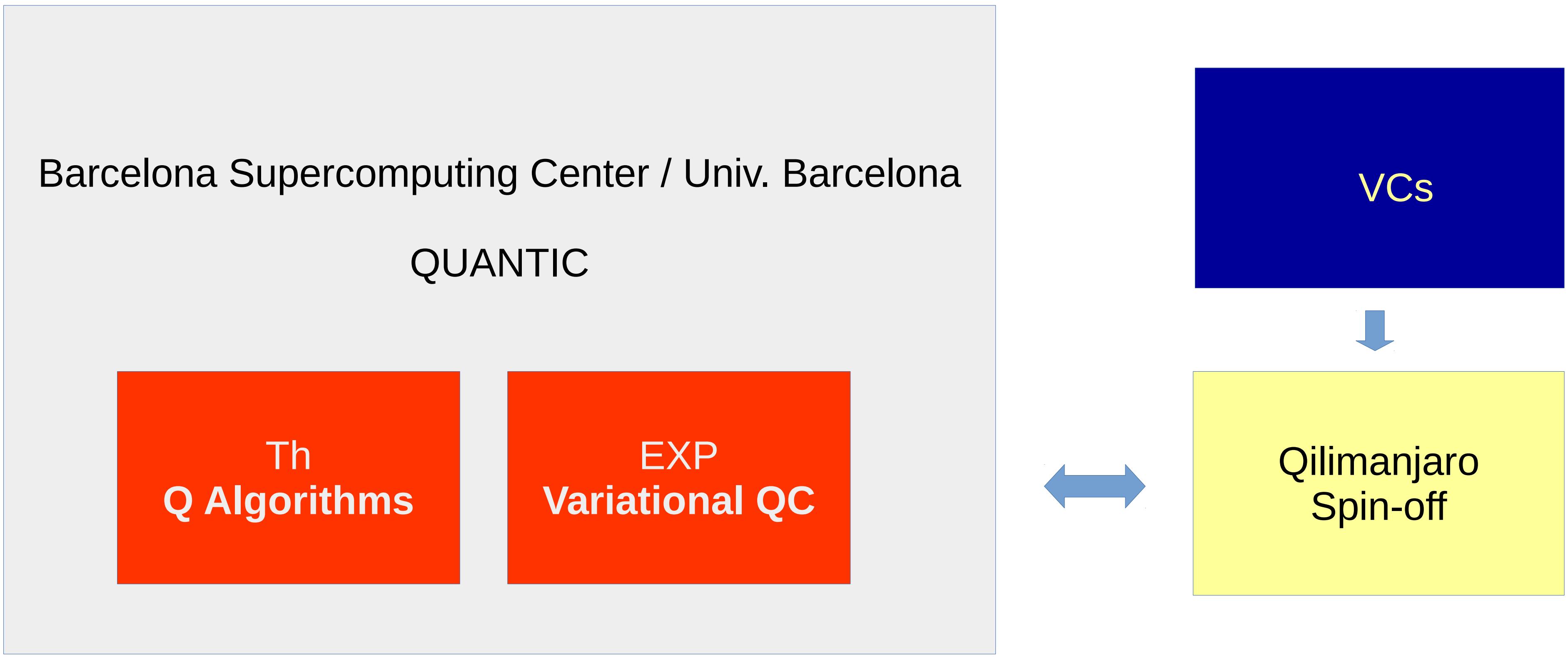
Quantum Computing @ Barcelona Supercomputing Center & Qilimanjaro

CERN, November 2018

José Ignacio LATORRE
Univ. Barcelona / National Univ. Singapore
Quantic@BSC-UB

UNIVERSITAT DE BARCELONA · NUS National University of Singapore · CENTRO DE CIENCIAS DE BENASQUE PEDRO PASCUAL · | Entanglement Partners_ >


Barcelona Supercomputing Center / Univ. Barcelona
QUANTIC
Th
Q Algorithms
EXP
Variational QC
VCs
Qilimanjaro
Spin-off

Quantum Algorithms

Known circuits

Search - Grover
QFT - Shor
Deutsch

Annealing

Direct Annealing
Adiabatic Evolution

Variational

Autoencoders
Eigensolvers
Classifiers

Remote benchmark of a quantum computer

D. Alsina, JIL (2016)

Mermin inequalities

$$M_3=(a_1' a_2 a_3+a_1 a_2' a_3+a_1 a_2 a_3')-(a_1' a_2' a_3')$$

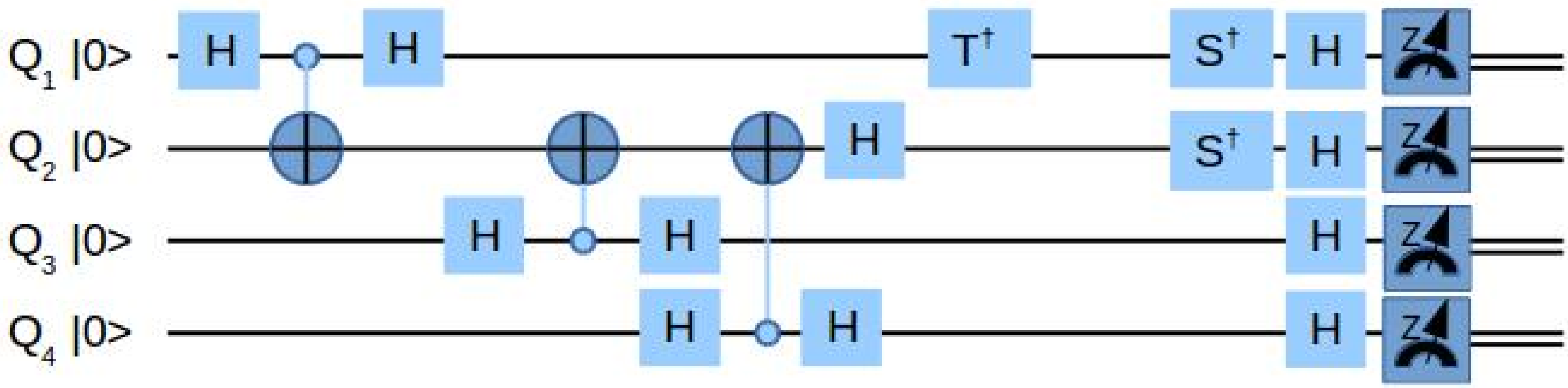
$$M_3^2=4I-[a_1,a_1'][a_2,a_2']-[a_1,a_1'][a_3,a_3']-[a_2,a_2']-[a_3,a_3']$$

$$\langle M_3\rangle^{LR}\leq 2 \qquad \langle M_3\rangle^{QM}\leq 4$$

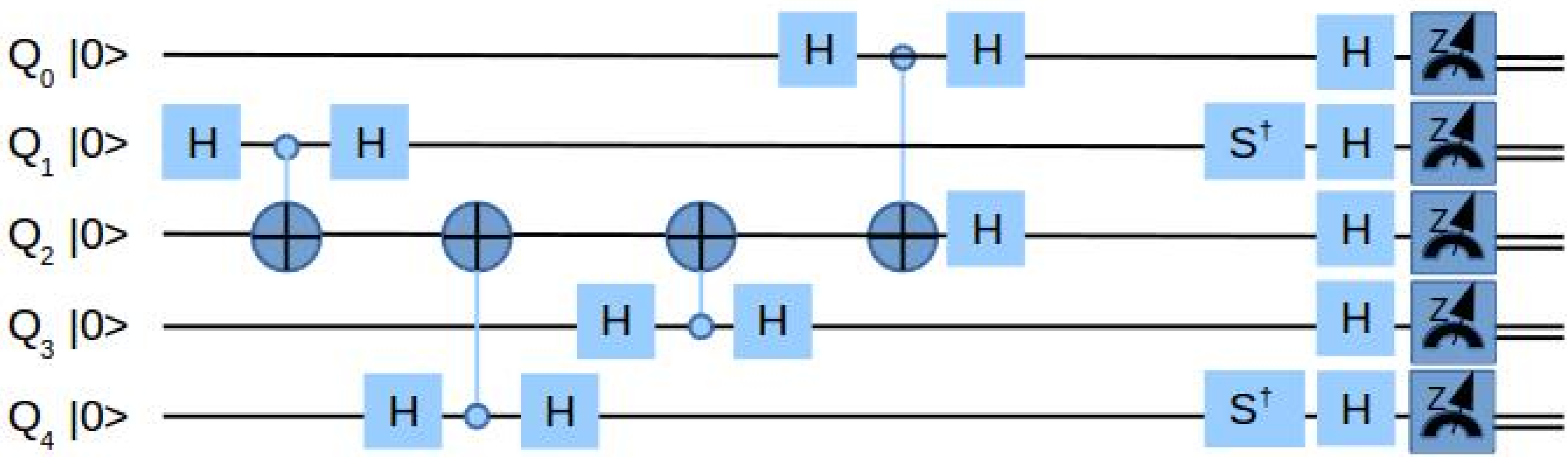
$$|\psi\rangle=\frac{1}{\sqrt{2}}(|000\rangle+i|111\rangle)$$

