

# Physics 371, Final Paper

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## **Abstract**

A discussion of the publication *Constraints on supernovae dimming from photon-pseudo scalar coupling* by Yong-Seon Song and Wayne Hu is presented. This paper considers the coupling of the photon to a pseudo scalar field, which in turn provides an alternative mechanism for the observed dimming of high-redshift supernovae.

# 1 Overview

The paper discussed here [1] is yet another response to the extraordinary claim made in 1999 that our universe contains some form of “dark energy” which is causing the expansion of the universe to accelerate. This claim [3] was based on the observation of Type Ia supernovae, which are believed to be standardizable candles. That is, upon observation of a supernova explosion, the absolute luminosity of the explosion may be calculated, within some region of confidence. The claim put forth by the Supernova Cosmology Project in 1999 was based upon the observation of high-redshift supernovae ( $z \geq 1$ ) that were fainter than is to be expected if the universe’s expansion is not accelerating.

Since this outstanding claim was put forth, there have been several attempts to explain the faintness of these supernovae by other means. This is for good reason - the existence of dark energy was not predicted theoretically and still evades a convincing fundamental explanation. Some of the more promising explanations are a pure cosmological constant (with an unnaturally small value), quintessence (a time evolving scalar field), and modifications of general relativity. None of these explanations are entirely satisfactory, so efforts to explain the faint supernova without invoking cosmic acceleration have certainly been reasonable endeavors. The types of alternative mechanisms for the supernova dimming include intergalactic dust, time evolution of supernova-progenitor environments, and gravitational lensing.

Yet another alternative explanation for the supernova dimming is that there may exist a very light ( $m \sim 10^{-16}$  eV), axion-like, pseudo-scalar field which couples to photons. In the presence of an external magnetic field, such a coupling would allow photons to oscillate into the pseudo-scalar field during their transit flight from the origin supernova to observers. The number of photons detected would decrease, and the supernovae would appear fainter. This dimming mechanism was originally proposed in 2002 [2], and the idea has been expanded upon in the last few years [6, 7, 9].

The Song & Hu paper discussed here expands upon the photon-pseudo scalar (p-p) coupling idea. It gives a brief introduction to the history of the p-p coupling idea and its basic role in explaining the dimming of supernovae. Next, a formal treatment of the equations of motion for the pseudo scalar field is presented, along with the modeling of the intergalactic magnetic fields which allow for photon-scalar field conversion. Next, the constraints placed on cosmological parameters (such as  $\Omega_M$  and  $w_\Lambda$ ) with and without p-p couplings are presented. Finally, the additional constraints placed on cosmological parameters by recent CMB acoustic peaks data and large-scale structure (LSS) baryon oscillations data. The paper concludes that, on the

basis of supernovae observations alone, a p-p coupling could explain the data *without* cosmic acceleration. However, when the CMB and LSS data are included, this ambiguity is removed, and a solution without cosmic acceleration does not exist. This combining of supernova data with CMB and LSS data, which in turn forces the existence of an accelerating cosmology (p-p coupling or no p-p coupling) is the most important result of this paper.

## 2 Probing the Expansion History

In order to fully understand the content of the photon-pseudo scalar coupling idea, it will be necessary to understand the supernova observations and what they actually measure. Accordingly, this section will discuss the means by which the observation of supernovae probe the expansion history (and thus matter/energy content) of the universe.

The telescopes which observe the supernovae explosions detect the flux  $F = \frac{\text{energy}}{\text{area} \cdot \text{time}}$  coming from the supernova in some wavelength band. In a Euclidean geometry, this is related to the luminosity  $L$  of the object by

$$F = \frac{L}{4\pi d^2},$$

where  $d$  is the distance to the observer. In a non-Euclidean geometry, this generalizes to

$$F = \frac{L}{4\pi d_L^2},$$

where  $d_L$  is the *luminosity distance*. Supernova experiments measure the flux  $F$  of an object, think that they know the absolute luminosity  $L$  of the object, and can therefore solve for the luminosity distance  $d_L$  of the object. Additionally, the luminosity distance is closely linked to the expansion history of the universe:

$$d_L = \frac{(1+z)H_0^{-1}}{\sqrt{|\Omega_{\kappa 0}|}} S_{\kappa}[\sqrt{|\Omega_{\kappa 0}|} \int_0^z \frac{dz'}{E(z')}].$$

