



Quantum Algorithms for Distributed Quantum Computing

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Quantum Algorithm R&D division

AQADOC++ Scientific Day

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Outline

Distributed Quantum Computing

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Distributed Quantum Computing

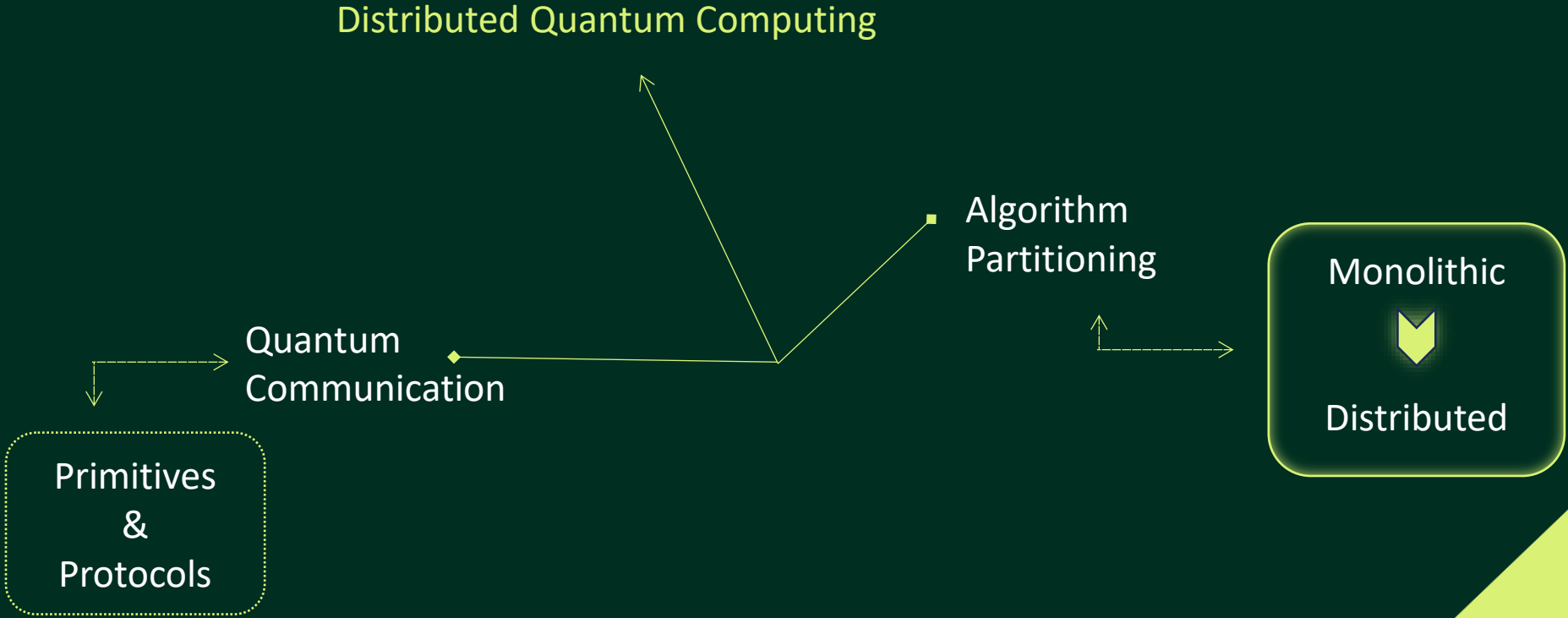
Algorithm
Partitioning

Monolithic

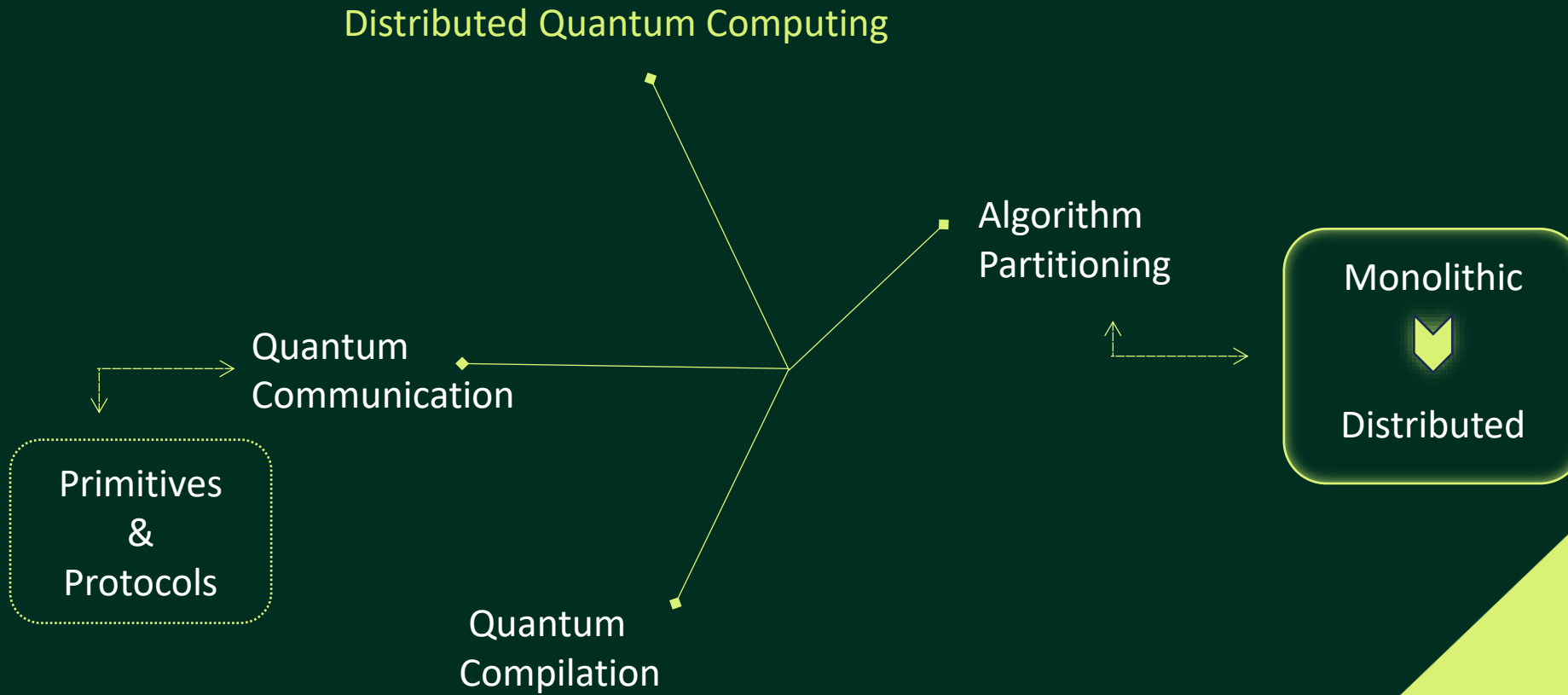


Distributed

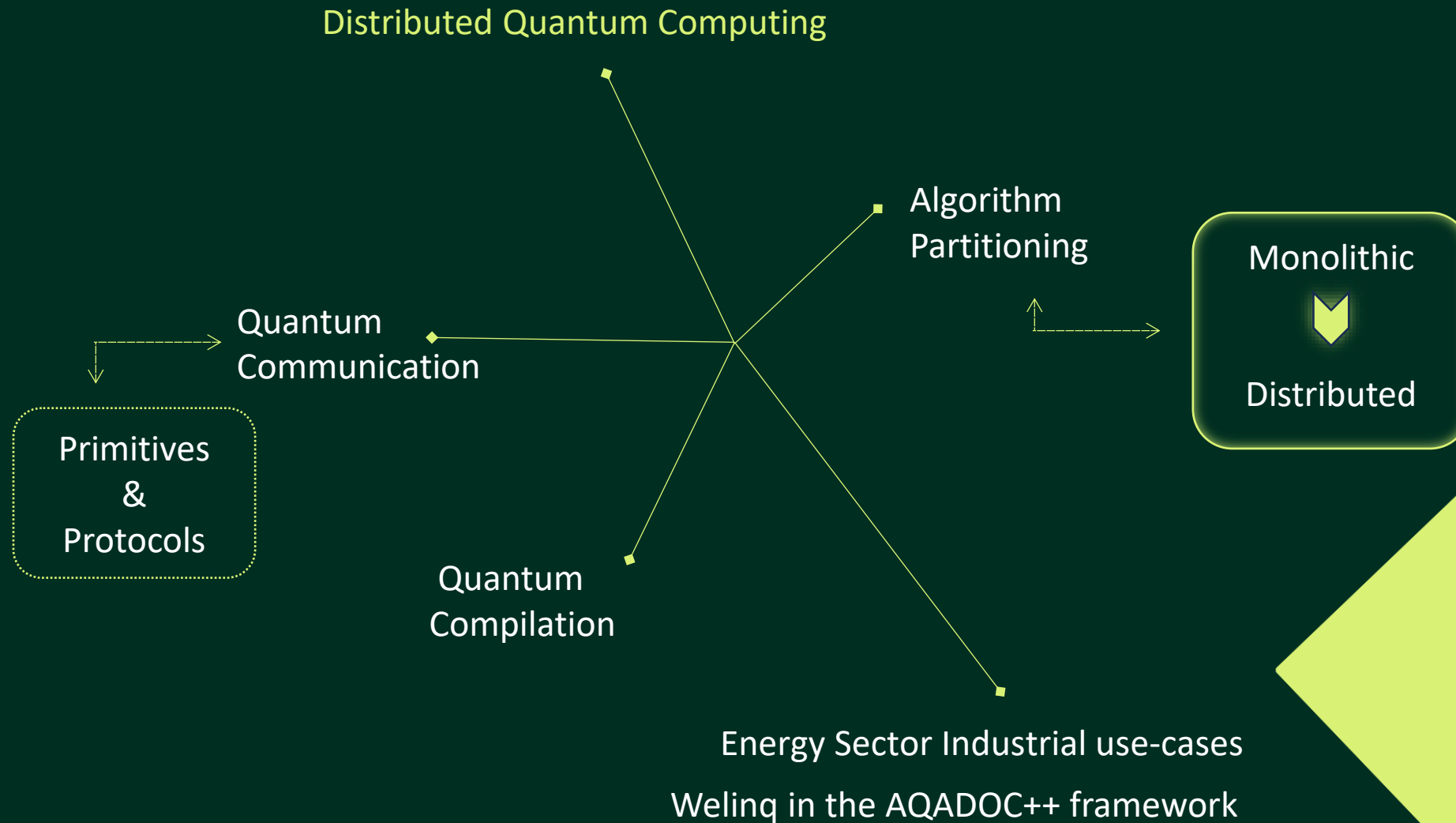
Outline



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Distributed Quantum Computing

Quantum advantage on real world applications



Demand for large-scale QC

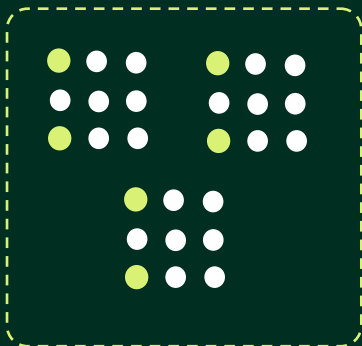
