QUANTUM SIMULATIONS FOR HIGH-ENERGY AND NUCLEAR PHYSICS

QS_HEP

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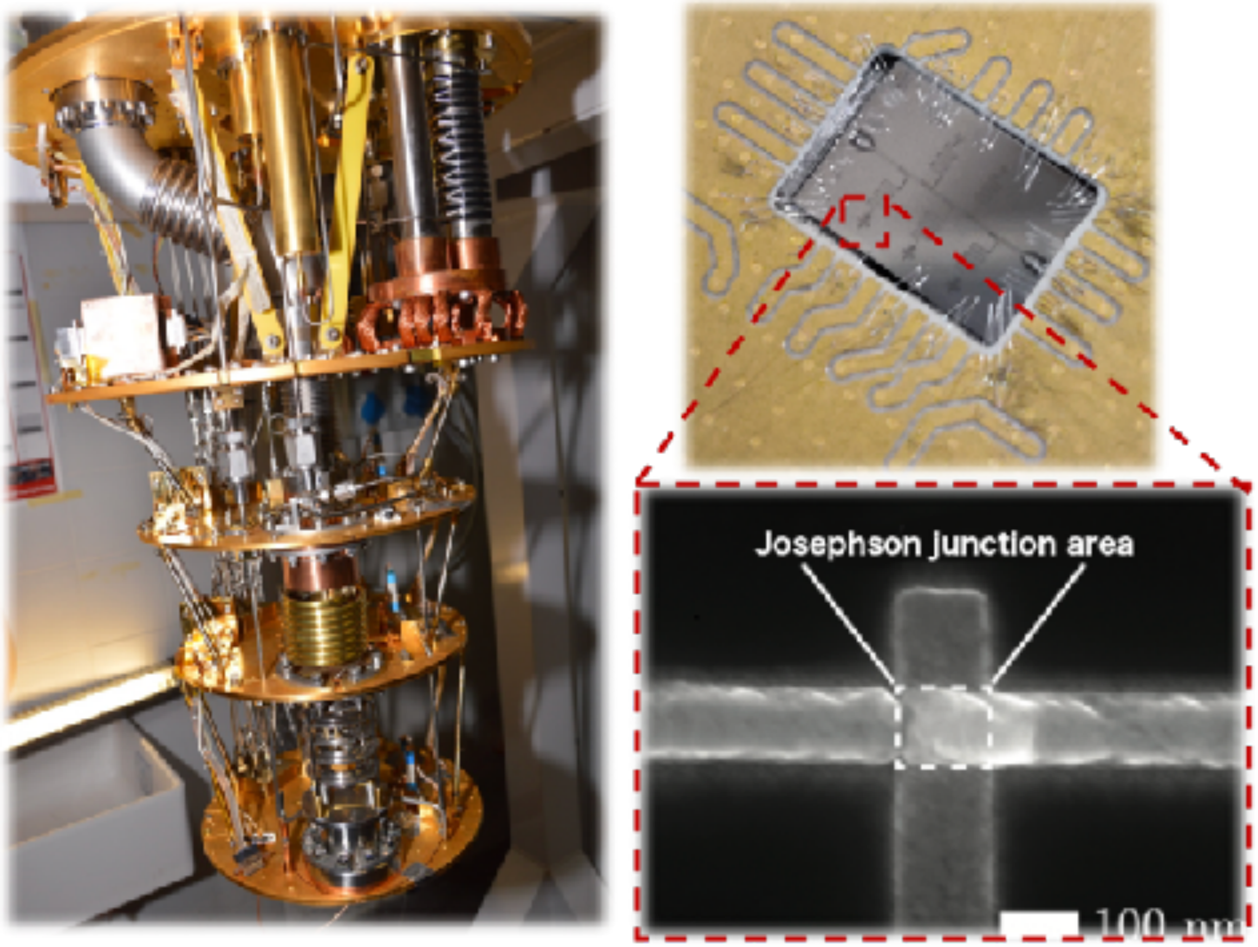
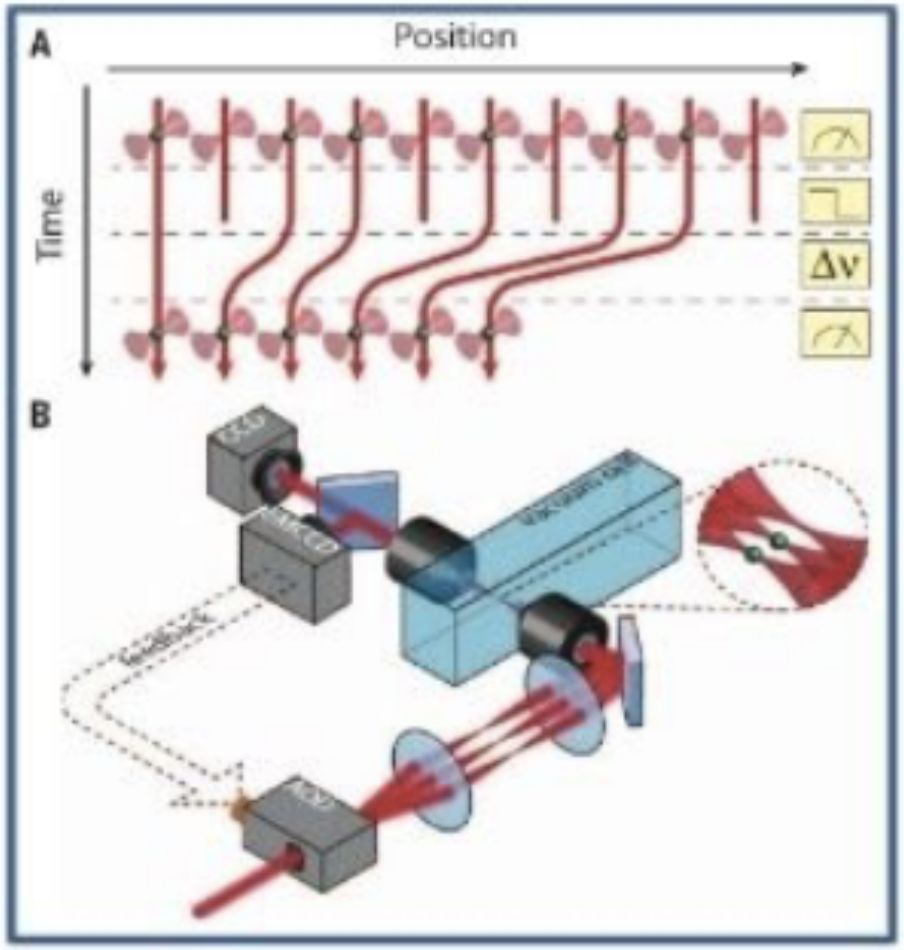
PROJECT GOAL

Develop experimental platforms and theoretical expertise aimed at the quantum simulation of lattice gauge theories

