Overview of use cases and experiences with quantum computers in the LRZ

ZKI-Herbsttagung – 10.09.2025

Devra Santana Lujan & Dr. Amit

Who are we?

Hardware Adapted Theory (HAT) consortium of the Munich Quantum Valley

amit.devra@tum.de

Theory support to enable the best possible experimental execution of quantum algorithms.

santana.lujan@dlr.de

Main research area: Quantum Control

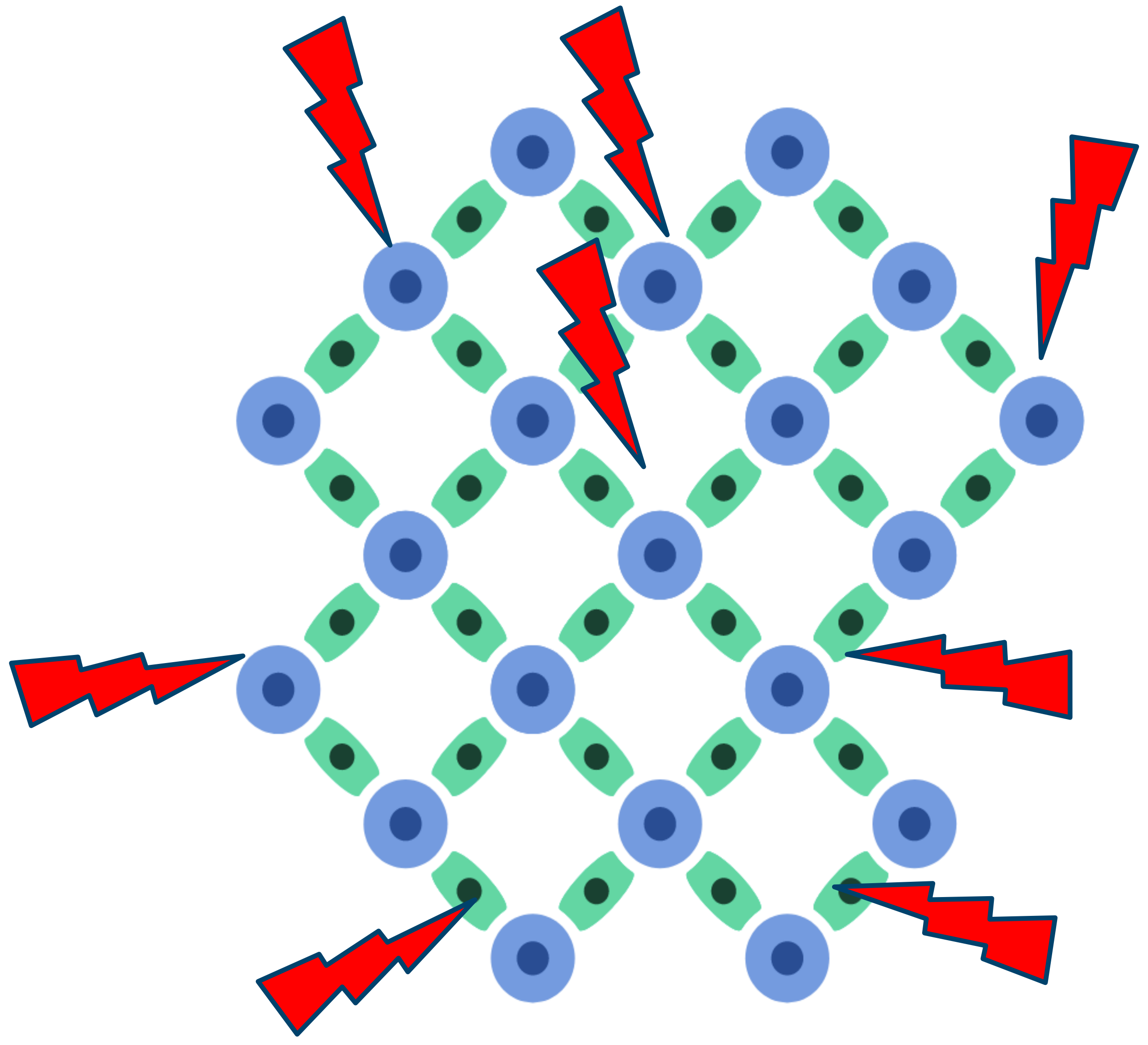
DLR

QSOC
Quantum Space Operations Center

Agenda

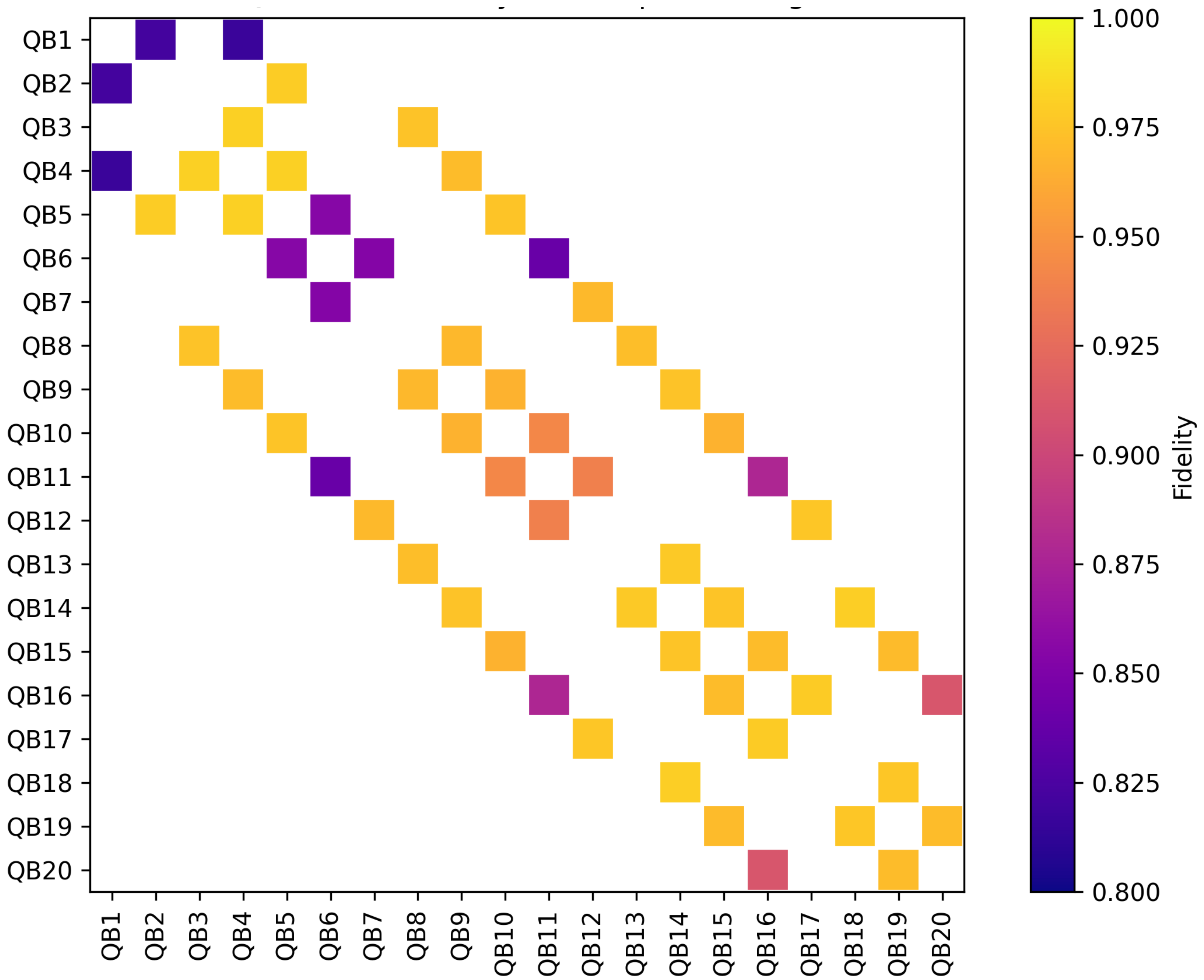
- Motivation
- Use case: Novel Dynamical Decoupling sequences
- Use case: Closed-loop pulse optimization
- Wrap-up

Why is pulse level important?



