Distributed quantum computing and other tasks

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Why connect quantum computers?

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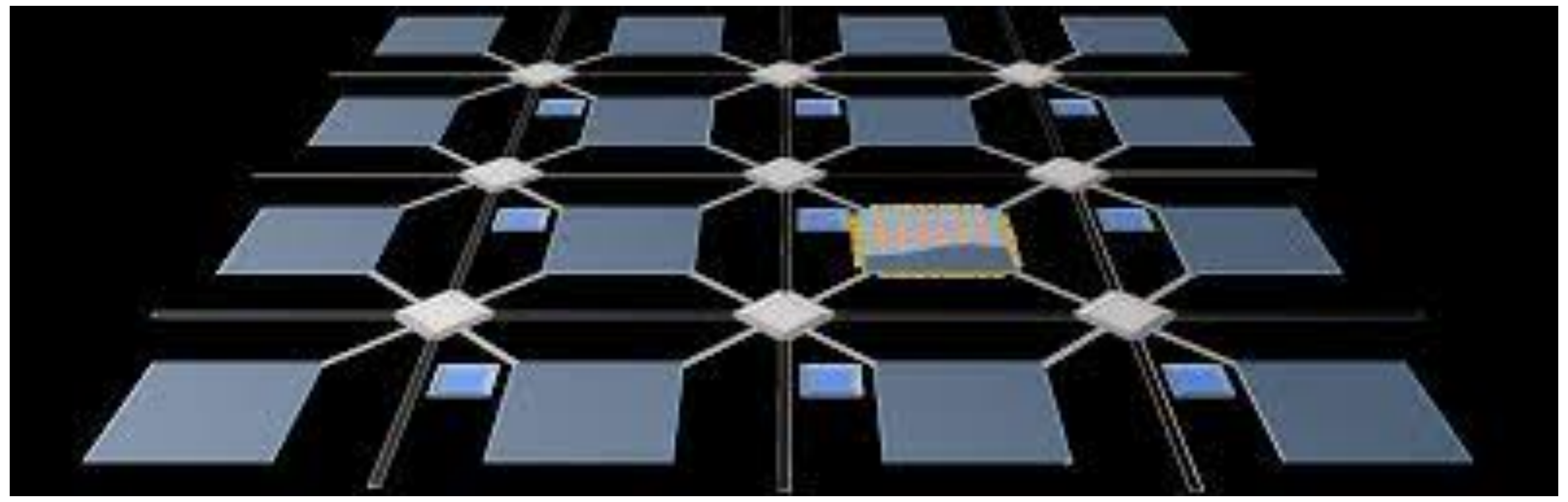
- Multi Q-core computing



Almost all QC architectures will scale with many small q-processors

How do we run an algorithm over many processors?

- Multi q-core algorithm compilation
- Optimal qubit routing
- Minimum storage
- Specialised fault tolerance techniques
- …

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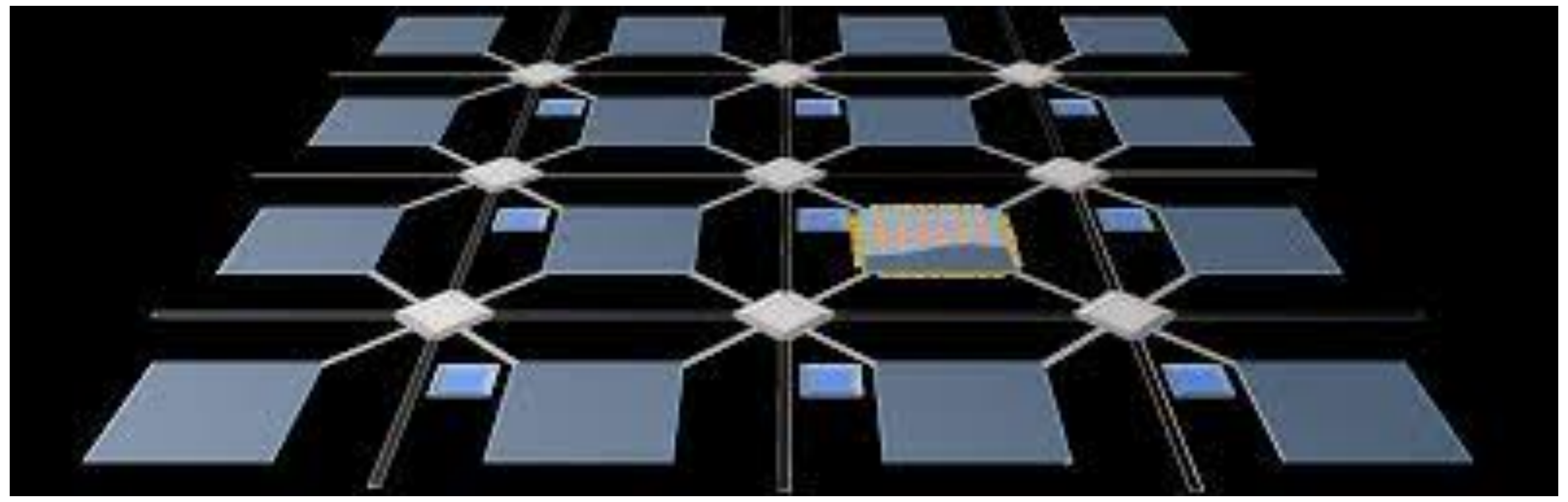

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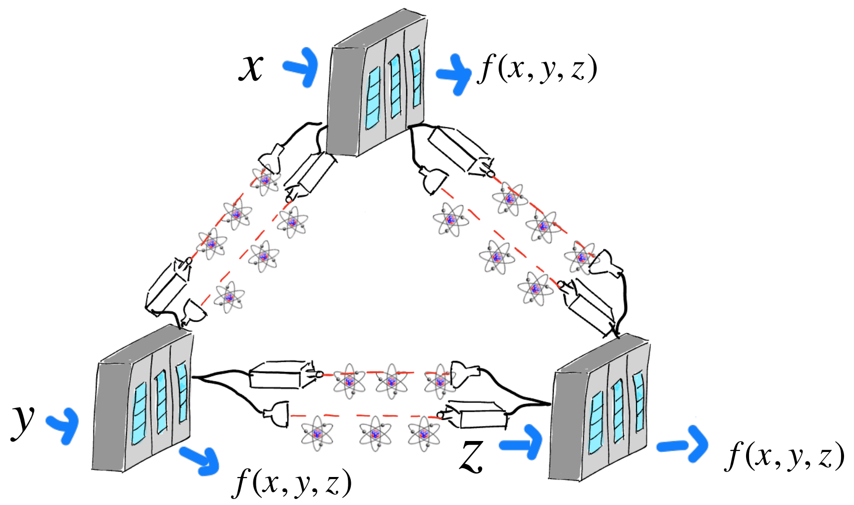
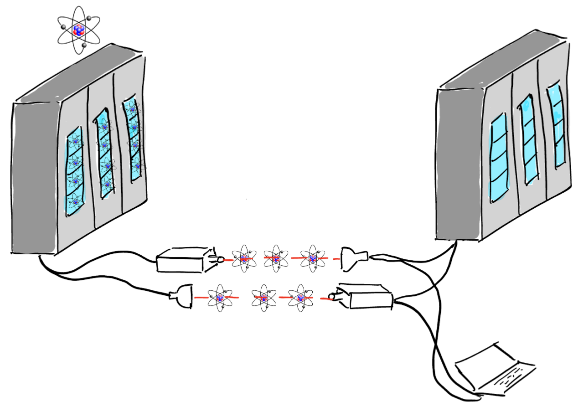
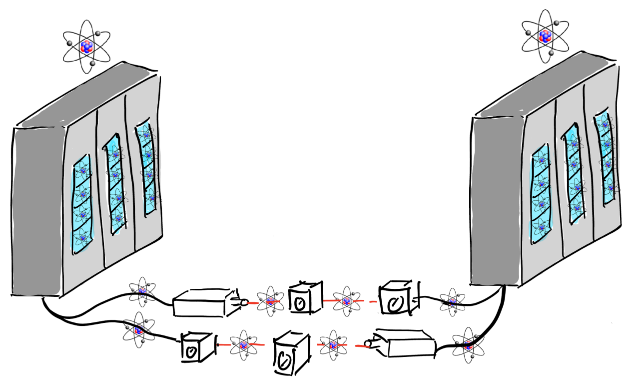
- New functionalities



