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Probing Dark Energy with Supernovae : a concordant or a convergent model?

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Abstract

We present a revised interpretation of recent analysis of supernovae data. We evaluate the effect of the priors on the extraction of the dark energy equation of state. We find that the conclusions depend strongly on the Ω_M prior value and on its uncertainty, and show that a biased fitting procedure applied on non concordant simulated data can converge to the "concordance model". Relaxing the prior on Ω_M points to other sets of solutions, which are not excluded by observational data.

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The existence and nature of dark energy is one of the most challenging issues of physics today. The publication of high redshift supernovae discovered by the Hubble Space Telescope, by the SCP collaboration [1] and recently by Riess et al. [2], has been interpreted as agreement of the data with the so named ΛCDM "concordance model" ($\Omega_M \approx 0.3$, $\Omega_\Lambda \approx 0.7$, $w = p/\rho = -1$). We have reconsidered some conclusions in the light of our previous analysis of simulated data [3].

Riess et al.[2] have selected 157 well measured SNIa, which they call the "gold" sample, a set of data we will use throughout this paper. Assuming a flat Universe ($\Omega_T = 1$) they conclude that: *i)* Using the strong prior $\Omega_M = 0.27 \pm 0.04$, a fit to a static dark energy equation of state yields -1.46< w <-0.78 (95%CL); *ii)* Looking at a possible redshift dependence of $w(z)$ (using $w(z) = w_0 + w_1 z$), the data with the strong prior indicate that the region $w_1 < 0$ and especially the quadrant ($w_0 > -1$ and $w_1 < 0$) are the least favoured. They reject large time variation and are compatible with the concordance model.

We have shown in [3] that it is unavoidable to get some ambiguities when trying to fit a particular fiducial cosmology with a "wrong" model. This "bias problem" has been mentioned several times in the literature, see *e.g.*[4, 5, 6, 7]. In this letter, we explore the effect of the Ω_M prior on the determination of $w(z)$.

Following [3], we assume a flat universe and keep the same parametrisation of $w(z)$ as in [2], for the sake of comparison. We call 3-fit (4-fit) the fitting procedure which involves the 3 (4) parameters M_S, Ω_M and w_0 (M_S, Ω_M, w_0 and w_1), M_S being a normalisation parameter (see [3] for definitions and formulae). We have performed 3-fits and 4-fits and compared the results in different cases, varying the central value and the uncertainty on the Ω_M prior.

TABLE I: Fit results obtained using the gold data from [2] for various fitting procedures. The χ^2 is very stable, it is around 173 (for 157 SNIa) for all procedures except for the 3-fit with the strong prior $\Omega_M = 0.27 \pm 0.04$ where $\chi^2 \approx 176$.

Fit	Ω_M prior	Ω_M	w_0	w_1
3-fit	no	0.48 ± 0.06	-2.2 ± 0.95	/
3-fit	0.27 ± 0.2	0.45 ± 0.07	-1.9 ± 0.73	/
3-fit	0.50 ± 0.2	0.48 ± 0.06	-2.3 ± 0.94	/
3-fit	0.27 ± 0.04	0.28 ± 0.04	-1.0 ± 0.15	/
3-fit	0.50 ± 0.04	0.49 ± 0.03	-2.5 ± 0.77	/
4-fit	no	0.48 ± 0.20	-2.2 ± 1.34	0.12 ± 23
4-fit	0.27 ± 0.2	0.35 ± 0.18	-1.6 ± 0.80	1.74 ± 1.3
4-fit	0.50 ± 0.2	0.49 ± 0.20	-2.6 ± 1.20	1.60 ± 18
4-fit	0.27 ± 0.04	0.28 ± 0.04	-1.3 ± 0.26	1.50 ± 0.84
4-fit	0.5 ± 0.04	0.49 ± 0.04	-2.6 ± 1.40	0.95 ± 10

Applying no prior or the strong prior on Ω_M (lines 1, 4 and 9 of the Table), we recover the results obtained by Riess et al.[2]. Nevertheless, some interesting points can be underlined:

• With no prior or a weak prior on Ω_M, the preferred Ω_M values are always greater than 0.3.
• Without any assumption on Ω_M nor w_1, the error on Ω_M is close to 0.2 (line 6 of Table I).
• Changing the central value of the Ω_M prior leads to a change in the w_0 values of more than 1σ. The w_0 values are strongly correlated to Ω_M and are thus always smaller than the ΛCDM value, when the strong prior on Ω_M is relaxed. χ^2 is very stable but the correlation matrix can vary a lot for the 4-fits and the (w_0,w_1) solution.
• If the Ω_M prior is strong, the conclusion on w_0 depends on the prior value : for Ω_M=0.27, w_0 is forced to values compatible with -1, in particular for the 3-fit and the errors are strongly reduced. For Ω_M=0.5, w_0 is more negative and the errors are significantly larger.
• The only cases where "reasonable" errors can be found on w_1 occur for Ω_M around 0.3.

