An Oxford New College-Johns Hopkins Centre for Cosmological Studies

Joseph Ivor Silk

2011 Balzan Prize for The Early Universe (From the Planck Time to the First Galaxies)

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Advisory Committeee: Adrienne Slyz, Marc Kamionkowski, John March-Russell
Researchers: Kearn Grisdale, Charlotte Owen, Rathul Nath Raveendran, Martin Stref, Mario Ballardini, Nick Choksi, Kevin Guo, Hayato Motohaski, Mojtaba Raouf, Priyanka Singh, Mike Zevin
Affiliated Institution: New College, University of Oxford
Period: 2013-2018
Website: http://balzan.new.ox.ac.uk/

Joseph Ivor Silk is at the Institut d'Astrophysique of the Pierre and Marie Curie-Sorbonne Universities in Paris. He is also Homewood Professor in the Department of Physics and Astronomy at Johns Hopkins University in Baltimore, Fellow at New College, and Senior Fellow in the Beecroft Institute of Particle Astrophysics and Cosmology of the Department of Physics at the University of Oxford.

Cosmology is in a golden age of discovery, and has succeeded in capturing the attention of wide swathes of society that extend well beyond the confines of academia. Such questions as the origin of the Universe, the nature of its predominantly dark material, and the question of its future, fascinate the public at large, and succeed in attracting the brightest young minds into physics research. Yet a deeper understanding of what is meant by a science of cosmology, in the fuller reaches of these words, is in its infancy. It must involve astrophysics, physics, philosophy, and cosmogony, and tackle genuinely fundamental questions in cosmology.

Silk has designated part of his Balzan research funds for the creation of a Centre for Cosmological Studies based at New College Oxford and at the Department of Physics

and Astronomy at the Johns Hopkins University in Baltimore. It also involves the Oxford University Department of Physics and the Institut d'Astrophysique of the Pierre and Marie Curie-Sorbonne Universities in Paris. The Centre's goal is to provide Balzan grants for young researchers in cosmology in frontier areas of research that are consistent with the scientific themes supported by the Centre, and to establish international links among leading young researchers to develop scientific interactions and collaborations that will benefit their careers as well as enhance the scientific life of the partner institution. In the five years of the Centre's existence, more than fifty early-career researchers have benefited from the fund's support to travel and to sustain collaborations at the participating institutions of Oxford, IAP and the JHU. They come from every corner of the world and have ended up working on every continent.

The first grants were awarded in the autumn of 2013 to Visiting Junior Research Fellows hosted at the institutions mentioned above. The researchers were selected from a large field of candidates, and chosen because of their outstanding science potential and their interactivity with cosmology faculty at the participating institutions. The goal is to choose brilliant young researchers who will boost their careers by developing new collaborations. Several visited New College, while others were at the Johns Hopkins University at IAP, Paris. Information on the most recent researchers is included in this entry. For further information on Silk's research project awardees from 2013 to 2017 and their publications, see previous editions of the *Overview* on the International Balzan Foundation website:
http://www.balzan.org/en/prizewinners/joseph-silk/research-project-silk.

Balzan Awardees 2017-2018

Kearn Grisdale, a postdoctoral researcher in the Department of Physics, University of Oxford, worked under the supervision of Julien Devriendt on a number of projects. One of his focuses was the impact of numerical star formation recipes on simulated galaxy evolution, with the principal goal to implement a star formation recipe into his Milky Way (henceforth MW)-like simulation. This new recipe only forms stars from gas that is gravitationally bound. Implementation of this new method was completed and two simulations were run. Results will be presented in a multi-author publication in preparation, alongside tests of resolution and an exploration of how the initial conditions used for the simulation affect the resulting galaxy.

