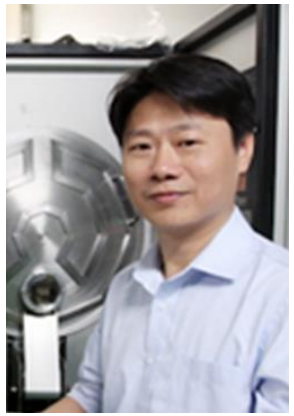
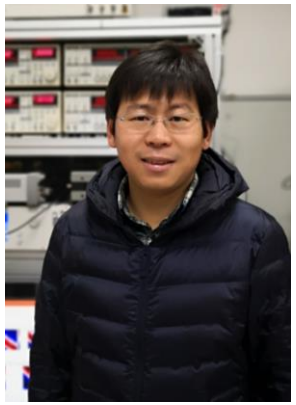
Giant Anisotropic Spin Relaxation and Spin-valley Mixing in a Silicon Quantum Dot

Xin Zhang
Supervisors: Hai-Ou Li , Guoping Guo

中国科学院量子信息重点实验室
CAS Key Laboratory of Quantum Information


Guangcan Guo


Guoping Guo


Hai-Ou Li


Gang Cao


Baochuan Wang


Zhuozhi Zhang

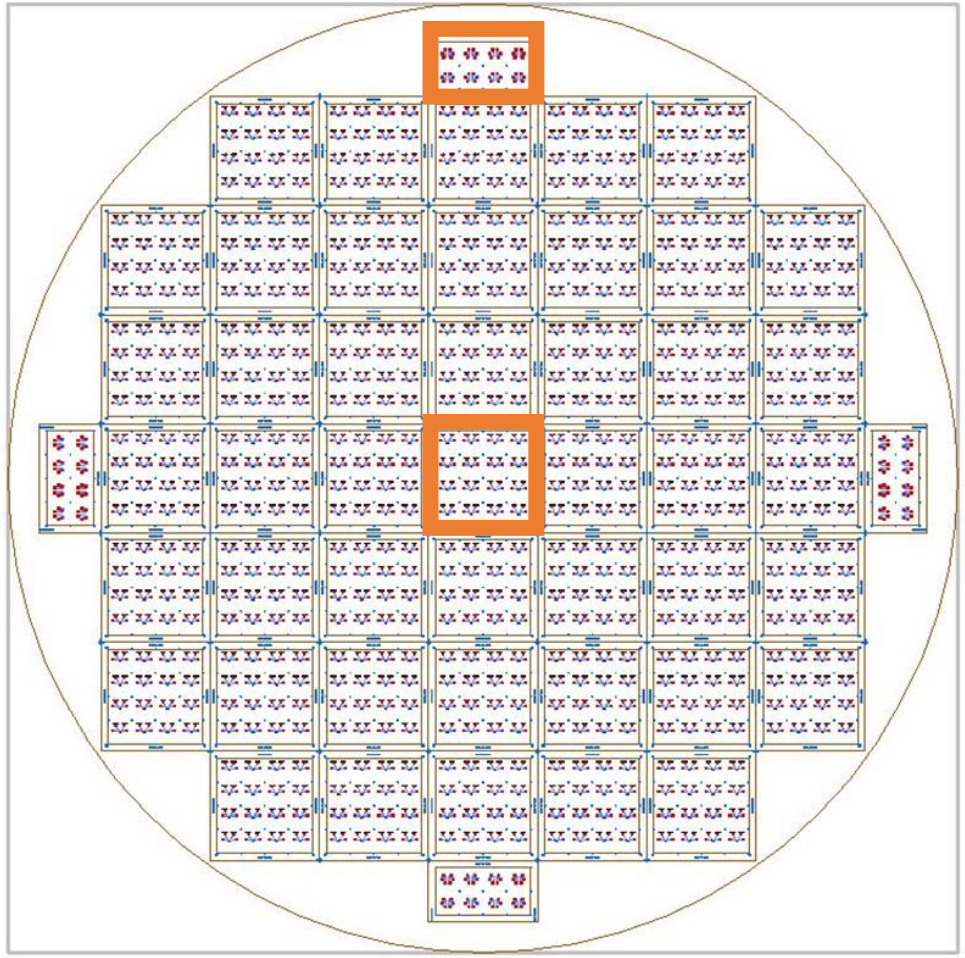

Xiangxiang Song


Yuchun Wu

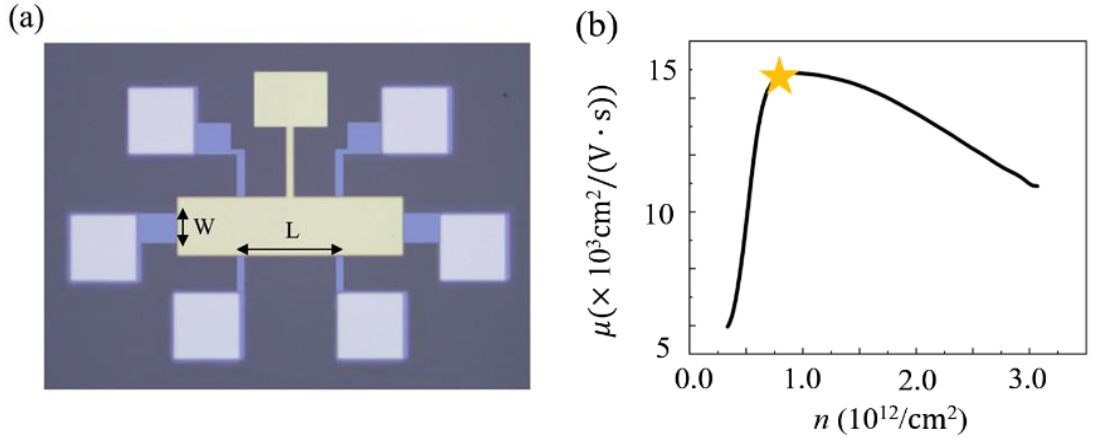
Solid-State Quantum Information Group

- Spin Control in Si MOS/Ge Hut Wire QD
- Hybrid cQED system
- Spin Control in Si/SiGe QD
- Nano-mechanical resonator
- Cryogenic Electronics
- Theory of Quantum Computation

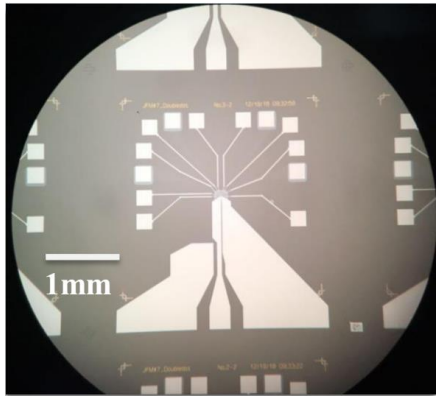
MOS QD fabricated from 200 mm commercial silicon wafer

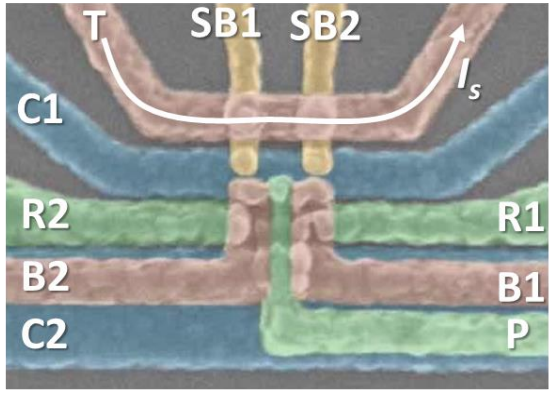


Peak mobility ~ $1.5*10^4$ $cm^2/(Vs)$



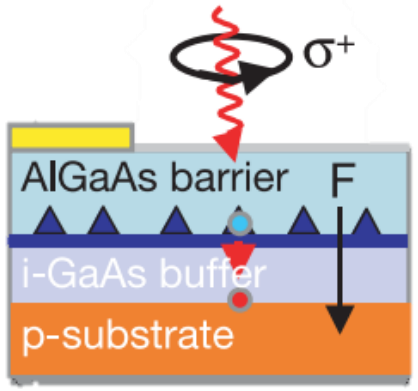
K. Wang et al, arxiv:1905.01581



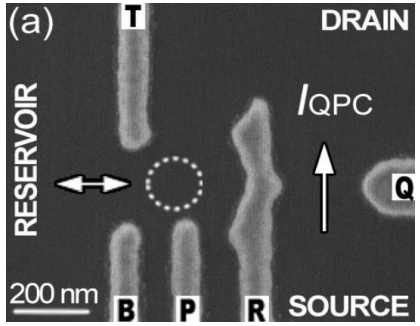


Motivation

B dependence

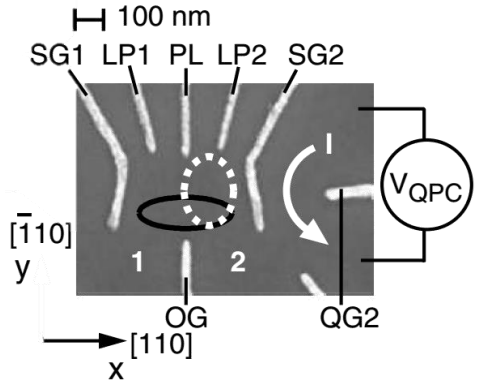


M. Kroutvar et al. Science 2004
L. C. Camenzind et al. Nat. Commun. 2018

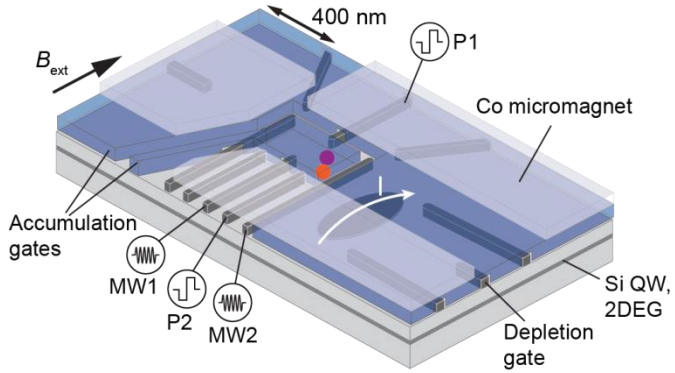


R. R. Hayes et al. arXiv: 0908.0173
M. Xiao et al. Phys. Rev. Lett. 2010
C. H. Yang et al. Nat. Commun. 2013
L. Petit et al. Phys. Rev. Lett. 2018
F. Borjans et al. Phys. Rev. Appl. 2019
A. Hollmann et al. arXiv:1907.04146v1

Gate voltage dependence

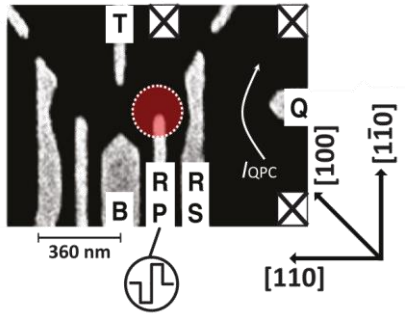


S. Amasha et al. Phys. Rev. Lett. 2008
V. Srinivasa et al. Phys. Rev. Lett. 2013

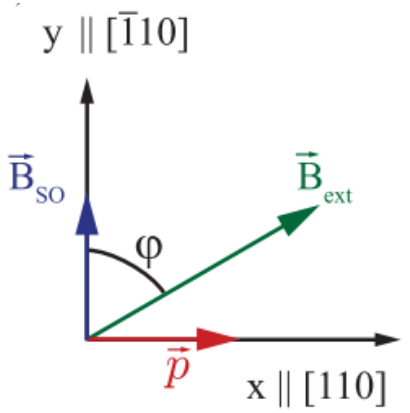


T.F. Watson et al. Nature 2018
W. Huang et al. Nature 2019
R. C. C. Leon et al. arXiv:1902.01550v3

Anisotropy

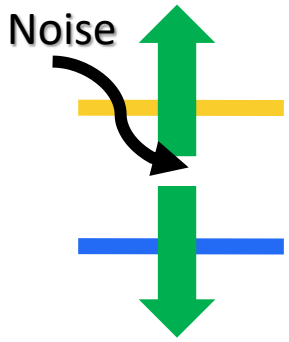


P. Scarlino et al. Phys. Rev. Lett. 2014
A. Hofmann et al. Phys. Rev. Lett. 2017
L. C. Camenzind et al. Nat. Commun. 2018

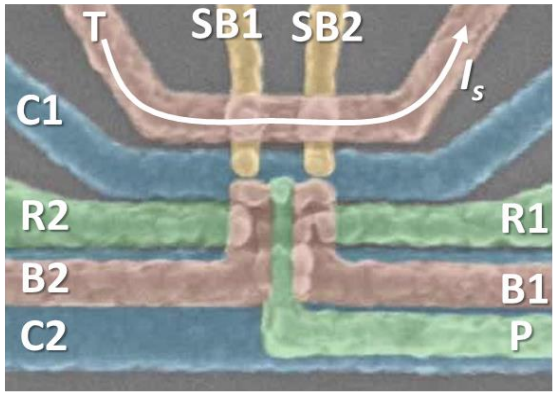


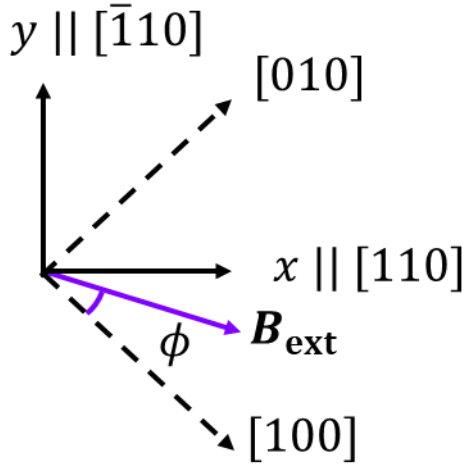
Variation: × 10

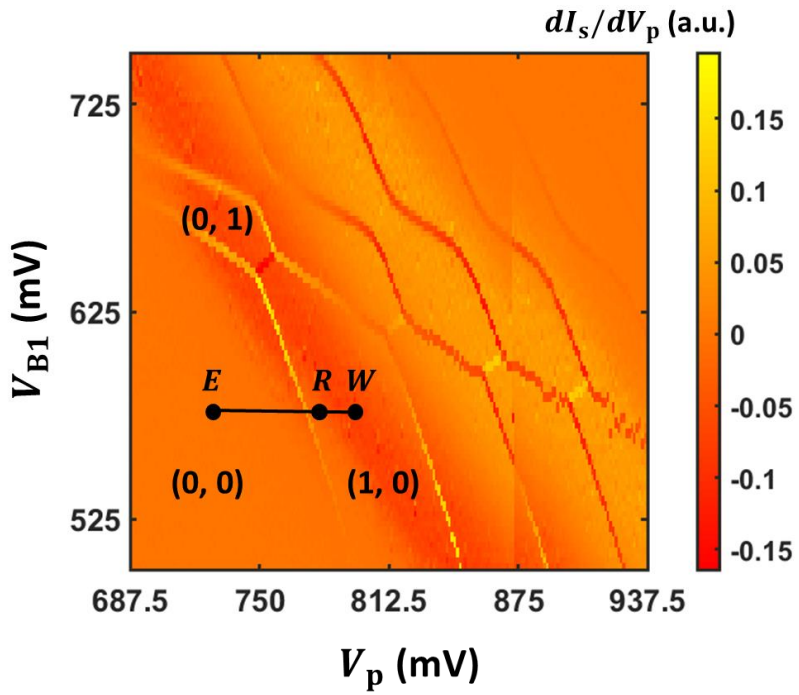
?



