High-Frequency Spin Pumping from Antiferromagnetic Insulator MnF_2

ENRIQUE DEL BARCO

Department of Physics – UCF Orlando

delBarco LAB

Nanomagnetism and Spintronics

Work done in collaboration with:

David Lederman (University of California – Santa Cruz)

Hans van Tol (National High Magnetic Field Laboratory / NHMFL – Tallahassee/FL)


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53 attoseconds
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An amazing team of students, from high school to graduate level, explore the beauty of Physics of nanoscale systems.

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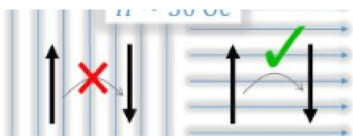
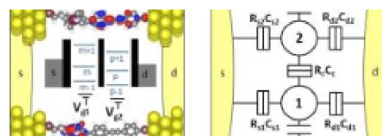
NEWS



A "high"temperature single-ion magnet

A single-ion quantum magnet with characteristics surpassing all previous quantum magnets reported to date (published in PRL 2018). Del Barco's group and collaborators in Germany have reported an outstanding analogy between the magnetism of "single Fe-atoms" embedded in solid state matrix (Li3N) and conventional molecular magnets.



Exploring the Marcus Regimes in a Molecular Double Quantum Dot

An international research team, which includes University of Central Florida Professor Enrique del Barco and Christian A. Nijhuis of the National University of Singapore, has found a way to understand and manipulate the transition of charges in molecular junctions. The results have been published in Nature Nanotechnology.

OCTOBER 2018

M	T	W	T	F	S	S
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8	9	10	11	12	13	14
15	16	17	18	19	20	21
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29	30	31				

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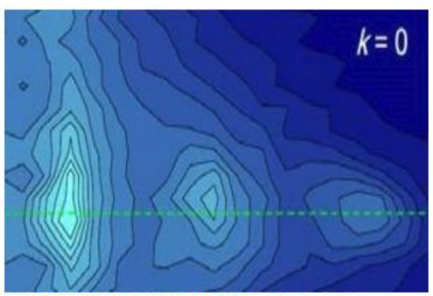
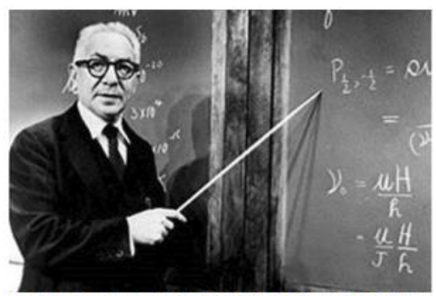
MOLECULAR MAGNETISM – QUANTUM DYNAMICS OF SPIN



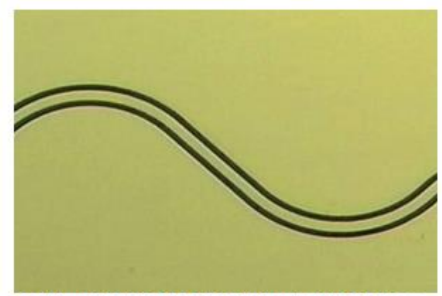
QUANTUM TUNNELING OF SPIN

Low-nuclearity molecules allow for a full numerical treatment of the multi-spin Hamiltonian, where degrees of freedom associated with the individual ions can be adequately tested.



RABI OSCILLATIONS IN ANISOTROPIC SPINS

The commutation between spin anisotropy operators leads to complex dynamics where the magnetic state of the molecule may develop excited precessional states.



SPIN QUANTUM ELECTRODYNAMICS

High-Q superconducting resonators designed with nano-constrictions may allow the coupling a photon cavity mode with a single molecular spin.

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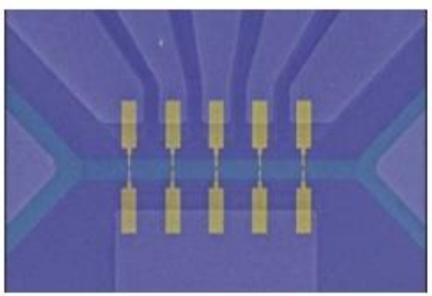
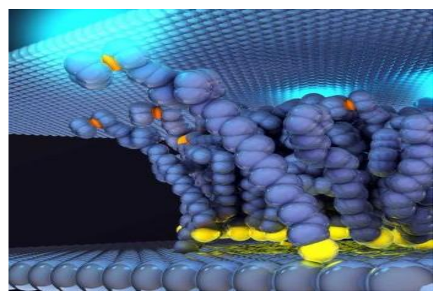
MOLECULAR ELECTRONICS – SINGLE-MOLECULE TUNNEL JUNCTIONS



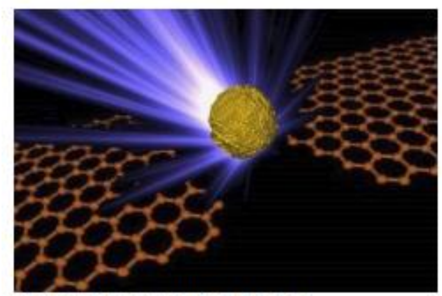
SINGLE-ELECTRON TRANSISTORS

Fabrication of electromigration-broken three-terminal single-electron transistors for transport spectroscopy at the individual molecule level.



CHARGE RECTIFICATION IN MOLECULAR TRANSISTORS

Study of charge rectification in tunnel junctions bridged by molecular chains including a ferrocene active conductive unit placed asymmetrically within the chain.



OPTOELECTRONICS AT THE NANOSCALE

Study of the transport properties of individual noble-metal nanoparticles in the presence of optical irradiation inducing plasmonic resonance.

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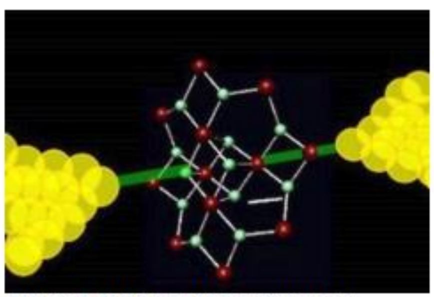
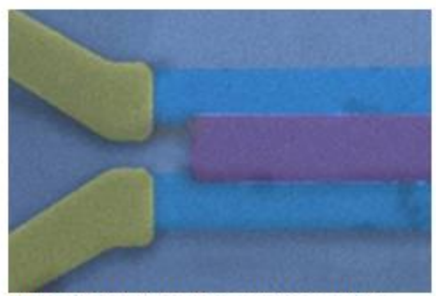
NANOSCALE SPINTRONICS – 0D, 2D and 3D DYNAMICAL SPIN PUMPING



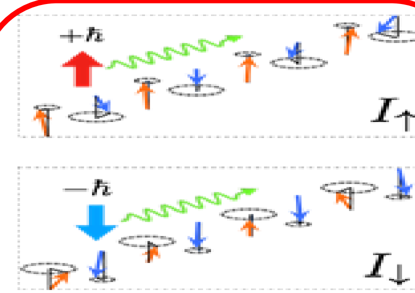
SINGLE-ELECTRON TRANSPORT THROUGH MOLECULAR MAGNETS

Investigation of the interplay between high-spin states of an individual SMM and conduction electrons in a three-terminal single-electron transistor.



TWO-DIMENSIONAL SPINTRONICS

An study aimed at understanding and controlling the injection of pure spin currents in graphene-based spintronics devices.



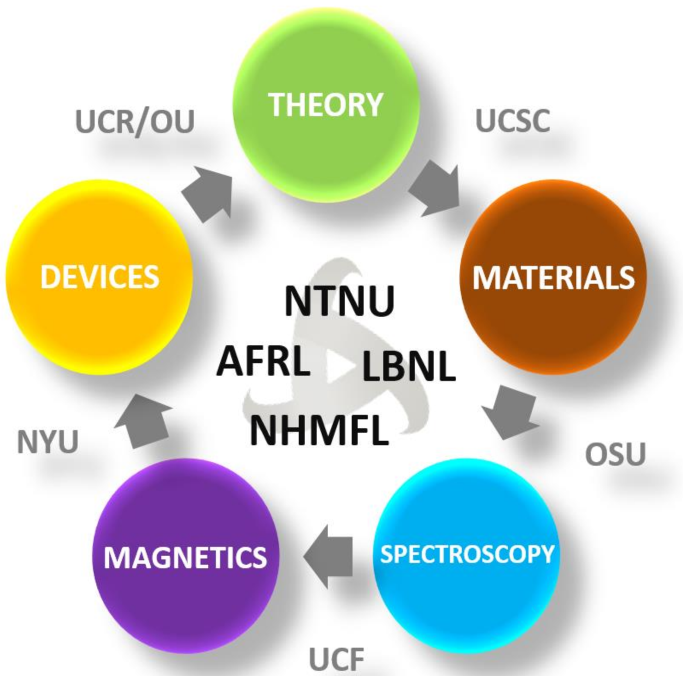
ANTIFERROMAGNETIC SPINTRONICS

Terahertz spintronics with antiferromagnetic insulators.

