Euclid – an ESA Medium Class mission

Benjamin Joachimi,[1]

[1] *Department of Physics & Astronomy, University College London, United Kingdom;* `b.joachimi@ucl.ac.uk`

Abstract. Euclid is an ESA Medium Class mission in the Cosmic Visions programme to be launched in 2020. With its 1.2m telescope, Euclid is going to survey $15,000\,\mathrm{deg}^2$ of extragalactic sky in a broad optical band with outstanding image quality fit for weak gravitational lensing measurements. It will also provide near-infrared slitless spectroscopy of more than 10^7 emission-line galaxies with the main goal of measuring galaxy clustering. Imaging in three near-infrared bands by Euclid will be complemented by ground-based follow-up in optical bands to supply high-quality photometric redshift estimates out to $z = 2$. In combination, its primary cosmological science drivers, weak gravitational lensing and galaxy clustering, will yield unprecedented constraints on the properties of dark matter and dark energy, as well as the validity of Einstein gravity on large scales. Euclid's rich datasets will facilitate further cosmological probes such as statistics of galaxy clusters or the study of galactic dark matter haloes, and a vast array of legacy science. In the following a brief overview on the Euclid mission and its key science is provided.

1. Galaxy survey cosmology from space

In the past few decades cosmology has undergone a rapid transition from a notoriously data-starved science to one that abounds in a variety of increasingly large sets of observations and simulations, to the point that the field faces a novel challenge in processing huge datasets and in extracting small cosmological signals from much larger noise and non-cosmological 'foregrounds'. A prime source of information that was instrumental in establishing and affirming the standard model of cosmology is the cosmic microwave background (CMB), as explored by the Planck satellite (Planck Collaboration et al. 2015) as well as its space-based predecessors and ground-based complements. While the CMB provides us with an accurate picture of the state of the Universe at a redshift $z \sim 1000$, we need a similarly precise census at low redshifts below unity in order to cover the recent phase of accelerated expansion and establish a baseline to the CMB which measures the growth rate of matter structures. This will allow us to get clues on the nature of dark matter and dark energy, which together comprise 95 % of the energy density in the Universe, and enables tests of Einstein's theory of gravity on unprecedentedly large scales.

Galaxy surveys are the prime candidates to deliver the measurements for precision cosmology at low redshift (Albrecht et al. 2006; Peacock et al. 2006). The three-dimensional clustering of galaxies as measured from spectroscopic redshift surveys probes the spatial geometry via the baryon acoustic oscillation peak, measures the distribution of galaxy velocities via redshift-space distortions, and constrains the amplitude and shape of the matter power spectrum. The small, coherent distortions of galaxy shapes due to the gravitational lensing effect by the large-scale structure in-between these galaxies and the observer are a powerful probe of geometry and the total matter distribution, including its evolution. This technique is known as weak gravitational lensing, where 'weak' refers to the fact that the changes in galaxy shapes are typically at the per cent level of the intrinsic galaxy shape and hence can only be detected by statistical analysis over large numbers of objects. Analysed jointly, in particular if in the same parts of the sky, these two probes are highly complementary in their constraints on key cosmological parameters (see Eriksen & Gaztanaga 2014, and references therein) and in their capabilities of self-calibrating systematic effects (see e.g. Bernstein 2009; Joachimi & Bridle 2010, for the case of astrophysical nuisance signals).

The European Space Agency's Euclid mission[1] follows this concept in adopting galaxy clustering and weak gravitational lensing as its primary probes which drive the mission. Its main science goals are at least order-of-magnitude improvements on parameters of the properties of dark energy (such as the equation of state), dark matter (such as mass constraints on neutrino species and more exotic dark matter candidates), and gravity (such as the growth rate of matter structures). The rich dataset that Euclid will accumulate will also allow for the study of secondary cosmological probes, such as galaxy cluster counts, galaxy-CMB cross-correlations, and strong lensing statistics, as well as a vast array of legacy science, especially in the field of galaxy evolution. For more details see Laureijs et al. (2011), the Definition Study Report which formed the basis of the selection of Euclid as a medium-class mission in ESA's Cosmic Visions programme.

