Center for Spintronic Materials, Interfaces, and Novel Architectures

Voltage Controlled Antiferromagnetics and Future Spin Memory

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NSF, KAUST

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Memory Focus Session, September 20, 2016

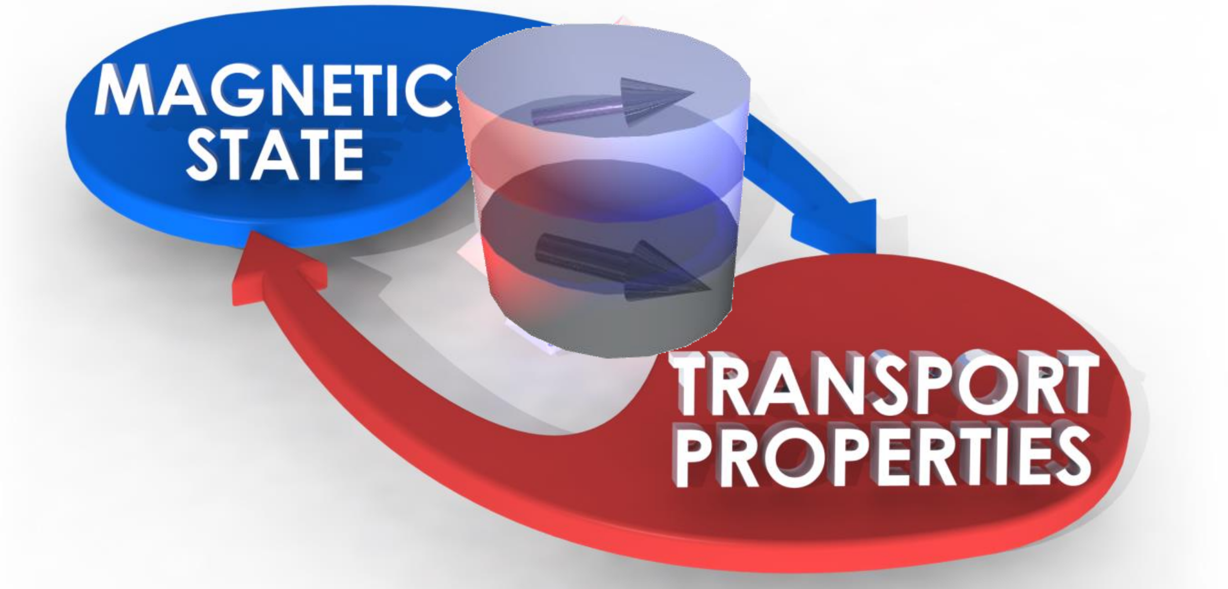
Outline

- **Introduction to Spintronics:**
  why antiferromagnets (AFMs)?
- **Results & progress:**
  new AFM materials and phenomena
- **Challenges: ultra-high frequencies**
- **Long term objectives: AFM devices**

Spintronics

built on a complementary set of phenomena

in which



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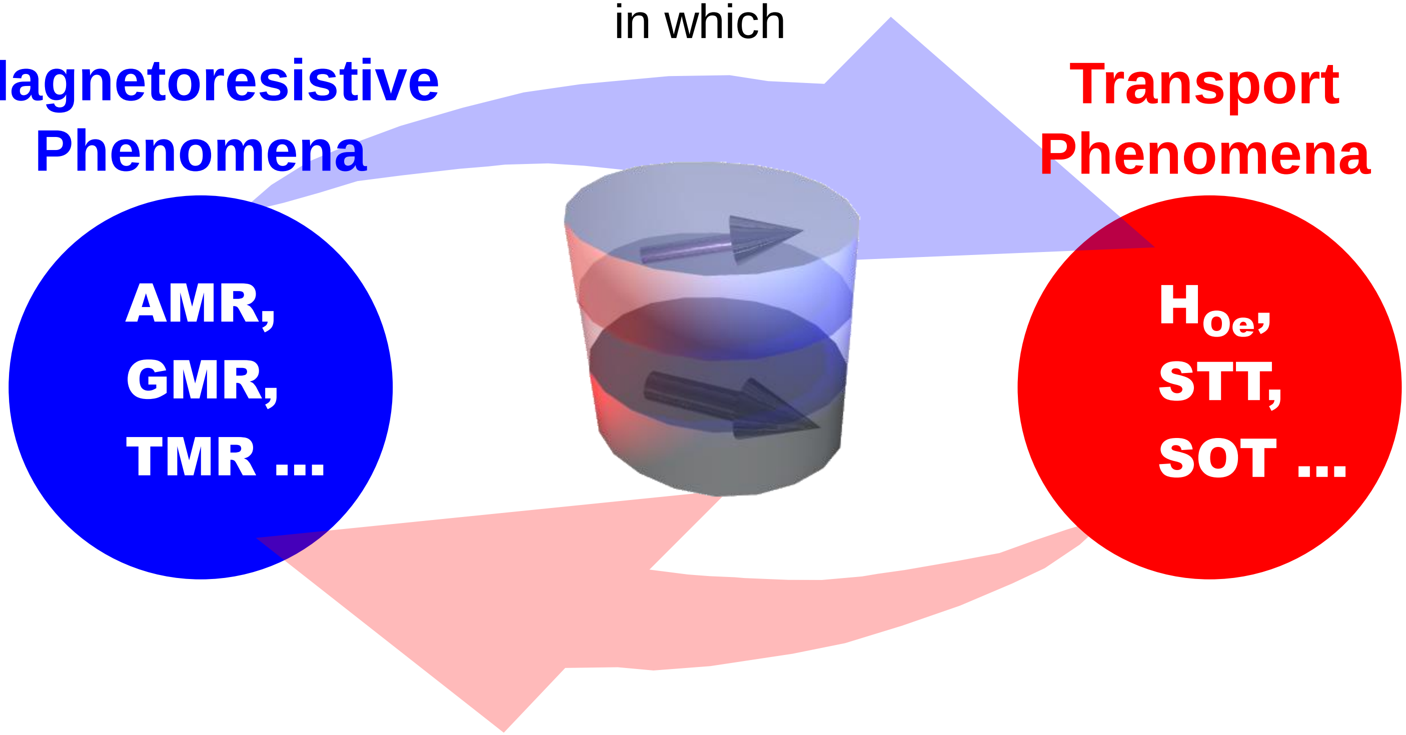


Magnetoresistive Phenomena

AMR,
GMR,
TMR ...

