Dark Matter: Probing the Arche-Fossil

Interview with Roberto Trotta

Dr. Roberto Trotta[1] *coordinates Oxford University's* Dark Sector Initiative,[2] *an enterprise dedicated to elucidating the nature of 'dark matter' and 'dark energy'. The cross-disciplinary nature of this project – described as an intense collaborative work involving mathematics, theoretical physics, phenomenology and statistics – anticipates the problematic status of its objects. Trotta's work as a theoretical cosmologist takes place at the intersection of cosmology (the attempt to construct a coherent model and narrative of the origin and evolution of the universe), astrophysics (the description in physical terms of the objects observed in the universe), and theoretical physics (positing models of the elementary constituents of matter and their interactions). Observations of astrophysical entities are interpreted in cosmology within the framework of theoretical physics, drawing upon powerful statistical techniques to derive probabilistic inferences on the fundamental phenomena under scrutiny, even in cases where the astrophysical objects themselves are poorly understood. Equally, some of the most advanced and speculative theoretical physics finds its best (and sometimes unique) testing-ground in models of the early universe.*

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[1] See http://www-astro.physics.ox.ac.uk/~rxt/

[2] See http://www-astro.physics.ox.ac.uk/darksector/

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Collapse interviewed Trotta at the Beecroft Institute for Particle Astrophysics and Cosmology (BIPAC) with a view to understanding how the process of determination of this field of research on the 'outer edge' of science, bounded equally by technological, probabilistic and logical constraints, brings to light the process of scientific thought, and problematises its very conceptual foundations, thus emphasising its continuities with traditionally 'philosophical' concerns.

COLLAPSE: We would like to investigate with you the general question of the status of the objects of your research. Could you describe to us how empirical observation, theoretical postulation, and the aspiration towards a coherent cosmological model interact to create this problematic object of study – 'dark matter' – and compel scientists to posit its reality?

ROBERTO TROTTA: We are interested in this 'dark matter', or 'dark sector' of the universe primarily because it enters, in an unexpected way, into our observations. Many different fundamental explanations for dark energy have been advanced, but the need for its postulation was brought forward primarily by empirical evidence; indirect, sometimes, but still empirical evidence, interpreted within the framework of a certain cosmological model.

According to the current paradigm, about 5 percent of the matter-energy of the universe is visible, and of this 5 percent only a fraction goes to form stars or planets or other heavenly bodies – the largest part is in the form of gas. 95 percent of the universe is 'dark', in one way or another: about 25 percent dark matter, 75 percent what we call dark energy.

The existence of dark matter is both predicted by fundamental models of theoretical physics, such as supersymmetry, and required by cosmological observations highlighting the problem of the 'missing mass' of the universe. In fact, many pieces of evidence strongly suggest that there is much more mass in the universe than the visible counterpart in the form of galaxies and clusters we can see. It is postulated that the missing mass does not interact with light, and this would explain why it is dark. But its existence is revealed by its gravitational effect on other massive bodies, for instance the distribution of galaxies in the universe, or the overall gravitational dynamics of the cosmos. This is how dark matter enters the cosmological model.

C: And what about 'dark energy'?

RT: The case for dark energy is even more puzzling: observations of stellar explosions called supernovae indicated that the expansion of the universe is accelerating, rather than slowing down as it should under the influence of gravity if its content were in the form of ordinary matter (both visible and dark) and radiation. The accelerated expansion thus requires the presence of a new 'substance' with negative pressure, which would act as an 'anti-gravity' of sorts on cosmological scales: this is what has been dubbed 'dark energy'. In contrast to dark matter, at the moment we do not have many fundamentally motivated models for dark energy, except perhaps Einstein's cosmological constant – which, however, has to be inserted by hand into Einstein's equations to explain the present-day acceleration of the universe. But cosmologists are an inventive lot, and people were quick to introduce into the game new, *ad hoc* forms of energy to explain the accelerated expansion, perhaps in the form of so-called scalar fields. Fittingly, such models have been christened 'quintessence', since dark energy would be a fifth substance in the universe on top of the known four, *i.e.* photons, neutrinos, baryons (*i.e.* visible matter) and dark matter.

It's a very unsatisfactory state of things, thinking that after all this work in cosmology, forty years after cosmology was born with Penzias and Wilson, eighty years after Hubble discovered the expansion of the universe, we are stuck with this most incredible situation: that 95 percent of the universe is 'dark'. But we do believe that we have good reasons – empirical reasons – to have to go out and explain this missing mass and energy.

And so, the research programme is cross-disciplinary in the sense that it is really a field where you have the empirical observations – which I'll describe in more detail – of dark matter and dark energy. You have theoretical modelling, which is used both to interpret the observations cosmologically, and to try to give us a framework to predict further phenomena, or to explain phenomena. Then you have statistics, which is used to govern the data, to interpret them in a statistically sound way. And you have mathematics, since all these formulations, all these theories, are heavily mathematical, and we're trying to use them to derive the logical consequences of our observations. But it's really all interrelated. You can jump into this cycle at any point. You can start the cycle from, say, observations;

this gives you evidence for unexplained phenomena. At this point, you get the observation right, then you gather the statistical evidence for the phenomenon you are interested in; then you model it within a certain theoretical framework, which gives you predictions which in turn can be tested against new observations. So it's a connected chain of reasoning.

C: Historically, which observations first suggested the need to postulate dark matter?

RT: One of the first pieces of evidence for the need for dark matter goes back to the 30s and has been confirmed ever since. It's something called the 'flat rotational curves' of galaxies, and it can be explained like this. If you have a galaxy, with the visible mass of that galaxy you see there is a bulge in the middle, and then it declines – so, if it's a spiral galaxy, you have less stars in the spiral arms. Now, the further out you go in respect to the centre of the galaxy, you'd expect the velocity of the stars orbiting this galaxy to be reduced, simply because – in rather the same way as, say, Neptune goes more slowly around the Sun than the Earth does, because it's further out in the solar system – if all the gravity comes from the visible part of the galaxy, then stars which are further out should circle the galaxy more slowly than the stars that are in the centre. But observations of these velocities actually show that the velocity is constant with radius – which means either that our theory of gravity is wrong, and Newtonian-Einsteinian gravity doesn't hold on galactic scales; or that we need more matter than the visible part to keep those stars on track.

C: Evidently, in defining research programmes, a certain decision is called for: which elements of the current theoretical paradigm to preserve, and which to relinquish. For instance, in the context of physics a century ago, a decision had to be made between abandoning the Maxwellian equations regarding the constancy of the speed of light, or abandoning the Newtonian postulate of absolute simultaneity and the aether. The correct decision seems obvious to us now – perhaps it was even obvious to Einstein at the time, who seems not to have been significantly influenced by the negative outcome of the Michelson-Morley experiment. But nevertheless, it constituted a real decision, a kind of branching-point for science. Now, since you have just described the issue of these empirical observations as pressing us into a decision, let us ask: is it a straightforward matter to know which part to jettison? In the case of dark matter, why is it more cogent to hypothesise missing mass rather than a correction to the fundamental laws? Since, up to this point – despite its reassuringly substantial-sounding name – 'dark matter' has remained the name for a particular *gap* in our systematic account of the universe, then, as you say, the possibility remains that it may be, for instance, the result of a shortcoming in our understanding of gravity rather than evidence of 'missing mass'. Are both possibilities pursued in a research environment?

RT: They are pursued in parallel, to a certain extent, even though the majority of scientists would say that the dark matter hypothesis in this case would be preferred to a change in the fundamental laws of gravity, for two reasons. One reason is that we are extremely reluctant to change a theory as successful as general relativity [GR], because it accounts for phenomena on all sorts of scales, and is an extremely successful theory that has been tested to a high degree of precision. So it would seem strange – you would really have to have a compelling reason – to abandon it. That's one reason. The second reason, more from the empirical point of view, is that recent observations of the collision of clusters of galaxies – as recently as August 2006, in fact – have shown that even within the paradigm of a modified gravity, you wouldn't be able to explain these kinds of observations. So there are both reasons of theoretical prejudice – we don't want to abandon GR unless we need to; and empirical reasons – empirical facts don't seem to fit with current brands of modified gravity.

C: The flat rotational curves were the first piece of evidence, then, but others followed.

RT: Yes, we have this indirect observation from the flat rotational curves which, admittedly, relies on the fact that we have a certain model for how things spin around, certain laws of gravity – this is one piece of evidence. Then we have gravitational lensing, which is the bending of light through a gravitational field, which again, gives spectacular results, and is actually a way of highlighting the distribution of matter in the universe no matter whether it is visible or dark. This again cannot be accounted for: in the so-called 'strong' gravitational lensing, we see these beautiful arcs, light from background galaxies being deflected and distorted by foreground masses, and the degree of deflection cannot be accounted for merely by invoking the visible part of the foreground mass. That's another piece of evidence. Then we've got this 'fossil' of the cosmic microwave background radiation [CMBR]. Let's go back to the discovery of CMBR by Penzias and Wilson in 1965. Those two guys had a radio telescope set up somewhere in New Jersey, they were not looking for the background radiation, they just happened to find it. For two years they pointed their telescope to the skies, and they found the same noise everywhere, no matter where they pointed it. And they didn't know where this noise came from. They tried to clean the telescope, they tried to get rid of this noise, they couldn't – and eventually they got the Nobel prize for this discovery, because they'd just discovered CMBR, which is nothing else but the fact that the light emitted by the Big Bang, while travelling to us, was stretched by the expansion of the universe, and now it fills the whole universe, with a very low temperature of 3 Kelvin – so that's minus 269° C below zero. It's all around us. So those photons, those particles of light, come straight from the Big Bang. And they found it no matter where they looked, no matter where they pointed their telescope, which was an indication of its cosmological origin – it was not some type of local stuff, coming from a galaxy, it was really everywhere at the same time.

The CMBR leads us to attribute a global geometrical property of flatness to the universe: we have measured this huge triangle – a 'cosmic triangle' – that is spanned by temperature differences in the CMBR thirteen billion light years away from us. So we have this cosmic triangle: we sit at one of the vertexes, with the other two vertexes being separated by the distance between fluctuations in the temperature of the CMBR, 13 billion light years away from us. Now we have measured the angle subtended by the distant side of the triangle, *i.e.* we have measured the angle between tiny temperature differences in the CMBR on the sky. This measurement tells us that we're living in a three-dimensional space that is analogous to a flat piece of paper, rather than a closed sphere. If I were stuck on a piece of paper like this, I would have Euclidean geometry on this piece of paper, the usual axioms of Euclidean geometry, say that parallel lines do not cross, and things like that. And that piece of paper would be a flat universe, flat, a two-dimensional universe. If we take a sphere, for instance, instead, that's a closed universe, we've got the great circles which intersect, we've got the angles of triangles on the sphere that do not add up to 180 degrees, but rather the sum has to be larger than 180 degrees, and so that's a closed geometry. We can measure the angles in this cosmic triangle, and they add up to 180 degrees with an accuracy better than 1 percent.

Now, if the CMBR tells us that the universe's spatial geometry must be flat, this means that we need something else to make up what's missing from the visible part; since the visible part, the dark matter, the dark energy, everything that's in the universe must add up to 1, in some appropriate units, if the universe is flat. And since in these units, the visible part is only 0.05, or 5 percent, we need another 0.95 to get up to 1, so that's another piece of evidence.

C: Again, an explanatory gap: the CMBR as a whole indicates overall flatness; the observations of visible matter give you a picture which can't be reconciled with that, and then the gap between them is the place where you postulate the dark matter.

RT: Yes, but again this is only one piece of evidence, there are at least three or four different lines of evidence coming from different observations that all add up to the same numbers. So it's not just one, there are many of them, all indicating the same thing.

This dark matter is puzzling, it's not visible yet. Even though we talk about 'detection', those are indirect pieces of evidence. Although there are lines of research that are being pursued now, putting big dark matter detectors deep in caves, to shield them from other influences – the strange idea of doing astronomy underground! – under kilometres of rock to shield them from influence. You put big tanks of whatever detectors you have, and just wait for the streaming dark matter particles to give you, every now and then, a signal in your detectors when they occasionally bounce of a proton. So that would be one way to visualise them, or to detect them for real – if you give the attribute 'reality' to the data from such a sophisticated apparatus.

There would be a nice analogy here, I think, with what happened in the 1930s when Wolfgang Pauli introduced the neutrino, a new particle, to solve the puzzle of the beta-decay of atoms. They didn't know how to solve this – there was missing energy, they didn't know where the energy went. So, he wrote this famous letter to his friends at the 'Radioactive Club', saying 'Dear Radioactive Friends, today I have done a terrible thing for a theoretical physicist, that is, to introduce a new particle that nobody will ever be able to see.' But sure enough, in 1954, Cowan and Reines detected it, and later on they got the Nobel prize for it, and now there are experiments which do detect neutrinos routinely. So, dark matter might be just the same.

Such experiments are big gambles on certain predictions of a certain scientific theory: like looking for the Higgs boson, which people reckon will be found, but there is no guarantee there. You've got theoretical predictions, and the important thing is that in these theoretical predictions you have the masses, that is to say, indications of where to look for these particles. These are just numbers that are not predicted by theory, they just have to be determined experimentally, so we don't know what those numbers represent.

C: Before we go on to discuss the other lines of evidence, perhaps we can suggest a counter-example to the analogy you have just mentioned, one which is arguably closer to the case in hand than the example of Pauli's postulation of neutrinos: namely, the infamous case of the planet Vulcan. 'Vulcan' was the name given by Urbain Le Verrier in 1859 to a 'hidden' planet that allegedly perturbed Mercury's orbit, and which thus 'explained' its observed deviations from the path predicted by Newtonian physics. For over half a century astronomers attempted to prove the existence of Vulcan, and there were numerous reports which claimed to have positively 'detected' the hypothetical planet. Now, as we know, despite serious efforts to prove its existence over a period of some five decades, and dozens of putative observations of the planet in transit, eventually Einstein's GR theory came along and explained the observed perturbations of Mercury as a mere by-product of the Sun's gravitational field. So here we have a case in which a 'missing mass' is postulated in order to provide an explanation of certain observed anomalies, and for a long time it is the only explanation in town. However, unlike in the case of Pauli's neutrinos, here it turns out that what was needed was not a more sophisticated means of detecting some hypothetical 'missing matter', but rather a suitable modification of the laws of gravity. Now, you have said that the postulation of 'dark matter' *might turn out to be* analogous to the case of Pauli's postulation of neutrinos. But then, by parity of logic, ought you not to also countenance the possibility that it might turn out instead to be rather more like the case of Le Verrier's 'Vulcan'?