4- and 5-qubit maximally violating GHZ-like states

4



5



First remote benchmark of a quantum computer (IBM)

Result XXY	**000**	*001*	*010*	**011**	*100*	**101**	**110**	*111*
Probability	0.229	0.042	0.024	0.194	0.043	0.203	0.231	0.033
Result YYY	**000**	*001*	*010*	**011**	*100*	**101**	**110**	*111*
Probability	0.050	0.188	0.188	0.028	0.258	0.026	0.041	0.221

	LR	QM	EXP
3 qubits	2	4	**2.85± 0.02**
4 qubits	4	$8\sqrt{2}$	**4.81± 0.06**
5 qubits	4	16	**4.05± 0.06**

Violation of 3- and 4-qubit

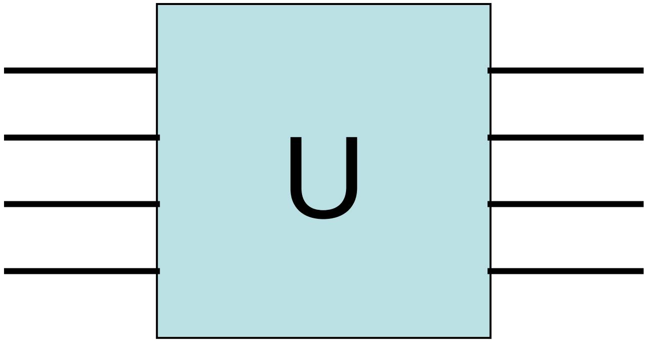
5-qubit remains very poor

Exact Circuits

F. Verstraete, I. Cirac, JIL (2008)
M. Hebenstreit, D. Alsina, JIL, B. Kraus (2017)
A. Cervera-Lierta (2018)

Quantum Simulation of a Quantum Phase Transition

Prepare
a product state



Obtain
the ground state Ising

$$|\psi\rangle_{ISING} = U|\psi\rangle_{trivial}$$

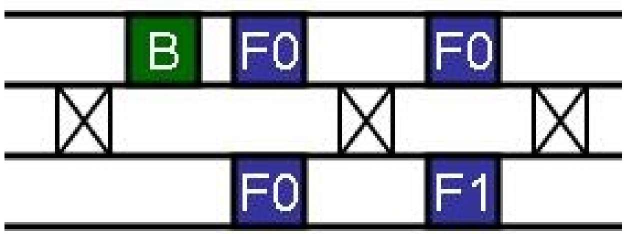
Thermal states $$e^{-\beta H_{ISING}} = U e^{-\beta H_{trivial}} U^{+}$$

Quantum circuit for 4-qubit Ising

$$H_{QI} = \sum_i \sigma_i^x \sigma_{i+1}^x + \lambda \sum_i \sigma_i^z$$

$$U(F0) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \frac{1}{\sqrt{2}} & \frac{\alpha}{\sqrt{2}} & 0 \\ 0 & \frac{1}{\sqrt{2}} & -\frac{\alpha}{\sqrt{2}} & 0 \\ 0 & 0 & 0 & -\alpha \end{pmatrix}$$

Bogoliubov



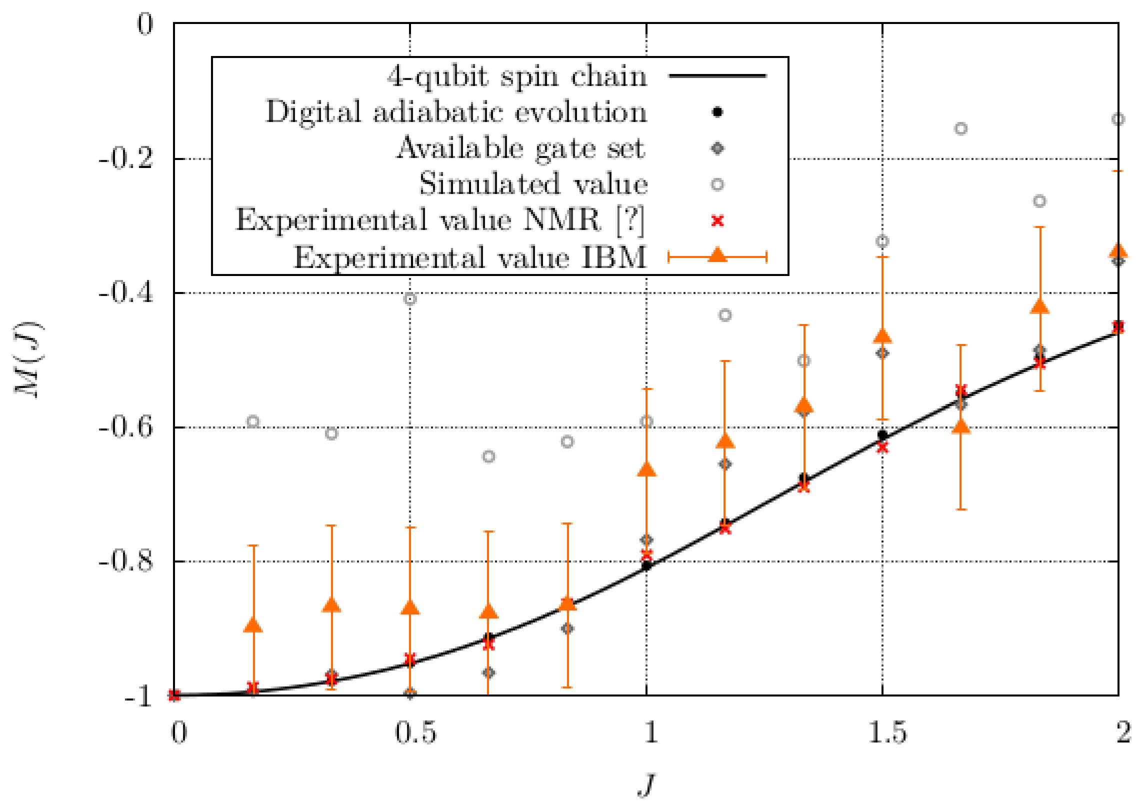
$$U(B) = \begin{pmatrix} \cos(\vartheta(\lambda)) & 0 & 0 & i\sin(\vartheta(\lambda)) \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ i\sin(\vartheta(\lambda)) & 0 & 0 & \cos(\vartheta(\lambda)) \end{pmatrix}$$

Follow fast Fourier transform

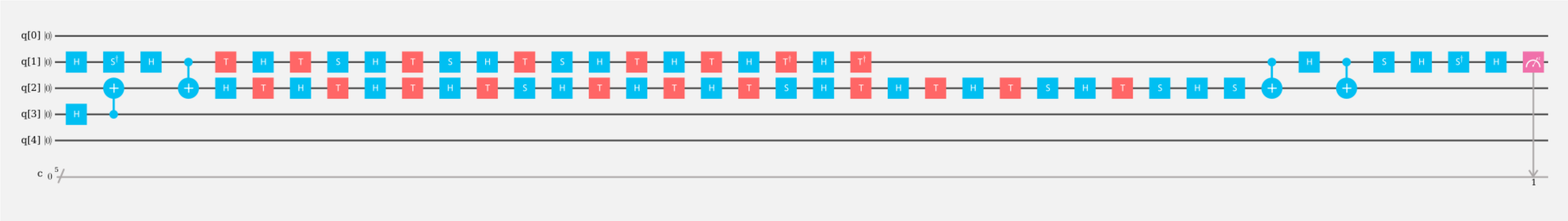
$$U(fSWAP) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

