

# A QUANTUM-INSPIRED TOOL FOR BRIDGING THE NISQ ERA

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Dipartimento  
di Fisica  
e Astronomia  
Galileo Galilei



UNIVERSITÀ  
DEGLI STUDI  
DI PADOVA

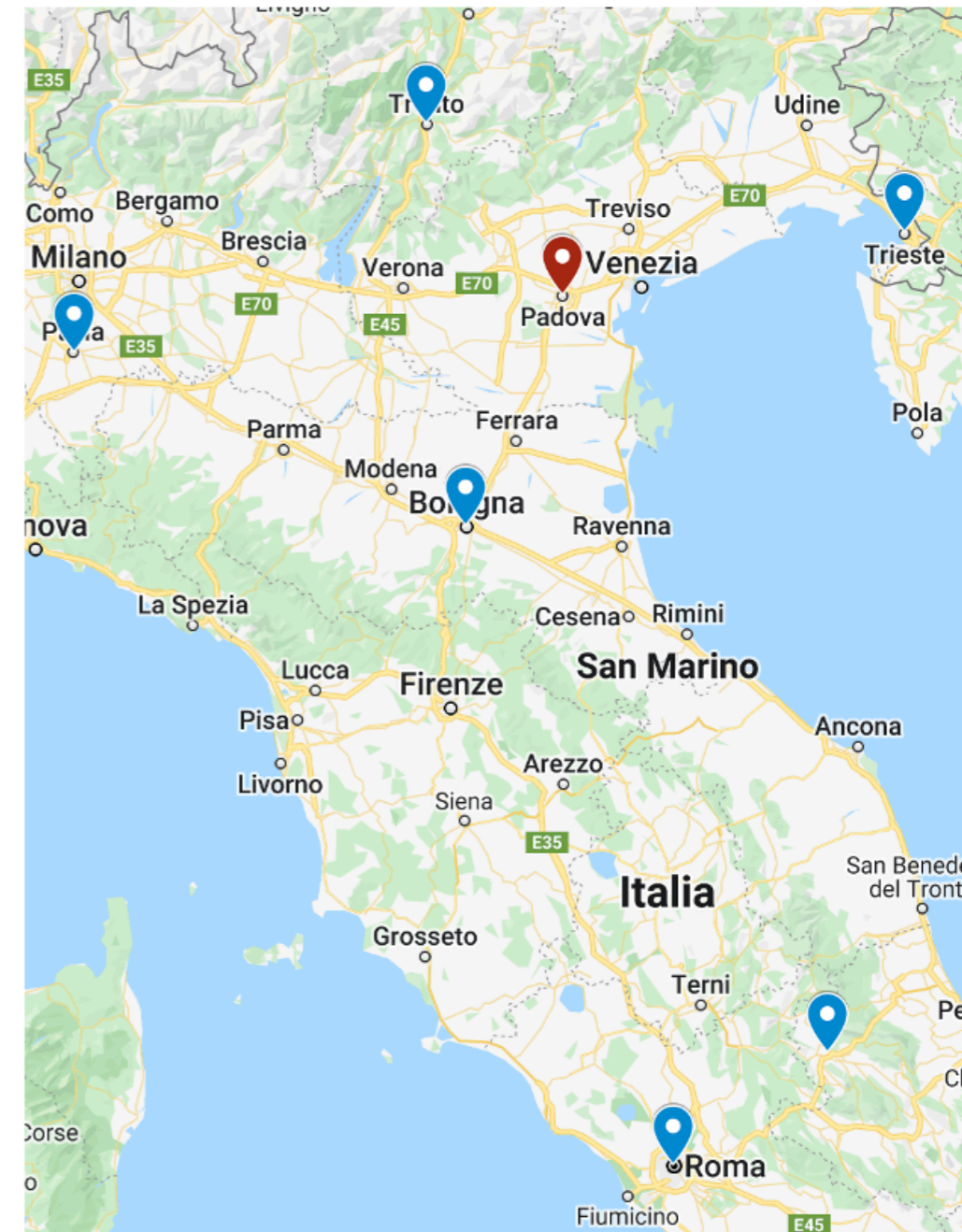
# QUANTUM COMPUTING AND SIMULATION CENTER

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*Investment of 6 M€*

*National strategic partnerships*

*Trapped ion quantum computer*





**ICSC**

**Centro Nazionale HPC,  
Big Data e Quantum Computing**

**Xc**

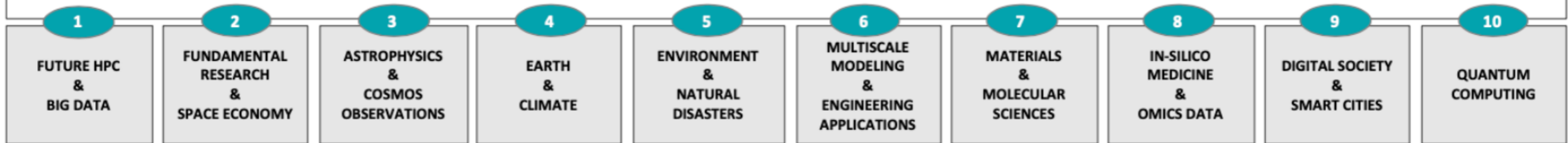




# ICSC Centro Nazionale HPC, Big Data e Quantum Computing



## SUPERCOMPUTING CLOUD INFRASTRUCTURE

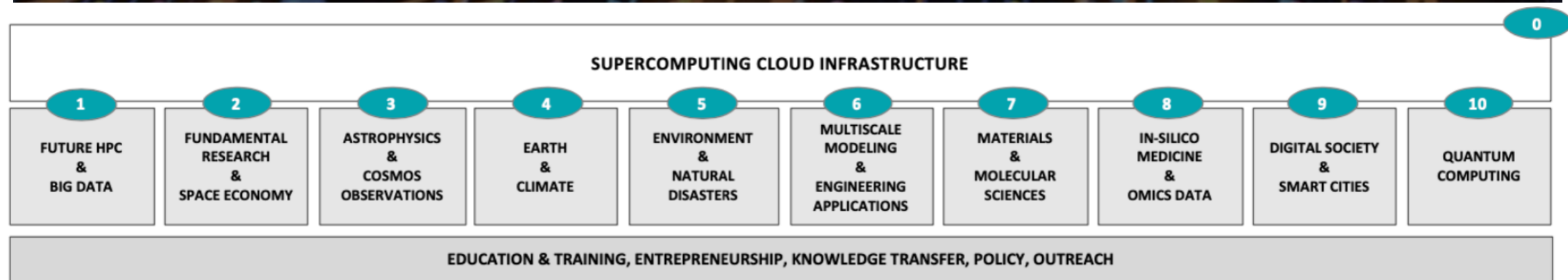


EDUCATION & TRAINING, ENTREPRENEURSHIP, KNOWLEDGE TRANSFER, POLICY, OUTREACH



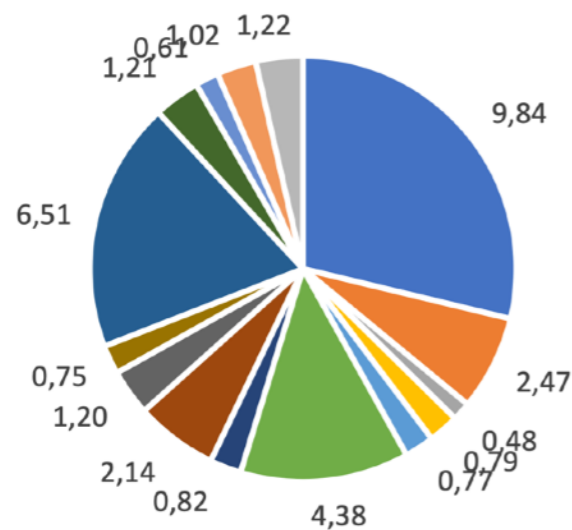
# ICSC Xc

## Centro Nazionale HPC, Big Data e Quantum Computing



- POLIMI
- UNIPD
- CINECA
- UNIBO
- UNICT
- CNR
- INAF
- INFN
- UNIPV
- UNIPI
- UNINA
- SAPIENZA
- IIT
- UNIBA
- UNIMIB

Quantum Computing



### Spoke 10 – Quantum Computing

**WP1. Software (Leader: INFN): Development and application of high-level quantum software for algorithms solving general purpose problems, scientific and industrial applications:** T1.1 New algorithms (Pavia, Bologna, IIT, Catania, CINECA, CNR, Pisa, Sapienza, Bari, Polimi, Padova); T1.2 Applications and use cases (IIT, Bologna, CINECA, CNR, INAF, INFN, Pavia, Pisa, Bari, Bicocca, Polimi, Padova)

**WP2. Mapping, compilation and quantum computing emulation (Leader: CINECA): Development of software toolchain for compilation, benchmarking, verification, emulation of quantum computers and algorithms:** T2.1 Mapping and compilation (Bologna, CNR, Pisa, Polimi); T2.2 Emulation (CINECA, INAF, Bari, Padova)

**WP3. Firmware and hardware platforms (Leaders: CNR, Catania): Development of low-level software for the physical operation of quantum computers. Development and support of the quantum computer hardware chain:** T3.1 Photonic (Sapienza, CNR, Bicocca, Pavia, Napoli); T3.2 Superconducting circuits (Napoli, INFN, Bicocca, CNR, Catania); T3.3 Atoms (CNR, Padova); T3.4 Ions (Padova, CNR); T3.5 Models and firmware (Catania, Polimi, Bari, Padova, Bicocca, CNR, Pisa)

# PASQuans

Programmable Atomic  
Large-Scale Quantum  
Simulation

iXblue

Atos

ALS AZUR LIGHT  
SYSTEMS

Laboratoire Kastler Brossel  
Physique quantique et applications  
COLLEGE DE FRANCE  
CNRS

Freie Universität  
Berlin

*Pilot Project*

*2018-2022*



PASQAL

INSTITUT  
d'OPTIQUE  
GRADUATE SCHOOL

JÜLICH  
Forschungszentrum



MYCRYO  
FIRM  
Cryodevices & Consulting

ÖAW  
ÖSTERREICHISCHE  
AKADEMIE DER  
WISSENSCHAFTEN

*FPA - PASQUANS2*

*2023-2030*

University of  
Strathclyde  
Glasgow

TOPTICA  
PHOTONICS

UNIVERSITÄT  
HEIDELBERG  
ZUKUNFT  
SEIT 1386



ParityQC

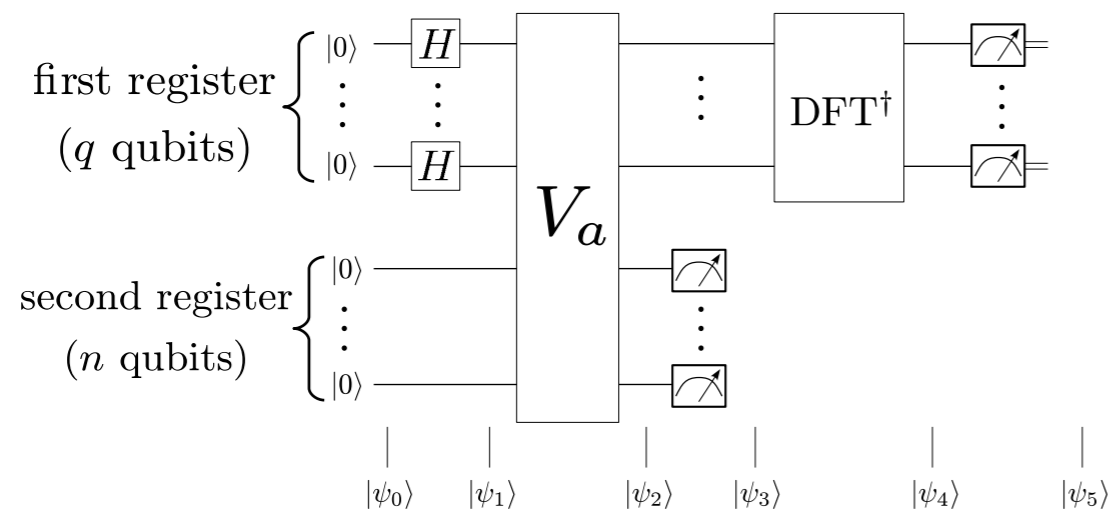
*Quantum simulator*

*with 10000 qubits!*



# QUANTUM COMPUTING

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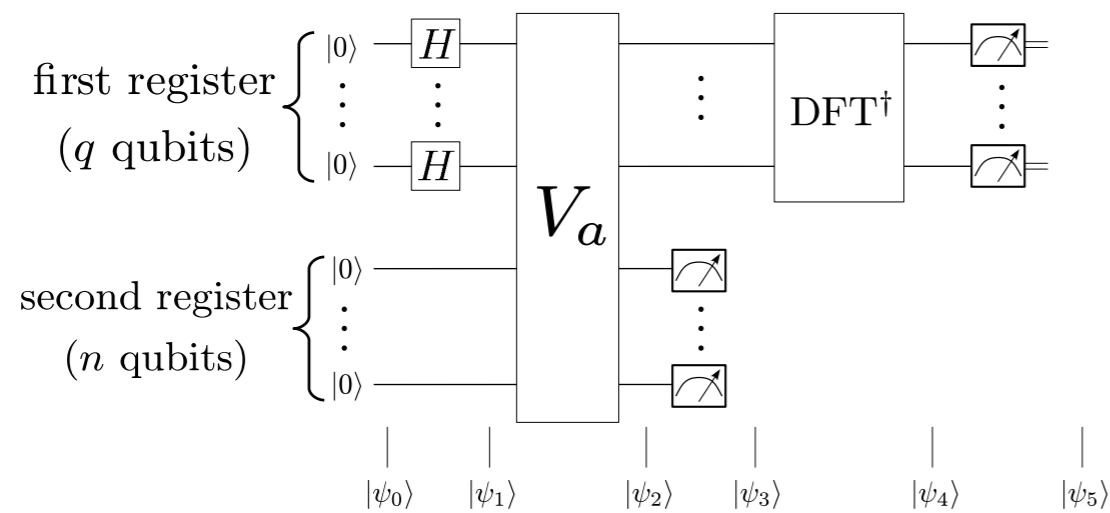