Spin Pumping from AFM Insulator MnF_2

Terahertz Spintronics with Antiferromagnetic Insulators

Collaborative Effort – Spintronics with AFM insulators



Experiment:
Enrique del Barco (UCF)
Chris Hammel (OSU)
Andrew Kent (NYU)

Materials:
David Lederman (UCSC)
Fengyuan Yang (OSU)
Michael Page (AFRL)
Madhab Neupene (UCF)
Hendrik Ohldag (LBNL)

Theory:
Ran Cheng (UCR)
Andrei Slavin (OU)
Arne Brataas (NTNU–Norway)

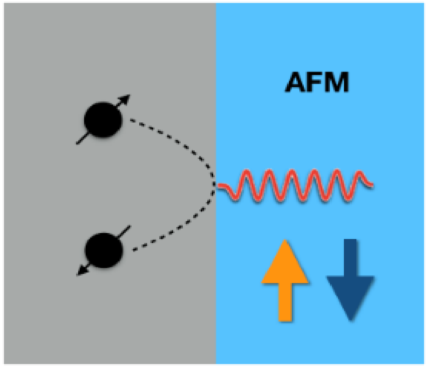
Spin Pumping from AFM Insulator MnF_2

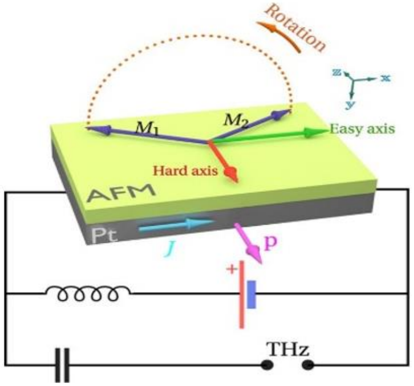
Terahertz Spintronics with Antiferromagnetic Insulators

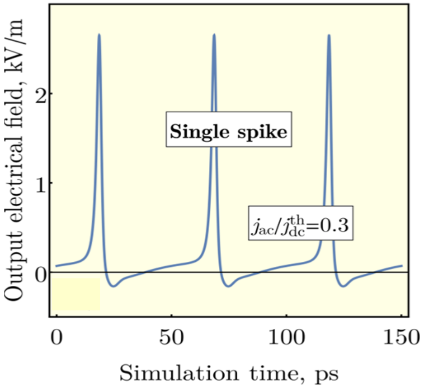
What AFM materials have to offer in spintronics?

THz spin dynamics (versus GHz in ferromagnets)

- Open a THz-frequency band for applications in communications technology, non-destructive testing, medicine, …
- Generation of THz signals – Nanoscale THz oscillators
- Ultra-fast switching – Picosecond logic / NV-RAM
- Ultra-short delta-function-like (ps) spikes - Artificial "neurons" for neuromorphic computation







THz oscillators: Cheng/Xiao/Brataas. PRL 2016 – Khymyn/Slavin et al. Sci. Rep. (2017)
Switching: Cheng/Xiao/Brataas et al. PRL (2014)
Ultra-short spikes: Khymyn/Slavin et al. JAP (2018)

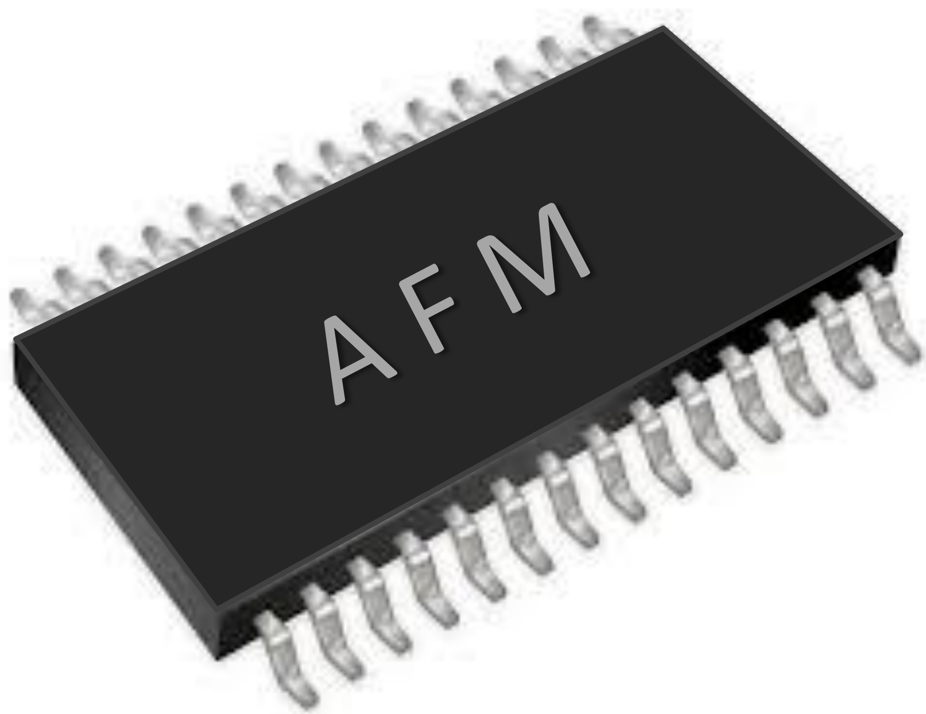
Spin Pumping from AFM Insulator MnF_2

Terahertz Spintronics with Antiferromagnetic Insulators

What AFM materials have to offer in spintronics?

No stray fields

- Ultra-high packing density



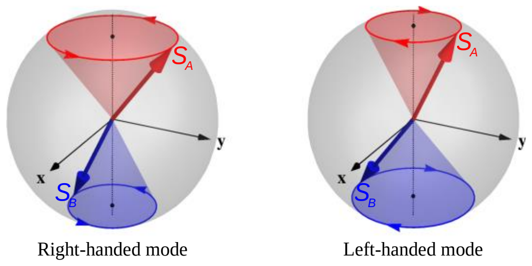
Spin Pumping from AFM Insulator MnF_2

Terahertz Spintronics with Antiferromagnetic Insulators

What AFM materials have to offer in spintronics?

Degenerate magnon modes

- Opposite chirality modes can be manipulated by circularly-polarized EM stimuli, electron spin currents, DC magnetic fields, etc.

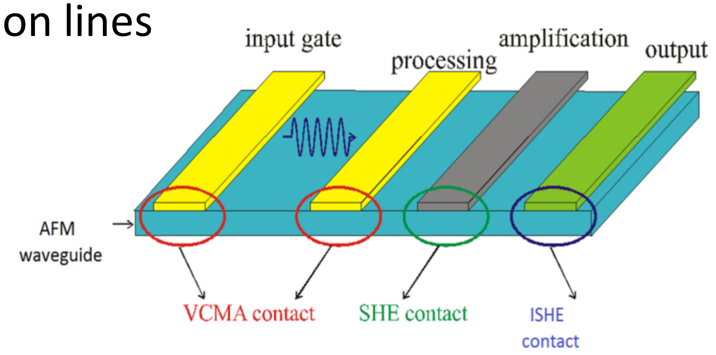


Extremely low damping (in insulating AFMs)

- Clean manifestation of magnetic quantum properties
- Pure spin transport in the absence of charge motion

Ultrafast "dissipationless" propagation

- Ultrafast transmission and processing of high-frequency spin signals in closely spaced and electrically non-interacting transmission lines



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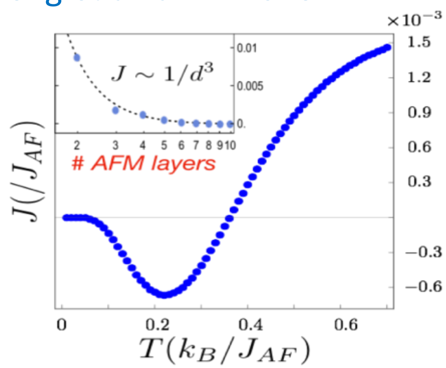
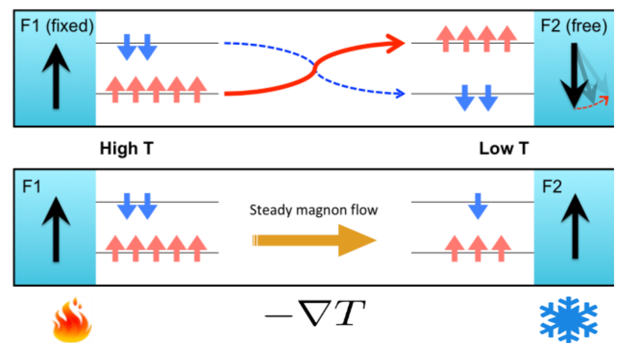
Terahertz Spintronics with Antiferromagnetic Insulators

What AFM materials have to offer in spintronics?