In the case of a spatially flat universe ( $\kappa = 0$ ), as has been strongly suggested by CMB data and is theoretically motivated by inflation, this expression reduces to

$$d_L = (1+z) \int_0^z \frac{dz'}{H(z')}.$$

And of course  $H(z)$  is a function of the matter/energy content of the universe:

$$H^2(z) = \frac{8\pi G}{3} \sum_i \rho_i, \quad i = \text{matter, radiation, } \Lambda, \kappa.$$

Therefore, if one is able to measure the  $d_L$  of an object, as well as its redshift  $z$ , then one can plot  $d_L$  as a function of  $z$ . Because  $d_L(z)$  is directly dependent on the matter/energy content of the universe, this provides a probe on the expansion history of the universe. Supernova searches find the best cosmological fit to the  $d_L(z)$  that they measure (as shown in Figure 1), and in this way measure  $\Omega_m$ ,  $\Omega_\Lambda$  and  $w_\Lambda$ .

### 3 Supernova Technique

Even as early as 1938 [4] it was suggested that supernovae could be used as standard candles to determine distances in our universe. Low-redshift supernovae could be used to determine the recent expansion history (i.e., expansion terms linear in  $z$ , such as  $H_0$ ) and high-redshift supernovae could be used to probe the older expansion history (i.e., higher order expansion terms such as the deceleration parameter). Despite the long history of this idea, it wasn't until the 1980's, when the more homogenous Type Ia supernovae were discovered, that supernovae were used to measure  $H_0$ .

Type Ia supernovae are "standardizable" candles, in the sense that they do not have a single absolute luminosity, but are believed to have a luminosity which is a function only of parameters which we can measure. These other parameters are contained in the duration and shape of the light curve of the supernova explosion. One of the key experimental challenges for these searches was identifying supernovae as they were still brightening, so as to measure the full light curve.

Once the light curve has been measured, the absolute luminosity  $L$ , and thus  $d_L$  has been measured. Next, the redshift  $z$  of the supernova - or, if possible, of the host galaxy - is measure by spectroscopic or photometric means. It is in this way that supernova searches [3, 5] measure  $d_L$ .

As stated previously, the main result of these supernova searches is that the expansion of the universe is accelerating. That is, if one looks back in time (into higher  $z$ ), one will find that  $H(z)$  is smaller than it would be if the Universe were not accelerating. If  $H(z)$  is smaller, then  $d_L$  is larger. If  $d_L$  is larger, then the measured flux  $F$  is smaller. That is, the supernova is fainter at a given  $z$  than would be expected in the absence of cosmic acceleration. This is why dim, high- $z$  supernovae suggest cosmic acceleration.

## 4 Alternative Mechanisms for Dimming

The extraordinary conclusion presented by the supernova data is that we live in a universe which contains a “dark energy” component - some matter/energy component which is causing the cosmic expansion to accelerate. Because there is no satisfactory fundamental explanation for the dark energy, it is very reasonable to look for an explanation for the supernova data which does not require dark energy. Essentially, one needs to explain the reason that high- $z$  supernova appear fainter than is expected in a non-accelerating cosmology. This section reviews some of these alternative mechanisms for supernova dimming.

### 4.1 Extragalactic Extinction

The simplest alternative explanation for the supernova dimming is that there exists an extragalactic dust which absorbs the light as it travels from the supernova to the observer. One such origin of this dust is the metallic vapor [8] thought to be expelled by supernova explosions. This vapor condenses into long (0.5-1 mm) and quite thin ( $10^{-5}$  mm radius) *whiskers*. However, a typical intergalactic dust will generally *redden* the light, such that the color,  $B - V$  of a supernova will change as the extinction of light increases ( $B$  and  $V$  are photometry bands). The conclusion of [3] is that this theory of dimming is inconsistent with observations.

### 4.2 Gravitational Lensing

Another alternative dimming mechanism is the gravitational lensing caused by mass located between the origin supernova and the observer. Due to the clumping of matter, this line-of-sight is typically under-dense; these supernova will appear dimmer than if the matter were more uniformly clumped. Conversely, occasionally the line-of-sight will intersect an over-dense region, and the supernova will appear brighter. With enough observed supernovae, these effects would average out. However, the most over-dense regions might be so rare that a sample of 10's of supernovae, as in [3, 5], may be biased toward measuring the fainter supernovae. This promising idea is probably not the source of dimming though; N-body simulations suggest that gravitational lensing cannot explain the amount of observed dimming.

