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## Cobalt-based Heusler alloys for spintronics

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

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# Cobalt-based Heusler alloys for spintronics

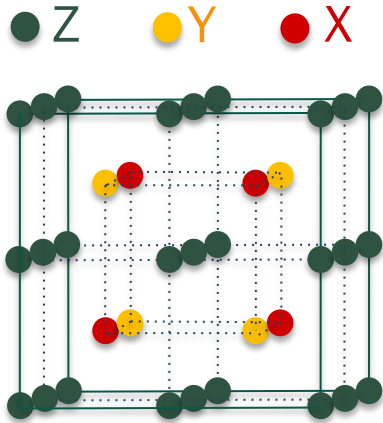
Half-metallicity and ultra-low damping investigation of the  
 $\text{Co}_2\text{MnX}$  series

*C. GUILLEMARD, C. ROJAS-SANCHEZ, S. PETIT-WATELOT, L. PASQUIER,  
A. M. BATAILLE, F. BERTRAN, S. ANDRIEU*

# Outline

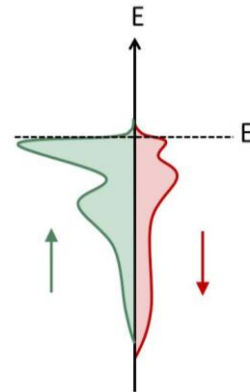
- I.  $\text{Co}_2\text{MnX}$  Heusler alloys & spintronics
- II. *In situ* SR-PES on the Cassiopée beamline
  - Elaboration of  $\text{Co}_2\text{MnX}$
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  - Low magnetic damping results
- IV. Summary

# Heusler alloys

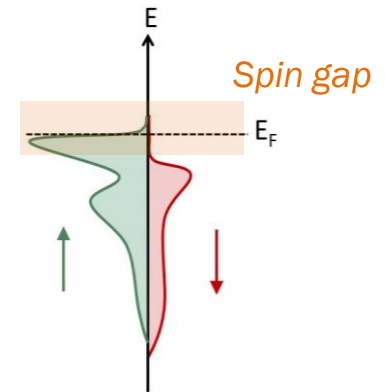


Some are predicted  
Half Metal Magnet

R. A. De Groot, *Phys. Rev. Lett.*  
50, 1983



Standard  
Ferromagnet



Half Metal Magnet  
(HMM)

Full Heusler  $Z_2YX$  :

$Co_2MnSi$ ,  $Rh_2YbPb$ ...

$$\eta = \frac{D_{\uparrow}(E_F) - D_{\downarrow}(E_F)}{D_{\uparrow}(E_F) + D_{\downarrow}(E_F)} = 1 \rightarrow 100\% \text{ spin polarization at } E_F$$



$$TMR = \frac{2\eta_1\eta_2}{1 - \eta_1\eta_2} \rightarrow \infty$$

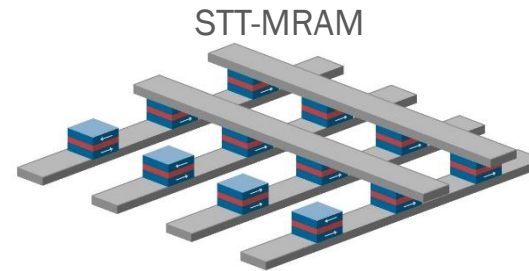
Exp: 1996 %

H. Liu et al, *App. Phys. Lett.* **101**, 2012

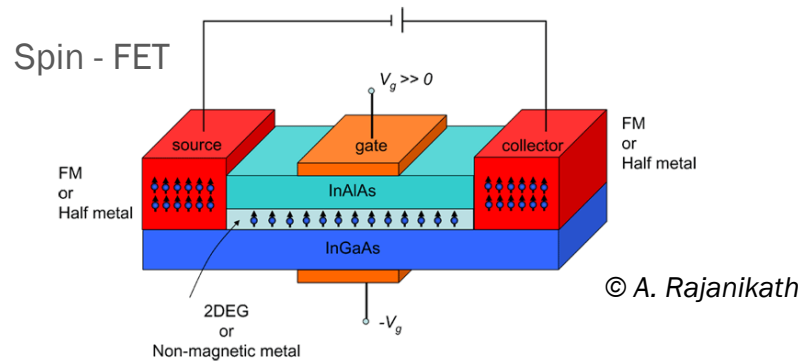
# Interest for spintronic devices :