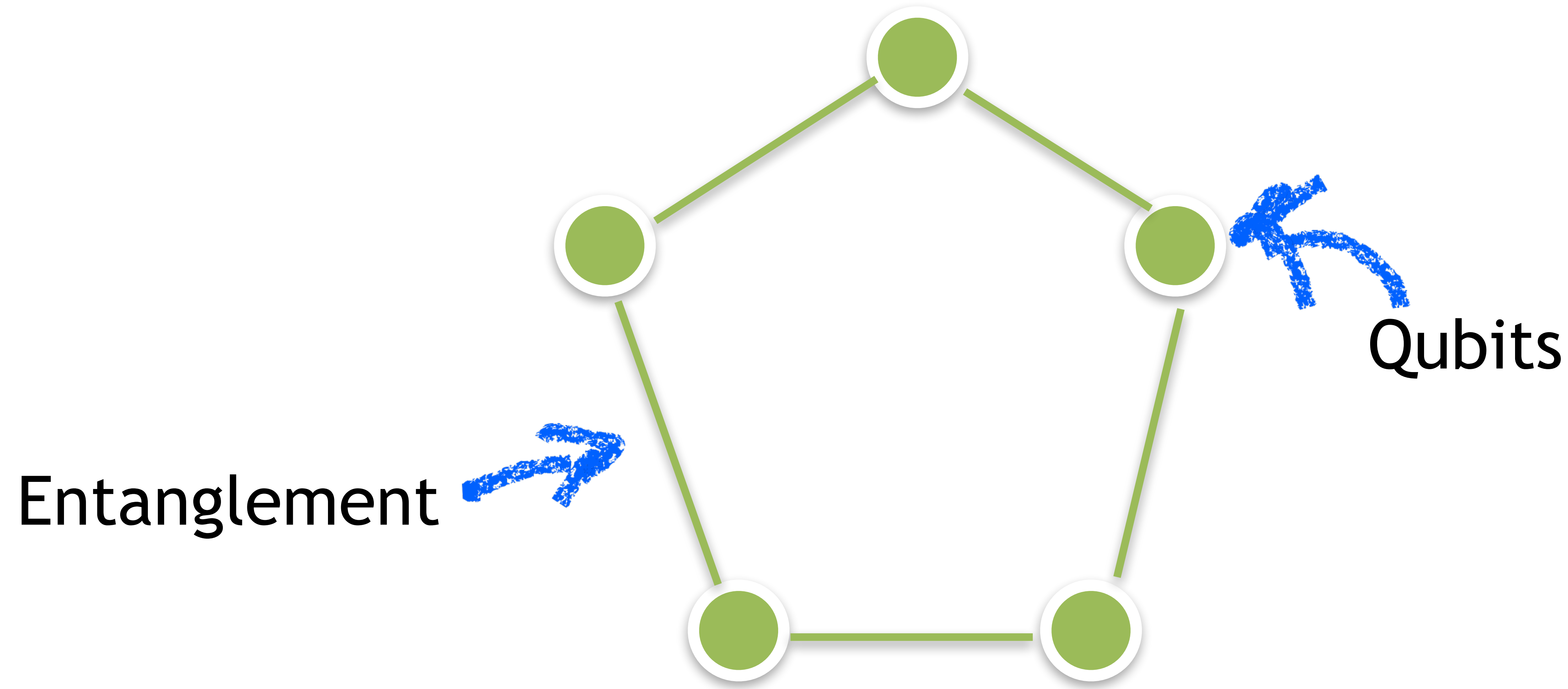




Quantum links connecting classical and quantum processors
What new functionalities can emerge?

- Quantum assisted private computing
- Long term storage
- Remote quantum data preparation
- Blind verified quantum computing
- Secure multiparty computation
- …

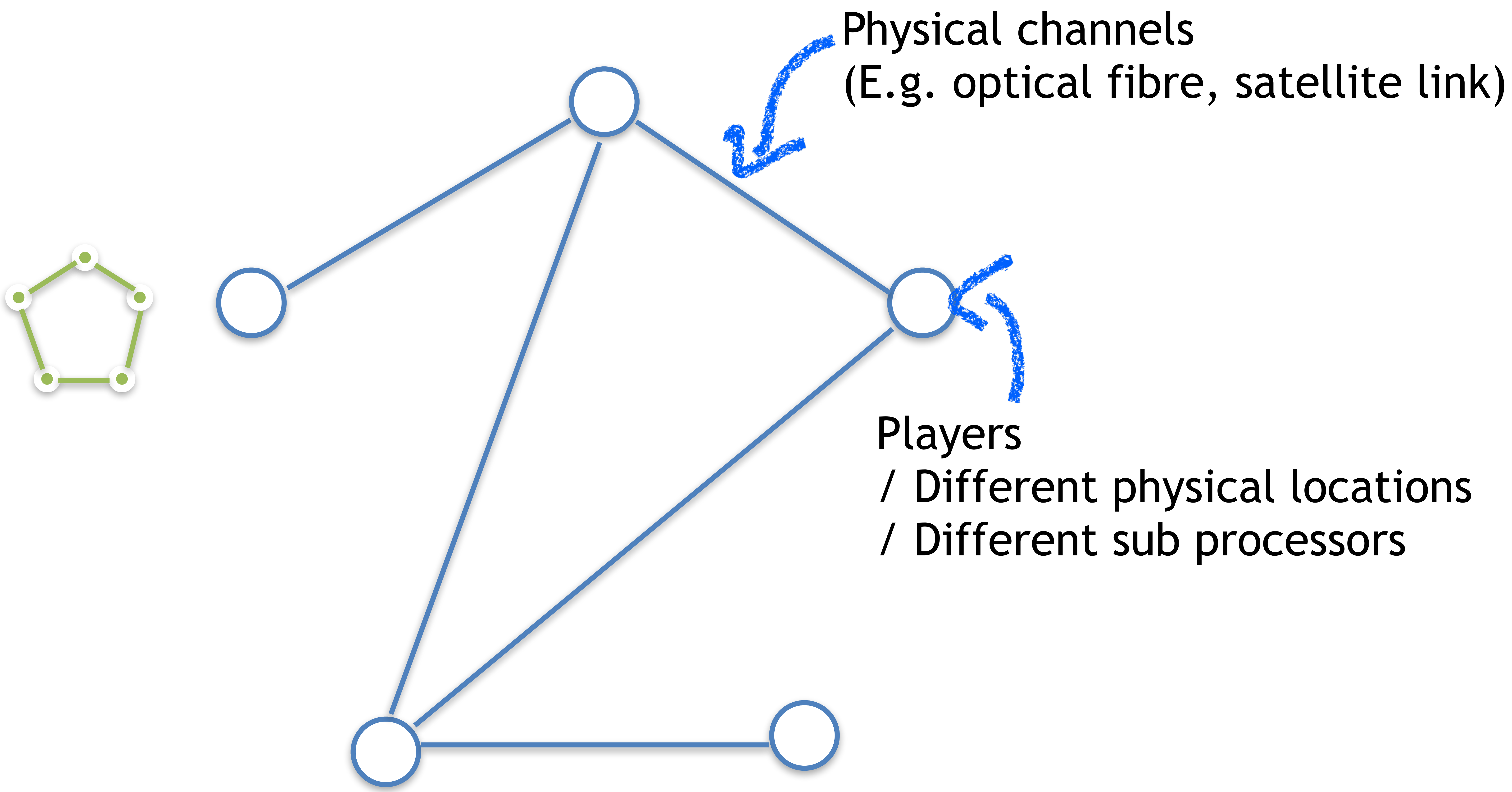
Universal resources: graph states



$$|G\rangle = \prod_{i,j \in E} CZ_{i,j} |++\ldots+\rangle$$

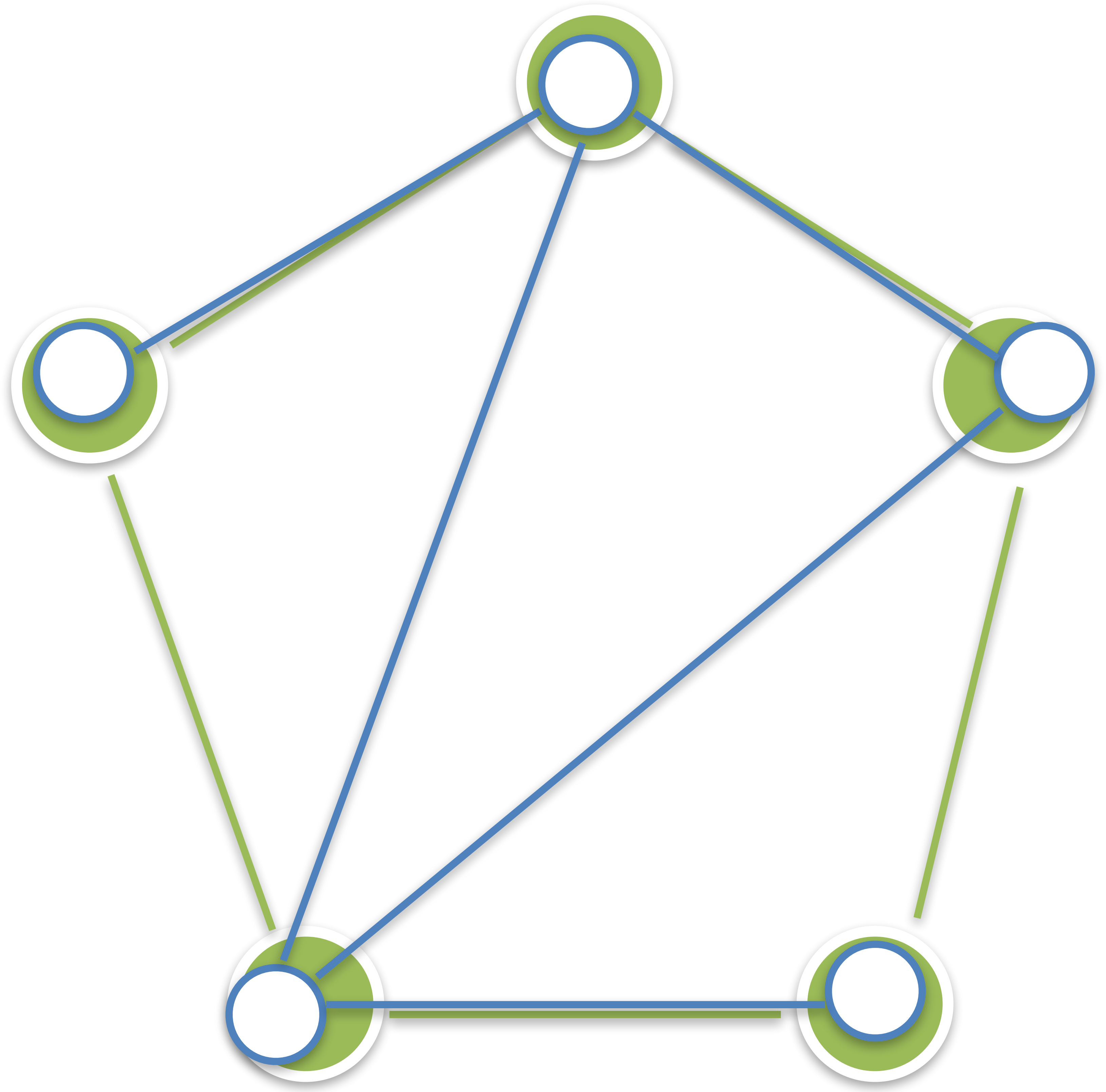
Entangled states useful for
- Universal quantum computation
- Error correction & fault tolerance
- Secret sharing
- Anonymous transmission
- Quantum sensing
- ...

