A.D. 1308
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DIPARTIMENTO
DI FISICA E GEOLOGIA

# Magnetism meets topology

ambito di ricerca n.5 (Nanoscienze)

PTRS kick-off meeting, Perugia 10/01/2022

Marco Madami

# Nanomagnetism & Spintronics group

GHOST
group of high resolution optical spectroscopy and related techniques

A.D. 1308 unipg
UNIVERSITÀ DEGLI STUDI DI PERUGIA

Consiglio Nazionale delle Ricerche
ISTITUTO OFFICINA DEI MATERIALI

INRiM
ISTITUTO NAZIONALE DI RICERCA METROLOGICA

Giovanni Carlotti

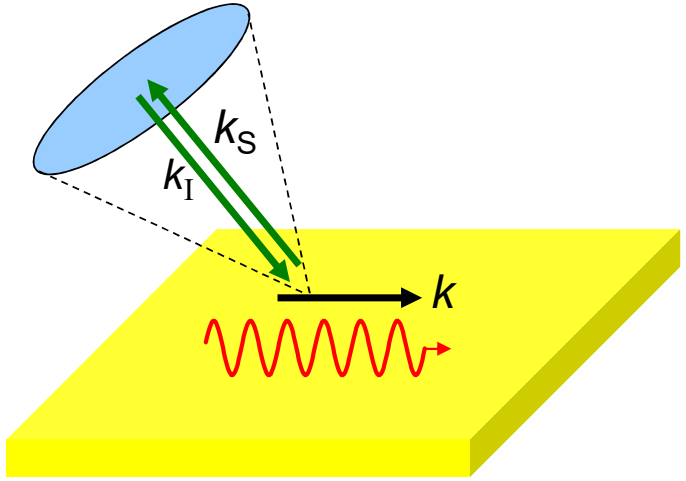
Gianluca Gubbiotti

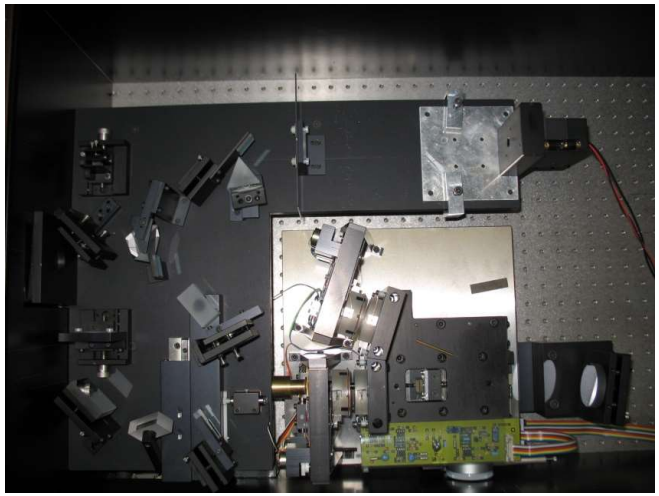
Raffaele Silvani

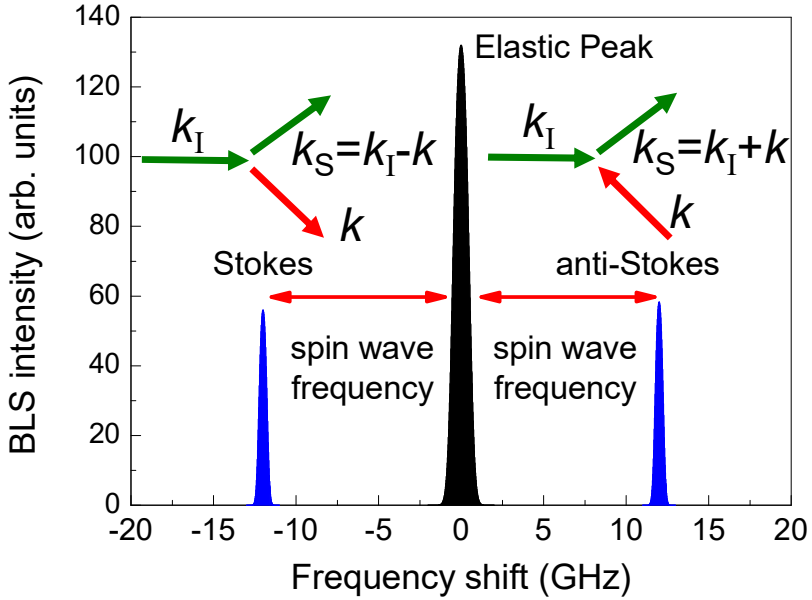
Marco Madami

Silvia Tacchi

# Brillouin light scattering (BLS)






wavelength range: $10^2$ nm – $10^1$ μm ➡ frequency range: $10^0$ – $10^1$ GHz

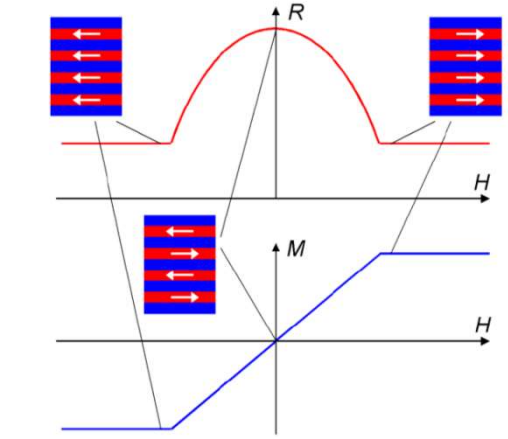
(elastic and spin waves)

