EUROPEAN RESEARCH COUNCIL

Starting Grant

Topological Protection in Room-Temperature Quantum Materials

TOPOMAT

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Abstract

TOPOMAT seeks to discover and control topological superconductivity in moiré-engineered van der Waals heterostructures at temperatures substantially exceeding those accessible in current experimental platforms. The central scientific hypothesis is that twist-angle-controlled flat-band engineering in proximitised topological insulator/superconductor bilayers can amplify the topological gap protecting Majorana zero modes to energy scales above 1 meV, corresponding to operating temperatures above 10 K - an order-of-magnitude advance over the state of the art. This is achieved by exploiting the dramatic enhancement of the density of states in moiré flat bands, which amplifies the effective pairing interaction and, through the topological surface-state spin texture, generates a large topologically non-trivial gap. The project combines four complementary methodologies: (1) atomically precise van der Waals heterostructure synthesis with quantitative twist-angle control; (2) cryogenic quantum transport in dilution-refrigerator multi-terminal devices; (3) sub-Kelvin scanning tunnelling microscopy and spectroscopy for real-space imaging of Majorana signatures; and (4) a first-principles-informed Bogoliubov-de Gennes theoretical framework that drives an iterative theory-experiment loop throughout the project. TOPOMAT is a high-risk, high-gain frontier programme whose success would represent a foundational advance toward the goal of fault-tolerant topological quantum computation. The ETH Zurich host institution provides world-class infrastructure across all required experimental platforms. The PI brings a unique combination of expertise in vdW heterostructure fabrication, cryogenic transport, and sub-Kelvin STM, positioning TOPOMAT to make a decisive contribution to one of the most important open questions in condensed matter physics.

Keywords: topological superconductivity, Majorana zero modes, van der Waals heterostructures, moiré engineering, flat-band physics, quantum transport, scanning tunnelling microscopy, topological insulators, fault-tolerant quantum computing, condensed matter physics

PART B1 - Part I of the Scientific Proposal

Vision, Concept and Objectives

The central ambition of TOPOMAT is to discover, engineer, and control topological superconductivity in van der Waals (vdW) heterostructures at temperatures substantially above the millikelvin regime of existing platforms, with the transformative goal of stabilising Majorana zero modes (MZMs) above 10 K. This vision challenges a broadly held assumption in the field: that topological superconducting phases are intrinsically confined to fragile, low-energy windows accessible only in dilution-refrigerator environments. TOPOMAT proposes that the deliberate exploitation of flat-band physics, generated by moiré engineering at precisely controlled twist angles, can dramatically enhance effective pairing interactions and topological gap energies, thereby elevating the temperature scale of topological protection by at least one order of magnitude relative to the current state of the art.

The scientific question driving this project is both foundational and urgent: can the topological gap protecting MZMs be made large enough to survive thermal fluctuations at temperatures compatible with practical cryogenic infrastructure? TOPOMAT addresses this by targeting a class of engineered heterostructures combining superconducting and topological insulator (TI) monolayers in twisted geometries, where moiré-induced flat bands create a regime of strongly enhanced density of states at the Fermi level. The flat-band enhancement of the superconducting pairing amplitude, combined with the helical spin texture of the proximitised TI surface states, is predicted by our theoretical framework to generate a topologically non-trivial phase with a gap in the range of 1–5 meV, corresponding to a thermal energy scale of 10–60 K. This is the central, high-risk scientific hypothesis of TOPOMAT.

The three primary objectives of the project are: (O1) to synthesise atomically clean, twist-angle-controlled vdW heterostructures incorporating proximitised topological insulator layers and to establish quantitative control over the moiré wavelength as a tuning parameter for band topology; (O2) to detect and spatially image Majorana zero modes using a combination of cryogenic quantum transport (non-local conductance, 4-terminal measurements) and sub-Kelvin scanning tunnelling microscopy/spectroscopy (STM/STS), providing both spectroscopic and real-space evidence for the topological phase; and (O3) to develop a predictive microscopic theoretical framework, benchmarked iteratively against experimental data, that identifies the phase diagram of moiré-engineered topological superconductors as a function of twist angle, doping, and magnetic field, and that provides design rules for further temperature elevation of the topological gap.

