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'Five year Wilkinson Microwave Anisotropy Probe (WMAP1) Observations: cosmological interpretation' *Astrophysical Journal Supplement Series*, **180**, 330, Institute of Physics Publishing;

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 Figure 4.1: adapted from Tegmark, M. and Zaldarriaga, M. (2002) 'Separating the Early Universe from the Late Universe: cosmological parameter estimation beyond the black box', *Physical Review D*, **66**(10), 103508, The American Physical Society; Figure 4.2: adapted from Lacey, C. and Cole, S. (1993) 'Merger rates in hierarchical models of galaxy formation', *Monthly Notices of the Royal Astronomical Society*, **262**, 627, The Royal Astronomical Society; Figure 4.5: Moore, B. et al. (1999) 'Dark matter substructure within galactic halos', *The Astrophysical Journal*, **524**, L19, American Astronomical Society; Figure 4.6: adapted from Rocca-Volmerange, B. and Guiderdoni, B. (1988) 'An atlas of synthetic spectra of galaxies', *Astronomy & Astrophysics Supplement Series*, **75**, 93, European Southern Observatory; Figure 4.7: Dr Henner Busemann, School of Earth, Atmospheric and Environmental Sciences (SEAES), The University of Manchester; Figure 4.8: adapted from Gordon, K. D. et al. (2003) 'A quantitative comparison of the Small Magellanic Cloud, Large Magellanic Cloud, and Milky Way ultraviolet to near-infrared extinction curves', *The Astrophysical Journal*, **594**, 279, The American Astronomical Society; Figure 4.9: Brammer, G. B. et al. (2008) 'EAZY: A fast, public photometric redshift code', *The Astrophysical Journal*, **686**, 1503, The American Astronomical Society; Figure 4.10: adapted

