Quantum-Limit Nanoscale Sensing of Spin Entanglement and Squeezing

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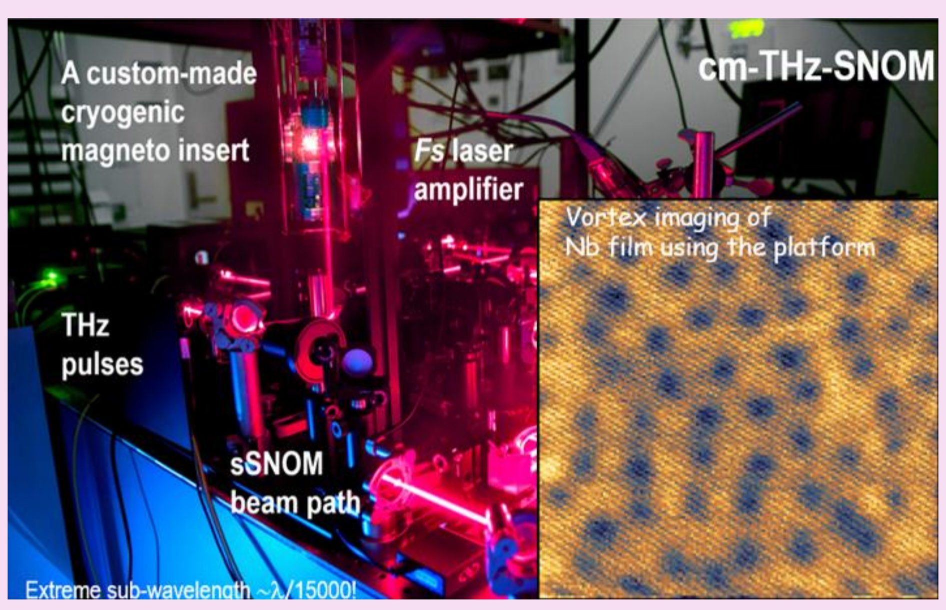
Introduction: Quantum spin fluctuations provide information about spin correlations, squeezing, and entanglement in quantum materials. However, conventional measurements often average over large ensembles, making few-spin correlations difficult to access. New approaches combining near-field THz excitation and nanoscale spin detection are needed to probe these fluctuations.

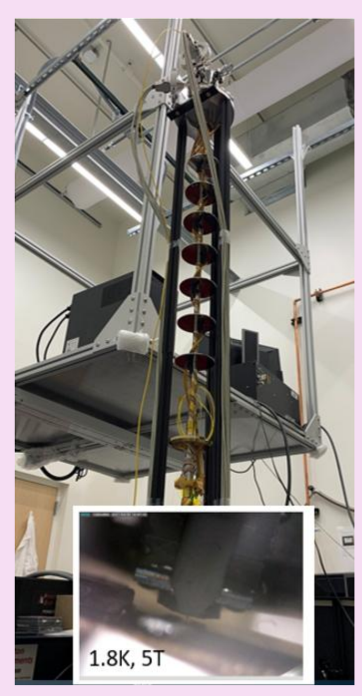
Objective: Develop nanoscale spin-sensitive photocurrent detection to probe local quantum spin fluctuations and correlations. Explore magnon squeezing and entanglement through complementary magneto-THz 2D coherent spectroscopy under magnetic field and high pressure.

Relevant prior works

A sub-2 K, 7 T cryogenic magneto-THz nanoscopy platform

This work establishes the experimental platform required for the proposed quantum spin fluctuation measurements.

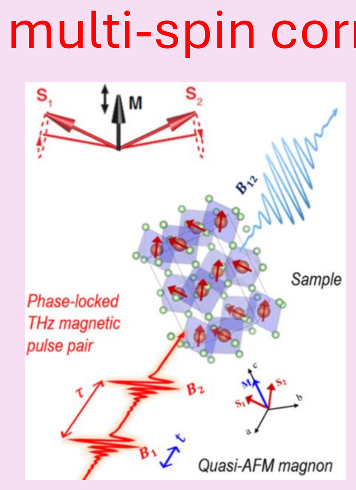




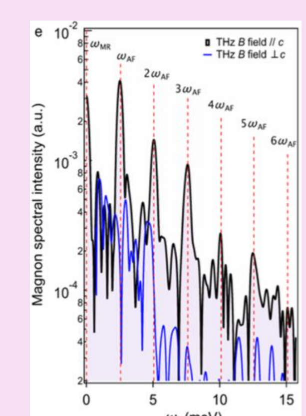
R. Kim et al., *Rev. Sci. Instrum.* **94**, 043702 (2023).
R. Kim et al., *J. Appl. Phys.* **139**, 164303 (2026).
S. Haeuser et al., *Nat. Nanotech.* **21**, 1090 (2026).

