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John Wheeler Between Cold Matter and Frozen Stars: The Road towards Black Holes

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Abstract. *One of the truly decisive figures in the flourishing of general relativity that began in the 1950s, the eminent physicist John A. Wheeler (1911-2008) is best known today to the general public because of the adoption of the phrase 'black hole'. Still, that seems quite a thin reason for scientific fame - the question, then, is: what did Wheeler actually do in that field? A proper answer has to take into account a plurality of levels, from Wheeler's peculiarly visual style to his interactions with his own school and other groups, from the pioneering uses of computers to his early visions of quantum gravity. That is what this paper offers, while tracing Wheeler's evolving positions - from rejection to enthusiastic acceptance and popularisation - during the fifteen years (ca 1952-1967) preceding the moment black holes became 'black holes'.*

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1. Following Wheeler's 'worldline'

Black holes are one of the main reasons, if not the main one, for which John A. Wheeler is known at large – more specifically, because of their name. Aside from the fact that the story of the name itself is more complex than its usual association with Wheeler, as we shall mention, it seems quite silly to repeatedly emphasise his adoption of the expression as his crowning achievement, no matter how catchy it could be. So, what exactly did Wheeler contribute to our understanding of black holes, especially when their investigation was still *ante litteram*?

Before trying to answer, a historiographical consideration is necessary. The reason to follow Wheeler's heuristic path and evolving ideas is not merely to fill a gap in available historical reconstructions; nor is it a simple attempt at intellectual biography. The remarks that will follow are not intended – or, at least, not only – as a 'psychology of research', even though we shall speak about Wheeler's peculiar style of doing physics. Our interest in following Wheeler's trajectory lies in the fact that, in such a heuristic flux, he drew in and involved a number of collaborators, a good part of whom were destined to become distinguished scientists. This was not merely a side effect, but rather an intentional part of his way of conceiving physics as a human enterprise and, more specifically in the period of our interest ('50s-'60s), of his way of considering the development of Einstein's legacy (or what he deemed so) as a collective effort. Wheeler's heuristic path is therefore a uniquely insightful 'worldline' that facilitates a more comprehensive understanding of research developments than what is usually accessible to individualistic approaches. Physicists and historians just looking at 'milestone papers', formulae and 'rock-solid' results are tendentially quite blind to Wheeler's crucial role in all of these developments, even if this role was certainly no less important than a first-class contribution. They thus face a paradox: while many of the main 'actors' of their stories – as achievers of clear-cut results – paid homage to and recognised the leading role and inspiration provided by Wheeler, the same man the community was going to follow when he adopted the name 'black hole', they (those looking at history in that way) have no clue why – or, at most, invoke some mentorship qualities and institutional functions,

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which remain vague and detached from the actual conceptual developments. With this in mind, let us try to follow Wheeler's footsteps, considering the kinds of influences he was under, his projects and goals, the results he had heard of, his other activities, and the people he interacted with or was aware of. Among the latter group, in a quite important position, there was also the young Roger Penrose; in these very days, people are celebrating him [2]: since I myself am a little in debt to him, I will gladly mention here and there a few curiosities I came across in archival material.

2. Wheeler vs. Oppenheimer at the 11th Solvay Conference ('58): the premises

Those who have looked more closely into Wheeler's activities during the '50s and '60s know that, at first, he was hostile to what came to be known as 'black hole', concept, which was slowly being developed following Oppenheimer and Snyder's results in '39 [1]. This opposition manifested publicly at the 11th Solvay Conference in '58, in Brussels. Einstein had died three years earlier; Wheeler, who had been a sort of *protégé* of his, was keen on presenting his work as an exploration and continuation of Einstein's vision – even though he meant by that general relativity, rather than his later unified field theory attempts. While he did not take the posture of 'Einstein's successor', since – as already said – he envisioned such a role for a whole community, he nonetheless liked to act as a sort of guardian of that legacy. These aspects are particularly evident in the very fact that he felt the need to explicitly discuss, in front of that public, the "Meaning of the term, 'Einstein's theory'" [2]. That was not the central point of the conference, of course. We have to then imagine the moment in which Wheeler took the floor and illustrated a number of results, by himself and his group, in gravitational physics – including the *vexata quaestio* of gravitational collapse. Oppenheimer too was among the audience. The result that he and Snyder got almost twenty years earlier was contested. At the end of Wheeler's talk, Oppenheimer took the word and disagreed with Wheeler. It was not much of a debate – indeed, Oppenheimer was not actively interested in the topic any longer. Wheeler, especially in light of an episode a few years later, would later maintain a bad memory of this disinterest, as he took it quite personally; for sure, they did not like each other, for a variety of reasons – and, after that brief clash of opinions, they went on their own separate ways. And yet, nine years later ('67, the same year as Oppenheimer's premature death), we find Wheeler in the act of baptising and enthusiastically popularising the term 'black hole', something that in return made him famous even beyond the specialists' community. What happened next is not the subject of this talk. What happened in-between is a story highly neglected, that I will try to reconstruct; but, in order to do so, it is first necessary to take a step back, to see what happened even before '58.

At the beginning of the '50s, Wheeler underwent a 'conversion', so to speak, that pushed him to gradually leave behind his established career as a nuclear physicist and invest instead in general relativity. That was not an ordinary move. As has been underlined by studies of the so-called 'Renaissance of General Relativity' [3], it is from this period on that a revival of research interest in that field took place – and Wheeler was certainly one of the key figures in this process. The very first years of this new phase of his have already been covered by Alexander Blum and Dieter Brill in their paper "Tokyo Wheeler *or* the Epistemic Preconditions of the Renaissance of Relativity" [4]. Still, there are a few things that I would like to highlight, since they played a role in the following and are important architectonic elements in a sort of *longue durée* view.

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[2] This speech was delivered a day before the ceremony awarding the Nobel prize for physics to Roger Penrose due to his theoretical contributions to the study of black holes or, more precisely, "the discovery that black hole formation is a robust prediction of the general theory of relativity". In his lecture, he indeed recognised the "instigation" of John Wheeler.