$$V_a : |x\rangle|y\rangle \rightarrow |x\rangle|y \oplus a^x \pmod{N}\rangle$$

*Circuit model*

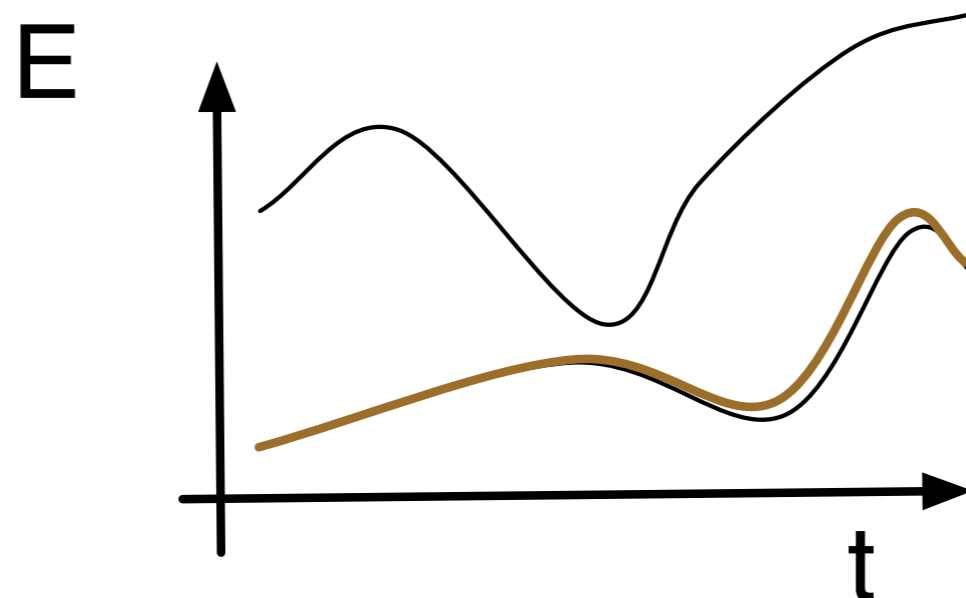


# QUANTUM COMPUTING

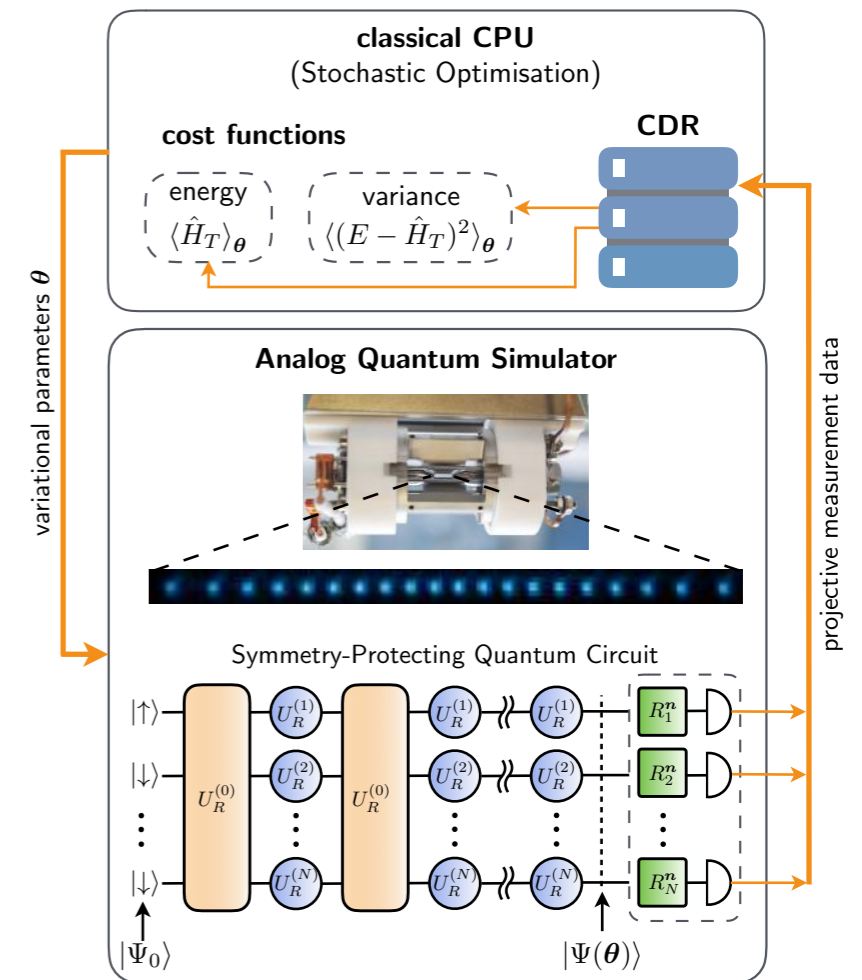


$$V_a : |x\rangle|y\rangle \rightarrow |x\rangle|y \oplus a^x \pmod N\rangle$$

*Circuit model*

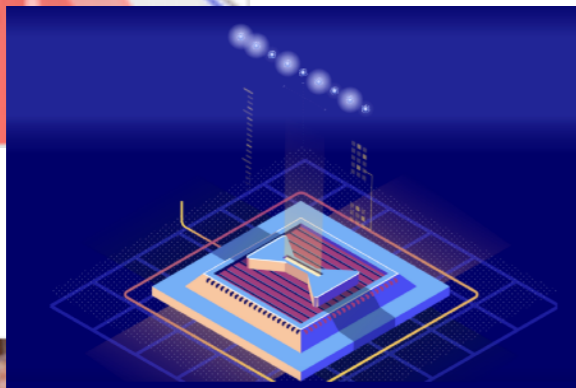
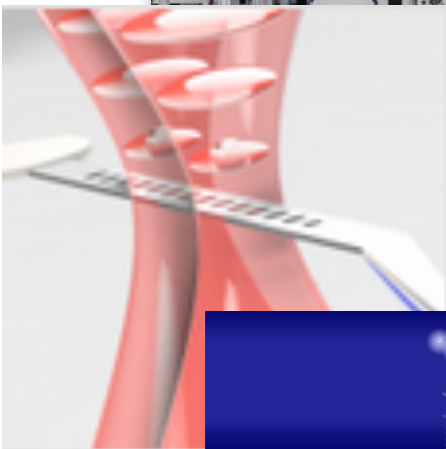


*Adiabatic - Quantum Annealing*



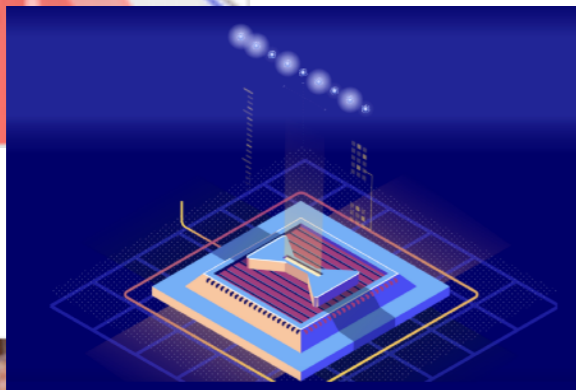
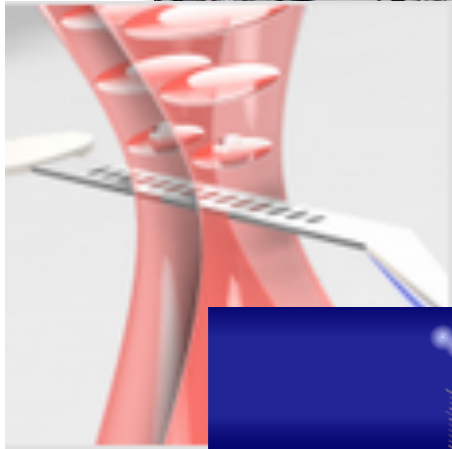
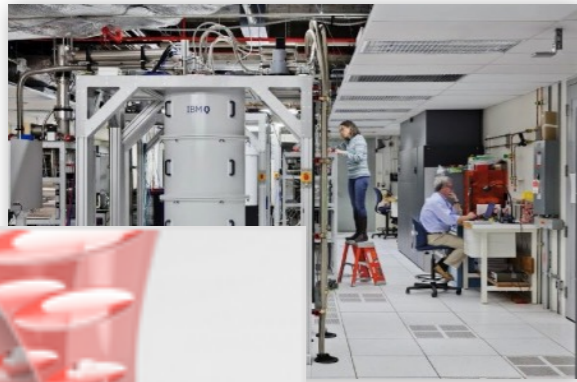
*Hybrid (VQE)*

# HOW TO GUIDE THE TRANSITION?



The New Quantum Era Podcast

# HOW TO GUIDE THE TRANSITION?

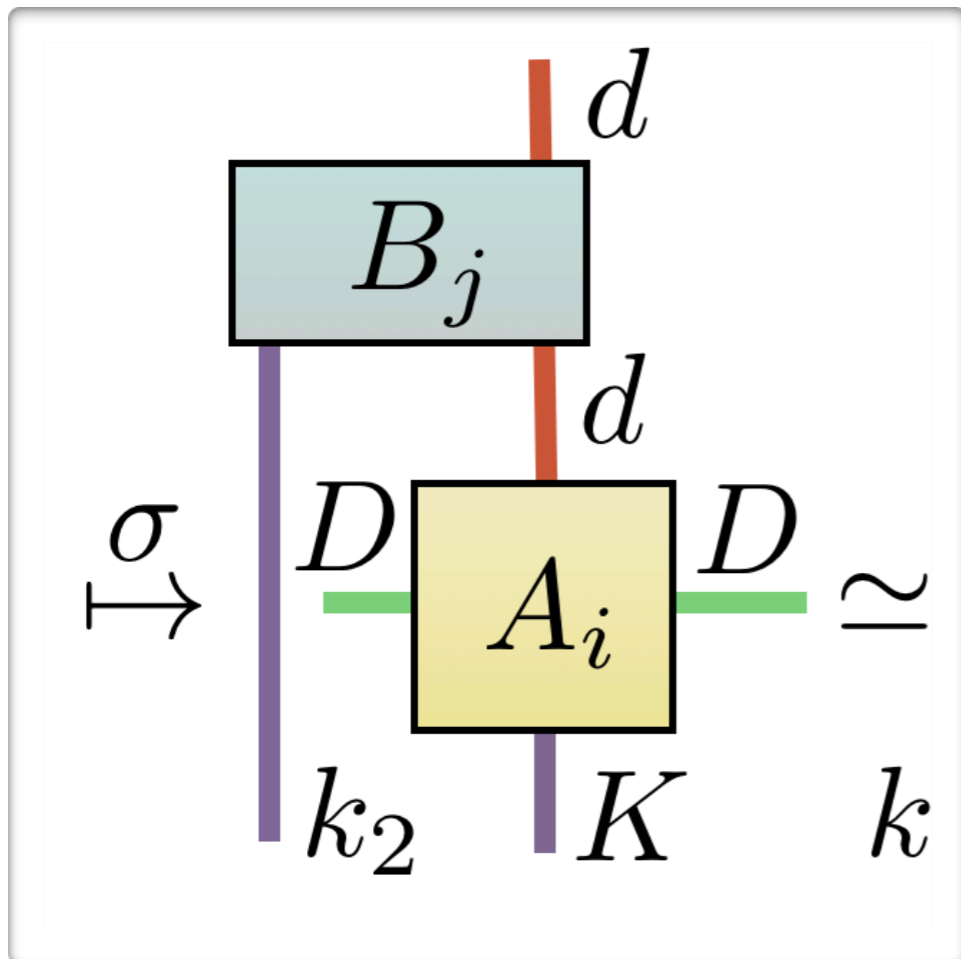


The New Quantum Era Podcast

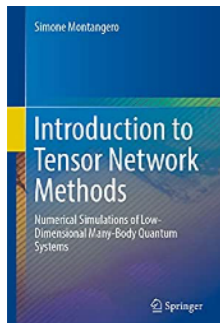


# TENSOR NETWORK ALGORITHMS

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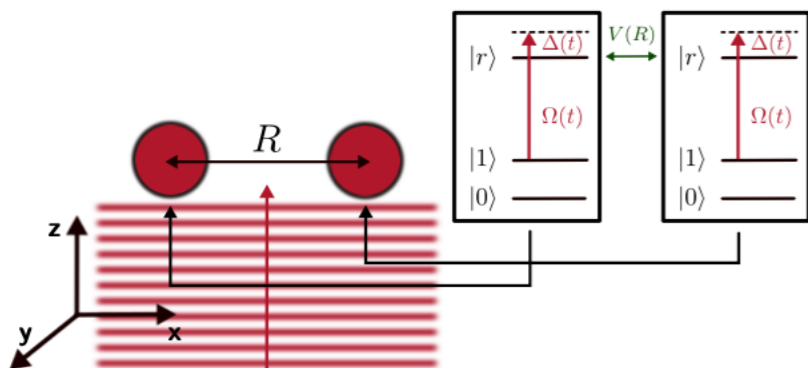
- *State of the art in 1D (poly effort)*
- *No sign problem*
- *Extended to open quantum systems*
- *Machine learning*
- *Data compression (BIG DATA)*
- *Extended to lattice gauge theories*
- *Simulations of low-entangled systems of hundreds qubits!*



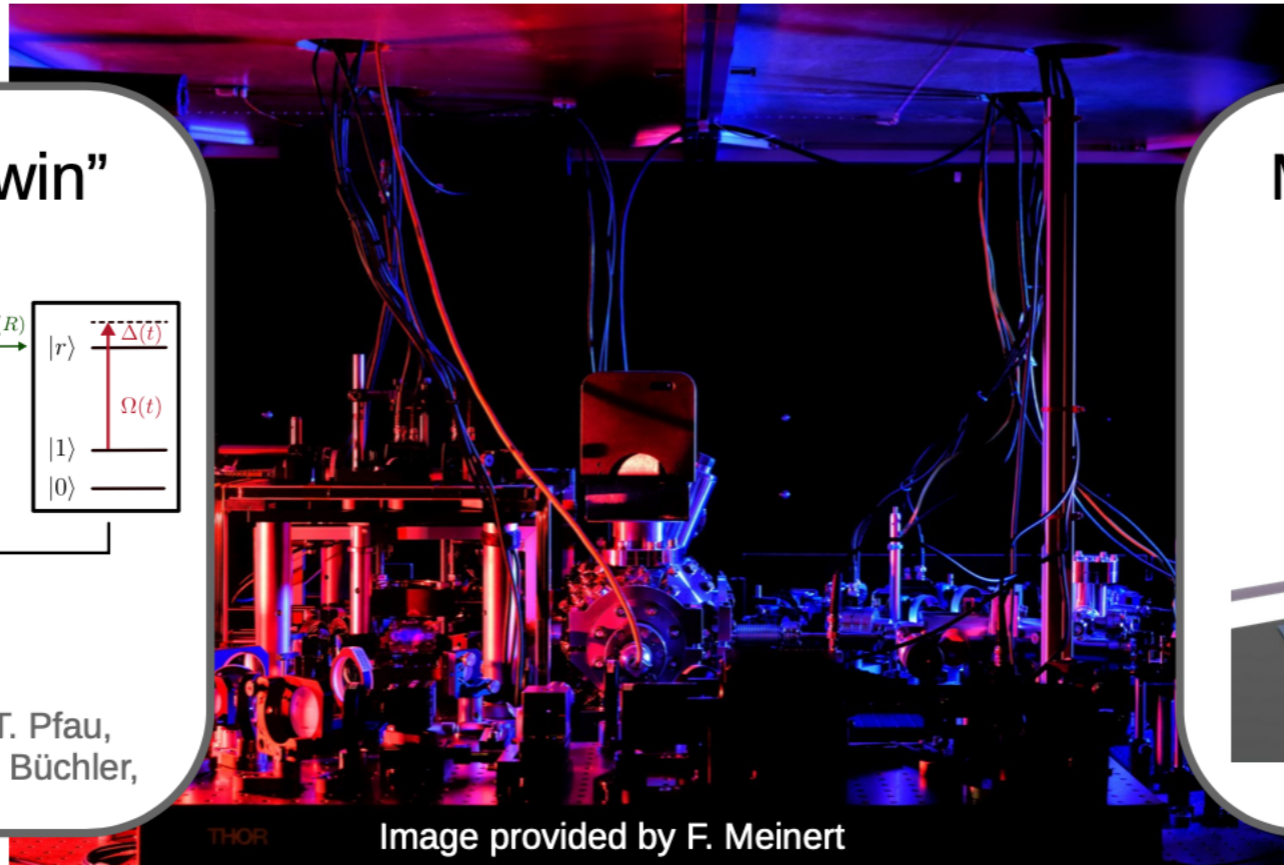
*“Introduction to tensor network methods”, S.Montangero, Springer (2019)*

