PART B TEMPLATE

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#@APP-FORM-HEMSCAPF@#

Part B-1

1. Excellence #@REL-EVA-RE@#

1.1 Quality and pertinence of the project's research and innovation objectives (and the extent to which they are ambitious, and go beyond the state of the art)

1.1.1 Quality and pertinence of the R&I objectives: Understanding the observational properties of magnetars—the most enigmatic isolated neutron stars (NSs)—remains a major challenge in high-energy astrophysics. These young NSs exhibit exceptionally high X-ray luminosities, frequent bursts, and unusually slow spin periods (1–12 s), features linked to their ultra-strong magnetic fields (up to a few 10^{16} G internally and 10^{14} G at the surface). Such fields drive rapid spin-down and set magnetars apart from other isolated NSs. From birth to death, NS evolution is shaped by major uncertainties in key physical parameters and their interpretation, limiting our ability to model magnetic field evolution and the complex physics of their interiors. During formation, turbulence driven by dynamo mechanisms amplifies magnetic fields—reaching up to 10^{16}G—primarily on small spatial scales. How these chaotic fields reorganize into the strong, large-scale dipole fields observed in mature magnetars remains an open question. Recent studies[1] highlight the crucial role of magnetic helicity in this reorganization process, enabling the transfer of energy across spatial scales and potentially explaining the emergence of the strong dipole component observed in magnetars. Magnetic helicity, being nearly conserved and only weakly dissipated by diffusivity, must be inherited at birth—making its initial content crucial for predicting the long-term magnetic structure and observable features of neutron stars.

Beyond birth conditions, the long-term evolution of these fields is highly complex. A key challenge lies in modeling the coupled dynamics of superfluid neutrons and superconducting protons—especially the behavior of quantized flux tubes—in extreme, variable conditions, without experimental validation. Despite its importance, this aspect, likely occurring in the NS core[2], has been largely overlooked.

Since neutron star interior conditions cannot be replicated in the lab, simulations are indispensable. Yet, most birth-condition models overlook the magnetic helicity content, ignore interplay between dynamo mechanisms, or fail to account for factors like boundary conditions that affect global helicity. Long-term evolution models, on the other hand, often focus solely on the crust, oversimplify the core, and neglect superconductivity and superfluidity. **The GENESIS (G**eneration and **E**volution of **NE**utron **S**tar's **I**nternal magnetic field**S) project tackles these gaps by: (1) quantifying global magnetic helicity at birth, (2) explicitly modeling superconducting and superfluid effects in the core, and (3) advancing numerical tools to better replicate neutron star conditions. This approach aims to overcome key computational limitations and deepen our understanding of both magnetic and also thermal evolution.**

To achieve these objectives, the project will draw on the expertise of a researcher specializing in neutron star magnetic field evolution, guided by a leading supervisor with extensive experience in turbulence theory, magnetic helicity, and large-scale astrophysical magnetic field simulations. The host institution, together with the Pencil Code collaboration led by the supervisor, is recognized for excellence in computational astrophysics and will provide an optimal environment for this research. GENESIS aims to build a robust computational framework spanning both the birth and death stages of neutron stars to study magnetic helicity generation at birth and properly modeling field evolution on longer timescales. Successful completion of the project will deepen our fundamental understanding of magnetism in NSs—particularly magnetars—and may also drive progress in solid-state magnetic field studies and computational simulation techniques.

1.1.2 State-of-the-art and ambition: Recent years have seen growing efforts in magneto-hydrodynamical (MHD) simulations of core-collapse supernovae (CCSN), which are crucial for understanding both the explosion mechanisms and the properties of the resulting proto-NS. This dynamic process unfolds in three main stages: (i) For about one second after the core bounce, the system consists of a relatively cool central region surrounded by a hot mantle, collapsing and radiating off neutrinos quickly, while still also accreting material. (ii) Over the next ~ 20 seconds, a slowly developing state of the proto-NS can be identified; the system first deleptonizes and heats up the interior parts of the forming star, later it cools down further through neutrino diffusion. The proto-NS is born extremely hot and liquid ($T \approx 10^{11}$ K), with a relatively large radius of about 100 km. (iii) After several minutes, it becomes transparent to neutrinos and shrinks to its final radius R ~ 10 to 14 km. Neutrino transparency marks the birth of a NS, which starts its long-term cooling, dominated first by neutrinos and later ($t \gtrsim 10^5$ yr) by photon emission from the surface.

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[1] B20, DB25, DP25

[2] Graber15

The magnetic field configuration of NSs at birth remains largely uncertain. The mechanisms responsible for generating the strong dipolar fields needed to explain magnetar timing properties are still debated. Several scenarios have been proposed, each with distinct implications for the star's later evolution.

