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Hubble diagram of gamma-ray bursts: Robust evidence for a Chaplygin gas expansion-driven universe with phase transition at $z \simeq 3$

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The Hubble diagram (HD) of Gamma-Ray Bursts (GRBs) having properly estimated redshifts is compared with the predicted one for the Chaplygin gas (CG), a dark energy candidate. The CG cosmology and that of Friedmann and Λ-CDM models are studied and confronted to the GRBs observations. The model-to-sample χ^2 statistical analysis indicates the CG model as the best fit. The present GRBs HD plot exhibits a marked trend: as one goes back in time, it gets much closer to the predict HD for a Friedmann universe. This clear trend conclusively demonstrates that a transition from decelerate to accelerate expansion did take place. However, contrarily to claims based on supernovae type Ia, the transition redshift lies somewhere between $\sim 2.5 < z \simeq 3.5$ rather than at $z \sim 0.5 - 1$. All of these striking features of the GRBs HD constitute the most robust demonstration that the Chaplygin gas can in fact be the universe's driving dark energy field.

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Introduction.— Observations of supernovae type Ia (SNIa) have led to the current view that our universe underwent a late-time transition to accelerate expansion at a redshift $z \sim 1$. The driver of such unexpected dynamics is an exotic component of the universe's content dubbed dark energy (DE), a smoothly sparsed energy field with no familiar counterpart among the currently known forms of matter-energy. Lots of theories have been conceived to explain this striking phenomenon in contemporary cosmology. One of these candidates for DE is the so-called Chaplygin gas (CG), a fluid described by an equation of state (EoS)

$$p = -\frac{A}{\rho}, \qquad (1)$$

where p represents the pressure, ρ the fluid density and A is a constant. It came after the russian aerodynamicist Chaplygin who in 1904 brought it in to explain the lifting force on a plane wing in some aerodymamic phenomena [1]. By 2001, Kamenschik, Moschella and Pasquier [2] recognised its relevance to cosmological studies, in particular, with respect to the claimed cosmic acceleration. They showed that the CG model exhibits excelent agreement with observations. Besides, the model predicts a larger value for the effective cosmological constant as compared to the model with cosmological constant Λ. The same researchers noticed then that the model can be generalized in the form: $p = -\frac{A}{\rho^\alpha}$, and consider the case with the density power-law exponent $\alpha = 1/3$ [2]. It was then realized that the CG EoS has a clearly stated connection with string and brane theories[3, 9, 10].[32]

Here we build the Hubble diagram (HD) of gamma-ray bursts (GRBs)[33], which already reach redshift $z \sim 7$, and SNIa, and confront it with predictions of the cosmological model in which the universe is filled-in with this sort of DE, the so-called Chaplygin gas. Three major achievements are attained in this investigation: a) for the first time is presented the HD of GRBs in confrontation to the CG theoretical prediction, and that of the Friedmann-Lemaître-Robertson-Walker (FLRW, the universe contains only matter) and Lambda Cold Dark Matter (Λ-CDM, Friedmann cosmology with Λ) models (see FIG. 1, 2). b) In comparing the HD of GRBs observations with that predicted by CG, FLRW and Λ-CDM scenarios, is verified that the best fit (χ^2-statistics) clearly cor-

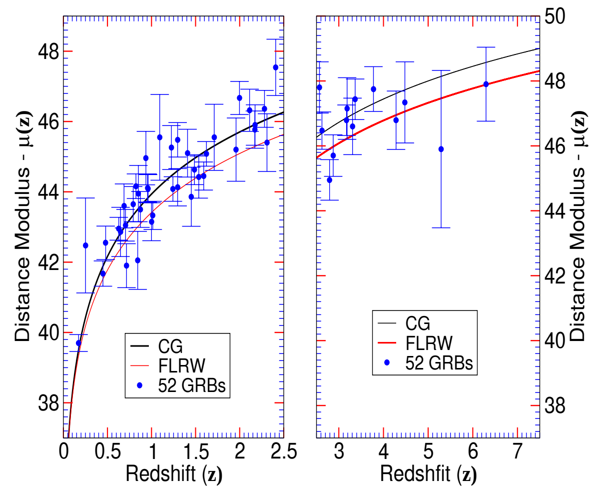


FIG. 1: (color on-line) HD of GRBs and the CG model of DE. The plot demonstrates that a phase transition did take place at a redshift $2.5 \lesssim z \simeq 3.5$, or even earlier (right panel)

