A Golden Age of General Relativity?

Some remarks on the history of general relativity.

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1 Introduction

In 1986, Jean Eisenstaedt has published a well received paper: "The low water mark of general relativity: 1925-1955" on activities concerning Einstein's general relativity [1], [3]. The first date coincides with the year of the break through to quantum mechanics by Werner Heisenberg, accompanied by Max Born and Pascual Jordan, with Schrödinger following them in 1926 via a different route. It also signifies the year from which on Einstein's interest shifted from general relativity to his unsuccessful unified field theory. The second date possibly is not intended to point to Einstein's death year but to coincide with the Jubilee-Conference in Bern, in 1955. For D. Kennefick who called Eisenstaedt's period "an interregnum in research in general relativity", the advent of quantum mechanics and the paucity of experiments in gravitation were sufficient reasons for an explanation ([4], p. 105). It was only consequent that Clifford C. Will, at the end of the 1980s, wrote of a "Renaissance of General Relativity": "by the late 1950s general relativity had become a sterile, formalistic subject, cut off from the mainstream of physics. [..] Yet by 1970, general relativity had become one of the most active and exciting branches of physics." ([8], p. 7). Other authors set the date for the demise of general relativity even a decade earlier: "In the 1940s the subject of general relativity was virtually dead - or at best dormant.[1] Peter [Bergmann] set up the first active research group in GR in the USA. Singlehandedly he resurrected the field. Several years later other schools of GR developed around J. Wheeler, H. Bondi, L. Infeld and P. Jordan, but it is clear that Peter was the first to understand the importance of resurrecting GR from its dormancy and placing it as an important part of fundamental

[1]It is unclear whether Bergmann's book of 1942 on general relativity was on the mind of the authors [9], or rather not.

physics and then actively pursuing this goal" [10]. Also, Robert Dicke was considered to have played a role: "He soon became a leading figure in what is known as 'renaissance of general relativity' "[11].

Another claim differs from these statements assuming a period of reduced activity in the field of general relativity and its applications: Kip Thorne wrote of "the golden age of general relativity" as "the period roughly from 1960 to 1975 during which the study of general relativity, which had previously been regarded as something of a curiosity, entered the mainstream of theoretical physics" ([5], p. 74). Ten years earlier, he had given an even more precise period, i.e., from 1963 to 1974 [6].

It is obvious that, after World War II, research on general relativity and other relativistic theories of gravitation broadened enormously both in the number of workers and the spread of universities which housed "relativists"; cf. e.g., table 1 in ([7], p. 614). My aim here is to show that a label like "renaissance of general relativity" rests on weak empirical ground while "the golden age of general relativity" is an exaggerated description of a period of rapidly growing activity. For historiography, both labels should be used with caution.

In order to assess such historiographic catchwords, a more precise definition of "Golden Age" must be given. With regard to this concept we might ask whether it is to describe:
- A period of great, publicly visible activity in general relativity?
- A period which brought great *theoretical* advances for general relativity?
- A period which brought great advances in *experimentation* and *observation* applicable to test general relativity?
Similar questions may be raised with regard to the "period of marginalization within the field of physics"[12], also coarsened to signify the "dark ages" of general relativity [13], both alternative interpretations for the "low water mark":
- Is the assumed low-level status of general relativity within the physics community from 1925 to the 1950s well grounded in the conceptual development of the theory?
- If such a period existed, to what degree was it due to reasons *external* to science proper?
- Do we have to distinguish different developments in different countries?

For the establishment of both claims beyond personal interests, we may ask whether:
- the authors quoted above have used any *quantitative* indicator?
- a naive comparison of the periods 1925-1955 and 1955-1975 is meaningful at all?

In the following we will discuss and try to answer some of these questions. We shall distinguish between *communications* (public awareness of the field, teaching, conferences) and *achievements* (conceptual progress, publication of research, institutions).

2 Manpower, funds, and activity-indicators

Before we can evaluate the development within the field of general relativity, we must look at physics as embedded in the larger area of society. As we know, physics was notably influenced by the impact of World War II, and by the ensuing "Cold War". It is common knowledge that World War II, e.g., due to the development of radar, rockets, or of the atomic bomb, by many was branded as "the physicists war" [17]. Keywords for some effects correlated with politics are the "increase in manpower in physics [including general relativity]" and the new "private and military funding of physics [including general relativity]".

2.1 Manpower and financing

Since September 1956, the US Air-force intensely supported research in gravitation through the "General Physics Laboratory of the Aeronautical Research Laboratories (ARL) at Wright-Patterson Air Force Base, Dayton, Ohio" ([15], p. 375). This financial source was brought to an end in 1969 by the Mansfield Amendment [16]. To my knowledge, the supported projects were not classified. In Europe, since 1958, the North Atlantic Treaty Organization (NATO) also supported science by both individual grants, by its conference series and the subsequent book publications. Although, in the past, only a trickle has flown into grants for gravity research, the program continues until this day [18].