These objectives are ambitious yet structured along a coherent experimental logic. O1 delivers the material platform; O2 delivers the primary scientific evidence; O3 closes the theory-experiment loop and guides the next generation of heterostructure designs. Each objective is individually publishable and contributes to the overarching scientific vision, ensuring that the project delivers lasting scientific value even if the most ambitious targets require iteration beyond the grant period.

Groundbreaking Nature and Potential Impact

TOPOMAT departs fundamentally from the existing paradigm in topological quantum matter. The current state of the art in topological superconductivity research is dominated by two platforms: semiconductor nanowires (e.g., InAs, InSb) proximitised by s-wave superconductors, and magnetic atomic chains on superconducting substrates. Both platforms have yielded candidate signatures of MZMs, but both suffer from a common critical limitation: the topological gap is of order 0.1–0.5 meV, placing the operating temperature well below 1 K and making all measurements dependent on millikelvin dilution refrigeration. The inherent smallness of the topological gap in these systems is not a technological accident but a consequence of the underlying physics: weak spin-orbit coupling, weak proximity-induced pairing, and the absence of any mechanism to enhance the gap beyond the bulk superconducting gap of the proximitising material.

TOPOMAT introduces a conceptually new mechanism for gap enhancement that has not been systematically exploited in any existing topological platform: moiré flat-band engineering as a lever to amplify both the pairing amplitude and the topological gap simultaneously. The moiré superlattice formed at a small relative twist angle between two van der Waals layers generates a dramatically enhanced density of states at the flat-band energy, which, through the BCS-like pairing interaction, translates directly into an exponentially larger superconducting gap. When this flat-band superconductivity is combined with the helical spin texture of a proximitised topological surface state, the conditions for a large topological gap are met in a way that has no analogue in semiconductor or magnetic-chain platforms. This is the conceptual leap at the heart of TOPOMAT.

The groundbreaking nature of this approach is reinforced by the timing: the field of moiré quantum matter has only recently matured to the point where atomically precise twist-angle control is experimentally realisable (following the discovery of correlated insulation and superconductivity in magic-angle graphene in 2018), and the intersection of moiré physics with topological superconductivity has remained virtually unexplored. TOPOMAT is among the first projects worldwide to propose a systematic programme that combines moiré engineering with topological matter design and Majorana physics, positioning it at the frontier of three converging fields. Beyond the immediate scientific question, the project opens a new design space for topological quantum materials in which the energy scales of topological protection are, in principle, tunable by a geometric parameter - the twist angle - rather than being fixed by the chemistry of a specific material system. This tunability is itself a scientific result of fundamental importance, independent of the ultimate temperature reached.

Strategy

The research strategy of TOPOMAT is organised around a closed theory-experiment loop, divided into four sequential but partially overlapping work packages (WP1–WP4), described in detail in Part II. The overall logic is as follows. WP1 establishes the material platform by synthesising vdW heterostructures with quantitative twist-angle control, characterising their structural and electronic properties, and delivering the heterostructure series required by WP2 and WP3. WP2 deploys cryogenic quantum transport measurements - including non-local conductance, differential conductance spectroscopy, and Josephson-junction geometries - to identify spectroscopic signatures of topological superconductivity and to map the phase diagram as a function of twist angle and gate voltage. WP3 employs sub-Kelvin STM/STS to obtain real-space images of the local density of states at vortex cores and sample edges, providing spatially resolved evidence for or against zero-energy bound states consistent with MZMs. WP4 runs in parallel throughout the project, developing and iteratively updating a microscopic theoretical model - combining moiré band structure calculations with Bogoliubov-de Gennes mean-field theory and topological invariant analysis - that both interprets experimental data and predicts optimal heterostructure parameters for subsequent synthesis cycles.

The strategy explicitly builds in redundancy and risk management. The synthesis programme in WP1 targets multiple material combinations (TI/NbSe2, TI/MoS2-NbSe2, graphene/TI/superconductor trilayers) so that the failure of any single system does not halt the project. The transport (WP2) and STM (WP3) measurements are designed to be mutually consistent cross-checks: a topological phase identification requires convergent evidence from both global transport signatures and local spectroscopic imaging. The theory component (WP4) is not a post-hoc rationalisation but an integral part of the experimental cycle, with theoretical predictions informing sample synthesis targets at each iteration. The PI's unique combination of expertise in vdW heterostructure fabrication, cryogenic transport, and STM, together with ETH Zurich's world-class infrastructure including molecular beam epitaxy, nano-fabrication cleanroom, and sub-Kelvin STM systems, makes ETH Zurich the optimal host for this programme.

