C2

3.1 Allgemeine Angaben zum Teilprojekt C2

3.1.1 Thema: Interpretation von Gravitationswellensignalen

3.1.2 Fachgebiete u. Arbeitsrichtung: Astronomie, Gravitationstheorie, Statistik

3.1.3 Leiter/in:

Schutz, Bernard (geb. 11.08.1946)

Max-Planck-Institut für Gravitationsphysik
Albert-Einstein-Institut
Am Mühlenberg 1
14476 Golm
Telefon: 0331–567 7220
Telefax: 0331–567 7298
E-Mail: schutz@aei.mpg.de

Ist die Stelle des Leiters/der Leiterin des Projektes befristet?

☒ nein ☐ ja, befristet bis zum __________

Schmeißer, Hans-Jürgen (geb. 09.03.1950)

Friedrich-Schiller-Universität
Mathematisches Institut
Ernst-Abbe-Platz 1-4
07743 Jena
Telefon: 03641-9 46125 / 9 46100
Telefax: 03641-9 46102
e-mail: mhj@minet.uni-jena.de

Ist die Stelle des Leiters/der Leiterin des Projektes befristet?

☒ nein ☐ ja, befristet bis zum __________

Schäfer, Gerhard (geb. 12.06.1948)

Friedrich-Schiller-Universität
Theoretisch-Physikalisches Institut
Max-Wien-Platz 1
07743 Jena
Telefon: 03641-9 47114
Telefax: 03641-9 47102
e-mail: gos@tpi.uni-jena.de

Ist die Stelle des Leiters/der Leiterin des Projektes befristet?

☒ nein ☐ ja, befristet bis zum __________

3.1.4 entfällt

3.1.5 In dem Teilprojekt sind vorgesehen:

- Untersuchungen am Menschen ☐ ja ☒ nein
- klinische Studien im Bereich der somatischen Gentherapie ☐ ja ☒ nein
- Tierversuche ☐ ja ☒ nein
- gentechnologische Untersuchungen ☐ ja ☒ nein

3.1.6 Bisherige und beantragte Förderung des Teilprojektes im Rahmen des Sonderforschungsbereichs/Transregio (Ergänzungsausstattung)

Haushaltsjahr	**Personalkosten**	**Sächl. Verw.-ausgaben**	**Investitionen**	**gesamt**
2003	**79,2**			**79,2**
2004	**79,2**			**79,2**
2005	**79,2**			**79,2**
2006	**79,2**			**79,2**
Summe 2003-2006	**316,8**			**316,8**

(Beträge in Tausend EUR)

3.2 Zusammenfassung

Ziel des Projektes ist die Entwicklung von Methoden für die Extraktion von Information aus Gravitationswellensignalen. Wenn die noch im Bau befindlichen Gravitationswellendetektoren ihre ersten Messungen vornehmen werden, wird das Signal-Rausch-Verhältnis groß genug sein, um interessante Informationen gewinnen zu können. Für das Design solcher Methoden sind entsprechende Beiträge aus der Astrophysik, Relativitätstheorie, Mathematik und Statistik erforderlich, und es müssen die Rausch-Charakteristiken der Detektoren mit einbezogen werden.

Die hierbei anzusprechenden Hauptfragen beinhalten die Abschätzung der Masse und des Spins der Schwarzen Löcher oder Neutronensterne in binärer Koaleszenz, die Entwicklung von Techniken für die gemeinsame Analyse von Daten von verschiedenen Detektoren und die Ableitung der physikalischen Natur von Signalen, die durch robuste und nicht speziell angepaßte Methoden nachgewiesen wurden.

3.3 Stand der Forschung

Many previous studies have investigated the extraction of information from detected gravitational wave signals, and indeed the subject has a solid basis in work done in signal detection theory over many decades. The current investigation will need to develop only those areas that are specific to the kinds of signals and detectors that we can now foresee.

There are standard monographs on signal extraction and parameter estimation. [1,2] Some of the first systematic studies of parameter estimation for gravitational wave detection can be found in the conference proceeding ref. [3]. Early papers on the subject include studies of radiation from coalescing binaries [4,5,6] and neutron stars [7]. Networks of detectors have been treated systematically as well for certain signals [8].