### 4.3 Supernova Progenitor Evolution

Another explanation of the observed dimming is that the progenitor stars of the supernovae (or the local environment of these stars) is not constant, but evolves with time (with redshift). For example, the metallicity of stars should be lower in high- $z$  stars, and this could affect the spectra and lightcurves of supernovae used to determine  $d_L$ . The changes that progenitor evolution would induce in the supernovae spectra has not been observed however, and progenitor evolution is not believed to be the cause of supernovae dimming.

### 4.4 Photon-Pseudo Scalar Coupling

The last alternative mechanism for supernova dimming mentioned here is the photon-pseudo scalar coupling described earlier. This idea would require the existence of a very light ( $m \sim 10^{-16}$  eV), pseudo-scalar field which couples to photons very weakly ( $\frac{1}{M_{coupling}} \sim \frac{1}{10^{11} GeV}$ ). In the presence of an external magnetic field, this coupling allows for the conversion of photons into the pseudo scalar particle (henceforth denoted by  $\phi$ ). Therefore, as a group of photons travels from a supernova to an observer, some fraction of them may oscillate into  $\phi$ 's and the supernova will appear dimmed. This is the mechanism put forth in 2002 [2] to explain the supernovae dimming.

## 5 Photon-Pseudo Scalar Coupling Theory

The Song & Hu paper considers the following action for the pseudo scalar field  $\phi$  and photons:

$$S = \int d^4x \sqrt{-g} \left[ \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - \frac{1}{2} m^2 \phi^2 - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{\phi}{4M} \tilde{F}_{\mu\nu} F^{\mu\nu} \right],$$

where  $\tilde{F}^{\mu\nu} = \frac{1}{2} \epsilon^{\mu\nu\alpha\beta} F_{\alpha\beta}$ ,  $\epsilon^{\mu\nu\alpha\beta}$  is the Levi-Civita tensor, and  $M$  is the  $M_{coupling}$  mentioned earlier that governs the photon- $\phi$  coupling strength. The  $\partial_\mu \phi \partial^\mu \phi$  and  $m^2 \phi^2$  terms are the kinetic and mass terms for the scalar field, respectively. The  $F_{\mu\nu} F^{\mu\nu}$  term is the standard Lagrangian density of the electromagnetic field. The  $\frac{\phi}{4M} \tilde{F}_{\mu\nu} F^{\mu\nu}$  term provides the interaction between the photon and pseudo scalar field  $\phi$ . The variation of this action produces the equation of motion for  $\phi$ :

$$\frac{\partial^2 \phi}{\partial t^2} - \nabla^2 \phi = -m^2 \phi - \frac{1}{M} \vec{E} \cdot \vec{B}.$$

The contributions to  $\vec{B}$  are the internal magnetic field of the photon and any external magnetic field. The external magnetic field considered here is

the extragalactic magnetic field ( $B \sim 10^{-10}$  Gauss, domain size  $\sim 1$  Mpc) and is assumed to dominate the total  $\vec{B}$ . Because the  $\vec{E} \cdot \vec{B}$  term is responsible for the photon- $\phi$  coupling, only the component of  $\vec{E}$  parallel to the external magnetic field,  $E_{\parallel}$ , is relevant in this discussion. The variation of the action given above leads to the equation of motion for  $E_{\parallel}$ :

$$\frac{\partial^2}{\partial t^2} E_{\parallel} - \nabla^2 E_{\parallel} = \frac{1}{M} \frac{\partial^2 \phi}{\partial t^2} B_{\parallel}.$$

These equations of motions may also be written in matrix form:

$$\left[ \frac{\partial^2}{\partial t^2} + \omega^2 \right] \begin{pmatrix} A_{\parallel} \\ A_{\perp} \\ \phi \end{pmatrix} = \begin{pmatrix} \omega^2 & 0 & \mu\omega \\ 0 & \omega_p^2 & 0 \\ \mu\omega & 0 & m^2 \end{pmatrix} \begin{pmatrix} A_{\parallel} \\ A_{\perp} \\ \phi \end{pmatrix},$$

where the vector potential  $\vec{A} = \vec{E}/\omega$ ,  $\mu = B_{\parallel}/M$ ,  $\omega$  is the frequency of radiation,  $\omega_p$  is the plasma frequency of the intergalactic medium, and  $l$  is the physical distance traveled in each magnetic domain. Note that the off-diagonal terms  $\mu = B_{\parallel}/M$  is responsible for the mixing between the photon and  $\phi$ . If  $B_{\parallel} = 0$  or  $M$  is arbitrarily large, then there is no conversion.