responds to this exotic fluid. c) the resulting HD clearly exhibits a transition from a Friedmann-dominated to a late-time accelerating universe, with the transition taking place at a redhsift around $2.5 \lesssim z \simeq 3.5$ (see FIG. 1), and driven by the CG. Besides, the similar (relative χ^2) analysis for SNIa allows one to verify that the HD for SNIa clearly violates the CG, FLRW and Λ-CDM expansion law (see FIG. 3). This disagreement with the Chaplygin gas HD, once again suggests that perhaps there is something wrong with the interpretation of SNIa observations, and that perhaps its astrophysics deserves to be revisited. [29, 30]

Chaplygin gas cosmology.— The enthusiasm about the Chaplygin gas dynamics stems from the possibility of unifying dark matter and dark energy in a cosmic fluid that could be represented by a scalar field. As one can notice from the evolution law for its energy density [2, 6]

$$\rho_c = \left(A + \frac{B}{a^{3(1+\alpha)}}\right)^{1/(1+\alpha)} \quad , \tag{2}$$

where a is the scale factor of the universe and B is an integration constant, the CG corresponds to the Λ-CDM scenario for the parameter $\alpha = 0$, and $A_s \equiv A/\rho_{c0}^{1+\alpha} = 1$. A direct analysis of Eq.(2) shows that the present acceleration phase, which should have taken place at a redshift

$$z_t = \left([3\omega(z_t) + 1]\frac{[\Omega_m - 1]}{\Omega_m}\right)^{\frac{-1}{\hat{\omega}(z_t)}} - 1 \ , \tag{3}$$

where $\hat{\omega}(z_a) = \frac{1}{\ln(1+z)}\int_0^z \frac{\omega(z')}{1+z'}dz'$, leads to an asymptotic ($a \to \infty$) stage where the EoS is dominated by a cosmological constant ($8\pi A^{1/1+\alpha}$), whereas at earlier epochs the energy density is dominated by a non-relativistic matter. Thus, in the case of a CG with $\omega_X = p_X/\rho_X = -A_s/\Omega_X$ constant [7], the transition redshift z_t can be estimated by computing $\hat{\omega}(z_a)$ for $A_s =\simeq 0.8$; from CMB constraints[7] and SNIa [8], and $\Omega_X = \frac{A_s}{1+\alpha(1-A_s)} = 1 - \Omega_m = 0.95$. One then obtains $z_t = 2.8$, which closely agrees to with the feature being exhibited by the GRBs HD. Recall also that the value a_t of the scale factor that signals the start of the late-time acceleration phase is given by the roots of the equation [27]

$$\ddot{a} = a(\dot{H} + H^2) \quad , \tag{4}$$

and is related to the redshift value z_t such that $\frac{a_t}{a_0} = \frac{1}{1+z_t}$.

The highlighted dual behavior is the basis of the unification scheme provided by the CG model. This unification becomes possible if one benefits of a complex scalar field Φ of mass m_ϕ that admits an inhomogeneous generalization, as demanded by models of structure formation in the universe, and is described by a Lagrangian density [2, 6]

$$\mathcal{L} = g_{\mu\nu}\bar{\Phi}^{\mu}\Phi^{\nu} - V(|\Phi|)^2 \tag{5}$$

where $\Phi = (\phi/\sqrt{2}\, m)\exp(-im_\phi\theta)$. The cosmic dynamics of this field was developed in Ref.[2, 3, 6].

