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The Zeldovich Universe: Genesis and Growth of the Cosmic Web

Edited by

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The skyline of the old town of Tallinn, with its characteristic towers and spires, against the background of a grid rendering of a cosmic density field evolved according to the Zeldovich formalism. Design: Niels Bos & Johan Hidding.

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THE ZELDOVICH UNIVERSE: GENESIS AND GROWTH OF THE COSMIC WEB

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OF THE INTERNATIONAL ASTRONOMICAL
UNION HELD IN TALLINN, ESTONIA
JUNE 23–28, 2014

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IAU Symposium No. 308 and this volume
are dedicated to

YAKOV B. ZELDOVICH (1914-1987)

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Preface

On Megaparsec scales, matter and galaxies have aggregated into a complex network of interconnected filaments and walls. This network, which has become known as the *Cosmic Web*, contains structures from a few Megaparsecs up to tens and even hundreds of Megaparsecs of size. It has organized galaxies and mass into a wispy web-like spatial arrangement, marked by highly elongated filaments, flattened wall-like structures and dense compact clusters surrounding large near-empty void regions. Its appearance has been most dramatically illustrated by the maps of the nearby cosmos produced by large galaxy redshift surveys such as the 2dFGRS, the SDSS, and the 2MASS redshift survey, as well as by recently produced maps of the galaxy distribution at larger cosmic depths such as VIPERS.

The Cosmic Web is one of the most striking examples of complex geometric patterns found in nature, and certainly the largest in terms of size. As borne out by a large array of computer simulations of cosmic structure formation, weblike patterns in the overall cosmic matter distribution do represent a universal but possibly transient phase in the gravitationally driven emergence and evolution of cosmic structure. These calculations have shown that weblike patterns defined by prominent anisotropic filamentary and planar features – and with characteristic large underdense void regions – are a natural manifestation of the gravitational cosmic structure formation process. The combination of these theoretical and observational studies have led to the recognition of the cosmic web as a key aspect of structure in the Universe, marking the transition from the early linear growth of the primordial Gaussian random density fluctuations as it evolves out of the primordial universe towards the emergence of complex patterns, structures and objects.

Instrumental in the development of this view of formation of structure have been the contributions by the Russian physicist and cosmologist Yakov B. Zeldovich (1914-1987). His seminal work paved the way towards a theoretical understanding of the complex weblike patterns observed in our Universe. In the year 2014 it was 100 years ago since his birth. He was born in 1914 in Minsk, Belorussia, at the time in the tsarist Russian Empire, a few months before the outbreak of World War I. In a sense, his life ran parallel to the Soviet Union, of which during the 20th century he became one of its most highly recognized and famous scientists. He played a key role in many areas of physics, with instrumental contributions in - amongst others - chemical physics, shockwave physics, nuclear physics, particle physics, astrophysics and cosmology. Besides his scientific contributions, he left a lasting legacy in terms of an impressive array of students, many of whom have become scientists of great fame.

The centenary year 2014 of Zeldovich has been celebrated by several international physics and astrophysics conferences. In Moscow and Minsk, the Zeldovich 100 conferences addressed the wide range of physical and astrophysical interests that Zeldovich touched upon in his work. In Tallinn, the symposium in honour of Zeldovich that we report in this volume exclusively devoted its attention on the field of which he was one of the founding fathers, the formation of structure in the Universe and the large scale structure of the Universe. The International Astronomical Union recognized that the major developments in the past decades would make a symposium addressing the cosmic web and the formation of structure very timely, and endorsed and sponsored it as IAU Symposium 308. The symposium had the objective of synthesizing the insights from many different observational and theoretical studies relating to the subjects, and to prepare this vibrant field for the host of upcoming surveys and data that will facilitate radically

new insights into the cosmic web, the information it entails on pressing cosmological issues and on our understanding of the formation of galaxies.

IAU Symposium 308 pays tribute in more than one way to the historical legacy of the field. While the Zeldovich formalism predicted and preceded the recognition and discovery of the beautiful and complex spatial patterns that large galaxy redshift surveys have uncovered over the past decades, the first observational indications for the reality of a weblike galaxy distribution came along as a result of the collaboration between Zeldovich and the cosmology group at Tartu Observatory lead by Jaan Einasto. In 1977 this culminated in a famous IAU Symposium, No. 79. This symposium was organized in Tallinn, the capital of Estonia, at the time located in the Soviet Union. This conference opened the subject of the large scale structure of the Universe by bringing together cosmologists from the Soviet Union and the Eastbloc with those from the West. The interaction between the different views in East and West of the way structure arose in the Universe started the field as one of the most vibrant and active areas of cosmology. By organizing IAU Symposium 308 in Tallinn, we wish also to pay tribute to the seminal significance of IAU Symposium 79 for the development of the field, and in particular in its instrumental role of exposing western cosmologists to the views of Zeldovich and his students and collaborators.

