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From Wood Chuck Holes to Worm Holes—A Look into the Notebooks of John A. Wheeler

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This article offers an introduction to the notebooks of the American physicist John Archibald Wheeler (1911–2008) and argues that they represent a unique historical source. Several salient features of these notebooks are highlighted by following the example of the emergence of the concept of a "wormhole," one of Wheeler's most famous ideas.

John Archibald Wheeler[1] was the inventor and promoter of some of physics' most iconic terms and phrases, such as black hole, wormhole, or "it from bit." He was a world-leading nuclear physicist, who provided the first full theoretical analysis of nuclear fission, together with Niels Bohr; and, after World War II, he became the leader of the renaissance of general relativity. To those who knew him, he was also famous for his notebooks. In a piece on Wheeler, published in the Alcalde (1978, Issue 1, p. 30), the alumni magazine of the University of Texas at Austin, we read:

> [W]hen he gets a new idea, what does he do with it? He records it in a hardbound, handwritten notebook. Dr. Wheeler has filled almost forty of these notebooks since he started keeping them during the war ("You had to keep classified notebooks then, to keep your work together so that you didn't end up with a lot of loose pages," said Dr. Wheeler, "who jokingly calls himself the most disorganized person in the world.") When he talks with a colleague, he records what the person told him and what he thought about it afterward. When he is asked to give a lecture, he organizes what he will say in the notebook, writing it out in black ink, in beautiful, legible script.

His students and collaborators also frequently mention Wheeler's notebooks in their recollections of him. Daniel Holz (Senior Thesis, 1992) remembers him "[h]unched over his notebook."[2] Edwin Taylor (who co-authored the book Spacetime Physics with Wheeler[3]) remembered how "[o]ut would come the bound notebook" whenever they were working on a hard problem (see Ref. [4], p. 482). Charles Misner (Ph.D. 1957) recalled:

> John did have this habit for I guess, all of his life of having bound notebooks. I looked at one at a bookstore the other day; it costs $ 90 to get one of these books—bound books of blank pages—but John had very nice bound books. They were always there. When he had a group of students in the office he would sit down and take notes as the discussion went on. He would also make notes to himself about the calculations he was doing, or the work he planned to do. What were the important questions in physics? and so forth (see Ref. [5], p. 18).

Even the painting of Wheeler in Jadwin Hall at Princeton University shows him writing in his notebook (**Figure 1**) (see Ref. [6], p. 56).

To give the reader an idea of the content of these notebooks, we will briefly look at the elaboration of one of Wheeler's most famous concepts: the wormhole. In the mid-1950s, Wheeler was pursuing a program he called "daring conservatism." It was based on the idea that – in general relativity, electrodynamics, and quantum theory – we already have the necessary components to construct a final theory of physics, a theory of everything. This was an explicit move away from the mainstream of high energy physics, where it was generally believed that a successful description of the manifold new particles being discovered at accelerators (what would become known as the "particle zoo") would require, at the very least, a new theory of nuclear forces. Wheeler, in contrast, wanted to explore whether the established theories of the electromagnetic and gravitational forces alone might not already provide the necessary building blocks to reconstruct, at least in principle, the newly discovered particles and the physics of the nucleus—from scratch, as it were.

With a quantum theory of gravity still unavailable, Wheeler began to try his hand by working only with gravitation and electromagnetism. The idea was to use the non-linearity of the Einstein–Maxwell equations to construct localized, particle-like solutions, that is, to construct particles from pure field configurations. This idea harkened back to Einstein's unified field theory, by which Wheeler was certainly inspired. In contrast to Einstein, Wheeler did not seek to combine electrodynamics and gravitation into a new, unified mathematical entity; he was happy to work with Einstein–Maxwell theory in a "conservative" manner, leaving the theory as he found it. Another difference to Einstein's program was that Wheeler