Magnetic flux conservation, for instance, can produce strong fields if the progenitor is highly magnetized—possibly due to stellar mergers—but such progenitors are typically slow rotators, making this scenario unlikely for millisecond magnetars. An alternative is magnetic field amplification by a turbulent dynamo during the proto-NS phase. Recent MHD simulations—both local and global—have attempted to quantify this process. Local models with simplified backgrounds show the development of the magneto-rotational instability (MRI), while global simulations explore large-scale dynamo effects, including the Taylor-Spruit mechanism, differential rotation, rigid rotation, and convection. As is typical in dynamo systems, the resulting magnetic fields reach a quasi-equilibrium: while not static, the energy distribution across scales stabilizes statistically due to force balance in the fluid. These simulations find that magnetic energy spreads over a broad range of spatial scales, with non-axisymmetric and toroidal components dominating, and only a subdominant large-scale dipole. Though the total energy is magnetar-like, it is concentrated on small scales (see Reboul-Salze et al. 2021). Follow-up studies (Dehman et al. 2023; Igoshev et al. 2025) tested whether such field configurations could account for the long-term observational properties of magnetars. Both concluded that they could not—indicating that an additional mechanism is needed. Indeed, most long-term simulations of magnetars begin with an ad hoc strong dipolar field ($10^{14} - 10^{15}$ G), without addressing its origin. While such a configuration matches observations, how it forms remains an open question.

Recent studies (Brandenburg 2020, Dehman & Brandenburg 2025, and Dehman & Pons 2025) have highlighted the role of magnetic helicity on the long term magnetic field evolution in transferring magnetic energy from small to large spatial scales, potentially explaining the emergence of the large-scale fields observed in magnetars. While Brandenburg (2020) and Dehman & Brandenburg (2025) investigated inverse cascades driven by the non-linear Hall drift in the presence of magnetic helicity, Dehman & Pons (2025) proposed a novel mechanism: under realistic NS conditions, magnetic helicity stored in turbulent small-scale fields at birth can, via the chiral anomaly and helicity conservation, redistribute energy to larger scales within centuries. This process naturally generates a strong dipolar field ($> 10^{14}$ G) from initially small-scale turbulence, offering a compelling explanation for magnetar formation. However, these studies rely on the assumption that NSs are born with a net global magnetic helicity—an assumption that remains largely untested. Core-collapse and proto-NS dynamo simulations rarely compute helicity explicitly, and the influence of numerical factors such as boundary conditions—essential for helicity conservation—has not been systematically examined. In standard MHD, helicity often develops with opposite signs in the northern and southern hemispheres, resulting in a globally vanishing helicity. Whether this symmetry arises from physical constraints or is imposed by the numerical setup—and whether it can be broken—is a promising question to explore.

While birth conditions are crucial, understanding the **long-term magnetic evolution**—over millions of years, when NSs are observed—is equally essential. The stellar core, which makes up ~90% of the NS volume, likely hosts **superfluid neutrons** and **superconducting protons**, yet the dynamics of **magnetic flux tubes** in such phases remain poorly explored despite their pivotal role in global field evolution. Most state-of-the-art 3D codes modeling coupled magneto-thermal evolution over long timescales neglect the core, focusing instead on **crust-confined fields** driven by Hall drift and Ohmic dissipation (Vigano et al 2012, Igoshev et al. 2022, Dehman et al. 2023a,b, Ascenzi et al. 2024). Attempts to model the core face challenges due to **proton superconductivity** (Ruderman et al. 1998; Elfritz et al. 2016; Bransgrove et al. 2018, 2025). Below a critical temperature $T_c \sim 10^9 - 10^{10}$K, protons form a **type-II superconductor**, where the magnetic field becomes quantized into **flux tubes.** The bunching of magnetic field lines into discrete flux tubes dramatically modifies the macroscopically averaged Maxwell stress. The enhanced anisotropic Maxwell stress of the superconductor plays a key role in the tension-driven motion of flux tubes, and is one of the main qualitative differences compared to the magnetohydrodynamics of normal conducting fluids (Easson & Pethick 1977; Jones 1991, 2006; Gusakov & Dommes 2016; Gusakov 2019; Rau & Wasserman 2020). Yet, **realistic numerical models** accounting for this physics are lacking. While some works simulate **ambipolar diffusion** in the core, recent theoretical estimates show that superfluidity and superconductivity greatly **slow down** this process (Glampedakis et al. 2011), underscoring the need to **explicitly model flux tube dynamics**. So far, only a few studies have addressed this, often limited to the **crust-core interface** (Bransgrove et al. 2025) or adopting **oversimplified velocity prescriptions** (Elfritz et al. 2016, Bransgrove et al. 2018).

GENESIS aims to revolutionize modeling of magnetic field evolution in NS interiors—from birth, by determining the net magnetic helicity imprinted during formation (which is largely conserved over time and plays a key role in transferring energy from small-scale fields formed at birth to the large-scale structures observed in magnetars), to million-year timescales, including the field's feedback on thermal evolution. This will significantly advance our understanding of observed isolated neutron stars. The project targets three key objectives: (i) WP1—Determine the magnetic helicity expected at birth and its distribution. (ii) WP2—Advance numerical modeling of proton superconductivity in the core to enable more realistic long-term magnetic field evolution. (iii) WP3—Enhance numerical performance to simulate realistic neutron star scenarios without computational limitations.