In much the same way that neutrino flavor eigenstates are a mixture of propagation (energy) eigenstates, the ‘‘flavor’’ eigenstates of the photon- $\phi$  coupling are mixtures of propagation eigenstates, which are

$$\begin{pmatrix} \lambda_- \\ \lambda_+ \end{pmatrix} = \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} A_{\parallel} \\ \phi \end{pmatrix},$$

where the ‘‘mixing angle’’  $\theta$  is given as

$$\tan 2\theta = \frac{2\mu\omega}{\omega_p^2 - m^2}.$$

Once again, if  $\mu = B_{\parallel}/M = 0$ , then there is no mixing.

As an aside, note that because  $E_{\parallel}$  couples to  $B$  and  $E_{\perp}$  does not, the photon- $\phi$  coupling will change the polarization of the photon. Because the orientation of extragalactic magnetic fields are expected to be random, there is no reason to expect that this effect will induce a net polarization in the light coming from a distant source. In fact, the photon- $\phi$  coupling will depolarize the light coming from distant, partially-polarized sources. A photon converts to a  $\phi$  in one magnetic field domain and then regenerates into a photon in another magnetic field domain which has a different  $\vec{B}$  orientation, thus destroying the polarization information of the light.

## 6 Modeling

The paper by Song & Hu presents its own modeling of photon- $\phi$  conversion. The model universe is divided up into domains of size  $\sim 1$  Mpc which have fixed magnetic fields with  $B \sim 10^{-10}$  Gauss. The probability for a  $||$ -polarized photon to  $\phi$  conversion as the photon passes through one domain is

$$P_{\gamma \rightarrow \phi} = \sin^2 2\theta \sin^2 \left[ s \frac{\sqrt{(\omega_p^2 - m^2)^2 + 4\mu^2 \omega^2}}{4\omega} \right]$$

where  $s$  is the size of the magnetic field domain. The need to include the effect of the finite plasma frequency of the intergalactic medium was suggested by [6]. As a reminder, electromagnetic waves cannot propagate through an electron gas if  $\omega < \omega_p = \sqrt{\frac{4}{\pi} n_e e^2 m_e}$ . Song & Hu make the assumption that  $\omega_p \gg m$ .

The next step is to evolve the photons through the different magnetic domains. It is assumed that the direction and magnitude of the extragalactic magnetic field  $\vec{B}$  is constant while the photons traverse that domain. The model does take into consideration the expansion of universe (which is driven by whichever cosmology is being simulated) such that the plasma frequency must scale with the scale factor  $a$ :

$$\omega_p = 1.2 * 10^{-14} \left( \frac{n_{e0}}{10^{-7} \text{cm}^{-3}} \right)^{1/2} a^{-3/2} \text{eV},$$

where  $n_{e0}$  is the extragalactic free electron density today. Note that this  $a^{-3/2}$  scaling is reasonable since  $\omega_p \sim n_e^{1/2} \sim (n_{e0} a^{-3})^{1/2} \sim a^{-3/2}$ .

The spatially oscillating part of the above conversion probability  $P_{\gamma \rightarrow \phi}$  is averaged to  $1/2$  if the requirement  $s \gg l_p$  is met, where the ‘‘plasma length’’  $l_p = 2\omega/\omega_p^2$ . These supernova searches are conducted in the optical frequencies, for which  $\omega \sim 1$  eV, and  $l_p \sim 100$  kpc. Because  $s \sim$  a few Mpc, the  $s \gg l_p$  condition will be met, and the spatial oscillating term averages to  $1/2$ , and

$$P_{\gamma \rightarrow \phi} = \frac{1}{2} \sin^2 2\theta.$$

Note that this conversion probability is achromatic, as would be required for the frequency-independent dimming of high-redshift supernovae. The populations of photons and  $\phi$ 's are kept track of by means of a density matrix, with the initial density matrix (at the supernova) given by

$$S_o^{ab}(s_0) = \begin{pmatrix} \frac{1}{2} & 0 & 0 \\ 0 & \frac{1}{2} & 0 \\ 0 & 0 & 0 \end{pmatrix},$$

where, for  $S_i^{ab}(l)$ ,  $a$  and  $b$  denote the components ( $\parallel, \perp, \phi$ ),  $i$  denotes the  $i^{\text{th}}$  magnetic field domain, and  $l$  denotes the location within the domain. The total conversion probability is then

$$P_{\gamma \rightarrow \phi} = S_{i=D(z)f/S}^{\phi\phi}(s),$$

where  $f$  is the one-dimensional fraction of the magnetic field domain between the observer, and  $D(z)$  is the comoving distance to the source supernova. The total conversion probability is a function of  $\mu f$ , and conversion probabilities for different values of  $\mu f$  are shown in Figure 2.

