様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

科学研究費助成事業　　研究成果報告書

令和　元 年　６ 月　６ 日現在

機関番号： １２６０１
研究種目： 研究活動スタート支援
研究期間： 2017～2018
課題番号： １７Ｈ０６５９９
研究課題名（和文） Intrinsic alignments in HSC

研究課題名（英文） Intrinsic alignments in HSC

研究代表者
Koehlinger Fabian（Koehlinger, Fabian）

東京大学・カブリ数物連携宇宙研究機構・特任研究員

研究者番号：７０８００５５６

交付決定額（研究期間全体）：（直接経費）　1,500,000円

研究成果の概要（和文）：アインシュタインの相対性理論によれば、宇宙の構造による重力は銀河から発せられた光の経路を妨げる重力レンズ効果と呼ばれる現象を引き起こす。重力レンズ効果による銀河の形状の歪曲は非常に小さな効果ではあるが、数百万個の銀河のイメージを組み合わせることで宇宙論パラメータの制限が可能である。銀河の形状と潮汐力場には相関があるためこれを無視して宇宙論パラメータを正確に制限することはできない。また、宇宙論解析はその他の宇宙論手法を用いた制限結果と比較する必要がある。この研究では銀河の形状と潮汐力場の相関を評価する手法を確立するだけでなく、様々な宇宙論手法による結果をより直接的に比較する統計手法を確立した。

研究成果の学術的意義や社会的意義
様々な銀河サーベイが行われている今、各サーベイが行った宇宙論解析結果を厳密に比較する統計手法の確立の重要性は計り知れない。宇宙論解析は、たとえそれが同じような手法であってもデータの性質や手法の細かな手順が異なるため単純に結果のみを比較することはできない。またそれ以前にデータの性質と解析手法の妥当性を評価する必要がある。そのためこの研究ではデータと解析手法の一貫性を評価する統計手法を確立した。これは宇宙論解析だけでなくその他の分野にも適用可能な汎用性の高い手法である。また、他に重力レンズ効果シグナルにおける銀河の形状と潮汐力場の相関の系統誤差としての寄与を間接的に測定することにも成功した。

研究成果の概要（英文）：When light rays of galaxies travel through the large-scale structure of the Universe to an observer, their paths are deflected by all intervening mass according to Einstein’s General Relativity theory. Measurements of these tiny deflections from millions of galaxy images taken in large surveys of the night sky are used to derive cosmological parameters.Measuring these tiny image distortions is a challenging task and further complicated by particular galaxy alignments along the line-of-sight which can dilute or strengthen the true cosmological signal. If these extra contributions are left unaccounted for, the derived cosmological parameters from this probe will be biased.Eventually, the derived cosmological parameters also need to be compared to results from other independent probes.Addressing both issues, i.e. measuring intrinsic galaxy alignments and presenting a novel and statistically robust way of comparing results within and across probes are the key achievements of this project.

研究分野： 理論物理学

キーワード： intrinsic alignments　consistency　cosmic shear

１．研究開始当初の背景

The cosmological concordance model successfully explains a wide range of observations such as the tiny temperature fluctuations in the cosmic microwave background (Planck 2016), the large-scale clustering of galaxies (BOSS 2015) or the Hubble diagram inferred from supernovae of type IA (Riess et al. 2016) with just a handful of parameters. However, the physical nature of two of these parameters, commonly termed dark matter and dark energy, is still unknown. Understanding these two species in detail is the key science driver in state-of-the-art cosmological research.

A powerful probe for cosmology is the (weak) gravitational lensing effect of the cosmic large-scale structure, also termed cosmic shear. By mapping the total matter distribution on cosmologically large scales and at different cosmic times, it is sensitive to the growth of structure in and the general geometry of the Universe. Hence, cosmic shear can be used to measure the evolution of dark matter and dark energy.

Measurements of the correlations between the tiny but coherent distortions, the shear, imprinted in the images of galaxies due to the weak lensing of the intervening large-scale structure require a statistical approach of averaging over millions of source galaxies.

Therefore, large optical wide-field surveys such as HSC (Miyazaki et al. 2015, Aihara et al. 2017), the Kilo Degree Survey (KiDS; de Jong et al. 2015, 2017; Kuijken et al. 2015), and the Dark Energy Survey (DES; Jarvis et al. 2016) are building up imaging data with the aim of covering (several) thousand square degrees on the sky over the next few years.

State-of-the-art constraints on the clustering amplitude of matter (σ8) at fixed total matter density (Ωm) inferred from cosmic shear measurements using 450 square degrees from KiDS are found to be in tension (Hildebrandt et al. 2017; Köhlinger et al. 2017) with constraints from cosmic microwave background measurements (Planck 2016).