This ambitious, timely proposal addresses a major gap in neutron star physics. By investigating how helicity and superconductivity shape magnetic evolution—both underexplored in NS studies—GENESIS bridges turbulence, computational astrophysics, solid-state, particle, and nuclear physics, impacting fields from core-collapse supernovae to long-term neutron star evolution.

The following table relates each objective with the current state of the art.

Objectives	State of the Art	State of the art after the project
WP1: Global magnetic helicity at birth	Current simulations rarely measure magnetic helicity, and those that do typically find it cancels between northern and southern hemispheres. However, they often neglect proper treatment of boundary conditions, which critically affect helicity conservation.	Understanding global magnetic helicity is crucial, as it governs the redistribution of magnetic energy inside neutron stars and explains the formation of their large-scale dipolar fields.
WP2: Study the magnetic field evolution in neutron star cores, explicitly incorporating proton superconductivity effects.	Current studies either ignore core magnetic field evolution or treat the core as normal matter—simplifying numerics but misrepresenting reality. Some consider superconductivity but use oversimplified velocity models without consistent treatment.	An extended 3D version of MATINS will model magneto-thermal evolution incorporating additional physics by solving the full MHD system—covering both the crust and the core—not just crustal magnetic field evolution.
WP3: Advance the numerical capabilities of MATINS and Pencil codes.	MATINS includes relevant microphysics but lacks parallelization; Pencil, an MHD code, struggles with spherical geometry due to its finite-difference scheme.	Integrating MATINS as an interface to Pencil will create a powerful combined supercode.

1.2 Soundness of the proposed methodology (including interdisciplinary approaches, consideration of the gender dimension and other diversity aspects if relevant for the research project, and the quality of open science practices).

1.2.1 Overall methodology: The proposed methodology for this project is fully computational, organized into work packages addressing key objectives. To estimate the global magnetic helicity expected at birth (**WP1**), which should be nearly conserved and imprinted at NS birth, we will employ the Pencil Code—a 3D high-order finite-difference MHD code developed by the host group and supervisor over the past decade. The first task (task 1.1) is to adapt the Pencil Code to simulate the proto-NS phase, a short-lived (~1 minute) transitional environment formed after core-collapse supernovae. This requires implementing appropriate physical setups and microphysical characteristics tailored to proton-NS scenario. Next (Task 1.2), we will analyze whether dynamo mechanisms likely coexisting on similar timescales and regions—such as the MRI and CMI—lead to constructive or competing effects on global magnetic helicity generation, crucial for understanding large-scale field emergence in NSs. Standard MHD dynamos tend to produce zero net helicity due to opposing signs across hemispheres. To test whether CMI can break this symmetry and drive net helicity, we will run controlled simulations varying boundary conditions (closed vs. open) and initial asymmetries. Special attention will be given to numerical convergence and robustness to ensure reliable conclusions and fulfill **WP1 milestones**.

To model magnetic field evolution in NSs—particularly in their cores (**WP2**)—a realistic approach must rely on reactive magnetohydrodynamics in multifluid systems. A full treatment is unfeasible due to the long evolutionary timescales, which far exceed those of fast magnetosonic or sound waves. Therefore, the methodology includes familiarization with these equations and commonly used approximations (e.g., Ogura & Phillips 1962). This foundation will support deriving a tailored system of equations that captures the relevant physics in the NS core, accounting for superconductivity and superfluidity (task 2.1). A core component of the project is extending the 3D code MATINS, which currently models coupled magnetic and thermal evolution in the NS crust. While the crustal evolution is state-of-the-art, MATINS currently neglects magnetic evolution in the core and treats the core temperature as isothermal—a valid simplification given its high thermal conductivity. However, magnetic field

evolution in the core remains unexplored and requires full 3D modeling, including a consistent treatment of the fluid velocities that are expected to govern field dynamics (task 2.2).
New numerical modules will be implemented in MATINS to enable realistic modeling of neutron star interiors. These will include microphysical inputs with temperature- and density-dependent transport coefficients, using numerical methods tailored to the system's complexity. The resulting advanced version of the code will constitute a new simulation framework capable of capturing multiple coupled physical processes. This state-of-the-art tool will offer a more complete and general view of magnetothermal evolution. A series of simulations will be carried out to systematically explore key regions of parameter space. This upgraded MATINS version will also enable direct comparison with observations of isolated neutron stars, in collaboration with Prof. Nanda Rea's group in Barcelona, to validate models and refine physical assumptions (task 2.3).
Performing high-resolution 3D simulations on realistic timescales is inherently challenging. To overcome time and resolution limitations, MATINS will be parallelized to enable full-volume 3D magnetic evolution in NSs (**WP3**). The plan is to implement MATINS, which uses cubed-sphere coordinates, as an interface to the Pencil code. This approach will integrate cubed-sphere geometry—resolving the axis singularity issue present in standard 3D finite-difference or finite-volume methods—into both frameworks. This dual advancement will not only enable efficient, high-resolution simulations within MATINS but will also enhance the Pencil code's numerical capabilities, with potential benefits across multiple fields of physics.