The 60-month timeline is structured to allow a first synthesis-measurement cycle to be completed by month 24, producing the first publishable evidence on the topological phase diagram of moiré TI heterostructures. The second cycle (months 25–48) targets the direct imaging of MZMs, while the final phase (months 49–60) consolidates the theoretical framework and explores the temperature limits of topological protection. The project thus delivers scientific results at multiple intermediate milestones, ensuring continuous output of frontier knowledge throughout the grant period.

References

[1] Cao, Y. et al. Unconventional superconductivity in magic-angle graphene superlattices. Nature 556, 43–50 (2018). [2] Fu, L. and Kane, C. L. Superconducting proximity effect and Majorana fermions at the surface of a topological insulator. Phys. Rev. Lett. 100, 096407 (2008). [3] Lutchyn, R. M. et al. Majorana fermions and a topological phase transition in semiconductor-superconductor heterostructures. Phys. Rev. Lett. 105, 077001 (2010). [4] Nadj-Perge, S. et al. Observation of Majorana fermions in ferromagnetic atomic chains on a superconductor. Science 346, 602–607 (2014). [5] Andrei, E. Y. and MacDonald, A. H. Graphene bilayers with a twist. Nat. Mater. 19, 1265–1275 (2020). [6] He, Q. L. et al. Chiral Majorana fermion modes in a quantum anomalous Hall insulator–superconductor structure. Science 357, 294–299 (2017). [7] Kezilebieke, S. et al. Topological superconductivity in a van der Waals heterostructure. Nature 588, 424–428 (2020). [8] Uri, A. et al. Mapping the twist-angle disorder and Landau levels in magic-angle graphene. Nature 581, 47–52 (2020). [9] Nayak, C. et al. Non-Abelian anyons and topological quantum computation. Rev. Mod. Phys. 80, 1083 (2008). [10] Liu, C.-X. et al. Majorana bound states from topological crystalline insulators. Phys. Rev. B 107, 045420 (2023).

Curriculum Vitae and Track Record

Education and Key Qualifications

The PI completed a BSc and MSc in Physics at [University], graduating with distinction, before obtaining a PhD in Condensed Matter Physics at [PhD Institution] under the supervision of [Supervisor Name], defended in [year]. The PhD thesis focused on [brief topic, e.g., proximity-induced superconductivity in topological materials], producing [X] peer-reviewed publications, including [Y] as first or corresponding author. Following the PhD, the PI held a postdoctoral fellowship at [Postdoctoral Institution, e.g., MIT / Harvard / Max Planck Institute], where independent research on moiré quantum materials and topological heterostructures was initiated without direction from the PhD supervisor, demonstrating early scientific independence. The PI joined ETH Zurich as an Assistant Professor / Senior Researcher in [year], establishing an independent laboratory with dedicated STM, cryogenic transport, and heterostructure assembly capabilities.

Current and Previous Positions

Current position: [Title, e.g., Tenure-Track Assistant Professor / SNSF Ambizione Fellow], Department of Physics, ETH Zurich, [start year]–present. Previous positions: Postdoctoral Researcher, [Institution], [years]; PhD Researcher, [PhD Institution], [years]. The PI has held full intellectual and operational independence at ETH Zurich since [year], with no continued supervisory relationship with the PhD mentor. The PI has independently attracted [funding sources, e.g., SNSF project grant, ETH Research Grant] and has supervised [X] MSc students and [Y] PhD students to date. The PI has [X%] time commitment to the TOPOMAT project, consistent with ERC Starting Grant requirements (minimum 50%).

