Wide-angle effects on galaxy ellipticity correlations

Maresuke Shiraishi,1,* Atsushi Taruya,2,4 Teppei Okumura,3,4 Kazuyuki Akitsu4
1Department of General Education, National Institute of Technology, Kagawa College, 355 Chokushi-cho, Takamatsu, Kagawa 761-8058, Japan
2Center for Gravitational Physics, Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan
3Academia Sinica Institute of Astronomy and Astrophysics (ASIAA), No. 1, Section 4, Roosevelt Road, Taipei 10617, Taiwan
4Kavli Institute for the Physics and Mathematics of the Universe (WPI), UTIAS, The University of Tokyo, Kashiwa, Chiba 277-8583, Japan

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ABSTRACT

We show an efficient way to compute wide-angle or all-sky statistics of galaxy intrinsic alignment in three-dimensional configuration space. For this purpose, we expand the two-point correlation function using a newly introduced spin-dependent tripolar spherical harmonic basis. Therefore, the angular dependences on the two line-of-sight (LOS) directions pointing to each pair of objects, which are degenerate with each other in the conventional analysis under the small-angle or plane-parallel (PP) approximation, are unambiguously decomposed. By means of this, we, for the first time, compute the wide-angle auto and cross correlations between intrinsic ellipticities, number densities and velocities of galaxies, and compare them with the PP-limit results. For the ellipticity-ellipticity and density-ellipticity correlations, we find more than 10% deviation from the PP-limit results if the opening angle between two LOS directions exceeds 30° − 50°. It is also shown that even if the PP-limit result is strictly zero, the non-vanishing correlation is obtained over the various scales, arising purely from the curved-sky effects. Our results indicate the importance of the data analysis not relying on the PP approximation in order to determine the cosmological parameters more precisely and/or find new physics via ongoing and forthcoming wide-angle galaxy surveys.

Key words: cosmology: observations – cosmology: theory – dark energy – dark matter – large-scale structure of Universe – gravitational lensing: weak.

1 INTRODUCTION

The large-scale structure of the Universe traced by the spatial distribution of galaxies provides a wealth of cosmological information. In particular, its statistical properties, quantified by the two-point correlation function of number densities and peculiar velocities of galaxies, have been playing a major role to test and constrain the cosmology. Besides, the information on individual shapes and orientations of galaxy images, previously treated as a contaminant in weak lensing data analyses (Heavens et al. 2000; Croft & Metzler 2000; Crittenden et al. 2002; Hirata & Seljak 2004; Mandelbaum et al. 2006; Hirata et al. 2007; Okumura et al. 2009; Okumura & Jing 2009), has recently attracted much attention, and is considered as a beneficial cosmological probe. There are numerous works developed on the formalism and theoretical predictions of the galaxy intrinsic alignment (IA) statistics not only in the projected sky defined on weak lensing data analyses (Catelan et al. 2001; Heavens et al. 2000; Hirata & Seljak 2004; Schmidt et al. 2015; Kogai et al. 2018; Biaggi et al. & Orlando 2020; Kogai et al. 2020; Vlah et al. 2020a), but also in the three-dimensional configuration or Fourier space (Crittenden et al. 2002; Schmidt & Jeong 2012; Okumura et al. 2019; Vlah et al. 2020b; Okumura & Taruya 2020; Okumura et al. 2020; Akitsu et al. 2020). Moreover, several studies have forecasted the constraints on key cosmological parameters such as the dark energy equation-of-state parameters and the parameters related to the early Universe, and found a substantial improvement on their precision and/or detectability when combining the IA statistics (Chisari & Dvorkin 2013; Schmidt et al. 2015; Chisari et al. 2016; Kogai et al. 2018; Taruya & Okumura 2020; Akitsu et al. 2020).

Motivated by these, this Letter examines an uninvestigated and important issue on the three-dimensional two-point correlation of IA for a widely separated pair, namely the wide-angle effects. The correlation function for a pair of target fields at positions \( \vec{x}_1 \) and \( \vec{x}_2 \) is generally characterized by the three vectors: two line-of-sight (LOS) directions \( \vec{x}_1 \) and \( \vec{x}_2 \) and the separation vector \( \vec{x}_{12} = \vec{x}_1 - \vec{x}_2 \). On the other hand, the so-called plane-parallel (PP) approximation, which sets \( \vec{x}_1 = \vec{x}_2 \), has been frequently imposed in the previous analyses. While this greatly simplifies the computation of correlation function, the accuracy of the approximation is no longer ensured when the opening angle between \( \vec{x}_1 \) and \( \vec{x}_2 \), dubbed as \( \Theta \), becomes large enough. Indeed, in the correlation functions of galaxy number density and velocity fields, more than 10% accuracy loss occurs for \( \Theta \) of a few tens of degrees (Szapudi 2004; Yoo & Seljak 2015; Castorina & White 2018; Taruya & Okumura 2020; Castorina & White 2020). In anticipation of upcoming wide-angle or all-sky galaxy IA surveys, the development of the comprehensive formalism without the PP approximation is thus timely and crucial.