This of course brings us back to the question raised earlier of why one should regard the postulation of dark matter as more scientifically compelling than the option of modifying the laws of gravity on galactic and intergalactic scales. In response to that you suggested that, apart from a general reluctance to attempt to modify a theory as successful as GR, there were also good empirical reasons for favouring the hypothesis of 'dark matter', some of these relating to very recent observations of galactic collisions.

The results of the observations in question were first presented back in August 2006 in a paper by Douglas Clowe *et al.* entitled 'A Direct Empirical Proof of the Existence of Dark Matter', which announced that the observations had enabled the 'direct detection of dark matter, independent of assumptions regarding the nature of the gravitational force law.'[3] A NASA press release promptly followed proclaiming that these observations constituted 'direct proof' and 'direct evidence' of the existence of dark matter[4] and the popular media was soon awash with headlines such as 'Dark Matter Observed', 'Dark Matter Witnessed After Galactic Collision', 'Galaxy Cluster Collision Proves Existence of Dark Matter', 'Scientists Offer Proof of Dark Matter' and so on. One could surely be forgiven for assuming that what had taken place here was a veritable *experimentum crucis*, indubitably proving the existence of dark matter once and for all and definitively ruling out all rival hypotheses. It was as if dark matter had suddenly been promoted in ontological status from its previously ethereal quasi-existence as hypothetical postulate to the rank of full-fledged 'substantial' reality. And yet, without wanting in any way to diminish the significance of these observations, it seems that, from what you have just said, things are not quite so assured as we might have been led to believe, that the postulation of dark matter remains something of a high-risk gamble. Is it not at least a little premature to say that dark matter is the 'only possible explanation' of the observations, as some cosmologists have been reported in the media as having

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[3] http://arxiv.org/abs/astro-ph/0608407

[4] http://www.nasa.gov/home/hqnews/2006/aug/HQ_06297_CHANDRA_Dark_Matter.html

claimed? Apart from the consideration that the postulation of a missing 95 percent of the universe represents perhaps the most audacious flouting of Ockham's razor in the history of modern science – especially when one considers that a mere tweaking of the laws of gravity might ultimately prove up to the job, even if none of the models so far constructed have done – is there not a case for saying that the kind of explanation proffered by the postulation of dark matter amounts to an example of 'explaining the obscure by the even more obscure'? To what extent is it the case that, even now, the very terms 'dark matter' and 'dark energy' serve less as names for a satisfactory explanation and more as a placeholders for possible explanations not yet envisaged?

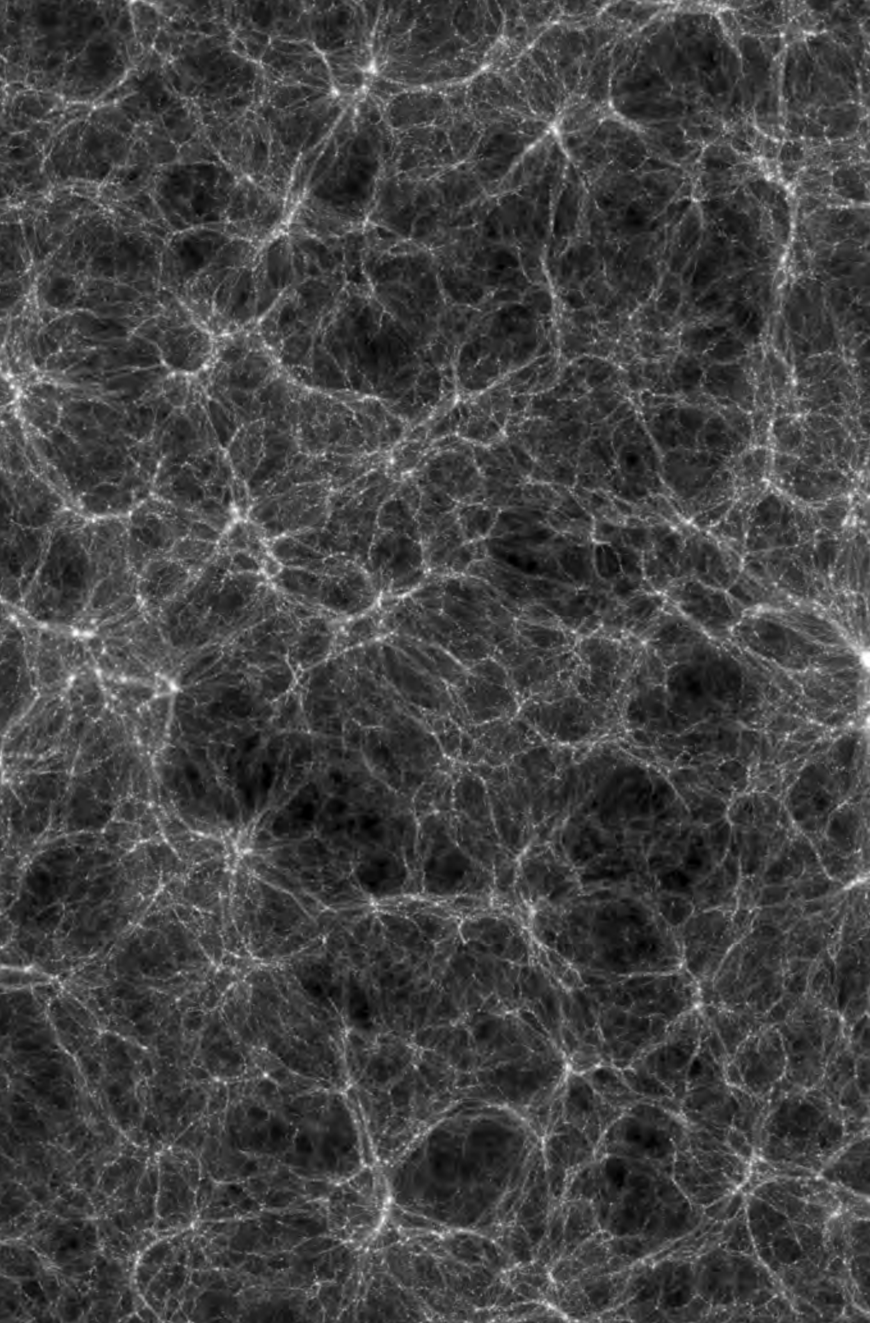
RT: As far as dark energy is concerned, yes, I would subscribe to the description you give of a placeholder for a more satisfactory explanation. In fact, one of the most pressing questions is to determine observationally whether dark energy lives on the right hand side or on the left hand side of Einstein equations. If it belongs to the left hand side – that's the side of the geometry of spacetime, where the structure of our gravity theory lives – then it's a manifestation of modified gravity of some sort, even if only in its mildest but actually quite disturbing incarnation, that's to say, Einstein's cosmological constant. If on the other hand it turns out that it belongs to the right hand side – that's where the matter-energy contents of the universe are written down – then it's really a new substance, and we have to think it over again in terms of a fundamental explanation of its physical origin.

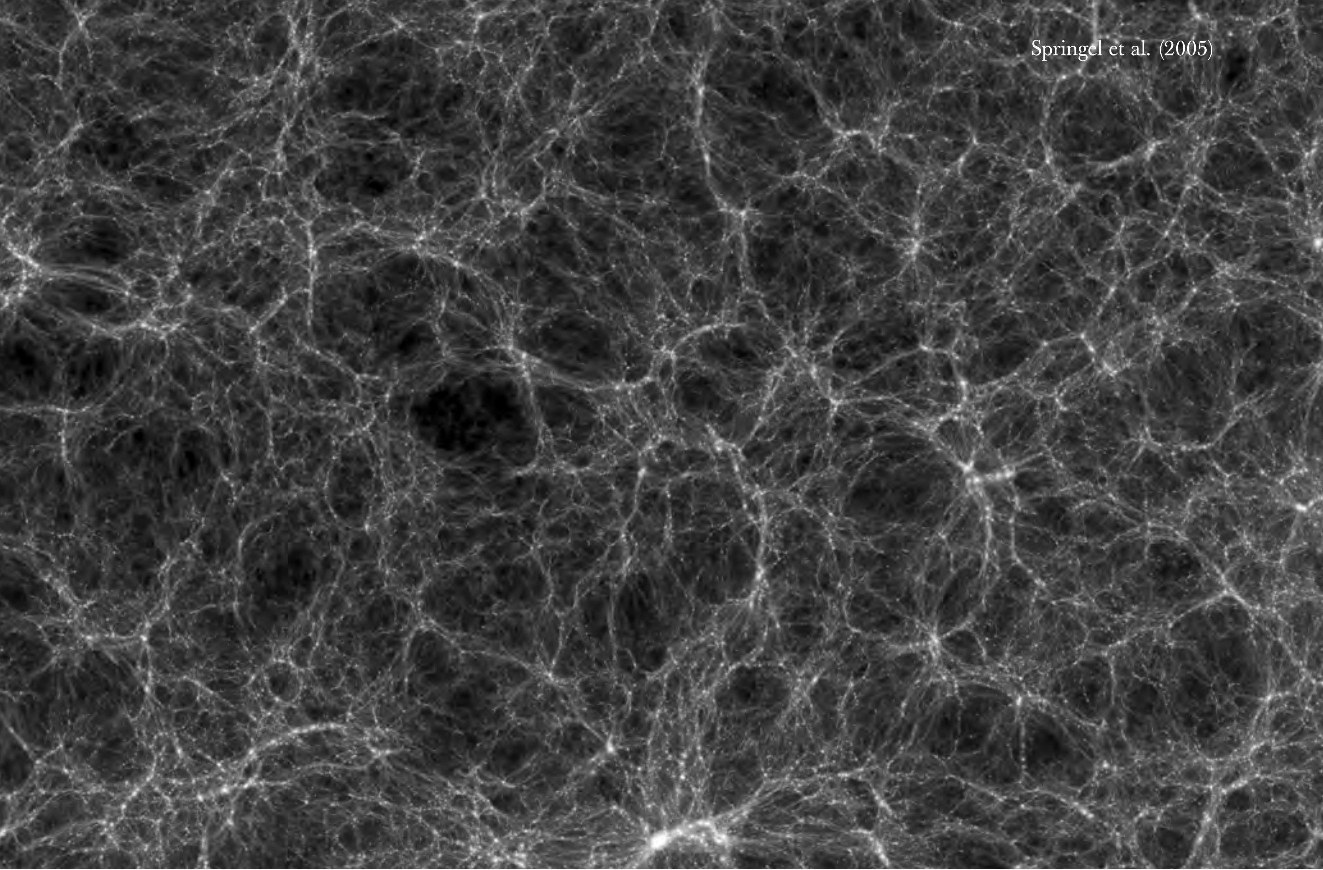
But if we are talking about dark matter, then its status is very different. I mentioned the multiple, orthogonal lines of evidence we have for it. I also briefly mentioned that we have many well-motivated candidates, usually in the form of some sort of particles beyond the Standard Model of particle physics. Now we know from other sources – for example, from the fact that neutrinos have mass – that the Standard Model cannot be complete. And we also have theories waiting in the wings to replace the Standard Model, theories that make many predictions about the existence of a plethora of new, yet-unobserved particles. For instance, in supersymmetry every known Standard Model particle acquires a so-called 'superpartner' – that's a new particle with the same properties as its Standard Model partner but with a much heavier mass. This immediately doubles the number of fundamental entities in the theory, but it seems there is really no other way around it if one wants to solve certain technical problems that we do not need to discuss now. So from the point of view of simplicity and economy, such a theory hardly ticks those boxes. But it also allows one to gain a much more complete picture of the particles and their interactions. In order to test such a theory, it remains to build a huge accelerator, smash together particles with very high energy and observe the products of the collision. Because energy is mass, if the energy achieved is large enough such collisions will transform energy into massive particles, and hopefully produce some of the heavy supersymmetric particles everybody hopes to detect. Unfortunately, the masses of the particles are just free numbers in the theory; they are not predicted, so nobody knows whether we are going to find them when the LHC is turned on later this year at CERN. People make educated guesses, but there is no guarantee. The point is that the lightest of these supersymmetric particles fits the bill for a dark matter candidate. Its properties are exactly the ones you need if you had engineered it to be the dark matter of the universe – and the thing is, you have not! The neutralino (that's the name of the particle) comes straight out of supersymmetry, and all of a sudden you realise that this could be what the cosmological dark matter is made of. So here you go, you have solved two problems at once, if only you could prove that supersymmetry exists and that the neutralino is the dark matter particle. And this is exactly what people are trying to do, both at CERN and by trying to detect dark matter particles directly.

But there is one more thing to consider, namely the fact that cosmology is fundamentally different from particle physics, or from any other brand of physics, in at least two respects. The first aspect is that cosmology is an observational science, not an experimental one. We simply cannot reproduce the universe many times, tweaking the parameters of the experiment to see whether our theory is correct. The second point is that the fundamental framework within which all observations are interpreted posits that the objects we observe are subjected to the very same laws of physics we have derived in our labs on Earth. This is an extremely strong assumption, if one keeps in mind that cosmological phenomena stretch over billions of light years in space, over the entire life of the universe in time, and over tens or hundreds of orders of magnitudes in energy. One might describe this as the ultimate scientific hubris. So in view of all this, it is important to recall that the status of the ‘substantial reality’ of cosmological objects must be understood within the limits imposed by the above considerations.

C: We’d like to come back to this question of the uniqueness of cosmology as an observational but non-experimental science a little later, but sticking for the moment with the question of the nature of the evidence for the ‘substantial reality’ of dark matter, one of the most intuitively accessible fruits of this research are the images which show the predicted distribution of dark matter in the universe [see pages 100-1]. Here we see something that to the naïve eye looks very ‘organic’, almost like a network of capillaries. Since dark matter is not visible, how are such images obtained?