<u>1.2.2 Integration of methods and disciplines to pursue the objectives:</u> This project adopts a strongly interdisciplinary approach, combining theoretical insight with advanced computational modeling. It brings together expertise from high-energy astrophysics, computational physics, turbulence, condensed matter physics, nuclear physics, and particle physics. Progress in modeling magnetic field evolution in NSs requires both numerical innovation and deep theoretical understanding: quantifying net global magnetic helicity (drawing on turbulence theory and chiral anomaly from particle physics), modeling magnetic field dynamics in superfluid and superconducting cores (using condensed matter and nuclear physics), and optimizing simulation performance (computational physics). Each component is essential to capture the complex, coupled processes governing magnetic fields in NSs (high energy astrophysics). By integrating methods from these diverse fields, the project will tackle challenges that cannot be addressed within a single discipline, enabling a comprehensive and realistic exploration of this multifaceted astrophysical problem.

<u>1.2.3 Gender dimension and other diversity aspects:</u> These activities of the proposed research are governed by universal physical laws and do not involve biological characteristics or socio-cultural factors. As such, sex, gender, and diversity do not influence the research content. No analysis of human differences is required, as the project relies solely on astrophysical and computational methods, with all relevant data generated through simulations.

<u>1.2.4 Open science practices and research data management:</u> Open science practices will be integrated into WP5 (see Section 3) and applied to all project outcomes. The researcher will ensure that all publications are open access, including those in peer-reviewed journals, primarily by using Nordita funding and a personal grant to cover publication expenses. Publications will also be deposited in repositories such as arXiv, ResearchGate, the <u>researcher's personal webpage</u>, and <u>Prof. Brandenburg's personal webpage</u>. A Data Management Plan (DMP), outlined in Deliverable 5.2, will be created using DMPonline and will adhere to FAIR principles. The DMP will encompass simulation results and datasets. These will be made openly accessible and can serve as a valuable resource for the astrophysics community in general and the high-energy astrophysics community in particular.

1.3 Quality of the supervision, training and of the two-way transfer of knowledge between the researcher and the host

<u>1.3.1 Qualifications and experience of the supervisor(s)</u>: Axel Brandenburg (ORCID <u>0000-0002-7304-021X</u>) is a leading astrophysicist and full professor with affiliations at Nordita and the Oskar Klein Centre (Sweden), Carnegie Mellon University (USA), and Ilia State University (Georgia). Internationally recognized for his pioneering contributions, Brandenburg has made landmark advances in astrophysical fluid dynamics, particularly in dynamo theory, turbulence, and magnetic helicity.
His research spans solar and stellar activity, helioseismology, convection, differential rotation, galactic magnetism, accretion disks, compact objects, the early universe, and magnetospheric physics. He also explores astrobiology, with a focus on the origins of homochirality. Among his key achievements are the first compressible dynamo simulations, foundational work on accretion disk turbulence demonstrating sustained magneto-rotational and dynamo-driven turbulence, and the development of the distributed solar dynamo model. He was also among the first to show that inverse cascade processes can generate large-scale primordial magnetic fields and has since 2011 developed methods to quantify magnetic helicity in astrophysical systems.
Brandenburg is the principal developer and maintainer of the Pencil Code, a widely used open-source simulation tool that will be central to this project. In 2009, he was awarded a prestigious ERC Advanced Grant (€2.22M), enabling him to expand research on astrophysical dynamos. He has published over <u>450 articles</u>, with ~30,000

citations and an h-index above 80 (Google Scholar). His most cited works are those where he is the lead author, reflecting his originality and leadership. He has supervised numerous PhD students and postdocs, including Marie Skłodowska-Curie Fellows, and led multiple international projects.
Elected as a foreign member of the Royal Swedish Academy of Sciences and honored with a professorship at Ilia State University, Brandenburg maintains global collaborations, organizes conferences, and serves on editorial and advisory boards. His expertise, mentorship, and leadership make him a central figure in computational astrophysics and magnetohydrodynamics.

1.3.2 Two-way transfer of knowledge between the researcher and host organisation and planned training activities:

Transfer of knowledge from the host to the researcher: Dr. Dehman will acquire advanced technical and theoretical skills through close collaboration with the host group. She will deepen her expertise in turbulence by studying its behavior in full MHD simulations and explore magnetic helicity and its link to chiral asymmetry—complex, underexplored aspects of NS physics. Her training will also include superconductivity and superfluidity in neutron star cores, with input from Nordita's solid-state matter group, adding interdisciplinary depth.
On the computational side, she will gain hands-on experience in high-performance computing, advanced programming, and code parallelization—specifically enhancing the MATINS code for high-resolution simulations. This will be supported by collaboration with the Pencil Code team, whose numerical expertise is highly complementary.
Training will be provided by the supervisor and other experts within the host group and external collaborators. Career development will be guided by a Career Development Plan (CDP, deliverable 4.1) and regular mentoring meetings. Dr. Dehman will integrate into the research community through weekly group meetings, seminars, and workshops organized by Nordita and the Albanova astrophysics network. These activities will ensure both deep technical training and broader career development, equipping her for a strong independent research trajectory.