To illustrate these points, Figure 1 shows the results in the (Ω_M,w_0) plane for the 3-fits(left) and the 4-fits(right), using no prior on Ω_M or two strong priors with the two central values: 0.27 and 0.5. As expected the contours strongly depend on the procedure used to analyse the data. For instance, the 95%CL contours for the two strong prior cases are disconnected. However, we note that $\Omega_M < 0.6$ is valid for all procedures, hence it is one of the strong conclusions from present SN data.

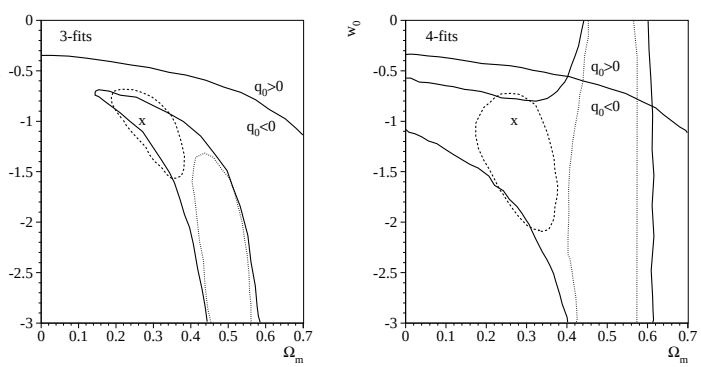

FIG. 1: 95%CL contours for 3-fits(left) and 4-fits(right) with no prior on Ω_M (plain) and two strong priors $\Omega_M = 0.27(0.5) \pm 0.04$ (dashed (dotted)). The (x) indicates the ΛCDM point ($\Omega_M = 0.27, w_0 = -1, w_1 = 0$). The plain line separates accelerating ($q_0 < 0$) from decelerating ($q_0 > 0$) models.

Simulation and interpretation :

We have simulated, as in our previous paper[3], SNIa data corresponding to the same statistical power as the data sample, where we vary the fiducial values to study the effects of the priors (on Ω_M or/and w_1).

We start with some illustrations of the bias introduced by the Ω_M prior when it is different from the fiducial value. We consider two fiducial models which are compatible with the data, when no prior is applied: one in acceleration with Ω_M^F =0.5, w_0^F=-2.2, w_1^F=1.6 and one in deceleration with Ω_M^F =0.5, w_0^F=-0.6, w_1^F=-10. We apply the 4-fit to the two models with the two strong priors: $\Omega_M = 0.27 \pm 0.04$ and $\Omega_M = 0.5 \pm 0.04$. Figure 2 shows how the prior affects the conclusions:

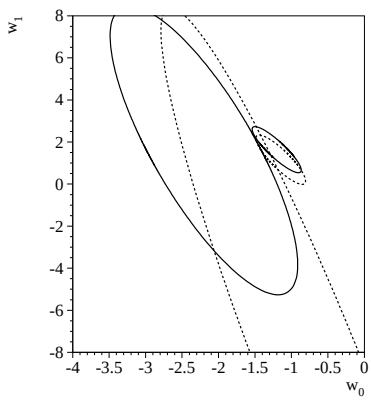

FIG. 2: Fisher contours in the (w_0, w_1) plane at 68.3%CL for the two fiducial models: (in acceleration) Ω_M^F =0.5, w_0^F=-2.2, w_1^F=1.6 and (in deceleration) Ω_M^F =0.5, w_0^F =-0.6, w_1^F=-10. The upper indice F is added to avoid confusion between Fiducial values and fitted values. The plain big and small ellipses correspond to the first model analysed with the strong prior $\Omega_M = 0.5 \pm 0.04$ (big ellipse) or with $\Omega_M = 0.27 \pm 0.04$ as in [2](small ellipse). The dashed big and small ellipses correspond to the second model.

• When the correct prior on Ω_M is applied, the central values are not biased but the errors are very large.
• When the wrong prior $\Omega_M = 0.27 \pm 0.04$ is applied, the fitted values are wrong but in agreement with the concordance model. The statistical errors are very small. In all cases, χ^2 is good and does not indicate that something is wrong.
• With the data, it is not possible to distinguish between these two models, but the prior value can lead to wrong conclusions both on values and errors of the fitted parameters.

