START PROPOSAL

Black Holes in AdS, the Universe, and Analog Systems

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Abstract

Black Holes have advanced to the forefront of current research in various disciplines: besides the obvious ones, general relativity, mathematical physics and astrophysics, also string theory, quantum chromodynamics, cosmology, computational physics, quantum gravity and even part of condensed matter physics devote a significant fraction of their resources to the study of Black Holes. It is thus both a fascinating and timely subject to investigate.

The main purpose of this project is a comprehensive study of Black Hole physics from a theoretic perspective, including the investigation of the impact that Black Holes have in disciplines other than general relativity. This will be a cooperative enterprise, especially for the part of it that requires expertise in fields such as quantum chromodynamics or condensed matter physics, and one of the main consequences for research in Austria will be the establishment of a Black Hole research group at the Vienna University of Technology.

I explain here in detail the connection with scientific work in the field, recent progress, open problems, a detailed work plan for the next six years, ongoing and future collaborations, aspects of human resources, expected spin-offs and financial aspects.

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1 Scientific Aspects

1.1 Aims

The scientific aim of this project is to address some of the unresolved key issues of Black Hole physics within national, European and international collaborations, and to build a research group at the Vienna University of Technology that is strongly interacting with the local community and competitive within the global community. The focus will be on theoretical aspects.

1.1.1 Introduction and relation to scientific work in the field

When John Wheeler coined the term "Black Hole" about four decades ago [1], Black Holes (BHs) were generally considered as rather esoteric objects of purely theoretical interest and little physical relevance (for a textbook on BHs and a more complete history see [2]). Even in the 1990ies the Nobel Prizer winner Martinus Veltman still suspected that BHs "are probably nothing else but commercially viable figments of the human imagination" [3]. During the past 15 years the assessment of the role of BHs in physics has changed dramatically, for several independent reasons:

- The theoretical collapse scenario provided originally by Subrahmanyan Chandrasekhar (for a textbook see [4]) predicts that (neutron) stars with masses greater than a couple of solar masses collapse, either to some unknown form of high density matter or to a BH. With the insights from elementary particle physics gained in the 1970ies-1990ies it seemed increasingly unlikely that the former variant is realized. Thus, the collapse of a star to a BH is supported indirectly by the Standard Model of particle physics.

- More importantly, the observational evidence for BHs has accumulated to a point where it is nearly impossible to dismiss BHs, as they provide the simplest explanation of the available data. The prime difficulty of BH phenomenology is that by its very nature a BH does not emit any light[2]. However, it can be detected through its interaction with surrounding matter (accretion disks, gas jets, X-ray emissions) and through its gravitational interaction (gravitational lensing, stars orbiting a BH in a binary system). Three different families of BHs have been identified so far: stellar-mass BHs, intermediate-size BHs and supermassive BHs. The stellar-mass BHs arise from the collapse of a star mentioned in the previous point, and it is often difficult to discriminate them from neutron stars, since also the latter exhibit accretion disks and X-ray emission. However, neutron stars often show additional features (magnetic fields, thermonuclear bursts, differential rotation) which are absent for objects with masses beyond the Chandrasekhar limit. This is a very good indication for stellar-mass BHs (see [6] for a review and a list of 20 confirmed stellar-mass BHs). Intermediate-size BHs weigh between hundred and ten-thousand solar masses. However, their existence is less established than the other two families because the first candidates were discovered only recently (see [7]

[2]At least not classically. Semi-classically BHs can evaporate [5], but this (Hawking-)effect is far too small to be of observational relevance in astrophysics.

for a review). Supermassive BHs can weigh up to 10^{10} solar masses and are found in the center of many galaxies [8, 9], including our own Milky Way [10]. Their formation process is less understood than for stellar-mass BHs, but the observational evidence for supermassive BHs is solid. In conclusion, the accumulated data provides evidence for BHs beyond reasonable doubt.

- About the time of discovery of supermassive BHs, Juan Maldacena proposed the celebrated AdS/CFT correspondence [11] (see [12] for a review), which provides a connection between gravitational physics in $(d+1)$-dimensional Anti-deSitter (AdS) space and conformal field theory (CFT) in d dimensions (the boundary of AdS). This correspondence allows to map problems that are very hard in gauge theory (namely the strong coupling regime) to problems that are comparatively simple in (super-)gravity. Besides considerable theoretical interest, the AdS/CFT correspondence and generalizations thereof which involve BHs in 5-dimensional AdS space have recently been applied to model quantum chromodynamics (QCD) at strong coupling and at high temperature and density and to explain in particular the experimental findings in relativistic heavy ion collisions. Hydrodynamical simulations of the latter [13] indicate that QCD at temperatures up to about twice the deconfinement phase transition temperature is strongly interacting and in particular behaves like a fluid with small shear viscosity [14–16] that is close to a conjectured lower quantum-theoretical bound [17–19] derived from the analysis of quasinormal modes of BHs in AdS_5, which is now also supported by direct lattice simulations [20]. Similar methods have been applied to evaluate other observables such as the jet quenching parameter [21–23], and their success has attracted a huge interest not just in the theoretical community but also in phenomenological nuclear and high-energy physics.

- Stephen Hawking has not only shown that BHs evaporate due to quantum effects [5], but he also demonstrated that, unfortunately, this effect is so tiny that it cannot be observed for stellar-mass BHs or heavier BHs because the Hawking temperature is far too small. Bill Unruh [24] suggested in the 1980ies to consider condensed matter analogs to scrutinize the Hawking effect. For instance, in perfect fluids there can be regions where the fluid velocity exceeds the speed of sound, and thus phonons cannot escape from these "sonic horizons", which provides a good analog of the situation in a real BH, where the escape velocity exceeds the speed of light (and thus photons cannot escape). While originally it was not expected that one could actually measure the Hawking effect in this way, the recent progress in condensed matter physics made it possible to propose experiments which are nearly sensitive enough to measure the fluxes of the particles created by the Hawking effect. Even though no such experiment has been performed yet, there is certainly no lack of proposals for experiments (with fluids, Bose-Einstein condensates, waveguides, superfluid Helium, etc.), for reviews cf. e.g. [25, 26]. Moreover, these considerations have led to interesting theoretical insights,[3] and there is a certain amount of cross-fertilization between the otherwise rather distinct fields of general relativity and condensed matter physics. Even if no "artificial BHs" will be produced in the laboratory in the near future, the geometric methods developed in the study of BHs are also useful in some condensed matter systems.

