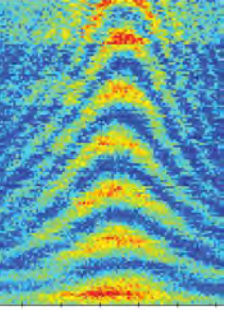
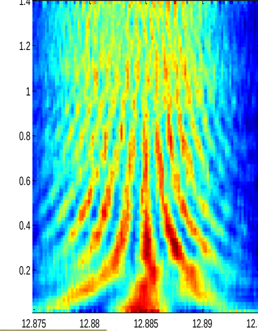
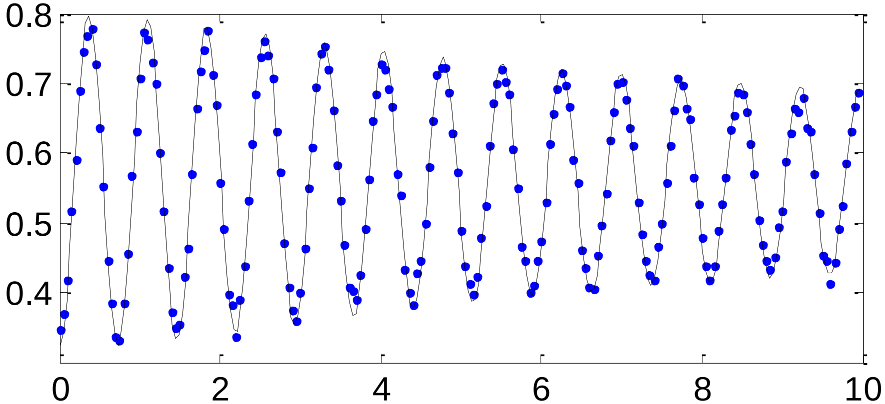
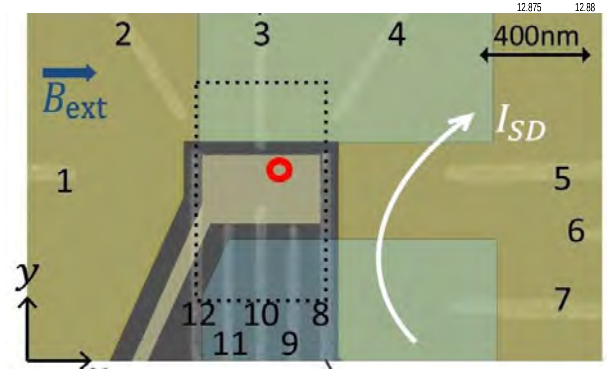


Spin and valley physics of a single electron confined in a Si/SiGe quantum dot







Pasquale Scarlino (ETH)
Erika Kawakami (TU Delft)
Thibaut Julien
Lieven Vandersypen

<u>Collaborators **(Wisconsin)**</u>
Dan Ward, Mark Eriksson
Sue Coppersmith, Mark Friesen
Don Savage, Max Lagally

TU Delft
Delft University of Technology

FOM

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European Research Council
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KAVLI INSTITUTE of Nanoscience Delft

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1951

Ep2ds 2015

http://vandersypenlab.tudelft.nl

QUANTUM ACOUSTICS

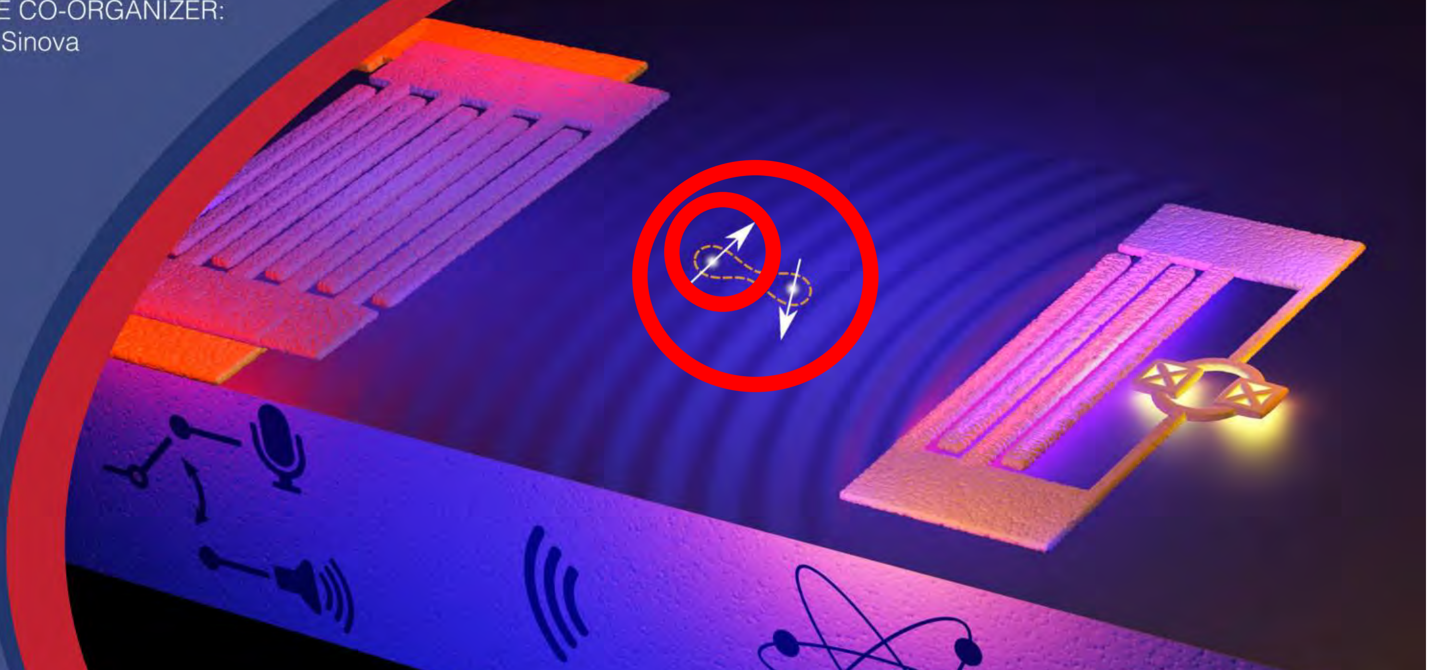
SURFACE ACOUSTIC WAVES MEETS SOLID STATE QUBITS

Workshop May 17th - 20th 2016
Schloss Waldthausen, Mainz, Germany

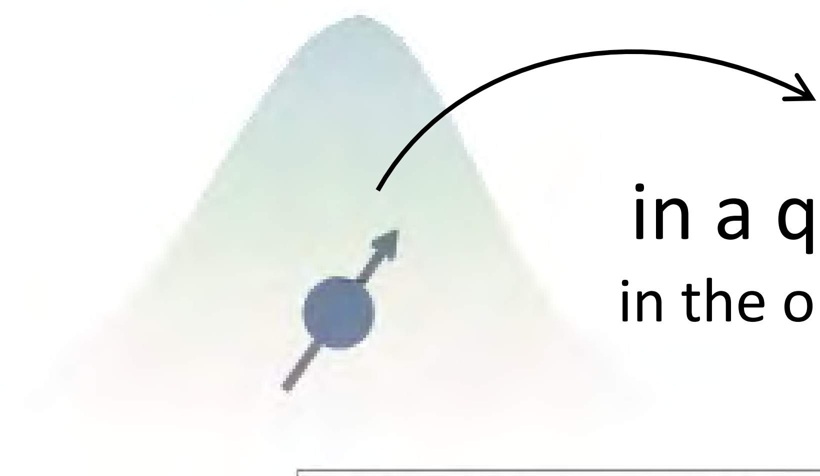
ORGANIZERS:
Chris Bäuerle (Institut Néel)
Göran Johansson (Chalmers)
Paulo Santos (Paul Drude Inst.)
Floris Zwanenburg (Twente)

SPICE CO-ORGANIZER:
Jairo Sinova

SPICE



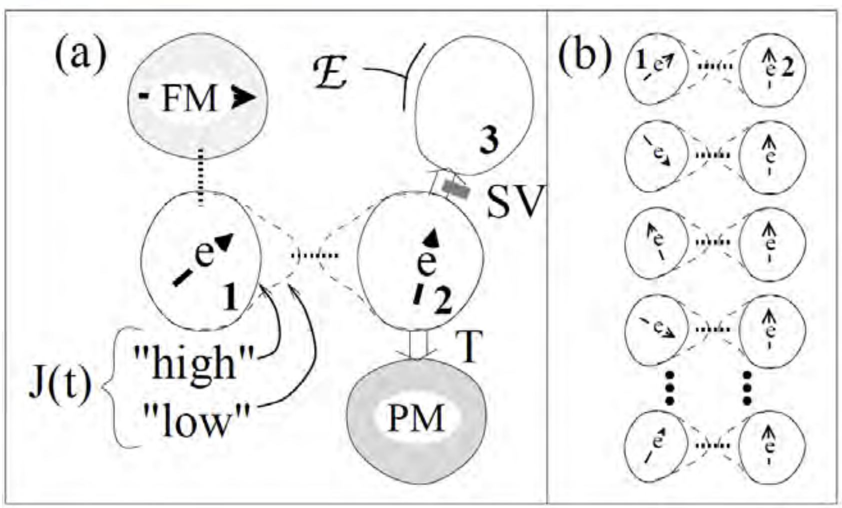
Loss–DiVincenzo quantum computer

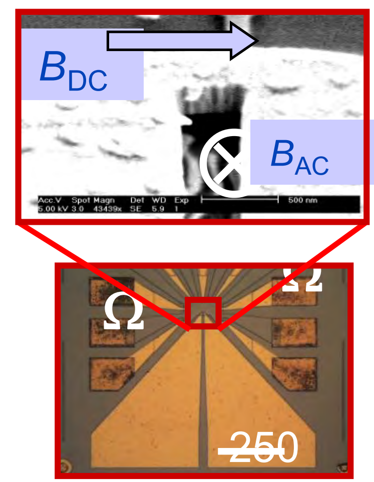


electron spin

in a quantum dot as a qubit

in the orbit (valley-orbit) ground state

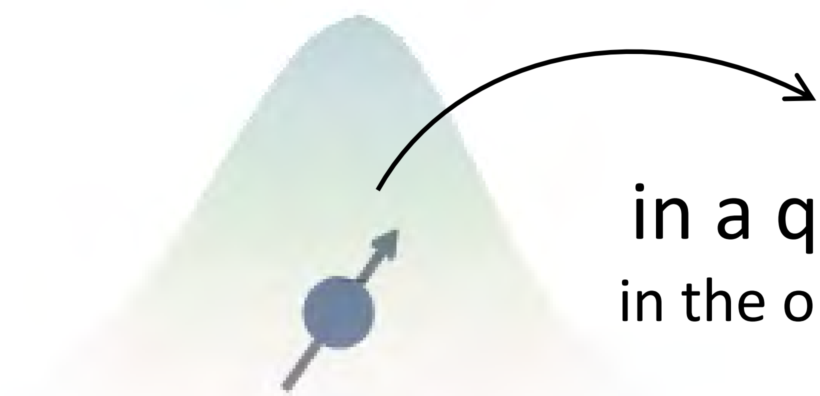




Koppens et al,
Nature 442, 766 (2006)

D. Loss and D. P. DiVincenzo, Phys. Rev. A **57**, 120 (1998).

All electrical control of Loss–DiVincenzo quantum computer

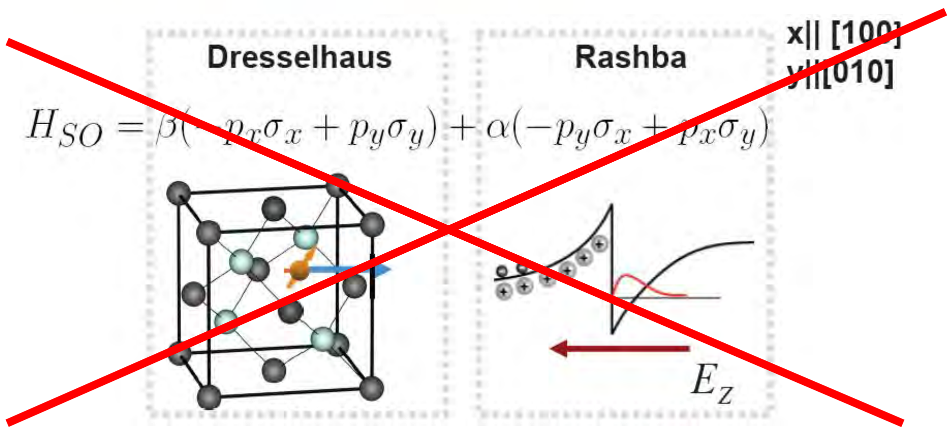


electron spin

in a quantum dot as a qubit

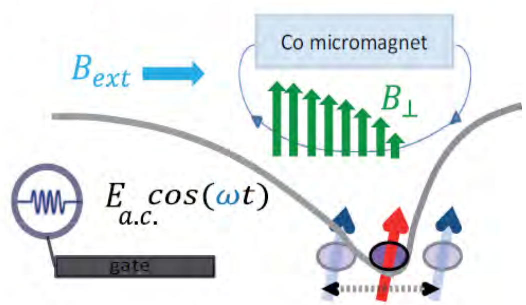
in the orbit (valley-orbit) ground state

in Silicon



Novack et al, Science 318, 1430(2007)

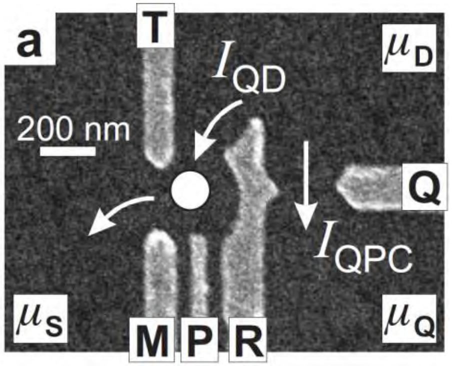
artificial spin-orbit

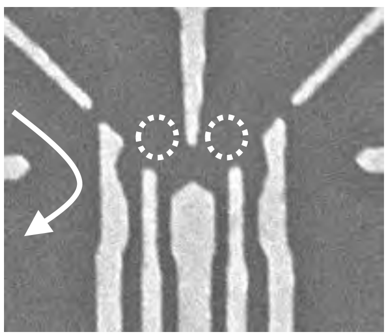


Y. Tokura et. al., PRL **96**, 047202 (2006)

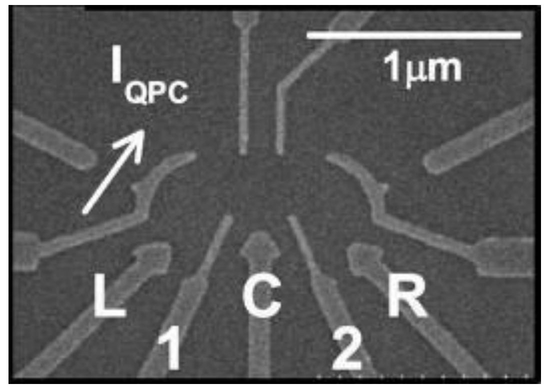
D. Loss and D. P. DiVincenzo, Phys. Rev. A **57**, 120 (1998).

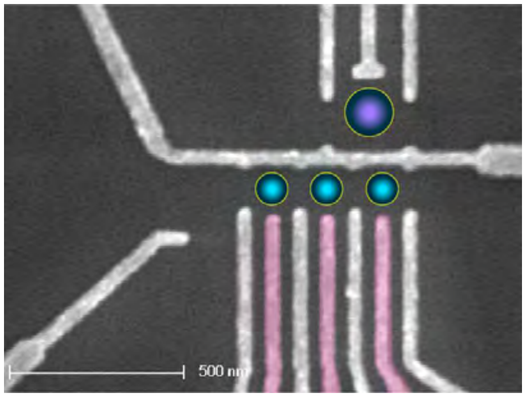
Scaling up in GaAs/AlGaAs QDs



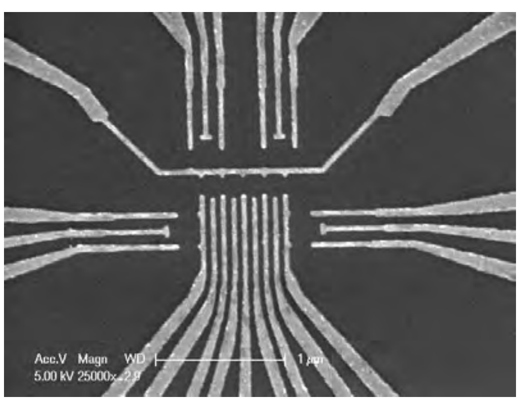


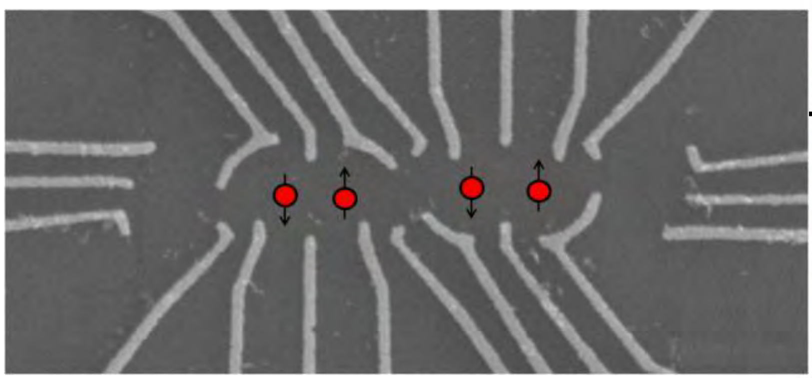
Harvard, Delft, NRC, ...