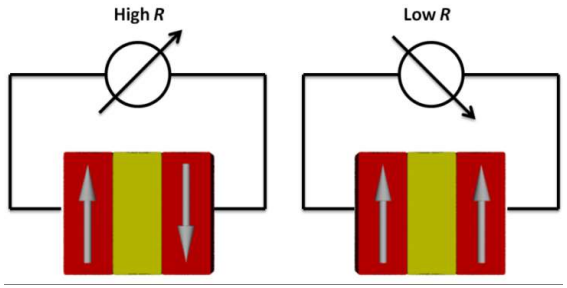
High **resolution** and **contrast** are needed

# 1988: discovery of the giant magneto resistance (GMR)

**Albert Fert**

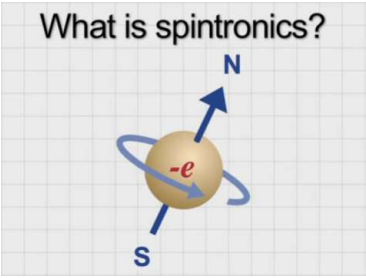
**Peter Grünberg**




**Nobel prize in physics in 2007**

**Spintronics**

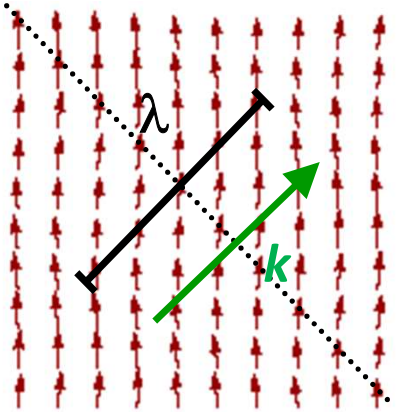



PRIN 2020, PE7, "The Italian factory of **micromagnetic** modeling and **spintronics**"

# Spin waves

- Collective excitations in a system of **interacting** spins.

  a) **Strong** but **short-range** exchange interaction
  b) **Weak** but **long-range** dipolar interaction




$$\frac{\partial \boldsymbol{M}(\boldsymbol{r})}{\partial t} = -\gamma\left(\boldsymbol{M}(\boldsymbol{r}) \times \boldsymbol{H}_{eff}(\boldsymbol{r})\right) + \frac{\alpha}{M_S}\left(\boldsymbol{M}(\boldsymbol{r}) \times \frac{\partial \boldsymbol{M}(\boldsymbol{r})}{\partial t}\right)$$

Landau-Lifshitz-Gilbert (LLG) equation

Precession

Energy dissipation (damping)

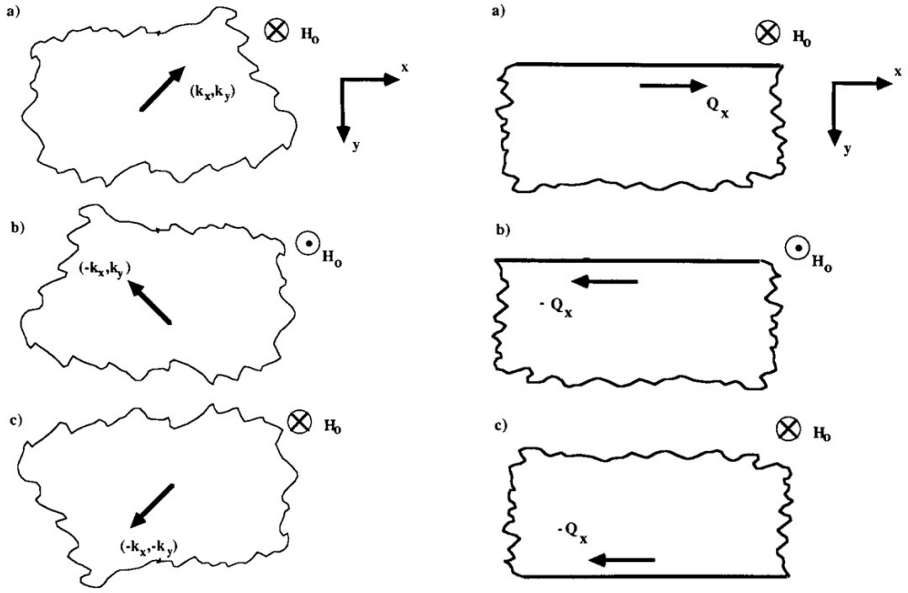
# Spin waves in low dimensional systems

Surface Science Reports 7 (1987) 103–187
North-Holland, Amsterdam

## NONRECIPROCAL SURFACE WAVES

R.E. CAMLEY

*Department of Physics, University of Colorado at Colorado Springs, Colorado Springs, CO 80933-7150, USA*