- BHs are complicated enough to be interesting, and yet simple enough to act as a theoretical laboratory where new concepts can be studied. In particular, BHs play a central role in quantum gravity (sometimes the simplest of all BHs, the Schwarzschild BH, is called "the Hydrogen atom of general relativity"). Specifically, the problem of information loss [28, 29], the holographic principle [30, 31] and the counting of microstates to account for the BH entropy [32] all involve quantum considerations and BHs. Since quantum gravity is still far from being an established theory BHs will continue to play an important role as systems which are relatively simple, but not too simple.

- BHs were studied originally exclusively in four spacetime dimensions [33, 34], but in the past two decades BHs in two [35, 36] and three dimensions [37, 38] were studied vigorously (for reviews see [39, 40]). The motivation to study lower-dimensional models of BHs is related to the previous point: quantum gravity in four dimensions is a challenging subject, and in order to gain conceptual insights it is important to study simpler BHs where the same conceptual issues arise, but where the technical problems can be overcome. Moreover, in highly symmetric situations (like spherical or cylindrical symmetry), four- or higher-dimensional BHs can be reduced effectively to lower-dimensional BHs, and thus the latter are not merely toy models. For instance, the quasi-local thermodynamical properties of many higher-dimensional BHs (Schwarzschild, Reissner-Nordström, Schwarzschild-AdS, BTZ, ...) can be derived from first

[3] For instance, the issue of trans-Planckian modes was addressed successfully, i.e., the question to what extent Hawking radiation depends on the behavior of the fields at arbitrarily high frequencies (see [27] and Refs. therein).

principles within a purely 2-dimensional approach [41]. Many other crucial results (classical and quantum integrability, reformulation in terms of Cartan variables and as a Poisson-sigma model, virtual BHs, calculation of S-matrix elements, quantum corrections to the specific heat of BHs, ...) were obtained by the "Vienna school of gravity" around Wolfgang Kummer, for reviews cf. [39, 42]. In the past year especially the interest in 3-dimensional quantum gravity was rekindled, cf. e.g. [43–47]. But not only lower-dimensional BHs are at the focus of current research: since the discovery of black rings in five dimensions [48] and their supersymmetric counterpart [49], there is considerable interest in higher-dimensional BH-like objects (for a review see [50]).

- In addition to the well-established results mentioned above, even today there is no lack of more exotic scenarios involving BHs, as they continue to inspire the imagination of physicists. As an example I mention the possibility that in scenarios of TeV scale quantum gravity BHs might be produced at the Large Hadron Collider (LHC) at CERN [51, 52] (for reviews cf. e.g. [53, 54]), which starts operating this year.
- To end this list I mention the tremendous progress that numerical relativity has made in the past two decades (for recent reviews see [55–57]). Many of these successes were specific to BH dynamics: the discovery of critical collapse [58], the numerical calculation of quasi-normal modes [59, 60] and the BH binary system, cf. e.g. [61–63].

In summary it is fair to say that the research on BHs has moved from a theoretic niche to the mainstream of science, with many issues remaining unresolved.

1.1.2 Innovative aspects, specific research goals and some scientific details

I shall now describe in some detail the nature of several problems I intend to investigate together with my collaborators and students, and some of the methods to be used. I also highlight specific research goals.

BHs in lower dimensions The recent interest in 3-dimensional classical and quantum gravity [43–47] provides a strong incentive to consider topologically massive gravity [37], i.e., an action

$$I=\int d^3x\,\sqrt{|g|}\,(R-2\Lambda)-\frac{1}{2\mu}\int d^3x\,\epsilon^{abc}\,\Gamma^d{}_{ae}\left(\partial_b\Gamma^e{}_{cd}+\frac{2}{3}\Gamma^e{}_{bf}\Gamma^f{}_{cd}\right)+\text{boundary terms} \tag{1}$$

The first integral is the Einstein-Hilbert action with a (negative) cosmological constant $\Lambda = -1/\ell^2$ and the second integral is the gravitational Chern-Simons term (all symbols have their standard meaning and the notation is the same as in [47]). Surprisingly few classical solutions of that theory are known [64–68], including pure AdS. By assuming axisymmetry the problem simplifies to a 2-dimensional one, and thus the methods of [39] are applicable. For instance, if only the gravitational Chern-Simons term is present not only interesting kink solutions can be found [69,70], but, in fact, *all* solutions can be found globally [71]. **One particular goal is the construction of a comprehensive class of classical solutions of topologically massive gravity, by exploiting axisymmetry and reduction to two dimensions.** While this is an interesting problem by itself, the main focus will be on quantum gravitational issues. In [47] it was found that only "chiral gravity" ($\mu\ell = 1$) is consistent with positivity of energy and unitarity, but this result so far is poorly understood. **Another goal is to understand in what sense topologically massive gravity becomes special at the chiral point $\mu\ell = 1$, by considering various reformulations of the theory and by studying the phase space for a tuned coupling constant μ.** The search for classical solutions mentioned before is likely to help in this endeavor.

Once BH solutions are found it is interesting to understand their thermodynamical properties, in particular the Bekenstein-Hawking entropy. The issue is complicated by the fact that the gravitational Chern-Simons term depends on the connection, and therefore standard methods like Wald's Noether charge technique [72] do not work [73]. Another method, the Euclidean path integral formalism [74], requires the specification of two kinds of boundary terms, a Gibbons-Hawking-York boundary term and a boundary counterterm. **A third goal in this context is to investigate the Euclidean path integral formulation of topologically massive gravity with different asymptotic behavior (asymptotically flat, asymptotically AdS) and the construction of all relevant boundary terms.** Again a reduction to two dimensional dilaton gravity [39],

$$I = -\int d^2x \sqrt{|g|} \left(XR - U(X)(\nabla X)^2 - 2V(X) \right) + \text{boundary terms} \tag{2}$$

where applicable, will be very helpful, because there all boundary terms can be derived in closed form from first principles, regardless of the asymptotics [41]. We will also investigate to what extent the results can be lifted to three dimensions.