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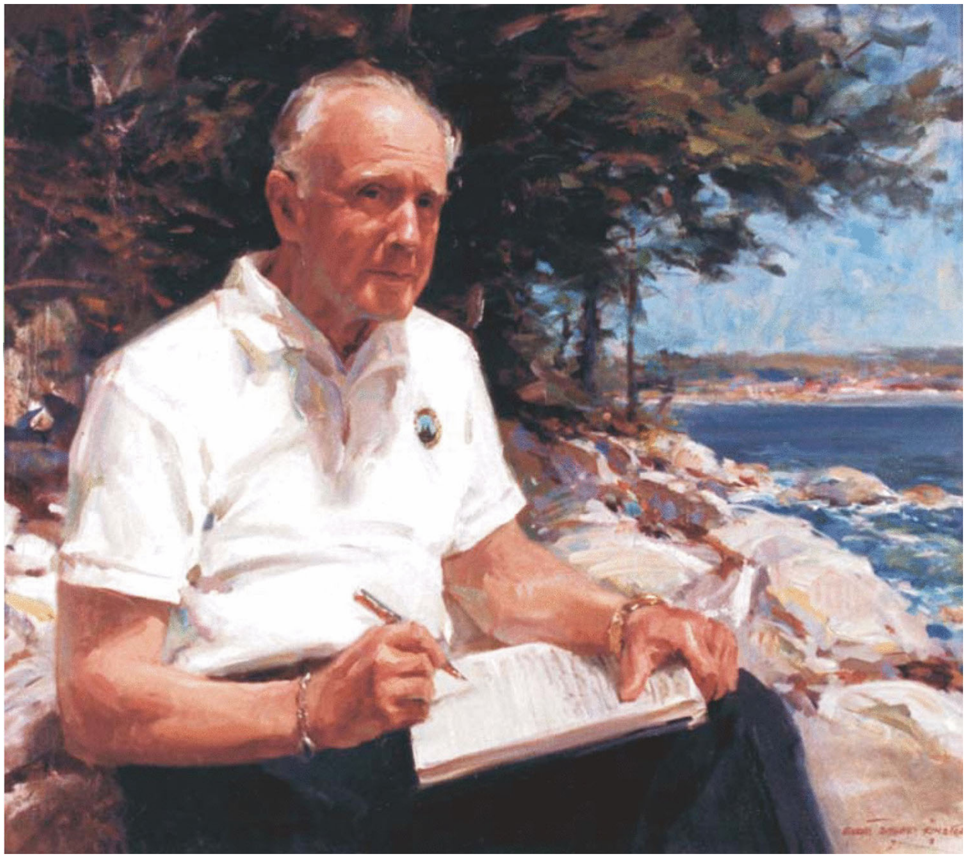


Figure 1. John Wheeler and his notebook in 1989 at his summer home on High Island, Maine, painted by Everett Raymond Kinstler. Reproduced with permission. Copyright 1989, Estate of Everett Raymond Kinstler.

