Probing quantum materials with nitrogen-vacancy spin qubit

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Okinawa Institute of Science and Technology Graduate School

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Aug. 19th 2025

My academic background

2010-2014
B.S. in Physics

Tsinghua University

- Mathematics and Physics for Fundamental Science

2019: Graduate Fellow

UC SANTA BARBARA
Kavli Institute for Theoretical Physics

2019-2021
Postdoctoral Scholar

University of California, Los Angeles

- Spintronics
- Topological transport
- Open quantum systems

2014-2019
Ph.D. in Physics

JOHNS HOPKINS UNIVERSITY
Institute for Quantum Matter

- Theoretical condensed matter physics
- Quantum magnetism
- Magnetic dynamics

2021-2024
Distinguished PKS Postdoctoral Fellow
2025
Leibniz Junior Group Leader

MAX-PLANCK-GESELLSCHAFT
mpipks
IFW
Leibniz Gemeinschaft

- Quantum transport in magnetic systems
- Quantum optics
- Driven-dissipative and nonlinear dynamics

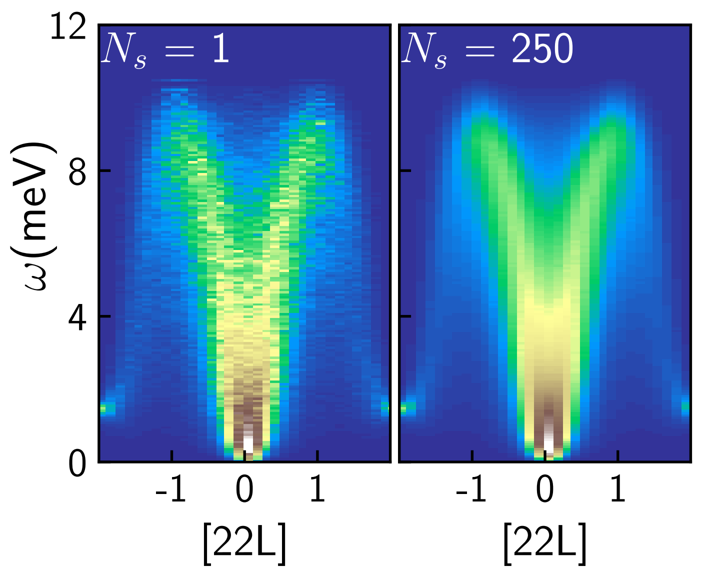
Image generated by DALL-E

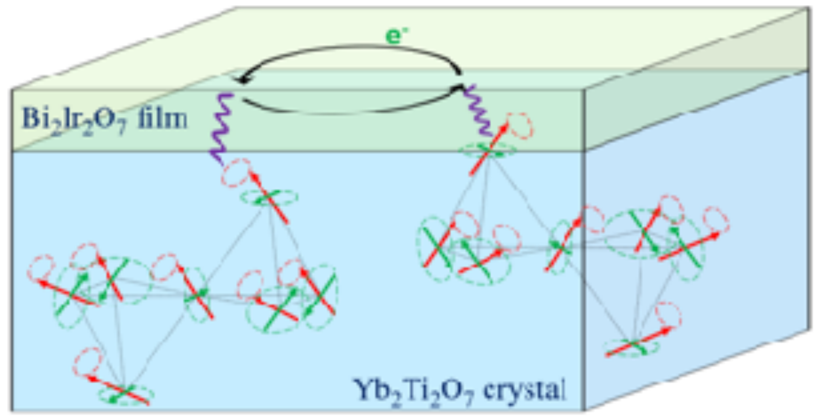
Collective Dynamics & Quantum Transport

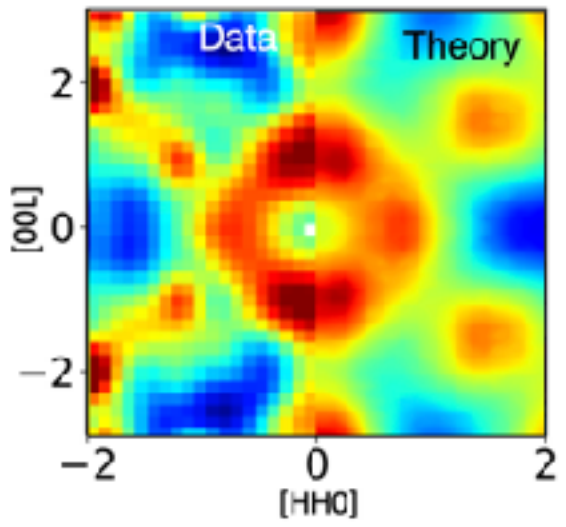
Quantum materials

- Quantum magnets
- Spin dynamics and excitations

SZ, *et al.* **Phys. Rev. Lett.** 2019
Plumb, Changlani, Scheie, **SZ**, *et al.* **Nat. Phys.** 2019
Scheie, Kindervater, **SZ**, *et al.* **Proc. Natl. Acad. Sci.** 2020
Bhardwaj, **SZ**, *et al.* **npj Quantum Mater.** 2022
Xing, **SZ**, *et al.* **Phys. Rev. Mater.** 2024

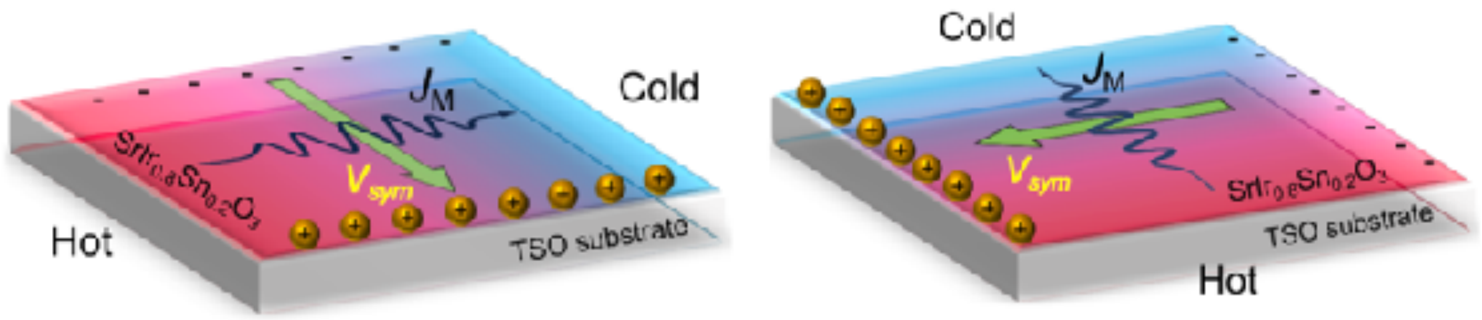


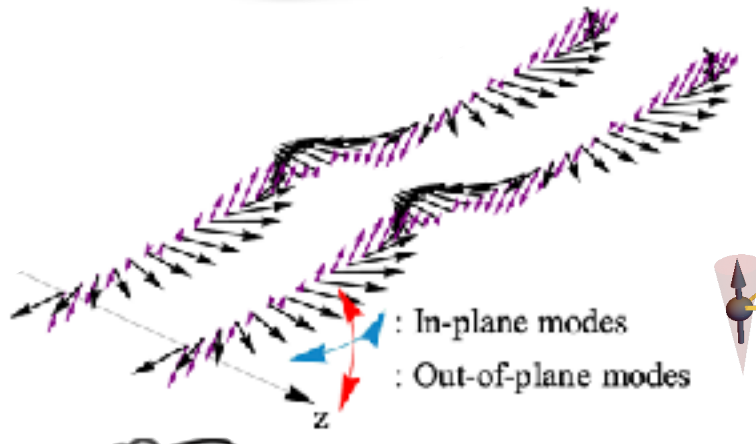


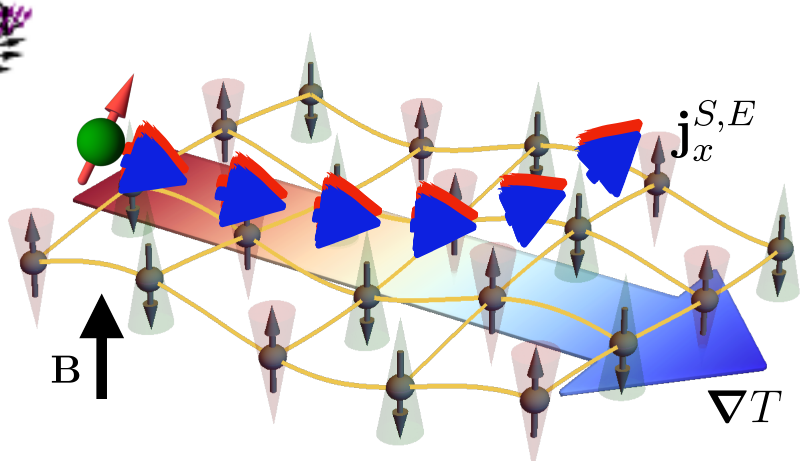


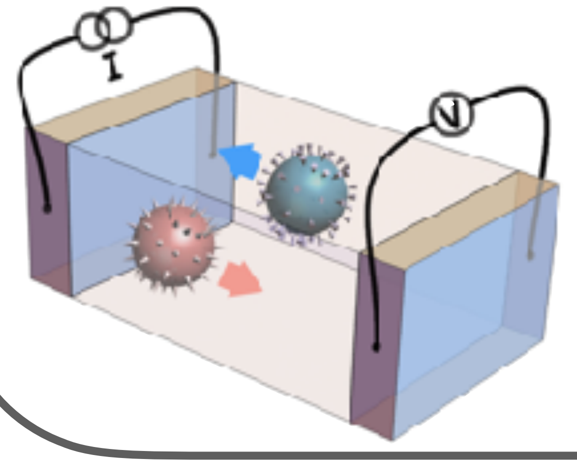
Quantum transport

- Topology enriched transport phenomena
- Joint transport of charge, spin, and heat





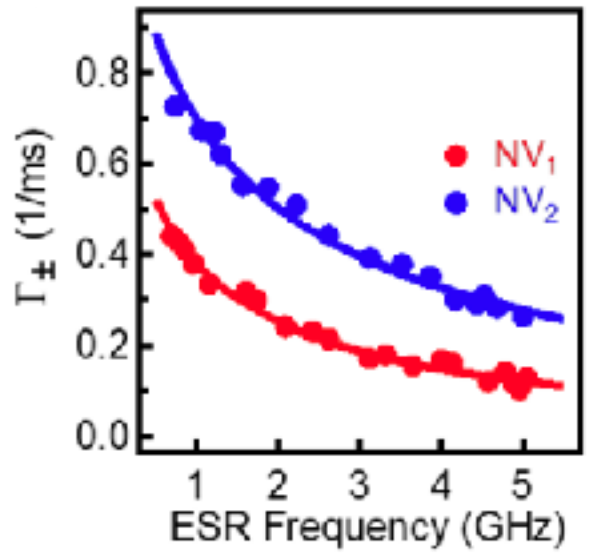


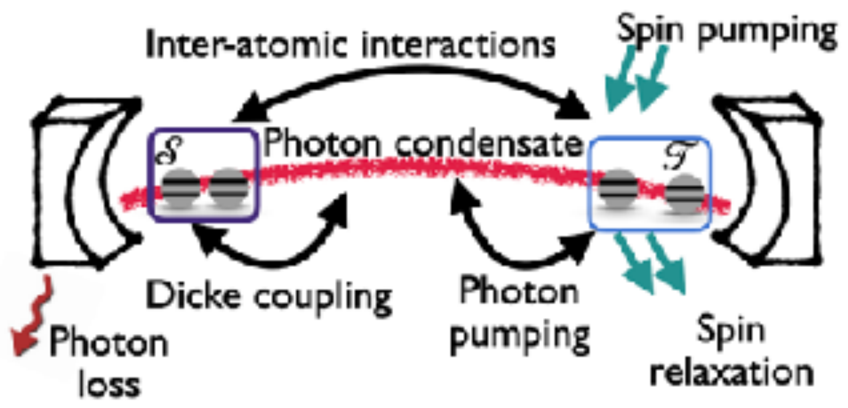


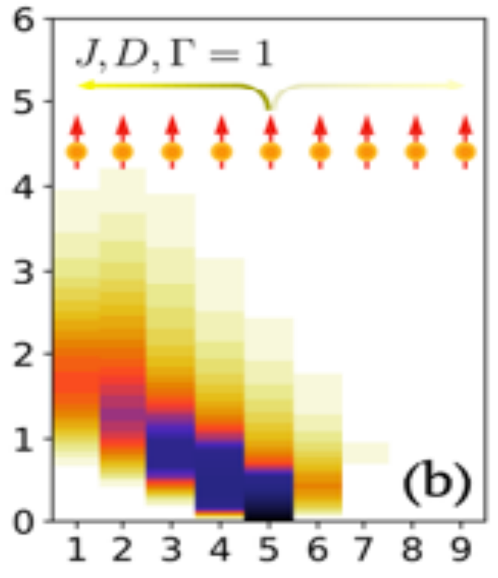
SZ, *et al.* **Phys. Rev. Lett.** 2020
Zou, **SZ**, *et al.* **Phys. Rev. Lett.** 2020
Ahari, **SZ**, *et al.* **Phys. Rev. B** 2021**(L)**
Lin, **SZ** **Appl. Phys. Lett.** 2024
Park, **SZ**, *et al.* **Phys. Rev. B** 2025

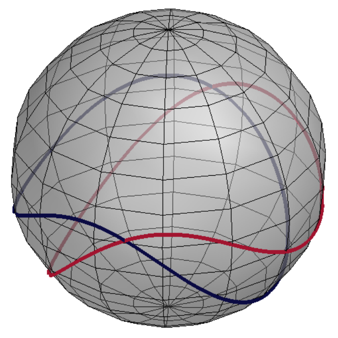
Quantum dynamics

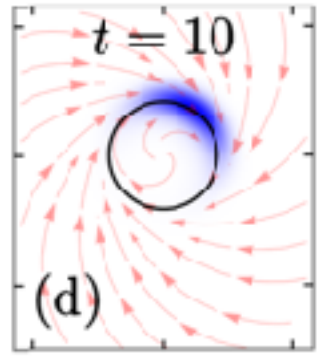
- Quantum sensing
- Open quantum systems









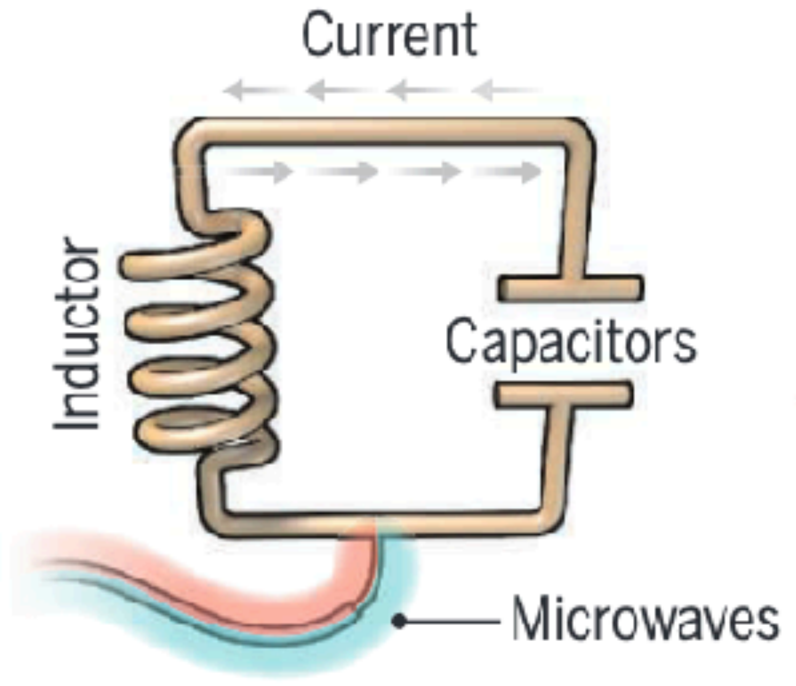


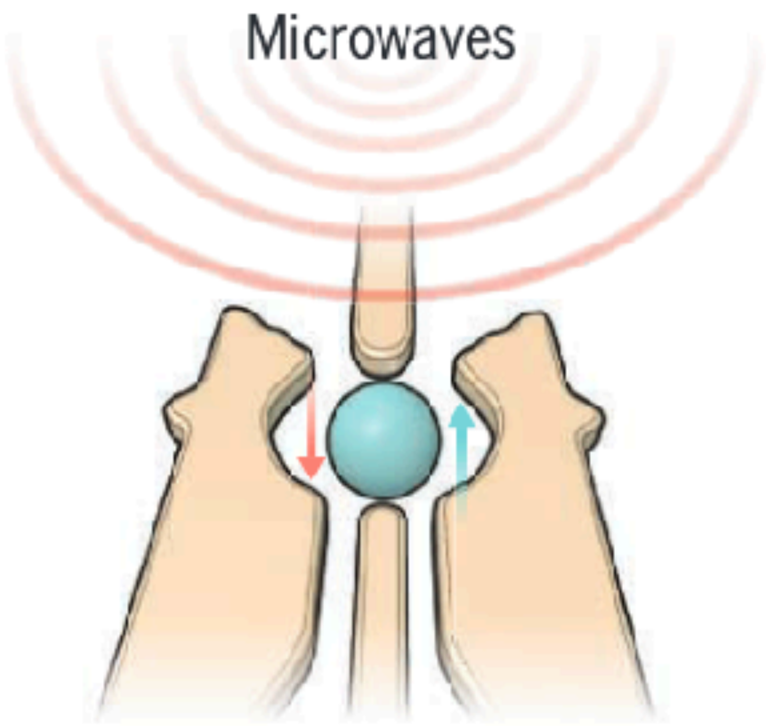
SZ, *et al.* **Phys. Rev. B** 2022**(L)**
Wang, **SZ**, *et al.* **Sci. Adv.** 2022
Li, Al Begaowe, **SZ**, Flebus, arXiv, 2023
Dutta, **SZ**, Haque, **Phys. Rev. Lett.** 2025
Chelpanova, Lerose, **SZ**, *et al.* **Phys. Rev. B** 2023

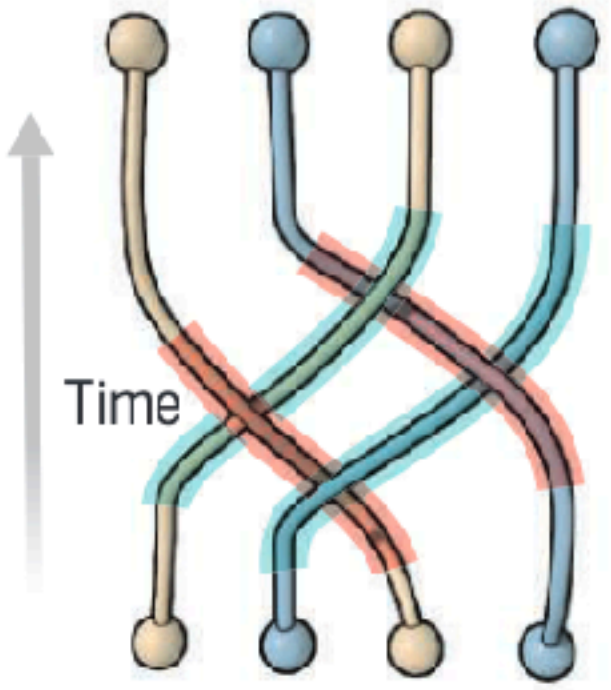
Outline

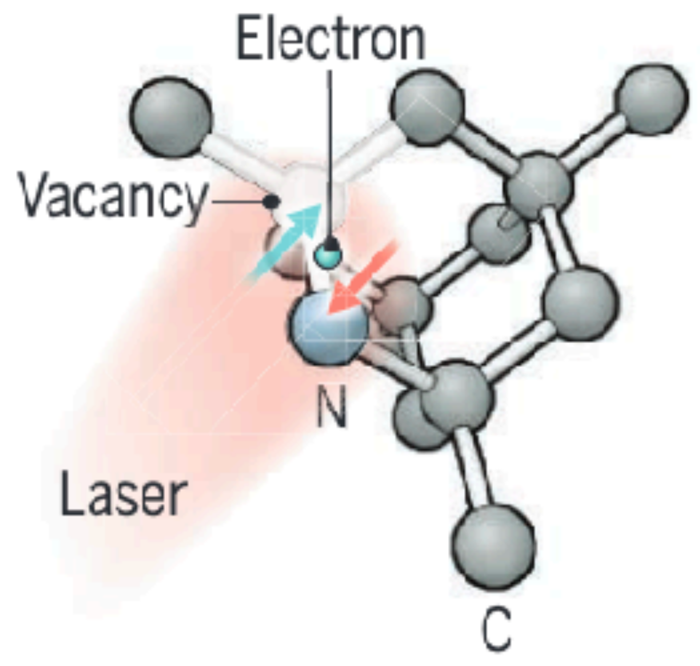
- Introduction to nitrogen-vacancy (NV) **spin qubit**
- Advantages of NV as a **quantum sensor** for quantum materials
- NV probing of **magnetic dynamics and transport** in quantum materials

Solid-state based qubits







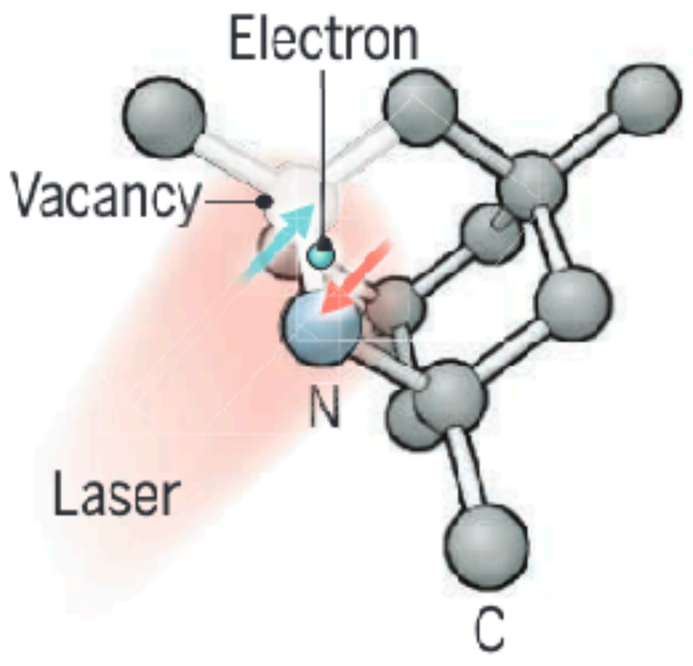


	Superconducting loops	Silicon quantum dots	Topological qubits	Diamond vacancies
	A resistance-free current oscillates back and forth around a circuit loop. An injected microwave signal excites the current into super-position states.	These "artificial atoms" are made by adding an electron to a small piece of pure silicon. Microwaves control the electron's quantum state.	Quasiparticles can be seen in the behavior of electrons channeled through semi-conductor structures. Their braided paths can encode quantum information.	A nitrogen atom and a vacancy add an electron to a diamond lattice. Its quantum spin state, along with those of nearby carbon nuclei, can be controlled with light.
Longevity (seconds)	0.00005	0.03	N/A	10 Long decoherence time
Pros	Fast working. Build on existing semiconductor industry.	Stable. Build on existing semiconductor industry.	Greatly reduce errors.	Can operate at room temperature.
Cons	Collapse easily and must be kept cold.	Only a few entangled. Must be kept cold.	Existence not yet confirmed.	Difficult to entangle.

