V. G. Baryakhtar Institute of Magnetism
of the NAS of Ukraine

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CONTROLLING NONLINEAR PROCESSES IN SPINTRONIC NANOSTRUCTURES

PI – D.Sc. Roman Verba

PARTICIPANTS

PI:
D.Sc. Roman Verba

Dr. Vladyslav Borynskyi

Dr. Pavlo Polynchuk

Dr. Julia Kharlan (in 2025)

PhD student Roman Teslia (in 2025)

Dr. Vladyslav Zamorskyi (in 2024)

Affiliation – V. G. Baryakhtar Institute of Magnetism of the NAS of Ukraine

OBJECTIVE & TASKS

The **objective** is a detailed study of ways to control nonlinear 3- and 4-magnon processes in single- and multilayer magnetic nanostructures and the development of methods for using the studied rules to expand the functional capabilities of spintronics nanodevices.

Tasks

A. Establishment of general regularities:

1) changes in the intensity and selection rules of three-magnon processes in magnetic nanoelements in a saturated state upon small changes in the static state from equilibrium;

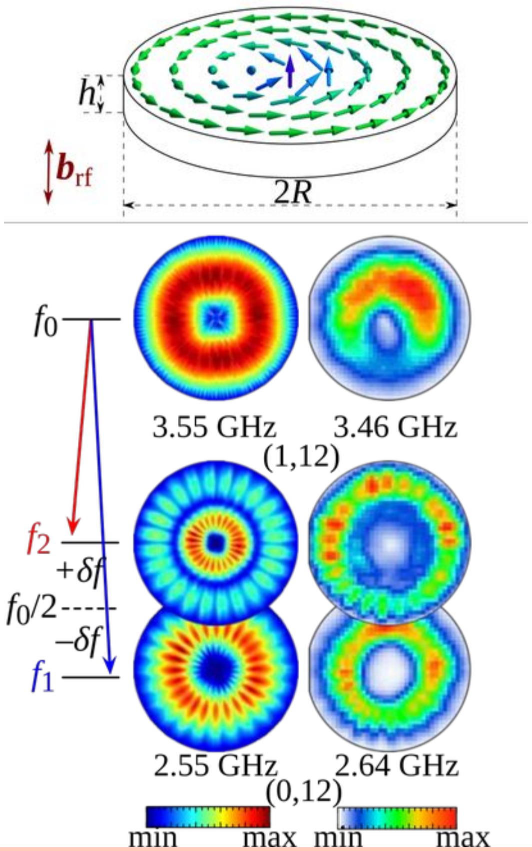
2) the influence of intermode hybridization in two-layer spintronic nanostructures on four-magnon processes;

3) three-magnon scattering of propagating spin waves on localized modes.

B. Applications:

4) studying the effect of changes in the intensity of four-magnon processes on the dynamics of spintronic nano-oscillators and the possibility of controlling oscillators;

5) application of three-magnon processes for amplification, detection, and/or other functional operations for the needs of magnonics.

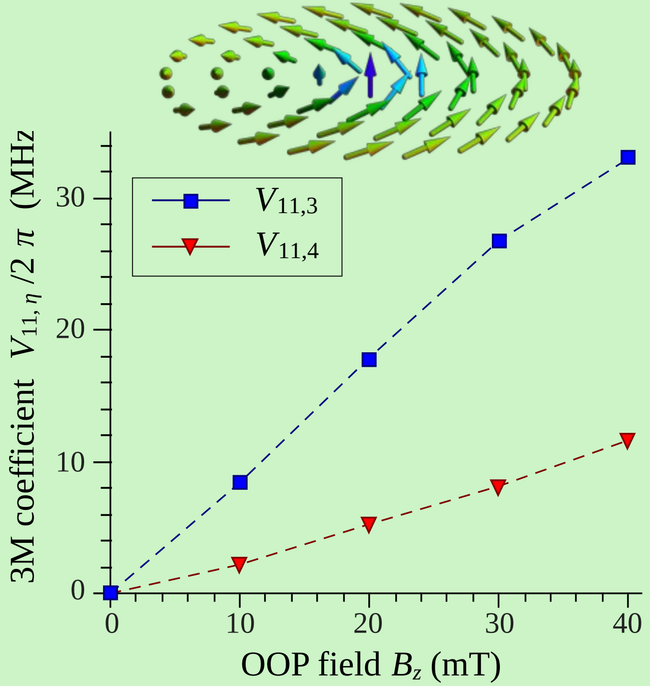


In perfect vortex state ***only nondegenerated processes are allowed***

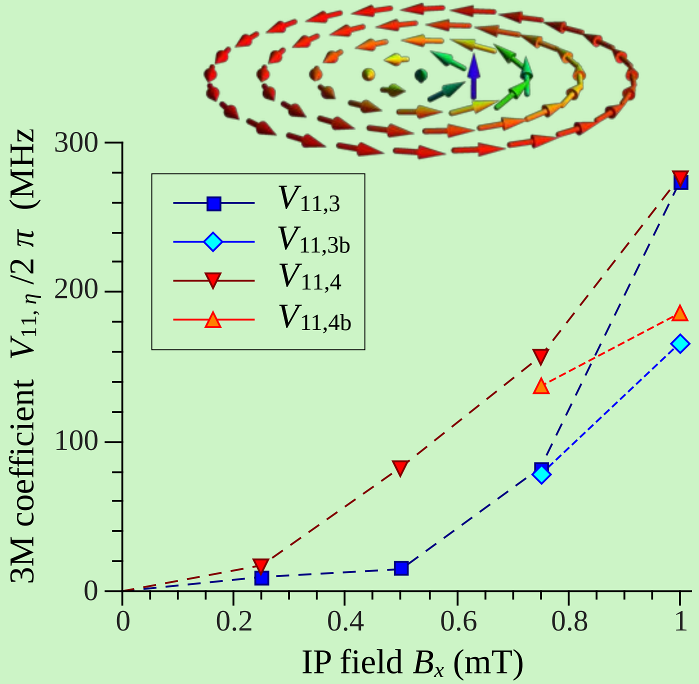
Considered processes: $(1,0)+(1,0)\rightarrow(3,0)$ & $(1,0)+(1,0)\rightarrow(4,0)$

In ideal state – prohibited. Responsible for nonlinear dissipation & 2nd harmonic.

