#@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 magnetars—the most magnetic neutron stars (NSs)—remains a major challenge in high-energy astrophysics. Their extreme X-ray luminosities ($\geq 10^{35}$ erg/s), recurrent outbursts, unusually slow spin periods (1–12 s), and ultra-strong magnetic fields ($\geq 10^{14}$ G at the surface and even higher internally) set them apart from other NSs[1]. Yet key uncertainties in their birth and long-term (up to millions of years) evolution—magnetic helicity[2] content, superconductivity (SC) and superfluidity (SF) in the core, and their coupling to crustal dynamics—still limit our ability to model magnetars and to explain how these internal processes shape their observed properties.

At birth, turbulent dynamo action can amplify magnetic fields to extreme strengths, typically manifesting itself on small spatial scales[3]. The resulting magnetic configuration may then relax into a lower-energy state while the magnetic helicity is conserved, leading to interlinked poloidal and toroidal components[4]. How these turbulent fields reorganise into the strong, large-scale dipoles observed in mature magnetars remains an open question. Recent studies[5] highlight magnetic helicity as a key factor in the reorganisation of magnetar fields: its initial value—set at birth—drives the transfer of magnetic energy to larger scales, governing the long-term magnetic structure and helping to explain the strong dipole fields and magnetar traits.

Beyond birth conditions, a major challenge is modelling the long-term evolution of the NS core, where neutrons are SF and protons SC[6]. Their coupled dynamics, in particular the behaviour of quantized flux tubes, strongly influence field evolution[7]. Nuclear SF in NSs was predicted even before pulsar discovery[8]. Observations such as glitches and post-glitch relaxation provide evidence for a SF interior[9]. The rapid cooling observed in Cassiopeia A further suggests enhanced neutrino emission from neutron SF and proton SC[10]. Theory also supports the presence of macroscopic quantum condensates: neutrons and protons form Cooper pairs—analogous to laboratory superconductors[11]—that condense into SF and SC phases. This is significant since magnetic fields couple the core to the magnetosphere, so internal changes can manifest as observable phenomena.

Because NS conditions cannot be recreated in the laboratory, simulations are essential. Yet, most supernova and proto-neutron star (PNS) models[3] do not quantify magnetic helicity, thereby failing to capture how dynamo interactions and boundary conditions regulate its evolution. Critically, the origin of magnetic helicity at birth remains unknown. In contrast, long-term field evolution models often focus solely on the crust[12] or oversimplify the treatment of the core, neglecting SC/SF[13] effects. The **HELIX** (***H**elicity at birth and **E**volution of **L**arge-scale magnetic fields, with **I**nternal e**X**ploration of superconducting and superfluid dynamics*) project addresses these gaps by **(O1|WP1)** quantifying, for the first time, the helicity content generated during PNS evolution; **(O2|WP2)** self-consistently simulating flux-tube dynamics in a SC/SF NS core—a capability absent from previous models; and **(O3|WP3)** advancing numerical tools to capture realistic NS physics and overcome computational limits.

To achieve these objectives, HELIX brings together complementary expertise: neutron-star physics and magnetic-field evolution (researcher), turbulence theory, helicity, and magnetohydrodynamic (MHD) simulations (supervisor), and advanced computational methods (host group and Pencil Code collaboration). This combination creates an ideal environment for the project. HELIX will develop a unified computational framework spanning both the birth and long-term evolution of NSs, enabling investigations of key processes that have so far remained inaccessible due to their complexity. HELIX's outcomes will deepen our understanding of magnetism in NSs—particularly magnetars—and contribute to advances in solid-state magnetism and computational physics.

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[1] **(a)** Mereghetti et al. (2015), *Space Sci. Rev. 191 315*; **(b)** Turolla et al. (2015), *Rep. Prog. Phys.* ***78*** *116901*; **(c)** Kaspi & Beloborodov (2017), *Annu. Rev. Astron. Astrophys. 55 26*; **(d)** Esposito et al. (2020), *Astrophys. Space Sci. Lib. 461 97*

[2] The magnetic helicity is a measure of the linkage between magnetic field lines. On large scales, it implies a coupling between the poloidal and toroidal fields.

[3] **(a)** Thompson & Duncan, *ApJ 408 194*; **(b)** Obergaulinger et al. (2014), *MNRAS 445 3169*; **(b)** Reboul-Salze et al. (2022), *A&A 667, A94*; **(c)** Aloy & Obergaulinger (2021), *MNRAS 500 4365*, **(d)** Matsumoto et al. (2024), *MNRAS letters 529 L96*

[4] **(a)** Flowers & Ruderman (1977), *ApJ 215 302*; **(b)** Braithwaite & Spruit (2006), *A&A 450 1097*

[5] **(a)** Brandenburg (2020), *ApJ 901 18;* **(b)** Dehman & Brandenburg (2025), *A&A 694 A39;* **(c)** Dehman & Pons (2025), *PRR 7 033231*

[6] **(a)** Baym, Pethick & Pines (1969), *Nature 224, 673*; **(b)** Baym, Pethick, Pines (1969), *Nature, 224, 674*

[7] **(a)** Glampedakis et al. (2011), *MNRAS 410 805*; **(b)** Glampedakis et al. (2011), *MNRAS 413 2021*; **(c)** Graber et al. (2015), *MNRAS 453 671*

[8] Migdal (1959), *Nuc. Phys. 13 655*

[9] Anderson & Itoh (1975), *Nature 256 25*

[10] **(a)** Page et al. (2011), *PRL. 106, 081101*; **(b)** Shternin et al. (2011), *MNRAS letters 412 L108*

[11] Bardeen, Cooper & Schrieffer (1957), *Phys. Rev. 108 1175*

[12] **(a)** Gourgouliatos et al. (2016), *PNAS 113 3944 3949*; **(b)** Igoshev et al. (2021) *ApJ 909 101*; **(c)** Igoshev et al. (2023), *MNRAS 525 3354*; **(d)** Dehman et al. (2023) *MNRAS 518 1222*; **(e)** Dehman et al. (2023) *MNRAS 523 5198*; **(f)** Ascenzi et al. (2024) *MNRAS 533 201*

[13] **(a)** Castillo et al. (2020), *MNRAS 498 3000*; **(b)** Igoshev & Hollerbach (2023), *MNRAS 518 821;* **(c)** Moraga et al. (2025), *PRD in press, arXiv: 2505.18733*

1.1.2 State-of-the-art and ambition: Recent advances in MHD simulations of core-collapse supernovae[14] have greatly improved our understanding of the mechanisms driving stellar explosions and refined our knowledge of their compact remnants, the hot PNSs[15]. The early evolution of a PNS unfolds in three stages: (i) within the first second after core bounce, a relatively cool core is surrounded by a hot, neutrino-emitting mantle that continues to accrete infalling material; (ii) over the next ~20 seconds, the PNS undergoes deleptonization and internal heating, followed by cooling through neutrino diffusion, while remaining extremely hot (~10^{11} K) with a radius of about 100 km; (iii) after several minutes, as the star becomes transparent to neutrinos, it contracts to its final NS radius (10–14 km) and enters a prolonged cooling phase, initially dominated by neutrino emission and later—over tens of thousands of years—by photon emission from the surface.