Information storage and processing

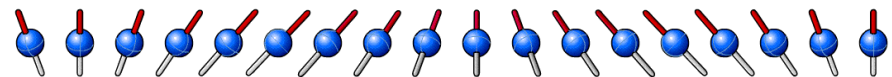
- MRAM
  - ↗ TMR / GMR
  - ↘  $J_C$  (STT)



- STNO
- Spin injection



- Magnonics : Long length SW propagation



# Motivations

Co<sub>2</sub>MnX Heuslers good candidates :

- ✓ Predicted HMM (*ab initio* calc.)
- ✓ Ultra-low damping materials (down to 10<sup>-5</sup>)
- ✓ High T<sub>C</sub>
- ✓ Lattice parameter close to MgO (tunnel barrier)

Our strategy :

- Elaboration of epitaxial Co<sub>2</sub>MnX thin films by MBE
- To confirm the predicted HMM behavior of Heuslers and tune the electronic structure (by switching X<sub>IV</sub> by X<sub>III</sub>, X<sub>V</sub> etc.)
- Measurement of the Gilbert damping by VNA-FMR
- Link the HMM behavior and damping value

# Outline

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# The Cassiopée Beamline

Mott detection SR-PES

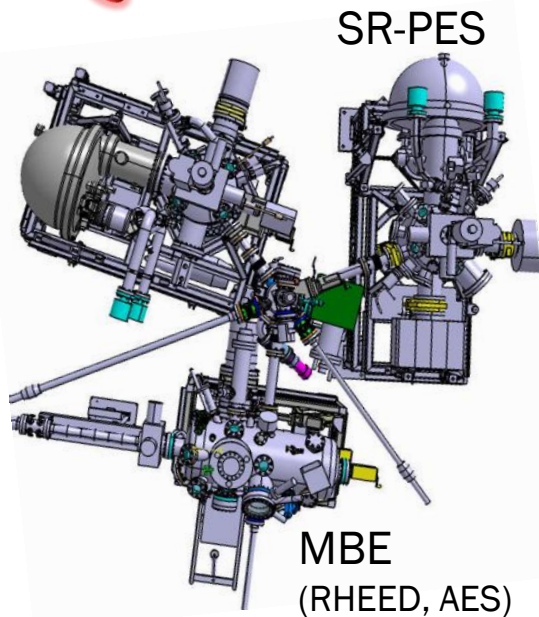


SOLEIL : 2,75 GeV storage ring, Saint Aubin, Fr.

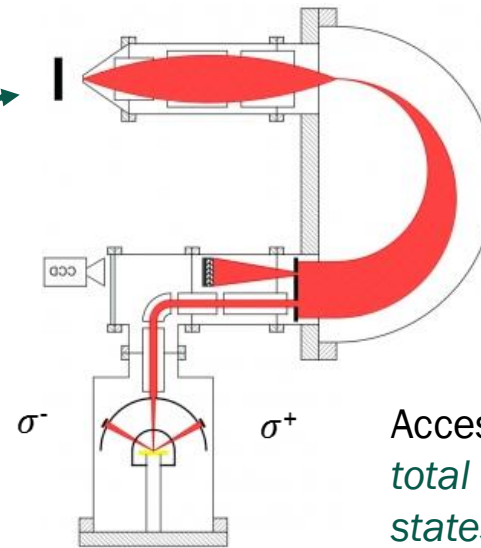
$h\nu$

AR-PES

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



Angular aperture of  $\pm 8^\circ$



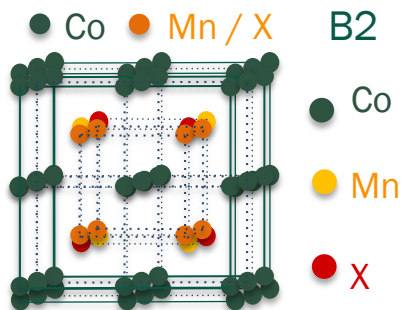
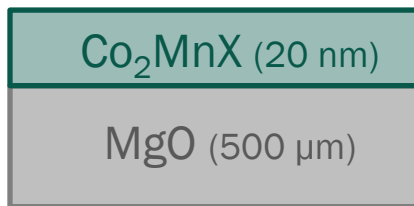
Access to the *total density of states resolved in spin*



