Magneto-optic Studies of Spin Dynamics and Spin Torque in High Spin-Orbit Materials

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Acknowledgements

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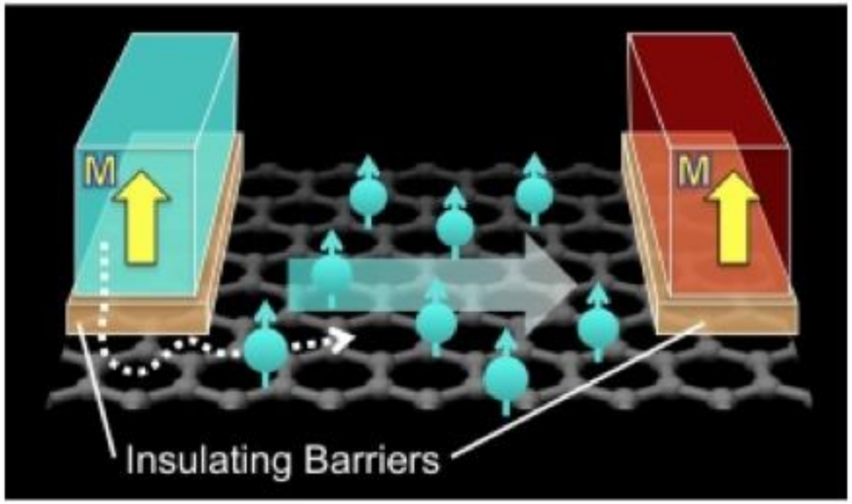
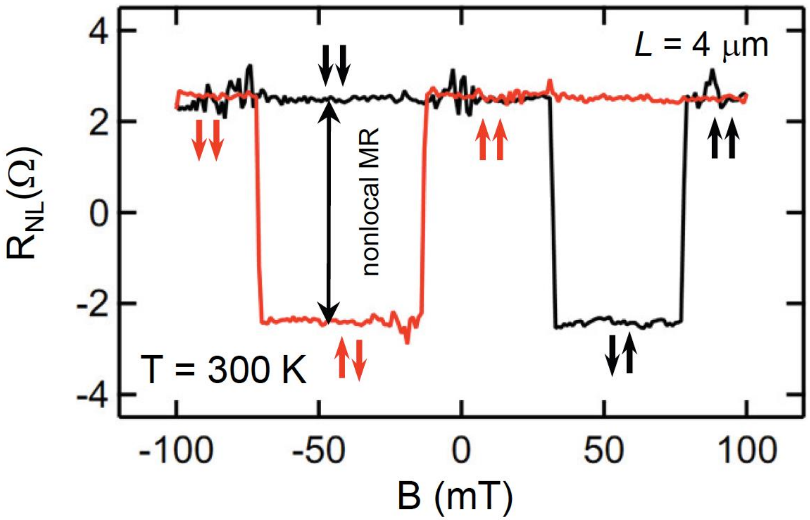
Outline

- Overview
- Spin Dynamics in Transition Metal Dichalcogenides
- Spin Torque Dynamics in FM/HM bilayers
- Summary

Overview: Spin-Orbit Coupling in 2D Materials

Low spin-orbit coupling is good for spin transport

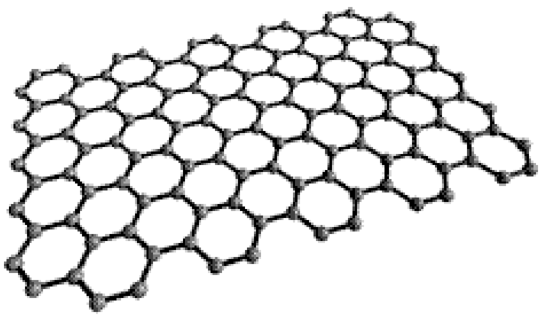




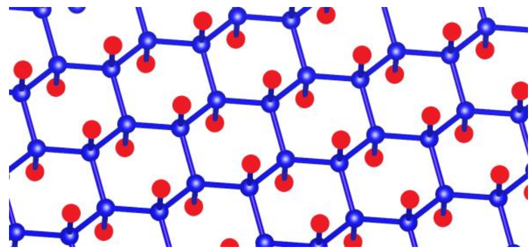
Graphene exhibits spin transport at room temperature with spin diffusion lengths up to tens of microns

W. Han, RKK, M. Gmitra, J. Fabian, *Nature Nano.* **9**, 794–807 (2014)

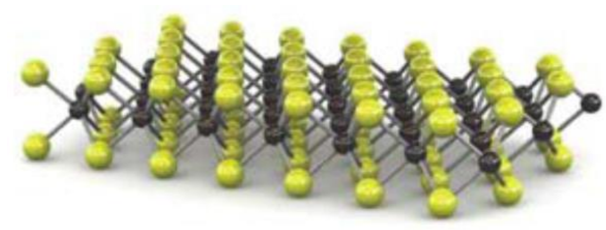
Overview: Spin-Orbit Coupling in 2D Materials



Heavy Graphene



Transition Metal Dichalcogenides (TMD)



Graphene (C) Silicene (Si) Germanene (Ge) Stanene (Sn) MoS_2 (TMD)

Weak SPIN ORBIT COUPLING Strong

- Long spin lifetimes
- Spin Transport at RT

- Spin Hall effect
- Quantum spin Hall effect

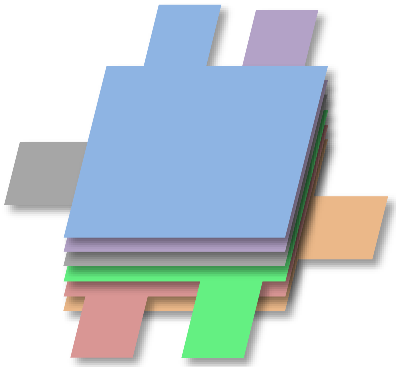
A wide range of spin-dependent phenomena can be a realized in 2D materials by tuning spin-orbit coupling

Overview: Spin-Orbit Coupling in 2D Materials

2D Spin Transport Channels (Low SOC)
- Graphene
- Phosphorene

2D Spin-Optical Materials
- TMDs

2D Spin Hall Materials, (High SOC)
- TMDs
- (?) Heavy graphene



2D Insulators/Barriers
- hex. Boron Nitride

2D Ferromagnets
- (?) Mn:WSe_2
- (?) $GeCrTe_3$
- (?) Doped Graphene

2D Topological Materials
- (?) Stanene
- (?) TMDs
- (?) Layered Zintl

Unprecedented ability to combine properties through vertical stacking and proximity effects

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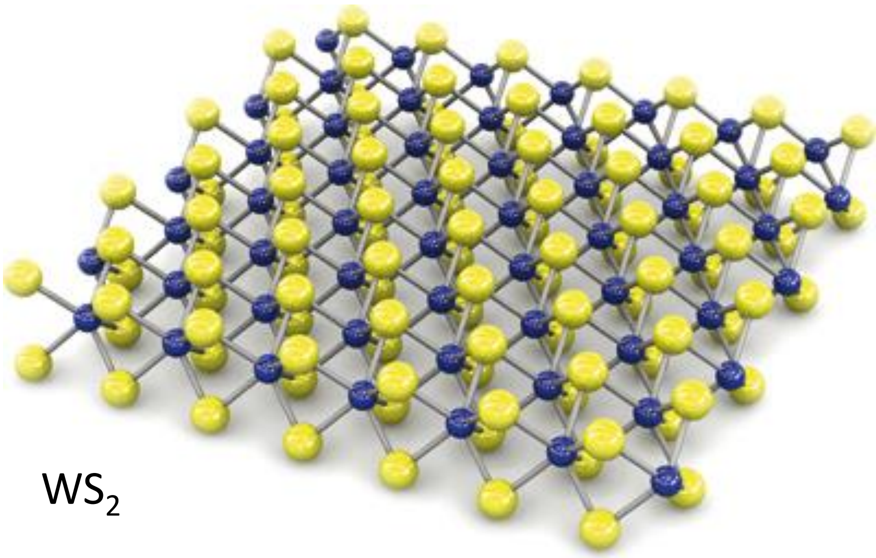
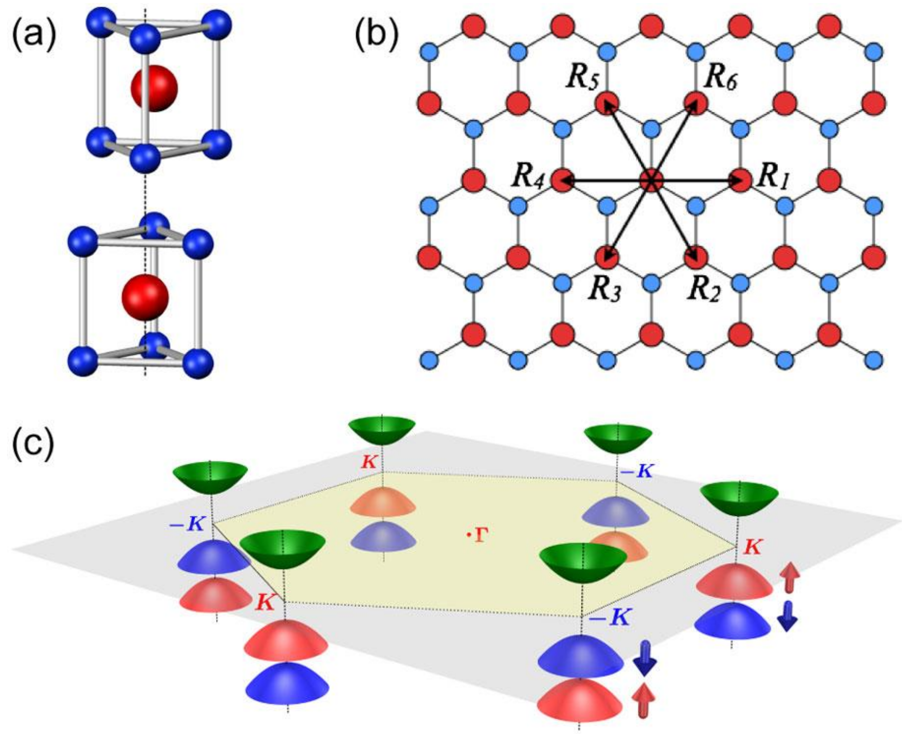
Monolayer Transition Metal Dichalcogenide

Monolayer TMD, such as WS_2, with hexagonal structure and inversion symmetry breaking

