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Exorcising $w < -1$

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We show that the combined dimming of Type Ia supernovae induced by both a cosmological constant and the conversion of photons into axions in extra-galactic magnetic fields can impersonate dark energy with an equation of state $w < -1$. An observer unaware of the presence of photon-axion conversion would interpret the additional dimming as cosmic acceleration faster than that induced by a cosmological constant alone. We find that this mechanism can mimic equations of state as negative as $w \simeq -1.5$. Our model does not have any ghosts, phantoms and the like. It is fully consistent with the conventional effective field theory in curved space, and all existing observational constraints on the axions are obeyed.

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Cosmological observations suggest that the expansion of the universe may have begun accelerating, entering a very late stage of inflation [1–4]. If this is true, then the universe ought be dominated by a dark, non-clumping, energy component, comprising as much as 70% of the critical energy density. In order to account for the cosmic acceleration the dark energy should have negative pressure, obeying roughly $w = p/\rho < -2/3$ [5, 6]. The "usual suspects" for dark energy are either a tiny cosmological constant or a time-dependent quintessence field [7, 8]. However both require ample fine tunings to fit the data [9]: an unnaturally tiny energy density, of the order of the current critical energy density of the Universe, $\rho_c \sim 10^{-12}$ eV^4, and in the case of quintessence a tiny mass m_Q smaller than the current Hubble parameter $H_0 \sim 10^{-33} eV$ and couplings to the Standard Model matter weaker than gravity [10]. In the few examples which are consistent with the 4D effective field theory, quintessence is a pseudo-scalar axion-like field [11], whose symmetries stabilize its mass and render its couplings to the visible matter sufficiently weak.

At present, the most sensitive probe of the nature of dark energy are the Type Ia supernovae (SNe) [1]. Among all the sources of cosmological data they give us the best bounds on the dark energy equation of state $w = p/\rho$. It is thus reasonable to ask if those observations imply that the universe must be accelerating, or if there might be other explanations. On the other hand, the improved observations of the CMB and the large scale structure are now beginning to strengthen the case for the accelerating universe, even without resorting to the SNe data [12–14]. Still the strongest bounds on the equation of state arise only after the SNe observations are included as well. More curiously, the analysis indicates that the values of $w < -1$ are allowed [18–20]. This is very puzzling, since in a four dimensional cosmology based on Einstein's gravity, this would normally appear to imply violations of the dominant energy condition, $|p| \leq \rho$, long held to be an important avatar of stability in General Relativity. Indeed, the simplest models that yield such behavior employ scalar fields with negative kinetic terms, or ghosts [18, 19, 21, 22]. They have been dubbed phantoms [18]. These models are in fact just an incarnation of the so-called superexponential inflation at a much lower scale, discussed originally by Pollock in 1985 [23]. These naive phantom models are plagued with instabilities. Quantum-mechanically, they are deeply problematic because they do not admit a stable ground state [21, 24, 25]. Instabilities also persist at the classical level [21], and in general there are difficulties in trying to make sense of these models within the framework of effective field theory* [24]. While quantum effects may violate the dominant energy condition, the violations do not appear at phenomenologically relevant scales [27].

Should we therefore take any indications of $w < -1$ seriously? The current data do not support this very strongly [12–14]. There are also claims that different averaging procedures are needed, possibly removing the support for $w < -1$ altogether [28]. Moreover, it has been argued [6] that a variable $w \geq -1$ is degenerate with a constant $w < -1$ within the current data sets. The debate on whether or not w may have dipped below -1 at low redshifts still continue [15–17]. Thus although the case for $w < -1$ is very weak, an attitude that an observer should keep an open mind to possibilities and ignore theorist's prejudice is a healthy one, and search strategies for $w < -1$ have been proposed [29]. But if the data at some future time really does support $w < -1$, what could this mean? A phantom would

*Notice that the ghost condensation mechanism of [26] would not appear to help the phantom much. Once the ghosts condense one would end up with cosmic acceleration driven by a cosmological constant-like term.

run counter to the established rules of effective field theory, and so if the cosmological data really support $w < -1$, would it mean that we have to give up the usual effective field theory altogether?