# DIGITAL TWIN

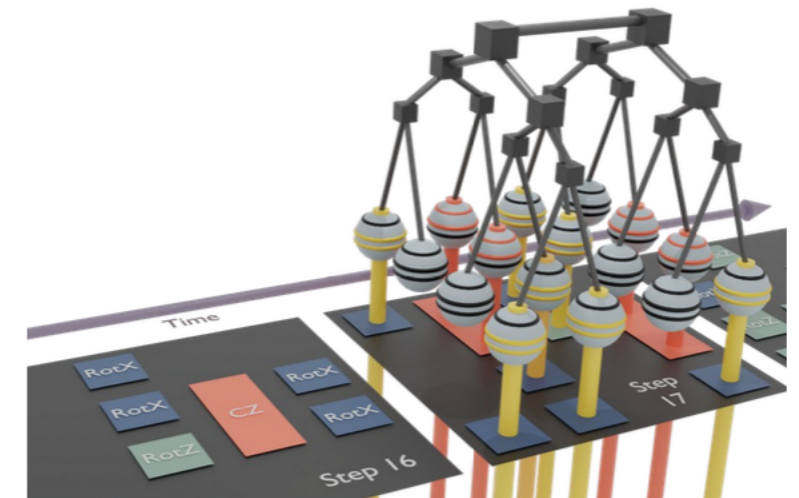
## Qubit-twin “digital twin”

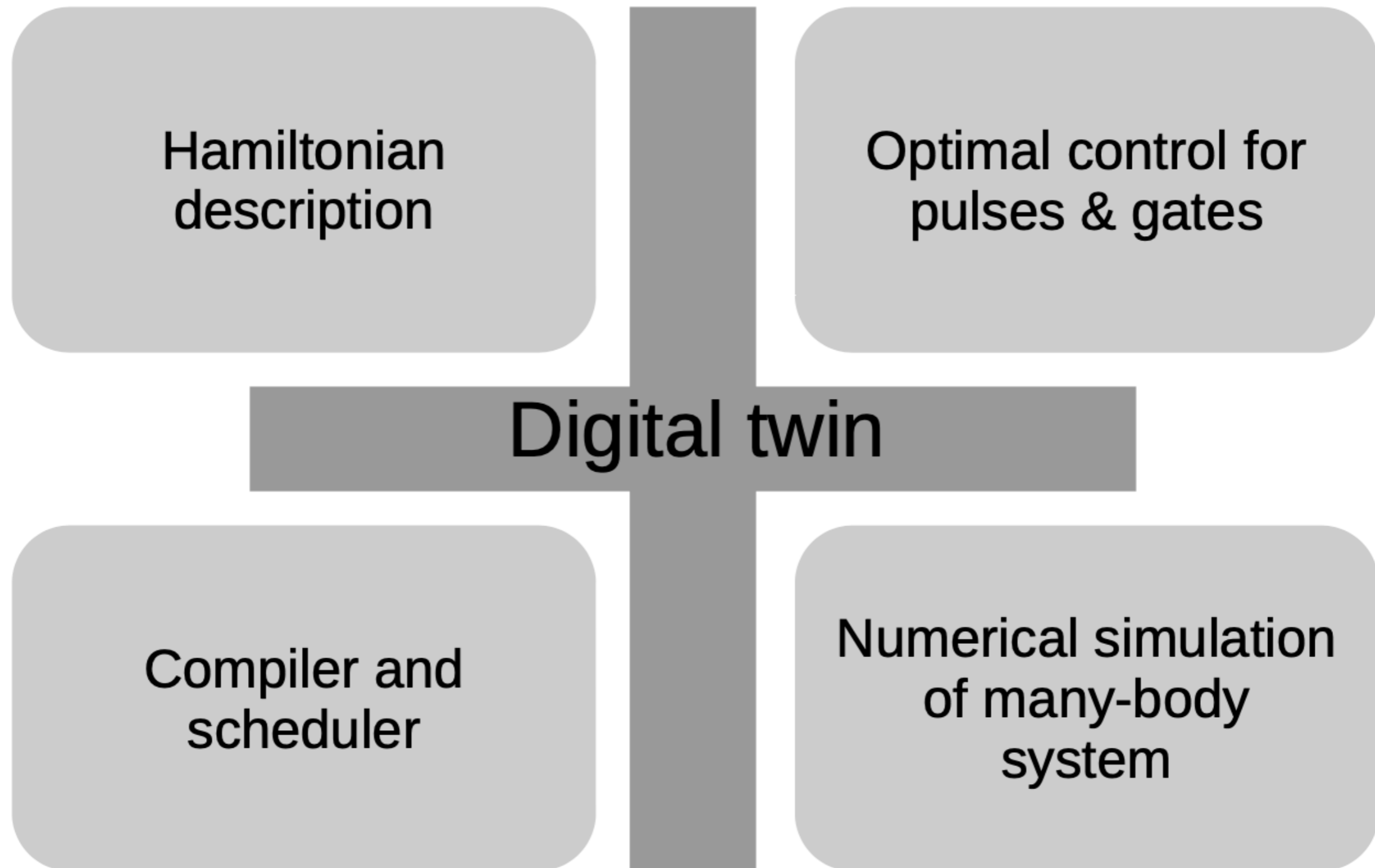


A. Pagano, S. Weber, D. Jaschke, T. Pfau,  
F. Meinert, S. Montangero, and H. P. Büchler,  
arXiv:2202.13849.



## Many-body digital twin?





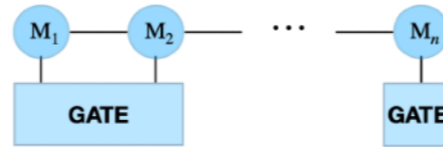


# QUANTUM COMPUTER EMULATORS

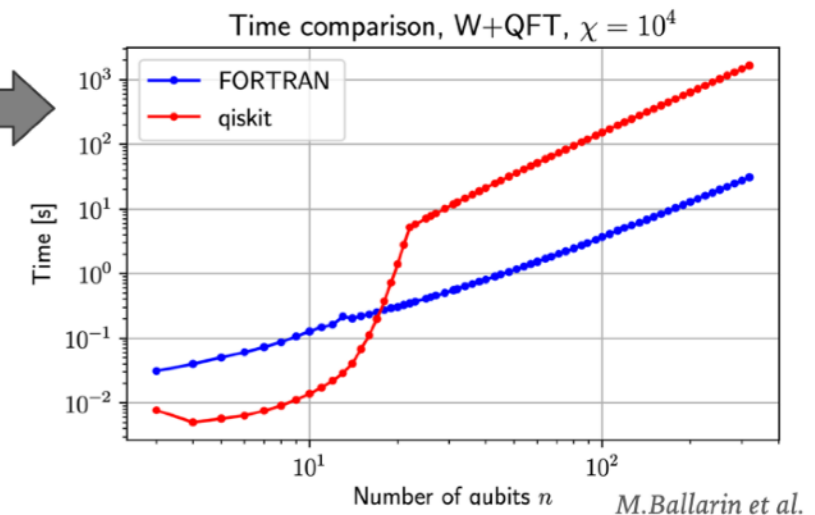
Quantum circuits

Quantum computing  
Platforms  
Superconducting,  
Trapped ions, or  
neutral atoms

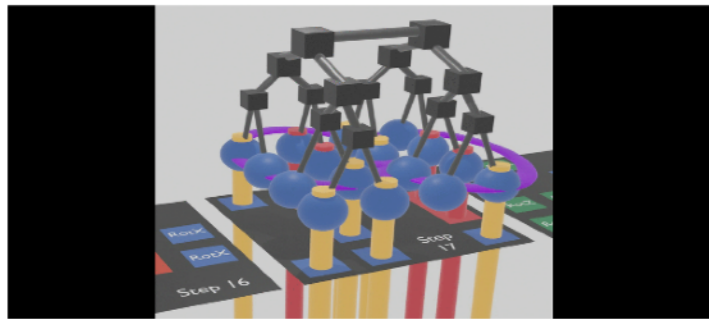
Quantum circuits emulator



- Quantum circuit as a tensor network
- Measurement of local observables
- Efficient sampling of the final state

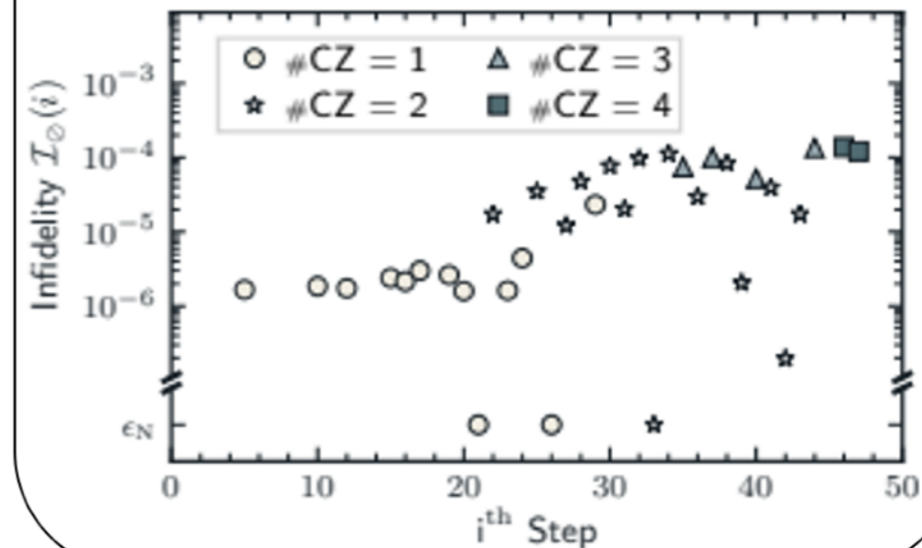


Digital twin approach



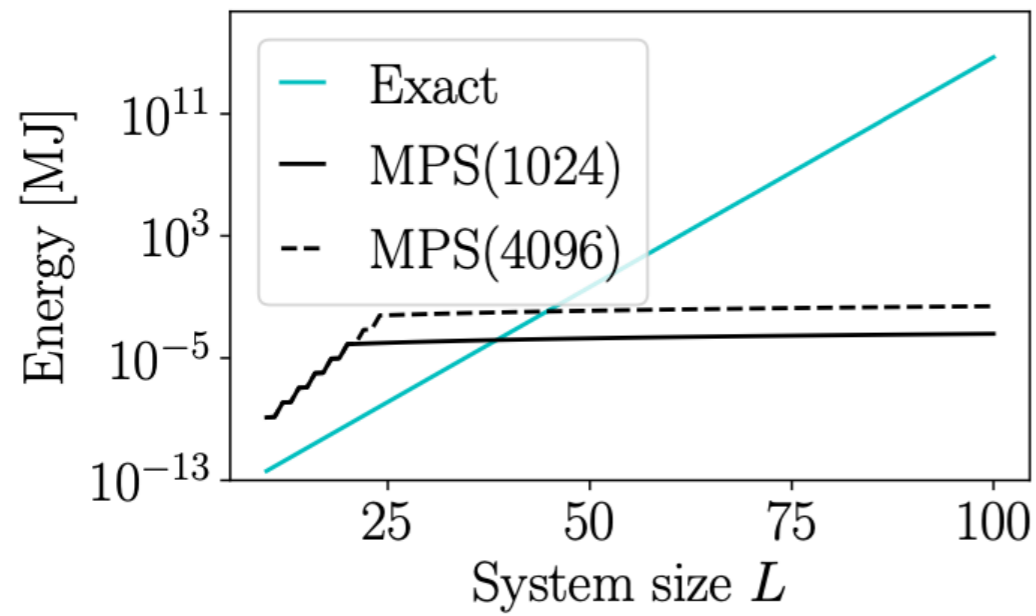
- 1) Up to 8x8 atoms
- 2) Schedule native gates
- 3) Gates as pulses
- 4) Study crosstalk
- 5) Run simulation

Comparison and resolve errors per  
step: GHZ state

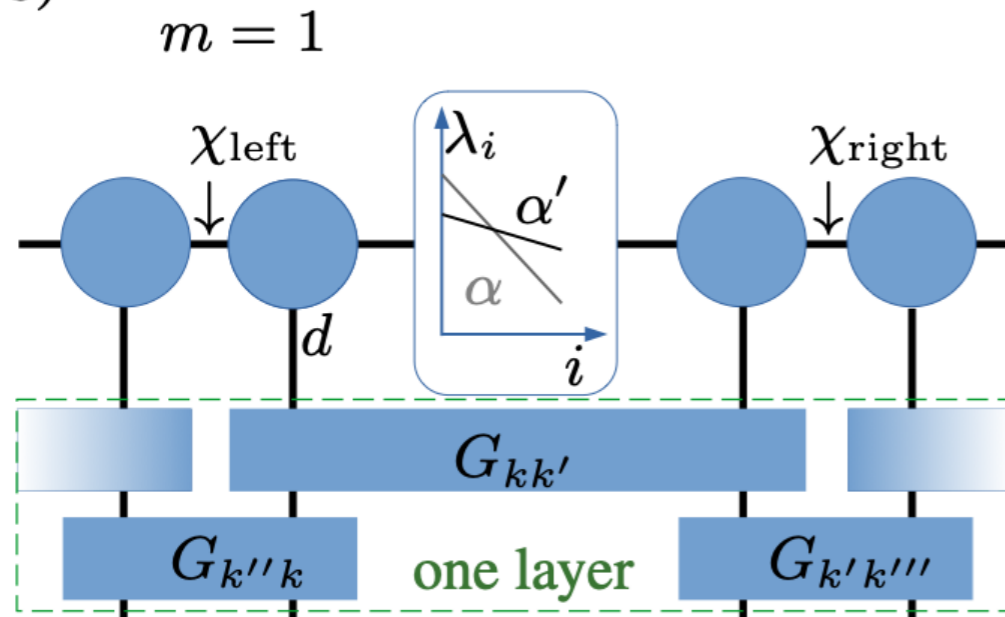


# GREEN QUANTUM ADVANTAGE

a)

