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CHAPTER 18

"Mock Observations" of Galaxies

Emilie Skulberg, Martin Sparre and Kristin Veel

After three months of runtime and using over 8,000 compute cores, a set of cosmological hydrodynamical simulations called Illustris was complete in 2013. Spanning over 13.8 billion years of cosmological evolution, this set of simulations represents a region of the universe in a cube (fig. 18.1). In the largest simulation, the side length of the simulation cube is 106.5 megaparsecs (a unit

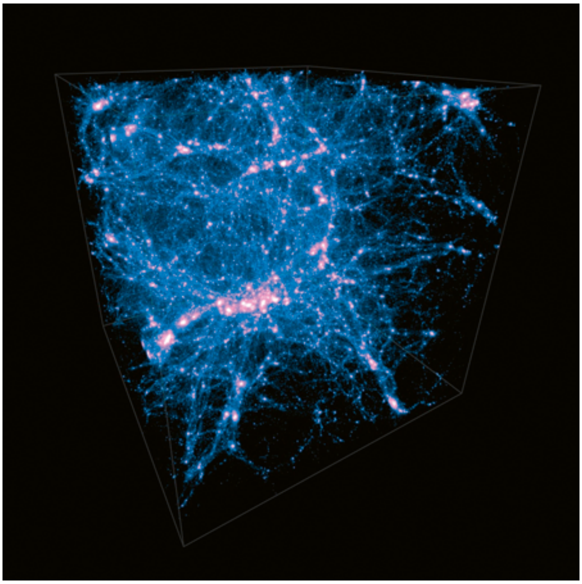

FIGURE 18.1 This visualisation represents the large scale structure of the universe, known as the 'cosmic web'. The density of the so-called 'dark matter' is shown here as the pink filaments, where the brightest areas represent the most dense concentrations of dark matter in Illustris. Original caption: 'Exterior view of the dark matter density distribution in the full Illustris-1 box at redshift zero' (Illustris Collaboration, 2015b)
CREDIT: ILLUSTRIS COLLABORATION, COURTESY OF MARK VOGELSBERGER

used to measure astronomical distances), which corresponds to 350 million light years.[1] This scale means that the simulation can represent the universe as a whole. We focus on visualisations based on Illustris, tying the question of mimesis to recent visual representations of the cosmos.

Illustris is the product of an international collaboration based primarily at Massachusetts Institute of Technology, Harvard-Smithsonian Center for Astrophysics, and Heidelberg Institute for Theoretical Studies. According to the Standard Model of Cosmology (also known as the LCDM model), normal (or baryonic) matter – that of which the Earth, stars and galaxies are made – is believed to account for only 5% of the cosmos, whilst the invisible dark matter and dark energy are thought to take up 26% and 69%, respectively.[2] Illustris marks a breakthrough in its realistic reproduction of a range of phenomena at different scales. Supermassive black holes, galaxy formation, and the large-scale structure of the universe come together in the simulation representing both visible and invisible matter as it develops over time. The output from simulations such as Illustris is often referred to as 'synthetic data', and in the case of Illustris takes up 200 terabytes of storage.[3] To perform research based on Illustris, an astrophysicist would typically download only part of the data output. This would then be stored as a matrix describing the characteristics and coordinates of particles in the three-dimensional space of the simulation cube (as an example, see fig. 18.2). The particles of the virtual universe of Illustris represent phenomena in the universe such as stars, dark matter, or black holes, and these particles have different properties depending on what they represent. The largest simulation, Illustris-1, contains 6,028,568,000

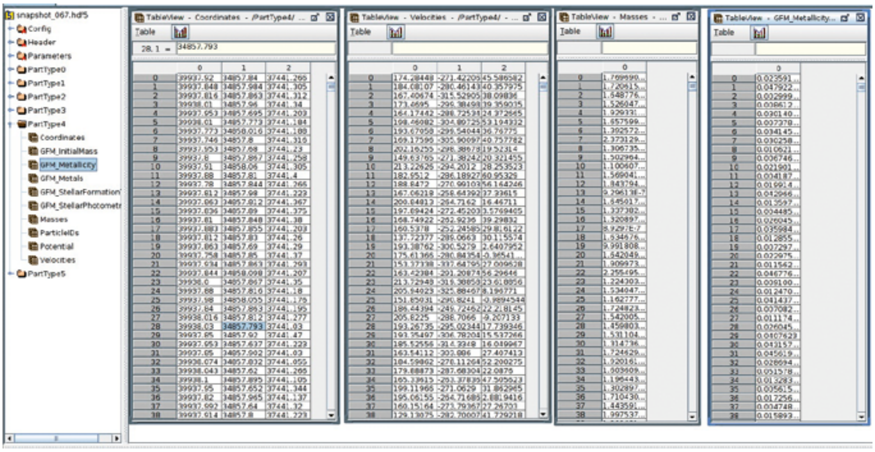

FIGURE 18.2 Example of synthetic data output from Illustris
PHOTO: MARTIN SPARRE

particles representing dark matter alone. This can be overwhelming, even to the trained eye of an astrophysicist working with computational theoretical physics.

Several theorists have described big data as 'messy'.[4] As the historian Orit Halpern (2015, 5) writes, 'data is not always beautiful. It must be crafted and mined to make it valuable and beautiful', recalling the Greek verb *kosmeō*, as described by the classics scholar Gregory Vlastos (2005, 3):

> In English *cosmos* is a linguistic orphan, a noun without a parent verb. Not so in Greek which has the active, transitive verb, *kosmeō*: to set in order, to marshal, to arrange [...] In the Greek the affinity with the primary sense is perspicuous since what *kosmos* denotes is a crafted, composed, beauty-enhancing order.

