INTRODUCTION TO QUANTUM TECHNOLOGIES

S.Montangero

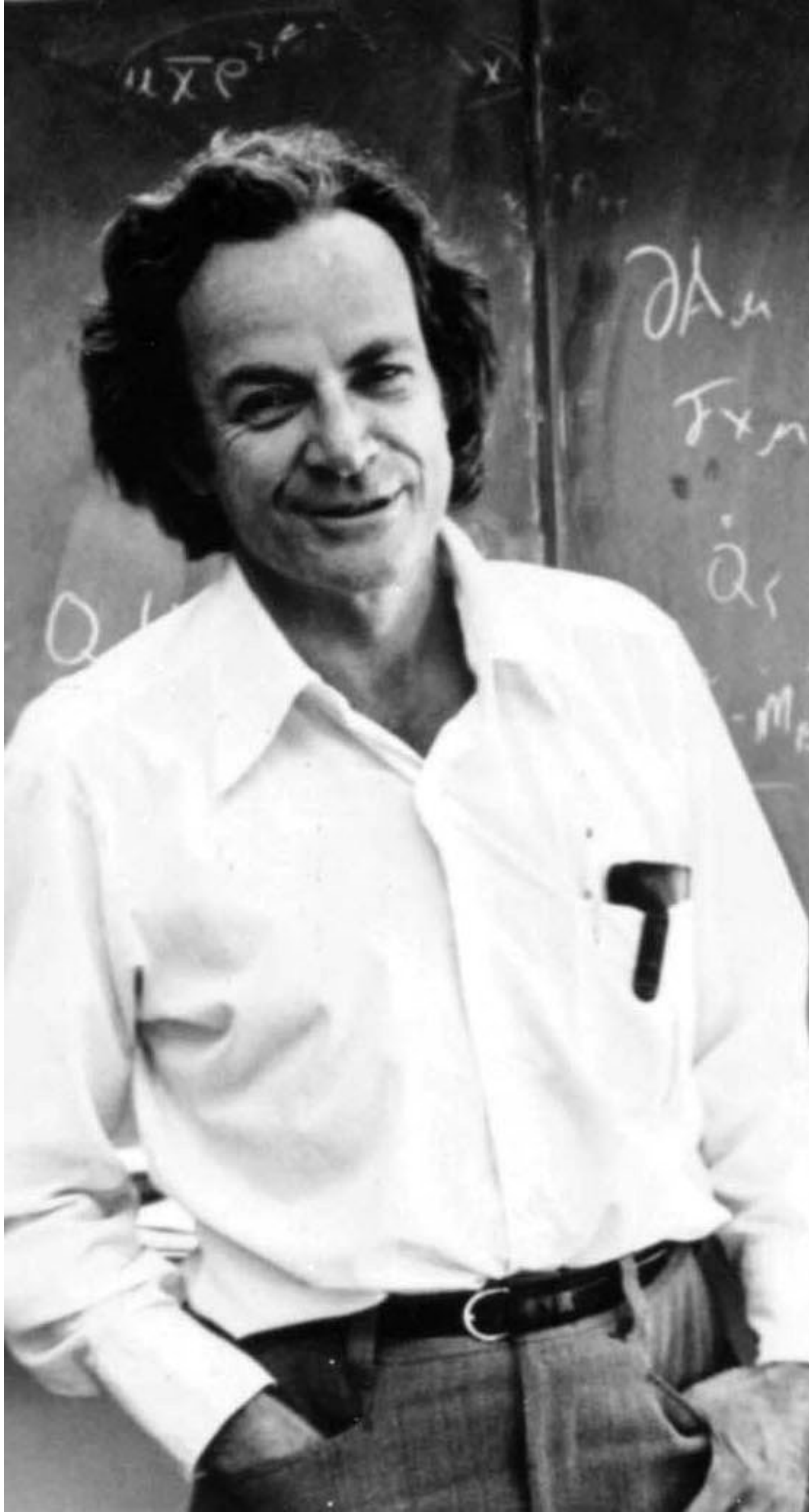
University of Padova

CERN 5/11/18

Dipartimento
di Fisica
e Astronomia
Galileo Galilei

UNIVERSITÀ
DEGLI STUDI
DI PADOVA

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



RICHARD FEYNMAN (1982)

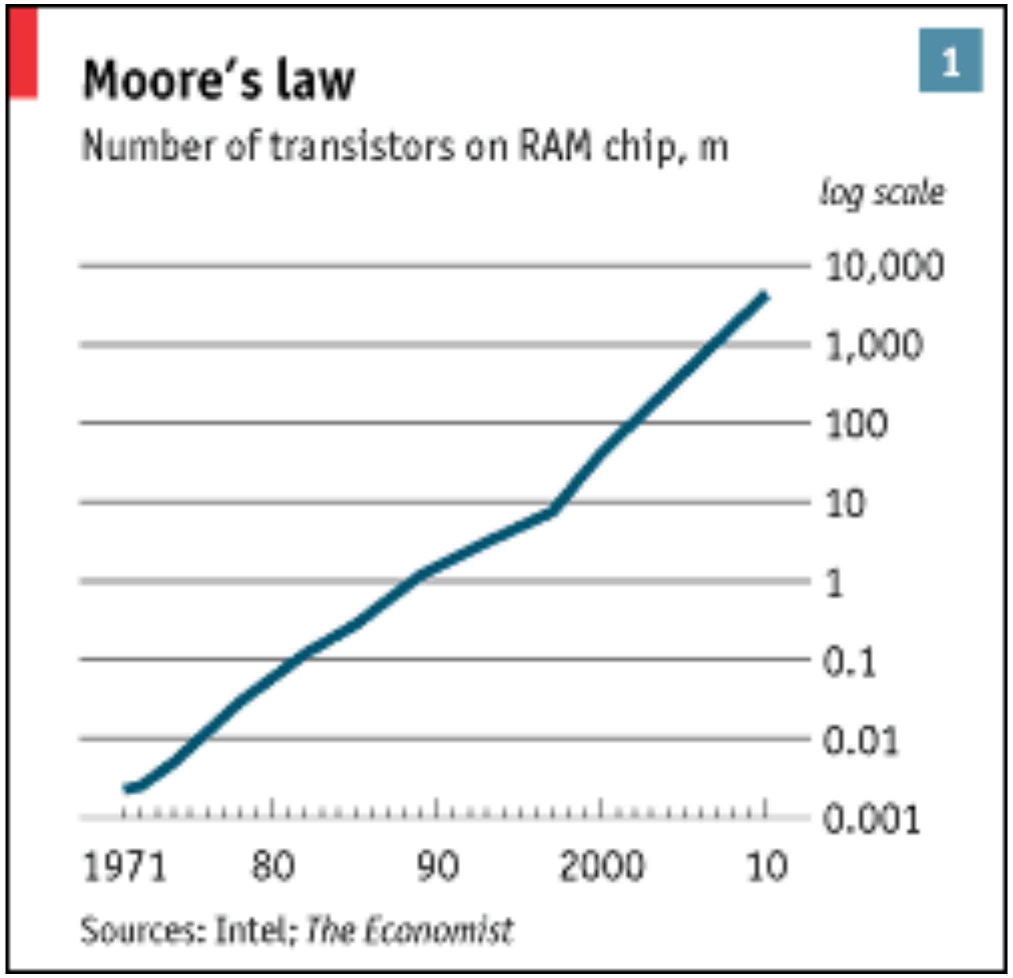
More generally, QIT studies what happens when one tries to

PROCESS INFORMATION VIA QUANTUM SYSTEMS

QUANTUM SCALE

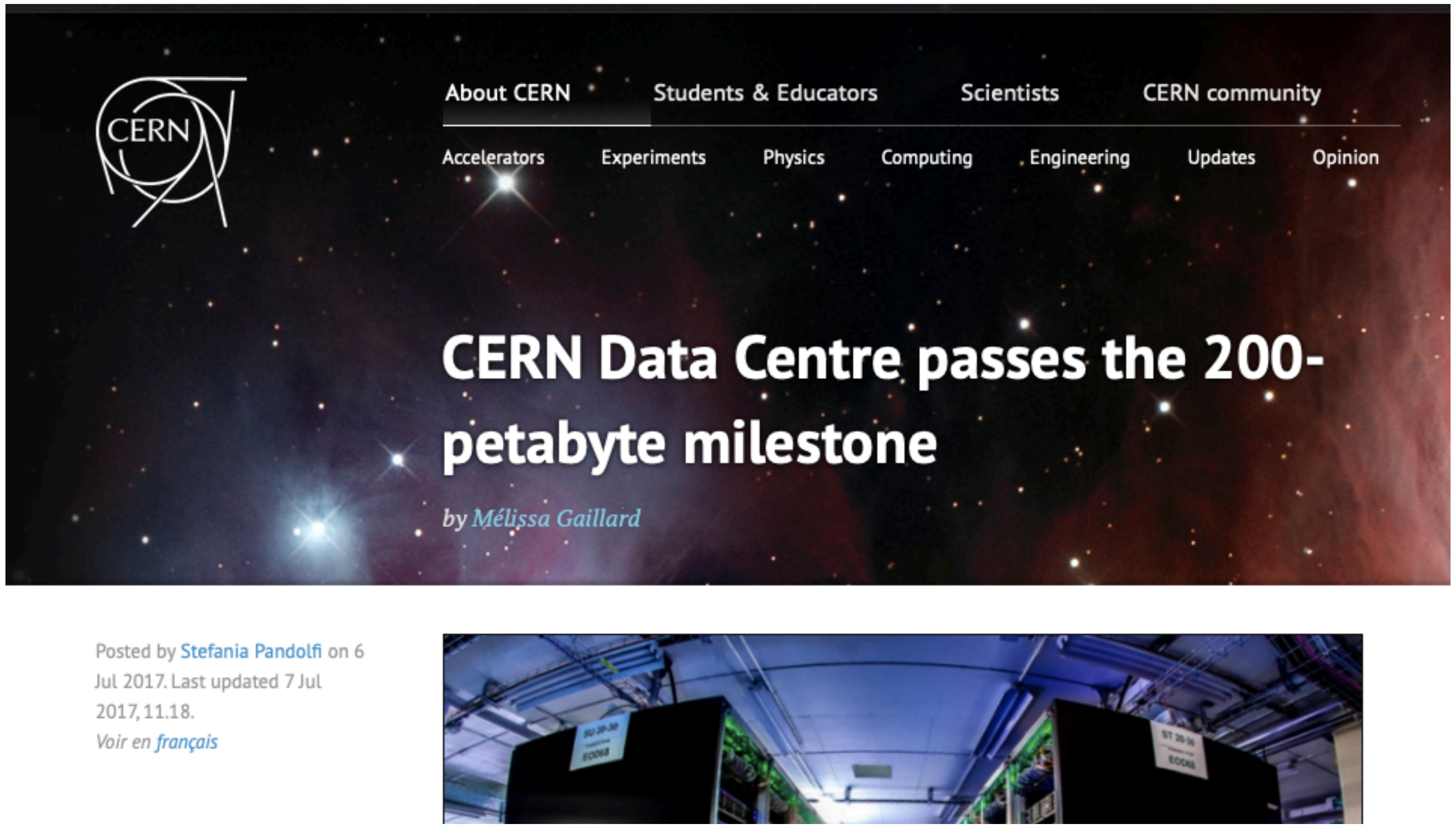
Touching the quantum limit

MINIATURIZATION & BIG DATA


Moore's law

Number of transistors on RAM chip, m

Sources: Intel; *The Economist*



CERN Data Centre passes the 200-petabyte milestone

by *Mélissa Gaillard*

Posted by Stefania Pandolfi on 6 Jul 2017. Last updated 7 Jul 2017, 11.18.