Most of this work has focussed on the ideal case, where detector noise is Gaussian and free from artifacts, and where the signal is well-predicted by a known template or a member of a parametrized family of templates. However, detectors will not be ideal, and the interpretation of signals seen in them must take into account the real characteristics of the observation. An exception is the pioneering work of B Allen and collaborators [9]. Allen spends half of every year in the Golm group.

A good example where more work is needed is the recognition of a short burst of gravitational radiation from a coincident observation of two or more detectors. In the ideal case, the data from the detectors could be combined coherently (added, with suitable time-delays and allowance for the different projections of polarization states on the detectors). But initial observations will instead use thresholding, where signals must cross minimum levels in each detector for the network to recognize them. This is more suitable for detectors with rare populations of large-amplitude noise events. However, no published study has so far compared the two methods quantitatively or indeed developed hybrid methods that depend on the detector characteristics.

Another example that does not fit previous work in this field is the detection of radiation from the merger of black holes. The Golm numerical relativity group is a leader in using simulations to predict these mergers, and Project B5 will make important contributions to our knowledge of what to expect. But during the next decade it is unlikely that we will have accurately parametrized families of signals to look for. Instead, we must find new ways of using the information from these simulations.

Similarly, early detections may reveal sources that were unexpected, so that signal recognition and information extraction are not trivial. Some work has been done in the field of signal recognition in such cases [eg 10,11], but there are no studies for the possibility of extracting information about the source once detected. Work in this area is far behind the literature in statistical signal analysis. For example, in the mathematical literature models of gravitational waves from binary inspiral are called frequency modulated signals or chirps. There exist several approaches to establishing a theory of "chirps" and there is no doubt that detecting such signals relies on describing and analyzing oscillating patterns. One of the problems will consist in extracting these unlikely gravitational waves from a signal which is corrupted by noise. In particular, detecting chirps in a noisy environment is a fascinating problem which is still open. As pointed out in Meyer [12] oscillating patterns cannot be formed by plain Fourier methods. Beyond Fourier analysis and its variants, new tools are available.

A windowed Fourier analysis (Gabor analysis, based on short-time-Fourier transforms) is analyzing signals in the time-frequency-plane (see [14], [18] and the pioneering work [19] by I. Daubechies) and is able to measure the local frequency content of a signal.

It is a form of local Fourier analysis that treats time and frequency simultaneously and symmetrically.

Using time-scale algorithms and wavelet analysis one is comparing several magnifications of a signal with distinct resolutions (Multiresolution analysis, see Mallat, Jaffard, Ryan [13], [20]).

In both situations we have common feature. The function under consideration is decomposed in a series of simple building blocks, called atoms, namely time-frequency atoms (Gabor frames, Malvar-Wilson wavelets) and time-scale wavelets, respectively. The use of this tools has led to new algorithms in data compression and denoising ([15], [16], [17]). Representing a signal as a sum of an high priority component, which we expect to be well-structured, and a low priority component, corrupted by noise, statistical models (wavelet shrinkage, thresholding) have been developped on that basis. For example, wavelet noise removal has been shown to work well for geophysical signals, astronomical data, synthetic aperture radar and acoustic data [12].

Both compression and denoising algorithms crucially rely on analyzing and modelling the intricate patterns which are present in signals. These are very often stored by their wavelet (or frame) coefficients because of the fast decomposition algorithms and the sparsity of the representation. The use of function spaces (in particular Besov spaces) is natural in this setting [12].

Analyzing, detecting and extracting oscillation patterns is a key issue. The described new tools help at defining and modelling the oscillating character of a function at given locations over a range of scales. The new challenges in analyzing gravitational waves require an interdisciplinary program of physicists and mathematicians.

Literatur

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3.4 Eigene Vorarbeiten

The gravitational wave data analysis group at Golm is one of the leading groups active in the field of gravitational wave data analysis and signal interpretation. The group has made important contributions to all the topics considered here. In the above list of references for previous work on this problem, refs [3,4,5,7,9,11] were published by members of the group. In addition to its long-term members, the group receives regular visits from collaborators such as B Allen, B Sathyaprakash, S V Dhurandhar and A Krolak, who are internationally recognized experts in gravitational wave data analysis.

