Spin waves in ferromagnetic nanostructures

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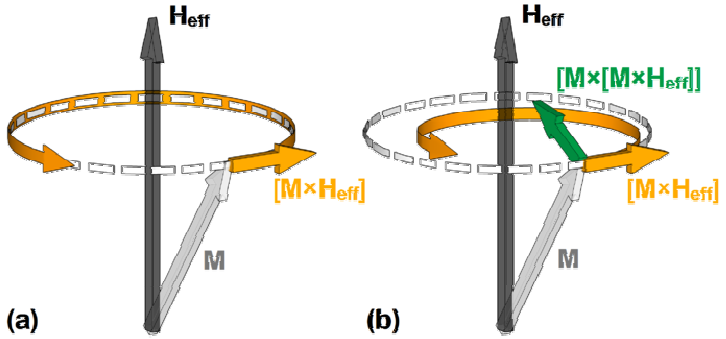
Spin waves in magnetic materials

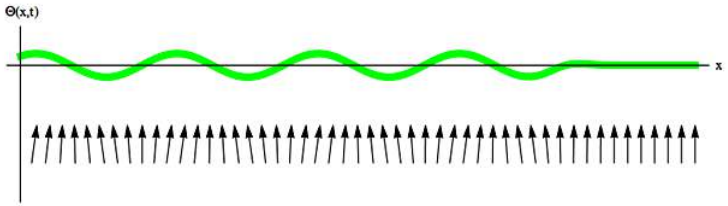
1. Spin Waves: Collective oscillations of the electron spins due to the **precession** of the corresponding magnetic moments around the direction of a magnetic field, governed by the **Landau-Lifshits-Gilbert** equation [harmonic oscillations (a), damped oscillations (b)]:

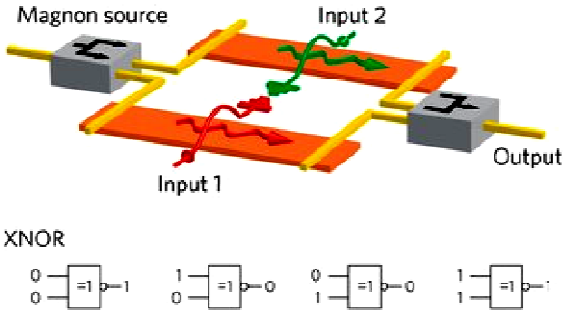
$$\mathbf{M} = \sum_{i=1}^{N} \frac{\boldsymbol{\mu}_i}{V}$$

$$\frac{d\mathbf{M}}{dt} = \gamma\mu_0 \mathbf{M} \times \mathbf{H}_{eff} + \alpha \frac{\gamma}{M_s} \mu_0 \mathbf{M} \times \left(\mathbf{M} \times \mathbf{H}_{eff}\right)$$



2. Formerly, SWs as background noise in writing/reading processes in magnetic memories, becoming crucial at the GHz range, where λ_{SW} ~ nanometric (use in nanotechnology)
3. More recently, spin waves as **information carriers**, alternative to electron motion: no ohmic losses / joule effect → assumed to improve device energy efficiency, even when integrated with conventional electronics. Use of spin waves to produce logic operations (Spintronics)

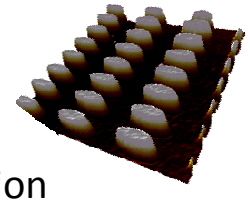


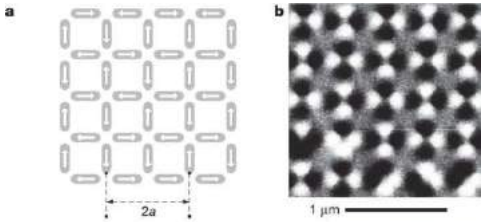


4. Materials: film, stripe, dots of any cross section….

Magnetic Meta-materials

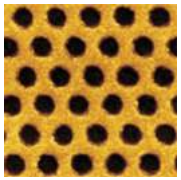
Nat. Lett. 500, 553 (2013) Sheng Zhang

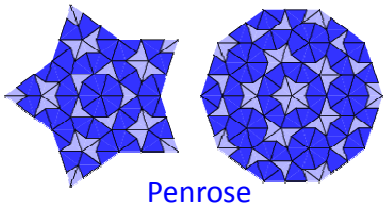




Artificial Crystals

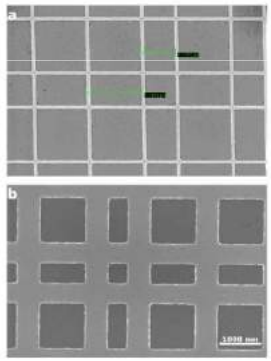
1. **Magnonic crystals**:
   a. periodic arrays of **nanomagnets** of any cross section
   b. periodic arrays of **holes** of any cross section tailored in a continuous film
   c. periodic modulation of **magnetic materials** in any combination
2. **Artificial spin-ices**
   a. periodic arrays of elongated nanomagnets (macrospins), simulating real spin ices.





Penrose
mathworld.wolfram.com

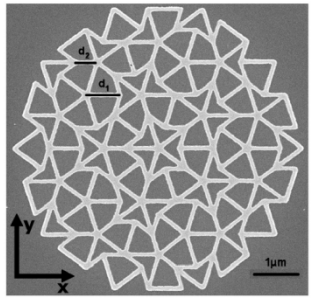
Fibonacci sequence



JAP 116 (2015) Farmer et al.

