Recent trends in quantum technologies

4th Professor Manoj Kanti Banerjee Memorial Lecture

ADITI

HARISH-CHANDRA RESEARCH INSTITUTE, PRAYAGRAJ, INDIA

Useful appliances

Classical World

Day-to-day life

~1900-30

Quantum Science

20th century: a new theory of matter and energy was emerging

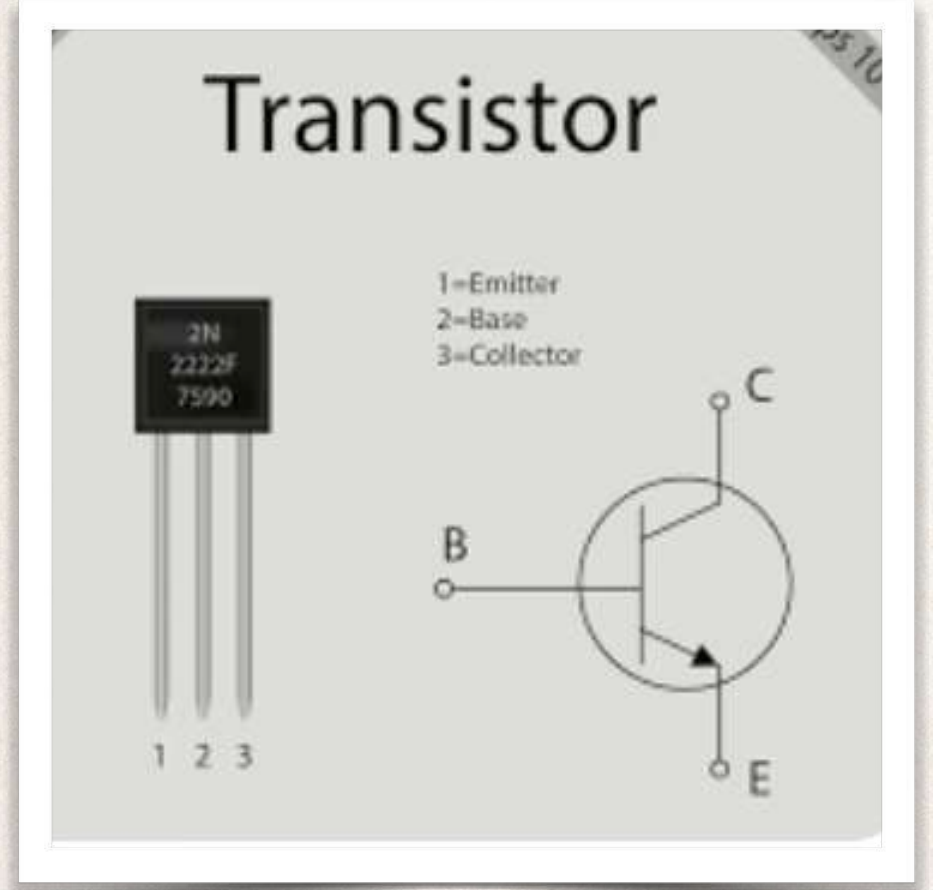
—unsatisfied with classical explanations

~1960

Useful appliances:

First revolution of quantum technology

Transistors,
nuclear magnetic resonance used for MRI scans,
Laser



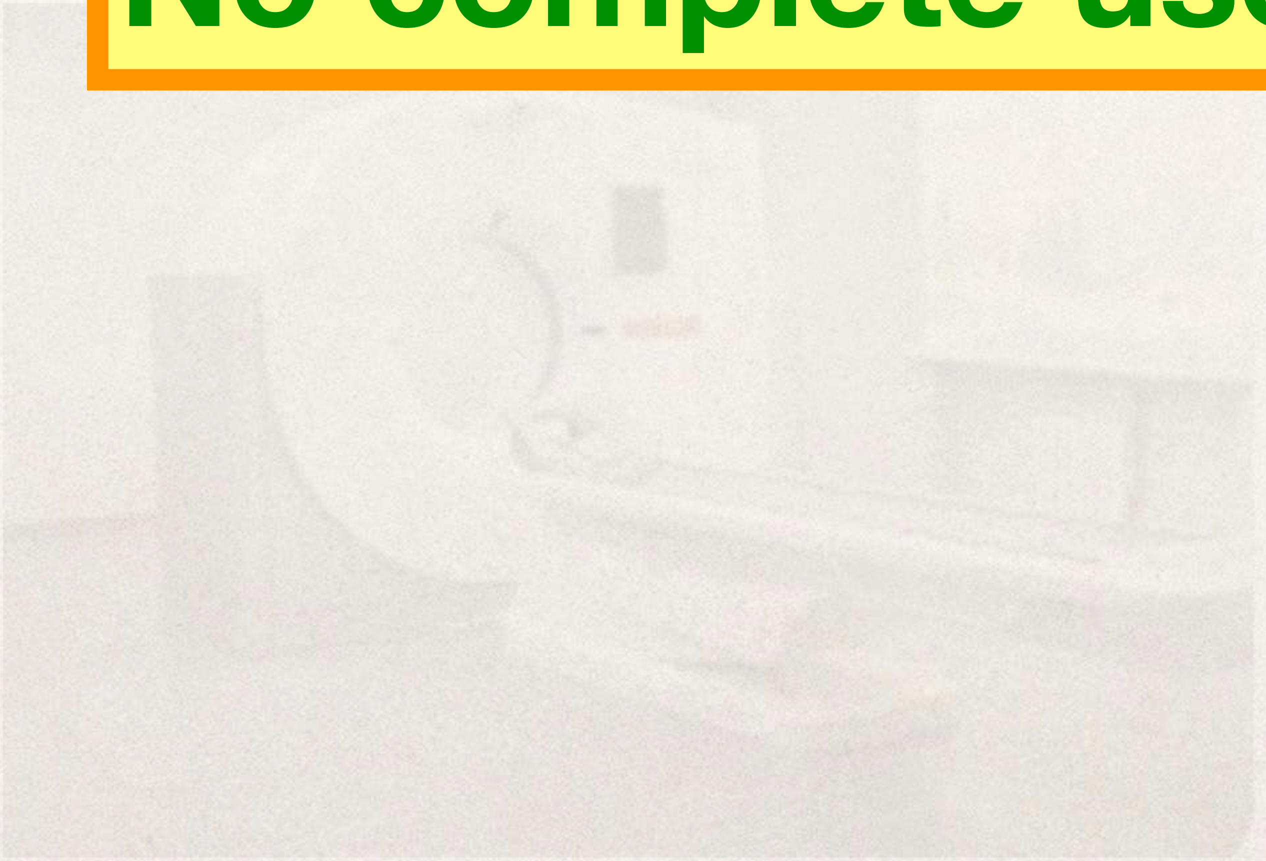
~1960

Useful appliances:

First revolution of quantum technology

Transistors,
nuclear magnetic resonance used for MRI scans, Laser

No complete use of quantum mechanics



~1990

Quantum Science

↓

Second revolution of Quantum Technologies

Pathways

- Quantum computer

Pathways

- Quantum computer
- Quantum communication
- Quantum cryptography

Pathways

- Quantum computer
- Quantum communication
- Quantum cryptography
- Other quantum devices

Q sensors, q batteries, q simulators

Pathways

- Quantum computer
- Quantum communication
- Quantum cryptography

Why?

- Other quantum devices

Q sensors, q batteries, q simulators

Pathways

- Quantum computer
- Quantum communication
- Quantum cryptography
- Other quantum devices
- Fundamental queries

Quantum Computer

Quantum cryptography

Potentially deep social impact

May lead to nation's further development

Quantum simulators

Quantum batteries

Second revolution of Quantum Technologies

Quantum Computer

Quantum Science

Quantum communication

Quantum cryptography

Quantum Sensors

Quantum simulators

Quantum thermal device

Second revolution of Quantum Technologies

Quantum Computer

Q Algorithms, Q error correction, Q gates….

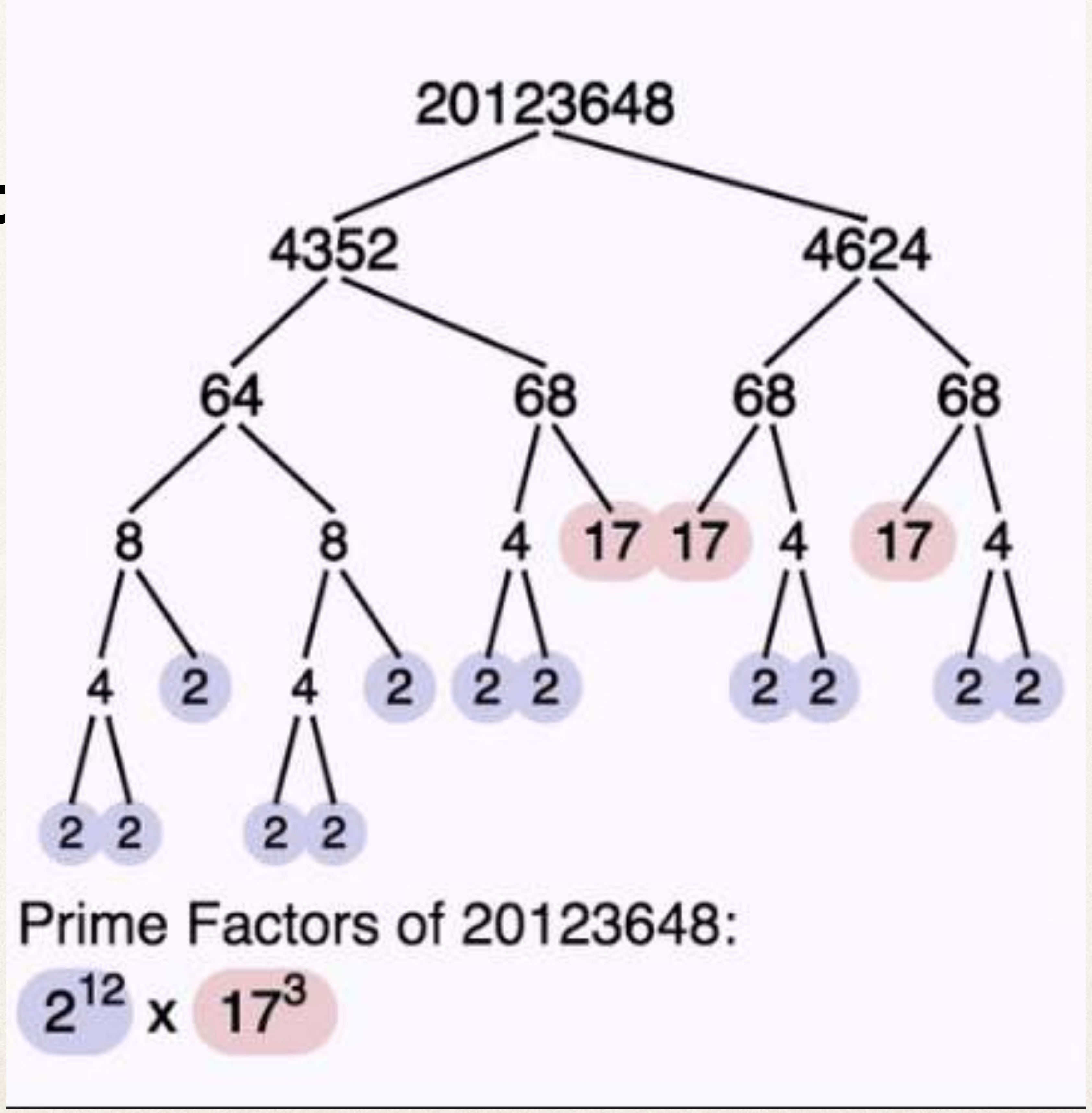
Why?

Q Computer

PRIME FACTORIZATION

Task : Finding prime factors of an integer

8 digit



PRIME FACTORIZATION

Task : Finding prime factors of an integer

56277861237612381238712387218372917 3 → 35 digit

PRIME FACTORIZATION

Task : Finding prime factors of an integer

562778612376123812387123872183729173 → 35 digit

$5.87521*10^{11}$ steps

At most

Time

130 seconds

Thanks to Tamoghna Das

PRIME FACTORIZATION

Digit	Tim
82	1.1 year
120	2100 years
200	25 Billion

PRIME FACTORIZATION

To factor an n-digit number, an algorithm in our computer may take huge time

$\exp(\Theta(n^{1/3} \log^{2/3} n))$

n-bit integer

M. Nielsen & I. Chuang, Cambridge University Press, (2010)

PRIME FACTORIZATION

$\exp(\Theta(n^{1/3} \log^{2/3} n))$

No efficient classical algorithm till date

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Quantum mechanics promises qualitatively better efficiencies than its classical counterpart:

"Shor's algorithm"

$O(n^2 \log n \log \log n)$ SHOR, '94

PRIME FACTORIZATION

$\exp(\Theta(n^{1/3} \log^{2/3} n))$

No efficient classical algorithm till date

Quantum mechanics promises qualitatively better efficiencies than its classical counterpart:

"Shor's algorithm"

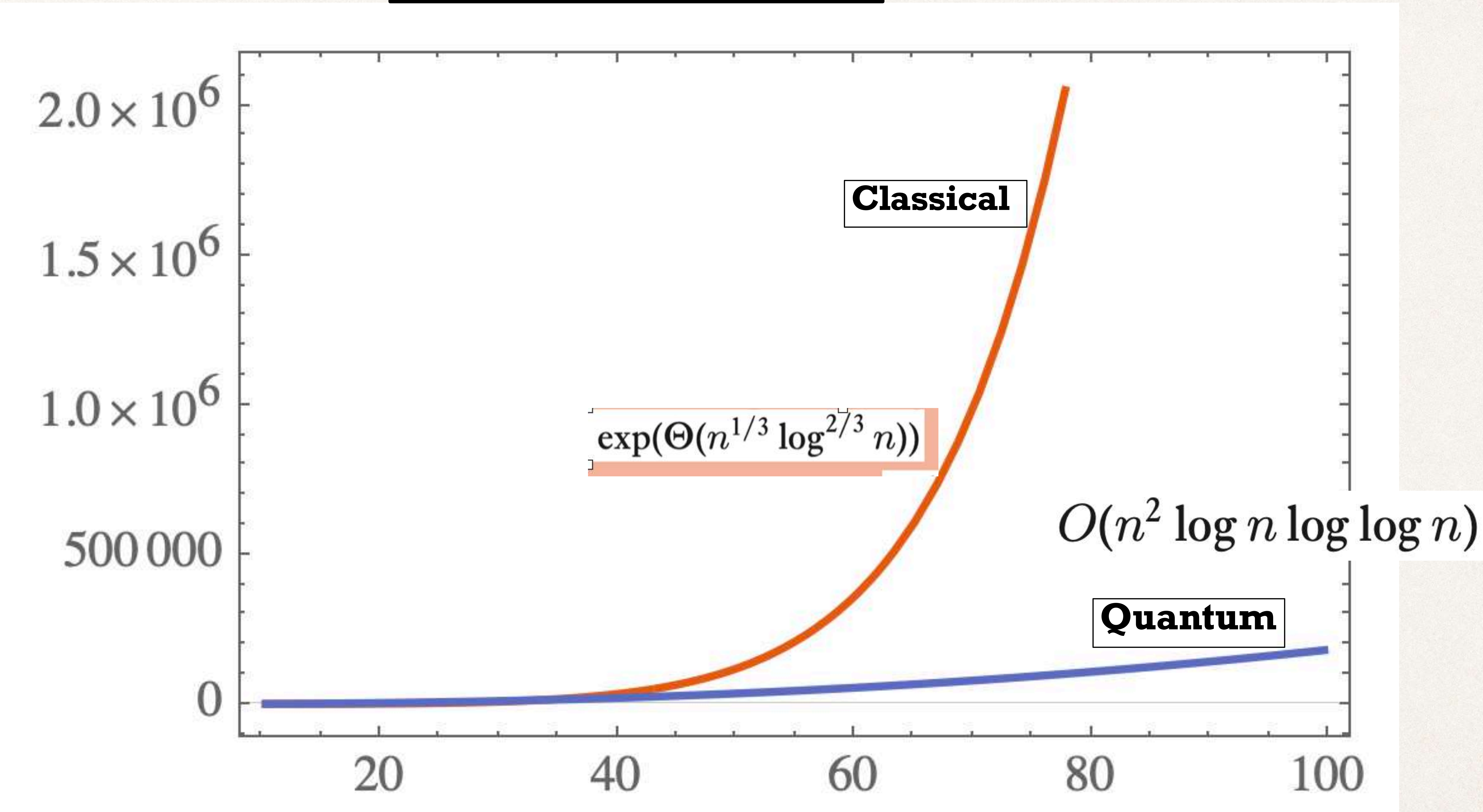
$O(n^2 \log n \log \log n)$

SHOR, '94

Breakthrough discovery & motivation for quantum computer

PRIME FACTORIZATION

Quantum vs Classical



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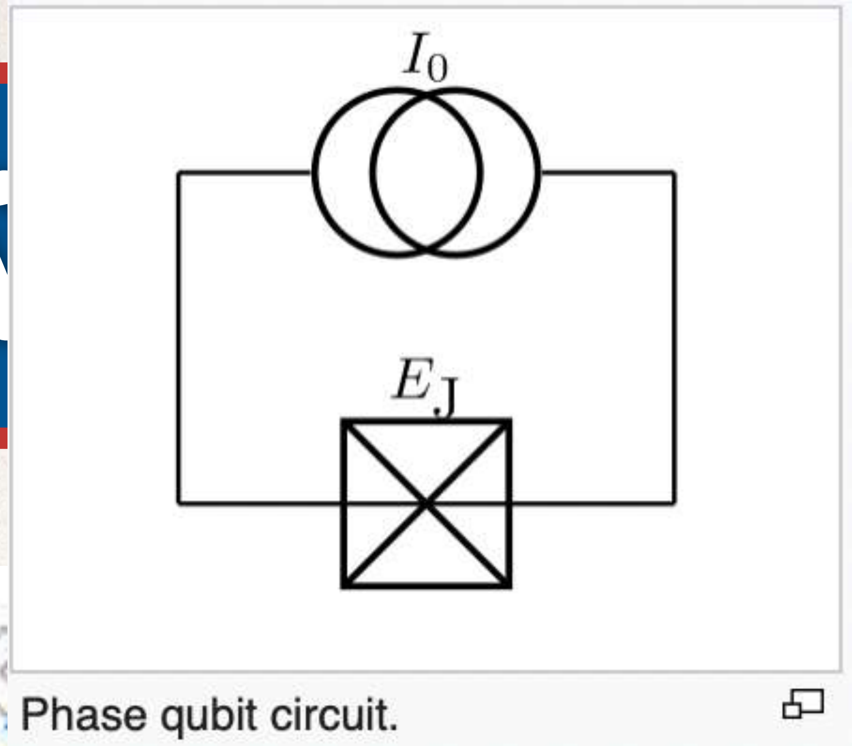
PRIME FACTORIZATION



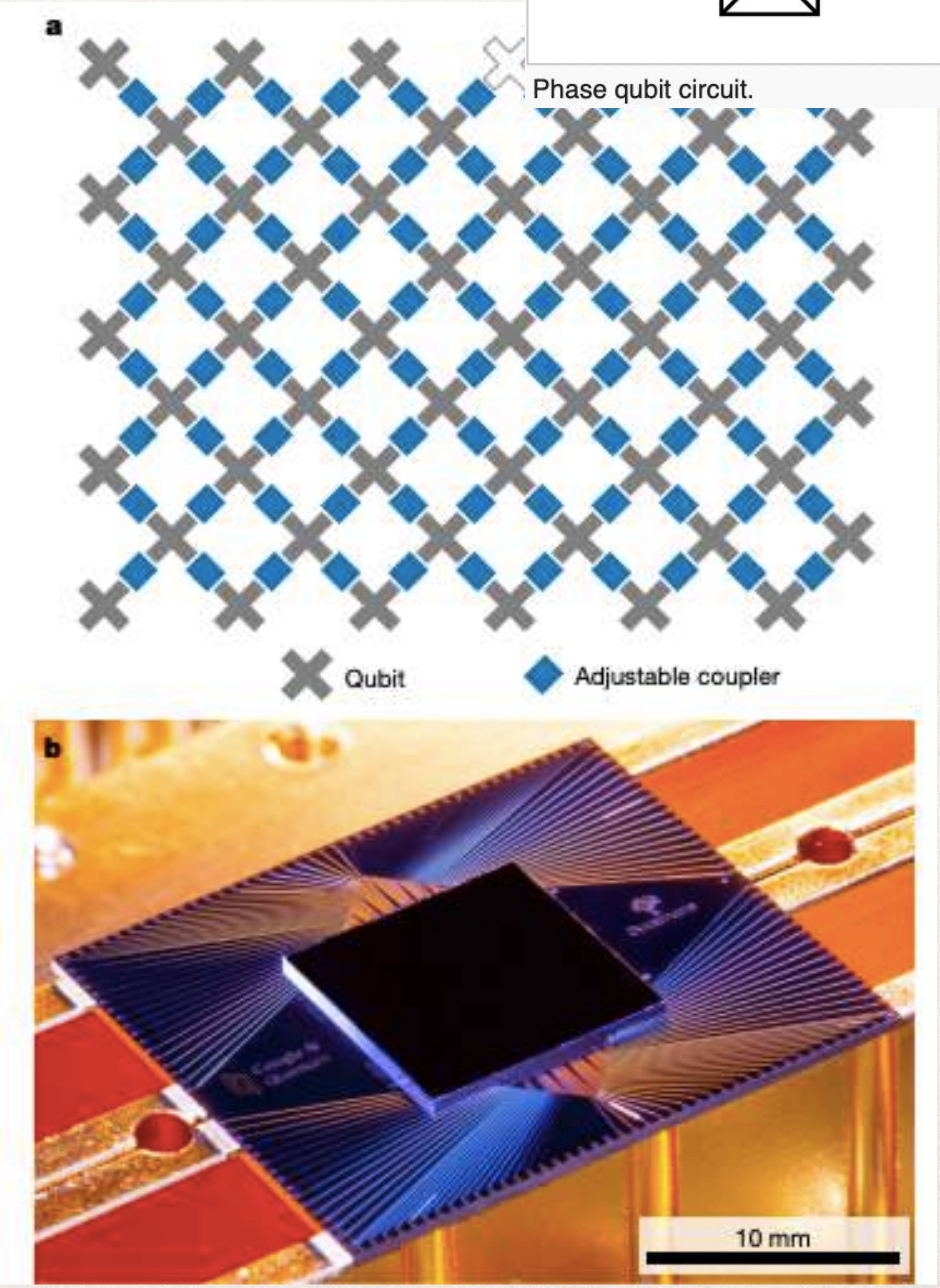
Phase qubit circuit.

