European Research Council
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Project No: 321263

Project Acronym: FISH

Project Full Name: FaInt Supernovae and Hypernovae: Mechanism and Nucleosynthesis

ERC-AG

Mid-Term Activity Report

Period covered: from 01/01/2013 **to** 31/12/2014

Start date of project: 01/01/2013

Duration: 48

Principal Investigator name:
Prof. Friedrich-Karl Wilhelm Thielemann

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Date of submission (SESAM):

Report submitted by:
UNIVERSITAET BASEL

Mid-Term Activity Report

GENERAL INFORMATION

Project No.:	321263
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Project full name:	FaInt Supernovae and Hypernovae: Mechanism and Nucleosynthesis
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Host Institution name:	UNIVERSITAET BASEL
Date of submission:	

Mid-Term Activity Report

Summary of the major achievements since the start of the project

The information provided in this section will be available to ERC staff, to members of the ERC panels, and to the Scientific Council

Briefly describe the work performed during the entire lifetime of the project, and in particular towards the objectives foreseen for the final reporting period.

Please specify the outcome in terms of:

- research and technological achievements and the impact and use of them

The ERC project FISH relates to the explanation of faint supernovae and hypernovae / gamma-ray bursts. In all cases finally a central black hole emerges (either via core collapse of massive stars or the merger of two neutron stars). The modeling relies on the sub-topics: the nuclear equation of state / energy generation of nuclear reactions, neutrino transport, relativistic multi-D magneto-hydrodynamics, and resulting ejecta which contribute in their nucleosynthetic composition to the evolution of galaxies. They are attributed to the following work packages.

WP1. Neutrino transport in high density proto-neutron stars and (black hole) accretion disks (III)
WP2. Fluid instabilities and multi-D magneto-hydrodynamics (in rotating models) based on the IDSA (isotropic diffusion source approximation) (IV)
WP3. Improved Microscopic Input Physics and Comprehensive Nucleosynthesis Yield Predictions
(a) equation of state of matter at extreme densities (and temperatures) (I)
(b) nuclear reaction predictions across the nuclear chart (II)
(c) nucleosynthesis in/of explosive ejecta and impact in galactic evolution (V)

We have regrouped these topics in the order I through V (see brackets behind subtopics of WPs), where topics I through III relate to input physics and the treatment of it in multi-D modeling, topic IV to the actual modeling of the events, and topic V to their nucleosynthetic impact on the evolution of galaxies. Our main achievements are:

I. Analysis of the asymmetry energy of nuclear matter, determination of its density dependence, analysis of the effect of finite temperatures, and constraints from astrophysical observations. As one of the key results we obtained the density functionals SFHo and SFHx (Steiner et al. 2013) with constraints on the asymmetry energy S (29-31 MeV) and its density dependence L (40-60 MeV), which lead to realistic mass-radius relations and good estimates of maximum neutron star masses slightly above 2 Msol (as observed recently). These (and other) results by postdoc M. Hempel come from parallel investigations supported by the SNF, but are included in further developments with ERC graduate student O. Heinimann.

II. Determination of key input parameters/uncertainties (nuclear masses, fission barriers, optical potentials for particle capture, level densities of excited states, giant electromagnetic resonances for gamma transitions, direct capture) in order to provide complete sets of reaction cross sections across the nuclear chart. One of the highlights is the resolution of the long-standing “apparent” alpha potential problem for heavier nuclei which disappears if Coulomb Excitations are included properly (Rauscher 2013). Based on this and many other efforts by T. Rauscher (ERC) a complete set of most advanced nuclear reaction rates is now available to us for all applications in this ERC project.

III. M. Liebendörfer has established during prior work the BOLTZTRAN neutrino transport scheme (based on the full solution of the relativistic Boltzmann transport equation for neutrinos). Further advances geared towards the computationally highly-demanding multi-D magneto-hydrodynamics resulted in the IDSA (isotropic diffusion source approximation) which can cover both, the free steaming and the diffusion limit of the Boltzmann transport equation. A mathematically rigorous derivation provided the prove of concept (Berninger et al. 2013) of this method, which by now has been tested in a number of publications (see e.g. Suwa et al. 2013, Nakamura et al. 2014, Kotake et al. 2014). In parallel, a new algorithm to compute optical depths (for neutrinos) in multidimensional hydrodynamic simulations (MODA) has been developed (Perego et al. 2014, involving ERC

personnel R. Cabezon and M. Liebendörfer), which is especially applicable to compact objects that are rotationally deformed. Graduate student M. Frensel (ERC) is making strong advances on neutrino transport and the treatment of collective neutrino oscillations in (resulting) black hole accretion disks. A. Lohs (PhD TU Darmstadt) has obtained new results on the effect of muon and tau neutrinos in core collapse neutrino transport and will join the ERC team in March 2015.

IV. R. Cabezon, K.-C. Pan, and T. Kuroda (together with M. Liebendörfer) form the core ERC-team on multi-D hydrodynamics. R. Cabezon introduced a highly sophisticated multi-D smooth particle hydrodynamics (SPH) code (SPHINX). K.-C. Pan has extended experience in the public-domain grid-based multi-D hydro-code FLASH with radiation transport. T. Kuroda came with a fully general relativistic (GR) multi-D hydrocode, permitting to follow black-hole formation. In a first step the IDSA neutrino transport has been implemented in all these codes and a large set of comparison calculations for core collapse have been performed. In addition, comparisons were done to spherically symmetric calculations with our full GR-code AGILE-BOLTZTRAN. A comparison paper is in preparation, indicating the most appropriate scheme during different periods of the simulations, in order to devise the best strategy for tackling the core theme of the project, the formation of a black hole, plus modeling of ejecta.

