

# The Crafoord Prize 2005

The Royal Swedish Academy of Sciences has decided to award the Crafoord Prize in Astronomy 2005 to **JAMES GUNN**, Princeton University, USA, **JAMES PEEBLES**, Princeton University, USA, and **MARTIN REES**, University of Cambridge, UK, “for contributions towards understanding the large-scale structure of the Universe”.

## How was the Universe formed?

One of the most obvious facts about the Universe is that it shows a wealth of structure on all scales from planets, stars and galaxies up to clusters of galaxies and super-clusters extending over several hundred million light years. Astronomical observations have shown that the galaxies are not evenly distributed, but are mainly found in clusters and enormous filaments (Fig. 1). Often this is referred to as the ‘cosmic web’. The origin and history of this structure has long been one of the most important problems for astronomy and cosmology. The recipients of this year’s Crafoord Prize have all made fundamental contributions to the dramatic increase in our understanding of how this large-scale structure was formed.

The first traces of structure in the Universe can be seen in the fluctuations of the cosmic microwave background radiation about 380,000 years after Big Bang (Fig. 2). The origin of the fluctuations can, however, be traced back to epochs much earlier in the history of the Universe when small quantum fluctuations gave rise

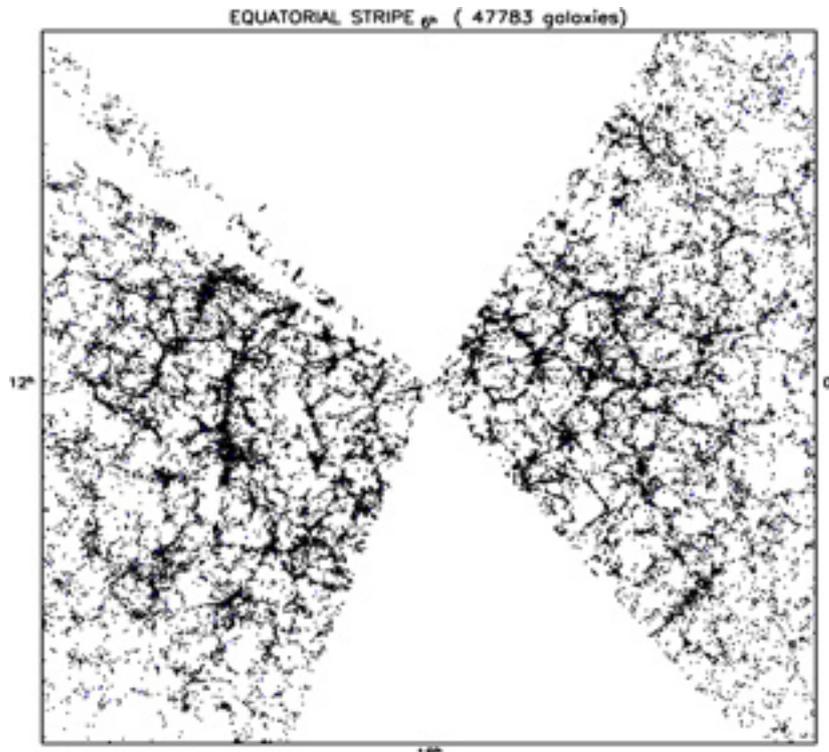


Fig. 1. Two dimensional distribution of galaxies from the Sloan Digital Sky Survey. The plot corresponds to a thin slice in the ‘vertical’ direction, but covering most of the sky in the other direction. The Milky Way is at the centre and the most distant galaxies at the edge of the plot are at a distance of two billion light years. The missing wedge in the centre is caused by the obscuration of the Milky Way. Nearly all galaxies are found in clusters or filaments, surrounding largely empty bubbles.