Quantum supremacy using a programmable superconducting processor

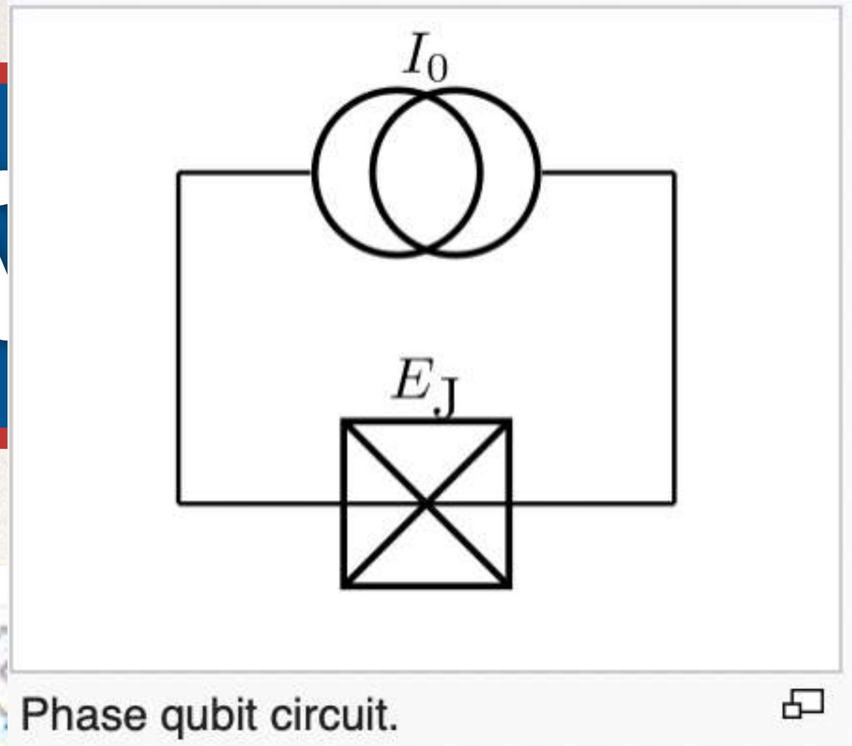
Frank Arute, Kunal Arya, [...] John M. Martinis

Nature **574**, 505–510(2019) | Cite this article

- Google claims that Q computer can finish a task in 3 minutes and 20 seconds while a classical supercomputer requires 10,000 years.



PRIME FACTORIZATION



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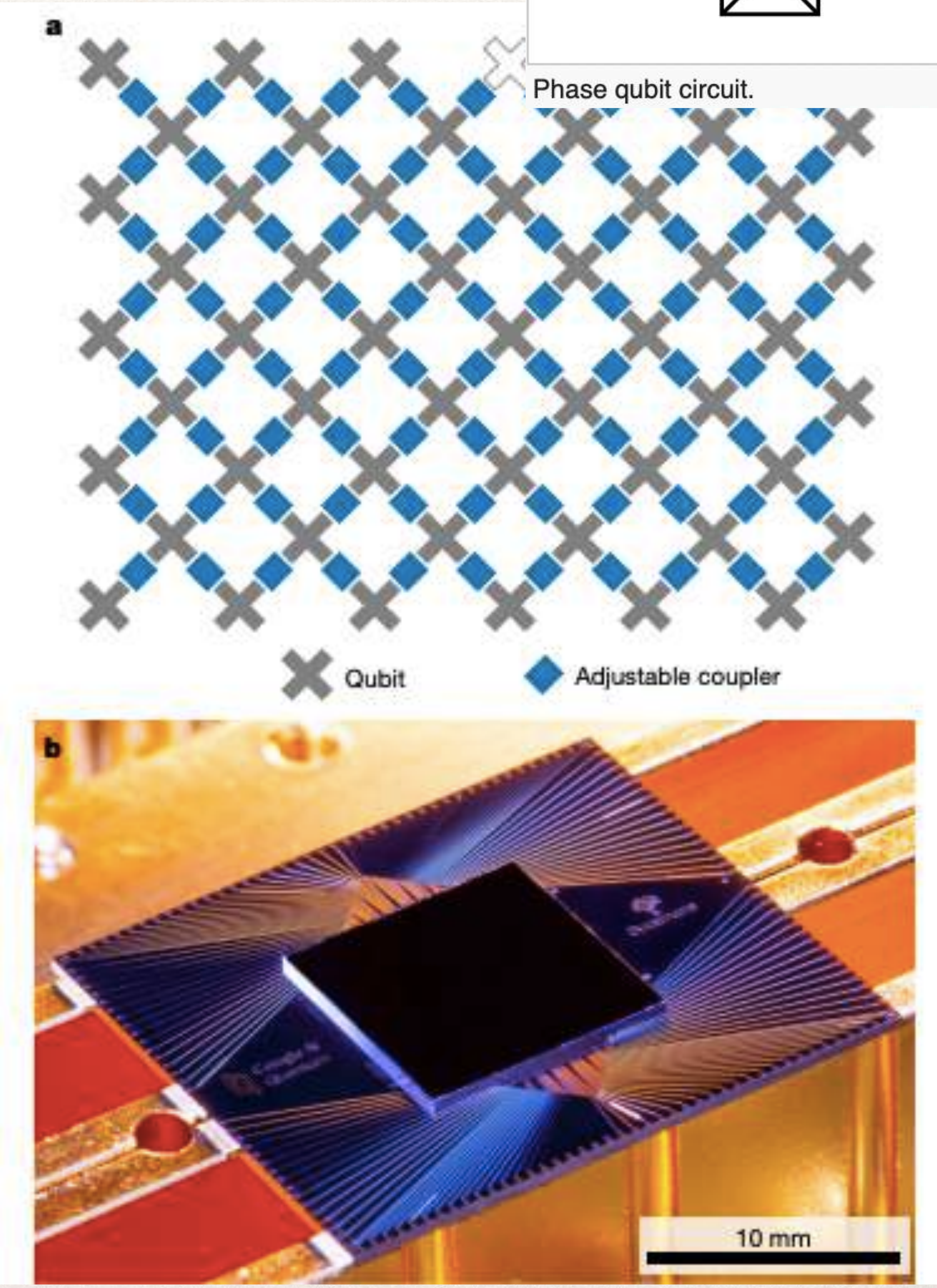

BBC

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Google claims 'quantum supremacy' for computer

23 October 2019

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Paul Rincon
Science editor, BBC News website

PRIME FACTORIZATION

Quantum supremacy using a programmable superconducting processor

Frank Arute, Kunal Arya, […] John M. Martinis

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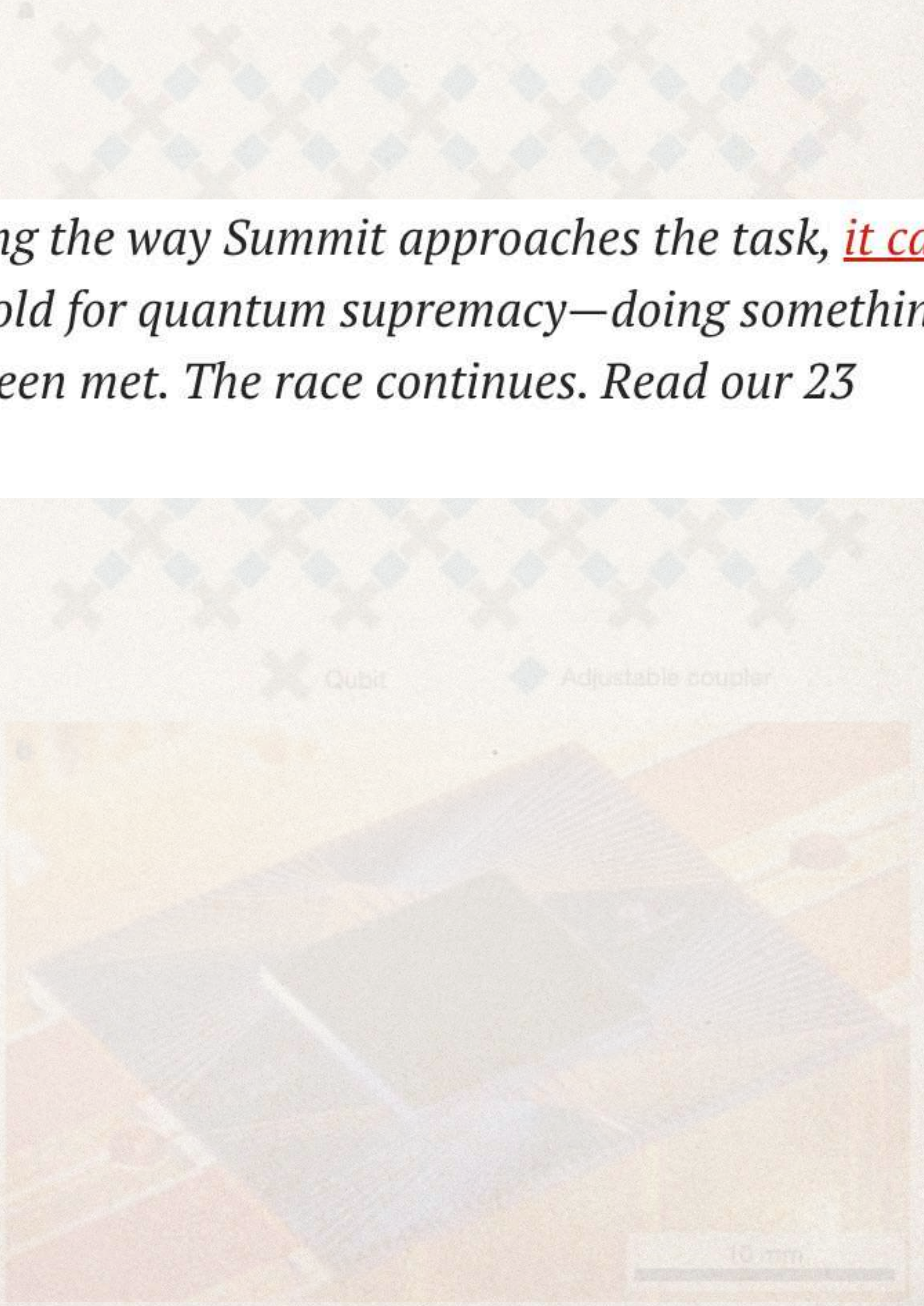
On 21 October, it announced that, by tweaking the way Summit approaches the task, it can do it far faster: in 2.5 days. IBM says the threshold for quantum supremacy—doing something a classical computer can't—has thus still not been met. The race continues. Read our 23 September story here:

- Google claims that Q computer can finish a task in 3 minutes and 20 seconds while a classical supercomputer requires 10,000 years.

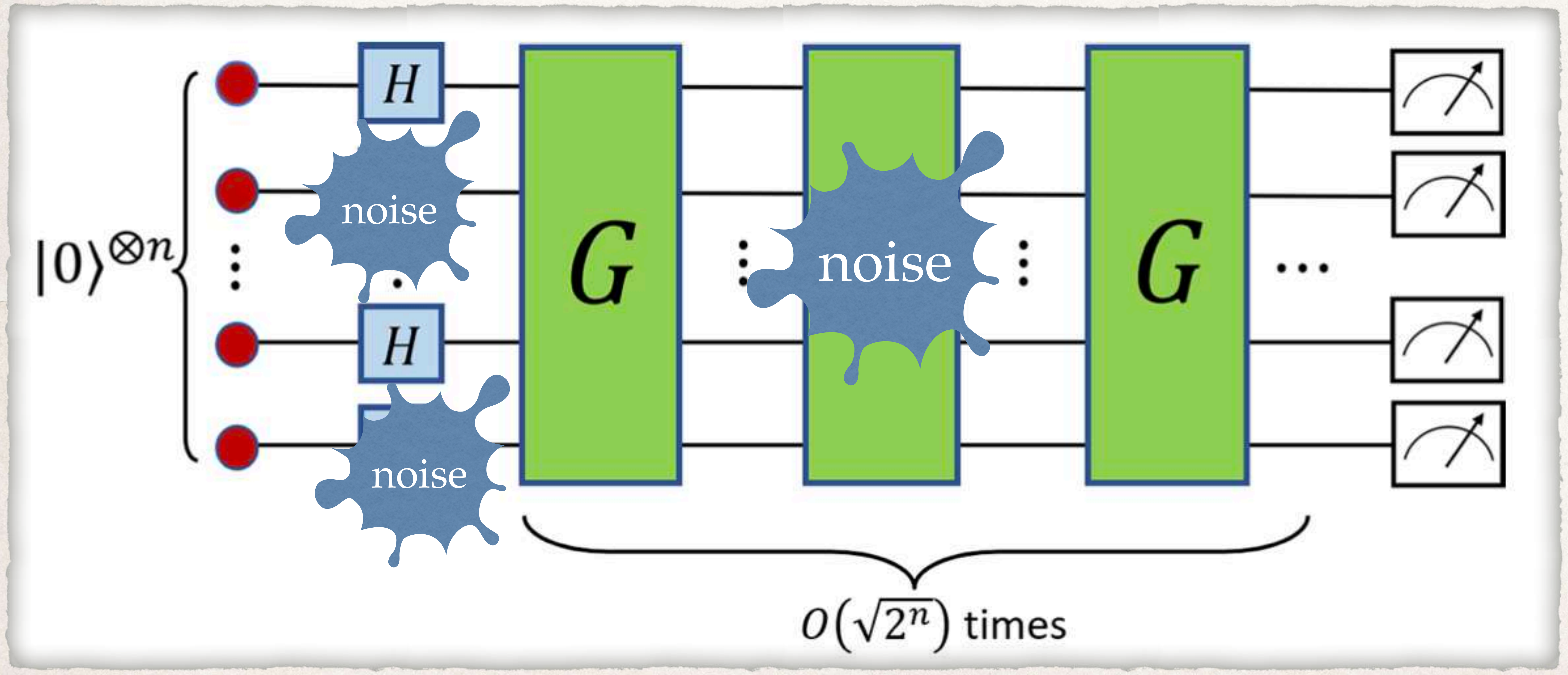
- Researchers in Beijing say they took a different approach that saw 60 graphics processors complete the job 'in about five days'



Quantum Computer @HRI

Q Algorithms, Q error correction, Q gates….

1. How quantum circuits gets affected by noise? so quantum algorithms?…



Quantum Computer @HRI

Q Algorithms, Q error correction, Q gates….

1. How quantum circuits gets affected by noise? so quantum algorithms?

2. Design of quantum circuits (bunch of quantum gates) — Characterization of q gates, robustness against noise, imperfections in circuits,…

3. Measurement-based quantum computation — implementable, eg. in ion-traps, supcon circuits

Universal quantum gates

Classical Gates

AND, OR and NOT

NAND

Universal quantum gates

Classical Gates

AND, OR and NOT

NAND

Quantum Gates

Hadamard gate

$$|0\rangle \rightarrow \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$$

$$|1\rangle \rightarrow \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle)$$