V. Based on the evolution of rotating massive stars (the progenitors of high mass core collapse systems), the composition of the wind ejecta has been predicted, involving for the first time (due to convective instabilities) heavy s-process nuclei (Yusof et al. 2013, Cescutti et al. 2013). The neutrino wind ejecta of massive core collapse systems have been reviewed by Arcones & Thielemann (2013). Detailed explosive nucleosynthesis predictions have been made by Perego et al. (2015, 2015arXiv150102845P). Polar jet ejecta of magnetars/collapsars, especially with respect to heavy element r-process nucleosynthesis, have been obtained with magneto-hydrodynamic simulations for various rotation rates and magnetic fields (Nishimura, Takiwaki & Thielemann 2015, 2015arXiv150106567). Neutron-star merger calculations, carried out by our group or in collaborations, with detailed nucleosynthesis predictions (and tests of nuclear input physics like mass models, fission and beta-decay) were performed by Panov et al. (2013ab), Rosswog et al. (2014) and Eichler et al. (2015, 2014arXiv1411.0974E), dominantly addressing dynamic ejecta from the emerging disk. Later phases, dominated by a neutrino wind, have been examined by Perego et al. 2014b), analyzing the option of also producing matter lighter than the second r-process peak. It turns out, that two options (magnetar jets and neutron star mergers) are viable candidates for a strong r-process, producing the heaviest elements in nature. The question is related to what role they play at different times during galactic evolution. ERC PhD student B. Wehmeyer (Wehmeyer, Pignatrai & Thielemann 2015, 2015arXiv150107749W) has addressed this question, coming to the conclusion that magnetar jets are needed to explain observations from the early Galaxy, while present solar abundances can result from a combination of both types of events during galactic evolution. Finally, we have also been involved in collaborations with astronomical observers to monitor the evolution of heavy element abundances during the evolution of galaxies, as a function of metalicity (Mishenina et al. 2013).

* citations with author names and year correspond to published results (see Annex A1), those with archive references are submitted / in press.

- novel and/or unconventional methodologies

With respect to WP1 (or topic III - neutrino transport)

Evaluation of techniques to treat the horizon at black hole formation:
When a black hole is formed in a computer simulation, a coordinate singularity appears in traditional comoving coordinates. Master student N. Maksimovic investigated in his project thesis three different coordinate systems that could help to circumvent this singularity, among others also the approach described in (Richmond & Liebendörfer 2004). However, he showed that a very attractive alternative option is the use of observer time coordinates because they directly focus on the observable aspects of black hole formation after stellar core collapse. N. Maksimovic will investigate the compatibility of these coordinate choice with the hydrodynamics codes in his master thesis.

With respect to WP2 (or topic IV - multi-D magneto-hydrodynamics):

1) The code 3D-FISH has been updated to include the last public version of the IDSA (Liebendörfer et al. 2009, Berninger et al. 2013) and a multi-dimensional Poisson solver. A. Perego et al. (2014) have published the MODA algorithm, which detects the neutrinospheres as hypersurfaces in 3D space and J. Michaud has implemented, tested and documented an improvement for the coupling of trapped and streaming particles in the IDSA. A corresponding paper has been submitted for publication. These improvements are planned to be included as well. Simulations are running robustly from stellar collapse to some hundred milliseconds postbounce time and include the evolution of magnetic fields. However, rotating models are affected by dissipation of angular momentum on the equidistant Cartesian mesh and the implementation of adaptive mesh refinement (AMR) has turned out to be difficult. In order to have alternatives and to work out the impact of the angular momentum loss we have started to implement the neutrino transport based on the IDSA in other hydrodynamics codes with complementary strengths and weaknesses:

2) K.-C. Pan has completed the implementation of the IDSA in the public domain code FLASH (http://flash.uchicago.edu), version 4 (Fryxell et al. 2000; Dubey et al. 2008; Lee 2013). FLASH is a parallel, multidimensional hydrodynamics code based on block-structured AMR. Our simulation setup is essentially similar to what has been implemented by Couch (2013), but replacing the neutrino treatment with our IDSA solver. We use the third-order piecewise parabolic method (PPM, Colella & Woodward (1984)) for spatial reconstruction, the HLLC Riemann solver, and the Hybrid slope limiter. AMR is implemented using PARAMESH4 (MacNeice et al. 2000). We use the nuclear equation of state (EOS) unit in FLASH which incorporates the #nite temperature EOS routines from O'Connor & Ott (2010) and Couch (2013). FLASH-IDSA is successfully running with the Lattimer & Swesty EOS (with incompressibility, K = 220 MeV; Lattimer & Douglas Swesty 1991) and the Hempel & Schaffner-Bielich (HS) DD2 EOS (Hempel & Schaffner-Bielich 2010). The Gravitational potential is solved by the new improved multipole solver in FLASH (Couch et al. 2013) with maximum Legendre order, lmax = 4. Simulations are performed in 3D cartesian coordinates. The center of a progenitor star is located at the origin of the simulation box. The simulation box includes ±4, 000 km in each spacial direction. Initial conditions are mapped from the pre-bounce 1D progenitor models from Woosley et al. (2002). To save computation time, we employ an AMR limiter which gives an average effective angular resolution $\Delta\# \#< \Delta xi /r >$, where Δxi is the linear zone space at AMR level i, and r is the distance to the center. The scaling of the code on a Cray XE6 is very promising. Additional physics (e.g. general-relativity corrections and magnetic #elds) are planned to be included when all tests of the current version are completed.

3) R. Cabezon has started to implement the IDSA in the code SPHYNX. SPHYNX is a state-of-the-art 3D SPH code that has been developed in Basel and adapted to perform numerical simulations of core collapse supernovae. It includes the Integral Approach to Derivatives (Garcia-Senz et al. 2012) and a flexible family of interpolating kernels (Cabezon et al. 2008), that has recently been proved to improve considerably the accuracy of SPH simulations (Rosswog 2014). For the simulation of faint supernovae and hypernovae, the use of such a Lagrangian approach will provide a complementary tool to the other available mesh codes. The intrinsic adaptive nature of SPH grants it with certain advantage in simulating the formation and evolution of the proto-neutron star with very high resolution, and its excellent energy and momentum conservation properties will allow us to simulate rotating progenitors with confidence. Besides, SPHYNX includes an accurate 3D gravitational solver and it is MPI+OpenMP parallelized. So far, SPHYNX has been successfully coupled with the Advanced Spectral Leakage, and a 1D implementation of the IDSA. A 3D implementation of the IDSA in SPHYNX is currently under development.