Distributing graph states



Task: share graph state over *physical* network (different topology)

Distributing graph states



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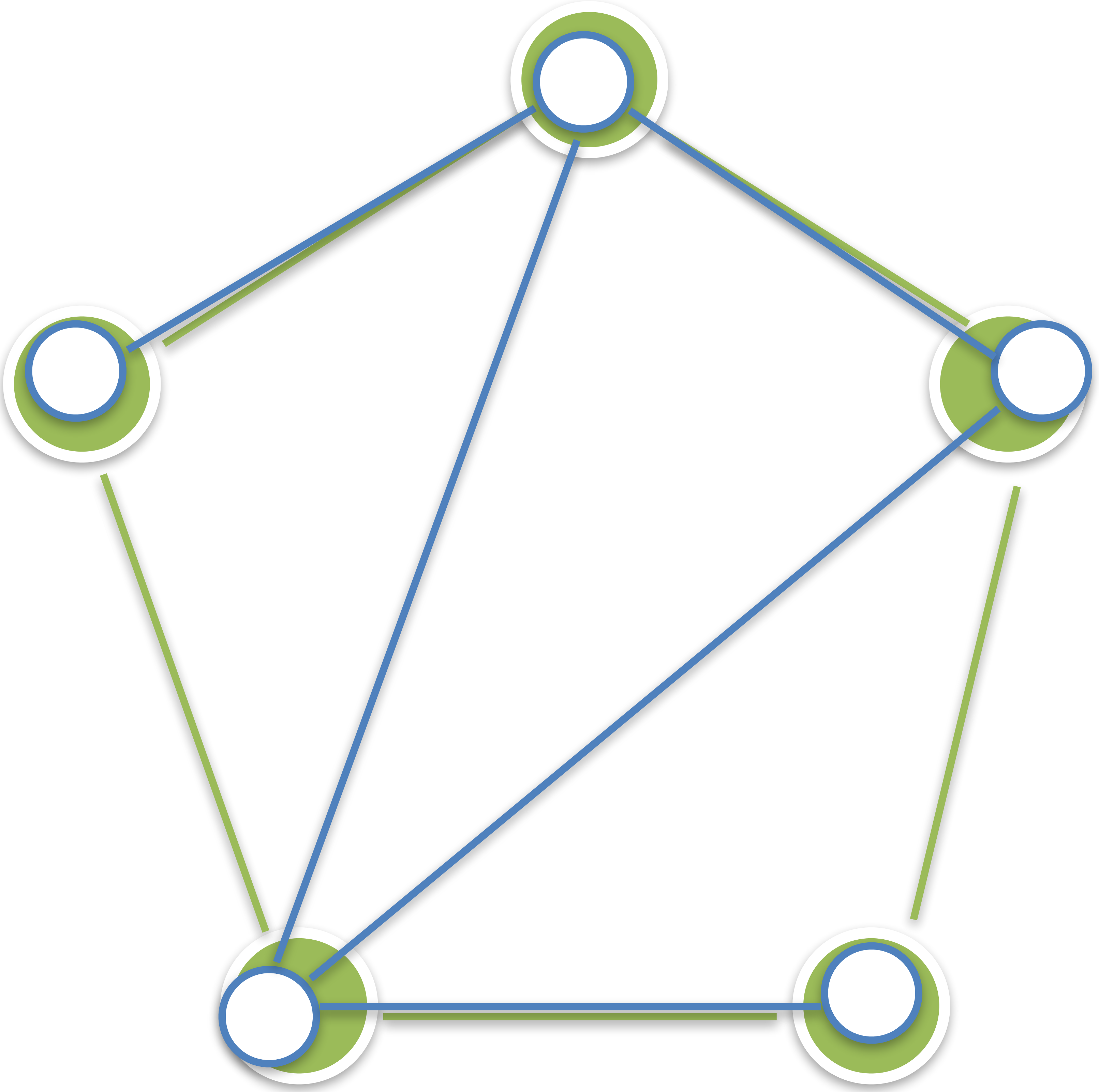
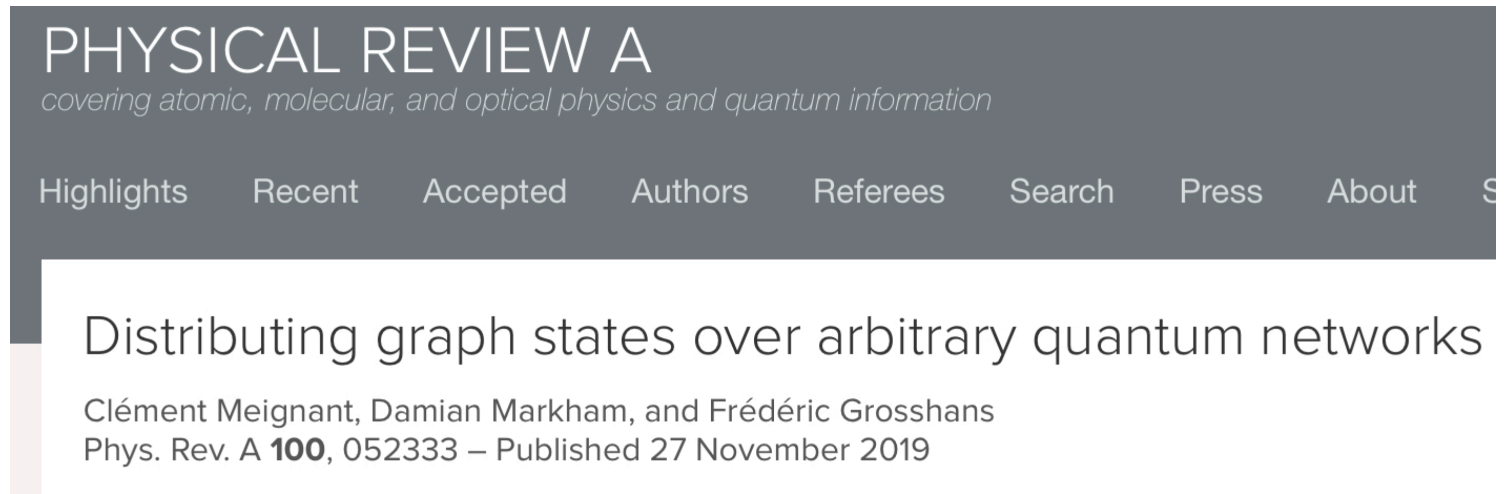