Charlotte Owen, a PhD Student at Lancaster University, UK, visited Johns Hopkins University and worked under the supervision of Marc Kamionkowski. During her visit, she was introduced to the code CLASS for simulating the evolution of perturbations in the Universe, in order to compute the observables of the cosmic microwave background (CMB). An axion oscillating in the minimum of its potential is a candidate explanation for dark matter; observing the CMB helps to constrain the axion mass range which makes it a feasible candidate. In the literature, axions have been modelled in this way in similar codes, with simplified potentials, using fluid approximations to ease the computational requirements. Specific scalar fields can be modelled in CLASS already and she has been working on extending this framework to various extra potentials relevant to axion cosmology. With others, she has a paper in preparation, which assesses the validity of a fluid formalism approach to modelling axions relative to solving the linear Klein-Gordon equations.

Rathul Nath Raveendran, postdoctoral researcher at The Institute of Mathematical Sciences CIT Campus, India, visited the D'Institut d'Astrophysique de Paris (IAP), and worked under the supervision of Patrick Peter on a project exploring bouncing scenarios as an alternative to the inflationary paradigm. In a bouncing scenario, the universe goes through an initial phase of contraction until the scale factor reaches a minimum value before it begins to expand. One of the issues plaguing the bouncing models is the rapid growth of anisotropies during the contracting phase. The problem can be diluted by including an ekpyrotic phase during the early contracting period of the universe. Moreover, the ekpyrotic evolution is an attractor, which is a promising feature of the model. Usually the effect of spatial curvature is ignored in the Friedmann equations during the bounce. But this is not clear: the curvature term near the bounce, where the Hubble parameter becomes zero can be neglected completely. During his visit at IAP, this project tried to investigate the effect of spatial curvature on the evolution of cosmological perturbations during the bounce phase. Interestingly, as far as background is concerned, it was found that the ekpyrotic contraction is an attractor even in the presence of curvature term. Currently, the effect of this curvature term in the evolution of perturbation was investigated.

Martin Stref, a postdoctoral researcher at the University of Montpellier, France, visited Johns Hopkins University and worked under the supervision of Joe Silk. His research project is centered on astrophysical searches for particle dark matter. The goal of his project is to model ultracompact minihalos and evaluate their contribution to the ionization rate of molecular clouds. This requires a careful modelling of the

tidal effects these objects experience at the centre of the Galaxy. Minihalos could also contribute significantly to the unexplained GeV gamma-ray emission at the Galactic centre observed by the Fermi Space Telescope. A population of minihalos could also be constrained by local probes such as cosmic-ray antiprotons and positrons. Finally, the project aimed at building the minihalo population consistently from given primordial power spectra motivated by specific inflationary scenarios. A first paper on the subject will soon be submitted by Prof. Silk, and more detailed studies will follow. Additional collaborations are planned with Dr. Mathieu Boudaud (LPTHE, Paris) and Dr. Tomohiro Nakama (JHU, Baltimore).

Mario Ballardini, a postdoctoral researcher at INAF – Istituto di Astrophysica Spaziale e Fisica Cosmica, Bologna, visited Johns Hopkins University and worked on two projects under the supervision of Marc Kamionkowski. The first one was dedicated to the study of the implications on single field slow roll inflation models, imposing the constraints from the latest Planck data on the scalar spectral index, in combination with new requirements to the tensor-to-scalar ratio inferred by BICEP/ Keck Array. They looked at a wide selection of inflation models able to describe the current CMB constraints, i.e., α-attractor inflation, hilltop inflation, and D-brane inflation, and also showed how the simplest model of natural inflation is at odds with CMB constraints at 2σ. Particular attention was paid to the reheating uncertainties to connect parameters of the inflationary potential to the scalar spectral index and tensor-to-scalar ratio, and they derived the constraints of the inflation parameters and reheating temperature allowed from the combined Planck BICEP/Keck Array results for each model. In parallel, they also studied the implication of the supernova activities from early stars on the CMB angular power spectrum. They investigated the connection between the measured new value of the optical depth and the number of ionized photons required to reionize the Universe, and predicted CMB fluctuations induced by the clustering of high-z supernovae. This collaboration has been fruitful and there are two articles in preparation.

