Valley Splitting Correlations Across a Silicon Quantum Well

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Quantum dots in SiGe/Si/SiGe heterostructures host coherent electron spin qubits, which are promising for future quantum computers. The silicon quantum well hosts near-degenerate electron valley states, creating a low-lying excited state that is known to reduce spin qubit readout and control fidelity. The valley energy splitting is dominated by the microscopic disorder in the SiGe alloy and at the Si/SiGe interfaces, and while Si devices are compatible with large-scale semiconductor manufacturing, achieving a uniformly large valley splitting energy across a many-qubit device spanning mesoscopic distances is an outstanding challenge. In this work we study valley splitting variations in a 1D quantum dot array manufactured by Intel. We observe correlations in valley splitting, at both sub-100 nm (single gate) and $> 1\,\mu$m (device) lengthscales, that are consistent with alloy disorder-dominated theory and simulation. Our results develop the mesoscopic understanding of Si/SiGe heterostructures necessary for scalable device design.

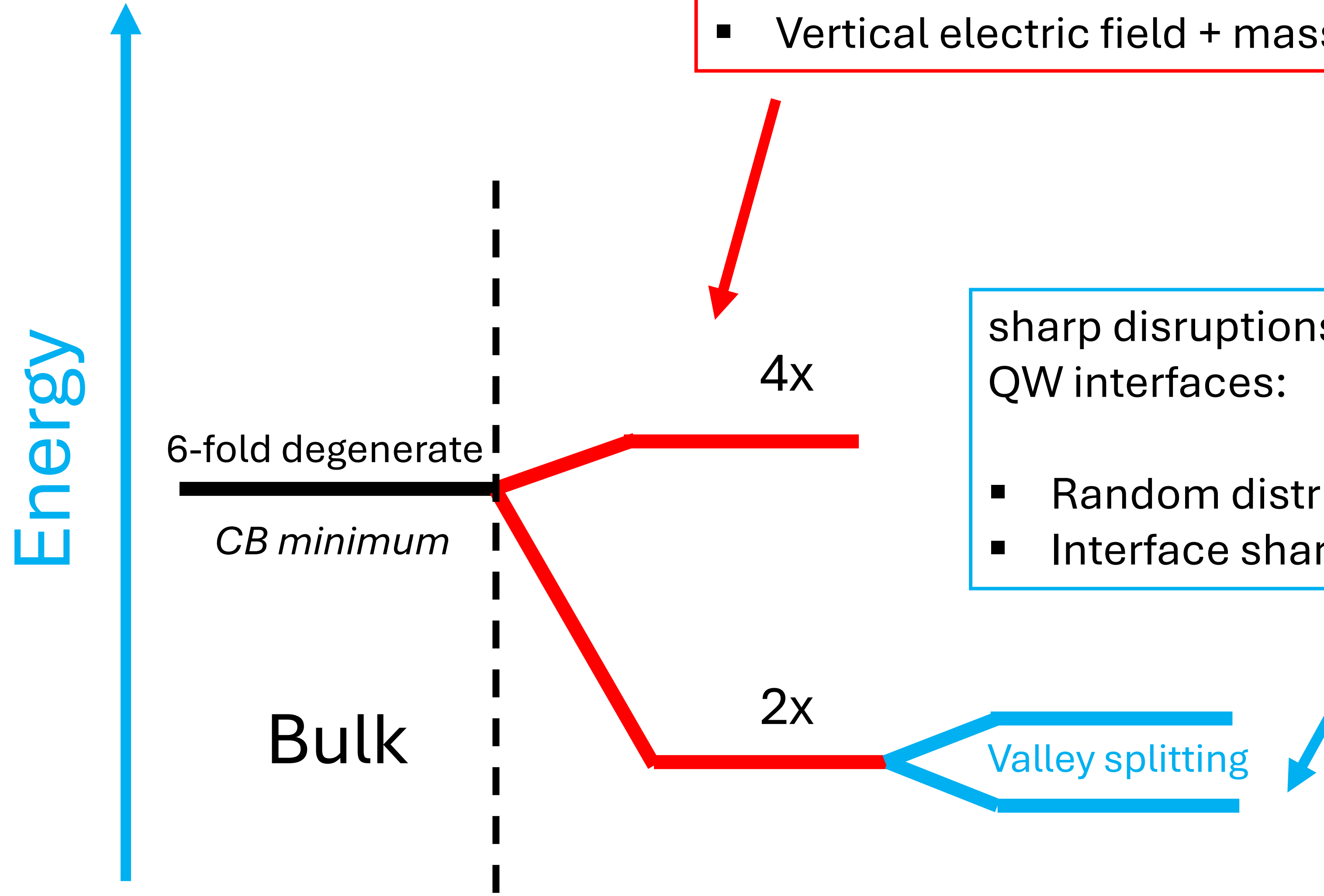
Journal Club
Speaker: Artemii Efimov
19 Sep 2025

Universität Basel

Valleys: INTRO

Tensile strain and spatial quantization:

- Lattice mismatch of Si with SiGe
- Vertical electric field + mass anisotropy in Si/SiO2



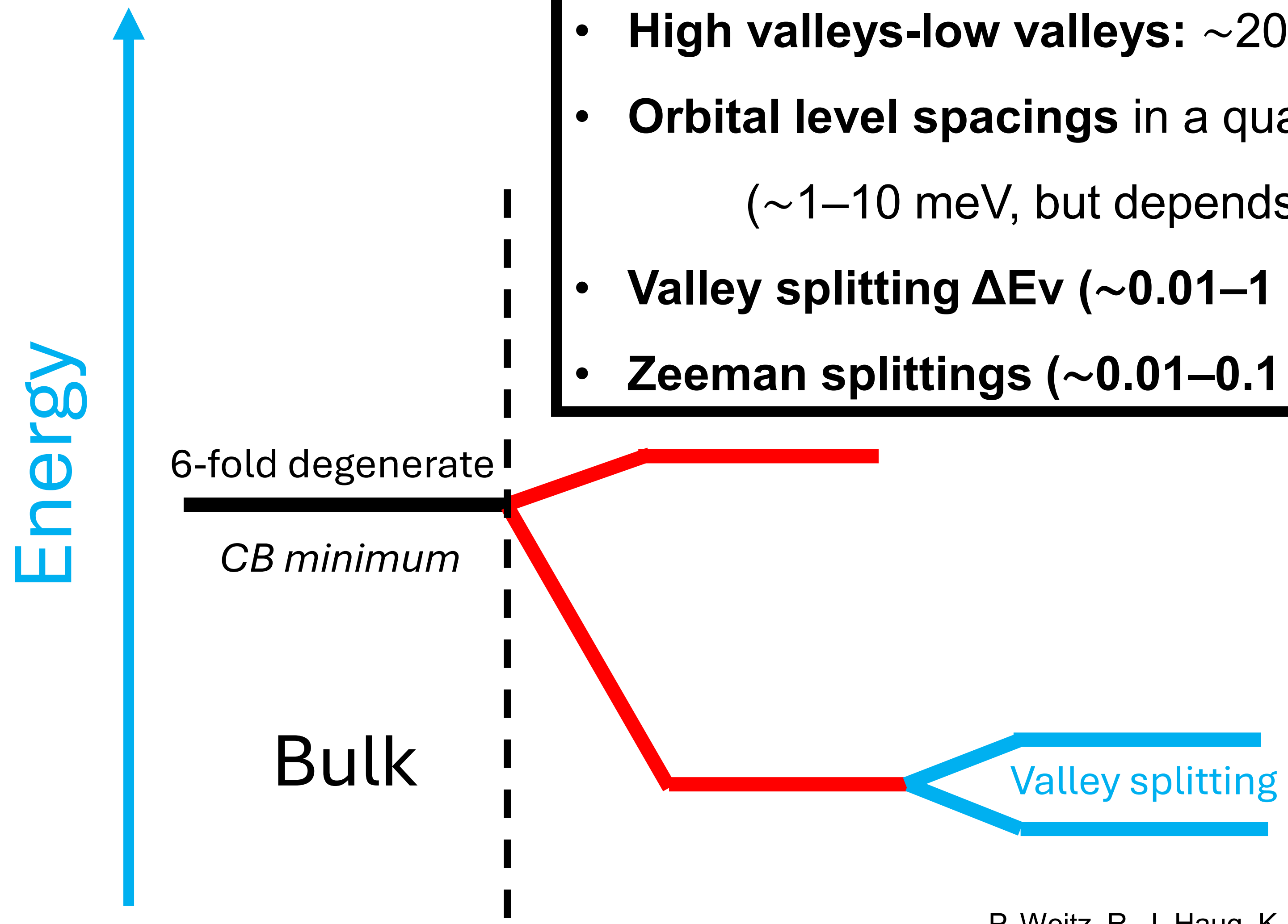
sharp disruptions of the periodic crystal potential at the QW interfaces:

- Random distribution of Ge atoms in SiGe
- Interface sharpness&disorder of Si/SiO2 interface