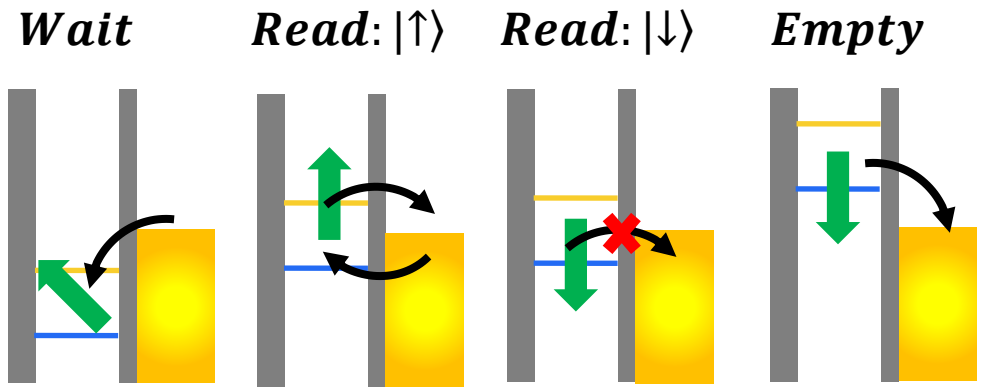
Device and measurement method



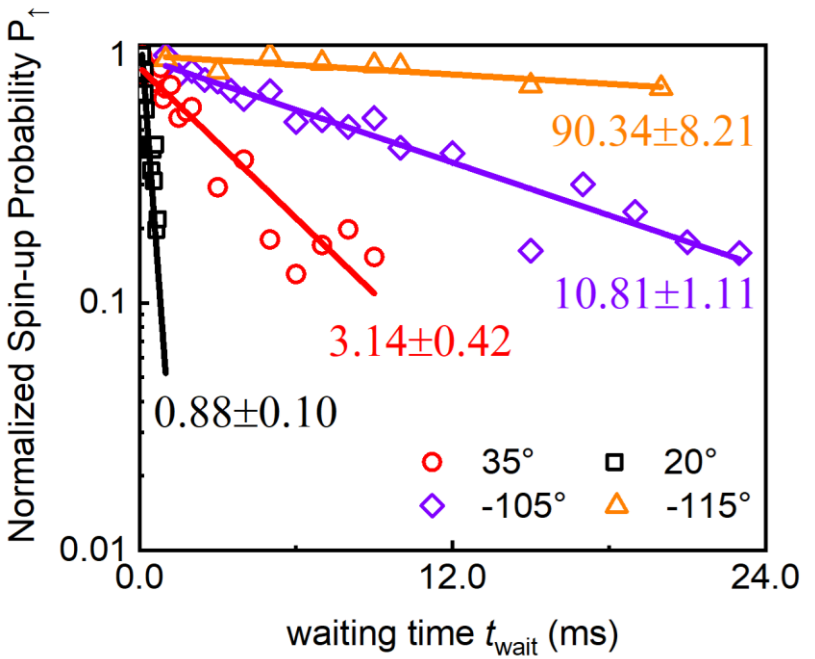




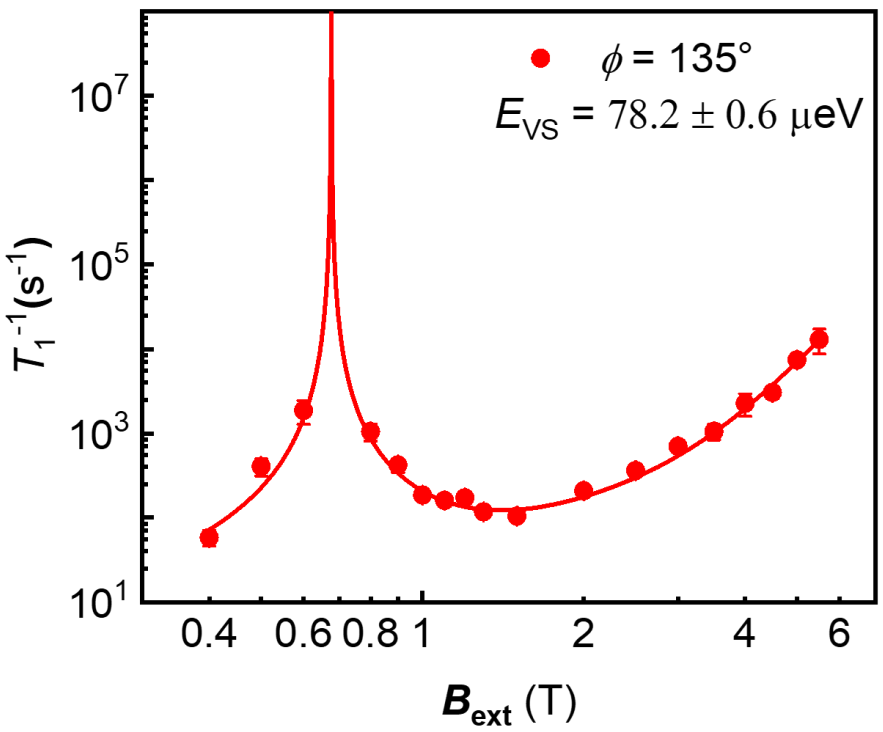
$$P_{\uparrow} = c_1 \exp(-t_{\mathrm{wait}}/T_1) + c_2$$

