Creation/Detection of Single Magnetic Skyrmions and Its Possible Applications in Quantum Computing

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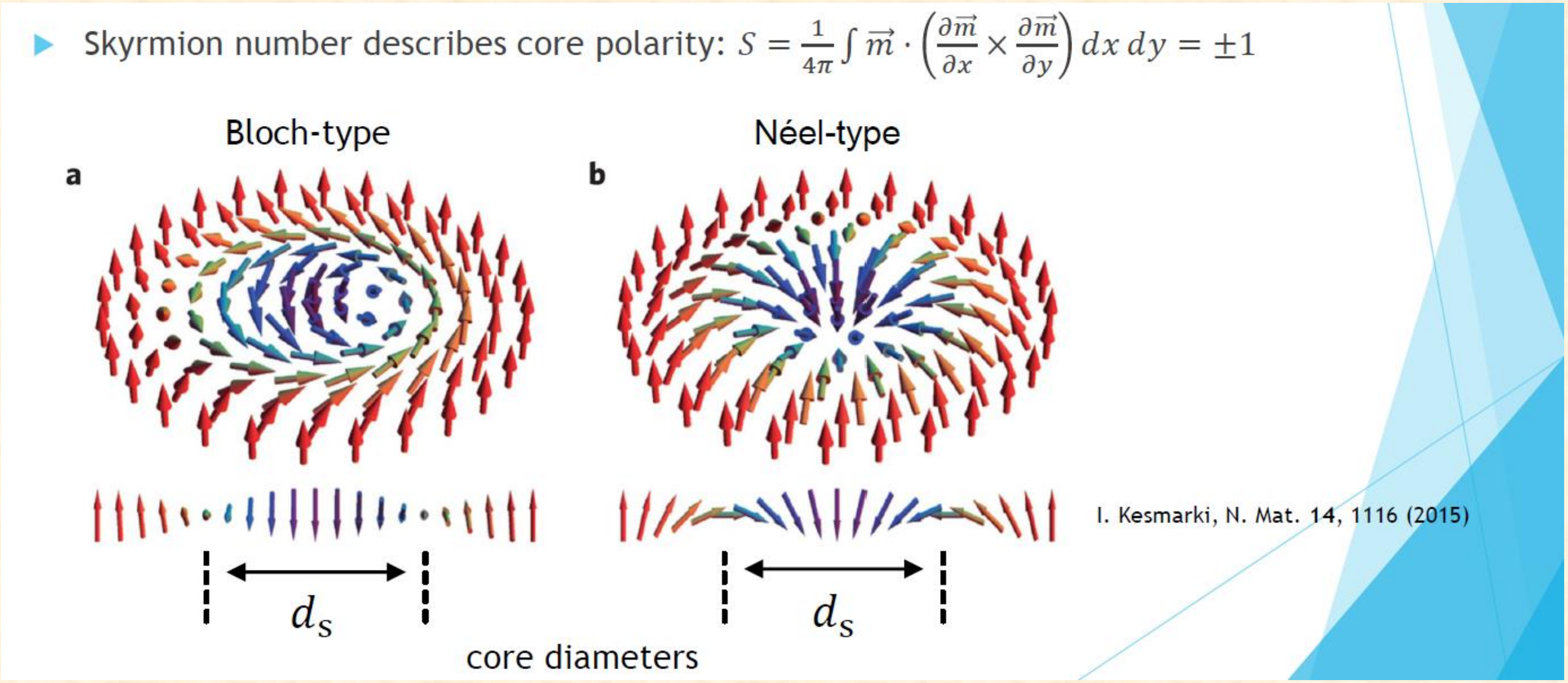
Outline

- Motivation: magnetic skyrmions for QC
- Single magnetic skyrmions in magnetic tunneling junctions
- Deterministic creation of a single skyrmion using spin-transfer-torque pulse and microwave radiation
- Detection of the skyrmion using RF resonance spectroscopy
- Future perspective for topological QC

Magnetic Skyrmions

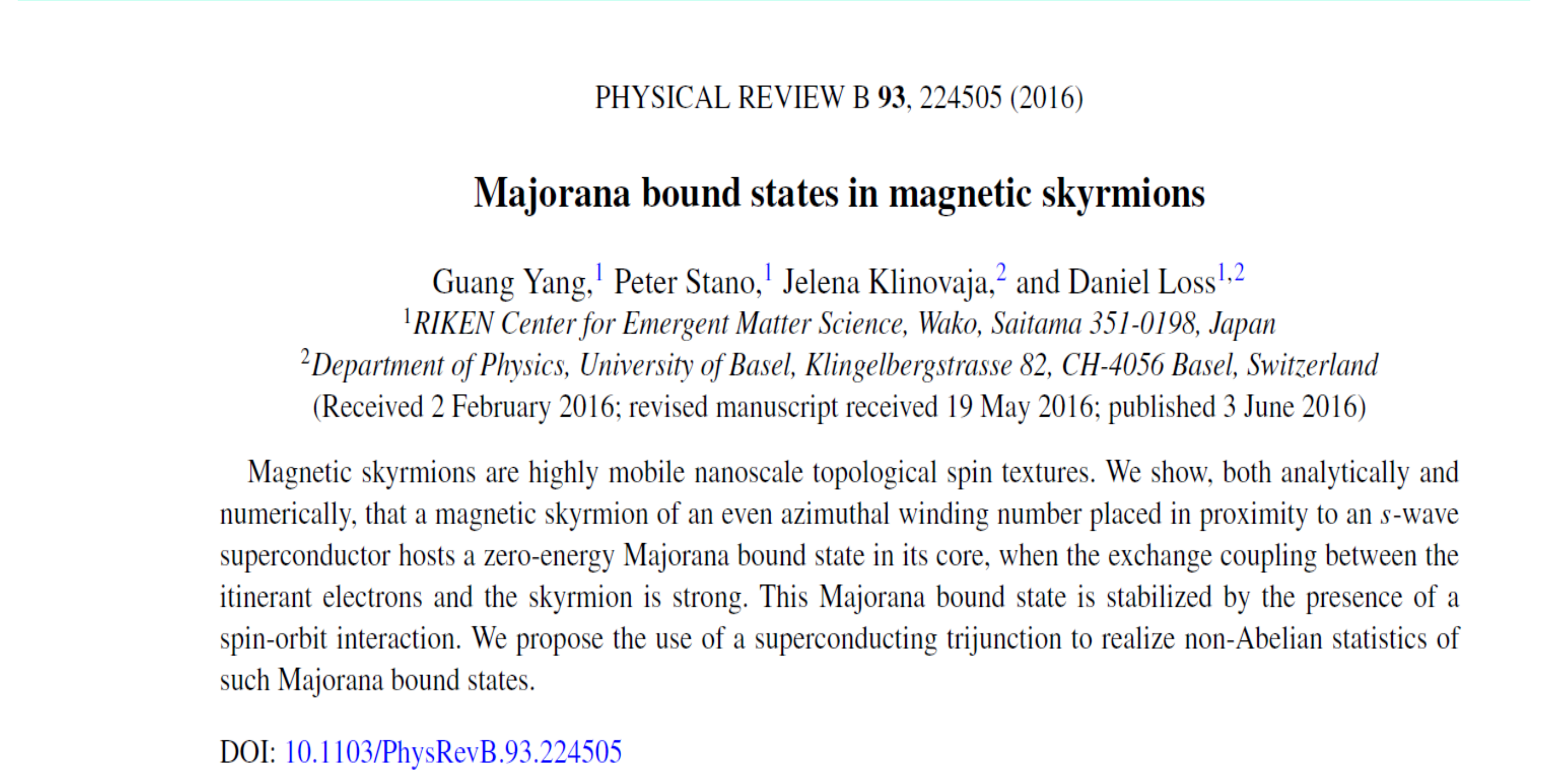


- Skyrmion number describes core polarity: $S = \frac{1}{4\pi}\int \vec{m}\cdot\left(\frac{\partial\vec{m}}{\partial x}\times\frac{\partial\vec{m}}{\partial y}\right)dx\,dy = \pm1$

I. Kesmarki, N. Mat. 14, 1116 (2015)

*Magnetic skyrmions can be generated in magnetic thin films
*Dzyaloshinskii-Moriya interaction (DMI) favors rotation of adjacent spins about the DM vector
*Topological protection: quantized topological charge number and winding numbers
*Low creation energy, proposed for storage, logic gates, and neuromorphic computing

Magnetic Skyrmions for Topological QC



PHYSICAL REVIEW B **93**, 224505 (2016)

Majorana bound states in magnetic skyrmions

Guang Yang,[1] Peter Stano,[1] Jelena Klinovaja,[2] and Daniel Loss[1,2]
[1]*RIKEN Center for Emergent Matter Science, Wako, Saitama 351-0198, Japan*
[2]*Department of Physics, University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland*

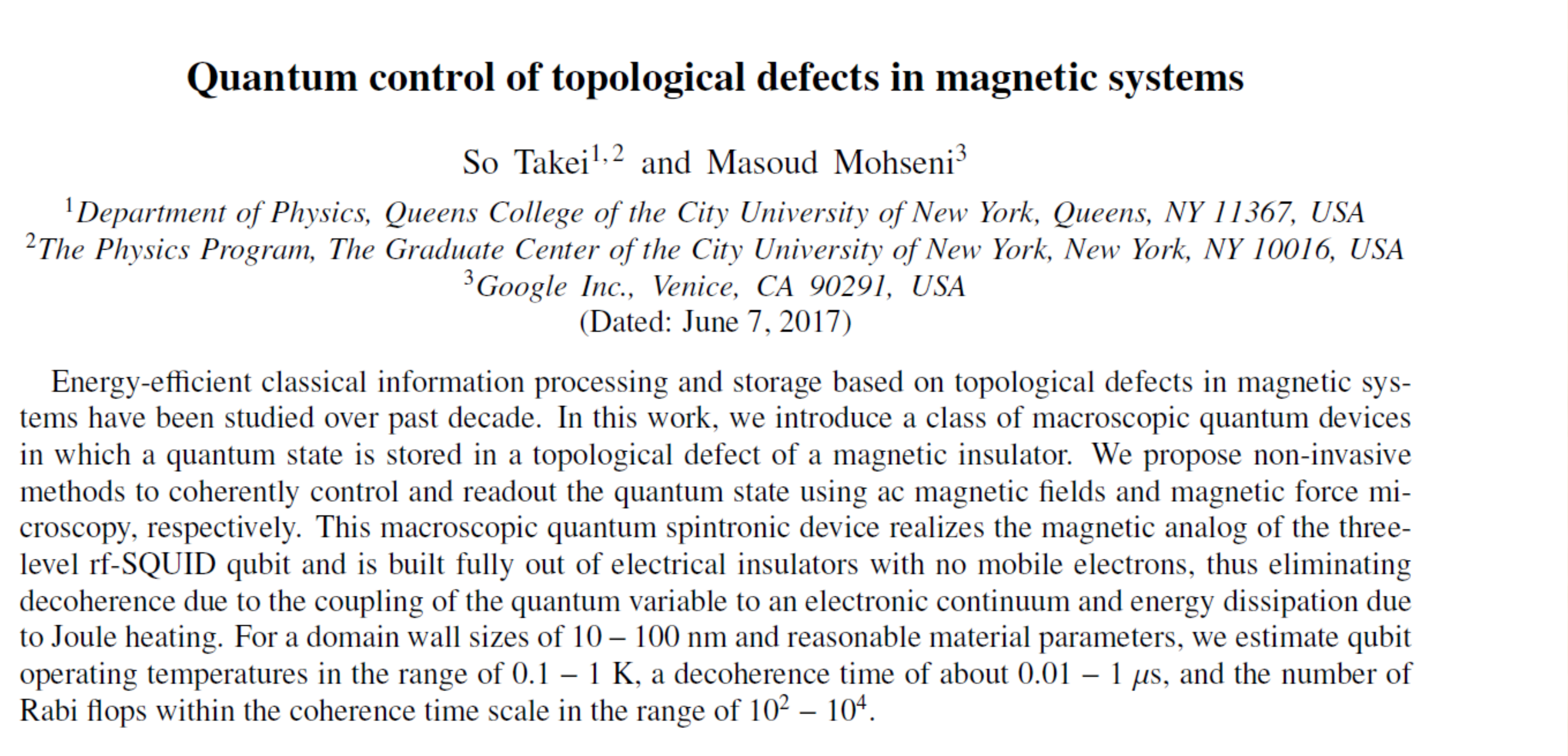
(Received 2 February 2016; revised manuscript received 19 May 2016; published 3 June 2016)

Magnetic skyrmions are highly mobile nanoscale topological spin textures. We show, both analytically and numerically, that a magnetic skyrmion of an even azimuthal winding number placed in proximity to an *s*-wave superconductor hosts a zero-energy Majorana bound state in its core, when the exchange coupling between the itinerant electrons and the skyrmion is strong. This Majorana bound state is stabilized by the presence of a spin-orbit interaction. We propose the use of a superconducting trijunction to realize non-Abelian statistics of such Majorana bound states.