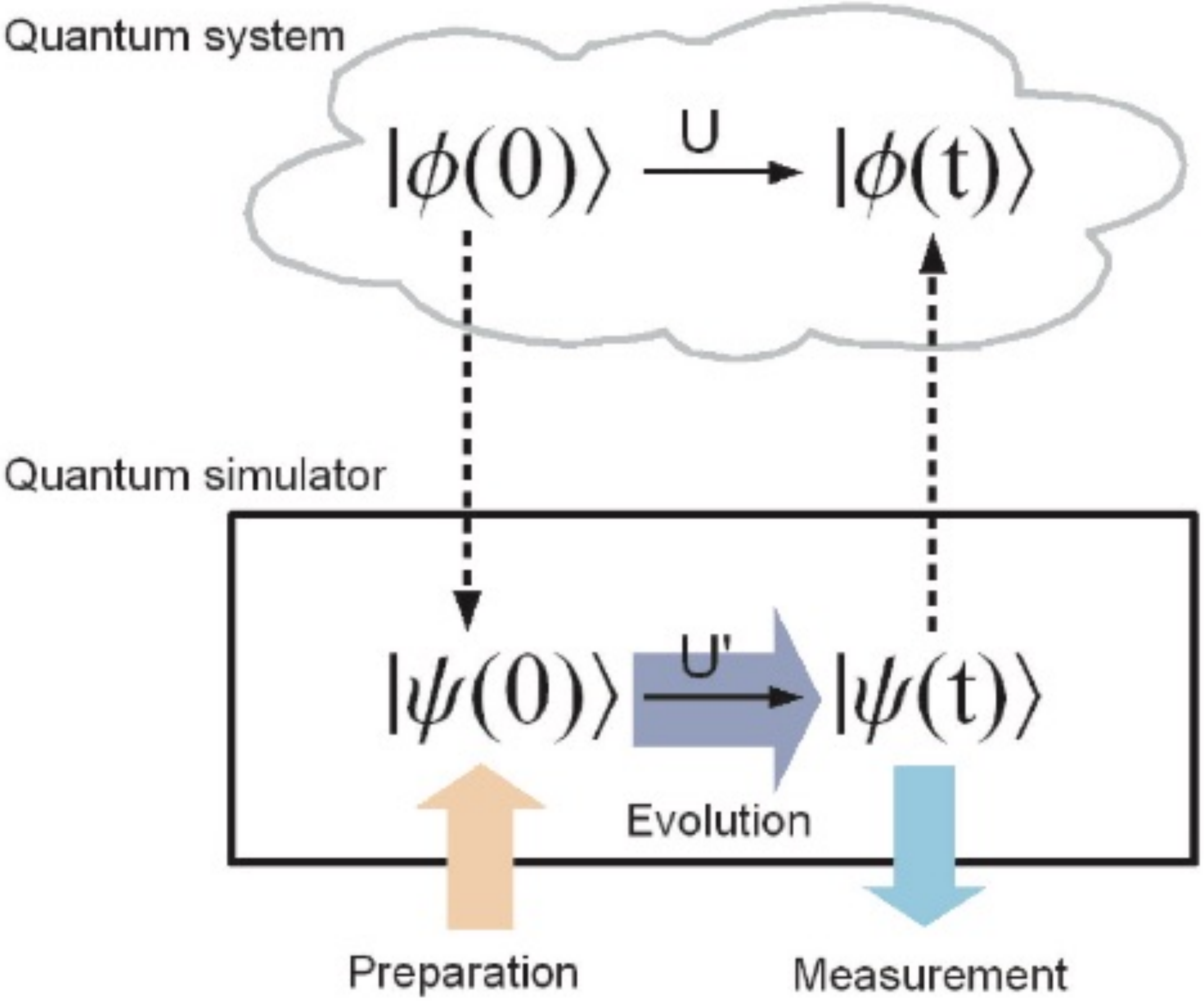


[NA] Superconductors



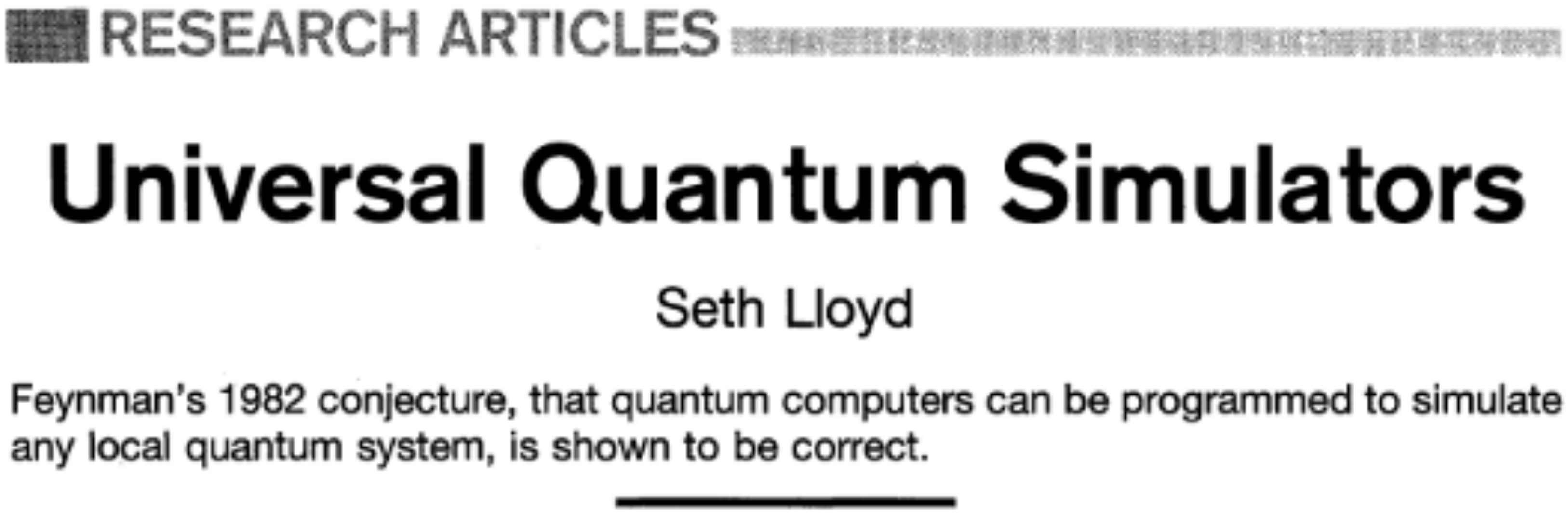
[TN] Rydberg atoms

QUANTUM SIMULATIONS



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

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.

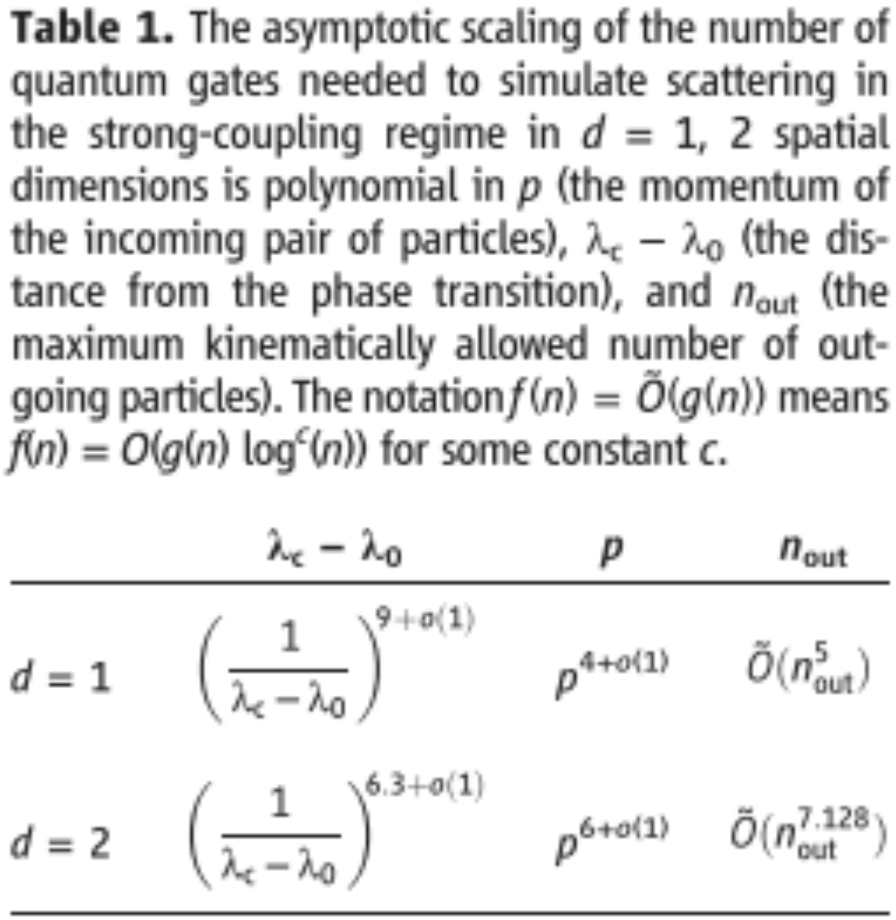
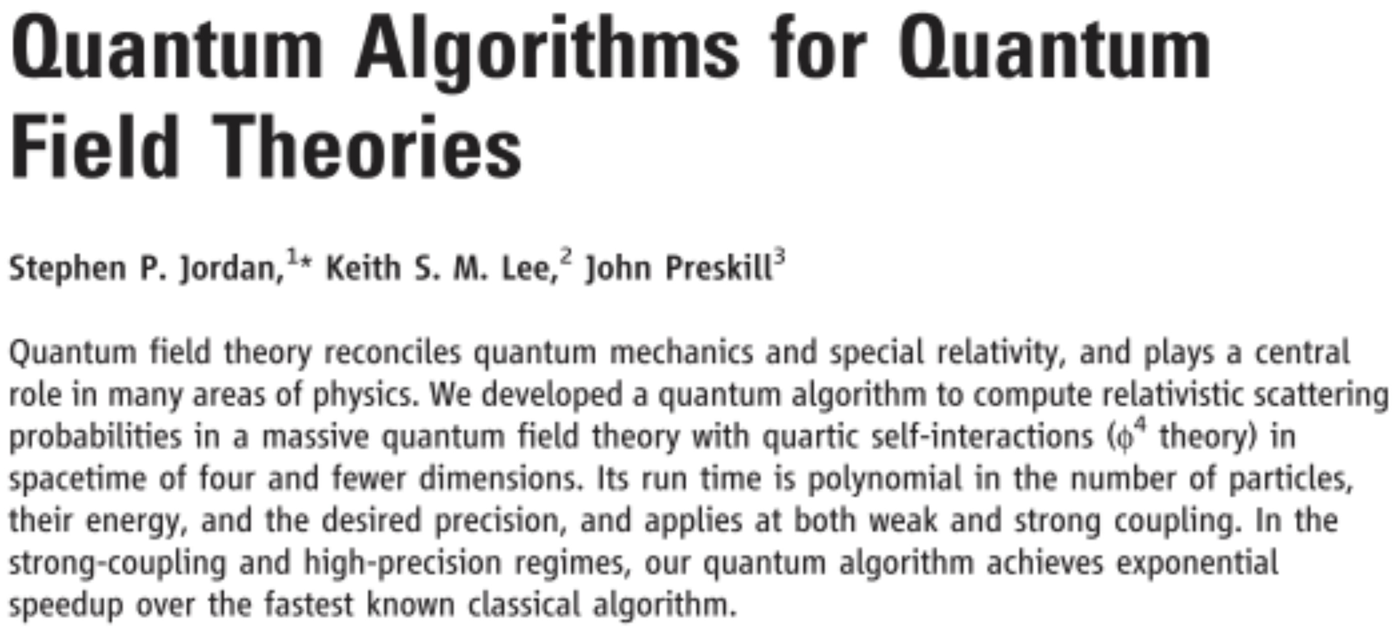


