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OPTIMIZATION

Exponentially-Biased Ground-State Sampling of Quantum Annealing Machines with Transverse-Field Driving Hamiltonians

Dr. Salvatore Mandrà

What is **fair sampling?**

Definition (fair sampling):

- The ability of an algorithm to find all solutions of a degenerate problem with equal probability when run in **repetition mode**

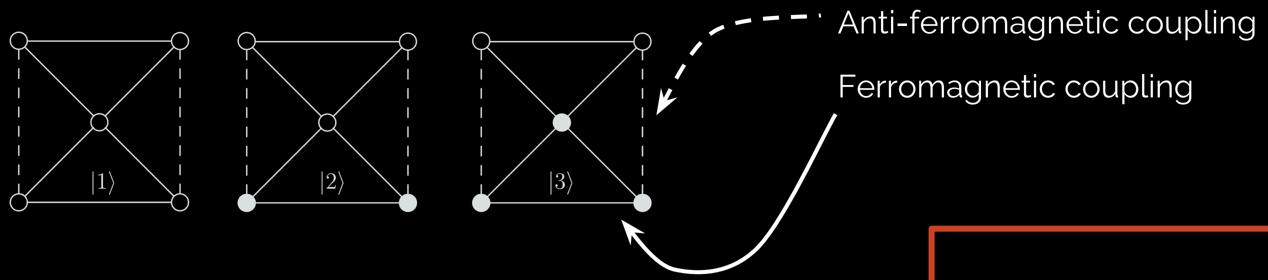
Why is it important?

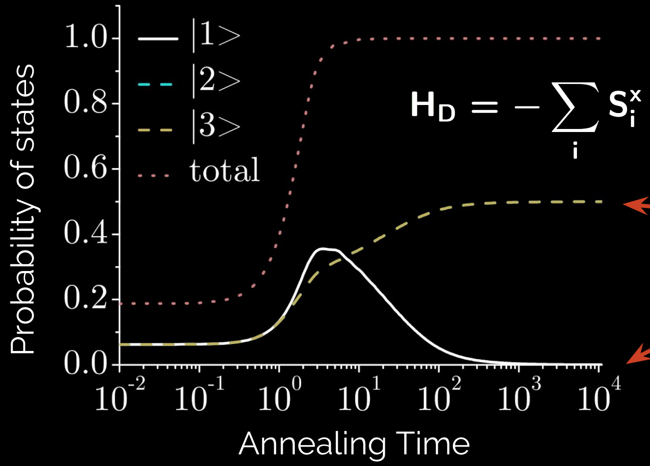
- In some contexts (SAT-Filter, #SAT, machine learning, …) finding a **good variety** of solutions is more important than finding a single solution quickly

Optimize benchmarking:

- Standard test: Find the ground-state energy **fast and reliably**
- Stringent test: Find **all minimizing configurations** equiprobably

Previous studies on transverse field QA [1]

