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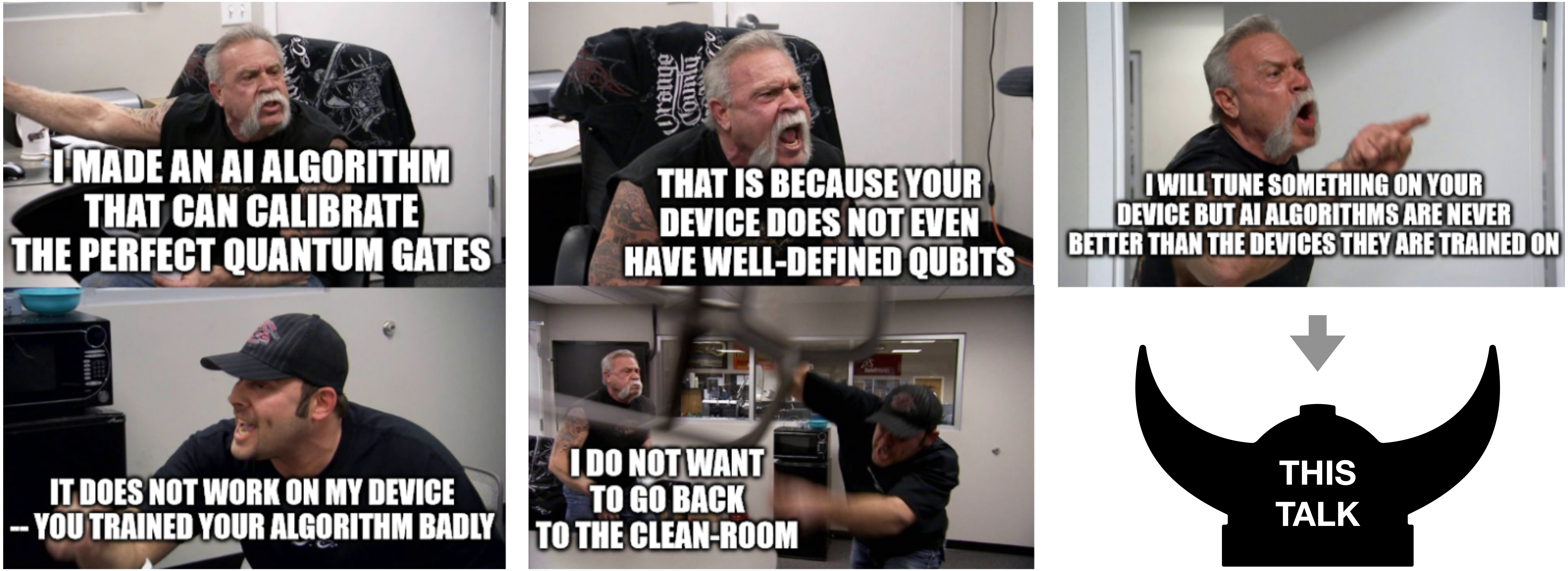
Autonomous Quantum Control in the Age of AI

ML4QT Erlangen

Sam Katiraee-Far, Joseph Rogers, Yuta Matsumoto, Valentina Gualtieri, Charles Renshaw-Whitman, Vinicius Hernandes, Brennan Undseth, Renato Durrer, Benedikt Kratochwil, Thomas Ihn, Lieven Vandersypen, and Eliska Greplova


I MADE AN AI ALGORITHM THAT CAN CALIBRATE THE PERFECT QUANTUM GATES
IT DOES NOT WORK ON MY DEVICE -- YOU TRAINED YOUR ALGORITHM BADLY
THAT IS BECAUSE YOUR DEVICE DOES NOT EVEN HAVE WELL-DEFINED QUBITS
I DO NOT WANT TO GO BACK TO THE CLEAN-ROOM
I WILL TUNE SOMETHING ON YOUR DEVICE BUT AI ALGORITHMS ARE NEVER BETTER THAN THE DEVICES THEY ARE TRAINED ON
THIS TALK

Contemporary quantum experiments

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Article | Published: 23 October 2019

Quantum s[redacted]using a programmable superconducting processor

Frank Arute, Kunal Arya, Ryan Babbush, Dave Bacon, Joseph C. Bardin, Rami Barends, Rupak Biswas, Sergio Boixo, Fernando G. S. L. Brandao, David A. Buell, Brian Burkett, Yu Chen, Zijun Chen, Ben Chiaro, Roberto Collins, William Courtney, Andrew Dunsworth, Edward Farhi, Brooks Foxen, Austin Fowler, Craig Gidney, Marissa Giustina, Rob Graff, Keith Guerin, ... John M. Martinis + Show authors

Nature **574**, 505–510 (2019) | Cite this article

Editors' Suggestion

Access by S

Solving the Sampling Problem of the Sycamore Quantum Circuits

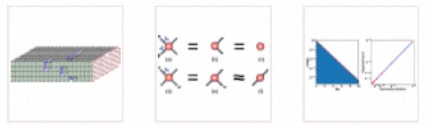
Feng Pan, Keyang Chen, and Pan Zhang

Phys. Rev. Lett. **129**, 090502 – Published 22 August 2022

Article | References | Citing Articles (23) | Supplemental Material | PDF | HTML | Export Citation

ABSTRACT

We study the problem of generating independent samples from the output distribution of Google's Sycamore quantum circuits with a target fidelity, which is believed to be beyond the reach of classical supercomputers and has been used to demonstrate quantum supremacy. We propose a method to classically solve this problem by contracting the corresponding tensor network just once, and is massively more efficient than existing methods in generating a large number of *uncorrelated* samples with a target fidelity. For the Sycamore quantum supremacy circuit with 53 qubits and 20 cycles, we have generated 1×10^6 *uncorrelated* bitstrings $\mathbf{s}$ which are sampled from a distribution $\hat{P}(\mathbf{s}) = |\hat{\psi}(\mathbf{s})|^2$, where the approximate state $\hat{\psi}$ has fidelity $F \approx 0.0037$. The whole computation has cost about 15 h on a computational cluster with 512 GPUs. The obtained 1×10^6 samples, the contraction code and contraction order are made public. If our algorithm could be implemented with high efficiency on a modern supercomputer with ExaFLOPS performance, we estimate that ideally, the simulation would cost a few dozens of seconds, which is faster than Google's quantum hardware.



Article | Open access | Published: 14 June 2023

Evidence for the utility of quantum computing before fault tolerance

Youngseok Kim, Andrew Eddins, Sajant Anand, Ken Xuan Wei, Ewout van den Berg, Sami Rosenblatt, Hasan Nayfeh, Yantao Wu, Michael Zaletel, Kristan Temme & Abhinav Kandala

Nature **618**, 500–505 (2023) | Cite this article

Efficient tensor network simulation of IBM's Eagle kicked Ising experiment

Joseph Tindall, Matt Fishman, Miles Stoudenmire, Dries Sels

We report an accurate and efficient classical simulation of a kicked Ising quantum system on the heavy-hexagon lattice. A simulation of this system was recently performed on a 127 qubit quantum processor using noise mitigation techniques to enhance accuracy (Nature volume 618, p.500–505 (2023)). Here we show that, by adopting a tensor network approach that reflects the geometry of the lattice and is approximately contracted using belief propagation, we can perform a classical simulation that is significantly more accurate and precise than the results obtained from the quantum processor and many other classical methods. We quantify the tree-like correlations of the wavefunction in order to explain the accuracy of our belief propagation-based approach. We also show how our method allows us to perform simulations of the system to long times in the thermodynamic limit, corresponding to a quantum computer with an infinite number of qubits. Our tensor network approach has broader applications for simulating the dynamics of quantum systems with tree-like correlations.

Comments: 18 Pages. 10 Figures. Updated to include improved BP-TNS data, simulation of the infinite system and improved error quantification

Subjects: **Quantum Physics (quant-ph)**

Cite as: arXiv:2306.14887 [quant-ph]

(or arXiv:2306.14887v2 [quant-ph] for this version)

https://doi.org/10.48550/arXiv.2306.14887

Computational s[redacted] in quantum simulation

Andrew D. King, Alberto Nocera, Marek M. Rams, Jacek Dziarmaga, Roeland Wiersema, William Bernoudy, Jack Raymond, Nitin Kaushal, Niclas Heinsdorf, Richard Harris, Kelly Boothby, Fabio Altomare, Andrew J. Berkley, Martin Boschnak, Kevin Chern, Holly Christiani, Samantha Cibere, Jake Connor, Martin H. Dehn, Rahul Deshpande, Sara Ejtemaee, Pau Farré, Kelsey Hamer, Emile Hoskinson, Shuiyuan Huang, Mark W. Johnson, Samuel Kortas, Eric Ladizinsky, Tony Lai, Trevor Lanting, Ryan Li, Allison J.R. MacDonald, Gaelen Marsden, Catherine C. McGeoch, Reza Molavi, Richard Neufeld, Mana Norouzpour, Travis Oh, Joel Pasvolsky, Patrick Poitras, Gabriel Poulin-Lamarre, Thomas Prescott, Mauricio Reis, Chris Rich, Mohammad Samani, Benjamin Sheldan, Anatoly Smirnov, Edward Sterpka, Berta Trullas Clavera, Nicholas Tsai, Mark Volkmann, Alexander Whiticar, Jed D. Whittaker, Warren Wilkinson, Jason Yao, T.J. Yi, Anders W. Sandvik, Gonzalo Alvarez, Roger G. Melko, Juan Carrasquilla, Marcel Franz, Mohammad H. Amin

Quantum computers hold the promise of solving certain problems that lie beyond the reach of conventional computers. Establishing this capability, especially for impactful and meaningful problems, remains a central challenge. One such problem is the simulation of nonequilibrium dynamics of a magnetic spin system quenched through a quantum phase transition. State-of-the-art classical simulations demand resources that grow exponentially with system size. Here we show that superconducting quantum annealing processors can rapidly generate samples in close agreement with solutions of the Schrödinger equation. We demonstrate area-law scaling of entanglement in the model quench in two-, three- and infinite-dimensional spin glasses, supporting the observed stretched-exponential scaling of effort for classical approaches. We assess approximate methods based on tensor networks and neural networks and conclude that no known approach can achieve the same accuracy as the quantum annealer within a reasonable timeframe. Thus quantum annealers can answer questions of practical importance that classical computers cannot.

Subjects: **Quantum Physics (quant-ph)**; Disordered Systems and Neural Networks (cond-mat.dis-nn); Statistical Mechanics (cond-mat.stat-mech)

Cite as: arXiv:2403.00910 **[quant-ph]**

(or arXiv:2403.00910v1 **[quant-ph]** for this version)

"What happens if we co-design experiments AND simulations?”

Contemporary quantum experiments

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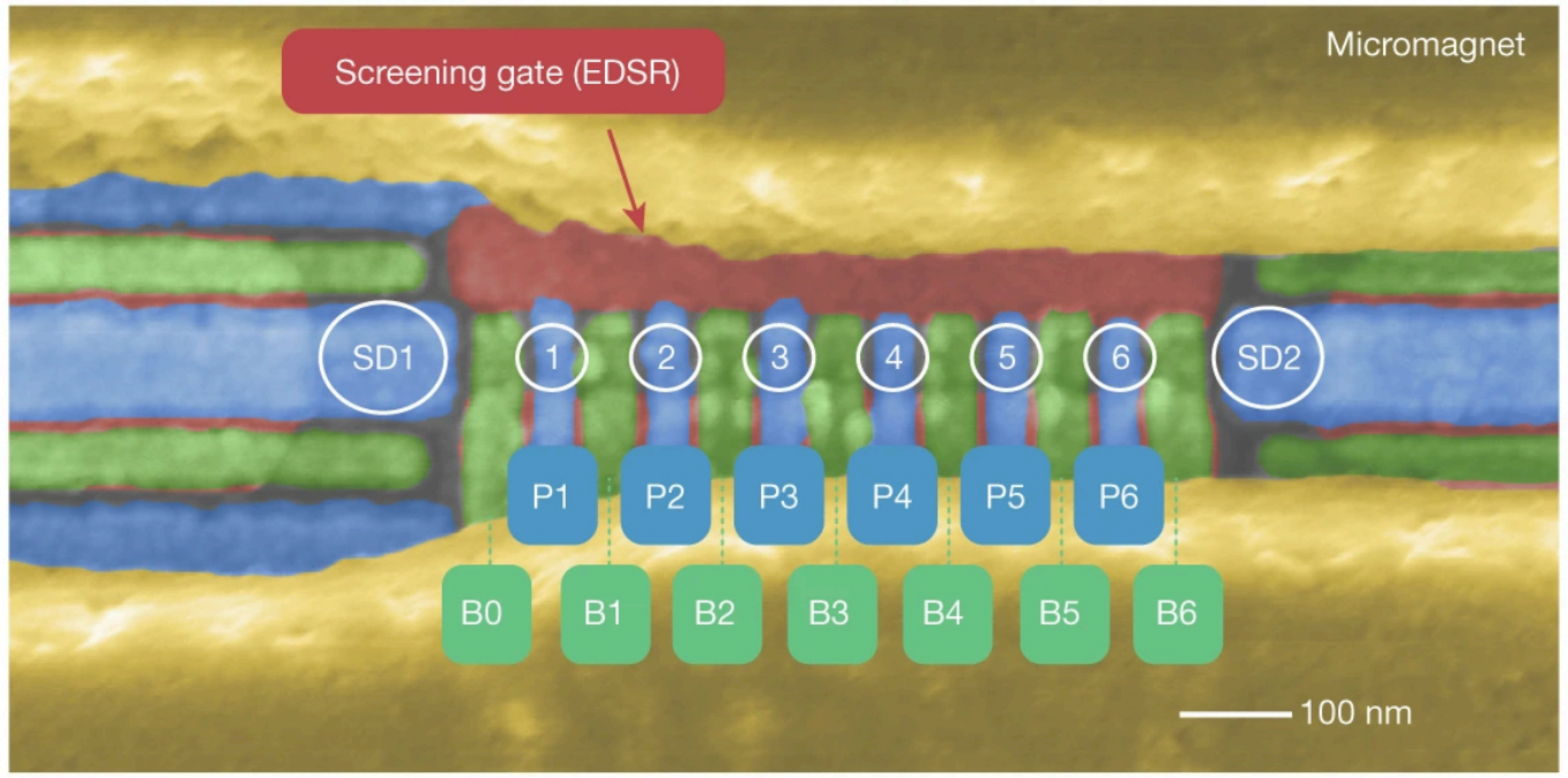