Table 1. The asymptotic scaling of the number of quantum gates needed to simulate scattering in the strong-coupling regime in $d = 1, 2$ spatial dimensions is polynomial in p (the momentum of the incoming pair of particles), $\lambda_c - \lambda_0$ (the distance from the phase transition), and n_{out} (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}
$d = 1$	$\left(\frac{1}{\lambda_c - \lambda_0}\right)^{9+o(1)}$	$p^{4+o(1)}$	$\tilde{O}(n_{\text{out}}^5)$
$d = 2$	$\left(\frac{1}{\lambda_c - \lambda_0}\right)^{6.3+o(1)}$	$p^{6+o(1)}$	$\tilde{O}(n_{\text{out}}^{7.128})$

S. Lloyd, Science (1996)



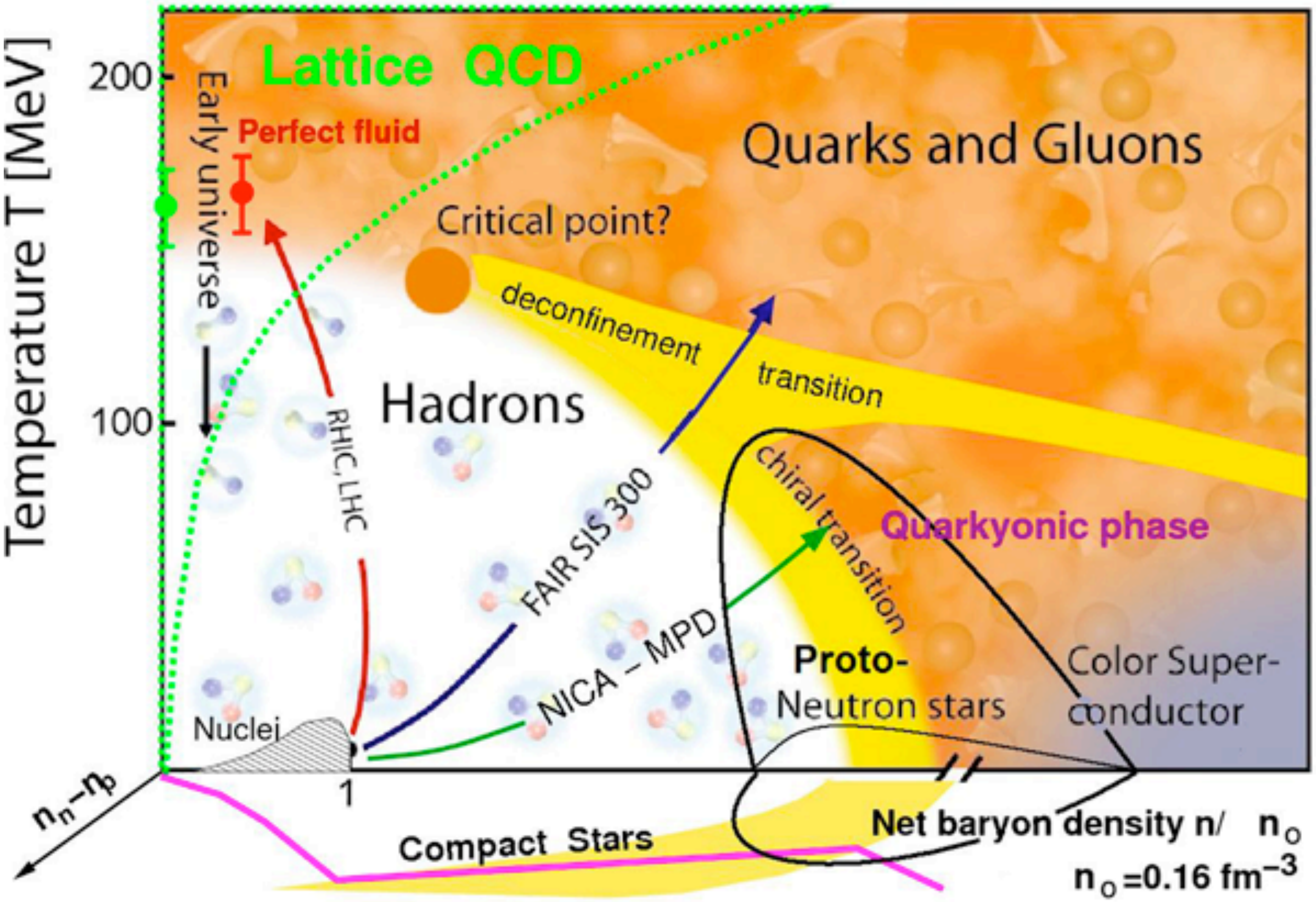
Quantum Algorithms for Quantum Field Theories

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)

SIGN PROBLEM



The current wisdom on the phase diagram of nuclear matter.

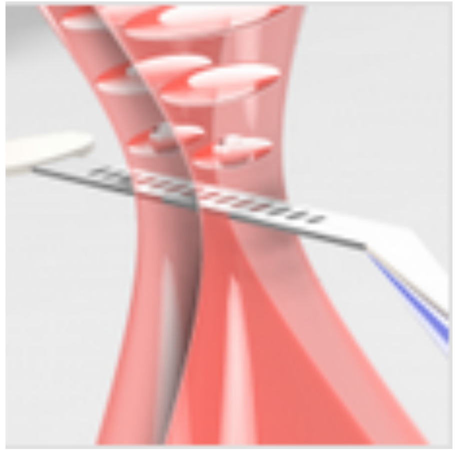
McLerran, L. Nucl.Phys.Proc.Suppl. 195 (2009) 275-280