DOI: 10.1103/PhysRevB.93.224505

magnetic skyrmion place in the proximity of an s-wave superconductor hosts a zero-energy Majorana bound state

Chairman Mao : Let one thousand flowers bloom



Quantum control of topological defects in magnetic systems

So Takei[1,2] and Masoud Mohseni[3]

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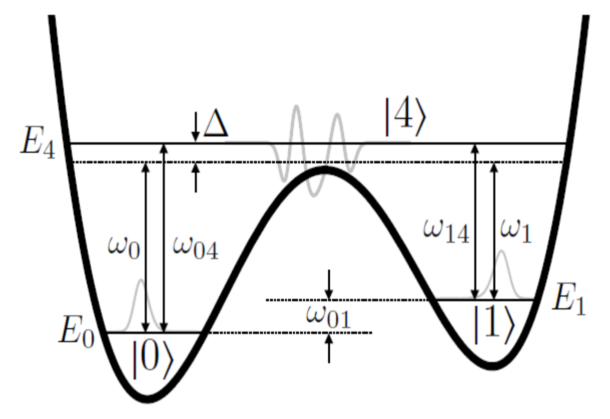
[2]*The Physics Program, The Graduate Center of the City University of New York, New York, NY 10016, USA*
[3]*Google Inc., Venice, CA 90291, USA*

(Dated: June 7, 2017)

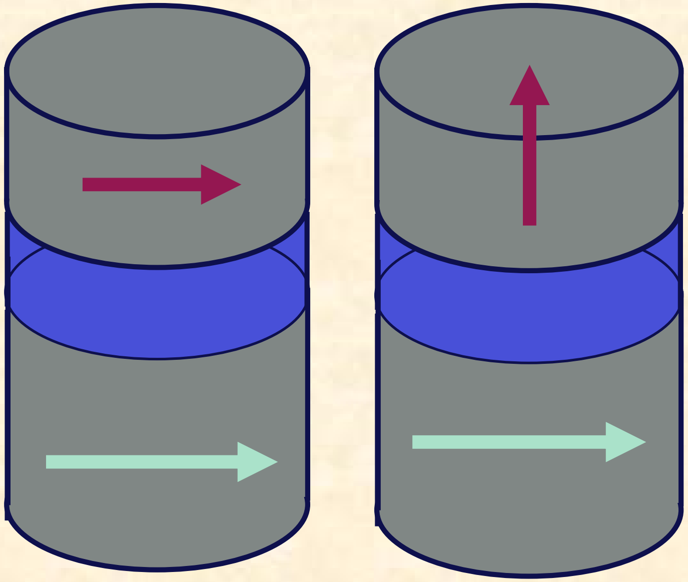
Energy-efficient classical information processing and storage based on topological defects in magnetic systems have been studied over past decade. In this work, we introduce a class of macroscopic quantum devices in which a quantum state is stored in a topological defect of a magnetic insulator. We propose non-invasive methods to coherently control and readout the quantum state using ac magnetic fields and magnetic force microscopy, respectively. This macroscopic quantum spintronic device realizes the magnetic analog of the three-level rf-SQUID qubit and is built fully out of electrical insulators with no mobile electrons, thus eliminating decoherence due to the coupling of the quantum variable to an electronic continuum and energy dissipation due to Joule heating. For a domain wall sizes of 10 – 100 nm and reasonable material parameters, we estimate qubit operating temperatures in the range of 0.1 – 1 K, a decoherence time of about 0.01 – 1 μs, and the number of Rabi flops within the coherence time scale in the range of $10^2 – 10^4$.



for Hilbert space QC
An alternative for SC qubits and semiconductor QD qubits

Magnetic Tunnel Junction (MTJ Devices)

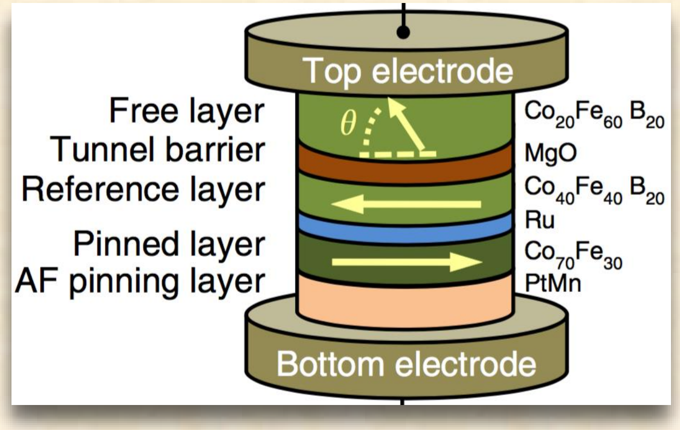
Conceptual Design



in-plane free layer
in-plane fixed layer

perpendicular free layer
in-plane fixed layer

Simplified MgO Based structure



top electrode
Ta (3nm)
CuN (40nm)
Ta (3nm)
CuN (40nm)
Ta (3nm)
Ru (10nm)
Ta (5nm)
PtMn (15nm)
$Co_{70}Fe_{30}$
Ru (0.85nm)
$Co_{40}Fe_{40}B_{20}$ (2.4nm)
MgO (< 1nm)
$Co_{40}Fe_{40}B_{20}$ (1.8nm)
Ta (5nm)
Cu (10nm)
Ru (5nm)
Ta (3nm)
bottom electrode

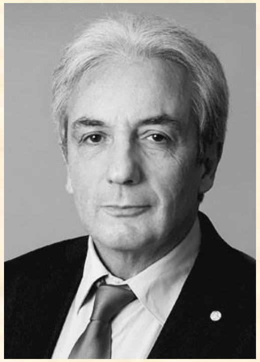
Actual Device

Utilizing 'Material Engineering'
to make the complicated fabrication
possible

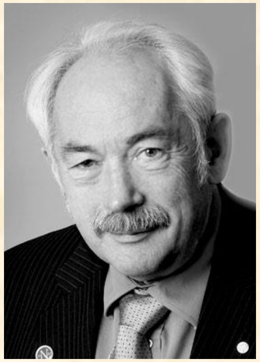
MTJs are most promising spintronic devices: robust, scalable, room temperature

Giant Magnetoresistance (GMR)

2007 Physics Nobel Prize

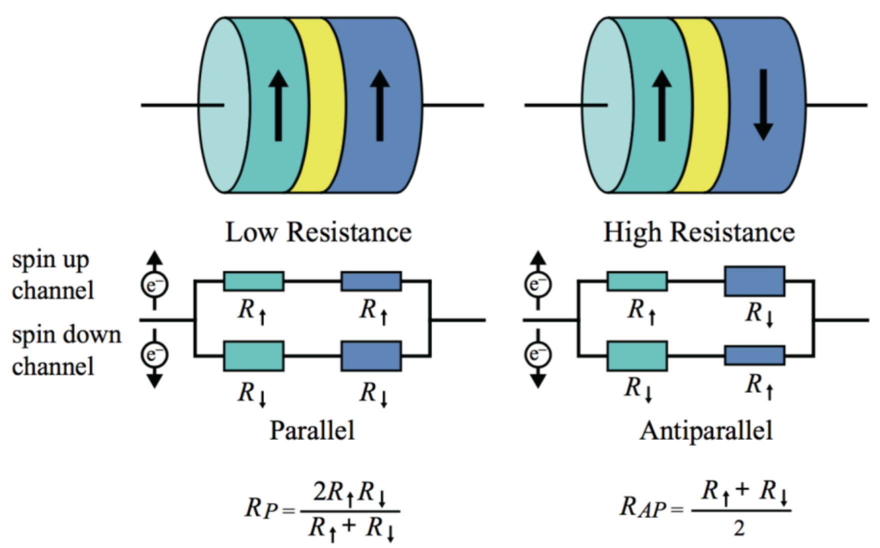


Albert Fert



Peter Grünberg

S. Peng, et al

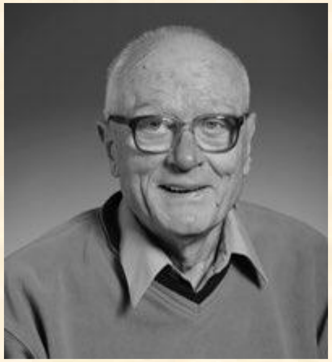


$$R_P = \frac{2R_\uparrow R_\downarrow}{R_\uparrow + R_\downarrow}$$

$$R_{AP} = \frac{R_\uparrow + R_\downarrow}{2}$$

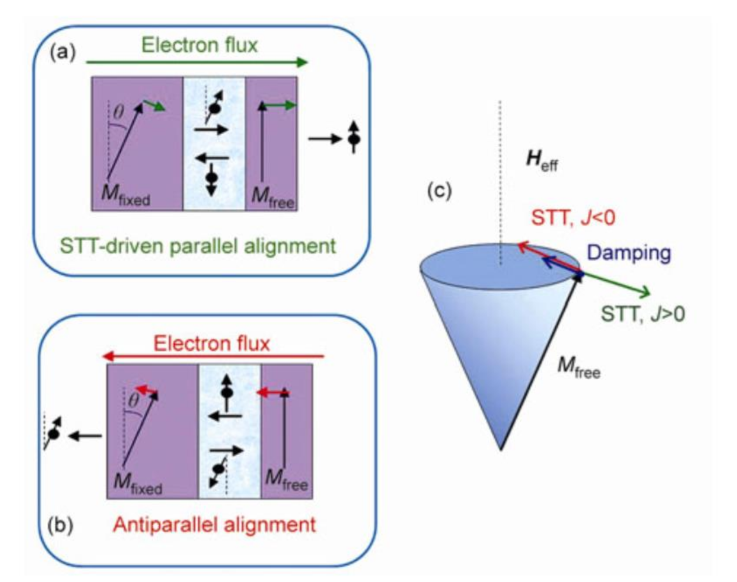
Spin Torque Transfer (STT)

Theoretically predicted in 1996



Luc Berger

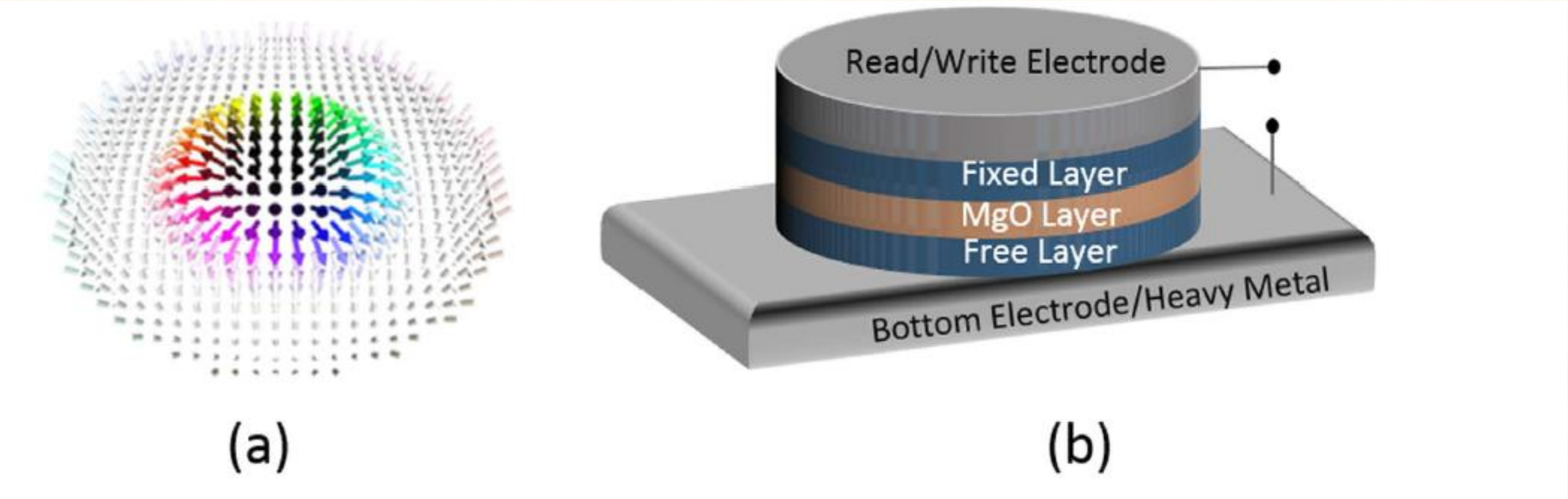
John Slonczewski



Liu Y W, et al.

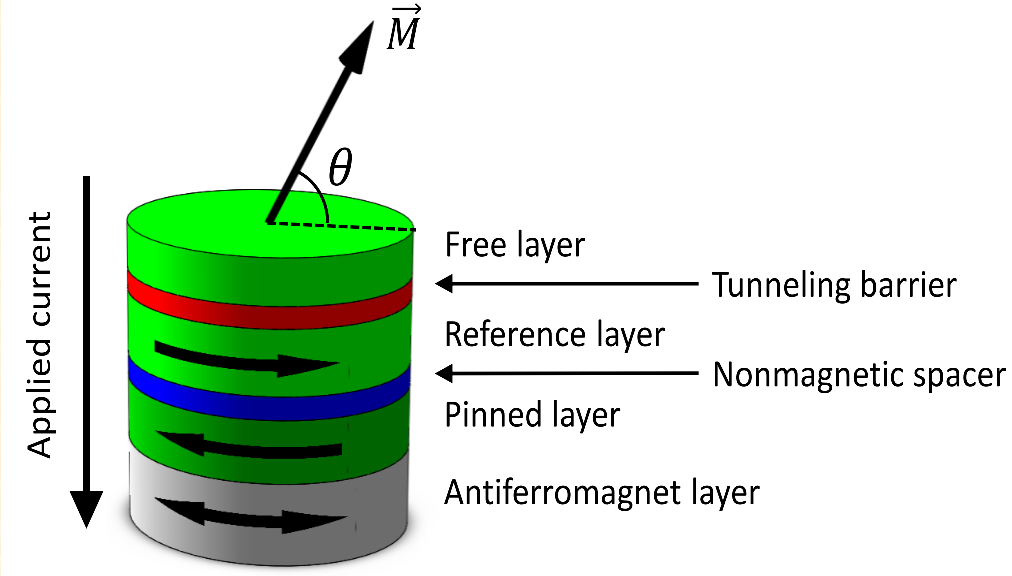
Single skyrmion creation in MTJ

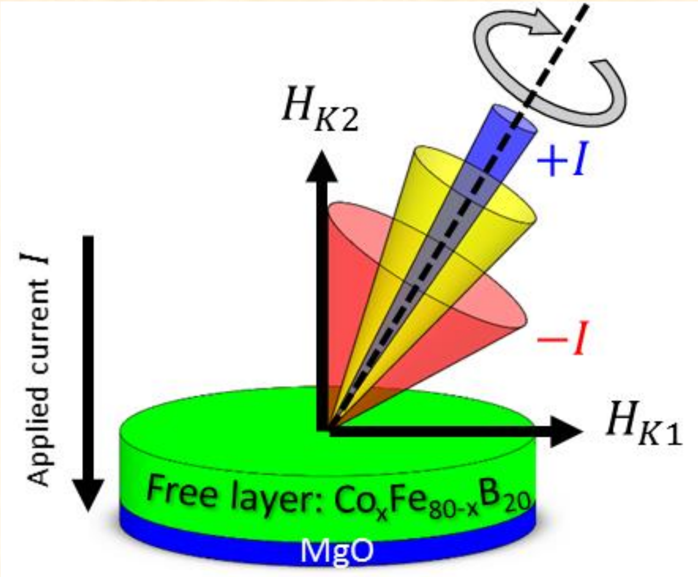
Skyrmions in the free layer stabilized by interfacial Dzyaloshinskii-Moriya interaction (DMI)



D. Bhattacharya *et al*, "Voltage controlled core reversal of fixed magnetic skyrmions without a magnetic field". Sci. Rep. 6, 31272 (2016)

Perpendicular Magnetic Anisotropy (PMA)