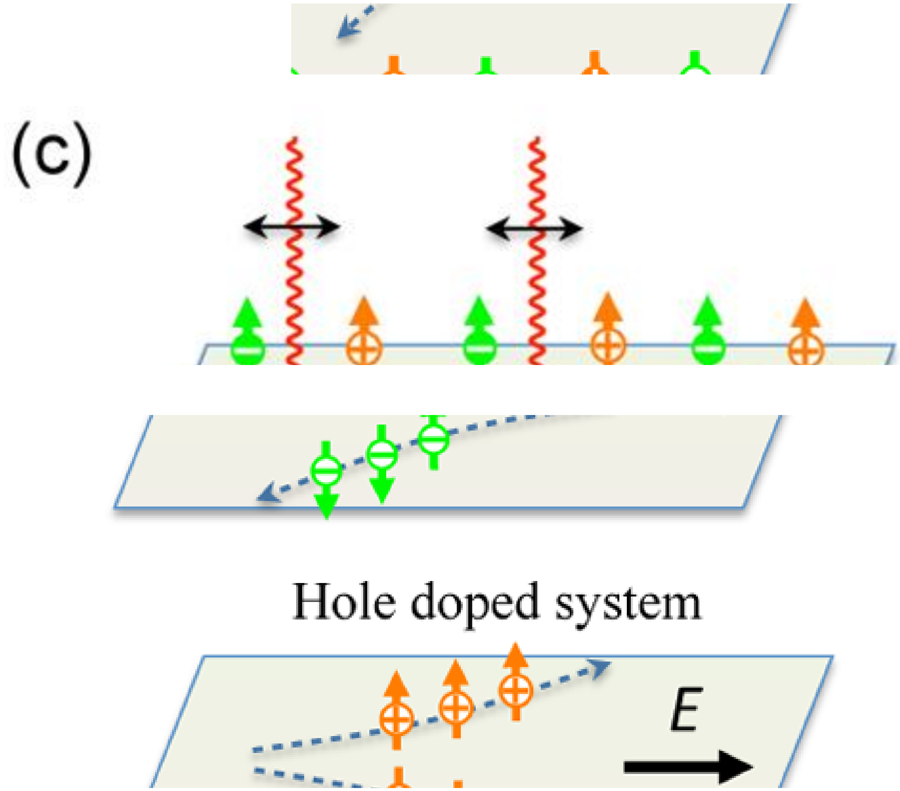


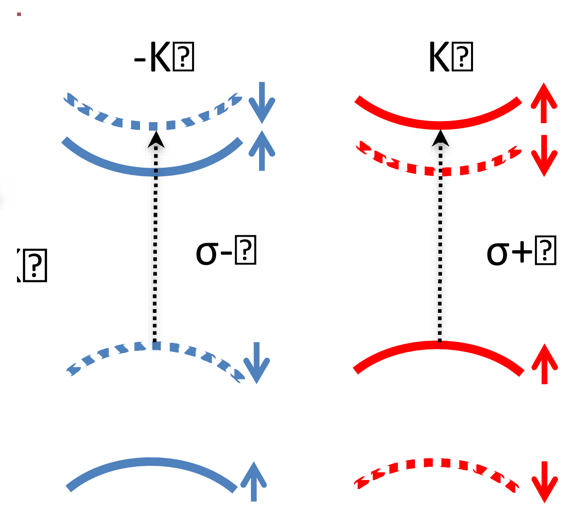
WS_2



Spin-valley coupling due to large spin-orbit interaction

Monolayer Transition Metal Dichalcogenide





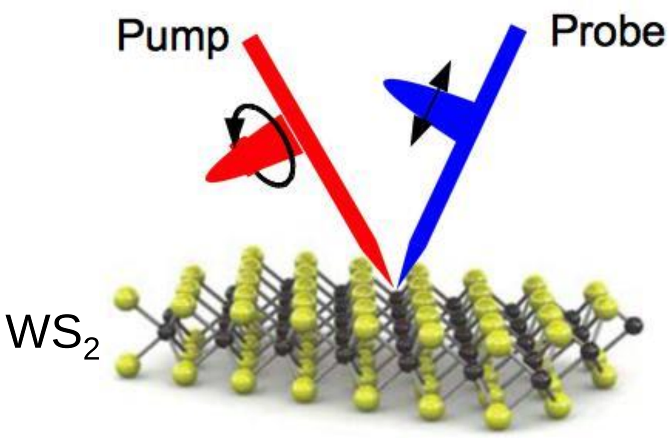
Berry curvature → Valley Hall Effect

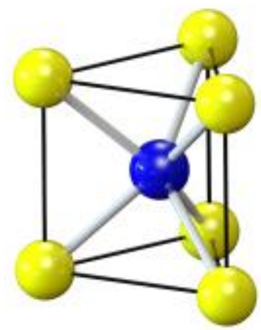
+ spin-valley coupling → Spin Hall Effect

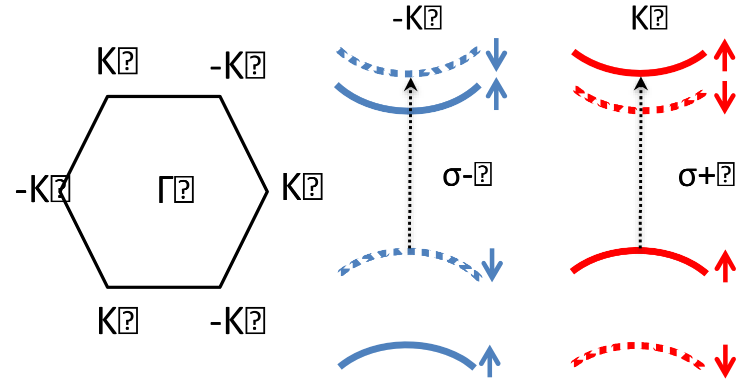
Theory: D. Xiao et al, PRL 108, 196802 (2012)

Experiment: K. F. Mak et al, Science 344, 1489 (2014)

Ultrafast Optical Microscopy of Spin Dynamics in Transition Metal Dichalcogenides



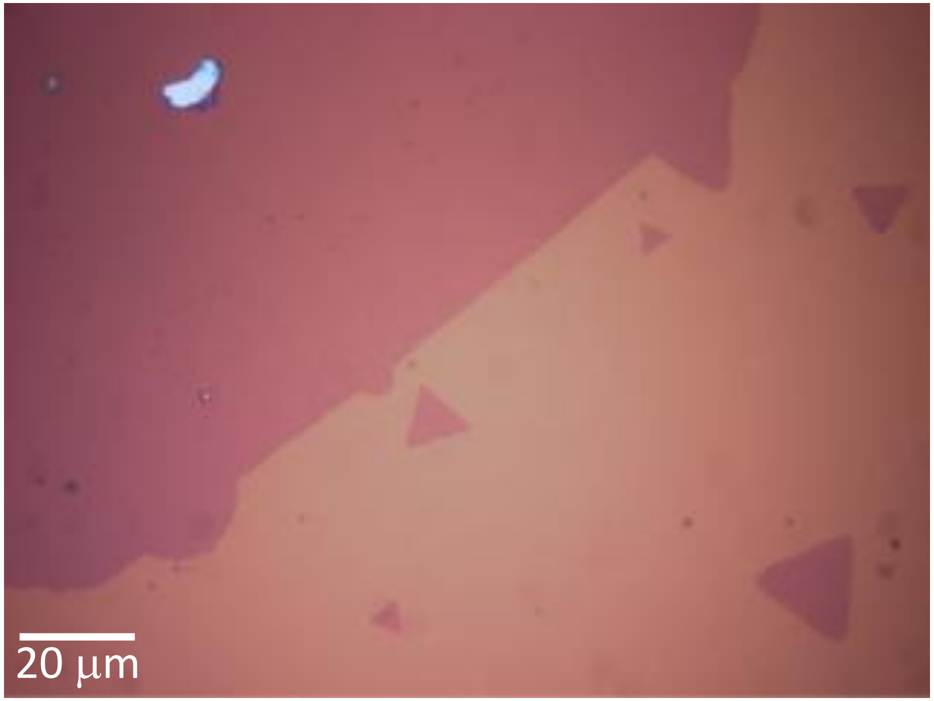




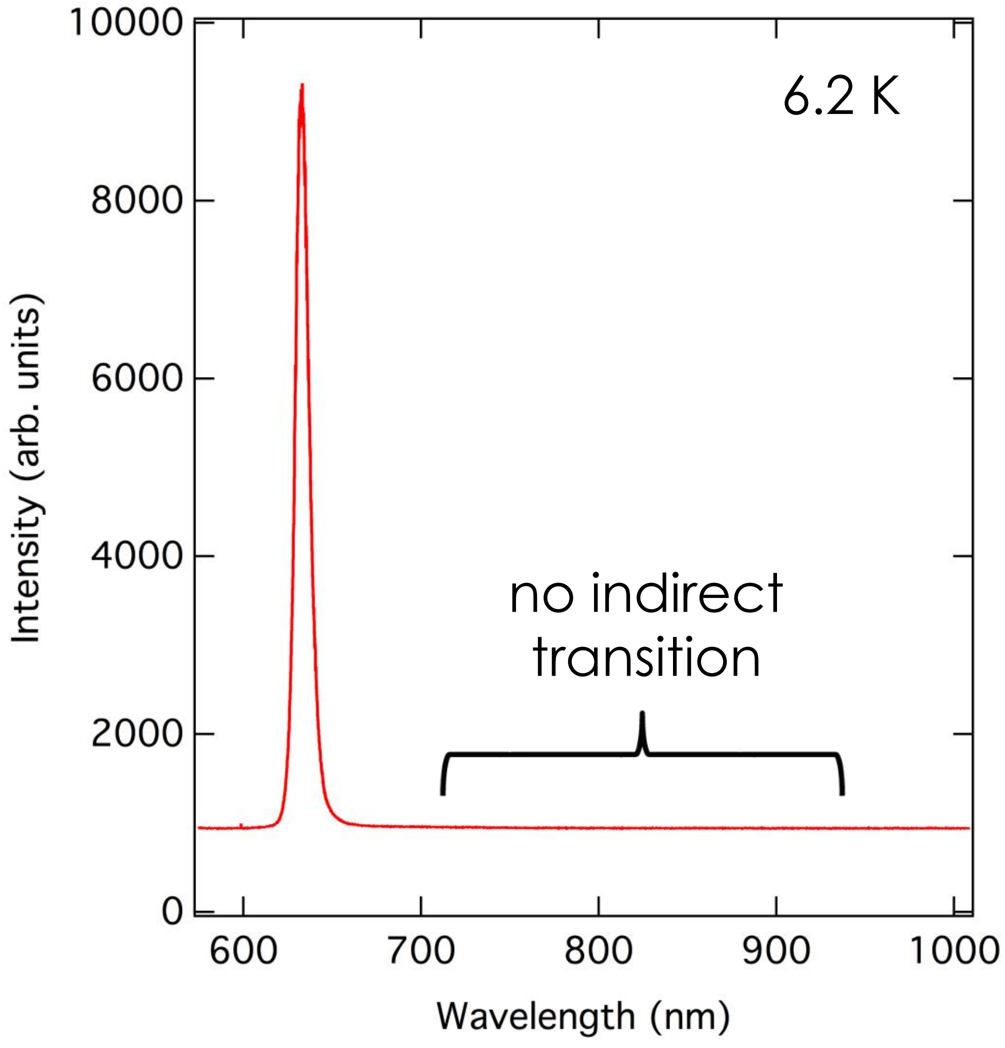
- What is the spin lifetime of WS_2?
- Strong Berry curvature for spin/valley Hall effect.
- How are the spin and valley degrees of freedom coupled?

Chemical Vapor Deposition Grown WS_2

- High quality, large area, single layer flakes
- n-type WS_2
- From collaborators at Naval Research Laboratory (NRL), Kathleen McCreary and Berry Jonker



