Theory and Phenomenology of Fundamental Interactions
UNIVERSITY AND INFN · BOLOGNA

Workshop Quantum Computing and High Performance Computing
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# Bayesian Adaptive Techniques for Quantum Optimization on NISQ devices

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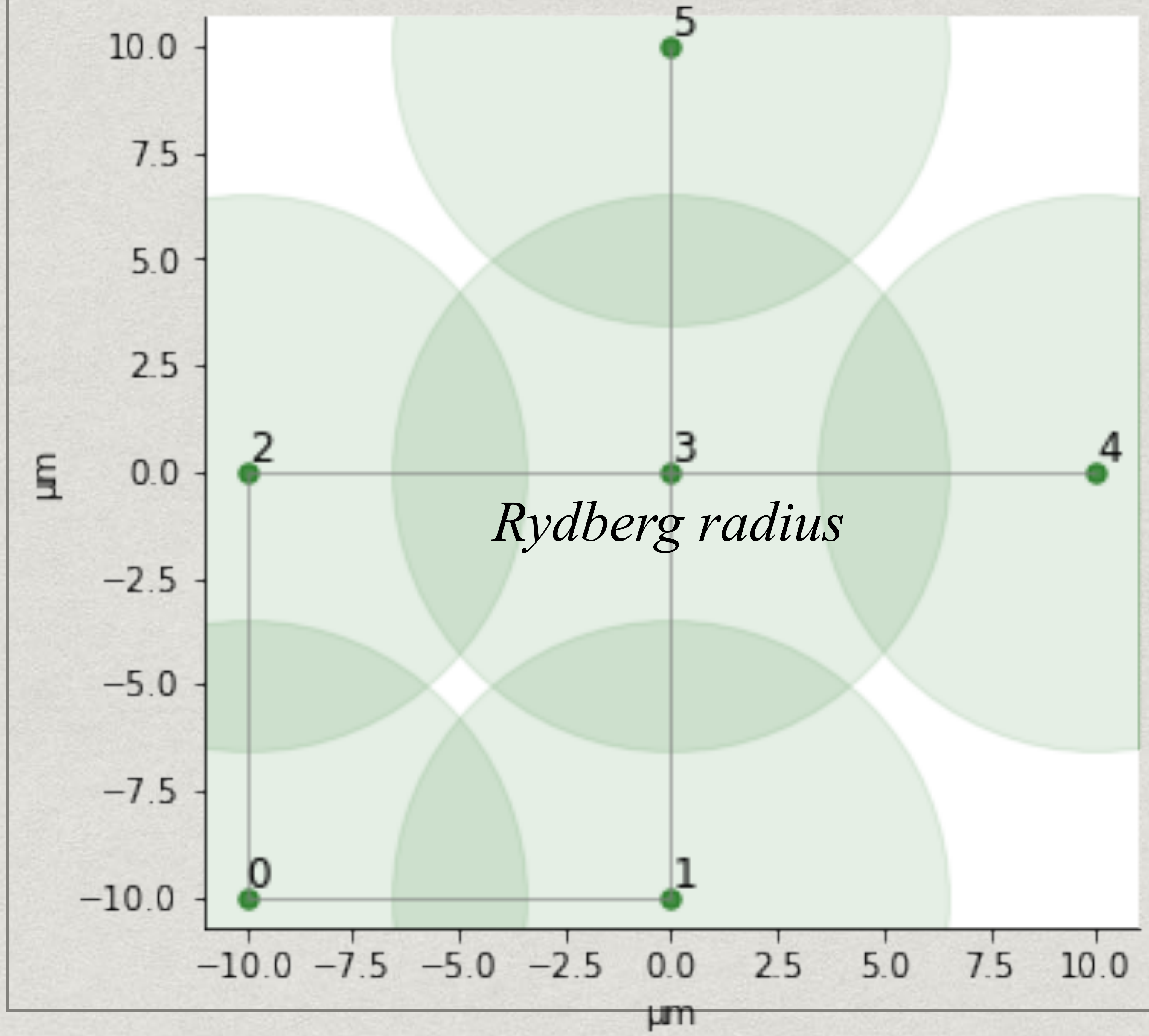
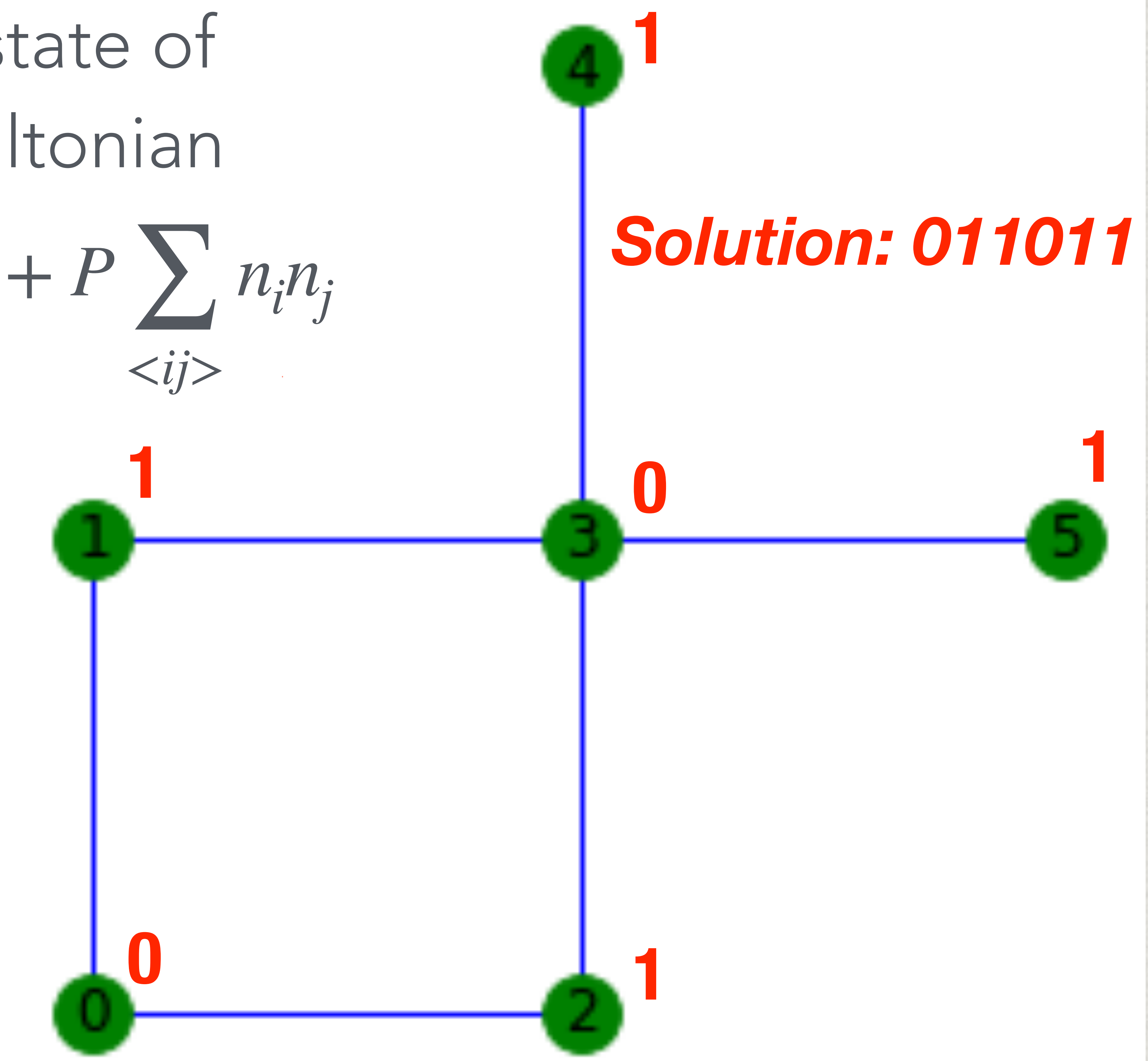
## Maximal Independent Set (MIS) problem:

find the set with the maximum number of vertices of a graph not linked to the others




ground state of the Hamiltonian

$$C = -\sum_j n_j + P \sum_{<ij>} n_i n_j$$



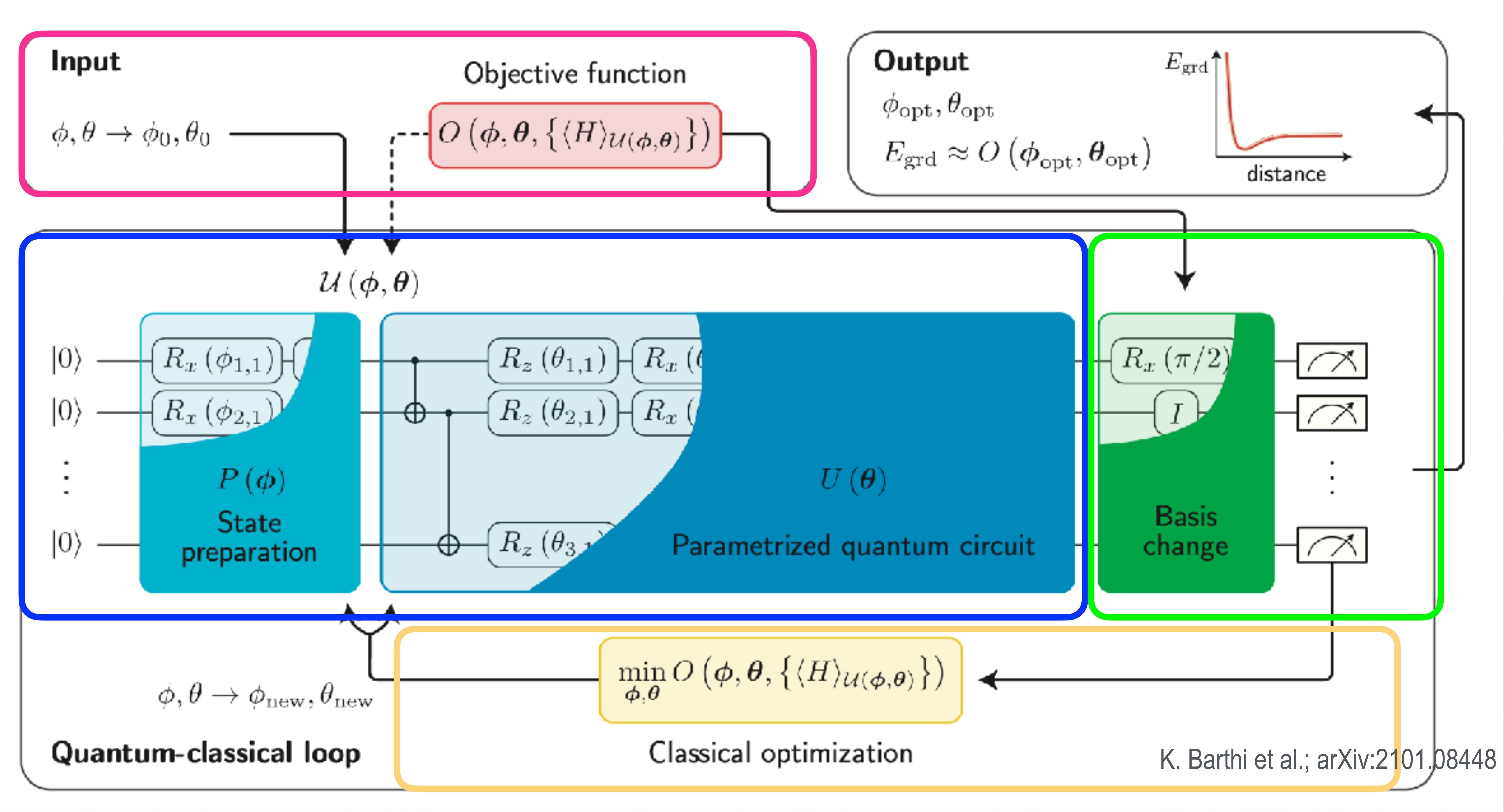

- *Topology* of the graph is encoded in the simulator through Rydberg blockade
- Assuming *analog processing* only (global pulses)

$$\mathscr{H}(t) = \frac{\hbar}{2}\boxed{\Omega(t)}\sum_j \sigma_j^x - \hbar\boxed{\delta(t)}\sum_j n_j + \sum_{i\neq j}\frac{C_6}{r_{ij}^6} n_i n_j$$

