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# Co<sub>2</sub> Mn-based Heusler compounds for spintronics: Chemical order and interplay between the magnetic damping and the underlying electronic structure

C. Guillemard, A. M. Bataille, S. Petit-Watelot, J.-C. Rojas-Sánchez, F.  
Bertran, S. Andrieu

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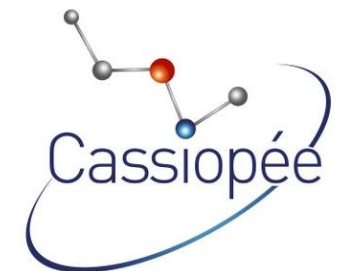
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# Co<sub>2</sub>Mn- based Heusler compounds for spintronics

Chemical order and interplay between the magnetic damping and the underlying electronic structure



Colloque Louis Néel XIX



C. Guillemard, S. Petit-watelot, F. Bertran, A. M. Bataille,  
J.-C. Rojas-Sanchez, S. Andrieu

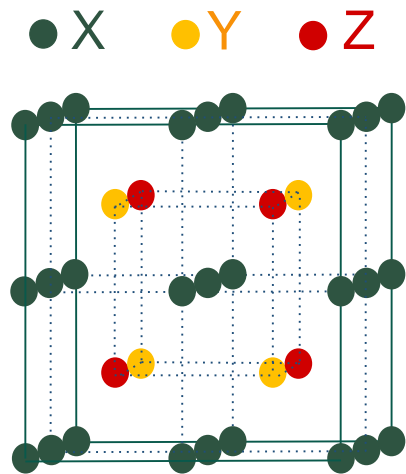
# Outline

1. Heusler compounds & spintronics
2. Crystal growth and structure
3. Testing the Half Metal Magnet behavior by SR-PES
4. Ultra-low damping materials

# Heusler compounds

## Half-Metal Magnets (HMM)

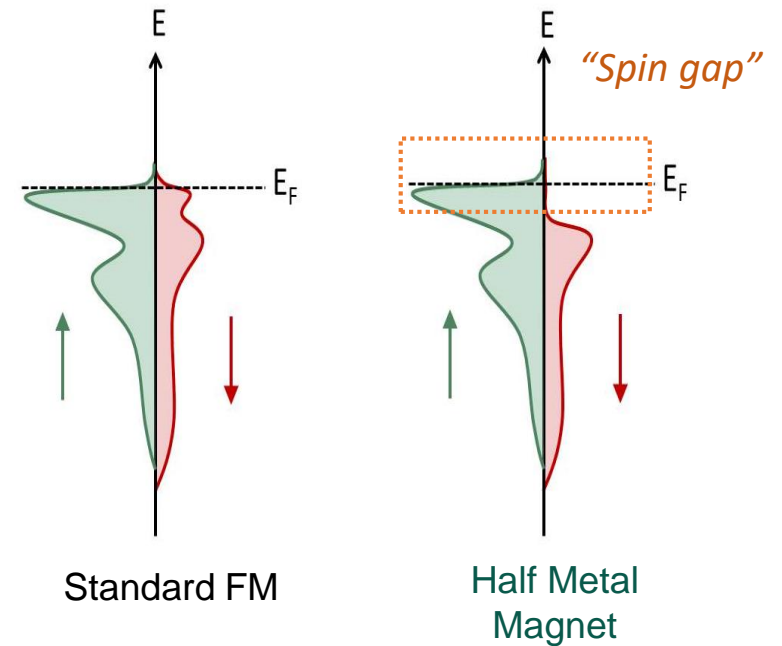
F. Heusler, *DPG* 5, p 219 (1903).



$Cu_2MnSn$ ,  $W_2PdSb$ ,  
 $Zr_2TiGe$  ...

Some of them are  
predicted HMM

R. A. De Groot *et al.*, *PRL* 50, 2024 (1983).

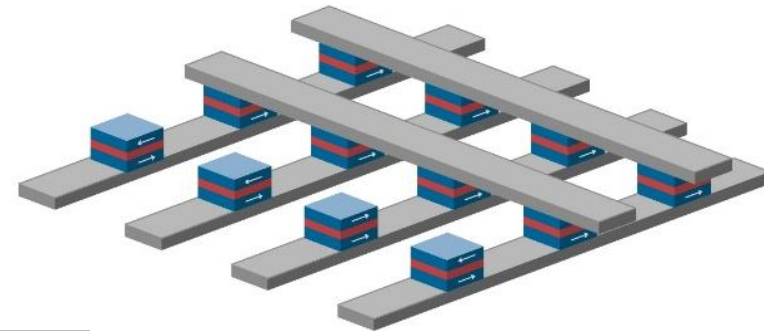


$$\frac{D_{\uparrow}(E_F) - D_{\downarrow}(E_F)}{D_{\uparrow}(E_F) + D_{\downarrow}(E_F)} = 1$$

# Half Metal Magnet

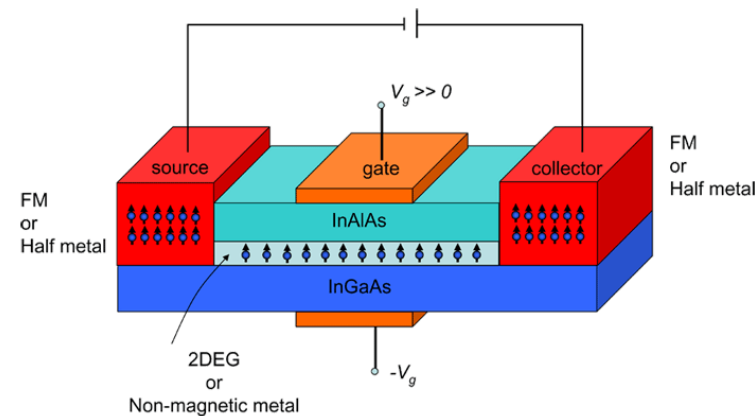
## Interest for spintronics

- Magneto-resistive devices :  
Ex: Spin valves, MTJ, STT-MRAM...