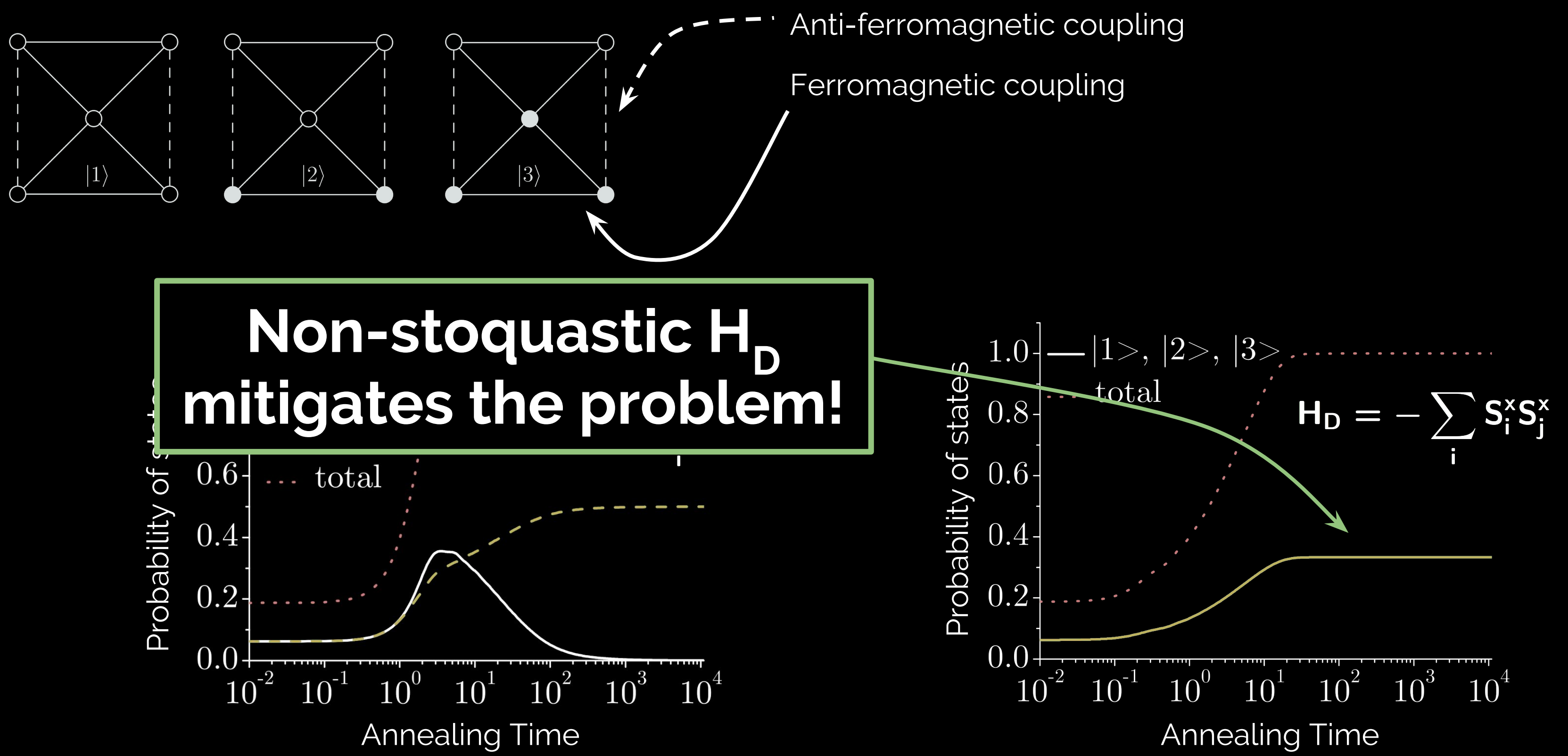




Transverse field QA is biased …

[1] Y. Matsuda, H. Nishimori & H. G Katzgraber, "Ground-state statistics from annealing algorithms: quantum versus classical approaches.", New Journal of Physics, 11(7), 073021 (2009)

Previous studies on transverse field QA [1]



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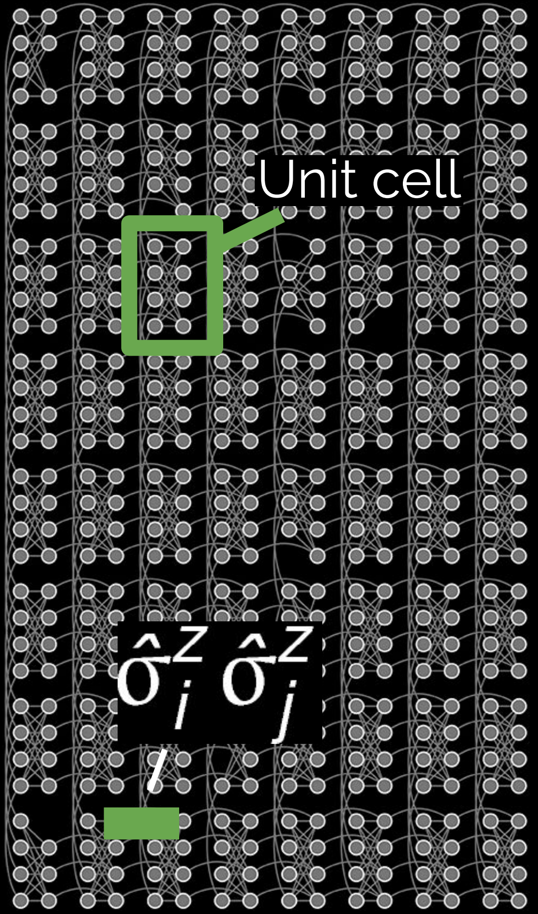
The D-Wave 2X quantum annealer



H_p

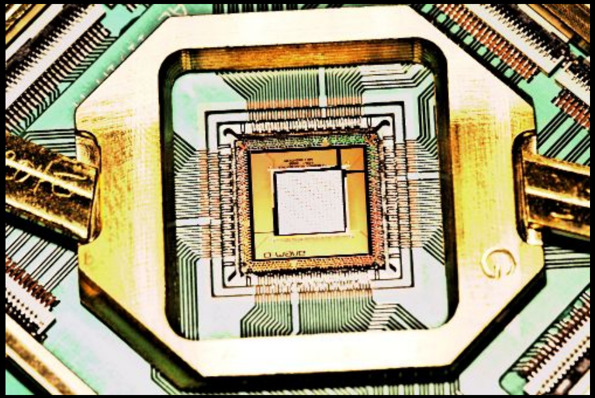
$$H_D = -\sum_i \hat{\sigma}_i^x$$

- Unavoidable **noise**

- Non-zero **temperature**

~1000 working qubits

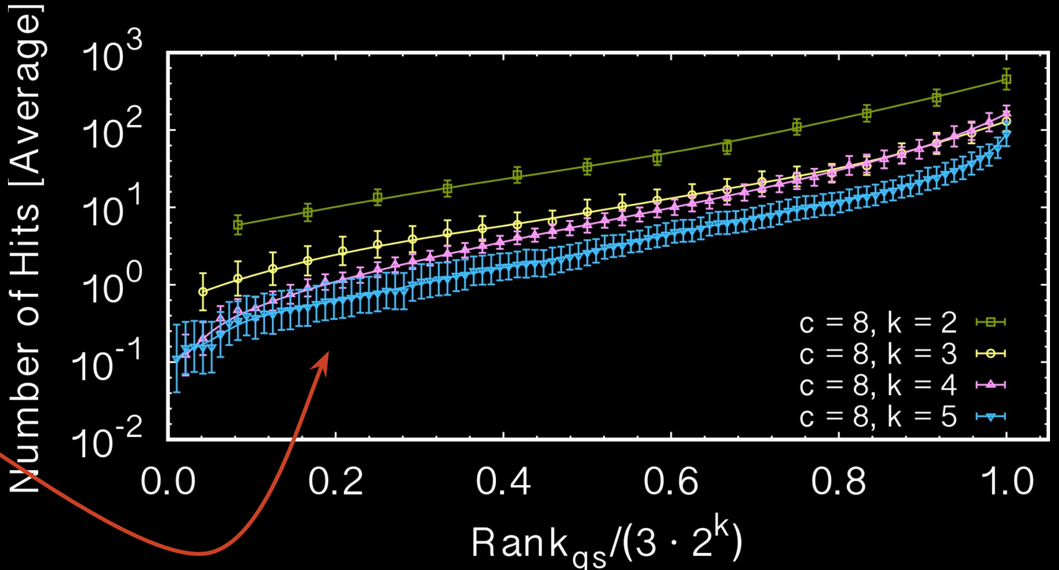
Superconducting qubit chip



Experimental analysis using DW2X device [1]