# • Hybrid classical-quantum protocol: QAOA

(quantum approximate optimisation algorithm)

Farhi et al.- arXiv:1411.4028 (2014)




### *quantum*

- Objective function to be minimised
- Quantum evolution (circuit) with variational parameters
- Measurement scheme for average Hamiltonian to get objective function

### *classical*

- Optimisation algorithm to get the best values of the parameters

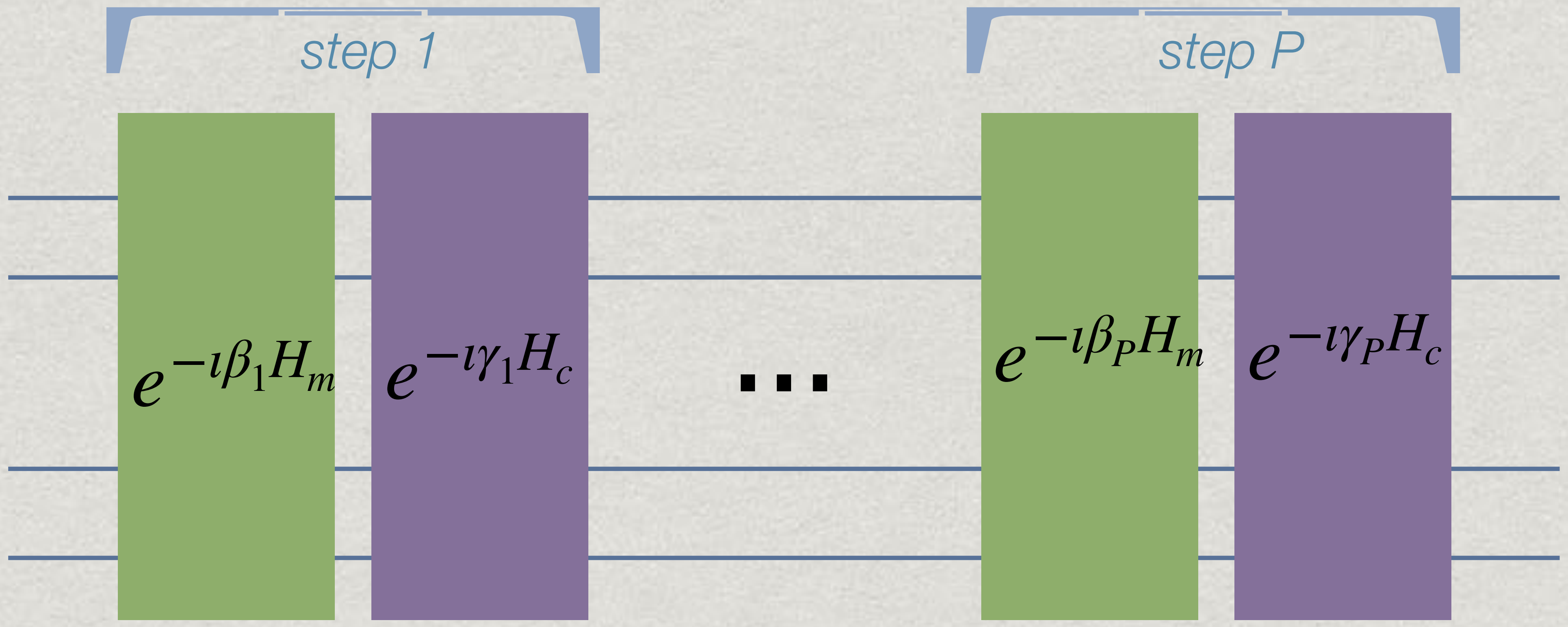
✓ All these steps have theoretical issues to be kept under control