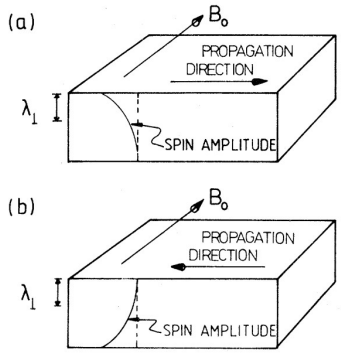



PHYSICAL REVIEW B VOLUME 26, NUMBER 5 1 SEPTEMBER 1982

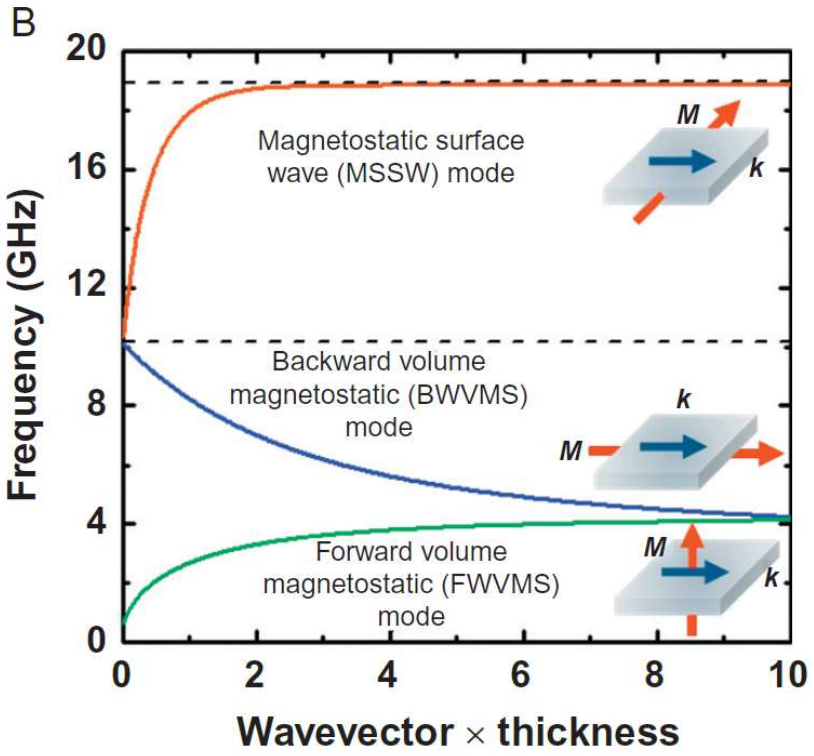
## Stokes—anti-Stokes asymmetry in Brillouin scattering from magnons in thin ferromagnetic films

R. E. Camley
*Department of Physics, University of Colorado, Colorado Springs, Colorado, 80907*

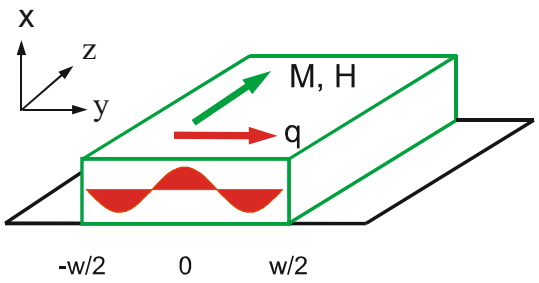
P. Grünberg and C. M. Mayr
*Institut für Festkörperforschung, Kernforschungsanlage, 5170 Jülich, West Germany*
(Received 9 March 1982)