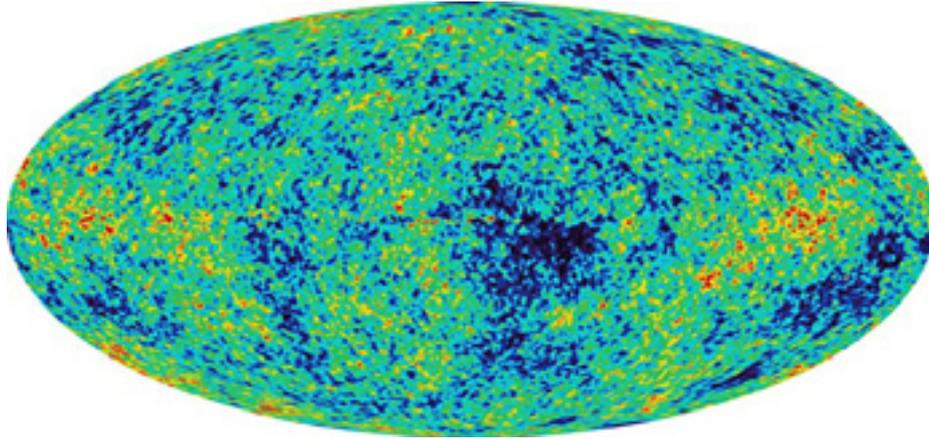


Fig. 2. Fluctuations in the cosmic microwave background as seen by the WMAP (Wilkinson Microwave Anisotropy Probe) satellite. The contrast between the bright and faint areas is only one part in 100,000 above the mean density in the Universe. These are the first indications we have of structure forming in the early Universe at an age of about 380,000 years after Big Bang. (NASA/WMAP Science Team)

to the first seeds. Currently, this is believed to have occurred at an unbelievably early stage of  $10^{-35}$  s!

Although extremely small, these fluctuations increased in amplitude at the same rate as the Universe expands, and by an age of a few hundred million years they were large enough for the first galaxies to form (Fig. 3). In the now most popular scenario, small galaxies form first, and from these building blocks larger galaxies subsequently form by mergers. Large galaxies, like the Milky Way, are therefore formed as a result of a gradual build-up of smaller galaxy fragments.

This process can be studied directly from observations of galaxies at very early epochs by the Hubble Space Telescope (Fig. 4). Even today galaxies are forming and merging

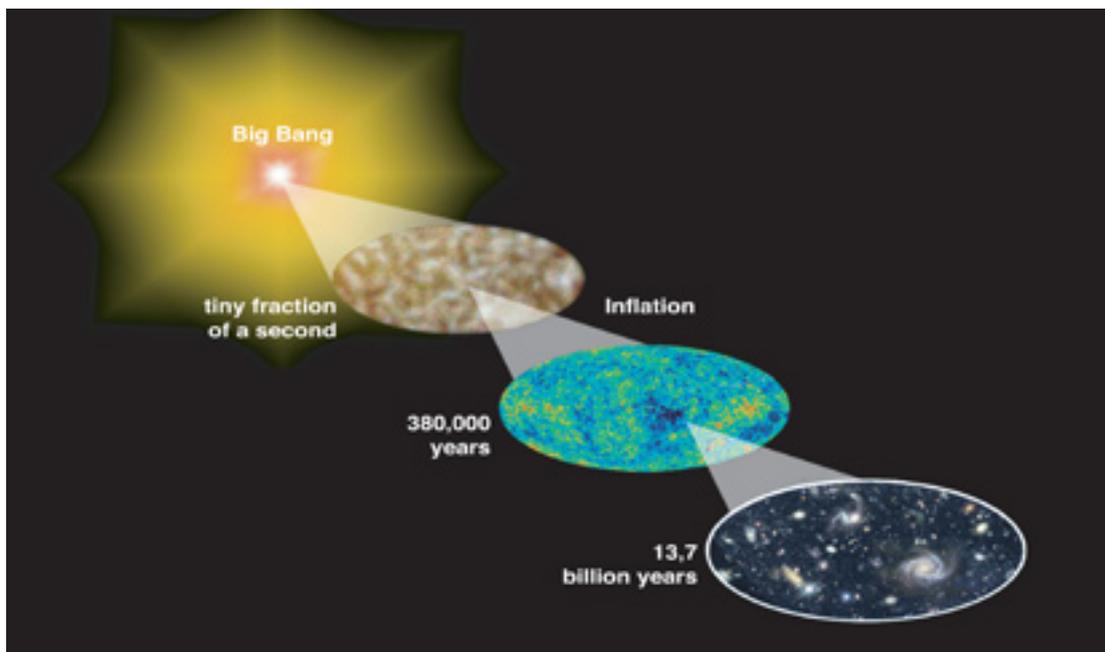
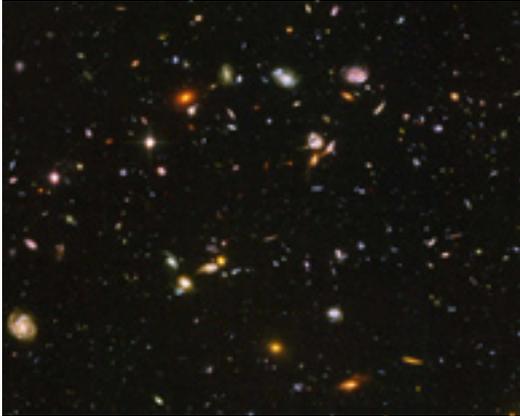


