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CONTRIBUTED PAPER

(Re)Assessing Galaxy Clusters with Cosmological Models: Scales, Anisotropies, and Scientific Explanation

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Abstract
Galaxy clusters are commonly used tracers of cosmology. Gravitational lensing analysis of the Bullet Cluster is claimed to evidentially support dark matter, an important component in the ΛCDM cosmology. I argue that such ΛCDM-based models of individual galaxy clusters should be explanatory to meet such claims, but hardly in an ontic sense, due to galaxy cluster anisotropies, empirically equivalent non-ΛCDM-based models, and currently unaccountable cases. I propose that adopting an alternative epistemic/representational conception of scientific explanation can maintain the explanatory nature of individual galaxy cluster models, cope with the three complications, and be potentially generalizable to other branches of astrophysics.

1. Introduction

The current standard model of cosmology is the ΛCDM (or LCDM) model. (C)DM stands for (cold) dark matter, a hypothetical form of matter that interacts only gravitationally, not electromagnetically—i.e. it neither absorbs nor emits electromagnetic radiation and hence cannot be detected directly. Λ, denoting a cosmological constant, is associated with dark energy (DE), a hypothetical form of energy that only interacts gravitationally at very large scales.

Galaxy clusters are among the largest known gravitationally bound structures in the local universe. A galaxy cluster is believed to consist of up to thousands of galaxies, X-ray-emitting superheated plasma called intracluster medium (ICM), and predominantly DM. (Molnar, 2015) Thus, galaxy cluster observations are crucial in DM research. As part of the evolution of the universe, the formation and evolution of such massive structures can also be used as cosmic "tracers" of the Large-Scale Structure (LSS) of the universe and help determine cosmological parameters. (Borgani and Guzzo, 2001) Probes and studies on them usually fall in extragalactic astronomy. The current philosophy of cosmology literature tends to focus on the *debate* between ΛCDM and an alternative called MO(dified)N(ewtonian)D(ynamics)—issues like whether mysterious entities like DM and DE should be adopted, and considerations tend to be multi-scale.[1] However, the methodology involved in galaxy cluster observations, modeling, and theorization, and how they are incorporated into cosmology, are relatively underdeveloped, which motivates this paper. In particular, three general methods are widely used and play significant roles in cosmology:

(1) individual modeling;
(2) statistical analysis;
(3) computer simulations.

Here I shall focus on (1) and (2), leaving out (3), as unlike the other two, it typically does not make use of galaxy cluster observations directly.

In §2, I shall present the theoretical background and predictions of ΛCDM (§2.1), relevant observational probes (§2.2), and the importance of scales in astrophysics (§2.3). I shall then introduce the individual modeling method with a notable case of the Bullet Cluster (§3), and the statistical analysis method with two recent studies (§4). The anomalous results of the latter pose challenges to the fundamental Cosmological Principle in ΛCDM (§5). I will then reconsider the individual modeling method and clarify two more complications (§6). Finally, I will adopt a non-traditional conception of scientific explanation to (re)assess individual galaxy cluster models and overcome the three complications coherently (§7).

2. Basics

2.1. ΛCDM

The ΛCDM cosmological model is established upon the current best theory of gravity, Einstein's general relativity (GR), mathematized by Einstein's field equations (EFEs). To define a cosmological model, one needs to specify the spacetime geometry, matter, and how they interact. The Friedmann–Lemaître–Robertson–Walker (FLRW) metric is an exact solution to EFEs, assuming that the universe is isotropic, homogeneous, and expanding. (Ellis and Van Elst, 1999) Σ denotes the spatial component of a cosmological model and consists of three-dimensional space. The curvature, k, is constant and unitless. $k = -1$ corresponds to hyperbolic space and an open universe, $k = 0$ to flat space and a flat universe, and $k = 1$ to spherical space and a closed universe. Our universe is approximately flat because its curvature is approximately 0.

ΛCDM predicts three major components of the universe. DE (∼68%) is used to account for the accelerating expansion of the universe, and DM (∼27%) for the gravitational effects in the CMB and galactic or larger systems; the third component is baryonic (or ordinary) matter (∼5%). (Aghanim et al., 2020) It makes up our surroundings on Earth and is described by the Standard Model of Particle Physics (SMPP) based on quantum mechanics (QM) at atomic and subatomic scales. Both DM and DE are beyond the SMPP.