Whether this tension is indeed evidence for a change in the late time physics compared to the physics about 380 000 years after the Big Bang or just pointing to residual systematic effects in the data, is hard to assess and decide within current uncertainties. For example, the cosmic shear analyses in Hildebrandt et al. (2017; based on correlation functions) and Köhlinger et al. (2017; based on a power spectrum estimator) require to marginalize over several sources of nuisance such as the shear calibration, uncertainty of the source redshift distribution or astrophysical systematics. The latter dominate the error budget by far and any attempt to resolve the tension must aim at reducing these error bars first.

In addition, it is paramount to critically assess the self-consistency of each data set to exclude systematic errors as sources for the discrepancy between different cosmological probes.

２．研究の目的

For this project we aimed at addressing two major issues for current cosmic shear studies:

1) the impact of intrinsic galaxy alignments as a major astrophysical systematic
2) developing a rigorous framework to assess (self-)consistency of a *correlated* data set (such as used for cosmic shear studies)

We intended to study intrinsic galaxy alignments as a major astrophysical systematic for cosmic shear studies (see Joachimi et al. 2015 and Troxel & Ishak 2015 for reviews), since estimating the gravitational shear correlations from observed ellipticities of galaxy images assumes that the intrinsic ellipticity of one galaxy is not correlated with either the intrinsic ellipticity of or the gravitational shear acting on another. These assumptions, however, do not hold, if intrinsic galaxy alignments occur, for example caused by tidal torqueing and stretching of galaxies by the gravitational field of the surrounding large-scale structure. These effects are fundamentally connected to galaxy formation and evolution including baryonic physics and thus limiting the modelling through analytical calculations or N-body simulations.

The bias on inferred cosmological parameters when ignoring intrinsic galaxy alignments is severe, Bridle & King (2007) for example estimated that for a Euclid-like survey the dark energy equation of state parameter can deviate by 50% from the value –1 if not accounting for intrinsic alignments. However, accounting for intrinsic galaxy alignments in current cosmic shear analyses (DES 2015, Hildebrandt et al. 2017, Köhlinger et al. 2017) by marginalizing over models for intrinsic alignments increase the uncertainty on cosmological parameters significantly.

Therefore, we wanted to use data from the most recent HSC release to put constraints on the intrinsic alignment amplitude.

For addressing the second goal, we aimed at developing a novel and statistically rigorous way to assess the (self-)consistency of a correlated data set, such as cosmic shear data, to exclude systematic errors as a source of the discrepancy in cosmological parameters inferred from current cosmic shear results and cosmic microwave background results, respectively.

３．研究の方法

For the first goal, i.e. the study of the impact of intrinsic galaxy alignments on cosmic shear studies, we attempted to make a direct measurement with a shear-density correlation estimator to constrain the intrinsic alignment amplitude independently from a cosmic shear measurement. For example, by using the MegaZ-LRG sample from the Sloan Digital Sky Survey (SDSS) as a density tracer and cross-correlating those with galaxy shape measurements from HSC, we anticipated to put strong and independent constraints on the intrinsic galaxy alignment amplitude. However, while implementing the pipeline for this estimator, we realized that the current overlap of the SDSS MegaZ-LRG sample, with the weak lensing data from the first-year data release from HSC (from the S16A campaign) is insufficient for a direct measurement of intrinsic alignment signals with high statistical significance. Therefore and while following the progress on the next internal release of a weak lensing catalog from HSC (based on the S18A campaign) closely, we contributed to a complementary cosmic shear measurement on the first-year HSC weak lensing catalog. Based on our publicly available likelihood pipeline, the inference of cosmological parameters from the cosmic shear measurement also yields an indirect measurement of the intrinsic galaxy alignment signal (as a nuisance parameter to be marginalized over).
For achieving the second goal, we developed a suite of three systematic tests for assessing the (self-)consistency of correlated data sets based on Bayesian statistics and posterior predictive distributions. We tested the performance of these tests extensively on mock data mimicking a cosmic shear data set and finally also applied all tests to a well-studied and publicly available cosmic shear measurement from KiDS.

４．研究成果

The results for the novel set of consistency tests can be summarized as follows: we developed three tiers of Bayesian consistency tests for the general case of *correlated* data sets. Building on duplicates of the model parameters assigned to each dataset, these tests range from Bayesian evidence ratios as a global summary statistic, to posterior distributions of model parameter differences, to consistency tests in the data domain derived from posterior predictive distributions. For each test we motivated meaningful threshold criteria for the internal consistency of data sets. Without loss of generality we focused on mutually exclusive, correlated subsets of the same data set in this study. As an application, we revisited the consistency analysis of the two-point weak lensing shear correlation functions measured from KiDS-450 data. We split this data set according to large vs. small angular scales, tomographic redshift bin combinations, and estimator type. We did not find any evidence for significant internal tension in the KiDS-450 data, with significances below 3σ in all cases.
Using the cosmic shear measurements from the HSC survey first-year shear catalog covering 137 deg^2 of the sky, we could put a constraint on the amplitude of intrinsic galaxy alignments, i.e. $A_{\mathrm{IA}} = 0.38 +/- 0.70$ when marginalizing over all other parameters of the cosmic shear model. Moreover, measurements of the intrinsic alignment amplitude for each redshift bin of the cosmic shear study indicates that the result is consistent with the hypothesis that only red galaxies contribute significantly to the intrinsic alignment signal.