## 7 Results

The results of the Song & Hu paper are the constraints placed on cosmological parameters by supernova, CMB, and LSS data, with and without pseudo scalar dimming. The constraints placed on  $\Omega_m$  and  $w$  are shown in Figure 3. The constraints placed by supernova (SN), CMB and LSS data are shown, with and without photon-pseudo scalar dimming. The most obvious result of photon-pseudo scalar dimming is the relaxed constrained parameter space of the SN data. The joint constraint produced by including CMB and LSS data *without* p-p dimming very slightly favors a  $w < -1$  dark energy, as shown in the left panel of Figure 3. As pointed out in Reference [9], if the dark energy is a pure cosmological constant ( $w = -1$ ), then the existence of photon-pseudo scalar coupling can bias the measurement of  $w$  to be more negative. That is, a “phantom” dark energy ( $w < -1$ ) might be inferred from a  $w = 1$  dark energy, if we are ignorant of a photon-pseudo scalar coupling which is dimming the supernova.

Figure 4 shows the constraints placed on the  $w - \mu$  parameter space ( $f$  has been fixed at  $2/3$ ). These panels most directly shows the impact of a p-p dimming. Without p-p dimming ( $\mu = 0$ ),  $w < -1$ . As the p-p dimming is allowed to be turned on ( $\mu > 0$ ), the most preferred value of  $w$  drifts to  $\sim -0.5$ . Interestingly, when the SN data is combined with the CMB and LSS data (top right panel), two “discrete” solutions exist: one solution with no p-p dimming and a cosmological constant ( $\mu \simeq 0$ ,  $w \simeq -1$ ) and one solution with significant dimming and a non-cosmological constant dark

energy ( $w \simeq -0.7$ ). Note that this non-cosmological constant solution still produces cosmic acceleration, because  $w < -\frac{1}{3}$ . This is the most significant result of this paper: on the basis of SN data alone, solutions exist which have p-p dimming and a non-accelerating cosmology, but the addition of CMB and LSS data removes the possibility of a non-accelerating cosmology. In short, photon-pseudo scalar coupling cannot make the observed cosmic acceleration go away.

## 8 Conclusions

The claim that our universe contains a dark energy component is largely based upon the observation of faint, high-redshift supernovae. The Song & Hu paper builds on the idea that a photon-pseudo scalar coupling can dim these supernovae and fake a cosmic acceleration. The paper models the conversion of photons into pseudo scalar particles as they traverse intergalactic magnetic field domains on their way to the observer. The most important result of the paper is that the addition of CMB and LSS data to the SN data eliminates the possibility of a non-accelerating universe faking an accelerating universe by means of the photon-pseudo scalar dimming.

## References

- [1] Y.-S. Song and W. Hu, astro-ph/0508002.
- [2] C. Csaki, N. Kaloper, and J. Terning, Phys. Rev. Lett. 88, 161302 (2002), hep-ph/0111311
- [3] S. Perlmutter et al. (Supernova Cosmology Project), Astrophys. J. 517, 565 (1999), astro-ph/9812133.
- [4] W. Baade, Astrophys. J. 88, 285.
- [5] A. G. Riess et al. (Supernova Search Team), Astrophys. J. 607, 665 (2004), astro-ph/0402512.
- [6] C. Deffayet, D. Harari, J.-P. Uzan, and M. Zaldarriaga, Phys. Rev. D66, 043517 (2002), hep-ph/0112118.
- [7] E. Mortsell, L. Bergstrom, and A. Goobar, Phys. Rev. D66, 047702 (2002), astro-ph/0202153.
- [8] R. G. Vishwakarma, astro-ph/0506217

- [9] C. Csaki, N. Kaloper, and J. Terning, *Ann. Phys.* 317, 410 (2005), [astro-ph/0404062](#).