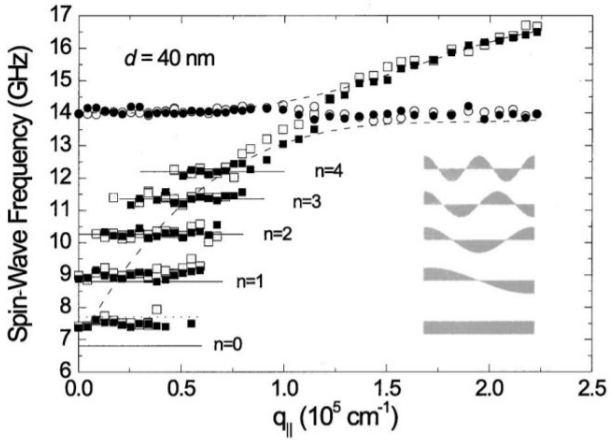


# Spin waves in low dimensional systems

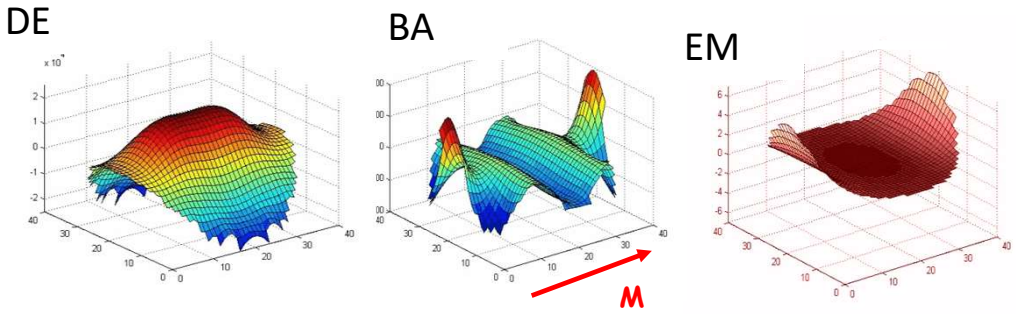



**2D systems (magnetic thin films)**



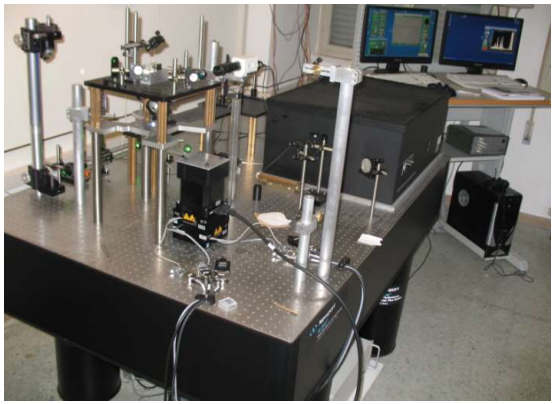




**1D systems (magnetic wires)**




**0D