from Dey, A. et al. (1998) ‘A galaxy at $z = 5.34$ ’, *The Astrophysical Journal*, **498**, L93, The American Astronomical Society; Figure 4.11: adapted from Bell, E. F. et al. (2003) ‘The optical and near infrared properties of galaxies. 1. luminosity and stellar mass functions’, *The Astrophysical Journal Supplement Series*, **149**, 289, The American Astronomical Society; Figure 4.12: NRAO; Figure 4.13: Sloan Digital Sky Survey; Figure 4.14: adapted from Yates, M. G. and Garden R. P. (1989) ‘Near-simultaneous optical and infrared spectrophotometry of active galaxies’, *Monthly Notices of the Royal Astronomical Society*, **241**, 167, The Royal Astronomical Society; Figure 4.16: adapted from Figure 2.3 of Peterson, B. M. (1997) *An Introduction to Active Galactic Nuclei*, Cambridge University Press; Figure 4.17: adapted from Richards, G. T. et al. (2006), ‘The Sloan Digital Sky Survey Quasar Survey: quasar luminosity function from data release 3’, *The Astronomical Journal*, **131**, 2766, The American Astronomical Society; Figure 4.18 left: A. Fujii; Figure 4.18 right: R. Williams (STScI), the Hubble Deep Field Team and NASA; Figure 4.19: Robert Williams and the Hubble Deep Field Team (STScI) and NASA; Figure 4.20: NASA/ESA, CXC, JPL-Caltech, STScI, NAOJ, J. E. Greach (Univ Durham) et al.; Figure 4.21: adapted from Gabasch, A. et al. (2004) ‘The evolution of the luminosity functions in the FORS deep field from low to high redshift’, *Astronomy & Astrophysics*, **421**, 41, ESO; Figure 4.22: NASA, ESA, S. Beckwith (STScI) and the HUDF Team; Figures 4.23 & 4.24: adapted from Bouwens, R. J. et al. (2009) ‘Constraints on the first galaxies: $z \sim 10$ Galaxy Candidates from HST WFC3/IR’, Submitted to Nature (arXiv:0912.4263); Figure 4.25: adapted from Cohen, J. G. et al. (1996) ‘Redshift clustering in the Hubble Deep Field’, *The Astrophysical Journal*, **471**, 5, The American Astronomical Society; Figure 4.26: adapted from Bouwens, R. J. et al. (2004) ‘Galaxy size evolution at high redshift and surface brightness selection effects: constraints from the Hubble Ultra Deep Field’, *The Astrophysical Journal*, **611**, 1, The American Astronomical Society; Figure 4.27: adapted from van Dokkum, P. G., Kriek, M. and Franx, M. (2009) ‘A high stellar velocity dispersion for a compact massive galaxy at redshift $z = 2.186$ ’, *Nature*, **460**, 717, Macmillan Publishers Limited; Figure 4.28: NASA Jet Propulsion Laboratory (NASA-JPL); Figure 4.29: H. Ferguson, M. Dickinson, R. Williams, STScI and NASA; Figure 4.30: adapted from Bell, E. F. et al. (2004) ‘Nearly 5000 distant early type galaxies in COMBO-17: a red sequence and its evolution since $z \sim 1$ ’, *The Astrophysical Journal*, **608**, 752, The American Astronomical Society; Figure 5.1: adapted from Hauser, M. G. and Dwek, E. (2001) ‘The Cosmic Infrared Background: Measurements and Implications’, *Annual Review of Astronomy & Astrophysics*, **39**, 249, Annual Reviews Inc; Figure 5.2: adapted from Hopwood, R. H. et al. ‘Ultra deep AKARI observations of Abell 2218: resolving the 15 m extragalactic background light’, *Astrophysical Journal Letters*, **716**, 45; Figure 5.3: <http://alma.asiaa.sinica.edu.tw>; Figure 5.4: adapted from Blain, A. W. et al. (2002) ‘Submillimeter galaxies’, *Physics Reports*, **369**, 111, Elsevier Science B.V.; Figure 5.5: adapted from Hughes D. H. et al. (1998) ‘High-redshift star formation in the Hubble Deep Field revealed by a submillimetre-wavelength survey’, *Nature*, **394**, 241; Figure 5.6: BLAST Collaboration; Figure 5.7: ESA and SPIRE Consortium; Figure 5.8: adapted from Serjeant, S. et al. (1998) ‘A spectroscopic study of IRAS F10214+4724’, *Monthly Notices of the Royal Astronomical Society*, **298**, 321, Royal Astronomical Society; Figure 5.9: adapted from Surace, J. A. et al. (1998) ‘HST/WFPC2 Observations

of warm ultraluminous infrared galaxies', *Astrophysical Journal*, **492**, 116, The American Astronomical Society; Figure 5.10 top: Brad Whitmore (STScI) and NASA; Figure 5.10 bottom: NASA/JPL-Caltech/Z. Wang (Harvard-Smithsonian CfA); Visible: M. Rushing/NOAO; Figure 5.11: Courtesy of JAXA; Figures 5.12 & 5.13: adapted from Condon, J. J. (1992) 'Radio emission from normal galaxies', *Annual Reviews of Astronomy & Astrophysics*, **30**, 575, Annual Reviews Inc; Figure 5.14: adapted from Dole, H. et al. (2006) 'The cosmic infrared background resolved by Spitzer', *Astronomy & Astrophysics*, **451**, 417, EDP Sciences; Figures 5.15 & S5.1: adapted from Griffin, M. et al. (2007) 'The Herschel-SPIRE instrument and its capabilities for extragalactic astronomy', *Advances in Space Research*, **40**, 612, ©COSPAR, Published by Elsevier Ltd; Figures 5.16, 5.17 & 5.18: Pérez-González, P. G. et al. (2008) 'The Stellar Mass Assembly of Galaxies from $z = 0$ to $z = 4$ ', *The Astrophysical Journal*, **675**, 234, The American Astronomical Society; Figure 5.19: adapted from Le Floc'h, E. et al. (2005) 'Infrared Luminosity Functions from the Chandra Deep Field-South', *The Astrophysical Journal*, **632**, 169, The American Astronomical Society; Figure 5.20: adapted from Di Matteo, T. et al. (2005) 'Energy input from quasars regulates the growth and activity of black holes and their host galaxies', *Nature*, **433**, 604, Nature Publishing Group; Figure 5.21: McNamara, B. R. et al. (2000) 'Chandra X-ray observations of the Hydra A cluster: an interaction between the radio source and the X-ray emitting gas', *Astrophysical Journal*, **534**, L135, The American Astronomical Society; Figures 5.22 & 5.23: Fabian, A. C. et al. (2003) 'A very deep Chandra observation of the Perseus cluster: shocks and ripples', *Monthly Notices of the Royal Astronomical Society*, **344**, L43, The Royal Astronomical Society;