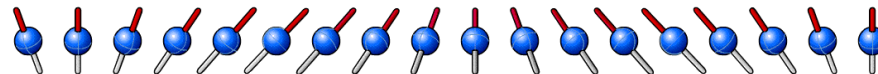
- Nano-oscillators

- Spin injection:  
ISHE, Spin transistor



- Magnonics:

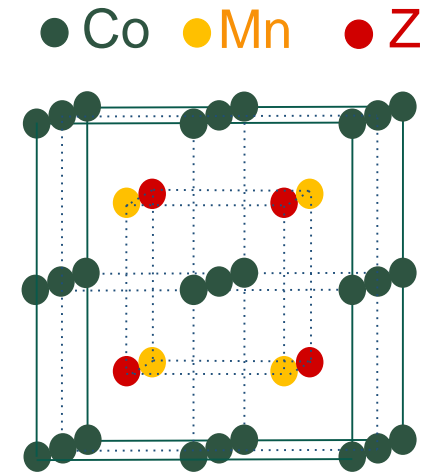
Logic gates & processing



# Motivations

## Why Co<sub>2</sub>Mn- based Heusler compounds?

- High Curie temperature
- Convenient lattice parameters
- Predicted HMM (*ab initio* calc.)
- Ultra low damping
- Spin gap confirmed in Co<sub>2</sub>MnSi S. Andrieu *et al.*, Phys. Rev. B **93**, 094417 (2016)



$$5,6 < a_{\text{Co}_2\text{MnZ}} < 6 \text{ \AA}$$

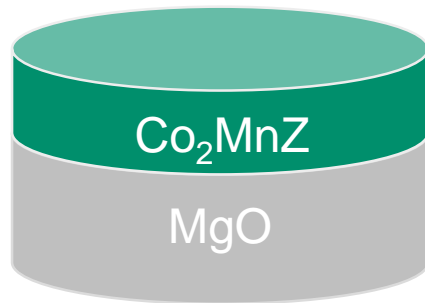
$$T_C > 800 \text{ K}$$

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# Elaboration

## Molecular Beam Epitaxy features

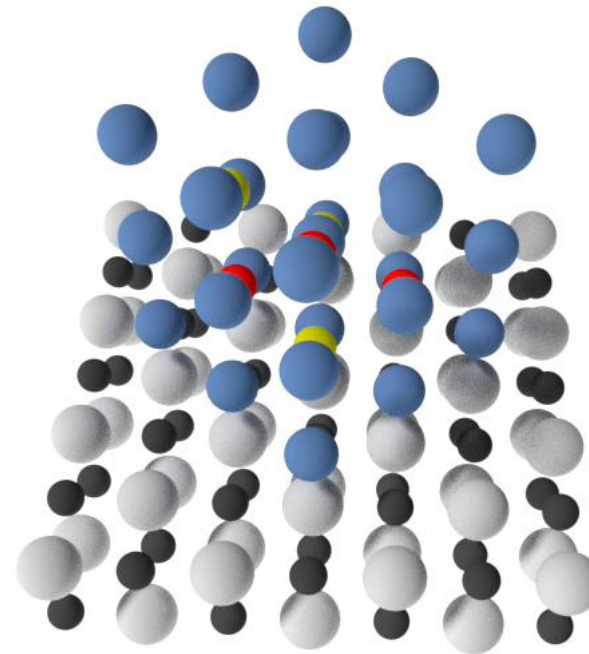


Co-evap of each element

Co: e-gun

Mn: K-cell

X: it depends



Growth temperature:  $\approx 450^\circ\text{C}$

Annealing  $\approx 800^\circ\text{C}$

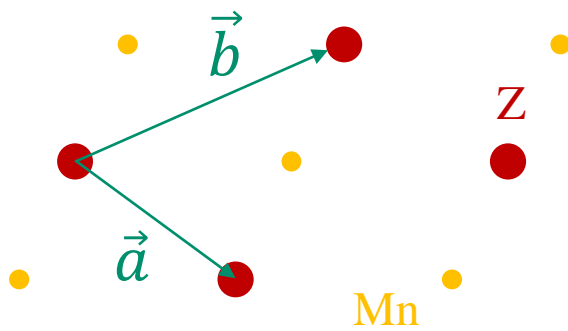
$\text{Co}_2\text{MnZ}$  [100] (001) //  $\text{MgO}$  [110] (001)



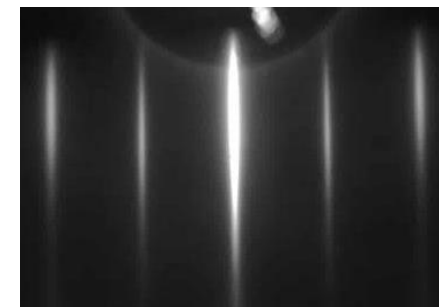
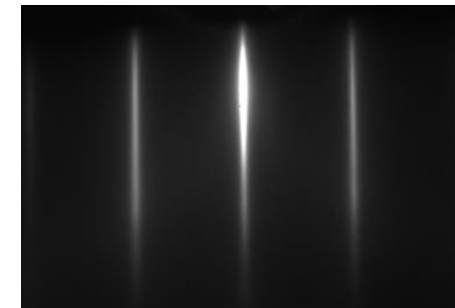
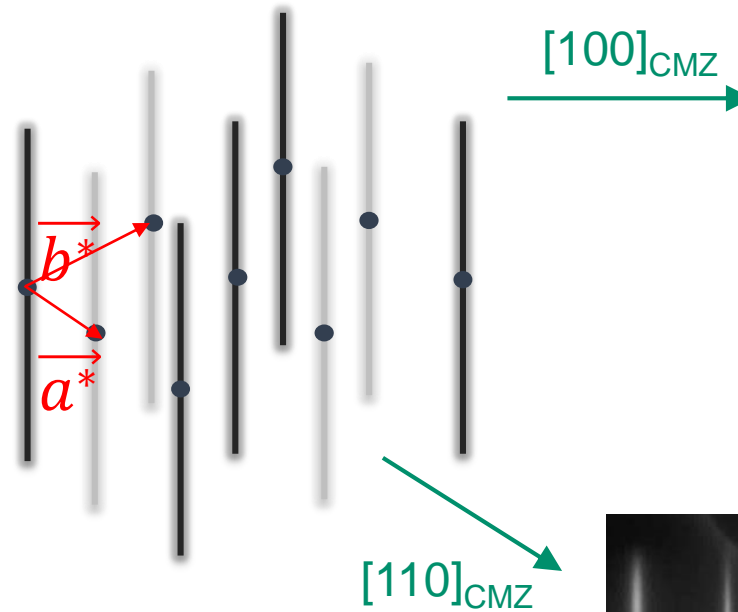
# Surface structure

## L2<sub>1</sub> RHEED patterns

2D real lattice:

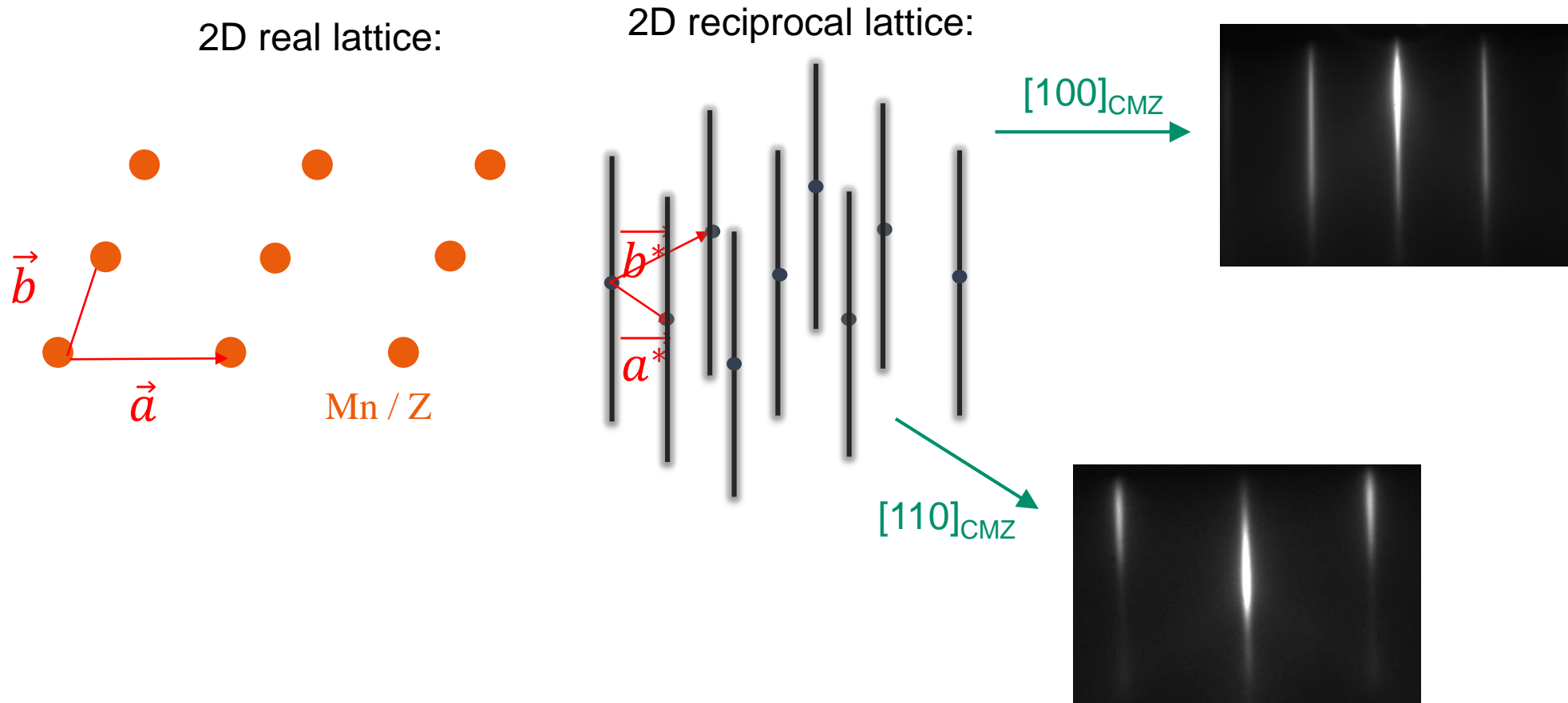


2D reciprocal lattice:



# Surface structure

## B2 RHEED patterns

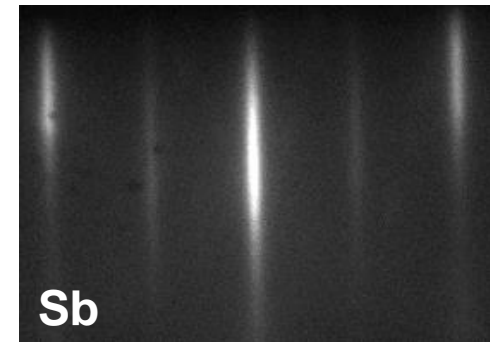
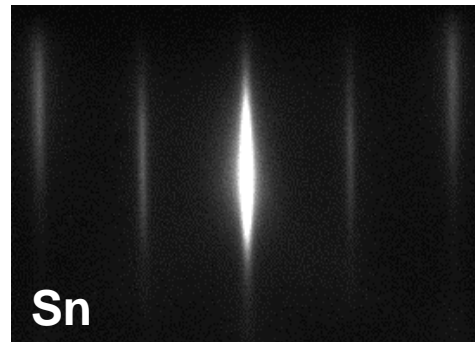
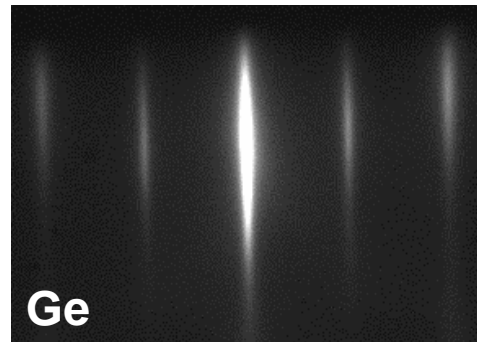
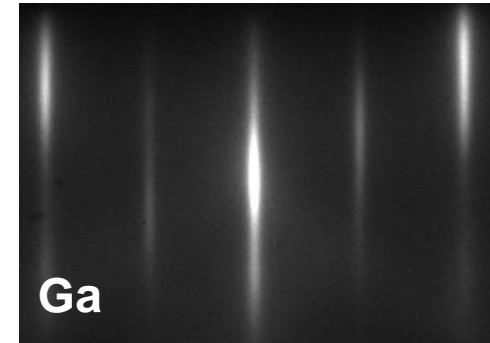
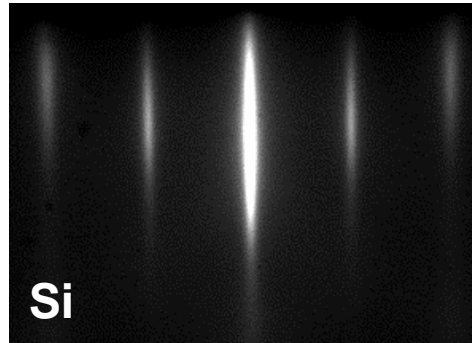