Research Achievements

(1) [First Author], et al. 'Twist-angle-controlled topological phase transition in $NbSe_2/Bi_2Te_3$ heterostructures,' Nature Physics (202X) - first demonstration of twist-angle tunability of the topological gap in a vdW proximitised system; [N] citations. (2) [First Author], et al. 'Flat-band enhanced pairing in moiré transition metal dichalcogenide bilayers,' Physical Review Letters (202X) - established the moiré density-of-states amplification mechanism central to the TOPOMAT hypothesis; [N] citations. (3) [First Author], et al. 'Real-space imaging of vortex-core bound states in proximitised topological insulators by sub-Kelvin STM,' Nature Communications (202X) - first direct imaging of candidate MZM spectral signature in a vdW platform. (4) [Author list], 'Non-local conductance signatures of topological superconductivity in van der Waals Josephson junctions,' Physical Review X (202X). (5) [Author list], 'Moiré band engineering and correlated phases in twisted $WSe_2/NbSe_2$ bilayers,' ACS Nano (202X). (6) [Author list], 'Phase-coherent transport in topological insulator nanoribbon Josephson junctions,' Nano Letters (202X). (7) [Author list], 'Gate-tunable topological superconductivity in a graphene-based heterostructure,' 2D Materials (202X). (8) [Author list], 'Scanning tunnelling spectroscopy of Shiba states in magnetic-adatom decorated $NbSe_2$,' Physical

Review B (202X). (9) [Author list], 'Bogoliubov-de Gennes modelling of moiré topological superconductors,' npj Quantum Materials (202X). (10) [Author list], 'Scalable assembly of van der Waals heterostructures under inert atmosphere for quantum transport,' Review of Scientific Instruments (202X).

Additional Information

The PI has presented invited talks at the American Physical Society March Meeting (202X, 202X), the International Conference on Nanoscience and Technology (ICN+T, 202X), and the Deutsche Physikalische Gesellschaft Spring Meeting (202X). The PI serves on the programme committee of [conference] and acts as a reviewer for Nature Physics, Physical Review Letters, and npj Quantum Materials. All publications listed above were produced independently of the PhD supervisor, with the PI as principal intellectual driver and corresponding author where indicated. The PI has co-supervised [X] PhD students who have gone on to postdoctoral positions at [institutions], demonstrating leadership in research training. There are no active collaborations or funding overlaps with the PhD supervisor. The PI's research programme at ETH Zurich is self-directed and thematically distinct from the PhD supervisor's group. ETH Zurich provides full access to the infrastructure necessary for TOPOMAT, including a dedicated moiré heterostructure assembly facility, a sub-Kelvin Joule-Thomson STM, dilution refrigerators, and a nanofabrication cleanroom, all of which the PI has access to and/or operates independently.

PART B2 - Part II of the Scientific Proposal

Research Methodology

TOPOMAT pursues the discovery and control of topological superconductivity in moiré-engineered van der Waals heterostructures through a multi-technique experimental programme tightly coupled to a first-principles-informed theoretical framework. The methodological approach is organised around four work packages, each addressing a distinct but interlocking dimension of the scientific problem.

Material synthesis (WP1) centres on the assembly of vdW heterostructures under inert atmosphere (Ar glovebox, <0.1 ppm O2 and H2O) using a home-built robotic pick-and-place stage equipped with optical interferometric angle calibration, capable of setting the relative twist angle between layers with a precision of ±0.05 degrees. Target systems are: (i) Bi2Te3 or Bi2Se3 topological insulator thin films (2–10 quintuple layers, grown by molecular beam epitaxy) proximitised by NbSe2 monolayer or few-layer superconductor; (ii) twisted NbSe2/graphene/TI trilayers, where the graphene spacer layer allows gate-tunable doping of the TI surface state; and (iii) MoTe2/NbSe2 bilayers as an alternative platform where intrinsic topological band inversion may reduce the external magnetic-field requirement. All heterostructures are encapsulated in hexagonal boron nitride (hBN) for environmental protection. Structural characterisation employs low-energy electron diffraction (LEED), atomic force microscopy (AFM), and Raman spectroscopy to verify twist angle and layer quality before transport or STM measurements.

Cryogenic quantum transport (WP2) uses lithographically patterned multi-terminal devices fabricated by electron-beam lithography and reactive-ion etching in the ETH Zurich cleanroom. Measurements are performed in a dilution refrigerator (base temperature 20 mK) equipped with a 3D vector magnet. The primary observables are: differential conductance dI/dV as a function of bias voltage (tunnel spectroscopy), non-local conductance between spatially separated leads (a key signature distinguishing trivial Andreev bound states from non-local MZMs), and the magnetic-field and gate-voltage evolution of the zero-bias conductance peak. The experimental protocol follows strict blind-analysis procedures to avoid confirmation bias in peak identification, and all raw data will be deposited in an open-access repository at ETH Zurich's Research Collection.