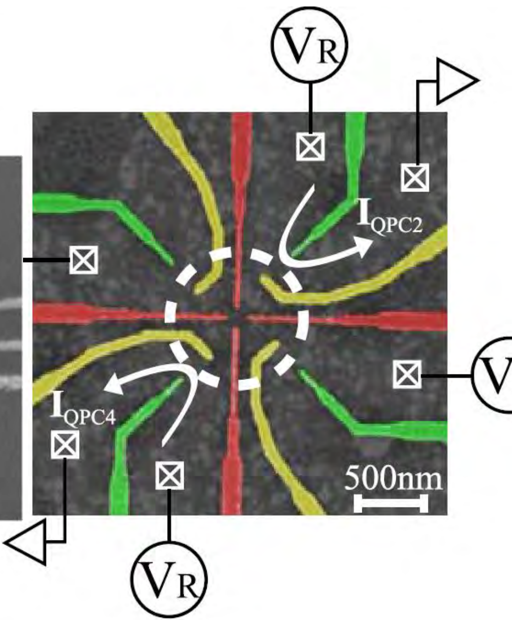




Harvard, Grenoble, Delft, Tokyo,…







Electron spin coherence – Si vs. GaAs

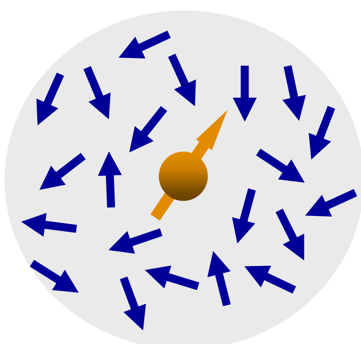
GaAs/AlGaAs

$$\mathcal{H} = g\mu_B \vec{S}\,\vec{B} + \vec{S}\sum_i A_i \vec{I}_i$$

Overhauser field

$\tilde{B}(t)$

No nuclear spin free isotopes



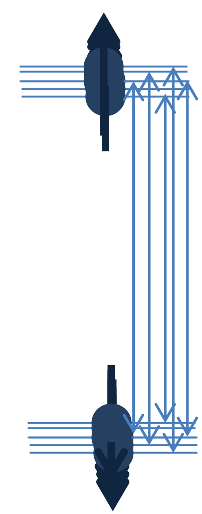
fluct. σ_{nuc}

1 mT

hyperfine coupling

$$g\mu_B(B_0 + \tilde{B}(t))$$

Zeeman splitting fluctuates



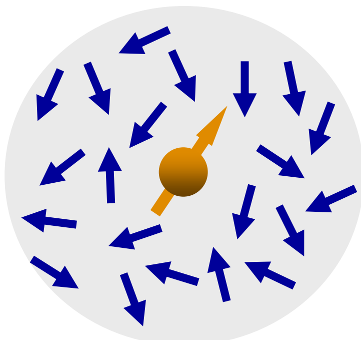
$T_2^* \sim$ 10-20 ns

$T_{2,\mathrm{Hahn}} \sim$ 0.5 μs

Electron spin coherence – Si vs. GaAs

GaAs/AlGaAs

No nuclear spin free isotopes



fluct. σ_{nuc}

1 mT

hyperfine coupling

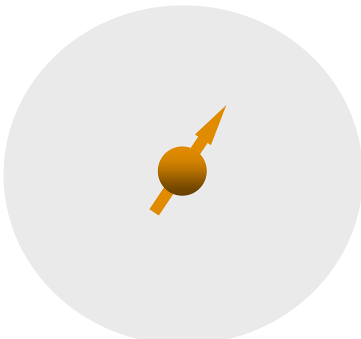
$T_2^* \sim$ 10-20 ns

$T_{2,Hahn} \sim$ 0.5 μs

Si/SiGe

^{28}Si is spinless

can purify isopically



Veldhorst et al.,
Nature Nano 2015

no hyperfine coupling

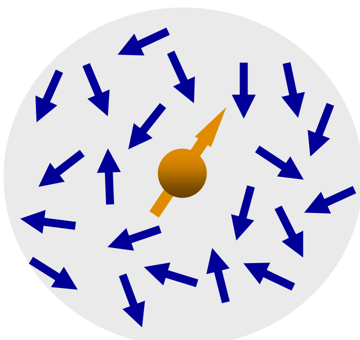
$T_2^* \sim$ 120 μs

$T_{DD} \sim$ 30 ms

Electron spin coherence – Si vs. GaAs

GaAs/AlGaAs

No nuclear spin free isotopes



fluct.σ_{nuc}

1 mT

hyperfine coupling

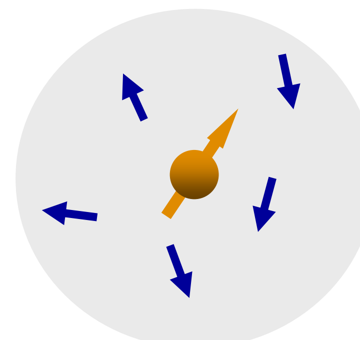
$T_2^* \sim$ 10-20 ns

$T_{2,Hahn} \sim 0.5\ \mu s$

Si/SiGe

Natural silicon

5% nuclei with spin



fluct.σ_{nuc}

8 uT

weak hyperfine coupling

THIS TALK

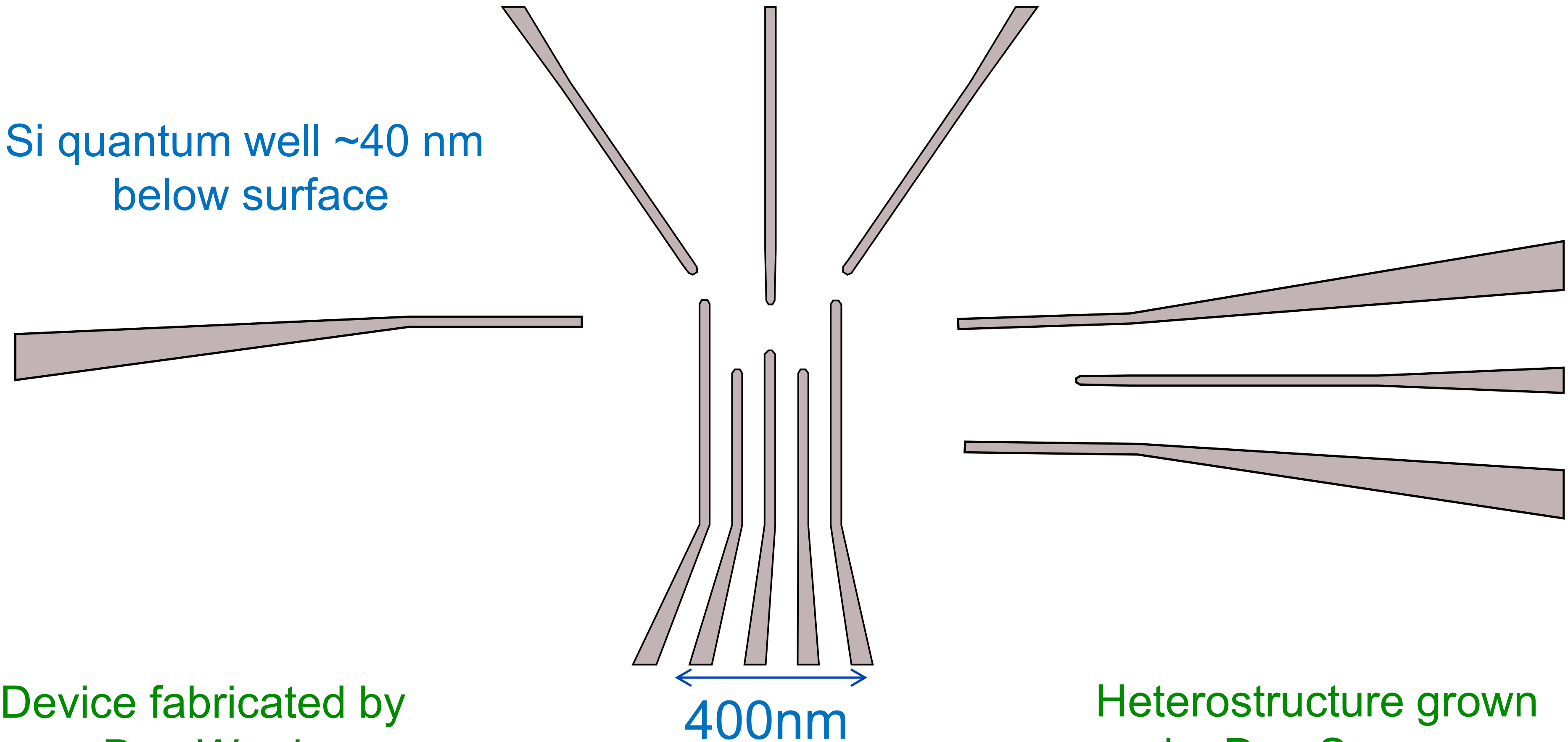
$T_2^* \sim 1\ \mu s$

$T_{DD} \sim 400\ \mu s$

Device schematic (top view)

depletion gates

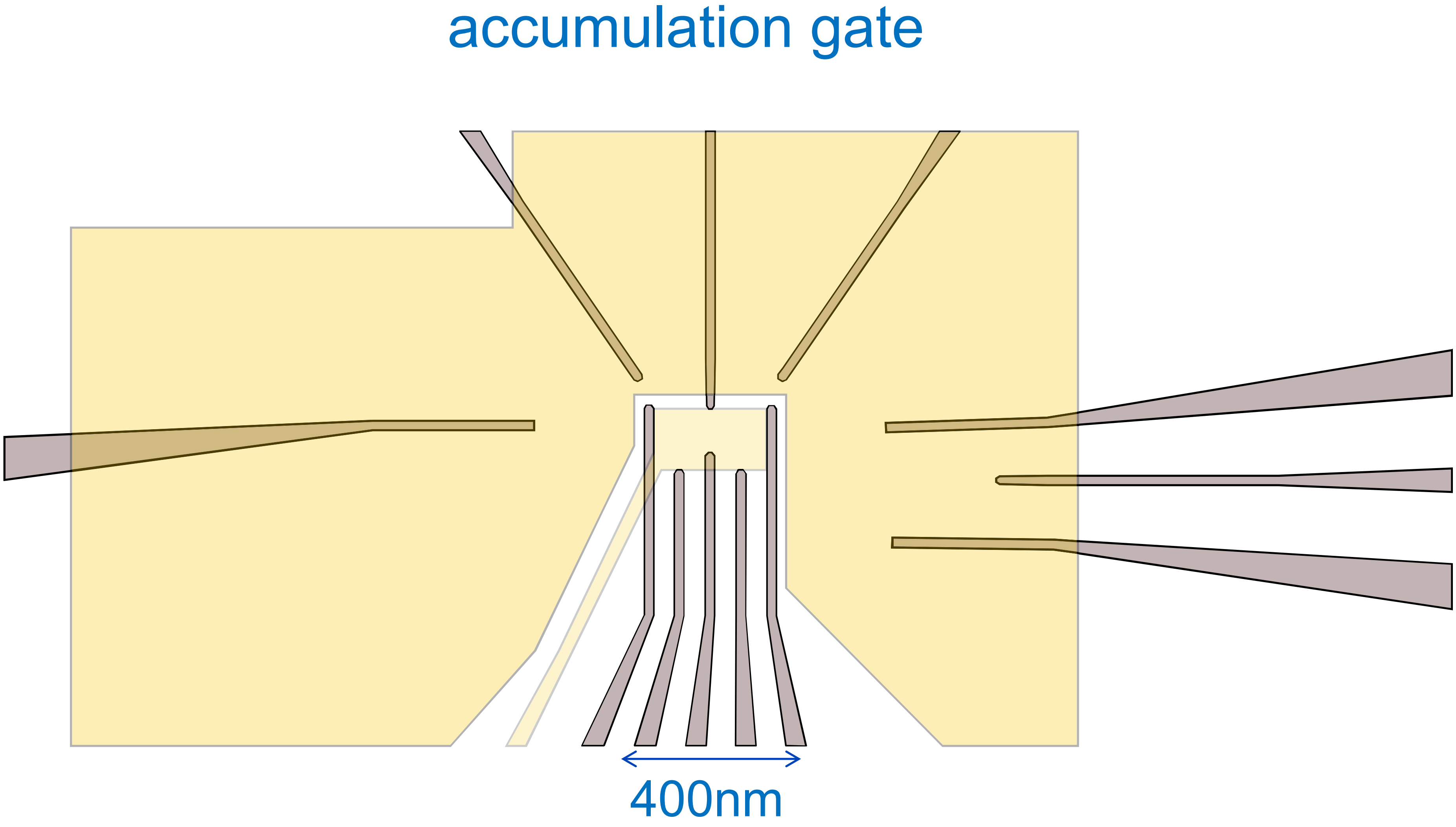
Si quantum well ~40 nm
below surface



Device fabricated by
Dan Ward
(Eriksson group,
Wisconsin University)

Heterostructure grown
by Don Savage
(Lagally group,
Wisconsin University)

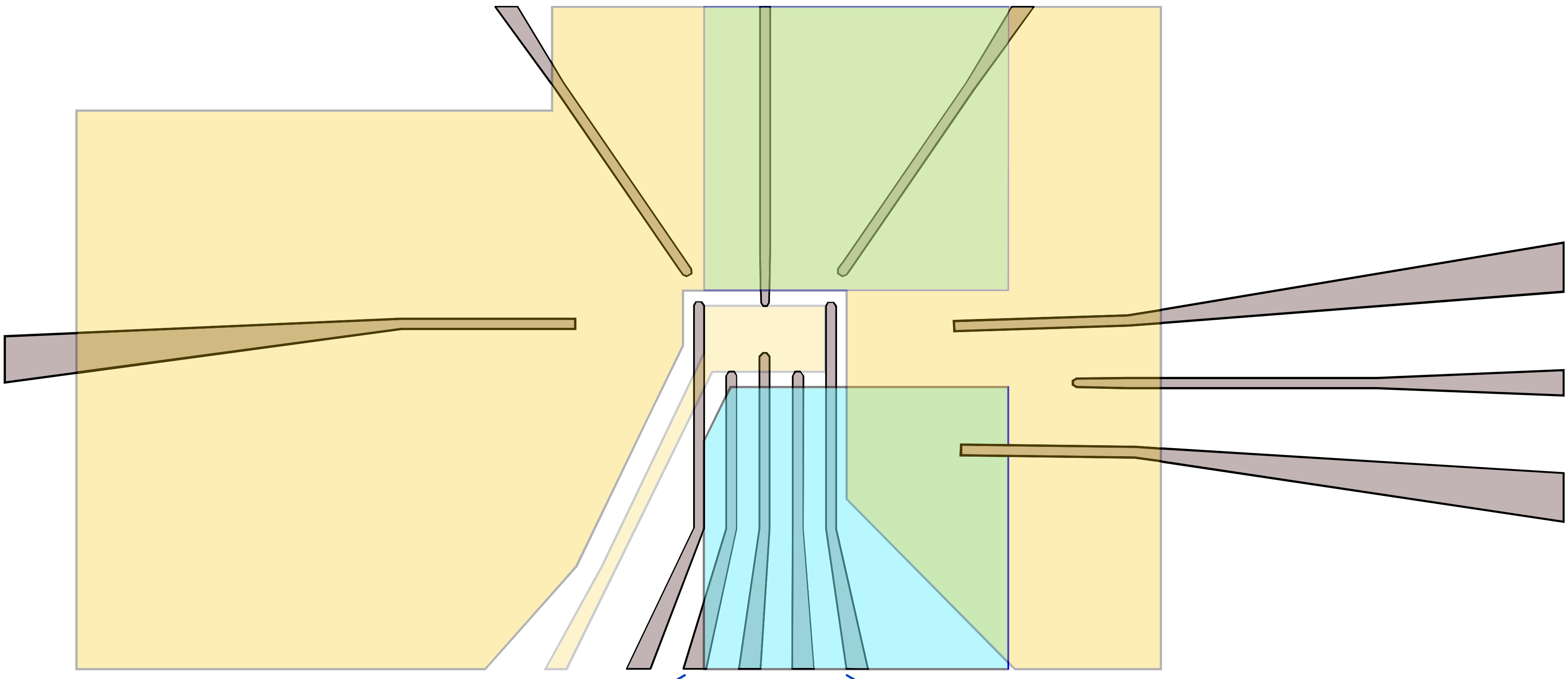
Device schematic (top view)



