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Co-Existence in Particle Physics

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Abstract

This article interrogates the role that concepts from physics play in Western-centric ontologies and epistemologies and explores how particle-physical descriptions of processes in the universe may be generative of an entangled and sympoietic understanding of the world. Through critical engagement with cosmologies of the West – which engendering the illusion of an absolute, representational reality legitimise the exploitation and objectification of *other-than-human* beings – the existential terrain put in place by atomistic ontologies is called into question. By thinking through the unimaginability and counter-intuitiveness of the scales and descriptions delineated by particle physics, alongside their meta/physical implications and their conceptual resonances with new materialism, I seek to explore conceptual tools for de-emphasising human exceptionalism and freeing the category of human from its ontological and epistemological isolation. To do so, I draw primarily from feminist science studies scholar Karen Barad's onto-epistemological framework of agential realism. The argument centres on the workings and entanglements of landscape-laboratories – new-generation astro-particle physics facilities embedded within elemental Earthly bodies. These hybrid eco-technical crossings embody situated and entangled modes of knowledge production and are traced as productive sites for reconfiguring Western-defined ontological and ethical frameworks. I argue that co-existence diffracted through particle physics cannot possibly be considered atomistic, static, or separative but is necessarily sympoietic, relational, and co-constitutive.

Keywords: co-existence; cosmologies; landscape-laboratories; particle physics; relationality

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PART I – ONTOLOGICAL GROUNDS OF THE MODERN WESTERN WORLD

The ancient Greeks [1] laid a cornerstone of modern thought with their idea that matter is composed of minuscule, uncuttable units – the 'indivisibles', or from the Greek: the atoms. The resulting metaphysical thesis of atomism asserts the existence of separate smallest entities (the atoms) as the ultimate nature of material reality and initiated a lineage of thought that has underpinned the development of Western understanding of reality. The hallmark of atomistic ontologies is the primacy of the separation of entities over the fundamental relations between them, which remains a foundational tenet within Western-centric cosmologies.

In today's post-Enlightenment Western world, whose worldview is substantially shaped by the dominance of the empirical sciences (Kimmerer 2013: 341–347), a scientific atomism prevails that is not primarily formed a priori from philosophical arguments, but by appeal to experimental results (Chalmers 2019). In particular, the advent of atomic physics was instrumental in the construction of a modular and static conception of the world which follows the doctrine that there are ultimate units of existence from which all

being is composed. The modernist Western notion of co-existence consequently implies an existence in parallel, that is, a co-existence of formally separate entities. More recently – in the light of the calamitous legacy of centuries of exploitation, objectification and extraction of other-than-human beings – such established interpretations, according to which each of these entities inter-act with 'other' (mutually exclusive) entities, are contrasted by notions such as, for instance, that of a 'sympoietic co-existence' (Haraway 2016). [2]

This article examines the role of physics in the construction of anthropocentric, atomistic ontologies and epistemologies. The existential terrain of Western scientific cosmologies is thereby called into question. Against this background, I critically engage with contemporary particle-physical descriptions of the world to explore their potential for generating alternative ontological imaginaries – ones that reconfigure human relations to the more-than-human beyond entrenched dualisms. The argument revolves around the workings and entanglements of *landscape-laboratories* [3] – new generation astro-particle physics laboratories built around and within elemental Earthly bodies. These hybrid eco-technical infrastructures – such as underground laboratories or underwater neutrino telescopes – co-constitute experimental practices with the environments in which they unfold, thereby unsettling established epistemic paradigms and revealing the materially situated nature of scientific inquiry. Drawing on feminist science studies – in particular, Karen Barad's (2007) framework of agential realism and Jane Bennett's (2001) theorisation of enchantment – the article argues that landscape-laboratories offer a productive lens through which to rethink the ontological stakes of contemporary physics. By attending to the material-semiotic workings of these apparatuses, I seek to trace how they embody situated modes of knowing that remain attentive to the more-than-human realm.

PART II – THINKING BEYOND WESTERN COSMOLOGIES

> *To use the world well, to be able to stop wasting it and our time in it,*
> *we need to relearn our being in it.*
>
> — Ursula Le Guin (2017: 214)

When confronted today – after centuries of human hubris in which Western subjects are assigning themselves a privileged position in the cosmos and in the order of being, and are perceiving themselves as the central element of existence – with the anthropocentric legacy of the modern Western world, the extent of the ongoing global environmental crisis becomes apparent: ecologies, relations between human and non-human natures, possibilities for survival of many species are on the verge of collapse. We – the post-Enlightenment humanity of the Global North – are driven by an insatiable consumerism, have instituted an ideology of constant growth and expansion, are facing rising inequalities, and are responsible for the exploitation of natural resources and the pollution of planet Earth. At the heart of this crisis lies the atomistic conception of the world, built on separations between human and nature, mind and matter, self and other. These separations, which are central to the post-Enlightenment logic of modernity, are, as Denise Ferreira da Silva (2007) argues, also integral to the history of racial capitalism. This history is underpinned by an onto-epistemological framework that renders racial and cultural signifiers as primary, unchangeable markers

of difference, shaping how beings and relations are understood, categorised and divided. This logic justifies the extraction of difference itself, and renders any 'other' (to the white, male, Western subject) as objects for control, possession and extraction. And as the detrimental effects of the primacy of separation in Western ontological thinking become ever more apparent, we are encountering a greater urge to imagine alternative worlds (Demos 2016: 228) – worlds which critically scrutinise the epistemological line between the self and other, which transcend the logic of mastery and appropriation and which eventually recast the existential terrain put in place by an atomistic ontology.