QUANTUM COMPUTERS/SIMULATORS

Google

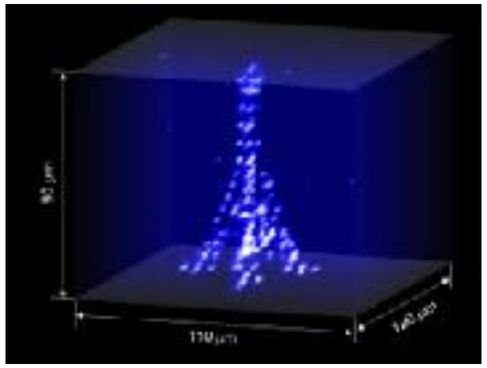
rigetti

Superconductors

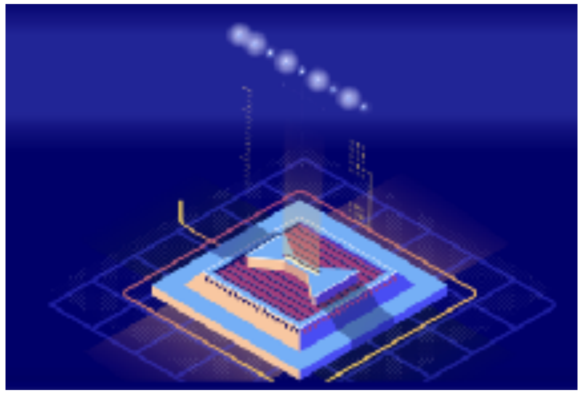


Lukin Group

INSTITUT d'OPTIQUE GRADUATE SCHOOL



Rydberg atoms

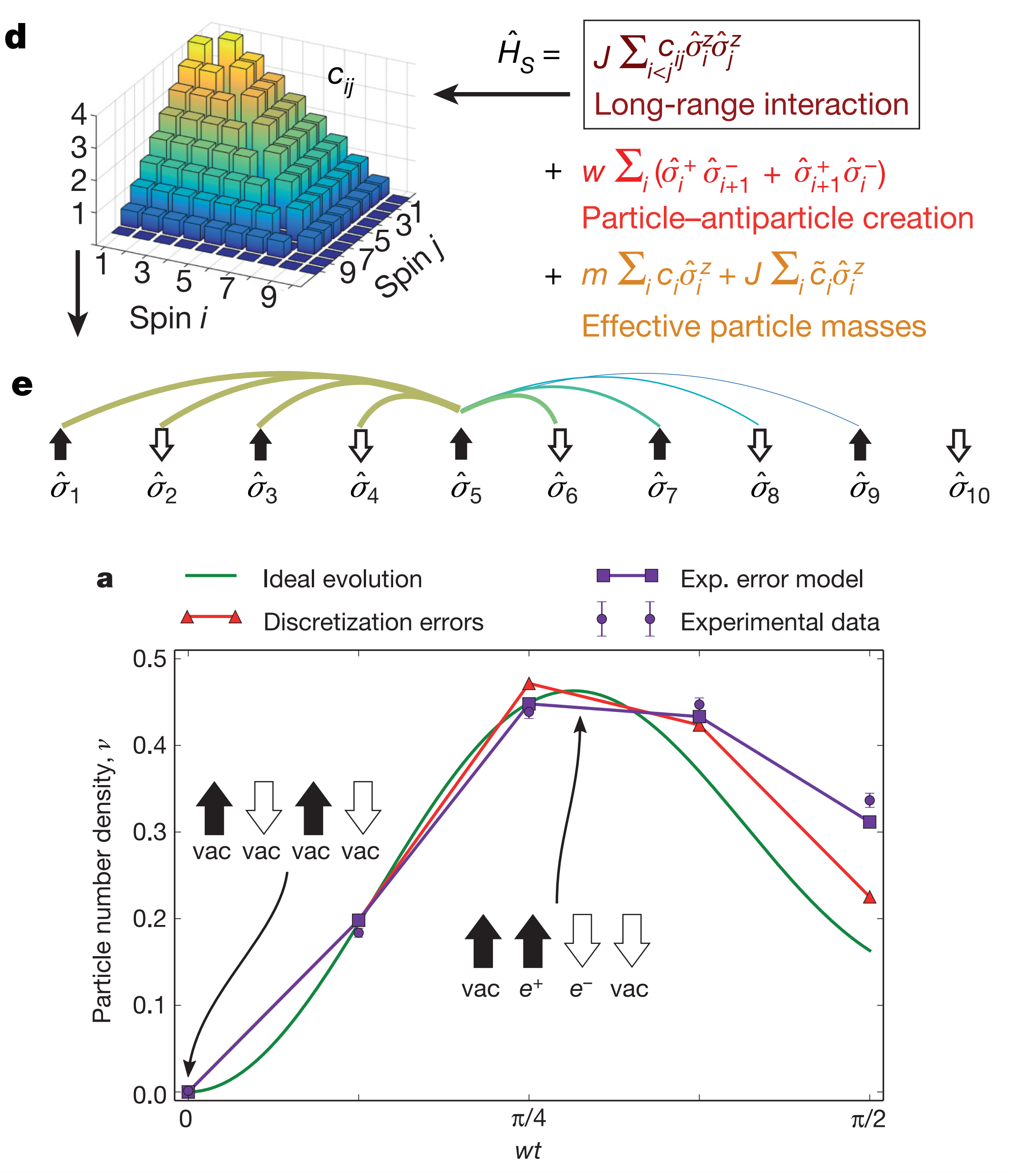


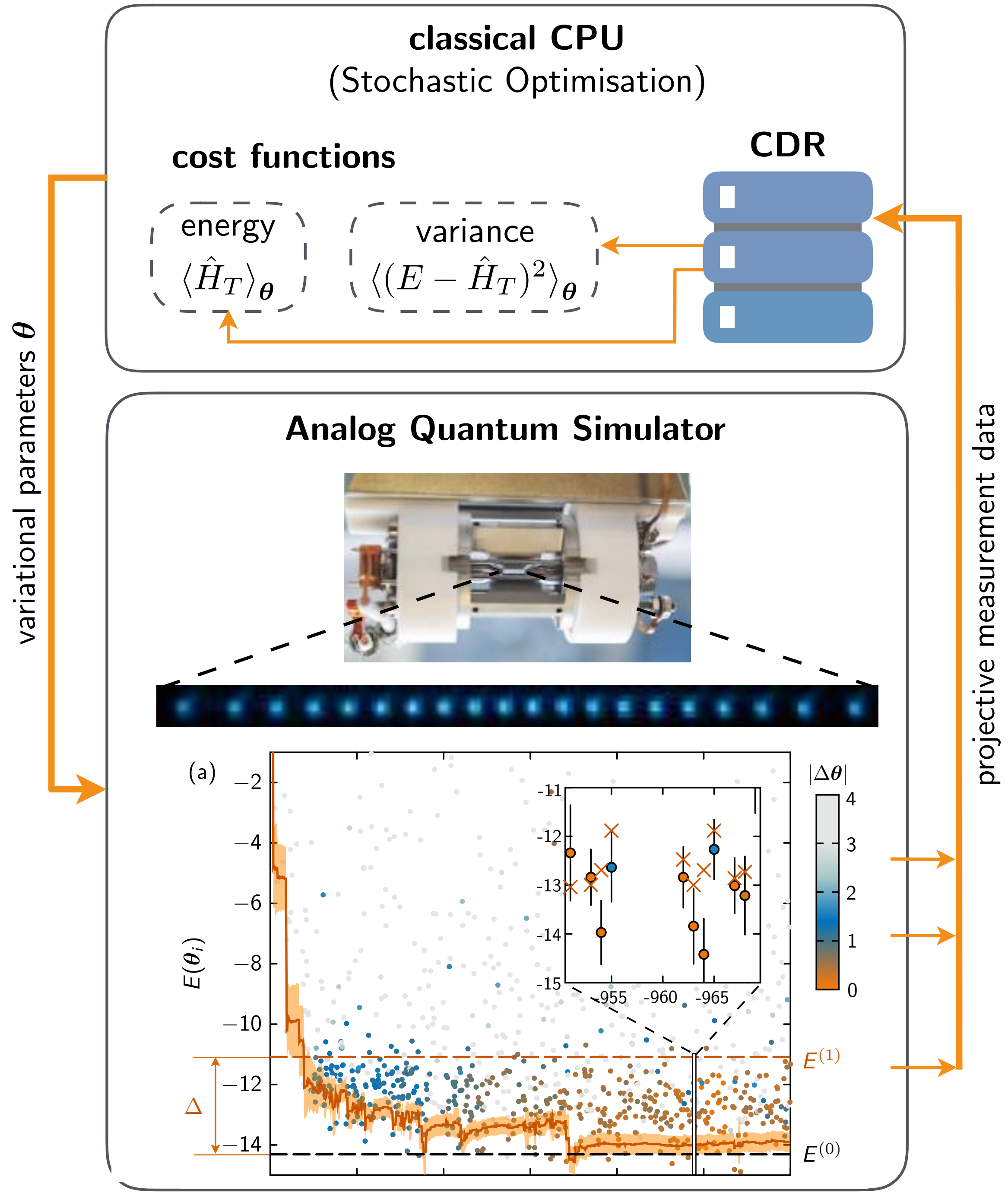
IONQ

AQT

Trapped ions

QUANTUM COMPUTING OF THE SCHWINGER MODEL