At the same time, roughly, funds from industrial companies went into research in gravitation. Exemplary is the “Research Institute for Advanced Studies” (RIAS), Baltimore, founded in 1955 by George Bunker of the Glenn L. Martin Company. The RIAS changed its name and turned its mission away from basic research in 1973. Another example is the manufacturer *Texas Instruments*. The university of Texas at Dallas began in 1961 as a research arm of Texas Instruments, and with it soon the “Southwest Center for Advanced Studies” (SCAS). In 1969 the founders bequeathed SCAS to the state of Texas. As is known, SCAS became a nucleus for gravitational physics, brought into flower mostly by European scientists holding a permanent job there (I. Robinson and W. Rindler from England/Vienna), and by some from Pascual Jordan’s Hamburg Relativity-Seminar with shorter engagements like those of J. Ehlers (1964-1965) or C. Bichteler (1966-1968, in the mathematics department); the last two moved on to the University of Texas in Austin.[2]

Another point to be made is the difference in *manpower* of physicists [relativists] working during the “low water”- and the “renaissance” -periods. Since the launch of Sputnik, in 1957, a shortage of physicists in the USA was claimed, and an advantage on the manpower front assumed for the Soviet Union ([19], p. 148). Countermeasures in the educational system were taken. In the report of the Physics Survey Committee of the National Academy of Sciences of the USA we read: “[..] between 1964 and 1970, the number of PhD physicists increased by 60 percent, the number of PhD astronomers by 62 percent, and the number of PhD’s in astrophysics and relativity[3] by 300 percent (from 65 to 257 individuals)” ([20], p. 840-841). Also, around 1970 the number of physicists in the subfield “astrophysics and relativity” amounted to only 1.5 % of the total of physicists with a PhD in the USA. This number is mentioned here in order to put into perspective the claim that, between the 1950s and 1970, general relativity was “one of the most active [..] branches of physics.” Around 1970, there were three times more astronomers n o t working in relativity. Although these figures refer to the USA, we may assume that a similar if less pronounced situation existed in (NATO-) Europe. We note that a quantitative comparison of the periods pre- and post-1955 could clearly only be made per head of scientists working

[2] Both, Ehlers (from 1966 to 1971) and Bichteler (1969 to retirement)

[3] This should not be misunderstood as refering to PhD’s produced; physicists *holding* PhD’s are meant.

on relativistic gravitation. A corresponding study has not yet been done. Naturally, manpower and funding are closely correlated. This is shown clearly by Fig. 1, relating Federal R & D expenditures and bachelors' student production in the physical sciences, mathematics and engineering in the United States ([21], p. 8):

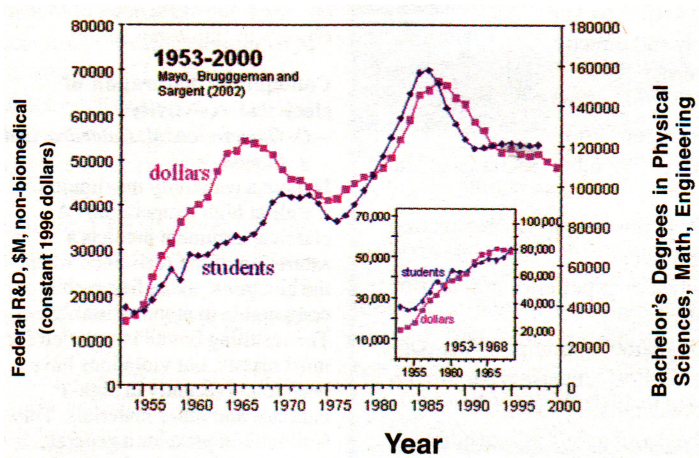

Figure 1.

The number of bachelor students almost doubled between 1957 and 1973 with the expenditures increasing by a factor 2 1/2 ! This remains unparalleled in the period 1925 to 1955; it is explained by reasons *external* to the field of gravitation. An indication that, at least in West-Germany, research in gravitation developed *smoothly* during the three decades from 1960 to 1990, is the number of PhD's produced there in the field of general relativity. It amounts to equally 13-14 for each decade. Thus, to a great extent what was named the "Golden age of relativity" in the United States, may have been nothing but a feature of a general trend in physics after the "Sputnik"-shock.

2.2 Activity indicators

As activity-indicators, we could take the number of national and international conferences organized, the number of groups/single persons working in relativity *relative to some reference group*, the number of books and papers published, the number of journals regularly printing papers on general relativity, or centers with a graduate program in general relativity. We also note that the necessary funds for international conferences including the travel costs had not been available before the 1950s.[4]

2.2.1 Publications

Not one of the indicators suggested above was checked by those claiming a "Golden Age" of General Relativity. Looking at the bibliographies by Combridge at King's College [23]

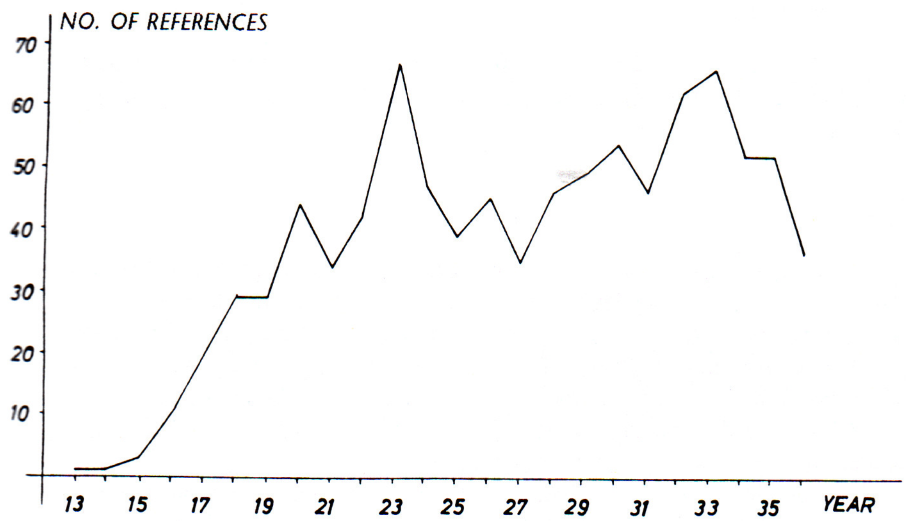

FIGURE 6. Combridge's statistics concerning research papers on relativity and differential geometry.