-> Minimise use of physical channels

-> Work for any graph state, and any Physical network



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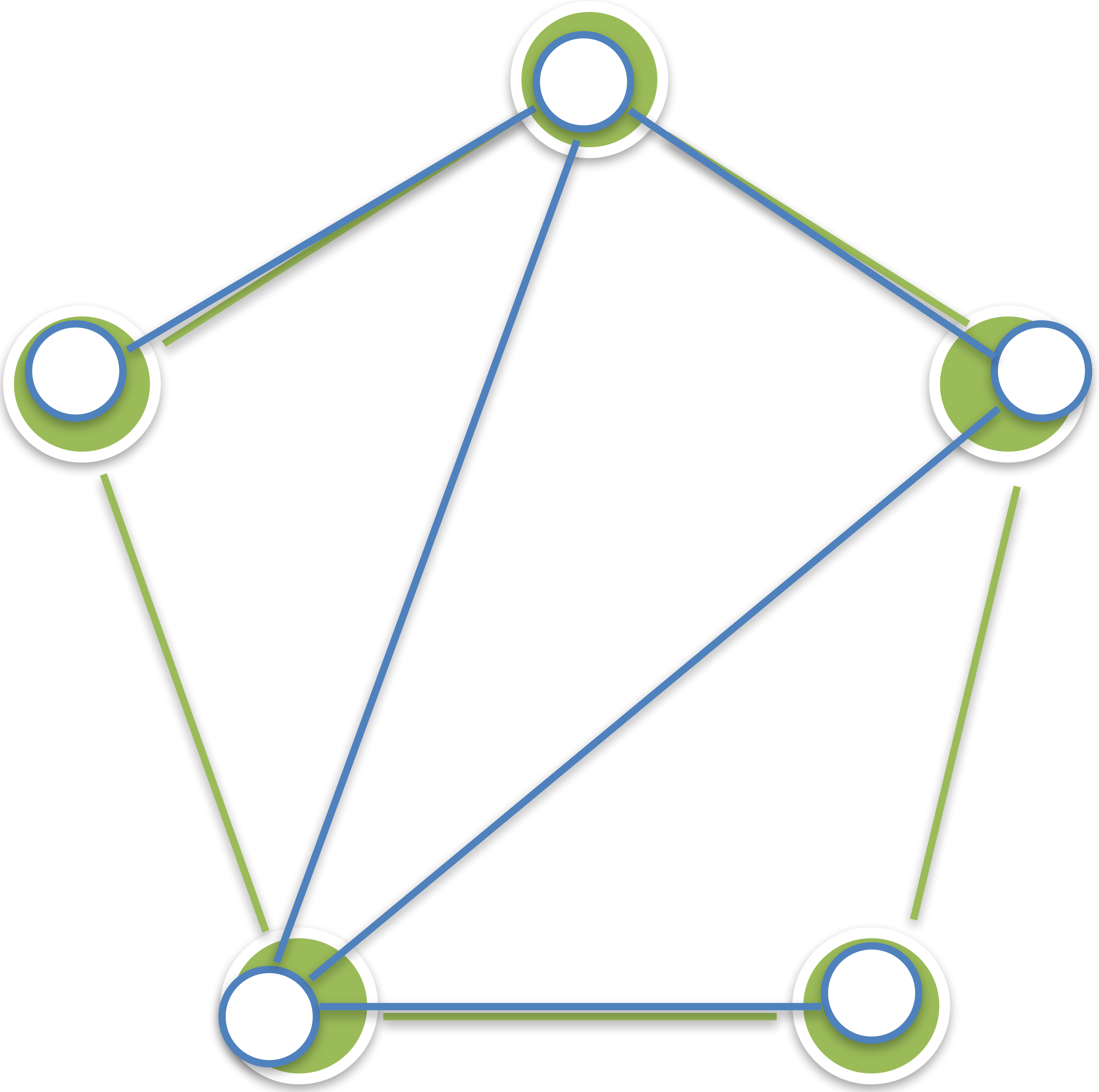
Distributing graph states over arbitrary quantum networks

Clément Meignant, Damian Markham, and Frédéric Grosshans
Phys. Rev. A **100**, 052333 – Published 27 November 2019

Task: share graph state over *<u>physical</u>* <u>network</u> (different topology)

Distributing graph states



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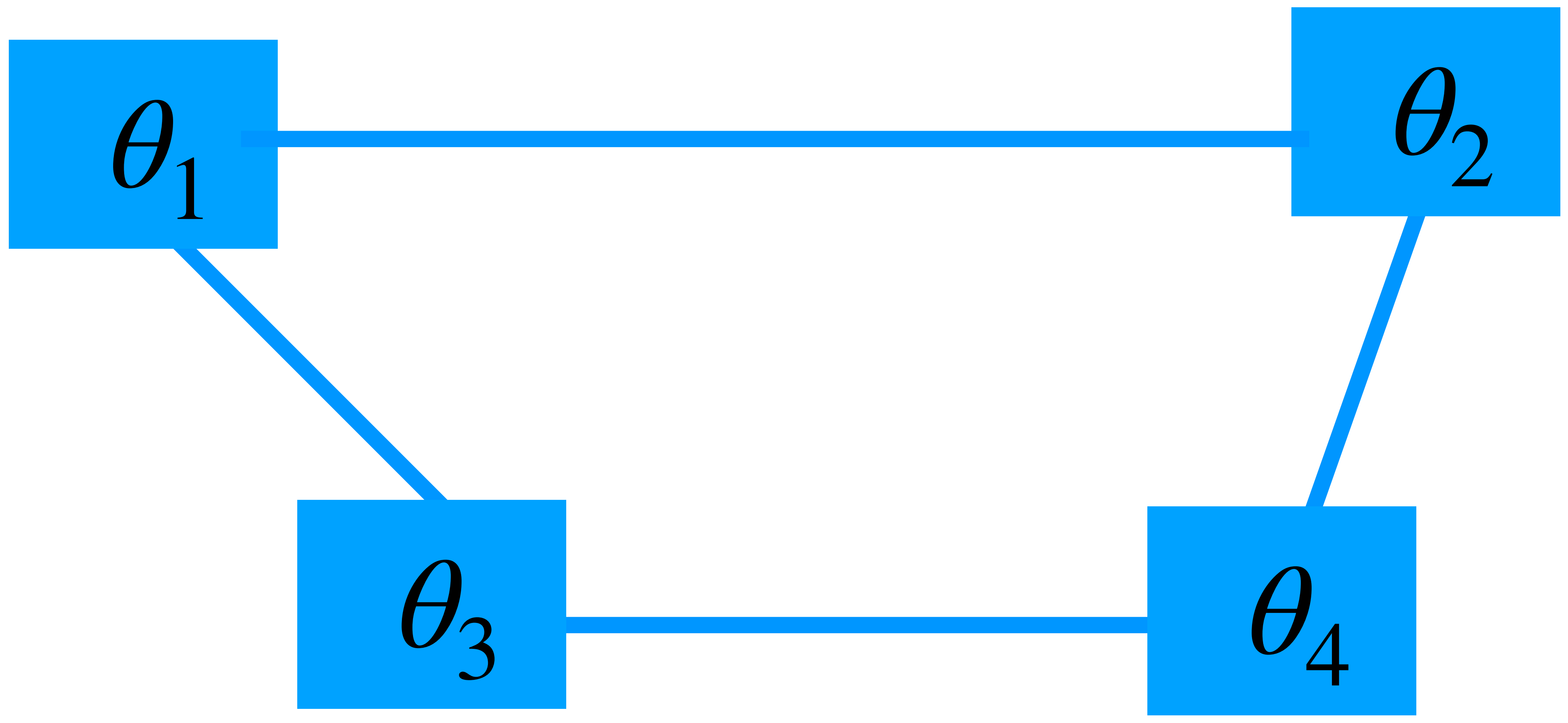
Techniques: mix of quantum and classical
=> Graph state techniques
=> Graph theory, Steiner tree problem....

Task: share graph state over *physical* <u>network</u> (different topology)

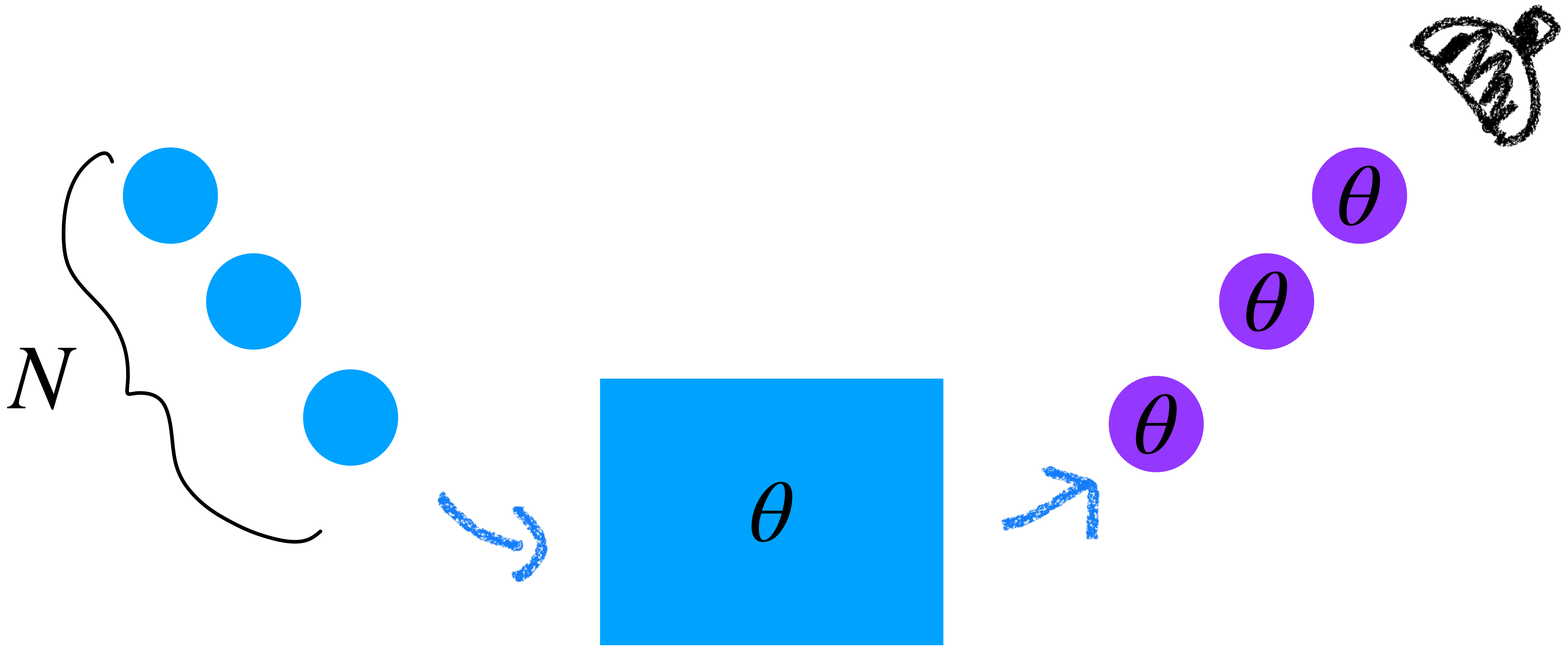
Applications: FTQC in multicore, q network protocols...

