

A Comparison of Local SNIa with the IRAS PSCz Gravity Field

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ABSTRACT

We compare the measured peculiar velocities of 98 local ($< 150 h^{-1}$ Mpc) type Ia supernovae with predictions derived from the PSCz survey. There is excellent agreement between the two datasets with a best fit $\beta_I (= \Omega_m^{0.6}/b_I)$ of 0.55 ± 0.06 . Subsets of the supernovae dataset are further analysed and the above result is found to be robust with respect to culls by distance, host-galaxy extinction and to the choice of reference frame in which the analysis is carried out. Alternative methods of determining β_I including density-density comparisons, dipole measurements and WMAP-based results are also discussed. We conclude that most recent determinations are consistent with a value of $\beta_I = 0.5$.

Key words: cosmology: observations – cosmological parameters – dark matter – galaxies: distances and redshifts – large-scale structure of Universe

1 INTRODUCTION

Peculiar motion studies are a powerful tool for examining the underlying mass distribution of the local universe. In the linear regime, where density fluctuations are small, the mass over-density, δ_m , can be related to the fluctuation in galaxy number-density, δ_g , via $\delta_g(r) = b\delta_m(r)$ where b is the linear bias parameter. This bias parameter together with the cosmological mass density parameter, Ω_m , can be used to predict peculiar velocity fields from all-sky redshift surveys via the equation

$$\mathbf{v}(\mathbf{r}) = \frac{\beta}{4\pi} \int \delta_g(\mathbf{r}') \frac{\mathbf{r}' - \mathbf{r}}{|\mathbf{r}' - \mathbf{r}|^3} d^3\mathbf{r}' \quad (1)$$

The dimensionless quantity $\beta (= \Omega_m^{0.6}/b)$ scales linearly with the predicted velocities and is the only free parameter of the model (Peebles 1980). Hence β can be directly determined from the comparison of measured peculiar motions with predictions made from galaxy density fields.

All-sky galaxy samples derived from *IRAS* satellite data have been used extensively to map the local density field. Currently the most complete redshift survey of *IRAS* sources is provided by the PSCz (Saunders et al. 2000b). This survey consists of redshifts for 15,411 galaxies uniformly distributed over 84.1% of the sky with a median redshift of 8500 km s^{-1} . The PSCz survey's depth, excellent sky coverage and density allow for the reliable mapping of the distribution of galaxies in the local universe. Several independent determinations of the PSCz density and velocity fields have therefore been made; most notably by Branchini et al.

(1999), Schmoldt et al. (1999) and Rowan-Robinson et al. (2000). Recent comparisons of these fields with peculiar velocity measurements typically yield values of β_I in the range 0.4 - 0.6 (see Zaroubi 2002).

A significant source of error in determining β arises from the uncertainty in the peculiar velocity measurements. Galaxy distance estimates from the Tully-Fisher and Fundamental Plane relations are subject to errors that are typically $\sim 20\%$ per galaxy. At depths greater than $\sim 50 h^{-1}$ Mpc this is considerably larger than the peculiar velocities of the individual galaxies. With distance errors less than 10%, Type Ia supernovae (SNIa) are less susceptible to inhomogeneous Malmquist bias (Hudson 1994a) and hence offer an important alternative probe of the local velocity field. An early attempt to use SNIa was carried out by Riess et al. (1997) who compared the peculiar velocities of 24 SNIa with the velocity fields predicted from the 1.2 Jy *IRAS* redshift survey (Fisher et al. 1995) and the Optical Redshift Survey (Santiago et al. 1995; Baker et al. 1998). They derived $\beta_I = 0.4 \pm 0.15$ and $\beta_O = 0.3 \pm 0.1$ respectively, with the relatively large error resulting from the small sample size.

Tonry et al. (2003) have recently produced a homogenized compendium of 230 SNIa for constraining cosmological quantities. The release of this compendium presents a new opportunity to measure β with a significantly smaller error. In this paper we compare peculiar velocities measured by the local SNIa in the Tonry et al. (2003) sample to the peculiar velocity field derived from the smoothed PSCz density field as determined by Branchini et al. (1999).

We briefly describe the Tonry et al. (2003) compilation of SNIa in Section 2 and review the derivation of the PSCz velocity field in Section 3. In Section 4 we describe the derivation of β_I . The robustness of this result is analysed in Section 5 and finally, in Section 6 we discuss the results and present our conclusions.