4) The "M1" code has originally been developed by Kuroda et al. (2012). It has been improved further to solve spectral neutrino transport of the radiation energy and momentum based on a truncated moment formalism employing an analytical closure relation (the M1 scheme). It implements multi-dimensional and fully general relativistic equations. Regarding neutrino opacities, we take into account the so-called standard set in state-of-the-art simulations, in which inelastic neutrino-electron scattering, thermal neutrino production via pair annihilation and nucleon-nucleon bremsstrahlung are included. In addition to gravitational redshift and Doppler effects, these energy-coupling reactions are incorporated in the moment equations in a covariant form. The code is designed to evolve the Einstein field equation together with the GR radiation hydrodynamic equations in a self-consistent manner while satisfying the Hamiltonian and momentum constraints.

While none of these codes (1)-(4) is perfect on its own, they have complementary uncertainties and virtues, e.g. (grid vs. SPH, IDSA vs. M1, effective potential vs. GR, etc.). In the Basel group we have undertaken a systematic comparison of these four codes for the collapse and postbounce evolution of a 15 solar mass progenitor star in order to detect, quantify and understand the uncertainties of the different approaches. Based on these results we plan to address the formation of a black hole in a potential faint supernova or hypernova more reliably and flexibly than with a single code.

Berninger, H., Frenod, E., Gander, M., Liebendorfer, M., Michaud, J., Derivation of the Isotropic Diffusion Source Approximation (IDSA) for Supernova Neutrino Transport by Asymptotic Expansions, SIAM J. Math. Anal. 45 (2013), 3229
Cabezón, R.M., García-Senz, D., Relaño, A., A one-parameter family of interpolating kernels for smoothed particle hydrodynamics studies" J. Comp. Phys. 227 (2008), 19
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Couch, S. M., Graziani, C., Flocke, N., Ap. J. 778 (2013), 181
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García-Senz, D., Cabezón, R.M., Escartín, J.A., Improving smoothed particle hydrodynamics with an integral approach to calculating gradients, A&A (2012), 538A
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Käppeli, R., Whitehouse, S. C., Scheidegger, S., Pen, U.-L.., Liebendörfer, M., Ap. J. Suppl. 195 (2011), 20
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MacNeice, P., Olson, K. M., Mobarry, C., de Fainchtein, R., Packer, C., Comput. Phys. Comm. 126 (2000), 330
Michaud, J., The IDSA and the homogeneous sphere: Issues and possible improvements, Discrete & Continuous Dynamical Systems, Series S (2014), in press
O'Connor, E., Ott, C. D., Class. Quant. Grav. 27 (2010), 114103
Pan, K.-C., Liebendörfer, M., Hempel, M., Thielemann, F.-K., Two-dimensional core-collapse supernova simulations with the isotropic diffusion source approximation for neutrino transport (2015) in preparation
Perego, A., Gafton, E., Cabezon, R., Rosswog, S., Liebendoerfer, M., MODA: a new algorithm to compute optical depths in multi-dimensional hydrodynamic simulations, A & A 568 (2014), AA11
Richmond, D., Liebendorfer. M., Singularity Excision for One Dimensional Relativistic Supernovae Simulations, Canadian Undergraduate Physics Journal II (2004), 13
Rosswog, S., Boosting the accuracy of SPH techniques: Newtonian and special-relativistic tests, (2014) arXiv1405.6034v1, MNRAS (2015), in press
Woosley, S. E., Heger, A., Weaver, T. A., Rev. Mod. Phys. 74 (2002), 1015

- inter and cross disciplinary developments

the project includes subprojects and collaborations which range from experimental and theoretical nuclear physics with relation to nuclear reactions and the nuclear equation of state, over particle physics with relation to neutrino-matter interactions and neutrino oscillations, stellar evolution with rotation and magnetic fields, general-relativistic magnetohydrodynamic simulations of core collapse and compact object collisions/mergers, up to specific nucleosynthesis predictions for the ejecta of such events, plus their impact in the chemical evolution of galaxies in close contact with astronomical observers.

We think this is quite a fruitful and successful basis for a very inter- and cross-disciplinary approach to very timely and important questions, addressing the formation and collisions/mergers of compact objects and the role of their explosive ejecta in the evolution of galaxies.

- knowledge and technology transfer

this is related mostly to numerical methods in multi-D hydrodynamics and radiation transport, plus the implementation on parallel machines

We will make the IDSA code publicably available on the webpage of the Physics Department http://phys-merger.physik.unibas.ch/users/group/
and we are contributing subroutines in the framework of a Swiss High Performance Computing project (PASC) to a trans-disciplinary radiative transfer library that is meant to be used in different scientific domain applications.