Large qubit number
vs
Performance factors

Distributed Quantum Computing:

- Viable path to *scalability*
- Quantum communication via entanglement

Distributed Quantum Algorithms

Distributed Quantum Architectures (DQA)



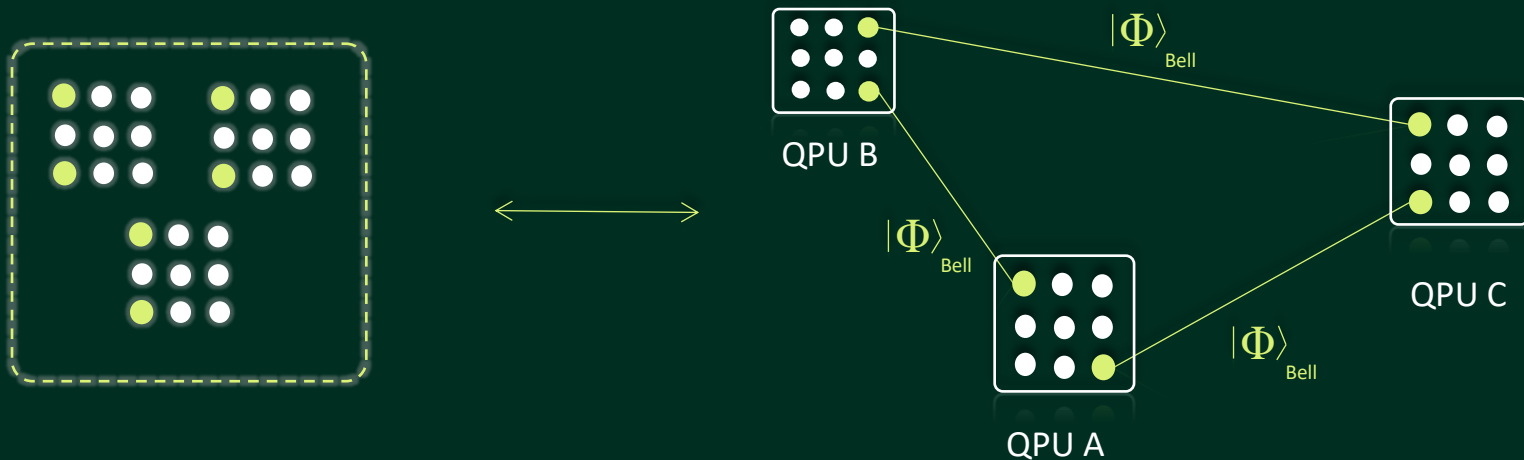
- Emulating large quantum computers as networks of *interconnected* smaller quantum computers