# MBE growth

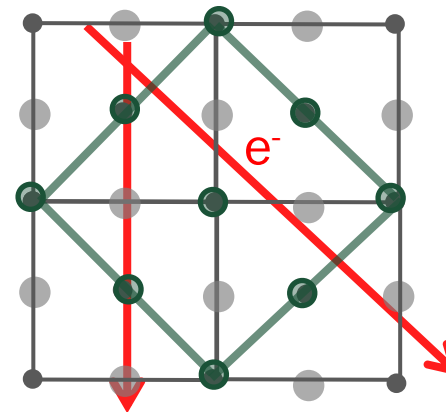
MgO(001) [100] // Co<sub>2</sub>MnX(001) [110]

Growth by co-evap.  
Controlled by QCM (error : 5%)

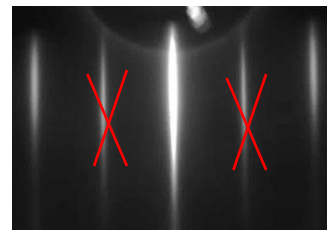


Same space group as MgO  
L2<sub>1</sub>

$Fm\bar{3}m$

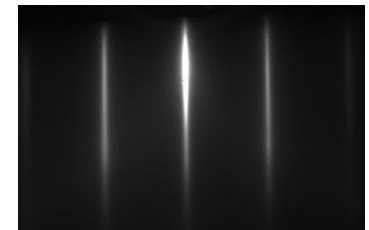


$[110]_{Co_2MnX}$



Typical RHEED patterns

$[100]_{Co_2MnX}$



# MBE growth

[110] RHEED patterns

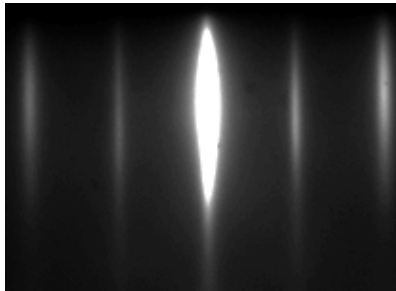
$\text{Co}_2\text{MnX}$  with  $X =$

Al

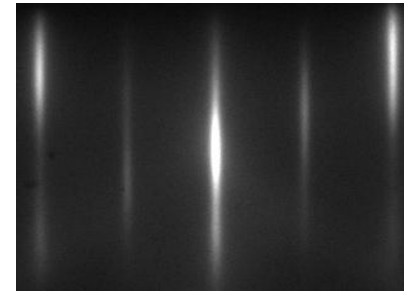


No half streaks :  
Chemical disorder

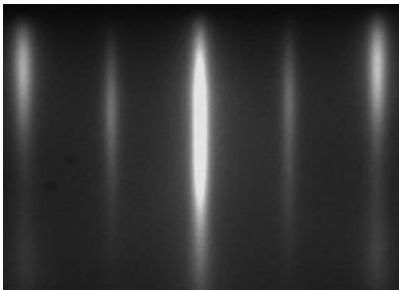
Si



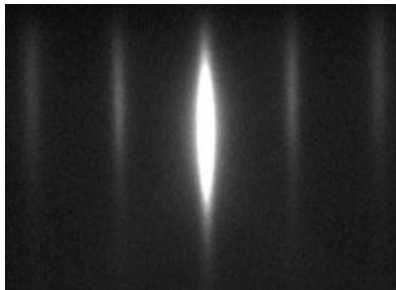