# [110] RHEED patterns

Co<sub>2</sub>MnZ with Z = Al, Si, Ga, Ge, Sn, Sb

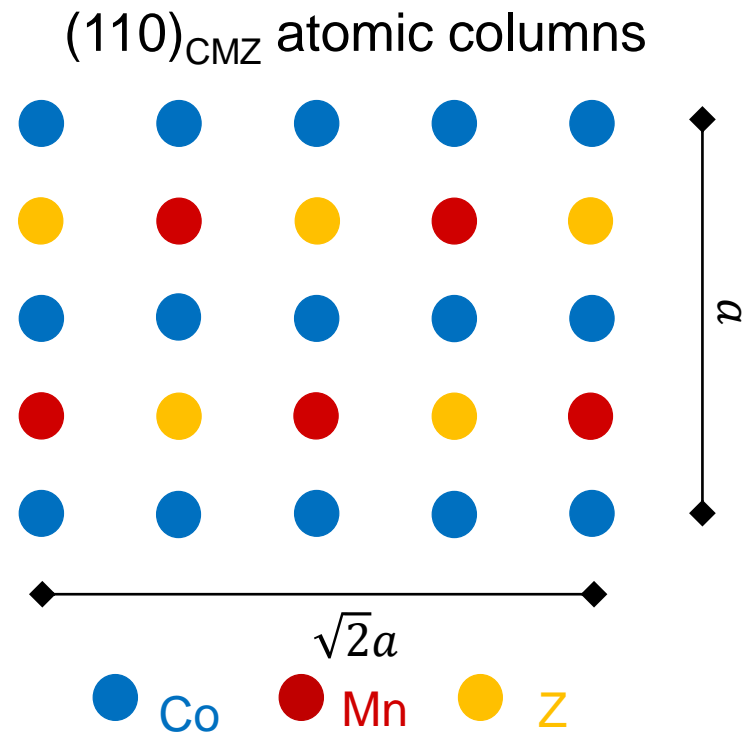
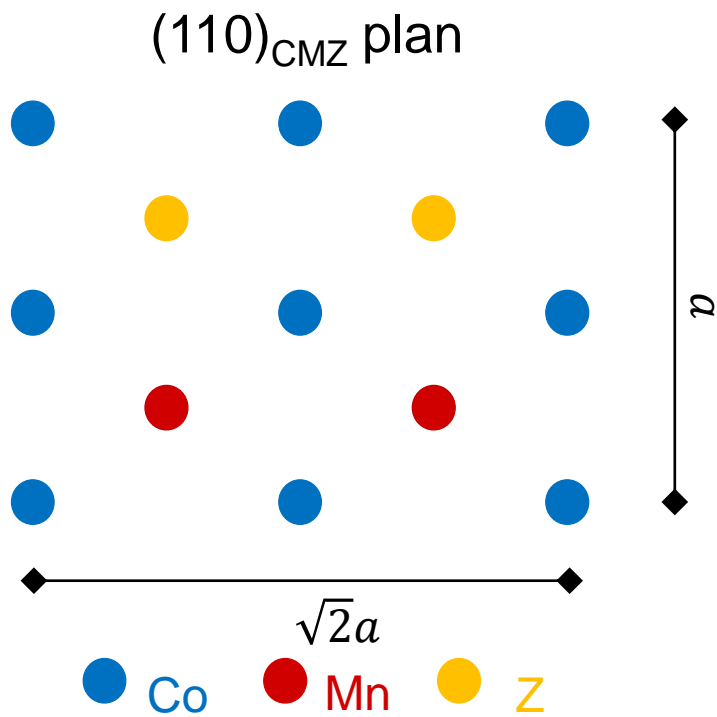


No half streaks = B2



# HR-TEM

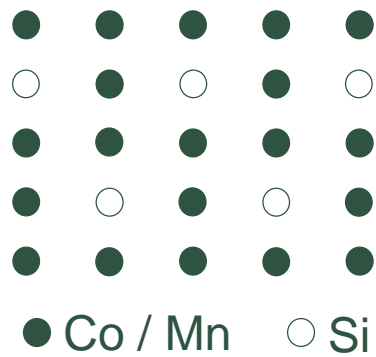
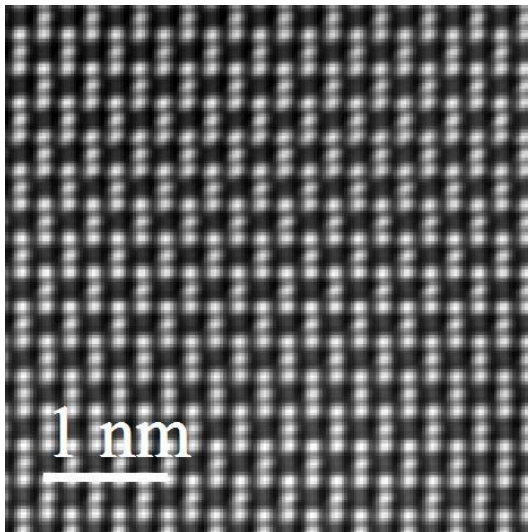
## Cross sections



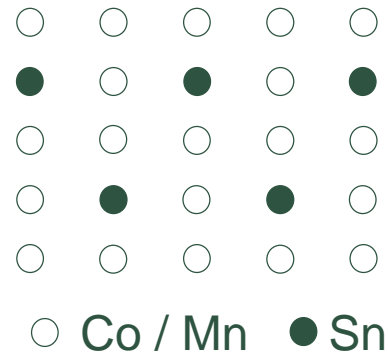
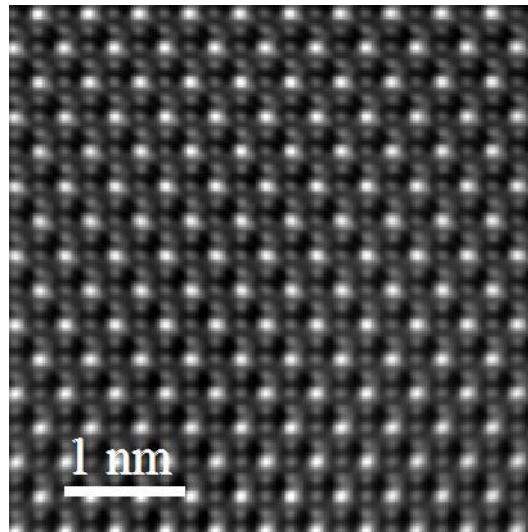
# HR-TEM

## HAADF

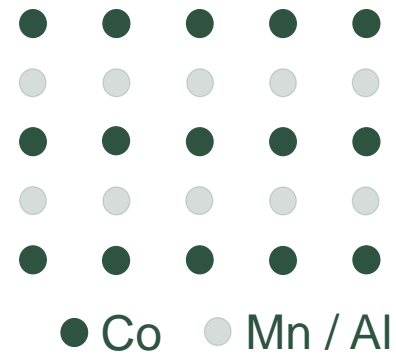
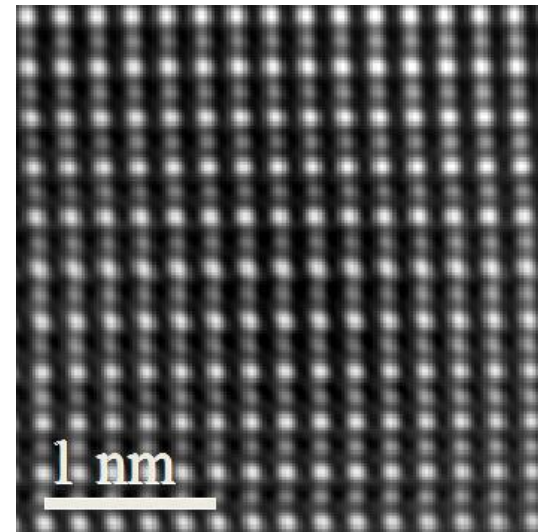
Co<sub>2</sub>MnSi