2. The Euclid mission

Figure 1 shows an image of the satellite and a sketch of its payload. Euclid consists of a three-mirror, on-axis telescope with a 1.2m primary mirror. It will carry two instruments, both with a 0.5deg^2 field of view. VIS (Cropper et al. 2014) is an optical imager with a $\sim$500 Megapixel CCD camera that observes in a broad band (RIZ) from $550 - 900$nm. With a pixel size of $0.1''$, VIS will produce galaxy images with a spatial resolution and stability of image quality that is impossible to achieve from the ground, making it ideally suited for the galaxy shape measurements required for weak gravitational lensing. NISP combines near-infrared broad-band photometry in the Y, J, and H bands and slitless grism spectra within the wavelength range $1 - 2\mu$m (exact limits within this range are still to be confirmed), with spectral resolution $R = 250$. The NISP instrument has a filter wheel that selects between the three broad filters and grisms in different orientations separated by 90deg to deal with the confusion of slitless spectra. Redshifts for the galaxy clustering sample will mainly be measured from the Hα emission line, with a baseline expectation of 2.5×10^7 galaxies in a redshift range that is complementary to existing and forthcoming ground-based galaxy redshift surveys.

Euclid builds on the philosophy that it only performs those measurements from space that cannot be done from the ground, or only so with severe limitations. This includes the optical imaging with weak lensing quality as well as near-infrared data. Optical broad-band photometry (*ugriz*) is readily obtained from the ground and therefore

---

[1] `http://sci.esa.int/euclid`

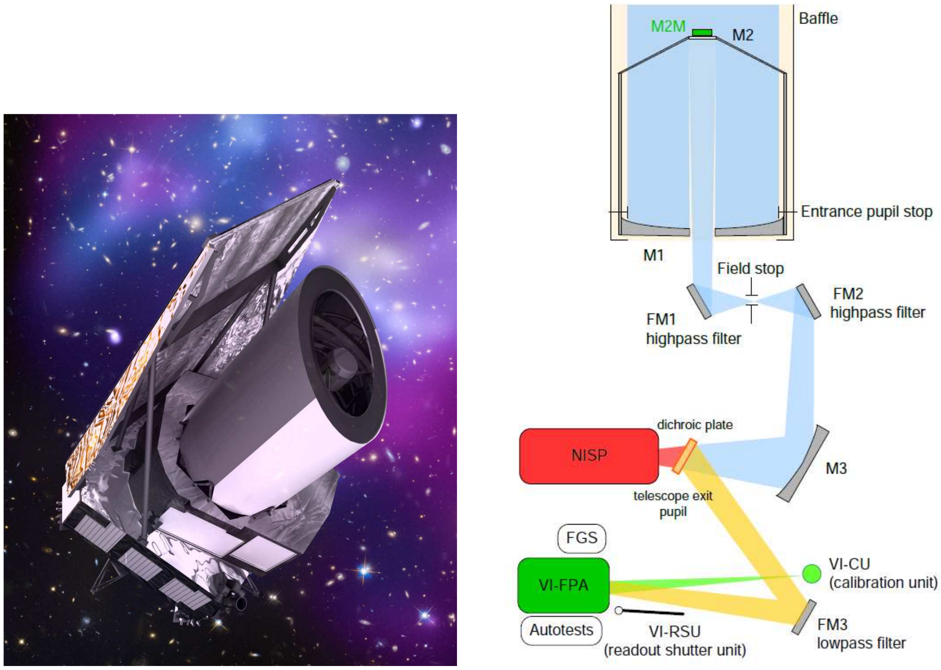

Figure 1. *Left:* Artist's impression of the spacecraft. © ESA. *Right:* Sketch of the Euclid payload module. It consists of a three-mirror telescope with a primary of 1.2m diameter. The two instruments are the visual imager (green) and the NISP instrument (red) which will perform near-infrared photometry and slitless spectroscopy. © Airbus Defence and Space. Figures accessed from `http://www.euclid-ec.org`.

will complement Euclid's own data, primarily for the purpose of determining photometric redshift estimates for the 1.5×10^9 galaxies expected in the Euclid weak lensing sample. Together with the on-board near-infrared bands, the photometric redshift scatter will be $0.05(1 + z)$ in the range $z = [0.2; 2]$, with no more than 10 % of catastrophic failures.