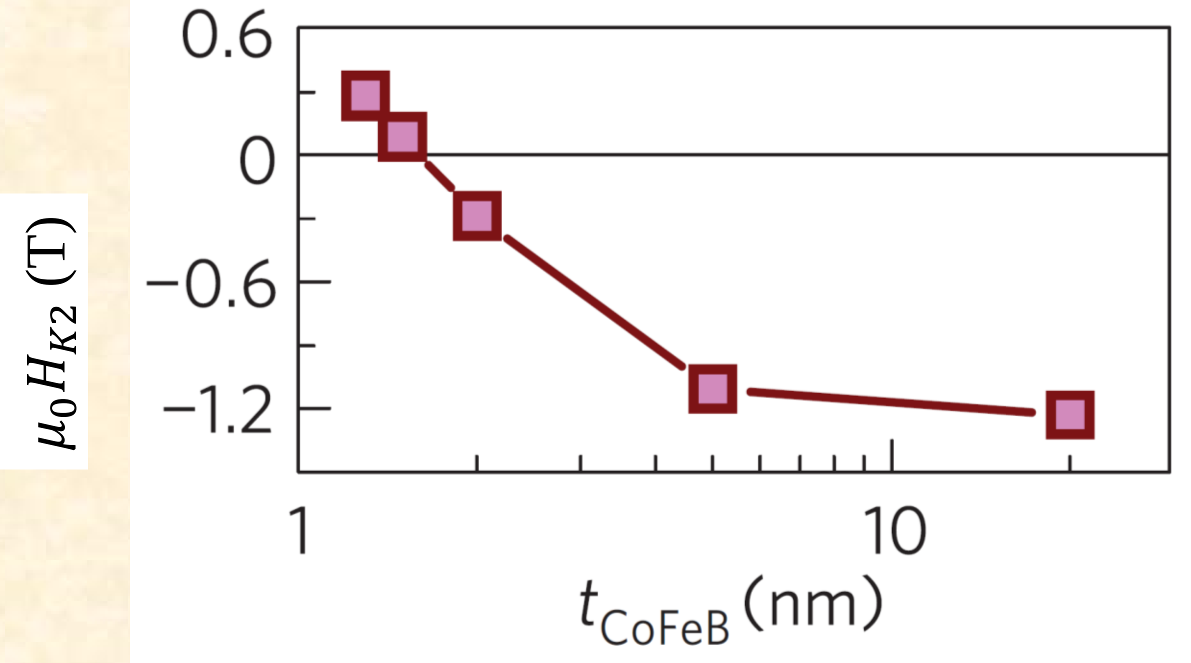


* No interface: in-plane H_{K1}, saturation magnetization, shape anisotropy

* CoFeB/MgO represents one of the best materials to control magnetic anisotropy by Fe concentration, by film thickness, and by voltage.

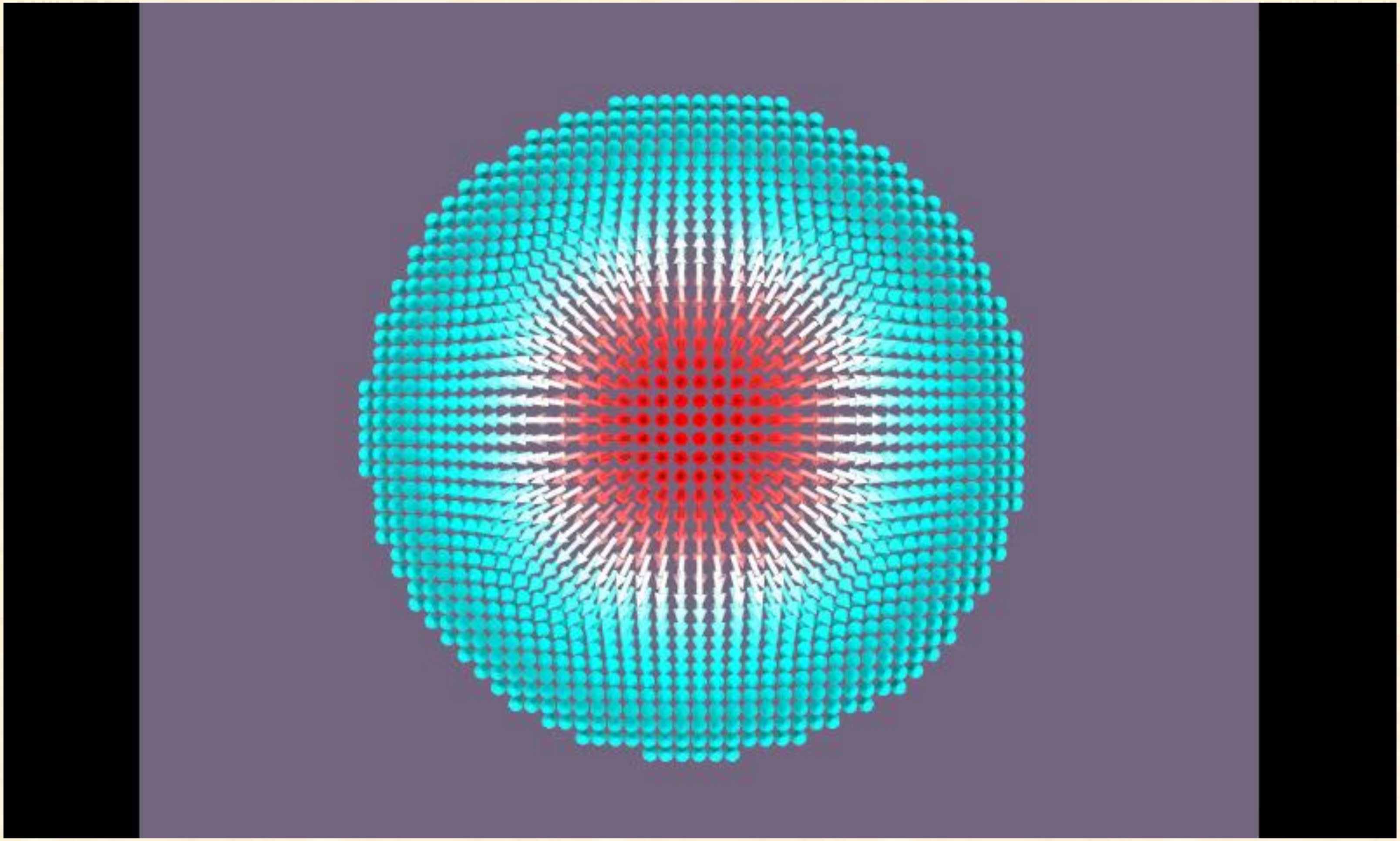
* H_{K2} due to the hybridization of Fe 3*d* and O 2*p* orbitals

Effect of CoFeB thickness on perpendicular anisotropy



S. Ikada et al., Nature Materials 9,724 (2010).

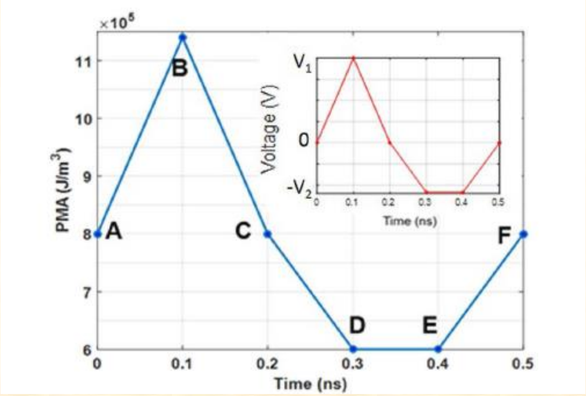
The perpendicular anisotropy enables large-amplitude magnetization precession under a small spin-torque, which allows for device operation in the absence of external magnetic field while significantly enhancing the efficiency of spin torque driven dynamics .



PMA controlled by voltage

$$\frac{d\vec{m}}{dt} = -\frac{\gamma}{1+\alpha^2}\left[\vec{m}\times\vec{H}_{\text{eff}} + \alpha\left(\vec{m}\times\left(\vec{m}\times\vec{H}_{\text{eff}}\right)\right)\right]$$

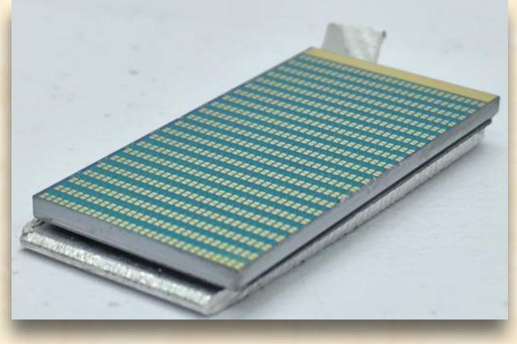
$$\vec{\tau}_{\text{SL}} = \frac{j_z\hbar}{M_s e d}\left[\frac{\epsilon-\alpha\epsilon'}{1+\alpha^2}(\vec{m}\times(\vec{p}\times\vec{m})) - \frac{\epsilon'-\alpha\epsilon}{1+\alpha^2}\vec{m}\times\vec{p}\right]$$

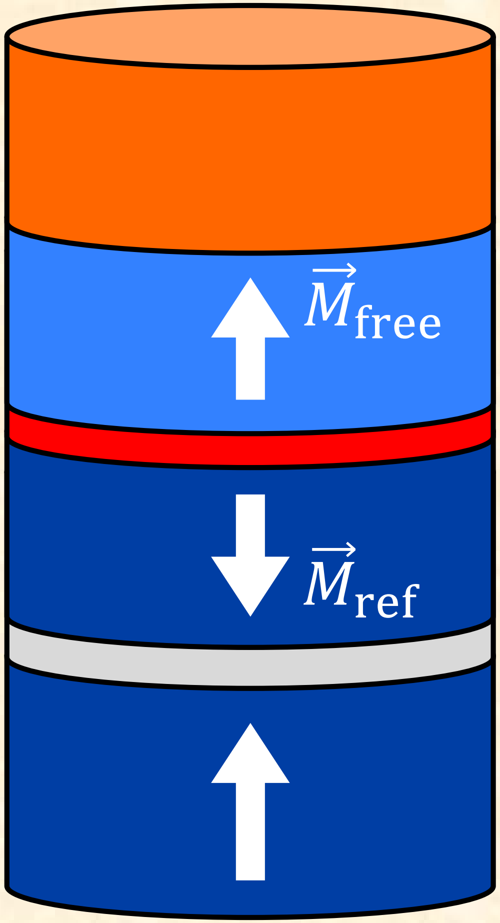


Searching for skyrmions in MTJs at UCLA

at cryogenic temperatures

- MTJs provided by Avalanche Technology
- circular nano-pillars with diameters ranging from 80 nm to 400 nm
- Data taken on MTJ pillars with diameters 400nm, 350nm
- All measurements performed at <4.2K





Heavy metal (Ta)
$D \approx 0.1\ \text{mJ/m}^2$

Free layer (CoFeB)

Tunnel barrier (MgO)

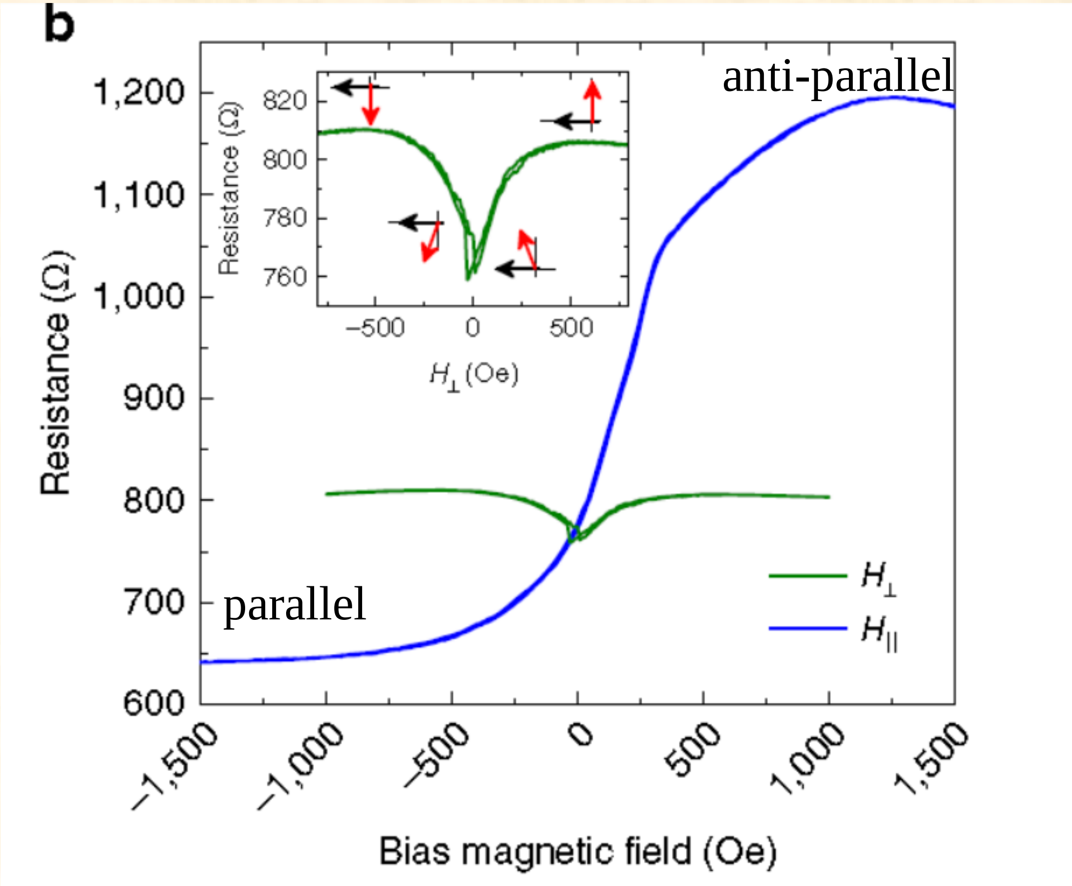
Ref. layer (CoFeB)

Spacer (Ru)