Finally, one of my key achievements in the past is to advance to a leading expert in 2-dimensional gravity, as evident from my CV attached (see also section 2.2 below). I have accumulated a significant list[4] of relevant open problems of varying degree of difficulty, most of which deal with classical, semi-classical or quantum BHs. This provides a rich source for possible topics for diploma- or PhD students (in fact, I have already supervised several theses and numerous student projects on this subject, see my CV). For sake of brevity I do not present here details of planned research projects and rather formulate a general **goal: to advance further research on 2-dimensional classical and quantum BHs in collaboration with local students and international collaborators, in particular with Dimitri Vassilevich and Roman Jackiw, and to remain one of the key experts in this field.**

BHs in AdS Through the AdS/CFT correspondence of Maldacena and in other conjectured gauge/gravity dualities, the thermodynamics of gauge theories at strong coupling is mapped to the thermodynamics of BHs in 5-dimensional AdS space [75]. The deconfinement transition in QCD is related to the Hawking-Page phase transition on the gravitational side [76]. Matter degrees of freedom are described by additional D-branes embedded in this background geometry, and several quantities of phenomenological interest have been worked out already: shear viscosity, thermalization times, meson spectra, energy loss and jet quenching parameters. In order to obtain next-to-leading order corrections in the strong 't Hooft coupling, generalizations of the Einstein-Hilbert action need to be considered, and have been studied only incompletely thus far. Another generalization involves finite chemical potential, which is either modeled through Reissner-Nordström BH solutions (for R-charge chemical potential) or D-branes with nonzero gauge potentials (for baryon and isospin chemical potential). These aspects are being studied by the group of Prof. Rebhan at VUT (in collaboration with Aleksi Vuorinen at CERN and Christopher Herzog at Princeton) and these make contact with the study of fundamental issues studied by myself in collaboration with Robert McNees. The present project nicely complements these existing research programs. **The main goal here is to bring together the expertise of Prof. Rebhan and his group with my own expertise on BH physics, and to address some of the issues above in common research projects.**

[4]To give at least a flavor of the items on this list I present here some of the topics: α' corrections to boundary counterterms, Ricci flow and 2D dilaton gravity, singularity theorems in 2D, Hamilton-Jacobi counterterm for BHs in dS, non-commutative BHs in 2D, AdS_2/CFT_1 correspondence, area scaling in Liouville gravity in Vienna school approach, quantization in presence of boundaries, boundary counterterms in presence of matter, algorithm to extract all 2n-point vertices in spherically reduced gravity with scalar matter, Bethe-Salpeter like resummation of virtual BH contributions to S-matrix, quantum scattering with metastable BH intermediate state, evaporating BHs with circular horizon topology.

BH analogs All BH analogs in condensed matter systems described so far mimic at most two features of a BH: a (sonic) horizon and particle creation at the Hawking temperature [24–26]. This means that many of the conceptually interesting problems in the context of evaporating BHs – for instance, the information loss problem and the microscopic origin of BH entropy – cannot be addressed in analog systems. It is fair to ask if this situation can be improved. Of course, condensed matter physics is fundamentally different from most gravitational theories as there are no graviton excitations. However, certain gravitational systems exhibit BH solutions with interesting thermodynamics, and yet they do not exhibit spin-2 excitations. In [41] the thermodynamics of a large class of such BHs was studied in great detail, and an expression for the Helmholtz free energy was derived that depends on two free functions. By tuning them appropriately one can obtain BH solutions with various thermodynamical properties (positive/negative specific heat, accordance with/violation of the third law of thermodynamics, positivity properties of surface pressure, etc.). This allows in principle to "engineer" BH solutions whose thermodynamical properties are adequately reflected in some condensed matter analog. The only 2-dimensional analog model proposed so far involves a specific Bose-Einstein condensate [77] and mimics the Jackiw-Teitelboim model [35]. **One goal is the search for condensed matter analogs that share the relevant thermodynamical properties, in particular entropy, with a corresponding BH by exploiting the possibility to "engineer" the Helmholtz free energy.** This search requires of course expertise from the condensed matter side, and I shall pursue this together with Alfredo Iorio and interested students. Actually, there is already one precedent to this program in a slightly different context, namely QCD. Here we could identify a particular BH, the exact string BH [78] which exhibits positive specific heat [79], as a good thermodynamical analog of QCD in the context of hadronic freeze out [80]. The seminal proposal of [81] was able to identify the correct Hawking temperature, but the BH analogs studied there all suffered from unusual thermodynamical properties (negative specific heat, violation of the third law of thermodynamics, no Hagedorn phase transition). By contrast, the analog BH model that we proposed [80] exhibits positive specific heat, is consistent with the third law of thermodynamics and has a Hagedorn phase transition at the critical temperature $T \sim 170 MeV$. **Another goal is to explore further the role of BH analogs for QCD processes such as hadronic freeze out.** This complements also the studies on AdS/CFT mentioned above.

BHs in modified theories of gravity While general relativity so far has passed all experimental tests with ever increasing accuracy [82], there is certainly no lack of attempts to go beyond general relativity. A particular proposal by Jackiw and Pi induces parity violation and leads to bi-refringence of gravitational wave amplitudes [83]. It may also lead to leptogenesis [84] and that model is studied currently by a growing number of groups, for a list of references cf. e.g. [85]. The action

$$I = \int d^4x \sqrt{|g|} \left(R - \frac{1}{4}\theta\,{}^*RR \right) \tag{3}$$

contains higher derivative terms and thus on general grounds problems with the variational principle are expected to arise, in the sense that it is not sufficient to specify Dirichlet boundary conditions for the metric. On the other hand, some specific higher derivative theories, like Lovelock gravity [86, 87], do not exhibit problematic features with the variational principle, essentially because of the topological nature of the higher derivative terms. Since also the correction to the Einstein-Hilbert action in (3) is of topological nature (the Chern-Pontryagin density), it could exhibit a well-defined variational principle. **One goal is to study the variational principle of (3), to construct all boundary terms and to discuss thermodynamical properties of BH solutions.** Regarding the latter, it is known that the Schwarzschild BH emerges as solution of the equations of motion descending from (3), but so far only physically unacceptable rotating BH solutions were found [85]. Since most of the BHs observed in astrophysics exhibit an appreciable amount of rotation it is quite important to find rotating BH solutions in the modified theory. Thus, **another goal is to either construct a physically acceptable rotating BH solution of (3), or to demonstrate that no such solution exists.** The first goal will be pursued in collaboration with Robert Mann and with Robert McNees, while the second goal will be pursued together with Nicolas Yunes. As in all other cases, future diploma- and PhD students will be encouraged to join.

