PHYSICAL COSMOLOGY GETS ITS FRECKLES: ABOUT PEEBLES'S NOBEL PRIZE IN PHYSICS 2019

LA COSMOLOGÍA FÍSICA SE HA MOTEADO: SOBRE EL PREMIO NOBEL DE FÍSICA DE PEEBLE EN 2019

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I. INTRODUCTION: WHAT DO WE CALL PHYSICAL COSMOLOGY?

Cosmology is the study of the Universe on the largest scales. Up to the 1950s, cosmological data was scarce and generally so inaccurate that the British-Austrian mathematician and cosmologist H. Bondi claimed that if a theory did not agree with data, it was about equally likely the data were wrong [1].

Our current cosmological models are based on the solutions to Einstein General Relativity's equations, making some general assumptions of isotropy and homogeneity, the so-called *Cosmological Principle*, of the Universe at large scales. In other words: the assumptions on which the models are based, were certainly not inspired nor suggested nor even confirmed by the data a century ago. In fact, Einstein's static model was shown to be unstable and so the expansion of the Universe could have been a prediction of the theory; surely it would have ranked as one of the most amazing predictions of the physical world based on pure thought. As it happened, Hubble's observational discovery of the expansion around the same time relegated the models to describing the data. At the 30th Meeting of the International Astronomical Union (IAU), the members of the General Assembly decided by simple majority to support the resolution: "from now on the expansion of the universe [should] be referred to as the Hubble-Lemaître law" [2].

Novel observational techniques have revolutionised cosmology over the past decade. The combined power of galaxy redshift surveys, and Cosmic Microwave Background (CMB) [3] experiments have lead us into the era of *Precision Cosmology*, from where we start to test the theoretical models, and determine their cosmological parameters to percent level. The past years have seen the emergence of a standard model in cosmology, described by around six parameters. Given how recently this has all happened, we certainly need to keep our minds open for surprises, but the degree to which the models agree with the data is simply astonishing: the current cosmological model is based on the believe of a Hot Big Bang from where the observed structures grew, from scale invariant gaussian fluctuations amplified by gravity and presently dominated by dark energy and dark matter. This is called a spatially flat, scale-invariant ΛCDM model, where Λ denotes the cosmological constant (a special case of dark energy), and CDM stands for cold dark matter.

Questions that arise, and have been the chalice for many cosmologists remain: is the ΛCDM model the end of the road? Cosmology is almost unique in the physical sciences, therefore it also demands an answer to the question of why the cosmological parameters have the values they do. Is the Big Bang truly a singularity? What happened before that? Can these questions make sense? Not so long ago, most cosmologists would have mumbled that time was created in the Big Bang, that it makes no sense to talk about things which are in principle unobservable, such as other universes, or anything before this singularity. Yet there is currently a flurry of theoretical activity addressing precisely these issues, but it is not clear how we will distinguish each scenario based on different models. From proving the validity of the ΛCDM model, where factors like tensions phenomena are arising between Planck [4] and other cosmological measurements as: Cefeids (SH0ES), strong lensing time delays (H0LiCOW), tip of the red giant branch (TRGB), Oxygen-rich Miras and surface brightness fluctuations [5], only justify the study of possible alternatives to the ΛCDM model. One of the most interesting approaches seeks for dynamical properties of dark energy, which should be able to mimic Λ at the present time as required by the cosmological observations. Some approaches start from quintessence scenarios [6,7], dark energy parameterisations [8–12], modified gravity [13, 14], extended theories of gravity [15], equations of state $w(z)$ reconstructions [16], non-parametric reconstructions of $w(z)$ [17, 18], to Bayesian reconstruction of a time-dependent $w(t)$ [19] or dynamical w_x from alternative gravity models [20], which represents a large overview on how we are trying to explain the effects of Λ. Furthermore, with the increase of computational techniques, many alternative options have emerged using machine learning techniques [21]. However, a consensus of a unique model is still missing and all the proposals imply a model dependency which can be significantly different by imposing a different theoretical scenario. Clearly, current and future data from the surveys will certainly clarify all the issues or at least shed some light on them.

