Abstract

Cosmologists take the ΛCDM model to be a permanent contribution to our knowledge of the universe, based on the success of precision cosmology. Consistent, independent determinations of the parameters in this model encourage physicists to take it seriously. This stance incurs an obligation to resolve any discrepancies, by reanalyzing measurements or adding further complexity. Recent observations in cosmology indicate a tension between "local" and "global" determinations of the Hubble constant. Here I will argue that this tension illustrates one of the benefits of taking the model seriously, and consider the challenges to making a case for the permanence of ΛCDM.

Trouble with Hubble: Status of the Big Bang Models

Chris Smeenk*

April 30, 2022

Contemporary cosmologists describe the universe with a strikingly simple concordance model, according to which the universe expands from a hot "big bang" state, then passes through a series of phases with the expansion rate varying as different forms of mass-energy come to dominate the dynamics. Observations are needed to fix just a handful of parameters in this model. The parameters characterize the universe's large scale geometry and the relative densities of its primary constituents. Cosmologists' confidence in this model has increased substantially with the advent of "precision cosmology," which has led to determining the model parameters at the 1% level from a diverse array of observations. Peebles' one-line summary reflects a widely shared view: "[...] I emphasize again the broad variety of observations that probe the universe in such different ways and offer a story that is close enough to consistency to make the case for the ΛCDM theory about as compelling as it gets in natural science" (Peebles, 2020, 339). Peebles takes this case to establish that the ΛCDM model should be regarded as a permanent contribution, in the sense that it will be retained, at least as some form of

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*Department of Philosophy and Rotman Institute of Philosophy, University of Western Ontario, London, Ontario N6A 5BY, Canada. Email: csmeenk2@uwo.ca

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approximation, in future cosmologies.

Philosophers have recently debated the nature and effectiveness of this kind of argument, exemplified by Perrin's famous defense of atomism based on convergent measurements of Avogadro's number. Van Fraassen (2009) takes Perrin to have shown how atomic theory can be "empirically grounded," which requires that: (i) significant theoretical parameters are measurable, and (ii) diverse theory-mediated measurements of them yield agreeing results. Clearly these arguments play a significant role in scientific practice, although it is more controversial what they establish. Van Fraassen contrasts his view, on which grounding does not imply that the parameters correspond to properties of real entities, with what he calls a "strange reading" offered by realists, who instead take Perrin to have established the reality of molecules. Smith and Seth (2020) frame their detailed historical case study as, in part, a rejoinder to van Fraassen. They argue that stable and convergent measurements of parameter values, amenable to increasing precision, did change the status of the molecular hypothesis: it began to be employed as a basic assumption guiding further inquiry, even though many pressing questions regarding molecules remained open. More generally, on their view successful measurements of fundamental parameters can anchor subsequent work and impose constraints on future theory, in much the sense that Peebles suggests. Isaac (2019) goes a step further, arguing in favor of a novel realist position: successful measurement give us evidence for "fixed points" (modally stable phenomena) in the world. The main epistemic challenge facing such arguments for permanence is a threat of circularity: how can one establish that these parameters are physically meaningful and worthy of preservation, rather than merely artifacts of modeling assumptions?

The challenge is particularly salient in cosmology. The model relies on enormous

extrapolations of physical theories, such as applying general relativity ~ 14 orders of magnitude beyond the solar-system scales where it is subject to high-precision tests. The model's name — ΛCDM — highlights the two novel types of mass-energy it posits: a non-zero cosmological constant Λ, and cold dark matter. Without the freedom to introduce new types of mass-energy, with densities far larger than that of "normal" matter, the same high-precision data would decisively rule out the expanding universe models. A vocal minority regards this flexibility with skepticism, and pursues models based on modified gravitational physics; even those who are not so skeptical often express dissatisfaction at treating the dark sector phenomenologically. These two points highlight the possibility of errors in the theoretical assumptions cosmologists rely upon in turning data into parameter constraints. Finally, whether the story is close enough to consistency has come into question with the increasing precision of several different observational programs. I will focus below on one prominent challenge to the ΛCDM model: "local" measurements of the Hubble constant H_0 suggest a higher value than that based on "global," early universe observations of the cosmic microwave background (CMB).[1]