Out-of-plane perturbation field



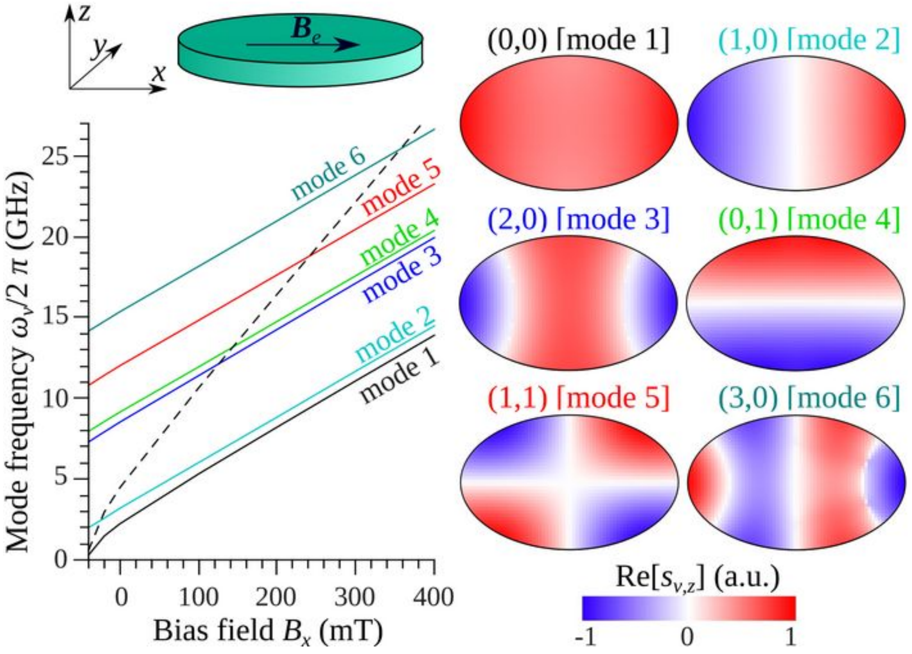
In-plane perturbation field



We found that ***perturbations of the vortex state allows for degenerate three-magnon processes*** to happen. ***Perturbations in the plane*** (shifting the vortex core) are a way ***more efficient*** to influence three-magnon processes.

IN-PLANE MAGNETIZED DOT

SW mode spectrum & profiles



In unperturbed state all modes are either symmetric (S) or antisymmetric (A) respective to the dot axes.
Selection rules for three-magnon interaction: **$\Sigma_\nu n_{\nu,x}$ & $\Sigma_\nu n_{\nu,y}$ – odd numbers**

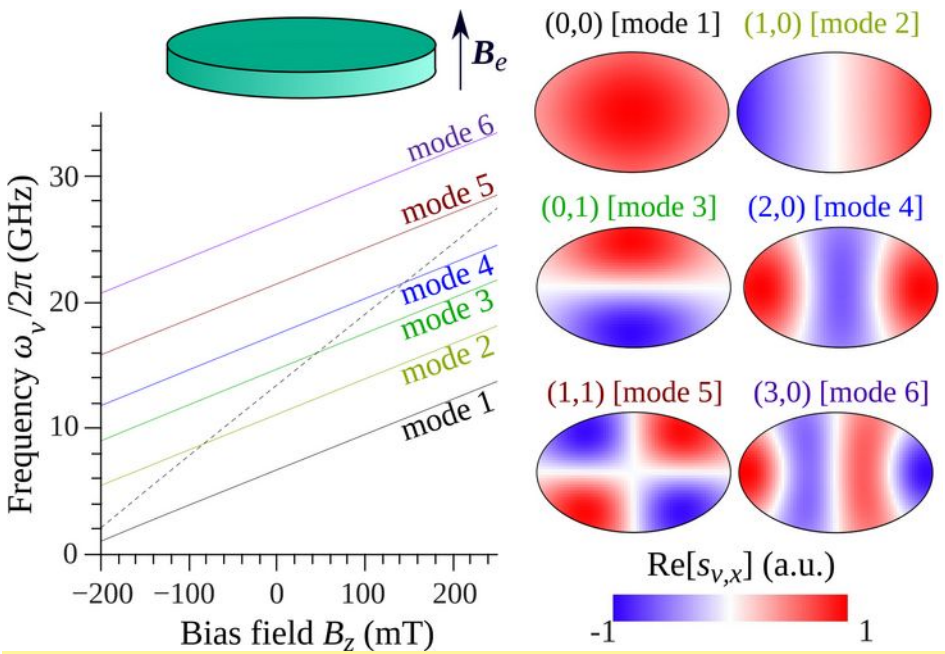
Perturbation effect on $(\nu + \nu) \rightarrow 2$ process

	Mode 2 symmetry			
Perturbation field	**(S, S)**	**(A, S)**	**(S, A)**	**(A, A)**
Unperturbed	-	-	-	+
B_y, B_z uniform/symmetric	+	weak	weak	+
$\Delta B_x(x)$ antisymmetric	-	-	+	+
$\Delta B_x(y)$ antisymmetric	-	+	-	+
$B_x(x,y)$ antisymmetric	+	+	+	+
$B_y(x)$ або $B_z(x)$ antisym.	-	+	-	+
$B_y(y)$ або $B_z(y)$ antisym.	-	-	+	+
$B_y(x,y)$ / $B_z(x,y)$ antisym.	-	-	-	+
IDMI	-	+	-	+

