Hidden Interfaces and High-Temperature Magnetism in Intrinsic Topological Insulator - Ferromagnetic Insulator Heterostructures

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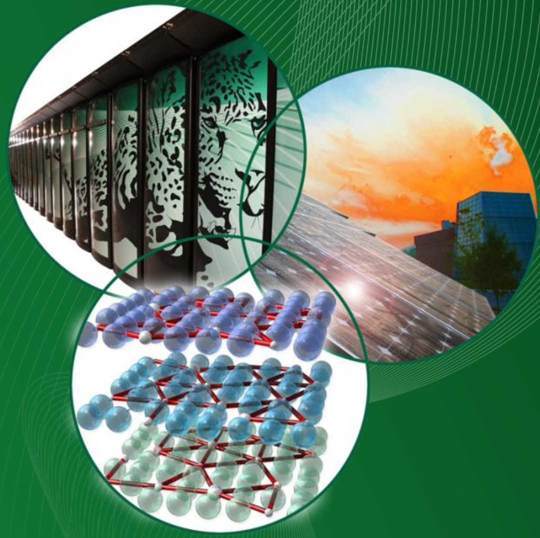
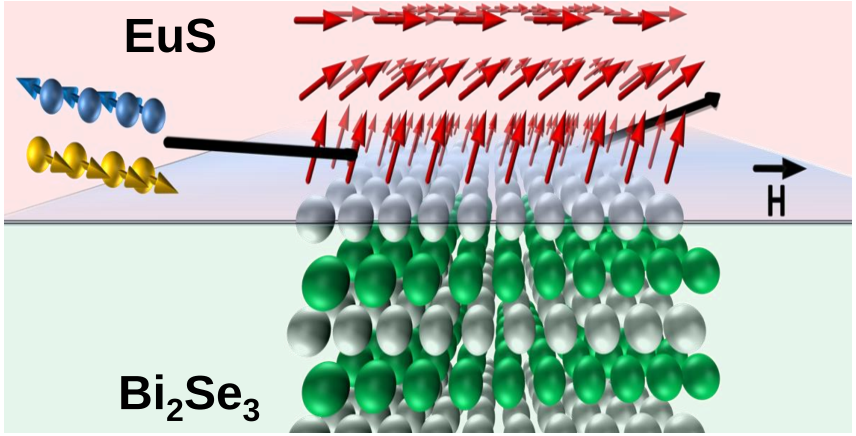
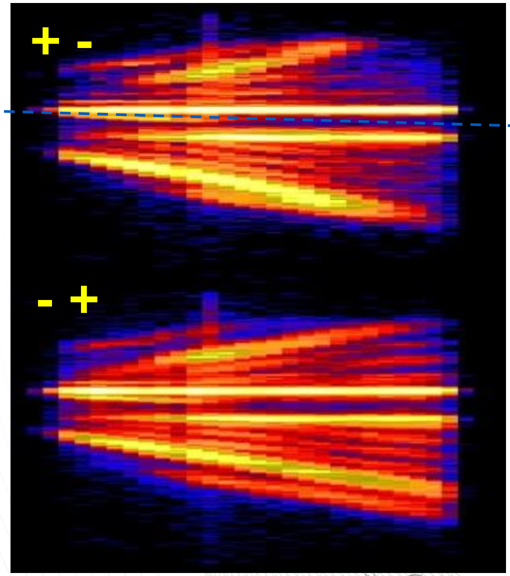


Outline

- **Topological Insulators - a new phase of matter with TRS**



- **Symmetry breaking in TI via *magnetic proximity***
- **Induce ferromagnetism in Topological Insulator via exchange coupling in TI-FMI**



- **Polarized Neutron Reflectometry: *depth resolved vector magnetometry* for TI – FMI heterostructures**

Interface ferromagnetism in TI via magnetic proximity

Introducing ferromagnetic order in TI:

- **by doping with specific elements:**
  - hard to separate the surface and the bulk phases.
  - introduces crystal defects, magnetic scattering centers, impurity states in the insulating gap are detrimental to mobility and the transport of spin-momentum locked surface electrons in TIs.

- **by uniformly depositing magnetic atoms (Fe) over the TI surface:**
  - the transport properties of a TI are influenced by the metallic ferromagnetic overlayer or atoms.

- **by magnetic proximity with FI:**
  - the spin-momentum locked helical electronic states in Tis and topological magneto-electric effect

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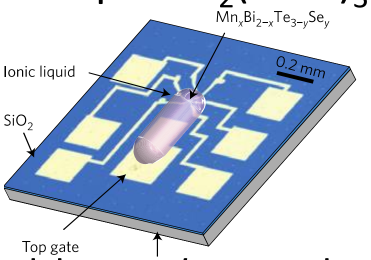
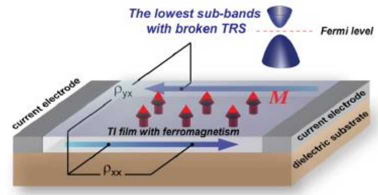
Topological insulator materials: Magnetic?

Mn-doped $Bi_2(TeSe)_3$



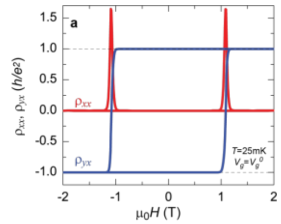
Checkelsky, *et al.*, Nat. Phys. (2012)

Cr-doped $(BiSb)_2Te_3$

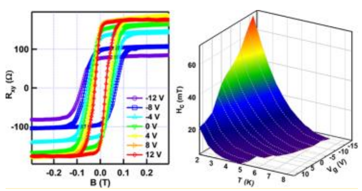


Chang, *et al.*, Science (2013)

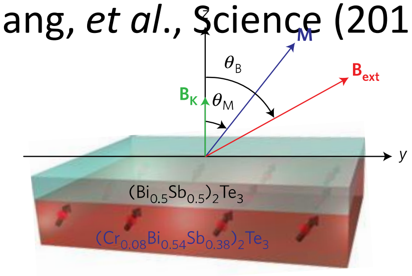
V-doped $(BiSb)_2Te_3$



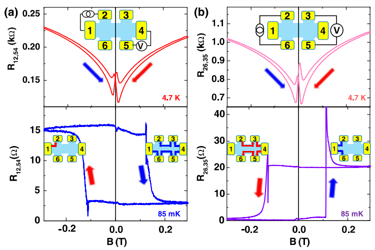
Chang, et al., Nat. Mat. (2015)



Kou, *et al.*, Nano Lett. (2013)

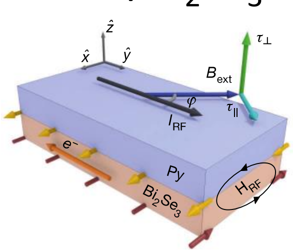


Fan, *et al.*, Nat. Mat. (2014)



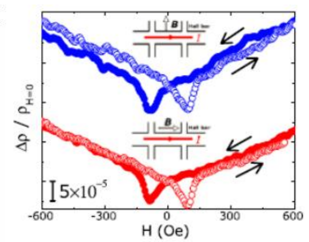
Kou, *et al.*, PRL (2014)

NiFe/Bi_2Se_3



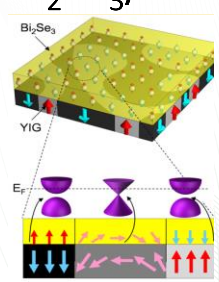
Mellnik, *et al.*, Nature (2014)