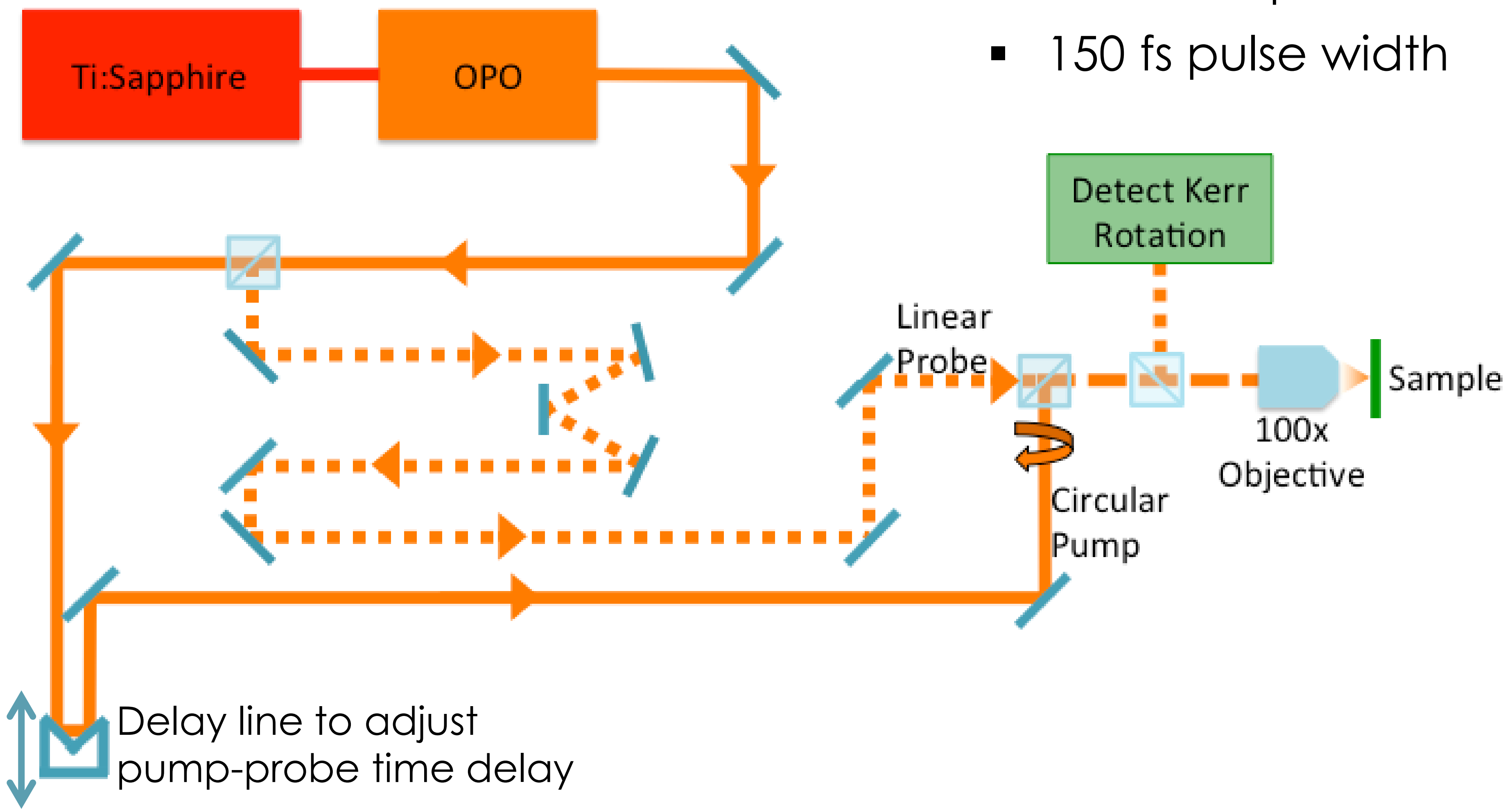
Monolayer WS_2 Photoluminescence



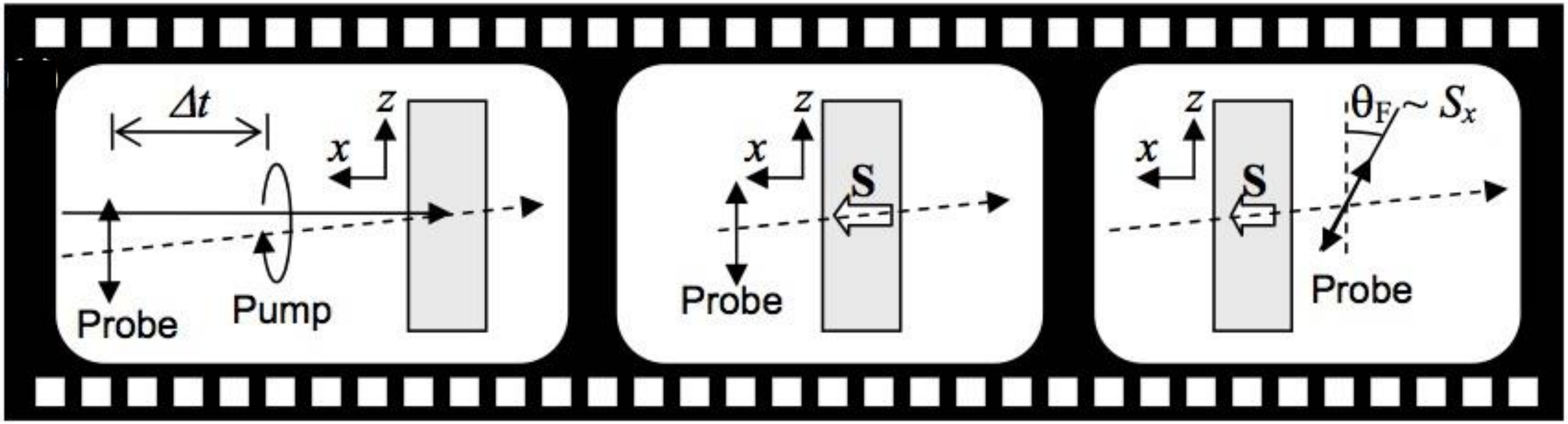
- 532 nm excitation
- Monolayer TMDs show strong PL, with no PL at lower energies
- Lower energy peaks indicate an indirect gap transition, characteristic of multi-layer WS_2
- PL peak is at 630 nm (A exciton)

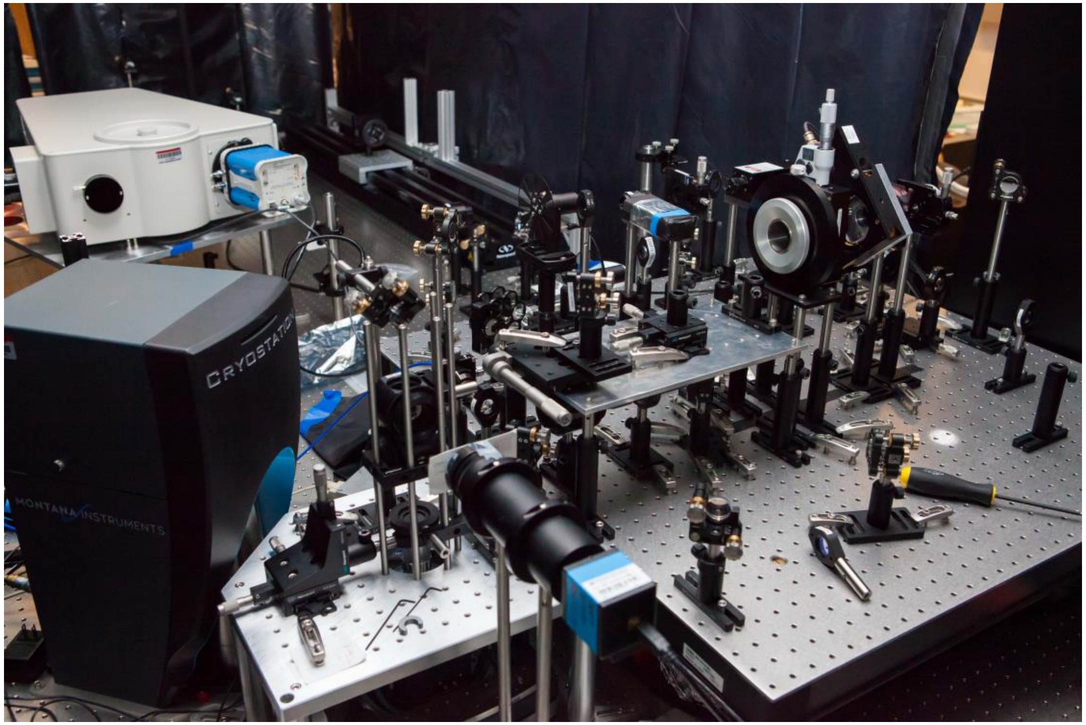
Time Resolved Kerr Rotation Microscopy Layout

- 625 nm wavelength
- 76 MHz rep rate
- 150 fs pulse width



Time Resolved Kerr Rotation Microscopy Layout





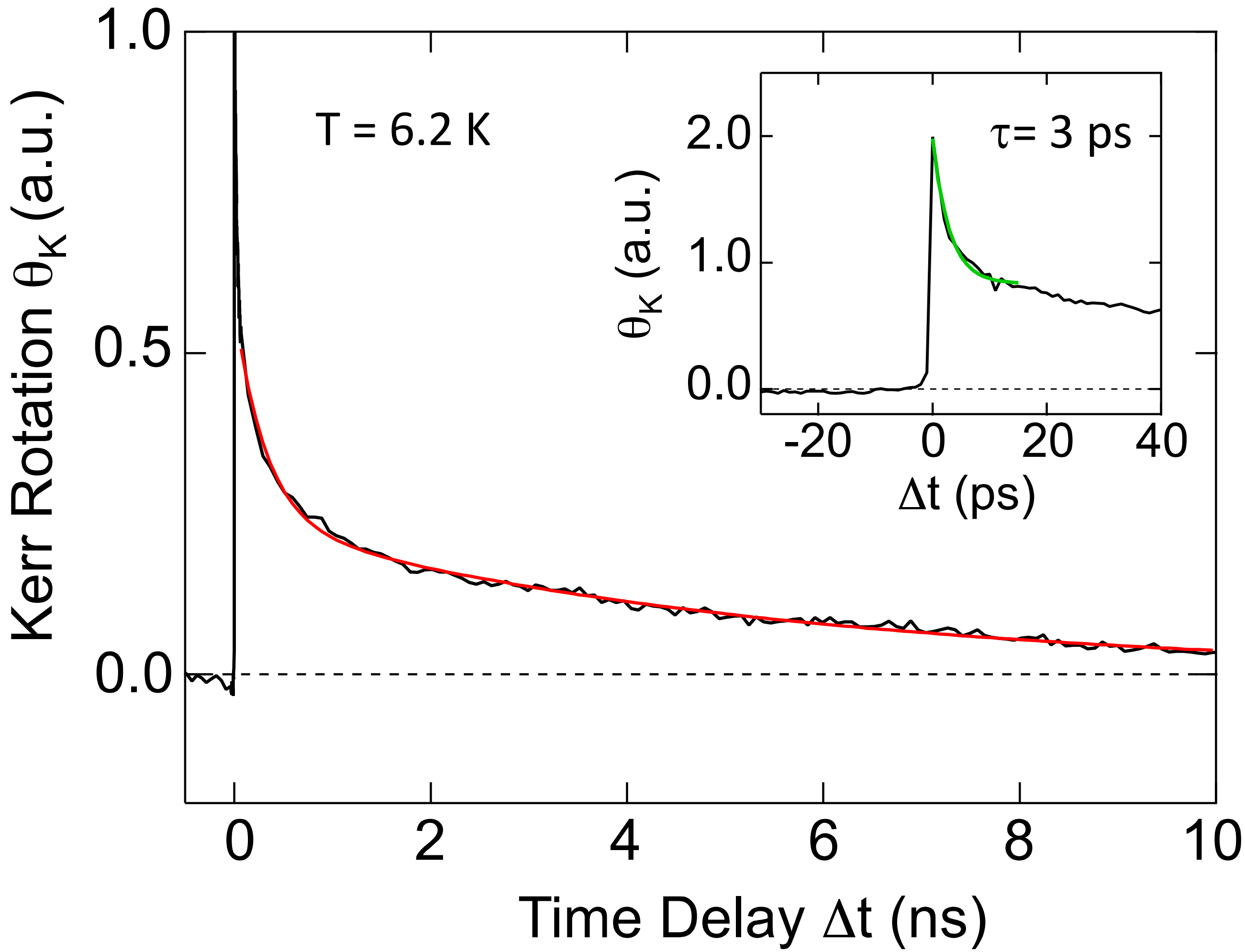
Recent Developments in TRKR on TMD

Zhu, et al. *Phys. Rev. B* **90**, 161302(R) (2014).	WSe_2: 6 ps at 4 K, 1.5 ps at 125 K
Plechinger, G., Nagler, P., C., S. & Korn, T. *ArXiv: 1404.7674* (2014).	MoS_2: 10 ps at 4 K
Dal Conte, S. et al. *ArXiv: 1502.06817* (2015).	MoS_2: <5 ps at 77 K
Yan, T., et al. *arXiv:1507.04599v1* (2015).	WSe_2: 120 ps at 10 K

Yang et. al (Crooker), *Nature Phys.* **11**, 830 (2015).	MoS_2: 5 ns at 10 K, signals up to 40 K Intervalley scattering model for spin relaxation
Hsu, W.-T., et al., *Nat. Commun.* 6:8963 doi: 10.1038/ncomms9963 (2015).	WSe_2: 1 ns at 10 K, signals up to RT

