Numerical Investigations of Collective Spin-Wave Dynamics in Complex Magnetic Textures and Patterned Ferromagnetic Films
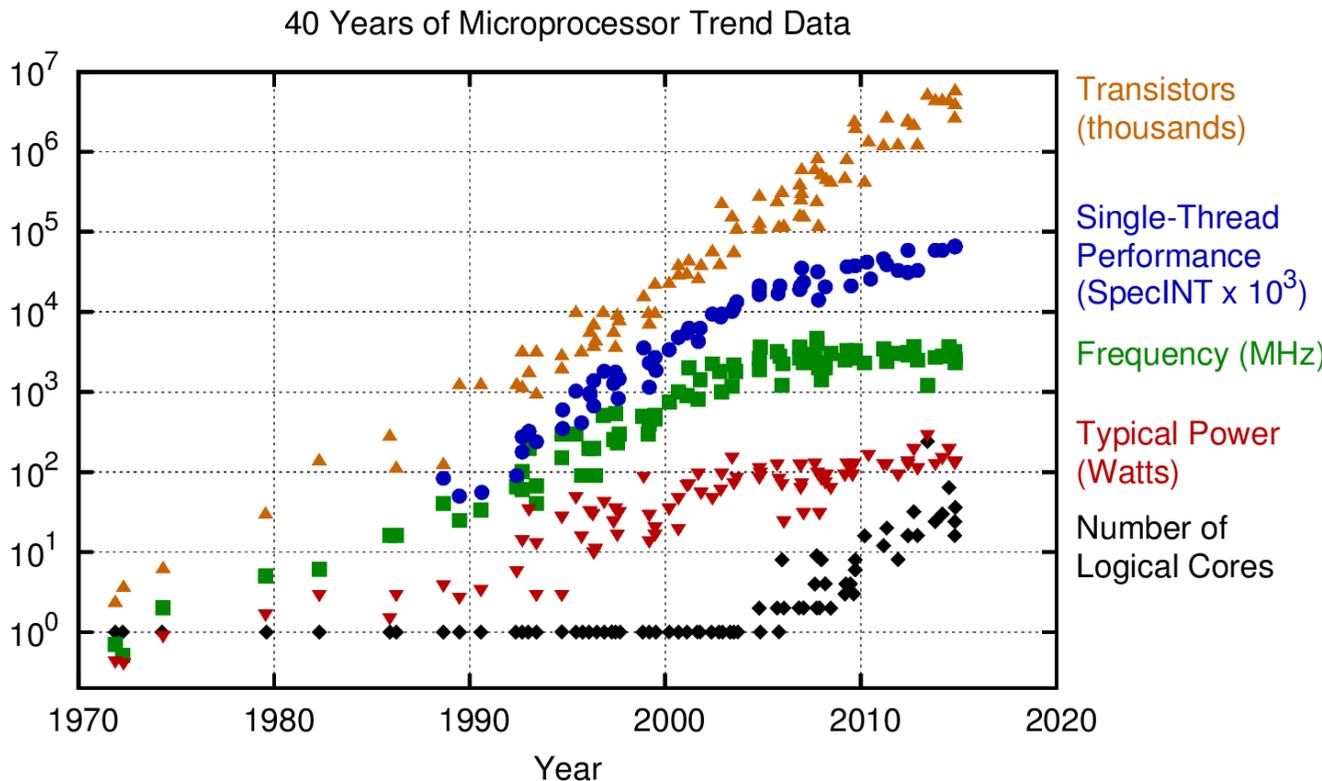
Mathieu Moalic

03.02.2026

Roadmap

- Context: Why magnons?
- Methods: Micromagnetics
- Paper 1: Deterministic fractals
- Paper 2: Experimental YIG nanocrystal
- Paper 3: Anisotropy-engineered edge modes
- Paper 4: Exchange-mediated strong magnon–magnon coupling
- Paper 5: Nonlinear frequency doubling
- Outlook

Motivation: beyond conventional electronics

40 Years of Microprocessor Trend Data

Transistors (thousands)

Single-Thread Performance (SpecINT x 10^3)

Frequency (MHz)

Typical Power (Watts)

Number of Logical Cores

Original data up to the year 2010 collected and plotted by M. Horowitz, F. Labonte, O. Shacham, K. Olukotun, L. Hammond, and C. Batten
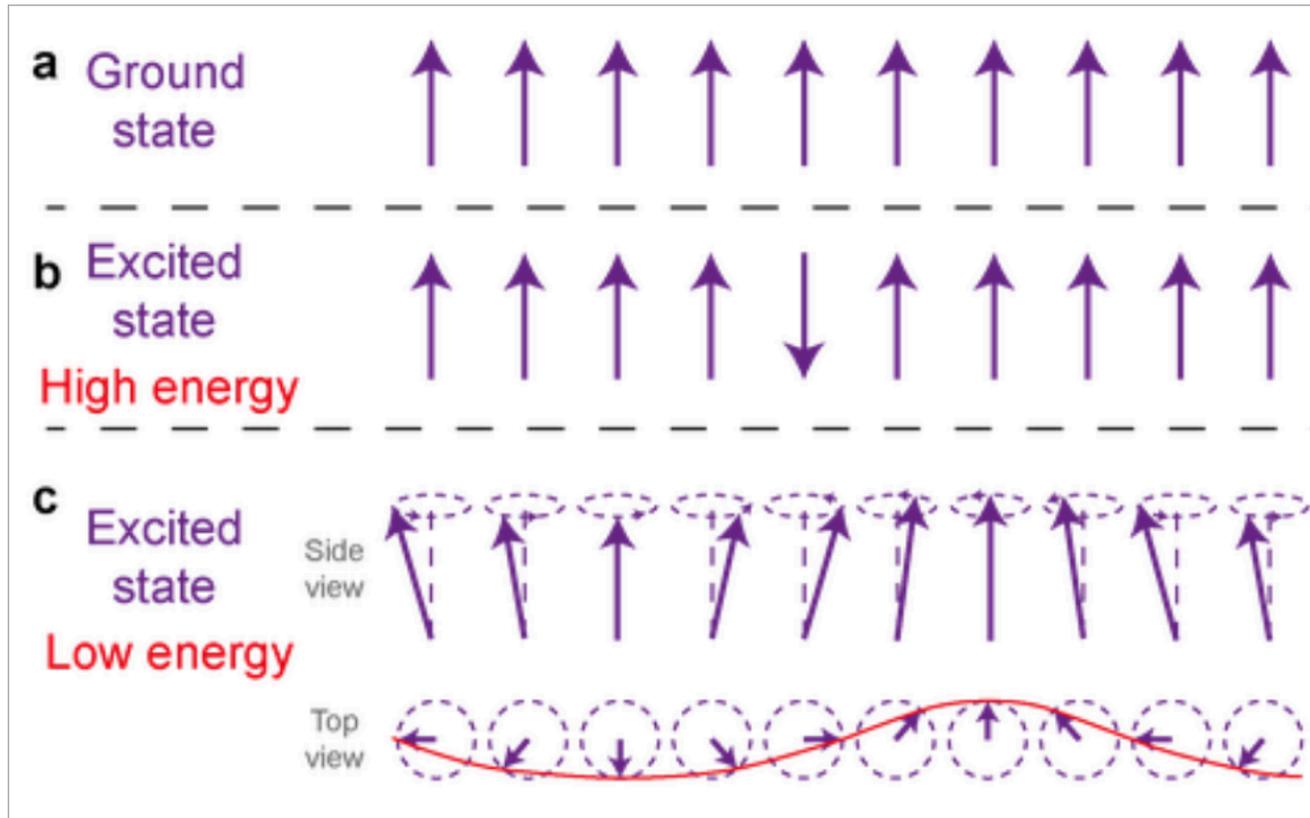New plot and data collected for 2010-2015 by K. Rupp

Key issues with electronics:
- power density and interconnect bottlenecks
- voltage scaling slowdown
- need for new physics for signal processing

Thesis angle: **Spin-Waves**
- No Joule heating
- Nanoscale systems
- GHz frequencies

What is a magnon ?

A magnon is a **collective precession** of magnetization. Why they are interesting:

- GHz (and beyond) operation
- wavelengths down to tens–hundreds of nm
- wave-based functions: filtering, delay, interference logic

https://www.fuw.edu.pl/wiki/images/f/f7/2019_Lecture_9_magnons.pdf
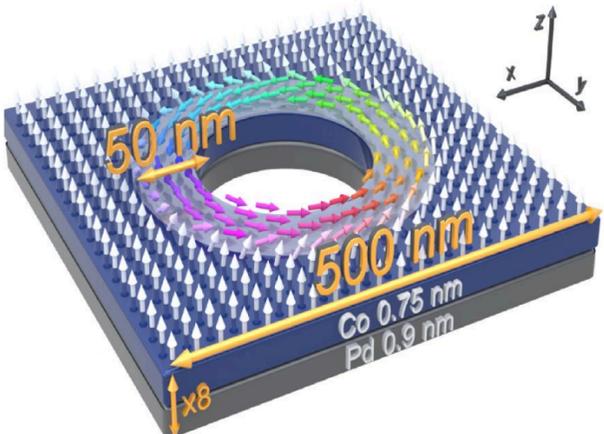
The three control knobs in this thesis

Geometry

- Periodic crystals
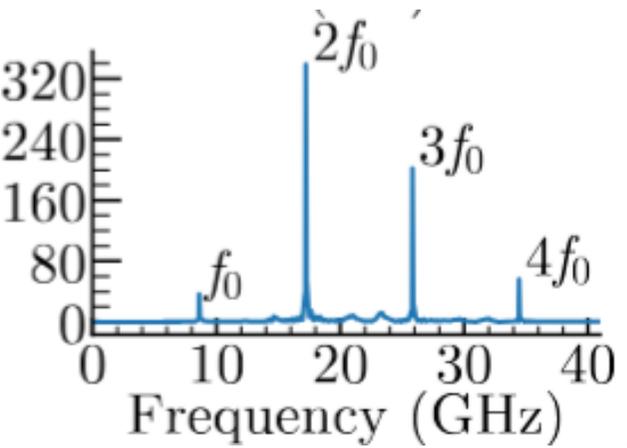- Multiscale fractals
- Bandgaps engineering
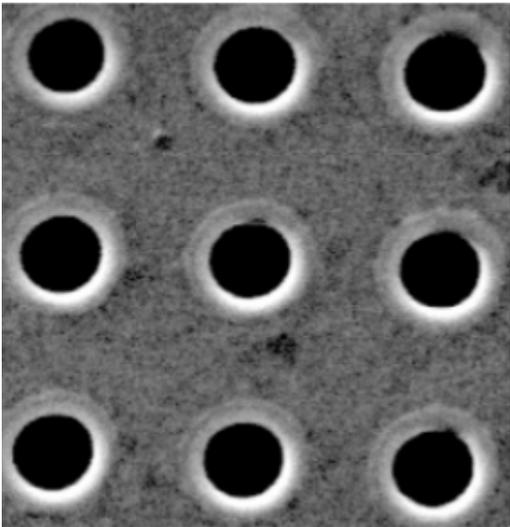
Anisotropy engineering