Ga



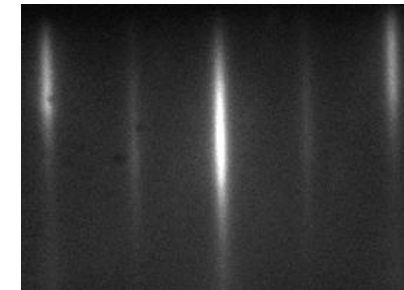
Ge



Sn



Sb

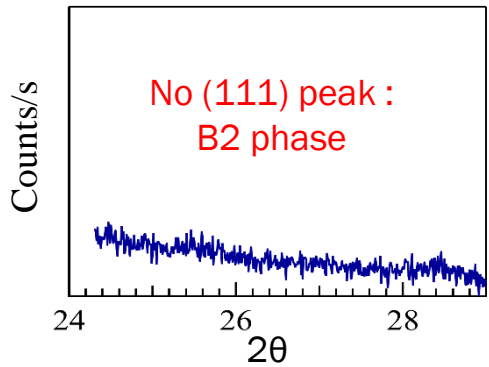


# MBE growth

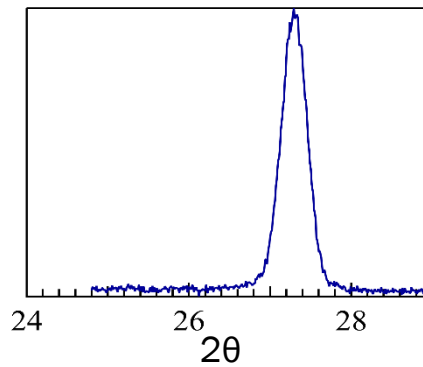
XRD: (111) reflection

$$I_{111} \propto |(f_X - f_{Mn})|^2$$

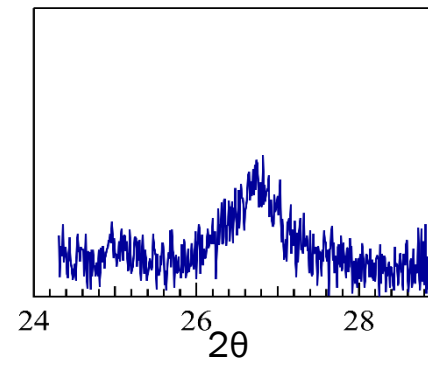
Co<sub>2</sub>MnX with X = Al



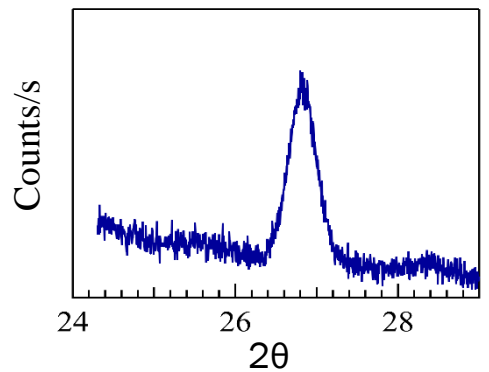
Si ✓



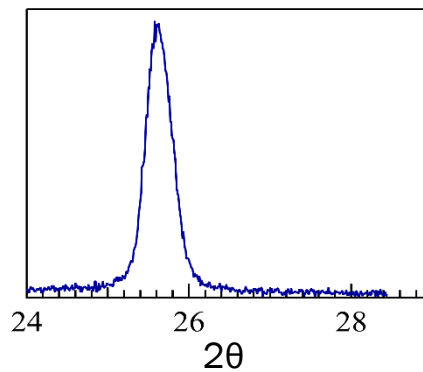
Ga ✓



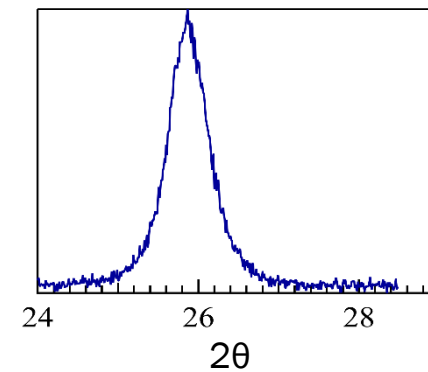
Ge ✓



Sn ✓

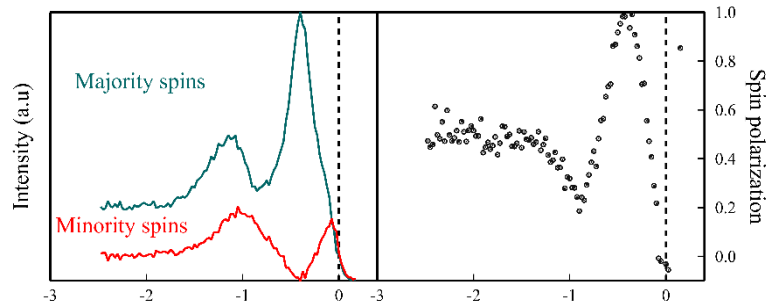


Sb ✓



# Spin Resolved Photoemission

Results on  $\text{Co}_2\text{MnX}_{\text{IV}}$  ( $\text{X}_{\text{IV}} = \text{Si, Ge, Sn}$ )