2 THE SNIa DATASET

The Tonry et al. (2003) dataset is a homogenized compendium of 230 SNIa compiled from many recent studies. Most notably from the Jha (2002), Perlmutter et al. (1999), Hamuy et al. (1996), Riess et al. (1999) and Germany et al. (2004) datasets, which comprise the majority of the data. Using a variety of fitting techniques such as MLCS (Riess et al. 1998 and the work of Jha and collaborators) and dm15 (Germany 2001), Tonry et al. (2003) have re-calculated the relative SNIa distances where the original photometric data is available. The systematic offsets of each dataset were reduced by minimising the differences between all pairs of datasets where overlaps exist. The residuals of this fitting procedure are 0.02 mag or better for the majority of the samples. Table 15 of Tonry et al. (2003) lists the redshift ($\log cz$), luminosity distance ($\log dH_0$), distance error and host galaxy V -band extinction (A_V) for each SNIa.

Tonry et al. (2003) fix the zero point of nearby SNIa ($0.01 < z < 0.1$) by assuming an ‘empty universe’ ($\Omega_m = 0, \Omega_\Lambda = 0$) cosmology. For our analysis, we have converted the Tonry et al. (2003) quoted distances to a Λ CDM cosmology ($\Omega_\Lambda = 0.7, \Omega_m = 0.3$). However, the derived β_I is unaffected by the choice of cosmology.

In this paper we only consider the 107 SNIa that lie within $150 h^{-1}$ Mpc as the PSCz density field is incomplete at greater distances for all galactic latitudes (Branchini et al. 1999). We further restrict the sample to SNIa with extinctions $A_V < 1.0$ mags, for reasons discussed below. These selection criteria leave 98 SNIa, which we refer to as the “default sample”. The median distance error for this local SNIa sample is $\sim 8\%$.

3 THE PSCZ VELOCITY FIELD MODEL

Branchini et al. (1999) used the PSCz redshift survey to determine the density and peculiar velocity fields in real space in a self-consistent way by using equation (1) under the assumption that mass follows the number density of *IRAS* galaxies. These fields are smoothed with a Gaussian filter of radius $5 h^{-1}$ Mpc. Analysis by Berlind, Narayanan & Weinberg (2000) indicates that this smoothing radius should yield unbiased results for β_I . In an independent analysis, Schmoldt et al. (1999) derived the PSCz velocity and density fields by using a Fourier-Bessel approach. They found the resulting fields to be consistent with the Branchini et al. (1999) fields used here.

The integral in equation (1) extends over all space. The PSCz survey, however, does not extend to infinite depth, nor does it have data in the Zone of Avoidance (ZoA). For the ZoA, Branchini et al. (1999) have implemented a similar approach to that of Yahil et al. (1991) by dividing the region ($|b| \leq 8^\circ$) into bins of 10° latitude by 1000 km s^{-1} .

These bins are then populated with enough synthetic galaxies to reflect the number density of the corresponding bins at greater $|b|$. The systematic effect on the derived value of β_I due to this interpolation procedure can be estimated from the results of Hudson (1994b). He compared β values derived from an optically-selected density field with a larger ZoA ($|b| \leq 12^\circ$) using different techniques to account for the missing structure. Only an 8% difference was observed between the β value derived from the interpolated density field and that derived from a density field in which the ZoA was assumed to be at average density. Since the average density assumption is rather extreme, this result may be taken as an upper limit on the systematic uncertainty. Therefore, as the PSCz ZoA is only two-thirds the thickness of this ZoA, we might expect a systematic uncertainty on our result of the order 5%. This is considerably smaller than our random errors.

As stated previously we have truncated the PSCz velocity field at $150 h^{-1}$ Mpc due to increasing shot noise. Sources beyond this depth, however, may still contribute to the LG’s motion. Because the statistical weight of the SNIa sample is dominated by nearby objects these external contributions can be modelled as a dipole term. For peculiar velocity comparisons in the LG frame this dipole term cancels out as the motions of the LG and SNIa are affected in the same way. LG-frame comparisons assume, however, that the LG’s motion is exactly given by linear theory. In practice, the LG is expected to exhibit a nonlinear ‘thermal’ component to its velocity that is not well modelled by linear theory. An alternative to the LG-frame comparison is to omit the LG from the analysis entirely. This can be achieved by fitting the SNIa peculiar velocities in the CMB frame with an additional dipole component to allow for contributions not included in the PSCz density field. Ideally, analyses in both these frames should produce similar results. However, due to the larger uncertainty in the CMB analysis, we regard the LG result as a more reliable solution.