Voir en français

Quantum effects will have to be taken into account,

better exploit them!

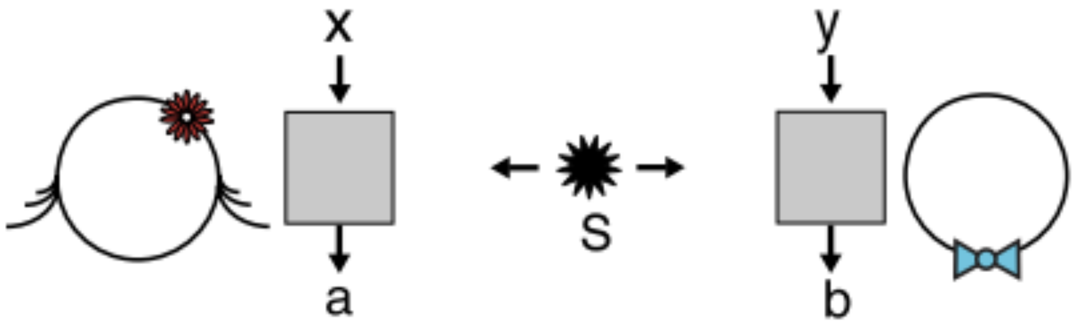
HIGHLY CORRELATED STATES

Entanglement

QUANTUM VS CLASSICAL CORRELATIONS

Clauser-Horne-Shimony-Holt (CHSH) inequality

Measure



Outcome

$p(ab|xy)$

Locality (no influence between space-time separate regions)

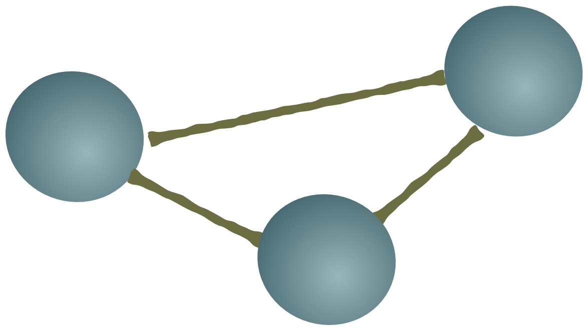
$$S = \langle a_0 b_0 \rangle + \langle a_0 b_1 \rangle + \langle a_1 b_0 \rangle - \langle a_1 b_1 \rangle \leq 2$$

Bell state (singlet):

$$S = 2\sqrt{2} > 2$$

N. Brunner et al. RMP 2014

INEFFICIENT COMPRESSIBILITY OF ENTANGLEMENT



$$|\psi\rangle = \sum \psi_{\alpha_1\alpha_2\alpha_3}|\alpha_1\alpha_2\alpha_3\rangle$$

For spins 1/2, if

$$\psi_{\alpha_1\alpha_2\alpha_3} = \frac{1}{2\sqrt{2}} \quad \Rightarrow \quad |\psi\rangle = \left(\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)\right)^{\otimes 3} = \left(\sum \psi_\alpha|\alpha\rangle\right)^{\otimes 3}$$

8 coefficients

Separable state
6 coefficients!

In general,

d ^ N coefficients

$$|\psi\rangle = \sum \psi_{\alpha_1\alpha_2\ldots\alpha_N}|\alpha_1\alpha_2\ldots\alpha_3\rangle$$

$$|\psi^{MF}\rangle = \left(\sum \psi_\alpha|\alpha\rangle\right)^{\otimes N}$$

dN coefficients

ENTANGLEMENT
THEORY

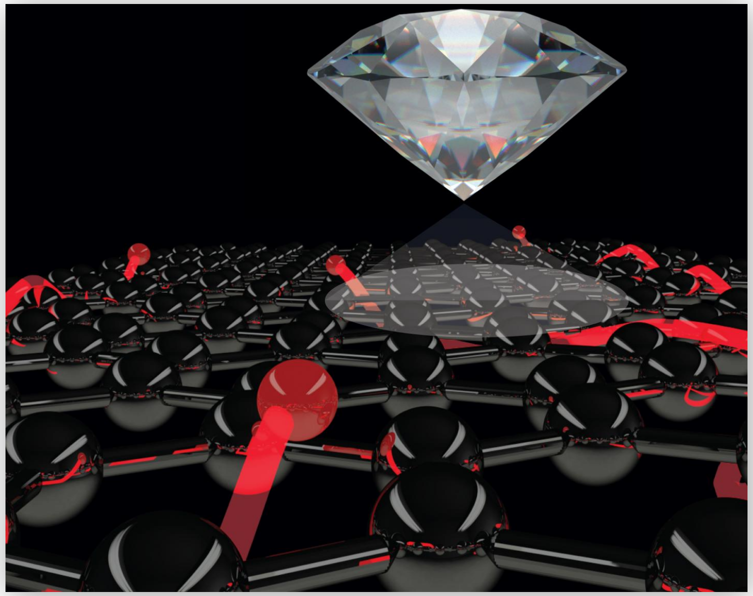
HEISENBERG
LIMIT

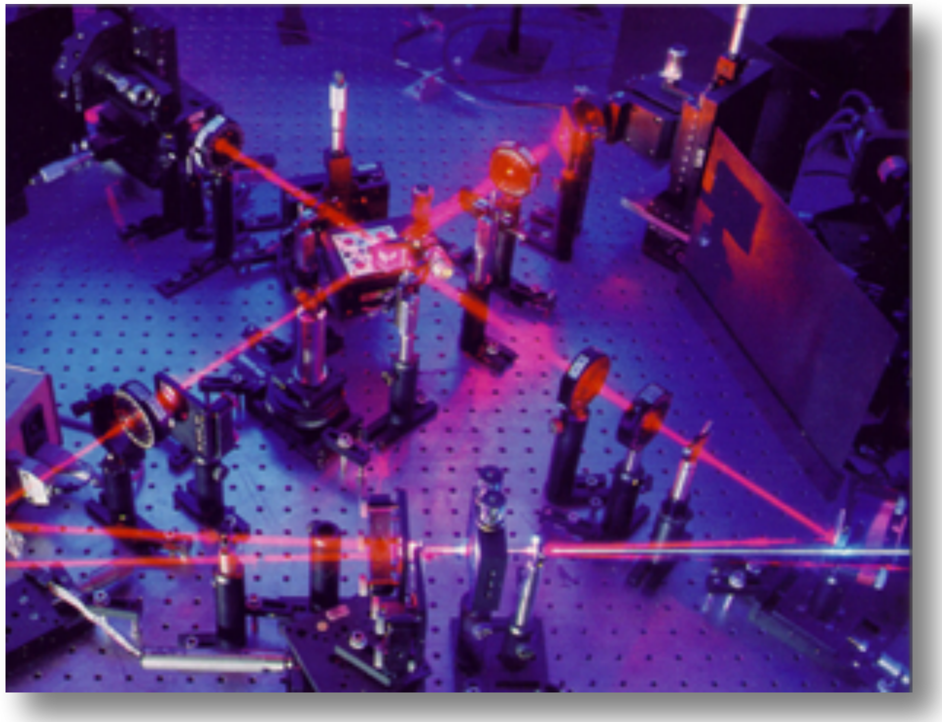
**QUANTUM
ADVANTAGE?**

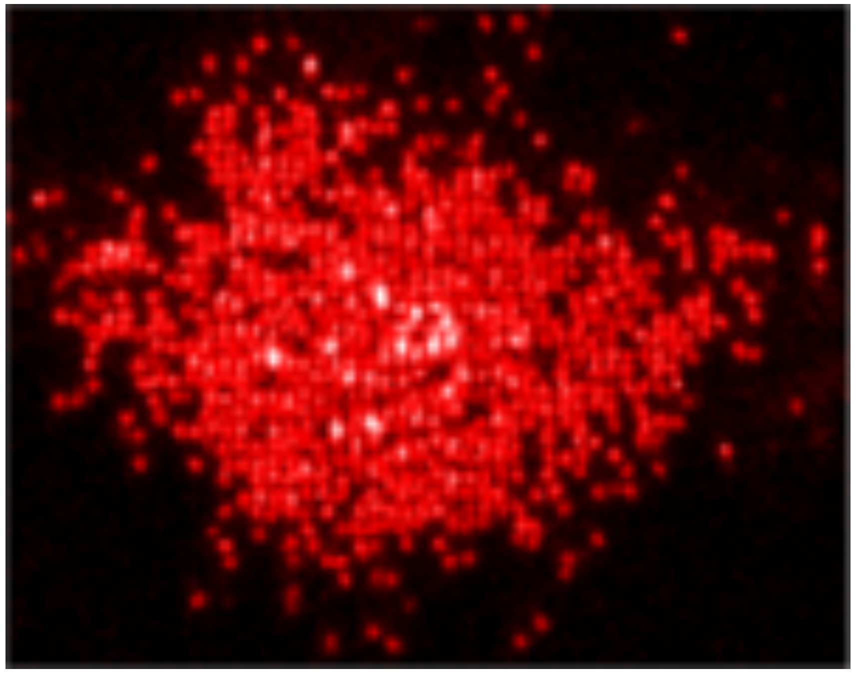
QUANTUM CHANNEL
CAPACITY

QUANTUM COMPLEXITY
CLASSES

QUANTUM SCIENCE







QUANTUM TECHNOLOGIES

EU QUANTUM INITIATIVES

www.qt.eu

www.quantera.eu

Quantum Flagship in a nutshell.

04 **140** Research and Innovation Actions (RIA) proposals submitted in response of the first Quantum Flagship call

01 **1b €** Quantum Technology will be funded with at least one billion Euro by the European Commission.

02 **10+ yrs** Flagship's timescale

03 **5000+** researchers residing in all EU and associated countries involved

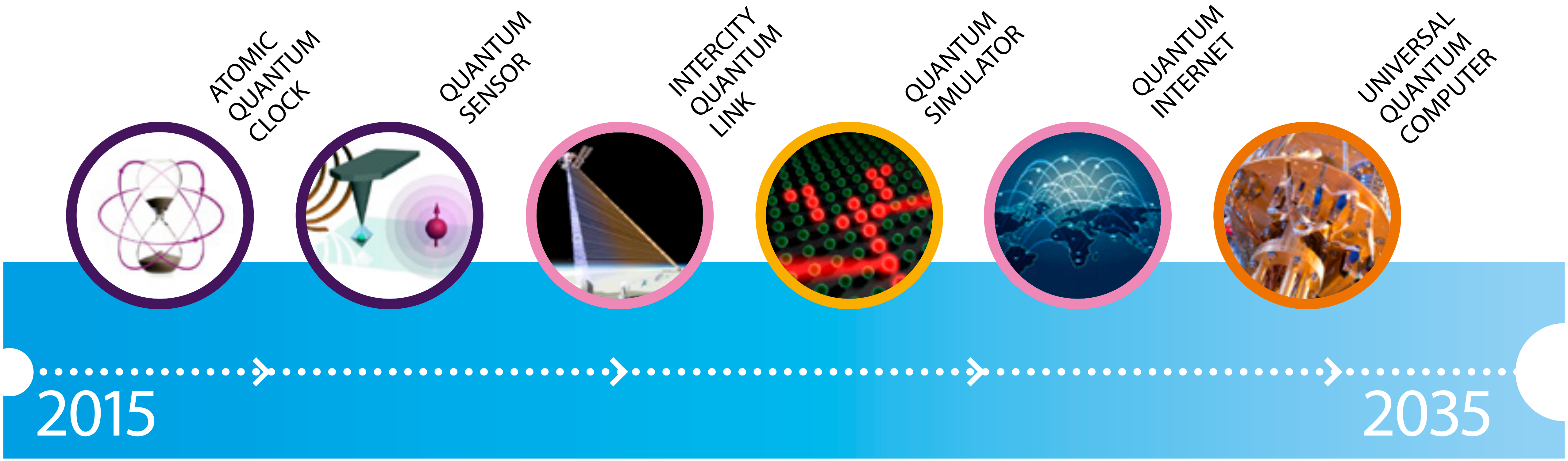
QuantERA Call 2019 Pre-Announcement

In November 2018 the QuantERA Consortium, coordinated by the National Science Centre, will announce a 2nd Call for Proposals in the field of quantum technologies.