- establishment and/or consolidation of the research group and team composition

1.1.2013: the first graduate student (Maik Frensel) started immediately with the beginning of the project (working on neutrino transport in/and black hole accretion disks) together with senior personnel PD Matthias Liebendörfer (MHD hydro-dynamics and neutrino transport), PD Thomas Rauscher (nuclear reaction input to nucleosynthesis aspects of faint supernovae and hypernova) as well as PI Friedrich Thielemann. The team is aided by SNF postdoc M. Hempel, being highly active in providing nuclear equation of state input for all simuations.
February 2013: the computer cluster was delivered and installed, three postdoc positions were advertized.
July 2013: postdoc Ruben Cabezon (PhD Barcelona/Spain), working on 3D smooth particle hydrodynamics started on the project.
August 2013: postdocs Takami Kuroda (PhD University of Tokyo), working on general relativistic hydrodynamics, which permits black hole formation, started his contract; also postdoc Kuo-Chuan Pan (PhD University of Illinois), working on 3D hydrodynamics with the FLASH grid-based code, started his contract.
March 2014: graduate student Benjamin Wehmeyer, working on the impact of MHD jets and neutron star merger ejecta on the „chemical evolution“ of galaxies, started his contract.
April 2014: graduate student Oliver Heinimann, working on the equation of state of matter at extreme conditions, related to maximum neutron star masses and the transition to the collapse to black holes, started his contract (partially supervised by SNF postdoc M. Hempel).
March 2015: postdoc A. Lohs, with a background on muon and tau neutrino interactions with matter, will join the team.

This team will remain until the end of the grant (December 2016). The last additional employment is possible due to late starts of the first series of postdocs and graduate students plus partial salary support for R. Cabezon and K.-C. Pan from a high performance computing activity of the Swiss Supercomputer Center in Lugano

- others

n/a

Publishable brief summary of the achievement of the project

This section should normally not exceed 1 page.

Stand alone description of the project and its outcomes

The project includes subprojects which range from experimental and theoretical nuclear physics with relation to (i) the nuclear equation of state (required for the collapse of matter to highest densities, possibly permitting the collapse to a black hole); (ii) nuclear reactions (permitting to follow the energy generation in explosions and the prediction of the elemental and isotopic ejecta composition); over particle physics with relation to (iii) neutrino-matter interactions, neutrino oscillations and the related neutrino (radiation) transport; late stages of stellar evolution with rotation and magnetic fields leading to (iv) general-relativistic magneto-hydrodynamic simulations of core collapse and compact object collisions/mergers; up to (v) specific nucleosynthesis predictions for the ejecta of such events, plus their impact in the chemical evolution of galaxies in close contact with astronomical observers.

Thus, this inter- and cross-disciplinary approach addresses the formation and collision/mergers of compact objects, accompanied by explosive events whose explosive ejecta play a key role in the evolution of galaxies.

Up to now we have provided

essential aspects of the input physics:

(i) a data base of nuclear equations of state in agreement with present knowledge from nuclear physics and astronomical observations http://phys-merger.physik.unibas.ch/~hempel/eos.html

(ii) a data base of nuclear reactions across the nuclear chart http://nucastro.org/reaclib.html

(iii) the isotropic diffusion source approximation (IDSA) code for multi-dimensional neutrino transport will be made publicly available soon on our webpage http://phys-merger.physik.unibas.ch/users/group/

a detailed code comparison for
(iv) magneto-hydrodynamic simulations of core collapse with an SPH code (SPHINX), the open source grid-based code FLASH, our 3D MHD codes FISH/ELEPHANT, and the general relativistic code M1 have been performed, analyzing in which regime which treatment is suited best. Production runs for such collapse calculations are now underway

finally
(v) nucleosynthesis predictions for magnetars/collapsars have been performed with varying rotation rates and magnetic fields. Similar investigations have been done for neutron star mergers. The results have been implemented to understand the temporal evolution of the heaviest elements during the evolution of galaxies and are in agreement with astronomical observations.

What remains to be done is to understand and simulate the production of intermediate mass and iron-group elements in collapsars/hypernovae/gamma-ray bursts (which still includes sufficient challenges for the remaining two years).

Major problems / Difficulties

The information provided in this section will be available to ERC staff, to members of the ERC panels, and to the Scientific Council

Please specify any major problems/difficulties you may have encountered until now or may anticipate in the near future. Please suggest possible corrective actions.

Scientific problems

n/a

Technical problems

n/a

Support provided by the Host Institution (Start-up facilities, working space, access to labs, equipments, resources, etc)

working space, local computing, library and administrative support for all ERC team members

Others

essential amounts of CPU hour support by the Swiss Supercomputer Center (CSCS) in Lugano, without which this project would not be possible.

Information you would only want to share with ERCEA

n/a

List of free Keywords

supernovae, hypernovae, gamma-ray bursts, nuclear equation of state, nuclear reactions, neutrino transport, nucleosynthesis, chemical evolution of galaxies

Annex: Project output records

A1. Publications partly or wholly resulting from the project

LIST OF SCIENTIFIC PUBLICATIONS, STARTING WITH THE MOST IMPORTANT ONES										
No.	Title / DOI	Main author	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Date of publication	Relevant pages	Is open access provided to this publication ?	Type
1	Derivation of the Isotropic Diffusion So urce Approximatio n (IDSA) for Supernova Neutrino Transport by Asymptotic Expansi ons 10.1137/12089 243X	H. Berninge r , E. Frýnod , M. Gander , M. Liebendý rfer , J. Micha ud	SIAM Journal on Mathematical Analysis	Vol. 45/Is sue 6	Society for Industrial and Applied Mathe matics Publications	United States	01/01/2013	3229-3265	Yes	Peer revie wed
2	Neutrino-driv en wind simulations and nuc leosynthes is of heavy elements 10.1088/0954- 3899/40/1/013201	A Arcones , F-K Thie leman n	Journal of Physics G: Nuclear and Particle Physics	Vol. 40/Is sue 1	Institute of Physics Publishing	United Kingdom	01/01/2013	013201	Yes	Peer revie wed
3	Probabilities of delayed processes for n uclei involved in the r-process 10.1134/S1063 778813010080	I. V. Panov , I . Yu. Korneev , Yu. S. Lu tostan sky , F. -K. Thielema nn	Physics of Atomic Nuclei	Vol. 76/Is sue 1	Maik Nauka-Interp eri odica Publishing	Russian Federation	01/01/2013	88-101	Yes	Peer revie wed
4	Influence of spontaneous fission rates on the yields of superheavy elements in the r-process 10.1134/S1063 773713030043	I. V. Panov , I . Yu. Korneev , G. Martinez -Pinedo , F. -K. Thielema nn	Astronomy Letters	Vol. 39/Is sue 3	Maik Nauka-Interp eri odica Publishing	Russian Federation	01/03/2013	150-160	Yes	Peer revie wed
5	ON THE IMPORTANCE OF THE EQUATION OF STATE FOR THE NEUT RINO-DRIV EN SUPERNOVA EXP LOSION MECHANISM ? ?10.1088/0004 -637X/764/1/ 99	Suwa, Yudai; Takiwaki , To moya; Kota ke, Kei; F ischer, To	Astrophysical Journal	764	Institute of Physics Publishing		01/02/2013	99	Yes	Peer revie wed