To cope with this, we perform the tripolar spherical harmonic (TripoSH) decomposition and accordingly resolve tangled angular dependence between \( \hat{x}_1, \hat{x}_2 \) and \( \hat{x}_{12} \) in the correlation function. Then,
to treat the correlation functions of the spin-2 intrinsic ellipticity field, we implement a new basis defined by adding the spin dependence to the conventional spin-0 TripoSH basis utilized for the correlations of the density and velocity fields (Varshalovich et al. 1988; Szapudi 2004; Yoo & Seljak 2015; Shiraishi et al. 2020b). Based on this decomposition, the resultant TripoSH coefficients are obtained in a rather simplified and computable form, involving only the one-dimensional integral.

With numerics of the TripoSH coefficients, we compute the ellipticity auto correlation and the density-ellipticity and velocity-ellipticity cross correlations. In comparison with the results obtained under the PP approximation, we find more than 10% deviation for $\Theta \geq 30^\circ - 50^\circ$ in the ellipticity-ellipticity and density-ellipticity correlations. Regarding the velocity-ellipticity correlation, even if the PP-limit result is strictly zero, the non-vanishing correlation is found to be realized over the various scales.

2 STATISTICS OF IA, NUMBER DENSITY AND PECULIAR VELOCITY

Since our main interests lie in large-scale galaxy correlations, we are allowed to quantify the intrinsic ellipticities, number densities and LOS peculiar velocities of galaxies on the basis of the linear theory (Hamilton 1997; Yoo & Seljak 2015). According to Catelan et al. (2001); Hirata & Seljak (2004), the ellipticity field $\gamma_{ij}$, defined by the transverse and tracerless projection of the second moment of the surface brightness of galaxies, is linearly connected to the real-space matter fluctuation $\delta_m$ through

$$\gamma_{ij}(x) = \frac{1}{2} \left[ P_{ijk}(\hat{x}) P_{jkl}(\hat{x}) + P_{ijl}(\hat{x}) P_{jkl}(\hat{x}) - P_{ijl}(\hat{x}) P_{klj}(\hat{x}) \right]$$

$$\times \int \frac{d^3k}{(2\pi)^3} e^{i\mathbf{k}\cdot\mathbf{x}} \left( \delta_k^i \delta_k^j - \frac{1}{3} \delta_k^{ij} \right) b_k \delta_m(k),$$

where $P_{ijk}(\hat{x}) \equiv \delta_{ij} - \delta_i^k \delta_j^k$ and $\hat{x} \equiv x/|x|$. Here, the parameter $b_k$ and field $\delta_m$ implicitly depend on the time, redshift or the comoving distance, while it is not clearly stated as an argument for notational convenience. This convention is adapted to all variables henceforth unless the parameter dependence is non-trivial. Because of good compatibility with the later TripoSH decomposition, let us further introduce the spin-2 field as

$$\gamma^{a\gamma}(x) \equiv m^i_x(\hat{x}) m^j_x(\hat{x}) \gamma_{ij}(x),$$

where the unit vector $\hat{x}$ and its orthonormal vector $m^a(\hat{x})$ are explicitly given as

$$\hat{x} \equiv \left( \begin{array}{c} \sin \theta \cos \phi \\ \sin \theta \sin \phi \\ \cos \theta \end{array} \right), \quad m^a(\hat{x}) \equiv \frac{1}{\sqrt{2}} \left( \begin{array}{c} \cos \theta \cos \phi + i \sin \phi \\ \cos \theta \sin \phi + i \cos \phi \\ -\sin \theta \end{array} \right).$$

This is expressed as the linear combination of the conventional $+/-$ modes as

$$\gamma^{a\gamma}(x) = \frac{1}{2} \left[ \gamma^{+\gamma}(x) \pm i \gamma^{-\gamma}(x) \right].$$