[1] For instance, see Massimi (2018), Jacquart (2021), and Smeenk and Weatherall (2024).

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2.2. Observations

ΛCDM's parameterization is specified by observational evidence. Two general types of probes that are commonly used and will be relevant here are:

(1) All-sky surveys targeting the entire sky, notably
  - WMAP (Wilkinson Microwave Anisotropy Probe) and more recently *Planck*, which detect the cosmic microwave background (CMB), a remnant of the Big Bang that covers the entire observable universe, and are commonly used to study the early universe (at very high redshift);
  - ROSAT (Röntgen Satellite) and more recently eROSITA (extended ROentgen Survey with an Imaging Telescope Array), which detect the X-ray band of the entire sky.

(2) Other more region- or wavelength-specific surveys, notably
  - *Chandra* and *XMM-Newton*, both of which detect X-rays in certain regions;
  - Hubble Space Telescope (HST), which detects optical, ultraviolet and near-infrared, and its successor, James Webb Space Telescope (JWST), which detects infrared.

As all of ROSAT, eROSITA, *Chandra*, and *XMM-Newton* detect the X-ray band, they sometimes overlap and cross-calibration studies are found in the astrophysics literature.[2]

2.3. Scales

Scales are very important in astrophysics. Although the same theories of physics (i.e. GR and QM) underlie astrophysics at different scales, astronomical objects and systems of different sizes are subject to different physical processes and phenomena, assumptions, observational means, and statistical analyses. While in stellar astronomy, a star (e.g. the sun) is modeled layer-by-layer from the core to the surface, in galactic astronomy, it is usually regarded as a body with a certain mass and luminosity in a direct gravitational N-body simulation. As previously noted, the focus here is galaxy clusters, ranging from about 1–10 million parsecs, which are scale-wise between galaxies and the LSS of the universe. The physical processes involved in the formation, structure, and evolution of galaxy clusters are studied by *galaxy cluster (astro)physics*.

Physics at the galaxy cluster scale can be relevant to other scales. As an analogy, consider wave/physical optics as an intermediate model of light in between ray/geometrical optics and quantum optics. Ray optics models light propagation in terms of rays. Wave optics studies wave effects (interference, diffraction, and polarization) of light. Quantum optics studies light in terms of individual quanta of light (photons). Ray optics applies broadly at macroscopic scales where wave effects are insignificant. At the large end, it is commonly used to build optical instruments to obtain observations for astrophysics. At the small end, it can explain and correct vision problems (e.g. nearsightedness and astigmatism) in optometry, and can account for diffuse reflection. Quantum optics, as part of QM, applies at atomic and subatomic scales. Wave optics'

[2] A recent example involving the latter three is Whelan et al. (2022) on the Abell 3158 galaxy cluster.

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applicable scales overlap, respectively, with ray optics' (e.g. polarized lenses) and with quantum optics' (e.g. the wave-particle duality of light). That is, wave optics is not mutually exclusive to either of the other two scale-wise.

Similarly, a crucial part of the formation of galaxy clusters is the clustering of galaxies, which means that galaxy cluster (astro)physics is closely related to galactic astronomy. Moreover, many of the studies of galaxy clusters are relevant in the cosmological context, and *galaxy cluster cosmology* uses galaxy cluster (astro)physics—most often as a source of evidence—to make inferences about the universe.

3. Individual Modeling

One method to study galaxy clusters, primarily for DM, is through gravitational lensing (GL). This refers to the effect of the gravity of a massive celestial body (e.g. a galaxy cluster) bending light like a lens. It is predicted by GR, but a mass discrepancy arises from observational evidence. By calculating the amount of ordinary matter present in a target galaxy cluster based on the GL observations, researchers found the result to be far less than enough to produce the observed GL effect, so they concluded that there must be a lot more (non-luminous) mass in that cluster, namely, DM.[3]

One interesting case to consider is the Bullet Cluster (1E 0657-56, BC), which technically refers to a small subcluster of galaxies that collided with and moved away from a larger cluster, and whose gravitational lensing has been extensively studied. Clowe et al. (2006) constructed a ΛCDM-based model of the BC which specifies the distribution of DM in the BC, and successfully reproduced the observed GL of the BC. The BC is accordingly regarded as *strong* (or "direct") evidence for the existence of DM (and thus for ΛCDM). A refined version is found in Paraficz et al. (2016).