Valleys: INTRO

- **High valleys-low valleys:** ~20–200 meV (Si/SiGe), 20-40meV (Si-MOS)
- **Orbital level spacings** in a quantum dot

  (~1–10 meV, but depends on dot size)
- **Valley splitting ΔEv (~0.01–1 meV)**
- **Zeeman splittings (~0.01–0.1 meV at Tesla-scale fields)**

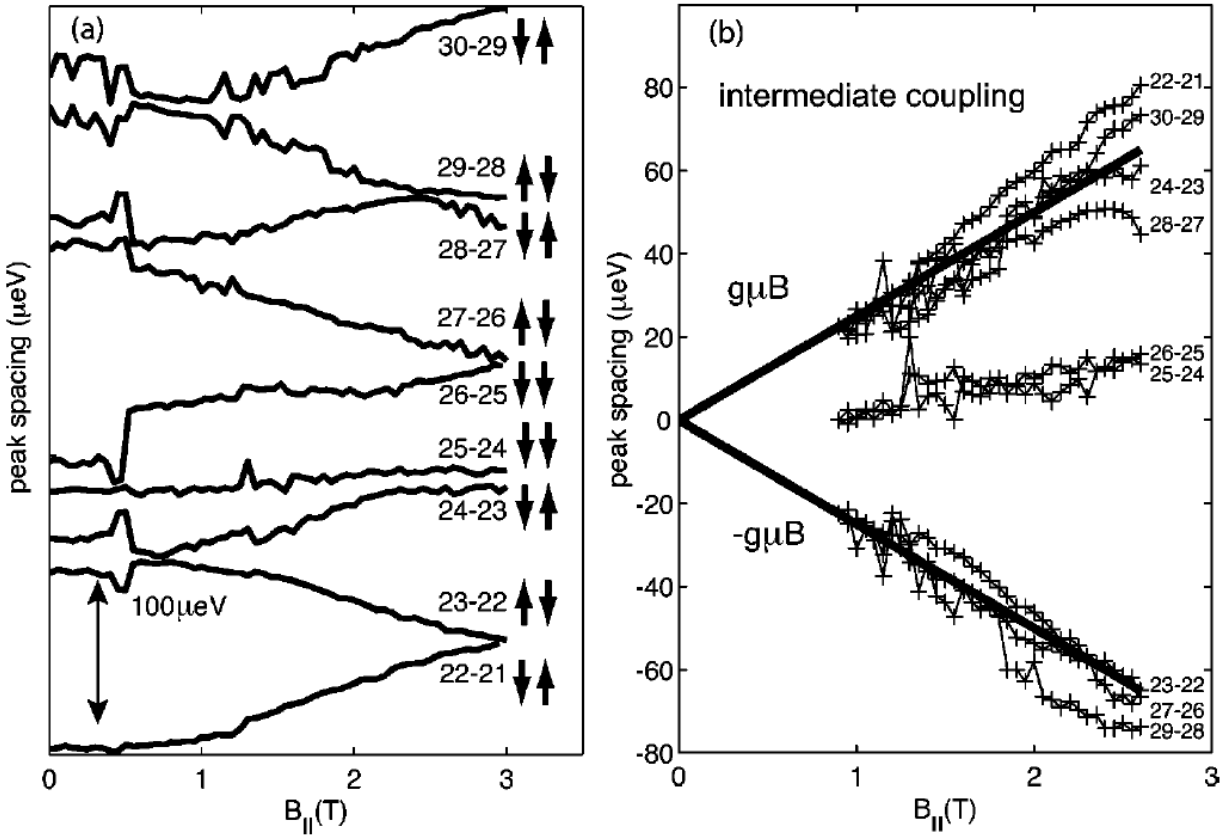


P. Weitz, R. J. Haug, K. von Klitzing, and F. Sch¨affler, Surf. Sci. 361/362, 542 (1996).

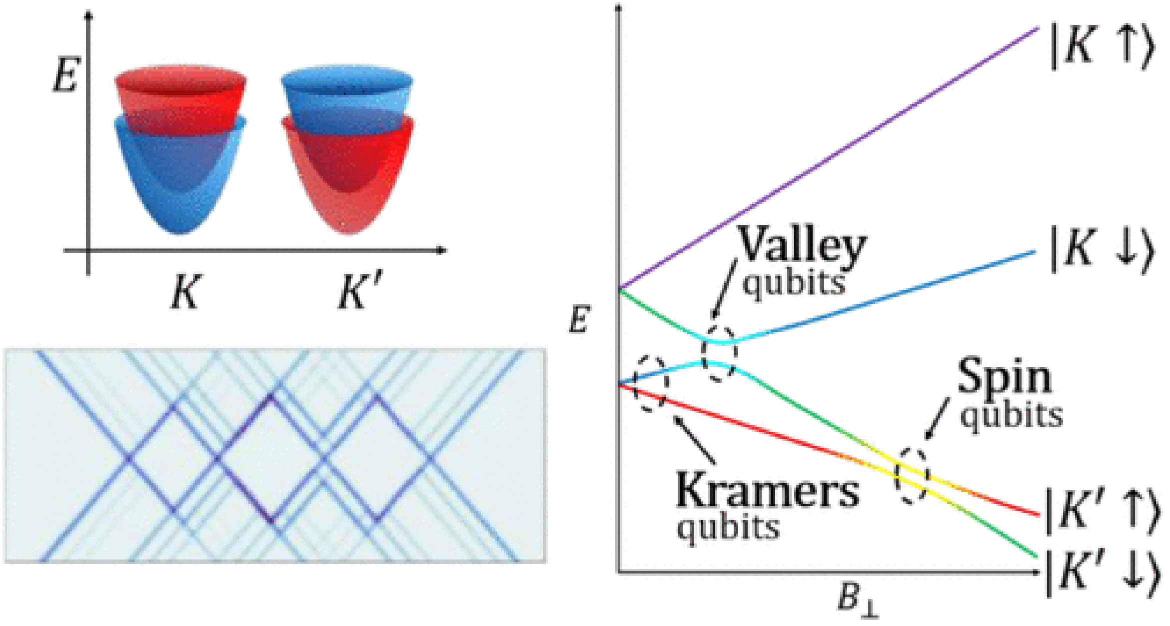
Valley splitting theory of SiGe/Si/SiGe quantum wells
Mark Friesen1,*, Sucismita Chutia1, Charles Tahan2, and S. N. Coppersmith1 (PRB, 2007)

Traditional approach

Magnetospectroscopy of different spin states

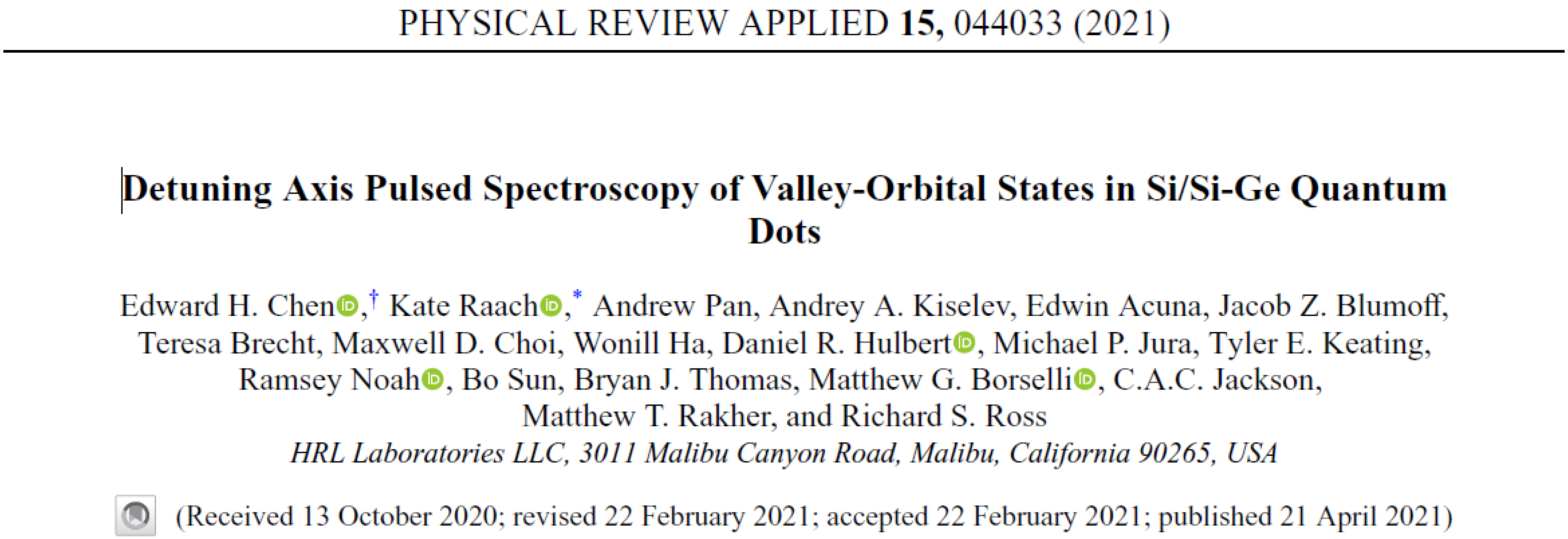


Stability of spin states in quantum dots S. Lindemann, T. Ihn, T. Heinzel*, W. Zwerger†, and K. Ensslin K. Maranowski and A. C. Gossard, PRB 2002