- Local PMA reduction
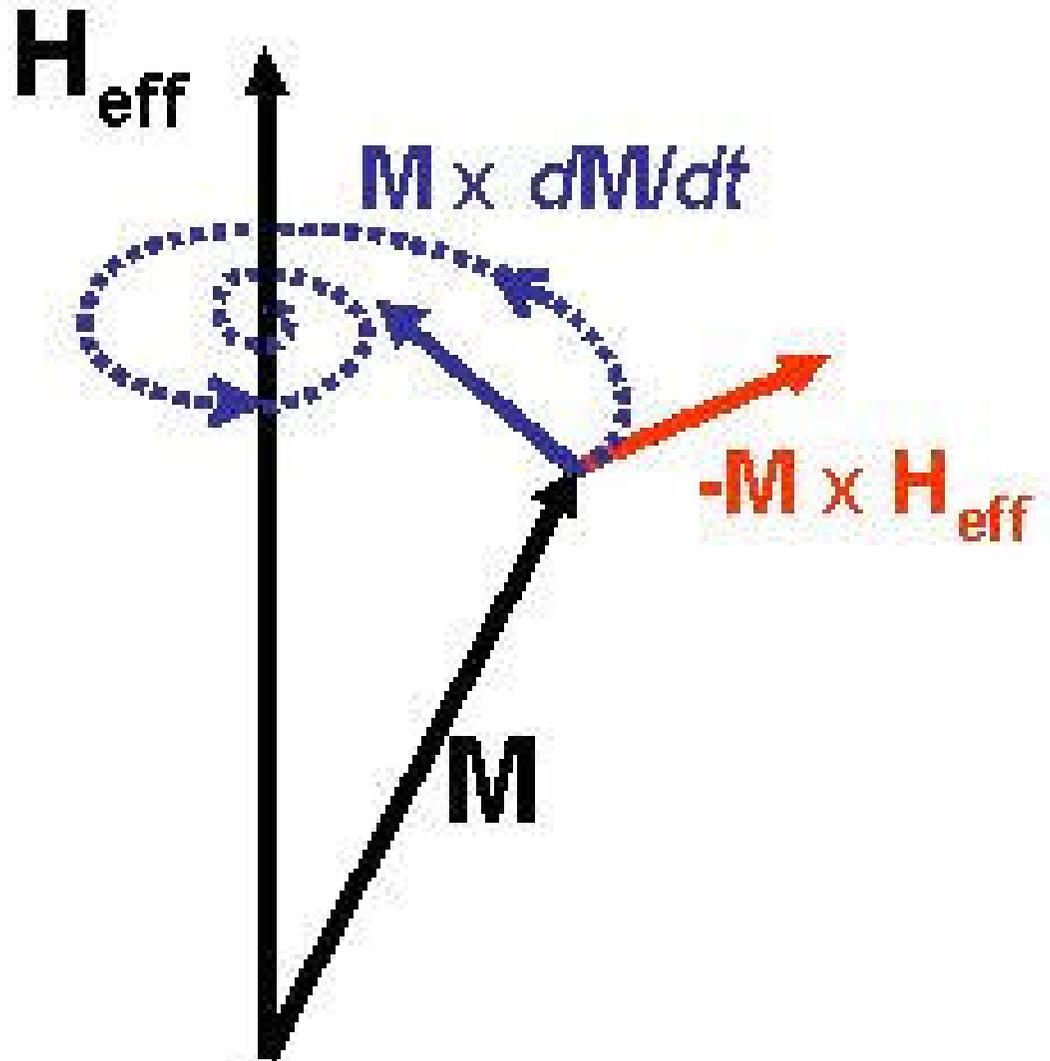- Complex texture
- Edge modes
- Reconfigurable spectra

Nonlinearity

- Confined mode as pump
- Harmonic generation
- Frequency conversion
- Propagating output

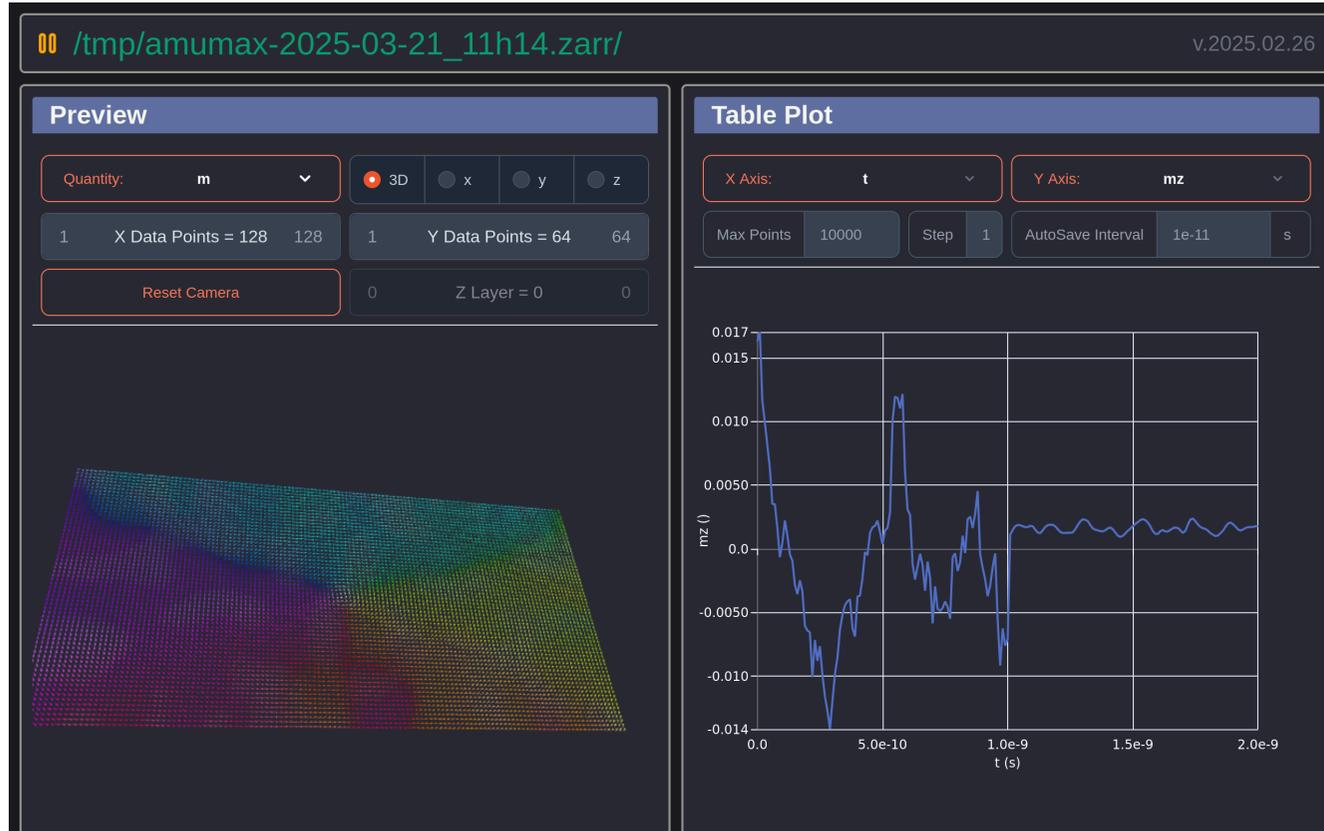# Numerical method: micromagnetics in 1 minute

Landau–Lifshitz equation:

$$\frac{\partial \boldsymbol{M}}{\partial t} = -\gamma \mu_0 \boldsymbol{M} \times \boldsymbol{H}_{\text{eff}}$$

where $\boldsymbol{H}_{\text{eff}}$ comes from exchange, demag, anisotropy, Zeeman...

Outputs used throughout:

- $m(t) = \frac{M(t)}{M_{\text{S}}}$
- spectra via FFT of $\boldsymbol{m}(t)$
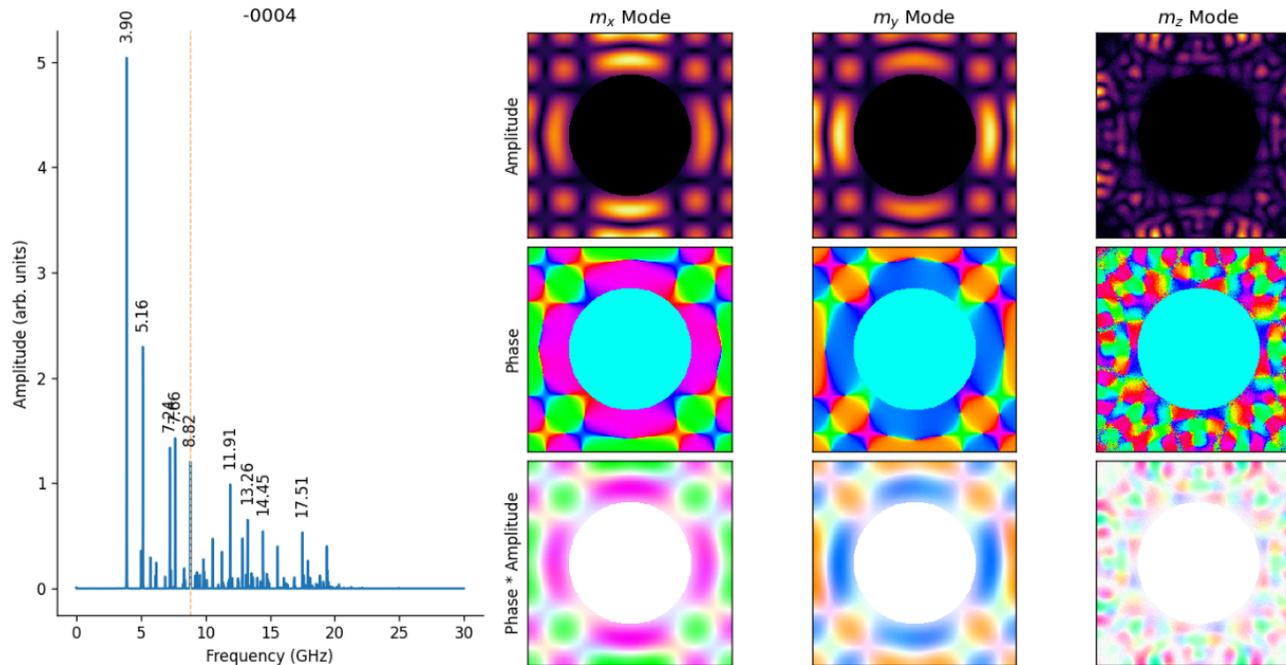- mode profiles: amplitude + phase maps

Simulation Software: Amumax

What I created:
- Zarr-backed output for large time-resolved datasets
- WebUI for monitoring + quick diagnostics
- Template-based parameter sweeps
- Mesh optimization
- Helper functions
- Bug fixes
- Much more!

Post-processing Software: Pyzfn

I also created a Python library: Pyzfn

Workflow:
- Load Zarr dataset lazily
- Compute larger than memory FFT spectra
- Interactive mode visualization
- Export for figures / comparisons

This is the backbone of all spectra and mode maps in the thesis.