We have then performed a complete fit analysis on the simulated data and scanned a large plane of fiducial values (w_0^F, w_1^F) with 3-fits and 4-fits, assuming a flat universe and using two fiducial values for Ω_M^F : 0.27 or 0.5. We always use in the fitting procedures, the strong prior $\Omega_M = 0.27 \pm 0.04$. The case $\Omega_M = \Omega_M^F$ is equivalent to a Fisher analysis and only the errors are studied. In the case $\Omega_M \neq \Omega_M^F$, biases are introduced in the fitted values.

Figure 3 shows the fitted w_0 and w_1 iso-lines for the 4-fits in the biased case. The iso-lines are straight lines (not shown on the figure) when $\Omega_M^F = 0.27$ (unbiased correct prior), but are biased when $\Omega_M^F = 0.5$. This is due to the strong correlations between w_0 and Ω_M, and between w_0 and w_1.

In this configuration, we observe that, for the 4-fit, when $-5 < w_0^F < 0$ (a relatively wide range), the fitted values for w_0 are in a narrow range centred on -1 : $-1.8 < w_0 < 0$. For w_1, the situation is even worse since with fiducial values $-8 < w_1^F < 8$, we get essentially positive values for the fitted w_1. The actual shapes of the distortions between the fiducial and the fitted values are

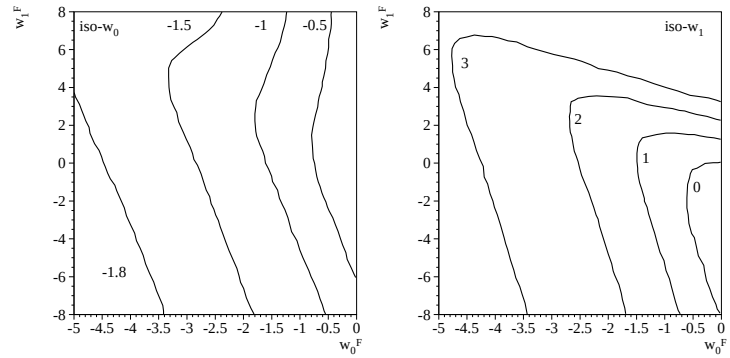

FIG. 3: Fitted w_0 (left) and w_1 (right) iso-lines with 4-fits for a fiducial with Ω_M^F =0.5 and a prior $\Omega_M = 0.27 \pm 0.04$, in the plane (w_0^F, w_1^F).

readable on Fig. 3.

A similar analysis performed with the 3-fit shows that the situation is even worse : one gets $-1.5 < w_0 < 0$ whatever the value of w_0^F. As w_1 is forced to 0 and Ω_M to 0.27, w_0 is closer to -1 which corresponds to the preferred solution for the fit.

One can illustrate further this very problematic point, by defining "confusion contours", namely some contours which identify the models in the fiducial parameter space (*e.g.* (w_0^F, w_1^F)) that could be confused with another model. For instance, the contours of Figure 4 give the models in the plane (w_0^F, w_1^F) with $\Omega_M^F = 0.5$ that can be confused (at 1 and 2σ) with the concordance model if the (wrong) strong prior is applied. The two models used for the illustrative Fig. 2 are taken from extreme positions in this confusion contour of Fig. 4.

For the 3-fit, the confusion contours with the concordance model are very large and include all models having roughly $w_1^F < (-5w_0^F - 10)$. The situation here is particularly bad since the fitting procedure is making two strong assumptions ($w_1 = 0$ and $\Omega_M = 0.27 \pm 0.04$) which are not verified by the fiducial cosmology (two biases).

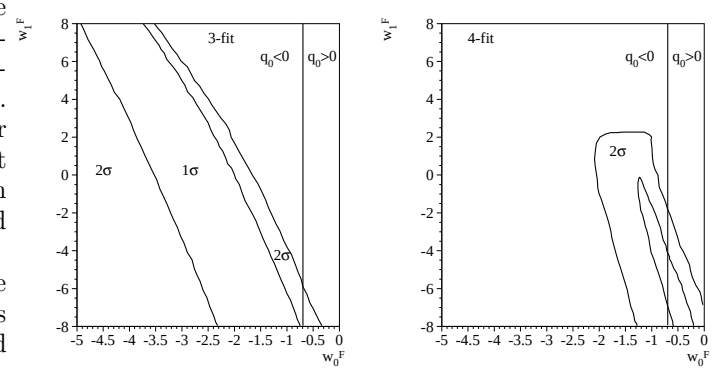

FIG. 4: Confusion contours in the fiducial plane (w_0^F, w_1^F) which identify the models that would be confused with the concordance model at 1 and 2σ for the 3-fit(left) and the 4-fit(right) procedures. The strong prior is $\Omega_M = 0.27 \pm 0.04$ whereas the fiducial model is $\Omega_M^F = 0.5$. The vertical line separates accelerating from decelerating models.