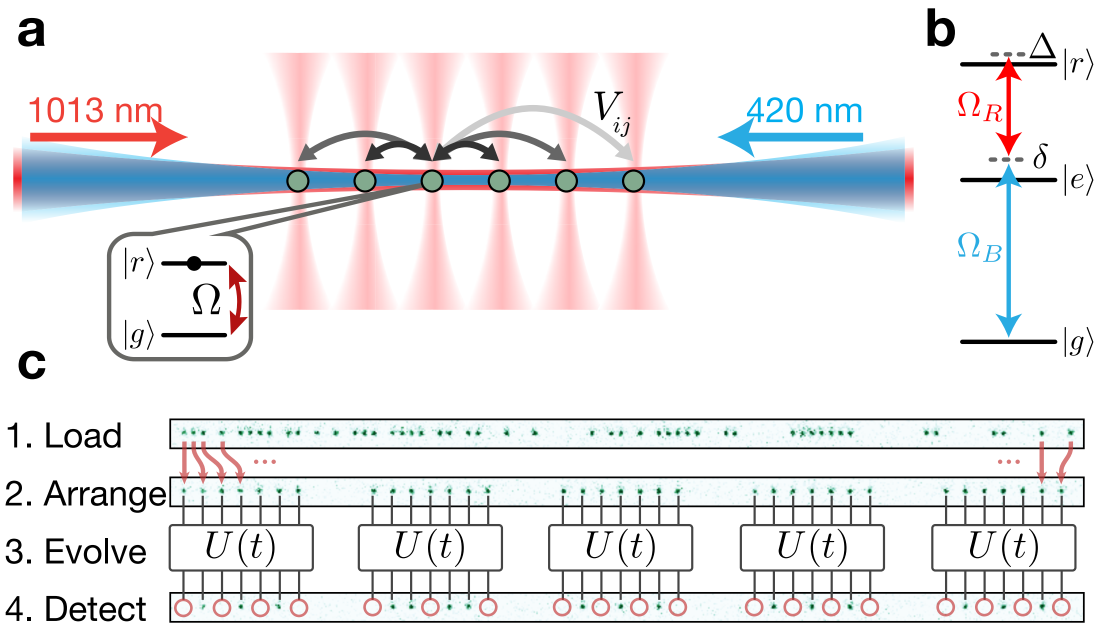
IQOQI Innsbruck

20 lattice sites

R. Blatt and P. Zoller's groups

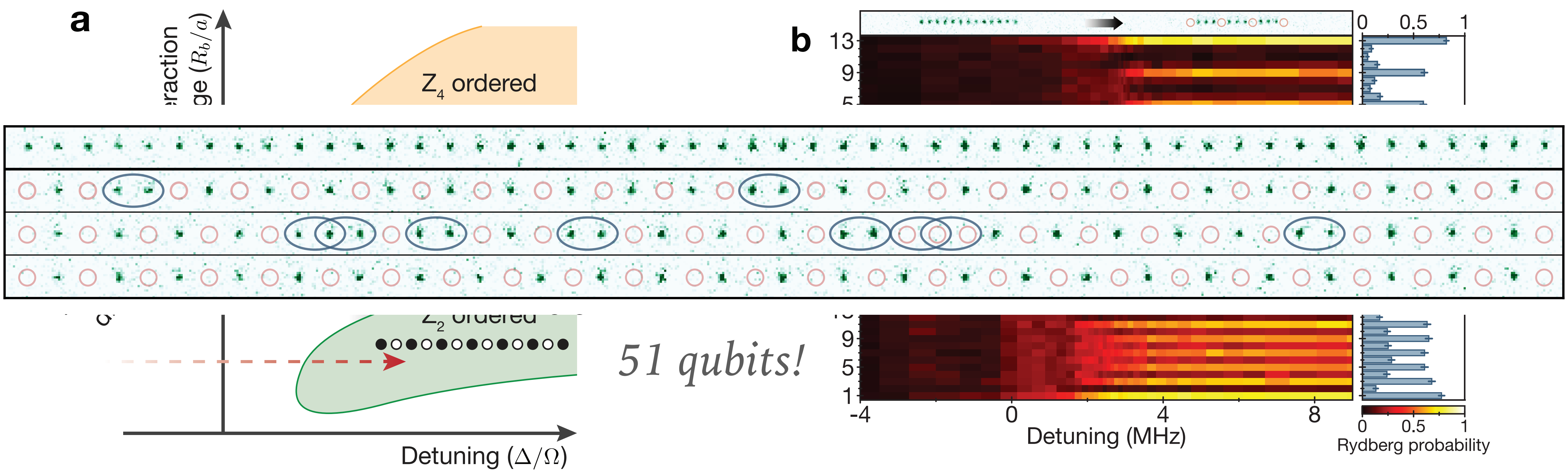
Nature (2016), Nature (2018)

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!

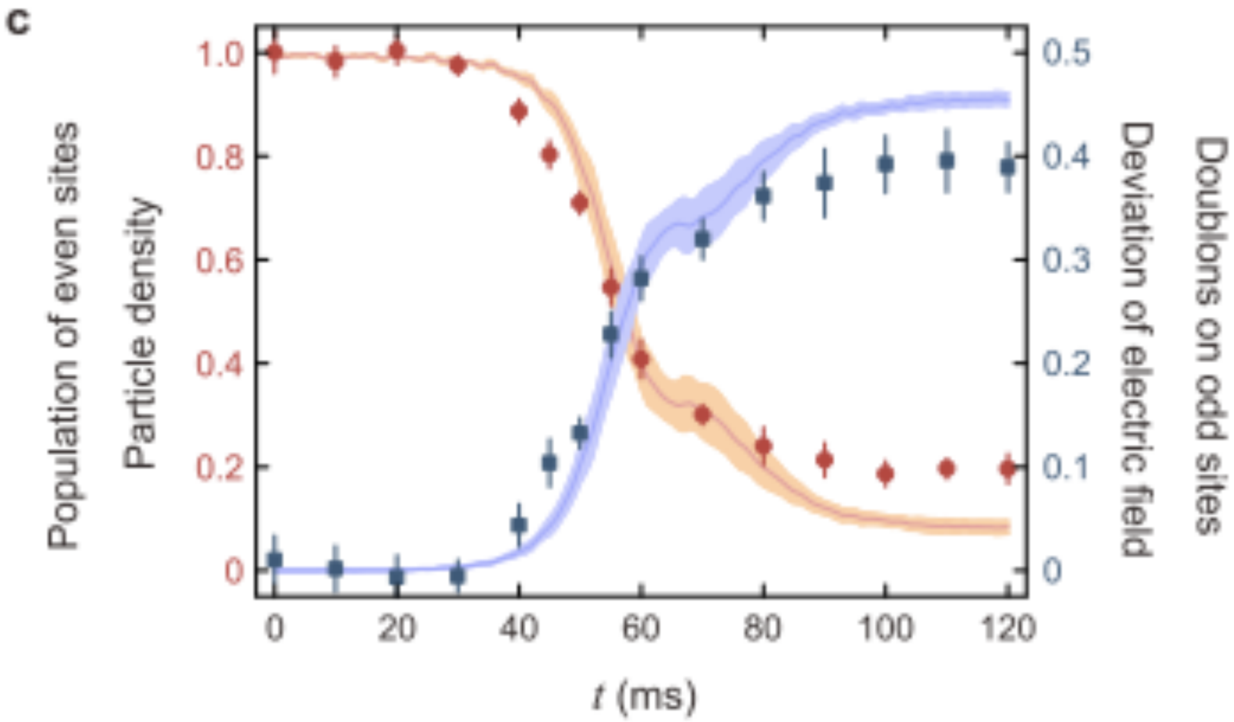
M. Lukin's group ***Nature*** *(2017)*

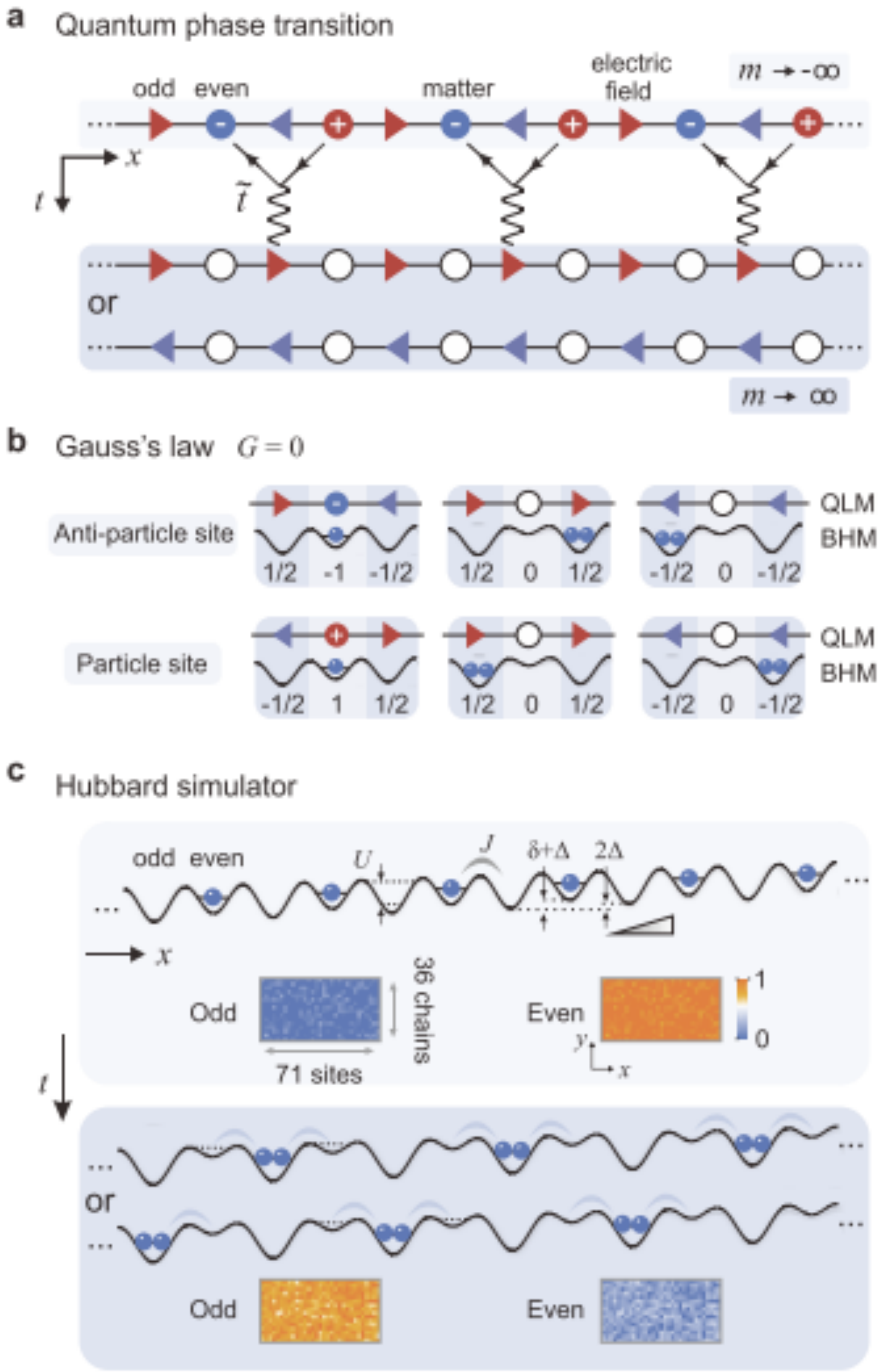
M. Dalmonte et al PRX (2019)