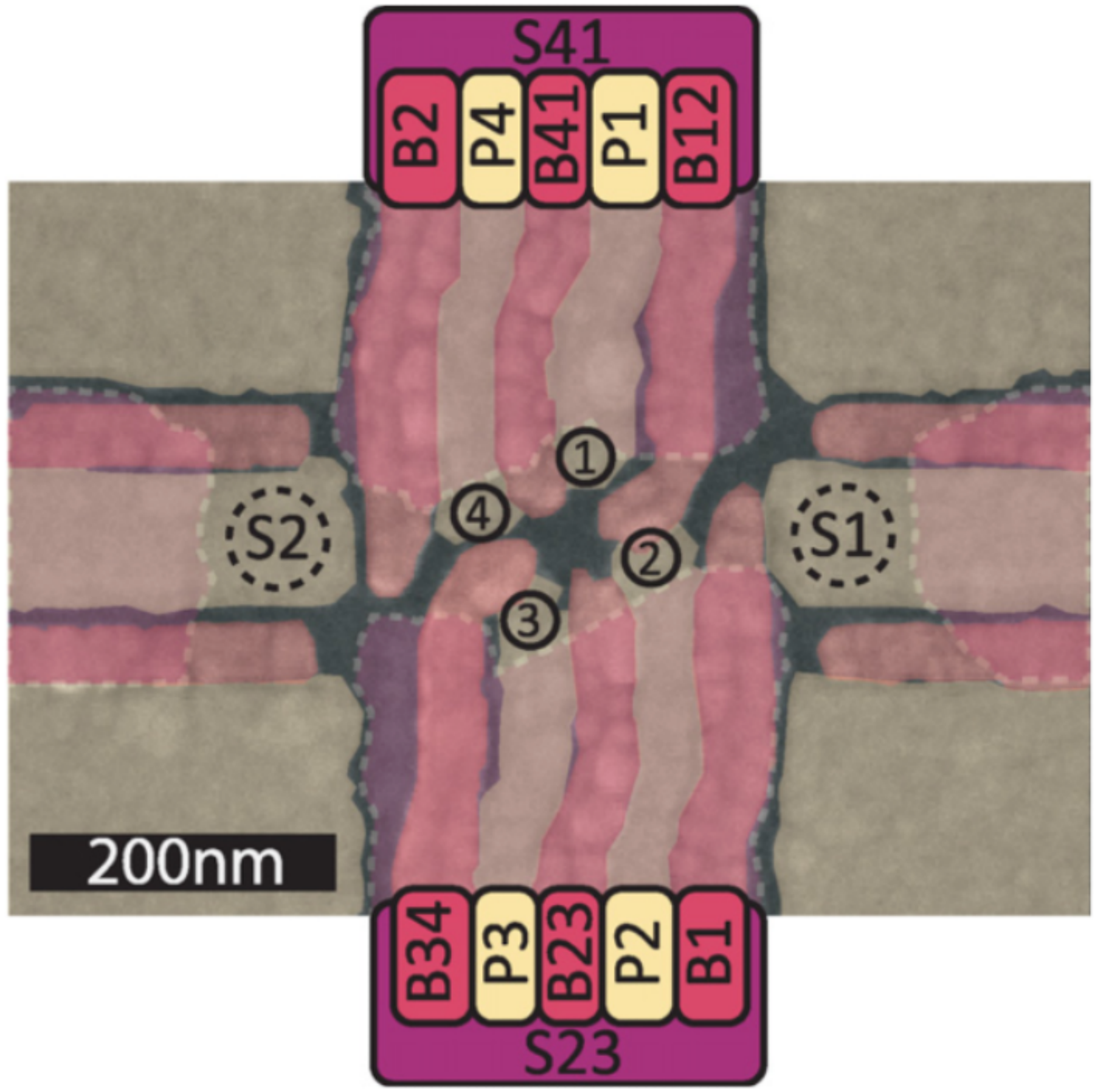

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Quantum Dots

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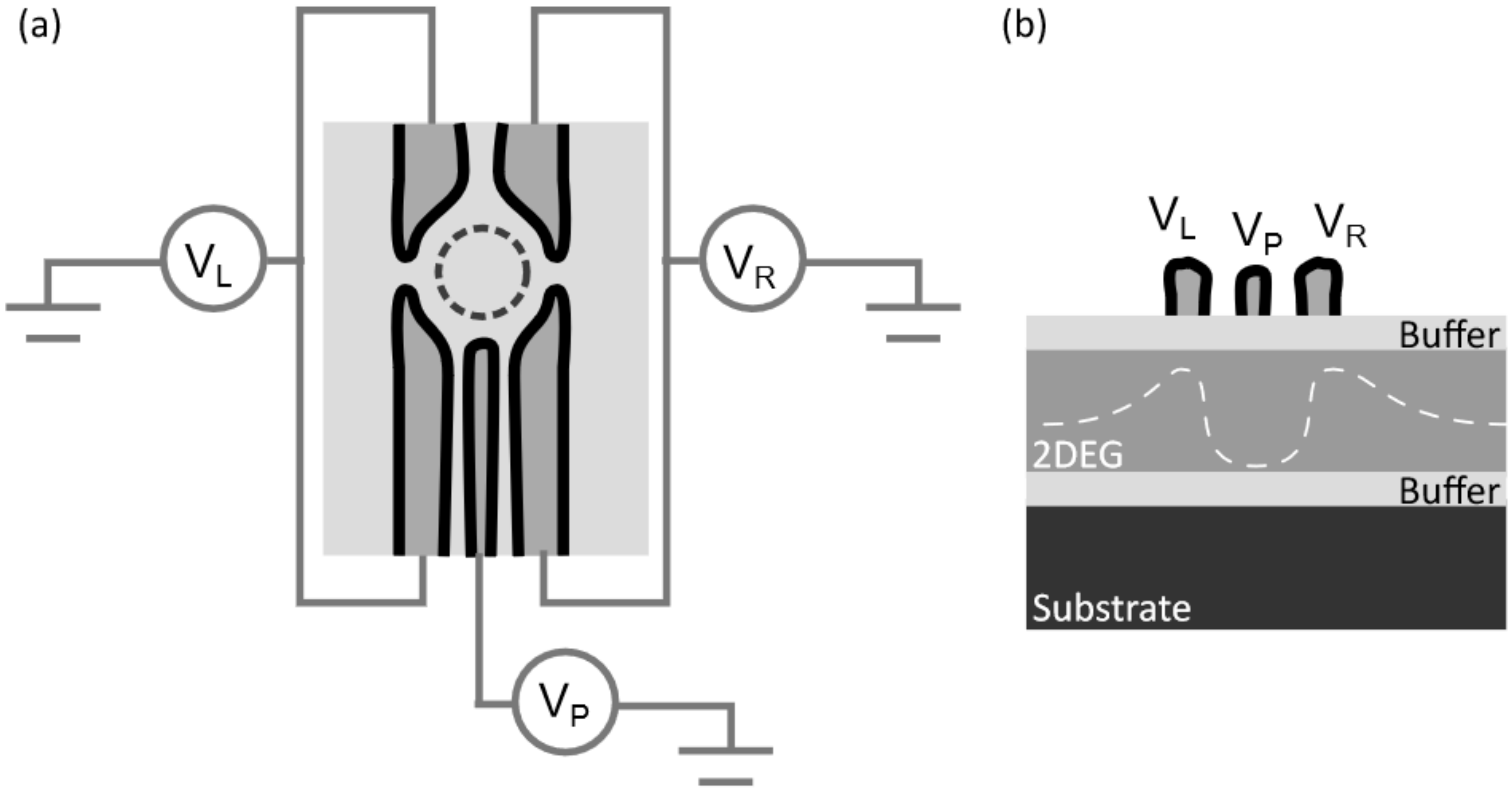

Andersen, Borregaard, Kjaergaard, Zinner, in preparation

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Automated calibration, control and readout of quantum systems

Tuning Engineered Quantum Materials

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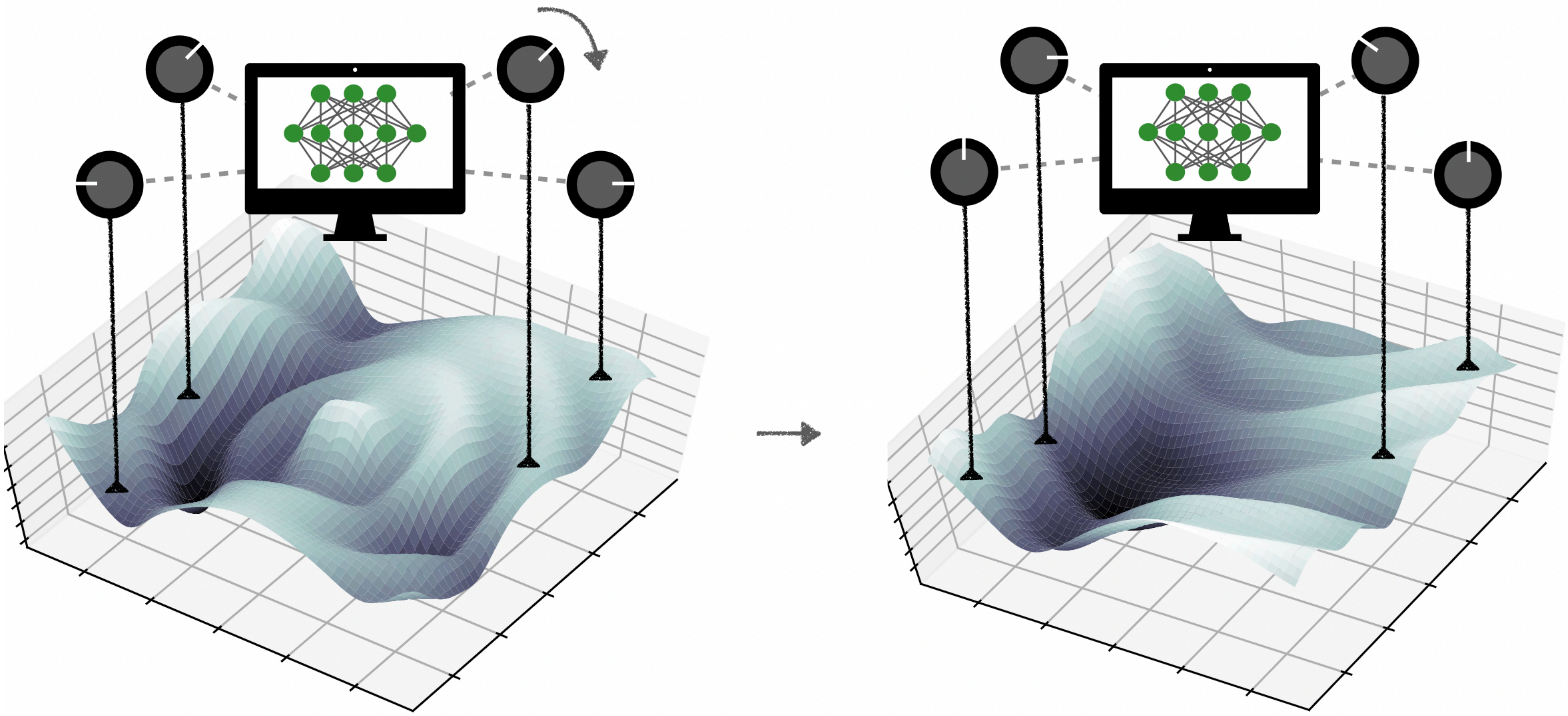
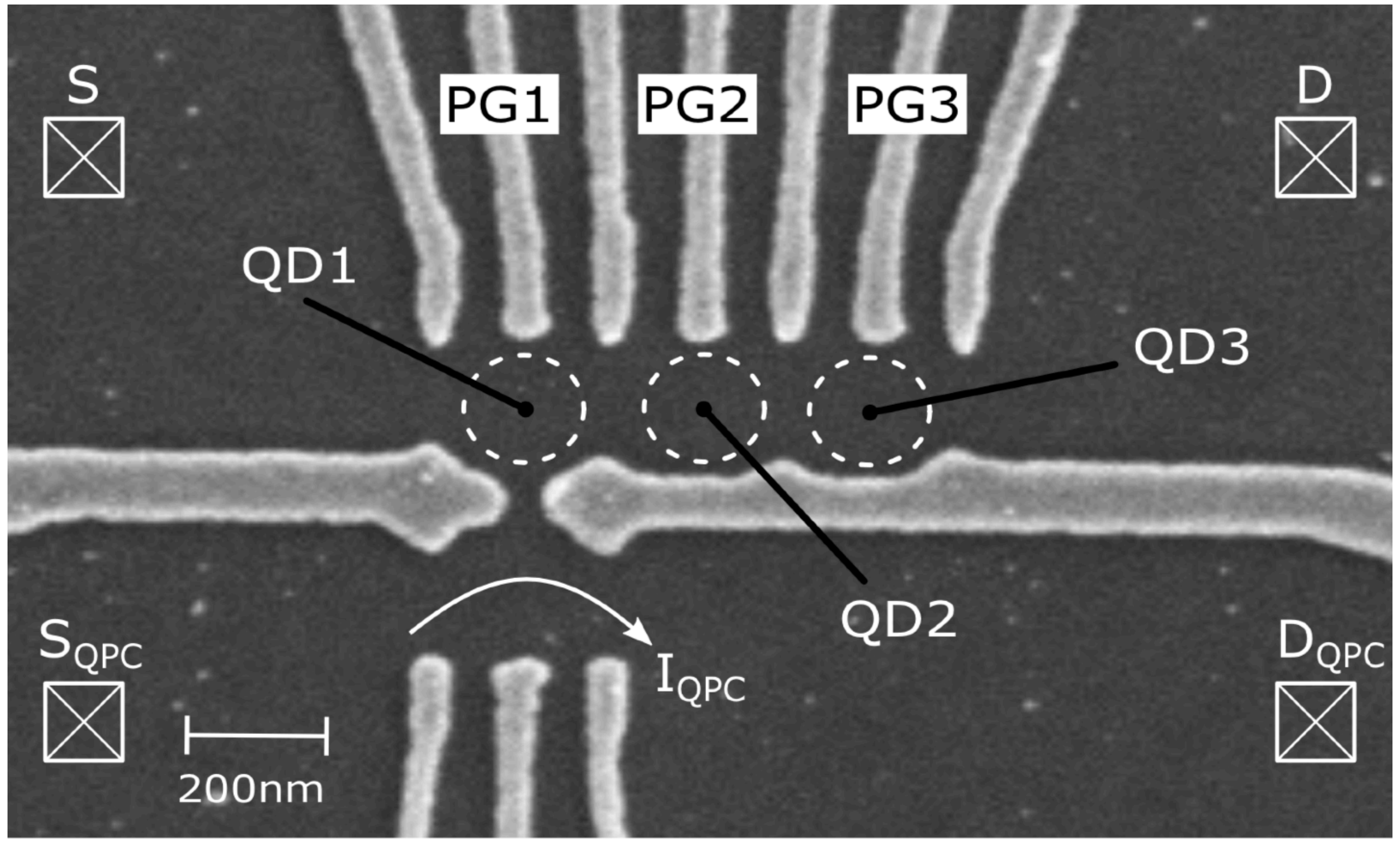
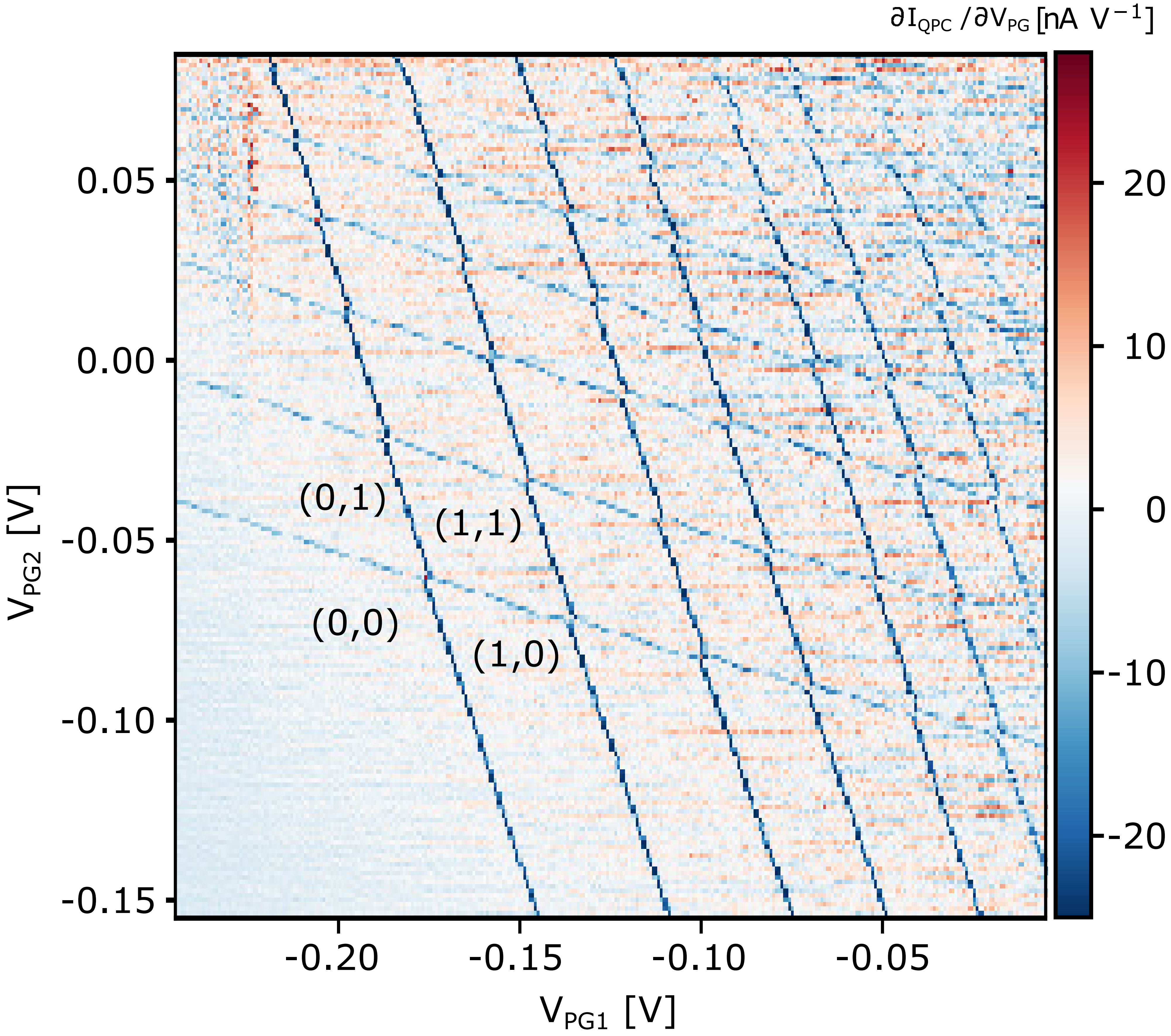


EG. "Solving optimization tasks in condensed matter." *Nature Machine Intelligence* 2.10 (2020): 557-558.