We thus might want to rethink modernist Western existential assumptions which are consolidated by such an atomistic ontology and explore renewed possibilities of relating to, as well as sensing and co-existing with the world and the more-than-human. That which Ursula Le Guin refers to as 'relearning our being in the world' (2017: 214) requires, according to Denise Ferreira da Silva, 'that we release thinking from the grip of certainty and embrace the imagination's power to create with unclear and confused, or uncertain impressions' (2016: 58). And this leads me to the central question of this text: Where do we start such a daring and radical undertaking of un-learning and re-learning? Or in other words: How can we, despite our limited relations to the more-than-human world engendered by Western cosmologies, connect with what lies beyond the limitations of what Western cosmologies lead us to believe and perceive? And how can we challenge our perceptions, question our understandings and, by doing so, eventually bring about a shift in our perspectives and our inherited conceptions?

This, I believe, is where the counter-intuitive results of experiments in particle physics and the concomitant descriptions of processes in the universe may come into play. Particle physics, as I will argue in the following, can be a trigger for a shift away from atomistic and anthropocentric perspectives by engaging with scales beyond human cognition, as well as an invitation to the construction of new imaginaries by upending post-Enlightenment Western ontological grounds.

Reimagining Atomistic Realities through Experiments in Particle Physics

To this end, I will turn first to the counter-intuitive results of experiments in particle physics, which, ever since the discipline's emergence, turned the assumption of the indivisibility of the 'indivisibles' (atoms) upside down and which continue today to yield descriptions of the 'nature of nature' that exceed the presuppositions of an atomistic ontology. The physicist Ernest Rutherford came to be known as the father of nuclear physics [4]: it was in 1909 – still under the scientific paradigm of the alleged indivisibility of atoms – that he paved the way towards an understanding of the subatomic world through a series of landmark experiments, in which he used nuclear radiation to examine the size and mass of the atomic nucleus directly. From the scattering distribution of the nuclear radiation striking a thin metal foil, Rutherford (1911) and his co-investigators deduced that every atom has a nucleus where all of its positive charge and most of its mass is concentrated. Three years later, in 1917, Rutherford (1919) performed the first artificially induced nuclear reaction: he exposed hydrogen atoms to nuclear radiation and as a result discovered the emission of a subatomic particle. After resolving [5] the atom into its nucleus, he had now resolved the nucleus itself: Rutherford had discovered the proton. However, these subatomic particles should not be understood as the new 'indivisibles' either: more than fifty years later, in 1968, deep inelastic scattering experiments conducted at the Stanford Linear Accelerator Center (SLAC) showed that the proton contained much smaller, point-like objects and was therefore not an elementary particle. By colliding electrons and protons,

the proton was found to consist of a certain number of elementary constituents, the quarks (Riordan 1992).

With the progressive unravelling of the atom, the world could no longer be described by means of classical physics: at the scale of atoms and subatomic particles, the physical properties of nature are governed by quantum mechanics. The probabilistic nature of quantum mechanics replaced the rigid certainty of the classical theory and revealed an unimaginably abstract world, which is strangely entangled and 'in which each existant's singularity is contingent upon its becoming one possible expression of all the other existants' (da Silva 2016: 59). With this in mind, da Silva ponders: What if we use the unimaginability and strangeness of the results and implications of particle-physical experiments as poetical descriptors and as an invitation to (re)imagine, as a trigger to question and rethink our blind faith in existing models of knowledge? In her account of an understanding of 'difference without separability', da Silva points to ways of opening up human understanding of the world to more imaginative modes of thought. By turning to the results of experiments in particle physics, she suggests thinking tools that do not reproduce the methodological and ontological grounds of the modern Western subject:

> What if, instead of the Ordered World, we imaged each existant (human and more-than-human) not as separate forms relating through the mediation of forces, but rather as singular expressions of each and every other existant as well as of the entangled whole in/as which they exist? What if, instead of looking to particle physics for models of devising more scientific or critical analysis of the social we turned to its most disturbing findings – such as nonlocality [6] (as an epistemological principle) and virtuality (as an ontological descriptor) – as poetical descriptors, that is, as indicators of the impossibility of comprehending existence with the thinking tools that cannot but reproduce separability [...]? (2016: 63)

While the dominant reliance on measurement, abstraction and quantification in positivist, mechanistic practices of science commonly reduces complex realities to mere data points – transforming the 'other' into a disenchanted, isolatable object of study and control – da Silva invites 'a figuring of The World nourished by the imagination' (2016: 58) that rejects separability as the foundational ontological principle. If we conceive of human existence through conceptual tools drawn from particle physics, the quintessence of co-existence lies in the impossibility of comprehending existence as separate and static, and of categorising existants as mutually exclusive subsets of the universe. Difference, as da Silva concludes, is thus no longer 'a manifestation of an unresolvable *estrangement*, but the expression of an elementary *entanglement*' (2016: 65, emphasis in original).

