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It is a honour for me to write a short commentary on the Nobel Prize allocation to Philip James Edwin Peebles, or Jim, as everybody calls him. I had the great chance to spend two years as a post-doc in Princeton, where Jim was leading the 'gravity-group' at the time. From him I learned that groups work best with a flat hierarchy where everybody can communicate her/his ideas, ask questions and participate in discussions in a relaxed and constructive atmosphere. This was the spirit of Jim's 'lunch seminars' with the famous 'hoagies' from the Hoagie Haven at Nassau street.

Jim Peebles was awarded the Nobel prize 2019 "*for theoretical discoveries in physical cosmology*". The Press release says: "*James Peebles' insights into physical cosmology have enriched the entire field of research and laid a foundation for the transformation of cosmology over the last fifty years, from speculation to science. His theoretical framework, developed since the mid-1960s, is the basis of our contemporary ideas about the universe.*"

This statement could not be more true. In the beginning of the 1960ties, it was still debated whether the 'steady state model' or the 'Big Bang model' was a better description of the physical Universe. The discovery of the Cosmic Microwave Background (CMB) put an end to this debate. This relic radiation from the Big Bang was natural only in an adiabatically expanding and cooling Universe, as it had been predicted already in the 1940ties by George Gamow and collaborators. James was co-author of the theoretical interpretation paper published in 1965 [1], back-to-back with the Nobel Prize (1978) winning CMB discovery paper by Penzias and Wilson [2].

The discovery of the CMB led to a paradigm change and convinced most workers in the field that Big Bang Cosmology was basically correct, nevertheless the details (like the matter and radiation content of the Universe or the value of its spatial curvature) were still completely unknown.

The Big Bang model of cosmology is based on Einstein's General Relativity with the assumption that on large enough scales, the distribution of matter and radiation in the Universe is homogeneous and isotropic with only small initial fluctuations. This assumption leads to an expanding and cooling Universe [1]. In the past, the Universe was very hot and its energy density was dominated by radiation. Subsequently it expanded and cooled down adiabatically. At a temperature of about $kT \sim 0.1$ MeV the first atoms, mainly Helium, but also Deuterium and traces of Lithium formed, a phase called 'primordial nucleosynthesis'. At $kT \sim 0.25$ eV the remaining protons and electrons recombined to neutral hydrogen and the Universe became transparent to the cosmic radiation which propagated freely, affected only by cosmic expansion redshifting the thermal radiation to the present CMB temperature of about 2.73 K. A picture of the CMB radiation is literally a 'photograph' of the Universe when it was about 380'000 years old.

Somewhat earlier, dark matter started dominating the energy density of the Universe and small initial fluctuations could start to collapse under their own gravity into the structures (galaxies, clusters, filaments and voids) which today make up the 'cosmic web'. In the absence of dark matter, radiation pressure would have prevented the growth of fluctuations until well after recombination and the time would have been too short to form the presently observed structures.

An interesting idea to generate initial fluctuations was proposed in the 1980ties via an 'inflationary phase', i.e., a phase of very rapid expansion which may have preceded the thermal state of the hot Big Bang. Quantum fluctuations of the scalar field dominating such a stage of inflation are stretched into large scale coherent classical fluctuations with a nearly scale invariant spectrum. Such fluctuations have been observed in the CMB (Nobel Prize 2006) and, in the presence of dominant, sufficiently cold, dark matter, they can evolve into the observed cosmological large scale structure (LSS).

Finally, at the end of the 20th century and beginning of the present century, it was becoming clear that the expansion of the Universe is presently accelerating (Nobel Prize 2011), not decelerating as one would expect from universal gravitational attraction. Such an accelerated expansion can be obtained by adding a cosmological constant, Λ, to Einstein's field equations (as actually Einstein himself did to obtain his static Universe in 1917). There are also other possibilities for a gravitationally repulsive component, today generically termed 'Dark Energy'.

All these ingredients have led to the standard model of cosmology, the so called ΛCDM model, with an energy density which is presently dominated by the cosmological constant, contributing about 68% followed by 27% of dark matter and

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[1] A contracting Universe would also be possible but it does not agree with observations.