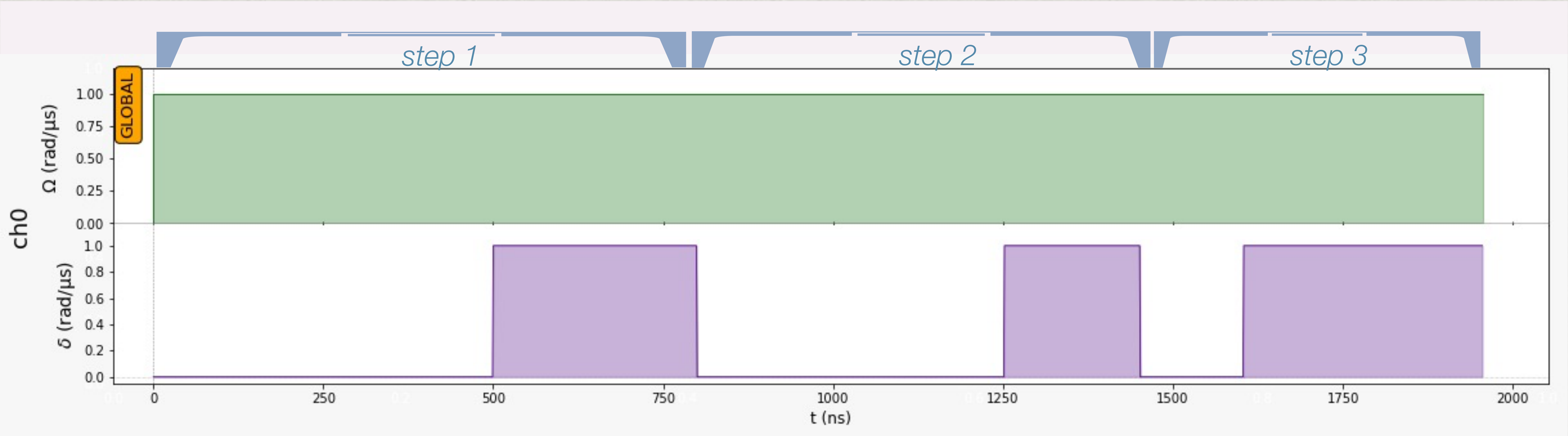
✓ All these steps might become easily very resource demanding: NISQ device?

# • The quantum circuit

$$H_m = \frac{\hbar\Omega}{2}\sum_i \sigma^x + \sum_{i<j} U_{ij} n_i n_j$$

$$H_c = \frac{\hbar\Omega}{2}\sum_i \sigma^x - \frac{\hbar\delta}{2}\sum_i \sigma^z + \sum_{i<j} U_{ij} n_i n_j$$