Aakash Shandilya, Sundeep Kapila, Radha Krishnan, Bent Weber, and Bhaskaran Muralidharan
ACS Applied Nano Materials **2025** *8* (30), 14949-14959
DOI: 10.1021/acsanm.5c01655

Novel Method: HRL Labs 2021



PHYSICAL REVIEW APPLIED **15,** 044033 (2021)

Detuning Axis Pulsed Spectroscopy of Valley-Orbital States in Si/Si-Ge Quantum Dots

Edward H. Chen,[†] Kate Raach,[*] Andrew Pan, Andrey A. Kiselev, Edwin Acuna, Jacob Z. Blumoff,
Teresa Brecht, Maxwell D. Choi, Wonill Ha, Daniel R. Hulbert, Michael P. Jura, Tyler E. Keating,
Ramsey Noah, Bo Sun, Bryan J. Thomas, Matthew G. Borselli, C.A.C. Jackson,
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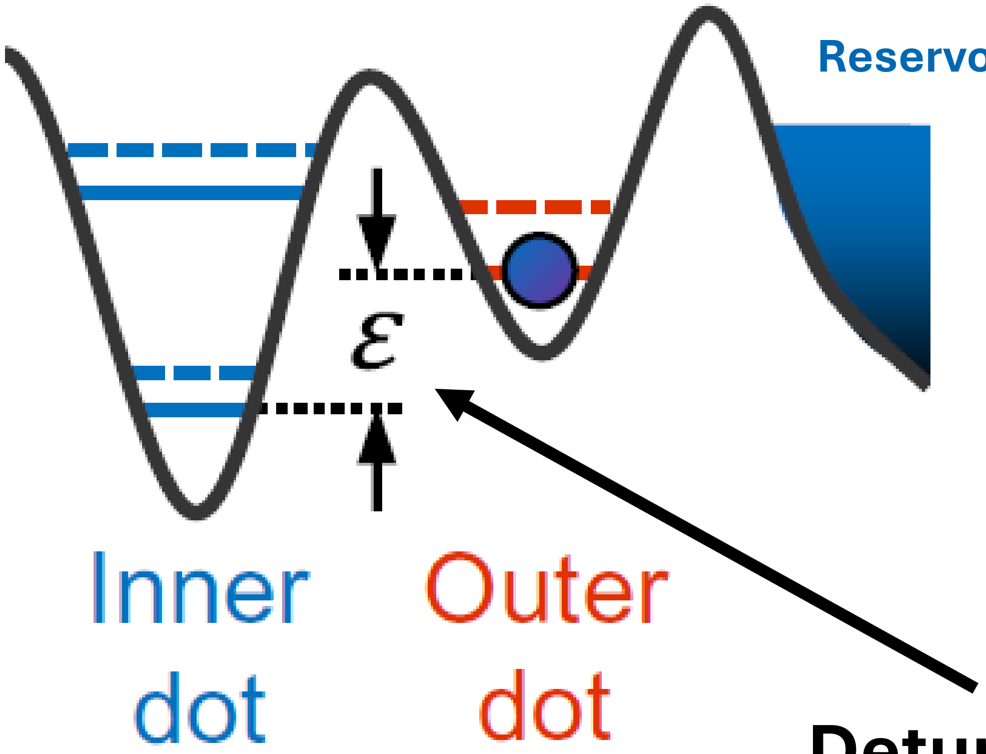
(Received 13 October 2020; revised 22 February 2021; accepted 22 February 2021; published 21 April 2021)

Orbital excitation

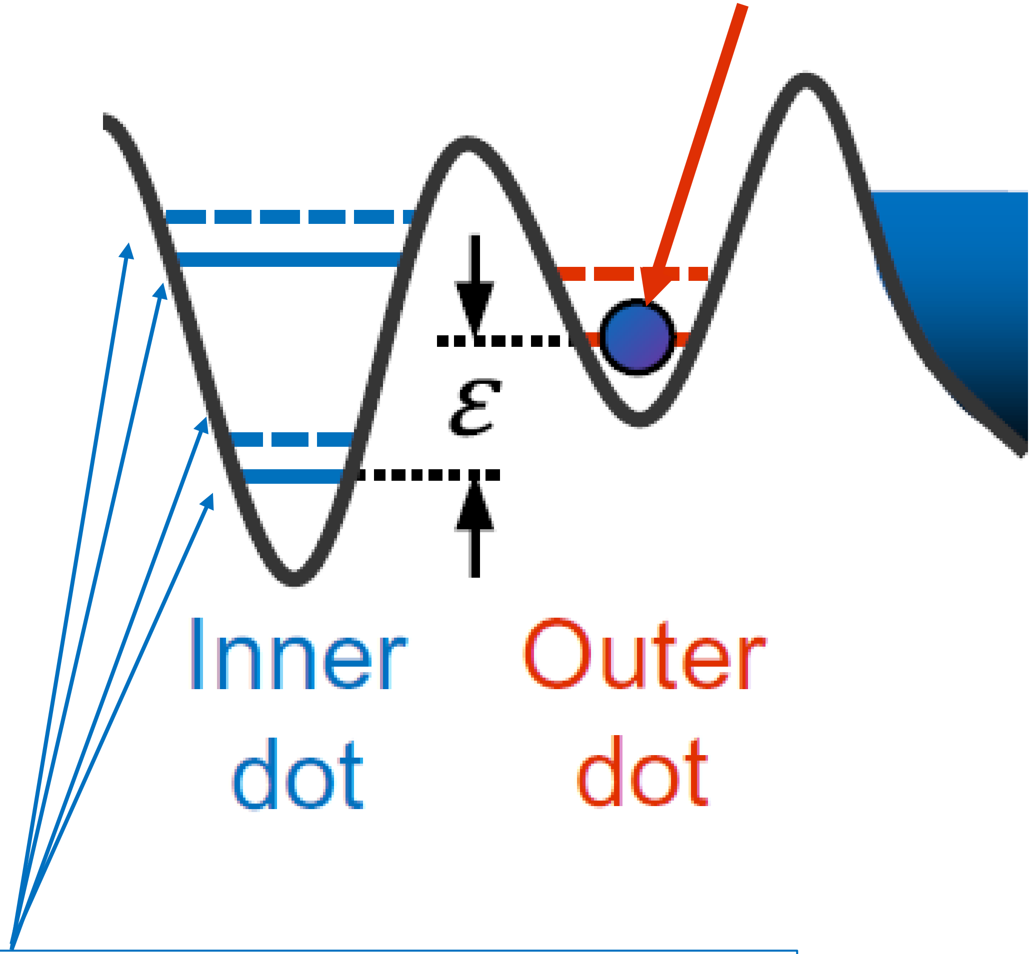
(associated) Valley excitation



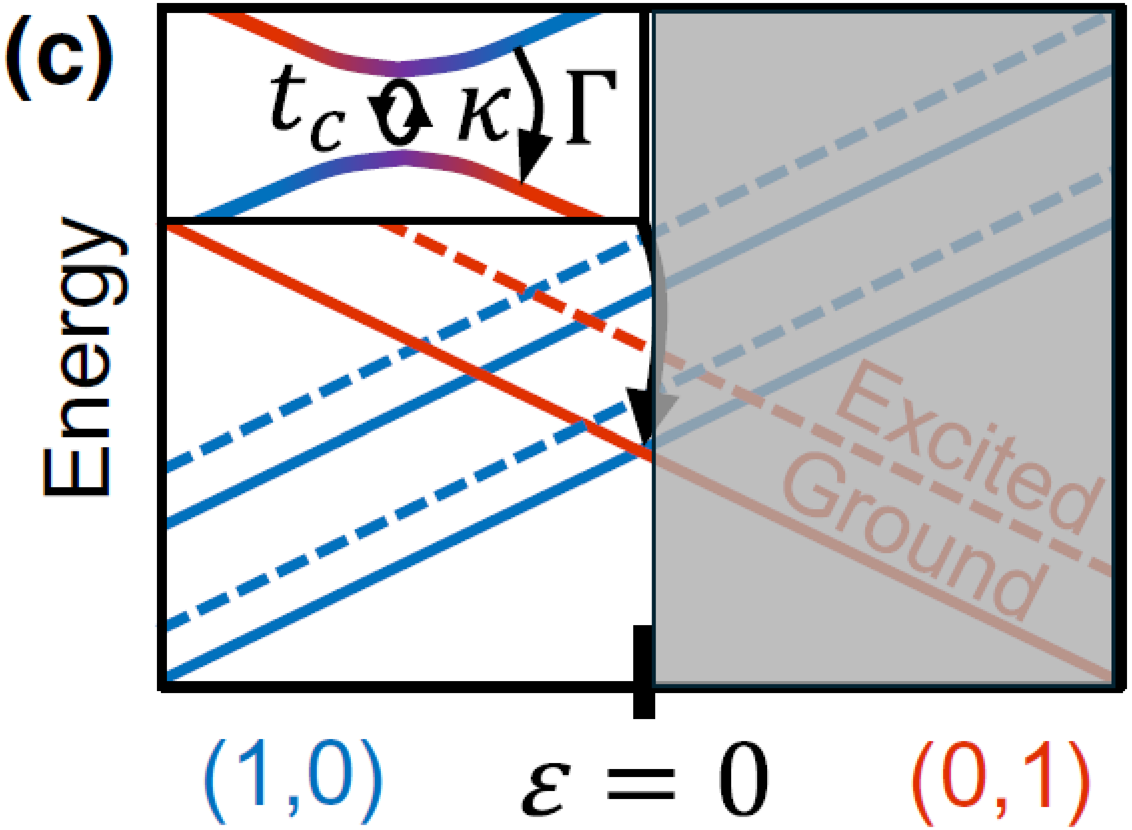
Preparing here!