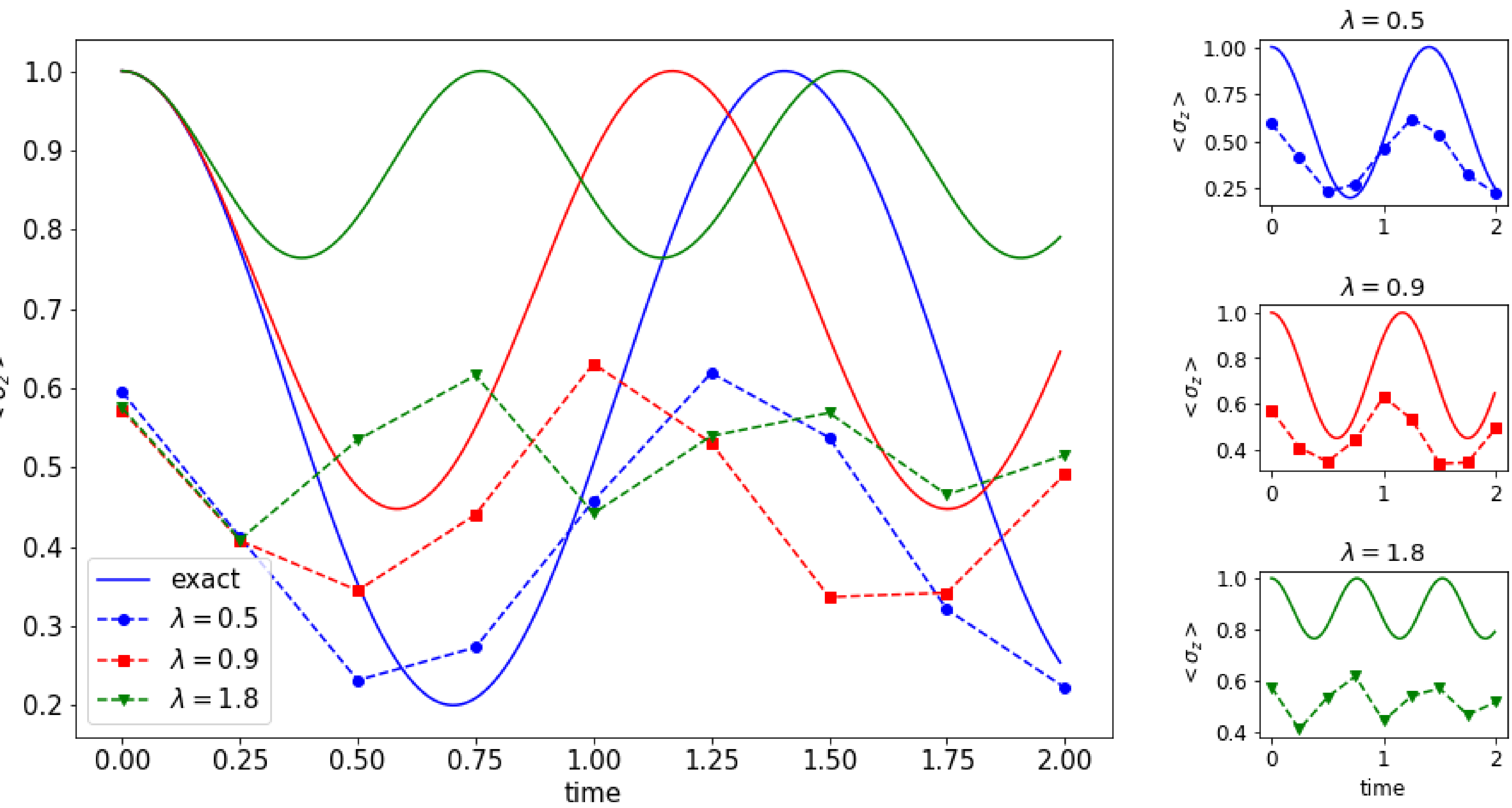
Cirac, Verstraete, JIL

M. Hebenstreit, D. Alsina, JIL, B. Kraus



Errors estimated with “validating circuits”





Alba Cervera-Lierta
IBM Notebook Prize

IBM 16 qubits

Prime State

$$|P(n)\rangle = \frac{1}{\sqrt{\pi(2^n)}} \sum_{p < 2^n \in Primes} |p\rangle$$

G. Sierra

Large entanglement

Rigetti + QUANTIC

caveat

Quantum algorithms that never develop large entanglement
can be efficiently simulated with tensor networks

Faithful benchmark of a quantum computer:

Build states which are largerly entangled in all their partitions

Strategy

- ✓ Identify large entangled states
- ✓ Identify optimal circuits
- Find optimal experimental implementation
- Run circuits
- Explore strategies for tomography
- Use the states for quantum protocoles

Quantum Algorithms

Gate circuits

Search - Grover
QFT - Shor
Deutsch

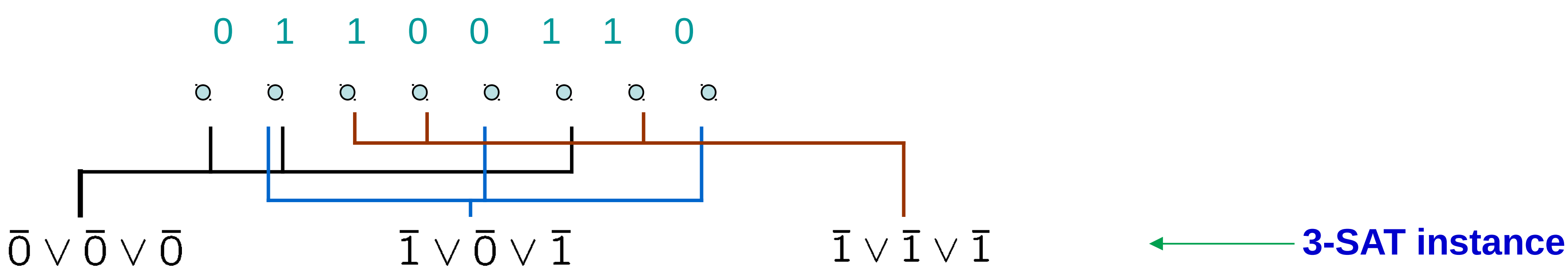
Annealing

Direct Annealing
Adiabatic Evolution

Variational

Autoencoders
Eigensolvers
Classifiers

Exact Cover



For every clause, one out of eight options is rejected

3-SAT is NP-complete
k-SAT is hard for k > 2.41
3-SAT with m clauses: easy-hard-easy around m=4.2n

Exact Cover

A clause is accepted if 001 or 010 or 100

Exact Cover is NP-complete

Adiabatic evolution (Farhi,Goldstone,Gutmann)

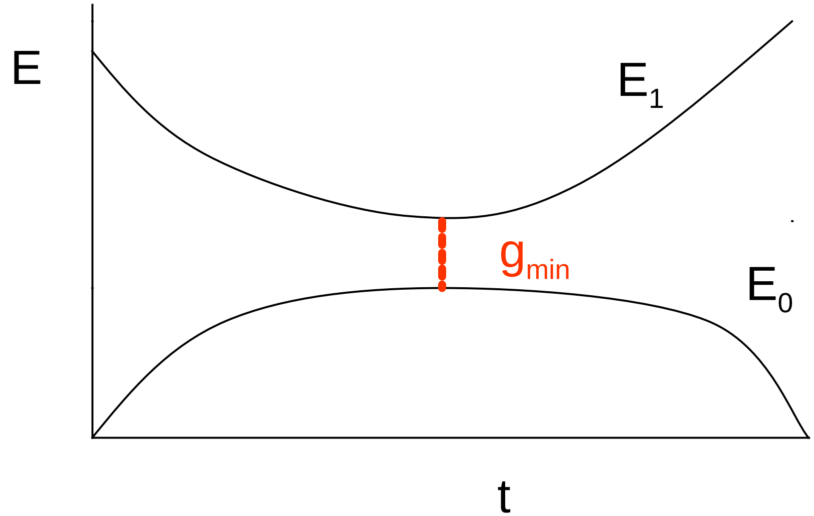
H(s(t)) = (1-s(t)) H_0 + s(t) H_p

$$s(0)=0 \xrightarrow{t} s(T)=1$$

Inicial hamiltonian ↑ ↑ Problem hamiltonian

Adiabatic theorem:

$$|\langle E_0; T|\psi(T)\rangle|^2 \geq 1-\epsilon^2 \quad \text{if} \quad \frac{\max|\frac{dH_{1,0}}{dt}|}{g_{min}^2} \leq \epsilon$$