As pointed out above, the GCG Model can be idealized by a perfect fluid with an EoS given by

$$p = -\frac{A}{\rho^\alpha} \quad , \tag{6}$$

where A and α are constants. When $\alpha = 1$ we re-obtain the EoS for the CG scenario (Eq.1). In principle, the parameter α is restricted in such a way that $0 \le \alpha \le 1$. However, possible values for $\alpha \neq (0, 1]$ are considered in the accompanying paper [11], where we also analyze the effects of imposing the energy conditions to the cosmic dynamics of the CG as to be compared with GRBs and SNIa observations.

The universe content can be envisioned as having a pressureless matter, needed to account for the presence of baryons in it, and also dark matter (also pressureless) and dark energy making-up the CG. Hence, the dynamics of the Universe is worked out through the Friedmann's equation and the evolution equations for non-interacting baryonic matter and Chaplygin gas[27]

$$\left(\frac{\dot{a}}{a}\right)^2 + \frac{k}{a^2} = \frac{8\pi G}{3}\left(\rho_m + \rho_c\right) \quad , \tag{7}$$

$$\dot{\rho}_m + 3\frac{\dot{a}}{a}\rho_m = 0 \quad , \tag{8}$$

$$\dot{\rho}_c + 3\frac{\dot{a}}{a}\left(\rho_c - \frac{A}{\rho_c^\alpha}\right) = 0 \quad , \tag{9}$$

where ρ_m and ρ_c stand for the pressureless matter and Chaplygin gas component, respectively. As usual, $k = 0, 1, -1$ indicates a flat, closed and open spatial section.

The conservation law for each of these fluids (8,9) reads: $\rho_m = \frac{\rho_{m0}}{a^3}$, and $\rho_c = (A + \frac{B}{a^{3(1+\alpha)}})^{1/(1+\alpha)}$, respectively. The value of the scale factor today is taken equal to unity, $a_0 = 1$. Hence, ρ_{m0} and $\rho_{c0} = (A+B)^{1/(1+\alpha)}$ are the pressureless matter and GCG densities today. Eliminating from the last relation the parameter B, the GCG density at any time can be re-expressed as

$$\rho_c = \rho_{c0}\left(\bar{A} + \frac{1 - \bar{A}}{a^{3(1+\alpha)}}\right)^{1/(1+\alpha)} \quad , \tag{10}$$

where $\bar{A} = A/\rho_{c0}$. This parameter $\bar{A}$ is connected with the sound velocity for the Chaplygin gas today by the relation $\frac{\partial p}{\partial \rho} = v_s^2 = \alpha\bar{A}$.

Our main purpose here is the theoretical distance modulus vs. redshift relation, i.e., the HD of the CG model, to compare it with GRBs observations. For this, we need the luminosity distance [23, 24]

$$d_L = \frac{a_0^2}{a}\ r_1 \quad , \tag{11}$$

with r_1 the co-moving coordinate of the source. As light propagates on a null geodesic, i.e.,

