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MODELLING THE RELATIVE VELOCITIES OF ISOLATED PAIRS OF GALAXIES

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Abstract. We study the comoving relative velocities, v_{12}, of model isolated galaxy pairs at $z = 0.5$. For this purpose, we use the predictions from the GALFORM semi-analytical model of galaxy formation and evolution based on a Λ cold dark matter cosmology consistent with the results from WMAP7. In real space, we find that isolated pairs of galaxies are predicted to form an angle t with the line-of-sight that is uniformly distributed as expected if the Universe is homogeneous and isotropic. We also find that isolated pairs of galaxies separated by a comoving distance between 1 and 3 h^{-1}Mpc are predicted to have $\langle v_{12} \rangle \sim 0$. For galaxies in this regime, the distribution of the angle t is predicted to change minimally from real to redshift space, with a change smaller than 5% in $\left\langle \sin^2 t \right\rangle$. However, the distances defining the *comoving regime* strongly depend on the applied isolation criteria.

Keywords: galaxies, semi-analytical models, cosmology

1 Introduction

The observed expansion of the Universe is attributed to a dark energy component of which little is known (e.g. Blake et al. 2011; Anderson et al. 2012). Marinoni & Buzzi (2010) (MB) derived a geometrical test on isolated pairs of galaxies that can provide an independent investigation of the abundance and nature of the dark energy. The idea of this test is to measure the relative angle, t, that isolated pairs of galaxies form with the line-of-sight (LOS). The pairs of galaxies can be thought off as dumbbells. In a homogeneous and isotropic universe, the orientation of these dumbbells in the sky will be uniformly distributed and thus, will have a probability distribution of the form $\sin t/2$. Thus, measuring the probability distribution of the angle t can put constraints on the cosmological parameters, in particular, on the characteristics of the dark energy (Alcock & Paczynski 1979; Phillipps 1994). However, galaxies are affected by local gravitational pulls which are separate to the effect of dark energy and MB developed a test taking these into account. Here, we study the average relative comoving velocities, $\langle v_{12} \rangle$, of pairs of galaxies at $z = 0.5$ drawn from a semi-analytical model of the formation and evolution of galaxies. We use the predicted average $\langle v_{12} \rangle$ to split the model galaxies into different velocity regimes in order to check the principles upon which the MB test is based.

2 The galaxy formation model

Galaxies are thought to form within haloes of dark matter, whose gravity allows the galaxies to exist. The formation and evolution of galaxies is affected by a multitude of other processes besides gravity and computational modelling is the only way we can attempt to understand all these processes. For this study we use the GALFORM semi-analytical model (Cole et al. 2000). Semi-analytical models use simple, physically motivated equations to follow the fate of baryons in a universe in which structure grows hierarchically through gravitational instability (see Baugh 2006). In particular, we use the Gonzalez-Perez et al. (2013) model, which exploits a Millennium Simulation class N-body run performed with the WMAP7 cosmology (Komatsu et al. 2011): matter density, $\Omega_{\mathrm{m0}} = 0.272$, cosmological constant, $\Omega_{\Lambda 0} = 0.728$, baryon density, $\Omega_{\mathrm{b0}} = 0.045$, a normalisation of density fluctuations given by $\sigma_8 = 0.807$ and a Hubble constant today of $H_0 = 100\,h$ km s^{-1}Mpc^{-1}, with $h = 0.704$.