The next step is to study the parameter errors. We look at the correlation of the errors using fiducial models where Ω_M^F =0.27 or 0.5. We determine the w_0 and w_1 errors, scanning the full plane (w_0^F, w_1^F) using 4-fits.

Some regions of the parameter space (see Figure 5) are favoured and always produce small errors. This is due to the correlation between w_0 and w_1. The error depends strongly on the fitted w_0 and w_1 values but not strongly on the Ω_M value: a different value of Ω_M affects the scale of the errors but not the shape of the plots. We find a linear scaling of the error when we change Ω_M from 0.27 to 0.5 (*i.e.* a factor 2).

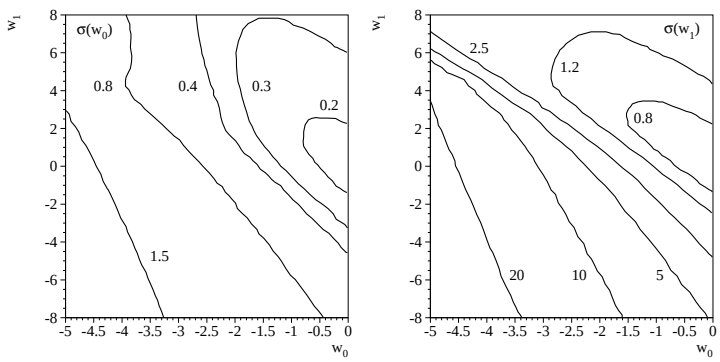

FIG. 5: w_0 and w_1 errors for a 4-fit with the correct strong prior, for a fiducial with Ω_M^F =0.27.

Combining this with the previous paragraph leads to an interesting point, *i.e.* the favoured fitted values of the fit ($w_0 > -1.8$ and $w_1 > 0$), which were shown to be mainly driven by the prior value, correspond also to the region of the plane where the parameters errors are always small.

We conclude that the applied fitting procedure with this strong prior can bias the conclusions by constraining the (w_0, w_1) solution near the (-1,0) solution, where the statistical error is always very small. In particular, Riess et al.[2] found a gain factor of order 8 on the accuracy of the neasurement compared to previous analysis. This is mainly due to the Ω_M prior and not to the inclusion of the high z HST events. The present observational constraints on Ω_M are thus an important issue.

Revisited conclusions on existing data :

Most reviewers of cosmological parameters favour a value close to the strong prior choice made by [2]. This result is based on WMAP[8] data combined with 2dF data[9] or more recently with SDSS data[10], and corresponds to [8]([10]) $\Omega_M = 0.27(0.3) \pm 0.04$ with $h = 0.71(0.70)^{+0.04}_{-0.03}$. However, these results are based on several prior assumptions in order to lift the degeneracies among the various cosmological parameters (*e.g.* Ω_M, h, σ_8, w ...). For instance, Spergel et al.[8] mention that a solution with $\Omega_M = 0.47$, $w = -0.5$ and $h = 0.57$ in the CMB is degenerate with the ΛCDM model. This kind of solution is excluded for three reasons: the Hubble Constant value is 2σ lower than the HST Key Project value and the model is a poor fit to the 2dF and SN data.

However, *i)* in spite of the precise HST result, the Hubble constant value is still controversial[11, 12]. *ii)* We have shown in the previous section that the SN data analysis can only conclude that $\Omega_M < 0.6$ (see Fig. 1).

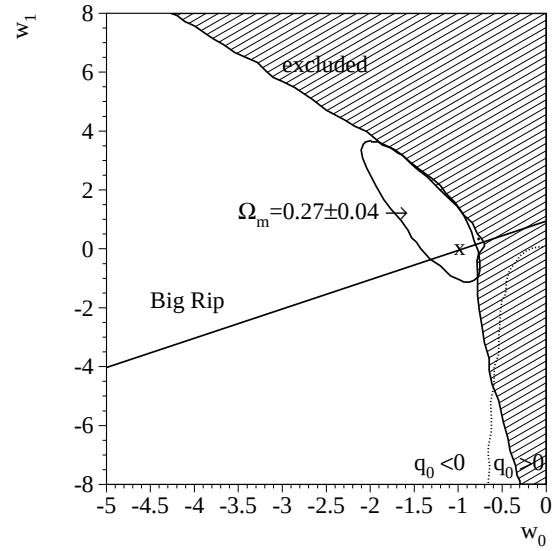

FIG. 6: The shaded region is excluded at 95%CL when no prior on Ω_M is applied. The ellipse corresponds to the strong prior constraints as in [2]. The (x) is ΛCDM. The dotted line separates accelerating from decelerating models.