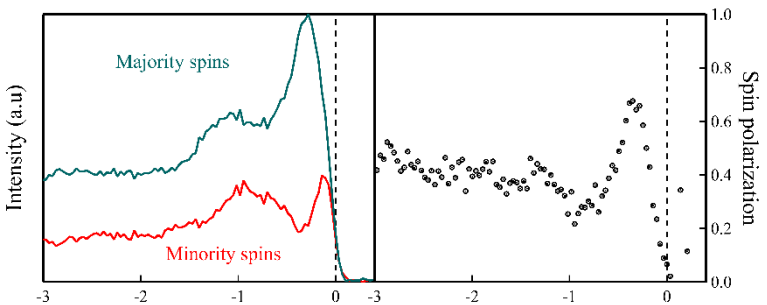


$\text{Co}_2\text{MnSi}$

$h\nu = 37 \text{ eV}$

Pol. = 100% below  $E_F$

(S. Andrieu et al. Phys. Rev. B, 2016)

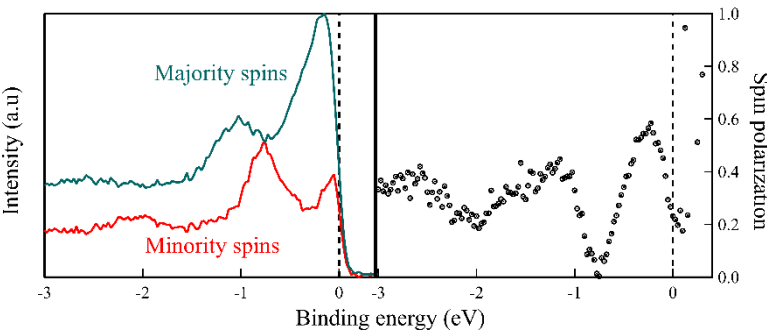


$\text{Co}_2\text{MnGe}$

$h\nu = 30 \text{ eV}$

Pol. > 70% below  $E_F$

not yet published



$\text{Co}_2\text{MnSn}$

$h\nu = 27 \text{ eV}$

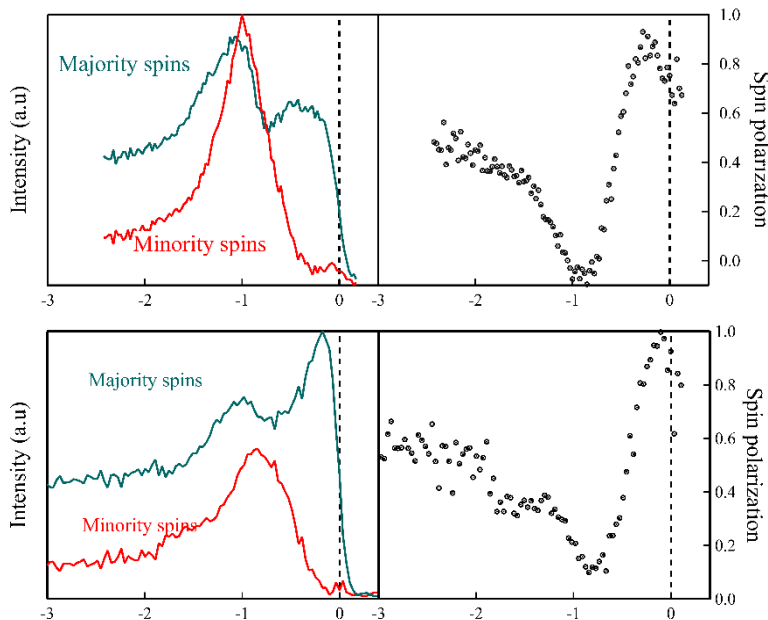
Pol. > 60% below  $E_F$

not yet published

- High spin polarization
- Surface states kill the polarization at  $E_F$

# Spin Resolved Photoemission

Results on  $\text{Co}_2\text{MnX}_{\text{IV}}$  ( $\text{X}_{\text{IV}} = \text{Si, Ge, Sn}$ )



