1.-Applicant.

Dr. Samuel Mañas-Valero (S.ManasValero@tudelft.nl), Marie Curie fellow at Dept. Quantum Nanoscience (QN), Kavli Institute of Nanoscience Delft (KIND) (van der Sar group).

Most recent significant achievements of the applicant relevant to the proposal:

- First example of artificial two-dimensional (2D) magnets obtained by twisting 90 degrees two CrSBr ferromagnetic monolayers (corresponding author in *Nat. Mater. 23, 212, 2024*; featured as News&Views in *Nat. Mater. 23, 174, 2024*), highlighting the emergence of hysteresis – absent in the untwisted layers – and impact in memory storage and spintronics.
- Construction of a single-spin scanning microscope based on diamond magnetometry and successfully imaging of spin waves in a room-temperature magnet as permalloy (**Fig. 1**).

2.- Title of the project

Twist-control of spin waves in two-dimensional magnets. The project is scheduled to start on June 1st, 2025.

3.- Kavli host groups.

- Dr. Toeno van der Sar (https://vandersarlab.tudelft.nl). Dept. of QN, KIND.
- Dr. Sonia Conesa-Boj (https://conesabojlab.tudelft.nl). Dept of QN, KIND.

4.- Abstract.

The twist angle in 2D crystals allows engineering material properties through Moiré superlattices, giving rise to phenomena such as superconductivity in twisted bilayer graphene. In 2D magnetic systems, twisting has mainly been used to tailor spin-reversal mechanisms. Theoretical predictions suggest that spin waves – collective excitations in magnets essential for energy-efficient information technologies – can also be controlled by the twist angle, but this remains experimentally unexplored. This project addresses this gap by combining complementary expertise: twisted 2D magnets fabrication (applicant's expertise), diamond-based imaging of spin waves (van der Sar's expertise), and transmission electron microscopy to correlate the spin wave transport with the underlying Moiré superlattice (Conesa-Boj's expertise). This synergetic approach aims to establish a new paradigm for tailoring spin waves via twist control, with potential applications in spintronics, magnonics or quantum technologies.

5.- Description of the proposed research.

Background/state of the art and motivation for the research:

The twist angle between 2D crystals plays a key role in defining their properties, exemplified by the emergence of superconductivity and strongly correlated phases in twisted bilayer graphene *[Nature 556, 43, 2018; Nature 556, 80, 2018]*. This has led to the development of *'twistronics'*, a field focused on controlling material properties by creating Moiré superlattices, which are periodic structures formed by overlapping two lattices with a different rotation or lattice constant *[Nat. Mater. 21, 844, 2022; Appl. Mater. Today 37, 102101, 2024]*. Because of their nanoscopic dimensions, these superlattices require advanced imaging techniques, such as scanning transmission electron microscopy (STEM) or scanning tunnelling microscopy *[Nat. Commun. 12, 1290, 2021]*. Prof. S. Conesa-Boj is a pioneer in Moiré imaging using STEM.

In twisted 2D magnets, experimental studies are scarce and primarily report complex magnetic multidomain structures *[Nature 632, 1045, 2024]*. A key promise of twisted 2D magnets is the potential ability to tune the spin wave dispersion using the twist angle, as predicted by theoretical studies *[PRB 102, 094404, 2020; Sci. Rep. 10, 15069, 2020; PRB 107, L020404, 2023; Nano Lett. 23, 6088, 2023; Nat. Comput. Sci. 3, 314, 2023; PRL 133, 206702, 2024]*. However, this effect has yet to be demonstrated experimentally. Crucially, I have already demonstrated my know-how on fabricating these challenging twisted 2D 'van der Waals' magnetic and non-magnetic heterostructures *[Nat. Mater. 23, 212, 2024; arxiv: 2410.21064, 2024; see CV]*.

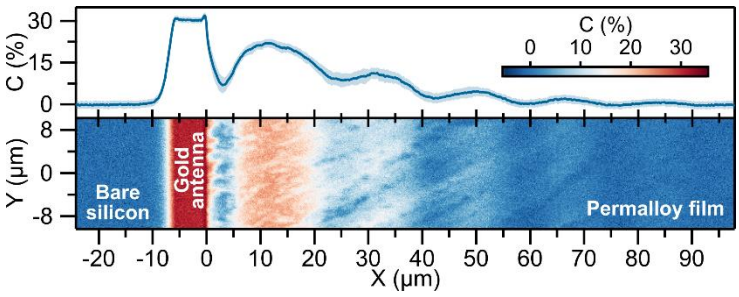


Fig. 1. *Spin waves in a permalloy magnet imaged using a single-spin scanning microscope developed by the applicant during his Marie-Curie fellowship. The bottom panel shows a spin-wave contrast map, while the top panel presents the average profile, highlighting the oscillatory contrast that identifies the spin waves.*

Spin waves, also named as magnons, are collective excitations of magnetically ordered systems (**Fig. 1**), offering potential for information transmission, storage, and processing *[Nat. Phys. 11, 453, 2015]*. Detecting spin waves in 2D magnets remains challenging, with diamond magnetometry being a highly sensitive approach *[Nat. Rev. Mater. 3, 17088, 2018]*. Prof. T. van der Sar is a world-wide recognized expert on quantum sensing using diamond magnetometry.