Vlastos' explanation of *kosmos* could certainly be relevant in relation to the visual dimension of Illustris, where the overwhelming matrix of numerical values is transformed into colourful visual representations showcasing the virtual universe. Halpern (2015, 21) reminds us that 'In the present, visualization is often understood not only as a process but also an object, a subject and a discipline, a vocation, a market, and an epistemology'. Despite the attention given to cosmological simulations in journals, magazines, preprint articles, the news, and social media, many of them have yet to be explored in existing scholarship within the humanities. Taking this as our cue, the present chapter will read visualisations based on the Illustris simulation against the theme of mimesis, as it appears in Plato's corpus, with an emphasis on the *Timaeus*. Mimesis here is seen on a cosmological scale, which is helpful for tackling the representational questions that are being rearticulated with a project such as Illustris. This chapter will examine visualisations of both normal and dark matter in Illustris, in order to show how the notion of mimesis can be used as a vehicle for unpacking these visualisations. We will employ the ambivalence of mimesis in Plato's corpus, from *Republic X* to the *Timaeus*, to qualify and inform the discussion of the visualisation of cosmological simulations. As the art historian Ernst Gombrich (1960, 83) writes in *Art and illusion* (1959), 'There are few more influential discussions on the philosophy of representation than the momentous passage in the *Republic* where Plato introduces the comparison between a painting and a mirror image. It has haunted the philosophy of art ever since'. In the *Timaeus*, however, the demiurge, a divine craftsman thought to be the personification of reason, transforms chaos into cosmos by giving shape to the visible world, based on the harmonic proportionality of the eternal model.[5] *Mimesis* is often translated to 'imitation' in concise definitions.[6] However in

Plato's work, mimesis plays a range of roles. As the classics scholar Stephen Halliwell (2002, 70–71) writes in his attempt to 'diagnose […] Plato's prolonged and profoundly ambivalent relationship with mimesis', there are two main ways in which mimesis is used in Plato's corpus.

> The first, a kind of 'negative theology', which leads sometimes in the direction of mysticism, is that reality cannot adequately be spoken of, described, or modeled, only experienced in some pure, unmediated manner (by *logos*, *nous*, *dianoia*, or whatever). The second is that all human thought *is* an attempt to speak about, describe, or model reality – to produce 'images' (whether visual, mental, or verbal) of the real. On the first of these views, mimesis, of whatever sort, is a lost cause, doomed to failure, at best a faint shadow of the truth. On the second, mimesis – representation – is all that we have, or all that we are capable of. In some of Plato's later writing this second perspective is expanded by a sense that the world itself is a mimetic creation, wrought by a divine artist who, at one point in the *Timaeus* (55c6), is expressly visualized as a painter.

In the *Timaeus*, the demiurge's creation can be seen as mimesis on a cosmological scale. Through reason, the visible universe, '*that which becomes*', resembles the eternal order '*that which always is*'.[7] The cosmos, as it appears in the *Timaeus*, is composed by geometrical shapes fitting perfectly together, reflecting the eternal, immutable model. This brings us back to Vlastos (2005, 3), who traces *kosmos* back to 'the active, transitive verb, *kosmeō*: to set in order, to marshal, to arrange'. In the present chapter, the team behind the Illustris project is viewed as a modern demiurge: in the creation of the simulation, massive amounts of theory and data from observations are used, and 'set in order' through the code, giving each particle its place in the virtual universe. The visualisations based on the simulation furthermore transform the 'messy' big data output to a harmonious re-creation of the cosmos.

As the philosopher of science Laura Perini (2010, 148–151) writes, it is important to distinguish between scientific models and visual representations in science (see also Anna Maerker's contribution in this volume). Visualisations from Illustris are visual representations, based on a simulation which is produced from AREPO (the simulation code used to construct Illustris), using both theoretical physics and astrophysics as input. The simulation is based on the Standard Model of Cosmology, but should not be conflated with the model. While mimesis has previously been applied to studies of representations in science, for instance in the case of scientific models, this chapter focuses on the visual aspect of the Illustris Project.[8] Although research on images in science has developed in recent decades, astrophysics is a discipline which has so far received little attention.[9] With this chapter we contribute an account of visualisations of both dark and normal matter. Key to this last category of visualisations is the distinction between real and 'mock' observations.

1 Mimesis and 'Mock Observations'

A researcher wishing to create a visualisation based on the data output from Illustris will typically start out by searching for the relevant synthetic data from Illustris, such as dark matter in a certain section of the simulation cube during a particular point in the time evolution of the simulation. The researcher then writes a code in Python, controlling the angle from which the pixels representing the particles are seen, as well as the colours used to represent certain phenomena.[10] Once the visualisation has been produced, they can zoom in and out of the image, to get an overview of particular pixels in the visualisation representing the data output. 'Mock observations' are visualisations based on the synthetic data output from a simulation, but produced with the purpose of resembling the real universe as it appears through observations. By creating images from Illustris in a fashion similar to the construction of Hubble Space Telescope (HST) observations, astrophysicists are able to compare the virtual universe of Illustris to observations.[11] On the website of the Illustris Collaboration (2015c), one of the mock observations is presented as a recreation of 'one of the most iconic images in astronomy, the Hubble Space Telescope "Ultra Deep Field" (the image below is split in half, to the left and right – one half is real, and one is simulated, can you tell which?)' (fig. 18.3). In order to find the separation between the two images, one has to look closely – the left-hand side of the image is the 'real observation' from the HST, while the mock observation from Illustris can be found on the right-hand side. It thus becomes apparent how the Illustris visualisations are carefully crafted to resemble images over whose representational power there is already a consensus.

A major result from Illustris was its realistic reproduction of different types of galaxies. Therefore, an important part of research done on it entails comparing 'synthetic images' of galaxies in Illustris with images of galaxies as they appear from observations.[12] Many astrophysicists performing research based on Illustris choose to investigate a single galaxy. When the simulation reaches the present time, however, it shows 41,416 galaxies.[13] To help astrophysicists navigate in this massive dataset, a catalogue of galaxies, called the 'Illustris Galaxy Observatory', is available from the Illustris website (Illustris

FIGURE 18.3 Original caption used to describe the visualisation on the website of the Illustris Collaboration (https://www.illustris-project.org/media/, see Illustris Collaboration, 2015b): 'Hubble eXtreme Deep Field observations (2.8 arcmin on a side) in B, Z, H bands convolved with Gaussian point-spread functions of sigma = 0.04, 0.08, and 0.16 arcsec, respectively. Divided down the middle: real observation (left side) and mock observation from Illustris (right side)'
IMAGE CREDIT, LEFT: NASA, ESA, G. ILLINGWORTH, D. MAGEE, AND P. OESCH (UNIVERSITY OF CALIFORNIA, SANTA CRUZ), R. BOUWENS (LEIDEN UNIVERSITY), THE HUDF09 TEAM. PUBLIC DOMAIN.
IMAGE CREDIT, RIGHT: THE ILLUSTRIS COLLABORATION, COURTESY OF MARK VOGELSBERGER

Collaboration 2015a). By means of a search tool, researchers can adjust several parameters, such as 'Black Hole Mass Limits' or 'Gas Mass Limits', enabling them to find the type of galaxy they are interested in amid the "messiness" of big data (the sample of mock observations in fig. 18.4, for instance, shows only disk galaxies).