Detuning!

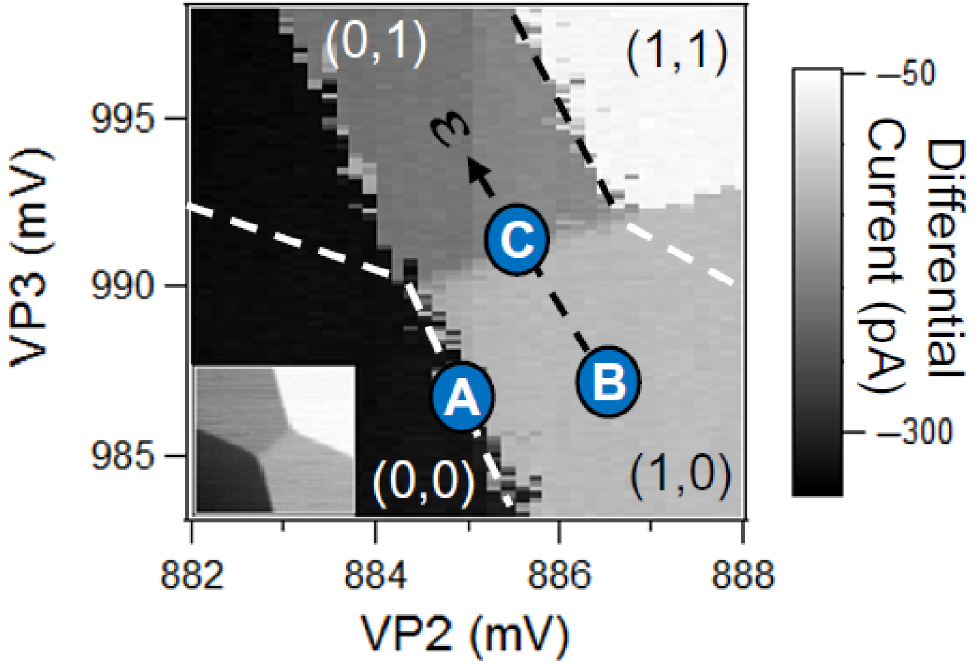
Ground state = reference

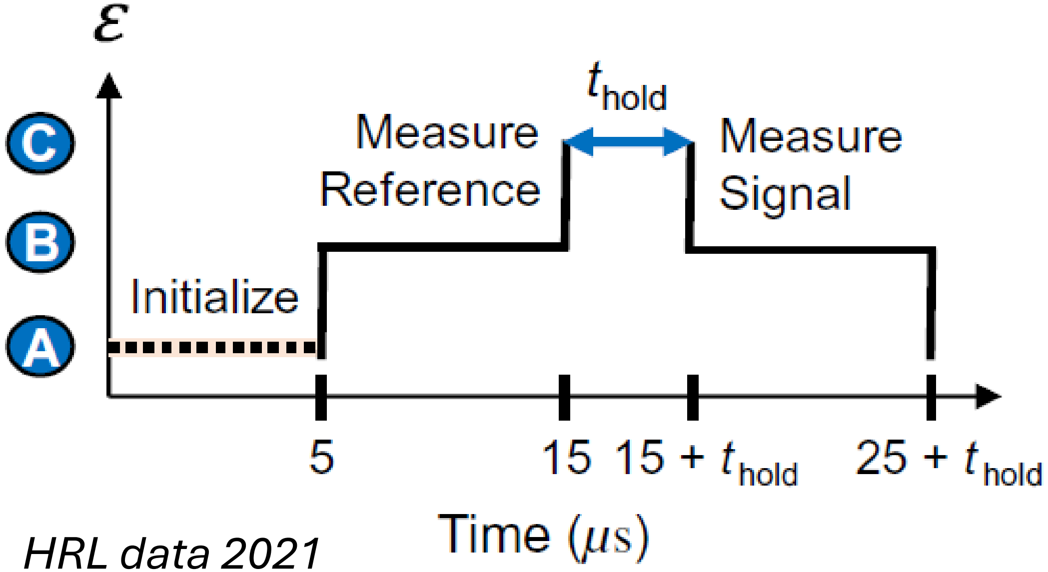


Probing these levels!



Working only on one side of detuning





HRL data 2021

A (Re-)loading from the reservoir to the **source** DOT to Ground State

B Pulse to the bulk of (1,0) region

Charge Sensor: Signal_(1,0)

C
- Diabatically going to to some **ε = …**
- Hold …
- Diabatically going back to some **ε = …**

1. Matched with the excited state of the target dot: **tunnels** -> **(0,1)**
2. No level matching -> still **(1,0)**

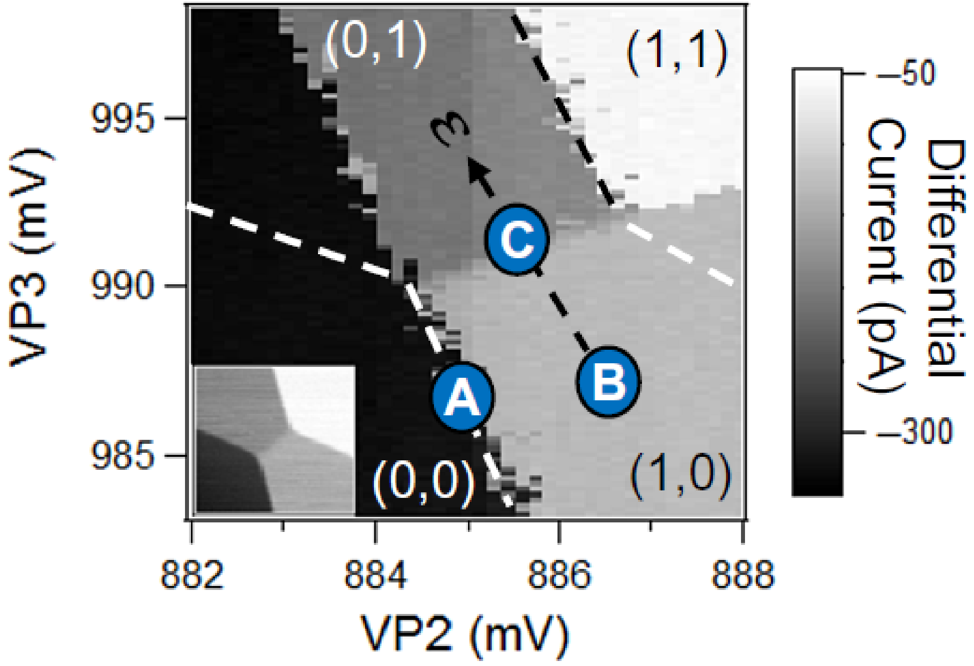
B Pulse back

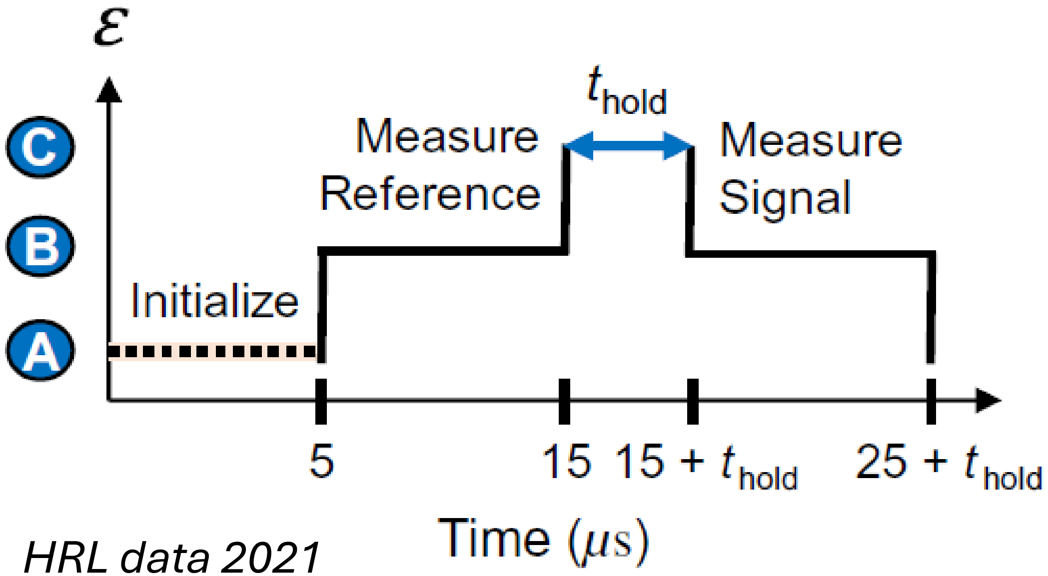
Charge Sensor: Signal(1,0**)** or Signal_(0,1)