Maune et al, HRL (2012)

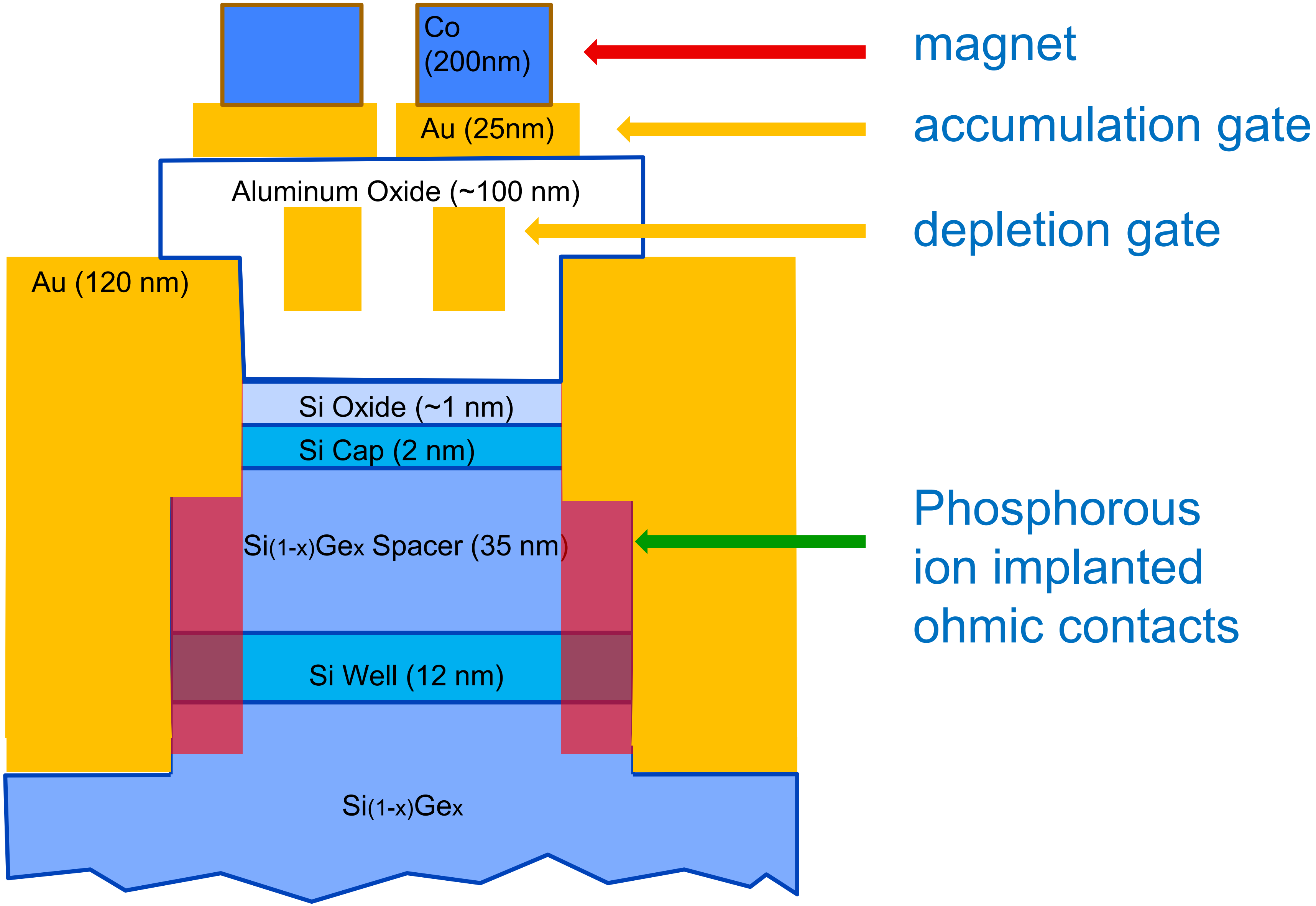
Device schematic (top view)

Co micro-magnet

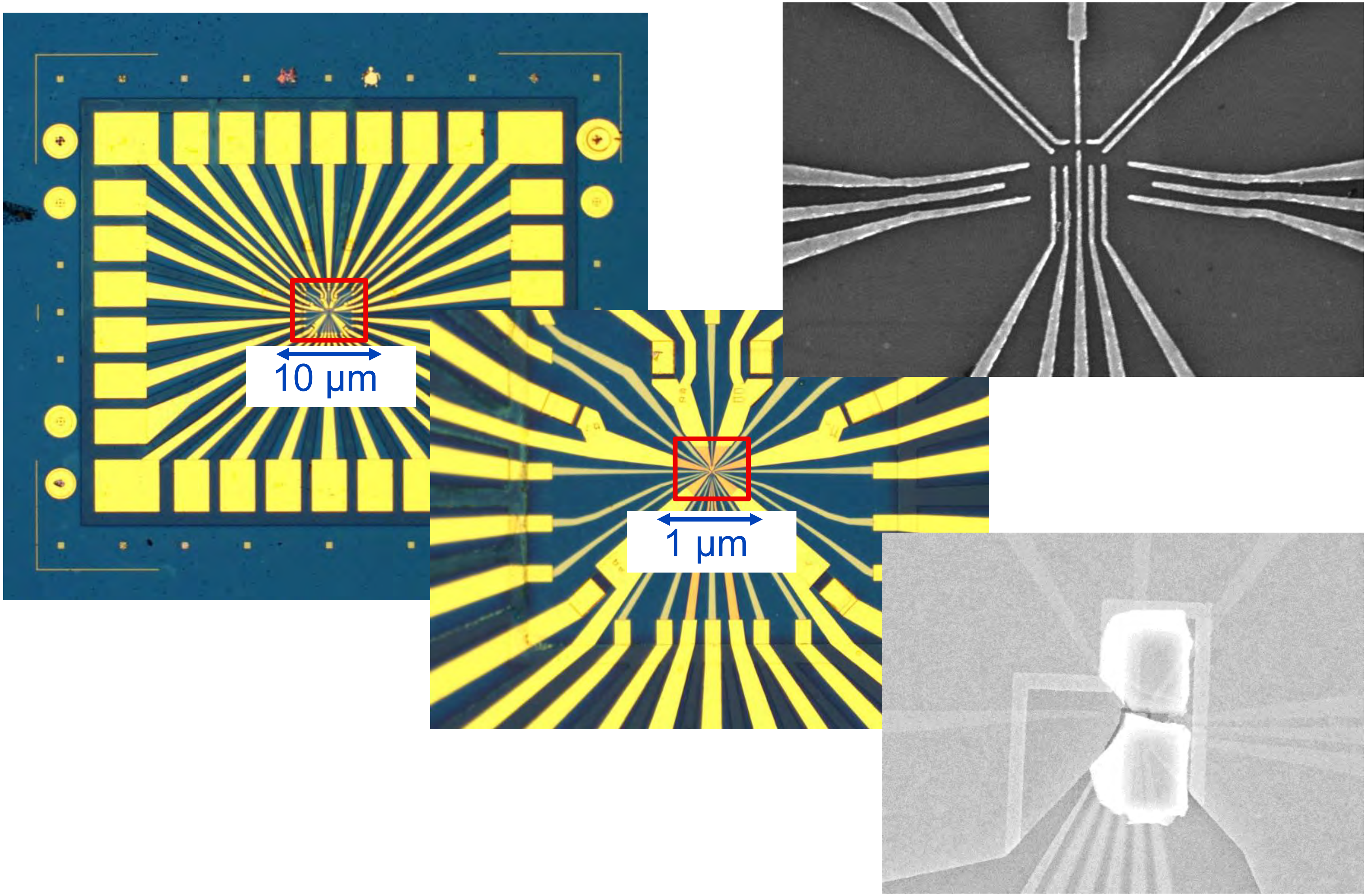


Pioro-Ladriere et al, Nat. Phys (2008)

Device schematic (side view)

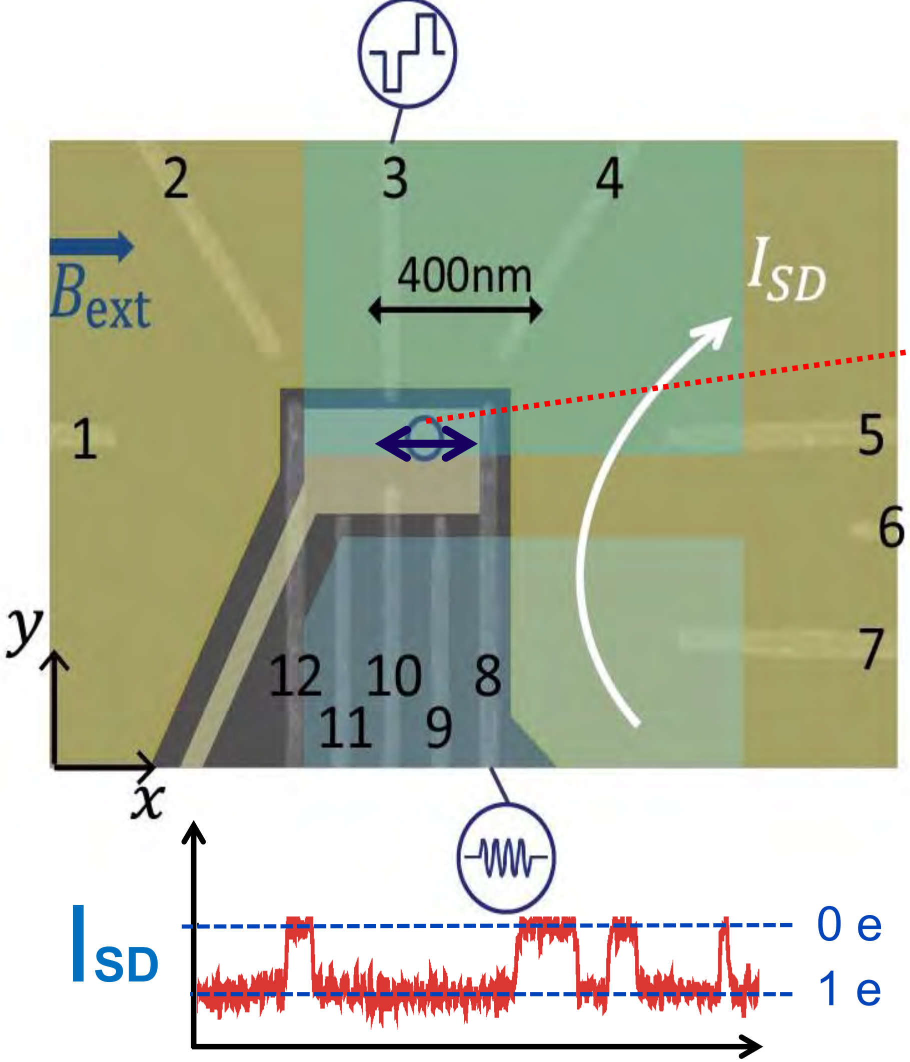


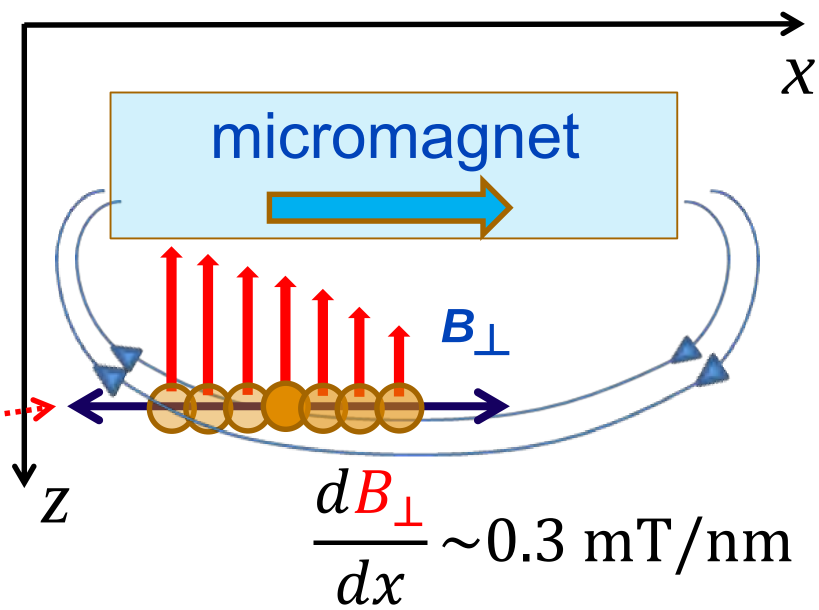
Si/SiGe DQD fabrication

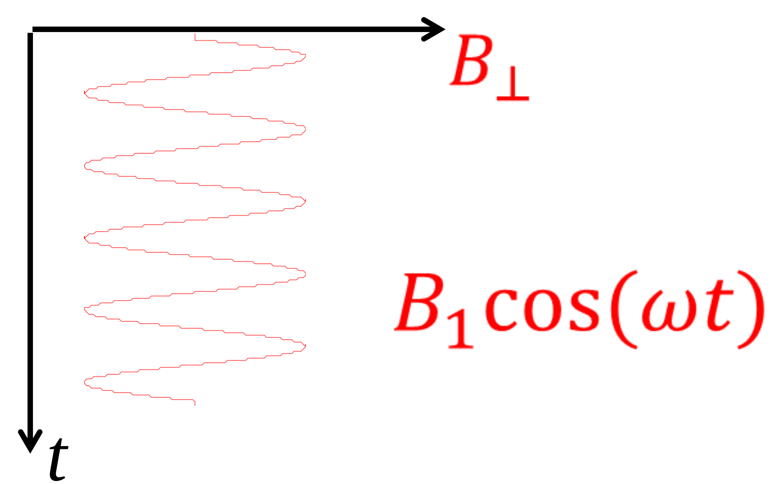


Spin manipulation: micromagnet and microwave *E*-field

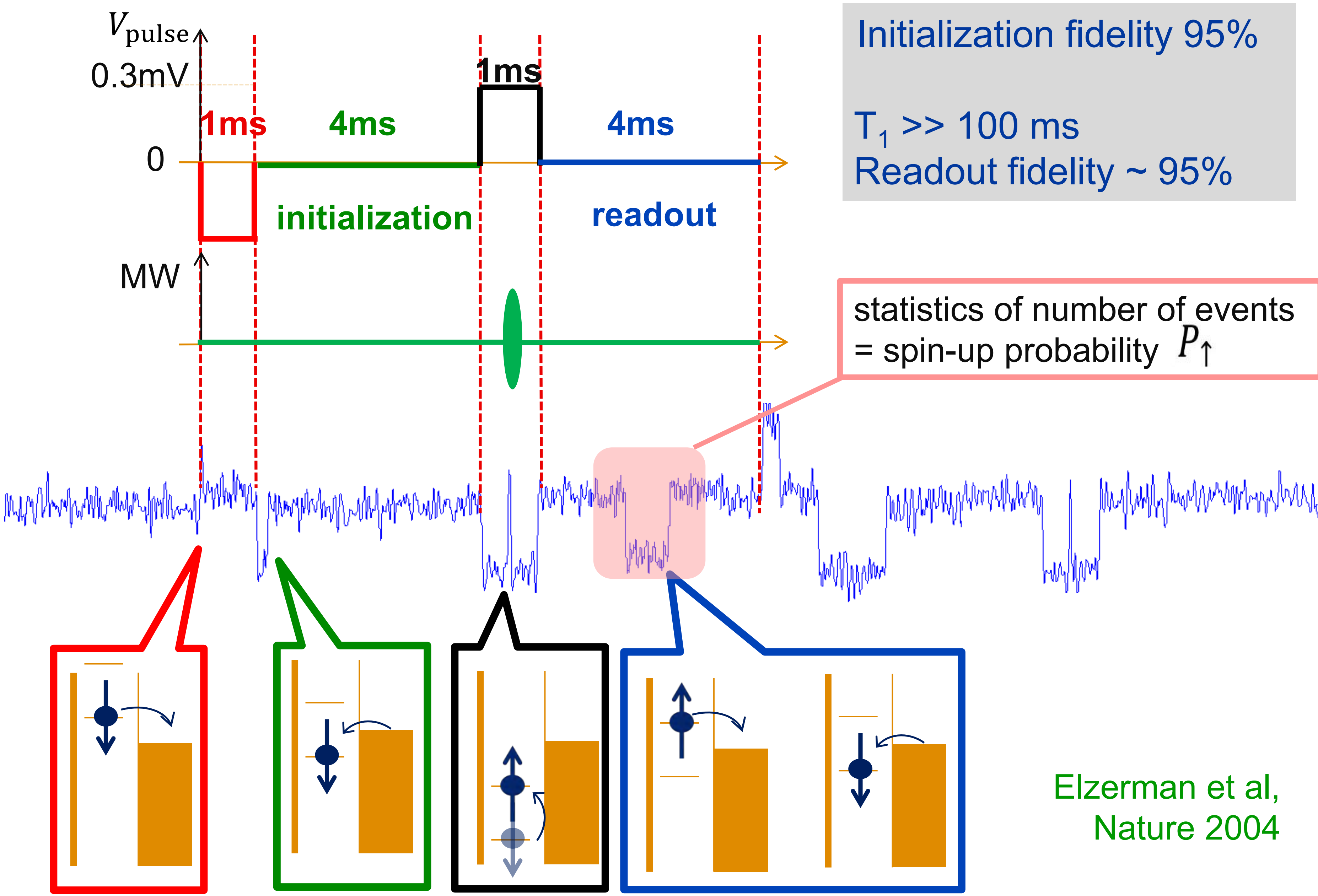
Y. Tokura et. al., PRL **96**, 047202 (2006)
R. Brunner et al., PRL **107**, 146801 (2011)