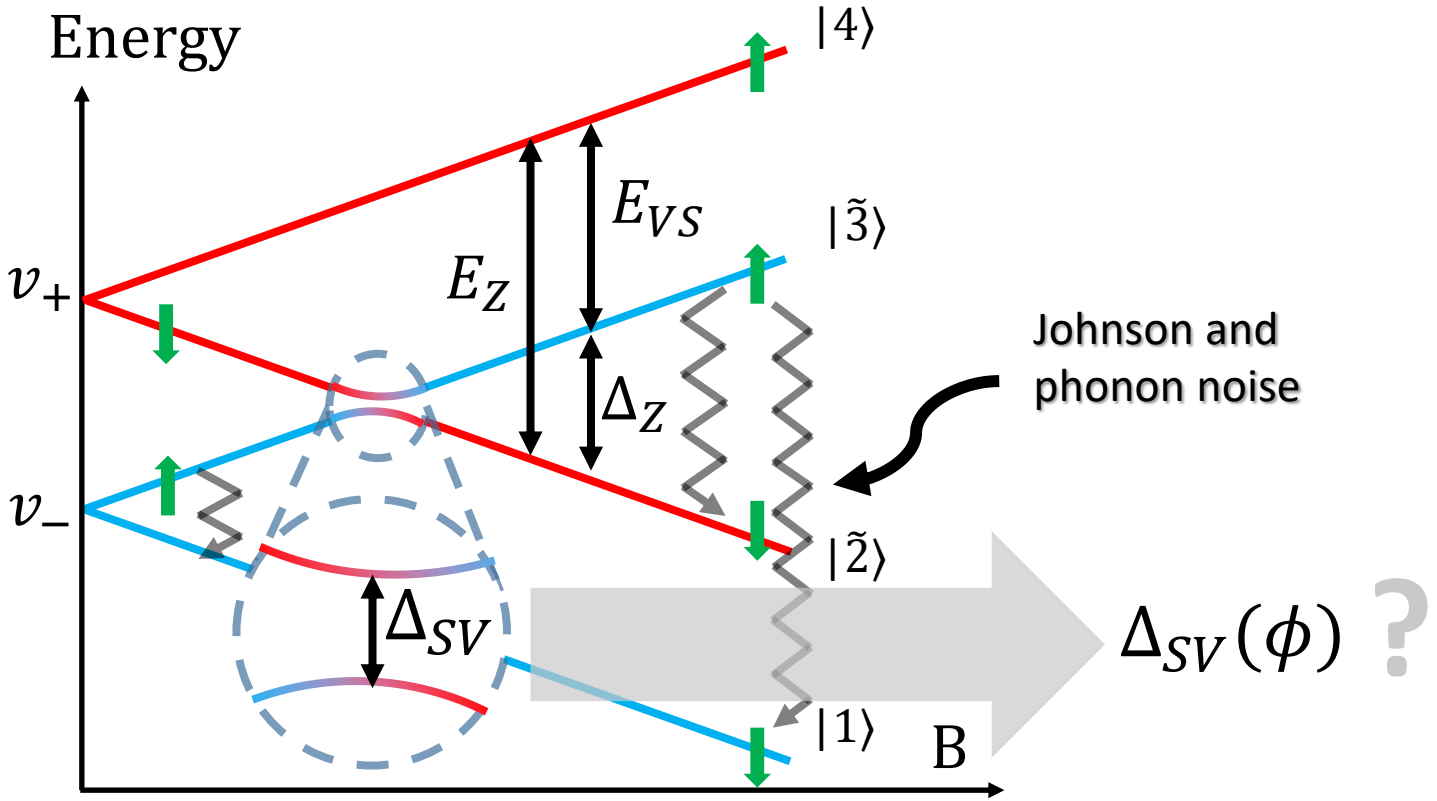


J. M. Elzerman et al. Nature 2004



B dependence: spin-valley relaxation hot-spot



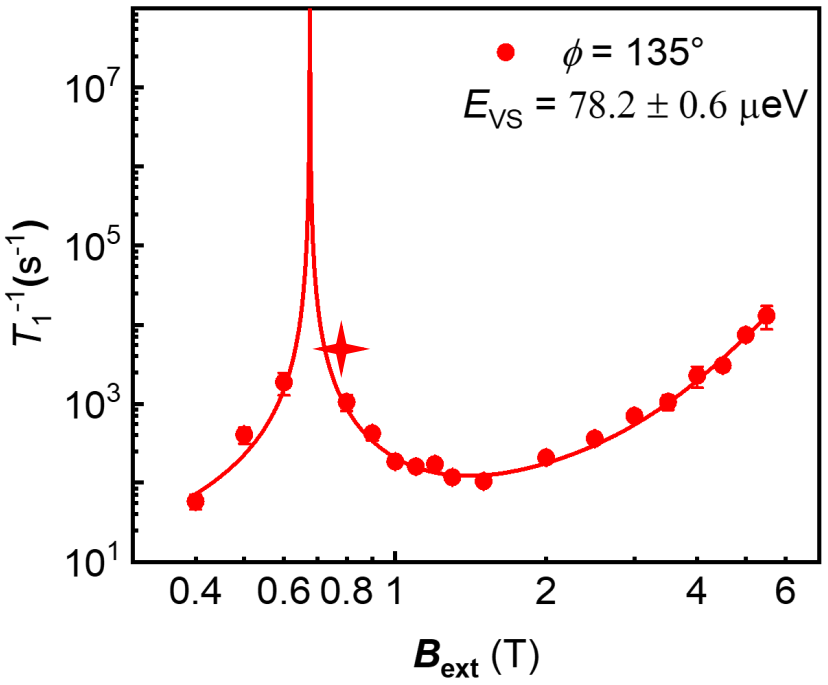


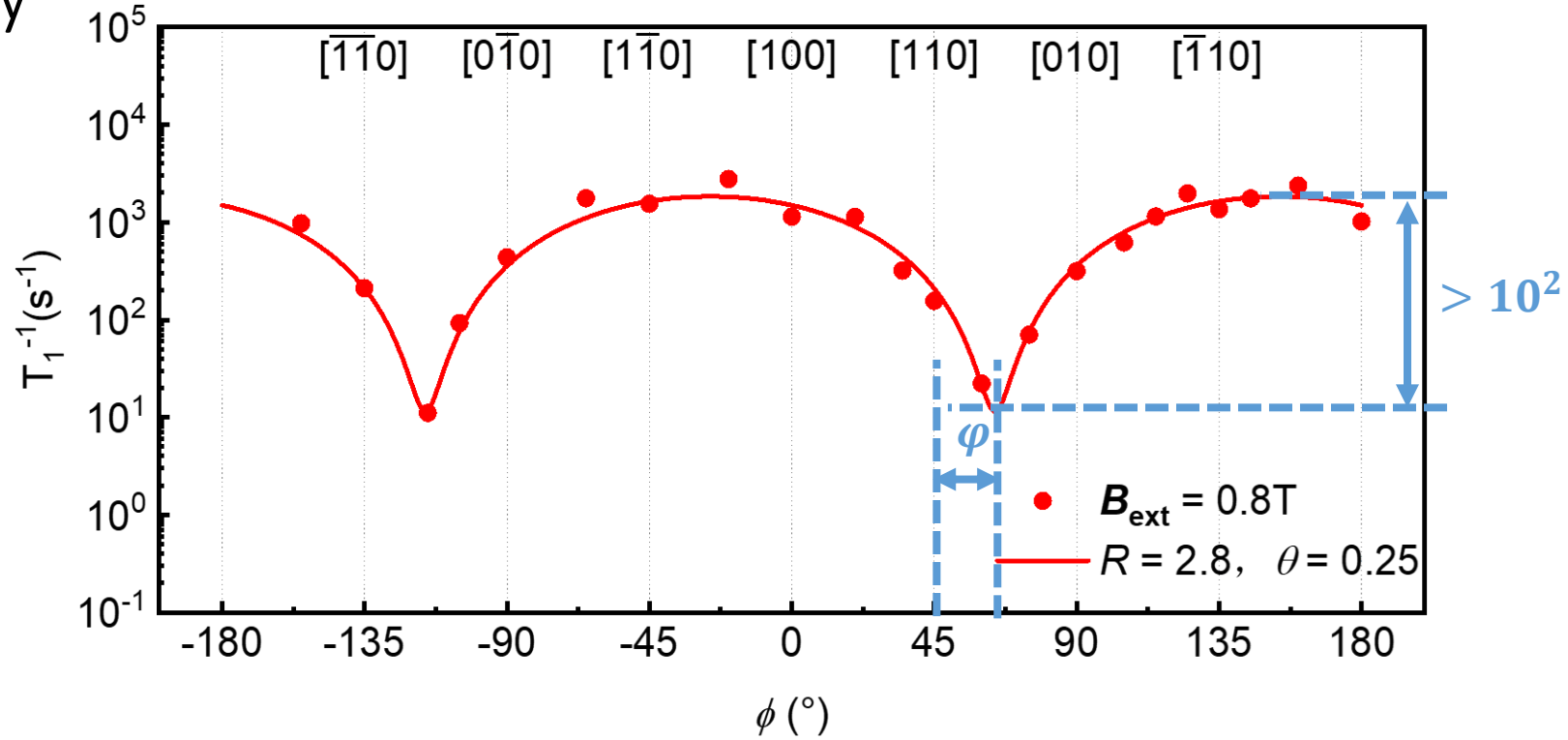
C. H. Yang et al. Nat. Commun. 2013
P. Huang et al. Phys. Rev. B. 2014
C. Tahan and R. Joynt. Phys. Rev. B. 2014
L. Petit et al. Phys. Rev. Lett. 2018
F. Borjans et al. Phys. Rev. Appl. 2019
A. Hollmann et al. arXiv:1907.04146v1

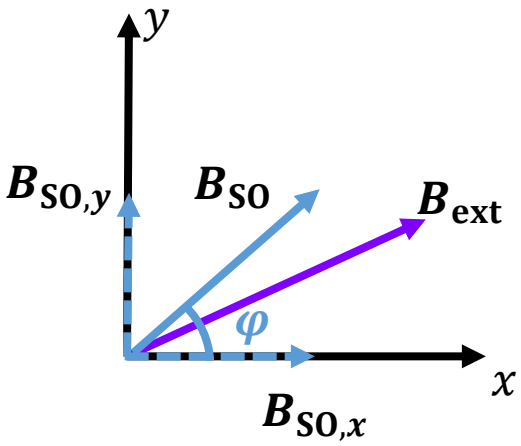
$$T_1^{-1} = \left(c_{\mathrm{J}}\omega_Z + c_{\mathrm{ph}}\omega_Z^5\right)F_{SV}(\omega_Z) + c_{\mathrm{p}}\omega_Z^p$$

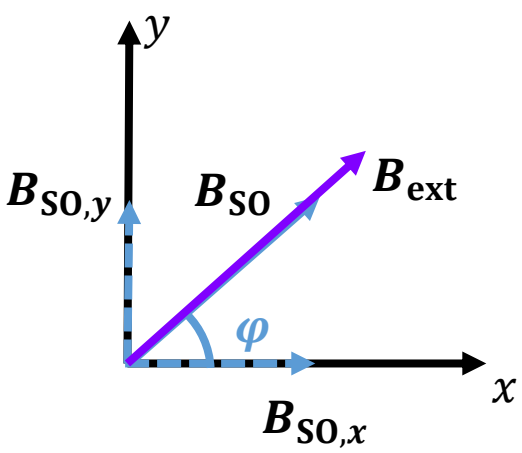
$$F_{SV}(\omega_Z) = 1 - 1/\sqrt{1 + (\Delta_{SV}/\Delta_Z)^2}$$

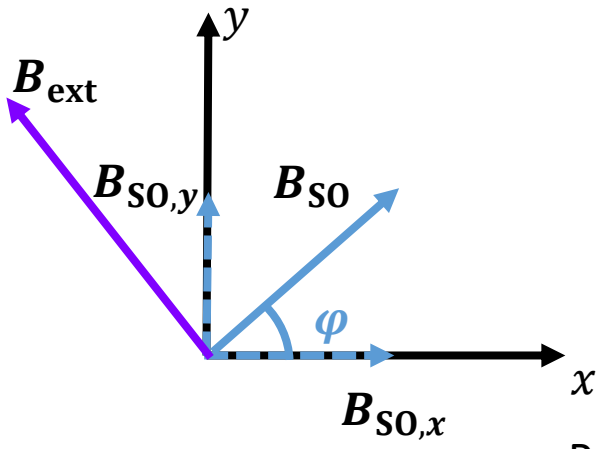
Spin relaxation anisotropy





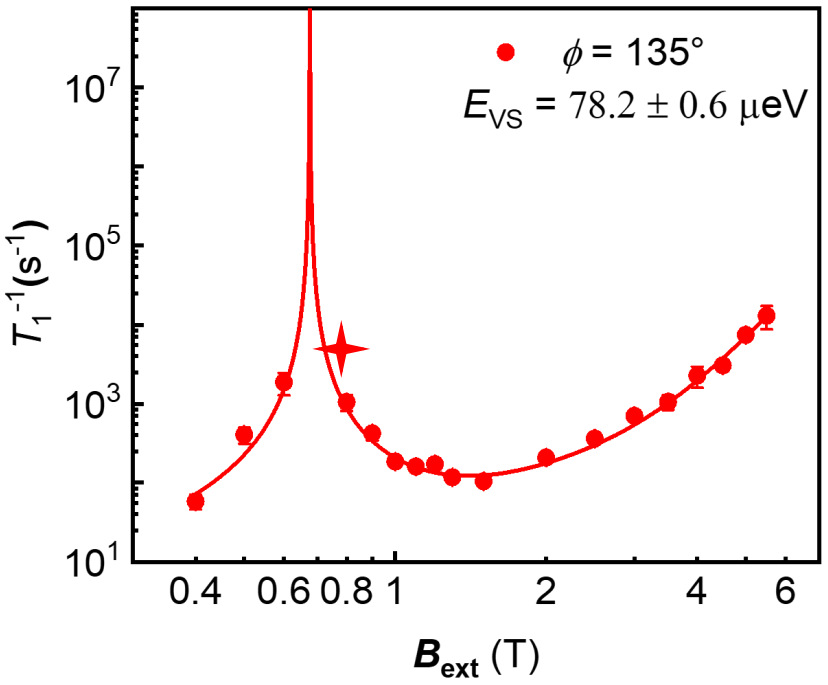


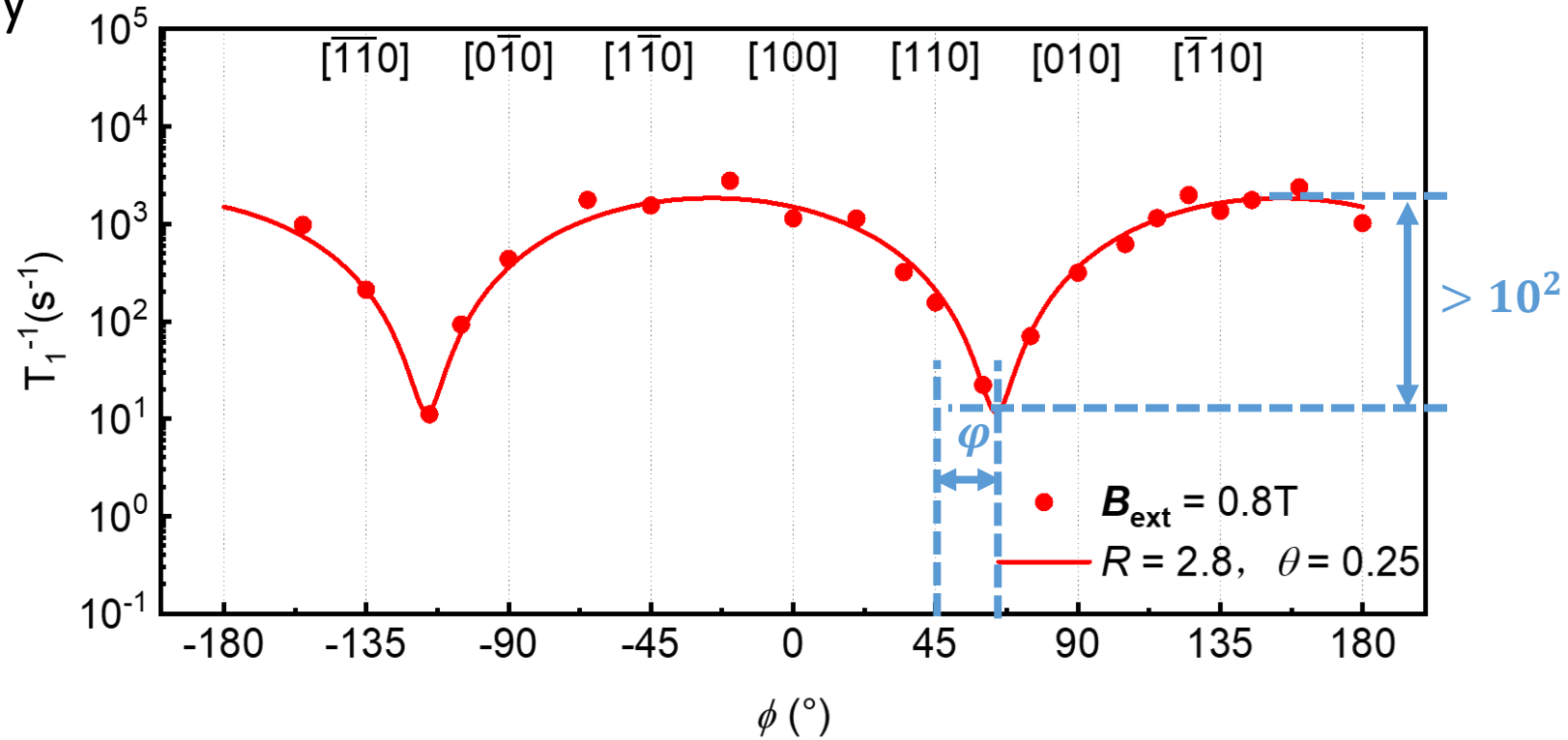




P. Stano and J. Fabian, Phys. Rev. B. 2005
A. Hofmann et al. Phys. Rev. Lett. 2017

Spin relaxation anisotropy





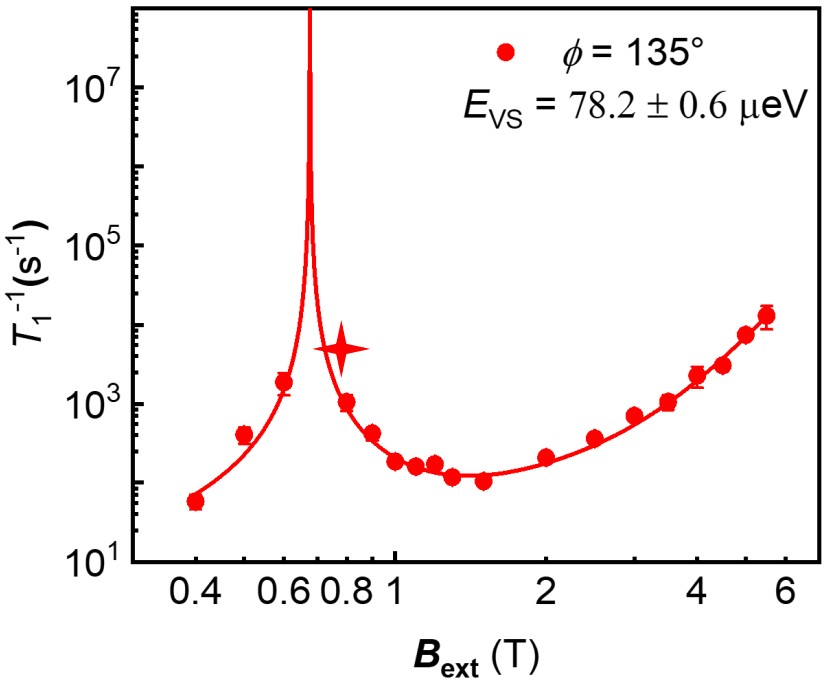
$$\Delta_{SV}(\phi) \sim \langle \uparrow_{ext}, -|\alpha_- r_y \sigma_x + \alpha_+ r_x \sigma_y| \downarrow_{ext}, + \rangle$$

