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Quantum Transport of Magnons in Ferromagnetic Insulators (QuTrFI)

HORIZON-MSCA-2023-PF-01-01: Postdoctoral Fellowships - European Fellowships

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)*

Magnetism is ubiquitous in engineering applications[1] such as magnetic field sensors, race track memory, and spin-torque oscillators. Recently, there has been an interest in devices based on ferromagnetic insulators[2] due to their lack of Ohmic losses and their resulting potential for energy-efficient devices. A premier material in this class is the ferrimagnet Yttrium Iron Garnet (YIG), partially owing to its exceptional magnetic quality[3]. The elementary excitations in YIG, called magnons, hold significant potential for data processing. They can be downscaled to nanometer sizes while retaining their high quality[4]. Their frequencies are tunable by external magnetic fields in the order of ~10GHz[5]. They can be tuned to have a pronounced non-linearity[5]. As they couple with a multitude of quasiparticles (microwaves[6], phonons[7], electrons[8], optical light[9], and spin centers[10]), they are very versatile as quantum transducers, e.g. for converting storage qubits to flying qubits. There is indirect evidence for long magnon coherence lengths via experiments using sub-mm YIG spheres as a high-quality magnonic cavity[6].

Due to these inherent advantages, magnons emerge as promising components in non-silicon computing[2], spanning applications from Boolean logic to wave computing and potentially even quantum computing. Magnets are solid-state candidates for bosonic qubits[11], where information is encoded in a carefully chosen two-dimensional subspace of the harmonic oscillator ladder. Furthermore, non-classical magnon states find use in metrology for speeding up magnetic field sensing[12]. The study of manipulating magnons in the quantum domain is called `quantum magnonics'. This field was pioneered through the recent demonstrations of magnetization measurements with an accuracy of a single magnon[13]. The experiment involves embedding a magnet within a cavity quantum electrodynamics (cQED) setup (see Fig. 1), comprising a microwave cavity and a superconducting transmon. In this system, a single magnon Fock state was experimentally demonstrated[14]. Several theoretical proposals for quantum magnon state generation exist[15], including a protocol to create an arbitrary quantum state[16].

1 MA Khan et al. *Engineering Research Express*, 3(2):022005, 2021; SSP Parkin, M Hayashi, L Thomas *Science*, 320(5873):190–194, 2008

2 AV Chumak et al. *IEEE Transactions on Magnetics*, 58(6):1–72, 2022;

3 V Cherepanov, I Kolokolov, V L'vov *Physics Reports*, 229(3):81–144, 1993

4 G Schmidt et al. *physica status solidi* (b), 257(7):1900644, 2020

5 DD Stancil, A Prabhakar, Spin Waves: Theory and Applications *Springer Publications*

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8 H Nakayama et al. *Phys. Rev. Lett.*, 110:206601, 2013; T Hioki et al. *Phys. Rev. B* 104, L100419, 2021

9 A Osada et al. *Phys. Rev. Lett.*, 116:223601, 2016; X Zhang et al. *Phys. Rev. Lett.*, 117:123605, 2016; S Sharma et al. *Phys. Rev. Lett.*, 121:087205, 2018

10 L Trifunovic, FL Pedrocchi, D Loss, *Phys. Rev. X*, 3:041023, 2013; T vd Sar et al. *Nature Communications*, 6(1):7886, 2015;

11 BM Terhal, J Conrad, C Vuillot, *Quantum Science and Technology*, 5(4):043001, 2020

12 CL Degen, F Reinhard, P Cappellaro, *Rev. Mod. Phys.*, 89:035002, 2017

13 D Lachance-Quirion et al., *Science*, 367(6476):425–428, 2020

14 D Xu et al., *Phys. Rev. Lett*., 130, 193603, 2023

15 S Sharma et al. *Phys. Rev. B*, 103:L100403, 2021; M Kounalakis, GEW Bauer, YM Blanter *Phys. Rev. Lett.*, 129, 037205, 2022