One possible way to accept $w < -1$ and circumvent the problems with instabilities could be to weaken gravity in the far infrared[†]. If the gravitational coupling becomes weaker at large distances, objects far away would move faster than they would have been moving if the coupling remained constant. An observer using the standard Friedmann equation to measure cosmic distances could interpret this as an effect of cosmic acceleration, and think of the agent driving acceleration as dark energy obeying $w < -1$, even though no such agent is really there. This approach has been pursued in the framework of generalized scalar-tensor gravity [30], and in the framework of DGP gravity [31] where not only the gravitational constant but the whole structure of gravity changes at large distances [32]. In the former case, arranging for an illusion of $w < -1$ is hard, and the effects are small. In the latter case, it appears that a transient stage with $w < -1$ is generic, but the effects are still not very large[‡]. More importantly, in all of these models, and also in the case of the more naive phantom cosmologies, the effects mimicking $w < -1$ are embedded in gravity and geometry, and so they would affect everything in the universe *equally*, because of the equivalence principle. Yet, a look at the data shows that at present it is mainly SNe on their own that might suggest $w < -1$. All other observations are consistent with $w \geq -1$.

In this article we will pursue a different approach. It is a variation of our recent proposal [33] that the observed dimming of the SNe arises as a *combination* of a faster expansion of the universe and conversion of photons emitted by SNe into ultralight axions. Photon-axion conversion will occur in external magnetic fields, along the lines of the mechanism exhibited in [34]. We found that it could contribute to the observed dimmer SNe if the photon-axion coupling scale is $M \sim 4 \cdot 10^{11}$ GeV and the axion mass is $m \sim 10^{-16}$ eV, assuming intergalactic magnetic fields $B \sim 5 \cdot 10^{-9}$ G coherent over distances of the order of a Mpc, all in agreement with observational bounds [36, 37]. In our mechanism the depletion of the photon flux due to the axion production automatically saturates at about a third of its value at the source, thanks to the random orientation of the extragalactic magnetic fields. In this way, we were able to significantly relax the bounds on the equation of state of the dark energy. While dark energy still comprised 70% of the contents of the universe, to explain the observed dimming of SNe together with the photon-axion conversion we needed the equation of state to be only as negative as $w = -1/3$. The combined effect of the expansion driven by it and the photon-axion conversion weakening the flux of photons from SNe by $1/3$ then conspired to impersonate precisely the effects of the cosmological constant alone [33].

Imagine now that the dark energy is really a cosmological constant. This is automatically consistent with the CMB and large scale surveys. However, enter the same axion as the one we considered in [33]. While the CMB and the large scale structure observations would remain completely unaffected by it, the optical sources, and in particular SNe would appear dimmer than they would be in the presence of the cosmological constant alone! An unsuspecting observer could thus conclude that the universe must be accelerating even faster than it would have if the dark energy equation of state obeyed $w \geq -1$, and may be tempted

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to resort to phantoms as an explanation. Yet, there is not a single trace of any supernatural degrees of freedom here - it is merely the ultralight axion, and the conversion of photons into it with hardly a trace of it left, which impersonates the phantom-like effects. In fact, we will show that the combination of photon-axion conversion and cosmological constant can mimic phantom-like dark energy with the equation of state as negative as $w \simeq -1.5$, coming very close to the lower bounds quoted in [12–14], and scanning the full interval between -1 and -1.5. This phenomenon affects bright objects differently than it does the dark ones: the extra dimming is only manifest with the sources of electromagnetic radiation and does not affect dark matter at all. Any attempt to accomplish this with modifications of the gravitational sector would clearly require violations of the equivalence principle. A key aspect of the mechanism is that since there are no negative contributions to the Hamiltonian, the theory is perfectly well behaved, and has a stable vacuum. This explanation is firmly rooted in the realm of simple effective field theory.