High-order THz nonlinear magnonics revealed by THz 2D coherent spectroscopy (THz-2DCS)

This work establishes THz-2DCS as a powerful control and probe of nonlinear magnon dynamics and multi-spin correlations.

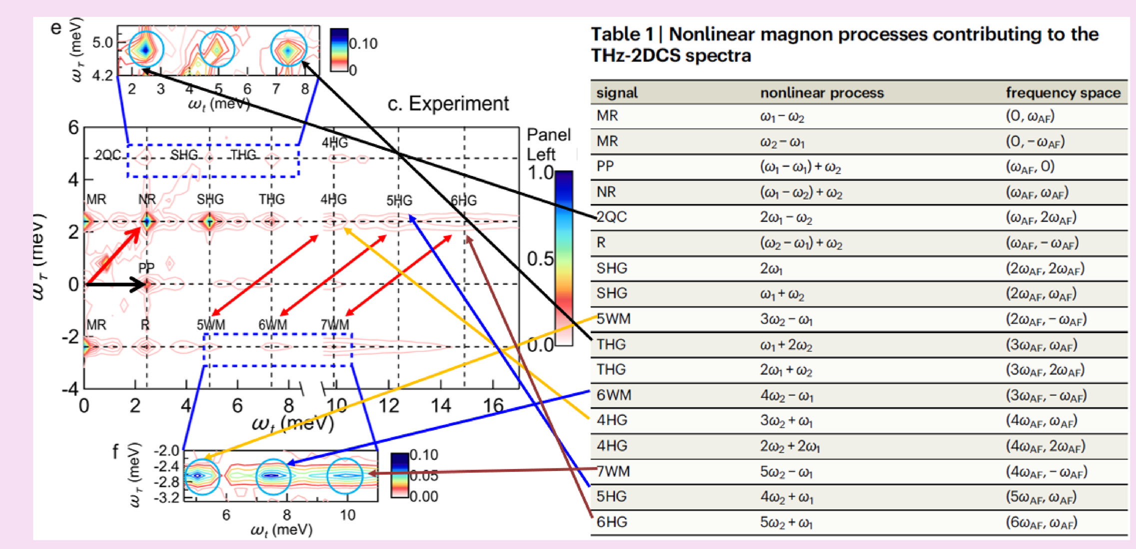


THz-driven magnon coherence

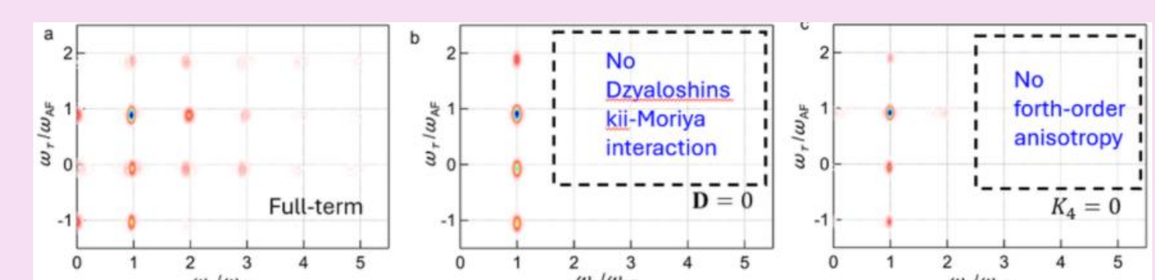


Nonlinear magnon emission

C. Huang et al., *Nat. Commun.* **15**, 3214 (2024).
M. Mootz et al., *Quant. Sci. Tech.* **9**, 035054 (2024).



THz 2D spectra (left) and multi-wave mixing processes (right)



Simulations of high-order nonlinear magnonic correlations

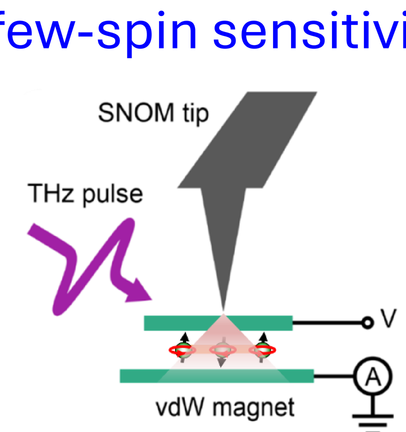
Proposed Work: Nanoscale photocurrent detection of quantum spin noise

Motivation: Quantum spin fluctuations encode many-body correlations, squeezing, and entanglement. However, directly detecting these fluctuations with nm spatial resolution and few-spin sensitivity remains challenging.