EuS/Bi_2Se_3



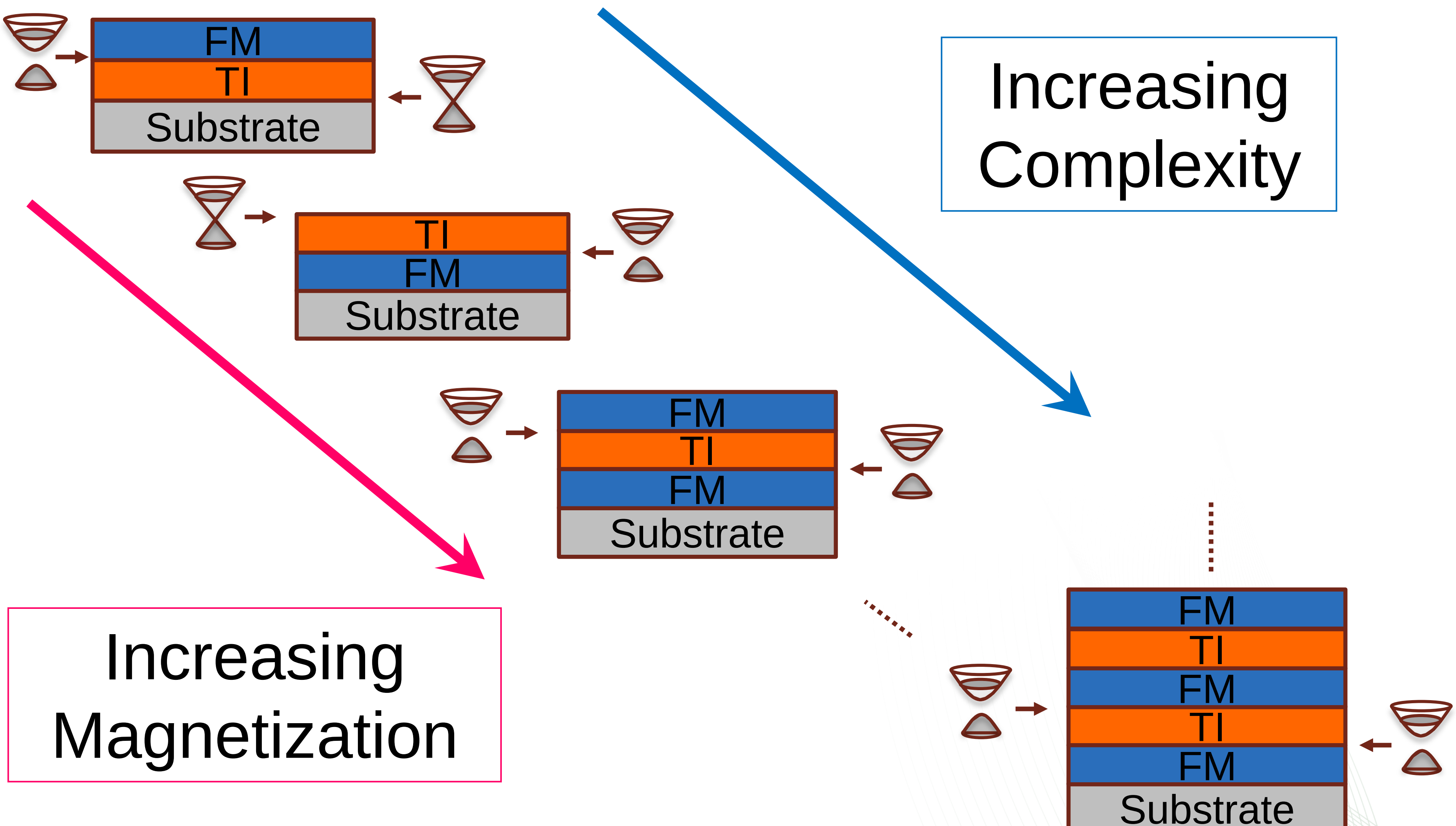
Wei, *et al.*, PRL (2013)

Bi_2Se_3/YIG



Lang, *et al.*, Nano Lett. (2014)

Topological insulator materials: Magnetism via proximity



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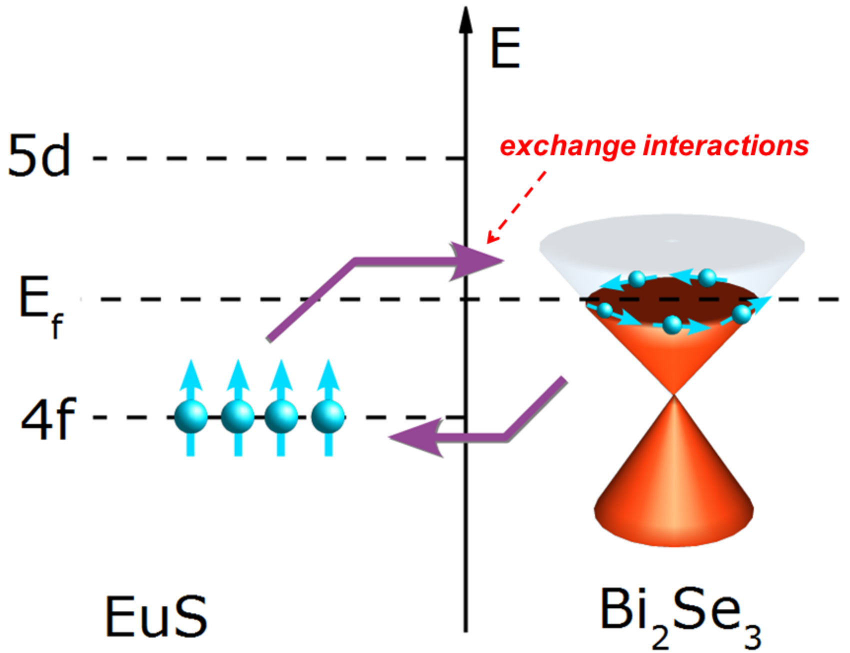
Interface ferromagnetism in TI via magnetic proximity

- The particular type of ***interface*** - between a ***topological insulator*** and a ***ferromagnet*** – might become key to the computer industry's future ability.

- The goal is the ability to manipulate surface electron states.

- We introduce ferromagnetic order onto the surface of TI Bi_2Se_3 thin films by using FI EuS.

- EuS 4f-5d energy gap 1.64 eV Fermi level inside the gap



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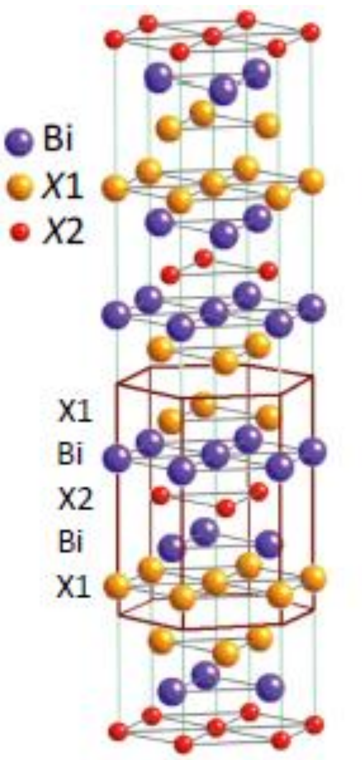
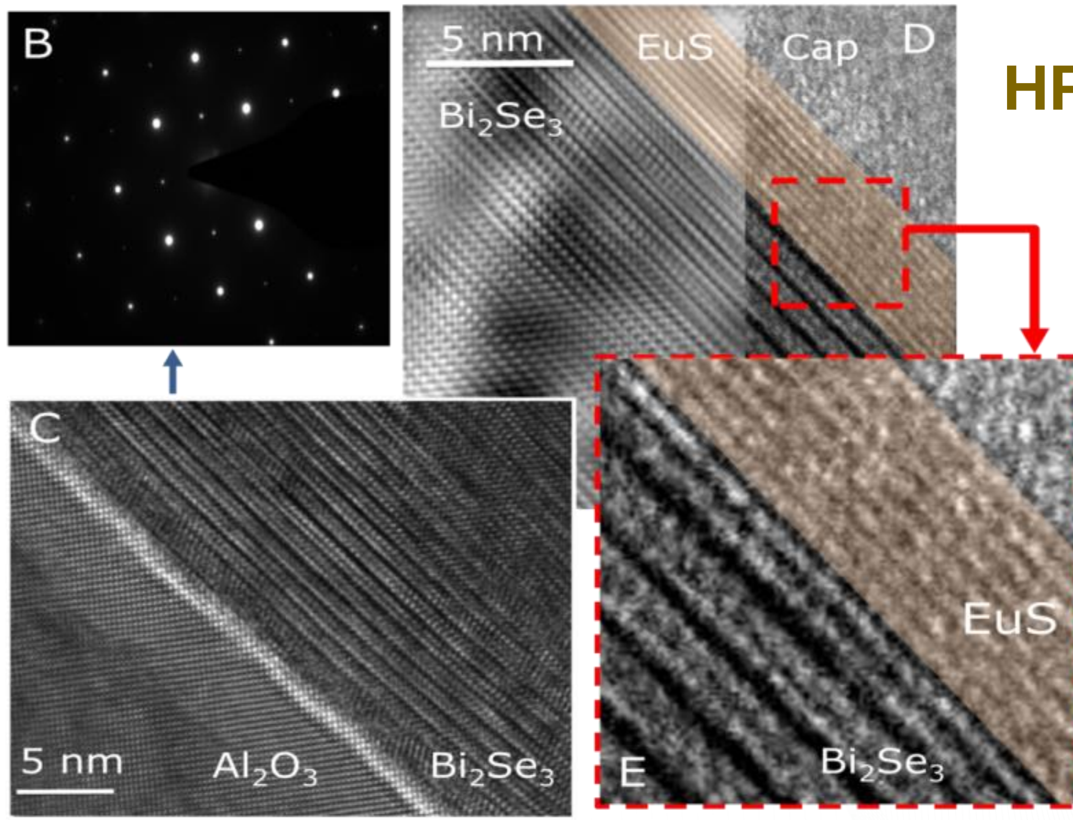
Characterization Bi2Se3/EuS bilayers