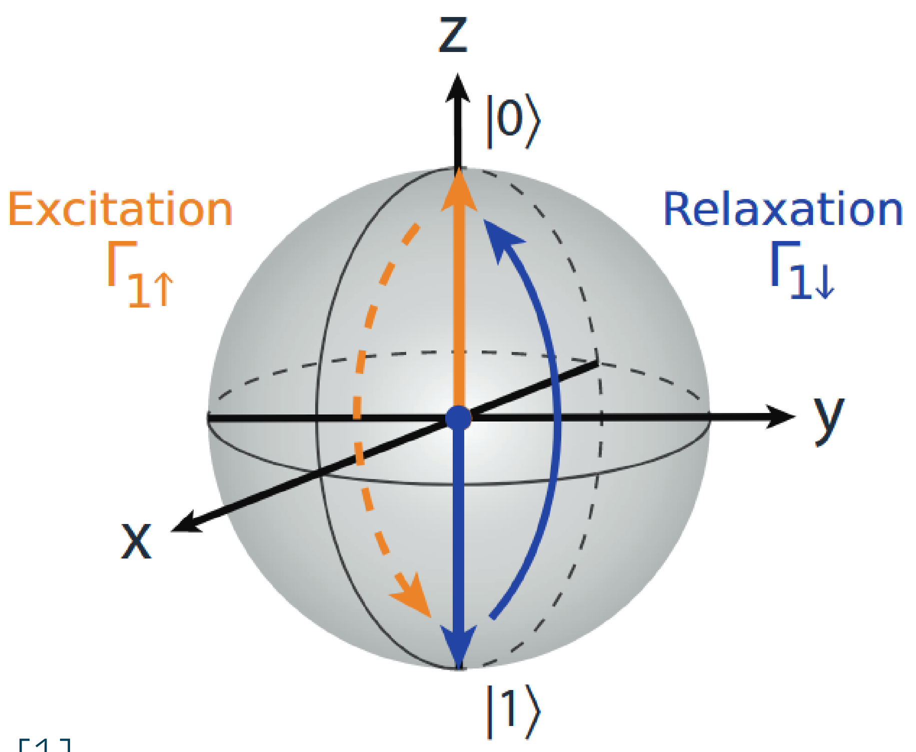
Layout of IQM's 20-qubit device

Two-qubit gate fidelity (CZ) per qubit-pair



Decoherence - Relaxation & Dephasing

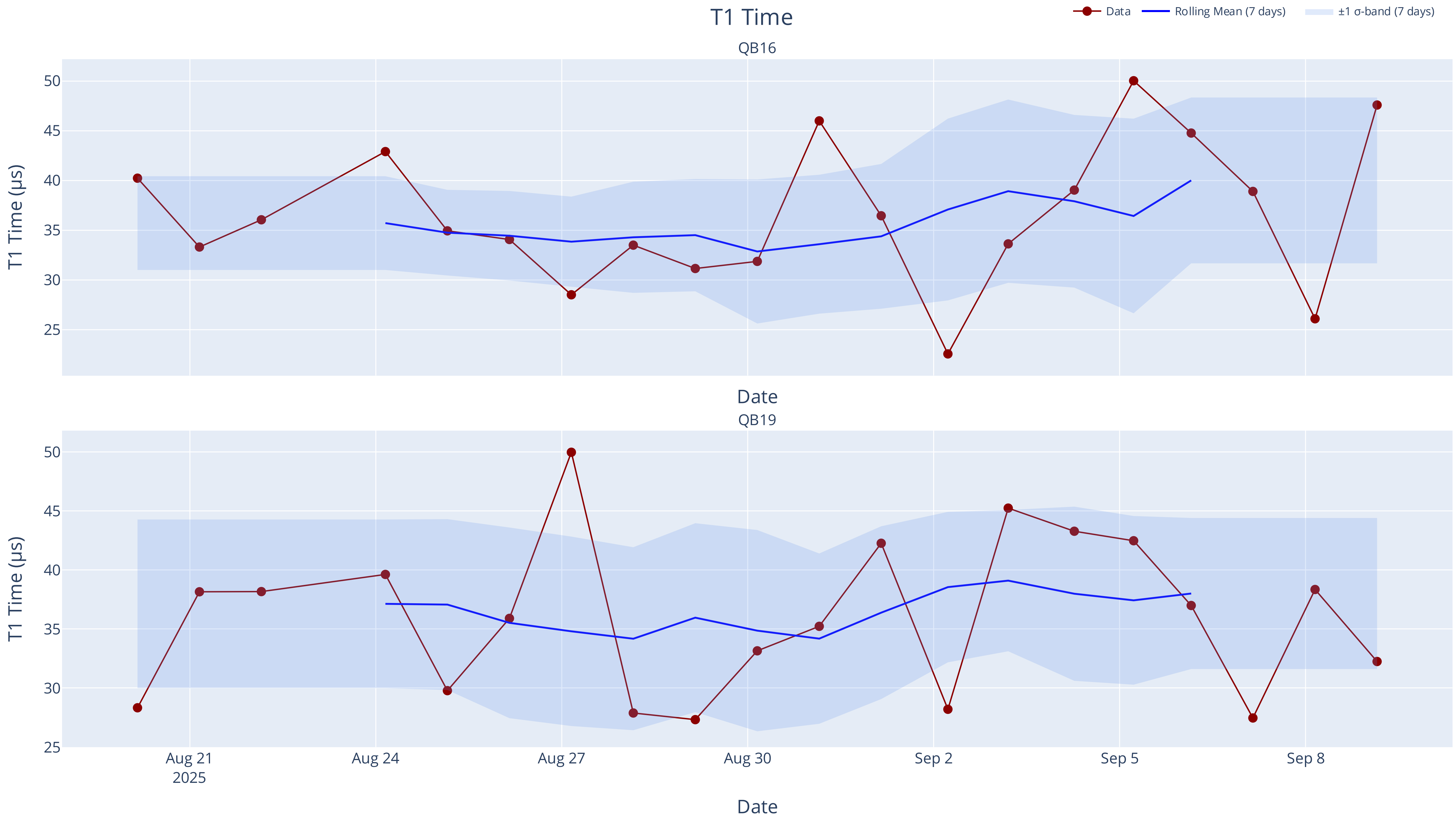
Munich Quantum Valley

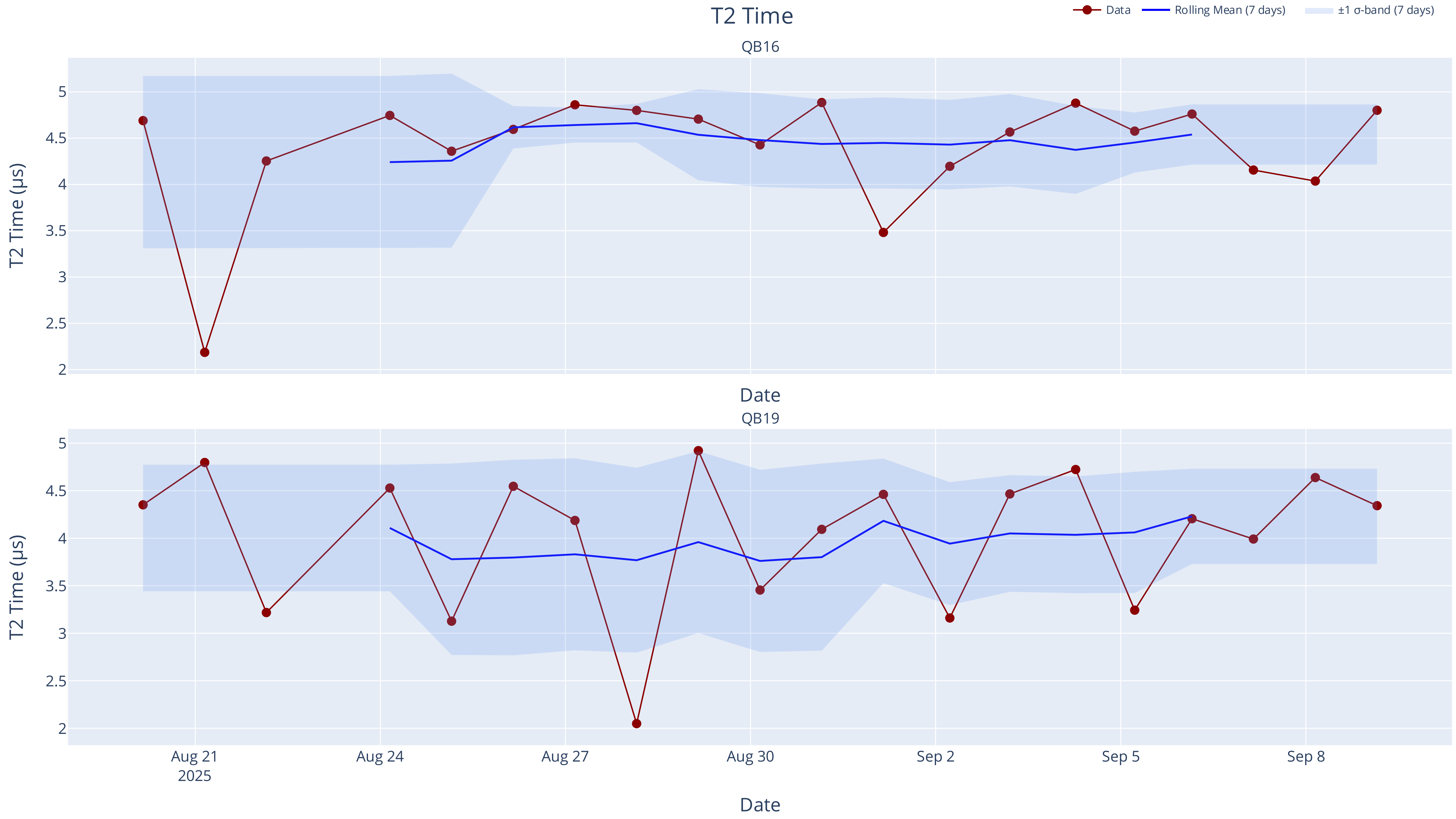


[1]

T1: Longitudinal relaxation time

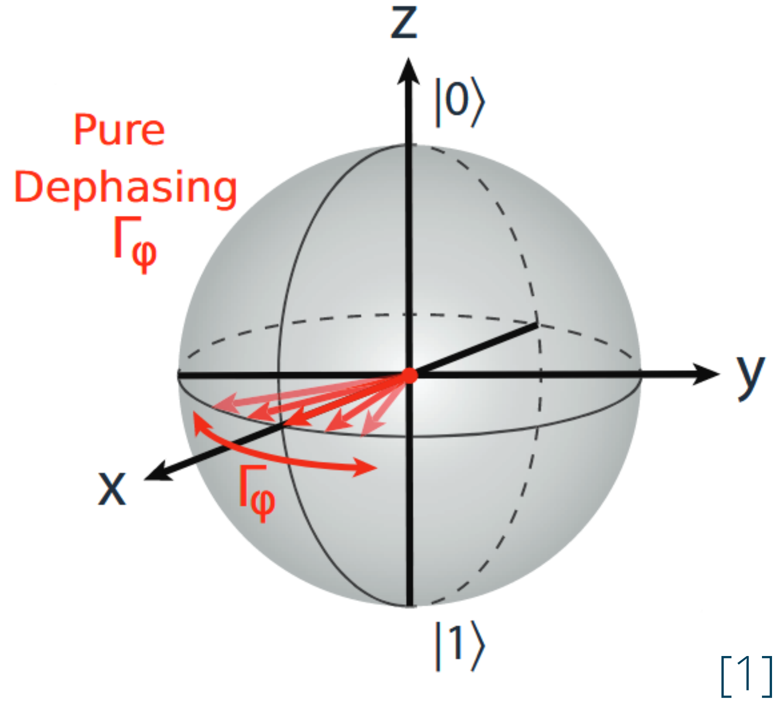
- Qubit relaxes to the ground state due to interaction with the environment
- Exponential decrease in excited state population
- Around 30µs – 60µs on IQM @ LRZ





T2: Transverse relaxation time

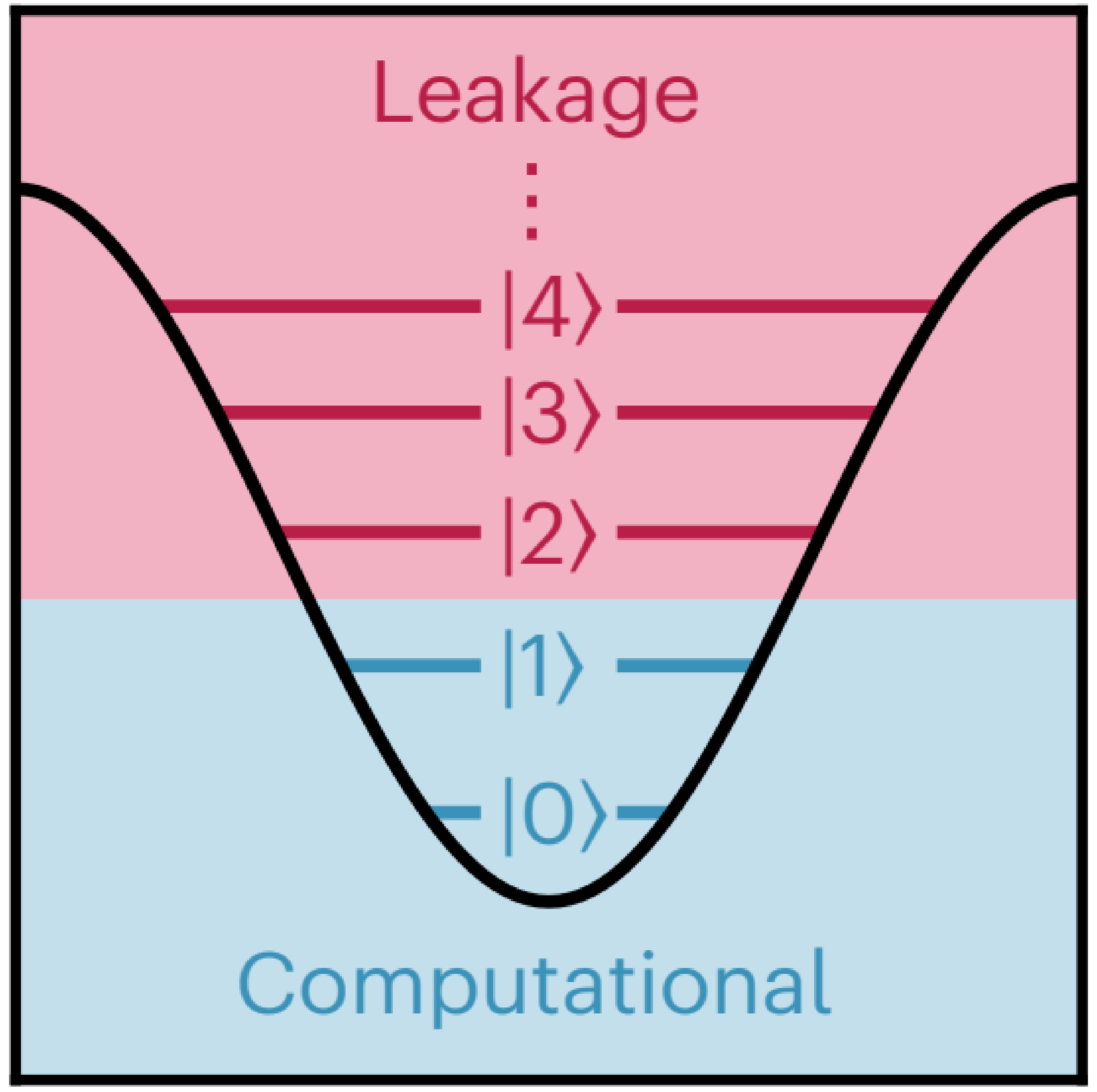
- Loss in phase information of the superposition state
- State evolves into a probabilistic mixture
- Around 1.5µs - 6µs on IQM @ LRZ



[1]

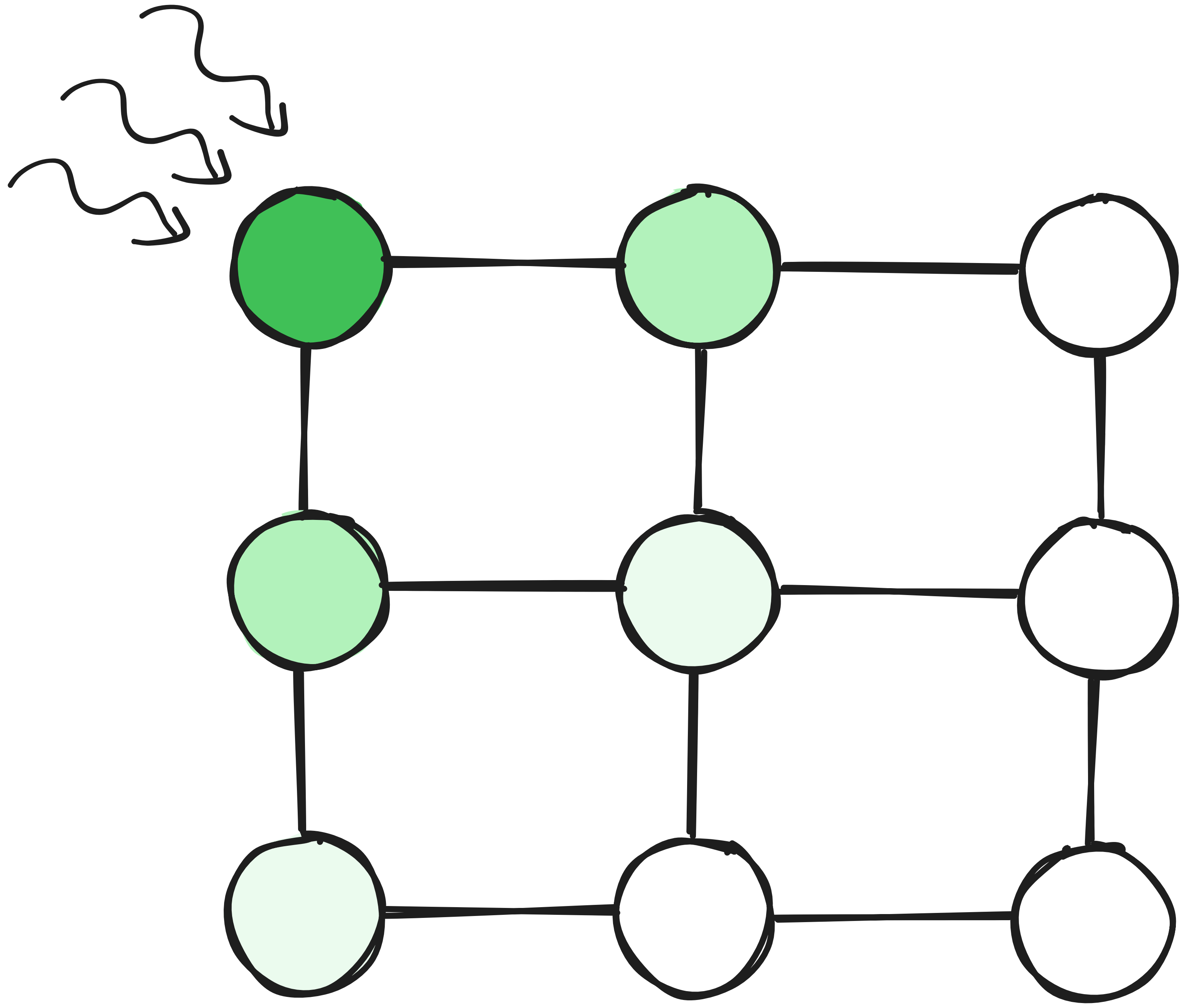
[1]: Krantz, Philip, et al. "A Quantum Engineer's Guide to Superconducting Qubits." *Applied Physics Reviews* 6, no. 2 (2019): 021318.

