Understanding intrinsic galaxy alignments

1 Abstract

The apparent distortions and alignments of faint galaxy images due to the gravitational lensing effect by the large-scale structure of the Universe is one of the potentially most powerful probes of cosmology. This so-called cosmic shear effect maps the matter distribution at different epochs and is thus sensitive to both the expansion history and the growth of structure. Forthcoming cosmic shear surveys such as the ESA Euclid mission will enable unprecedented insight into the properties of dark matter and dark energy, and test the validity of general relativity on cosmological scales.

The anticipated high-quality measurements of cosmic shear require an accurate understanding and treatment of systematic effects. The major astrophysical effect that contaminates the cosmic shear signal is the intrinsic alignment of galaxies. During their formation and evolution, galaxies are subjected to tidal forces exerted by the surrounding large-scale structure, which causes the galaxies to align with the matter distribution and neighbouring galaxies. These alignments can exactly mimic the gravitational lensing signal and have been demonstrated to potentially yield a systematic signal that is up to two orders of magnitude above the statistical errors expected for Euclid. To date, observational constraints are weak and models simplistic, so that a major effort is needed to ensure the success of the Euclid mission and other cosmic shear surveys.

The planned workshops will bring together leading observational, theoretical, and numerical expertise on intrinsic alignments, with the goal to decisively advance the understanding of this astrophysical effect. The international team, whose core will be formed by members of the Euclid Intrinsic Alignments Tiger Team, is going to write a review on the state of the art of intrinsic alignment research and will construct and test a new comprehensive, physically motivated intrinsic alignment model. The results will then be used to update the Euclid survey strategy, identify what external calibration data needs to be acquired, and optimise the treatment of intrinsic alignments in the Euclid analysis pipeline.

By virtue of the infrastructure and financial support of ISSI, the team is going to advance the knowledge of intrinsic alignments and disseminate its findings to the community via a review, peer-reviewed articles, and technical documentation in a timely and critical step towards the reliable interpretation of the forthcoming cosmic shear measurements.

2 Scientific rationale

The small, coherent distortions of faint galaxy images induced by the gravitational lensing of the intervening large-scale structure constitute potentially one of the most powerful probes of cosmology (Albrecht et al. 2006, Dark Energy Task Force Report, astro-ph/0609591), with a signal that in principle is straightforward to interpret physically (Bartelmann & Schneider 2001, Phys. Reports, 340, 291). This so-called cosmic shear effect allows for a statistical analysis of the properties of the full matter distribution at different epochs, as well as of the spatial geometry of the Universe. Therefore it is capable of answering some of the key open questions in fundamental physics: what are the properties of dark matter, what is the explanation for the accelerated expansion of the cosmos, and is general relativity the correct theory of gravity on cosmological scales.

Consequently, cosmic shear has become one of the main drivers of a new generation of large imaging surveys including the Dark Energy Survey (DES, `http://www.darkenergysurvey.org`), the Hyper Suprime-Cam Survey (HSC, `http://www.naoj.org/Projects/HSC/index.html`), and the Kilo Degree Survey (KiDS, `http://www.astro-wise.org/projects/KIDS`). Cosmic shear will constitute one of the two primary probes of the ESA Cosmic Vision mission Euclid (`http://www.euclid-ec.org`; Laureijs et al. 2011, Euclid Assessment Study Report for the ESA Cosmic Visions, astro-ph/0912.0914), to be launched in 2020. Over the course of six years Euclid will survey the full extragalactic sky in the optical and near-infrared with a 1.2m telescope, with a strong focus on superior image quality and excellent redshift information for about 2×10^9 galaxies.

