Tensions in the LCDM paradigm

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The establishment of the Lambda cold dark matter paradigm in cosmology has brought together physics on very diverse scales, with a mesmerizing variety of observational techniques and a unique theoretical effort. Today the consistency of this paradigm is hindered by some tensions, either of internal consistency between datasets of different nature or of seeming friction between theoretical predictions and observations. Observational and theoretical efforts are currently under way in order to both understand the possible sources of systematics affecting the data and to explain these frictions on theoretical grounds.

This topical workshop aimed at bringing together the communities involved in this effort, building a bridge between observers and data analysists, theorists, and simulators, in order to address the following fundamental questions about the tensions in the CDM paradigm: Is the current tension in the determination of Hubble constant by different probes due to new physics or to systematics? What are the real sources of the inconsistencies between theoretical predictions and observations at the smallest galactic scales? Is it a problem that we see no new physics at LHC?

The ideal two-fold goal of the topical workshop was that of understanding whether tensions appearing on several scales are only episodical and disconnected from each other – and to which extent they are due to experimental systematics – or if they represent real cracks in the building of the ΛCDM. In the latter case, it remains to be assessed whether they are structural, thus hinting toward a major revision of our vision of the cosmological universe, or whether they can be cured separately with minor modifications at different scales.

Thus, the main aim of the topical workshop was to identify the leading sources of debate on the internal consistency of the ΛCDM paradigm, often referred to as "tensions in cosmology", in order to critically assess their current status, the actual occurrence of real frictions either between different data-sets or techniques for the same observable, or between the predictions of the model and the observables. The question to be considered was also if they present the serious threat to the internal consistency of the currently leading cosmological paradigm. "Tensions" in the cosmological paradigm, as commonly addressed during this topical workshop, are of different nature. Yet they can be grouped into two broad categories: those affecting the "large scales", i.e. the determination of cosmological parameters as a global property, with different observables, and those on galactic and sub-galactic scales. Most notably, the first group comprises the discrepancy between the determination of the Hubble parameter H_0 with different observables as well as some seeming inconsistencies in the determination of cosmological parameters when different data sets are adopted. To the second group belong some of the longest standing problems in the astro–cosmological communities such as the so–called "missing satellite" problem. Before summarizing the debate on each (and more), as discussed in the topical workshop, it is worth mentioning here that while on the scale of galaxies the potential frictions arise from a mismatch (or an alleged one) between the predictions of the framework/model and the observational data, in the case of the "cosmological scales" the nature of the frictions is the mismatch of results between different data-sets or techniques.

The "large-scale" tensions: The Planck best fit model presents interesting mild differences with a few astrophysical datasets, while being in very good agreement with others. The Planck measurements (talk by Karim Benabed) are in fact in remarkable agreement with the latest baryon acoustic Oscillations (BAO) measurements from the SDSS-BOSS galaxy survey (talk by Andreu Font-Ribera, Hector Gil-Marin), the high redshift supernovae data from the JLA and Pantheon catalogues (talk by Dan Scolnic) or measurements of primordial element abundances and Big Bang Nucleosynthesis measurements. Moreover, tests of agreement between the Planck data and other CMB experiments such as WMAP (talk by Chuck Bennett) and SPT (talk by Wai Ling Kimmy Wu) indicate that in the overlapping range of multipoles and sky fraction observed by these experiments there is a good consistency, suggesting that the CMB data yield a coherent picture (although some $\sim 2\sigma$ discrepancy between Planck and SPT best-fit cosmologies arise if one includes the very small scales probed by SPT alone).

On the other hand, Planck presents differences with supernovae data in the determination of the Hubble constant H_0 (talk by Adam Riess). The latest Planck measurements in fact yield $H_0 = 67.36 \pm 0.54$ km s^{-1} Mpc^{-1}, while direct, local measurements using supernovae data calibrated on Cepheid variable stars favor a value of $H_0 = 73.48 \pm 1.66$ km s^{-1} Mpc^{-1}, a difference of 3.6σ. It is interesting to note that also the inverse distance ladder method, which combines BAO and primordial deuterium measurements, yields low values of H_0, e.g. 66.98 ± 1.18 km s^{-1} Mpc^{-1} (talk by Graeme Addison, Eduardo Rozo).

Similarly, the Planck measurements yield a value of the parameter σ_8, which is a measure of the root mean square of matter perturbations today at 8 Mpc h^{-1} and is about 1.5σ higher than the one measured with galaxy cluster counts (talk by Laura Salvati) or by weak lensing experiments (talk by Hendrik Hildebrandt, Elisabeth Krause).

There are three possible explanations for these tensions. The first is that they are due to systematic effects, either in the Planck and/or in the other astrophysical datasets. The second, possibly more interesting explanation, is that these tensions are pointing towards a modification of the ΛCDM model. In fact, most of the statistical power of the Planck measurements come from observing the primary CMB anisotropies at high redshifts, z=1100. Therefore, parameters such as H_0 or σ_8 which provide information about the status of the universe today, are inferred from the Planck measurements under the assumption of the ΛCDM model. Therefore, changing this assumption, for example by allowing extensions of the ΛCDM model that predicts a different late time evolution of the universe, could reduce these tensions (talk by Vivian Miranda). The third possibility, still applicable to the σ_8 case (but hardly to the H_0 tension) is that these differences are just due to statistical fluctuations. Upcoming and future CMB (talk by Thibault Louis) and large-scale structure (talk by Tim Eifler) experiments will therefore be able to discriminate between these possibilities. Confirming that the source of these tensions is due to a failure of the ΛCDM model would have important consequences from a fundamental physics point of view, potentially leading to a deeper understanding of the nature of our universe.