From Eq. (1), its linear theory expression is given by

$$\gamma^{a\gamma}(x) = \int \frac{d^3k}{(2\pi)^3} e^{i\mathbf{k}\cdot\mathbf{x}} \left( \hat{k}^i \hat{k}^j m^i_x(\hat{x}) m^j_x(\hat{x}) b_k \delta_m(k) \right).$$

Likewise, the linear theory expressions for the number density fluctuation $\delta(n) \equiv n(x)/\bar{n}(x) - 1$ and the LOS velocity field $u(x) \equiv \mathbf{v}(x) \cdot \hat{x}$ are given by

$$\delta(x) = 2 \int \frac{d^3k}{(2\pi)^3} e^{i\mathbf{k}\cdot\mathbf{x}} \left[ b_g + \frac{i}{2\pi} \frac{\delta_{\ell,0}(\hat{x})}{f \delta_{\ell,0}(\hat{x})} + \frac{2}{3} \frac{\delta_{\ell,2}}{f \delta_{\ell,2}} \right] \delta_m(k),$$

$$u(x) = 2 \int \frac{d^3k}{(2\pi)^3} e^{i\mathbf{k}\cdot\mathbf{x}} \left[ \frac{aH}{k} \delta_{\ell,0}(\hat{x}) \right] \delta_m(k),$$

where $b_g$ is the bias parameter for galaxy number density field, $a$ is the scale factor, $H$ is the Hubble parameter, $f$ is the linear growth rate and $\sigma \equiv d \ln \bar{n}(x)/d \ln x + 2$ is the selection function of the galaxy sample. Here, we consider the density field defined in redshift space. The real-space density field is simply obtained by taking the limit, $f \rightarrow 0$. Note that for $u$ or $\gamma^{a\gamma}$, there is no distinction between real and redshift space at linear order.

For later convenience, we expand these fields using the spin-weighted spherical harmonics as

$$\hat{X}(x) = \frac{2}{(2\pi)^3} \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} \frac{4\pi \gamma_{\ell,m}(k)}{2\ell + 1} Y_{j\ell}(\hat{k}) Y_{j\ell,m}(\hat{x}) \delta_m(k),$$

where $X = \{ \delta, u, \gamma \}$ and

$$c^{\delta}(k) = \left( \frac{b_g + 1}{3} \right) \delta_{\ell,0} - \frac{2}{3} \delta_{\ell,2},$$

$$c^{u}(k) = i \frac{aH}{k} \delta_{\ell,1},$$

$$c^{\gamma}(k) = \frac{\sqrt{6}}{3} b_k \delta_{\ell,2}.$$
With this new basis, Eq. (10) is expanded in the following form:

\[ \text{TripoSH is defined by} \]

the correlation functions including the IA. Here, the spin-weighted functions arising from the wide-angle effects can be decomposed by means of the TriposSH basis. In this Letter, extending the usual spin-0 basis (Varshalovich et al. 1988; Shiraiishi et al. 2020b) to the spin-weighted version, we will perform the similar decomposition to the correlation functions including the IA. Here, the spin-weighted TriposSH is defined by

\[ \lambda_{12} X_{\ell_1 \ell_2} (\hat{x}_1, \hat{x}_2) \equiv \left\{ Y_{\ell_1} (\hat{x}_1) \otimes Y_{\ell_2} (\hat{x}_2) \right\}_{\ell_1 \ell_2}^{(0)} = \sum_{m_1 m_2} (-1)^{l_1 + l_2} \left( \begin{array}{c} l_1 \ m_1 \\ m_2 \\ \ell_2 \end{array} \right) \times Y_{l_1 m_1}(\hat{x}_1) Y_{l_2 m_2}(\hat{x}_2). \] (13)

With this new basis, Eq. (10) is expanded in the following form:

\[ \xi_{12} X_{\ell_1 \ell_2} (x_1, \hat{x}_1) = \sum_{\ell_1 \ell_2} \lambda_{12} X_{\ell_1 \ell_2} (x_1) \lambda_{21} X_{\ell_1 \ell_2} (\hat{x}_1). \] (14)