$\text{Co}_2\text{MnSi}$   
**Spin gap**  
 (S. Andrieu et al. Phys. Rev. B, 2016)

$h\nu = 37 \text{ eV}$   
 Pol.  $s$

$\text{Co}_2\text{MnGe}$   
**Spin gap**  
 not yet published

$h\nu = 30 \text{ eV}$   
 Pol.  $s$

Measurement next week !

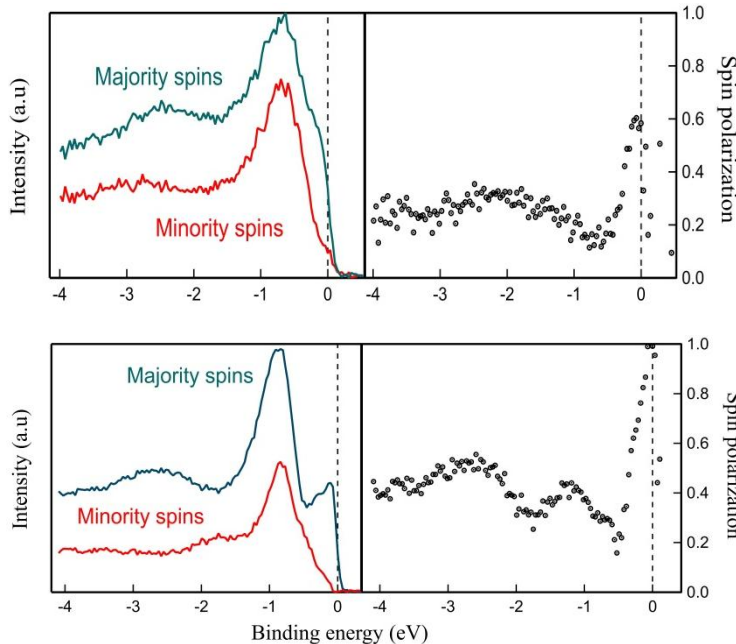
$\text{Co}_2\text{MnSn}$

$h\nu = 27 \text{ eV}$   
 Pol.  $s$

Spin gap for  $\text{Co}_2\text{MnGe}$  and  $\text{Co}_2\text{MnSi}$  with pol.  $s$

# Spin Resolved Photoemission

Results on  $\text{Co}_2\text{MnX}_{\text{III}}$  ( $\text{X}_{\text{III}} = \text{Al, Ga}$ )



$\text{Co}_2\text{MnAl}$

60% spin polarization at  $E_F$

$h\nu = 37 \text{ eV}$

$\text{Co}_2\text{MnGa}$

100% spin polarization at  $E_F$

$h\nu = 37 \text{ eV}$

not yet published

For the  $\text{Co}_2\text{MnX}_{\text{III}}$ , the Fermi level slides down since there is one less valence  $e^-$