16 S Sharma, VASV Bittencourt, S Viola Kusminskiy, *Journal of Physics: Materials*, 5(3):034006, 2022

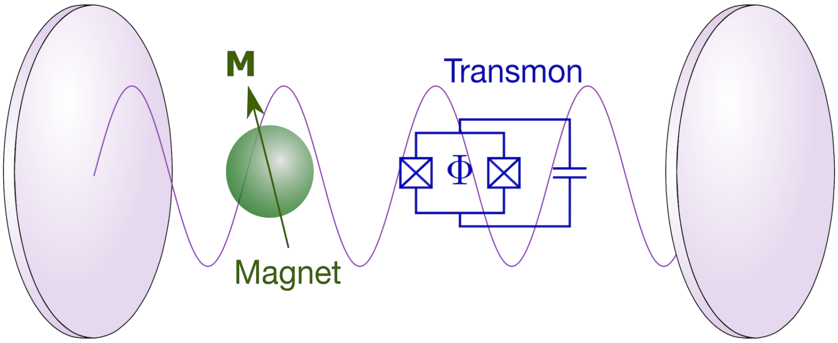

Fig. 1: A typical setup in quantum magnonics consists of a microwave cavity mediating a coupling between a magnet and a transmon. Magnon Fock state generation[14] were experimentally demonstrated in this setup. The image is taken from Ref.[16] where a protocol to generate an arbitrary quantum state of the magnons was proposed and evaluated.

While state generation of magnons has been discussed at length, a complete computing system based on magnonics necessitates the transportation of quantum information between distinct magnets (or other quasiparticles). This step is crucial not only to communicate between distinct processing nodes, but also to generate entanglement between them. A promising avenue to achieve this objective is by coupling the computing nodes to a magnetic film or a wire, employing the pure spin current carried by magnons[17]. Classical magnon transport theory is very rich due to their non-monotonic and anisotropic dispersion relation with a minimum at a non-zero wave-vector capable of hosting a Bose-Einstein condensate[18]. Spin current in YIG sustains classical phase coherence over sub-mm distances[19]. However, the feasibility of transporting quantum information across YIG over comparable distances remains uncertain.

Objective: to develop a quantum transport theory of magnons in ferromagnetic insulators, with an emphasis on YIG, and an experimental procedure to probe coherence in magnon transport.

Concretely, the project aims to

- predict classical and quantum coherence lengths using the known spin-spin interactions and a microscopic model of dissipation involving impurities (in particular, rare-earth impurities in YIG). This analysis will cover bulk, quasi-1D, and quasi-2D geometries.
- propose and evaluate an experimental setup for measurement. This task involves using two cQED setups, each with a superconducting transmon and a microwave cavity. One serves as a quantum source of magnons and the other is for quantum detection, as shown in Fig. 2.

Quantum transport of magnons across Heisenberg (exchange-coupled) spin chains has been studied extensively. For example, dissipationless 1D chains were proposed for near-perfect communication[20]. The effect of a phenomenological dissipation, namely Gilbert damping, on Heisenberg chains was discussed using Green's functions[21]. However, within the existing state-of-the-art theoretical tools, several key aspects are missing when it comes to modeling a realistic magnet, that will be taken into account in the proposed theory. **(1)** I will include long-range dipolar interaction. This interaction is essential for modeling magnons with long wavelengths, >100nm in YIG, which contribute significantly to coherent transport. **(2)** Three different geometries will be considered: bulk (for simplicity in understanding the microscopics), quasi-1D (for maximum efficiency of transport), and

17 Y Kajiwara et al. *Nature* 464, 262-266 (2010)

18 S. O. Demokritov et al. *Nature*, 443 (7110):430–433, 2006

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20 S Bose *Contemporary Physics*, 48(1):13–30, 2007; K. Nakata, P. Simon, D. Loss *J. Phys. D: Appl. Phys.* 50, 114004, 2017

21 J Zheng et al. *Phys. Rev. B*, 96:174422, 2017

quasi-2D (for networks). In contrast to 1D, the effects of elastic scattering are prominent in 2D and bulk geometries. **(3)** A realistic microscopic model of dissipation will be included. It is imperative not only for quantitative predictions but also to differentiate between different dissipation length scales: decay lengths (for energy transport), classical wave coherence length (for wave computing), and quantum coherence length (for quantum computing). The framework for this dissipation model will draw from existing ferromagnetic resonance experiments conducted on YIG[22], which elucidates the microscopic origins of dissipation. The dissipation is dominated by rare earth impurities at sub-Kelvin temperatures, whereas the intrinsic magnon-magnon and magnon-phonon couplings dominate only at room temperature.