The magnetic field configuration of NSs at birth remains poorly constrained, and the mechanisms responsible for generating the strong dipolar fields inferred from magnetar timing properties are still debated. Several formation scenarios have been proposed, each with distinct implications for the star's subsequent evolution. If turbulence is ignored, magnetic flux conservation could, in principle, produce strong fields if the progenitor is highly magnetized[16]—for instance, through stellar mergers. However, such progenitors are typically slow rotators, making this pathway unlikely for millisecond magnetars[17]. A more plausible route is field amplification through a turbulent dynamo during the PNS phase[18]. Recent local and global MHD simulations have quantified the efficiency of this process: local box setups with idealized background fields demonstrate magneto-rotational instability (MRI)[18], while global simulations explore dynamo action under differential rotation, convection, and the Taylor–Spruit mechanism[19]. As expected for dynamo systems, the outcome is a quasi-equilibrium with magnetic energy distributed across many spatial scales, dominated by non-axisymmetric and toroidal components, and only a weak large-scale dipole. Although the total magnetic energy can reach magnetar-like values, it remains concentrated on small scales. Long-term magneto-thermal evolution studies of such field configurations[20] show that they cannot reproduce observed magnetar properties, suggesting that an additional field-generation or reconfiguration mechanism is required. Indeed, most long-term magnetar models assume an ad hoc strong dipolar field to match observations[12], but the physical origin of this configuration remains unresolved.

Recent studies have underscored the critical role of magnetic helicity in the long-term evolution of NS magnetic fields[5]. By transferring magnetic energy from small to large scales, it may help explain the strong dipolar fields observed in magnetars. Building on earlier work on inverse cascades driven by nonlinear Hall drift[5a,b], Dehman & Pons (2025)[5c] proposed a microscopic mechanism in which magnetic energy, first stored in small-scale turbulent fields at birth, can grow to larger scales within centuries, constrained by helicity conservation and mediated by the chiral anomaly. This process naturally generates a strong dipolar field from small scales, offering a compelling framework for magnetar formation. However, these models[5] rely on a crucial assumption: that NSs are born with net magnetic helicity—an assumption that remains untested and whose astrophysical origin is unclear.

Standard MHD simulations typically preserve reflectional symmetry, so every twisted field configuration is balanced by a mirror image of opposite handedness[21]. As a result, magnetic energy can be amplified while net helicity remains close to zero[22]. These simulations often omit the contribution of the chiral magnetic effect (CME) during the PNS phase[23], a quantum phenomenon where a chiral asymmetry of electrons—an imbalance between left- and right-handed states generated in core collapse—induces an electric current along magnetic field lines. Although the CME can in principle induce helicity growth[24], the emergence of a net value depends on global symmetries and boundary conditions. If reflectional symmetry is enforced—by the physical environment or the numerical setup—any generated helicity is canceled by its mirror counterpart. In contrast, open boundaries can break this symmetry by allowing a preferential escape of helicity[25], a situation more realistic for PNSs embedded in surrounding supernova ejecta. Thus, both microphysical processes such as the CME and global properties such as boundary conditions determine whether net helicity can arise in NS formation. Determining whether reflectional symmetry is physical or numerical, and how its breaking enables net helicity, remains a central challenge.

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[14] Mösta et al. (2014), *ApJL 785 L29*; **(b)** Obergaulinger et al. (2014), *MNRAS 445 3169*; **(c)** Bugli et al. (2020), *MNRAS 492 58* ; **(d)** Aloy & Obergaulinger (2021), *MNRAS 500 4365***;** **(e)** Powell et al. (2023), *MNRAS 522 6070* ; **(f)** Matsumoto et al. (2024), *MNRAS letters 529 L96*

[15] **(a)** Pons et al. (1999), *ApJ 513 780*; **(b)** Barrère et al. (2022), *A&A 668 A79*

[16] **(a)** Ferrario & Wickramasinghe (2006), *MNRAS 367 1323*; **(b)** Makarenko et al. (2021), *MNRAS 504 5813*

[17] Shultz et al. (2018), *MNRAS letters 478 L39*

[18] **(a)** Balbus & Hawley (1991), *ApJ 376 214*; **(b)** Akiyama et al. (2003), *ApJ 584 954*; **(c)** Obergaulinger et al. (2014), *MNRAS 445 3169*; **(d)** Rembiasz et al. (2017), *ApJS 230 18*; **(e)** Aloy & Obergaulinger (2021), *MNRAS 500 4365*

[19] **(a)** Raynaud et al. (2020), Sci. Adv. 6 2732; **(b)** Reboul-Salze et al. (2022), *A&A 667, A94*; **(c)** Masada et al. (2022), *ApJ 924 75*; **(d)** Matsumoto et al. (2024), *MNRAS letters 529 L96;* **(e)** Barrère et al. (2025), *A&A 695 A183*

[20] **(a)** Dehman et al. (2023), *MNRAS 523, 5198;* **(b)** Igoshev et al. (2025), *Nature Astro. 9 541-551*

[21] **(a)** Woltjer (1958), *PNAS 44 489;* **(b)** Taylor (1974), *PRL 33 1139*; **(c)** Bodo et al. (2017), *ApJ 843 86*

[22] Brandenburg & Subramanian (2005), *Phys. Rep. 417 1*

[23] **(a)** Dvornikov et al. (2020), *PRD 101 083009*; **(b)** Matsumoto et al. (2022), *PRD 105 123029*; **(c)** Kamada et al. (2022), *Prog. Part. Nucl. Phys. 129 104016*

[24] Boyarsky et al. (2012), *PRL 108 031301*

[25] **(a)**Vishniac & Cho (2001), *ApJ 550 752*; **(b)** Käpylä et al. (2010), *A&A 518 A22*; **(c)** Hubbard & Brandenburg (2011), *ApJ 727 11*

While the birth conditions of NSs are critical in setting their initial magnetic configuration, understanding their long-term magnetic evolution—over millions of years during which NSs are observed—is equally essential. The core, comprising ~90% of the stellar volume, likely hosts SF neutrons and SC protons. In these extreme conditions, magnetic fields behave very differently from normal matter (non-SF/SC). If the protons form a type-II SC, as expected below a critical temperature of order 10^9 K typical of NS cores[26], magnetic flux becomes quantized into discrete flux tubes (also known as fluxoids), with a critical field strength on the order of 10^{15} G. This fundamentally alters the star's magnetic properties: flux is confined to tubes rather than permeating the plasma (see Figure 1). Conventional coupling mechanisms such as Ohmic dissipation are strongly suppressed due to proton pairing[6], so macroscopic evolution is governed by the interactions between flux tubes and their environment. The dominant coupling process, known as mutual friction, arises from the electrons scattering off flux-tubes fields[27]. Importantly, invoking Meissner-type flux expulsion (type-I SC) to justify crustal confinement is inconsistent with the type-II or mixed states expected for NS cores[7,28], and realistic magnetic configurations are thought to lie between these extremes, as shown in Figure 1.