QuantERA ERA-NET Cofund in Quantum Technologies

2ND QUANTUM REVOLUTION

Quantum Technologies Timeline



ATOMIC QUANTUM CLOCK

QUANTUM SENSOR

INTERCITY QUANTUM LINK

QUANTUM SIMULATOR

QUANTUM INTERNET

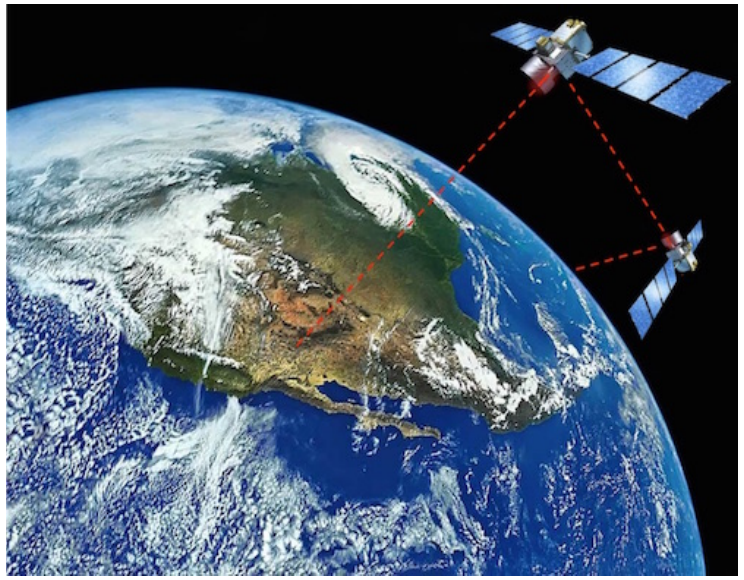
UNIVERSAL QUANTUM COMPUTER

2015

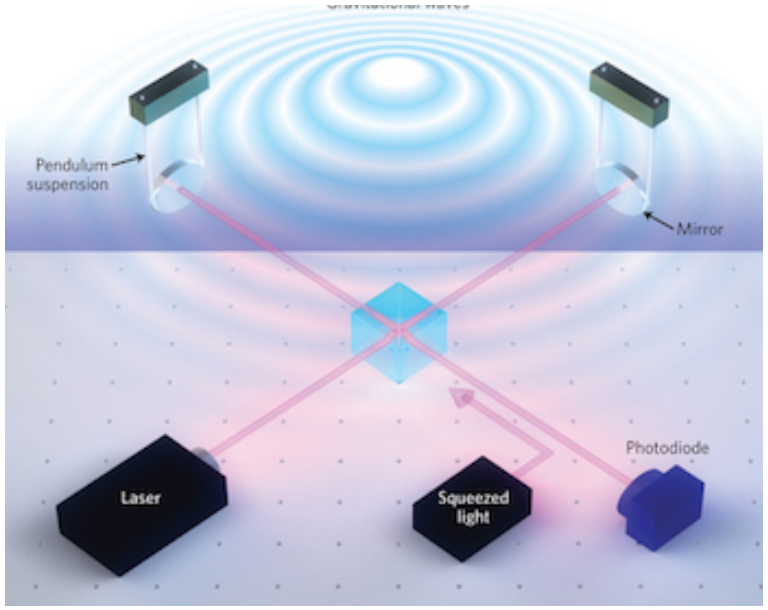
2035

Quantum Manifesto (2015)

