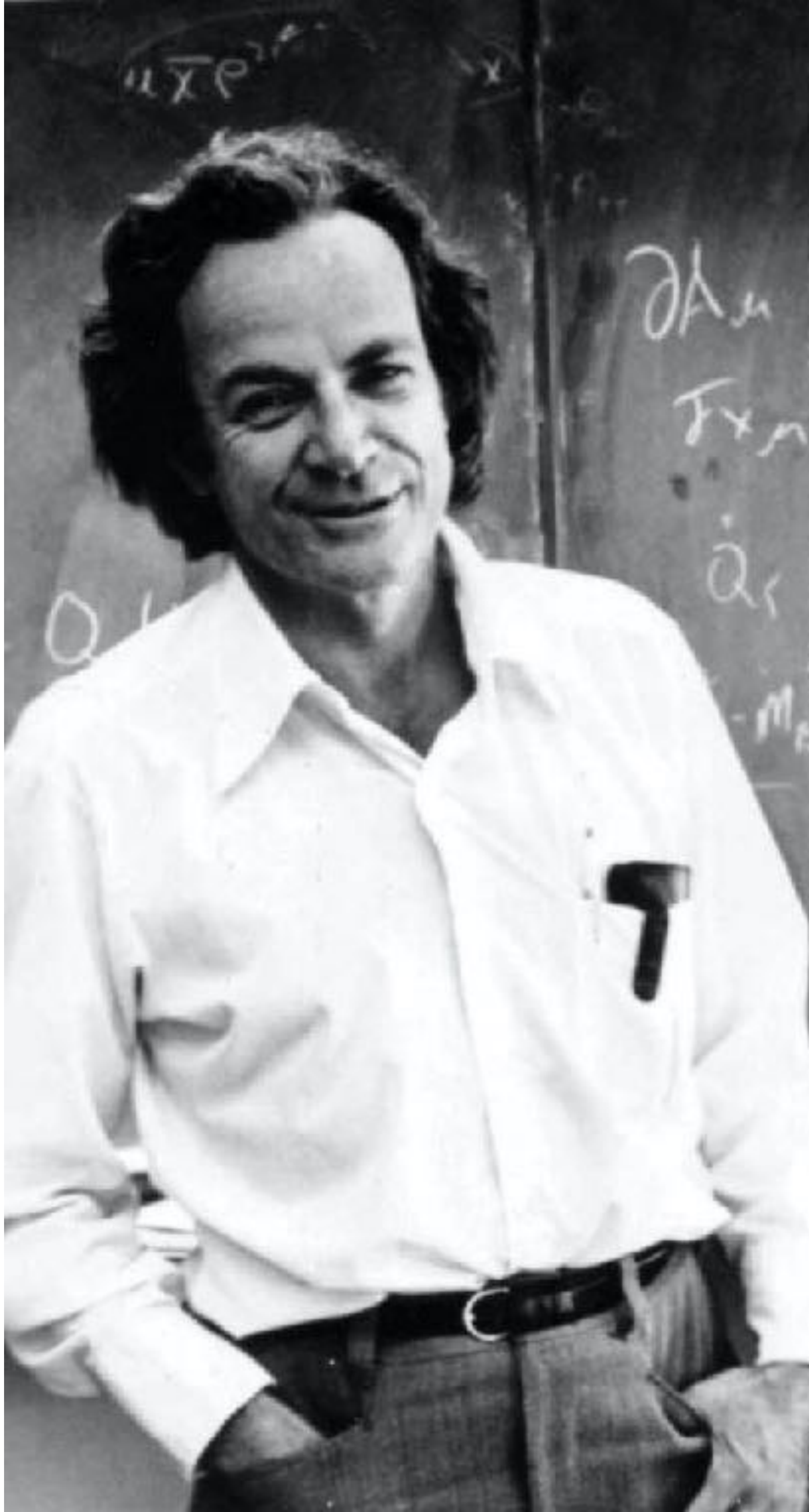
QUANTUM COMPUTING FOR HIGH ENERGY PHYSICS

Simone Montangero

University of Padova

"Let the computer itself be built of quantum mechanical elements which obey quantum mechanical laws."



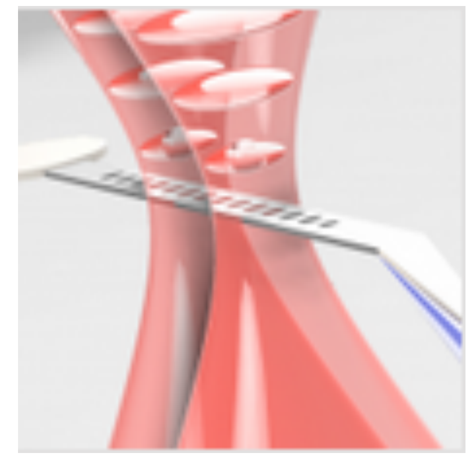
RICHARD FEYNMAN (1982)

QUANTUM COMPUTERS

Google

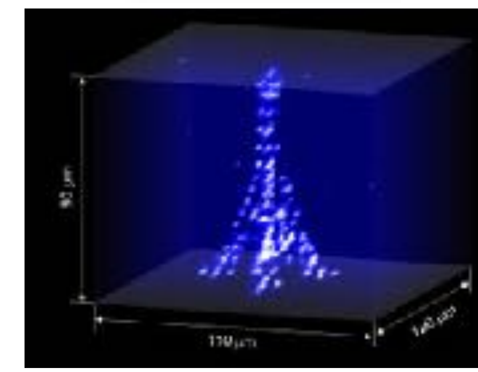
rigetti

Superconductors

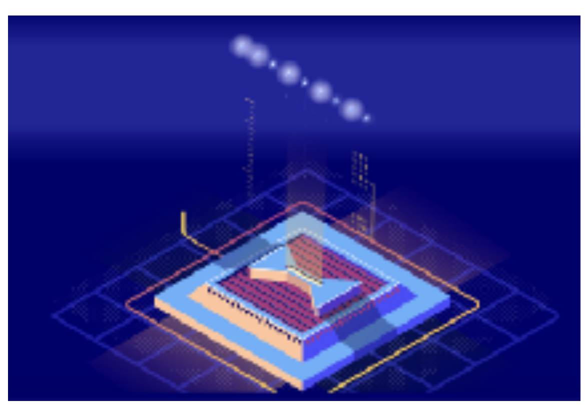


Lukin Group

INSTITUT d'OPTIQUE GRADUATE SCHOOL



Rydberg atoms

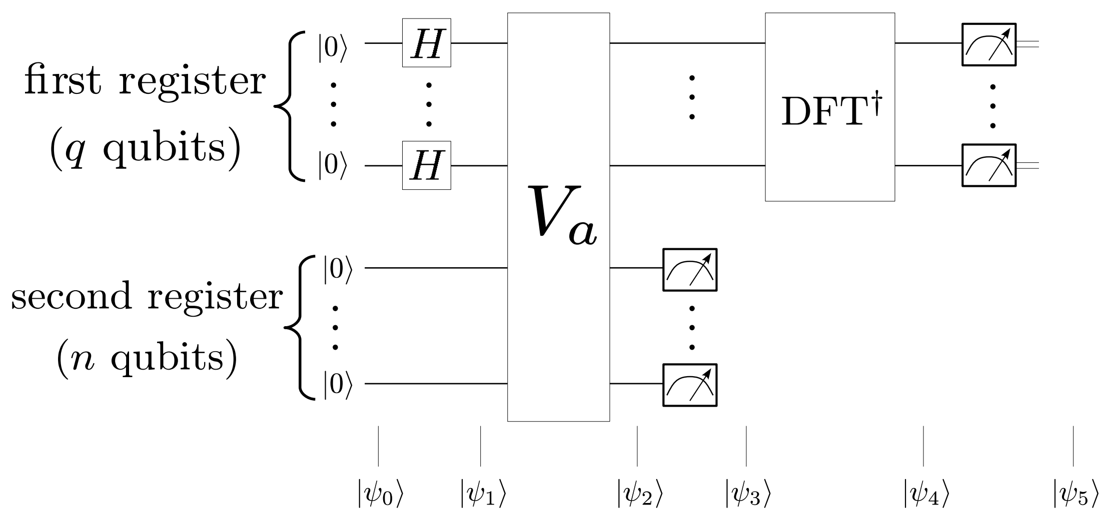


IONQ

AQT

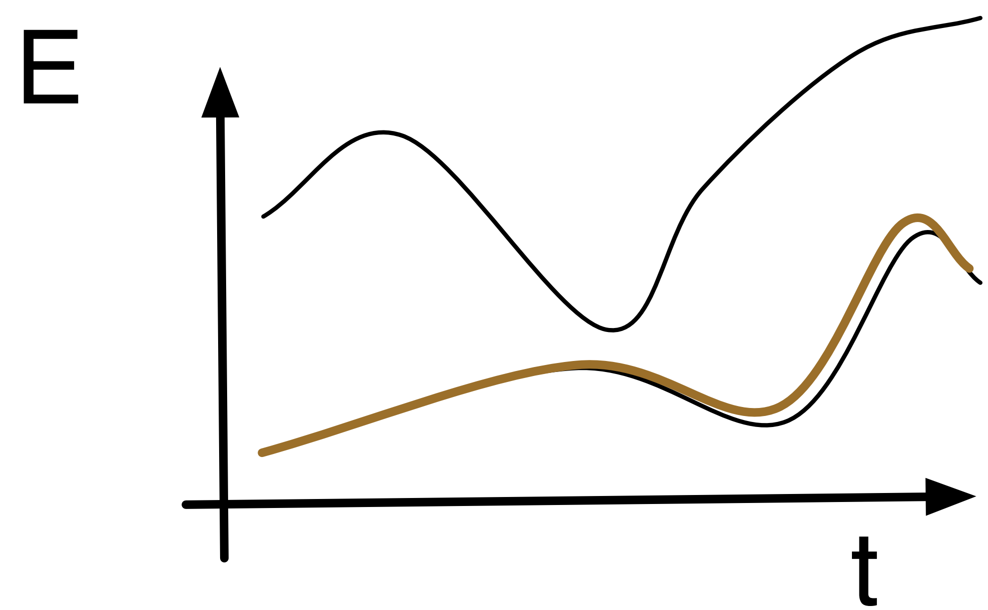
Trapped ions

QUANTUM COMPUTING

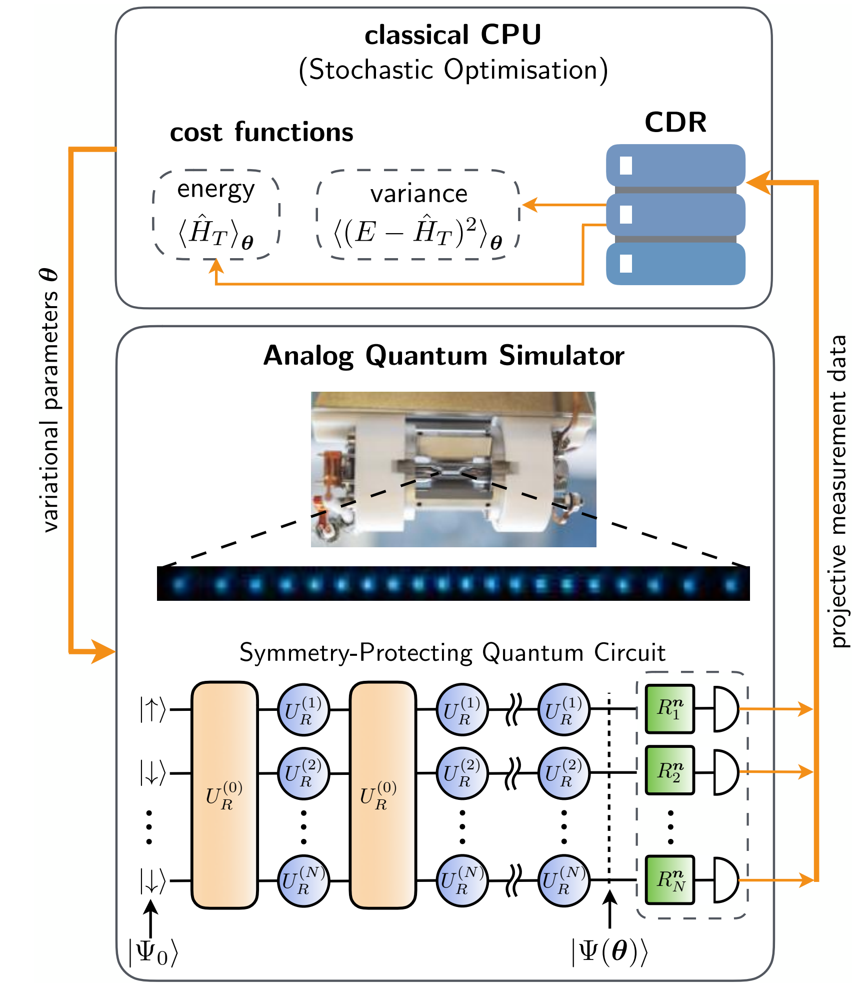


$$V_a : |x\rangle|y\rangle \rightarrow |x\rangle|y \oplus a^x \mod N\rangle$$

Circuit model



Adiabatic - Quantum Annealing



Hybrid (VQE)

QUANTUM COMPUTERS AND SIMULATORS

RESEARCH ARTICLES

Universal Quantum Simulators

Seth Lloyd

Feynman's 1982 conjecture, that quantum computers can be programmed to simulate any local quantum system, is shown to be correct.

Table 1. The asymptotic scaling of the number of quantum gates needed to simulate scattering in the strong-coupling regime in $d = 1, 2$ spatial dimensions is polynomial in p (the momentum of the incoming pair of particles), $\lambda_c - \lambda_0$ (the distance from the phase transition), and n_{out} (the maximum kinematically allowed number of outgoing particles). The notation $f(n) = \tilde{O}(g(n))$ means $f(n) = O(g(n) \log^c(n))$ for some constant c.