The following studies would have been impossible without this software

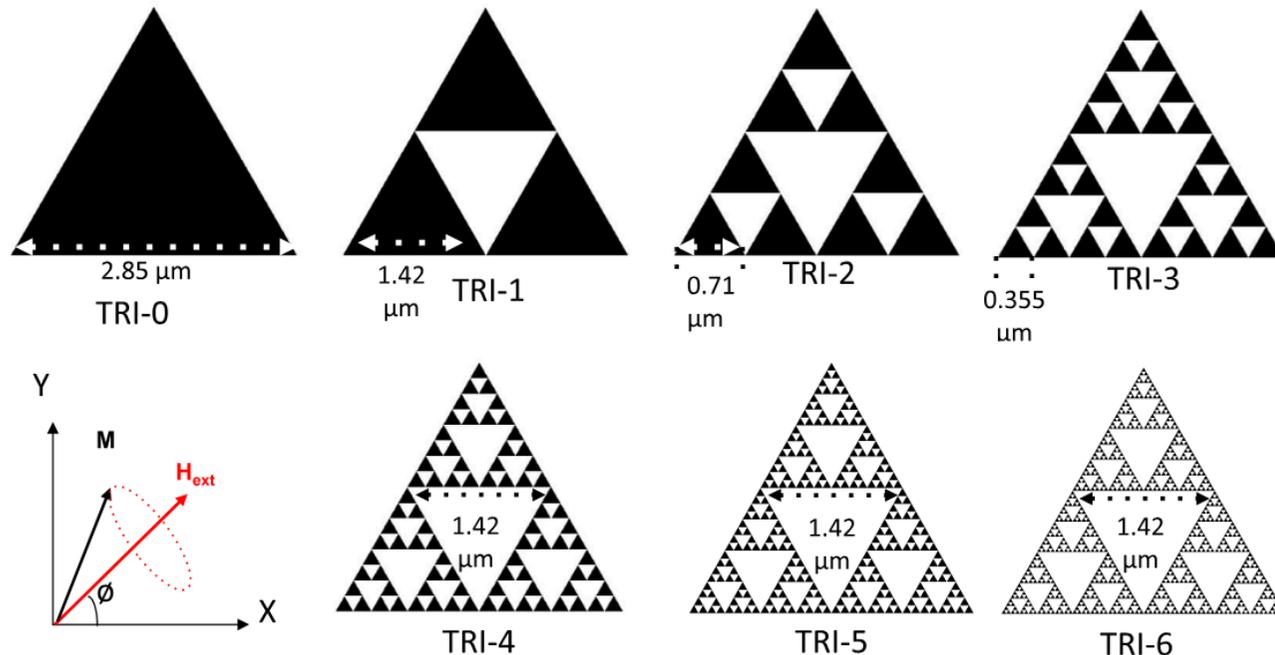# Paper 1 — Deterministic magnonic fractals: hierarchical minibands
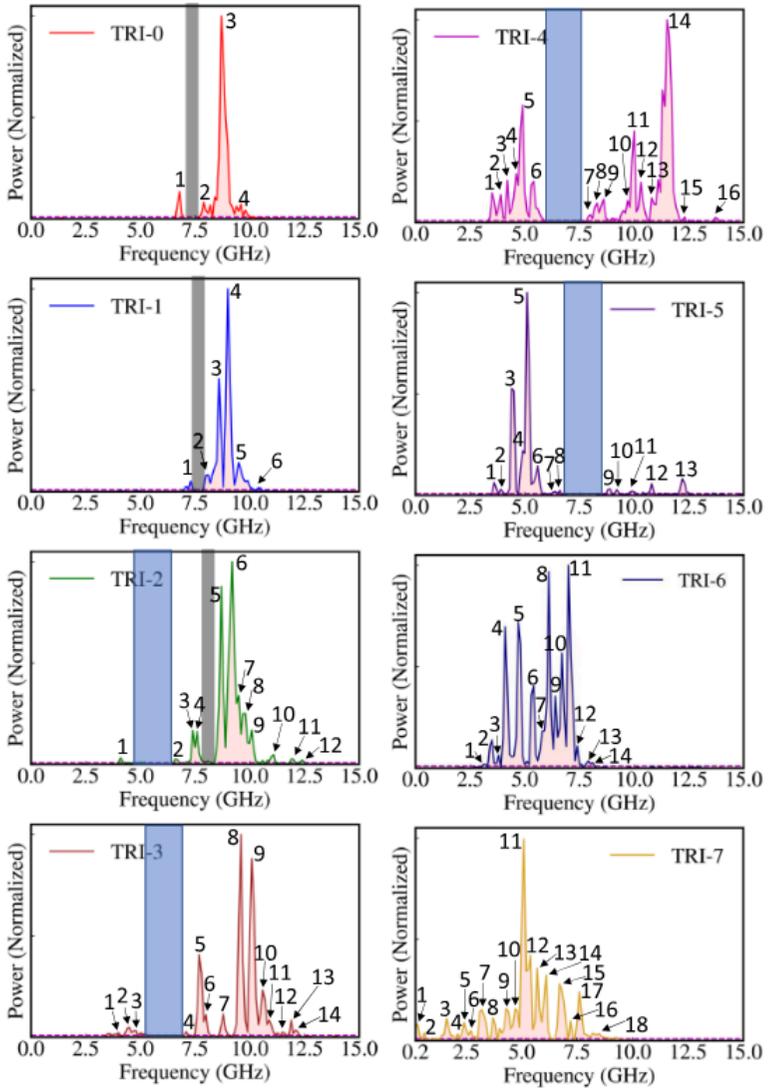
Study of Sierpinski triangles

Collaboration with Riya Mehta and Susmita Saha of Ashoka University in India

I ran detailed simulations of the full scale fractal and periodic systems.

Paper 1: Fractal geometry reprograms spin-wave bands in a Sierpinski triangle

- **We need bandgaps:** They enable filtering, routing, and on/off control of magnonic signals.

- **Method:** Micromagnetic LLG (Py); FFT of time-domain $M_{z(t)}$ after a broadband pulse; fixed $H_{\text{ext}} = 0.1$ T, $\varphi = 0 \deg$.

- **Key result:** Iteration number acts like a "reprogramming knob": rich multimode spectra $\rightarrow$ band formation + a frequency gap that widens strongly at high iteration.

- **Why it matters:** The gap is field-tunable and shows angular control; angle can even close the gap $\rightarrow$ reconfigurable aperiodic magnonic crystal behavior.

Paper 1: Take-home message

Fractal geometry = a new way to control magnonic bandgaps

Increasing Sierpinski iteration reshapes the spectrum into bands and opens a wide bandgap—then field/angle tuning can strengthen or even close it.
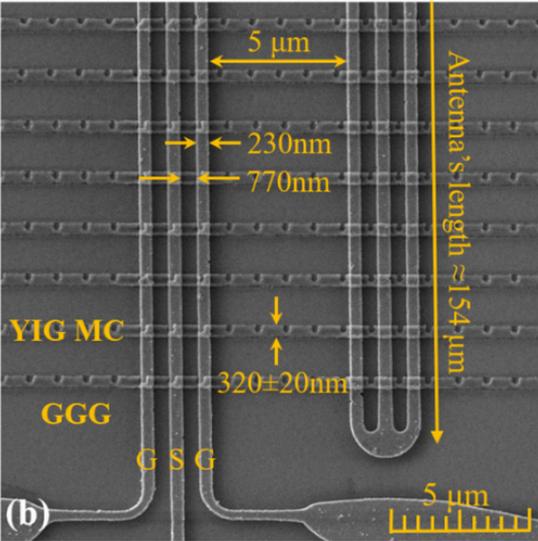
1D YIG hole-based magnonic nanocrystal

K. O. Levchenko; K. Davídková; R. O. Serha; M. Moalic; A. A. Voronov; C. Dubs; O. Surzhenko; M. Lindner; J. Panda; Q. Wang; O. Wojewoda; B. Heinz; M. Urbanek; M. Krawczyk; and A. V. Chumak

Appl. Phys. Lett. 127, 17240   **2025**
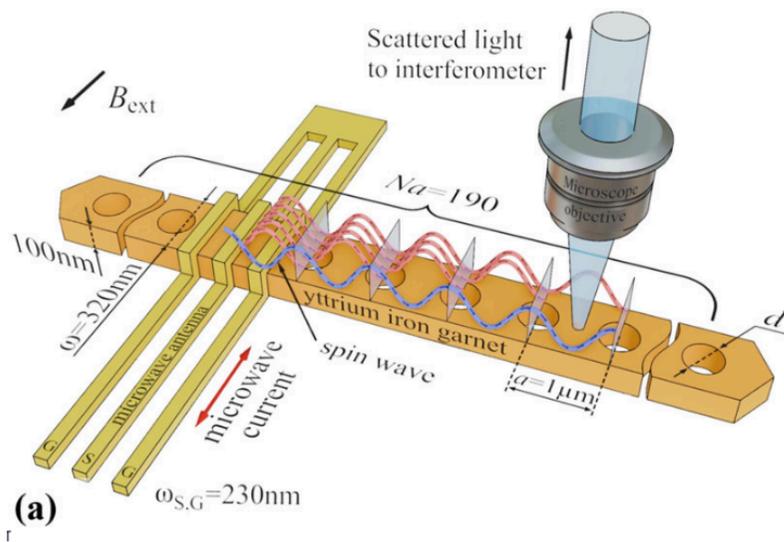
Collaboration with the University of Vienna, CEITEC and more.

I did not take part in the experiments. I ran detailed simulations of the 1D magnonic crystal and calculated its band structure.