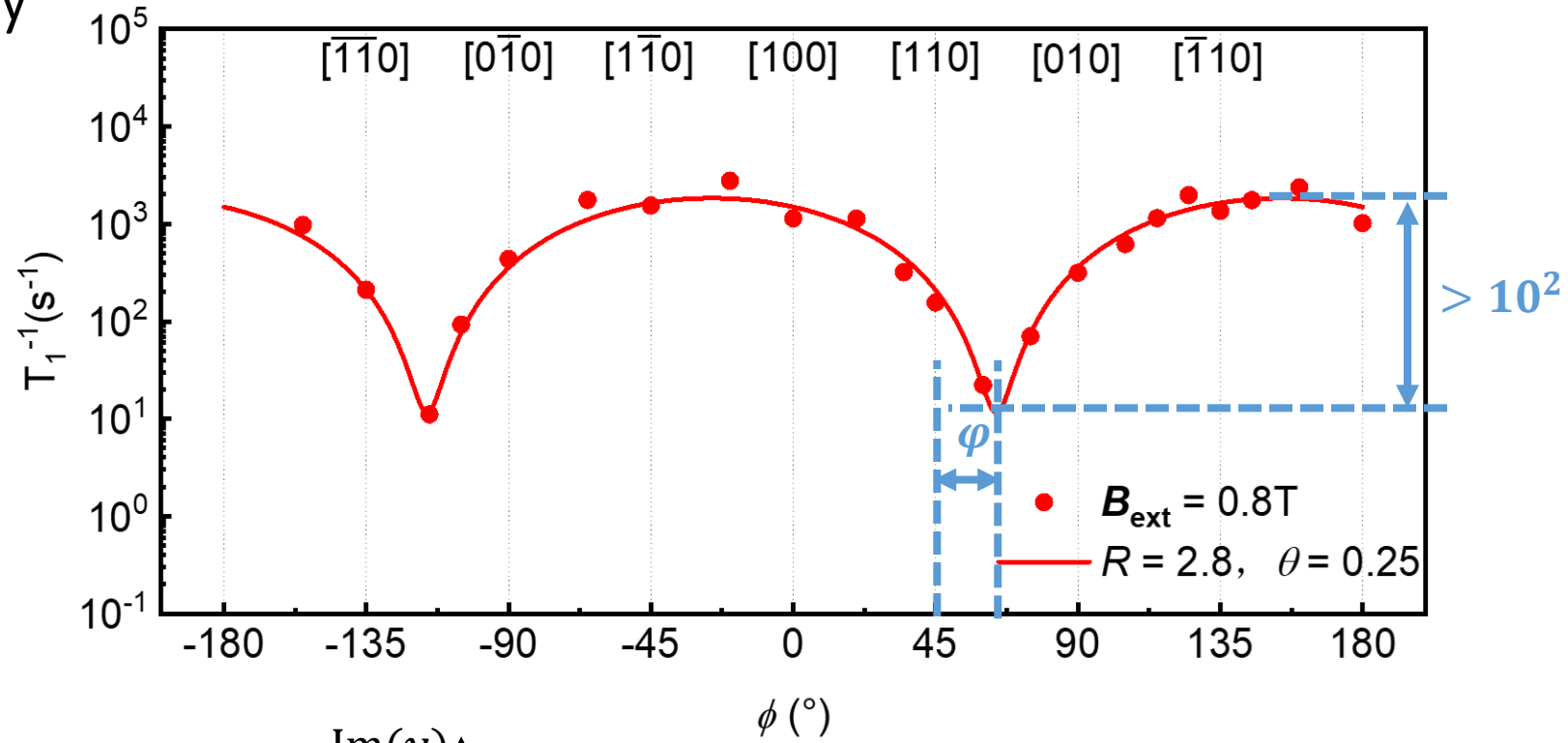
$$\alpha_- = \beta - \alpha \qquad \alpha_+ = \beta + \alpha$$

$$r_y^{-+} = \langle -|r_y|+ \rangle \qquad r_x^{-+} = \langle -|r_x|+ \rangle$$

P. Huang et al. Phys. Rev. B. 2014

Spin relaxation anisotropy

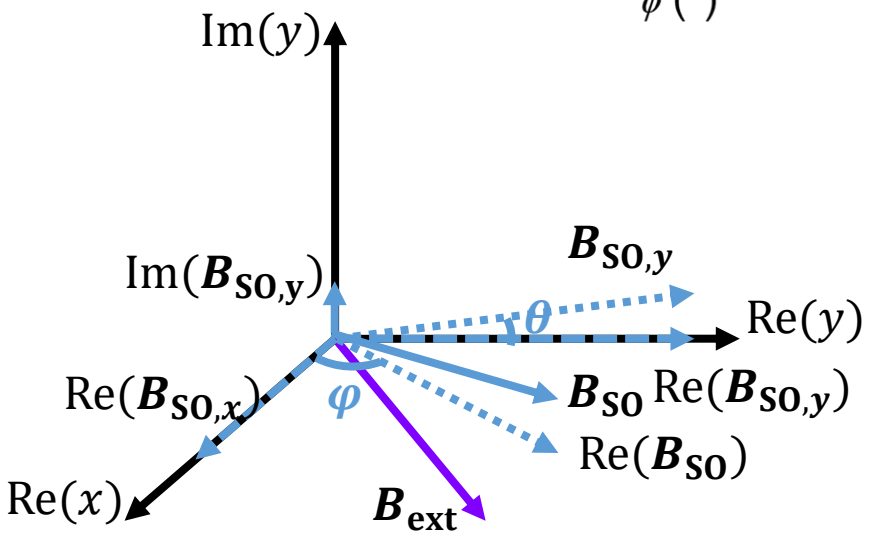




$$\Delta_{SV}(\phi) \sim \langle \uparrow_{ext}, - | \alpha_- r_y \sigma_x + \alpha_+ r_x \sigma_y | \downarrow_{ext}, + \rangle$$

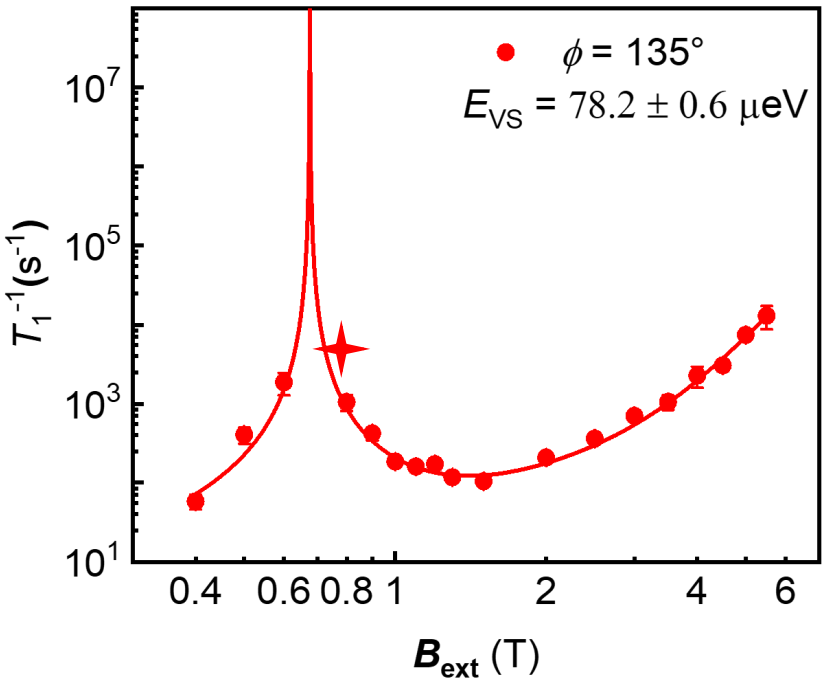
$$\boldsymbol{B}_{\mathbf{so},x} \sim \alpha_- r_y^{-+}/\gamma \qquad \boldsymbol{B}_{\mathbf{so},y} \sim \alpha_+ r_x^{-+}/\gamma$$

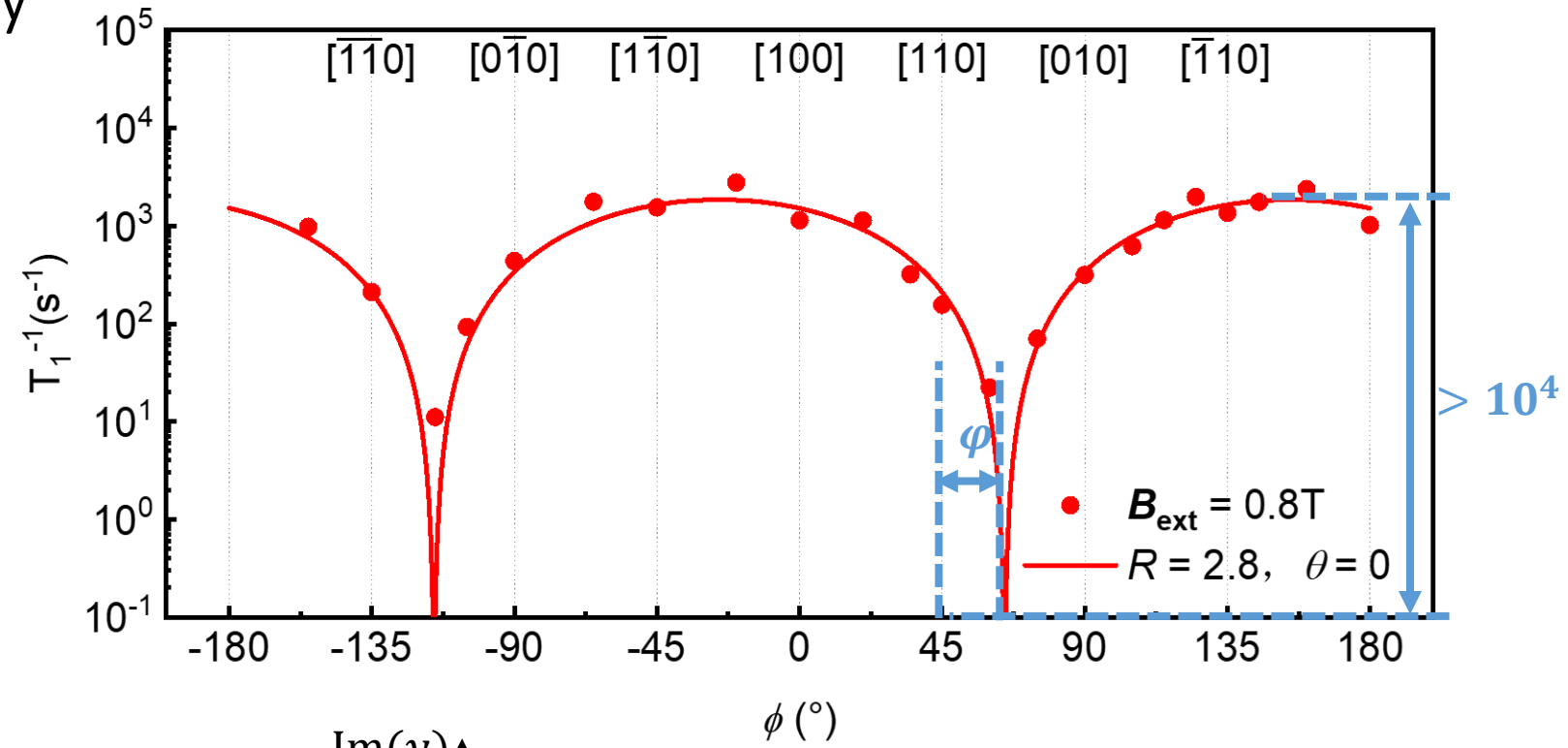
$$\boldsymbol{B}_{\mathbf{so},x}/\boldsymbol{B}_{\mathbf{so},y} = \alpha_- r_y^{-+}/\alpha_+ r_x^{-+} = \boldsymbol{R} = Re^{-i\theta}$$