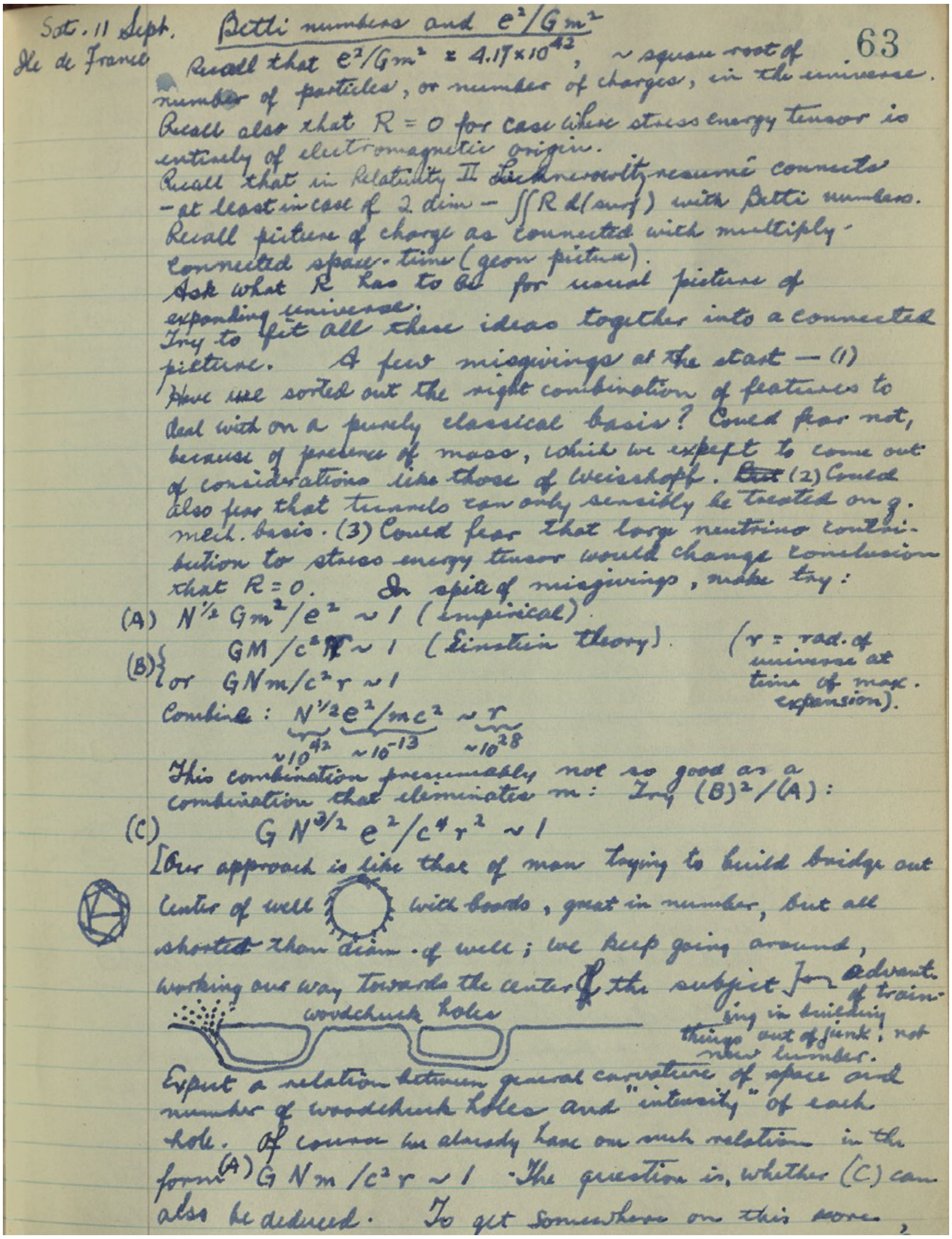
ultimately anticipated the construction of a quantum theory. This made the construction of particles from fields more of a proof of principle, rather than an actual physical hypothesis; any discrepancy (especially quantitative ones) between the particles constructed in this way and the particles actually observed in experiment could be interpreted as arising from the neglect of quantum effects.[7]

The first particle-like entity that Wheeler constructed in this manner was the gravitational-electromagnetic entity (geon), an (approximately) localized and stable solution to the Einstein–Maxwell equations, whose condensed energy could be interpreted as the mass of a particle; mass without mass, in Wheeler's words. But these particles, solutions of the source-free field equations, did not carry any charge. In a long paper on geons,[8] received by the Physical Review on 8 September 1954, Wheeler also gave a brief sketch on how one might obtain charge without charge: by having electric field lines apparently emerging from a point in space (like a charge), when in fact they continued through a tunnel in a space-time that is not simply connected and re-emerged at some other, distant point in space, simulating a charge of opposite sign.

The idea of a tunnel connecting two distant points in space will be familiar to the contemporary reader. But while such wormholes are nowadays known primarily as physics-inspired portals for fast intergalactic travel in sci-fi movies and novels, they originated in Wheeler's thinking as potential models of elementary charged particles. The idea of using spatiotemporal tunnels as particle models was not entirely new: Albert Einstein and Nathan Rosen had proposed a similar idea some 20 years earlier;[9] but their "bridges" had connected two different universes (rather than two distant points in the same one) and had not contained electromagnetic field lines.

In the geon paper, Wheeler had not fleshed out this model, nor had he given it a name. But one can track the further development of the idea through Wheeler's notebooks. In Wheeler's Relativity Notebook III, on page 63, we find an entry dated Saturday, 11 September (1954), shortly after completion of the geon paper. The entry is located on the "Ile de France," the ship on which Wheeler was traveling back from the United States after a visit to Europe. The peace and quiet of the transatlantic travel clearly provided Wheeler with ample time to think. And what makes Wheeler's notebooks such an intriguing historical resource is that he really thought with and through his notebooks, penning down his reflections in flowing (and perfectly legible) prose.