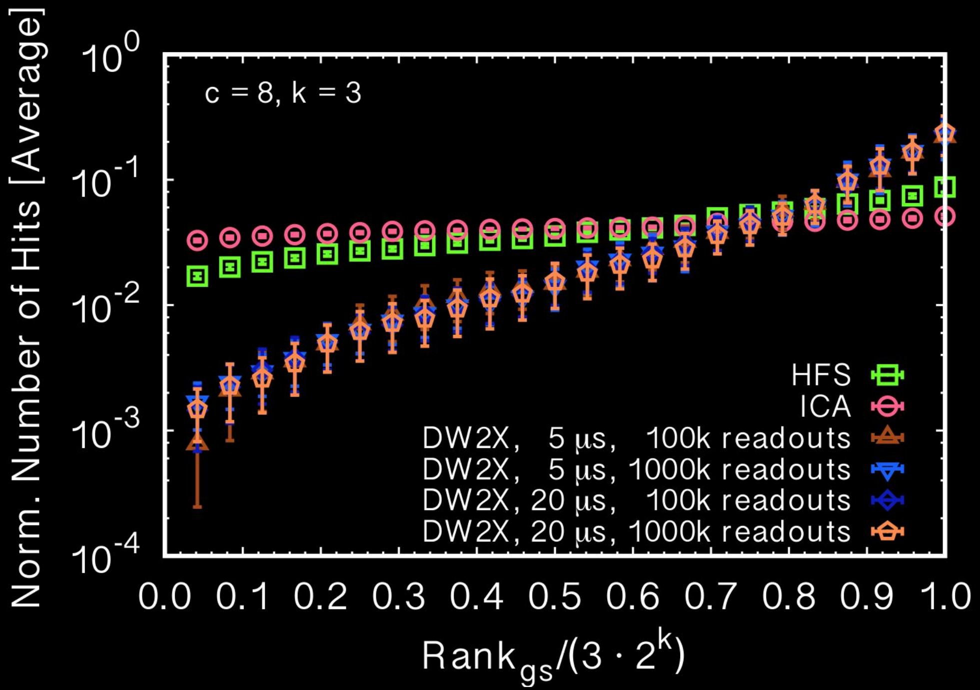
- Random couplings from **Sidon set** (J_{ij} = ±5, ±6, ±7 on Chimera of *c x c* unit cells)
- Limit the study to instances with **well controlled degeneracy** ($\#_{gs} = 3 \cdot 2^k$)
- No **trivial** degeneracy
- 100 gauges x {10k, 100k} readouts
- T_{ann} = 5μ, 20μ, 200μ

DW2X is exponentially biased!



[1] **S. Mandrà**, Z. Zhu & H. G. Katzgraber, "Exponentially-Biased Ground-State Sampling of Quantum Annealing Machines with Transverse-Field Driving Hamiltonians", arXiv:1606.07146

Classical algorithms sample more homogeneously



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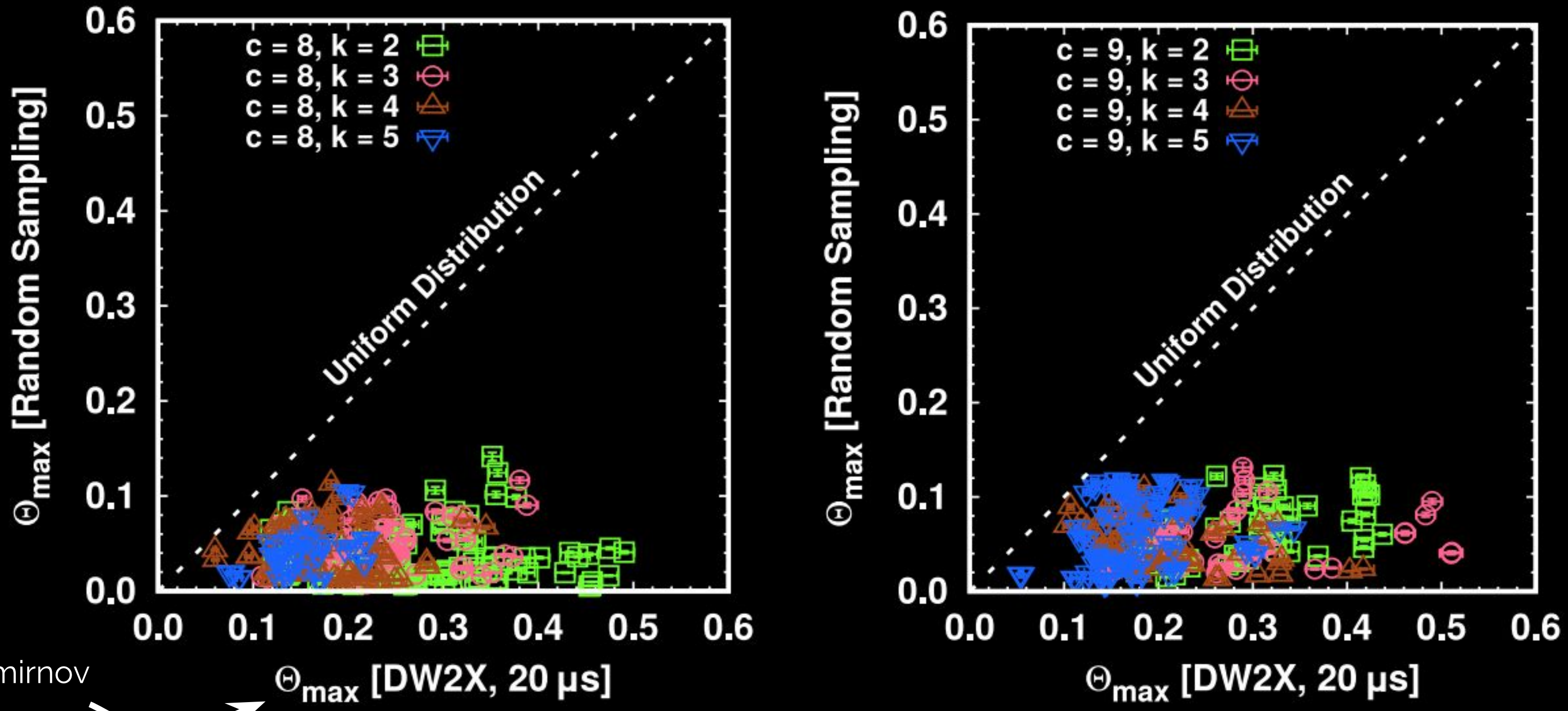
[2] F. Hamze & N. de Freitas, Proceedings (2004), A. Selby, arXiv (2014)