RT: These images depict what we call the ‘cosmic web’ – fittingly, I think. And this is a computer simulation: this is what we think you should be able to see if you could see the dark matter distribution in the universe – those filamentary structures represent the dark matter distribution within the universe. But it’s computer-simulated: what you do is to take the initial universe, which was homogeneous, but not perfectly homogeneous – you had small initial fluctuations in density within it which were the seeds, that we still see today in the CMBR, and from which eventually those structures formed – you take this universe, put it into a supercomputer. Then you switch on gravity and you let gravity do its work. So regions that are





Springel et al. (2005)

dense will accrete matter from around them. Regions that are overdense would in time become critical overdense regions and this filamentary pattern appears during time.

So that's just a simulation. From the data we observe from gravitational lensing we are also able to extract some statistical properties of these filaments: we can quantify the filamentary structure itself, whether it's very filamentary or more sparse, more dense, and we can compare the numbers that we get out of the simulations with the observations. And this is the great game, to produce very many simulated universes with different values of parameters, to fit them to our observations, and to try to figure out which are the ones we actually observe in our universe.

C: Earlier you linked the 'puzzling' nature of dark matter with the fact that it is 'not yet visible', and indeed one of the ways in which the abstract mathematical sense given to 'matter' in contemporary physics is reconciled with our intuitive sense of materiality is through these kinds of images. There can be no doubt that images purporting to represent dark matter boast an all-important sense of immediacy which speaks to an interested general public. But is this engagement of the imagination also of significance for scientists themselves, providing a sort of milestone and an opportunity to 'zoom out' of the technical details of the research process?

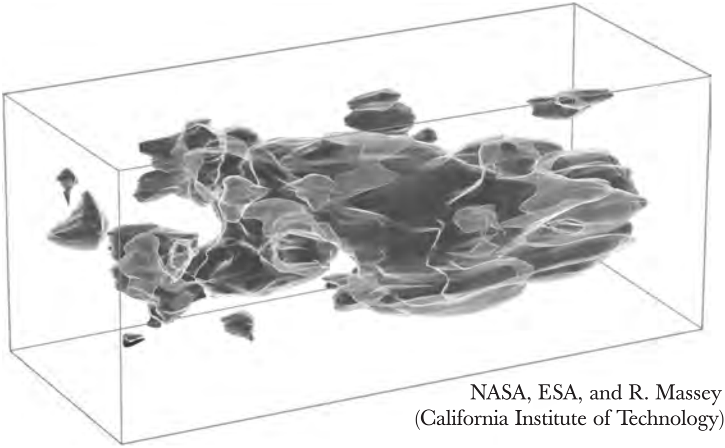
RT: Yes, I think that's a good point, in the sense that until a few years ago scientists – especially cosmologists – we didn't have those images to look at, we hardly had any of the data we have now. So in that respect having these images is a way of anchoring ourselves to the reality of those objects. Although images that you can really look at and just understand by looking at them are very rare. Most of them have to be interpreted through statistical analysis, distilling the statistical content of the image into spectra or probability distributions or whatever. Having the 'real object' – with whatever qualifications you want to give to the term 'real' here – having the real object in front of your eyes is a way of anchoring yourself to the object so as to understand it. Although, as I say, the images, as fantastic as they are for reaching out to the public, have little informative content for scientists. They must be heavily processed, they must be analysed, they must be cross-correlated, and most of those procedures do not happen in an image space; they happen in a mathematical space, a statistical space, spaces that are highly idealized and so, in a sense, also highly immaterial. So the images are just the starting point for a much more complex process that goes on behind the scenes. It's rarely just the image that gives you the answer you're looking for; it's the content of the image that's distilled through a heavily mathematical process, and that's what's interesting for the scientist. But the images are great as the first point of contact to try to convey what we get out of the image to the general public, in a more understandable way, a way which is less arid.

C: Is there a danger that they may serve to conceal – or so to speak, shortcut – uncertainties within the theoretical model? For instance, if you have an image purporting to show 'the distribution of dark matter', you're in a sense already guilty of reifying dark matter.

RT: Yes, but professional scientists, when they look at these images, are supposed to remember this. Sometimes the shortcut is taken consciously in order to make the image more 'saleable' to the public, in order to promote the field more effectively. But it's a thin line you have to tread. For example, what's described as the imaging of dark matter is actually the imaging of gravitational potentials, which has been recovered through a set of statistical techniques, transformed through false-colour images purporting to show dark matter. So yes, it is a shortcut that's consciously taken sometimes in order to make the content more directly accessible. But we should never forget that, in taking these shortcuts, we bypass our interpretation of the data we have gathered, which is done through the optic of a particular theory, and a particular narrative as to how these data have been gathered and what they mean. The point is that the very interpretation of the physical reality of the objects we observe is dependent on an underlying theory which explains them in the first place; so they're not objects we can relate to in an immediate way.

C: The essential theory-dependence or 'theory-ladenness' of observation is of course something very well-established in the philosophy of science, and it's something which has given rise to no end of philosophical debate – regarding, for example, instrumentalist versus realist interpretations of scientific statements. The very idea that knowledge is a matter of obtaining a faithful 'copy' of a reality-in-itself, as something knowable without theoretical mediation, is one which has lost favour in the philosophical tradition since Kant. We'd like to touch on some of these questions later, but for the moment, sticking to the point of view of a 'naïve realism', one might feel almost 'cheated' to learn that so much necessary theoretical and instrumental mediation is involved in gaining access to these objects. From the layperson's point of view the 'substantial reality' of a thing is precisely something that *ought to be* accessed in an 'immediate' way, without the kinds of theoretical contrivance you have described. Is there a sense in which all this necessary mediation amounts to a diminution of the reality itself, or is it rather the case that science has first to 'constitute' that reality in some sense – to 'bring it into being' almost – in order to determine it?

RT: I wouldn't call it a diminution, I would call it an *enhancement* of reality. Perhaps an artificial enhancement to a certain extent – mediated by the theories and instrumental apparati we use – but a necessary one, for the simple reason that we simply do not have immediate access to the reality of those objects. I would even be tempted to say that the true, the most informative reality of those objects, often is *only* revealed *after* these very complex processes, and often only in a statistical sense, which is very impalpable, giving us only access to certain relations, probability distributions and so on, whose very interpretation, once again, rests on what our understanding of probability fundamentally is, rests on many assumptions on the way the world is *supposed* to behave even on a statistical level – even for



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(California Institute of Technology)

objects for which we don't have a statistical realisation, such as the universe itself. So in conclusion I would say that this is an enhancement of reality that necessarily takes place in order to bring into the open underlying patterns and regularities that are not visible to the 'naked eye'.

C: Coming back, then, to the images which purport to in some sense 'represent' dark matter, apart from the computer simulations – the 'cosmic web' images we've just been talking about – Hubble have very recently released 3-D images [see above] which were headlined in the media as 'The First 3-D Images of Dark Matter'. How do these differ from the 'cosmic web' in terms of how they are produced?

RT: Well, they are supposed to be real observations showing exactly the same patterns which, as we've just said, are computer simulations. But as I said before, they are not direct observations of dark matter, since dark matter is, obviously, invisible. They are obtained by using the gravitational properties of dark matter, the gravitational distortion that dark matter is supposed to bring about, by using background galaxies as sources of light. Let me describe this in a little more detail. The light coming from background galaxies goes through a field of clumpy dark matter and gets distorted, the shapes of galaxies get distorted – this is what we call 'gravitational lensing' – in a special way depending on where the clumps of dark matter lie, just as a real lens distorts the image which sits behind it; a bending of light – but not really a bending since light travels always in a straight line in spacetime, but since spacetime itself is bent by the mass concentration, we experience this as a distortion. You see now already that in order even to formulate the observation we have to have this general-relativistic theory of spacetime, so you see how the significance of even our raw data is heavily dependent on our underlying world model.

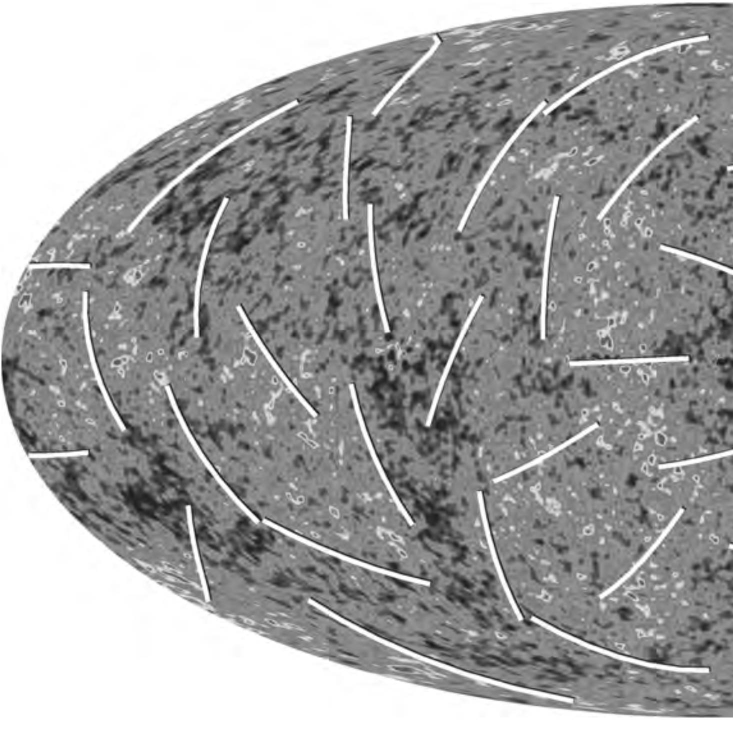
This relates back to what we were saying about the 'enhancing' aspects. There are pictures of visually impressive distortions of background galaxies that you can pick out 'by eye'; you can really see background galaxies being distorted in what we call 'Einstein rings' around the clumpy object – this is called 'strong gravitational lensing'. But that's not how the technique used to reconstruct the Hubble 3D images works. This technique is called 'weak gravitational lensing' and it works by observing tiny distortions of background galaxies, distortions in the shape of the galaxies. So if you had galaxies that were perfectly round as sources in the background and you observed them and saw their shape being distorted by 1 percent, or perhaps just a fraction of a percent, then you would be able to map exactly – by telling how the distortion behaves across the sky – the intervening dark matter distribution. Now, the thing is, we don't even have regular galaxies in the background. Instead we have galaxies that come in all different shapes and sizes, and so we are measuring distortions of shapes that we don't even know in the first place, because we don't have access to the undistorted shapes. That's where the enhancing techniques come in, because in order to get access to coherent distortions of galaxy shapes, you've got to make a statistical average. So, making the assumption that all galaxies are randomly oriented, with random shapes, if there were no coherent distortion, if you make an average, you ought to obtain zero. But since there is intervening dark matter – and that's where the enhancing techniques come in – you do these correlations, these statistical observations, and you find coherent patterns of distortions that do not average away because they are not intrinsic to the galaxies but are imprinted on them through the dark matter lens distortion. And, again, that's not something you could pick up by eye.

C: Another line of evidence is indicated by your work on acoustic oscillations of the early universe which are 'frozen' into the fabric of matter – a sort of primordial 'sound-fossil'.

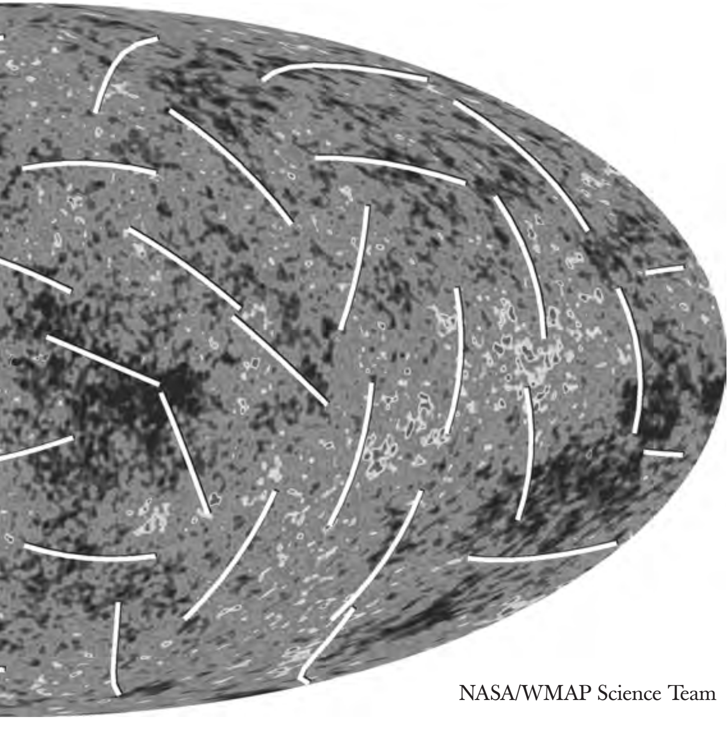
RT: Yes, these acoustic oscillations are, in a way, a natural fossil. The relevance of the sound waves of the early universe in general for cosmological parameters is that it's all relatively simple to calculate, because the universe was fairly young, and these density fluctuations which eventually grew to galaxies were still very small – actually one part in a hundred thousand. So they were so small that we can calculate them with very high accuracy, and we can follow their evolution up to the point where the CMBR was released, very accurately. And so from this we can confidently infer several properties of the universe at the time, for instance how much dark matter there was, how much visible matter there was, what were the characteristics of the seeds, how the seeds were sprinkled with scale, whether there were more seeds on small scales, on large scales, or whether they were uniformly sprinkled on all scales and so on. These sorts of things can be inferred from sound waves in the CMBR, because we know the physics very well. And so it's a nice spot between the very high-energy physics of the very beginning, which we don't fully understand, and the messy, non-linear physics of gravitational collapse and evolutionary structure that we do understand, but which gets difficult to follow because it gets very complicated, as you can see from the filamentary structures you obtain through the computer simulations we discussed.

C: How do you go about reading these 'recordings' of the Big Bang?