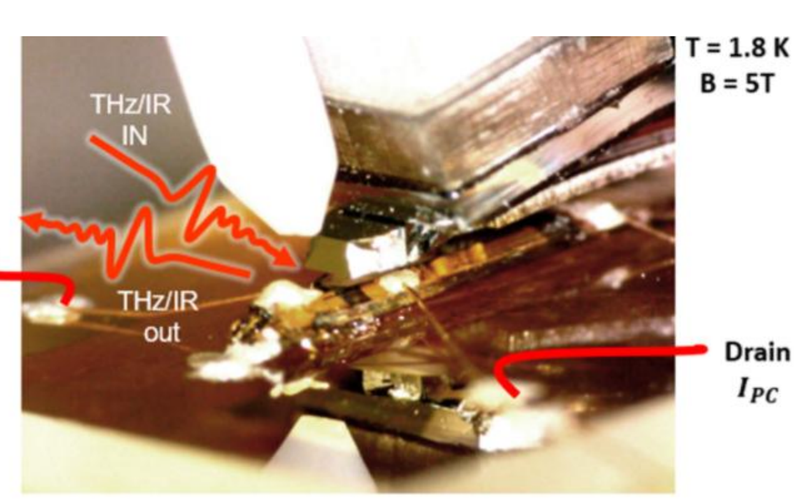
Approach: Use a metallic tip with THz near-field excitation and B field to drive spin-polarized carriers. Measure spin-sensitive current fluctuations to probe quantum spin noise with ~20 nm resolution, $I(t) \sim I_0 + \delta I_{spin}(t)$.

Metallic tip + THz + B field → spin-polarized carriers → spin-sensitive current → spin-dependent current fluctuations → signatures of squeezing & entanglement.

Innovation: Combine nanoscale spin-sensitive photocurrent detection with near-field THz excitation under B field to access local quantum spin fluctuations with few-spin sensitivity.



scheme

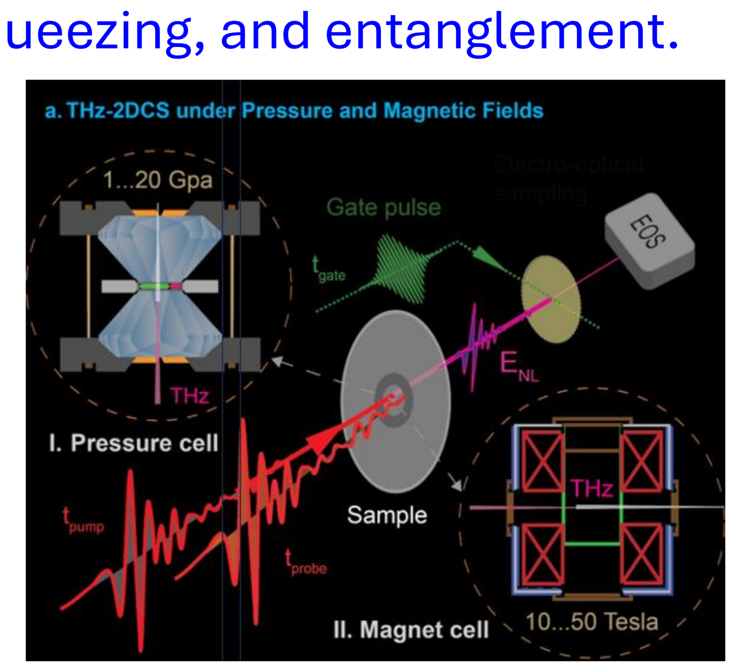


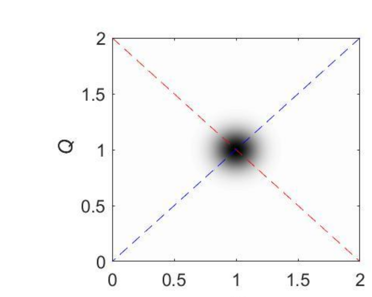
Complementary Work: Single-shot magneto-THz 2DCS of magnon squeezing and entanglement

Motivation: Magnon squeezing and entanglement reflect quantum correlations in spin excitations. Directly resolving them and their ultrafast dynamics under magnetic field and high pressure remains challenging.