Leakage



[2] Overcoming Leakage on Error-Corrected Quantum Processors, Google Research Blog (2025)
https://research.google/blog/overcoming-leakage-on-error-corrected-quantum-processors/

Crosstalk



Parameter drift over time

Goals of control techniques

Munich Quantum Valley

We want our control pulses to have:

- Robustness w.r.t parameter drifts and inhomogeneities
- Decoherence suppression
- High selectivity and spectral isolation

Munich Quantum Valley

Use case: Novel Dynamical Decoupling sequences

Dynamical Decoupling

Dynamical decoupling (DD) is one of the earliest methods used for error suppression:

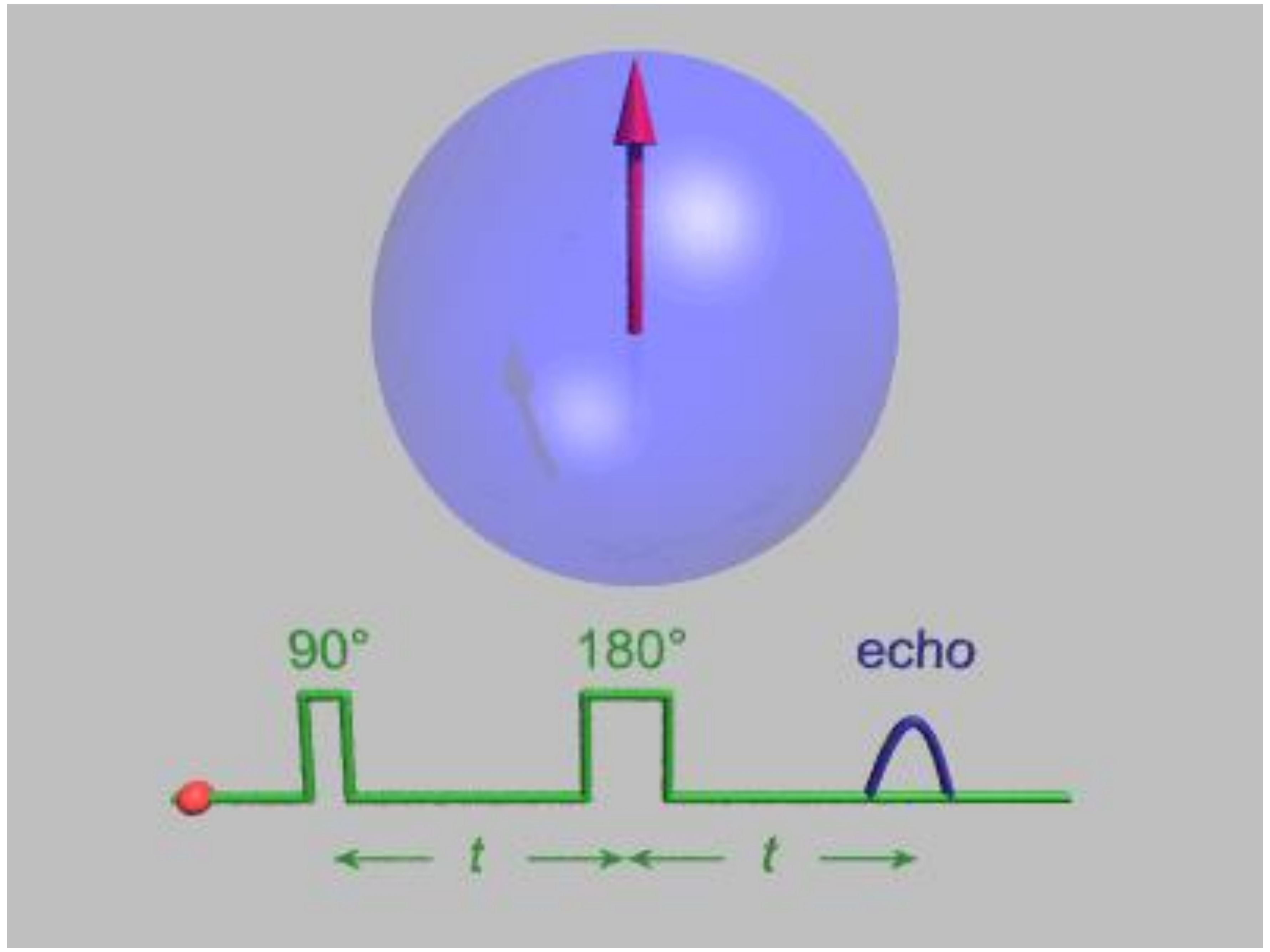
✅ Suppress decoherence from environmental noise (e.g., dephasing)

✅ Extend coherence times, preserving quantum information longer

✅ Requires minimal hardware overhead, compatible with existing platforms

Idea of DD

- To minimize the dephasing of qubits → maximizing T_2 relaxation time

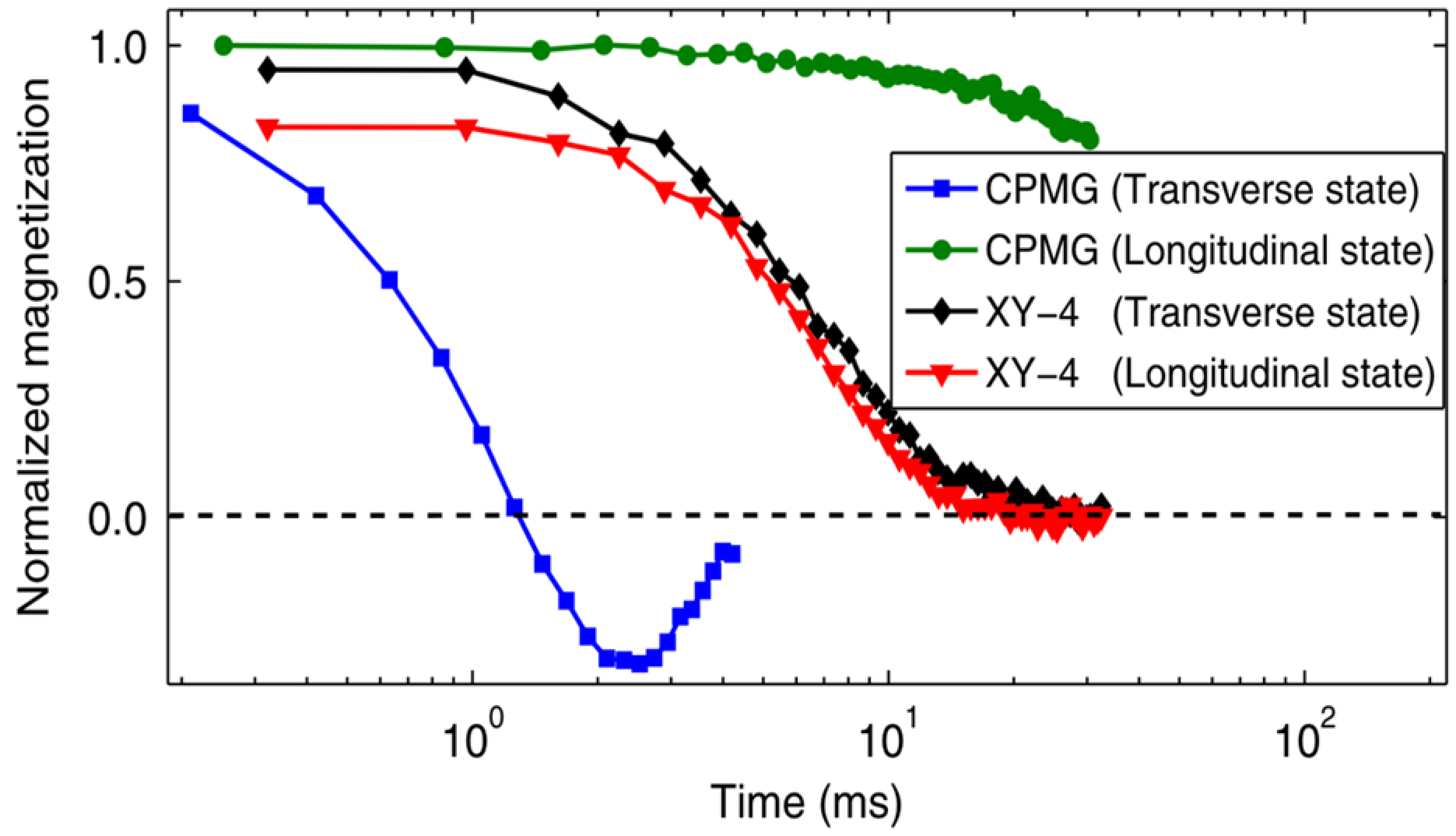


Hahn Echo
GavinMorley - Wikimedia

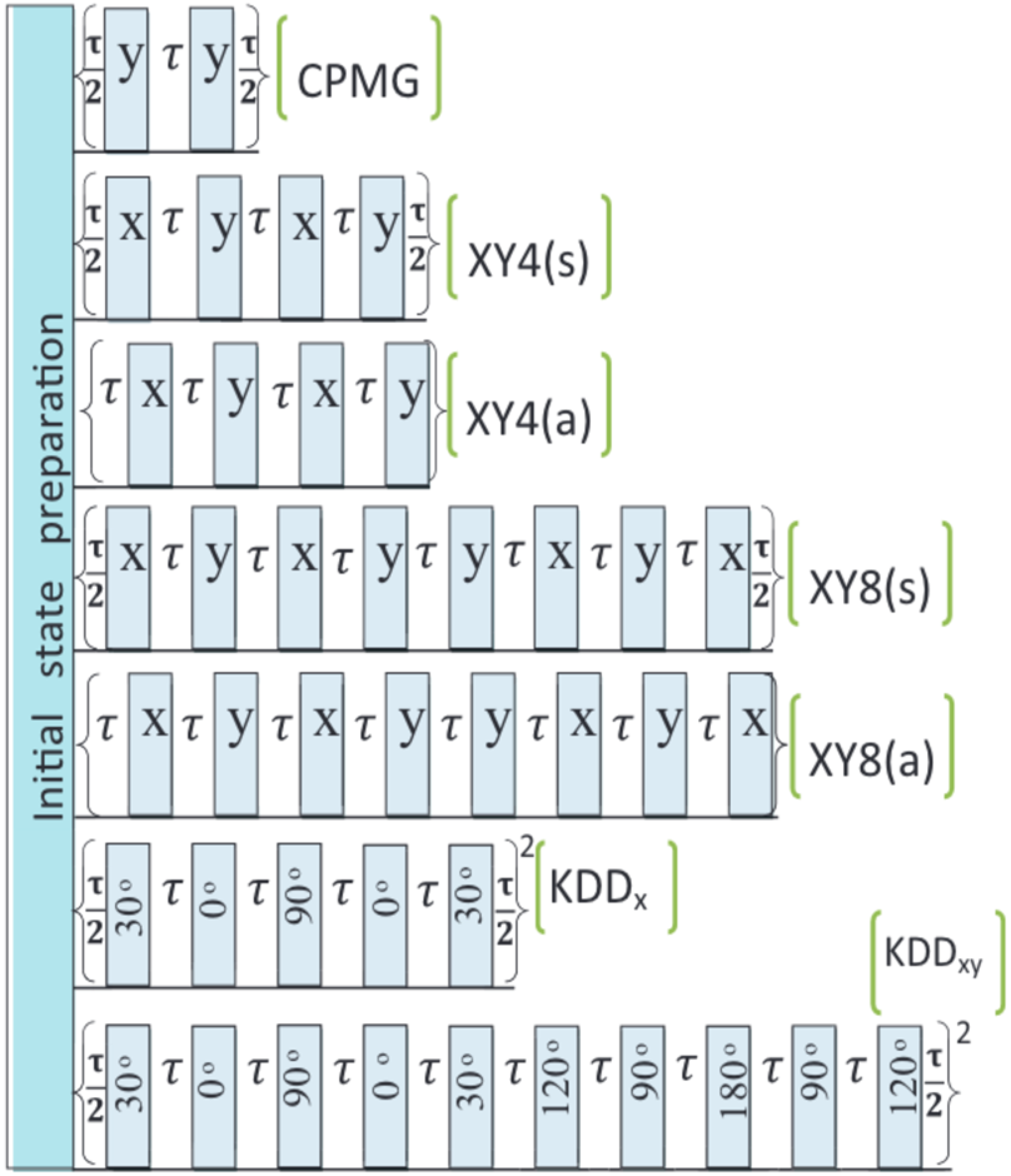
Munich Quantum Valley

Existing DD Sequences

- Many of them are **not universal**.



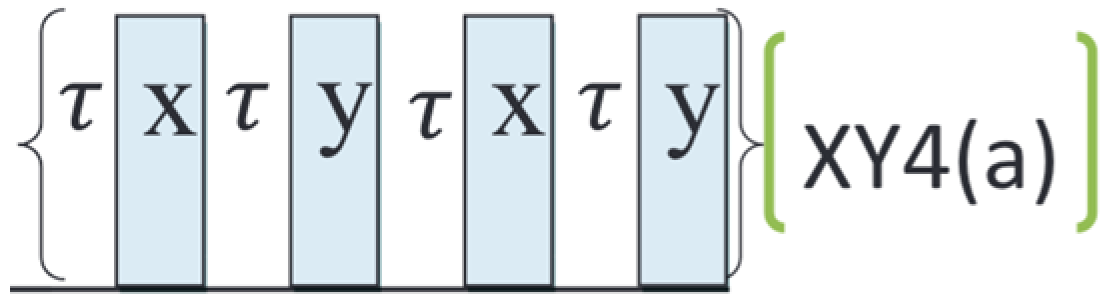
PRL 106, 240501 (2011)



Dynamical Decoupling

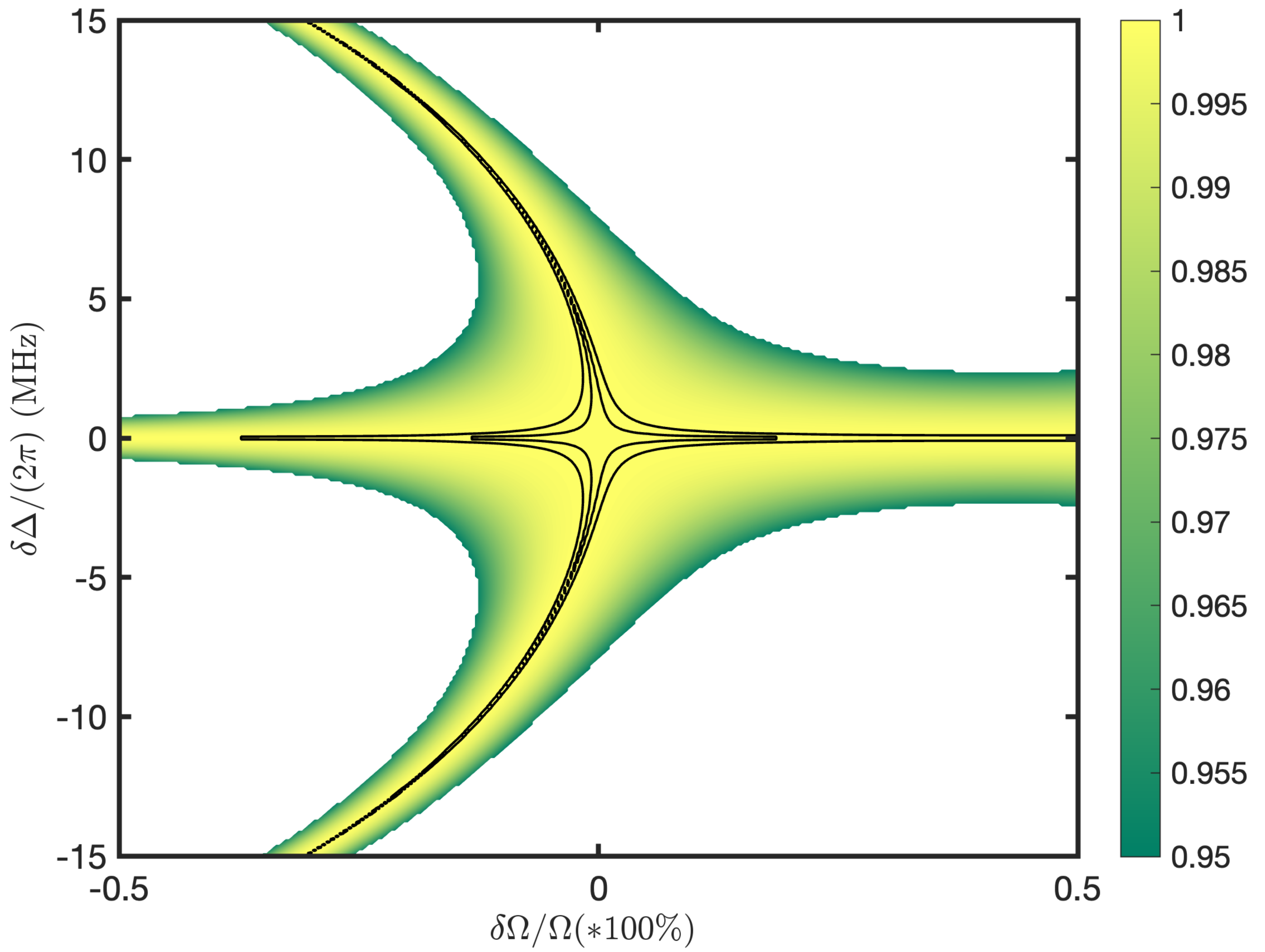
Existing DD Sequences

- Many of them are **not universal**
- **Not robust** enough against pulse imperfections and parameter drift