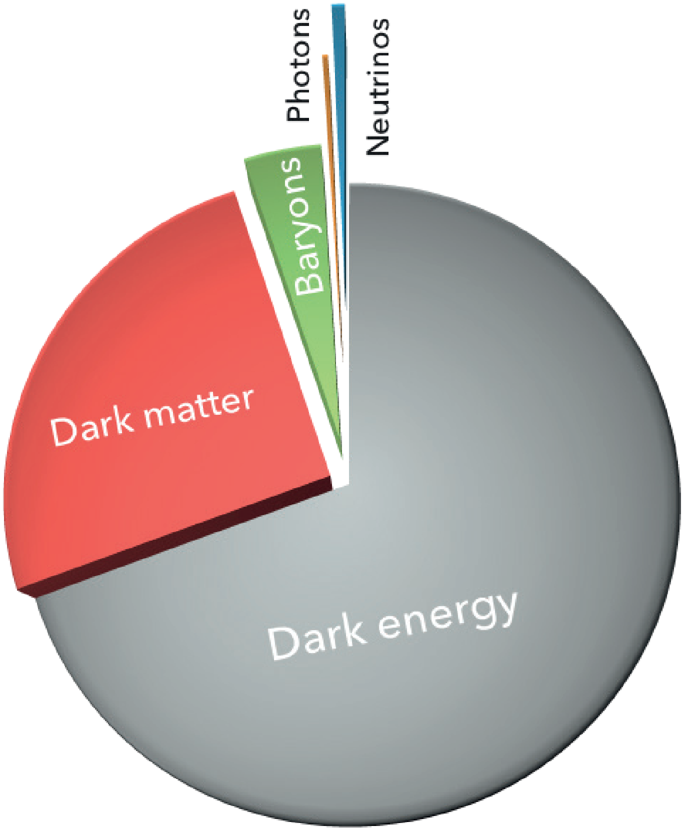

Figure 1: Composition of the Universe today. Ordinary matter makes up only 5% of the energy density of the Universe. Dark Matter, an unknown form of matter that does not emit light, contributes about 27% while Dark Energy, an even more mysterious component associated with the accelerated expansion of the universe, makes up 68% (Neutrinos and photons even though much more numerous contribute far less than 1% to the present energy density of the Universe.).

only about 5% of ordinary matter, baryons. The CMB radiation contributes at present only a fraction of about 5.4 × 10^{-5} to the energy budget of the Universe, much less than the neutrinos which contribute (1.4 to 5) × 10^{-3}, depending on the sum of the neutrino masses [2], see Fig. 1. This is the minimal cosmological model with only 5 fundamental parameters (the present dark matter and baryon densities, the cosmological constant, as well as the amplitude and the slope of the primordial spectrum of scalar fluctuations) and 1 fudge factor (the optical depth to the CMB or the redshift of re-ionisation). It fits most present cosmological data and its 6 parameters are determined with a precision of about 1% or better. As an example, the fit to the about 2500 CMB temperature fluctuation data points from the Planck satellite is shown in Fig. 2.

There are a few tensions with some data, most notably the different methods to measure the value of the Hubble constant, H_0. These may or may not hint towards shortcomings of the ΛCDM model, which certainly from the theoretical side is far from satisfying. But then, a model which agrees with all data must be wrong, because some data are wrong.

James Peebles contributed in many very important ways to establishing the present cosmological standard model. I think it is fair to say that he is the world's leading theoretical cosmologist.

He has pioneered our understanding of primordial nucleosynthesis and has calculated the abundance of the light elements [4]. Together with Robert Dicke he has predicted the existence of the Cosmic Microwave Background and together with David Wilkinson and Peter Roll they actually searched for this radiation while Penzias and Wilson discovered it accidentally. He studied the formation of cosmological large scale structure by gravitational instability and predicted the existence of cold dark matter (CDM), needed to explain the clumpy structure of matter together with the smoothness of the CMB [5, 6]. Already in the 1980ties and 90ties he advocated that the matter density of the Universe was not sufficient for a flat so called 'Einstein de Sitter' solution and that either negative curvature or a cosmological constant was needed to explain the data, see e.g. [7]. He developed not only the basic ideas but also analytical and numerical tools to

- calculate primordial nucleosynthesis
- study anisotropies in the CMB
- investigate the formation of large scale structure
- describe the statistical properties of the galaxy distribution.

In all these major fields of cosmology, James Peebles played a leading role.