Paper 2: 1D YIG hole-based magnonic nanocrystal: bandgaps + mode-selective transmission

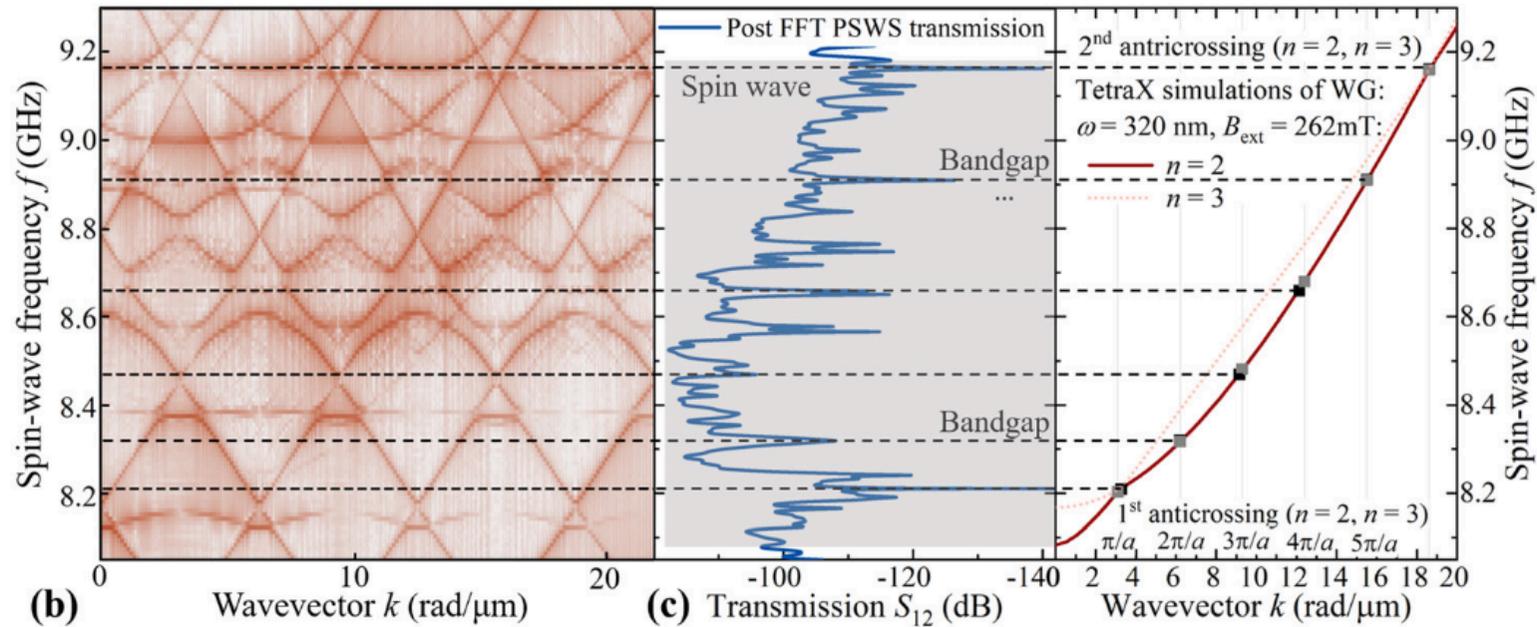- **Key result:** Well-defined bandgaps (rejection up to $\simeq 26$ dB) + spin-wave transmission over $\simeq 5, \mu m$; multiple gaps arise from the sharp periodic modulation.

- **Physics / design rule:** Dispersion shows two prominent anticrossings; below the first, operation is close to single-mode (narrow window), and between anticrossings most energy is carried by the $n = 2$ width mode $\rightarrow$ efficient passbands despite multimode complexity.

Nanopatterned YIG can deliver RF-grade magnonic bandgaps

A simple 1D hole lattice creates deep, tunable rejection bands, and the dispersion/anti-crossings tell you which mode carries the signal in the passbands.

Geometry coming forward
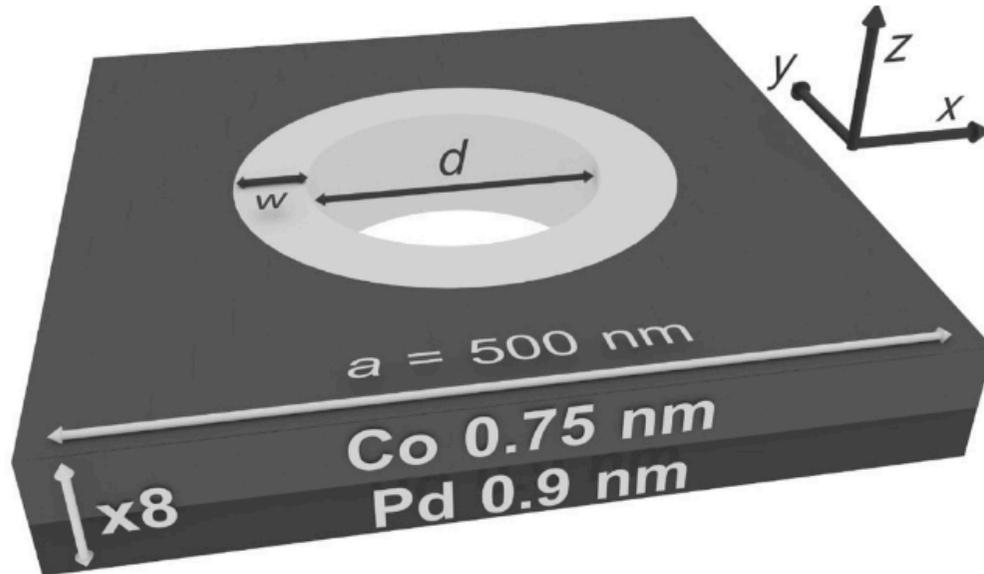
- Thin film (13.2 nm) of $[\mathrm{Co/Pd}]_8$
- Material parameters taken from:
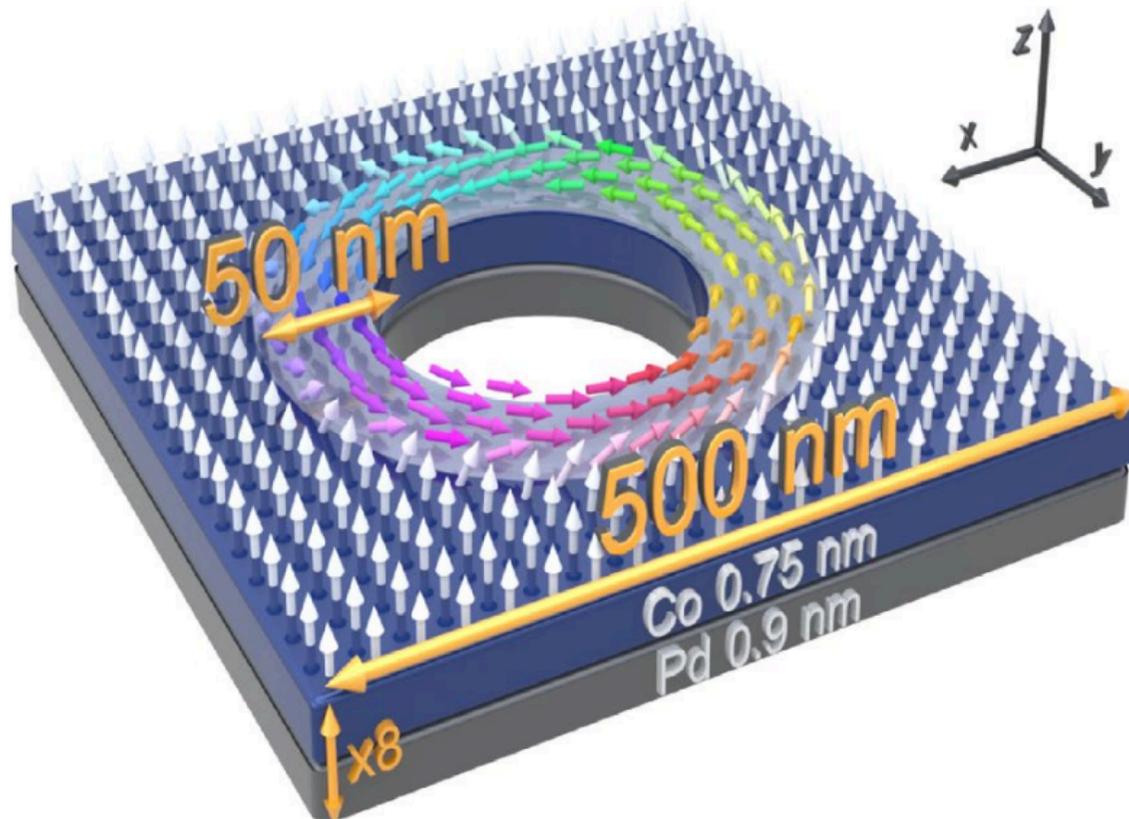
  S. Pal et al., "Tunable magnonic frequency and damping in $[\mathrm{Co/Pd}]_8$ multilayers with variable Co layer thickness," *Appl. Phys. Lett.* 98, 082501 (2011).

  ‣ $M_{\mathrm{S}} = 810$ kA/m
  ‣ $A_{\mathrm{ex}} = 13$ pJ/m
  ‣ $K_u = 450$ J/m^3 (out-of-plane)

- Hole made by focused ion beam
- Side effect: Anisotropy is reduced around the hole
- Hole diameter ~ 100 nm
- Rim width ~ 50 nm
- Lattice parameter ~ 500 nm

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Complex magnetization texture

- "Bulk" is the region with high anisotropy between holes
- "Rim" is the region with low anisotropy around the holes
- Without external field, the magnetization is:
  - ‣ Out-of-plane in the bulk
  - ‣ Tilted in-plane in the rims
- I ran all simulations, did all the post-processing and figures.

Paper 3 — Anisotropy-engineered edge modes in PMA antidot lattices

> ### Spin-wave spectra in antidot lattice with inhomogeneous perpendicular magnetic anisotropy
>
> M. Moalic; M. Krawczyk; M. Zelent
>
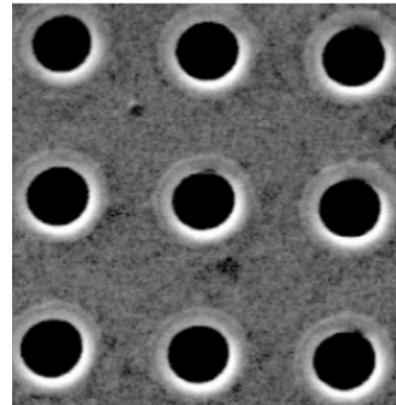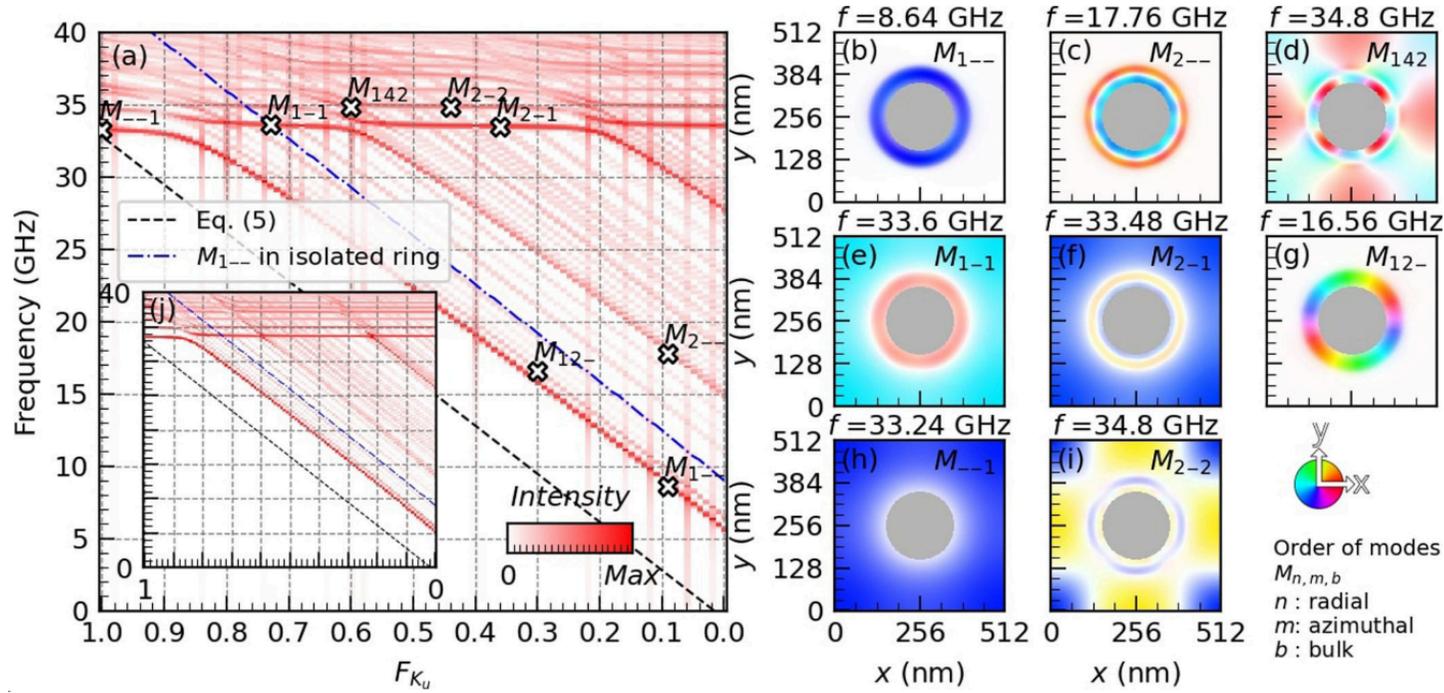> J. Appl. Phys. 132, 213901   **2022**

Goal of this study:

Can we use the rims to tune the spin-wave response ?

