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1 PROJECT FINAL REPORT

GRANT AGREEMENT NUMBER: 231113

PROJECT ACRONYM: BAO and Dark Energy

PROJECT TITLE: "Probing Dark Energy with Baryonic Acoustic Oscillations"

FUNDING SCHEME: Marie Curie International Reintegration Grants (IRG)

FINAL REPORT: 1/10/2008–30/9/2012

BENEFICIARY

ORGANISATION PIC: 999976396

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2 Publishable Summary:

2.1 Summary of project objectives

This project sought to find robust ways to constrain the cosmological model using future large-scale structure data sets. In particular, it sought to improve our understanding and modelling of galaxy clustering so that we may develop robust tests of the cosmological model and in particular tests for Dark Energy. The main scientific objectives were:

1. Develop new analytic tools and estimators that enable us to accurately interpret galaxy clustering data. The important systematics to control are: *I.* the nonlinear evolution of the mass density distribution; *II.* the nonlinear scale-dependent biasing of galaxies with respect to the mass; *III.* the nonlinear scale-dependent redshift space distortions.

2. Generate a large ensemble of large volume hi-resolution N-body simulations to rigorously test the advances in our understanding.

3. Develop theoretical and numerical tools to explore the importance of the light-cone effect for large-scale structure tests from future surveys.

4. Understand how large-scale structure tests, such as the BAO signal and shape of the galaxy power spectrum, might also help us to understand the primordial seeds of structure.

2.2 Final major results:

O1: A number of developments were made. These were presented in a series of publications:

- In Smith et al. (2009), the researcher has developed an improved model of the nonlinear cross-power spectrum of haloes and matter. In Smith (2009), the researcher has shown how cross-correlation measures provide more optimal estimators for LSS studies than the standard auto-correlation measures. In a similar spirit, in Hamaus et al. (2010) the researcher and his collaborators explored new ways in which one might weight the galaxy density field in order to extract more cosmological information. It was demonstrated that a mass weighting of the galaxy field would reduce terms associated with shot-noise.

- In Somogyi & Smith (2010), the researcher has explored the nonlinear evolution of structure growth in a coupled fluid of baryon and CDM perturbations. A late-time large scale baryon bias was discovered. This has important consequences for baryonic probes that hope to extract the sound horizon scale from BAO measurements.

- In Pollack et al. (2011) the researcher tested the standard methods for extracting nonlinear galaxy bias from galaxy redshift surveys and demonstrated that, in order to obtain robust conclusions from higher order statistics, one needs to model the matter bispectrum exactly. This work has led us to propose a new method for modelling nonlinear galaxy bias and this will be the subject of a forthcoming paper (Pollack et al 2013).

- In Smith & Markovic (2011) and (Schneider et al., 2012) the researcher along with their collaborators explored the consequences of structure formation in the Warm Dark Matter model. This work has led the way to the development of new tests of the dark matter model, using weak gravitational lensing.

- In Baldauf et al. (2010) the researcher explored how best to directly reconstruct the matter correlation through the combination of the information from weak lensing and galaxy clustering surveys. This technique was further used in the works (Mandelbaum et al., 2010; Reyes et al., 2010; Mandelbaum et al., 2012).

O2: The researcher has used supercomputers at the University of Zurich to generate a suite of 274 large volume, $L = 1500h^{-1}$ Mpc and intermediate resolution N-body simulations, $N = 750^3$. These simulations have been used for a large number of projects related to understanding the cosmological information content of large-scale structure data. The most recent study was Smith et al. (2012), in which the researcher explored how uncertainties in the true numerical simulation parameters might degrade the cosmological constraints from measurements of the matter power spectrum. It was shown that if one can not identify the 'true' simulation parameters, then on marginalizing over them, the dark energy figure of merit would be reduced by almost a factor of 2.

Another example of the usefulness of these simulations was demonstrated in Smith & Marian (2011), in which it was shown how large-scale structure would make the different mass bins of the mass function covariant. In this work, the simulations were used to explore the cosmological information content of the mass function using simulations, taking into account the full covariances in the data. This suite of simulations will be useful for a wide number of new projects and will help with improving cosmological forecasts for future galaxy and lensing surveys of the Universe, such as Euclid and LSST.

O3: The researcher supervised a masters student through their diploma thesis on this topic. Title: *Spatially Deep, Full-sky, Lightcones from N-body Simulations.* The aim of this thesis was to write a module for the cosmological N-Body simulation code `Gadget-2` (Springel, 2005), which would enable spatially deep, full-sky light cone outputs to be made on-the-fly. The masters student completed their thesis, but then left the field to pursue a PhD in computer science. The `Gadget-2` version of the code was completed. The code was successfully tested for a WMAP5 cosmological simulation of 1024^3 particles. In this simulation a full-sky light cone output was generated from $z = 0$ to $z = 0.75$. The researcher is currently implementing the same algorithm into the new simulation code `L-Gadget-3`. Once this extension is completed and the scientific papers finished, they intend to make the code public.