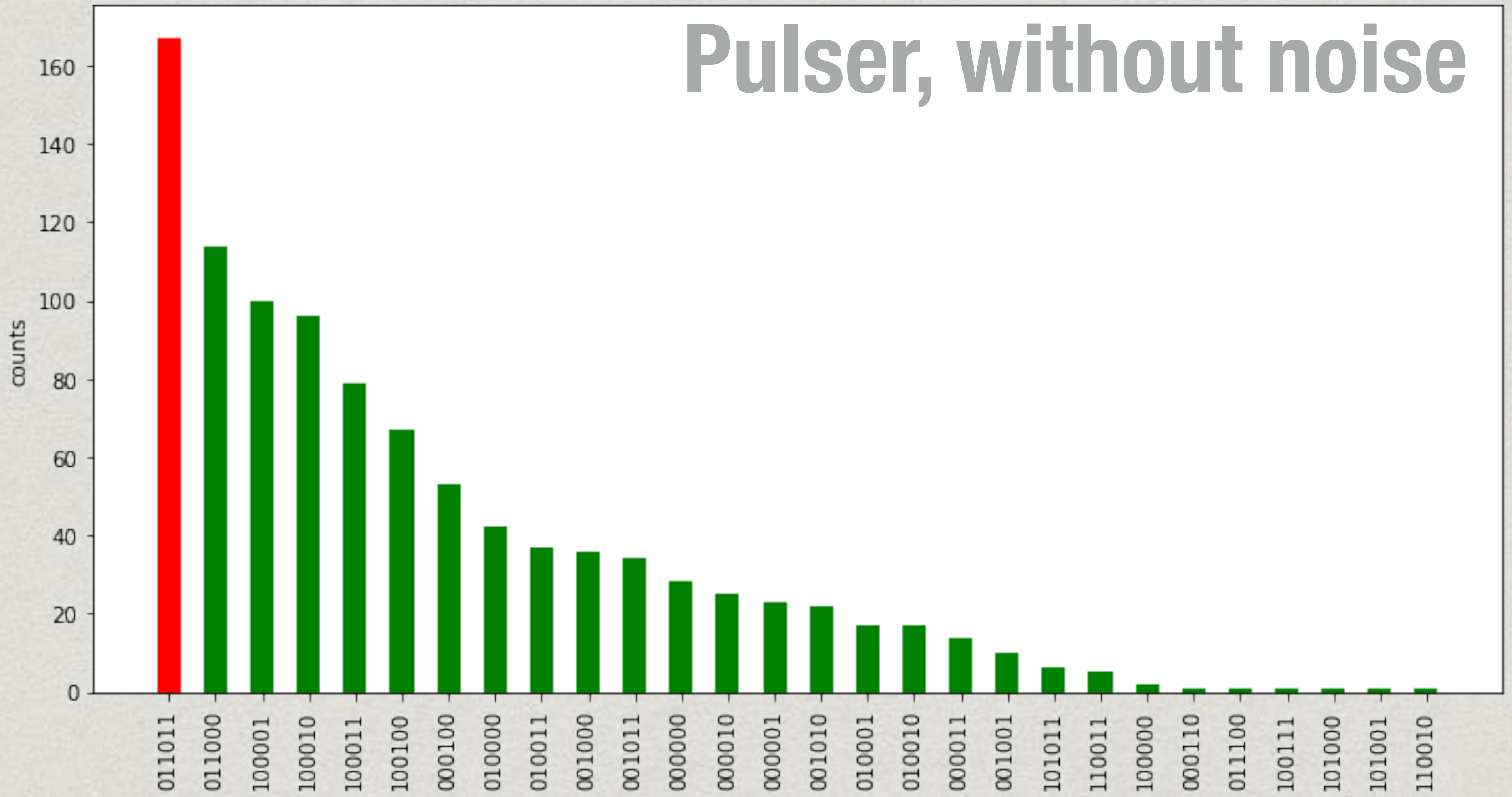


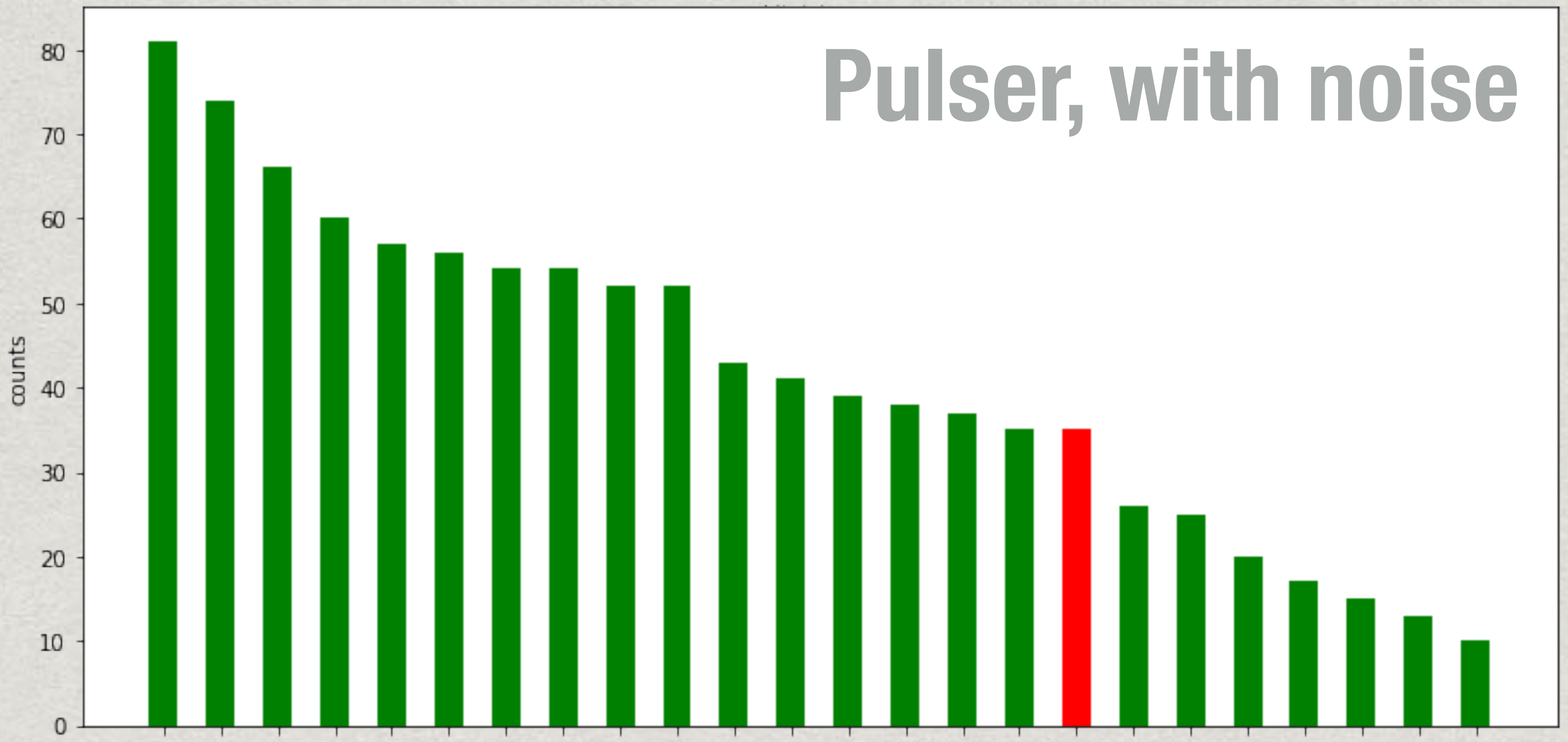




*Pulser emulators: signals for P=3*

*Time: T~2 $\mu s$*

# Measurement of the cost function




- On the final state, we measure the value of the objective function

$$C = -\sum_{j} n_j + P \sum_{<ij>} n_i n_j \quad (P = 2)$$

- We repeat the evolution and the measure $N_{shot}$ times to get an histogram of the probability to find each computational state, from which one gets the average value of $C$