Fig. 3. The development of structure from the first quantum fluctuations during the first tiny fraction of a second, to the fluctuations in the cosmic microwave background at 380,000 years, and finally to the first large galaxies at about one billion years after Big Bang and to present. (Illustration: Typoform after NASA/WMAP Science Team)



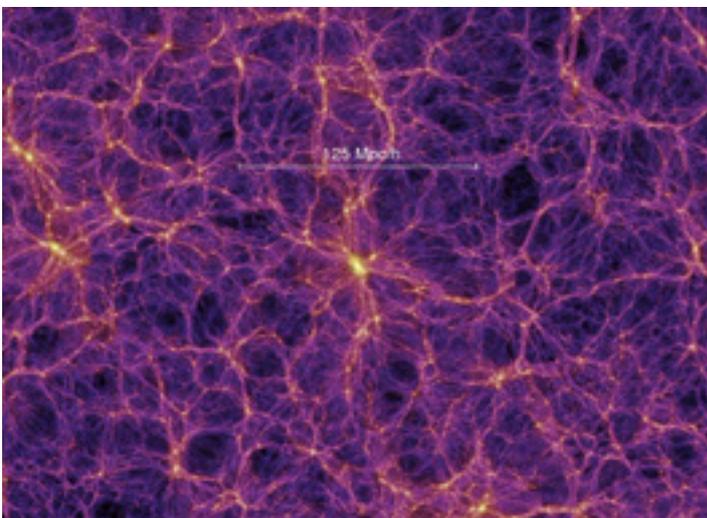
*Fig. 4. The deepest picture of the Universe. The faintest galaxies in this picture are seen only one billion years after Big Bang. Many of the galaxies are fragmented and are undergoing mergers to form larger galaxies. (Hubble Ultra Deep Field, Hubble Space Telescope, NASA/ESA)*

with each other, albeit at a much lower frequency than in the early Universe. Not only galaxies were formed in this way, but structures of all sizes and masses formed as a result of this hierarchical process. This includes clusters of galaxies of up to a thousand galaxies, as well as even larger structures, clusters and filaments of clusters (See Fig. 1).

### **Dark matter governs the visible**

Although the visible galaxies, consisting of ordinary matter made up of electrons, protons and neutrons, act as the most important tracers of this structure, the dominant ingredient in this galaxy formation scenario cannot be seen directly. Today we know that there is about five times as much ‘dark matter’ as that which is visible. The nature of this dark matter is unknown, and represents one of the main puzzles in physics and astrophysics today. We only know that it interacts extremely weakly with other matter, except for by gravitational attraction. The most popular candidates for dark matter come from the so-called supersymmetric particle physics theories.