The group has developed methods for detecting and extracting information from coalescing binaries, spinning neutron stars, and neutron star vibrations. As with the other work in this field worldwide, most of this has assumed ideal detector characteristics. The groundwork for working with more realistic detectors is reference [9] above, which was started when Allen was in Golm.

The Golm group works closely with the Golm numerical relativity group. See Project B5 for their previous work.

In Jena, in the research group of G. Schäfer, detailed work using matched filtering methods has been performed on the accuracy of the extraction of binary system parameters from gravitational waves from coalescing binaries where analytic information about the second post-Newtonian motion, spin and backscattering (tails) has been taking into account [30 - 36]. The investigations included single detectors as well as networks of detectors.

The Jena School on "Function Spaces" which started ist activities under supervision of Hans Triebel in the seventies is a well-known centre of research in the field. Methods of Fourier and functional analysis are successfully used studying systematically function spaces (Besov-Sobolev-Hardy type) and various applications to approximation processes, signal theory, spectral theory of differential operators or nonlinear analysis (refs. [21] – [23], [27] – [29] as far as the subject here is concerned). Important progress has been achieved in a unified approach to wide classes of function spaces based on atomic and subatomic (quarkonial) decompositions of functions ([22], [23]). The papers [24] – [26] can be seen as a contribution to the present research in time-frequency and wavelet analysis. The representations given there characterize the global, local and pointwise regularity of the function (distribution) considered. The main point of our approach is the combination of the wavelet-philosophy with the Taylor expansion - philosophy. One gets comparatively simple explicit wavelet frames which reflect simultaneously global and local behaviour. We expect to be able to construct effective smoothness and oscillation detectors using these simpler building blocks.

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(Siehe auch [3, 4, 5, 7, 9, 11])

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3.5 Arbeitsprogramm (Ziele, Methoden, Zeitplan)

There are three main areas of work, which will be worked on simultaneously: coalescing binary signals, robust network detection, and the study of unexpected signals. Indeed these areas overlap, and this overlap will be described after the research plan for each area is given.

The first research area will be coalescing binaries. These can consist of black holes and/or neutron stars. The radiation from their inspiral is well-predicted, and will probably dominate the signal-to-noise ratio for detection. From this inspiral radiation we will be able to infer the bodies’ masses and perhaps their spins. But the radiation from the merger event is likely to be significant, both for detection and for parameter extraction. It will be much more sensitive to the spins of the bodies; radiation from black-hole mergers will contain information about the validity of general relativity; and radiation from neutron stars will contain information about their equation of state. By working closely with Projects B5 and B6, we will make use of the most accurate available information from simulations. What is more, the transition from inspiral to merger also needs to be modelled, and we will work with Project B4 to improve search methods using the best models of this transition. The goal will be to create signal-matching methods that take into account the facts that (a) modelling the transition from inspiral to plunge may have uncertainties, (b) the simulations will only sparsely sample the likely parameter space of masses and spins of the objects, and (c) the simulations will themselves contain errors that make their predictions only approximate.

Suitable methods are not yet available in the literature. The most rudimentary would be the excess-power statistic, as in ref [10] above. By using time-frequency methods, such as wavelets and spectral methods, we hope to improve on these methods by localizing the signal to regions of a parameter space determined by the search method rather than the template family. This is related to work that will be done in the third area below.

The second research area is robust network detection. As mentioned above, current studies of network detection of known signals divide into two methods, that can be thought of as the two extremes: thresholding of data from individual detectors protects the detection statistic from large-amplitude non-Gaussian random events in one detector, but rejects signals that might otherwise be detected; on the other hand, coherent “aperture-synthesis” has the best detection statistic, but is vulnerable to non-Gaussian noise. We plan to develop hybrid methods that use a mixture of these two tests, and we expect that the mixture will depend on the characteristics of the noise of each detector. The work of Allen et al [9] points the way to how this can be done. Allen will work closely with this project during the six months per year that he spends in Golm. Once we have a suitable hybrid method, we will go on to examine how it determines parameters of the source: position on the sky, polarization, physical parameters. We will apply these methods to searches for gravitational collapse radiation, and will work closely with Project B3 on this.