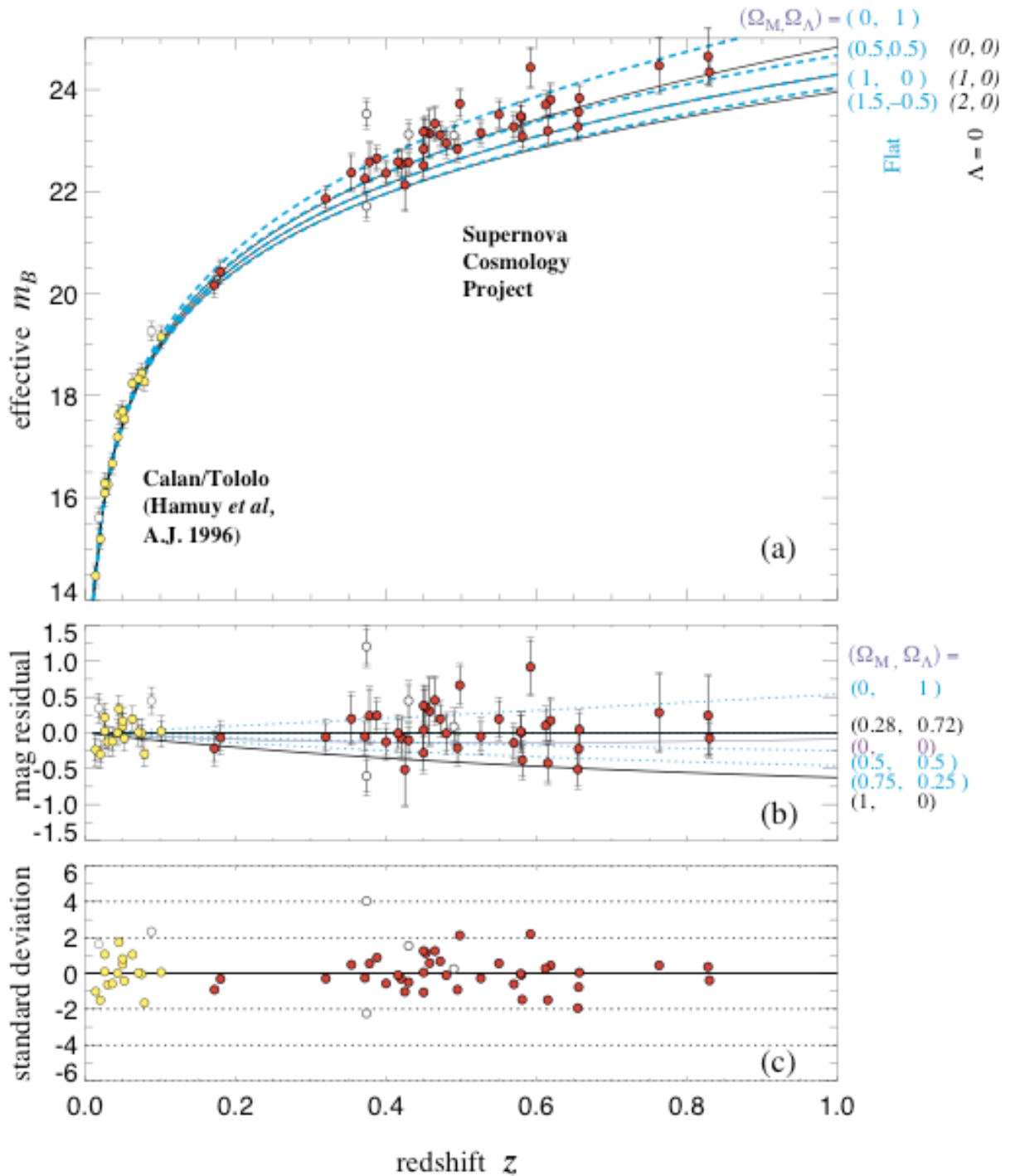


Figure 1: The magnitude  $m_B$  (which is related to the luminosity distance  $d_L$ ) versus the redshift  $z$  of distant supernovae. The faint supernovae at high redshift provide evidence for an accelerating cosmology. Figure taken directly from Reference [3]