Quantum Processing Unit (QPU)

Qubits distinguished into two sets:

- **Data** qubits () for *processing*
- **Communication** qubits () for *interconnection*

Distributed Quantum Architectures (DQA)



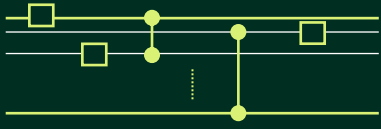
- Emulating large quantum computers as networks of *interconnected* smaller quantum computers
- Algorithms demanding large number of qubits are *partitioned*, with its fragments executed on QPUs of smaller qubit capacity, constituting a *quantum network*
- How is algorithm distribution implemented & optimized..?

Quantum Processing Unit (QPU)

Qubits distinguished into two sets:

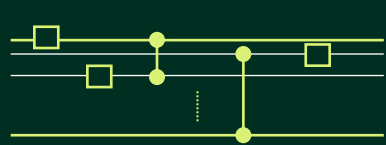
- **Data qubits** () for *processing*
- **Communication qubits** () for *interconnection*

Quantum Channels () set by distributing entanglement (links/ Bell pairs $|\Phi\rangle_{\text{Bell}}$) over communication qubits

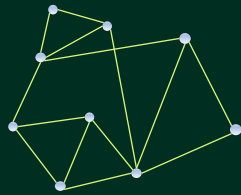


Quantum Circuit

$$c(q_i, U_{ij})$$



Mapping
→

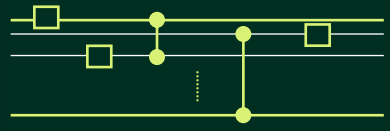


Quantum Circuit

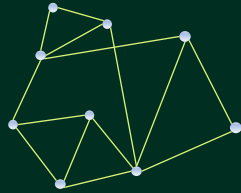
Graph

$$C(q_i, U_{ij})$$

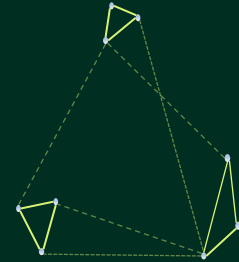
$$G(V, E)$$



Mapping



Partitioning



Quantum Circuit

Graph

Sub-graphs

$$C(q_i, U_{ij})$$

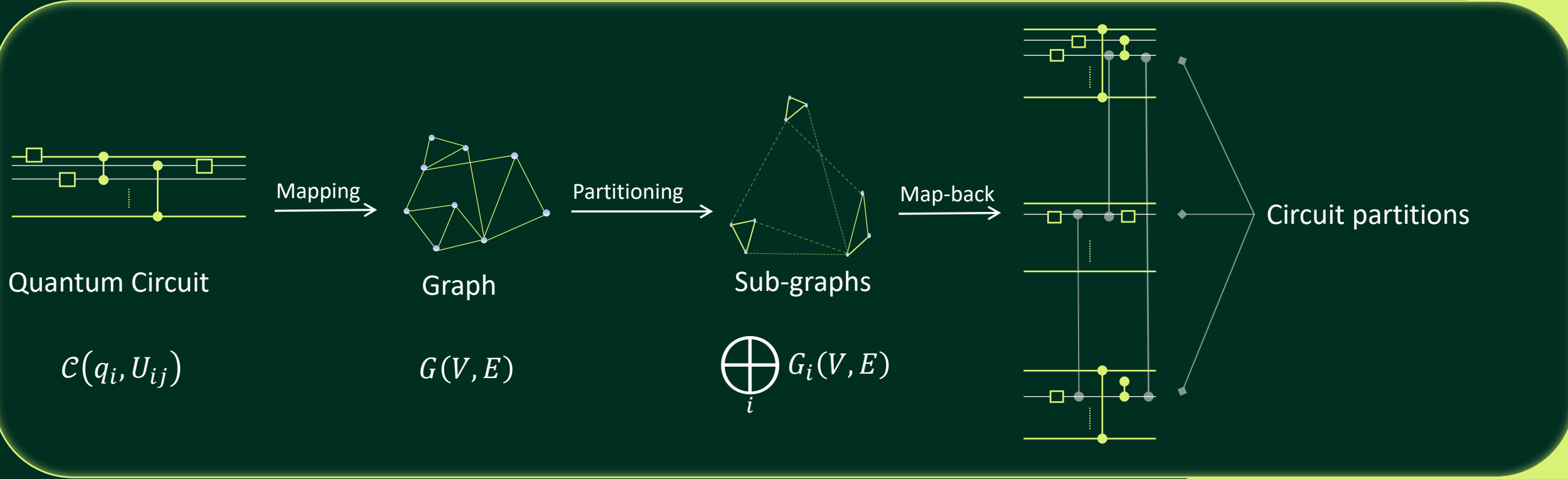
$$G(V, E)$$

$$\bigoplus_i G_i(V, E)$$

Quantum Algorithm



Quantum Algorithm partitions



- How to implement non-local operations ()?