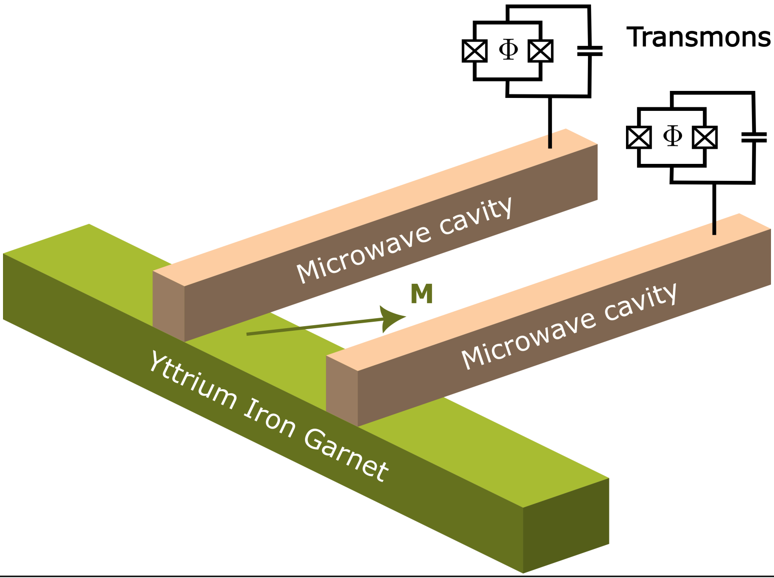

Fig. 2: The setup that will be studied in this proposal. A source transmon excites the magnons in YIG that are measured by a second detector transmon. Each of the transmons couples to the magnet via a lambda/4 microwave resonator, with the magnetic field maxima at the magnet and the electric field maxima at the transmon. The cavity dimensions can be taken to be ~1μm and the magnet's thickness to be <100nm (similar to the experiment in Ref.[23]). The width of the magnet should also be <100nm for a 1D geometry but infinitely long for the 2D case.

The developed theory will be valid for other ferromagnetic insulators besides YIG such as vanadium tetracyanoethylene (V[TCNE]$_x$) as well as any new materials that may emerge in the future. I choose cQED systems as they are experimentally achievable. Nonetheless, the results of this research will directly translate to scenarios involving alternate carriers (such as magnets, mechanical oscillators, spin centers, etc.) coupled via a long magnet, a system crucial for the vision of spin wave computing.

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).*

The objectives put forth on Pg2 are achieved using the following varied set of theoretical tools with details to follow.

- ***[Mic]***: A microscopic description for the spins in a ferromagnetic insulator in Fig. 3 will be found using tools from open quantum systems. Then, a bulk quantum transport model will be found by generalizing existing quantum transport models of electrons to magnons (which are bosons), in particular the Keldysh formalism.

22 H Maier-Flaig et al. *Phys. Rev. B*, 95:214423, 2017; S Kosen et al. *APL Materials*, 7(10):101120, 2019; M Pfirrmann et al. *Phys. Rev. Res.*, 1:032023, 2019

23 Q. Wang et al. *Science Advances 9, 32, 2023*

- ***[Coup]***: The coupling of the subsystem containing a microwave cavity and a transmon to a magnetic waveguide will be studied using tools from cavity QED, as is typically done in quantum magnonics.
- ***[Mag]***: These two analysis will pave the way for analyzing more realistic geometries, such as quasi-1D wire (Fig. 2) and a quasi-2D film. In these cases, these magnon modes are found using classical magnetization dynamics, particularly the Landau-Lifshitz equation, and magnetostatics, particularly the Poisson equation.