Bi_2Se_3

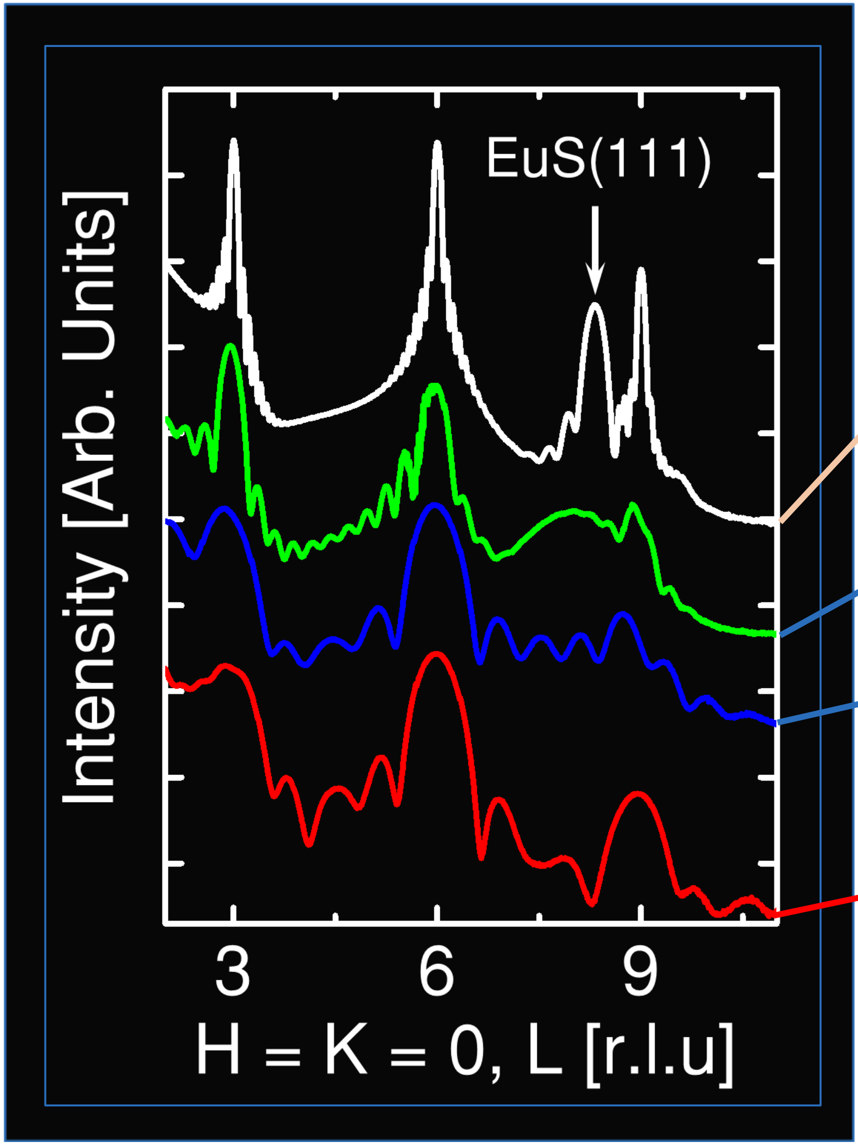




HRTEM

(**B**) electron diffraction image with an hexagonal symmetry of Bi_2Se_3
(**C**) HRTEM image for substrate and Bi_2Se_3
(**D**) HRTEM images for EuS and Bi_2Se_3 interface

Epitaxial relationship between EuS & Bi_2Se_3



- Heterostructures grown on Al_2O_3 (0001)

30 QL Bi_2Se_3 with 10 nm EuS

10 QL Bi_2Se_3 with 3 nm EuS

5 QL Bi_2Se_3 with 1 nm EuS

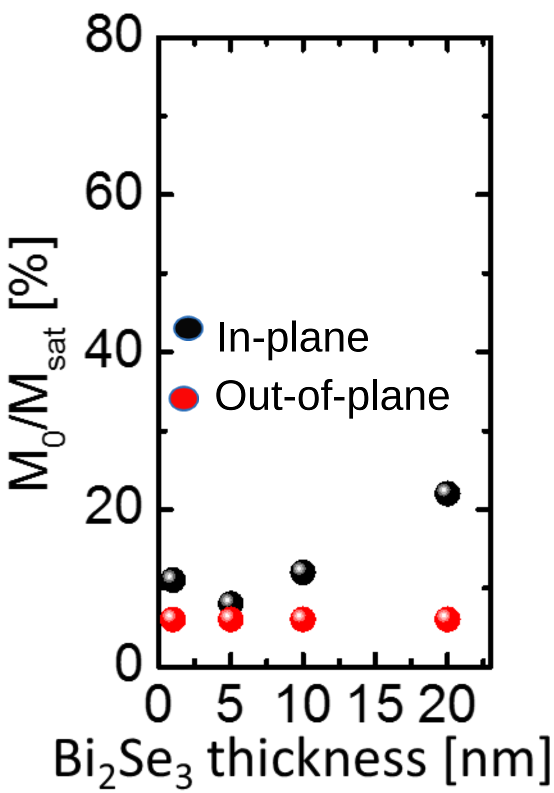
5 QL Bi_2Se_3

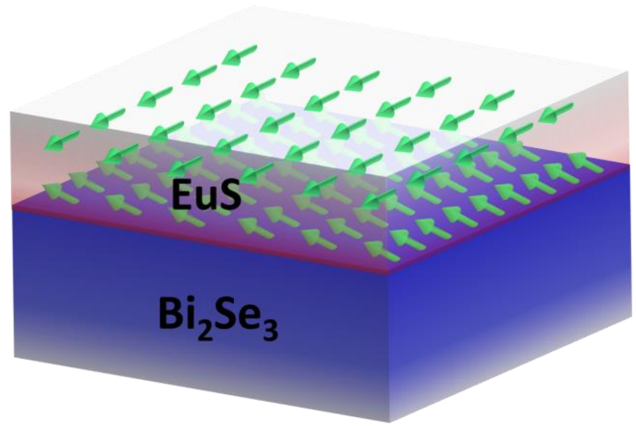
- Bi_2Se_3 (0001) // Al_2O_3 (0001)
- EuS (111) // Bi_2Se_3 (0001)

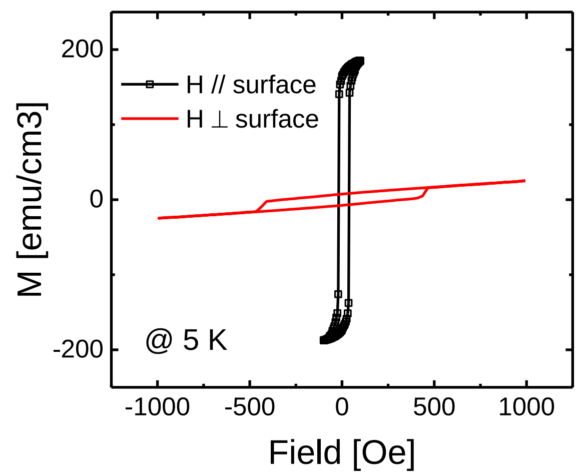
Strong interface magnetization

SQUID

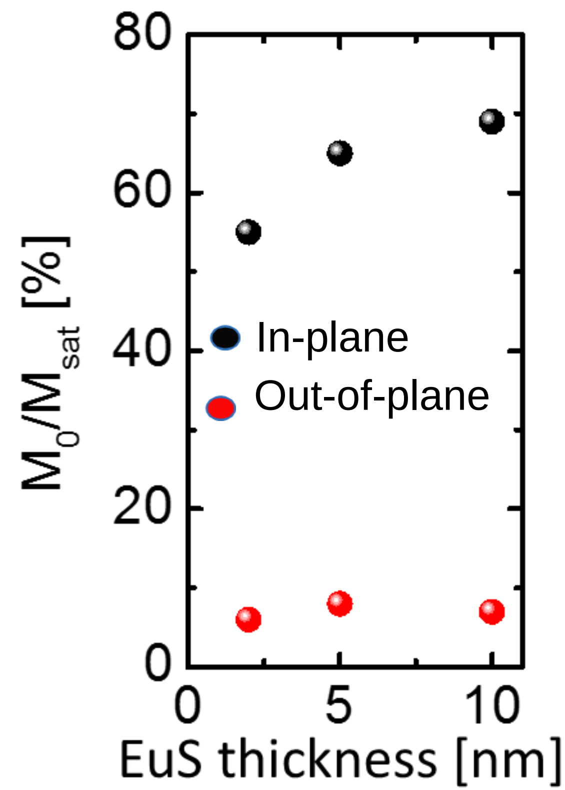
EuS = 1 nm







Bi_2Se_3 = 20 nm



- All samples display ferromagnetism
- Out-of-plane remanance ratio does not depend on thicknesses ------->