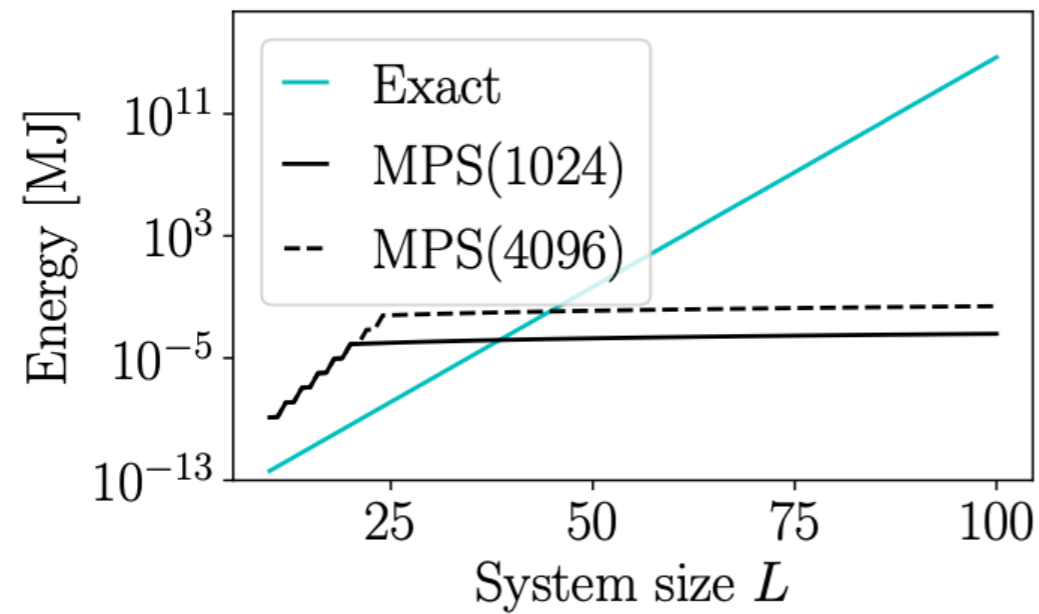


b)



# GREEN QUANTUM ADVANTAGE

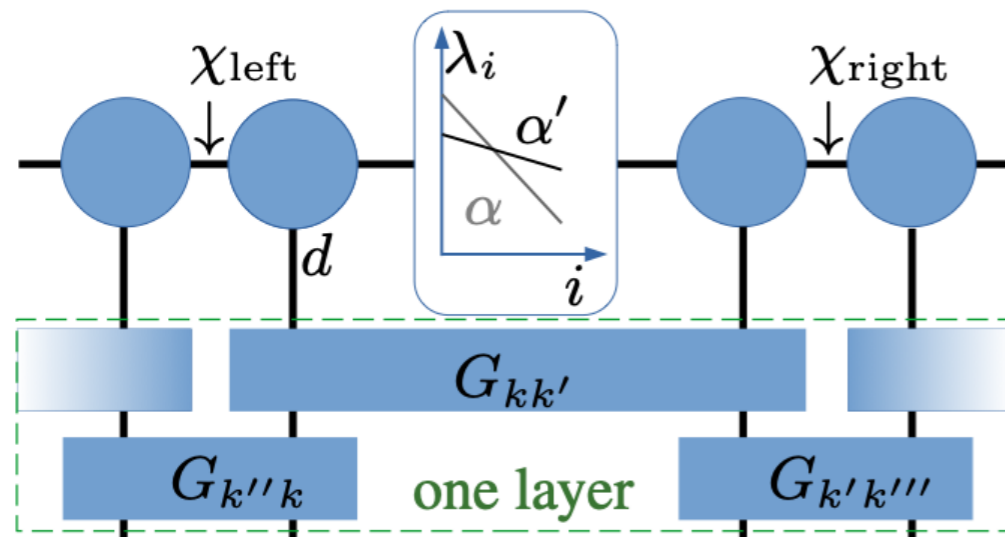
a)



*Equality of Fidelity and Energy Point (EFEP)*

b)

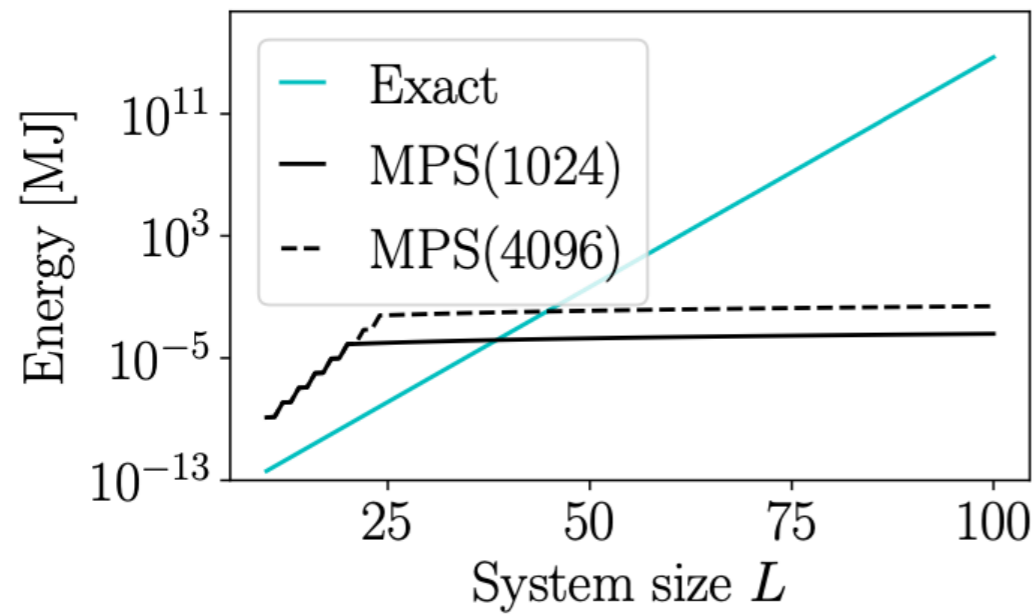
$$m = 1$$



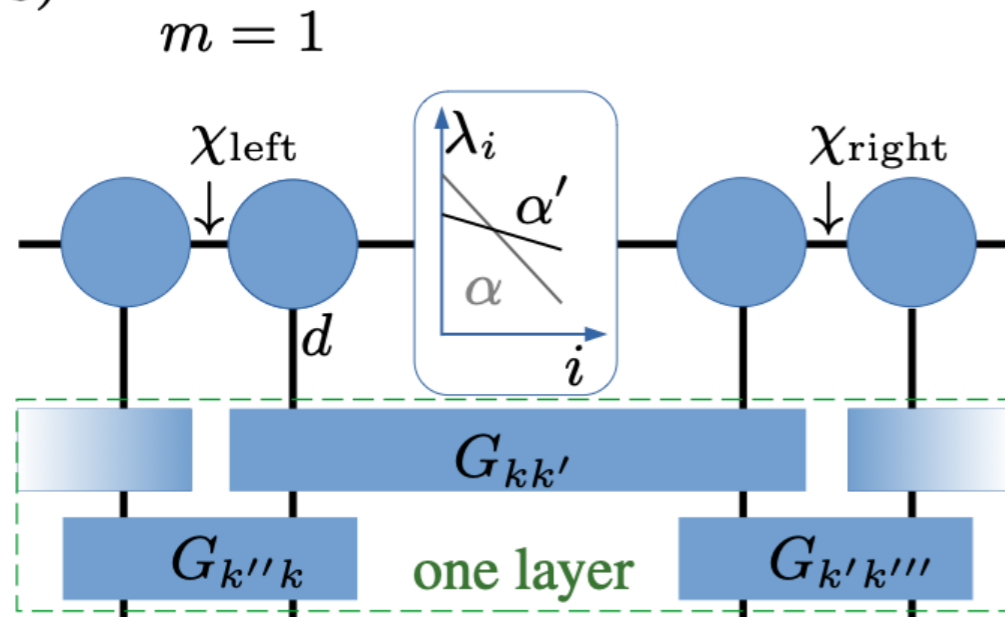


# GREEN QUANTUM ADVANTAGE

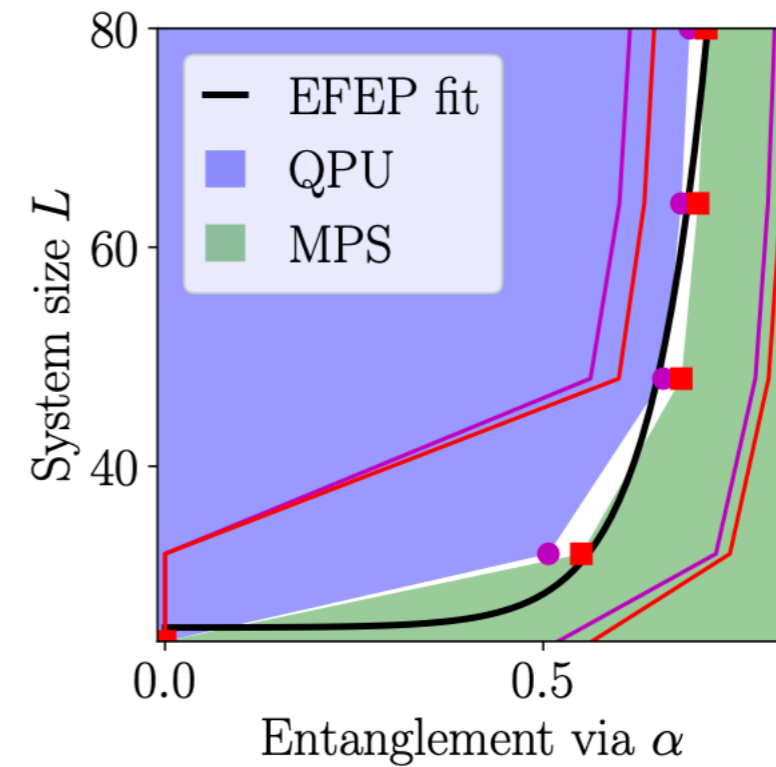
a)



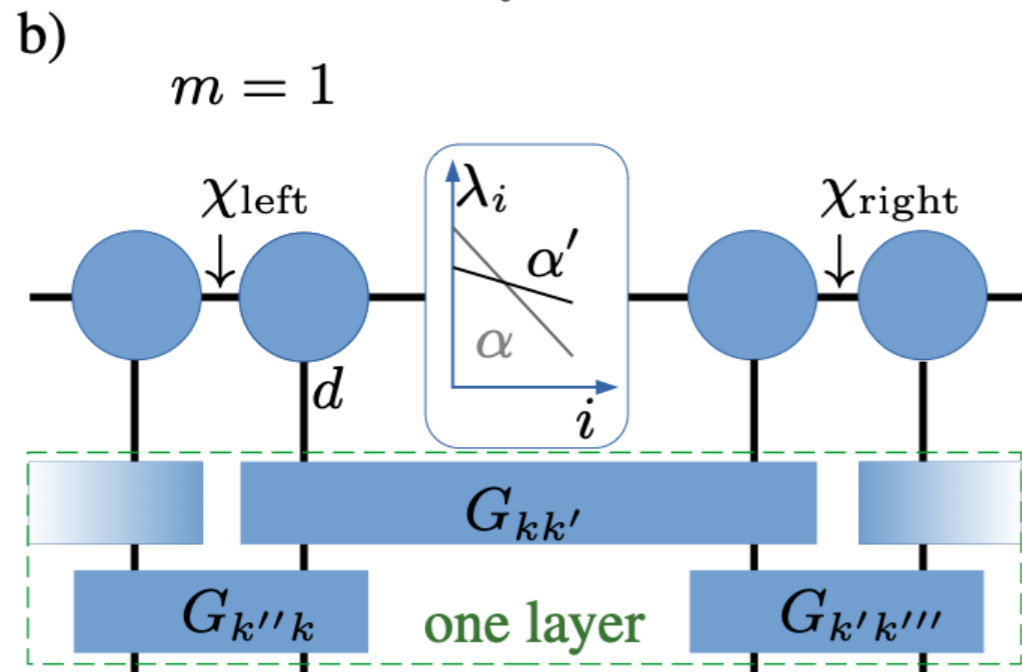
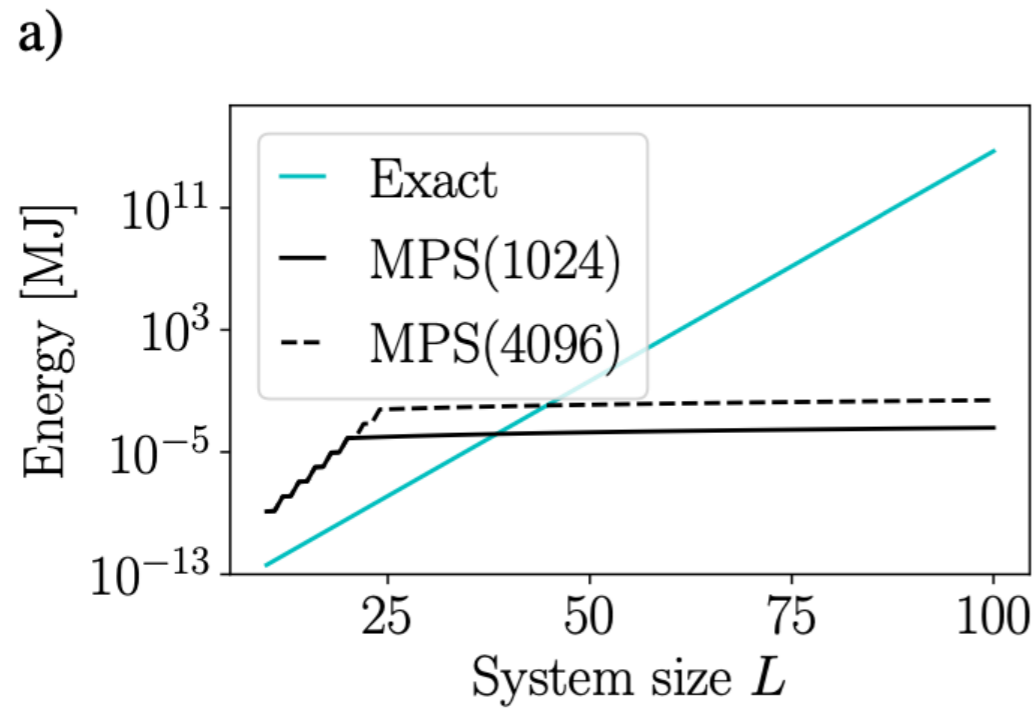
b)