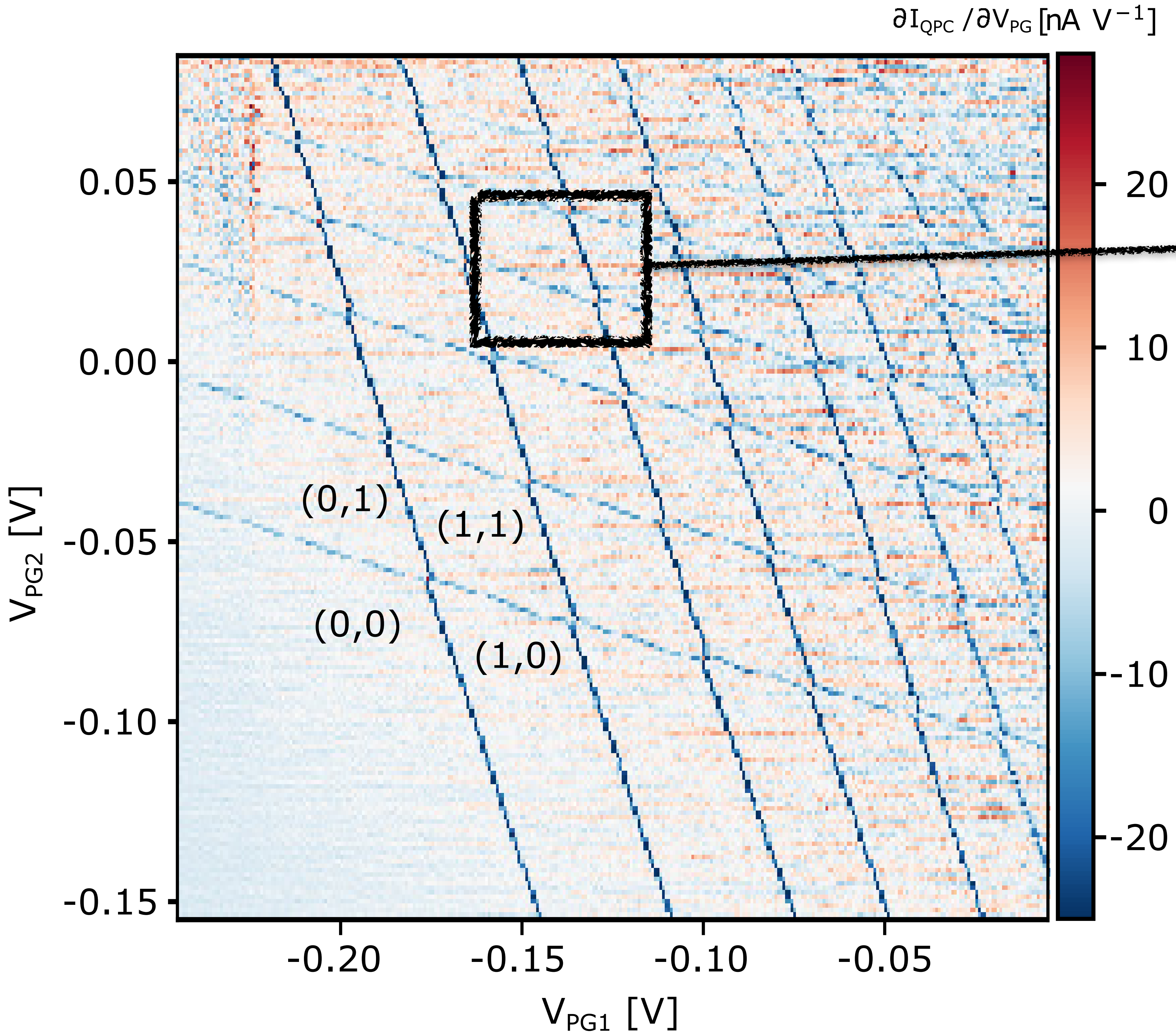
Automatic Tuning: Simple example

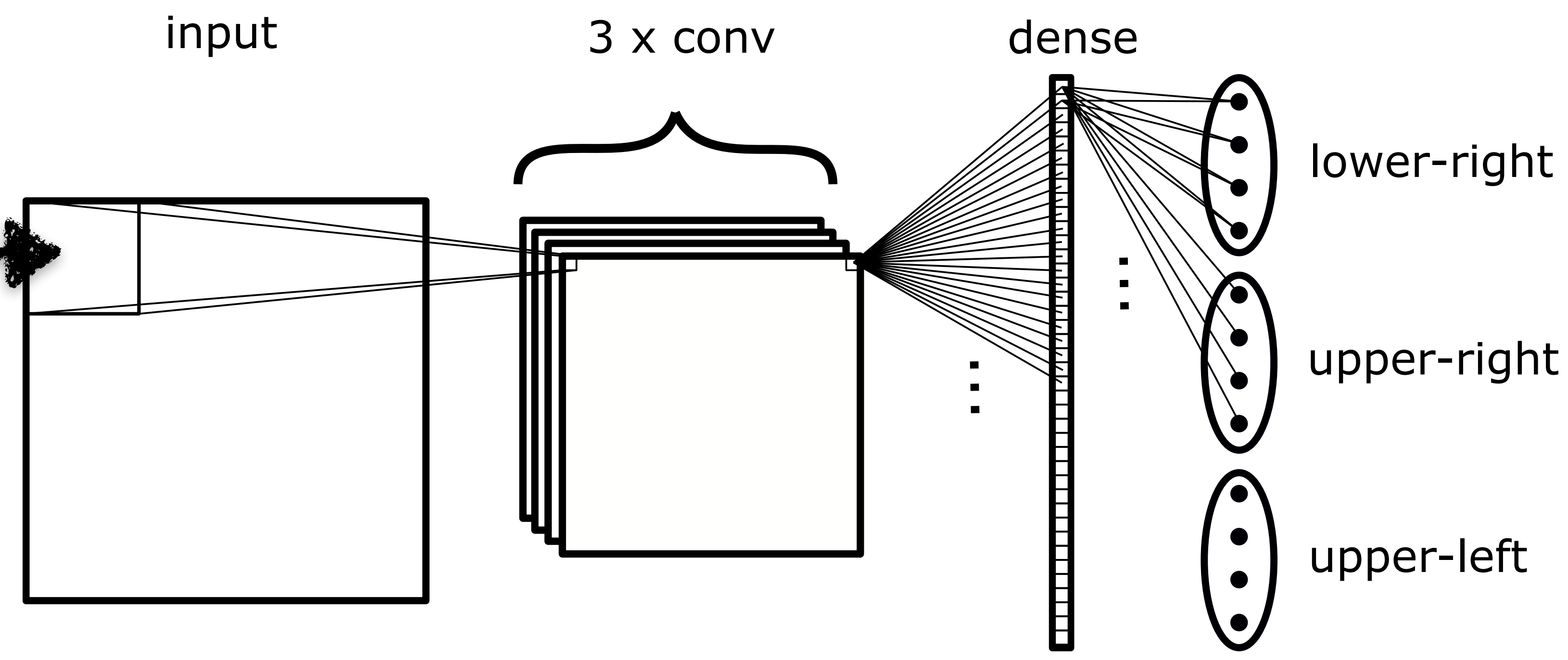


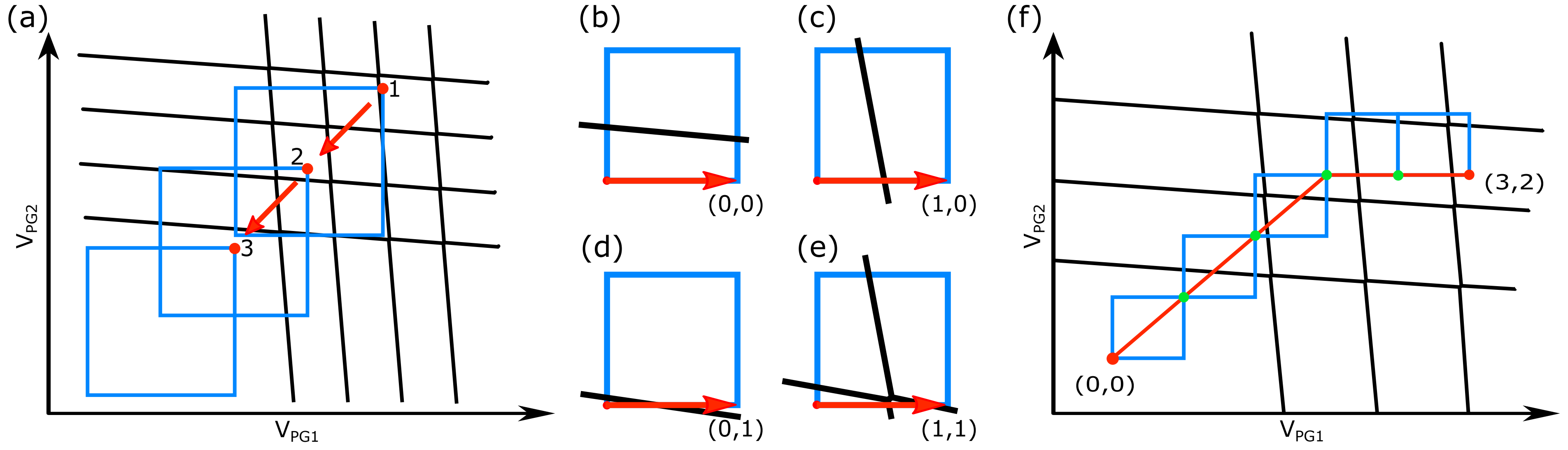


R Durrer, B Kratochwil, JV Koski, AJ Landig, C Reichl, W Wegscheider, T Ihn, **EG**, Phys. Rev. Applied 13, 054019 (2020)

Preparing Specific Charge States

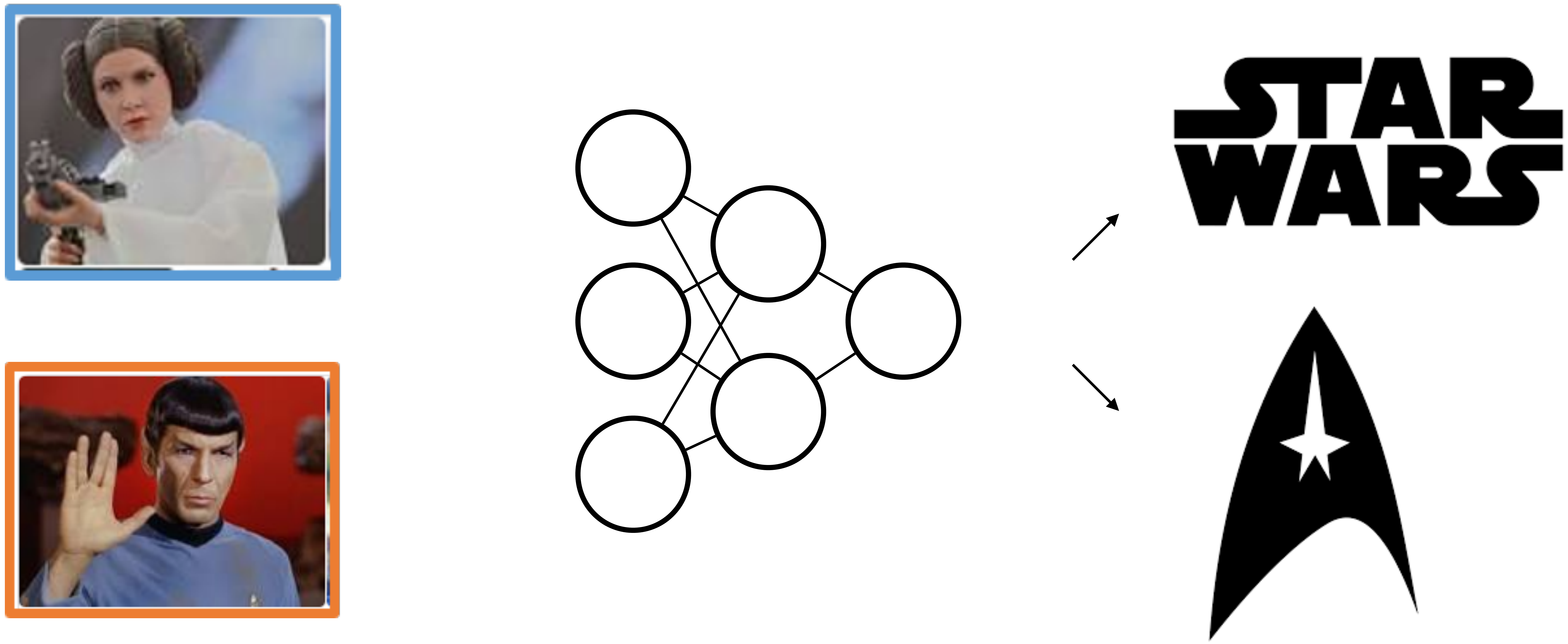




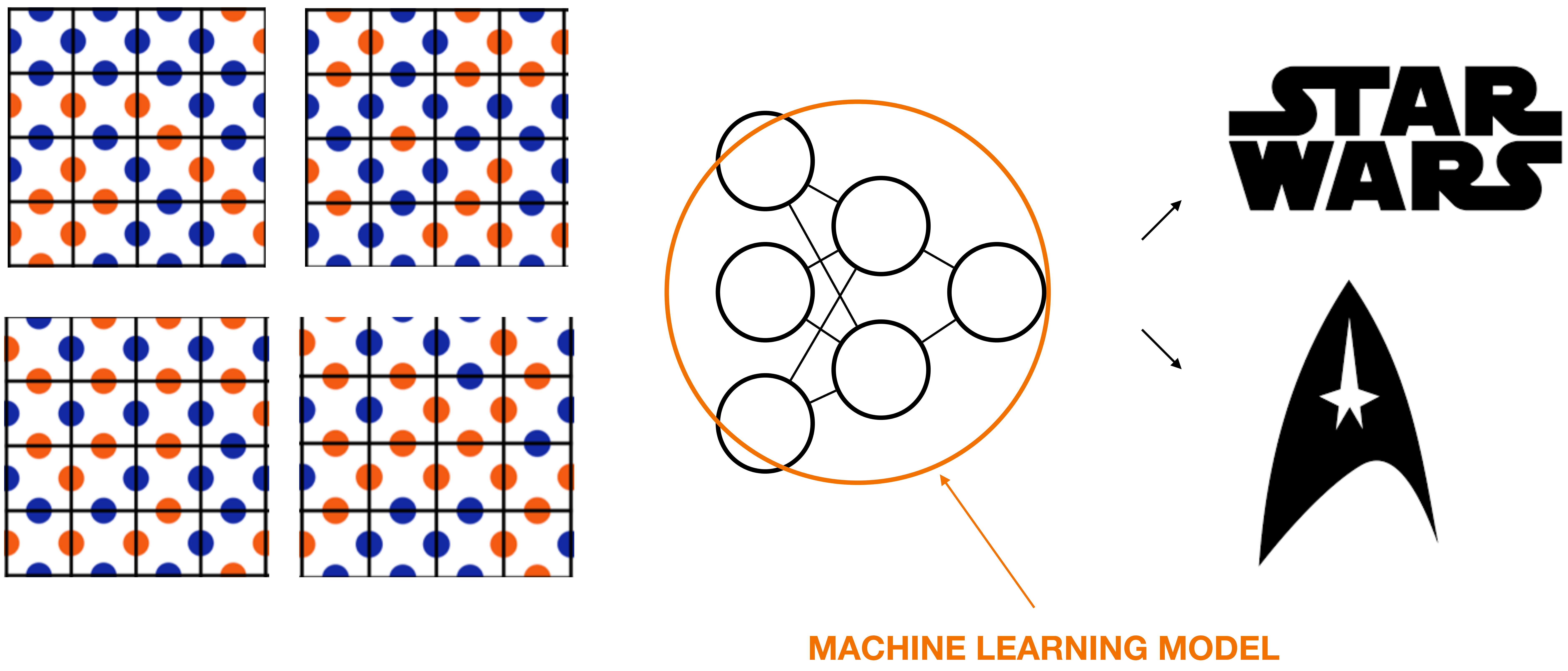


R Durrer, B Kratochwil, JV Koski, AJ Landig, C Reichl, W Wegscheider, T Ihn, **EG**, Phys. Rev. Applied 13, 054019 (2020)