We can thus observe him reflecting again on his attempts to construct particles from classical general relativity and electrodynamics: "Recall picture of charge as connected with multiply-connected space–time (geon picture)."[10] We can see him aware of the difficulties involved in trying to do things at a purely classical level at first: "Could also fear that tunnels can only sensibly be treated on q. mech. basis." And we see him brushing these worries away: "In spite of misgivings, make try."



Sat. 11 Sept. Betti numbers and e^2/Gm^2 63
Ile de France

Recall that $e^2/Gm^2 = 4.17 \times 10^{42}$, ~ square root of number of particles, or number of charges, in the universe.
Recall also that $R = 0$ for case where stress energy tensor is entirely of electromagnetic origin.
Recall that in Relativity II Lichnerowicz résumé connects – at least in case of 2 dim – $\iint (R\, d(\text{surf}))$ with Betti numbers.
Recall picture of charge as connected with multiply-connected space-time (geon picture).
Ask what R has to be for usual picture of expanding universe.
Try to fit all these ideas together into a connected picture. A few misgivings at the start – (1) Have we sorted out the right combination of features to deal with on a purely classical basis? Could fear not, because of presence of mass, which we expect to come out of considerations like those of Weisskopf. ~~But~~ (2) Could also fear that tunnels can only sensibly be treated on q. mech. basis. (3) Could fear that large neutrino contribution to stress energy tensor would change conclusion that $R = 0$. In spite of misgivings, make try:

(A) $N^{1/2} Gm^2/e^2 \sim 1$ (empirical).

(B) $\left\{ \begin{array}{l} GM/c^2\cancel{R} \sim 1 \text{ (Einstein theory).} \\ \text{or } GNm/c^2 r \sim 1 \end{array} \right.$ (r = rad. of universe at time of max. expansion).

Combine: $\underbrace{N^{1/2}}_{\sim 10^{42}} \underbrace{e^2/mc^2}_{\sim 10^{-13}} \sim \underbrace{r}_{\sim 10^{28}}$

This combination presumably not so good as a combination that eliminates m: Try $(B)^2/(A)$:

(C) $G N^{3/2} e^2/c^4 r^2 \sim 1$

[Our approach is like that of man trying to build bridge out center of well with boards, great in number, but all ~~shorter~~ shorter than diam. of well; we keep going around, working our way towards the center of the subject for advant. of training in building things out of junk, not new lumber.

Expect a relation between general curvature of space and number of woodchuck holes and "intensity" of each hole. Of course we already have one such relation in the form (A) $GNm/c^2 r \sim 1$. The question is, whether (C) can also be deduced. To get somewhere on this score,

Figure 2. Page from Wheeler's notebook *Relativity III* including a drawing of a "woodchuck hole." Reproduced with permission. Copyright 1954, American Philosophical Society Library.

The page also contains the first drawing by Wheeler of a wormhole, which he was, however, still calling a "woodchuck hole" at the time (**Figure 2**). But Wheeler was not yet trying to construct a woodchuck hole as a solution of the Einstein–Maxwell equations; instead he was trying to integrate them into cosmology. This was characteristic of Wheeler's approach, which very often tried to connect the macro- and the microphysical. In this case it meant trying to find a "relation between general curvature of space and number of woodchuck holes and 'intensity' of each hole," that is, between the size of the universe, the number of charged particles, and the elementary charge *e*.

Wheeler tried to find such a relation by drawing upon topological invariants (the number of woodchuck holes was connected to the Betti number) and the so-called large number relations first popularized by Arthur Eddington and Pauli Dirac, for example, the empirical observation that the square root of the number of particles in the observable universe is of the same order of magnitude as the ratio between electrostatic and gravitational force in the hydrogen atom, namely about 10^{40}.[11] This was a strange brew, and it is hardly surprising that Wheeler did not succeed. But while the ideas that Wheeler was trying out in his notebooks often seem crazy—crazier even than the ones he published—one sees here quite impressively Wheeler's ability to connect apparently unrelated fields of knowledge. And while these connections often did not produce immediate results, they often proved to be very fruitful in the long run, as was the case for the connection between mathematical topology and field theory that Wheeler was pioneering here.