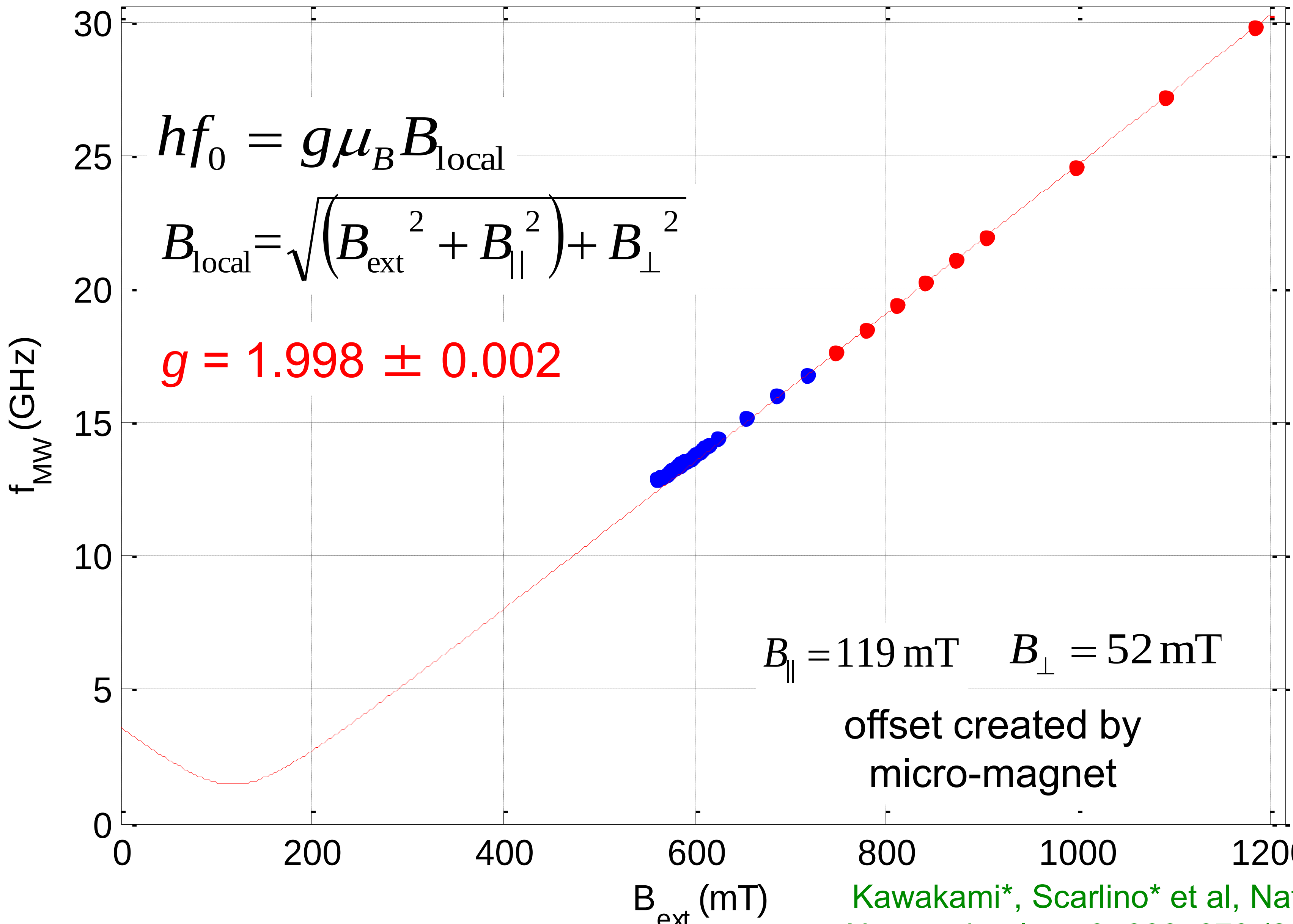


Pulse scheme for EDSR



Elzerman et al,
Nature 2004

Spin spectroscopy (CW)



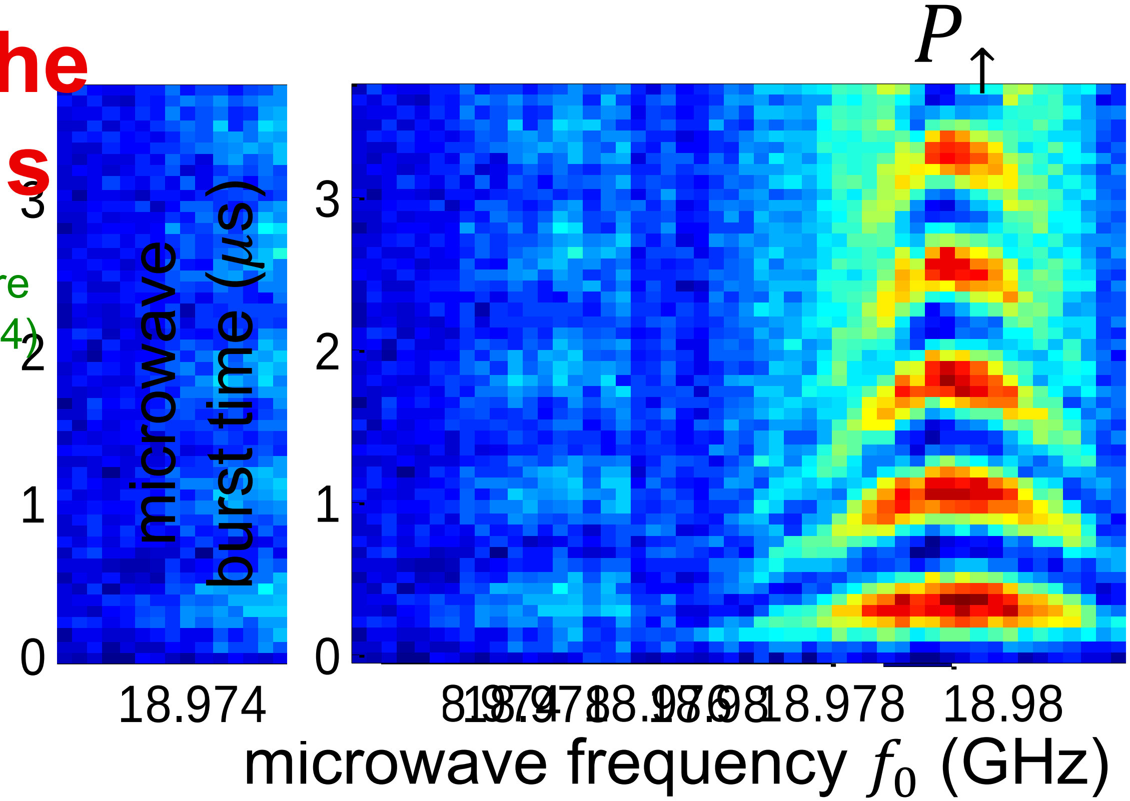
Kawakami*, Scarlino* et al, Nature Nanotechnology 9, 666–670 (2014)

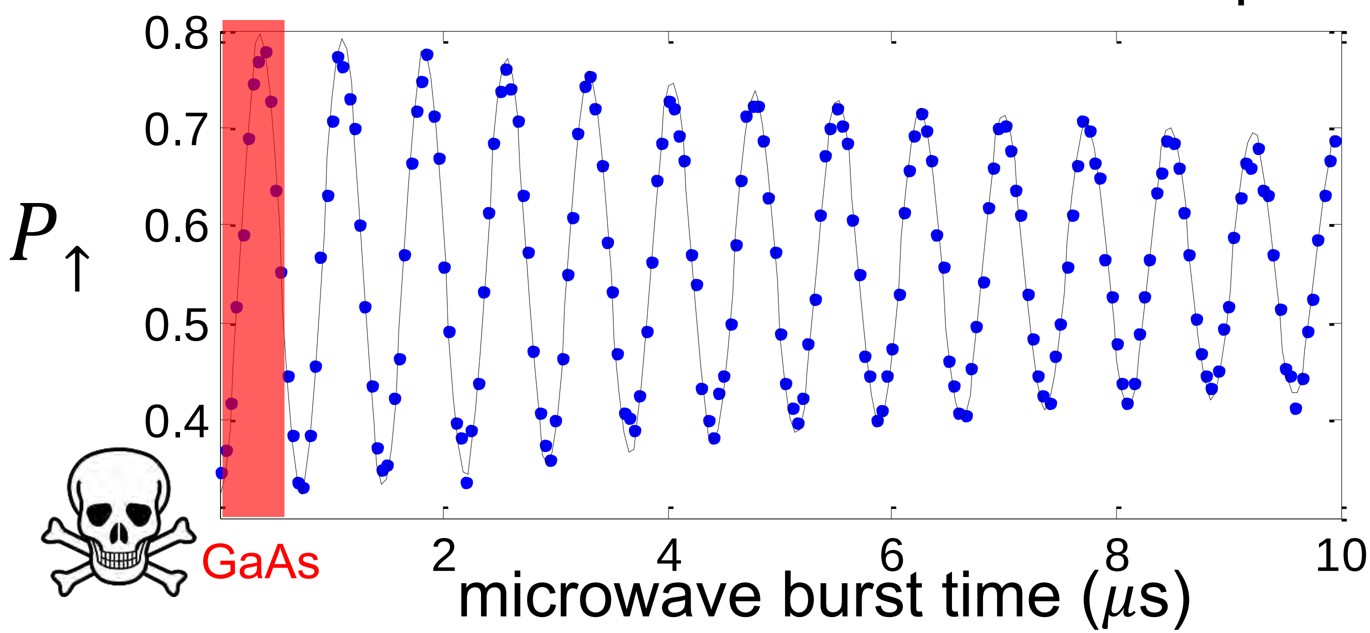
Closer look at the Rabi oscillations

Kawakami*, Scarlino* et al, Nature Nanotechnology 9, 666–670 (2014)

Rabi frequency up to ~ 5 MHz

Rabi decay limited by hyperfine coupling ($T_2^* \sim 1\ \mu s$)



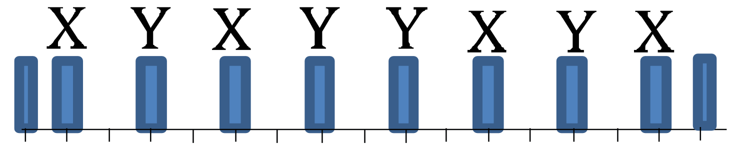


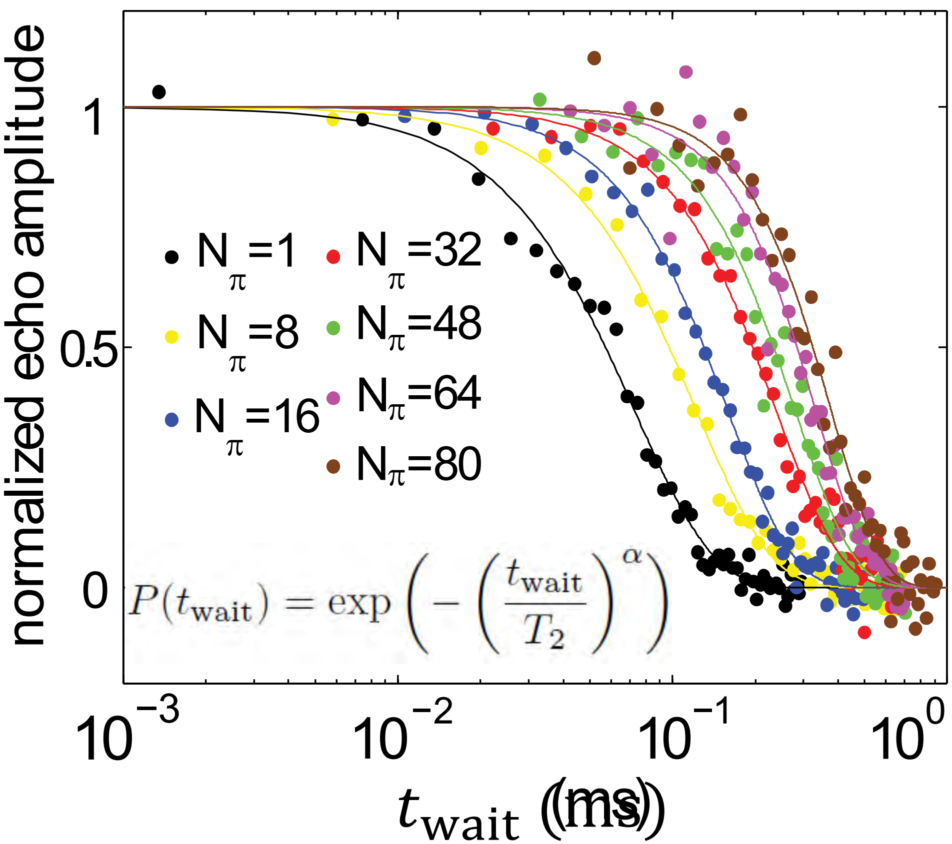
$B_{ext} = 0.794$ T

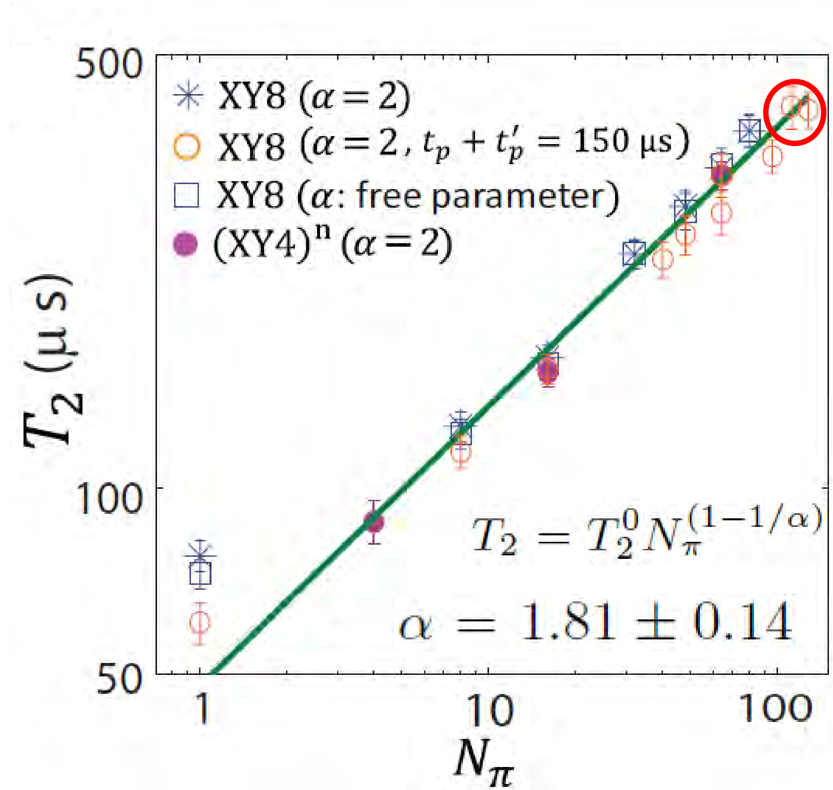
$f_0 = 18.98$ GHz

Dynamical decoupling: XY8

Kawakami et al., arxiv:1504.06436.