The first is Wheeler's heuristic methodology – he called it ‘daring conservatism’ (other versions include ‘dynamic conservatism’, which was also a slogan of Eisenhower) and it consisted, to put it simply, in rejecting all ‘free novelties’ in theorisation, while being faithful to already well-established principles and bringing them to their extreme consequences without additional elements. Even from the nomenclature the political overtones are evident; however, it would be misleading and oversimplifying to assume that it became an undue ideological interference in Wheeler's research. Actually, we shall have occasion to remark how daring conservatism, besides this quite straightforward definition, took other interesting shapes – in the same way that, in later decades, Wheeler used to remark about the shapeshifting character of quantum mechanics, with its different formulations, so we could say something similar about his shapeshifting daring conservative attitude. We may first of all notice that it represented, with its minimalist ontology and assumptions, a reaction to the particle zoo of those years, called by Wheeler, with a note of contempt, ‘pion industry’ [5a, 5b]. That was a period of crisis, in the etymological sense of ‘requiring a judgement’, and physicists had to take a moment and reflect upon the balance between theory and experiments, how to deal with the overflow of experimental data, how to face theoretically the new problems. Some were just adding *ad hoc* terms or building phenomenological models without much theoretical breadth, depending on the latest empirical inputs, and that was a way of doing physics that did not appeal to Wheeler. So, in that situation of uncertainty, he took a gamble and decided to dedicate himself to dusting off his mentor Einstein's legacy – according, of course, to the guidance of daring conservatism, that he claimed to have learned from his other inspiring figure, Niels Bohr.

Nonetheless, even if Wheeler detached himself from the mainstream of particle physics, the ambitious and fundamental problems he had tried to address would follow him in that new phase of his career. As paradoxical as it may sound today (at least if one does not have some historical perspective), general relativity was not, back then, a promising field of research: after successfully passing its tests, it did not seem to offer much room for experimental developments, and theoretically too it seemed quite a foreign body to the latest developments of physics. It was a theory in need of problems, in need of something to put people to work on – and this was soon going to be provided by Wheeler himself, among others. Given this, I propose that we consider the early sprouts of daring conservatism – that is, geons and wormholes, as we shall see in a moment – in a quite different way from the usual: namely, that they provided problems and models to work on, and their daring conservative character should be considered less apodictic and more interrogative. They were not accompanied by the entitlement of what had been ‘necessarily’ derived from established starting points – they were rather ways to explore and interrogate those starting principles themselves. This could already be seen as another ‘shape’ of daring conservatism.

So, what were these theoretical entities, geons and wormholes, and what purpose were they intended to serve? A geon is a mathematically possible, but physically unstable, solution of Einstein-Maxwell equations: a wave that, because of its own energy, self-gravitates and thus remains confined in a limited region of space, as if it were a body. Indeed, at first Wheeler was hoping that geons could offer him a new angle to tackle the ‘particle problem’, that is trying to derive the spectrum of purported elementary particles from something deeper. In the previous decade, his research was led by the slogan ‘everything is particles’, but now, after his conversion, he changed it to ‘everything is fields’: that means starting from a purely field ontology and somehow deriving particles. The geon, a field entity resembling a massive body, was thus meant to play the role of an intermediate step in Wheeler's ‘mass without mass’ program, i.e. considering mass not as a given, but as something derivable without introducing any ‘free novelty’, according to the principles of daring conservatism. More interestingly, during the '58 Solvay Conference Wheeler was already considering geons as simplified models to understand what goes on during gravitational collapse.

Now, ‘wormholes’. One should not think of them, in this context, as cosmic-scale Einstein-Rosen bridges, with cataclysmic processes leading to their formation, but mainly as handles in a topologically non-trivial [3] spacetime manifold: their use was to explain ‘charge without charge’, i.e. to reduce electric charge to a property of geometry, of field lines trapped in the throat of wormholes. The reason Wheeler considered them in the mid-'50s was related to the fluctuations of metric that he assumed took place near the Planck scale because of quantum effects: what he famously called ‘quantum foam’. Still, the '35 Einstein-Rosen paper [6] probably played a role in influencing Wheeler's attitude and program towards the elimination of singularities, as we shall see in more detail.

Next to these two attempts, there was also ‘spin without spin’, whose story is more contrived and less directly interesting for our purposes here, even though it did have an impact. This was related, clearly, to the ‘particle problem’, since, in the end, from pure geometry Wheeler also wanted to derive fermions. Through this spin without spin program, if it may be called like that, Wheeler put to work or inspired people such as David Finkelstein, and resonated a few years later with some ideas of Penrose. Similar facts, even if they did not result in a direct ‘solution’ to his problem, eventually paid Wheeler back for his efforts in unexpected ways.

So, to make a first summary, this early period can be characterised (at least for our purposes), into its fundamental guidelines of theorisation, by mass without mass, charge without charge, and spin without spin. All three of them were incarnated into concepts and calculations that could not really be called a success, in terms of short view of problem-solving; but, besides staying as a fundamental inspiration, the tools and results developed by Wheeler's students and collaborators were soon to find a sort of fruitful exaptation, being applied to a partly different situation from the original one in which they were conceived. They were, in a sense, recycled in the new questions that were gradually imposing more and more on Wheeler's attention – among these, needless to say, was gravitational collapse.

3. Gravitational collapse and mental blocks

Now, this problem, as we shall see, was strictly connected to other issues, which today we consider quite distinct. Without a doubt, however, Wheeler already recognised its importance in a list that he made right when he started to teach and learn (the two went hand-in-hand for him) general relativity. On one hand, there was the destiny of a massive-enough star at the end of its life; and that was indeed what brought Oppenheimer and Snyder, at the end of the '30s, to their result of ‘never-ending collapse’. On the other, there were the limits of the theory of general relativity and the nature of singularities, intertwined with cosmological issues and the destiny of the universe itself. No wonder that gravitational collapse was going to be a turning point in Wheeler’s thought as well.

Wheeler's strategy to avoid singularities and other problematic conclusions was to intervene in the analysis of the process that purportedly leads to them: and that is why in '58 he contested Oppenheimer, on the basis of the results he himself had obtained with his collaborators Harrison and Wakano [2, 7]. Let us mention a couple of relevant points.

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[3] Indeed, the rise of modern topology in theoretical physics has in these matters – from Wheeler’s early intuitions about its role.to Misner’s and Finkelstein’s pioneering efforts, to Penrose’s use of it in his fundamental results – an important chapter which, in good part, is still waiting to be written.