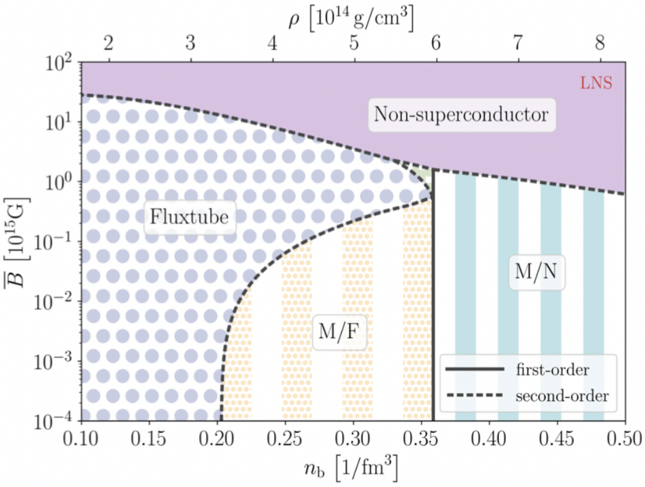

Figure 1. Adapted from Wood et al. (2020). Ground states of proton SC in NS cores across a range of baryon densities and mean magnetic fluxes for a given EOS. Regions correspond to flux tube (type-II), non-superconducting, and mixed states (M/F, M/N), with solid and dashed curves marking first- and second-order transitions, respectively.

Despite these expectations, the collective dynamics of fluxoids and their impact on field evolution remain largely unexplored. Most 3D magneto-thermal simulations focus on the crust[12], where fields evolve via Hall drift and Ohmic dissipation, while the core is typically neglected owing to the computational and theoretical challenges of SC/SF. Some studies[13] have attempted to model core evolution through ambipolar diffusion—the drift of charged particles and field lines relative to the neutrons—which can transport flux toward the crust and induce field decay. However, these simulations[13] assume normal (non-SF/SC) matter, yielding diffusion timescales of several hundred thousand years for 10^{14} G fields. Theoretical studies[7,31] show that SF/SC suppress ambipolar diffusion even further, stretching these timescales and making the process ineffective on observational timescales—particularly in the first million years, when NSs remain thermally bright and detectable in X-rays. This underscores the need for explicit modeling of flux-tube dynamics in SC cores to capture internal evolution and its observational signatures, including flux expulsion into the crust. Such physics is still absent from realistic 3D simulations, leaving a major gap in our understanding of magnetar and NS magnetic evolution.

To date, only a handful of studies have explored the evolution of magnetic flux tubes in NS cores restricted to 2D axial symmetry and without treating consistently the crust–core interface[29]. Elfritz et al. (2016)[32a] estimated fluxoid drift velocities by combining the relevant forces acting on flux tubes, including SC, but computed trajectories without evolving the magnetic field self-consistently with core MHD. As a result, their study could not assess the global implications of fluxoid motion for long-term field evolution. More recently, Bransgrove et al. (2025)[32c] investigated the crust–core interface, showing that the continuity of tangential magnetic stress, together with type-II SC in the core, strongly influences magnetic dynamics. They demonstrated that, under these conditions, magnetic flux can be expelled from the core into the crust via Hall waves, triggering avalanches of magnetic activity and ultimately depleting the core's field. This behaviour arises from the quantized nature of flux tubes in the SC state, which alters the Maxwell stress compared to normal (non-SC) matter and drives their tension-mediated evolution[30]. These findings highlight the need for global simulations that treat SC core physics self-consistently, as this is likely to have significant consequences for crustal field evolution and the observable properties of NSs.

Addressing these challenges requires advanced numerical tools to evaluate helicity at birth and to model long-term evolution in SC/SF cores. Several 3D MHD codes have been developed each with distinct numerical

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[26] Abrikosov (1957), *J. Phys. Chem. Solids 2 199*

[27] **(a)** Alpar et al. (1984), *ApJ 282 533*; **(b)** Mendell (1991), *ApJ 380 515;* **(c)** Andersson et al. (2006), *MNRAS 368 162*

[28] **(a)** Wood et al. (2020), *arXiv: 2011.02873*; **(b)** Wood et al. (2022), *Universe 8 228*

[29] **(a)** Elfritz et al. (2016), *MNRAS 456 4461*; **(b)** Bransgrove et al. (2018), *MNRAS 473 2771;* **(c)** Bransgrove et al. (2025), *ApJ 979 144*

[30] **(a)** Easson & Pethick (1977), *PRD 16 275*; **(b)** Jones (1991), *MNRAS 253 279*; **(c)** Jones (2006), *MNRAS 365 339*; **(d)** Gusakov & Dommes (2016), *PRD 94 083006*; **(e)** Gusakov (2019), *J. Phys.: Conf. Ser. 1400 022006*; **(f)** Rau & Wasserman (2020), *PRD 102, 063011*

strategies—for example MagIC[31], Parody[32], the Pencil Code[33], MATINS[34], and other proprietary frameworks[13,14]. The Pencil Code[37], developed by the supervisor and host group, is a high-order, MPI (Message Passing Interface)-parallelized finite-difference framework for nonlinear, compressible MHD in Cartesian and spherical geometries. In spherical coordinates, it simulates selected sectors of a 3D shell by excluding the axis, thereby circumventing coordinate singularities that affect spherical grids in finite-difference schemes. For long-term magnetic evolution, specialized codes have also been developed[36,38]. MATINS[38], primarily designed by the researcher, is a 3D finite-volume code for magneto-thermal evolution of isolated NS crusts. It employs a cubed-sphere (CS) grid[35], representing the sphere with six connected faces like a cube and avoiding axis singularities inherent to finite-volume schemes, models a spherical star based on an equation of state (EOS) from the CompOSE database, and accounts for relativistic corrections. The code also includes temperature-dependent microphysics from the IOFFE repository[36] and evolves thermal and magnetic fields self-consistently. Its current limitations are the treatment of core magnetic-field evolution and the absence of parallelization, restricting high-resolution simulations. Together, the Pencil Code and MATINS provide a strong foundation for modeling NS magnetic fields, but major numerical challenges remain. Overcoming these—axis singularities in the Pencil Code, and core field evolution and parallelization in MATINS—will enable efficient, high-resolution 3D simulations, and lay the groundwork for a unified and extensible numerical platform for NS physics and broader applications.

