commentary

Thinking outside the simulation box

Abraham Loeb

Any ambitious construction project requires architects and engineers. As research shifts towards large groups that focus on the engineering aspects of linking data to existing models, architectural skills are becoming rare among young theorists.

Albert Einstein once said: "If you always do what you always did, you will always get what you always got." Indeed, too few theoretical astrophysicists are engaged in tasks that go beyond the refinement of details within a commonly accepted paradigm. It is far more straightforward today to work on these finer points than to review whether the paradigm itself is valid. Although there is much work to be done in the analysis and interpretation of experimental data, the unfortunate by-product of the current state of affairs is that popular, mainstream models with which data are interpreted are rarely challenged. Most cosmologists, for example, lay one brick of phenomenology at a time in support of the standard (inflation + cosmological constant Λ + cold dark matter, or LCDM) cosmological model, resembling engineers that follow the blueprint of a global construction project, without pausing to question whether the architecture of the project makes sense when discrepancies between expectations and data are revealed.

The problem with researchers focusing on the engineering aspects of a prevailing paradigm rather than on questioning its foundation is that their efforts to advance scientific knowledge are restricted to a conservative framework. For example, cosmological data are often analysed in the programmatic mindset of a community-wide effort to reduce the error budget on measurements of the standard cosmological parameters. The cosmology community has become so conservative that when a discrepancy was identified recently between different methods for deriving the matter density parameter Ω_m and power-spectrum normalization σ_8 (using microwave background anisotropies sourced at redshift $z \sim 10^3$ and cluster abundance measurements at $z \lesssim 1$) in the latest data from the Planck satellite, the mundane possibility of assigning a mass of 0.2 eV to neutrinos is being debated as a wild deviation from the mainstream comfort zone. Deviations of this magnitude were trivial for previous generations of cosmologists, who were debating the underlying physical principles that control the Universe while entertaining dramatic excursions from conservative guidelines.

Conservatism is possible today because we now have the LCDM model, which was not the case several decades ago. It is nevertheless disappointing to see conformism among young cosmologists who were born into this standard model and are supposed to be least biased by prejudice. The experience resembles seeing the children of hippies from the 1960s transform surprisingly quickly into establishment executives. This phenomenon has its obvious reasons. The unfortunate reality of young astrophysicists having to spend their most productive years in lengthy postdoctoral positions without job security promotes conformism, as postdocs aim to improve their chance of getting a faculty job by supporting the prevailing notions of senior colleagues who serve on selection committees. Logically, however, one might argue that an opposite strategy of choosing innovative projects should improve the job prospects of a candidate, as it would separate them from the competing crowd of indistinguishable applicants that selection committees are struggling through.

The orthodoxy exhibited by young cosmologists today raises eyebrows among some of the innovative 'architects' who participated in the design of the standard model of cosmology. Too soon after the enigmatic ingredients of the standard cosmology were confirmed observationally, they acquired the undeserving status of an absolute truth in the eyes of junior cosmologists. In the scientific quest for the truth, we still need architects (theorists), not just engineers (who implement/test theory).

One would have naively expected scientific activity to be open-minded to critical questioning of its architectural design, but the reality is that conservatism prevails within the modern academic setting. Orthodoxy with respect to mainstream scientific dogmas does not lead to extreme atrocities such as burning at the stake for heresy but it propagates other collective punishments, such as an unfair presentation of an innovative idea at conferences, bullying and drying up of resources for creative thinkers.

The problem is exacerbated by the existence of large groups with a rigid, prescribed agenda and a limited space for innovation when unexpected results emerge. In large groups, such as the Planck or SDSS-III collaborations, young cosmologists often decide not to challenge the established paradigm because other group members, and particularly senior scientists who are considered experts on the issue, accept this framework. If hundreds of names appear on the author list of a paper, the vast majority of them have limited space for manoeuvres — resembling a dense swarm of fish in a small aquarium. The fact that letters of recommendation are written by a few group leaders adds pressure to conform to mainstream ideas. True, some scientific goals require a large investment of funds and research time, but under these circumstances efforts should be doubled to maintain innovative challenges to conventional thinking. For example, federal funding agencies should not always insist on predictable research products, but rather allocate a small fraction of their resources to risky projects. It is imperative that individual scientists feel comfortable expressing critical views in order for the truth to ultimately prevail.

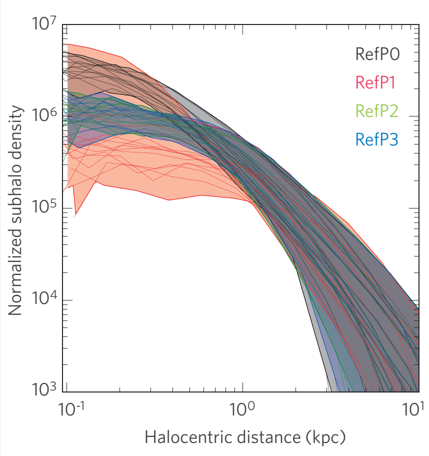
And there is no better framework for critically challenging a prevailing dogma than at the architectural 'blueprint level'. Sometimes, a crack opens in a very particular corner of a dogma due to a localized discrepancy with data. But conceptual anomalies are much more powerful as they apply to a wide range of phenomena and are not restricted to a corner of parameter space. Quantum mechanics emerged as a surprising departure from the intuitive notions of classical physics. Albert Einstein's thought experiments are celebrated stepping stones that identified earlier conceptual anomalies and paved the way to the theories of Special and General Relativity in place of the fixed spacetime blueprint of Isaac Newton. And before Galileo Galilei came up with his conceptual breakthrough, it was standard to assume that heavy objects fall faster than light objects under the influence of gravity.