Launched from Kourou in a Soyuz rocket, Euclid will be delivered to the Sun-Earth Lagrange point 2 for a total of six years of main science programme. Apart from extensive calibration observations (e.g. on the deep fields observed by the Hubble Space Telescope, HST), this programme consists of the Wide Survey, covering $15,000\,\mathrm{deg}^2$ of extragalactic sky (note the dominant contribution to the background in the images comes from zodiacal light) and the Deep Survey of $40\,\mathrm{deg}^2$. Wide Survey areas are visited once (with typically four dithers per field) and observed in step-and-stare mode to a depth of 24.5mag (10σ extended source) in the RIZ band, to 24 mag (5σ point source) in YJH, and to $3 \times 10^{-16}\,\mathrm{ergs}^{-1}\mathrm{cm}^{-2}$ (3.5σ line flux) for the spectroscopy. The Deep Survey fields will be located at, or close to, the Ecliptic poles (details are still under discussion) and revisited to become eventually 2 magnitudes deeper than the Wide Survey. While the Wide Survey is the driver of Euclid's cosmological constraining power, the Deep Survey has high legacy value and is instrumental for characterising the success rate of spectroscopic redshifts as well as the intrinsic distribution of galaxy ellipticities required for gravitational shear estimation.

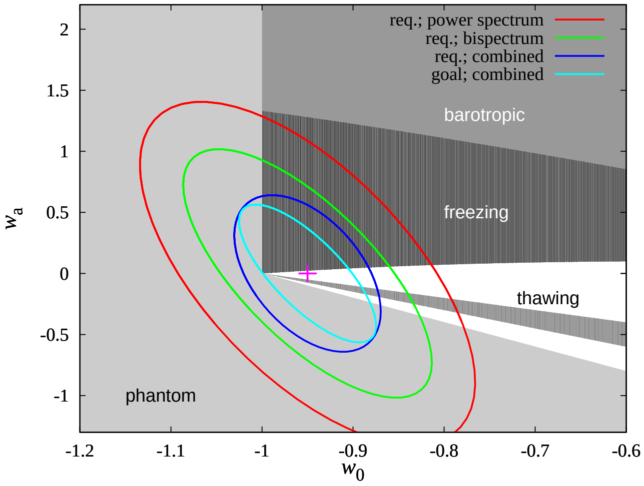

Figure 2. Predicted constraints on the dark energy equation of state parameters w_0 and w_a with Euclid weak lensing. The grey areas indicate different classes of dark energy models (Barger et al. 2006). Contours are 2σ for constraints from two-point statistics (power spectrum) and three-point statistics (bispectrum), for the reference Euclid survey (req.) and a more optimistic performance (goal). From Joachimi (2010), with updated survey area.

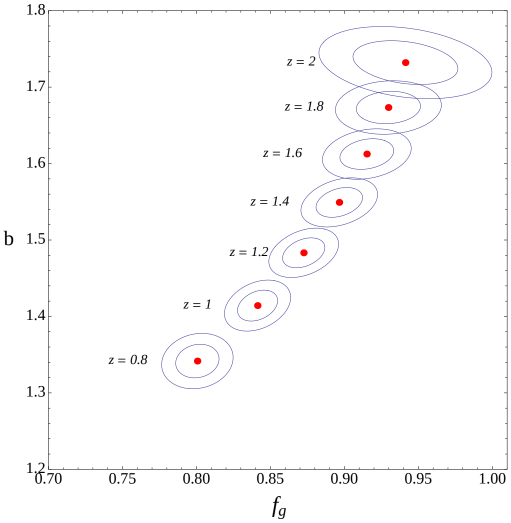

Figure 3. Predicted constraints on the linear deterministic galaxy bias b and the growth rate of structure f_g with Euclid spectroscopic galaxy clustering. Contours are 68 % and 98 % and shown for seven out of 14 redshift bins, where both b and f_g are varied independently in each bin. Reproduced with permission from Amendola et al. (2013).