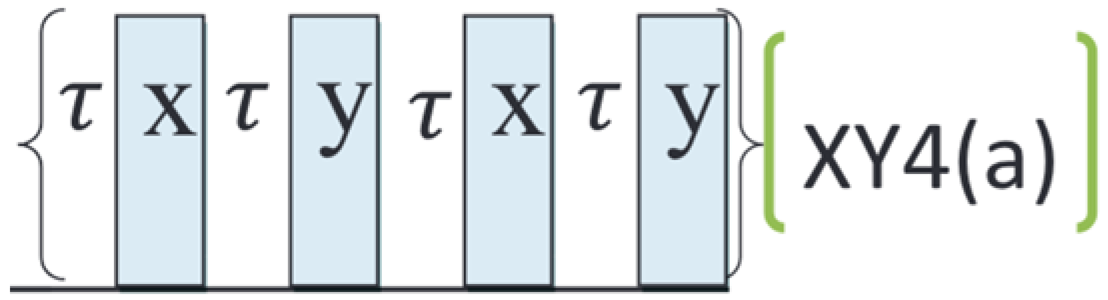
- Delay: 0
- N = number of blocks XY4

N = 2



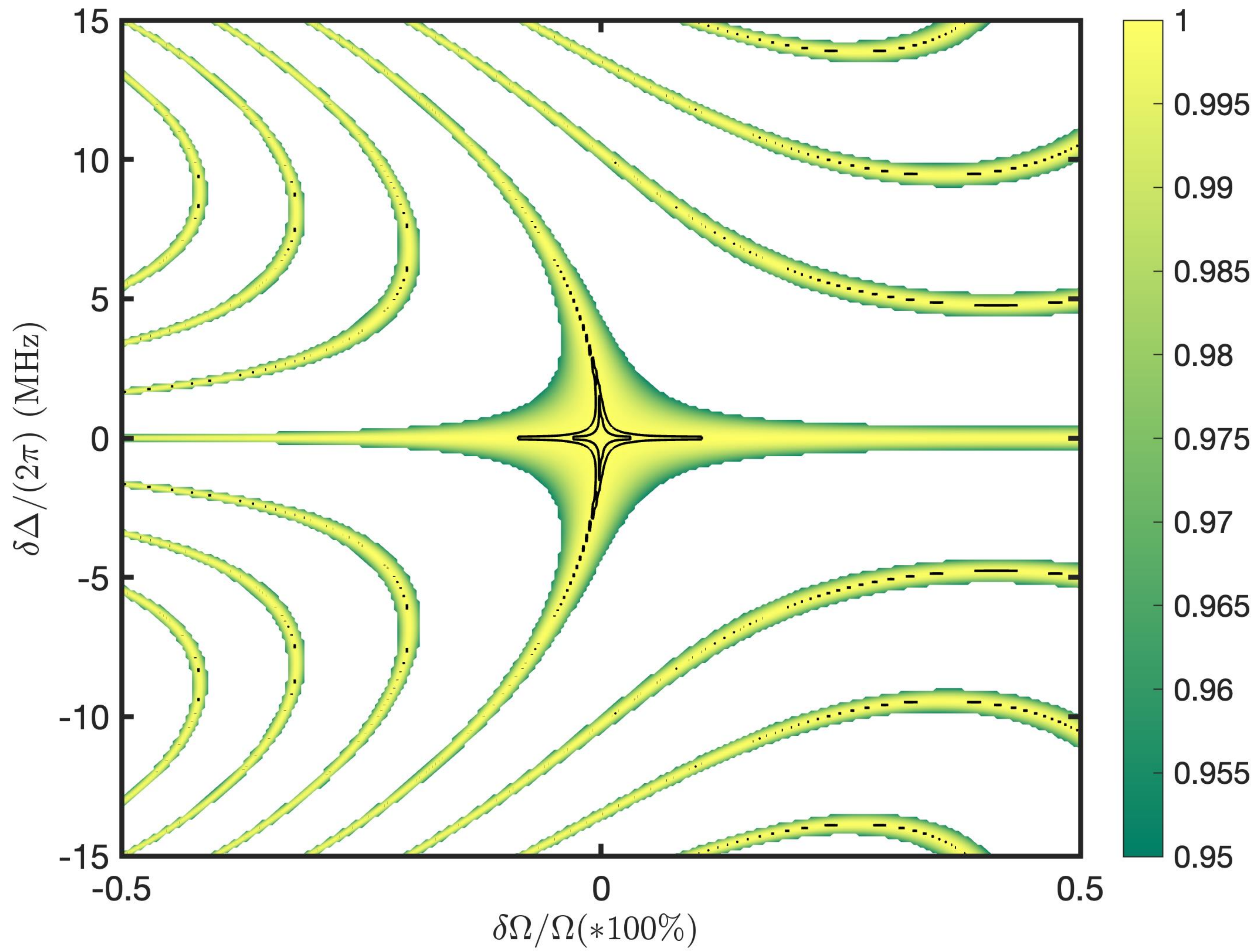
Existing DD Sequences

- Many of them are **not universal**
- **Not robust** enough against pulse imperfections and parameter drift



- Delay: 0
- N = number of blocks XY4

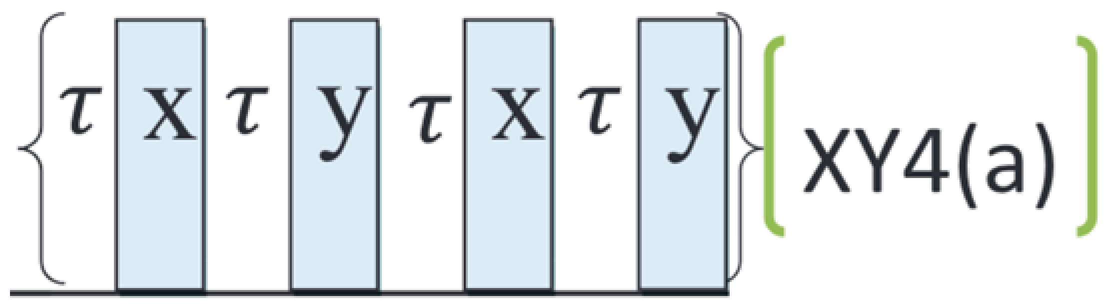
N = 10



Dynamical Decoupling

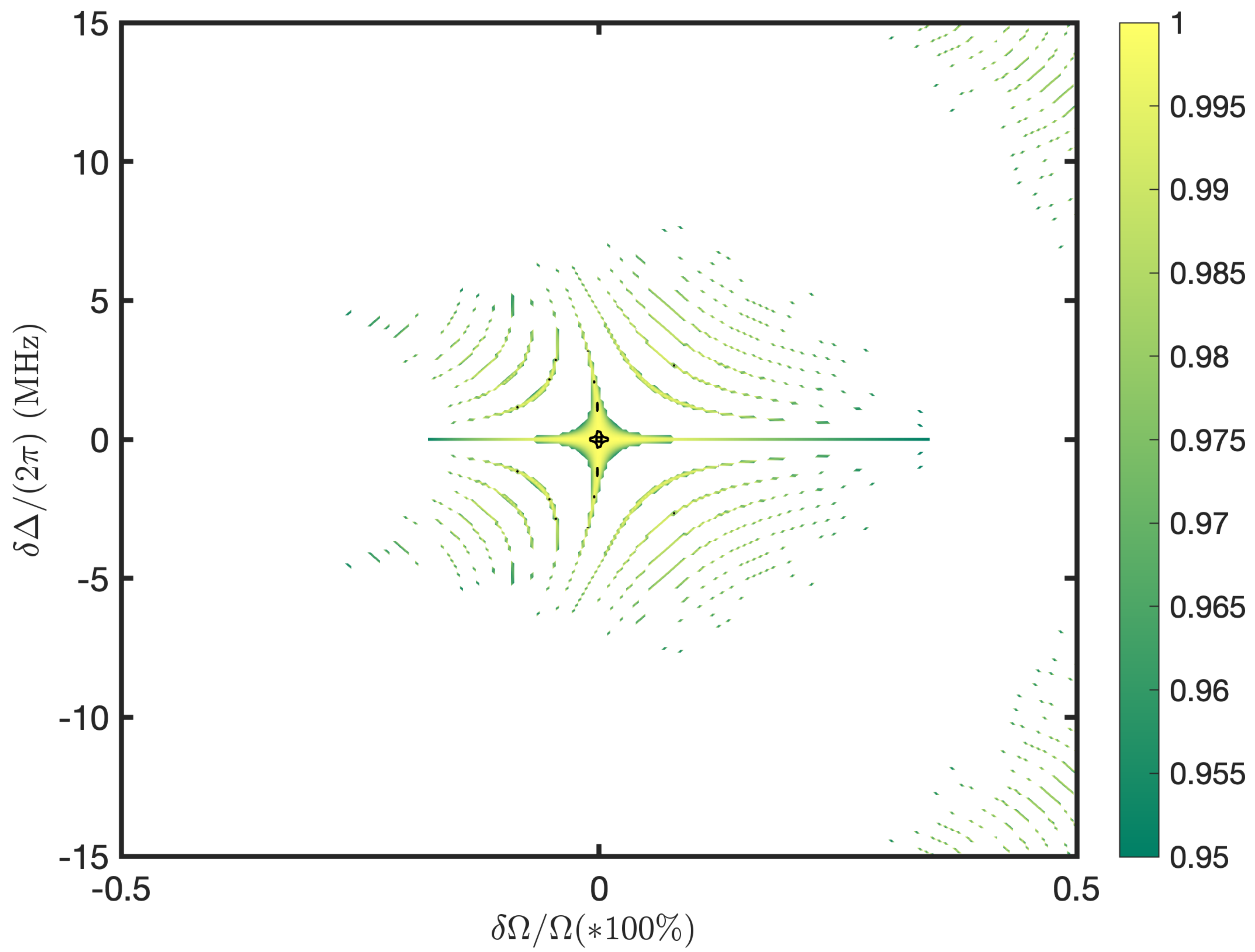
<u>Existing DD Sequences</u>

- Many of them are **not universal**
- **Not robust** enough against pulse imperfections and parameter drift