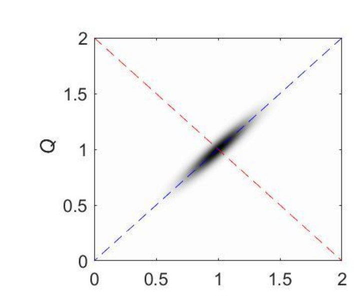
Approach: Use single-shot magneto-THz 2DCS to resolve higher-order spin correlations and track signatures of magnon squeezing and entanglement at THz frequencies and sub-picosecond time scales.

Innovation: Extend THz 2DCS to single-shot measurements under magnetic field and high pressure to probe higher-order magnon correlations, squeezing, and entanglement.





unsqueezed magnon state



squeezed magnon state

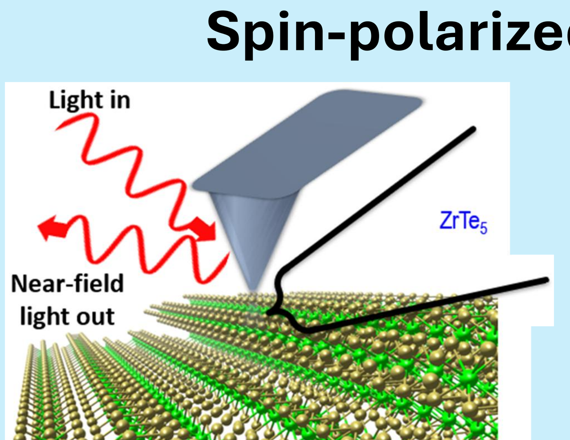
C. Huang et al., *Nat. Commun.* **15**, 3214 (2024).
D. Kim et al., *Sci. Adv.* **11**, adt1691 (2025).
J. Fransson et al., *Phys. Rev. B* **81**, 115454 (2010).

Potential impact: advance nanoscale quantum sensing and precision metrology, spin-based quantum information, and ultrafast spintronic technologies.

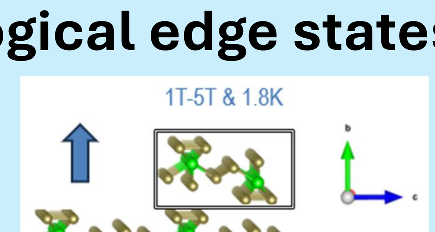
Demonstrated nanoscale spin-sensing capabilities & preliminary results

Our previous measurements demonstrate nanoscale (~20 nm) detection of spin-polarized edge currents under magnetic field, establishing the experimental capability for proposed quantum spin-noise measurements.

Spin-polarized topological edge states in $ZrTe_5$



Quantum spin hall (QSH) insulators
Spin up and down 1D channels
Topological two-lane edge transport