An important outcome of the topical workshop was the insight that the resolution of the H_0 tension as an extension of the Standard Model of cosmology cannot easily be found as a non-standard late-time evolution of dark energy. Rather it would require a change in the early time physics of the universe, most probably from a change in the expansion rate of the universe before the time of recombination, leading to a change in the physical dimension of the sound horizon (allowing the change in the H_0 measured by CMB and the inverse distance ladder method.).

The “small scale” tensions: The importance of cosmological simulations as a tool to investigate the assembly and evolution of structures populating the universe has seen a steadily increased in recent years. Indeed, this type of simulations is becoming the standard theoretical approach for studying the small-scale tensions between ΛCDM paradigm and the observations. The actual status of historical, “classical” small-scale problems was discussed in detail during the workshop. These include: (i) the “missing satellite” problem. Too many satellites galaxies are produced in pure dark matter simulations compared to observations; (ii) the too big to fail problem: Most massive satellites produced in cosmological simulations seem to have a circular velocity profile (i.e., with a too large peak velocity) that is inconsistent with observational constraints; (iii) the core/cusp problem: Observations of the circular velocity profiles of dwarf galaxies seem to prefer a cored dark matter distribution at the center, rather than a cuspy one as predicted by cosmological simulations.

It emerged as a generally agreed lore, that the use of the outcome of simulations addressing only the gravitational clustering of collision-less dark matter particles, in the comparison with observations (more on this later), is not fair. Neglecting small-scale (i.e. sub-galactic scale) physical effects either arising from dark matter and baryons coupling (talks by Azadeh Fattahi, Cecilia Scannapieco, and Christine Simpson) or because self-interaction of dark matter particles (talk by Mark Vogelsberger), highly biases the results of simulations, thus preventing a reliable representation of "reality" (wrong "modelling"). Moreover, progress has been made from the observational side as well. For instance, more and more satellites have been discovered (the DES survey being a prominent example), thus reducing some of the observational tensions such as the missing satellite problem. Furthermore, mock observations of simulation data are rapidly becoming an essential technique for interpreting observational effects (talk by Kyle Oman). However, uncertainties still remain in the interpretation of data relative to the dark matter distribution in the halo centers, with studies arguing for cored profiles and others sustaining that the evidence for cores is still inconclusive.

Finally, additional problems have emerged from the analysis of the available observational evidence. Among these are: (iv) the "plane of satellites". Satellite galaxies tend to be on kinematically coherent planes (talk by Marius Cautun and Oliver Müller); (v) the "radial acceleration relation" (RAR): An empirical and extremely tight relationship between the observed total radial acceleration with the one due to the baryons only, which is present in galaxies of all types (talk by Federico Lelli), (vi) the "diversity problem": Contrary to ΛCDM expectations, there seems to exist a spread in the value of the inner (at 2 kpc) rotation velocity at fixed maximum circular velocity in dwarf galaxies (talk by Peter Creasey and Kyle Oman). They present additional challenges to the ΛCDM paradigm at galactic scales. It is important to address these challenges in order to understand whether non-standard DM models and the complications they might add to the galaxy formation physics processes (talk by Pier Stefano Corasaniti) are really needed.

During the topical workshop, a vast array of models that alleviate the classical ΛCDM small-scale tensions were presented. These can be loosely divided into two categories: baryonic models and self-interacting dark matter models. The first type of solutions is the most studied one and the field in which much of the progress has been achieved in the past. At its core ls the argument that the small scale-tensions can be alleviated if one considers the mutual interplay between the baryonic sector with the dark matter sector. Particularly important is the role played by (stellar) feedback in transferring energy from the baryons to the dark matter sector. It is generally agreed by the vast majority of groups working with cosmological simulations that efficient stellar feedback is needed to form a realistic galaxy population and, at the same time, solve the classic small-scale tensions.

However, there are several ways of achieving these goals. This is especially true for tensions related to the inner structures of dark matter haloes, i.e. the the too-big-to-fail and the cusp-core problems. Indeed, while some baryonic models find that a solution to these issues lies in the formation of dark matter cores at the centers of haloes, other models predict a reduction of the dark matter density at the centers of haloes (necessary to alleviate these tensions) which is a natural consequence of efficient feedback that does not necessarily require the formation of a core. This duality of results appears to be linked to the locations where stars are formed in the simulations and the way feedback energy is distributed to the gas, both of which are model dependent. Further work is needed to reach a full understanding of these aspects and come up with a coherent physical scenario. Self-interacting dark matter models also have progressed in terms of accuracy and sophistication. However, despite the promising results in reproducing the properties of satellites of the Milky Way, the exploration of the combination between self-interacting dark matter and baryons, which are necessary to model in order to investigate whether the simulated dwarf galaxies are realistic in terms of the available observational evidence, has just recently started. Other problems, such as the formation of the planes of satellites, which should be unlikely in the context of ΛCDM, were also discussed at the topical workshop. No clear solution was proposed, but it is unclear whether a more accurate statistical analysis can refute the claim that prominent planes of satellites are not a routinely occurrence in ΛCDM.

To sum up, in order to arrive at a definitive answer to the key question of the workshop "What are the real problems on the smallest galactic scales?", further theoretical investigations, in synergy with observational work, are needed. Indeed, although the solutions to small-scale ΛCDM tensions seems within reach, the lack of a coherent physical framework and the multiplicity of solutions proposed are still an unsatisfactory aspect of the theoretical research in the field that urgently needs to be addressed.