Result ≠0 if matched with an excited state

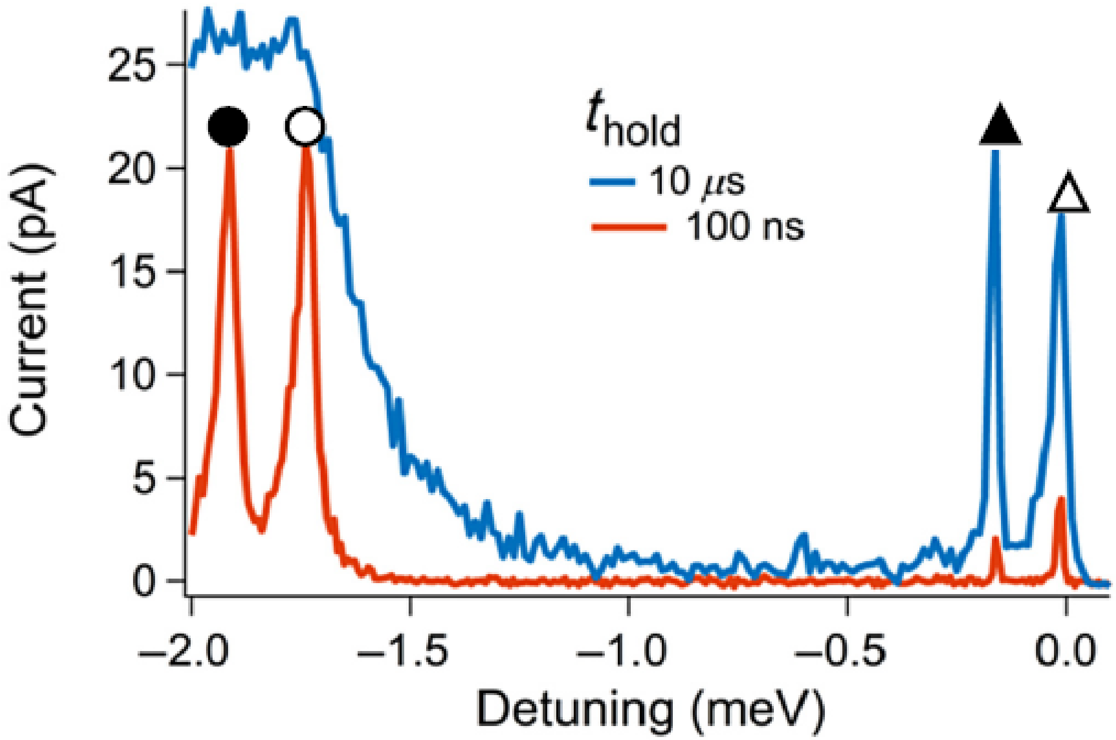
Result = 0 if not matched with an excited state