	$\lambda_c - \lambda_0$	p	n_{out}
$d = 1$	$\left(\frac{1}{\lambda_c - \lambda_0}\right)^{9+o(1)}$	$p^{4+o(1)}$	$\tilde{O}(n_{out}^5)$
$d = 2$	$\left(\frac{1}{\lambda_c - \lambda_0}\right)^{6.3+o(1)}$	$p^{6+o(1)}$	$\tilde{O}(n_{out}^{7.128})$

S. Lloyd, Science (1996)

Quantum Algorithms for Quantum Field Theories

Stephen P. Jordan,[1*] Keith S. M. Lee,[2] John Preskill[3]

Quantum field theory reconciles quantum mechanics and special relativity, and plays a central role in many areas of physics. We developed a quantum algorithm to compute relativistic scattering probabilities in a massive quantum field theory with quartic self-interactions (ϕ^4 theory) in spacetime of four and fewer dimensions. Its run time is polynomial in the number of particles, their energy, and the desired precision, and applies at both weak and strong coupling. In the strong-coupling and high-precision regimes, our quantum algorithm achieves exponential speedup over the fastest known classical algorithm.

S.P. Jordan et al., Science (2012)

GAUGE THEORIES

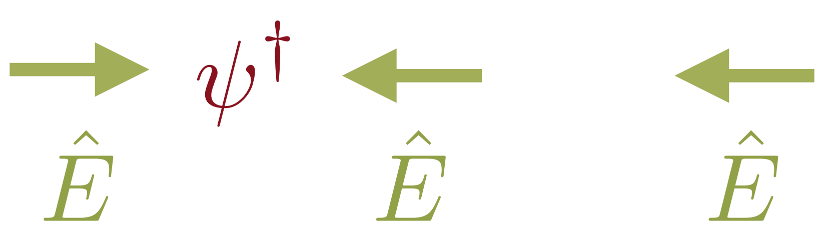
Theories with local symmetries (to be satisfied at every point)

CLASSICAL (electrodynamics)

$$\rho = \vec{\nabla} \cdot \vec{E}$$

QUANTUM (QED)

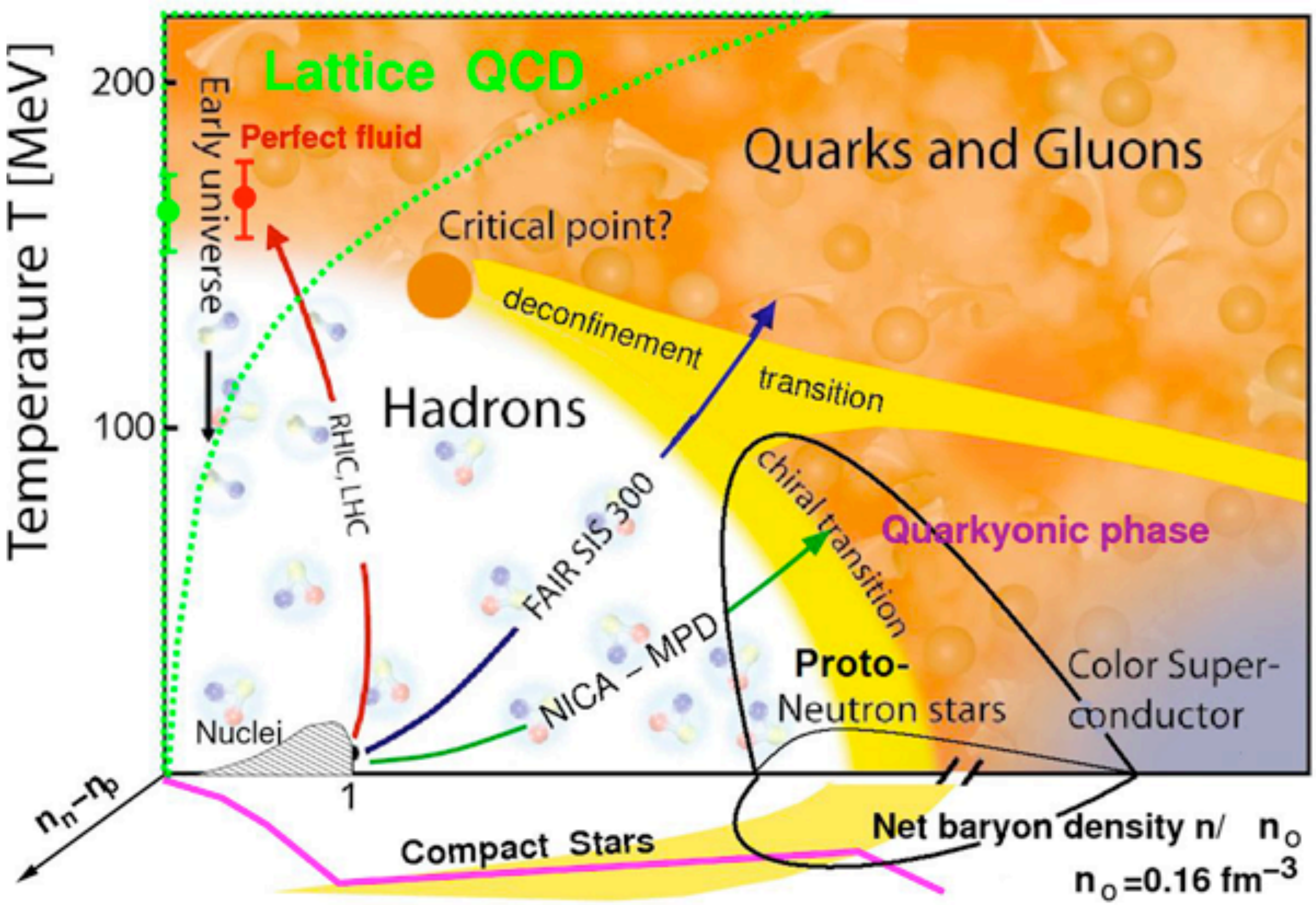
Gauss' law



$$\psi_x^\dagger \psi_x |\Psi\rangle = \Delta E_{x,x+a} |\Psi\rangle$$

$$H = -t \sum_x [\psi_x^\dagger U^\dagger_{x,x+1} \psi_{x+1} + \psi^\dagger_{x+1} U_{x,x+1} \psi_x]$$

SIGN PROBLEM



The current wisdom on the phase diagram of nuclear matter.

McLerran, L. Nucl.Phys.Proc.Suppl. 195 (2009) 275-280

LGT HAVE APPLICATIONS IN

High-energy physics

QED,
QCD, …

Condensed matter

Quantum spin ice,
Kitaev model, …

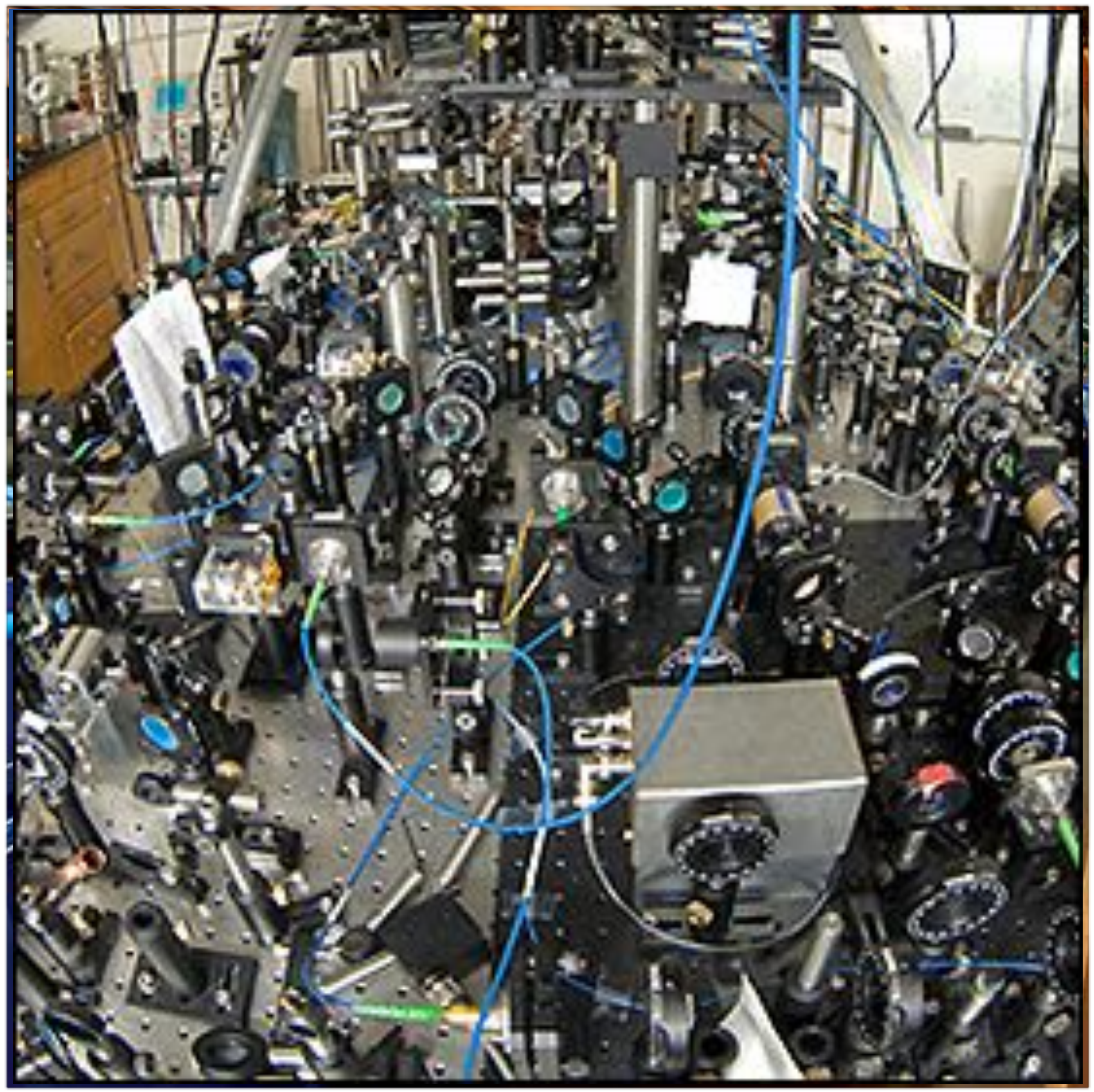
Quantum science

Quantum
simulations, …

Computer science

Adiabatic
computation

QUANTUM SIMULATION OF HEP PROCESS

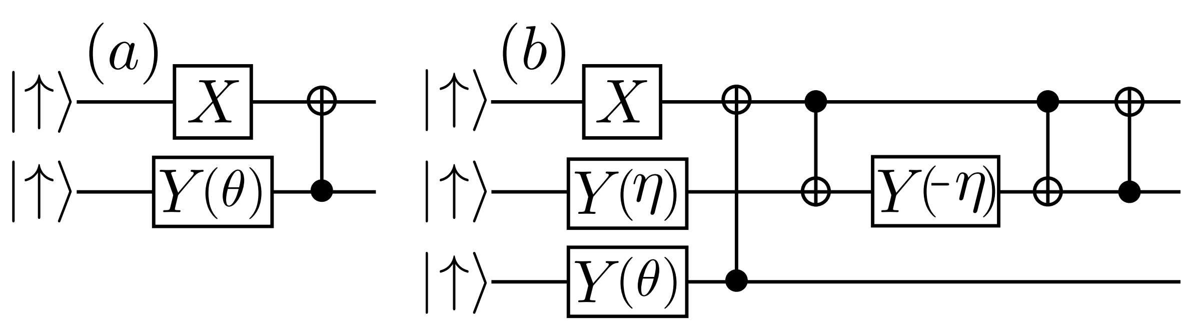


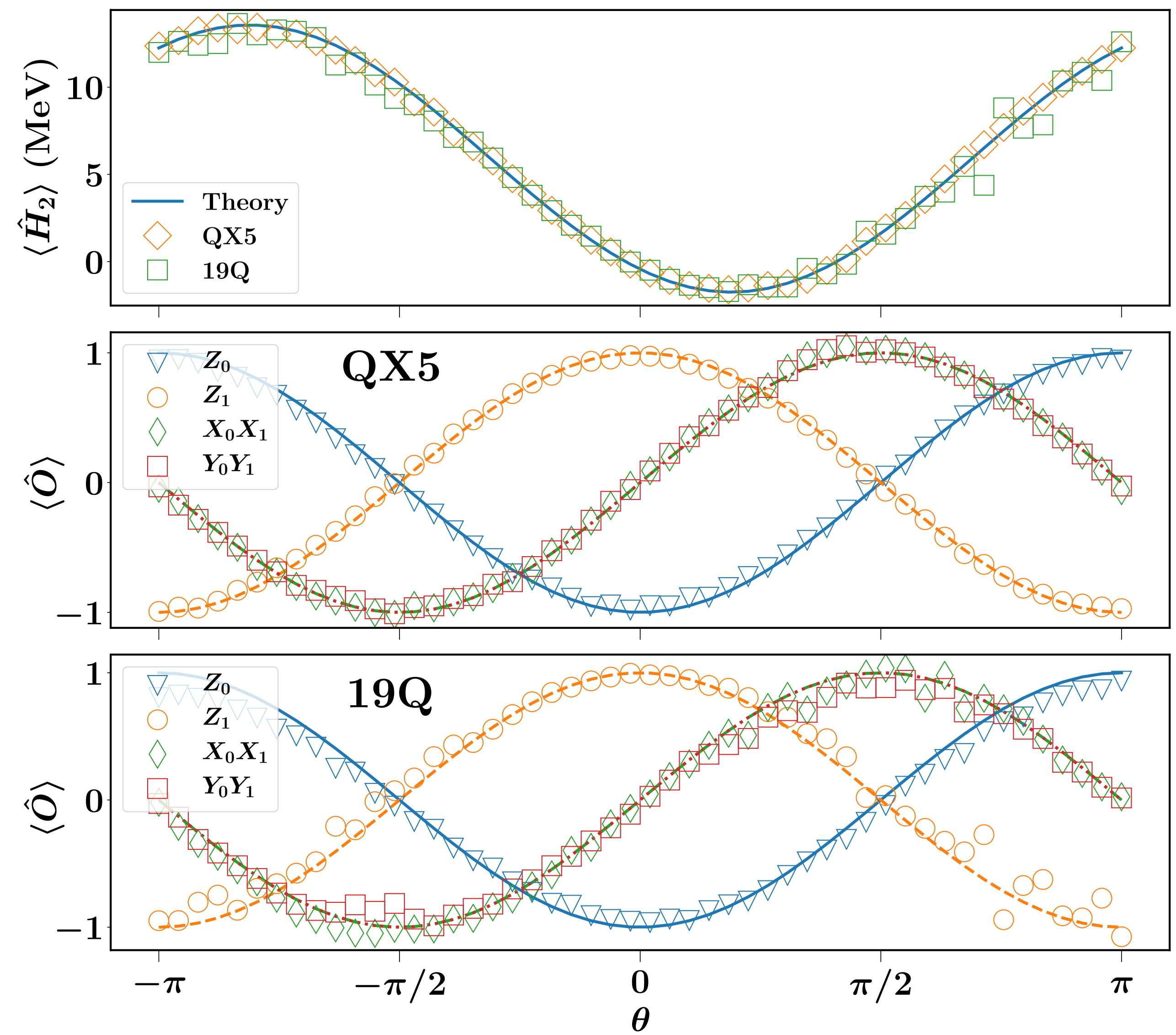
CLOUD QUANTUM COMPUTING OF AN ATOMIC NUCLEI