$$T \sim \frac{1}{g_{min}^2}$$

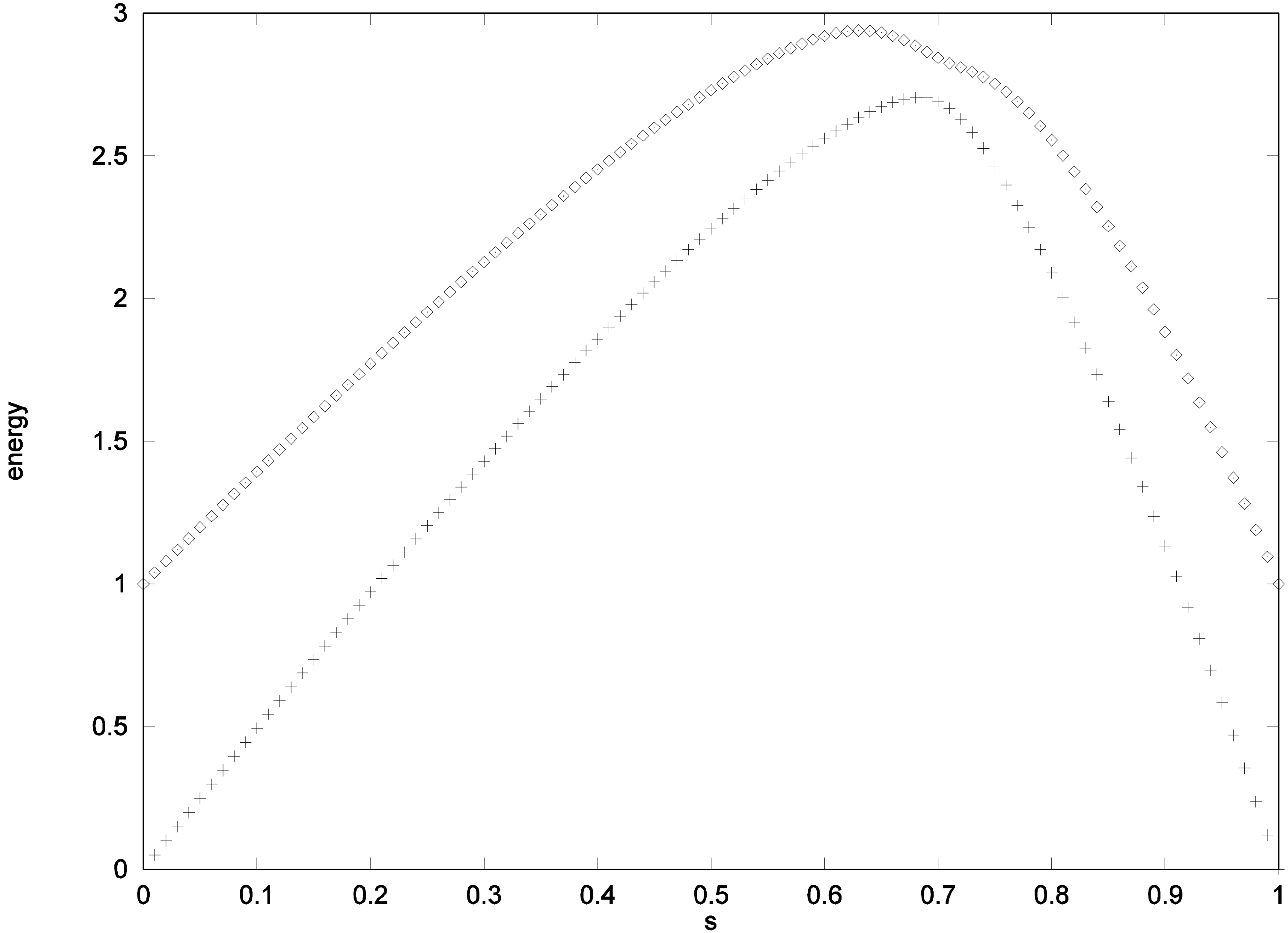
Mapping Exact Cover to a quantum computer

$$H_0 = \sum_i \frac{d_i}{2} \sigma_i^x$$

$$H_P = \sum_c H_{c(ijk)}$$

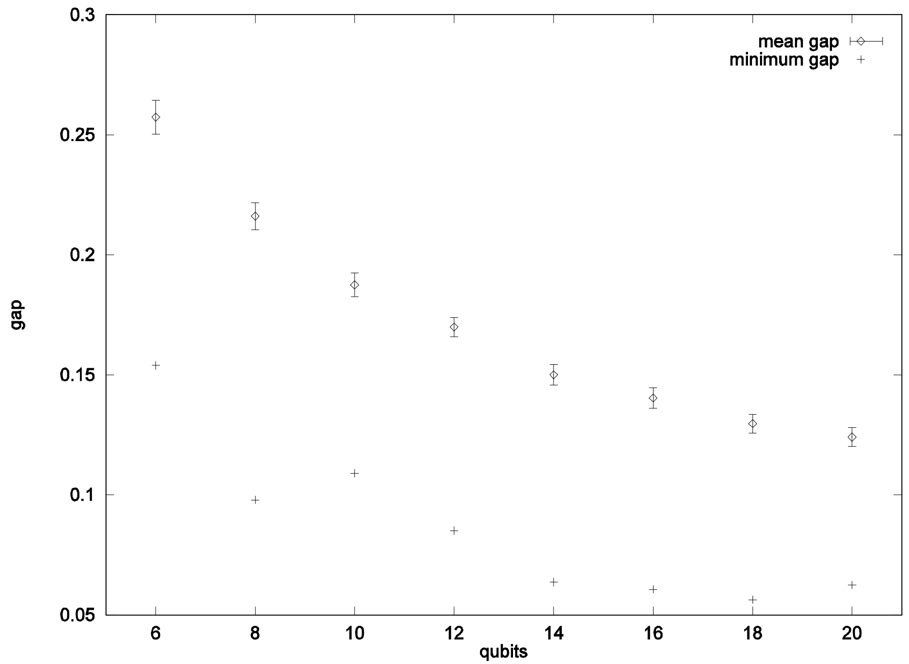
$$H_{c(ijk)} = \left(z_i + z_j + z_k - 1 \right)^2$$

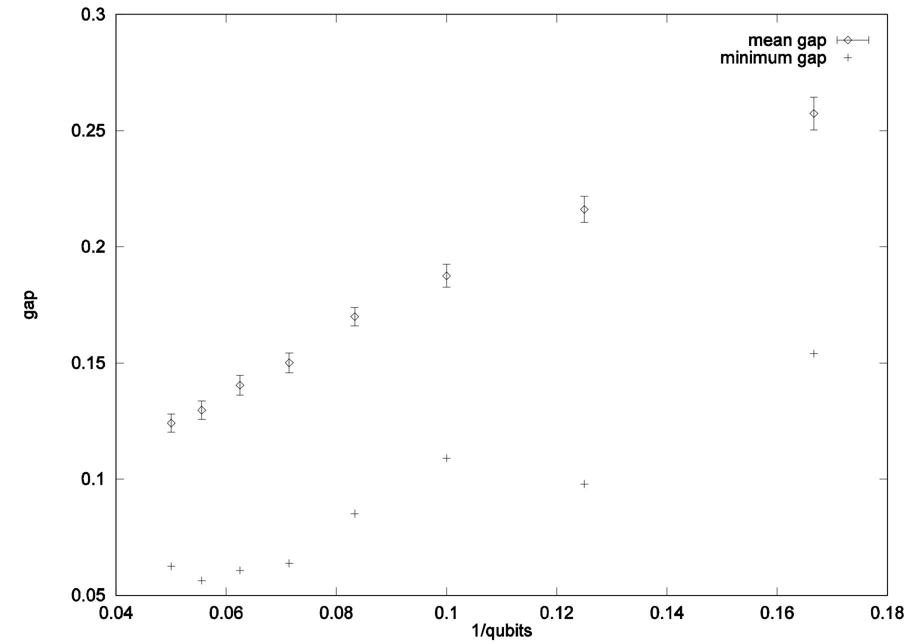
H_P is diagonal, quadratic, non nearest-neighbor (spin glass)