Let us now briefly review the key ingredients of the photon-axion conversion mechanism [33, 35]. The operator governing photon-axion coupling is

$$\mathcal{L}_{int} = \frac{a}{M} \vec{E} \cdot \vec{B} \,, \tag{1}$$

where the scale M parameterizes the strength of the axion-photon interactions. In the extragalactic magnetic fields this induces a bilinear mixing between the photon and the axion [34]. At distances small compared to the size of a typical magnetic domain ($\sim$ MPc), a photon whose electric field is orthogonal to $\vec{B}$ remains unaffected by this mixing, but a photon whose electric field is parallel to $\vec{B}$ mixes with the axion, and these two flavors oscillate into each other during propagation. Small variations in the magnetic field absorb the (tiny) rest mass difference between them. If the line of sight is along the y-direction, and the magnetic field along the z-axis, the field equations are

$$\Big\{ \frac{d^2}{dy^2} + \mathcal{E}^2 - \begin{pmatrix} \omega_p^2 & i\mathcal{E}\frac{B}{M_L} \\ -i\mathcal{E}\frac{B}{M_L} & m^2 \end{pmatrix} \Big\} \begin{pmatrix} |\gamma\rangle \\ |a\rangle \end{pmatrix} = 0 \,. \tag{2}$$

We have used the Fourier-transforms of the fields in the energy picture $\mathcal{E}$ and defined the state-vectors $|\gamma\rangle$ and $|a\rangle$ for the parallel photon and the axion. Here $B = \langle \vec{e} \cdot \vec{B} \rangle \sim |\vec{B}|$ is the averaged projection of the extra-galactic magnetic field on the photon polarization $\vec{e}$. When the photons propagate in the ionized interstellar medium, they couple to the sonic wave in the charged plasma, and acquire an effective mass term ω_p^2, where ω_p is the plasma frequency [34]. It is given by $\omega_p^2 = 4\pi\alpha n_e/m_e$, with n_e the electron density, m_e the electron mass, and α the fine structure constant.

Because the mixing matrix in Eq. (2),

$$\mathcal{M} = \begin{pmatrix} \omega_p^2 & i\mathcal{E}\mu \\ -i\mathcal{E}\mu & m^2 \end{pmatrix} \,, \tag{3}$$

where $\mu = B/M$, is not diagonal, interaction eigenstates $|\gamma\rangle, |a\rangle$ oscillate into each other. Defining the propagation eigenstates $|\lambda_-\rangle$ and $|\lambda_+\rangle$ [33], which diagonalize the matrix (3), with eigenvalues $\lambda_\mp = \frac{\omega_p^2+m^2}{2} \mp \sqrt{\frac{(\omega_p^2-m^2)^2}{4} + \mu^2\mathcal{E}^2}$, we can solve the Schrödinger equation (2).

The survival probability $P_{\gamma\to\gamma} = |\langle\gamma(y_0)|\gamma(y)\rangle|^2$ of the photon interaction eigenstate which travelled a distance Δy is then [33, 34]

$$P_{\gamma\to\gamma} = 1 - \frac{4\mu^2\mathcal{E}^2}{(\omega_p^2 - m^2)^2 + 4\mu^2\mathcal{E}^2}\sin^2\left[\frac{\sqrt{(\omega_p^2 - m^2)^2 + 4\mu^2\mathcal{E}^2}}{4\mathcal{E}}\Delta y\right] . \tag{4}$$

From this formula we see that in the limit $\mathcal{E} \gg (m^2 + \omega_p^2)/\mu$, the mixing is maximal, and the oscillation length is practically independent of the photon energy. Hence high-energy photons will oscillate achromatically. On the other hand, in the low energy limit $\mathcal{E} \ll (m^2 + \omega_p^2)/\mu$, the mixing is small, and the oscillations are very dispersive, due to the energy-dependence of both the mixing angle and the oscillation length. To decide which of these limits is appropriate we must turn to the selection of realistic parameters for the scales in the problem.