Distribution Toolbox:

Quantum Communication protocols for interconnected QPUs via entanglement

- Optimal partitioning given QPU connectivity constraints?

Quantum Compiler

Distribution Toolbox

Quantum communication Protocols

Introduce **quantum link** to interconnect & use **entanglement** to apply:

Communication
Primitives

Teleport

Cat-Entangler

Cat-DisEntangler

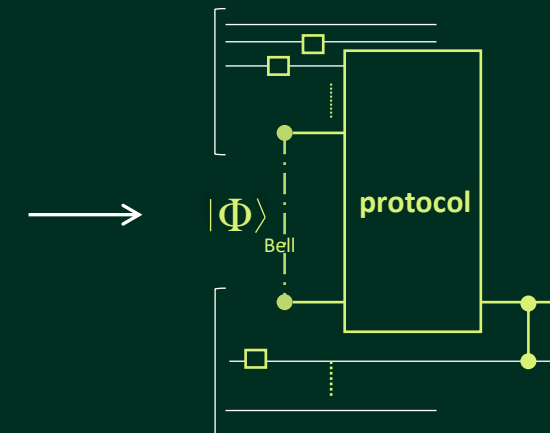
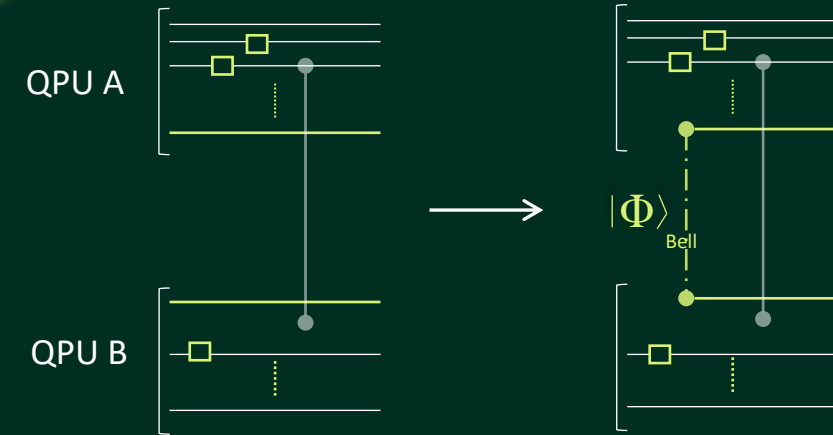
Communication
Protocols