[3] Z. Zhu, A. J. Ochoa & H. G. Katzgraber, PRL (2015)

Experimental analysis using DW2X device [1]



Kolmogorov-Smirnov Test

[1] **S. Mandrà**, Z. Zhu & H. G. Katzgraber, “Exponentially-Biased Ground-State Sampling of Quantum Annealing Machines with Transverse-Field Driving Hamiltonians”, arXiv:1606.07146

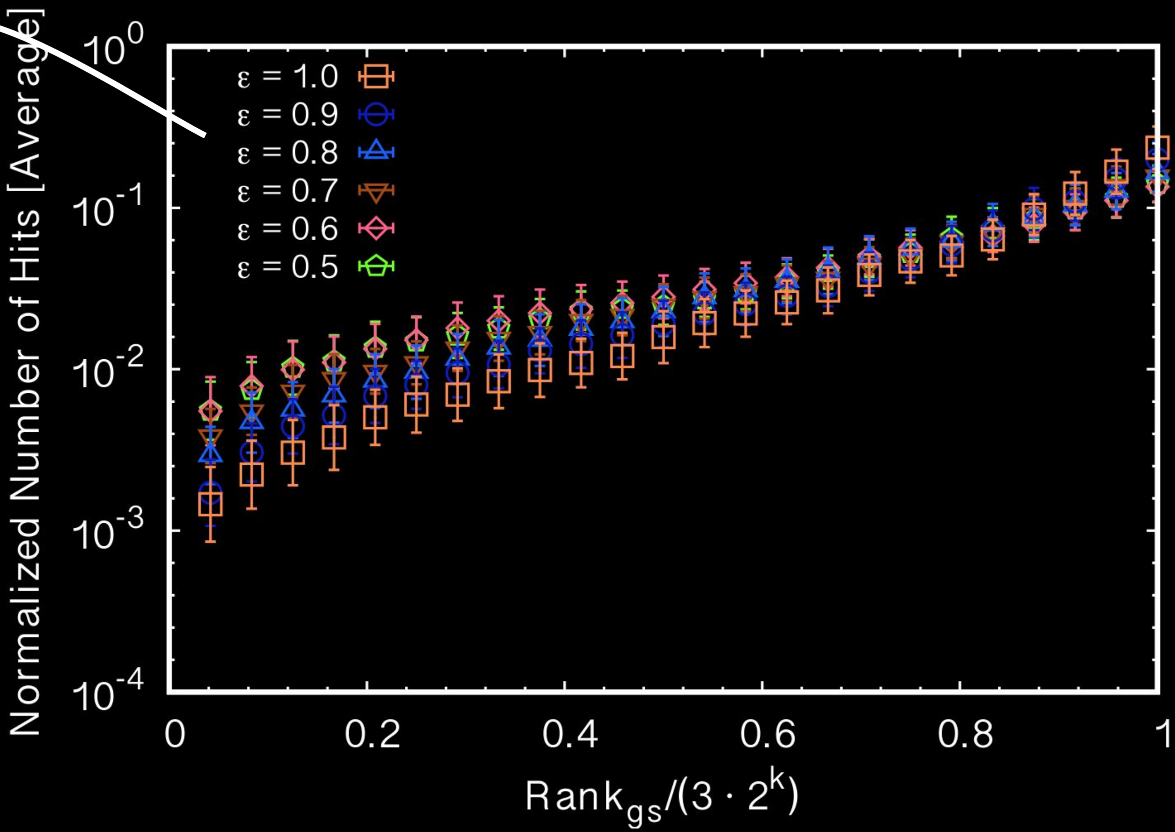
Could the bias be a consequence of the intrinsic noise of the DW2x?

No.