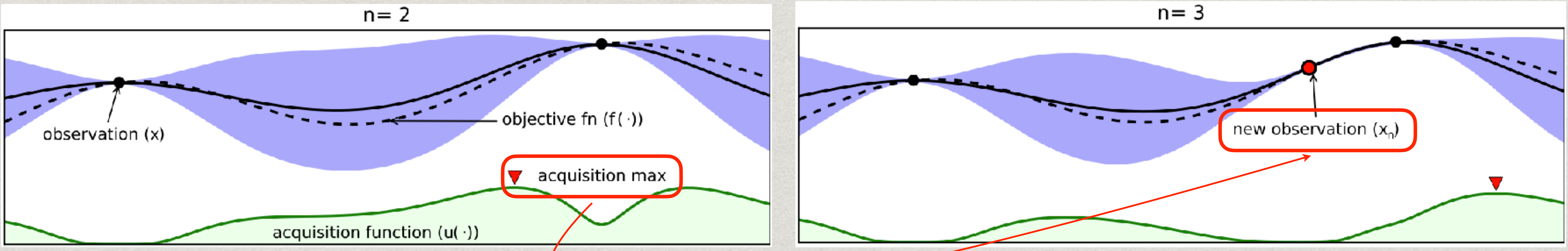
**On real computer: TIME =** $0.2\ s \times N_{shot}$

# • Classical optimisation: Bayesian approach

✓ Use Bayesian inference to reduce the number $N_{shot}$ of experimental acquisitions

✓ The optimization problem shifts from finding the min in the energy landscape to the max in the acquisition function landscape, which - *on the basis of previous measurements- gives us the best point where to perform the new measurement*

✓ Genetic (differential evolution ) algorithm: a starting set of points are "mutated" into new one, keeping only the best ones - up to convergence




Convergence parameters:

STD ENERGY < 10E-5
(ensures every point tends to same value)

$$Kernel: \quad K(x_1, x_2) = \sigma_f^2 \exp[-|x_1 - x_2|^2/(2l^2)]$$

*constant* *correlation length*

AVERAGE SQUARED DISTANCE < 10E-2
(ensures convergence to the same spot in flat landscapes)