-------> evidence that the out-of-plane component is at the interface

Samples for PNR experiments

$Al_2O_3/EuS/Bi_2Se_3//Al_2O_3$

MBE with a base pressure of 10^{-10} Torr on **substrates Al_2O_3**

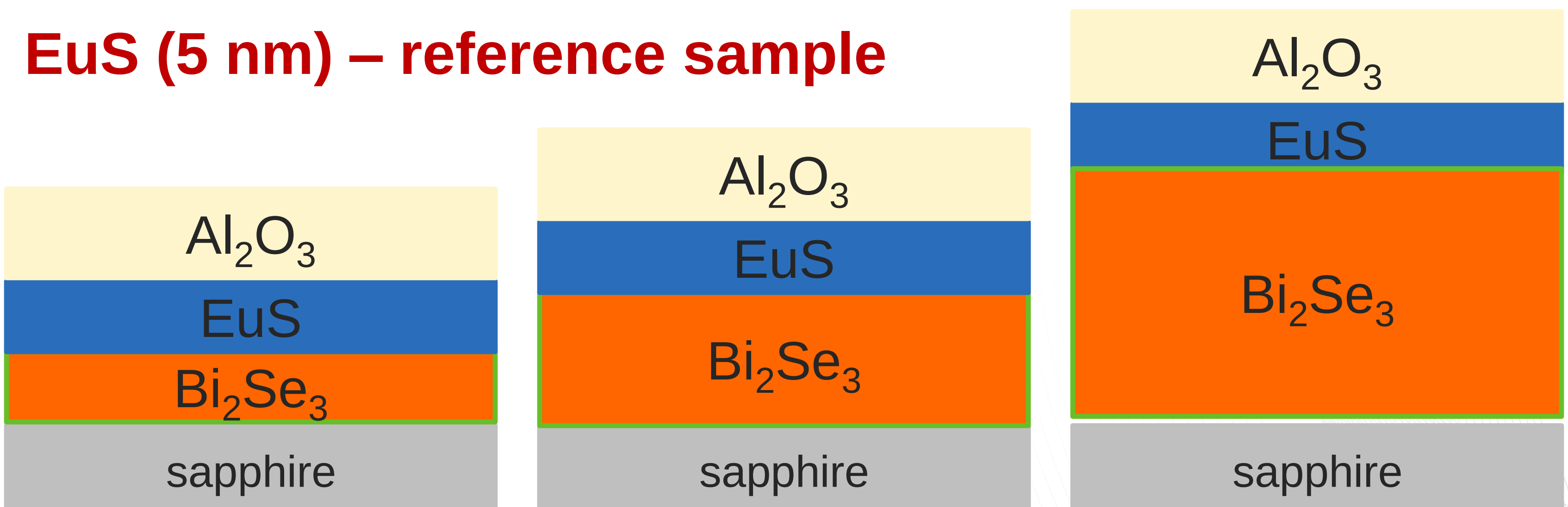
EuS (5 nm)Bi_2Se_3 (5nm)

EuS (5 nm)Bi_2Se_3 (10nm)

EuS (5 nm)Bi_2Se_3 (20nm)

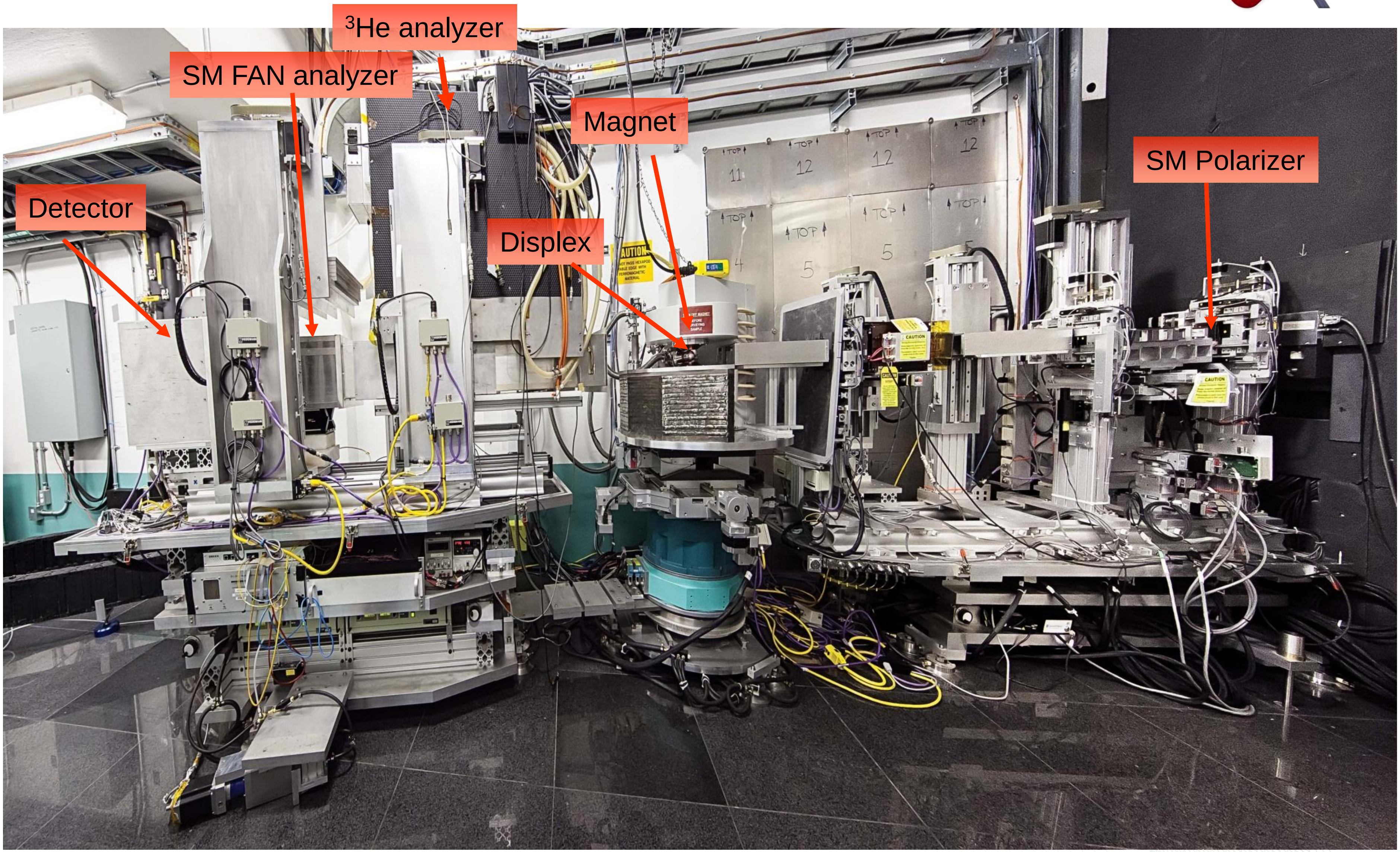
EuS (5 nm) – reference sample

Sample size
20 X 20 mm^2



Spallation Neutron Source, ORNL,TN

Magnetism Reflectometer at SNS



Magnetism Reflectometer at SNS

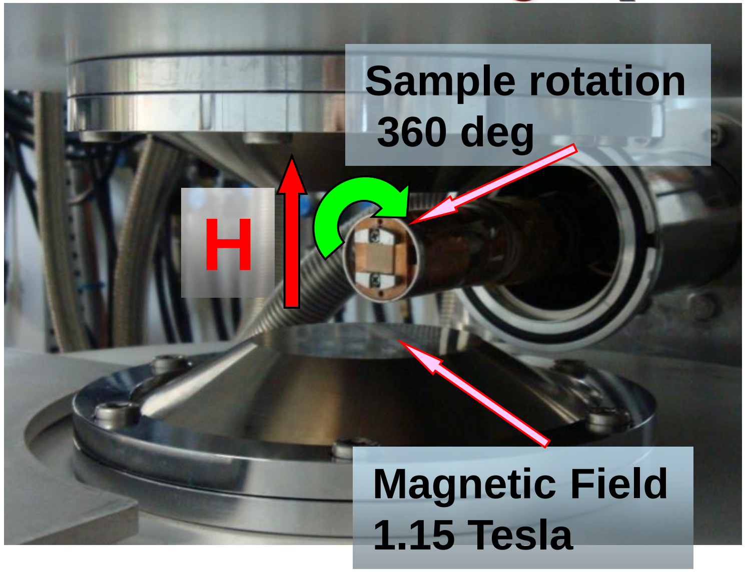
High intensity	sample size 5x5 mm^2
Low background	10^{-8}
High polarization	98.5%
Polarization analysis	

Polarized and unpolarized beam
Fast laser pre-alignment
Efficient thermal cycling (5K – 750K)

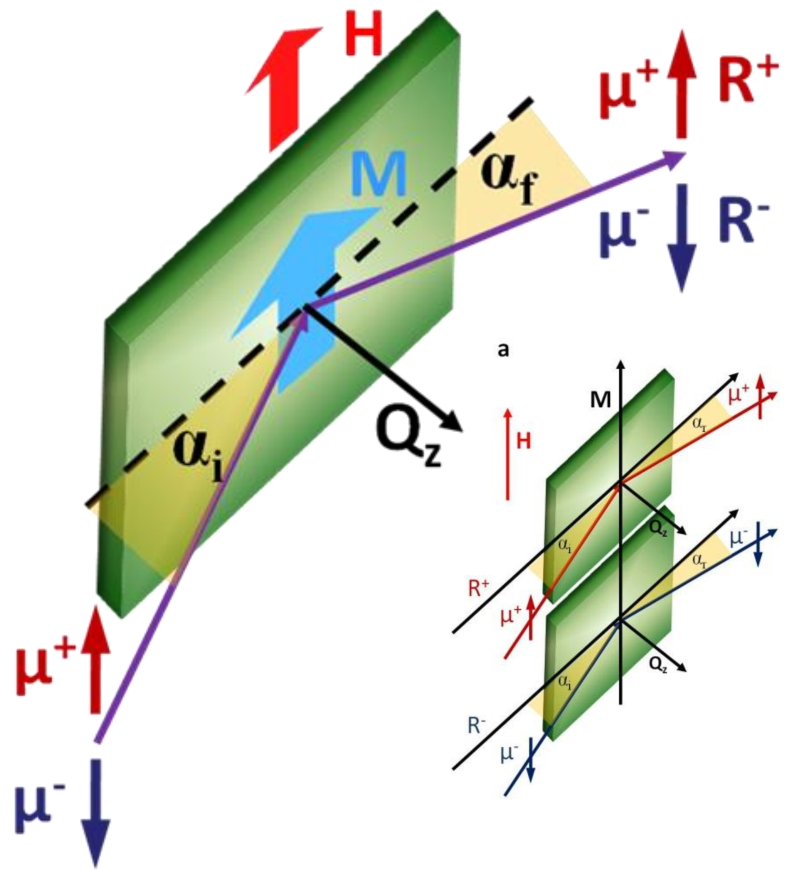
Sample environment new features:

Displex:
- In-situ annealing
- Sample rotation
- Bias voltage

Electromagnet 1.15 Tesla (50 mm gap)
1.24 Tesla (46 mm gap)
2.40 Tesla (15 mm gap)



Polarized Neutron Reflectometry experiment on Al_2O_3/EuS/Bi2Se3//Al_2O_3



Fermi pseudopotential:

$$V_\pm = 2\pi\hbar/m\ N(b_n \pm b_m)$$

Momentum transfer

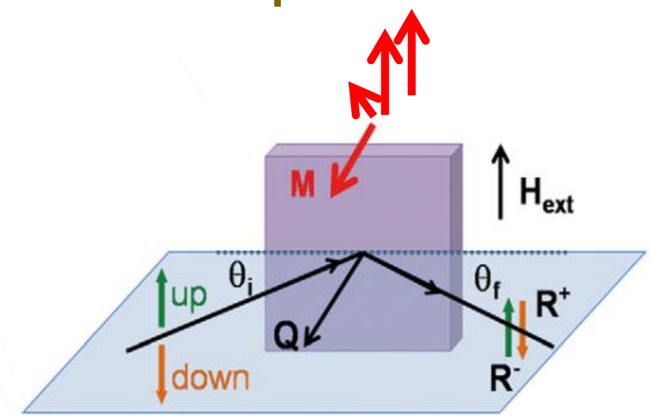
$Q = 4\pi \sin \alpha_i / \lambda$

Nb_n – structural composition

Nb_m – *absolute* magnetization vector profile $\vec{M}$!

NIm_b- absorption profile

Perpendicular M

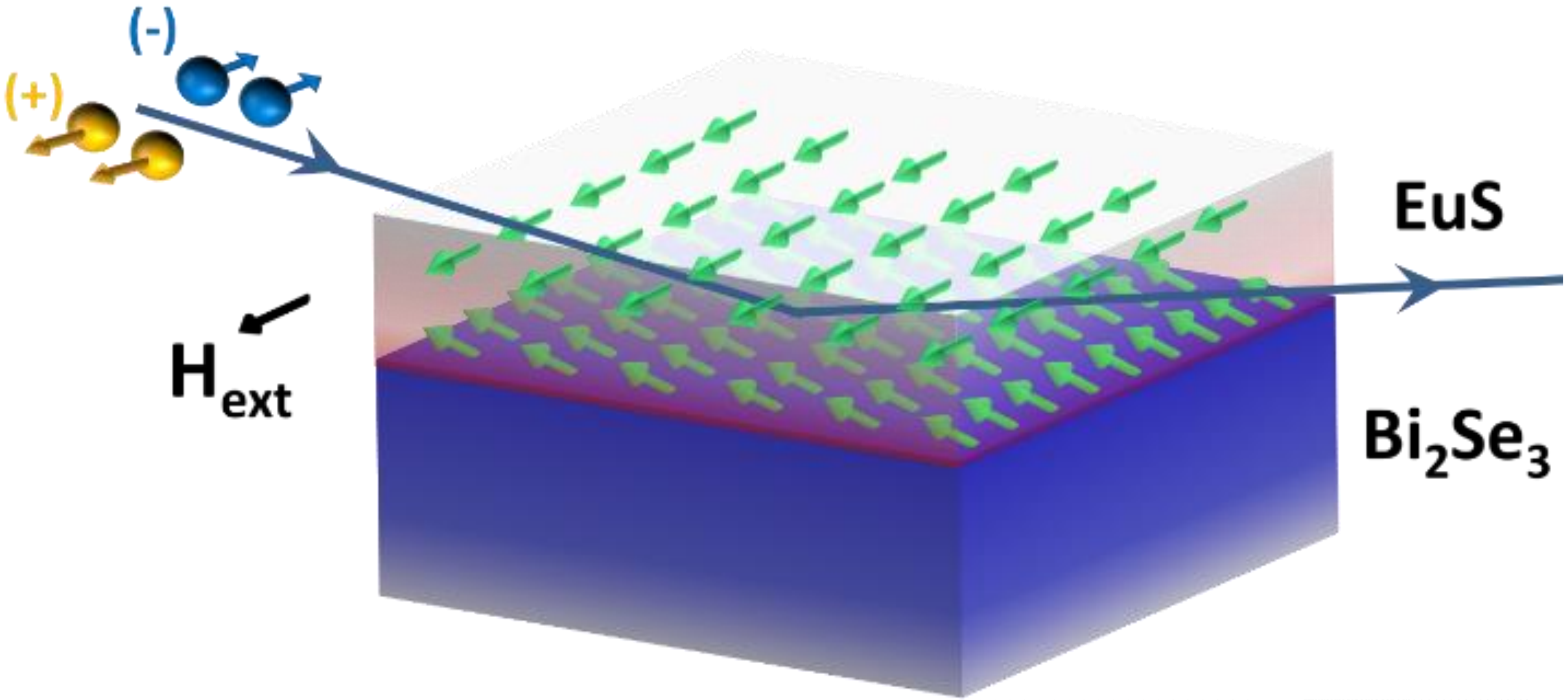


Al_2O_3/EuS/Bi_2Se_3//Al_2O_3 – structure profile

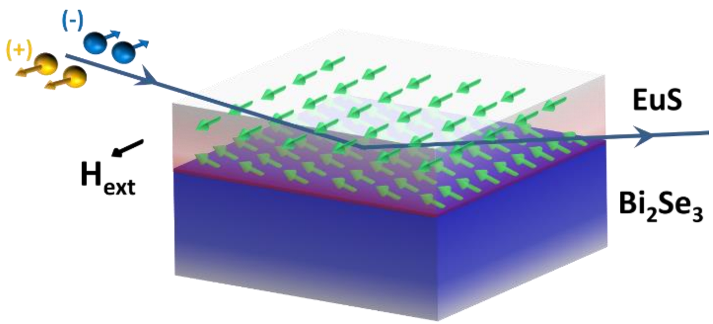
Al_2O_3/EuS/Bi_2Se_3//Al_2O_3 – **magnetization profile**

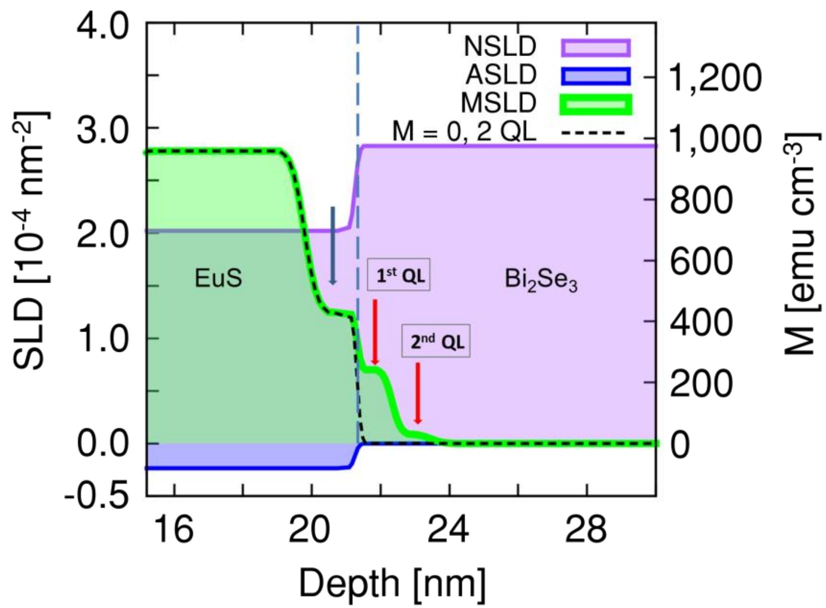
Al_2O_3/EuS/Bi_2Se_3//Al_2O_3 – absorbtion profile

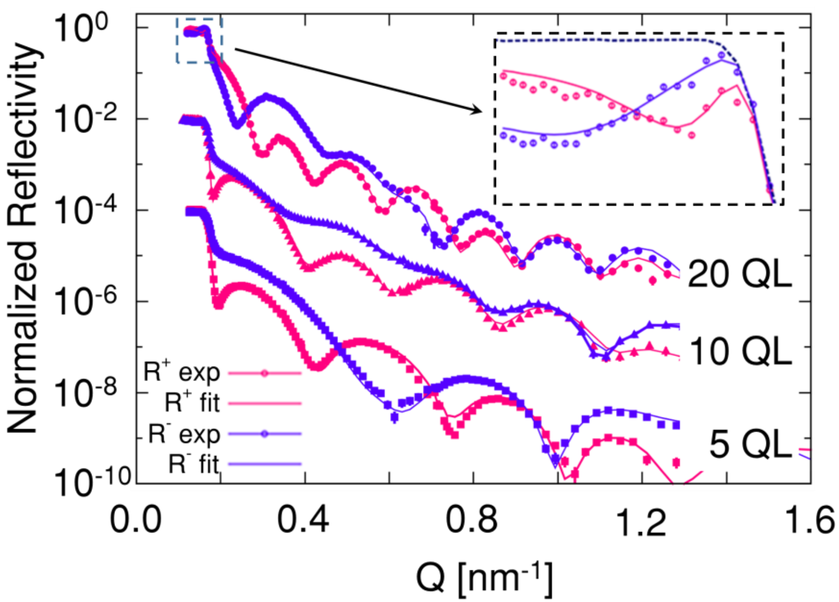
Configuration of PNR experiment probing the magnetic moment distribution *inside* Bi2Se3/EuS interface