Though Clowe et al.'s result is widely accepted and referenced in the astrophysics community, MOND advocates Banik and Zhao (2022) defend a proposal to account for the BC in MOND by incorporating a hypothetical sterile neutrino with a mass of $11\ \mathrm{eV}/c^2$ which supposedly only affects galaxy clusters but not single galaxies. This MOND-based model also seems successful in reproducing the observations of the BC, so the two BC models can be taken as empirically equivalent. More importantly, they seem methodologically similar, as both introduce hypothetical entities to eliminate the mass discrepancy. Hence, though the ΛCDM-based BC model may be more attractive for various other reasons, neither clearly outstands the other if considering the BC observations alone. A contrastive underdetermination issue[4] thus arises.

[3] Of course, the idea of DM has a very complicated history and fosters its own literature, but I shall not dive into it here.

[4] As Stanford (2023) defines, contrastive underdetermination "questions the ability of the evidence to confirm any given hypothesis *against alternatives*."

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4. Statistical Analysis and Anisotropies

4.1. The Cosmological Principle

As noted earlier, the ΛCDM cosmological model has two fundamental assumptions required by the FLRW metric: (1) homogeneity—matter is distributed uniformly across the universe; (2) isotropy—the universe looks the same in all directions. They together are called the Cosmological Principle (CP). CP is supposed to hold statistically at *a sufficiently large scale*. Anisotropy, as opposed to isotropy, refers to the property of structural direction-dependency—certain properties (of interest) of an anisotropic object differ when measured in different directions.

In the case of the early universe, anisotropies in the CMB based on *Planck* (and WMAP) have been analyzed in the recent cosmology literature. A major one is the hemispherical power asymmetry, meaning that the power distributions of the two sides of the universe differ, but this anomaly is not significant enough to eliminate the possibility of "the effect being just a statistical fluke." (Fantaye, 2014)

Nevertheless, recent attempts to test cosmic isotropy have also focused on the late universe. Some found statistically significant anisotropies in galaxy clusters. Here I shall present two such (likely related) studies.

4.2. Scaling Relations

One commonly used statistical method to study interesting physical parameters of a target system (or systems) is to study scaling relations (SRs)—empirically established correlations between physical parameters used to describe the target system(s). The applicability of an SR is size-, type- and scale-dependent. Celestial systems at other scales can also be studied by establishing SRs. In stellar astronomy, we cannot measure the mass of a star directly, but if it is a main sequence star, its mass can be calculated from its directly measurable luminosity, using the following:

$$\frac{L}{L_{\odot}} = (\frac{M}{M_{\odot}})^{3.5} \tag{1}$$

for $\frac{1}{3}M_{\odot} < M < 40M_{\odot}$, and

$$\frac{L}{L_{\odot}} = (\frac{M}{M_{\odot}})^{4.5} \tag{2}$$

for $\frac{1}{2}M_{\odot} < M < 2.5M_{\odot}$, where $M_{\odot}$ is solar mass and $L_{\odot}$ solar luminosity. (Kuiper, 1938)

Similarly, a frequently studied SR for galaxy clusters is the X-ray luminosity–temperature ($L_X - T$) relation. The X-ray luminosity depends on the adopted cosmological model, so is "cosmology-dependent," whereas the X-ray temperature is cosmology-independent.[5] Migkas et al. (2020) conducted a study on this relation with the following form:

$$\frac{L_X}{10^{44}\ \mathrm{erg/s}} E(z)^{-1} = A \times (\frac{T}{4\ \mathrm{keV}})^{B} \tag{3}$$

[5]More specifically, this SR is established between the luminosity and temperature of ICM.