In the *Timaeus*, we also find a frequent alternation in scales between macrocosm and microcosm, aptly described by philosopher Thomas Kjeller Johansen (2004, 6), whose work we will discuss several times throughout this chapter, because of his engagement with the intersection between mimesis, *ekphrasis*, and natural philosophy in *Plato's natural philosophy*:

> Whilst devoid of neither argument nor conceptual analysis, the work equally persuades by *painting a picture* in words of our world as predominantly good and beautiful […] As a picture, the work draws us in by its detail and completeness, 'from the creation of the cosmos down to the nature of man' (27a6). The *Timaeus-Critias* can in part, then, be viewed as a philosophical *ekphrasis*, or depiction in words, of the whole cosmos.

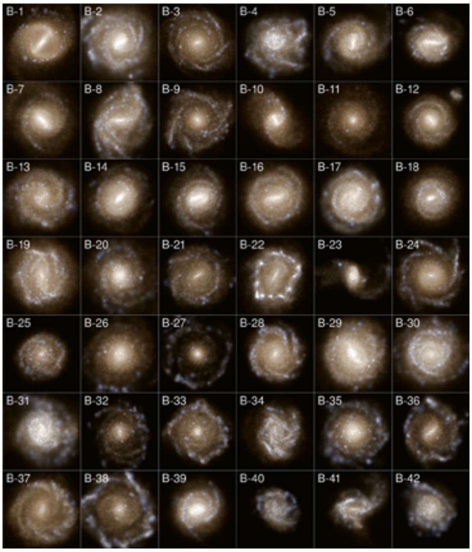

FIGURE 18.4
Original caption used to describe the visualisation on the website of the Illustris Collaboration (https://www.illustris-project.org/media/, see Illustris Collaboration, 2015b): ‘Sample of 42 blue, disk galaxies, showing the stellar light distribution (SDSS g,r,i band composites)’
IMAGE CREDIT: ILLUSTRIS COLLABORATION, COURTESY OF MARK VOGELSBERGER

One could add that it is not only ‘by *painting a picture* in words’, but also by painting one in numbers, that Plato expresses the beauty and harmony of the cosmos. In the cosmogony of the *Timaeus*, the creator of the cosmos is described as moulding existence by forming a harmony out of parts. In *Tim.* (35c2–36b5), Timaeus combines words and numbers in his description of the role of proportions in the creation of the universe.

> These connections produced intervals of 3/2, 4/3, and 9/8 within the previous intervals. He then proceeded to fill all the 4/3 intervals with the 9/8 interval, leaving a small portion over every time. The terms of this interval of the portion left over made a numerical ratio of 256/243.[14]

Throughout the *Timaeus*, the reader travels between different scales and follows the ways in which each component fits into the whole. The geometrical aspect of the image of the cosmos ‘painted’ by Plato in the *Timaeus* is what the ‘full-blooded mathematical [Platonist]’ Johannes Kepler (1571–1630) would build upon in his modified version of the Copernican system in *Mysterium Cosmographicum* (1596) (fig. 18.5).[15] The Platonic Solids, described in *Timaeus* as the construction elements of the universe, are five geometrical figures, where the tetrahedron represents fire, the octahedron air, the cube earth, the icosahedron water, and the dodecahedron is the shape of the universe itself.

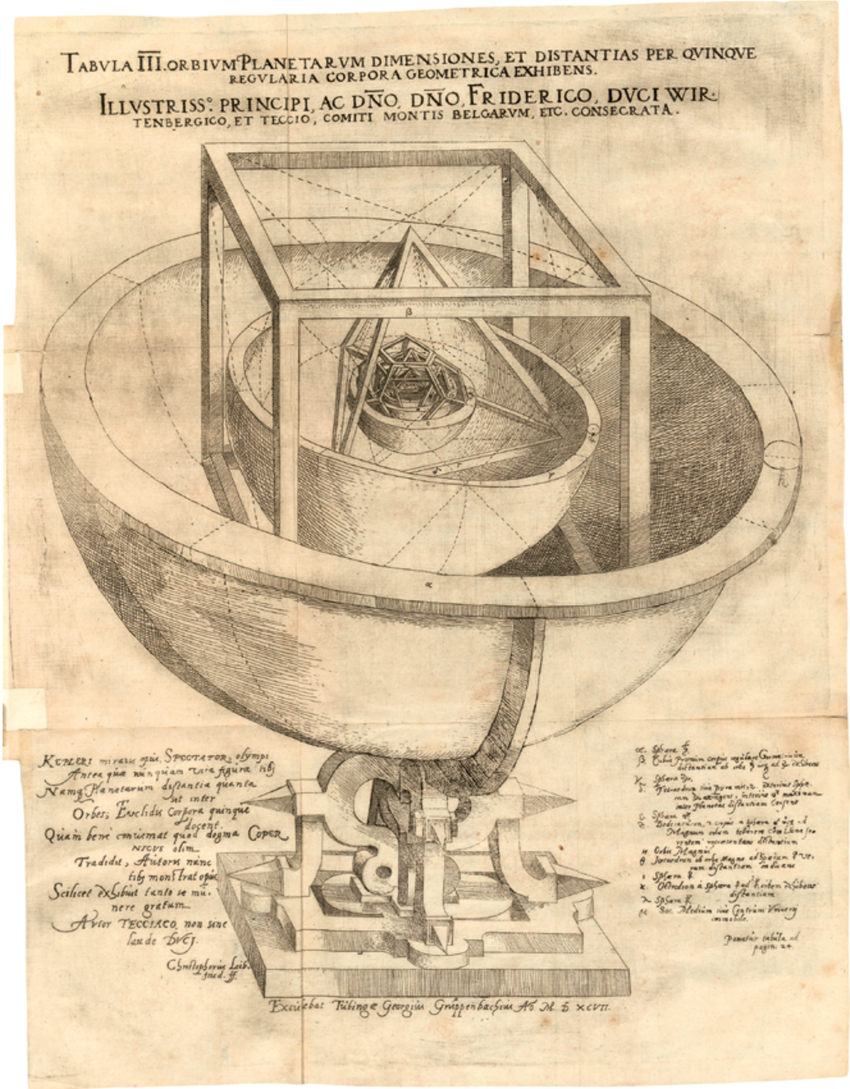

FIGURE 18.5 Johannes Kepler's illustration of the orbits of the planets in the Solar System, in *Mysterium Cosmographicum* (Tübingen 1596)
PUBLIC DOMAIN MARK

When nested inside each other, the distances between these convex regular polyhedra resemble the distances between the orbits of the planets in the solar system (Gaukroger 2006, 176–178).