Pinned layer (Co/Pt)

topological protection for infinite geometry, a gap in finite size

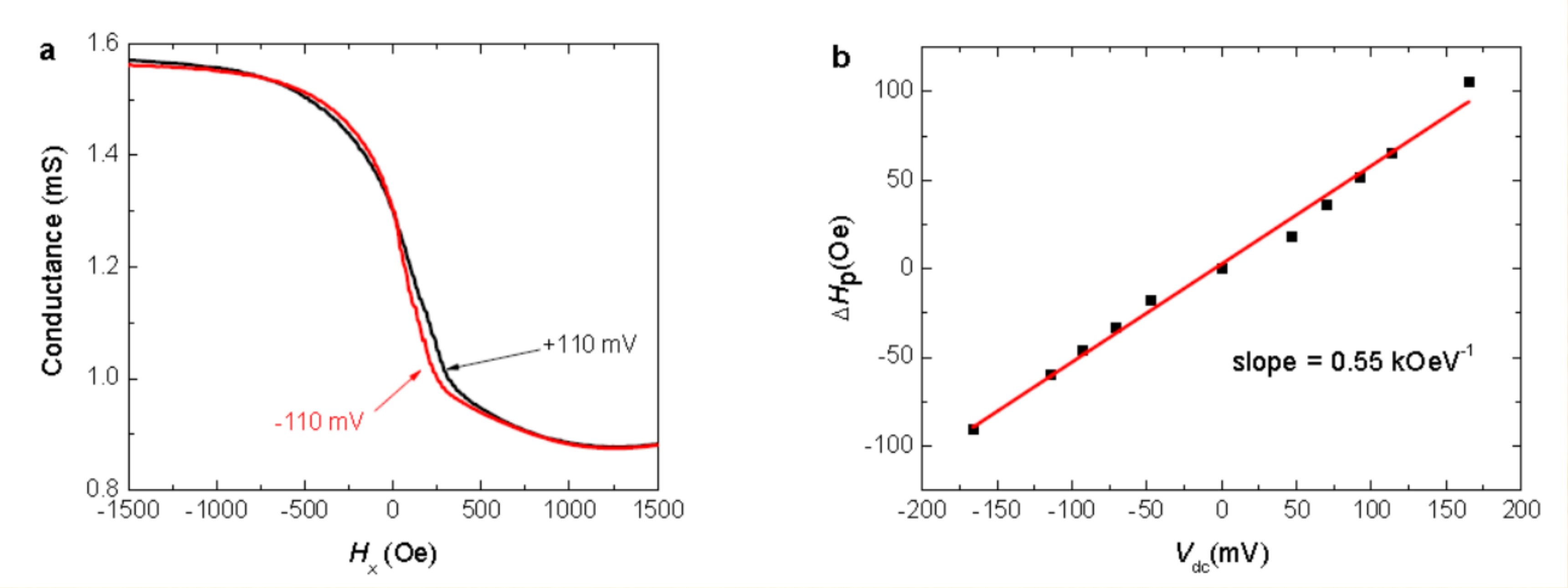
Characterization of PMA



$$R^{\;1}(\theta)=\frac{R_{\mathrm{P}}^{\;1}+R_{\mathrm{AP}}^{\;1}}{2}+\frac{R_{\mathrm{P}}^{\;1}-R_{\mathrm{AP}}^{\;1}}{2}\cos(\theta)$$

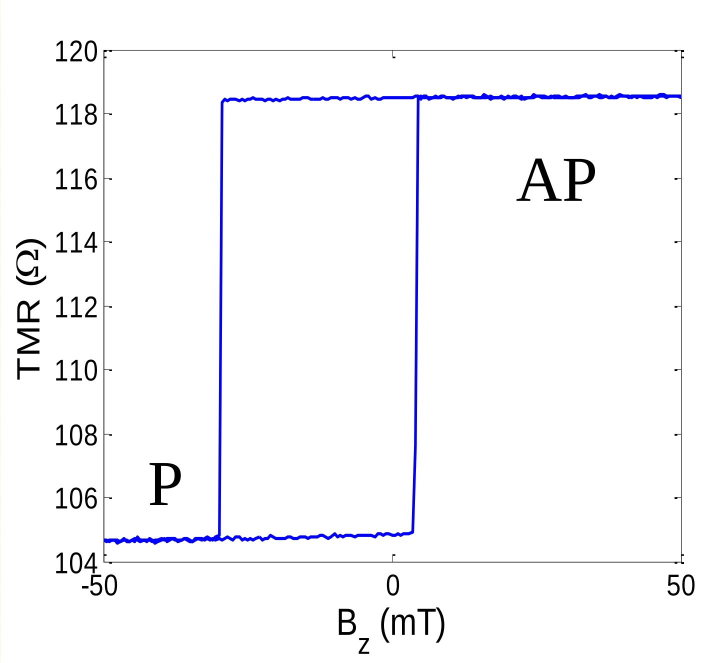
titling angle:
76 degrees from film plane

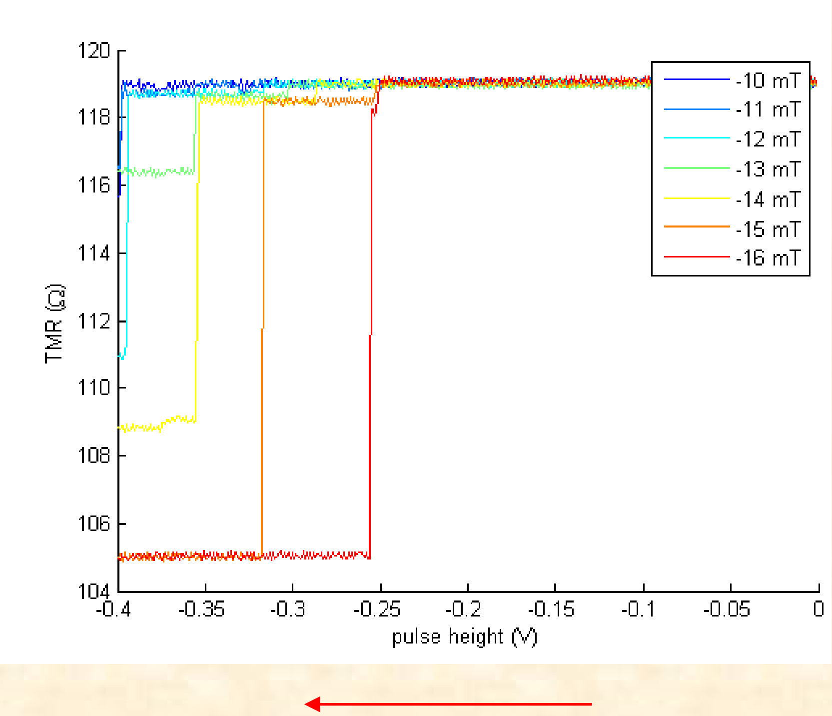
Voltage-Controlled PMA



effective anisotropy field varies continuously as a function of voltage

Creation of a topological spin texture by short current pulse

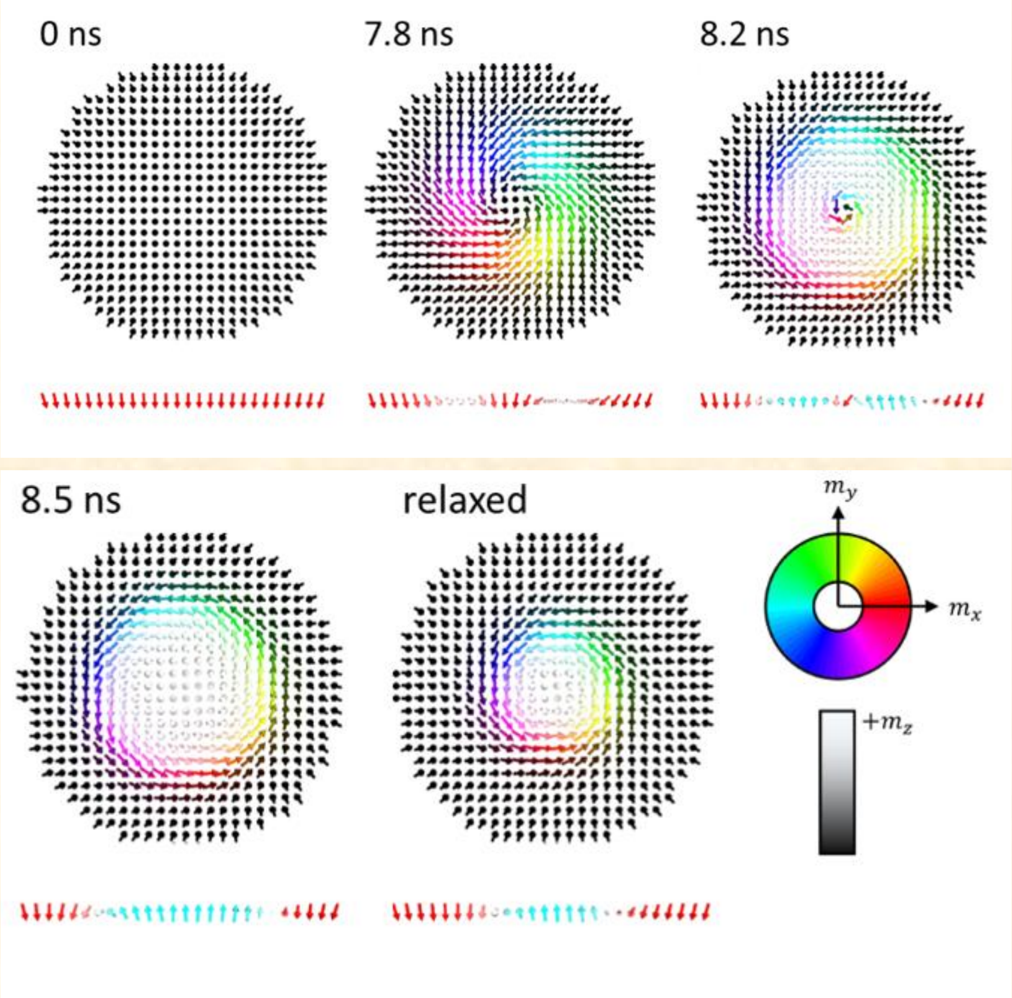


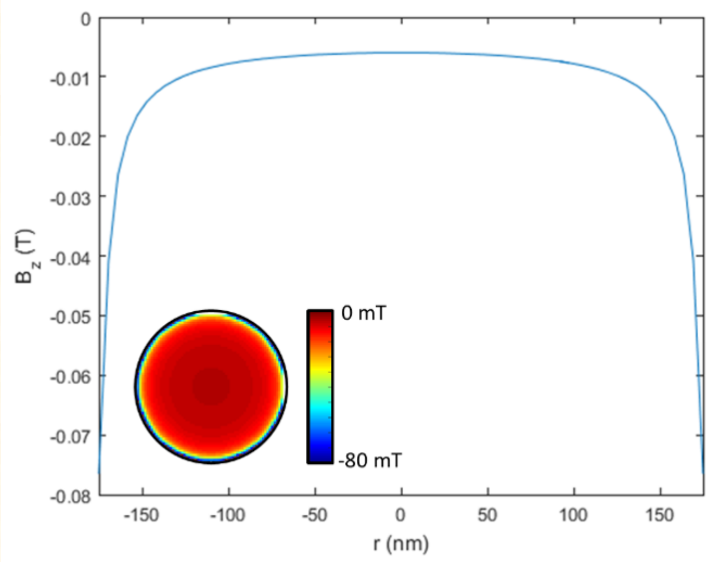


*non-collinear (intermediate) resistance state is excited by a single 10 ns voltage pulse between coercive fields 11mT-14 mT

* the intermediate state is field dependent in sharp contrast to the FM transitions

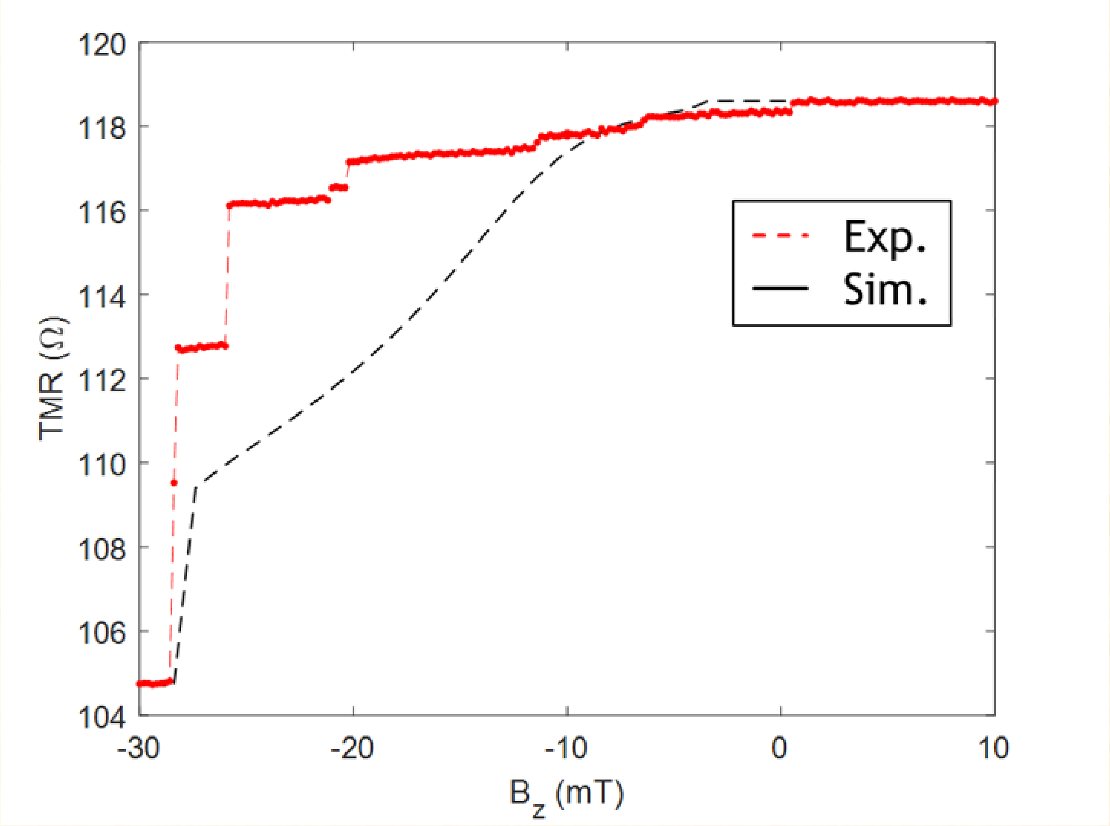
Simulation of spin texture under a current pulse





It is interesting to note that the resulting skyrmion is of Bloch type rather than Neel type; this is consistent with the observation that Bloch domain walls are energetically favorable over Neel walls in ferromagnetic thin films with PMA but no DMI (Benitez 2015)