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where $E(z)^{-1}$ is a term for the redshift (z) evolution and A is a normalization parameter. The sample consists of 313 galaxy clusters homogeneously selected[6] from the Mega-Catalogue of X-ray detected Clusters of galaxies (MCXC), whose parent catalogues are based on ROSAT. Migkas et al. (2020) also required that the sampled clusters' observations obtained in *Chandra* or *XMM-Newton* are of good quality and the clusters are not "strongly contaminated by point sources like Active Galactic Nuclei (AGN)." (Migkas et al., 2020) They found[7] that all the relevant parameters appear to be "consistent[ly] and strong[ly]" direction-dependent and the sky overall presents a dipole pattern, both showing inconsistency with cosmic isotropy, and hence are considered statistically significant anisotropies. Moreover, there is a significant angular separation between the dipole pattern found here and the CMB dipole, implying that "the correlation" between them is "not strong." Migkas et al. (2020) also pointed out that though a combination of "galaxy cluster physics, X-ray analysis and systematic biases" may undermine their results, each of these effects, at least examined respectively, seems insignificant.

Later, a methodologically similar but more comprehensive study was conducted on up to 570 galaxy clusters whose X-ray, microwave, and infrared observations were all taken into account to establish 10 SRs.(Migkas el al., 2021) Unlike the first study on $L_X - T$, Migkas el al. (2021) did not use the exact same sample of galaxy clusters to establish all ten SRs, but rather subsamples of the extremely expanded HIghest X-ray FLUx Galaxy Cluster Sample (eeHIFLUGCS)[8], except $L_X - Y_{SZ}$ which was established based on the full MCXC.[9] Some of the SRs have been well-studied elsewhere (e.g. $L_X - Y_{SZ}$), though they also acknowledge that some others are either less often (e.g. $R - T$ where R is the effective radii of galaxy clusters) or never studied previously (e.g. $R - L_X$).[10] Migkas el al. (2021) also found statistically significant anisotropies—among which is a dipole pattern of the entire sky, similar to the finding in the first study—which cannot be accounted for by any currently known systematics.

Both studies assumed that the expansion rate of the universe, described by the Hubble constant H_0, is constant. The anisotropies could be due to an anisotropic expansion rate[11], but we know even less about how that might be the case.

[6]Namely, the sampled clusters are distributed evenly across the sky.

[7]Migkas et al. (2020) clarified that the study has a "null" hypothesis that this SR holds across the sky. Challenging the SR seems to be a technical or scientific matter, not a philosophical one.

[8]eeHIFLUGCS consists of the brightest (highest X-ray flux) galaxy clusters in the MCXC. (Ramos-Ceja et al., 2019)

[9]Y_{SZ} is a parameter related to the Sunyaev-Zel'dovich (SZ) effect where the CMB radiation is slightly distorted towards galaxy clusters. (Birkinshaw, 1999; Carlstrom et al., 2002). Being redshift-independent, it is important to study in both cosmology and astrophysics.

[10]Again, examination of each SR is a technical or scientific matter, not a philosophical one, so I just take their results here.

[11]A (more well-known) tension is the discrepancy of the H_0 measurements in the early and late universe (see Verde et al. 2019). Though no conclusive result can be drawn for now, Migkas el al. (2021) discussed several possible interpretations of anisotropic H_0.

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4.3. A Scale-Specific Breakdown

What do these statistically significant anisotropies show? One may think that they suggest a failure of the CP and can hence be regarded as a threat to the ΛCDM cosmological model. It seems unclear to me whether this is the case without further scientific investigation.

Nevertheless, it also seems uncompelling to claim that statistically significant galaxy cluster anisotropies are not troublesome for ΛCDM at all. Recall the mass-luminosity relation of main-sequence stars. This relation is consistent with Chandrasekhar's stellar model (Kuiper, 1938), so a sort of "mutual corroboration" exists between the theoretical and empirical aspects of stellar astronomy. However, no such "mutual corroboration" exists in the current case, as isotropy is a fundamental assumption in the ΛCDM cosmology, while SRs established on galaxy clusters seem to imply an anisotropic (late) universe.