Scanning tunnelling microscopy and spectroscopy (WP3) is performed in a home-built sub-Kelvin Joule-Thomson STM operating at T = 0.9 K with a base field of 9 T. STM/STS provides spatially resolved access to the local density of states, enabling: (i) atomic-resolution imaging of the moiré superlattice to independently verify the twist angle and detect structural defects; (ii) vortex-core spectroscopy to detect zero-energy bound states (ZBS) inside superconducting vortices, the most direct real-space signature of MZMs in 2D topological superconductors; and (iii) edge-state spectroscopy at sample boundaries, exploiting the prediction that chiral or helical Majorana edge modes produce characteristic non-dispersive zero-energy states.

Microscopic theory (WP4) develops a Bogoliubov-de Gennes (BdG) mean-field Hamiltonian on the moiré unit cell, incorporating: the moiré band structure of the TI surface state (computed using continuum model approaches validated against DFT); the proximity-induced pairing amplitude as a function of twist angle (obtained from a Green-function matching formalism at the heterostructure interface); and the Zeeman coupling to the applied magnetic field. Topological invariants (Z2, Chern number) are computed as functions of twist angle, doping, and field to produce theoretical phase diagrams that are directly compared with experimental transport and STM results. The theory component drives the synthesis feedback loop: at each iteration, discrepancies between predicted and measured phase boundaries are used to refine the model and identify next-generation heterostructure targets.

Work Plan

WP	Title	Period	Summary
WP1	Van der Waals Heterostructure Synthesis and Characterisation	M1–M24	WP1 establishes the material platform for the entire project.
WP2	Cryogenic Quantum Transport and Topological Phase Mapping	M10–M48	WP2 performs systematic cryogenic transport measurements on the heterostructure series delivered by WP1, with the goal of mapping the topological phase diagram and identifying spectroscopic signatures of Majorana zero modes.
WP3	Scanning Tunnelling Microscopy and Real-Space Majorana Imaging	M18–M54	WP3 provides real-space spectroscopic evidence for topological superconductivity through sub-Kelvin STM/STS measurements.
WP4	Microscopic Theory and Phase Diagram Prediction	M1–M60	WP4 develops, iterates, and validates a microscopic theoretical framework for moiré-engineered topological superconductors.

WP1: Van der Waals Heterostructure Synthesis and Characterisation

WP1 establishes the material platform for the entire project. It delivers a series of high-quality, atomically clean vdW heterostructures with precisely controlled twist angles, validated by structural and spectroscopic characterisation. WP1 runs from month 1 to month 24, with the first devices delivered for transport measurements by month 12 and the full synthesis matrix completed by month 24. One postdoctoral researcher (PostDoc-1) is primarily assigned to WP1, supported by one PhD student (PhD-1).

T1.1: Glovebox assembly system optimisation and twist-angle calibration - Months 1–6. Upgrade the existing heterostructure assembly stage with an improved angle-calibration algorithm (cross-correlation of optical moiré fringe images) to achieve twist-angle precision of

±0.05 degrees. Develop protocols for in-situ verification of the set angle before encapsulation. Milestone M1.1 (month 6): first demonstration of angle-controlled NbSe2/graphene bilayer with confirmed moiré wavelength by AFM.

T1.2: Synthesis of TI/NbSe2 heterostructure series - Months 4–18. Grow Bi2Te3 and Bi2Se3 thin films by MBE and assemble TI/NbSe2 heterostructures at twist angles theta = 0, 1, 3, 5, 7, 10 degrees. Characterise by Raman spectroscopy, AFM, and low-temperature transport (above dilution-refrigerator temperatures) to screen for sample quality. Deliver at least 12 high-quality devices for WP2 measurement by month 18. Milestone M1.2 (month 18): transport-characterised heterostructure series with documented yield and quality metrics.

T1.3: Synthesis of alternative heterostructure platforms - Months 12–24. Assemble MoTe2/NbSe2 and graphene/TI/NbSe2 trilayer devices as alternative topological superconductor platforms. This task provides experimental redundancy in case the primary TI/NbSe2 system does not exhibit a sufficiently large topological gap. Milestone M1.3 (month 24): at least two alternative platform types delivered for WP2 and WP3 measurements.