Magnon-mediated "exchange" interaction

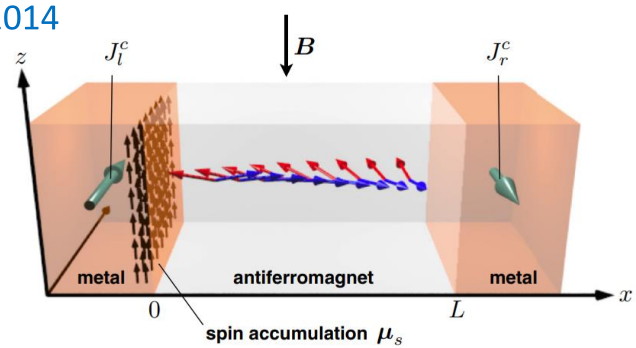
- Magnonic analog of the RKKY interaction in a FM/AFM/FM structure
  Cheng et al. arXiv 2018





Superfluidity

- Spin supercurrent mediated by the AFM texture condensate
  Takei et al. PRB 2014



Spin Pumping from AFM Insulator MnF_2

Terahertz Spintronics with Antiferromagnetic Insulators

Magnetization dynamics in an antiferromagnet

Free energy (macrospin)

$$F = \hbar\omega_E \mathbf{m}_1 \cdot \mathbf{m}_2 - \hbar\omega_H \mathbf{e}_z \cdot (\mathbf{m}_1 + \mathbf{m}_2) - \tfrac{1}{2}\hbar\omega_A \left[(\mathbf{m}_1 \cdot \mathbf{e}_z)^2 + (\mathbf{m}_2 \cdot \mathbf{e}_z)^2 \right]$$

exchange — magnetic field — anisotropy

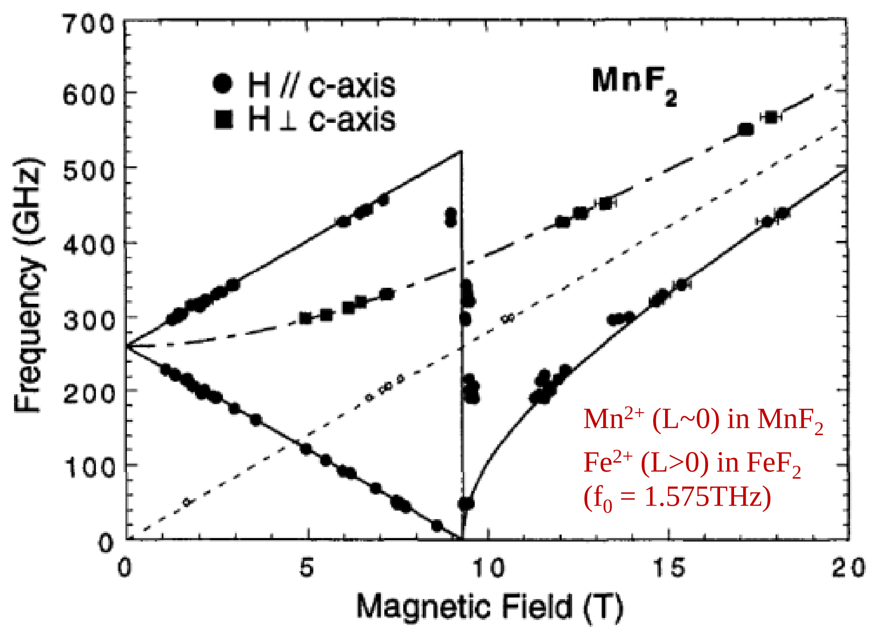
Equations of motion

$$\dot{\mathbf{m}}_1 = \mathbf{m}_1 \times \left[-\omega_E \mathbf{m}_2 + \omega_H \mathbf{e}_z - \omega_A \mathbf{e}_z (\mathbf{m}_1 \cdot \mathbf{e}_z) \right]$$

$$\dot{\mathbf{m}}_2 = \mathbf{m}_1 \times \left[-\omega_E \mathbf{m}_1 + \omega_H \mathbf{e}_z - \omega_A \mathbf{e}_z (\mathbf{m}_2 \cdot \mathbf{e}_z) \right]$$

Resonance frequency

$$\omega_R = \sqrt{2\omega_E \omega_A} \pm \omega_H$$



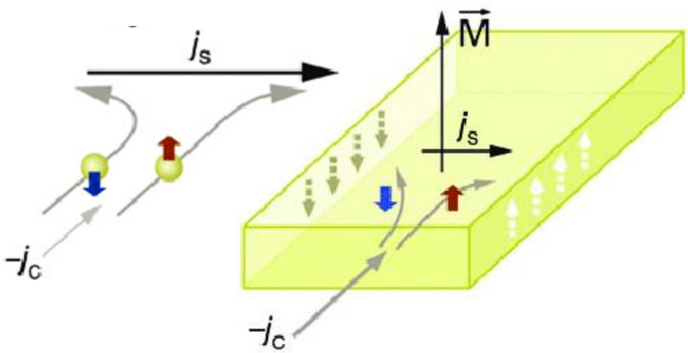
Hagiwara *et al.* 1996

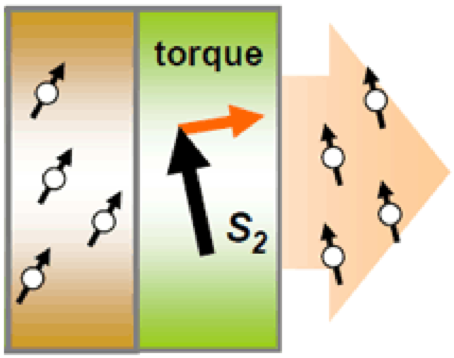
Spin Pumping from AFM Insulator MnF_2

Terahertz Spintronics with Antiferromagnetic Insulators

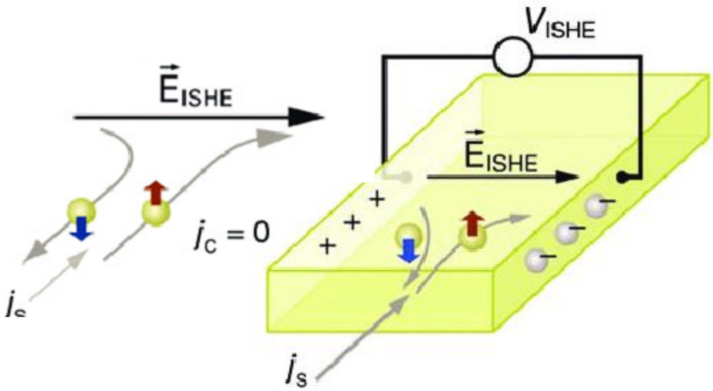
Spin-Charge interconversion with AFMs

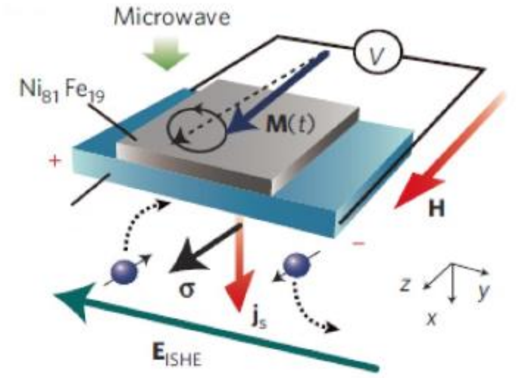
Spin Hall Effect (SHE) + Spin Transfer Torque (STT)





Inverse Spin Hall Effect (ISHE) + Dynamical Spin Pumping (DSP)

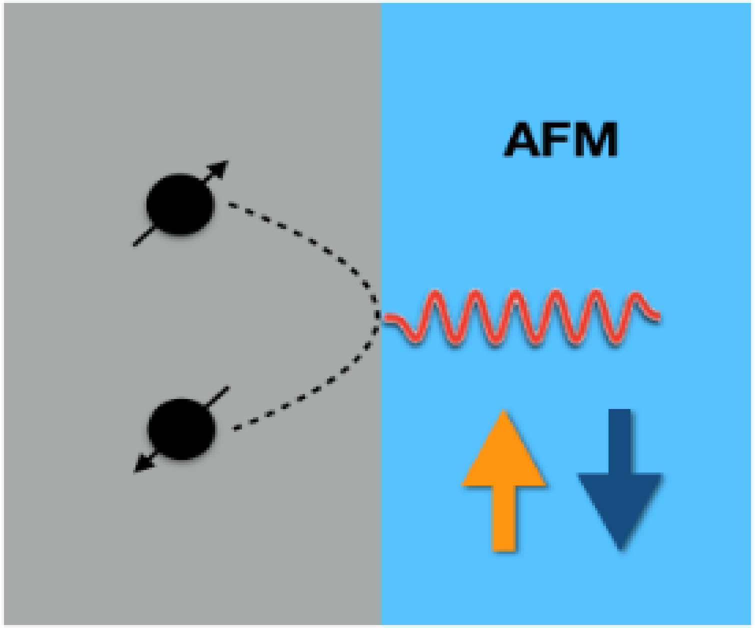




Spin Pumping from AFM Insulator MnF_2

Terahertz Spintronics with Antiferromagnetic Insulators

Spin-Charge interconversion with AFMs



Spin-pumping in YIG-AFMI-Pt
Wang et al. PRL (2014)
Wang et al. PRB (2015)
Hung et al. AIP Adv (2017)

ST-FMR in Pt-NiO-FeNi
Moriyama et al, APL (2015)

AFMR in MnF_2-Pt
Ross et al. JAP (2015)

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Spin pumping at AFM/NM interfaces

$$F = \hbar\omega_E \mathbf{m}_1 \cdot \mathbf{m}_2 - \hbar\omega_H \mathbf{e}_z \cdot (\mathbf{m}_1 + \mathbf{m}_2) - \tfrac{1}{2}\hbar\omega_A \left[(\mathbf{m}_1 \cdot \mathbf{e}_z)^2 + (\mathbf{m}_2 \cdot \mathbf{e}_z)^2 \right] + \delta F$$

a.c. field

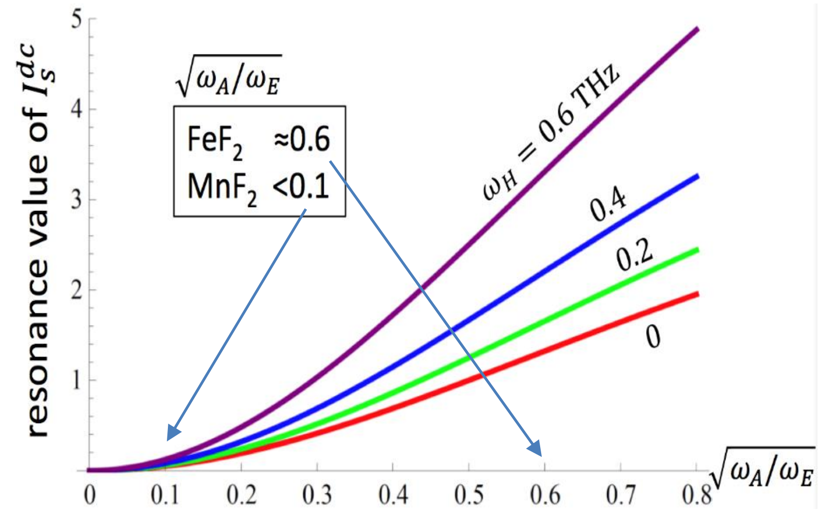
$$\delta F = (\mathbf{m}_1 + \mathbf{m}_2) \cdot \left[\omega_{Hx} \mathbf{e}_x \cos(\omega t + \theta_x) + \omega_{Hy} \mathbf{e}_y \cos(\omega t + \theta_y) \right]$$