RT: We saw that the CMBR is very homogeneous because of its cosmological origin. But now we have very sensitive detectors, telescopes and satellites that measure this background radiation to a very high degree of accuracy. And if you look carefully enough, you will see that this CMBR is not perfectly homogeneous; it has temperature differences in it. So if you look with your telescope in this direction, we see a slightly colder spot, if we look in that direction we see a slightly hotter spot. We can build a map



[see below] of the sky, showing the temperature distribution of the background radiation. In order to measure the differences between the hot and cold spots with your telescope you need a sensitivity that's equivalent to the sensitivity you'd need with an optical telescope to see a mouse walking on the moon from the earth. So it's very tough. The guys who first did it in 1992 got the Nobel prize in 2006. These fluctuations you see in this map are the sound waves from the early universe, that's exactly



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what they are. When you throw a pebble in a pond you've got waves that go out in all directions; if you throw many pebbles in a pond you get a nice superposition of waves. In our case the pebbles were quantum fluctuations in the early universe, and they got frozen in at the moment this image was produced, and this is what we see – we really image them with our telescopes.

C: Calling them 'sound waves' is not just a figurative way of speaking, then?

RT: No, it's a technical definition: they're compression waves. The universe at this point was a plasma, that's a hot gas of electrons and protons, separated by the temperature, because the temperature was so high. So those were really acoustic waves, just like the waves in the air now as I speak, only they were travelling in the primordial plasma. And we can see them, as we can see in this map: it's real, it's been predicted, and we find this fantastic agreement with our models.

We usually talk about the CMBR being the uniform radiation coming to us from the Big Bang. When we talk about the temperature differences or anisotropies, we're talking about the very same radiation, but now looked at through a much more powerful telescope, so that you can highlight the temperature differences. It's one and the same thing, but you need a more powerful telescope to see the sound waves in it. I'm working more on the theoretical side of it, but people here also build such instruments. I'm interested in finding out how we can use those instruments to learn more about the conditions of the universe back then, or the conditions of the universe in the far future.

C: Let's return to the cosmological narrative, and to the 'seeds' you already mentioned briefly. For the first 300,000 years after the Big Bang, the universe is thought to have been remarkably homogeneous, surprisingly 'smooth'. The gravitational clustering which, it is supposed, ultimately structured this featureless continuum, was driven somehow by the properties of dark matter, via tiny fluctuations imprinted upon matter during the initial expansion.

Here dark matter seems to be invoked to answer a most traditional philosophical question: Why is the universe 'uneven' at all? Why does it consist of great voids and small concentrations of matter? Why is there something rather than nothing – or pure homogeneity, or chaos? The probing of anisotropy practiced by cosmologists rather recalls the original philosophical materialist, Lucretius, who, refusing divine intervention, posited an originary *clinamen* or 'swerve' which disturbed the atoms in freefall and led to the creation of nature. And unless some principle such as the *clinamen* intervenes, this heterogeneity, or what we could call the high information content of the universe, seems quite at odds with the received image of physical laws as linear and predictable. Are we to understand that some fundamentally nondeterministic processes must intervene at those crucial early stages to introduce these 'blueprints for differentiation'?

RT: Some fundamentally nondeterministic process, that's quite right, in fact. We just discussed the fact that these seeds are the ones that give rise to clusters, to galaxies, and eventually to all inhomogeneities in the universe. It's also the same seeds that we can observe in the CMBR from when the universe was very very young, 300,000 years after the Big Bang. And the ultimate origin of those seeds, we believe, lies in the very first fractions of a millisecond – actually 10^{-32} seconds after the Big Bang – during the period of very fast expansion which is called 'cosmological inflation', which takes the universe from a very small size up to cosmological scales. And at this point, since you are going so far back in time, the universe was compressed almost into a point, as it were. The overall size of the universe was so small that the microphysics governed by quantum mechanics [QM] was important. So you would have quantum fluctuations at the level of the whole universe, that then were stretched out to cosmological scales, and that's what the seeds were. Now, remember that all the evolution afterwards, the gravitational evolution of these seeds, is completely deterministic – we have the equations for gravity, we can follow them on the computer. But the 'seeding' of these fluctuations belongs to QM with its element of unpredictability, probability. The fundamental nature of it is quantum-mechanical, and so any understanding of this fluctuation is probably to be found in our understanding of what quantum-mechanical probability is.

C: This is where the intersection between fundamental physics and astrophysics comes in.

RT: Yes, it's where you close the circle: from the infinitely large scales of cosmology, you meet the infinitely small scales of particle physics, and quantum theory.

C: And presumably it's precisely here that the question of how to bring together GR with QM becomes a crucial and urgent one. To what extent does an adequate understanding of what happened in these first fractions of a millisecond after the Big Bang await the unification of these two foundational theories of modern physics in a successful quantum theory of gravity, whether that ultimately comes about in the form of some version of string theory, M-theory, loop quantum gravity, or something else altogether?

RT: Yes, that's absolutely fundamental, because all those big questions come together in the very first fraction of a millisecond, where all the interesting physics we don't yet know about happens. When, at the origin of the universe, we reach the highest possible energy scale, which is the Planck energy scale, at that point our theories essentially break down. That's the point where GR breaks down and we need to quantize spacetime itself. Remember, spacetime in our current vision of GR, is a sort of classical 'rubber–band' as it were, an arena in which quantum-mechanics take place. But when you get to this sort of energy scale, these types of miniscule length scales, it might be possible that fundamentally the quantization of spacetime itself begins to play a role. In other words spacetime stops being just an arena in which all the interactions of QM take place, but becomes a player in the quantum mechanical game, and nobody yet knows the rules of this quantum game.

C: GR and QM both break down – now, do they each break down independently in the sense that they no longer work at these extreme energy scales, so it's just a fuzzy area; or, do they break down because that's where they come together and you don't yet have a proper theory of how they can be combined?

RT: GR breaks down by itself because when you take the universe to size zero then – if you go analytically to zero in the equations describing the metric of spacetime – the zeros 'blow up' the equations, you end up with divisions by zero and our equations stop working. And the other problem is that no-one knows how QM and gravity work together because no-one is able to quantize gravity, for many different technical reasons. So yes, each breaks down on its own, and they break down together.

C: So that's a fuzzy area that's awaiting a successful theory of quantum gravity. Does it work that way, that you need a successful theory of quantum gravity in order to understand these very earliest fractions of a millisecond, these ten-millionths of a second after the Big Bang, or can cosmology itself help to solve the problem of the relation between QM and GR?

RT: Well, let me say that the fact that we don't have a successful quantum theory of gravity doesn't stop people from playing with some bold ideas. For instance, there is a scenario, called 'ekpyrotic universe', where the universe is supposed to be cyclic, that's to say it undergoes an infinite succession of expansions and contractions. So if you go back in time close to the moment of the Big Bang, when the universe is compressed at this incredibly high energy in this extremely small size, there might be some fuzzy physics, perhaps coming from extra dimensions, that makes it 'bounce back', rather than collapse to a point. Time does not start with the Big Bang, but rather you can describe the previous universes, as it were, before the Big Bang, by invoking some previously unknown phenomenon that actually prevents the Big Bang singularity, as we call it, from happening and gives you a bounce instead. So people do work on this kind of model at the level of their phenomenology, that's to say their effective description, but those are models that fundamentally are not strongly motivated at the moment. But people have these models in mind. So yes, it awaits resolution, but people are not *waiting* for it to happen.

C: The parameter z also plays a major role in constructing the cosmological 'narrative' of the universe. You are able to tell a story about what was happening at different stages of the history of the cosmos – *e.g.* 'the universe at $z = 20$'.

RT: This cosmological parameter z refers to redshift, and it has a very simple physical interpretation: it tells you that, for instance, if you're looking at the patch of the universe at $z = 20$, this is the state of the universe as it was when the size of the universe was twenty times smaller than it is today. This redshift is therefore not some abstract quantity, it's something we actually measure, by looking at the spectrum of whatever object we're observing. So if you look at a galaxy, the galaxy will contain certain elements, for instance hydrogen, iron, whatever. And these elements will emit light at particular wavelengths, particular colours: the 'signature' of the element. Hydrogen will have a particular line at a certain wavelength, iron will have a more complex signature consisting of a more elaborate pattern of lines. So we can determine, first of all, which elements are present in distant galaxies, because every element has got this set of colours which is particular to it, which comes from the quantum-mechanical structure of the atom. And by observing those lines, we can tell that on the Sun there is hydrogen, because we observe the hydrogen lines, and in the Andromeda galaxy there is hydrogen because we observe the very same lines. But the important thing is that the light of these spectroscopic signatures gets stretched while *en route* from distant galaxies to us, because of the expansion of the universe. So if the light gets stretched, that means that the wavelength of the light gets longer, and the light gets redder. In other words, we observe the same set of lines from a distant galaxy that we would observe from a local galaxy, but that set of lines is shifted towards the red end of the spectrum – what we call a 'redshift'. So by measuring the amount of redshift, we can measure how much of a stretch there has been between us and that galaxy. We can measure the redshift and we know whether this object is far away or nearby. It's uniformly shifted toward the red end of the spectrum.

Of course, as I mentioned before, there is an assumption which underlies everything here, and which is very strong, actually, especially from an ontological perspective. We assume all along – and we couldn't do without it – that the laws of physics are the same here, on Andromeda, and at the very beginning of time, which is a very major assumption. But there is little we can do if we don't make this very strong assumption.

C: Historically speaking, one might even say that it was just this very strong assumption of the uniformity of nature on the largest scales, of the universal applicability of the laws of physics, that inaugurated modern science itself. Copernicus' overcoming of the Aristotelian tradition of 'saving the appearances' by asserting the truth (rather than the mere empirical adequacy) of his cosmological system ultimately paved the way for Newton's synthesis of celestial and terrestrial mechanics via his law of universal gravitation. Of course we now know that, while the Newtonian laws of motion and gravity hold to an extremely good degree of approximation for almost all phenomena ordinarily encountered (*i.e.* for the everyday macroscopic world in which gravitational fields are relatively weak and objects move relatively slowly compared to the speed of light), they represent at best an approximate special case of the still more general laws of Einstein's GR, in which the notion of gravitational force acting instantaneously at a distance is replaced by that of the curvature of spacetime itself. But here, unlike the world described by Newtonian mechanics, which is more or less entirely consonant with the 'manifest image' of the world we derive from ordinary experience, the universe as described by relativity theory is, like that of quantum physics, deeply counter-intuitive. This is perhaps above all the case with regard to our commonsensical notions of space and time, to which the Minkowskian-Einsteinian notion of a four-dimensional spacetime continuum appears to bear little if any resemblance. The very idea that the beginning of the universe with the Big Bang was not an event which took place *in* space and time, but was rather the very coming into being of spacetime itself, is one which most people have a great deal of trouble coming to terms with. More difficult still is the related notion that there is no such thing as the 'objective present' – that there can no more be an objective division of the world into past, present and future than there can be an objective division of a region of space into east and west, or here and there. And at the submicroscopic levels where we enter into the utterly baffling world of quantum probabilities, things become a good deal stranger still. Here not just some but *all* of our habitual notions of space and time appear to break down completely, to become entirely meaningless.

All this gives rise to a number of questions relating to the very meaning of cosmological statements regarding time. For example, regarding the redshift observations which you have just been telling us about – by measuring the relative distances of observable galaxies in this way, you are also peering back into time, and determining things about the universe billions of years ago, when it was considerably smaller than it is today. These measurements, as you have indicated, are also crucial in estimating the age of the observable universe, which cosmologists have now dated rather precisely to 13.7 billion years. Such statements seem to be readily comprehensible and their meaning unproblematic. To what extent is this an illusion fostered by the isomorphism of such statements with everyday statements involving time? Must we not in some sense suspend our intuitive, commonsensical (and implicitly anthropomorphic) notions of time in order to properly comprehend statements about time in cosmology and in physics more generally?

RT: Well, as I was describing, the physically observable quantity is the redshift of the objects. It then turns out that the correspondence between redshift and cosmological time – when you do this mathematically through the equations of GR – depends on what the matter-energy content of the universe is. In other words, it depends on the relative amount of dark matter, dark energy, visible matter, radiation and so on. And so time becomes a function of the very properties we are trying to reconstruct.

C: Time evolves along with the universe.

RT: Yes, perhaps you could say that the link between the observable properties of the universe and its history as parameterized by cosmological time, goes through the very same properties of the universe, that is to say, its mass-energy density and its cosmic energy budget, which is interesting, because time becomes a function of them. At its heart this goes down to the fact that GR is a theory that links geometry on one hand, and the matter-energy content on the other. So we have matter which tells spacetime how to bend, and the bending of spacetime tells matter how to move. So we've got this inextricable mix of spacetime and matter-energy.

C: But if that is the case and if, according to GR, space and time are not to be regarded as anything like an absolute and universal stage against the background of which cosmic events play themselves out, but rather as flexible and dynamic actors – an integral part of the cast, as it were – in the cosmic drama itself, how is it that cosmologists are nevertheless able to define a concept of time that is applicable to the universe as a whole? Doesn't the passage of time depend on the speed of motion of the observer, and on the gravitational field in which the observer happens to be immersed?

RT: Well, in general, time *does* depend on the observer and the status of motion of the observer – different observers will observe different times – that's a generally acknowledged result of the theory of relativity, of course. But when you describe this evolving spacetime arena for the universe as a whole, then you introduce a sort of global co-ordinate system which you parameterise in terms of coordinates of time and space, *x*, *y* and *z*, and so the time you attach to this – which is the time that gets quoted as the age of the universe, and that I called above 'cosmological time' – would be the time that is measured by what we call a 'co-moving observer'. That is to say, a hypothetical observer that is swept along with the expansion of the universe, which we all are to a certain extent – our galaxy is swept along by the expansion of the universe. So that is what this time refers to: not just *any* observer, but an ideal observer that is postulated to be a co-moving observer, being swept along by the expansion of the universe.