		bias; Lieb endör fer, Matthias ; Sato, Kats uhiko								
6	The internal structure of neutron stars and white dwarfs, and the Jacobi virial equat ion. II. ?10.1051/0004 -6361/201220 565	A. Claret , M. Hempel	Astronomy and Astrophysics	Vol. 552	EDP Sciences	France	01/04/2013	A29	Yes	Peer revie wed
7	Abundances of neutron-capt ure elements i n stars of the Galactic disk substructure s 10.1051/0004- 6361/201220687	T. V. Mish enina , M. Pignatari , S. A. Korotin , C . Soubiran , C. Charbonne l , F.-K. Thiel ema nn , T. I. Gorbanev a , N. Yu. Basak	Astronomy and Astrophysics	Vol. 552	EDP Sciences	France	01/04/2013	A128	Yes	Peer revie wed
8	Making the Elements in the Universe ? ?10.1051/epn/ 2013304	Karlheinz Langanke , Friedrich -Karl Thie leman n	Europhysics News	Vol. 44/Is sue 3	EDP Sciences	France	01/05/2013	23-26	No	Peer revie wed
9	Systematic study of (p,ý) reactions on Ni isotopes 10.1103/PhysR evC.87.055802	A. Simon , A. Spyrou , T. Rauscher , C. Frýhlich , S. J. Quinn , A. Ba ttagli a , A. Be st , B. Bucher , M. Couder , P. A. DeYou ng , X. Fang , J. Gýrres , A. Kontos , Q. Li , L.-Y. Lin , A . Long , S. Lyons , A. Ro berts , D. Robertson , K. Smith , M. K. Smith , E. Stech , B. Ste	Physical Review C - Nuclear Physics	Vol. 87/Is sue 5	American Physical So ciety	United States	01/05/2013	055802	Yes	Peer revie wed

		fanek , W. P. Tan , X. D. Tang , M. Wiescher								
10	The 10.1051/0004- 6361/201220809	G. Cescutti , C. Chiappini , R. Hirschi , G. Meynet , U. Frischknecht	Astronomy and Astrophysics	Vol. 553	EDP Sciences	France	01/05/2013	A51	Yes	Peer revie wed
11	Constraining the astrophysical origin of the p-nuclei through nuclear physics and met eoritic data 10.1088/0034- 4885/76/6/066201	T Rauscher , N Dauphas , I Dillmann , C Frýhlich , Zs Fýlýp , Gy Gyýrky	Reports on Progress in Physics	Vol. 76/Is sue 6	Institute of Physics Publishing	United Kingdom	01/06/2013	066201	Yes	Peer revie wed
12	A comparative study of statistical models for nuclear equation of state of stellar ma tter 10.1016/j.nuc lphysa.2013.03.010	N. Buyukciz meci , A.S. Botvina , I.N. Mishusti n , R. Ogul , M. Hempel , J. Schaffne r-Bielic h , F.-K. Thie leman n , S. Furusawa , K. Sumiyoshi , S. Yamada , H. Suzuki	Nuclear Physics A	Vol. 907	Elsevier	Netherlands	01/06/2013	13-54	Yes	Peer revie wed
13	SILICON CARBIDE GRAINS OF TYPE C PROVIDE EVIDENCE FOR THE PR ODUCTION OF THE UNSTABLE ISOTOPE ?10.1088/2041 -8205/771/1/ L7	M. Pignatar i , E. Zinner , M. G. Bertolli , R . Trappitsch , P. Hoppe , T. Rauscher , C. Fryer , F. H erwig , R. Hirschi , F. X. Timmes , F.-K. Thi elemann	Astrophysical Journal Letters	Vol. 771/I ssu e 1	Institute of Physics Publishing	United Kingdom	01/07/2013	L7	Yes	Peer revie wed
14	Noncongruence of the nuclear liquid-gas and deconfinemen t phase transitions ?10.1103/Phys RevC.88.0149 06	Matthias H empel , Ve ronica Dex	Physical Review C - Nuclear Physics	Vol. 88/Is sue 1	American Physical So ciety	United States	01/07/2013	014906	Yes	Peer revie wed