The resulting sub-percent precision on the cosmic shear signal anticipated for Euclid needs to be matched with equally outstanding constraints on potential systematic effects. The main astrophysical systematics affecting cosmic shear are generated by the intrinsic alignment of galaxies. The physical alignment of galaxy shapes mimics the apparent correlations of the shapes of galaxy images created by

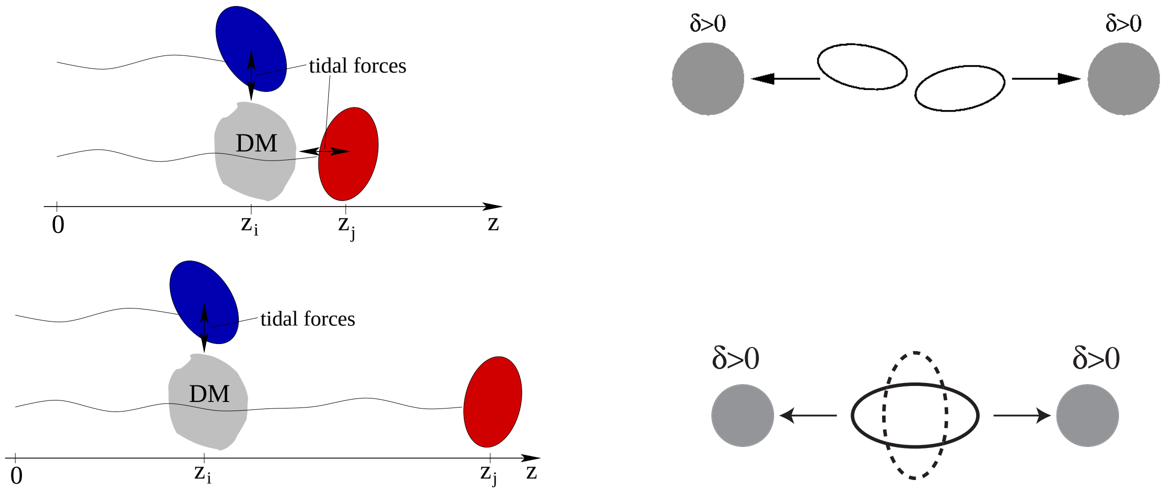

Figure 1: Illustration of intrinsic galaxy alignments, as seen along the line of sight (left panels) and on the sky (right panels). *Top row*: The intrinsic shapes of galaxies become correlated with each other when they are subjected to tidal forces exerted by the same matter structures. For this to happen, galaxies have to be close both in redshift and on the sky. Due to this so-called II effect galaxy shapes tend to point towards matter overdensities and become collinear, i.e. positively correlated. *Bottom row*: Alignments of galaxy shapes are also observed if a matter structure aligns a nearby galaxy and at the same time contributes to the lensing distortion of the image of a galaxy in the background. While the foreground galaxy tends to point towards matter overdensities, the lensing distortion of the background object is preferentially tangential around mass concentrations, so that this correlation, called GI effect, is negative. (Bottom right panel from Hirata & Seljak 2004)

the gravitational lensing effect. Thus it is vital to understand the intrinsic alignment signal and separate it from cosmic shear in order to extract the cosmological information in an unbiased way. Provided the separation of the signals works, the high-precision measurements achievable with the forthcoming surveys will also put tight constraints on intrinsic alignment models, thereby converting intrinsic alignments from a mere nuisance signal to an independent and valuable astrophysical probe of the role of the large-scale environment in galaxy formation and evolution.

However, the current knowledge of the physics behind intrinsic galaxy alignments is poor, threatening the successful cosmological exploitation of the forthcoming large imaging surveys. Surveys like DES, HSC, and KiDS are already taking data, or will shortly go into survey mode, and will yield a statistical accuracy on cosmic shear measurements that requires considerable improvement in the calibration of intrinsic alignments on timescales of not much more than a year from now. In the same period any calibration samples or high-level requirements that are needed to guarantee the robust calibration of Euclid cosmic shear measurements must be identified in order to be integrated into the implementation phase in time.