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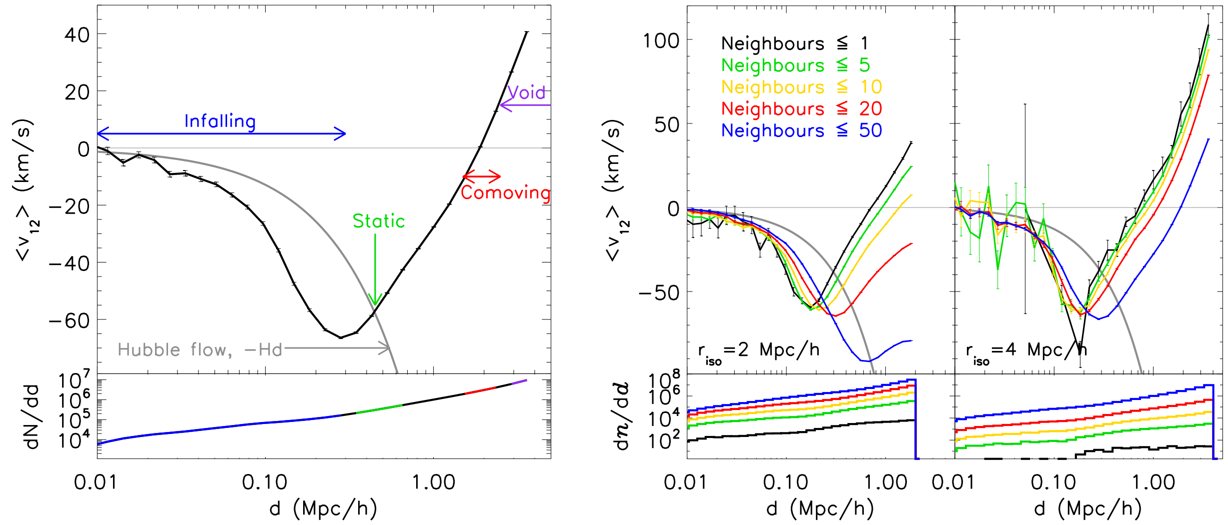

Fig. 1. *Left panel:* In the main panel, the black solid line shows the mean comoving relative velocity, $\langle v_{12} \rangle$, of pairs of galaxies at $z = 0.5$ as a function of their comoving real-space separation, d, as measured from simulations. The pairs of galaxies were selected among those with a maximum of 50 neighbours within a sphere of comoving radius $r_{iso} = 4h^{-1}$Mpc. The different regimes are indicated by arrows. *Right panel:* $\langle v_{12} \rangle$ as a function of d for pairs of galaxies selected by assuming $r_{iso} = 2h^{-1}$Mpc (left) and $r_{iso} = 4h^{-1}$Mpc (right), and different N_{max}, as indicated in the legend. In both panels, the thick grey solid line shows the Hubble flow, $-H(z)d$, and the lower panels show the number of isolated pairs of galaxies per bin in comoving distance.

The Gonzalez-Perez et al. model accounts for the physical processes shaping the formation and evolution of galaxies, including: (i) the collapse and merging of dark matter haloes; (ii) the shock-heating and radiative cooling of gas inside dark matter haloes, leading to the formation of galactic discs; (iii) the quiescent star formation in galactic discs, for which the mass of molecular and atomic gas content is followed explicitly (Lagos et al. 2011); (iv) feedback from supernovae, from active galactic nuclei and from photoionization of the inter galactic medium; (v) chemical enrichment of the stars and gas; (vi) galaxy mergers driven by dynamical friction within common dark matter haloes, leading to the formation of stellar spheroids, which also may trigger bursts of star formation. The end product of the calculation is a prediction of the number and properties of galaxies that reside within dark matter haloes of different masses. The free parameters in the Gonzalez-Perez et al. model were chosen in order to reproduce the rest-frame luminosity functions in b$_J$ and K-bands at $z = 0$ and to give a reasonable match to the observed evolution of the rest-frame ultra violet and K-band luminosity functions.