*Equality of Fidelity and Energy Point (EFEP)*

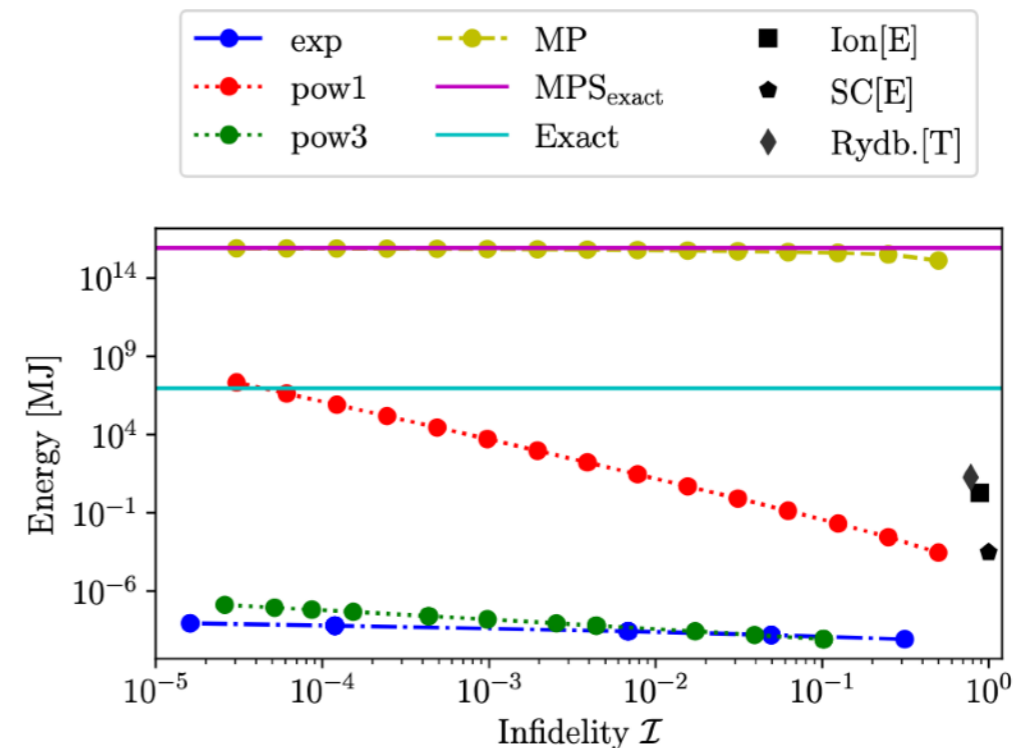
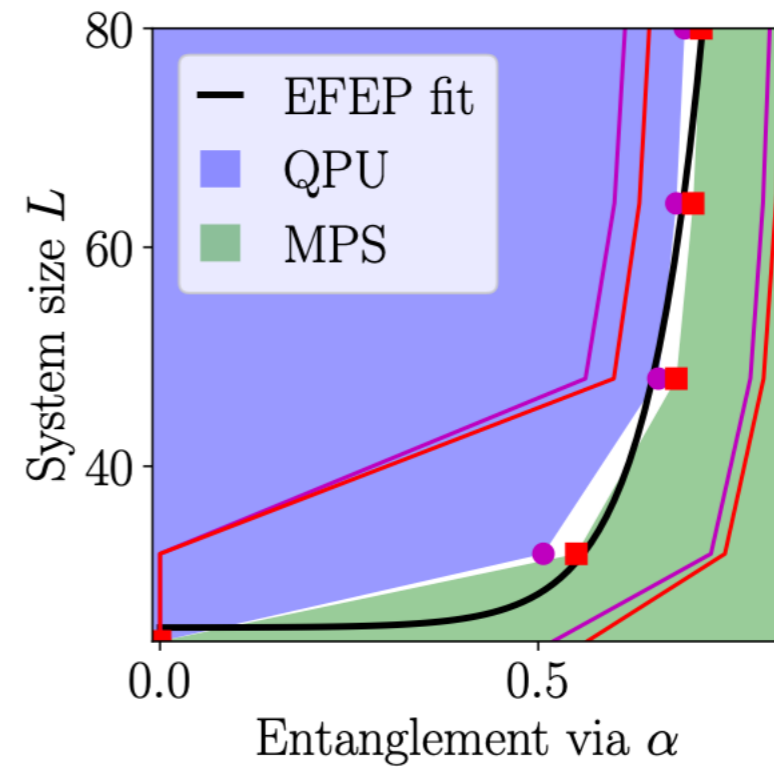


# GREEN QUANTUM ADVANTAGE



*D. Jaschke and SM arxiv:2205.12092*

## Equality of Fidelity and Energy Point (EFEP)



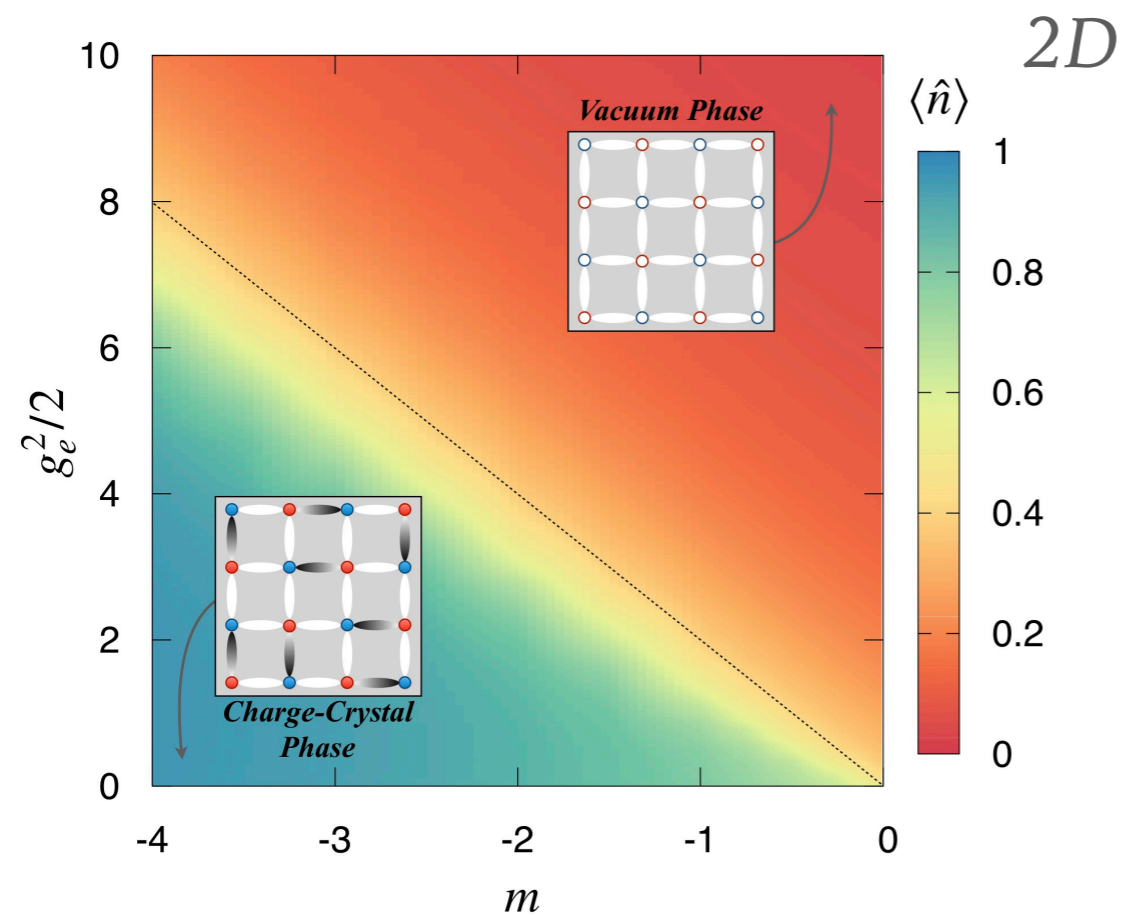
“

When do we really need a quantum simulation/computation?



# LGT AT FINITE DENSITY

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



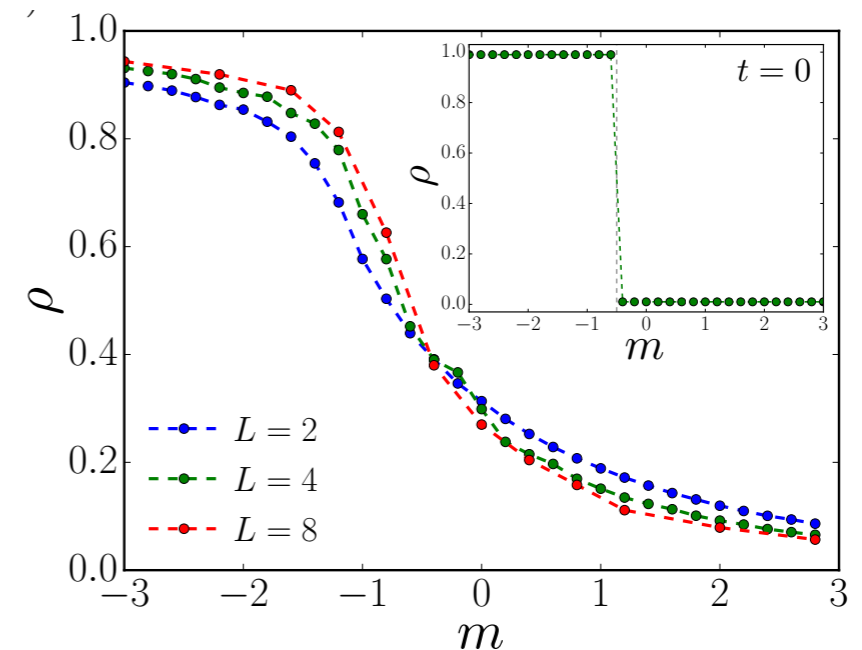
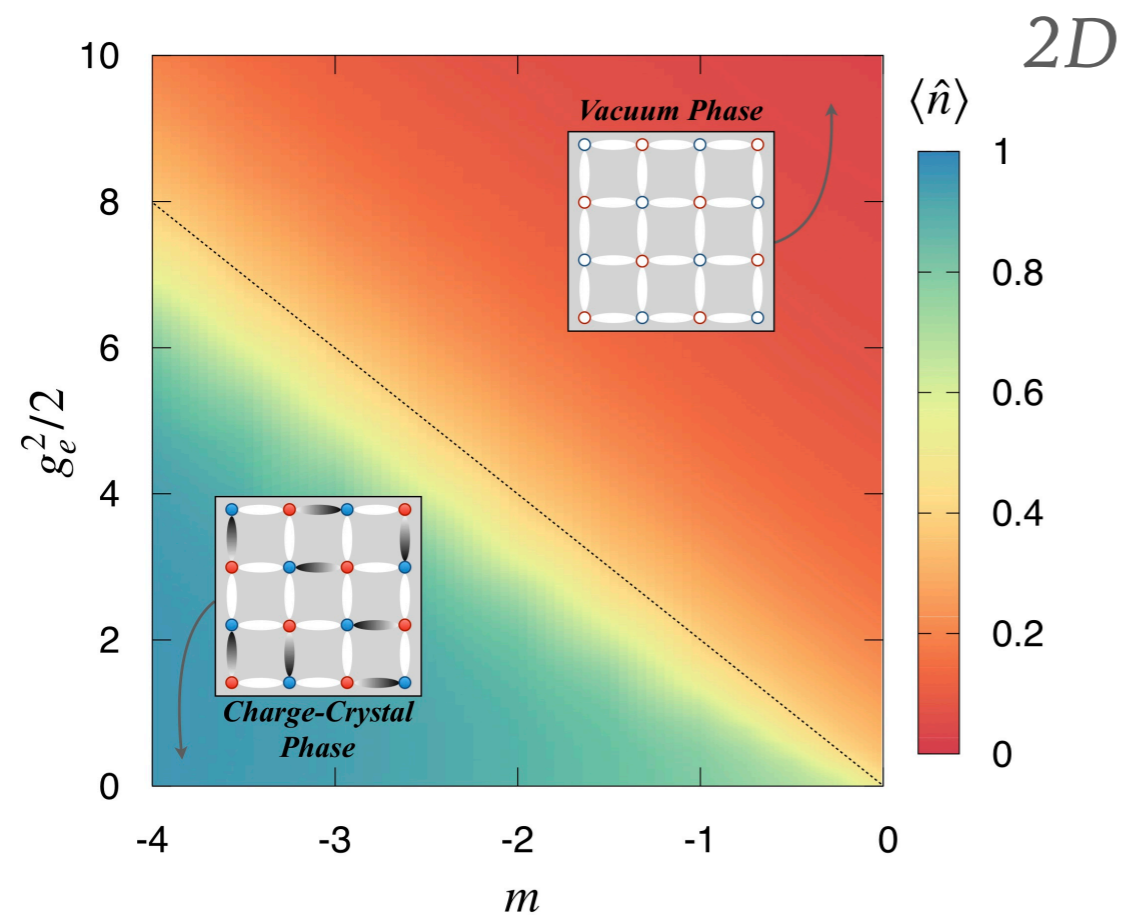
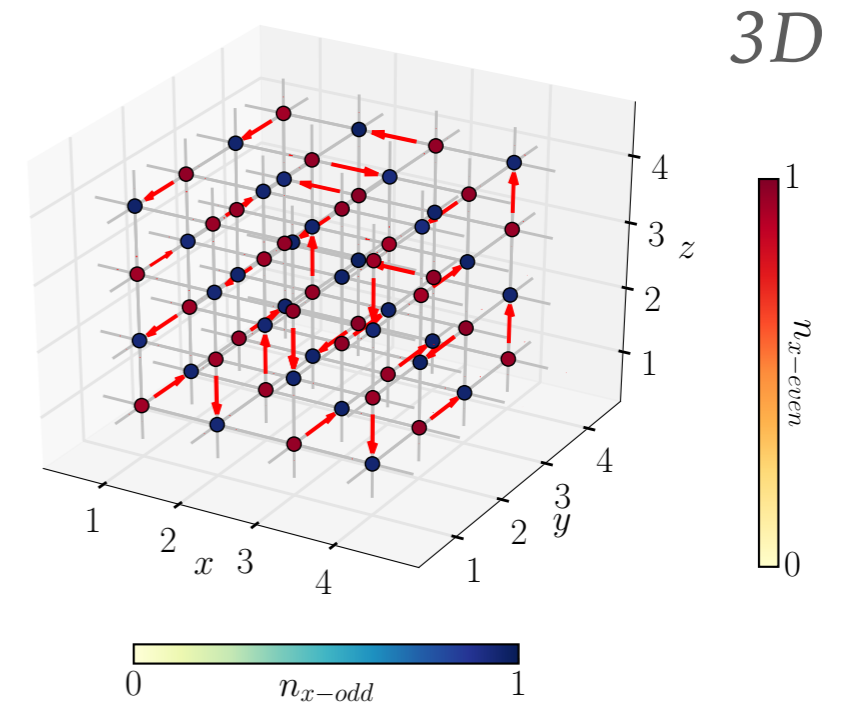
# LGT AT FINITE DENSITY

Hilbert space of

200Kb QRAM

~64x64x64 qubits!