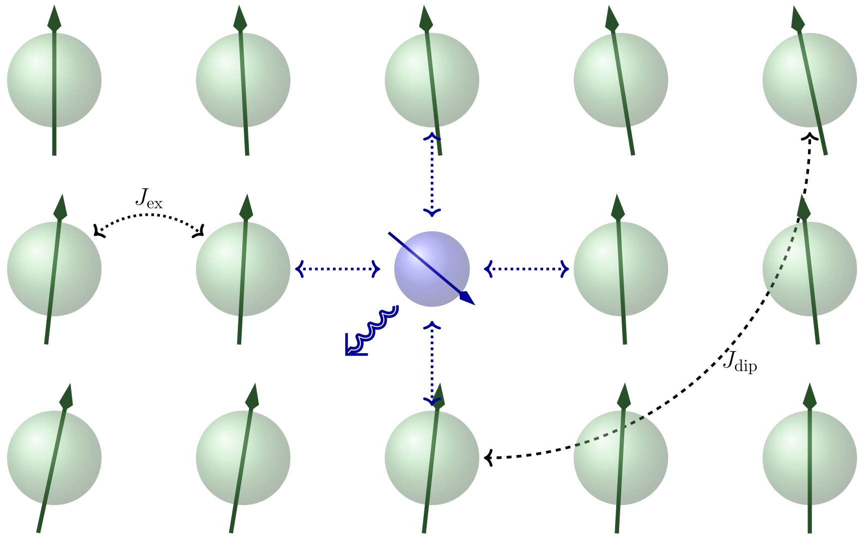

Fig. 3: The model of a ferromagnetic insulator. The individual spins are coupled via exchange coupling J_{ex} (on the order of lattice distances) and dipolar coupling J_{dip} (long range). An impurity couples to the nearby spins with another exchange constant and can dissipate into the bulk phonons.

Microscopic theory [Mic]

Before analyzing the system in Fig. 2, I will first study a bulk magnet. This initial analysis will yield a microscopic Hamiltonian including the effect of the impurities. Furthermore, I will evaluate the anisotropic wave-vector dependence of magnon coherence length in order to identify those that offer optimal potential for information transfer.

Dissipation Model: Dissipation in ferromagnetic insulators is typically introduced phenomenologically, with Gilbert damping introduced into the Landau-Lifshitz equation. However, this approach predicts a linear frequency dependence of the linewidth, inconsistent with experiments[22]. Thus, a realistic model is needed. Below 50K, dissipation in YIG originates from various rare-earth impurities, whose models can be categorized into three distinct types: fast-relaxing, slow-relaxing, and broad two-level impurities. Such an impurity model is general enough to be applicable to other ferromagnetic insulators/semiconductors.

The microscopic Hamiltonian can be found by the following two steps (see Fig. 3): (1) Model the three classes of impurities mentioned above with an exchange coupling to nearby spins. (2) Determine the relevant microscopic parameters such as impurity density and coupling. This task is achieved by finding the effective Lindblad operator(s) for the Kittel mode (zero momentum magnons) employing a Markovian limit of the Nakajima-Zwanzig equation[24]. Then, the frequency and the temperature dependence of the magnon's linewidth can be fitted with the experimental data[22] to find the parameters. Note that the dissipation of the Kittel mode is used only as a method to determine relevant microsopic parameters, after which the dissipation of magnons will be taken care of in the Keldysh equations of motion.

24 HP Breuer, F Petrucccione, The Theory of Open Quantum Systems, *Oxford University Press*

Keldysh formalism: With the microscopic Hamiltonian at hand, the Green's functions, i.e. the spatio-temporal correlations of ferromagnetic spins, will be found employing the Keldysh formalism. Notably, the spatial decay of the Green's functions will give the bulk coherence length. In bulk, the problem is simplified by translational symmetry that gives plain waves as magnon modes. In other geometries, explicit calculations of magnon modes are necessary as discussed below. If required, one can take a linear approximation (valid at low temperatures) to ignore higher-order correlations that may appear in the Keldysh formalism. By analyzing the Green's functions for different wave-vectors, we can find the directions with the longest coherence length.

If it becomes infeasible to solve the Keldysh equations of motion analytically, then a semi-numerical approach would be employed. A magnon with a given wave-vector scatters by impurities, whose amplitudes can be found from the Dissipation model. Then, a numerical integral over the scattering channels will give an estimate of the coherence length in each geometry.

Coupling to cQED [Coup]

Analogous to the typical system in quantum magnonics, see Fig. 1, one can couple the traveling magnons to a cQED setup as shown in Fig. 2. Microwaves couple to the magnet via Zeeman interaction and to the transmon via their electric fields. The following techniques apply to both 1D and 2D geometries.

A traveling magnon wave-packet has a finite probability of decaying into the microwave cavity. Then, a dispersively-coupled transmon can be used to perform a quantum tomography of the microwave cavity that will give evidence, or lack thereof, of non-classicality in the magnon wave-packet. Using an input-output theory in the magnet, similar to an optical waveguide, I will find the efficiency of conversion from magnons to microwaves for a given wave-packet.

Conversely, an excitation in the transmon has a finite probability of decaying into the magnet via the microwave cavity, creating a non-classical wave-packet containing one magnon. As the cQED subsystem can be diagonalized exactly and we already found an input-output theory for the magnet, it should be a straightforward extension to find the probability of decay of the transmon excitation and the resulting shape of the magnon wave-packet. One can also excite the microwave cavity coherently to create a semi-classical magnon wave-packet, and with different excitations, we can differentiate between classical and quantum coherence lengths.