P. Huang et al. Phys. Rev. B. 2014

Spin relaxation anisotropy





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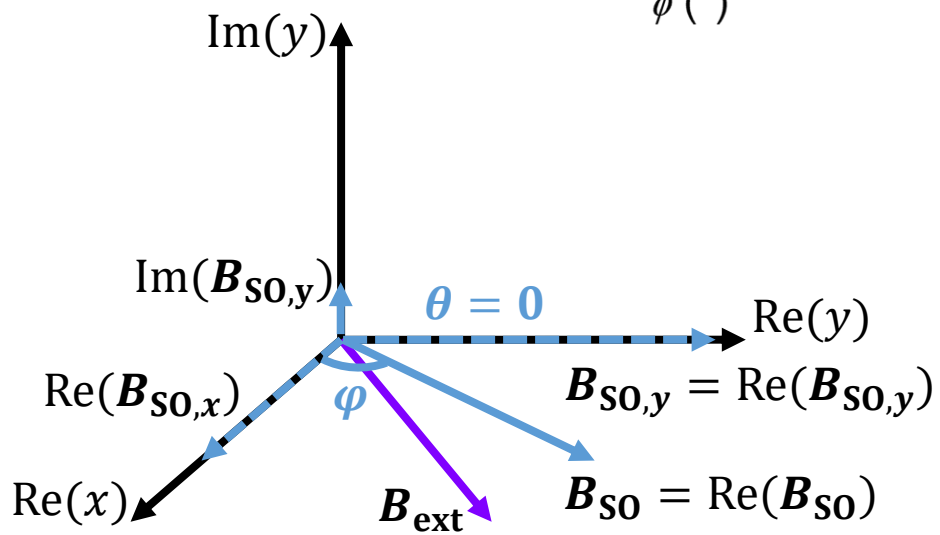
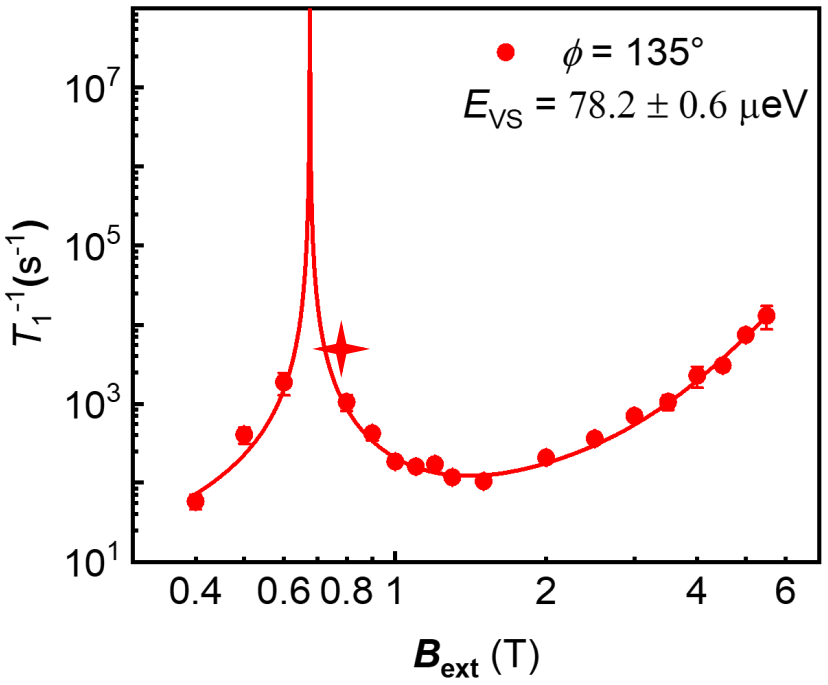
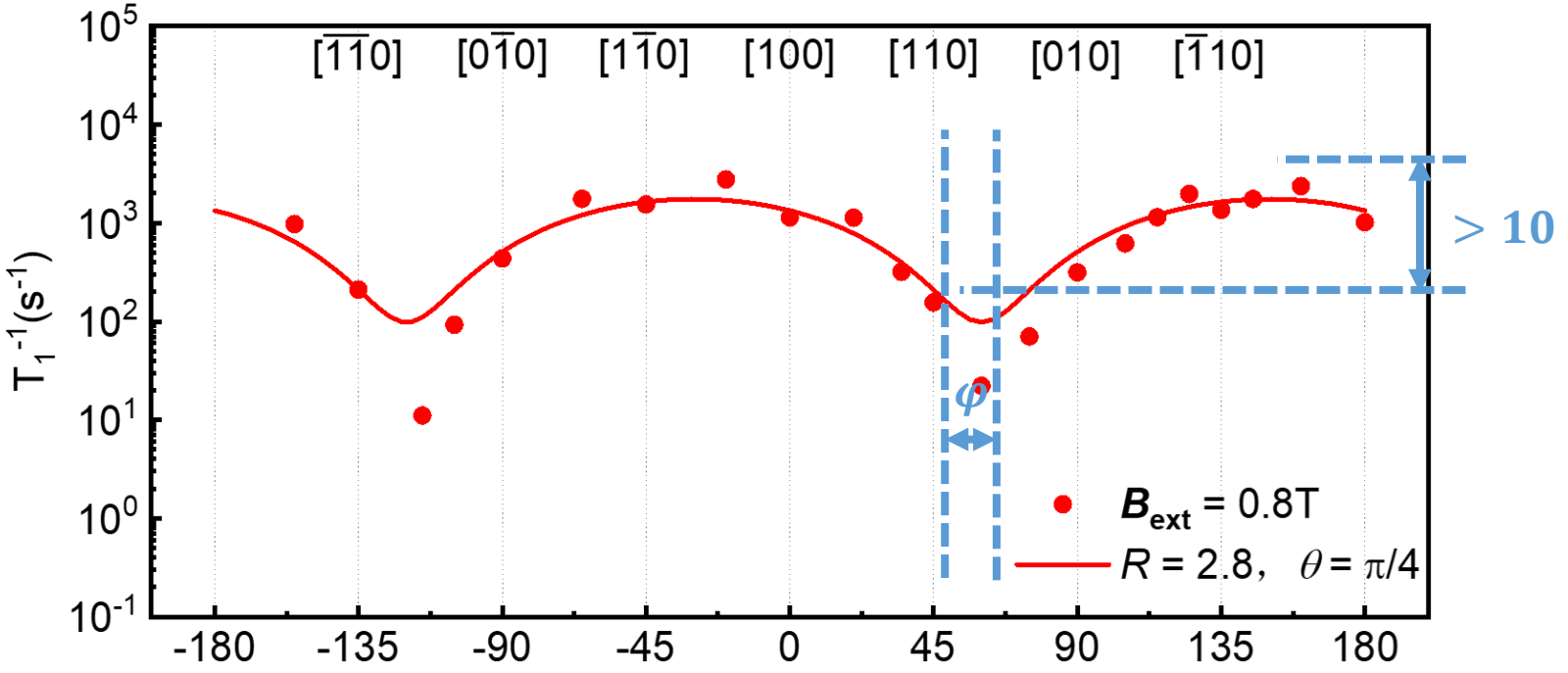


P. Huang et al. Phys. Rev. B. 2014

Spin relaxation anisotropy





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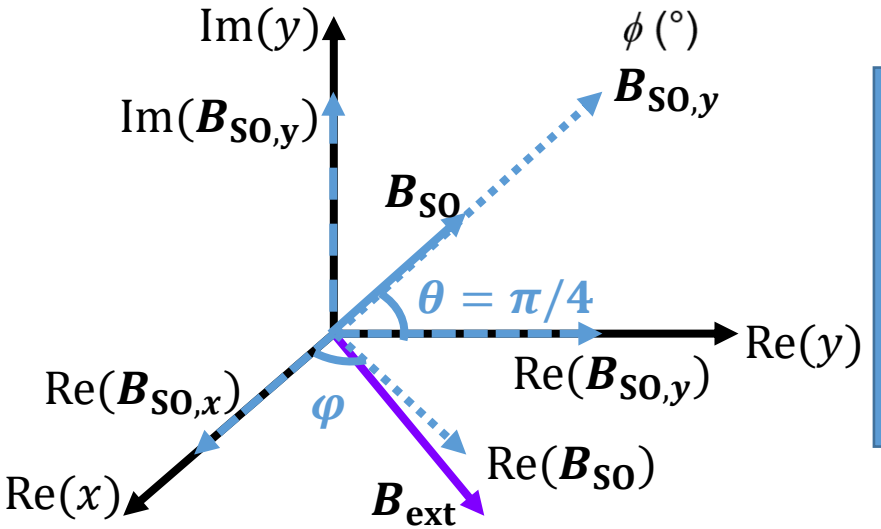
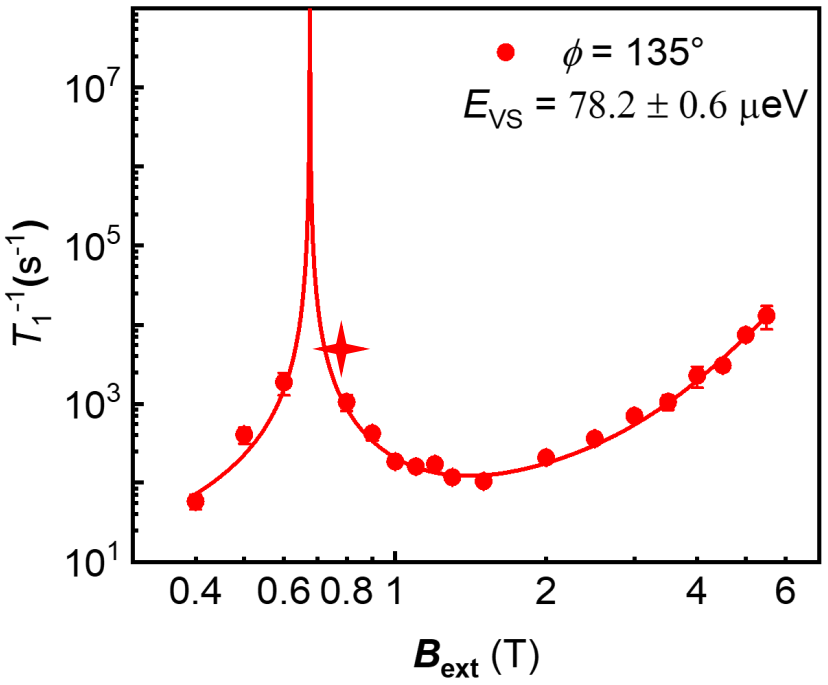


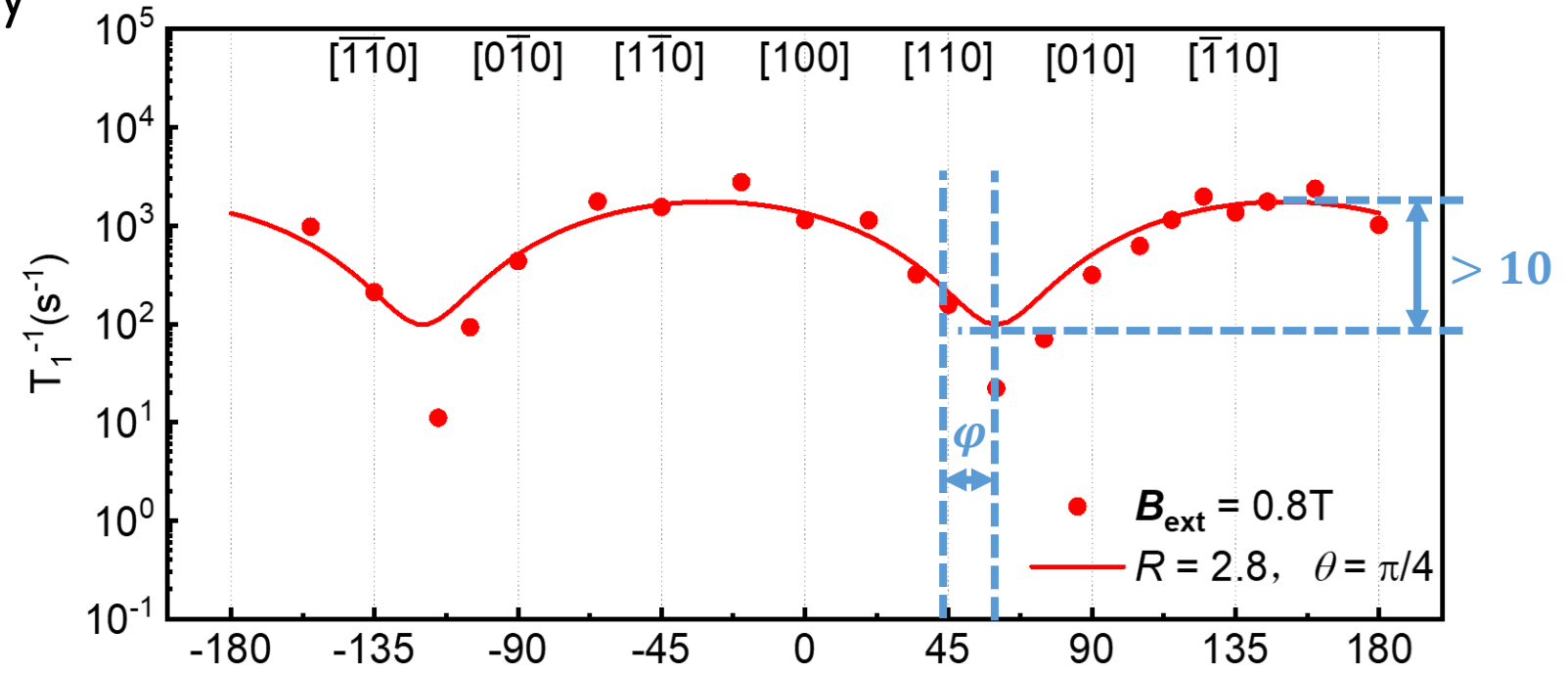
Origin of large anisotropy:

Small θ from nearly isotropic valley orbit coupling.