Transfer of knowledge from the researcher to the host: Dr. Dehman will bring valuable expertise to the Astrophysics group, particularly in the physics of NSs and high-energy astrophysics, combining both theoretical and observational perspectives on compact objects—an area currently underrepresented in the host group. Her deep understanding of NS microphysics, including its key role in cooling and magnetic field evolution, will enhance the group's efforts to connect thermal and magnetic processes. Her background in nuclear physics will also complement ongoing research, as nuclear reactions are central to many astrophysical environments studied by the group.
Computationally, her development of the cubed-sphere grid for the MATINS code will facilitate its integration into the Pencil Code. This implementation will directly contribute to the Pencil Code by resolving the axis singularity in 3D spherical coordinates and will significantly boost the code's capabilities, benefitting both the host group and the broader user community.
Knowledge transfer will occur through close collaboration, supervision, and regular presentations at group meetings and seminars. Dr. Dehman will also lead training sessions open to group members and external researchers, promoting inclusive learning environment. She will contribute to teaching at KTH and Stockholm University and supervise Bachelor's and Master's thesis projects.
Importantly, she will strengthen the group's observational and high-energy astrophysics dimension through her active collaborations with leading researchers in Spain (J. A. Pons, M. Centelles, X. Viñas, N. Rea, D. Viganò, J. M. Alarcón), Japan (K. Kotake), Australia (F. Anzuini, A. Melatos), the UK (V. Graber), and the USA (R. Perna, S. Reddy, Y. Levin, G. Younes). These collaborations—focused on NSs, nuclear physics, and high-energy phenomena—might significantly expand the host group's expertise and international reach.

1.4 Quality and appropriateness of the researcher's professional experience, competences and skills

As detailed in her CV (Section 4), Dr. Dehman specializes in magnetic field evolution in compact astrophysical objects, particularly NSs. She is a leading expert in the field and the principal developer of MATINS, a state-of-the-art 3D code for magneto-thermal evolution in isolated NSs (see publications 1, 2, and 8 in Section 4). Developing MATINS from scratch during her PhD—an ambitious, high-risk project—demonstrates her strong initiative, independence, and technical skill.
Her research addresses key open questions, including the formation of large-scale magnetic fields, the role of magnetic helicity, and the potential for an inverse cascade within NS interiors—previously thought unlikely. These studies use both MATINS and the Pencil Code. Notably, she pioneered the application of the chiral magnetic effect in long-lived NSs, showing its ability to transfer energy from small-scale turbulence to large-scale structures, offering new insight into the origin of magnetar dipolar fields.
Dr. Dehman also contributes to nuclear physics studies of neutron star interiors, supported by her Master's training in the field. She was the author of a paper presenting a new unified equation of state (EOS) at finite temperature, applicable to the late stages of proto-NSs and post-merger events, and published a *Nature Astronomy* article proposing a new constraint on nuclear EOSs.

Her leadership is reflected in 20 peer-reviewed publications (7 first-author, 2 corresponding author with equal contribution), an h-index of 12, over 360 citations, and student supervision in the area of NS magnetic field evolution. She has delivered over 13 invited talks across Europe, the USA, and Japan.
Her broad expertise spans numerical development, magnetic field evolution, neutron star cooling, chiral magnetic effects and helicity, nuclear microphysics, and the equation of state. To further strengthen her profile, the project will provide advanced training in MHD and turbulence theory, superconductivity and superfluidity, and high-performance computing. These goals, supported through knowledge transfer and training at Nordita (Section 1.3), will foster her scientific independence and maturity. With a strong track record and deep technical expertise, Dr. Dehman is well-positioned to lead the proposed research while gaining valuable professional growth, as detailed in the next section.

2. Impact #@IMP-ACT-IA@#

2.1 Credibility of the measures to enhance the career perspectives and employability of the researcher and contribution to his/her skills development