Popkin, Science 2016

NV center as a quantum sensor

- Noninvasive method
- Atomic size—can be placed close to target
- Can operate at room temperature
- Optical readout and spin manipulations



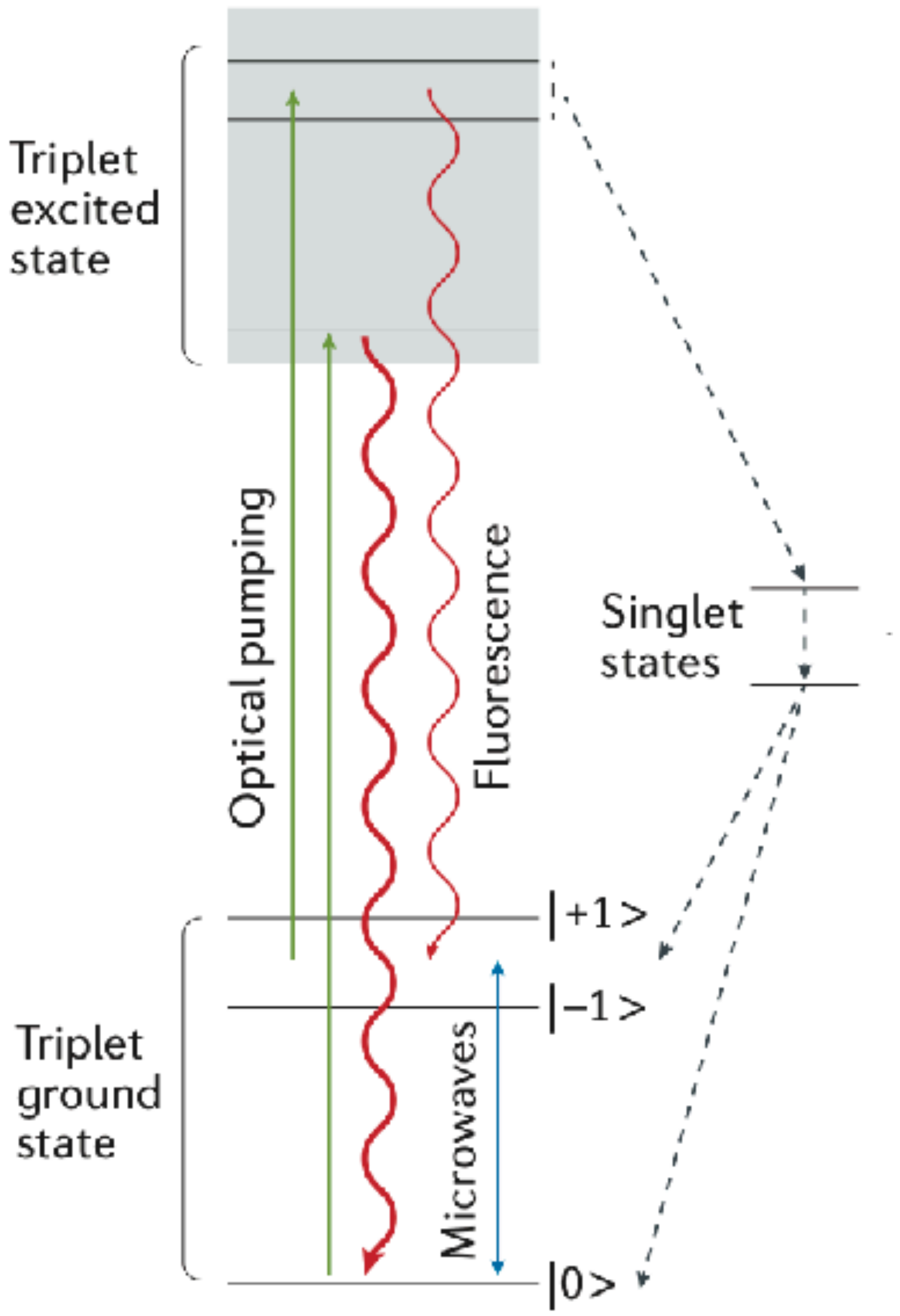
Diamond vacancies

A nitrogen atom and a vacancy add an electron to a diamond lattice. Its quantum spin state, along with those of nearby carbon nuclei, can be controlled with light.

10 Long decoherence time

Can operate at room temperature.

Difficult to entangle.



Popkin, Science 2016
Casola, van der Sar, Yacoby, Nat. Rev. Mat. 2018
Onizhuk and Galli Rev. Mod. Phys. 2025

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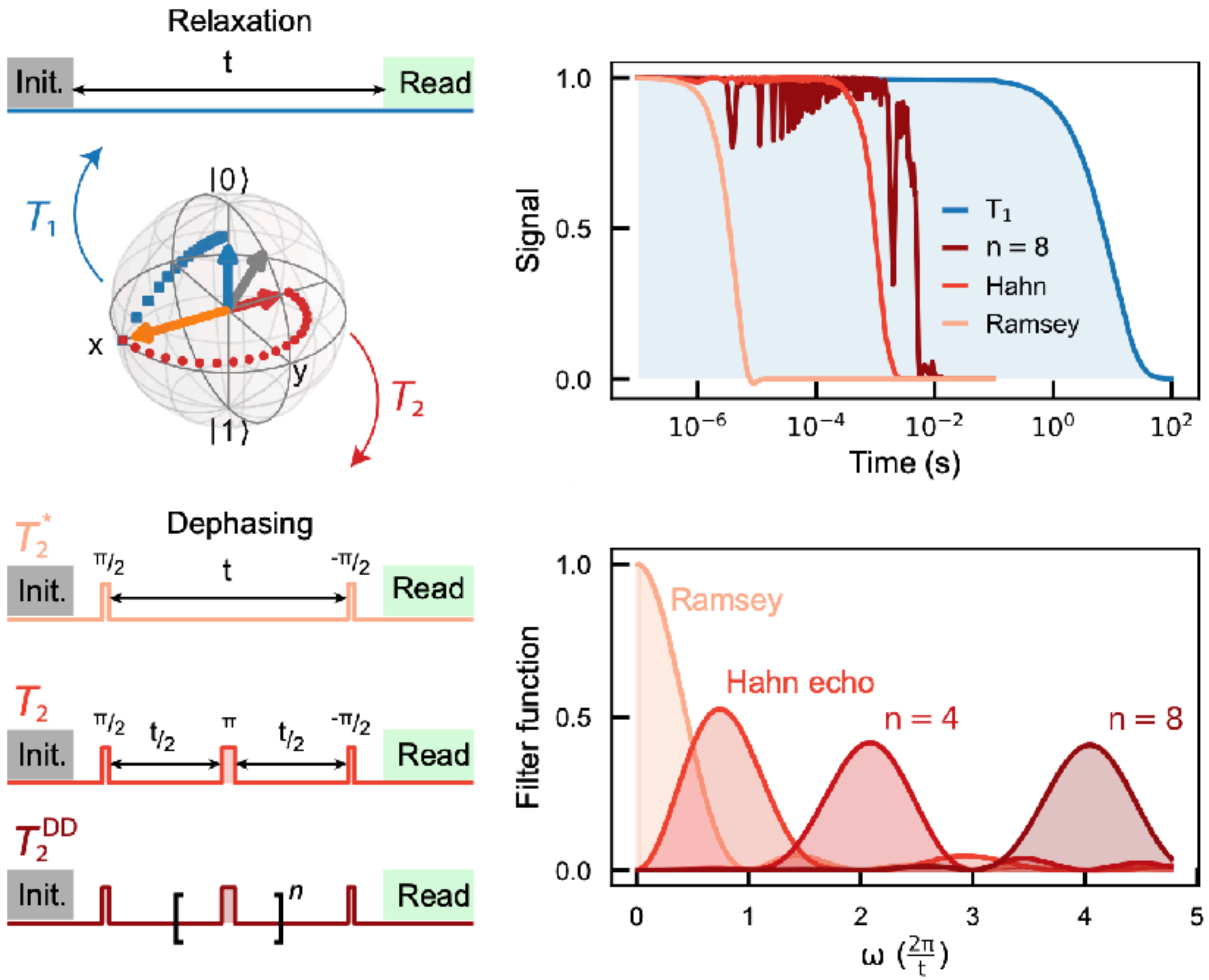
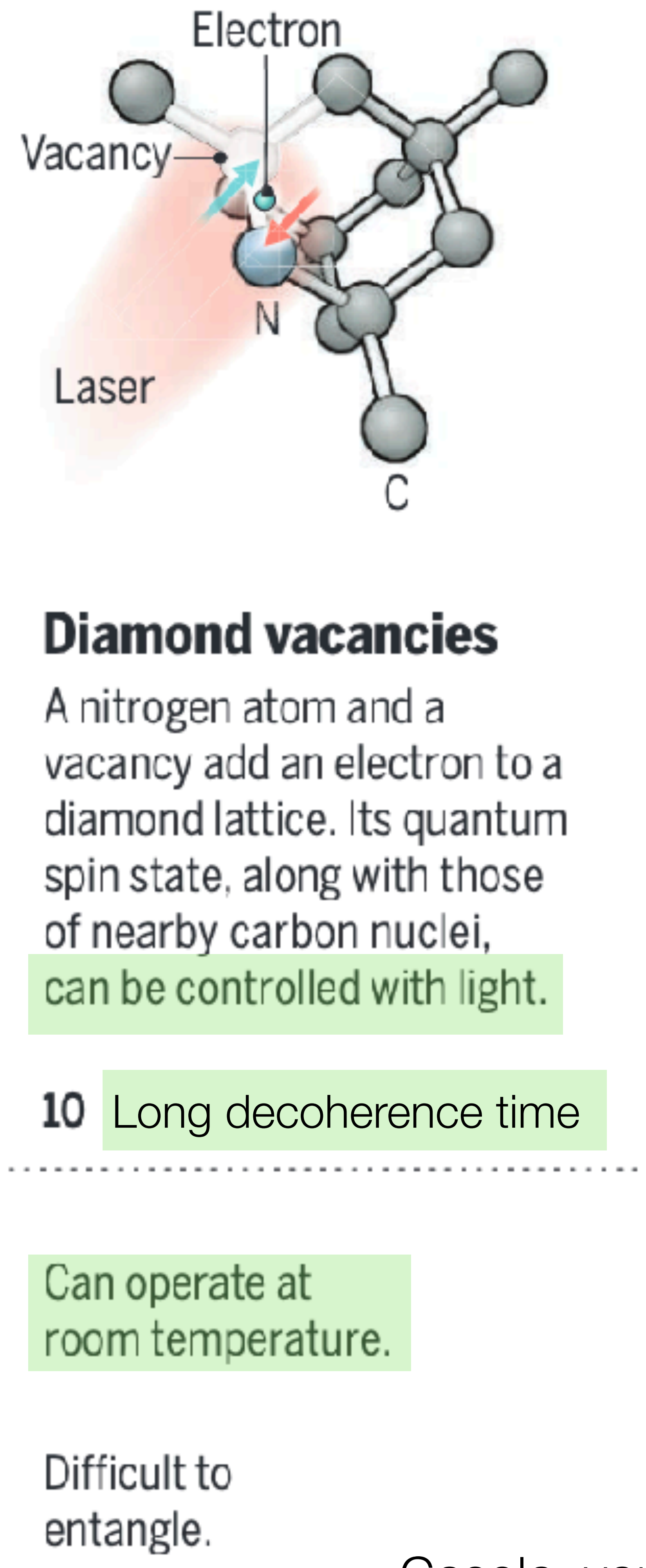
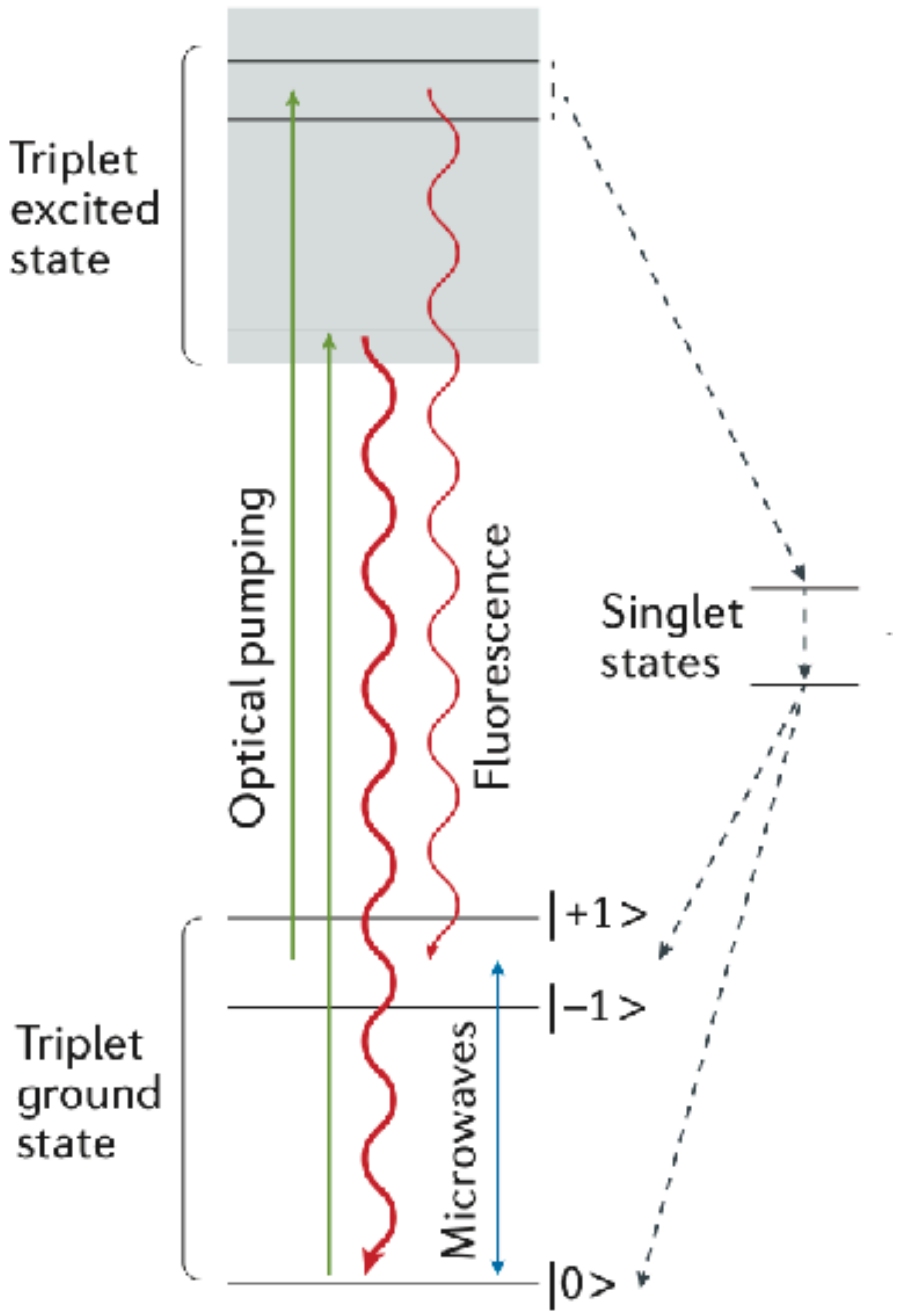


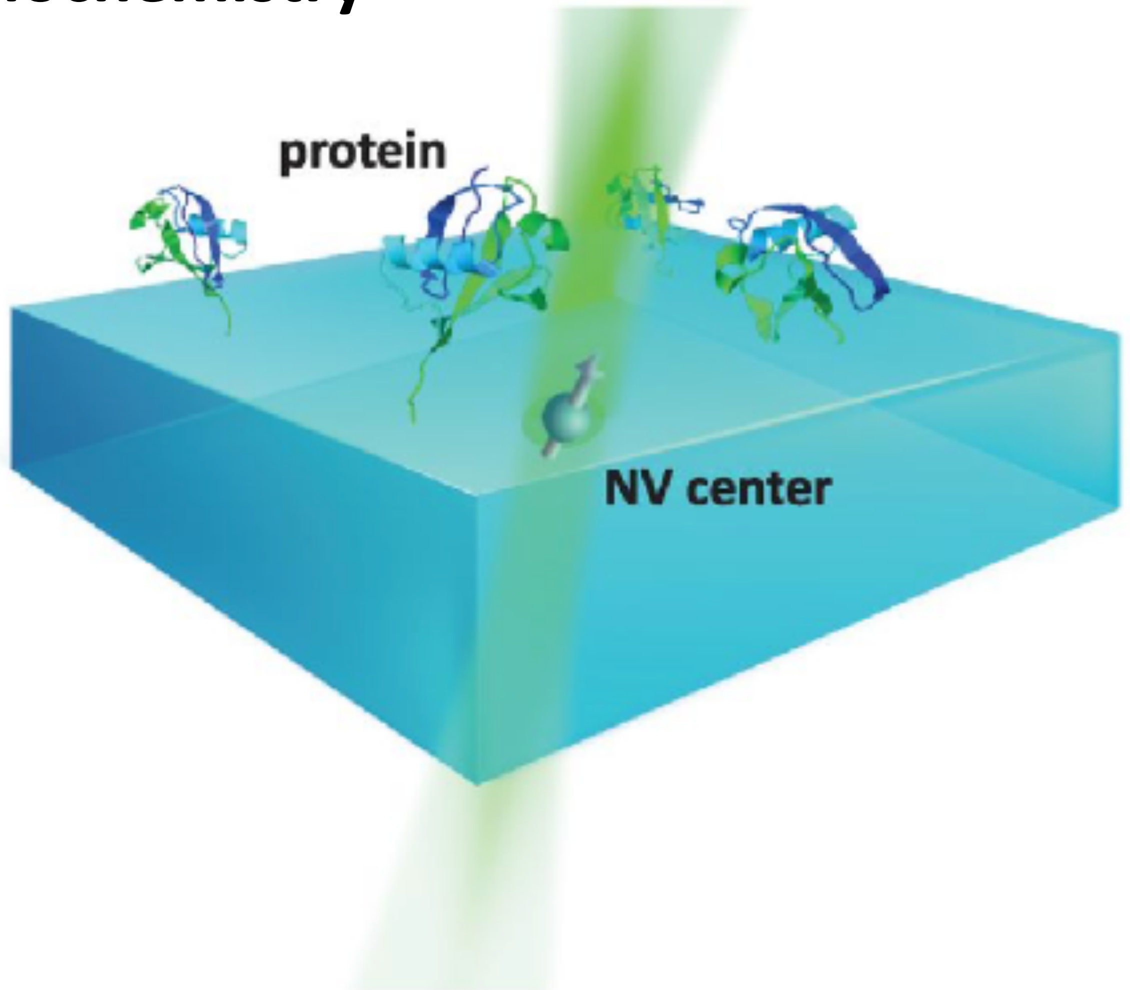




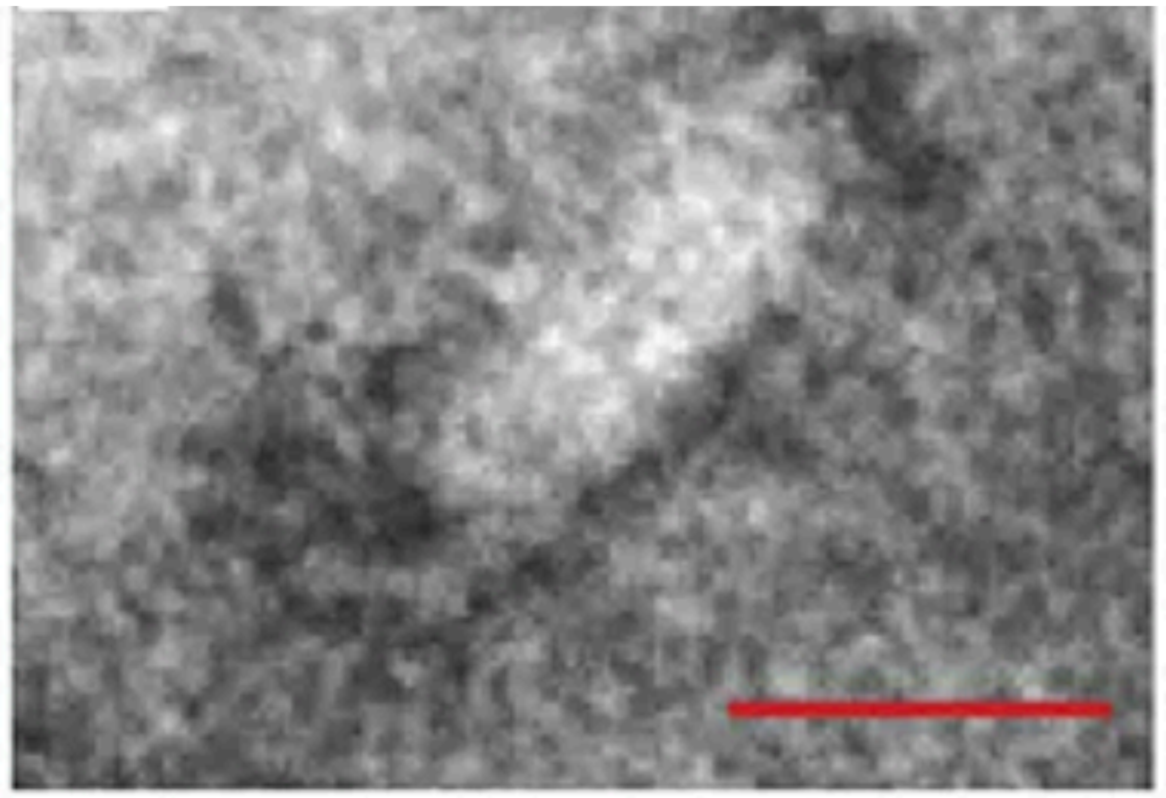
Popkin, Science 2016
Casola, van der Sar, Yacoby, Nat. Rev. Mat. 2018
Onizhuk and Galli Rev. Mod. Phys. 2025