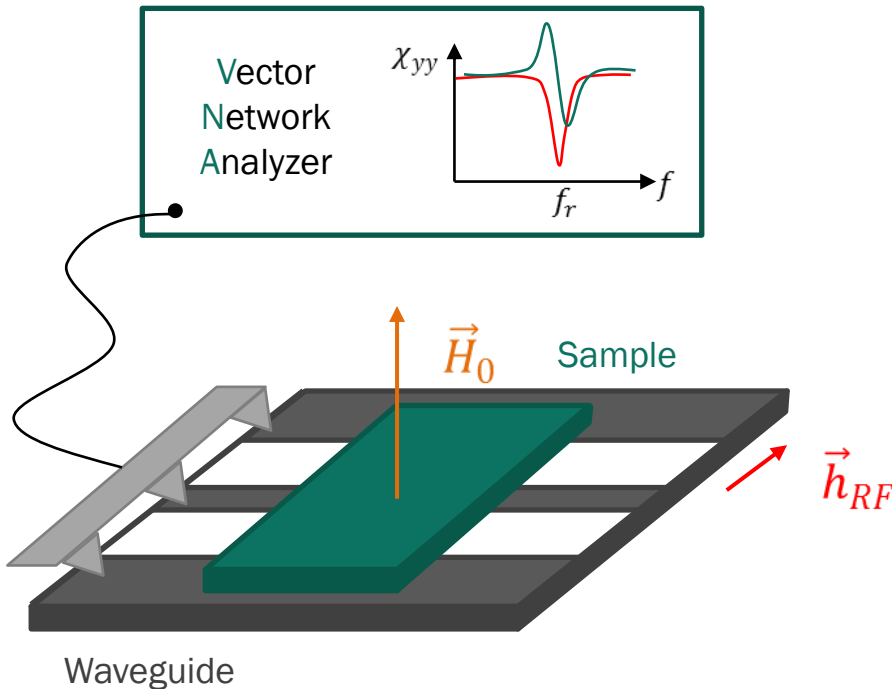
Spin gap at  $E_F$  for  $\text{Co}_2\text{MnGa}$

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# Ferromagnetic resonance

Perpendicular magnetic field VNA-FMR



$H_0$  from 0 to 2.5 T

- Kittel law :  

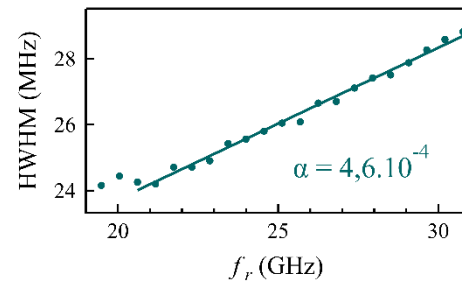
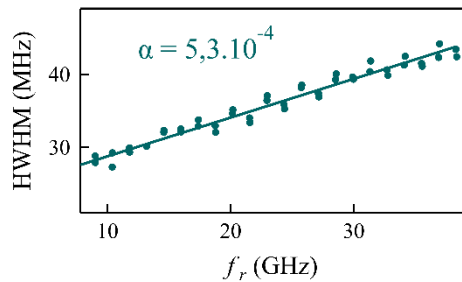
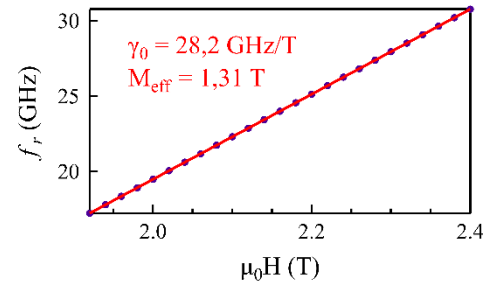
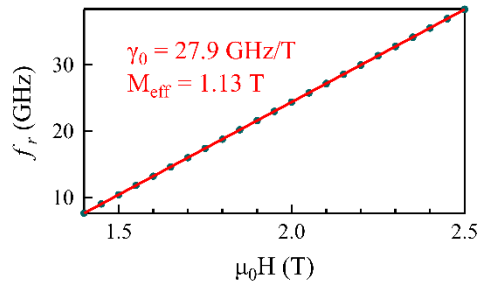
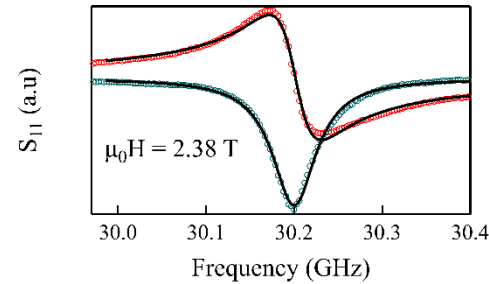
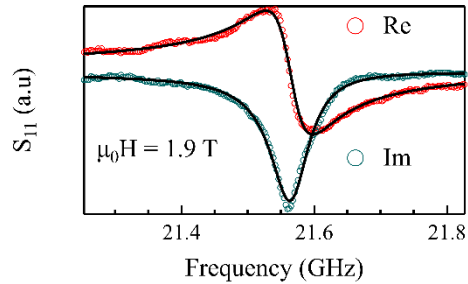
$$f_r = \gamma_0 (H_0 - M_{eff})$$
- Gilbert damping given by HWHM  

$$\Delta f = 2\alpha f_r$$
- 2-magnons scattering avoided
- No corrections (raw effective values)