GAUGE INVARIANCE ON A 71 SITES QUANTUM SIMULATOR

$$\hat{H}_{\mathrm{QLM}} = \sum_{\ell} \left[-\frac{i\tilde{t}}{2} \left(\hat{\psi}_{\ell} \hat{S}^{+}_{\ell,\ell+1} \hat{\psi}_{\ell+1} - \mathrm{H.c.} \right) + m \hat{\psi}^{\dagger}_{\ell} \hat{\psi}_{\ell} \right]$$

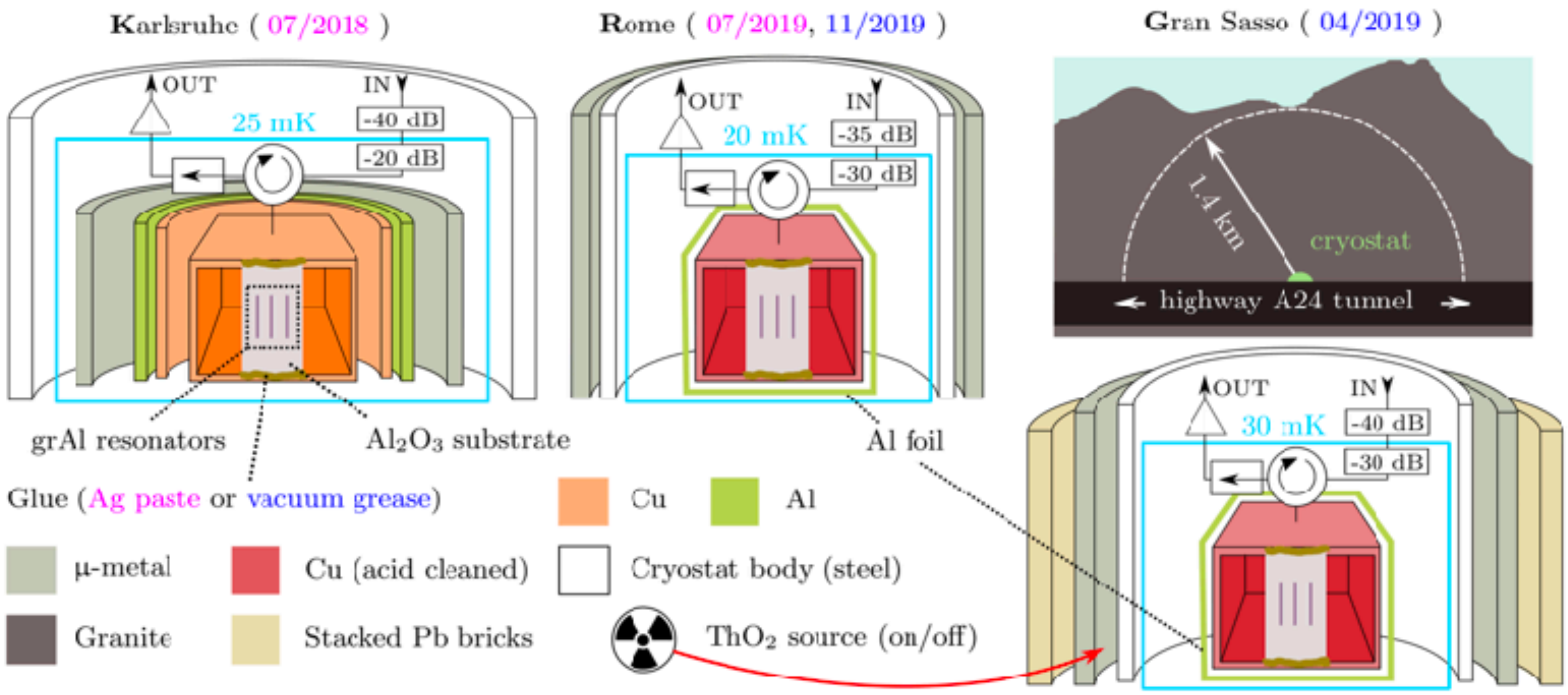
Arrays of bosonic atoms in an optical superlattice





J.W Pan group ***arXiv: 2003.08945 (Heidelberg)***

REDUCING DECOHERENCE ON QUANTUM CIRCUITS AT LNGS



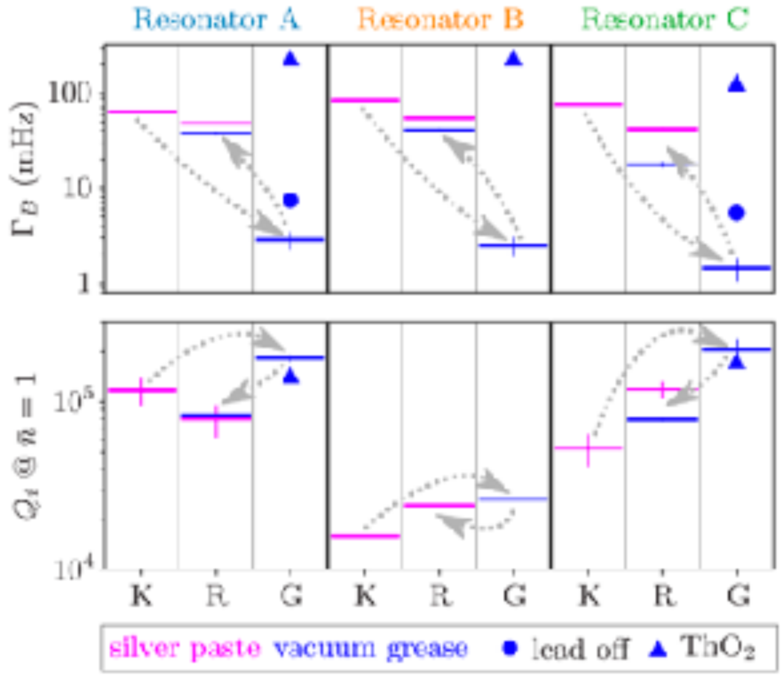
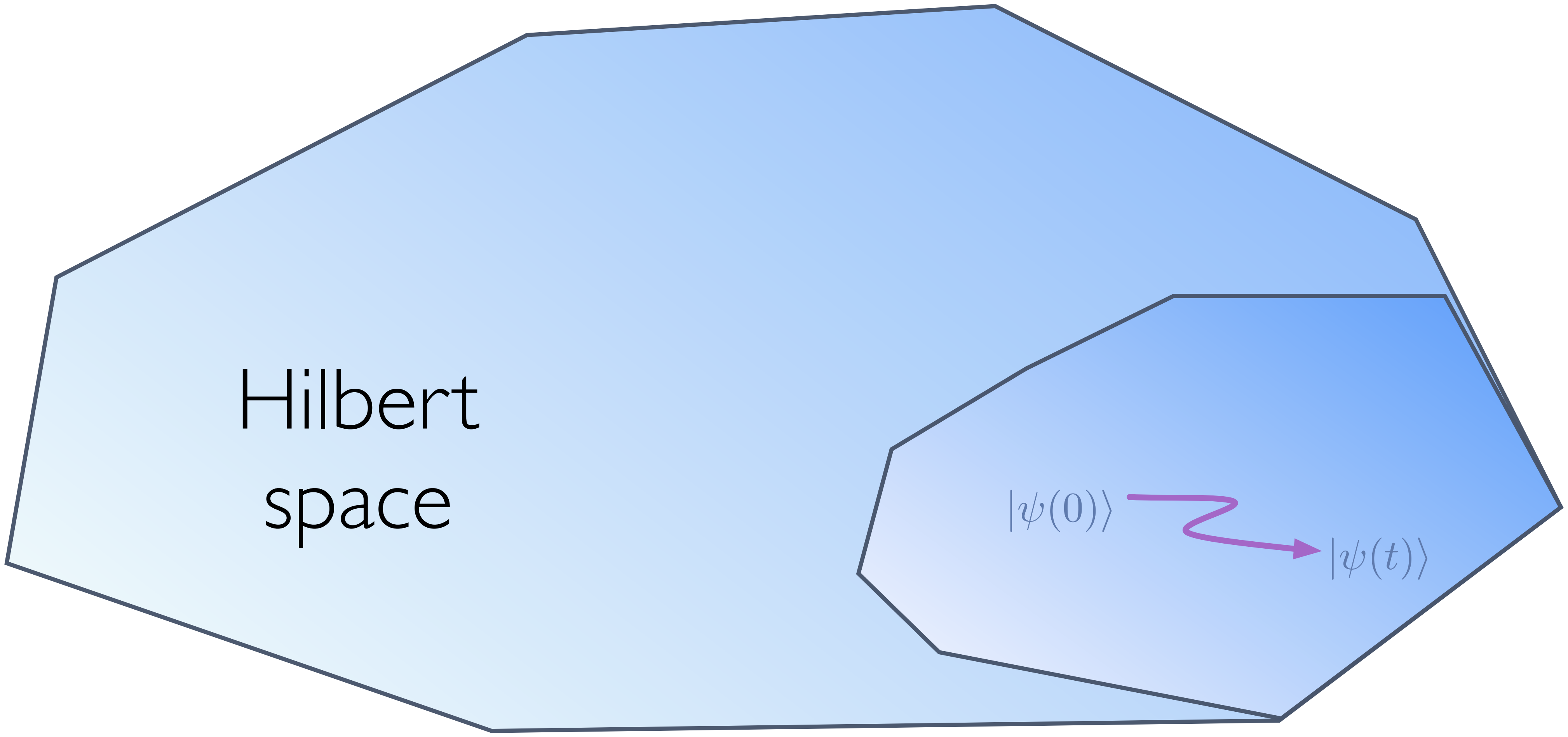