AI Image Classification



AI Image Classification



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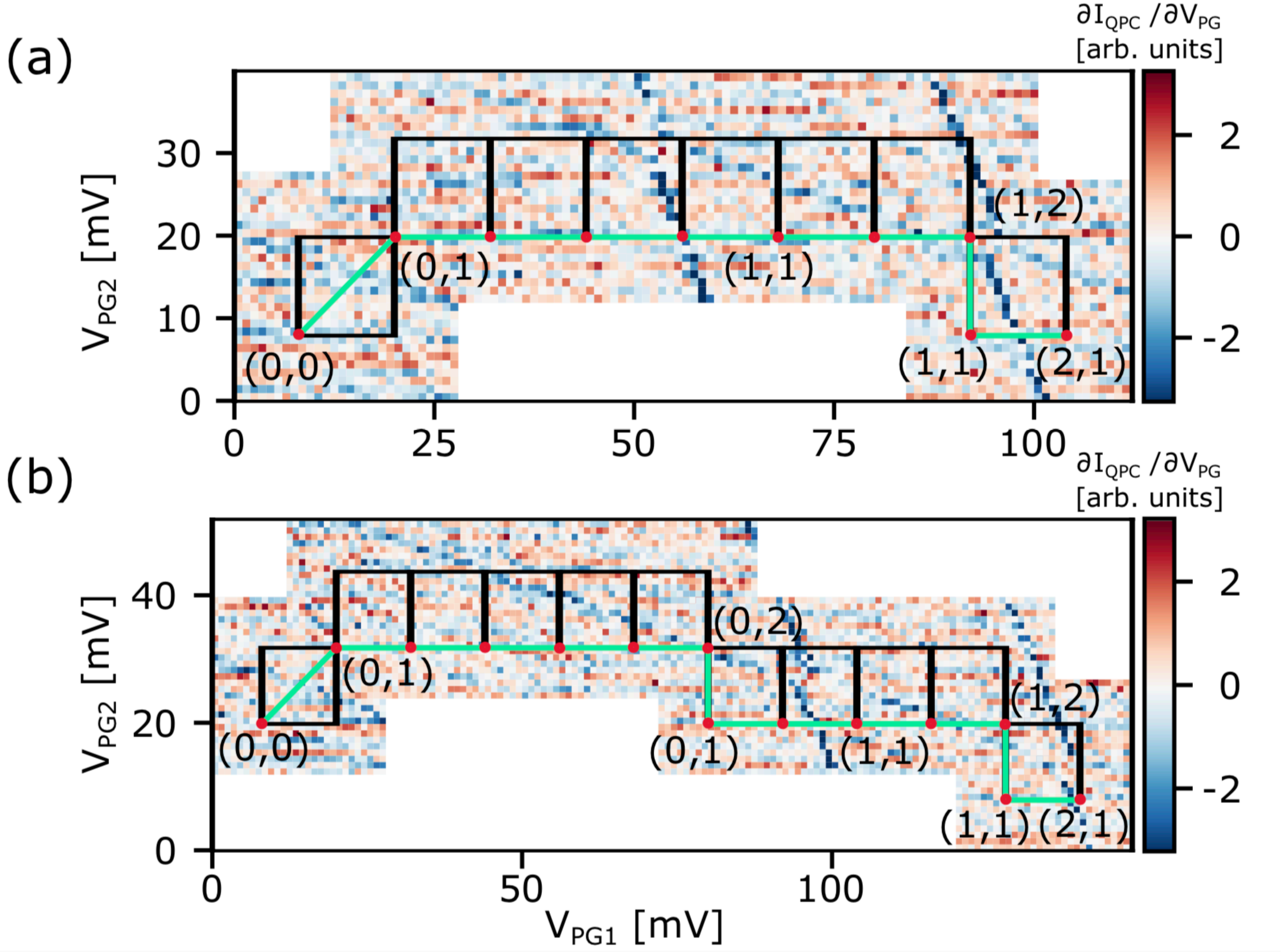
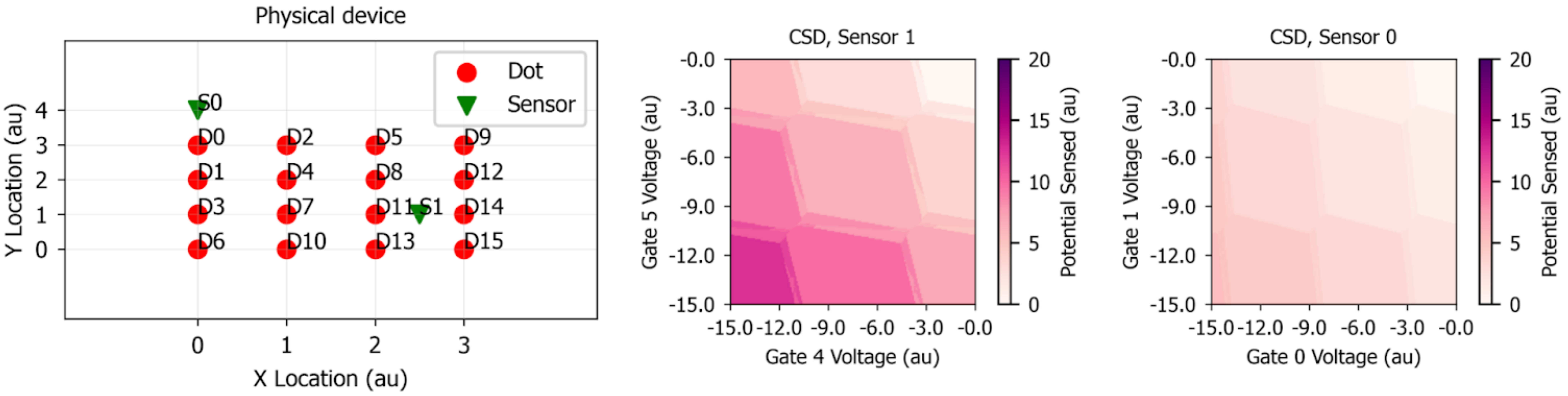
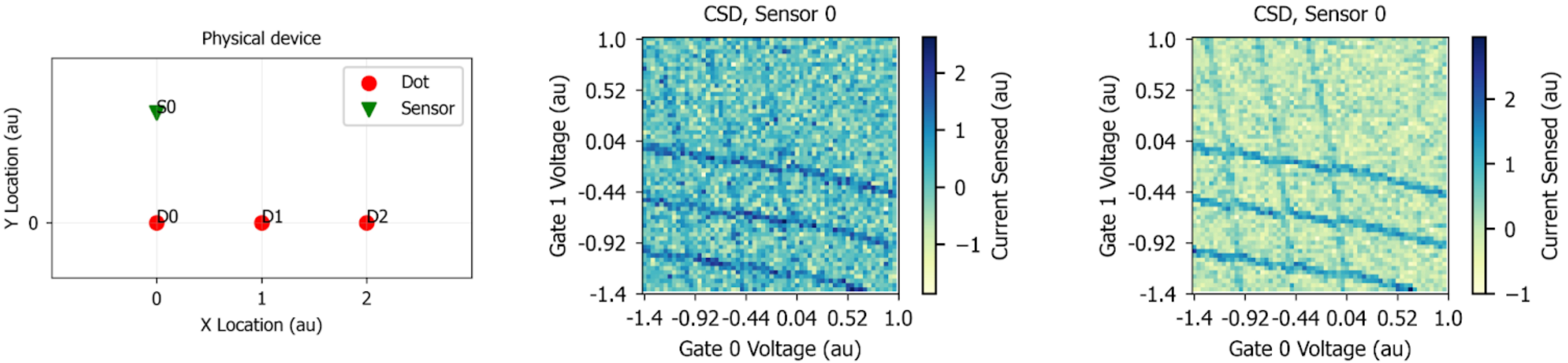
Tuning Runs on the Device



R Durrer, B Kratochwil, JV Koski, AJ Landig, C Reichl, W Wegscheider, T Ihn, **EG**, Phys. Rev. Applied 13, 054019 (2020)

QDsim: Simulator of arbitrary geometries





Gualtieri, Valentina, Hernandes, Vinicius, Renshaw, Charles and **EG**. “QDSim: Quantum Dot Array Simulation package.” arXiv:2404.02712(2024), to appear in SciPost Physics.

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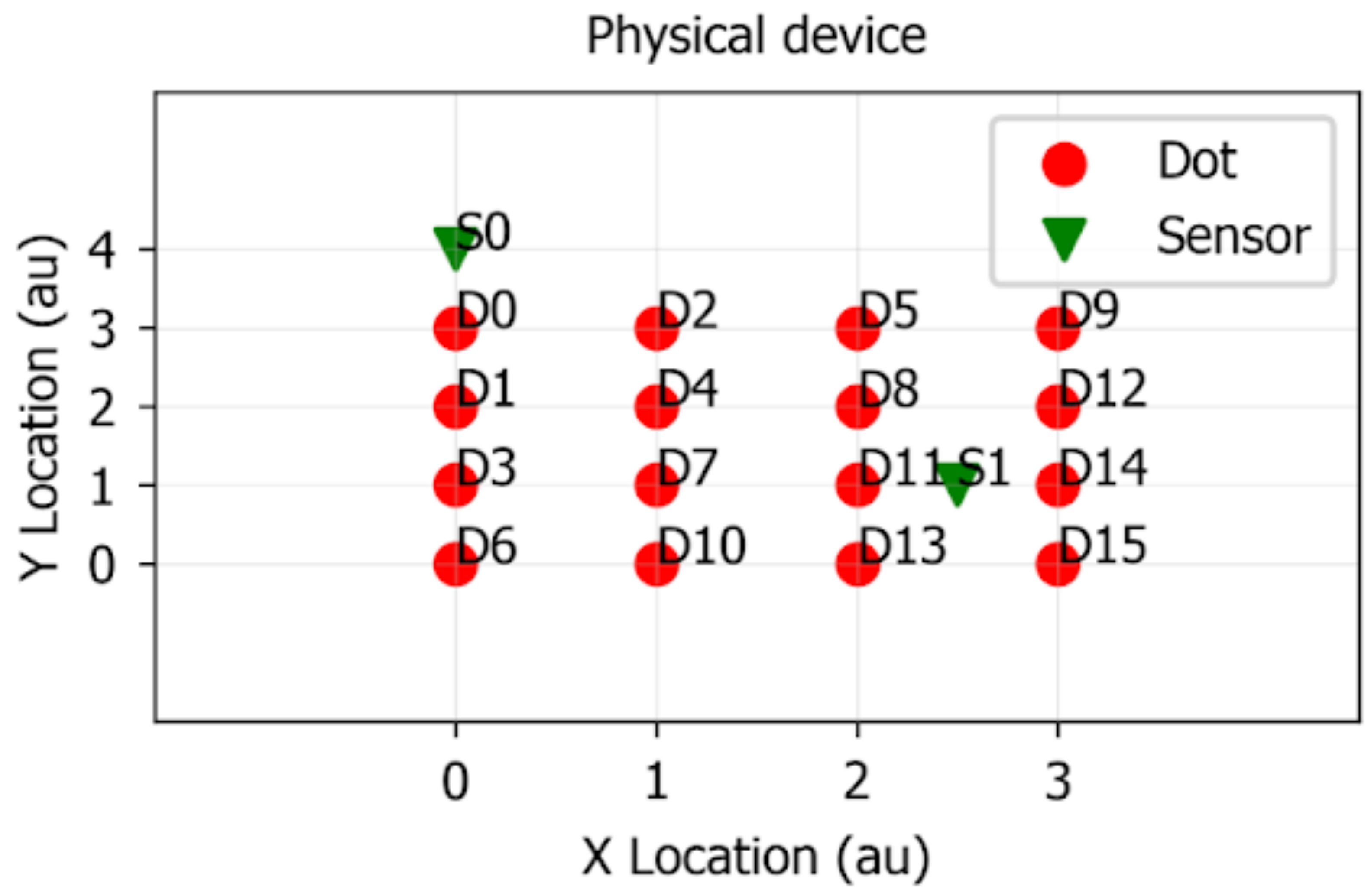
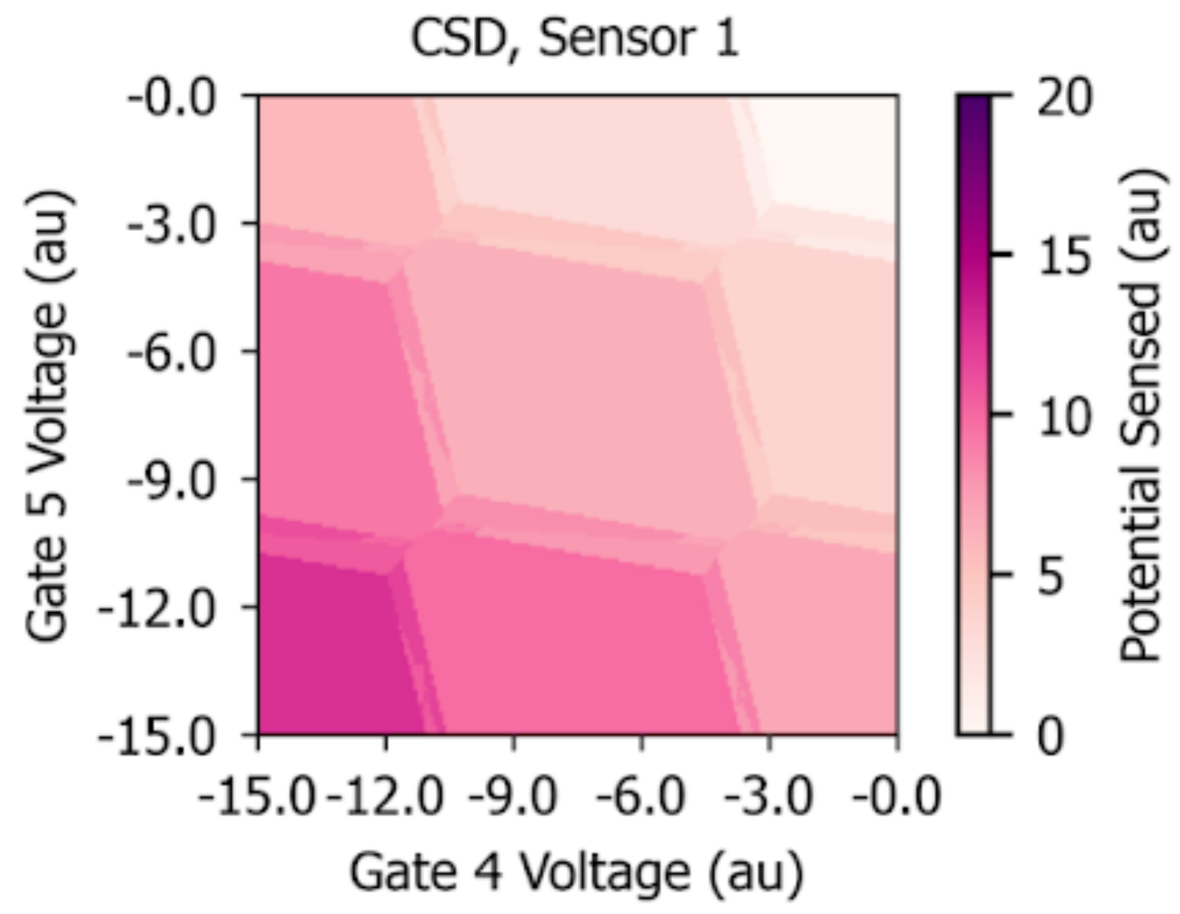
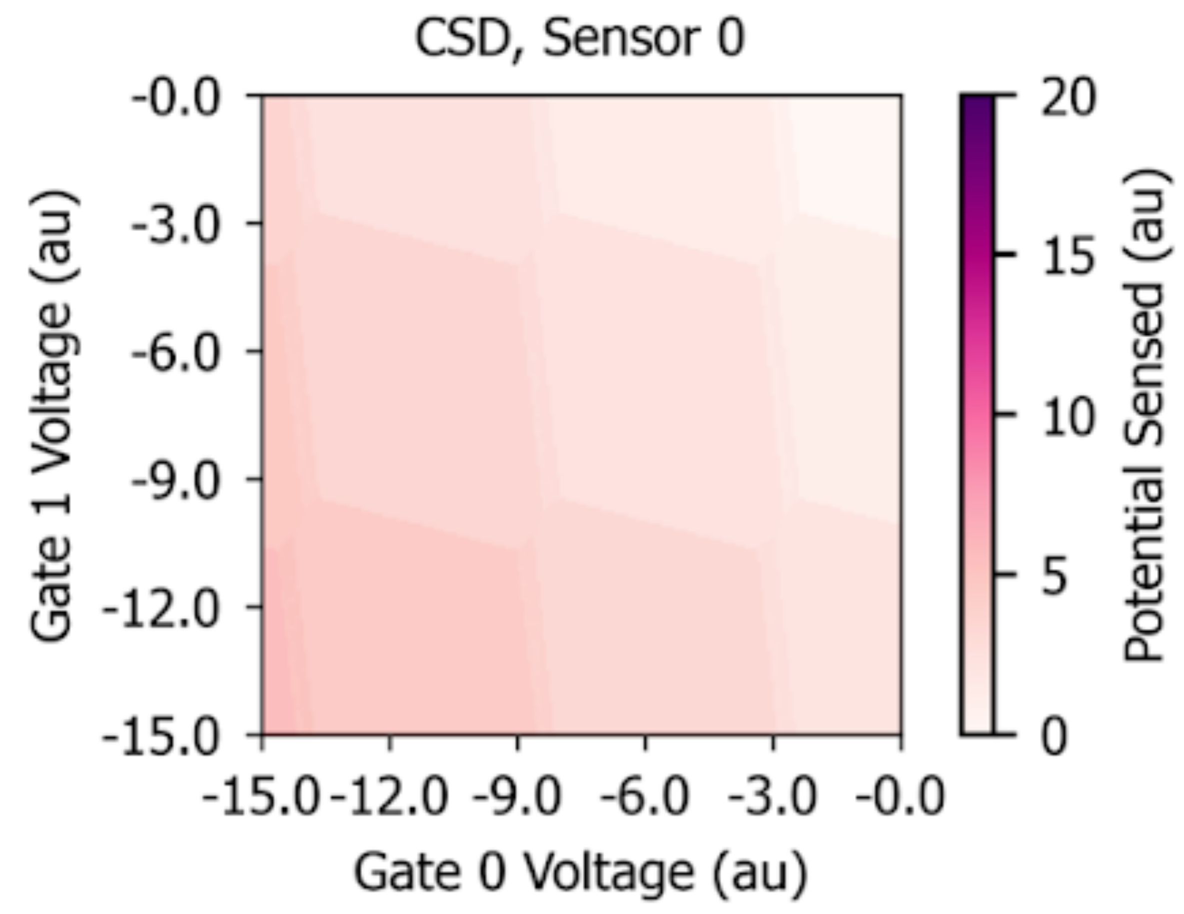
QDsim: Simulator of arbitrary geometries







CONSTANT INTERACTION MODEL → MINIMIZE ENERGY → CONVEX OPTIMIZATION PROBLEM

pip install qdsim

Gualtieri, Valentina, Hernandes, Vinicius, Renshaw, Charles and **EG**. “QDSim: Quantum Dot Array Simulation package.” arXiv:2404.02712(2024), to appear in SciPost Physics.