2.1 The current knowledge of alignment processes

If galaxies are subjected to tidal fields generated by their large-scale environment during formation and evolution, it is expected that their shapes (e.g. measured via the quadrupole of the light distribution) become correlated with the large-scale gravitational field (see Fig. 1 for an illustration). Then the intrinsic shapes of two physically close galaxies become aligned if they are influenced by the same gravitational forces (called the II effect). If a certain matter distribution aligns a nearby galaxy and at the same time contributes to the lensing distortion of a background galaxy image, one obtains correlations between gravitational distortion and intrinsic shape (called the GI effect).

In a simple analytical ansatz, referred to as the linear alignment model, it is assumed that the (projected) ellipticity of early-type galaxies is proportional to the quadrupole of the gravitational field at the time of the galaxy's formation (e.g. Hirata & Seljak 2004, PRD, 70, 063526). For late-type galaxies the alignment is assumed to be governed by their angular momentum, which in turn is quadratic in the gravitational potential according to tidal torquing theory (Peebles 1969, ApJ, 155, 393). This quadratic alignment model predicts a null signal to first order, while the linear alignment model results in two-point statistics for the II and GI signals that are rescaled versions of the linear matter power spectrum.

The linear alignment model has been phenomenologically extended by using the non-linear matter power spectrum instead of the linear one to account for small-scale effects (Bridle & King 2007, NJPh, 9, 444), or adding luminosity or extra redshift dependencies (see e.g. Joachimi et al. 2011, A&A, 527, 26). While these models are found to be in good agreement with current observations (Joachimi et al. 2011, A&A, 527, 26; Heymans et al. 2013, astro-ph/1303.1808), they lack physical motivation beyond the basic linear alignment model.

Schneider & Bridle (2010, MNRAS, 402, 2127) made a first attempt at a more consistent description of intrinsic alignments on small scales by devising a halo model. **The current implementation of the intrinsic alignment halo model simplistically assumes that the shapes of satellite galaxies all point towards the centre of the host halo and misses essential dependencies such as those on galaxy type and colour. However, the halo model can readily be extended to incorporate these and other more complex features, providing a clear framework to identify the free ingredients of the model (such as luminosity functions or radial alignment profiles of satellite galaxies) and how they can be constrained observationally.**

Complementary to the halo model ansatz, one can study intrinsic alignment signals in simulations. However, the accuracy which can eventually be achieved in this approach is currently unknown. Hydrodynamic simulations with a dark matter and baryon component could in principle produce realistic galaxy shapes and alignments, but their results depend strongly on the input sub-grid physics (see e.g. Semboloni et al. 2011, MNRAS, 417, 2020) and it is unclear if and when computational power will allow us to run sufficiently large simulations to beat down sample variance on intrinsic alignment signals. It will be possible to run hierarchical suites of dark matter-only simulations which jointly reach the required cosmological volume and mass resolution, but there remains a lot of freedom in modelling the link between dark matter halo shapes and alignments and the corresponding galaxy properties (Joachimi et al. 2013, astro-ph/1203.6833).

2.2 Observational constraints on intrinsic alignments

Due to the degeneracy with the cosmic shear signal, intrinsic alignments are difficult to constrain directly via observations. Measurements of the II signal are restricted to low redshifts where the contribution by gravitational lensing is negligible (e.g. Brown et al. 2002, MNRAS, 333, 501). Constraints on the GI term are inferred from measurements of how strongly the orientation of intrinsic shapes of galaxies is aligned with the large-scale distribution of galaxies. This requires a translation from the clustering of galaxies to the clustering of the underlying dark matter distribution, at present done via the assumption of linear galaxy bias (see Mandelbaum et al. 2006, MNRAS, 367, 611). This step limits the interpretation of measurements to relatively large scales (comoving galaxy separations above $\sim 10\,\mathrm{Mpc}/h$). A physically motivated and sufficiently complex halo model could simultaneously predict the clustering signal of relevant galaxy samples and hence remove this barrier.