Quantum Sensor Networks



Quantum Sensing

Goal: Estimate θ , corresponding to some physical process (strength of field, e.t.c.)



Output: estimate $\hat{\theta}$

Classically $Var(\hat{\theta}) \geq \frac{1}{\sqrt{N}}$

Cramér-Rao [Cramér 1946, Rao1945]

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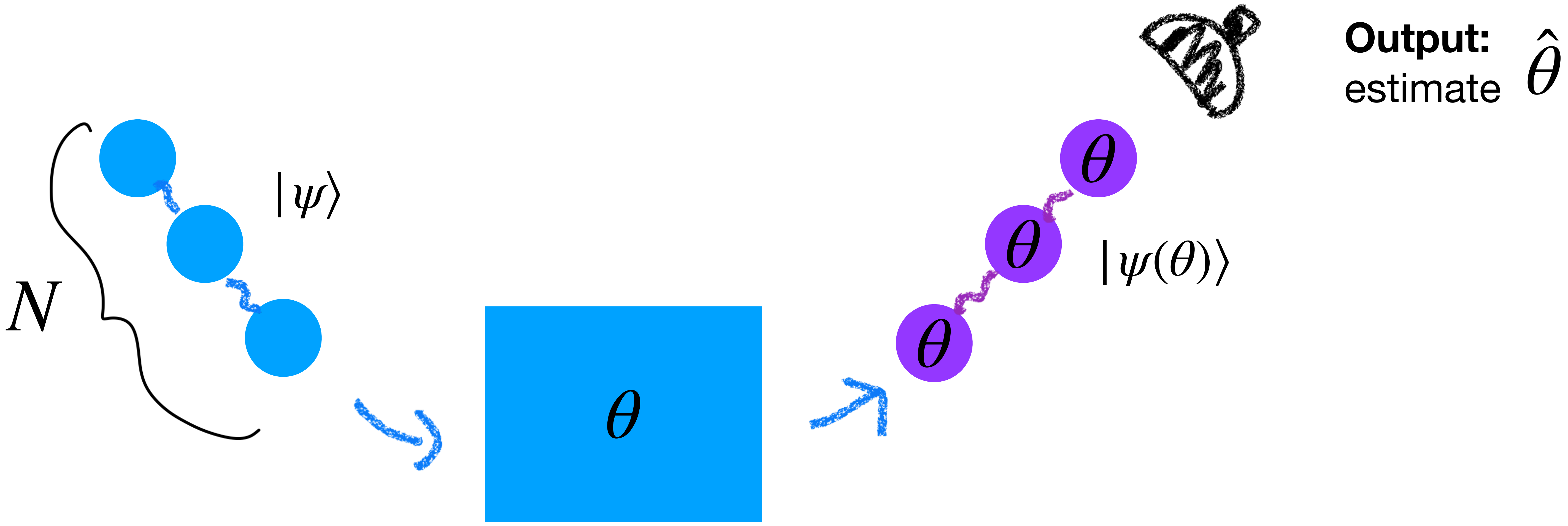

Classically $Var(\hat{\theta}) \geq \frac{1}{\sqrt{N}}$ ➡ QM $Var(\hat{\theta}) \geq \frac{1}{N}$

Cramér-Rao [Cramér 1946, Rao1945]

Q Cramér-Rao [Braunstein, Caves 1994]

e.g. - Gravitational wave detection
- Bio sensing

photons burns mirrors / cells

Works!

Quantum Sensing

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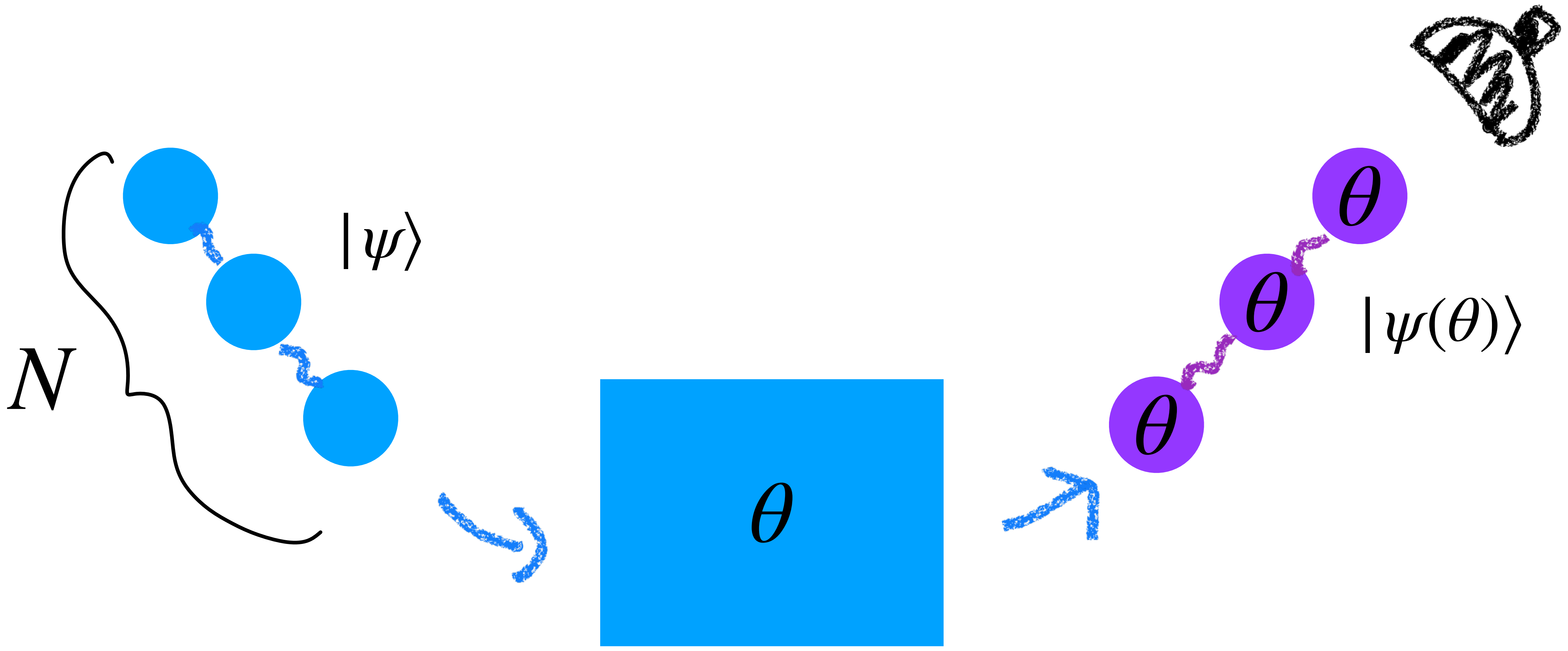


Output: estimate $\hat{\theta}$

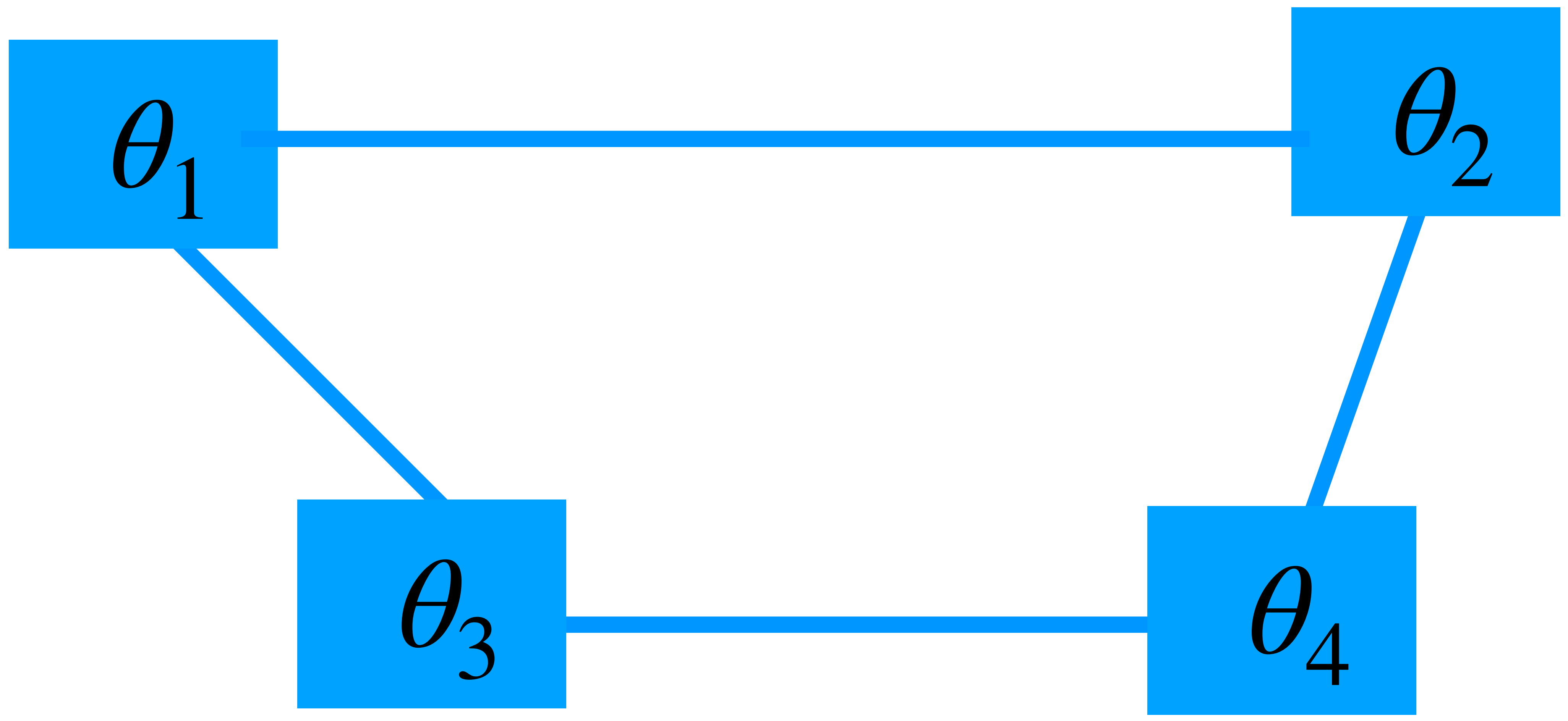
Most advanced quantum information technology

- Many applications and startups
- Industrially deployed

μQUANS

Challenge: largely untreated in network setting
-> quantum data, sharability? distributability? security?
how to place in quantum networks?