$$H_N = \sum_{n,n'=0}^{N-1} \langle n'|(T+V)|n\rangle a^\dagger_{n'} a_n$$

$$H_2 = 5.906709 I + 0.218291 Z_0 - 6.125 Z_1 - 2.143304\,(X_0X_1 + Y_0Y_1)\,,$$

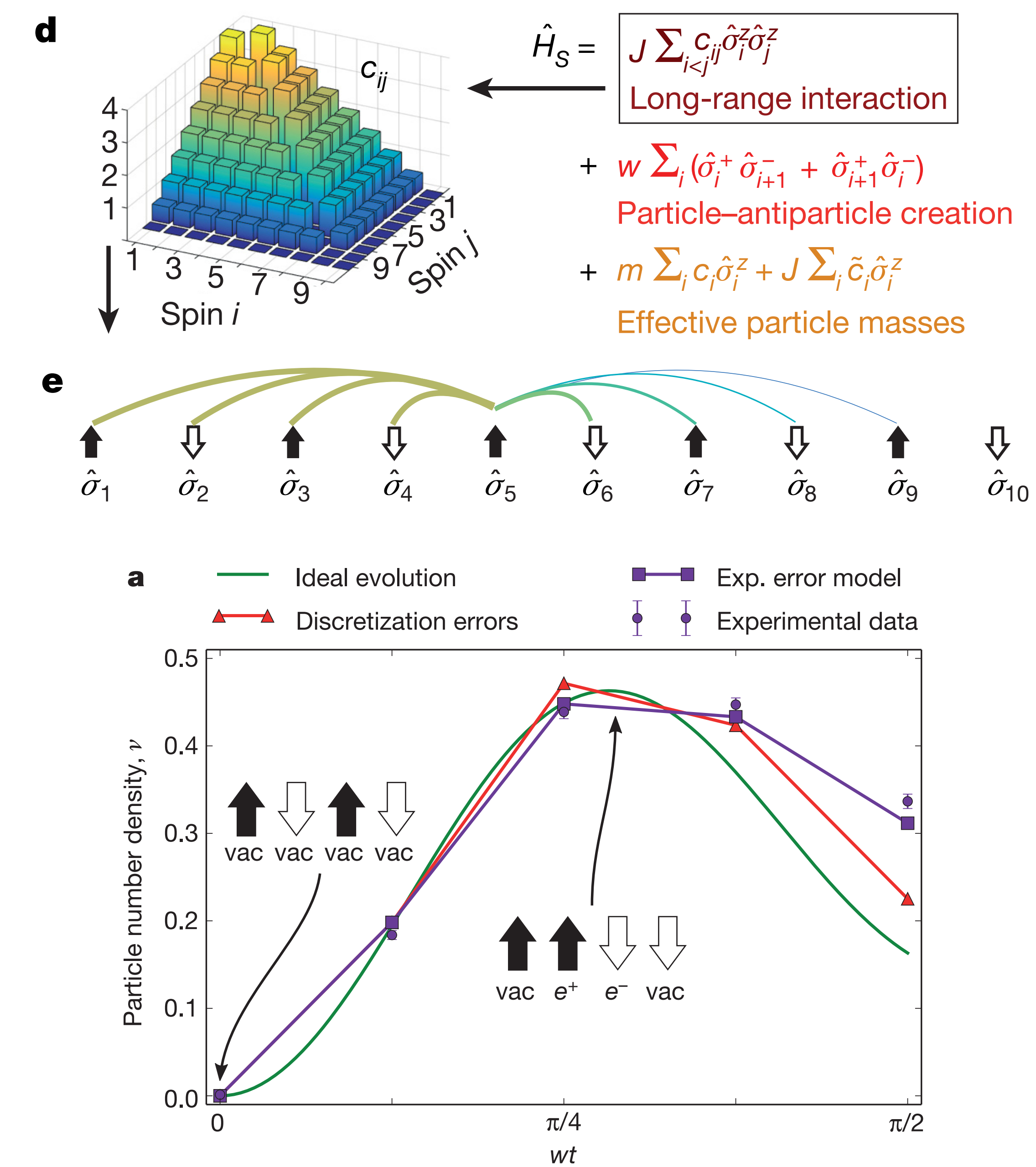
Computation of the deuteron ground state energy via quantum variational eigensolver algorithm

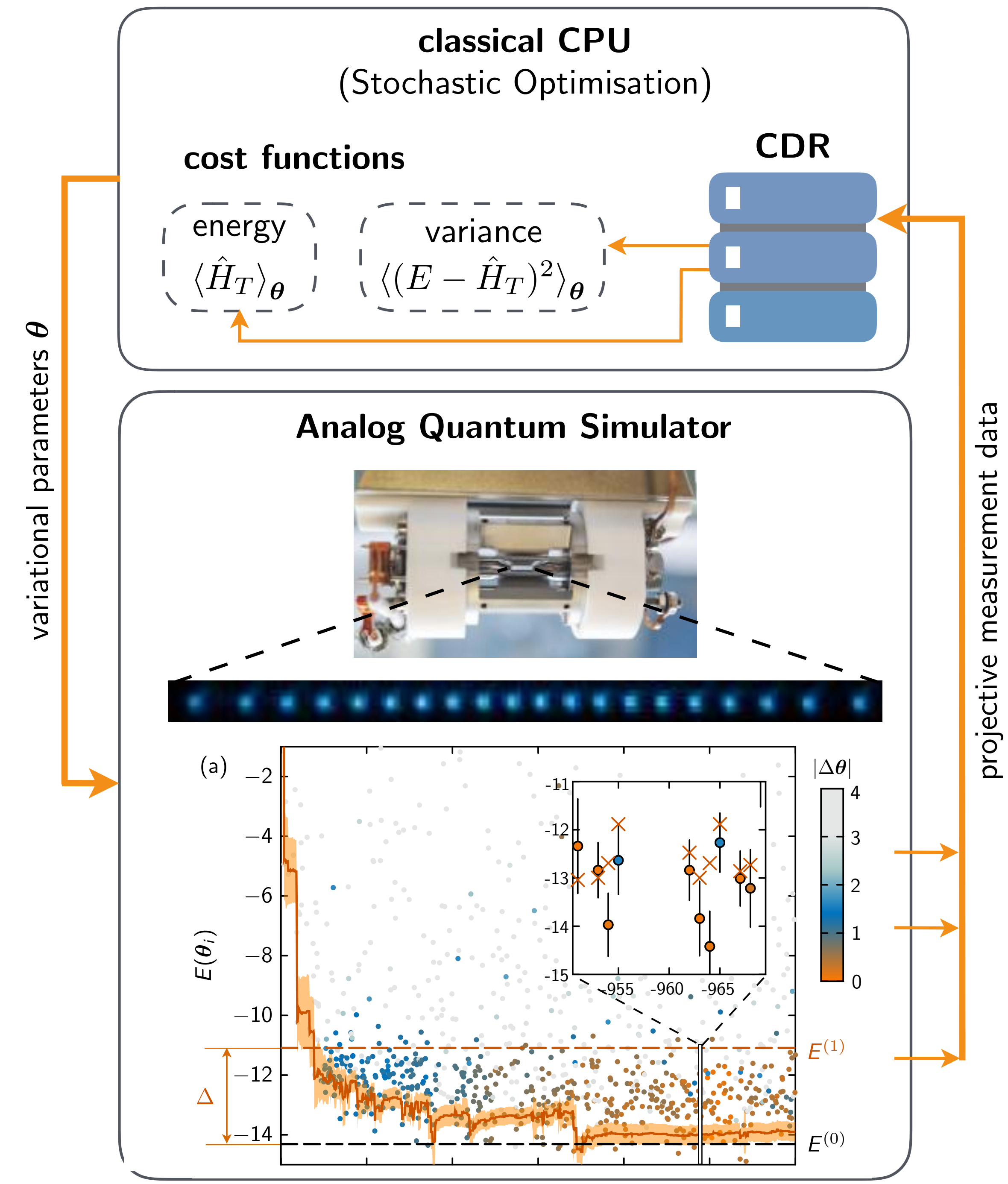




E.F. Dumitresku PRL (2018)

QUANTUM COMPUTING OF THE SCHWINGER MODEL





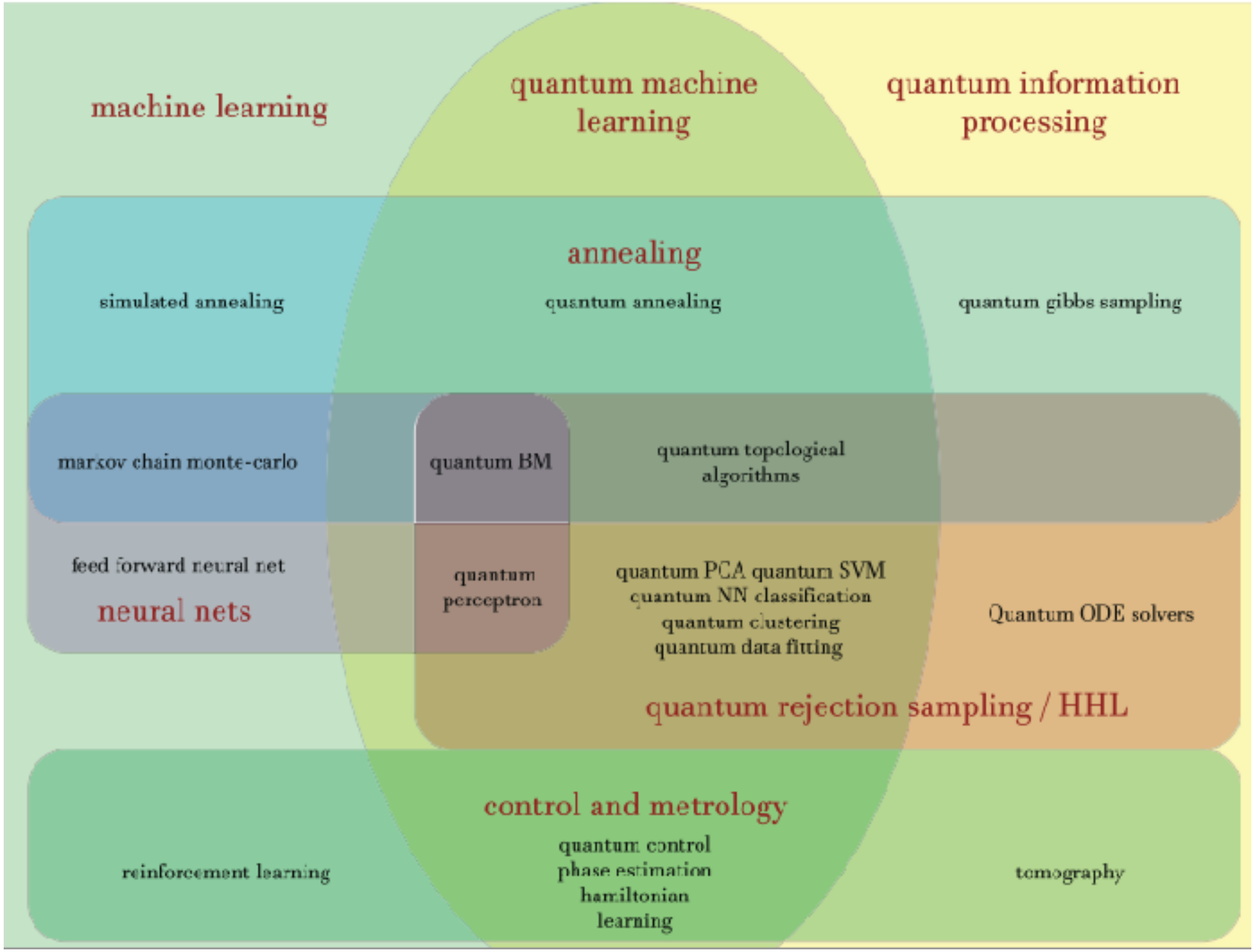
IQOQI Innsbruck

R. Blatt and P. Zoller's groups

20 lattice sites!