I shall call this "a (likely) breakdown of cosmic isotropy (hence the CP) at the galaxy cluster scale." To be clear, cosmic isotropy, as part of the CP, is used to describe the universe and is specifically supposed to hold statistically at a sufficiently large scale, but not for individual galaxy clusters. If galaxy clusters are by themselves homogeneous and isotropic, they would have no internal structure worth studying. Rather, as noted earlier, galaxy clusters are used as cosmic tracers of the LSS of the universe and play a crucial role in the determination of some cosmological parameters. It hence seems reasonable to assume that cosmic isotropy *should hold at the galaxy cluster scale*, meaning that the cosmological inferences from (individual or statistical) galaxy cluster studies should comply or show consistency with the isotropy assumption (hence with the CP). However, the two studies seem to suggest the opposite, namely, the relevant cosmological inferences from the two galaxy cluster studies seem inconsistent with cosmic isotropy. In other words, cosmic isotropy *may break down, or not apply, at the galaxy cluster scale*.

5. The Real Trouble

So far, I have introduced two methods used to study cosmology via galaxy clusters: individual modeling and statistical analysis. Individual modeling (e.g. of the BC) can be used to test the DM hypothesis, and statistical analysis (based on galaxy cluster SRs) can be used to test cosmic isotropy. The former's result shows agreement with the DM hypothesis, whereas the latter's results show disagreement with cosmic isotropy. It should be noted that both the DM hypothesis and cosmic isotropy are in this sense *evidentially dependent* on galaxy clusters. It may be argued, rather rightfully, that the dependencies are on different *aspects* of galaxy cluster (astro)physics—internal structure of individual galaxy clusters for the former and statistical SRs based on hundreds of galaxy clusters for the latter. However, different aspects of the same type of celestial system should be coherent with each other—being "mutually corroborating," similar to the aforementioned case of stellar astronomy. When some aspects suggest a crack in ΛCDM, the crack is scale-specific and hence does not suffice to disprove ΛCDM. Granted that the statistical method based on SRs is well-established, what is nonetheless challenged is galaxy cluster cosmology, namely, whether galaxy clusters

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can be used as tracers for cosmology as expected. If galaxy cluster cosmology is at stake, skepticism of other cosmological inferences based on galaxy clusters (e.g. the existence of DM supported by the BC) naturally arises.

Even just considering the usage of data in observational cosmology (and more generally in astrophysics), the situation is also problematic. Different groups of researchers with different research interests and goals rely on data collected from large collaborative probes (such as ROSAT and *Chandra*), which means that the data they end up using likely overlap or are at least systematically coherent.[12] The relevant physical parameters are also likely to overlap. In this sense, the bodies of evidence respectively used in these different studies are effectively subsets of the same total body of evidence consisting of all the relevant probes. When one subset produces negative results, without any good reason to believe that this subset is poorly selected for the intended purpose or that the data processing and analyzing method is flawed, the total body of evidence would be questioned, so are inferences made based on positive results produced by some other subset(s). One may argue that in such a scenario, skepticism should not be infectious—it should only be raised upon the probe(s) actually used in the study with negative results, but not the total body of evidence consisting of all of them. This may be true for other scientific disciplines, but the practice of cross-calibration in observational cosmology grounds the systematic coherency between different probes, which can lead to an undesirable infectious effect if one probe is suspected to be contaminated.[13]

6. Individual Modeling Revisited

It is also important to clarify in detail the nature of individual galaxy cluster models. Recall that the CP, being fundamental in the ΛCDM cosmology, applies statistically at a sufficiently large scale, and that galaxy clusters are neither homogeneous nor isotropic by themselves. One nonetheless needs to maintain that ΛCDM can offer some insight into the physics of a galaxy cluster, say, the BC—a target system supposedly outside of its intended domain of applicability—so that it is reasonable to use ΛCDM to construct a model to account for the BC observations. As DM is a crucial component in the ΛCDM cosmology, to make strong claims on, say, how DM affects gravitational phenomena at very large scales, or what the composition of the universe is, it seems reasonable to require the ΛCDM-based BC model to be explanatory so that DM is (part of) the explanan of the explanandum (i.e. the observed GL in the BC).