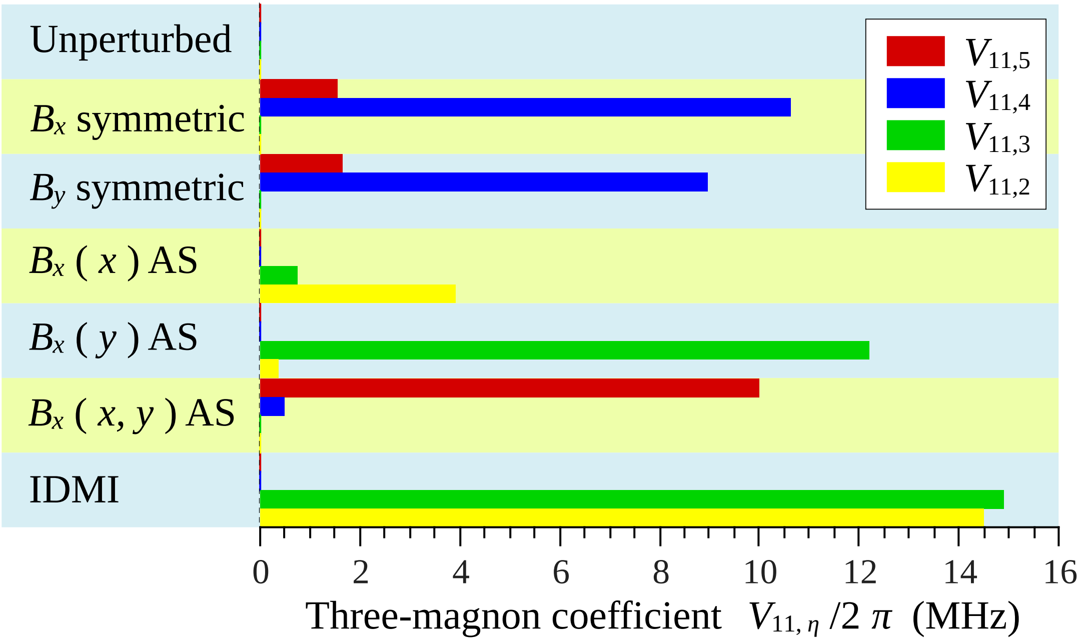
Impact of perturbations of all the possible symmetries on three-magnon interaction is systematized.
Most of perturbations shows mode-selective impact.

OUT-OF-PLANE MAGNETIZED NANODOT

SW mode spectrum & profiles



Effect of perturbation on (1+1) → *v* process



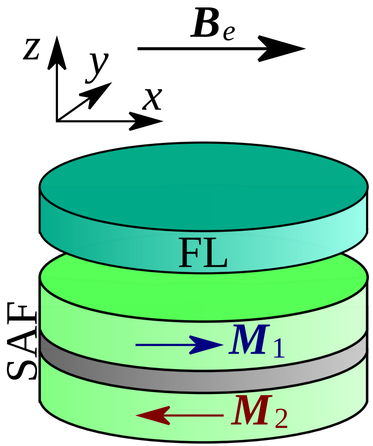
Perturbation field magnitude 10 mT, IDMI Db/h = 0.05 mJ/m^2.

In an unperturbed state, the modes are similar to the previous case of an in-plane magnetized nanodot.
However, ***three-magnon processes are prohibited completely.***

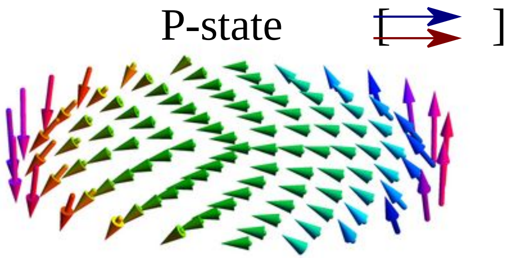
Two groups of modes – fully symmetric/antisymmetric and of mixed symmetry – are sensitive to different perturbations. There is no selectivity within the group.

NANOSCALE REALIZATION

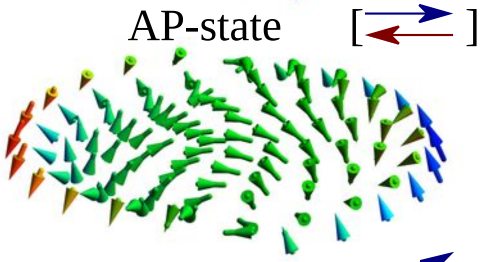
SAF/FL (free layer) nanopillar



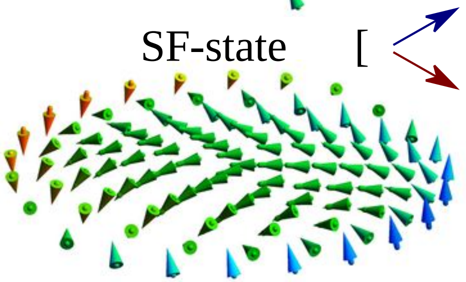
Stray fields created by SAF in FL



B_x – (S,S)
B_y – (A,S)



Weak stray fields



Mixed symmetry (nor S, not AS)

Synthetic antiferromagnetics (SAF) can exist in different states: parallel (P), antiparallel (AP), and spin-flop (SF), including ***bistability*** (hysteresis).
Significantly ***different symmetry of stray fields*** allows using ***SAF state change*** (by field/current pulse) ***to control three-magnon processes in FL***.

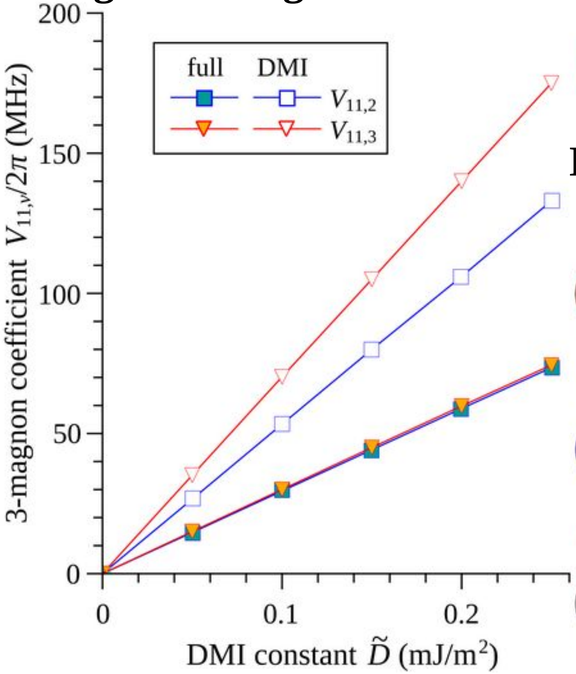
Other possible alternatives:
transition vortex - saturated state,
single-/multi-domain state, etc.