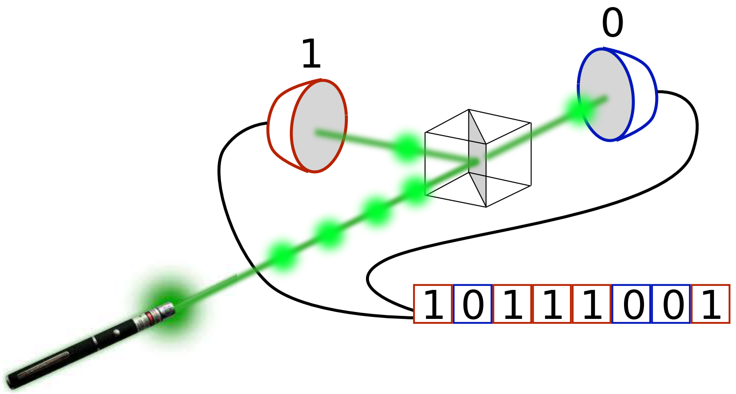
QUANTUM COMMUNICATIONS



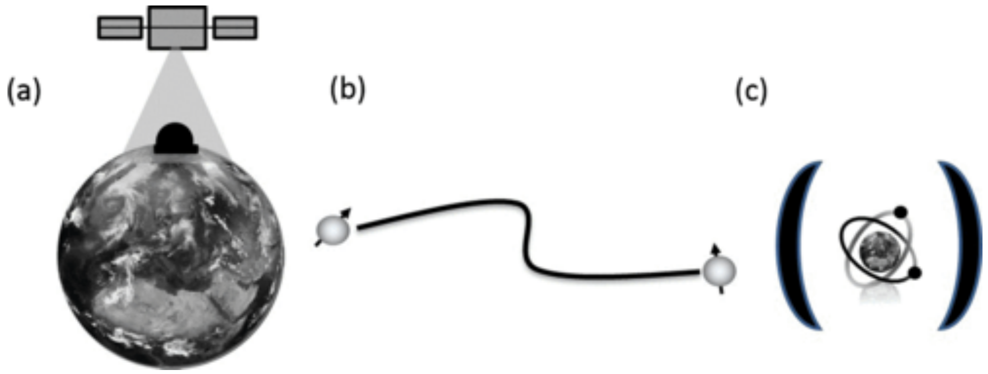
Quantum cryptography



Quantum metrology

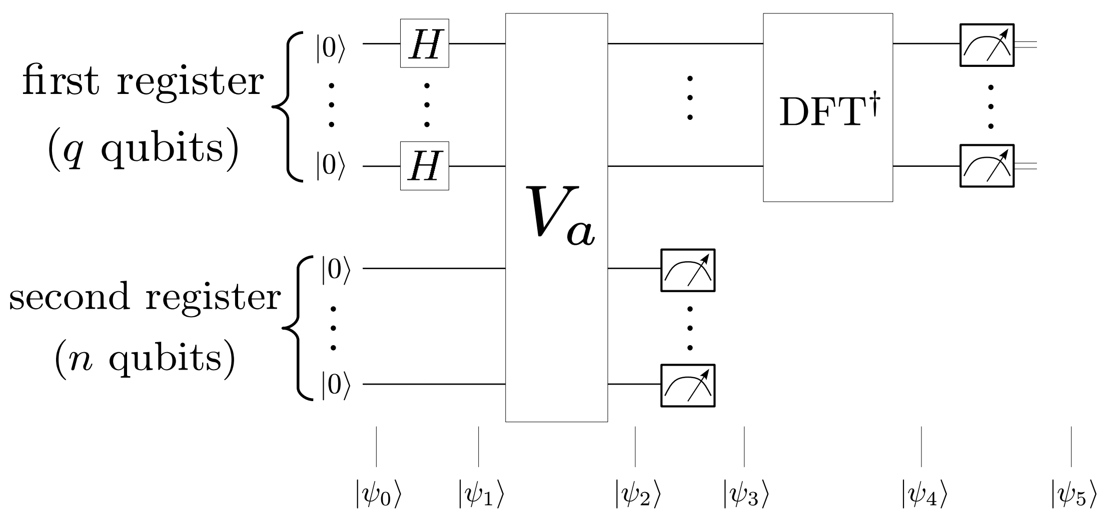


Quantum random numbers



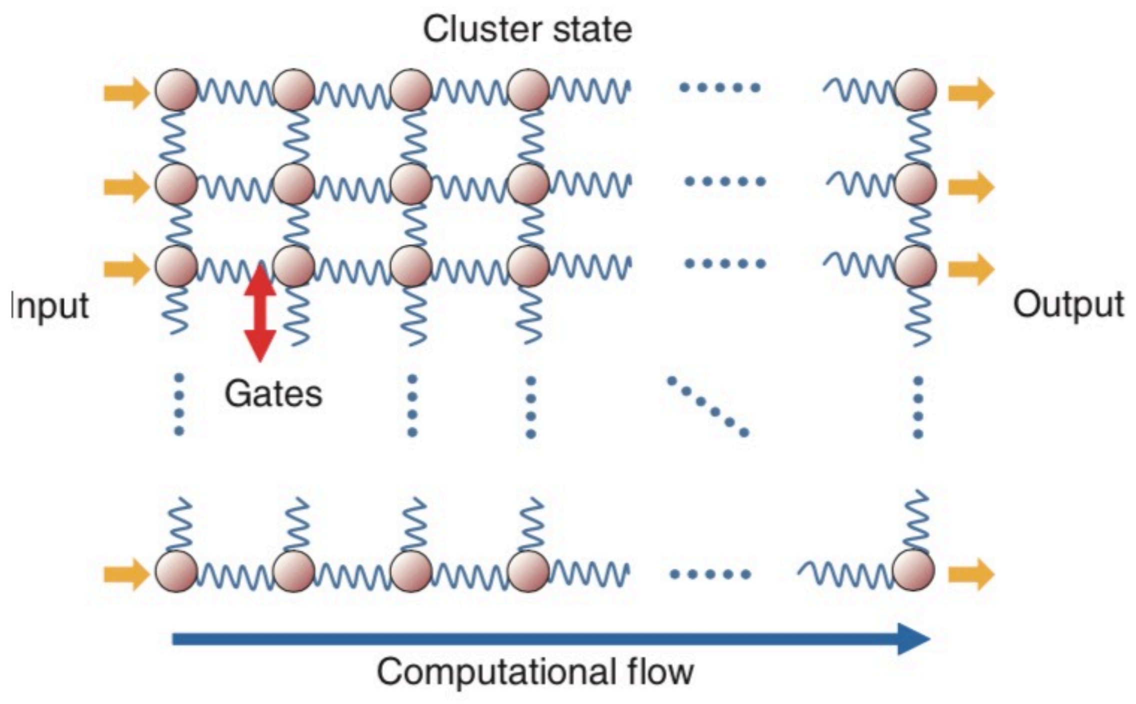
Quantum channels

QUANTUM COMPUTING

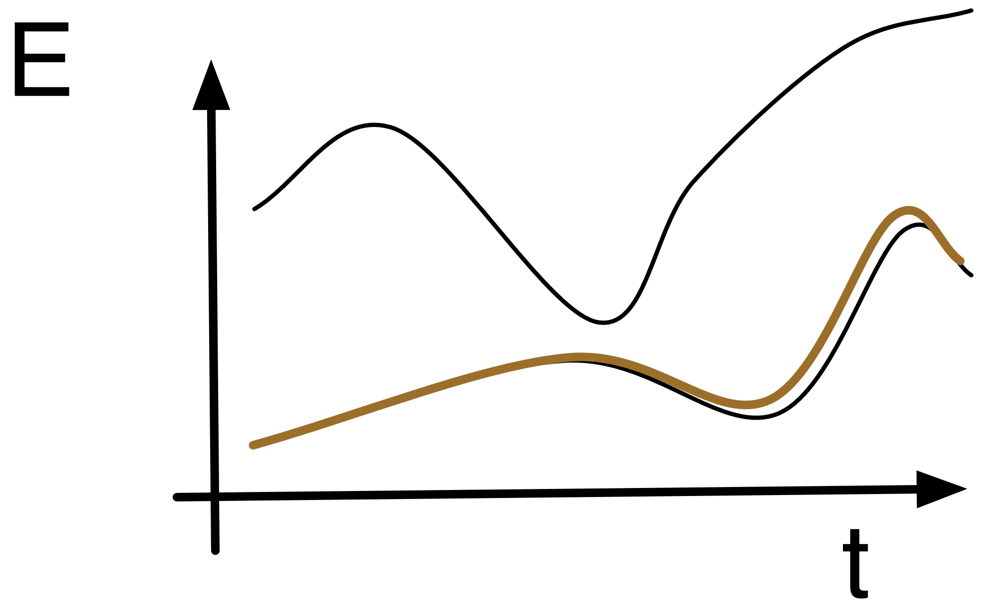


$$V_a : |x\rangle|y\rangle \to |x\rangle|y \oplus a^x \mod N\rangle$$

Circuit model

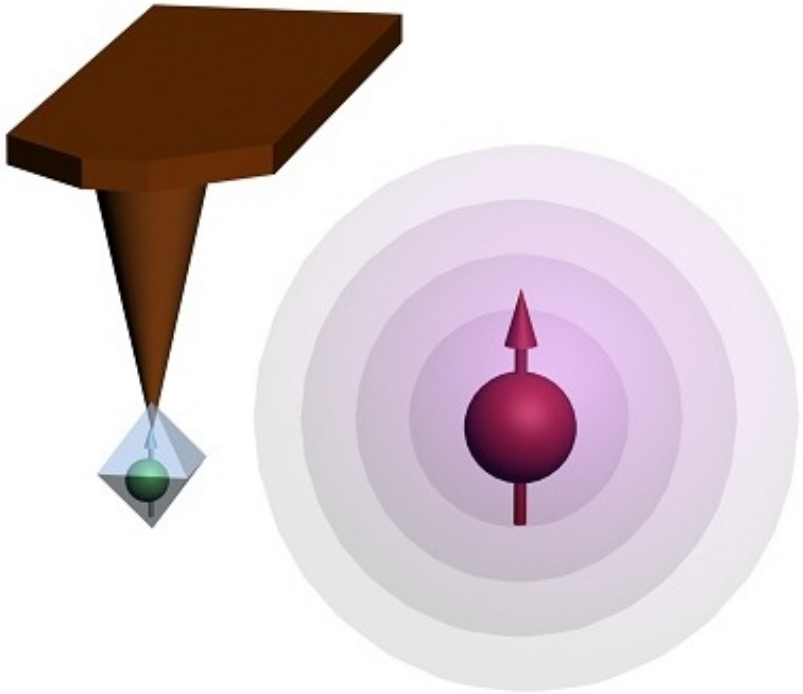


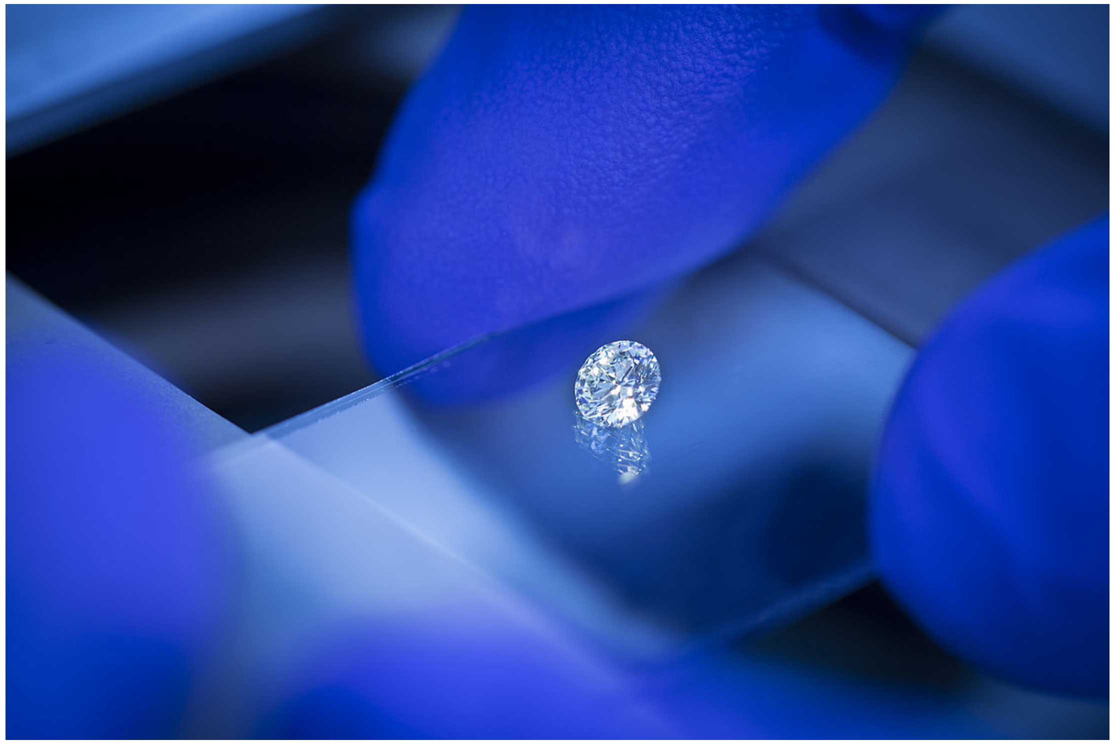
One-way



Adiabatic - Quantum Annealing

QUANTUM SENSING





credits: F. Jelzko IQST

Quantum sensing is typically used to describe:

(I) Use of a quantum object to measure a physical quantity (classical or quantum).

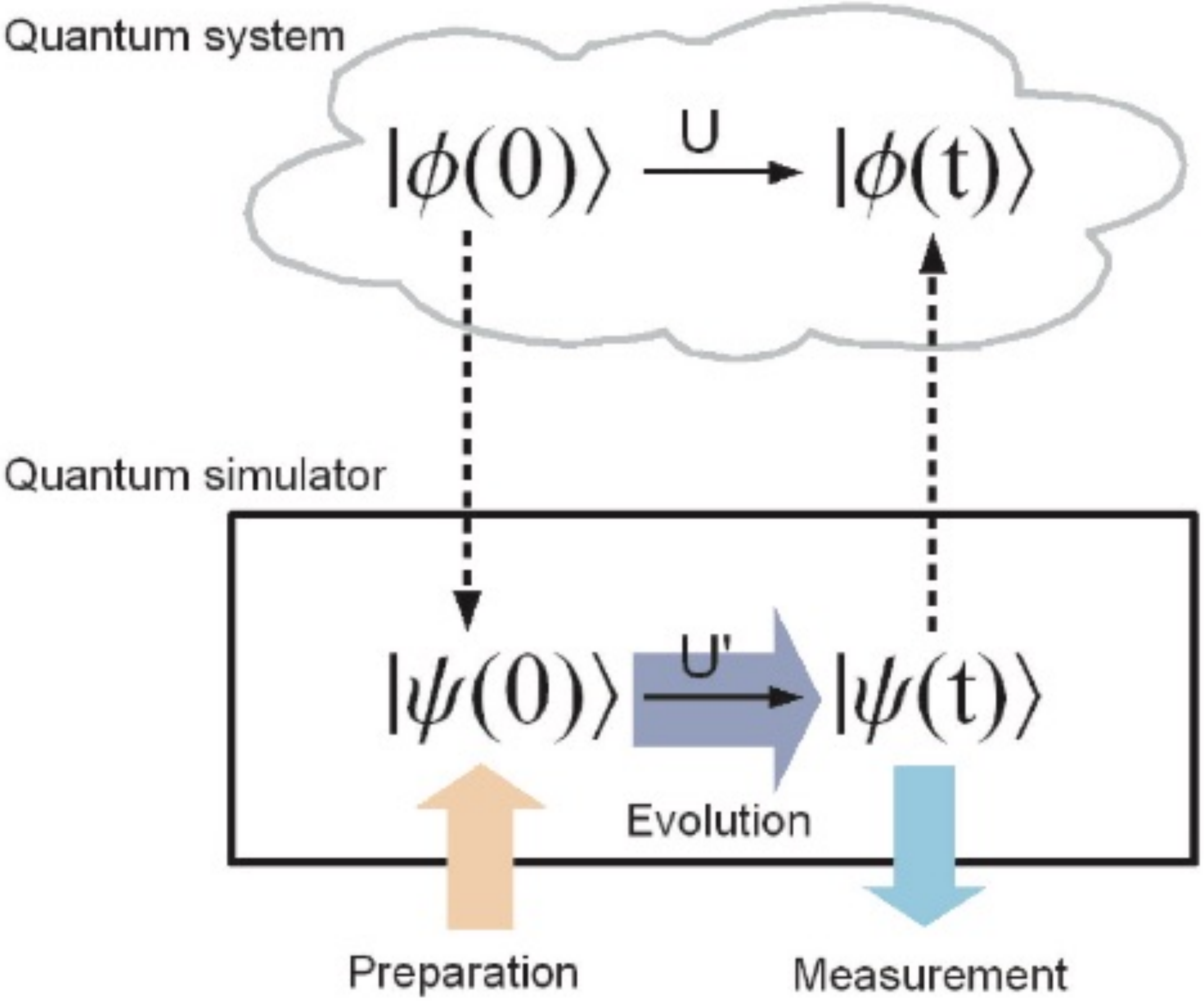
(II) Use of quantum coherence (i.e., wavelike spatial or temporal superposition states) to measure a physical quantity.

(III) Use of quantum entanglement to improve the sensitivity or precision of a measurement, beyond what is possible classically.