Quantum Sensor Networks



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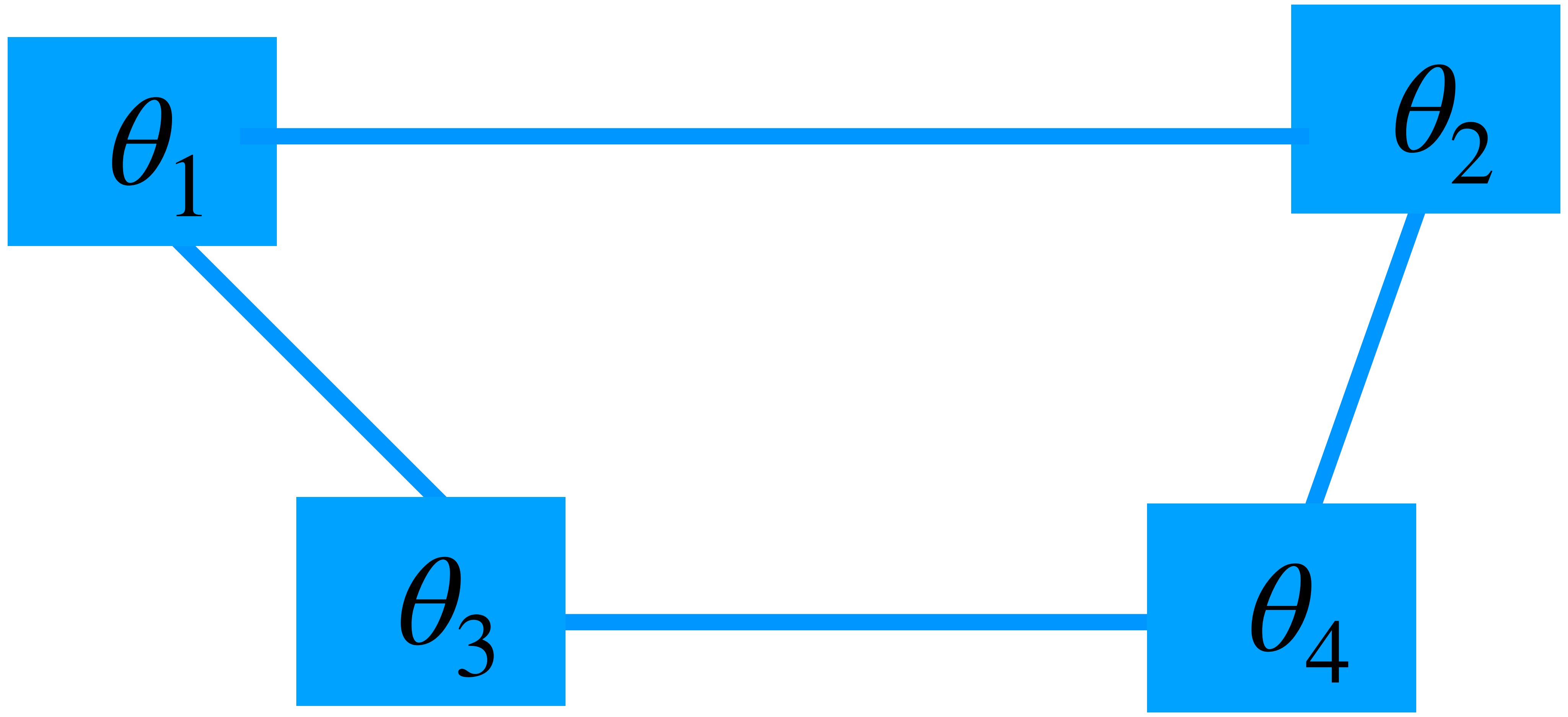

- Entangled probes estimate global network functions better

$$f(\{\theta_1, \theta_2, \ldots\}) = \sum_i \alpha_i \theta_i$$ Linear function

$$\Delta \hat{f}^2 = \frac{1}{N}$$ Entangled advantage

[Komar et al, *A quantum network of clocks*, Nature Physics, 2014]

[T. Proctor, P. Knott, J. Dunningham, *Multiparameter estimation in networked quantum sensors,* PRL 2018]

[K. Qian, et a., *Heisenberg scaling measurement protocol for analytic functions with quantum sensor networks,* PRA 2019]

Quantum Sensor Networks

Applications: expressing problems as linear functions

[L. Bugalho, M. Hassani, Yasser Omar, DM, Quantum 2024]

$$f(\{\theta_1, \theta_2, \ldots\}) = \sum_i \alpha_i \theta_i \qquad \Delta \hat{f}^2 = \frac{1}{N}$$

Quantum Sensor Networks

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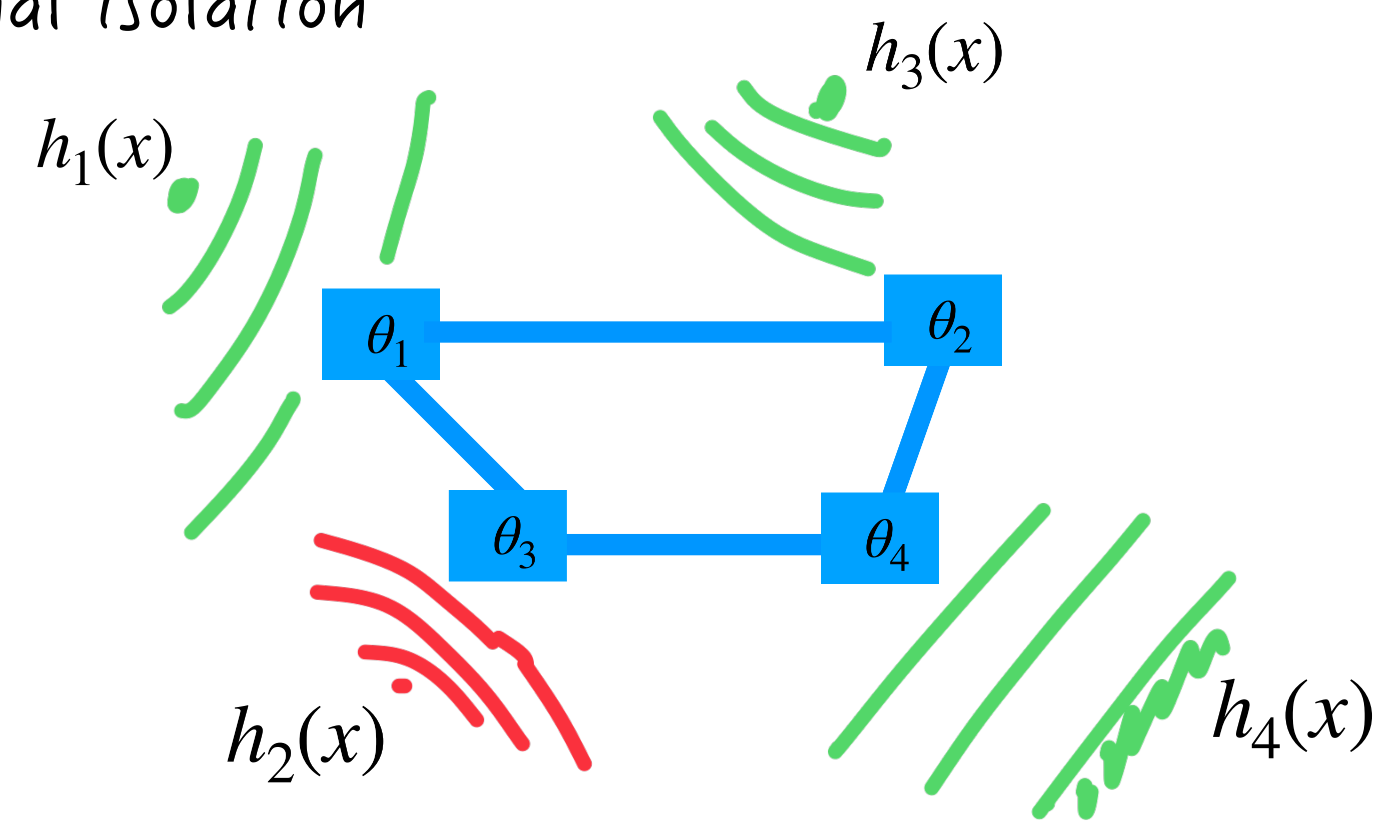
E.g.s