Artificial Quasi-Crystals

3. Systems characterized by extremely reduced symmetry
   a. Created by a deterministic algorithm (rigorous order - reproducibility)
   b. Characterized by **no translational symmetry**
   c. Occasional rotational symmetry is broken by an applied field (in case of magnetic AQC)
   d. quasi-crystals are ideal for designing controlled irregularities



PRL 111, 077201 (2013), Bhat et al.

Dynamical Matrix Method: Outline

1. Investigate the spin wave dynamics of model systems for understanding basic physics
2. Provide theoretical support, interpretation and understanding of experimental data
3. Suggest new theoretical models/aspects, new experiments, new applications

1. **Hybrid of micro-magnetic and analytical methods** – developed at Ferrara University
2. **Micromagnetic framework**: the magnetic areas are divided into elemental cells (typical size: 5 nm < λ_{exch})

all the physical properties are computed as interaction among the magnetic moments of the elemental cells

OOMMF*
Equilibrium magnetic configuration of the particle

If the system is periodic, calculations are made on the primitive cell with PBC

Dynamical matrix (PBC)
B

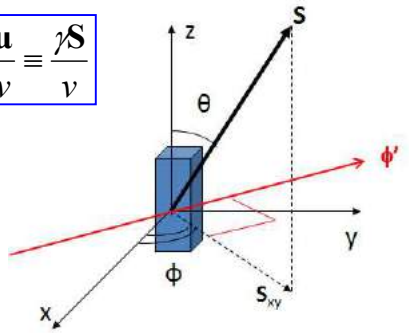
Hamilton equations of precession motion →

$$\begin{cases} \frac{\partial q_n}{\partial t} = \frac{\partial H}{\partial p_n} \\ \frac{\partial p_n}{\partial t} = -\frac{\partial H}{\partial q_n} \end{cases}$$

Diagonalization

$(\mathbf{B}-\lambda_{\mathbf{k}}\mathbf{I})\mathbf{v}_{\mathbf{k}}=0$
for any given **k**

$$\mathbf{M} \equiv M_s \mathbf{m} = \frac{\boldsymbol{\mu}}{v} \equiv \frac{\gamma \mathbf{S}}{v}$$



Eigenvalues
$\lambda_{\mathbf{k}}$ → frequency ω

Eigenvectors
$\mathbf{v}_{\mathbf{k}}$ → $\delta\mathbf{m}_{\mathbf{k}}$ mode profile

$$\delta\mathbf{m}(\mathbf{r}) = \delta\tilde{\mathbf{m}}_{\mathbf{k}}(\mathbf{r})e^{i\mathbf{k}\cdot\mathbf{r}}$$

(Bloch wave)

* The Object Oriented MicroMagnetic Framework by Donahue&Porter, at NIST (USA)

DMM: The Hamiltonian

1. Exchange: (short range) the origin of the (ferro)magnetic **order**

$$H = -\sum_{i \neq j} J_{ij} \mathbf{S}_i \cdot \mathbf{S}_j$$ **Heisemberg Hamiltonian** for a set of elementary/discrete spins pairs

$$H = -\frac{1}{2}\left(\frac{2m}{g_s |e| \hbar}\right)^2 \mu_0 \iint J(\mathbf{r}'-\mathbf{r}) \mathbf{M}(\mathbf{r}) \cdot \mathbf{M}(\mathbf{r}') d\mathbf{r}' d\mathbf{r}$$ Heisemberg Hamiltonian in a continuous distribution of magnetic moments with volume density **M**

Exchange energy density:

$$U_{exch} = -A \sum_i \left(\frac{\nabla M_i}{M_s}\right)^2 \rightarrow U_{exch} = -A \int \left(\frac{\nabla M(\mathbf{r})}{M_s}\right)^2 d\mathbf{r}$$ where $$A = \left(\frac{2m}{g_s |e| \hbar}\right)^2 \int J(\mathbf{r}) |\mathbf{r}|^2 d\mathbf{r}$$

Exchange length: $$\lambda_{exch} = \sqrt{\frac{2A}{\mu_0 M_s^2}}$$

2. Demagnetization: (long range) the origin of the (ferro)magnetic **disorder** (dipolar fields)

$$\mathbf{H}_{dem} = -\vec{\vec{N}} \mathbf{M}$$

$$\vec{\vec{N}}(\mathbf{r}_{ij}) = -\frac{1}{\tau} \int_{\tau} \int_{\tau'} \nabla \cdot \nabla' \left(\frac{1}{\mathbf{r}-\mathbf{r}'}\right) d\tau' d\tau$$

τ,τ' are uniformly magnetized volumes

Demagnetizing energy density

$$U_{dem} = -\frac{1}{2} \mu_0 \mathbf{M} \cdot \mathbf{H}_{dem} = +\frac{1}{2} \mu_0 \mathbf{M} \cdot \vec{\vec{N}} \mathbf{M}'$$