All results derived within this project were published in two independent and peer-reviewed publications in journals well-renowned in the field of cosmology. One of the two publications was fully led by the PI of this project (i.e. Köhlinger et al. 2019) and we contributed as a co-author to the second study (i.e. Hikage et al. 2019).
Both publications received attention in the academic literature and collected already further citations in other peer-reviewed studies despite their very recent publication dates.

Finally, the results presented in both papers will be very useful for the analyses of upcoming releases in the currently ongoing HSC, KiDS and DES surveys, but also for future and close to all-sky surveys such as LSST (Ivezic et al. 2008) or the space-borne Euclid mission (Laureijs et al. 2011).

References:
Aihara H., et al., 2017, preprint, (arXiv:1702.08449); BOSS Collaboration, 2015, Phys. Rev. D, 92, 123516; Bridle S., King L., 2007, New J. Phys., 9, 444; de Jong J. T. A., et al., 2015, A&A, 582, A62; de Jong J. T. A., et al., 2017, preprint, (arXiv:1703.02991); DES Collaboration, 2016, Phys. Rev. D, 94, 022001; Hikage et al., 2019, PASJ, 71; Hildebrandt H., et al., 2017, MNRAS, 465, 1454; Hirata C. M., Seljak U., 2004, Phys. Rev. D, 70, 063526; Hirata C. M., Mandelbaum R., Ishak M., 2007, MNRAS, 381, 1197; Ivezic Z., et al., 2008, preprint (arXiv:0805.2366); Jarvis M., et al., 2016, MNRAS, 460, 2245; Joachimi B., Mandelbaum R., Abdalla F. B., Bridle S. L., 2011, A&A, 527, 26; Joachimi B. et al., 2015, SSRv, 193, 1J; Kuijken K., et al., 2015, MNRAS, 454, 3500; Köhlinger F. et al., 2017, MNRAS, 471, 4412; Köhlinger F. et al., 2019, MNRAS, 484, 3126; Laureijs R., et al., 2011, preprint (arXiv:1110.3193); Li C., Jing Y. P., Faltenbacher A., Wang J., 2013, ApJ, 770, L12; Mandelbaum R., Hirata C. M., Ishak M., Seljak U., Brinkmann J., 2006, MNRAS, 367, 611; Miyazaki S., et al., 2015, ApJ, 807, 22; Planck Collaboration, 2016, A&A, 594, A13; Riess A. G., et al., 2016, ApJ, 826, 56; Singh S., Mandelbaum R., More S. 2015, MNRAS, 450, 2195; Troxel M. A., Ishak M., 2015, PhR, 558, 1T;

５．主な発表論文等

〔雑誌論文〕（計2件）

1) Fabian Koehlinger, Benjamin Joachimi, Marika Asgari, Shahab Joudaki, Tilman Troester, “A Bayesian quantification of consistency in correlated data sets”, Monthly Notices of the Royal Astronomical Society, 484, 2019, 3126 – 3135, 10.1093/mnras/stz132, Refereed
2) Chiaki Hikage, Masamune Oguri, Takashi Hamana, Surhud More, Rachel Mandelbaum, Masahiro Takada, Fabian Koehlinger et al., “Cosmology from cosmic shear power spectra with Subaru Hyper Suprime-Cam first-year data”, Publications of the Astronomical Society of Japan, 71, 2019, 10.1093/pasj/psz010, Refereed

〔学会発表〕（計2件）

1) Fabian Koehlinger, ‘A consistent approach to inconsistencies’, Statistical challenges for large-scale structure in the era of LSST, 2018
2) Fabian Koehlinger, ‘Cosmology with KiDS’, Studying the Universe with GAlaxy suRveys – Revealing the Unlimited in ShangHai, 2018
3) Fabian Koehlinger, ‘KiDS-450: The tomographic weak lensing power spectrum and constraints on cosmological parameters’, COSMO17, 2017

〔図書〕（計0件）

〔産業財産権〕
○出願状況（計0件）

名称：
発明者：
権利者：
種類：
番号：
出願年：
国内外の別：

○取得状況（計0件）

名称：
発明者：
権利者：
種類：
番号：
取得年：
国内外の別：

〔その他〕
ホームページ等

Reference 1) from Section 5:
https://arxiv.org/abs/1809.01406

Reference 2) from Section 5:
https://arxiv.org/abs/1809.09148

Parts of the code developed within this project are made publicly available at the following URL:
https://github.com/fkoehlin/montepython_2cosmos_public

６．研究組織

(1)研究分担者
研究分担者氏名：

ローマ字氏名：

所属研究機関名：

部局名：

職名：
研究者番号（8 桁）：

(2)研究協力者
研究協力者氏名：
ローマ字氏名：