TeleGate

TeleData

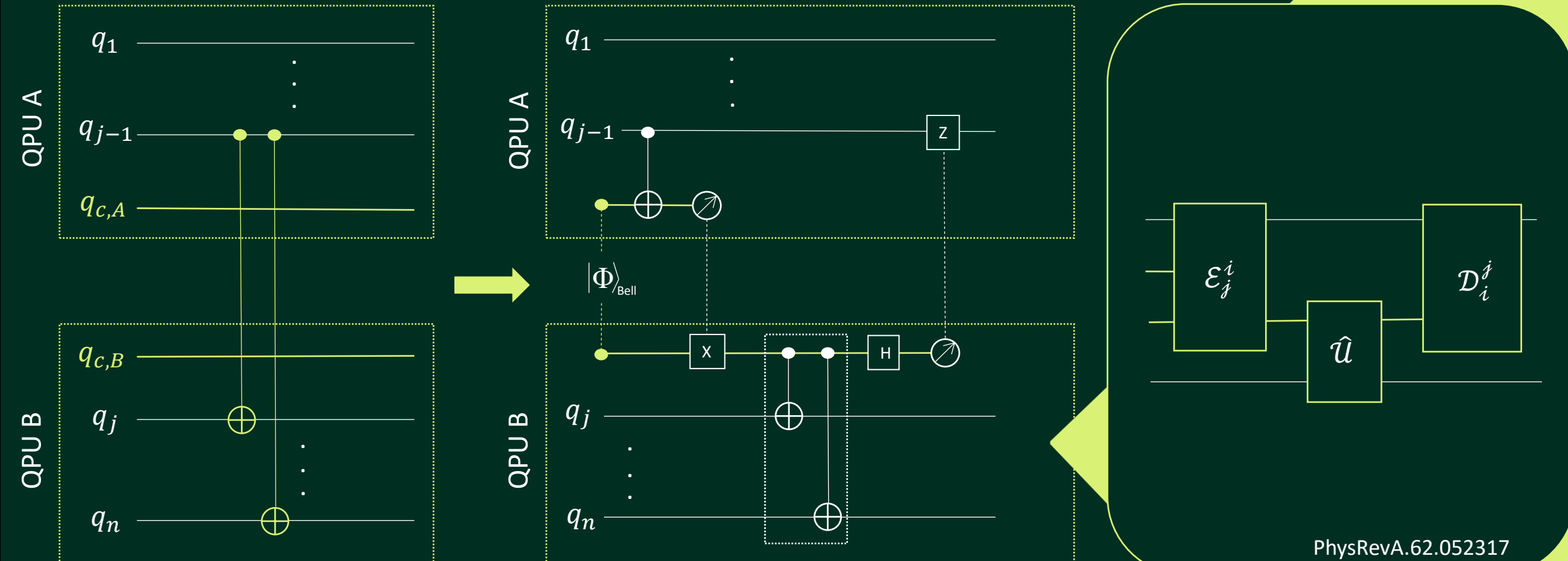
Alternatively: Circuit-Cutting

Cut into sub-circuits and execute in parallel. **No physical entanglement used**, but rather simulated.