To date detections have mostly been limited to luminous early-type samples (Mandelbaum et al. 2006, MNRAS, 367, 611; Hirata et al. 2007, MNRAS, 381, 1197; Joachimi et al. 2011, A&A, 527, 26), covering redshifts out to $z \sim 0.7$. Mandelbaum et al. (2011, MNRAS, 410, 844) analysed the largest late-type galaxy sample hitherto based on WiggleZ redshifts, but do not detect intrinsic alignments largely due to very large uncertainties induced by the low number density of the sample. On small scales the alignment of satellite galaxy shapes in galaxy clusters have been studied, but so far detections are tentative and partially in conflict with each other (see e.g. Hao et al. 2011, ApJ, 740, 39; Hung & Ebeling 2012, MNRAS, 421, 3229).

A typical galaxy in the Euclid cosmic shear survey for which intrinsic alignments will need to be well understood will be a quiescent late-type galaxy around redshifts of unity. **In the parameter space spanned by redshift, luminosity, and galaxy type we are currently far from constraining intrinsic alignments observationally among galaxies typically analysed with Euclid. Forthcoming surveys will explore much larger portions of this parameter space but will still find it hard to yield tight direct constraints on the intrinsic alignment signals relevant for Euclid. Therefore it is paramount to be able to rely on a robust physical intrinsic alignment model which can be extrapolated to the faint high-redshift objects that dominate the Euclid galaxy samples.**

Any future observations that will help improving our understanding of intrinsic alignments require top-quality imaging combined with precise redshift information (either spectroscopic or very precise photometric redshifts from multi-band photometry; see e.g. the proposed PAU Survey, `http://www.pausurvey.org`) for all galaxies. The resulting galaxy sample needs to cover significant cosmological volumes to beat down sample variance, and has to be reasonably dense on the sky to suppress shot noise in the error budget. Such tight requirements require careful and early planning with regards to making sure that suitable planned surveys take intrinsic alignments into consideration as a major science case.

2.3 Intrinsic alignment mitigation strategies in cosmological weak lensing

Both observations and simulations suggest that for certain galaxy samples intrinsic alignments could contribute up to $10\,\%$ to the correlation signal of galaxy shapes (Heavens et al. 2000, MNRAS, 319, 649; Heymans et al. 2006, MNRAS, 371, 750; Mandelbaum et al. 2006, MNRAS, 367, 611), so that ignoring intrinsic alignments would have a devastating effect on imminent and future cosmic shear analyses. All forthcoming surveys will obtain good photometric redshifts for each galaxy which can be used to isolate intrinsic alignment signals to some extent without further knowledge about the underlying physical processes. The II signal is restricted to physically close pairs of galaxies (since the galaxies have to be subjected to the same tidal gravitational field) and is thus straightforward to suppress (King & Schneider 2002, A&A, 396, 411). The GI term has a contribution from gravitational lensing and therefore a scaling with redshift that is very similar to cosmic shear. Nonetheless it is possible to remove the GI signal, but one can only do so robustly with a substantial loss in cosmological constraining power which is unacceptable for surveys like Euclid (Joachimi & Schneider 2008, A&A, 488, 829; Joachimi & Schneider 2009, A&A, 507, 105).

Further proposed mitigation techniques exploit information from polarised emission from galaxies (currently tested in SuperCLASS, `http://www.e-merlin.ac.uk/legacy/projects/superclass.html`) or spatially resolved radial velocity maps. These quantities are unaffected by gravitational lensing and can be used to extract the intrinsic galaxy orientation (Brown & Battye 2011, MNRAS, 410, 2057; Morales 2006, ApJ, 650, 21). These methods would only be directly applicable to radio observations (e.g. with the SKA), but could help calibrate intrinsic alignments in optical data that overlaps with radio surveys.