Figure 3. **Effect of ionizing radiation shielding on resonator performance**. Quasiparticle burst rate (Γ_B, top) and internal quality factor at single photon drive (Q_i, bottom) for all resonators and setups. When the sample is cleaned and tested in the R setup, the measured Γ_B and Q_i values are comparable to those obtained in K. Nevertheless, we observe a consistent lowering of Γ_B when using vacuum grease instead of Ag paste. Measurements in the G setup show a reduction in QP burst rate Γ_B (factor fifty) and dissipation (up to a factor four). In G, removing the lead shielding increases Γ_B by a factor two. Adding a ThO_2 radioactive source next to the cryostat body yields a Γ_B greater than the one measured above ground, and decreases the internal quality factor Q_i by 18±3%. Error bars are not shown when smaller than the marker size. The chronological order of measurements in the three different setups is indicated by the dotted gray arrows.

L. Cardani et al.

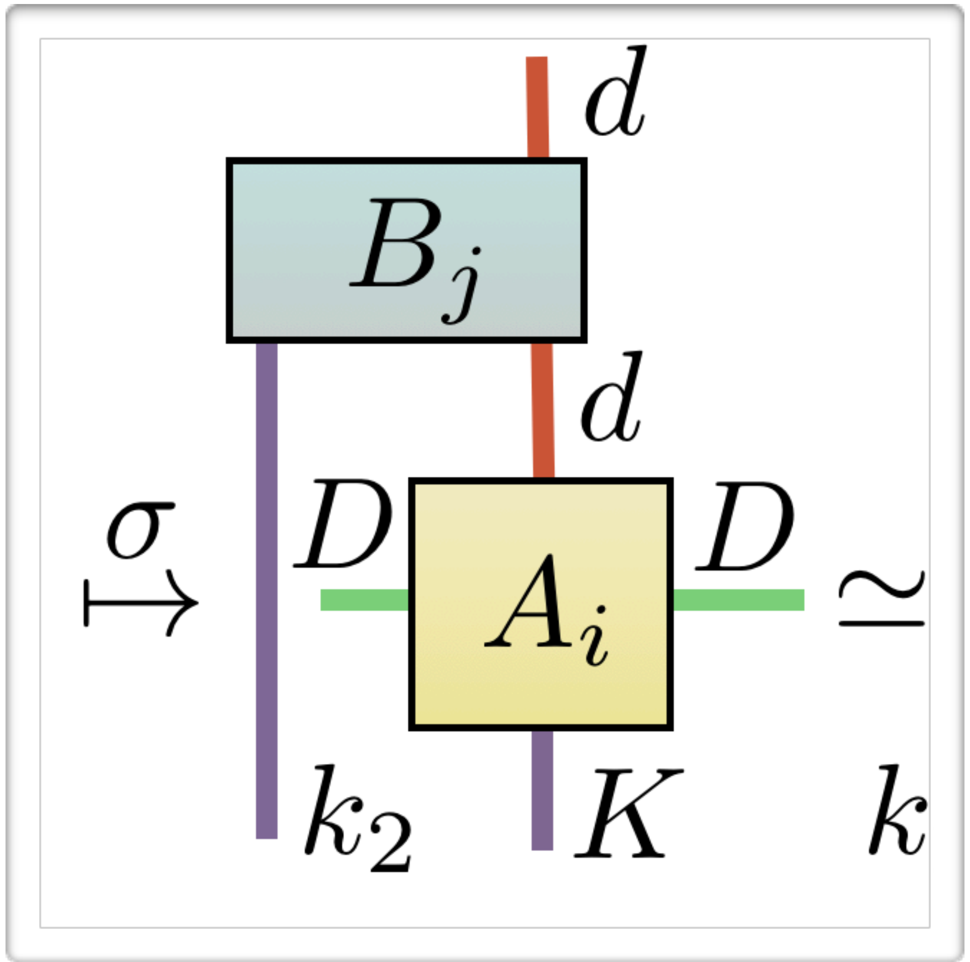
arXiv:2005.02286

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



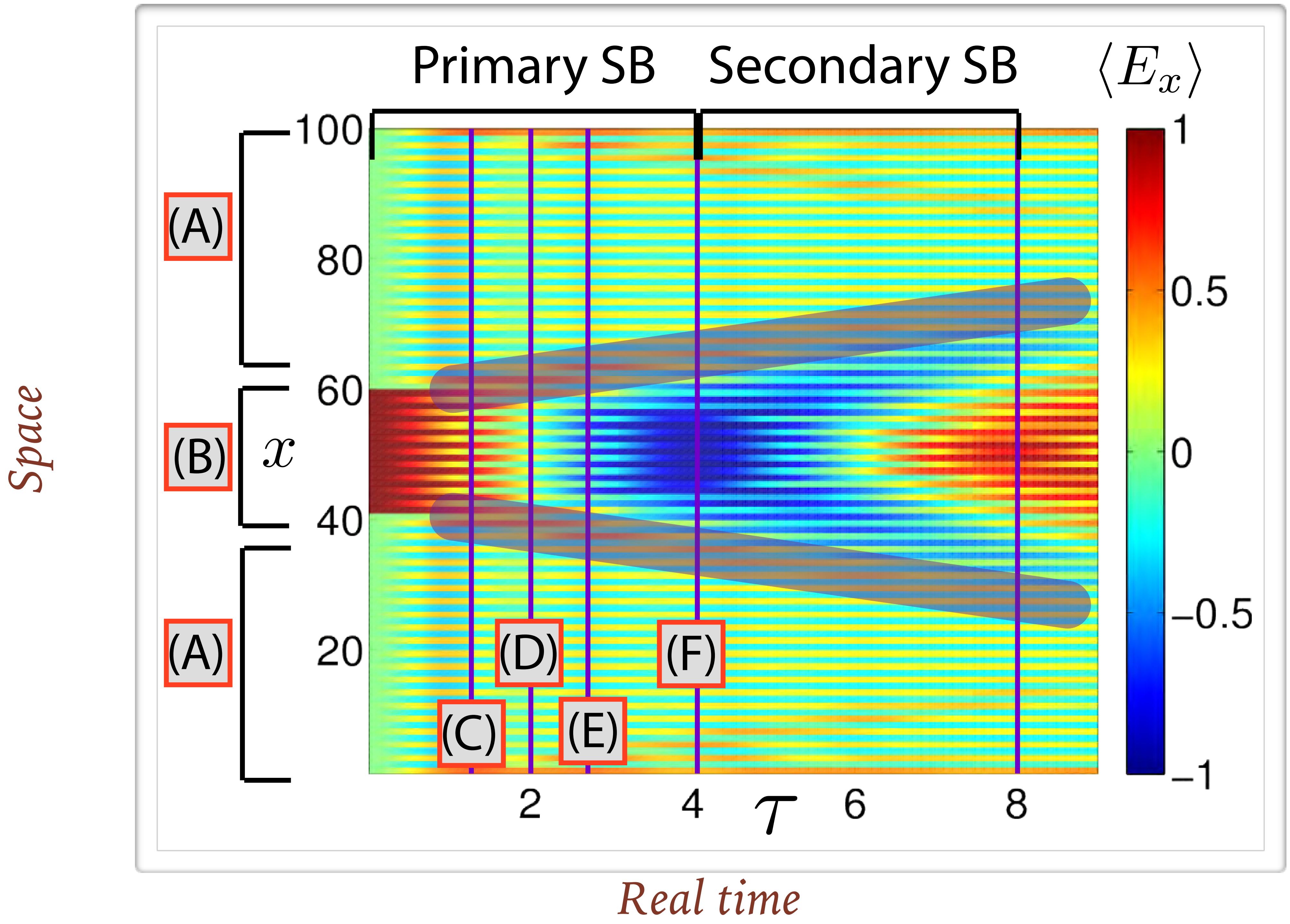
Hilbert
space

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)*



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)