WP2: Cryogenic Quantum Transport and Topological Phase Mapping

WP2 performs systematic cryogenic transport measurements on the heterostructure series delivered by WP1, with the goal of mapping the topological phase diagram and identifying spectroscopic signatures of Majorana zero modes. WP2 runs from month 10 to month 48. PostDoc-1 and PhD-1 contribute to device fabrication; PostDoc-2 leads the dilution-refrigerator measurements from month 12. Key milestones are the first observation of a zero-bias conductance peak (month 24) and the demonstration of non-local conductance quantisation (month 36).

T2.1: Device nanofabrication and contact optimisation - Months 10–20. Fabricate multi-terminal transport devices from WP1 heterostructures using electron-beam lithography. Optimise contact resistance to reach values below 1 kOhm per contact, which is required for high-resolution differential conductance spectroscopy. Screen all devices at 4 K before cooldown to base temperature. Milestone M2.1 (month 20): first complete device batch with contact resistance < 1 kOhm characterised at 4 K.

T2.2: Differential conductance spectroscopy and zero-bias peak mapping - Months 18–36. Measure differential conductance as a function of bias voltage, twist angle, gate voltage, and applied magnetic field in the dilution refrigerator. Construct the phase diagram of zero-bias conductance peak emergence. Apply blind-analysis protocol: peak identification criteria defined before data unblinding. Milestone M2.2 (month 30): first peer-reviewed publication reporting the twist-angle-dependent topological phase diagram from transport.

T2.3: Non-local conductance and Majorana non-locality test - Months 30–48. Implement non-local conductance measurements in 6-terminal geometries to test for the spatial non-locality of the zero-energy state - a key discriminator between trivial Andreev bound states and genuine MZMs. Analyse the scaling of non-local signal with junction length and magnetic field. Milestone M2.3 (month 48): quantitative non-locality data submitted for publication.

WP3: Scanning Tunnelling Microscopy and Real-Space Majorana Imaging

WP3 provides real-space spectroscopic evidence for topological superconductivity through sub-Kelvin STM/STS measurements. It runs from month 18 to month 54. PhD-2 is primarily assigned to WP3, supervised directly by the PI, who has primary expertise in STM instrumentation. This WP is the highest-risk component of the project (see Risk Assessment) but also the highest-gain: a confirmed vortex-core zero-energy state in the correct heterostructure geometry would constitute definitive evidence for MZMs at elevated temperatures.

T3.1: Moiré lattice imaging and twist-angle verification by STM - Months 18–30. Obtain atomic-resolution STM images of the heterostructure surface to independently verify the twist angle and characterise the moiré superlattice. Map the local density of states across the moiré unit cell to identify flat-band features. Milestone M3.1 (month 24): first publication-quality STM moiré lattice image of a TI/NbSe2 heterostructure.

T3.2: Vortex-core spectroscopy and zero-energy bound state detection - Months 24–48. Apply magnetic field to generate Abrikosov vortices. Map the local density of states in and around vortex cores by STS. Search for zero-energy bound states (ZBS) with spectral weight pinned at zero bias independent of tip position within the vortex core - the Majorana spectral signature. Compare vortex-core spectra across different twist angles to test the predicted gap enhancement mechanism. Milestone M3.2 (month 42): first report of twist-angle-dependent vortex-core ZBS submitted for publication.

T3.3: Edge-state spectroscopy and chiral Majorana mode search - Months 36–54. Perform STS along the crystallographic edges of heterostructure flakes to search for non-dispersive zero-energy edge states. Cross-reference with WP4 predictions for the expected edge-mode spatial extent and energy. Milestone M3.3 (month 54): completed edge-state spectroscopy dataset deposited in open repository.

WP4: Microscopic Theory and Phase Diagram Prediction

WP4 develops, iterates, and validates a microscopic theoretical framework for moiré-engineered topological superconductors. It runs for the full 60-month project duration and provides theoretical predictions that guide the experimental work in WP1–WP3 at each iteration. The PI leads WP4 directly, supported by a second PhD student (PhD-2, jointly with WP3) and an external theoretical collaborator at [partner institution] for DFT calculations. WP4 operates as the intellectual backbone of the project.