O4: Standard single-field inflationary models lead to a generation of perturbations that are close to Gaussian. Testing the Gaussianity of the perturbations, therefore, leads to constraints on the model of inflation. The researcher has made progress in understanding how the statistics of the initial primordial density field affect the late time observed properties of the large-scale structures.

In (Smith et al., 2011) the researcher developed the ingredients of the halo model for exploration of models with local primordial non-Gaussianity. They showed that the mass function, density profiles, mass power spectra, and mass correlation functions are all sensitive to primordial non-Gaussianity. They found that the halo model could describe the matter clustering to a good accuracy. This work also showed that there must be an additional correction to the scale dependence of the bias. These findings led to the conclusion that, besides galaxy clustering surveys, weak lensing surveys of the Universe, which probe the total mass distribution, would be sensitive to changes to the primordial statistics.

In subsequent works, Marian et al. (2011) and Hilbert et al. (2012), the researcher demonstrated using N-body simulations and gravitational lensing ray-tracing simulations, that weak lensing probes would also be able to provide constraints on non-Gaussianity that were competitive with those arising from the CMB.

The researcher is currently exploring how small modifications of the Gaussian assumption affect tests such as the BAO signature in the large scale clustering of haloes and galaxies. The paper is close to completion.

2.3 Potential impact (including socio-economic impact and wider societal implications)

In their future work, the researcher will continue to develop good analytic modelling of structure formation. They are currently developing analytic perturbation theory techniques for application to redshift space distortions, taking into account nonlinear galaxy bias. They are also developing the resummation of the baryon plus CDM coupled fluid perturbation theory. The researcher will also continue to mine the information content of the large suite of cosmological N-body simulations that they have generated. They are also currently exploring the impact of primordial non-Gaussianity on the BAO signal in the correlation function. Early results show that the imprint of the sound horizon scale in the galaxy distribution is very sensitive to the Gaussianity of the initial perturbations. Understanding this will be extremely important for future surveys that attempt to constrain Dark Energy and primordial non-Gaussianity.

It is hard to assess the full socio-economic impact a pure research field like cosmology. In one way, the analytic and computational tools that are developed in this work potentially may have important consequences in other areas of research with application to industry. Further, the training of students, leads to a significantly more technically capable workforce. On a more philosophical level, understanding the origins and evolution of the Universe has long been one of mans greatest puzzles. This kind of research should enrich our knowledge and hopefully lead the way to important new break throughs in fundamental physics.

2.4 Summary of the progress of the researcher training activities/transfer of knowledge activities/integration activities

Since their return to Europe, the researcher was invited to join EUCLID – a mission to perform an all sky, deep multi-colour imaging and spectroscopic study of the Universe between $z = 0$ and 2 (Refregier et al., 2010). They are currently taking an active role in the cosmological simulations, weak lensing and galaxy clustering working groups.

The researcher gave a number of invited talks in Europe and has presented work at number of international conferences and workshops (see Sec. 3 for full details).

The researcher cosupervised Mr Aurel Schneider through his final PhD project at the University of Zurich. The researcher has supervised two masters students Mr Tobias Baldauf, who is currently performing a PhD with Prof. Uros Seljak and Mr. Lorenz Muller.

The researcher has given a number of lectures at the University of Zurich on theoretical cosmology.

The researcher taught half of the introduction to astrophysics course at the University of Zurich in the spring semester of 2011.

2.5 Explanation of deviations from Annex I

There are no significant deviations.

3 Dissemination activities

3.1 Publications

The following papers were possible through the support from the Marie Curie Grant.

1. Title: *"Precision cosmology in muddy waters: Cosmological constraints and N-body codes"*
   Authors: R. E. Smith D. S. Reed, D. Potter, L. Marian, M. Crocce, B. Moore
   Journal: Submitted for publication in MNRAS (2012).
   Archive: `http://arxiv.org/abs/1211.6434`

2. Title: *"Cosmological parameter constraints from galaxy-galaxy lensing and galaxy clustering with the SDSS DR7"*
   Authors: R. Mandelbaum, A. Slosar, T. Baldauf, U. Seljak, C. Hirata, R. Nakajima, R. Reyes, R. E. Smith
   Journal: Submitted for publication in MNRAS (2012).
   Archive: `http://arxiv.org/abs/1207.1120`