Spin qubits, NV-centres in diamonds, trapped ions, flux qubits…

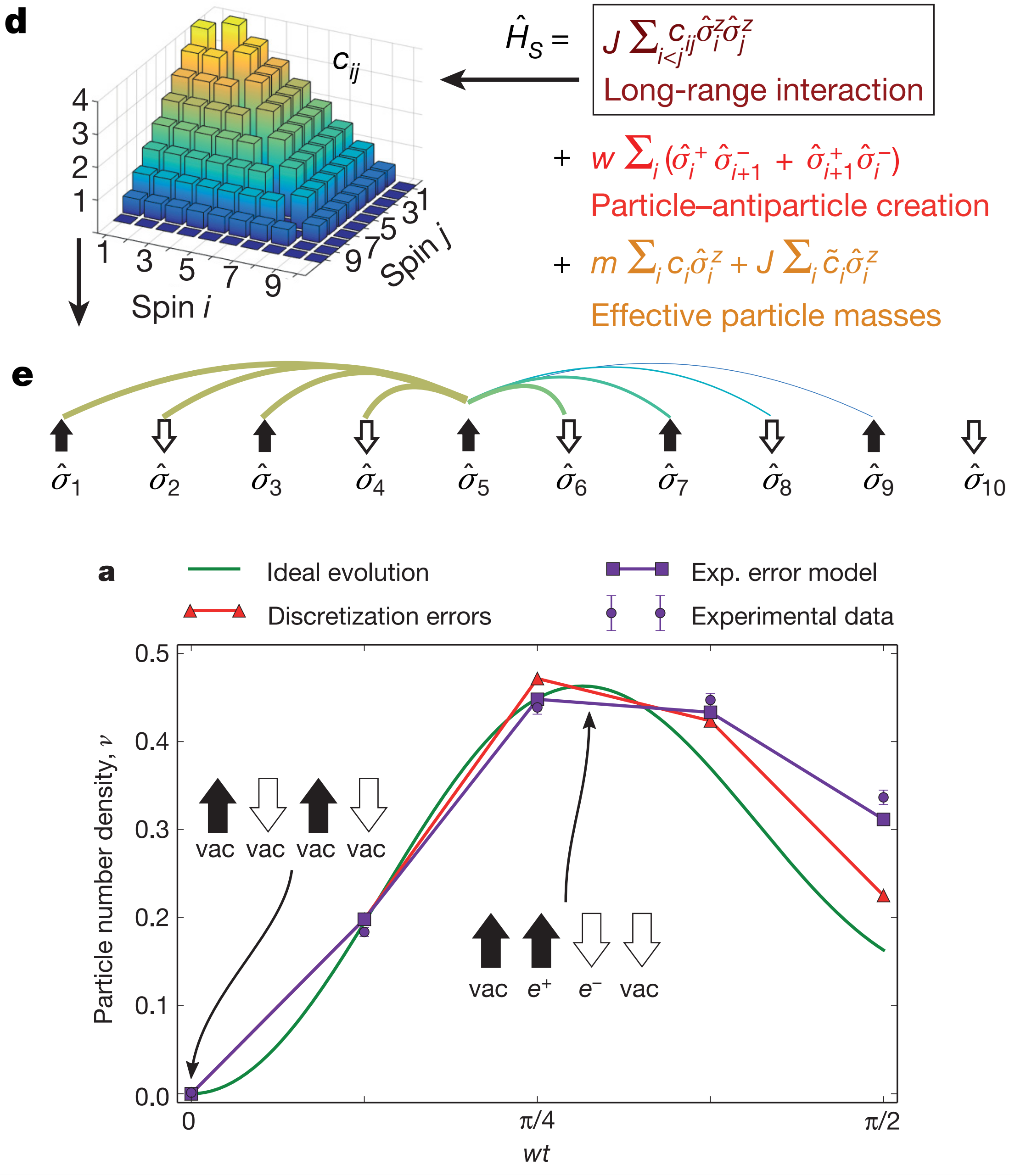
Degen et al. RMP 2017

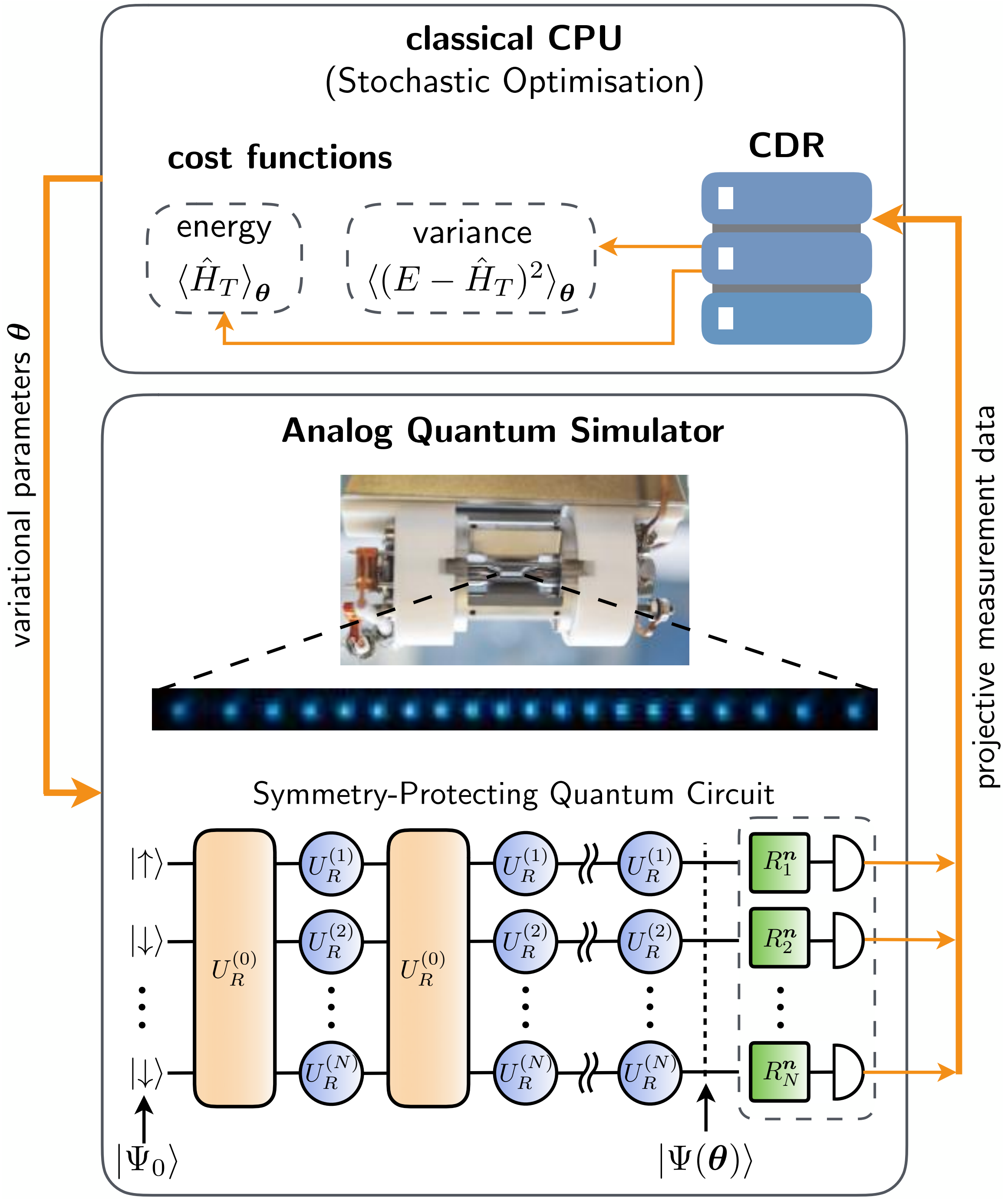
QUANTUM SIMULATIONS



***Quantum Simulation**, Rev. Mod. Phys.(2014)*

QUANTUM SIMULATIONS OF THE SCHWINGER MODEL





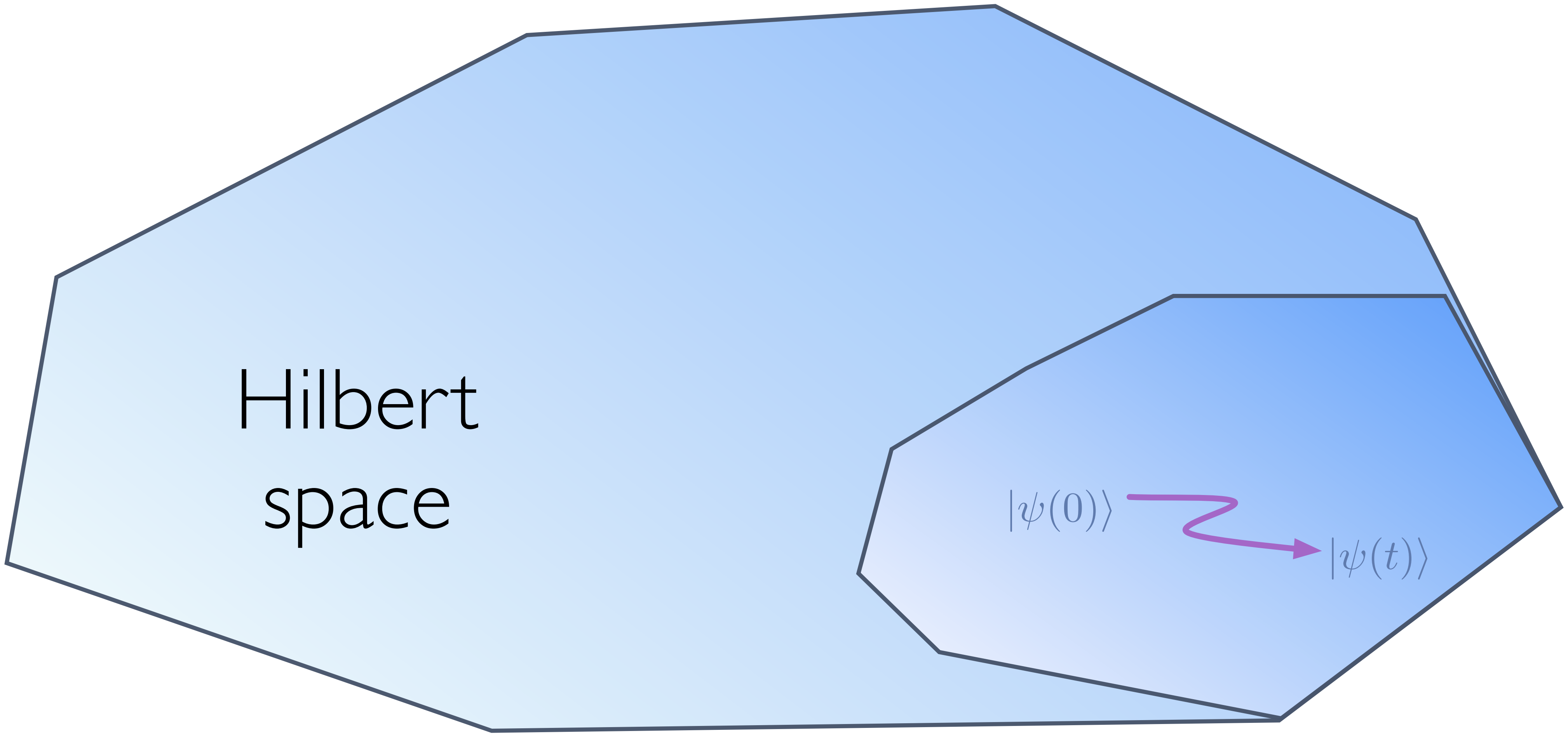
IQOQI Innsbruck

21 lattice sites!

R. Blatt and P. Zoller's groups

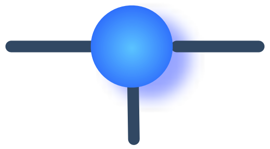
Nature (2016), arXiv:1810.03421

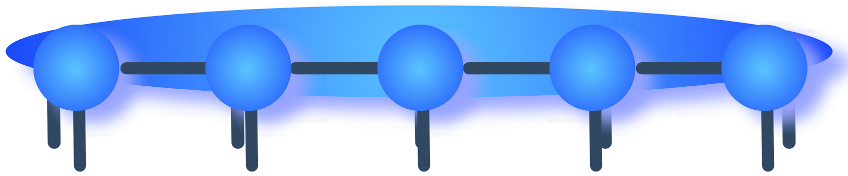
> When do we really need a quantum simulation/computation?