HELIX will deliver the first integrated framework for understanding and modelling NS magnetic fields, from their birth to their evolution over millions of years, by addressing three critical gaps.

- ***WP1 — Helicity at birth*** *(Pencil Code)* **|** ***Medium risk***

  SoTA: Helicity is rarely quantified in PNS studies; symmetric setups enforce reflectional symmetry, yielding vanishing net helicity; CME is omitted, and boundary/symmetry effects remain unresolved.

  Objective: Quantify net and spatial helicity in PNS simulations; evaluate the role of CME and boundary/symmetry conditions in generating net helicity; disentangle physical from numerical effects.

  Expected outcome: First quantitative helicity budgets at birth; quantification of the CME contribution and boundary dependence; identification of the physical conditions that allow net helicity to arise.
- ***WP2 — 3D Superconducting/superfluid core*** *(MATINS)* **|** ***High risk***

  SoTA: The NS core is often frozen or treated as normal matter. SF/SC studies are limited to 2D, with flux-tube and superfluid velocities imposed ad hoc, inconsistent with force balance. Crust–core coupling is weak or neglected, and self-consistent flux-tube dynamics are absent from 3D simulations.

  Objective: Develop the first self-consistent 3D model of magnetic evolution in an SF/SC core, including key multifluid processes, with stress/flux continuity across the crust–core interface, magneto-thermal feedback, and observational diagnostics.

  Expected outcome: 3D SC/SF module with flux-tube dynamics and crust-core coupling solves force balance and yields predictions for magnetar activity, flux expulsion, and thermal evolution.
- ***WP3 — Interoperability & High-Performance Computing (HPC) optimisation:*** *(Pencil Code ↔ MATINS)* **|** ***Medium risk (lower than WP1 and WP2)***

  SoTA: MATINS is non-scalable, lacking MPI-parallelization. Pencil Code in spherical-polar coordinates suffers from axis singularities that cause time-step bottlenecks and polar artifacts.

  Objective: Build an HPC-ready platform by parallelizing MATINS with MPI and implementing the CS mesh to Pencil to remove polar singularities, enabling efficient coupling of the two codes.

  Expected outcome: Coupled **open-access** MATINS–Pencil framework with a shared MPI layer, strong scaling (*≥70 % efficiency up to ~10^3 cores, based on Pencil Code benchmarks*), and removal of the polar time-step bottleneck, yielding a robust platform for high-resolution 3D simulations.

These interdisciplinary and ambitious objectives address long-standing gaps in NS physics. HELIX will integrate concepts from turbulence, computational astrophysics, solid-state physics, particle physics, and nuclear physics, creating synergies that link core-collapse supernovae to the long-term evolution of NSs.

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).

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[31] Wicht J. (2002), *Phys. Earth Planet. Inter. 132 281*

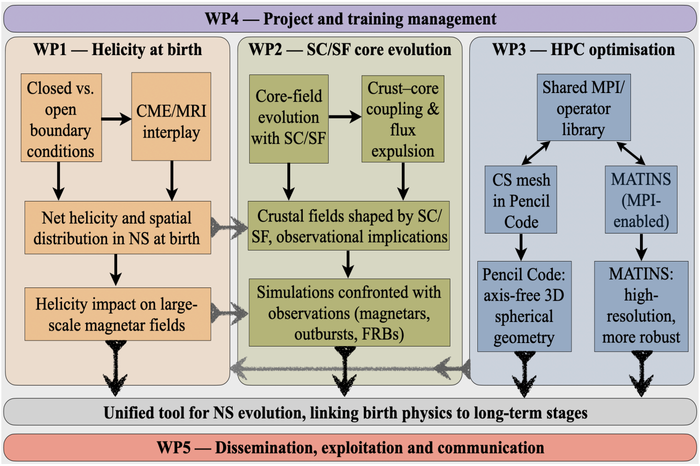
[32] **(a)** Wood et al (2015), *PRL 114 191101*; **(b)** Gourgouliatos et al. (2016), *PNAS 113 3944 3949*; **(c)** Igoshev et al. (2021) *ApJ 909 101*; **(d)** De Grandis et al. (2022), *ApJ 939 99*; **(e)** Igoshev et al. (2023), *MNRAS 525 3354*

[33] **(a)** Pencil Code Collaboration (Brandenburg, A., et al.) (2021), *JOSS 6 2807*; **(b) Repository:** https://github.com/pencil-code

[34] **(a)** Dehman et al. (2023) *MNRAS 518 1222*; **(b)** Dehman et al. (2023) *MNRAS 523 5198*; **(c)** Ascenzi et al. (2024) *MNRAS 533 201*; **(d)** Dehman & Pons (2025), *PRR 7 033231*

[35] Ronchi et al. (1996), *J. Comput. Phys. 124 93*; implemented in MATINS by Dehman et al. (2023) *MNRAS 518 1222*

[36] The public routines implemented in MATINS are available at http://www.ioffe.ru/astro/conduct/; see also Potekhin et al. (2015), *Space Sci. Rev 191 239.*



1.2.1 Overall methodology: The methodology is fully computational, structured into work packages with defined tasks and deliverables. A workflow figure illustrates their interconnection and interdisciplinary scope. Progression is milestone-based, focusing effort on impactful goals while safeguarding deliverables.

WP1 — Helicity at birth (Pencil Code). I will quantify the conditions under which net magnetic helicity can emerge in PNS simulations.

Task 1.1 — Baseline validation. I will model a differentially rotating, stably stratified PNS in a global shell using core collapse supernova (CCSN)–derived profiles, with an anelastic MHD approximation in the low-Mach regime, and realistic transport coefficients (including neutrino-mediated viscosity and Ohmic conductivity)[37]. As a baseline, I will reproduce a published MRI-adapted setup to validate linear growth rates and nonlinear saturation. This step ensures confidence in the physical regime and its implementation in the Pencil Code, providing a robust foundation for the subsequent tasks.

Task 1.2 — Boundary conditions. Using the validated baseline, I will compare closed (perfect-conductor) and open (vertical-field) magnetic boundary conditions, combined with standard velocity conditions (impenetrable, stress-free), to assess impact on the relative helicity budget[38]. Diagnostics will include global and hemispheric helicity, radial profiles and spectral distributions, and helicity fluxes through the boundaries (advective and electromotive), supported by resolution and domain-size convergence checks.

Task 1.3 — CME–MRI interplay. I will extend CME coupling to the MHD system using the Pencil Code's CME module[39], adapted to PNS conditions. The chiral density will be evolved with temperature-dependent spin-flip damping[40] (caused by electromagnetic scattering processes that flip electron handedness owing to the finite electron mass), and I will map the competition between MRI growth, CME growth, and spin-flip suppression across PNS profiles, highlighting the cooling window from ~100 down to ~50 MeV where spin-flip is weaker[41] and residual chiral asymmetry can bias the net helicity.