We can also observe an essential element of Wheeler's eclectic approach: the intellectual milieu of postwar Princeton, replete with refugees from Europe, such as Einstein. There is hardly a notebook entry without reference to some Princeton colleague, and this one is no exception, with Wheeler remarking: "To get somewhere on this score, need better idea of Betti number relations. See book by Bochner and collaborators" —a reference to the book *Curvature and Betti Numbers* by Salomon Bochner and Kentaro Yano,[12] the former having joined Princeton in 1933 after being forced out of his position at the University of Munich by the Nazis.

Wheeler was always pursuing many different, and often even contradictory, ideas in parallel. So one has to page a bit further for the woodchuck holes to resurface again. On page 113, we find another brief woodchuck hole calculation, which ends, however, just as inconclusively as the first one. A few pages on, we see a first mathematical breakthrough and it comes from a source, whose importance to Wheeler's thinking is highlighted by the notebooks time and again: his students. Wheeler was famous for his mentoring activity[6] and he was also a master at making use of his students' special abilities. Glued in between page 116 and 117, we find a typescript manuscript (dated 13 December 1954) by Wheeler's Ph.D. student Charles Misner, an expert in modern mathematics. It is a mathematical study of the simplest possible wormhole, a wormhole without a universe attached to it, that is—this wormhole closes in on itself and is really just a toroidal universe with electromagnetic field lines circling around it. Misner attempted to establish whether such a Wormhole could be a solution of the Einstein–Maxwell equations.

This calculation remained inconclusive (like many in Wheeler's notebooks). But more inspirational than Misner's concrete calculations on this toy wormhole were the new mathematical tools that he introduced to Wheeler. After another long lull, we find insert on page 209, apparently typed by Wheeler. It is dated 13 November 1955 and is entitled: "Questions incited by Charles Misner's nice way (based on Cartan) of putting the mathematics of general relativity," a reference to the formulation of general relativity in terms of differential forms.[13] The list of questions also includes one on finding conserved fluxes through a tunnel, and this question also contains the first recorded use of the term "worm hole," though still written as two words.

This renaming coincides with a great intensification of Wheeler's work on wormholes in the notebooks, culminating in a joint paper with Misner.[14] Soon we see Wheeler worrying about more detailed wormhole questions, such as travel through them; though as a problem, not as an opportunity. On 11 February 1956 (page 246), he noted an issue his student Peter Putnam had alerted him to:

> [M]omentum flowing into one worm hole may come out another one in entirely different direction. Apparent violation of law of conservation of linear momentum, no to mention angular momentum. But field eq[uatio]ns that govern everything permit no violation. Therefore we know that there must be something like a recoil of the walls or generation of grav[itatio]n[a]l wave or similar effect that makes linear [and] ang[ular] mom[entum] come out OK. Would be most interesting to analyze this recoil effect.

The problem of transport through wormholes would occupy Wheeler for several years to come. While he would conclude that this was not a problem, that not even light signals could travel through a wormhole,[15] he ultimately abandoned the idea of modeling particles with gravitational and electromagnetic fields around 1970.[16] But the concept of wormhole, now re-imagined as traversable portals, survived within science fiction (see Ref. [17] for an early example.), and in the 1980s the study of traversable wormholes (re-)entered the scientific discourse.[18] The wormhole is thus a perfect example of how a new concept emerged in Wheeler's thinking, was explored and tested from various angles in his notebooks, ultimately emerging (in spite of numerous inconclusive results) as an idea interesting and robust enough to henceforth lead a life of its own, even after Wheeler had lost interest in it.

I have here only provided a small glimpse at a short episode from Wheeler's notebooks. The notebooks have served as the basis for a number of in-depth historical investigations, for example, of how Wheeler came to work in general relativity in the first place,[7] of how in the 1970s he came to question the concept of physical law,[16] or even of Wheeler's multifaceted reception of the philosophy of Leibniz.[19] And physicists, too, should be able to profit from perusing Wheeler's notebooks, from his eclectic yet never aimless method or from his crazy yet never sterile ideas. Thankfully, the Library of the American Philosophical Society in Philadelphia, where Wheeler deposited his notebooks,[20] has begun digitizing the notebooks and making them freely available on their website. Now everyone can share the "wonderful experience" that used to be reserved for those few students who got to borrow one of Wheeler's notebooks for a few days (see Ref. [5], p. 18).