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

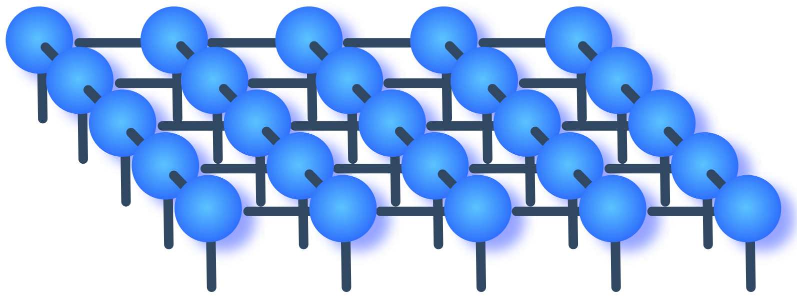
TENSOR NETWORKS STATES

$\psi_{\alpha_1,\alpha_2,\ldots\alpha_N}$ $\mathcal{O}(d^N)$

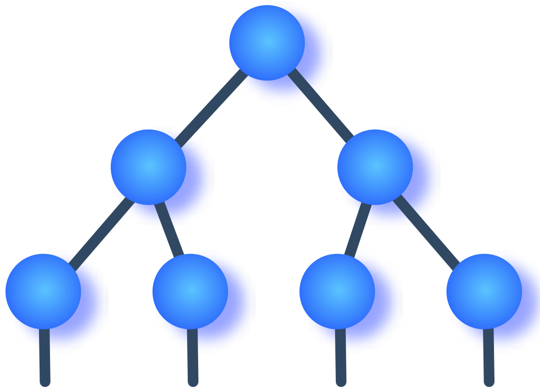
$A_{\alpha_i}^{\beta_i,\beta_{i+1}} \equiv$ 



$A_{\alpha_1}^{\beta_1} A_{\alpha_2}^{\beta_1\beta_2} \ldots A_{\alpha_N}^{\beta_{N-1}}$ $\mathcal{O}(Ndm^2)$



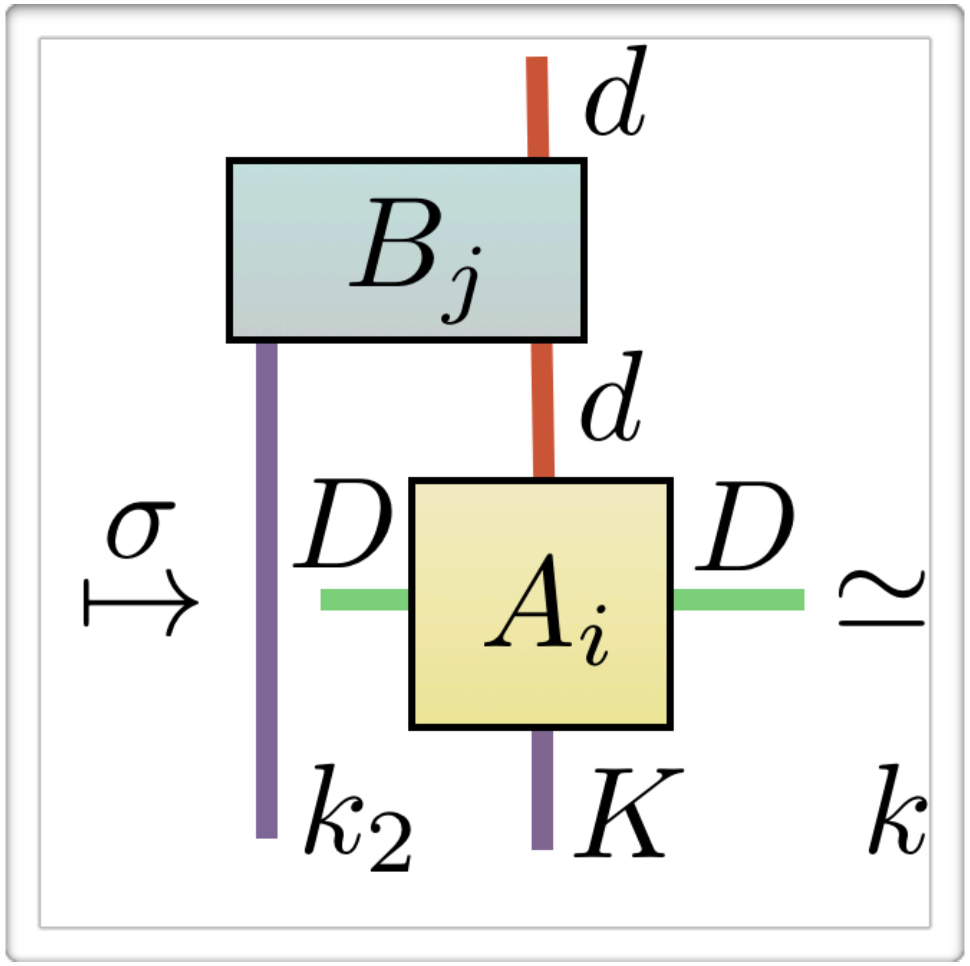
PEPS



Tree Tensor Network

Tensor networks states are a faithful adaptive description of the system tunable between mean field and exact

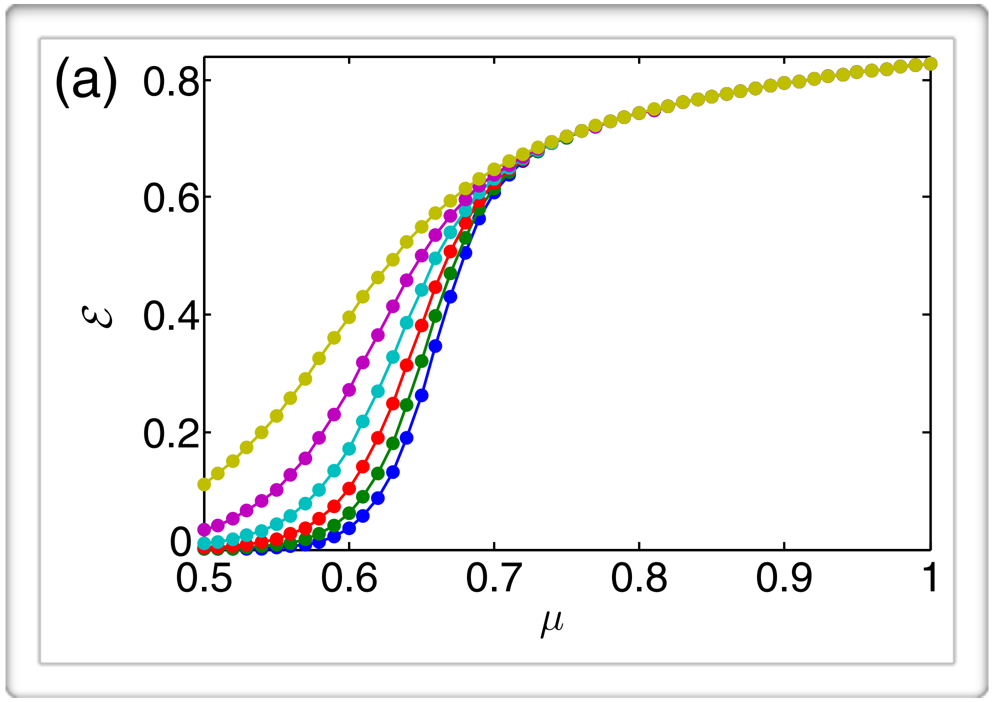
TENSOR NETWORK ALGORITHMS

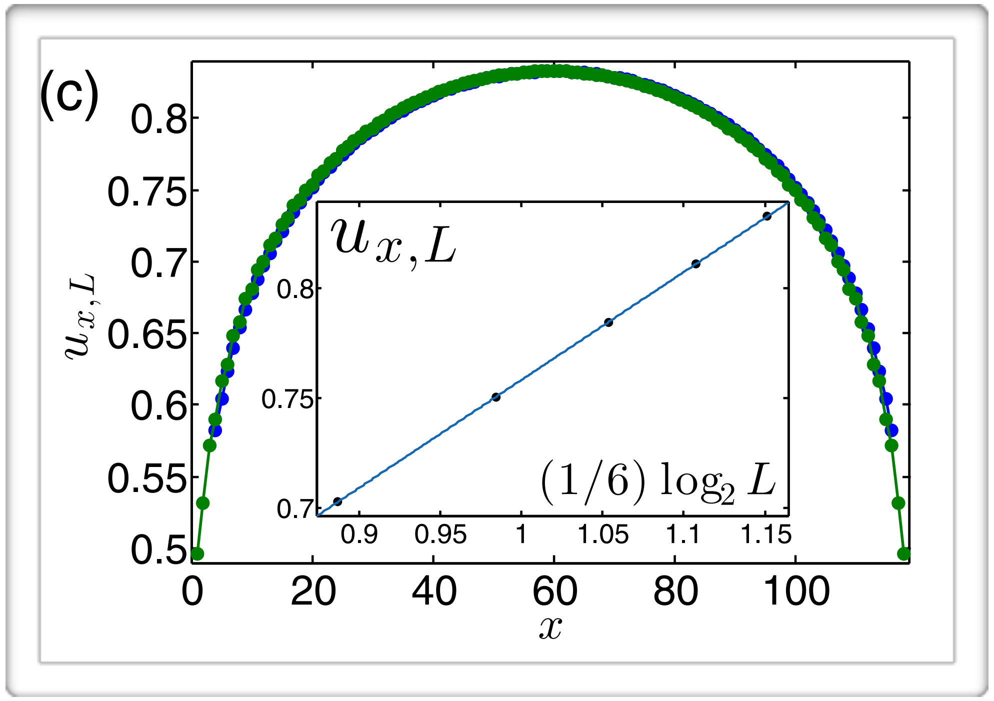


- *State of the art in 1D (poly effort)*
- *No sign problem*
- *Extended to open quantum systems*
- *Machine learning*
- *Data compression (BIG DATA)*
- *Extended to lattice gauge theories*