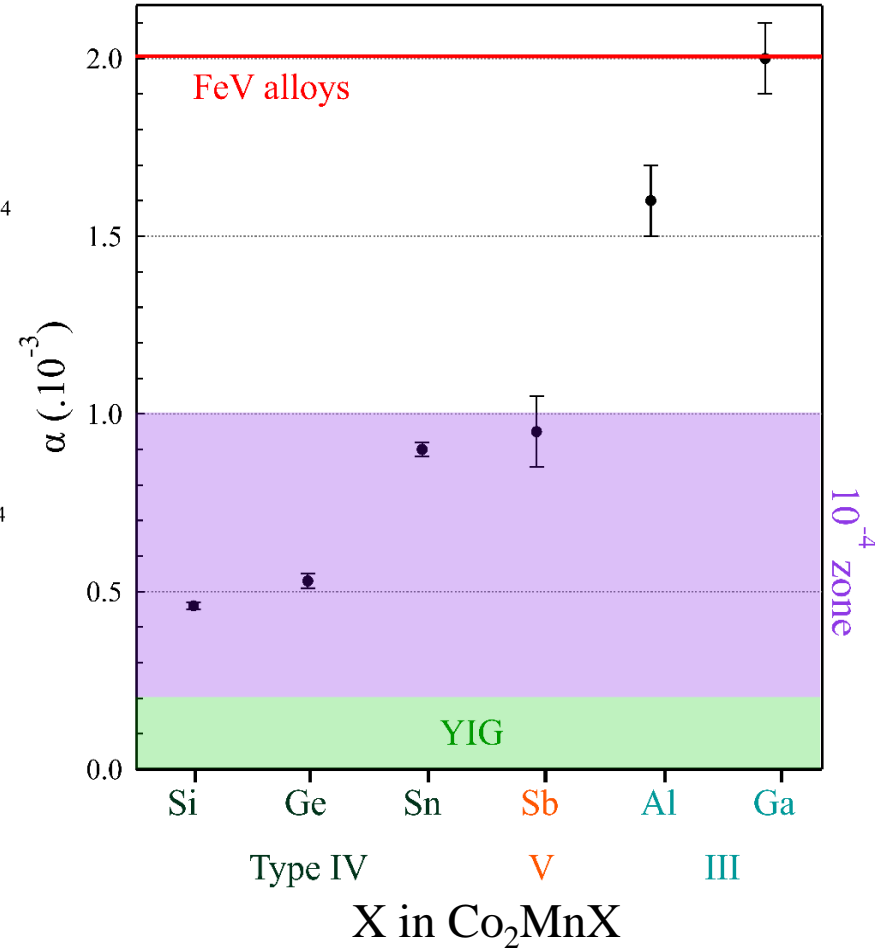
# Ferromagnetic resonance

Low magnetic damping on Heuslers



Co2MnGe

Co2MnSi



# Summary

- Epitaxial  $\text{Co}_2\text{MnX}$  thin films grown by MBE
  - Low chemical order for  $\text{Co}_2\text{MnAl}$
- High spin polarization for almost all of them
  - HMM confirmed for  $\text{Co}_2\text{MnSi}$ , Ge and Ga!
- Ultra-low magnetic damping also confirmed
  - 4 out of 6 in the  $10^{-4}$  range
- How does the chemical disorder impact the physical properties?
- Link the SR-DOS with the calculated band structures
- Find connections between the magnetic damping and the spin polarization (and the electric conductivity)
- Insertion in devices (MTJ)

Thank you for your attention !



Institut Jean Lamour  
101 team

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S. Petit-Watelot  
L. Pasquier



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Cassiopee beamline

F. Bertran †  
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