4 DETERMINING β_I

There is a very good agreement between the peculiar velocities measured by the SNIa and predicted from the PSCz. This is shown in Fig. 1 where the scatter around the Hubble flow before and after the PSCz velocities for $\beta_I = 0.5$ are removed. In the range $20 - 80 h^{-1}$ Mpc, where the majority of SNIa lie, the removal of the predicted PSCz peculiar velocities reduces the rms scatter around the Hubble flow from 490 km s^{-1} to 390 km s^{-1} . In Fig. 1, nine SNIa with $A_V > 1.0$ are plotted as open circles, three of which are distinct outliers. In our analysis we have chosen to exclude these objects because we expect that their errors are underestimated.

To determine β_I in the LG frame we minimise the χ^2 relation:

$$\chi^2 = \sum_i \left(\frac{(v_{i,PSCz} - v_{i,SN})^2}{\sigma_{i,cz}^2 + \sigma_{i,d}^2} \right) \quad (2)$$

where v_i is the peculiar velocity of the i^{th} supernova, $v_{i,PSCz}$ is the PSCz-predicted peculiar velocity which depends on β_I from (1), σ_d is the distance error and σ_{cz} incorporates both

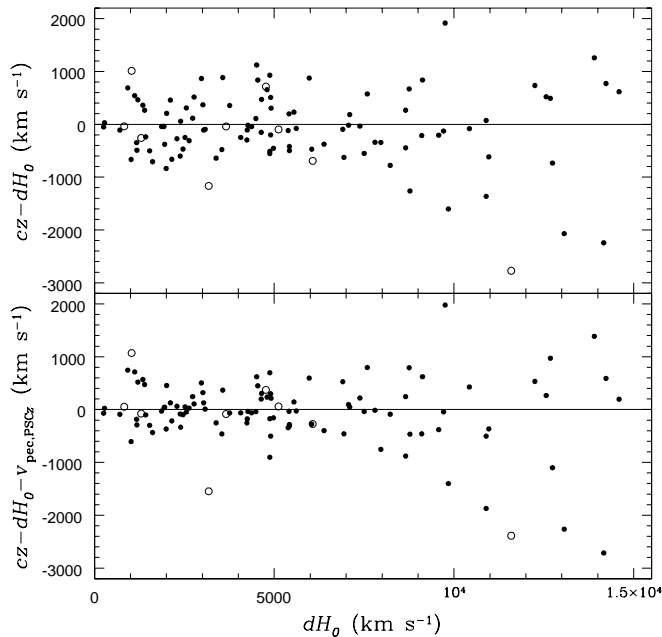


Figure 1. The Hubble flow residuals for all 107 SNIa lying within $150 h^{-1}$ Mpc in the LG frame. The upper panel shows the original uncorrected data whilst the lower shows the data with the predicted PSCz peculiar velocities removed. Note the reduction in scatter, particularly in the distance range $20\text{--}80 h^{-1}$ Mpc. SNIa with host-galaxy extinctions $A_V \geq 1.0$ are plotted as open circles whilst filled circles show the default sample used in this paper.

an estimate of the error in redshift determination as well as errors in the PSCz predictions due to shot noise or non-linear peculiar velocity contributions.

Various studies have adopted different schemes for σ_{cz} . Riess et al. (1997), adopt a value of 200 km s^{-1} for all the SNIa, whilst Blakeslee et al. (1999) use values of 150 km s^{-1} and 200 km s^{-1} . However Blakeslee et al. (1999) also account for the extra velocity dispersion of cluster galaxies using two different approaches. Their ‘Trial 1’ method adds in quadrature an extra factor of $\sigma_{cl}(r) = \sigma_0/\sqrt{1+(r/r_0)^2}$ to σ_{cz} where $\sigma_0 = 700$ (400) km s^{-1} and $r_0 = 2$ (1) Mpc for galaxies in Virgo (Fornax). Their ‘Trial 2’ scheme uses the standard σ_{cz} but resets the individual galaxy velocities for group members to the group-average velocities as listed in Tonry et al. (1997) for 37 separate clusters. In our analysis we extended both these techniques to account for galaxies which lie near one of the X-ray selected clusters of the NOAO fundamental plane survey (Smith et al. 2004).