and in Synge's book on general relativity [24], the average yearly output of papers amounted to $\simeq 14/year$, and from 1925 to 1955 to roughly $12/year$, whereas between 1955 and 1965 the rate of published papers rose to ca. $15/year$. Papers on general relativity published in the prestigious French journal Comptes Rendus grew from a yearly total of 10 in 1957 to a maximum of 23 in 1959 and stayed at about this yearly rate until 1964. Although not representative, these inspections do not point to remarkable variations in publications listed between 1915 and 1960, in particular not between 1925 and 1935, or in the first half of the 1960s.

[4]Of course, all such indicators do have their weaknesses [22].

J. Eisenstaedt , in his first article of 1986, gave the yearly number of papers in relativity for the five years 1932-1936 to be around sixty. This figure goes well with Combridge's statistics.[5] He also gives the number of 30 articles on general relativity published in 1955 (from Physics Abstracts).
This is in stark contrast to the stable growth rate in the number of physics publications *in all fields of physics* between 1920 and 1960, an exponential growth, doubling the number of papers in approximately 15 years [25]. Of course, exponential growth need not be present in special fields of physics as shown by a study on weak interactions [26]. In another study three periods of growth in scientific publications (all fields) are given: compared with less than 1% growth before, to 2 to 3% up to the period between the two world wars and 8 to 9% to 2012 [27]. Some *representative* empirical material for the time after 1945, may be obtained from the core collection of the "web of science".[6] From 1945 up to today, there was a continuous growth of publications in general relativity with the steepest increase between 1960 to 1970, 1995 to 2000, and 2010 to 2015.[7]

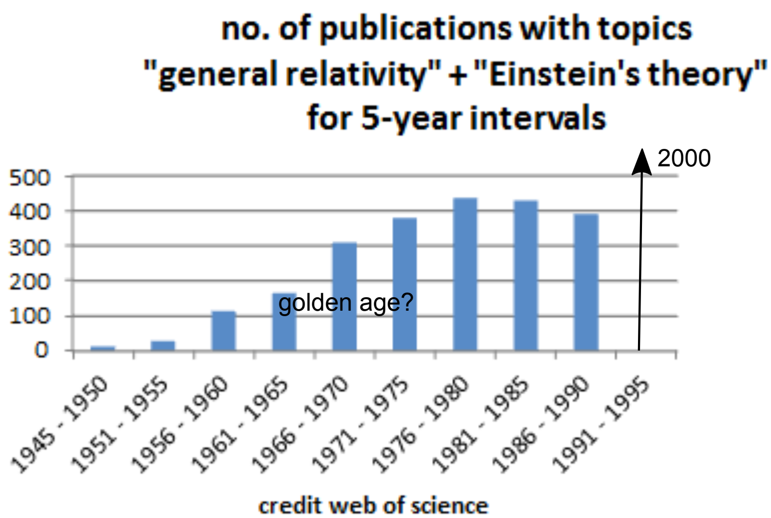

Figure 3.

[5]He did not say whether papers on special relativity are in- or excluded. His data were taken from Physics Abstracts and Physikalische Berichte.

[6]We have searched for the topics "general relativity" and "Einstein's theory". From the latter list all references not related to general relativity have been removed.

[7]The 5-fold increase in the decade after 1990 possibly is due to a changed data base used by the web of science (more journals included in the database?).

If the past “Golden Age” is identified with the steepest growth of publications on general relativity, then the period of 1960 to 1970 is the correct one. .

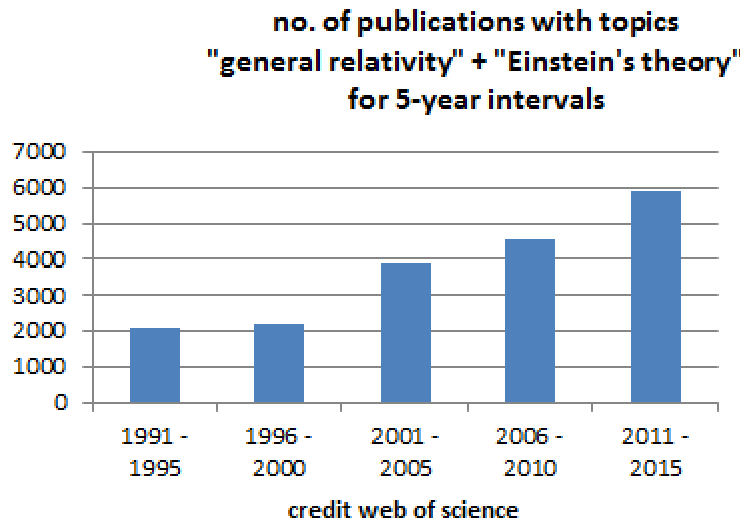

Figure 4.