Figures 2 to 4 show a small selection of cosmological constraints that Euclid will be uniquely positioned to obtain: constraints on the dark energy equation of state parameter w_0 and w_a from Euclid weak lensing statistics (Figure 2), joint constraints on

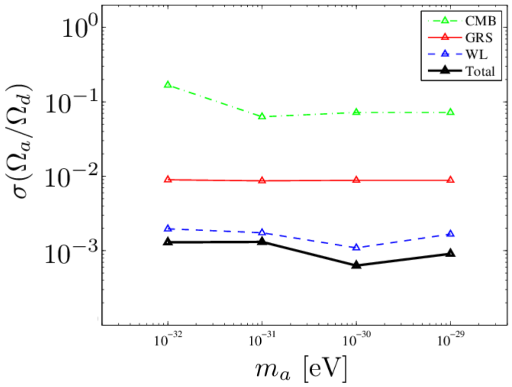

Figure 4. Predicted 1σ constraints on the fraction Ω_a/Ω_d of the contribution by axions (light dark matter candidates) to the total dark matter density. Individual constraints are for a Planck-like survey (CMB), Euclid clustering (GRS), and Euclid weak lensing (WL). The combined measurement yields a $\sim$ 0.1 % error driven by weak lensing, independent of axion mass. Reproduced with permission from Marsh et al. (2012).

the growth rate of matter structures and galaxy bias from Euclid galaxy clustering (Figure 3), and constraints on the fraction of a potential contribution by axions to the total dark matter density from a joint Planck and Euclid primary probes analysis (Figure 4).

Euclid was originally created by merging two independent proposals in the Cosmic Visions programme, DUNE for weak gravitational lensing and SPACE for galaxy clustering. While these origins are still reflected in Euclid's two instruments, there is now a single Euclid Consortium[2], which forms the largest collaboration of astrophysicists on the planet and is responsible for building Euclid's instrument and data analysis pipelines. For more details on the Euclid mission see e.g. Laureijs et al. (2014b).

3. Some key challenges

In the following a few important challenges for the mission design and data analysis of Euclid are highlighted. This selection is strongly biased towards the main activities of the author and should merely serve as a starting point for further reading and to give a flavour of the on-going research activities in the Euclid Consortium.

3.1. Slitless spectroscopy

The main issue for the analysis of spectroscopic data is the confusion of the slitless spectra, which is alleviated by two to three different grism positions per pointing (see Zoubian et al. 2014 for details and NISP instrument simulations). The required purity is at least 80 % (increasing to > 99 % for the Deep Survey), with a minimum completeness of 45 %. Moreover, the number density of Hα emitters at $z > 1$ is still uncertain,

---

[2] `http://www.euclid-ec.org`

with recent results pointing to a lower density than originally expected (L. Pozzetti, C. Hirata, J. Geach, in prep.).

3.2. Galaxy shape measurement

The main challenge on the weak lensing side is the precise measurement of gravitational shear on faint, small, and pixelated galaxy images. Much progress has taken place over the last few years, as demonstrated, and indeed fostered, by the GREAT challenges (Mandelbaum et al. 2014; Kitching et al. 2012; Bridle et al. 2010). The sources of systematics on shear measurement and their propagation are now well understood and have been translated into requirements on the Euclid design and analysis (Cropper et al. 2013; Massey et al. 2013). In particular, the important so-called noise bias, generated by the non-linear propagation of pixel noise in the image to galaxy ellipticity, has been thoroughly investigated from first principles (Viola et al. 2014, and references therein). Semboloni et al. (2013a) looked at the subtle colour-gradient bias, which is important for Euclid with its wavelength-dependent point spread function (as it is diffraction-limited) and very broad optical filter, and proposed to calibrate the effect with existing multi-colour HST observations.