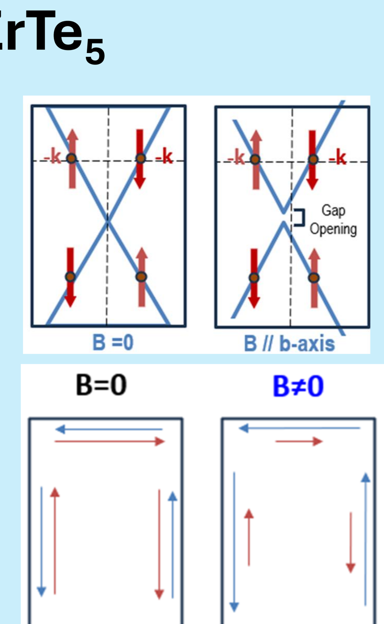


Topological field, spin imbalance, transport asymmetry

$\omega_{CT}=|e|B_{topo}/m^*$

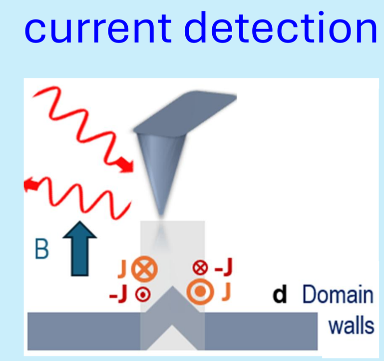
$\omega_{CB}=|e|B/m^*$

$B_{topo}\times\Delta N/N\sim30$ T

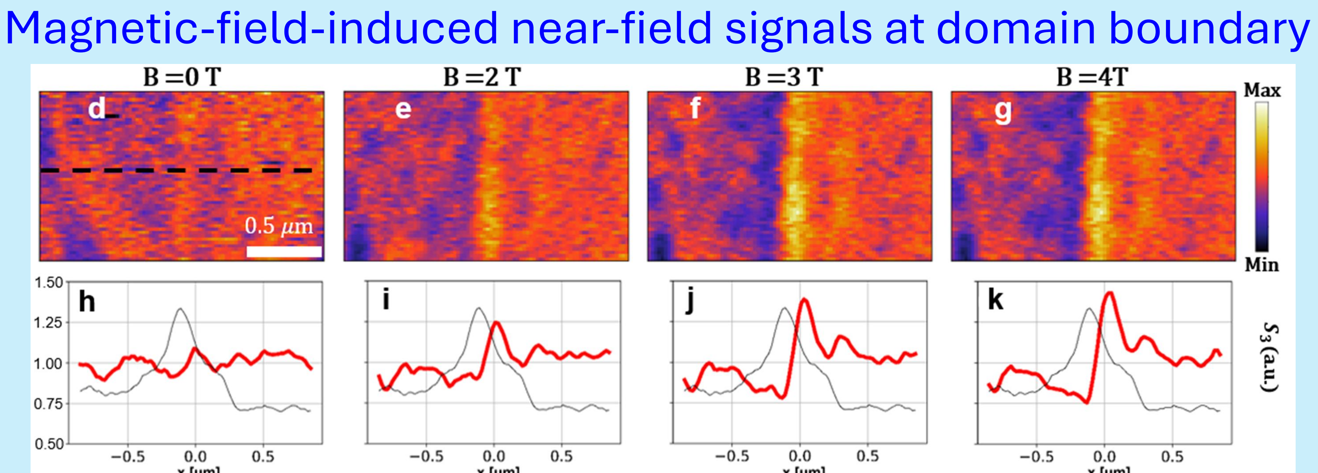


Nanoscale near-field images of spin-polarized edge currents

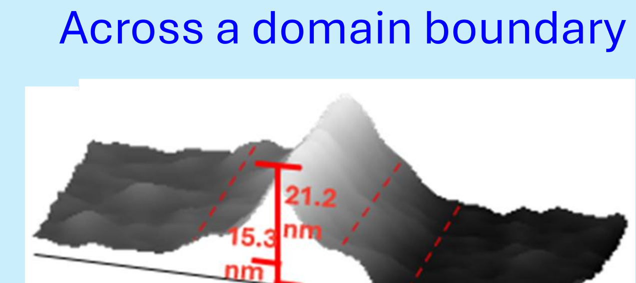
Nanoscale spin current detection



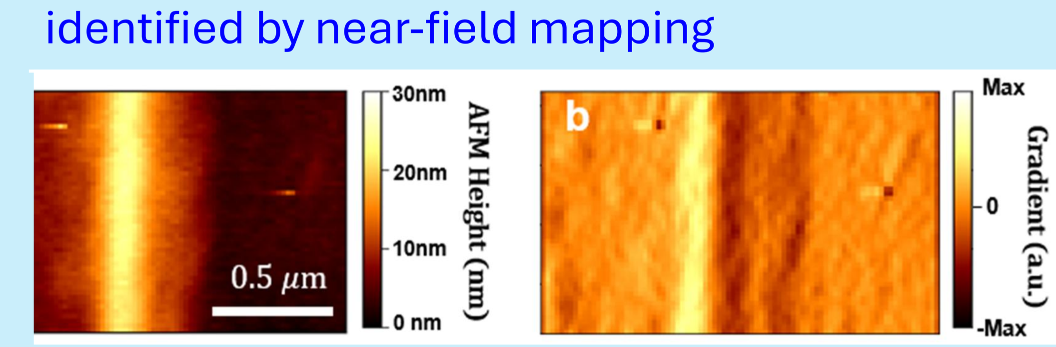
Magnetic-field-induced near-field signals at domain boundary



Across a domain boundary



Structural stacking variations or crystalline facets identified by near-field mapping



This work is supported by the Laboratory Directed Research and Development (LDRD) project of Ames National Laboratory
The research is performed at the Ames National Laboratory, which is operated for the U.S. DOE by Iowa State University under contract # DE-AC02-07CH11358