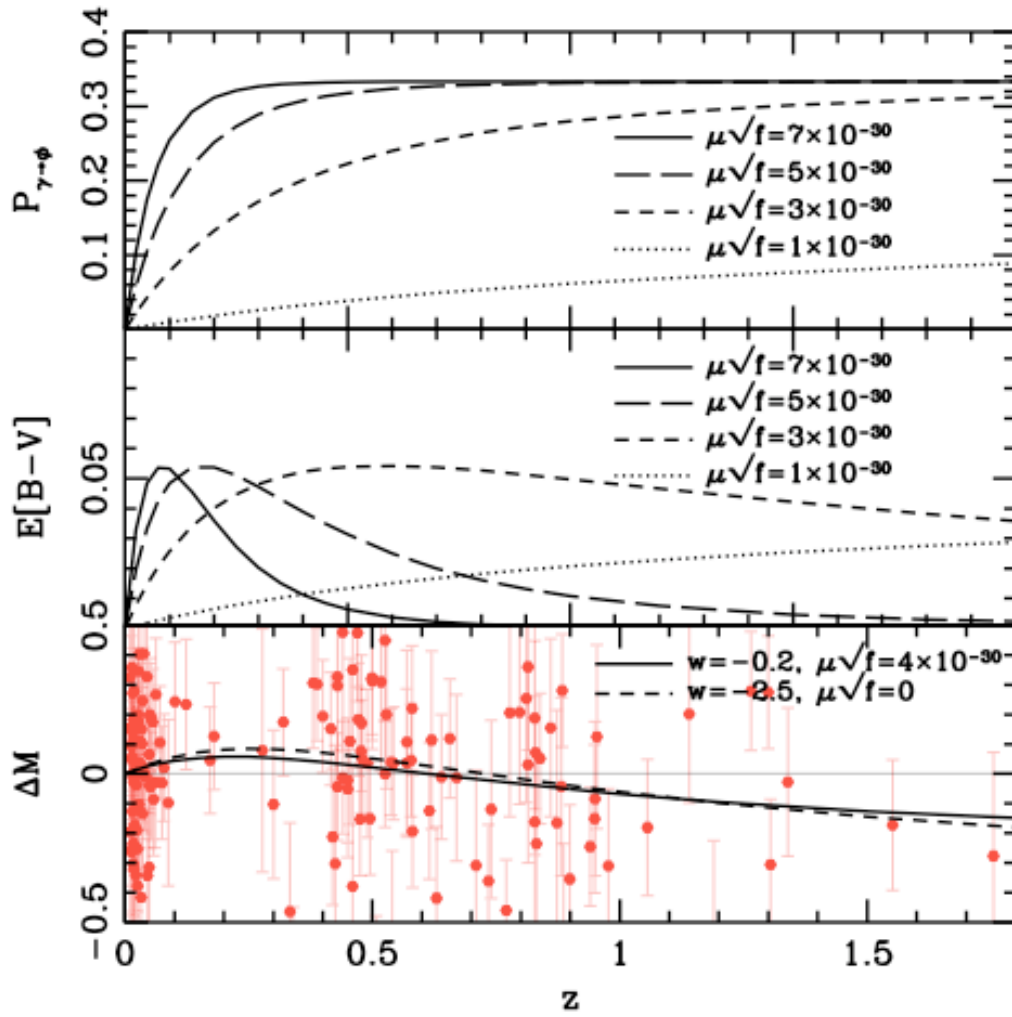


Figure 2: The conversion probability as a function of  $z$  for different values of  $\mu f$ . Also shown are the closely related color  $E[B - V]$  and change in magnitude  $\Delta M$ . Figure taken directly from Reference [1]