NV center as a quantum sensor

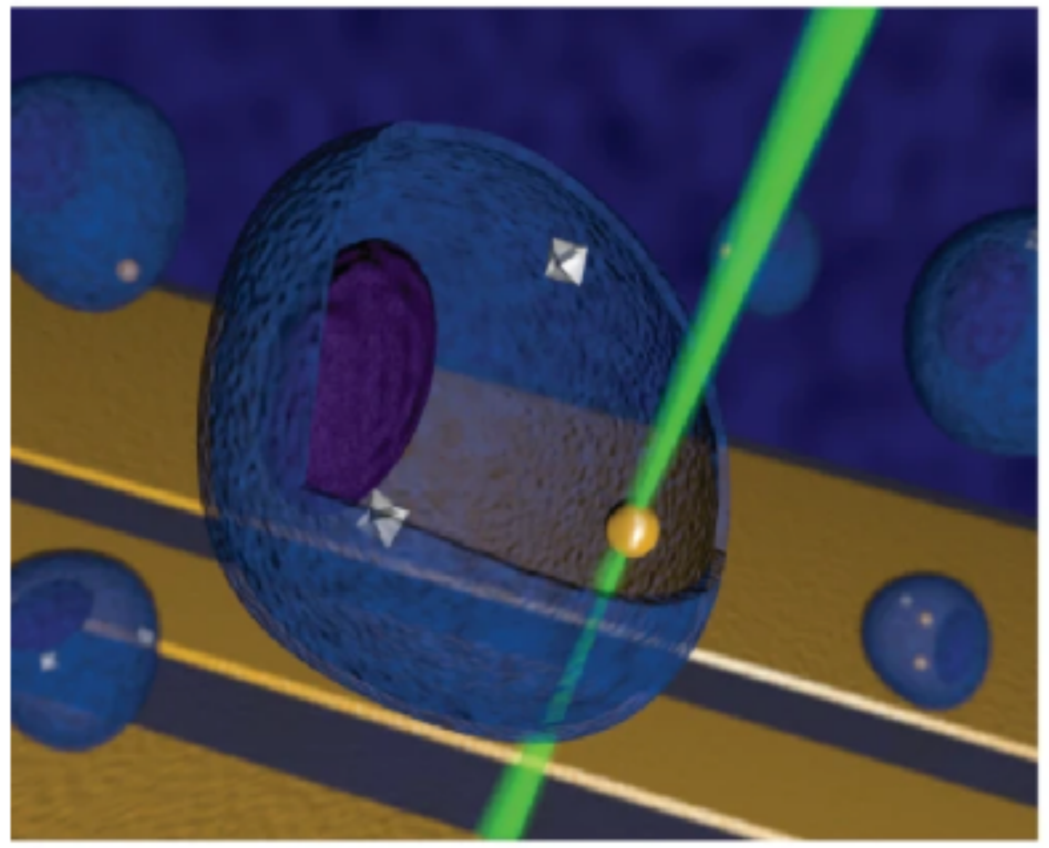
Biochemistry



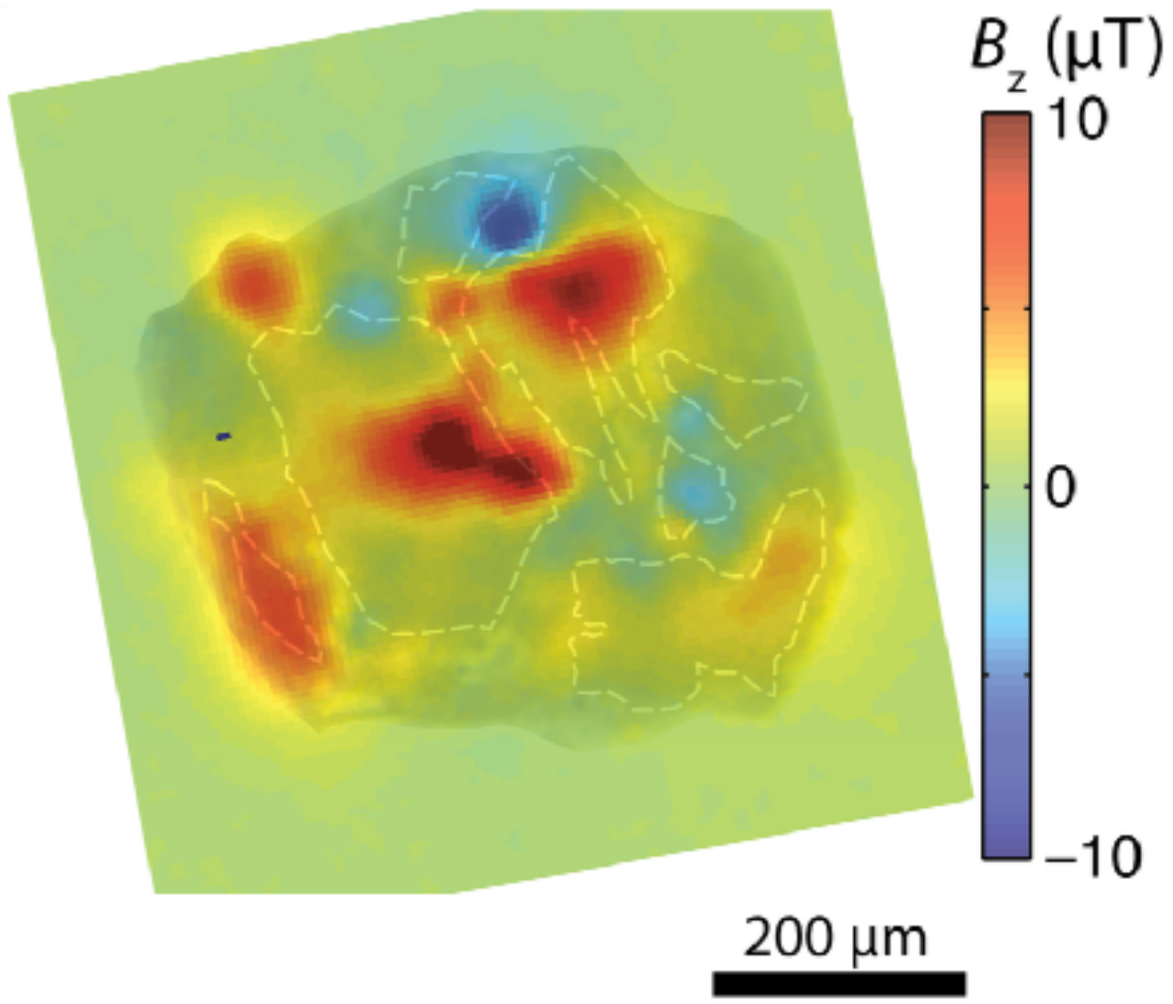
Bio imaging

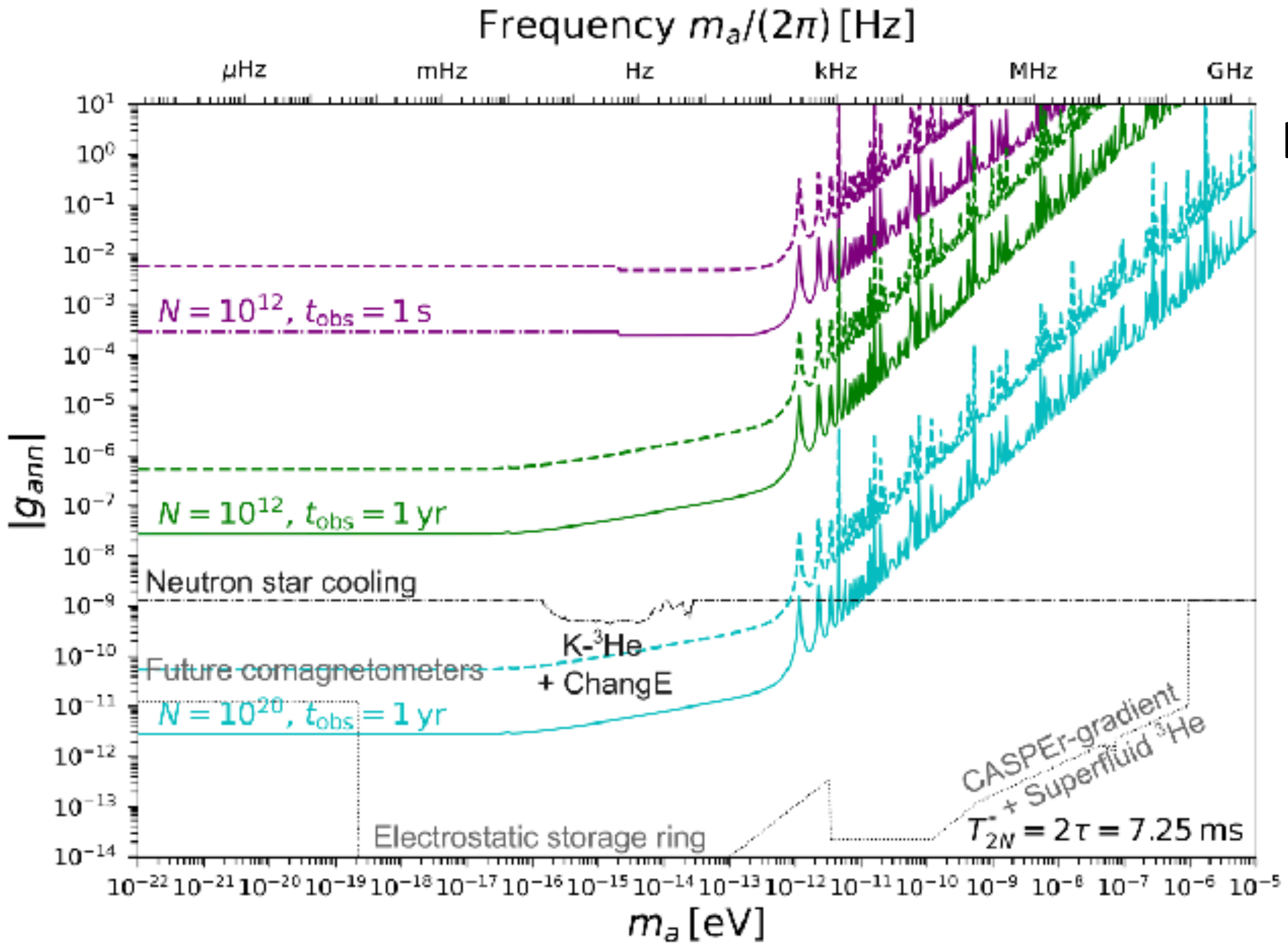


Living cell sensing



Geoscience & astrophysics



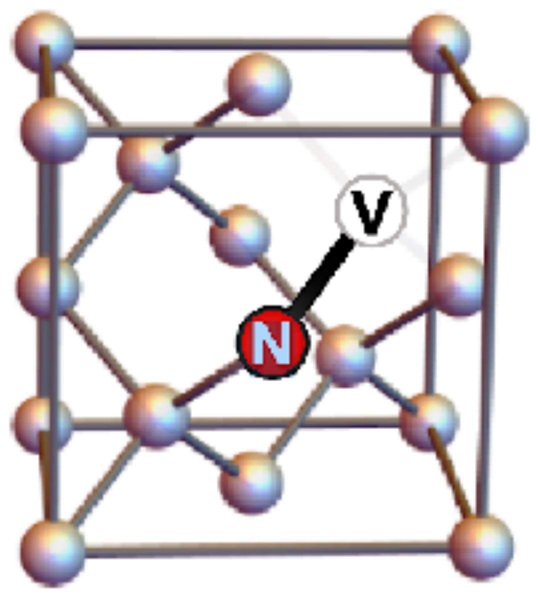


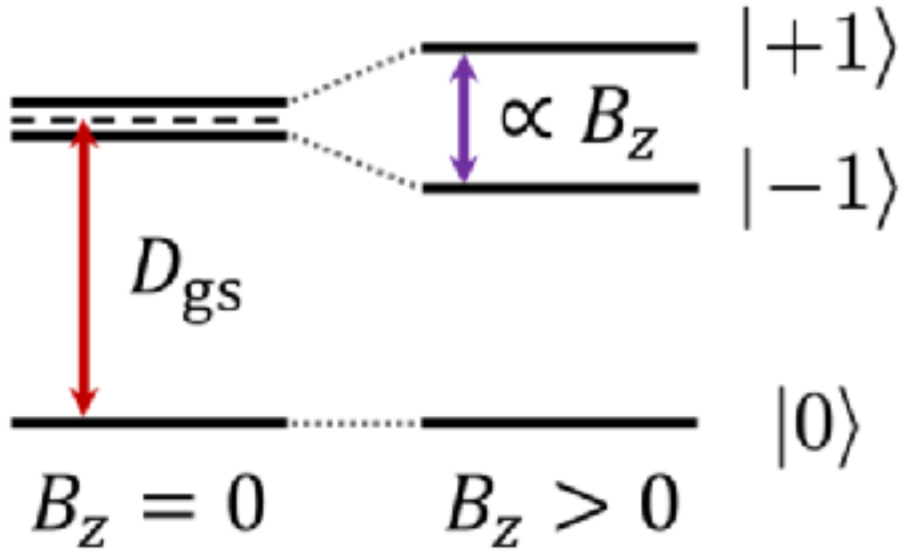
High energy physics & cosmology

Lovchinsky, et al. Science 2016
Zhang et al. ACS Sens. 2021
Kucsko, et al. Nature 2013
Fu et al. Science 2014
Chigusa, Phys. Rev. D 2025

NV center as a probe for quantum materials

- Noninvasive method
- Atomic size—can be placed close to target
- Can operate at room temperature
- Optical readout and spin manipulations
- Pure spin states sensitive to magnetic field





Casola, van der Sar, Yacoby, Nat. Rev. Mat. 2018
Rovny, Gopalakrishnan, Jayich, Maletinsky, Demler, de Leon, Nat. Rev. Phys. 2024
Liu, …, Chatterjee, Zu, arXiv:2502.04439

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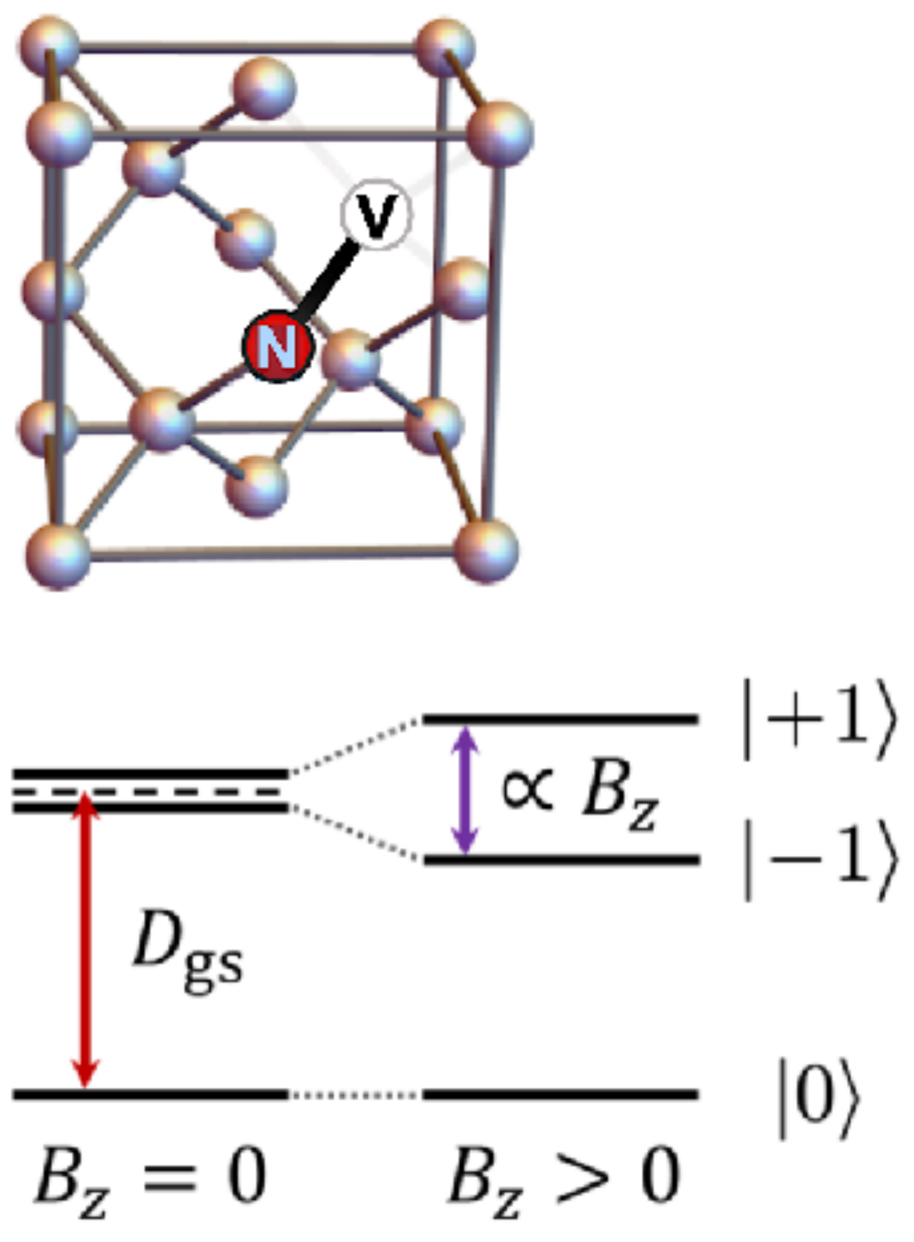

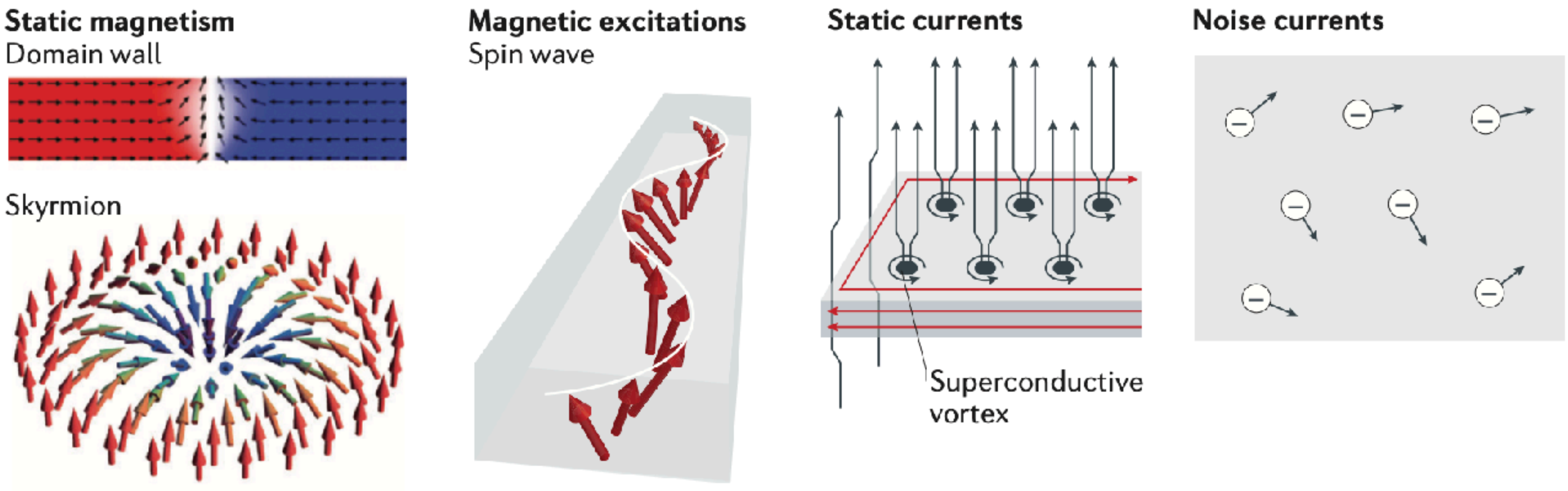

Casola, van der Sar, Yacoby, Nat. Rev. Mat. 2018
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NV center as a probe for quantum materials