C: But would the construction of this global spacetime co-ordinate system – this universal clock, so to speak – still be possible if the 'cosmic fossils' we have been discussing, such as redshift and the CMBR, revealed a non-uniform, non-homogeneous universe on the largest scales, rather than the surprisingly uniform, isotropic one which they appear to indicate? In a passage of his book *The Fabric of the Cosmos* which it seems appropriate to cite here, Brian Greene suggests that this background radiation not only 'gives astronomers what tyrannosaurus bones give paleontologists: a window into earlier epochs that is crucial to reconstructing what happened in the distant past', but that it is the *uniformity* of that radiation which is crucial in enabling cosmologists to define a concept of time applicable to the universe as a whole. The uniformity of the radiation is 'a fossilized testament to the uniformity of both the laws of physics and the details of the environment across the cosmos', and it is this homogeneity which, suggests Greene, makes it possible to meaningfully speak of a 'universal synchrony': 'if the universe did not have symmetry in space – if, for example, the background radiation were thoroughly haphazard, having wildly different temperatures in different regions – time in a cosmological sense would have little meaning.'[5]

RT: Yes, in fact the CMBR itself could be used by our co-moving observer to define a cosmic clock, obtained by measuring the uniform temperature of the microwave radiation and monitoring it as it cools down with the cosmic expansion. But even in the extreme case where you had a cosmological expansion that proceeded differentially in different directions, a so-called 'anisotropic universe', instead of describing the expansion with just one number – redshift – then you would have one number for each direction. You could then possibly conceive of having different dimensions evolving differently with time. What is absolutely crucial, however, about the homogeneity of the CMBR that we observe, is that this informs us about the extreme uniformity of the conditions of the universe at the epoch when the CMBR was formed. The overall temperature of the CMBR is the same everywhere across the sky, even when we compare remote locations, points so far away from each other that light would not have had the time to travel between them by the time the CMBR was formed. So how is it that such distant points all have the same temperature today, if no causal mechanism could possibly have connected them? The answer is, again, 'inflation', the extremely short period of faster-than-light expansion of the universe that we encountered earlier when we discussed the mechanism that spread the quantum-mechanical seeds on cosmological scales. During

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[5] Brian Greene, *The Fabric of the Cosmos* (London: Penguin Books, 2004), 227-8.

inflation, the size of the universe grew exponentially, and patches originally close-by were stretched out to cosmological distances. This would explain why we observe them to have the same temperature today: they were once in causal contact and were then separated by the inflationary expansion. So the expansion of the universe during inflation can happen faster than the speed of light without violating the basic tenet of GR, since in this case it is spacetime itself that is stretching faster than light, not a particle or other object within it that is moving faster than light. I should also add that the fundamental mechanism that drives and powers inflation has not yet been established, even though there is no shortage of speculative ideas, some of them linked to dark energy, for example.

C: Another issue regarding time we might just mention briefly is the problem of the so-called 'arrow of time'. Do cosmologists take it for granted that time has a definite *direction*?

RT: Yes, because causality is ingrained in the very structure of GR. It's unavoidable because GR comes out from two assumptions, two axioms: one of which is the constancy of the speed of light, the other being the causal structure of space-time. So yes, it's built in.

C: But is *asymmetrical* causality is built into GR? Are the equations themselves not time-reversal symmetric?

RT: Yes, they are on a microscopic level, but the global structure of spacetime is such that you distinguish between timelike and spacelike intervals, and timelike intervals are intervals between spacetime points between which there can be a causal flow of information, whereas spacelike intervals are intervals where there cannot be such a causal connection. And because of the finitude of the speed of light – which again, is built-in to GR – the two domains are disconnected: you can't make a timelike interval into a spacelike interval. So in other words, there are spacetime points that cannot be causally connected, the ones separated by spacelike intervals, because for instance, two events that are simultaneous for a given observer will not be for another observer. So by going from one observer to another you would be able to change the order of events, which would clearly result in paradoxes if the two events were causally connected. For example, you would be able to find an observer that would see the effect precede the cause. So this causality is built into GR in a hardwired way.

But let me just come back to what you said about our intuitive ideas of space and time breaking down and becoming meaningless. And my reaction is – why shouldn't they? After all, our intuitive perception of reality is an *immediate* perception of reality that has developed from our brains and our experience of the world shaped by evolution, and clearly evolution knows nothing of quantum reality, nor does it know anything about the vast expanse of time and space of cosmology. And so, it's not astonishing that those notions become counter-intuitive since we are actually extending our capability of making statements about realities way beyond the scales which our brains were designed to interact with. And so it's not an astonishing thing.

Let me give an example, the example of mathematical symmetries, which I think is very fitting in this context. We all know what a spatial symmetry is – a sphere is spherically symmetric because however we turn it in 3-D space it looks the same, so that's a spherical symmetry. So we know what a spherical symmetry is like in space, and can associate a mathematical description with this symmetry. For instance the mathematical group that describes this symmetry in space is called SO(3). But now it turns out that we can equally well define more abstract symmetries that apply to subatomic particles, symmetries that pertain to the postulated internal state of those particles – isospin, for instance. So those are just transformation groups that do not transform, do not move things around in real space; they move things around in an abstract mathematical space that we have defined to have certain properties. But then those symmetries – which have nothing to do with real symmetries, but which take their origin from our observations of real three-dimensional symmetries in the world that we *can* perceive – those symmetries turn out to play a fundamental role in describing the state of those particles, the possible energy levels that those particles can take, for example. So these principles of symmetry play an absolutely fundamental role in all of physics. I think this is a case where we start from the immediate experience of the world, where we have a symmetric configuration of things, and then we take the very same tool, put it in a completely abstract mathematical space that *a priori* has nothing to do with any domain of reality, physical or otherwise. We apply it in this other context and end up with predictions about phenomena that were not observed before and, again, can *only* be observed through these 'enhancing' powers that we discussed before, and actually turn out to be true. This is an incredible application of extending, reaching out, from the time and length scales, and also conceptual scales, of our immediate experience, into domains that are definitely beyond the realm of our immediate perception.

C: The comment about the deeply puzzling, counter-intuitive notions of space and time in fundamental physics was of course not to say – 'How astonishing, how can it be?!' – much less to make some objection to them on the grounds that they don't conform to our ordinary or commonsensical notions. But, when it gets translated into ordinary language, when we're talking about space and time on universal scales, we can't help but assimilate what we're being told to what we know intuitively, and the question is whether our intuitive concepts are adequate to even begin to comprehend what's being said in physics.

RT: But again, I think it's another example of the phenomenon we were discussing before, when were talking about weak lensing – images that we take almost for granted, making dark matter 'visible'; yet if you are equipped with knowledge of how the evidence is collected, and how those images are produced, you understand that you cannot quite interpret them in such an immediate way. And statements about the age of the universe, I think it's the same kind of 'filter' that ought to be applied to them.

C: What is perhaps most remarkable about this whole discussion from the perspective of contemporary philosophy is that the 'big questions' about the universe as a whole which philosophers themselves have long-since regarded as constitutively beyond the limits of human reason, have now quite suddenly – that is, over the past fifty years or so – reappeared, though this time not as subjects of *a priori* speculation, but rather as concrete objects of scientific, cosmological research.

Your particular field of research is theoretical cosmology – the scientific study of the large-scale structure, properties and evolution of the universe as a whole. But apart from its scope – as we have seen, taking in both the inscrutably small and unfathomably large scales of the universe – how does theoretical cosmology differ significantly from other scientific fields?

RT: Well, as I said before, I think it's important to highlight that cosmology is very different from any other physical science in one fundamental respect: namely, that we can't perform experiments. We can only perform observations of the universe, which are intrinsically limited by many factors.

C: The distinction being that with experiments you can control parameters?

RT: And that you can reproduce your data at will. If you're not satisfied after a hundred trials you can do a hundred more, and gather more data, whilst for the universe we are intrinsically limited by the fact that we have only one universe, and we cannot create the universe a second time, as it were. And that's a fundamental distinction, one that's very important to understanding the nature of the cosmological enterprise. We can only make observations, look for correlations among observations, and make inferences using probability theory. So that's where probability theory comes into the story. For instance, if I have a theory that predicts that blue galaxies are more massive, I cannot simply grow a massive galaxy in the lab and observe if it's blue. But what I *can* do is to go out, observe as many galaxies as I can with a telescope, and then ask of my data whether I do observe such a correlation, that is, whether the more massive galaxies in my sample tend to be the blue ones. But that's a statistical connection between observed properties.

So that's a fundamental aspect, and it's limited in nontrivial ways. You might think our work is limited by the need for a certain budget to build a telescope of a certain size, for instance. But that only holds up to a certain point. For instance, for the CMBR, we have an effect that is called 'cosmic variance', which means, in other words, that we cannot get to these fluctuations as precisely as we would like, even by building bigger and better telescopes. There is an intrinsic limit to the ultimate statistical precision we can obtain, set by the fact that we have only one universe to observe. We can't travel to a very distant galaxy and observe the differences from another perspective, we're stuck here. And so this sets a limit on the amount of information you can ever collect, process, and analyse about the universe.

C: With regard to these intrinsic limitations upon, or conditions of, cosmological research, isn't this also in part where so-called 'anthropic reasoning' comes in – because the very fact of these, as you say, non-trivial limits, is something which has to be explicitly taken into account and, as it were, factored into the results of one's research? Of course, taking into account and 'correcting for' the 'subjective biases' of one's observations is part and parcel of all empirical science worthy of the name. However, in the case of cosmology in particular, there's something more fundamental at stake, isn't there, which follows from the apparently trivial and platitudinous fact that we cannot observe in an environment that does not support our existence? In other words, apart from the specific kinds of limitations you've just mentioned, there is also the basic fact that our evidence about the universe is restricted by the conditions necessary for our presence as observers.

RT: Yes, this is the so-called 'Weak Anthropic Principle' [WAP]. The way to understand this properly, I think, is not as if we are saying that human beings, or humankind, has a special role as observers *per se*. Rather, the question you could ask is: What does the fact that there are observers such as ourselves, tell us about the global properties of the universe as a whole – if anything at all? Obviously, we have to live in a very special place in the universe in order for us to be here at all. It's not just an average, randomly-picked place in the universe; we have to have the right conditions for life to be here and to be able to ask the question in the first place. So I think the only reasonable way to approach this is to start from the observation that we exist, and then try to consistently take into account the fact that all of our observations are implicitly conditional on the fact that we must be here to make them, and then carry on from there, in terms of probability statements; all the probability statements we make – such as, is our universe probable or not – we have to take into account this piece of information.

C: Part of the difficulty with the use of probability in theoretical cosmology is that it's difficult to understand how the 'frequentist' paradigm, the idea that a probability relates to a number of possible cases, could make sense. The frequentist paradigm is not only related to the repeatability of scientific experimentation but also in its origins, to gambling, to being able to play the same game over and over.

RT: Yes, absolutely. Although, from the point of view of the history of science, the Bayesian framework was born first, with Laplace, who applied it to problems in celestial mechanics, but was then superseded by what became the orthodoxy in the early decades of the twentieth century, by the work of people like [Sir Ronald Aylmer] Fisher. The frequentist approach to probability may be natural in the case of particle physics, because you have a certain number of particles, you count how many of them you have, and you count relative outcomes. But the Bayesian way of understanding probability is arguably a way which is more natural, in the sense that it's probably connected with the way that a naturally-selected mind works. Let me give you an example. If I ask, what is the probability that if I cross the road now I will be run over by a car, I am asking a question of an experiment, and I am naturally making a Bayesian inference as to what are my chances of crossing safely or not in that particular situation – I certainly don't want to repeat the experiment a hundred times and see how many times I get run over! So, in nature, actually, you want to be able to assess probabilities, chances, in terms of situations that are intrinsically unique, that cannot and will not be repeated. Now, the universe is clearly one of those cases. We have one universe – or, if it *is* repeated we certainly have no access to the repetitions, to other organisations or different laws of physics in the multiverse. And so we have one sample to work with. And we should stick to that, by understanding probability statements not as an outcome of frequencies, but rather as a state of knowledge. In other words, probability is in the eye of the beholder, in a sense. Probability is my state of knowledge conditional upon all the information and prior beliefs.

C: The problem of the applicability of concepts such as probability and chance to the universe as a whole has a long history. In his *Dialogues Concerning Natural Religion* Hume argued that, since the cosmos only happens once, we cannot hope to gain any knowledge of any regularities in how it is created. One can question the very propriety of attributing 'probabilities' to these initial or overall conditions of the world at all. Attributions of probability, it has been argued, depend upon observed relative frequencies in the world from which probabilities are inferred. To talk about the probability of a universe is, for this point of view, incoherent.[6] In a recent paper co-authored by Glenn Starkman entitled 'What's the Trouble With Anthropic Reasoning?', you raise precisely this issue, and suggest that some of these difficulties might be addressed by taking what you call a 'fully Bayesian approach to the problem' which, as you were just saying, would understand the prior as 'an expression of our state of knowledge'.[7] Could you, in simple terms, explain how Bayesian methods, and this notion of probability as a state of knowledge rather than as a relative frequency of outcomes, can work for a singular-case scenario such as the cosmological one?

RT: Yes, there has been a misunderstanding here, historically speaking, in that there has been this notion of probability as frequency, and that an event which happens only once cannot be deemed either probable or improbable – it just happens. But the connection between frequency of outcomes and probability is a limited one, which doesn't necessarily cover much ground, and in particular not the ground we're interested in covering, which is events that

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[6] These formulations of the objection are taken from C. Callender, 'Measure, Explanations and the Past: Should 'Special' Initial Conditions be Explained?', *British Journal of the Philosophy of Science* 55, 2004: 204 and L. Sklar, *Physics and Chance* (Cambridge: Cambridge University Press, 1993), 313, respectively.