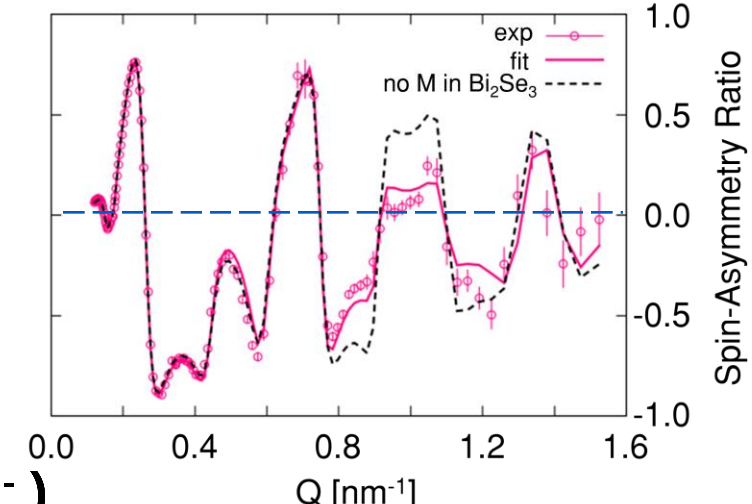


Magnetization – PNR @ 5 K





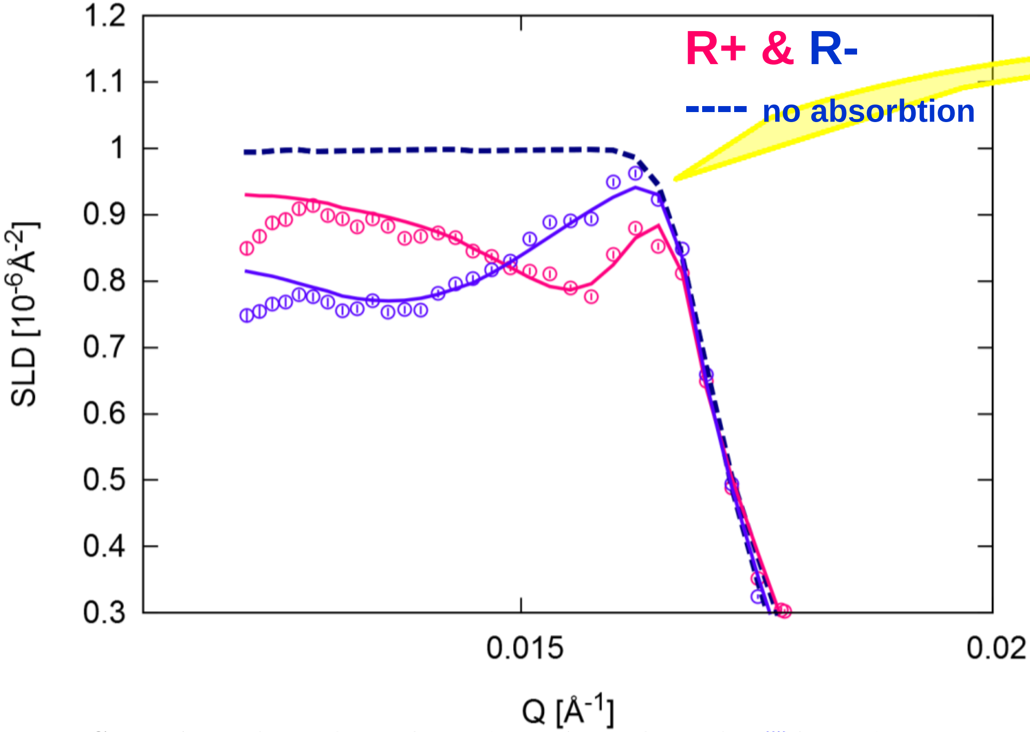


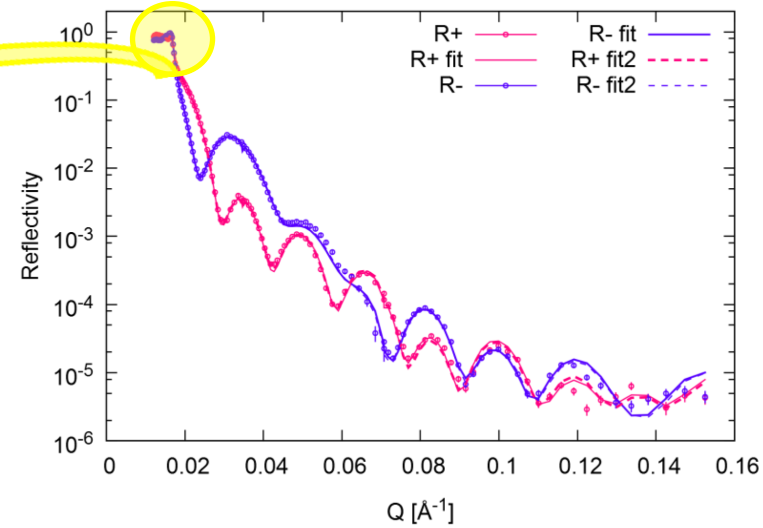


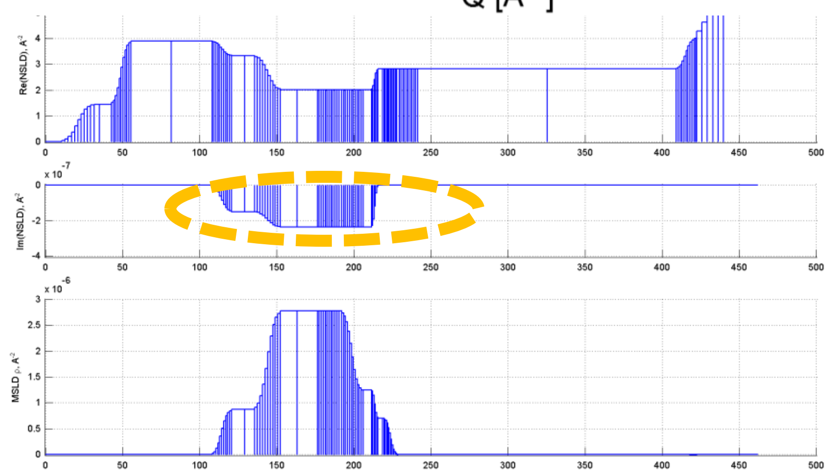
$Q = 4\pi \sin \alpha_i / \lambda$

Spin-Asymmetry : $SA = (R^+ - R^-)/(R^+ + R^-)$

Absorption effect



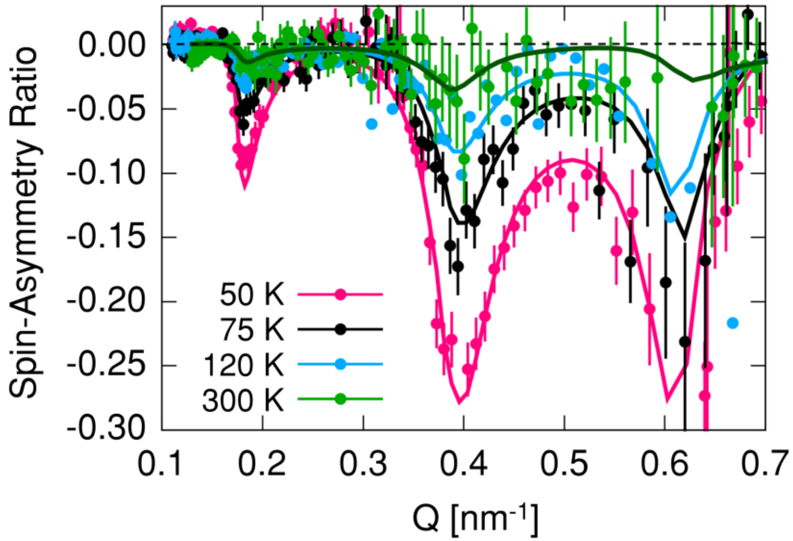


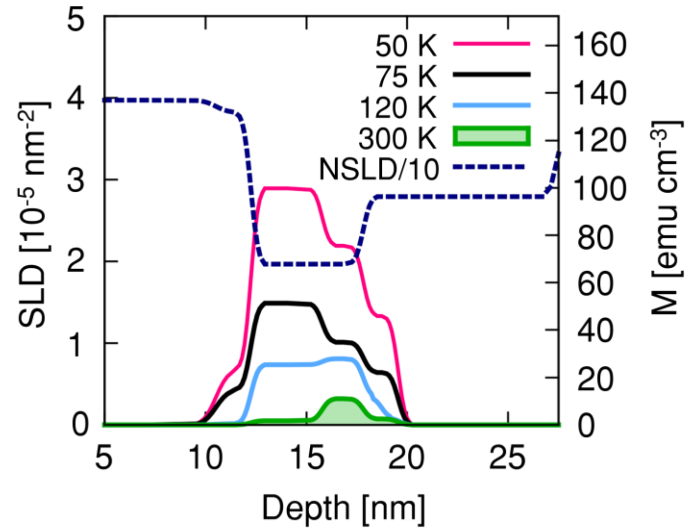


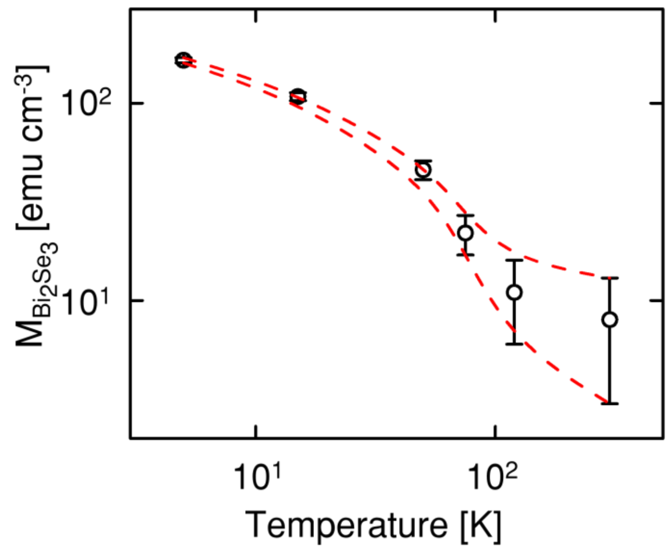
- Absorption: Im part of the SLD provides additional information about Eu distribution
- No Eu atoms are determined in Bi_2Se_3

$Al_2O_3/EuS/Bi_2Se_3//Al_2O_3$ – structure profile