Wheeler's idea was that Oppenheimer and Snyder had neglected too many physical aspects in their simplified (or oversimplified) collapsing dust model. Besides the highly symmetric starting conditions, which were considered 'unrealistic' by others as well, as we shall mention, Wheeler's two main objections concerned the neglect of the possibility of radiative processes that could make mass-energy escape from the collapse; and the neglect of what happens when nucleons are put together at tremendous pressures and densities. Wheeler expected a new phase of equilibrium for 'cold matter', that is, stellar matter after the thermonuclear cycle of the star had finished; on the contrary, Oppenheimer and Snyder suggested that no equilibrium was ever reached. Even presuming that their assumptions were valid, there was the issue of making sense of such a conclusion and of the consequent cutting off of a system from the rest of the universe. That was something quite hard to conceive as acceptable, especially for someone like Wheeler (like a good number of others, at the time) who was trying to make use of (his own) version of Mach's principle: if someone entertains the idea of explaining mass through interconnection, how come the 'compression' of mass itself could lead instead to some sort of isolation?

Thanks to the MANIAC – the computer wanted in Princeton too by von Neumann – Wheeler asked Wakano to perform integrations and explore computationally what they expected. I think this offers a new angle to look at daring conservatism and make a couple of further observations about it. One is that it seemed to interact well, even in these pioneering phases, with computers, which were, in a sense, a sort of accelerator in the process of surveying the ultimate consequences of given assumptions. That is another metamorphosis of daring conservatism. The other point, however, is that, at this stage, Wheeler seems to have betrayed daring conservatism, by introducing that 'new phase of matter', otherwise unmotivated. Sure, it is possible to object that he was acting like that in order to avoid apparently meaningless or unphysical consequences and, before accepting them, he was thus daring-conservatively exploring the possibilities left open by more general and habitual assumptions about our physical picture of the world. There is, nonetheless, some tension between this postulated new phase of cold matter and daring conservatism.

If all that was not enough, we should also speak about the issue of singularities. 'Singularities', plural: even if we are dealing with the Schwarzschild solution, and nowadays everybody knows that the one corresponding to the Schwarzschild radius is fictitious and can be removed through a mere change of coordinates, the situation was much more confused at the time. If, in general, Wheeler was probably influenced by Einstein's attitude (even if that had quite a complex story of its own, too), namely – as the latter had written in the already mentioned '35 paper with Rosen – "a singularity brings so much arbitrariness into the theory that it actually nullifies its laws" [6], he was probably aware of Einstein's '39 work [8] too (the same year of Oppenheimer and Snyder's). In that paper Einstein had got the result that the spherical orbits of a system of gravitating masses have as a minimal radius a quantity still larger than the Schwarzschild radius; and Einstein was hoping that something similar would hold also in more general cases. This was mainly done for his own satisfaction, as suggested by Earman and Eisenstaedt [9a], rather than as a contribution to the literature on that topic, in which Einstein was not interested – something similar, in fact, had already been obtained first by Hilbert and then by Hagihara. All in all, these aspects may have contributed considerably to Wheeler's early rejection of Oppenheimer and Snyder's work: if he already had doubt about the physical relevance of the process they had sketched, their conclusion almost seemed a *reductio ad absurdum.* Not to mention the issue of the central singularity: even for the 'fictitious' one there was that sort of prejudice, reinforced by the paradox that the Schwarzschild radius was supposed to be reached within a finite time for an observer on the surface of the collapsing star, whereas for an external observer it would appear as taking an infinite time. Nonetheless, Wheeler's '57 work with Tullio Regge [9b] already shows an attempt at getting geometrical insights into what they called "Schwarzschild singularity".

All those factors, in any case, gave substance to that 'mental block' which, in Kip Thorne's words [10], affected Wheeler and other scientists at the time, preventing them from embracing and developing Oppenheimer and Snyder's result. The way Wheeler gradually overcame this mental block allows us to see how something that at first seemed inconceivable turned out to be, echoing Chandrasekhar [11], a most perfect incarnation of geometry in nature. It is not a coincidence that, in such a process of understanding black holes, a key role was played by people who had a distinctively pictorial or concrete way of conceiving physical processes, such as Wheeler and Zel'dovich, or markedly geometrical, such as Penrose. This, by the way, is not something that can be said only in retrospect: Wheeler himself was aware of it, as he would later (and not so later) write in a '69 letter, when he was asked to express a judgement about Penrose [4]:

> I always rate in the top category Zel'dovich in the USSR […], Penrose in the UK, Misner at Maryland and Thorne at Cal Tech […]. Each of the first four stands at the top of the quartet in at least one regard: Zel'dovich in overall physical insight; Penrose in powers of mathematical analysis and absolutely unique depth of his geometrical insight; Misner in physical originality; and Thorne in his unmatched productive power in applying general relativity to issues of lively astrophysical interest.

There is no need to add that, among these four people, there was Wheeler's homologous in the Soviet Union [5], two of Wheeler's students and collaborators, and one from Wheeler's enlarged circle, so to speak.

3. Lifting the paradox

Going back to Wheeler's path from '58 on, we can see how the previous points substantiating the mental block were either solved or transformed. We will now highlight a few important steps that directly show Wheeler's involvement, as well as the ways he was able to involve other people. The paradox of finite/infinite time and of the singularity in correspondence to the Schwarzschild radius was to be lifted thanks to a series of results that helped understand better the Schwarzschild solution. Nowadays the Schwarzschild solution is usually presented as a simple topic in all introductory courses on general relativity, together with a discussion on coordinate changes and so on. In this way, all the stratigraphy, so to speak, of the gradual comprehension of those properties is thrown away. We have to instead keep in mind that a good number of the insights that we take for granted today, as if they must have been evident to Schwarzschild himself, are actually the result of a long and quite contrived story, interconnected with a more general debate on singularities, to which an impressive list of names gave their contributions: from Hilbert to Hadamard, from Felix Klein to Weyl, just to name the eminent mathematicians involved in the first few years; and then, of course, Eddington, Lemaître, Richardson, Synge, besides Einstein himself [9]. The various discoveries and re-discoveries of coordinate systems and singularity treatment attest to the

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[4] Wheeler to McCrea, 2 December 1969, in J.A. Wheeler Papers, Box 20, American Philosophical Society Library, Philadelphia.

[5] This parallelism is not a mere coincidence: both involved in the hydrogen bomb projects, they realised how the understanding of related physical processes and the computational resources that had been developed in view of that weapon could be applied also to the study of gravitational collapse. Throughout the '60s, they were keeping an eye on each other's work and, after meeting in person, they established an admired and cordial relationship, even more evident in the friendship between their respective pupils, Thorne and Novikov. A nice conclusion to the story, from a human point of view and not only.

confusion with which the ‘actors’ themselves were affected.