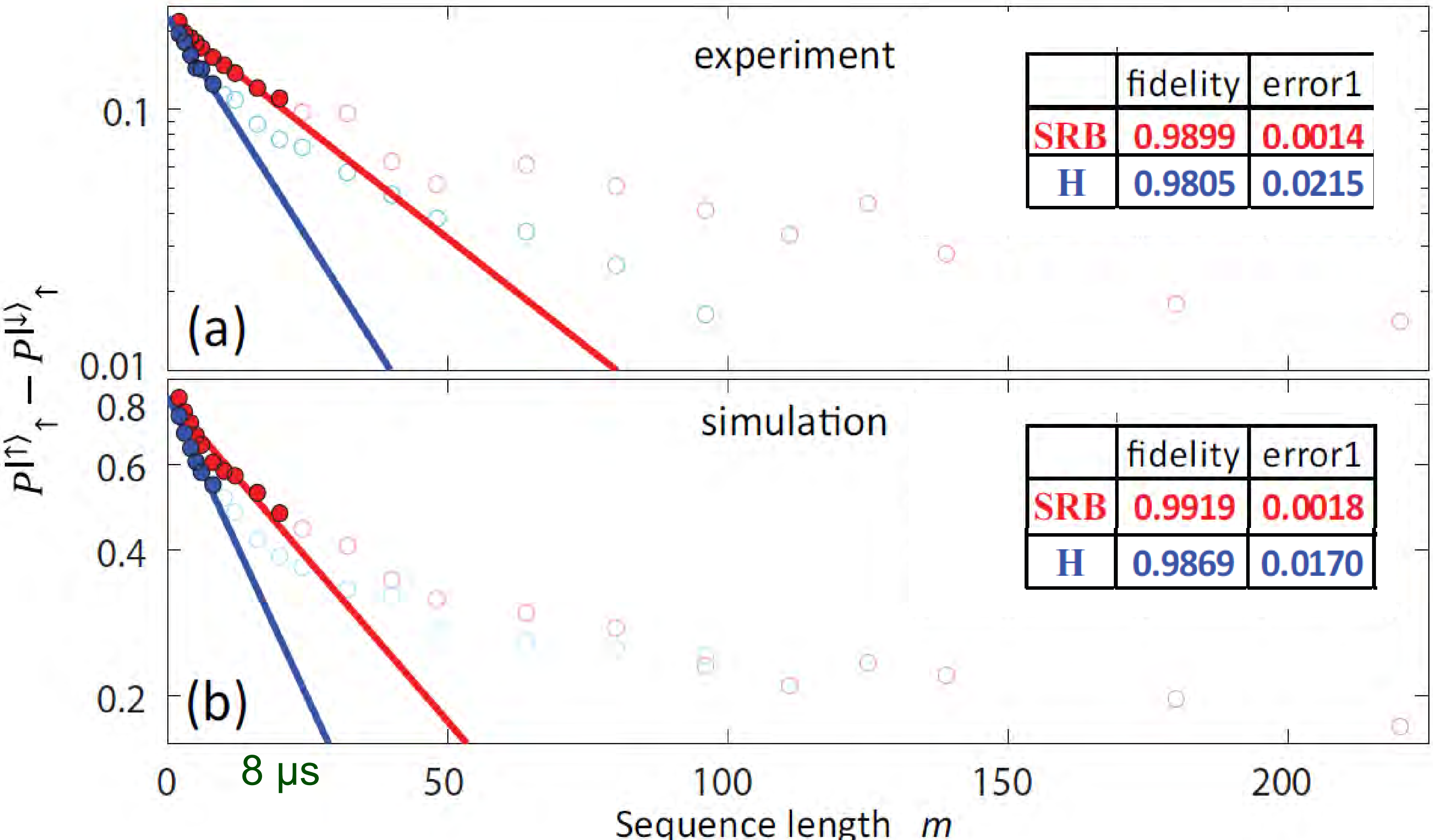
$T_{2,\text{Hahn}} = 78 \pm 3$ μs

longest coherence time measured $T_2 = 400\ \mu s$ $(N_\pi = 128)$

Gate fidelity: randomized benchmarking

Kawakami et al., arxiv:1504.06436.

state fidelity $= A\,p^m$



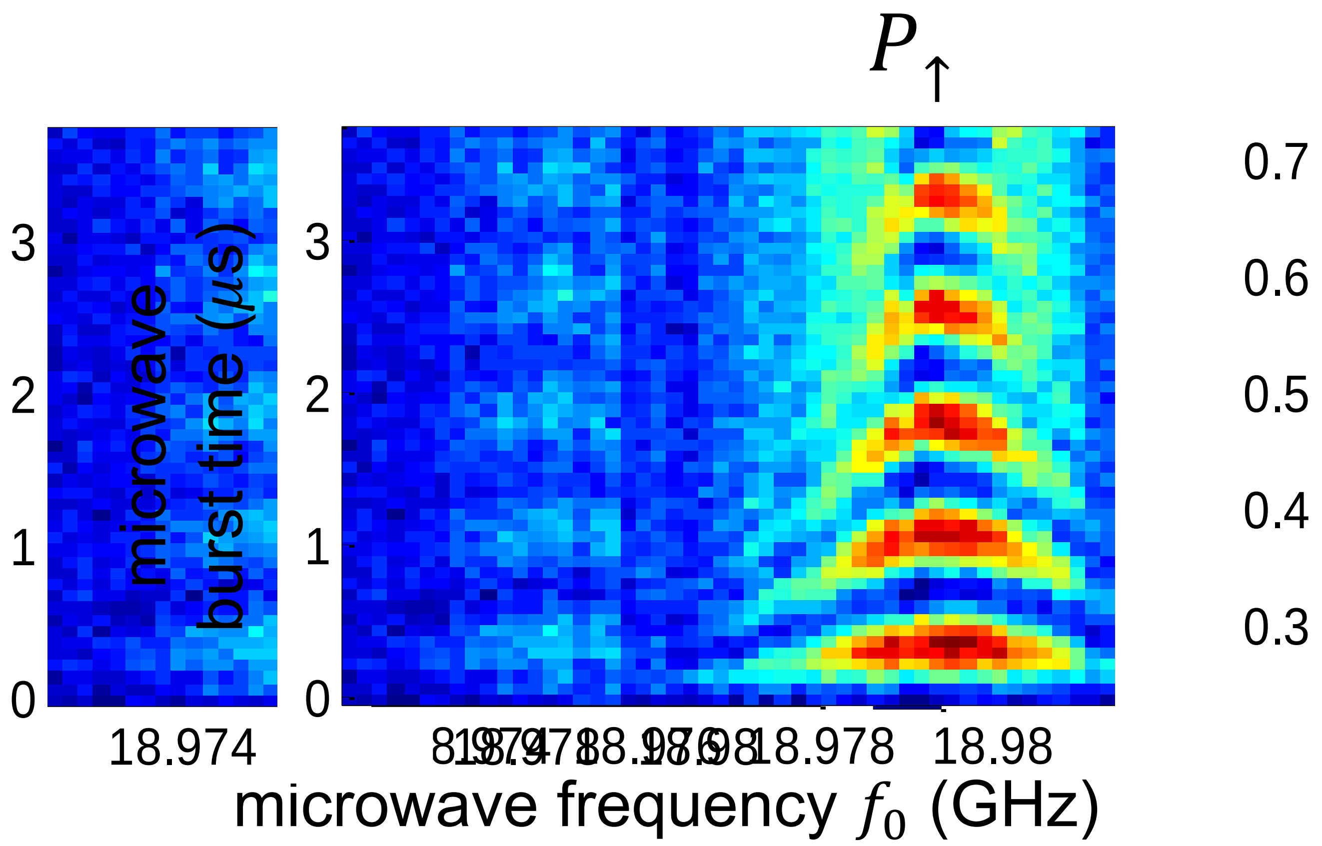
	fidelity	error1
SRB	0.9899	0.0014
H	0.9805	0.0215

	fidelity	error1
SRB	0.9919	0.0018
H	0.9869	0.0170

average gate fidelity
$\mathbf{99.0 \pm 0.1}$ %

See also M. A. Fogarty et al., arXiv:1502.05119

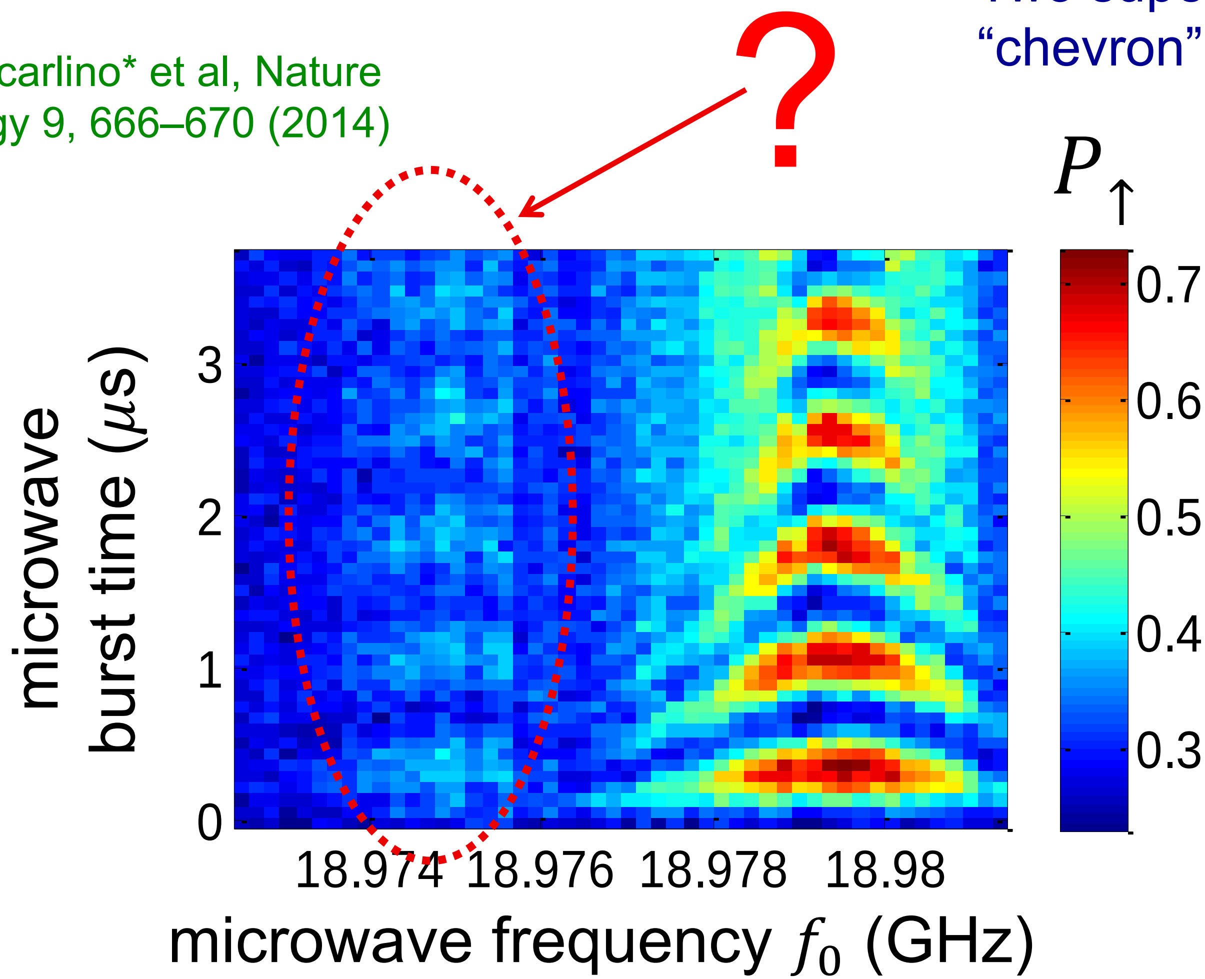
Closer look at the Rabi oscillations



Closer look at the Rabi oscillations

Kawakami*, Scarlino* et al, Nature Nanotechnology 9, 666–670 (2014)

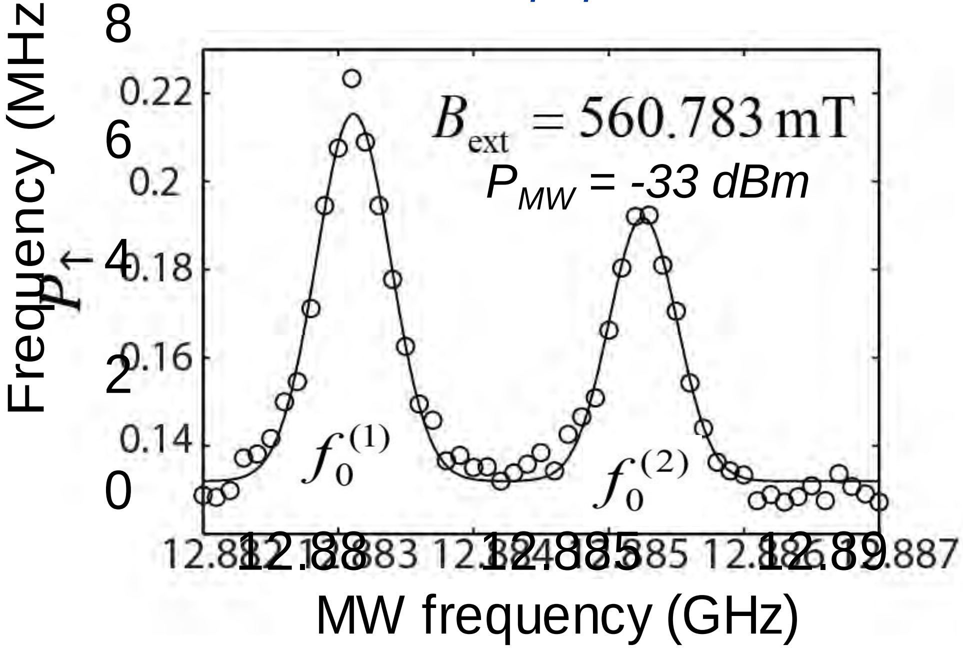
Two superimposed "chevron" patterns



Why two resonances?

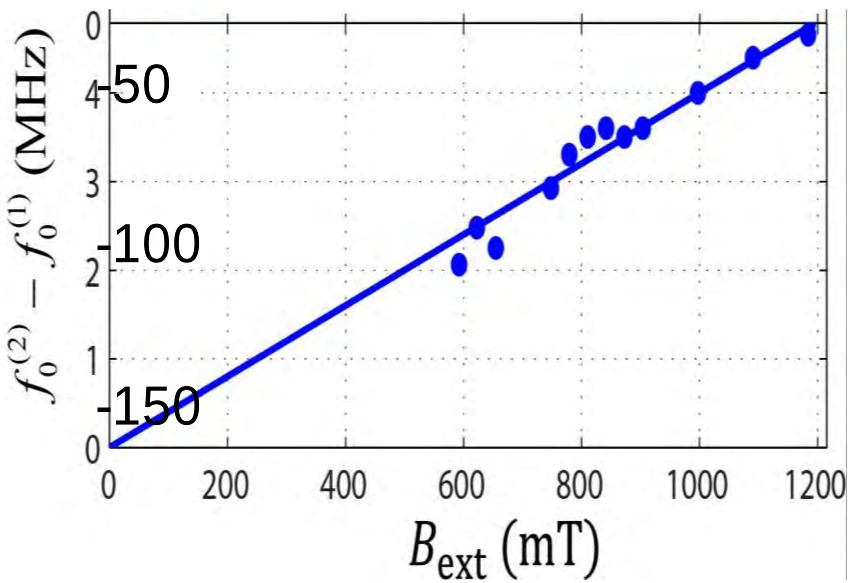
~5/3 ratio in Rabi frequency

30% and 70% populations



different Zeeman splitting

0.015% difference in g-factor



Hypothesis:

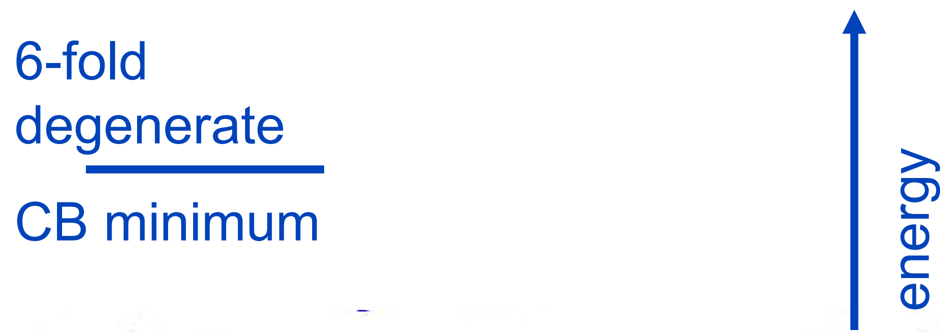
Two **valleys** populated

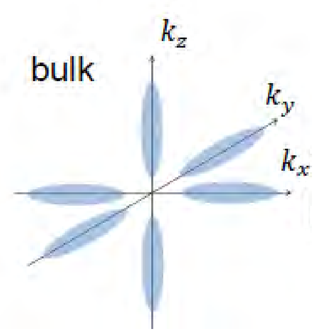
with different charge envelope wave function

and thus different g-factor and Rabi frequency

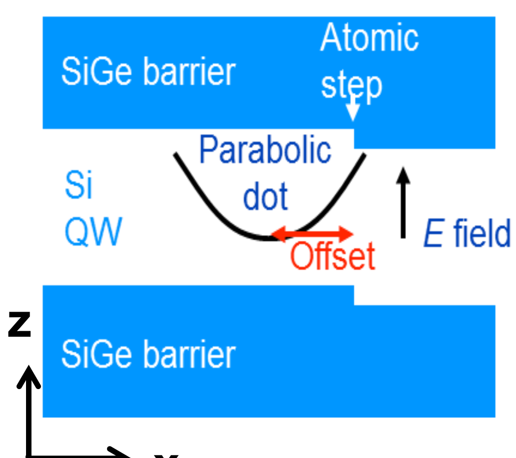
Kawakami*, Scarlino* et al., Nature Nanotechnology 9, 666–670 (2014)