Multi-scalar Entanglements

I became vividly aware of my own entangled being in the following encounter: while participating in the transdisciplinary project *#eco-techno-cosmo-logical* (SFB42 2019) between diploma art students of the Academy of Fine Arts, Munich and graduate astroparticle physics students of the Technical University of Munich, we came to measure a fragment of a bark – a piece of matter that once formed the indispensable protective layer for a tree trunk in the Munich outskirts – for its intrinsic radioactive decays in an underground-laboratory of the TU Munich. This measurement surprisingly revealed the occurrence, in the cells of this bark, of the radioactive Cesium-isotope ^{137}Cs, which does not naturally occur and whose emission can only be associated with the nuclear reactor accident at Chernobyl in present-day Ukraine more

than 35 years ago, more than 1500 kilometers away.

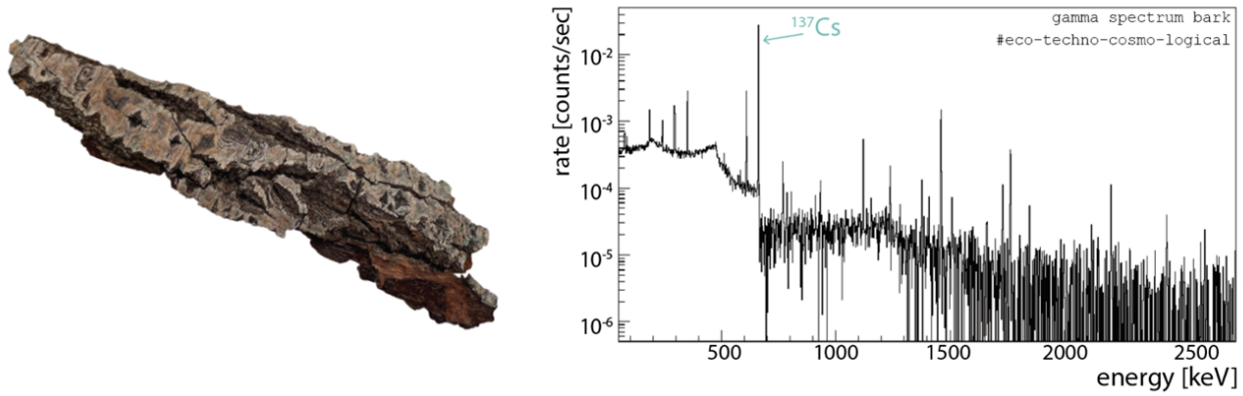


Figure 1: The gamma-ray spectrum (right) of the bark fragment (left) measured with a Germanium detector shows multiple discrete lines superimposed on a smooth continuum. Each discrete line corresponds to gammas (i.e. the highest-energy form of electromagnetic radiation) emitted at discrete energy levels that correspond to the characteristic energy levels in nuclei. The most dominant peak at an energy level of ~661keV can be unambiguously assigned to gamma rays emitted by decaying ^{137}Cs. Gamma Spectrum Bark, Munich, 2019. Courtesy of the SFB42.

Radioactive ^{137}Cs released into the atmosphere during a nuclear reactor accident can enter trees through leaf, root or bark uptake (Ertel 1991), lodge throughout the tree and remain there for decades. The manifestation of this substance, which imperceptibly outlasts long stretches of time and so unobtrusively and delicately traverses space, hence complicates any atomistic, static conception of external bodily boundaries as well as of the identity of the examined bark: the bark is not *just* bark, it is not ever clearly delineated, it is always open to its environment and is actively engaging in relations with the atmosphere, the soil, high-tech nuclear power plants and decaying subatomic particles. Just like the bark, also the human body is a natural emitter of radioactive gamma radiation (Health Physics Society 2016). Radionuclides are most commonly ingested through food intake and, such as in the case of ^{40}K, are often essential elements for the proper functioning of the human body. Conversely, the human body is then also always permeated with and traversed by imperceptible (yet in large doses biologically harmful) radiation from the outside, which may originate from natural radioactivity from the atmosphere, the earth, or, for instance, the bark of a tree. The radiation does not stop at what is conceived in an atomistic ontology as a seemingly defined, impenetrable bodily barrier.

So now I myself engage in an active relation as a researcher with the decaying subatomic particles in the bark that constituted in our measurement, and which since then have brought me to a far-reaching insight: understanding the complex dynamics of co-existence between the human and the more-than-human cannot be narrowed to a static and atomistic approach of scales and, emerging from this to separated and mechanistically determined classifications. Particle physics, and the experimental possibilities accessible therein, reveals how scales as well as boundaries are fluidly transcended and shows how the human body is constantly encountering unknowable others, thus being essentially 'transboundary' (Griffiths 2015: 43). The unique transdisciplinary setting of this inquiry inspired me to embrace more imaginative, fractal modes of thinking – namely thinking that resists linearity and reductionism and instead considers multiple scales simultaneously: the cosmic, the historical, the political, the organic and the quantic. Against this backdrop, human perception is rendered an effect of our particular space-time conditions and as such is always

specific to a certain context and to a certain scale. Thus, we know from the inadequacy of classical (human sensory-based) physics at the microscopic domain that the validity of human cognition is lost once the human scale is subceeded. It is, for instance, a human (and not an intrinsically physical) impossibility to intuitively grasp the properties of nature on the subatomic level – one might say we are conceived on the wrong scale. The ingrained universalism of Western cosmologies, which tends to ignore the situatedness of human perception, thus crumbles under consideration of the scales delineated by particle physics.