$$ds^2 = c^2dt^2 - \frac{a^2dr^2}{1 - kr^2} = 0 \quad , \tag{12}$$

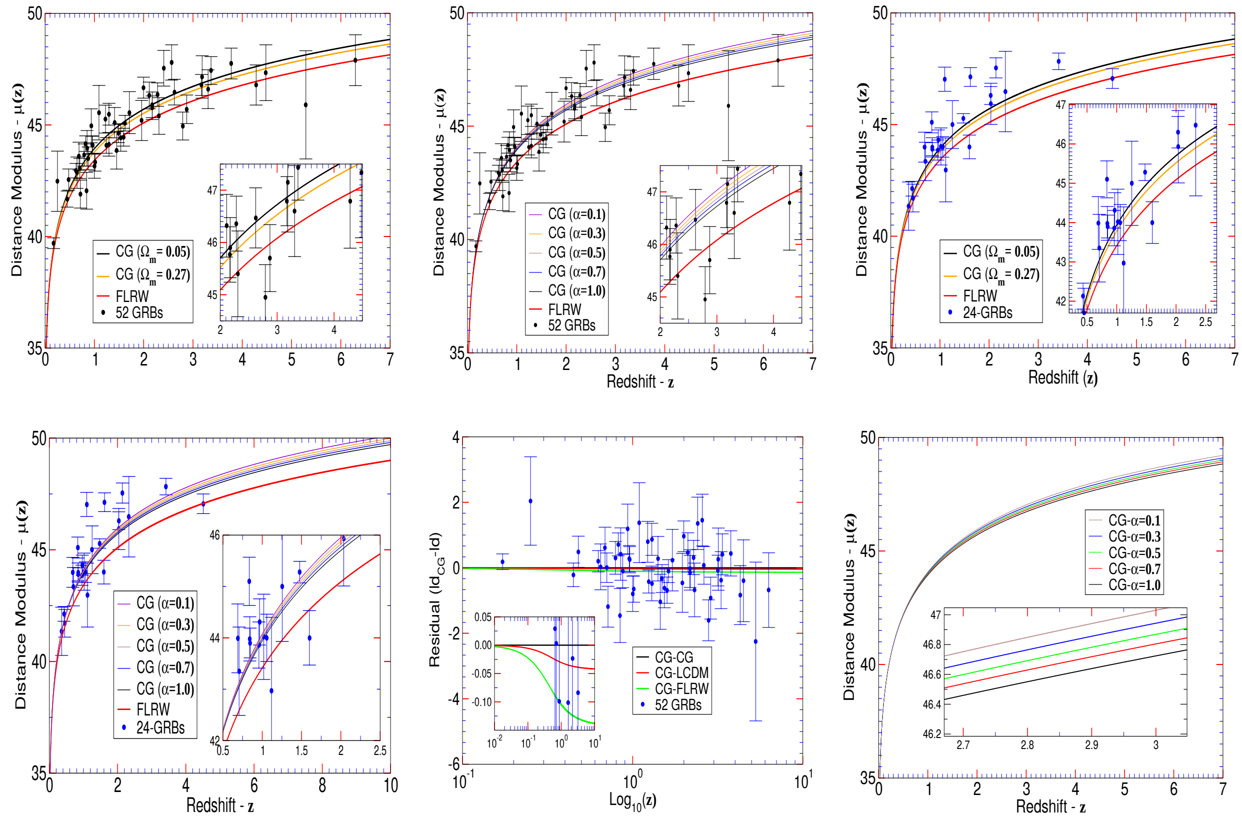


FIG. 2: (color on-line) HD of GRBs and the CG model of DE for the 52 (first pair of plots) and 24 GRBs (second pair) samples, including the case of a cosmological constant with $\Omega_\Lambda = 0.73$. Also the residual HD of the CG vs. Friedmann models confronting the 52 GRBs sample, and the HD small variation for several values of the CG α-parameter are presented.

the Friedmann's equation (7) allows to re-cast the luminosity distance as

$$d_L = (1+z) S[f(z)] \quad , \tag{13}$$

where $S(x) = x \quad (k=0)$, $S(x) = \sin x \quad (k=1)$, $S(x) = \sinh x \quad (k=-1)$, and the function $f(z)$ being given by

$$f(z) = \frac{c}{H_0} \int_0^z \frac{d\,z'}{\{\Omega_{m0}(z'+1)^3 + \Omega_{c0}[\bar{A} + (z'+1)^{3(1+\alpha)}(1-\bar{A})]^{1/(1+\alpha)} - \Omega_{k0}(z'+1)^2\}^{1/2}} \quad , \tag{14}$$