Nature (2016), Nature (2018)

QUANTUM MACHINE LEARNING



J. Biamonte et al. Nature (2017)

QUANTUM ALGORITHMS FOR BIG DATA

Speed up

Grover like	*SQRT(N)*
Shor algorithm (QFT)	*Exponential*

Tasks

Solving sets of linear equations $Ax=b$

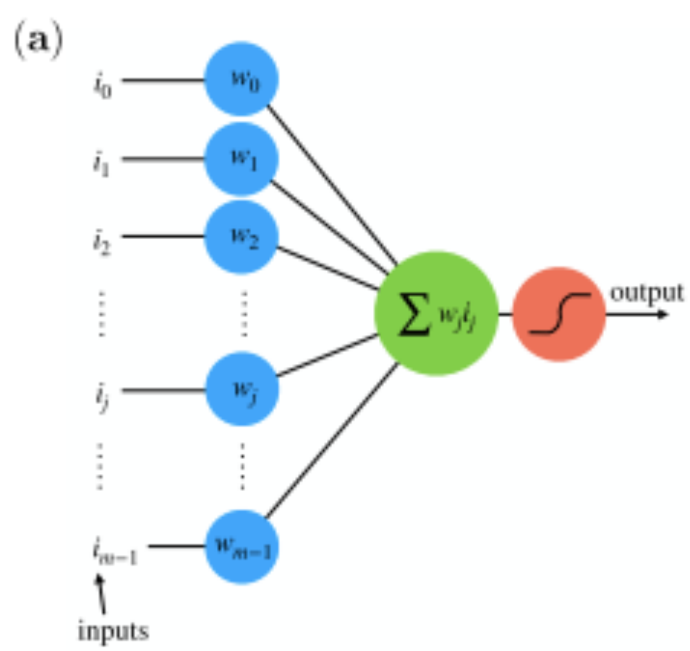
Find a concise function that approximates the data to be fitted and bound the approximation error

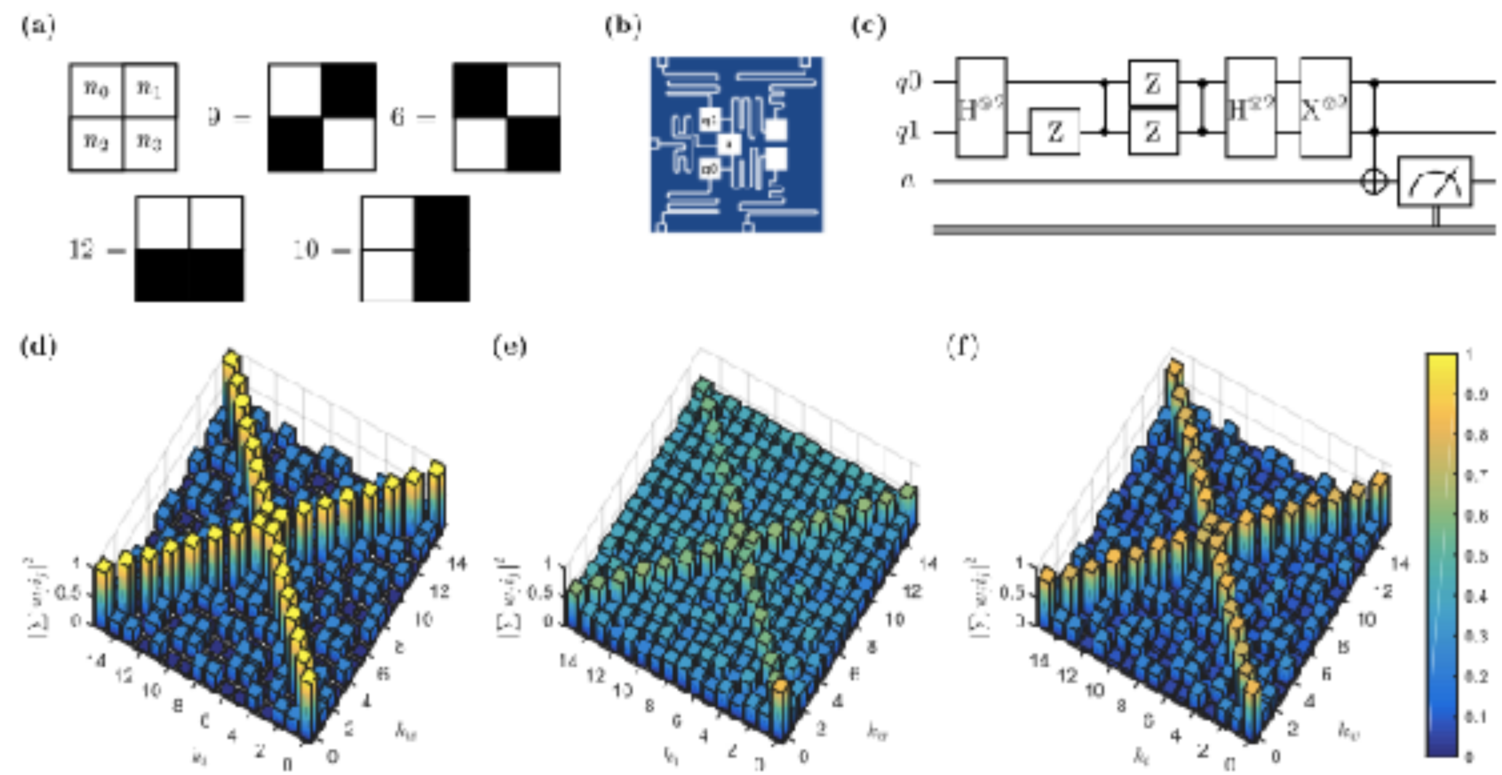
Support vector machine

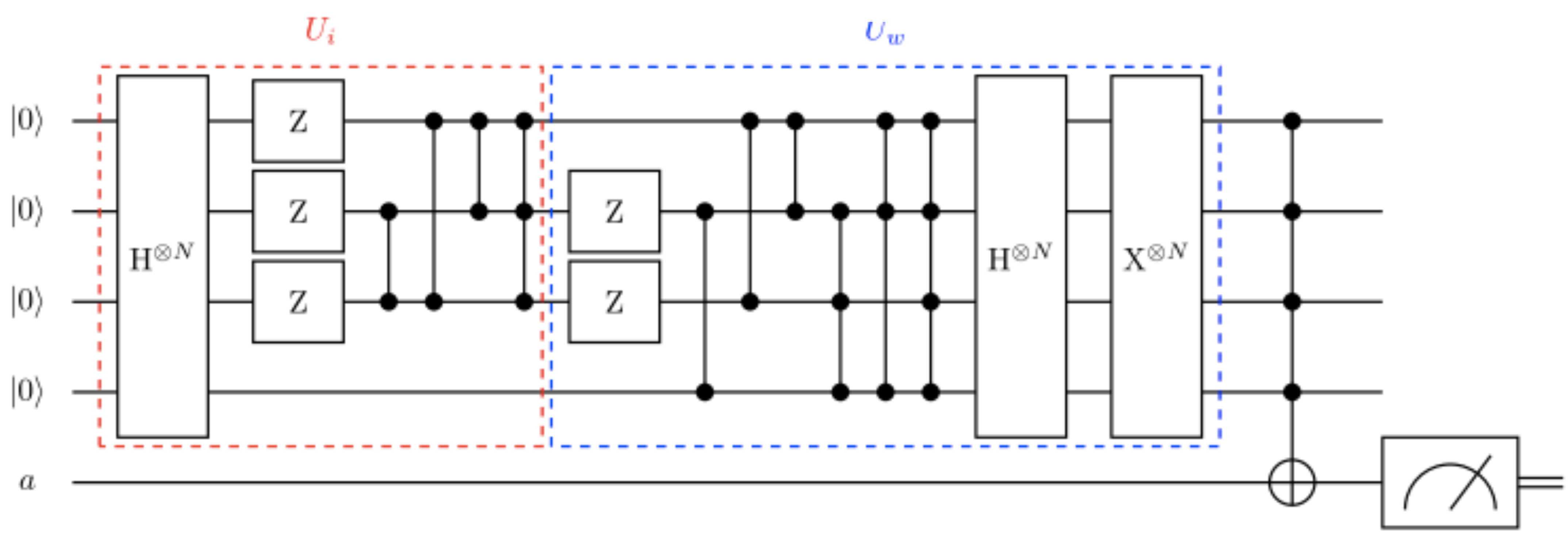
Cluster assignment and finding

…

QUANTUM PERCETRON







F. Tacchino et al. npj Quantum Information (2019)

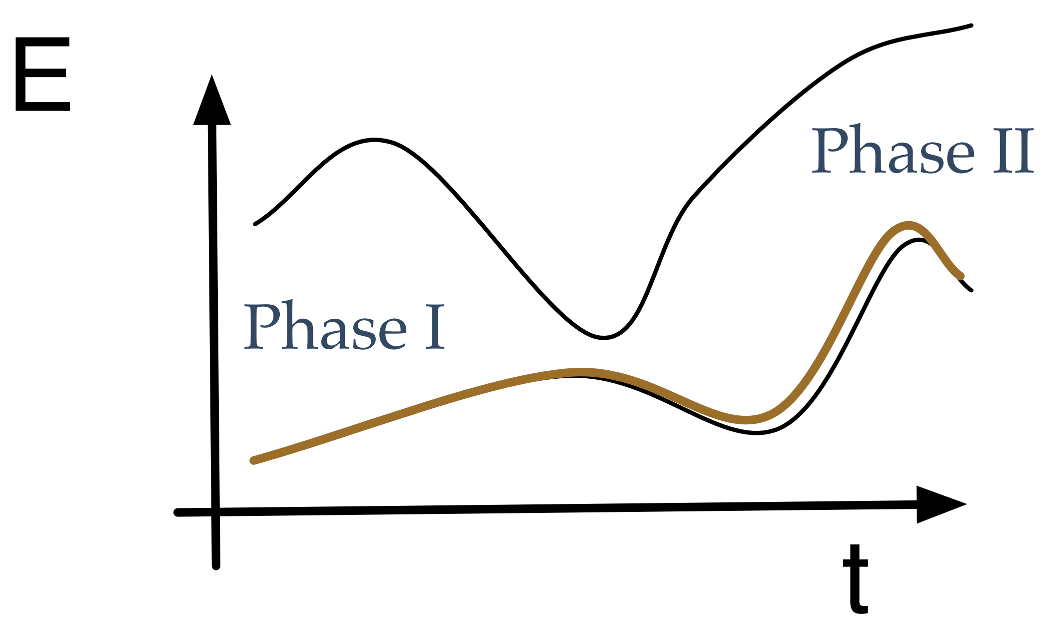
ADIABATIC QUANTUM COMPUTING

- *Preparation of the system in an "easy" state* $\downarrow\downarrow\downarrow\ldots\downarrow\downarrow\downarrow$

- *Slowly change the system Hamiltonian to reach another ground state which encodes the solution of the problem* $\downarrow\uparrow\downarrow\ldots\downarrow\downarrow\uparrow$

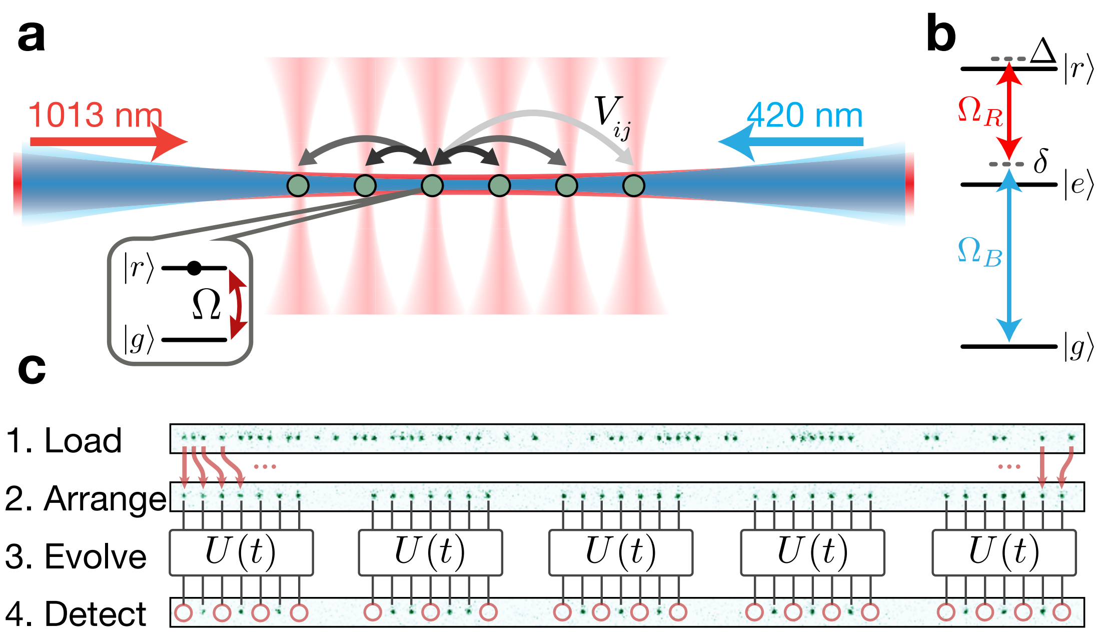
$$H_0 = -h_0 \sum_{i=1}^{N} s_i \qquad s_i = \{\uparrow, \downarrow\} \qquad H(t) = \left(1 - \frac{t}{T}\right) H_0 + \frac{t}{T} H_P$$

Slow



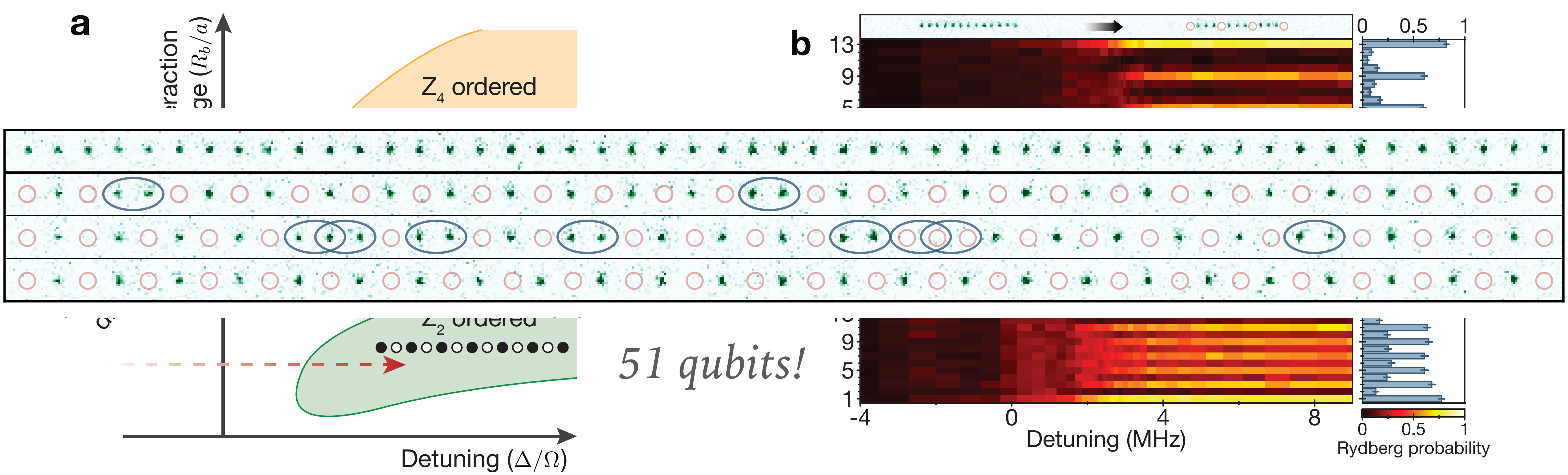
Adiabatic strategy

QUANTUM SIMULATION OF MANY-BODY CORRELATED DYNAMICS



$$\frac{\mathcal{H}}{\hbar} = \sum_i \frac{\Omega_i}{2}\sigma_x^i - \sum_i \Delta_i n_i + \sum_{i<j} V_{ij} n_i n_j,$$

Rydberg Blockade



51 qubits!