Interfacial Dzyaloshinskii-Moriya interaction (IDMI) is an antisymmetric exchange interaction present at ferromagnet-heavy metal interfaces.

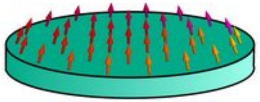
$$W_{\mathrm{IDMI}} = (\tilde{D}/M_s^2)\,[M_z \nabla \cdot \boldsymbol{M} - \boldsymbol{M} \cdot (\nabla M_z)]$$

Nanodot in perpendicular state

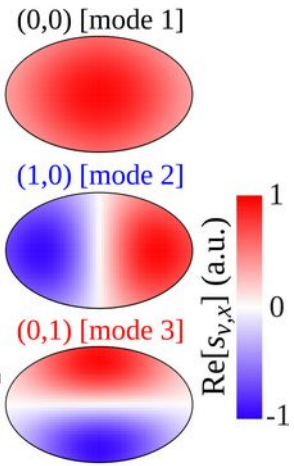
Change in 3-magnon coeff.



Static state

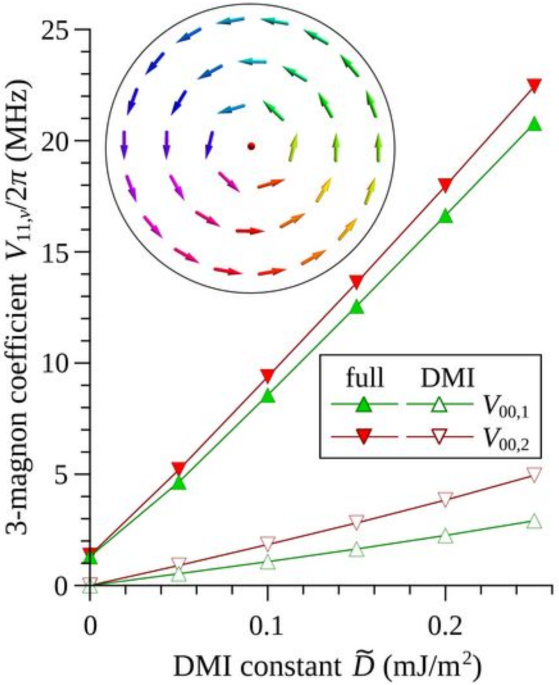


Mode profiles

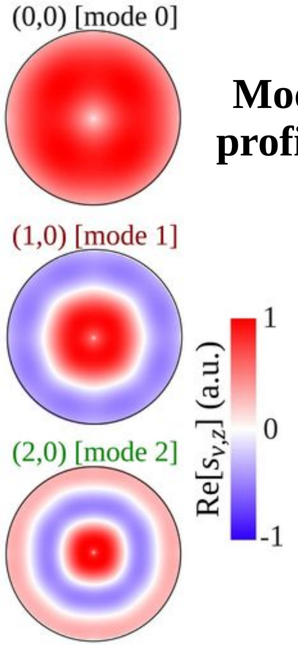


Magnetic disk in vortex state

Change in 3-magnon coefficients



Mode profiles



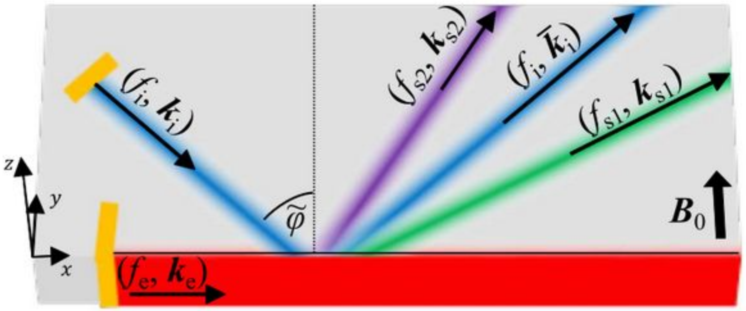
IDMI has a ***strong effect*** on three-magnon processes =

Σ direct contribution + indirect one due to change in static state.

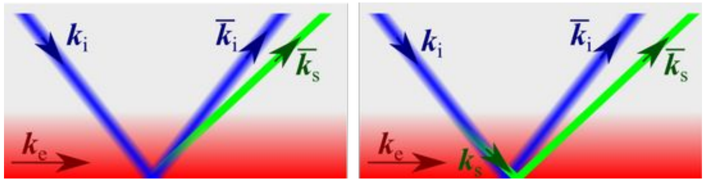
IDMI is present in most spintronic structures → ***possible complications in interpreting results and control.***

Electrically controlled IDMI → ***a new way of control***

Interacting spin waves



2 elementary processes: scattering after reflection & before reflection



Effective 3-magnon interaction coeff.

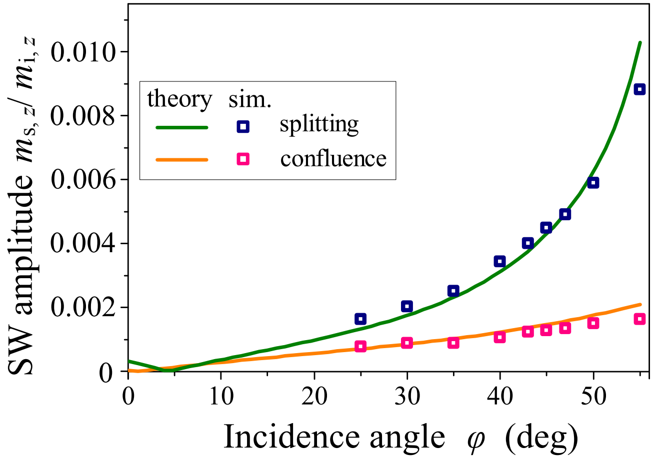
$$V_{\text{conf}} = V_{\text{ie,s}} e^{i\phi_s} + V_{\text{i}\bar{\text{e}},\bar{\text{s}}} e^{i\phi_i}$$