3.3. Astrophysical systematics

Galaxy surveys contain a wealth of information on small scales, which, however, is difficult to extract because of the non-linear evolution of structures, the influence of processes driven by baryonic matter, and astrophysical contaminants which become increasingly complicated to model on small scales. Prime examples of the latter class are non-linear, stochastic, and scale-dependent galaxy bias for galaxy clustering (e.g. Percival et al. 2007) and intrinsic galaxy alignments for weak lensing (Joachimi et al. 2015; Kiessling et al. 2015; Kirk et al. 2015). New large-volume hydro-dynamic simulations indicate that much work is also still to be done on modelling the matter power spectrum on small scales, which are affected by as yet little-understood baryonic processes (Semboloni et al. 2013b).

3.4. Data analysis

The large data volume including the ingestion of ground-based and external data and the involved, inter-dependent data processing steps make for a complex analysis pipeline in the Euclid ground segment (see Laureijs et al. 2014a). In addition, a huge simulation effort will be required for testing algorithms and the end-to-end pipeline, as well as determining the statistical uncertainties of the cosmological measurements (Taylor et al. 2013). Closely related to this are purely statistical considerations, such as the cosmology dependence of covariance matrices (Kalus et al. 2015) or the impact of noise in the covariance matrix (Percival et al. 2014; Taylor & Joachimi 2014).

4. Status and timeline

In June 2012 Euclid was approved for implementation by ESA, with a launch date scheduled for the end of 2020. Further important milestones will be the critical design reviews of the two instruments later this year and of the mission and ground segment in 2017. The nominal mission will end in 2027, while the data analysis is likely to keep researchers busy until the end of that decade. This makes Euclid a contemporary of other, largely complementary surveys such as LSST[3], DESI[4], NASA'S WFIRST[5] mission (which exploits similar probes but is deeper and covers less area), and the first stages of the SKA[6]. Together with these other projects, Euclid is expected to drive a decisive advancement of our knowledge of cosmology, structure formation, and extragalactic astrophysics in the coming decade.

Acknowledgments. The author is grateful to D. Marsh for providing him with an updated figure and helpful explanations. The vast majority of the work presented here is that of members of the Euclid Consortium and ESA. BJ acknowledges support by an STFC Ernest Rutherford Fellowship, grant reference ST/J004421/1.

References

Albrecht, A., Bernstein, G., Cahn, R., Freedman, W. L., Hewitt, J., & et al. 2006, astro-ph/0609591

Amendola, L., Appleby, S., Bacon, D., Baker, T., Baldi, M., Bartolo, N., Blanchard, A., Bonvin, C., Borgani, S., Branchini, E., Burrage, C., Camera, S., Carbone, C., Casarini, L., Cropper, M., de Rham, C., Di Porto, C., Ealet, A., Ferreira, P. G., Finelli, F., García-Bellido, J., Giannantonio, T., Guzzo, L., Heavens, A., Heisenberg, L., Heymans, C., Hoekstra, H., Hollenstein, L., Holmes, R., Horst, O., Jahnke, K., Kitching, T. D., Koivisto, T., Kunz, M., La Vacca, G., March, M., Majerotto, E., Markovic, K., Marsh, D., Marulli, F., Massey, R., Mellier, Y., Mota, D. F., Nunes, N., Percival, W., Pettorino, V., Porciani, C., Quercellini, C., Read, J., Rinaldi, M., Sapone, D., Scaramella, R., Skordis, C., Simpson, F., Taylor, A., Thomas, S., Trotta, R., Verde, L., Vernizzi, F., Vollmer, A., Wang, Y., Weller, J., & Zlosnik, T. 2013, Living Reviews in Relativity, 16, 6. `1206.1225`

Barger, V., Guarnaccia, E., & Marfatia, D. 2006, Phys. Lett. B, 635, 61

Bernstein, G. M. 2009, ApJ, 695, 652

Bridle, S., Balan, S. T., Bethge, M., Gentile, M., Harmeling, S., Heymans, C., Hirsch, M., Hosseini, R., et al. 2010, MNRAS, 405, 2044

Cropper, M., Hoekstra, H., Kitching, T., Massey, R., Amiaux, J., Miller, L., Mellier, Y., Rhodes, J., Rowe, B., Pires, S., Saxton, C., & Scaramella, R. 2013, MNRAS, 431, 3103. `1210.7691`