2.2.2 International Conferences

As to conferences *before* world war II, there existed very few such events. Among them were the Volta Conferences in Italy by the Royal Academy of Science in Rome. The first such conference in 1927 was the Como Conference, held at Lake Como in 1927 about the uncertainty principle by Niels Bohr and Werner Heisenberg. A well known older series of Conferences were the Solvay Conferences in Brussels. We note those conferences relevant for relativity and gravitation:
- 1911 “La théorie du rayonnement et les quanta; The theory of radiation and quanta” (Einstein present);
- 1958 La structure et l’évolution de l’univers (The structure and evolution of the universe);
- 1964 The Structure and Evolution of Galaxies;
- 1973 Astrophysics and Gravitation.

Before the 1940s, international conferences could be financed only by scientific academies and wealthy entrepreneurs (like Ernest Solvay). Due to the increase in state funds for science and education, from the mid of the 1950s, national and international conferences on gravitation and cosmology,

partially as continuing series, began to sprout and became a regular feature of activity in the field of gravitation. An (incomplete) list of the best known such conferences is given in Appendix 1. If taken as an indicator for activity, the organization of conferences on gravitation fulfills the claim that the period starting around 1960 to 1975 brought both the weaving of a net of "relativists" and the awareness for the field in the physics community.
However, due to the lack of funds and the lower amount of working power in physics, such an increase in conferences could not have happened during 1925 up to the decade after World War II. In this context, the "low water mark of general relativity" seems to be a projection from the present into the past.

3 Advances in research about general relativity

Since the 1920s, during Einstein's lifetime and thereafter, a number of important results were obtained. For briefness, we present a choice of them - after 1920 - chronologically in four lists. The first collects results from *the time before world war II*:

1923/24 Exact solutions describing an expanding universe with space sections of constant curvature (Friedman);
1925 -1933 The universe as an exploding primordial atom (Lemaître) with a beginning later derisively named "the big bang";
1929 Hubble-law.
1936/1937 Gravitational lensing; theory by A. Einstein. Application to galaxy clusters by F. Zwicky.
1938 Equations of motions for point particles in linear approximation. Unlike in Maxwell's theory, the equations of motion in the gravitational field cannot be postulated independently of the field equations (Einstein-Infeld-Hoffmann).
1939 Gravitational collapse (Oppenheimer, Snyder, Volkoff) Tolman- Oppenheimer-Volkoff-limit (TOV). This triggered a development leading eventually to the concepts of "white dwarfs", "neutron stars" both as stellar remnants, and of "black holes" (treated as solutions of the vacuum field equations).

In the **next list**, results obtained *after world war II* until the mid 1950s are assembled:

> **1946/48 The theory of Cosmic Background Radiation. (Dicke, Gamov, Alpher & Herman)** It is one of the pillars of present cosmology.[8]
> **1949 Gödel-cosmos (K. Gödel)** This is a locally rotating exact solution of Einstein's equations with dust matter. Universal space sections do not exist, but closed timelike worldlines.
> **1954/58 Petrov-Pirani classification. (Petrov 1954, Pirani 1958)** An application is the peeling theorem describing the asymptotic behavior of the Weyl tensor in a lightlike direction.
> **1956/58 Event horizon (Rindler, Finkelstein)** W. Rindler formulated the concept within cosmology (event- and particle horizons). Finkelstein applied it to a collapsing star and showed that an event horizon develops.
> Gödel, Petrov, and Penrose are mathematicians, Dicke, Gamov, Alpher, Herman, and Finkelstein physicists.

The **third list** contains progress *during the 1960s* achieved in general relativity. It falls into the categories: mathematical physics without empirical backing, new mathematical methods, and the application of general relativity to astrophysics.

> **1960/62 Spinors: Newman-Penrose formalism.** A technique for formulating general relativity with spinors in place of tensors introduced by R. Penrose and E. T. Newmann. The formalism is helpful for the characterization of outgoing gravitational radiation in asymptotically Minkowskian space time.
> **1962 Exact solutions as an initial-value problem (Arnowitt-Deser-Misner, ADM)** Einstein's field equations are decomposed into hyperbolic time-evolution equations and elliptic constraint equations. The formalism is also important for numerical calculations.
> **1963 Kerr-metric (Roy Kerr)** (Exact solution describing the field outside of a star rotating about a fixed axis. As no interior

[8] Its first observation occured in 1964 (Penzias & Wilson); that this radiation has a black-body spectrum corresponding to a temperature of approximately 2.725 K was convincingly measured much later.

solution (with matter) is known, the Kerr- metric is interpreted as a black hole with 2 parameters: mass and angular momentum.
1965 Kerr-metric with electric charge (Newman) (A rotating black hole with 3 parameters: mass, angular momentum, electric charge. It is a solution of the Einstein-Maxwell (vacuum) equations.)
1964 Popularization of the name "Black Hole" (Wheeler)
1966-1970 Singularity theorems (Penrose, Hawking)

The **fourth list** collects some of the important developments of the 1970s. Note that most of them concern purely theoretical statements and conjectures with no empirical basis.