The third area of research is in the recognition and interpretation of unexpected signals. There is a large literature on signal recognition methods using time-frequency techniques, particularly wavelets. These work well if the signal matches, for at least some of the time, a particular basis element of these search methods. We expect that this will be true of some class of potential gravitational wave sources, namely that they will exhibit wave trains with a well-defined but variable frequency: this can be expected from astrophysical systems dominated by the effects of rotation during wave emission. Besides “clean” systems like binaries, this could apply to the emission of gravitational radiation in gravitational collapse, where a rapidly spinning neutron-star core is formed at least as an intermediate stage (Project B3); and to radiation from normal modes of neutron stars (Project B2).

As pointed out in 3.3 detecting chirps (frequency modulated signals) in a noisy Environment is still an open problem from the mathematical point of view. We plan to study what information can be extracted from a detection using new tools in signal analysis such as time-frequency decompositions (Gausslets), wavelet frames based on subatomic (quarkonial) building blocks, as well as new methods in dicretization and sampling approximation. This part of basic mathematical research is a fourth area which will support and supplement the work which can be done on the basis of existing literature and algorithms. It will be important doing finer search in a second step of investigation. The main tasks are an improvement of mathematical modelling of the objects considered, the elaboration of new decomposition techniques, searching for optimal reconstruction, the development of new tools for data compression and denoising, the construction of effective algorithms and the investigation of their computational complexity.

Supposing that a signal is strong enough to be seen, what is the confidence with which we will be able to infer measured parameters like frequency, frequency derivative, amplitude, polarization; and from them the physical conditions in the source, like density, mass, angular momentum, and so on. A particular problem is that some parameters, like polarization and amplitude, can only be inferred from networks of detectors, but since we have no a priori polarization model, the signals can look very different in different detectors. This reduces the confidence with which such parameters can be measured, and it is important to quantify this. Essentially, we want to remove as much of the noise from the signal stream as possible, making use of the existing literature on denoising. Only by reconstructing the waveform of the signal can we learn whether our models of gravitational radiation sources are correct. This information could in principle be used by Projects B1, B2 and B3 to improve their models.

There are clear areas of overlap among these projects. The detection of coalescence radiation (first area) could well use methods developed for unexpected sources (third area). The inferences made in the third area about unexpected signals seen in multiple detectors needs to use the robust statistical methods developed for networks in the second research area. And it is clear that coalescence radiation can be more accurately interpreted if the events are seen in a network of detectors.

Because of these overlaps, the work will proceed simultaneously on all projects. The robust network detection will involve Allen, so it will receive more attention during his time in the group in Golm. The coalescence radiation work will be done closely with Projects B4, B5 and B6, and so its rate of progress will depend partly on those projects. Similarly, the time-frequency work will take input f rom B2 and B3, although in this case the time-scale for progress is not dependent on this input. The recognition of unexpected signals can proceed most rapidly of the three, and whatever results it achieves will help the first. But it will depend at some point on progress in the network detection area.

3.6 Stellung innerhalb des Sonderforschungsbereichs/Transregio

B2, B3, B4, B5 and B6 will contribute signal models that we will use for coalescence radiation search methods. Information extracted from gravitational wave signals will be useful to these projects and to B1. This information could also be of indirect benefit to projects A1, A2, and A4. There is a fruitful interaction with C1 as well, where it may be possible to modify the design of a detector to make it suitable for providing the information that the methods developed here will need for detecting and interpreting a particular signal.

3.7 Abgrenzung gegenüber anderen geförderten Projekten

3.8 Ergänzungsausstattung für das Teilprojekt

PK: Personalbedarf und -kosten (Begründung vgl. 3.8.1)
SV: Sächliche Verwaltungsausgaben (Begründung vgl. 3.8.2)
I: Investitionen (Geräte über 10.000,- EUR brutto; Begründung vgl. 3.8.3)

	Bewilligung 2002 1)			2003			2004			2005			2006		
PK	**Verg.-Gr.**	**Anz.**	**Betrag EUR**	**Verg.-Gr.**	**Anz.**	**Betrag EUR**	**Verg.-Gr.**	**Anz.**	**Betrag EUR**	**Verg.-Gr.**	**Anz.**	**Betrag EUR**	**Verg. Gr.**	**Anz.**	**Betrag EUR**
				BAT IIa	1	56.400	BAT IIa	1	56.400	BAT IIa	1	56.400	BAT IIa	1	56.400
				1/2 BAT IIa Ost	1	22.800	1/2 BAT IIa Ost	1	22.800	1/2 BAT IIa Ost	1	22.800	1/2 BAT IIa Ost	1	22.800
	zus.:			**zus.:**	**2**	**79.200**	**zus.:**	**2**	**79.200**	**zus.:**	**2**	**79.200**	**zus.:**	**2**	**79.200**