Simulation details:

- Holes are arrange in a square lattice
- Spin-waves excited by a specially designed multi-mode antenna
- We collect the magnetization in time and in space to analyse the rim and bulk modes

Paper 3: Reducing the anisotropy in the rim

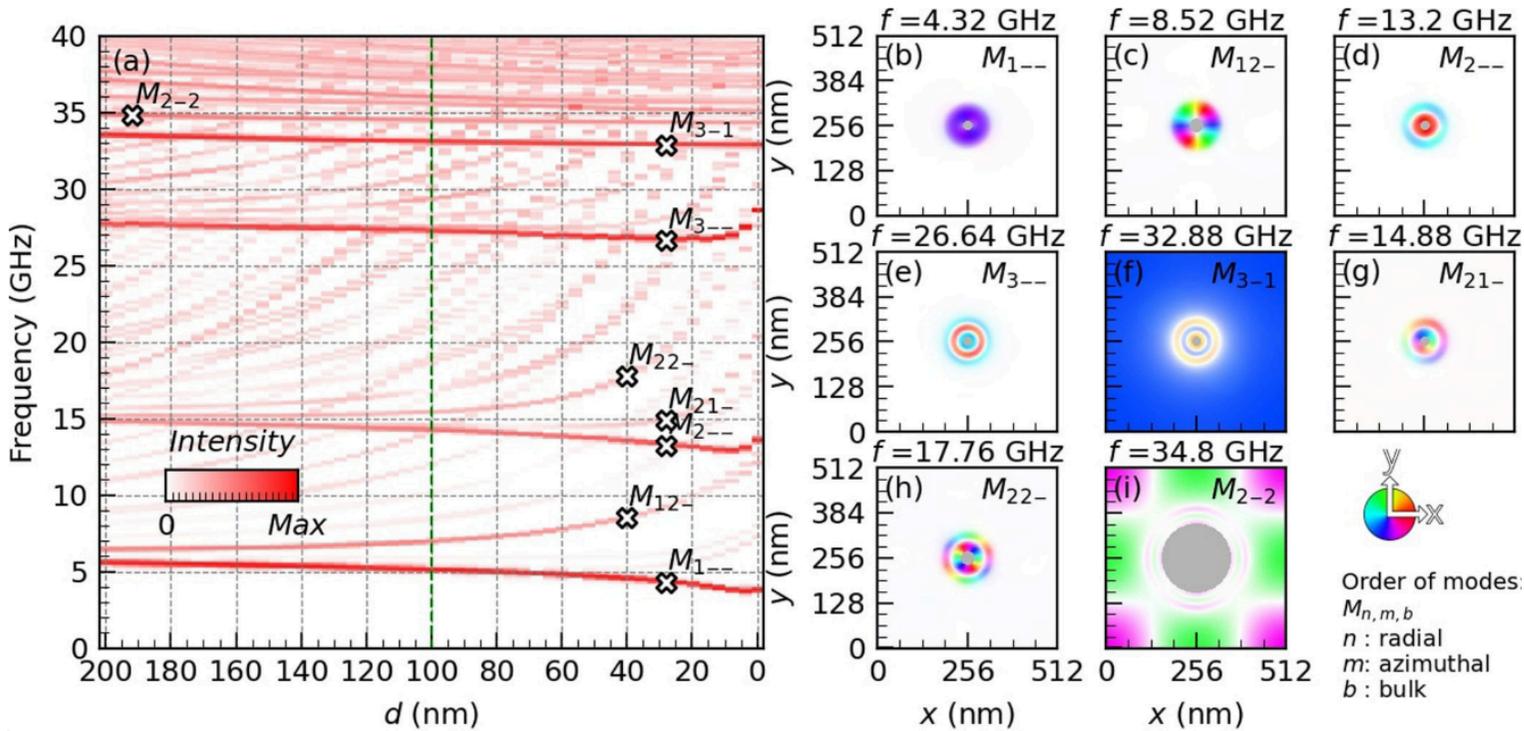$$F_{\mathrm{Ku}} = \frac{F_{\mathrm{Ku,rim}}}{F_{\mathrm{Ku,bulk}}}$$

Reduced PMA near antidot edges:

- locally softens magnetization (edge texture)
- supports **edge-localized modes**
- provides a controllable "second subsystem" (rim) coupled to bulk

Paper 3: Reducing the hole diameter

- Shows the SW spectrum as d is varied (with fixed $w = 50$ nm and reduced rim anisotropy), i.e. how **geometry of the hole** reshapes the mode ladder.

- Bulk modes (fundamental + higher-order) are only **weakly affected** by d, while **azimuthal rim modes** shift strongly: decreasing d shortens the rim
- Radial rim modes show a **non-monotonic** trend: they slightly decrease with d at first, then increase again for very small d (10 nm) due to the topology change toward a continuous film / changed demag factors; many crossings appear but avoid-crossings vs d are not prominent.
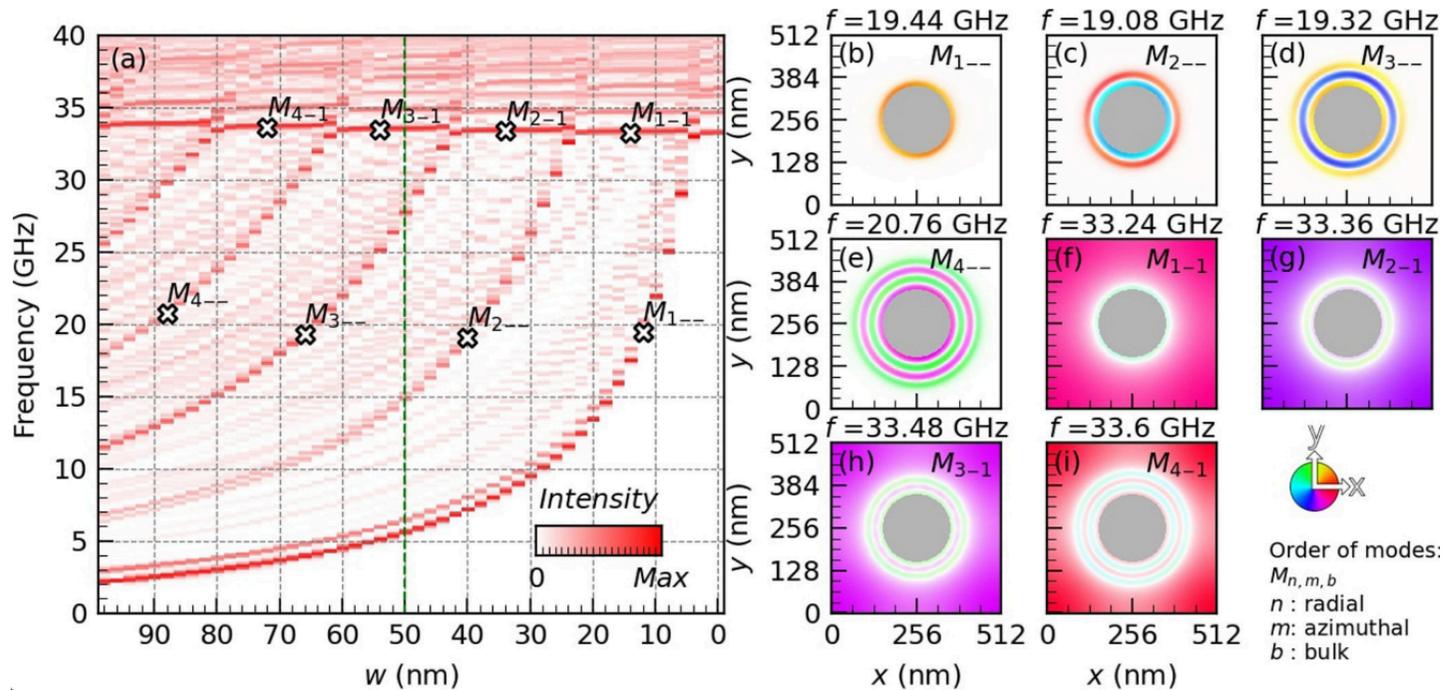
Demonstrates that w is a **strong tuning knob** for rim-localized (radial + azimuthal) modes, while bulk-mode frequencies remain nearly unchanged.

- As w decreases, rim confinement tightens → rim-mode frequencies increase (at mode-dependent rates); the fundamental rim radial mode can be tuned up to the bulk fundamental frequency and hybridizes with it (mixed bulk+rim character).
- Multiple hybridizations occur between the bulk fundamental and higher-order radial rim modes; the paper notes the hybridization strength can increase with radial order n.