M. Lukin's group ***Nature*** *(2017)*

M. Dalmonte et al (2019)

OPTIMAL CROSSING OF QPT

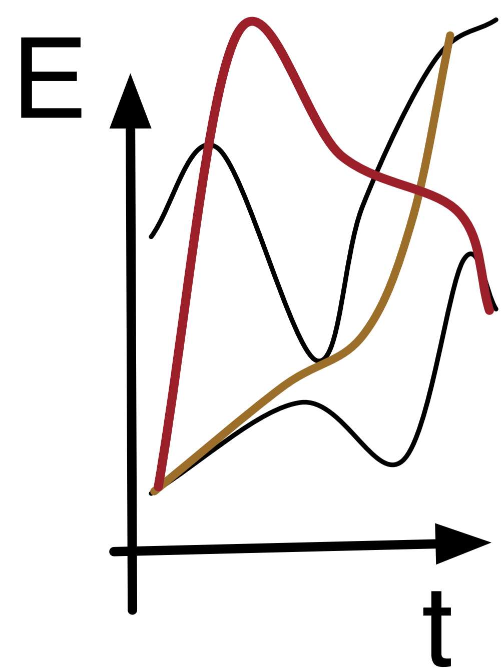
RedCRAB

Optimal control

$$i\frac{\partial}{\partial t}|\psi(t)\rangle = (H_0 + f(t)H_1)\,|\psi(t)\rangle$$

$$\min_{f(t)} J(|\psi(T)\rangle)$$

Fast

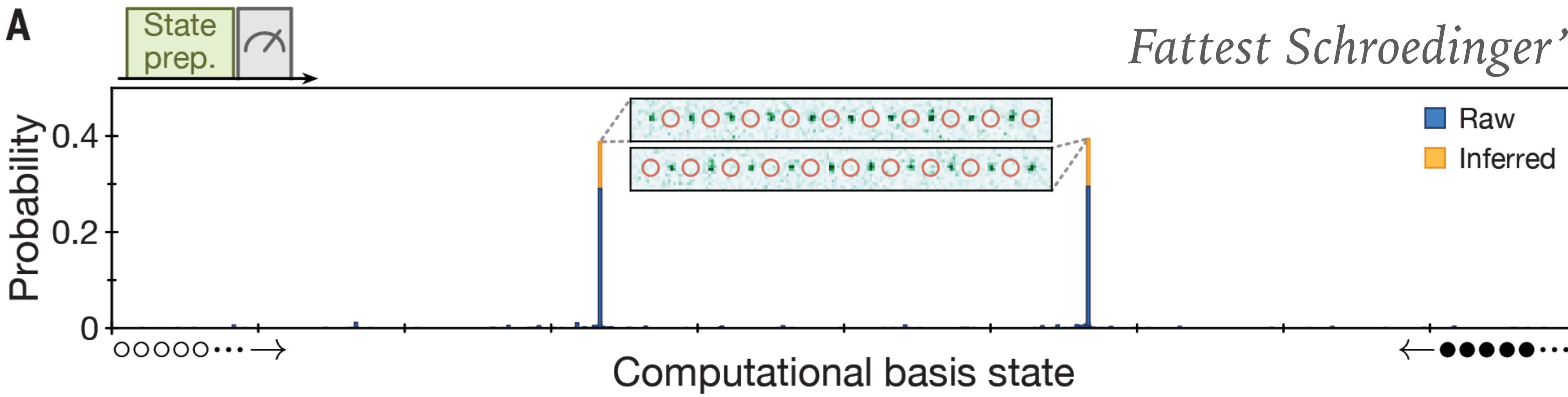


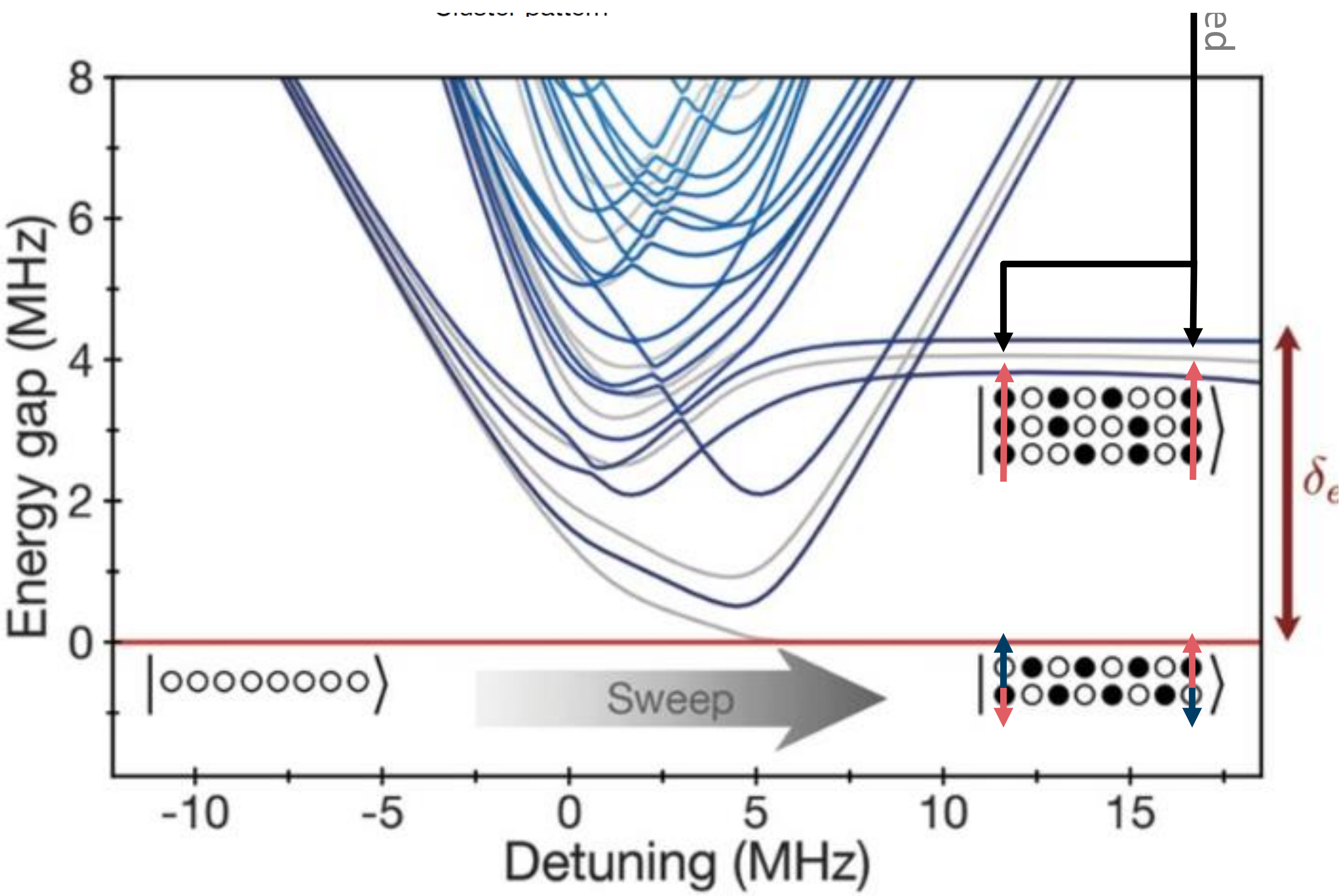
Optimal control

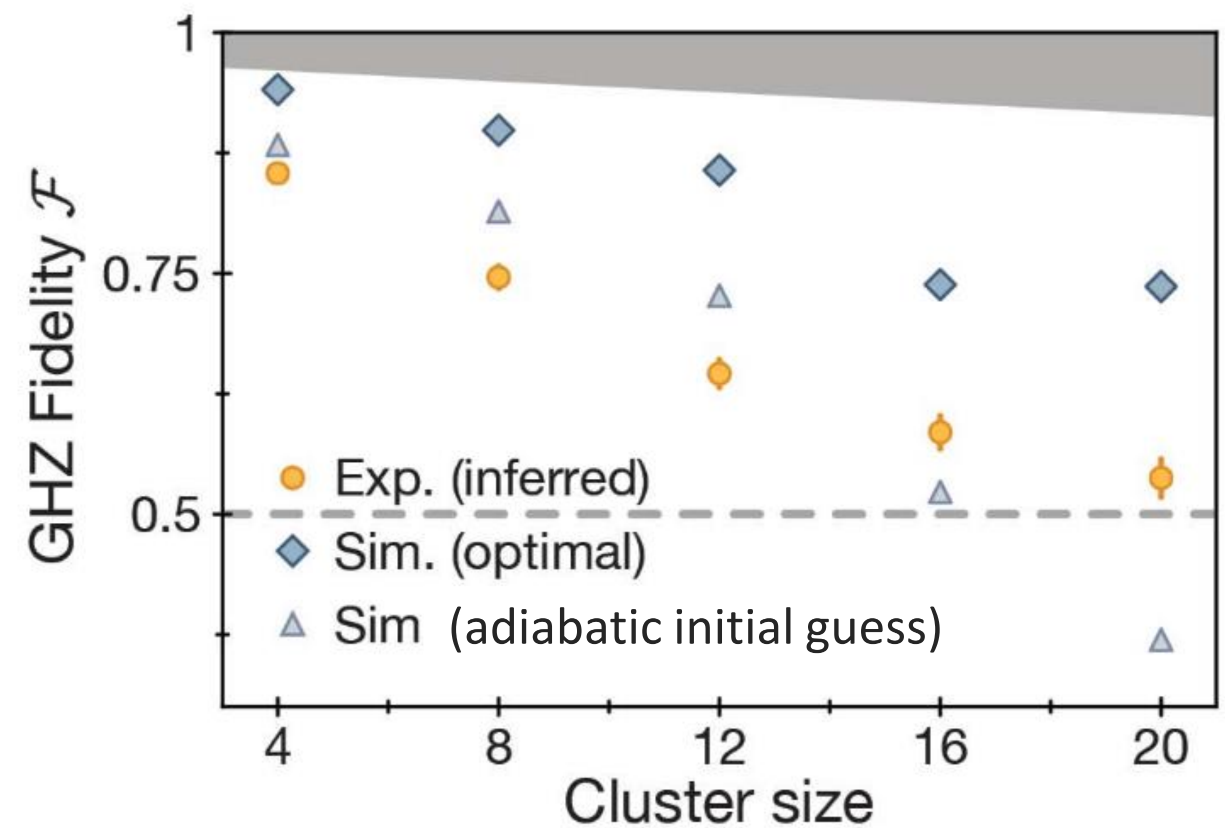
P. Doria et al PRL (2010), T. Caneva ***et al.*** ***PRA (2014)***

GHZ STATE PREPARATION ON RYDBERG

Fattest Schroedinger's cat!







Omran et al Science (2019)

QUANTUM GATES ON RYDBERG ATOMS

RedCRAB Optimization!

PHYSICAL REVIEW LETTERS **123,** 170503 (2019)

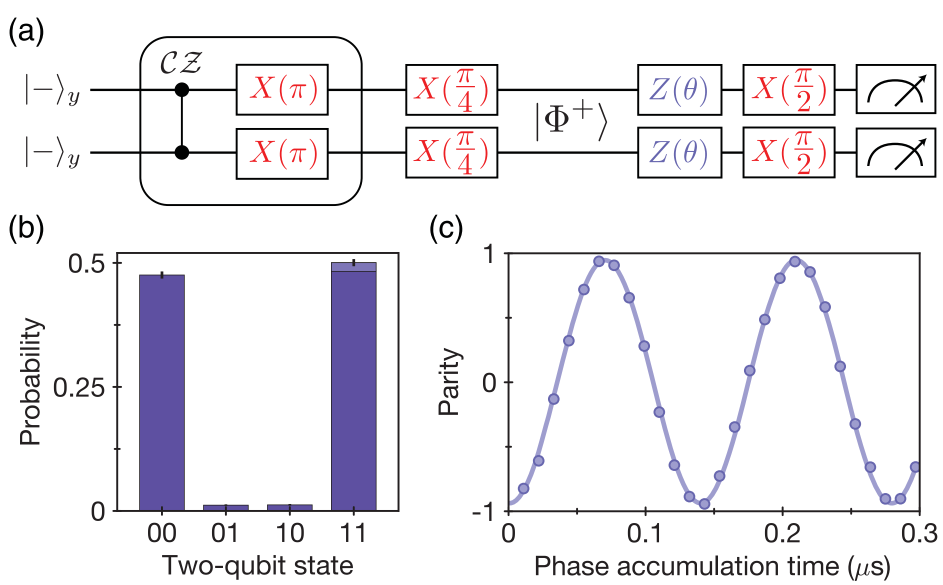
Editors' Suggestion | Featured in Physics