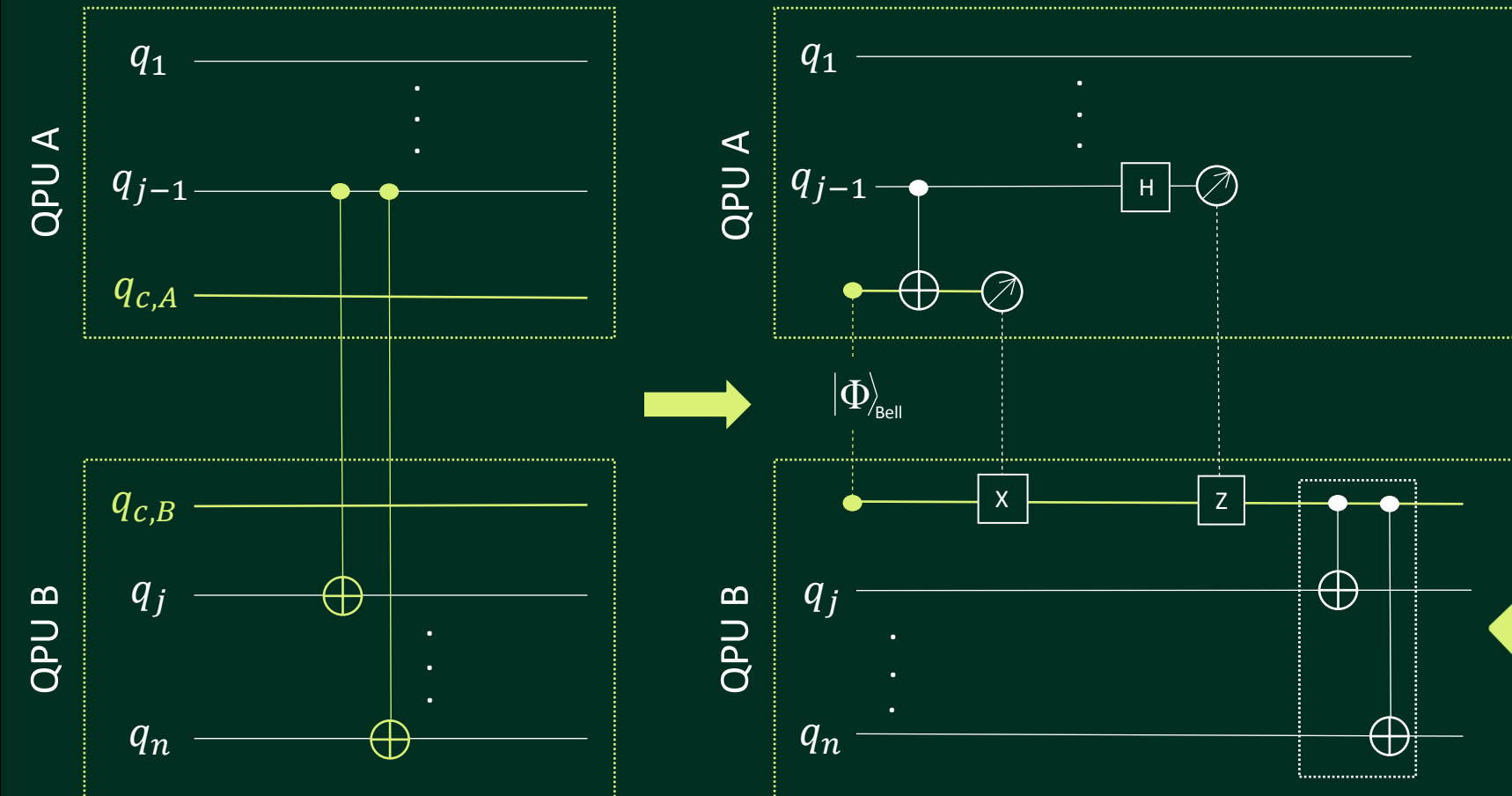
Quantum Communication

The TeleGate protocol

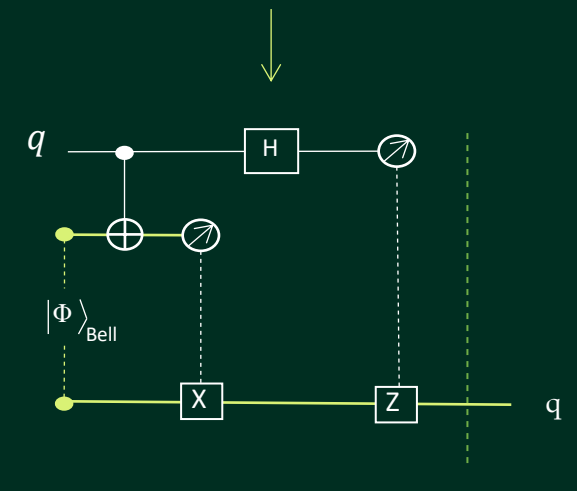


Quantum Communication

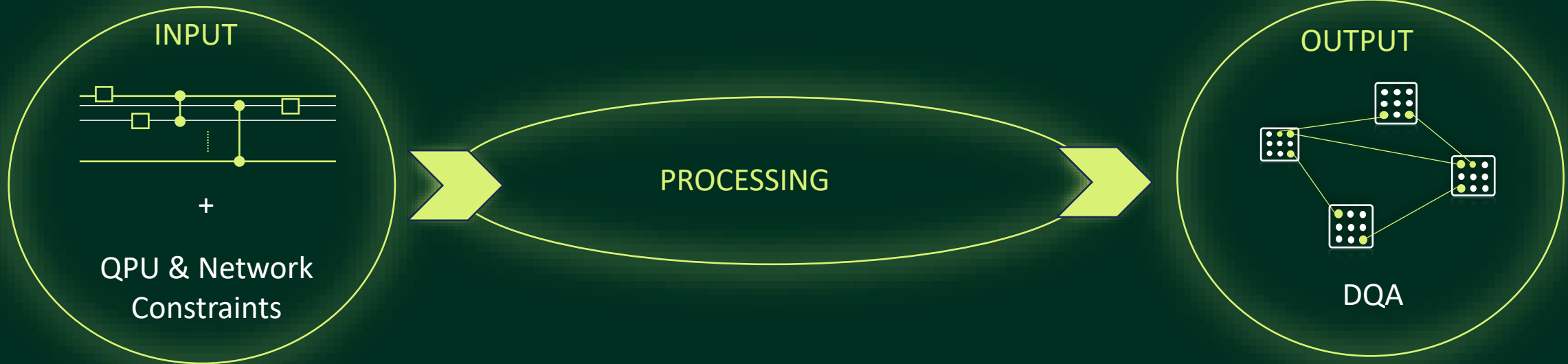
The TeleData protocol



The quantum state is transferred via teleportation and the operations are executed *locally* in QPU_B



Quantum Compiler



- Optimizing Quantum Algorithm **partitioning & distribution** given architecture constraints (global & local)

📺 talk by M. Amoretti

📺 TQE.2023.3303935

A Bottom-Up approach

Distributed Quantum Algorithm
natively exploiting hardware and network



Hardware (QPU)