The already mentioned David Finkelstein, although he was not Wheeler's pupil *stricto sensu*, had been influenced by the agenda set by him, such as spin without spin, and had various interactions with Wheeler's most important collaborator of that period, Charles Misner. And it was in '58 that Finkelstein noticed, while working (in dialogue with Misner) on spin-without-spin-inspired ideas (as he recalled in a later interview [12]), how in a Schwarzschild scenario time reversal symmetry no longer holds and the surface corresponding to the Schwarzschild radius is not a true singularity, acting instead, in his words, “as a perfect unidirectional membrane: causal influences can cross it but only in one direction” [13]. That is the reason for the title of the short paper “Past-Future Asymmetry of the Gravitational Field of a Point Particle”, which is nowadays recognised as providing the decisive interpretation of what later came to be known as the black hole horizon. The paper is often referenced when speaking about the so-called Eddington-Finkelstein coordinates, even if they are not explicitly present there – besides an early recognition to Finkelstein by Penrose in his '65 paper on singularities [27], the nomenclature of coordinates was made popular by Wheeler himself and Misner and Thorne, in their well-known textbook “Gravitation”. The paper was not particularly noticed in the West, while in the Soviet Union it caught Landau’s attention and that of people related to him such as Lifshitz and Khalatnikov. Nonetheless, also in the West, Wheeler must have taken notice of it. Later, when Finkelstein went to London to give a lecture about his results, Dennis Sciama, who was, together with Wheeler and Zel’dovich, the third great leader of the main groups that were going to work on gravitational collapse and related topics throughout the '60s, invited Roger Penrose to go and listen to him. This ability to put the right people to work on the right problems is something that notoriously characterised Sciama’s mentorship; a quality he shared with Wheeler, we may add.

Penrose was already interacting with Wheeler’s circle during those years: in '59-'60 he went to the US as a NATO fellow, and there still exists a fragment of the letter from Sciama to Wheeler, dated March '59, in which he wrote [6]: “I would like to mention that a pure mathematician turned physicist would like to visit your department for a year. His name is Roger Penrose…”. In any case, going back to our story, Penrose followed Sciama’s advice and, after a discussion with Finkelstein at the end of the talk, he got from him an interest in black holes – with the usual anachronism of the expression, of course – and Finkelstein received in return some ideas about modelling spacetime as emergent from a combinatorics of discrete elements, which he would develop in ways not too different from Penrose’s twistors.

At the time of his paper, Finkelstein, as he later recalled [12], also spoke about such matters with Kruskal, who in turn knew Wheeler since he was involved in the Matterhorn project. Kruskal was procrastinating on the publication of his own work on coordinate change, which would appear two years later, in 1960, in the paper “Maximal Extension of Schwarzschild Metric” [14]. If that is not enough, that paper was in part co-written anonymously and sent for publication by Wheeler himself, who had realised its importance.

In ‘60 another paper came from Wheeler’s circle, by Dieter Brill and John Graves: “Oscillatory Character of Reissner-Nordström Metric for an Ideal Charged Wormhole” [15]. The adjective ‘ideal’ is quite a meaningful frame for the way wormholes were being considered by Wheeler and collaborators; indeed a number of those results, also in light of the symmetry with respect to the throat of the wormhole, were later employed in the ‘halved’

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[6] Sciama to Wheeler, 16 March 1959, in J.A. Wheeler Papers, Box 20, American Philosophical Society Library, Philadelphia.

scenario of a black hole (in the Reissner-Nordström case, a charged one). An important point mentioned in the abstract is the awareness of pseudo-singularities that can be removed through coordinate transformation; after all, there was no automatic and universal criterion to determine whether or not a singularity was due to an arbitrary system of coordinates behaving badly. The genesis of this paper, as Brill told me, involved the undergraduate John Graves playing with coordinate transformations on the blueprint of the Kruskal one; after finding something that seemed curious, he involved Brill, who systematised and added a few pieces, and they discussed it with Wheeler, who offered further insights based on his physical intuition. In particular, it was shown that, thanks to the electric flux in the wormhole, the throat oscillates instead of pinching off as in the case of a Schwarzschild-like wormhole. In consideration of how a further physical aspect such as electric flux could change the scenario, it is not too far-fetched to remark that something similar was already hoped for by Wheeler in his objections to Oppenheimer and Snyder. However, the intrinsic curvature near the throat becomes infinite, so the singularity issue was still there. The throat being open could also present a problem in terms of causality, when considering two points in the regions connected by the wormhole as a 'shortcut'.

It is not surprising that a couple of years later, in '62, a sort of follow-up paper to Brill and Graves was published by Wheeler himself with another young student, Robert W. Fuller. Together they tackled similar issues in the case of the Schwarzschild-like wormhole; the title was "Causality and Multiply Connected Space-Time" [16a]. A couple of aspects are worth highlighting. One is that, since it was shown and accepted that even light could remain trapped, the strategy that Wheeler adopted to avoid the central singularity was one that he continued using from that point on in order to propagate his bolder ideas. Rather than trying to pre-emptively halt the process leading to that problem, hoping that some form of radiative mechanism could do the job, he invoked the quantum gravitational Planck-scale effects he had been preaching since the mid-'50s, under the label of 'quantum foam'(just 'foam' in that paper). The singularity was obviously an inadequate representation of what was physically happening, an *asylum ignorantiae* that also marked the limits of the theory (and thus, of daring conservatism applied to 'Einstein's vision'); but it indicated even more the need for that 'fiery marriage' between quantum physics and general relativity, which is the still open question of quantum gravity. Wheeler was starting to see the 'opportunity' offered by the singularity, in a sense combining Einstein's aforementioned attitude with that of Landau, one of whose maxims said that "physics begins where a singularity occurs" [17] – a *new* physics, Wheeler may have added. Another curious aspect of this '62 paper is that Niels Bohr himself is mentioned in the acknowledgements. This seems quite bizarre, since, at least to the best of my knowledge, there is no story about 'black holes' directly involving him. Apparently, according to what is written there, during a visit to Bohr in '58 Wheeler expressed his concerns about these matters and Bohr's oracle suggested that he should investigate causality, as he did four years later. Now, we may even surmise that Wheeler used some loosely related conversation as a pretext in order to get Bohr interested (unfortunately, he died a month after the publication); or we could remark that invoking Bohr was a typical strategy for Wheeler, who was always keen on paying tribute to him and, at the same time, grounding his own attempts under his illustrious 'patronage'. In any case, with quantum foam 'patching' for the moment the singularity, and with the throat being *de facto* closed even for a photon, causality was secured in the sense that shortcuts in a communication between two points in a multiply-connected spacetime manifold did not seem allowed. In another paper by Wheeler [16b], published in the same month (October '62), he wrote that "it would seem essential to establish a theory […] which would connect the issues of topology, causality, and singularities"; and, even more interestingly, he refers to the "[c]onjecture that every 'properly closed space' ultimately develops a singularity" and repeats: "Inevitability of singularity in classical solution implies conditions always develop where quantum character of geometry cannot be escaped”. In short, from the inevitability of the singularity to the inevitability of quantum foam. That “conjecture”, by the way, obviously rings a bell when thinking about Penrose’s first result developed a couple of years later; we may also remark that Wheeler had already heard something similar in the previous decade, from his former student A. Komar (for an overview of those early results, I redirect to [16c]). Wheeler was starting to come to terms with all of this in physically relevant terms as well; this is something which should not be taken for granted, since during that period Lifshitz and Khalatnikov, for instance, were convinced to have shown that the formation of singularities occurred only under very specific and unrealistic circumstances [16d].