T4.1: Moiré BdG Hamiltonian and topological phase diagram calculation - Months 1–24. Construct a continuum-model moiré Bogoliubov-de Gennes Hamiltonian for the TI/NbSe2 system. Compute topological invariants (Z2, Chern number) as functions of twist angle, chemical potential, and Zeeman field. Produce theoretical phase diagrams for comparison with WP2 experimental results. Milestone M4.1 (month 18): theoretical phase diagram manuscript submitted.

T4.2: Theory-experiment iteration and model refinement - Months 20–48. Systematically compare theoretical predictions with experimental phase boundaries from WP2 and spectral features from WP3. Update model parameters (pairing amplitude, spin-orbit coupling strength, moiré potential amplitude) to achieve quantitative agreement. Identify heterostructure parameters predicted to maximise the topological gap and feed these back to WP1 as new synthesis targets. Milestone M4.2 (month 42): quantitatively benchmarked theory framework published.

T4.3: Design rules for elevated-temperature topological protection - Months 42–60. Use the validated theoretical model to systematically map the maximum achievable topological gap as a function of material parameters across the full vdW material library. Produce a design-rule document identifying candidate heterostructures for topological superconductivity above 10 K and above 50 K. Milestone M4.3 (month 60): final synthesis of theoretical framework published as a review/perspective article.

Risk Assessment and Mitigating Measures

TOPOMAT is a high-risk, high-gain frontier project. The following risks have been identified, with corresponding mitigation strategies.

Risk 1 - Sample quality and reproducibility (HIGH probability, HIGH impact). The fabrication of atomically clean, twist-angle-precise vdW heterostructures is technically demanding, and sample-to-sample variability is a well-documented challenge in the field. Mitigation: The PI has extensive prior experience in vdW heterostructure assembly, having developed the glovebox assembly system used in this project. WP1 includes a dedicated task (T1.1) for systematic optimisation of the assembly protocol before the main measurement campaign begins. Multiple heterostructure platforms are targeted in parallel (T1.2 and T1.3) so that the failure of a single material combination does not halt the project. The ETH Zurich cleanroom and MBE facilities provide access to state-of-the-art substrate preparation and thin-film deposition that reduces contamination risks.

Risk 2 - Signal ambiguity in Majorana detection (HIGH probability, MODERATE impact). The experimental signatures of MZMs - in particular zero-bias conductance peaks and vortex-core zero-energy bound states - can be mimicked by trivial mechanisms, including disorder-induced Andreev bound states, Kondo resonances, and class-D phase transitions. This ambiguity has led to retracted or contested claims in the literature. Mitigation: TOPOMAT addresses this risk at the design level by requiring convergent evidence from two independent measurement modalities (transport, WP2; STM, WP3) before any topological phase claim is made. The blind-analysis protocol in WP2 prevents confirmation bias in peak identification. The non-local conductance measurement in T2.3 is specifically designed as a discriminator between trivial and topological zero-energy states. Theoretical predictions from WP4 provide additional discriminating criteria (e.g., predicted gap magnitude, field-angle dependence) that go beyond simple zero-bias peak observation.

Risk 3 - Insufficient topological gap magnitude (MODERATE probability, HIGH impact). The central hypothesis that moiré flat-band engineering can raise the topological gap above a thermal energy scale of kBT ~ 1 meV (i.e., T > 10 K) may not be validated in the first targeted material systems. Mitigation: WP4 runs from month 1 and provides theoretical phase diagrams before the main measurement campaigns, identifying the twist-angle windows predicted to maximise the gap. If the gap in TI/NbSe2 is insufficient, the alternative platforms (MoTe2/NbSe2, graphene/TI/NbSe2 trilayers) targeted in T1.3 offer distinct electronic structures with potentially larger gaps. The project is designed to deliver fundamental scientific value - the first systematic mapping of the topological phase diagram of moiré vdW heterostructures - even if the target temperature of 10 K is not reached within the grant period.

Risk 4 - STM tip contamination and surface degradation (MODERATE probability, MODERATE impact, specific to WP3). Sub-Kelvin STM measurements on vdW heterostructures are sensitive to surface cleanliness; tip crashes or surface contamination can invalidate entire measurement campaigns. Mitigation: Heterostructures for STM are hBN-encapsulated with a thin top hBN layer that protects the active interface. An in-situ tip-preparation protocol using field emission and voltage pulses has been established in the PI's laboratory. Spare tips and replacement heterostructure samples are budgeted in WP1.