Deliverable 1.1: Quantitative helicity budgets and maps of net helicity emergence in PNS simulations, including conditions under which chiral asymmetry biases the net helicity.

WP2 — SC/SF core (MATINS). MATINS solves the TOV structure with a realistic nuclear EOS across crust and core. It also computes temperature-dependent microphysical ingredients in both regions[39], which are essential for coupled thermal and magnetic evolution. The core is treated as a highly conducting thermal reservoir, where thermal anisotropies decay rapidly due to strong conductivity[37,39]. In WP2, I will extend MATINS to model the magnetic evolution of the SC/SF NS core in 3D, which requires advancing the treatment of flux-tube motion.

Task 2.1 — Core transport. I will extend the induction equation to include flux-tube transport, Ohmic diffusion, and advective terms consistent with SC/SF dynamics. Transport velocities will be computed self-consistently from a local force balance on proton flux tubes[7], including lift, tension, buoyancy under composition stratification, and electron drag. Where SC breaks down —when the lower and upper critical fields converge, or when the magnetic field exceeds the upper critical value[7,31] (Figure 1)—the system switches locally to normal MHD, including Hall transport. The contribution of the CME will be evaluated a posteriori and included if found non-negligible, since spin-flip damping processes driven by electron scattering off magnetized neutron vortices in the SF core are expected to dominate under typical conditions[42]. This provides a closure for flux-tube motion, ensuring consistency with microphysical inputs from the EOS and pairing-gap tables already available in MATINS[37,39].

Task 2.2 — Crust–core interface. I will enforce continuity of stresses and fields across the crust–core interface, accounting for magnetic and elastic contributions[32c]. This will be implemented by matching normal and tangential magnetic components and by introducing simplified pinning/slip prescriptions on flux-tube motion at the interface.

Deliverable 2.1: Validated MATINS module for SC/SF transport and crust–core interface.

Task 2.3 — Targeted runs and comparison with observations. Using the project's simulation framework, I will run models varying selected inputs (e.g., EOS, pairing gaps), track outputs (magnetic-field evolution, spin-down, helicity budgets, dipole strength, thermal luminosity), all already available in MATINS[37,39], and compare with public observations[43] of isolated NSs (timing, dipole estimates, X-ray luminosities).

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[37] Following Reboul-Salze et al. (2022), *A&A 667, A94*, where the transport coefficients were formulated for application in the PNS context.

[38] **(a)** Käpylä et al. (2010), *A&A 518 A22*; **(b)** Zyuzin & Burkov (2012), *PRB 86 115133*; **(b)** Gorbar et al. (2015), *PRB 92 245440*

[39] **(a)** Rogachevskii et al. (2017), *ApJ 846 153*; **(b)** Schober et al. (2018), *ApJ 858 124* ; **(c)** Brandenburg et al. (2023), *PRR 5, L022028*

[40] **(a)** Grabowska et al. (2015), *PRD 91 085035*; **(b)** Sigl & Leite (2016), *JCAP 2016 25*; **(c)** Dvornikov (2016), *Phys. Lett. B 760 406*

[41] See Figure 1 of Sigl & Leite (2016), *JCAP 2016 25*

[42] **(a)** Feibelman (1971), *PRD 4 1589*; **(b)** Alpar et al. (1984), *ApJ 282 533*

[43] **(a)** Viganò et al. (2013); *MNRAS 434 123*; **(b)** Potekhin et al. (2020), *MNRAS 496 5052*; **(c)** Rea et al. (2025), *arXiv: 2503.04442*

Deliverable 2.2: Model–data comparison from runs and observations to improve observational interpretation.
Caveat/future: rotation-driven neutron-vortex physics (e.g. glitches, turbulence) and full magnetosphere coupling are beyond the present scope, but provide natural directions in future work.

WP3 — Interoperability and HPC optimisation (Pencil Code ↔ MATINS). WP3 paves the way for an open-access unified tool by advancing the computational infrastructure for high-resolution 3D simulations. Building on the physics developments in WP1 and WP2, it focuses on scalability, removal of polar bottlenecks, and interoperability between Pencil Code (high-order MHD for early phases) and MATINS (microphysics-rich long-term evolution). This ensures the physics tasks can be performed at the required resolution and timescales.

Task 3.1 — CS mesh in Pencil Code. I will implement a six-patch CS mesh[38] in Pencil Code. Unlike overlapping schemes (e.g. Yin–Yang), this approach simplifies vector operations and reduces inter-patch interpolation. An MPI communication layer, common to both codes, will coordinate the exchange of field values across patch interfaces.

Task 3.2 — Shared operator library and interoperability. I will develop a shared operator library providing CS metric factors and high-order operators (grad, div, curl, cross, dot), validated through unit tests. Both codes will call this library at runtime to ensure numerical consistency and avoid duplication. Standardized Input/Output (I/O) will enable data exchange between Pencil Code (PNS simulations, WP1) and MATINS (long-term evolution, WP2), while diagnostics for divergence control, energy/helicity budgets, boundary fluxes, and scaling will also be implemented in the shared library for consistent use in both codes, with full compatibility for MPI parallelisation.

Task 3.3 — MPI-parallelization of MATINS. Building on the shared operator library, I will parallelize MATINS with MPI to enable efficient scaling on HPC architectures for long-term NS simulations. MATINS will reuse routines from Task 3.2, ensuring full consistency with the Pencil Code. Accuracy and stability will be validated using strong-scaling benchmarks and the shared diagnostics from Task 3.2.

Deliverable 3.1: Interoperable open-access MATINS–Pencil framework with CS mesh, unified operators, I/O, and basic scaling, incorporating the physics modules developed in WP1 and WP2.

WP1, WP2 & WP3 collectively lay the foundation for a unified open-access tool to model NS evolution from birth to long-term stages. This plan is feasible within 24 months, supported by my experience developing MATINS, using the Pencil Code, implementing CS grids, and my expertise in helicity, CME, and NS physics.

1.2.2 Integration of methods and disciplines to pursue the objectives: This project takes a strongly interdisciplinary approach, combining theoretical insight with advanced computational modeling. It unites expertise in high-energy astrophysics, computational physics, turbulence, condensed matter, nuclear, and particle physics. Progress in modeling NS magnetic-field evolution requires both numerical innovation and a solid theoretical basis: quantifying helicity (drawing on turbulence theory and chiral anomaly concepts), modeling magnetic dynamics in superfluid and superconducting cores (informed by condensed matter and nuclear physics), and optimizing simulation performance (via computational physics). Each element is essential to capture the complex processes underlying NS field evolution, providing a foundation for meaningful comparison with observations. By bringing together methods from these disciplines, the project addresses challenges that cannot be fully resolved within a single field, enabling a rigorous and comprehensive investigation of this astrophysical phenomenon.