SV	**Kosten-kategorie oder Kennziff.**	**Betrag EUR**	**Kosten-kategorie oder Kennziff.**	**Betrag EUR**	**Kosten-kategorie oder Kennziff.**	**Betrag EUR**	**Kosten-kategorie oder Kennziff.**	**Betrag EUR**

I	**Investitionsmittel insges.**	**Investitionsmittel insges.**	**Investitionsmittel insges.**	**Investitionsmittel insges.**

1) nur bei Fortsetzungsanträgen
*) Werkstattarbeiten

3.8.1 Begründung des Personalbedarfs

	Name, akad. Grad, Dienststellung	**engeres Fach des Mitarbeiters**	**Institut der Hochschule oder der außeruniv. Einrichtung**	**Mitarbeit im Teilprojekt in Std. /Woche (beratend: B)**	**auf dieser Stelle im SFB/TR tätig seit**	**beantragte Einstufung in BAT**
Grundausstattung						
3.8.1.1 wissenschaftl. Mitarbeiter [1] (einschl. Hilfskräfte)	1) B. Schutz, Prof. Dr. Direktor 2) H.-J. Schmeißer, Prof. Dr. Univ.-Prof. 3) G. Schäfer, Prof. Dr. Hochschuldozent	Relativ. Astrophysik Analysis Relativ. Astrophysik	MPI f. Gravitationsphysik Mathematisches Institut Theoret.-Physik. Institut	12 8 2		
3.8.1.2 nichtwissenschaftl. Mitarbeiter [1]						
Ergänzungsausstattung						
3.8.1.3 wissenschaftl. Mitarbeiter [1] [2] (einschl. Hilfskräfte)	4) N.N., Dipl.-Phys., Dr. wiss. Mitarbeiter 5) N.N., Dipl.-Math. wiss. Mitarbeiter	Relativ. Astrophysik Analysis	MPI f. Gravitationsphysik Mathematisches Institut	40 20		BAT IIa 1/2 BAT IIa Ost
3.8.1.4 nichtwissenschaftl. Mitarbeiter [1]						

(Stellen, für die Mittel neu beantragt werden, sind mit **X** gekennzeichnet)

[1] Bitte durchnumerieren und Aufgabenbeschreibung nachfolgend erläutern

[2] Bitte Verfahrensgrundsätze der DFG zur Bezahlung wissenschaftl. Mitarbeiter beachten

Aufgabenbeschreibung von Mitarbeitern der Grundausstattung

2) Schmeißer, H.-J.

Mathematische Modellbildung zur Erkennung frequenzmodulierter Signale auf der Grundlage subatomarer Zerlegungen in Funktionenräumen.

Aufgabenbeschreibung von Mitarbeitern der Ergänzungsausstattung

5) N.N.

Konstruktion effektiver Algorithmen zur optimalen Rekonstruktion von Signalen basierend auf Zerlegungstechniken.

3.8.2 Aufgliederung und Begründung der Sächlichen Verwaltungsausgaben (nach Haushaltsjahren)

	2003	**2004**	**2005**	**2006**
Für Sächliche Verwaltungsausgaben stehen als **Grundausstattung** voraussichtlich zur Verfügung:	10.000	10.000	10.000	10.000

Für Sächliche Verwaltungsausgaben werden als **Ergänzungsausstattung** beantragt (entspricht den Gesamtsummen "Sächliche Verwaltungsausgaben" in Übersicht 3.8): Begründung zur Ergänzungsausstattung				

(Alle Angaben in EUR)

3.8.3 Investitionen (Geräte über 10.000,- EUR brutto und Fahrzeuge)

	Beantragt für das Haushaltsjahr			
	2003	**2004**	**2005**	**2006**
Summe:				

(Alle Preisangaben in Tausend EUR einschl. MwSt., Transportkosten etc.)