Co<sub>2</sub>MnSn



Co<sub>2</sub>MnAl



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# Spin-Resolved PES

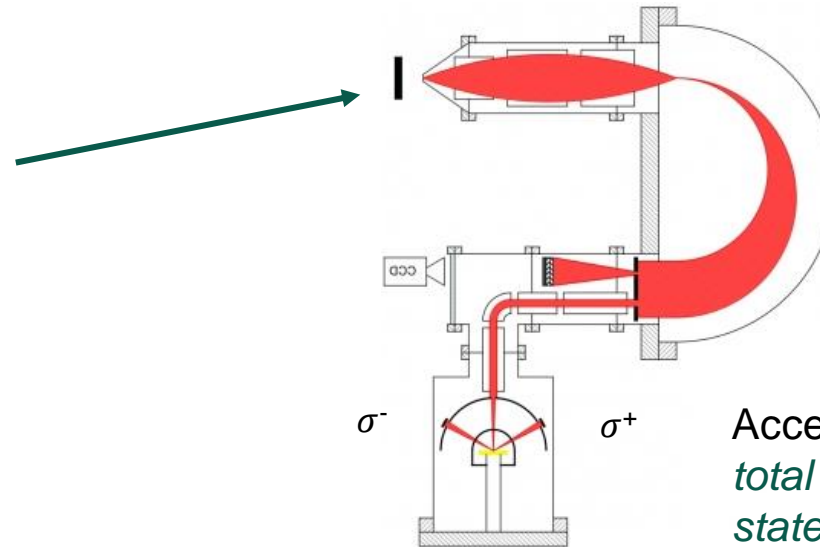
## The Cassiopée Beamline



SOLEIL : 2,75 GeV storage ring, Saint Aubin, Fr.

Mott detection SR-PES

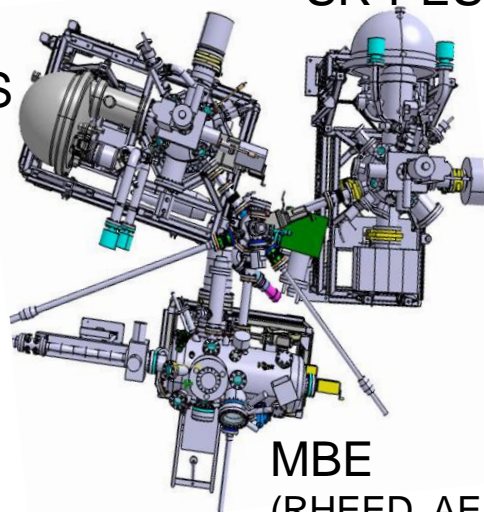
Angular aperture of  $\pm 8^\circ$



Access to the *total density of states resolved in spin*

AR-PES

2 e-guns (5 pockets)  
4 effusion cells  
=  
14 materials in the MBE

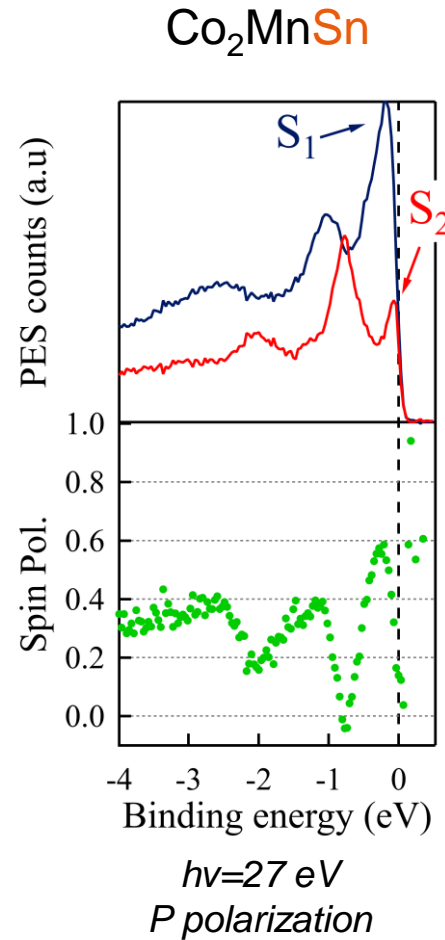
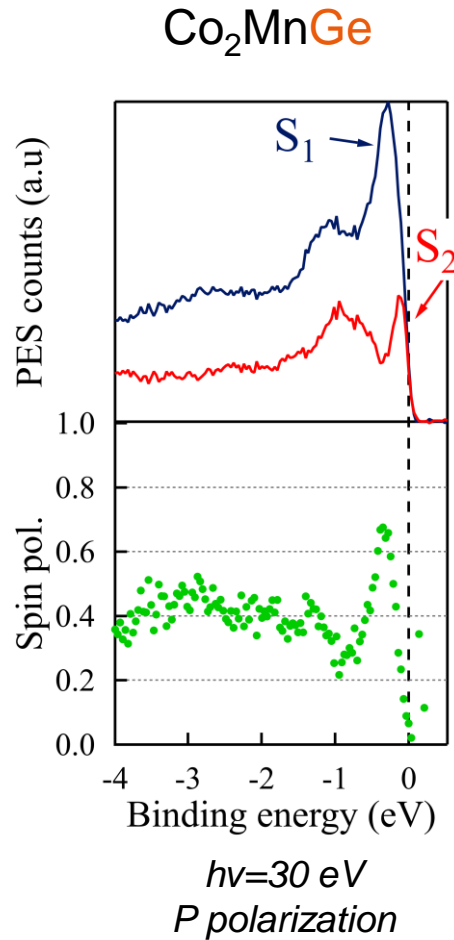
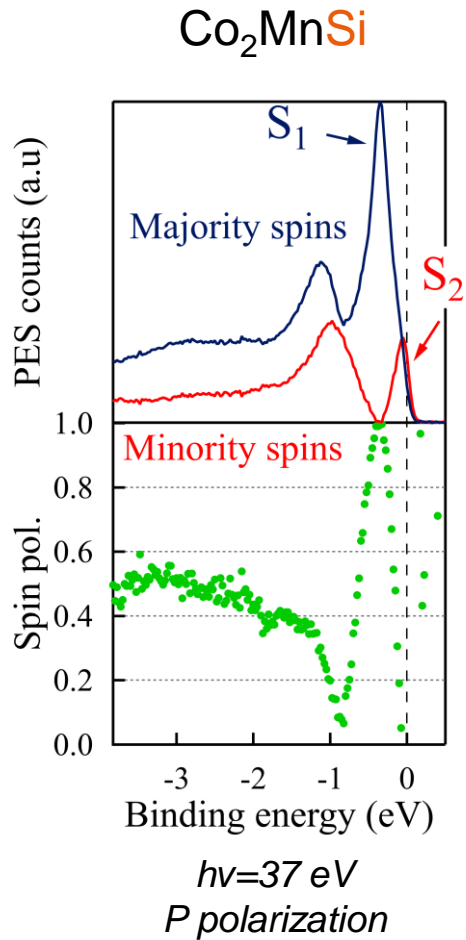