To conclude, this piece of bark is an active agent and an archive carrying historical legacies and material traces across time and space. In the process, it weaves together the history and politics of nuclear power in the Soviet Union, the subatomic realm, scientific practices and technological tools, the growth of a tree in the Munich outskirts, a group of inspired students of arts and physics – and becomes an emblem for the entanglement of the micro and the macro scale, the eco- and the technological, subatomic and macroscopic entities.

Landscape-Laboratories

When considering the concept of *landscape-laboratories* – these hybrid eco-technical infrastructures in astro-particle physics, where planetary bodies, terrestrial substances, and ecosystems merge with technical, scientific, and social entities – this entanglement becomes palpable. These complex experimental facilities – such as underground laboratories (in one of which the measurement of the bark's intrinsic radioactivity has been performed) or underwater neutrino telescopes – are constitutively transforming elemental terrestrial bodies into vast, multi-scalar sensory apparatuses.

Underground laboratories, such as the Laboratori Nazionali del Gran Sasso (located beneath the Gran Sasso d'Italia massif in Abruzzo, Italy) harness the shielding effect of the surrounding sedimentary rock in order to minimise the naturally occurring cosmic radiation that would – if not attenuated – render the search for rare events (i.e. imperceptible neutrinos and weakly interacting dark matter) impossible. The surrounding geological formations are not merely the infrastructural setting or situatedness of the experimental setups but their vital component and the indispensable condition for their functioning. Yet this 'natural shielding' differs fundamentally from technological artifacts purposefully designed and engineered to shield against cosmic radiation, such as low-radioactivity lead shields, polyethylene layers or active veto systems. Unlike these controlled materials, landscape-laboratories are inherently tied to the contingencies of the natural world. For instance, the flux of cosmic muons penetrating deep underground is subjected to seasonal variations. With the seasons, the water content in the rock changes, and with it the shielding power of the mountain. To enable the search for rare events, it is crucial to remain sensitive to such contingent variations and develop accurate and tailored models of the background particles reaching the situated detectors. Moreover, this specific situatedness brings about profound ethical, ecological and social responsibilities: while the Laboratori Nazionali del Gran Sasso is deeply embedded in the local ecosystem, its communities, culture and infrastructure (Jackson 2010) – thereby shaping the region's socio-economic fabric – it has also sparked protests and concerns from environmentalists and residents fearing, for instance, the potential leakage of toxic chemicals used in the neutrino detectors into the aquifers of the surrounding protected natural park (Nosengo 2003). In these underground laboratories, when elusive subatomic particles from distant cosmological sources in remote spacetime regions are being detected (in physics terminology, this is when the wave function of a particle collapses [7] upon observation), then the radiation 'rendered visible'

reveals itself as an imperceptible actor orchestrating post-human sensing assemblages and the implicated infrastructures, communities, collaborations, systems of knowledge. The particles' distant origins are found to be projected into our midst and the entanglement between cosmological sources, subatomic particles, planetary bodies, technical instruments, scientific institutions, local communities and eventually modern Western society is becoming tangible.

In a similar way, underwater neutrino telescopes take advantage of the properties of naturally occurring volumes of optically transparent water to identify high-energy neutrinos from distant astrophysical sources by measuring the secondary Cherenkov effect – an effect where high-energy particles generate faint electromagnetic radiation as they move faster than light in a given medium. These telescopes (such as ANTARES or P-ONE) usually consist of detector strings with light-sensitive optical modules embedded in the deep sea and distributed over a large volume of up to one cubic kilometre, where they are attuned to the faint Cherenkov light traces induced by cosmic particles. Yet they do not operate in a void there: these technologies are intimately interwoven with their natural, biological, material environments. For instance, underwater neutrino telescopes are not only attuned to neutrino-induced Cherenkov photons, but are also sensitive to their surrounding marine ecosystems: bioluminescent activity from marine organisms and the echoes of whale calls are among the environmental factors that must be carefully considered – thereby contributing to our understanding of deep-sea biology and marine ecosystems (Coyle 2022; Reeb 2023).

Thus, these landscape-laboratories are not laboratories in the traditional, positivist sense – they are not isolated, purified spaces cleaved out from the dirt, the noise and the intricacies of the natural world. They are dynamic sites that do not merely mediate the interaction between researchers and the phenomena under investigation but actively participate in shaping the conditions of knowledge production. The *laboratory* is no longer an evacuated, abstracted environment for experimentation, but is materially situated and deeply entangled with its surrounding *landscape* and is thereby engaging with the agencies, contingencies and complexities of nature. Far from being a passive or inert backdrop, the shielding rock in underground laboratories or the aquatic target in underwater neutrino telescopes actively shape what measurements are possible and what can be known and are thus inextricably linked to the functions and epistemic goals of the detectors. These laboratories embody a network of material agents and technological artifacts that, together with the prevailing scientific narratives and epistemic paradigms co-constitute research practices and their meta/physical implications, thereby reconfiguring the boundaries between *landscape* and *laboratory*, nature and technology, subject and object.