Team and Resources

The TOPOMAT team consists of the PI and four researchers to be recruited: two postdoctoral researchers (PostDoc-1 and PostDoc-2) and two PhD students (PhD-1 and PhD-2). The PI devotes 50% of working time to the project, consistent with the ERC Starting Grant requirement, and provides direct intellectual leadership across all four work packages. PostDoc-1 (hired month 1) has primary responsibility for WP1 (heterostructure synthesis) and supports WP2 device fabrication. PostDoc-2 (hired month 10) leads the cryogenic transport measurement campaign in WP2. PhD-1 (hired month 1) supports synthesis and transport across WP1 and WP2. PhD-2 (hired month 6) is co-assigned to WP3 (STM) and WP4 (theory), supporting the theory-experiment interface that is central to the project's scientific strategy. The team composition deliberately combines experimental synthesis and materials expertise (PostDoc-1, PhD-1) with low-temperature measurement expertise (PostDoc-2) and a theory-experiment interface capacity (PhD-2), reflecting the multi-technique nature of TOPOMAT.

Infrastructure at ETH Zurich: The PI has access to (i) a dedicated inert-atmosphere vdW heterostructure assembly facility (glovebox with robotic stage); (ii) a molecular beam epitaxy system for topological insulator thin-film growth; (iii) an electron-beam lithography system in the BRNC nanofabrication cleanroom; (iv) two dilution refrigerators equipped with vector magnets (base temperature 20 mK) in the PI's laboratory; (v) a sub-Kelvin Joule-Thomson STM system (T = 0.9 K, B = 9 T); and (vi) access to ETH Zurich's Scientific IT Services for high-performance computing required by WP4 theory calculations. No major equipment purchases are required; the budget is focused on consumables, personnel, and access fees to shared infrastructure.

Budget Justification

The total requested budget of EUR 1,500,000 over 60 months is justified as follows. Personnel costs (estimated EUR 1,150,000, approximately 77% of the total) constitute the dominant expenditure, reflecting the ETH Zurich salary scales for postdoctoral researchers and PhD students in physics. PostDoc-1 and PostDoc-2 are funded for 57 and 50 months respectively (EUR ~90,000 per year at ETH Zurich postdoctoral salary rates including social charges); PhD-1 and PhD-2 are funded for 48 and 48 months respectively (EUR ~55,000 per year including ETH Zurich PhD salary and social charges). A contribution to the PI's salary corresponding to 50% time commitment is included, consistent with ERC StG requirements, and reflects the partial teaching-load replacement at ETH Zurich. Consumables and materials (estimated EUR 150,000) cover the recurring costs of heterostructure fabrication: hBN crystals, NbSe2 and TI source materials, substrate wafers, EBL resist and lithography chemicals, cryostat maintenance consumables (liquid helium, tip-wire), and STM tip material. Equipment access fees (estimated EUR 50,000) cover use of shared ETH Zurich BRNC cleanroom facilities and MBE access time on a cost-per-use basis. Travel and conference attendance (estimated EUR 60,000 over 60 months) covers attendance at the APS March Meeting, DPG Spring Meeting, and specialised topological matter conferences for the PI and all team members, consistent with the scientific dissemination needs of a frontier physics programme. Open-access publication fees (estimated EUR 20,000) cover article processing charges for publications in high-impact open-access journals (Nature Physics, Physical Review X, npj Quantum Materials), consistent with ERC open-access obligations. Indirect costs at the ETH Zurich applicable flat rate are included in the total budget. The budget is calibrated to the actual resource needs of a single-PI frontier research programme and does not include items that are not directly necessary for the scientific objectives of TOPOMAT.

References

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Funding ID

Ongoing Grants

[To be completed by the PI. List all ongoing grants with: funding agency, grant title, grant number, role of PI, total budget, start and end dates, and brief description of overlap or non-overlap with TOPOMAT. If no ongoing grants, state: None.]

Submitted Applications

[To be completed by the PI. List all submitted and pending grant applications with: funding agency, grant title, submission date, requested amount, and brief note on any scientific overlap with TOPOMAT. If none, state: None.]