He invented the 'cold dark matter' (CDM) model. Together with B. Ratra he wrote one of the first papers on quintes-

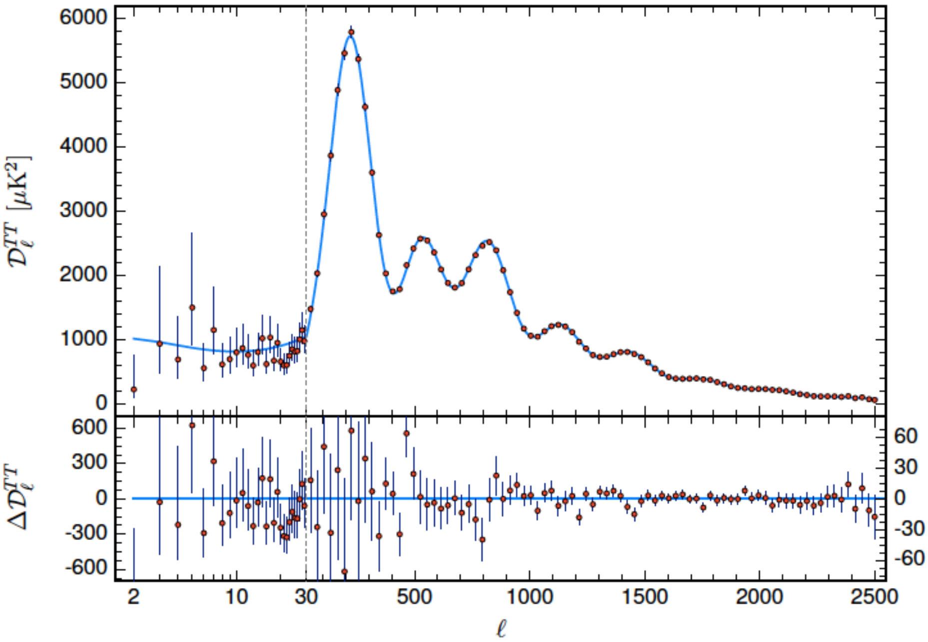

Figure 2: The temperature fluctuation spectrum $\ell(\ell + 1)C_\ell / (2\pi)$ as measured by the Planck satellite (the red points with error bars represent binned data points) and the 6 parameter basic model (blue line). Figure from [3].

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[2] For 1.4 × 10^{-3} I assume the minimal allowed value from neutrino oscillations of 0.06 eV while for 5 × 10^{-3} I assume a Planck limit of about $\sum_i m_{\nu_i} < 0.23$ eV.

sence or dark energy at a time when nobody was working on this subject [8].

However, during all this time, when he was leading what later became the main stream models in cosmology, he always also studied alternatives like his baryon isocurvature model [9] or models of large scale structure with negative spatial curvature [10] and more. He always kept an open mind, remained critical and identified loopholes in arguments which tried to 'cement' the standard wisdom at any time.

A few words to Jim's career:
James Peebles was born in Saint-Boniface near Winnipeg in Canada and did his undergraduate studies in Manitoba. In 1958 he move to Princeton where he started a PhD under the supervision of Robert Dicke. In an interview with the CERN EP Newsletter in 2016 he said about this time:

> *"I felt very uncomfortable about the modest experimental evidence in support of any cosmology theories. I did not think I would spend much time in this field, but, surprisingly, I kept finding things to explore during my entire career."*

He spend most of his professional life in Princeton, since 1984 as Albert Einstein Professor of Science.

Peebles received many awards and distinctions like, e.g., the Eddington Medal (1981), the Dannie Heineman Prize (1982) the Georges Lemaître Prize (1995), the Peter Gruber Prize in cosmology (with A. Sandage, 2000) and the Tomalla Prize (2003). I was happy to be able to hand over to him this last distinction.

Peebles' Nobel Prize marks the fourth one during this century for the field of cosmology and gravity after the 2006 Prize for the COBE experiment (Mather & Smoot), the 2011 Prize for the discovery of accelerated expansion with Supernova measurements (Perlmutter, Schmidt & Riess) and the 2017 Prize for the LIGO experiment (Weiss, Barish & Thorne). These past prizes were mainly for experimental work, this year's prize goes to a theoretical cosmologist.

Peebles is certainly an excellent choice in a time when cosmology will enter a new area by mapping out the distribution of galaxies in the entire visible Universe. To interpret these data, the statistical tools pioneered by James Peebles will remain of utmost importance.

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