The bias is unchanged by rescaling the energy

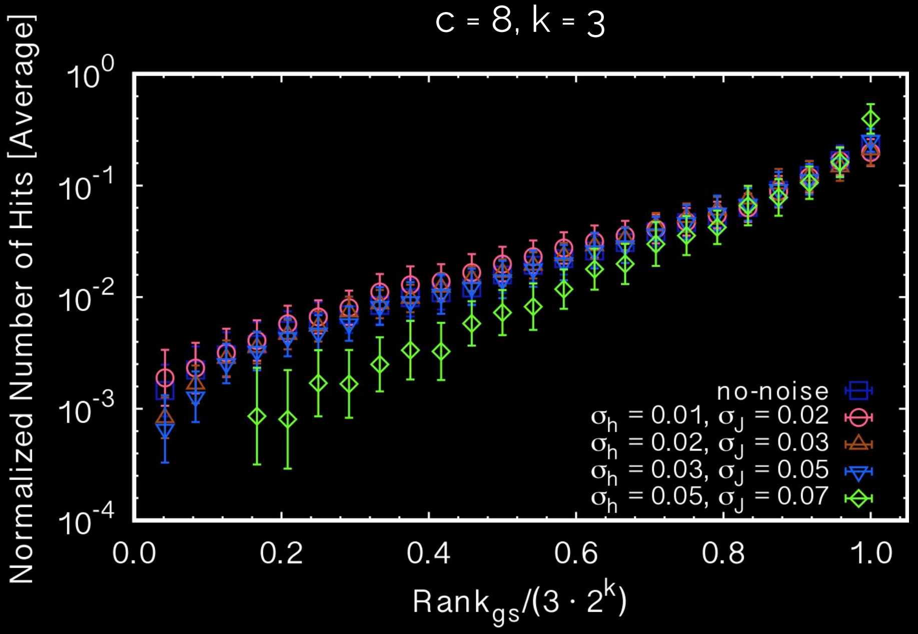
- Energy of the target problem rescaled by a factor ε

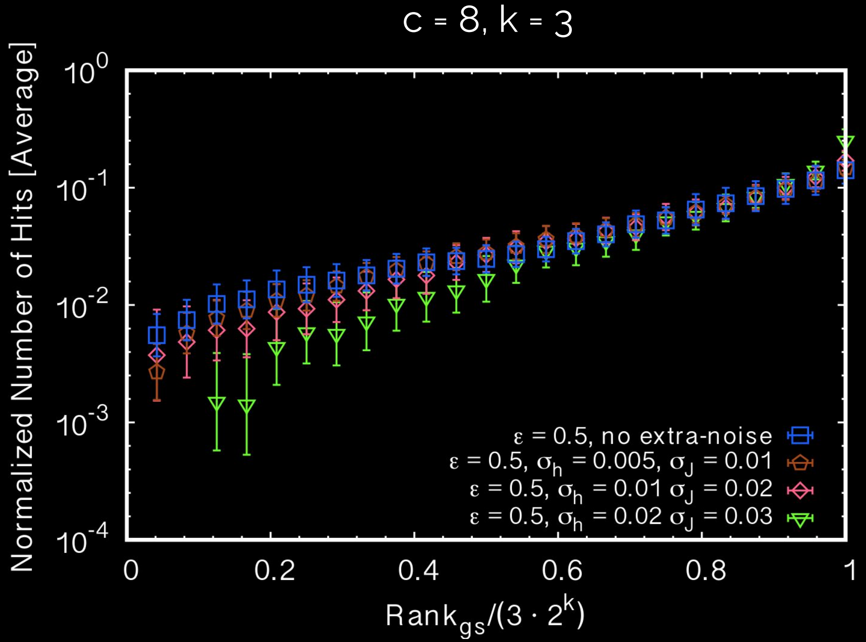
- Intrinsic noise rescaled by a factor 1/ε



[1] **S. Mandrà**, Z. Zhu & H. G. Katzgraber, In preparation (2017)

Adding extra noise does not change the bias





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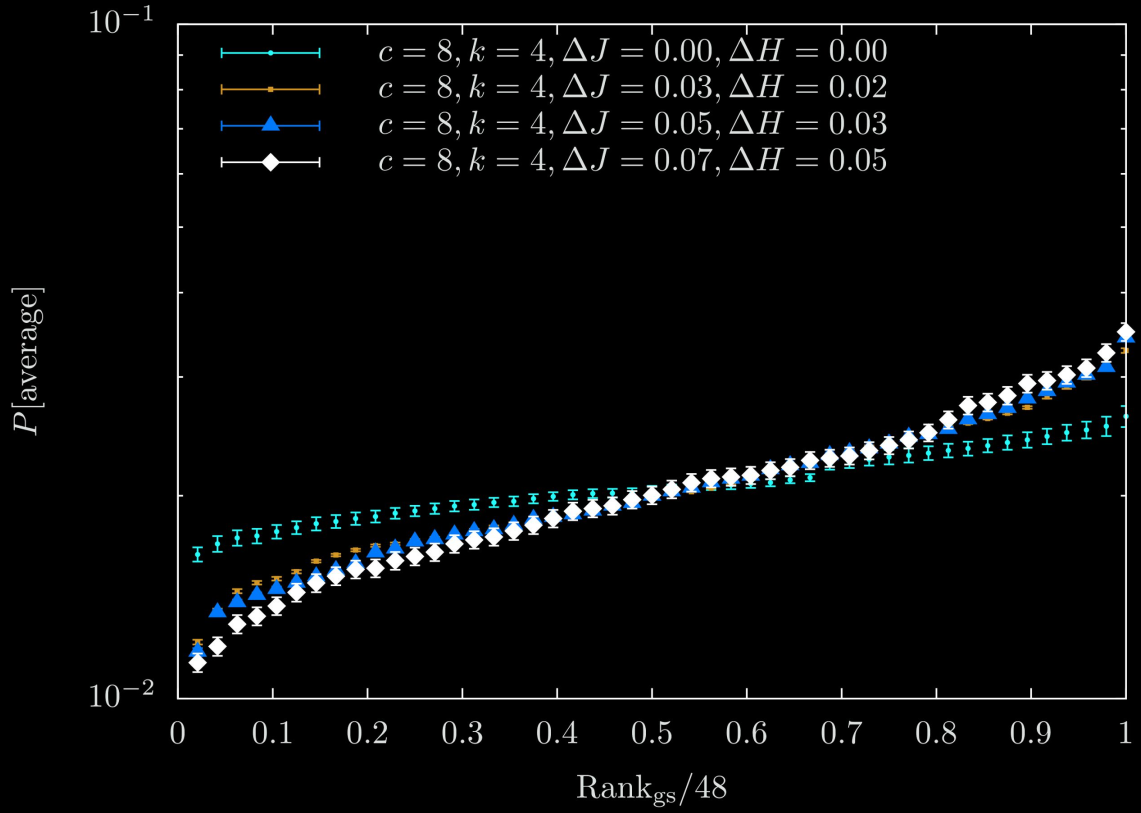
Classical algorithms are marginally affected by the noise