If it turns out that the coupling of magnon waveguide with the cQED setup is too small for such a study, I will look at other methods for injection/detection of magnons, e.g. Brillouin light scattering or NV centers.

Magnon mode calculations [Mag]

Applying the Keldysh formalism requires an explicit form of the magnon modes. They are found by linearizing the Landau-Lifshitz equation for magnetization and combining it with the Poisson equation for the magnetic field. This procedure gives an eigenvalue equation that can be further reduced using the relevant symmetries of the system under consideration.

Magnetic Wire: I will initially consider a particular case of a cylindrical wire and the magnetization along the wire, implying that the magnon wave-vector is parallel to the magnetization: $k||M$. In this azimuthally symmetric case, the magnon modes can be found analytically[25]. Its possible that $k||M$ is too sub-optimal for information transfer, then the general case without cylindrical symmetry would be numerically solved. This would require a numerical evaluation of the magnon modes to be inserted into the Keldysh equations of motion.

Thin Film: In a 2D magnetic thin film, the exchange-dipolar magnon modes can be found in a closed form[26] again by Fourier transforming in the plane and finding an effective linear differential equation across the thickness.

25 J Rychły et al. *Journal of Physics D: Applied Physics*, 52(7):075003, 2018; S Sharma et al. *Phys. Rev. B*, 99:214423, 2019

26 RE de Wames, T Wolfram *Journal of Applied Physics*, 41(3):987–993, 1970; JS Harms, RA Duine *JoMMM* 557, 1-6, 2022

Open Science

All the publications will be uploaded on the open-source platform arXiv at the same time as being submitted to relevant journals. This allows for a detailed discussion on my project with fellow researchers across the world, as early as possible. All the codes to generate any scientific plots will be uploaded on my github account[27] like I have done for my previous projects.

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

Host: I am eager to collaborate with Prof. Rembert A. Duine at the Institute for Theoretical Physics, Utrecht University (UU), Netherlands[28]. He finished his PhD (cum laude) at UU in 2003 and went on to do a post-doc in the group of Prof. AH MacDonald at the University of Texas. He became an Ass. Prof. at UU in 2006. Soon after, he received the prestigious Dutch Vidi Grant (2007) and the ERC Starting Grant (2008). Since then, he has received about 10 research grants including the ERC Consolidator Grant (2016) and the Dutch Vici Grant (2019). Presently, he holds a position of a full professor at UU (since 2019) and a part-time professor at Eindhoven University of Technology (since 2016). He has (co-)supervised around 17 PhD candidates and 11 postdocs.

Training: With Prof. Duine's extremely impressive track record, his mentorship for my future grant applications and PI positions will be indispensable. We will discuss the progress in the project on a regular basis, where his expertise will be valuable. Furthermore, I plan to attend UU's courses on proposal writing and career planning to facilitate my career development. I will continue supervising undergraduate students and PhD candidates as I have done so far[29].

Two-way transfer of knowledge: Prof. Duine's research covers various facets of spintronics. Combined with my expertise across various topics of magnetism, this positions me to collaborate effectively with his group members. His recent works on *quantum transport in spin chains* and *microscopic mechanisms of decoherence of magnons* align seamlessly with this proposal. His research interests include *topological transport in van der Waal's magnets*. In this context, my expertise on *quantum protocols and cQED systems* presents a promising avenue for manipulating topological magnon transport. With my specialized knowledge in *magnonic crystals*, it will be interesting to utilize the tunability of van der Waal's magnets for engineering unique magnonic band structures. My expertise on *quantum magnonics* fits well with his expertise on *non-linear magnetization dynamics*, as non-linearity is an essential resource for quantum applications. His own pioneered field of *anti-magnonics* involves complex magnetization dynamics that can serve as potent modulators of light useful in *cavity optomagnonics*, a theme that was the central focus of my PhD thesis. As both of our expertise are related and complementary, I will fit well in his group.