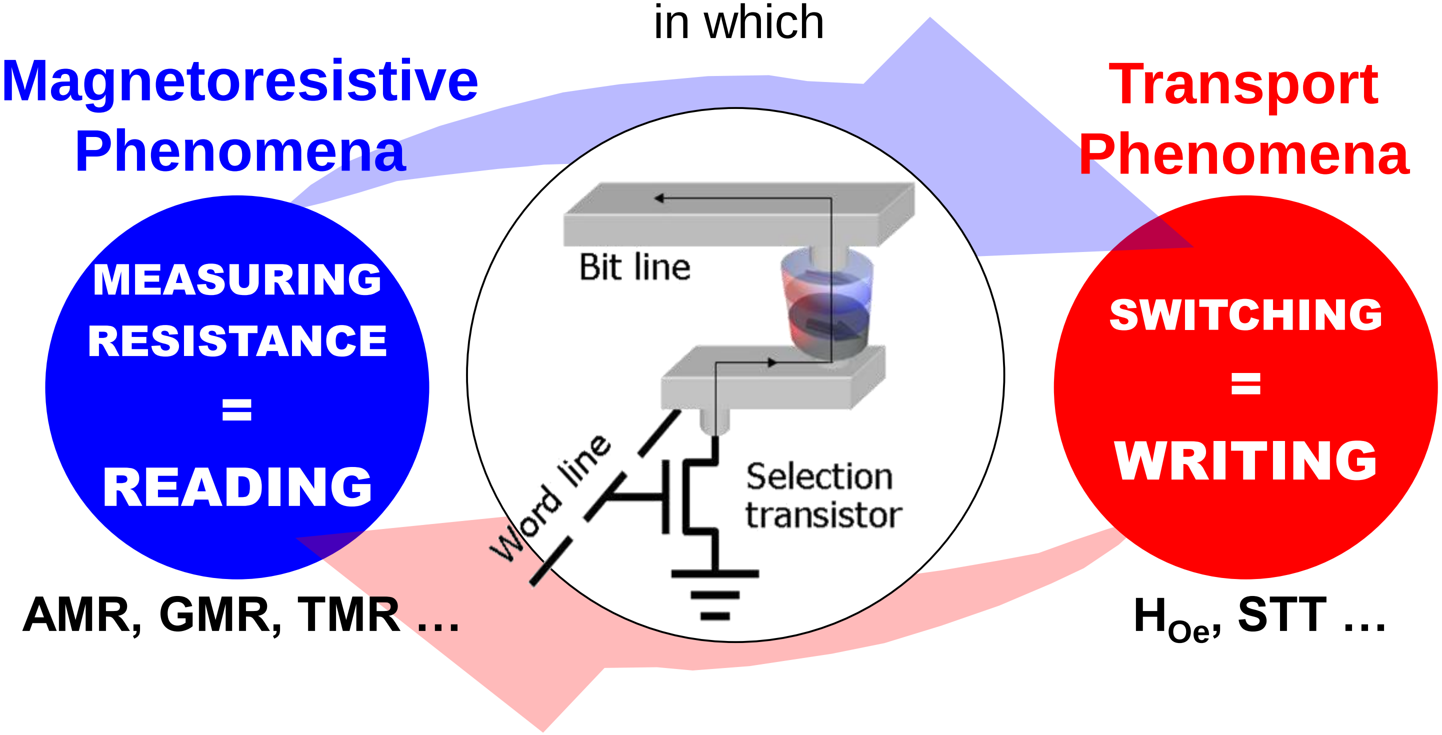
Transport Phenomena

H_{Oe},
STT,
SOT ...