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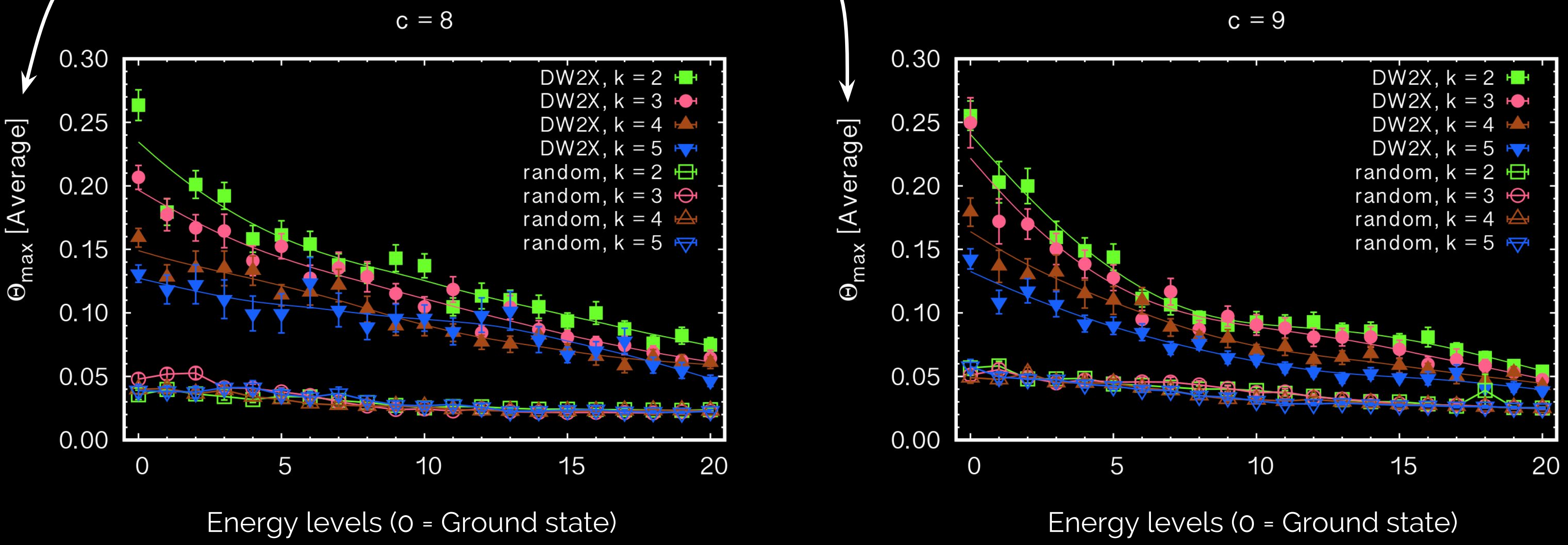
The bias persists up to the 20th excited state!

Different of the sampling respect to the flat distribution (**larger is worse**)



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Implications & Future directions

The bias can limit the use of QA for sampling

- Applications like SAT-Filter and machine learning may not be suitable for QA without mitigating the sampling problem

How to mitigate the sampling problem?

- Explore different driver Hamiltonians (e.g. non-stoquastic)

How to understand the bias problem better?

- Theoretical understanding of the role of the driver Hamiltonian in sampling
- Theoretical exploration of the implication of many-body localization

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Thanks for the attention!

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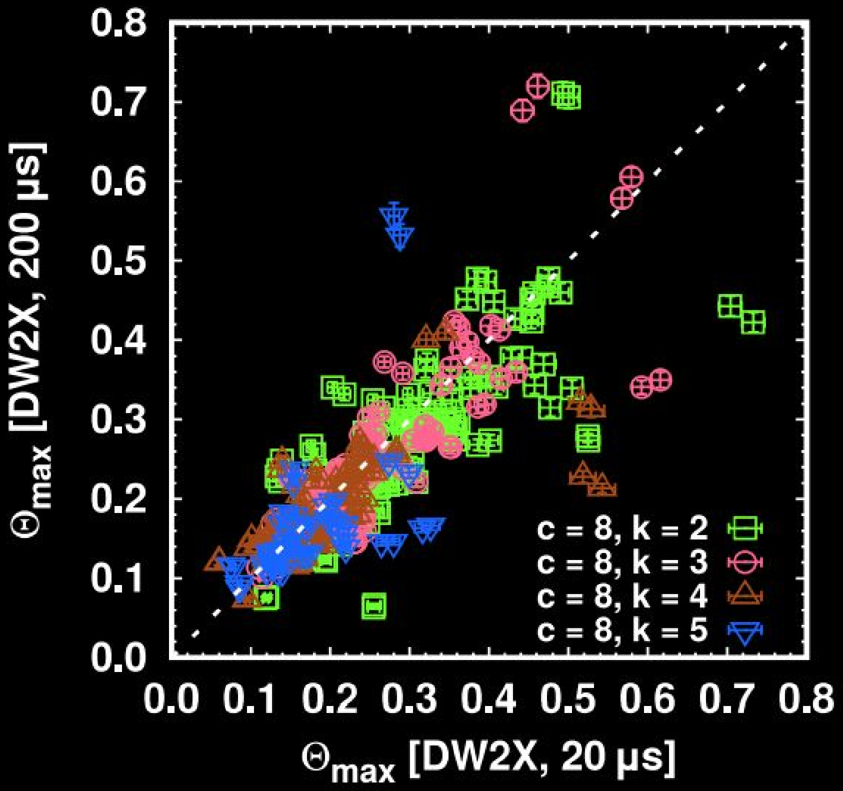