BHs in astrophysics At the Massachusetts Institute of Technology (MIT) I have recently started a collaboration with Bruno Coppi and Paola Rebusco on BH accretion disks (for a textbook cf. e.g. [88]), one of the main observational features in the detection of stellar-mass BHs. This part of the project involves topics where my own expertise (BHs, general relativity, mathematical physics) is substantially complemented by the experience of my collaborators: Bruno Coppi's expertise in plasma physics and accretion disks, and Paola Rebusco's expertise in X-ray physics and high frequency quasi-periodic oscillations. **The goal of our joint efforts is to obtain a better understanding of the dynamics in accretion disks.** Another topic where strong gravitational effects and rotating systems are of relevance is encountered in galaxies. In September 2007 the European Space Agency (ESA) launched a call for proposals, in particular the call 07/1301 [89], which is of relevance for the present context and which quotes one of my papers with Herbert Balasin [90]. Thereby encouraged, we submitted a proposal [91], and in December 2007 we won the competition. This medium-sized project starts in Spring 2008 and lasts till Summer 2008. Depending on the outcome of our study, we might be interested to pursue follow-up work on the dynamics of gravitationally bound rotating systems. Thus, **another goal is to build upon our ESA study if the results of the latter are promising and to study in detail non-perturbative effects in gravitationally bound rotating systems.**

BH formation in numerical simulations Critical phenomena in gravitational collapse were discovered in pioneering numerical investigations by Matthew Choptuik [58]. He studied a free massless scalar field coupled to spherically symmetric Einstein gravity in four dimensions with sophisticated numerical techniques that allowed him to analyze the transition in the space of initial data between dispersion to infinity and the formation of a BH. Thereby the famous scaling law

$$M_{BH} \propto (p - p_*)^\gamma \,, \tag{4}$$

was established, where $p \in [0, 1]$ is a free parameter characterizing a one-parameter family of initial data with the property that for $p < p_*$ a BH never forms while for $p > p_*$ a BH always forms with mass M_{BH} determined by (4) for p sufficiently close to p_*. The critical parameter $p_* \in (0, 1)$ may be found by elaborate numerical analysis and depends on the specific family under consideration; but the critical exponent $\gamma \approx 0.37$ is universal, albeit model dependent. Other systems may display a different critical behavior, cf. the review [92]. The critical solution $p = p_*$, called the "Choptuon", in general exhibits remarkable features, e.g. discrete or continuous self-similarity and a naked singularity. Since the original system studied by Choptuik is a special case of (2) supplemented by a Klein-Gordon action, cf. e.g. [42], it is not only natural to inquire about generalizations of critical phenomena to arbitrary 2-dimensional dilaton gravity with scalar matter, but such a study might reveal connections between critical exponents in various dimensions and provide hints how to extract them by analytical methods, since all models are treated on an equal footing. In isolated cases this approach led already to an analytical understanding of critical collapse: in [93] a critical exponent $\gamma = 1/2$ was derived analytically for the so-called RST model [94], a semi-classical generalization of the so-called CGHS model [95]. Later, in [96] critical collapse within the CGHS model was considered the result $\gamma \approx 1/2$ was confirmed numerically. More recently the generalization of the original Choptuik system to arbitrary dimensions was considered [97–99], and this can also be described in a 2-dimensional way based upon (2), but with different potentials U and V. Remarkably, so far no comprehensive study exists that investigates critical collapse in generic 2-dimensional dilaton gravity coupled to scalar matter. The basic equations derived in [42] will be the starting point of such a study, but of course it remains a challenge to implement them in a numerical simulation. The proximity to the group of Peter Aichelburg in Vienna, a local expert on numerical relativity, will allow to use his expertise to achieve the following **goal: a comprehensive study of critical collapse in 2-dimensional dilaton gravity with scalar matter, using numerical and analytical techniques.** The achievement of this goal will require a PhD student or postdoc who is prepared to face the computational challenges, and will be recruited either from the pool of VUT students, from Peter Aichelburg's students at the University of Vienna or internationally.

1.1.3 Importance of the expected results

I summarize below the importance of the expected main results for BH physics:

- **Lower-dimensional BHs** The understanding of the quantum theory of BHs in two and three dimensions will help us to resolve difficult conceptual issues in quantum gravity that exist regardless of the dimension. Much like in quantum mechanics, where a decisive breakthrough was the thorough understanding of the simplest of all atoms, the Hydrogen atom, it is expected that in quantum gravity a decisive breakthrough will be a thorough understanding of simple BH systems, and certainly BHs in two and three dimensions are the simplest BHs possible.

- **BHs in AdS** Surprisingly, BHs in 5-dimensional AdS space are now of great practical importance for the ongoing research in quark-gluon-plasma, which beginning in late 2008 will enter a new phase by the start of the heavy-ion program at the LHC at CERN. In collaboration with the group of Prof. Rebhan, the aim will be to contribute to the very active field of using the AdS/CFT correspondence to obtain predictions for the phenomenology of strongly coupled QCD at high temperature and/or high chemical potential.

- **BH analogs** The theoretical construction of BH analogs that display not only the same kinematical features as gravitational BHs, but also share some key dynamical properties can be exploited in two directions: one can learn something about BHs (like the microscopic origin of BH entropy) by studying the analog system, and one can learn something about the analog system (like hadronic freeze-out in QCD) by studying specific BHs. These features engender a cross-fertilization between otherwise disconnected fields in physics.

- **BHs in modified theories of gravity** Several well-motivated extensions of general relativity exist, most of which contain higher derivative interactions. Often very little is known about solutions of such models, beyond the gravitational wave approximation. Since we know that (rotating) BHs exist in astrophysics it is important for the self-consistency and the better understanding of these extensions to construct such BH solutions, to reveal their physical properties and to contrast them with BHs from general relativity.

- **BHs in astrophysics** The prime motivation to study BHs is because they exist. With the ever increasing influx of astrophysical and cosmological precision data the interaction of BHs with surrounding matter can be studied phenomenologically in great detail. Therefore, it is important to confront these data with theoretical predictions and refine the latter. In particular, the physics of gravitationally bound rotating systems, such as BH accretion disks, brings together different communities – plasma physics, X-ray physics, general relativity – and has great potential for future discoveries.