Nick Choksi, a graduate student at the University of California, Berkeley, visited the Institut d'Astrophysique de Paris (IAP) and worked under the supervision of Marta Volonteri. The project studied the formation of black hole binaries which could eventually merge and serve as sources for gravitational wave detectors on Earth (e.g., LIGO, VIRGO). To understand the contribution of all types of clusters, they coupled a cosmological model of GC formation and evolution with analytic prescriptions for the dynamical evolution of BHs in GCs. This approach made it possible to identify the

subset of the full cluster parameter space that contributed significantly to the black hole merger rate, and to calculate, for the first time, the BH merger rate for an evolving and cosmologically representative population of GCs. The work at the IAP resulted in a paper which has been posted to the arXiv (1809.01164) and submitted to the *Astrophysical Journal*. This work will continue remotely by performing a more detailed calculation of the merger rate from our model.

Kexin Guo, a postdoctoral researcher at Kavli Institute for Astronomy and Astrophysics, Peking University, visited the Department of Physics, University of Oxford, and worked under the Supervision of Martin Bureau on a project studying the impact of structure build-up on galaxy evolution. The work focused on barred galaxies selected from the MaNGA dataset, with the aim of finding what is crucial in driving the difference in quenching star formation between barred and un-barred galaxies during the fading of galactic disks. From comparing profiles of both stellar mass and star formation rate between barred and unbarred galaxies, the resolved star formation rate in different bins reveals two main points: 1) no difference is found between red-sequence barred and unbarred galaxies, indicating that the bar-related process is a secondary factor in quenching star formation disks; and 2) barred green-valley galaxies show a ring between galaxy center and outer disks where star formation is absent, suggesting a redistribution of gas by bar-driven dynamical processes.

Hayato Motohashi, postdoctoral researcher at Yukawa Institute for Theoretical Physics, visited the Institut d'Astrophysique de Paris (IAP), and worked under the supervision of Cedric Deffayet and Sebastian Garcia-Saenz on an investigation of the so-called involutive counting method of the number of degrees of freedom, which is an alternative method to the Hamiltonian analysis commonly used in the community. Using the correspondence of two sets of Euler-Lagrange equations before and after the derivative-dependent field redefinition of the Lagrangian which had been obtained in my previous work, Motohashi clarified that the involutive counting gives consistent result with the standard counting for a wide class of derivative-dependent field redefinitions. After his visit to Paris, he attended the 15th Marcel Grossmann Meeting at the University of Rome "La Sapienza", and gave talks related to the topic. Discussions with De Fayette and Garcia-Saen have continued, and the group is working on clarifying the so-called symbol of the system, and preparing a paper about their results.

Mojtaba Raouf, a postdoctoral researcher at the School of Astronomy IPM Araj IRAN, visited the Institut d'Astrophysique de Paris (IAP), and worked under the

supervision of Joe Silk and Gary Mamon. During this visit, they first worked on the impact of supermassive black hole accretion on the star formation rate via semi-analytic modelling using Radio-SAGE model in which providing to publish in MNRAS. This paper mainly focused on the description of a physical model of the outflows produced as a result of gas accretion onto a black hole to modify star formation rates and efficiencies in galaxies. Secondly, they worked on a paper entitled "Merger history of central galaxies in semi-analytic models of galaxy formation" (published in ApJ, Raouf et al, 2018). In this investigation of the dynamical evolution of galaxies in groups with different formation epochs, they showed that the radio luminosities of central galaxies, considered to be a tracer of AGN activity, are enhanced in halos that assembled more recently, independent of the time since the last major merger.

Priyanka Singh, a postdoctoral researcher at INAF Italy, visited Johns Hopkins University and worked under the supervision of Joe Silk on a project aiming to constrain H0 using stacked SZ measurements [Planck Collaboration et al. (2013)] and stacked X-ray luminosity measurements [Anderson et al. (2015)]. They are currently working on refining gas density and temperature profiles to include the uncertainty in H0 originating from the uncertainty in gas temperature and density profiles, with hopes of finalizing and publishing these results.