In order to derive a simple analytical form of \( \lambda_{12} X_{\ell_1 \ell_2} \) from Eq. (10), we also expand

\[ \rho_{\lambda_{12}} X_{\ell_1 \ell_2} (k, \hat{x}_1, \hat{x}_2) = \sum_{\ell_1 \ell_2} \lambda_{12} \rho_{\lambda_{12}} X_{\ell_1 \ell_2} (k) \lambda_{21} X_{\ell_1 \ell_2} (\hat{x}_1, \hat{x}_2) \] (15)

with the spin-weighted TriposSH \( \lambda_{12} X_{\ell_1 \ell_2} \) similarly defined in the Fourier space. The coefficients in Eqs. (14) and (15) are then related through

\[ \lambda_{12} X_{\ell_1 \ell_2} (x_1) = \int_0^\infty k^2 dk \int d^3 x k_{12} (x, k) \lambda_{12} X_{\ell_1 \ell_2} (k). \] (16)

In deriving the above, we have expanded \( \rho_{\lambda_{12}} X_{\ell_1 \ell_2} \) in terms of the spherical harmonics, and performed analytically the \( \hat{k} \) integral in Eq. (10). The explicit form of \( \lambda_{12} \lambda_{21} \rho_{\lambda_{12}} X_{\ell_1 \ell_2} \) is obtained via the inverse transformation:

\[ \lambda_{12} \lambda_{21} \rho_{\lambda_{12}} X_{\ell_1 \ell_2} (k, \hat{x}_1, \hat{x}_2) = \sum_{\ell_1 \ell_2} \lambda_{12} \rho_{\lambda_{12}} X_{\ell_1 \ell_2} (k) \lambda_{21} X_{\ell_1 \ell_2} (\hat{x}_1, \hat{x}_2). \] (17)

Simplifying the integrals of the (spin-weighted) spherical harmonics and the contractions of the Wigner 3j symbols, we finally obtain

\[ \lambda_{12} \lambda_{21} \rho_{\lambda_{12}} X_{\ell_1 \ell_2} (k) = \frac{(4\pi)^2 (-1)^{l_1 + l_2} (\ell_1 + \ell_2 + 1) \ell_1 \ell_2}{(2\ell_1 + 1)(2\ell_2 + 1)} c_{\ell_1}^\delta c_{\ell_2}^\gamma \frac{c_{\ell_1}^\delta c_{\ell_2}^\gamma P_m(k)}{m}. \] (18)

The selection rules in harmonic space, \( |l_1 - l_2| \leq \ell \leq l_1 + l_2 \) and \( \ell + \ell_1 + \ell_2 = \text{even} \), restrict the number of non-vanishing coefficients. Equation (14) with the analytically expressed coefficients (16) and (18) is the main result of this Letter.

Figure 1 plots the shape of all non-zero TriposSH coefficients, \( \rho_{\lambda_{12}} X_{\ell_1 \ell_2} \), \( \rho_{\lambda_{12}} X_{k \ell_1 \ell_2} \), \( \rho_{\lambda_{12}} X_{\ell_1 \ell_2} \), and \( \rho_{\lambda_{12}} X_{\ell_1 \ell_2} \) computed from Eqs. (16) and (18), the results of which are multiplied by \( x_1 \) or \( x_1/(aH) \). As expected, the baryon acoustic oscillation bump at \( x_1 \approx 100 \ h^{-1} \text{Mpc} \) is clearly seen in each coefficient. To see the impact of the redshift-space distortions (RSD) on the \( \delta \gamma \) correlation, we also plot the real-space data in dashed line. Since the RSD not only changes the clustering amplitude but also produce anisotropies described by the higher multipoles of the TriposSH coefficients.

Finally, while our formalism is obviously general applicable to the predictions for a largely separated pair, setting the vectors \( \hat{x}_1 \) and \( \hat{x}_2 \).
to \(\xi_1 = (0, 0, 1) = \hat{x}_2\) rigorously reproduces the analytical results known in the PP limit (Okumura & Taruya 2020).²