In Plato's vertical world of thought, mathematics ranks very high (Shapiro 2005, 3). It is also central in relation to astronomy. In 'one of the most disputed passages of Greek literature, Plato in the *Republic*' tells us that we should 'study astronomy by means of problems, as we do geometry, and leave the things in the sky alone’.[16] In one school of thought, the passage is regarded as favouring a ‘purely speculative study of bodies in motion having no relation to the celestial bodies that we see’, while others hold that ‘what Plato meant was that astronomers must get to know the real motions of the heavenly bodies as opposed to their apparent motions as seen by us on earth’ (Bulmer-Thomas, 1984, 107). How can this vertical line of thinking in relation to the world of appearances, contrasted with the eternal forms modelling the construction of the universe, inform our present understanding of Illustris as a simulation meant to build a bridge between theory and observation? The purpose of mock observations is to appear as close as possible to real observations. Recalling mimesis as it appears in *Republic* X, mock observations might be seen as imitations of observations of visible phenomena. In line with this interpretation, one could speak of mock observations as an inversion of the vertical thinking of Plato, using mathematics and reason in order to reach downwards, to replicate the visible phenomena best.[17] If we look at the ontology of the virtual universe in relation to the visualisations, however, the simulation is bound together by encoded mathematics and data: a harmonic unification of numbers, resembling the ‘mimetic model of the cosmos’ found in the *Timaeus*.[18] In the *Timaeus*, if we follow Johansen, we see a painting of the universe in words, attracting the reader with the harmonic interplay between the whole and its parts. The part of this painting describing the Platonic Solids is not a representation in the sense of a mirror image of the visible world – rather, it is the cosmos seen from a perspective above sensory perception – a universe of theory, painted with words and numbers. The data visualisations based on Illustris, too, show us a universe recreated through the use of theory. Mortals, Timaeus tells us, are not able to completely grasp the otherworldly order. All we can hope to do is to provide a likely myth or story (*eikōs muthos*) or a likely account (*eikōs logos*).[19] The *account* of the universe could be seen as yet another level of mimesis present in the *Timaeus*. Following Johansen, in *Critias*, Critias describes his own account, as well as the explanation given by Timaeus, as:

> ‘imitations’ (*mimēsis, apeikasia* 107b5), perhaps echoing Timaeus’ wish that *his* account be received as a mere *eikōs logos* or *eikōs muthos* of an *eikōn* of an intelligible paradigm (*Tim.* 29d). Both *logoi*, then, are presented to us as imitations of a sort.[20]

The reader, Johansen continues (2004, 31), is encouraged to take into consideration the famed passage in the *Republic* describing mimesis (595a–608b), in relation to the status of the account in the *Timaeus-Critias*, through the reference to painting found in *Critias*:

> It is inevitable, I suppose, that everything we have all said is a kind of representation and attempted likeness. Let us consider the graphic art of the painter that has as its object the bodies of both gods and men and the relative ease and difficulty involved in the painter's convincing his viewers that he has adequately represented the objects of his art.[21]

However, whereas in *Republic* X the artist's painting is negatively viewed, on account of the superficial reproduction of the appearance of the phenomena, akin to that of a mirror's reflection, the account of Timaeus is another story altogether. Timaeus is described as being very knowledgeable in astronomy, and the explanation of the cosmos is based on his expertise. On this point, Johansen (2004, 35) argues, mimesis as it appears in the *Timaeus-Critias* differs from mimesis in the notorious passage in *Republic* X. Furthermore, Timaeus acknowledges that he cannot give certain answers to the origin and hidden nature, of the cosmos – by emphasising the status of his account as 'likely', he avoids the deceptive character of mimesis, unlike the seducing mirror-like painting described in *Republic* X. Rather than seeing mock observations as imitations of mirror images, recalling *Republic* X, one could also argue that Illustris works within the Platonic world of thought: Illustris visualisations are produced by specialists in the field of astrophysics, making the simulation one of the most 'likely accounts' of the cosmos seen today. The likelihood of the account is emphasised through the publication of images such as the Hubble eXtreme Deep Field mock observations from Illustris.

2 Touching Dark Matter

The Illustris Project has gained international attention in major news media, with eye-catching headlines such as: 'Universe evolution recreated in lab' (7 May 2014, *BBC news*), 'Universe recreated in massive computer simulation' (7 May 2014, *The guardian*), 'Stalking the shadow universe' (16 July 2014, *The New York times*), and 'How our universe grew up' (8 May 2014, *CNN*).[22] Much like large-scale projects such as the HST, communicating the success of Illustris would have been important to its creators as they prepared for new simulations using AREPO. Results from two projects building upon Illustris have already been released: a series of simulations in a project called IllustrisTNG, which improved upon the original version, and the Auriga Project, which gave a detailed view of the Milky Way.[23] Several studies of recent astronomical imaging have found that publicity and funding are significant factors in pushing researchers to produce observations intended for communication to the general public.[24] False-colour observations, sometimes referred to as 'pretty pictures', have been a topic of contention amongst the art historians who have studied them. While James Elkins introduces them as 'hopped-up versions of legitimate photographs, with the colours intensified or falsified', Elizabeth A. Kessler argues that false-colour images from the HST are aesthetically valuable, as they are processed in such a way as to evoke the feeling of the sublime.[25] Our aim here is not to contribute to this highly interesting discussion of the aesthetic value of false-colour observations. Rather, we want to shift the focus slightly by noting, firstly, that we see a similar development within computational theoretical physics, where it has become common practice to produce colourful, dynamic, and sometimes interactive visualisations from cosmological simulations. Secondly, we note that although funding and publicity likely played a role in pushing researchers to produce the compelling 'synthetic images', Illustris is one example of how the demarcation between 'pretty pictures' and images used in communication to specialised audiences within astronomy or astrophysics is not clear-cut. Although the visual representations most commonly used in peer-reviewed literature on Illustris are plots (understood here as graphical visual representations of data), synthetic images are also used in articles within journals such as *Nature* and *Monthly notices of the Royal Astronomical Society*. Moreover, the ways in which the visualisations are used are similar across communication to intended audiences of varying degrees of specialisation. Synthetic images work to persuade the viewer of the accuracy of the simulation as aids for gaining an overview of Illustris, or for navigating within it. The comparison between the HST observation and the synthetic image in fig. 18.3, for example, appeared in a press release as well as in *Nature*, in both cases functioning as a visual argument for the quality of the simulation.[26] Another example is navigation within the virtual universe. We saw how Illustris Galaxy Observatory uses synthetic images to help researchers find galaxies relevant to their research. Similarly, both in videos used in communications with the general public, and in oral presentations to specialists, information about scale and time provides a way for viewers to orient themselves both spatially and temporally within Illustris. Studies of diagrams in theoretical physics have shown the important role diagrammatic 'paper tools' have played to help students and researchers approach challenging topics.[27] Although Illustris visualisations do appear in print form – in 2018, for instance, one of them came to decorate an official stamp in Germany (fig. 18.6) – they are more commonly encountered on screens of sizes ranging from smartphones to planetariums. Where Penrose diagrams helped 'physicists struggling through the notorious conceptual and mathematical subtleties of GR', virtual tools in