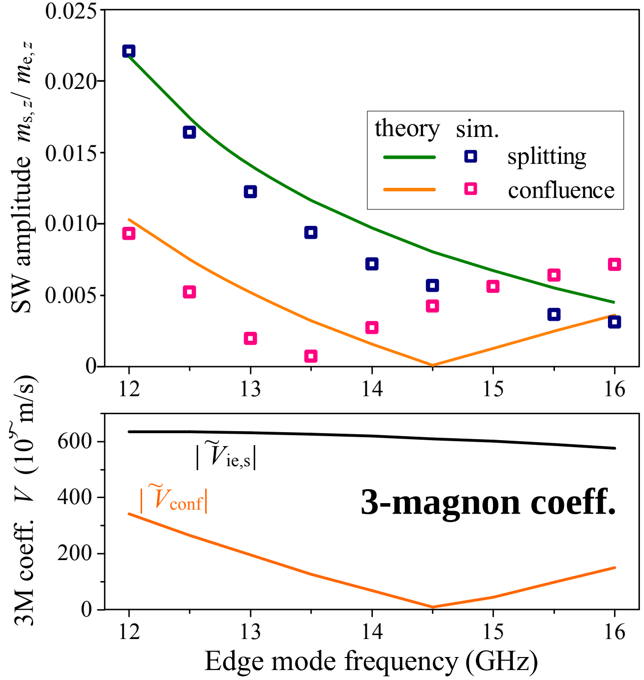
ϕ_α – phase accumulation upon reflection

Scattered wave amplitude

$$|c_s| = V c_i c_e (\varepsilon v_s)^{-1} e^{-\Gamma y / v_s}$$

Scatterd SW amplitude vs incidence angle & vs edge mode frequency



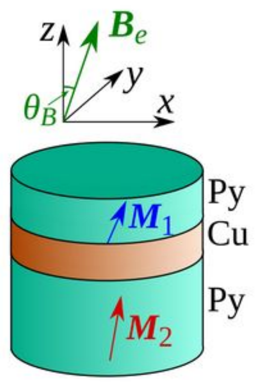


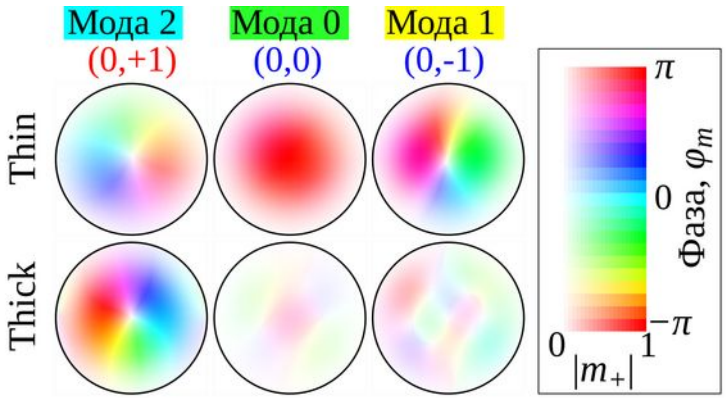
General trend of three-magnon interaction $V \sim \sin[2\varphi]$.

The amplitude of the scattered wave is inversely proportional to the projection of its group velocity → additional angular dependence.

The fundamental role of ***partial wave interference*** has been established → high sensitivity to frequencies SW = ***a method of effective control***

CONTROLLING FOUR-MAGNON PROCESSES

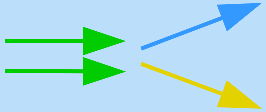




Controlling 4-magnon processes is more complex. **Symmetric selection rules are absent in general**.

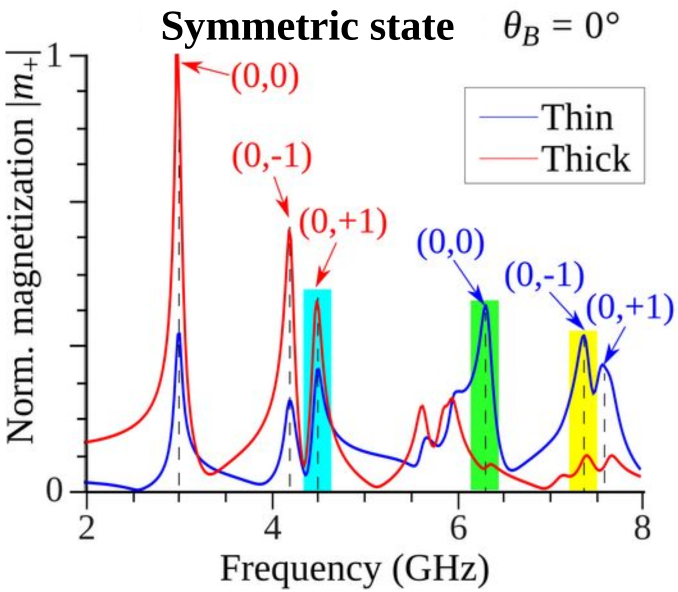
Possible process – 2nd order Suhl instability