- **BH formation in numerical simulations** The exciting discovery of critical collapse by Choptuik was one of the early significant successes of numerical relativity, but it is still poorly understood, especially from an analytical point of view. The comprehensive approach advocated in this proposal will provide not only new critical exponents, but it will also allow to derive connections between critical exponents of different models by putting BHs in various dimensions on an equal footing with 2-dimensional BHs. Moreover, an analytical understanding of the critical exponents is more accessible within a 2-dimensional approach.

1.2 Methods

The scientific methods were addressed concisely above. In this section I focus on non-technical aspects, namely the work plan and collaborations.

1.2.1 Work plan

Implementation of research and teaching plans It is very fortunate for the implementation of this project that I shall return to Vienna already a year prior to its start (see the time plan below). This means that all the issues that arise when moving with a family between continents will be settled, and similarly most of the administrative issues should be settled as well. Moreover, I can actually prepare the implementation of my research and teaching plans several months before the project start, by discussing with my local collaborators in detail the adjustment of lectures, proposal for seminar topics, invitation of visitors, co-supervision of students and some of the technical details of relevance for our common research interests.

Taken together this means that the project will start at full speed already in the first year, in Summer 2009. In that Summer I shall chair a session on lower-dimensional gravity at the prestigious Marcel-Grossmann meeting (see below), which provides a good "kick-off" for the lower-dimensional topics. In Fall 2009 my lectures on BHs will start as well as our weekly theory seminar on a topic which I plan to choose in accordance with the objectives of this project (either in collaboration with Herbert Balasin or with Anton Rebhan). From these interactions with students I expect to recruit the first candidates for PhD and/or diploma students. While according to my experience it seems more likely to me that the first students will start working with me towards the end of the first year, I want to remain open to the possibility that a student starts working with me immediately in the first year, and therefore I have scheduled the personnel costs accordingly (see section 4.2 and the "Antragsformular"). The first year will also serve as an opportunity to connect my international collaborators more closely with VUT, by inviting them and also by visiting them. Regarding the research aims, my collaborators and I shall be working on all of them from the very beginning, probably except for the sub-project on numerical simulations. The latter is more suitable for a later stage since it requires substantially the programming skills of a PhD student or postdoc, and they will be easier to recruit once my position in Vienna is well-established. However, I will certainly announce possible postdoc positions to this and also to all other topics covered in the proposal. The goal is to choose the best candidate among all topics covered in this proposal, rather than choosing only one specific topic, and to this end I plan to post corresponding announcements at various local, international and especially on-line bulletin boards. If a suitable candidate appears, (s)he could start already in the second year, otherwise I would aim for the third year as start for the first postdoc. Moreover, the early announcement of several postdoc positions also has the advantage that it opens up the possibility to attract external research money, if a suitable postdoc candidate manages to obtain a corresponding grant from some external funding agency – like a Research Fellowship by the German Research Foundation (DFG), an intra-European Marie-Curie fellowship or a Fulbright Fellowship for postdocs from the US. Finally, I would like to launch the outreach activities mentioned briefly in section 3, and to this end I plan to recruit a programmer for the webpage `http://www.teilchen.at`, who should work continuously on updates and refinements of this webpage during the whole period of the START project. For that purpose a local recruitment is sufficient.

In the second year I plan to start the Habilitation process, with the aim to finish it in the fourth or fifth year. An important step is again the announcement of a postdoc position in Fall 2010, with similar remarks as above. I expect to work with at least two students (diploma or PhD) towards the end of the second year. Towards the third/fourth year the activities should peak, as I plan to recruit a second postdoc, which will allow not only collaborations with me and my other collaborators, but also between the postdocs and between postdocs and students. The ensuing discussions will be stimulating for both, junior and senior collaborators. In that period it will be very beneficial to organize a workshop in Vienna devoted to the subject of BHs, for instance at the International Erwin Schrödinger Institute, as this will further enhance the stimulation for my collaborators, students and me, and it will bring together experts from around the world. Since I have experience in the organization of such workshops and because Dimitri Vassilevich signaled already his willingness to co-organize with me such an event I am confident that we shall succeed in this endeavor. Because I intend to attract money from external sources for this workshop no additional costs will arise for FWF.

In the final two years an important focus is the future of my group and thus also my own future. By that time my collaborators and I will have accumulated a significant number of results and I expect that most of the research aims will have been achieved until the fifth year. Thus, it will be time to review my options and the options of my collaborators and to make decisions concerning job positions. I am aiming for a permanent position in Vienna, possibly at VUT, but clearly this depends on funding issues, which are notoriously difficult to predict.

Time plan A brief time plan is presented in the following table:

Period	Summary of most relevant activities besides research
Summer 2008	Moving to Vienna with family, Edit Wolfgang Kummer Memorial
Fall/Winter 2008	Settling in at VUT, Work with collaborators at VUT commences
Spring 2009	Prepare implementation of teaching and research plans of START proposal
Summer 2009	**Start of START**, Chair session at Marcel-Grossmann meeting in Paris
Fall 2009 – Summer 2010	Lectures on BHs and organize weekly seminar, Start research program
Fall 2010 – Summer 2011	Select first students for diploma/PhD, Start Habilitation process
Fall 2011 – Summer 2012	Select first postdoc, Provide intermediate report for START
Fall 2012 – Summer 2013	Select second postdoc, Organize workshop on BHs
Fall 2013 – Summer 2014	Finalize Habilitation, Apply for permanent positions (focus on Vienna)
Fall 2014 – Summer 2015	Finalize project

Dissemination of results The main way to distribute our results is of course by means of scientific publications in peer reviewed international journals of high impact. In addition, all our results will be published as e-prints in the freely accessible physics archive at `http://arXiv.org`, in accordance with FWF policy.

Additionally, key results will be presented at various international conferences. At the beginning of the project a major conference, the Marcel Grossmann meeting, takes place, where I will chair a session on lower-dimensional gravity. This will provide a prime opportunity to forge new contacts of relevance for the project and to announce progress of my own research. That meeting takes place every three years, so in 2012 (after the first half of the project) and in 2015 (after the termination of the project) there are again excellent possibilities for my collaborators and me to present our results. Moreover, I intend to visit a major research institute outside Europe – like MIT or the Perimeter Institute — each year, which will permit to present results in seminar talks at a location with considerable impact. Another relevant conference is the International Conference on General Relativity and Gravitation, which will take place in Summer 2010 and 2013. Both will provide good opportunities to present our results to an international audience and experts in the field. In addition, I plan to visit 1-2 European conferences per year, if they are adequate for the presentation of our results.