Table 1 lists the derived β_I values for these different weightings for our default sample. The 1σ quoted errors are calculated from bootstrap re-samples of the dataset. If the nine $A_V > 1.0$ SNIa had not been removed, the resulting χ^2 would be larger by ~ 40 .

Increasing the redshift error σ_{cz} for SNIa lying close to nearby clusters has a sizeable effect on the χ^2 but appears to have no significant effect on the value of β_I . Overall, little variation from the preferred value of $\beta_I = 0.55 \pm 0.06$ is observed and β_I is effectively independent of the weighting schemes used.

Table 1. ‘Redshift error’, σ_{cz} , comparison for the default sample of 98 SNIa in the LG frame. The errors have been determined from the 1σ deviation in the distribution of the medians of 1000 bootstrap re-samples.

σ_{cz}^2 ($\text{km}^2 \text{ s}^{-2}$)	β_I	χ^2
150^2	0.55 ± 0.06	167
200^2	0.54 ± 0.06	131
$150^2 + \sigma_{cl}^2$ ‘Trial 1’	0.55 ± 0.06	98
$200^2 + \sigma_{cl}^2$ ‘Trial 1’	0.54 ± 0.06	89
150^2 ‘Trial 2’	0.57 ± 0.05	97
200^2 ‘Trial 2’	0.57 ± 0.06	88

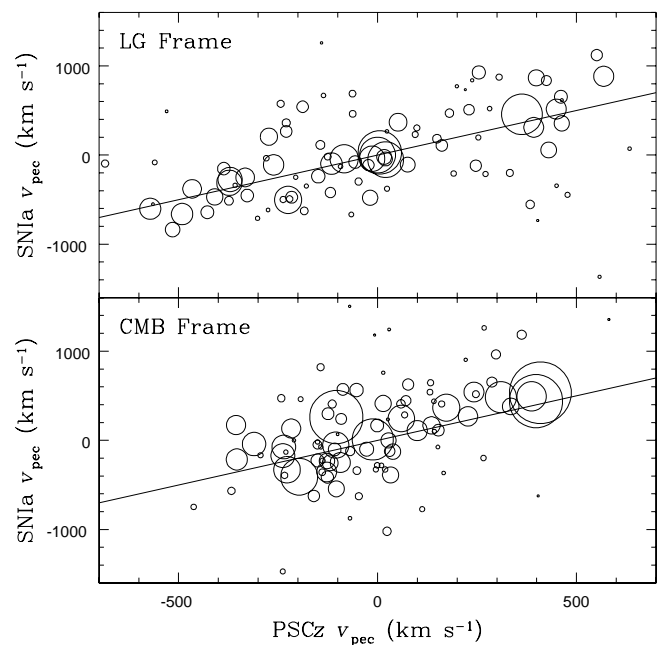


Figure 2. Comparison of SNIa peculiar velocities to PSCz predicted peculiar velocities in the range $0 h^{-1}$ Mpc to $150 h^{-1}$ Mpc with $A_V < 1.0$, $\sigma_{cz}^2 = 150^2 + \sigma_{cl}^2$ and $\beta = 0.55$. The top panel shows comparisons in the LG frame, and the bottom panel shows the comparison in the CMB frame (without the extra dipole component). The size of the data point is inversely proportional to the total error ($\sigma = \sqrt{\sigma_d^2 + \sigma_{cz}^2}$) on each SNIa. The smallest and largest circles correspond to values of $\sigma = 1290 \text{ km s}^{-1}$ and 170 km s^{-1} respectively. The lines indicate a 1:1 ratio.

In order to determine β_I in the CMB frame an extra dipole component is added as an extra free parameter in the minimization of equation (2). Using the default sample with σ_{cz} given by ‘Trial 1’ as $\sqrt{150^2 + \sigma_{cl}^2}$, the best fit has $\beta_I = 0.48 \pm 0.09$ and $V_{dipole} = 206 \pm 97 \text{ km s}^{-1}$ towards $l = 290^\circ \pm 25^\circ$, $b = 0^\circ \pm 18^\circ$. This extra dipole component is consistent with zero but is also consistent with the value of $V_{dipole} = 372 \pm 127 \text{ km s}^{-1}$ towards $l = 273^\circ \pm 17^\circ$, $b = 6^\circ \pm 15^\circ$ as found by Hudson et al. (2004) for the SMAC sample. The calculated value of β_I agrees well with the result derived in the LG frame.