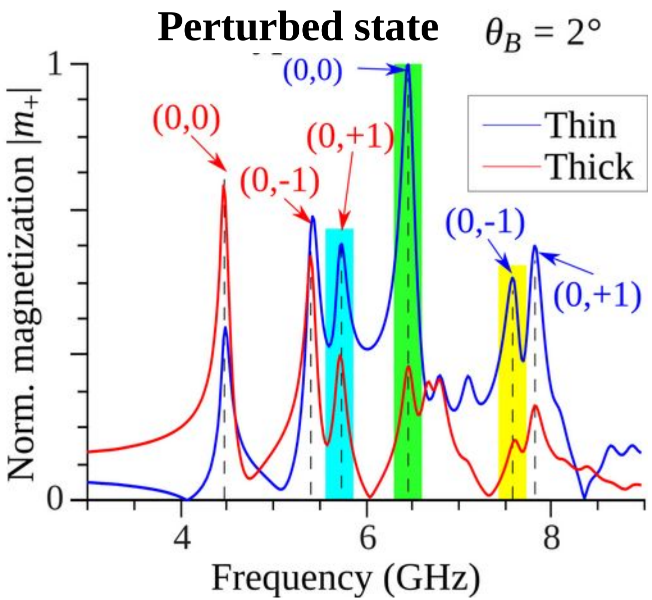
$$0 + 0 \to 1 + 2$$

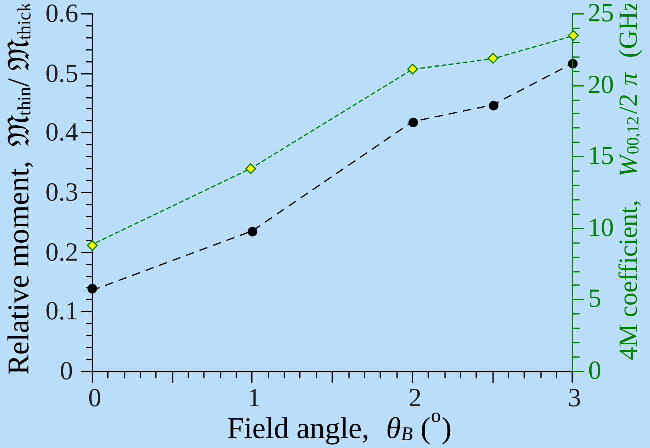


Perturbation (bias field tilt) **changes much hybridization** between free and fized layers modes.

Consequence: **change of 4-magnon coefficient in 2 times under 3° tilt.**

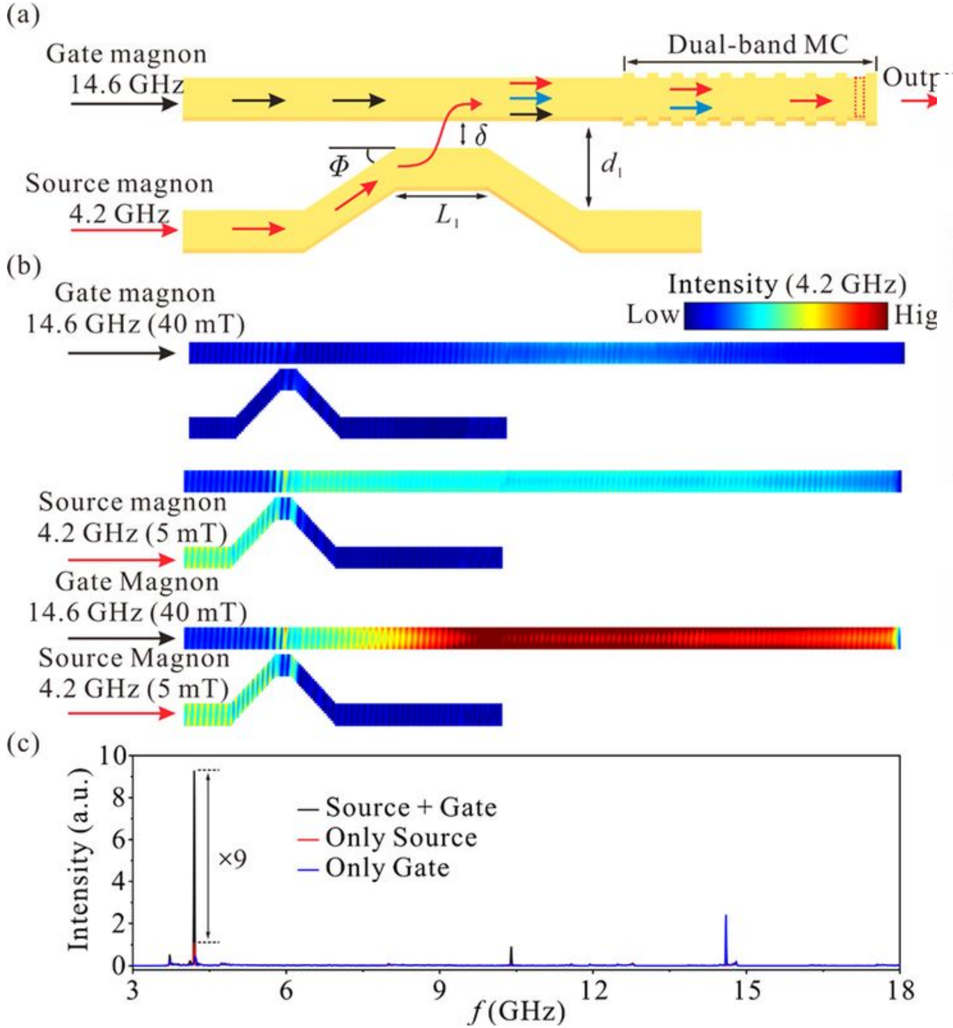






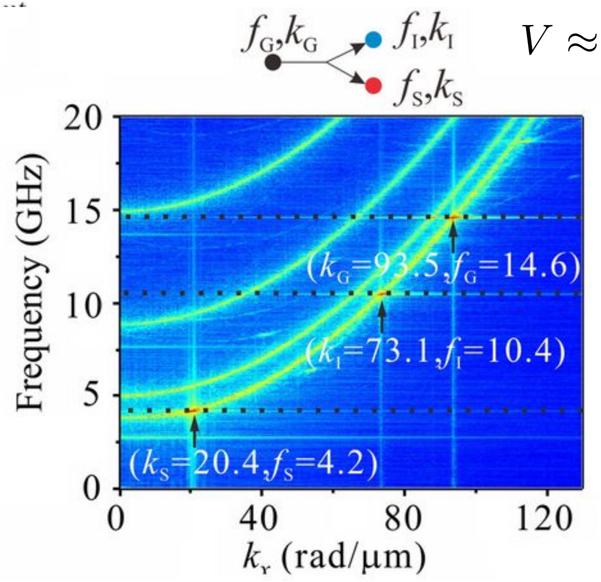
Hybridization of modes – an alternative for control 4M processes.