Modern Techniques: Use diffusion and measure less!

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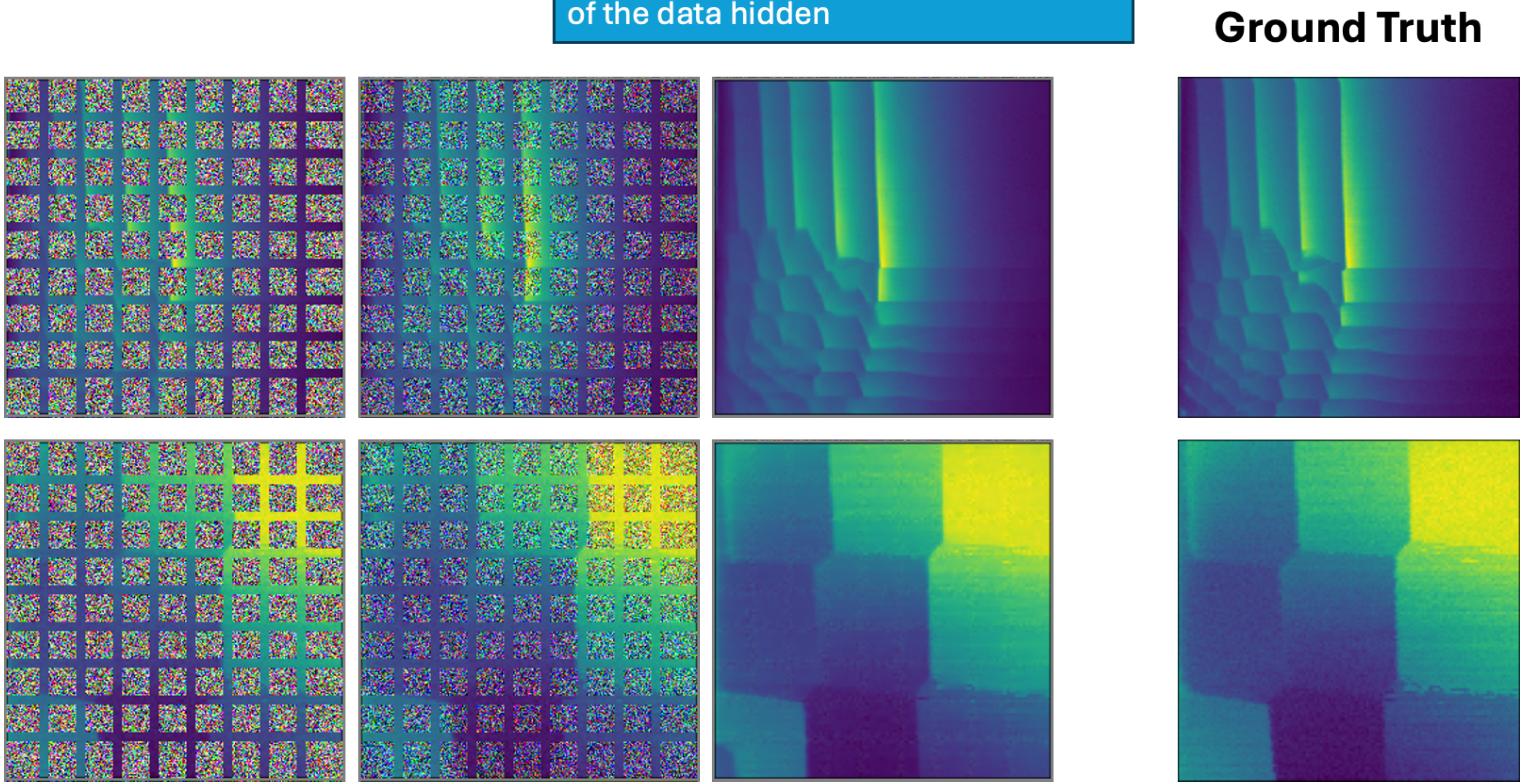
On average, 91% accuracy with 61% of the data hidden



“Can we move beyond direct ML image recognition?”

Bottleneck: Readout

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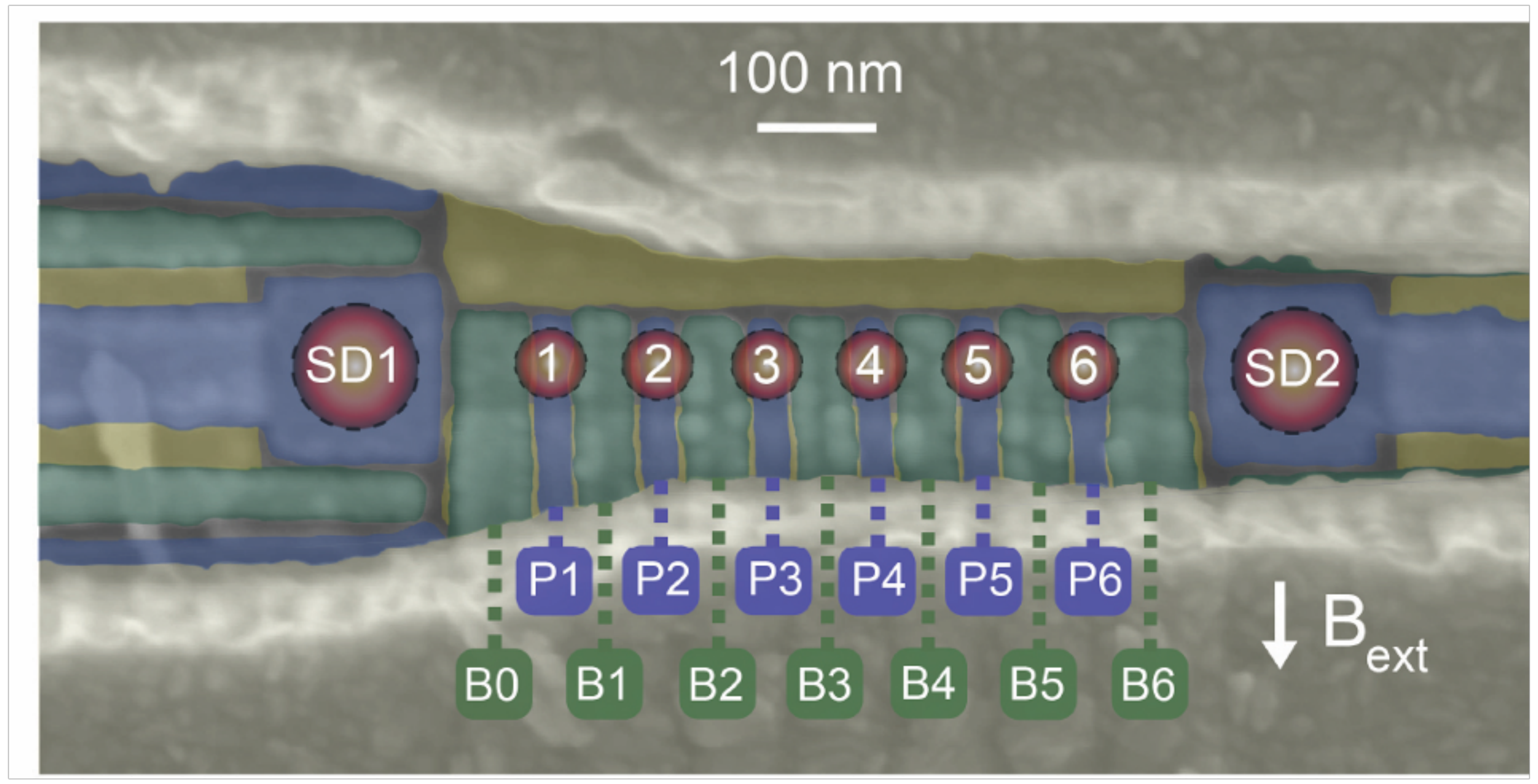

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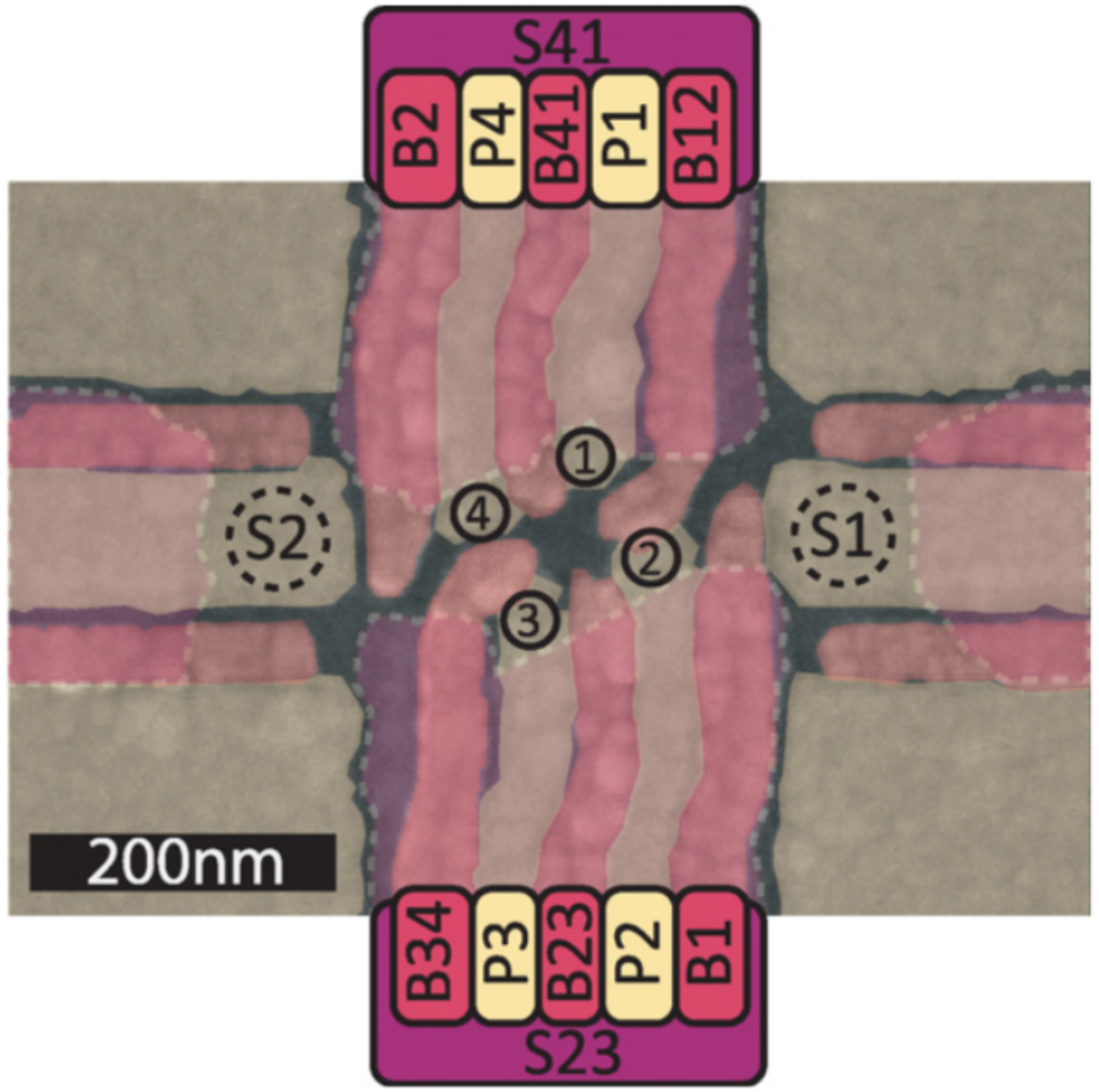
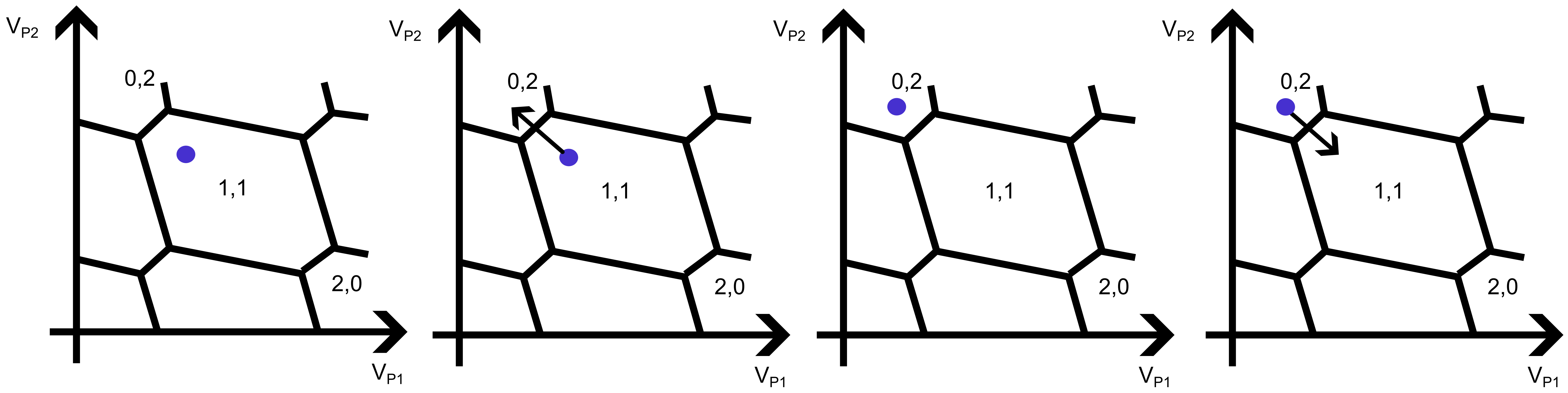


Unseld, F.K., Meyer, M., Mądzik, M.T., Borsoi, F., de Snoo, S.L., Amitonov, S.V., Sammak, A., Scappucci, G., Veldhorst, M. and Vandersypen, L.M., 2023. A 2D quantum dot array in planar 28Si/SiGe. *Applied Physics Letters*, *123*(8).