PART III – RESOLVING ATOMS: A QUANTUM ONTOLOGY

> *In my agential realist account, humans do not merely assemble different apparatuses for satisfying particular knowledge projects; humans are a part of the configuration or ongoing reconfiguration of the world – that is, they/we too are phenomenon. In other words, humans (like other parts of nature) are of the world, not in the world, and surely not outside of it looking in.*
>
> — Karen Barad (2007: 206)

Although these hybrid, multi-scalar infrastructures urge us to understand scientific inquiry as a relational, entangled endeavour – where non-human actors and material agencies co-shape the production of knowledge alongside humans – it seems to me, in my own work as an experimental physicist, that the modern sciences still lack reflexivity around their own epistemic practices. Scientific knowledge, along with its generative technologies, is commonly abstracted from the social, cultural and material conditions, in an attempt to cast an omniscient, disembodied, universal perspective (Haraway 1997). Nature itself, which is sought to be understood, is thereby rendered inert, passive and meaningless – a mere canvas for human investigation and interpretation. This is the classic disenchantment tale – so fervently fostered by modern sciences – which, as Jane Bennett (2001: 7) argues, 'construes the modern West as a radical break from other cultures' and portrays non-human nature as nothing but inert 'matter', stripped of all meaning and spirit. In the words of artist and researcher Jol Thomson, it is indeed 'an undeniable fact of history: over centuries of development the articulation of the modern sciences has constructed and upholds the deeply flawed notion of an indifferent universe, a disenchanted world and reality, where the liveliness of planets, planetary bodies, stars and nebulae, [...] are all essentially dead, without "purpose", knowledge, thought or life' (2021: 17). The largely unquestioned conventions of mainstream scientific jargon, through which physical descriptions and processes are communicated, draw from such Western-defined ontological ground and are profoundly entrenched in an atomistic ontology and commonly articulated through representational, objectifying conceptions of nature. In such articulation, the meaning of the terrestrial bodies is inevitably reflected merely in their physical significance and organised along the lines of a linear mathematics, unravelling them from their mattering and their latent possibilities. For instance, the terrestrial environs surrounding landscape-laboratories are quantified in terms of their overburden (i.e. the material that lies above an underground experimental site) in the units of *meter water equivalent* (m.w.e.), which is a standard measure of cosmic ray attenuation and corresponds to an attempt to unify and mathematise the soil. Similarly, in underwater neutrino telescopes, water is primarily characterised and referred to in terms of its optical properties, such as transparency, absorption length or refractive index. The rich vital, cultural, biological, dynamic dimensions and histories of the surrounding sedimentary rock, soil, water or ice of landscape-laboratories lie untapped. Also, the enfolding entanglements of landscape-laboratories with(in) a variety of (human as well as more-than-human) entities naturally remain unaddressed in a representational description of nature. Thus, I argue for considering the potentiality of particle-physical descriptions of the world to bring about a new ontological understanding, which transcends the existential terrain of an atomistic ontology and fundamentally reconsiders human relations to the more-than-human.

Recognising and questioning the conceptual lineages of theories and conventions elaborated in Western science, physicist and philosopher Karen Barad's (2007) theory of *agential realism* paves the way for such a reconsideration by substituting a representational understanding of phenomena with a performative one, and an atomistic ontology with a relational one:

> Shifting our understanding of the ontologically real from that which stands outside the sphere of cultural influence and historical change to agential reality allows a new formulation of realism (and truth) that is not premised on the representational nature of knowledge. If our descriptive characterizations do not refer to properties of abstract objects or observation-independent beings but rather describe agential reality, then what is being described by our theories is not nature itself but our participation within it. (Barad 2020: 235)

Barad's onto-epistemological framework of agential realism – a framework that builds upon the philosophical groundwork of quantum physicist Niels Bohr – reformulates our atomistic, human-independent, static and absolute conception of reality as an agential reality – a reality that is constituted from our participation within it. The phenomena, subjects and objects of this agential reality do not precede their interaction; instead, they co-constitute themselves from within their relationality and emerge through particular *intra*-*actions*. According to Barad, intra-actions can be understood as 'the mutual constitution of entangled agencies' (2007: 33). Or, in other words, since subjects and objects do not preexist as such, no agency can inhere in them as separate entities. 'Crucially', as Barad emphasises, 'agency is a matter of intra-acting; it is an enactment, not something that someone or something has' (2007: 178). Hence, in Barad's agential reality, agency is not attributed to mutually exclusive entities but rather emergent from the ongoing constitution of relations themselves and is thus 'cut loose from its traditional humanist orbit' (2007: 235).