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The Royal Astronomical Society; Figure 6.17: Weisberg, J. M. and Taylor, J. H. (2005) ‘The relativistic binary pulsar B1913+16: thirty years of observations and analysis’, Rasio, F. A. and Stairs, I. H. (eds) *Binary Radio Pulsars*, *ASP Conference Series*, **328**, 25, Astronomical Society of the Pacific; Figure 6.18: CalTech; Figure 6.19: adapted from Boroson, T. A. and Lauer, T. R. (2009) ‘A candidate sub-parsec supermassive binary black hole system’, *Nature*, **458**, 53, Nature Publishing Group;

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Digital Sky Survey II-data release 7', *Astronomy & Astrophysics*, **505**, 1087, European Southern Observatory; Figure 8.10: Prochaska, J. X. et al. (2005) 'The SDSS damped Ly alpha survey: data release 3', *Astrophysical Journal*, **635**, 123, The American Astronomical Society; Figure 8.12: Reynolds, S. C. (2007) 'Quasar Absorbers and the InterGalactic Medium', taken from a pedagogical Seminar at the Royal Observatory, Edinburgh, 8 March 2007, www.roe.ac.uk/ifa/postgrad/pedagogy/2007_reynolds.pdf; Figure 8.13: Möller, P. and Warren, S. J. (1993) 'Emission from a damped Ly alpha absorber at $z = 2.81$ ', *Astronomy & Astrophysics*, **270**, 43, European Southern Observatory; Figure 8.15: Smette, A. et al. (1992) 'A spectroscopic study of UM 673 A & B: on the size of the Lyman-alpha clouds', *Astrophysical Journal*, **389**, 39, The American Astronomical Society; Figure 8.16: Nick Gnedin, Department of Astronomy & Astrophysics, The University of Chicago; Figures 8.17 & 8.19: Fan, X. et al. (2006) 'Observational constraints on cosmic reionization', *Annual Review of Astronomy & Astrophysics*, **44**, 415 ©2006 by Annual Reviews; Figure 8.18: Becker, G. D. et al. (2007) The evolution of optical depth in the Ly alpha Forest: evidence against reionization at $z \approx 6$, *The Astrophysical Journal*, **662**, 72, The American Astronomical Society; Figure 8.20: adapted from Möller, P. and Jakobsen, P. (1990) 'The Lyman continuum opacity at high redshifts: through the Lyman forest and beyond the Lyman valley', *Astronomy & Astrophysics*, **228**, 299, European Southern Observatory; Figure 8.21: Smette, A. et al. (2002) 'Hubble Space Telescope Space Telescope Imaging System Observations of the He II Gunn–Peterson effect toward HE 2347-4342', *Astrophysical Journal*, **564**, 542, The American Astronomical Society; Figure 8.23: Carilli, C. L. et al. (2002) 'H I 21 centimeter absorption beyond the epoch of reionization', *The Astrophysical Journal*, **577**, 22, The American Astronomical Society; Figures 8.24 & 8.25: Cristiani, S. et al. (2007) 'The CODEX-ESPRESSO experiment: cosmic dynamics, fundamental physics, planets and much more ...', *Il Nuovo Cimento*, **122B**, 1165, Societa Italiana di Fisica.

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