FIGURE 18.6 German stamp featuring a visualisation based on the Illustris simulation
COURTESY OF ANDREA VOSS-ACKER, WUPPERTAL (DESIGN) AND © THE ILLUSTRIS COLLABORATION (IMAGE), COURTESY OF PETER SAUERESSIG

the form of synthetic images are used to help viewers grasp a virtual universe on the scale of megaparsecs (Wright 2013, 134).

Quite unlike synthetic images, the visual style of the plots used in peer-reviewed literature on Illustris are perhaps best characterised by what art historian Kemp has called *non-style* – the 'draining of obvious ornamentation, stylishness, and pictorial seductions'.[28] In various ways, synthetic images are instead crafted to look naturalistic, depending on whether they represent dark or normal matter. In the case of mock observations of galaxies, we saw how their close resemblance to observation was emphasised. Visualisations of *invisible* phenomena instead appear naturalistic because they are shown in perspective, whereby some strands within the cosmic web appear closer than others. Visual representations using a naturalistic style do not necessarily portray objects as they are observed, or even phenomena which exist.[29] With visualisations of dark matter, the viewer sees dark matter illuminated, as though crawling up from Plato's cave. Indeed, the Latin *illustris* can be translated to 'bright', 'brilliant', 'shining' or 'pervaded with light'.[30] Although dark matter cannot be observed, in synthetic images the elusive matter is not only luminous but, as we shall see, becomes yet more tangible and material through rotation and close-up shots in videos.

Some videos from Illustris showcase the simulation in its full size, where the viewer sees the simulation cube from an outside viewpoint; while in others the viewer appears to be placed inside the simulation. In 'A virtual universe', a video appearing in a *Nature news* feature on Illustris, moving visualisations from both within and outside the simulation are used.[31] In the following, we study this feature as an example of how the visualisations are contextualised and used to communicate Illustris to non-specialists, as well as the ways in which they allow for audiences to interact with Illustris.

'A virtual universe' begins by zooming in on an animation of a galaxy, whereupon we see an explosion, while in voiceover, we are told about the Big Bang. This is followed by an explanation of Illustris: 'To test our theories scientists have built a computer model of the universe. A simulation so complex that calculating it on a single desktop would take 2,000 years'. We now see the simulation as a whole in a cube, spinning before us, before shifting to a different video from Illustris. Here, we start out by viewing dark matter, zooming in (see Figure 18.7). The field shifts, showing stellar light from a galaxy instead. The video then zooms out, while the scale in parsec is visible on the left side.

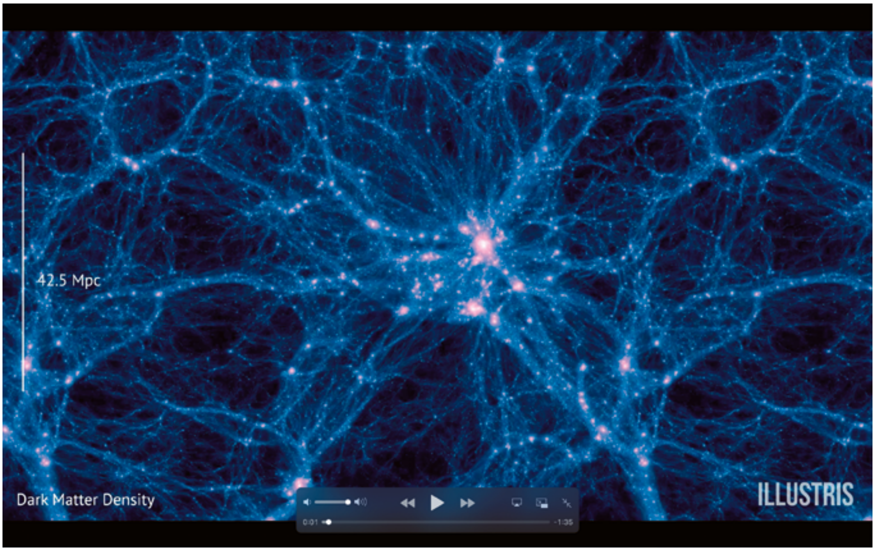

FIGURE 18.7 Screenshot from the original video on the Illustris Project's website [Illustris Collaboration, 2015b]. Original caption: 'Continuous zoom-in from the scale of the entire simulation volume (100 Mpc) to the scale of an individual spiral galaxy (10 kpc), highlighting the diversity of structure across spatial scale, the large dynamic range of the simulation (106 per dimension), and the relationship between dark matter, gas, and stars' [Illustris Collaboration, 2015b]