This work: Bushong et. al., arxiv: 1602.03568 (2016) WS_2: Imaging TRKR

Time Resolved Kerr Rotation of WS_2

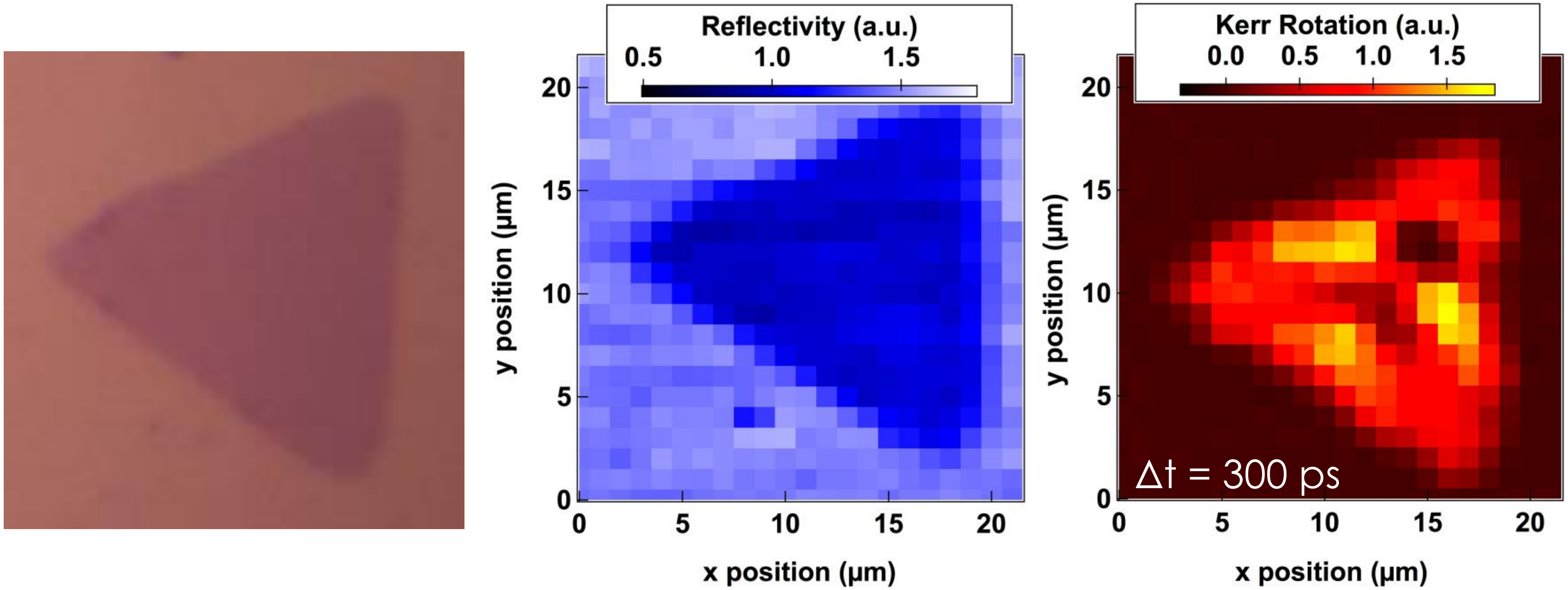


Bi-exponential decay

τ = 5.6 ns

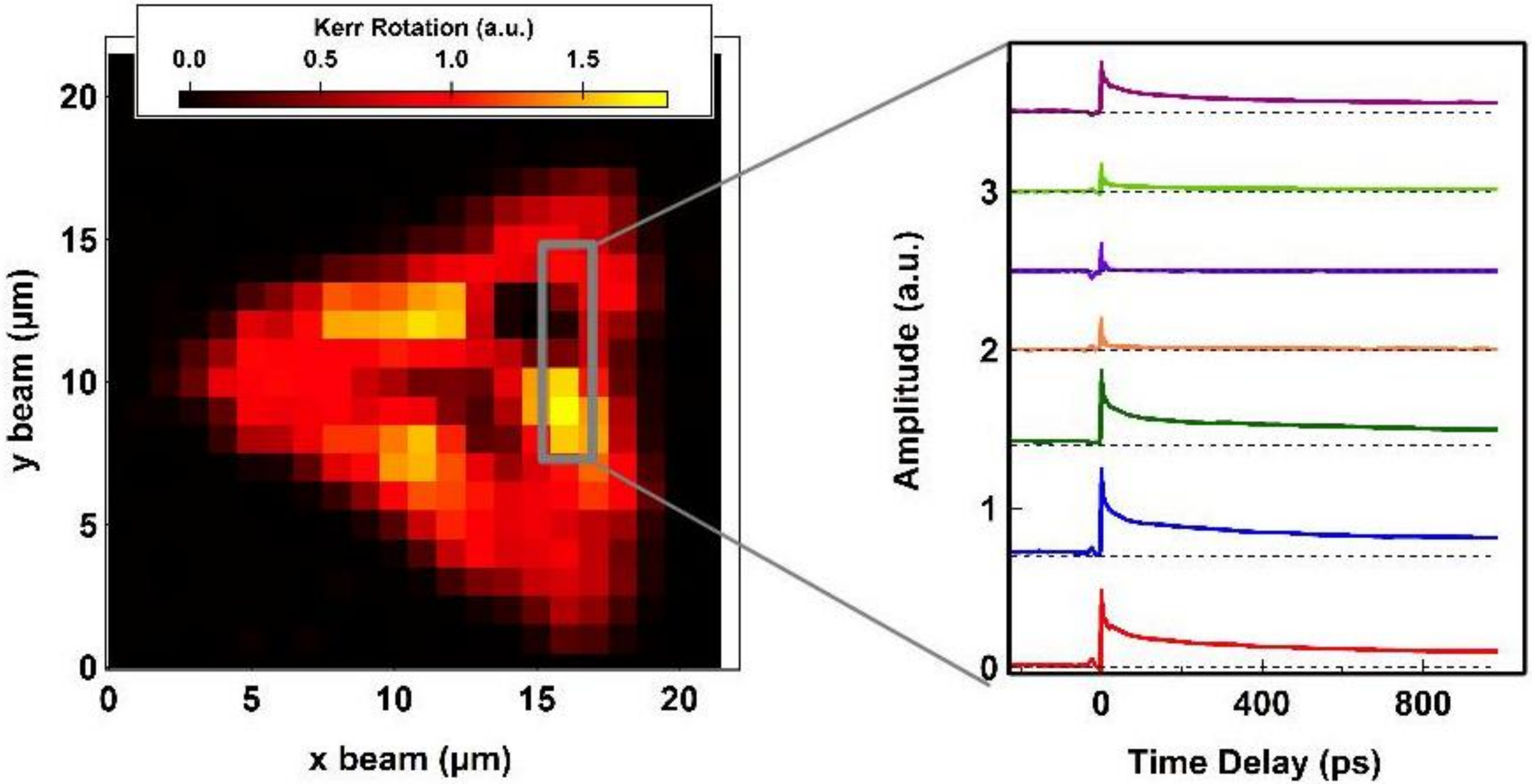
Monolayer WS_2 exhibits long spin lifetimes

Spatial Mapping of the Kerr Rotation



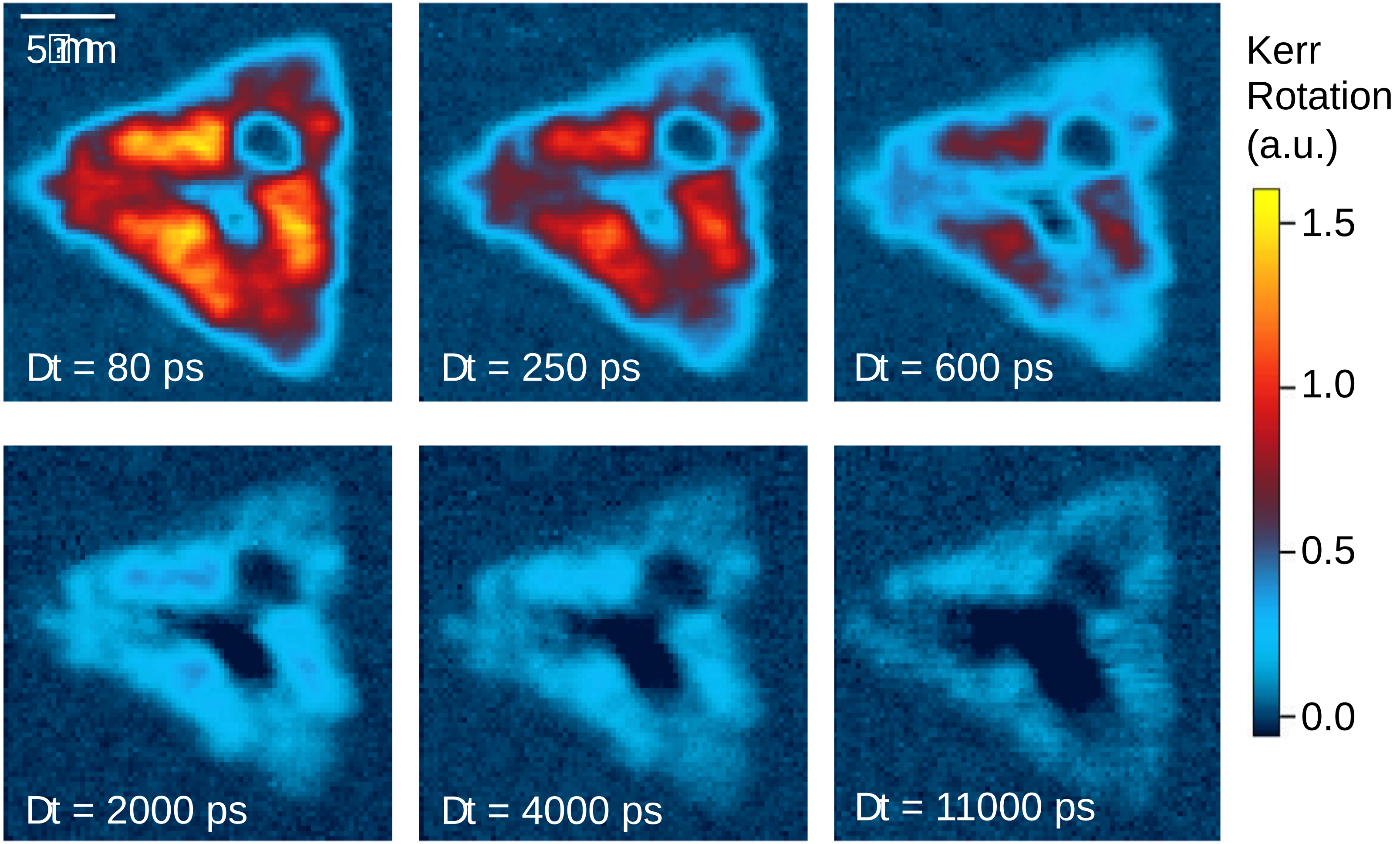
Spatial variation of spin polarization in WS_2