Spin pumping (at resonance $\omega = \omega_R$, $\omega_H = 0$)

$$\mathbf{m}_1 \times \dot{\mathbf{m}}_1 + \mathbf{m}_2 \times \dot{\mathbf{m}}_2 = \sqrt{\frac{\omega_A}{\omega_E}} \frac{1}{\alpha^2} \frac{\omega_{Hx}\omega_{Hy}}{\omega_E} \sin(\theta_x - \theta_y)$$

anisotropy enhancement

polarization dependence (no DSP with linear)



MnF_2 — $w_A \sim 10^{-3} w_E$

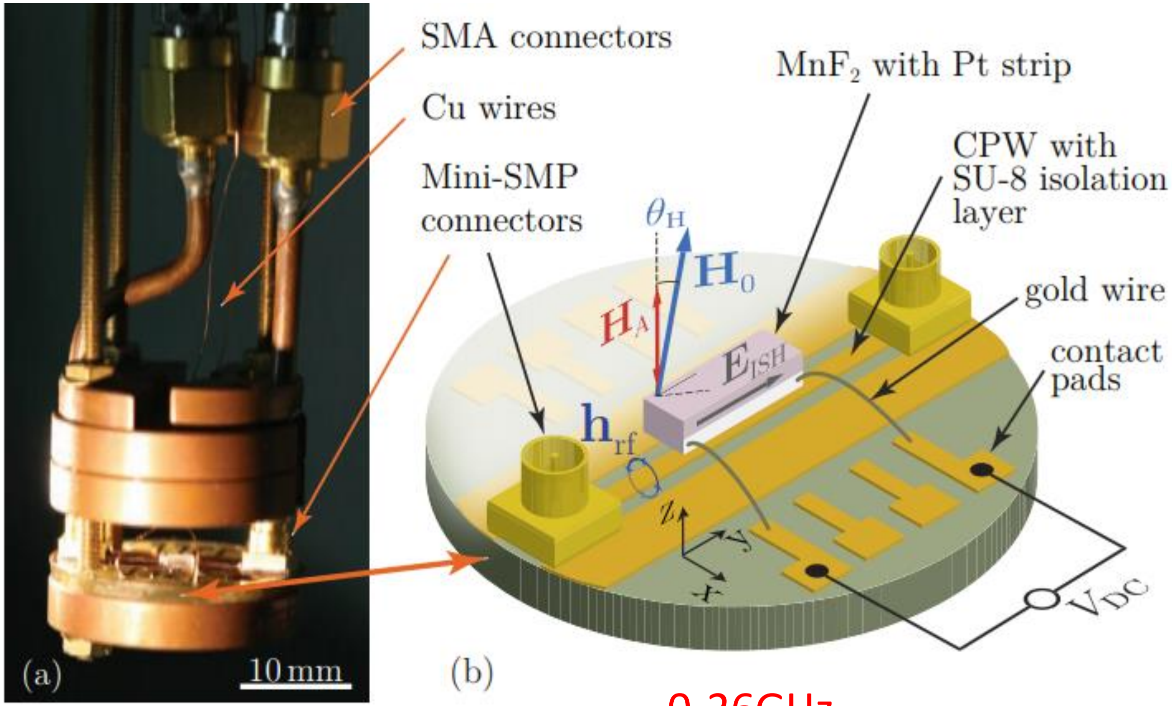
FeF_2 — $\omega_A \approx 0.36\omega_E$

Spin Pumping from AFM Insulator MnF_2

Terahertz Spintronics with Antiferromagnetic Insulators

Spin pumping at AFM/NM interfaces

Previous attempts by Ross et al. JAP (2015) and Ross' PhD thesis (TUM)



0-26GHz

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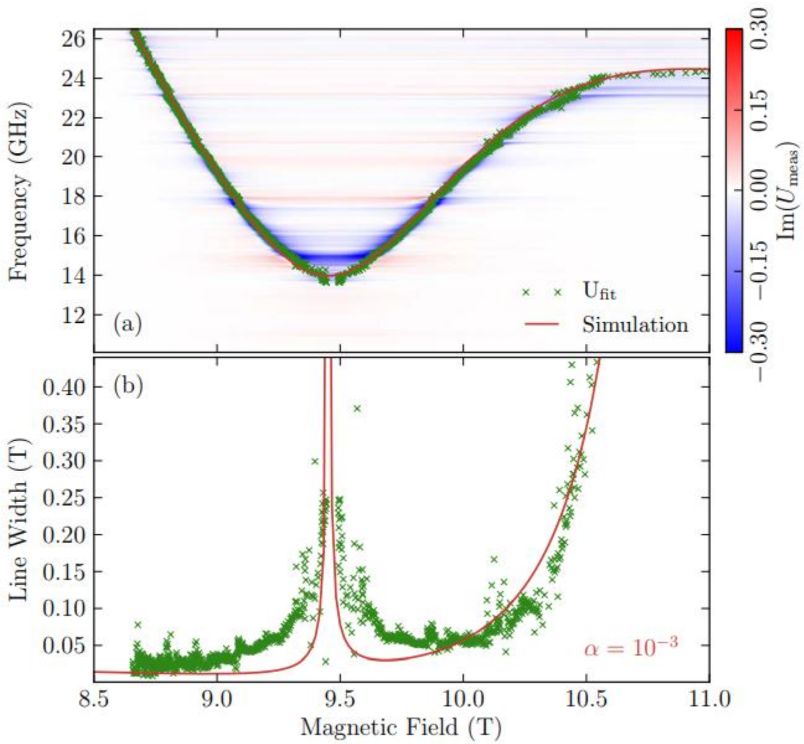

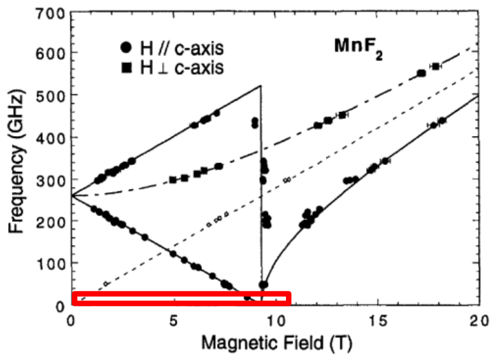

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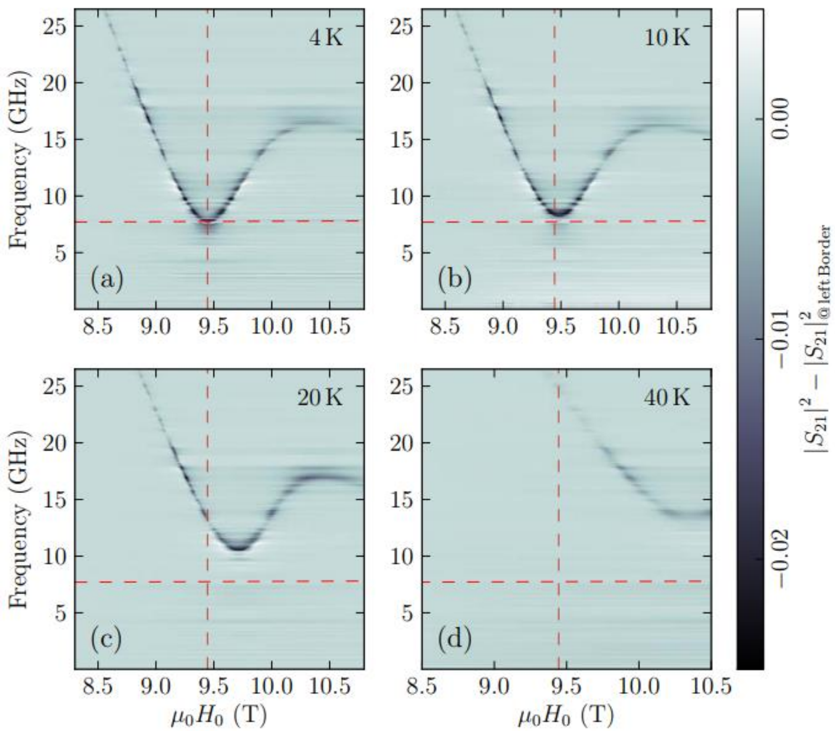