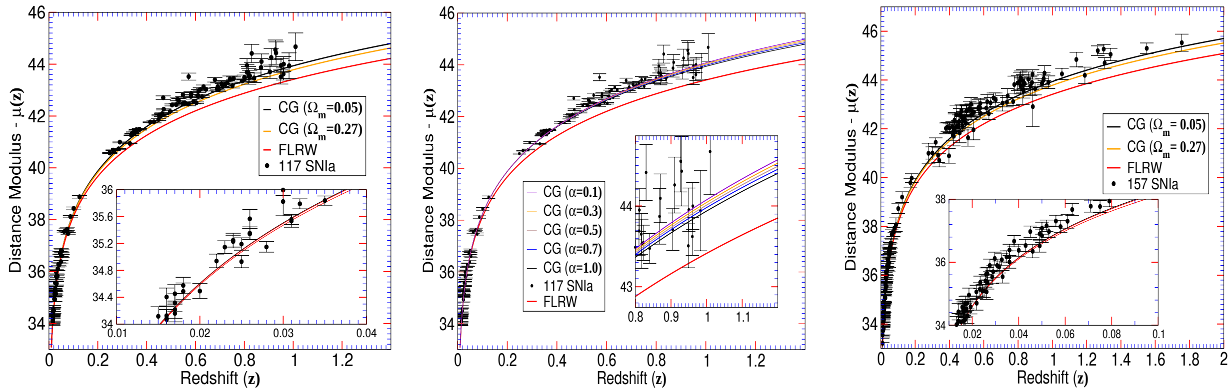
with the definitions

$$\Omega_{m0} = \frac{8\pi G}{3}\frac{\rho_{m0}}{H_0^2} \,, \Omega_{c0} = \frac{8\pi G}{3}\frac{\rho_{c0}}{H_0^2} \,, \Omega_{k0} = -\frac{k}{H_0^2} \,, \tag{15}$$

such that the condition $\Omega_{m0} + \Omega_{c0} + \Omega_{k0} = 1$ holds. To get the final equations used was done of the redshift vs. scale factor relation: $1 + z = \frac{(a_0 =)1}{a}$.

Data analysis and results.— For the present analysis we have taken benefit of two samples of GRBs as compiled by Schaefer [18], 52 GRBs that were analyzed by five different methods, and by Bloom, Frail and Kulkarni [19], 24 GRBs. Both having properly estimated distance modulus, $\mu(z)$, and redshifts. We also used the SNIa data as collected in the GOLD sample [26], and the SuperNova Legacy Survey (SNLS) [25]. Our main results are collected in Figures 1, 2 and 3 (color on-line). They were obtained upon exact numerical integration of the luminosity distance function in Eqs.(13,14), for a flat universe with $\Omega_{m0} = 0.05$ and $\Omega_{c0} = 0.95$, and for a cosmological constant-like CG with $\Omega_{c0} = 0.73$ and $\Omega_{m0} = 0.27$.

Conclusions.— We presented the Hubble diagram of a large sample of GRBs having properly estimated redshifts together with the equivalent plot predicted by the cosmology of the Chaplygin gas, one of the various candidates to make-up the dark energy; the exotic fluid driving the universe late-time accelerated expansion, and FLRW



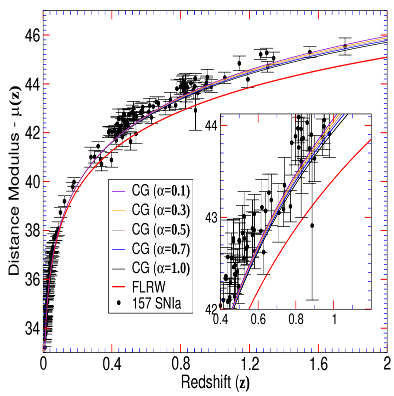


FIG. 3: (color on-line) Hubble diagram of SNIa: GOLD sample (leftish pair) and LEGACY sample (rightish pair), and the prediction of the CG model of DE, including the case of a cosmological constant with $\Omega_\Lambda = 0.73$. Similar plots are also given for $\alpha = 0.1, 0.3, 0.5, 0.7$.