[7] Roberto Trotta and Glenn D. Starkman, 'What's the trouble with Anthropic Reasoning?', *AIP Conference Proceedings* Vol. 878 (2006), 323-329.

are by definition non-replicable. I gave the example just now of walking across the road. As I've said, most situations in which we are interested in making predictions about the outcomes of future actions are intrinsically unrepeatable. Let's take the most basic probability example, that of tossing a coin – one of the paradigmatic examples. If asked to assess whether the coin is fair, most of us would think of tossing this coin perhaps a hundred times and seeing whether there are, say, fifty heads and fifty tails, or sixty and forty, and then based on that, we ask what is the probability of getting heads or tails, and if that's 50 percent, we deem the coin to be 'fair'. And so, when we do these kinds of tests, paradigmatic tests, we are setting out to establish, as it were, a physical property of the coin – that the coin is either fair or not, meaning that it's either well-balanced or not. A die can be loaded or not, for instance. But, if you think about it for a second you'll realise that there's no such thing as a *physical property of the coin* that determines the outcome of heads or tails. In fact, if I was skilled enough and made my 'random' throw with sufficient finesse and precision, regardless of whether the coin was 'intrinsically fair' or not, I could get it landing heads 100 percent of the time. In other words, when I'm doing random tosses of the coin, the *randomness* is the key ingredient. The randomness of the toss means that my skill in tossing the coin is not good enough in order to determine in advance what will be the final outcome. But in principle, if I could determine the initial conditions of the toss with a high enough precision, I would be able to predict exactly, or to achieve any particular sequence I wanted, by having a better knowledge of the initial conditions of the problem – since, for non-chaotic, classical systems at least, the physics is completely deterministic. So by tossing a coin, we're not testing it for fairness, we're not measuring a physical property of the coin. Rather, we're making a statement about our state of knowledge of the randomness of the toss. In other words, we're making a statement *about our knowledge of the initial conditions of the problem*.

So, how does this fit into the discussion of probability? Well, probability as a measure of *frequency* is one possibility: I define a probability intrinsic to the coin as a physical property of the coin, as the number of tosses divided by the number of tails of my series. But in the light of what I've just said, it's perhaps more useful to regard this not as a measurement of a physical property – since this property doesn't exist, as shown by the fact that I can completely change the outcome without changing physically the coin, just by changing my state of knowledge about the system I'm investigating … So it's perhaps more interesting to look at probability as expressing not an *intrinsic property of the objects* of study that has to do with their behaviour over long sequences of repetition, but rather to see that it has to do with *our state of knowledge of the object* based on our previous interaction with the object, the previous data. In this way, I can iteratively update my state of knowledge as new data come along. Based on previous knowledge – what we call the 'priors' – we can update it through new observations and get to a more informed state of knowledge.

Now, to go back to the universe, clearly we have no access to a repetition of the universe. But what we *do* have is access to information about the particular realisation we live in, and so by using this Bayesian technology, as it were, we can make statements not about the probability of an outcome of an infinite series of universes which is only posited *ad hoc* – which is ontologically debatable, in my opinion – but we can make statements about our state of knowledge of the particularisation that we happen to observe, which gets more and more informed and refined as we gather more and more information. Of course, all I've said here about probability holds at classical level – physical systems as deterministic. When we go over to the quantum level where probability is an intrinsic feature of the system, then the discussion has to take this into account, which opens up a completely new can of worms.

C: What you've said about Bayesian techniques certainly seems to problematise Quentin Meillassoux's recent critique of probabilistic arguments as applied to the universe itself, given that this critique appears to limit itself to narrowly 'frequentist' construals of probability.[8] But Meillassoux also takes issue with applications of anthropic reasoning which begin by envisaging a multitude of logically possible worlds – worlds in which the physical constants differ from those of the universe which we actually observe – and which then, having calculated that the probability of universes which permit the conditions necessary for life is astonishingly low, go on to infer that some hidden necessity must be at work which uniquely determines the constants of the observable universe.[9]

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[8] See present volume 64-7, and Q. Meillassoux, *Après la finitude* (Paris: Seuil, 2006), Ch. 4.

[9] See present volume 77-8.

Meillassoux's argument is pitched at a purely *a priori* philosophical level, but the problem of the so-called 'fine-tuning' of the physical constants of the observable universe is a rather precisely-defined problem for cosmology, one which would seem to cry out for an explanation. While one will agree with Meillassoux that these 'fine-tuning coincidences' in no way license the reintroduction of teleological explanations such as one finds in the so-called 'strong' versions of the Anthropic Principle [AP], there is nevertheless a very real question here, is there not?

RT: Yes, indeed, from the point of view of cosmology and theoretical physics, the issue of fine-tuning you refer to is precisely the question that string theory has set out to answer – and so far has *failed* to answer. Which is to say, the hope of string theory – which is a theory that hopes to explain in heavily mathematical fundamental terms all of the structure of the particles and interactions in the universe – the hope was that it would turn out that there was a single mathematically consistent and logically possible realization of the theory, one which would account for all phenomena, structures, symmetries, particles, interactions, and so on. It didn't turn out to be the case, however. We now know that string theory has many different possible 'realisations', different corners of string theory space that are all equivalent to each other in some way, but none of which is unique. So it doesn't seem that the promise of string theory of being *the* final theory of physics – in terms of being unique and explaining all the phenomena – will be realised.

C: The hope was that it would explain those twenty or so free parameters of the Standard Model – the values of the constants which have to be, so to speak, 'written in by hand' – that are always invoked in discussions about fine-tuning?

RT: Yes, the hope was to explain in a unique and fundamental way all the parameters, and all the symmetries as well. But now, this hasn't turned out to be the case, and so we're stuck in a position where string theory doesn't make a unique prediction, as one had hoped, since there are multiple realisations of string theory which give you what is called the 'landscape' of solutions, which is a multidimensional mathematical object. It's called a 'landscape' because it's configured in terms of 'mountains' and 'valleys', and it turns out that at the bottom of each valley there is what's called a 'vacuum state'. Now, each of these vacuum states at the bottom of every valley represents one possible outcome for the universe. All this, so far, is of course mathematical theory, and so the question is to know which of these valleys in the landscape *our* universe occupies. But the number of possibilities for these logically possible universes, which Meillassoux mentions in a philosophical context, possibilities which are actually realised in this mathematical theory, the number of these possible universes is huge – it's something like 10^{500} – a huge, huge number. So again we have to resort to statistical techniques in order to analyse this landscape of possibilities.

The question then is, given this 10^{500} universes, our universe corresponding to the realization has been singled out in reality – how do we go from these potential universes to the actual, realised universe that we observe? This is where AP comes in, in saying that we have to count how many of these valleys are habitable. And this will restrict enormously the number of viable possibilities. Of course, we could not happen to live in one of the valleys which do not support life, say because the constants of nature there are such that life is not possible. And so you see modern physics seems to flesh out, as it were, in a very mathematically hard way, in the form of the landscape of string theory, precisely this idea of logically possible universes mentioned by Meillassoux. And now AP comes in as a possible solution, to try to explain the contingency of *our* particular realisation. Whether it's successful or not remains to be seen.

I personally have this criticism of this landscape of string theory: first of all, it's all dependent on the assumption that the heavily mathematical theory that describes this landscape is correct in some sense. And secondly, it introduces this plethora of universes, or alternative realisations, that are non-observable in principle. It introduces lots of possibilities that remain in the domain of the potential, just in order to explain how it comes about that we appear to inhabit a particularly fine-tuned realisation. But the moment you open up the space of infinite different universes you cannot observe, I think you are falling on the other side of this thin line dividing scientific enquiry from pure speculation, which cannot be scientifically tested. Which is fine – I don't want to give you the impression that I'm against these kinds of speculations. I'm only against them when you claim that you are able to do quantitative tests on things which, meaningfully, cannot be tested.

C: Indeed, in the paper mentioned earlier you dismissed the multiverse scenario precisely because, firstly, it seems not to be very economical, in terms of Ockham's razor; and secondly, because, as you have just said, it's not testable. Now, to take up the second point, it's obviously not 'testable' in any straightforward positivistic or verificationist sense; yet we know that a lot of things in modern physics are not testable in *that* sense. Is it not perhaps conceivable, however, that a number of quite different theories, coming from different domains of physics, perhaps as solutions to quite disparate problems, might ultimately all seem to point in the same direction – that is, in the direction of the multiverse scenario? In other words, one might reject the idea that fine-tuning *alone* is strong enough evidence to postulate a multiverse, but what if it turned out that there were other, independent reasons, to favour it? One thinks, for example, of Everett's 'many-worlds' interpretation of QM, or the very fact, as you were just saying, that string theory seems to admit of a multitude of 'solutions', or possible realisations. Is it not conceivable that a number of such theories, or interpretations of theories, might ultimately amount to a sort of evidence – indirect evidence, granted, but mutually corroborative – for some version of the multiverse idea?

But if not, what are the remaining alternatives? Do we just say that the values of these free parameters are 'brute facts' that we simply have to accept without any further explanation? But to say that – to say, in effect, 'The universe had to be *some* way, so why not *this*?' – that seems to be against the spirit of science itself …

RT: Yes, absolutely. But you see I think the problem here is that with string theory and the landscape, and this accumulation of extra layers postulated to explain physical reality, what we are doing in effect is moving away from trying to find out what are the laws of the physical universe; we are effectively crossing the boundary into trying to determine *meta*-laws governing the laws we have discovered in the first place. So if you think of these constants – one can say this is merely a brute fact, that that's just the way the universe is, but as you say, we're not content with that, we want to push forward and dig out another explanation. And one hope would be that it was possible to use this very powerful principle that we've used very successfully in the last couple of hundred years, which is the principle of symmetries. As I discussed before, these symmetries do not have to be tied up with real world symmetries – they might be the most abstract symmetries that live in a mathematical space. If those symmetries were in place, one would perhaps be able to explain these constants, because only a specific set of symmetries would allow for those particular values. For example, if dark energy is a manifestation of a cosmological constant, than the value of this constant is a very small number, and yet it's non-zero. If it were zero, everybody would be happy because – even though on the real line of numbers zero has a dimension or length of none, of zero – in fact zero is an extremely special place, so if something is zero in physics there's a symmetry which requires, which demands it to be zero. But if something is non-zero but extremely small – say 124 orders of magnitude below what you'd expect it to be – this is an astonishing fact that cries out for explanation. It could just be a brute fact and we might have to accept it as such and that's the best we can do. But, what people really are trying to look for, is to uncover the fundamental structure that will explain the smallness of this number when compared to the known energy scales in physics. So we are looking into discovering the laws or the mechanisms that possibly underlie and explain those numerical values. But even if we were to discover those laws in the form of a Grand Unified Theory or whatever – and we are not there yet – the question would remain: What is the meta-law that singles out *that* specific set of symmetries in the first place?

C: There's the risk of an infinite regress.

RT: Yes, exactly. That's what I'm trying to say. So, we're not giving up yet, but I can already peel off this layer and see where we're going.

C: The fact that you might end up with an infinite regress isn't a reason to stop.

RT: No, absolutely not …

C: There's a regulative ideal in play, such that you keep pushing on …

RT: Yes, absolutely. But you were asking whether it was possible that this explanation for fine-tuning would be testable or whether there would be enough cumulative indirect evidence. Again, you can always push the game one layer down, and find yourself asking deeper and deeper questions, and this is an infinite regression that is difficult to break, whose solution is not in sight, especially after string theory didn't offer such a way out.

C: In this respect Meillassoux introduces his distinction between chance and contingency as a sort of shortcut, or regress-stopper – he says, in effect, that you *can't* go back another level since there's an absolute, radical contingency which can't be submitted to any law whatsoever …[10]

RT: Yes, whilst cosmologists have, at least in principle, these meta-laws governing even the contingency of our universe.

C: We said that your own rejection of the multiverse proposal rests firstly upon the impossibility of experimental confirmation, and secondly upon its apparent flouting of Ockham's razor. Again, sticking to the first point for the moment, what if it turned out that something like string theory *did* ultimately manage to consistently account for the phenomena on all scales – in such a case, would experimental confirmation still be important?

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[10] See present volume, 76.

RT: Certainly, yes, I would say so. I described before how our work involves a kind of cycle of data-gathering, modelling within a theoretical framework, and observational confirmation. The trouble in this loop comes when you get to a certain point where theories are constructed in such a way as to avoid experimental confirmation or falsification altogether. So when you get to the point where you need to postulate a possibly infinite number of unobservable parallel universes in order to explain why the constants of nature are the ones that we now observe – this, I think, crosses the boundary of scientific, verifiable theories; because for such theories, experimental or observational input is *designed* to be impossible.

C: And this brings us to your second objection, that such theories needlessly postulate entities. But isn't it possible that in the future you will be faced with the alternative of accepting theories which account very well for phenomena, but which cannot be experimentally confirmed, on the one hand, and experimentally-confirmed theories which permit a relatively inferior mastery of the phenomena, on the other? In other words, is there a disparity between the potential reach of speculative theories can have, and their grounding on experimental evidence?

RT: Yes, and dark matter is an instance of this. Some of this disparity is closed, or will be closed, by improvements in experimental instruments; so, we'll build bigger, better detectors, and we'll get there eventually – even though one has to bear constantly in mind the limitations to our knowledge that are peculiar to cosmology and that I was mentioning before. But the problem is where this theoretical reach is exercised in a domain where experimental proof or disproof cannot happen *in principle*. At this point I think you are losing all the power of theory, and from a scientific point of view you give in to pure speculation, which has no testable consequence and therefore is outside the proper realm of anything we could call scientific investigation. And I think the multiverse idea is an example of this, since even if these parallel universes were real in some sense, they are constructed to be undetectable because they are outside the reach of any particle, any possible experiment you could possibly do, and so you have to question what type of reality you could attribute to this theory, if any.

C: But hasn't the progress of modern science been precisely this movement towards extremely counter-intuitive ways of thinking? Most of us find even the most basic statements of modern physics counter-intuitive. They seem to be talking about a world entirely alien to that in which we live every day.

RT: Does the progress of science show us that we are going inevitably towards a realm where our intuition doesn't apply? I think there are a few things to mention here. One is what has been termed the 'unreasonable effectiveness of mathematics'[11] – why does mathematics describe the world

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[11] Eugene Wigner, 'The Unreasonable Effectiveness of Mathematics in the Natural Sciences' in *Communications in Pure and Applied Mathematics* Vol. 13, No. 1 (New York: John Wiley and Sons, Inc., 1960).

in the first place? It can be argued that mathematics is ultimately just a product of the mind, which is arguably a manifestation of our brain structure, which, in turn, as a biological entity, must be a product of evolutionary forces that have shaped our cognitive behaviour in terms of responses to the world. But then this wouldn't explain why we're able to grasp things like QM or GR, of which we have no experience at all. I'm not sure whether there is an explanation for the fact that there are things of which we don't have any immediate experience – QM, something which is completely counterintuitive, weirder than you could possibly think – but which are accounted for by our mathematical constructs. This for me is the biggest puzzle of all – why should mathematics have anything to do with physical reality, and why should physical reality conform to this very abstract product of our minds? I don't have an answer for this question, but I think it is something that tends to be swept under the carpet, in operational terms.