Skyrmion model appears to be consistent with data

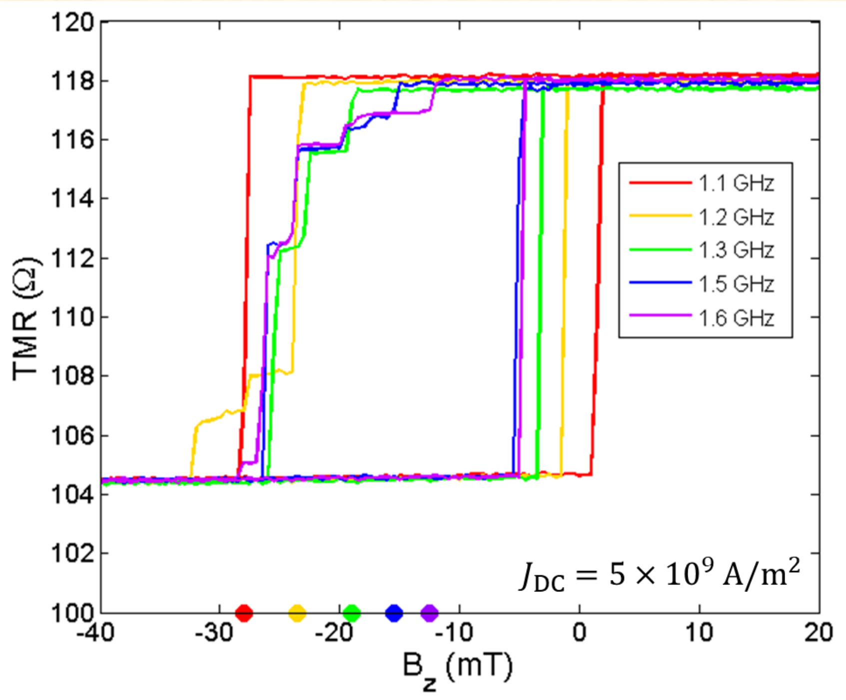


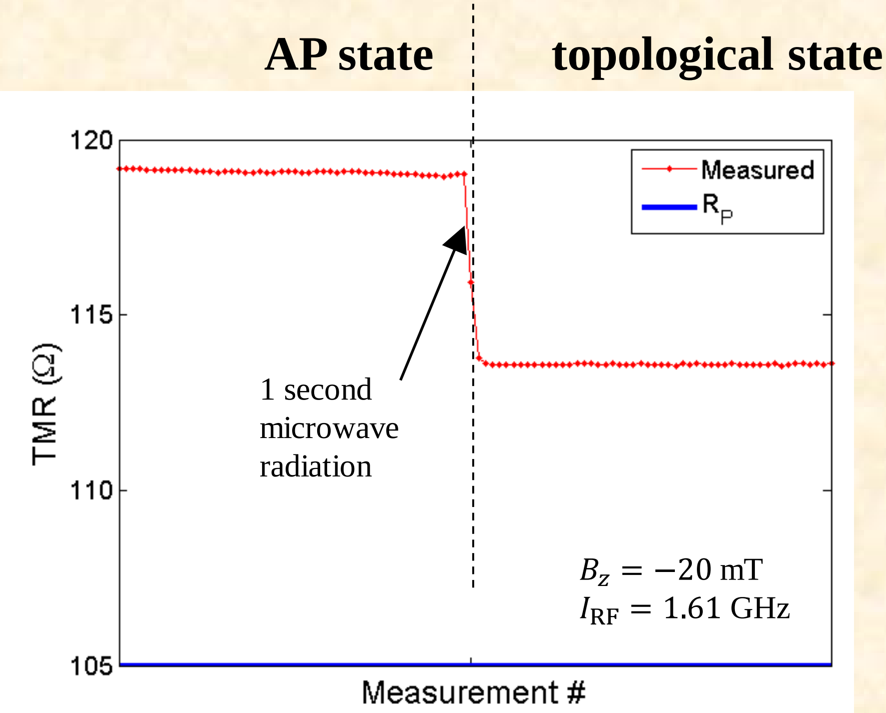
- Microwave current nucleates skyrmion via high-amplitude spin precession
- Size of skyrmion is reflected in junction TMR

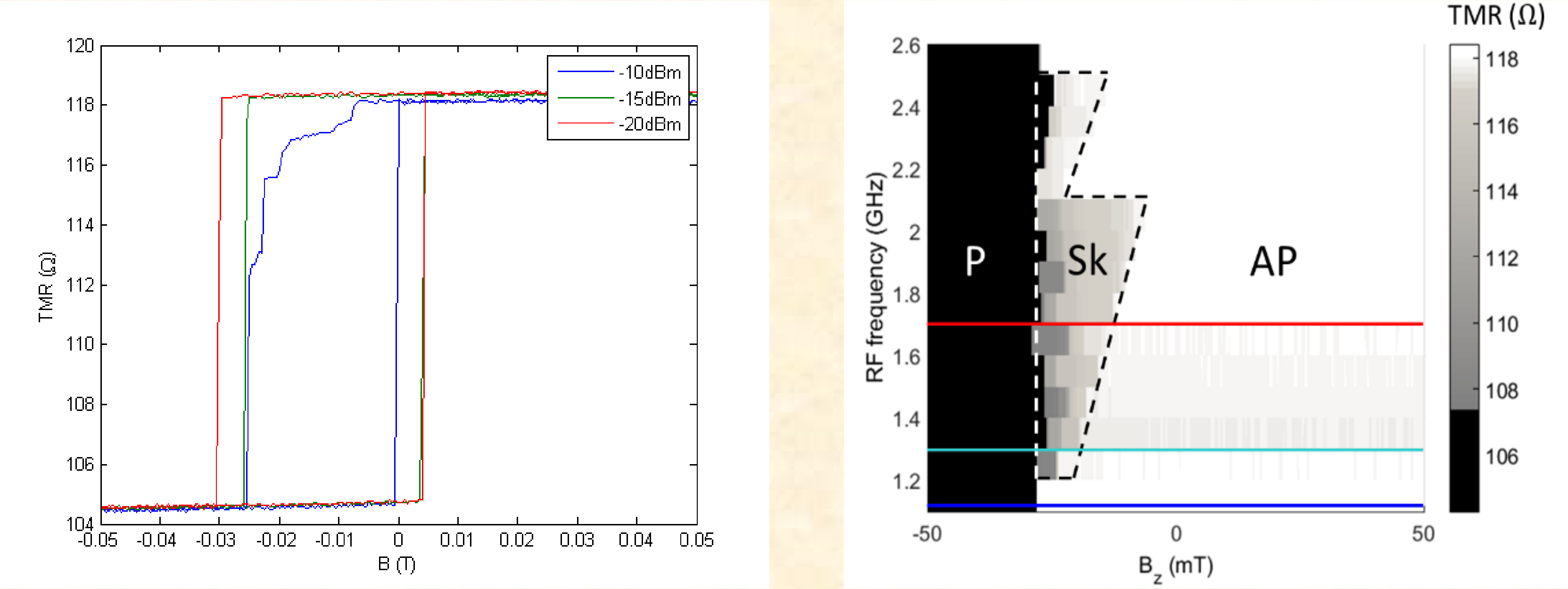
Nucleation of the intermediate-resistance state by microwave

Unusual spin texture is created under microwave radiation

Once created, state remains stable in the absence of RF current



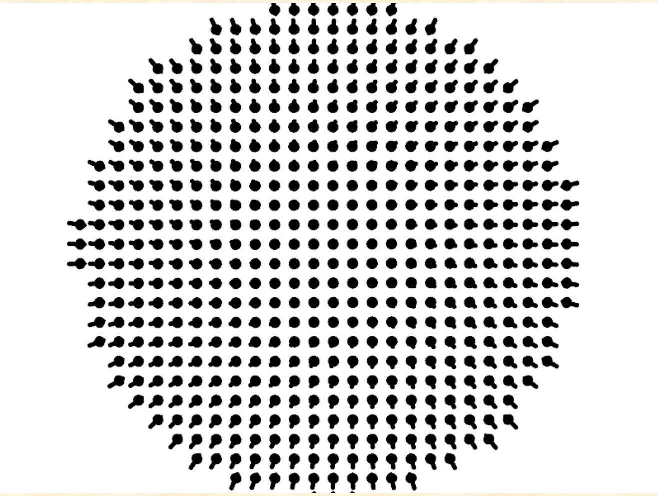




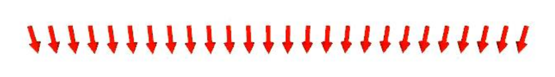
* when the microwave power is decreased, the IRS region diminishes

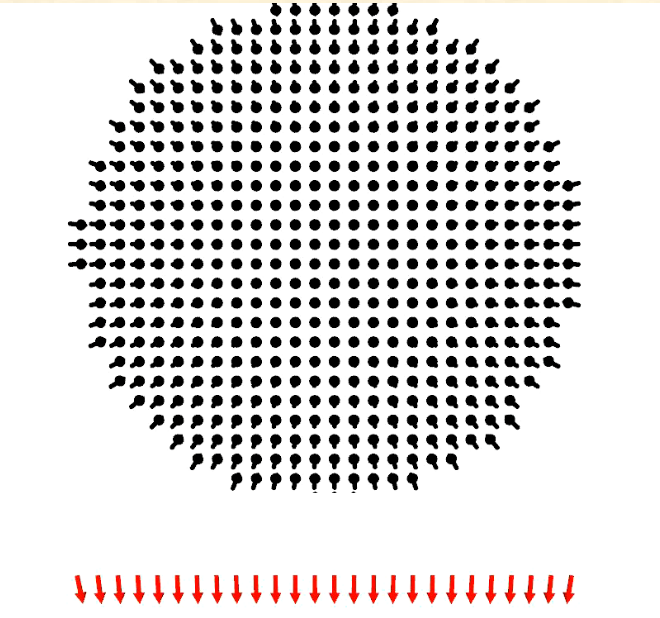
* microwave-assisted switching is typically found to be most efficient when the microwave frequency matches a ferromagnetic resonance (FMR) mode of the free layer

Simulating skyrmion creation in our device



10 ns pulse creation

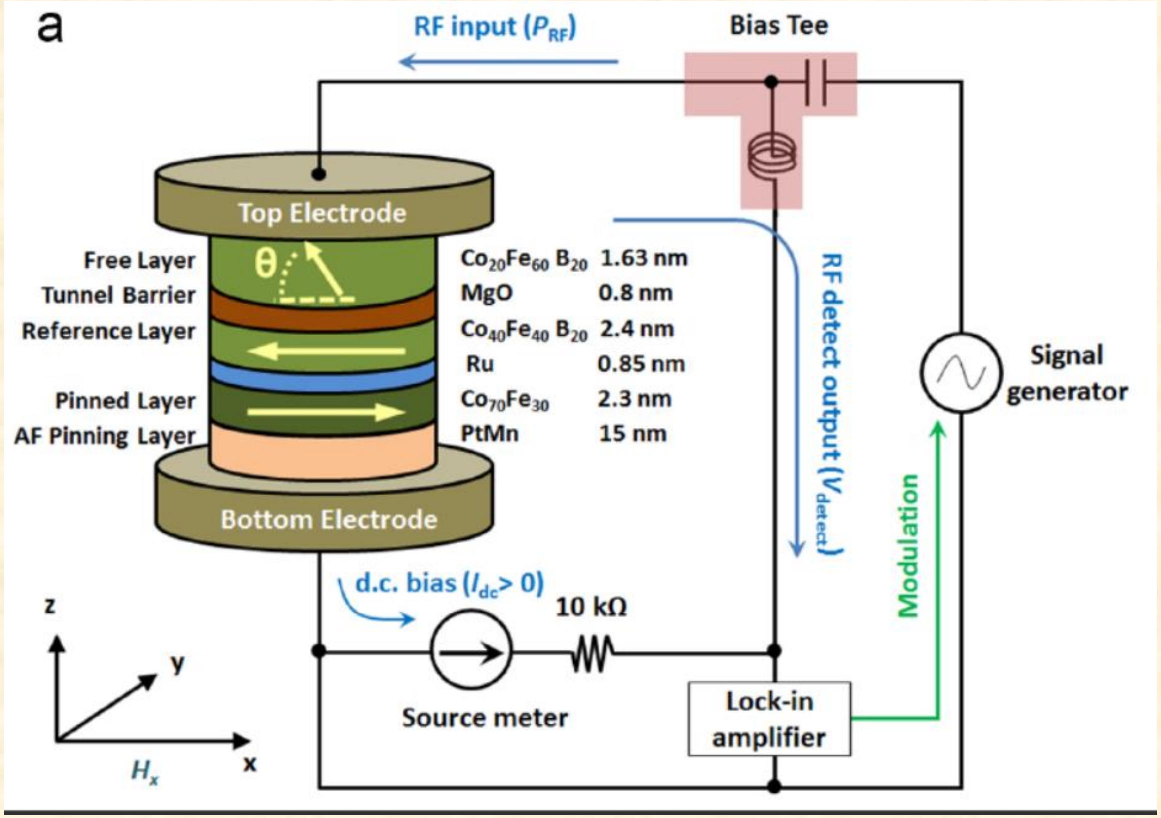




Microwave current creation

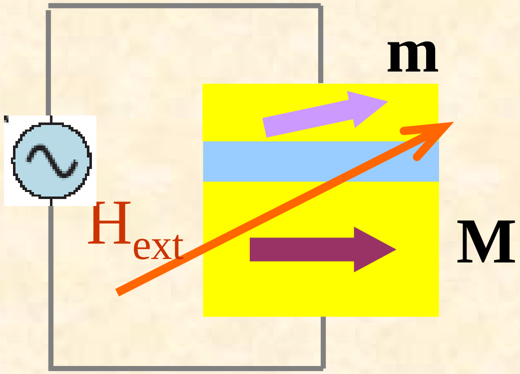
Simulating shows a qualitatively similar skyrmion transition, with increasingly large oscillations of spins in a ring around the disk center. This implies that the nucleation mechanism in the pulse scenario is equivalent to the nucleation mechanism in the microwave current scenario: both excite large-amplitude ferromagnetic resonance which is suppressed at the disk edge and center

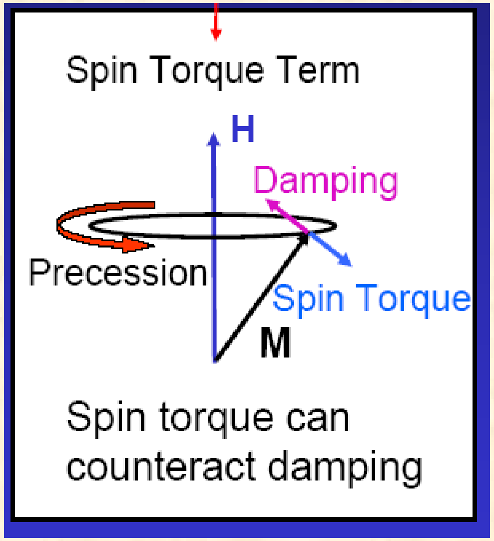
Identification of skyrmion by RF resonance spectroscopy



perform homodyne-detected spin-transfer driven FMR measurements

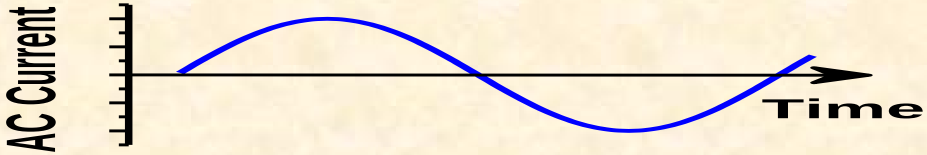
Electrical detection are extremely sensitive



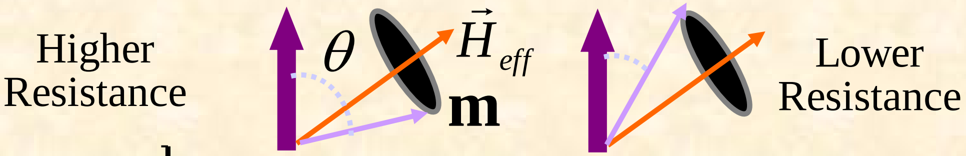


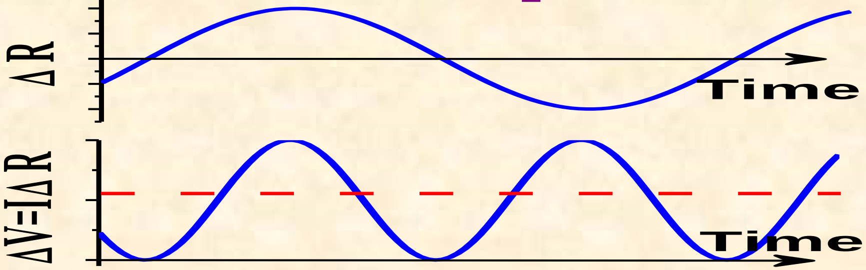
Spin torque can counteract damping

where does the rectifying effect come from?