We will assume that the averaged value of $\vec{B}$ is close to its observed upper limit, and take for the magnetic field amplitude $|\vec{B}| \sim 5 \cdot 10^{-9}$ G [37]. To avoid affecting the small primordial CMB anisotropy, $\Delta T/T \sim 10^{-5}$, we choose the axion mass m to be large enough for the mixing between microwave photons and the axion to be small. In order to maximize the couplings of optical range photons, we take the mass scale M to be as low as possible to remain allowed by the current bounds on ultralight axions [36]. These parameters are in the range of

$$m \sim 10^{-16}\text{eV}\,, \qquad M \sim 4 \cdot 10^{11}\text{GeV}\,. \tag{5}$$

These scales maximize the couplings of optical photons and cut off the mixing in the microwave range. While at early times the CMB photons were much more energetic, the mixing then was cut off because there were no sizeable extra-galactic magnetic fields yet, since their origin is likely tied to structure formation [38].

So far we have been discussing the evolution of the photon-axion system inside a coherent magnetic domain. However the cosmological magnetic fields aren't uniform. Taking $L_{dom} \sim$ Mpc for the size of a typical coherent magnetic domain [37], we solve for the quantum mechanical evolution of unpolarized light in a distribution of magnetic domains with random field directions along the line of sight. Analytic considerations show that for maximal mixing, when $\cos(\mu L_{dom}) > -1/3$, the photon survival probability is monotonically decreasing:

$$P_{\gamma\to\gamma} = \frac{2}{3} + \frac{1}{3}e^{-\Delta y/L_{\rm dec}}\,. \tag{6}$$

The decay length is given by [33]

$$L_{\rm dec} = \frac{L_{\rm dom}}{\ln\left(\frac{4}{1+3\cos(\mu L_{\rm dom})}\right)}\,. \tag{7}$$

For $\mu L_{\rm dom} \ll 1$ this reduces to

$$L_{\rm dec} = \frac{8}{3\mu^2 L_{\rm dom}}\,. \tag{8}$$

After the voyage through many magnetic domains the initial system of unpolarized photons undergoes equilibration between the two photon polarizations and the axion. Hence on average a third of all photons will become axions after a long trip through many magnetic domains.

This effect contributes to the total dimming of distant sources because we should account for the loss of luminosity due to the axion production. We should replace the absolute luminosity $\mathcal{L}$ by an effective one, taking into account the photon survival rate:

$$\mathcal{L}_{eff} = \mathcal{L}\ P_{\gamma\to\gamma}\,. \tag{9}$$

As a result of $P_{\gamma\to\gamma} < 1$, the effective luminosity distance determined from $\mathcal{L}_{eff}$ will appear larger than the actual distance to the source.

Various aspects of the photon-axion conversion mechanism were investigated in [39–41]. The most important effects arise from the presence of the photon plasma mass. This yields a weak frequency dependence of the dimming, which would be a direct signature of the mechanism, while still being unobservable on the current SNe samples [35, 39–41]. It is reasonable [35] to imagine that over large fractions of space at redshifts $z \lesssim 1$ the electron density is at most $n_e \leq 6 \cdot 10^{-9}\text{cm}^{-3}$, and possibly even less than that. This value of the electron density yields the plasma frequency $\omega_p \leq 3 \cdot 10^{-15}$ eV. In this regime the frequency dependence of the supernova dimming remains below the current experimental sensitivity. The intergalactic plasma relaxes the lower bound on m in (5) since the plasma-generated effective photon mass by itself has the right magnitude to suppress the photon-axion mixing at sub eV energies.

More recently, in [42] the authors looked at the frequency dependence of the spectra of quasi-stellar objects (QSOs) in the SDSS early data release [44], with the conclusion that QSO spectra limit the maximal amount of dimming at $z = 0.8$ to be less than about a 0.15 increase in magnitude. It would be interesting to repeat this with the QSOs in the new SDSS data release, which has appeared since. It would also be interesting to see the effects of allowing the coherence length of the magnetic fields to be smaller than MPc by only a factor of a few. One then could not average over the phase factor in the mixing probability (see eq. (4) below), which might suppress the frequency dependence. Nevertheless here we will just adopt the constraint from [42] and show that even with this bound in force there can still be very important observable effects coming from photon-axion conversion.