Repeat

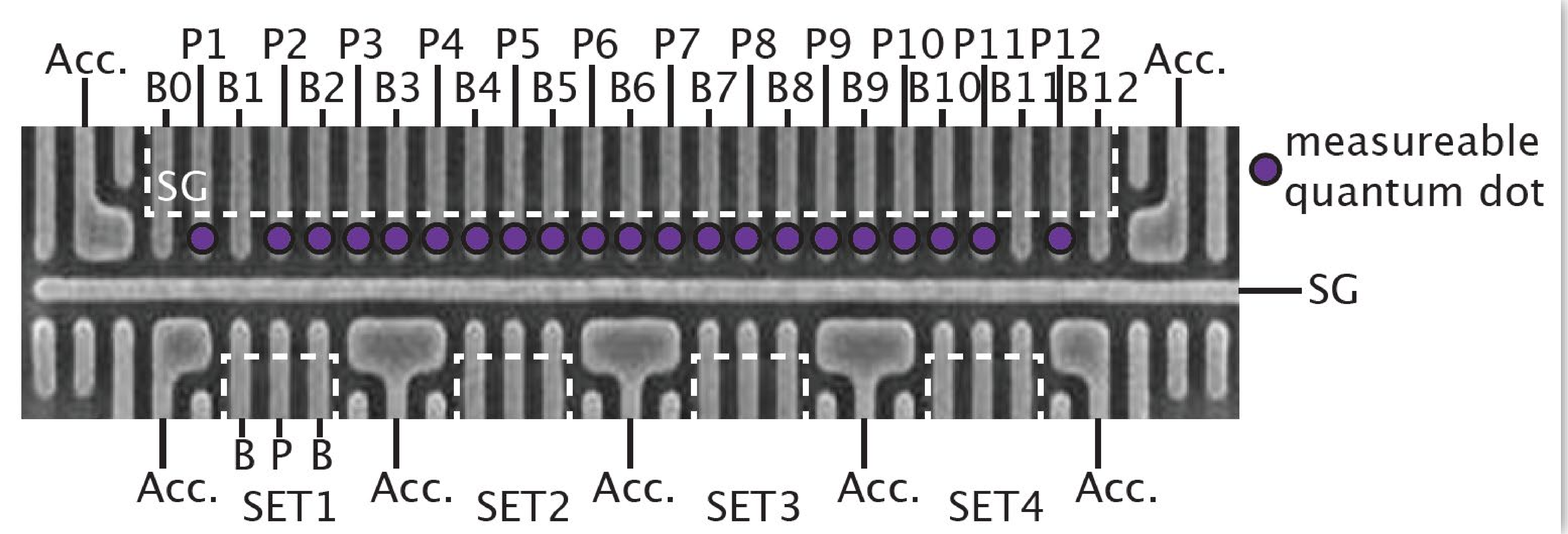


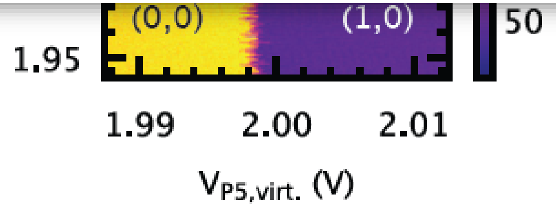


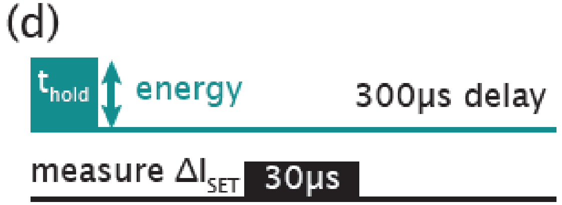
HRL data 2021

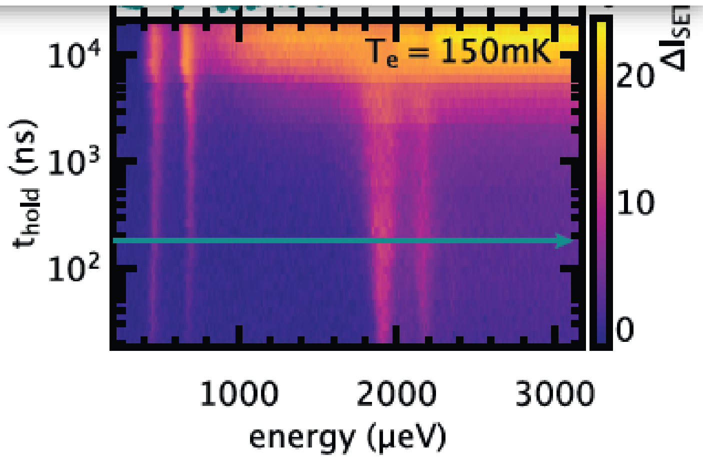


$$\kappa t_c^{-2} < t_{hold} < \Gamma_{decay}^{-1}$$



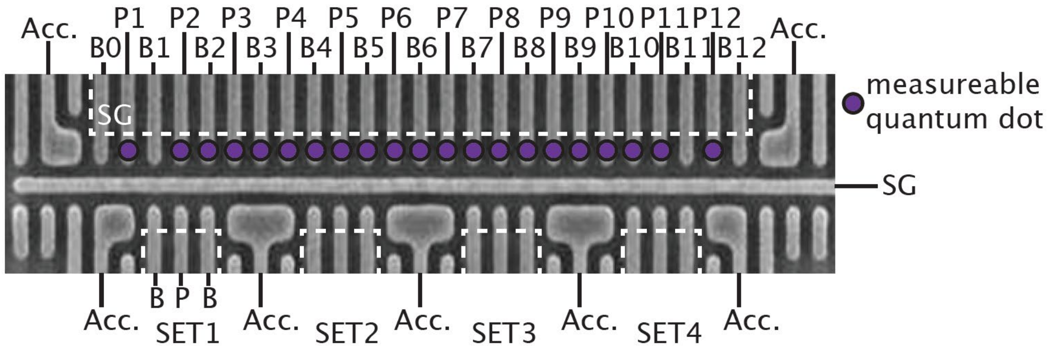






The tool is working, let's go deeper into material physics

M. Eriksson lab data 2025



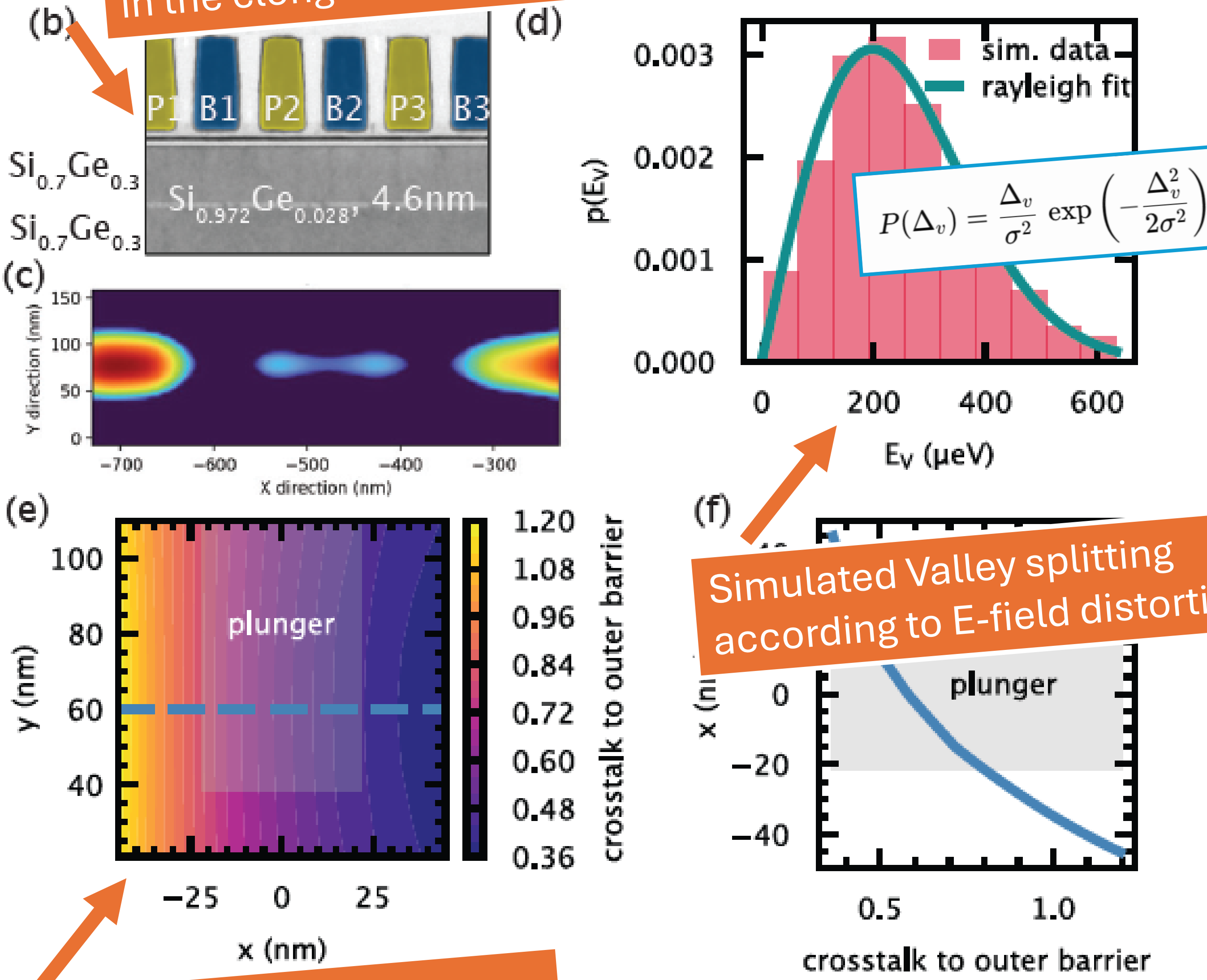
ADD theory = Alloy disorder-dominated valley splitting

Key point of the paper: **To verify the ADD model**

=> <u>conclusion about the valley splitting’ variations</u>

Hint: 2.8 % Ge doping

M. Eriksson lab data 2025



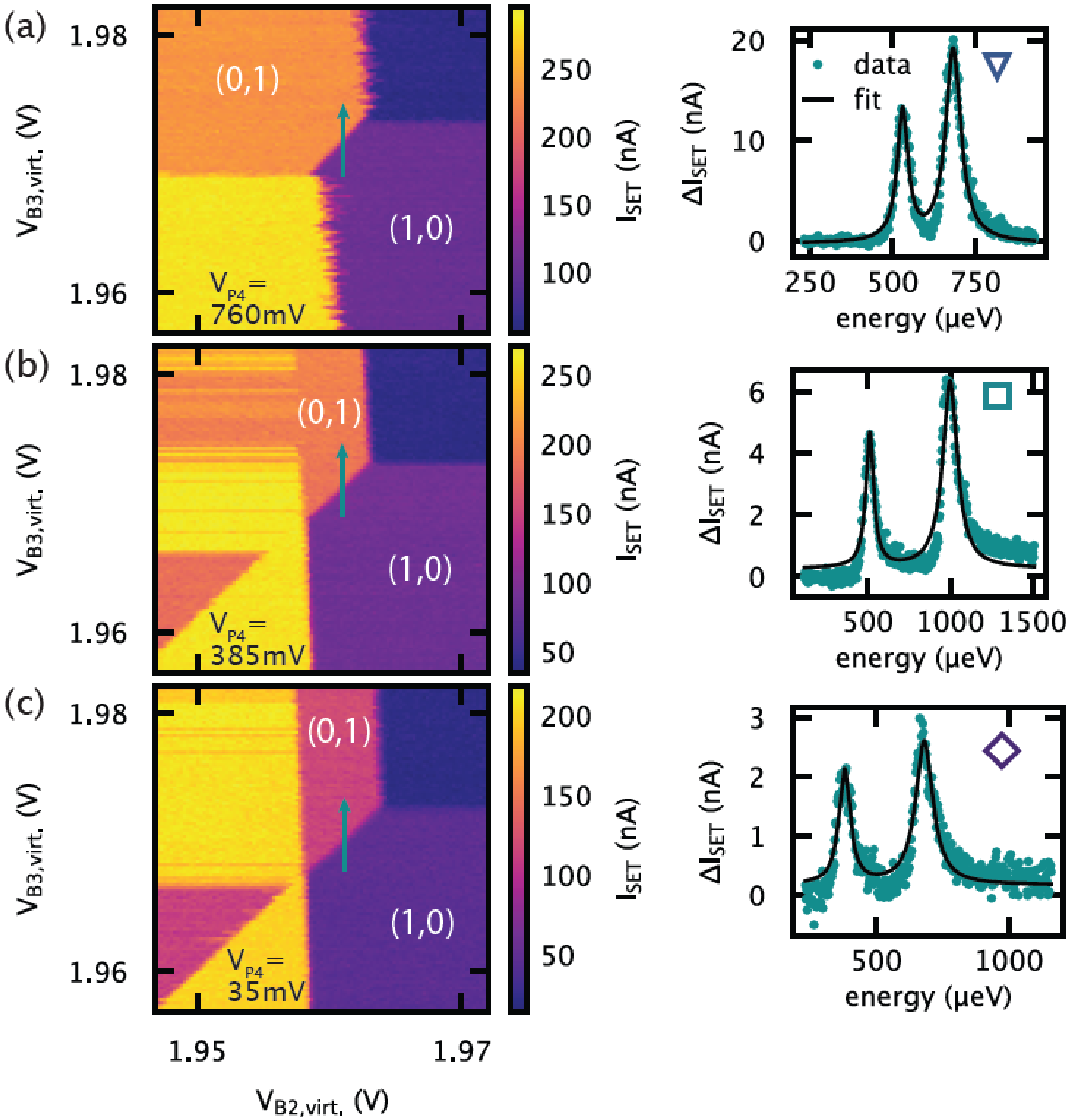
$$P(\Delta_v) = \frac{\Delta_v}{\sigma^2}\exp\left(-\frac{\Delta_v^2}{2\sigma^2}\right)$$

