasar variability. *Ap. J. letters* **553**(2), L97. https://arxiv.org/abs/astro-ph/0105073.

[99] Hawkins, M. (2010). On time dilation in quasar light curves. *Mon. Not. Roy. Astron. Soc.* **405**(3), 1940–1946.

[100] Kocevski, D. & Petrosian, V. (2013). On the lack of time dilation signatures in gamma-ray burst light curves. *Ap. J.* **765**(2), 116.

[101] Littlejohns, O. & Butler, N. (2014). Investigating signatures of cosmological time dilation in duration measures of prompt gamma-ray burst light curves. *Mon. Not. R. Astron. Soc.* **444**(4), 3948–3960. https://arxiv.org/abs/1408.6525.

[102] Drell, P.S., Loredo, T.J. & Wasserman, I. (2000). Type Ia supernovae, evolution, and the cosmological constant. *Ap. J.* **530**(2), 593.

[103] Crawford, D.F. (2017). A problem with the analysis of type Ia supernovae. *Open Astron.* **26**(1), 111–119.

[104] Bondi, H. & Gold, T. (1948). The steady-state theory of the expanding universe. *Mon. Not. Roy. Astron. Soc.* **108**(3), 252–270.

[105] Hoyle, F. (1948). A new model for the expanding universe. *Mon. Not. Roy. Astron. Soc.* **108**, 372.

[106] Bondi, H. (1957). *Cosmology.* Cambridge University Press.

[107] Narlikar, J.V. (1987). Alternative cosmologies. In *Observational cosmology*, pages 447–459. D.Reidel Co.

[108] Eddington, A.S. (1930). On the instability of einstein's spherical world. *Mon. Not. R. Astron. Soc.* **90**, 668–678.

[109] Simonsen, J.T. & Hannestad, S. (1999). Can dust segregation mimic a cosmological constant? *Astron. Astrophys.* **351**(1), 1–9. https://arxiv.org/abs/astro-ph/9909225.

[110] Robaina, A.R. & Cepa, J. (2007). Redshift-distance relations from type ia supernova observations-new constraints on grey dust models. *Astronomy & Astrophysics* **464**(2), 465–470.

[111] Heeck, J. (2013). How stable is the photon? *Phys. rev. lett.* **111**(2), 021801. https://arxiv.org/abs/1304.2821.

[112] Lesgourgues, J. & Pastor, S. (2006). Massive neutrinos and cosmology. *Phys. Rep.* **429**(6), 307–379.

[113] Holanda, R., Silva, K.V. & Busti, V. (2018). X-ray surface brightness observations of galaxy clusters, cosmic opacity and the limits on the matter density parameter. *J. Cosmol. Astrop. Phys.* **2018**(03), 031. https://arxiv.org/abs/1706.08463.