CNOT gate

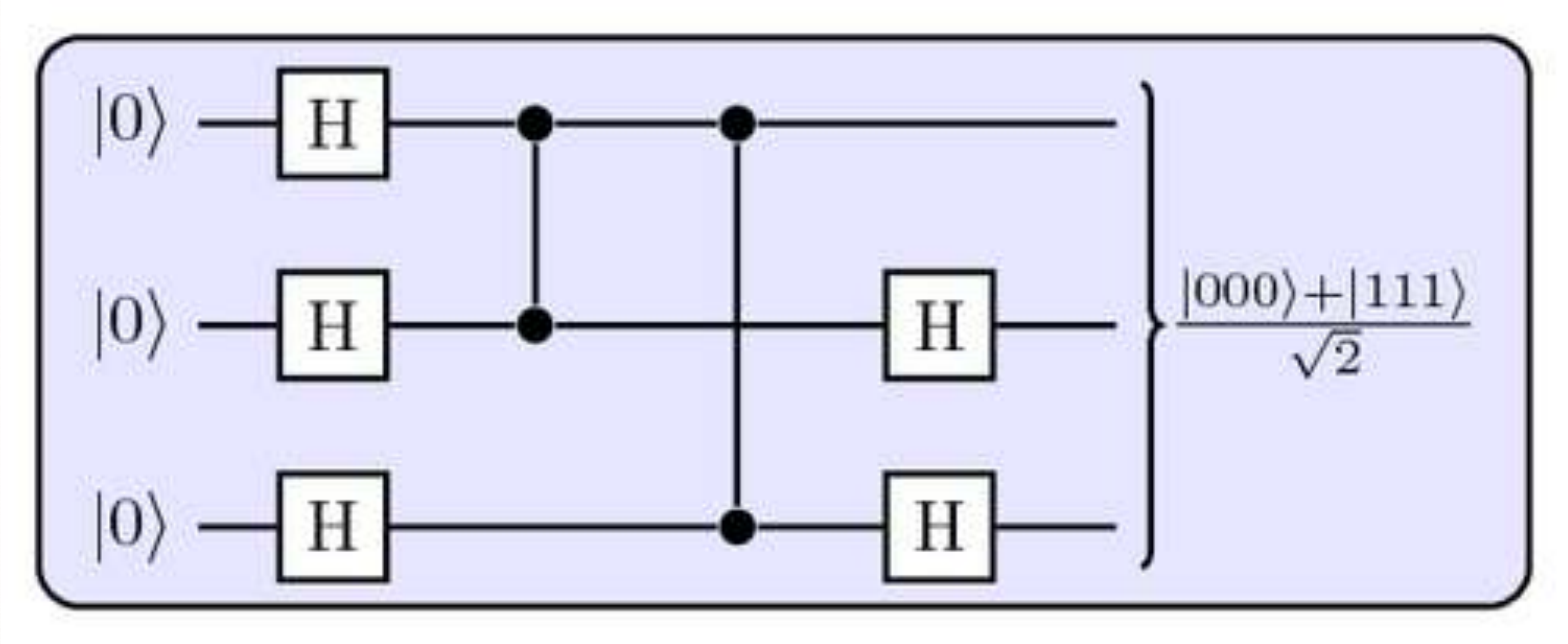
$$|00\rangle \rightarrow |00\rangle$$

$$|01\rangle \rightarrow |01\rangle$$

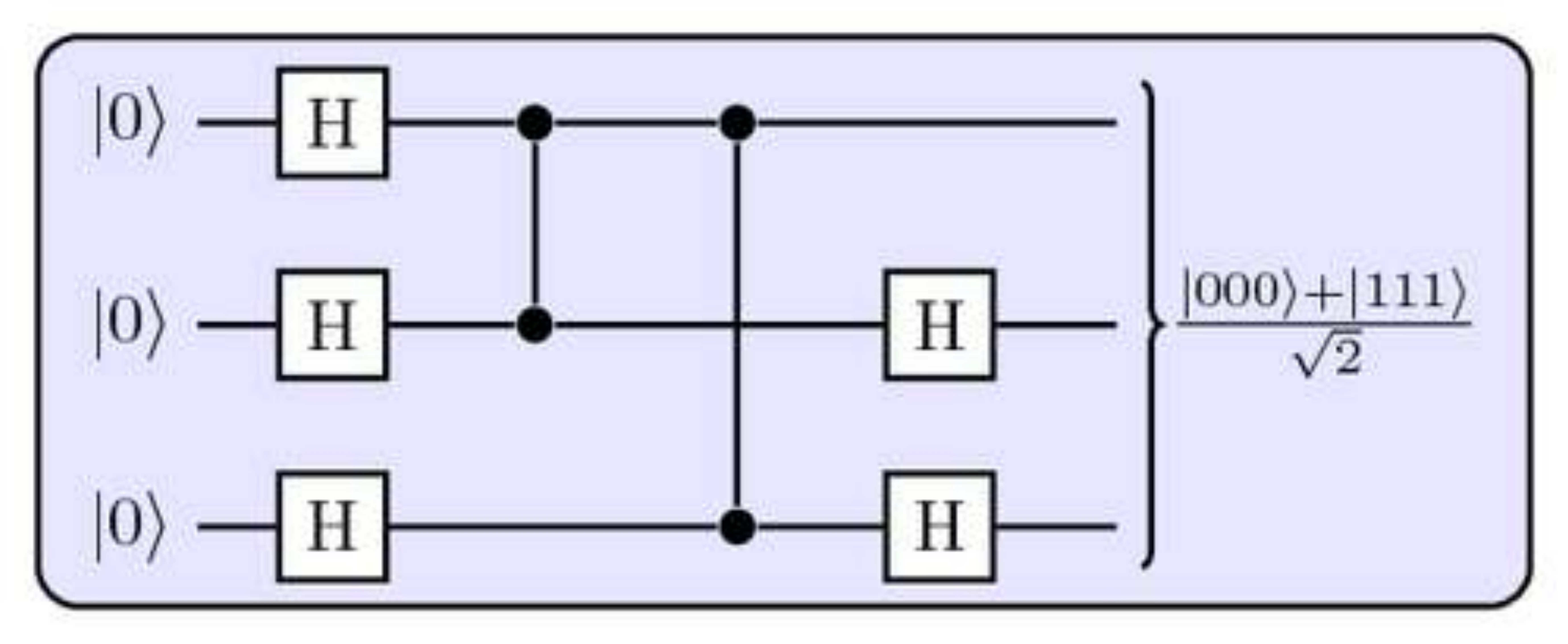
$$|10\rangle \rightarrow |11\rangle$$

$$|11\rangle \rightarrow |10\rangle$$

Quantum circuits

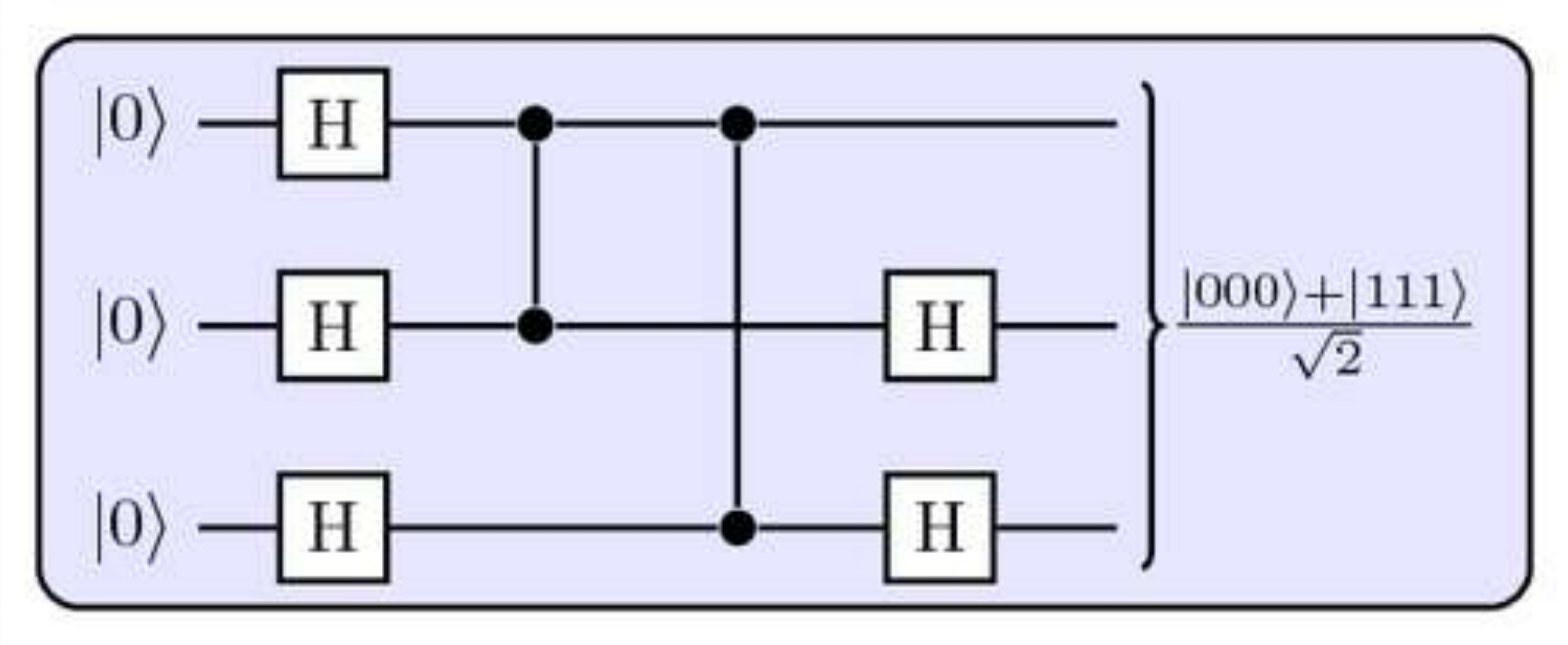


Quantum circuits



Quantum Circuits consisting of quantum gates execute quantum algorithms

Quantum circuits

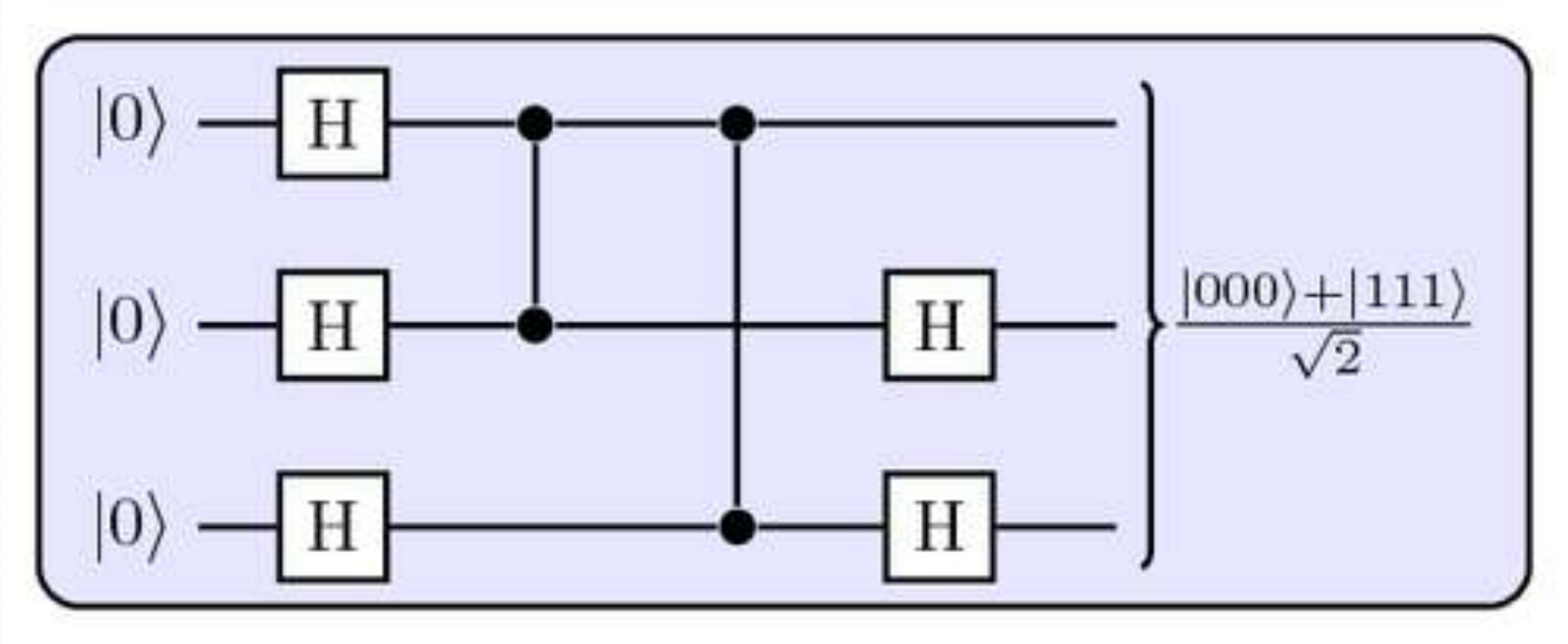


Quantum Circuits consisting of quantum gates execute quantum algorithms

Finding optimal q circuits — a challenge

Quantum circuits

S. Mondol, S. K. Hazra, ASD, arXiv:2302.06574



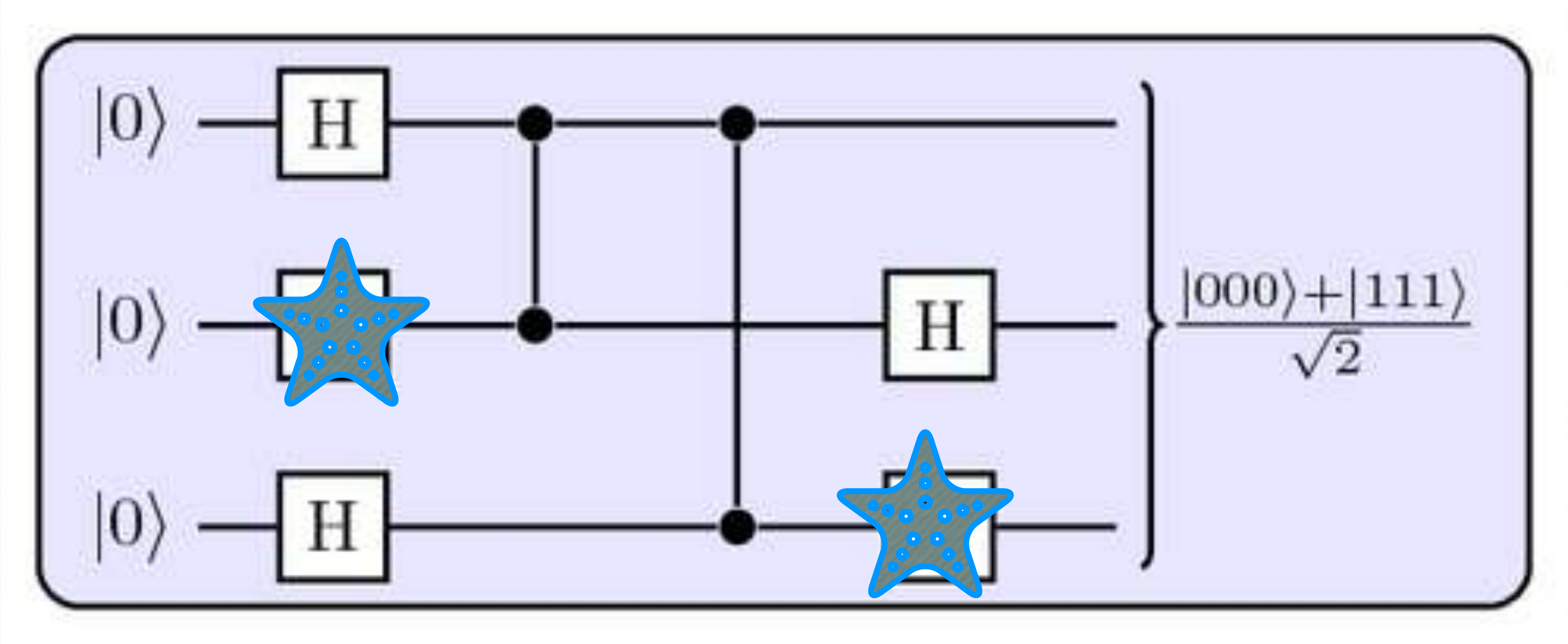
Quantum Circuits consisting of quantum gates execute quantum algorithms

Finding optimal q circuits — a challenge

Understanding — capabilities of q gates

Quantum circuits

S. Mandal, S. K. Hazra, ASD, arXiv soon



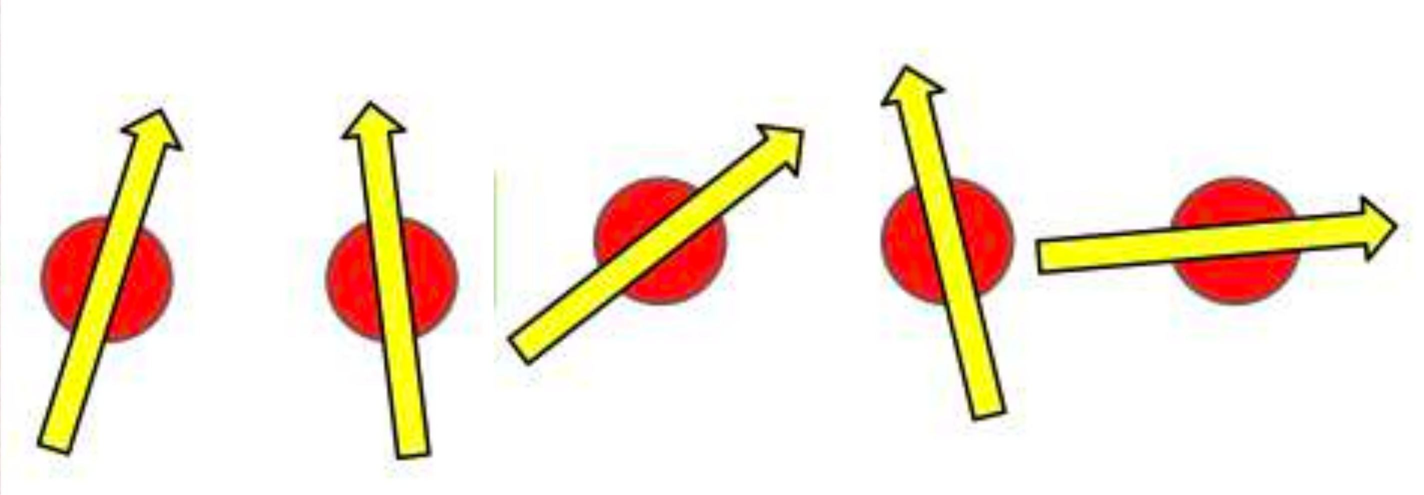
Quantum Circuits consisting of quantum gates execute quantum algorithms

Finding optimal q circuits — a challenge

Robustess of quantum gates

Measurement-based Q computer

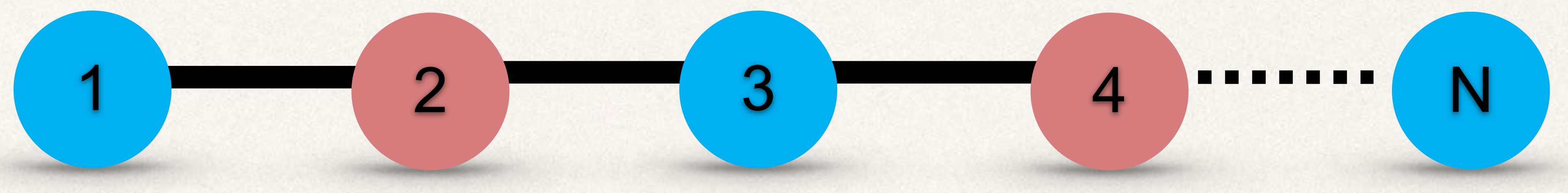
Initial state preparation



Measurement-based Q computer

nearest-neighbor interactions

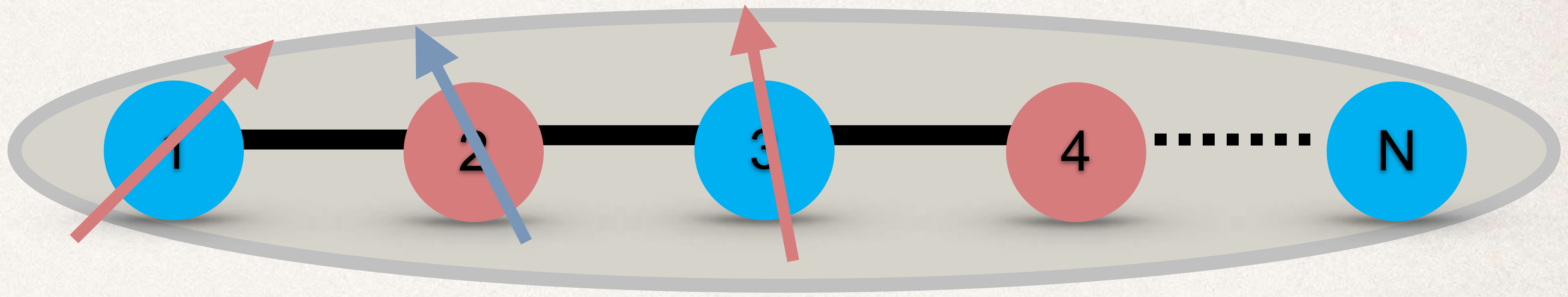
Initial state preparation → Evolve with suitable Hamiltonian



Measurement-based Q computer

nearest-neighbor interactions

Initial state preparation → Evolve with suitable Hamiltonian → Measurements on evolved state (gate implementation)



Raussendorf, Briegel: Phys. Rev. Lett (2001), Nat Phys. 2009

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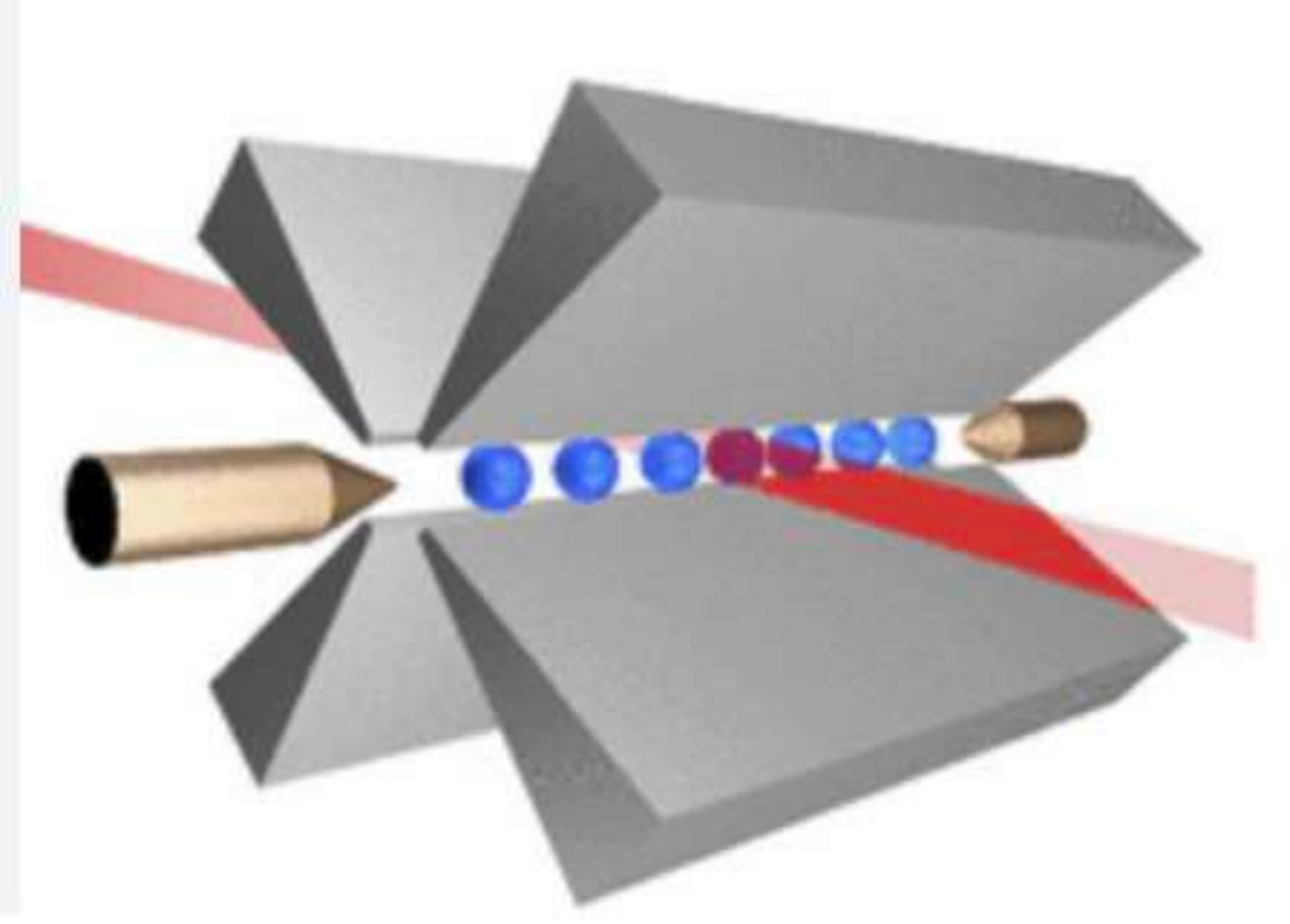