In order to permit my postdocs and PhD students the presentation of results at workshops and conferences, the support requested contains a sizable amount of travel money, see section 4.2. Finally, the outreach activities described briefly in section 3 allow to present results to a local but otherwise broad audience.

1.2.2 Collaborations

Here is an overview on my collaborations of relevance for the project[5]. Details on the quality of the scientists involved can be found in section 2.1.

I start with a table of **local collaborations**:

Name	Affiliation	n	Adm.	Start	Field
Herbert Balasin	VUT	3	yes	2000	General relativity
Anton Rebhan	VUT	0	yes	1999	AdS/CFT applied to QCD
Maximilian Kreuzer	VUT	0	yes	1999	BHs in string theory

With the same notation as above here is a table of **international collaborations**:

Name	Affiliation	n	Adm.	Start	Field
Dimitri Vassilevich	Sao Paulo University	9	yes	2000	BHs in two dimensions
Roman Jackiw	MIT	5	no	2006	BHs in lower dimensions
Alfredo Iorio	Charles University	2	no	2003	Analog models of BHs
Dharam Ahluwalia	Canterbury University	2	yes	2004	Editorial duties
Muzaffer Adak	Pamukkale University	1	no	2007	Mathematical aspects of BHs
Nicolas Yunes	Penn State University	1	no	2007	BHs in astrophysics
Robert Mann	Waterloo University	0	no	2007	BHs in modified theories

Finally, here is a table with **collaborations of potential relevance** for the START project:

[5]The number n denotes the number of joint scientific papers so far; 'Adm.' refers to collaboration at the administrative level – teaching, organization of conferences, editorial duties etc.; 'Start' provides the year when the collaboration commenced; the collaborators are ordered primarily by numbers of joint publications and secondarily by starting year. The final entry 'Field' denotes the field of mutual interest of relevance to the project.

Name	Affiliation	n	Adm.	Start	Field
Luzi Bergamin	ESA	8	yes	2003	Supergravity in two dimensions
René Meyer	MPI for Physics	3	no	2005	Quantum gravity and AdS/CFT
Robert McNees	Perimeter Institute	2	no	2006	BHs in string theory
Paolo Castorina	Catania University	1	no	2007	Analog models of BHs in QCD
Paul Romatschke	Washington University	0	no	2007	AdS/CFT applied to QCD
Bruno Coppi	MIT	0	no	2008	Accretion disks
Paola Rebusco	MIT	0	no	2008	Accretion disks

In the first three cases of the last table the future prospect of the collaboration depends essentially on the job situation of my collaborator. For instance, if René Meyer is able to obtain a postdoc position after his PhD then we will continue to collaborate for sure, and similar remarks apply to Luzi Bergamin and to Robert McNees. In the other cases the collaborations are too recent to allow an authoritative statement about future prospects.

Judging from my past experience it is very likely that new collaborators – both at a local and an international level – will join while the project is running.

Finally I would like to mention that my existing local contacts with other research institutions in Vienna – the gravity group at the University of Vienna where I have given seminar talks repeatedly, the international Erwin Schrödinger Institute where I have organized a program and participated at several other programs, and the High Energy Physics Institute of the Austrian Academy of Sciences, where colleagues and I initiated a weekly lunch for discussions – will also be beneficial for the project.

2 Human Resources

2.1 Qualifications of the scientists involved

Qualifications of personnel The qualifications of the applicant are evident from the CV attached. The qualifications of the remaining personnel is crucially related to the selection process. The postdocs will be recruited internationally through a competitive process (see section 4.2). The PhD and diploma students will be recruited mostly locally, which is why my teaching responsibilities and contacts with students will play an important part in the project, to ensure that the best candidates are hired.

Qualifications of collaborators Below a brief description of the collaborators listed in section 1.2.2 is provided (in the same order), together with the key roles of each collaborator:

- Herbert Balasin plays an important part in my project with the ESA. Scientific collaboration with him will be focused on general relativistic aspects. Balasin gives lectures on general relativity, and thus my advanced lectures on BHs can rely on the basics that he provides. Balasin is always willing to share his expertise in general relativity in discussions with students and collaborators.

- Anton Rebhan is the successor of Wolfgang Kummer at VUT, and we have a long history of collaboration at an administrative level (supervision of students, seminars – including a seminar on BHs, webpages and my current Marie-Curie fellowship). More recently we started to collaborate as co-editors for a Memorial Volume devoted to Wolfgang Kummer. Rebhan is an expert in quantum field theory at finite temperature and applications to QCD. More recently, he has begun to apply the AdS/CFT correspondence to problems of relevance for QCD and relativistic heavy ion collision experiments (such as the ones performed at RHIC and scheduled for LHC). Thus, BHs in AdS are a topic of common interest and we plan to collaborate on it.

- Maximilian Kreuzer is the local expert on string theory and we have worked together in the past with students (lectures on quantum mechanics, seminars). While the project does not rely heavily on collaboration with Kreuzer it will certainly benefit from interactions with him.

- Dimitri Vassilevich was the most active collaborator of Wolfgang Kummer and, after my PhD advisor, also my main collaborator. In particular, we have worked together on an invited review article of monographic size and considerable impact, and we organized an extensive program at the Erwin-Schrödinger Institute in Vienna. In 2006 Vassilevich accepted a professorship in Sao Paulo and I moved to Boston, which is why our collaboration was reduced in the past two years. However, we are in permanent e-mail contact and the START project would allow to rekindle this fruitful collaboration by providing me a more stable position and by providing Vassilevich a target for future visits without draconian travel restrictions[6]. Vassilevich will play a key role in studies of lower-dimensional BHs.

[6] Once he had to wait for a year to obtain a visum for the US.