- Delay: 0
- N = number of blocks XY4

N = 100

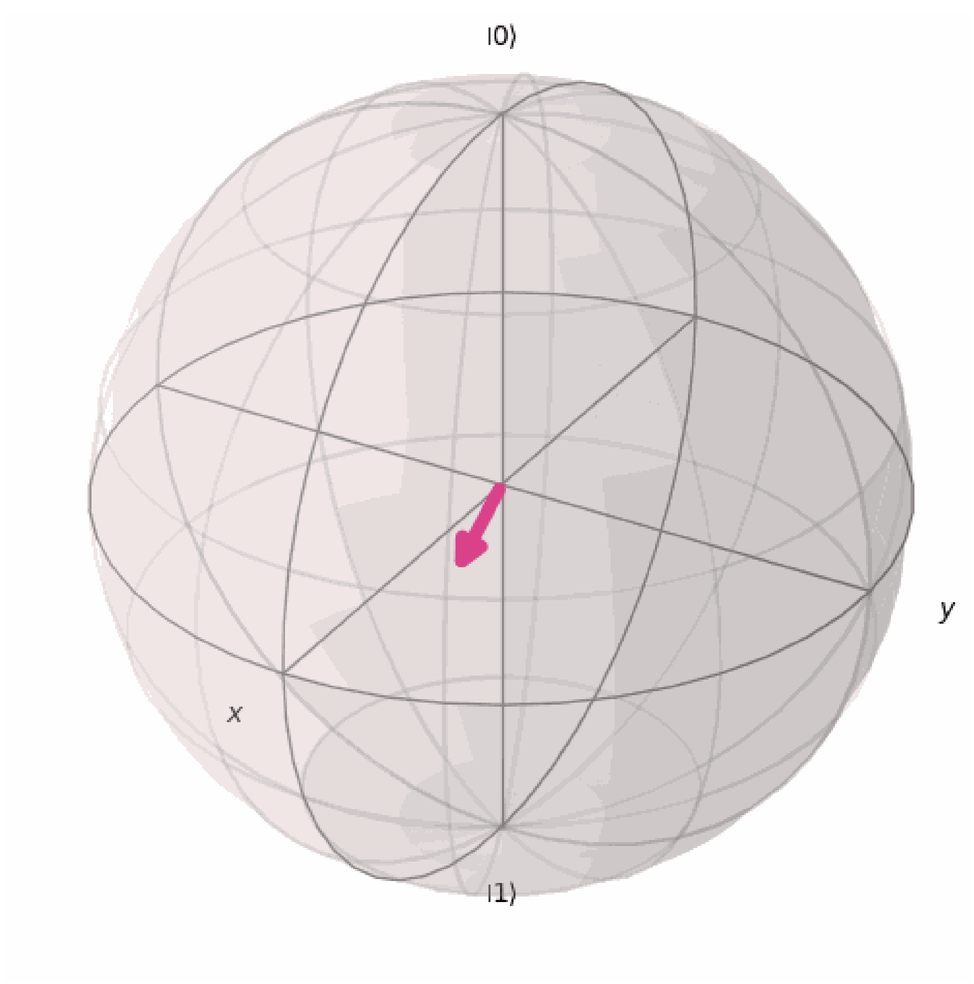


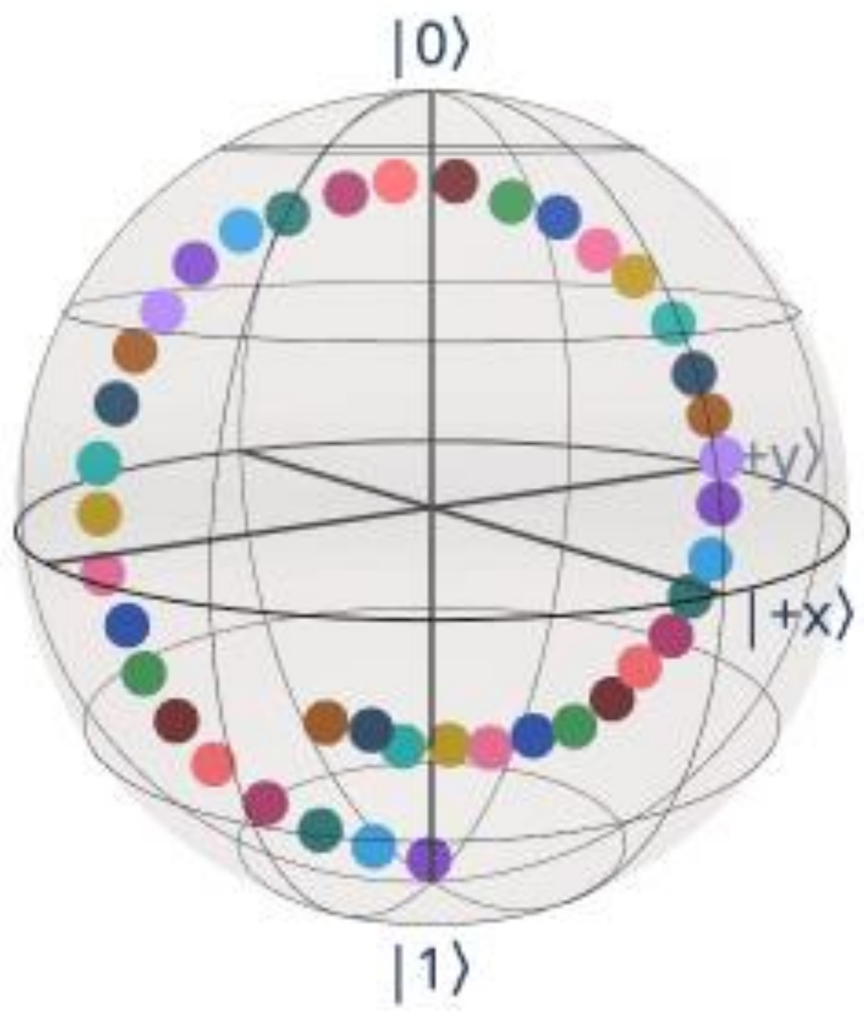
Dynamical Decoupling

Existing DD Sequences

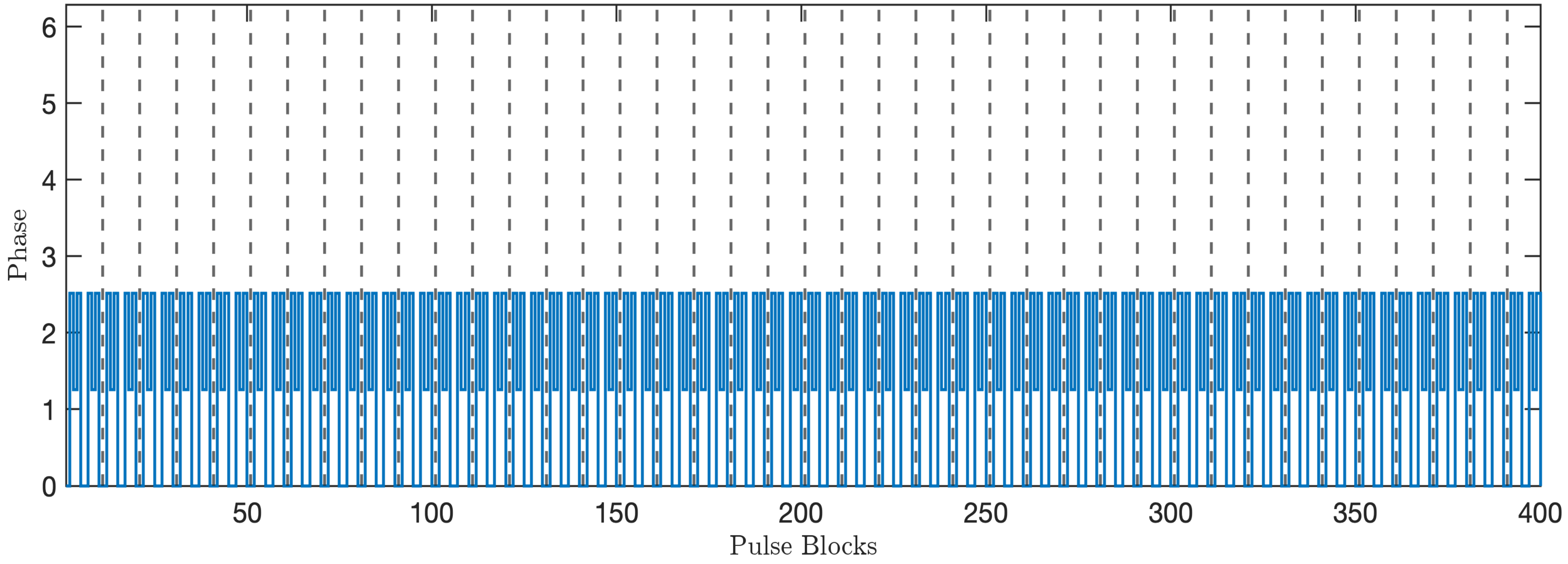
- Many of them are **not universal**
- **Not robust** enough against pulse imperfections and parameter drift
- **Do not keep** track of the qubit state

UR10: N = 40





UR 10 pulse phases



Experimental result from IQM @ LRZ

UR sequences: Genov, et al., PRL 118, 133202 (2017)

Dynamical Decoupling

<u>New DD Sequences</u>

- Numerically **optimized** to be **universal** and **robust**
- **Tracking enabled:**

Compensation for imperfection: Imperfections that can't be corrected on short timescales **don't accumulate**, as they can be addressed over longer timescales.

Global effect of control: Actions taken during a specific time slice **influence the entire future evolution**, not just the immediate next step.

Original tracking paper:
Neves, et al., Journal of Magnetic Resonance, 201(1), 7-17.

Dynamical Decoupling

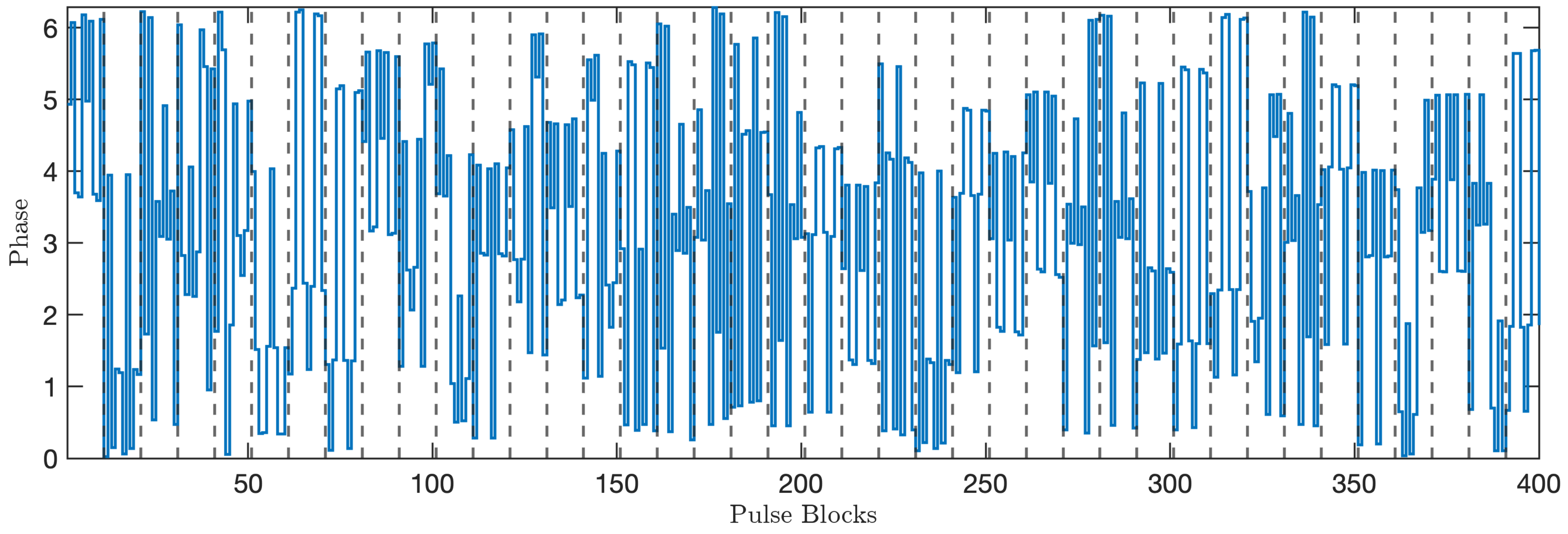
Munich Quantum Valley

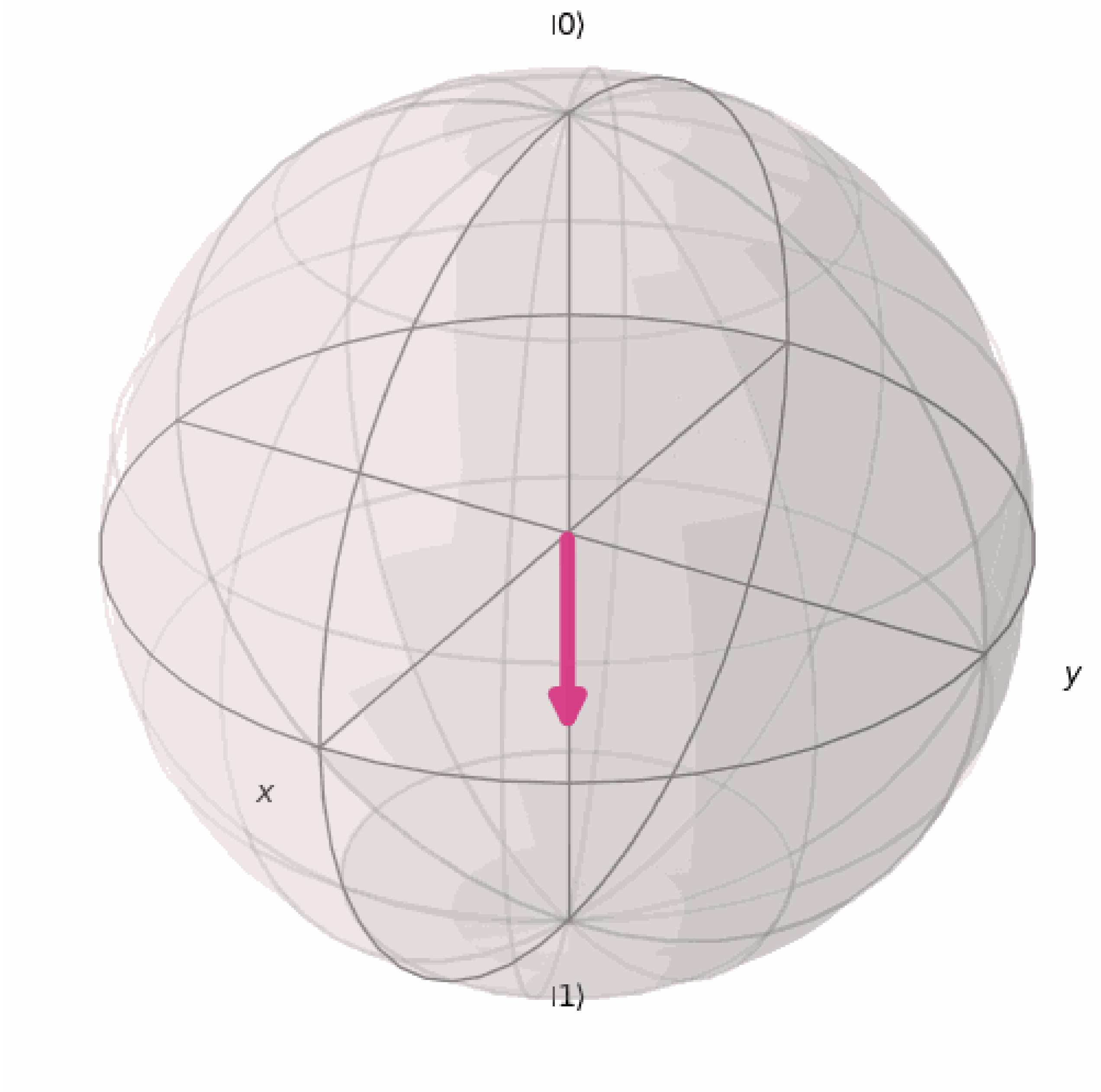
New DD Sequences

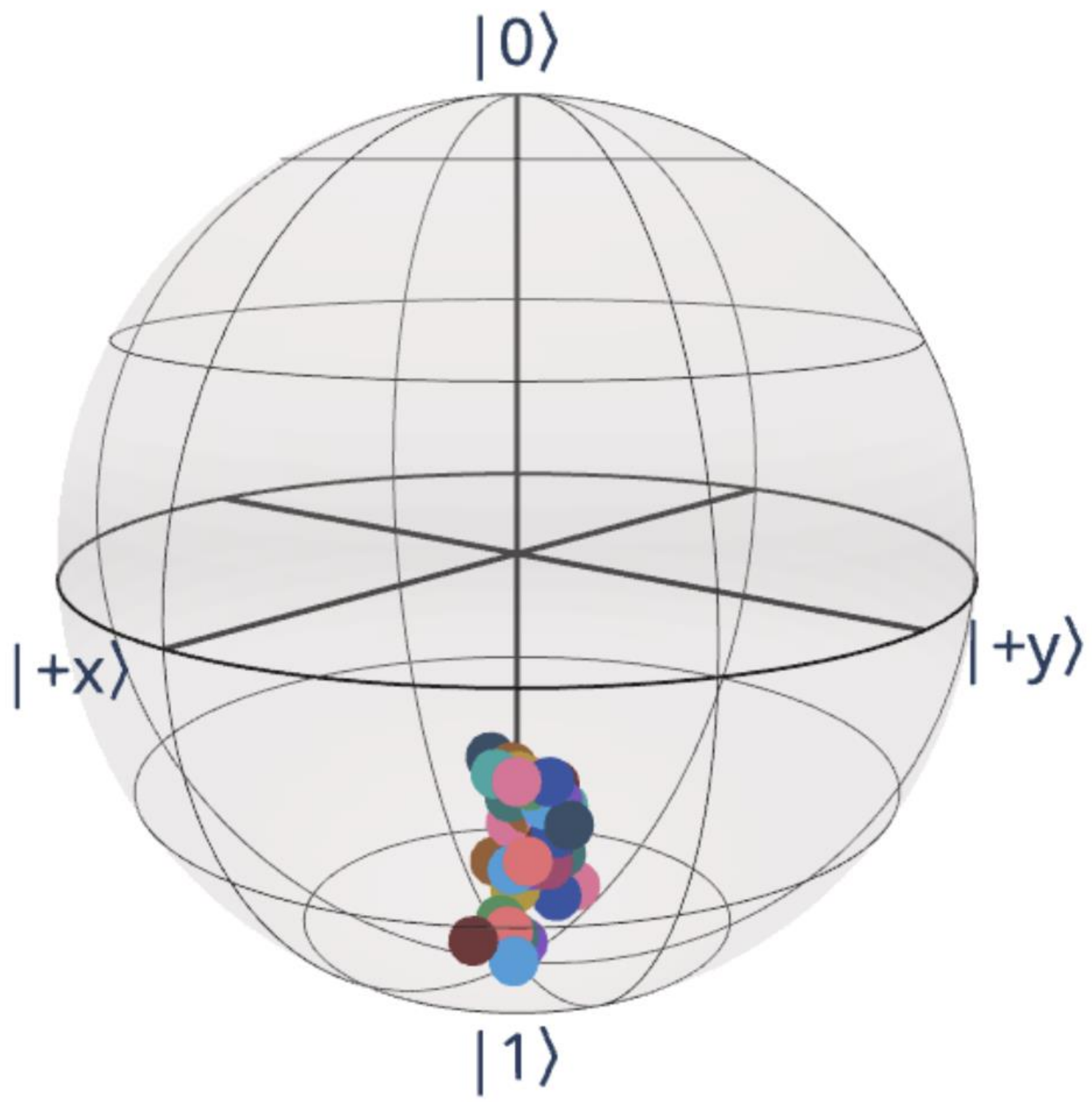
- Numerically **optimized** to be **universal** and **robust**
- **Tracking enabled**

