DOI: 10.18727/0722-6691/5307

4MOST Complete Calibration of the Colour-Redshift Relation (4C3R2)

Daniel Gruen[1]
Jamie McCullough[2,3,1]
Alexandra Amon[4,5]
Gary Bernstein[6]
Jan Luca van den Busch[7]
Rebecca Canning[8]
Francisco Castander[9,10]
Joseph DeRose[11]
William Hartley[12]
Hendrik Hildebrandt[7]
Konrad Kuijken[13]
Jochen Liske[14]
Daniel Masters[15]
Ramon Miquel[16,17]
Andrea Pocino Yuste[9,10]
Aaron Roodman[2,3]
Stella Seitz[1]
Roberto Saglia[1]
Daniel Stern[18]
Luca Tortorelli[1]
Angus H. Wright[7]

[1] University Observatory, Faculty of Physics, Ludwig Maximilians University, Munich, Germany
[2] Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, USA
[3] SLAC National Accelerator Laboratory, USA
[4] Institute of Astronomy, University of Cambridge, UK
[5] Kavli Institute for Cosmology, University of Cambridge, UK
[6] Department of Physics & Astronomy, University of Pennsylvania, USA
[7] German Centre for Cosmological Lensing, Astronomical Institute, Faculty of Physics and Astronomy, Ruhr University Bochum, Germany
[8] Institute of Cosmology and Gravitation, University of Portsmouth, UK
[9] Catalunya Institute of Space Studies, Barcelona, Spain
[10] Institute of Space Sciences (ICE, CSIC), Barcelona, Spain
[11] Lawrence Berkeley National Laboratory, Berkeley, USA
[12] Department of Astronomy, University of Geneva, Switzerland
[13] Leiden Observatory, Leiden University, the Netherlands
[14] Hamburg Observatory, University of Hamburg, Germany
[15] IPAC, California Institute of Technology, USA
[16] Institute of High-Energy Physics, Barcelona Institute of Science of Technology, Spain
[17] Catalan Institution for Research and Advanced Studies, Barcelona, Spain
[18] Jet Propulsion Laboratory, California Institute of Technology, USA

Accurate knowledge of the redshift distributions of faint samples of galaxies selected by broad-band photometry is a prerequisite for future weak lensing experiments to deliver precision tests of our cosmological model. The most direct way to measure these redshift distributions is spectroscopic follow-up of representative galaxies. For this to be efficient and accurate, targets have to be selected such that they systematically cover a space defined by apparent colours in which there is little variation in redshift at any point. 4C3R2 will follow this strategy to observe over 100 000 galaxies selected by their KiDS-VIKING *ugriZYJHK$_s$* photometry over a footprint identical to that of the WAVES survey, to constrain the colour-redshift relation with high multiplicity across two-thirds of the colour space of future Euclid and Rubin samples.

Scientific context: the colour-redshift relation for weak lensing surveys

Our cosmological model predicts the growth of large-scale structure to be highly sensitive to the densities and fundamental physical laws of the different constituents of cosmic energy density, among them the elusive dark matter, dark energy, and massive neutrinos. Photometric surveys can directly probe the large-scale matter density distribution via the apparent distortion of the shapes of galaxy images. These distortions are caused by tidal gravitational forces that act on the distant galaxy's light along its path to us, the so-called weak gravitational lensing effect. The strength of the distortion depends not only on the matter distribution these experiments intend to measure, but also on the distances to the lensed galaxies. This has motivated the development of a range of techniques to not just estimate photometric redshifts but also accurately calibrate the redshift distributions of photometrically selected samples of galaxies (see, for example, Newman & Gruen, 2022 for a review). The direct determination of the redshift distribution with spectroscopy is advantageous in multiple ways. However, present samples of spectroscopic redshifts allow for a calibration of galaxy distances that is only scarcely sufficient for the ongoing lensing experiments (Hildebrandt et al., 2021; Myles et al., 2021; Rau et al., 2022). The currently required calibration uncertainties on the mean redshift are of order $|\Delta z| \sim 0.01$. But the next generation of surveys by Euclid, Vera C. Rubin Observatory, and the Nancy Grace Roman Space Telescope are predicted to need an order of magnitude improvement, with the calibrated mean redshift accurate to a few parts in a thousand and stringent requirements as well on the calibration of the width of redshift distributions. We will thus be severely limited in testing cosmological models unless large, systematically selected and highly complete spectroscopic samples can be obtained.