3 Results

We use model galaxies at $z = 0.5^*$ to study the comoving relative velocities of isolated pairs of galaxies, v_{12}. The isolation criteria is defined by counting the number of neighbours a galaxy has within a sphere of a given comoving radius, $r_{iso}\, h^{-1}$Mpc. If that number is below a certain threshold, N_{max}, we consider the galaxy to be isolated and, thus, it can become part of an isolated pair of galaxies (note that in this way a galaxy can be part of more than one pair). The LOS radial comoving distance to a galaxy with redshift z_A can be defined as (c is the speed of light):

$$\chi(z_A) = \frac{c}{H_0}\int_0^{z_A} \frac{\mathrm{d}z}{E(z)}\,, \quad \text{with} \quad E(z) = \sqrt{\Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda} \quad \text{and} \quad H(z) = H_0 E(z). \tag{3.1}$$

The Hubble expansion rate, $H(z)$, can also be defined in terms of the expansion parameter, $a = 1/(1+z)$, as $H = \dot{a}/a$. The physical distance to a galaxy, r, is proportional to its comoving distance, χ: $r = a\chi$. Thus, if we

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[*] In the future, we would like to apply the MB test to galaxies from BOSS, which have $\langle z \rangle \sim 0.5$ (Dawson et al. 2013).

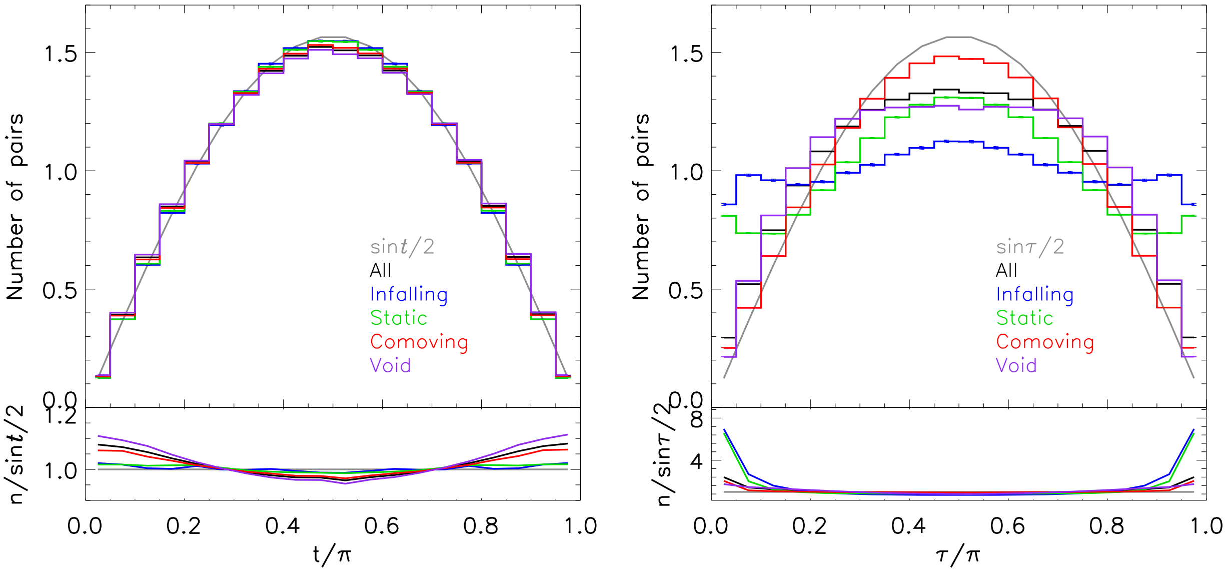

Fig. 2. The main panels show the predicted distribution of the angles that isolated pairs of galaxies form with the LOS in real space (t, left) and redshift space (τ, right). All curves are normalized to have unit area. The grey lines show the theoretical expectation of sin $t/2$. The black histograms show the prediction of all modelled isolated pairs of galaxies ($r_{iso} = 4\,h^{-1}$Mpc, $N_{max} = 50$), the other histograms show the behaviour of the subsample of pairs of galaxies selected by their comoving separation to account for the different regimes of $\langle v_{12}\rangle$, as indicated in the legend. Poisson error bars are shown for each predicted histogram, though they are too small to be seen. The lower panels show the ratio between the predicted distributions and the theoretical expectation.