CREDIT: ILLUSTRIS COLLABORATION, COURTESY OF MARK VOGELSBERGER

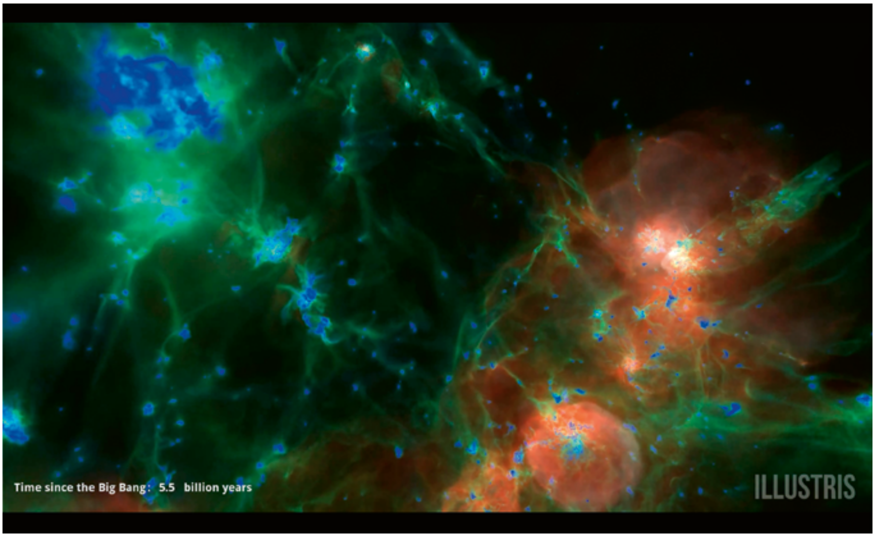

FIGURE 18.8 Screenshot from the original video on the Illustris Project's website. Original caption: 'Time evolution of a 10Mpc (comoving) region within Illustris from the start of the simulation to z = 0. The movie transitions between the dark matter density field, gas temperature (blue: cold, green: warm: white: hot), and gas metallicity' [Illustris Collaboration, 2015b]
CREDIT: ILLUSTRIS COLLABORATION, COURTESY OF MARK VOGELSBERGER

'The model', the voiceover narrates, 'doesn't just tackle the universe's huge range of scales. It also richly describes the forces at work. Much better than previous attempts'. The next video shows gas temperature in a cube on the left side, and dark matter on the right. Another cut is made to an Illustris visualisation where we see the cosmic web spinning before us, in what could be described as a close-up, portraying the dark matter as if the viewer could stretch out their hand and touch the large-scale structure of the universe. The field shifts from dark matter to normal matter, where the distribution of colour (from blue through green to red, and finally white) represents temperatures from low to high (fig. 18.8).[32]

Supermassive black holes dominate the largest galaxies, and cause gas to be blown out 'in these violent, white bursts'. Again we see a shift, as the video now shows the chemical composition of the region within the simulation, and soon we see dark matter again. At this point, we are close to the universe in its present state. '14 billion years of the universe's evolution has pulled a tightly woven dark matter web into a looser network of giant galaxy clusters', the voiceover tells us, while the visualisation of dark matter gradually shifts to show galaxy clusters.[33] Again, a video which zooms in and out of a galaxy is shown, followed by an animation of an explosion. Finally, we see an animation depicting galaxies, moving close to an individual galaxy, before the animation shows a space telescope in the foreground, and the Earth in the background.

In these videos of the virtual universe, we see current theories and data ‘in action’, with explosions, zoom effects, and rotation in 360 degrees. Commenting on the mapping of dark matter, David Turnbull has argued that dark matter and energy represents a ‘whole new ontology and epistemology’, with the new understanding of mass and existence bringing with them new forms of cosmological research. Turnbull has described this as a ‘hyperbolic’ line of argumentation used in order to make what is invisible visible. We suggest a more subtle view of the ‘new ontology’ introduced with dark matter visualisations, one which considers their contextualisation.[34] Although dark matter can be ‘[brought …] into existence’ (Turnbull 2017, 208) through maps or visualisations from simulations, these often appear in the context of verbal descriptions stressing the lack of certainty around what, as physicist Max Tegmark (2014, 70) puts it, ‘is really little more than a name for our ignorance’. In the case of Illustris, dark matter is illuminated and made to appear yet more material using a range of visual techniques, but is at the same time framed as artificial and virtual. This framing of the visualisations as a way of representing the ontology of a *virtual* universe is characteristic of communications about Illustris targeting the general public. This was likely encouraged by members of the Illustris Collaboration, as the press releases and interviews take the same approach. Interestingly, we see the same in the case of visualisations of normal matter in peer-reviewed papers, where they are referred to as *mock observations*, constructed from *synthetic data*, or alternatively as ‘mock UDF’ (i.e. ‘Ultra Deep Field’), ‘mock images’, ‘mock data products’, and ‘synthetic images’.[35] While the accuracy of the simulation is emphasised, so is its artificiality, which, when combined, serves to showcase the abilities of the creators of the virtual universe. Although science has travelled far from the view of the universe seen in the *Timaeus*, Illustris seems to be driven by a desire resembling that expressed in the *Timaeus*: to reveal the laws governing the behaviour of the universe, in order to recreate this harmony.

3 ‘Move over, Matrix’

At the thought of divine power, the philosopher, politician, and writer Edmund Burke (1729–1797) tells us, ‘invested upon every side with omnipresence, we shrink into the minuteness of our own nature, and are, in a manner, annihilated before him' (Burke 2015, 56). In the Illustris visualisations, the cosmos is visualised on a scale which surpasses that of the Earth, since planets are too small to appear in the simulation. While we cannot speak of anything resembling a geocentric worldview in the visualisations, we could describe the view of the cosmos, given to us through Illustris, as anthropocentric, since creators of Illustris and beholders of its visualisations can gain a sense of control of the virtual universe. Kemp (2006, 35–36) makes a similar observation, although in connection with a much earlier illustration of the universe – Johannes Kepler's reinterpretation of the Platonic Solids in the *Timaeus*, in his illustration of the Solar System (fig. 18.5):

> Kepler has depicted his scheme for the construction of his own cosmological model […] as if he were acting as a microcosmic emulator of God […] The model, whether God's or made by human agency, is by implication something which can potentially be viewed and envisaged perspectivally from any point within or outside the system.

While this God's-eye view of the cosmos offers a myriad possibilities in relation to perspective, it is placed on a plinth. From this foundation we can clearly determine the angle from which we view the model. On its plinth, the 'great folding plate' is exhibited as a model, resembling, indeed, an armillary sphere, as if placed in the study of a scholar. The model, then, seems to illustrate the possibility of a human omnipresent gaze, enabled by natural philosophy. The same could be said about the Illustris visualisations, which are exhibited as man-made constructions, as images based on 'synthetic data'. It is in taking up a God's-eye view that Earth's place in the cosmos shrinks into the minuteness. Through the Illustris visualisations, the beholder is shown a rotating three-dimensional view based on the Standard Model of Cosmology, at multiple scales. The virtual universe is shaped by the modern demiurge of the Illustris Collaboration. The viewer takes on the same position as that of the reader of the *Timaeus*, gaining access to a 'painted' picture of the cosmos, attracting us with the harmonic interplay between whole and parts in the account of the formation of the cosmos. If we regard the Illustris simulation as an anthropocentric view of the cosmos, it is so in the sense that the virtual universe is constructed, and under the control, of the team behind Illustris. Yet as the output of AREPO is not predictable, Illustris escapes from that control. The sense of control a viewer can experience comes from the virtual medium in which they encounter the visualisations: in the videos of the development of the cosmos from shortly after the Big Bang to the present, the viewer can fast-forward, stop, or rewind the visualisation of the cosmological evolution.