Typical gap for an instance of Exact Cover

R. Orús, JIL

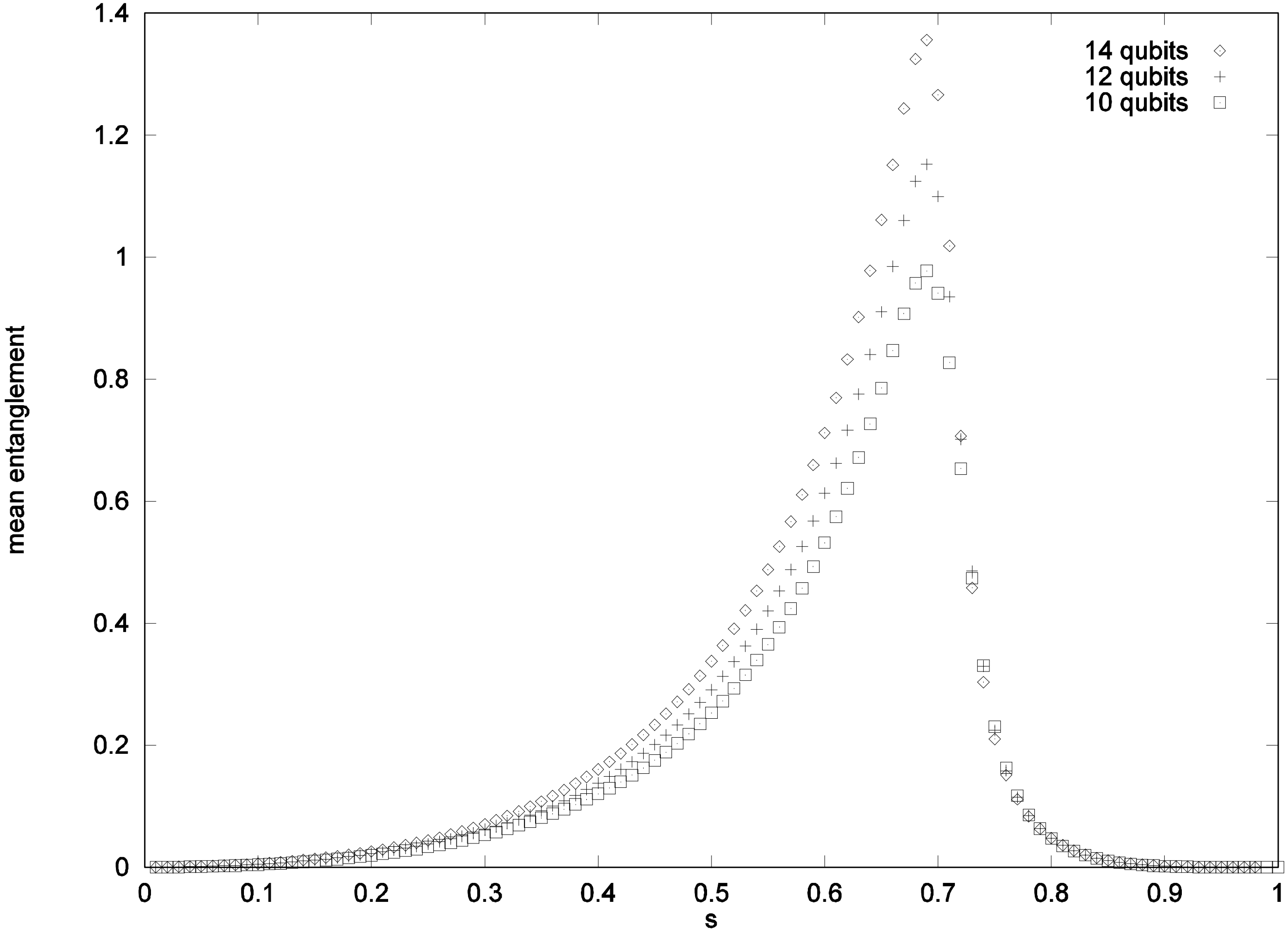




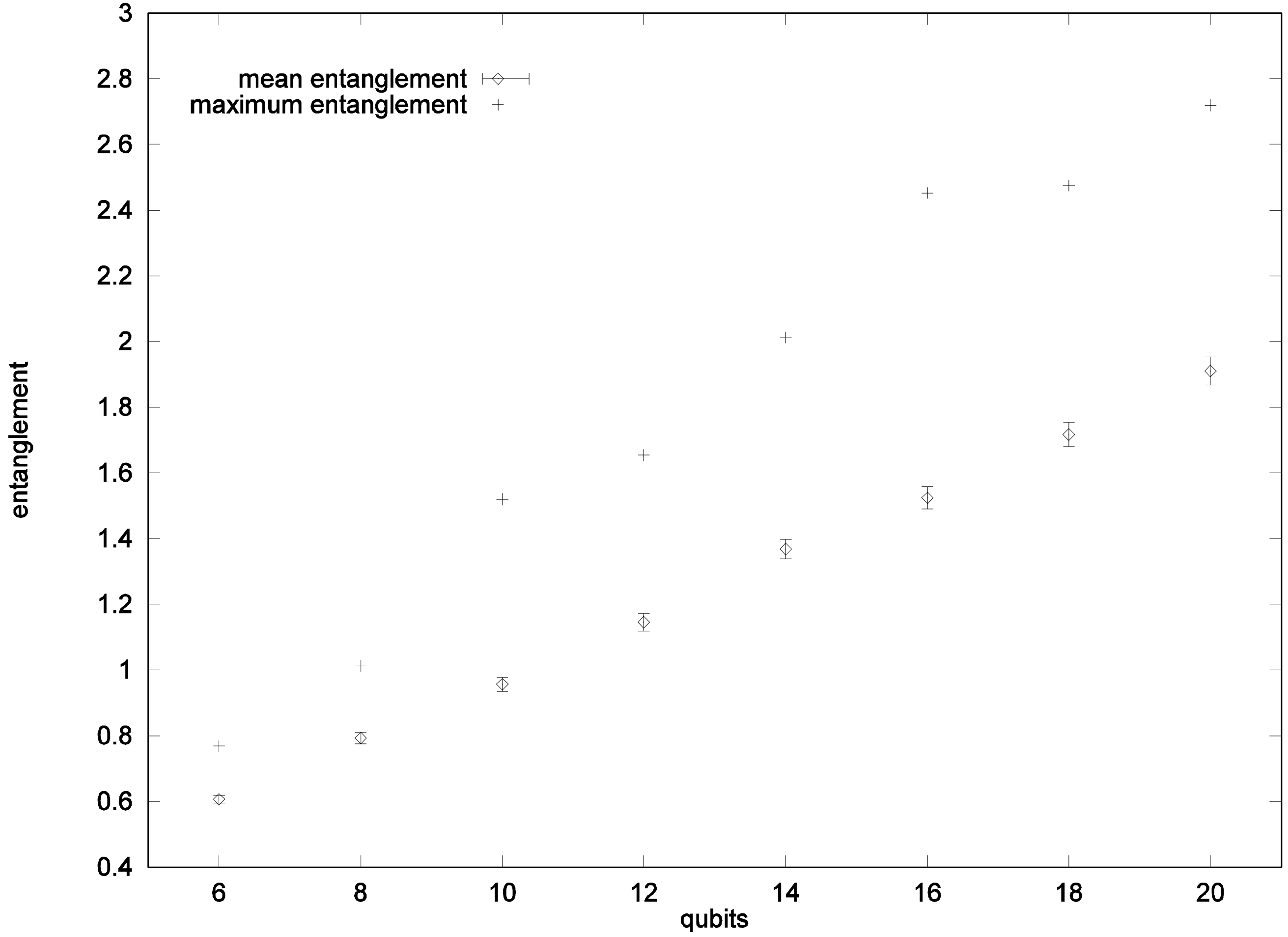
Scaling for averaged instances is consistent with gap ~ 1/n

NP is defined on the worst instance

Scaling of entropy for Exact Cover



A quantum computer passes nearby a dramatic quantum phase transition!