3. Zeeman: the applied magnetic field H_0

$$U_Z = -\mathbf{M} \cdot \mu_0 \mathbf{H}_0$$ **Zeeman energy density**

4. Anisotropy: if there exists any direction along which the magnetization is easily aligned

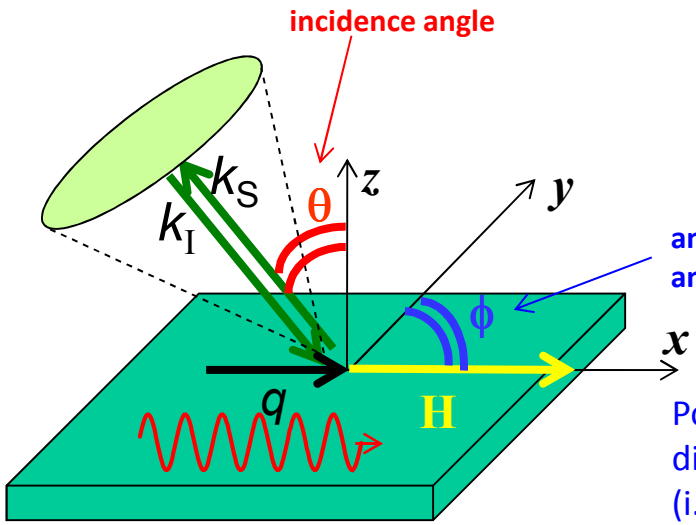
[ϕ : angle btw. **M** and easy axis (ϕ=0)]

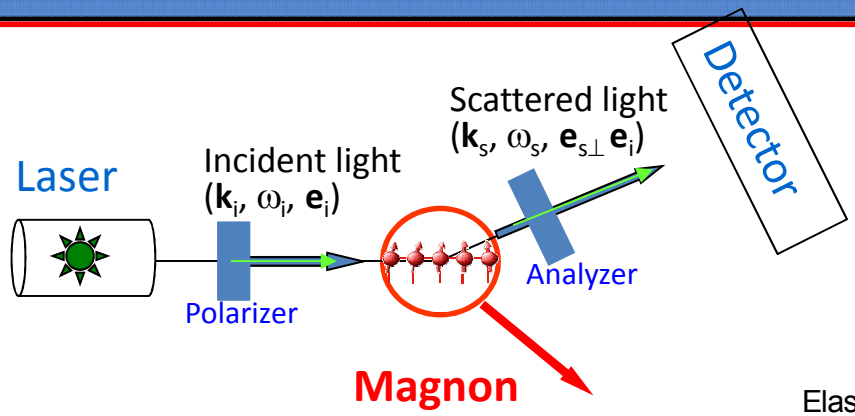
$$U_{anis} = K_1 \sin^2 \phi$$ **Anisotropy energy density**

Brillouin light scattering

Spin waves can be seen as quasi-particles "**magnons**" with energy $\hbar\omega$ and momentum k.
Typically, ω=0.1÷150 GHz, k=10^5÷10^6 cm^{-1}
→magnon energy $\hbar\omega$ is in the μeV range
→magnons are **thermally activated**
→use of scattering techniques to detect them:

- Laser light λ=532 nm by a single mode diode pumped solid state laser
- Probed area diameter ~30 μm
- Laser Power on the sample: ~ 200 mW
- Sandercock interferometer

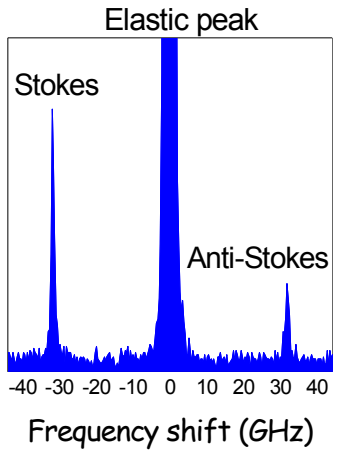




Magnon
creation/annihilation

$\omega=\omega_s-\omega_i$ $\quad$ $\mathbf{q}=\mathbf{k}_s-\mathbf{k}_i$

The frequency shift ω can be positive (annihilation) or negative (creation).
|ω| is the magnon frequency



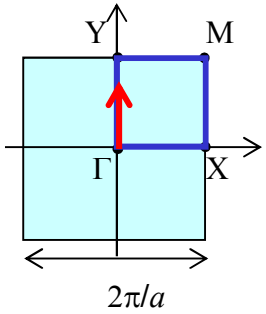
$$\sigma_{p\to s}=\frac{\cos^2\theta_i}{\cos\theta_s}\langle S_s\rangle\propto\left|\mathbf{E}_{scatt}(\mathbf{q},\delta\boldsymbol{\varepsilon})\right|^2$$

angle betweent the incidence plane and the direction of the applied field

Possibility of investigating all directions in the 1° Brillouin zone (i.e., any wavevector direction and value)

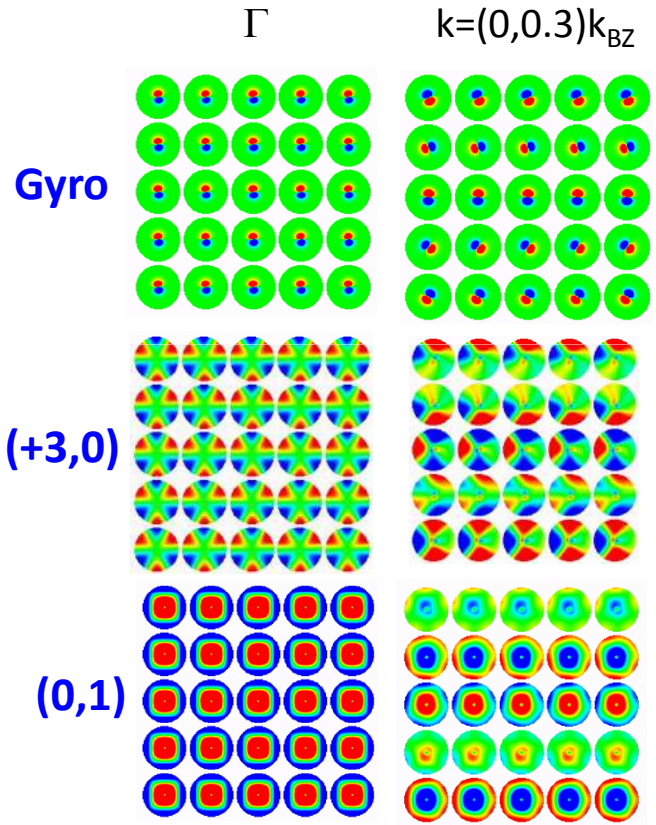
In collaboration with Perugia University