On the back of discussions following Thomas Nagel's concept of the 'view from nowhere', the historian of science Charlotte Bigg has analysed planetariums in the early twentieth century.[36] Bigg shows how viewpoints were embodied in pedagogy through certain placements of bodies of students and other spectators visiting, or preparing to visit, planetariums. Here we see a context in which disembodiment is an important part of the point of view, but in the context of a visualisation where dark matter is given body.

Unlike the imagined viewpoint of mock observations (a telescope), in dark matter visualisations, the point of view is not framed as a telescope, since dark matter is not visible through observation. HST observations, some of which the mock observations from Illustris seek to emulate, have given us magnificent views of the cosmos – from false-colour images showing 'a universe filled with glowing gases in vivid colours, galaxies swirled together in bands of light and dark, and innumerable stars' to the famed Hubble Deep Field images.[37] 'As a mechanical eye', Kemp (2006, 242) writes, 'the Hubble telescope stands in a long succession of human endeavours to create the ultimate form of sight'. To Kessler (2012, 19), the HST 'stretches humanity's vision beyond what Galileo ever imagined' from its orbit above the Earth's atmosphere. Elkins (2008, 101) focuses on the intense pursuit to expand the limits of what can be observed. With the Hubble Deep Field North, the 'most wonderful visual act was the attempt to see *beyond* the faintest galaxies on the plate – to see something in the black regions between the faint bright spots, at the very end of the visible universe'. Kemp and Kessler characterise the HST in terms of a technological extension of human vision, in part due to its physical extension into outer space, and Elkins in terms of an expansion of the boundaries of the visible universe, through the approach and treatment of observations. While the HST observes in all directions, it is still bound in its orbit around the Earth. With the Illustris visualisations, the viewer's position is disembodied: any point in the simulation can be taken as a centre, and become a point of view. This sense of control over a virtual replication of our universe brings to mind works of science fiction such as Lana and Lilly Wachowski's movie *The Matrix* (1999).

Indeed, there is a direct connection between *The Matrix* and the communication of Illustris. On 7 May 2014, a press release introducing Illustris was published on the website of the Harvard-Smithsonian Center for Astrophysics. *The Matrix* was here used to introduce the reader to the universe of Illustris, appearing in the first sentence: 'Move over, *Matrix* – astronomers have done you one better. They have created a realistic universe using a computer simulation called "Illustris"' (Aguilar & Pulliam 2014). In *The Matrix*, the majority of the human population lives in the Matrix, unaware that their bodies are in fact placed in cells, in order to exploit body heat and electrical impulses as sources for energy. The film has been tied to several philosophical discussions and traditions, including Plato's allegory of the cave. The Matrix is a simulated reality, created by machines that dominate the territory of the Earth. Human rebels fight against agents, computer programmes disguised as humans within the Matrix. Towards the ending of the film, the protagonist, Neo, is shot and killed by Agent Smith, but rises again. When agents shoot at Neo, he stops the bullets. Neo now sees the code of the Matrix and is able to bend the laws of the system through his insight. The viewer, here, sees the universe through Neo's point of view: the hallway and agents, written in code. There is a similar allure to the visualisations from Illustris: they showcase the current conception of the universe, as it is reproduced from a code written by astrophysicists. 'The matrix', as the philosopher and lawyer Paul W. Kahn writes (2013, 122), 'is a perfect system of representation, on the one hand, and a completely illusory world, on the other [...] There is a logic – the code – that guarantees coherence'. The reference to *The Matrix* in the Illustris press release works to emphasise the closeness of the Illustris simulation compared to observations. Yet Illustris is not naturalised in the way the Matrix is. In the press release from the Harvard-Smithsonian Center for Astrophysics, Shy Genel, a member of the Illustris Collaboration, is quoted saying: 'Illustris is like a time machine. We can go forward and backward in time. We can pause the simulation and zoom into a single galaxy or galaxy cluster to see what's really going on'.[38] The possibility of travelling through time and space in the virtual universe of Illustris recalls the ending of *The Matrix* where 'we see [Neo] flying, free of gravity, above other humans, as he dissolves the Matrix and offers them release' (Freeland 2002, 213). Similarly, no source of gravity limits the beholder to a particular point of reference within Illustris. This brings us back to Kepler's illustration. While being able to see both individual galaxies and the cosmic web in 360 degrees, viewers of an Illustris visualisation are unable to position themselves within the virtual universe. There is no plinth indicating what viewpoint the viewer takes up within the simulation cube. It is not only the Earth which can be said to 'shrink into the minuteness' in the Illustris simulation – by achieving the omnipresent God's-eye view, the viewer, too, disappears into the space of Illustris.

4 Conclusion

In this chapter, we have examined 'mock observations' and visualisations of dark matter from the Illustris simulation in terms of mimesis on a cosmological scale. The Illustris Collaboration can be seen as a modern demiurge, constructing an orderly cosmos out of the chaos of big data, connoting not only the *Timaeus*, but the root of the word *kosmos*, found in the Greek verb *kosmeō*. Through data visualisation, the team behind Illustris opens up the black box of big data, enabling the viewer of the Illustris visualisations to access this God’s-eye view of the virtual universe. Videos from Illustris permit the viewer to see the simulation in rotation, in multiple fields and scales, and to perform a virtual travel through 13.8 billion years of cosmological evolution. The view of the cosmos seen in the Illustris visualisations seems to have left behind anything resembling a geocentric image of the world – planets which could have created associations to the Earth are too small to appear in the simulation, and unlike the HST, which orbits the Earth, in Illustris any point in the simulation cube can become a point of view.

Whereas the HST is described as a technological extension of the human gaze, or a ‘mechanical eye’, the viewpoint in the Illustris visualisations is a disembodied one. While the Illustris visualisations cannot be described as in any sense resembling a geocentric view of the cosmos, they may be understood as anthropocentric, in the sense that the virtual universe is under the control of the Illustris Collaboration, and the viewer of the visualisations can achieve a similar experience as that of the Illustris Collaboration when controlling, for instance, a video showing the development of the universe. Whereas Kepler places his illustration of a cosmological model on a plinth, with the visual dimension of Illustris, the achievement of the omnipresent gaze renders the beholder unable to establish their own viewpoint in relation to the visualisation.