1960 - 2000 Uniqueness theorems for stationary Black Holes (Israel, Carter, Mazur) "A black hole has no hair" (J. Bekenstein).
1969 Cosmic-censorship-hypothesis (Penrose) Singularities are always hidden behind event horizons; otherwise, the theory would become unpredictable.
1970/71 Post-Newtonian approximation (Nordveth, Will) It is the modern form of the EIH-method and is used to describe observable effects and to discern alternative gravitational theories.
1970/73 Gravitation as Poincaré gauge theory (F. Hehl).
1972 Black-Hole-Thermodynamics (J. Bekenstein), A hypothesis about a relation between the area of the event horizon of a black hole and thermodynamical entropy is introduced. The main theorem of thermodynamics are postulated, analogously.
1974 Hawking-radiation of a Black Hole By a hypothetical quantum mechanical effect, a black hole, which by definition cannot send a signal from the inside through the event horizon, now can radiate its energy away.
1975 Begin of numerical relativity (L. Smarr; axial symmetry, 2 dimensions)

Note that the important exact solutions for a rigidly rotating disk formed by dust [28], [29], or its generalization to differentially rotating disks [30] were found only during the 1990s.

From the preceding enumeration, it looks as if conceptual and methodical progress in the understanding of general relativity and of its consequences has continued *uninterrupted* and em unweakened - with somewhat smaller growth rates from 1920s to the 1960s than from the 1960s until 1975. In my view, these small differences do not warrant the conclusion that a low water mark for the period 1925 to 1955 existed.

4 A new field: Relativistic astrophysics

What usually is not in the focus of the proponents claiming a "renaissance of general relativity", is the birth of the new field of "Relativistic Astrophysics" since the 1950s, particularly from the beginning of the 1960s on [31]. The need for an explanation of observations on quasars (1963), pulsars (1967), neutron stars (1971), binary pulsars (1974), with the indirect evidence of gravitational waves, led to the introduction of general relativity into astronomy. Moreover, with the theory and subsequent observation of the cosmic background radiation, cosmology no longer remained an academic subfield of general relativity but became part of relativistic astrophysics.[9] It is questionable, whether the many papers on "relativistic astrophysics" and on "cosmology" can be simply subsumed under "general relativity". In any case, they contributed substantially to the increasing output of publications in relativistic gravitation during the 1960s and 1970s - without constituting a renaissance: "relativistic astrophysics" just did not exist before the 1950s.

5 Universities with sizeable production of PhDs in general relativity after world war II

We concentrate on the years after world war II until the 1950s. Three places stand out: Princeton with John A. Wheeler (1911-2008), Syracuse with Peter G. Bergmann (1915-2002) [33] and Hamburg with Pascual Jordan (1902-1980) and Otto Heckmann (1901-1983). While R. Feynman and A. Wightman obtained their PhD degrees with J. Wheeler already in the 1940s (unrelated to gravitation), 5 PhDs followed in the 1950s, 3 in the 1960s,

[9]As a matter of fact, in 1992 the astrophysicist David Schramm used the label "A Golden Age of Cosmology" refering to the much later period beginning with the 1990s [32].

and 4 during the 1970s.[10] Seven fall into Thorne's "Golden-Age"-period. As Clifford Will and Daniel Kennefick were PhD-students of Kip Thorne, they might have been inclined to share the enthusiasm of their adviser. Interestingly, those of Wheeler's students with PhDs related to gravitation before 1960 like A. Komar, D. Brill, H. Everett, or Ch. Misner did not speak of a "Golden Age". Likewise, from PhD-students of Peter Bergmann like Ralph Schiller, Rainer K. Sachs and Joshua N. Goldberg, I have seen no statements about "renaissance" or "Golden Age". The same is true with Jordan's (Heckmann's) students J. Ehlers, W. Kundt, M. Trümper, E. Schücking. The spawning of doctor's degrees from the three theoretical physicists Bergmann, Jordan and Wheeler gradually brought into existence a net of well known relativists, and through them led to growing activity on relativistic theories of gravitation. Since the mid 1950s, one of such became the regular "Stevens Relativity Meeting" which received its name from the Stevens Institute of Technology in Hoboken, N.J., where R. Schiller and J. Anderson taught. An institutionalising of the field was still far away.[11] Of course, in the 1960s, in many further places research on general relativity was taken up like in London (Bondi, Hoyle), Warsaw (Infeld), Austin (Schild), Philadelphia (P. Havas) etc. In view of these developments, it is understandable when Wheeler's student Kip Thorne felt like living in golden times. In his obituary for Wheeler, D. Overbye reformulated his role as expected: "He rejuvenated general relativity; he made it an experimental subject and took it away from mathematicians [..]"[12] [34].
Who could have advised doctoral students in general relativity *before* the second world war? Einstein never cared for PhD-students and never had one, in Berlin and in Princeton. De Sitter, Lorentz (PhD student J. Droste), Max von Laue, Thirring, and mathematicians Hilbert, Klein and Weyl? For all of them, general relativity was not central to their work, and was not the reason for their fame. Nevertheless, M. v. Laue had several doctoral students in special and general relativity, from e.g., Ernst Lamla (PhD 1912 on special relativistic hydrodynamics) [35] to Max Kohler (PhD 1933 on general relativistic optics and cosmology) [36]. This has to be considered if periods before and after 1950 are compared and a "low-water-mark in dissertations"

[10] These are lower limits; there might have been further doctorates in general relativity with Wheeler.

[11] In the American Physical Society, a topical group "gravitation" was established not before 1995.