SR-PES

MBE  
(RHEED, AES)

# Spin-Resolved PES

## Co<sub>2</sub>MnZ<sub>IV</sub> with Z<sub>IV</sub>=Si, Ge, Sn

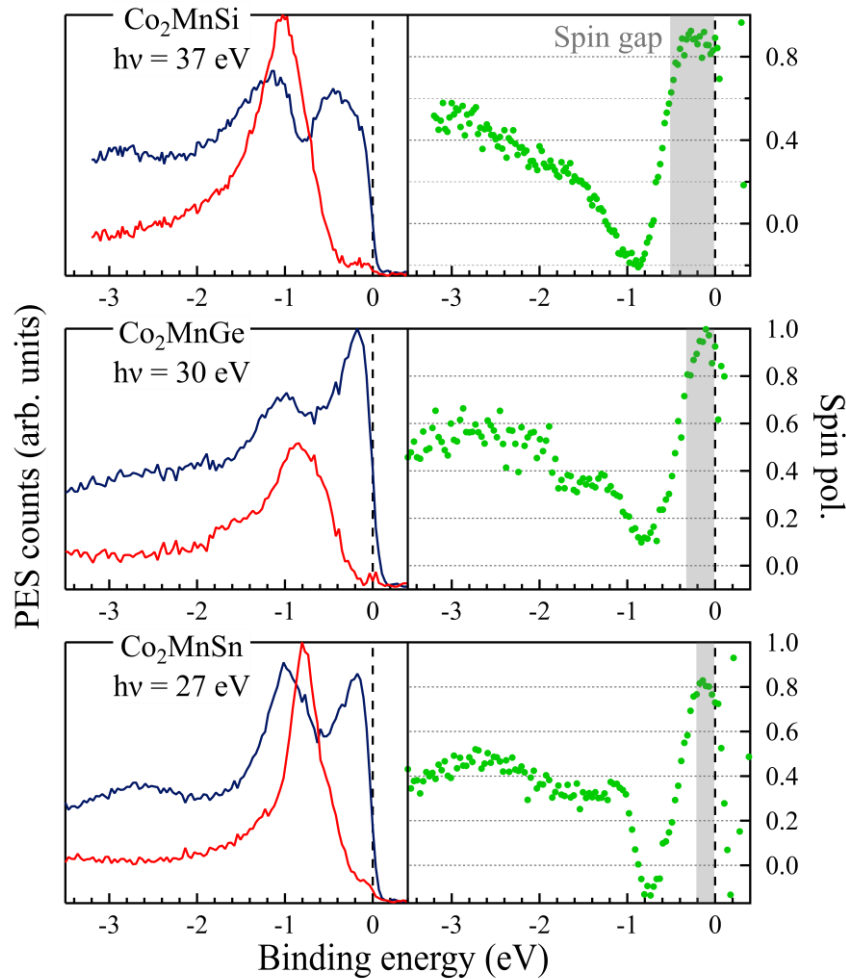


- Same shape
- Surface resonant state. [S. Andrieu *et al.*, Phys. Rev. B **93**, 094417 (2016)]
- Loss of polarization at  $E_F$



# Symmetry & Spin-Resolved PES

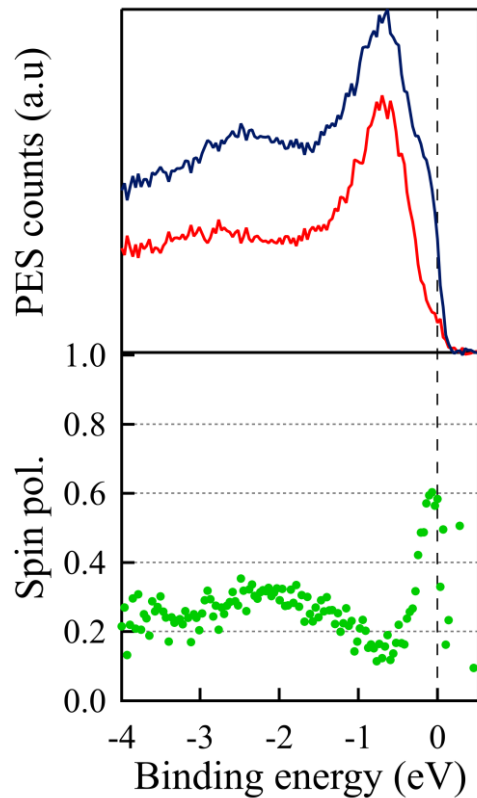
## Co<sub>2</sub>MnZ<sub>IV</sub> with Z<sub>IV</sub>=Si, Ge, Sn



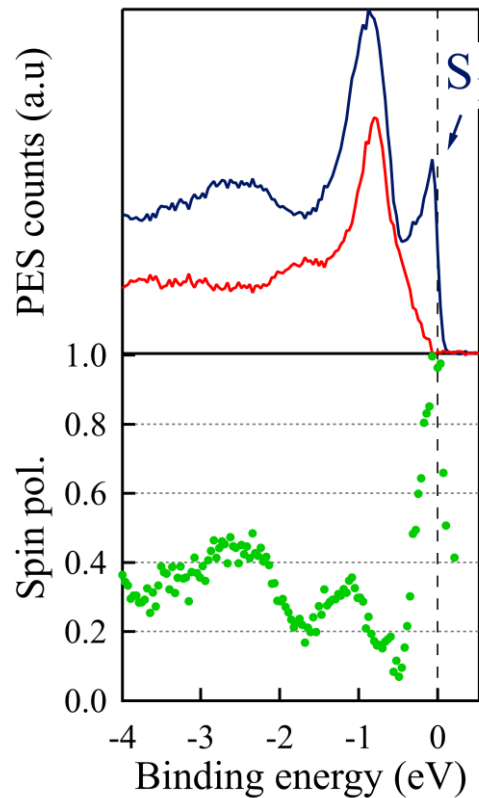
- ✓ With S polarization, S<sub>1</sub> and S<sub>2</sub> are no longer excited
- ✓ Max of SP at E<sub>F</sub>
- ✓ Spin gaps !