Collective vortex modes



$$\delta\mathbf{m}(\mathbf{r}) = \delta\tilde{\mathbf{m}}(\mathbf{r}) \cdot e^{i\mathbf{k}\cdot\mathbf{r}}$$

$$\delta\tilde{m}_z(r) = f_{(m,n)}(\mathbf{r})\, e^{i(m\phi+\omega t)}$$

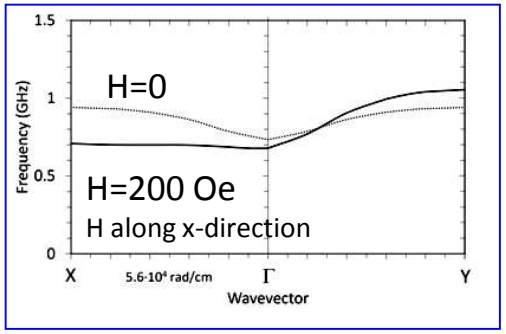


$$v_g = \frac{d\omega}{dk}$$

$$\langle v_g \rangle = 2\pi \frac{|\nu_\Gamma - \nu_{ZB}|}{k_{ZB}}$$

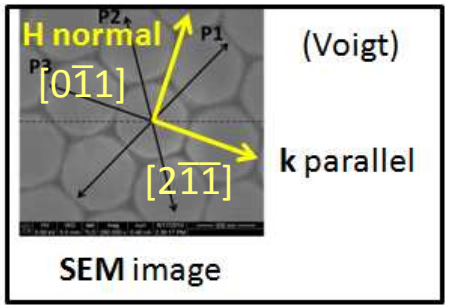
For the **gyrotropic mode**: The application of $H<H_{an}$ results in:

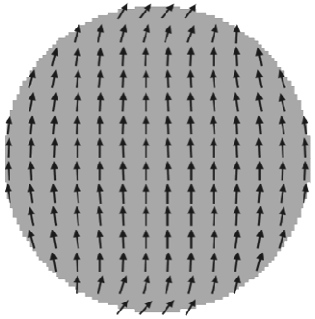
- Slowing down propagation parallel to H
- Speeding up propagation perpendicular to H