G10: N = 40

G10 pulse phases







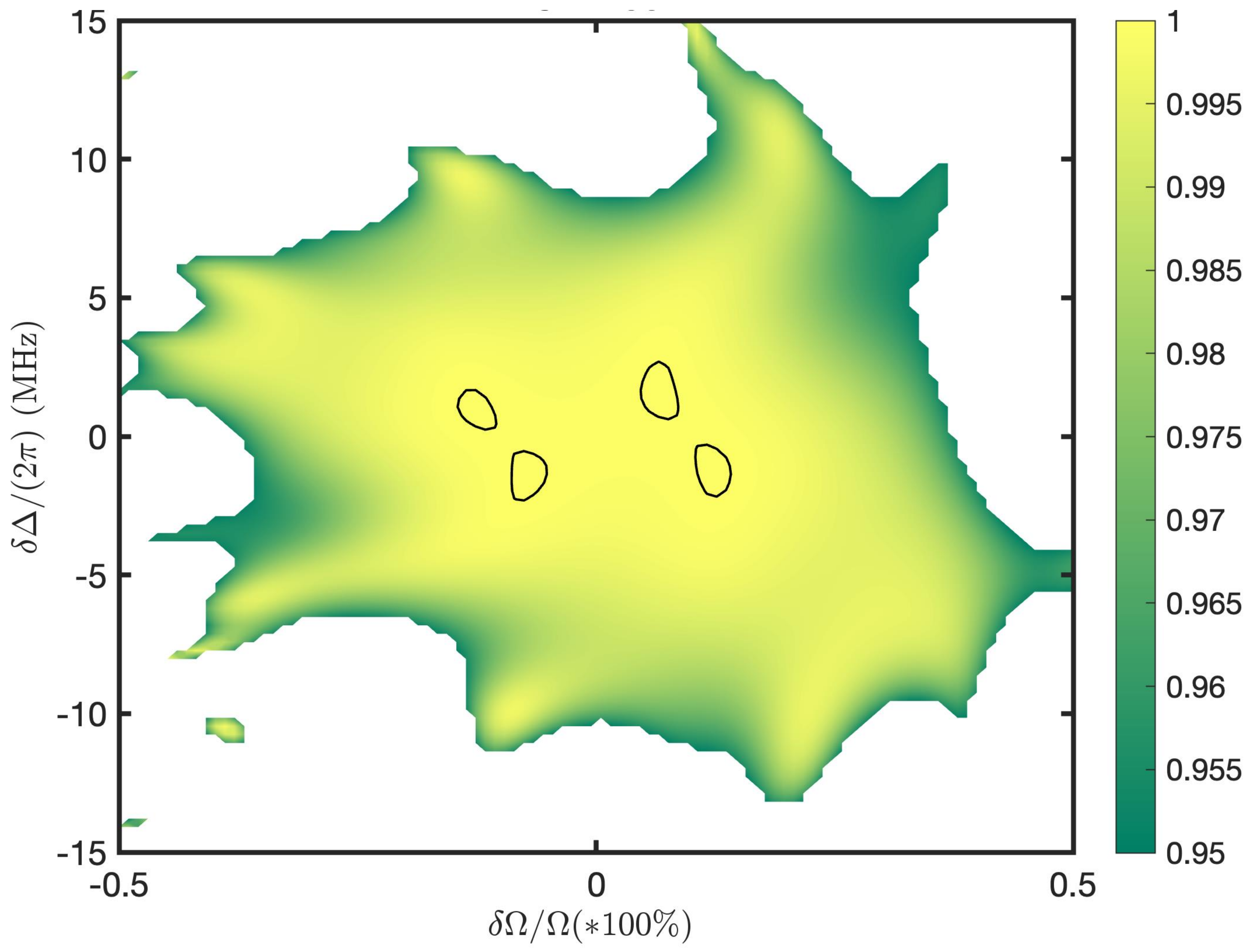
Manuscript under preparation

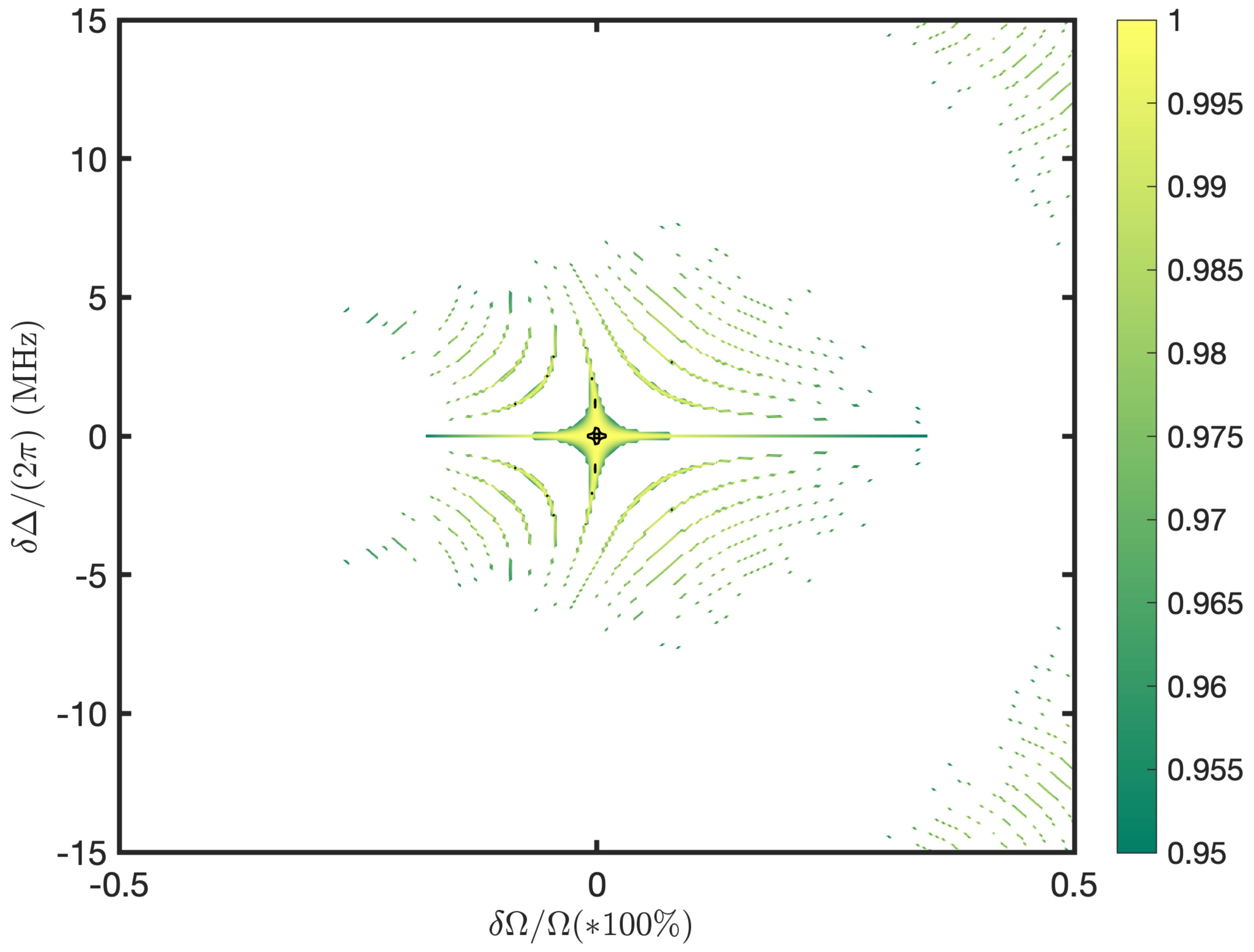
Dynamical Decoupling

New DD Sequences

- Numerically **optimized** to be **universal** and **robust**
- **Tracking enabled**

Robustness comparison after N = 100





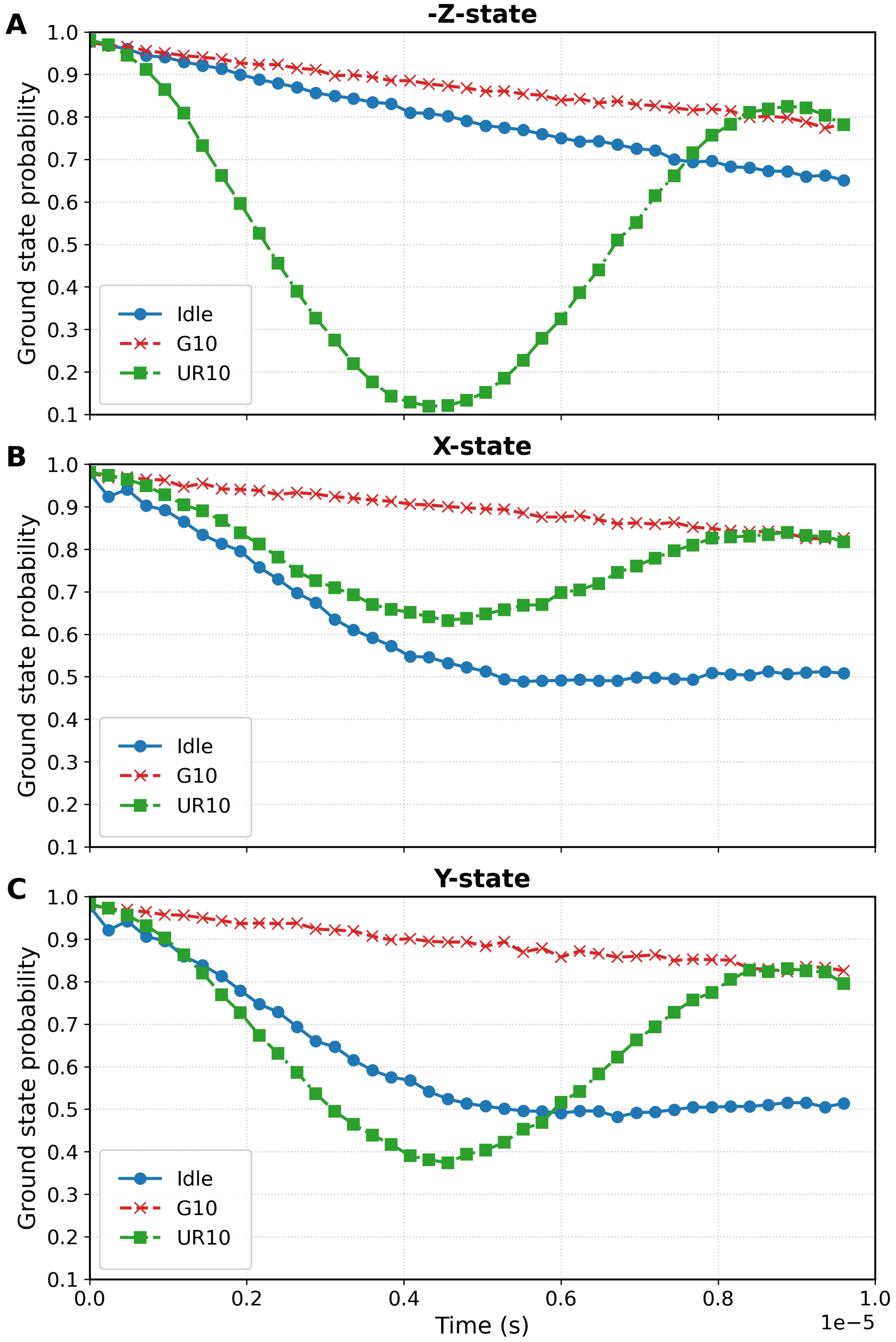
Manuscript under preparation

Dynamical Decoupling

New DD Sequences

- Numerically **optimized** to be **universal** and **robust**
- Tracking enabled

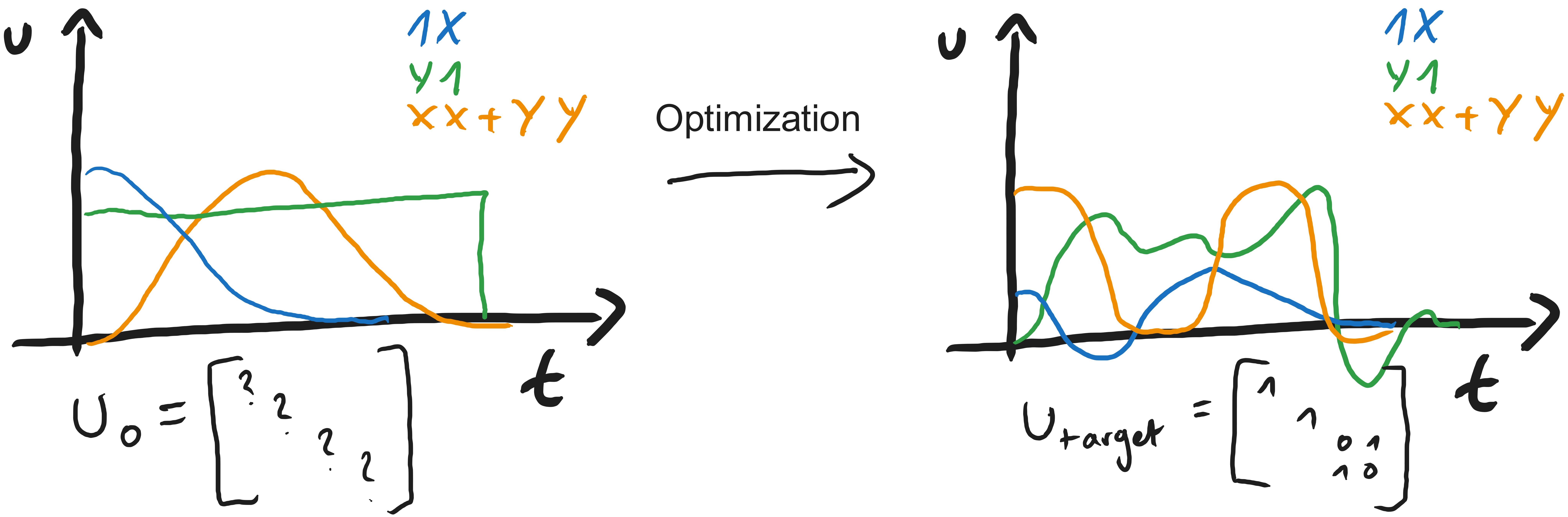
- Allows for longer protection for all states
- Extend the coherence times.
- Useful for suppressing errors during the execution of deep quantum circuits → an avenue to useful quantum computing!