Conceptual work is often undervalued in the minds of those who work on the details. A common misconception is that the truth will inevitably be revealed by working out the particulars. But this highlights the biggest blunder in the history of science: that the accumulation of details can be accommodated in any prevailing paradigm by tweaking and complicating the model. A classic example is Ptolemaic cosmology — a theory of epicycles for the motion of the Sun and planets around the Earth — which survived empirical scrutiny for longer than it deserved.

A modern analogue is the conviction shared by mainstream cosmologists that the matter density in the Universe equals the critical value, $\Omega_m = 1$. This notion dominated in the 1980s and the early 1990s for nearly two decades after inflation was proposed, a period during which discrepancies between data and expectations were assigned to an unknown 'bias parameter' of galaxies, even when data on the mass-to-light ratio on large spatial scales indicated clearly that $\Omega_m \sim 0.3$ as we now know to be the case. Today, when inconsistencies between the observed distribution of dark matter inside galaxies and theoretical expectations for cold-dark-matter haloes are revealed, these discrepancies are commonly brushed aside as being due to 'uncertain baryonic physics' — even in dwarf galaxies where the baryons make a negligible contribution to the overall mass budget. Similarly, when a hemispherical asymmetry in the power spectrum of temperature fluctuations in the cosmic microwave background was reported a decade ago, it was quickly dismissed by mainstream cosmologists; this anomaly is now confirmed by the latest data from the Planck satellite, but is still viewed as an unlikely (< 1% probability) realization of the sky in the standard, statistically isotropic cosmology. Given that progress in physics was historically often motivated by experimental data, it is surprising to see that a speculative concept with no empirical basis — for instance, the 'multiverse' — gains traction among some mainstream cosmologists, whereas a data-driven hypothesis, such as dark matter with strong self-interaction (to remedy galactic scale discrepancies of collisionless dark matter), is much less popular.

Box 1 | An example of observational 'discrepancies' that do not fit the model.

The LCDM model assumes that dark matter is made of exotic particles that have very weak interactions with light, ordinary matter or among themselves. The nature of these particles remains elusive. Numerical simulations of collisionless cold dark matter predict that collapsed objects (haloes) in an expanding universe generically develop a density cusp at their centre. However, observations of low-mass galaxies (subhaloes) that are dominated by dark matter reveal a central density core. The discrepancy can be explained if the dark matter particles have a large cross-section for scattering off each other (but still interact weakly with light and are hence 'dark'). The figure shows examples of density profiles in dark matter haloes from state-of-the-art simulations of collisionless dark matter (RefP0), and strongly interacting dark matter with high (RefP1) and more modest (RefP2 and RefP3) values for the collision cross-section. Collisional dark matter develops a core — consistent with observations — as long as the cross-section per particle mass is of order the value associated with neutron–neutron collisions. Incidentally, if the neutron were less massive than the proton, it would have been stable and a possible dark-matter candidate, as it is electrically neutral and so interacts weakly with light. Figure reproduced with permission from M. Vogelsberger, J. Zavala & A. Loeb *Mon. Not. R. Astron. Soc.* **423,** 3740–3752 (2012) © Oxford Univ. Press.



The most efficient way to simplify the interpretation of data is to work at the metalevel of architecture, similar to the heliocentric interpretation developed by Copernicus in the days when the Ptolemaic theory ruled. An engineering project that aims to study the strength of rods and bricks might never lead to a particularly elegant blueprint for the building in which these ingredients are finally embedded.

Some argue that architects were only needed in the early days of a field like cosmology, when the fundamental building blocks of the standard model — such as cosmic inflation, dark matter and dark energy — were being discovered. As fields of study mature to a state where quantitative predictions can be refined by detailed numerical simulations, the architectural skills are no longer required for selecting a winning world model based on comparison with precise data. Ironically, the example of cosmology demonstrates just the opposite. On the one hand, we measured various constituents of our Universe to two significant digits and simulated them with accurate numerical codes. But at the same time, we do not have a fundamental understanding of the nature of the dark matter, dark energy or inflation. In searching for this missing knowledge, we need architects who could suggest to us what these constituents might be in light of existing data and which observational clues should be searched for. Without these hints we will never be sure that inflation really took place, or that dark matter and dark energy are real and not ghosts of our imagination due to a modified form of gravity.

It is true that numerical codes allow us to better quantify the consequences of a prevailing paradigm, but systematic offsets between these results and observational data cannot be cured by improving the numerical precision of these codes. The solutions can only be found outside the simulation box through conceptual thinking. For example, observations of X-ray clusters are now being calibrated at the per cent level using hydrodynamic simulations as a precise tool for inferring cosmological parameters. However, important physical effects that may influence the temperature and density distribution of the hot intracluster gas — such as heat conduction, thermal evaporation and electron-ion temperature equilibration — are left out of these simulations despite the fact that the Coulomb mean-free-path of protons in the outskirts of clusters is comparable to the cluster radius.

Conceptual thinkers are becoming an extinct species in the landscape of present-day astrophysics. I find this trend worrisome for the health of our scientific endeavours. In my view, it is the duty of senior scientists to encourage young researchers to think critically about prevailing paradigms and to come up with simplifying conceptual remedies that take us away from our psychological comfort zone, but bring us closer to the truth. ❐

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