Mike Zevin, a postdoctoral researcher at Northwestern University, visited the Department of Physics, University of Oxford, and worked under the supervision of Chris Lintott on a project entitled "The Synergy of Humans and Machines: Improving the Efficiency of Classification Schemes". Crowdsourcing has proven a fruitful tool for scientific data analysis. However, the sheer amount of data expected in upcoming scientific endeavours requires a cleverer means of analysis. By combining the intuition of human volunteers to identify new features in the data with the rapidity of machine learning algorithms in performing a comprehensive classification, the Gravity Spy project hosted by Zooniverse leverages the benefits of both humans and machines to characterize noise in the LIGO gravitational-wave detectors, while providing a platform for exploring techniques that will facilitate the next generation of citizen science projects. One unique aspect of Gravity Spy is the combination of machine learning scores and volunteer classifications that is utilized to expedite the "retirement" of data from the project. Many tuneable parameters go into this retirement, such as the relative weighting between the human and machine classifications, the probability threshold that must be reached before an image is retired, and how best to deal with

data for which the aggregate cannot reach a consensus. These parameters can largely influence the accuracy and efficiency of a project and have yet to be empirically tested. In this study, they investigated how such choices in retirement parameters influenced the purity and completeness of data in the project, and how such techniques of combining human and computer classification schemes can help efficient data analysis scale with the immense datasets of the future.

Publications

Grisdale, K., Agertz, O., Renaud, F., Romeo, A.B., Devriendt, J., Slyz, A. 2019. On the observed diversity of star formation efficiencies in Giant Molecular Clouds. Monthly Notices of the Royal Astronomical Society 486, 5482.

Dimopoulos, K., Karvciauskas, M., Owen, C. 2019. Quintessential inflation with a trap and axionic dark matter. Physical Review D 100, 083530.

Raveendran, R.N., Sriramkumar, L. 2019. Primordial features from ekpyrotic bounces. Physical Review D 99, 043527.

Choksi, N., Volonteri, M., Colpi, M., Gnedin, O.Y., Li, H. 2019. The Star Clusters That Make Black Hole Binaries across Cosmic Time. The Astrophysical Journal 873, 100.

Raouf, M., and 6 colleagues. 2019. Feedback by supermassive black holes in galaxy evolution: impacts of accretion and outflows on the star formation rate. Monthly Notices of the Royal Astronomical Society 486, 1509.

The Oxford New College-Johns Hopkins Centre for Cosmological Studies: Activity 2013-2017

The first grants were awarded in the autumn of 2013 to Visiting Junior Research Fellows hosted at the institutions mentioned above. During the first three years of operation of the Oxford New College-Johns Hopkins Centre for Cosmological Studies, some twenty-four young researchers were hosted at the participating institutions for periods of up to two months each. The researchers were selected from a large field of candidates, and chosen because of their outstanding science potential and their interactivity with cosmology faculty at the participating institutions. The goal is to choose brilliant young researchers who will boost their careers by developing new collaborations. Several visited New College, while others were at the Johns Hopkins University at IAP, Paris.

The New College Balzan fellows initiated a series of Balzan Conversations, well-attended informal discussions about their research, to which the New College fellowship as well as undergraduate and postgraduate physics students were invited. New College Balzan guests also participated in many high table and lunchtime discussions with fellows. Their research interests spanned subjects including the origin of cosmic structure and the fossil radiation echo from the Big Bang.

An indication of the success of the programme may be gleaned from the fact that nearly 50% of the researchers were doctoral students and one-third were female, all first-choice candidates and highly likely to continue successful careers in research boosted by the opportunity offered by the Balzan grant to Silk for enabling them to become better acquainted with leading institutions. As in previous years, in 2016-2017 researchers were selected from a large field of candidates, chosen with support from faculty at each institution and based on their potential to carry our outstanding work of international importance. While the centre's work remains focused on cosmology, 2016-2017 saw a broader scientific reach than ever before. Moreover, the program reaches participants at crucial times in their careers, namely at the end of their PhD work or in transition to a first postdoctoral fellowship. Balzan funds help them make these transition points scientifically productive, thus ensuring that Balzan scholars go on to great careers.