In [43] the authors have pursued the violations of the reciprocity relation between the luminosity distance and angular-diameter distance, using the SNe Ia data to measure the luminosity distance and the FRIIb radio galaxy data [46] to measure the angular-diameter distance. Their bound on photon-axion mixing can be stated as $(L_{dec}H_0)^{-1} < 0.6$. This is just slightly stronger (but of similar magnitude) than the bound from the QSO spectra. However, in a recent paper [47] different data was used to test the reciprocity relation. The authors of [47] have used the data from X-ray and SZ observations of clusters, and their analysis finds a weak support for a violation of the reciprocity relation between the luminosity distance and angular-diameter distance. This would be consistent with the photon-axion mixing. In addition it is difficult to quantify the systematic errors due to evolution effects in structures formed at different redshifts. Therefore in our analysis we will only be adopting the constraint from [42]. However any modifications of the results presented here that might ensue from the constraint of [43] would not be significant.

Hence it is fair to say that to date the possibility that the photon-axion conversion contributes to the observed SNe dimming [1] has not been ruled out. In fact, as we will see later on, apart from the bounds from [42, 43], the original proposal [33] would still provide a very good fit to the most recent SNe data, including the farthest points and not conflicting with the WMAP bounds. Here however we will not assume that the dimming is dominated by photon-axion conversion. Instead we will imagine that there is a cosmological constant (or some form of dark energy with w near -1) providing the bulk of the dimming, while the photon-axion conversion gives an additional contribution. This way the relative contribution of the photon-axion conversion to the total dimming of supernovae is reduced with respect to the case of dark energy with $w = -1/3$ which we discussed previously [33]. Therefore the axion side-effects will be reduced accordingly, further weakening the already weak frequency dependence. Thus, as we will see, many interesting examples can be brought in accord with the bounds from [42, 43].