Spintronics

built on a complementary set of phenomena

in which



Magnetoresistive Phenomena

MEASURING RESISTANCE

=

READING

AMR, GMR, TMR …

Transport Phenomena

SWITCHING

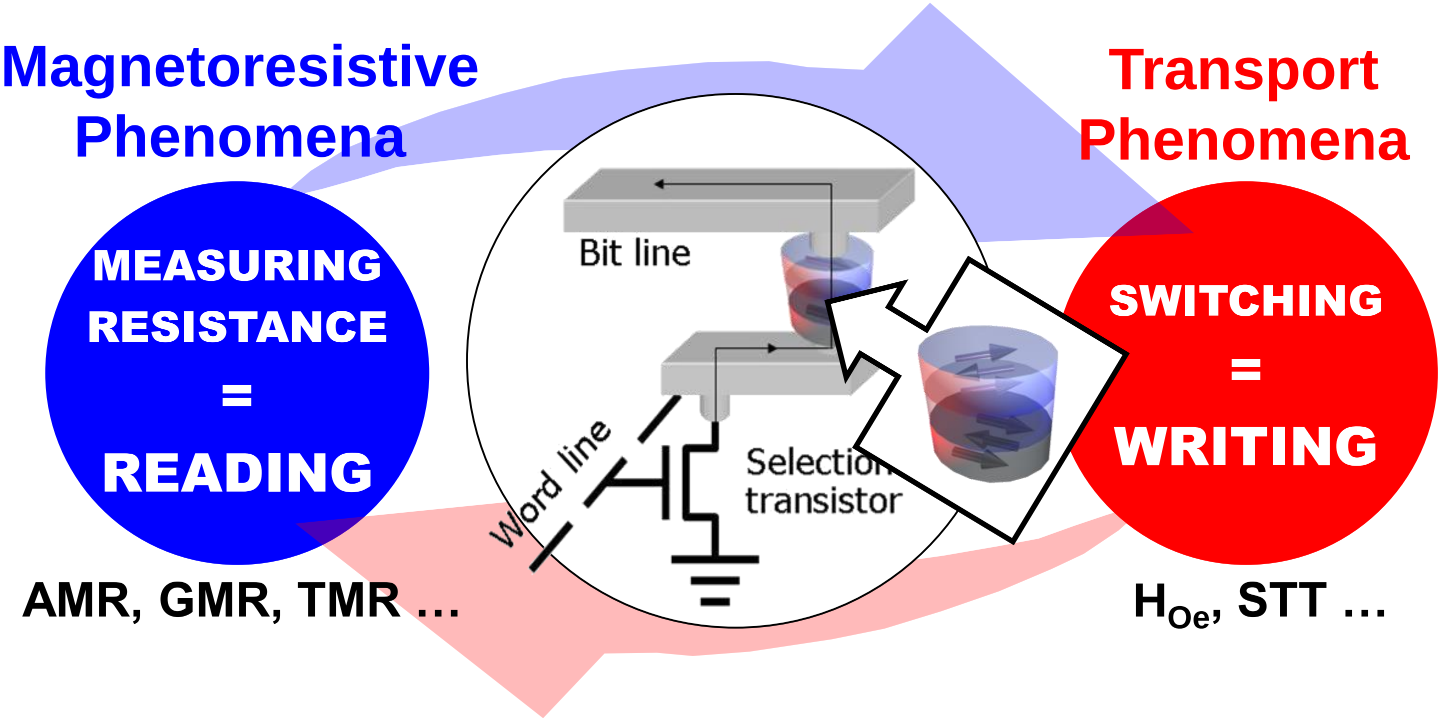
=

WRITING

H_{Oe}, STT …

AFM Spintronics

Unique advantages of AFM materials



Magnetoresistive Phenomena

MEASURING RESISTANCE = READING

AMR, GMR, TMR …

Transport Phenomena

SWITCHING = WRITING

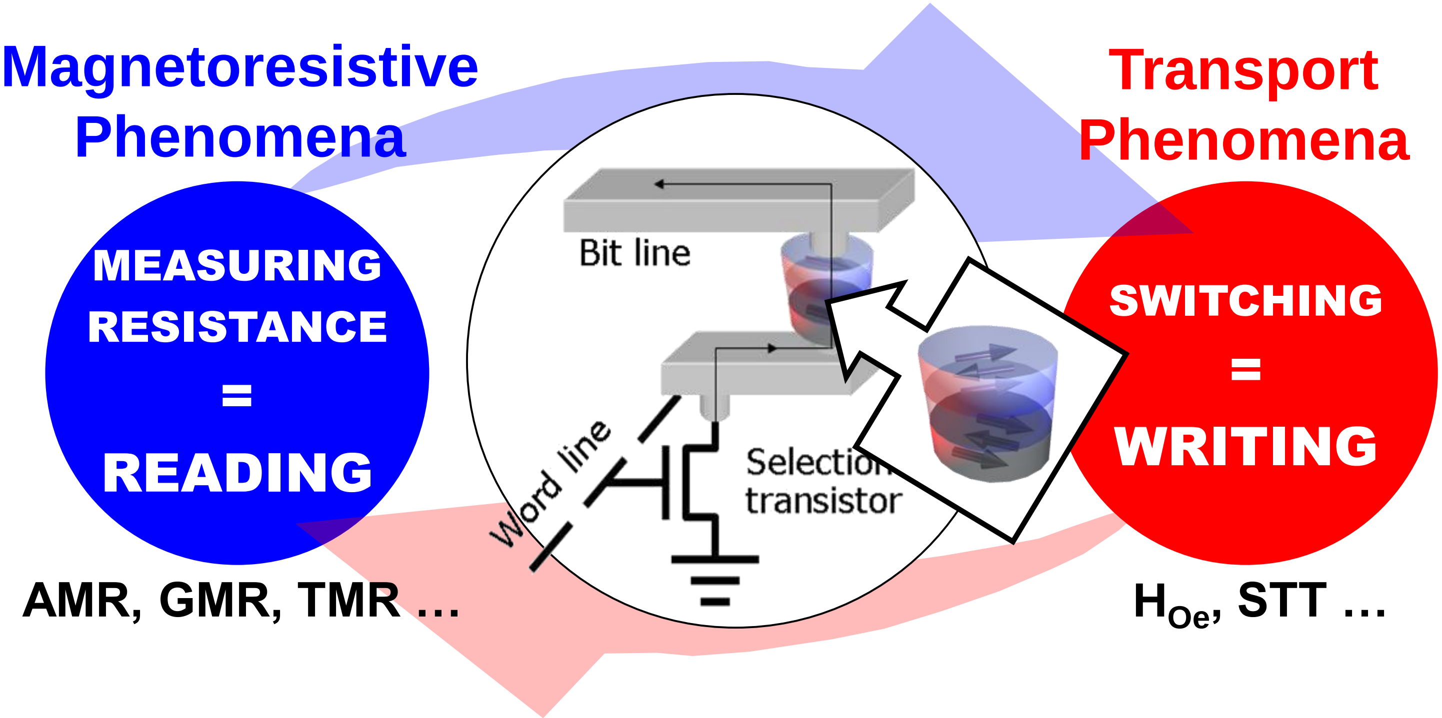
H_{Oe}, STT …

- **insensitive to H-perturbations** → *more robust/stable*
- **stray-field-free** → *no cross-talk between devices*
- **ultra-high frequencies** → *ultra-fast writing schemes*

- **Explore AFM potential for spintronic devices**

AFM Spintronics

Challenges being addressed



Magnetoresistive Phenomena

MEASURING RESISTANCE = READING

AMR, GMR, TMR …

Transport Phenomena

SWITCHING = WRITING

H_{Oe}, STT …

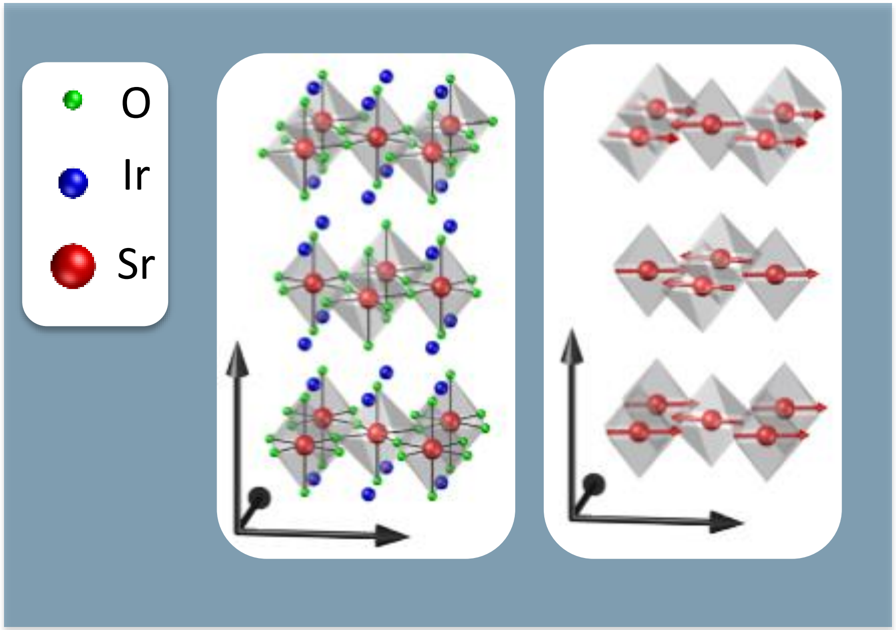
- **exploring new AFM materials**
- **demonstrating new transport phenomena**
- **developing new concepts**