Parallel Implementation of High-Fidelity Multiqubit Gates with Neutral Atoms

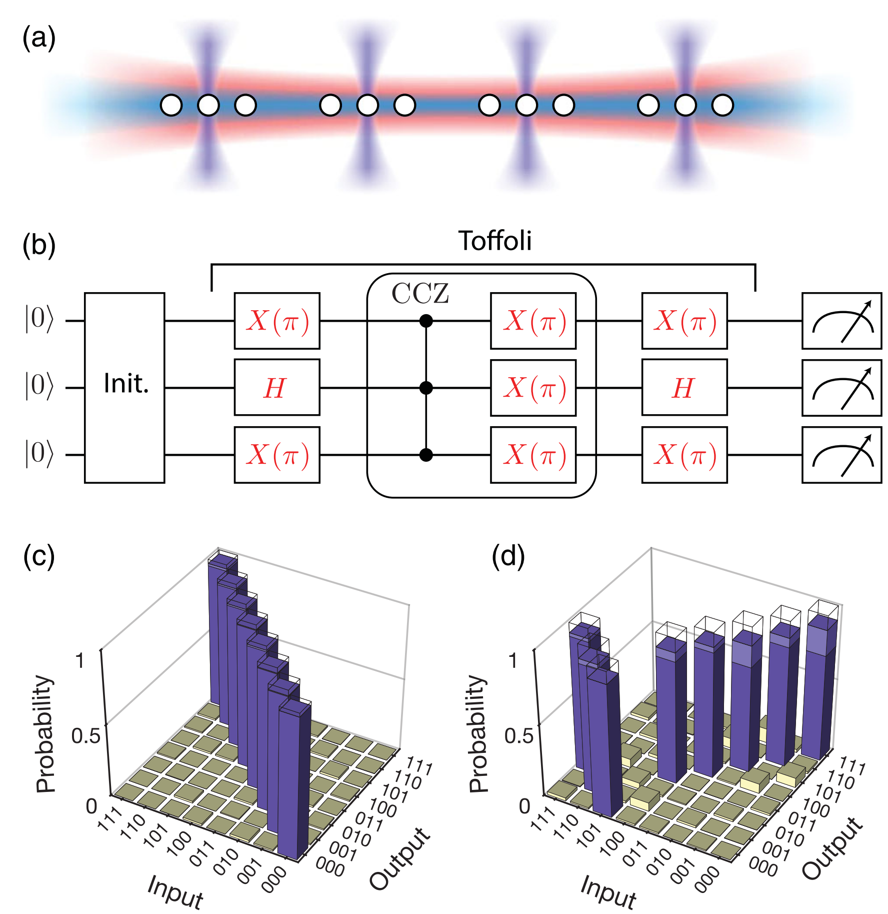
Harry Levine,[1,*] Alexander Keesling,[1] Giulia Semeghini,[1] Ahmed Omran,[1] Tout T. Wang,[1,2] Sepehr Ebadi,[1] Hannes Bernien,[3] Markus Greiner,[1] Vladan Vuletić,[4] Hannes Pichler,[1,5] and Mikhail D. Lukin[1]

[1]*Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*
[2]*Department of Physics, Gordon College, Wenham, Massachusetts 01984, USA*
[3]*Pritzker School of Molecular Engineering, University of Chicago, Chicago, Illinois 60637, USA*
[4]*Department of Physics and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
[5]*ITAMP, Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts 02138, USA*

Toffoli Gates

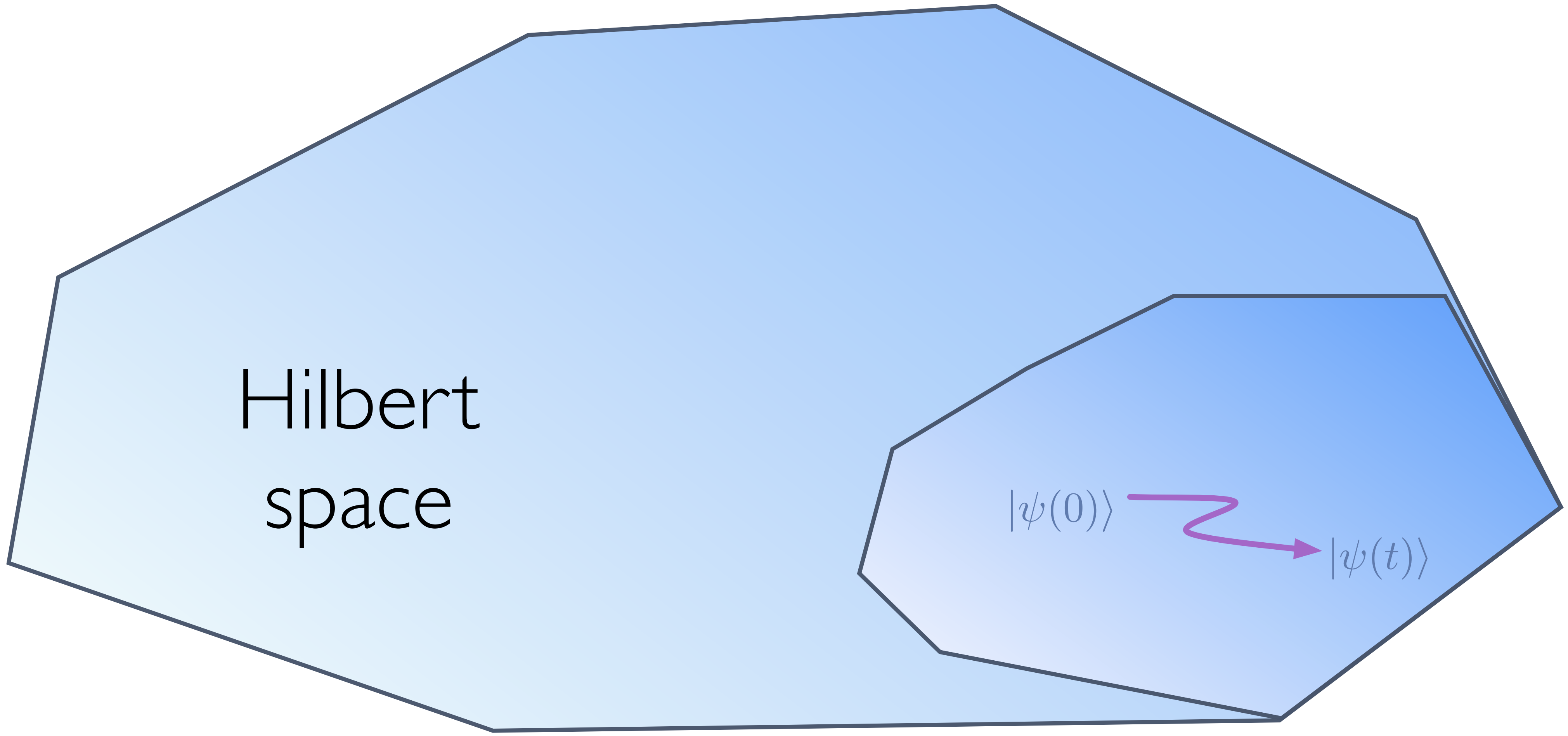


Bell state preparation

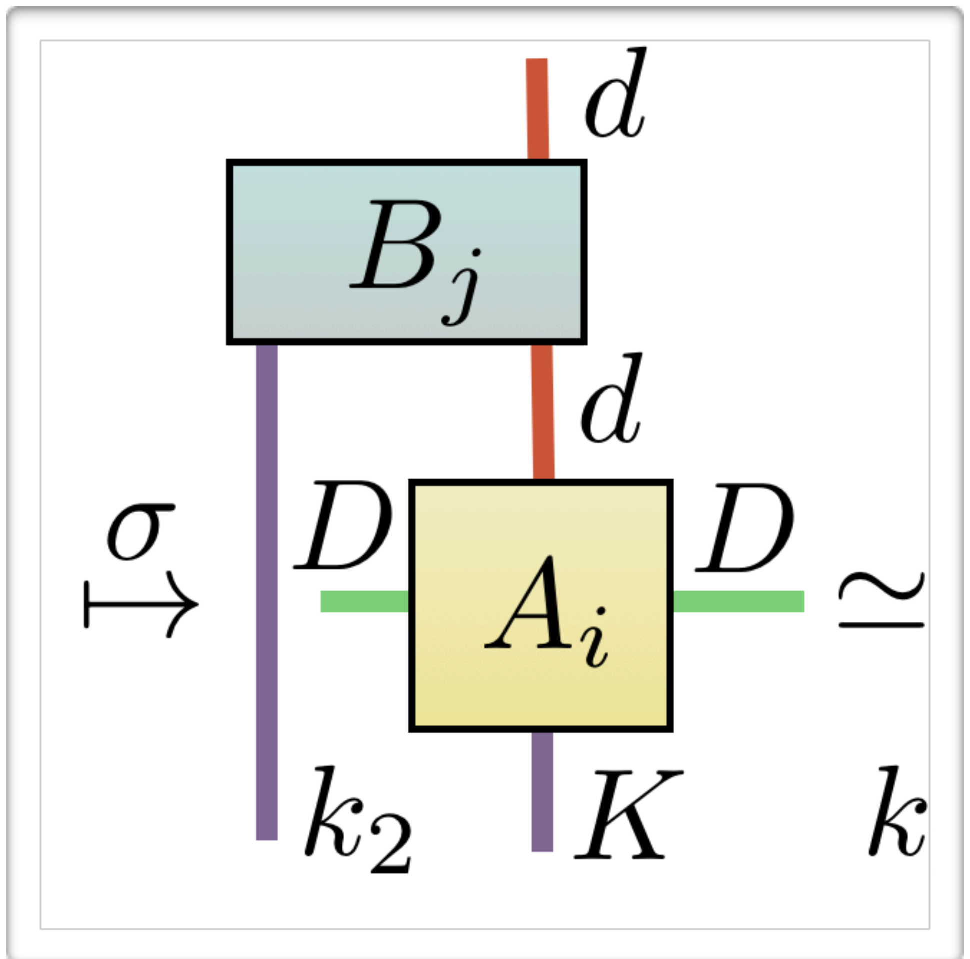


“

When do we really need a quantum simulation/computation?


Hilbert
space
$|\psi(0)\rangle$
$|\psi(t)\rangle$

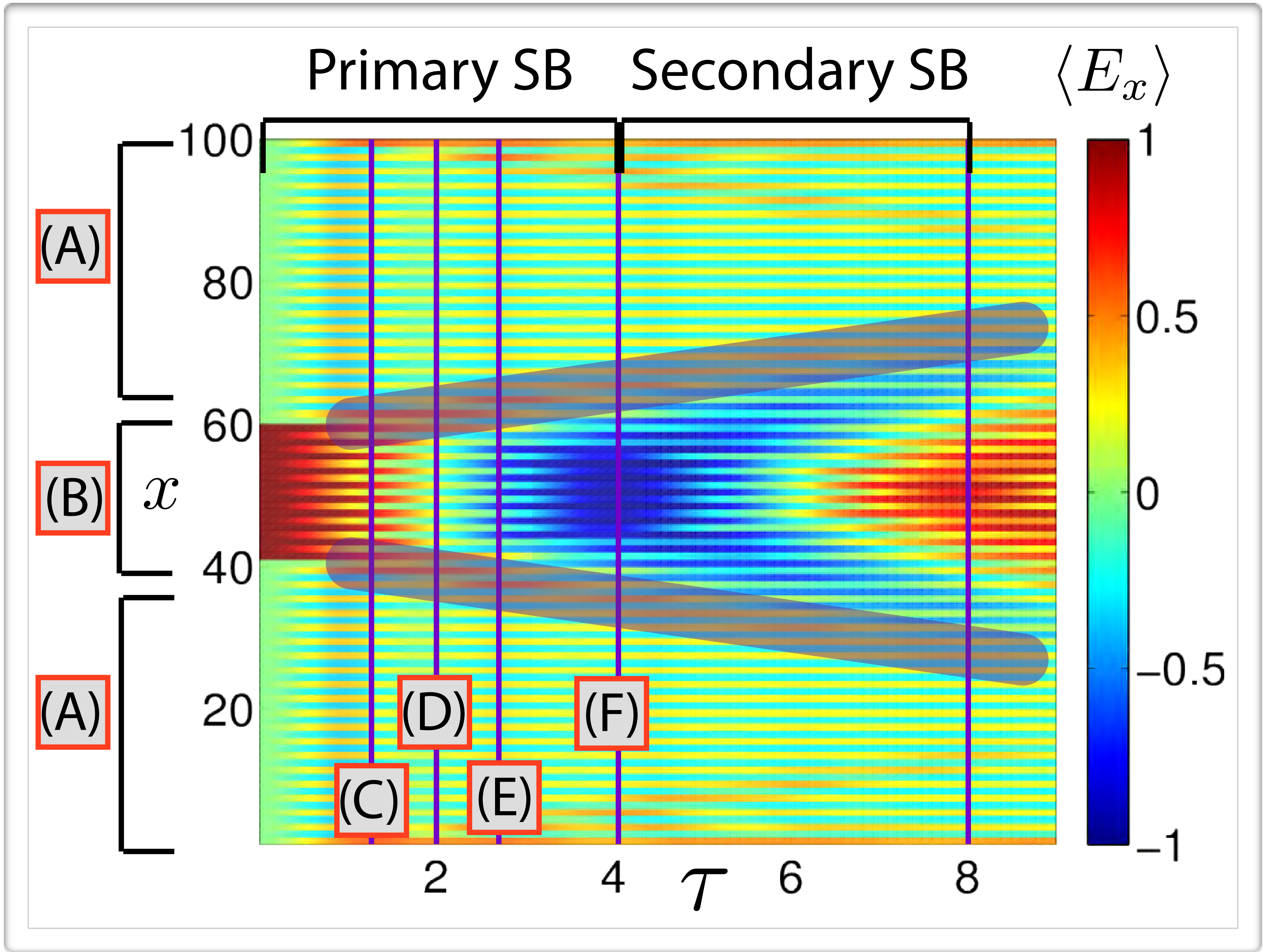
TENSOR NETWORK ALGORITHMS



- *State of the art in 1D (poly effort)*
- *No sign problem*
- *Extended to open quantum systems*
- *Machine learning*
- *Data compression (BIG DATA)*
- *Extended to lattice gauge theories*
- ***Simulations of low-entangled systems of hundreds qubits!***