# Spin-Resolved PES

## Co<sub>2</sub>MnZ<sub>III</sub> with Z<sub>III</sub>=Al, Ga



Co<sub>2</sub>MnAl  
 $h\nu=37$  eV  
*P* polarization

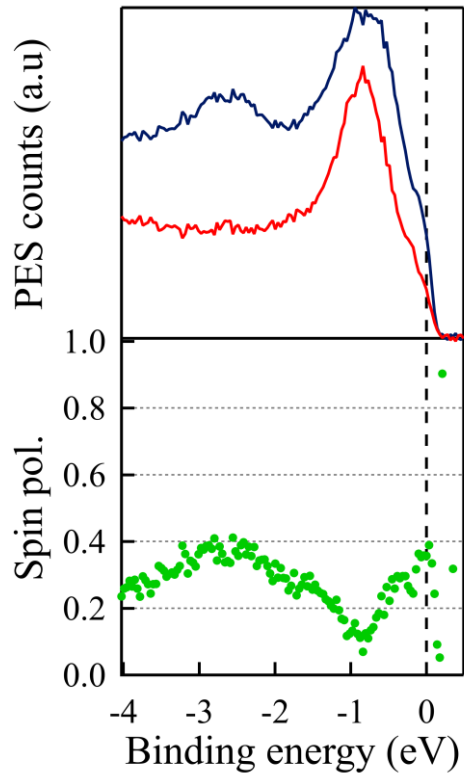


Co<sub>2</sub>MnGa  
 $h\nu=37$  eV  
*P* polarization

- ✓ 1 less e<sup>-</sup> = Surface states above E<sub>F</sub>
- ✓ Max of SP at E<sub>F</sub>
- ✓ Spin gap for Co<sub>2</sub>MnGa

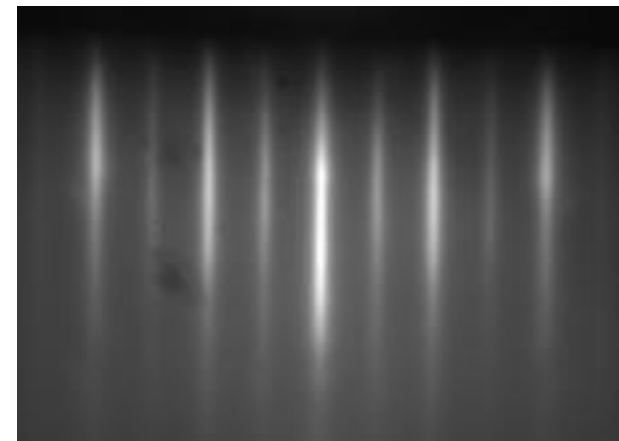
# Spin-Resolved PES

## Co<sub>2</sub>MnZ<sub>v</sub> with Z<sub>v</sub>=Sb



Co<sub>2</sub>MnSb  
 $h\nu=37$  eV  
*P* polarization

- ✓ Weakly polarized
- ✓ Certainly due to Sb segregation and/or reconstruction at the surface

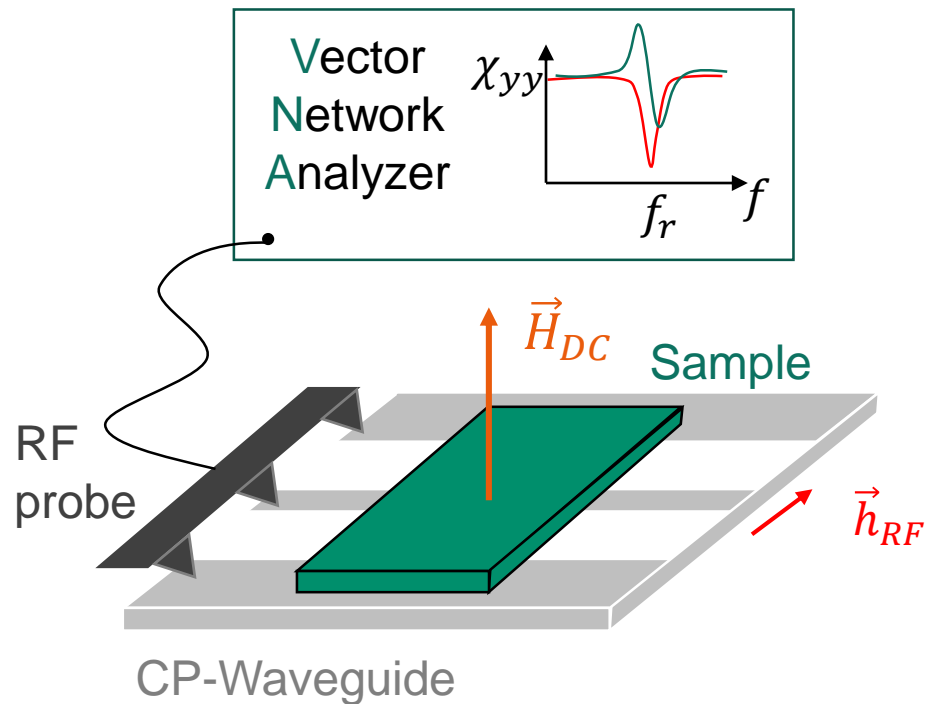


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# ⊥VNA-FMR

## Set-up



$\vec{H}_{DC}$  : out-of-plane static magnetic field

$\vec{h}_{RF}$  : in-plane RF magnetic field

- $H_{DC}$  up to 2.5 T

- Kittel law :

$$f_r = \gamma_0(H_0 - M_{eff})$$

- Gilbert damping given by HWHM

$$\Delta f = 2\alpha f_r + 2\Delta f_0$$

- 2-magnons scattering avoided

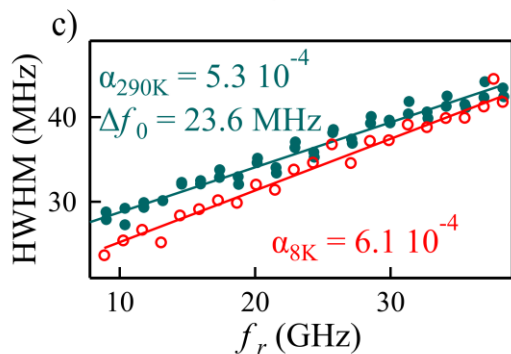
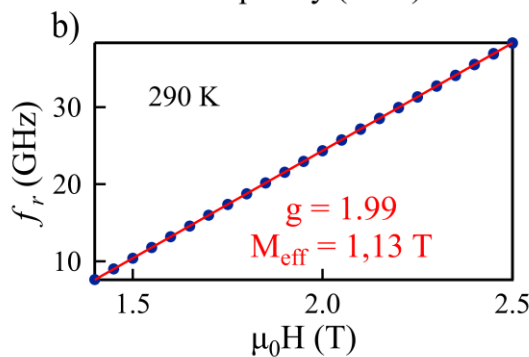
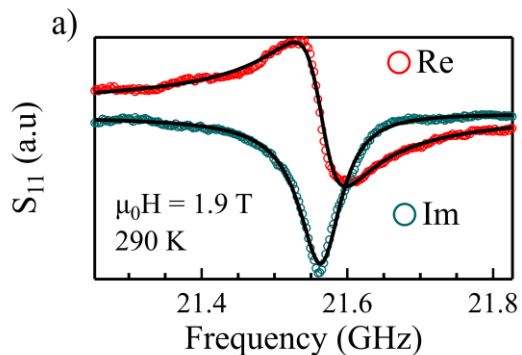
- No corrections (raw effective values)