Pauli Spin Blockade readout



Pauli Spin Blockade readout

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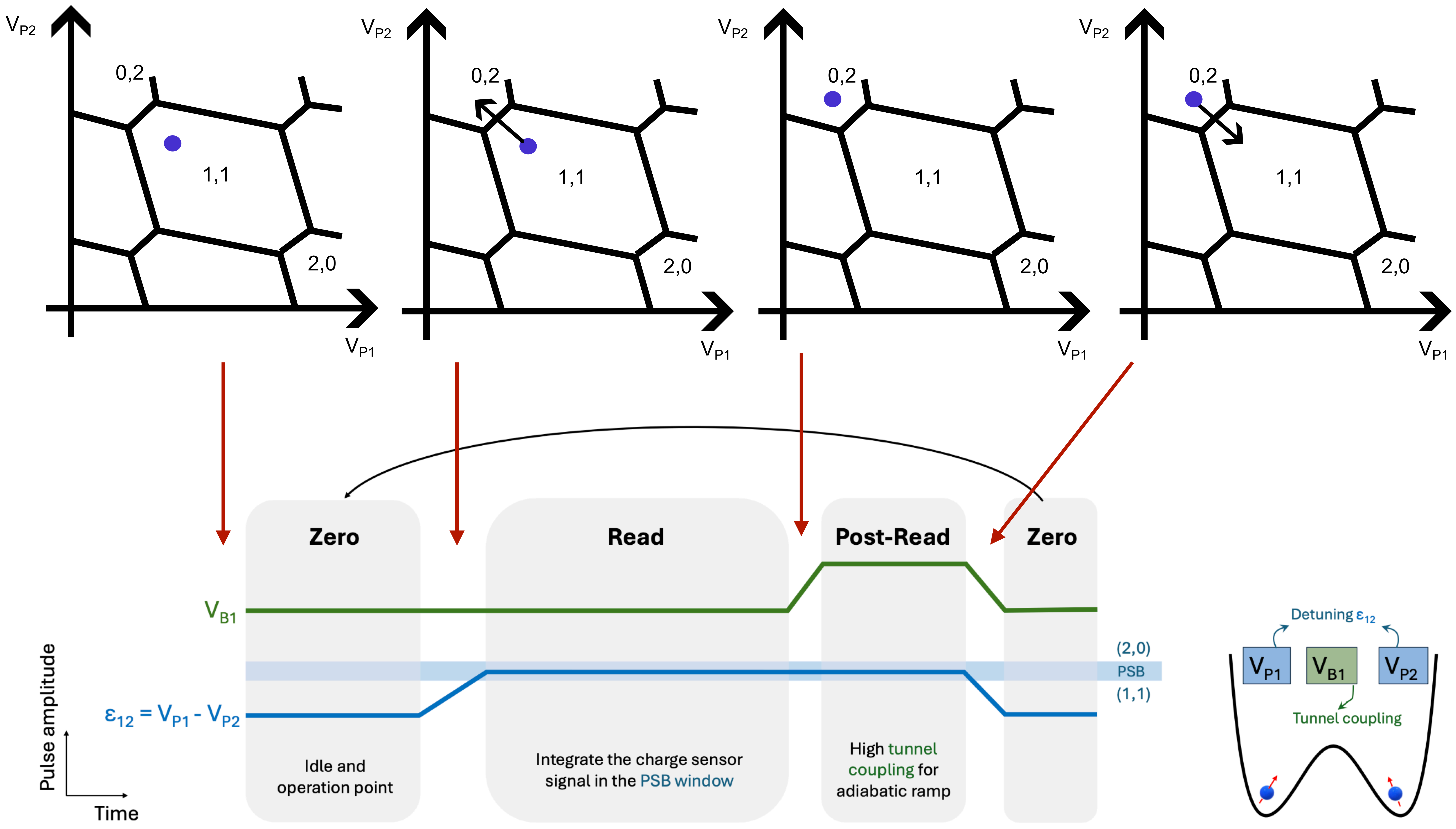
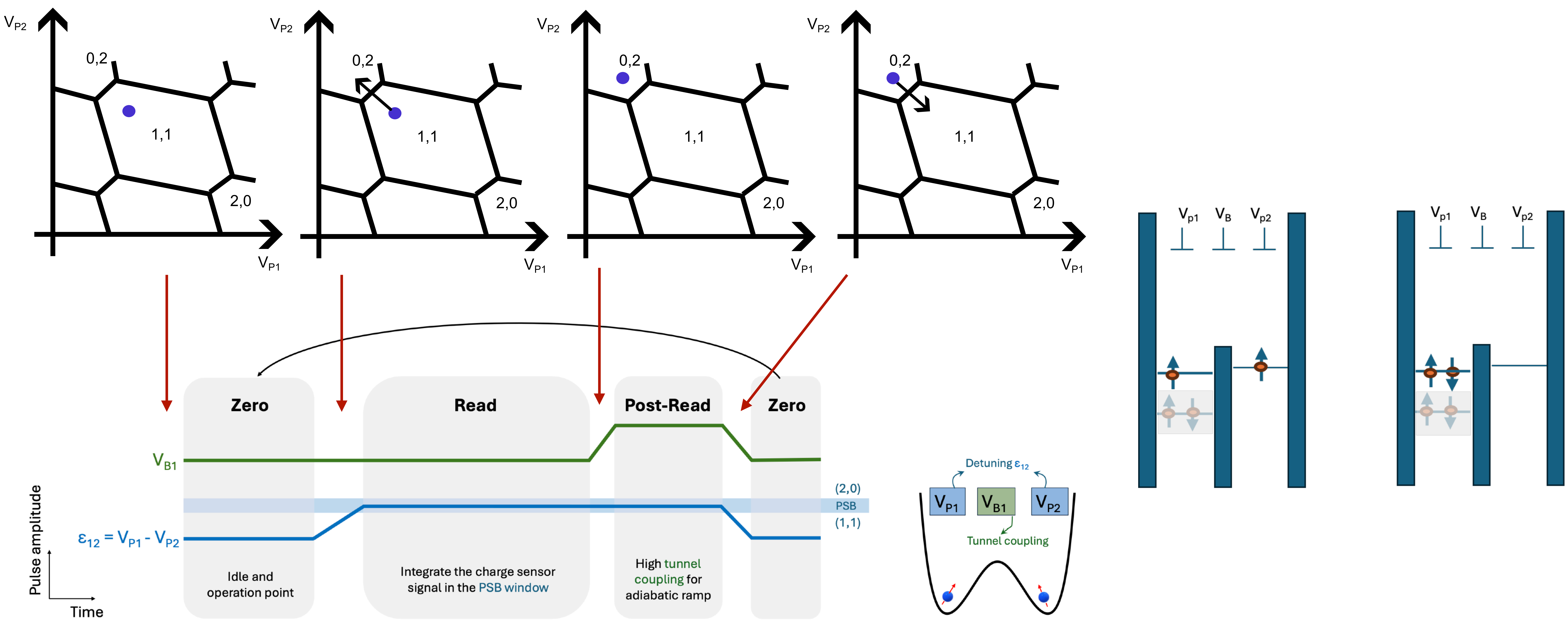


Pauli Spin Blockade readout



Optimizing the readout sequence

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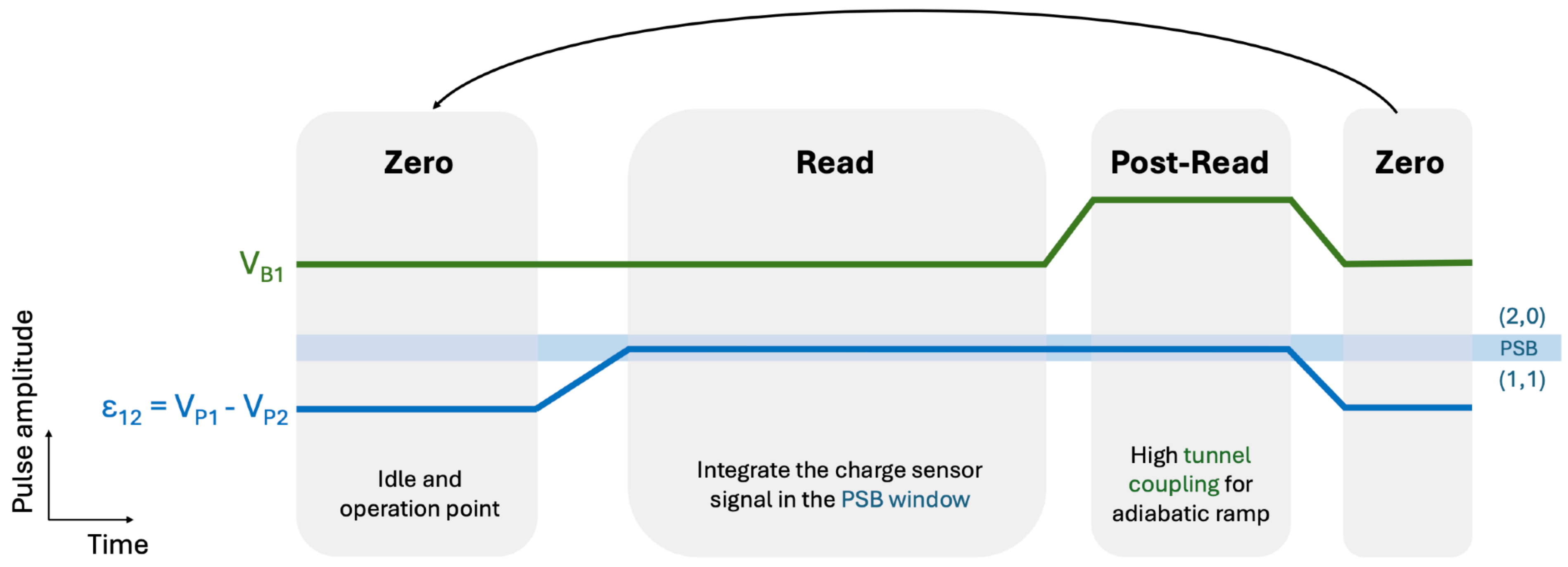
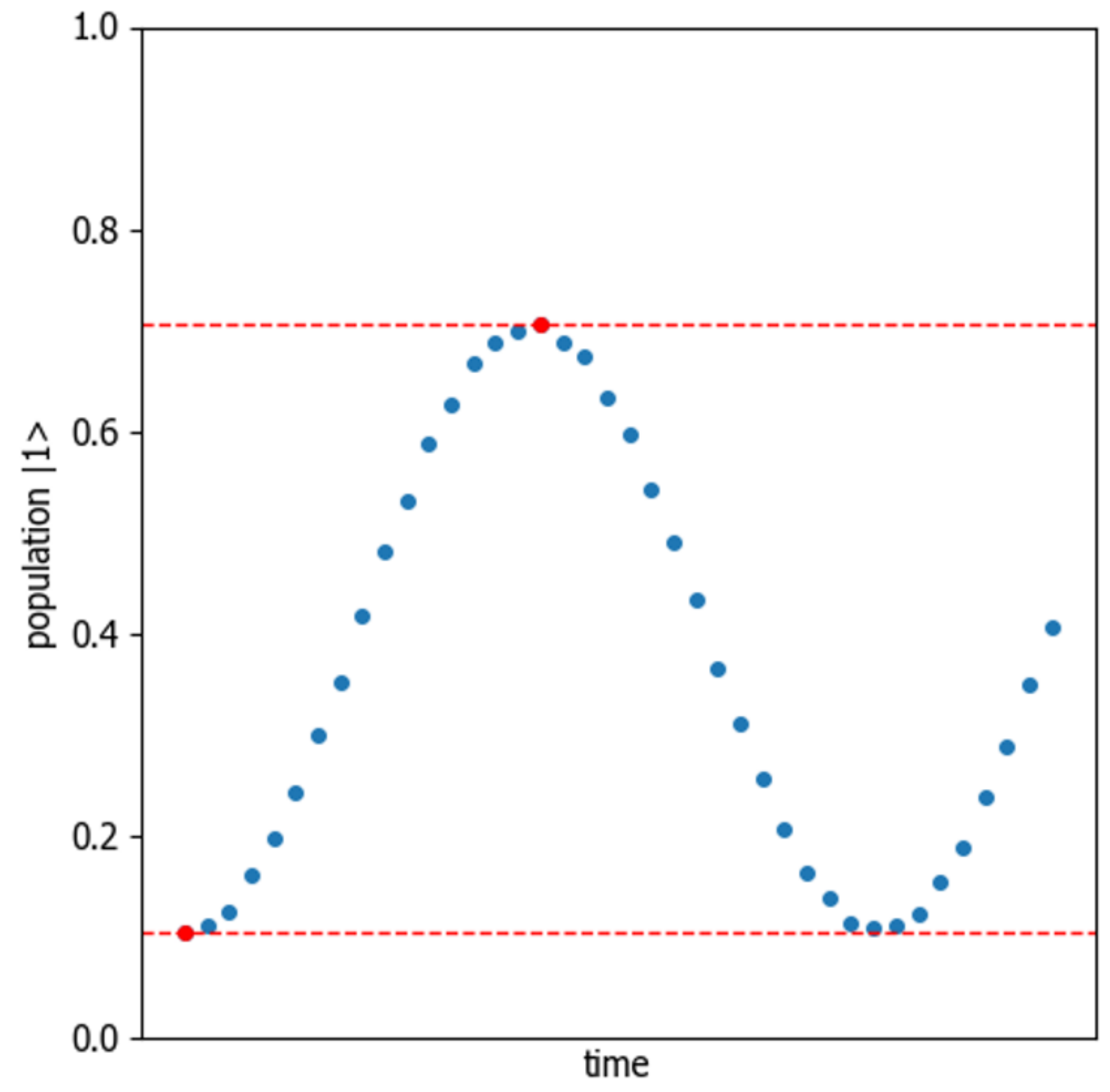
Voltages and ramp times as optimisation parameters



The Algorithm



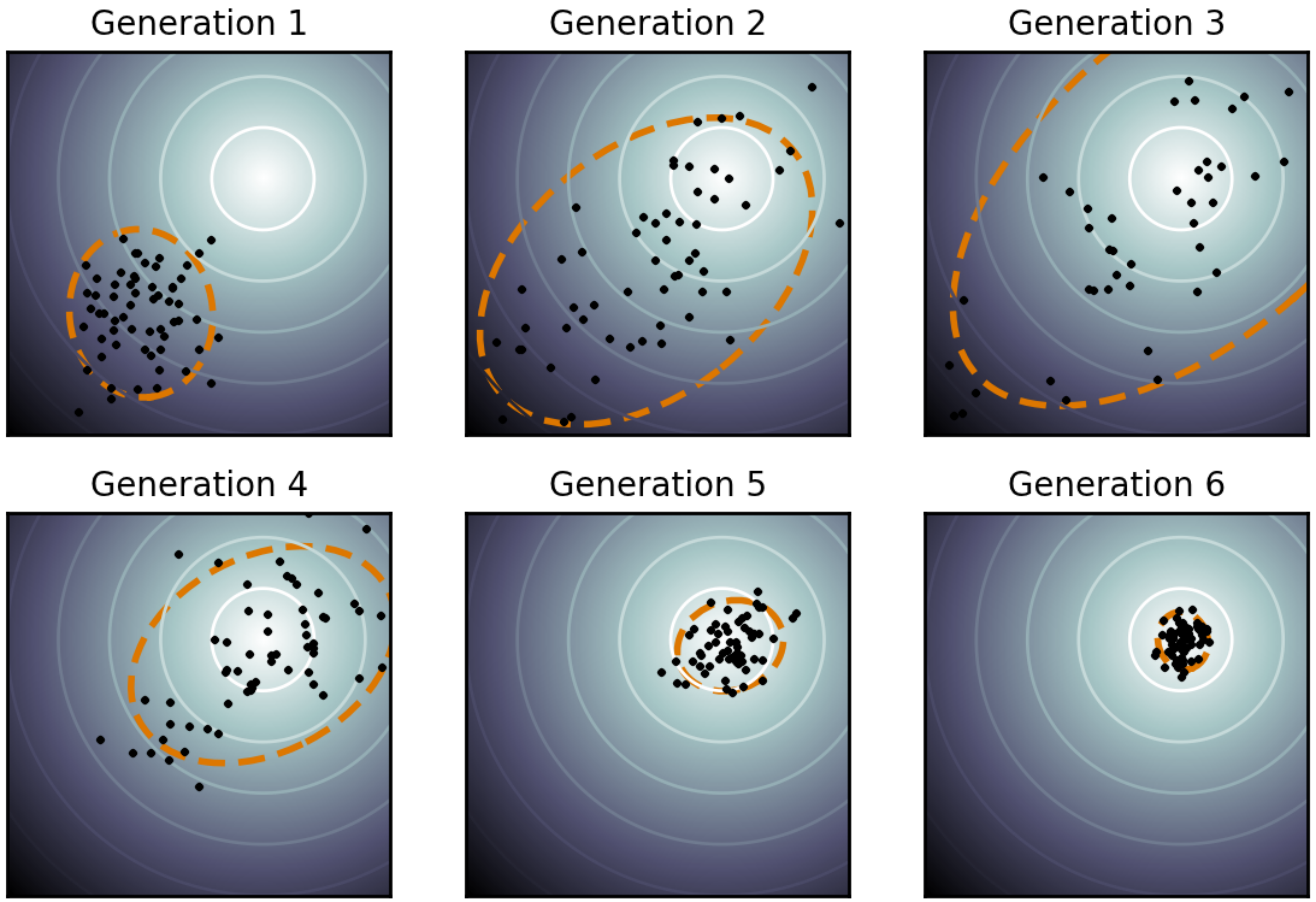
Readout visibility

(measure |0⟩ | initialize |0⟩) - (measure |0⟩ | initialize |0⟩ + π-pulse)

The algo: CMA-ES

Covariance matrix adaptation evolution strategy

- Global optimisation
- Gradient free genetic algorithm
- Covariance matrix stores correlations