This project offers targeted measures to significantly strengthen the researcher's career prospects and employability. While she already possesses strong expertise in developing and applying advanced numerical codes for modeling magnetic field evolution in neutron stars, further training is needed to broaden her skill set and foster greater independence as a researcher. A central component of the project is hands-on training in advanced MHD numerical codes, particularly in multi-fluid modeling—an area not yet fully explored in her previous work but essential for advancing in the field of astrophysical simulations. Under the supervision of a leading expert, the researcher will acquire this knowledge through direct mentorship and collaboration, enabling her to move beyond single-fluid models and address more complex, realistic scenarios. In addition, the project will provide exposure to state-of-the-art computational techniques, such as code parallelization and optimization, which are critical for handling large-scale simulations. These skills, while rooted in computer science, are indispensable for advancing the MATINS code and for tackling the computational challenges inherent in studying magneto-thermal evolution in neutron stars. The research environment at the host institute, Nordita, offers further opportunities for professional growth. Participation in a vibrant scientific community, regular workshops, and networking events will enhance the researcher's visibility and facilitate collaborations with leading scientists in the field. These experiences will not only support the publication of high-impact research but also inspire future grant proposals and research directions.
Securing a prestigious MSCA fellowship will further elevate the researcher's profile, providing a strong foundation for future funding applications, such as an ERC Starting Grant, and supporting the eventual establishment of her own research group. Overall, the combination of advanced technical training, exposure to cutting-edge research, and expanded professional networks will equip the researcher with the comprehensive skill set needed for leadership roles in academia and beyond.

2.2 Suitability and quality of the measures to maximise expected outcomes and impacts, as set out in the dissemination and exploitation plan, including communication activities #@COM-DIS-VIS-CDV@#

The measures outlined in our dissemination and exploitation plan are well-suited to maximize the expected outcomes and impacts of the project. The knowledge generated will significantly advance understanding of the physics governing magnetic field evolution in neutron stars, leading to improved magnetic simulations and insights into their observable properties. This research also holds potential value for the solid-state physics industry, particularly in understanding magnetic field effects in superconductive and superfluid states—regimes that naturally occur under the extreme conditions present in neutron stars. Additionally, the project will contribute to advancements in computational science by developing or applying novel numerical techniques to enhance code performance. The planned measures to maximize impact are detailed in Table 2.2 a-c and will be systematically implemented through our dissemination plan and communication activities (see Deliverable 5.1).

Table 2.2a: Key expected results (IP protection and exploitation measures and target industries)

Key results	IP management	Exploitation measures	Target industries
Magnetism modeling in extreme environments	IP register	R&D projects, Technical consultancy	Software companies specializing in solid-state physics and computer science.

Table 2.2b: Dissemination measures

Action (tools & channels)	Objectives	Target groups	Timeline
Publications in high impact journals (ApJ, MNRAS, A&A, Phys. Rev, or higher impact).	Raise interest in astrophysical magnetism, superconductive magnetism, magnetic helicity, and the chiral anomaly; disseminate knowledge.	Researcher in academia/ industry	Month 6 onwards . At least 6 papers (100% in Q1 journals)
Attendance and presenting work at Conferences: Cost Action e.g., Pharos, EAS, XMM-Newton, IAU Symposium 363, Equations of State workshops.	Raise interest in astrophysical magnetism, superconductive magnetism, magnetic helicity, and the chiral anomaly; disseminate knowledge and seek feedback.	Reseacher in academia	Month 5 onwards
Presenting and scientific visits at Swedish, European, & non-european institute linked to the hosting group or researcher: ICE-CSIC (Barcelona, Spain), Fukuoka University (Japan), Princeton University (USA), Alicante University (Spain), INT (Washington state, USA), KTH, Stockholm University (Sweden).	Raise interest, spread knowledge and actively seeking feedback and discussion with experts.	Reseacher in academia	Month 5 onwards

Table 2.2c: Communications and outreach measures

Action (tools & channels)	Objectives	Target groups	Timeline
Articles in social media. Effective use of the platforms X, Youtube, Facebook and Instagram via the researcher personal account and/or official host institution accounts.	Raise awareness about the research activities and results. Achieve societal endorsement.	General public, public authorities , policy makers and broader scientific community	Month 2 onwards
Participation in outreach activities for kids including visits to school, night of research and observations of the planets. High school seminar and visits in Stockholm city but also in other small villages in Sweden.	Raise awareness about the research activities and engage young people in science.	General public, particularly younger audiences	Month 6 onwards
Scientific notes in press releases, radio, TV, newspapers, websites via Nordita website and the personal webpage of the researcher.	Raise awareness about the research activities and results. Achieve societal endorsement.	General public, public authorities , policy makers and broader scientific community.	Month 6 onwards

2.2.2: Strategy for the management of intellectual property, foreseen protection measures: The project will advance the MATINS and Pencil Code numerical codes by improving their computational performance and developing new physics modules. These developments may generate intellectual property, separate from scientific publications. At Nordita, any potentially transferable results will be assessed with the support of the technology transfer office, following established protocols and EU Intellectual Property Rights policies. If protection is appropriate, measures such as copyright, patent, or software licensing will be applied. Protected results can then be made available for public use or transferred to relevant stakeholders or industry partners as appropriate.