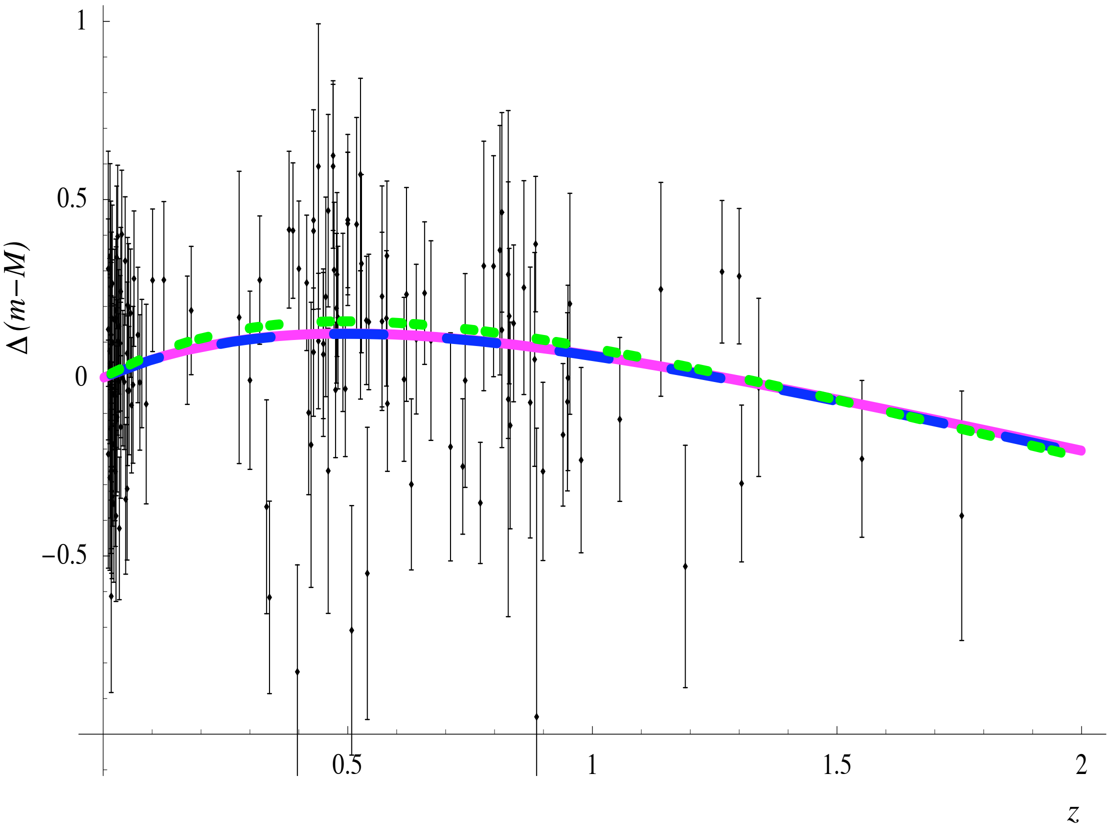

Figure 1: The observed differential distance modulus of high-redshift SNe from [2] relative to an empty universe together with with the the curves for three models: a cosmological constant with $\Omega_m = 0.3$ (blue dashed curve), a cosmological constant with $\Omega_m = 0.35$ plus photon-axion oscillations with $(L_{dec}H_0)^{-1} = 0.25$ (purple solid curve) and a phantom matter with $w = -1.25$ and $\Omega_m = 0.35$ (green double-dashed curve). The three curves are practically all indistinguishable, and fit the data equally well.

So let us consider the combined effect of dark energy with $w \simeq -1$ and the photon-axion conversion. We can compare the Hubble diagrams for SNe in the universe with and without photon-axion mixing, and also with the universe dominated by dark energy with a phantomlike equation of state. Assuming spatial flatness and taking $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$, in Fig. (1) we have plotted Hubble diagrams for the case of cosmological constant without photon-axion conversion (blue dashed line). Almost exactly underneath it we see the case when $\Omega_m = 0.35$, $\Omega_\Lambda = 0.65$ and photon-axion conversion with $(L_{dec}H_0)^{-1} = 0.25$ (purple solid line). Finally we plot $\Omega_m = 0.35$ and a phantom with $w = -1.25$ (green double dashed line). We have also plotted the measured differential distance moduli from the 157 Type IA SNe reported recently in the "gold sample" of [2] (relative to an empty universe corresponding to $\Delta(m - M) = 0$), which include the most distant SNe discovered using the Hubble Space Telescope. We can see from Fig. (1) that the curves based on these scenarios are almost indistinguishable from each other, and thus each fit the observations equally well. Therefore, we conclude that the combined effect of cosmological constant and photon-axion conversion is practically indistinguishable from a phantom with $w < -1$. To get an idea of what the value of the best-fit "phantomlike" dark energy would be, we have compared the differential distance modulus vs. redshift curves of the cosmological constant plus axion system with those of some phantomlike dark energy, and minimized the distance between these curves. In this way we obtain an approximate expression for the value of w that a cosmological constant plus photon-axion oscillations would fake:

$$w^{fake} \simeq -1 - (2.13\,\Omega_m + 0.04)(L_{dec}\,H_0)^{-1} \quad . \tag{10}$$

In order to find out which of these fake values of w can occur we have performed a fit to the gold sample of the SNe luminosity distances in [2]. In the first fit we have not restricted