- **Explore AFM potential for spintronic devices**

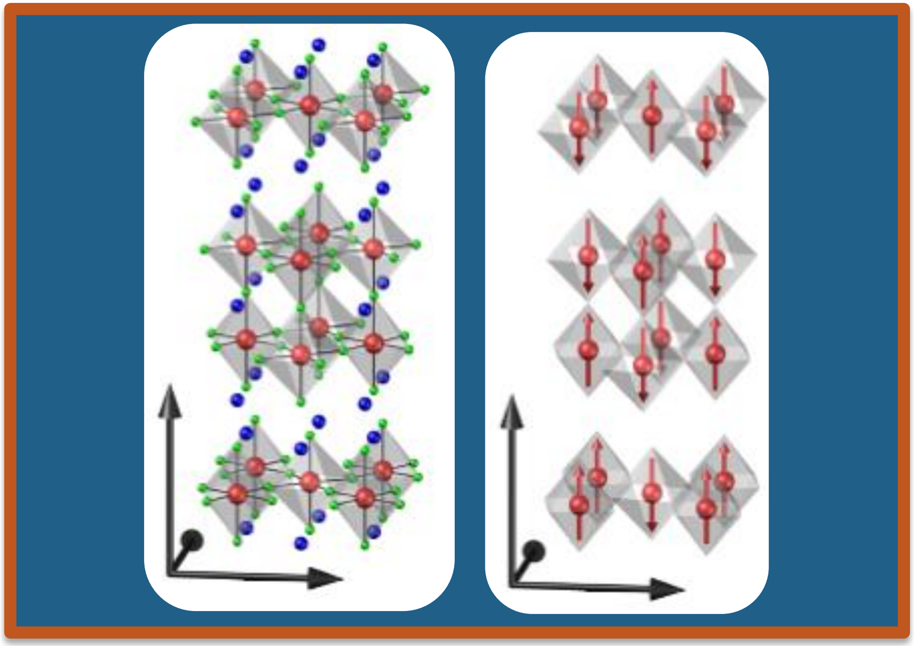
AFM Materials

Comparative study of AFM iridates

- **Sr_2IrO_4**



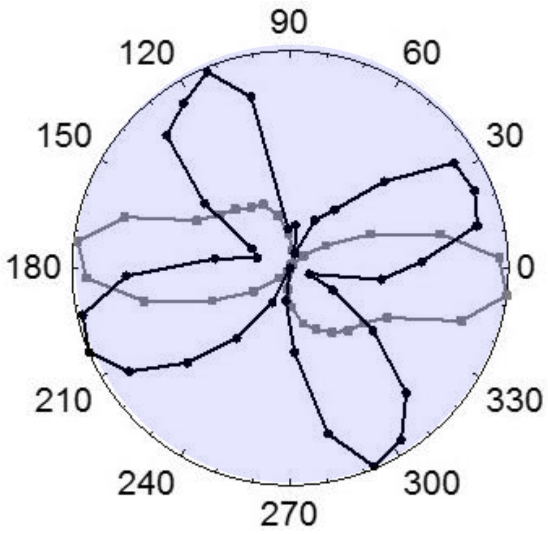
- **$Sr_3Ir_2O_7$**

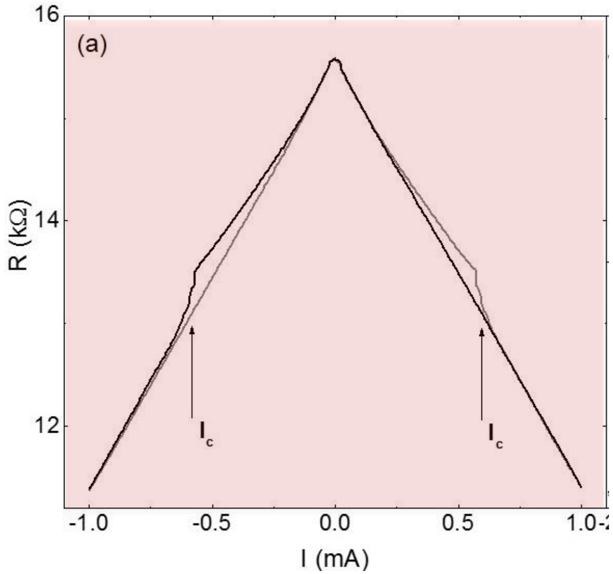


- Single vs double layer of distorted octahedra
- Sr_2IrO_4 → ab-plane canted AFM structure (T_C=240 K)
- $Sr_3Ir_2O_7$ → c-axis collinear AFM structure (T_C=285 K)
- Semiconductor with a band gap of ~30-200 meV

Sr_2IrO_4

OBSERVED: a complete set of interconnections between magnetic state and transport currents





- We found a very large anisotropic magnetoresistance (AMR) which can be used to monitor (read) the magnetic state of AFM
- We demonstrated the feasibility of reversible resistive switching driven by high electric bias fields

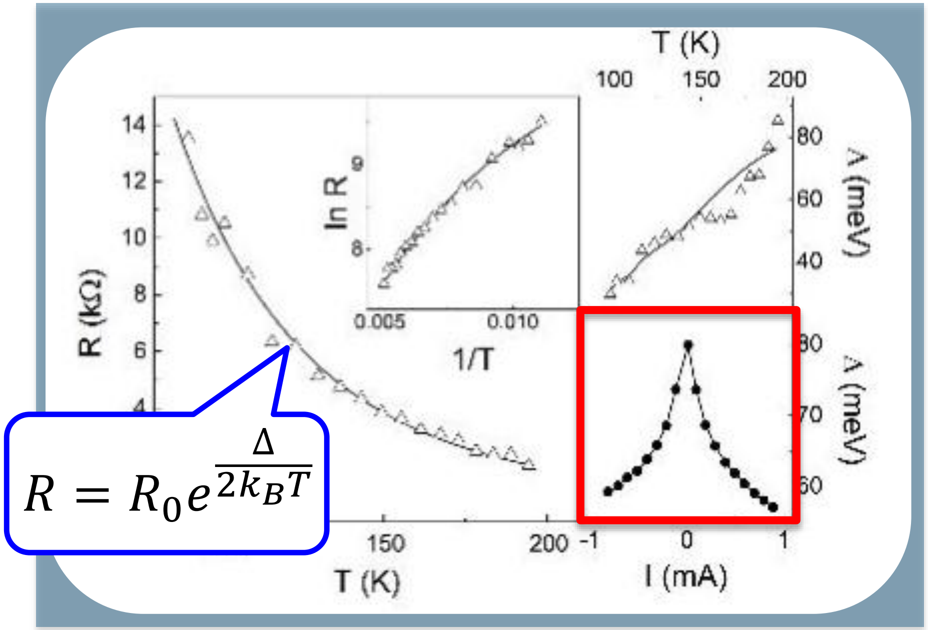
- **the promise of AFM spintronics is very appealing**