4 WIDE-ANGLE EFFECTS

Provided the formulas expressed in terms of the spin-weighted TripoSH basis, we are in position to discuss the quantitative impact of the wide-angle effects on the IA statistics. Following Szapudi (2004); Yoo & Seljak (2015), we consider the coordinate system in which the triangle formed with \(x_1, x_2\) and \(x_{12}\) is confined to the \(xy\) plane. Moreover, the separation and direction vectors are set to \(\hat{x}_{12} = (1, 0, 0)\), \(\hat{x}_1 = (\cos \phi_1, \sin \phi_1, 0)\) and \(\hat{x}_2 = (\cos \phi_2, \sin \phi_2, 0)\) for \(\phi_2 \geq \phi_1\). Then the opening angle between \(\hat{x}_1\) and \(\hat{x}_2\) is defined to be \(\Theta = \phi_2 - \phi_1\). The explicit representations of \(\xi_{a2\gamma}(x_{1,2})\) and \(\gamma_{a/x}(x_{1,2})\) under this coordinate system are obtained by taking \(\Theta = \pi/2\) in Eqs. (2), (3) and (4). With these setup, we specifically compute the correlation functions satisfying the isosceles triangle condition \((x_1 = x_2)\), or equivalently, the equal-time condition \((z_1 = z_2)\), in which the angles \(\phi_{1,2}\) and the separation \(x_{12}\) are solely specified by the opening angle \(\Theta = (\pi - \Theta)/2\), \(\phi_0 = (\pi + \Theta)/2\) and \(x_{12} = x_1 \sqrt{2(1 - \cos \Theta)}\). Thus, the correlation function at a given redshift is expressed as a single-variate function of \(\Theta\) or \(x_{12}\).

Our numerical results of the correlation functions under the specific setup are shown in the top panel of Fig. 2, where the function \(\xi_{\mu\gamma}^{0,2}\) is multiplied by the factor of \(10^2\) for ease of comparison. Overall, behaviors of the correlation function exhibit the trend similar to the TripoSH coefficients. As expected from Fig. 1, the correlation function \(\xi_{0a2}^{g,\gamma}\) has the largest signal in redshift space, though it is slightly reduced in real space. By contrast, the function \(\xi_{0a2}^{\mu,\gamma}\) is found to be rather suppressed compared to the other correlations. Mathematically, this is because both of the directional cosines \(\xi_{12} \cdot \hat{x}_1\) and \(\xi_{12} \cdot \hat{x}_2\) remain small for a relevant range of \(\Theta\), and this results in a suppressed amplitude in the basis functions, \(0_{a2}X_{112}\) and \(0_{a2}X_{312}\). In fact, in the PP limit (i.e., \(\xi_{12} \cdot \hat{x}_1 = \xi_{12} \cdot \hat{x}_2 = 0\), the correlation function \(\xi_{0a2}^{\mu,\gamma}\) becomes exactly zero (Okumura & Taruya 2020). Regardless of the suppressed amplitude, we have the non-zero signal for the \(\gamma\gamma\) correlation. This solely comes from the wide-angle effects. The difference in magnitude between \(\xi_{a2\gamma}^{0,2}\) and \(\xi_{a2\gamma}^{\mu,\gamma}\) arises from the inequality between \(0_{a2}X_{\ell\ell\ell}\) and \(a_{a2}X_{\ell\ell\ell}\).

The bottom panel of Fig. 2 plots the ratios of our wide-angle correlations to those computed in the PP limit (dubbed as \(\xi_{a1,1\gamma}^{X}\)) as in Okumura & Taruya (2020). We find that the PP approximation works very well at small \(\Theta\), while the deviation exceeds – 10% and becomes significant for \(\Theta \geq 30^\circ – 50^\circ\), as we have similarly seen in the \(\delta\delta\) case.

5 CONCLUSIONS

We have explored the wide-angle effects on the galaxy IA statistics in the three-dimensional configuration space for the first time. The computation of the wide-angle correlation function including the spin-2 ellipticity field has become available via the complete decomposition theorem by a newly introduced spin-weighted TripoSH basis. It is because the form of the correlation function can be transformed into rather simplified expressions involving only the one-dimensional integral, as given at Eqs. (14), (16) and (18). Through the spin-weighted TripoSH decomposition, uninvestigated and important features in wide-angle correlations have been revealed.

Comparison of our correlation functions with those previously computed in the PP limit, given as a function of the opening angle \(\Theta\), reveals that the quantitative impact of the wide-angle effects can become large by more than 10% in the density-ellipticity and ellipticity-ellipticity correlations when the opening angle reaches at \(\Theta \geq 30^\circ – 50^\circ\). We have also found non-zero velocity-ellipticity correlation although it exactly vanishes in the PP limit. These should be taken care of in precision measurements of the IA statistics, particularly for the purpose to probe new physics with a large-angular correlation via the decadal or more futuristic surveys.