All the above work has been possible thanks to original discoveries in the theoretical framework of cosmology over the past century. This year's Nobel Laureate James Peebles has made seminal contributions in this science [22]. Through detailed modelling, with the help of analytic methods, he has explored fundamental properties of our Universe and discovered unexpected new physics. We have now at hand an unified model capable of describing the Universe from its earliest fraction of a second up to the present and into the distant future. Let us take a general look how these ideas were develop.

II. IF EVERYTHING STARTED WITH A BIG BANG...

Our current understanding of the Universe is based upon the successful Hot Big Bang theory, which explains its evolution from the first fraction of a second to our present age, almost 14 billion years later (see Figure 1). This theory rests upon four strong pillars, a theoretical framework based on General Relativity, as was put forward by A. Einstein and A. Friedmann in the 1920s, and three observational facts: first, the expansion of the Universe, discovered by E. Hubble in the 1930s, as a recession of galaxies at a speed proportional to their distance from us. Second, the relative abundance of light elements, explained by G. Gamow in the 1940s, mainly that of helium, deuterium and lithium, which were cooked from the nuclear reactions that took place at around a second to a few minutes after the Big Bang, when the Universe was a few times hotter than the core of the sun. Third, the CMB, the afterglow of the Big Bang, discovered in 1965 by A. Penzias and R. Wilson as a very isotropic blackbody radiation emitted when the Universe was cold enough to form neutral atoms, and photons decoupled from matter, approximately 500 000 years after the Big Bang. Today, these observations are confirmed to within a few percent accuracy, and have helped establish the Hot Big Bang as the preferred model of the universe.

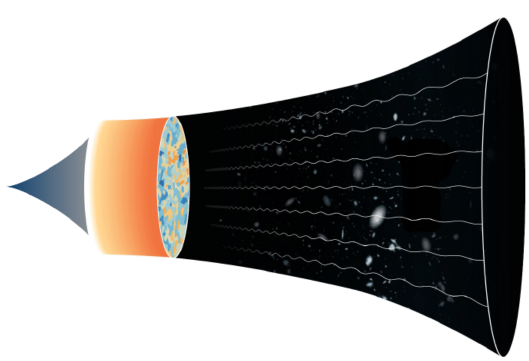

Figure 1. Schematic timeline of our Universe extending from an unknown origin on the left to a darkening future on the right. Figure from [22].

Even today, this CMB ancient radiation is all around us and, coded into it, many of the universe's secrets are hiding. Using his theoretical tools and calculations, J. Peebles was able to interpret these traces from the infancy of the Universe and discover new physical processes.

III. THE COSMOLOGICAL CHALICE: ON HOW TWO QUESTIONS OPEN THE DISCUSSION OF THE CENTURY

If we consistently follow a model where the CMB has an origin in a cosmological Big Bang, then we should be able to observe different values when measured in different directions. This is what we call *anisotropies* – where physical cosmology gets its freckles –, which should indicate deviations of the real Universe with respect to a homogeneous and isotropic idealisation. This is fundamental, since otherwise we would not observe cosmological structure.

Due to our inherent inability to experiment with the universe, its origin and evolution has always been prone to wild speculation. However, Cosmology was born as a science with the advent of General Relativity and the realization that the geometry of space-time, and thus the general attraction of matter, is determined by the energy content of the universe. Therefore, since 1915, the first question that came as a consequence was *where are we in the universe?* An expert in the field starts with Einstein's equations to give an answer to this question,

$$G_{\mu\nu} \equiv R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}, \tag{1}$$