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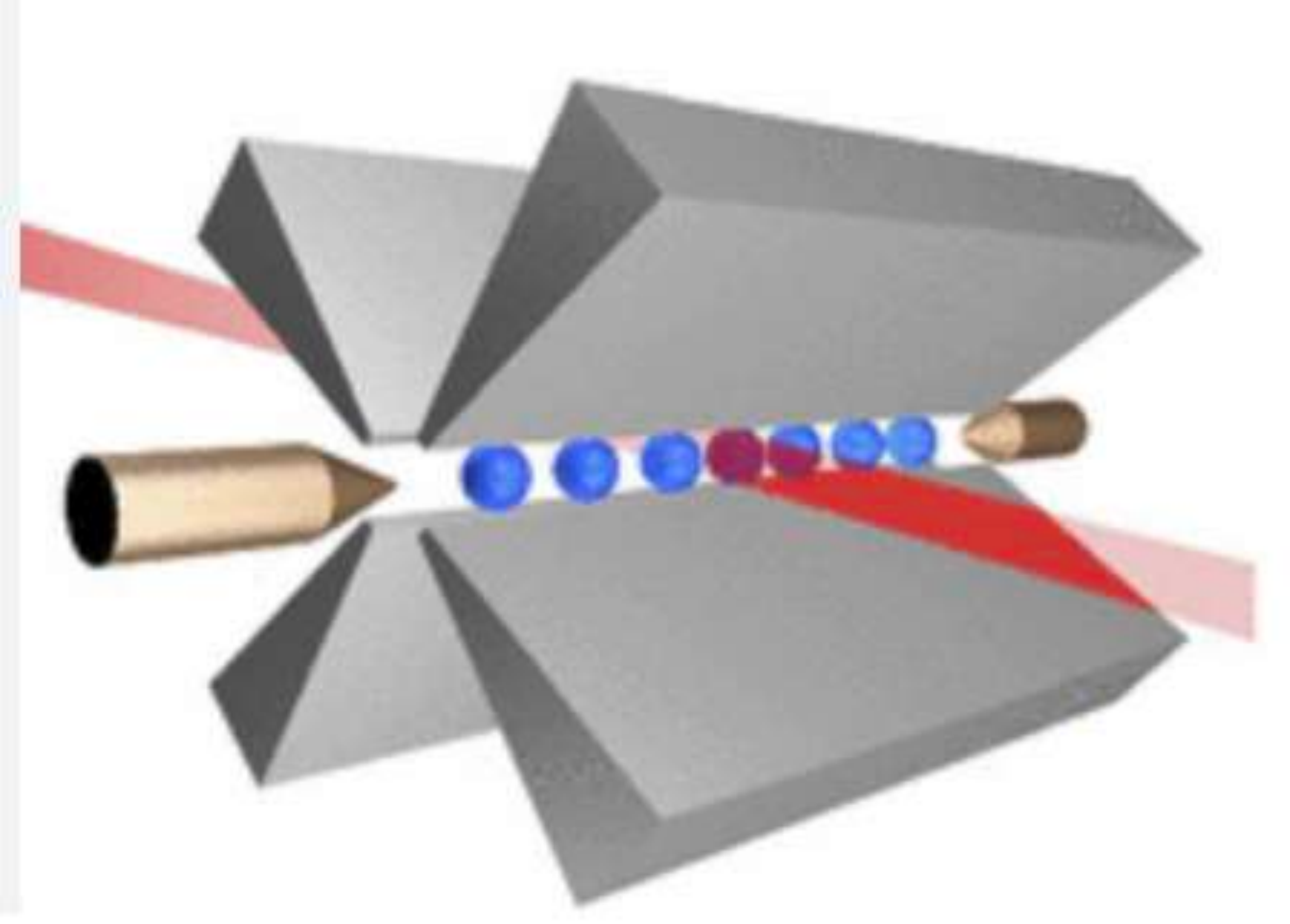

Long-range interactions

Measurement-based Q computer

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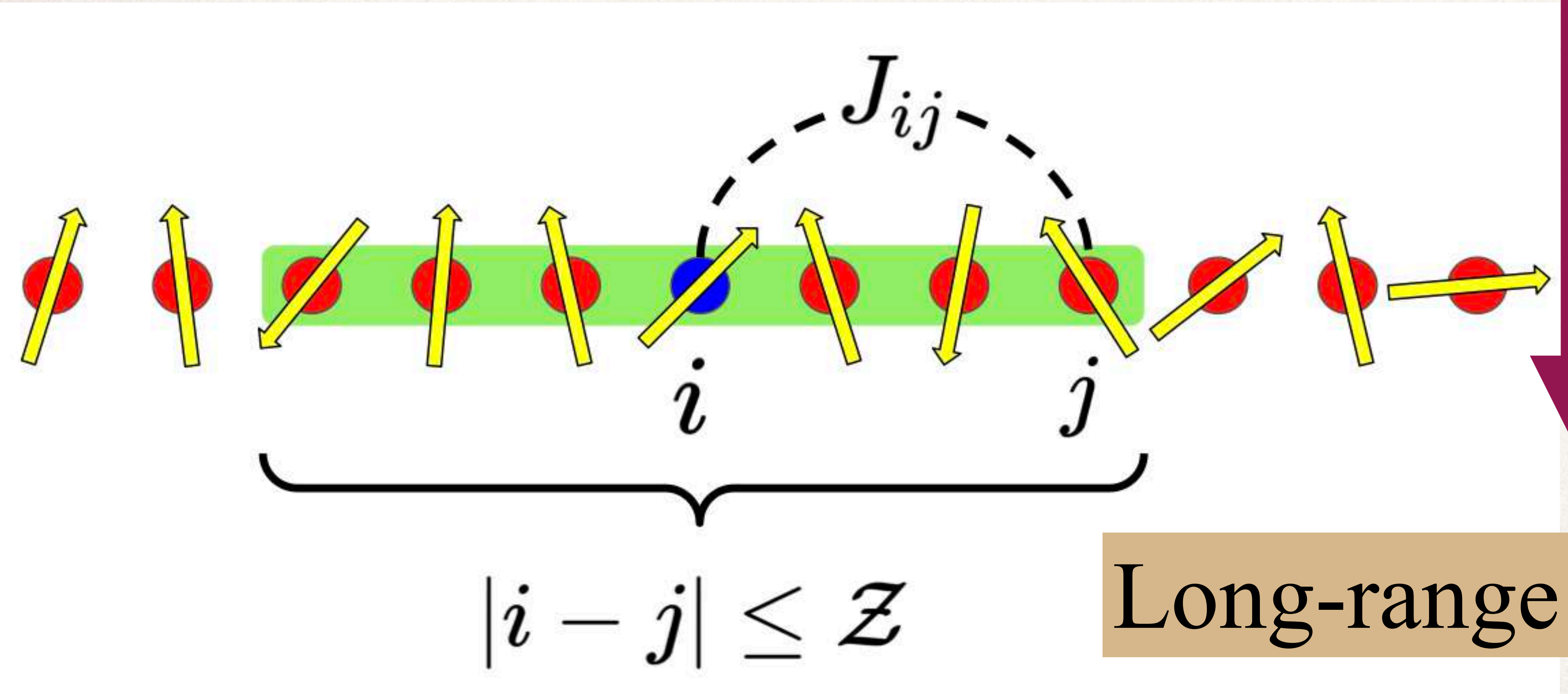

Long-range interactions

$$H_{ij} = \phi_{ij}\left(\frac{1-\sigma^z_{(i)}}{2}\right)\left(\frac{1-\sigma^z_{(j)}}{2}\right)$$

$$\phi_{ij} = |i-j|^{-\alpha} = r_{ij}^{-\alpha}$$

Spatial distance between the lattice sites, i and j.

Measurement-based Q computer

Initial state preparation → Evolve with suitable Hamiltonian → Measurements on evolved state (gate implementation)

Evolve with suitable Hamiltonian ↓ Long-range interactions

Is it suitable for MBQC?
``Entanglement" properties?

$$H_{ij} = \phi_{ij}\left(\frac{1-\sigma^z_{(i)}}{2}\right)\left(\frac{1-\sigma^z_{(j)}}{2}\right)$$

$$\phi_{ij} = |i-j|^{-\alpha} = r_{ij}^{-\alpha}$$

Spatial distance between the lattice sites, i and j.

Ghosh, Agarwal, Halder, ASD: Phys. Rev. A (2024)

Measurement-based Q computer

Long-range interactions

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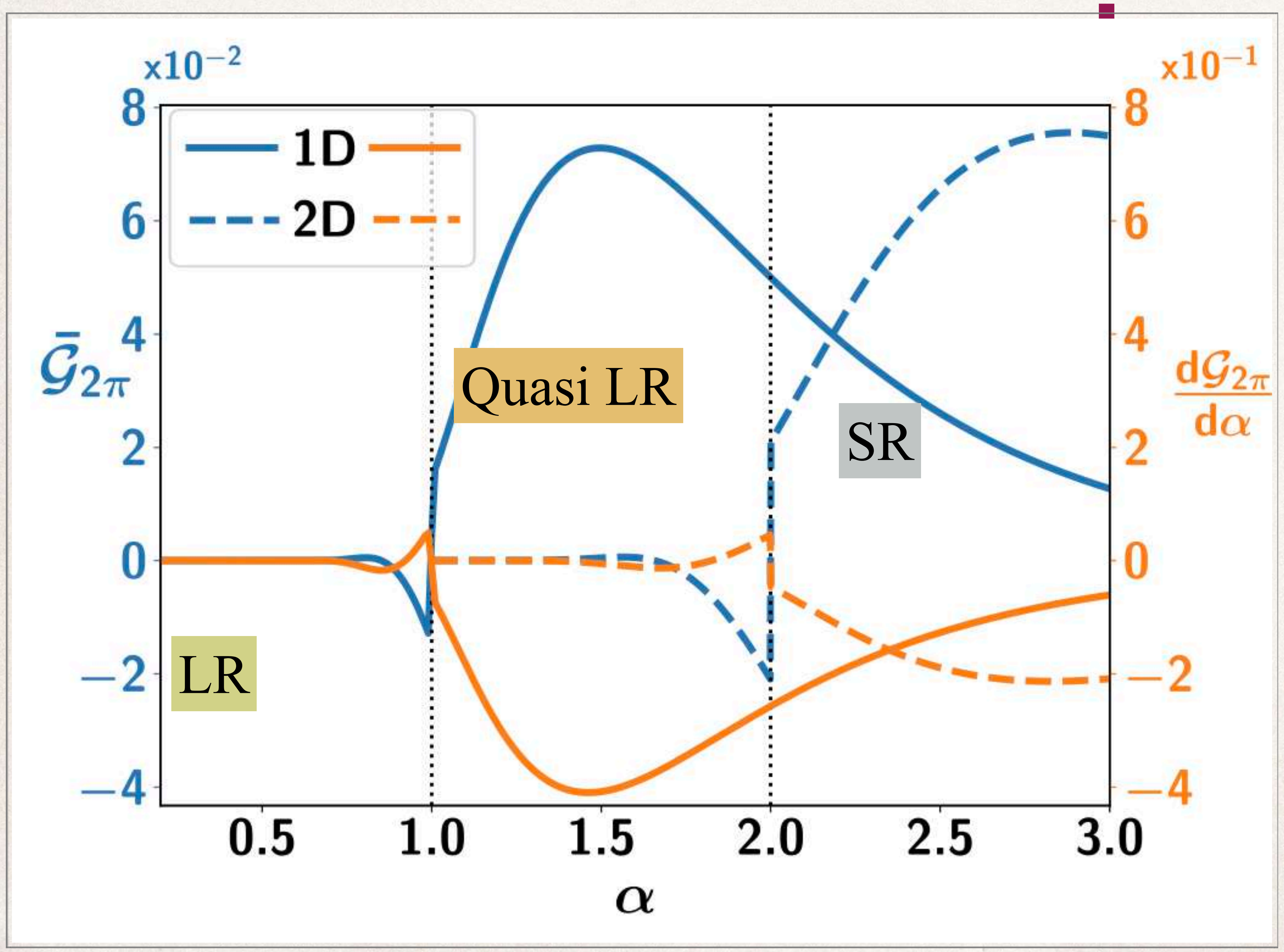

(1) Possible to create maximum multipartite entanglement as NN case.

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Measurement-based Q computer

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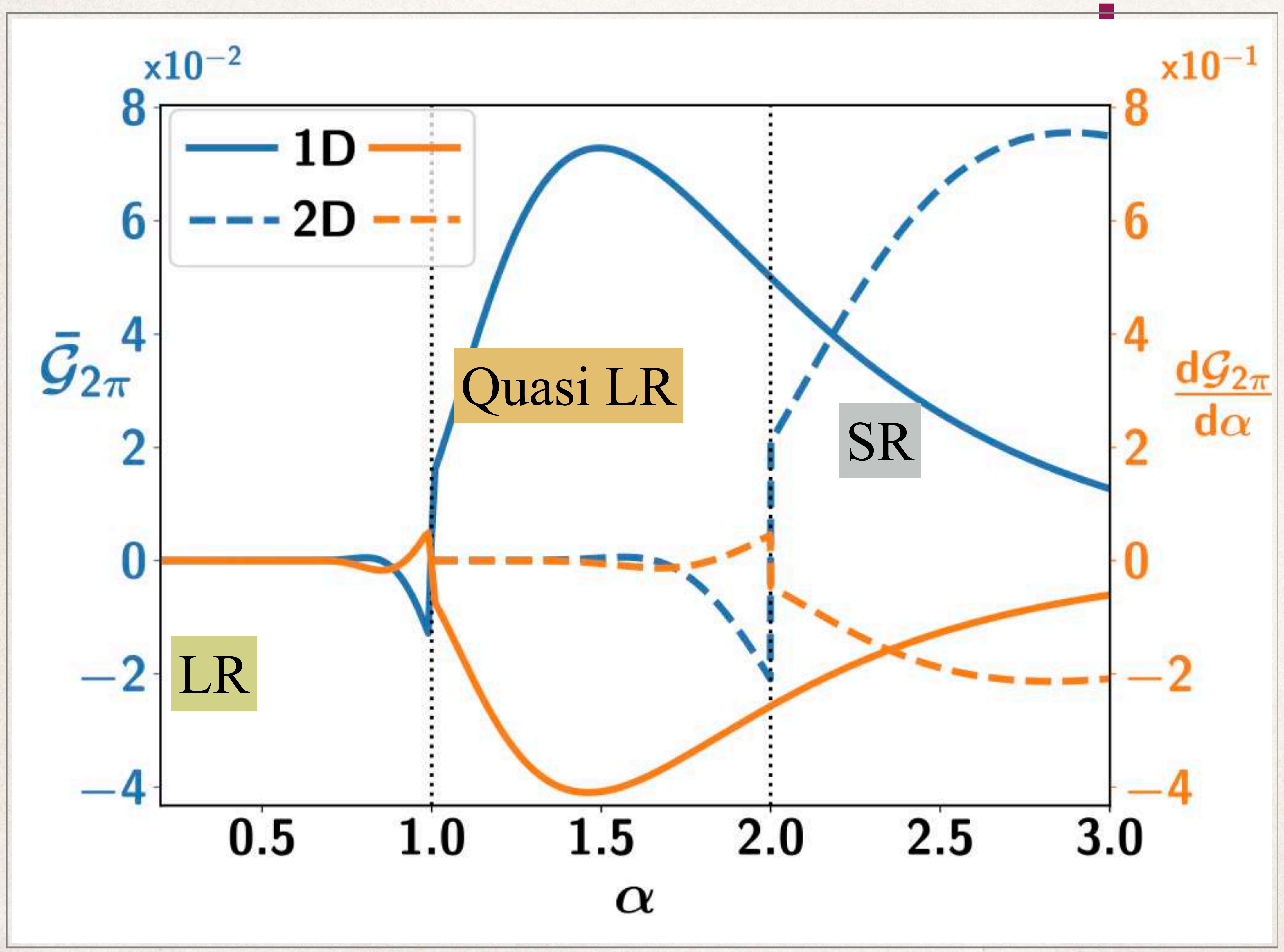


(1) Possible to create maximum multipartite entanglement as NN case.

(2) It can detect transition points efficiently.