1.2.3 Gender dimension and other diversity aspects: The proposed research is entirely theoretical and computational, based on universal physical laws. Consequently, sex, gender, and other diversity factors are not relevant to its content or methodology. As the work relies solely on astrophysical modeling and numerical simulations, all data are generated independently of biological or socio-cultural variables.

1.2.4 Open science practices and research data management: Open science practices will be integrated into WP5 (see Sec. 3) and applied to all project outcomes. All publications, including peer-reviewed articles, will be open access, supported through Bibsam consortium agreements at Nordita (Stockholms Universitet), with additional support from Stockholms Universitet funds and personal grants when needed. Publications will also be deposited in repositories such as arXiv and mirrored on the researcher's and Prof. Brandenburg's webpages. A Data Management Plan (DMP), outlined in Deliverable 5.2, will be created using DMPonline in line with FAIR principles, covering simulation outputs, datasets, and open-source code improvements. Data will be deposited in open repositories (e.g., Zenodo), providing a lasting resource for the astrophysics community.

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

1.3.1 Qualifications and experience of the supervisor(s): Axel Brandenburg (ORCID 0000-0002-7304-021X) is a leading astrophysicist and professor affiliated with Nordita (Stockholms Universitet), the Oskar Klein Centre (Sweden), Carnegie Mellon University (USA), and Ilia State University (Georgia). He is internationally recognised for pioneering work in astrophysical fluid dynamics—dynamo theory, turbulence, and magnetic helicity—with applications in diverse areas, including compact objects, directly relevant to HELIX's focus on turbulence, helicity, and multi-scale MHD processes. His key contributions include the first compressible dynamo simulations; foundational demonstrations of sustained magnetorotational and dynamo-driven turbulence in disks; the distributed solar dynamo model; inverse-cascade generation of large-scale primordial fields; and methods to quantify magnetic helicity. He received an ERC Advanced Grant (€2.22 M, 2009) to expand research on astrophysical dynamos and has published >460 articles (>29,500 citations; h-index >85). He has led international projects and collaborations, notably through the open-source Pencil Code community (ascl:1010.060, >600 publications worldwide) and Nordita's visitor programmes. He has supervised 15 PhD students, numerous postdoctoral researchers including MSCA Fellows, and mentored early-career scientists. He is a foreign member of the Royal Swedish Academy of Sciences and serves on international editorial and advisory boards. His leadership and supervisory experience make him well placed to guide HELIX and support the researcher's career development. He will remain fully active in supervision, and an affiliated Nordita professor, throughout the fellowship period.

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 and magnetic helicity in full MHD simulations, and extend into superconductivity and superfluidity in NS cores with input from Nordita's solid-state group. On the computational side, she will gain hands-on training in high-performance computing, code parallelization, and optimization, enhancing MATINS for large-scale simulations with support from the Pencil Code team. Planned training also covers **project management, grant writing, communication, and supervision**, guided by a **Career Development Plan** (D4.1), regular mentoring, and participation in Nordita's workshop organization and outreach activities. Weekly group meetings, seminars, and the Albanova network will consolidate her integration and visibility, providing deep technical training and transferable skills for an independent research trajectory.

Transfer of knowledge from the researcher to the host: Dr. Dehman will bring valuable expertise to the Nordita Astrophysics group, particularly in high-energy astrophysics, combining theoretical and observational perspectives on compact objects—an area currently underrepresented in the host group. Her expertise in NS microphysics, particularly its impact on cooling and magnetic-field evolution, will help integrate thermal and magnetic modelling in the group, while her nuclear-physics background adds depth to ongoing studies of dense-matter physics relevant across many astrophysical environments. Computationally, her development of the CS grid for MATINS enables integration with the open-access Pencil Code, enhancing the group's modelling capabilities. Knowledge transfer will occur through close collaboration, supervision of students, and active contributions to group meetings and seminars, complemented by short research visits to collaborators abroad. She will also lead training sessions for group members and external researchers, contribute to teaching and student supervision at Stockholm University, and take a leading role in outreach initiatives. Importantly, she will broaden the group's observational and theoretical reach through collaborations with N. Rea (Spain) and G. Younes (USA) on X-ray observations; with V. Graber (UK), J.A. Pons, D. Viganò and M. Centelles (Spain), and Y. Levin (USA) on SC/SF in NS cores; and with K. Kotake (Japan) and J. Guilet (France) on PNS magnetic fields at birth. These collaborations, reinforced by short visits, will raise the host's international profile in astrophysics and related fields.

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

Dr. Clara Dehman (ORCID 0000-0003-0554-7286) specialises in the magneto-thermal evolution of neutron stars and leads development of **MATINS**, a 3D crustal MHD code. She pioneered applying the **chiral magnetic effect** to long-lived neutron stars by using helicity encoded in the initial magnetic-field structure to trigger CME growth—directly motivating this project's search for the origin of helicity, its role in inverse cascades, and the emergence of magnetar-scale dipoles. With formal training in theoretical nuclear physics (finite-temperature EOS), she bridges microphysics and MHD. The fellowship will consolidate this foundation and extend her expertise in turbulence, superconductivity/superfluidity, and large-scale HPC at Nordita. **Track record:** 21 publications (7 first-author, 2 co-first, incl. a Living Review); h-index 12, >380 citations (see Sec. 4).

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

HELIX introduces targeted measures to strengthen the researcher's career prospects and employability. She has established expertise in developing and applying advanced codes for modeling NS magnetic-field evolution, but further training is needed to broaden her skills and independence. A central component is hands-on training in advanced MHD, particularly multifluid modeling—essential for realistic astrophysical simulations yet not fully explored in her past work. Through direct mentorship with a leading expert, she will move beyond single-fluid approaches to more complex scenarios. The project also provides training in computational techniques such as code parallelization and optimization, crucial for large-scale simulations and for advancing MATINS within Pencil Code. **Developing an open-access MATINS–Pencil framework** will further strengthen her visibility, foster collaborations, and demonstrate leadership in community software. At Nordita, a vibrant environment with workshops, collaborations, and networking will boost her visibility and professional growth, supporting high-impact publications, competitive grants, and new research directions. An MSCA fellowship will raise her profile, lay the groundwork for ERC-level proposals, and prepare her for leadership 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 dissemination and exploitation measures are well-suited to maximise project outcomes and impacts. The research will improve understanding of magnetic-field evolution in NSs, strengthen numerical simulations and tools, and link them to observable properties. It also offers cross-disciplinary value: insights relevant to the solid-state industry (magnetic effects in SC/SF states) and contributions to computational science through novel numerical techniques and the release of the **open-access MATINS–Pencil framework**. Planned measures are detailed in Table 2.2a–c and will be systematically implemented through 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 collaborations; Technical consultancy	Software companies in solid-state physics and computational science