n=6-20 qubits

300 instances

n/2 partition

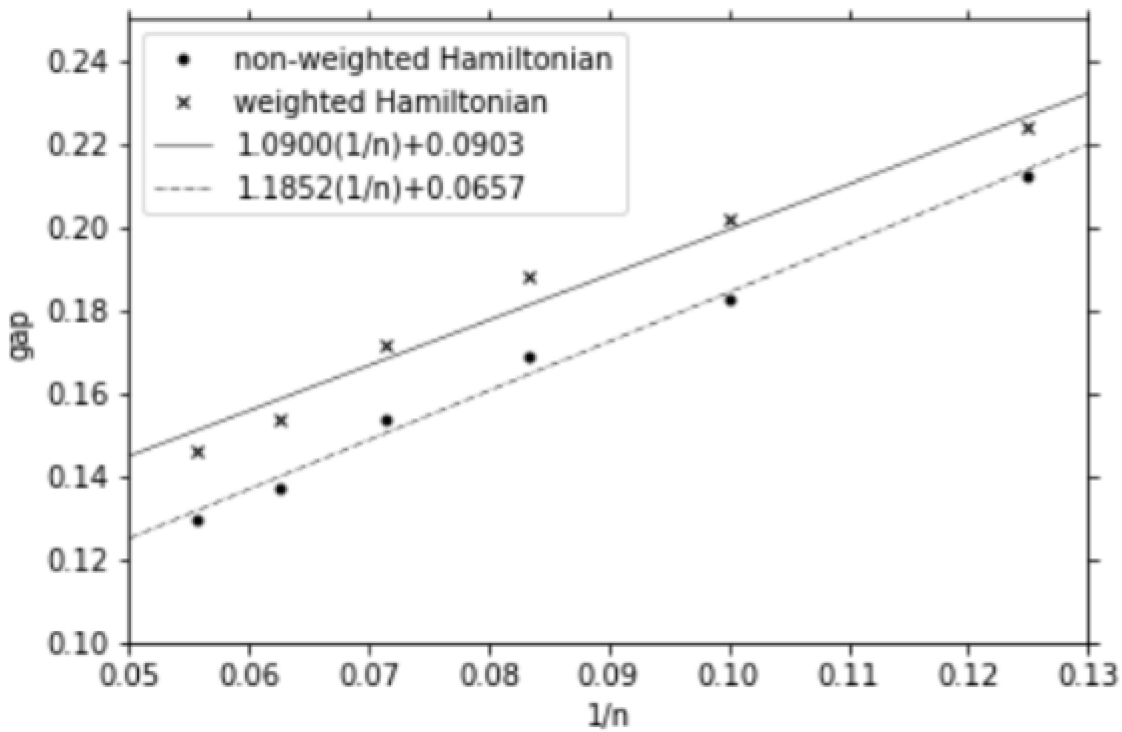
S ~ .2 n

Average entropy scales maximally

S. Ramos, JIL

$$H = \sum_{clauses\ ijk} w_{ijk} H_{ijk}$$

Optimize weights for clauses

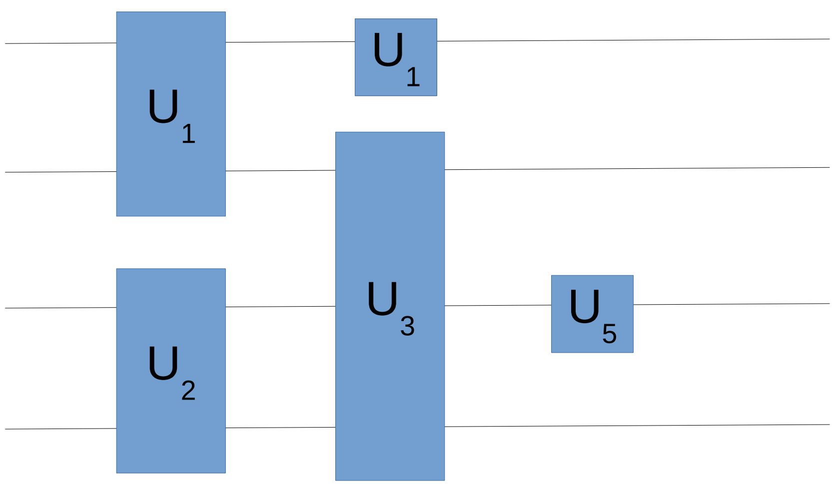


Gap increase

Quantum Algorithms

Gate circuits	Annealing	Variational
Search - Grover QFT - Shor Deutsch	Direct Annealing Adiabatic Evolution	Autoencoders Eigensolvers Classifiers

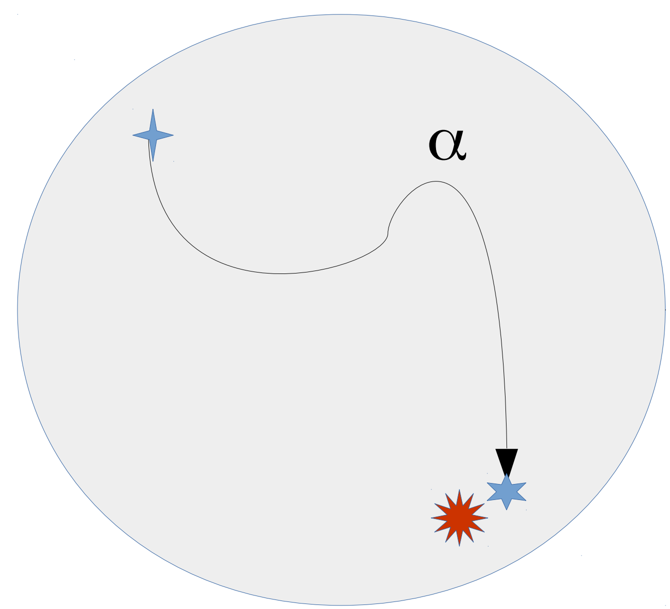
Variational circuits



$$U(\vec{\alpha}) = U_n \ldots U_2 U_1$$

Delivers quantum states

Explores a large (Hilbert) space



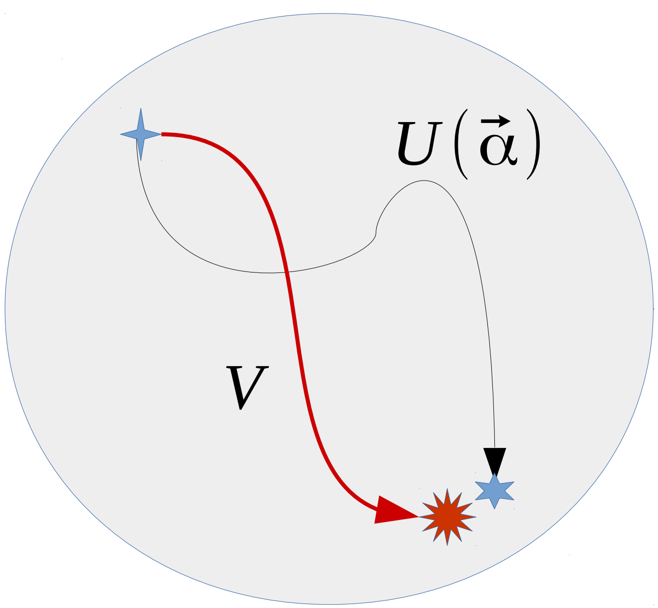
near optimal solution

Classical characterization of a global unitary

Q Computer is a machine that generates variational states

Variational Quantum Computer!!