Following endorsement and sponsoring by IAU Commissions No. 28 (Galaxies) and No. 47 (Cosmology) and Division J (Galaxies and Cosmology), and subsequent approval by the IAU Executive Committee in May 2013, the organization of the symposium was set into motion and the community at large informed. The response was overwhelmingly positive, culminating in a conference that took 6 days, with 22 keynote review papers, 29 invited papers, 41 oral contributions and 62 posters, entertaining 186 participants from 31 countries. Shortly before the symposium, we learnt that one of the organizers, Jaan Einasto, was awarded the Gruber prize in cosmology, along with one of the keynote reviewers, Brent Tully. Given the participation to IAU308 of no less than 7 Gruber cosmology prize winners, on the 5th day a special Gruber prize panel discussion was organized on the subject of the remaining questions in cosmology, actively moderated by Alar Toomre.

Against the beautiful setting of the old and remarkably well preserved medieval Hansa city of Tallinn - a Unesco World Heritage Site - the participants of IAU Symposium 308 gathered from June 23-29, 2014, in the Conference Centre of Tallinn University. Today Tallinn is a vibrant city, priding itself in its modern digital and ICT infrastructure. But, above all, it is the historic heritage that offered IAU308 the serenity and inspiration of past centuries - while wandering through its cobbled streets, along its houses, city walls and towers - to contemplate about the structure of the Universe. IAU308 underlined this with a historic conference banquet in the White Hall of the 16th century House of the Brotherhood of the Black Heads (Schwarzhauptherhaus), where the atmosphere of true medieval brotherhood got framed in a beautiful musical performance by the famed Estonian TV girl's choir, directed by Arne Saluveer.

The symposium was a great success, a midsummer celebration of our fascination with the intricacies of the cosmic web. It provided a wonderful lookback on the giant leaps in understanding and insight that marked the past decades since IAU Symposium 79, and was honoured by the participation of many of whom have been responsible for important contributions. Perhaps even more important were the many new and innovative contributions by young scientists, who traced and defined new unexplored avenues of exploration of the large scale Universe. Just to name a few amongst the many notable contributions and discussions. Advances in observational, computational, as well as analytical work have started to uncover the intimate link between the nature of galaxies and

the filamentary or voidlike environments in which they are born. In recent years physical insight into the formation of structure has steeply risen as several studies have opened up 6-dimensional phase space, and representatives of all major contributions along these lines present keynote and invited lectures. The coming surge in available data on the distribution of galaxies and mass has already been marked as a new era, that of big data. Profound new sophisticated computational and statistical formalisms are revolutionizing the way in which we assess such databases and will facilitate a far richer harvest of new insights and accurate measurements of cosmological data. These were presented and discussed at this symposium. There was even much ado about nothing. Amongst the many noteworthy observations was the huge increase in studies on voids. Perhaps in coming years we will conclude IAU308 to have been a watershed in the recognition of the large potential of voids towards answering fundamental cosmological questions.

It is a great pleasure to acknowledge the financial support of our sponsors listed on page xx of these Proceedings, the active support of the members of the LOC in realizing the numerous details always associated with such a symposium. This concerns its chairman Enn Saar, and Jaan Einasto, Elmo Tempel and Antti Tamm. The nice set of conference photographs to be found throughout the book was taken by Antti Tamm (unless stated otherwise). In particular we owe great gratitude to Tiia Lillemaa and Evelyn Silvet for the practical support that made the symposium possible and so enjoyable. Also we wish to thank Niels Bos and Johan Hidding for designing a poster and cover image that honoured both the legacy of Zeldovich' work and the beautiful city of Tallinn. We also wish to thank Lorraine Webb, Elisabeth Woodhouse, and Vince Higgs at CUP for their flexibility, friendliness and patience in the light of the challenges posed by our seemingly never-ending line of requests.