and Λ-CDM models. After doing the cosmology of these models, we performed the statistical analysis and computed the model-to-sample χ^2. It was found that the CG definitely fits much better the HD of GRBs used in the present study, in comparison to the Friedmann and the pure Λ-CDM models. The present GRBs HD plot exhibits a marked trend indicating that as one goes back in time, i.e., to very high redshifts, it gets much closer to the predict HD for a Friedmann universe. This clear convergence demonstrates that a transition from decelerate to accelerate expansion did take place. However, and contrarily to claims based on supernovae type Ia (SNIa), the transition redshift lies somewhere between $2.5 \lesssim z \simeq 3.5$ rather than at $z \sim 0.5 - 1$. Therefore, this GRBs HD constitutes the most robust demonstration that the Chaplygin gas can indeed be the universe's driving dark energy field. "En passin", as still the GOLD and LEGACY SNIa HD locate far-above the CG predicted expansion law (Fig. 3), this is further evidence of their intrinsic problems: or the *Phillips relation* should be revisited [29], or perhaps there is some interrelation between the estimated luminosity distance residuals and internal extinction of the host galaxy that should be taken into the data analysis, as some researchers have pointed out recently [30]. Finally, it is worth to quote that a similar conclusion regarding the transition redshift $z \sim 3$ was achieved quite recently by Amendola, Gasperini and Piazza[28] upon the admission that dark matter and dark energy can strongly interact and evolve through a scaling regime $\rho_{\rm DM} \sim \rho_{\rm DE} \sim a^{-3(1+\omega_{\rm eff})}$, with $\omega_{\rm eff}$ a constant. However, although the present analysis here do confirm the transition around $z \sim 3$, as we pointed out here, and in Refs.[11, 31], the GOLD and LEGACY SNIa observations seem to violate the general relativistic energy conditions (see Figure 3) for the (generalized) Chaplygin gas and Friedmann models, a problem that GRBs observations do not face.

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[32] From now on we will refer to the generalized Chaplygin gas (GCG) model with the α-parameter since it will be the base of a detailed study that will be presented in the accompanying paper to this *Letter*[11]. Nonetheless, in the discussion ahead we will restrict ourselves to the case wherein $\alpha = 1$.
[33] Gamma-ray bursts (GRBs) are the biggest explosions in the universe. The 1997 february 28 Beppo-SAX discovery of the X-ray afterglow of a gamma-ray burst (GRB) allowed the first precise determination of the redshift of a GRB. This major breakthrough came to confirm the long-standing suspicion waving in the high energy astrophysics community that GRBs arrive from, and their sources lie at, cosmological whereabouts. Since then, the possibility of using them as actual cosmological probes has estimulated the search for self-consistent methods of bringing GRBs into the realm of cosmology. A handful of attempts have been on trial. Since the introduction of the *Amati relation* [13], other largely promising techniques have appeared in an attempt to turn GRBs into reliable cosmological probes. These include the *Ghirlanda relation* [14], the *Liang-Zhang relation* [15], and the recently discovered *Firmani et al. relation* [16], all of which taking into account the most relevant physical properties of GRBs as the peak energy, jet openning angle, and both time lag and variability. Such discoveries hints at the long-sought *Holy Grail* of creating a cosmic ruler from GRBs observables to be achievable. Presently, after the first series of controversial statements on the viability of granting to GRBs the status of standard cosmic rulers [17, 19, 20], a definite consensus appears to be arising, and the hope to have a *Holy Grail* to do cosmology upon GRBs is renascenting [14, 18, 20, 21]. Besides, we bring to the reader's attention a historical fact that has a clear correspondance with the present situation regarding the GRBs cosmology. Despite having still large error bars, and in several cases a not so clear estimate of the redshift of some events, the present state of the cosmology based on GRBs emulates the days during which Hubble discovered the expansion of the universe by using inhomogeneous and badly calibrated data from the nebulae he, Humason and others had observed [12]. Nobody nowadays thinks of that his analysis as null and void, in spite of his methods having been not so standardized. Keeping these arguments in mind one can be confident of the worthiness for cosmological studies of the analysis being presented here.