The gravitational attraction of this dark matter determines the growth of the gravitational wells, where the normal, visible matter ‘falls in’ and forms the structure we see today in the form of galaxies and larger structures. The resulting structure therefore reflects the properties of the dark matter. Depending on the mass and temperature of the particles making up the dark matter, the structure formation may either begin from large structures, that gradually fragment (‘Hot Dark Matter’), or from small structures that then merge to form larger ones (‘Cold Dark Matter’). From comparison of computer



*Fig. 5. The largest computer simulation of the Universe, which is shown at 13 billion years after Big Bang. The bar is 600 million light years long. Note the similarity with the structure in Fig. 1. What can be seen here is the structure of dark matter, closely related to the visible. (V. Springel et al., Virgo Consortium)*

simulations of the Universe (Fig. 5) and the maps of the large-scale structure (See Fig. 1) one has concluded that only Cold Dark Matter simulations agree with the observations. There is therefore a fascinating connection between physics on the smallest scales and the largest structures we have in the Universe.

### **An active and influential trio**

**JAMES GUNN, JAMES PEEBLES** and **SIR MARTIN REES** have all contributed fundamentally to our understanding of the various ingredients of this picture. As early as in the 1960s Peebles predicted some of the most important properties of the cosmic microwave background radiation. In particular, he made detailed calculations of the crucial epoch when the Universe evolved from being completely opaque to the radiation to becoming transparent. He later developed the main formalism to quantify the observed clustering of galaxies, and the evolution of the structure with time. Peebles has been one of the main proponents of the now most popular version of galaxy formation, the Cold Dark Matter theory, with the hierarchical evolution of the structure as its main characteristic.

Most of Gunn's early contributions on galaxy formation concerned the theoretical development of galaxy formation and the properties of the gaseous medium between the galaxies. He also suggested important observational tests for dark matter candidates in galaxies. His later work has been closely related to observational projects. In particular, he has been central in several instrumental projects for understanding the formation of galaxies, in particular using the Hubble Space Telescope. A recent project, which to a large extent is a result of his ideas, is the hitherto most extensive three-dimensional mapping of the Universe to date in the form of the Sloan Digital Sky Survey (see Fig. 1). When completed it will have distances to and other properties of one million galaxies, and has already had large consequences for many fields of observational astrophysics and cosmology.

Rees's work on galaxy formation includes the understanding of physical processes determining the observed properties of galaxies. This includes such parameters as their typical masses. Together with Simon White he first pointed out the central role of dark matter for the formation of the large-scale structure. This later inspired a whole generation of detailed computer simulations of the development of structure in the Universe. He has lately developed important ideas in relation to the epoch when the first stars and galaxies formed, and suggested important observational tests of this 'dark age' in the history of the Universe. He is also a well-known author of popular-scientific books.

Together these three scientists are responsible for most of the current picture of galaxy and structure formation in the Universe. Although much of the fundamental work acknowledged by the prize was done two or three decades ago, this remains one of the most active areas of cosmology. All three recipients are today highly active and are among the most influential cosmologists.

## Links and further reading:

### Books by Sir Martin Rees:

"Just Six Numbers" (in 'Science Masters' series: Basic Books (US) (Feb 2000, paperback April 2001) and Weidenfeld and Nicolson (UK).

"Our Cosmic Habitat". Princeton University Press, US, (2001) Weidenfeld & Nicolson (UK) (2002).

"Our final century" Random House (UK) (published in US as "Our Final Hour" by Basic Books) (2003).

"What we still don't know" Penguin Press (UK) (2004).

### Links:

WMAP (Wilkinson Microwave Anisotropy Probe): <http://map.gsfc.nasa.gov/>

Sloan Digital Sky Survey: [www.sdss.org/background/science.html](http://www.sdss.org/background/science.html)

The Virgo consortium, simulation of the Universe:

<http://www.mpa-garching.mpg.de/galform/virgo/index.shtml>

The Hubble telescope:

<http://hubblesite.org/>

Hubble Ultra Deep Field:

<http://hubblesite.org/newscenter/newsdesk/archive/releases/2004/07/>

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