# • COMPLETE PROTOCOL

## RECAP OF THE PARAMETERS

- BOUNDS for ANGLES: $\beta, \gamma \in [100{,}3000]$
- $N_{shot} = 128$

quantum circuit

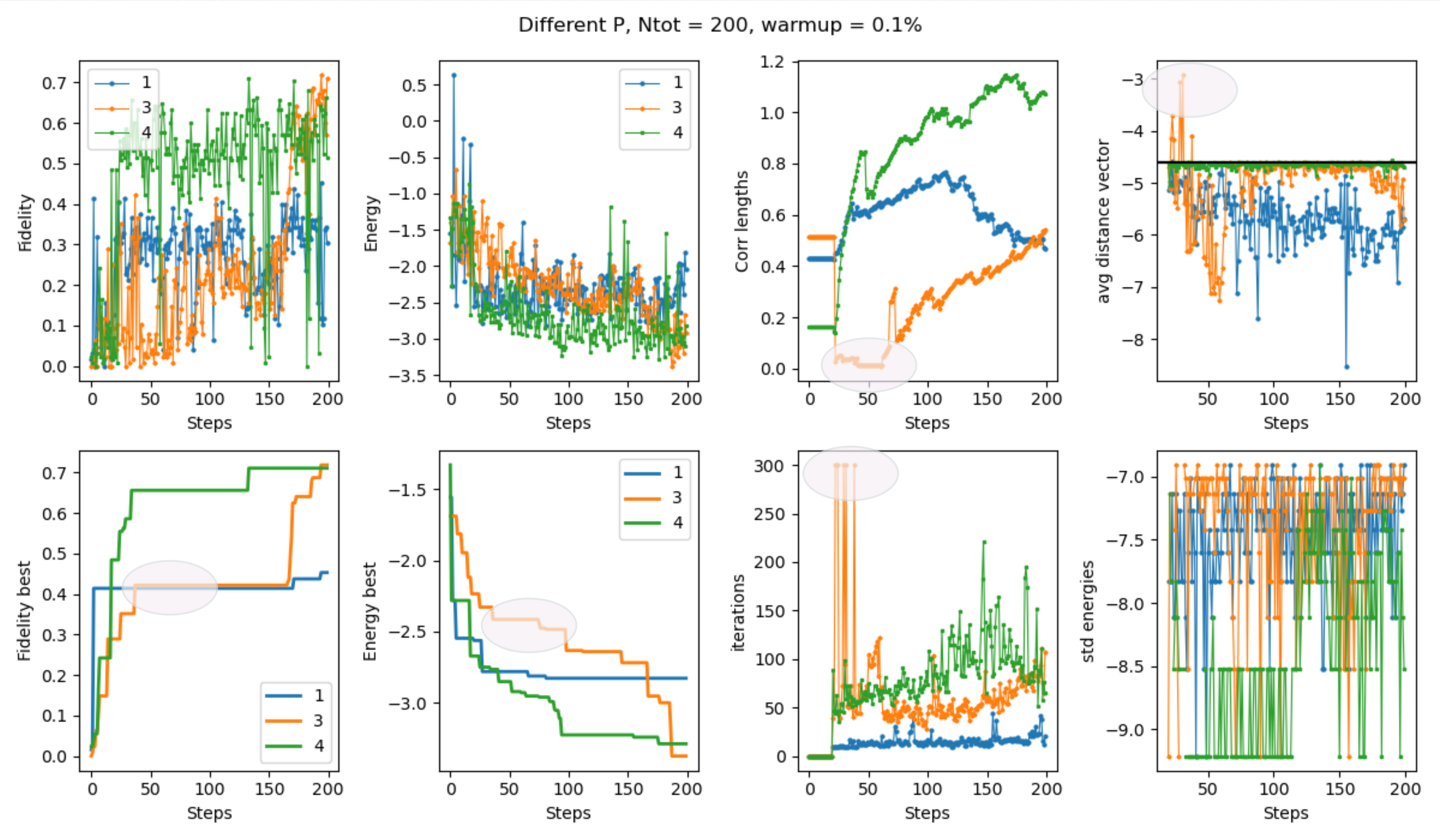
QAOA protocol

- DEPTH P=1,2,…,9
- # initial points: 10-20
- # steps: ~ 200

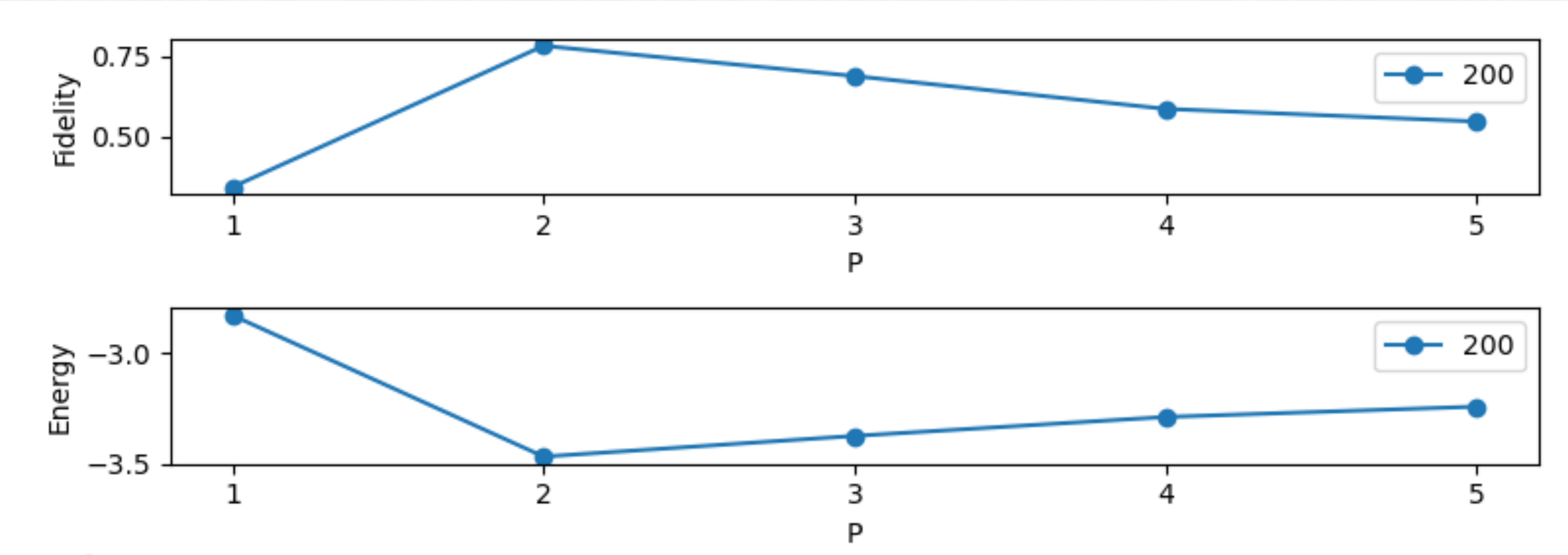
- max # iteration: 100*P
- STD ENERGY CONVERGENCE: 10E-5
- AVG DISTANCE CONVERGENCE: 10E-2
- kernel corr. length bounds: [10e-2, 10e2]
- kernel constant bounds: [10E-5, 10E5]