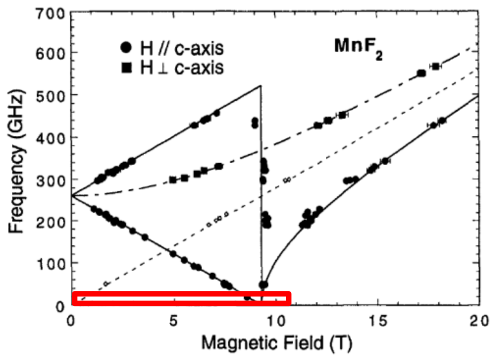

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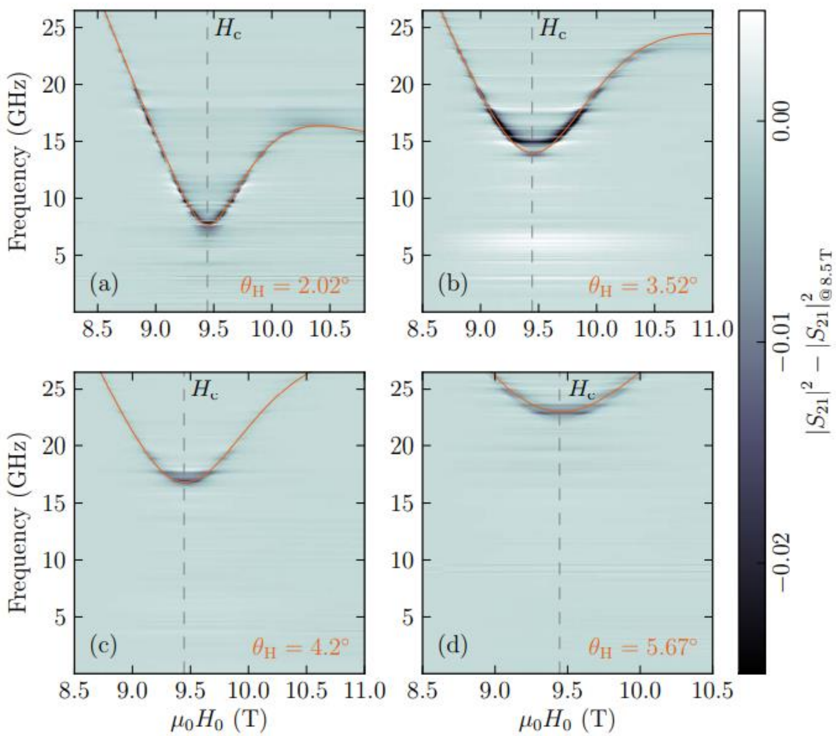

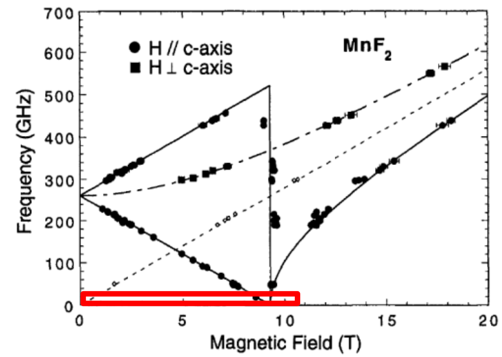

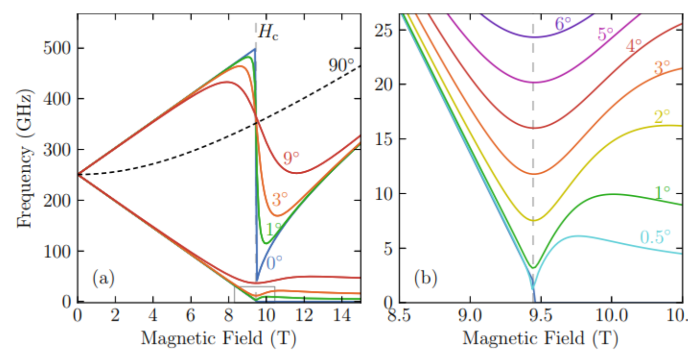

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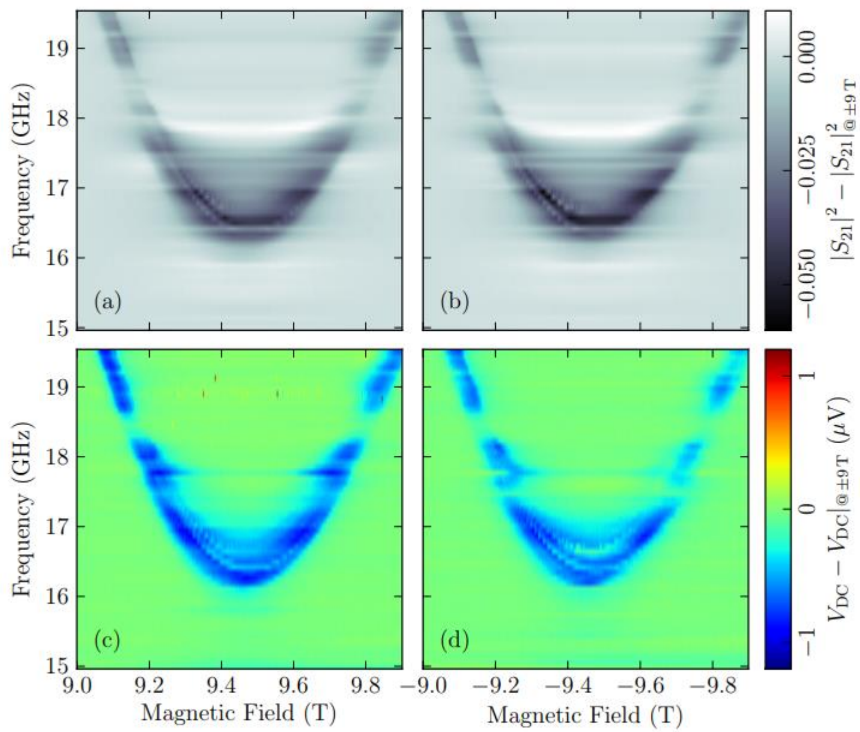

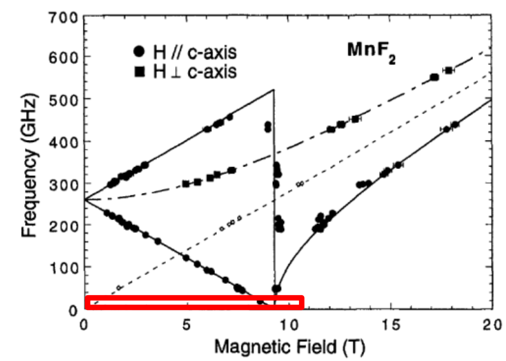

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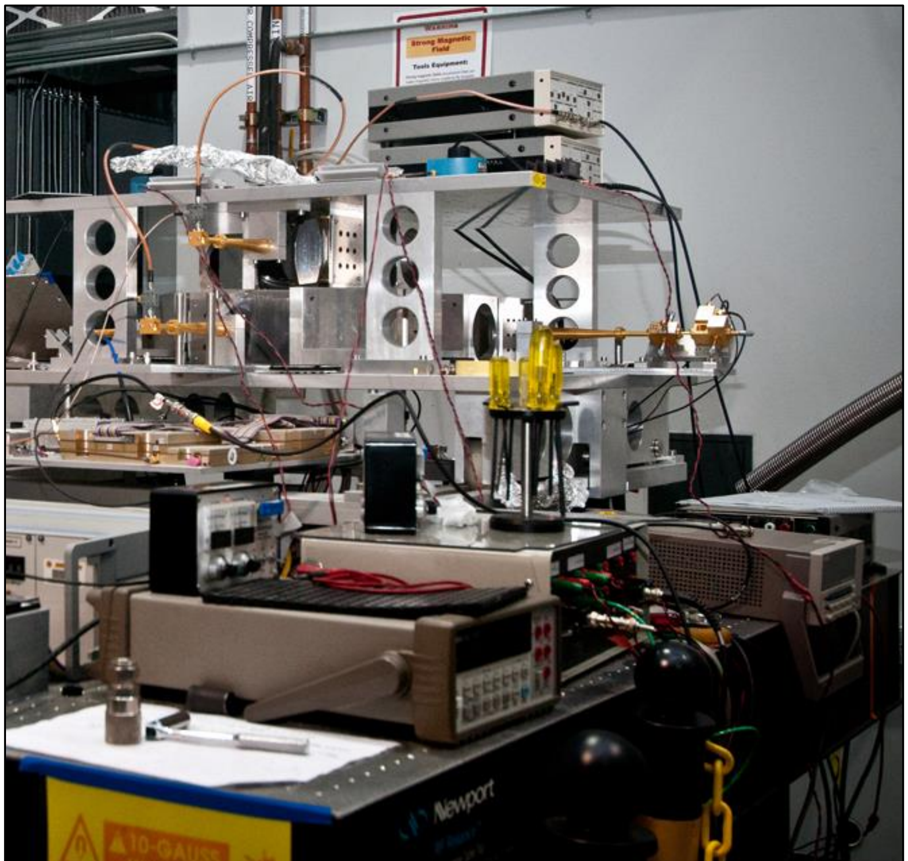
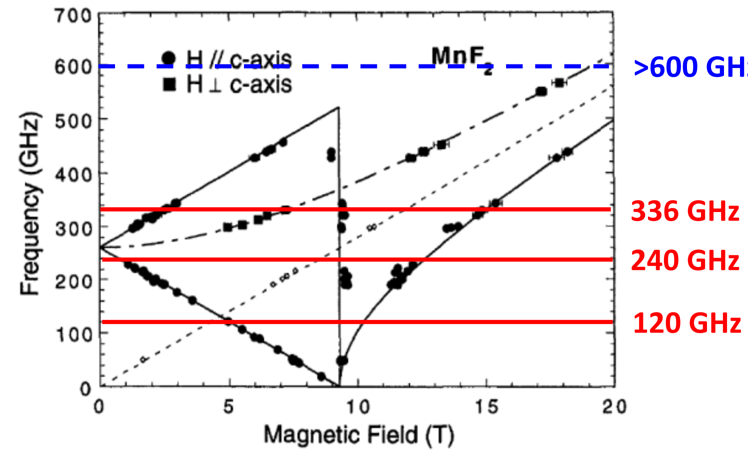
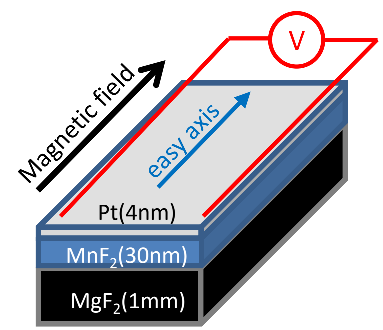
Spin pumping at AFM/NM interfaces