I will have the valuable opportunity to engage with Prof. Duine's extensive network of both experimentalists (e.g., Prof. Bart van Wees and Prof. Toeno van der Sar) and theorists (e.g., Prof. Bert Koopmans and Dr. Benedetta Flebus). Similarly, Prof. Duine can draw from my own network of theorists (e.g., Prof. Silvia Viola Kusminskiy, Prof. Benjamin Stickler, Dr. Mehrdad Elyasi) and experimentalists (e.g., Prof. Alexy Karenowska and Dr. James Haigh). Furthermore, I am enthusiastic about the possibility of collaborating with other researchers at Utrecht University who specialize in related fields, such as Prof. Fritz, who focuses on Kagomé magnets, and Prof. Morais Smith, who has recently collaborated with Prof. Duine on magnetization dynamics.

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

27 https://github.com/sancharsharma

28 His updated CV: https://www.uu.nl/medewerkers/RestApi/Public/GetFile?Employee=9035&l=EN&t=null

29 I have supervised 5 undergraduate students and 3 PhD candidates as detailed in my CV

Over the past few years, my research has primarily focused on the field of quantum magnonics, with a vision of exploring the practical potential of magnetic systems for quantum applications. This includes state generation, quantum tomography techniques, and the investigation of hybrid systems involving magnets. The proposed project naturally aligns with the trajectory I've been following.

The core set of skills required for successfully finishing this project constitute (1) Quantum magnonics: I have an expertise in the coupling of magnons and superconducting qubits, along with state generation and detection. (2) Magnon mode calculations: I have a solid grasp of such calculations, particularly in the exchange-dipolar regime relevant here. (3) Quantum transport: I look forward to the opportunity to adapt methodologies commonly employed in electronic systems, notably the Keldysh formalism, to the realm of bosonic quasiparticles, specifically magnons. In this pursuit, I am fortunate to have the guidance and expertise of my supervisor, Prof. Duine.

I believe that I am well-positioned on the path to become an independent researcher. I have performed research in Germany, Netherlands, and India over long periods of time and in Japan for two short 1-month visits. Further, I am experienced in working with international collaborators from UK, China, Iran, and Canada. With my extensive experience in supervision and teaching (see my CV) and several projects that I have proposed and implemented over the years, I am also scientifically equipped to finish a project from scratch till the end.

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

Scientific Skills: The success of this project hinges not only on my current expertise in quantum magnonics and magnon mode calculations, but also on the assimilation of a fresh theoretical toolkit of quantum transport, including impurity modeling and Green’s functions. This project will position me at the forefront of the overarching objective of the eventual realization of quantum applications for magnets, a goal for which I am excited to work in the foreseeable future.

Independence: Since the middle of my PhD, I have proposed and executed several projects independently. Along the way, I've had the chance to guide 3 undergraduate and 2 graduate students, and help several PhD candidates towards their theses as detailed in my CV. Now, this will be my first experience with project management from scratch till the end, supplementing my scientific independence. It will be a foundational step for me to pursue larger funding opportunities such as ERC Starting Grants in the next two years and eventually a PI position.

Collaborations: Thanks to my supervisor, Prof. Duine, I'll have the opportunity to connect with a large and respected group of physicists as I have detailed in Sec 1.3, which is crucial for staying up-to-date in the fast-evolving field of magnetism, covering both theoretical analysis and experimental advancements.

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 primary audience for this project will be the research community, contributing to the advancement of quantum magnonics. The findings will be shared through publications in relevant journals, such as the Physical Review series and Scipost. Before submission, the results will be made available on arXiv for open access. Additionally, they will be accessible on Prof. Duine's webpage[30]. The project is anticipated to yield three publications, as detailed in Section 3.1, which is a very likely outcome given the technological relevance and the scientific importance of magnetism. It will further

30 https://www.uu.nl/staff/RADuine/Publications

foster new collaborations and exchange of ideas triggering further joint publications. I intend to participate in several international conferences, such as the Magnonics conference, Gordon conferences, and the APS March Meeting, to present this work and receive feedback from fellow researchers.

Furthermore, I plan to create a personal website along with a blog, e.g. getting a Wordpress sub-domain. This blog will explain my research with increasing complexity, starting from a level understandable to undergraduate students and progressing to engage more experienced researchers. This initiative aims to inform students interested in research (academic or industrial) about quantum magnonics and my research therein. For experienced researchers, the blog will complement the published abstracts with a more informal narrative, fitting my research into the larger context of realizing practical quantum applications involving magnets.

Although the real horizon of this work largely exceeds the duration of the fellowship, I fully expect that the results of this project can be exploited for further ideas and development in quantum magnonics, by me and other researchers around the world as discussed further in Sec 2.3.