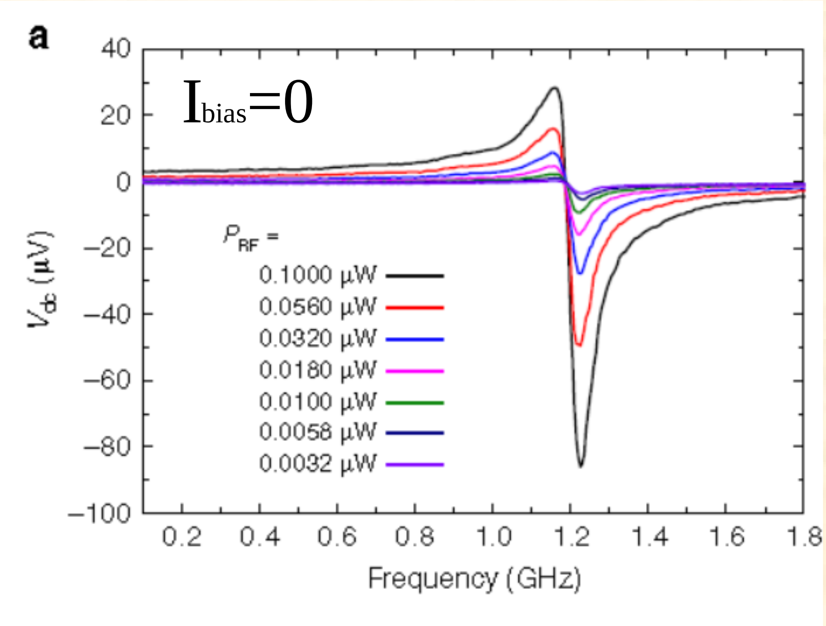
If Larmor frequency ≈ MW Frequency

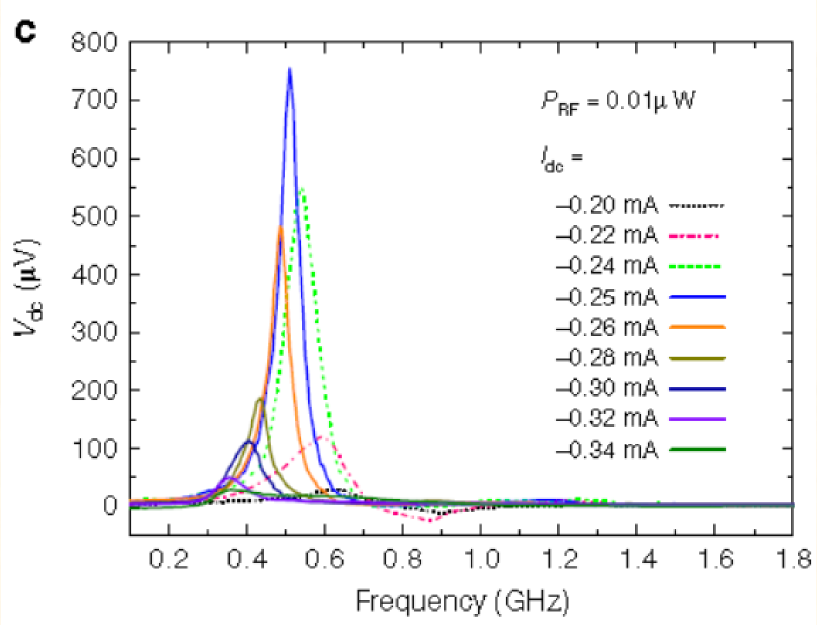


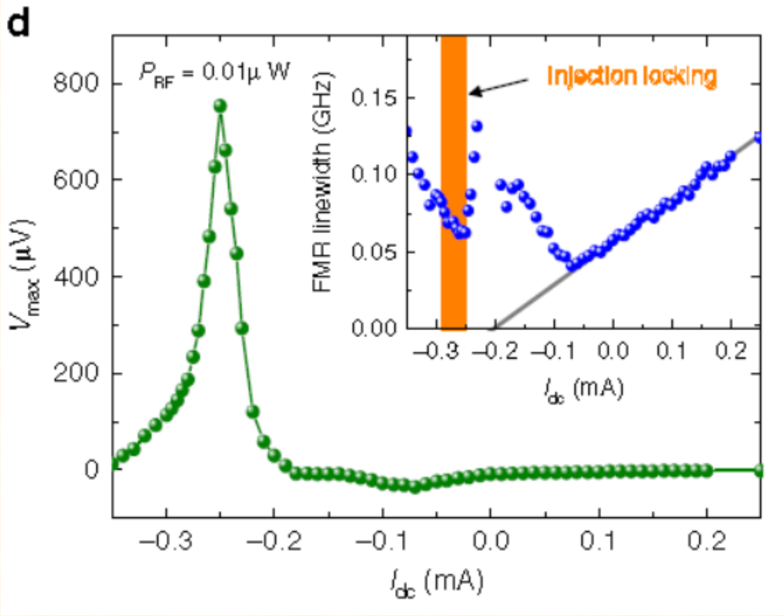


$$V_{dc} \approx \frac{1}{4}\Delta R \sin^{2}(\theta) I_{a.c.}^{2}\ \mathrm{Re}\left[ST, FT\right]$$

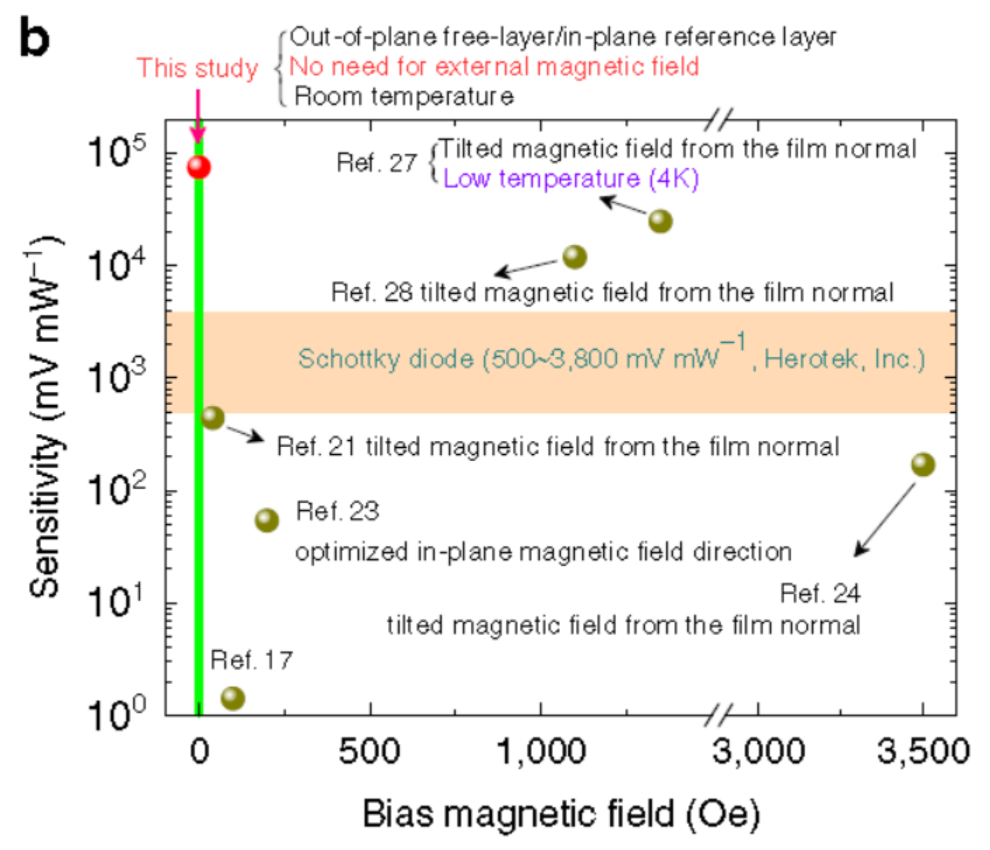
Spectral Selective Detection of Microwave







Ultra High Sensitivity

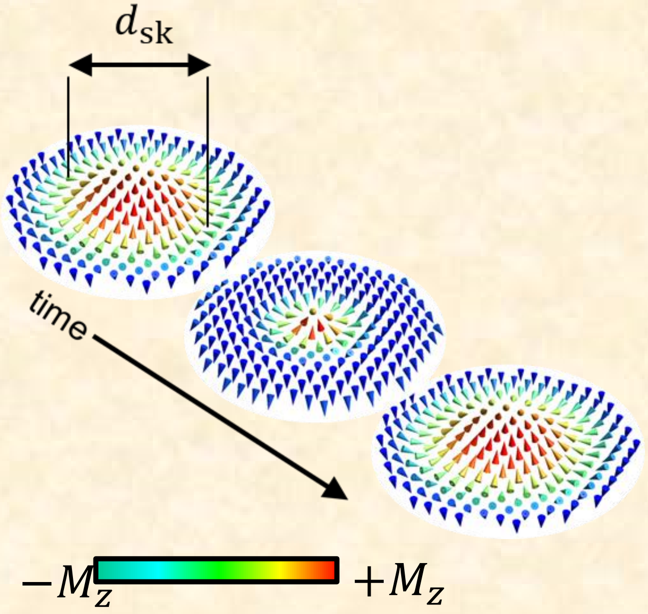


- Higher rectification sensitivity (75,400 mV/mW) is achieved, considerably higher than semiconductor Shottky diodes and other spintronics devices.
- Operation at room temperature and zero applied field.

Bin Fang et al., Nature Communications 7, 11259 (2016).

Magnetic skyrmion resonance

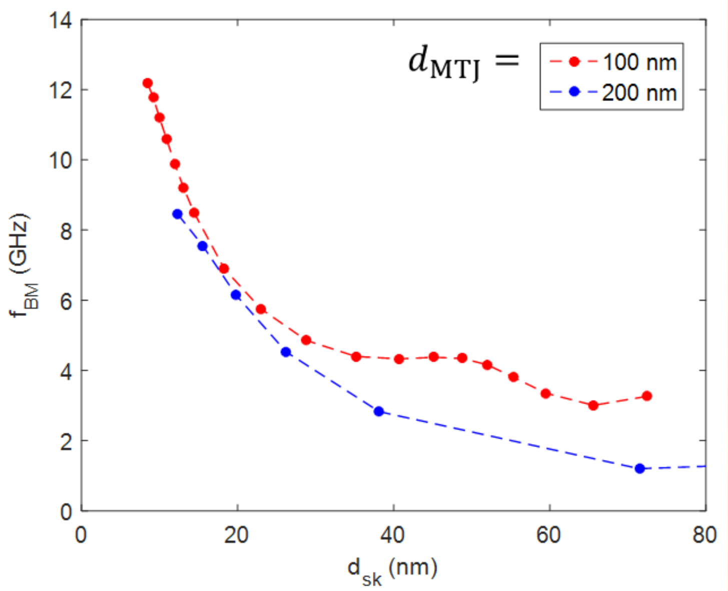
- **Breathing mode**: fundamental resonance of a stationary skyrmion: expansion and contraction of skyrmion core



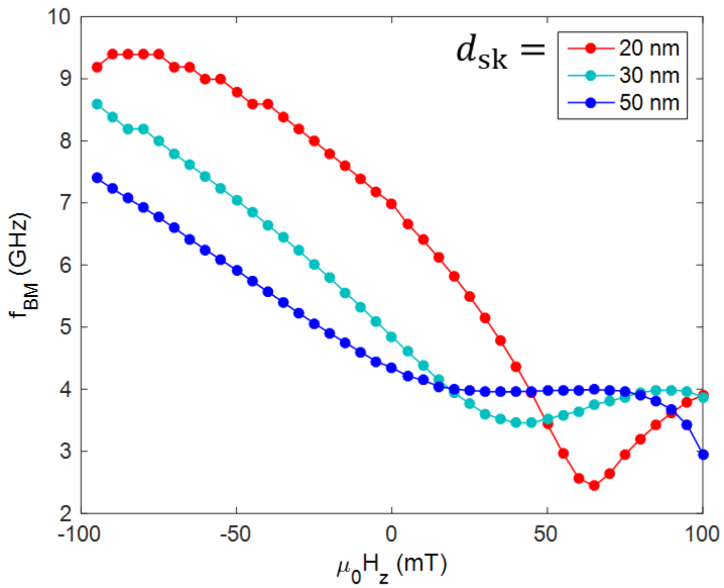
Y. Onose *et al*, “Observation of Magnetic Excitations of Skyrmion Crystal in a Helimagnet Insulator Cu_2OSeO_3”. Phys. Rev. Lett. 109, 037603 (2012)