iii) The 2dF and the SDSS Collaborations [9, 13] have extracted $\Omega_M h$ from an analysis of the power spectrum of galaxy redshift surveys. The degeneracy between $\Omega_M h$ and the baryon fraction is lifted thanks mainly to the precise determination of the baryon fraction by CMB data (see Fig.38 of [13]). Should that prior change, the preferred values from SDSS would indicate a higher value of $\Omega_M h$.

In addition, a large variety of observations give constraints on Ω_M, which is found to vary from 0.16 ± 0.05 [14] up to a value above 0.85 [15].

Conversi et al.[12] provide an interesting critical analysis on the present constraints on cosmological parameters, especially on Ω_M, h, and w. Through the study of the degeneracies, they show that the result $\Omega_M = 0.27 \pm 0.04$ is obtained under the assumption of the ΛCDM model, and provide specific examples with smaller h ($h < 0.65$) and higher Ω_M ($\Omega_M > 0.35$) which are in perfect agreement with the most recent CMB and galaxy redshift surveys.

In conclusion, we follow the point of view of Bridle et al.[16], who argue that it may be "that the real uncertainty is much greater" than the 0.04 error obtained from the combination of CMB and large scale structure data.

Returning to SN data analysis, we suggest, for the time being, to reevaluate the conclusions by relaxing the Ω_M central value. Figure 6 shows the 95%CL constraints in the (w_0,w_1) plane obtained from the gold sample [2] with no prior assumption on Ω_M. Taking an uncertainty of 0.2, which is the intrinsic sensitivity of SN results (see Table I, line 6), does not change the conclusions:

• Large positive variations in time of the equation of state are excluded (at 95%CL) since the dark energy density blows up as $e^{3w_1 z}$ [17].

• The quintessence models which have in general ($w_0 >$

-1, $1 > w_1 > 0$) [5] are seriously constrained. For instance, the SUGRA model [18] characterized by $w_0 \approx -0.8$ and $w_1 \approx 0.3$[5] is close to the border of the $95\%CL$ contour (precisely, one gets $\Delta\chi^2$=3.5 corresponding to an exclusion at $80\%CL$).

• The quadrant ($w_0 > -1$, $w_1 < 0$) corresponding to k-essence models [19] or some Big Crunch models [2, 20], is not the "least favoured", contrary to the conclusions drawn with the strong prior [2]. We find that if w_0 goes towards 0, then w_1 should be more and more negative.

• If $w_0 < -1$, the constraints on w_1 are weak (except for large positive values). This region of the plane corresponds to phantom models [21] which have unusual properties and may have very different consequences for the fate of the Universe (*e.g.* models with $w_1 > w_0 + 1$ will end in a Big Rip [17]). Models with very exotic $w(z)$ may come from modified gravity[22]. The class of models with $w_1 < 0$ is roughly excluded at $95\%CL$, if the strong prior $\Omega_M = 0.27 \pm 0.04$ is used [2], but is perfectly allowed for higher Ω_M values (or larger prior errors).

• As can be seen on Fig. 6 (and also on Figures 1, 4 and the decelerating model used to draw Fig.2), our analysis without assumptions on Ω_M and w_1, allows decelerating models with specific properties : low w_0, $\Omega_M \approx 0.5$ and $w_1 << 0$. One can wonder if this result is not in tension with the geometrical test performed in [2] where the only assumption is to use a linear functional form for $q(z)$ (*i.e.* $q_0 + q_1 z$). It can be shown that a varying equation of state implies a non-linear $q(z)$, in particular, the linear approximation breaks down if $w_1^F < -1.5$. More details on this more subtle analysis will be presented in a forthcoming paper [23].

To go further, a coherent combined analysis of all data is mandatory, with a proper treatment of correlations and no prior assumptions. Some recent papers go in that direction [17, 24, 25, 26].

In addition, as soon as the statistical errors will become smaller, systematic questions cannot be neglected and should be controlled at the same level of precision. This is the challenge for the next generation of experiments. A promising approach is to combine SNIa with weak lensing, as proposed by the future dedicated SNAP/JDEM mission [27].

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