Wang et al., Phys. Rev. X 3, 041034 (2014); Wang et al., Phys. Rev. B 92, 115136 (2015)

Bias-dependent activation energy

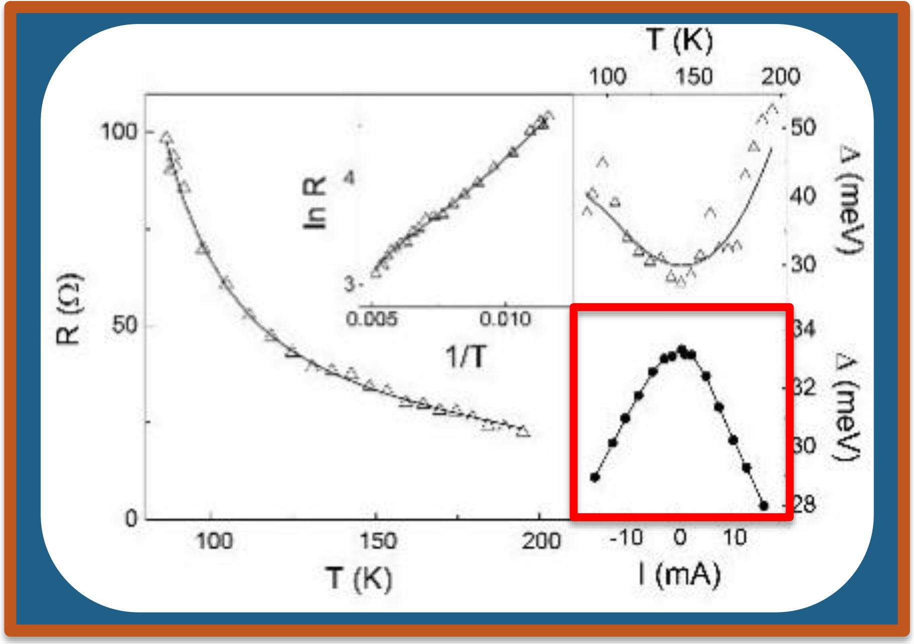
T-dependent resistivity measurements

- **Sr_2IrO_4**



$$R = R_0 e^{\frac{\Delta}{2k_B T}}$$

- **$Sr_3Ir_2O_7$**



- Activation energy can be directly probed with standard temperature-dependent resistivity measurements
- Arrhenius plots (lnR vs T^{-1}) at different biases show the bias-dependent band-gap

- **Electrically tunable band-gap**

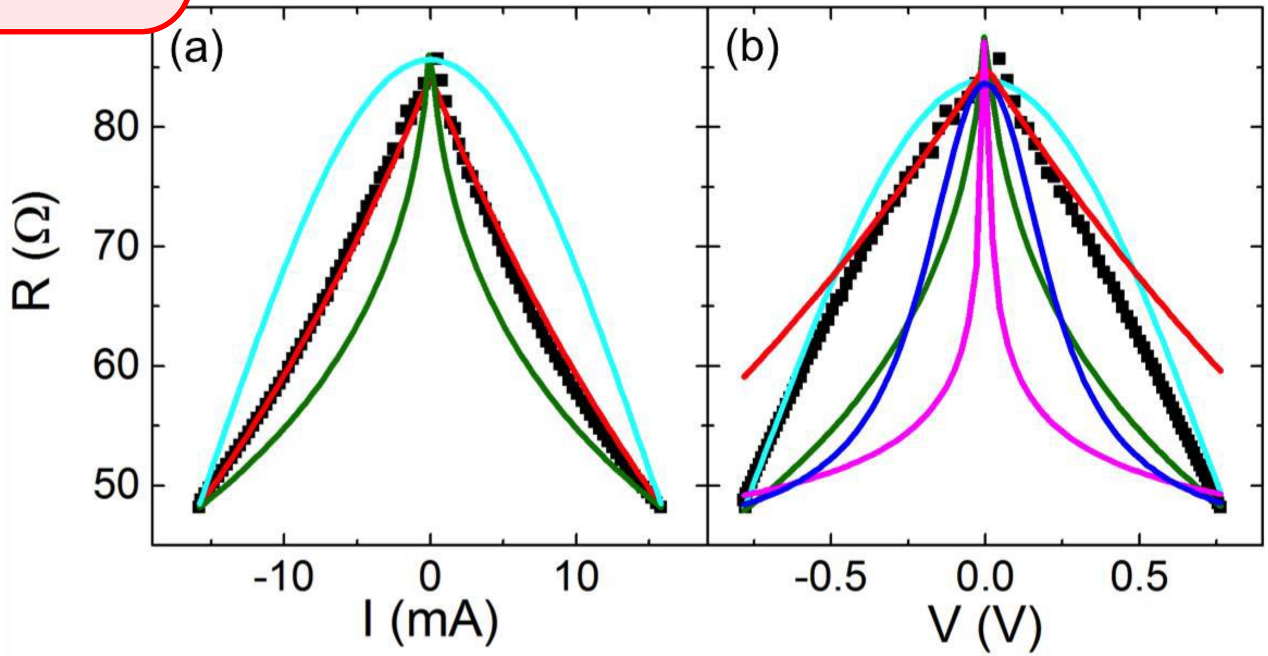
Bias-dependent resistance

Field effect model:

$$R(I) = A * e^{\frac{\Delta(I)}{2k_BT}}$$

$$\Delta(I) = \Delta_0 - B * |I|$$

IV characteristics



Schottky

Tunneling

Joule heating

$\rho \propto e^{\Delta/2k_BT_{pc}}$

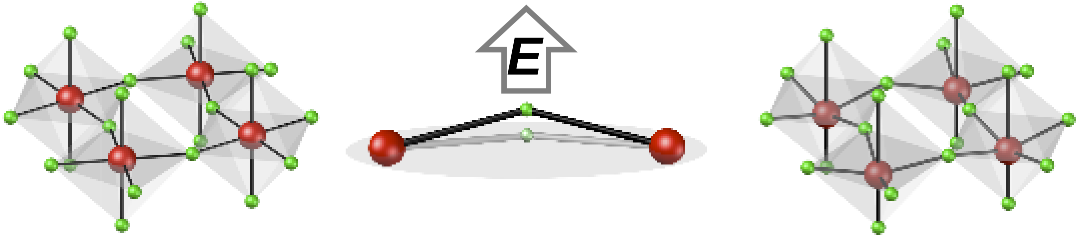
$T_{pc} \propto V^2$

Poole – Frenkel

$j = j_0 e^{-\beta E^{1/2}}$

SCLC

$I \sim V^{\alpha}$



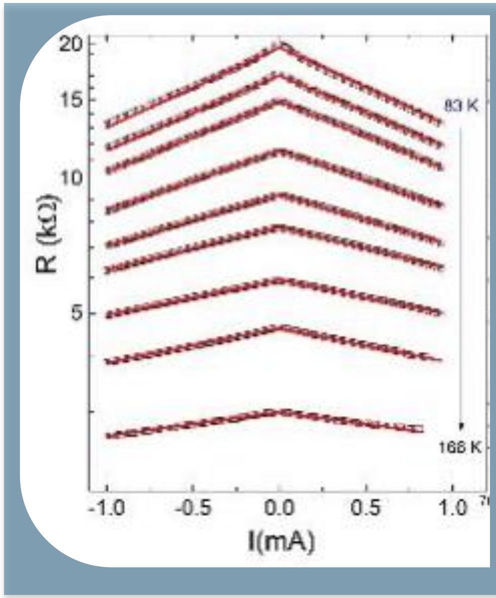
- High electric fields can displace oxygen ions along the c-axis

- **Electrically tunable band-gap**

Bias-dependent resistance

IV characteristics

- **Sr_2IrO_4**



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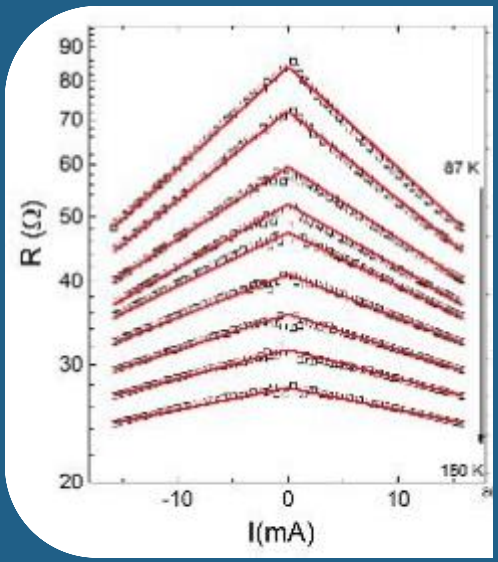
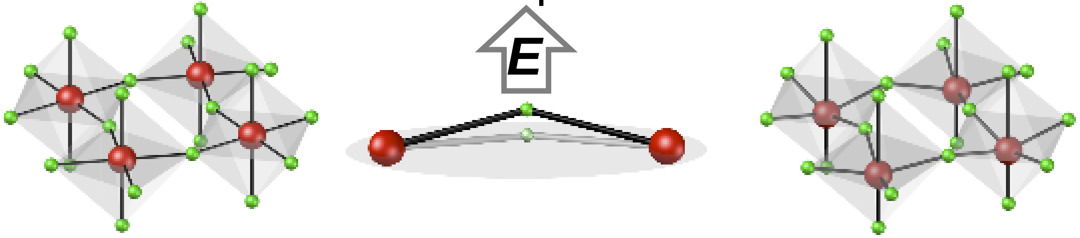


Field effect model:

$$R(I) = A * e^{\frac{\Delta(I)}{2k_BT}}$$

$$\Delta(I) = \Delta_0 - B * |I|$$

- Temperature dependent *R(I)* curves can be well fitted by field effect model



- High electric fields can displace oxygen ions along the c-axis

- **Electrically tunable band-gap**

Electronic band gap

- *conventional semiconductors (Si)* → fixed by crystal structure and chemical composition
- *defines transport and optical properties* → of great importance for performance of semiconductor devices (diodes, transistors, lasers)

- **Tunable band gap**

→ enhanced functionality and flexibility of future electronic and optical devices

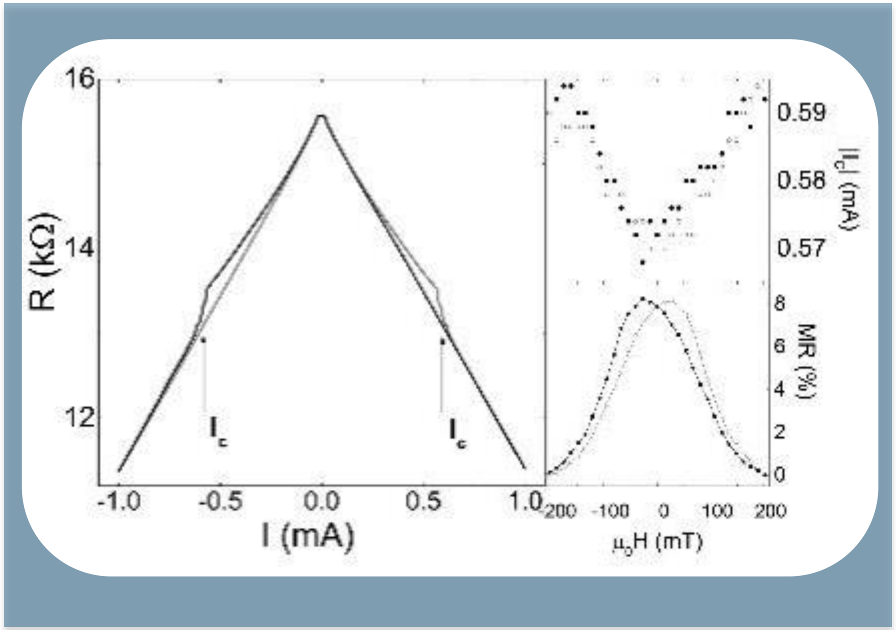
- *Previously realized* → in a 2D material – electrically gated bilayer graphene   Oostinga et al. *Nature Materials* **7**, 151 (2007)
- *Our study* → in a 3D antiferromagnetic iridates