UCF + UCSC + NHMFL results - MgF_2(1mm)/MnF_2(30nm)/Pt(4nm) thin film







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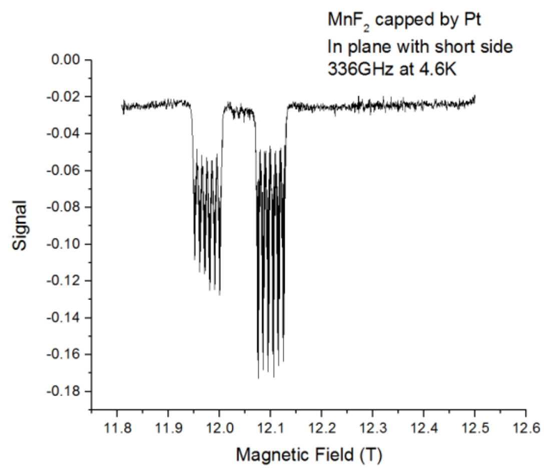

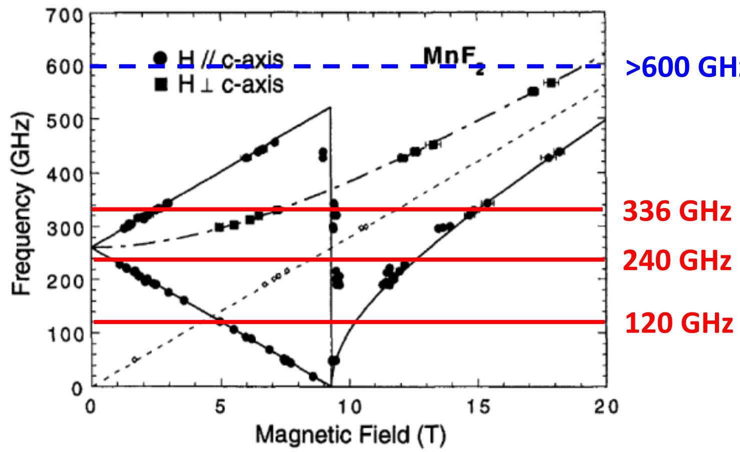

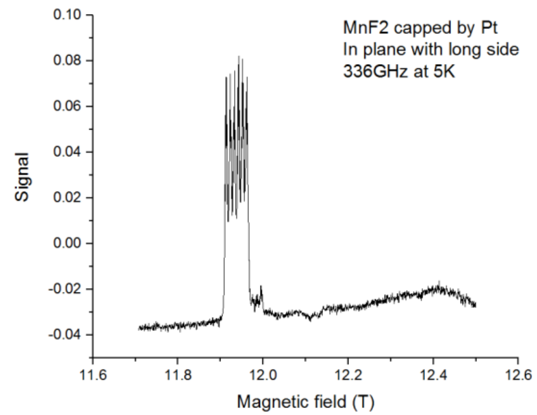

No AFMR detected

MgF_2 identification of the easy axis

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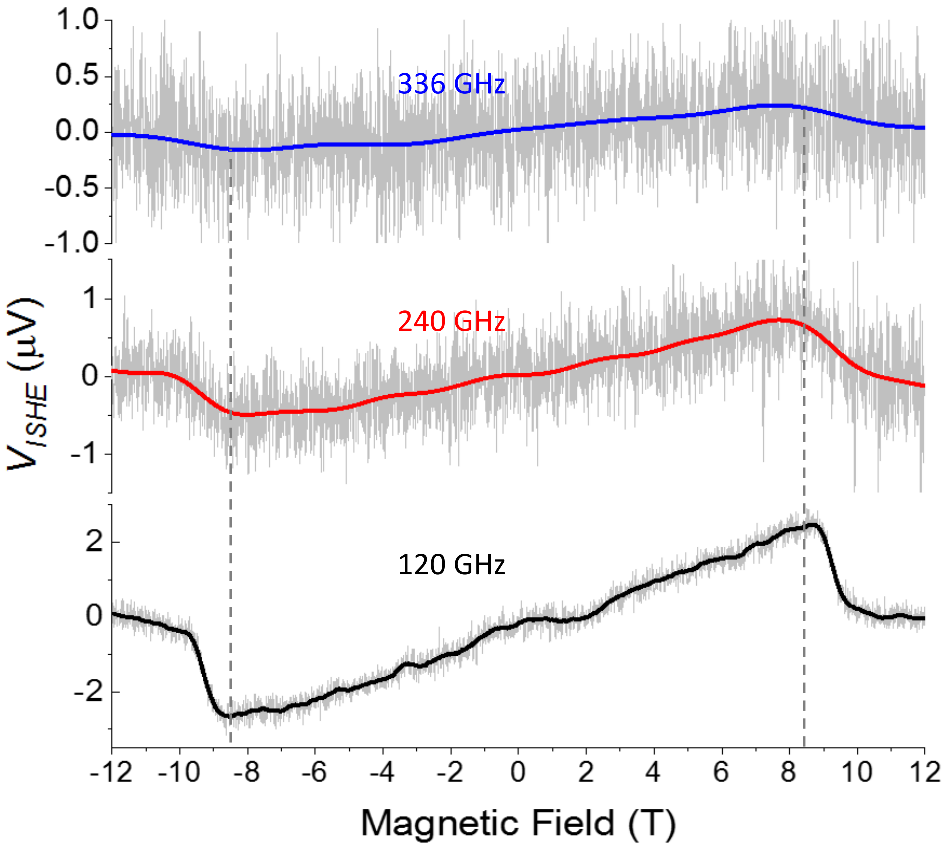
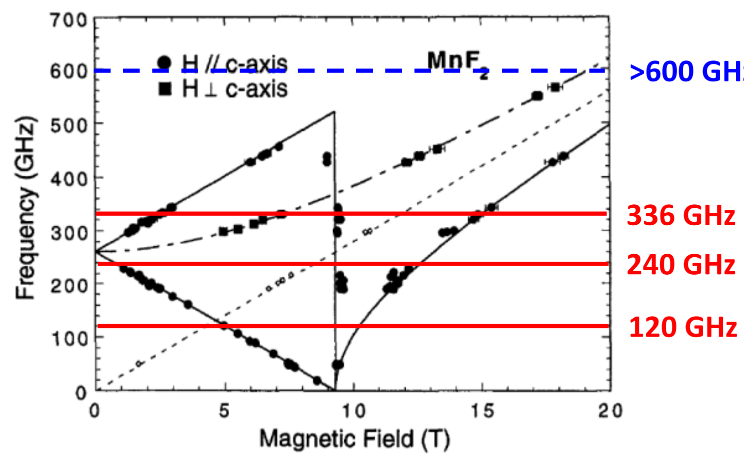
UCF + UCSC + NHMFL results - MgF_2(1mm)/MnF_2(30nm)/Pt(4nm) thin film