Paper 3: Take-home message

Anisotropy rims create a second, tunable edge-mode subsystem

Edge modes shift strongly with rim parameters and hybridize with bulk modes to open controllable gaps—turning "fabrication rims" into a deliberate design knob.
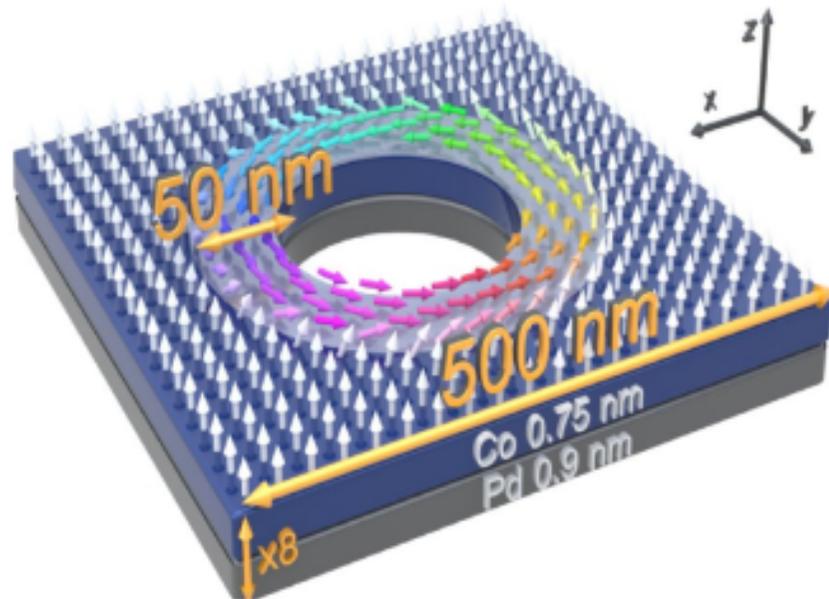
Paper 4 — Strong magnon–magnon coupling: bulk ↔ rim

The role of non-uniform magnetization texture for magnon–magnon coupling in an antidot lattice

M. Moalic; M. Zelent; K. Szulc; M. Krawczyk

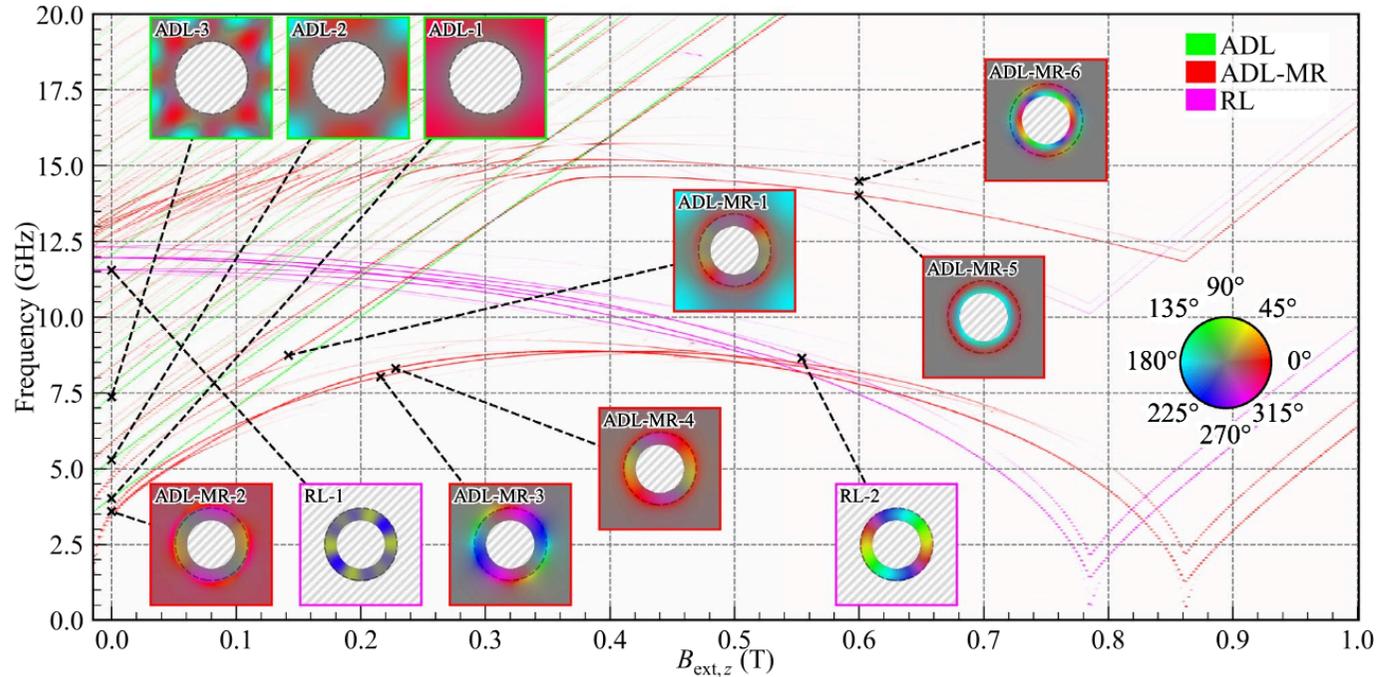Sci. Rep. 14, 11501   2024

The question:

When do two magnon subsystems couple **strongly** and **deterministically**?

Method:

- Vary out-of-plane external field to tilt the magnetization inside the rim
- Study simpler subsystems to understand the core principles

Paper 4: Quantifying strong coupling

- All are lattices:
  - ADL (green): Bulk
  - ADL-MR (red): Bulk + Rim
  - RL (pink): Ring
- Bulk-like modes rise linearly, while rim azimuthal modes split/soften and create multiple crossings in ADL-MR.

- ADL-MR shows avoided crossings $\rightarrow$ bulk and rim modes are coherently coupled (not a simple ADL + RL sum).
- Splittings map where bulk–rim modes become near-degenerate $\rightarrow$ defines the effective coupling window vs $B_{ext,z}$.

Paper 4: Adding a tiny spacer between the rim and bulk
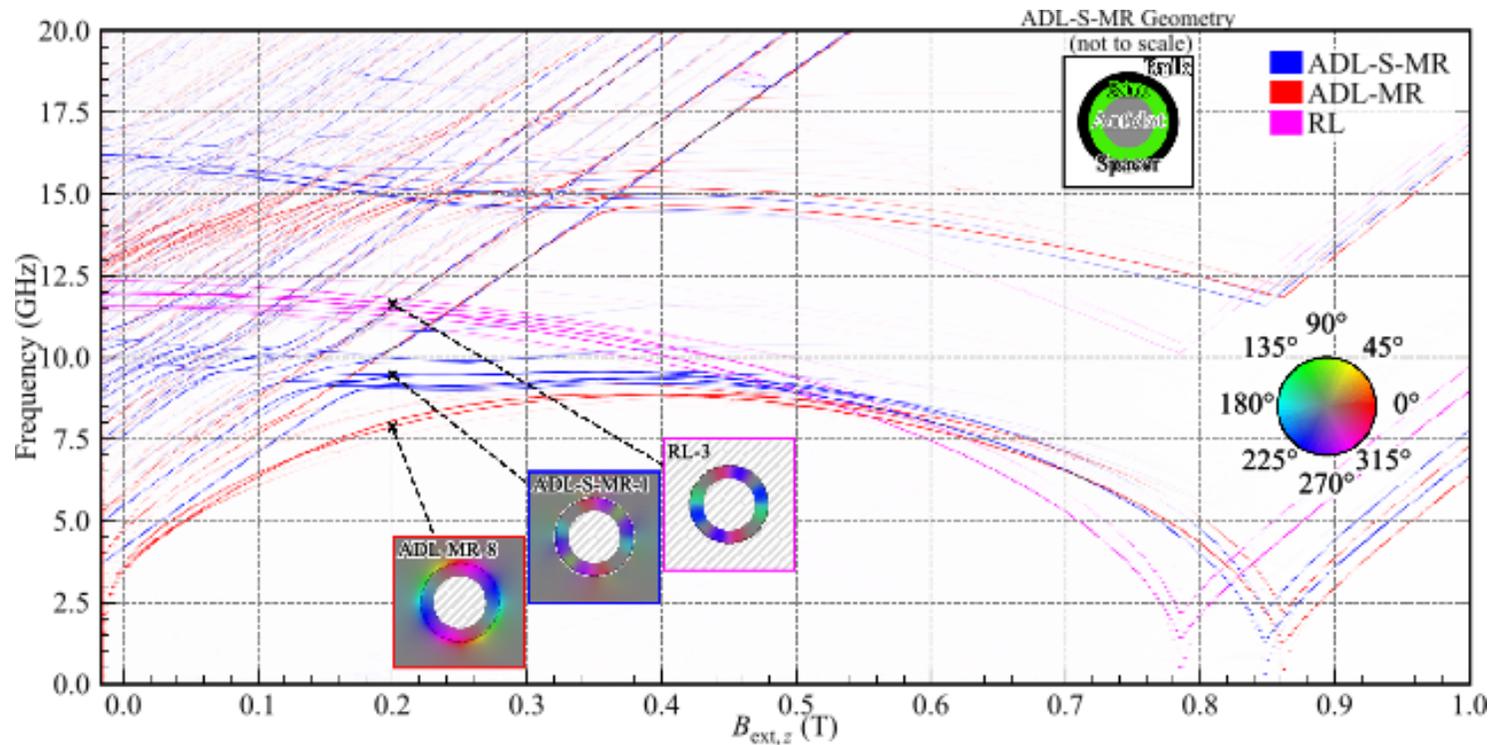
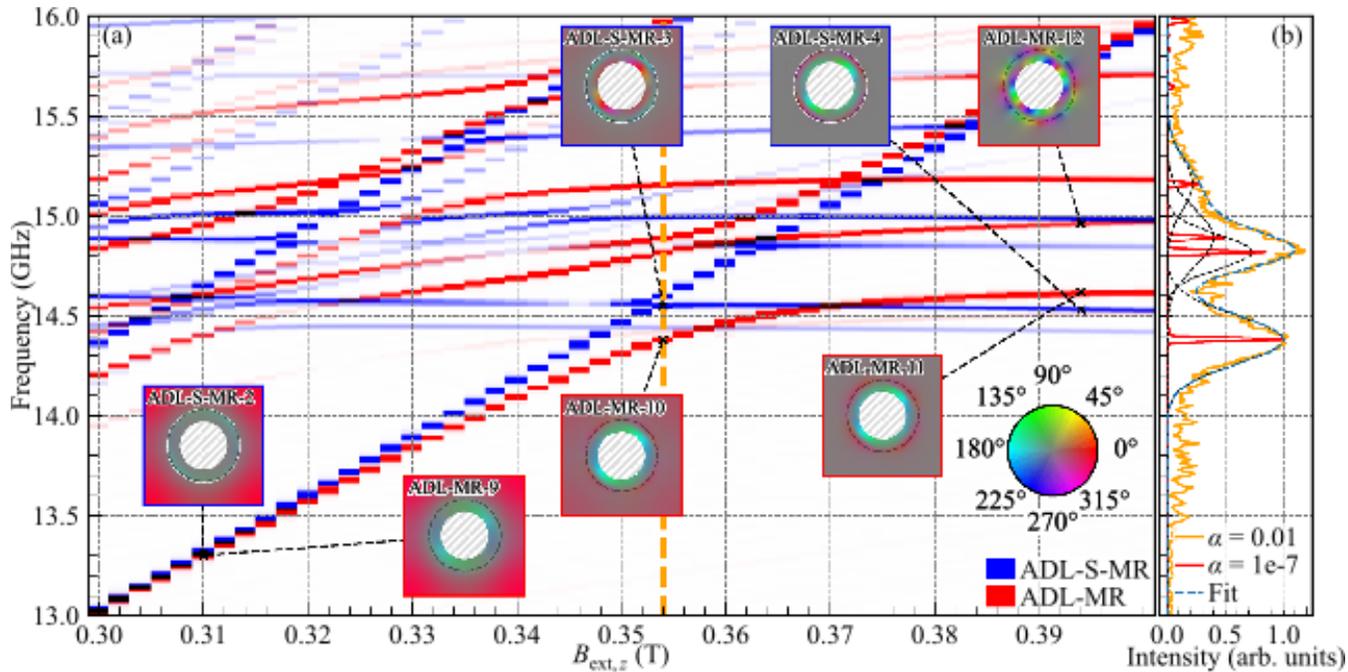- We separate exchange+dipolar coupling from dipolar-only coupling by inserting a non-magnetic spacer.
- ADL-S-MR retains only small hybridization gaps (dipolar), while ADL-MR shows stronger deviations/ anti-crossings (exchange-enhanced coupling).