$$|U_n \ldots U_2 U_1 - V| < \delta$$

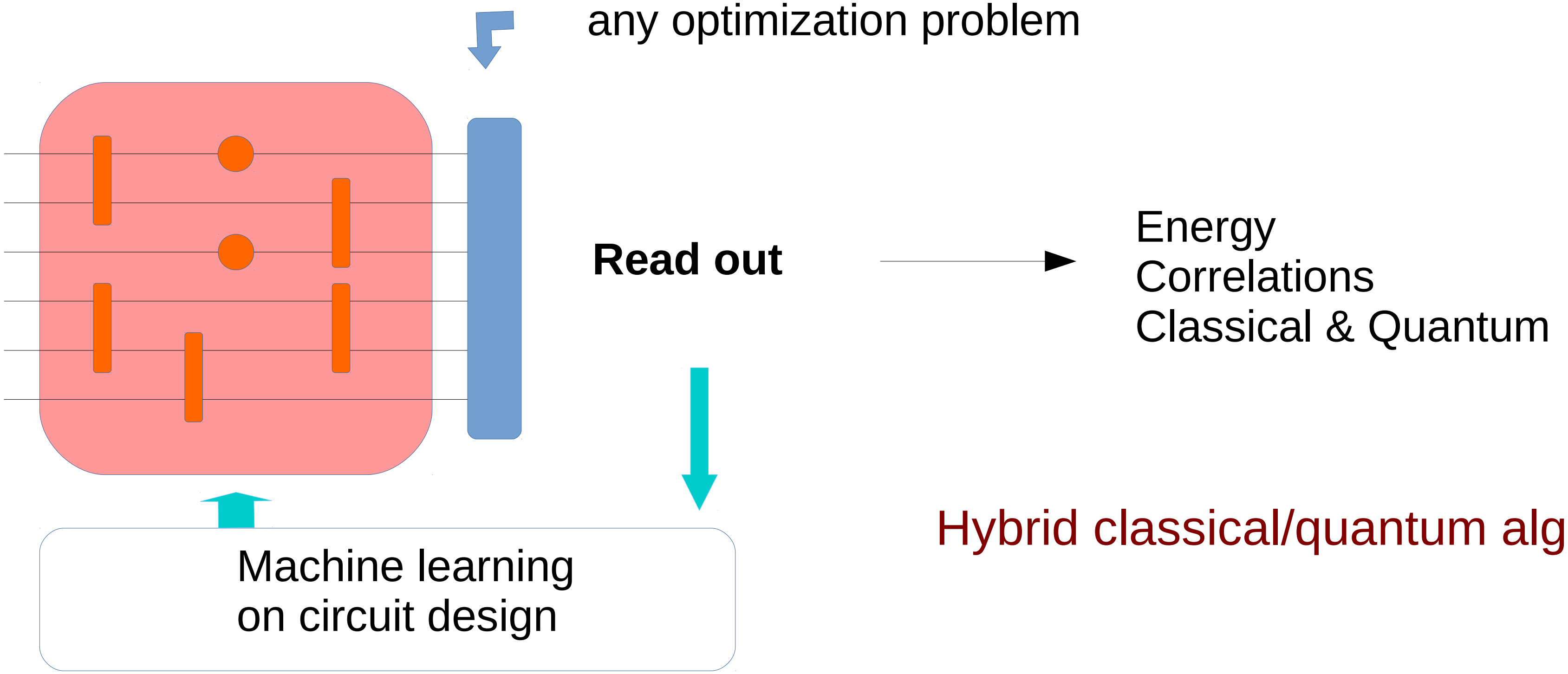


Solovay-Kitaev Theorem

$O\left(\log^c \frac{1}{\delta}\right)$ operations

Variational Quantum Eigensolvers

Aspuru-Guzik et al.
+ IBM



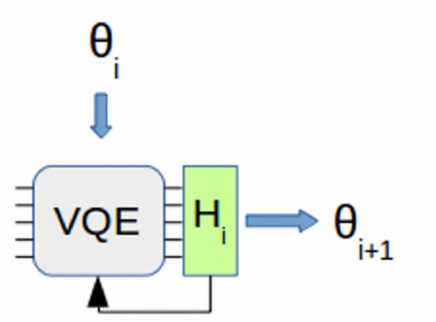
Hybrid classical/quantum algorithms

Quantum Chemistry

Adiabatically Assisted Variational Quantum Eigensolver

A. Garcia-Saez, JIL (2018)

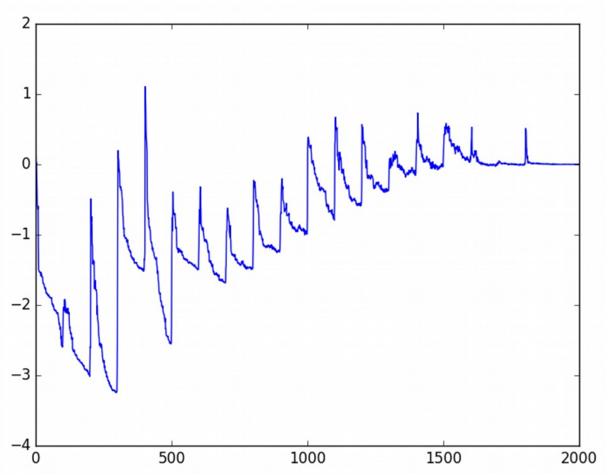
$$H(s) = (1-s) H_0 + s H_P$$



i) Find circuit for ground state H_0, s=0, with VQE.

ii) Increase s, solve new H(s) with VQE using as initial condition the previous circuit.

Iii) Reach H_P

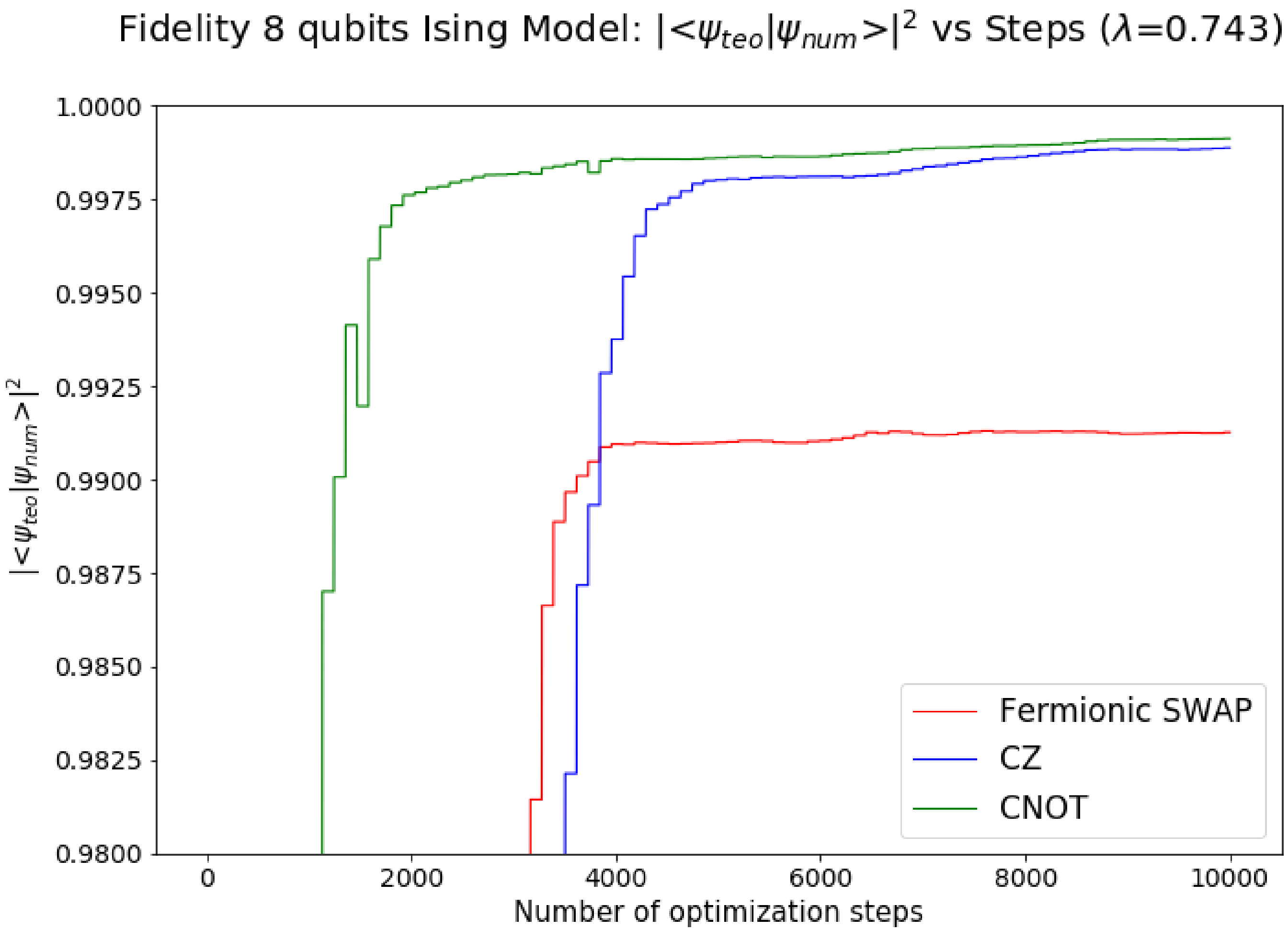


AAVQE finds a path away avoiding local minima

Solves hard instances of
Exact Cover (NP-complete)

VQE fails!!!!

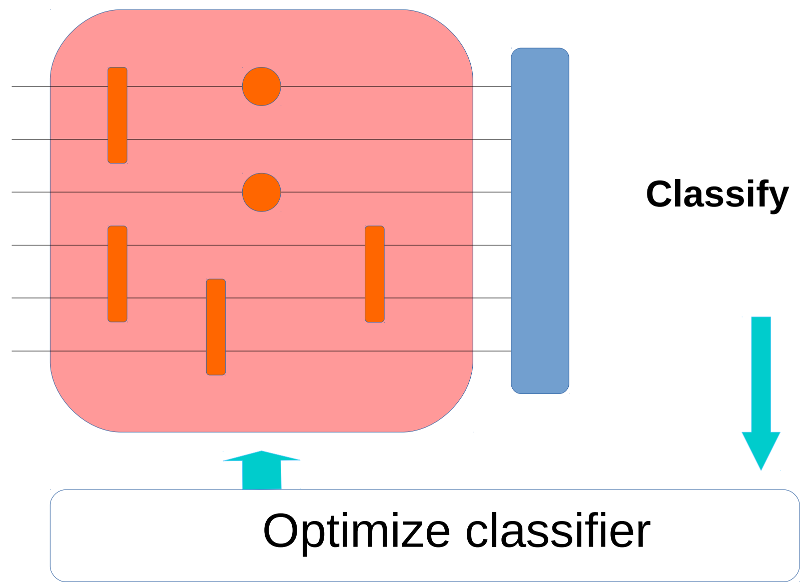
Which gates are better?