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

The project will have a high impact on two scientific communities:

- *Magnonics*: With the recent demonstration of spin wave quantization and a number of emerging ideas for quantum magnonics applications, there is an increasing interest in both experimental and theoretical aspects of this field. As experimental feasibility is an important consideration in this project, it will contribute to advancing experimental techniques. A quantum transport theory for magnons complements the existing methods for state and entanglement generation, setting the stage for a magnonic implementation of quantum algorithms.
- *Quantum Communication*: In the ongoing pursuit of suitable platforms for short-distance quantum communication, Heisenberg spin chains stand out as promising candidates[20]. A magnet has a remarkable spin density, so it is a feasible experimental platform for such a spin-spin communication. While a real magnet differs from a Heisenberg spin chain in several key aspects, as outlined in Section 1.1, these differences present an exciting opportunity for research involving modifications and re-evaluations of established spin chain protocols.

With this project, I do not anticipate immediate societal or economic impacts. Nevertheless, the potential for employing magnets in computing beyond the Silicon paradigm is very promising. In this context, this project represents a substantial contribution toward achieving that overarching goal.

#§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 program is divided into 3 work packages (WPs) based on the geometries: bulk, quasi-1D, and quasi-2D. The bulk analysis helps to understand the microscopic dynamics, including the effect of impurities on magnon transport. A 1D magnetic wire is interesting as it maximizes efficiency in point-to-point communication. A 2D magnetic film is useful for connecting multiple nodes in a network.

The WPs are based on the methodologies discussed in Sec 1.2: Microscopic theory (***[Mic]***), Coupling to cQED (***[Coup]***), and Magnon mode calculations (***[Mag]***). In the WPs below, I also discuss the <u>risks and secondary plans</u> associated with each milestone.

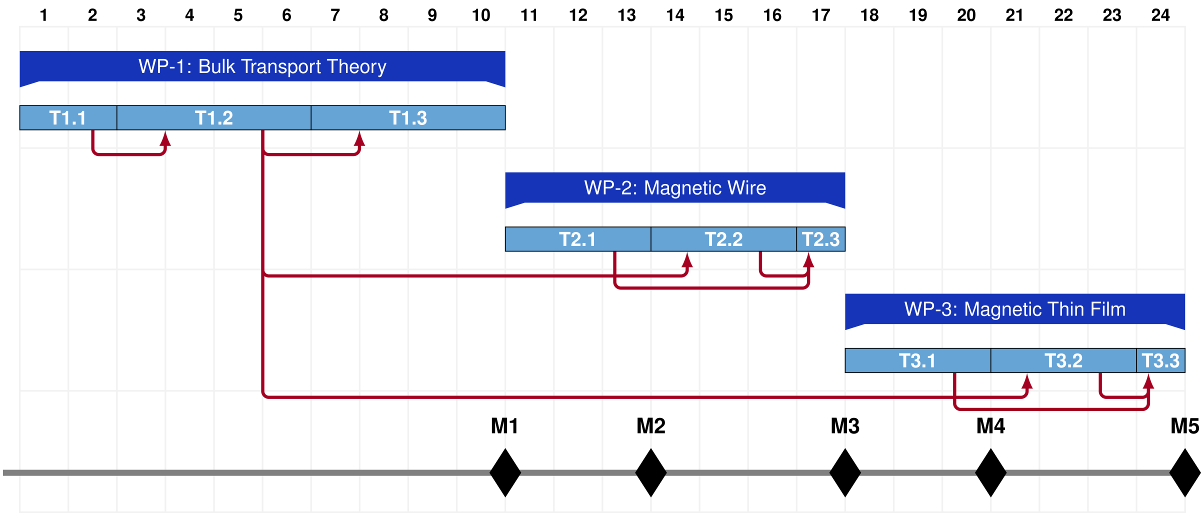

Fig. 4: Schedule of WPs per month showing the dependencies of different tasks Tx.x within the work packages, and the milestones Mx.

WP-1: Bulk Transport Theory

Task 1.1: Find the microscopic Hamiltonian, as discussed in ***[Mic]***:*Dissipation Model*. This requires modeling the impurities with parameters fitted from ferromagnetic resonance experiments.

Task 1.2: Derive the Keldysh equation of motion for the Green's functions, as discussed in ***[Mic]***:*Keldysh formalism* using the Hamiltonian from **T1.1**. This will involve a Markovian approximation to trace out the impurities and get an effective spin-spin self-energy term.