To address these challenges, **I propose to unravel and rationalize the relation between the twist-angle (with the formation of Moiré superlattices) and spin wave propagation in twisted 2D magnets.** Success relies on complementary expertise of the applicant in twisted 2D magnet fabrication, of Dr. van der Sar in spin wave detection using diamond magnetometry, and of Dr. Conesa-Boj in imaging Moiré superlattices via STEM (**Fig. 2**). The project targets to establish the twist angle as a tool for tailoring spin wave transport, with potential applications in data storage, quantum materials, and quantum technologies.

Approach:

Three integrated work packages (WPs) drive the project:

WP1.- Fabrication of Twisted Magnets. I will prepare twisted magnets by the deterministic assembly of exfoliated ferromagnetic monolayers, specifically CrSBr, building upon my expertise *[Adv. Mater. 34, 2204940, 2022; Nat. Mater. 23, 212, 2024; arXiv 2410.21064, 2024]*. Initial experiments will focus on a 90° twist-angle configuration *[Nat. Mater. 23, 212, 2024]*, with subsequent exploration of angles between 0° and 90°. Based on CrSBr's structure, a twist of 36.8° is anticipated to yield patterns with large periodicity.

WP2.- Sensing of Spin Waves via Diamond Magnetometry. I will probe spin waves in the twisted magnets using diamond magnetometry, where a scanning single-spin tip is employed for detecting the magnetic stray fields. This technique, developed by the group of T. van der Sar *[Science 382, 430, 2023]*, is fully available and supported by my previous experience in setting up and operating such advanced instrumentation (**Fig. 1**).

WP3.- Imaging Moiré superlattices using STEM. I will visualize Moiré patterns in twisted magnets using atomic resolution STEM measurements with a Cs-probe corrected JEOL microscope. This method enables nanometer-scale strain mapping, technique pioneered by S. Conesa-Boj *[Small Science 4, 2300249, 2024; Adv. Func. Mater. 34, 2307893, 2024]*. These capabilities provide unique insights into the correlation between strain and spin wave behaviour observed in WP2.

These WPs operate in parallel to maximize synergies, with theoretical support provided by Prof. Y. Blanter (KIND) and Prof. J. Ferrer (University of Oviedo), the latter being a visiting professor at QN in late 2025. At least two high-impact publications are anticipated.

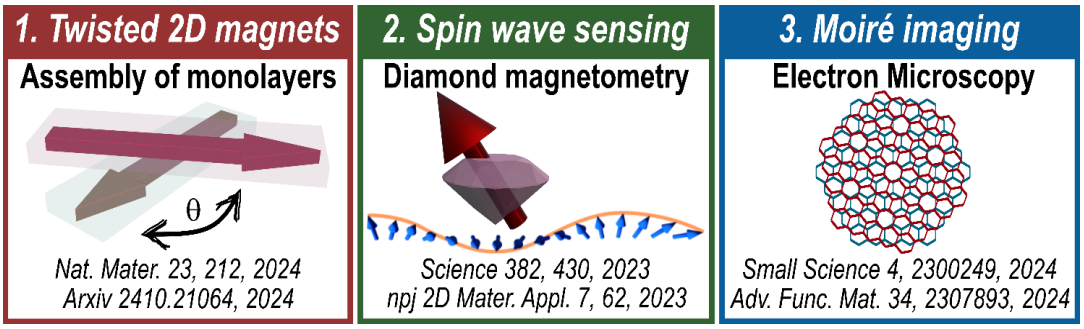


Fig. 2.- Goal of this project: *Twist-control of spin waves in 2D magnets. Unravelling the relationship between spin waves and twist-angle in 2D magnets relies on (1) fabricating twisted 2D magnets (Mañas-Valero), (2) sensing spin waves via diamond magnetometry (van der Sar), and (3) determining Moiré superlattices using TEM (Conesa-Boj).*

6.- Host environment.

The host groups provide the necessary infrastructure and knowhow for realizing the proposed research. The van der Sar group offers advanced equipment and extensive experience in diamond magnetometry, while Conesa-Boj group brings pioneering expertise in STEM and strain mapping. This combination of complementary skills ensure that the experimental needs of the project are fully met. Running costs are covered by ongoing grants from both groups, ensuring seamless execution of the work.

7.- Benefit to the career of the fellow.

It is my future ambition to start a lab in which I combine different advanced imaging techniques to explore low-dimensional magnetic phenomena. This proposal is crucial for establishing my independence as a researcher, expanding my expertise in diamond magnetometry and STEM. In addition, this fellowship will demonstrate my leadership role, enhancing my competitiveness for grants like the ERC Starting Grant and serve as a springboard for securing an assistant professor position.

8.- Benefit to the synergy of KIND.

This project establishes a novel collaboration between the van der Sar and Conesa-Boj groups, bridging magnetometry and STEM expertise to address challenges in 2D materials. This collaboration will drive co-supervised PhD projects, competitive funding applications, and the development of cutting-edge experimental approaches, significantly enhancing KIND's research portfolio.