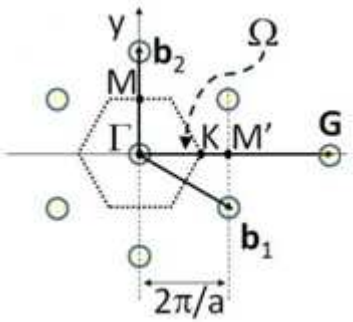


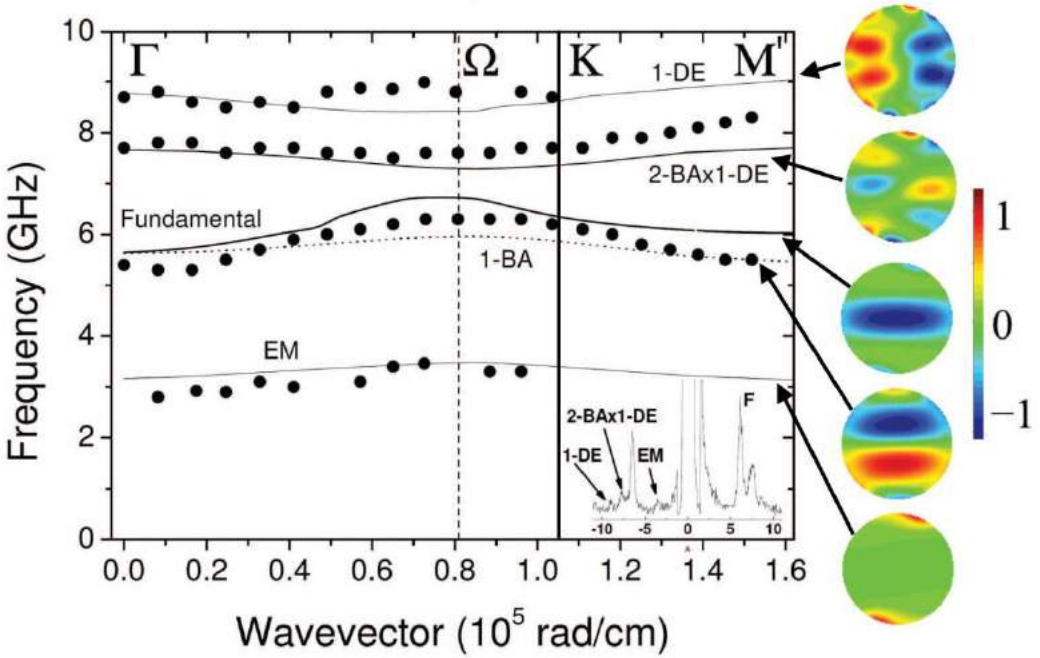
Magnetized disks in hexagonal lattice

Predictions confirmed by
BLS measurements by Perugia University









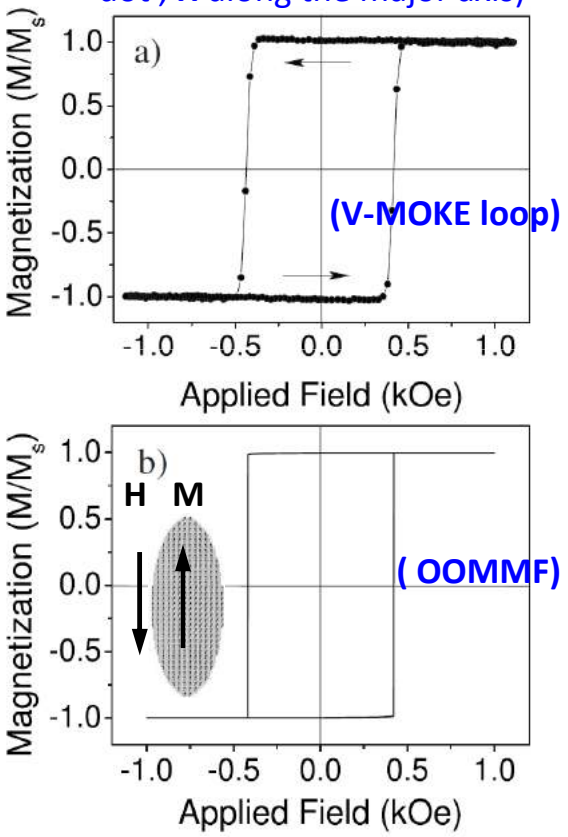
Magnetic transitions

TRADITIONAL: Transitions between magnetic and non-magnetic states

IN THIS CONTEXT: Transitions between two magnetic "**phases**":

1. **Magnetic phase:** any equilibrium magnetic configuration at a given applied field (e.g. saturated state, vortex state…)
2. **Magnetic phase transition**: change in the equilibrium magnetic configuration involving some fundamental change of symmetry (e.g. by operations like i, C_2, σ_h)
3. **Critical field**: the field at which any given magnetic configuration undergoes instability and switches to a different configuration through non-linear evolution of the magnetic moments (sometimes with transitory vortexes etc.)
4. **Order of transition**: depends on the changes in the magnetization curves **M**(**H**):
   - First order (discontinuous): discontinuity in **M**(**H**) curve
   - Second order (continuous): discontinuity in the first derivative of **M**(**H**) (i.e. a change of slope)

(Example: reversal of an elliptical dot , **H** along the major axis)



First order transition

Magnetic transitions

Mode softening

Far from transitions, the modes of the spectrum show a Zeeman (linear) behavior with the applied field (magnetic moments do not change their equilibrium position)

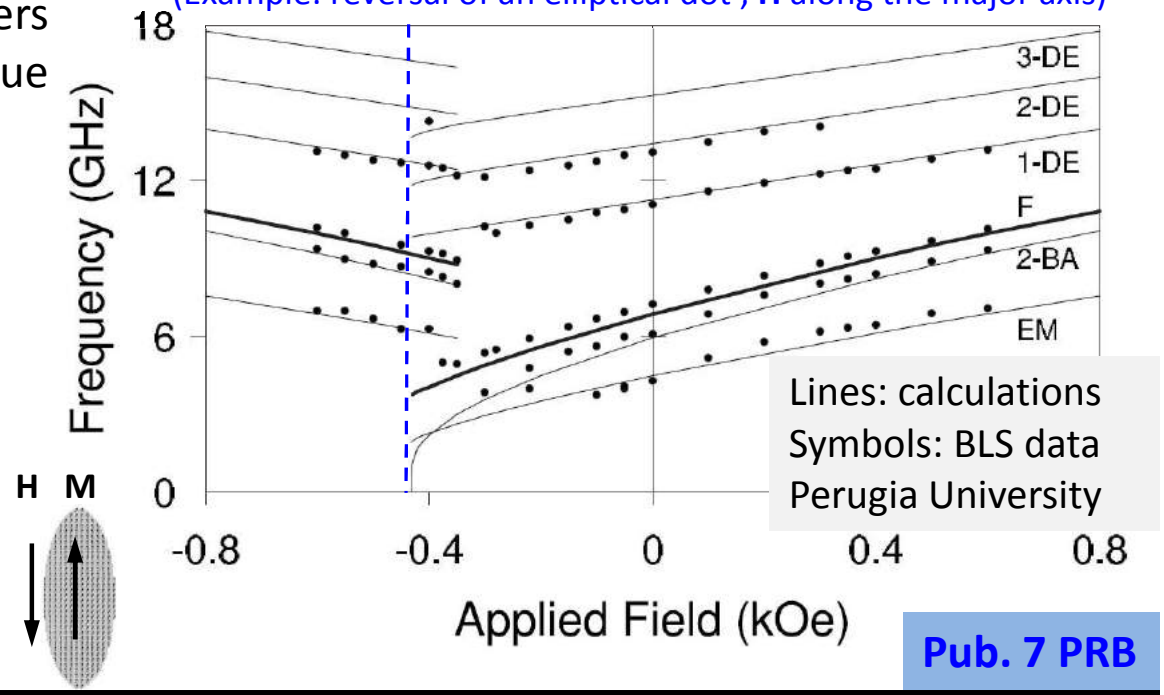
Approaching transitions, dipolar (and exchange) contributions are critical and determine a non-linear behavior (magnetic moments change gradually their equilibrium position

One mode of the spectrum decreases its frequency faster than others (mode crossing), reaching zero value ideally at the critical field.