This case study supports two claims related to recent philosophical assessments of measurement (e.g., Chang, 2004; Tal, 2016). First, an effective response to the concerns regarding circularity requires a more fine-grained assessment of the role of theory in particular measurements. Philosophers have overstated circularity worries based on crude treatments of "theory-dependence." Smith and Seth (2020) distinguish three

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[1]There are other challenges: in particular, there is an unexplained discrepancy between the observed primordial lithium abundance and what would be expected from big bang nucleosynthesis.

aspects of measurement, based on their case study of Perrin, that are illuminating when applied to the cosmological case as well: stability, amenability to increasing precision, and convergence. Stability refers to the constancy of a parameter value (or values) determined by a particular measurement technique over some range of observational data. Establishing whether a given technique is amenable to increasing precision requires a detailed physical account of how the measurement tracks a particular target quantity. Such an account can be used, among other things, to identify sources of systematic error. As we will see below, both of these aspects of a measurement can often be assessed with aspects of physics or astrophysics that are relatively independent of the cosmological model. Cosmologists can then take the measurements as the basis for further inquiry while remaining agnostic on open research questions, and this makes it more plausible that the parameter measurements could anchor further research even through significant theory change. The degree of convergence among different measurements, by contrast, typically does depend sensitively on the cosmological model. In many cases, the model links together observations at different epochs through a description of the universe's intervening evolution.

This leads to the second overall point, namely to acknowledge the advantages of taking theory seriously as a starting point for further inquiry and what this stance entails. This stance allows cosmologists to bring data to bear on a variety of questions, due to the systematic relationships – such as those between parameter values at different epochs – ΛCDM entails. Complementary measurements of the same parameters can be used to expose systematic errors in different measurement techniques. Taking ΛCDM seriously incurs an obligation to resolve any discrepancies in the parameter measurements, by (i) reanalyzing the measurements (changing calibration, identifying

new sources of systematic error), or (ii) adding further complexity to the model to mitigate the conflict. Persistent failure in pursuing either of these two options would force cosmologists to reject the physical significance of the model, and abandon Peebles' position that the ΛCDM model makes a permanent contribution to cosmology.

The next section sets the stage with a sketch of the ΛCDM model, before turning to the debate regarding the Hubble constant in §2. In §3, I evaluate the limited sense in which this line of argument supports a realist stance regarding the theoretical parameters appearing in ΛCDM, before concluding in §4.

1   The ΛCDM Model

ΛCDM takes perturbed Friedmann- Lemaître (FL) models to represent the large scale structure of the universe. These are solutions of Einstein's field equations (EFE) with maximal symmetry: they describe spacetime as foliated by a collection of three-dimensional hypersurfaces of constant curvature over cosmic time, $\Sigma(t)$ (see, e.g., Weinberg, 2008). The worldlines of "fundamental observers," moving along geodesics and at rest with respect to matter, are orthogonal to these surfaces, and clocks carried by fundamental observers would measure cosmic time. The scale factor $R(t)$ represents spatial distance in Σ between nearby fundamental observers, flowing along with the cosmic evolution. Spatial volume changes as a function of cosmic time, proportional to $\frac{\dot{R}(t)}{R(t)}$. This quantity is called the (time-varying) Hubble "constant" $H(t)$, with H_0 specifying the value at the present time. Due to symmetries, EFE reduce to 2 ordinary differential equations for the scale factor, which can be solved given the equations of state and relative densities of the postulated material constituents. The pristine

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symmetry of these models has to be perturbed slightly in order to account for the existence of large-scale structures: structures such as galaxies arise via gravitational enhancement of small "seed" perturbations in the early universe.

Free parameters in the ΛCDM model characterize the spacetime geometry and the constituents of the universe. One set of parameters characterize the spacetime geometry, given by a flat FL model (characterized in part by $H(t)$), and the seed perturbations (fully characterized by two parameters, if they are Gaussian). A second set specifies how much of each different type of matter is present, in terms of density parameters Ω_i. The list of different "types of matter" extends beyond familar types of matter (such as baryonic matter, Ω_b) to include cold dark matter (Ω_c) and "dark energy." The third and final set includes parameters that need to be specified in order to interpret observations, such as the ionization state of the early universe. There is some variation in the list of parameters cosmologists use in finding an optimal fit depending on the type of observations; cosmologists typically fit CMB data, for example, with 6 to 9 parameters. The Hubble parameter is not included in this list for CMB observations, but is treated instead as a derived quantity.