		heimer , S tefan Schr amm , Igor Iosilevsk iy								
15	Solution of the ý-Potential Mystery in the ý Process and Its Impact on the Nd/Sm Ratio in Meteorites ? ?10.1103/Phys RevLett.111. 061104	Thomas Rau scher	Physical Review Letters	Vol. 111/I ssu e 6	American Physical So ciety	United States	01/08/2013	061104	Yes	Peer revie wed
16	Evolution and fate of very massive stars 10.1093/mnras /stt794	N. Yusof , R. Hirschi , G. Meynet , P. A. Crowther , S. Ekstrom , U. Frischkn echt , C. Georgy , H. Abu Ka ssim , O. Schnurr	Monthly Notices of the Royal Astronomica l Society	Vol. 433/I ssu e 2	Blackwell Publishing	United Kingdom	01/08/2013	1114-1132		Peer revie wed
17	CORE-COLLAPSE SUPERNOVA E QUATIONS OF STATE BASED ON NEU TRON STAR OBSERVATIONS ? ?10.1088/0004 -637X/774/1/ 17	A. W. Steiner , M. Hempel , T. Fischer	Astrophysical Journal	Vol. 774/I ssu e 1	Institute of Physics Publishing	United Kingdom	01/09/2013	17	Yes	Peer revie wed
18	Suppression of excited-stat e contribution s to stellar reaction rates 10.1103/PhysR evC.88.035803	T. Rauscher	Physical Review C - Nuclear Physics	Vol. 88/Is sue 3	American Physical So ciety	United States	01/09/2013	035803	Yes	Peer revie wed
19	Nuclear masses and neutron stars 10.1016/j.ijm s.2013.02.015	S. Kreim , M. Hempel , D. Lunney , J. Sc haffne r-Bi elich	International Journal of Mass Spectrometry	Vol. 349-350	Elsevier	Netherlands	01/09/2013	63-68	Yes	Peer revie wed
20	High precision ^{113}In(ý,ý)^{113}In ela stic scattering at energies near the Coulomb barrier for the astrophysical ý process ? ?10.1103/Phys RevC.88.0458 04	G. G. Kiss , P. Mohr , Zs. Fýl ýp , T. Ra uscher , Gy. Gyýrky , T. Szýcs , Z. Halýsz , E. So morjai , A. Ornelas , C. Yalý1n , R. T. Gýray , N. ýzkan	Physical Review C - Nuclear Physics	Vol. 88/Is sue 4	American Physical So ciety	United States	01/10/2013	045804	Yes	Peer revie wed

21	Symmetry energy impact in simulations of core-collapse supernovae ?10.1140/epja /i2014-14046 -5	Tobias Fis cher , Mat thias Hempel , Irina Sagert , Yudai Suwa , Jýrgen Schaf fne r-Bielic h	European Physical Journal A	Vol. 50/Is sue 2	Springer New York	United States	01/02/2014	46	Yes	Peer revie wed
22	Gravitational wave signatures from low-m ode spiral instabilities in rapidly rotating supernova cores ?10.1103/Phys RevD.89.0440 11	Takami Kur oda , Tomoya Takiwaki , K ei Kotake	Physical Review D - Particles, Fields, G ravitation and Cosmology	Vol. 89/Is sue 4	American Physical So ciety	United States	01/02/2014	044011	Yes	Peer revie wed
23	The long-term evolution of neutron star merger remnants - I. The impact of r-pro cess nucleosynthe sis 10.1093/mnras /stt2502	S. Rosswog , O. Korobkin , A. Arcones , F.- K. Thi elemann , T. Piran	Monthly Notices of the Royal Astronomica l Society	Vol. 439/I ssu e 1	Blackwell Publishing	United Kingdom	21/03/2014	744-756	Yes	Peer revie wed
24	Challenges in nucleosynthe sis of trans-iron elements ? ?10.1063/1.48 68239	T. Rauscher	AIP Advances	Vol. 4/Iss ue 4	AIP	United States	01/04/2014	041012	Yes	Peer revie wed
25	Measurement of the <math xmlns="http://www .w3.org/ 1998/Math/MathML"><msup>< mrow></mrow><mn>58</mn></ ms up><mi>Ni(</mi><mi>ý</m i></mat h>,<math xmlns="http: //www.w3.org/ 1 998/Math/Ma thML"><mi>ý</ mi></m ath></ span>)<math xmlns="http:/ /www.w3.org/ 1998/Math/Mat hML"><msup>< mrow ></mrow>< mn>62</mn></ msup><mi> Zn</ mi></math></ span> reaction and its astrophysica l impact ?10.1103/Phys RevC.89.0546 11	S. J. Quinn , A. Spyrou , E. Bravo , T. Rauscher , A. Simon , A. Battagli a , M. Bowers , B. Bucher , C. C asarell a , M. Couder , P. A. DeYoung , A. C. Dombos , J . Gýrres , A. Kontos , Q. Li , A. Long , M. Moran , N. Paul , J. Perei ra , D. Roberts o n , K. Smith , M. K. Smith , E. Stech , R. Talwar , W. P. Tan , M. Wi escher	Physical Review C - Nuclear Physics	Vol. 89/Is sue 5	American Physical So ciety	United States	01/05/2014	054611	Yes	Peer revie wed

26	Neutron Capture Reactions on Fe and Ni I sotopes for the Astrophysical s-process ? ?10.1016/j.nd s.2014.07.04 6	Lederer, C. et al.	Nuclear Data Sheets	120	Academic Press Inc.		01/06/2014	201-204	Yes	Peer revie wed
27	Experimental cross sections of Ho165(±,n)Tm1 68 and Er166(±,n)Yb1 69 for optical potential studies relevant for the astrop hysica l gamma-process 10.1103/PhysR evC.89.065808	J. Glorius , K. Sonnabend , J. Görres , D. Ro bertso n , M. Knörzer , A. Kontos , T. Ra uscher , R. Reifarth , A. Sauerwein , E. Stech , W. Tan , T. Thom as , M. Wi escher	Physical Review C - Nuclear Physics	Vol. 89/Is sue 6	American Physical So ciety	United States	01/06/2014	065808	No	Peer revie wed
28	Alpha induced reaction cross section mea surements on 162Er for the astrophysical ý process ?10.1016/j.ph ysletb.2014. 06.011	G.G. Kiss , T. Szýcs , T. Rauscher , Zs. Týrýk , Zs. Fý lýp , Gy. Gyýrky , Z. Halýsz , E. S omorjai	Physics Letters, Section B: Nuclear, Ele mentary Particle and High-Energy Physics	Vol. 735	Elsevier	Netherlands	01/07/2014	40-44	Yes	Peer revie wed
29	MODA: a new algorithm to compute op tical depths in multidimensio nal hydrody namic simulations ? ?10.1051/0004 -6361/201423 755	Albino Perego , Emanuel G afton , Rubýn Cabezýn , S tephan Ros swog , Mat thias Lieb endýr fer	Astronomy and Astrophysics	Vol. 568	EDP Sciences	France	01/08/2014	A11	Yes	Peer revie wed
30	SEARCH FOR SURVIVING COMP ANIONS IN TYPE Ia SUPERNOVA RE MNANTS ? ?10.1088/0004 -637X/792/1/ 71	Kuo-Chuan Pan , Paul M. Ricker , Ro nald E. Taam	Astrophysical Journal	Vol. 792/I ssu e 1	Institute of Physics Publishing	United Kingdom	01/09/2014	71	Yes	Peer revie wed
31	Asymmetric neutrino production in strong ly magnetized proto-neutro n stars ? ?10.1103/Phys RevD.90.0673 02	Tomoyuki M aruyama , Myung-Ki C heoun , Jun Hidaka , Tosh itaka Kajino , Takami Kur	Physical Review D - Particles, Fields, G ravitation and Cosmology	Vol. 90/Is sue 6	American Physical So ciety	United States	01/09/2014	067302	Yes	Peer revie wed