If this model is merely descriptive and predictive, the existence of DM (as *strongly* supported by this model) is significantly undermined for two reasons. The first reason is the aforementioned contrastive underdetermination issue that there is an empirically equivalent MOND-based BC model that DM is not part of. One can surely argue that it is the many other observations and ΛCDM's success in accounting for them collectively with its success in the BC that makes ΛCDM better than MOND in the case of the BC. Nonetheless, this seems to undermine the BC's *per se* strength in supporting the

[12] In the BC case, Clowe et al. (2006) used *Chandra*, and Paraficz et al. (2016) used both ROSAT and *Chandra*. In the SR case, MCXC is based on ROSAT and eeHIFLUGCS is based on ROSAT, *Chandra* and *XMM-Newton*.

[13] The point made here needs further investigation, which I shall leave for another paper.

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existence of DM, the latter being a crucial part of the ΛCDM cosmology.

The second reason is that ΛCDM is not always successful in accounting for galaxy cluster observations. Another frequently studied galaxy cluster, El Gordo (lit. *the Fat One*, ACT-CL J0102-4915), is challenging. Some of the mass estimates of El Gordo based on observations—the highest one (based on the HST data) being approximately $2.8 \times 10^{15} M_{\odot}$ (Jee et al., 2014)—are in tension with the maximum allowable mass at its redshift in ΛCDM, $\lesssim 2 \times 10^{15} M_{\odot}$ (Harrison and Coles, 2012). Recently, Diego et al. (2023) estimated that the mass is about $2.1 \times 10^{15} M_{\odot}$ based on the latest JWST data, closer to the upper limit.[14]

What is needed, I think, is a regime of (re)assessing galaxy cluster cosmology that also coherently overcomes the three complications discussed above, namely:

- (R0) how successful individual galaxy cluster models (e.g. the ΛCDM-based BC model) can be taken as *explanatory*;
- (R1) how galaxy cluster anisotropies found in statistical studies can be taken as *harmless*;
- (R2) the contrastive underdetermination issue, given that a MOND-based alternative exists;
- (R3) challenging cases like El Gordo.

Considering mainly (R0), the proposal I shall present in the following adopts a non-traditional conception of scientific explanation introduced by Bokulich (2018).

7. Scientific Explanation

The traditional conception of scientific explanation is the ontic conception, whose basic idea is, as Craver (2014) states,

> Conceived ontically... the term explanation refers to an objective portion of the causal structure of the world, to the set of factors that produce, underlie, or are otherwise responsible for a phenomenon. Ontic explanations are not texts; they are full-bodied things. They are not true or false. They are not more or less abstract. They are not more or less complete. They consist in all and only the relevant features of the mechanism in question. There is no question of ontic explanations being "right" or "wrong," or "good" or "bad." They just are. (Craver, 2014)

In the case of the ΛCDM-based BC model, if one takes that this model is, supposedly, explanatory, and claims that its success in reproducing the observations of the BC implies that the BC provides strong ("direct") evidence for the existence of DM, one is

[14] Though not discussed in this paper, El Gordo research also relies heavily on simulations. For instance, Asencio et al. (2021) conducted a MOND-based cosmological simulation by which they claim that El Gordo analogs are more likely to exist in a MOND cosmology than the ΛCDM one. Recently, Valdarnini (2024) suggests that El Gordo may support self-interacting dark matter (SIDM) instead of the conventional collisionless DM based on a ΛCDM N-body/hydrodynamical simulation.

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likely to have the ontic conception in mind. That is, a certain large amount of DM must *be* objectively out there in the BC and be distributed exactly as the DM distribution given in the ΛCDM-based BC model, so that the observed GL is produced. However, such claims are not epistemically well-grounded due to (R1) and (R2). Regarding (R2), one may prefer the ΛCDM-based model of the BC to the MOND-based one due to, say, holistic reasons. Or, by inference to the best explanation (IBE) as formulated by Lipton (2017), one may reckon the MOND-based model as implausible (say, for its abolition of GR) or less explanatorily powerful than the ΛCDM-based one. Such preference is still grounded by the (past and current) scientific practice of physical cosmology and extragalactic astronomy, and it can hardly ground this explanation as an ontic one. Moreover, regarding (R1), to maintain that the likely breakdown of cosmic isotropy at the galaxy cluster scale does not undermine DM as (part of) the explanan, one can conceivably reckon it as (supposedly harmless) simplification or idealization.