Complete calibration of the colour-redshift relation

Direct calibration of redshift distributions (for example, Hildebrandt et al., 2017) effectively consists of making a histogram of spectroscopic redshifts. For this estimate of the redshift distribution to be unbiased, the spectroscopic sample has to be representative of the set of galaxies in question that results from some photometric selection. For the estimate to be of sufficiently small statistical uncertainty, the spectroscopic sample has to be collected over a large enough volume and with high multiplicity. With current instruments this is prohibitively demanding of exposure time for weak lensing source galaxy samples. This is not just because the galaxies in these samples are faint and thus their spectroscopic redshifts difficult to acquire. In addition, the large variation in the redshifts of galaxies selected from noisy, few-broadband photometry means (i) that incompleteness can strongly bias the sample if the success of a spectroscopic observation depends on the redshift of a targeted galaxy (for example, Gruen & Brimioulle, 2017), and (ii) that a very large number of randomly sampled spectroscopic redshifts is required to achieve a sufficiently small

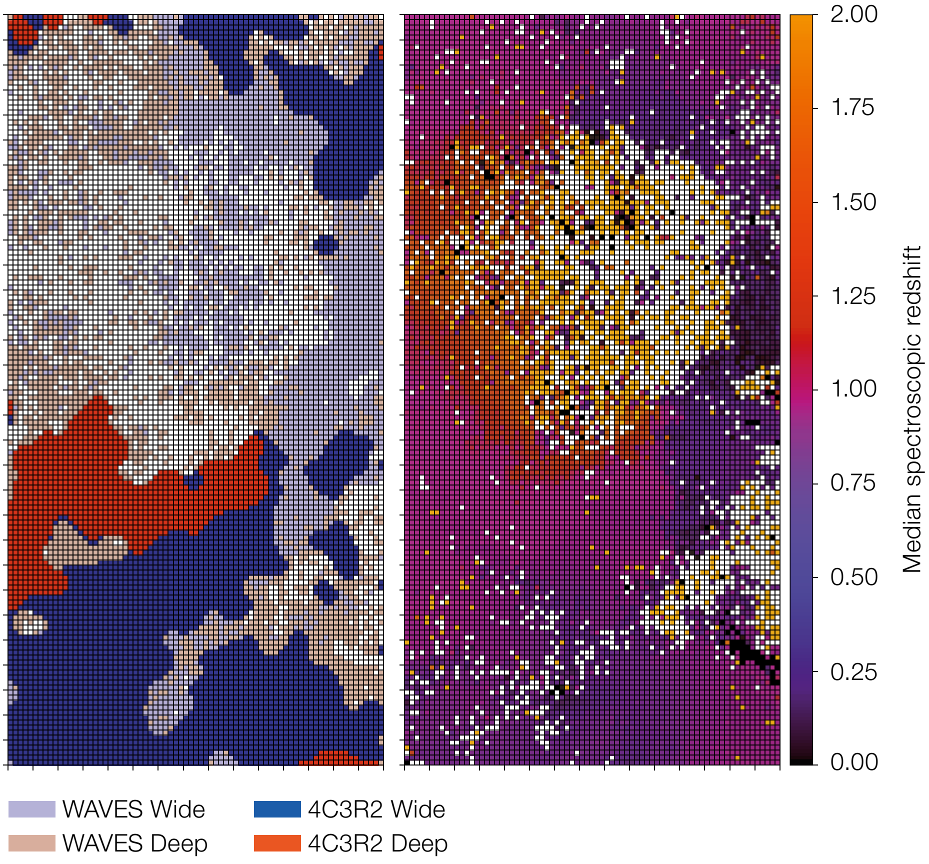

Figure 1. The *ugriZYJHK*$_s$ colour space of galaxies is discretised by the self-organising map (SOM) of Masters et al. (2015) that is shown in two ways here. The left panel illustrates which cells of the SOM constitute the colour selections for 4C3R2-Wide/Deep and parts of colour space covered by the preliminary WAVES-Wide/Deep selections, which are not always cell-complete. The right panel shows the median redshift of existing archival samples across the same SOM. Of importance for our selections are the z = 0.2 and z = 0.8 transitions where WAVES-Wide/Deep become incomplete by design, and above which 4C3R2 selects representative subsets of galaxies for targeting.

statistical error (for example, Newman & Gruen, 2022, their section 3.3).

A much more efficient strategy is to bin galaxies by colour in a set of bands such that in each bin there is as little scatter in redshift and as little evolution of redshift with apparent magnitude as possible. A technique that has been used for this extensively in the literature involves so-called self-organising maps (SOMs). These are few-dimensional grids of colour values contiguously embedded into the high-dimensional space of observed galaxy colours. The embedding is optimised in such a way that each galaxy can be assigned to a grid cell with small colour separation. Figure 1 shows the SOM of Masters et al. (2015). By appropriately sampling each bin, i.e., each cell of the map, relatively few spectroscopic observations of relatively bright galaxies constrain the statistical relation between colour and redshift. For surveys observing in a smaller or slightly different set of photometric bands, or observing at higher noise levels, any selection of galaxies can still be approximately expressed as a linear combination of the original SOM cells, and thus its redshift calibration can be related to the SOM's colour-redshift relation (Buchs et al., 2019; Myles et al., 2021). This has motivated a set of optical and near-infrared spectroscopic surveys to sparsely cover the cells of this particular SOM (Masters et al., 2017, 2019; Euclid Collaboration et al., 2020), in addition to survey data from the Dark Energy Spectroscopic Instrument (McCullough et al., in preparation). The right panel of Figure 1 shows the state of spectroscopically calibrating the median redshift across this SOM. The achievable effective resolution of this map is limited by photometric noise in the observing survey, as galaxies can scatter (also asymmetrically) between neighbouring cells.