Table 2.2b: Dissemination measures

Action (tools & channels)	Objectives	Target groups	Timeline
Publications in top-tier journals (ApJ, MNRAS, A&A, Phys. Rev., **Q1 only**).	Disseminate findings; promote interest in astrophysical and SC/SF magnetism, helicity, and CME	Researchers in academia/ industry	Month 6 onwards; ≥6 papers (Q1 journals)
Attendance and presentations at conferences (e.g., Pharos, EAS, XMM-Newton, IAU Symp. 363, Cost Action, Equations of State workshops).	Disseminate findings; promote interest in SC/SF magnetism, helicity, and the chiral anomaly; **gather feedback**.	Researchers in academia	Month 5 onwards
Presentations & research visits (host-linked): KTH, Stockholm Univ. (SE); CSIC Institutes (ES); Princeton Univ., INT (US); Fukuoka Univ. (JP).	Raise interest, share knowledge, and seek expert feedback and discussion.	Researchers in academia	Month 5 onwards

Table 2.2c: Communications and outreach measures

Action (tools & channels)	Objectives	Target groups	Timeline
Social media: X, YouTube, Facebook, and Instagram on the researcher's and host institution's accounts.	Raise awareness of research activities and results; foster societal engagement.	General public, policymakers, broader scientific community	Month 2 onwards
Outreach: Activities for children and schools (Researchers' Night, visits, planetary observing) and high-school seminars across Sweden.	Raise awareness of research and inspire young people in science.	General public, especially younger audiences	Month 6 onwards
Scientific notes: Press releases and media coverage (radio, TV, newspapers, online), disseminated via Nordita's site and the researcher's webpage.	Publicize research activities and results; foster societal endorsement.	General public, policymakers, broader scientific community	Month 6 onwards

<u>2.2.2: Strategy for the management of intellectual property, foreseen protection measures</u>: The project will advance the MATINS and Pencil Code frameworks by improving computational performance and developing new physics modules. While scientific publications remain the primary route of dissemination, potentially transferable results will be assessed with Nordita's technology transfer office, in line with EU Intellectual Property Rights policies. Where appropriate, protection may be secured through copyright, patents, or software licensing, while maintaining open-source access to community code developments. Protected results could then be released for public use or transferred to stakeholders and industry partners, particularly in sectors reliant on HPC and large-scale simulations.

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

This project will advance high-energy astrophysics by addressing fundamental questions on the origin and evolution of NS magnetic fields, particularly in magnetars. By incorporating SC/SF into numerical models, it will extend current understanding and reinforce Europe's leadership in the field. The enhanced MATINS code, integrated into the Pencil Code framework, will introduce new microphysics together with the cubed-sphere mesh, strengthening Pencil's capabilities and enabling more computationally efficient simulations of NS observations across diverse astrophysical scenarios. As Pencil Code is an open-source community code, these advances will also benefit other domains reliant on large-scale simulations, including geophysics and selected industrial applications. HELIX-driven optimizations will further promote efficient HPC practices, reducing computational cost and environmental footprint. In parallel, HELIX results will inform the interpretation of NS observations with current and upcoming X-ray facilities (XMM-Newton, NICER, Athena), and may also support the understanding of radio transients to be probed with SKA, thereby strengthening the bridge between theoretical models and observations. #§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@#

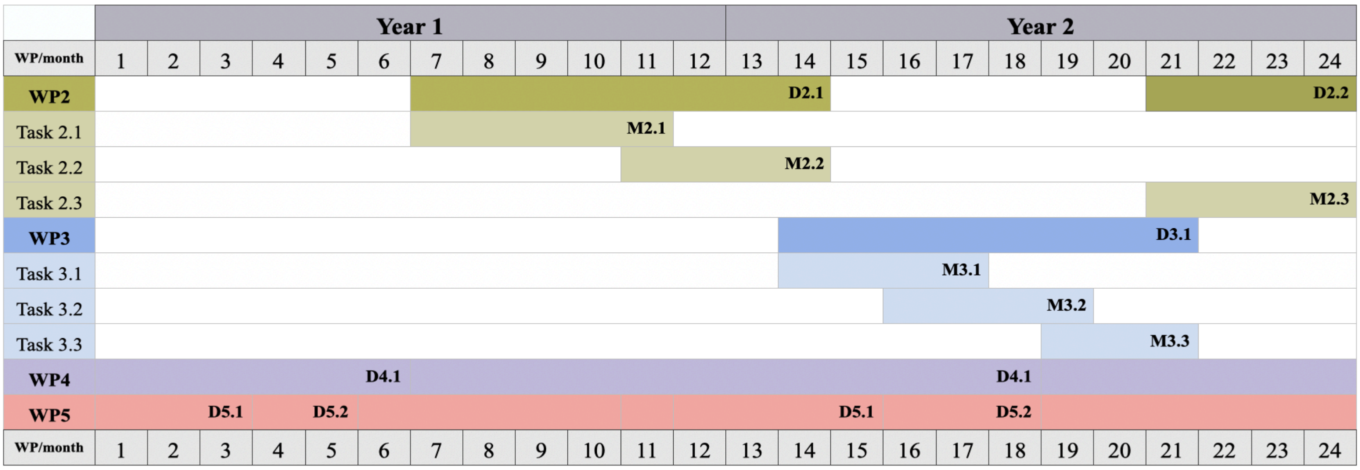
3.1 Quality and effectiveness of the work plan, assessment of risks and appropriateness of the effort assigned to work packages

The work plan is summarized in the table below, outlining the Work Packages (WPs). With experience developing MATINS and applying the Pencil Code, I am well positioned to deliver it within 24 months.