Zero frequency →
Zero **restoring torque**→
Uncontrolled increase of
precession amplitude→
nonlinear terms involved→
change of equilibrium position
(i.e. change of magnetic phase)

Elliptical precession of modes $\mathbf{m}_z << \mathbf{m}_x$
→ **Instability** as in-plane perturbation

(Example: reversal of an elliptical dot , **H** along the major axis)



Lines: calculations
Symbols: BLS data
Perugia University

Pub. 7 PRB

Magnetic transitions

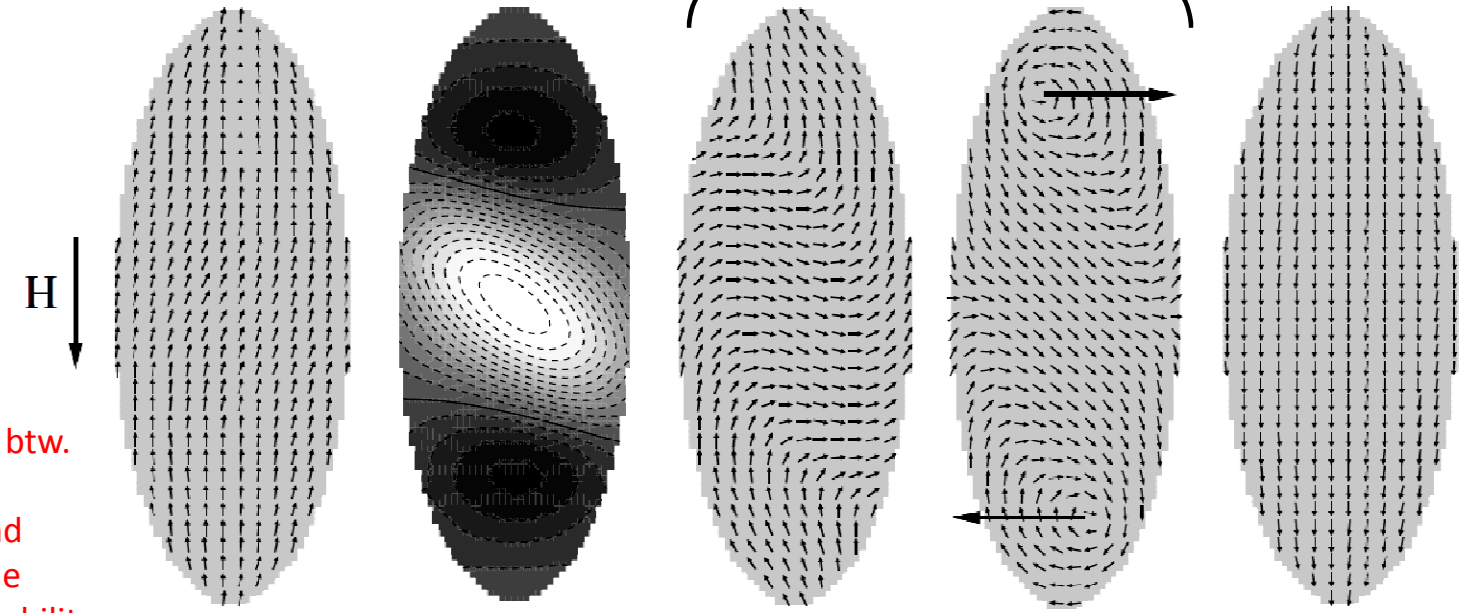
Elliptical dot: 500x200x 15 nm^3
Permalloy (800.E3 A/m, 1.3E-11 J/m).

Mode softening:
Triggering instability

Soft mode intensity determines the areas where magnetic moments undergo max change (and phase determines direction)

$$\mathbf{M}_{H_c+\delta H} = \mathbf{M}_{H_c} + \delta\mathbf{m}$$

Non-equilibrium states during evolution



Correlation btw. soft mode intensity and region of the inset of instability

Soft modes and information delivery

Interacting elliptical dots: H along the short axis

Onion-to-C-state transition: the Bloch wave at X, with EM cell function, softens earlier:

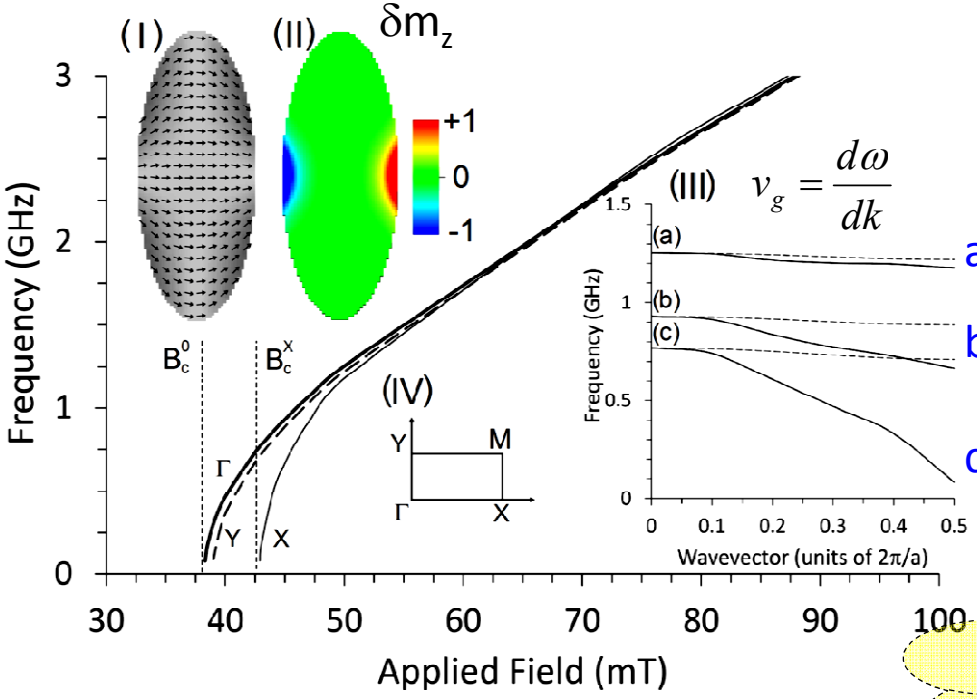
Γ: B_c^{Γ} = 38.44 mT

X: B_c^{X}= 42.25 mT

$$\delta\mathbf{m}(\mathbf{r}) = \delta\tilde{\mathbf{m}}_{\mathbf{k}}(\mathbf{r})e^{i\mathbf{k}\cdot\mathbf{r}}$$

Close to instability the soft mode turns **from stationary to travelling** along the direction of the field

data storage-recovery



a) 50 mT (stationary wave)

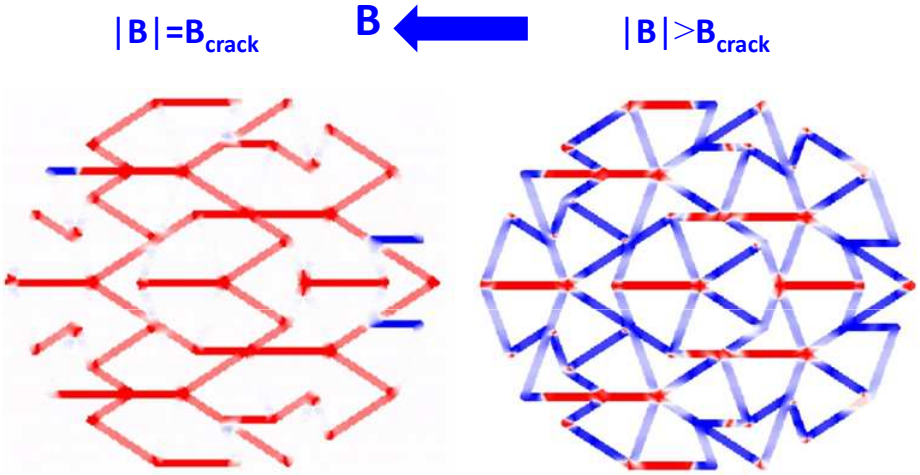
b) 45 mT

c) 42.9 mT (propagating wave close to transit.)

Field costs: $\Delta B/B_0$ = (7 mT) / (50 mT)
Band increases of more than 10 times!

Artificial Quasi-Crystals for data encryption

1. "Irregularity by demand": rigorous geometric order, but no periodicity
2. Each macrospin is preliminarily "saturated" (e.g., to the right), then a field is applied in the opposite direction (left)
3. Unpredictable reversal order (macrospin sequence), strictly dependent on the applied field
4. Each macrospin is assigned to a code, the **cipher** is the right macrospin reversal sequence
5. The field value is the key to crack the code (i.e., the reversal sequence)

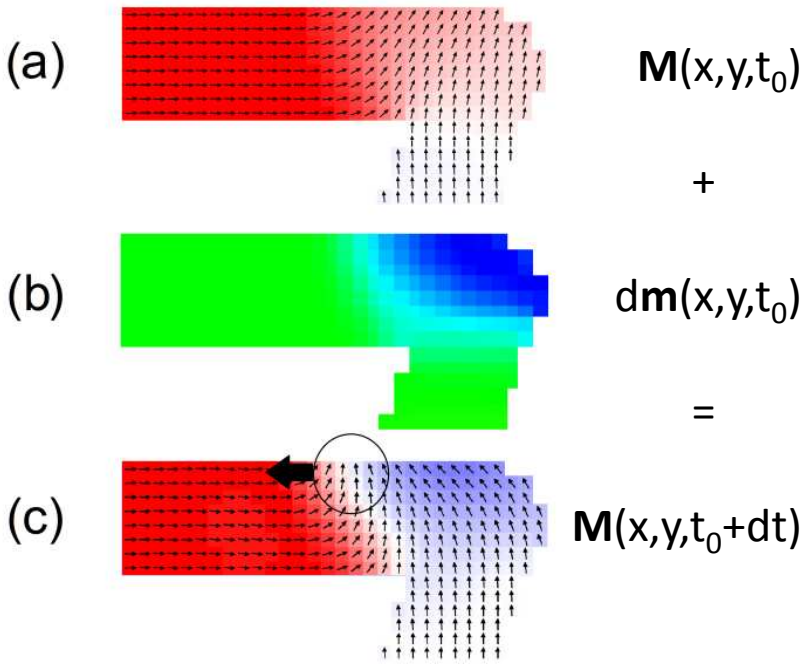


Origin and behavior of the irregular path

(in collaboration with Kentucky University, US)