- Field sensing

Signal isolation



$$F(x) = \sum_i \beta_i h_i(x) \qquad \theta_i = tF(x_i)$$

$$\beta_2 = \sum_j \alpha_j \theta_j$$ (from invertion of F(x) via alternant matrix)

[P. Sekatski, S. Wölk, W. Dür, PRR 2022]

[L. Bugalho, Yasser Omar, DM in preparation]

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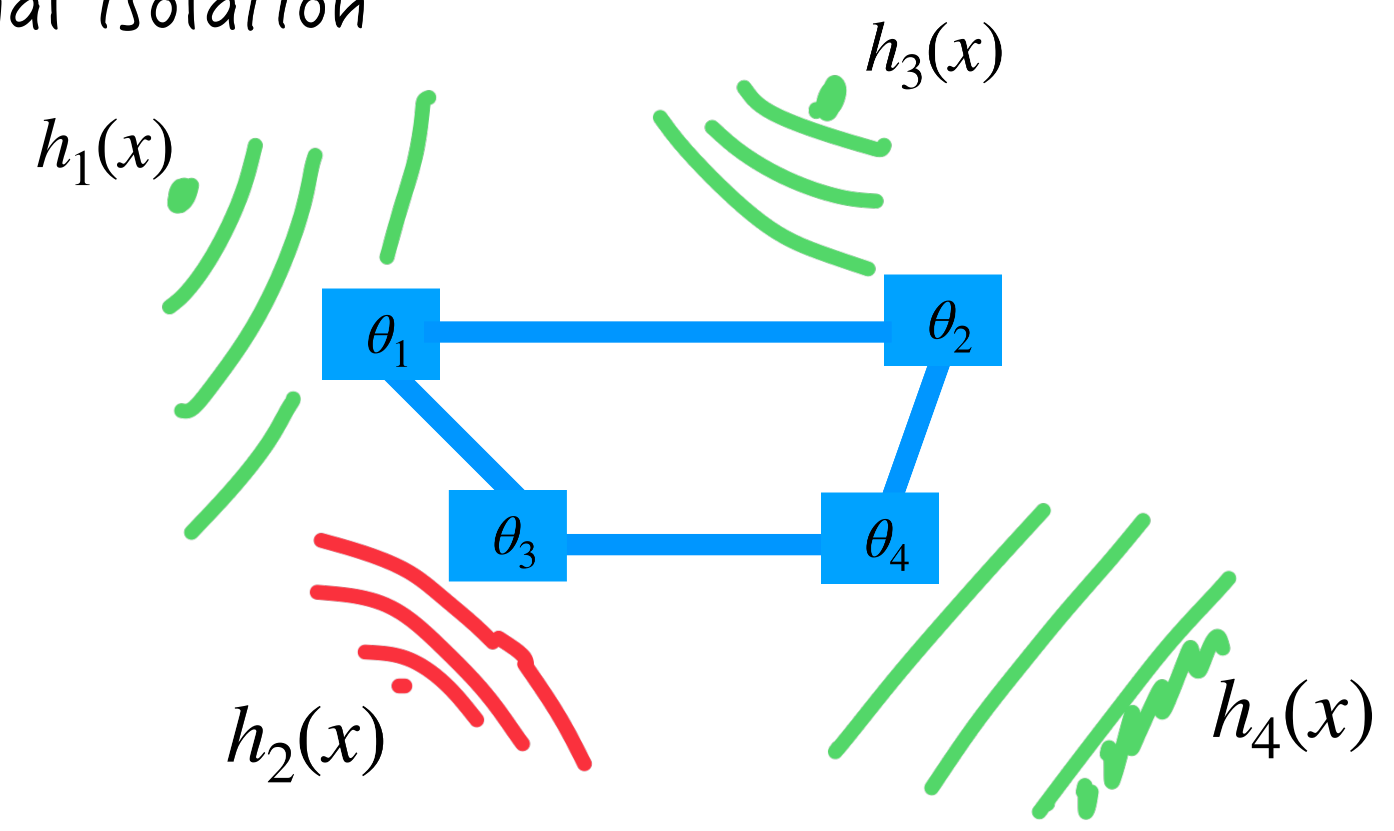

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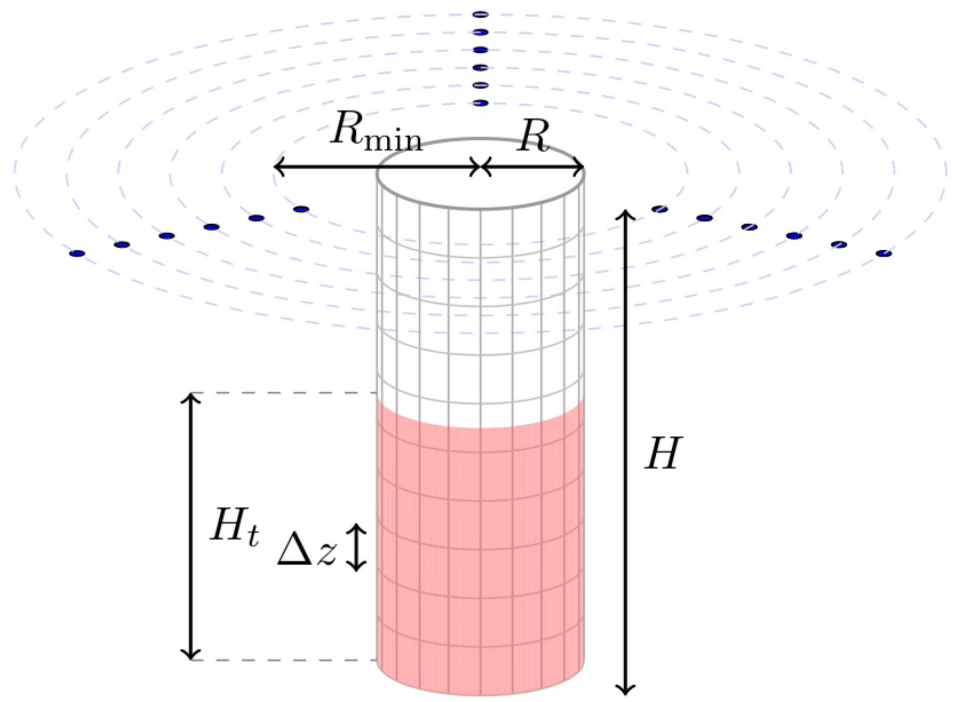
- Networks of gravimeters

Estimating underground liquid volume



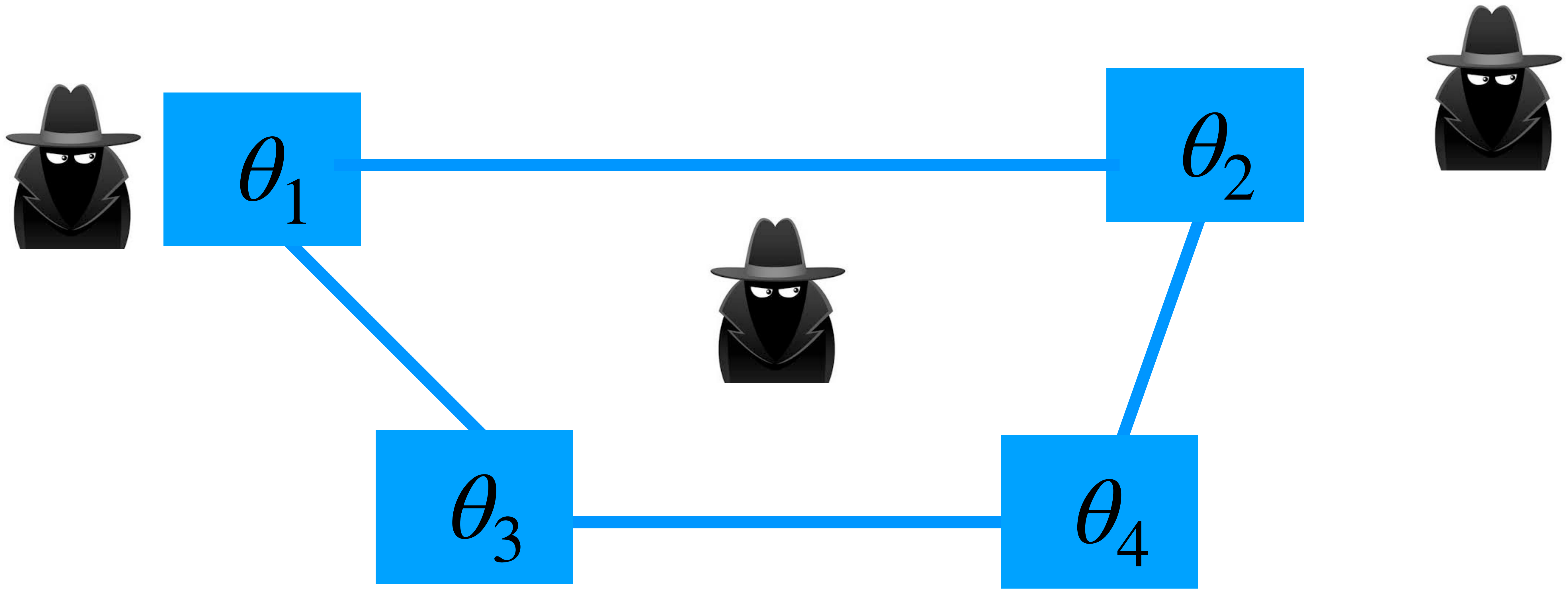
Estimation of point masses at different heights

$$F(x) = \sum_i M_i \frac{1}{||x - z_i||^2} \qquad \theta_i = tF(x_i)$$

$$M_i = \sum_j \alpha_j \theta_j$$

[L. Bugalho, J. Laurier-Gaud, Yasser Omar, DM in preparation]

Secure networks of quantum sensors?