Simulated Electron Density in the elongated QD

Simulated Valley splitting according to E-field distorti

Dot Center position as a function from the Crosstalk

Continuous electron valley probe



M. Eriksson lab data 2025

Continuous electron valley probe

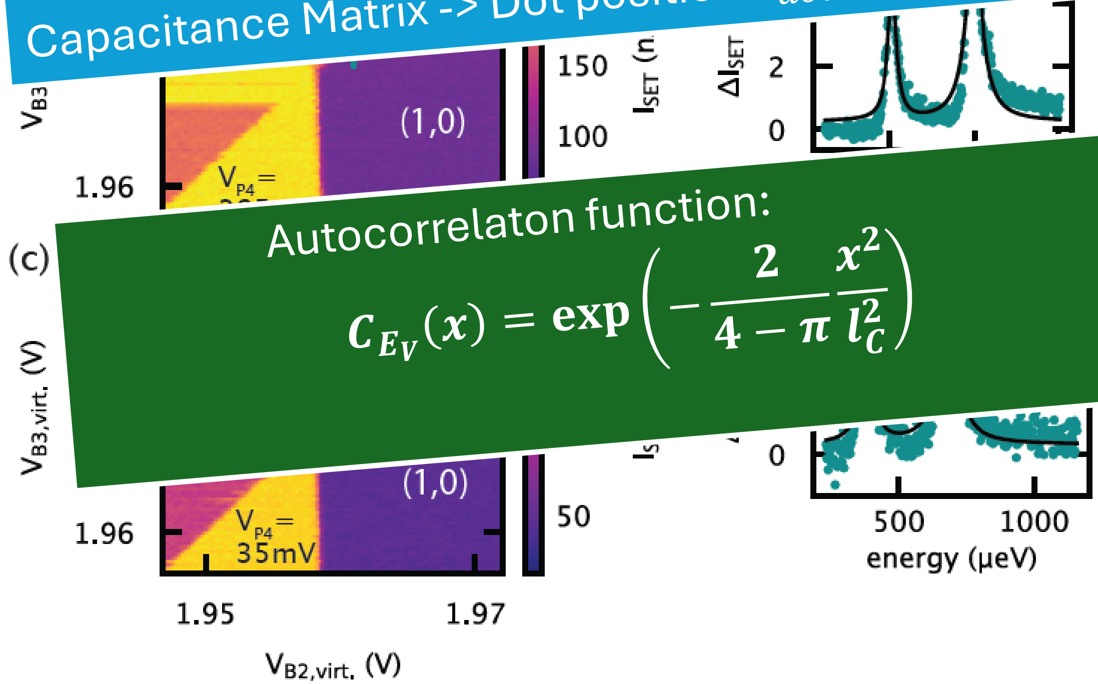
Three Dots:

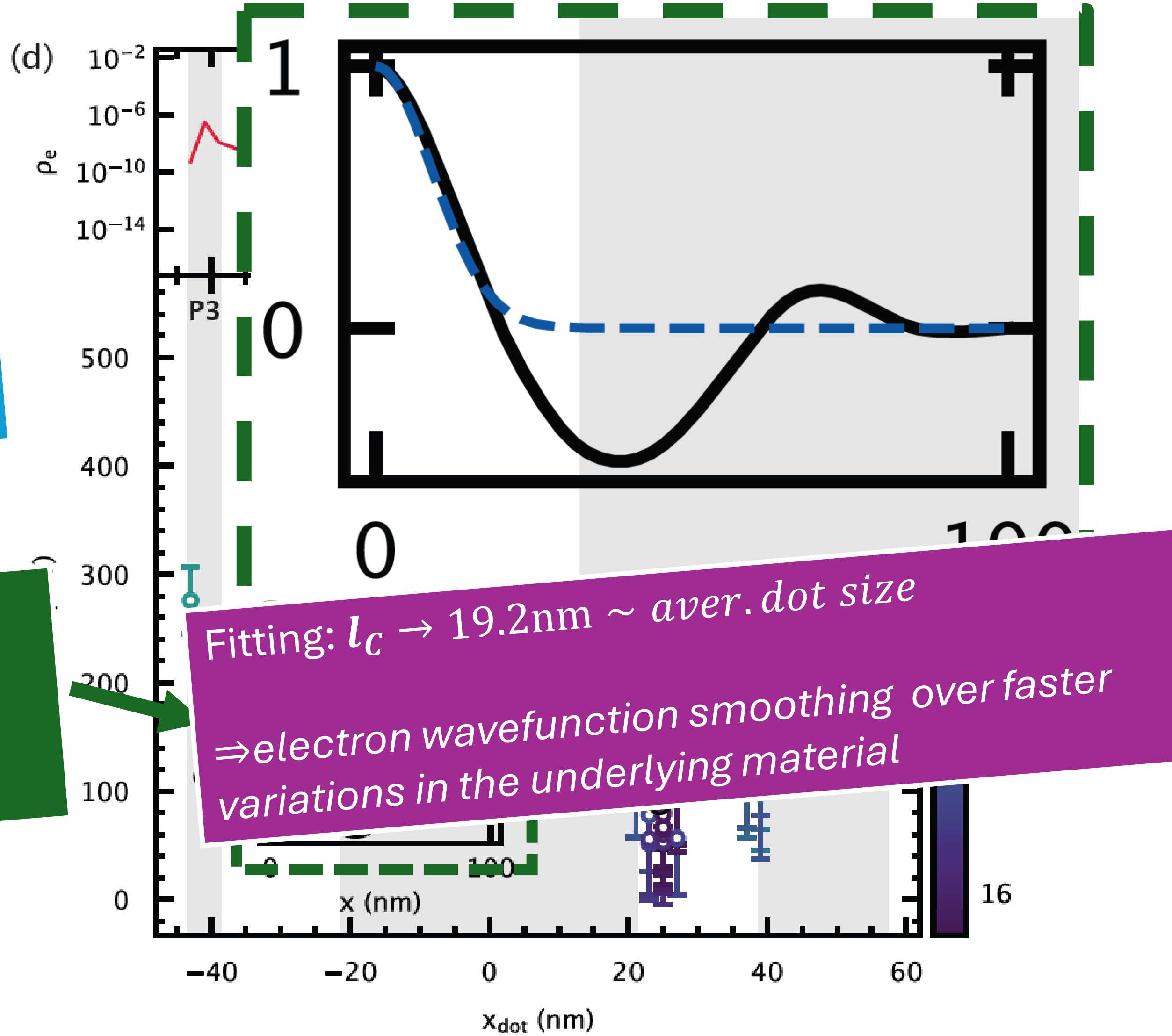
Varying the confinement

Orbital splitting -> **Dot size** $r_x = \sqrt{2\hbar^2/m_e^* E_o}$

Ev splitting -> **Thermal population** ρ_e (Tel = 150mK)

Capacitance Matrix -> Dot position x_{dot}





Autocorrelaton function:

$$C_{E_V}(x) = \exp\left(-\frac{2}{4-\pi}\frac{x^2}{l_C^2}\right)$$

Fitting: $l_C \rightarrow 19.2\text{nm} \sim aver.\,dot\ size$

⇒electron wavefunction smoothing over faster variations in the underlying material