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

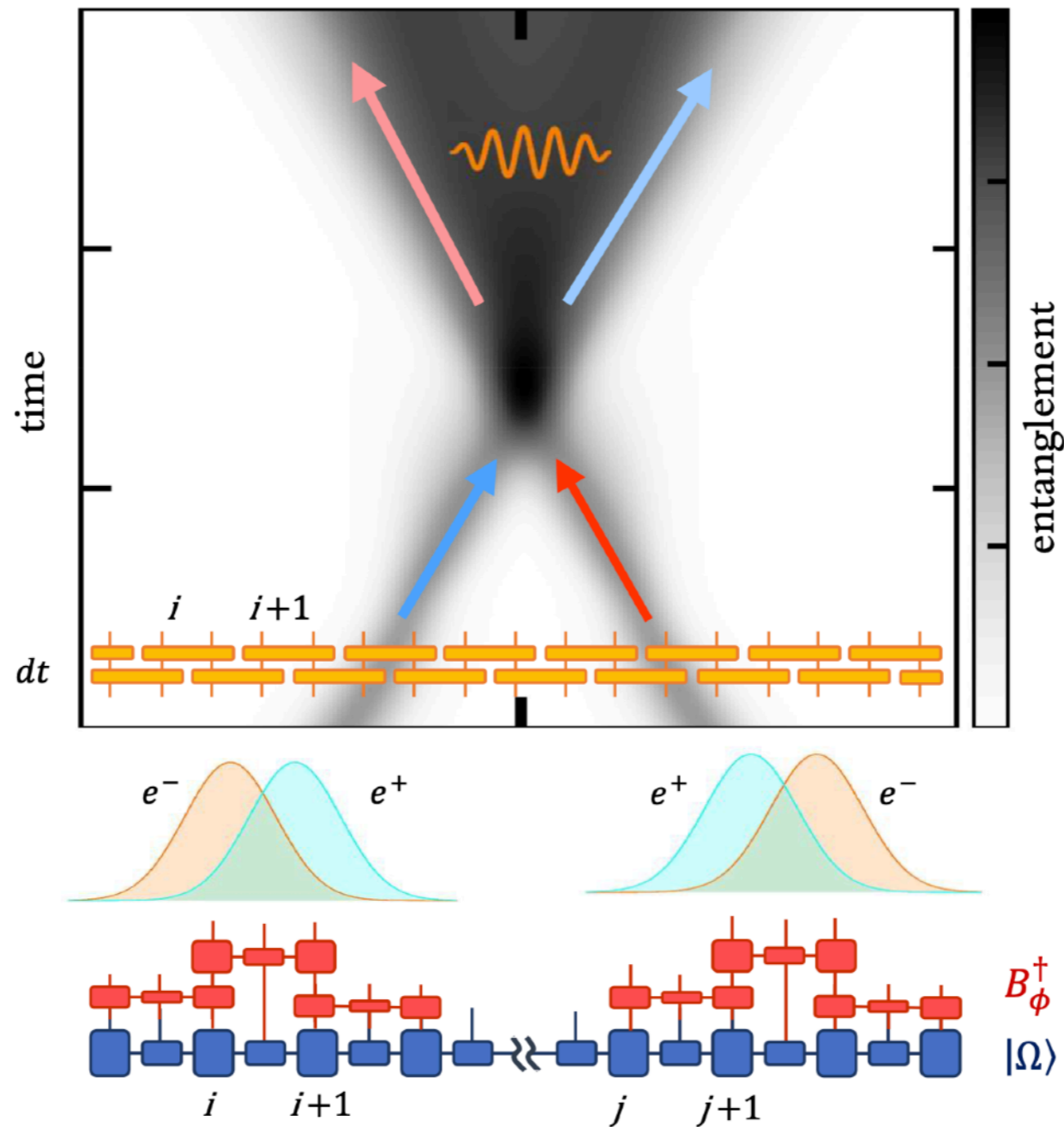


PRX (2020)

Nature Comm. (2021)

# ENTANGLEMENT GENERATION IN QED SCATTERING PROCESSES

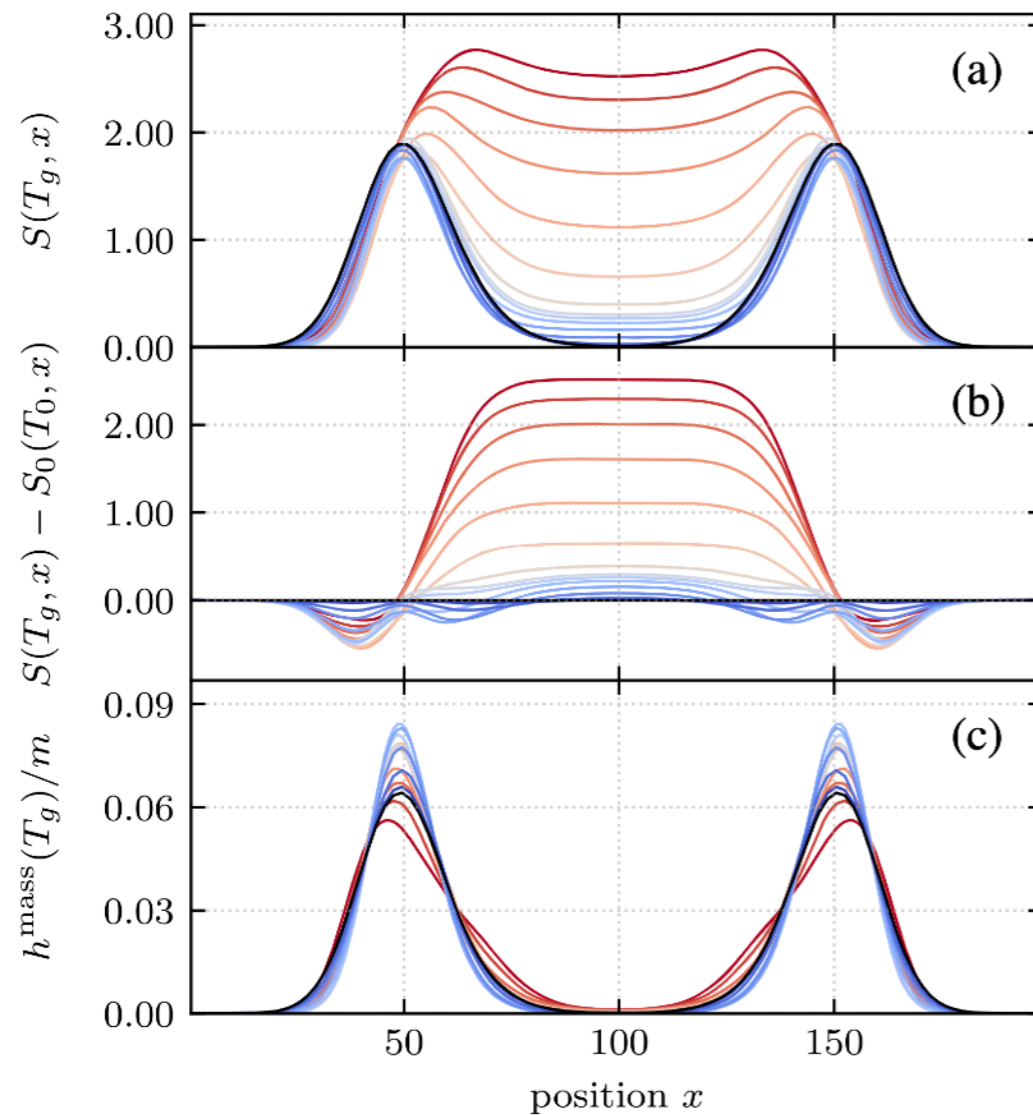
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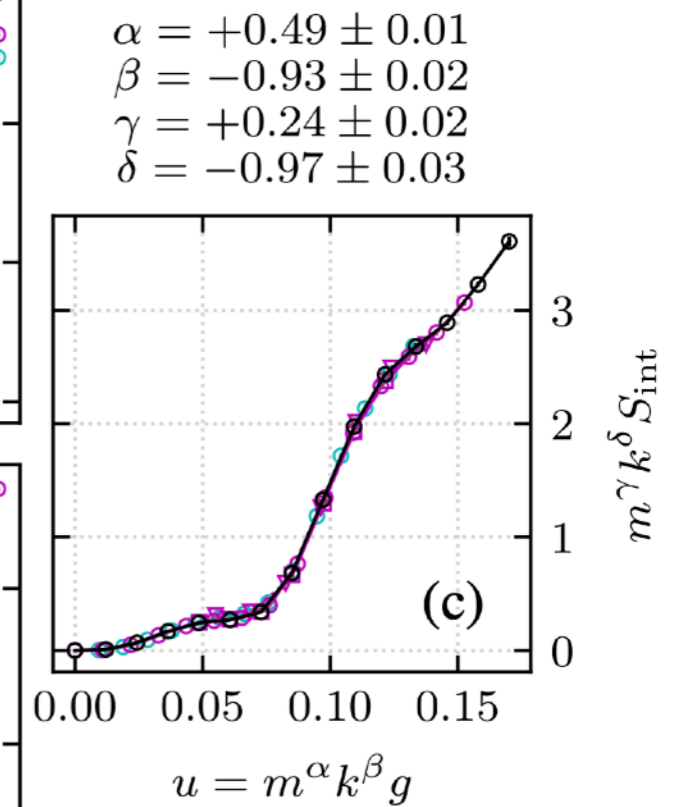
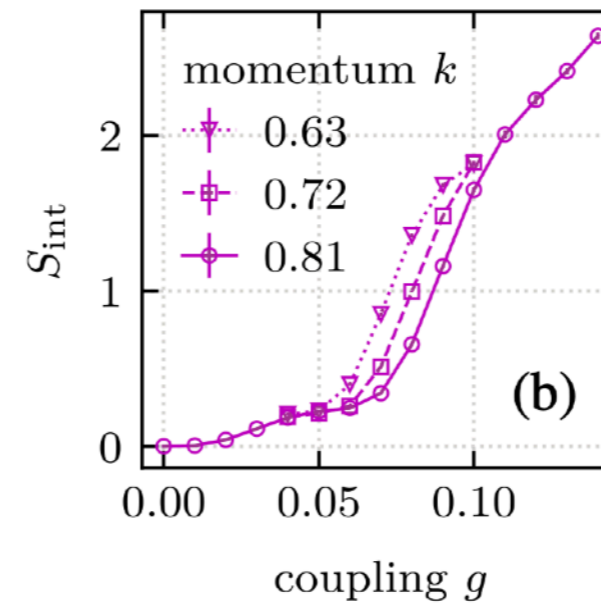
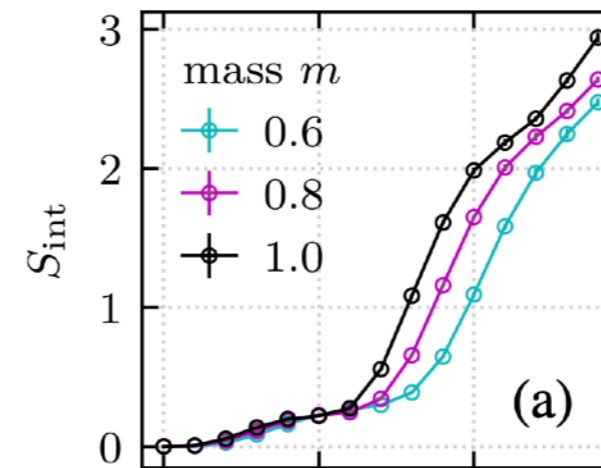
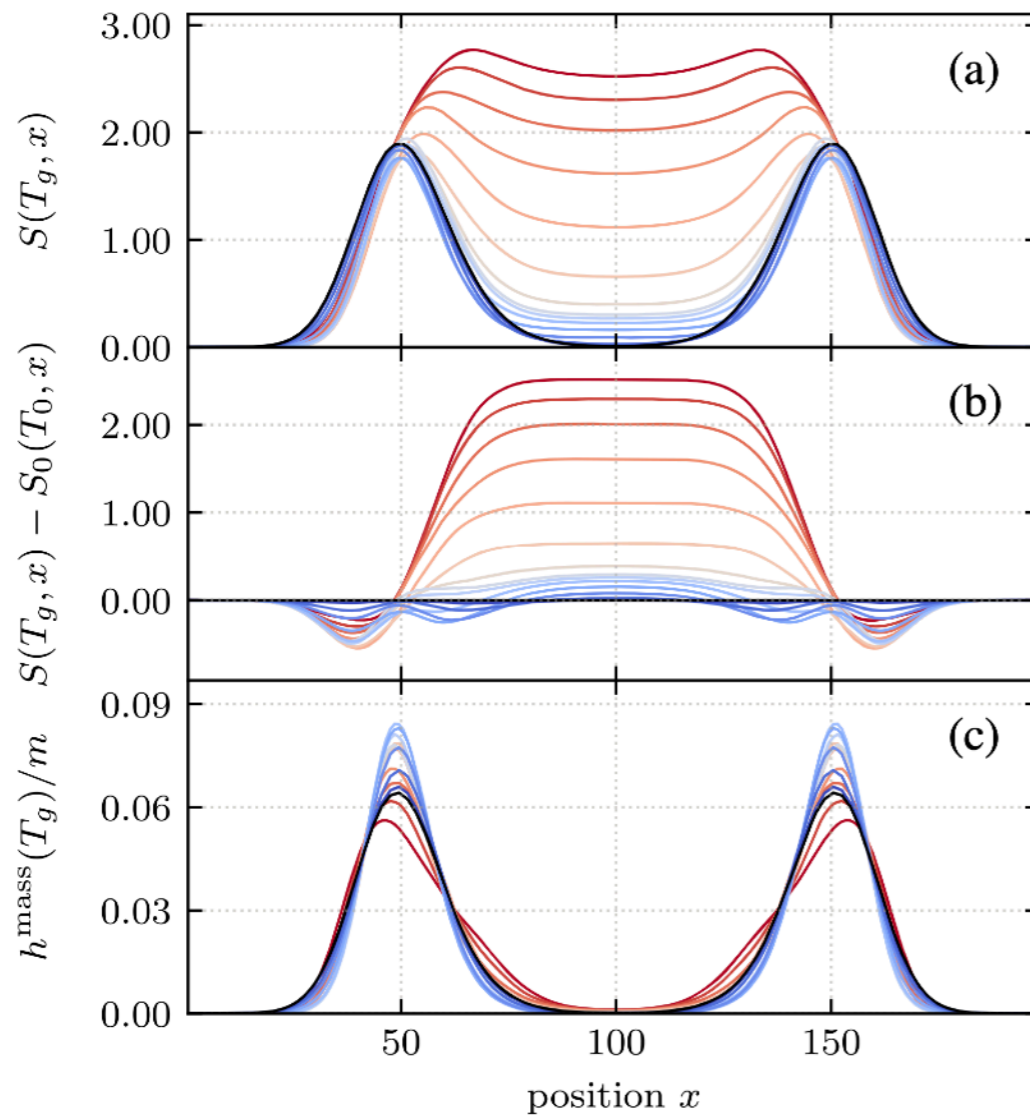