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Optimising visibility

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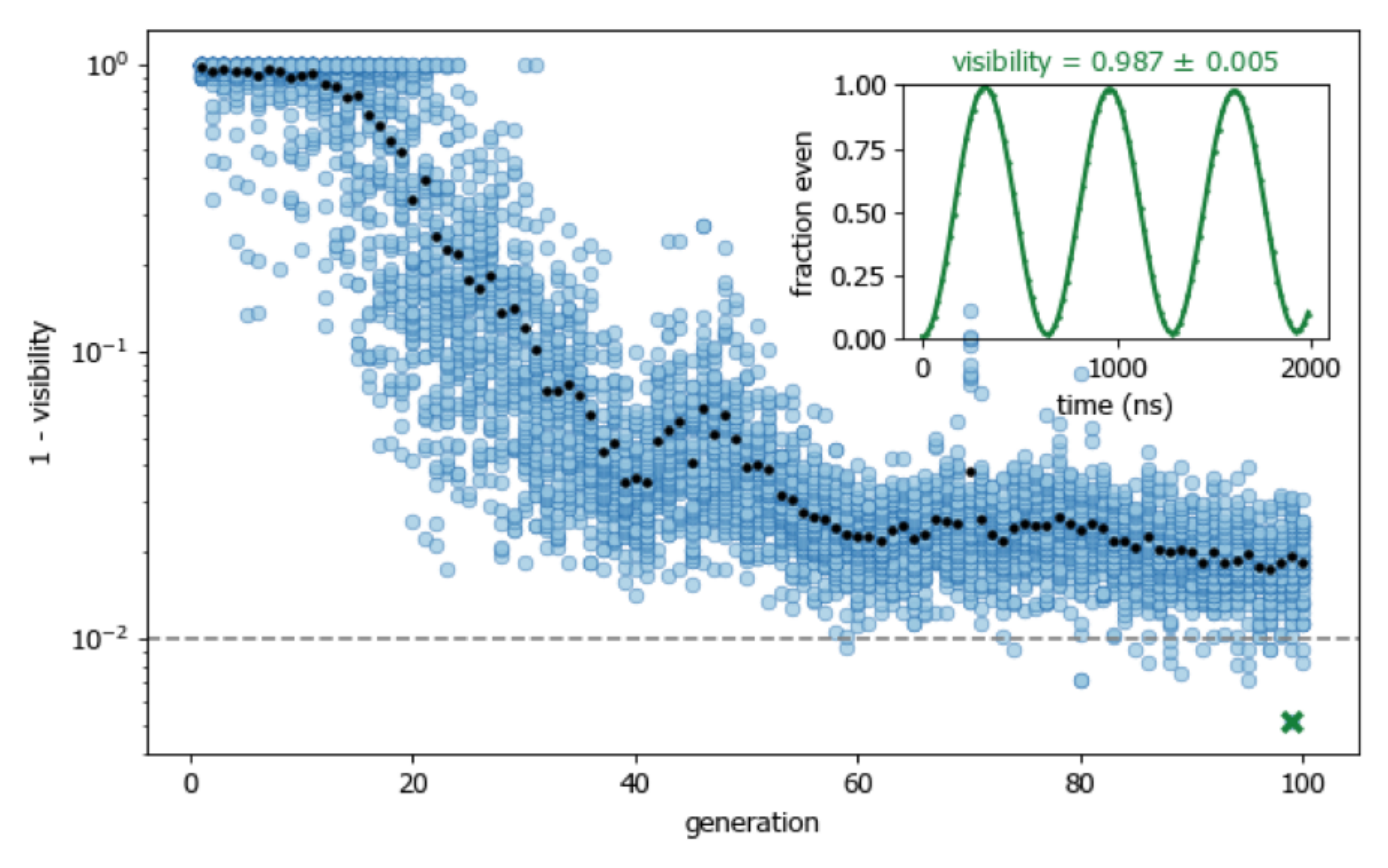
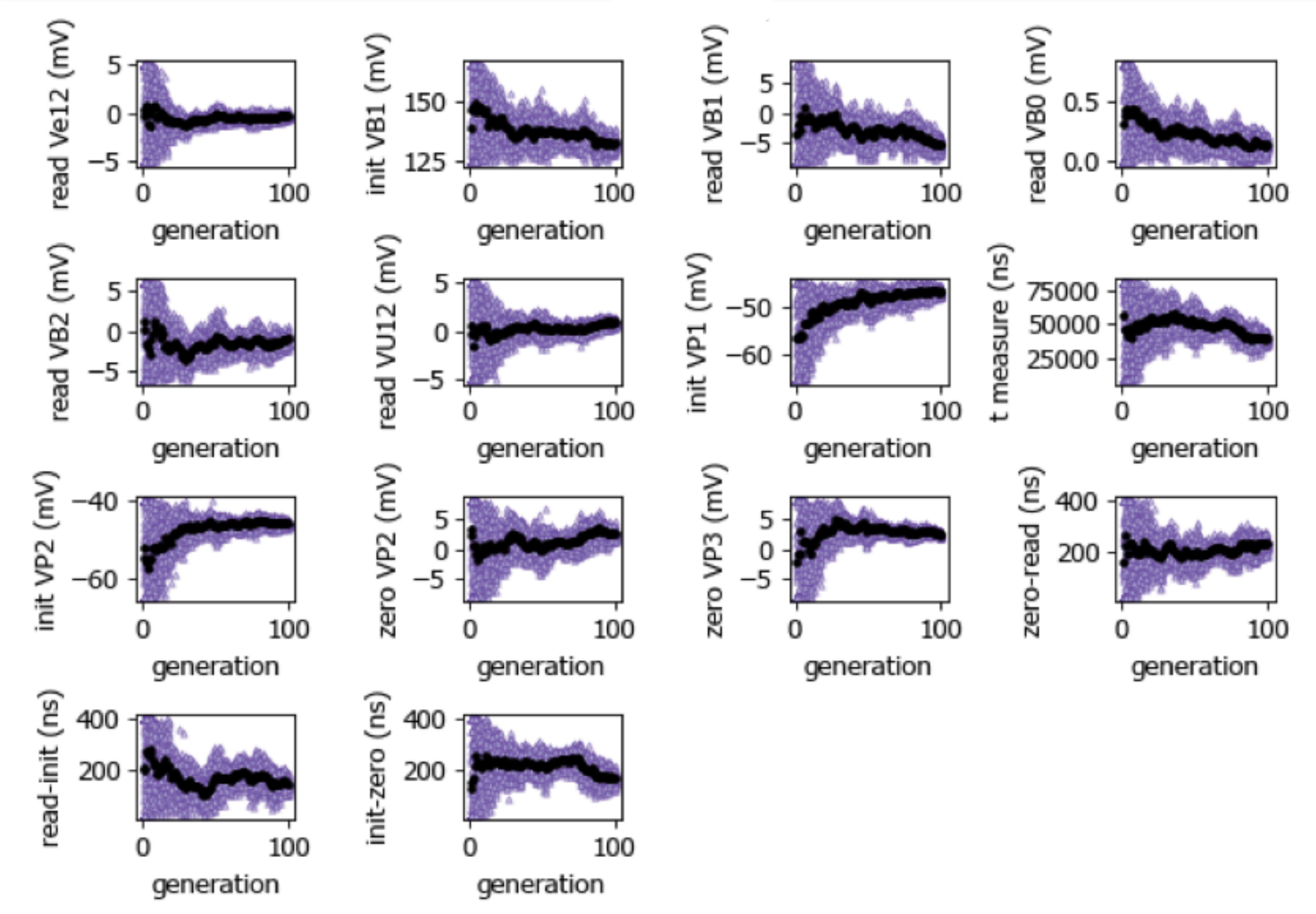
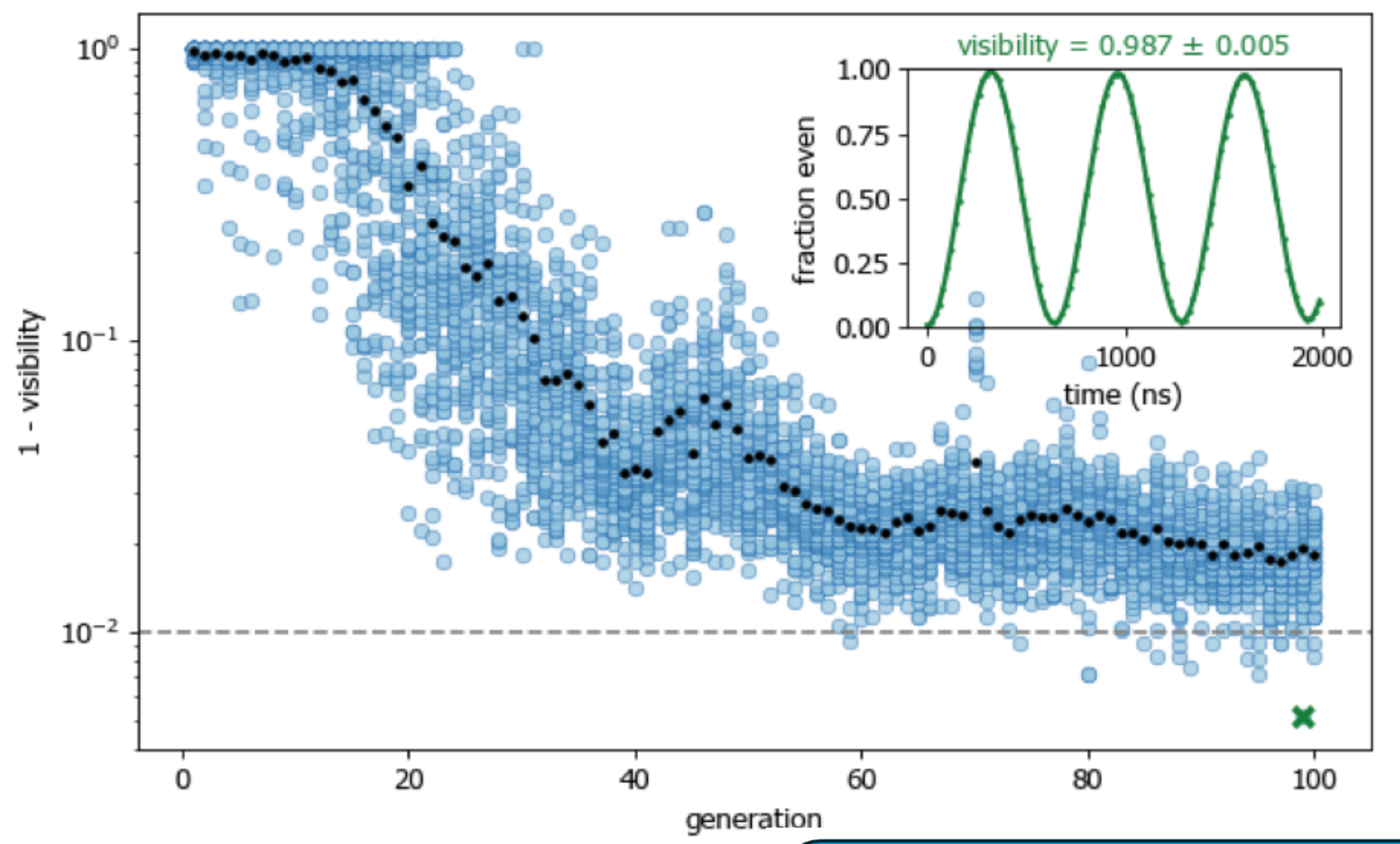
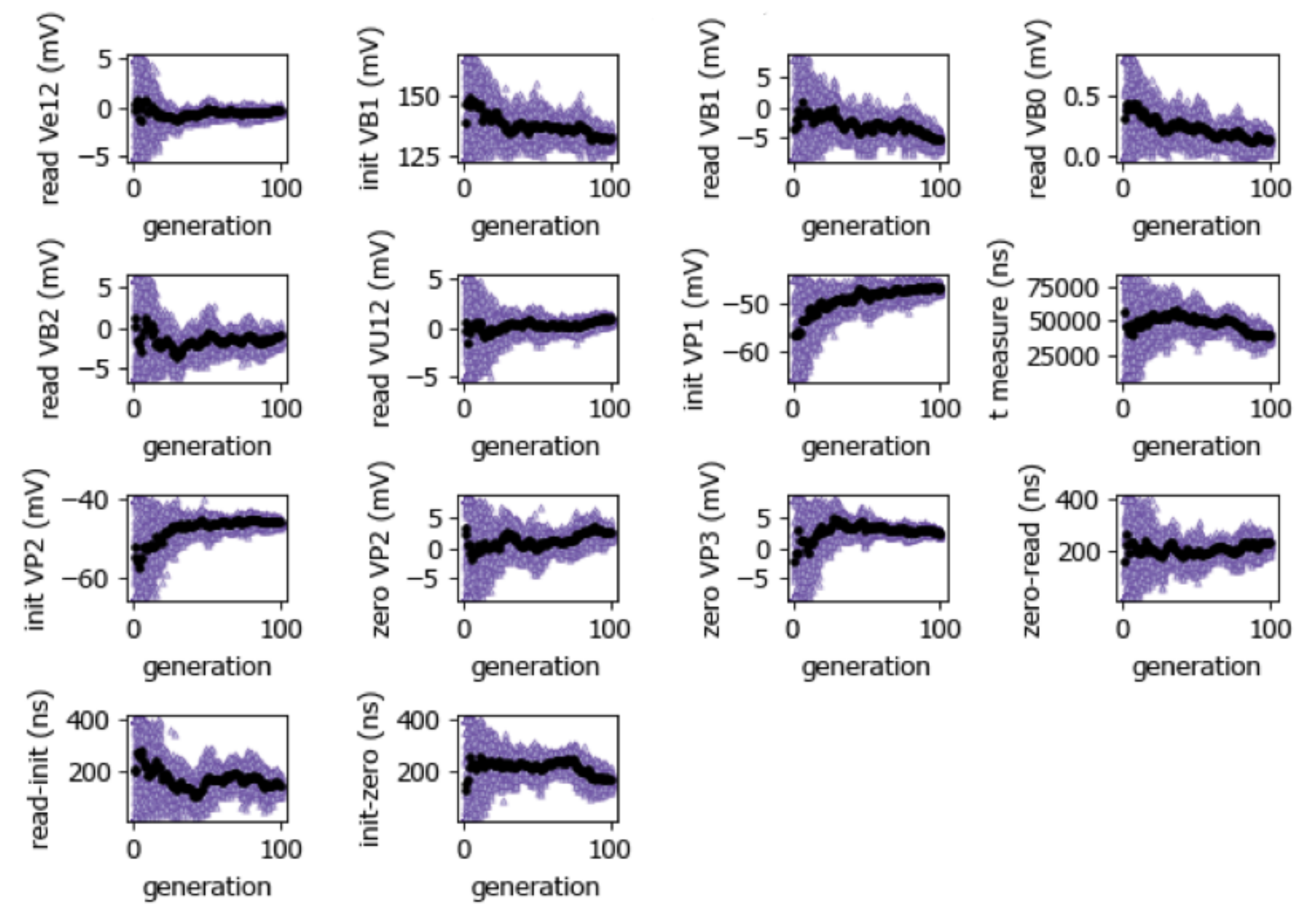




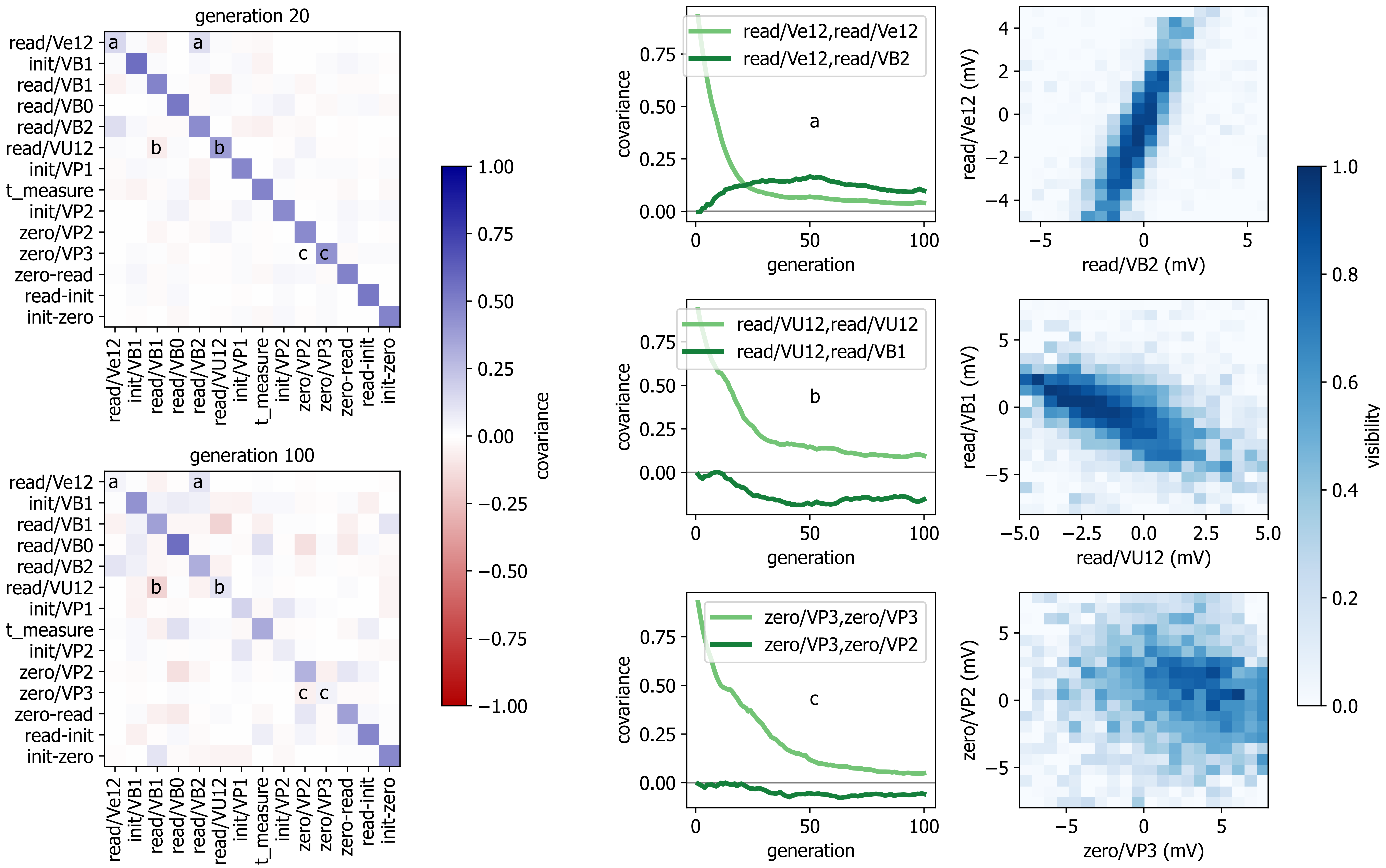
Optimising visibility





We can frequently finetune PSB readout visibility from 90% to >98% within one hour.