$Al_2O_3/EuS/Bi_2Se_3//Al_2O_3$ – magnetization profile
$Al_2O_3/EuS/Bi_2Se_3//Al_2O_3$ – absorbtion profile

Magnetization – PNR @ 50,75,120,300 K

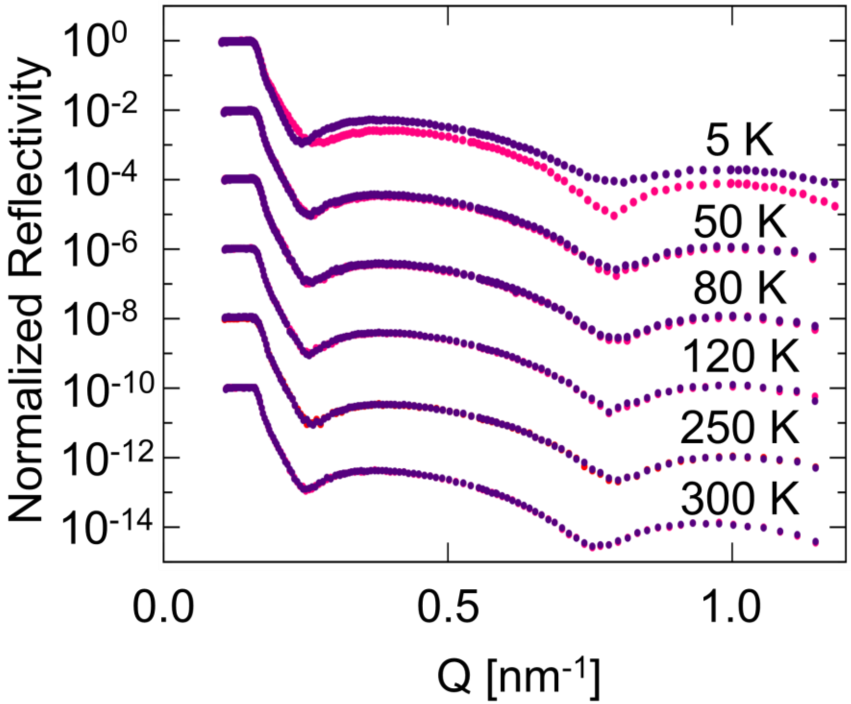


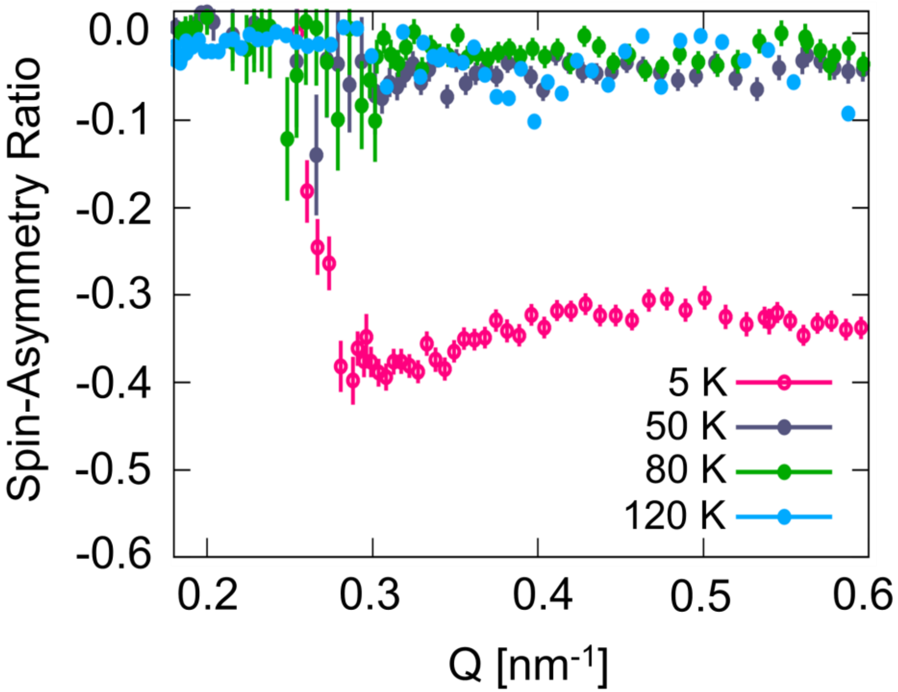


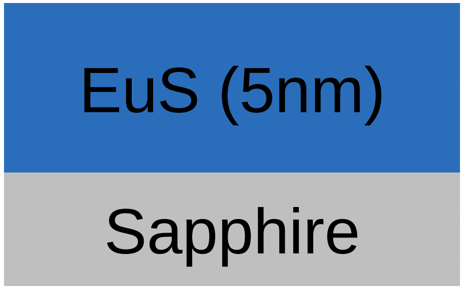


- Magnetization behavior of bilayers (10 QL/ 5 nm)
- Non-zero magnetization present in the 2 QL Bi_2Se_3 interfacial layer also penetrates into the EuS layer
- Magnetization reduced by an order of magnitude at higher temperatures
- No magnetization was detected above ~50 K in the pure EuS film.