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Paper 4: Zoom on the hybridization area

- Zoom reveals large anticrossing gaps in ADL-MR between bulk modes and second-order radial rim modes; gaps largely collapse in ADL-S-MR → exchange-driven strong coupling.
- At $B_{ext,z}$ = 0.354 T:
  - Frequency gap ≈ 220 MHz
  - Cooperativity C ≈ 5.7 (strong coupling)

Non-collinear texture enables deterministic strong magnon–magnon coupling

A bias-field sweep brings bulk and rim modes into resonance, and interfacial exchange sets a robust avoided crossing—an engineered route to hybrid modes and controllable mode conversion.

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Efficient generation of second-harmonic propagating spin waves in a thin, out-of-plane-magnetised ferromagnetic film

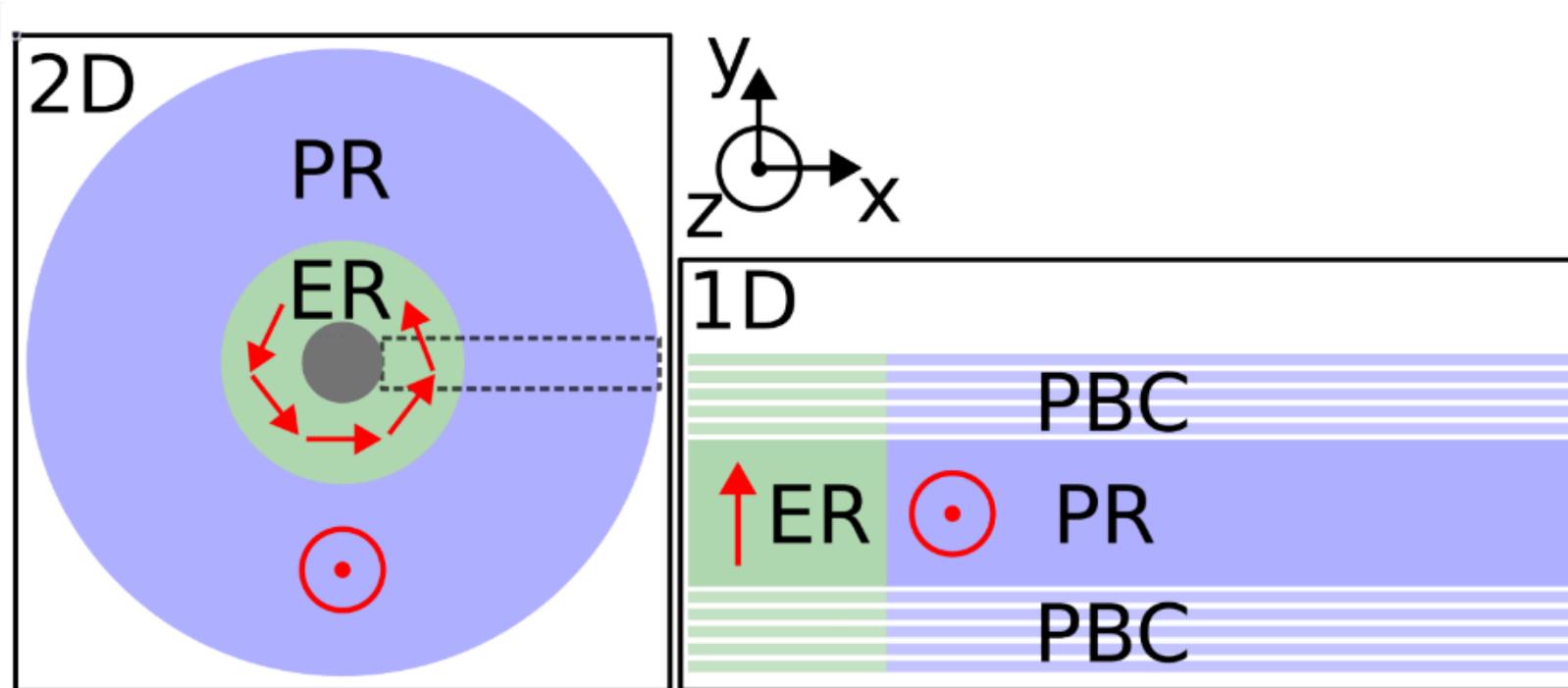M. Moalic; Y. Patat; M. Zelent; M. Krawczyk

arXiv preprint   2025

Not a lattice

Goal: Create a compact on-chip source of **short-wave-length**, **high-frequency** propagating waves

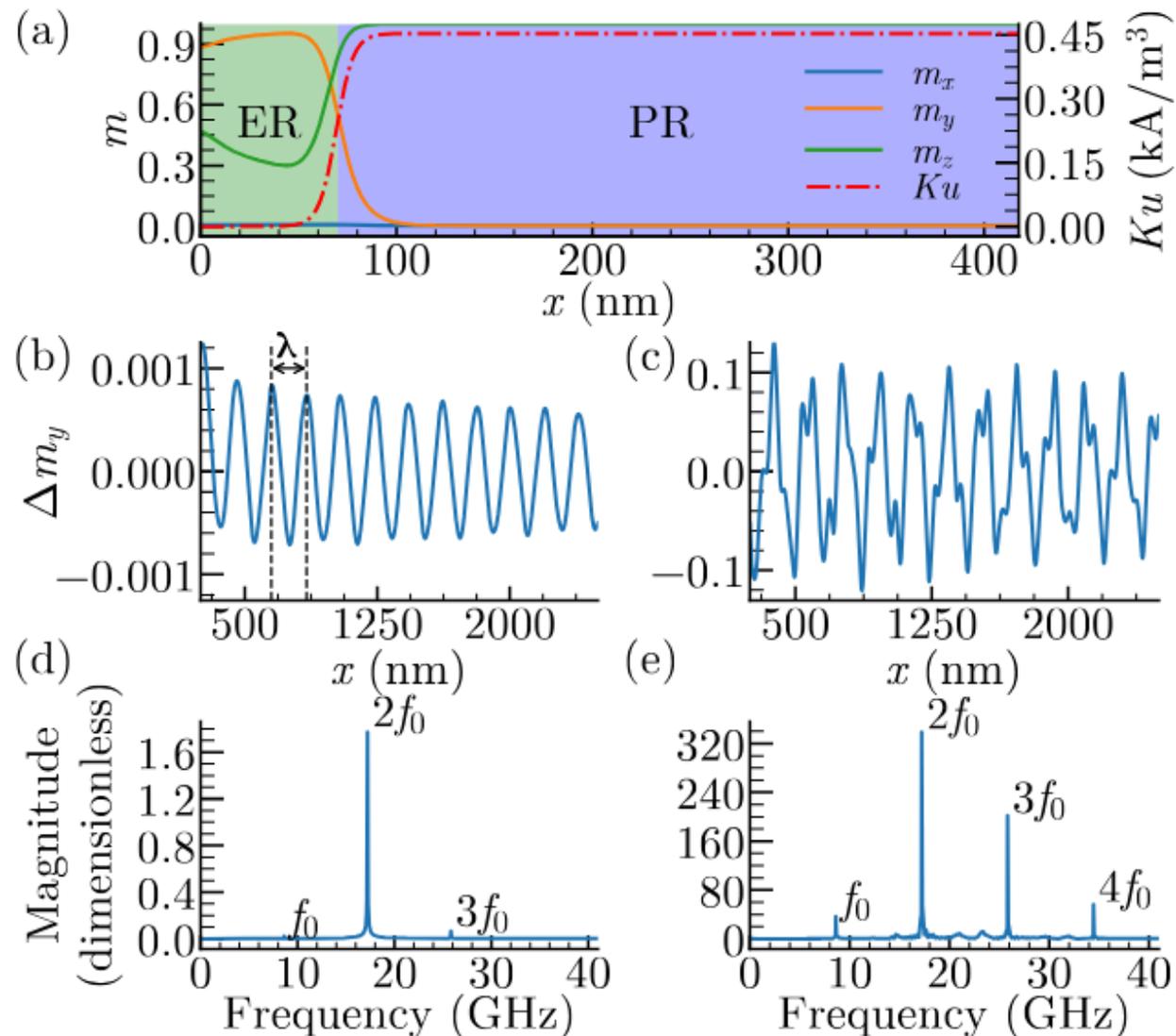- Rim → ER
- Bulk → PR

Paper 5: The concept

- Excitation Region (ER): locally in-plane magnetized region (reduced PMA)
  ‣ confined fundamental mode
- Propagation Region (PR): out-of-plane magnetized film/strip
  ‣ supports propagating exchange-dominated waves
- uniform out-of-plane microwave pump excites ER efficiently, PR weakly