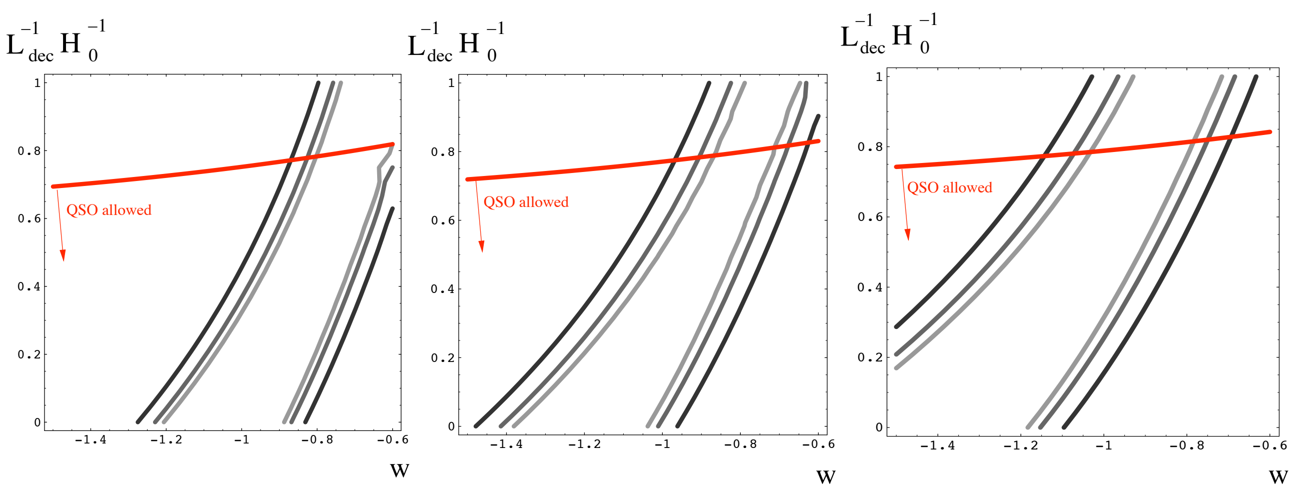

Figure 2: The regions allowed by the latest SN observations [2] at 90, 95 and 99 % confidence level in the $w - L_{dec}$ plane. The red curve shows the region allowed by the study of the energy dependence of quasar spectra [42]. The left panel corresponds to $\Omega_m = 0.3$, the middle one to $\Omega_m = 0.35$ while the right one to $\Omega_m = 0.4$.

the dark energy component to be a cosmological constant, but rather allowed for a generic constant equation of state w. We then varied the photon-axion oscillation decay length L_{dec} and plotted the contours of constant χ^2's in Fig. (2) for several values of Ω_m. Note, that for lower values of Ω_m, the case of a cosmological constant without photon-axion conversions is close to providing the best fit to the data, while for larger values of Ω_m this point is not even within the allowed region. The minimal χ^2 values for all cases are around 176 for the 157 data points from [2]. We have also demarcated the bound on the decay length coming from the study of the energy dependence of the quasar spectra from [42].

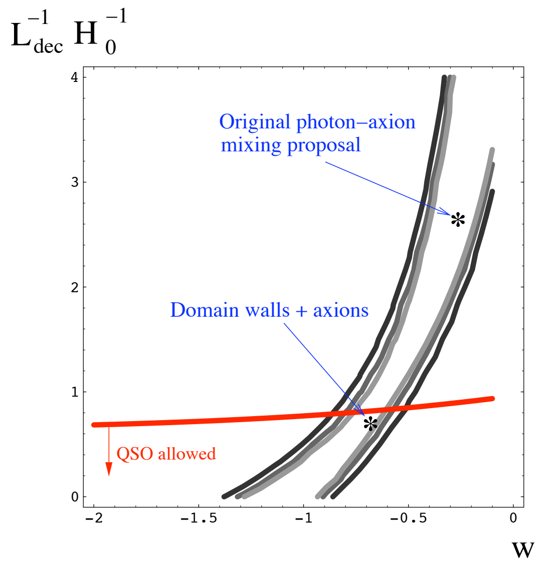

Figure 3: The same as in Fig. 2 for $\Omega_m = 0.35$, except the region for a larger region of w and L_{dec}. This plot illustrates the fact that the original photon-axion mixing proposal [33] would still fit all the SNe observations (and also the WMAP constraints). The only real constraints on the model that disfavor it as an explanation for the majority of the dimming come from the study of the energy dependence of quasar spectra [42] or from violations of reciprocity [43]. The red curve shows the approximate bound from the quasar studies.

In Fig. (3) we have repeated the same analysis except for a bigger region of the $w - L_{dec}$ parameter space, for $\Omega_m = 0.35$. The point of this analysis is to demonstrate that the originally proposed mechanism for explaining all the SNe dimming ($w = -1/3, L_{dec} \sim 0.5H_0^{-1}$) still fits the SNe observations very well. The only arguments disfavoring the case of $w = -1/3$ combined with photon-axion conversion as the source of all the dimming are the bounds from [42, 43]. If for any reason these bounds would turn out to be unreliable (which is likely the case with [43], given [47]) then even the original proposal would still be a viable explanation. More importantly, we can see both from this figure and from Fig. (2) that the case of a domain wall [48] equation of state ($w = -2/3$) combined with photon-axion conversion is still well within the allowed region for lower $(0.3 - 0.35)$ values of Ω_m.