but let us generalise these non-linear equations as the relationship between the geometry ($G_{\mu\nu}$) of the universe and the matter ($T_{\mu\nu}$) that its contained in it. Around the 1920s, the known (observed) universe extended a few hundreds of parsecs away, to the galaxies in the local group, Andromeda and the Large and Small Magellanic Clouds: the universe looked extremely anisotropic. Nevertheless, both Einstein and Friedmann speculated that the most reasonable symmetry for the Universe at large should be homogeneity at all points, and thus isotropy. It was not until the detection, a few decades later, of the CMB radiation that this important assumption was finally put onto firm experimental ground. So, what is the most general metric satisfying homogeneity and isotropy at large scales? The Friedmann-Robertson-Walker (FRW) metric

$$ds^2 = -dt^2 + a(t)[d\psi^2 + f(\psi) d\Omega^2], \tag{2}$$

where $f(\psi)$ represents a curvature constant K as $f(\psi) = [\sin^2\psi, \psi^2, \sinh^2\psi]$. The dynamics of the metric is contained in one function: the scale factor $a(t)$, which is related to the redshift z of the light that came from others galaxies as $a = 1/(1+z)$. We can also define the Hubble parameter, $H = \dot{a}/a$, where the dot stands for time derivation. If we introduce this metric in Einstein's equations we should verify not only the dynamics, but also the matter content, which is represented by a perfect fluid. The entire dynamic is determined by

$$H^2 = \frac{8\pi G}{3} \sum_i \rho_i + \frac{\Lambda}{3} - \frac{K}{a^2}, \tag{3}$$

where ρ_i is the energy density of each component of matter in the Universe (radiation, baryons, neutrinos, Λ – possibly associated with the vacuum energy of quantum field theory –, etc.) and we can establish whether the universe has a closed ($K = 1$), flat ($K = 0$) or open ($K = -1$) topology. The latter can be written as

$$\Omega_K \equiv \frac{K}{a^2 H^2} = \sum_i \Omega_i - 1, \tag{4}$$

where all the density parameters are defined as $\Omega_i = \rho_i/\rho_{\text{crit}}$, with $\rho_{\text{crit}} = 3H^2/8\pi G$. To illustrate how the evolution of the universe works, we can write (3) as

$$\frac{\dot{a}^2}{2} - \frac{GM}{a} - \frac{\Lambda}{6}a^2 = -\frac{K}{a} = \text{constant}, \tag{5}$$

where $M \equiv 4\pi/3\rho a^3$ is the equivalent of mass for the whole volume of the universe. In other words, (5) can be understood as the energy conservation law $E = T + V$ for a test particle of unit mass in the central potential

$$V(r) = -\frac{GM}{r} + \frac{1}{2}kr^2, \tag{6}$$

which corresponds to a Newtonian potential plus a harmonic oscillator potential with a negative spring constant $k \equiv -\Lambda/3$. On the one hand, we notice that, for vanishing Λ, a critical universe, defined as the division between indefinite expansion and recollapse, corresponds to a flat universe. On the other hand, a spatially open universe corresponds to an eternally expanding universe and for a spatially closed universe to a recollapsing one in the future. Only in a case when $\Lambda \neq 0$, spatially open universes may recollapse while closed universes can expand forever. In Figure 2 we can observe some possible evolutions of the scale factor in a $(\Omega_\Lambda, \Omega_m)$ concordance region.

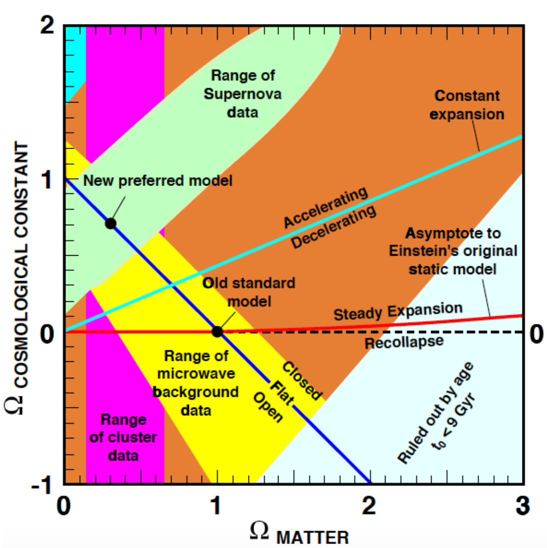

Figure 2. Evolution of a with respect to t for different values of matter and cosmological constant. Color regions stand for the range of observations. The current best cosmological model is a flat scenario with a third of the energy density in the form of non-relativistic matter and two thirds in the form of vacuum energy or a Λ. Figure from [23].