differential evolution

# • Analysis of results

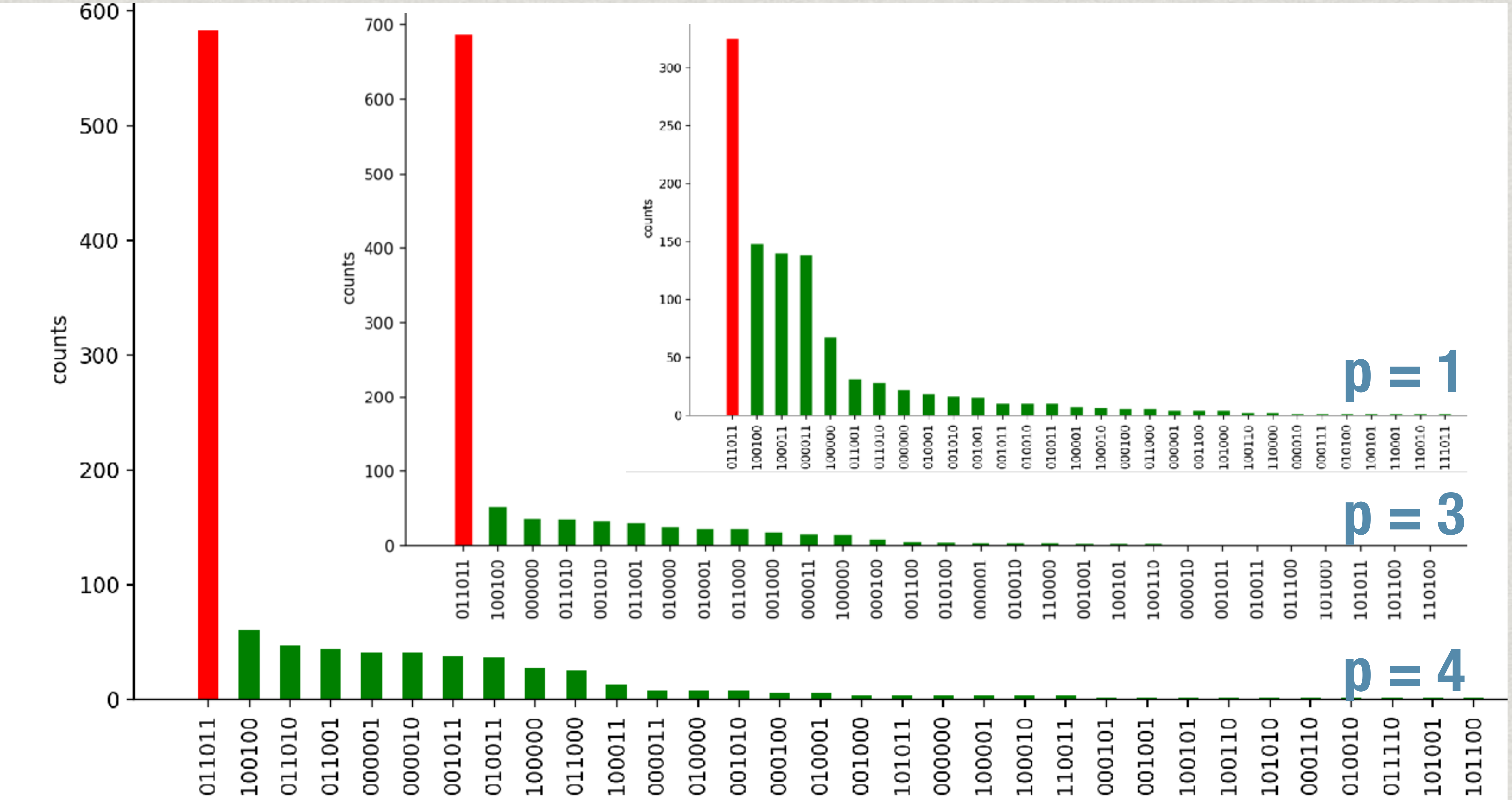


- Summary: best energy/fidelity vs. depth P



- # Analysis of final state

The ratio of counts between the solution and second most likely state



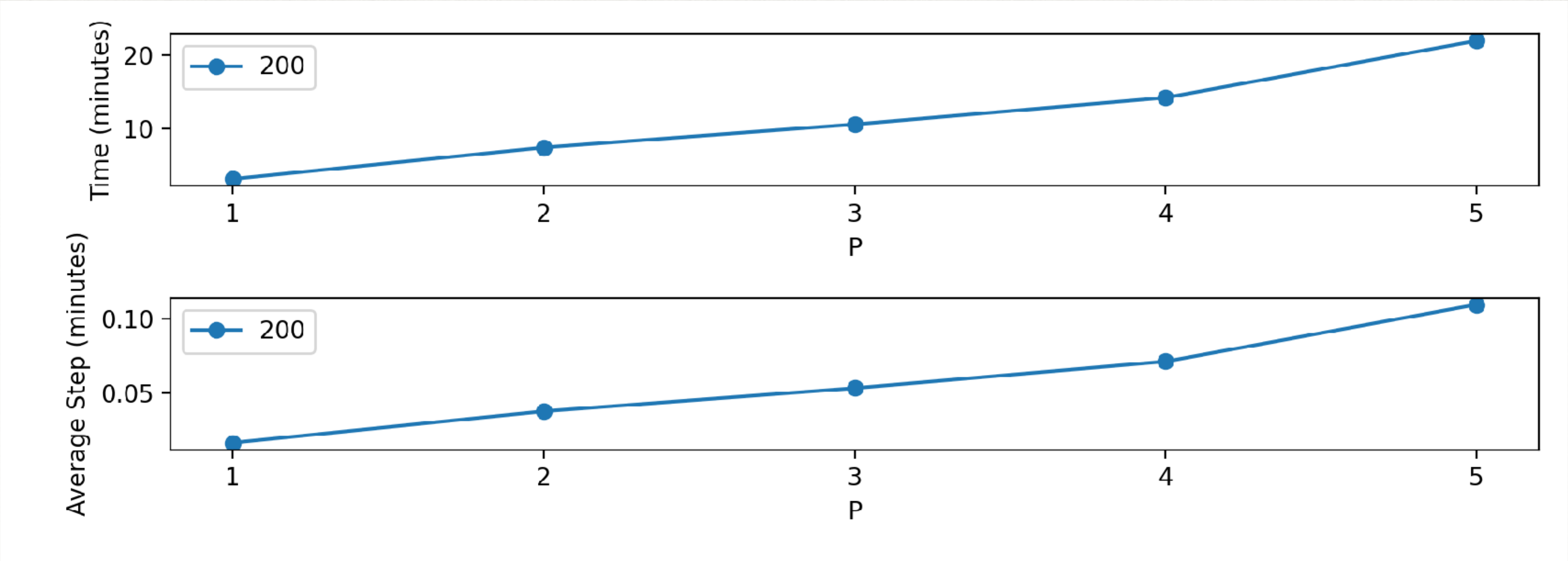

**RATIO**

**2.1**

**11.3**

**9.1**

# • Time (total=quantum+classical simulation)




- Differential evolution is slow, about 90% of computation time
- Total # quantum circuit evolutions: $N_{shot} * N_{step}$

# WHAT'S NEXT?

CINECA

- Optimise our software and run on Galileo 100
- Benchmark Baysian approach with other classical optimisation strategies

PASQAL

- Run simulations on Pulser with (different kinds of) noise
- Run on real atomic platform