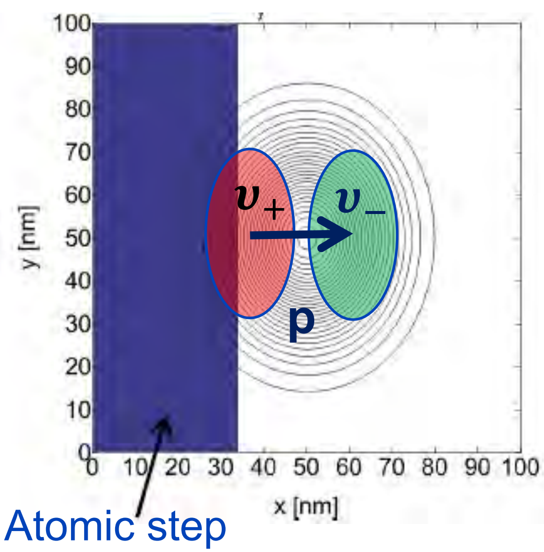
Valley degree in Silicon





disorder

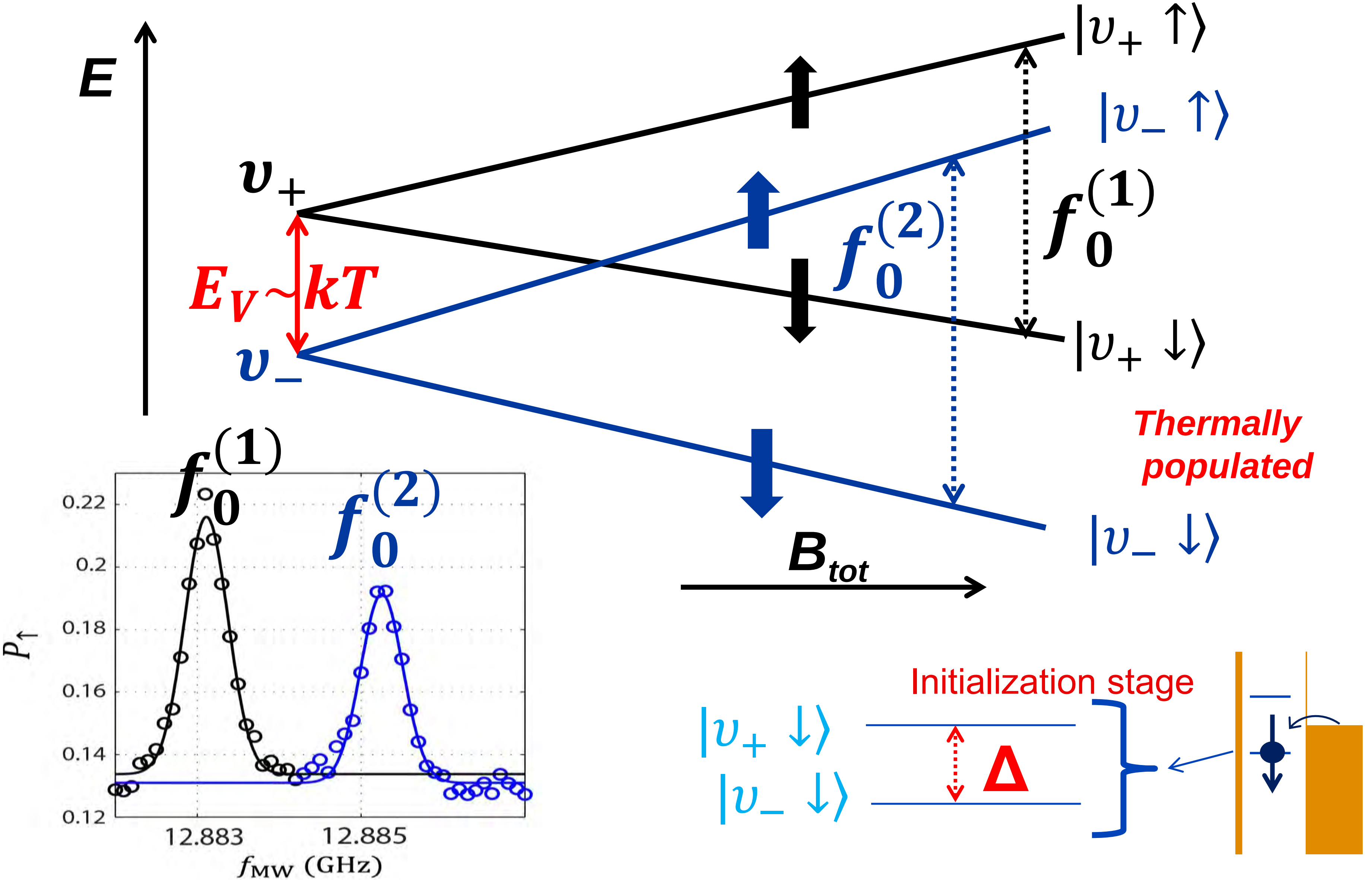




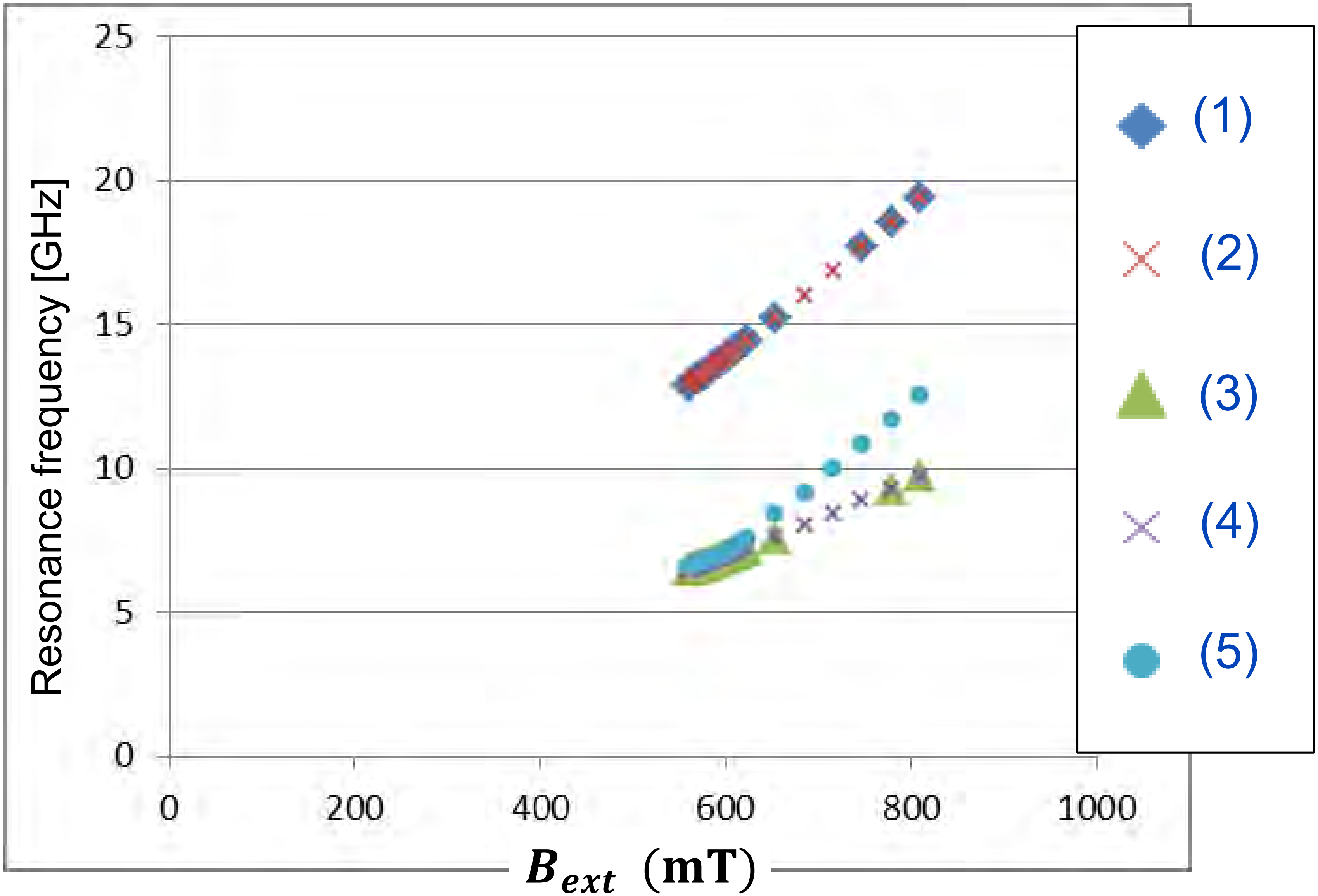
Gamble et al.,
PRB 88, 035310 (2013)

disorder
↓
valley orbit coupling
↓
different electron envelop function

Spin intra-valley spectroscopy

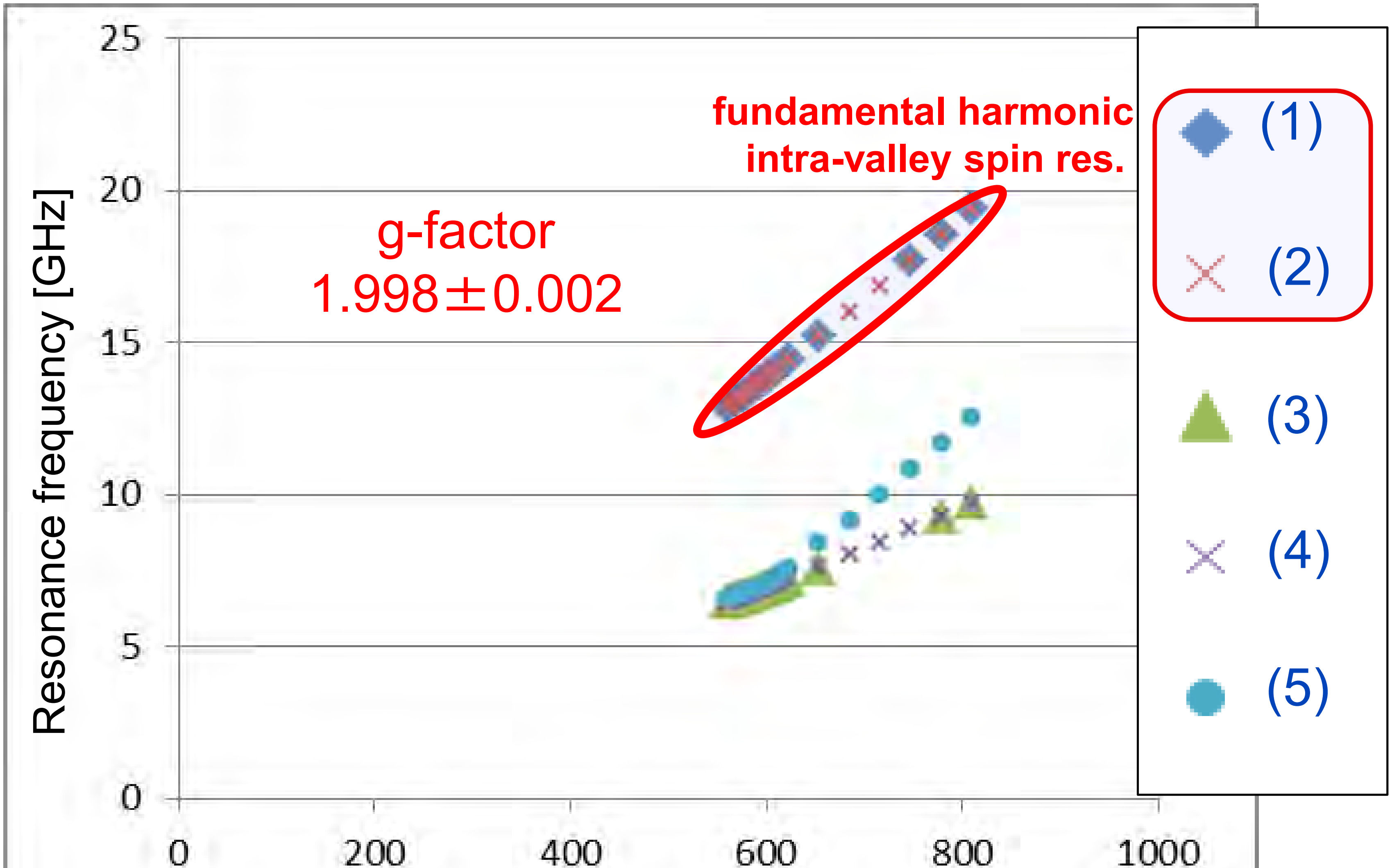


Complex spin resonance spectrum



Scarlino*, Kawakami* et al., in preparation

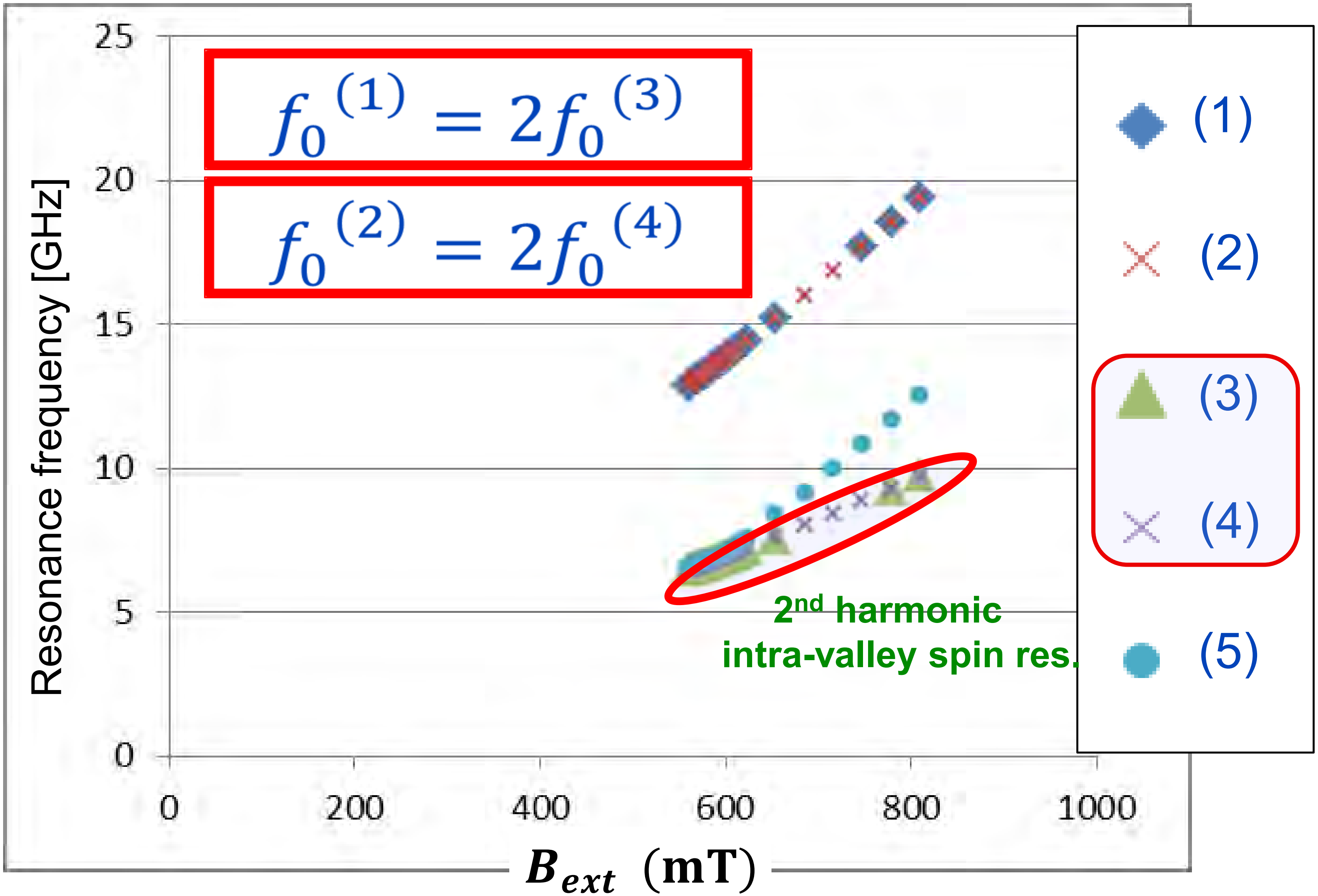
$f_0^{(1)}$ & $f_0^{(2)}$



B_{ext} (mT)