Task 1.3: Solve the equations found in **T1.2** to get the Green's functions in bulk. This will be simplified by translational symmetry as the magnon modes are plain waves. We will get the bulk coherence length from the spatial decay of the Green’s functions. Additionally, I will evaluate the anisotropic wave-vector dependence of the coherence length of magnons to find the ones that are most suitable for quantum information transfer. If it turns out that the Keldysh equations of motion cannot be solved analytically, then a semi-numerical approach would be considered, as detailed in ***[Mic]***:*Keldysh formalism*.

Milestone 1: Find the bulk coherence length of magnons as a function of wave-vector direction.

Deliverable 1: A publication on the theory of quantum transport of magnons in bulk magnets.

WP-2: Magnetic Wire

Using the results from WP-1, I will model the proposed experimental setup in Fig. 2, i.e. coupling of two cQED setups via a quasi-1D magnet. I will predict the measured classical and quantum coherence lengths in this system.

Task 2.1: Find the efficiency of conversion from magnons to microwaves for a given wave-packet, using ***[Coup]***. One can derive an input-output theory in the magnet, similar to an optical waveguide. Furthermore, it will give the magnon observable, say O_M, to which the cavity is sensitive, which will be used in later tasks. Next, I will model the decay of a transmon into the magnet, giving the probability of decay and the resulting shape of the magnon wave-packet, again using ***[Coup]***.

Milestone 2: Modeling information transfer between a magnetic wire and a cQED setup.

Task 2.2: Solve the Keldysh equation of motion to find the spatio-temporal correlations of the observable O_M in the case of a magnetic wire with the magnetization along the wire. In this case, the magnon modes can be explicitly calculated as discussed in ***[Mag]***:*Magnetic Wire*. I expect an analytical solution for the correlations because of the high amount of symmetry.

In case an analytical solution is not feasible, I would numerically solve the 1D equation of motion for the correlations. If it turns out from **T1.3** that $k||M$ is too sub-optimal for information transfer, then the general case without cylindrical symmetry would be numerically solved, as detailed in ***[Mag]***:*Magnetic Wire*.

Task 2.3: Find the fidelity of transfer for both the classical and the non-classical excitation as a function of distance between the cavities. For both the conditions, the only difference is the initial condition of the magnon wave-function, so the equations of motion found in **T2.2** can be directly applied. Then, we can differentiate between the classical and the quantum coherence length.

Milestone 3: Find the classical and the quantum coherence lengths for magnons for a quasi-1D wire.

Deliverable 2: A publication on magnon coherence length in wires.

WP-3: Magnetic Thin Film

This involves a similar set of goals as WP2 but with a 2D film geometry, so the tasks and milestones are analogous.

Task 3.1: Model the exchange between the traveling magnons in 2D and a cQED setup, using ***[Coup]***. This will give the magnon operator that is sensitive to the cQED excitations.

Milestone 4: Modeling information transfer between a magnetic thin film and a cQED setup.

Task 3.2: Solve the Keldysh equations of motion to find the spatio-temporal correlations of the operator found in **T3.1**. This will require the analytically calculated magnon modes in a 2D thin film, as discussed in ***[Mag]***:*Thin Film*. I expect an analytical solution for the correlations. In case an analytical solution is not feasible, a numerical 2D differential solver can be used to find the correlations.

Task 3.3: Find the fidelity of transfer for both the classical and the non-classical excitation as a function of the location of the cavities, i.e. not only the distance between them but also the direction with respect to the magnetization.

Milestone 5: Find the classical and quantum coherence lengths for magnons for a quasi-2D thin film.

Deliverable 3: A publication on magnon coherence length in films.

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

Utrecht University is a renowned institution equipped with world-class facilities. Given the purely theoretical nature of this project, the necessary facilities encompass an office space, access to scientific publications, and requisite software tools such as Mathematica. All these essentials will be provided. Just like a regular member of Prof. Duine's group, I will engage in daily interactions with fellow group members, fostering a collaborative environment. Thanks to its central location in the Netherlands, it is conveniently situated within 30 minutes away from other distinguished universities in Delft, Leiden, and Amsterdam, all of which boast leading researchers in condensed matter.

#§CON-SOR-CS§# #§PRJ-MGT-PM§# #§QUA-LIT-QL§# #§WRK-PLA-WP§#