- Untrusted channels and sources
- Untrusted agents
- Untrusted devices
- …

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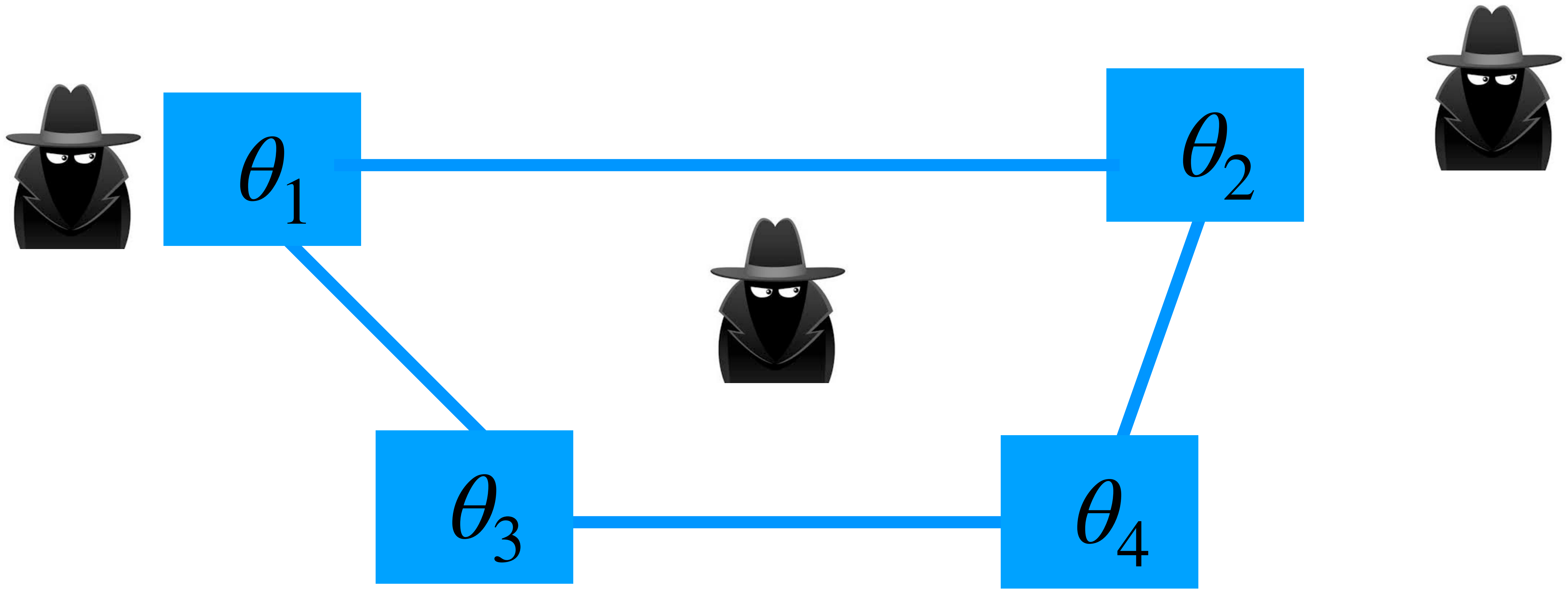

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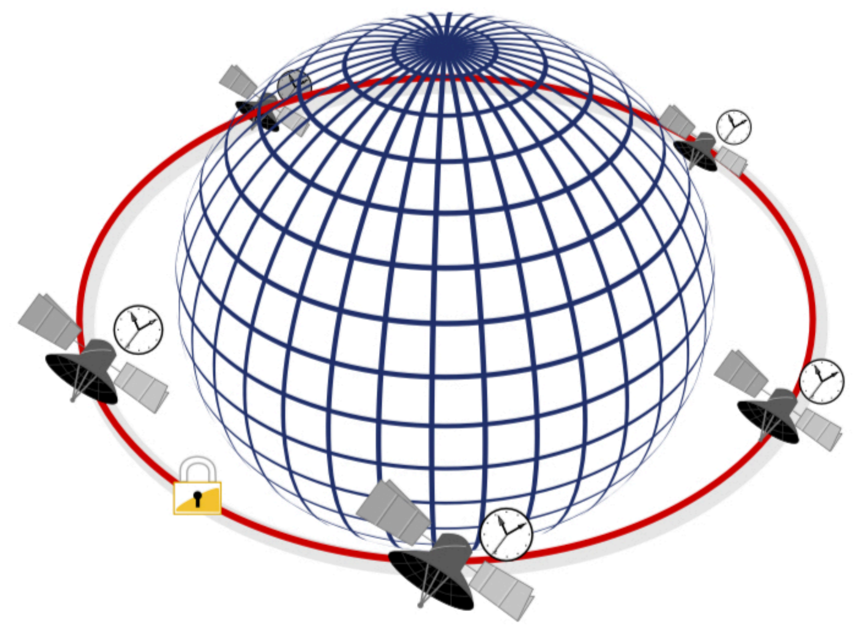
Applications to networks of quantum clocks



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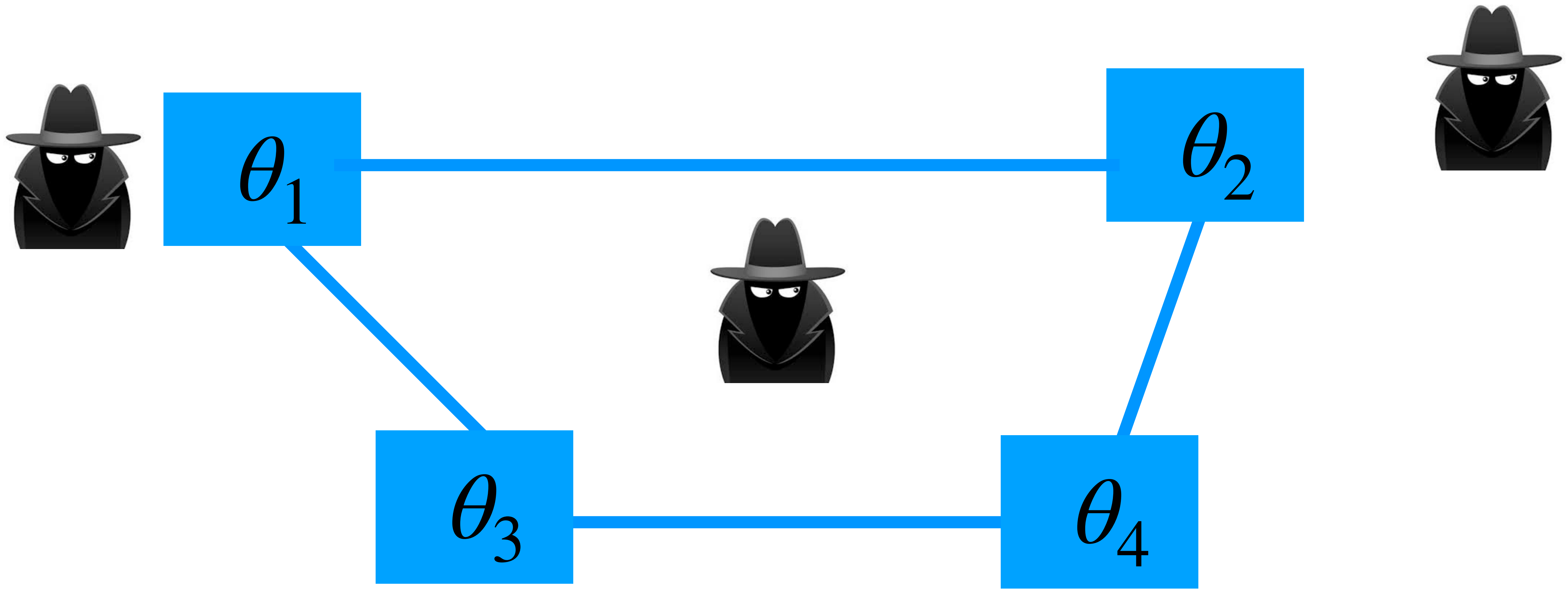

- Optimal estimation of

$$f(\bar{\theta}) = 1/n \sum_i \theta_i$$

- Privacy and integrity

$$\rho_E \propto I \qquad \left| \tilde{f}(\bar{\theta}) - f(\bar{\theta}) \right| \leq \epsilon \qquad \left| \Delta \langle \tilde{f}(\bar{\theta}) \rangle^2 - \Delta \langle f(\bar{\theta}) \rangle^2 \right| \leq \epsilon$$

- Distributed privacy (sensing meets SMPC)

$\{\theta_i\}$ cannot be known by any parties!

[N. Shettel, M. Hassani, DM arxiv 2207.14450] [M. Hassani, S. Scheiner, M. Paris, DM PRL 2025] [L. Bugalho, M. Hassani, Yasser Omar, DM, Quantum 2024]

Thanks!

https://qi.lip6.fr

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