WP1 — Helicity at birth (Pencil Code)	Person-month: 5	Start-end-months: 1-6
Objective. Quantify conditions for net helicity emergence in PNS simulations		**Medium risk**
Tasks. T1.1: Baseline validation (MRI setup). **T1.2:** Boundary conditions (closed vs open). **T1.3:** CME–MRI interplay (spin-flip window).		
Milestones. M1.1 (Mo 4): Baseline validated and boundary-condition tests completed; helicity diagnostics operational. **M1.2 (Mo 6):** CME module adapted and tested. ***Mo = month of the fellowship.***		
Deliverable. D1.1 (Mo 6): Quantify helicity in PNS simulations, assessing boundary conditions and CME effects.		
WP2 — SC/SF core (MATINS)	Person-month: 10	Start-end-months: 6-18 & 21-24
Objective. Extend MATINS to model 3D field evolution in the SC/SF NS core, advancing flux-tube transport and crust–core coupling.		**High risk**
Tasks. T2.1: Core transport (flux-tube dynamics + closure). **T2.2:** Crust–core interface modelling. **T2.3:** Systematic runs and comparison with observations.		
Milestones. M2.1 (Mo 11): Core transport module implemented. **M2.2 (Mo 14):** Crust–core coupling validated. **M2.3 (Mo 24):** targeted runs compared with public observations.		
Deliverables. D2.1 (Mo 14): Validated SC/SF transport and crust–core interface module in MATINS. **D2.2 (Mo 24):** Model–observational data comparison from targeted runs.		
WP3 — Interoperability & HPC optimisation (Pencil ↔ MATINS)	Person-month: 6	Start-end-months: 7-14
Objective. Build an interoperable, scalable framework linking Pencil Code and MATINS for high-resolution 3D simulations.		**Medium risk** *(lower than WP1 & WP2)*
Tasks. T3.1: CS mesh in Pencil Code. **T3.2:** Shared operator library + I/O interoperability. **T3.3:** MPI-parallelisation of MATINS.		
Milestones. M3.1 (Mo 17): CS mesh benchmarked in Pencil Code. **M3.2 (Mo 19):** Interoperability framework operational. **M3.3 (Mo 21):** MPI-enabled MATINS validated with scaling benchmarks.		
Deliverable. D3.1 (Mo 21): Interoperable **open-access** MATINS–Pencil framework with CS mesh, unified operators, I/O, and scaling, paving the way for a unified tool to model NS evolution from birth to long-term stages.		
WP4 — Project and training management	Person-month: 1	Start-end-months: 1-24
Objective. Ensure all milestones and deliverables are met on time and within budget.		
Task. T4.1: Project management and monitoring to ensure timely, on-budget delivery of objectives, milestones, and deliverables.		
Deliverable. D4.1 (Mo 6-18): Preparation of Career Development Plan (CDP).		
WP5 — Dissemination and communication	Person-month: 2	Start-end-months: 1-24
Objective. Plan for dissemination and exploitation of results, communication, and public engagement (PDEC).		
Task T5.1: Dissemination, communication & public engagement activities: to be carried out as foreseen in Sec. 2.2		
Deliverables. D5.1 (Mo 3-15): Dissemination Plan. **D5.2 (Mo 5-18):** Data Management Plan.		

The Gantt chart below shows milestones (M#.#) and deliverables (D#.#).

	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	▨	▨	▨	▨	▨	**D1.1**																		
Task 1.1	▨	▨																						
Task 1.2		▨	▨	**M1.1**																				
Task 1.3				▨	▨	**M1.2**																		



	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
WP2							▨	▨	▨	▨	▨	▨	▨	**D2.1**							▨	▨	▨	**D2.2**
Task 2.1							▨	▨	▨	▨	**M2.1**													
Task 2.2											▨	▨	▨	**M2.2**										
Task 2.3																					▨	▨	▨	**M2.3**
WP3														▨	▨	▨	▨	▨	▨	▨	**D3.1**			
Task 3.1														▨	▨	▨	**M3.1**							
Task 3.2																▨	▨	▨	**M3.2**					
Task 3.3																			▨	▨	**M3.3**			
WP4	▨	▨	▨	▨	▨	**D4.1**	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	**D4.1**	▨	▨	▨	▨	▨	▨
WP5	▨	▨	**D5.1**	▨	**D5.2**	▨	▨	▨	▨	▨	▨	▨	▨	▨	**D5.1**	▨	▨	**D5.2**	▨	▨	▨	▨	▨	▨
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

Prof. Brandenburg will provide overall scientific supervision and integration of tasks. His direct contributions include training in turbulence, dynamos, and MHD simulations (WP1, 0.5 person-month); multi-fluid modelling relevant to SF/SC in NS cores (WP2, 0.5 person-month); HPC optimization and parallelization with the Pencil Code (WP3, 0.5 person-month); and guidance on manuscript preparation and co-authorship (WP4, 0.5 person-month). Complementary training will be provided by the host group at Nordita: Dr. Frederick Gent (and Dr. Rheinhardt) on advanced HPC techniques (WP3, 1.0 person-month); Dr. Igor Rogachevskii on the CME in PNS (WP1, 0.5 person-month); and Prof. Chris Pethick on dense-matter microphysics, including SF/SC in NS cores (WP2, 0.5 person-month). Nordita will support WP4–5 through its administrative and dissemination infrastructure.

Regular **risk management** and **reassessment**, based on the principles below, will be a key topic in group meetings.

Description of risk	**Likelihood; severity**	**WP**	**Proposed mitigation measures**
Obstacles in understanding the origin of net magnetic helicity	Medium, medium	1	If net helicity is small, shift focus to long-lived NSs where CME effects might remain testable
Challenges in simulating SC/SF	High; medium	2	Use a 3D velocity assumption if self-consistent fails
Interoperability limitations	Medium; low	3	Optimise shared operators between the two codes
Training outcomes below expectations	Low, medium	4	Career Development Plan (CDP, deliverable 4.1)
Results deviating from predictions	Medium; medium	1-3	PDEC (WP5, deliverable 5.1)

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

3.2.1 Hosting arrangements: Nordita, jointly operated by KTH Royal Institute of Technology and Stockholm University, has a strong record of supporting and training researchers (Sec. 5). It provides cutting-edge infrastructure, hosts ERC and MSCA projects, and runs high-level programs, workshops, and long-term visitor activities across theoretical physics. Excellent working conditions are ensured through Work Environment and Equality, Diversity and Inclusion committees. Researchers benefit from administrative support (relocation, visa, housing) and access to powerful computational facilities via the PDC Center for High Performance Computing and the National Academic Infrastructure for Supercomputing in Sweden (NAISS). With leading expertise in fluid dynamics and astrophysics, the host group led by Prof. Brandenburg is internationally recognized in turbulence and dynamo theory. The researcher will join a collaborative environment with weekly seminars and group meetings, receiving guidance and access to Prof. Brandenburg's international network for career development.

3.2.2 Quality and capacity of the participating organizations: Nordita is internationally recognized for excellence in theoretical physics, with a strong track record in MSCA and ERC awards, reflecting both scientific strength and institutional support. Its reputation is further underscored by associations with Nobel laureates such as Frank Wilczek and Ben R. Mottelson. ***Supervisor and group:*** Prof. Brandenburg is a leading authority in astrophysical fluid dynamics, with seminal work on dynamos and magnetic helicity directly aligned with this project (Sec. 1.3). He leads an active, interdisciplinary team spanning astrophysical turbulence, stellar and early-Universe dynamics, and high-energy astrophysics. Frequent visits by experts such as Igor Rogachevskii (CME) further enrich the environment. ***Computational capacity:*** A major asset is the Pencil Code community, coordinated by Prof. Brandenburg with collaborators, providing expertise that maps directly onto WP1 and WP3. Nordita provides access to the PDC Dardel supercomputer (HPE Cray EX; CPU/GPU; 1,278 nodes, 163,584 cores), ensuring capacity for SoTA simulations. This environment provides advanced training, top-tier computing, and an interdisciplinary, collaborative setting—ideal conditions for delivering the proposed work.

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