Cosmologists have developed a number of independent observational techiques for constraining these parameters, exemplified by the baryonic mass density Ω_b (see Peebles, 2020, for a detailed discussion). Two of the most precise constraints on Ω_b derive from early universe physics. According to big bang nucleosynthesis, primordial light element abudances are fixed by nuclear physics applied to the early universe. Primordial isotope abundances, in particular that of deuterium, depend sensitively on Ω_b (at the time of nucleosynthesis, $t \approx 10^2 s$). A second constraint follows from observations of the acoustic peaks in the CMB (from $t \approx 10^{11} s$). Prior to recombination, the speed of sound in the

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coupled plasma - radiation oscillations that produced these peaks depends on Ω_b, and the relative magnitude of the second peak measures its value. In both cases, cosmologists have derived equations relating an observable quantity — the primordial deuterium abundance, or features of the acoustic peaks in the CMB – to Ω_b. The great appeal of these early universe parameter constraints is the relative simplicty of the physics involved: the equations follow from well-understood nuclear and plasma physics, respectively. Astrophysical estimates of Ω_b (from the "late universe," $t \approx 10^{17}s$) are subject to much greater uncertainty, as they are based on a census of known baryonic matter or employ assumptions about how luminous objects trace the mass distribution. For example, applying the virial theorem to the motion of galaxies in clusters yields constraints on Ω_b. Peebles (2020, 337) reports a "crude estimate" of $\Omega_b h^2 \approx 0.015$ based on astrophysical constraints, compared to $\Omega_b h^2 = 0.022 \pm 0.001$ from Planck observations of the CMB and 0.021 ± 0.002 from big bang nucleosynthesis.

All three techniques for estimating Ω_b are strongly "theory-dependent" — but the theory and background knowledge in each case is quite different. There is also a clear contrast between two different ways that assumptions about the background cosmological model play a role: first, in establishing a link between a specific observable quantity and Ω_b, and then evaluating the stability of that link and how precision could be increased; and second, in making the case that different measurement techniques converge on the same physical quantity. Regarding the first, the connection between Ω_b and isotopic ratios, for example, does not depend on the more contentious aspects of the ΛCDM model – dark matter and dark energy. The connection is also stable to variation of various other observable quantities, and physicists have clarified the impact of a wide variety of changes to background theory (including gravitational theory as well as

nuclear physics). Cosmology enters into these calculations through the expansion timescale and its interplay with reaction rates, and little else.

The background cosmological model plays a more substantial part, by contrast, in making the case that the three measurements (and several others) target the same quantity. Dynamical evolution as described by the ΛCDM model connects measurements of Ω_b at three different epochs — from $10^2 s$ all the way to $10^{17} s$. Making the case in favor of convergence, so that constraints obtained in different epochs can be used as cross-checks, depends directly on the validity of the ΛCDM model. Hence worries about circularity are more pressing in evaluating the case that we have multiple convergent measurements. To the point in slightly different terms, accepting the ΛCDM model allows individual measurements of the fundamental parameters to be systematically interlinked. What the convergence of complementary measurement adds, over and above the fact that individual measurements are stable and well-behaved, is evidence for these connections. In place of a general concern about circularity and theory-dependence, cosmologists can then assess how robust the comparisons of different measurements of Ω_b are to specific modifications of the ΛCDM model.[2] As we will see next, we can also turn this inference around: assuming the ΛCDM model makes it possible to assess systematic uncertainties in different measurement techniques.

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[2]Ritson and Staley (2021) defend a similar response to the threat of circularity, for experimental science, based on a case study of W boson decay measurements.