Now we are ready to address the second question that arises as a direct consequence of the general covariance of the theory: the conservation of energy, or *what is the universe made of?* To follow the above discussion, we can write this conservation of energy in terms of the FRW metric and the perfect fluid tensor as

$$\frac{d}{dt}(\rho_i a^3) + p_i \frac{d}{dt}(a^3) = 0, \tag{7}$$

where ρ_i and p_i represent the density and pressure of matter components, respectively. Now, to find an analogy between the above expression and the Second Law of Thermodynamics, $TdS = d(\rho a^3) + pdV$, we observe that (7) implies that the universe is expanding adiabatically ($dS = 0$), therefore the entropy per comoving volume is $S = a^3(\rho_i + p_i)a^3/T$, which is conserved. The consequence of this conservation is that, during the adiabatic expansion of the universe, the scale factor grows as $a \propto T^{-1}$. This implies that in the past the universe must have been much hotter and denser and eventually it would be colder and dilute. Since a can be written in terms of the redshift, we can measure the temperature of the CMB at high redshift as $T = T_0(1+z)$. These measurements have been carried out systematically, however the results do not ensure that the temperature of the CMB has varied as expected [24].

To track the consequences of the above ideas, we should go back in time, when the universe started to become hotter and hotter and thus the amount of energy available for particle interactions increased. At this point, the interactions goes from those described at low energy by gravitational and electromagnetic physics, to atomic physics, nuclear physics till high energy physics at the electroweak scale, followed by a speculative grand unification epoch and finally the not well understood quantum gravity. And here comes Peebles's idea [25]: a connection between temperature and the density of matter. Based on the observed temperature of the Universe, it is possible to constrain the amount of matter that consists of nucleons (baryonic matter), which in the early 1965 observations showed less matter than predicted by Peebles. And the solution is one of the most remarkable achievements in the history of science: observational data matches perfectly the predictions of a theoretical model. The theoretical model presented by Peebles et al. in [26] states: "A critical factor in the formation of galaxies may be present as a black-body radiation content of the universe". In other words, emitted radiation by the early universe (for our purposes, the 'body') should be distributed between the various wavelengths of the electromagnetic spectrum, and the shape of that spectrum depends entirely on temperature. Therefore, if we know the temperature of such a black-body we can precisely predict what the resulting spectrum should look like. Twenty four years after this publication was released, NASA launched the Cosmic Background Explorer (COBE) satellite, and got the first results after a mere nine minutes of observations. The accumulated data points formed a perfect black-body spectrum – the universe is a perfect emitter and absorber of radiation. From this, we were able to measure the fluctuations temperature in the CMB to date 2.726 K, and therefore in which epoch the matter in the universe began to aggregate. The story did not end with COBE. Missions as BOOMERang and Maxima added even more details to the CMB. Later the WMAP project supplied the best values for such critical cosmological parameters as the actual age of the universe, the curvature of spacetime, and when the first atoms and stars began to form. The Planck 2015 mission, as the successor to COBE and WMAP, reveals a map where dark matter makes up about 26.8 percent of our universe, an increase from the previously measured 24 percent, while normal matter contributes 4.9 percent rather than 4.6 percent. The results also indicated that dark energy constitute 67.9 percent of the universe rather than the 71.4 percent previously estimated [4].