Bokulich (2018)'s alternative *eikonic* conception, as a version of epistemic/representational conception of scientific explanation, is intended to "help us understand what scientists are actually doing when they offer scientific explanations." She states,

> ... [T]hey (scientists) study a simplified representation of the phenomenon contextualized within a particular field, research program, or explanatory project. This is in order to make the phenomenon tractable with the conceptual, theoretical, instrumental, methodological, and so on, tools available within a particular subfield. (Bokulich, 2018)

As I take it, ΛCDM is a framework (or paradigm) whose theoretical *tool* available for gravity is GR. The representation of an interesting phenomenon may be (partly) dependent on the framework. The ΛCDM cosmological model has more constraints (e.g. cosmic isotropy), some of which may be scale-dependent (e.g. applicable only at a sufficiently large scale) and are not applicable in a different context within this framework (e.g. individual galaxy clusters). The resulting model that reproduces the observations of the interesting phenomenon is explanatory, epistemically/representationally, so that the explanan would become a new (epistemic/representational) *tool* in the framework, and hence can be used in another model within the framework with more constraints. For clarification, the word "tool" here is metaphorical and should not be taken as a commitment to instrumentalism. Bokulich (2018) actually maintains her account's compatibility with epistemic realism of science.

The eikonic conception can also handle (R1)–(R3). First, Bokulich (2018) differentiates the explanandum from the *explanandum phenomenon*. The latter is "the phenomenon-in-the-world"—here it would be the actual physics underlying GL—whereas the former is "the particular conceptualization or representation of the explanandum phenomenon that is the immediate (although of course not ultimate) target of our explanations." One way by which "an explanandum phenomenon gets simplified and conceptualized within an explanatory context" is due to its "particular *level of abstraction*." (Bokulich, 2018). Although both types of galaxy cluster studies are conducted at the same astronomical scale, the respective levels of abstraction involved

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differ. Similar to how a star is treated differently in stellar and galactic astronomy, the internal structure of a target galaxy cluster is essential in individual modeling but is much less important in SR-based statistical analysis. Accordingly, the likely breakdown of cosmic isotropy at the galaxy cluster scale found in the latter can be taken as harmless for individual galaxy cluster models and their cosmological inferences. Second, as Bokulich (2018) states, this conception allows explanatory pluralism due to a possible plurality of representations. Although multi-scale disagreements (e.g. on DM and DE) are still in place, scale-specific questions on individual galaxy clusters can also be asked: e.g. which of the two empirically equivalent BC models is more powerful in explaining the observed GL? IBE as discussed above can be used to answer it. Lastly, cases like El Gordo remain challenging for ΛCDM, but this challenge should not be taken as a "massive blow for ΛCDM" as some MOND advocates claim (Asencio et al., 2021), but rather as that the ΛCDM framework has yet to find appropriate representations of them.

8. Final Remarks

For clarification, though Bokulich (2018) seems to argue against the ontic conception while establishing her eikonic one, I think while adopting the eikonic conception of scientific explanation, cosmologists can still pursue ontically explanatory models (of the universe or individual celestial systems) within the ΛCDM framework. My point is that the eikonic conception is more suitable for supposedly explanatory ΛCDM-based models of individual galaxy clusters, and can reasonably and coherently account for the three relevant complications in galaxy cluster cosmology. Galaxy cluster anisotropies found in statistical analysis can be taken as harmless due to the different levels of abstraction involved in the two types of studies. The contrastive underdetermination issue arising from the existence of a MOND-based alternative is addressed by explanatory pluralism, and IBE can be a remedy. Challenging cases like El Gordo are due to ΛCDM's current lack of appropriate representations of them. Moreover, due to methodological similarities (broadly construed), the above (re)assessment should be generalizable to other already-constructed models or future models of other galaxy clusters, and perhaps even other celestial systems used to trace certain aspects of the ΛCDM cosmology (e.g. quasars). Finally, as a further investigation, a closer examination of the statistical analysis method based on scaling relations under a philosophical scope would also be crucial for a more comprehensive understanding of the connection between galaxy cluster (astro)physics and cosmology.

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