C: It's perhaps precisely here that the convergence of physics and philosophy – their shared space of problems, so to speak – becomes most visible. Indeed, the very questions you have just posed – 'Why should mathematics have anything to do with physical reality?' and 'Why should physical reality conform to this very abstract product of our minds?' – are precisely the problems which Kant set out to definitively resolve in his *Critique of Pure Reason* and *Prolegomena to Any Future Metaphysics.* Kant's solution, of course, is comprised within what he called his 'Copernican experiment' in philosophy, which basically states that the reason why physical reality conforms to our mathematical concepts is that these concepts provide the 'synthetic *a priori*' *conditions* of natural science itself. In other words, empirical reality conforms to our concepts because these concepts are not derived *from* experience, but exist rather *for the sake of* experience: that is to say, they make experience, and the objects of experience (and for Kant this meant, first and foremost, the objects of natural science) *possible*. This was perhaps a compelling solution in terms of the mathematics and natural science of Kant's own day – that is, Euclidean geometry and Newtonian mechanics – which, as we were saying earlier, are more or less entirely isomorphic with the middle-sized world of our everyday experience. But as you have just remarked, when it comes to twentieth century physics – to QM and GR – one finds no such isomorphism, and so the problem becomes far more difficult.

This is perhaps an appropriate place to touch upon some questions we were hoping to broach regarding a certain parallel we had noticed between the use of so-called 'anthropic reasoning' in cosmology – which has already come up in our discussion several times – and certain aspects of the Kantian legacy in contemporary philosophy. Brandon Carter, who first introduced the term 'Anthropic Principle' in 1974,[12] later had some cause for regret that he had not called it something else – the 'Cognizability Principle' or some such – given the somewhat inevitable misunderstanding that it entails some of kind of anthropocentrism or 'anti-Copernicanism', whereas the real point has to do with possible 'observational selection effects'

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[12] B. Carter, 'Large number coincidences and the anthropic principle in cosmology' in (ed.) M. S. Longair, *Confrontation of Cosmological Theories with Observational Data* (Dordrecht: D. Reidel, 1977), 291-8.

entailed by 'observership' in general, not *anthropos*, or *homo sapiens* in particular. Carter's original point was that it is a mistake to infer from the fact that we do not occupy a privileged *central* position in the universe the conclusion that our situation cannot be 'special' *in any sense whatsoever*. The problem with what he called 'exaggerated subservience to the "Copernican principle"' is the risk that, from the presumption of our *non-specialness* we might infer that we are *average*, and from this that we are *representative*, and hence *neutral*. In striving to avoid anthropocentrism in this way we would, paradoxically, be reintroducing it in another form, because we would fail to take into account the specific limitations on our knowledge entailed by the fact of the very special physical conditions which must be in place if we are to exist as observers – and be the specific kind of observers we are – in the first place.

In this regard WAP invites comparison with Kant's 'Copernican experiment' in philosophy. Kant faulted the metaphysical tradition which came before him precisely for failing to take into account the fact of the essential limits of our modes of cognition – that is, of the conditions which must be in place for cognition to be possible in the first place – and thus for assuming that the (epistemological) conditions of human knowledge were also the (ontological) conditions of things in themselves. In the most simple and general terms, Kant's point was that one cannot know a thing in abstraction from the very conditions of cognition itself. Because previous metaphysics had not undertaken a properly 'critical' investigation of the epistemological conditions of its own inquiries, it had inevitably proceeded 'dogmatically' by assuming that its own conditioned vantage-point on things amounted to an unconditioned access to things as they are in themselves. Thus, as with WAP, rather than attempting to illegitimately infer metaphysically dubious anthropocentric conclusions from trivial or truistic premises, one might argue that Kant too was attempting to precisely *avoid* the anthropocentrism which follows from failing to take into account the non-trivial limitations upon and conditions of the possibility of cognition itself.

But however one interprets Kant on these matters, it has often been claimed that his 'Copernican turn' in philosophy, as a matter of historical fact, inaugurated a way of doing philosophy which, far from complementing the natural sciences by providing second-order epistemological critiques of their first-order claims, in fact runs counter to the 'Copernican' spirit of modern science itself by effectively placing man (or the knowing subject) back at the centre from which Copernicus had dethroned him. Meillassoux's *After Finitude* presents a particularly forceful example of such a cricitism.[13] According to Meillassoux, the mainstream of philosophy since Kant cannot but fail to make sense of the literal import of cosmological and other scientific statements about the universe so long as it remains within the paradigm of what he calls 'correlationism' – this being the name he gives to the long-prevailing consensus regarding the supposed absurdity of the idea of 'things-in-themselves' (i.e. the idea of obtaining knowledge of things as they are regardless of human experience), along with a positive doctrine which states that all possible objects must be understood strictly in terms of their

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[13] *Op. cit.* For a critical appraisal, see R. Brassier, present volume, 15-54.

correlation with either possible experience, subjective consciousness, intentional acts, language, conceptual schemes, or theories. A strong 'correlationist' position on dark matter would not merely claim (like WAP) that our cosmological models are necessarily conditional upon certain cosmological parameters which permit the empirical advent of life and of consciousness, thus putting us on our guard against neglecting these factors in our reasoning. It would affirm the much stronger thesis that in principle the very existence of dark matter is conditional upon our cognition of it, that astrophysical objects can only be said to *exist* by virtue of the conditions of our cognition – whether these conditions are intersubjective linguistic networks or the historical corpus of mathematical learning. In sum, dark matter exists, according to the correlationist, only 'for us' but not 'in itself'.

Now, this seems particularly difficult to accept in the field of cosmology where, as Meillassoux points out, 'experimental science is capable of producing statements concerning events anterior to the appearance of life and of consciousness.'[14] How, within the 'correlationist' framework – which is happy to accept scientific statements only along with the caveat that they are true only 'for us' – can we understand the meaning of a statement which purports to provide us with knowledge of entities and events which existed billions of years *before* there was any 'us' to cognize them?

The question is fundamental: does scientific objectivity allow us to in some sense 'get out of ourselves', to transcend the conditions of our experience and to achieve

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[14] Meillassoux, *op. cit.*, 24.

genuine cognition of the universe in itself? WAP appears to be optimistic here, suggesting that, precisely by taking into account possible observational selection effects and other biases intrinsic to our existence as observers, this is precisely what can be achieved. What we might call the 'Correlationist Principle', on the other hand, forecloses the question immediately, in accord with its assumption that everything is necessarily conditional upon the conditions of our cognition.

Now, these questions are obviously somewhat philosophically involved, and perhaps belong to epistemology rather than science proper. But one might think that, if anywhere in modern science they become urgent and uncircumventible, it is here, in the domain of cosmology. Similar questions have, of course, been central to the problem of the correct metaphysical interpretation of quantum physics for almost a century. Do you think that your own work, and modern cosmology in general, might ultimately be able to contribute something towards resolving these long-standing disputes? To what extent are such problems real and live ones for the working physicist or cosmologist? If a 'naïve realism' is no longer a real option, both because of what modern science has discovered and the sheer tide of philosophical arguments against it, what are the remaining alternatives?

RT: Well, first of all, I would certainly subscribe to the idea that the knowledge we gain of these objects which preceded the possibility of us experiencing them comes out of something like a time-shift – it's like time-travel. Because we have to remember that as we look back in time by observing distant objects we are witnessing different stages in the evolution of the universe. However, when we look at a distant galaxy we don't, of course, obtain knowledge of how the universe is 'now', as we observe it – indeed the whole concept of simultaneity is rather counter-intuitive in relativity, as we discussed. Rather, we have knowledge of the universe as it was when the light first left it. So now, when we look back to the very beginning of the universe, in a way we are looking at a point of the universe which may be billions of light years away, but since the Big Bang happened everywhere in the universe, and since we assume that the universe is isotropic – that there is no special place in the universe – then we are also looking at the universe as it was 'here', in a sense, in our location, only timeshifted.

But you asked whether scientific objectivity – perhaps supplemented by AP, purporting to correct for subjective bias – whether it allows us to have a genuine cognition of the world in itself. In science we can certainly have this sort of counter-intuitive narrative of disembodied entities, that we like ourselves to compare with. However, the selection effects expressed by AP remind us that such disembodied observers are an artifact of our cognitive process, and that quite on the contrary we have to carefully consider the physically and biologically necessary conditions for our presence. But we have to bear in mind that in order for AP to work, we have first of all to postulate, to apply this selection effect to a collection of samples, be it a class of objects in terms of realisations of the universe, different parts of the multiverse, multiple inflationary patches, whatever. And after that you need to define a reference class of observers – and this is the criticism I make in the paper you mentioned earlier. You have to define what counts as an observer in order to establish what is the probability of our being in such and such a universe. We have to define very precisely what it means for us to be observers: what is the reference class of observers we belong to – cockroaches, for instance – do they count as observers or not? That's a very fundamental point.

I think this is relevant to the question of the relation between AP and the 'Correlationist Principle' in the sense that, in order to achieve logical consistency when considering a reference class of observers, we must require consistency between the outcomes of inferences made by different members of the same reference class of observers. And this, I think, is very relevant with regard to correlationism. In other words, in order for probabilistic inference to work, we have to require that different observers, say us and some alien species on Andromeda – if we postulate that they use the same logic, that the rules of logic are valid throughout the universe, which is again one of the main postulates – we have to require that different observers in the same class of reference will necessarily achieve a consistent inference by making the same observations. And so I think that debunks, in a way, the Correlationist Principle. Because if this is true – AP supplemented by the requirement of logical consistency between observers in the same reference class – if this is true, then necessarily we don't have this freedom anymore for different observers in the same reference class to experience the world in a different way. In other words, the arche-fossil[15] has got to

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[15] See R. Brassier, present volume, 15-6.

be an entity of its own that can’t be processed at will by interaction with different observers of the same reference class – *if* AP is to work at all.

So in other words, I think what you have represented very nicely in your question is two different ends of the spectrum of possible cognitive experiences: correcting for subjective bias through a careful use of AP, on the one hand, and introducing a new way of subjectively experiencing the world in the correlationist approach. I suspect that the two of them can’t live together. I would claim that for AP to work in a consistent way – if we accept logical consistency as one basic rule of inference, for instance, which it’s hard to do without – then it requires consistency among observers in the same reference class, however defined. If this is the case then it means that the entities upon which we condition in our application of AP as a selection effect – those entities must have some common, intrinsic properties of their own, properties which every observer in the reference class of observers reasoning consistently has got to agree upon.

C: This introduces the problem of relativism, of alternative conceptual schemes. But correlationism need not necessarily entail relativism, since even if all observations agreed, and even agreed *necessarily* – as in Kant’s case, where the transcendental conditions are *a priori* (that is, universal and necessary) – the correlationist would still insist that intersubjective consensus is an insufficient basis upon which to claim that such observations reveal properties of things *as they are in themselves*. In fact, the correlationist would claim that it is precisely this consensus amongst observers in the same reference class which makes the objectivity of objects possible, thus collapsing the ontological problematic into a matter of intersubjective agreement or heuristic pragmatism,[16] which is precisely what the critique of correlationism seeks to avoid.

To put it as starkly as possible, the fundamental question here is whether there is any prospect of obtaining knowledge of things as they are in themselves – regardless of there being actual or possible observers – or whether it is something constitutive about cognition that it will always be a matter, not of 'nature in itself', but only of 'nature as exposed to our method of questioning' (Heisenberg)?[17] Kant's metaphor was one of reason as a judge, 'constraining nature to give answers to questions of reason's own determining',[18] and perhaps in your account of the methods and objects of theoretical cosmology you have already implicitly ratified this metaphor, whilst making it clear that it is nevertheless by no means a question of a simplistic 'correlationism'.

Another way of approaching the issue is in terms of the problem of the theory-dependency of observation which we touched upon earlier. You said that all the necessary theoretical and instrumental mediation required to access

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[16] See Meillassoux's critique of Goodman, present volume, 56-9.

[17] 'In classical physics science started from the belief – or should we say from the illusion? – that we could describe the world or at least parts of the world without any reference to ourselves […] [But] we have to remember that what we observe is not nature in itself but nature as exposed to our method of questioning.' W. Heisenberg, *Physics and Philosophy: The Revolution in Modern Science* (NY: Harper & Row, 1962), 43, 46. See also Kristian Camilleri's 'Heisenberg and the Transformation of Kantian Philosophy' in *International Journal of the Philosophy of Science* Vol. 19, No. 3, 2005: 271-287.

cosmological objects amounted not to a diminution but to an 'enhancement' of reality – almost as if there is a sense that one is 'producing' the reality. Does scientific knowledge, as you understand its process, fit more closely with the classical philosophical idea of knowledge as a kind of 'copying' or 'representing' of an already fully-determinate reality, or is there a sense in which the objects of physics have to be 'constituted' via the theoretical and technical 'mediating processes' you were describing earlier?