Ghosh, Agarwal, Halder, ASD: Phys. Rev. A (2024)

Pathways

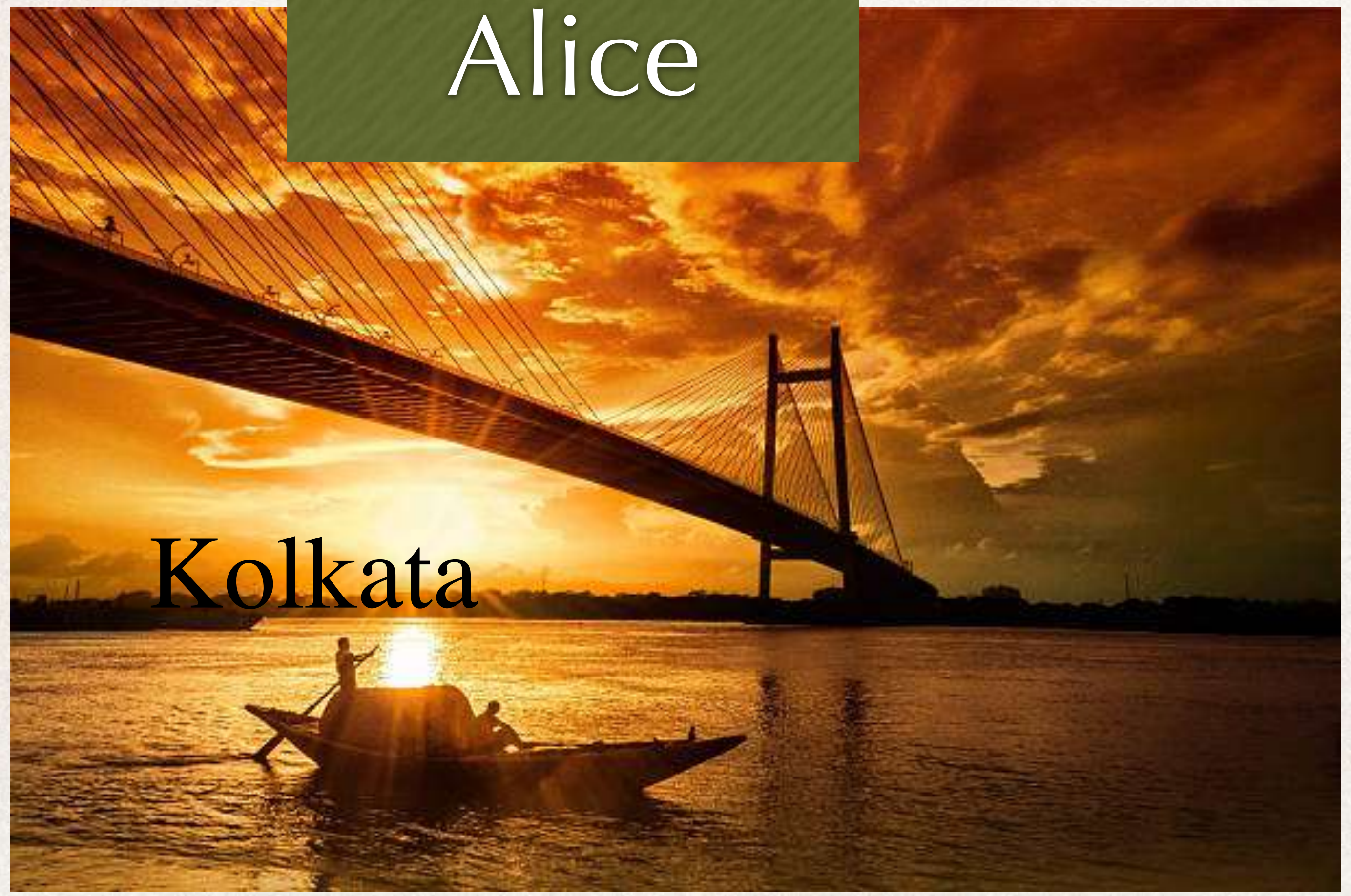
- Quantum computer
- Quantum communication
- Quantum cryptography
- Other quantum devices
- Fundamental queries

Communication

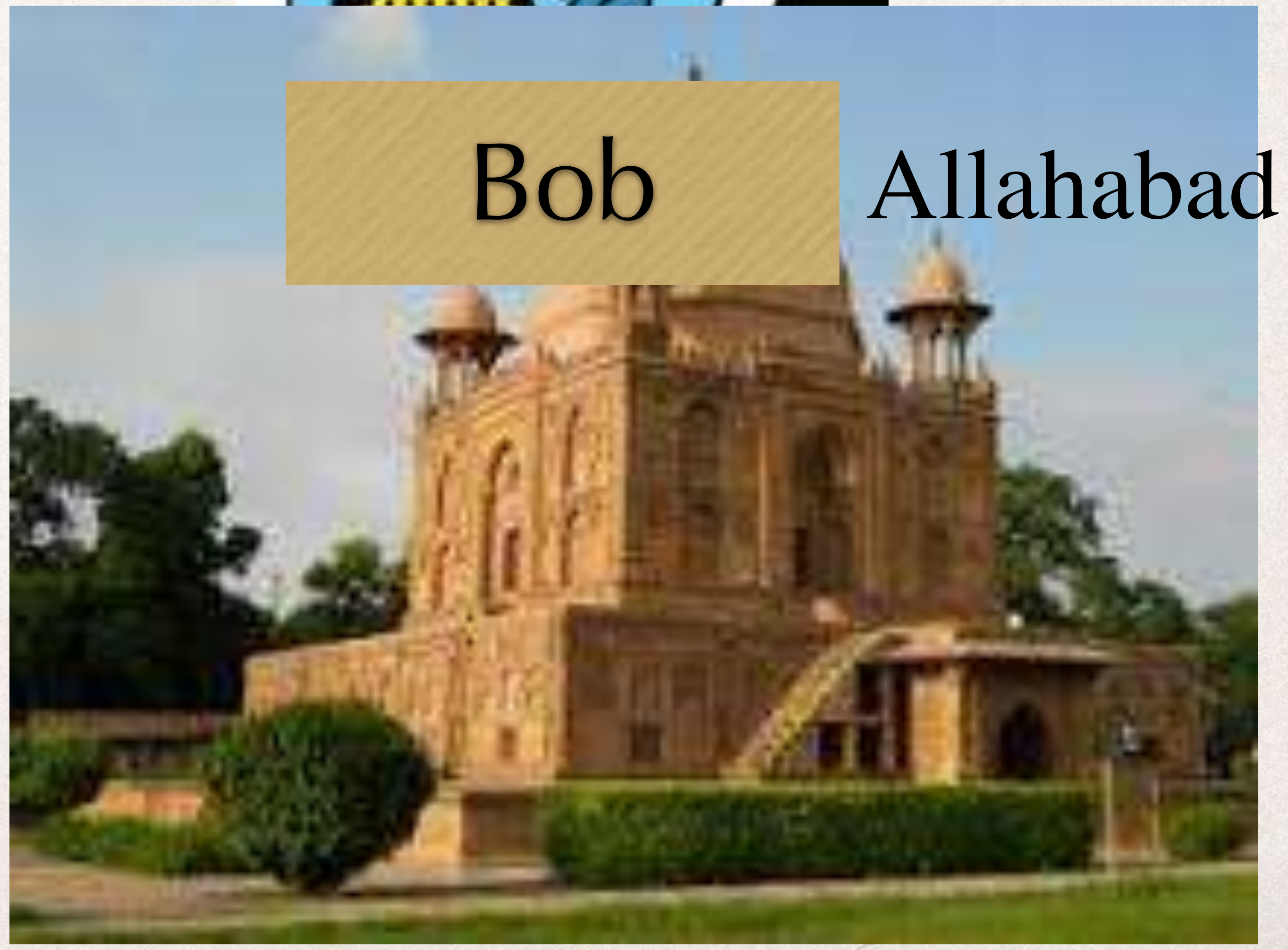
Alice

Communication

Alice



Bob

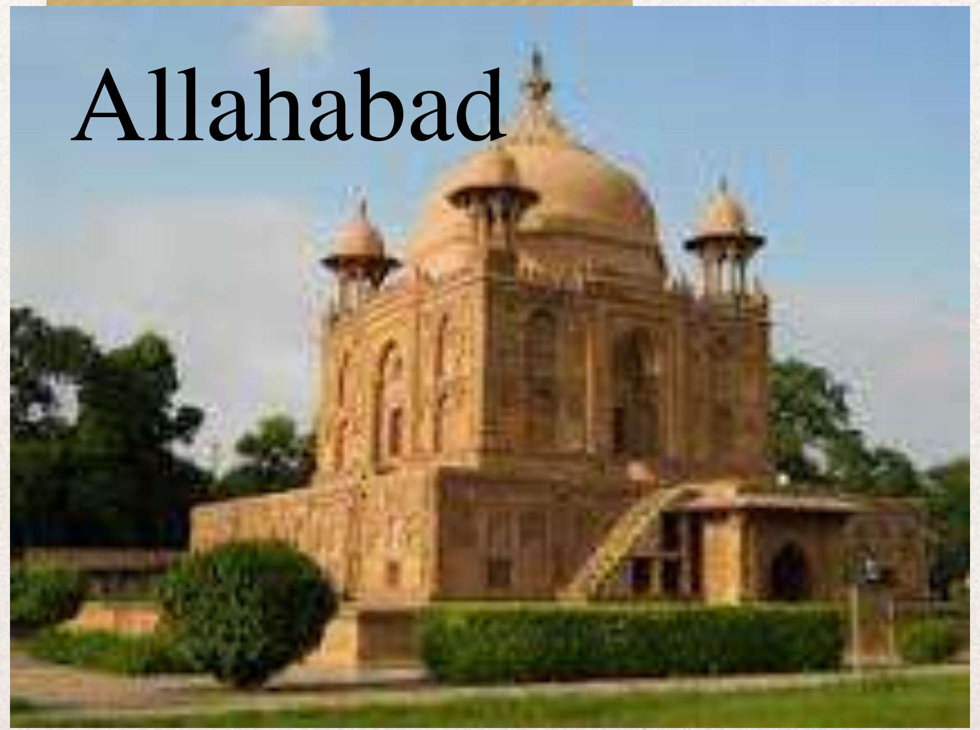


Allahabad

Communication

Alice

Bob



Communication

Alice

Sender

Bob

Receiver

Communication

Alice

Sender

Aim: Sending info from A to B

Bob

Receiver

Communication

Alice

Sender

Aim: Sending info from A to B

classical or quantum

Bob

Receiver

Communication

Alice

Sender

Aim: Sending info from A to B

classical or quantum

Classical computer unit:
Bit = one of {0, 1}

Bob

Receiver

Communication

Alice

Sender

Aim: Sending info from A to B

$\vee$

classical or quantum

Classical computer unit:
Bit = one of {0, 1}

quantum state

Bob

Receiver

Communication

Alice

Sender

Bob

Receiver

Aim: Sending info from A to B

$\vee$

classical or quantum

Classical computer unit:
Bit = one of {0, 1}

Bhubaneswar —> 01100011001010….

quantum state

Communication

Alice

Sender

Aim: Sending info from A to B

classical or quantum

Classical computer unit:
Bit = one of {0, 1}

qubit

Bob

Receiver

Communication

Alice

Sender

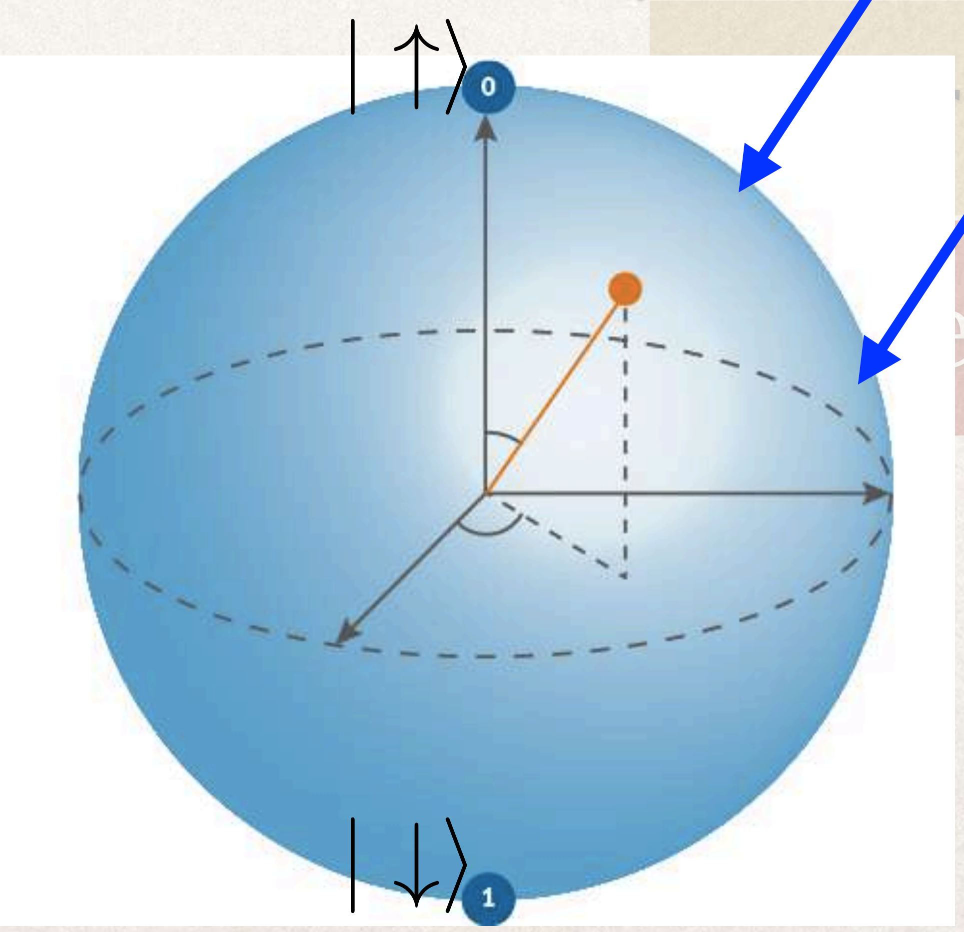
Aim: Sending info from A to B

classical or quantum

Classical computer unit:
Bit = one of {0, 1}

$$|\phi\rangle = \alpha|\uparrow\rangle + \beta|\downarrow\rangle$$

qubit



Quantum version

Communication

provides better efficiency than their classical counterparts

Aim: Sending info from A to B

classical or quantum

Classical computer unit:
Bit = one of {0, 1}

quantum state

Quantum version

Communication

provides better efficiency than their classical counterparts

Aim: Sending info from A to B

classical or quantum

Q dense coding

Q teleportation

1992-93

Quantum version

Communication

provides better efficiency than their classical counterparts

Aim: Sending info from A

classical or quantum

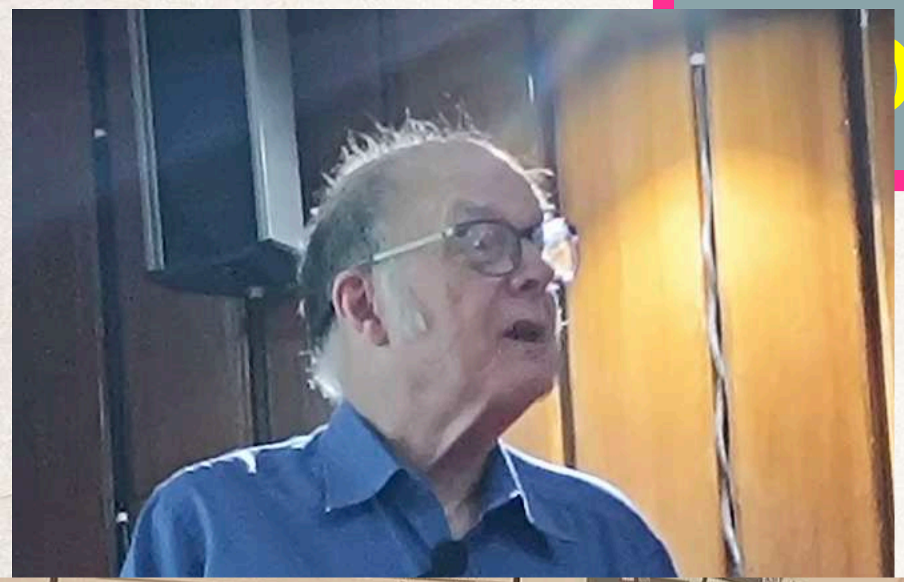
Q dense coding

Q teleportation

1992-93

Quantum version

Communication



…vides better efficiency than their classical counterparts

Aim: Sending info from A to B

classical or quantum

Q dense coding

Q teleportation

2004 —-

Quantum Cryptography

Classical information transfer **securely**

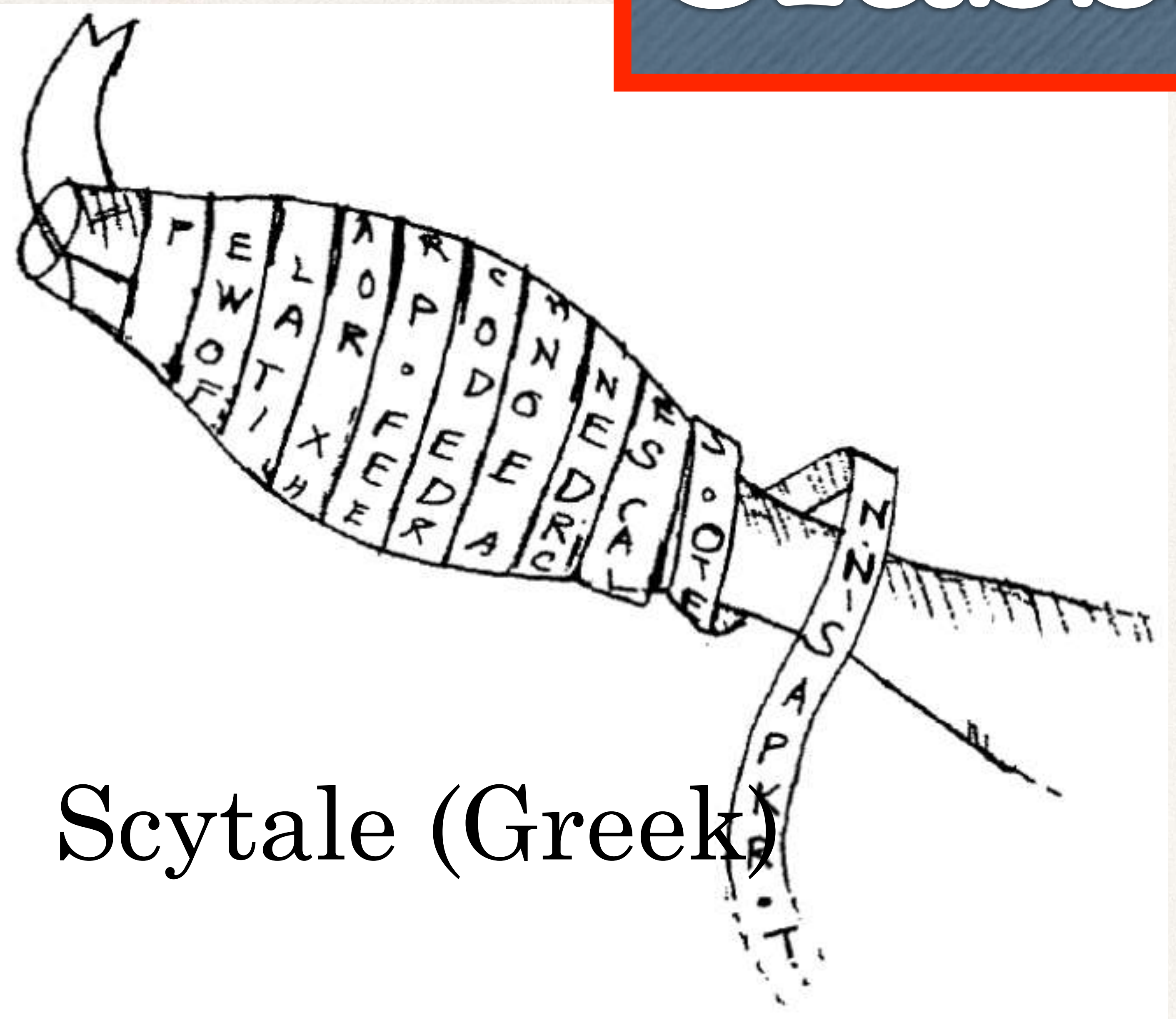
Alice

Eavesdropper

Bob

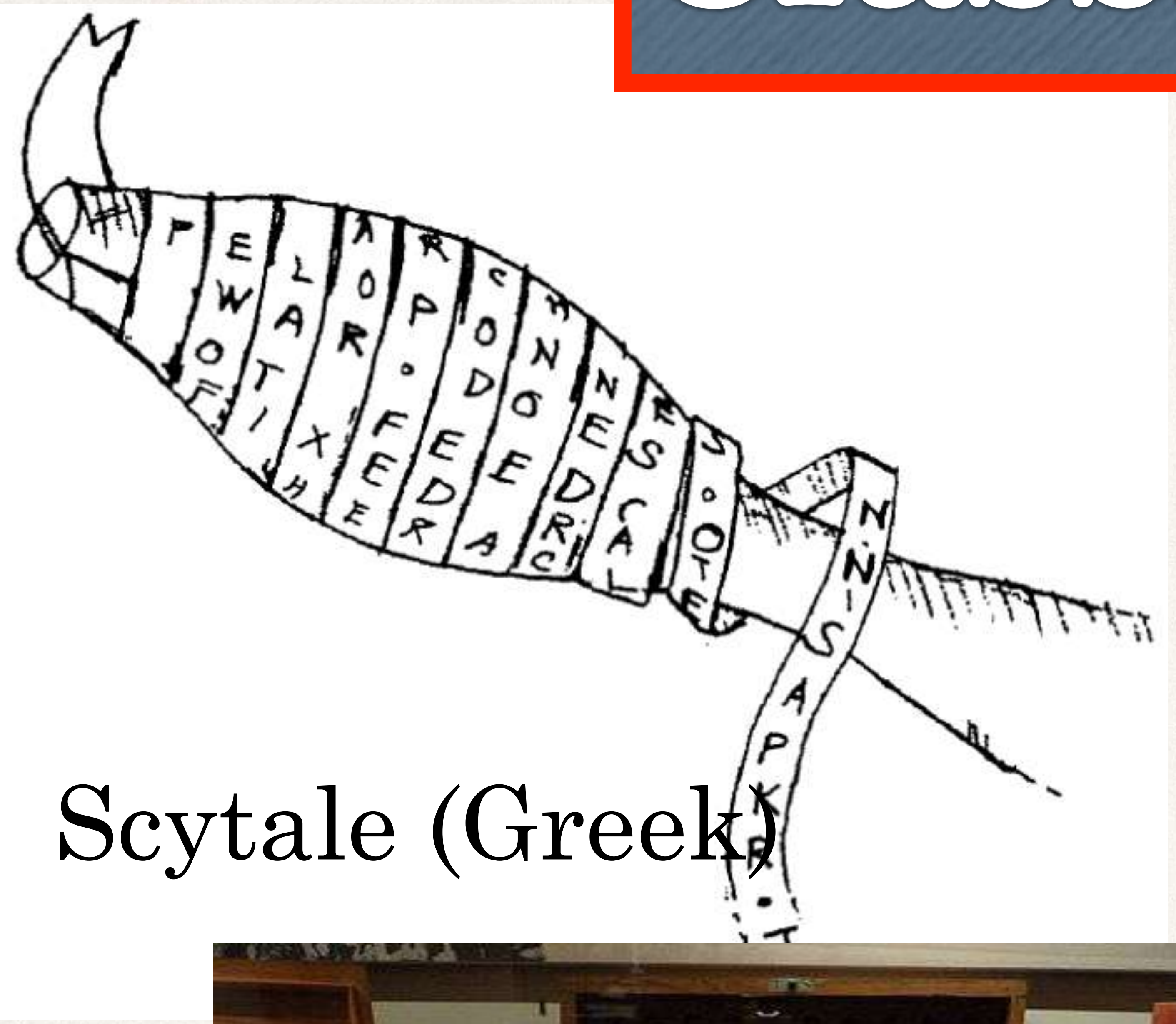
Usefulness of Secure Communication

Classical Cryptography



Scytale (Greek)