Paper 5: How it works in the disk
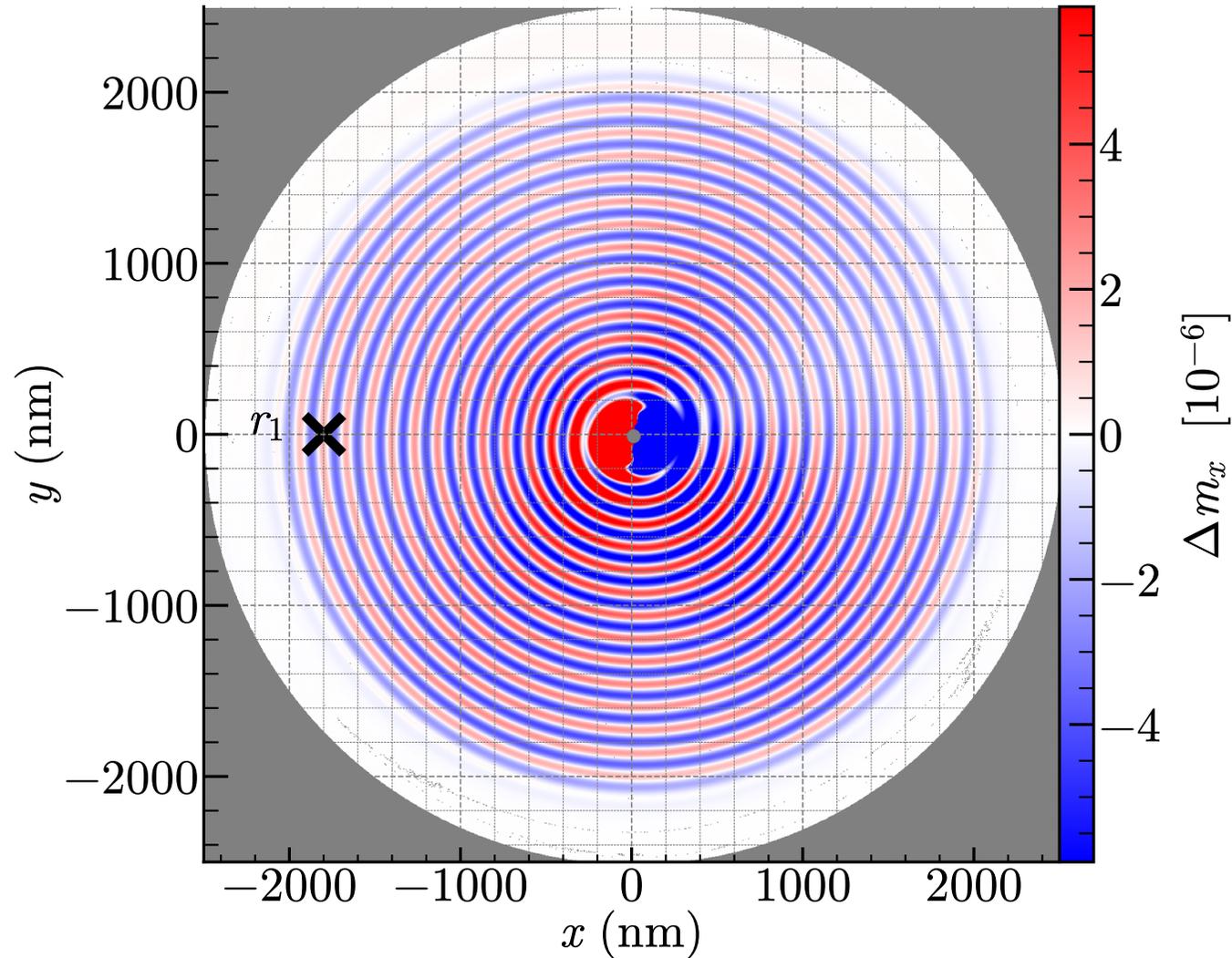
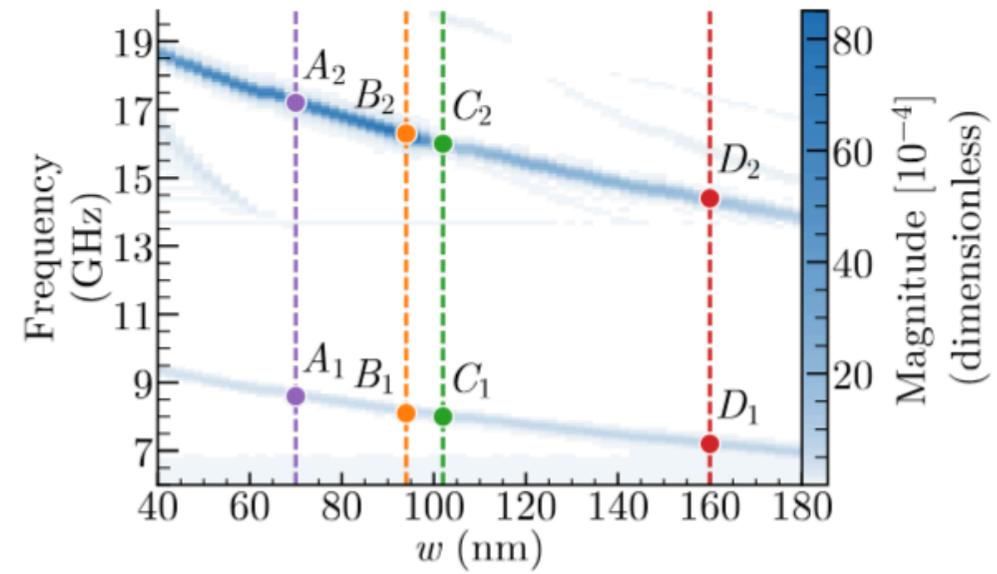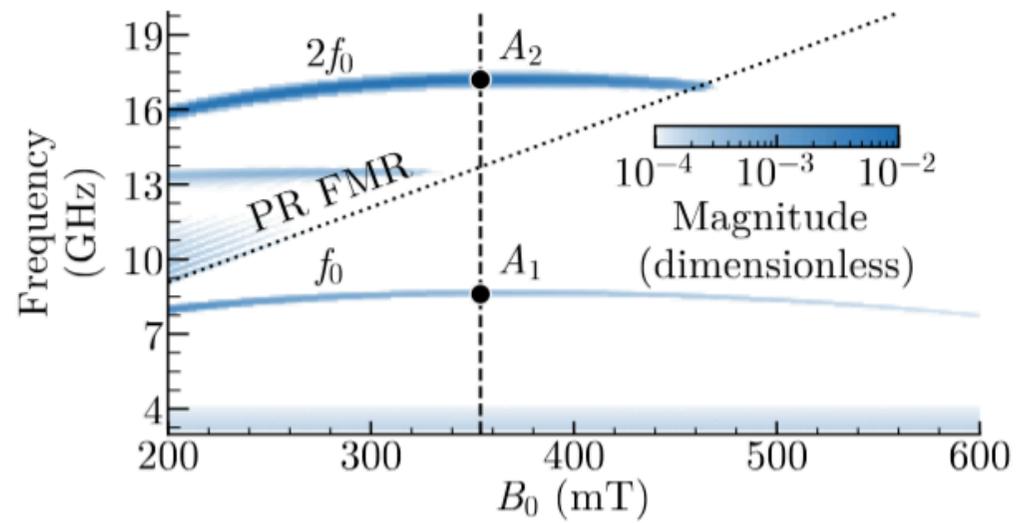- Single frequency f_0, global, out-of-plane excitation, below the FMR of the PR

- Nanocavity convert f_0 to higher harmonics

- Higher harmonics propagate in the PR

- f_0 below PR FMR $\rightarrow$ evanescent

- $2f_0$ above threshold $\rightarrow$ propagating

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Paper 5: Also works in 1D

- Uniform out-of-plane pumping at f_0 mainly excites the ER mode, while a strong propagating second-harmonic ($2f_0$) spin wave is launched into the PR (short $\lambda \approx 261$ nm).
- Boosting the drive amplitude enhances nonlinear conversion and introduces higher harmonics ($3f_0$, $4f_0$) in the PR spectrum, though $2f_0$ remains dominant.

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Paper 5: Changing the external field and ER width

- Sweeping B_0 shifts $2f_0$ with the ER mode (f_0); beyond the FMR, the PR becomes evanescent.

- Tuning the ER width w shifts f_0 (and $2f_0$): larger $w \to$ lower frequency.

- $2f_0$ emission vs w is resonant, maximizing around $w \approx 94$ nm.
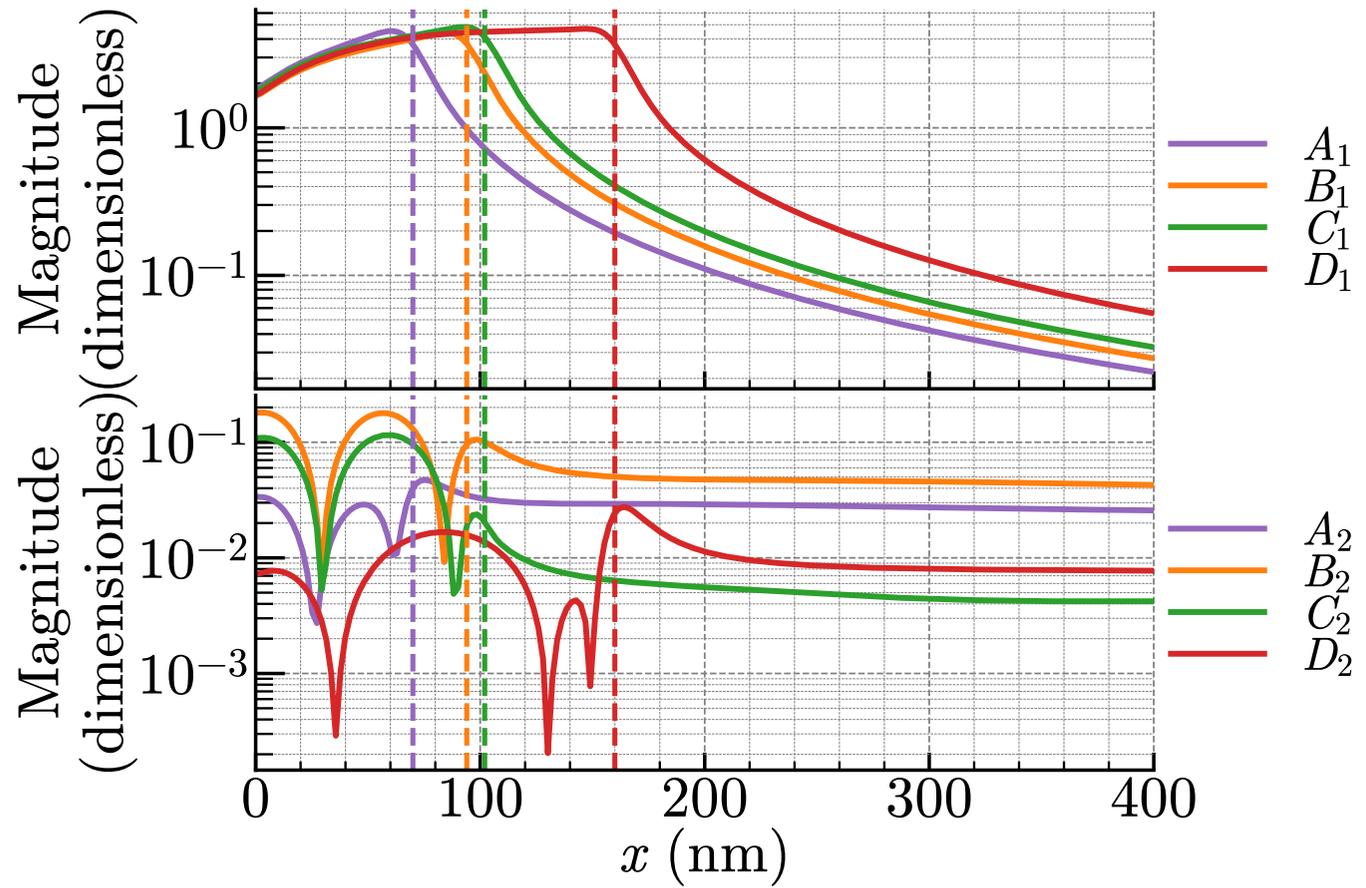
- The pumped f_0 mode stays localized in the ER and decays into the PR (below PR FMR), largely independent of w.
- The $2f_0$ mode develops nodes/ standing-wave character inside the ER

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A nanocavity can frequency-double into propagating, short-wavelength magnons

Uniform pumping excites a confined fundamental mode; its second harmonic is efficiently launched into an extended region, with tunable output frequency and enhanced efficiency via cavity matching.

Synthesis: one framework, three knobs

Across five papers:

- **Anisotropy** creates new subsystems (rim) and reconfigurable hybridization
- **Geometry** creates band structures, in 1D, 2D or fractals
- **Nonlinearity** adds frequency conversion and wavelength scaling on-chip

My core contributions:

- numerical design rules + mode interpretation
- scalable simulation + post-processing tooling (Amumax, Pyzfn)

Thank you.