- Roman Jackiw is one of the pioneers of lower-dimensional gravity and quite a universal and famous mathematical physicist. Our first e-mail exchange actually dates back to 2001, when he contacted me as a response to my PhD thesis, and since then the interaction with Jackiw increased steadily, with mutual invitations, papers on the same subject and finally my postdoc position at MIT, with five joint publications so far. Besides the obvious advantages from a collaboration with Jackiw, he provides also a link to MIT and encourages future visits there. In addition to the insights he will provide on the scientific side, his ability to give excellent pedagogical talks and his activity at conferences, workshops and schools will also help to disseminate our research results.

- Alfredo Iorio is located in Prague, i.e., quite close to Vienna, which will facilitate the collaboration. He will play an important role in the study of BH analogs, since we have started to explore together the search for BH analogs in (and beyond) QCD recently. The combination of Iorio's field theoretic background, expertise in BH entropy and the diversity of his interests will be very useful in this context.

- Dharam Ahluwalia has worked on certain conceptual aspects of quantum BHs, but his main focus lies outside the physics of BHs. However, he has a long history of editing essays for the Gravity Research Foundation and we have collaborated in the past not just on scientific issues but especially as co-editors. His editorial expertise will be helpful for my own editorial and referee duties.

- Muzaffer Adak is a young professor in Denizli, Turkey, and our collaboration on lower-dimensional gravity has started recently, focusing mostly on mathematical aspects of BHs. I am going to visit him at a conference in April 2008, which will allow to discuss in detail our mutual plans of future collaborations.

- Nicolas Yunes is a PhD student at Penn State University and has recently accepted a postdoc position in Princeton. He is mostly interested in astrophysical aspects of BHs and gravitational waves. Since his position is stable for the next two years and a half our plans for collaborations should not be impeded too much by issues of moving or job applications. He will play an important part in investigations of Chern-Simons modified gravity.

- Robert Mann is another pioneer of 2-dimensional gravity working at the Waterloo University and his proximity to the Perimeter Institute makes visits to him doubly attractive. Collaboration with him started recently, but we have already many plans for future projects, some of which were described briefly above. He will thus play an important role in investigations of lower-dimensional gravity and of BHs in modified theories.

Since the status of the remaining seven collaborators listed in section 1.2.2 is not completely clear – either because of job insecurity or because the collaboration is too recent – I shall restrict myself to the most likely candidate, René Meyer. He was my diploma student in Leipzig and is now working under the supervision of Johanna Erdmenger at the Max-Planck Institute for Physics in Munich. He will finish his PhD around the time the START project is projected to start, and he is a likely candidate for one of the postdoc students (either directly after his PhD or after his first postdoc position elsewhere). His expertise in 2-dimensional gravity, quantum gravity and AdS/CFT surely would be a valuable asset for the project.

2.2 Relevance of the project for career development

Besides the scientific output the project will have a significant impact on my career development:

- The close contact with excellent research institutions such as MIT, the Perimeter Institute, the ESA or the Max-Planck Institute in Munich will be beneficial for those institutions, the VUT, my collaborators and especially for myself.
- The teaching responsibilities will allow intensive contact with students, some of which can be recruited as future collaborators. The interaction can reach from student talks in our weekly seminar to a PhD thesis, with the option of a diploma thesis in between.
- In addition, the teaching responsibilities together with my research will permit me to aim for a "Habilitation" (a postdoctoral lecture qualification), which is an important component in the Austrian academic system. I expect to finish my Habilitation thesis in the second half of the project.
- Relatedly, my experience so far at the University of Leipzig and at MIT is that it typically takes 1-2 years until students become sufficiently aware of my activities to consider collaboration: in Leipzig my diploma student René Meyer contacted me in the middle of the second year after I was recommended to him by a colleague, and a group of students asked me to

conduct a seminar on BHs in the year when I left Leipzig; similarly, at MIT Bruno Coppi asked me recently if I could collaborate with some of his students. In both cases it was somewhat unfortunate that a typical postdoc position does not provide sufficient time to deepen these contacts with students. Clearly, with the six years provided by START (and the one year I shall be in Vienna in advance) this is not an issue anymore and thus I expect fruitful interactions with students over an extended period.

- The establishment of a small but active group of young scientists (2 postdocs, 3 PhD students and several diploma students) will provide the incentive for complementary and follow-up projects. It will also help to attract European (and international) research money for these projects, for workshops and for the invitation of guest scientists.
- Moreover, re-building a gravity group at the VUT is also attractive because the label "Vienna school of gravity" is attached to it. This name was coined by Stanley Deser and Roman Jackiw and basically describes the work by my PhD advisor Wolfgang Kummer and his collaborators and students on 2-dimensional gravity. Since I used to be part of that group for eight years and a large fraction of my research is devoted to 2-dimensional topics I am confident that I shall achieve the re-establishment of the "Vienna school".
- Finally, all of the above will certainly bring me closer to the goal of acquiring a permanent position in Vienna.

3 Expected Spin-Offs

Besides the impact on research, teaching and career development pointed out in the previous sections the following spin-offs are anticipated:

- Anton Rebhan and I (together with Christian Gottfried) were the driving forces behind the outreach webpage `http://www.teilchen.at`. Its current webmaster, Wolfgang Waltenberger works at walking distance from VUT. The webpage has reached a stage where it is presentable to a large audience and requires permanent attention for updates. Since all key players will be closely together during the project and because I plan to hire a programmer/web-developer for precisely this purpose I expect a major increase in outreach activities and the impact of `http://www.teilchen.at`.

- In Leipzig and Massachusetts my lectures on BHs have led to the invitation to give popular talks at high schools/colleges and to the collaboration with artists (an art teacher in Boston, Paul Andrade, and the dramaturgist Birgit Rasch for the theater production "Drei mal Leben" by Yasmina Reza). It is not unlikely that similar interactions will take place in Vienna, because I am keeping contact with high school teachers I know from my student times.

4 Financial Aspects

4.1 Infrastructure at the Vienna University of Technology

The Institute for Theoretical Physics at the Vienna University of Technology (VUT) hosts two groups, the theoretical condensed matter physics group led by Joachim Burgdörfer and the fundamental interactions group led by Anton Rebhan. In the fundamental interactions group there are additionally Herbert Balasin, Ulrike Kraemmer and Maximilian Kreuzer (see section 1.2.2 above), as well as a constantly changing number of visitors, postdocs, graduate students and undergraduates. Three secretaries guarantee the professional administration of the institute and the institute's library. Sufficient office space is available and equipped with up-to-date hardware and software. Of course, the institute also provides standard services, such as network, system administration, printing, fax, copy machine, phones, a tea kitchen etc. The institute has its own seminar room, which is used to host special lectures, seminars and guest speakers. In occupation-free times it can be used for discussion groups. It is equipped with up-to-date presentation technology.