P. Huang et al. Phys. Rev. B. 2014

Spin relaxation anisotropy





$$\Delta_{SV}(\phi) \sim \langle \uparrow_{ext}, - | \alpha_- r_y \sigma_x + \alpha_+ r_x \sigma_y | \downarrow_{ext}, + \rangle$$

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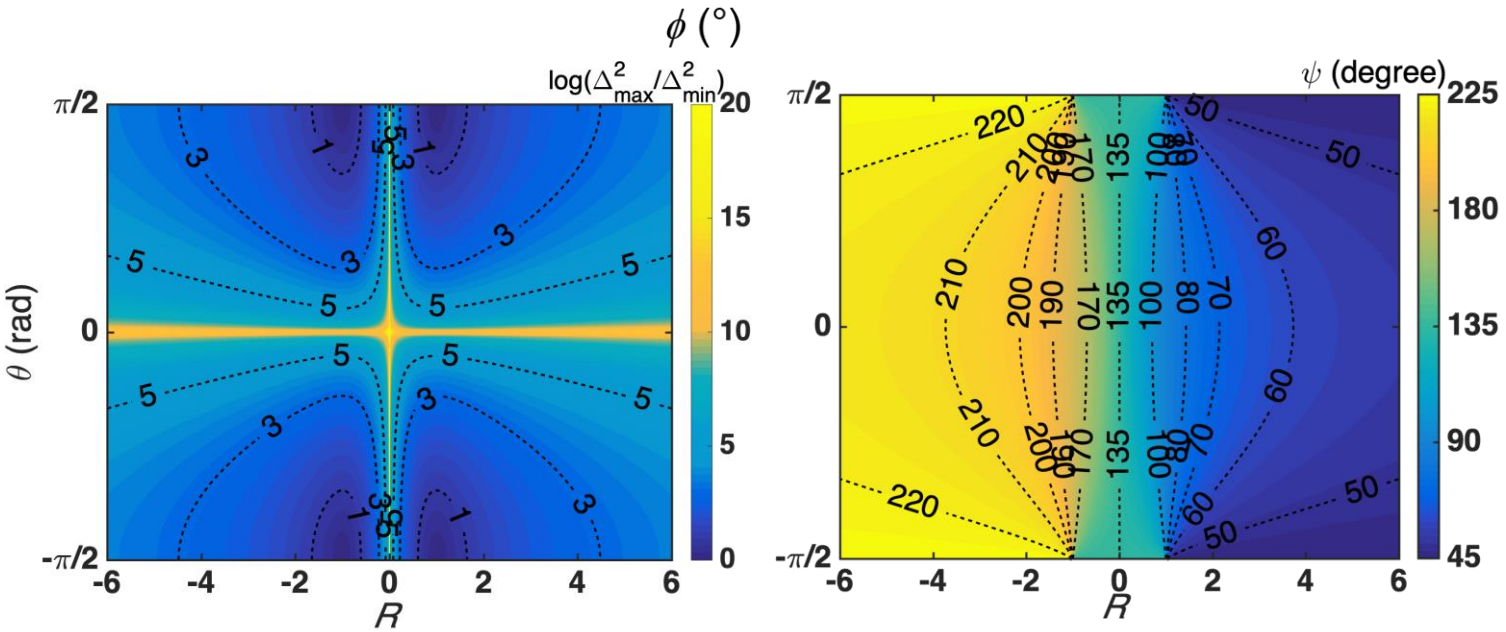
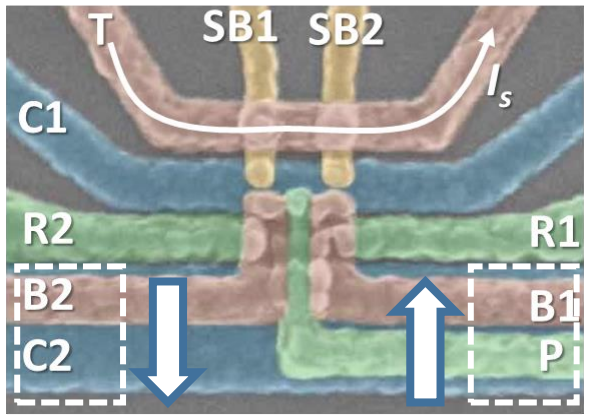
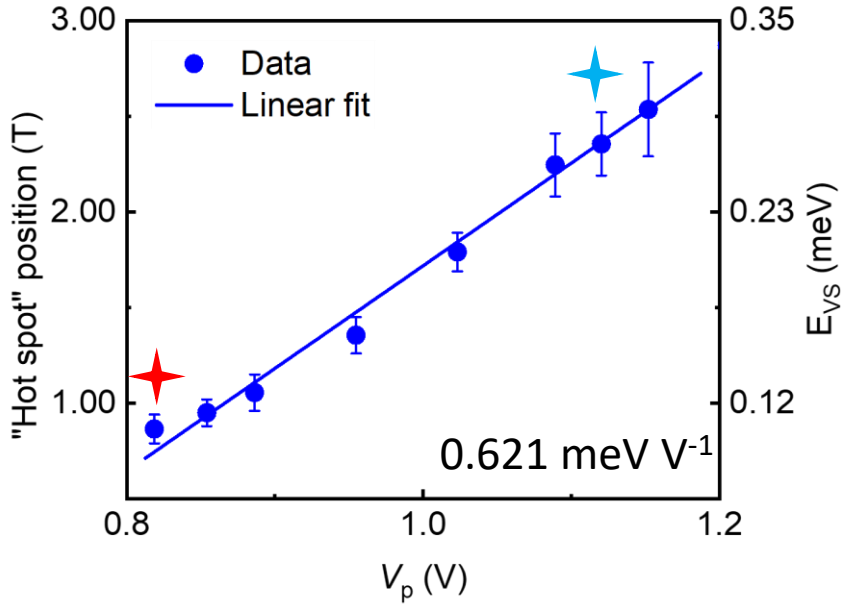
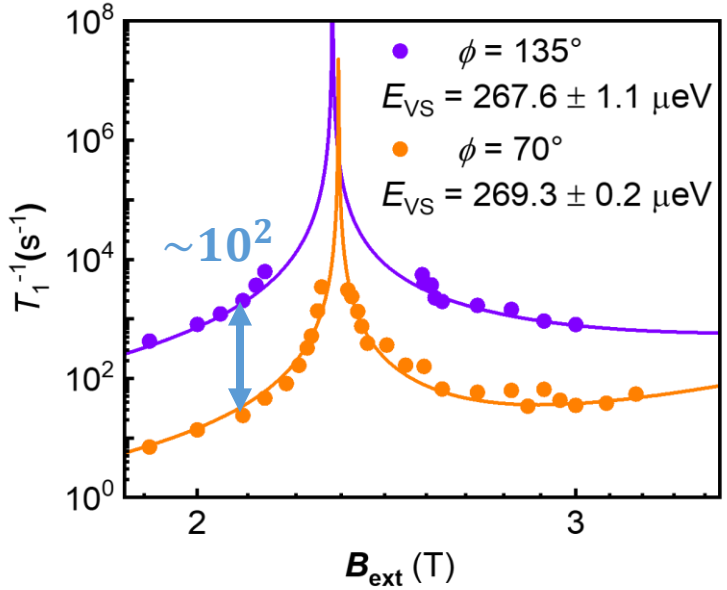
$$\boldsymbol{B}_{\mathbf{so},x}/\boldsymbol{B}_{\mathbf{so},y} = \alpha_- r_y^{-+}/\alpha_+ r_x^{-+} = \boldsymbol{R} = Re^{-i\theta}$$



Spin relaxation anisotropy with a large valley splitting



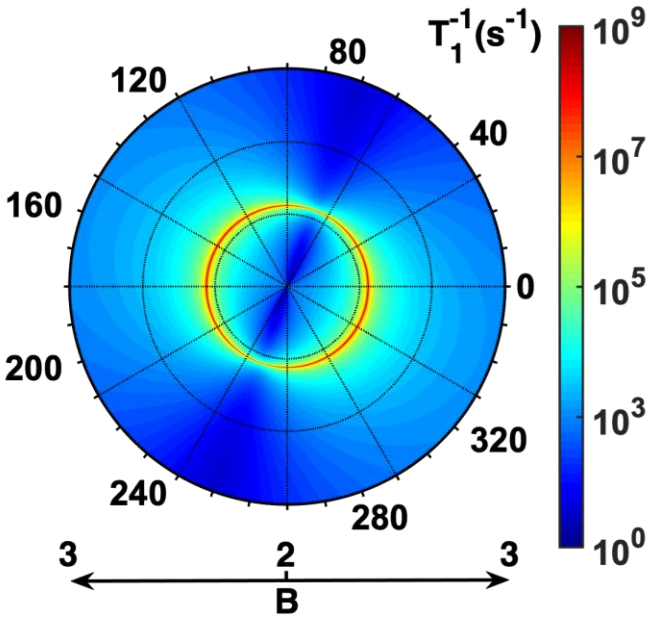




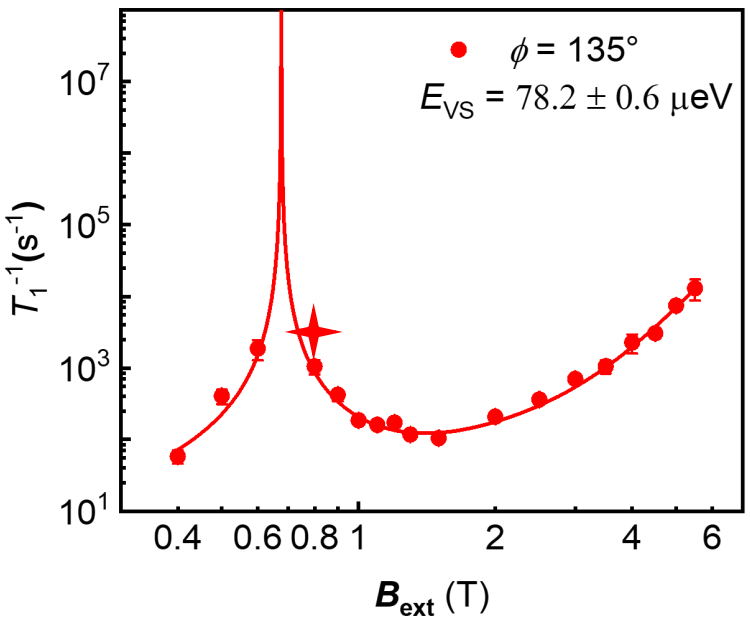
$$\Delta_{SV}(\phi) \sim \langle \uparrow_{ext}, - | \alpha_- r_y \sigma_x + \alpha_+ r_x \sigma_y | \downarrow_{ext}, + \rangle$$

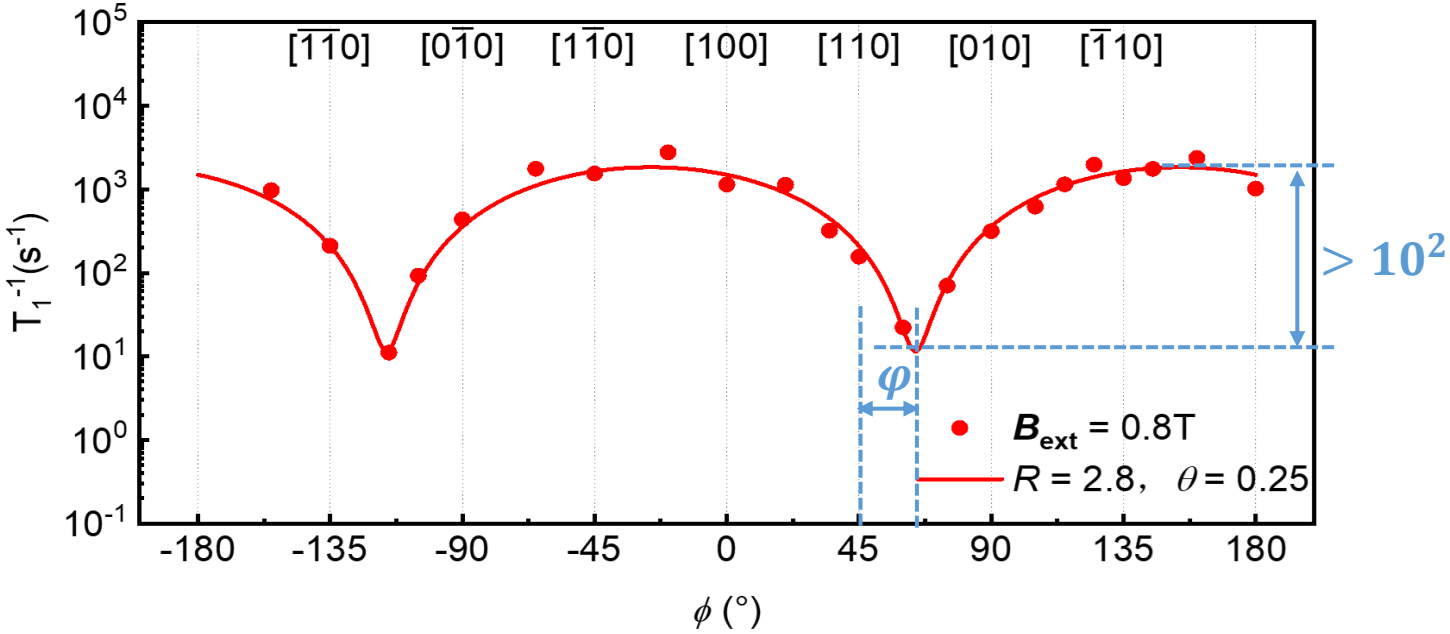
$$\boldsymbol{B}_{\mathrm{SO},x}/\boldsymbol{B}_{\mathrm{SO},y} = \alpha_- r_y^{-+}/\alpha_+ r_x^{-+} = \boldsymbol{R} = Re^{-i\theta}$$

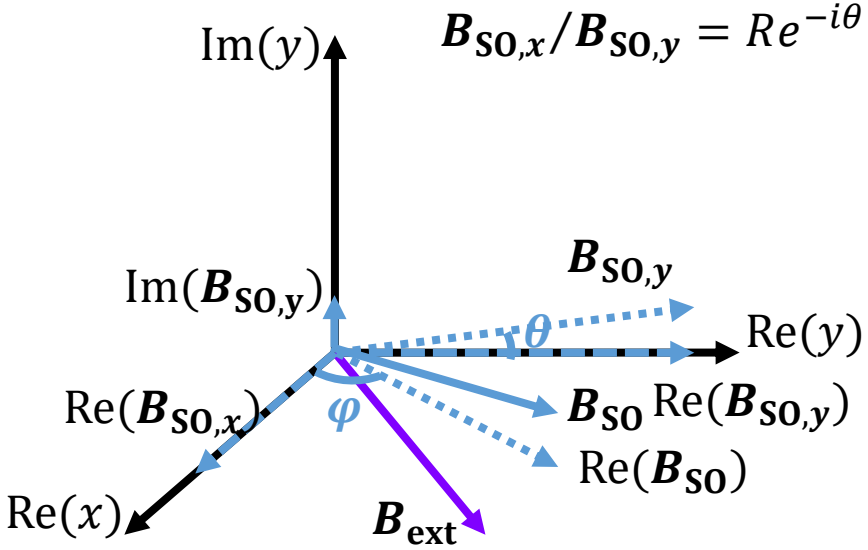
$$T_1^{-1} \sim \left(c_{\mathrm{J},1}\omega_Z + c_{\mathrm{ph},1}\omega_Z^5\right)\frac{\Delta_{SV}(\phi)^2}{2{\Delta_Z}^2} + c_{\mathrm{p}}\omega_Z^p$$