2.3. The magnitude and importance of the project's contribution to the expected scientific, societal and economic impacts

This project will make a significant contribution to the advancement of scientific knowledge in high-energy astrophysics by addressing fundamental open questions about the origin and evolution of magnetic fields in neutron stars, particularly magnetars. By incorporating previously unexplored aspects such as superconductivity and superfluidity into models of magnetic field evolution, the project will push the boundaries of current understanding and establish Europe as a leader in this research area. The development of an advanced version of the MATINS code, integrating these new physical processes, will provide the astrophysics community with a state-of-the-art tool for simulating and interpreting X-ray observations of neutron stars. This code will not only facilitate breakthroughs in astrophysics but also serve as a valuable resource for modeling a wide range of astrophysical scenarios. Beyond

its scientific impact, the project's focus on optimizing and parallelizing numerical codes will promote the adoption of efficient computational strategies, reducing the energy consumption and environmental footprint of large-scale simulations. These advances in numerical methods have broad applicability, extending to other academic disciplines as well as to industrial sectors focused on computational engineering and technology.
#§COM-DIS-VIS-CDV§# #§IMP-ACT-IA§#

3. Quality and Efficiency of the Implementation #@QUA-LIT-QL@# #@WRK-PLA-WP@# #@CON-SOR-CS@# #@PRJ-MGT-PM@#

3.1 Quality and effectiveness of the work plan, assessment of risks and appropriateness of the effort assigned to work packages

The work plan is detailed in the following table, which outlines the proposed Work Packages (WPs):

WP1: Magnetic helicity at birth	Person-month:7	Start-end-months: 1-8
Objectives: Study the global magnetic helicity formed during core-collapse supernovae		
Task 1.1: Adapting the Pencil Code supernovae simulations by implementing the relevant physical parameters **Task 1.2:** Accounting for different dynamo mechanisms present in the supernovae and proton-neutron stars **Task 1.3:** Simulating the net magnetic helicity generated accounting for the impact of the boundary conditions.		
Milestones: M 1.1 Successful adaptation of the Pencil Code for supernova simulations (Month-4). **M 1.2** Preliminary analysis and validation of net magnetic helicity results (Month-6).		
Deliverables: D 1.1 Comprehensive report on the global net magnetic helicity generated in core-collapse supernovae simulations. (Month-8)		

WP2: Modeling core field	Person-month: 10	Start-end-months: 8-20
Objectives: Studying the magnetic field evolution in the superconductive and superfluid core of neutron stars		
Task 2.1: Advancing the MATINS code to account for superconductive/superfluid flux tubes. **Task 2.2:** Properly computing the velocity in these different regions of the neutron star core. **Task 2.3:** Performing a global simulation using MATINS and with the new developed core field physics.		
Milestones: M 2.1 MATINS advanced to handle superconductive flux tubes in neutron star cores (Month-13). **M 2.2** First global simulation of the superconductive core in neutron star with MATINS (Month-16).		
Deliverables: D 2.1 Completion of initial analysis of field behavior under superconductivity (Month-19).		

WP3: Parallelized MATINS and Advanced Pencil Code	Person-month: 4	Start-end-months: 20-24
Objectives: enhancing the numerical performance of MATINS and the Pencil Code.		
Task 3.1: advancing the optimization and the parallelization of the MATINS code **Task 3.2:** Implementing the cubed-sphere coordinates in the Pencil Code.		
Milestones M 3.1 MATINS parallelized and interfaced for use within the Pencil Code environment (Month-23).		
Deliverables D 3.1 New version of the MATINS code with high numerical performance (Month-24)		

WP4: Project and training management	Person-month: 1	Start-end-months: 1-24
Objectives: Monitor the project to ensure that objectives, deliverables, and milestones are achieved on time and within budget.		
Task 4.1: Project management and monitoring, ensuring that objectives, deliverables and milestones are met in time and within budget.		
Deliverables: D 4.1 Preparation of Career Development Plan (CDP) (Month-2-14)		

WP5: Dissemination and communication	Person-month: 2	Start-end-months: 1-24
Objectives: Plan for dissemination and exploitation of results, and communication and public engagement.		
Task 5.1: Dissemination, communication and public engagement activities: to be carried out as foreseen in Sect. 2.		
Deliverables: D 5.1 Dissemination Plan (DP) (Month-3-15); **D 5.2** Data Management Plan (DMP) (Month-4-18)		

The project's Gantt chart is shown below. Milestones are denoted by "M #.#" and deliverables as "D #.#". See Sect. 1.3.1 for details. The project will run for 24 months, an adequate time to carry out the proposed activities

	Year 1												Year 2											
WP/month	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
WP1																								
Task 1.1				D1.1																				
Task 1.2						D1.2																		
Task 1.3								M1.1																
WP2																								
Task 2.1													M2.1											

	Year 1												Year 2											
WP/month	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Task 2.2																M2.2								
Task 2.3																			D2.1					
WP3																								
Task 3.1																							M3.1	
Task 3.2																								D3.1
WP4																								
Task 4.1		D4.1												D4.1										
WP5																								
Task 5.1			D5.1	D5.2											D5.1			D5.2						

Supervision activities to be performed by Prof. Axel Brandenburg include tracking of on-time completion of the project tasks and deliverables (WP4, 0.5 person-month), providing training on turbulence and MHD simulations (WP1, 0.5 person-month) at the host institution as well as supervision on articles writing and co-authorship (0.5 person-month). Prof. Brandenburg will also supervise training provided by other members of the Astrophysics and the Pencil Code groups: Dr. Matthias Reinhardt will provide training on computer techniques and parallelization (WP3, 0,5 person-month) together with Frederick Gent. Discussions will take place with Igor Rogachevskii (WP1, 0,5 person-month) to progress the understanding of the chiral magnetic effect in supernovae and neutron stars. Nordita will provide support on WP4 and WP5. (Part of Axel group at nordita they work on supernovae, so this should be mentioned).