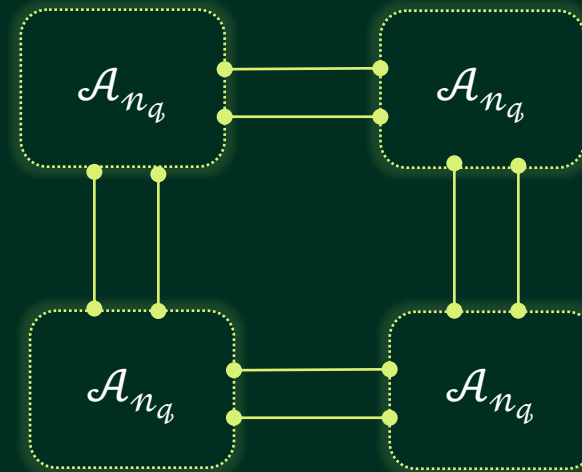


A Bottom-Up approach

Distributed Quantum Algorithm
natively exploiting hardware and network



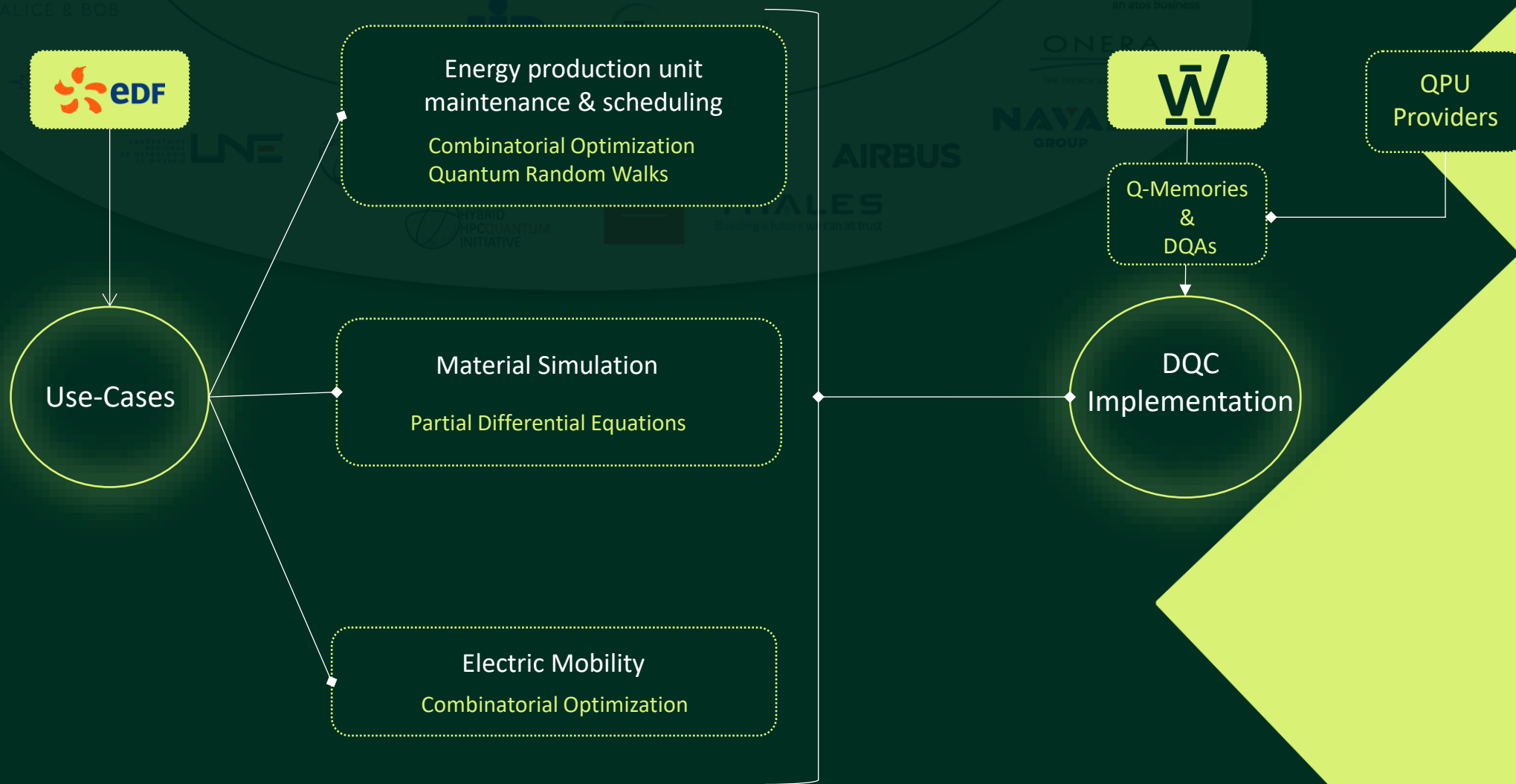
Hardware (QPU & Net)



- Given a network of N -QPUs, exploit entanglement to implement a natively Distributed Quantum Algorithm (Approx. \mathcal{A}_{Nn_q})

AQADOC++

- **Aim:** Development of distributed quantum algorithms for resolving use-cases in the context of the **energy sector**



The background is a solid dark green color. On the right side, there is a large, stylized yellow arrow pointing towards the right. The arrow is composed of several geometric shapes: a large yellow triangle at the top right, a smaller yellow triangle at the bottom right, and a central yellow shape that forms the shaft of the arrow, all meeting at a point on the right edge.

Thank you for your attention!