3. Title: *"Toward an accurate mass function for precision cosmology"*
   Authors: D. S. Reed, R. E. Smith D. Potter, A. Schneider, J. Stadel, B. Moore
   Journal: Accepted for publication in MNRAS (2012).
   Archive: `http://arxiv.org/abs/1206.5302`

4. Title: *"How covariant is the galaxy luminosity function?"*
   Authors: R. E. Smith.
   Journal: Accepted for publication in MNRAS (2012).
   Archive: `http://arxiv.org/abs/1205.4240`

5. Title: *"Measuring primordial non-Gaussianity with weak-lensing surveys"*
   Authors: S. Hilbert, L.Marian, R. E. Smith, V. Desjacques. Journal: Accepted for publication in MNRAS (2012). Archive: `http://arxiv.org/abs/1204.4530`

6. Title: *"Nonlinear evolution of cosmological structures in warm dark matter models"*
   Authors: A. Schneider, R. E. Smith, A. Maccio, B. Moore.
   Journal: Accepted for publication in MNRAS (2012).
   Archive: `http://arxiv.org/abs/1112.0330`

7. Title: *"Optimized detection of shear peaks in weak lensing maps"*
   Authors: L. Marian, R. E. Smith, S. Hilbert, P. Schneider.
   Journla: MNRAS in Press (2012).
   Archive: `http://arxiv.org/abs/1110.4635`

8. Title: *"Cluster Density Profiles as a Test of Modified Gravity"*
   Authors: L. Lombriser, F. Schmidt, T. Baldauf, R. Mandelbaum, U. Seljak, R. E. Smith.
   Journal: PRD, **85** 102001 (2012)
   Archive: `http://arxiv.org/abs/1111.2020`

9. Title: *"Modelling large-scale halo bias using the bispectrum"*
   Authors: J. Pollack, R. E. Smith, C. Porciani
   Journal: MNRAS, 420, 3469 (2012)
   Archive: `http://arxiv.org/abs/1109.3458`

10. Title: *"What do cluster counts really tell us about the Universe?"*
Authors: R. E. Smith, and L. Marian
Journal: MNRAS, 418, 729 (2011)
Archive: `http://arxiv.org/abs/1106.1665`

11. Title: *"Testing the Warm Dark Matter paradigm with large-scale structures"*
Authors: R. E. Smith and K. Markovic
Journal: PRD, **84**, 063507 (2011)
Archive: `http://arxiv.org/abs/1103.2134`

12. Title: *"Measuring primordial non-Gaussianity through weak lensing peak counts"*
Authors: L. Marian, S. Hilbert, R. E. Smith, P. Schneider, V. Desjacques
Journal: PRL Submitted
Archive: `http://arxiv.org/abs/1010.5242`

13. Title: *"Nonlinear clustering in models with primordial non-Gaussianity: the halo model approach"*
Authors: R. E. Smith, V. Desjacques, L. Marian
Journal: PRD Submitted
Archive: `http://arxiv.org/abs/1009.5085`

14. Title: *"Minimizing the Stochasticity of Halos in Large-Scale Structure Surveys"*
Authors: N. Hamaus, U. Seljak, V. Desjacques, R. E. Smith, T. Baldauf
Journal: PRD, **82**, 043515 (2010)
Archive: `http://arxiv.org/abs/1004.5377`

15. Title: *"Precision cluster mass determination from weak lensing"*
Authors: R. Mandelbaum; U. Seljak; T. Baldauf; R. E. Smith
Journal: MNRAS **405** 2078 (2010)
Archive: `http://arxiv.org/abs/0911.4972`

16. Title: *"An algorithm for the direct reconstruction of the dark matter correlation function from weak lensing and galaxy clustering"*
Authors: T. Baldauf, R. E. Smith, U. Seljak, R. Mandelbaum
Journal: PRD, **81**, 063531 (2010)
Archive: `http://arxiv.org/abs/0911.4973`

17. Title: *"Test of gravity at cosmological scales using weak gravitational lensing and velocity flows"*
Authors: R. Reyes, R. Mandelbaum, U. Seljak, T. Baldauf, J. E. Gunn, L. Lombriser, R. E. Smith Journal: Nature , **464**, 256 (2010)
Archive: `http://arxiv.org/abs/1003.2185`

18. Title: *"Cosmological perturbation theory for baryons and dark matter: One-loop corrections in the renormalized perturbation theory framework"*
Authors: G. Somogyi, R. E. Smith
Journal: PRD, **81**, 023524 (2010)
Archive: `http://arxiv.org/abs/0910.5220`

19. Title: *"The impact of correlated projections on weak lensing cluster counts"*
Authors: L. Marian, R. E. Smith, G. M. Bernstein
Journal: ApJ, **709**, 286 (2010)
Archive: `http://arxiv.org/abs/0912.0261`