The good agreement between the observed and pre-

dicted peculiar velocities in both the LG and CMB frames is shown in Fig. 2. If the peculiar velocities predicted by the PSCz and observed from the SNIa are in exact agreement for the chosen value of β_I , the SNIa would be expected to lie along the 1:1 line. This trend is indeed observed. The differences between the measured and predicted velocities are as expected given the errors in both distance and velocity measurements, i.e. the data is consistent with a reduced χ^2_ν of ~ 1 . Thus the two datasets agree exceptionally well.

5 ROBUSTNESS

To assess the robustness of the derived β_I we have examined various sub-samples of the local SNIa dataset. Unless otherwise stated all sub-samples use our default sample in the LG frame with $\sigma_{cz} = \sqrt{150^2 + \sigma_{cl}^2}$ determined using the ‘Trial 1’ approach. Table 2 lists the best fit β_I together with the associated χ^2 for each sub-sample.

Importantly, β_I is found to be independent of the distance range considered. Any derivation of β is expected to be strongly weighted by the very nearby SNIa where measurement errors are smallest. Hence we have tested the dependency of our calculations on SNIa at different distances by dividing the data into two distance ranges. The position of this division is chosen such that the bootstrap errors on each derived β_I are of similar magnitude. For a distance range of $0 - 30 h^{-1}$ Mpc we derive a value of $\beta_I = 0.55 \pm 0.07$ and for $30 - 150 h^{-1}$ Mpc, $\beta_I = 0.54 \pm 0.10$. Table 2 also includes a variety of different distance ranges all of which yield similar values of β_I ($0.49 < \beta < 0.58$).

The determination of β_I is also revealed to be independent of the cull by host-galaxy extinction with β_I varying by only ± 0.05 for culls down to $A_V < 0.3$. It is found that the reduced χ^2_ν is ~ 1 for all culls of host-galaxy extinction < 1.0 . Overall, for all the sub-samples considered, β_I is found to range by only 0.10.

Another source of bias which we do not account for in our analysis is inhomogeneous Malmquist bias. Generally, not correcting for this will lead to higher values of β . However, this bias scales with the square of the distance error. Thus for the SNIa sample used here we expect this bias to be considerably smaller than the random error in β_I .

6 DISCUSSION

Table 3 lists a representative set of recent determinations of β_I from comparisons of predicted and observed peculiar velocities. Previously, the tightest constraints on β_I were from the merged spiral and elliptical peculiar velocity samples such as Mark III (Willick et al. 1997) and SECat (Zaroubi 2000) as well as the SBF sample of Tonry et al. (1997). This work adds a result from local SNIa, a fourth independent data source of comparable statistical power. Recent comparisons of predicted and observed peculiar velocities (‘velocity-velocity’), including the result presented here, all yield results consistent with a value of $\beta_I = 0.5$.

Some of the earliest estimates of β were obtained by matching the gravity at the LG to the measured CMB dipole. While the LG has the most accurate observed CMB-frame velocity, a weakness of this method is that one needs

to integrate the density field over all space to obtain the predicted gravity at the LG. This contrasts with the velocity-velocity comparison performed above in which large-scale contributions to the predicted peculiar velocities either drop out of the analysis (if the fits are performed in the LG frame) or can be fitted independently of β (if the fits are performed in the CMB-frame). This degeneracy cannot be broken when using the LG alone as one would be attempting to fit 4 parameters (β and three components of an external dipole) to 3 degrees of freedom (the Cartesian components of the LG’s CMB-frame motion). Consequently, in order to apply this method one needs either a deep, full-sky redshift survey (so that the external dipole is known to be zero) or, failing that, accurate estimates of the uncertainties arising from shot noise at large distances and from incompleteness in the ZoA. As an example of the latter, Hudson et al. (2004) have suggested, based on the ‘Behind the Plane’ extension of the PSCz (Saunders et al. 2000a), that additional structure in the ZoA beyond $100 h^{-1}$ Mpc may increase the PSCz dipole by $\sim (170 \pm 85) \text{ km s}^{-1}$. Until these issues are fully resolved, β determinations by this method remain subject to larger systematic errors than velocity-velocity comparisons.