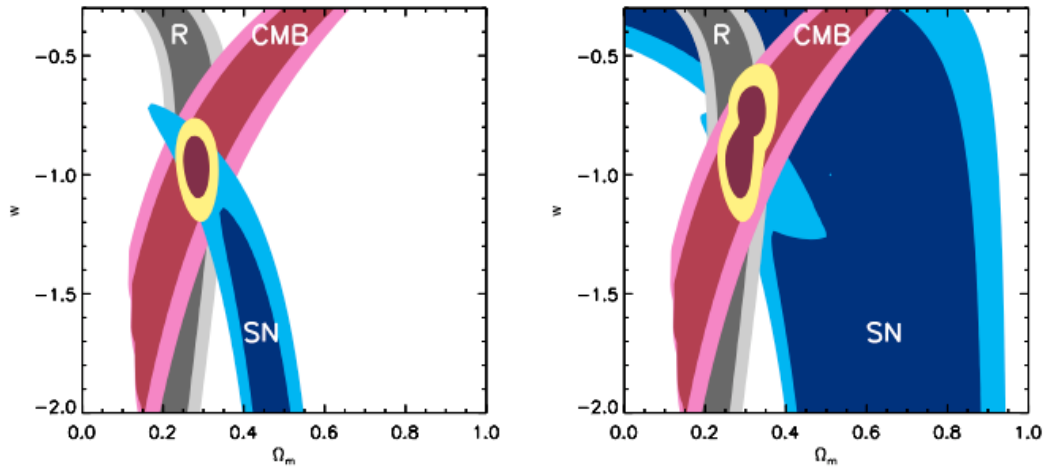


Figure 3:  $\Omega_m - w$  constraints at the 68%, 95%, and 99% confidence levels, with different sets of data placing the constraints. The left and right figures show constraints with and without photon-pseudo scalar conversion, respectively. The inclusion of photon-pseudo conversion relaxes the supernova constraints significantly. Figure taken directly from Reference [1]

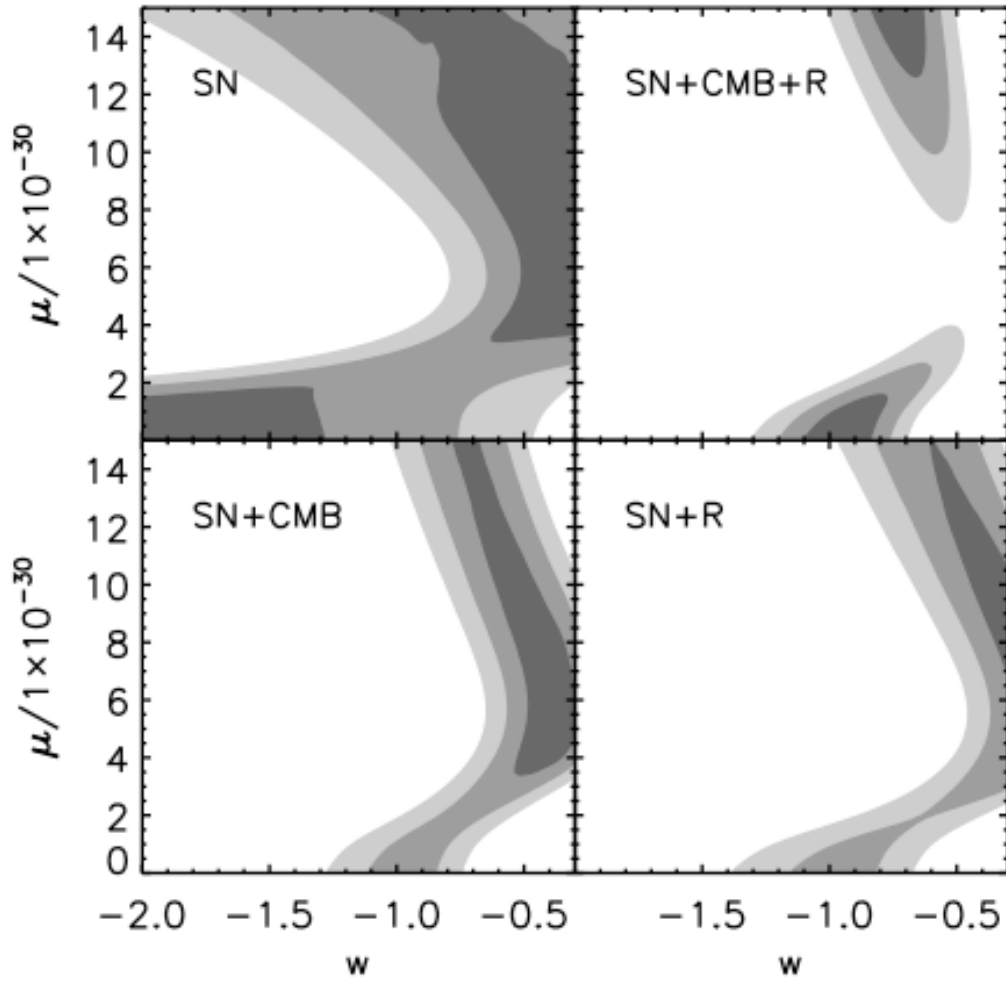


Figure 4:  $w - \mu$  constraints at the 68%, 95%, and 99% confidence levels, with different sets of data placing the constraints in the four different panels. Figure taken directly from Reference [1]