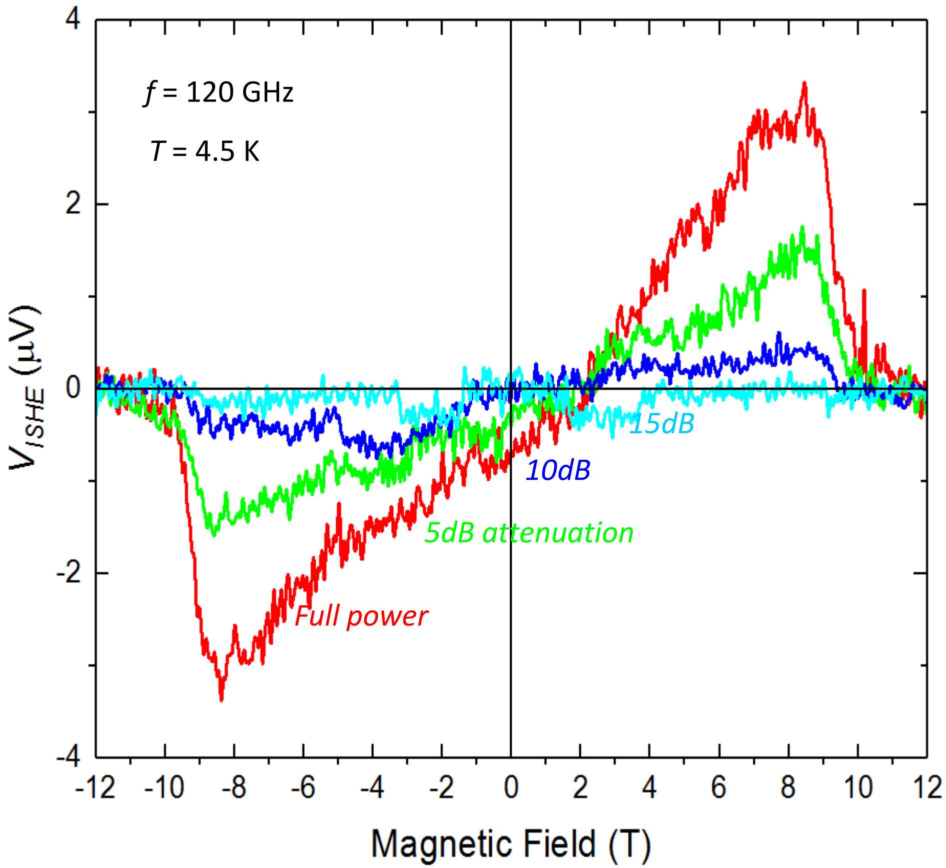


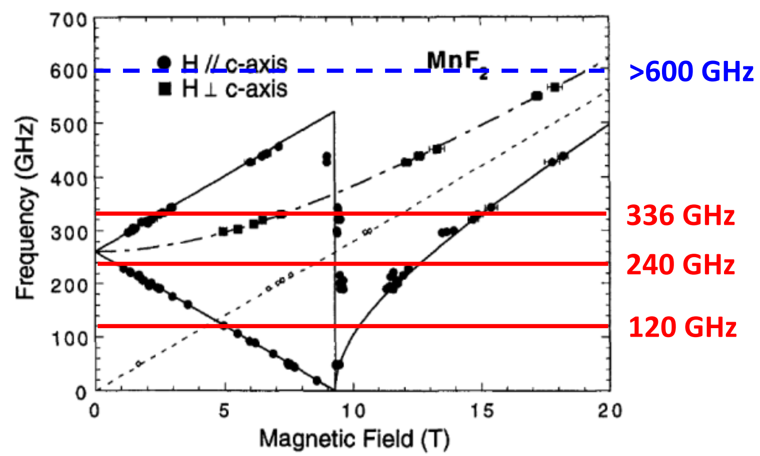
Spin Pumping from AFM Insulator MnF_2

Terahertz Spintronics with Antiferromagnetic Insulators

Spin pumping at AFM/NM interfaces

UCF + UCSC + NHMFL results - MgF_2(1mm)/MnF_2(30nm)/Pt(4nm) thin film



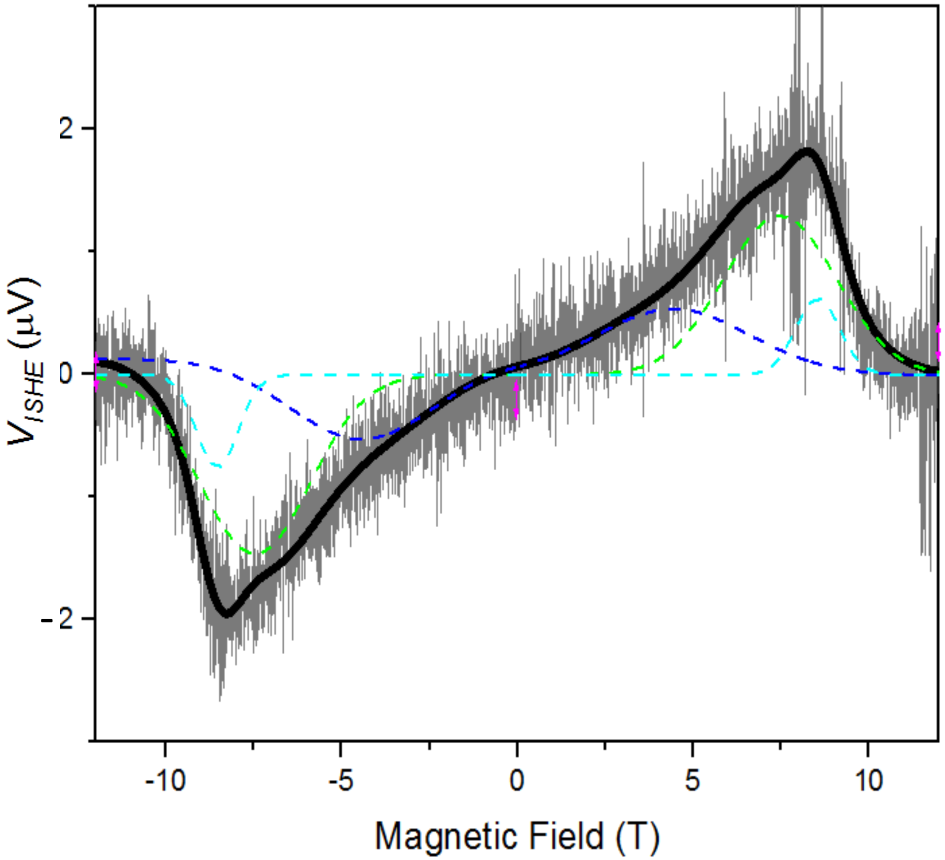


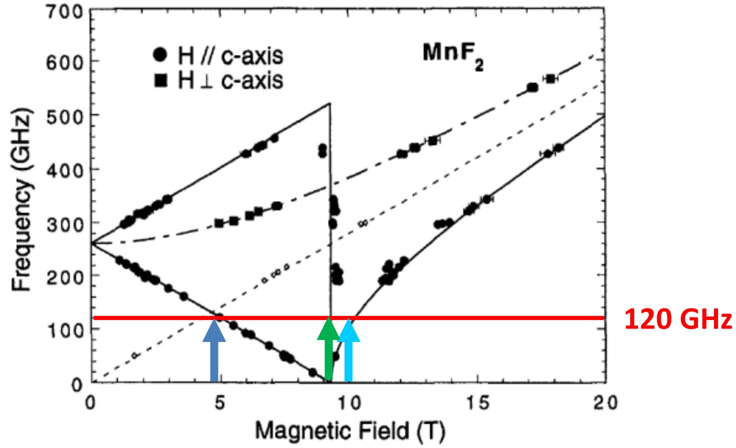
Spin Pumping from AFM Insulator MnF_2

Terahertz Spintronics with Antiferromagnetic Insulators

Spin pumping at AFM/NM interfaces

UCF + UCSC + NHMFL results - MgF_2(1mm)/MnF_2(30nm)/Pt(4nm) thin film



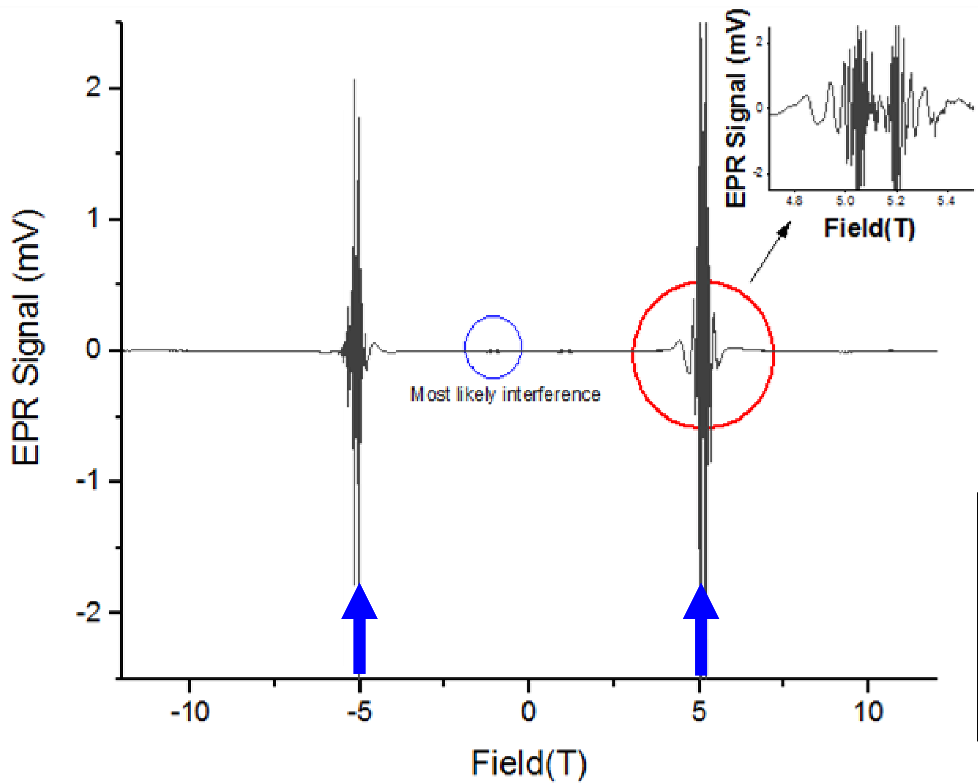


Spin Pumping from AFM Insulator MnF_2

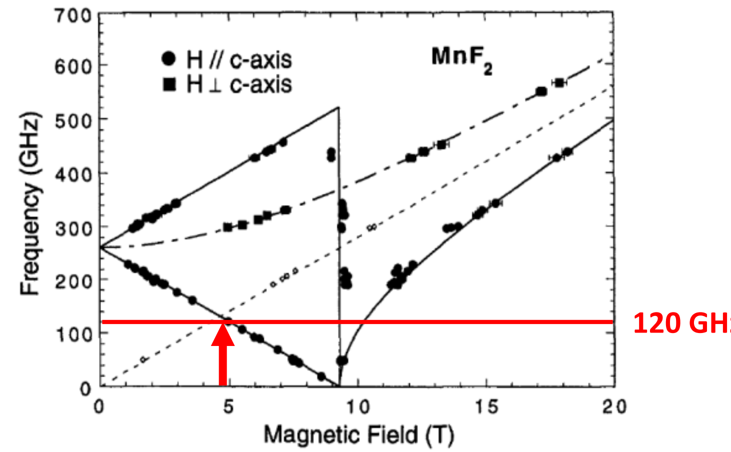
Terahertz Spintronics with Antiferromagnetic Insulators