Optimising visibility: Interpretation

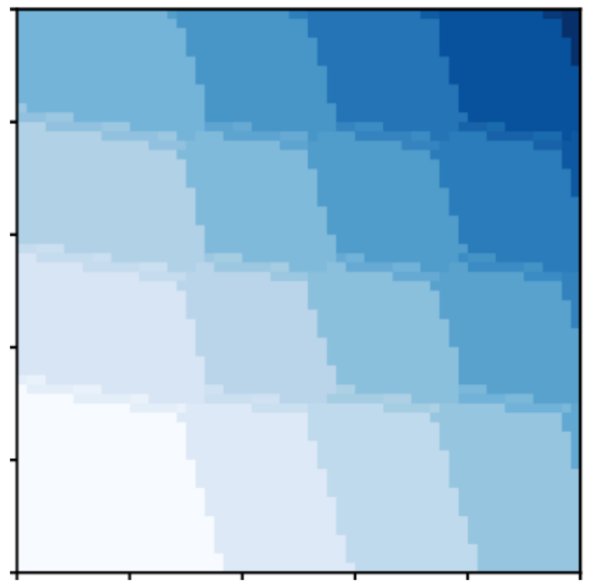


Going forward

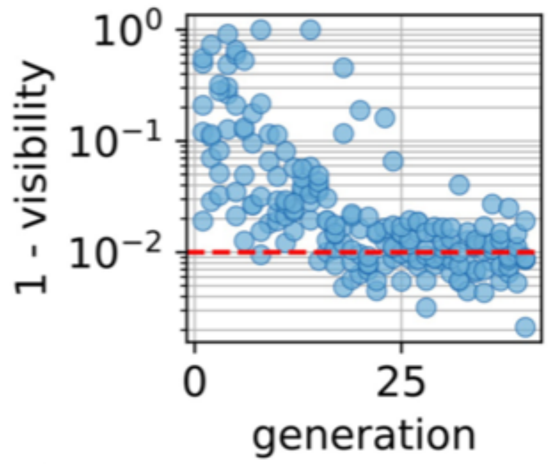
SCALE

Polytope finding in multidimensional CSDs

Automated operation



QDsim released



PSB readout

optimized readout + gates

BETTER INDIVIDUAL CONTROL

Gualtieri, Valentina, Hernandes, Vinicius, Renshaw, Charles and **EG**. “QDSim: Quantum Dot Array Simulation package.” arXiv: 2404.02712 (2024).

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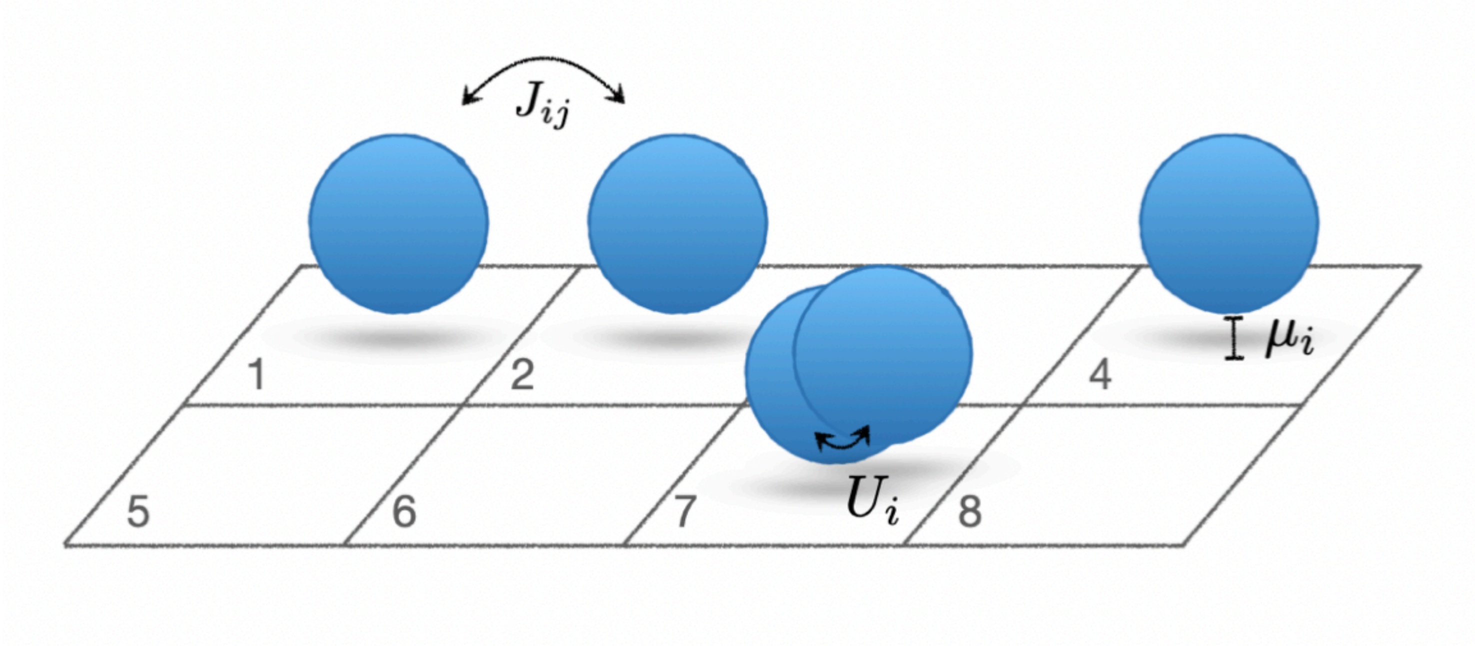
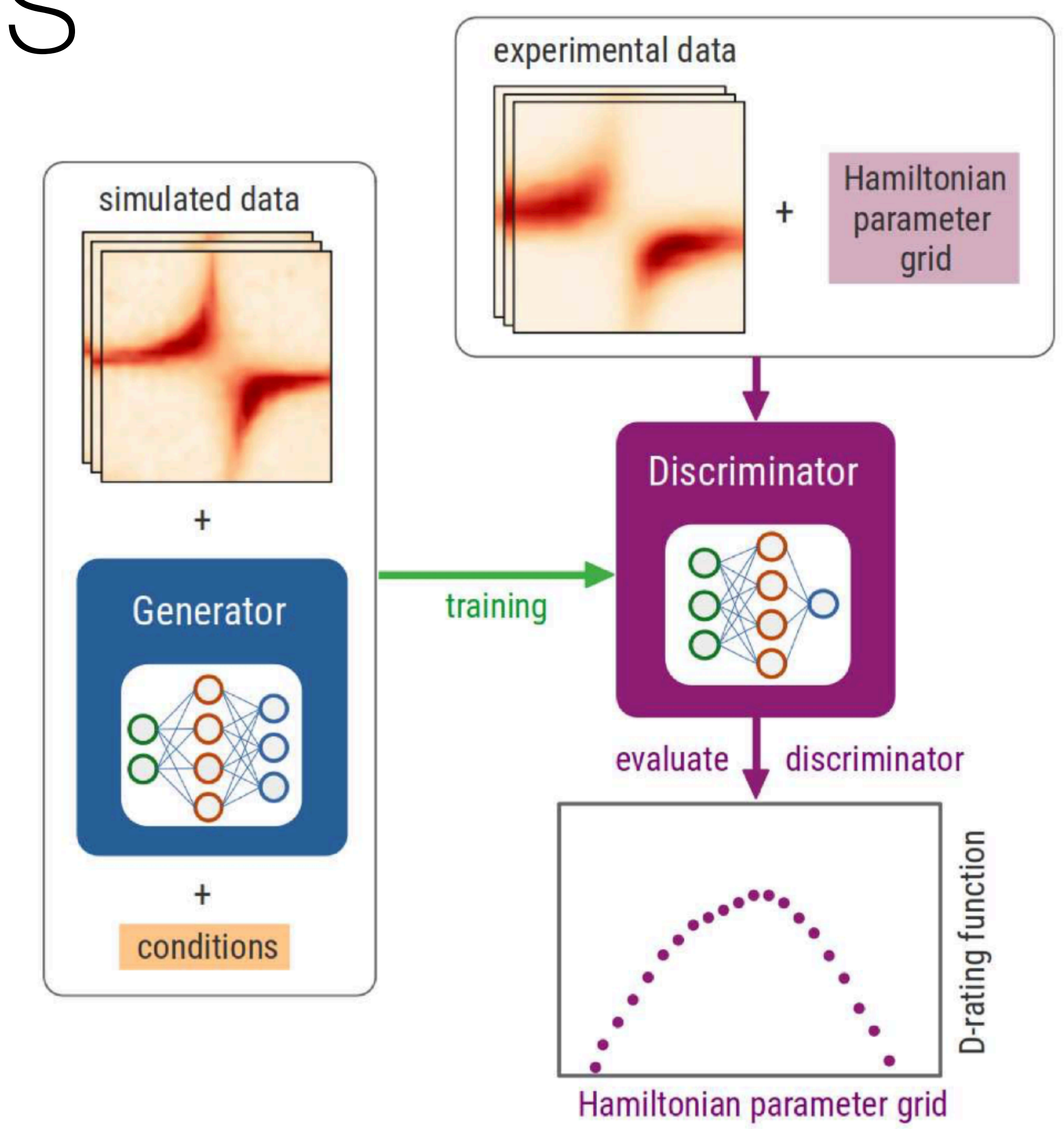
QMAI tuning applications



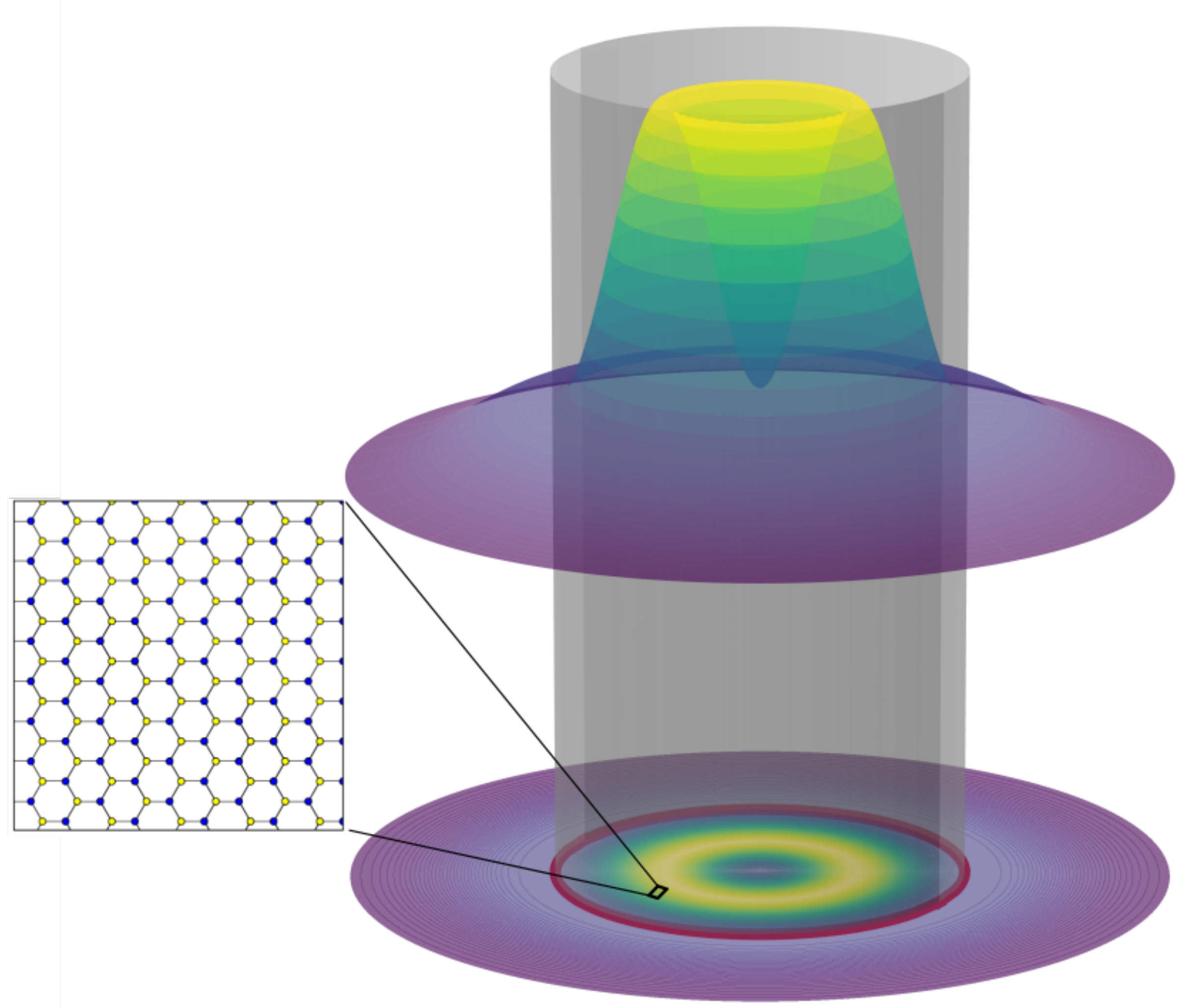
DEEP FEED-FORWARD NETWORKS

Valenti, A., Jin, G., Léonard, J., Huber, S. D., & **EG**. (2022). Scalable Hamiltonian learning for large-scale out-of-equilibrium quantum dynamics. *Physical Review A*, *105*(2), 023302.



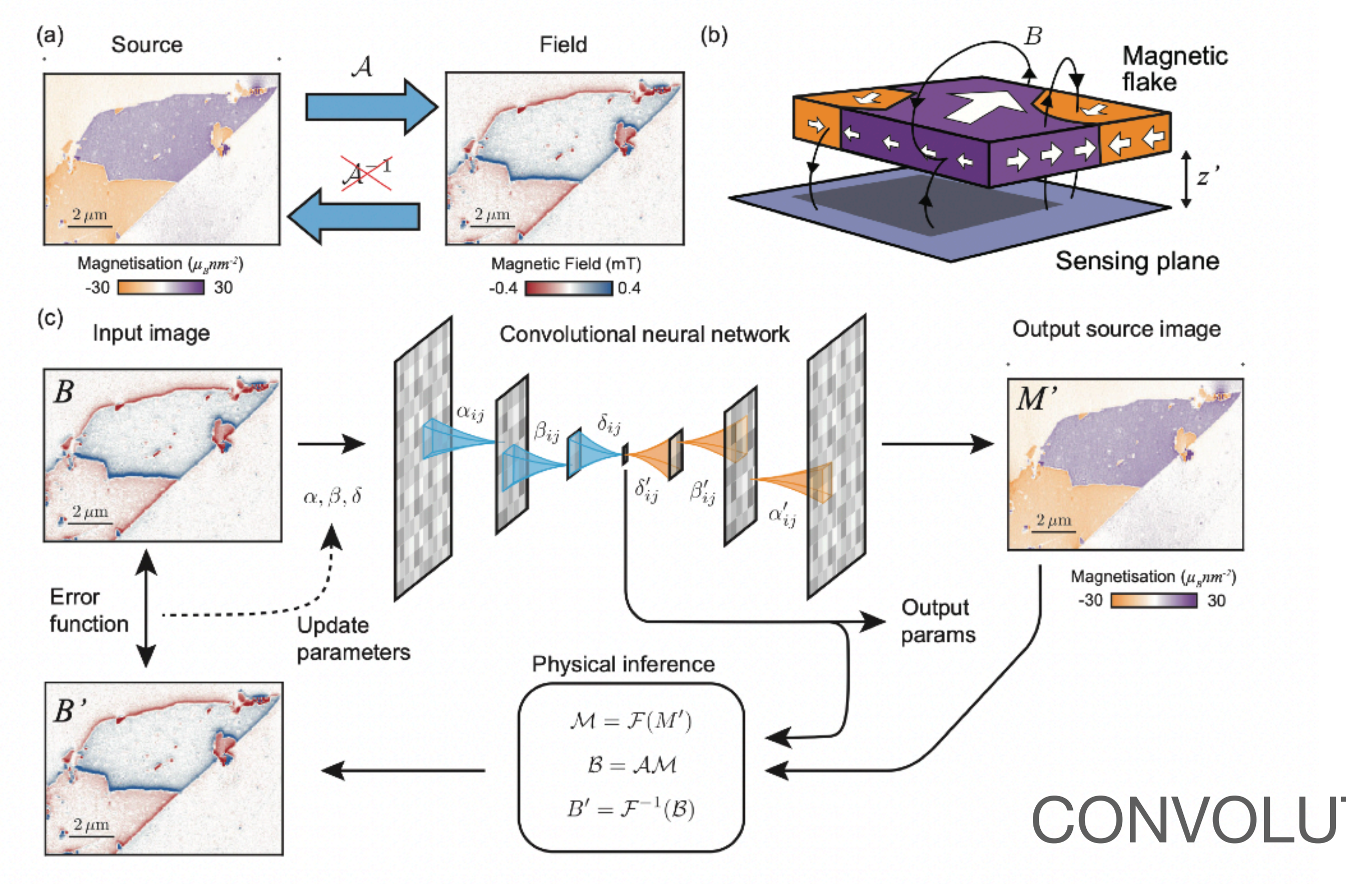
GENERATIVE MODELS

Koch, R., van Driel, D., Bordin, A., Lado, J. L., & **EG**. Adversarial Hamiltonian learning of quantum dots in a minimal Kitaev chain. Phys. Rev. Applied **20**, 044081 (2023)



CUSTOM OPTIMIZERS

Bucko, J., Schäfer, F., Herman, F., Garreis, R, Tong, C, Kurzmann, A, Ian T., & **EG**. (2023). Automated reconstruction of bound states in bilayer graphene quantum dots. Physical Review Applied 19, 024015 (2023).



CONVOLUTIONAL U-NETWORKS

Dubois, A. E. E., D. A. Broadway, A. Stark, M. A. Tschudin, A. J. Healey, S. D. Huber, J-P. Tetienne, **EG**, and P. Maletinsky. "Untrained physically informed neural network for image reconstruction of magnetic field sources." *Physical Review Applied* 18, no. 6 (2022): 064076.

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