[12] One of those mathematicians might have been V. Hlavatý of Indiana University.

could be asserted.

6 Are the arguments for the "Low water mark" and "Golden Age" of General Relativity convincing?

From 1915 until the 1990s, general relativity amounted to "Little Science" in the terminology of de Solla Price[13] [25]. Compared to the overall physics community, workers on relativistic gravitation never surpassed 1% to 2% of all physicists. Without a definition of what *mainstream* is to mean, dates for the entrance of general relativity into the mainstream are unconvincing. Does it mean that more universities have hired physicists working in relativistic gravitation? In Germany this *never* did happen. Does it mean that more courses on general relativity were held? This would be unspecific: with the increase in the workforce in general relativity and astrophysics, more people could and did give regular classes in general relativity and/or cosmology.[14] Eisenstaedt's remark that general relativity was at its peak in the 1920s ([2], p. 280) is true only if public awareness of the theory is considered (*media hype*) [37], not in terms of research. As shown in section 3, in the years thereafter, many conceptual advances equal to or even outclassing the previous body of results and alleviating the understanding of the theory were made. According to B. Schutz [13], while such advances occured only within the mathematical "skeleton" of the theory, heuristic concepts, all taken from relativistic astrophysics like "black hole", "gravitational waves" or "gravitational lenses" were still missing until the 1970s.[15] For B. Schutz they are necessary for communication with "non-relativists". In this context, he asserts that general relativity became a "complete theory" only in the 1970. In view of the many discussions among philosophers of science as to when a scientific theory may be called "complete"[16], the introduction of

[13] "Little Science" is done by single researchers and small groups with modest monetary resources. "Big Science" involves a large number of collaborators and large funding.

[14] The fact that J. Wheeler held the first such course in Princeton only in 1952 despite Einstein's presence there since 1933/1934, seems due to Einstein's reluctance toward holding courses.

[15] The concept "graviton" was present, though.

[16] Is quantum mechanics complete? Many would negate this due to open questions around measurement. Cf. also [14].

such a concept is not helpful. A similar point of view may be found in [12] where the uncertain "epistemic status" of general relativity theory (during the low-watermark-period) is emphasized. The discussions about the epistemic status of a quantum state again show that this concept leads away from physics into the philosophy of science.
In the end, it is the lack of experiments, the pull of quantum theory, and the approximative Newtonian approach in the decades between the first and the second world war that are mostly offered to explain the low-watermark-period.
At present, in addition to the three effects from general relativity, well known since the 1920s, half a dozen new effects have been observed: Time delay effect, cosmic background radiation, frame dragging, de Sitter geodetic precession, gravitational lensing effect, gravitational waves. Only the first two were observed in 1964, i.e., within the period claimed as "the golden age".[17]
In spite of being known since the 1920s and 1930s, all the other predictions had to wait for 60 years until the 1980s to 1990s and longer (until 2015) to be measured. If there has been a low-watermark-period, then *for experimentation and observation related to general relativity*, and it has nothing to do with the asserted period 1920 to 1955.

From the first bets on the direct discovery of gravitational waves in the mid 1960s ([38], p. 53) to their first observation, fifty years have passed - notwithstanding "renaissance" and "Golden Age". Resistance to pouring big funds into the possible observation of gravitational waves persisted until the 1980s ([13], p. 261). Today, the only subdiscipline of general relativity deserving the name "Big Science", is research related to gravitational waves.[18]
With the new field of "relativistic astrophysics" the application of general relativity to objects astronomers previously had looked at, mainly boosted research on relativistic theories of gravitation. Quasi-stellar sources, pulsars, and neutron stars were not known in the period interpreted as constituting the "low water mark". Black Holes (stellar and galactic), gravitational lensing and gravitational waves were bearing fruit *in astrophysics*. Probably, the emergence of relativistic astrophysics has helped generating the feeling of a "Golden Age" for general relativity .

[17]The experiment by Dicke, Roll, and Krotkov about the equivalence of inertial and gravitational mass also was published in 1964.

[18]The use of Earth-Satellites on which experiments are flown for the test of general relativity could also be called "big science".

It seems to me also that the route quantum mechanics has taken since 1925/1926, was unconsciously used as a model for how general relativity *should have developed*. In view of the scarce number of gravitational effects beyond those following from Newtonian theory and for which general relativity is needed, this theory could not claim to be of central importance to the physics community - fundamental issues related to space and time notwithstanding.

7 Conclusion

Writing the history of a discipline requires the introduction of guidelines for emphasizing certain periods, or for smoothing irregularities in the development. I consider the concepts "low water mark" and the ensuing "renaissance" of general relativity as a means of ordering and valuing events. It was shown here that, unfortunately, these labels are resting on a weak factual basis. Research on general relativity needed not to be "resurrected" or "reinvigorated" after the 1950s: *it had yet "to begin" at all on a broad scale after world war II.* The claim of a "Golden Age" of general relativity between 1960 and 1975 is a reflection of the growing activity in the field during these years. It is backed by the advent of relativistic astrophysics and a considerable growth of the increase in publications on general relativity during this period.[19] A golden age needs no *prior* period of *reduced* activity.