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

U(1) LATTICE GAUGE THEORY IN 1+1D



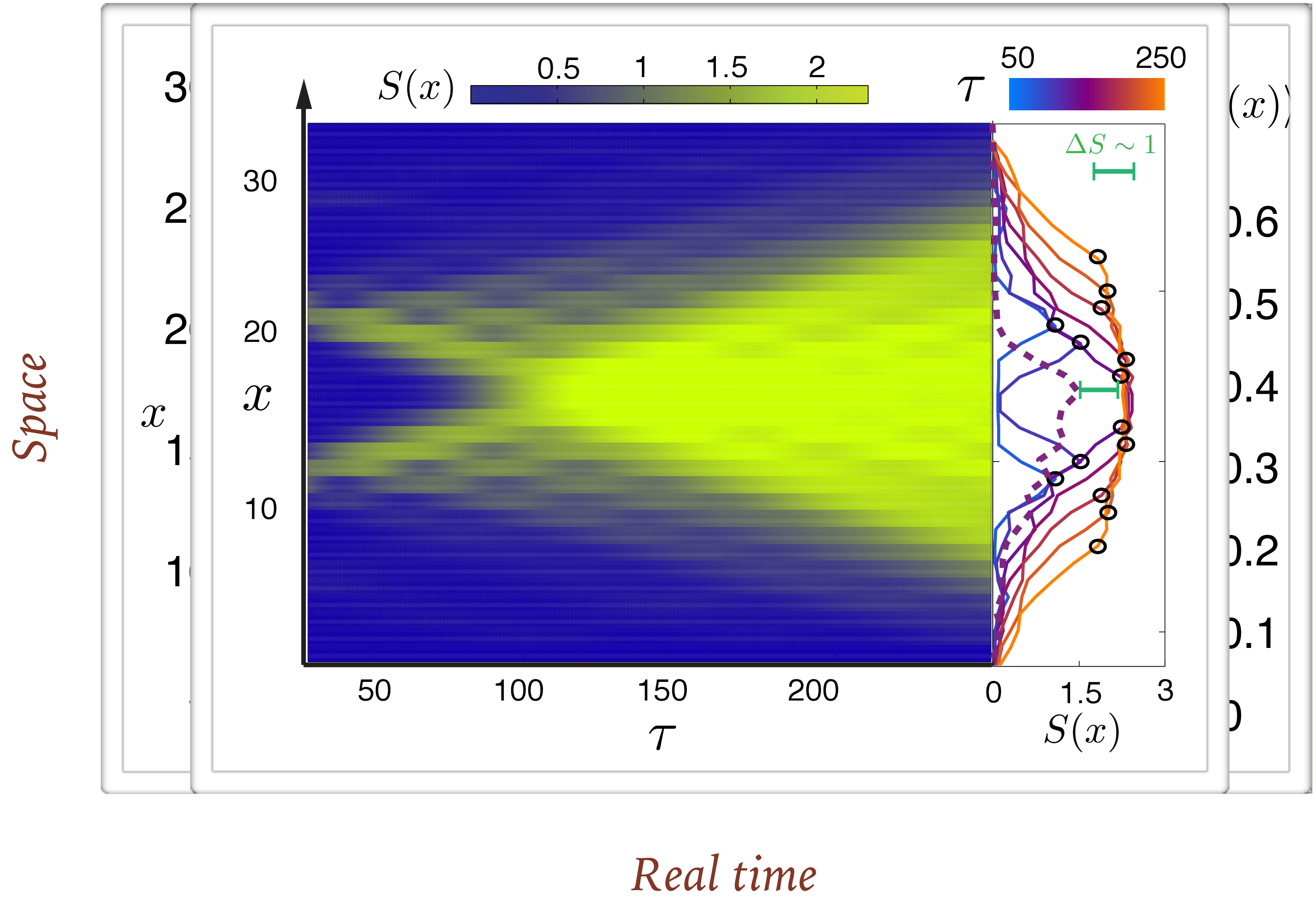


$$H = -t\sum_x \left[\psi_x^\dagger U_{x,x+1}^\dagger \psi_{x+1} + \psi_{x+1}^\dagger U_{x,x+1}\psi_x\right]$$
$$+m\sum_x (-1)^x \psi_x^\dagger \psi_x + \frac{g^2}{2}\sum_x E_{x,x+1}^2.$$

$$\mathcal{E} = \sum_x \langle E_{x,x+1}\rangle / L$$

- *Quantum link representation*
- *Staggered fermions*
- *Ising universality class*
- *Central charge* $c = 0.49 \pm 0.01$
- *Confirmed by higher-link representation*

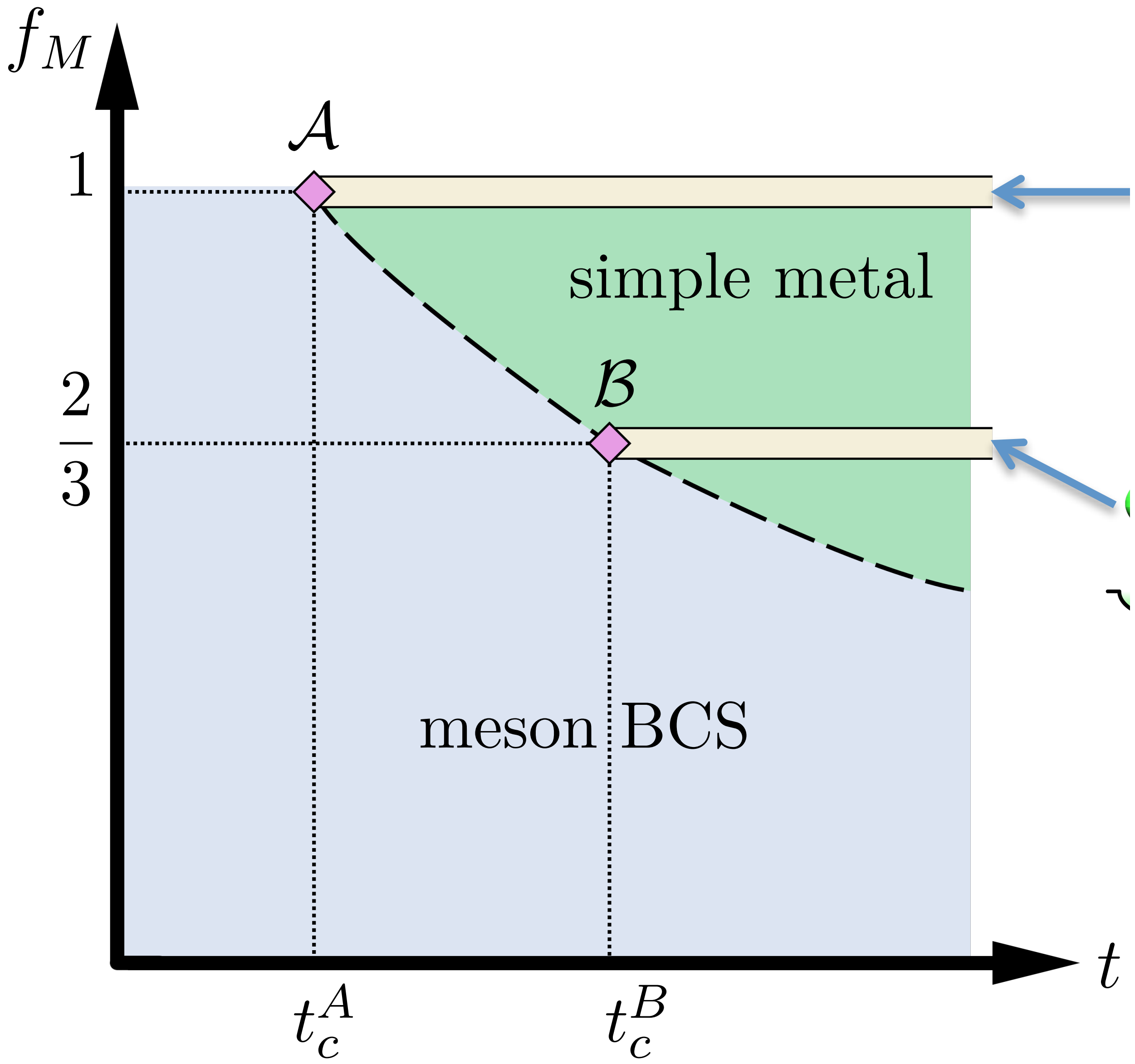
E. Rico, T. Pichler, M. Dalmonte, P. Zoller, and SM, PRL (2014)



MESONS SCATTERING

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

S(2) LATTICE GAUGE THEORY IN 1+1D



$$H = H_{\text{coupl}} + H_{\text{free}} + H_{\text{break}}$$

$$H_{\text{coupl}} = t \sum_{j=1}^{\mathrm{L}-1} \sum_{s,s'=\uparrow,\downarrow} c^{[M]\dagger}_{j,s} U_{j,j+1;s,s'} c^{[M]}_{j+1,s'} + \text{h.c.}$$

$$H_{\text{free}} = \frac{g_0^2}{2} \sum_{j=1}^{\mathrm{L}} \left[\vec{J}^{[R]}_{j-1,j}\right]^2 + \left[\vec{J}^{[L]}_{j,j+1}\right]^2$$

Phase diagram at

finite chemical potential

P. Silvi et al Quantum (2017)

LGT HAVE APPLICATIONS IN

High-energy physics

QED,
QCD, …

Condensed matter

Quantum spin ice,
Kitaev model, …

Computer science

Adiabatic
computation

Quantum science

Quantum
simulations, …

HAMILTONIAN FORMULATION OF CLASSICAL PROBLEMS

Graph partitioning
Complete subgraph finding (clique)
Binary integer programming
Covering and packaging problems
k-sat problems
Minimal maximal matching…

A. Lucas, Front. Phys. (2014)

ALL-TO-ALL TO LGT MAPPING

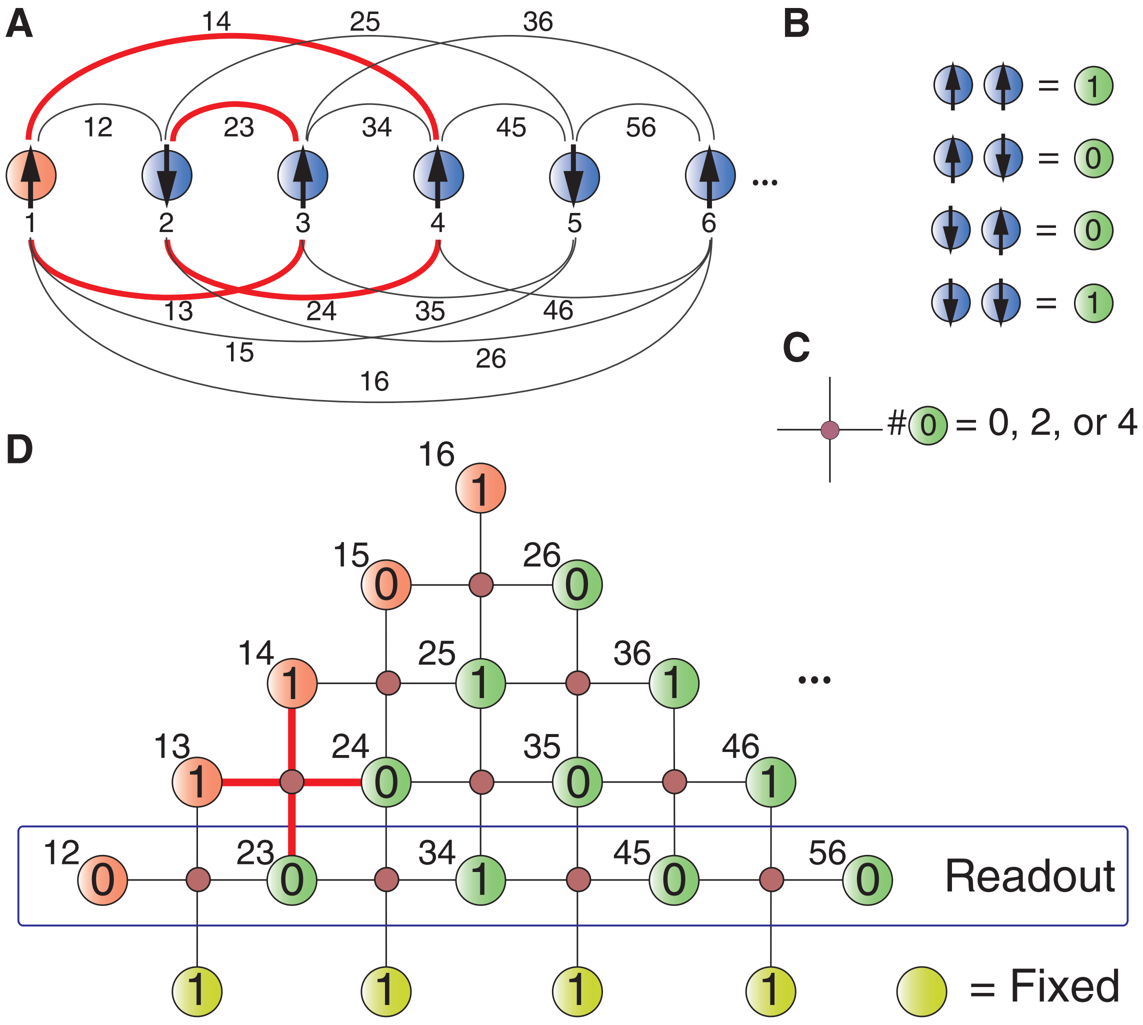
$$H_I = \sum \sigma_x^{[k]}$$

$$H_F = \sum_{i<j} V^{[i,j]} \sigma_z^{[i]} \sigma_z^{[j]}$$

$$\Downarrow$$

$$H_F = \sum_{k=1}^{K} f^{[k]} \sigma_z^{[k]} \; +$$

$$H_C = -\sum_{p=1}^{P} c^{[p]} \sigma_z^{[k_1]} \sigma_z^{[k_2]} \sigma_z^{[k_3]} \sigma_z^{[k_4]}$$