Skyrmion breathing mode is highly dependent on equilibrium skyrmion size

Zero-field breathing mode frequency vs. skyrmion diameter d_{sk}



Breathing mode frequency vs. out-of-plane field



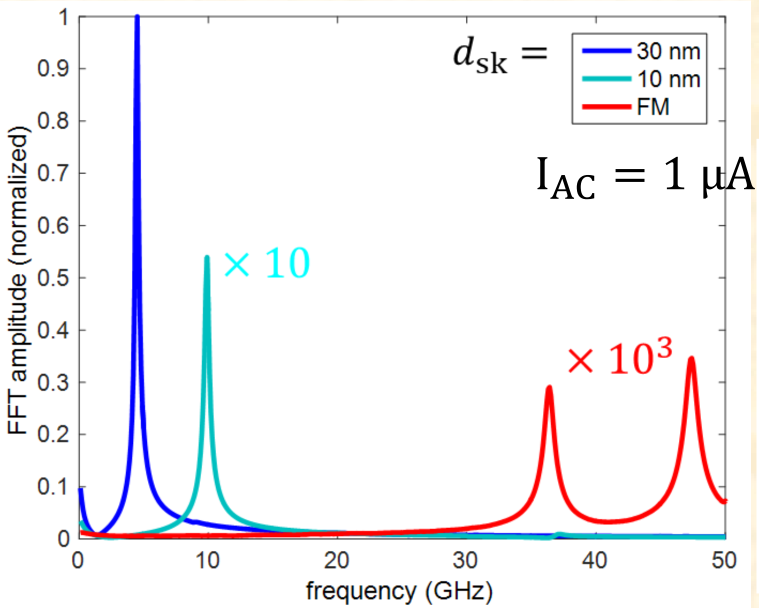
MTJ tunnel magnetoresistance is sensitive to breathing mode dynamics

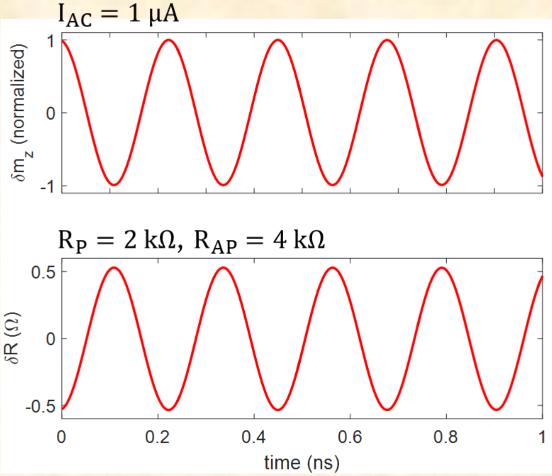
Skyrmion resonance can be efficiently excited with current-induced spin-transfer torque

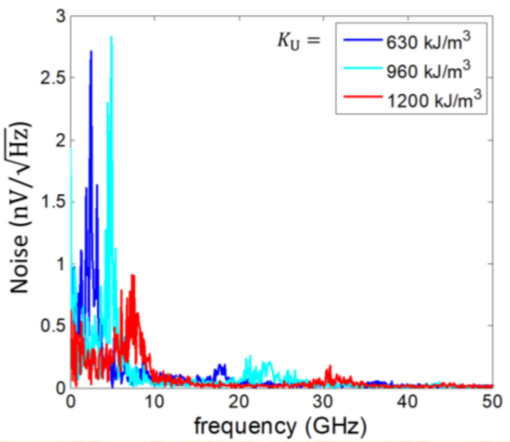
Breathing mode oscillations are measured as resistance oscillations

Junction resistance $R(m_z)$:

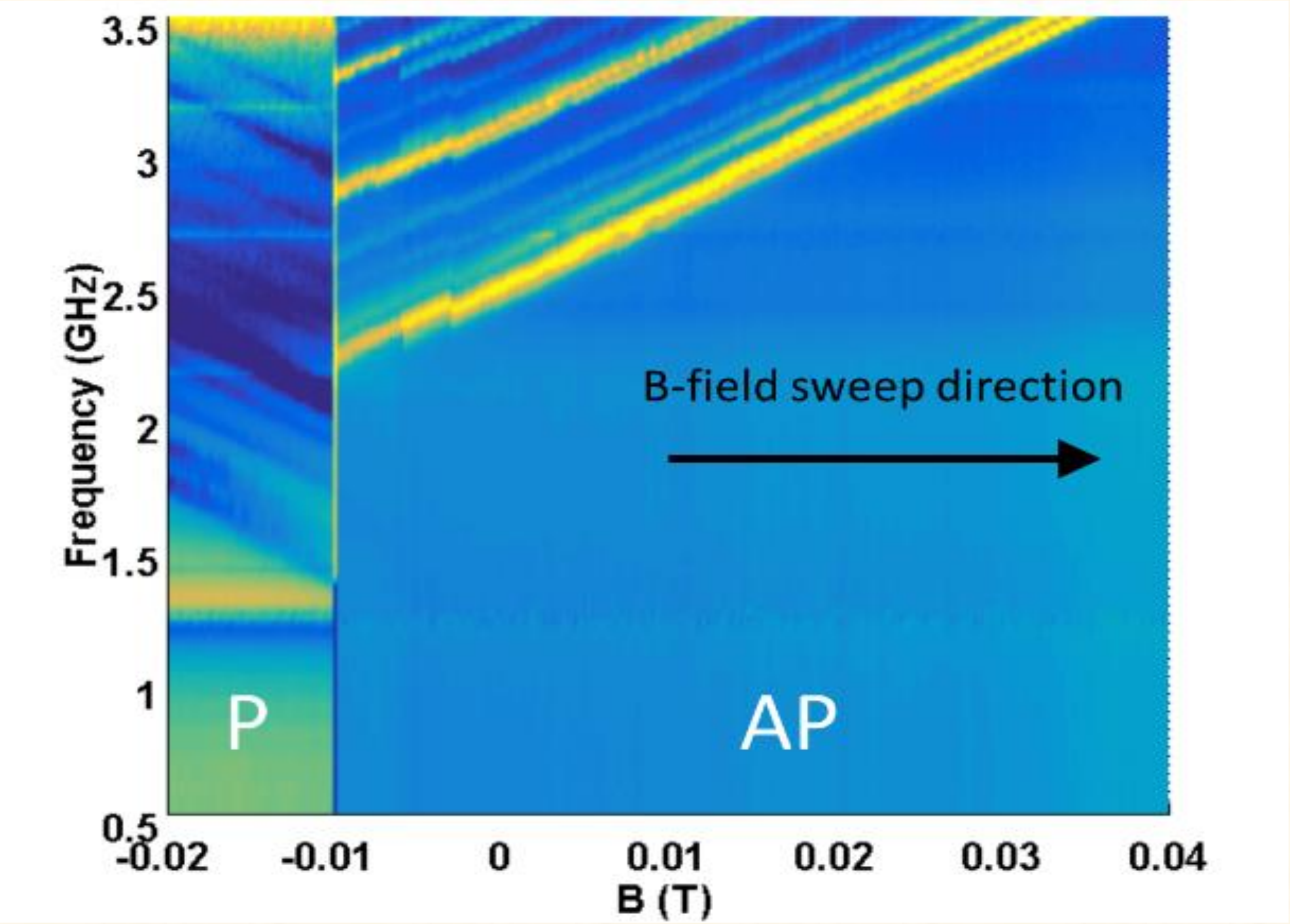
$$\frac{1}{R(m_z)} = \frac{1}{2}\left(\frac{1}{R_\mathrm{P}} + \frac{1}{R_\mathrm{AP}}\right) + \frac{1}{2}\left(\frac{1}{R_\mathrm{P}} - \frac{1}{R_\mathrm{AP}}\right)\langle m_z \rangle$$





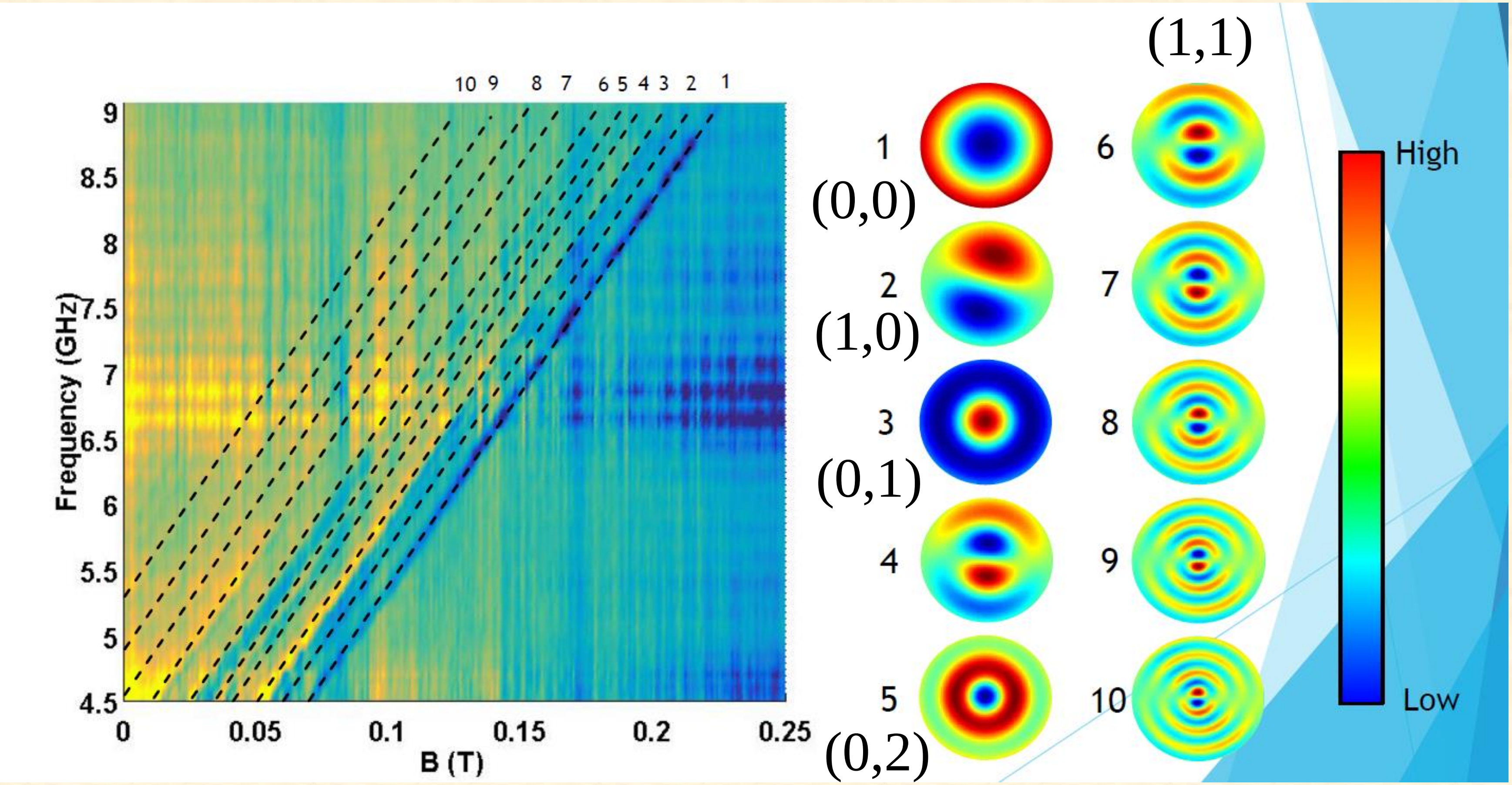


Detection of FM spin-wave modes



Identifying FM spin-wave modes

(azimuthal, radial)



(0,0)

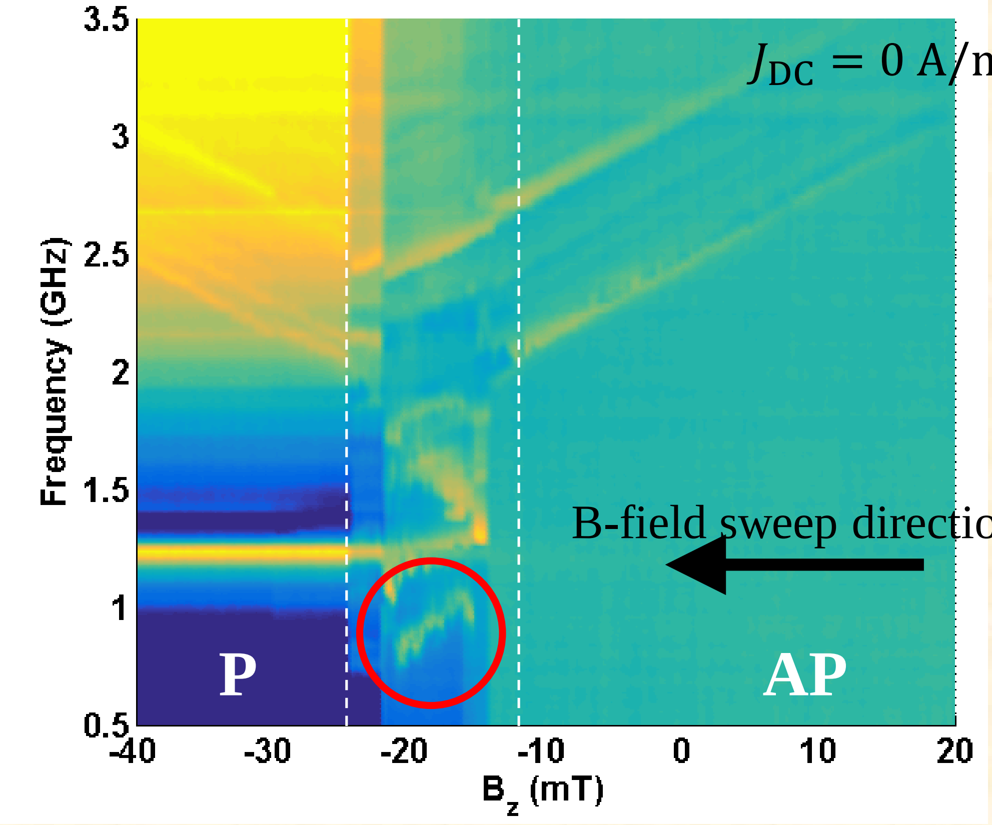
(1,0)

(0,1)

(0,2)