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Adiabatic Quantum Optimization (AQO)

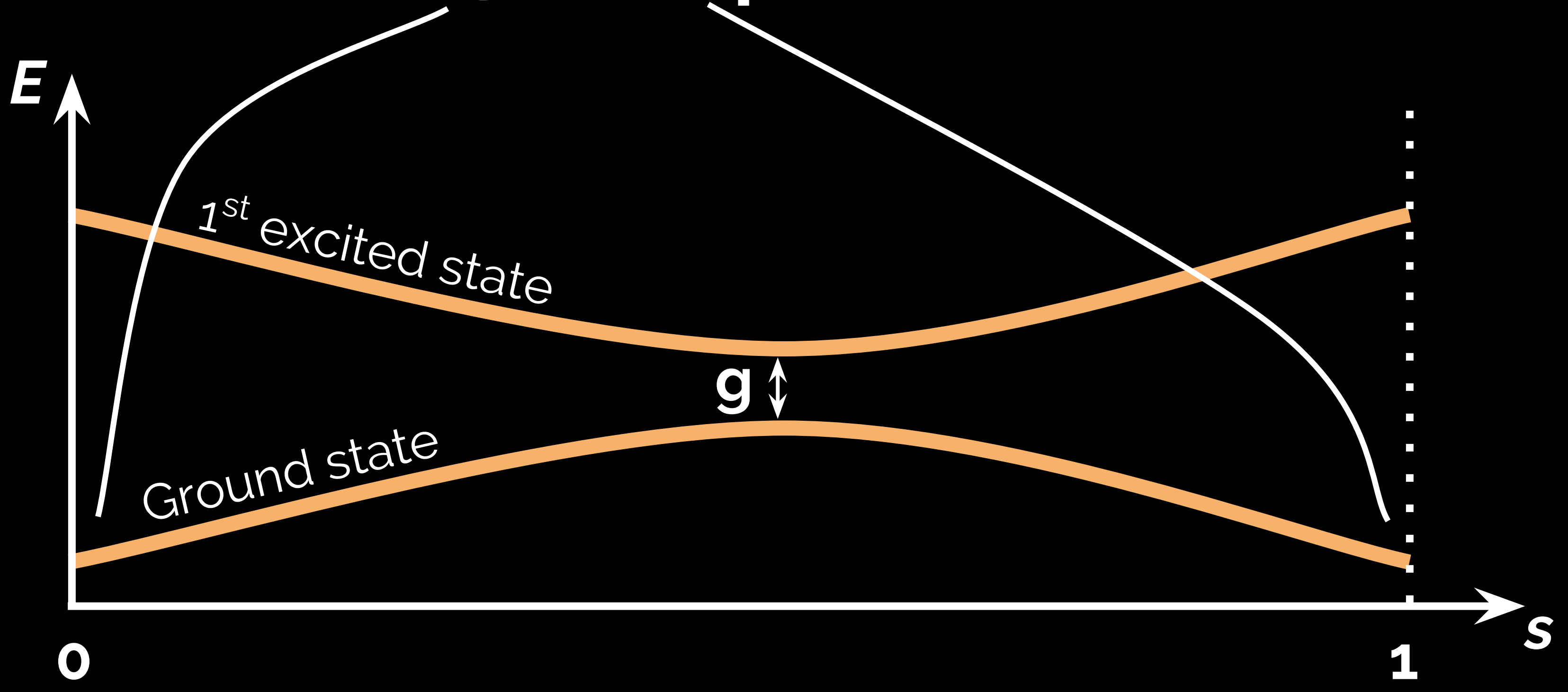
$$\mathbf{H} = (1 - \mathbf{s})\mathbf{H_d} + \mathbf{s}\mathbf{H_p}$$