2   Trouble with Hubble?

Hubble's observations of a linear relationship between the redshift and distance of 24 nearby galaxies provided the first evidence that the universe is expanding. Astronomers have pursued more precise determinations of the Hubble constant ever since, with measured values decreasing substantially from Hubble's value of $H_0 \approx 500$ (in units km s^{-1} Mpc^{-1}). Astrophysical objects are not fundamental observers in an FL model, and their individual motions (also called "peculiar velocities") result from gravitational interactions with nearby galaxies and clusters of galaxies, adding "noise" to the underlying "Hubble flow". This is an obstacle to using local objects to measure H_0, but the error decreases at larger distances because the peculiar velocities become smaller, in ratio, to the ever-increasing recessional velocities due to the Hubble expansion. Ideally one could measure the Hubble flow based on the distance-redshift relation for a population of standard candles or rulers, objects with known luminosity or scale, at sufficiently large distances. Astronomers have a variety of techniques for determining distances to astrophysical objects that apply at a variety of (often overlapping) scales. The distance ladder extends rung by rung to cosmological scales, starting with parallax measurements for nearby stars and using these to callibrate different distance indicators, and iterating the process. Observations of large samples of Type Ia Supernovae have significantly extended the distance ladder out into the pure Hubble flow, leading to the discovery that the expansion rate is accelerating, and enabling higher precision determinations of H_0.

As the precision of these "local" measurements of H_0 increased, the contrast with "global" measurements based on observations of the CMB has become sharper. The

Planck results led Bernal et al. (2016), for example, to prominently identify this as a serious tension in the ΛCDM model. Local measurements favor a higher value, falling in the interval of $70-76$ and are reasonably consistent given stated uncertainties, but they contrast with the lower value measured by the Planck Collaboration: 67.27 ± 0.6 (assuming a flat model as a prior, with the stated uncertainty at 1σ). Riess et al. (2021) find a value of 73.2 ± 1.3, leading to a 4.2σ discrepancy given the stated uncertainties.[3]

CMB observations do not directly measure H: they constrain the product of H with other cosmological parameters, such as Ω_b and the total mass Ω_m. Observations of the acoustic peaks essentially determine the geometry of the FL model at the time of last scattering. The angular scale of the first peak depends on the scale factor at that time and our distance from the surface. But observations of the acoustic peaks provide further parameter constraints: the relative height of the second peak measures $\Omega_b h^2$ and that of the third peak measures $\Omega_m h^2$. The degeneracy can be broken by assuming a flat model or by using other data sets to fix parameter values, leading to the value just cited. Although the determination of H is indirect and depends on the background ΛCDM model, Planck can achieve such high precision due in part to the simplicity of the physics governing the CMB. Planck's results agree well with those of other CMB observations, and it is striking that the conflict with local measurements seems to have had little impact in confidence in the Planck parameter values.

The Hubble tension has already generated a vast literature, with Di Valentino et al.

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[3] The local to global contrast oversimplifies: some measurements constrain the value of H at intermediate times, so the challenge is really to fit H as a function of cosmic time. There is a further question regarding what a 4σ discrepancy means here, as the familiar understanding of 4σ in experimental contexts does not apply.

(2021) counting over 850 papers exploring different theoretical resolutions. The expansion history according to the ΛCDM models connects the CMB and local measurements, and the proposed resolutions nearly all modify this linkage without modifying the understanding of the CMB measurements. There are some proposals based on modifying general relativity and adopting a quite different framework. But the majority of these responses reflect cosmologists' confidence in the ΛCDM model: rather than abandoning the model entirely, these are minor modifications to the model's dynamics, such as introducing a new form of dark energy that has a targeted impact on the expansion history. Specific modifications have often been criticized as ad hoc, but to my mind there is a more striking downside of such changes. In effect, these modifications break the connection between these two types of measurements that allowed them to function as cross-checks of each other. While one of these modifications could be correct, in general they make it much more challenging to constrain cosmological models.

A different line of response takes the conflict as a prompt to look for further possible sources of systematic errors, a persistent challenge in measuring astrophysical distances since Hubble's time. "Local" measurements extend into the Hubble flow using SNIa. There are different techniques to establish distances to the galaxies hosting the closest supernovae in order to calibrate the lowest rungs of the distance ladder. One approach relies primarily on Cepheids, a kind of variable star with a period-luminosity relationship discovered by Henrietta Leavitt. The advantages and disadvantages of using Cepheids as distance indicators have been scrutinized carefully, given the central role of this technique in earlier work, including the Hubble Space Telescope key project to measure H_0. The SHoES collaboration (e.g. Riess et al., 2021) uses Cepheids and claims to attain precision just below the 2% level, with a goal of reaching the 1% level based on new

parallax measurements (compared to $\approx 5\%$ level two decades ago).