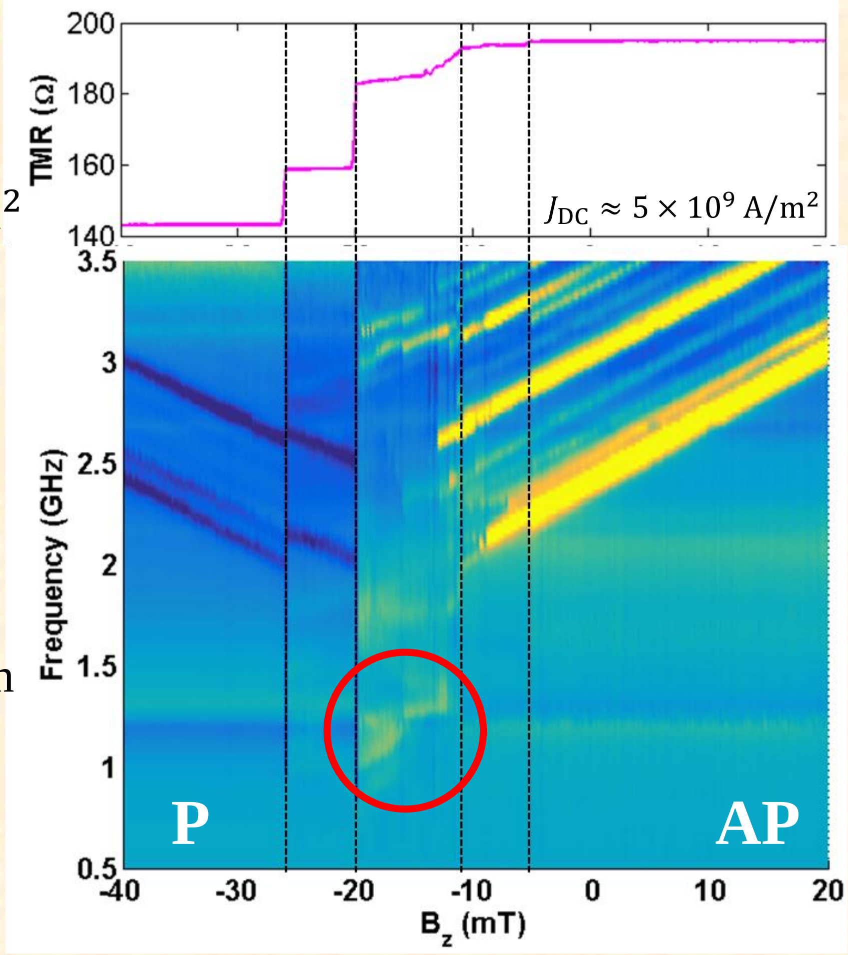
(1,1)

Emergence of new mode in RF spectrum



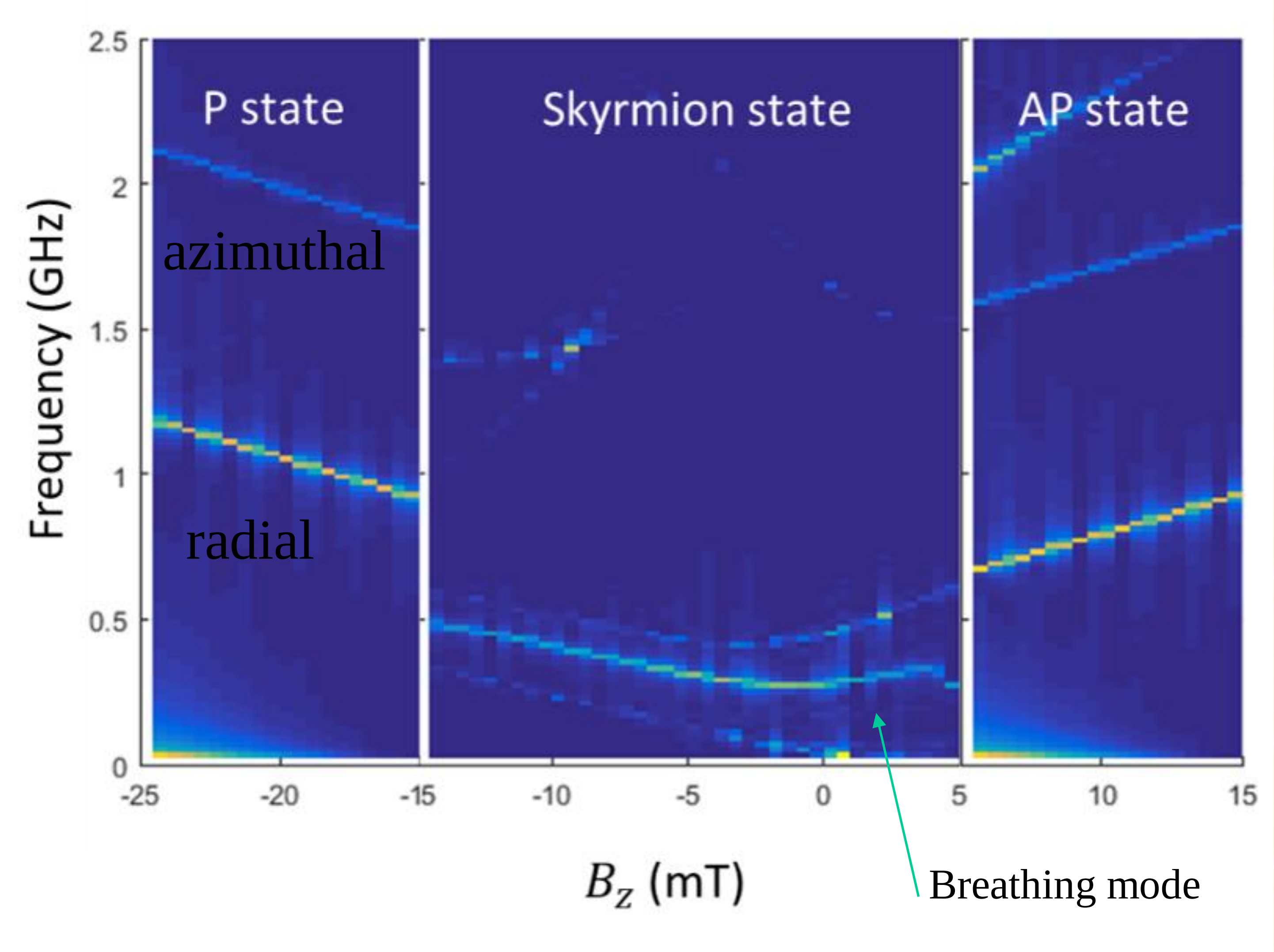
$J_{\mathrm{DC}} = 0\ \mathrm{A/m^2}$

B-field sweep direction



$J_{\mathrm{DC}} \approx 5 \times 10^9\ \mathrm{A/m^2}$

Simulation of FM and skyrmion resonance



Summary of key observations

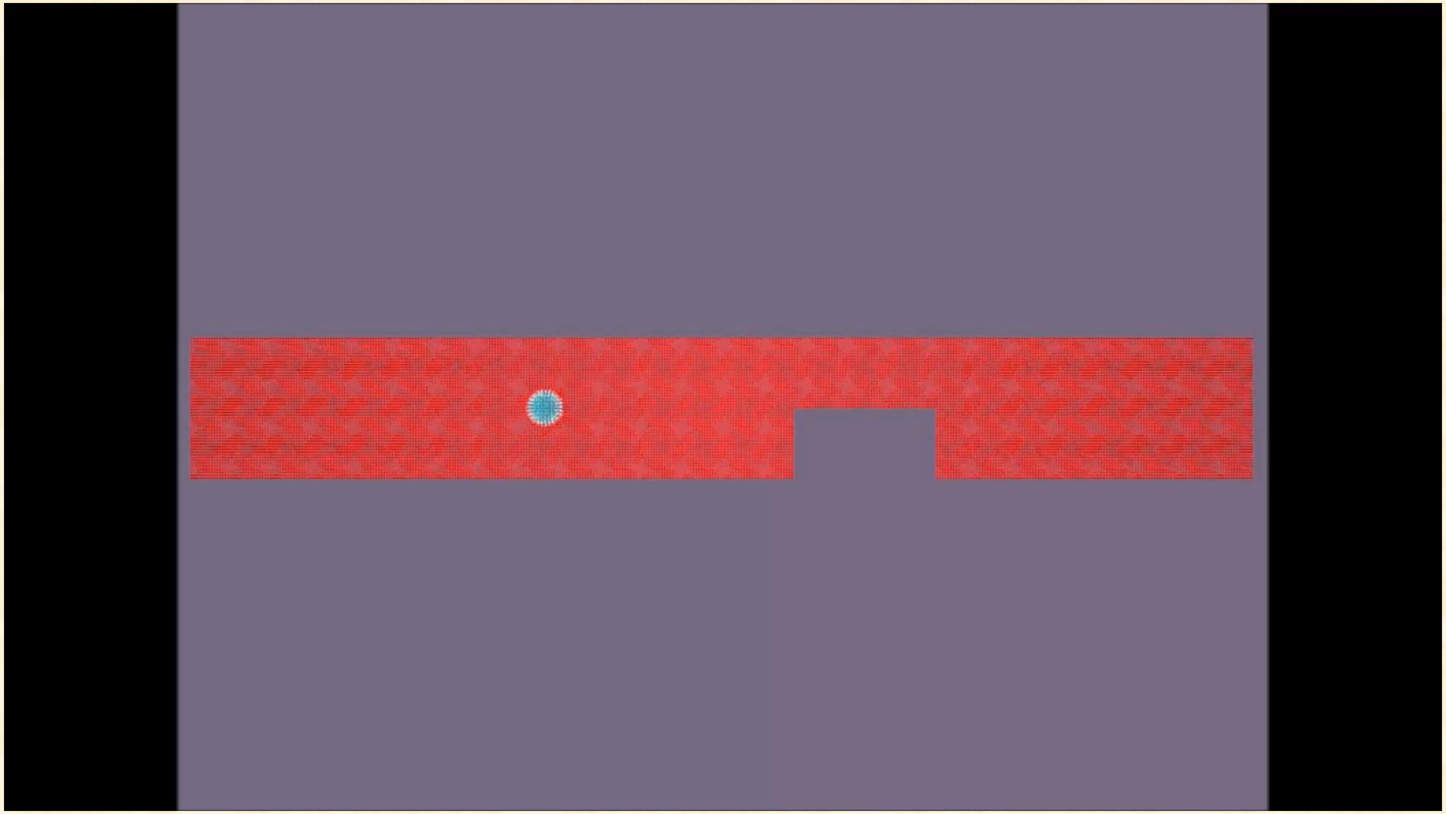
* Unusual spin texture (intermediate-resistance state) can be deterministically generated by a 10 ns electrical pulse.

* The unusual topology can also be nucleated by microwave – induced spin wave excitations.

* A new mode emerges, consistent with the breathing mode of skyrmions

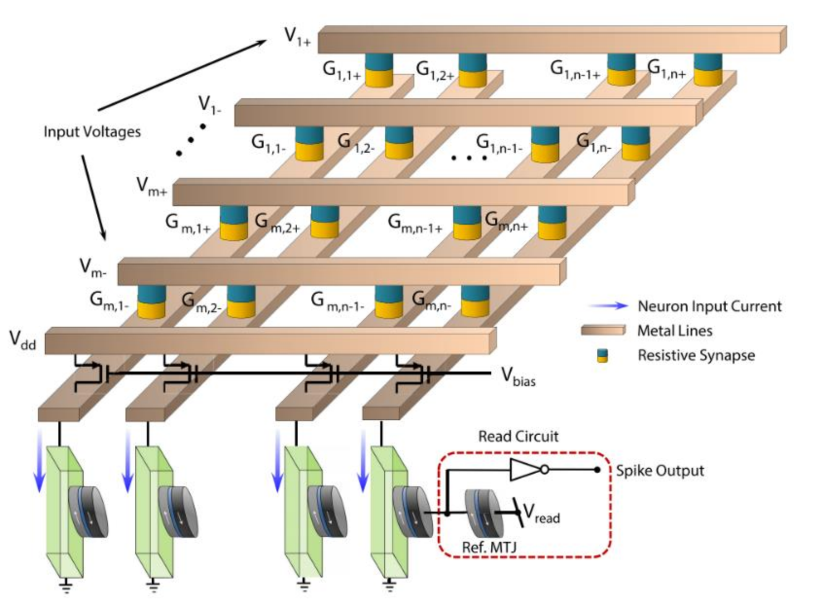
after the transition to the skyrmion state, the FM radial modes all vanish and the azimuthal modes experience a frequency shift

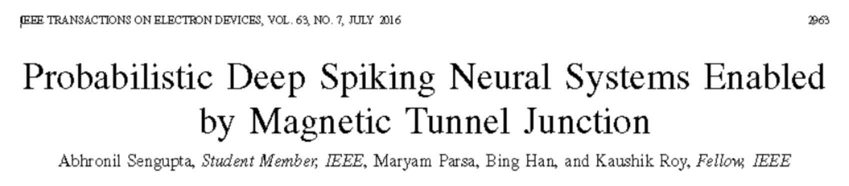
Skymion can be moved by spin-polarized current path for braiding



Gerald Yan

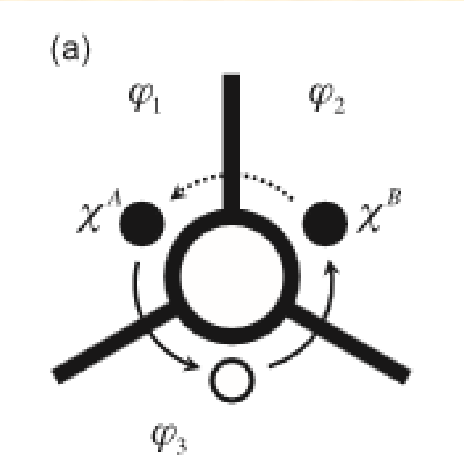
Physical implementation of qubits

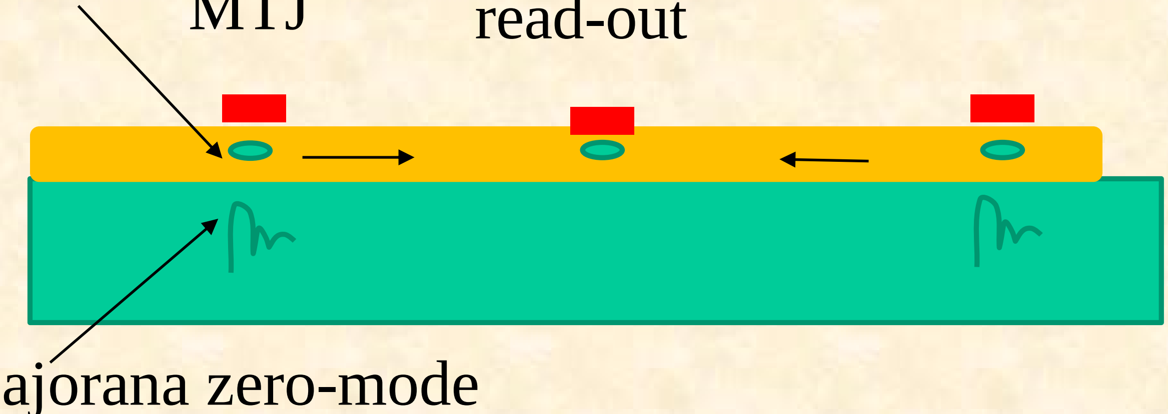



IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 63, NO. 7, JULY 2016 2963

Probabilistic Deep Spiking Neural Systems Enabled by Magnetic Tunnel Junction

Abhronil Sengupta, *Student Member, IEEE*, Maryam Parsa, Bing Han, and Kaushik Roy, *Fellow, IEEE*




skyrmion

MTJ

read-out

magnetic free-layer

superconductor

Majorana zero-mode

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