# ⊥ VNA-FMR

## Ultra-low magnetic damping

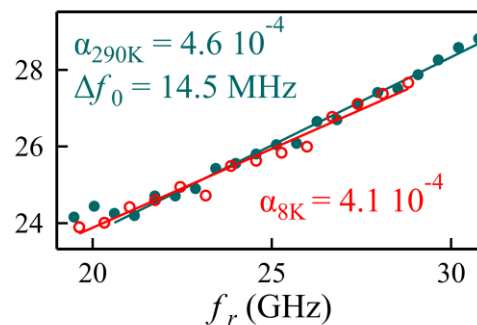
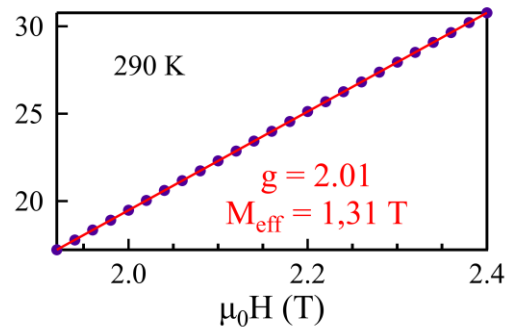
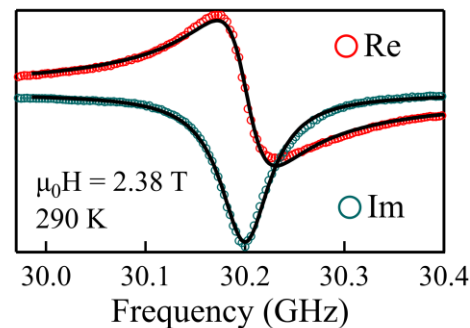
Co<sub>2</sub>MnGe

- $\alpha = 5,3 \cdot 10^{-4}$
- $g = 1,99$
- $\Delta f_0 = 23,6 \text{ MHz}$



Co<sub>2</sub>MnSi

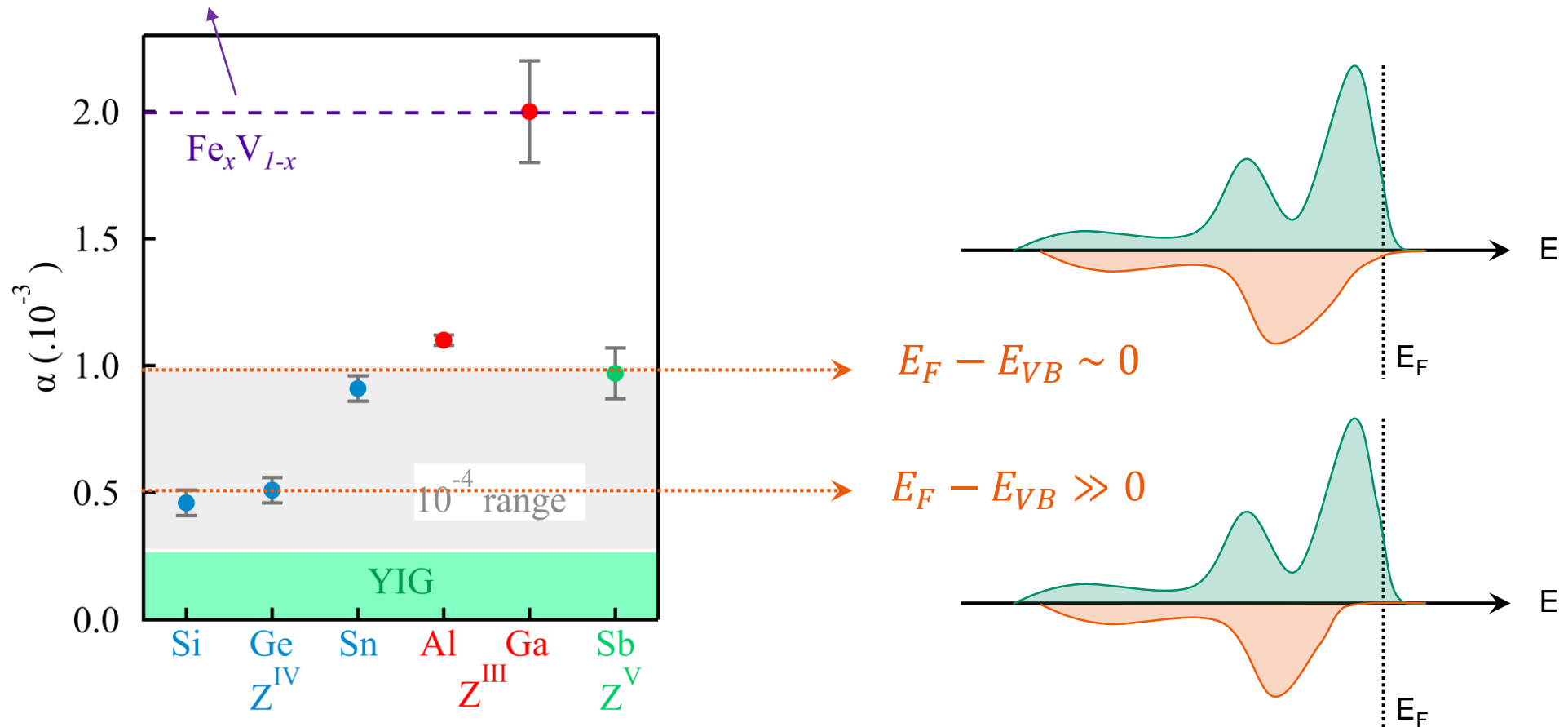
- $\alpha = 4,6 \cdot 10^{-4}$
- $g = 2,01$
- $\Delta f_0 = 14,5 \text{ MHz}$



# ⊥VNA-FMR

## Co<sub>2</sub>MnZ damping results

T. Devodler *et al.*, *Appl. Phys. Lett.* **103**, 242410 (2013)



# Summary

- Elaboration of epitaxial films precisely controlled & chemical order resolved
  - Trouble with Sb !
- $\text{Co}_2\text{MnZ}$  are high spin polarized materials with very small damping
- Reduction of the damping when  $E_F$  far from any minority DOS
- Next step is to get PMA



# Thank you