		oda , Grant J. Mathews , Chung-Ye ol Ryu , Tomoya Takiwaki , Nobutosh i Yasutake								
32	IMPACTS OF ROTATION ON THREE-D IMENSIONAL HYDRODYNAMICS OF CORE-COLLAPSE SUPERNOVAE ? ?10.1088/0004 -637X/793/1/ 45	Ko Nakamura , Takami Kuro da , Tomoya Takiwaki , Ke i Kotake	Astrophysical Journal	Vol. 793/I ssu e 1	Institute of Physics Publishing	United Kingdom	20/09/2014	45	Yes	Peer revie wed
33	NEW HYPERON EQUATIONS OF STATE FOR SUPERNOVAE AND NEUTRON STARS IN DENSITY-DEPEN DENT HADRON FIELD THEORY ?10.1088/0067 -0049/214/2/ 22	Sarmistha Banik , Ma tthias Hempel , Debades B andyopa dhy ay	Astrophysical Journal, Supplement Series	Vol. 214/I ssu e 2	Institute of Physics Publishing	United Kingdom	01/10/2014	22	Yes	Peer revie wed
34	Equalizing resolution in smoothed-par ticle hydrodynamics calculations using self-adap tive sinc kernels ? ?10.1051/0004 -6361/201424 260	Domingo Ga rcýa-S enz , Rubýn M. Cabezýn , Josý A. Escart ýn , Kevin Ebinger	Astronomy and Astrophysics	Vol. 570	EDP Sciences	France	01/10/2014	A14	Yes	Peer revie wed
35	Neutrino-driv en winds from neutron star merger remnants ? ?10.1093/mnra s/stu1352	A. Perego , S. Rosswog , R. M. Cabezon , O. Korobkin , R. Kappeli , A. Arcones , M. Liebendo rfer	Monthly Notices of the Royal Astronomica l Society	Vol. 443/I ssu e 4	Blackwell Publishing	United Kingdom	01/10/2014	3134-3156	Yes	Peer revie wed
36	RADIOGENIC ?10.1088/0004 -637X/795/2/ 141	C. Travagli o , R. Gallino , T. Rauscher , N. Dauphas , F. K. Rýpke , W. Hillebrandt	Astrophysical Journal	Vol. 795/I ssu e 2	Institute of Physics Publishing	United Kingdom	10/11/2014	141	Yes	Peer revie wed
37	TESTING THE ROLE OF SNe Ia FOR GALACTIC CHEMICAL EVOLUTION O F ? ?10.1088/0004 -637X/799/1/ 54	C. Travagli o , R. Gallino , T. Rauscher , F. K. Rýpke , W. Hillebra ndt	Astrophysical Journal	Vol. 799/I ssu e 1	Institute of Physics Publishing	United Kingdom	20/01/2015	54	Yes	Peer revie wed

	Supernovae and their Nucleosynthes is	Thieleman n, F.-K., Lieben do erfer, M.	Encyclopedia of Nuclear Physics and its Applications		Wliey		01/09/2013	475-502	No	Article
	Die Entstehung der Atome - Eine Synthese von Mikro- und Makrokosmos 10.1007/978-3 -658-04158-8	Thieleman n, F.-K.	Studium generale		Springer Fachmedien Wiesbaden	Wiesbaden	01/01/2014	97-108	No	Article
	Cutting-edge issues of core-collapse sup ernova theory ?10.1063/1.48 74078	Kei Kotake , Ko Nakamura , Takami K uroda , To moya Takiw aki	AIP Conference Proceedings, Volume 1594, ORIGIN OF MATTER AND EVO LUTION OF GALAXIES 2013		AIP Publishing LLC		01/01/2014	250-257	No	Conference
	Three-dimensi onal simulation of a rotating supernova ?10.1063/1.48 74084	K. Nakamura , T. Kuroda , T. Takiwaki , K. Kotake	AIP Conference Proceedings, Volume 1594, ORIGIN OF MATTER AND EVO LUTION OF GALAXIES 2013		AIP Publishing LLC		01/01/2014	290-295	No	Conference
	Asymmetric neutrino production in magnet ized proto-neutro n stars in fully relativistic mean-field approach ? ?10.1063/1.48 74075	Tomoyuki M aruyama , Toshitak a Kajino , N obutosh i Y asutake , Jun Hidaka , Ta kami Kuroda , Tomoya Taki waki , Myu ng-Ki Cheoun , Chung-Ye ol Ryu , Grant J. Mathews	AIP Conference Proceedings, Volume 1594, ORIGIN OF MATTER AND EVO LUTION OF GALAXIES 2013		AIP Publishing LLC		01/01/2014	234-238	No	Conference
	Measurement of alpha-induce d reaction cr oss sections on erbium isotopes for # pr ocess studies ?10.1063/1.48 74067	G. G. Kiss , T. Sz#cs , Zs. T# r#k , Zs. F#l#p , Gy. Gy#rky , Z. H al#sz , E. Somorjai , T. Rauscher	AIP Conference Proceedings, Volume 1594, ORIGIN OF MATTER AND EVO LUTION OF GALAXIES 2013		AIP Publishing LLC		01/01/2014	196-200	No	Conference
	Deconfinement to quark matter in neutron stars - The influence of strong magnetic fie lds ? ?10.1063/1.47 95968	V. Dexheime r , R. Negreiro s , S. Sc hramm , M. Hempel	XII Hadron Physics. AIP Conference Proce edings, Volume 1520.		AIP		01/01/2013	264-269	No	Conference