4. The turning point: the pieces of the puzzle

We have noticed how in the '62 paper there seems to be a change of strategy – indeed, Wheeler would go on to transform the issue of the central singularity into an opportunity to propagate and push his own ideas and expectations about quantum gravity and future physics. But what brought about this change? This question is strictly linked to our attempt at identifying the precise moment of Wheeler’s new ‘conversion’. Once our reconstruction reaches this point, however, we are faced with the two existing accounts of how Wheeler got ‘convinced’; both of them are relevant not only for this particular issue, but for broader considerations as well. One is given by Kip Thorne [10], Wheeler's student and subsequent collaborator since the early '60s, who indicates the turning point in new geometrical insights. The other is to be found in an interview [11] with Stirling Colgate, who worked with Wheeler in the Matterhorn Project before pioneering the use of computers in astrophysical matters; indeed, he implies that the decisive role was played by computers. Let us examine the two versions in more detail, in light of the previous considerations.

According to Thorne, the turning point for Wheeler (and for him as well) was a Master's thesis in ‘62 by Beckedorff [18],a student of Misner’s, whose development presumably took place in '61. Thorne called it an “eye-opener”, in the literal sense: building upon the new systems of coordinates that had become available and their related insights, it determined the boundary conditions between external and internal regions in a Schwarzschild scenario, thus providing the first ‘embedding diagrams’ that gave a dynamic idea of what happens in the process of collapse. These were the powerful visual tools that Wheeler needed to form a satisfying mental simulation or image without which, as he used to say in full generality about physics, he could not achieve a proper understanding. Beckedorff’s thesis can thus be regarded as the culmination of the previous series of results. However, reducing or dismissing the whole process of overcoming prejudice and rejection by just saying that some change of coordinates convinced Wheeler is clearly over-simplistic and wrong. On the one hand, those developments allowed him to solve the issues represented by the rough contrast of finite/infinite time and the fictitious singularity at the Schwarzschild radius. On the other, they did not only offer a visualization tool to imagine what could happen, but rather a different *point of view*, helping Wheeler realize that the exclusive focus on the star getting smaller and smaller was, so to speak, a distraction preventing him (and others) from realizing what goes on in terms of spacetime geometry. After all, at the 11th Solvay Conference, while speaking of an already ‘very Einsteinian’ Riemann, he himself had declared, with a beautiful expression, that “space is not an abstract mathematical construction that stands unmoved above the battles of matter and energy” [2]. This shift of attention is also the reason Wheeler later liked to emphasize the aspect of ‘hole’, instead of referring to the star undergoing collapse, while earlier the nomenclature focused precisely on the star: ‘collapsed star’ or, in the Soviet Union, ‘frozen star’ (not to be mistaken for another usage of the phrase in more recent times).

For someone unconvinced by Oppenheimer and Snyder's results, or better by their physical relevance, all those mathematical developments, as much as they could offer physical insights, could still be not enough to overcome the previous resistance. After all, at the beginning of Beckedorff's thesis, Wheeler is explicitly engaged as *the* objector, and his expectations of finding some new phase of stability for ‘cold matter’ are mentioned. Oppenheimer and Snyder had neglected so many physical processes that Wheeler argued it was no wonder that they ended up with nothing to prevent a paradoxical ‘continued collapse’. While Wheeler was asserting that the conclusion of no equilibrium being reached was a *petitio principii*, the same objection was levelled against him by Misner and Beckedorff: the assumption that an equilibrium phase had to be found, with a new state of matter, was also debatable. This is, we may say, that kind of tension with daring conservatism we previously commented upon. While they did not expand much on their remark, it is worth adding at this point that another Master’s thesis in that period, by Allen Mills [19], convinced Wheeler (with whom he was working directly) that, in his own words, “[a]ll radiation of all kinds […] can be fully trapped around a sufficiently concentrated mass” [5a]. That delivered a lethal blow to his early strategy of singularity avoidance, abandoned in the '62 paper with Fuller.

All that seems to offer a confirmation of Kip Thorne’s account of Wheeler’s conversion. Let us listen now to the other account. According to Colgate, the turning point was represented by the results offered by computers, and he even said that he was there when Wheeler somehow got ‘converted’. The suggested timing seems, again, around '62. Now, the two accounts are not necessarily in contradiction: they are surely both reliable in pointing out crucial factors in the development of Wheeler's positions; the challenge, of course, is to combine them coherently and chronologically. One must, first of all, remark that the two sources are not on an equal footing: while Thorne's account is based on a more comprehensive personal involvement with those issues, as well as on conversations and interviews (and he does not neglect the role of Colgate himself), Colgate's account is definitely more unilateral and fluctuating, based exclusively on personal memories – indeed, that is what often happens in interviews made a good number of years after the fact. Another problem is that, due to military secrecy, a relevant part of Colgate's work is still obscure, and he has definitely received less historical attention than he deserves. There is also a short written recollection by Richard White [20], Colgate's collaborator in that period, which adds some details that allow us to reach a slightly different interpretation to Colgate's recollections. Let us see how.