TEAM AND WORKPLAN

[BA] S. Pascazio

[BO] - E. Ercolessi

[LNGS] - S. Pirro

[NA] - F. Tafuri

[PD] - S. Montangero

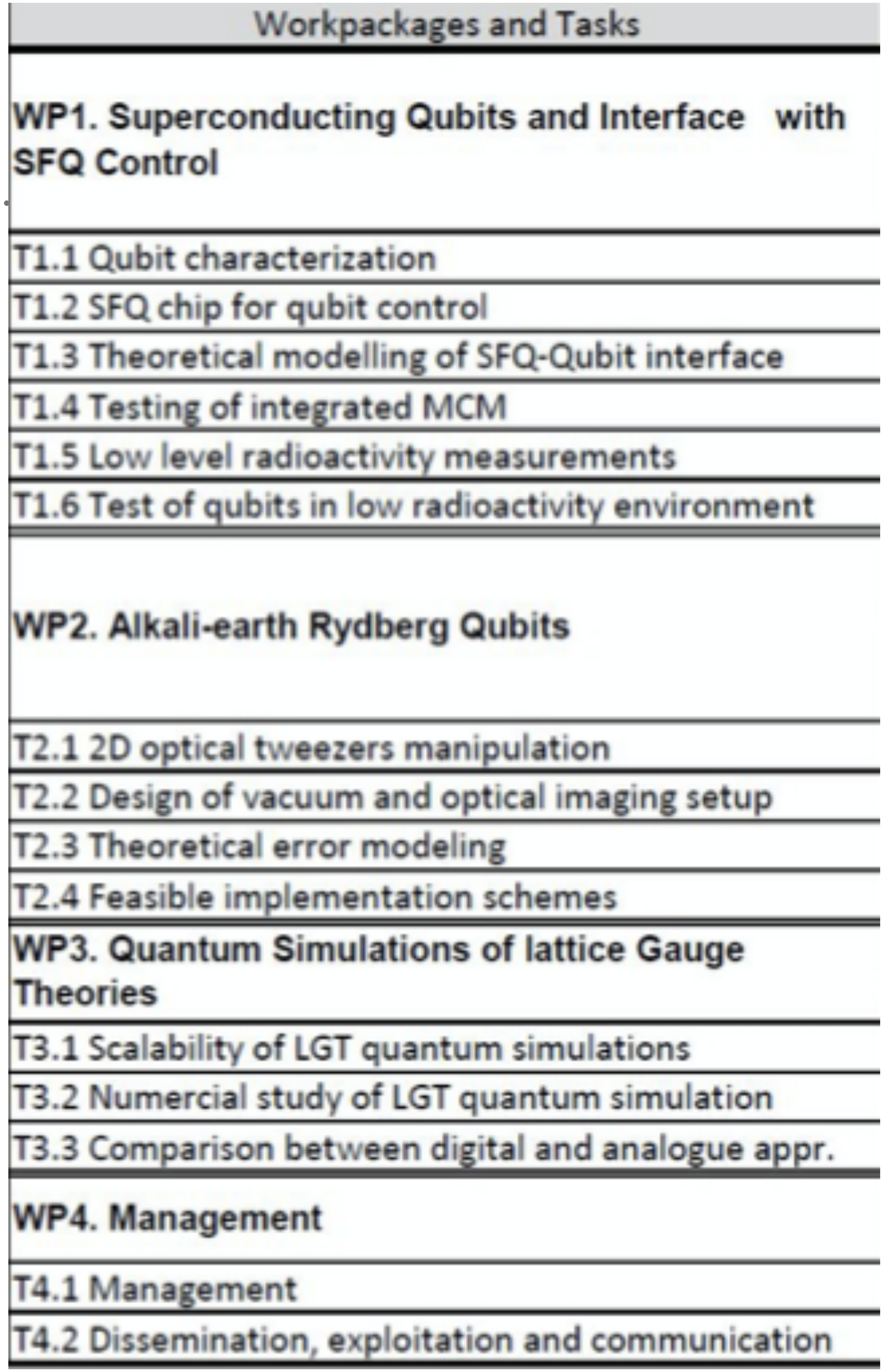
[PI] - M. D'Elia

[RM1] - L. Cardani

[TN] - G. Ferrari

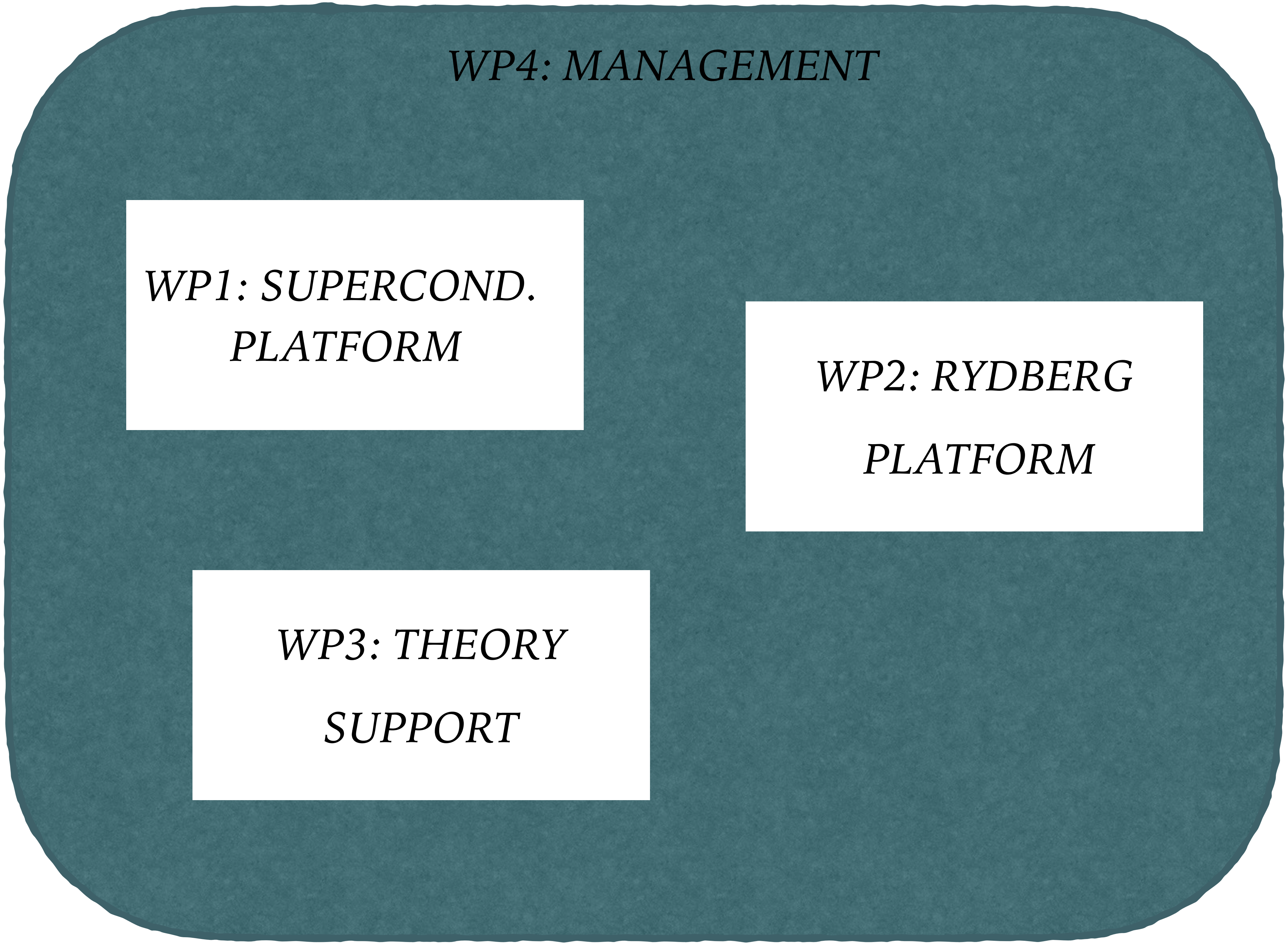
[TS] - A. Scardicchio

Budget: 990K



Workpackages and Tasks
WP1. Superconducting Qubits and Interface with SFQ Control
T1.1 Qubit characterization
T1.2 SFQ chip for qubit control
T1.3 Theoretical modelling of SFQ-Qubit interface
T1.4 Testing of integrated MCM
T1.5 Low level radioactivity measurements
T1.6 Test of qubits in low radioactivity environment
WP2. Alkali-earth Rydberg Qubits
T2.1 2D optical tweezers manipulation
T2.2 Design of vacuum and optical imaging setup
T2.3 Theoretical error modeling
T2.4 Feasible implementation schemes
WP3. Quantum Simulations of lattice Gauge Theories
T3.1 Scalability of LGT quantum simulations
T3.2 Numercial study of LGT quantum simulation
T3.3 Comparison between digital and analogue appr.
WP4. Management
T4.1 Management
T4.2 Dissemination, exploitation and communication

QUANTUM SIMULATIONS FOR HIGH-ENERGY AND NUCLEAR PHYSICS



WP4: MANAGEMENT

WP1: SUPERCOND. PLATFORM

WP2: RYDBERG PLATFORM

WP3: THEORY SUPPORT