Finally, we wish to state that we are particularly indebted to Tartu Observatory for enabling the success of the symposium and, even more essential, its viability. We therefore wish to thank the director of Tartu Observatory, dr. Anu Reinart, and via her all the members of the institute for enabling the 2nd Tallinn IAU Symposium on Large Scale Structure.

July 2016

Rien van de Weygaert, Sergei Shandarin, Enn Saar and Jaan Einasto

CONFERENCE PHOTOGRAPH



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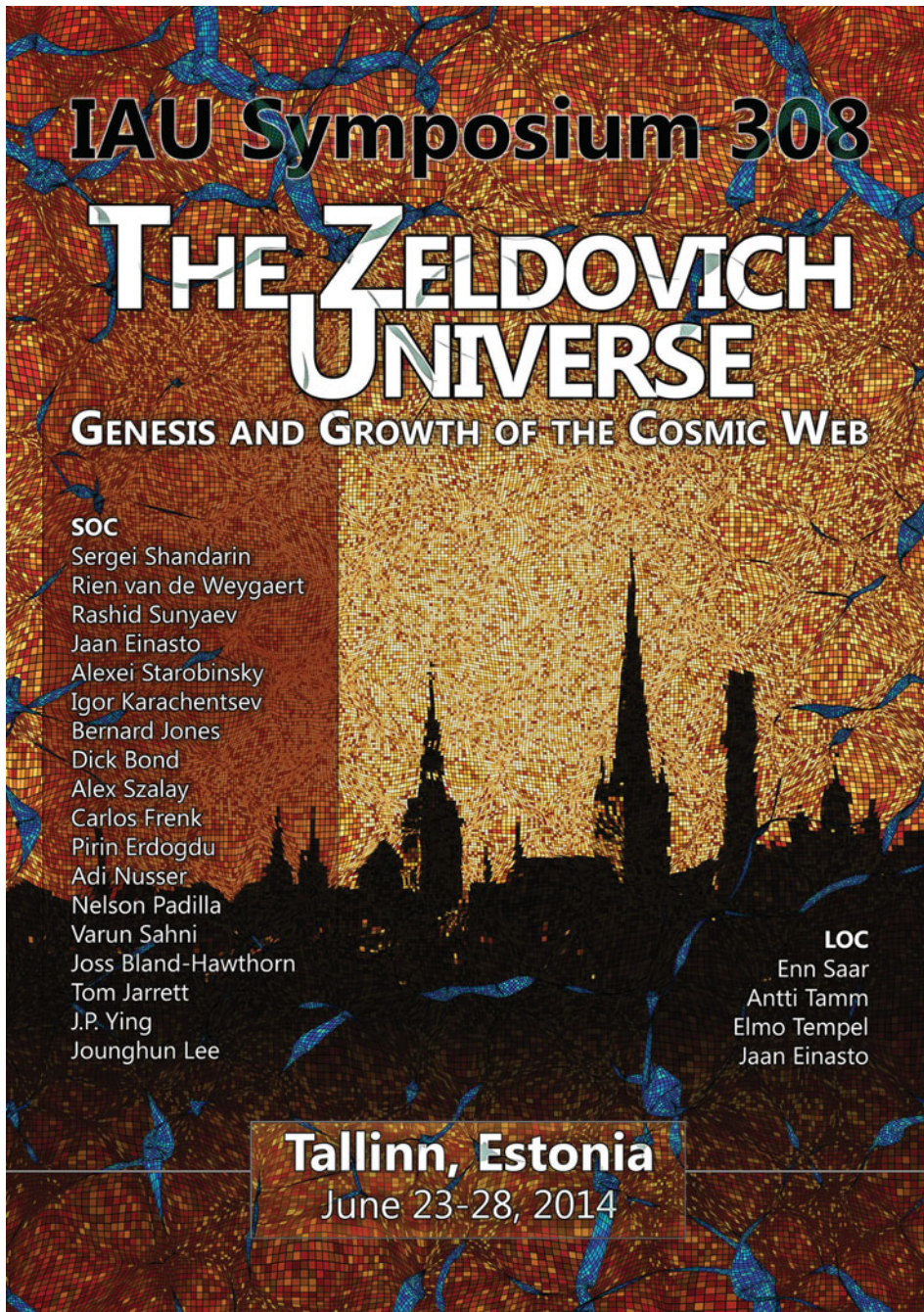
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Yakov B. Zeldovich
a collection of historic impressions