U. Schollwock, RMP (2005) *A. Cichocki, ECM (2013)* *I. Glasser, et al. PRX (2018)*

Space

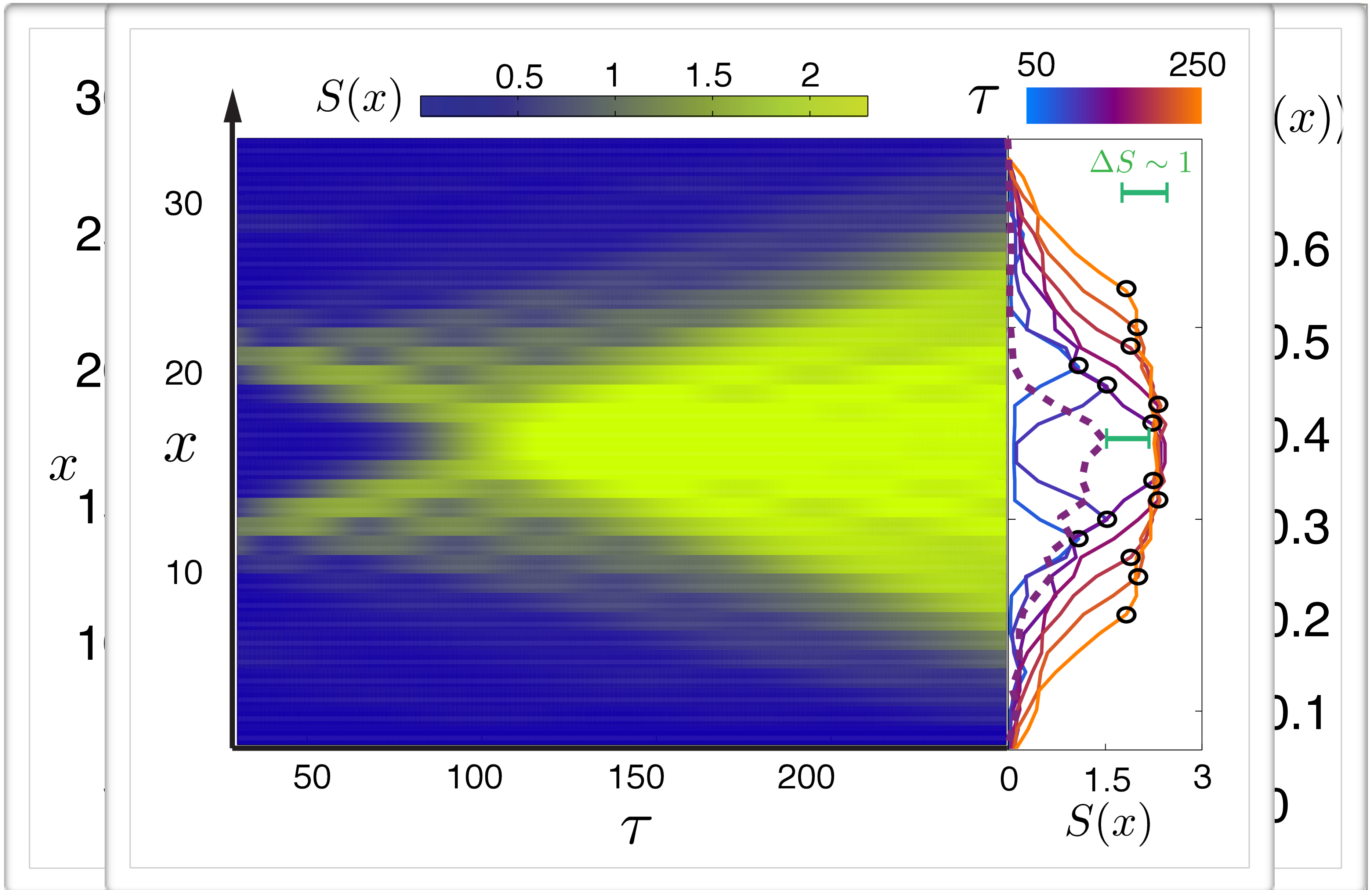


Real time

STRING BREAKING DYNAMICS

$$H = -t \sum_x \left[\psi_x^\dagger U_{x,x+1}^\dagger \psi_{x+1} + \psi_{x+1}^\dagger U_{x,x+1} \psi_x \right] + m \sum_x (-1)^x \psi_x^\dagger \psi_x + \frac{g^2}{2} \sum_x E_{x,x+1}^2 .$$

T. Pichler, E. Rico, M. Dalmonte, P. Zoller, and SM, PRX (2016)



Space

Real time

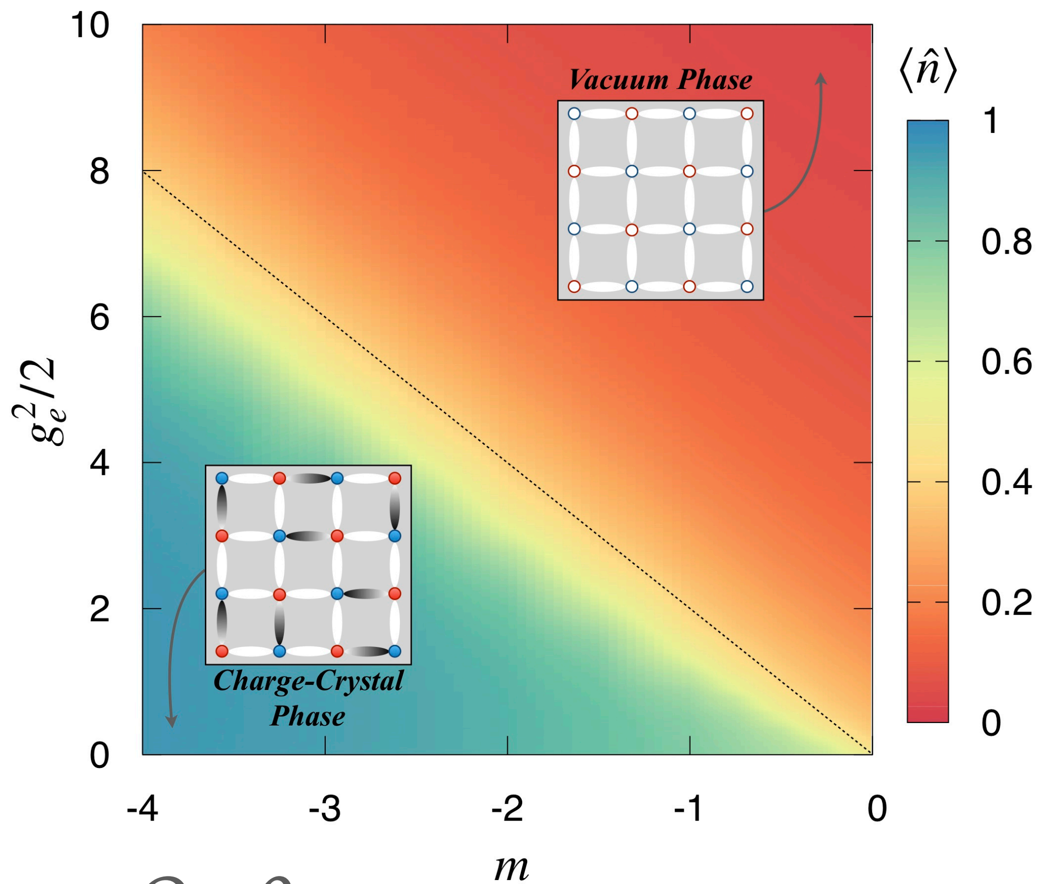
MESONS SCATTERING

T. Pichler, E. Rico, M. Dalmonte, P. Zoller, and SM, PRX (2016)

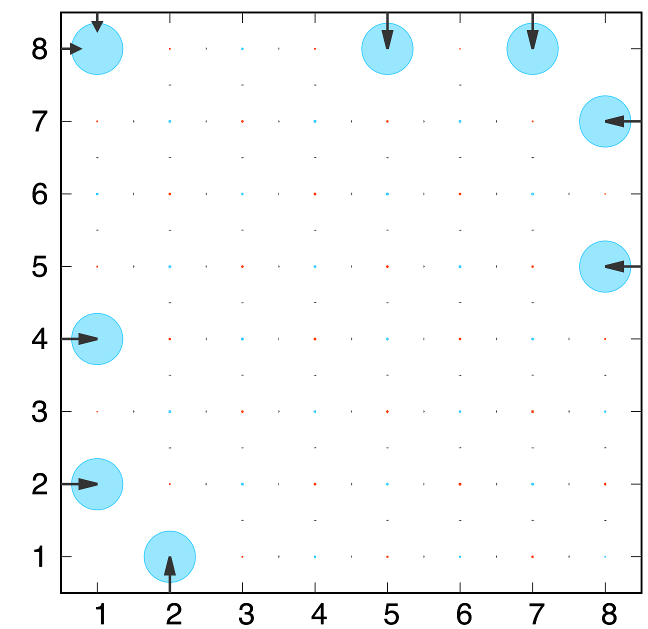
TWO DIMENSIONAL SIMULATION OF A LGT AT FINITE DENSITY

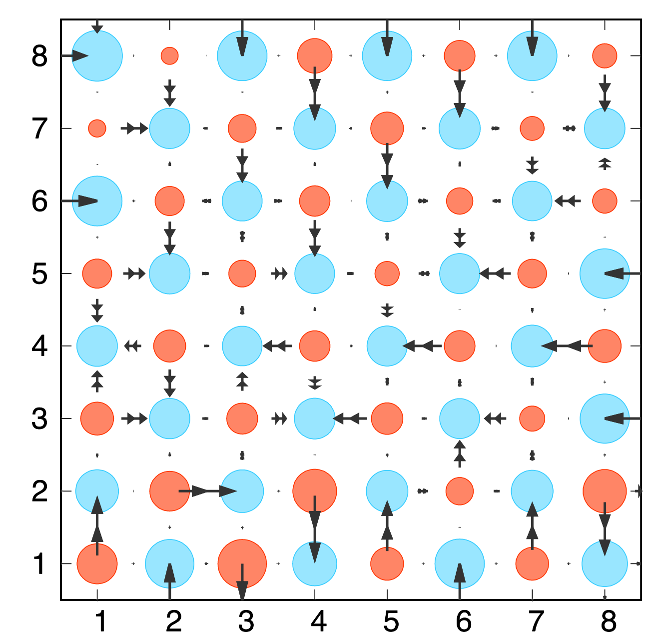
Hilbert space of ~80x80 qubits!

$$\hat{H} = -t \sum_{x,\mu} \left(\hat{\psi}_x^\dagger \hat{U}_{x,\mu} \hat{\psi}_{x+\mu} + h.c. \right) + m \sum_x (-1)^x \hat{\psi}_x^\dagger \hat{\psi}_x + \frac{g_e^2}{2} \sum_{x,\mu} \hat{E}_{x,\mu}^2 - \frac{g_m^2}{2} \sum_x \left(\hat{U}_{x,\mu_x} \hat{U}_{x+\mu_x,\mu_y} \hat{U}_{x+\mu_y,\mu_x}^\dagger \hat{U}_{x,\mu_y}^\dagger + h.c. \right)$$



Q=0





Q= - 8

arXiv:1911.09693

COMPARISON WITH MACHINE LEARNING

$$\psi_w(\mathbf{s}) = \prod_i \cosh\left(b_i + \sum_j w_{ij} s_j\right)$$

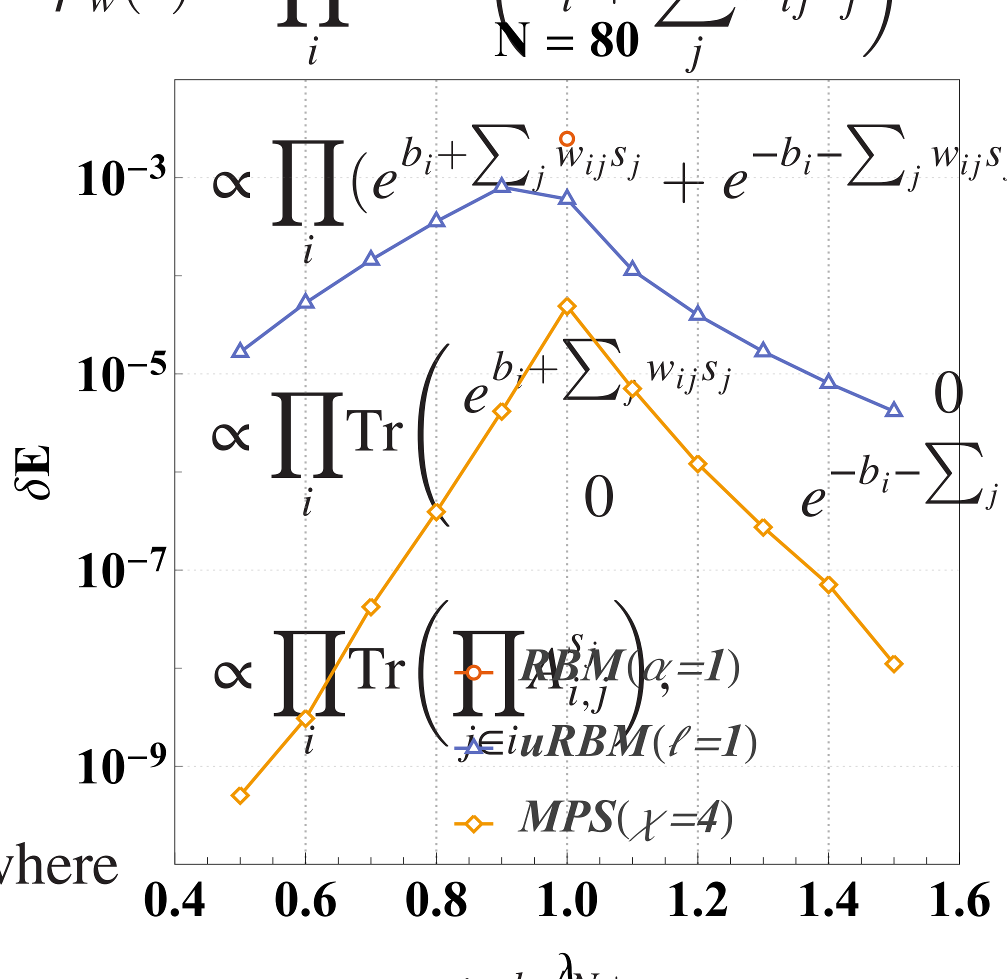
$$\propto \prod_i \left(e^{b_i + \sum_j w_{ij} s_j} + e^{-b_i - \sum_j w_{ij} s_j}\right)$$