systems (magnetic dots)**

# micro-focused BLS





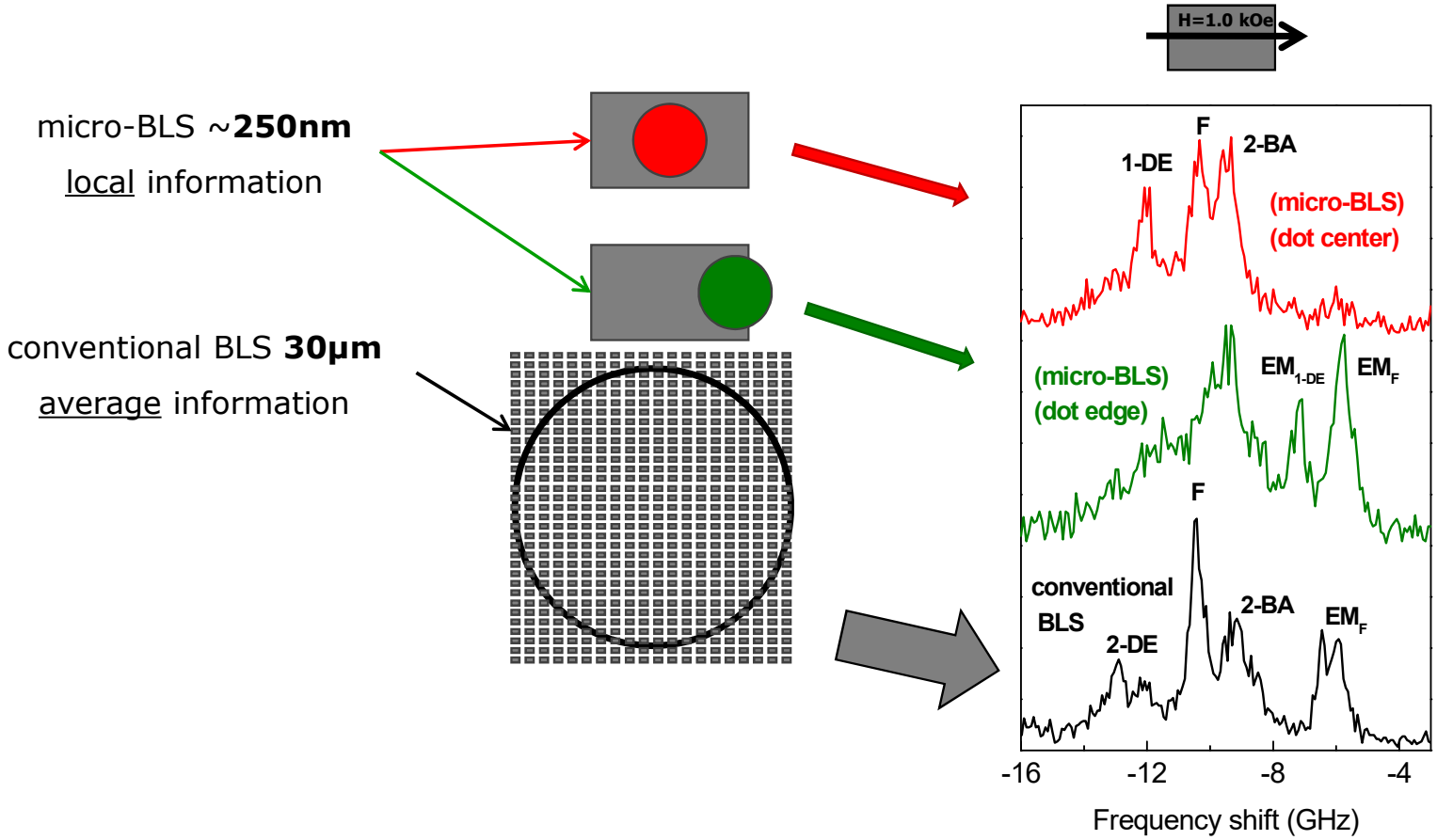

**Active stabilization of sample position and 2D mapping**

TFPDAS4 MICRO

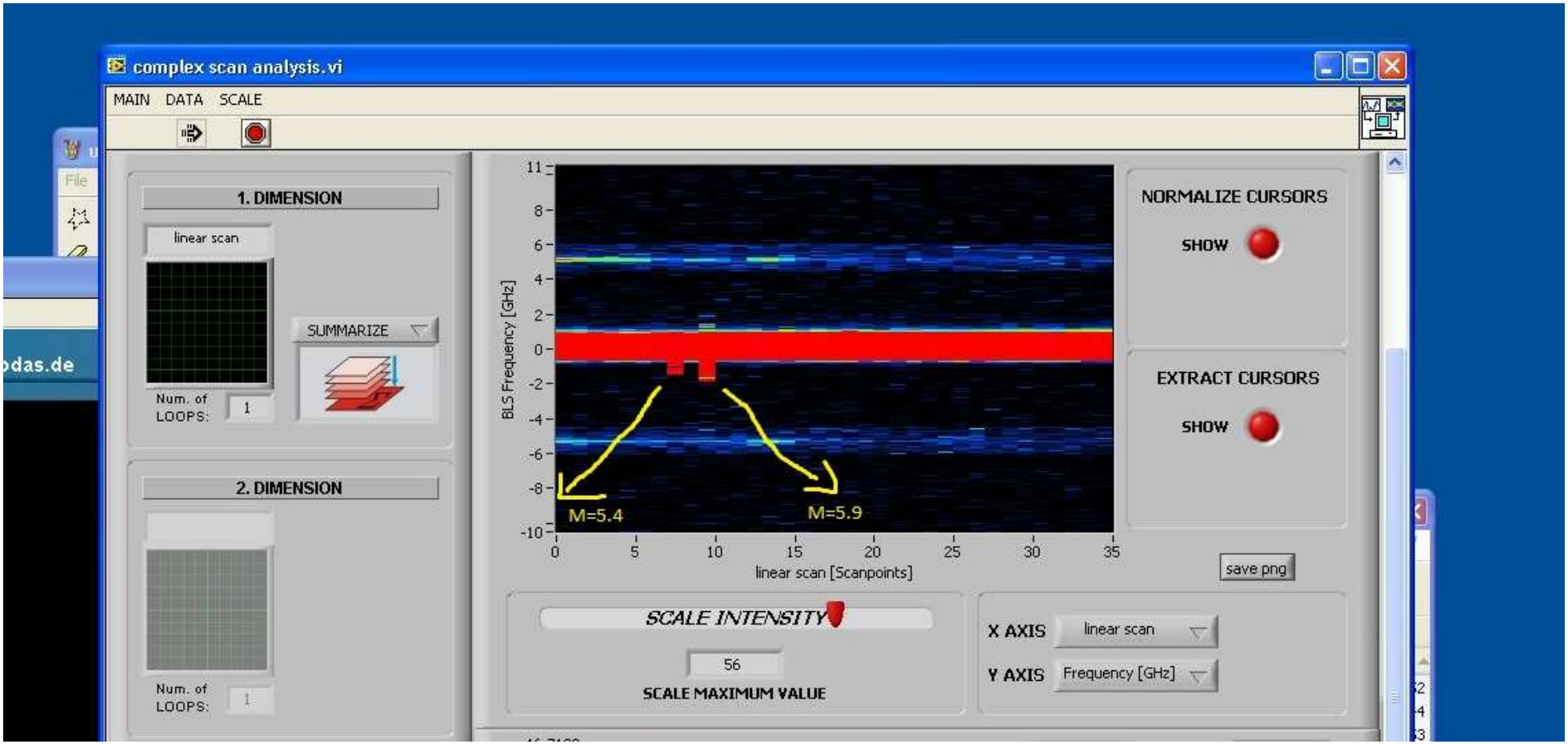
Lateral resolution down to ~ **250 nm** !!