Following Barad in describing the world based on quantum-mechanical observations, we find the material entities classified by particle physics as elementary or fundamental – particles such as electrons or quarks – as 'interwoven relations of becoming' (2014: 162): according to quantum field theory, an individual particle cannot reside as an independent entity – even when placed in the void of a vacuum – but is instead continuously intra-acting with the surrounding electromagnetic field via the emission and absorption of virtual particles (i.e. quantum fluctuations of the vacuum). Hence, from an agential perspective, the historical 'Rutherfordian' question of the potential divisibility of the 'indivisibles' – and correspondingly the formerly prevailing scientific taxonomy of elementary particles as indeed ultimate and separate entities – is deprived of its ontological fundament, which at its core assumed the existence of atomistic entities. Even more so, since although the transient virtual particles teeter in the realm of indeterminacy between being and non-being, they do *matter*. In this context, it is captivating to think that the bulk of the effective mass of a proton (and thus the mass of atoms and baryonic matter as a whole) does not originate from its constituent (valence) quarks but from the contributions of virtual particles. [8] Hence, contrary to a (classical) atomistic ontology and its conception of a dualism between particles and the void, a relational ontology drawn from quantum mechanics (thus a *quantum ontology*) manifests a world in which particles 'are not *in* the world, but *of* the world' and therefore, are inseparable from the void (Witzgall 2016: 97). In this respect, the void is to be understood as a realm of inter-agential becoming, where all things are formed in mutually constitutive relations to other things. And so it is, in this sense, the advances in particle physics that, by *resolving* the substructure of atoms and their constituents, have provided the intellectual framework to *resolve* the long-standing inadequacy of an atomistic ontology to encompass the complexities of entangled worlds.

Beyond the *being* of things, in Barad's agential realism also the *meaning* of things is contingent upon their relation to other things in perpetual formation: the ontological 'relations of becoming' thus have an epistemological counterpart in the relational becoming of phenomena and thereby in the generation of new knowledge. When we now, from this point of view, consider landscape-laboratories in their relationality, Barad's agential realism allows us to go even one step further than merely describing their ambient elementary-earthly matter as a condition (albeit an indispensable one) for their functioning. These laboratories do function and form new knowledge not because the Earth is instrumented as part of the experiment (or put even more brutally and from an anthropocentric perspective, because 'we make' the Earth part of the experiment), but – understanding relations as ontologically precedent – because of the becoming-Earth of the shielding, the target and the experiment as a whole. Hence, the *hyphen* which renders the two mutually dependent elements – landscape and laboratory – into a common one is the

operative nexus here. In other words, new knowledge arises from an inter-agential becoming of the observed phenomena in the mutually constituting relationality of the experiment with the Earth, and it thus emerges from the intra-actions between technical devices, soil, scientists, elementary particles, mathematical theories, systems of knowledge. Through this lens, landscape-laboratories emerge as crossings that are not 'amenable to the established categorical distinctions' (Bennett 2001: 96). They are sites of enchantment, where the wildness and contingencies of nature co-constitute the epistemic processes at work. Scientific inquiry does not unfold in an abstract, sanitised setting, but within the dynamic, living, agential matter of the natural world. To be accountable for the science conducted within these sites requires attending to what usually goes unnoticed: the marine species whose habitat these technologies invade; the subtle seasonal atmospheric or climatic variations that could bias the measured signals; the ethical and ecological responsibilities for engaging in these remote, often protected landscapes; the fears and concerns of the residents; the ties with local communities, their culture and histories. Attuning to these manifold constituting relations of landscape-laboratories in terms of their fusion with planetary bodies and organisms, terrestrial substances, local communities and their intra-actions further allows us to address their enfolding entanglements and – quoting Jol Thomson – is thus 'one way of gaining vital understanding of the lively agential capacities of earthly materials and non-human bodies – their complex modes of symbi-o(n)tic co-existence' (2021: 95). Becoming perceptive of this relationality in the context of landscape-laboratories also allows us to address a series of conundrums that inevitably arises from mechanistic models of classification: *Is the mountain that is shielding the experiment from naturally occurring cosmic radiation considered part of the experiment – or are there fixed boundaries between the two? What about the cosmological source generating the particles or the Earth's atmosphere against which they might collide? And the scientists who conceived this experiment – are they distinct? So, where does the laboratory end and the universe begin?* In agential realism, boundaries are never fixed, and distinctions are never rigid. Instead, they are momentary stabilisations of specific qualities of agential components which mark a reality that is open-ended and continuously unfolding. Only through specific intra-actions, these boundaries take on a certain character. Landscape-laboratories are not absolute, not passive, not precedent – on the contrary, 'they are productive of (and part of) phenomena' (Barad 2007: 146). Embracing boundaries in terms of a changing relationality thus dissolves the subject-object relation and overcomes the conditions that give rise to an understanding of planetary bodies and terrestrial substances as passive entities to be instrumentalised. Similarly, an ecology diffracted through a *quantum ontology* would recognise the landscape-laboratories' very intimate relation to land and their ontological co-constitution in the generation of new knowledge (epistemes) and acknowledge the agential capacities of elementary-earthly matter and terrestrial substances. Consequently, such a *quantum ecology* would necessarily be 'an eco-social political philosophy, a new cosmology' (Thomson 2021: 91). Hence, in view of the ecological responsibilities and ethical considerations that these landscape-laboratories evoke, what becomes clear is that the techno- cannot be untwined from the cosmo- cannot be untwined from the eco-logical.

CONCLUSION – PALPABLE CO-EXISTENCE IN PARTICLE PHYSICS

Thinking of co-existence from a perspective of particle physics conveys a radically new sense of co-existence: one in which the existence of entities is only constituted through their particular intra-actions with each other, thus revealing a fundamental entanglement; one which is characterised by the impossibility of

conceiving existants as separate, as unique, as static, as atomistic.