Munich Quantum Valley

Use case: Pulse optimization

Pulse optimization



Design waveforms to drive a desired a **state-to-state** transfer or a **unitary evolution**

- Can be made time-optimal or robust to specific noise types, e.g. optimization in relaxation-free subspaces
- Pulses can be more time efficient than complex decompositions from basis gates

Gradient ascent pulse engineering (GRAPE)

Propagator for a single timestep

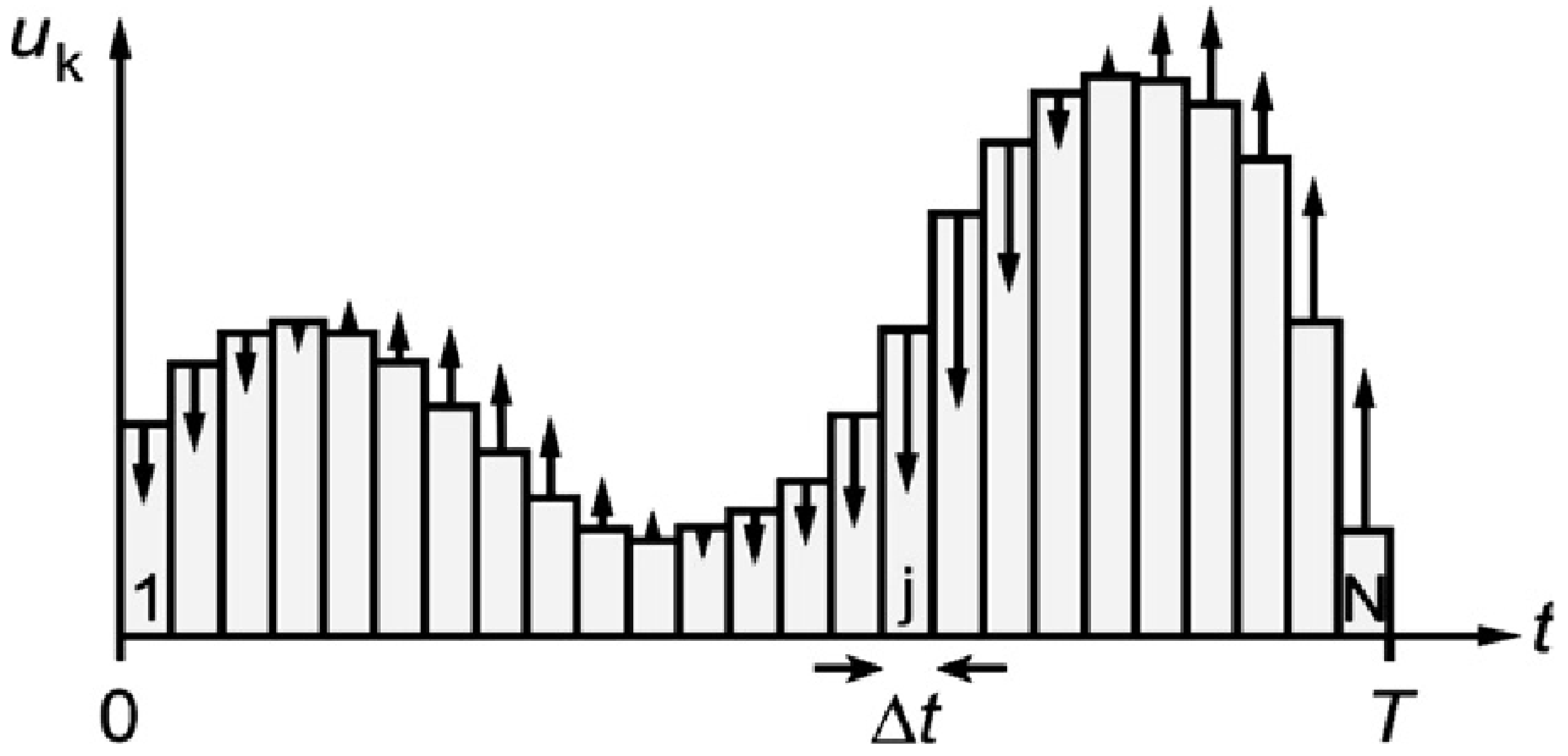
$$U_j = \exp\left[-i\Delta t\left(H_0 + \sum_{k=1}^{K} u_k(j) H_k\right)\right]$$

Cost function

$$\Phi = \frac{1}{d}\mathrm{Re}\,\langle U_{target}|U_N \dots U_1\rangle$$

Gradient per timestep per control

$$\frac{\delta\Phi}{\delta u_k(j)} = -\frac{1}{d}\,\langle U_{target}|U_N \dots U_{j+1} i\Delta t H_k U_j \dots U_1\rangle$$



[3] Khaneja et al.: Optimal control of coupled spin dynamics: Design of NMR pulse sequences by gradient ascent algorithms.

- N samples / propagators
- K controls
- K x N gradients per iteration

Closed-loop optimization

System Model

H $\mathcal{L}$

Target

U ρ

Initial control parameters

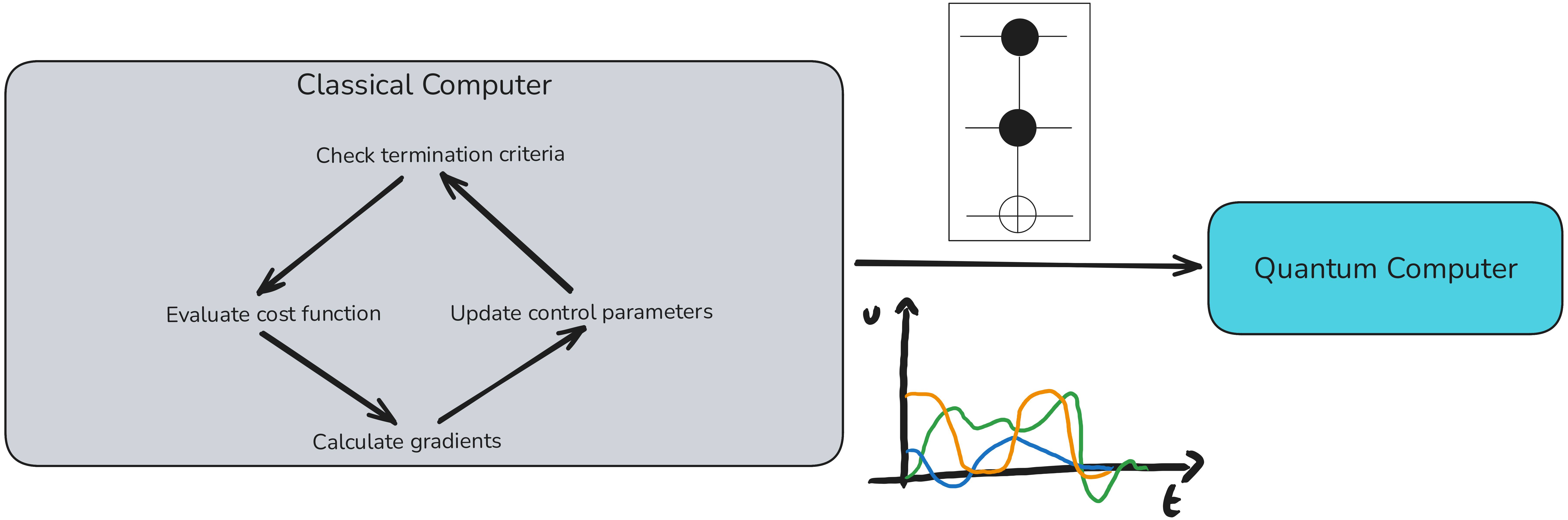
- Amplitudes
- Phases
- Frequencies
- ....

Constraints

- Maximum amplitudes
- ...

Hyperparameters

- Optimizer
- Learning rate (Stepsize)
- ...



✅ Use battle-proven classical optimizers

✅ Insight into every step of the dynamics

✅ Easy to incorporate robustness into the optimization

❌ Calculating the propagators ($\sigma(n^2)$) and their products ($\sigma(n^3)$) is exponentially expensive in the number of qubits

❌ Reliance on system model => cumbersome characterization to incorporate error sources, such as decoherence

Open-loop optimization

Munich Quantum Valley

~~System Model~~

~~$H \quad \mathcal{L}$~~

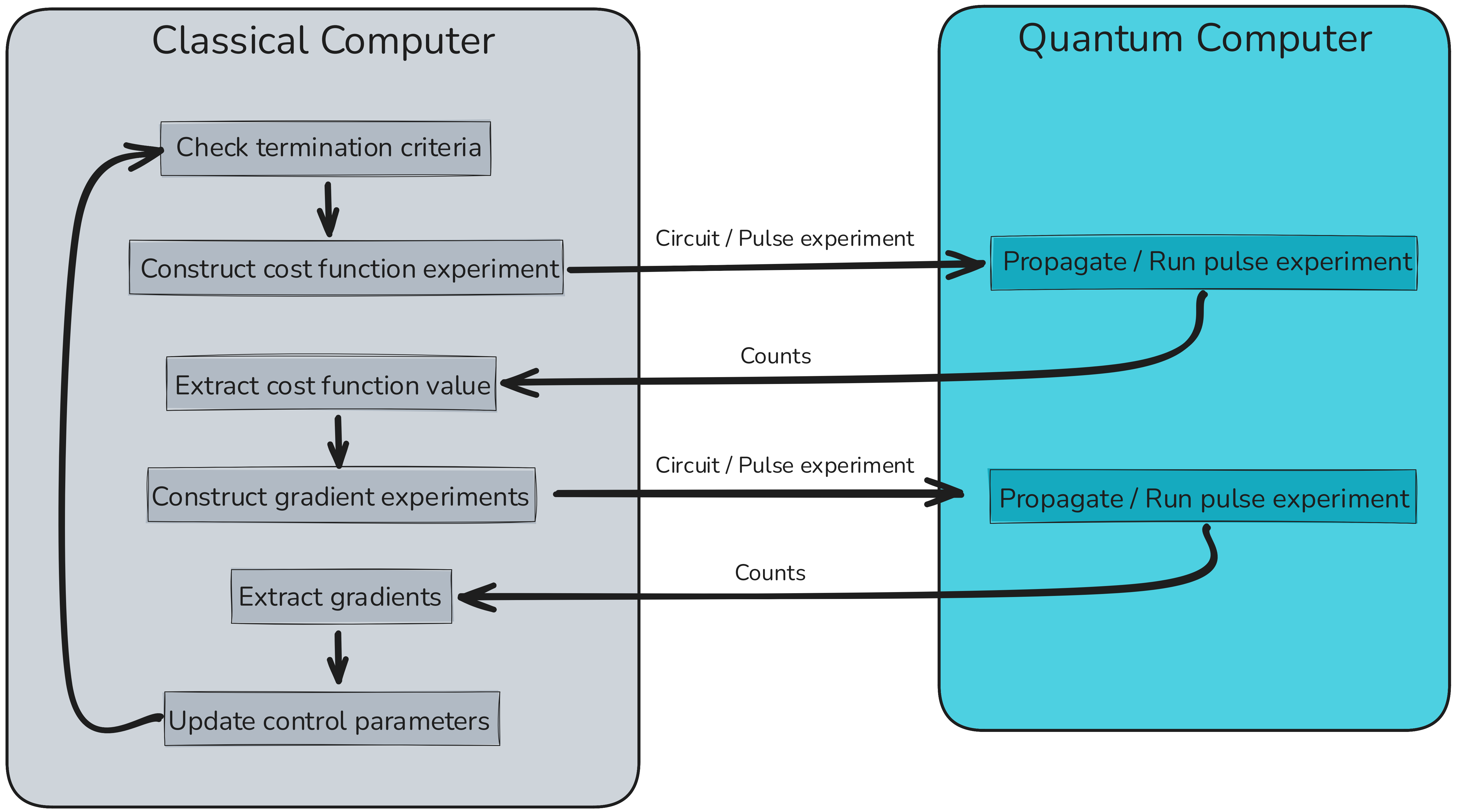
Target

$U \quad \rho$

Initial control parameters
- Amplitudes
- Phases
- Frequencies
- ....

Constraints
- Maximum amplitudes
- ...

Hyperparameters
- Optimizer
- Learning rate (Stepsize)
- ...