Initial “driver” Hamiltonian

Target Problem

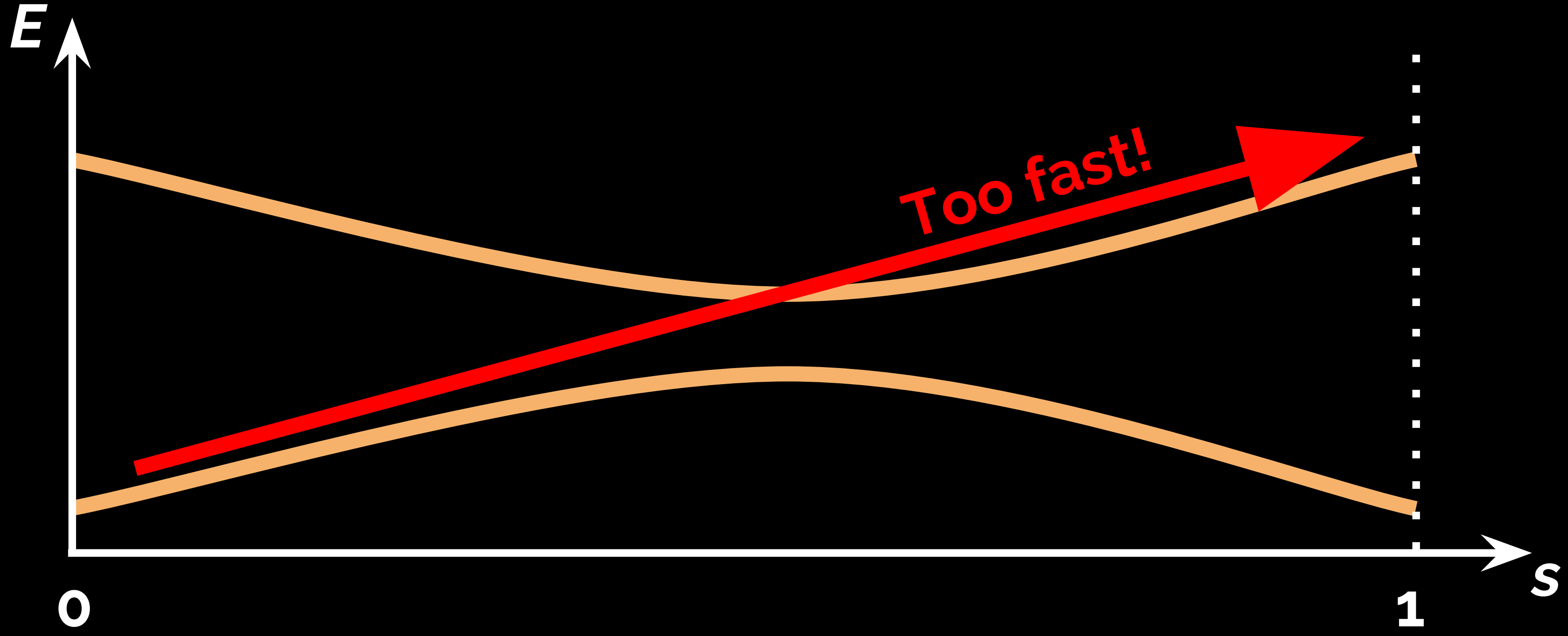
Adiabatic Quantum Optimization (AQO)

$$\mathbf{H = (1 - s)H_d + sH_p}$$



Adiabatic Quantum Optimization (AQO)

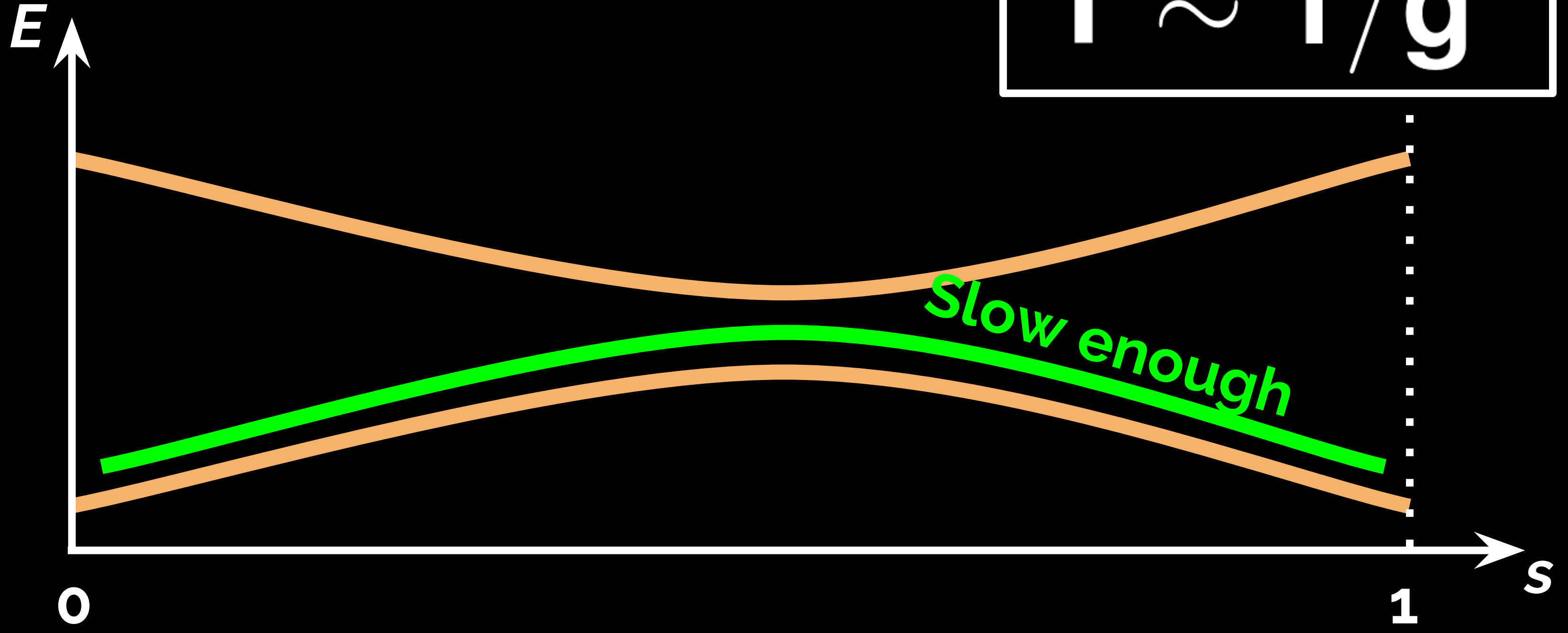
$$H = (1 - s)H_d + sH_p$$



Adiabatic Quantum Optimization (AQO)

$$H = (1 - s)H_d + sH_p$$

$$T \sim 1/g^2$$



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$$H = (1 - s)H_d + sH_p$$