# ENTANGLEMENT GENERATION IN QED SCATTERING PROCESSES

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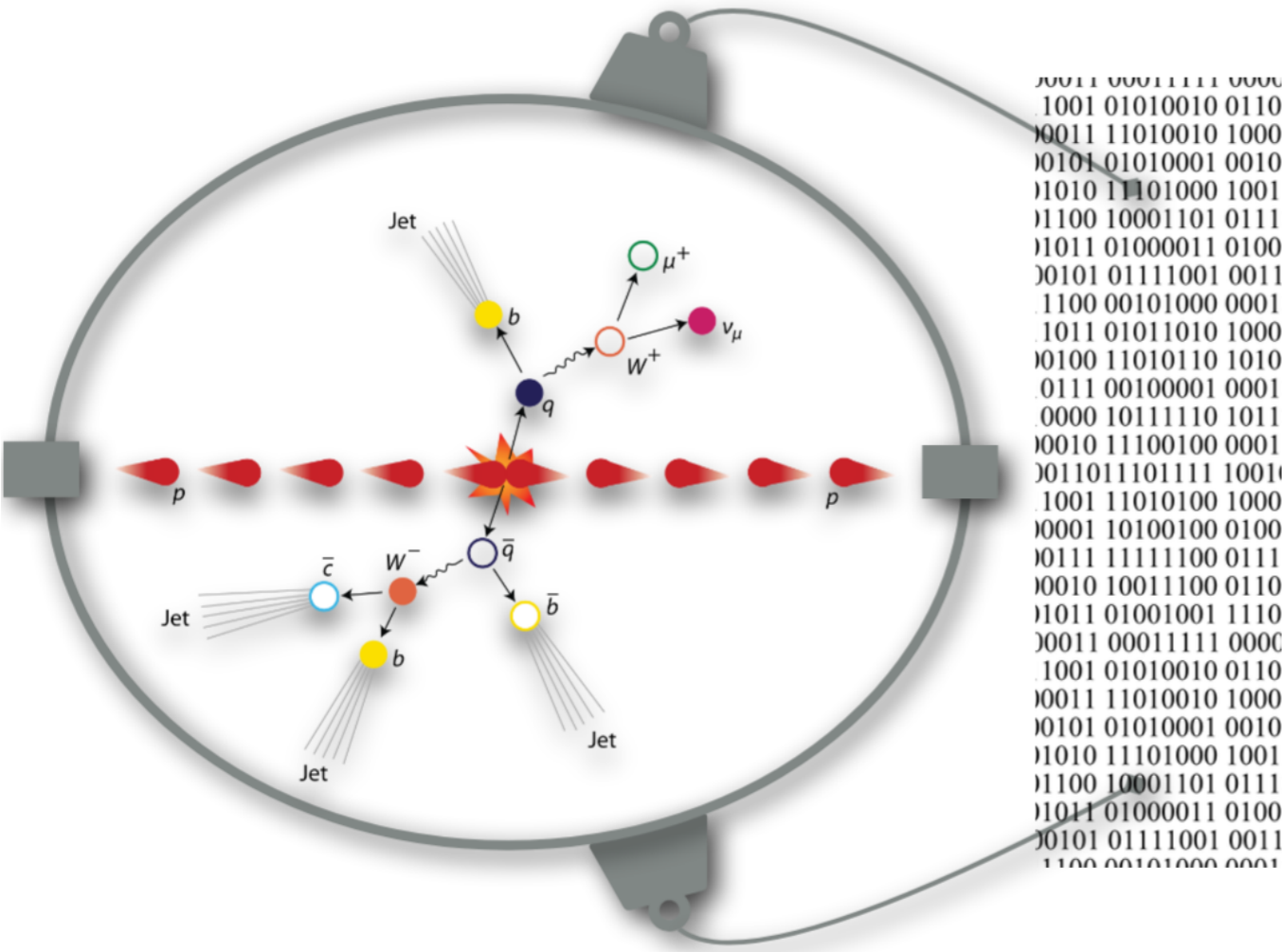


# ENTANGLEMENT GENERATION IN QED SCATTERING PROCESSES



*Universal Scaling Relation?*

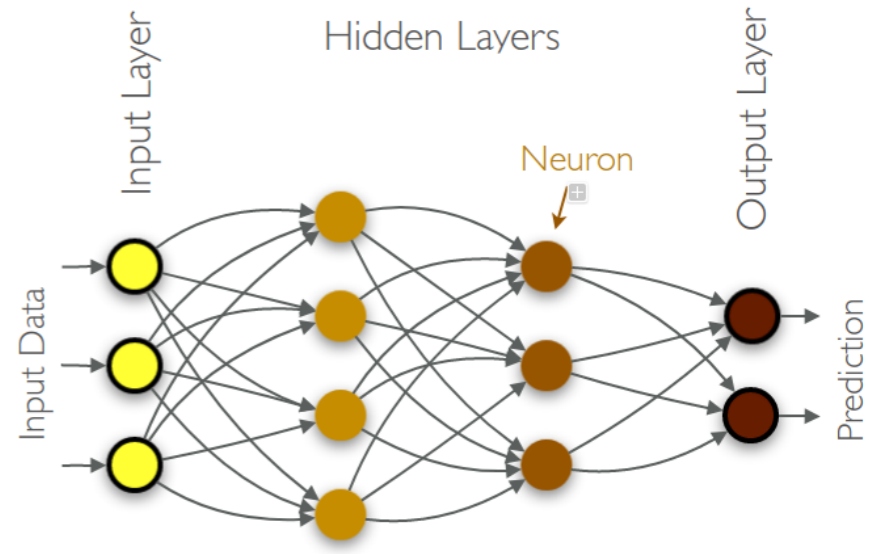
# TENSOR NETWORK MACHINE LEARNING



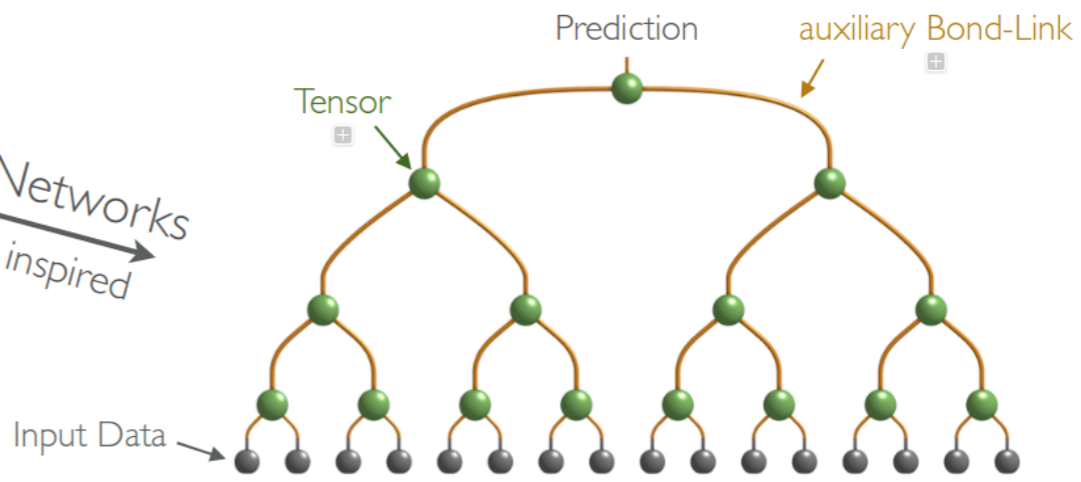
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0011 11010010 1000
0101 01010001 0010
11010 11101000 1001
1100 10001101 0111
11011 01000011 0100
0101 01111001 0011
1100 00101000 0001
1011 01011010 1000
0100 11010110 1010
0111 00100001 0001
0000 10111110 1011
0010 11100100 0001
011011101111 1001
1001 11010100 1000
0001 10100100 0100
0111 11111100 0111
0010 10011100 0110
11011 01001001 1110
0011 00011111 0000
1001 01010010 0110
0011 11010010 1000
0101 01010001 0010
11010 11101000 1001
1100 10001101 0111
11011 01000011 0100
0101 01111001 0011
1100 00101000 0001
    