Classical Cryptography



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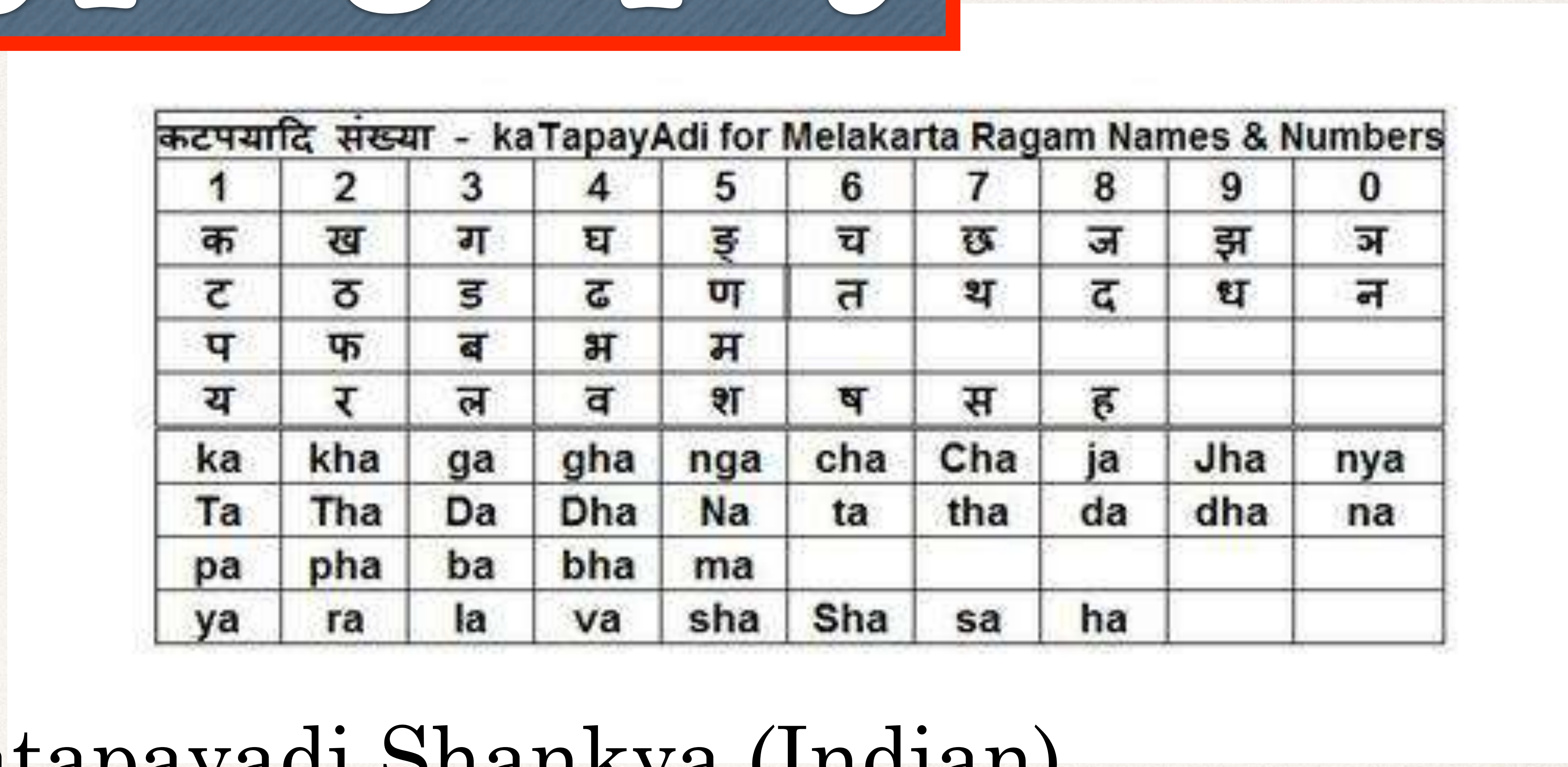
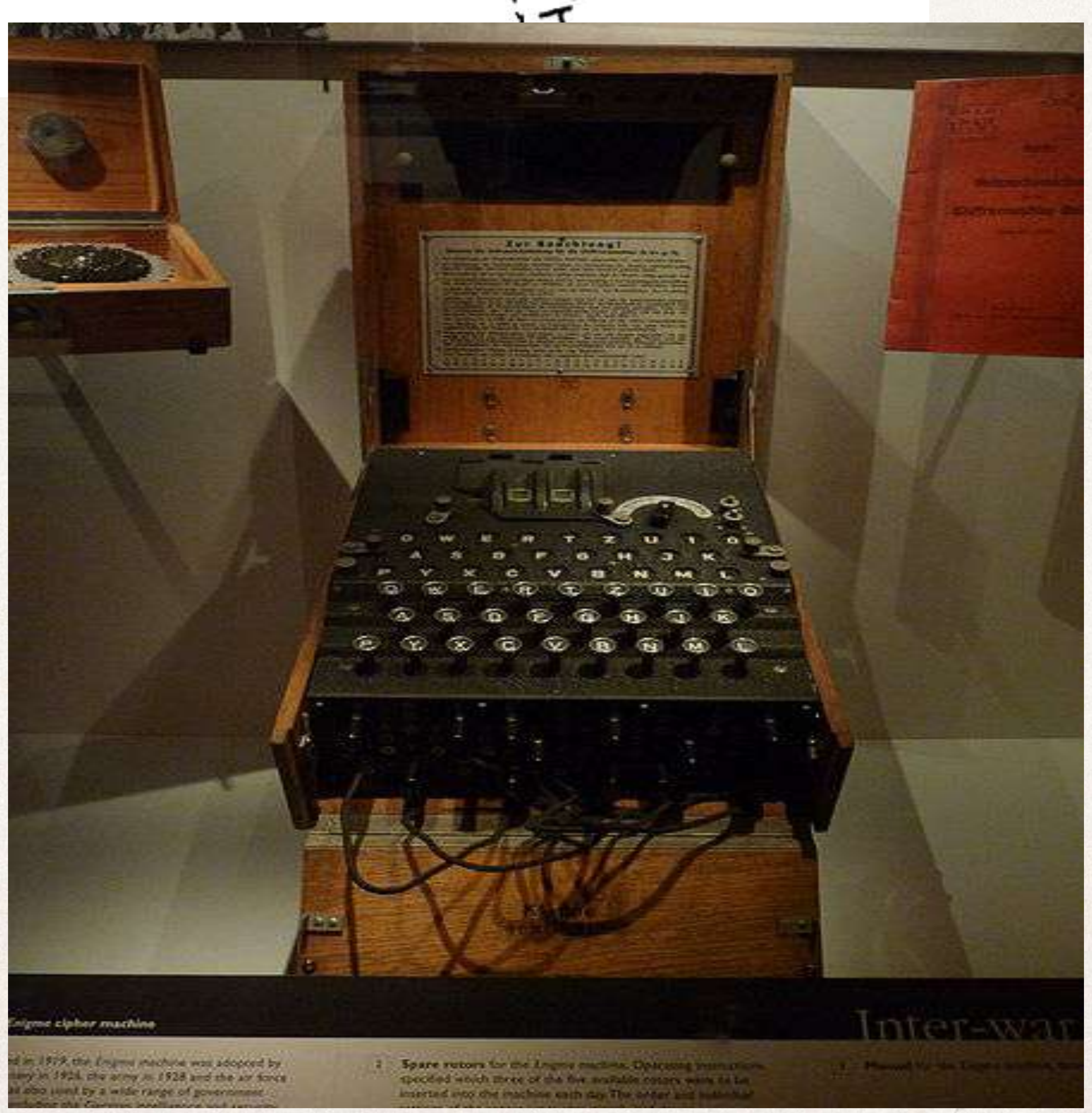


कटपयादि संख्या - kaTapayAdi for Melakarta Ragam Names & Numbers									
1	2	3	4	5	6	7	8	9	0
क	ख	ग	घ	ङ	च	छ	ज	झ	ञ
ट	ठ	ड	ढ	ण	त	थ	द	ध	न
प	फ	ब	भ	म					
य	र	ल	व	श	ष	स	ह		
ka	kha	ga	gha	nga	cha	Cha	ja	Jha	nya
Ta	Tha	Da	Dha	Na	ta	tha	da	dha	na
pa	pha	ba	bha	ma					
ya	ra	la	va	sha	Sha	sa	ha		

The Katapayadi Shankya (Indian)



Enigma (German)

Classical ways to hide info

Substitution cipher

Example: Caesar cipher

Plaintext (message):	P	U	N	E
Ciphertext:	S	X	Q	H

Method: shift 3 places forward to encode

shift 3 places backward to decode

One-time pad

Alice

Bob

Plaintext: 01010110

One-time pad

Alice

Plaintext: 01010110

Key: 00111001

Bob

One-time pad

Alice

Plaintext: 01010110

Key: 00111001

Ciphertext: 01101111

Encoding:
Ciphertext =
Plaintext + key (modulo 2)

Bob

One-time pad

Alice

Plaintext: 01010110

Key: 00111001

Ciphertext: 01101111

Sending

Encoding:
Ciphertext =
Plaintext + key (modulo 2)

Bob

Ciphertext: 01101111

One-time pad

Alice

Plaintext: 01010110

Key: 00111001

Ciphertext: 01101111

Encoding:
Ciphertext =
Plaintext + key (modulo 2)

Sending

Bob

Ciphertext: 01101111

Key: 00111001

One-time pad

Alice

Plaintext: 01010110

Key: 00111001

Ciphertext: 01101111

Sending

Encoding:
Ciphertext =
Plaintext + key (modulo 2)

Bob

Ciphertext: 01101111

Key: 00111001

Plaintext: 01010110

Decoding:
Plaintext =
Ciphertext + key (modulo 2)

One-time pad

- It is completely secure.
- BUT, one must have a method for Alice and Bob to share a ***secret key,*** i.e.

One-time pad

- It is completely secure.
- BUT, one must have a method for Alice and Bob to share a ***secret key***, i.e.

a random binary sequence at Alice, & the same at Bob, but no-one else has it.

Classical Case

Classical:
Security depends on whether
a mathematical problem can be solved or not.

Current
Secure Communication

Classical Cryptography

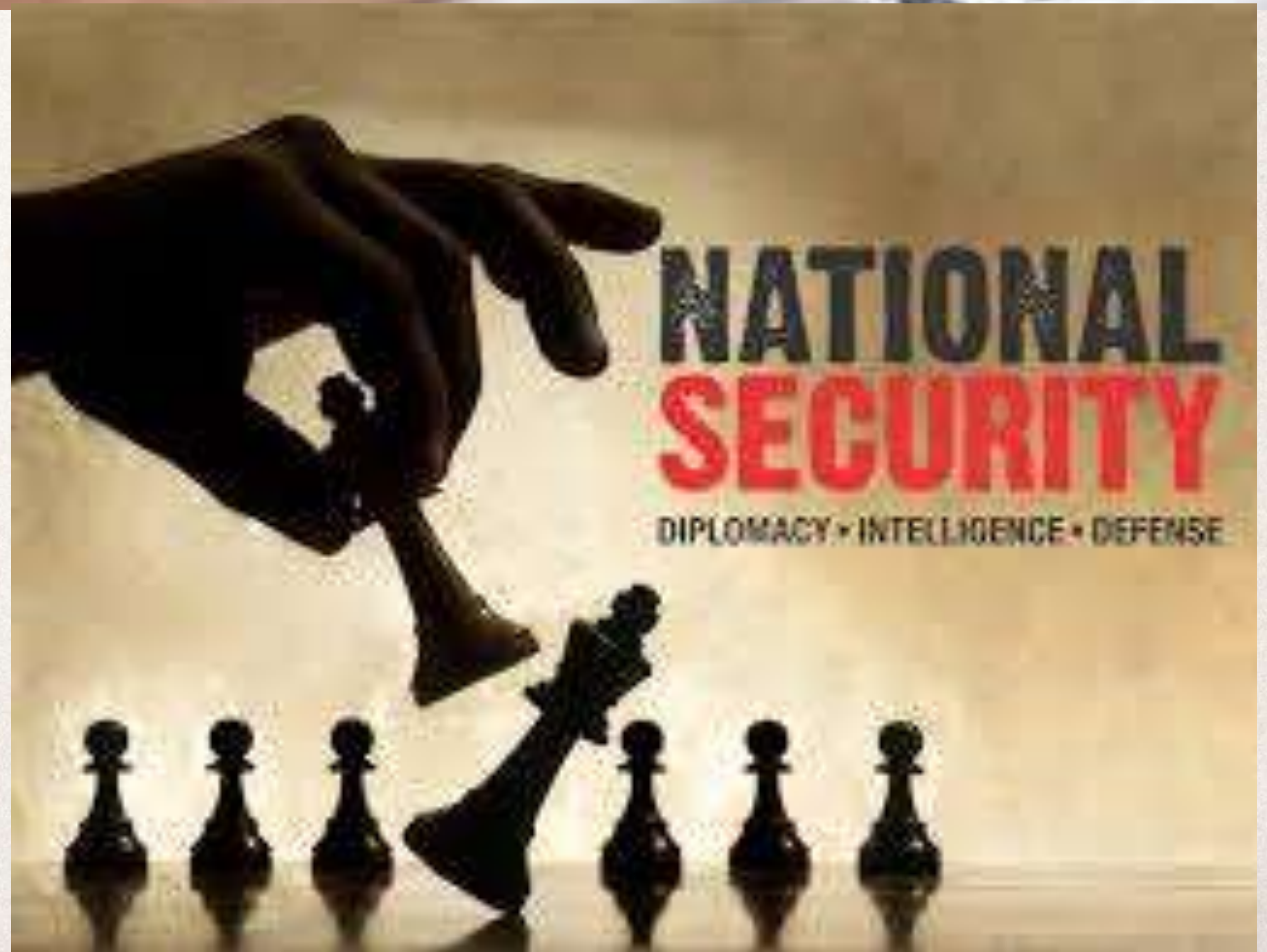
Security based on the **belief** that some mathematical problems cannot be solved in classical computer (in polynomial time)

Ex: Prime factors of a given integer

QM makes all current crypto systems insecure

These mathematical problems can be solved using quantum mechanics

Eg. Shor algorithm 1994



Quantum cryptography

Security based on validity of quantum mechanics

Secure
even when quantum computer exists

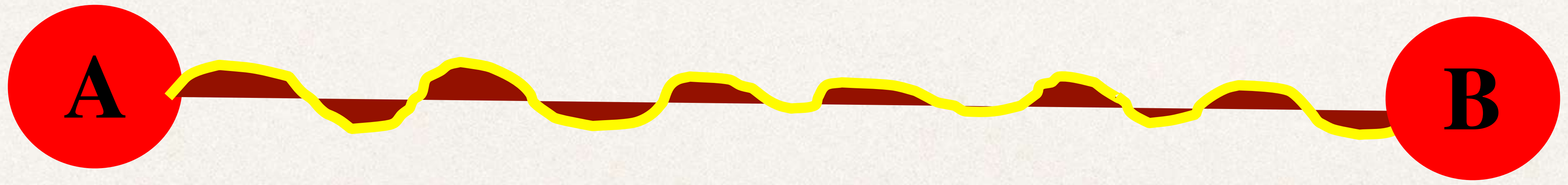
THE REMEDY

Quantum cryptography

Bennett, Brassard, Ekert

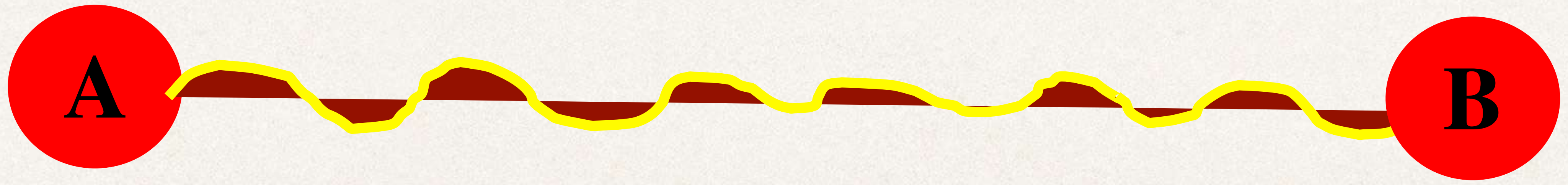
Quantum key distribution
1984, 1991

Resource?



Properties of composite q system

Resource?

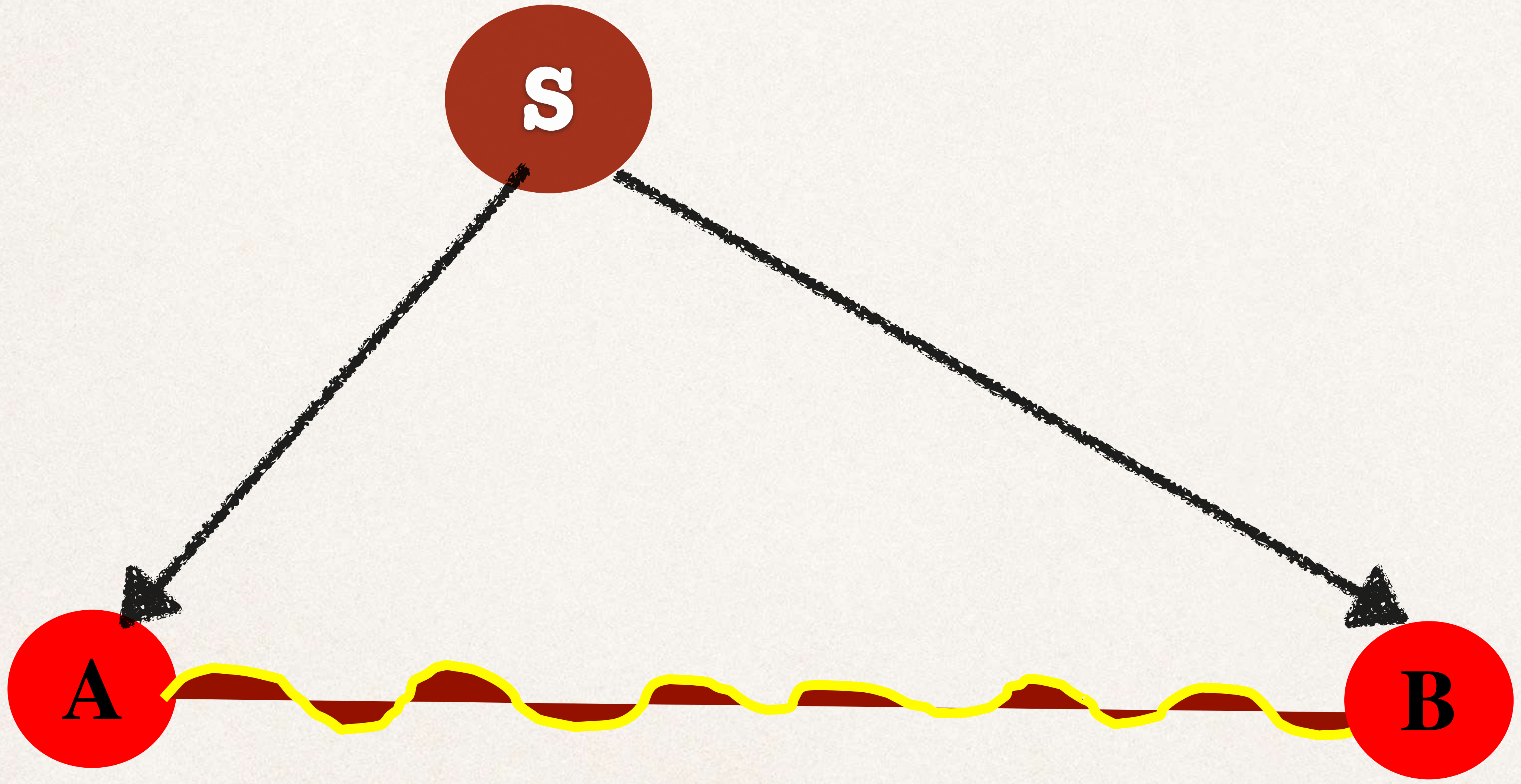


Entanglement : key ingredient

Resource?