Risk management and reassessment will be conducted regularly, following the principles outlined below, and will be a key topic during group meetings.

Description of risk	**likelihood; severity**	**WP**	**Proposed mitigation measures**
Obstacles in explaining the formation of global magnetic helicity	Medium, medium	1	Focusing instead on the long lived neutron stars to show that with zero or near zero global helicity, chiral anomaly can still act locally on forming magnetars strong large scale field
Difficulties in simulation the field evolution in the core on a descent time	High;	2	Adapting a simple prescription for the velocity
Temporary unavailability of the host high performance computer cluster	Low, low	1-2	The researcher already has access to other computer clusters. Also application for computer time will be filled in EU-based centers and time can be spend on code development.
Training of the researcher not meeting the expectations	Low, medium	4	Career Development Plan (CDP, deliverable 4.1)
Results not meeting the expectations	Medium	1-3	Plan for the dissemination and exploitation including communication activities (PDE, deliverable 5.1)

3.2 Quality and capacity of the host institutions and participating organisations, including hosting arrangements

3.2.1 Hosting arrangements: Nordita (Nordic Institute for Theoretical Physics), jointly operated by KTH Royal Institute of Technology and Stockholm University, has a strong record of supporting and training postdoctoral researchers, including MSCA fellows (see section 5). Renowned for its vibrant atmosphere, Nordita offers cutting-edge infrastructure and top-tier resources for high-quality research. It hosts numerous European and Nordic grants and fellowships and organizes high-level scientific programs, workshops, and long-term visitor activities year-round across all areas of theoretical physics, including astrophysics.

Nordita ensures excellent working conditions through its Work Environment Committee and a dedicated Equality, Diversity, and Inclusion (EDI) committee. It provides modern office space, administrative support, and access to powerful computational resources via the PDC Center for High Performance Computing and the National Academic Infrastructure for Supercomputing in Sweden (NAISS). Relocation, visa, and housing assistance are available through its administrative office.

With strong expertise in fluid dynamics and astrophysics, the host group and supervisor, Prof. Axel Brandenburg, are leaders in these fields. The researcher will be integrated into a collaborative environment featuring weekly group meetings and seminars on astrophysics and turbulence, fostering interaction and team cohesion. Prof. Brandenburg will offer expert mentorship and career guidance, providing access to an extensive academic network.

3.2.2 Quality and capacity of the participating organizations: My supervisor, the host group, and Nordita together create an exceptional setting for carrying out the proposed research. Nordita is internationally recognized for excellence in theoretical physics, consistently attracting prestigious European fellowships and grants, including MSCA and multiple ERC Advanced and Synergy Grants. This strong funding record reflects both scientific excellence and robust institutional support. Nordita's reputation is further elevated by its connection to Nobel laureates like Frank Wilczek and Ben Roy Mottelson, underscoring its tradition of high-impact, groundbreaking research. My supervisor, Prof. Axel Brandenburg, is a leading expert in astrophysical fluid dynamics. He received an ERC Advanced Grant in 2009 and is widely known for seminal work on turbulent dynamos, magnetic helicity, and the generation of cosmic magnetic fields. His expertise aligns closely with the project's goals (see Section 1.3) and will be essential for its success. Prof. Brandenburg leads an active, interdisciplinary group at Nordita, including senior and junior researchers working on solar physics, early universe dynamics, supernova turbulence, gravitational waves, cosmology, and high-energy astrophysics. Regular visits from top scientists—e.g., Igor Rogachevskii, expert on the chiral magnetic effect—further enrich the group's collaborative and intellectually stimulating environment. A key asset is the Pencil Code community. Prof. Brandenburg, along with Matthias Rheinhardt (numerical methods, Aalto University), Philippe Bourdin (Pencil Code expert), and Jennifer Schober (CME, University of Bonn), forms the core development team. Their combined expertise directly supports the computational demands of WP1 and WP3. Nordita also offers access to the PDC Dardel supercomputer—an HPE Cray EX system with CPU and GPU nodes totaling 1,278 nodes and 163,584 cores—ensuring the computational capacity needed for state-of-the-art simulations. As a researcher at Nordita, I will benefit from high-level theoretical training, access to top-tier computational resources, and engagement with interdisciplinary research.
#§CON-SOR-CS§# #§PRJ-MGT-PM§# #§QUA-LIT-QL§# #§WRK-PLA-WP§#

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