A promising way to self-calibrate intrinsic alignments, in particular the GI term, with data accessible from a cosmic shear survey alone was investigated by Bernstein (2009, ApJ, 695, 652) and Joachimi & Bridle (2010, A&A, 523, 1). The method takes advantage of the galaxy clustering information that comes for free with cosmic shear data. This can be used to measure galaxy bias as well as the alignment of galaxy shapes towards galaxy overdensities, which yields an estimate of the GI contribution. Joachimi & Bridle evaluated the performance of the self-calibration technique (see also Kirk et al. 2012, MNRAS, 424, 1647), choosing a minimum-knowledge ansatz by parametrising intrinsic alignments and galaxy bias as a grid flexible in both redshift and spatial scales, with more than a hundred nuisance parameters in total. Even so one can recover the cosmological information provided by a pure cosmic shear signal to a good degree.

This approach has subsequently been applied in forecasts of the performance of the Euclid mission, impacting on the top-level cosmological constraints achievable with Euclid, as well as the requirements on photometric redshift measurements, which are driven by the need to separate intrinsic alignments and cosmic shear (Laureijs et al. 2011, astro-ph/0912.0914). For a given amount of observation time, a medium-deep survey with maximal survey area optimises cosmological constraints achievable with cosmic shear (Amara & Refregier 2007, MNRAS, 381, 1018). Including intrinsic alignments drives the optimum towards a deeper and smaller survey because of the need for a long baseline in redshift which again helps separating the intrinsic alignment and cosmic shear signals (Laureijs et al. 2011, astro-ph/0912.0914).

However, the general grid parametrisation may be too flexible and involves fairly arbitrary choices (such as the number of grid nodes) about the degree of flexibility. Moreover it is difficult to link the nuisance parameters of this parametrisation to physical observables, so that prior constraints are challenging to incorporate. **Replacing the minimum-knowledge approach for intrinsic alignments in Euclid performance forecasts by a robust, physically motivated intrinsic alignment model will minimise the number of ill-motivated choices in the modelling and dramatically simplify the identification and inclusion of prior information on the model. Consequently, key science requirements for Euclid as well as its survey and analysis strategy will be verified or updated with much improved confidence.**

Furthermore, the alignment mechanisms of a well-working halo model could readily be used to create mock cosmic shear surveys from large suites of N-body simulations that include a realistic intrinsic alignment signal. This will be paramount for the central task of developing and optimising intrinsic alignment mitigation and calibration techniques to be employed in the Euclid cosmic shear data analysis.

3 Scope of the project

The goal of this proposal is to bring together an international team of experts on intrinsic galaxy alignments who are going to

1. gain an overview and discuss in detail the current state of the art in the understanding of intrinsic alignments, including modelling attempts, results from simulations and observations, and mitigation strategies in cosmic shear analyses;
2. jointly work towards a comprehensive halo model of intrinsic alignments, identifying key parameters and ways to constrain them observationally;
3. review the Euclid science requirements impacted on by intrinsic alignments, repeat cosmological forecasts with the updated intrinsic alignment model, and update requirements, survey strategy, and analysis methods if needed.

The two proposed meetings at ISSI Bern constitute the central part of this effort where the work is initiated, organised, and reviewed. It is expected that the project will yield the following outcomes:

1. an extensive review paper on the current knowledge of intrinsic alignments;
2. a novel, comprehensive, and physically motivated intrinsic alignment halo model, tested against current observations (resulting in at least one refereed publication);
3. a road map to constrain free parameters of the intrinsic alignment model observationally, including the planning of survey involvement and/or preparation of proposals;
4. an update/verification of Euclid science requirements, survey strategies, and analysis methods (one refereed publication).

These results will mark critical and timely steps towards a successful cosmological exploitation of Euclid as well as the forthcoming ground-based imaging surveys because, as outlined above, significant progress in the understanding of intrinsic alignments is required on time scales of about a year.

4 Proposal details

4.1 Schedule

We plan to have a kick-off meeting before the end of the year, ideally in autumn, to review the state of the art in intrinsic alignment research and identify the tasks to be worked on in the following months. This will be followed by a second meeting after 6 to maximally 12 months, where the results of our work will be presented and steps towards finalising the projects, such as writing up papers, be undertaken. Both meetings are planned to last 5 days. All team members are committed to attending both meetings, should academic duties such as teaching obligations allow.