The Institute for Theoretical Physics is integrated into a building complex known as "Freihaus", which hosts several physics and mathematics institutes, a feature that facilitates collaborations across the boundaries of institutes. Several lecture halls, student facilities and food courts are in the same building, which promotes closer contact with students. The physics library is also contained in the "Freihaus" and provides access to most of the relevant physics journals. The main library of the VUT is located in an adjacent building and complements the institute's selection of textbooks and monographs. Several campus licenses allow the acquisition of papers from standard journals via web portals. Moreover, the Central Physics Library of Vienna provides on-line loans of more exotic or antique papers and as a special service sends scanned versions thereof as PDF file by e-mail, which considerably expediates literature research.

Finally, the "Freihaus" is one walking minute away from the main building of the VUT, from a central subway station and from the "Ring" encircling downtown Vienna. Thus, it is located quite favorably in the city and accessible easily by public transport.

4.2 Information on the support requested

Total amount of support requested: 1.089.830, 00 EUR

The project costs comprise personnel costs and travel costs. The bulk part of the project costs are personnel costs, listed in the following table (p denotes the number of persons requested and y the number of years for each person):

Personnel requested	p	Cost per y per p	y	Involvement	Total cost
Senior Postdoc	1	61.240,00 EUR	6	100%	367.440,00 EUR
Postdoc	2	54.180,00 EUR	3	100%	325.080,00 EUR
PhD student	3	31.670,00 EUR	3	75%	285.030,00 EUR
Undergraduate student	4	0,00 EUR	1	50%	0,00 EUR
Programmer	1	27.080,00 EUR	1	17%	27.080,00 EUR
Total					**1.004.630,00 EUR**

The requested travel costs are summarized in a similar table:

Travel costs requested	p	Cost per y per p	y	Total cost
Senior Postdoc	1	5.000,00 EUR	6	30.000,00 EUR
Postdoc	2	2.500,00 EUR	3	15.000,00 EUR
PhD student	3	1.000,00 EUR	3	9.000,00 EUR
Undergraduate student	4	300,00 EUR	1	1.200,00 EUR
Dimitri Vassilevich	1	2.500,00 EUR	6	15.000,00 EUR
Alfredo Iorio	1	1.500,00 EUR	6	9.000,00 EUR
International Visitor	1	1.000,00 EUR	6	6.000,00 EUR
Total				**85.200,00 EUR**

Justification of the personnel requested The one Senior Postdoc position will support the applicant. My temporary position at MIT/VUT will end in July 2009, which should be the starting point of the START project. As evident from my CV, my research has been based in Austria for at least three of the previous 10 years (100% in 1999–2003 and 33% since August 2006), which is one of the necessary pre-requisites imposed by FWF. The two postdoc positions will be recruited internationally by posting at various bulletin boards, and the involvement of the postdocs will be essential for a successful implementation of the project and the establishment of a small but significant group devoted to research on BHs. My plan is to recruit the first postdoc in the second year (so that (s)he can start to work on the project in the third year), and the second postdoc in the third year. This will allow for ample collaboration between the postdocs, myself and further collaborators. The proposed timing is chosen so that the initial phase of the project is terminated by the time the first postdoc arrives, which should optimize the research output (see section 1.2.1). However, if I receive suitable applications at an earlier stage I will take the liberty to recruit a postdoc before the third year. Each position should last three years to give the postdocs ample time for research[7]. Because of my teaching activities I expect to raise interest of local students in pursuing a PhD (see section 1.2.1). Each PhD is estimated to take three years. As evident from my CV I have experience in advising students and scientific collaborations with them, and thus the PhD students will become a relevant part of the project. I estimate that within six years I shall recruit three PhD students. However, if the financial situation of the FWF does not allow to grant all personnel costs requested, then I propose to pay only two PhD students from the START project, and I shall try to provide other (international, European or Austrian) money sources for eventual further PhD students. Similarly, I expect to supervise about four diploma students. Because the policy of the Institute for Theoretical Physics at VUT is to provide no financial support for diploma students no personnel costs arise for them. Finally, as explained in section 1.2.1 I shall also be involved in outreach activities. For this purpose I intend to hire a part-time programmer for webpage development and script programming, to be recruited locally in Vienna (most likely from the VUT).

Justification of the travel costs Because of my international collaborations I shall travel frequently. In particular, my plan to keep close contact with MIT implies that I shall travel there about once a year for a month, which accounts for approximately half of my travel cost (2.500

[7] Usually the first year requires at least a month for settling in (longer if the postdoc has family), and the last year requires the postdoc to write applications for his or her next position. Thus, a three year position allows at least one full year exclusively devoted to research and is preferable to two year positions.

EUR). The other half is reserved for the visit of two-three conferences/workshops per year. Since I want to encourage my postdocs to visit also two-three conferences/workshops per year (to present some of our results and/or to ignite new collaborations), 2.500 EUR are proposed as travel money for each postdoc/year. For my PhD students I suggest the visit of one major conference per year (to present results and to get to know the community) and one-two local workshops/schools (for their personal benefit and education). I estimate that this requires about 1.000 EUR per person and per year. Even though no personnel costs arise for diploma students, I want to provide the possibility of their participation at some conference or workshop. The amount of 300 EUR per person seems adequate. No travel costs will arise for the part-time programmer. Finally, international collaboration plays a key role in the project. Therefore it is necessary to invite some of my collaborators for research visits to Vienna, with benefits not only for the research project but also for local students at VUT. In particular, I intend to invite Dimitri Vassilevich and Alfredo Iorio for extended research visits in Vienna at a rate of about once each year. In the case of Dimitri Vassilevich this will require about the same amount of travel money as scheduled for my annual visits at MIT, i.e., 2.500 EUR per year. In the case of Alfredo Iorio the cost is slightly reduced to about 1.500 EUR per year because no transatlantic travel is required. In order to invite other collaborators, like Roman Jackiw, Muzaffer Adak, Nicolas Yunes, Robert Mann or eventual future collaborators every other year I would require additionally about 1.000 EUR per year.

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