It is also possible to estimate β by comparing the density field inferred from redshift surveys, to the mass density field constructed from peculiar velocity data. Such comparisons are difficult because the mass density field is based on an inversion of sparse and noisy peculiar velocity samples. The POTENT reconstruction of the Mark III catalogue by Sigad et al. (1998) yields $\beta_I = 0.89 \pm 0.12$. However, a new improved inversion method based on an unbiased variant of the Weiner filter (Zaroubi et al. 2002) finds $\beta_I = 0.57 \pm 0.12$, in good agreement with the velocity-velocity results.

An alternative estimate of β_I can be obtained from other independent analyses not directly based on peculiar motion studies. One noteworthy route is via the combination of parameters: $\Omega_m^{0.6} \sigma_8$, where σ_8 is the rms amplitude of mass fluctuations, δ_m , averaged within a top-hat sphere of $8 h^{-1}$ Mpc radius. This combination may be related to β_I by the dependence of $\sigma_{8,I}$, the number density fluctuation of *IRAS* galaxies, on the bias parameter b_I . Since we are assuming linear biasing, $\delta_I = b_I \delta_m$ and it follows that $\sigma_{8,I} = b_I \sigma_8$. We can thus write:

$$\beta_I = \frac{\Omega_m^{0.6}}{b_I} = \frac{\Omega_m^{0.6} \sigma_8}{\sigma_{8,I}}$$

Spergel et al. (2003) have used data from WMAP and other CMB and non-CMB sources to derive a value of $\Omega_m^{0.6} \sigma_8 = 0.38^{+0.04}_{-0.05}$. By directly integrating the PSCz power spectrum Hamilton & Tegmark (2002) found $\sigma_{8,I} = 0.80 \pm 0.05$. Combining these two results gives $\beta_I = 0.48 \pm 0.06$. The good agreement of the results from all these methods suggests that β_I is now known at the 10% level.

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Table 2. β_I dependency on sampling

Sample	No. SNIa	β_I	Total χ^2_{min}
$0 h^{-1}$ Mpc < distance < $150 h^{-1}$ Mpc	98	0.55 ± 0.06	98
$0 h^{-1}$ Mpc < distance < $30 h^{-1}$ Mpc	31	0.55 ± 0.07	26
$30 h^{-1}$ Mpc < distance < $150 h^{-1}$ Mpc	67	0.54 ± 0.10	74
$20 h^{-1}$ Mpc < distance < $150 h^{-1}$ Mpc	80	0.55 ± 0.07	84
$40 h^{-1}$ Mpc < distance < $150 h^{-1}$ Mpc	60	0.49 ± 0.13	67
$0 h^{-1}$ Mpc < distance < $100 h^{-1}$ Mpc	85	0.58 ± 0.06	78
$0 h^{-1}$ Mpc < distance < $125 h^{-1}$ Mpc	90	0.56 ± 0.06	84
No A_V cull	107	0.50 ± 0.08	141
$A_V < 0.5$	80	0.57 ± 0.06	79
$A_V < 0.3$	58	0.57 ± 0.08	57
CMB frame + dipole	98	0.48 ± 0.09	98

Table 3. Recent determinations of β_I from velocity-velocity comparisons

Comparison	β_I	Reference
Mark III vs. IRAS 1.2 Jy	0.50 ± 0.10	Davis et al. (1996)
SNIa vs. IRAS 1.2 Jy	0.40 ± 0.15	Riess et al. (1997)
SBF vs. IRAS 1.2 Jy	$0.42^{+0.10}_{-0.06}$	Blakeslee et al. (1999)
Mark III vs. IRAS 1.2 Jy	0.50 ± 0.04	Willick & Strauss (1998)
Mark III vs. PSCz	0.60 ± 0.10	Saunders et al. (1999)
ENEAR vs. PSCz	0.50 ± 0.10	Nusser et al. (2001)
SFI vs. PSCz	0.42 ± 0.04	Branchini et al. (2001)
SEcat vs. PSCz	0.51 ± 0.06	Zaroubi et al. (2002)
SNIa vs. PSCz	0.55 ± 0.06	This Study

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