4.2 Facilities

We will require standard facilities that should readily be available at ISSI. This includes two meeting rooms (to allow for work being carried out in parallel) equipped with projectors, plenty of white board space, and a stable, fast WiFi connection. Power adaptors to the Swiss system will also be needed for team members' laptops.

4.3 Financial support

We apply for the standard financial support offered by ISSI, covering a per diem for the team members during their stay at ISSI and travel costs for the team leader. We will also benefit from the Young Scientist scheme by requesting funding for one or two senior PhD students or junior postdocs important to the success of our project.

4.4 Added value

The role of ISSI will be critical to the success of the proposed project via its financial and in-kind support that enables two focused week-long meetings of international experts in intrinsic galaxy alignments. We will have the opportunity to meet in an inspiring location and atmosphere, avoiding the usual distractions faced at institutes or during conferences.

5 Team members

1. **Benjamin Joachimi** (*coordinator*): IfA, University of Edinburgh, Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ, United Kingdom; phone: +44-131-6688351; fax: +44-131-6688416; email: bj@roe.ac.uk
2. **Christopher Bonnet**: Institut de Ciencies de l'Espai, CSIC/IEEC, Fac de Ciencies, Torre C5 par-2, Barcelona 08193, Spain; phone: +34-935-868042; fax: N/A; email: c.bonnett@gmail.com
3. **Michael Brown**: Jodrell Bank Centre for Astrophysics, School of Physics & Astronomy, University of Manchester, Oxford Road, Manchester M13 9PL, UK; phone: +44-161-3063913; fax: +44-161-2754247; email: mbrown@jb.man.ac.uk
4. **Marcello Cacciato**: Leiden Observatory, Leiden University, Niels Bohrweg 2, 2333 CA Leiden, The Netherlands; phone: +31-71-5278467; fax: +33-71-527574; email: cacciato@strw.leidenuniv.nl
5. **Henk Hoekstra**: Leiden Observatory, Leiden University, Niels Bohrweg 2, 2333 CA Leiden, The Netherlands; phone: +31-71-5275594; fax: +33-71-5275743; email: hoekstra@strw.leidenuniv.nl
6. **Alina Kiessling**: NASA Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, 91109 CA, USA; phone: +1-626-2981495; fax: +1-818-3548895; email: alina.a.kiessling@jpl.nasa.gov
7. **Donnacha Kirk**: Department of Physics & Astronomy, University College London, Gower Street, London WC1E 6BT, UK; phone: +44-79-977410621; fax: N/A; email: donnachakirk@gmail.com
8. **Thomas Kitching**: Mullard Space Science Laboratory, Holmbury St. Mary, Dorking, Surrey RH5 6NT, UK; phone: +44-1483-204218; fax: +44-1483-278312; email: t.kitching@ucl.ac.uk
9. **Rachel Mandelbaum**: Department of Physics, Carnegie Mellon University, 5000 Forbes Avenue, Pittsburgh, PA 15213, USA; phone: +1-412-2681714; fax: +1-412-6810648; email: rmandelb@andrew.cmu.edu
10. **Anais Rassat**: LASTRO, EPFL, Observatoire de Sauverny, 1290 Versoix, Switzerland; phone: +33-671183365; fax: N/A; email: anais.rassat@epfl.ch
11. **Uros Seljak**: Department of Physics, Le Conte Hall, UC Berkeley, Berkeley CA 94708, USA; phone: +1-510-6662627; fax: N/A; email: useljak@berkeley.edu

Experts who potentially will contribute to the project:

- Ami Choi (Edinburgh)
- Alan Heavens (Imperial)
- Catherine Heymans (Edinburgh)
- Christopher Hirata (Ohio State)
- Adrienne Leonard (Saclay)
- Reiko Nakajima (Bonn)
- Peter Schneider (Bonn)