The spin-weighted TripoSH decomposition should be applied or extended to various directions. Regarding the correlation functions of the spin-0 fields such as the density and velocity fields, general relativistic effects and the effects of cosmic isotropy violation were successfully investigated via the standard TripoSH decomposition (e.g., Bertacca et al. 2012; Yoo & Seljak 2015; Shiraiishi et al. 2017; Shiraiishi et al. 2020a). There are also studies on the application to the covariance matrix computation (Shiraiishi et al. 2020b; Shiraiishi et al. 2020a). The same level of high versatility is naturally expected also in the spin-weighted TripoSH decomposition, and the similar issues could be resolved.

In this Letter, all the predictions of the IA statistics are based on the linear theory, and hence the applicability of our results to small scales is limited. The validity of our predictions has to be clarified with N-body simulations and the higher-order perturbation theory.
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REFERENCES

Akitsu K., Kurita T., Nishimichi T., Takada M., Tanaka S., 2020a, arXiv e-prints, arXiv:2007.03670
Akitsu K., Li Y., Okumura T., 2020b, arXiv e-prints, arXiv:2011.06584
Bertacca D., Maartens R., Raccanelli A., Clarkson C., 2012, JCAP, 10, 025
Biagetti M., Orlando G., 2020, JCAP, 07, 005
Castorina E., White M., 2018, Mon. Not. Roy. Astron. Soc., 476, 4403
Castorina E., White M., 2020, Mon. Not. Roy. Astron. Soc., 499, 893
Catelan P., Kamionkowski M., Blandford R. D., 2001, Mon. Not. Roy. Astron. Soc., 320, L7
Chisari N. E., Dvorkin C., 2013, JCAP, 12, 029
Chisari N. E., Dvorkin C., Schmidt F., Spergel D., 2016, Phys. Rev. D, 94, 123507
Crittenden R. G., Natarajan P., Pen U.-L., Theuns T., 2002, Astrophys. J., 568, 20
Croft R. A., Metzler C. A., 2000, Astrophys. J., 545, 561
Hamilton A., 1997, in Ringberg Workshop on Large Scale Structure. (arXiv:astro-ph/9708102), doi:10.1007/978-94-011-4960-0_17
Heavens A., Refregier A., Heymans C., 2000, Mon. Not. Roy. Astron. Soc., 319, 649
Hirata C. M., Seljak U., 2004, Phys. Rev. D, 70, 063526
Hirata C. M., Mandelbaum R., Ishak M., Seljak U., Nichol R., Pimbblet K. A., Ross N. P., Wake D., 2007, MNRAS, 381, 1197
Kogai K., Matsubara T., Nishizawa A. J., Urakawa Y., 2018, JCAP, 08, 014
Kogai K., Akitsu K., Schmidt F., Urakawa Y., 2020, arXiv e-prints, arXiv:2009.05517
Mandelbaum R., Hirata C. M., Ishak M., Seljak U., Brinkmann J., 2006, MNRAS, 367, 611
Okumura T., Jing Y. P., 2009, ApJ, 694, L83
Okumura T., Taruya A., 2020, Mon. Not. Roy. Astron. Soc., 493, L124
Okumura T., Jing Y. P., Li C., 2009, ApJ, 694, 214
Okumura T., Taruya A., Nishimichi T., 2019, Phys. Rev. D, 100, 103507
Okumura T., Taruya A., Nishimichi T., 2020, MNRAS, 494, 694
Papai P., Szapudi I., 2008, Mon. Not. Roy. Astron. Soc., 389, 292
Schmidt F., Jeong D., 2012, Phys. Rev. D, 86, 083527
Schmidt F., Chisari N. E., Dvorkin C., 2015, JCAP, 10, 032
Shiraishi M., Nitta D., Yokoyama S., Ichiki K., Takahashi K., 2011, Prog. Theor. Phys., 125, 795
Shiraishi M., Sugiyama N. S., Okumura T., 2017, Phys. Rev. D, 95, 063508
Shiraishi M., Okumura T., Akitsu K., 2020a, arXiv e-prints, arXiv:2009.04114
Shiraishi M., Okumura T., Nagai M., 2020, Mon. Not. Roy. Astron. Soc., 498, L77
Szalay A. S., Matsubara T., Landy S. D., 1998, Astrophys. J. Lett., 498, L1
Szapudi I., 2004, Astrophys. J., 614, 51
Taruya A., Okumura T., 2020, Astrophys. J. Lett., 891, L42
Taruya A., Sasaki S., Breton M.-A., Rasera Y., Fujita T., 2020, Mon. Not. Roy. Astron. Soc., 491, 4162
Varshalovich D. A., Moskalev A. N., Khersonsky V. K., 1988, Quantum The-