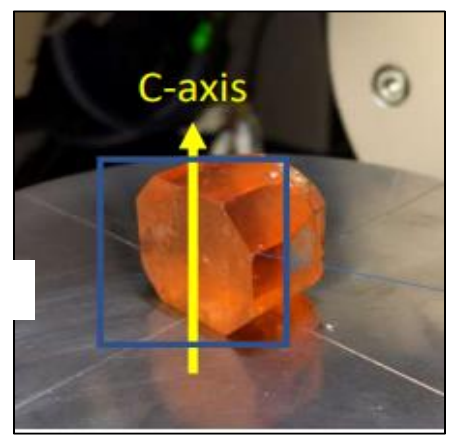
Spin pumping at AFM/NM interfaces

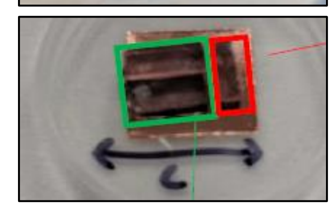
UCF + UCSC + NHMFL results - MnF_2(1mm)/Pt(4nm) single crystal

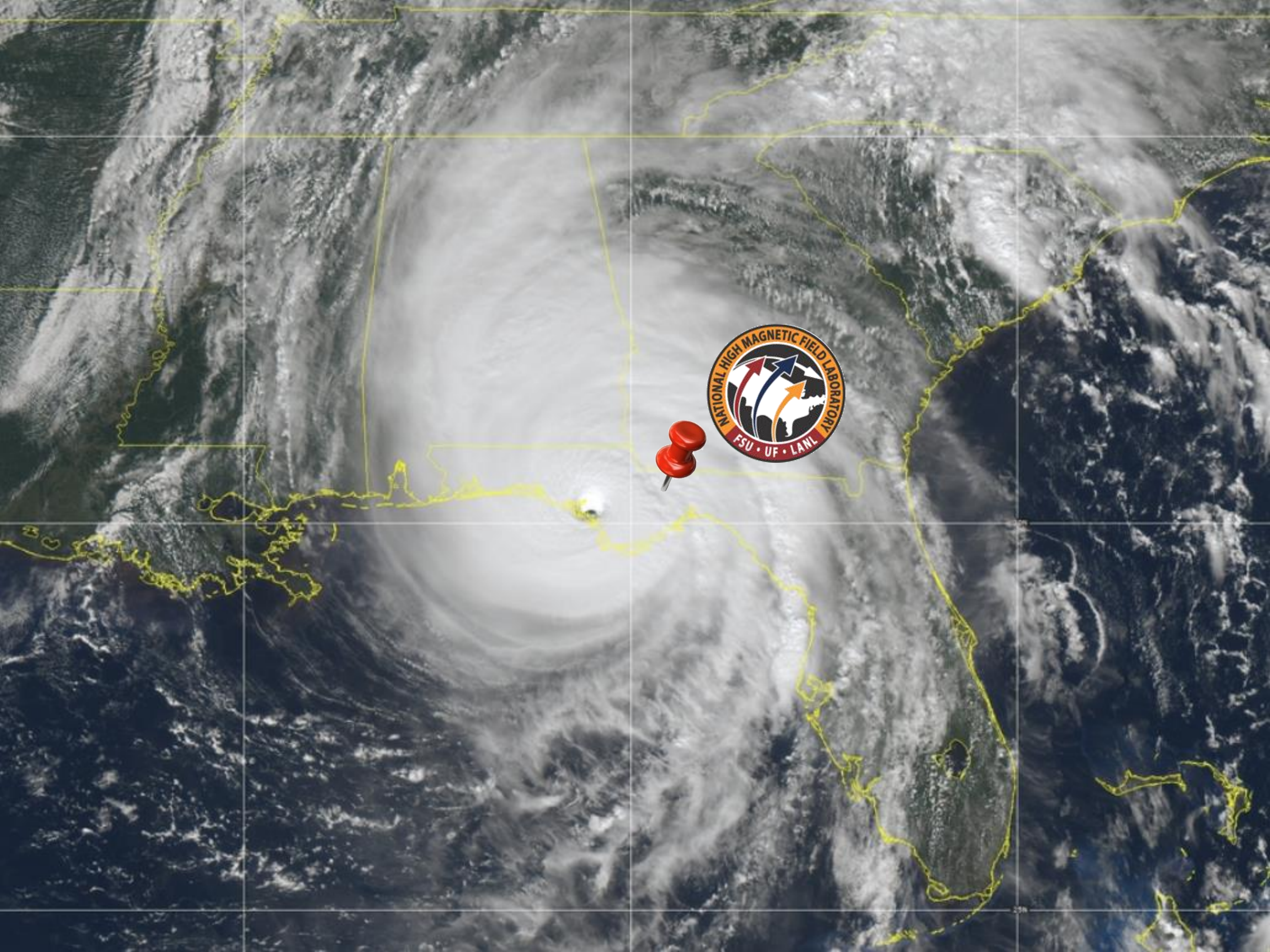


AFMR detected (too strong)





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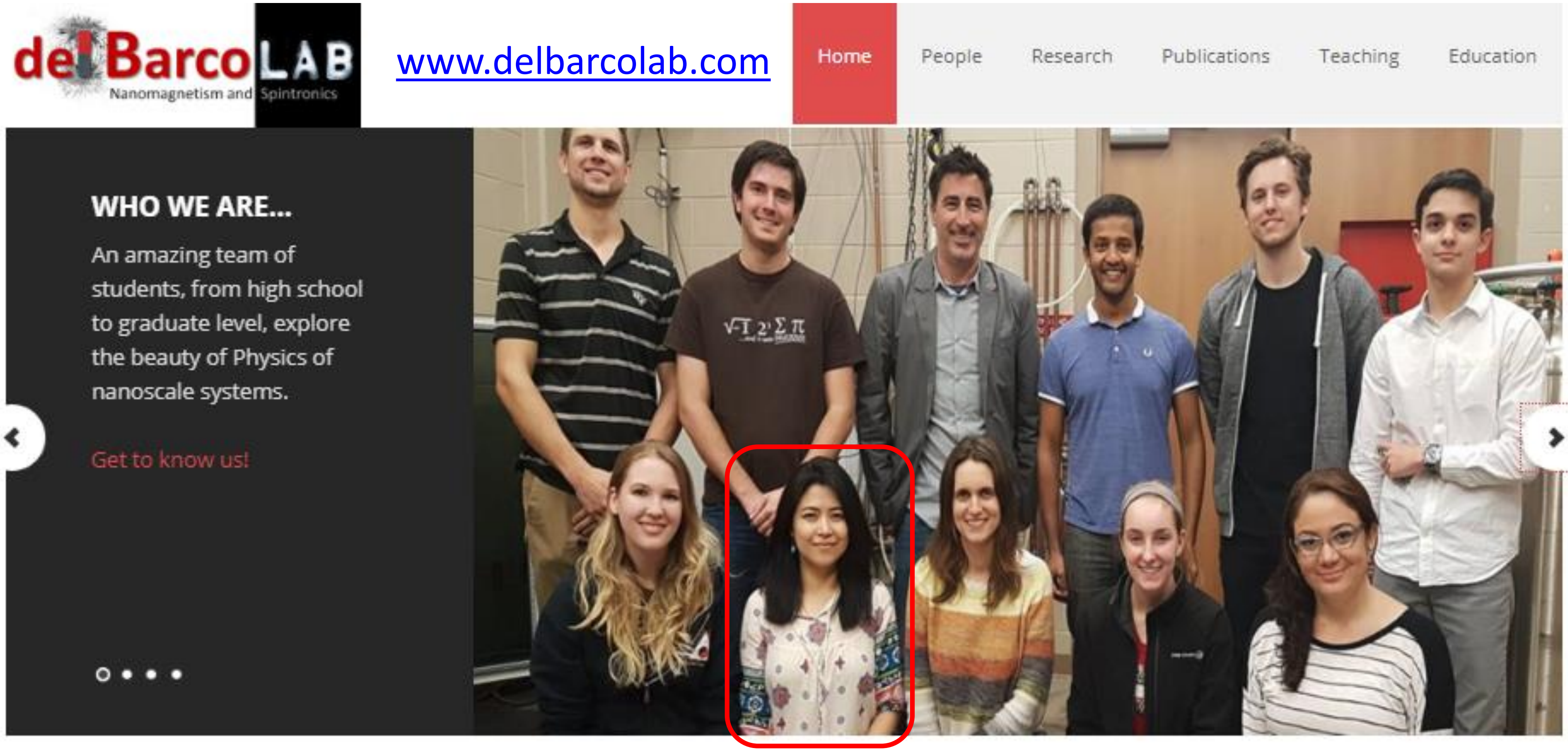
Spin Pumping from AFM Insulator MnF_2

Terahertz Spintronics with Antiferromagnetic Insulators

Spin pumping at AFM/NM interfaces

- First observation of sub-THz spin pumping at a AFM/Pt interfaces
- Very preliminary results / Work needs to be completed
- Higher frequencies for observing polarization effects (low field)
- Better control of the easy axis orientation for spin flip-flop
- Thinner crystalline MnF_2 samples for resolution of AFMR linewidths
- Other AFMs will need to be explored (axial and bi-axial)
- Current-induced THz dynamics as next step



Priyanka Vaidya

THANKS FOR YOUR ATTENTION

Work done in collaboration with:

David Lederman (University of California – Santa Cruz)
Hans van Tol (National High Magnetic Field Laboratory / NHMFL – Tallahassee/FL)