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- Atomic size—can be placed close to target
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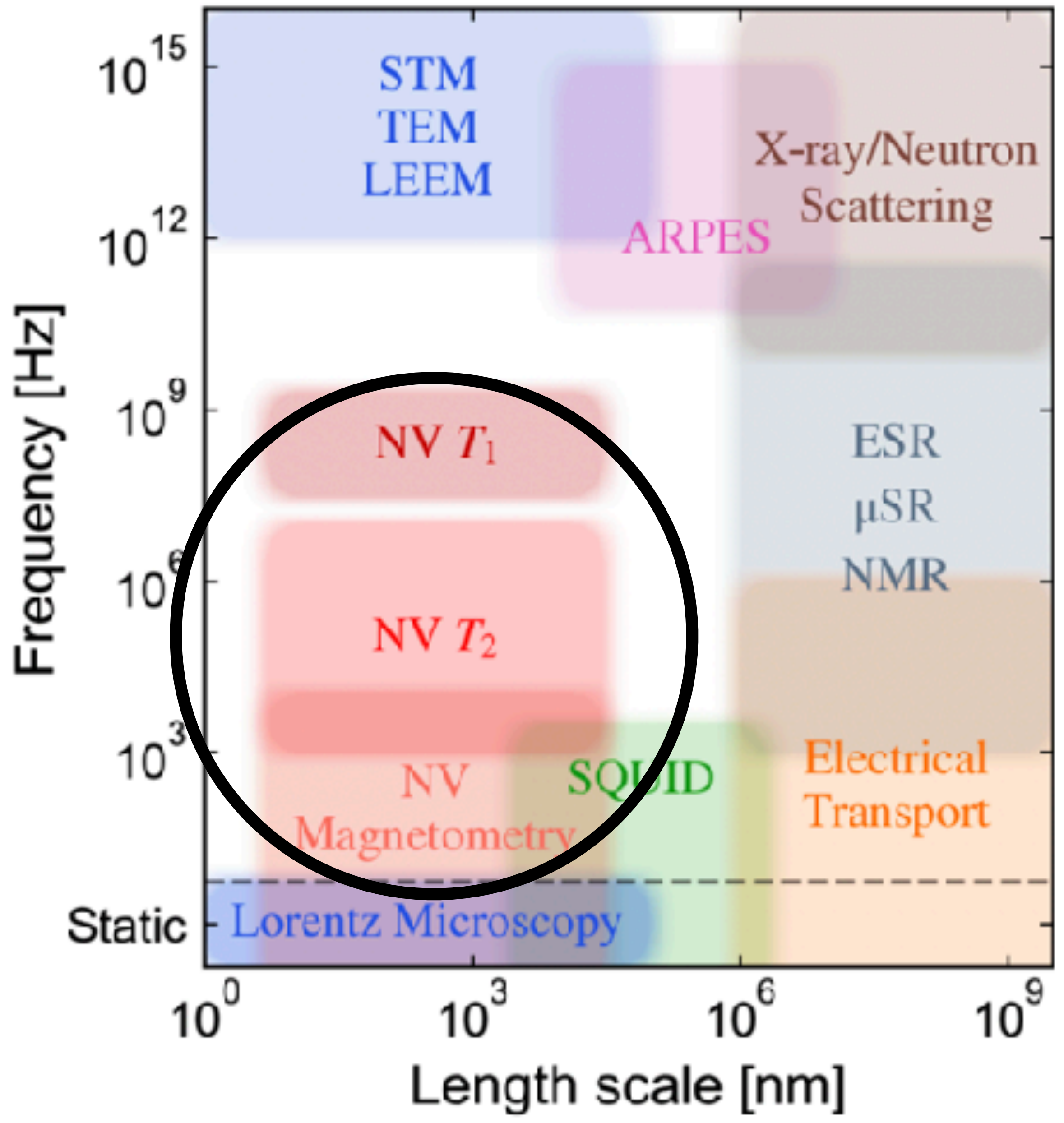
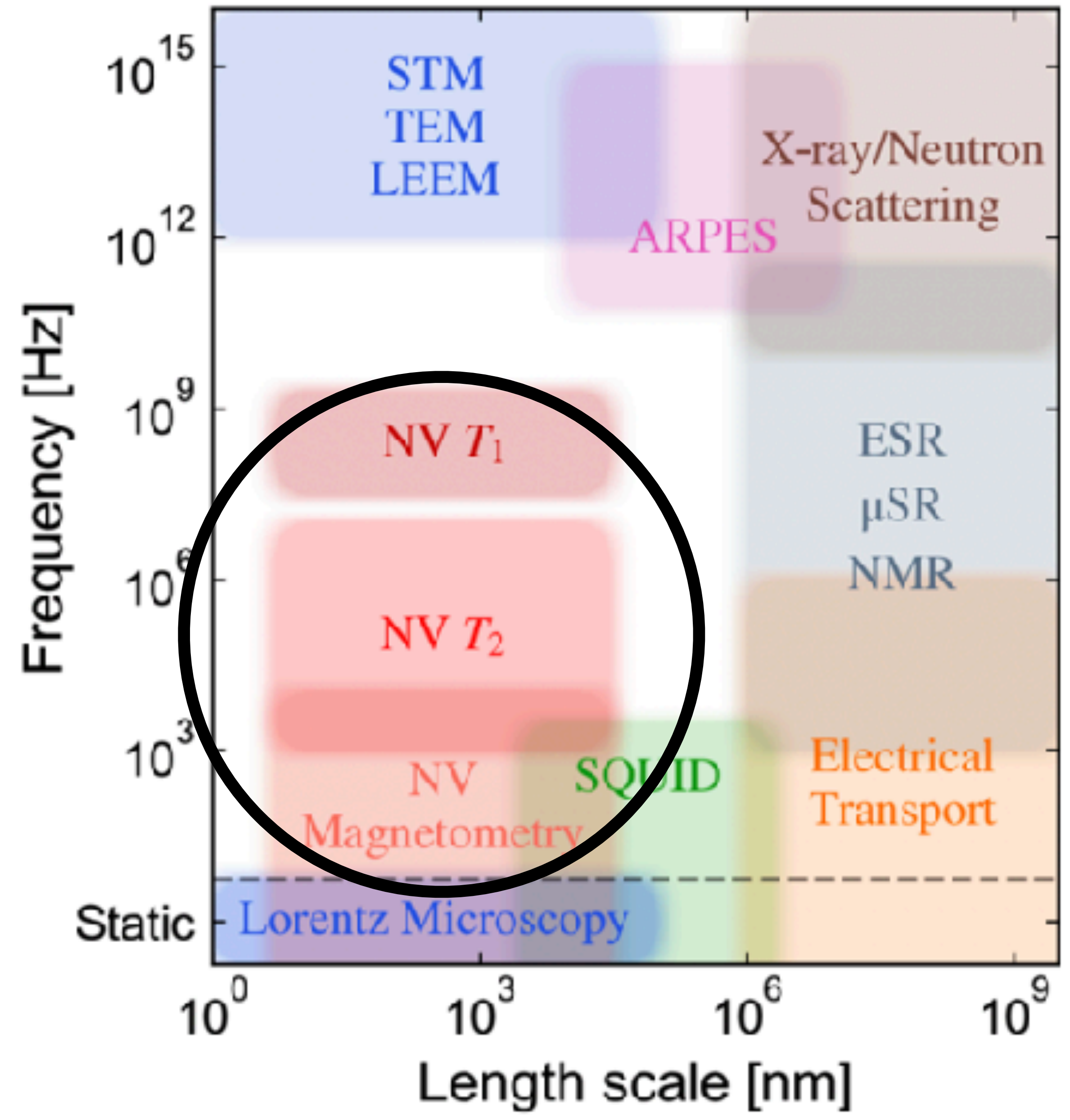
- Optical readout and spin manipulations
- Pure spin states sensitive to magnetic field
- Complementary to conventional material characterization



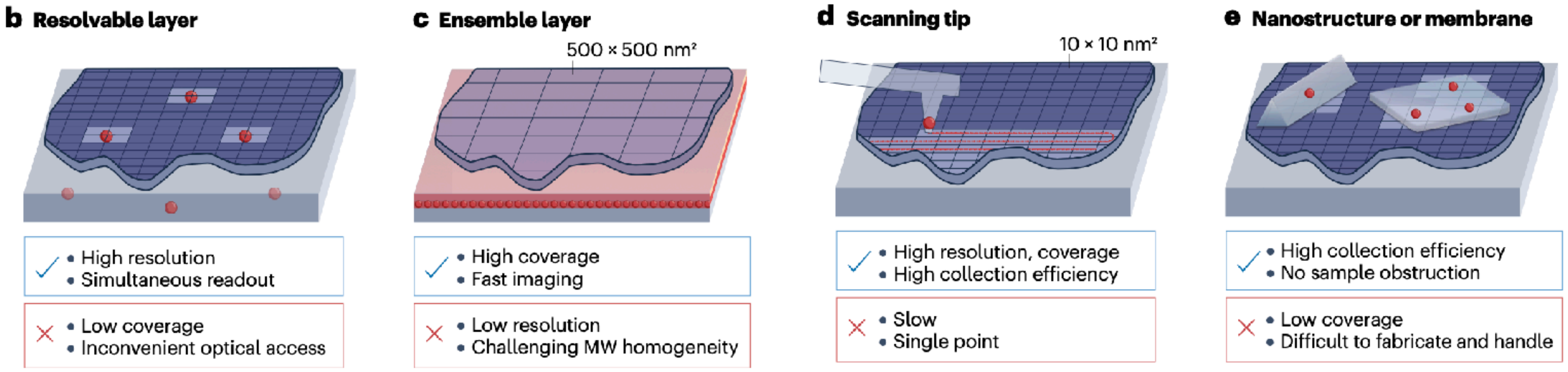
Casola, van der Sar, Yacoby, Nat. Rev. Mat. 2018
Rovny, Gopalakrishnan, Jayich, Maletinsky, Demler, de Leon, Nat. Rev. Phys. 2024
Liu, …, Chatterjee, Zu, arXiv:2502.04439

NV center as a probe for quantum materials

- Noninvasive method
- Atomic size—can be placed close to target
- Can operate at room temperature
- Optical readout and spin manipulations
- Pure spin states sensitive to magnetic field
- Complementary to conventional material characterization
- Various sensing platforms to suit different needs

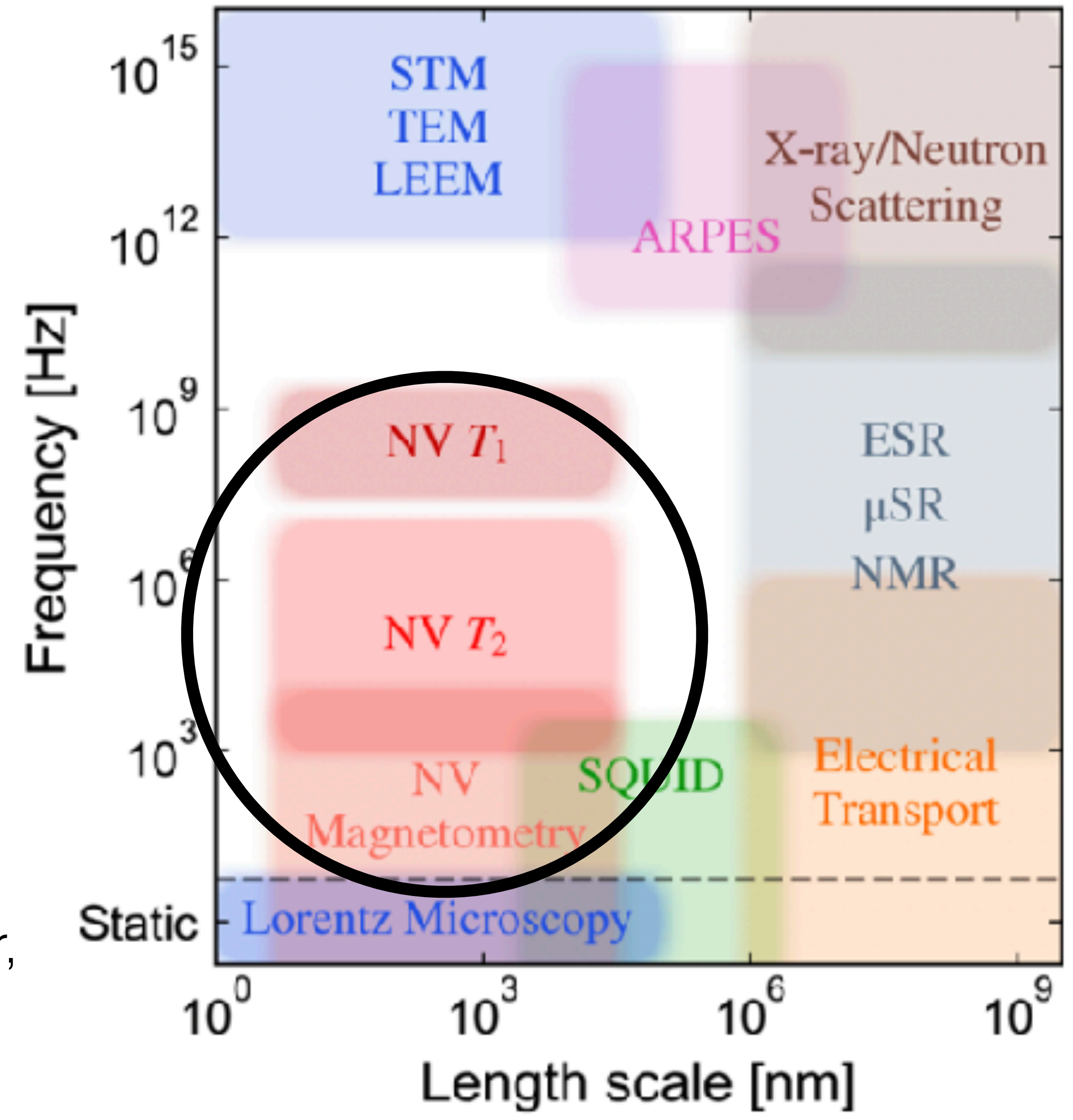


Casola, van der Sar, Yacoby, Nat. Rev. Mat. 2018
Rovny, Gopalakrishnan, Jayich, Maletinsky, Demler, de Leon, Nat. Rev. Phys. 2024
Liu, …, Chatterjee, Zu, arXiv:2502.04439

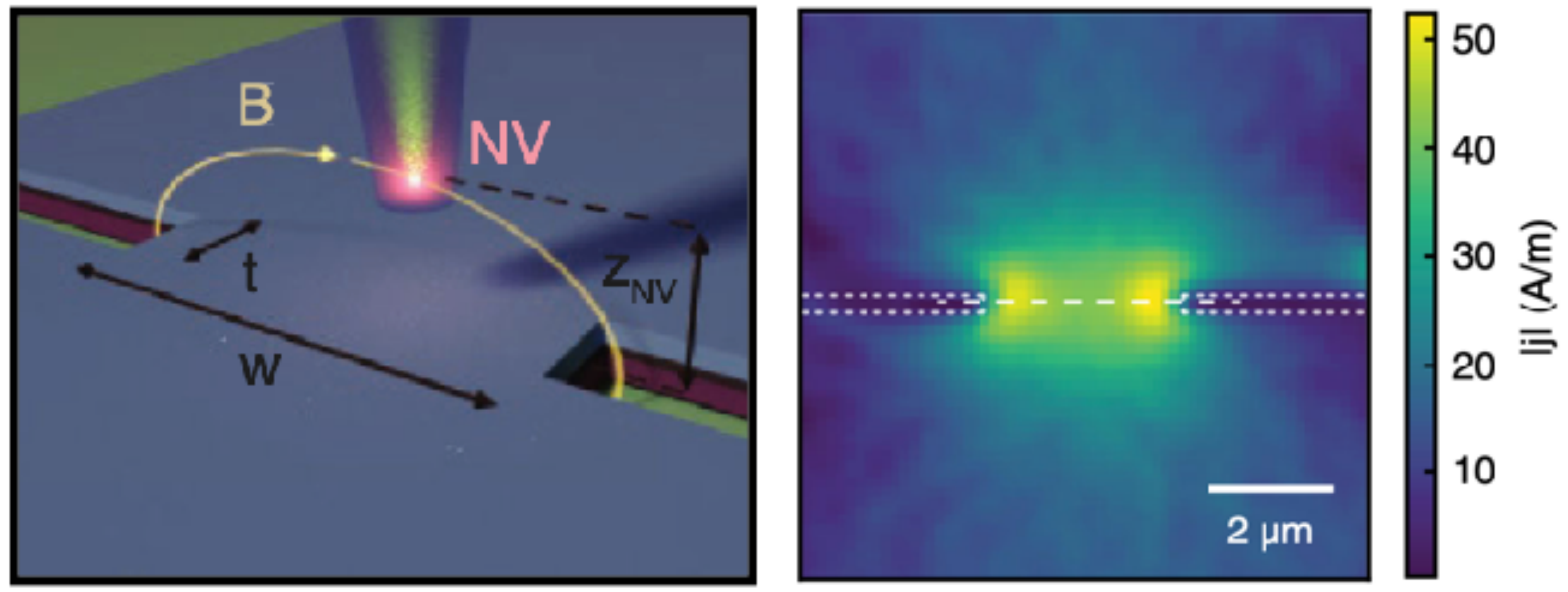


NV noise spectroscopy of quantum materials

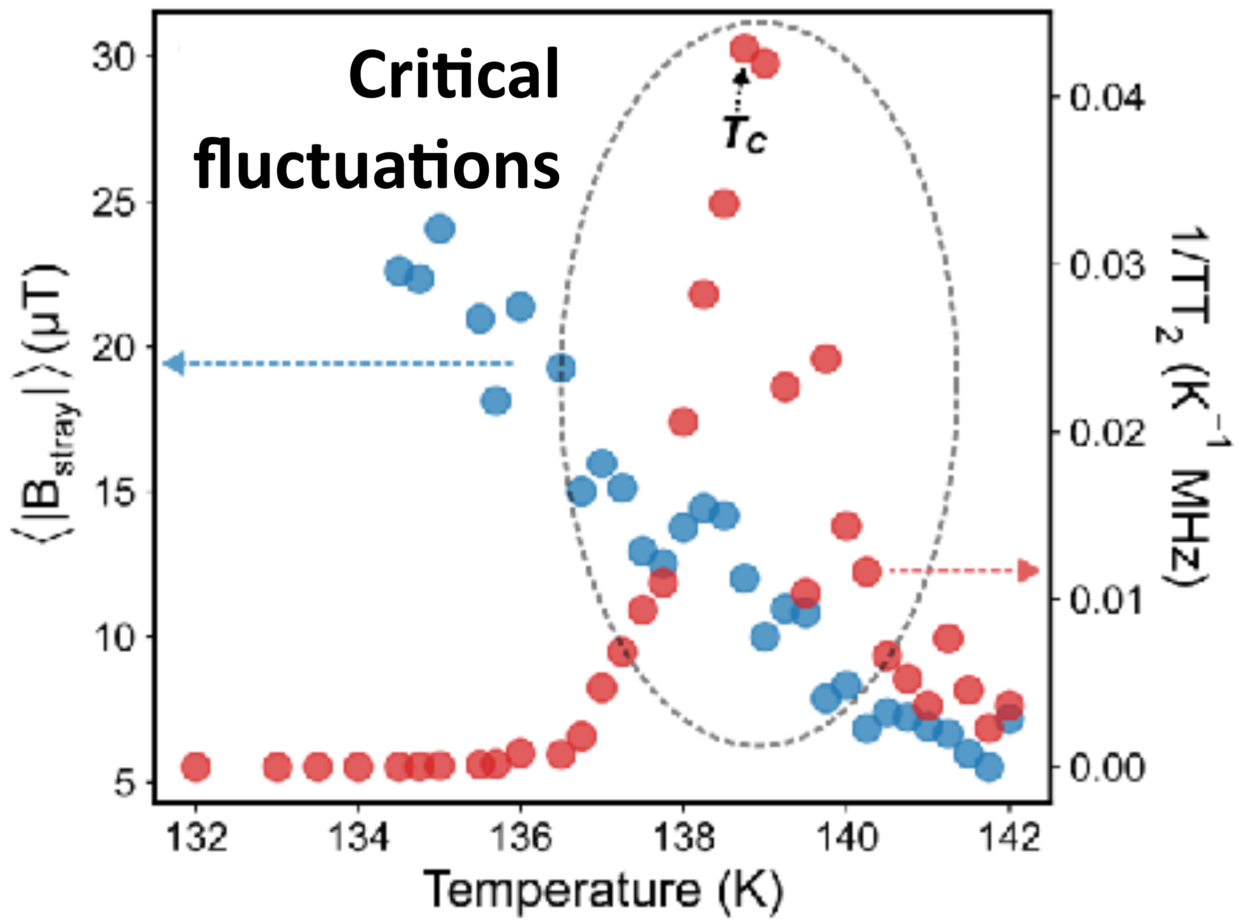
- Mesoscopic dynamics and transport properties
- Mesoscopic phase transitions
- New magnetic phases/excitations…



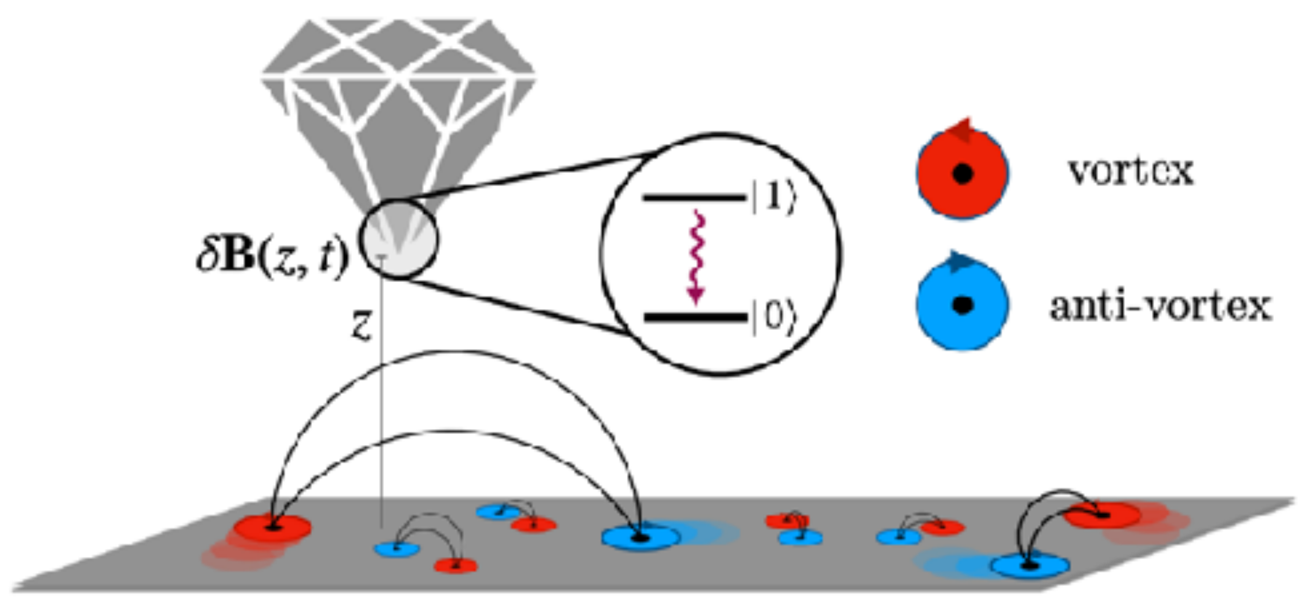
Electron hydrodynamics



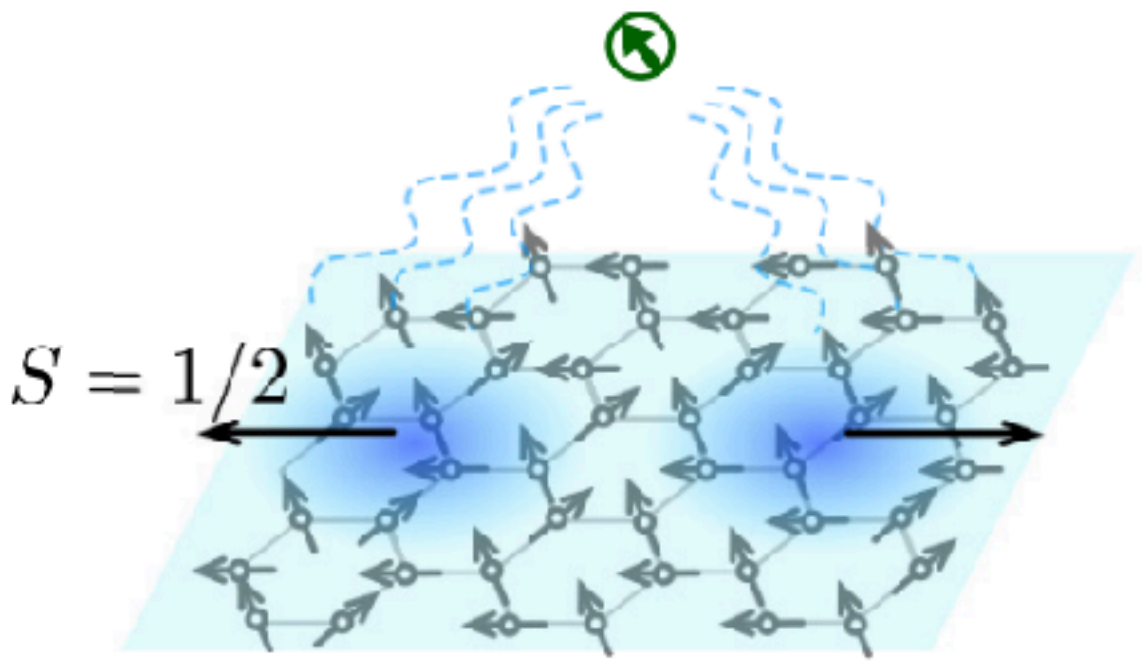
Liu, …, Chatterjee, Zu, arXiv:2502.04439
Jenkins et al. Phys. Rev. Lett. 2022
Chatterjee, Rodriguez-Nieva, and Demler, Phys. Rev. B 2019
Curtis, …, Demler, Phys. Rev. B 2024
Ziffer et al. arXiv:2407.05614