IV. OUR LOPSIDED UNIVERSE

With these results a new window opened in the 1980s, where researchers realised the impact of indications of unknown components of matter in the Universe. In addition, calculations based on an open universe, with a density less than ρ_{crit}, did not predict anisotropies compatible with observations at hand. If the universe had been open, the anisotropies would already have been discovered. Yet there was no sign of them. As an extension, if the density of ordinary matter had been at the critical value, the galaxies we have observed could never have formed. In [27], Peebles proposed a scenario with a non-relativistic cold dark matter in order to couple the anisotropies in the CMB to large-scale structures in the universe. Small as it is, $\delta T(\theta,\phi)/T(\theta,\phi) = 5\times 10^{-6}$, but consistent with the measurements given by the COBE. According to the position in the sky, these anisotropies can be written as an expansion of spherical harmonics

$$\delta T(\theta,\phi) = \sum_{l,m} a_l^m Y_{lm}(\theta,\phi), \tag{8}$$

where $\theta = \pi/l$ gives the relationship between the observed angle and the multipole index. The spectrum derived has acoustic peaks as Fourier modes of the primordial plasma (the epoch where the radiation and the baryons were coupled). This spectrum shows the evolution of the amplitude of the nodes until the decoupling time. As a result, we can extract information about the shape of the universe and the matter and energy it contains. According to the Planck 2018 results (see Figure 3), (a) the first peak shows that we live in a universe with a small curvature $\Omega_K = 0.001\pm0.002$. The (b) second peak shows that baryonic matter is just $\Omega_b h^2 = 0.0224\pm0.0001$ of the matter and energy in the universe. The (c) third peak shows that $\Omega_{\rm CDM} = 0.120\pm0.001$, corresponding to dark matter. From these peaks, it is possible to compute the last component to fulfil the requirement for a flat universe, a dark energy with $\Omega_\Lambda = 0.679 \pm 0.013$.

V. OVERVIEW

The essence of *Precision Cosmology* allows us to deepen the explanation of the structure and evolution of the Universe and to discover New Physics. It is a universally acknowledged fact that we still do not understand the physics of the cosmological constant – perhaps its value is not constant – and perhaps a time-varying dark energy plays an important role in the evolution of the Universe. J. Peebles has already contemplated this possibility many years ago – a scientist ahead of his era. The nature of dark matter is not known either. Some interesting explanations include new particles, but until such a new particle is discovered, we cannot be sure that any of the current theoretical explanation of cold dark matter is the right one.

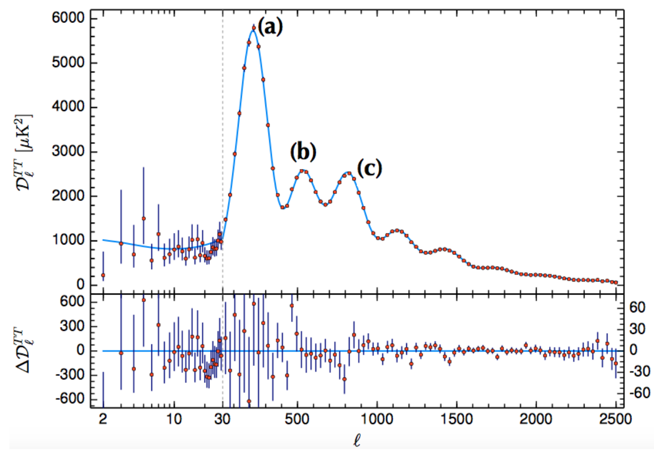

Figure 3. Anisotropies in the temperature of the CMB as measured by the Planck mission. Modified from [4].

The progress on how the theory and observations now fit is notable and there are few cosmological parameters. Still, there are observations that cannot be entirely explained at present and measurements of the Hubble parameter in the late-time Universe do not quite match predictions of CMB physics [28]. This issue perhaps hints to new physics that is hiding somewhere. As the measurements become more precise, new and unexpected phenomena are likely to be discovered, therefore *Physical Cosmology* will have unexpected things on the front, and J. Peebles is the one who has shown us the path to discover them. As his Shaw Prize citation states "He laid the foundations for almost all modern investigations in cosmology, both theoretical and observational, transforming a highly speculative field into a precision science".