Since agency is understood as emergent from the ongoing constitution of the relations between these entities, it is no longer a purely human quality – in fact, in Barad's agential realism, agency is not a quality that can be understood as belonging to any singular entity. As such, it extends beyond the category of the human. Instead, the agential capacities of more-than-human entities are brought to the fore. The human is dethroned from its privileged position in the order of being and freed from its ontological and epistemological isolation. In such a revitalised understanding of human complexities and entanglements, it is also evident that new knowledge is never generated from a distance; instead it is constituted from our direct, situated and embodied engagement with the world and arising from an inter-agential becoming. Scientific inquiry, understood as relational and participatory endeavour, thus becomes a practice of *becoming-with*.

In practicing this process of knowledge generation, landscape-laboratories in particular emerge as sites of enchantment where the epistemic goals, possibilities and limitations of scientific inquiry are determined not purely by human intentions, but by the *becoming-Earth* of the experimental apparatus. By embodying entangled and situated modes of knowledge production, they hold the potential to reconfigure the Western-defined ontological and ethical frameworks through which we engage with the world. Landscape-laboratories challenge static notions of boundaries and question traditional dichotomies – between *landscape* ~ *laboratory*; *technology* ~ *nature*; *human* ~ *non-human*; *self* ~ *other*; *mind* ~ *matter*; *animate* ~ *inanimate*. The notion of humans as objective, disembodied observers, standing hermetically outside an absolute, human-independent reality is rendered untenable. [9] As such, these embedded laboratories are places of palpable relational co-existence.

ENDNOTES

[1] The basic ideas marking the starting point of this text are found in the philosophies of Leucippus and his pupil Democritus, who proposed that all matter consists of small indivisible particles, which they named 'atoms'. Along the line of reasoning of the text, the description of the historical move via Descartes towards 'modernity' is simplified, omitting complementary philosophical streams that exhibit atomistic features, e.g. those of Leibniz (Wilson 1982) or Spinoza (Buyse 2021).

[2] The 'modern Western notion of co-existence' referred to in the text contrasts with the definition of a 'sympoietic co-existence' as it is essential, for instance, in Donna Haraway's (2016) conceptual framework of the *Chthuhulucene*. The word 'sympoiesis' is derived from the Greek words *sún* ('together') and *poíēsis* ('creation, production') and means 'making-with' (Haraway 2016: 58). As reconfiguration of the *Anthropocene* – a more-or-less vague framing of a proposed geological era in the history of the planet shaped by significant human impact on Earth's geology and ecosystems (Rafferty 2022) – the Chthuhulucene de-emphasises human exceptionalism in favour of a multispecism. In this sense, humans are not the only important actors: they, along with other beings, are with and of the Earth, and the world is made up of ongoing multispecies stories and practices of becoming-with. The concept of the Chthuhulucene centres around the life of all species and creatures and their co-existence, and hence requires a fundamental rethink of relationality.

[3] I first encountered the evocative concept of *landscape-laboratories* in 2018 while hiking through the woods of the *Parco nazionale del Gran Sasso* together with Jol Thoms, Sille Kima and others.

[4] For a more physically accurate, historical account of the events leading up to Ernest Rutherford's discovery of the proton, I refer the readers to the article 'Rutherford, transmutation and the proton' (Campbell 2019) published in the CERN Courier.

[5] The term *resolution* is occasionally used in particle physics in the context of experiments that are intended to provide information about the substructure of particles. Analogous to the use of the term in photography – where *resolution* quantifies the amount of information contained in an image and, accordingly, the size of the structures that can still be visibly *resolved* – the term is used in particle physics in the sense that the substructure of an object (e.g. an atom or a particle) can be *resolved* by an experimental apparatus.

[6] The principle of nonlocality refers to measurements of a property of one particle that instantaneously provide the measurement of a related property of another particle, regardless of the distance between the two. Quantum nonlocality refutes the principle of locality, according to which an object can only be influenced directly by its immediate surroundings and any influence cannot propagate faster than light. It therefore 'goes against all the usual ideas about cause and effect and the nature of reality' (Nobel Prize Outreach 2022). However, due to the probabilistic nature of quantum mechanics, nonlocality does not imply that information can be transmitted faster than light.

[7] According to Bohr and Heisenberg's Copenhagen interpretation of quantum mechanics, the wave function – i.e. the mathematical description of a quantum state – provides a probability distribution for the outcomes of each *possible*measurement in a quantum mechanical system. The essence of an *actual* measurement in quantum mechanics, which connects the wave function with classical observables like the position of a particle, is the wave function collapse, namely its reduction from a superposed to a single eigenstate.

[8] The quark masses only add up to a mere 1% of a proton's mass – the bulk of the effective mass comes from the dynamics of virtual particles (Walker-Loud 2018).

[9] Through the figure of the 'modest witness', Donna Haraway (1997) conceptualises scientific knowledge and authority as inherently gendered, culturally specific and reinforcing dominant social structures. She exposes that 'objectivity understood as impartiality and a "view from above, from nowhere" is a perspective that under the guise of neutrality, or nowhere (but embracing all), hides a very specific position (male, white, heterosexual, human) and thus makes this position universal' (Rogowska-Stangret 2018). Karen Barad's work builds on Haraway's critique of the 'absolute observer' and points to liberatory ways of understanding scientific knowledge practices beyond the entrenched power structures of institutional research. Barad's (2007) agential realism offers an approach to the central question of how objectivity (as required for scientific research) can be achieved while allowing for situated and partial perspectives beyond patriarchal absolute control. To conceive of practices of knowledge generation from the standpoint of a Barad-inspired relationality – as discussed here in the case of landscape-laboratories – is to be responsible and accountable for the ways in which practices of knowledge are interwoven with the phenomena under study, and to acknowledge the mutual constitution of the observer and the observed.