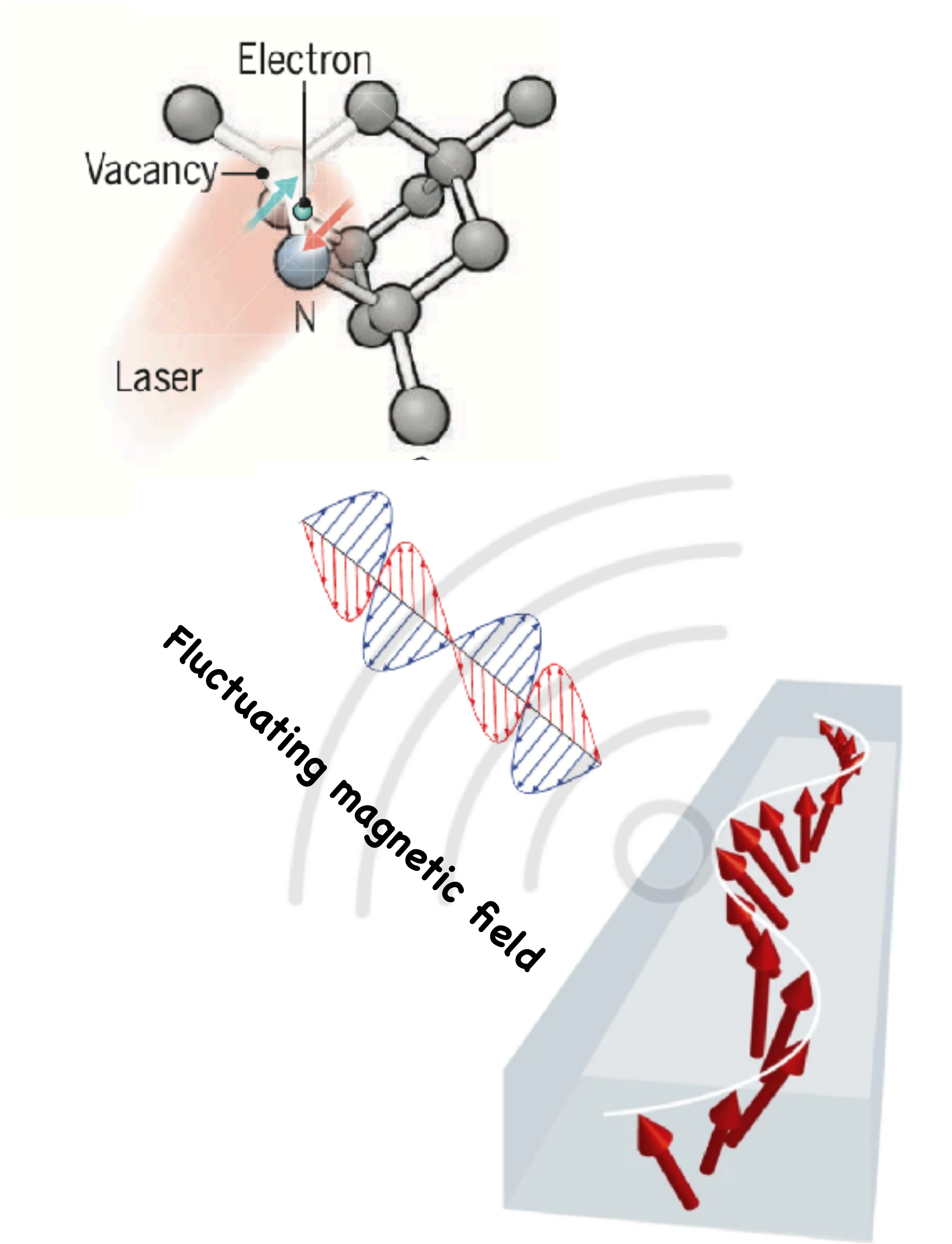
Unconventional superconductors



Quantum spin liquid

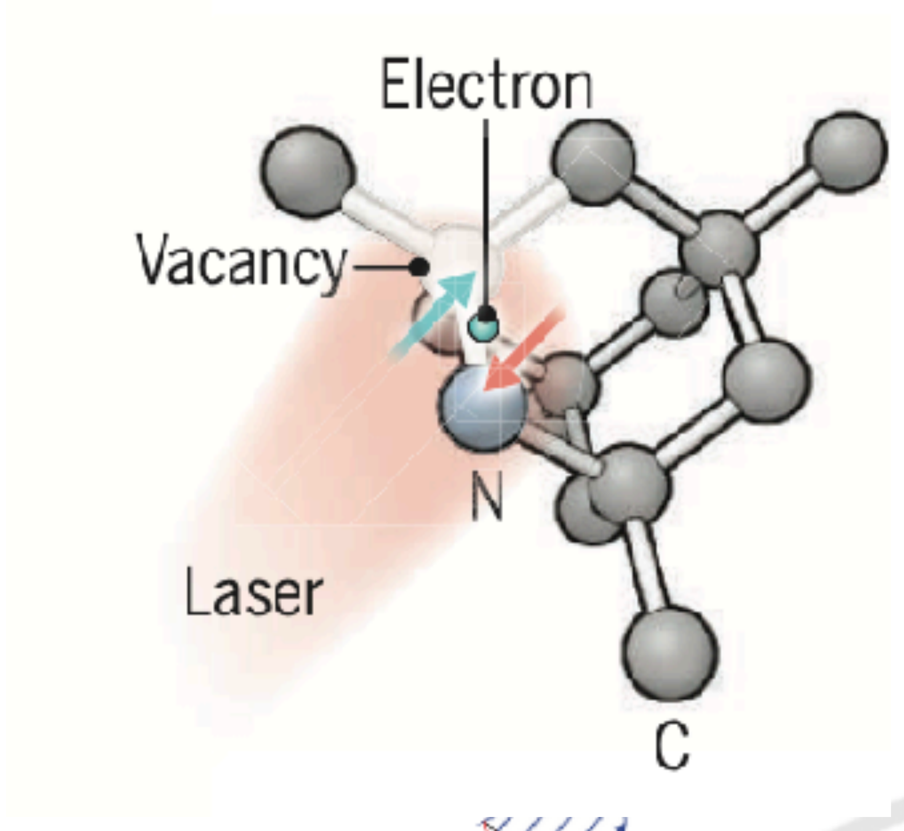


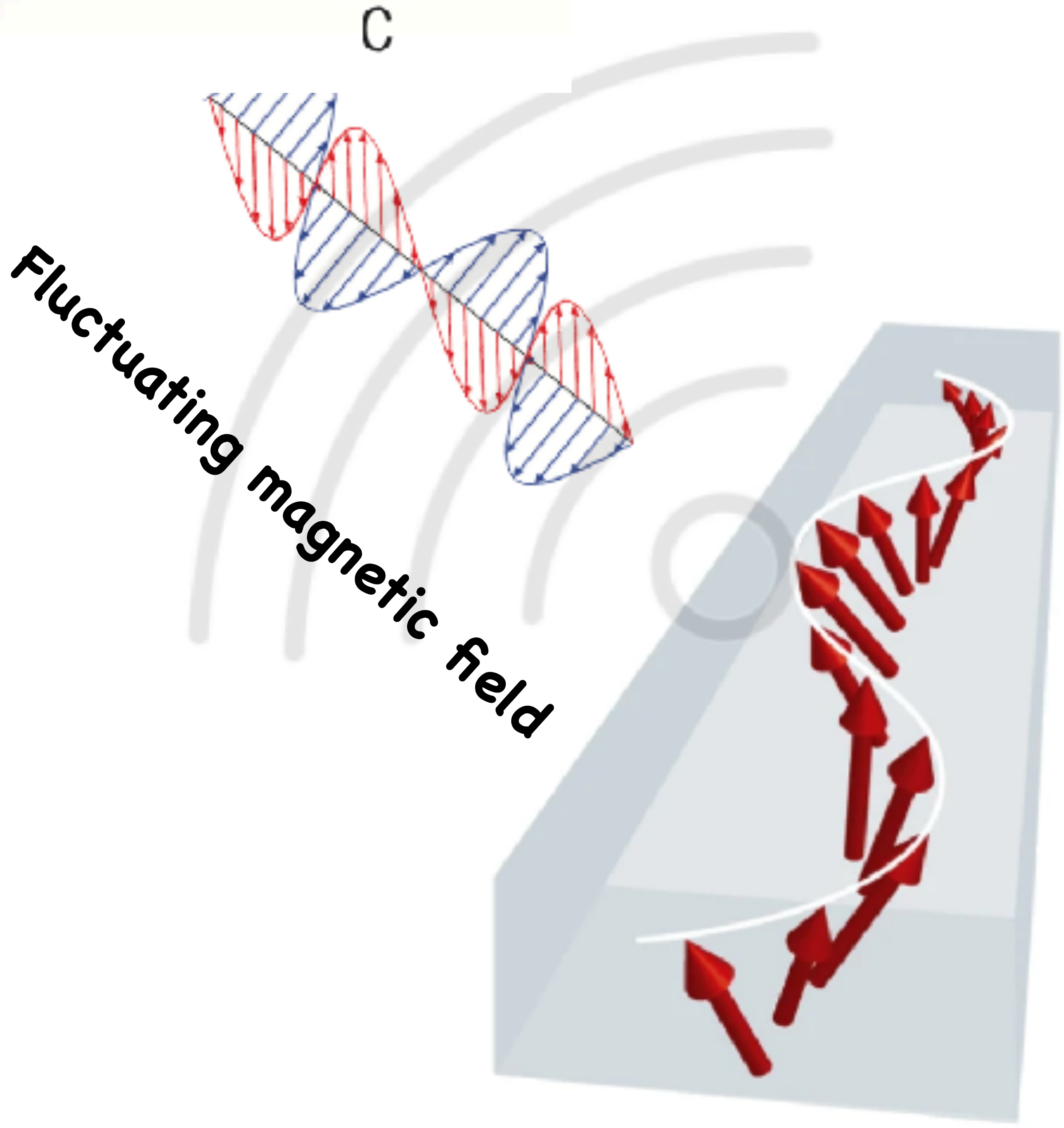
NV probe of spin dynamics and transport

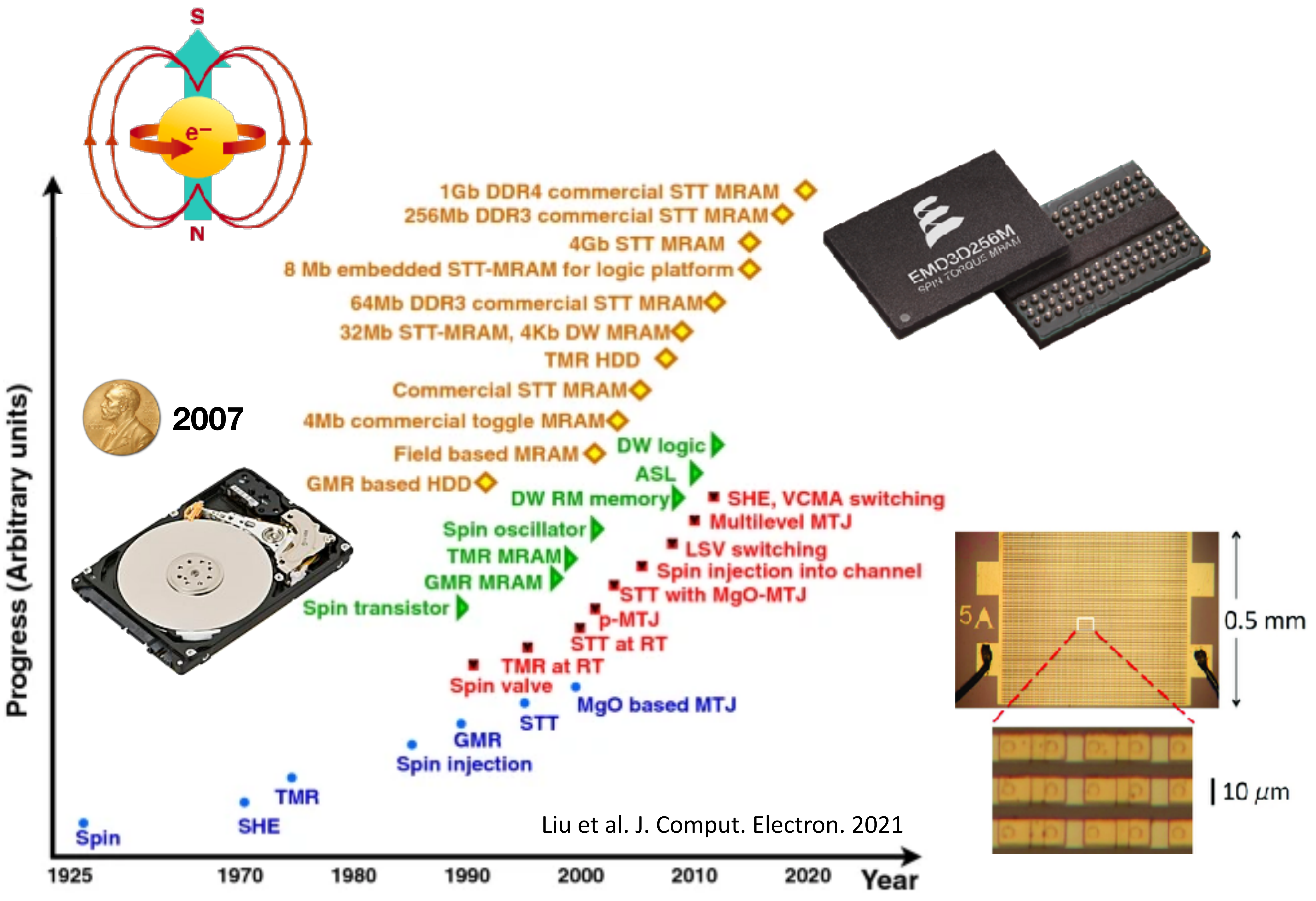


NV probe of spin dynamics and transport

Spintronics

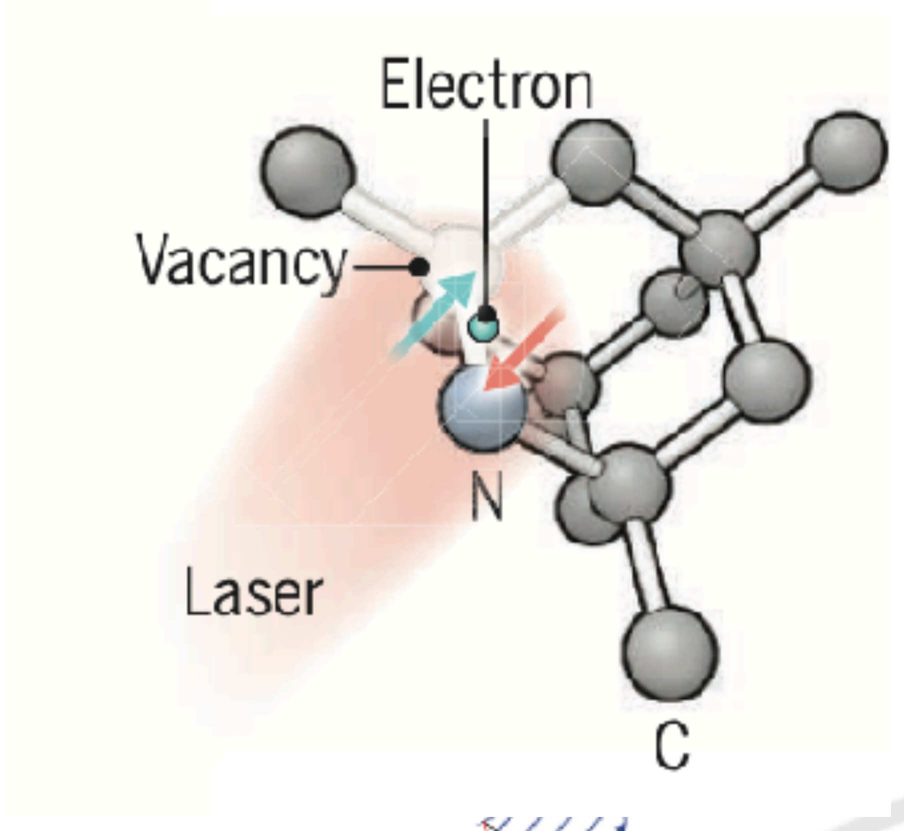


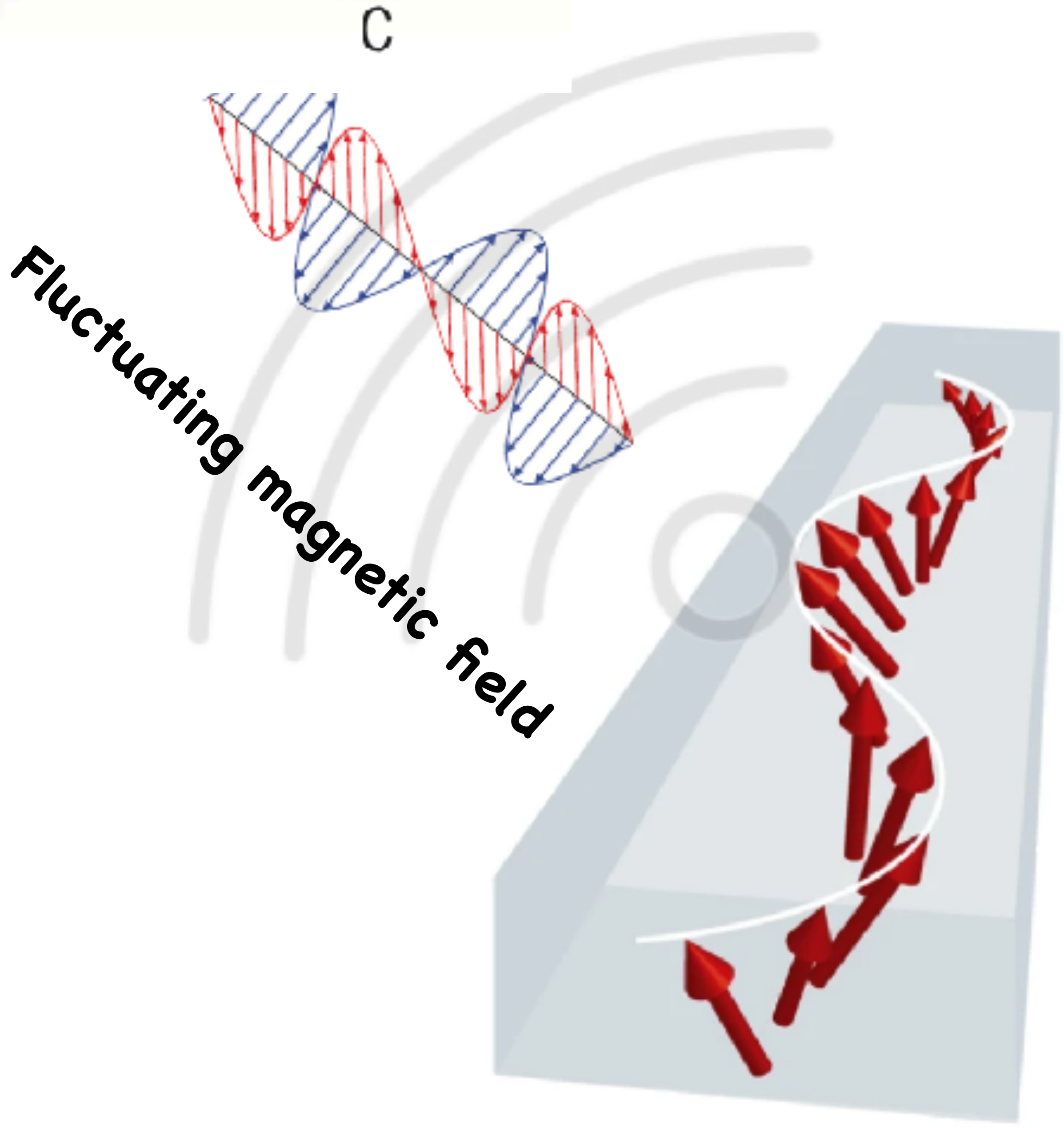


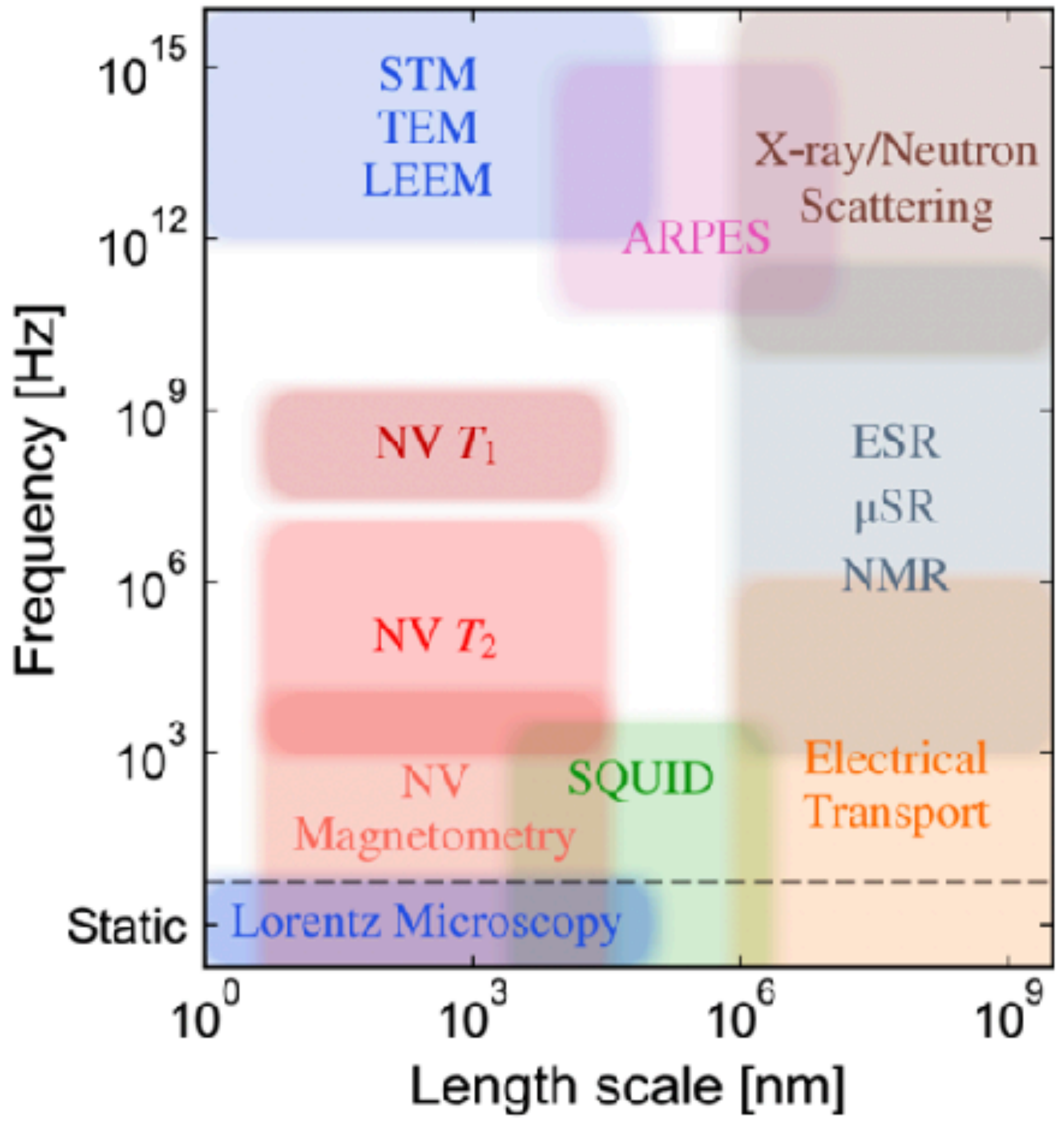


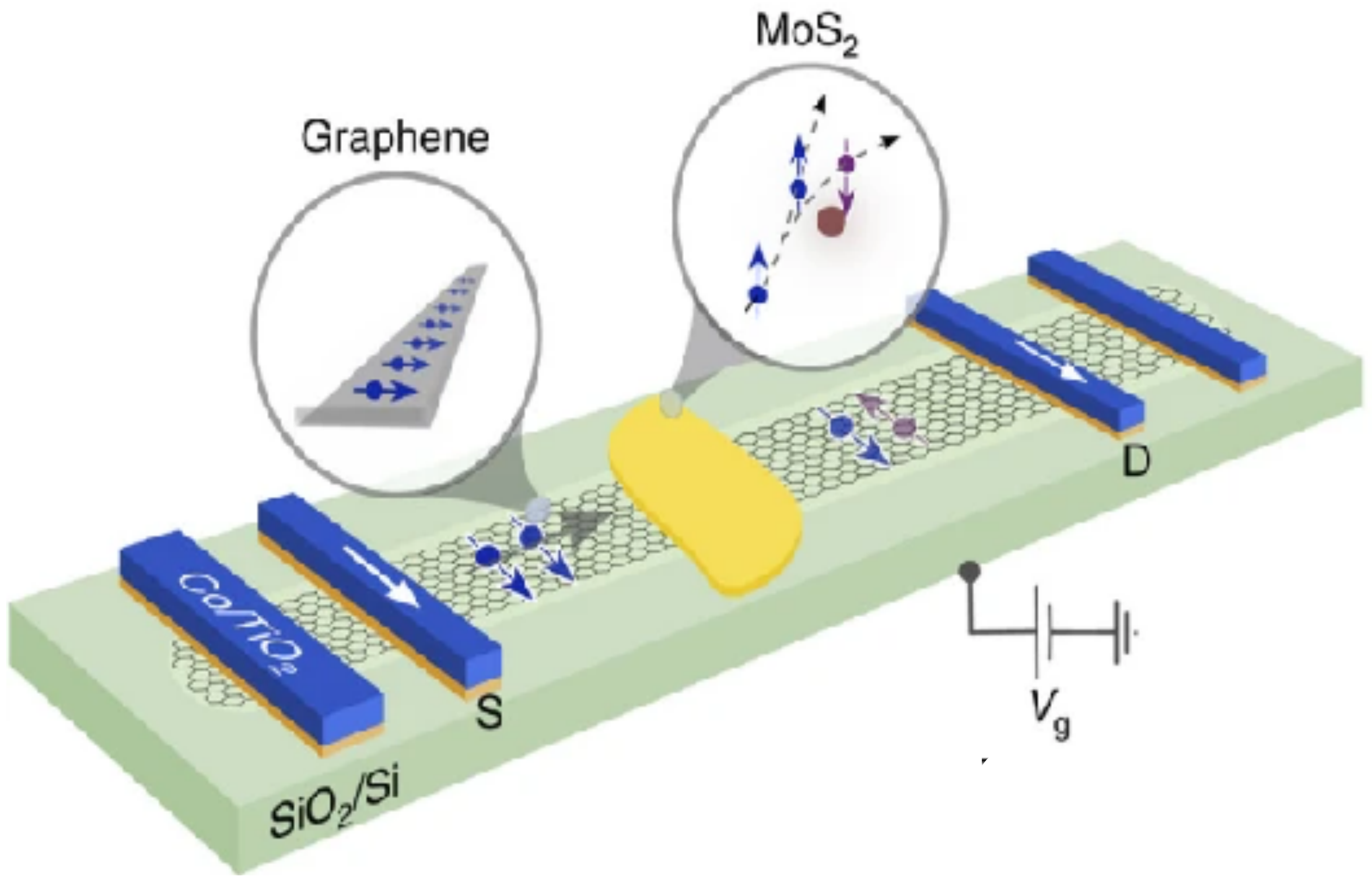