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REFERENCES

[1] Oral History interview transcript with Hermann Bondi 1978-03-20, American Institute of Physics, Niels Bohr Library and Archives. American Institute of Physics.

[2] https://www.iau.org/static/archives/announcements/pdf/ann18029e.pdf Accessed 12.12.2019.

[3] T. Matos and L. Ureña. La Radiación Cósmica de Fondo. Colofón Ed. Académicas. IAC. 2019.

[4] N. Aghanim *et al.* [Planck Collaboration], arXiv:1807.06209 [astro-ph.CO].
[5] L. Verde, T. Treu and A. G. Riess, arXiv:1907.10625 [astro-ph.CO].
[6] B. Ratra and P. J. E. Peebles, Phys. Rev. D **37**, 3406 (1988).
[7] C. Armendariz-Picon, V. F. Mukhanov and P. J. Steinhardt, Phys. Rev. Lett. **85**, 4438 (2000).
[8] I. Sendra and R. Lazkoz, Mon. Not. Roy. Astron. Soc. **422**, 776 (2012).
[9] G. B. Zhao, D. Bacon, R. Maartens, M. Santos and A. Raccanelli, arXiv:1501.03840 [astro-ph.CO].
[10] C. Escamilla-Rivera, Galaxies **4**, no. 3, 8 (2016).
[11] M. Rezaei, M. Malekjani, S. Basilakos, A. Mehrabi and D. F. Mota, Astrophys. J. **843**, 65 (2017).
[12] C. Escamilla-Rivera and S. Capozziello, Int. J. Mod. Phys. D (2019).
[13] L. G. Jaime, L. Patiño and M. Salgado, Phys. Rev. D **89**, 084010 (2014).
[14] R. Lazkoz, M. Ortiz-Baños and V. Salzano, Eur. Phys. J. C **78**, 213 (2018).
[15] T. Harko and F. S. N. Lobo, Int. J. Mod. Phys. D **21**, 1242019 (2012).
[16] J. Alberto Vazquez, M. Bridges, M. P. Hobson and A. N. Lasenby, JCAP **1209**, 020 (2012).
[17] M. Seikel, C. Clarkson and M. Smith, JCAP06 (2012).
[18] A. Montiel, R. Lazkoz, I. Sendra, C. Escamilla-Rivera and V. Salzano, Phys. Rev. D **89**, 043007 (2014).
[19] G. B. Zhao *et al.*, Nat. Astron. **1**, 627 (2017).
[20] L. G. Jaime, M. Jaber and C. Escamilla-Rivera, Phys. Rev. D **98**, 083530 (2018).
[21] C. Escamilla-Rivera, M. A. C. Quintero and S. Capozziello, arXiv:1910.02788 [astro-ph.CO].
[22] `https://www.nobelprize.org/prizes/physics/2019/press-release/` Accessed 12.12.2019.
[23] J. Garcia-Bellido, Phil. Trans. Roy. Soc. Lond. A **357**, 3237 (1999).
[24] M. Lopez-Corredoira, astro-ph/0310214.
[25] (a) P.J.E. Peebles, Phys. Rev. Lett. **16**, 410 (1966). (b) P.J.E. Peebles, Astrophys. J. **146**, 542 (1966).
[26] R.H. Dicke, P.J.E. Peebles, P.G. Roll and D.T. Wilkinson, Cosmic black-body radiation, Astrophys. J. **142**, 414 (1965).
[27] P.J.E. Peebles, Astrophys. J. **263**, L1 (1982).
[28] E. Di Valentino, A. Melchiorri and J. Silk, Nat. Astron. (2019), doi:10.1038/s41550-019-0906-9.