→ band gap engineering in 5d transition-metal oxides

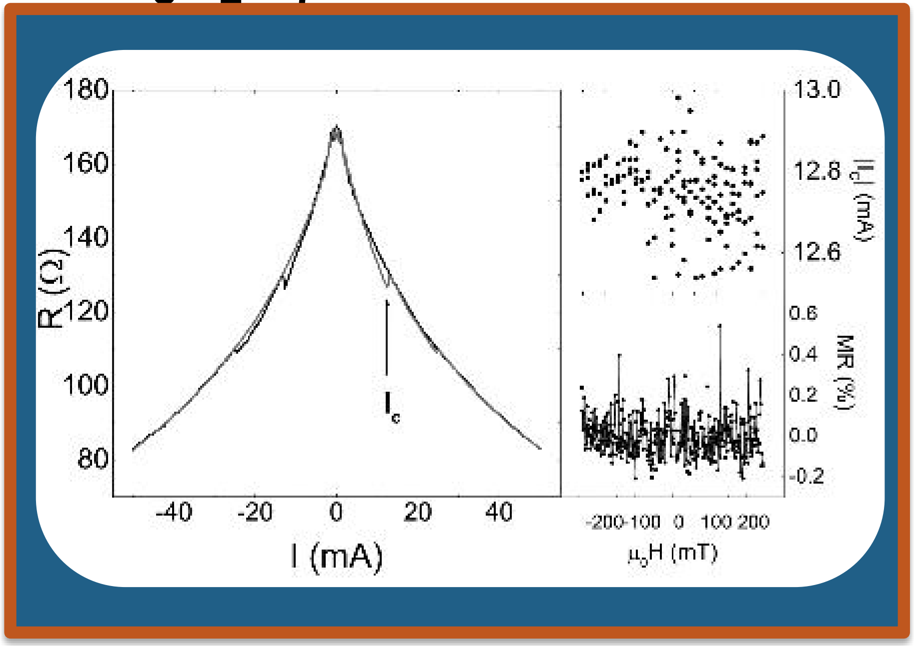
Reversible resistive switching

driven by high currents/electric fields

- **Sr_2IrO_4**



- **$Sr_3Ir_2O_7$**



- Above a critical current both samples show reversible resistive switching
- Switching may be associated with field induced structural transition between two metastable states in the crystal structure
- Switching is magnetic field dependent in Sr_2IrO_4

- **Electrically driven resistive switching**

High-frequency measurements

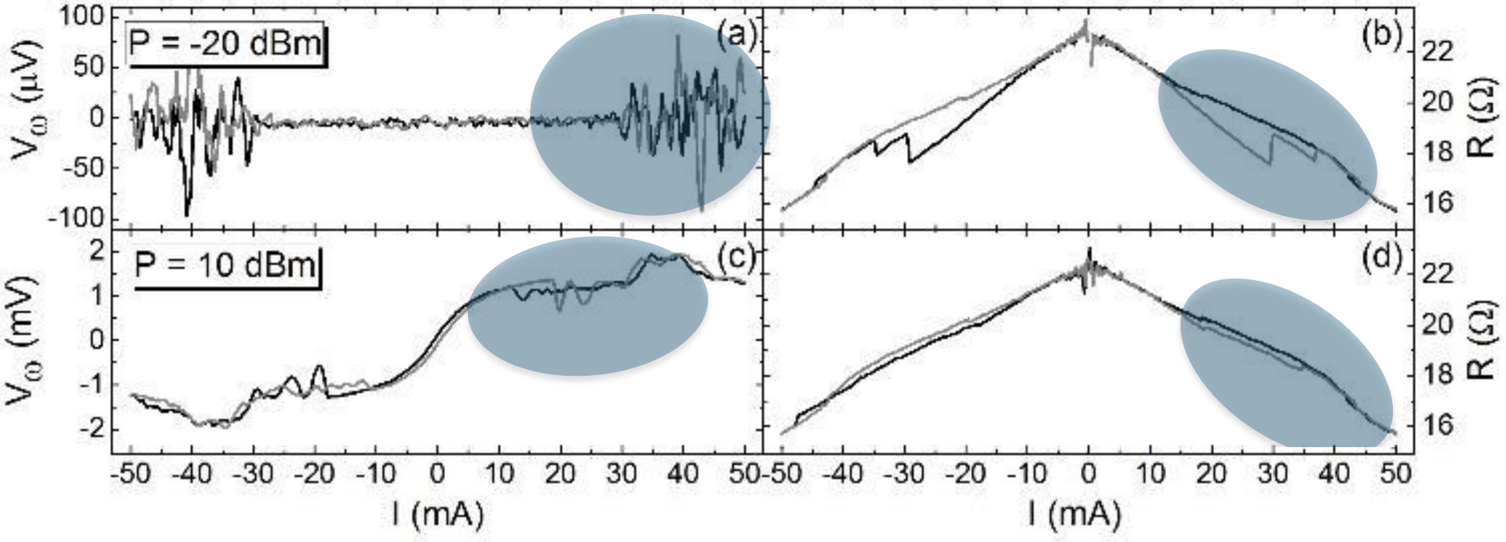
Suppression of switching and resonance-like structure in $Sr_3Ir_2O_7$

Rectification V_ω

Resistance R

3 GHz

Power



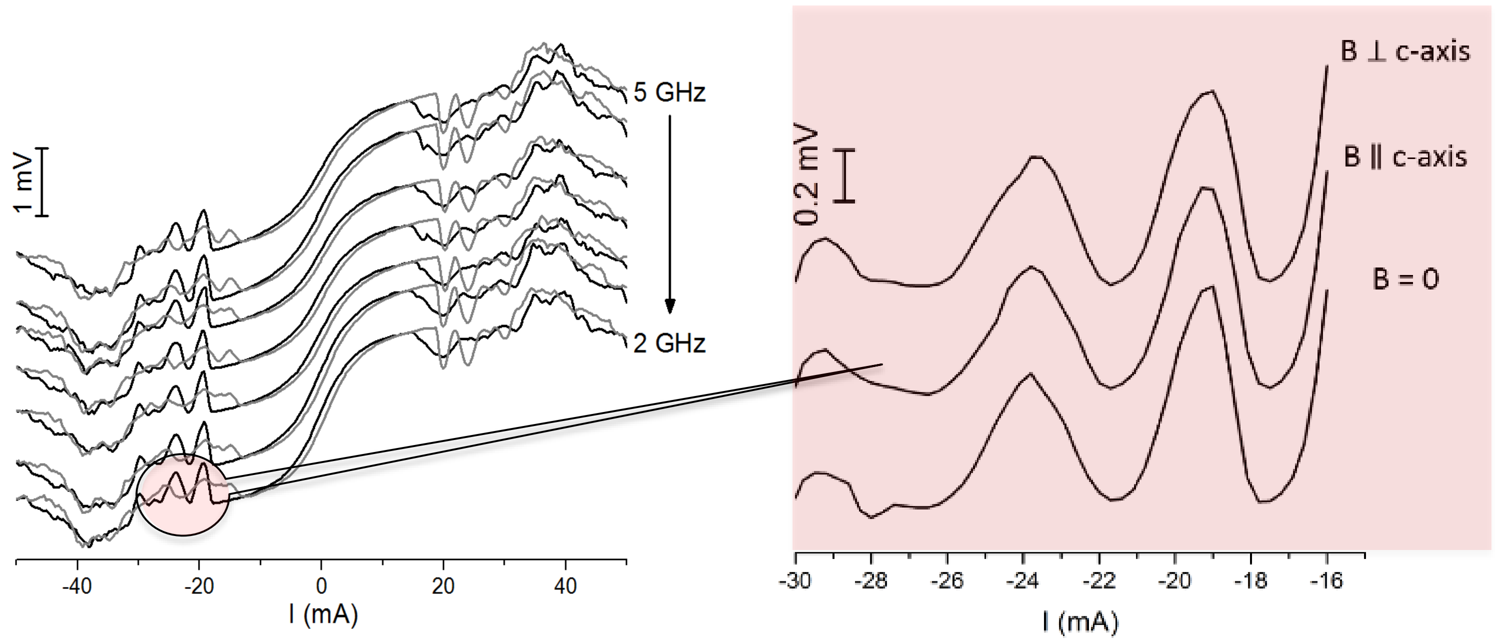
- Microwaves suppress switching
- Microwaves produce resonance-like structure