The conflict with the Planck results suggests that there may be unknown systematics that continue to plague local distance estimates. But a more compelling case has been made recently relying on a new method, using "tip of the red giant branch" (TRGB) stars. At the end of the red giant phase, stars undergo a core helium flash, leading to a sharp and readily observable discontinuity in the color-magnitude diagram, with a characteristic luminosity, for populations of low-mass stars. The CCHP project (e.g., Freedman et al., 2019) aims to avoid the systematics plaguing Cepheids by building an entirely new distance ladder using this feature as a standard candle. The results that have been obtained so far provide compelling evidence that one or both of these projects has failed to identify some systematic errors (Freedman, 2021). The two methods disagree even about the distance of nearby galaxies, with $2 - 3\sigma$ discrepancies. We can see the need for further scrutiny of the local distance ladder at this level of precision, even without comparison to early universe parameter measurements. The resolution of this debate will directly impact the Hubble tension as well, if for no other reason than that the TRGB method leads to a lower value, $H_0 = 69.6 \pm 1.9$. But in addition, on Freedman (2021)'s analysis, contrasting zero-point callibrations for SNIa is not the primary reason for the divergence between the estimates given by the two methods, and unraveling the full reasons for the discrepancy is essential for the assessment of the Hubble tension and its ramifications.

Although debates about the Hubble tension will certainly continue, to my mind this episode illustrates the advantages of adopting the ΛCDM model: it makes it possible to leverage high precision measurements of the CMB to isolate systematic uncertainties, as local distance ladder measurements are pushed to increasing levels of precision. This

leverage is particularly valuable because the stability and agreement of closely related measurements often fail to expose systematic errors they all share. Smith and Seth (2020) pointedly note that this is true even of Perrin's celebrated experimental measurements of Avogadro's number: his preferred values fell in the range $65 - 72 \times 10^{22}$, and he substantially underestimated systematic errors shared by all of these measurements. The introduction of novel techniques by Millikan and others led to a lower value and a reassessment of Perrin's measurements.

3   Realism and the Cosmological Parameters

The strength of Peebles' case that the ΛCDM model is a permanent contribution to cosmology depends on the wide array of diverse data sets that yield stable, convergent measurements of its basic theoretical parameters. Obviously I have only had the space here to indicate the structure of the argument, and to identify one area of active research and debate. Suppose, however, that we grant that the story is "close enough to consistency": does that establish that we should regard the cosmological parameters as real properties of the universe? Here I will argue that even though we should, as Van Fraassen suggested, resist a straightforwardly realist reading of the parameters, they can still anchor further work in cosmology.

A detailed description of the spacetime geometry in the neighborhood of the Milky Way, according to general relativity, would resemble something like "Swiss cheese" — with the "holes" consisting of small-scale regions with large spacetime curvature (say, near black holes), and sharp density contrasts, embedded within an expanding universe model. The parameters appearing in the ΛCDM model characterize, by contrast, slight

perturbations away from a completely uniform matter distribution at large scales. The relationship between the more realistic description and a "smoothed out" or "averaged" model is far from straightforward in a non-linear theory like general relativity. Ellis (1984) showed that an "averaging operator" that smooths out non-uniformities below some length scale, when applied to a solution to EFE, does not generate a new solution.[4] More generally, there is not a straightforward procedure to generate a "best fit" model from the bottom up, starting from a detailed description of spacetime geometry at shorter length scales. It is a familiar lesson from other areas of physics that averaged parameters are not always physically meaningful — their utility depends on the relevant dynamics and justification for washing out details at different scales. These considerations block a straightforward reading of the parameters appearing in the ΛCDM model as corresponding, in some direct sense, to actual properties of the universe at cosmological scales.