Specific scientific goals: densely probe galaxy colour space with 4MOST spectra

The observing programmes outlined above have the common goal of a complete calibration of the colour-redshift relation (C3R2) and this survey adds a 4MOST component to that effort. Approximately two thirds of the colour bins defined by C3R2 (Masters et al., 2015) contain galaxies bright enough to achieve high redshift completeness with 4MOST spectroscopy in a feasible exposure time. Unlike many of the deep, sparse surveys performed so far, 4MOST offers the unique possibility of achieving high multiplicity in each of these cells, i.e., to probe the full distribution of redshift given colour. This will allow us to address pressing questions about redshift calibration with the colour-SOM method, such as whether the presence of rare redshift outliers at a given observed colour is a relevant effect. It also allows the dependence of redshift on magnitude at fixed colour to be accurately tested and calibrated. The latter is critical for utilising the relatively bright subset of galaxies observed spectroscopically for calibrating the redshift distributions of faint, photometric samples of equal colour. The resulting sample will form the broad basis for a wedding-cake C3R2 strategy that continues to require 8-metre-class and/or infrared spectroscopy for the parts of colour and magnitude space inaccessible to 4MOST.

Target selection and survey area: synergies with KiDS-VIKING and WAVES

Photometry in the *ugriZYJHK*$_s$ bands from the Kilo-Degree Survey and the VISTA Kilo degree Infrared Galaxy survey (KiDS-VIKING) provides the basis for selecting targets across a highly informative colour space and over an unprecedented volume for a photometric redshift calibration survey. 4C3R2 does this from the same photometric catalogue and over the same area as the Wide Area Vista Extragalactic Survey (WAVES), spanning more than 1170 square degrees (Driver et al., 2019). Unlike the high completeness strategy of WAVES, 4C3R2 requests only a small subset of the potential targets. This allows for flexible fibre assignment and a high degree of synergy. The two surveys are currently optimising their joint selection through simulations, including an exploration of whether entirely disjunct target selections or partial overlap between the two surveys' samples is the most efficient option. The preliminary choice of the limiting magnitude of $z = 21.6$ in 4C3R2-Wide is slightly deeper than WAVES, with a $z = 22$ selection in 4C3R2-Deep that matches WAVES-Deep. The left panel of Figure 1 depicts the colour selection of 4C3R2 targets for both the wide and deep surveys. Cells that contain WAVES targets, estimated according to existing photometric redshifts, are indicated by light colours. 4C3R2 intentionally does not select from areas in the map that are dominated by low-redshift galaxies, for example the low-redshift ($z < 0.2$) filament that runs across the right half of the left panel of Figure 1. This results in a complementary proposal of acquiring redshifts that are representative (4C3R2) by colour and magnitude where they cannot be complete (as for the WAVES selection) for as much of the physical manifold of colour and redshift as possible. Specifically, 4C3R2 aims to sample targets from cells whose redshifts have a high probability of being within the range of $0.2 < z < 1.55$ in wide, and similarly $0.8 < z < 1.55$ in deep. The lower limit is motivated by the WAVES selection, while the upper limit is constrained by spectroscopic features redshifting out of 4MOST's sensitivity wavelength range. While colour-redshift calibration is the primary purpose of 4C3R2, the survey data will thus also optimally complement WAVES. 4C3R2 empirically determines the targeting incompleteness of WAVES over the redshift ranges the latter intends to cover. In addition, the 4C3R2 sample extends the subset of galaxy evolution science cases that can be studied with representative but incomplete sampling over a wider redshift range and to somewhat fainter objects.

Acknowledgements

This work was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy – EXC-2094 – 390783311. DG (daniel.gruen@lmu.de) and JM (jmccull@stanford.edu) as corresponding authors acknowledge support by the Bavaria California Technology Center (BaCaTeC).

References

Buchs, R. et al. 2019, MNRAS, 489, 820
Driver, S. P. et al. 2019, The Messenger, 175, 46
Euclid Collaboration et al. 2020, A&A, 642, A192
Gruen, D. & Brimioulle, F. 2017, MNRAS, 468, 1, 769
Hildebrandt, H. et al. 2017, MNRAS, 465, 1454
Hildebrandt, H. et al. 2021, A&A, 647, A124
Masters, D. et al. 2015, ApJ, 813, 53
Masters, D. C. et al. 2017, ApJ, 841, 111
Masters, D. C. et al. 2019, ApJ, 877, 81
Myles, J. et al. 2021, MNRAS, 505, 4249
Newman, J. A. & Gruen, D. 2022, ARAA, 60, 363
Rau, M. M. et al. 2022, arXiv:2211.16516

Zdeněk Bardon (bardon.cz)/ESO

In this picture, Venus is shining brightly over ESO's La Silla Observatory in Chile. The picture was taken just before dawn, towards the East, and also features the diffuse zodiacal light — sunlight scattered by dust particles in the Solar System. The three domes to the left of the road are the BlackGEM telescopes, built by Radboud University, the Netherlands Research School for Astronomy (NOVA), and KU Leuven in Belgium. BlackGEM will search for the afterglow of some of the most dramatic events in the Universe, such as the collision of black holes and neutron stars.