GLOSSARY

Atoms are particles consisting of a nucleus (of protons and neutrons) and a surrounding cloud of electrons. An atom is the smallest unit of (baryonic) matter that has the characteristic properties of a chemical element – and as such is the basic building block of chemistry. Contrary to what is classically imagined, the electrons do not follow fixed orbits, but their positions are described by quantum mechanics as probability distributions (referred to as electron clouds) that gradually taper off the further one moves away from the atomic nucleus. The typical atomic radius is of the order of about 100 picometres. Compared to the distribution of electrons, the atomic nucleus is about 10000 times smaller and very dense. It contains more than 99.9 % of the mass of an atom (McGrayne 2023).

Baryonic Matter refers to matter composed of so-called baryons, a type of composite subatomic particle that contains three or more quarks. The proton and the neutron, both consisting of three quarks each, are the best-known representatives of baryonic matter. For this reason, the term 'baryonic matter' is also commonly used to refer to all objects made of normal atomic matter – i.e. for a large part of the matter present in the known universe (Britannica 2022a).

Eigenstates (the word is derived from the German word 'eigen', meaning 'inherent' or 'characteristic') are the measured states of some object possessing quantifiable characteristics, such as position or momentum. The state being measured and described must be observable (i.e. something that can be experimentally measured either directly or indirectly), and must have a definite value, called an eigenvalue. The eigenstate corresponds to a physical quantity of a quantum mechanical state described by the wave function (Bowman 2008: 8-10).

Electrons are stable subatomic particles with a negative electric charge. Electrons are thought to be elementary particles because they have no known components or substructure. Along with neutrons and protons, electrons are one of the three basic constituents that make up atoms. Inside the atom, electrons are distributed around the central atomic nucleus (Britannica 2024a).

Elementary Particles are subatomic particles that, according to the current formulation of the Standard Model of particle physics, have no discernible structure, i.e. they cannot be broken down or separated into smaller components. Accordingly, these particles are considered to be point-like (see 'Particle Physics'). For instance, quarks and electrons, among others, are described as elementary particles. In the past, this taxonomy was unwittingly applied to protons or atoms, which later were found to be composite particles containing two or more elementary particles (Sutton 2023). Historically, elementary particles were understood to be distinct entities. However, the contemporary concept of elementary particles is much more nuanced in the sense that particles are understood as excited states of their underlying quantum fields (see 'Quantum Field Theory').

Particle Physics is the branch of physics that deals with the properties, relationships and interactions of fundamental particles and forces that constitute matter and radiation. It is concerned with the structure of nature at the subatomic level and below. Elementary particles possess properties such as electric charge, mass and other complex characteristics, but are considered to be point-like (i.e. they have no known internal structure and are hence described as not spatially extended). All theories in particle physics are governed by quantum mechanics (Britannica 2022b).

Protons are stable subatomic particles with a positive electric charge. Protons are composite particles consisting of three valence quarks and transitory pairs of virtual particles. Along with neutrons and electrons, protons are one of the three basic constituents that make up atoms. Inside the atom, protons, together with electrically neutral neutrons, form the atomic nucleus (Britannica 2024b).

Quantum Field Theory is a mathematical and conceptual framework used in particle physics to construct physical models of subatomic particles. It uses principles of quantum mechanics to form an extended theory describing particles as excited states (also called quanta) of their underlying quantum fields (e.g. the electromagnetic field), which are more fundamental than the particles (Britannica 2022c).

Quantum Mechanics is a fundamental theory in physics providing a description of the behaviour of matter and light on the atomic and subatomic scale. It differs from classical physics in that properties of particles, such as energy or momentum, are restricted to discrete, quantised values. Importantly, quantum mechanics asserts a fundamental limit to the accuracy with which the values of certain pairs of physical quantities of a particle, such as position and momentum, can be predicted from a complete set of initial conditions. This uncertainty is not the consequence of technically remediable shortcomings of a corresponding measuring instrument, but of fundamental nature. Hence, other than the deterministic universe described by classical physics, the quantum universe is fundamentally probabilistic (Bowman 2008; Squires 2022).

Quarks are a type of elementary particle and a fundamental constituent of matter. They combine to form composite particles, the most stable of which are protons and neutrons, the components of atomic nuclei. All commonly observable (baryonic) matter is composed of quarks and electrons (Britannica 2022d).

Virtual Particles are theoretical interstate particles that exhibit some of the properties of ordinary particles. In quantum field theory, interactions between ordinary particles are being described in terms of the exchange of virtual particles, that is, of transient quantum fluctuations of the vacuum. Hence, virtual particles are 'quantised indeterminacies-in-action' (Barad 2012: 11). Their existence, however, is a purely quantum-mechanical phenomenon and limited by their fundamental uncertainty. Therefore, virtual particles cannot be directly detected, but are known to affect physical quantities, such as the mass of a particle, in measurable ways (Kane 2006).

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