Very good **isolation** from external vibrations is required

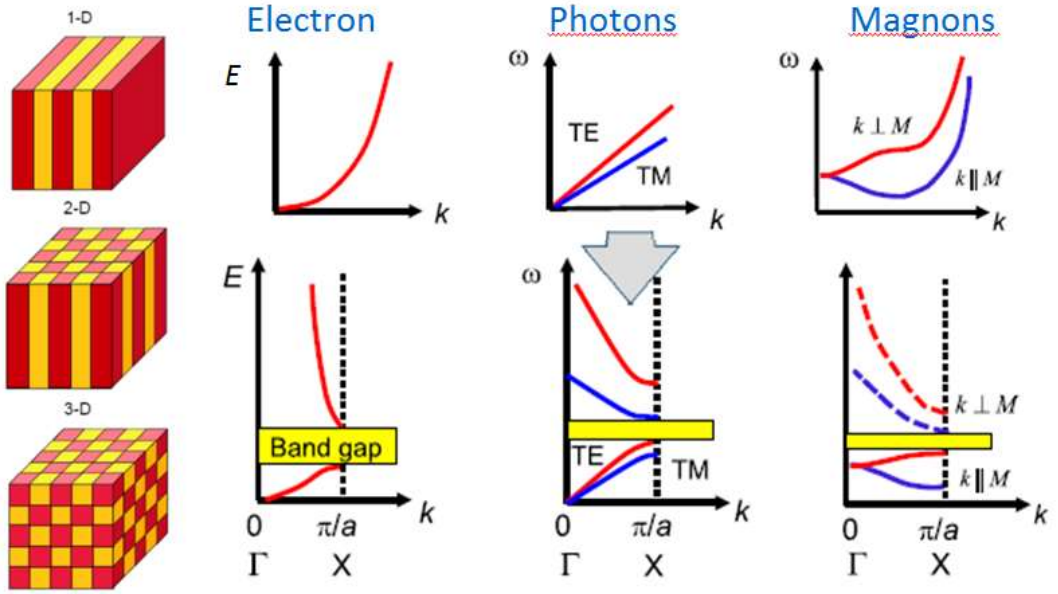
# micro-focused BLS on magnetic dots



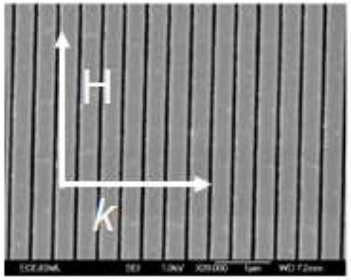
# micro-focused BLS (October 26th 2016, earthquakes)