Time Resolved Kerr Rotation Mapping



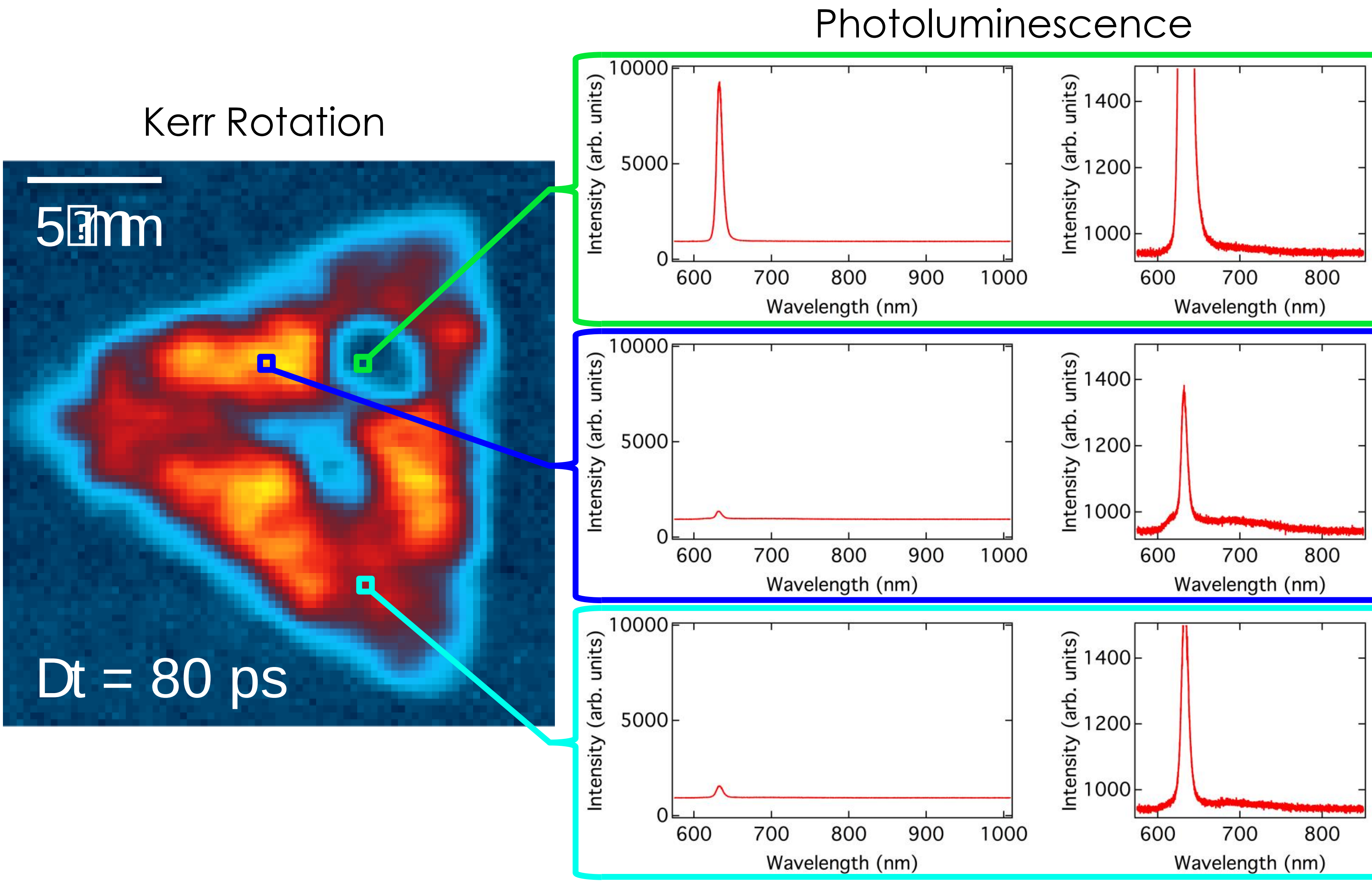
Spatial variation of spin density in WS_2

High Resolution Imaging of Spin Dynamics

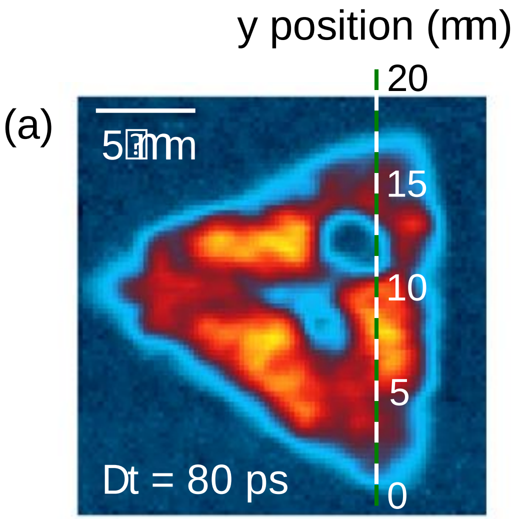


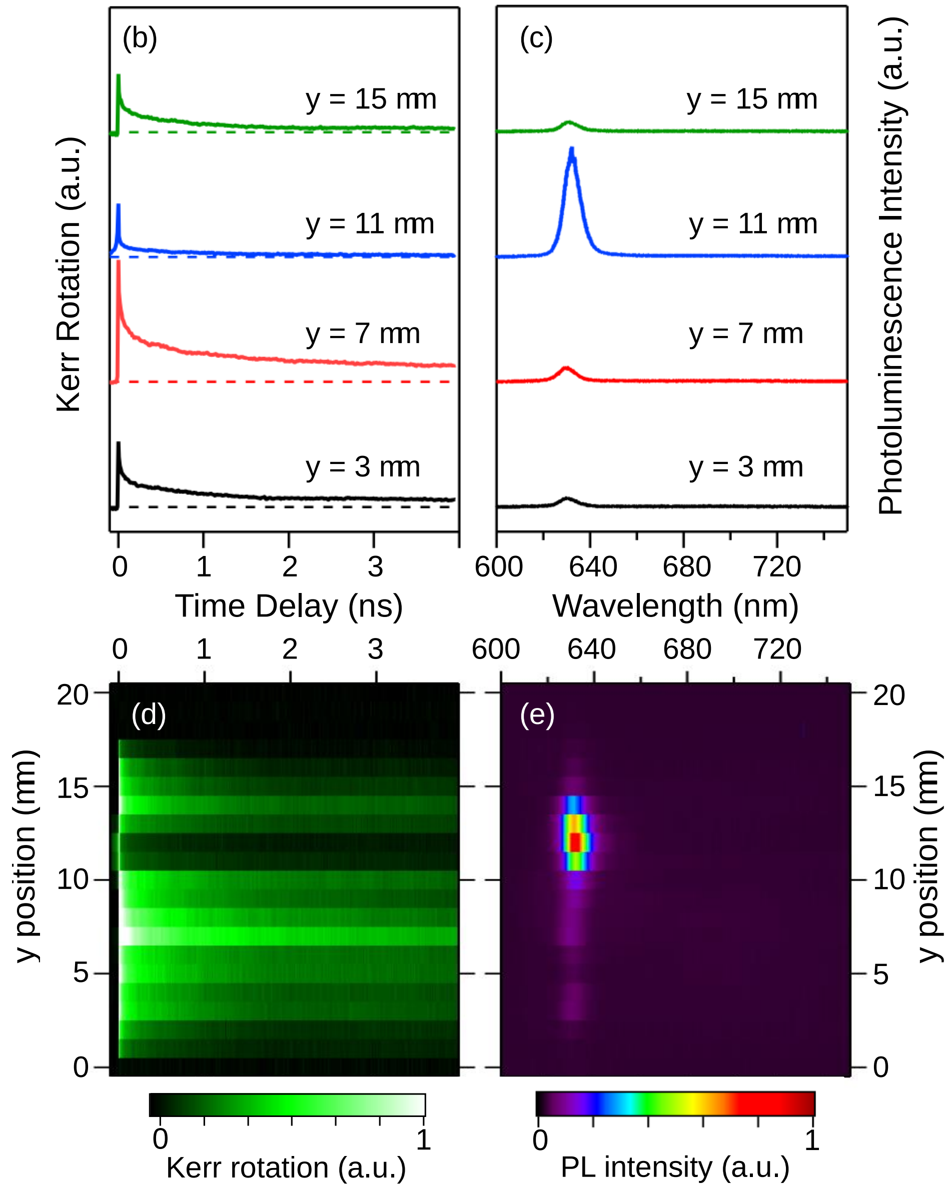
Images appear to be more symmetrical with increasing time delay

Spatially Resolved Photoluminescence



TRKR vs. Photoluminescence

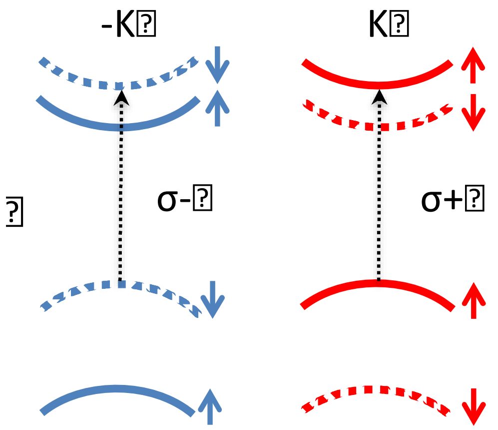




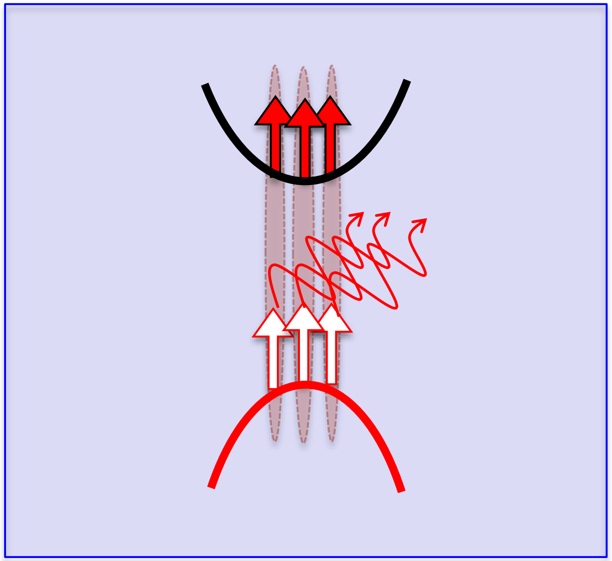
Regions of bright PL have short spin lifetimes

Possible Explanation

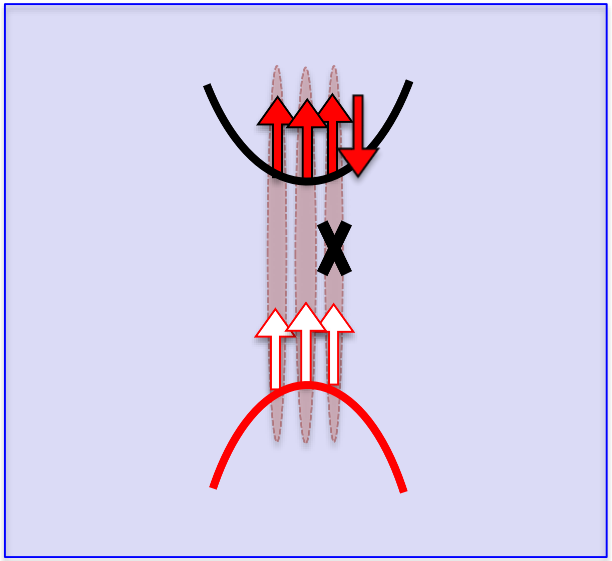
Selectively excite spins into the conduction band



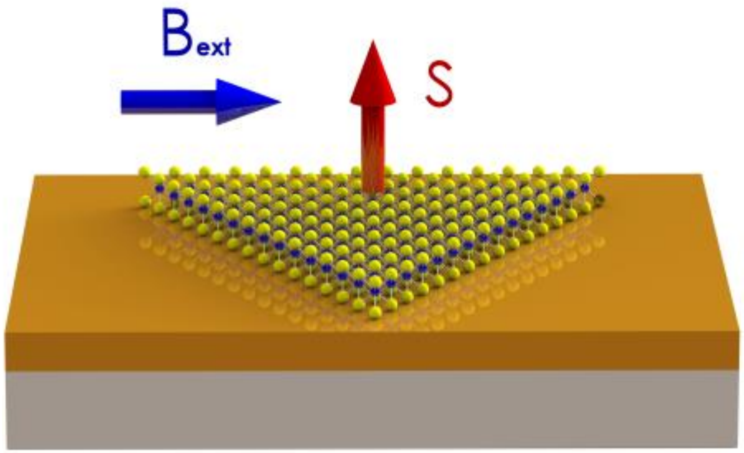
Short Spin Lifetime, Strong Photoluminescence