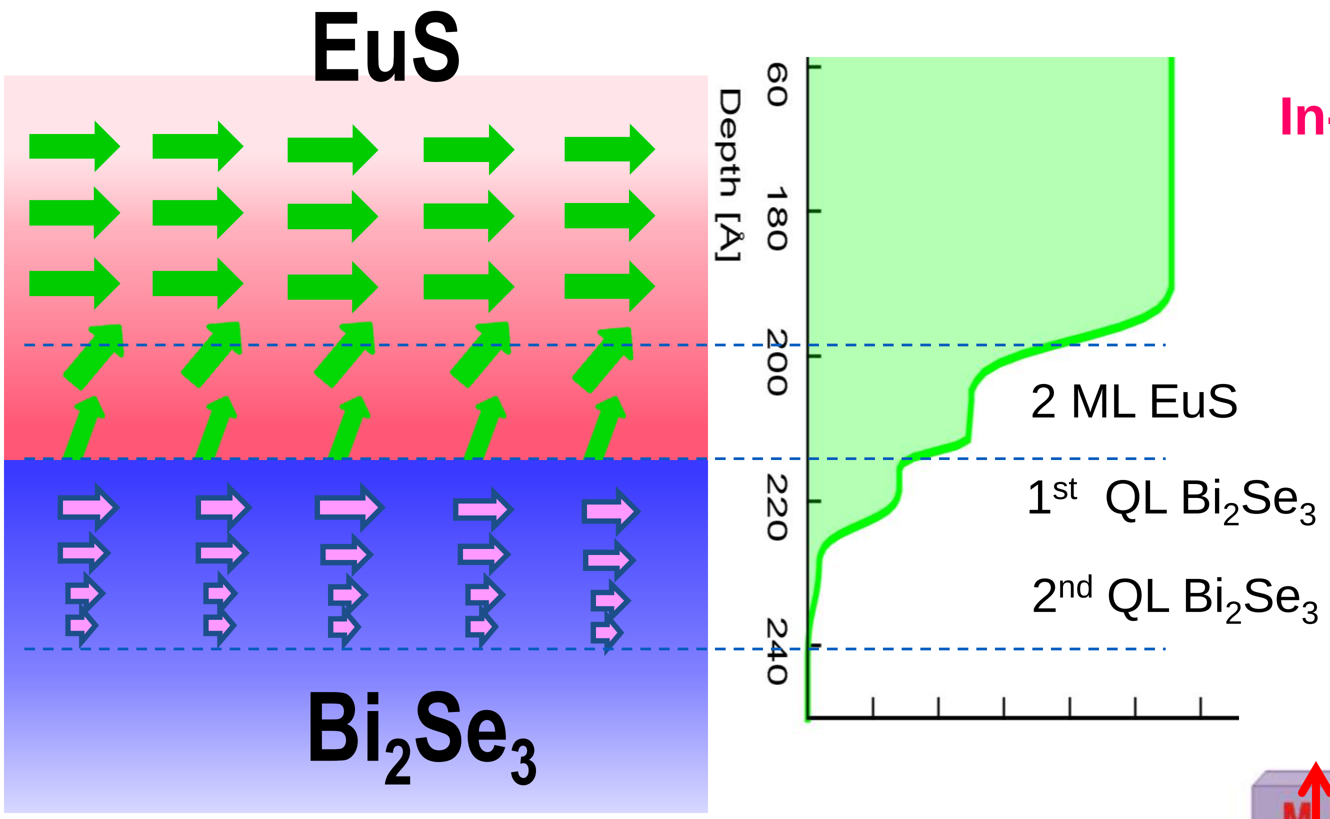
Reference Sample - EuS//Sapphire



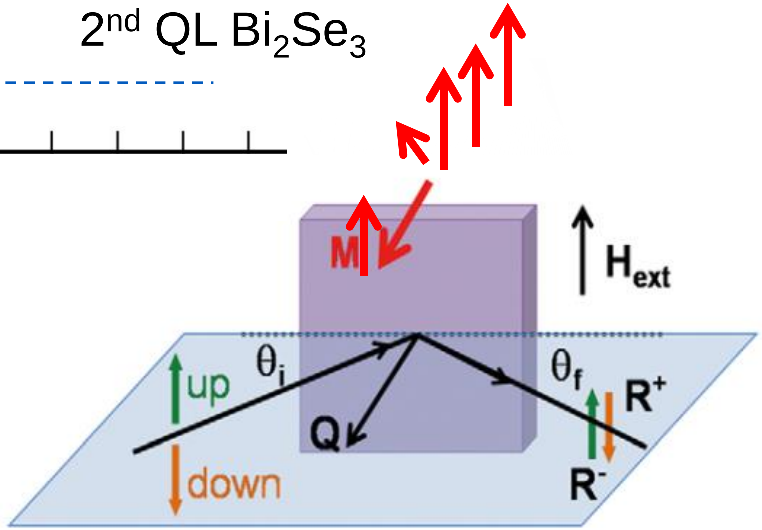




PNR: Magnetic moment distribution



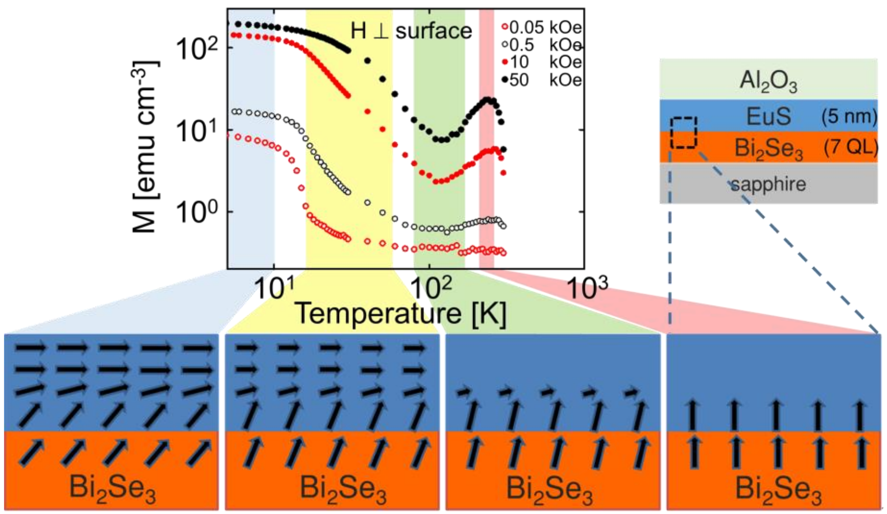
PNR measures In-plane projection of M

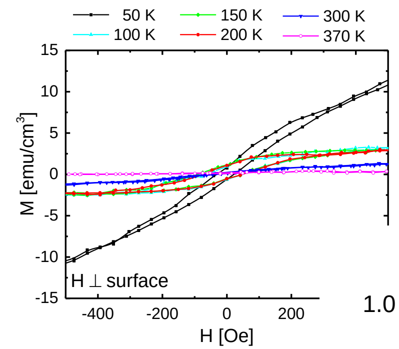


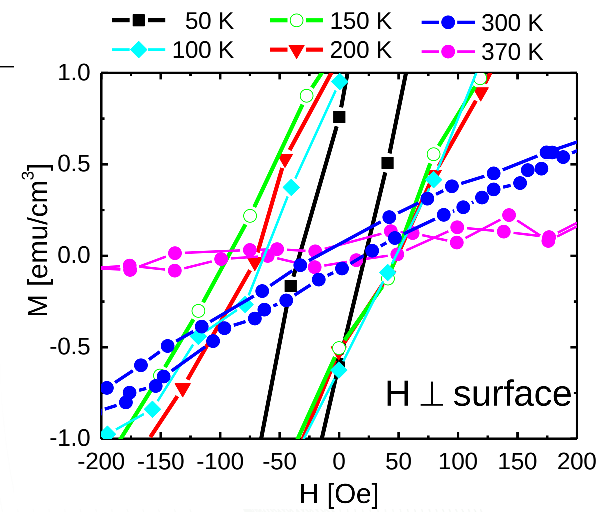
At the interface EuS/Bi_2Se_3, the strong spin-orbit coupling affects anisotropy direction, leading to an out-of-plane magnetic moment and results in generating a gap in the TI surface state

SQUID magnetometry measurement

Magnetization versus Temperature at various perpendicular applied fields

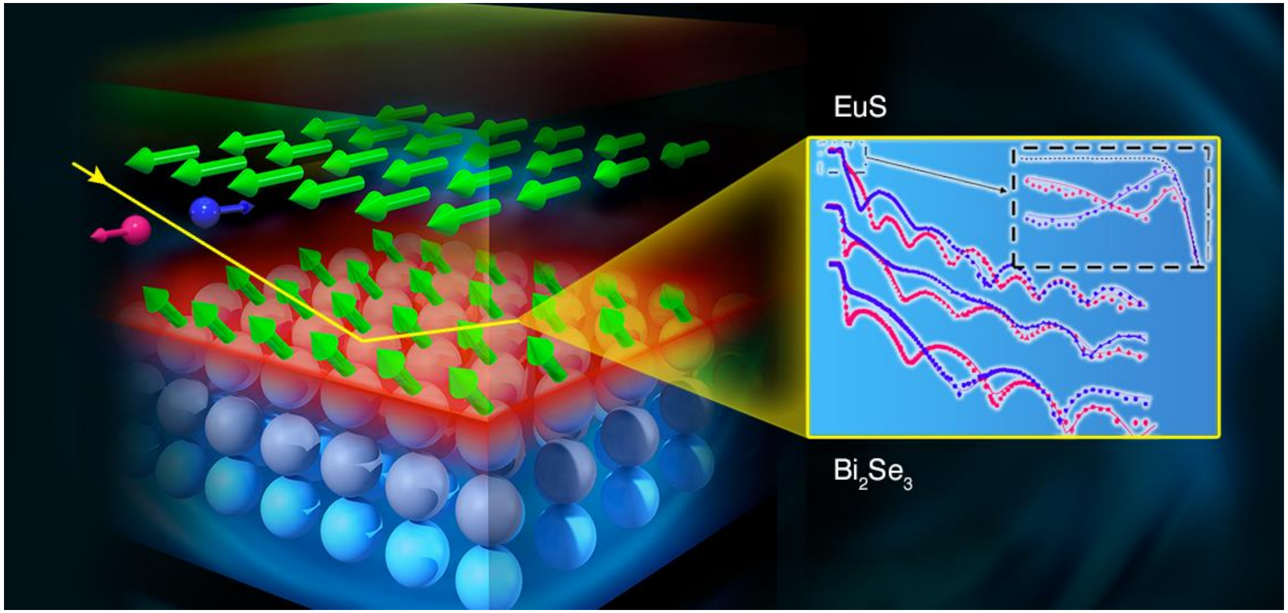






At the interface

- Large S-O interaction, the spin-momentum locking at Dirac surface state creates strong anisotropy and stabilizes the ferromagnetic state!



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A high-temperature ferromagnetic topological insulating phase by proximity coupling

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* *Authors contributed equally to this work*

Results

- **PNR - depth resolved vector magnetometry- measures the spatial distribution of magnetization at the buried interfaces of Bi_2Se_3/EuS bilayers and the detailed chemical composition of the heterostructre**

- **The magnetization in the interfacial 2 ML EuS layer has an out-of-plane component.**

- **PNR provides evidence that Bi_2Se_3/EuS heterostructures exhibit proximity-induced interfacial magnetization in 3QL layer of Bi_2Se_3**

- **This effect originates through exchange interaction without structural perturbation at the interface**

- **Magnetism persists up to high T above the Tc of EuS**

Acknowledgements
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