```

Neural Network  
 biologic inspired

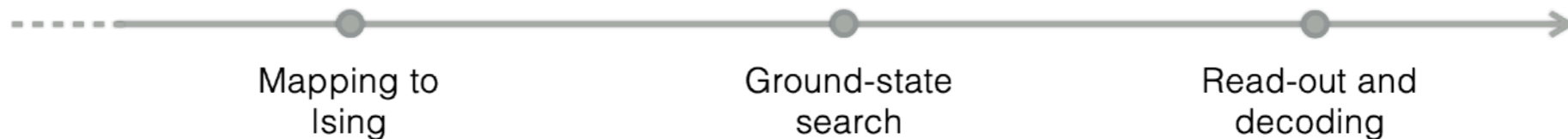
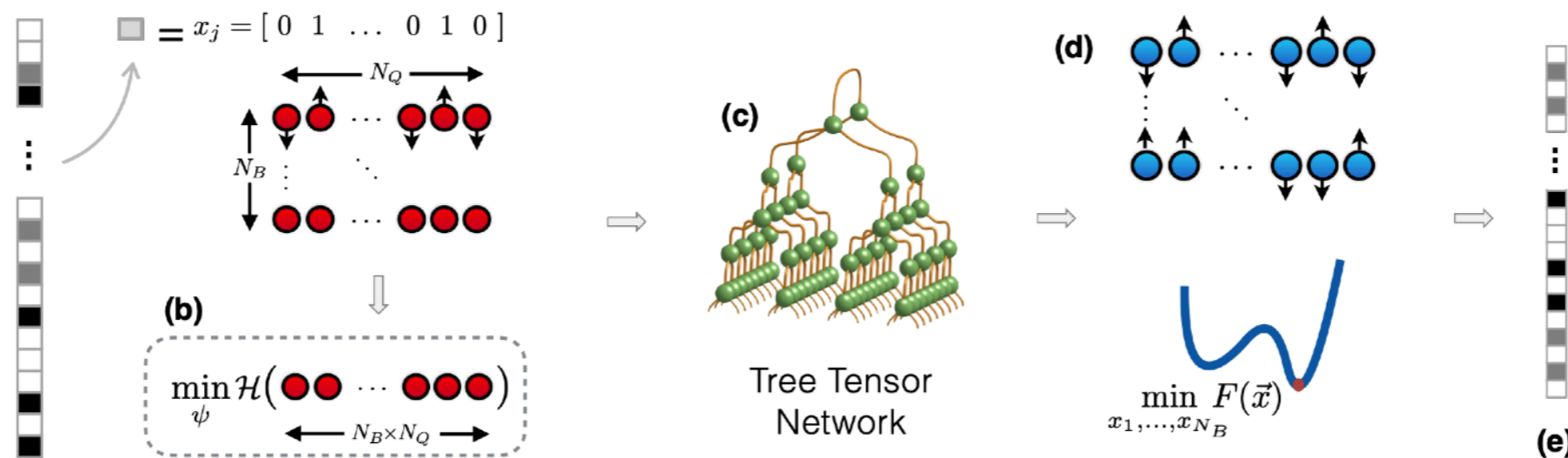
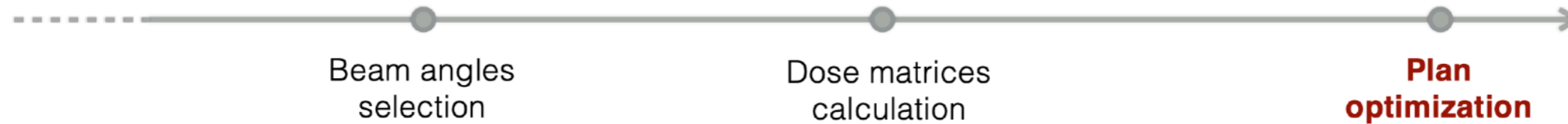
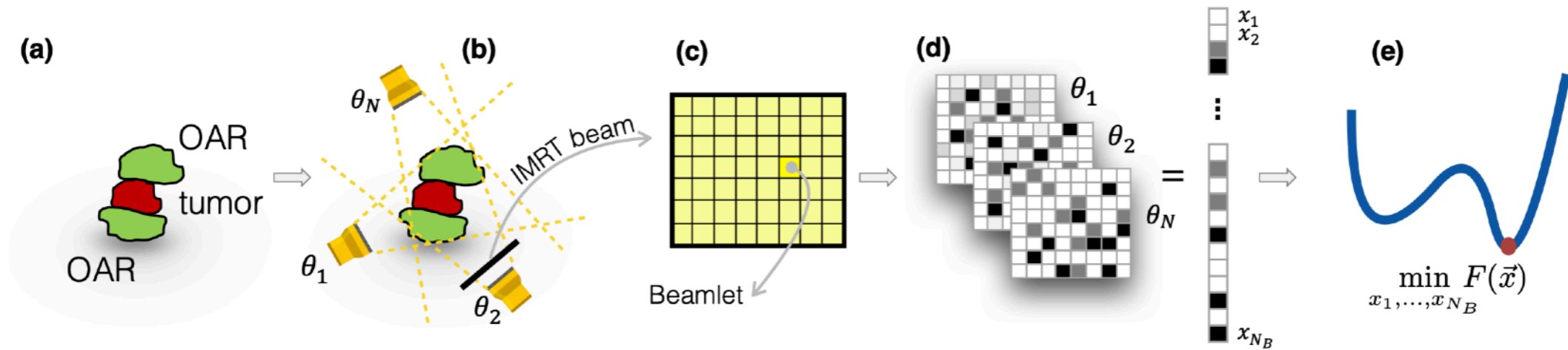


Tensor Networks  
 quantum inspired





# RADIOTHERAPY PLAN OPTIMIZATION



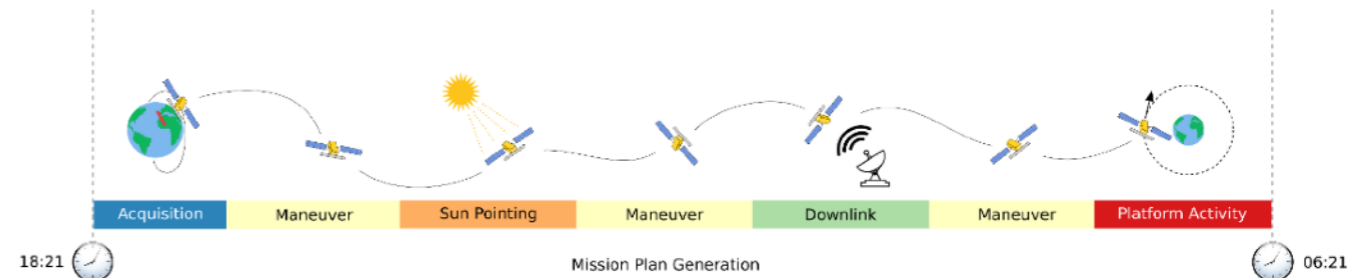
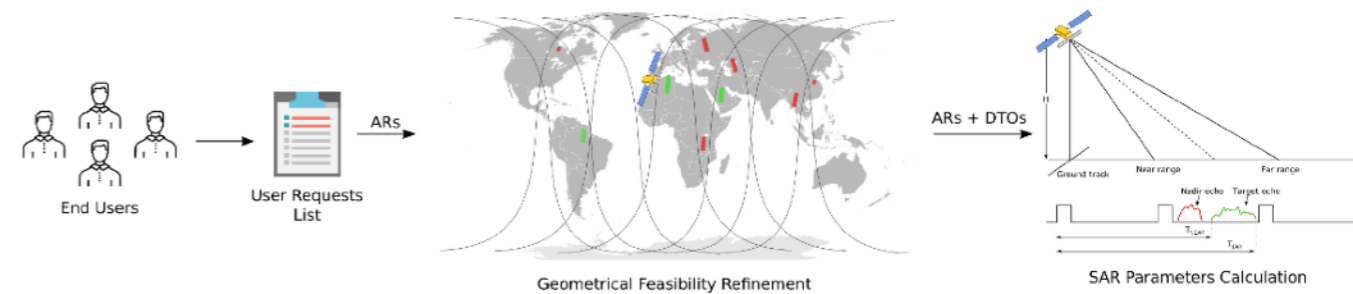
# INDUSTRY APPLICATIONS



Agenzia Spaziale Italiana

Hard optimization problems

## Mission planning for earth observation



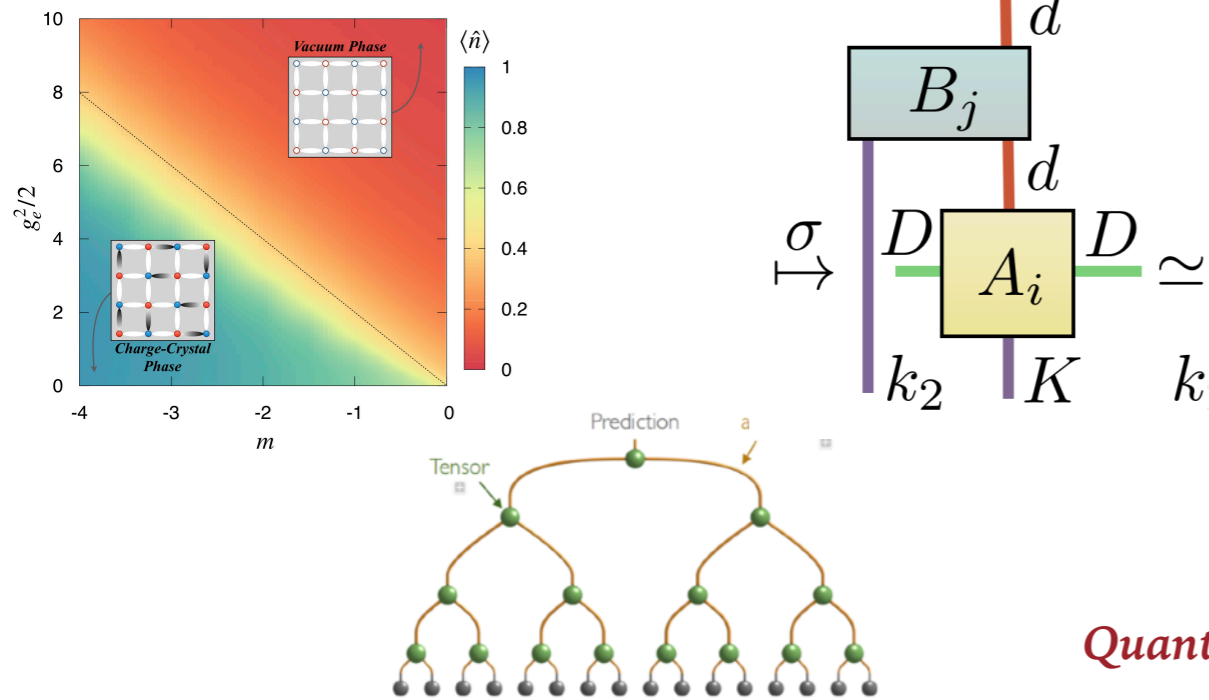
combinatorial optimization (Knapsack problem)

from single satellite to constellations

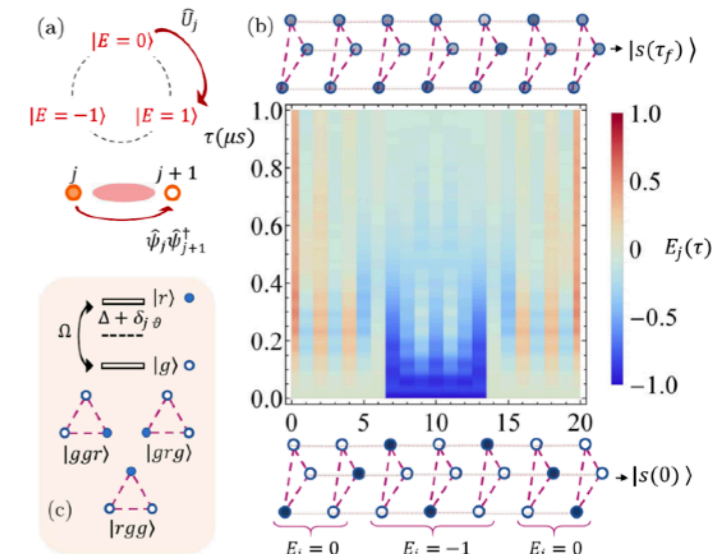
- Identification of use cases in the field of mission planning
- Estimate (hybrid) QPU-specs for realistic problems

# RESEARCH LINES

## Classical simulations and methods

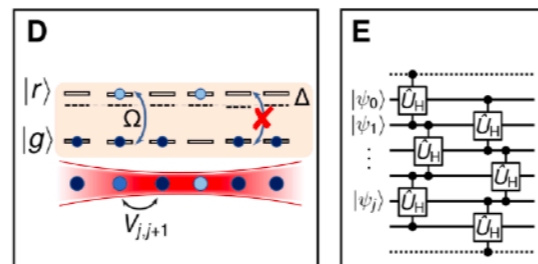
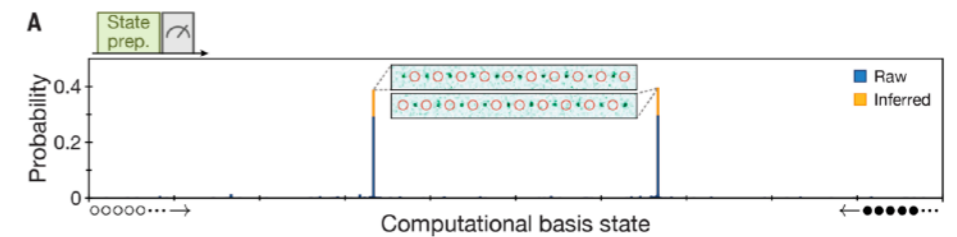
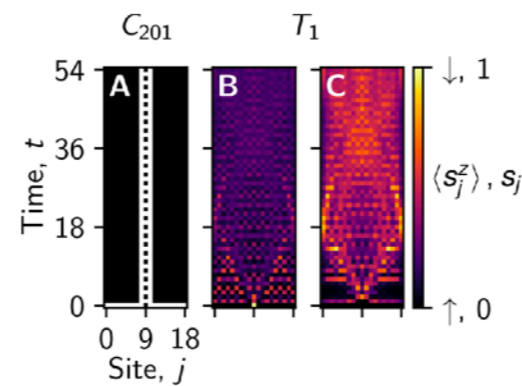
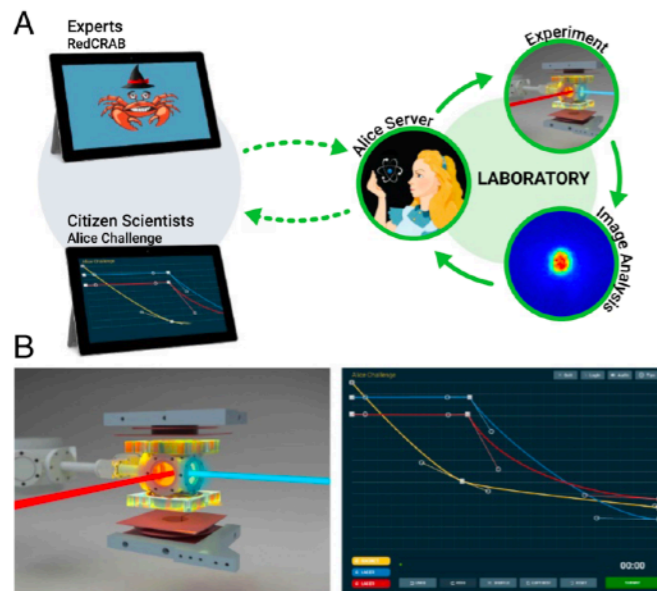


## Theoretical development and analysis



## Quantum computer emulation

## Experiment benchmarking, support and optimisation



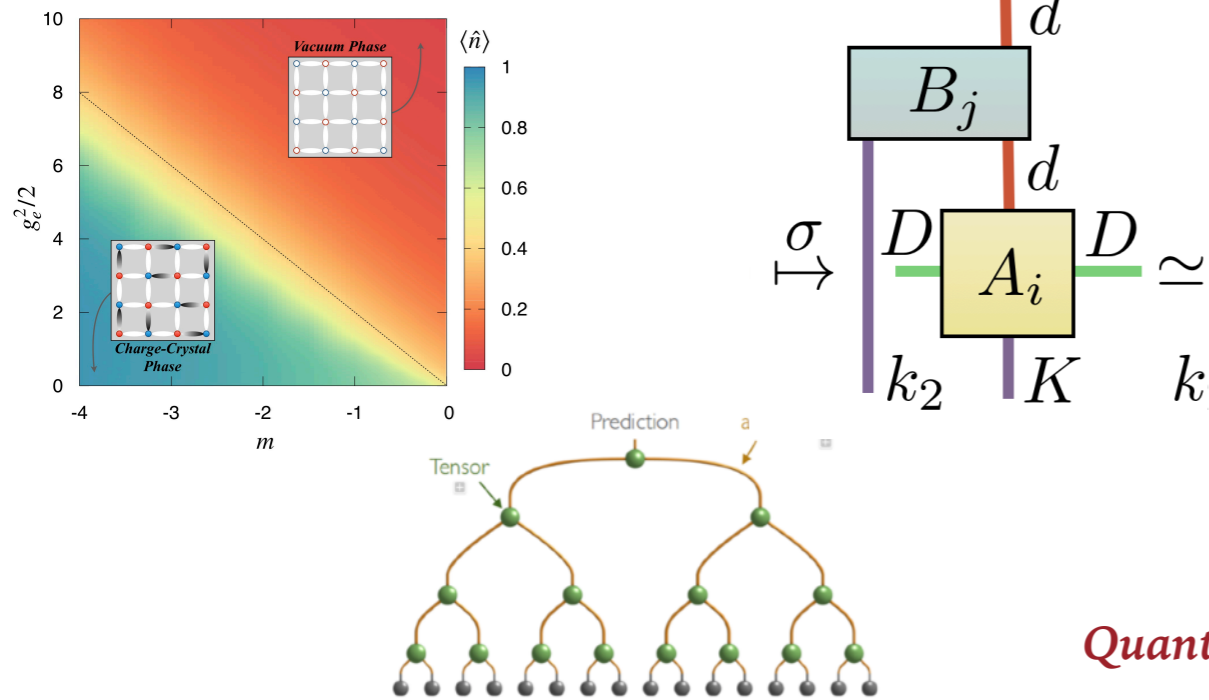
Science

Generation and manipulation of Schrödinger cat states in Rydberg atom arrays

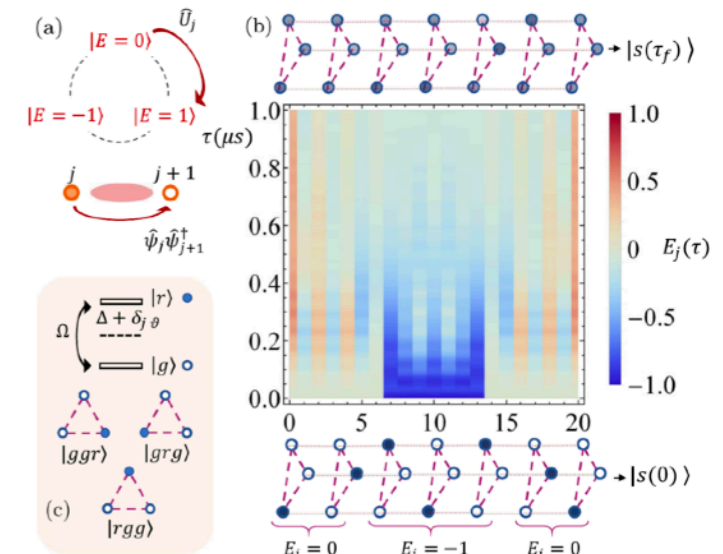
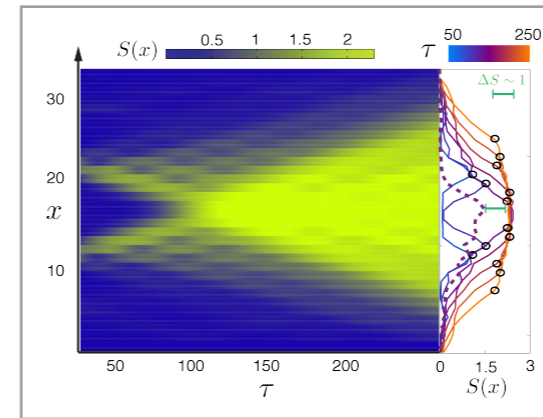
Remote optimization of an ultracold atoms experiment by experts and citizen scientists

# RESEARCH LINES

## Classical simulations and methods

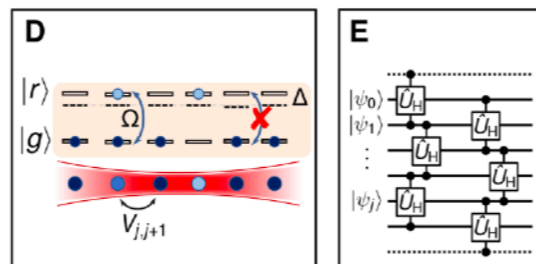
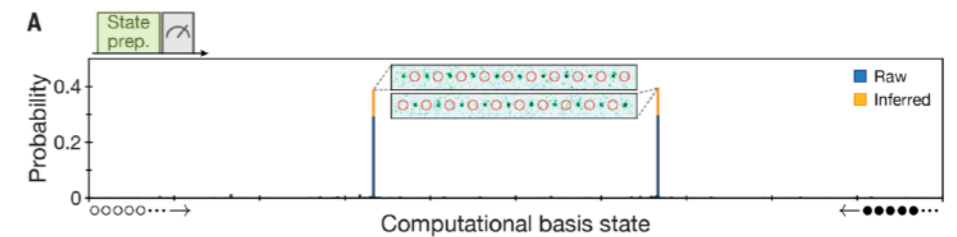
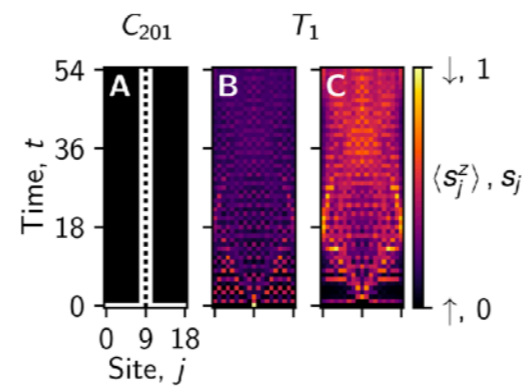
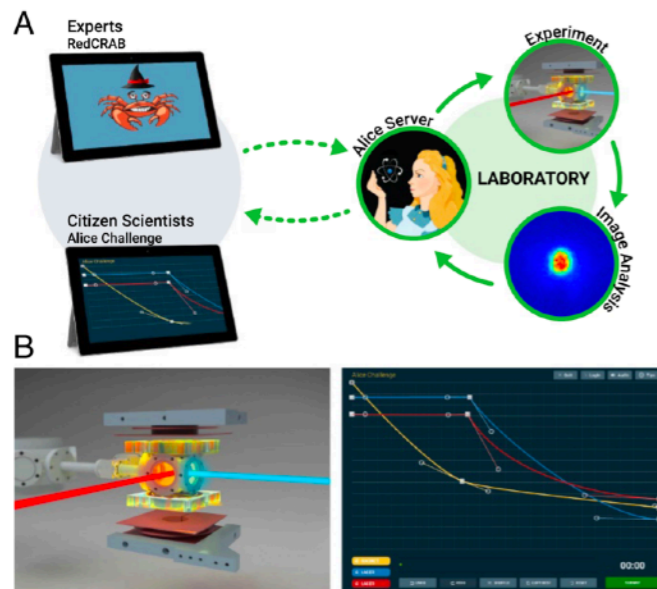


## Theoretical development and analysis



## Quantum computer emulation

## Experiment benchmarking, support and optimisation



Science

Generation and manipulation of Schrödinger cat states in Rydberg atom arrays

Remote optimization of an ultracold atoms experiment by experts and citizen scientists



# CONCLUSIONS

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  - Quantum sensing
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# Thank you for your attention!

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