# Magnonic crystals

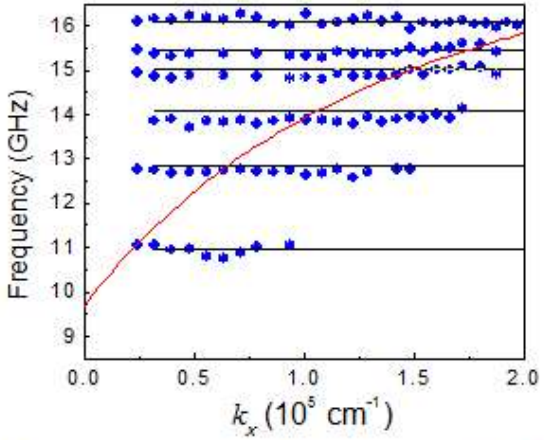


# Spin wave bands in 1D MC

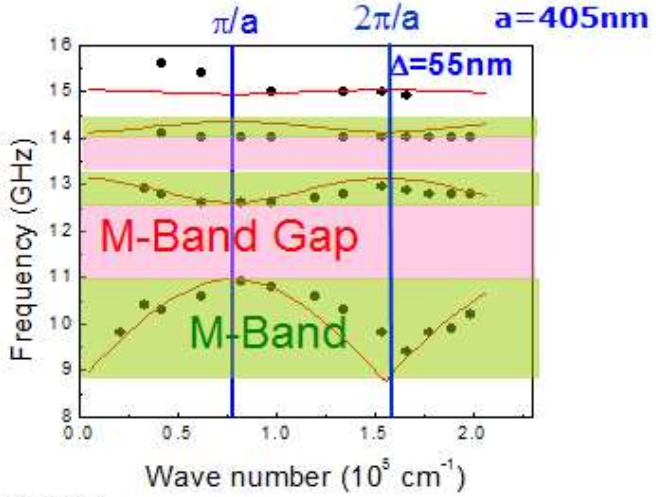



w=350nm
s=55nm

Isolated nanowire



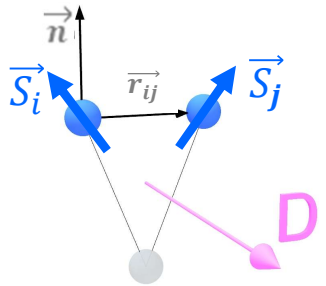

Coupled nanowires

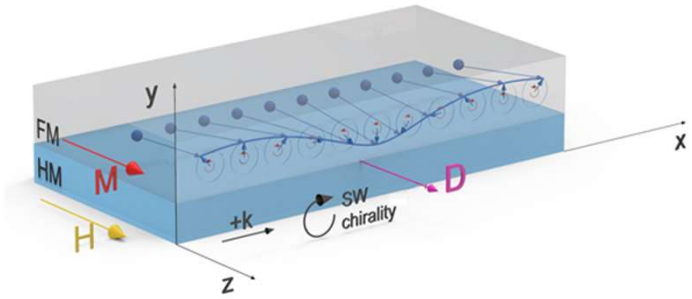


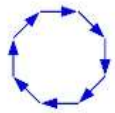

G. Gubbiotti et al., **Phys. Rev. B 72**, 224413 (2005); **Appl. Phys. Lett. 90**, 092503 (2007).

# DMI induced SW non reciprocity

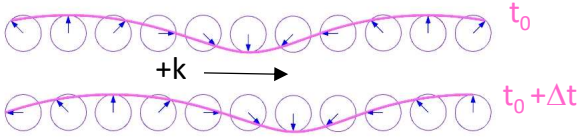
$$\vec{D} = D\frac{\vec{r}_{ij}}{r_{ij}} \times \vec{n} \qquad E_{DMI} = \vec{D} \cdot (\vec{S_i} \times \vec{S_j})$$



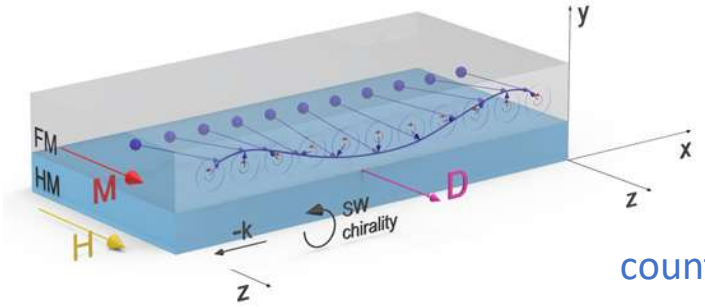



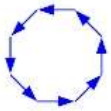



RH
clockwise

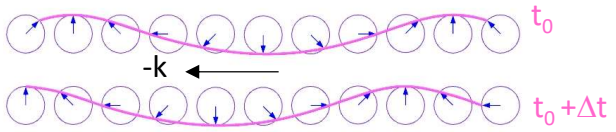



For D>0 the right-handed (RH, or clockwise) chirality associated to spin waves propagating along +k (Stokes peak in BLS spectra) is favoured, so their absolute frequency is down-shifted by DMI



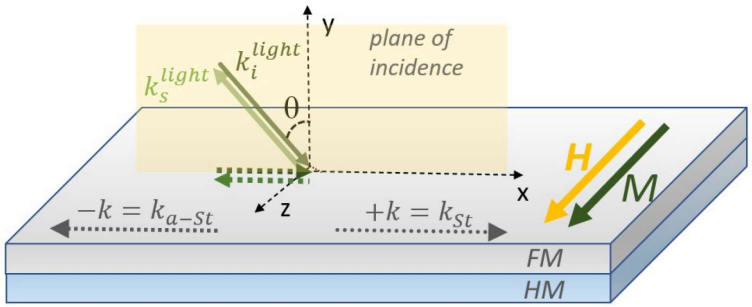



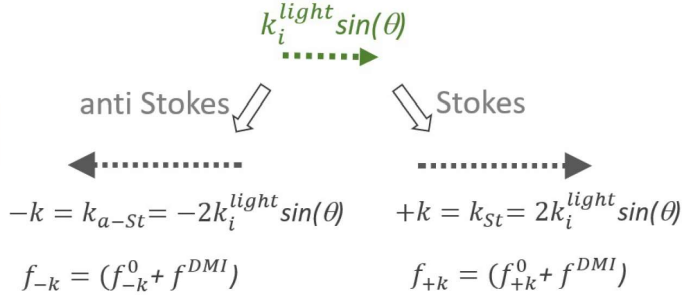
LH
counterclockwise



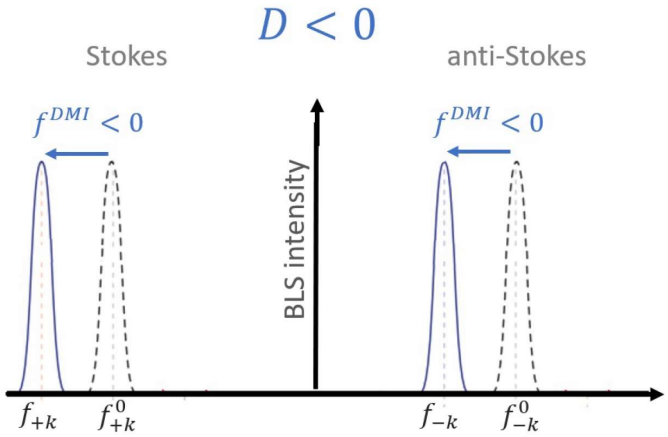

For D>0 the left-handed (LH, or counterclockwise) chirality associated to spin waves propagating along –k (anti-Stokes peak in BLS spectra) is disfavoured, so their absolute frequency is up-shifted by DMI