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Conflict of Interest

The author declares no conflict of interest.

Keywords

John Wheeler, wormholes, scientific notebooks, scientific creativity, general relativity

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[1] Wheeler (1911–2008) got his Ph.D. from Johns Hopkins in 1933. After several postdoctoral positions, in particular with Niels Bohr in

Copenhagen, he joined the Princeton faculty in 1938. He worked on reactor design in the Manhattan project and on the development of the hydrogen bomb. After retiring from Princeton in 1976, he spent another 10 years at the University of Texas at Austin. For more biographical information, see his autobiography.[21]

[2] https://www.discovermagazine.com/the-sciences/goodbye-07 (accessed: 22 April 2022).

[3] E. F. Taylor, J. A. Wheeler, *Spacetime Physics: Introduction to Special Relativity*, W. H. Freeman, New York, NY **1966**.

[4] E. F. Taylor, in *Magic Without Magic: John Archibald Wheeler* (Ed: J. R. Klauder), W. H. Freeman, San Francisco **1972**, pp. 474–485.

[5] C. W. Misner, in *John Archibald Wheeler and General Relativity* (Eds: I. Ciufolini, R. A. Matzner), Springer, Berlin **2010**, pp. 9–27.

[6] T. Christensen, *Phys. Today* **2009**, *62*, 55.

[7] A. S. Blum, D. Brill, in *The Renaissance of General Relativity in Context* (Eds: A. S. Blum, R. Lalli, J. Renn), Einstein Studies, Vol. 16, Birkhäuser, Basel **2020**, pp. 141–187.

[8] J. A. Wheeler, *Phys. Rev.* **1955**, *97*, 511.

[9] A. Einstein, N. Rosen, *Phys. Rev.* **1935**, *48*, 73.

[10] Wheeler's use of the term "multiply-connected" is somewhat idiosyncratic and differs from usual mathematical terminology. He means "not simply connected". Cf. [22] fn. 48.

[11] H. Kragh, *Varying Gravity: Dirac's Legacy in Cosmology and Geophysics*, Springer, Switzerland **2016**.

[12] K. Yano, S. Bochner, *Curvature and Betti Numbers*, Princeton University Press, Princeton **1953**.

[13] In their joint paper, Misner and Wheeler [14], p. 556, would later emphasize the special importance of the coordinate-free Cartan formulation for topologically non-trivial (i.e., non-Euclidean) spaces.

[14] C. W. Misner, J. A. Wheeler, *Ann. Phys.* **1957**, *2*, 525.

[15] R. W. Fuller, J. A. Wheeler, *Phys. Rev.* **1962**, *128*, 919.

[16] A. S. Blum, S. Furlan, in *Rethinking the Concept of Laws of Nature: Natural Order in the Light of Contemporary Science* (Ed: Y. Ben-Menahem), Jerusalem Studies in Philosophy and History of Science, Springer, Cham **2022**.

[17] J. Haldeman, *The Forever War*, St. Martin's Press, New York, NY **1974**.

[18] M. S. Morris, K. S. Thorne, *Am. J. Phys.* **1988**, *56*, 395.

[19] S. Furlan, Merging Labyrinths: Leibniz in J.A. Wheeler's Quest. *Studia Leibnitiana* **2022**.

[20] While surprising at first glance, for once Wheeler was not being overly idiosyncratic when choosing the American Philosophical Society to deposit his papers; indeed, the APS library houses the papers of quite a few famous physicists, such as Freeman Dyson, Val Fitch, John Slater, Edward Condon, or Stanislaw Ulam.

[21] J. A. Wheeler, K. Ford, *Geons, Black Holes & Quantum Foam*, W. W. Norton, New York **2000**.

[22] A. S. Blum, T. Hartz, *Eur. Phys. J. H* **2017**, *42*, 107.