Interpretation through soft mode analysis

$$\mathbf{M}(x,y,t_0+dt) = \mathbf{M}(x,y,t_0) + d\mathbf{m}(x,y,t_0)$$



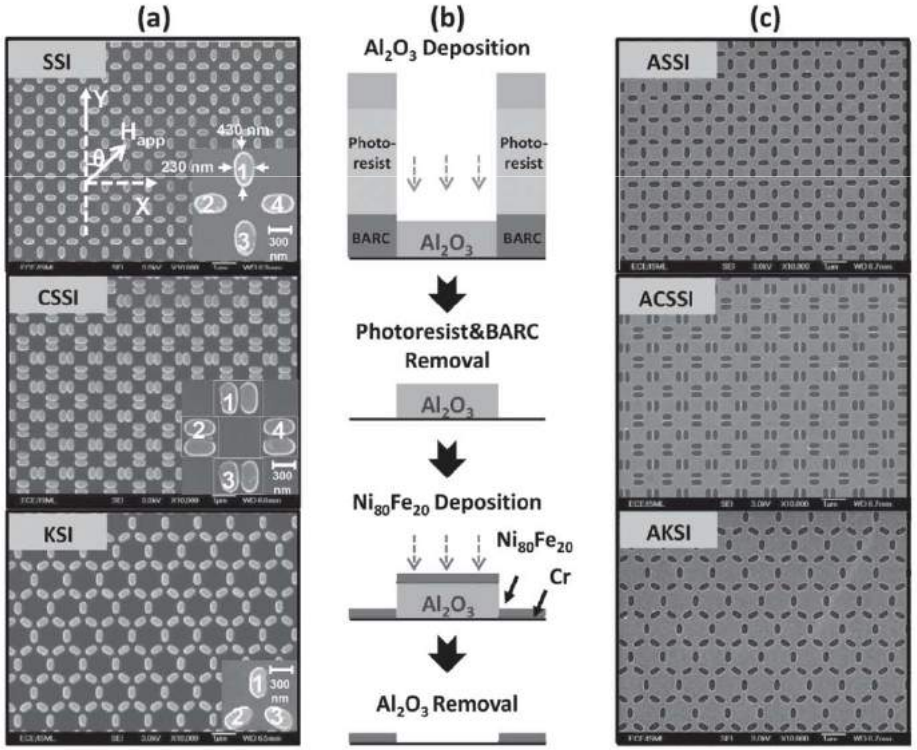
The soft mode triggers the macrospin instability and is at the origin of the DW emission & expulsion

U. S. National Science Foundation Program in Condensed Matter Physics. Collaborative Research on "**Controlled Disorder and Topological Defects in Magnetically Frustrated Thin Film Metamaterials**" (Years: 2015-2018) Award Number: 1506979.

Artificial spin ices

A joint theoretical+experimental thesis

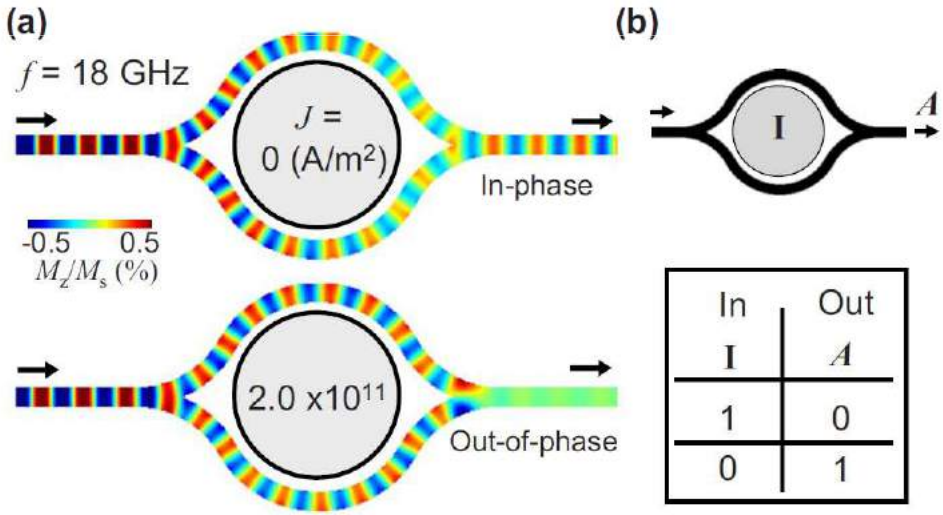
In collaboration with Perugia University (BLS) – Need to travel there (1-2 weeks) required…
Study of the spin dynamics in ASI with square and Kagome symmetry
Theoretical prediction compared to experimental BLS measurements



Prof. A. O. Adeyeye
U. Singapore

Spin wave interferometry

If coherent spin waves are delivered along two paths, and the **interference pattern** is collected at the path end, then any phase change can be detected, due to magnetization changes in the exposed path, which are possibly due to:
-Magnetic fields localized in one path only
-Current flow
-Adsorbed magnetic molecules
-Other



In	Out
I	A
1	0
0	1

Ki-Suk Lee and Sang-Koog Kim
http://dx.doi.org/10.1063/1.2975235

Depending on the level/extension of the investigation
all the above topics can be the subject for

- **Bachelor** thesis (LT)
- **Master** thesis (LM)
- **Doctoral** thesis

End

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