Liu et al. J. Comput. Electron. 2021

NV probe of spin dynamics and transport



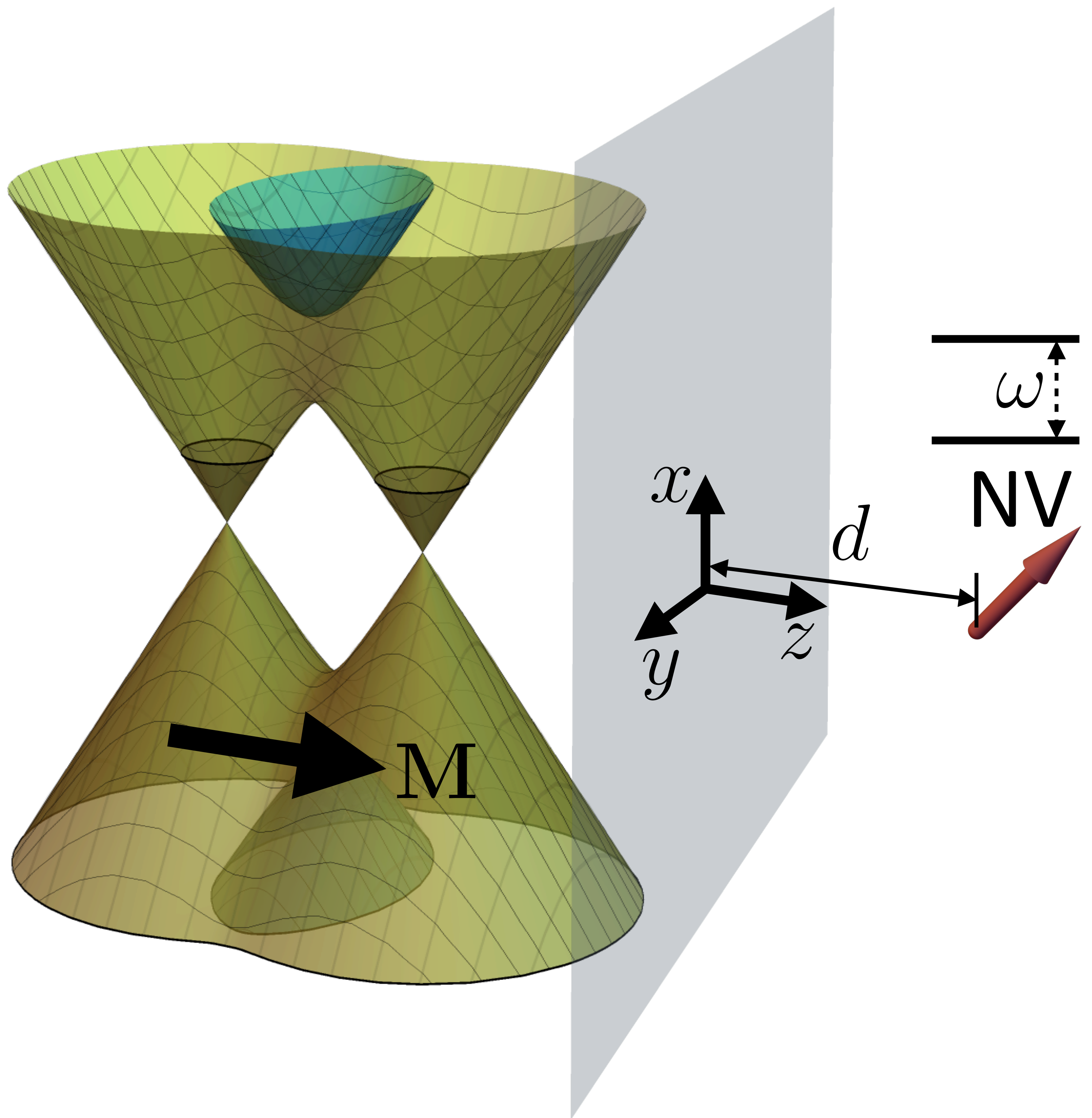




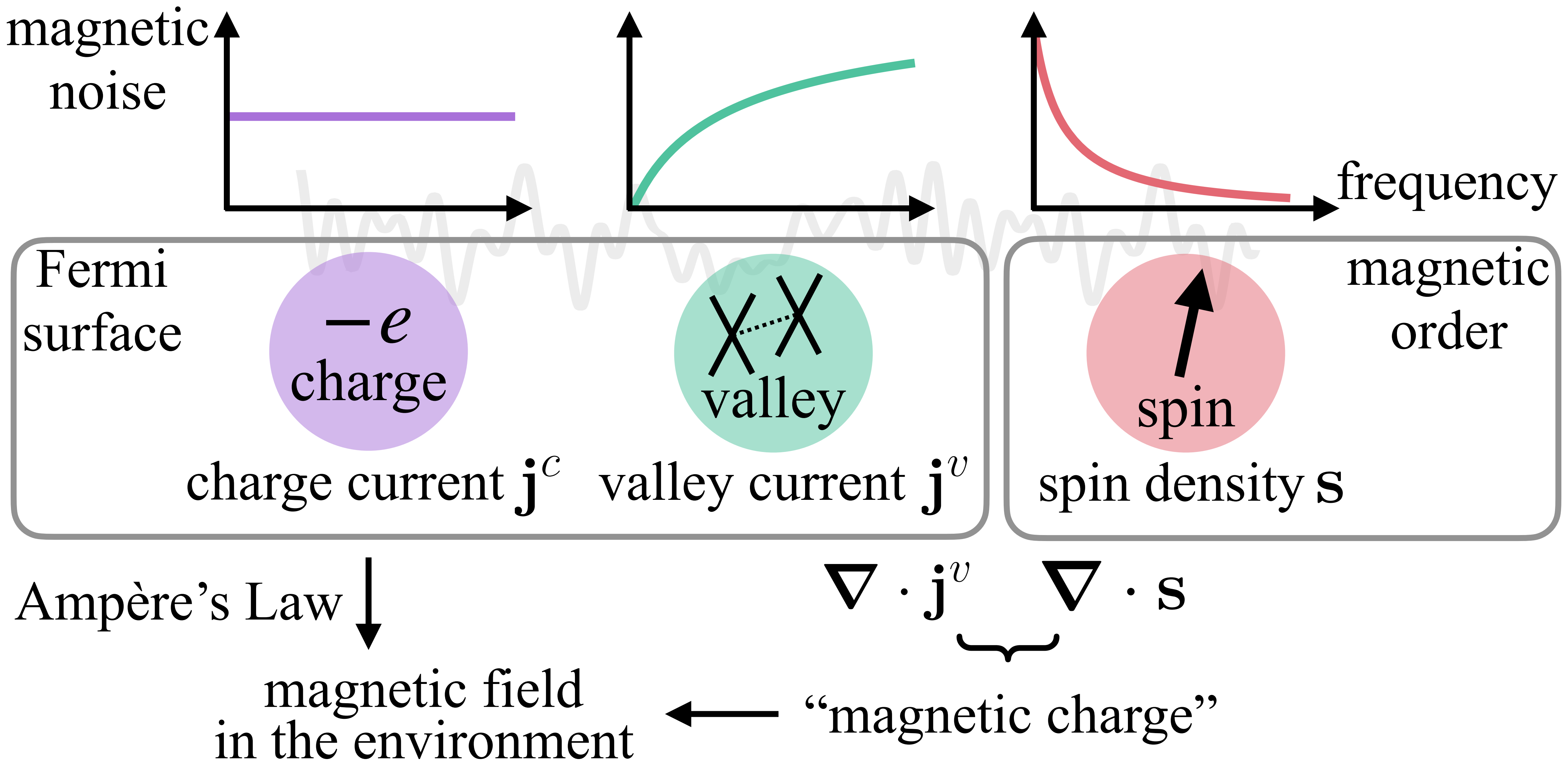


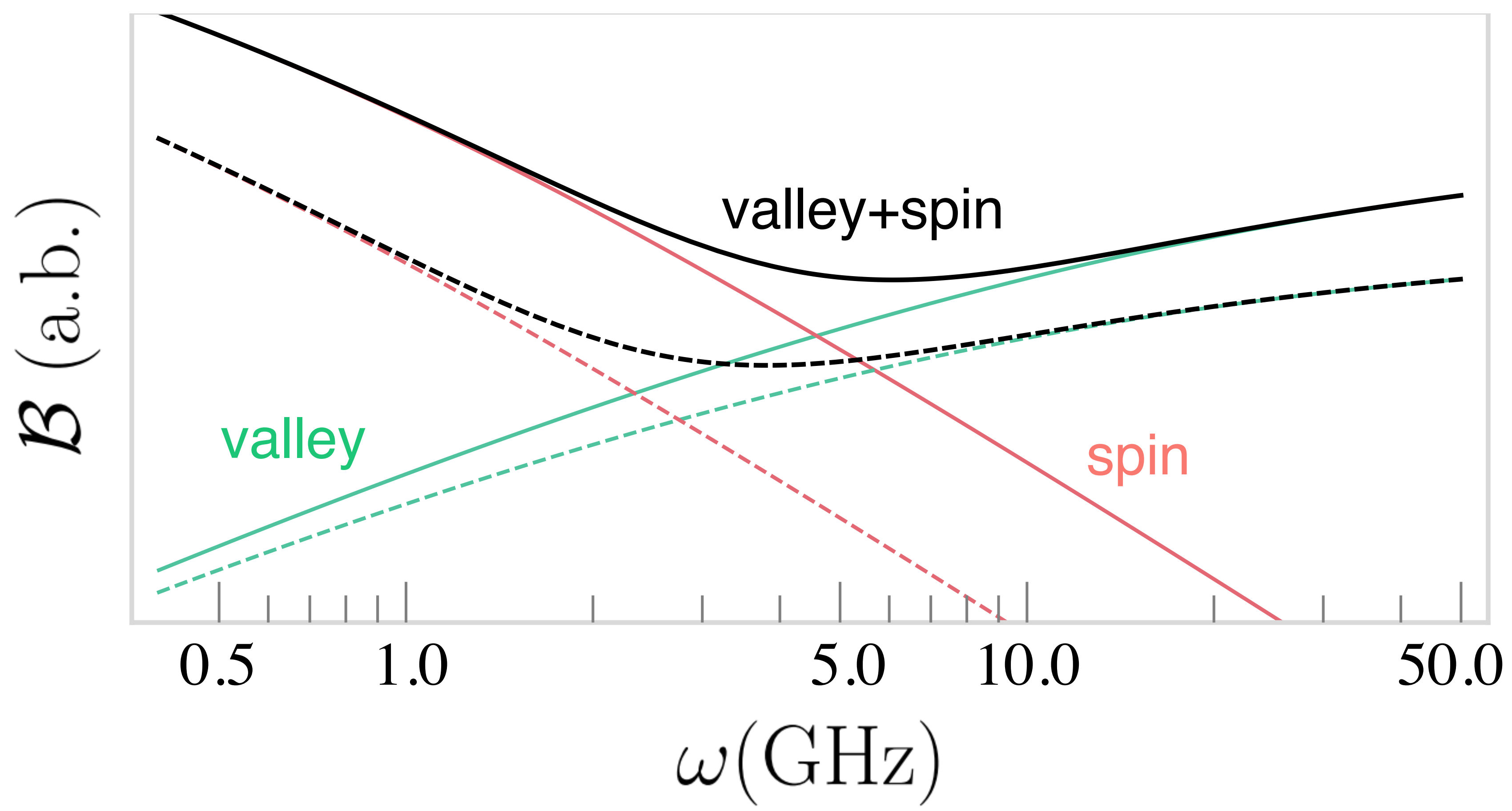
Liu, …, Chatterjee, Zu, arXiv:2502.04439
Dankert and Dash, Nat. Commun. 2017

Ex1. Charge-neutral transport channels



SZ and Tserkovnyak, *Phys. Rev. B. Letter* 2022

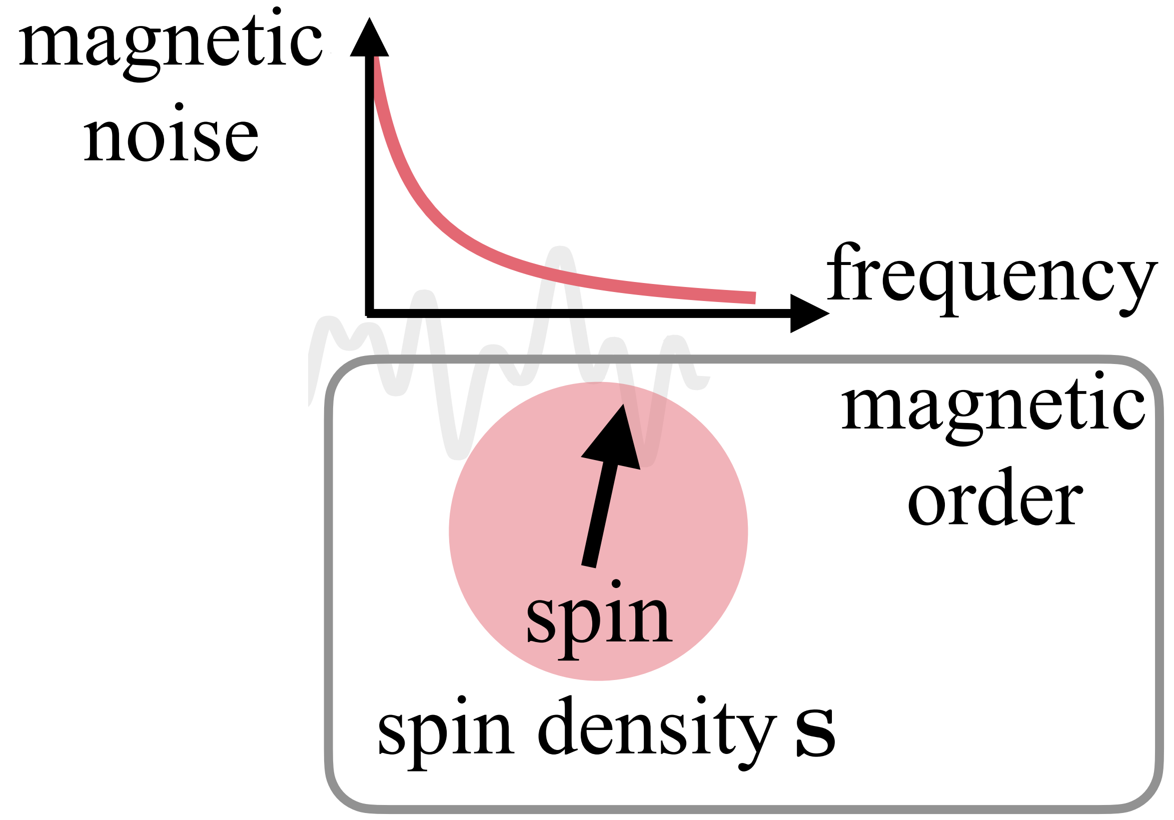




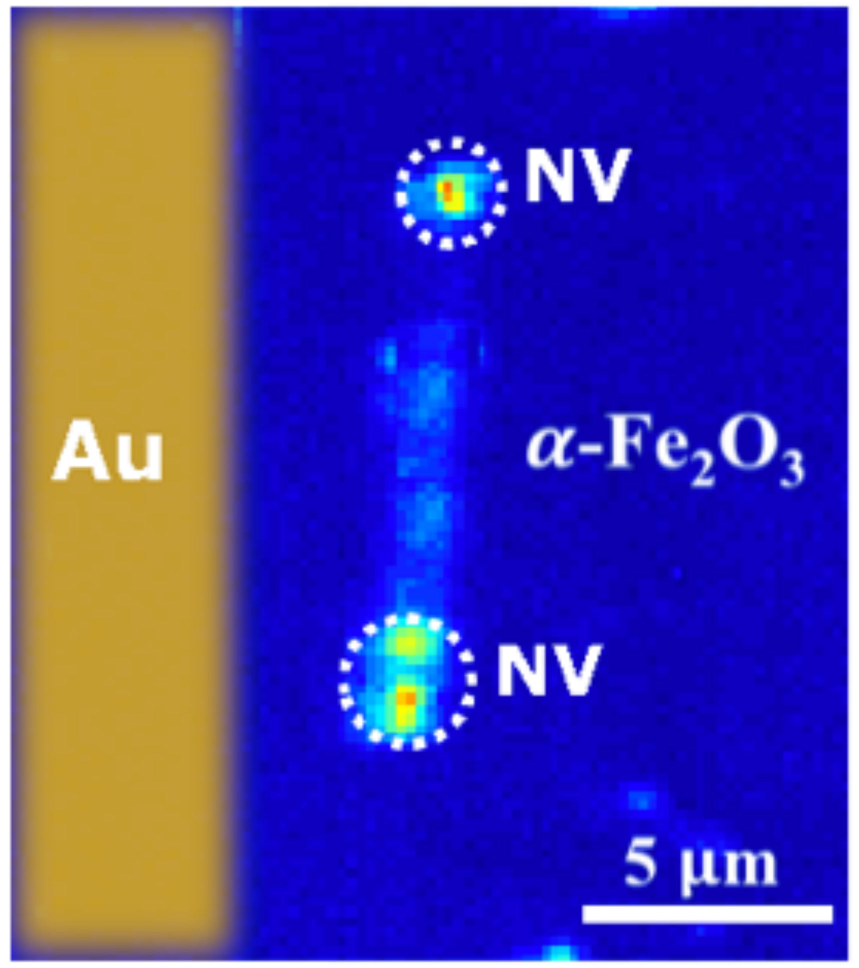
Ex2. Spin transport in antiferromagnetic insulators