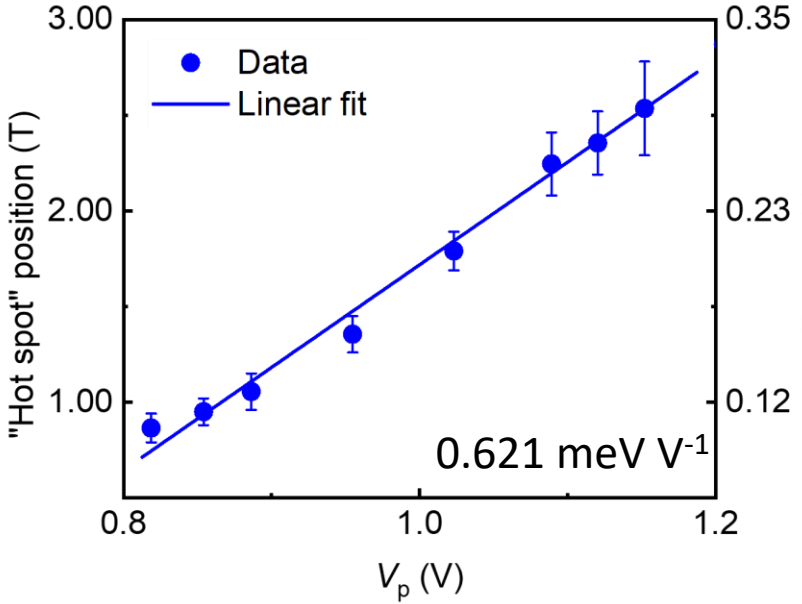


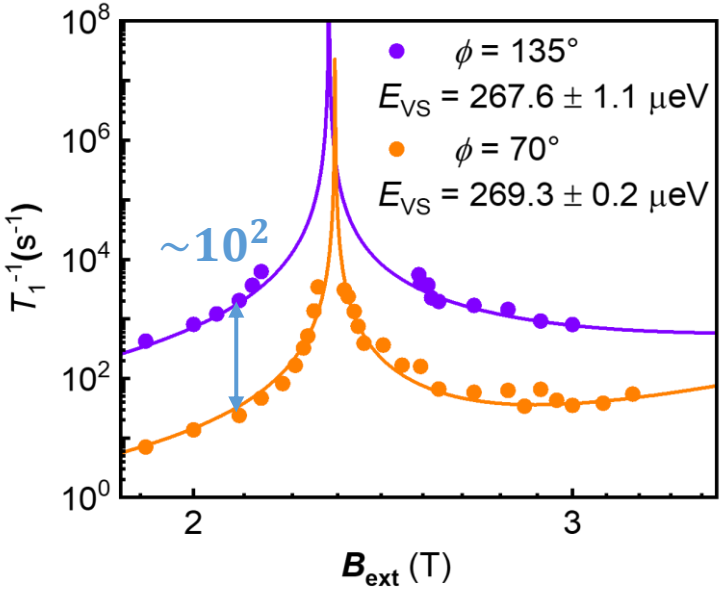
Summary

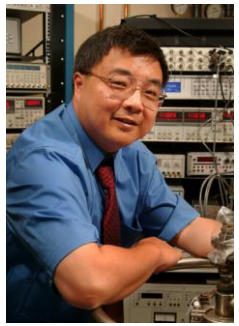

ϕ = 135°
E_{VS} = 78.2 ± 0.6 μeV
T_1^{-1}(s^{-1})
B_{ext} (T)


[1̄10] [01̄0] [11̄0] [100] [110] [010] [1̄10]
T_1^{-1}(s^{-1})
φ
B_{ext} = 0.8T
R = 2.8, θ = 0.25
> 10^2
ϕ (°)

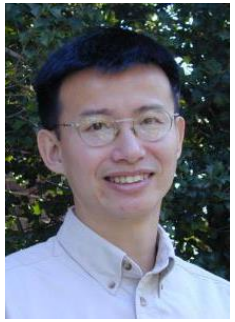

$B_{so,x}/B_{so,y} = Re^{-i\theta}$
Im(y)
Im($B_{so,y}$)
$B_{so,y}$
θ
Re(y)
Re($B_{so,x}$)
φ
B_{so}
Re($B_{so,y}$)
Re(B_{so})
Re(x)
B_{ext}


Data
Linear fit
0.621 meV V^{-1}
"Hot spot" position (T)
E_{VS} (meV)
V_p (V)


ϕ = 135°
E_{VS} = 267.6 ± 1.1 μeV
ϕ = 70°
E_{VS} = 269.3 ± 0.2 μeV
~10^2
T_1^{-1}(s^{-1})
B_{ext} (T)



HongWen Jiang



Xuedong Hu

Peihao Huang

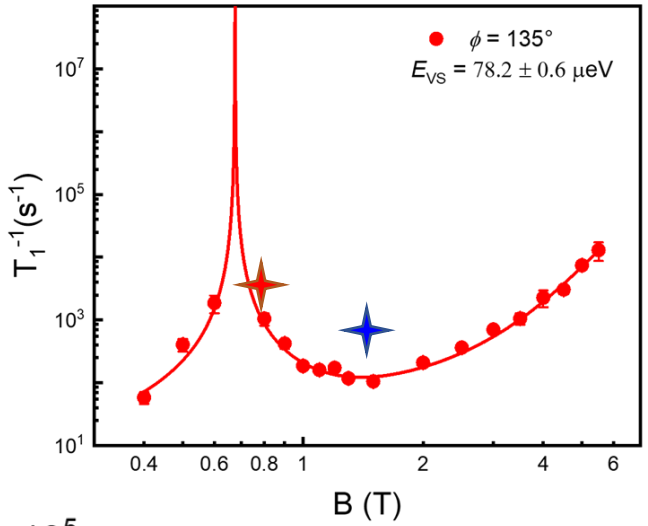
Thank you!

Dimitrie Culcer

Jianjun Zhang

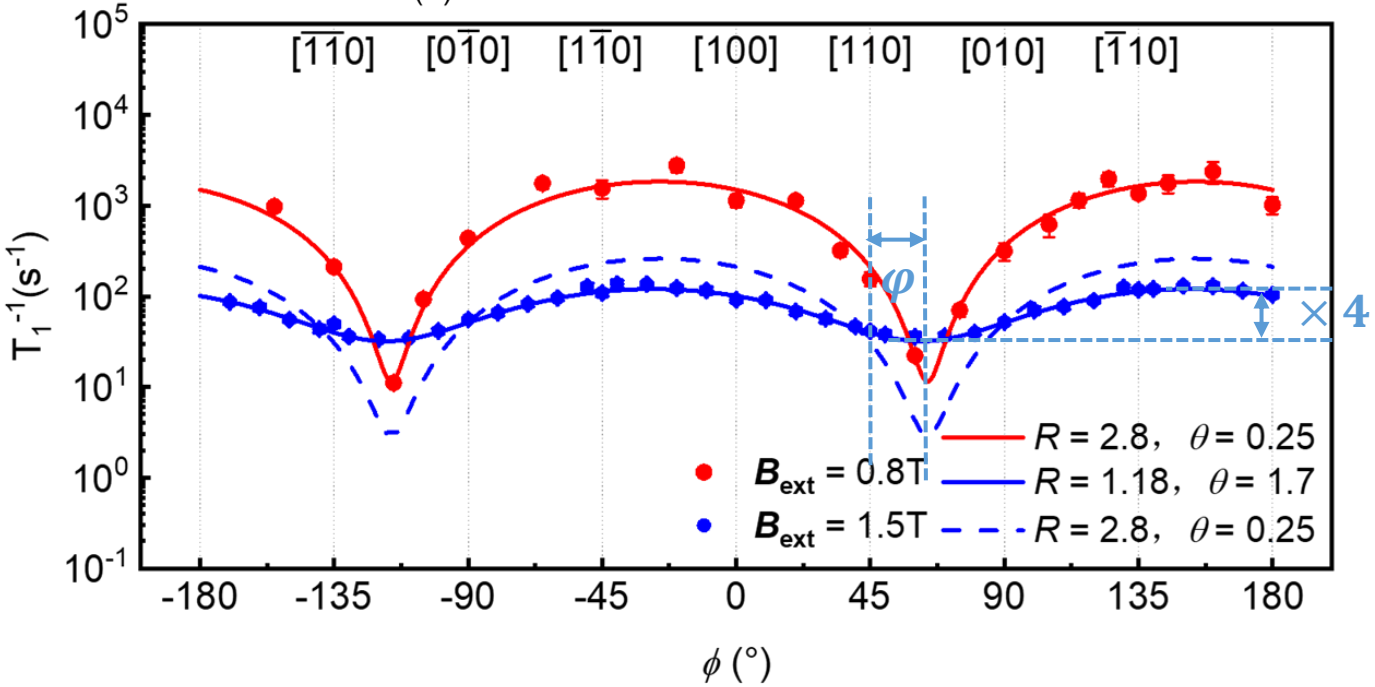
Guilei Wang

The anisotropy away from the “hot spot”



$$T_1^{-1} \sim \left(c_{\mathrm{J}}\omega_Z + c_{\mathrm{ph}}\omega_Z^5\right)\frac{\Delta_{SV}(\phi)^2}{2\Delta_Z{}^2} + c_{\mathrm{p}}\omega_Z^7$$

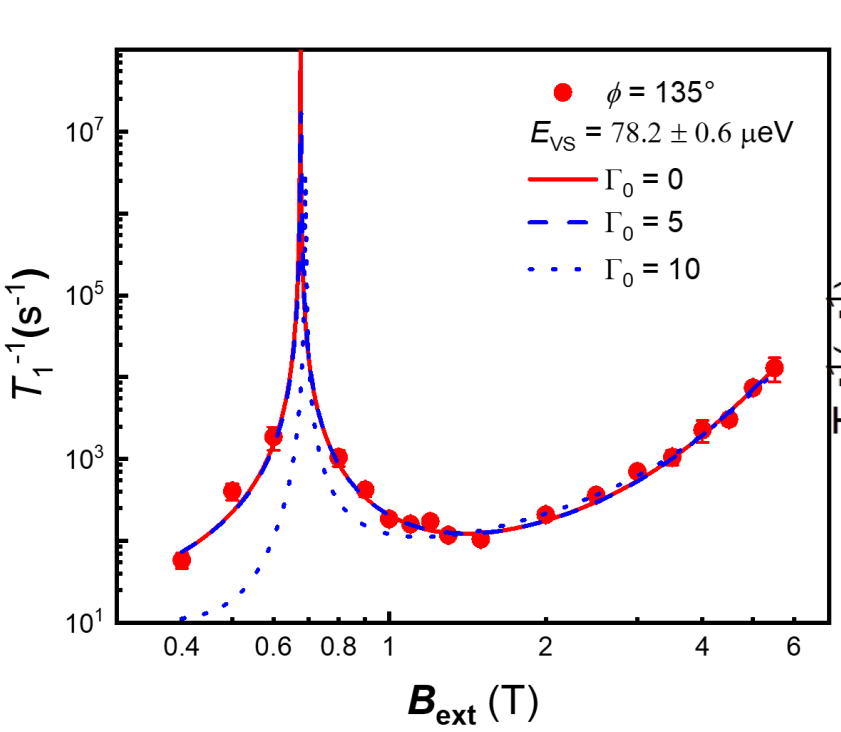
Total variation

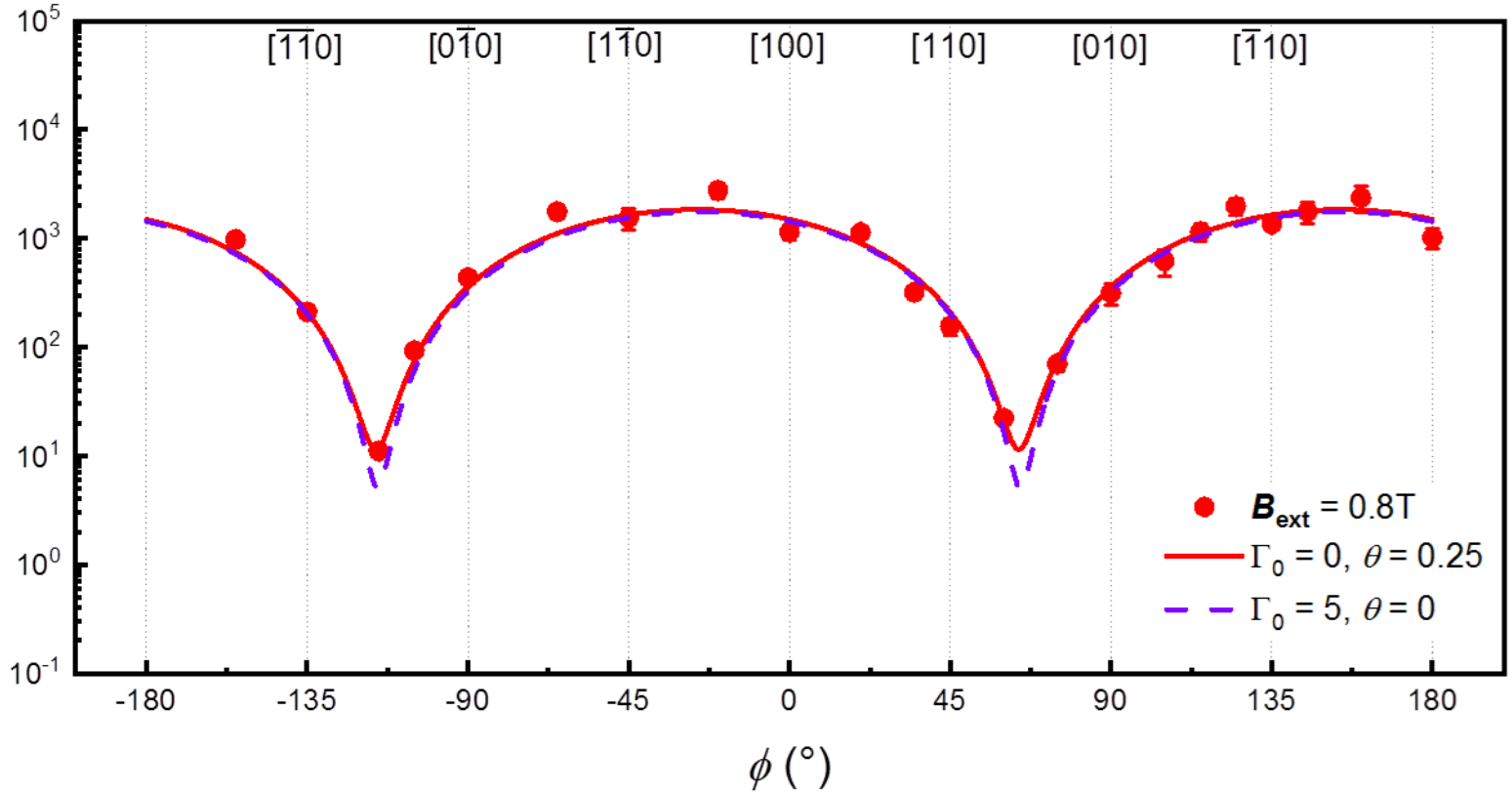


Possible explanation:

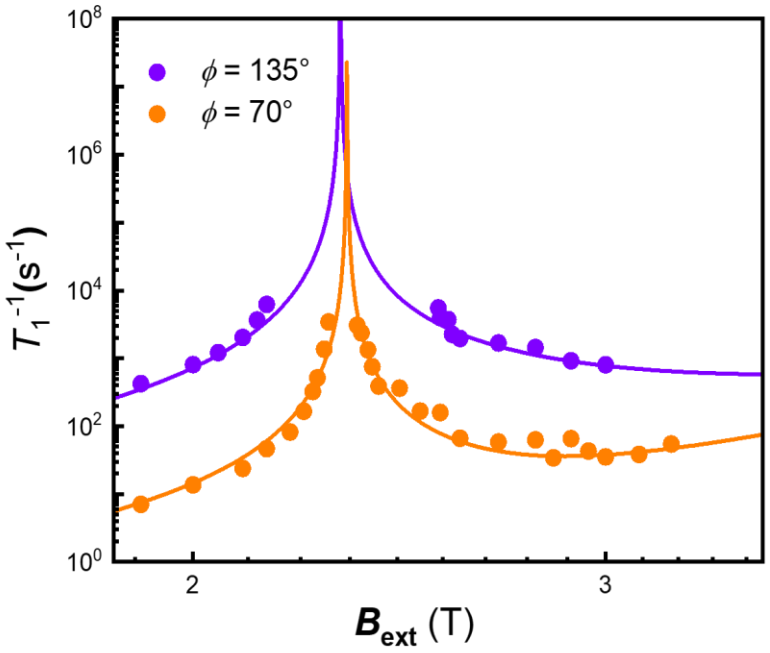
Other $c_{\mathrm{p}}\omega_Z^p$ law exists!

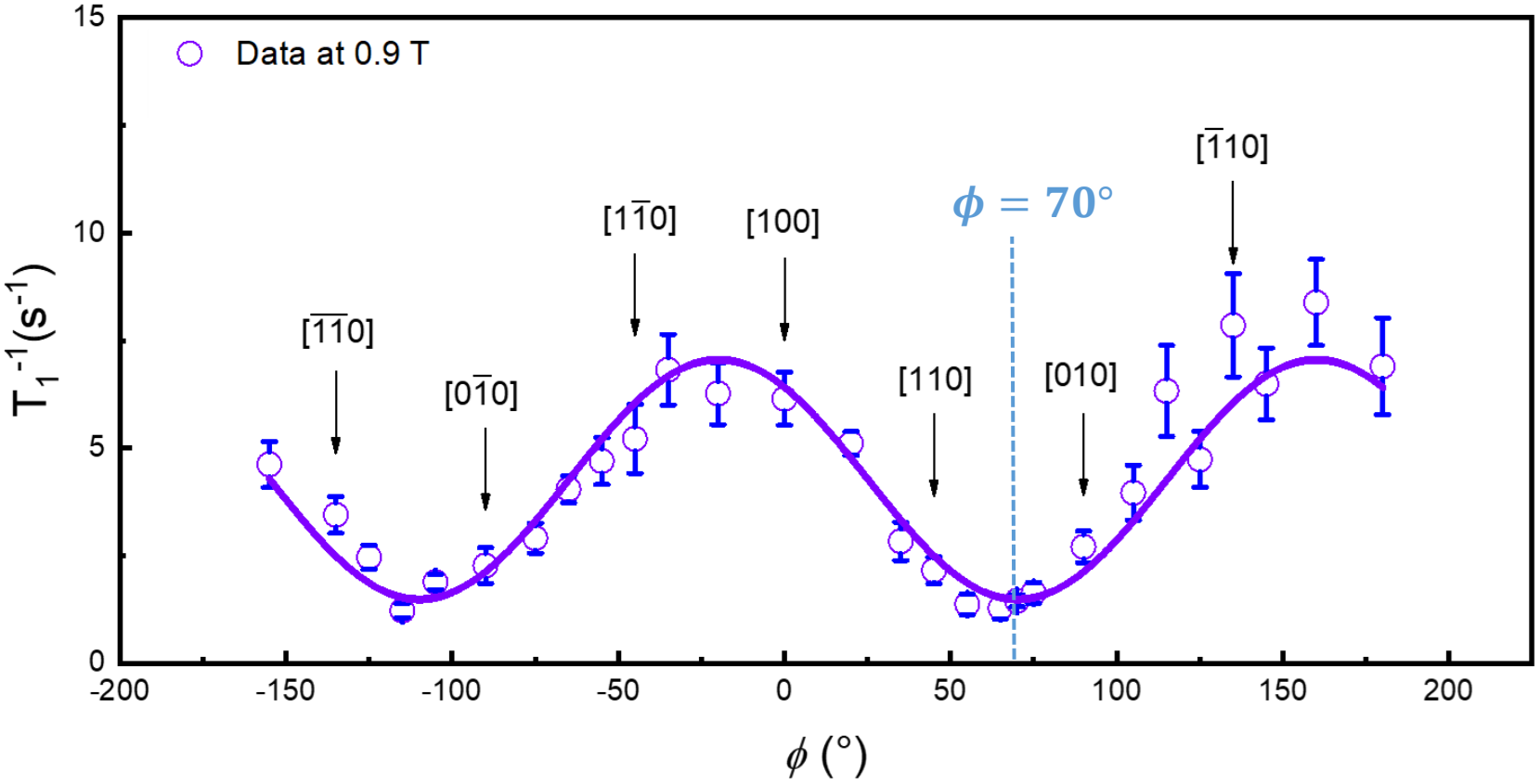
Discussion about Γ_0



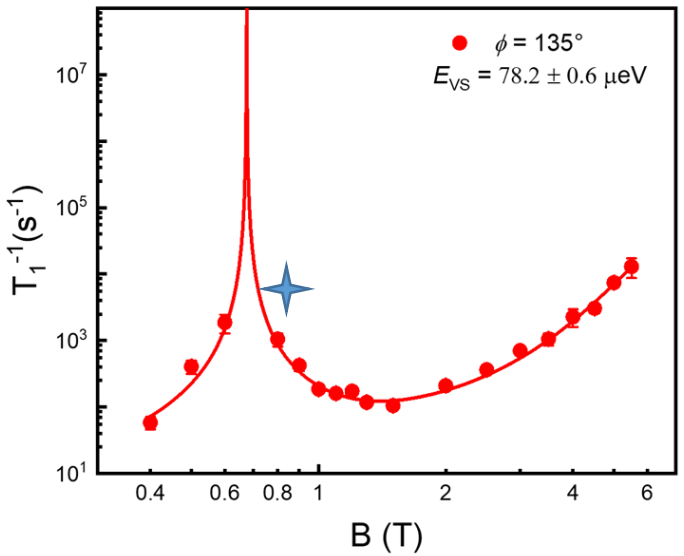


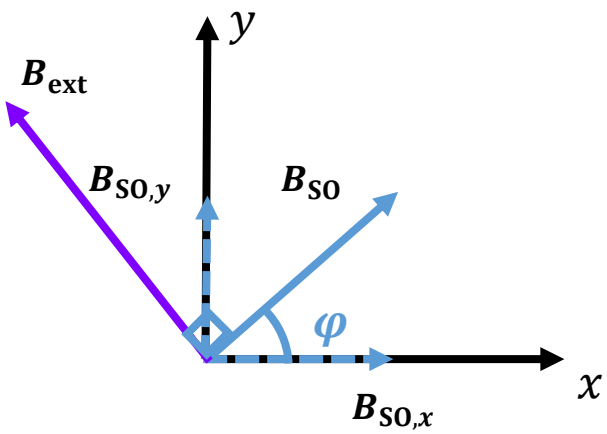
Position of the extrema in the large valley splitting regime

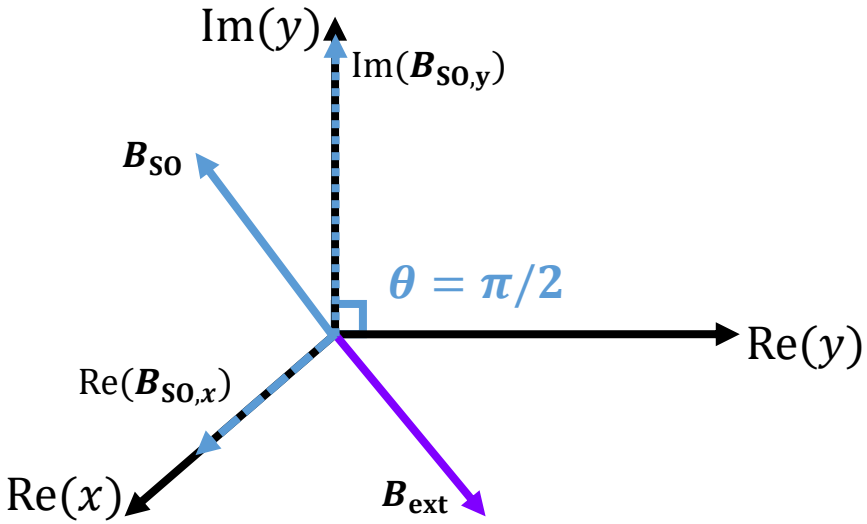


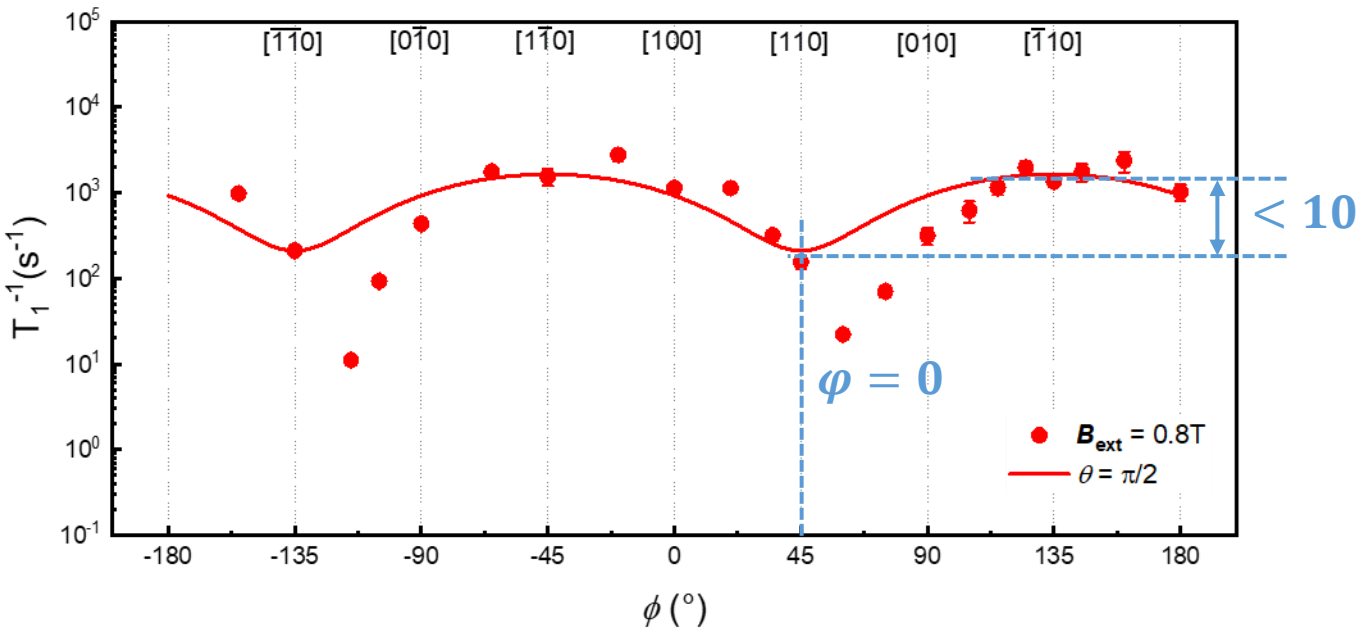


Spin relaxation anisotropy









$$|\Delta_{SV}(\varphi)|^2 = c_{SV}(R^2 \sin^2\varphi + \cos^2\varphi - R\cos\theta \sin 2\varphi)$$

$$F_{SV}(\omega_Z, \varphi) = 1 - 1/\sqrt{1 + (\Delta_{SV}(\varphi)/\Delta_Z)^2}$$

$$T_1^{-1} = (c_J\omega_Z + c_{ph}\omega_Z^5)F_{SV}(\omega_Z, \varphi) + c_p\omega_Z^p$$