M. Eriksson lab data 2025

across the gate

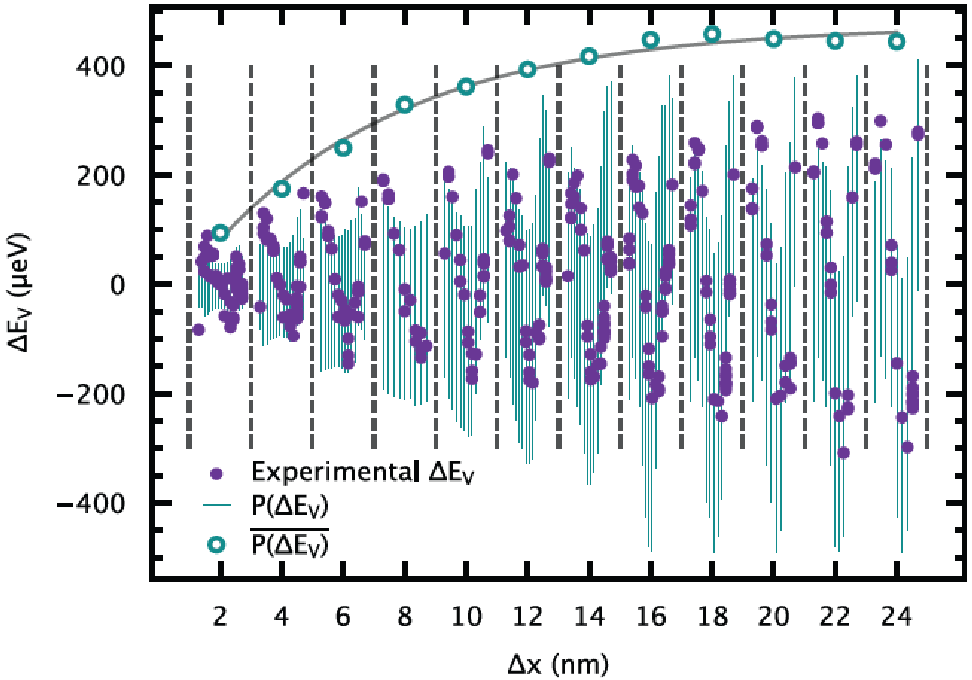
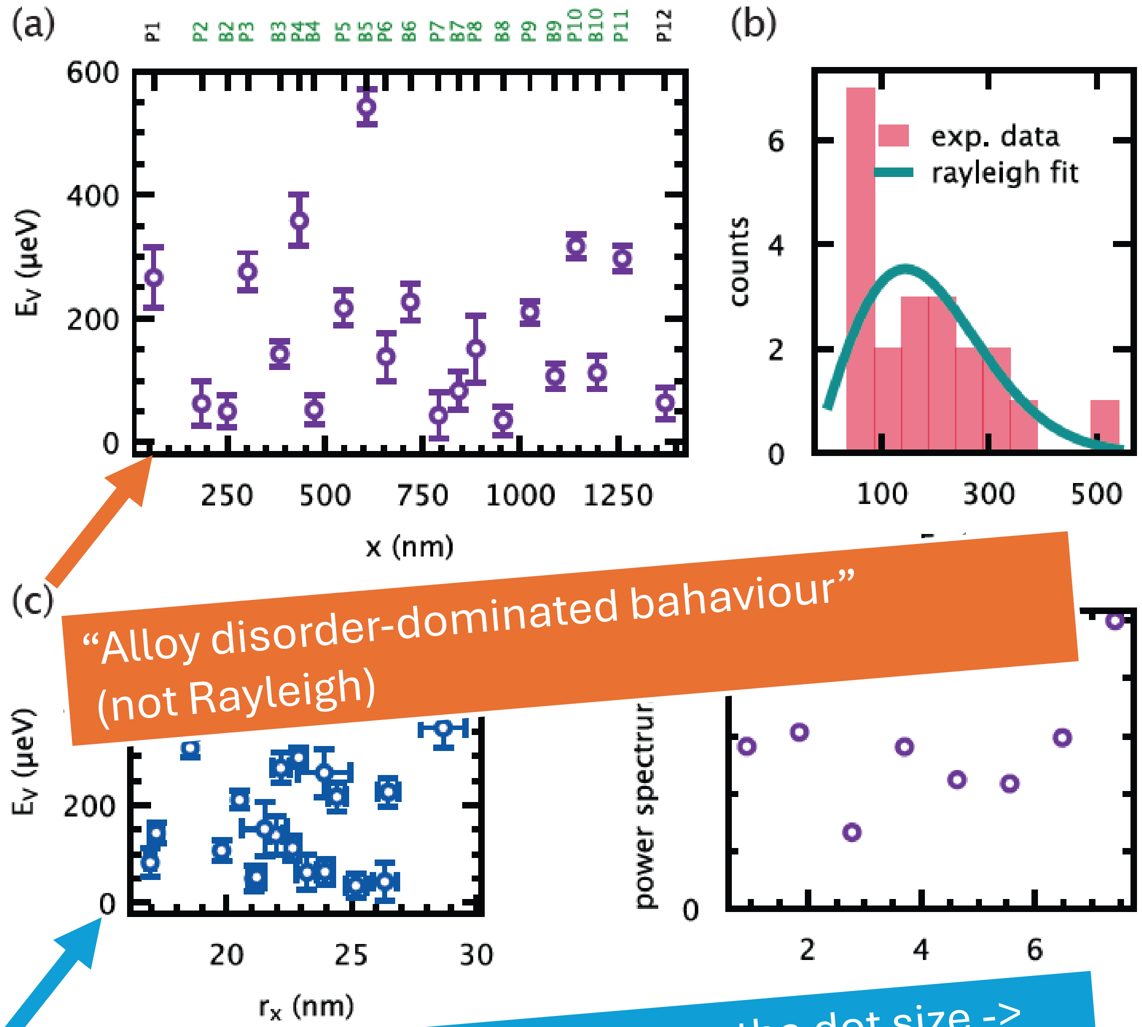


FIG. 4. **Expected E_V variations.** The valley splitting difference ΔE_V (purple filled in circles) is plotted alongside the 5%–95% range $P(E_V)$ of valley splitting at some distance Δx (teal lines). The mean expected range for each distance $\overline{P(E_V)}$ is plotted atop the data (open teal circles), fit to an exponential decay (gray line).

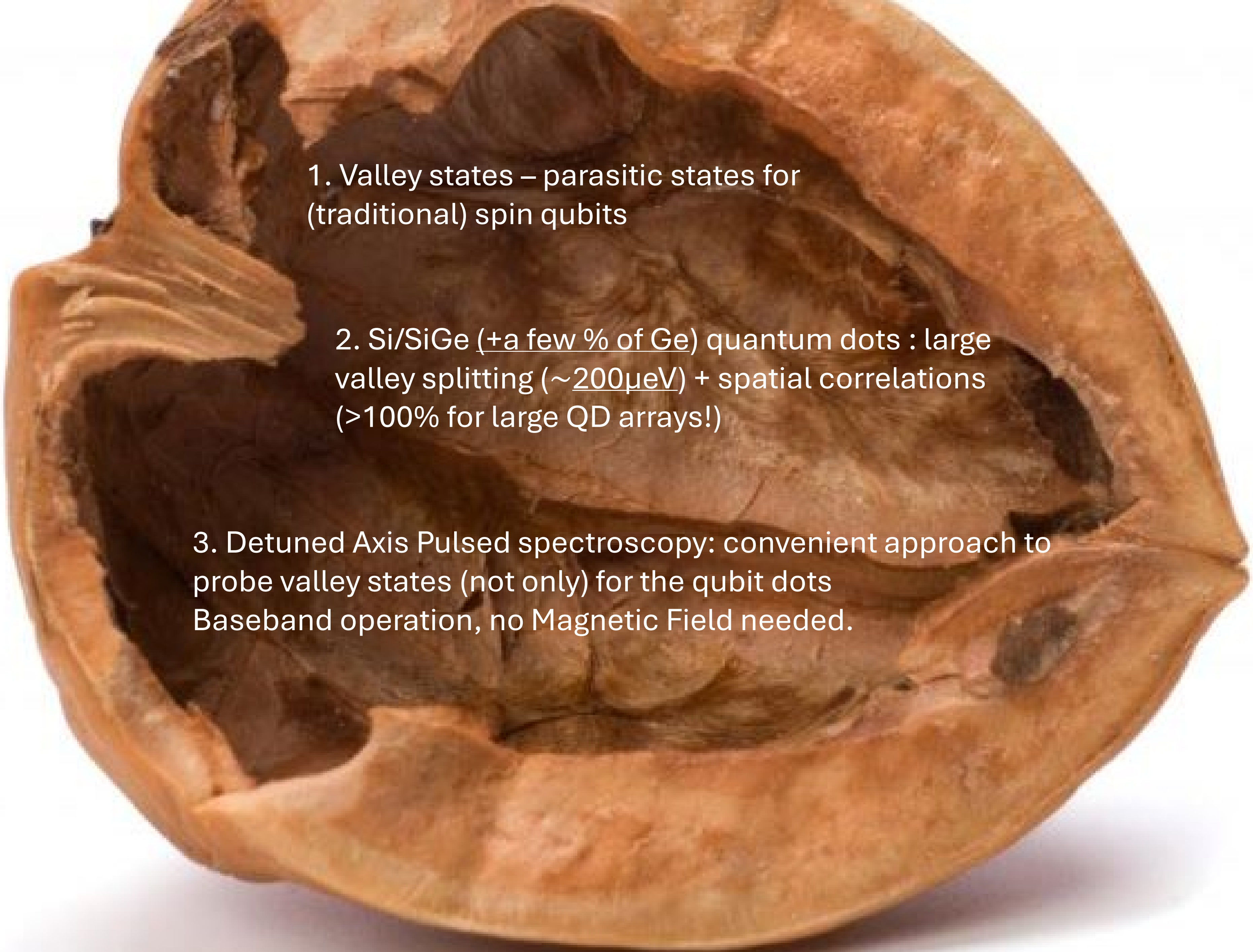
“Local correlations die out on/below electron wavefunction size”

across the device



“Alloy disorder-dominated bahaviour” (not Rayleigh)

No (significant) dependence Ev from the dot size -> “Domination of underlying material disorder”



1. Valley states – parasitic states for (traditional) spin qubits

2. Si/SiGe (+a few % of Ge) quantum dots : large valley splitting (~200μeV) + spatial correlations (>100% for large QD arrays!)

3. Detuned Axis Pulsed spectroscopy: convenient approach to probe valley states (not only) for the qubit dots
Baseband operation, no Magnetic Field needed.