Cropper, M., Pottinger, S., Niemi, S.-M., Denniston, J., Cole, R., Szafraniec, M., Mellier, Y., Berthé, M., Martignac, J., Cara, C., di Giorgio, A. M., Sciortino, A., Paltani, S., Genolet, L., Fourmand, J.-J., Charra, M., Guttridge, P., Winter, B., Endicott, J., Holland, A., Gow, J., Murray, N., Hall, D., Amiaux, J., Laureijs, R., Racca, G., Salvignol, J.-C., Short, A., Lorenzo Alvarez, J., Kitching, T., Hoekstra, H., & Massey, R. 2014, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, vol. 9143 of Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, 0

Eriksen, M., & Gaztanaga, E. 2014, ArXiv e-prints. `1412.8429`

Joachimi, B. 2010, Cosmic shear and the intrinsic alignment of galaxies (Bonn University, urn:nbn:de:hbz:5N-23320)

Joachimi, B., & Bridle, S. L. 2010, A&A, 523, 1

Joachimi, B., Cacciato, M., Kitching, T. D., Leonard, A., Mandelbaum, R., Schäfer, B. M., Sifón, C., Hoekstra, H., Kiessling, A., Kirk, D., & Rassat, A. 2015, ArXiv e-prints. `1504.05456`

---

[3] `http://www.lsst.org/lsst`

[4] `http://desi.lbl.gov/cdr`

[5] `http://wfirst.gsfc.nasa.gov`

[6] `https://www.skatelescope.org`

Kalus, B., Percival, W. J., & Samushia, L. 2015, ArXiv e-prints. `1504.03979`

Kiessling, A., Cacciato, M., Joachimi, B., Kirk, D., Kitching, T. D., Leonard, A., Mandelbaum, R., Schäfer, B. M., Sifón, C., Brown, M. L., & Rassat, A. 2015, ArXiv e-prints. `1504.05546`

Kirk, D., Brown, M. L., Hoekstra, H., Joachimi, B., Kitching, T. D., Mandelbaum, R., Sifón, C., Cacciato, M., Choi, A., Kiessling, A., Leonard, A., Rassat, A., & Schäfer, B. M. 2015, ArXiv e-prints. `1504.05465`

Kitching, T. D., Balan, S. T., Bridle, S., Cantale, N., Courbin, F., Eifler, T., Gentile, M., Gill, M. S. S., Harmeling, S., Heymans, C., Hirsch, M., Honscheid, K., Kacprzak, T., Kirkby, D., Margala, D., Massey, R. J., Melchior, P., Nurbaeva, G., Patton, K., Rhodes, J., Rowe, B. T. P., Taylor, A. N., Tewes, M., Viola, M., Witherick, D., Voigt, L., Young, J., & Zuntz, J. 2012, MNRAS, 423, 3163. `1202.5254`

Laureijs, R., Amiaux, J., Arduini, S., Auguères, J., Brinchmann, J., Cole, R., Cropper, M., Dabin, C., et al. 2011, Euclid Definition Study Report, ESA/SRE(2011)12, astro-ph/1110.3193

Laureijs, R., Hoar, J., Buenadicha3, G., Mellier, Y., Pasian, F., Dabin, C., Sauvage, M., & Euclid Collaboration 2014a, in Astronomical Data Analysis Software and Systems XXIII, edited by N. Manset, & P. Forshay, vol. 485 of Astronomical Society of the Pacific Conference Series, 495

Laureijs, R., Racca, G., Stagnaro, L., Salvignol, J.-C., Lorenzo Alvarez, J., Saavedra Criado, G., Gaspar Venancio, L., Short, A., Strada, P., Colombo, C., Buenadicha, G., Hoar, J., Kohley, R., Vavrek, R., Mellier, Y., Berthe, M., Amiaux, J., Cropper, M., Niemi, S., Pottinger, S., Ealet, A., Jahnke, K., Maciaszek, T., Pasian, F., Sauvage, M., Wachter, S., Israelsson, U., Holmes, W., Seiffert, M., Cazaubiel, V., Anselmi, A., & Musi, P. 2014b, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, vol. 9143 of Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, 0