Entangled states

Alice and Bob are unable to prepare these states when they are far apart



$$|\phi_{AB}\rangle \neq |\phi_A\rangle \otimes |\phi_B\rangle$$

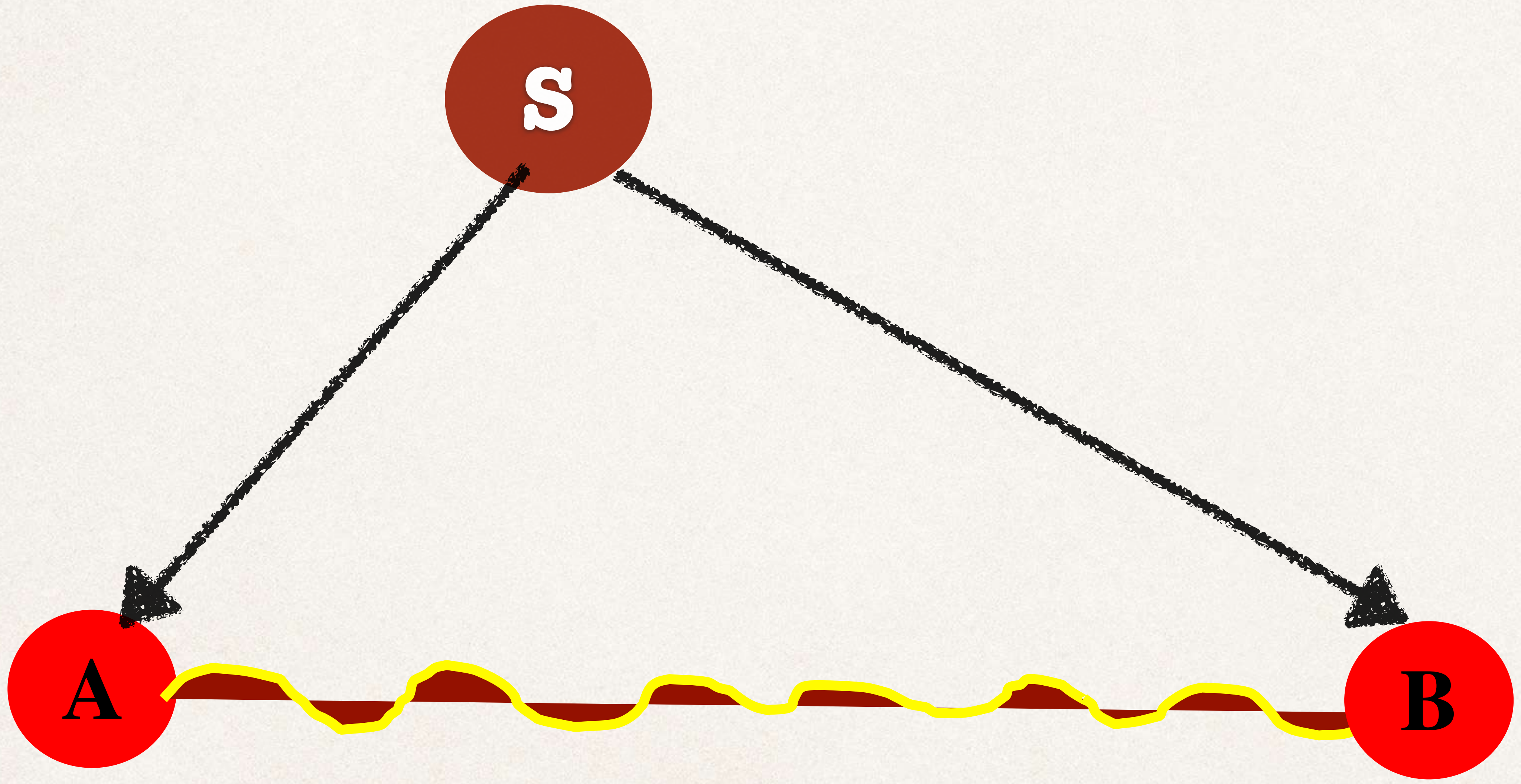
$$|\psi^-\rangle = \frac{1}{\sqrt{2}}(|\uparrow\rangle \otimes |\downarrow\rangle - |\downarrow\rangle \otimes |\uparrow\rangle)$$

Singlet state

Resource?

Entangled states

Alice and Bob are unable to prepare these states when they are far apart



$$|\phi_{AB}\rangle \neq |\phi_A\rangle \otimes |\phi_B\rangle$$

$$|\psi^-\rangle = \frac{1}{\sqrt{2}}(|\uparrow\rangle \otimes |\downarrow\rangle - |\downarrow\rangle \otimes |\uparrow\rangle)$$

Singlet state

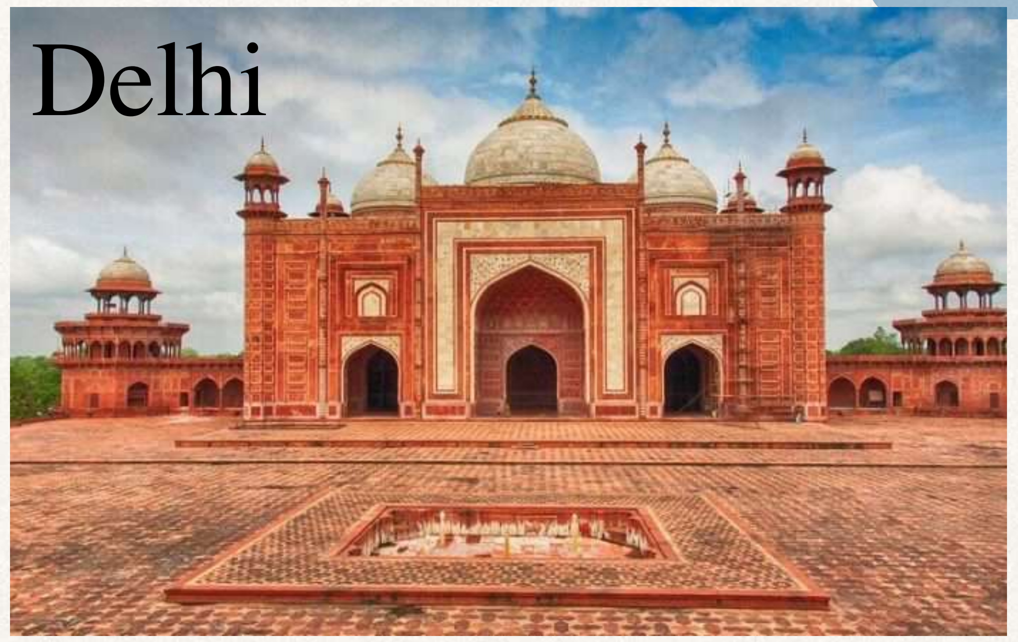
Product states $|\phi_{AB}\rangle = |\phi_A\rangle \otimes |\phi_B\rangle$ Ex: $|0\rangle \otimes |1\rangle$

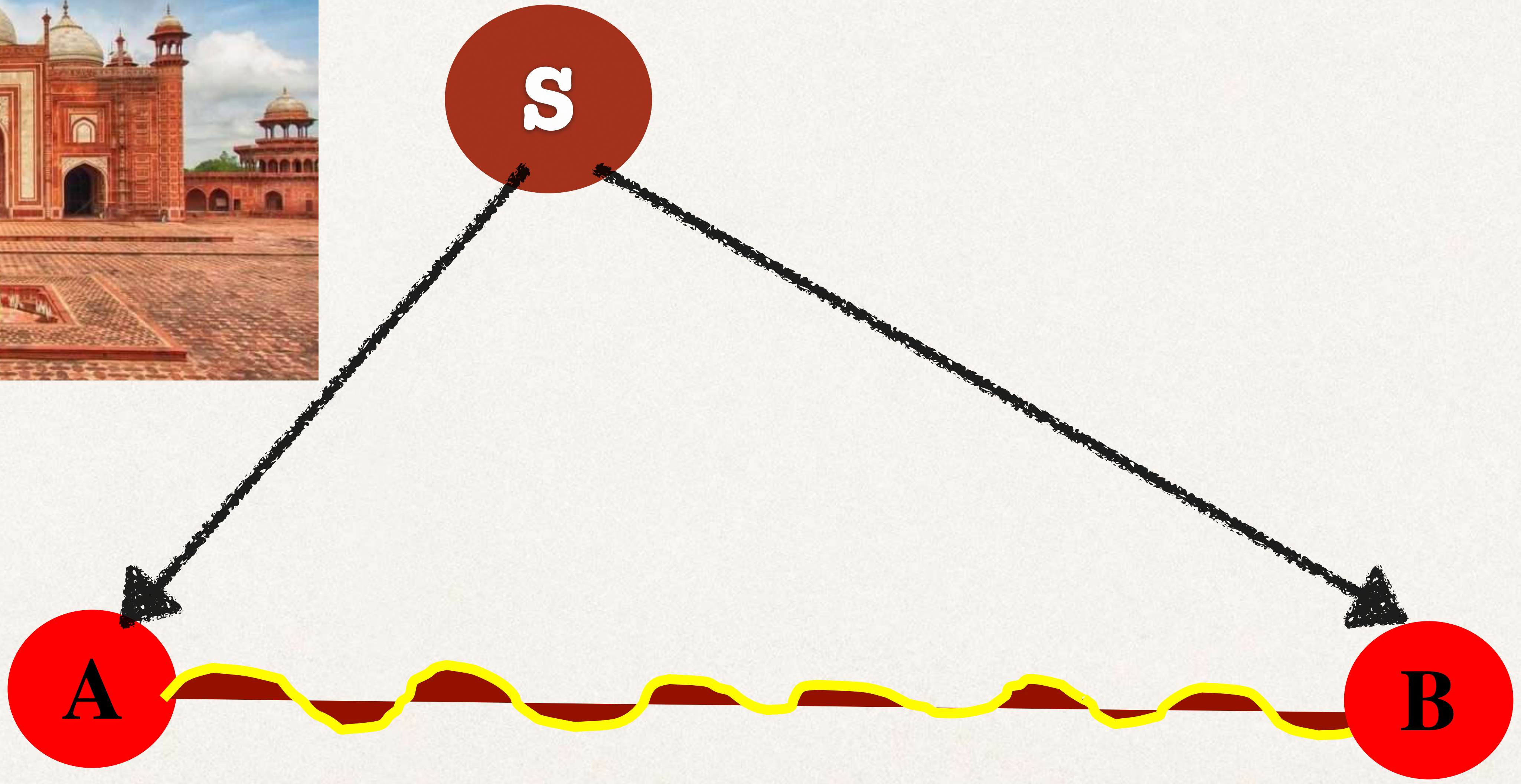
$|0\rangle \otimes |0\rangle$

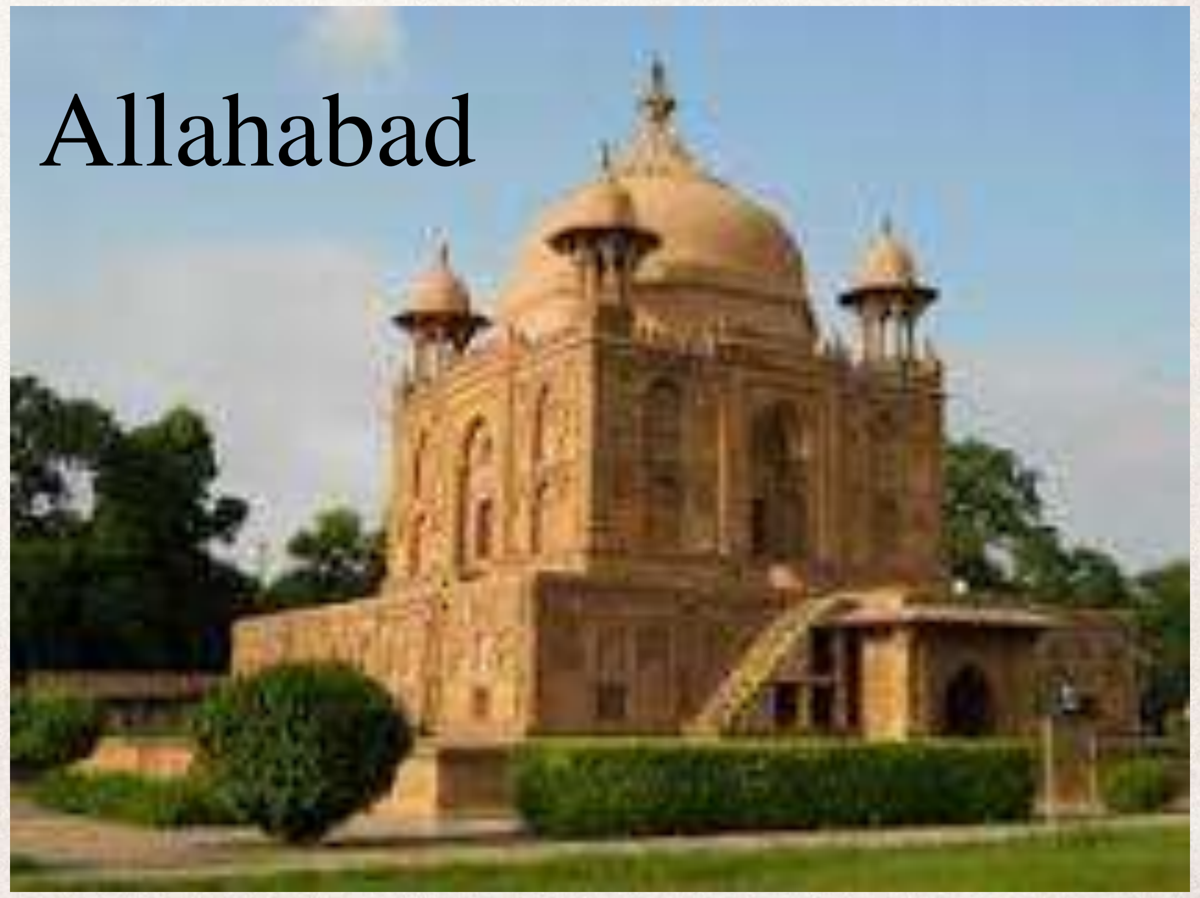
Resource?