The history of general relativity before the 1920s is not taken into account by many narrations. Besides Einstein and his entourage, and a few researchers in Berlin, Leiden and Vienna, very few studied general relativity, particularly in France, England and the United States. With the expatriation of Einstein, the focus of research on general relativity shifted from Germany to other countries, notably to the United States [42]. World War II then slowed down, or even stopped research for about 25% of the assumed low-watermark-period. I do not contest that the Bern Jubilee Conference of 1955 gave an impulse to the field of general relativity. It was the *first* international conference on Einstein and his relativity theories since the introduction of

[19] The story of a "Golden Age" was taken up though by a recent book [39]. After the erroneously interpreted BICEP-observations, the concept of Golden Age has been applied to hold for our times [40]; cf. also [41] in another context.

these theories. Now, funds were available for organizing such conferences: a golden era for "conference-tourism" started (cf. appendix 1). The beginnings of relativistic astrophysics, the new impressive variety of communications and technical improvements leading to the possibility for experimentation, to me seem to be main factors for establishing general relativity as an accepted subfield of research within the physics community. Yet, the writing of the history of general relativity in the past hundred years needs further detailed studies.

References

[1] Jean Eisenstaedt. "La relativité générale à l'étiage: 1925-1955." *Archive for History of the Exact Sciences* **35** No. 2 (1986), 115-185.

[2] Jean Eisenstaedt. "The Low Water Mark of General Relativity, 1925-1955." In: *Einstein Studies* **1**, 277-292. Boston/Basel/Berlin: Birkhäuser (1989).

[3] Jean Eisenstaedt. *The curious History of Relativity.* How Einstein's theory of gravity was lost and found again. Princeton, University Press 2006.

[4] David Kennefick. *Traveling at the speed of thought.* Princeton, University Press 2007.

[5] Kip Thorne. "Warping spacetime". The future of theoretical physics and cosmology: Celebrating Stephen Hawking's 60th birthday. Cambridge University Press. p. 74. (2003).

[6] Kip Thorne. *Black Holes and Time Warps: Einstein's Outrageous Legacy.* New York: W. W. Norton & Company (1994); Reprint edition (1995).

[7] Alexader S. Blum, Roberto Lalli, and Jürgen Renn. "The Reinvention of General Relativity: A Historiographical Framework for Assessing One Hundred Years of Curved Space-time." *Isis* **106** Nr. 3, 598-620 (2015).

[8] Clifford C. Will. “The renaissance of General relativity”, in: C. W. Davies, ed., *The New Physics*. Cambridge: University Press 1989.

[9] Peter Gabriel Bergmann. *Introduction to the theory of relativity*. Englewood Cliffs N. J.: Prentice-Hall, 1942.

[10] De Sabbata, V., Gillies, George T., Melnikov, Vitaly N. (eds.) “The Gravitational Constant: Generalized Gravitational Theories and Experiments.” NATO Science Series Volume 141. Springer (2004).

[11] Helge Kragh. Varying Gravity. Dirac’s Legacy in Cosmology and Geophysics. (Science Networks. Historical Studies 54.) 185 pp. Dordrecht: Springer International Publishing 2016.

[12] Alexander S. Blum, Roberto Lalli, and Jürgen Renn. “The renaissance of General Relativity: How and why it happened.” *Annalen der Physik* **528** Nr. 5, 344-349 (2016).

[13] Bernard F. Schutz. “Thoughts about a conceptual framework for relativistic gravity.” In: *Einstein Studies* **12**, 259-269. New York/ Dordrecht/Heidelberg: Birkhäuser-Springer (2012).

[14] Erhard Scheibe. *The locical analysis of quantum mechanic*. Oxford: Pergamon Press (1973).

[15] Louis Witten (1998). “Introductory remarks on the gravity research foundation on its fiftieth anniversary.” Presented at the 15th International Conference on General Relativity and Gravitation. In N. Dadhich and J. Narlikar (Ed.) Gravitation and relativity: at the turn of the millennium . Pune, India: Inter-University Centre for Astronomy and Astrophysics.

[16] Joshua Goldberg. “United States Air Force support of general relativity: 1956-1972.” In: J. Eisenstaedt & A. J. Kox (Eds.), Studies in the History of General Relativity. *Einstein Studies* **3**, 89-102 (1988).

[17] Davis Kaiser. “History: From Blackboards to bombs.” *Nature* **523**, Issue 7562, 523-525 (2015).

[18] Program Science for Peace and Security. Cf. http://www.nato.int/cps/en/natolive/87260.htm

[19] David Kaiser. “Cold war requisitions, scientific manpower, and the production of American physicists after World War II.” *Historical Studies in the Physical and Biological Sciences* **33**, Part I, 131-159 (2002).

[20] Eds. Physics Survey Committee & National Reseach Council. *Physics in Perspective* Vol. II, Part B: The Interfaces. Washington D.C.: National Academy of Sciences (1973).

[21] Merrilea J. Mayo. “Oversupply, Undersupply: Can We Ever Get Workforce Issues Right?” The Back Page. *American Physical Society News* **12** No. 10 (Nov.) (2003).

[22] Peder Olesen Larsen and Markus von Ins. “The rate of growth in scientific publication and the decline in coverage provided by Science Citation Index.” *Scientometrics* **84** No. 3, 575-603 (2010).

[23] J. T. Combridge. *Bibliography of Relativity and Gravitation Theory, 1921 to 1937* London: Kings College (1965).

[24] J. L. Synge. *Relativity: The general theory.* Amsterdam: North-Holland Publishing Co. (1960).