RT: Let me give you an example which I think illustrates how a reality comes into being through the scrutinizing power of the scientific methodology. Leaving cosmology for a while and turning to quantum physics – another field which is often on or across the boundary of interpretation and reality – if you take for example a *two-dimensional electron gas*, which is something that has been realized only in the last few years, thanks to various developments in sub-microscopic technology. This two-dimensional electron gas has a set of nice properties that we can investigate: we can

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18. 'When Galileo caused balls, the weights of which he had himself previously determined, to roll down an inclined plane; when Toricelli made the air carry a weight which he had calculated beforehand to be equal to that of a definite volume of water […] a light broke upon all students of nature. They learned that reason has insight only into that which it produces after a plan of its own, and that it must not allow itself to be kept, as it were, in nature's leading-strings, but must itself show the way with principles of judgment based upon fixed laws, constraining nature to give answer to questions of reason's own determining. […] Reason, holding in one hand its principles, according to which alone concordant appearances can be admitted as equivalent to laws, and in the other hand the experiment which it has devised in conformity with these principles, must approach nature in order to be taught by it. It must not, however, do so in the character of a pupil who listens to everything the teacher has to say, but of an appointed judge who compels the witnesses to answer questions which he has himself formulated.' I. Kant, *Critique of Pure Reason* (trans. N. K. Smith, Basingstoke: Macmillan Press, 1929 [1789]), B xii-xiii.

put it into magnetic fields and see how it behaves, see quantised energy levels, and different types of effects which, in a way, are the expression of a potentiality which is in nature or in the laws of nature that we've discovered. But in a way it's a purely technological object – it was potentially in the structure of nature, but one might surmise that it has never been created before in the history of the universe, because it's a very particular object that needs to be very carefully engineered in order for those electrons to bind up in a certain type of state and then express or substantiate those abstract potential properties that our theories describe they have, and then go there, measure it and see what is real. So in a sense this is not just a step ahead of the process of setting up an experiment and making a verification; this is more about *creating a particular state of nature*, actualising potential properties of an object in order to display them in such a way that we can verify them. So in this sense we have achieved in some domains a level where we have a description of nature in terms of its fundamental properties, and we can engineer physical systems, and push them across boundaries that arguably have never been crossed in natural systems because of the very particular set-up that this requires, and so design and engineer new natural conditions that are actually artificial – new artificial natural conditions – which actualise the potentiality of our theory. And here you are at the boundary where you can ask of this system: well, that's a natural system because its actual properties are governed by laws which are natural laws, of course, but those particular properties that you are looking for, their actualisation is only possible in a highly artificial, highly engineered environment that we have now created.

C: A longstanding philosophical problem is how to separate out what belongs to the human input to reality and what belongs to reality itself. In the context of physics generally, and more specifically in the context of the kind of example you've just given, is that in principle even intelligible, this process of 'factoring-out'?

RT: No, I don't think that we can draw a clear boundary between the two. This is an example where we have a little liberally gone across the boundary both ways, and there's no way you can draw a line, but it's just a suggestion to say that there are systems that sit beyond the Galilean distinction of the impartial observer who sets up the experiment and then simply lets it go ahead on its own. We know that the observer plays a crucial role in quantum mechanical observations, and the whole paradigm of setting up an experiment and letting nature run its course in an impartial neutral way, I think it belongs to the past, since our decisions of which properties to observe and which to ignore, for example, will directly influence the system. So there are limitations to the Copernican Principle of the separation between observer and nature. I think science is going in this direction. In one way we are getting more and more sophisticated observations of reality, and at the same time those same observations, to an extent that is difficult to define, determine which reality one can observe in the first place, at both extremes of the spectrum – the microscopic world of QM, of course, and cosmology.

And the other thing that has to be said here is, if you peel away all the layers of the onion, for me it comes down to the issue of consciousness. Why consciousness? We have this 'correlationist' idea that the world wouldn't be there if there was no observer to observe it, but what do we mean by 'observer'? It's a problem that goes back all the way to the root of QM, Schrödinger's cat: What makes the wave function collapse, what makes the cat go from a position of living *and* dead to either living *or* dead? And again it's a fundamental problem for which there is no agreed explanation. It's more about the interpretation we give to the quantum theory. In and of itself, QM works perfectly well, it's only the interpretation as to the reality of the wave function that is disputed. Let me briefly summarise the interpretations. Firstly there's what is called the 'Copenhagen interpretation', which says that the wave function collapses into one of two states when the observer observes it. Now at this point we can question whether the observer is a machine, an electron or photon that hits the object we observe – so the universe would be observing itself all the time; or whether there is space, as people such as Roger Penrose would argue, for a special role for consciousness: consciousness would play the role of the fundamental observer that would make the wave-function of the universe collapse, like in quantum cosmology: in quantum cosmology you have the wave function of the whole universe.

C: But then you're introducing a strange gap into causality: a special agent.

RT: But that gap is in the equations, that's exactly the point: the equations of QM are deterministic. We've got the Schrödinger equation, and we've got initial or boundary conditions. And then the equations will evolve through time this mysterious wave-function, whose square gives you the probability of events happening. And when there is an observation the wave-function collapses from a superposition of different events to just the event that is observed. And so, the point is, everything is deterministic up to the point where the collapse happens, and we don't know what makes the collapse happen, and we cannot give deterministic predictions for the collapse, only probabilities. That's why the deterministic picture breaks down, we can only make probabilistic predictions about what happens: in the case of the cat, in the case of the seeds for the quantum fluctuations, and in the case of the universe. And there are different views. The Copenhagen interpretation will tell you that it is the observation that makes the wave-function collapse, and the alternative will die out, mysteriously. Then there is the 'many-worlds' interpretation, which tells you that at the moment an observation is made, the observer splits into multiple copies, each one of them observing at the same time different events, all possible events that can happen *do* happen, and that our particular reality is but one branch of this unimaginably vast tree. And to a certain extent there are testable predictions that have been done, that have excluded certain interpretations – the hidden variables interpretation, which was put forward by Einstein, has been partially excluded by tests of the so-called 'Bell inequalities'. But this remains very much a contentious issue, I think, and so we cannot really make up our minds as to what makes a wave-function collapse here and there, much less what makes the wave-function of the whole universe collapse, if anything at all.

But you see I think the whole point is that we try to make a narrative out of the scientific framework we're working in, so we tend to talk about cosmological time in pretty much the same way as if we were talking about our subjective time as we know it, we talk about the collapse of the wave-function without really knowing whether this object is just a model of reality or whether it has anything to do with the fundamental reality of the object, the object of the scientific enterprise. The fundamental reality of the 'nature' we're trying to investigate in particle physics and cosmology, I think, comes out from a hundred years of mathematical explanation as one or two things. One is a set of mathematical symmetries, which live in an abstract mathematical space and which give reality its structure. So for instance, conservation of impulse – as we know, if you throw a ball and there's no friction it will keep on going forever – comes from translational symmetry. Conservation of angular momentum comes from rotational symmetry. And then at the deeper level, you can say that conservation of mass, conservation of energy, come from other types of symmetry that are ingrained in the mathematical structure that we ascribe to reality. Now, when we try to uncover this structure through observations, the question arises: even if we were able, with supersymmetry or string theory, to uncover the fundamental structure of nature, the question would be, what principle put this structure in place in the first place? And the hope of string theory, for example, was that you'd find a mathematical theory which could only be consistently formulated within a certain structure: there was no other structure within which it could be formulated. And that would answer the question. But it didn't turn out that way: as we discussed, string theory has failed to yield that kind of paradigm, and Gödel's theorem, perhaps, puts a fundamental limit on how far such a programme can be carried out.

C: Yes, we note that you finish one of your public lectures[19] by juxtaposing a quote from Einstein where he asks 'whether God had a choice in creating the universe' with one from Gödel: 'If an axiomatic system can be proven to be consistent and complete from within itself, then it is inconsistent. It is impossible to find an all-encompassing axiomatic system which is able to prove all mathematical truths.'

RT: Gödel comes in precisely at this level of speculation, when you're trying to push your mathematical tools to the very extreme, to say, will I ever be able to formulate the structure of physical reality in terms of a set of mathematical symmetries that will describe reality in some sense, and then demonstrate, by requiring mathematical consistency, that this is the only possible set? The correlative Einstein quote I use is: 'what I'm interested in understanding is whether God had a choice in creating the universe' – *i.e.*, in imposing this set of symmetries. And Gödel's theorem, apparently sets a limit to this programme, tells us that there

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19. See http://www-astro.physics.ox.ac.uk/~rxt/html/public.htm#course

is no way every axiomatic consistent set of rules – mathematics – can be complete: for every such system there will always be a statement that is true, but cannot be proven from inside. So this seems to put outside the grasp of any such tool such a fundamental question, it seems to me.

C: Thus leaving room for something to have 'planted' the seeds, so to speak …?

RT: It's a possibility. The fascinating thing is that everybody can make up his or her own mind on this. Leaving the door open for a designer – I don't know about that. But in trying to get out of intelligent design, if the solution is invoking an infinite set of universes that only exist in our mind, then I don't know whether this is any kind of solution. It doesn't seem to be a fundamental explanation in the sense in which we have always understood fundamental explanations before in physics.

If 'correlationism' insists that we can only posit objects as objects of possible experience, it seems to me that if we think of this idea of the multiverse – broadly speaking, this idea of 'pocket universes' everywhere, in some higher-dimensional space, with different laws of physics – it seems to be that by resorting to this kind of extreme complexification of reality, science has gone full-circle and is actually positing a series of objects which are definitely, by construction, outside the domain, not only of our experience, but of *any* possible experience. So, rather than reconciling philosophy with science, it seems to me that if you go down this route of the multiverse, you would be going full-circle and bringing science in line with philosophy, rather than vice-versa.

C: In that science would become extremely speculative?

RT: More than that, I think, it would really embrace the idea that in order to explain the one universe we observe, you need to postulate a series of unobservable universes devoid of any possible experience – so it seems to me that it's ironical, paradoxical, that certain ways of thinking of this problem will lead you to such a 'solution'.

C: Yet one might argue that the 'many-worlds' interpretation of QM, for example, while doubtless ontologically profligate, does at least possess the very real virtue of providing an interpretation which is both fully consistent with the equations and which avoids the idealistic, dualistic and vitalistic consequences of other influential interpretations. Leading proponents of the Copenhagen interpretation, on the other hand, have been prone to espouse an idealism so radical it would 'make even Berkeley blush' – one thinks, for example, of Wheeler's notion of a 'participatory universe' according to which 'the observer is as essential to the creation of the universe as the universe is to the creation of the observer.'[20] Similarly, the postulation of a 'multiverse' or 'ensemble universe' as an answer to the fine-tuning problem, AP being introduced in

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[20] J. A. Wheeler, 'Genesis and Observership' in R. Butts and J. Hintikka (eds.), *Foundational Problems in the Special Sciences* (Dordrecht: D. Reidel, 1977), 27.

order to explain the apparent ‘coincidences’ in terms of an observational selection effect, seems in many ways more compelling than a teleological interpretation which would make life and observership a necessary outcome of uniquely specified laws.

So with regard to what you have just said about the impossibility of separating out reality in-itself and our theoretical donation, or nature and the observer, would you put the point as a purely epistemological or methodological one – that it’s simply too messy in practice – or would you say there’s some legitimacy in this idea of a ‘participatory universe’, that observership is in some sense necessarily interwoven with the very fabric of the universe?

RT: Again, you’ll find the whole spectrum of views on this, from the idea of the participatory universe, or the whole universe as a huge living being, to the most rationalist, scientistic point of view which says that the brain is just a very complex computing machine, consciousness just an emergent phenomenon. So you’ll find a lot of different points of view. If I were to give an ‘average position’ of scientists I know, to position them on this scale, I would put most of them on the rationalistic, positivistic side of it. But having said that, clearly if one wants to be rational and consistent throughout, this implies restricting one’s point of view regarding the possibilities of human experience to experiences that are open to any other physical system – you have to abide by the laws of nature without room for any other phenomena that might go beyond them. So far, consciousness is the one phenomenon that seems to be peculiar to humans, and whether this will ever be explainable in the same way we can explain the working of, say, a diesel engine, is a very open debate.

C: You've said a couple of times that, when it comes to the ultimate ontological interpretation of science, 'everyone can make up their own minds' – almost as if it's simply a matter of personal preference. Is this not a huge problem? In a way one might be disappointed, after all the great progress of science, in particular over the last century, to be told that science itself is unable to instruct us regarding its own ontological interpretation. It seems as if you're saying that one can 'cherry-pick' whatever interpretation one wishes, that science itself doesn't place any constraints upon the kinds of metaphysics one might be able to extract from it. But one might have hoped that science would have offered us clues – indeed, more than just clues – to these questions about the ultimate nature of reality.

RT: I think it's too much to hope from or to ask of science, to put the onus of making this decision, passing this judgement, on science itself.

C: But if not science, then who?

RT: I think the methodology of science itself finds its expression and its field of applicability within a domain that is ever-growing but that is delimited by the way science explicates itself in a reflective way. So the main way you can apply science is defined by its methodology; but the context in which you place this methodology and this narrative cannot be analysed by the same methods. In other words you need a bigger arena in which to place science, and I think it's ill-conceived to try and ask of science to determine those answers – they should come as an input from the outside, as a different discourse.

C: But we *do* look to science to guide us in these questions, and if science is itself not capable of providing these guidelines for its own ultimate interpretation, or if the question of its ontological or metaphysical interpretation is something extraneous to science itself, then it seems as if science itself will never be able to do what it is its explicit aim to do, which is to tell us what the structure of reality is.

RT: I disagree that this is the goal of science – to tell us about the structure of reality itself. I think we can only describe it as a logically-consistent narrative of the structures of our models, models that conform to the observed inputs of the world, and in those terms the most we can ask of it is for it to be *consistent*. In fact that's the way we expand its domain of applicability. But we ask only for a consistent narrative of the world – I think it's hopeless to ask of science to give us a 'true reflection of reality'. The only thing we can ask from science is to provide us with a logically-consistent, experimentally observable, predictive narrative of a model of reality. Apart from that, in order to interpret this model, to delimit its applicability, we need another form of discourse which necessarily sits beyond the methodology of science itself.

C: A philosophy of science?

RT: Yes. Because science itself, in its becoming, is mindless.

C: So it would seem, from all that you've said, that cosmology works precisely on the boundary between this 'becoming of science' and philosophy.

RT: Yes, because it's by no means a sharp cut-off point: there is a foggy region where you don't really know what you're doing.

C: And presumably that is the most exciting region to be working in?

RT: Yes, it's a region where you don't know where the boundaries are. It's very exciting to be able to give a small contribution towards clearing this fog, and mapping this region. But I don't think it's clear. There might be an actual gap somewhere, only we don't know where it is. So we keep pushing forward.