APPLICATION: MAGNON TRANSISTOR

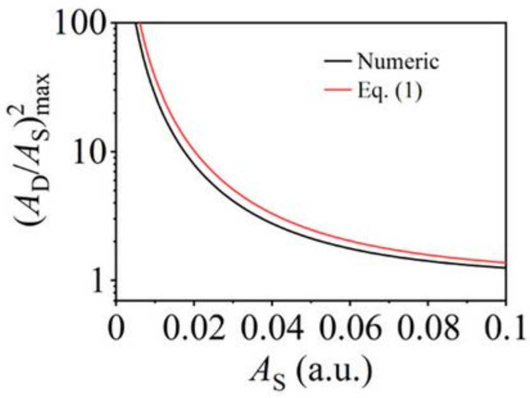


Scheme of three-wave interaction & its efficiency

$$V \approx \frac{\omega_M \sin 2\varphi_M}{4\sqrt{2}} \left(f(k_1 t) + f(k_2 t)\right)$$



Gain rate



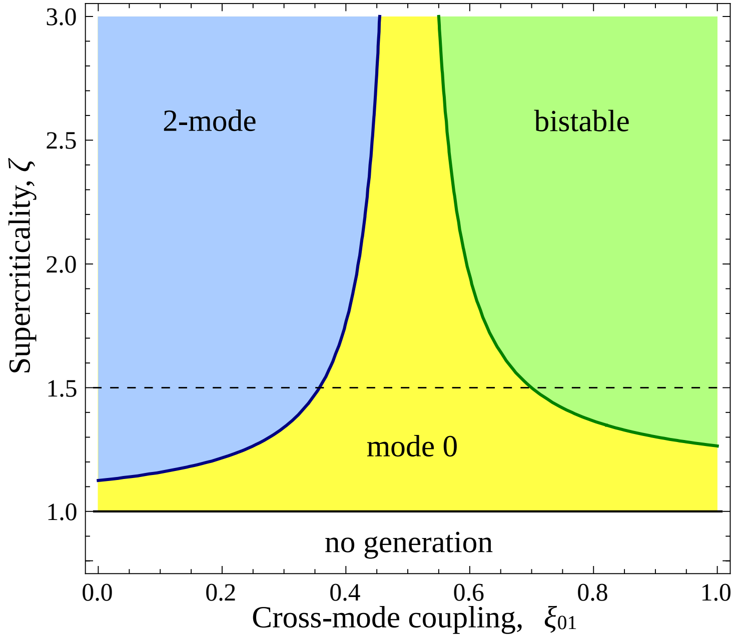
The operation of a **magnon transistor** based on stimulated three-magnon splitting has been demonstrated using numerical methods. A spin-wave coupler is used to mix the signal and pumping, and a two-band magnon crystal is used to filter idler magnons and pumping at the transistor drain. **A gain coefficient of 9** has been achieved. The phase of the drain magnons depends only on the phase of the output magnons.

Two-mode auto-oscillator model

$$\dot{a}_j + i\tilde{\omega}_j a_j + \tilde{\Gamma}_j a_j = \Lambda_j e^{-i\omega_e t},\ j \neq k = 1,2$$

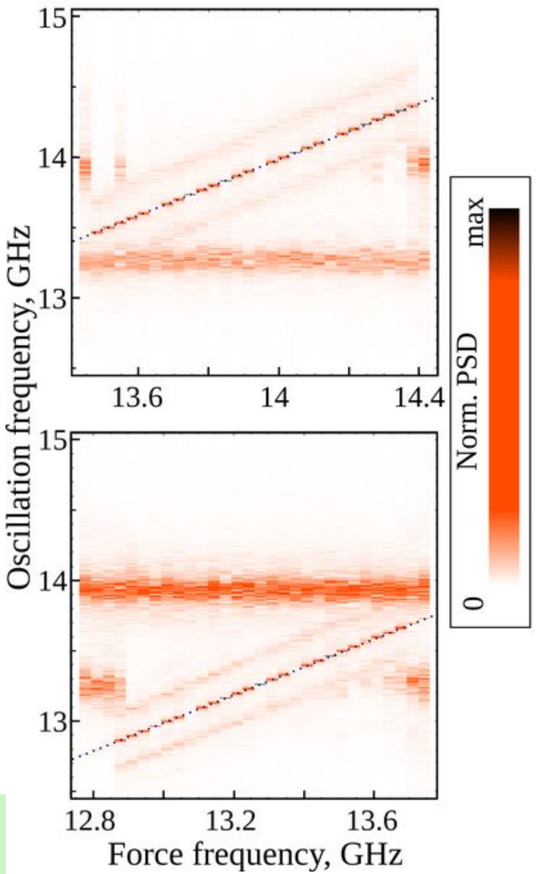
$$\tilde{\Gamma}_j = \Gamma_j(1 + \xi|a_j|^2 + \xi_{01}|a_k|^2)$$
$$-\sigma I(1 - \xi|a_j|^2 + \xi_{01}|a_k|^2)$$

Generation regimes map

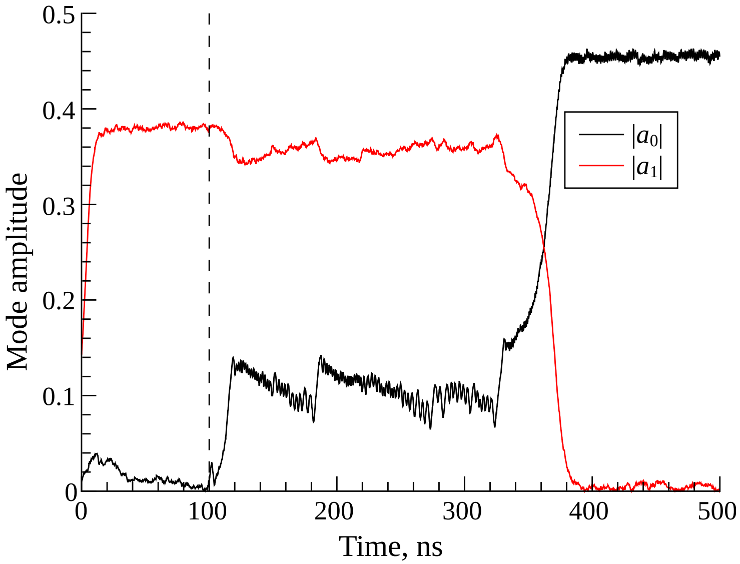


Changing the intermodal interaction leads to ***different generation regimes***.