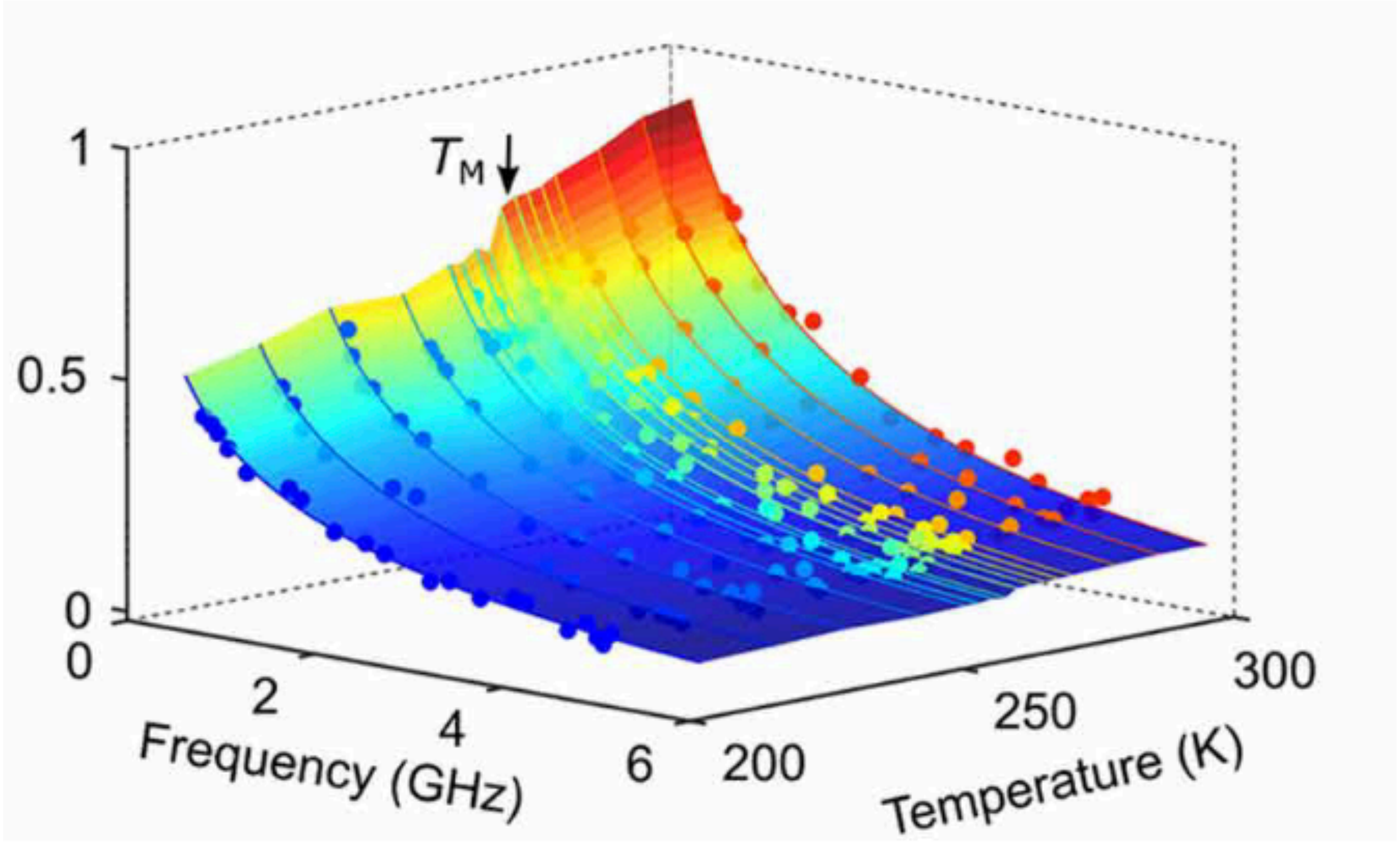
$$\partial_t s_\parallel - D\nabla^2 s_\parallel = -\frac{1}{\tau_s} s_\parallel$$

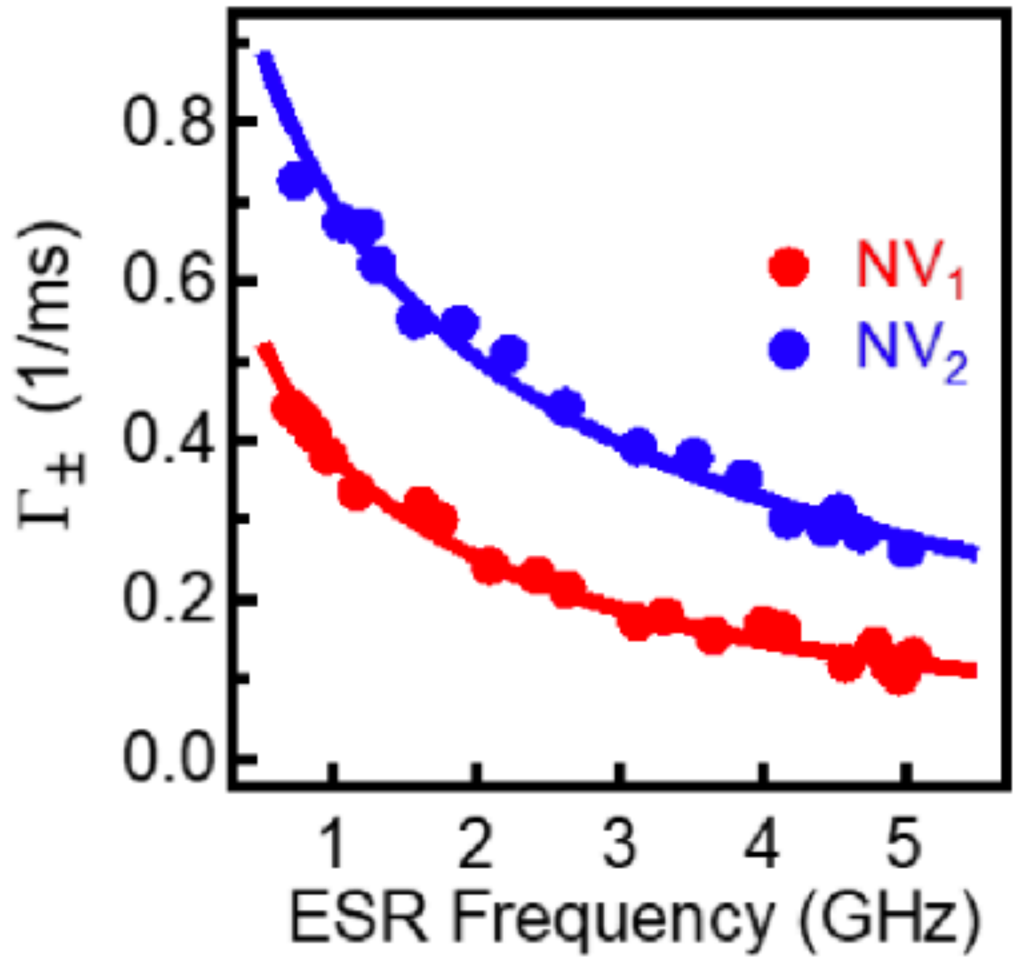
Longitudinal spin density **Spin diffusion constant** Spin relaxation time



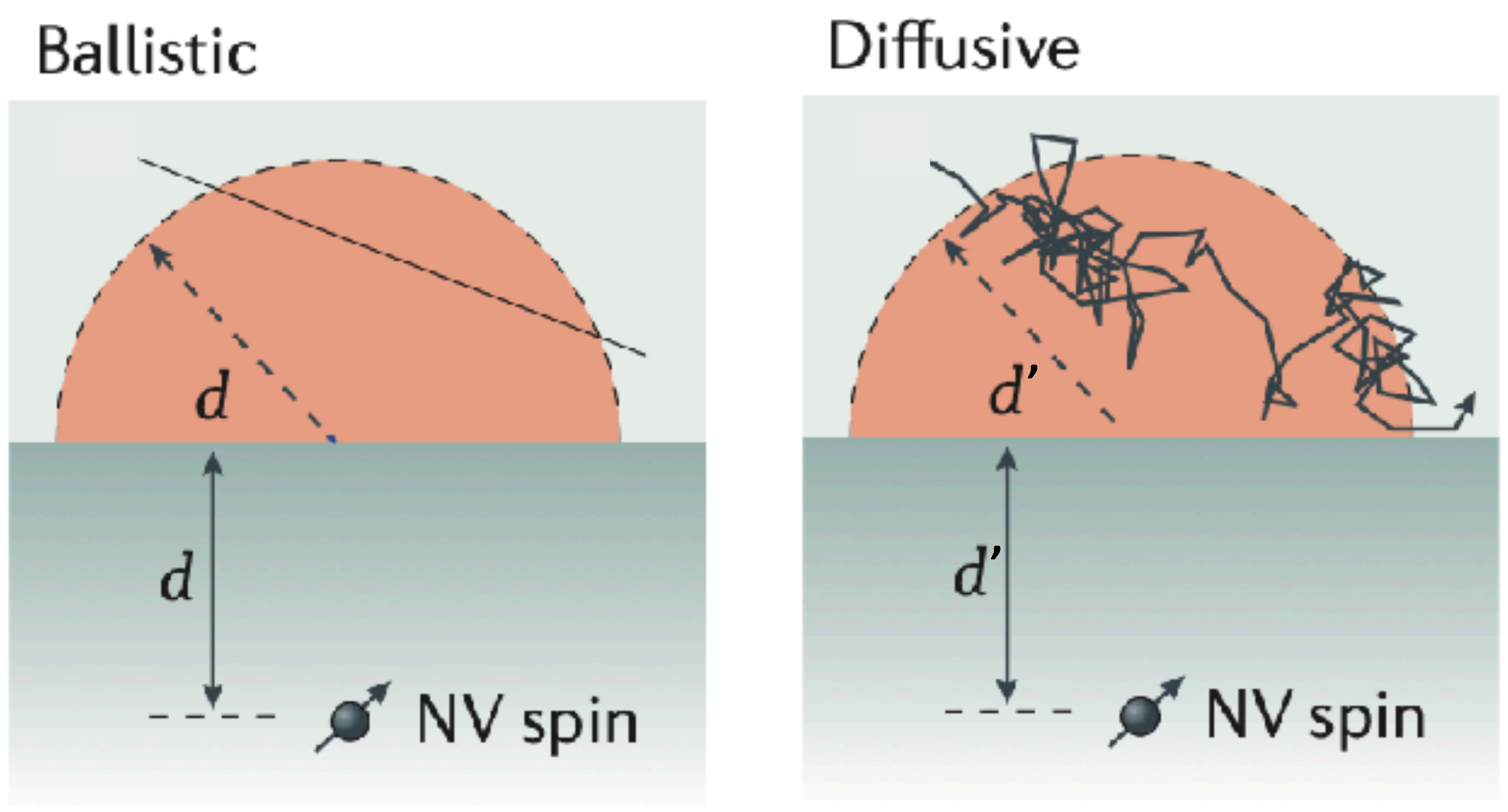
Wang, **SZ**, …, Tserkovnyak, Du, Sci. Adv. 2022

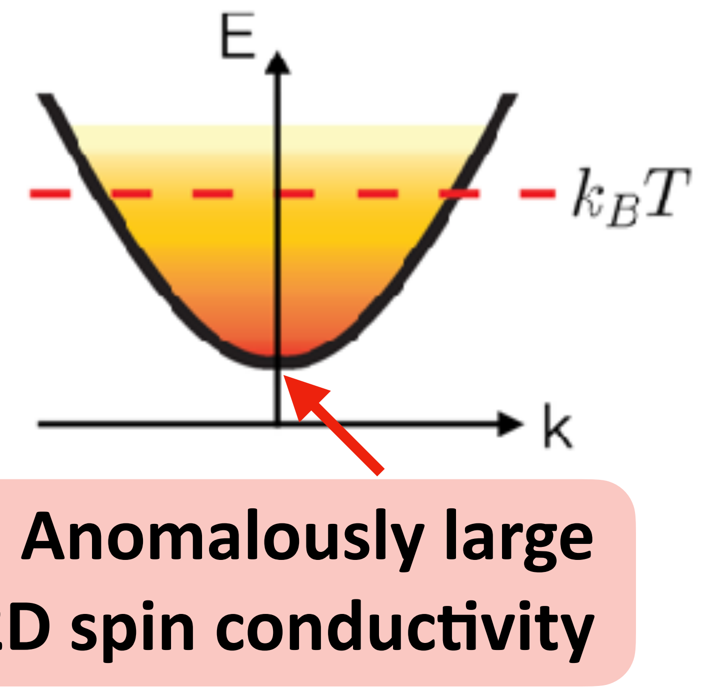




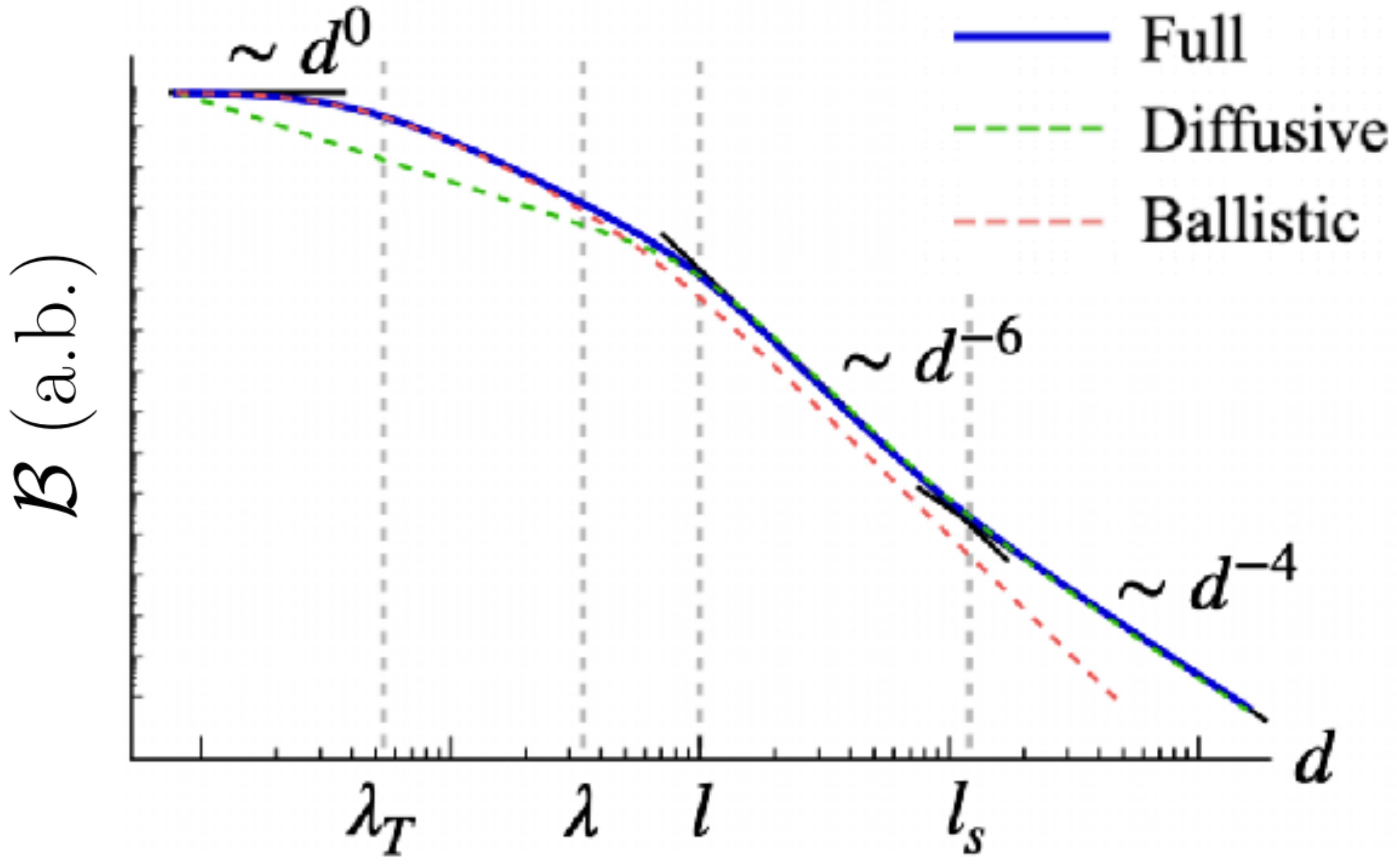


Ex3. Different regimes of spin transport





Wei, …, van Wees, Nat. Mater. 2022



Ballistic < Momentum relaxation < Spin relaxation

Length scales:

- λ_T thermal magnon wavelength
- λ dominating in spin diffusion
- l magnon mean free path
- l_s magnon diffusion length