neglect higher order terms of the total velocity of a galaxy, v, we can express v as the sum of the Hubble flow and the peculiar velocity, v_p: $v = \dot{r} = \dot{a}\chi + a\dot{\chi} = H(z)r + v_p$, or in comoving coordinates, $(1+z)v = H(z)\chi + (1+z)v_p$. For a pair of galaxies, we can define v_{12} as the rate of change in their comoving real-space separation $\dot{d}$ (Bueno Belloso et al. 2012):

$$v_{12} = (1+z)\Delta\overrightarrow{v_p}\hat{d}\,, \quad \text{with} \quad \Delta\overrightarrow{v_p} = \overrightarrow{v_{p2}} - \overrightarrow{v_{p1}} \quad \text{(difference in peculiar velocities)} \quad \text{and} \quad \hat{d} \text{ unitary vector} \qquad (3.2)$$

Thus, when $v_{12} = 0$, the pair of galaxies will follow the Hubble flow, $(1+z)(v_2 - v_1) = H(z)d$. If $v_{12} = -H(z)d$ the peculiar velocities of the galaxies will be compensating the Hubble flow, i.e. they will be static with respect to each other in physical space. When $v_{12} < -H(z)d$, the galaxies will be infalling and when $v_{12} > -H(z)d$, they will be moving apart. These different regimes are indicated in the left panel in Fig. 1, which shows the predicted average $\langle v_{12}\rangle$ for isolated model galaxy pairs. The right panel in Fig. 1 shows the average $\langle v_{12}\rangle$ for model galaxy pairs at $z = 0.5$ when different isolation criteria are applied. Increasing N_{max} implies that larger separations between the two galaxies are needed in order for their $\langle v_{12}\rangle$ to approach zero (as shown by Bueno Belloso et al. 2012). In fact, if no isolation criteria is applied, on average, no galaxy pairs are found with $\langle v_{12}\rangle = 0$ (see also Bueno Belloso et al. 2012). Reducing r_{iso} can have a similar effect as increasing N_{max}. Applying observational limits to the model galaxies, such as a range in magnitude or stellar mass, has a similar effect to changing the N_{max}. As an example, pairs of galaxies with $N_{max} = 5$, $r_{iso} = 4h^{-1}$Mpc and $m_{AB}(i) < 20$ have $\langle v_{12}\rangle \sim 0$ only for separations close to $2h^{-1}$Mpc, instead of the $1h^{-1}$Mpc. This happens because when we only take into account either bright or massive galaxies, we are missing galaxy neighbours that interact with those galaxies passing the selection criteria and are thus affecting their peculiar velocities. We have also studied the predicted $\langle v_{12}\rangle$ in simulations with a dynamical dark energy (Jennings et al. 2010, 2012). We find that $\langle v_{12}\rangle$ is less sensitive to changes in the cosmology from an evolving dark energy, than to changes in N_{max}.

3.1 The distribution of the angle that isolated galaxy pairs form with the line-of-sight

MB derived a test based on the idea that, in real space, the probability distribution of the angle t between the pair and the LOS follows sin $t/2$ with $\langle \sin^2 t\rangle = 0.667$. We have measured the distribution of the angles t in real space (for a flat universe: sin t =sin $\theta \cdot \chi_{z_B}/d$) and τ in redshift space for the model galaxies. Fig. 2 shows the distribution of these angles for all isolated pairs. In real space, the distribution for isolated model pairs of galaxies is very close to the theoretical expectation of sin $t/2$, with a difference smaller than a factor 1.1. In redshift space, when peculiar velocities are included to estimate the observed positions of galaxies, there is an increase in pairs which are aligned along the LOS and we find deviations from the uniform distribution which are largest for angles $\tau/\pi < 0.2$ and $\tau/\pi > 0.8$.