[25] Derek J. de Solla. *Little Science, Big Science*. Columbia Paperback Edition 1963.

[26] D. Sullivan, D. H. White, and E. J. Barboni. “The State of a Science: Indicators in the Specialty of Weak Interactions.” *Social Studies of Science* **7**, 167-200 (1977).

[27] Lutz Bornmann and Rüdiger Mutz. “Growth rates of modern science: A bibliometric analysis based on the number of publications and cited references.” *Journal of the Association for Information Science and Technology* **66** Issue 11, 2215 - 2222 (2015). https://arxiv.org/pdf/1402.4578.pdf

[28] G. Neugebauer and R. Meinel. “The Einsteinian Gravitational Field of the Rigidly Rotating Disk of Dusk.” *Astrophysical Journal* **414** No. 2, L97-L99 (1993).

[29] G. Neugebauer and R. Meinel. "General Relativistic Gravitational Field of a Rigidly Rotating Disk of Dust: Solution in Terms of Ultraelliptic Functions." *Physical Review Letters* **75** No. 17, 3046-3047 (1995).

[30] M. Ansorg, R. Meinel. "Differentially rotating disks of dust." *General Relativity and Gravitation* **32**,1365-1380 (2000).

[31] Engelbert Schücking. "The First Texas Symposium on Relativistic Astrophysics." *Physics Today* **42**, Issue 8, 46-52 (1989).

[32] David N. Schramm. "Meeting Overview". In: *Physical Cosmology–National Academy of Sciences Colloquia* March 27-28, 1992, Irvine, CA.

[33] Ezra T. Newman. "Biased and Personal Description of GR at Syracuse 1951-1961." *Einstein Studies* **11** Eds. J. Kox and J. Eisenstaedt, pp. 375-385. Boston: Birkhauser (2005).

[34] Dennis Overbye. "J. A. Wheeler, Physicist Who Coined the Term 'Black Hole' is dead at 96." *The New York Times*, April 14, 2008.

[35] Ernst Lamla. "Über die Hydrodynamik des Relativitätsprinzips." Dissertation, Friedrich-Wilhelms Universität zu Berlin. Berlin: Trowitzsch & Sohn (1912).

[36] Max Kohler. "Beiträge zum kosmologischen Problem und zur Lichtausbreitung in Schwerefeldern". Dissertation, Friedrich-Wilhelms Universität zu Berlin. Leipzig: Barth (1933).

[37] Hubert Goenner. "The Reception of the Theory of Relativity in Germany as Reflected by Books Published Between 1908 and 1945." In: *Einstein Studies* **3**, 15-38. Eds. J. Eisenstaedt and A. J. Kox. Boston/Basel/Berlin: Birkhäuser (1992).

[38] Dicke, Robert H., and John A. Wheeler. "Physics in Transition: Dialogues with Wheeler and Dicke." *Scientific Research* **2** May, p. 50-56 (1967).

[39] Fulvio Melia. *Cracking the Einstein Code. Relativity and the Birth of Black Hole Physics*. Chicago: The University of Chicago Press 2009.

[40] Pedro G. Ferreira. "Einstein's perfect theory: General relativity rebooted." *New Scientist* Feature 30 July 2014.

[41] Neil Turok. "A New Golden Age." *Perimeter Magazine* Press Releases, Dec. 18. 2015.

[42] Hubert Goenner. "General relativity and the growth of a sub-discipline "gravitation" in the German speaking physics community." To be published. (2016).

Appendix 1:

List of best known national and international conferences in the field of gravitation and cosmology.

- Jubilee Conference “50 years of Special Relativity”, Bern 1955.
- The Conferences GR 1 (1957, Chapel Hill) to GR 21 (2016, New York)
- Since 1958 NATO Advanced Study Institutes
- Enrico Fermi Summer Courses, Varenna. (Gravitation started to be a theme in 1961; then also in 1969, 1972, 1976)
- “Symposium on Gravity” at Research Institute for Fundamental Physics in Japan 1962.
- Les Houches Summer Schools (University of Grenoble). 1963 “Relativity, Groups and Topology” was the 1st about gravity; 1972 “Black Holes/Les Astres Occlus” was the second about gravity.
- “Texas Symposium on Relativistic Astrophysics” from the 1st one in 1963 to the 50th in 2013.
- Colloques internationaux du Centre National de la Recherche Scientifique - No. 167 1967 Fluides et champ gravitationnel en relativité générale; No. 220 1973 Ondes et Radiations Gravitationnelles; No. 236 1974 Théories cinétiques classiques et relativistes.
- Brandeis Summer Institute 1964 (on gravitation). 1968 Astrophysics and Gravitation (11th Brandeis Summer Institute) [Start of the series in 1958]
- American Mathematical Society Conference 1967 (on gravitation).
- International School of Cosmology and Gravitation “Etore Majorana”, Erice starting in 1972, another in1979 (NATO advanced study series).
- Marcel Grossmann-Conferences. From MG 1 in Trieste in 1975 to MG 15 (2015) in Rome.
- Edoardo Amaldi Conferences on Gravitational Waves. Begin 1994.

CONTEXT FROM ORIGINAL DOCUMENT

(PUBLIC DOMAIN) - 1961 — Texas Instruments establishes the Southwest Center for Advanced Studies and later hires I. Robinson, W. Rindler, J. Ehlers and C. Bichteler to work on gravitational physics.

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