Mandelbaum, R., Rowe, B., Armstrong, R., Bard, D., Bertin, E., Bosch, J., Boutigny, D., Courbin, F., Dawson, W. A., Donnarumma, A., Fenech Conti, I., Gavazzi, R., Gentile, M., Gill, M. S. S., Hogg, D. W., Huff, E. M., Jee, M. J., Kacprzak, T., Kilbinger, M., Kuntzer, T., Lang, D., Luo, W., March, M. C., Marshall, P. J., Meyers, J. E., Miller, L., Miyatake, H., Nakajima, R., Ngole Mboula, F. M., Nurbaeva, G., Okura, Y., Paulin-Henriksson, S., Rhodes, J., Schneider, M. D., Shan, H., Sheldon, E. S., Simet, M., Starck, J.-L., Sureau, F., Tewes, M., Zarb Adami, K., Zhang, J., & Zuntz, J. 2014, ArXiv e-prints. `1412.1825`

Marsh, D. J. E., Macaulay, E., Trebitsch, M., & Ferreira, P. G. 2012, Phys.Rev.D, 85, 103514. `1110.0502`

Massey, R., Hoekstra, H., Kitching, T., Rhodes, J., Cropper, M., Amiaux, J., Harvey, D., Mellier, Y., Meneghetti, M., Miller, L., Paulin-Henriksson, S., Pires, S., Scaramella, R., & Schrabback, T. 2013, MNRAS, 429, 661. `1210.7690`

Peacock, J. A., Schneider, P., Efstathiou, G., Ellis, J. R., et al. 2006, in ESA-ESO Working Group on ”Fundamental Cosmology”, edited by J. A. Peacock, et al.

Percival, W. J., Nichol, R. C., Eisenstein, D. J., Frieman, J. A., Fukugita, M., Loveday, J., Pope, A. C., Schneider, D. P., Szalay, A. S., Tegmark, M., Vogeley, M. S., Weinberg, D. H., Zehavi, I., Bahcall, N. A., Brinkmann, J., Connolly, A. J., & Meiksin, A. 2007, ApJ, 657, 645. `astro-ph/0608636`

Percival, W. J., Ross, A. J., Sánchez, A. G., Samushia, L., Burden, A., Crittenden, R., Cuesta, A. J., Magana, M. V., Manera, M., Beutler, F., Chuang, C.-H., Eisenstein, D. J., Ho, S., McBride, C. K., Montesano, F., Padmanabhan, N., Reid, B., Saito, S., Schneider, D. P., Seo, H.-J., Tojeiro, R., & Weaver, B. A. 2014, MNRAS, 439, 2531. `1312.4841`

Planck Collaboration, Adam, R., Ade, P. A. R., Aghanim, N., Akrami, Y., Alves, M. I. R., Arnaud, M., Arroja, F., Aumont, J., Baccigalupi, C., & et al. 2015, ArXiv e-prints. `1502.01582`

Semboloni, E., Hoekstra, H., Huang, Z., Cardone, V. F., Cropper, M., Joachimi, B., Kitching, T., Kuijken, K., Lombardi, M., Maoli, R., Mellier, Y., Miller, L., Rhodes, J., Scaramella,

R., Schrabback, T., & Velander, M. 2013a, MNRAS, 432, 2385. `1211.5025`
Semboloni, E., Hoekstra, H., & Schaye, J. 2013b, MNRAS, 434, 148. `1210.7303`
Taylor, A., & Joachimi, B. 2014, MNRAS, 442, 2728. `1402.6983`
Taylor, A., Joachimi, B., & Kitching, T. 2013, MNRAS, 432, 1928. `1212.4359`
Viola, M., Kitching, T. D., & Joachimi, B. 2014, MNRAS, 439, 1909. `1309.7844`
Zoubian, J., Kümmel, M., Kermiche, S., Apostolakos, N., Chapon, A., Ealet, A., Franzetti, P., Garilli, B., Jullo, E., & Paioro, L. 2014, in Astronomical Data Analysis Software and Systems XXIII, edited by N. Manset, & P. Forshay, vol. 485 of Astronomical Society of the Pacific Conference Series, 509