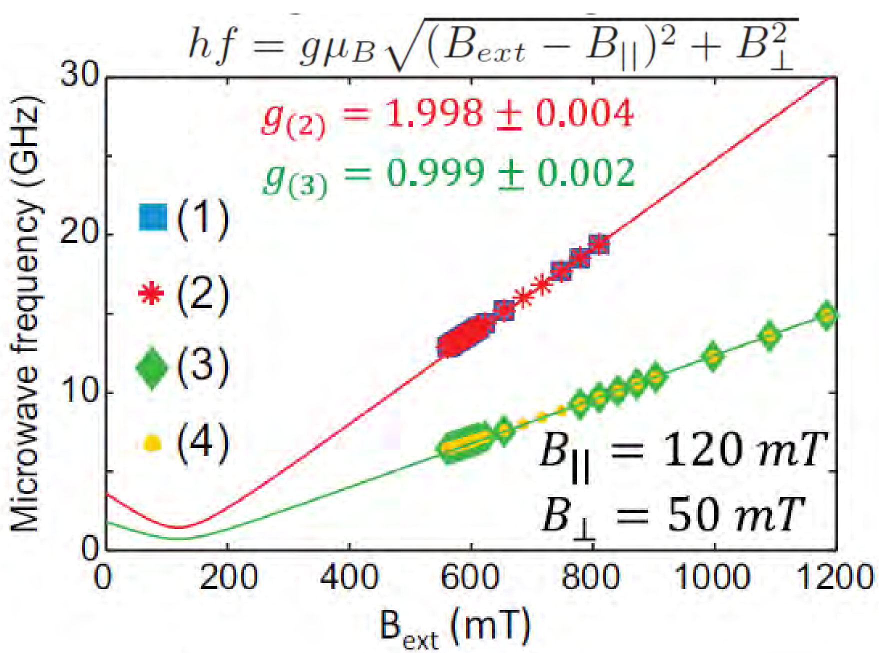
Scarlino*, Kawakami* et al., in preparation

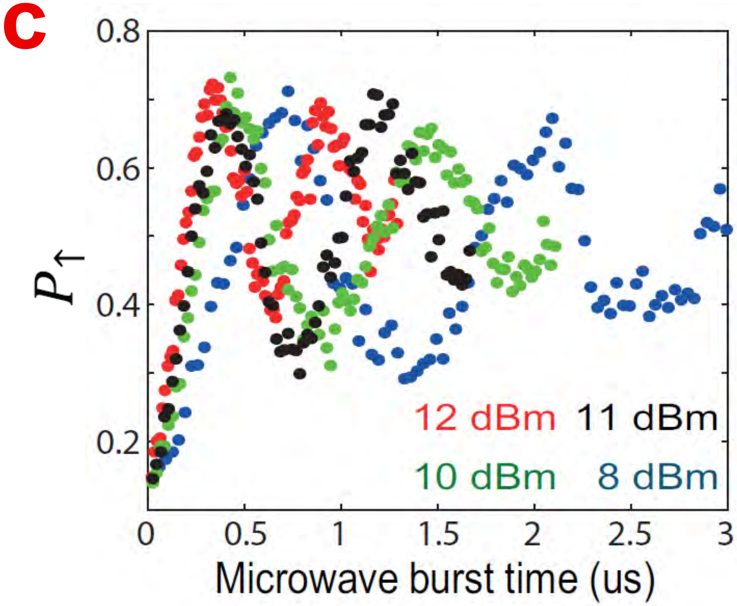
$$f_0^{(3)} \quad \& \quad f_0^{(4)}$$

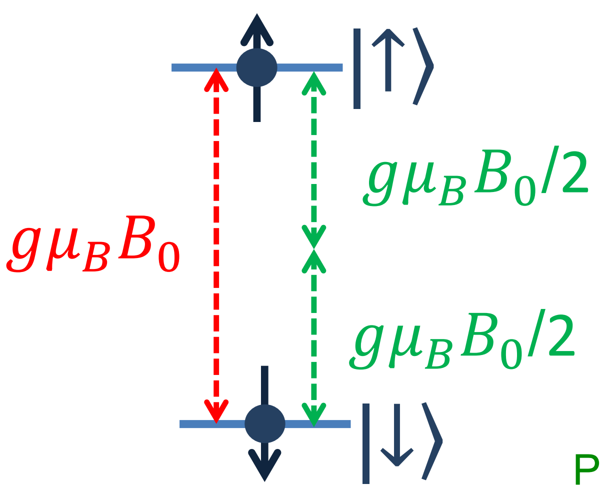


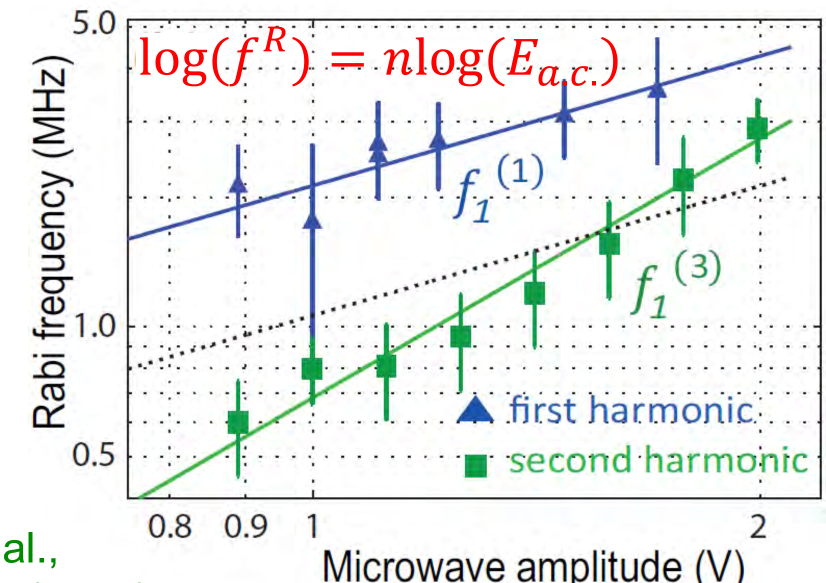
Scarlino*, Kawakami* et al., in preparation

Electric-dipole spin resonance coherently driven at second harmonic



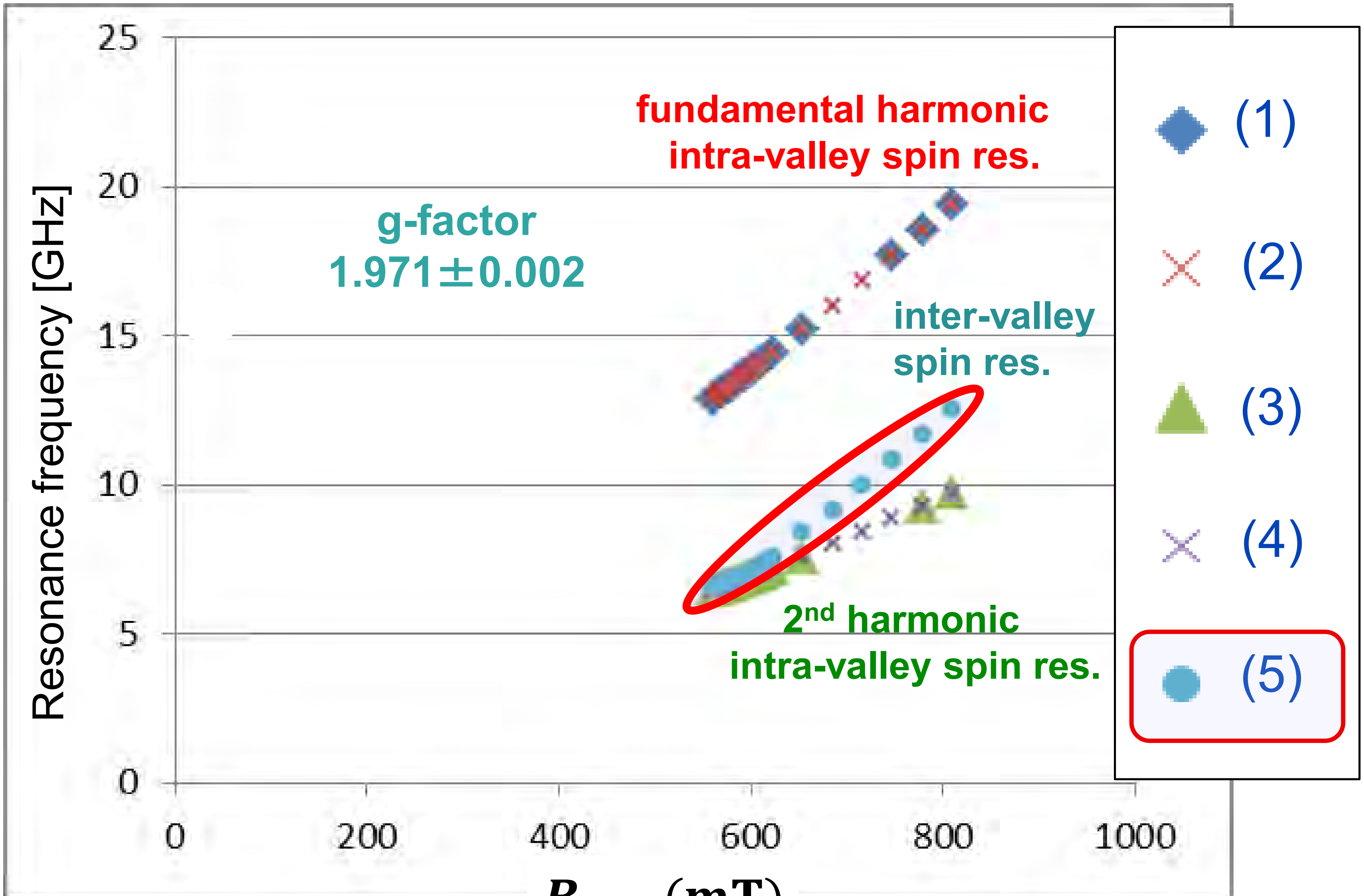






Scarlino, et al.,
PRL 115, 106802 (2015)

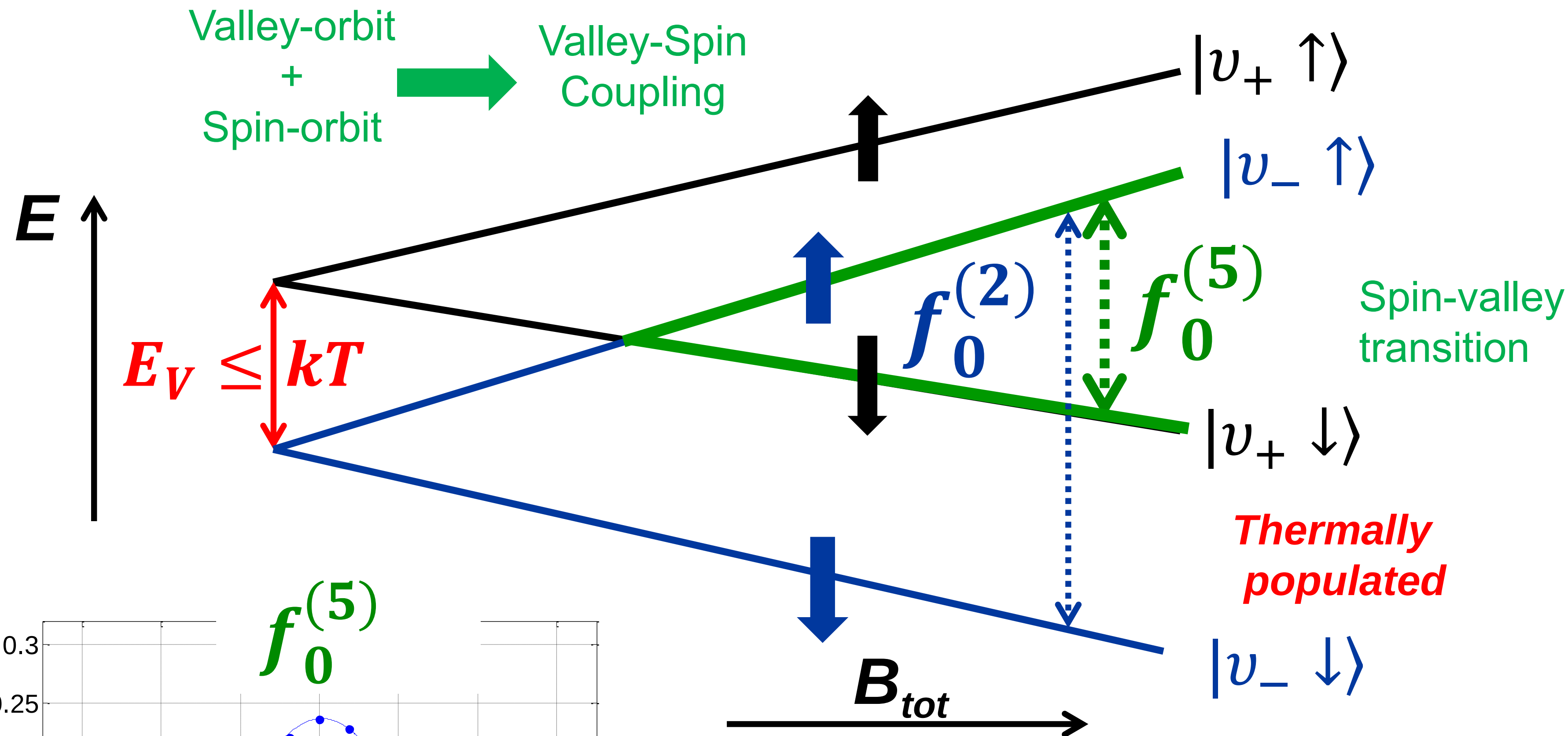
$f_0^{(5)}$

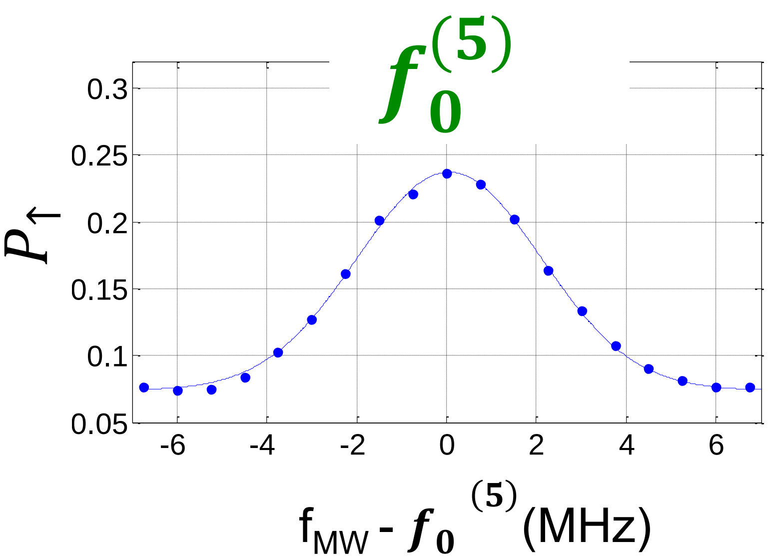


B_{ext} (mT)

Scarlino*, Kawakami* et al., in preparation

Inter-valley transition





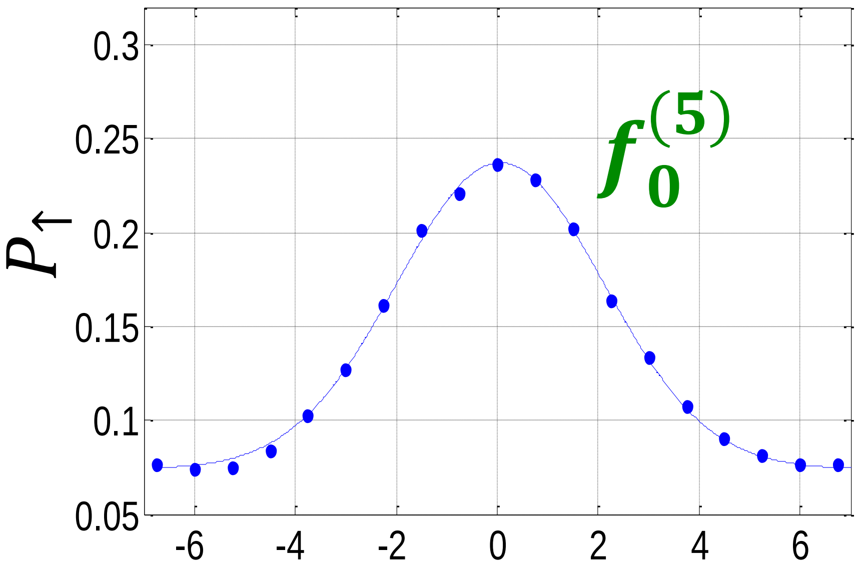
$$E_V = \left[f_0^{(2)} - f_0^{(5)}\right]$$