In ‘60 Colgate, concerned with cosmic rays, was already working on supernovae; soon White joined his efforts, thanks to his expertise in computer coding. Livermore was their base, where there was also Teller, Wheeler’s friend – but they were quite far away from Princeton. As Wheeler himself would write in '68, “at the Lawrence Radiation Laboratory of the University of California at Livermore, California, there stands an impressive electronic computer. It predicts the performance of fission and fusion bombs far more complex than the Alamogordo device” [21]. If one pays attention to Wheeler and Fuller’s '62 paper, it is possible to notice that “Part of this work was done at the University of California, Berkeley, California while the author (JAW) was on leave of absence from Princeton University” [16]. That puts our actors together in the right geographical area. While it is not entirely clear, at least at the moment (while waiting for other sources), what Colgate and White’s early attempts consisted of, we can be sure that they did not involve general relativistic effects at all. As White himself says [20], it was only in '63 that Wheeler, with quite a long trip, brought them some people from his circle, in order to implement general relativity as well; and only in '65 that the same

White, with Michael May, had some results ready, after tackling directly the issue of gravitational collapse [22]. All this is confirmed not only by checking Colgate and White's publications from those years, but also by a letter I found recently , dated November '64 [7], in which Misner suggests to White some basic references to learn the Schwarzschild metric. Without a shadow of a doubt, we may conclude that, even giving credit to Colgate's recollections, what ‘convinced’ Wheeler around '62 was *not* some general relativistic calculation. At this point, we could decide to postpone the year that, perhaps incorrectly, he was referring to, but then the role of calculators would have been (at least for Wheeler's path) limited to mere corroboration. Alternatively, considering that in '63 Wheeler decided to deploy those resources and interact more with the West Coast, it is also reasonable, if not unavoidable, to assume that he saw something worth investigating in the previous year.

Even without general relativity, Colgate and White had found in their computer work on supernovae, that, following Fowler and Hoyle’s assumptions about certain stars at the end of their thermonuclear evolution, the different kinds of pressures that were expected to counterbalance the gravitational one were insufficient to prevent collapse. Now, it is worth remembering that Wheeler too came from a background similar to e.g. Fowler, a nuclear one *lato sensu*, and he too was expecting physical mechanisms – neglected by Oppenheimer and Snyder – that were capable of stopping the collapse. It is not at all far-fetched to assume that, seeing those results by Colgate and White, Wheeler also abandoned part of his resistance on that point, exclaiming, according to Colgate [11]: “The big deal, Stirling, is that it makes a reality of these things!” – and here I call the philosophers’ attention to the phrasing. Another comment: Colgate was not shocked by the results they were obtaining, as he somehow just accepted the physics he was using at face value. Something similar happened during those years – not in front of a computer, but with paper and pen – for Novikov, Zel’dovich’s main collaborator in the theoretical study of black holes, who in turn accepted at face value what his calculations were telling him, without mental blocks or other epistemological concerns. We could say that this younger generation were being indeed daring conservative with the physics they were receiving in their hands; or, perhaps, they were just bolder and more naïve, as is typical of the lack of experience. In any case, after that moment Wheeler decided that, at the very least, a full general relativistic model was worth investigating thanks to the calculators – hence the importance of bringing his team together from coast to coast.

We may have doubts that Wheeler was entirely convinced like that about ‘black holes’ – it would be better to say that he promptly integrated the new results in the mental picture that he was composing. This is quite different from the epistemological status granted by many accounts of the role of computer calculations and simulations, wherein writers often project their assumptions back to those early years: for gravitational collapse, the role was surely not played by analogue ‘experiments *in silico*’ or ‘one-shot’ simulations. Instead of a model offering the eyes a ready-made way of putting together a pictorial narrative of what is going on, in this case there were numerical results obtained in some outdated (gravitationally speaking, even Newtonian) theoretical scheme of calculation, which nevertheless, thanks to Wheeler's expertise and acumen, became relevant in informing and constraining his mental picture of the essential processes. A mental picture that was not merely mimetic, in the sense of ‘copying’ and picturing what an entity should look like: especially in heuristic phases like that, the focus is more on a few dynamical aspects that, once understood, have to innervate the space in which a synthesis takes place *later*, to offer everyone an image of the phenomenon under examination. With a bit of a provocation but in all seriousness, I would even suggest

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[7] Misner to White, 6 November 1964, in J.A. Wheeler Papers, Box 18, American Philosophical Society Library, Philadelphia.

that, in order to grasp this, a distinction made by Reviel Netz [23a] between ancient Greek and modern geometrical diagrams is more useful than the usual literature on computer simulations and visualisations. Netz has commented on the way ancient geometric diagrams were "schematic", not being meant to offer a refined mimetic picture given all at once; for this very reason, they played an important and *active* role in reasoning, even while leaving unspecified or open-ended some elements in a "productive ambiguity", to borrow but use in our own way Emily Grosholz's expression [23b]. On the other hand, nicely polished and detailed modern diagrams seem – rather than schematic – pictorial, even ornamental, at most a pedagogical aid [8]. Perhaps something similar to the latter case can be attributed to some of the representations of black holes that Wheeler himself was going to disseminate in the following decades, on his colourful blackboards and in textbooks such as "Gravitation", but the partial aspects he was trying to integrate during the heuristic phase we are considering here were just providing some guidelines or relations that he had to synthesise in a sort of mental picture. In other words, all the heuristic process sketched above could be considered like a sort of 'schematic' macro-diagram [9]; more conventionally, we could add that, at least for Wheeler's demands, even those simple-looking (indeed, schematic in the colloquial sense of the word) 'embedding diagrams' could hold the key to the apparently inconceivable extreme events under exam. Both observations can be reinforced by Thorne's somewhat vague recollection [10] of a day in the early '60s when Wheeler came back enthusiastically from a visit to Colgate and started to draw "diagrams" on the blackboard: even in the case they were not yet full-fledged embedding diagrams, the results on supernovae that were being obtained by Colgate and White triggered Wheeler's mental simulation or visualisation of what is physically supposed to happen. Actually, we may even suggest that, precisely because of the peculiar character of *black* holes, their study needed first a 'schematic', even topological ability to highlight the relevant processes, and then years of joint work to provide 'pictorial', or better (given the fame obtained only very recently by their 'picture') proto-pictorial, representations. Staying within the topic of black holes, we could also add that the famous Penrose's diagrams too, of course, could be called 'schematic' in the aforementioned sense; something similar was suggested in [24], with reference to the notion of 'paper tool' (which stresses, in turn, that active role remarked above).