Setting aside a naïve realist understanding of cosmological parameters does not, however, imply that they are merely artifacts, little more than a convenient way to summarize a large body of data. It is an old instrumentalist idea that the significance of a model should be characterized in terms of its role in guiding inquiry, not only in terms of fidelity to actual states of affairs. Miyake and Smith (2021) articulate a version of this view in a discussion that has parallels to the cosmological case. As they describe in detail, molecular spectroscopy has led to the determination of (among other things) molecular constants that characterize the structural properties of diatomic molecules —

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[4]That is, if the smoothing operator is applied to both the Einstein tensor and the stress-energy tensor for a given solution, the two new tensors generally do not satisfy EFE.

represented as dumb-bell shaped bodies, with rotational and vibrational degrees of freedom. The constants specify structural features of this body, with the "rotation constant," for example, interpreted as the inverse of its moment of inertia. Yet it would be a mistake to take this structural description as mapping onto the actual state of a molecule. For a molecule with an anharmonic potential, the rotational degrees of freedom couple to the vibrational modes; as a result, the atoms fluctuate around an equilibrium distance. Furthermore, taking electron-electron and electron-nuclei interactions requires time-averaging over much shorter time-scales. The full picture of a molecule includes fluctuations and interactions on several distinct time scales, and the simple interpretation of the rotation constant only applies if we, counterfactually, ignore all of these details. Similarly, in the cosmological case, the parameters of the ΛCDM model represent what the large-scale properties of the universe would be, if we were to neglect complications due to structures at lower scales and the non-linearities of general relativity. But, by contrast with spectroscopy, we lack a comparably clear understanding of the approximations involved in obtaining the large-scale model and the domain of validity of inferences based on it.

Miyake and Smith (2021) propose that such counterfactual representations qualify as physically meaningful insofar as they can be used to guide inquiry, in the sense that systematic discrepancies between the model and observations have a physical source (as exemplified in the discovery of the isotopes of oxygen). On this view a physically meaningful model is the first step in a series of successive approximations that are guided by ongoing comparisons with observations. Smith's work has characteristically focused on long-term evaluation of the evidence developed in different areas of physics, to assess whether scientists have used physically meaningful models as a starting point

and succeeded in identifying new features of nature through a process of refinement. While we do not yet have a similarly long view in cosmology, the ΛCDM model has clearly been the essential starting point for research in cosmology for several decades, and the model has (arguably) enabled the discovery of entirely new constituents of the universe (dark matter and dark energy).

Returning to the second methodological theme from the introduction, "taking the model seriously" is precisely to take it as physically meaningful in this sense and hence to treat any discrepancies as targets for further investigation. This should not be read as a straightforwardly realist commitment, because the model has an essentially counterfactual character. The contrast here is not between realism and instrumentalism, but rather, following Stein (1989), between a commitment to seeing the model as a source of further physical insights, such as opening up possibilties for measurements of the fundamental parameters, rather than merely a convenient tool for organizing a body of knowledge.

4   Conclusion

Ongoing disputes regarding H_0 illustrate the value of using a model to leverage high precision measurements from one domain to gain further insight regarding systematic errors in another domain. Dedicated empirical work will be required to determine whether the current tension traces back to systematic errors in the local distance ladder, or instead indicates a need to modify ΛCDM. But in closing we can return to the more philosophical issue: in what sense should we take ΛCDM as a permanent contribution, based on convergent measurement of fundamental parameters? There is a common

aspect of recent philosophical discussions of how successful measurements can establish permanence. Isaac (2019) argues that measurement practices can identify objective fixed points in the world, that are not subject to the familiar concerns about commitments shifting through periods of theory change. Permanence of these fixed points follows, on this account, from the theory-neutrality of measurement: theory "factors out" in light of convergence, and success can be characterized in theory-neutral terms (namely, increasing precision). Despite several other contrasts, Smith and Seth (2020) similarly emphasize that in exemplary cases, the analysis of stability, convergence, and amenability to increasing precision of some set of measurements depends on "local regularities" (such as specific equations relating sets of accessible quantities, within a specified domain) rather than fundamental laws. In both lines of argument, excessive reliance on higher level theory opens up the possibility of impermanence. With this in mind, it is striking that efforts to develop an increasing rich web of different measurement techniques in cosmology has led to the identification of many more "local regularities," and relatively weaker reliance on higher level theory. Regardless of the fate of the ΛCDM model, taking the model seriously as a way of studying the universe has generated an enormous amount of detailed knowledge regarding the properties of systems, and local regularities governing how their properties relate to their cosmic environment, over an enormous range of scales.

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