- **Antiferromagnetic resonance?**

High-frequency measurements

Antiferromagnetic resonance?

$$\omega_{res}/\gamma = H_0 \pm \sqrt{2H_A H_E}$$



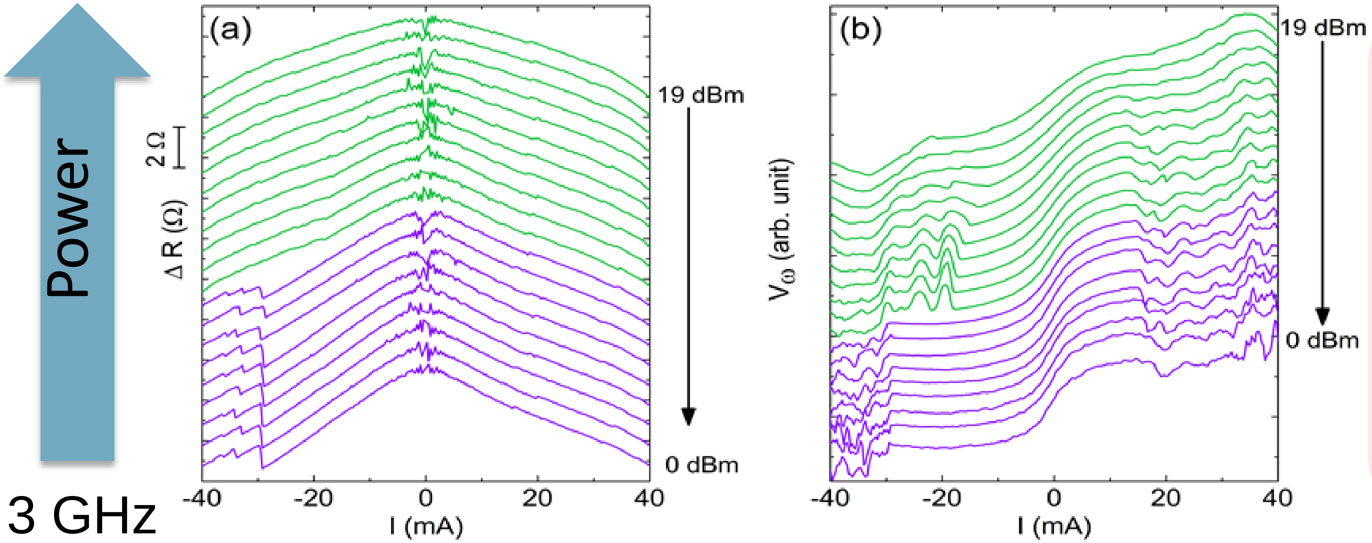
- Frequency and magnetic field have no effect on shape or position of resonance-like structure

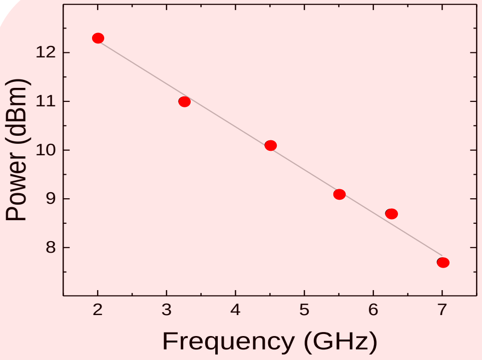
High-frequency measurements

Frequency dependence of switching in $Sr_3Ir_2O_7$

Resistance R

Rectification V_ω





- **Frequency-dependent power threshold**

- Resonant structure only appears above a critical power level
- Critical power depends on the frequency of applied microwaves

- **Evanescent waves?**
- **Dissipationless magnonics?**

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Theory: Dissipationless Multiferroic Magnonics

PRL **114,** 157203 (2015) PHYSICAL REVIEW LETTERS week ending 17 APRIL 2015

Dissipationless Multiferroic Magnonics

Wei Chen[1,2] and Manfred Sigrist[2]

[1]*Max-Planck-Institut für Festkörperforschung, Heisenbergstrasse 1, D-70569 Stuttgart, Germany*
[2]*Theoretische Physik, ETH-Zürich, CH-8093 Zürich, Switzerland*

Dissipationless magnonics can be excited by an ac electric field in coplanar multiferroric insulators with AFM spiral order

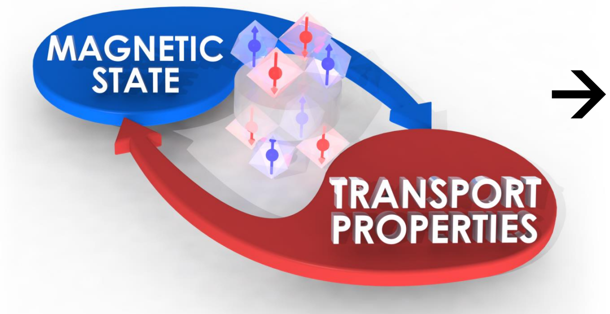
- Displacement of oxygen ions due to the dc bias can lead to electric polarization and lattice deformations, which may change magnetic structure to AFM spiral-like order via spin-orbit coupling

  → ac bias can excite electrically controlled magnonics
- dc voltage originates from rectification of ac current and time-dependent resistance due to small lattice distortions

Voltage Controlled Antiferromagnetics and Future Spin Memory

- **Results & progress:**
  → **new AFM phenomena:** *confirmed in Sr_2IrO_4 and $Sr_3Ir_2O_7$*
  → **intriguing high-frequency effects:** *1st step towards fast AFMs?*

- **Challenges:**
  → **high-temperature materials:** *Copper oxides have demonstrated Cu Néel temperatures 300–500 K*
  → **ultra-high frequencies:** *THz detection*



- **Long term objectives:**
  → **AFM devices:** *from AFM-MTJ to AFM-RAM*