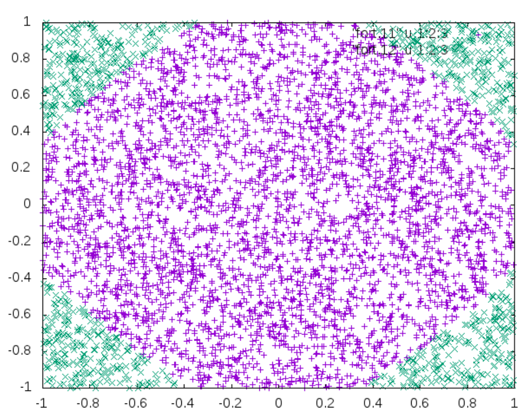


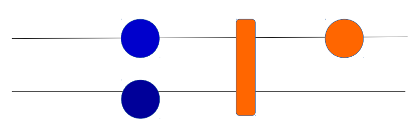
Variational quantum classifier

$U(\vec{\alpha})$

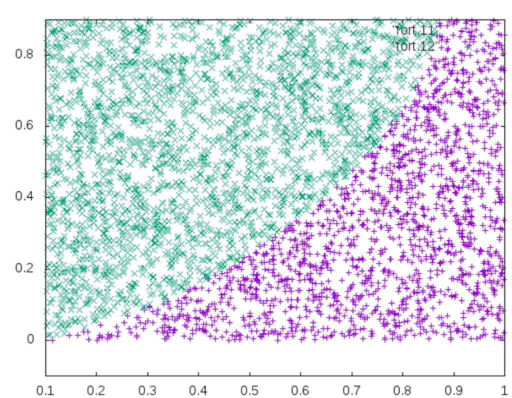
Codify data in gates







97% success

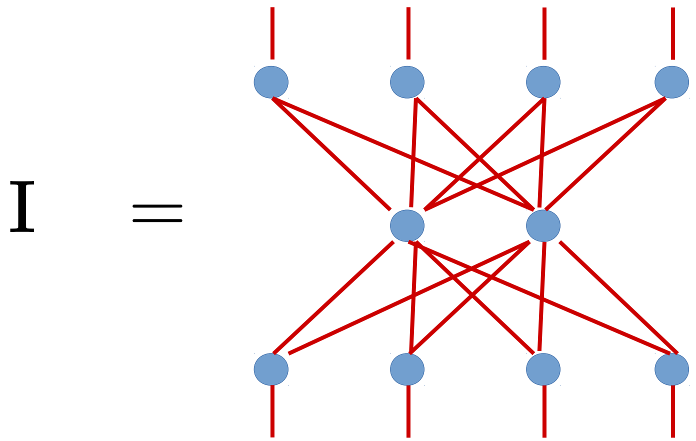


Detect a relevant subspace in data

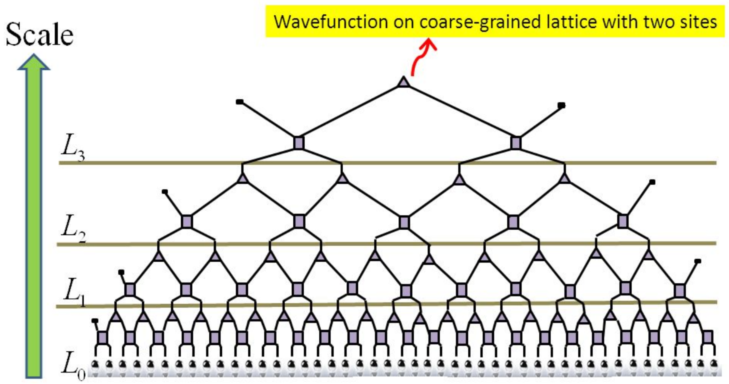
Compressor

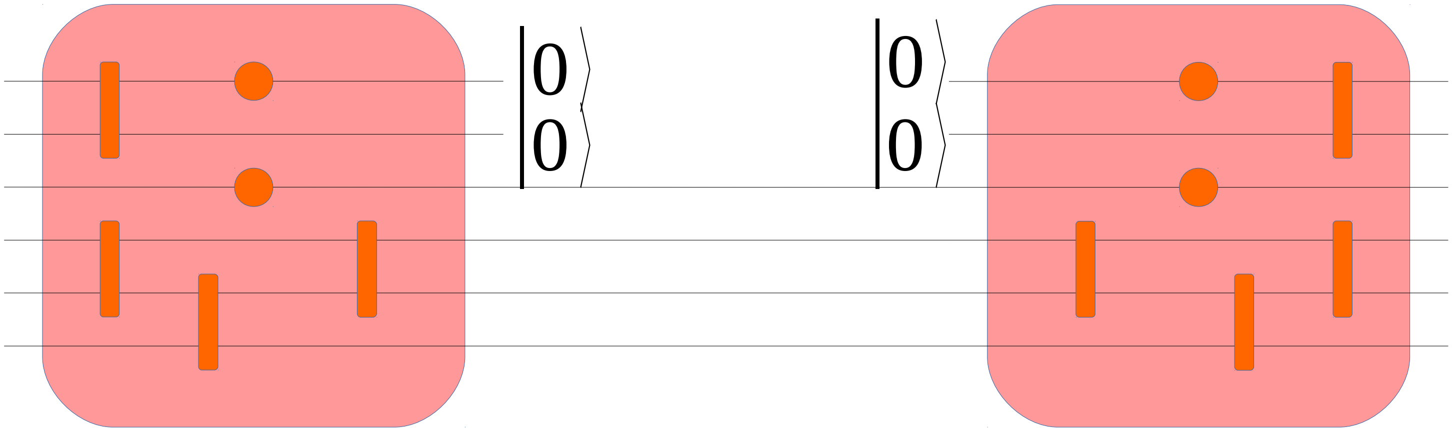
Generate patterns

Variational Autoencoder



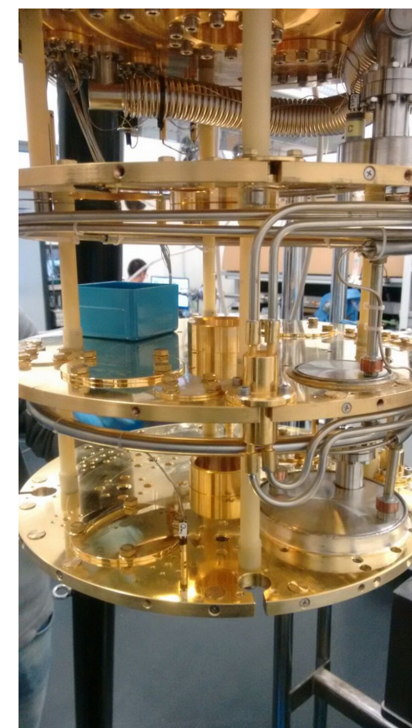
MERA defines an RG flow





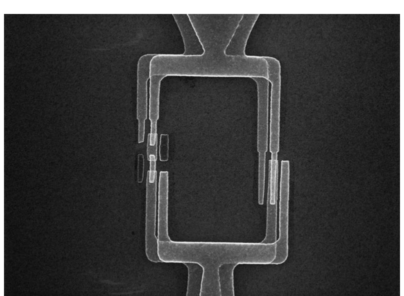
QUANTIC

@ BSC/UB



Coherent quantum annealer

Variational quantum computer



First superconducting qubit-qutrit

Variational quantum algorithms on pulses

TEAM

Artur García-Sáez
AAVQE, QML

Pol Forn-Díaz, Chris Warren
Variational quantum computer

Daniel Alsina
Mermin inequalities

Alba Cervera-Lierta (IBM prize)
Exact circuits, MaxEnt, Classifiers

Carlos Bravo (W. Zeng grant)
VQE, AAVQE

Román Orús, Sergi Ramos
Adiabatic Evolution

Germán Sierra, Diego García, Eduard Ribas
Prime state, arithmetics

Josep Lumbreras, Katarzina Kowalska
Solvay-Kitaev th

Elias Gil
Classifiers

Adrián Pérez
AAVQE

Stefano Carrazza
Boltzmann machine

+ first contract with large bank
+ VC

CONCLUSION:

TIME TO COLLABORATE, NOT TO COMPETE