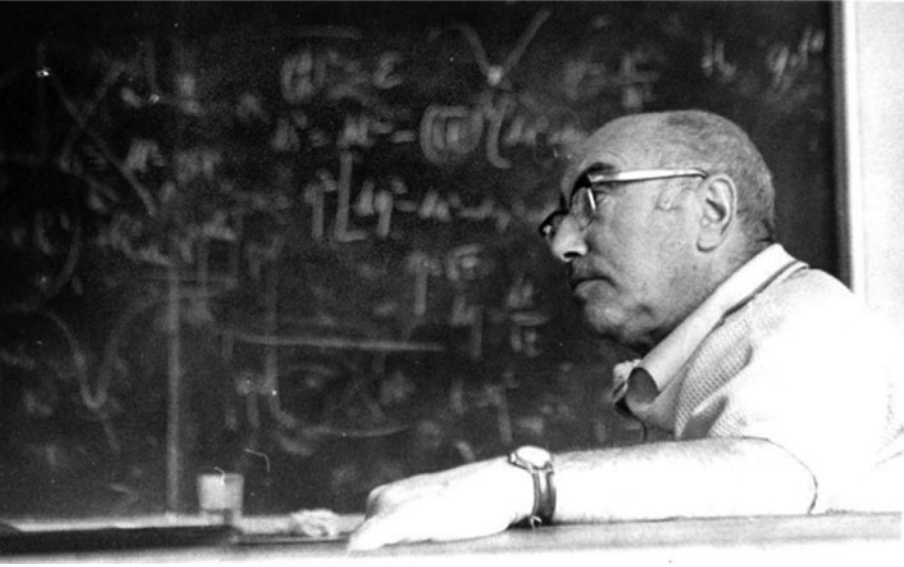
*Yakov B. Zeldovich
portrait, around 1950.*



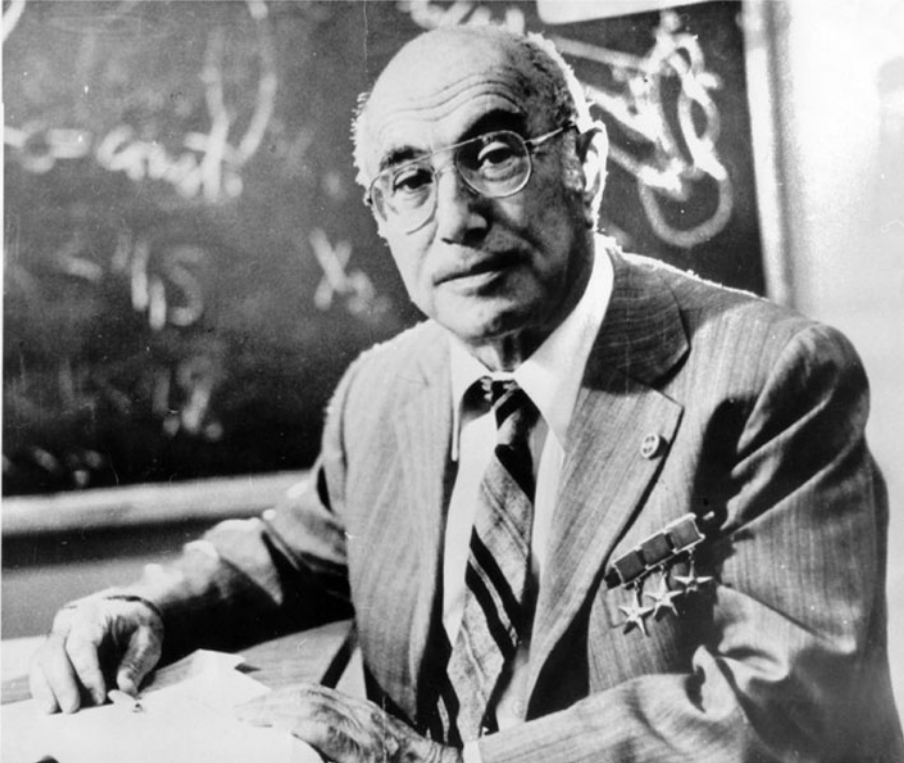
*Yakov B. Zeldovich, Andrei Sacharov and David A. Frank-Kamenetskii,
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Yakov B. Zeldovich and David A. Frank-Kamenetskii, 1947.



*Zeldovich, after a lecture on cosmology, in 1975.
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*Yakov B. Zeldovich and astrophysicist Iosif Shklovsky
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*Zeldovich with his wife visiting Estonia, late 1970s.
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