Aside from these distinctions, what has to be underscored here is a form of mental imagery shaped by numerical results, technical details, formulae: this can be used, more generally, to understand the pictorial way of thinking by physicists such as Wheeler. I believe it is misleading, at least at these levels, to consider a mental picture as some sort of crutch for those who do not feel at ease in the realms of abstraction, or as a mere idiosyncratic epiphenomenon. Rather than regarding it as some kind of inferior act of cognition, we are dealing with something that is gradually prepared at higher levels: it should perhaps be considered as a sort of analogical calculus in which one does not merely play, *cum grano salis*, with more or less inadequate pictures while looking for inspiration, but, after black-boxing some aspects, actually manipulates and shapes those pictures, thanks to the technical and punctual information they encode in the mind of the visual thinker. We could speak of a coarse-graining without the loss of the relevant details: a highly effective, at least when it

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[8] Of course, the point here, daring conservatism notwithstanding, is not the contraposition ancient/modern, with the visceral reactions it may create out of context…

[9] As much as this may sound bizarre, Wheeler himself used to have the fancy idea of depicting all physics in the form of a giant diagram, not unlike the ceiling of the Sistine Chapel. Besides this, we should also comment that our emphasis on heuristics is not a contingency due to the topic we happen to be dealing with: when a satisfying analytical treatment is already available too, one *may* feel more the pressure of the 'rigorous' counterpart of treatment and, therefore, get more rigid and over-informatively 'pictorial' (in Netz's sense) in the visual reasoning as well. Hence, at least in this case, our focus on heuristics, even if, in principle at least, those results could have accessible through an analytical treatment too.

works, way of handling complexity. It is not a coincidence that Wheeler's teaching, instead of simply leading to generations of people gullible to pictures (or inclined to over-emphasise them), impressed its mark on other distinguished physicists who, in turn and in their own effective ways, employed considerable visual styles in their contributions to science.

Apart from these considerations, it seems quite reasonable to conclude that, next to the work by Allen Mills, what Wheeler saw in Colgate and White's early research undermined his matter-related objections to Oppenheimer and Snyder, while Beckedorff would soon provide a satisfying tool for visualisation; and so, we can coherently integrate Colgate's version into our extended framing of Kip Thorne's account. Then, even if it is not entirely possible to pinpoint a day of 'conversion', we may nonetheless state with confidence that, by '62, Wheeler had overcome his first rejection and that, at the very least, he had not only assessed the pursuit-worthiness – or better, to use an expression of von Neumann, the "worth-whileness" [23c] – of those studies, but he himself was by then highly interested and involved.

5. The road ahead

The moment Wheeler really faced the conceptual unavoidability of the 'black hole', at least in published material, was his '64 paper "Geometrodynamics and the Issue of the Final State" [25]. With the length of a book in its own right, even though it was published in '64, it was clearly discussed and written in the preceding months, at the very least. If we consider that it was actually born out of a series of lectures given at the summer school in Les Houches in July '63, certainly prepared quite in advance, we even have a nice continuity in our coverage of the different phases of Wheeler's thought. This paper is indeed a large synthesis of his views and of the work of his collaborators; it is definitely meaningful (also for the reliability of the account we have endorsed) that, while thanking them collectively in the acknowledgement at the end of the paper, the only one mentioned explicitly was his new student "Mr. Kip Thorne". The incipit is very telling as well: "If Einstein's general relativity has a close connection with the inner structure of physics – and there is no indication that it does not – then there is a good reason to spell out and understand its consequences": daring conservatism, once again. Even the title itself is quite resonant with the title of Beckedorff's thesis, i.e. "Terminal Configurations of Stellar Evolution". Wheeler's is obviously broader, because by then he had also linked together the issue of the final state of a star to that of the initial and final state of the universe. In the following decades Wheeler's writings were, in fact, going to be constellated by the idea that black holes allow us to study the destiny of the universe 'in miniature', and their prediction as a consequence of gravitational collapse is presented as the fourth test of general relativity, getting intertwined – in Wheeler's characteristic way of assembling and distorting historical events – with Hubble's discovery. Given his Machian ideas, it is not surprising that Wheeler almost took for granted a Big Crunch, or a similar event to be more properly treated by a future theory (since, of course, it would involve problematic singularities). Having in mind an expanding and contracting universe, Wheeler would later even venture into highly speculative quantum connections between cyclic cosmology and anthropic considerations – and, at least for the former, he also inspired later work by Penrose to a certain degree[26]. Indeed Penrose, in contrast to other more standardised accounts of the history of cyclic models of the universe, recognised Wheeler's impact in this regard as well.

Speaking of Penrose, he too went to the summer school in Les Houches in '63, although, as it can be seen from a letter to Wheeler [10], having arrived after the start, he had missed the latter's lectures. As he mentions there, Penrose, during that period, was going to spend a year in Austin, Texas (there is also a '62 letter [11] from Wheeler to Schild where Penrose is recommended by him); and he was looking forward to seeing Wheeler again "at the Dallas conference". That conference was the famous First Texas Symposium on Relativistic Astrophysics, in December '63, and it is usually understood to represent the birth of relativistic astrophysics, as the name suggests; and Schild was one of the organisers. The topic, "Quasi-stellar sources and gravitational collapse", marks the moment in which the predictions of general relativity about the extreme consequences of gravitational collapse (though more on the side of quasars – a different story from ours) start to be connected, for a larger community, to the actual work of astrophysicists. Later, in '65, Penrose would publish [27] his first theorem on the inevitability of singularities, given quite general assumptions (a result made stronger at the end of the decade thanks to the work of Hawking, too); and, in that same year (but published at the beginning of '66), after a few months, the first simulation of a collapsing star with a relativistic treatment was obtained by Michael May and the already mentioned Richard White [22], with some help from Wheeler's circle and collaborators.