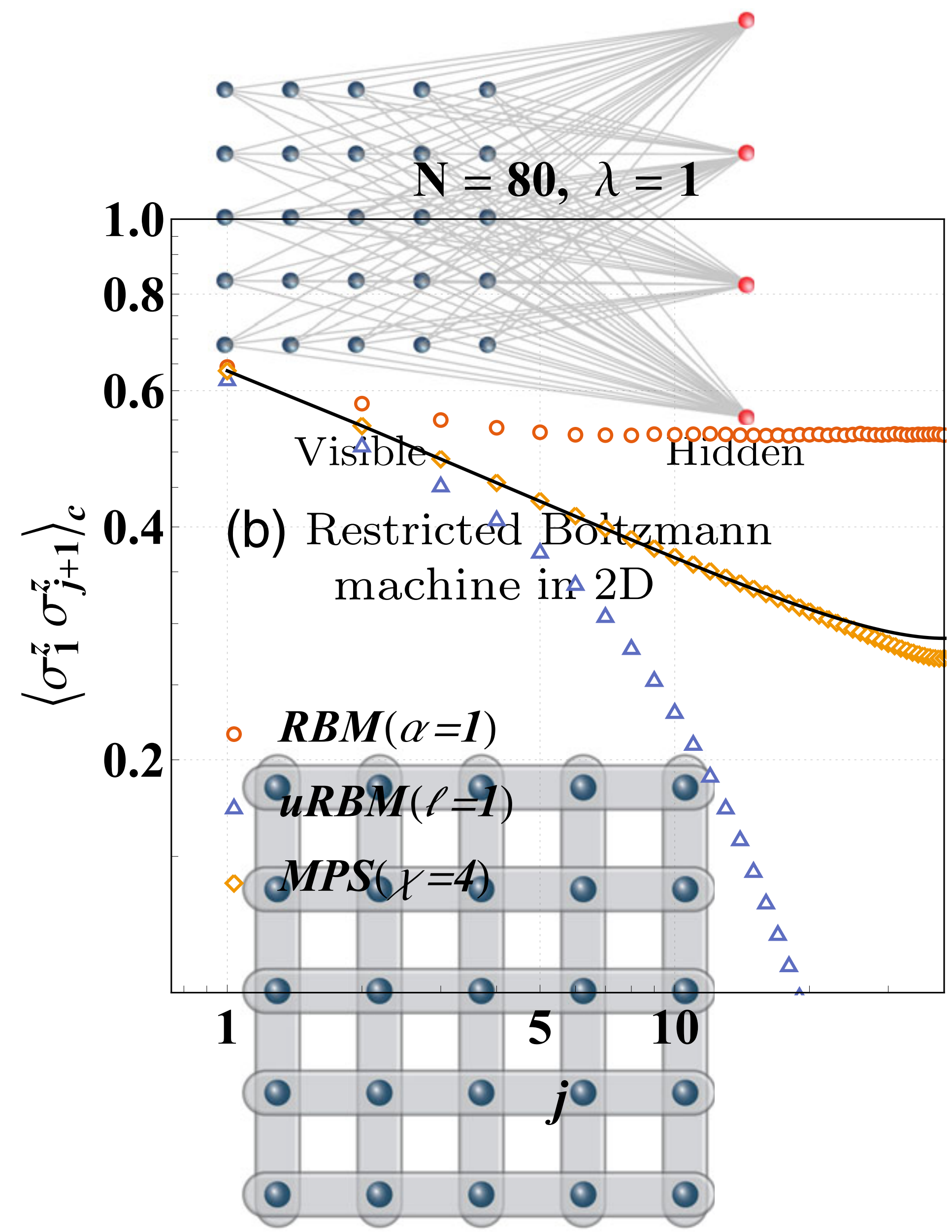
$$\propto \prod_i \mathrm{Tr}\begin{pmatrix} e^{b_i + \sum_j w_{ij} s_j} & 0 \\ 0 & e^{-b_i - \sum_j w_{ij} s_j} \end{pmatrix}$$

$$\propto \prod_i \mathrm{Tr}\left(\prod_j A_{i,j}^{s_j}\right)$$

where

$$A_{i,j}^{s_j} = \begin{pmatrix} e^{b_i/N + w_{ij} s_j} & 0 \\ 0 & e^{-b_i/N - w_{ij} s_j} \end{pmatrix}$$





(b) Restricted Boltzmann machine in 2D

(d) SBS

G. Carleo, M. Troyer Science (2017)

Ivan Glasser et al PRX (2018)

M. Collura et al, arXiv:1905.11351

TN MACHINE LEARNING OF HEP DATA

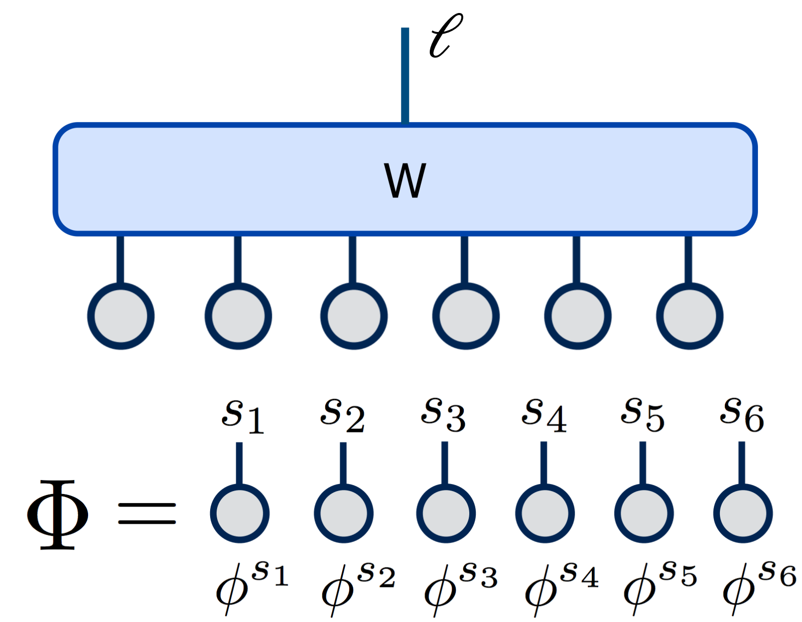
Hypothesis class: $f^{\ell}(\bar{x}) = \boldsymbol{W}^{\ell} \cdot \Phi(\bar{x})$

$$f^{\ell}(\bar{x}) = \sum_{\mathbf{s}} W^{\ell}_{s_1 s_2 \ldots s_N} \phi(x_1)^{s_1} \phi(x_2)^{s_2} \ldots \phi(x_N)^{s_N}$$

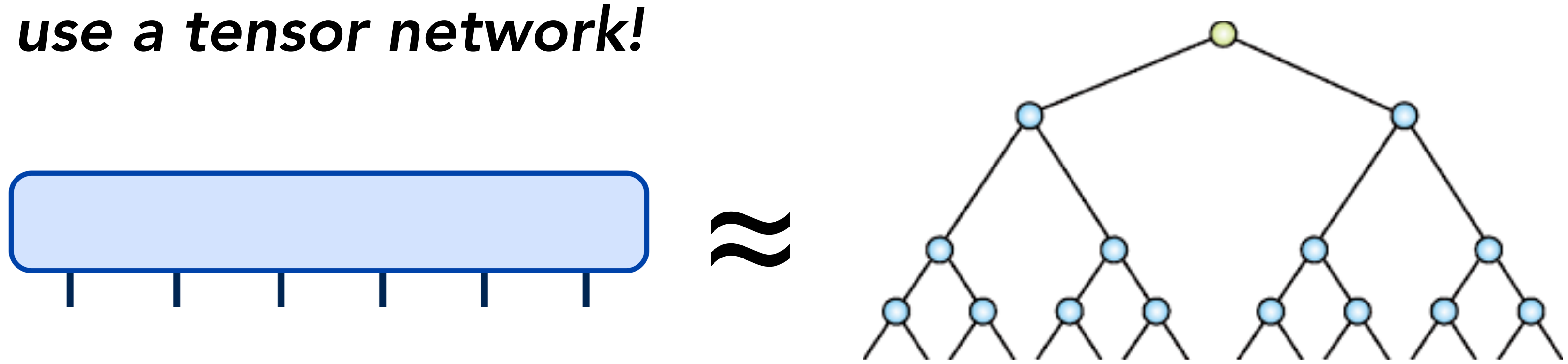
f^{ℓ} ***map input data to the space of labels***

PROBLEM: ***W is a N+1 order tensor that grows exponentially with the input data***

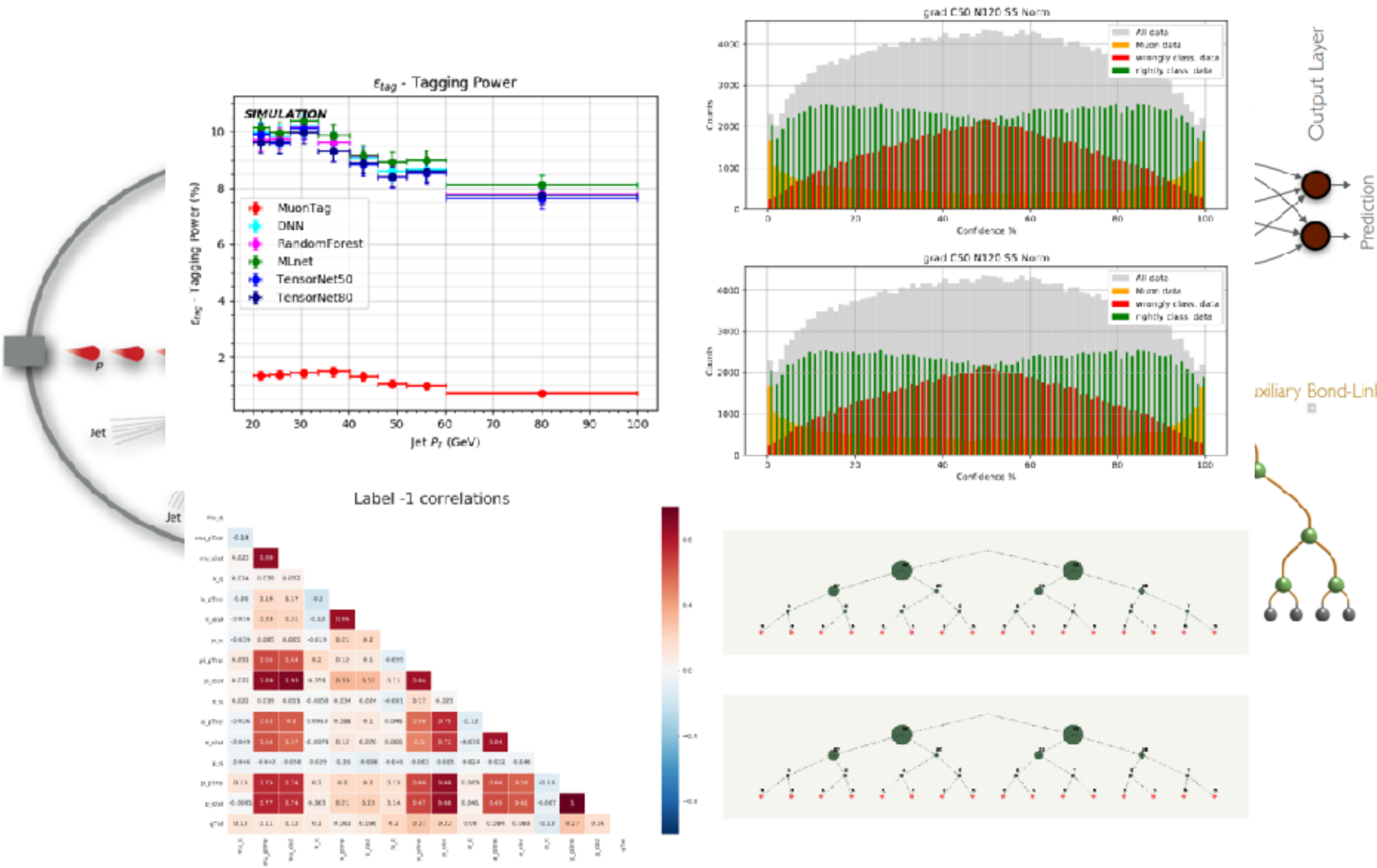
Tensor diagram notation



SOLUTION: ***use a tensor network!***



TENSOR NETWORK MACHINE LEARNING OF HEP EVENT



In collaboration with A. Gianelle, D. Lucchesi, L. Sestini, D. Zuliani

TAKE HOME MESSAGE

- Quantum technologies are fast developing, hybrid solutions will play a fundamental role
- Tensor network algorithms can be used to benchmark, verify, support and guide quantum simulations/computations
- Synergies between quantum technologies and high-energy physics can lead to unexpected developments:
    - Sign-problem-free solutions
    - Machine learning
    - Quantum sensing
    - Optimized protocols
- Quest for quantum advantage is open

Thank you for your attention!

Simone Montangero
Simone Notarnicola
Giuseppe Magnifico
Luca Arceci
Timo Felser
Marco Rossignolo
Marco Trenti

Tommaso Calarco

Ressa Said
Matthias Gerster
Ferdinand Tschirsch
Fedor Jelezko
Boris Naydenov

Misha Lukin
Hannes Pichler
Ahmed Omran

S. Lloyd

Peter Zoller
Pietro Silvi
Wolfgang Lechner

Enrique Rico Ortega

Rosario Fazio
Marcello Dalmonte

Jacob Sherson

Immanuel Bloch
Marc Cheneau
Sebastian Hild

Mario Collura
Giuseppe Santoro

Jörg Schmiedmayer
Thorsten Schumm
Sandrine van Frank

QTFLAG
QuantHEP

ECT* Ph.D. School Summer 2020