Fang, **SZ**, Tserkovnyak, Phys. Rev. B 2022

Ex4. Topological phase transition in 2D magnets

Algebraic spin correlation

Berezinskii-Kosterlitz-Thouless phase

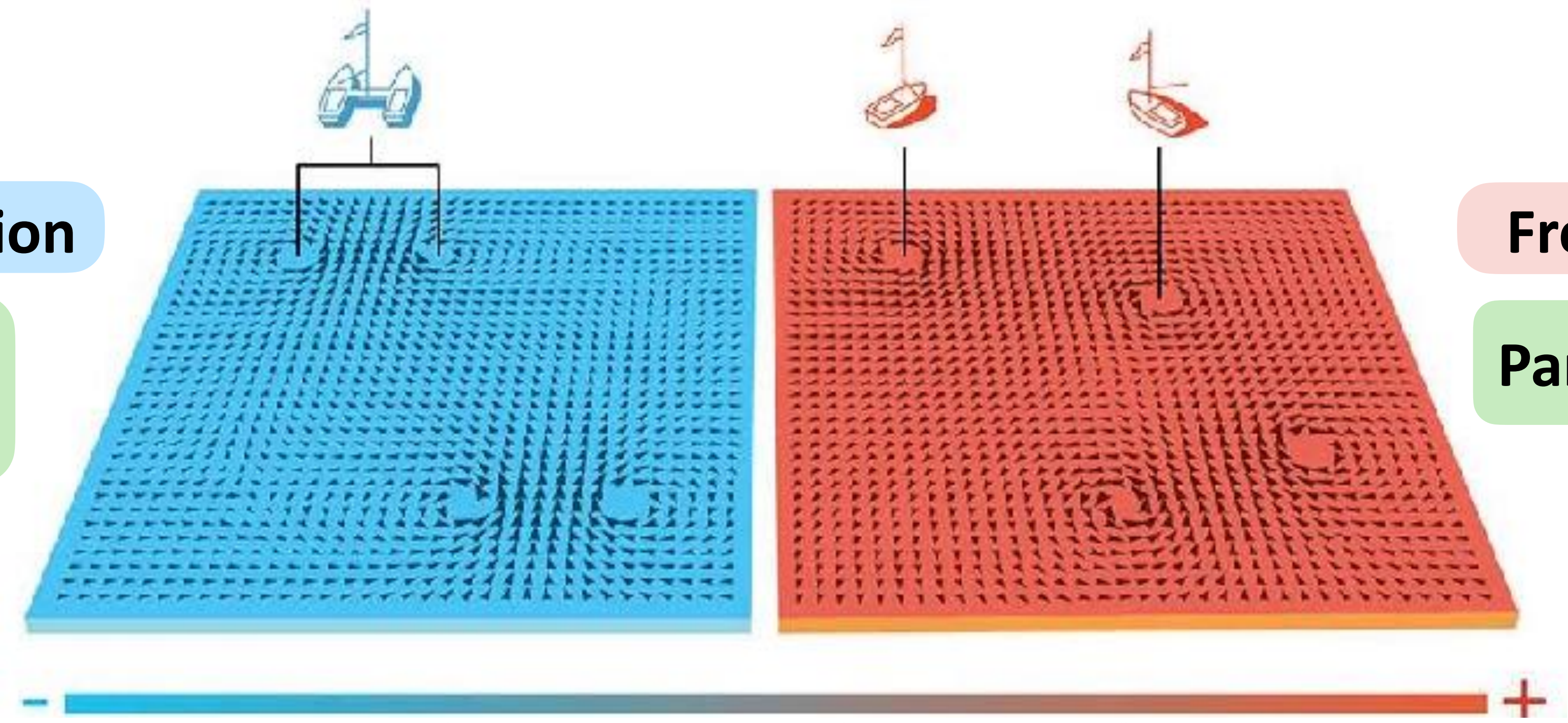
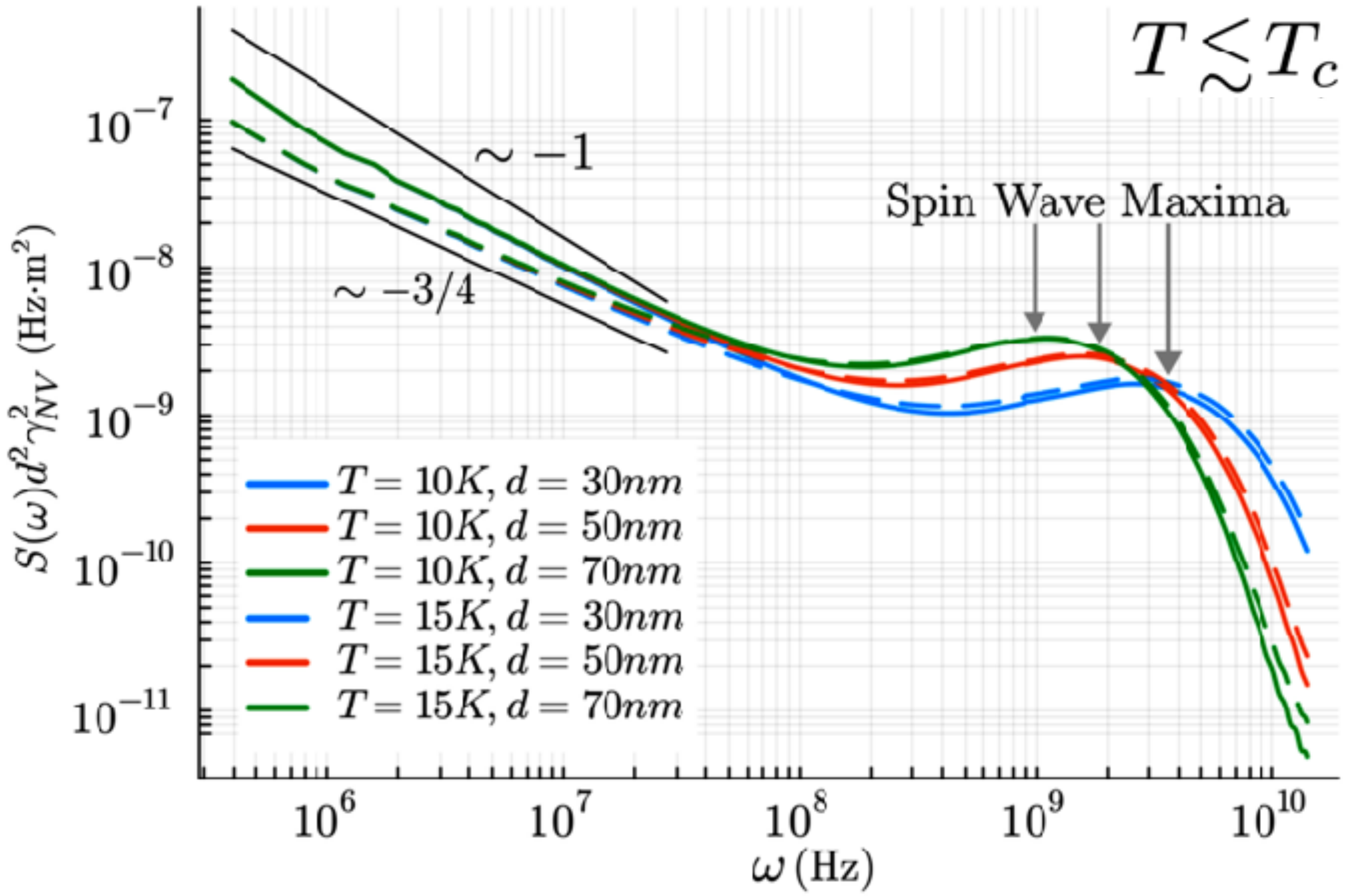
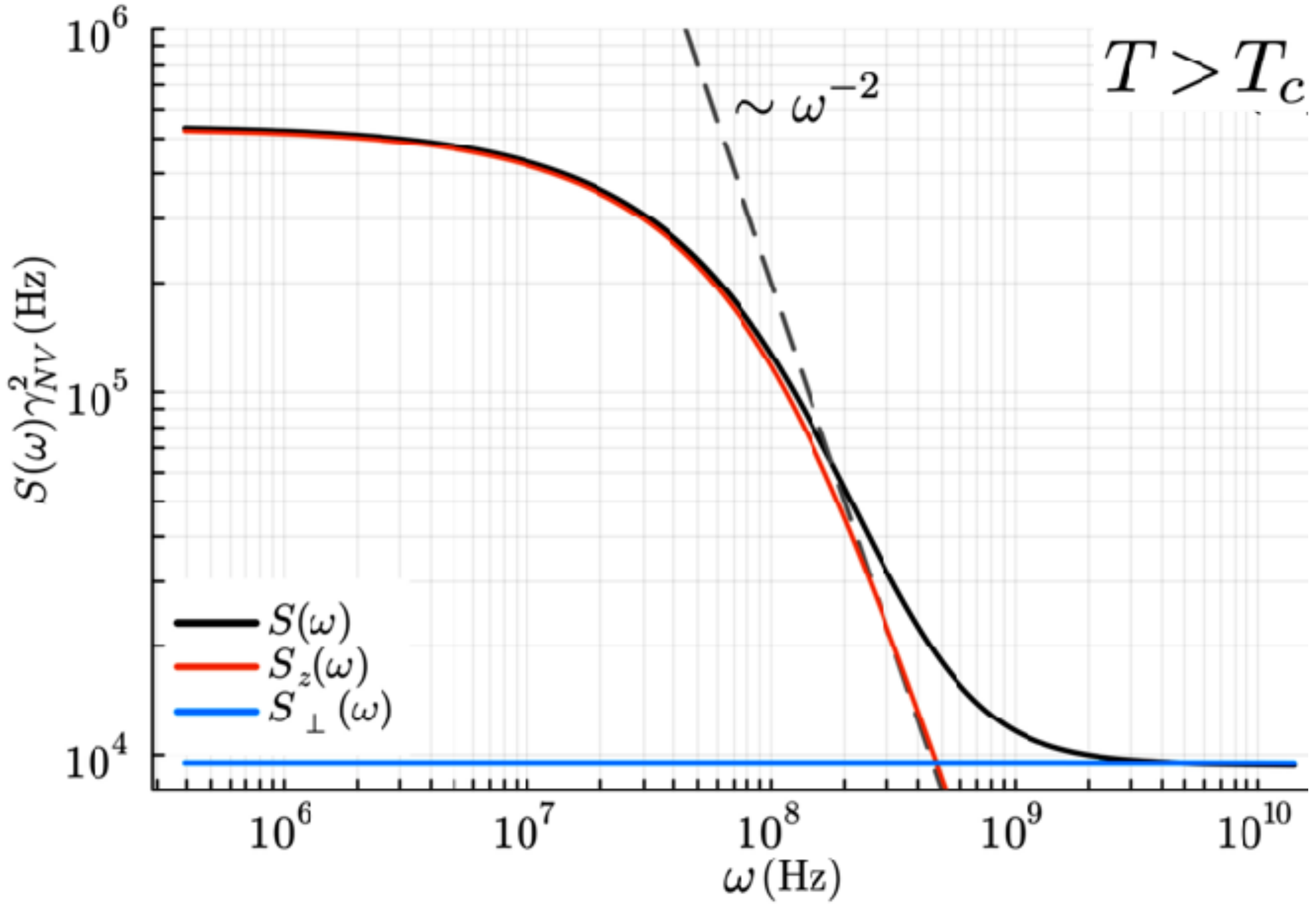


Illustration: ©Johan Jarnestad/The Royal Swedish Academy of Sciences

Free vortex plasma

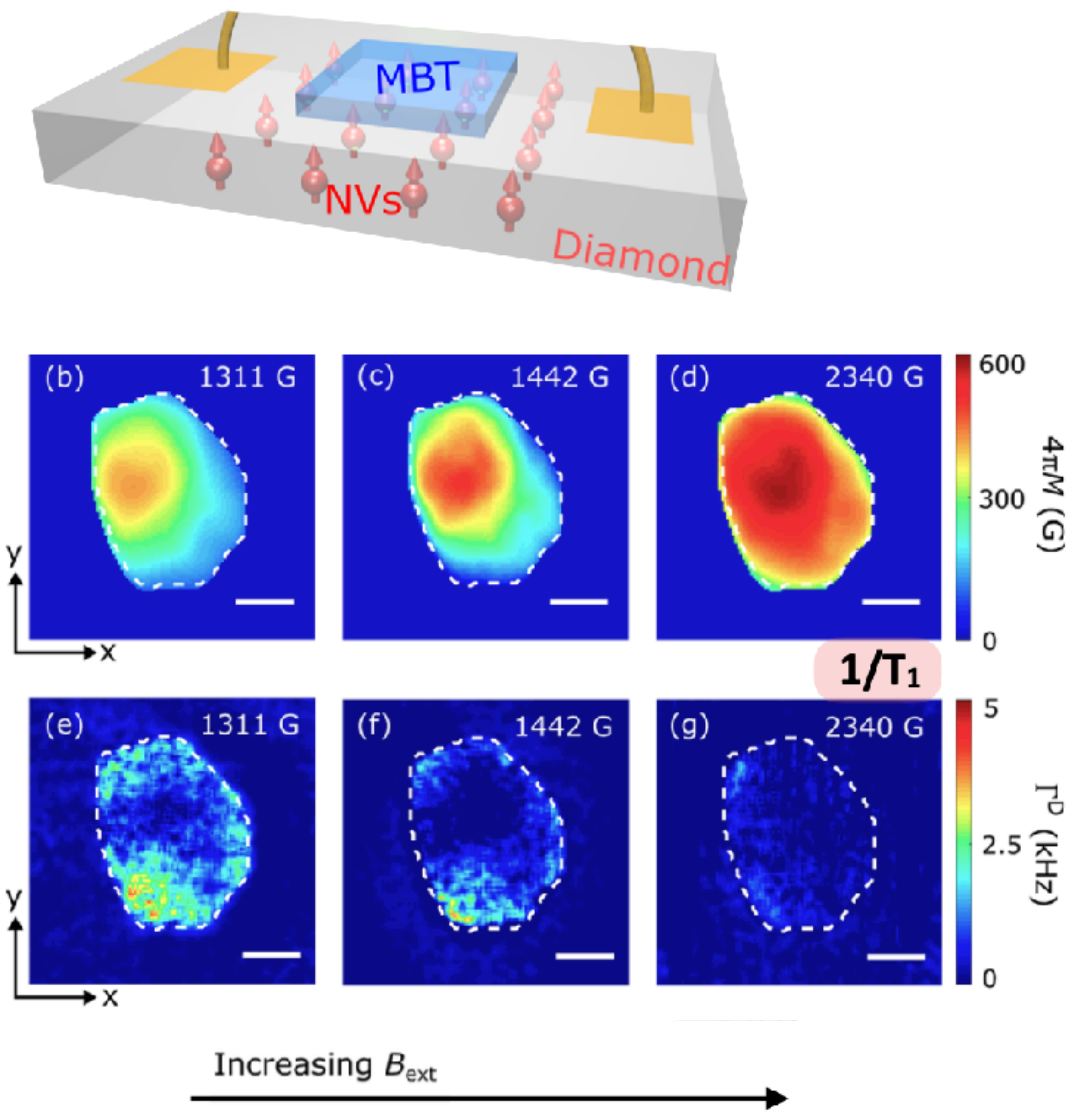
Paramagnet

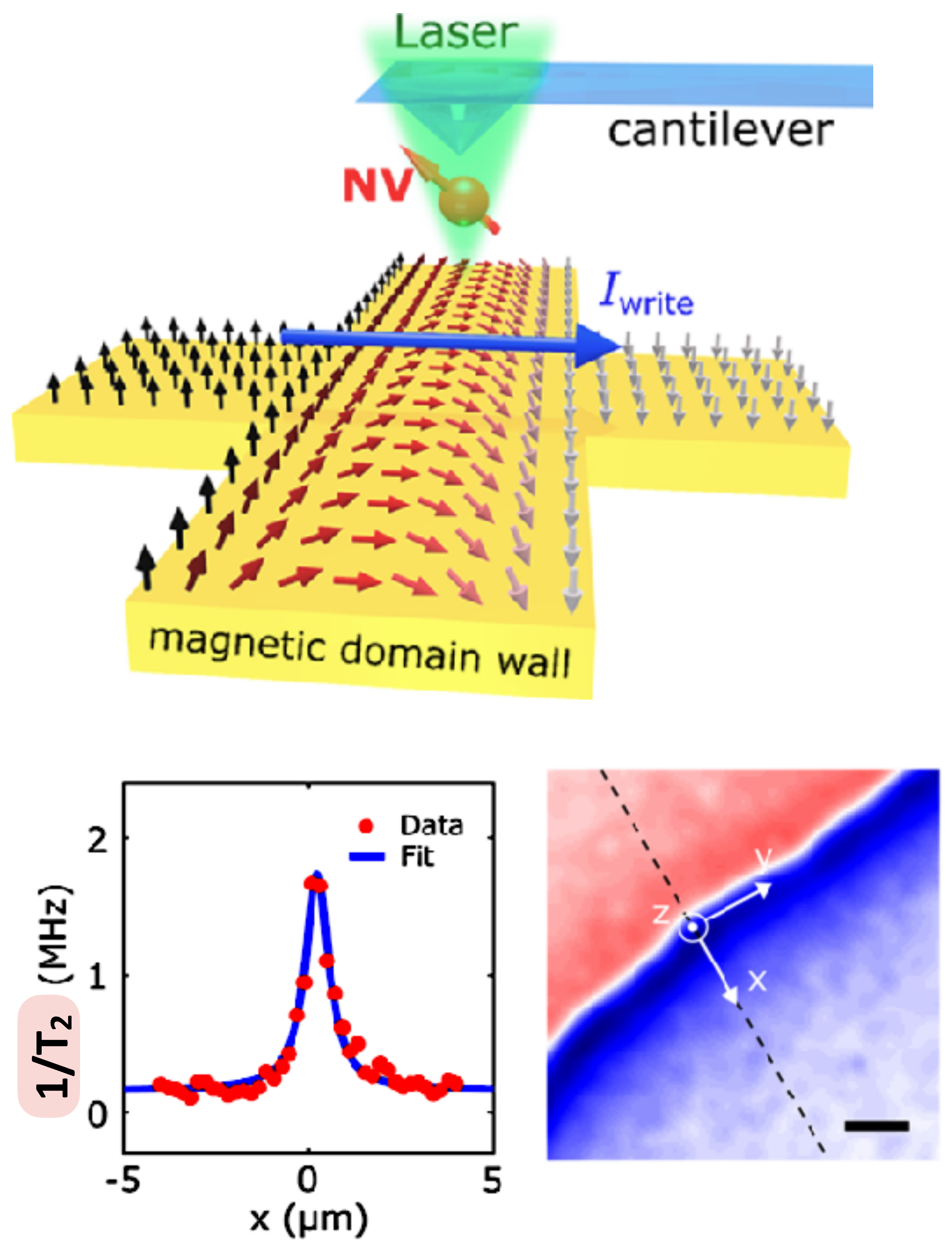




Potts, **SZ**, In preparation

Ex5. Spin fluctuations at magnetic domain walls





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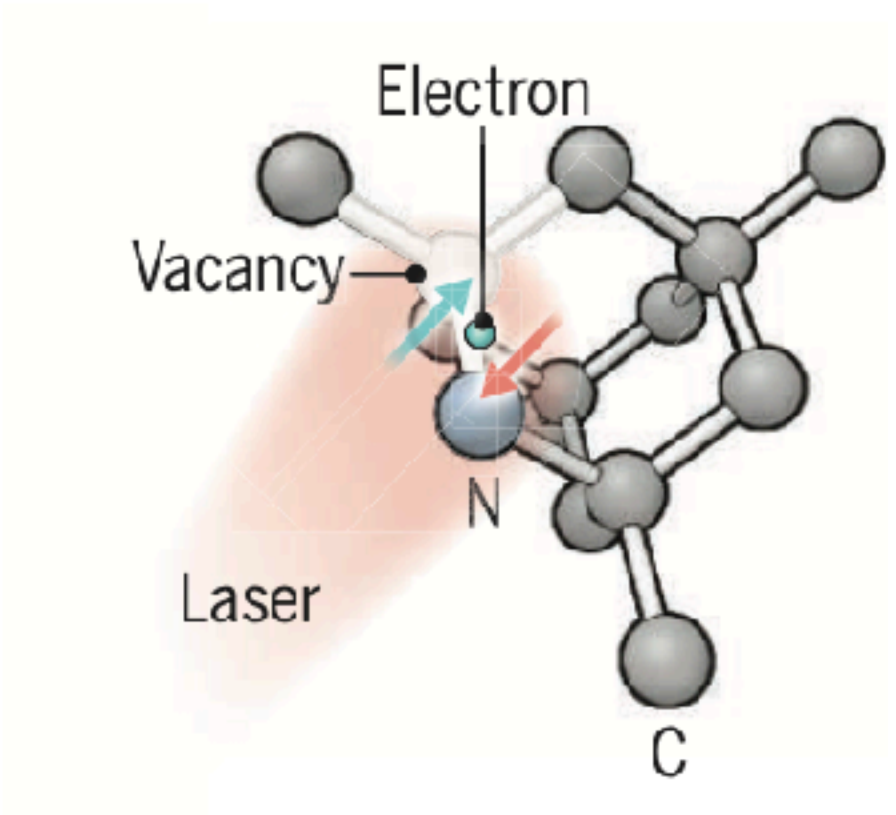
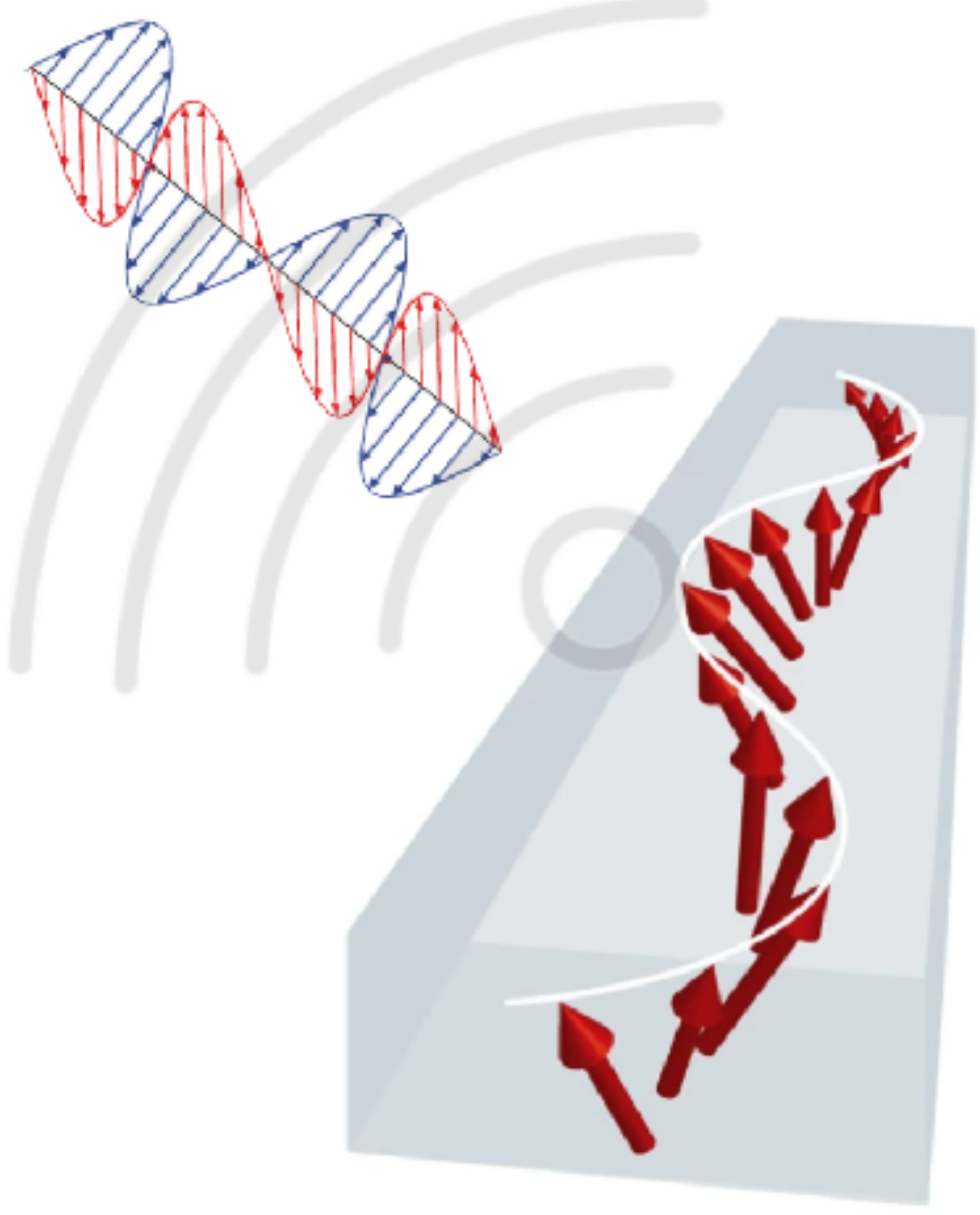
Summary

- Introduction to nitrogen-vacancy (NV) **spin qubit**
- Advantages of NV as a **quantum sensor** for quantum materials
- NV probing of **spin dynamics and transport** in quantum materials



- Charge-neutral transport channels
- Spin transport in antiferromagnetic insulators
- Different regimes of spin transport
- Topological phase transition in 2D magnets
- Spin fluctuations at magnetic domain walls



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