✅ No hardware characterization required

❌ No numerical access to propagators / states

❌ Experimental constraints

❌ Dependency on readout fidelity and existing gates

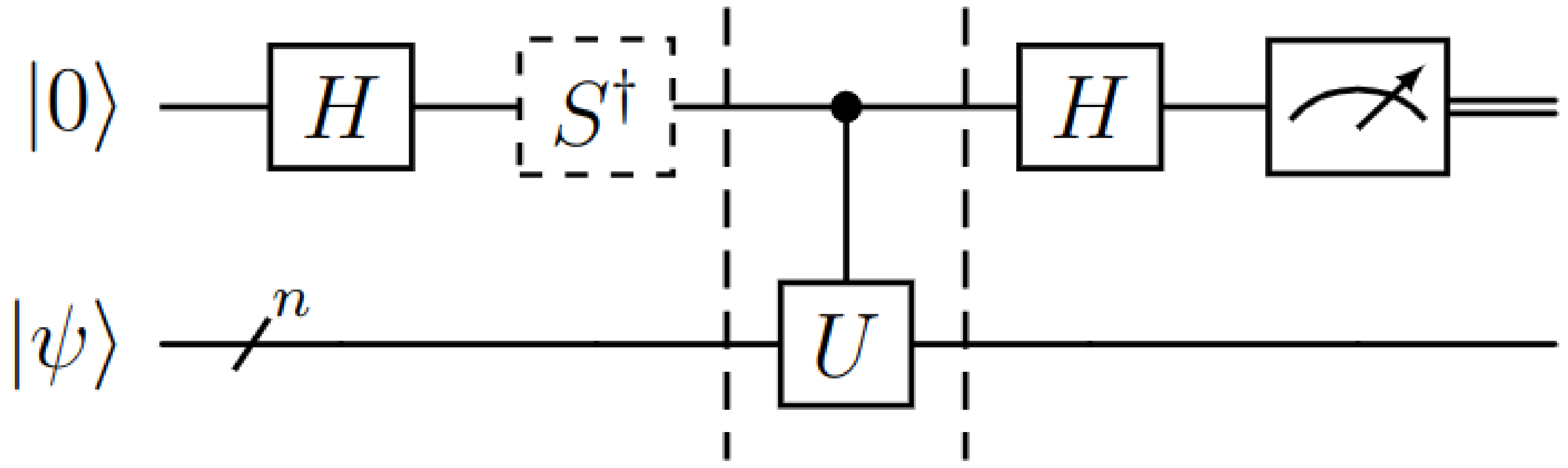
QGRAPE

- Closed–loop extension of GRAPE
- Leverage feedback of the system
- Optimize pulse-sequence towards existing processes (gates, gate-sequences) or ideal targets in special cases (Identity, π-rotations)

$$\Phi = \frac{1}{d} Re\left\{Tr\left[U^{\dagger}_{target} U_N \cdots U_1\right]\right\}$$

$$U = \begin{bmatrix} u_{11} & & & \\ & u_{22} & & \\ & & \ddots & \\ & & & u_{2^n 2^n} \end{bmatrix}$$

$$u_{ii} = \langle i | U | i \rangle, \text{ for basis states } \{|i\rangle\}$$

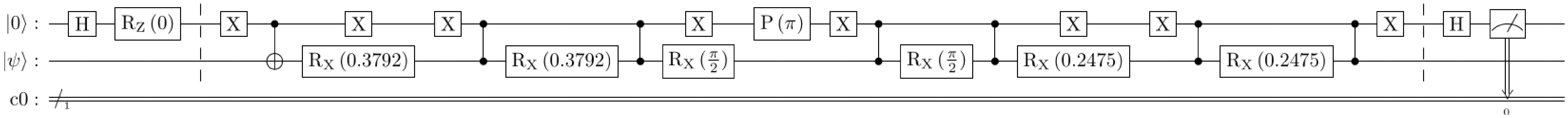


Hadamard test to extract $Re\left(\langle\psi| U |\psi\rangle\right)$ or $Im\left(\langle\psi| U |\psi\rangle\right)$ (with dashed gate)

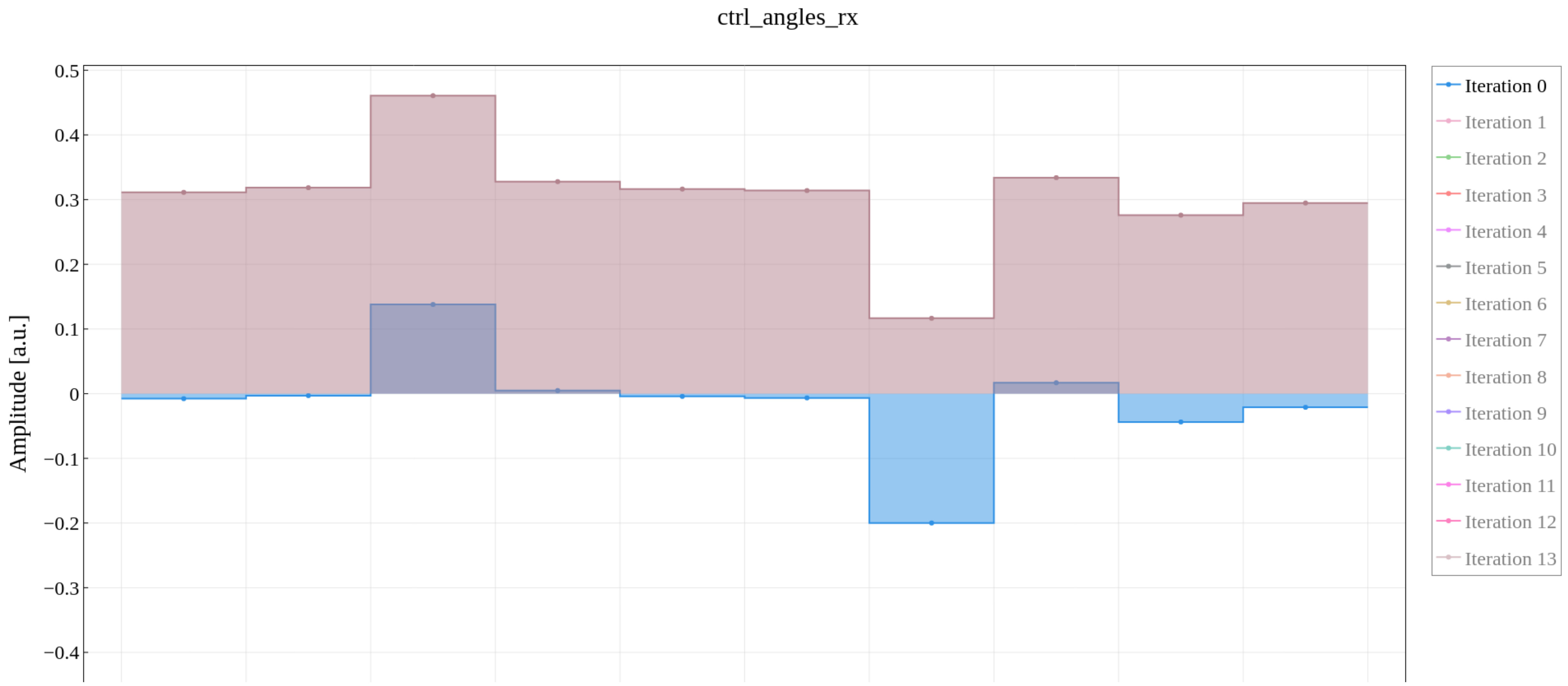
- Requires an implementation of a controlled U

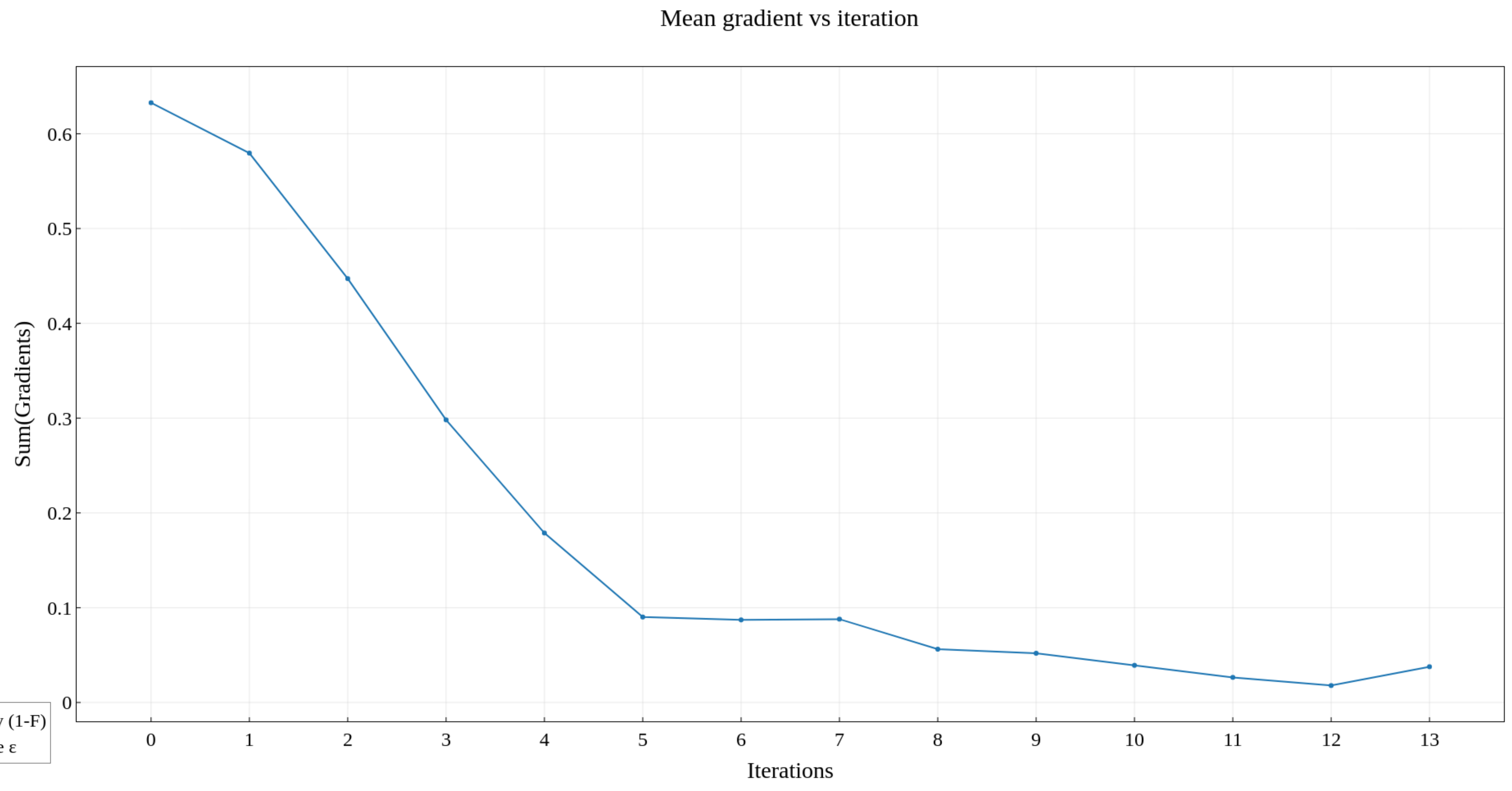
Manuscript under preparation

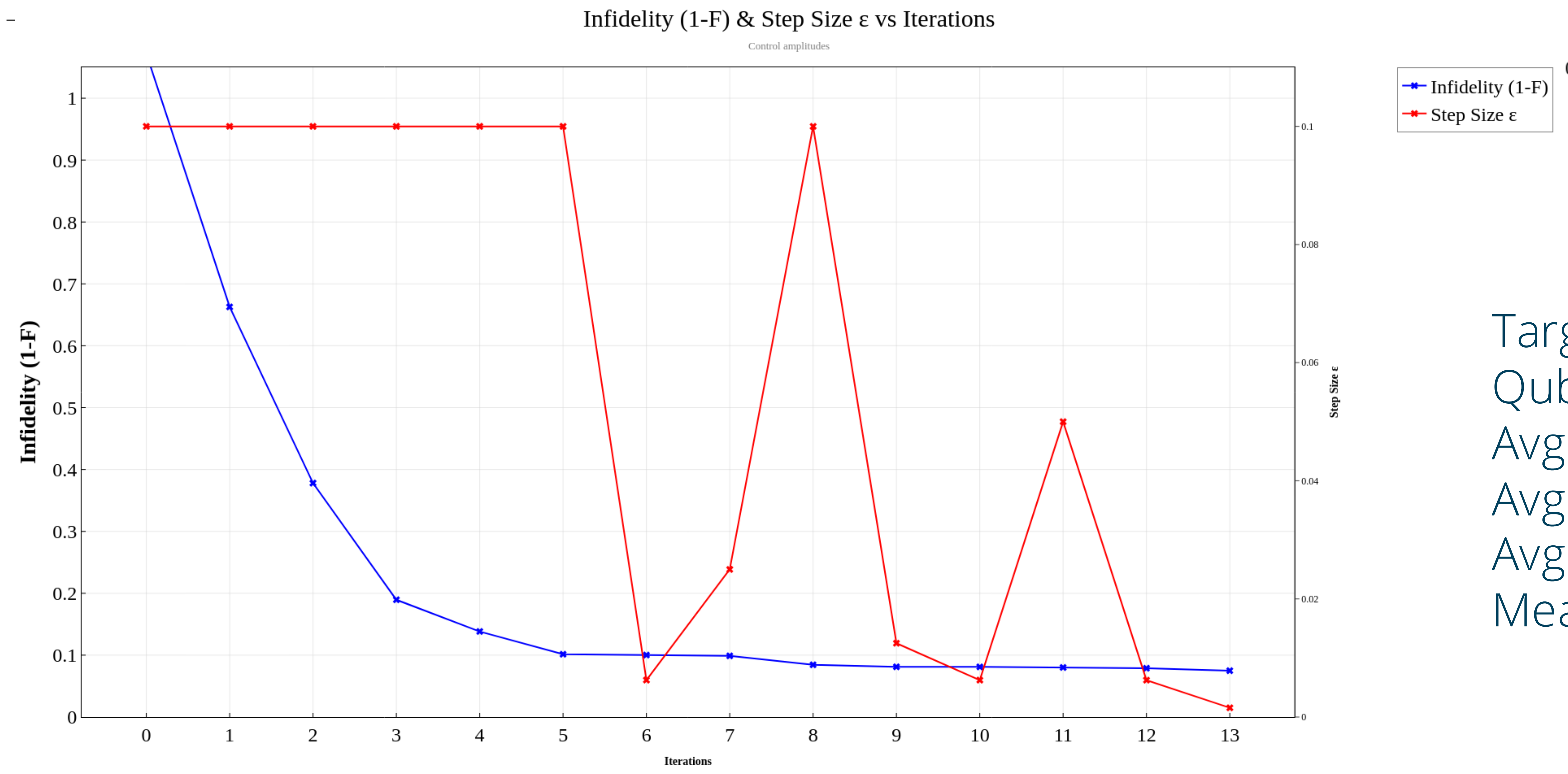
QGRAPE on IQM



QGRAPE on IQM







Target: σ_x
Qubits: 1,4 (QB2, QB5)
Avg. Gate error QB2: 0.8e-3
Avg. Gate error QB5: 1e-3
Avg Gate error CZ QB5-QB2: 6e-3
Measurement error QB2: 20e-3

After final iteration:

- Infidelity w.r.t. target: 80e-3
- Gradient Sum: 20e--3

Experimental result from IQM @ LRZ

Summary

- Relaxation creates a race against the clock for achieving useful quantum computation
- Drifting parameters diminish the fidelity of pre-calibrated pulses / gates
- Other noise sources, such as leakage and crosstalk

- Use case: Dynamical Decoupling to fight against relaxation and parameter drifts

- Use case: Pulse optimization to create low-noise, robust gates

- Great support from the LRZ and the hardware vendors

References

[1]: Krantz, Philip, et al. "A Quantum Engineer's Guide to Superconducting Qubits." *Applied Physics Reviews* 6, no. 2 (2019): 021318.
[2]: Overcoming Leakage on Error-Corrected Quantum Processors, Google Research Blog (2025)
https://research.google/blog/overcoming-leakage-on-error-corrected-quantum-processors/
[3]: Khaneja et al.: Optimal control of coupled spin dynamics: Design of NMR pulse sequences by gradient ascent algorithms