6. What's in a name?

What about Wheeler himself? If, by the mid-'60s, Zel'dovich had actively started to hunt black hole candidates in person, Wheeler, while of course following such developments among his collaborators very closely, assumed as his personal duty and mission to immediately push on the conceptual implications of the new results. 'Implications' is perhaps a misleading word – since Wheeler was skipping many steps 'ahead', trying to evoke his vision of a new physics. This can be seen in a sort of double interview of '67, featuring also Robert Dicke [28] – and there, it is also quite easy to perceive a certain tension (albeit not a personal one) between the two. Dicke, after all, had proposed a modification of Einstein's general relativity, the Brans-Dicke theory, and Wheeler, while it is perhaps a matter of taste to say that, with black holes, his daring conservatism faded away or assumed other forms, still wanted to present himself as the legitimate guardian of Einstein's legacy against heterodox 'free novelty'. With this insight in mind, we may contribute another meaningful layer here to the history of the phrase 'black hole', as presented for instance by Marcia Bartusiak [29]. The story goes that, at the end of '67, during a talk by Wheeler, when he was illustrating the consequences of gravitational collapse with a recurring long periphrasis to designate its 'product', someone from the public shouted something like: "Why don't you just call it 'black hole'?" Wheeler, with his own talent for catchy expressions, immediately liked it and adopted it, and the rest of the community, thanks to his authoritative status (and his subsequent dissemination of the phrase), soon followed him. Variants of the story suggest that Dicke himself was the shouter; others refer to an earlier use, originating in Dicke's group (which, of course, was interacting with Wheeler's – the aforementioned Dieter Brill, for instance, spent time in both), as a reference to the 'black hole' of Calcutta, an infamous prison, if it may be called like that, in which people were literally constipated. In any case, we could perhaps see in Wheeler's own version of the story, and in its omission of Dicke, a sign of those basic tensions in the attitude towards general relativity. That is not to say that some injustice was perpetuated or that there was a harsh relationship between the two, who, in the following decade, became in a sense allied in proposing and supporting early views of the so-called anthropic principle. Besides using the unclear origin of the name as a sort of float to perceive

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[10] Penrose to Wheeler, 9 September 1963, in J.A. Wheeler Papers, Box 20, American Philosophical Society Library, Philadelphia.

[11] Wheeler to Schild, 15 October 1962, in J.A. Wheeler Papers, Box 20, American Philosophical Society Library, Philadelphia.

something about the ‘tides’ of the *milieu* in which it came to birth, there is another interesting aspect worth remarking about, as I have already mentioned. When compared to the previous nomenclature – ‘frozen star’, ‘collapsed star’ – it is clear that the ‘hole’ redirects the focus on that peculiar geometry of spacetime itself, from which not even light can escape, and then ‘black’, with all its concreteness, simply *nails* this aspect. Commenting on this, one may invoke “conceptual blending” [30] and other scholastic notions that are of course welcome, but we are here in front of a nice and concrete example of something that has been around for thousands of years – what Horace, in his “Ars Poetica”, called *callida iunctura*, a cunning juxtaposition of common words that interact to convey aptly and powerfully a new meaning. That is something quite important: as Wheeler once put it quoting Mark Twain, “the difference between the right word and the nearly right word is the difference between lightning and a lightning-bug” [31]. Let us just notice that a *callida iunctura*, as opposed to a cheap neologism, could also be seen as a sort of daring conservatism.

7. Towards a new view of the cosmos

Let us conclude with a brief overview of Wheeler's trajectory, adding a few panoramic elements from the years that were to follow. When he was asked in a later interview [31] why he had entered the field of gravitational physics, Wheeler replied as if black holes were his focus from the very start. We know that it did not go exactly like that – still, we have no reason to dismiss what he was trying to convey with his words. He recalled when he was in a helicopter returning from witnessing a nuclear explosion; indeed, Wheeler had always been particularly keen on all kinds of explosions: it would not be easy to find someone who could utter more aptly, and almost literally, Nietzsche’s “I am dynamite”. What he adds later is quite meaningful: he was thinking about the destructive power he had just witnessed with his own eyes, and which he had partly contributed to releasing – at that point, however, instead of feeling like Arjuna and quoting the Bhagavad-Gita, he felt how small those effects were in front of the explosions that take place in the universe and realised how great it would be to understand such phenomena. To this movement of feelings, one could, quite unexpectedly, apply the Romantic – or proto-Romantic (Burke and Kant come to mind) – notion of the sublime, with man realising first his smallness and irrelevance in front of the extreme manifestations of nature, but soon getting a sort of payback thanks to his soul and intellect, capable of feeling and understanding all of that. It may sound odd, since the ‘inspiration’ comes, after all, from weapons of mass destruction, but that was Wheeler’s perception, which was going to play a role in the picture of the cosmos he was developing.

During the '60s, in the midst of the gloomy Cold War atmosphere – at least for some aspects – Wheeler contributed to the release in the popular imagination of a new entity that soon became a powerful image of inevitability and destruction, albeit fascinating. And yet, while the evocation of the black hole was grabbing people’s attention and fantasies – such as a housewife complaining about this new impeding cataclysmic event, after all that had happened in the previous decades – Wheeler enthusiastically considered black holes as a unique opportunity to get deeper and deeper into the comprehension of our universe, of its origin, of its destiny: beyond the current physics, beyond its current concepts. On the basis of such an assumption, he started to meditate again on the lesson of the quantum, reaching the idea of the participative observer: we do not just shape our surroundings or influence the system under exam, but we even have a cosmogonic role. In the early '70s, after Jacques Monod had once again depicted the silent immensities of the universe that terrified Pascal, declaring however that mankind was – existentialistically, we could say – thrown in there without any meaning, Wheeler, the godfather of black holes (a sort of colossal hypostatization of ‘Being-for-death’), enounced a joyful, luminous new cosmic view. Later it would be associated with the name “participative anthropic principle” – but, before that, Wheeler expressed it on occasion of the celebrations for the 500 years of Copernicus, ironically [32]. From then on, even though he later tried to de-anthropomorphise such positions, he nonetheless kept building and promoting a new picture of the cosmos, partly revealed or suggested, at least according to him, by black holes, with all their fascination and place within the economy of the totality of existence; in his own words, he wanted to transmit a vision of nature which could allow us to feel, using his expression, “at home in the universe” [33]. Some people thought that he had gone crazy, others complained about his appeal to the religious root of mankind under the disguise of science. Whatever the case, there is no doubt that, even in such an operation, he set the example for a whole new kind of fascinating popular science writing that, thanks to people such as Penrose, who fell in their own way under Wheeler’s spell, marked the image of the frontiers of science in the last decades.

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