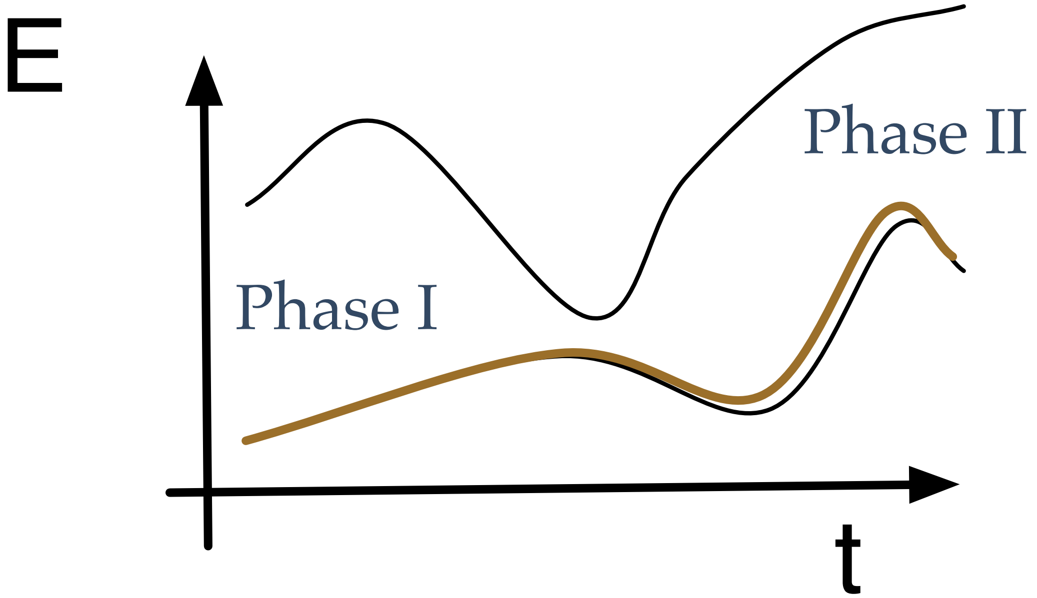
W. Lechner, P. Hauke, and P. Zoller, Sci. Adv.. (2015)

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 OPTIMAL CONTROL

$$i\frac{\partial}{\partial t}|\psi(t)\rangle = \left(H_0 + f(t)H_1\right)|\psi(t)\rangle \qquad \min_{f(t)} J(|\psi(T)\rangle)$$

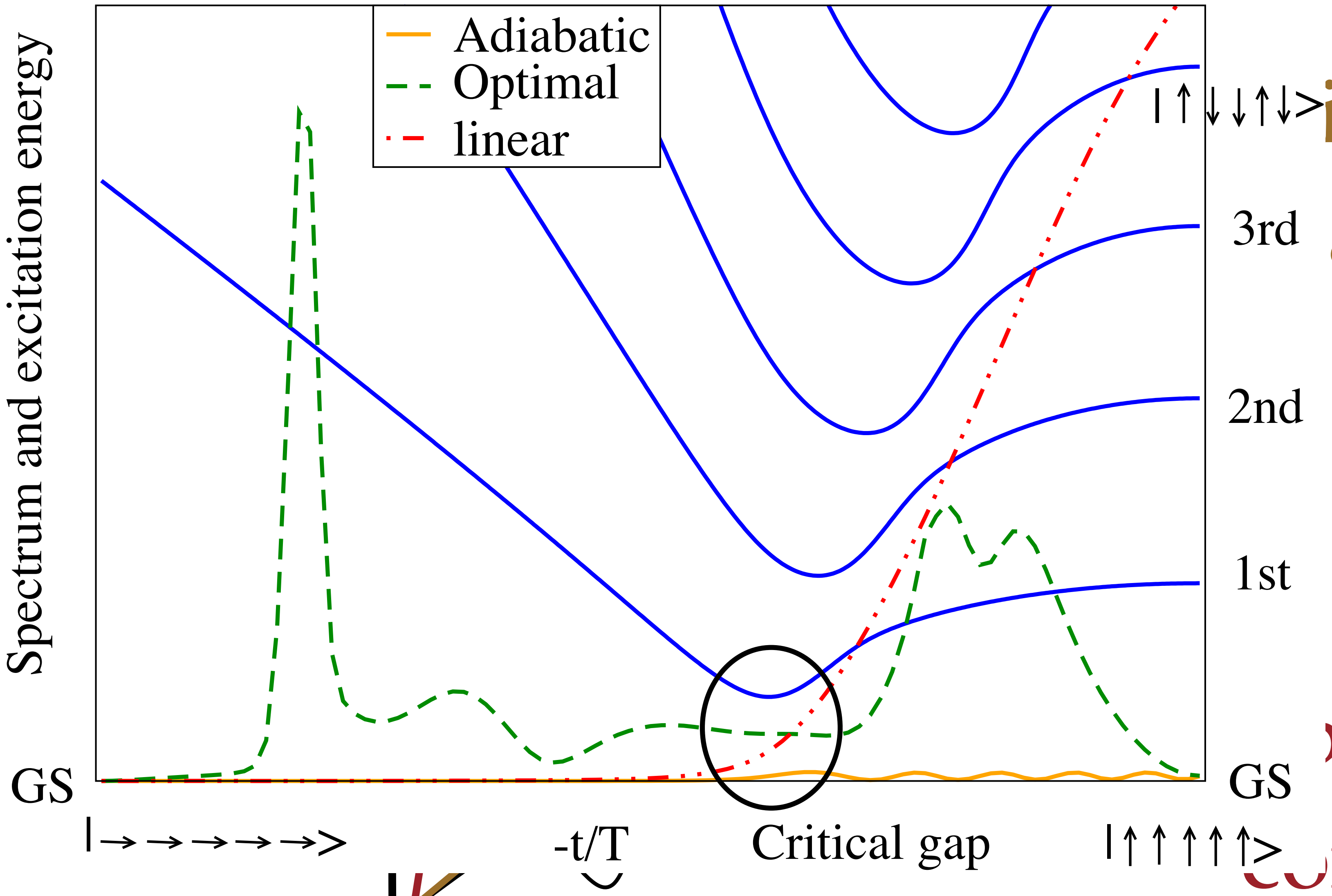
- *Few-body: standard optimal control*
  (high-accuracy, many iterations, complete knowledge…)
- *Many-body: dCRAB*
  (high-efficiency, few iterations, minimal knowledge…)

H. Rabitz et.al. NJP (2009)   P. Doria et al. PRL (2011)

OPTIMAL QUANTUM COMPUTING

Slow

Fast



iabatic
ategy

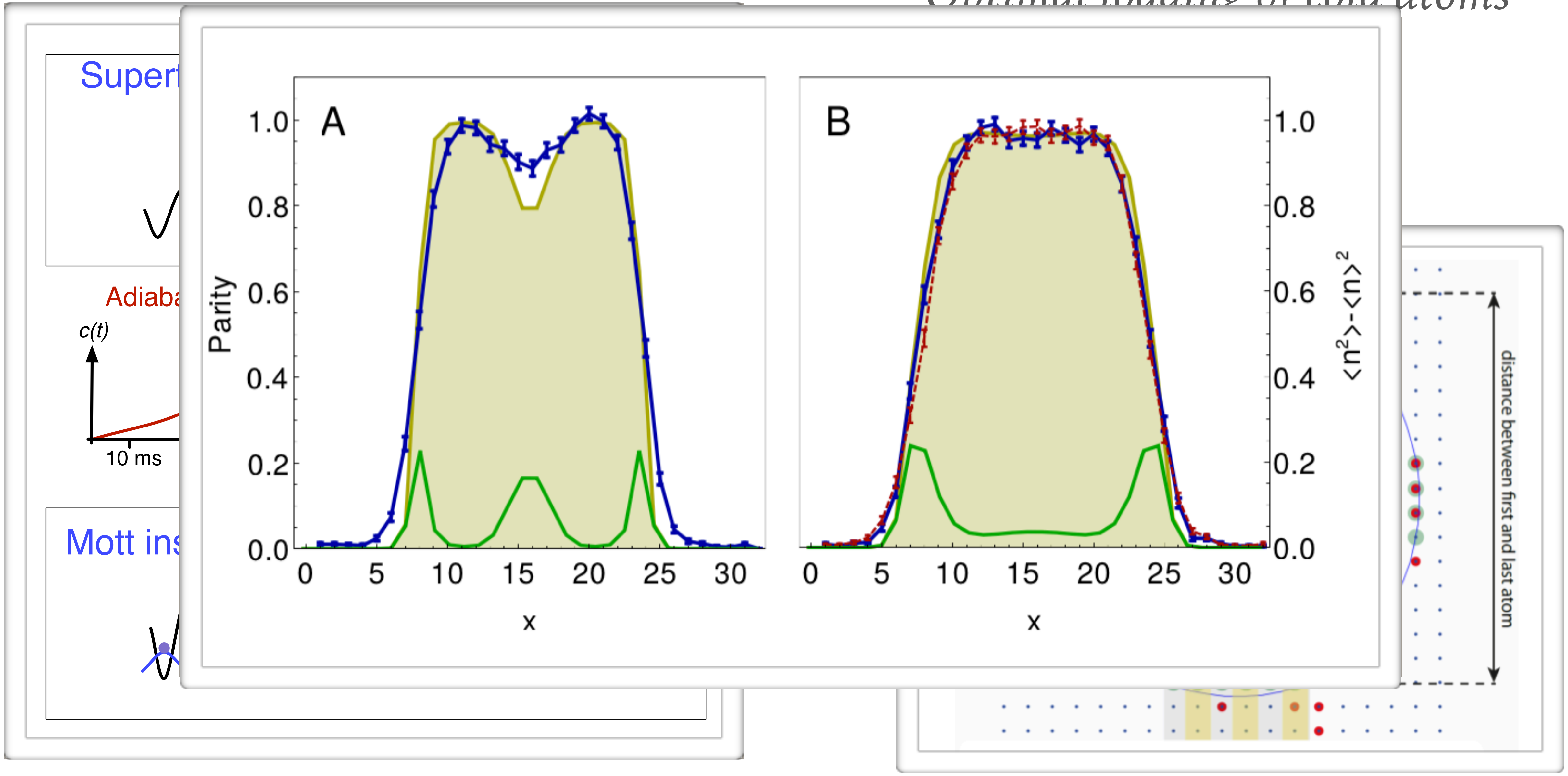
ptimal
ontrol

$$H = -\frac{1}{N}\sum_{i<j}(\sigma_i^x\sigma_j^x + \gamma\sigma_i^y\sigma_j^y) - \Gamma(t)\sum_i^N \sigma_i^z$$

T. Caneva ***et al.*** ***PRA (2014)***

EXPERIMENTAL OPTIMAL QPT CROSSING

Optimal loading of cold atoms



Speed up of one order of magnitude

Compatible with the quantum speed limit

Ulm-Munich collaboration,

Sci. Rep. (2016)

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

Thank you for your attention!

Simone Montangero
Mario Collura

Tommaso Calarco
Pietro Silvi
Ressa Said
Thomas Pichler
Tommaso Caneva
Matthias Gerster
Ferdinand Tschirsich
Werner Weiss
Jonathan Zoller
Fedor Jelezko
Boris Naydenov

Matteo Rizzi

Tilman Pfau

S. Lloyd

Peter Zoller
Wolfgang Lechner
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Rosario Fazio

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Immanuel Bloch
Marc Cheneau
Sebastian Hild

Alessandro Silva
Giuseppe Santoro

Jörg Schmiedmayer
Thorsten Schumm
Sandrine van Frank

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