A2. Research fieldwork

List of fieldworks		
Period (start-end)	Place	Purpose

A3. Awards and recognitions

List of awards and recognitions					
Award type	Title of the award	Person to whom the award was made	Year	Short description of the reason the award was made (if applicable)	Any further information / clarification
Research Prize / Research Medal	Hans A. Bethe Prize	Friedrich K. Thielemann	2008	For his many outstanding theoretical contributions to the understanding of nucleosynthesis, stellar evolution and stellar explosions through applicati ons to individual objects and to cosmic chemical e volution	APS Prize
Research Prize / Research Medal	Humboldt Research Award	Friedrich K. Thielemann	2009		Humboldt Foundation
Research Prize / Research Medal	Lise Meitner Prize	Friedrich K. Thielemann	2012	for seminal contributions to the description of nu clear processes in astrophysical environments that have changed our modern understanding of stellar evolution, supernovae explosions and nucleosy nthesis	EPS prize
Membership of editorial boards	Associate Editor, Nuclear Physics A	Friedrich K. Thielemann	1998		
Membership of editorial boards	Associate Editor for Astrophysics, Reviews of Modern Physics	Friedrich K. Thielemann	2006		

A4. Patents, licensing, intellectual property

List of patents, licensing, intellectual property					
Type of IP Rights	Confidential	Foreseen embargo date dd/mm/yyyy	Application reference(s) (e.g. EP123456)	Subject or title of application	Applicant(s) (as on the application)

A5. Dissemination to non-academic audience

List of disseminations								
No.	Type of activities	Main Leader	Title	Date	Place	Type of audience	Size of audience	Countries addressed
1	Media briefings	UNIVERSITAET BASEL	Past and Present Challenges in Nuclear Astrophysics	01/03/2013	SPG Mitteilungen, Vol 39, Progress in Physics (31)	Scientific community (higher education, Research) - Industry		Switzerland
2	Media briefings	UNIVERSITAET BASEL	Making the Elements in the Universe,	18/06/2013	Europhysics News 44, 23	Scientific community (higher education, Research)		Europe
3	Presentations	UNIVERSITAET BASEL	Formation of the Elements in the Universe	07/03/2013	50 Years of TRIGA Research at ATI Vienna, Vienna	Scientific community (higher education, Research) - Industry - Civil society - Policy makers - Medias	400	Austria
4	Presentations	UNIVERSITAET BASEL	Wo alles herkommt: Die Entstehung der Elemente im Universum	15/11/2013	Marienstatter Zukunftsgespraeche, Hachenburg, Germany	Civil society - Medias	200	Germany
5	Presentations	UNIVERSITAET BASEL	Der Stoff der von den Sternen kam	23/01/2014	Planetarium Mannheim	Civil society - Medias	200	Germany
6	Presentations	UNIVERSITAET BASEL	Interface of Nuclear Physics and Astrophysics	10/02/2014	Institut Pluridisciplinaire Hubert Curien, Strassburg	Scientific community (higher education, Research)	100	France, UK; Belgium
7	Presentations	UNIVERSITAET BASEL	Warum gibt es Gold und Silber im Universum?	13/05/2014	Kinderuniversität Basel	Civil society - Medias	300	Switzerland
8	Presentations	UNIVERSITAET BASEL	Stellar Evolution / Explosions, Nuclear/ Particle Physics Input, Origin of the Elements and Evolutio of Galaxies	30/09/2014	University of Basel	Scientific community (higher education, Research)	40	France, Germany, Israel, Italy, Japan, Russia, Switzerland, Taiwan, Ukraine, UK, USA
9	Other forms of dissemination	UNIVERSITAET BASEL	Brainstorming and Fun: Stellar Evolution / Explosions, Nuclear/Particle Physics Input, Origin of the Elements and Evolutio of Galaxies	30/09/2014	http://phys-merger.physik.unibas.ch/~group/brainstorm2014.html	Scientific community (higher education, Research)		entire world

10	Other forms of dissemination	UNIVERSITAET BASEL	Researching how stars explode	31/10/2014	http://www.hpc-ch.org/researching-how-stars-explode/	Scientific community (higher education, Research) - Industry - Civil society - Policy makers - Medias		Switzerland

A6. Other significant outputs / information

Information on other important outputs which have arisen - wholly or partly - from this project.

see databases listed in the "summary" and "knowledge and technology transfer"

plus code developments discussed in "novel and/or unconventional methodologies"

(Only for ERC projects selected from the 2012 and 2013 calls for proposals)

This grant agreement includes special clause 39, requiring you to make best efforts towards open access to publications resulting from this project. Should, despite your best efforts, not all publications be available in open access, please give reasons why this is the case.

All journal publications are publicly available on the SAO/NASA ADS archive

There exist a few (less important) exceptions for conference contributions/proceedings and book chapters

Attachments	
Project No.:	321263
Project acronym:	FISH
Project title:	FaInt Supernovae and Hypernovae: Mechanism and Nucleosynthesis
Project starting date:	01/01/2013
Project duration:	48
Principal Investigator name:	Prof. Friedrich-Karl Wilhelm Thielemann
Report submitted by:	UNIVERSITAET BASEL
Date:	