Since the completion of Illustris in 2013, two sets of simulations have been produced using the AREPO code. New cosmological simulations are constantly being developed, growing in both scale and complexity. One could argue that the visual dimension of Illustris is one of the ways in which the public can best view the current state of understanding of the universe within astrophysics. To the layman, the data output of Illustris is entirely inaccessible. Yet the striking visualisations based on the simulation open the black box of these data – through the visual dimension of the project, everyone, including the general public, can view the cosmos, as it is reproduced based on the Standard Model of Cosmology. As noted in the beginning, despite the attention given to cosmological simulations in academic writing as well as public media, many of these simulations have yet to be explored in existing scholarship within the humanities. The release of cosmological simulations gives us a way to study portrayals of our view of the cosmos given by astrophysicists, and, due to the widespread attention they gain, the ways in which a variety of audiences engage with them. As yet more cosmological simulations are released, future studies are needed to analyse their production; the written, verbal, and visual communication of them; their circulation in printed and online media; as well as the responses they solicit, and ultimately how these simulations contribute to how we think about and imagine the universe we inhabit.

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Endnotes

1 Hydrodynamics is the study of fluid motion, which in this instance refers to cosmic gas. A simulation is here understood as an ‘imitation of the operation of a real-world process or system over a period of time’, following Banks & Sokolowski 2009, 5. See works by Galison (such as 1997) and sources cited therein for literature on simulations within the history and philosophy of science, Frigg & Reiss 2009 for a critical review of literature in philosophy, and Durán 2018 for a general introduction. While several simulations exist within the Illustris Project, the Illustris simulation is often referred to in the singular, since Illustris-1, the simulation containing the most particles, is usually used for research and to create visualisations. For information on the various simulations, see Nelson *et al.* 2015.

2 These are estimates based on the 2015 results from the Planck Satellite (Ade *et al.* 2016).

3 See e.g. Vogelsberger *et al.* 2014 and Springel 2010 on Illustris, and Borgman 2015, 89–90 for an introduction to synthetic data in astrophysics.

4 See Aiden & Michel 2013, 19; Mayer-Schönberger & Cukier 2013, 32–49.

5 See Vlastos 2005, 26; Plato & Cornford 1997, 27; Johansen 2004, 95, note 6.

6 See for instance Blackburn 2008, 235; Bunnin 2004, 434. For discussions of this translation and the etymology of mimesis, see Halliwell 2002, 13–14, 17–22.

7 *Tim.* (27d5–6), following Plato 1997. Original emphasis.

8 For a discussion of the use of the concept of mimesis in relation to different kinds of representations in science, amongst others, see Galison 1997 and Frigg & Hunter 2010, and references cited therein. For an analysis of the Standard Model of Cosmology in light of the account of the cosmos in the *Timaeus*, see Brisson & Meyerstein 1995.

9 See Cambrosio *et al.* 1993, 662 for an introduction to pioneering work within this field. For an overview of research on scientific imaging, see Hentschel 2002, 2014; Pauwels 2006, and further references cited in Hopwood 2015, 309, n. 10. For existing research on contemporary astronomical imaging, see Lynch & Edgerton jr. 1988, 1996; Elkins 1999, 2008; Hannestad 2018; Kessler 2011, 2012; Turnbull 2017; Vertesi 2015, and references cited therein. See Hentschel 2014, 258 for literature on visualisations from the Millennium simulation.

10 Most visualisations based on Illustris are constructed using Python, a standard programming language in astronomy (Goodman 2012, 7).

11 See Torrey *et al.* 2015 for a detailed description of the construction of mock observations.

12 For an example of this, see Snyder *et al.* 2015.

13 Vogelsberger *et al.* 2014, 177.

14 *Tim.* (35c2–36b5), Plato 1997.

15 Shapin 1996, 59. On Kepler’s so-called polyhedral theory, see Stephenson 1994 and references cited therein.

16 Bulmer-Thomas 1984, 107; *Rep.* VII (530b5–6), in Plato 1997.

17 Regarding astronomy in the *Timaeus*, Plato allows for an exchange between reason and perception (see, e.g., *Tim.* 47a1–b2). See Johansen 2004, 160–176 for a detailed analysis of astronomy in the *Timaeus*, as well as Gregory 2000 and Vlastos 2005.

18 Halliwell 2002, 321, n. 24.

19 *Tim.* (29c8–d3; see also 68c–d and 59c–d); *Tim.* (30b, 48d, 53d, 55d, 56a, 57d, 90e).

20 Johansen 2004, 31. *Critias* is the unfinished dialogue following the *Timaeus*, in a projected trilogy where *Hermocrates* – likely never written – is assumed to be the third dialogue.

21 *Crit.* (107b5–c2), translated by Diskin Clay in Plato 1997.

22 Ghosh 2014; Sample 2014; Overbye 2014; Landau 2014.

23 For IllustrisTNG, see Pillepich *et al.* 2018; Springel *et al.* 2018; Nelson *et al.* 2018. For the Auriga project, see Grand *et al.* 2017.
24 Lynch & Edgerton Jr. 1988; Elkins 1999, 2008; Kessler 2011, 2012; Vertesi 2015.
25 Elkins 2008, 87; Kessler 2011, 2012.
26 For the press release, see Aguilar & Pulliam 2014; for the *Nature* publication, Vogelsberger *et al.* 2014.
27 On 'paper tools', see Klein 2003. On paper tools in theoretical physics, see Kaiser 2005; Wright 2013, 2014.
28 Kemp 2000, 4; id. 2010.
29 Kemp 1990; Kusukawa 2012.
30 *OLD* 1968, 830.
31 Stoddart & Gibney 2014 links to the video.
32 Transcriptions from the voiceover in the video 'A virtual universe'; see Stoddart & Gibney 2014.
33 Stoddart & Gibney 2014.
34 Turnbull 2017, 207. See also de Swart *et al.* 2017, de Swart 2020, Bertone & Hooper 2018, and sources cited therein for the history of research on dark matter.
35 Vogelsberger *et al.* 2014, 177–178; Torrey *et al.* 2015, 2753.
36 Nagel 1986, Bigg 2017: see 204–205 for an introduction to the discussion following Nagel's work.
37 Kessler 2012, 57.
38 Quoted in Aguilar & Pulliam 2014.