20. Title: *"Impact of scale dependent bias and nonlinear structure growth on the ISW effect: angular power spectra"*
Authors: R. E. Smith, C. Hernandez-Monteagudo, U. Seljak
Journal: PRD, **80**, 063528 , (2009)
Archive: `http://arxiv.org/abs/0905.2408`

21. Title: *"The cosmology dependence of weak lensing cluster counts"*
Authors: L. Marian, R. E. Smith, G. M. Bernstein
Journal: ApJL, **698**, 33 (2009)
Archive: `http://arxiv.org/abs/astro-ph/0811.1991`

22. Title: *"Covariance of cross-correlations: towards efficient measures for large-scale structure"*
Authors: R. E. Smith
Journal: MNRAS, **400**, 851, (2009)
Archive: `http://arxiv.org/abs/astro-ph/0810.1960`

Journal abbreviations:

ApJL – Astrophysical Journal Letters;
ApJ – Astrophysical Journal;
PRD – Physical Review D;
PRL – Physical Review Letters;
MNRAS – Mon. Not. of the Royal Ast. Soc.

3.2 Professional conferences, workshops and colloquia over the reporting period

- (9/2012) Theory Group CERN, Geneva, Switzerland "Thereotical methods for non-linear cosmology": Invited Speaker.
- (7/2012) ICE, Barcelona, Spain. "EUCLID CSWG + OUSIM joint Meeting": Invited Speaker.
- (4/2012) MPA-IFT, Madrid, Spain. "Workshop on open questions in Large-Scale Structure". Oral presentation.
- (2/2012) University of Edinburgh, Edinburgh, Scotland. "Euclid Weak Lensing Working Group Kick Off Meeting": Coordinator of simulation discussion.
- (1/2012) Astro simulation conference, Davos, Switzeralnd. Participant.
- (11/2011) Observatoire de Paris, France. "Meudon Workshop: Galaxies and the Structure of the Universe": Invited speaker.
- (9/2011) Institute of Theoretical Physics CEA, Saclay, France. "PTChat: Hardcore techniques in cosmological perturbation theory". Oral presentation.
- (4/2011) Argelander Institute for Astronomy, University of Bonn, Germany. Cosmology seminar.
- (3/2011) ICTP, Trieste, Italy. Cosmology Seminar.
- (12/2010) University of Geneva, Switzerland: "Euclid Workshop" for Swiss Euclid members. Oral presentation.
- (11/2010) 'Cosmological simulations and cosmology – requirements for future large surveys', Edinburgh, Scotland. Oral presentation: *"Open problems in structure formation on the path to enlightenment"*.
- (8/2010) 'Modern Cosmology', Benasque, Spain. Oral presentation: *"Renormalized perturbation theory for baryons and CDM"*.
- (7/2010) 'Ten Years of Cosmic Shear', Edinburgh, Scotland. Oral presentation: *"Measuring the information content of Large-Scale Structure statistics through N-body simulations"*.
- (11/2009) Autonomous University de Catalunya, Barcelona, Spain. Cosmology seminar. *"Impact of scale-dependent bias and nonlinear evolution on the ISW"*.
- (6/2009) 'Windows on the Universe' 21st Rencontres de Blois, France. Oral presentation: *"Impact of scale-dependent bias and nonlinear evolution on the ISW"*.
- (6/2009) 'The Invisible Universe' Paris, France. Participant.
- (4/2009) ICE, Barcelona, Spain. Cosmology Seminar.
- (2/2009) Max Planck Institute for Astrophysics, Garching, Germany. Cosmology seminar. *"Measuring the information content of Large-Scale Structure statistics through N-body simulations"*.

4 Project management: Final comments

The researcher has fulfilled all of the tasks required of him.

At the end of September 2012, the researcher was offered a fixed term staff-scientist position at the Max-Planck Institiute For Astrophysics in Germany in the group of Professor Simon White (FRS). This position will run until the end of 2014.

Whilst they have not yet found a permanent position, there is evidence to show that the reintegration was successful:

- The researcher is a member of Euclid.
- Their next position was at MPA.
- From 1/10/2008–30/9/2012 they wrote 22 scientific papers.
- They were invited to speak at a number of research centers in Europe.
- They helped supervise three students.
- They contributed to the teaching courses.
- They largely ran the day-to-day business of the cosmology group at the University of Zurich for 4 years.

Additional comments:

- **Changes to the legal status of any beneficiaries:** None.
- **impact of changes to planned milestones:** None.
- **Development of the project website:** N/A.
- **Gender issues:** N/A.
- **Justification of subcontracting:** N/A.
- **Justification of real costs:** N/A.

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