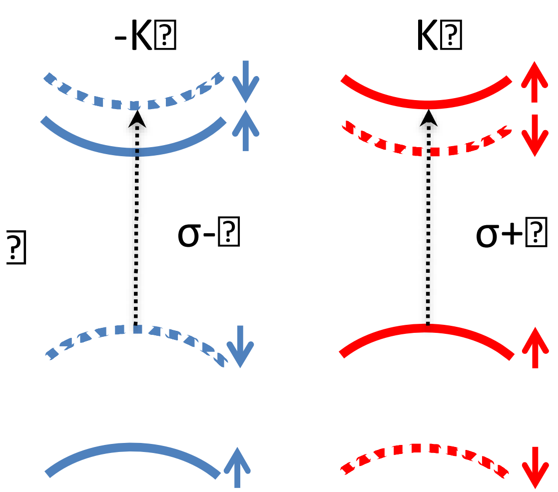


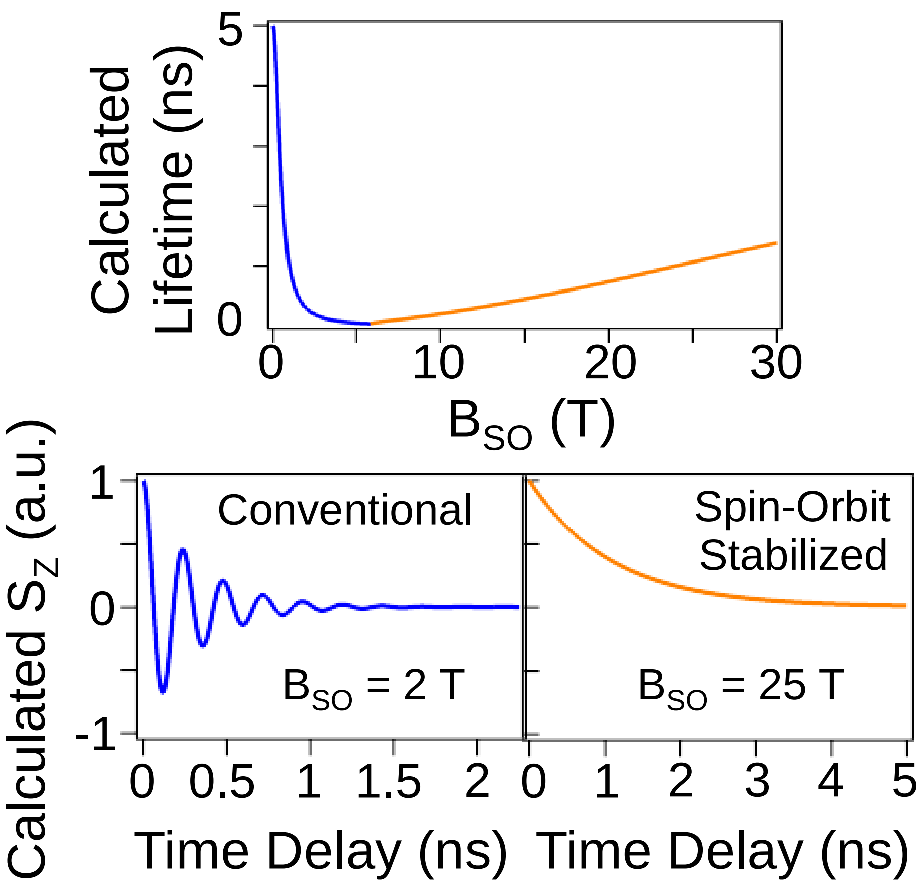
Long Spin Lifetime, Weak Photoluminescence



Role of spin-orbit splitting



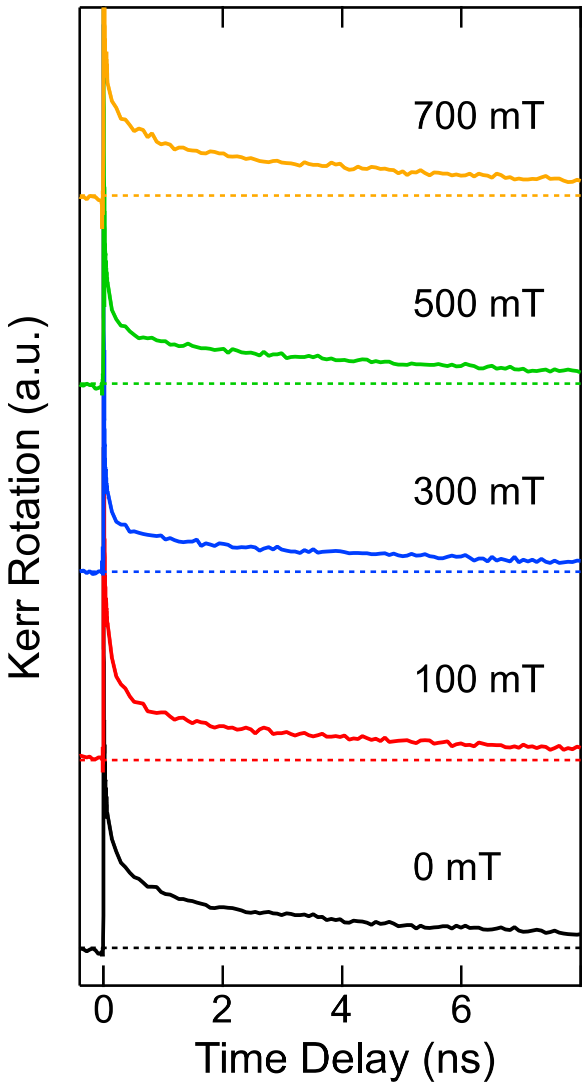


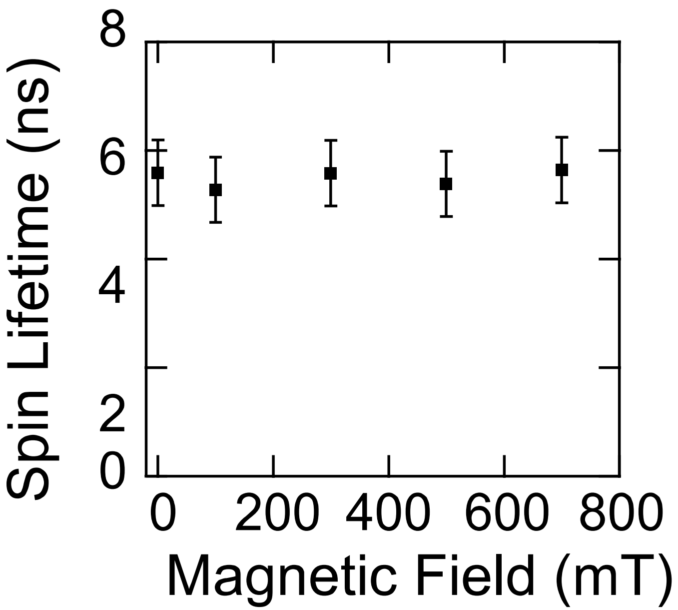


Intervalley scattering model for spin relaxation

Yang et. al (Crooker), *Nature Phys.* **11**, 830 (2015).

In-Plane Magnetic Field Dependence

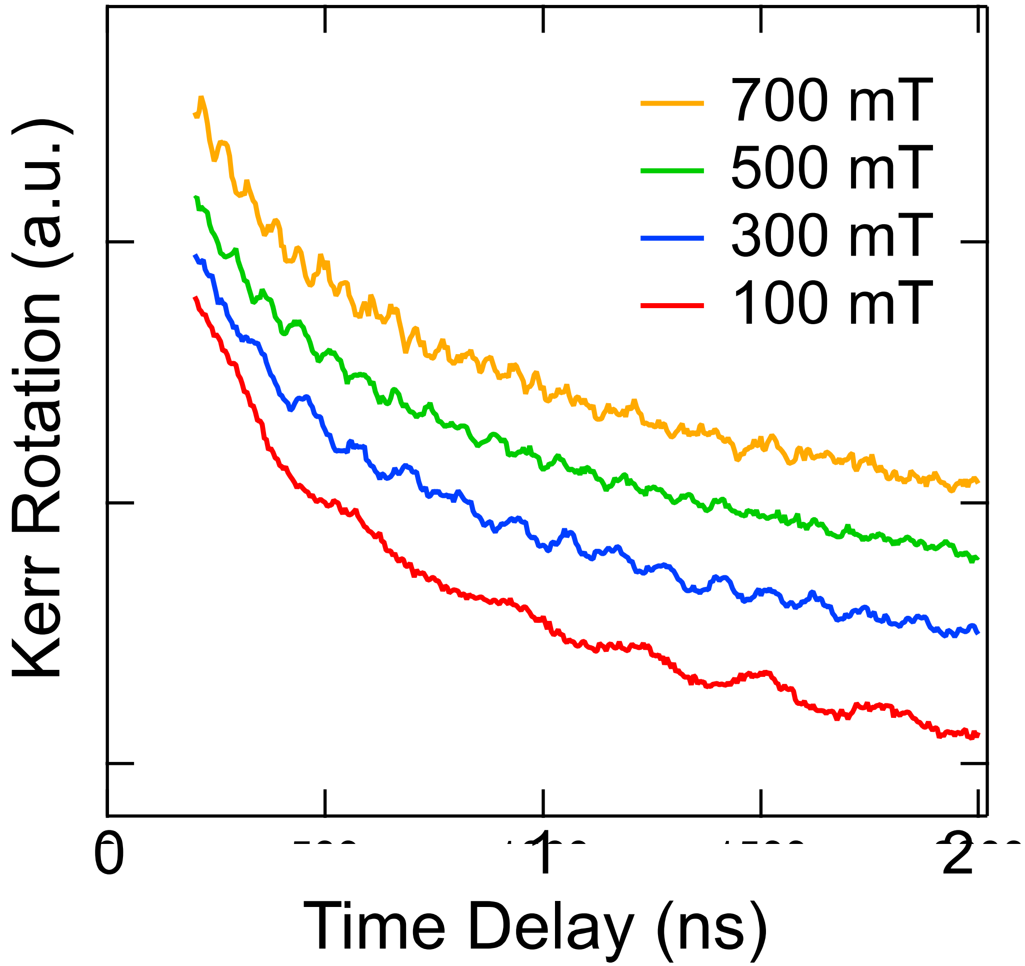




Non-precessing spin in the spin-orbit stabilized regime

In-Plane Magnetic Field Dependence

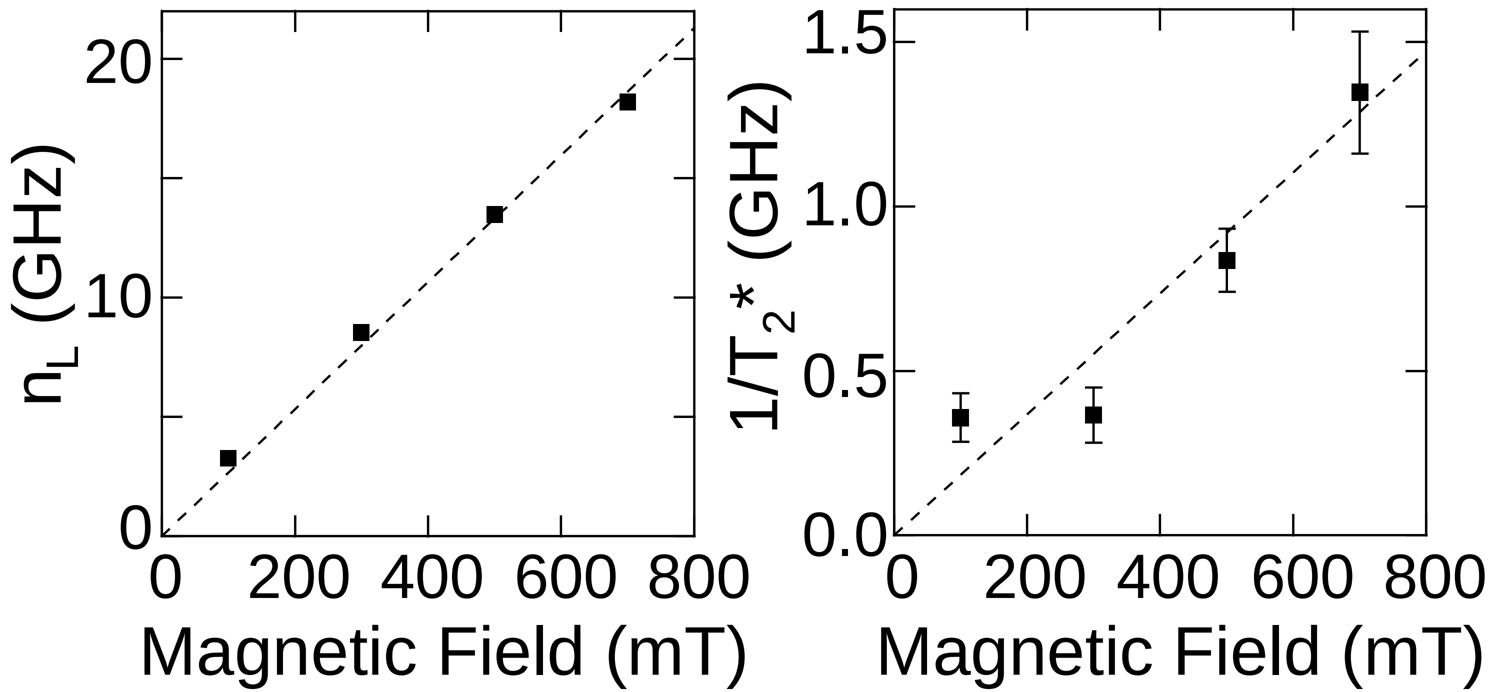
Zoom in with finer scans:



Zoomed in and offset

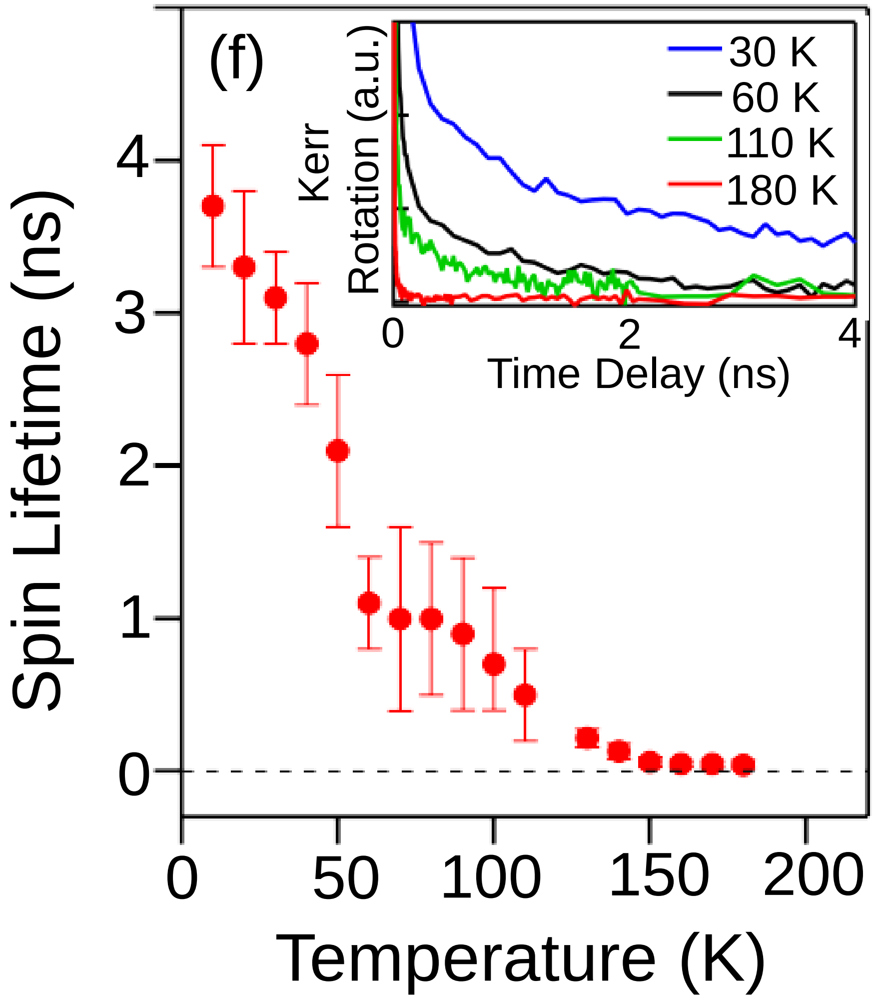
Oscillations are ~3% of total signal

In-Plane Magnetic Field Dependence



Small population of precessing spins

Temperature Dependence



Next steps

Tune Fermi level

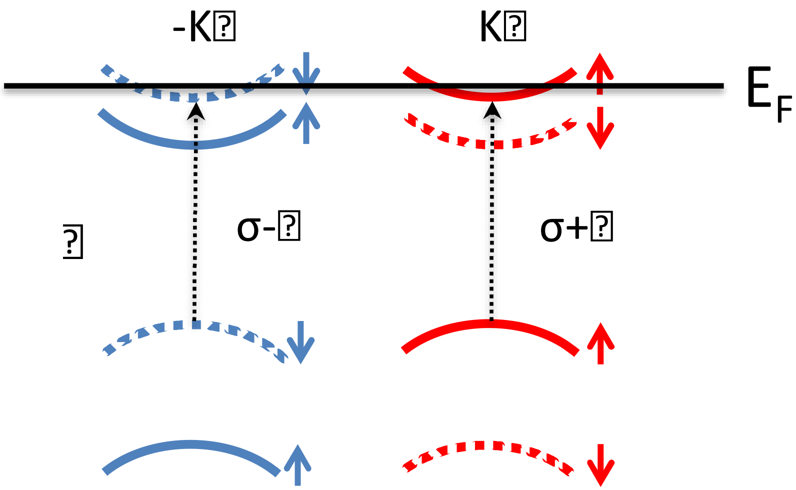
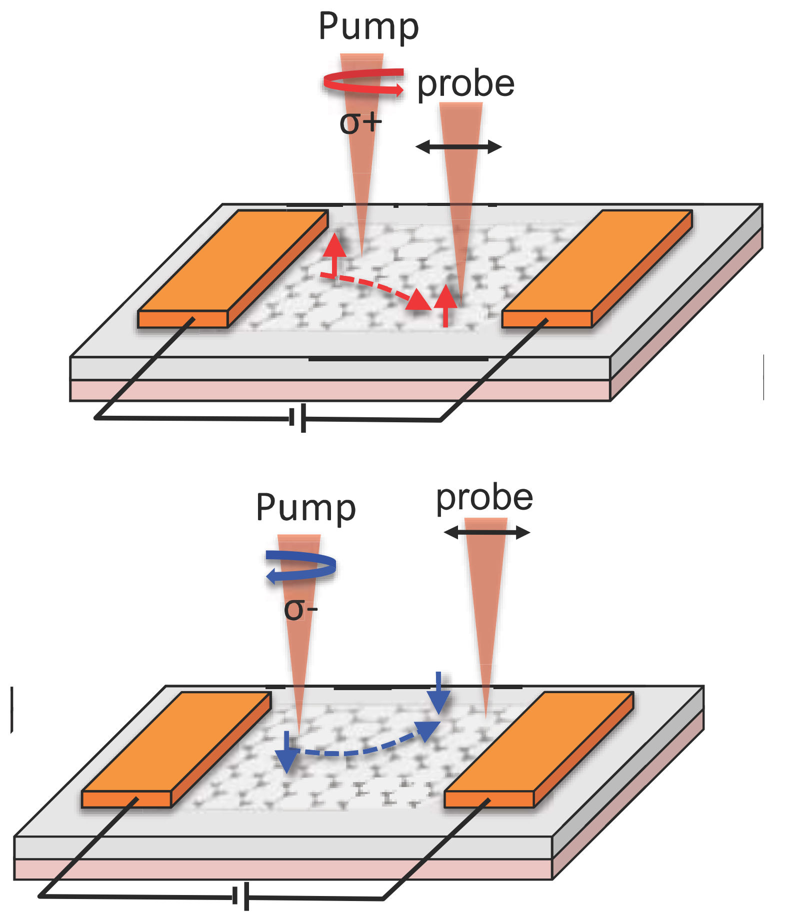


Image Dynamics of Spin Hall Effect



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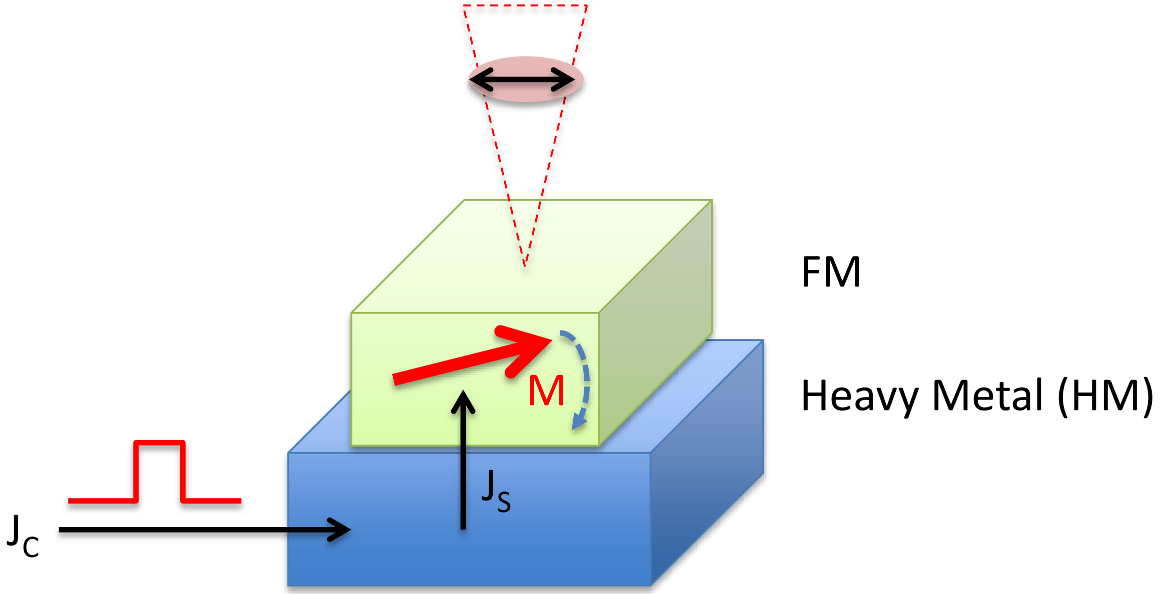
Spin Torque Dynamics in FM/HM Bilayers

Use TRKR microscopy to image magnetization switching dynamics

- **Spin-orbit torque switching**
- **Magneto-electric switching**
- **...**



- Sub ps temporal resolution → explore faster switching mechanisms
- Submicron spatial resolution

Quantifying spin-orbit torques

ARTICLE

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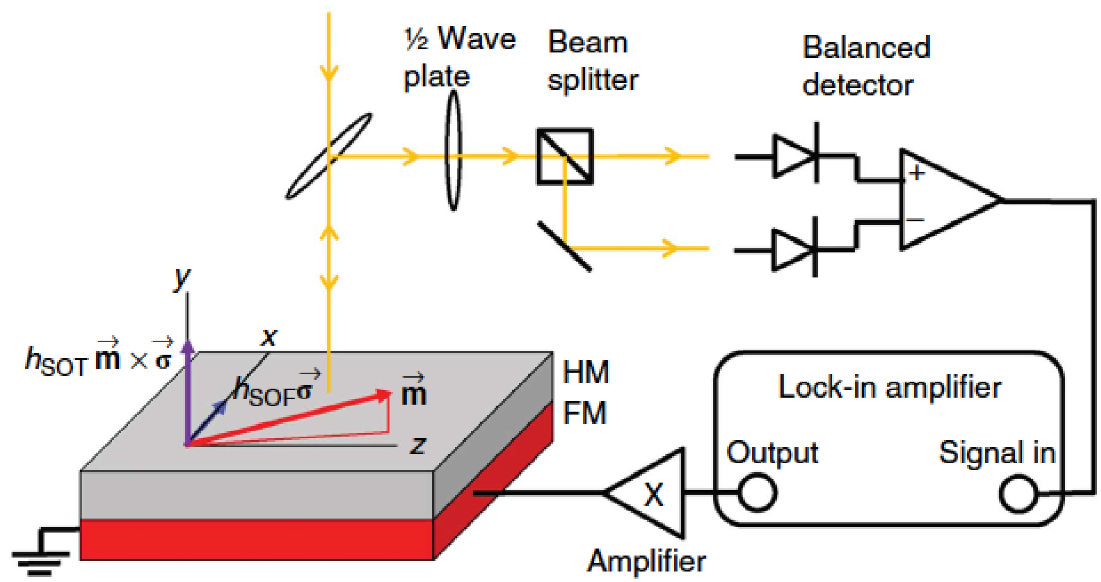
Quantifying interface and bulk contributions to spin-orbit torque in magnetic bilayers