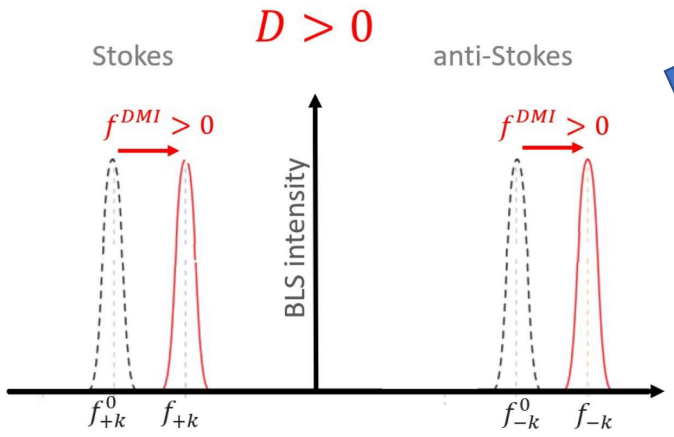
# DMI measured by BLS




$$f_{DMI} = \omega_{DMI}/2\pi = (\gamma D k)/(\pi M_s)$$



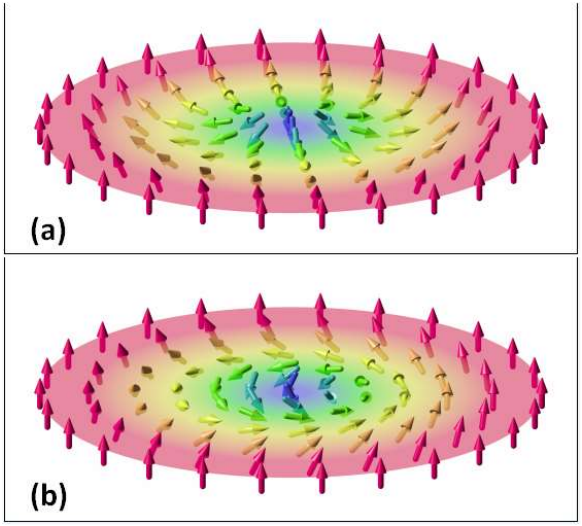



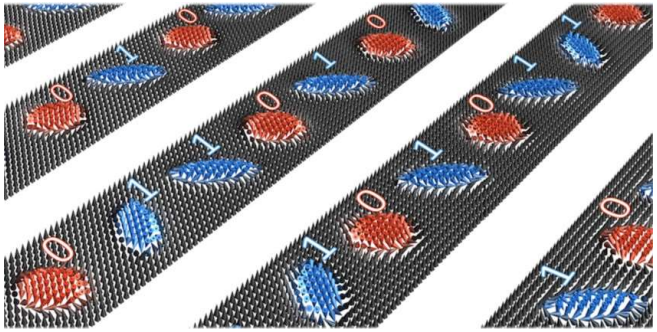

EMPIR EURAMET
The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

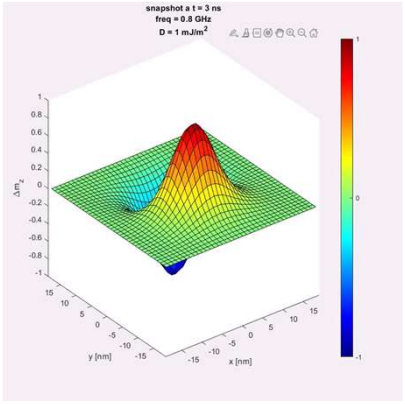
TOPS
Metrology for topological spin structures

https://www.ptb.de/empir2018/de/tops/home/

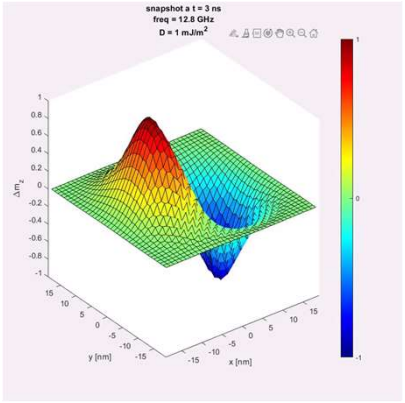
# Skyrmions



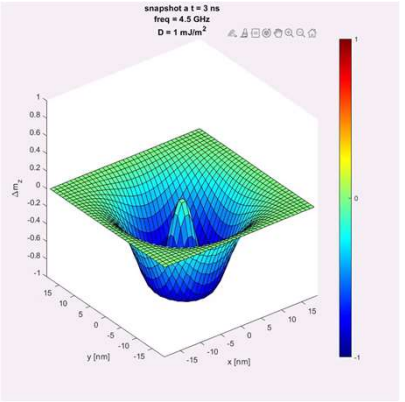






CCW
(0.8 GHz)




CW
(12.8 GHz)




BR
(4.5 GHz)

# Grazie dell’attenzione