Finally, we have scanned the parameter space in Ω_m and L_{dec}, fixing the equation of state of the dark energy to be that of a cosmological constant, $w = -1$. The allowed region together with the approximate "fake values" of w, which one would attribute to this system, are shown in Fig. (4). We can see from this plot that with this simple system effective values of w as low as -1.5 can be obtained, without violating any experimental bounds.

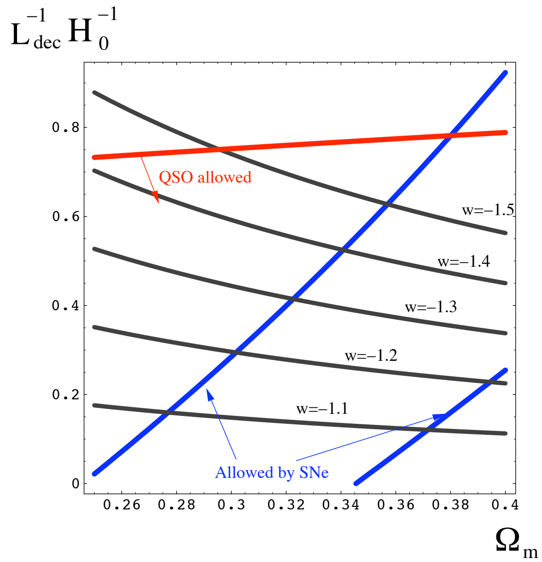

Figure 4: The region allowed by the latest SN observations [2] at the 95 % confidence level in the $\Omega_m - L_{dec}$ plane (blue curves). The equation of state of the dark energy is fixed to be $w = -1$. The red curve again shows the bound from the quasar spectra, while the black contours show the approximate effective values of the equation of state one would obtain by trying to fit the luminosity-distance curves. We can see that values as low as -1.5 can be obtained for w^{fake}.

To conclude, we have considered the effect of conversion of photons into axions, which evade detection on earth, in a universe dominated by a cosmological constant on the dimming of distant supernovae. The supernovae appear dimmer than they would with a cosmological constant alone, and the effect turns around at redshifts $z > 1$ just like any dark energy, thanks to the saturation of the photon conversion into axions at a third of the initial flux. Therefore the combined effect of conversion of photons into axions and a cosmological constant may appear like a phantom dark energy with $w < -1$ to an observer bent on interpreting the observations of dimming of SNe by dark energy alone. The combination of photon-axion conversion with a cosmological constant also makes it much easier to get within the axion observational bounds, since it reduces the axion contribution relative to the case which we have studied previously, with dark energy obeying $w = -1/3$ [33]. Our model does not involve any ghost-like degrees or freedom, and the Hamiltonian of the system remains bounded from below, guaranteeing vacuum stability. Thus the usual effective field theory in curved space applies and there are no problems with the instabilities plaguing theories with phantoms and (uncondensed) ghosts. We should stress that our mechanism only affects bright sources, and electromagnetic radiation at frequencies above the microwave, and so the observations involving CMB and large scale structure would remain unaffected and fully consistent with cosmological constant as dark energy. This is unlike the attempts to include $w < -1$ impersonators in the gravitational sector, which would affect everything in the same way as long as one maintains the principle of equivalence. Thus any disparity between different observations of the equation of state parameter w could be a very strong signature of our mechanism. Additional signatures were discussed in [33, 35, 39–43], and this host of signals makes the mechanism amenable to verification and constraints. The axions might even lead to super-GZK cosmic rays generated by photon primaries [49]. In light of this we believe that an exploration of ultra-light axion effects in cosmology is a profitable endeavor. Either such axions are really there, and may be within observer's reach, or we may achieve the strongest bounds on the ultra-light axions available today.

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