We have split the isolated pairs of galaxies according to their comoving real-space separations, d, which defines the different $\langle v_{12} \rangle$ regimes described above. In real space, the distribution of angles are rather insensitive to the cut in d. The distributions are at most a factor of 1.2 different with respect to the expected sin $t/2$. However, in redshift space, the distortion of the distribution of τ does depend on the value of $\langle v_{12} \rangle$, since this is a measure of the relative peculiar velocities of the pair. Pairs of galaxies with $\langle v_{12} \rangle \sim 0$ show a very small change between the distributions of t in real space and τ in redshift space. Isolated pairs of galaxies with $N_{max} = 50$, $r_{iso} = 4h^{-1}$Mpc and in the *comoving regime* are predicted to have $\langle \sin^2 t \rangle = 0.658$ in real space, and $\langle \sin^2 \tau \rangle = 0.645$ in redshift space, while galaxies in the other regimes are predicted to have a stronger variation of these quantities. Therefore, pairs of galaxies in this regime can be used to constrain cosmology, as we can accurately predict their distribution in redshift space.

4 Conclusions

We have used the Gonzalez-Perez et al. (2013) semi-analytical model of galaxy formation and evolution to study the average comoving relative velocities of isolated pairs of galaxies, $\langle v_{12} \rangle$. This model uses a Millennium Simulation class N-body run performed with the WMAP7 cosmology. We have found that, on average, two isolated galaxies with comoving separations below $\sim 0.5\,h^{-1}$Mpc are infalling towards each other, while two galaxies with separations above $\sim 2\,h^{-1}$Mpc are moving apart. For separations somewhere in between, a regime is found for which $\langle v_{12} \rangle \sim 0$. The exact range in comoving real-space distances that define this *comoving regime* strongly depends on the definition of the isolation criteria used to select pairs of galaxies. For isolated pairs of model galaxies at $z = 0.5$ we have measured in real space the angle that they form with the LOS, finding an excellent agreement with the theoretical expectation for uniformly distributed pairs of galaxies. This finding is practically independent of the average $\langle v_{12} \rangle$ and, thus, validates the assumption made by MB for their cosmological test. In redshift space, due to the effect of peculiar velocities, we find more pairs of galaxies which appear closely aligned with the LOS, though the deviations do depend on $\langle v_{12} \rangle$. We find that isolated pairs of galaxies selected with $\langle v_{12} \rangle \sim 0$ form an angle with the LOS which is practically independent of the effect of peculiar velocities and so are uniformly distributed in both real and redshift space, with $\langle \sin^2 t \rangle / \langle \sin^2 \tau \rangle \sim 1$. Pairs of galaxies in this regime are therefore a potentially promising probe of cosmology.

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References

Alcock, C. & Paczynski, B. 1979, Nature, 281, 358
Anderson, L., Aubourg, E., Bailey, S., et al. 2012, MNRAS, 427, 3435
Baugh, C. M. 2006, Reports of Progress in Physics, 69, 3101
Blake, C., Davis, T., Poole, G. B., et al. 2011, MNRAS, 415, 2892
Bueno Belloso, A., Pettinari, G. W., Meures, N., & Percival, W. J. 2012, Phys. Rev. D, 86, 023530
Cole, S., Lacey, C. G., Baugh, C. M., & Frenk, C. S. 2000, MNRAS, 319, 168
Dawson, K. S., Schlegel, D. J., Ahn, C. P., et al. 2013, AJ, 145, 10
Gonzalez-Perez, V., Lacey, C. G., Baugh, C. M., et al. 2013, arXiv 1309.7057
Jennings, E., Baugh, C. M., Angulo, R. E., & Pascoli, S. 2010, MNRAS, 401, 2181
Jennings, E., Baugh, C. M., & Pascoli, S. 2012, MNRAS, 420, 1079
Komatsu, E., Smith, K. M., Dunkley, J., et al. 2011, ApJS, 192, 18
Lagos, C. D. P., Lacey, C. G., Baugh, C. M., Bower, R. G., & Benson, A. J. 2011, MNRAS, 416, 1566
Marinoni, C. & Buzzi, A. 2010, Nature, 468, 539
Phillipps, S. 1994, MNRAS, 269, 1077