~6GHz ~300mK

Scarlino*, Kawakami* et al., in preparation

T_2^* much shorter and no Rabi

inter-valley



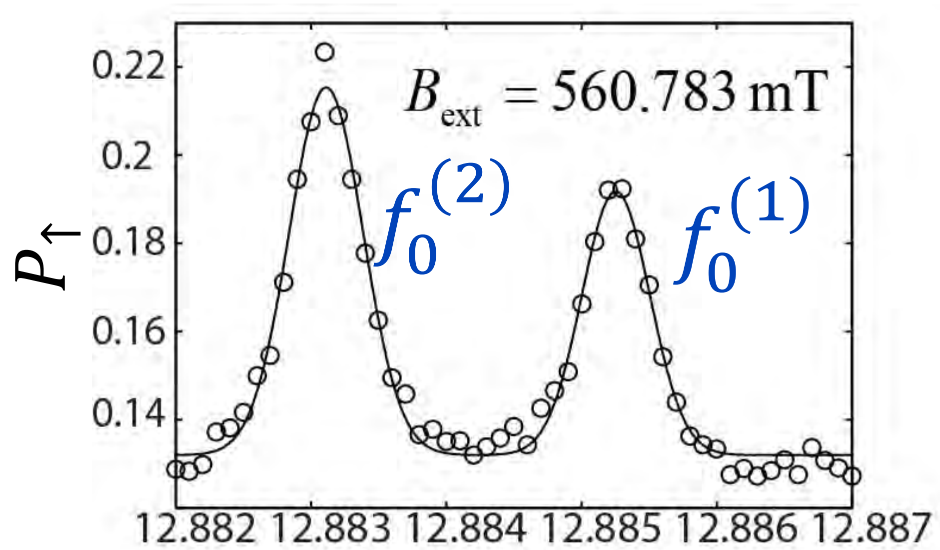
$f_{MW} - f_0^{(5)}$ (MHz)

FWHM = 4.0 MHz

T_2^* ~100 ns

Affected by charge noise

intra-valley



f_{MW} (GHz)

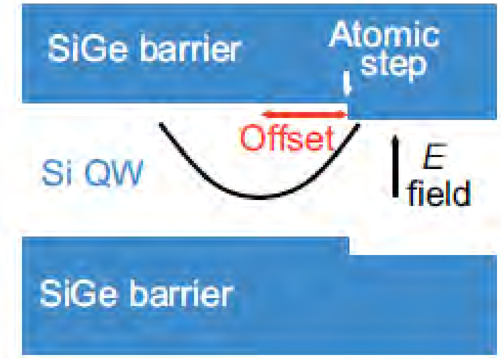
FWHM = 0.55 MHz

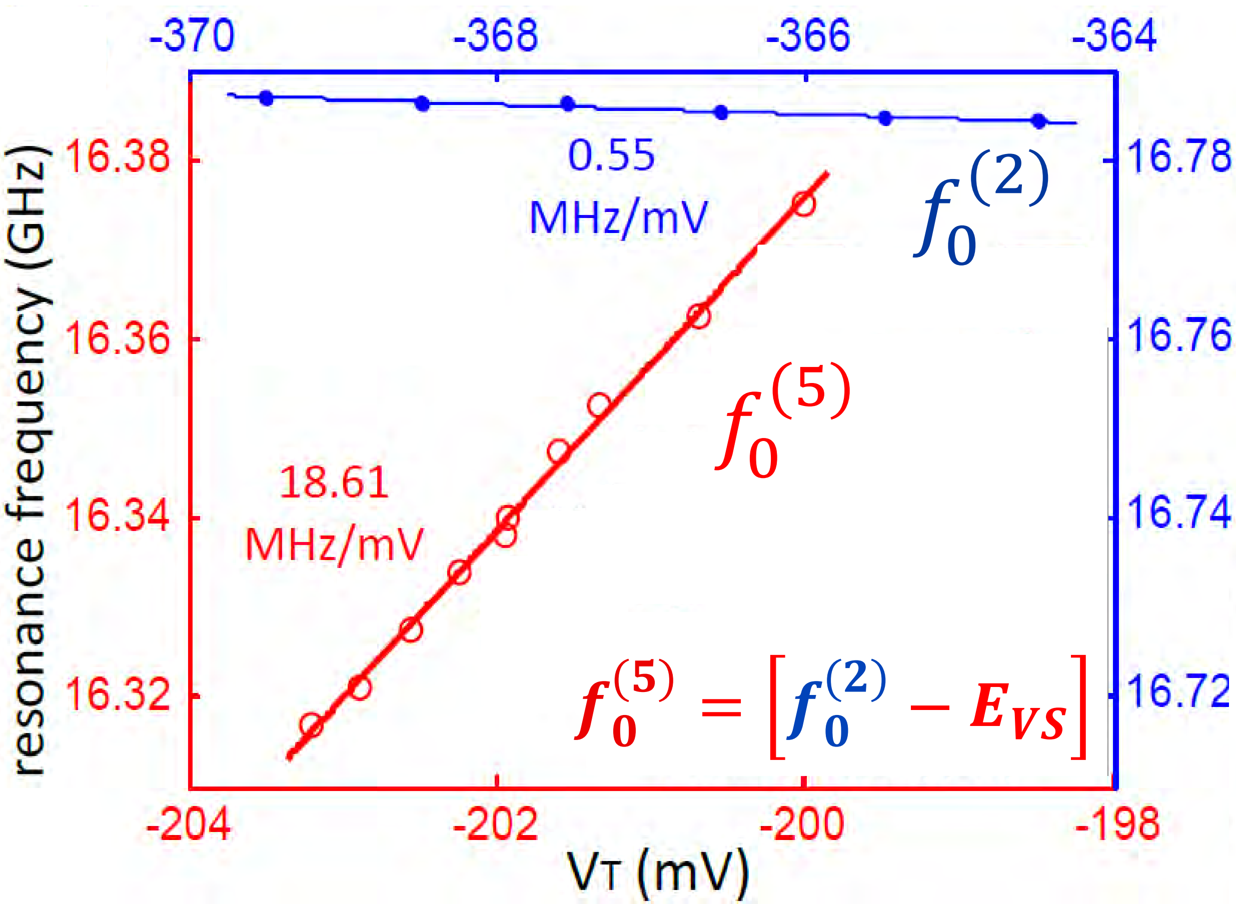
T_2^* ~1 μs

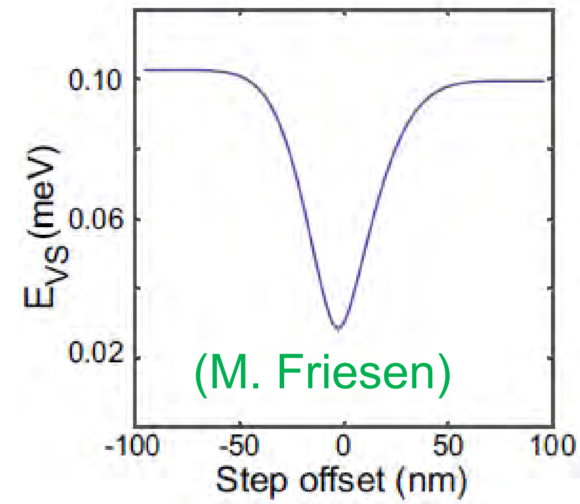
Affected by hyperfine noise

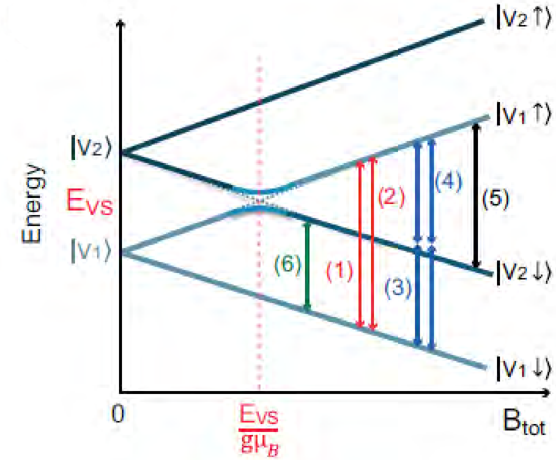
Scarlino*, Kawakami* et al., in preparation

Resonance frequency v.s. d.c. gate voltage







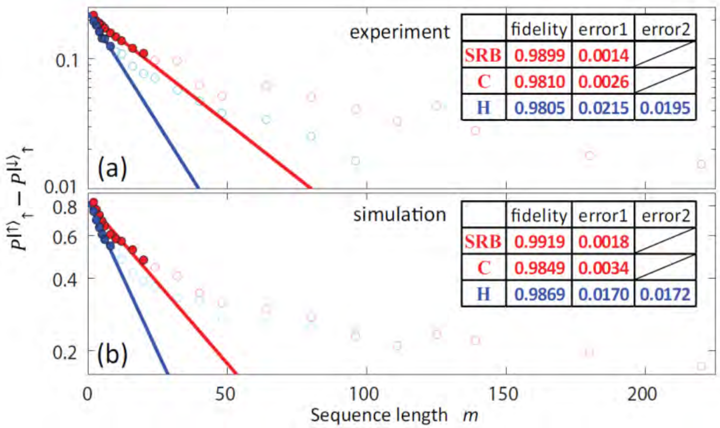


Scarlino*, Kawakami* et al., in preparation

Summary

Excellent electron spin qubit in natural Si/SiGe QD

- gate fidelity ~ 99 %



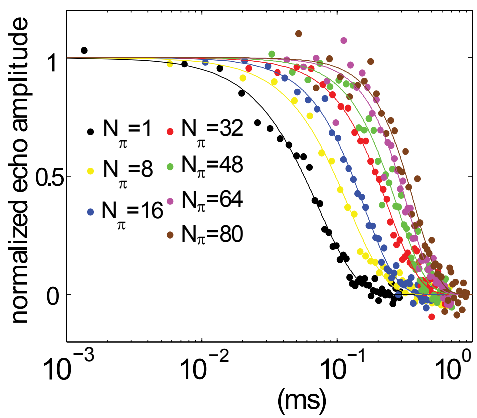
experiment

	fidelity	error1	error2
SRB	0.9899	0.0014	
C	0.9810	0.0026	
H	0.9805	0.0215	0.0195

simulation

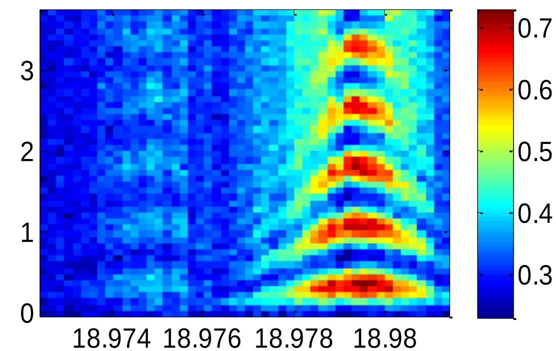
	fidelity	error1	error2
SRB	0.9919	0.0018	
C	0.9849	0.0034	
H	0.9869	0.0170	0.0172

- coherence time ~ 400 μs

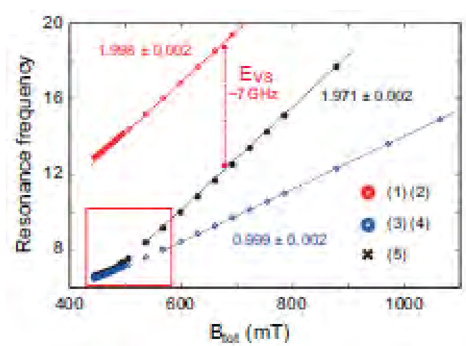


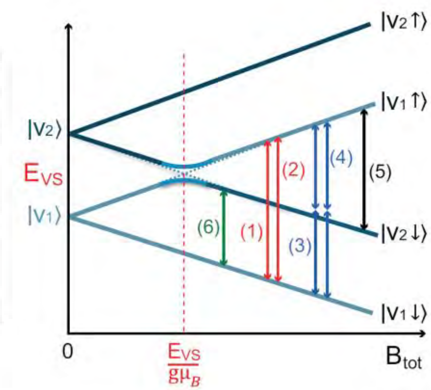
Small valley energy splitting affects the qubits

- Both lowest valley states are thermally populated

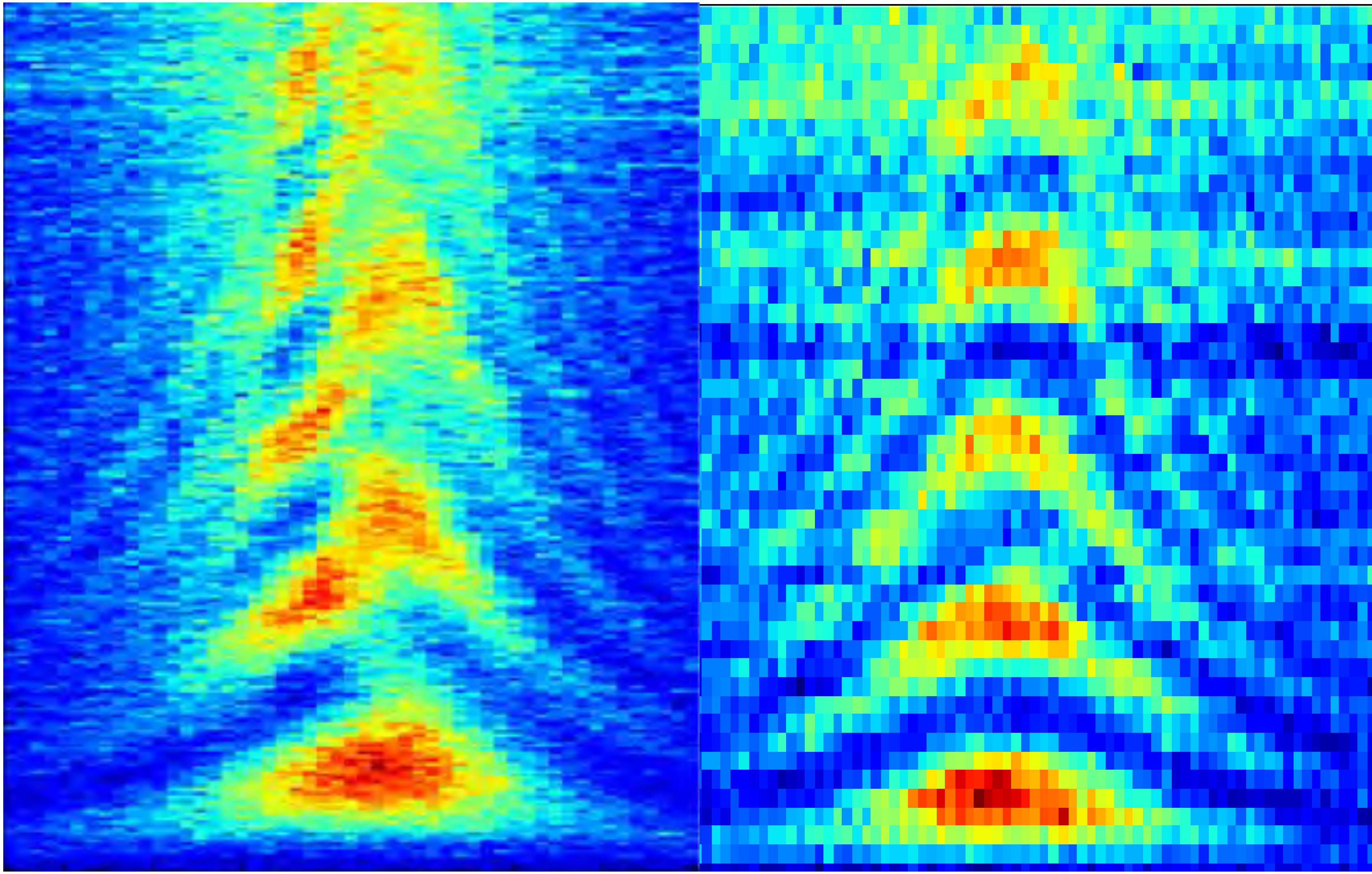


- Second harmonic coherent driving and inter-valley spin resonance





THANK YOU



FOR YOUR ATTENTION