Phase-locking in two-mode regime



Auto-oscillating mode switching by RF pulse in bistable regime



Two-mode regime – ***phase-locking of each mode*** is possible.
Bistable regime – ***dynamic switching of the generation mode*** (and, accordingly, frequency) by a synchronization pulse.

CONCLUSIONS

- controlled symmetry breaking of the magnetic state is shown to be an efficient tool for the control of the intensity and selection rules of three-magnon scattering processes; for nanodots in a saturated state, the correspondence of the interacting modes symmetry to the symmetry of the perturbation, affecting their three-magnon coupling, has been established;
- a theory of three-magnon scattering of bulk spin waves on edge modes has been developed, and the sensitivity of this process to boundary conditions has been established, opening the way for its control;
- the functionality of a spin wave amplifier based on stimulated three-magnon scattering has been demonstrated;
- mode hybridization in multilayer nanostructures is shown to be an efficient mechanism for controlling four-magnon processes and, respectively, second-order parametric instability;
- nonlinear intermode interaction is shown to be crucial parameter determining the generation regime of spin-torque oscillators; the conditions fro the realization of single-, dual-mode, and bistable generation regimes, as well as dynamic switching of generation, have been formulated.

Book chapters:

1. ***R. Verba***, ***J. Kharlan, V. Borynskyi***, D. Slobodianiuk, A. Etesamirad, I. Barsukov, Controlling multimagnon interaction in magnetic nanodots and spintronic nanostructures // In: I. Vladymyrskyi, et al. (eds.) *Functional Magnetic and Spintronic Nanomaterials. NATO SPS Series B* (Springer, Dordrecht, 2024), P. 89-132.

Articles:

1. X. Ge, ***R. Verba***, P. Pirro, A. V. Chumak, Q. Wang, Nanoscaled magnon transistor based on stimulated three-magnon splitting, Appl. Phys. Lett. **124**, 122413 (2024).
2. K. Davídková , K. Levchenko, F. Bruckner, ***R. Verba***, F. Majcen, Q. Wang, M. Lindner, C. Dubs, V. Vlaminck, J. Klíma, M. Urbánek, D. Suess, and A. Chumak, Nanoscale spin-wave frequency-selective limiter for 5G technology, Phys. Rev Appl. **23**, 034026 (2025).
3. ***V. Borynskyi, J. Kharlan, and R. Verba***, Effect of interfacial Dzyaloshinskii–Moriya interaction on three-magnon processes in thin magnetic nanodots, Low Temp. Phys. **51**, 986 (2025).
4. D. Slobodianiuk, A. Slavin, V. Tyberkevych, and ***R. Verba***, Auto-oscillations and phase-locking in a multimode spin-torque oscillator, Low Temp. Phys. **51**, 804 (2025).
5. ***J. Kharlan, R. Verba***, K. Sobucki, P. Gruszecki, M. Krawczyk, Three-magnon scattering of spin wave on edge-localized mode in thin ferromagnetic film, Phys. Rev. B **112**, 214438 (2025).

Ph.D. theses:

1. ***Polynchuk P. Yu.*** Relaxation-free switching of magnetic memory cells based on multilayer nanosystems with antiferromagnetic coupling: Ph. D. thesis, specialty 104 - Physics and astronomy, Institute of Magnetism. – Kyiv, 2024.

Conference abstracts:

1. K. Sobucki, ***J. Kharlan***, ***R. V. Verba***, et al., Nonlinear Effects in Inelastic Scattering of Spin-Wave Beams on Localized Modes for Controlling Propagation of Scattered Beams // INTERMAG 2024 (Rio de Janeiro, Brazil, 2024).
2. Yu. Dzhezherya, ***P. Polynchuk***, A. Kravets and V. Korenivski, Ultrafast inertia-free switching of double magnetic tunnel junctions // «Topical problems of semiconductors physics» (Drohobych, Ukraine, May 27-31, 2024).
3. ***R. Verba***, ***J. Kharlan, V. Borynskyi***, D. Slobodianiuk, A. Etesamirad, I. Barsukov, Controlling multimagnon processes in magnetic nanostructures // «Condensed matter & low temperatures» (June 3-7, 2024, online).
4. ***J. I. Kharlan, V. Yu. Borynskyi***, A. Etesamirad, I. Barsukov, ***R. V. Verba***, Symmetry breaking as an efficient tool for controlling three-magnon scattering in nanomagnets // NANO-2024 (21–24 August 2024, Uzhgorod, Ukraine).
5. ***R. Teslia***, O. Kolezhuk, I. Gerasimchuk, Current-driven dynamics of domain walls in low-dimensional helimagnets // International Workshop on Unconventional Magnetism in Quantum Materials (July 14-15, 2025, Kyiv, Ukraine).
6. A. Hamadeh, ***R. Verba***, D. Slobodianiuk, ***V. Borynskyi***, G. De Loubens, P. Pirro, O. Klein, Coherent magnon interactions and multitone microwave emission in spintronic nano-oscillators: bridging nonlinear dynamics and phsa-locked synchronisation // Magnonics 2025 (Cala Millor, Mallorca, Spain, July 28 - August 01, 2025).
7. ***P. Yu. Polynchuk***, Yu. I. Dzhezherya, A. F. Kravets, V. Korenivski, Ultrafast inertia-free switching of double magnetic tunnel junctions // NANO-2025 (August 20-23, 2025, Bukovel, Ukraine).
8. D. V. Slobodianiuk, ***R. V. Verba***, Multimode generation regime in spin-torque nano-oscillator // NANO-2025.