Xin Fan[1], Halise Celik[1], Jun Wu[1], Chaoying Ni[2], Kyung-Jin Lee[3,4], Virginia O. Lorenz[1] & John Q. Xiao[1]

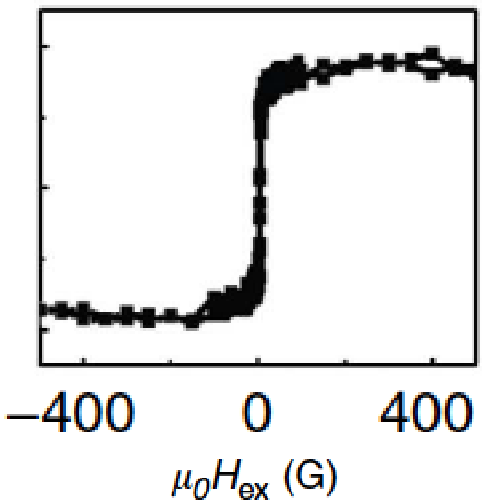
Spin-orbit torques change the equilibrium direction of M



Quantify the Anti-Damping Torque and Field-Like Torque

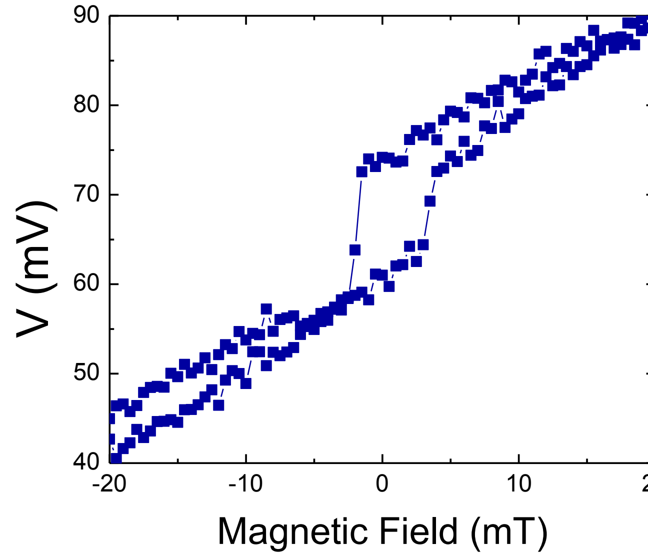
Quantifying spin-orbit torques

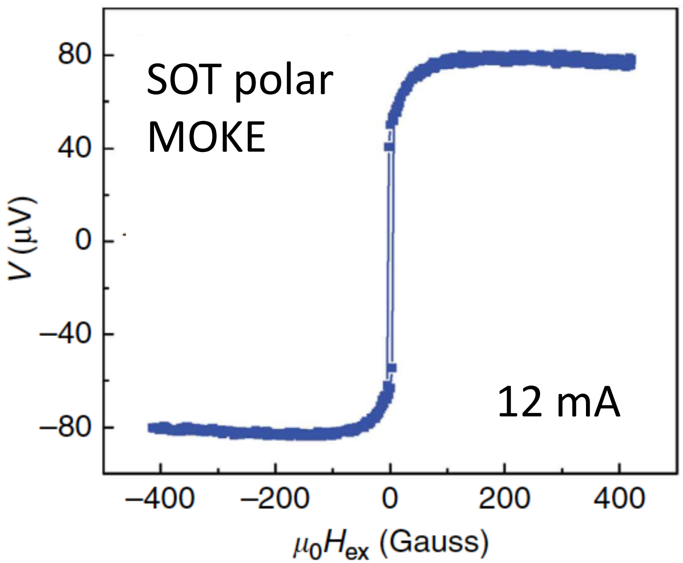
John Xiao's data:
Pt(5nm)/CoFeB(0.85nm)



Regular Longitudinal MOKE hysteresis loop

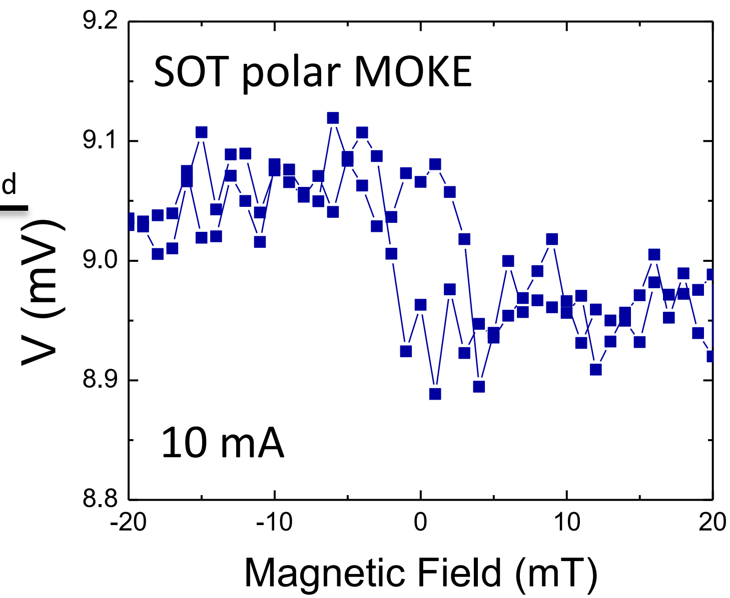
Our data: Pt(6nm)/Fe(4nm)





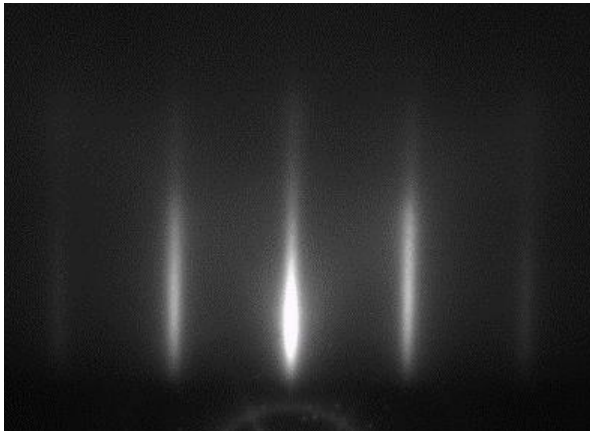
$$\Delta m_{polar} = \frac{h_{SOT} + h_{oersted}}{H_{eff} + M_{eff}}$$

$$h_{SOT} \sim \tau_T (m \times \sigma)$$

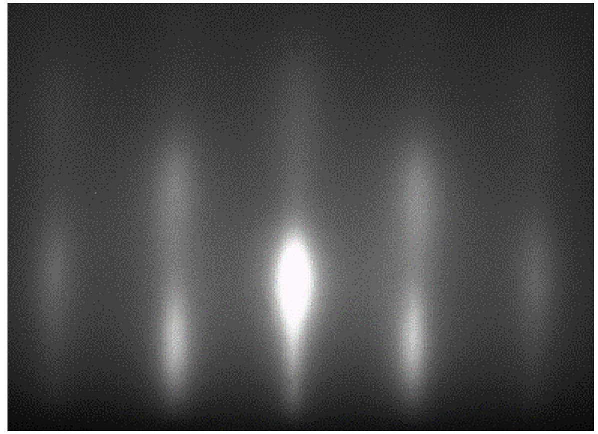


MBE growth of magnetic multilayers

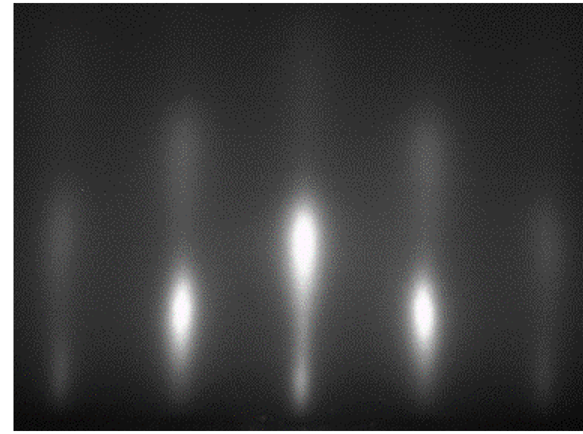
MBE growth: Fe, Pd, Cu, Bi, Ag



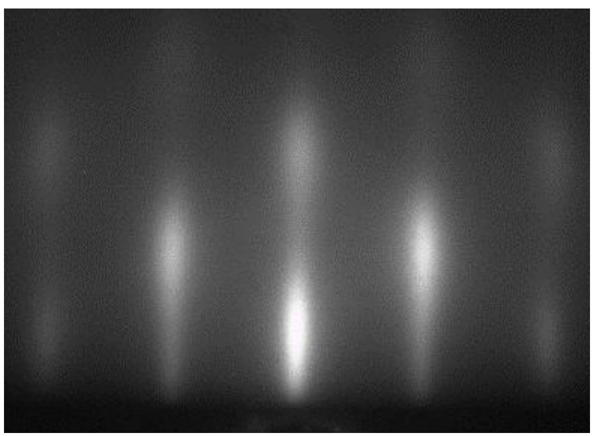
Fe on MgO(001)



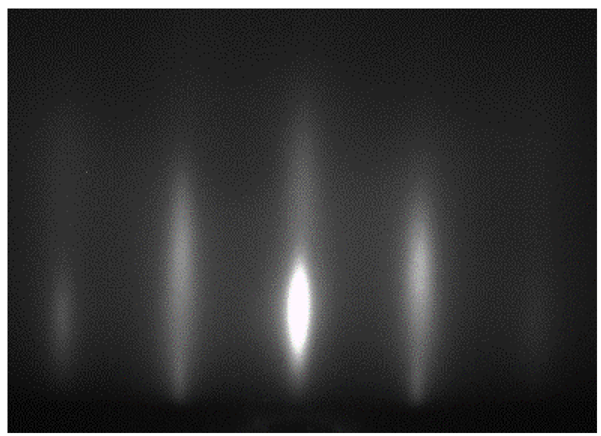
Pd on Fe(001)



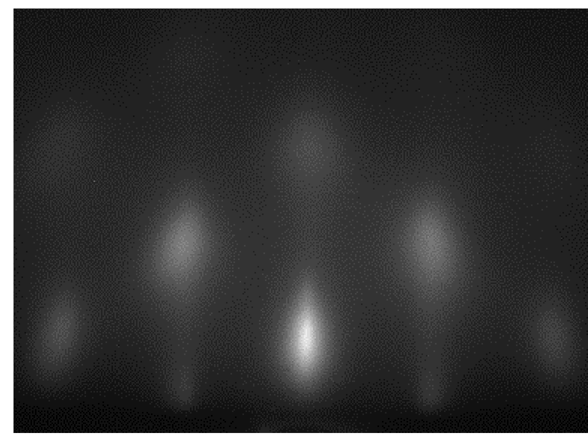
$Bi_{0.03}Pd_{0.97}$ on Fe(001)



Cu on Pd(001)



Fe on Cu(001)



Cu on Fe(001)

Summary

- **Observed complex spatial depedence of spin density in WS_2**
- **Anticorrelation between PL and TRKR in WS_2**
- **Spin in WS_2 are stabilized by spin-orbit against external fields and thermal fluctuations**
- **Progress on spin-orbit torques in FM/HM bilayers**