Entangled states

Alice and Bob are unable to prepare these states when they are far apart







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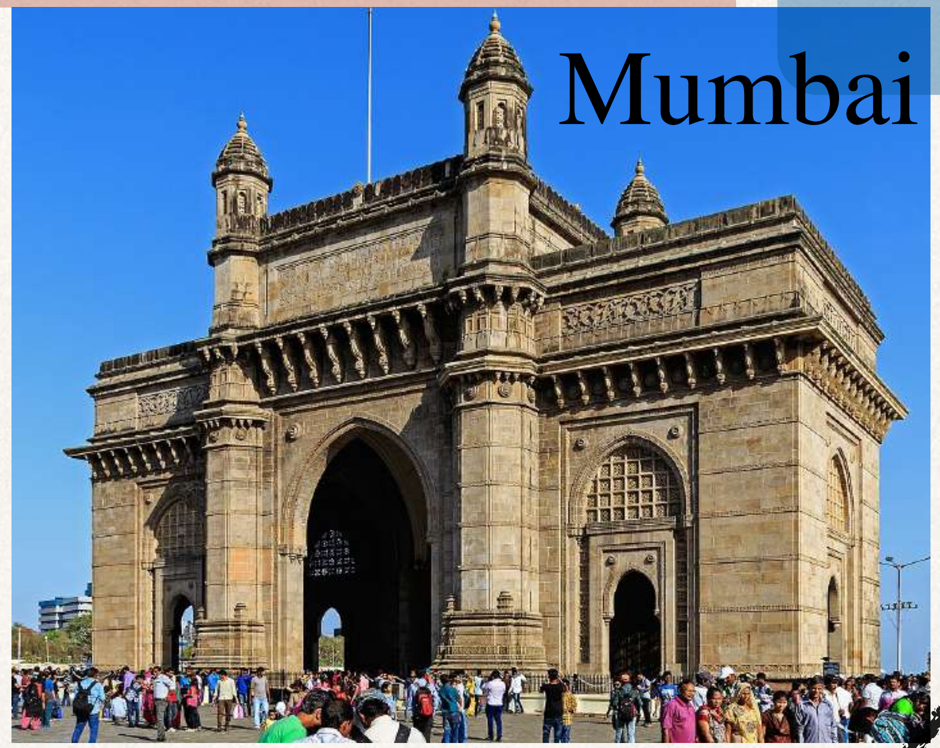
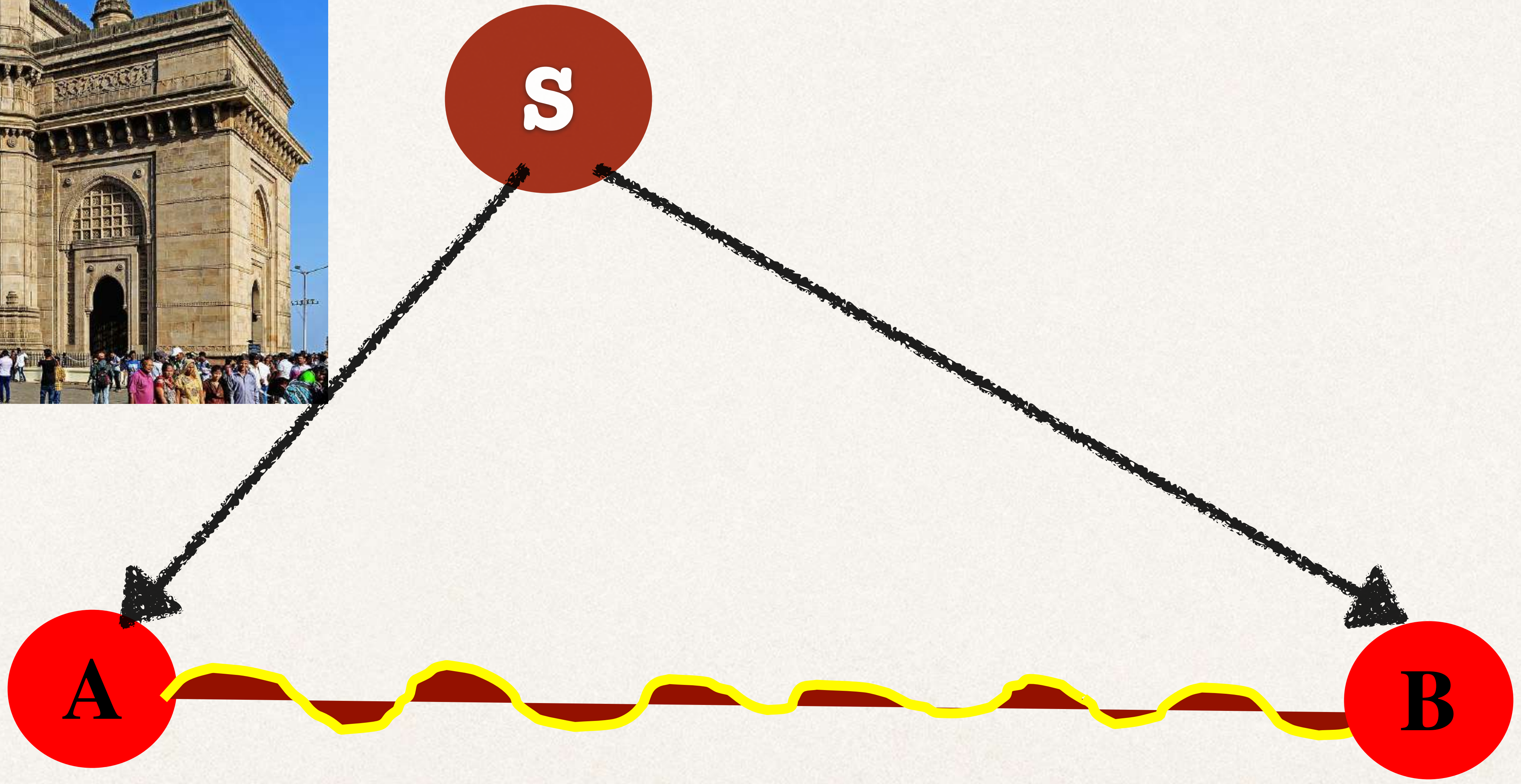
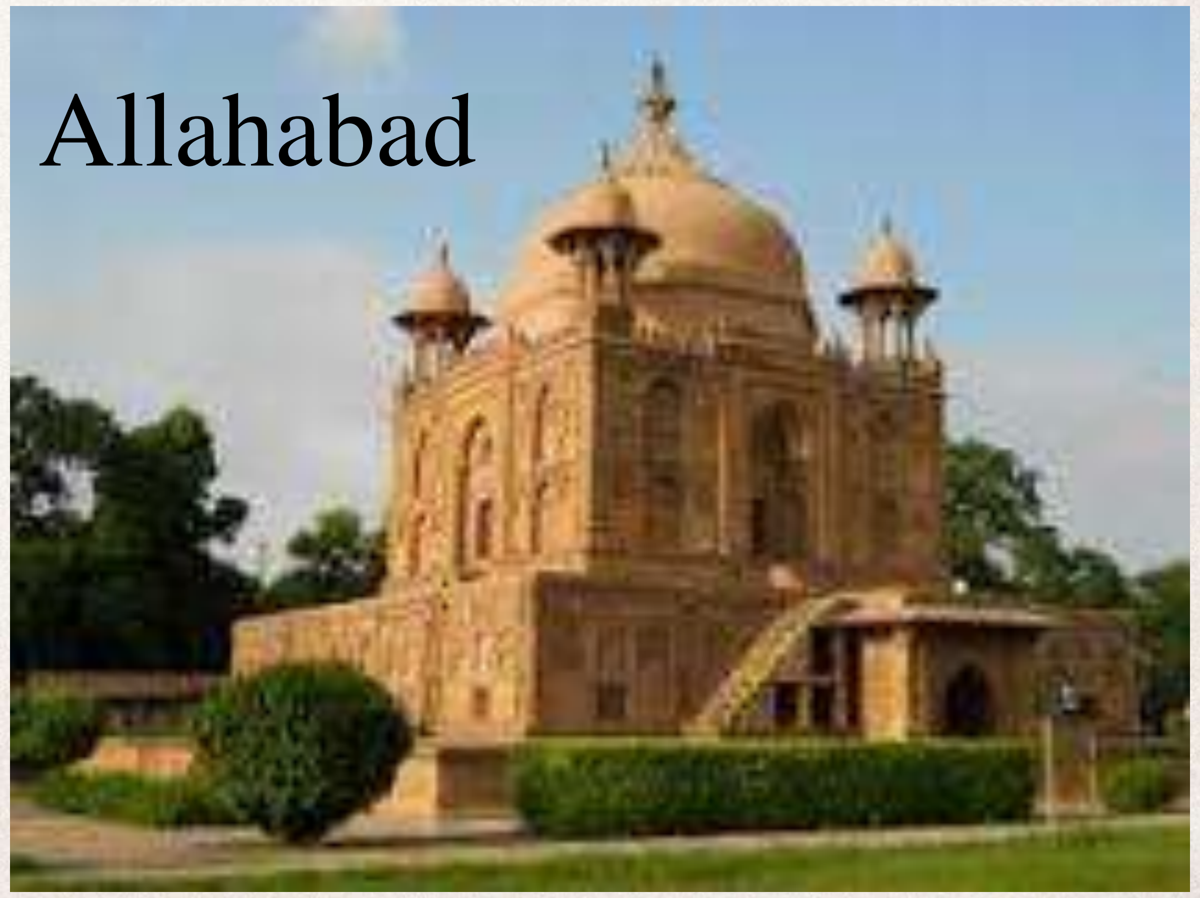
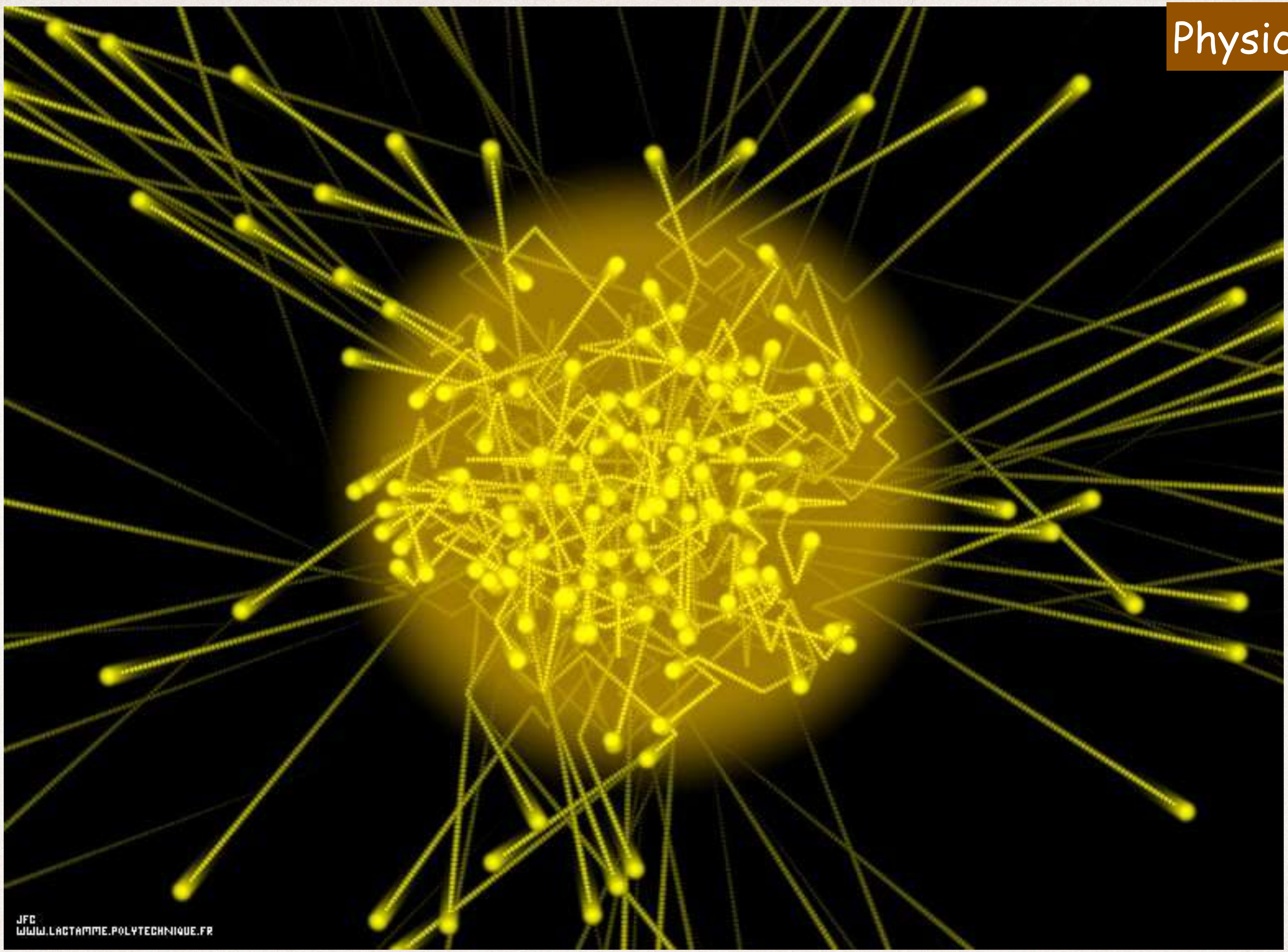






Physical System:1



Individual particles of light

Right-handed and left-handed circular polarization: ideal candidate for a qubit

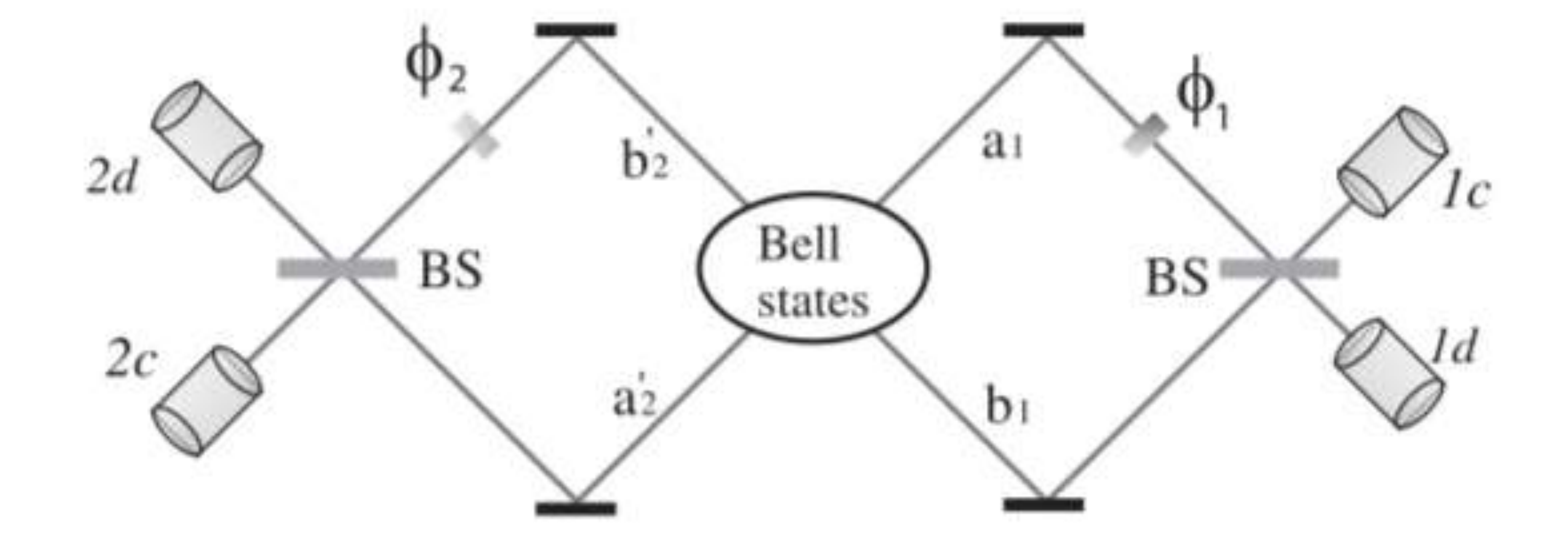
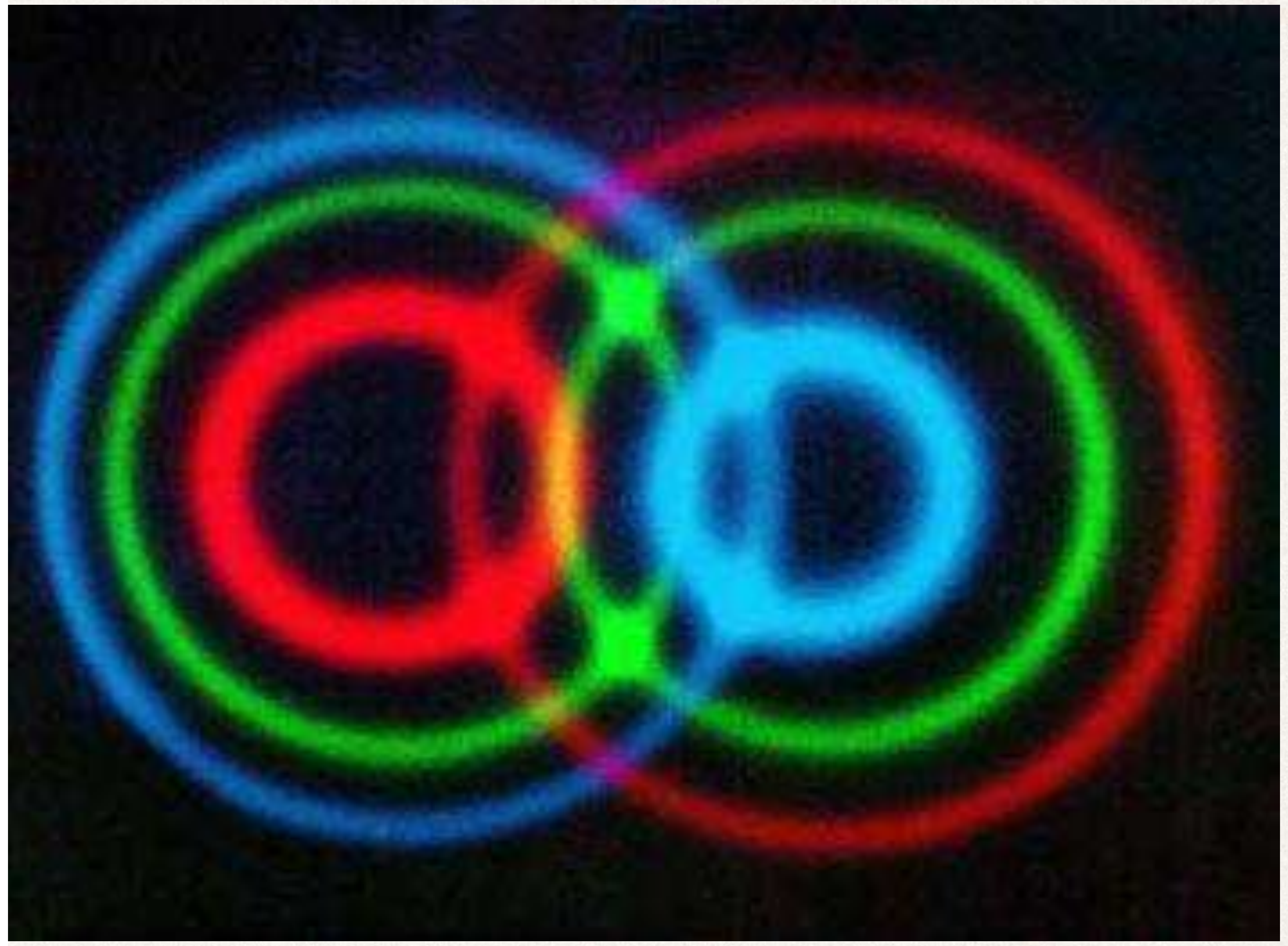


FIG. 1. A two-photon interferometer with variable phase shifts ϕ_1 and ϕ_2. Before being combined at the 50:50 beam splitter (BS) and then subject to single-photon detections, the two paths of each photon acquire a relative phase shift. For experimental realization of



RMP, 84, 777 (2012)

The Nobel Prize in Physics 2022

The Nobel Prize in Physics 2022 was awarded jointly to Alain Aspect, John F. Clauser and Anton Zeilinger "for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science"

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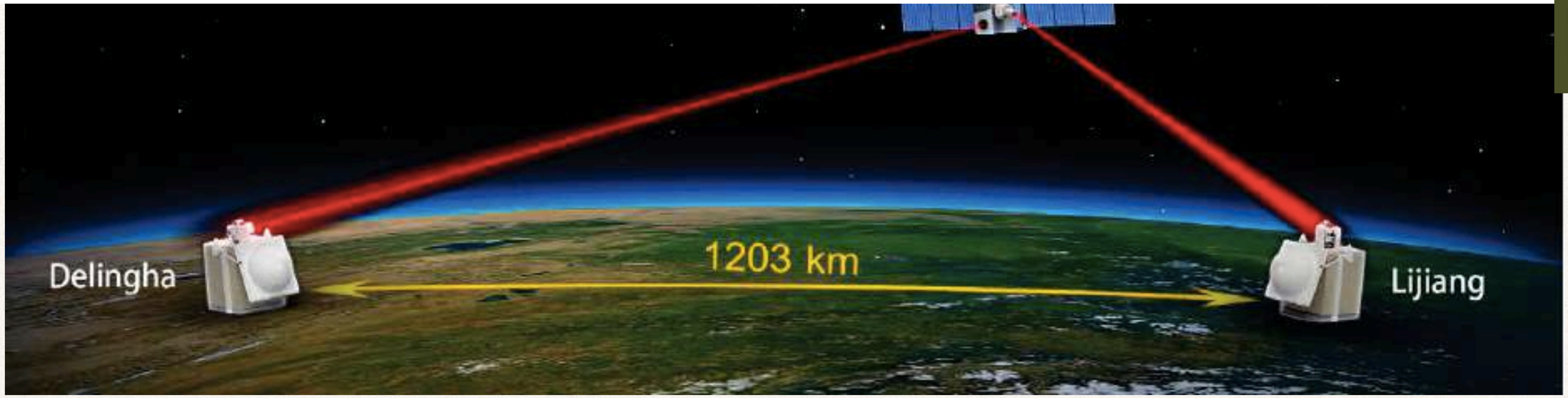
How far?

Experimental Achievements

Satellite-Based Entanglement Distribution Over 1200 kilometers



Photons

Science 356, 1140-1144 (2017)

Experimental Achievements

Satellite-Based Entanglement Distribution Over 1200 kilometers

Photons

Breakthrough experiment

2024

Reality

Kolkata

~1300 Km

Delhi

2024

Reality

Indore

~1300 Km

Bengaluru

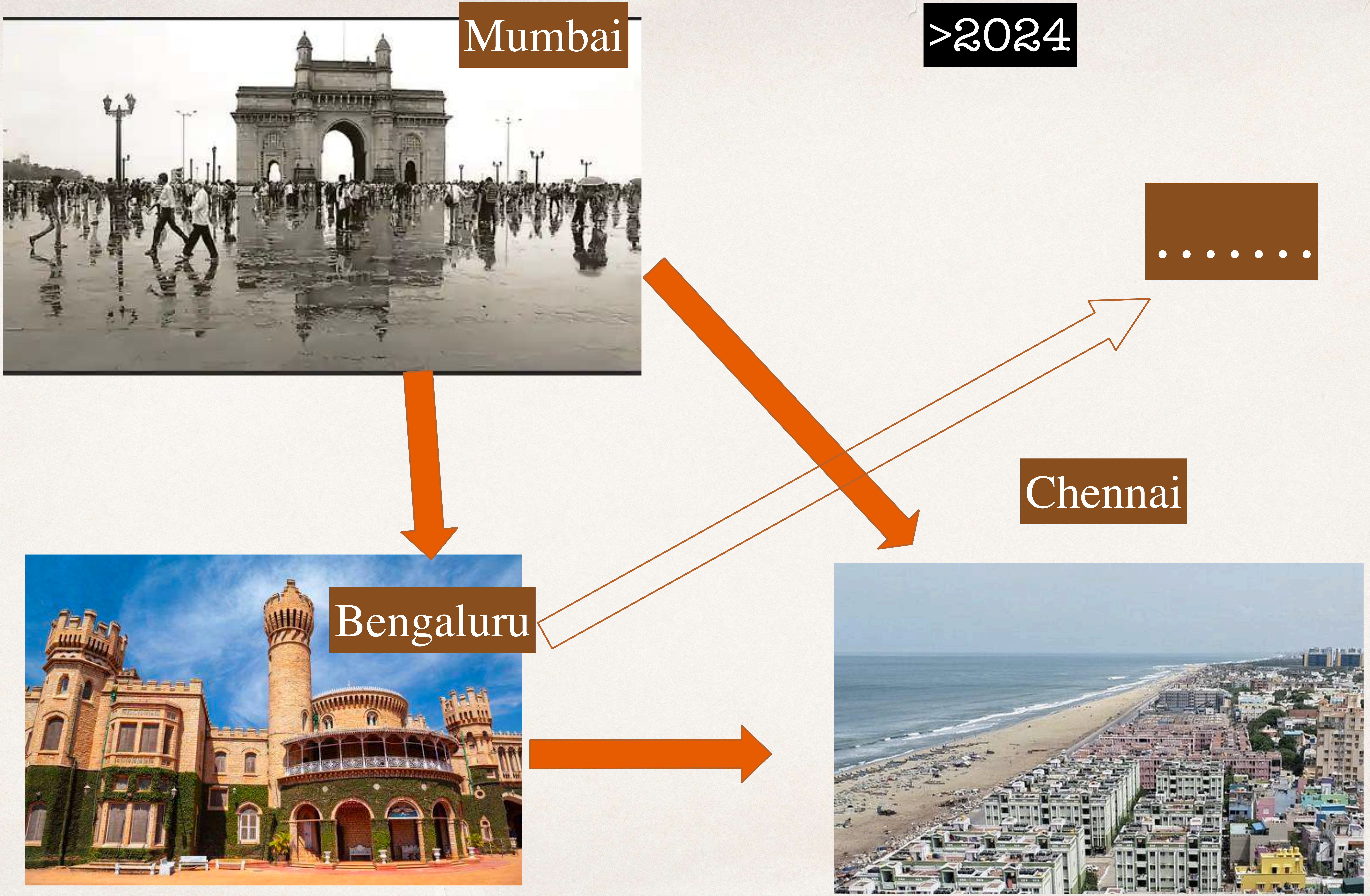
2024

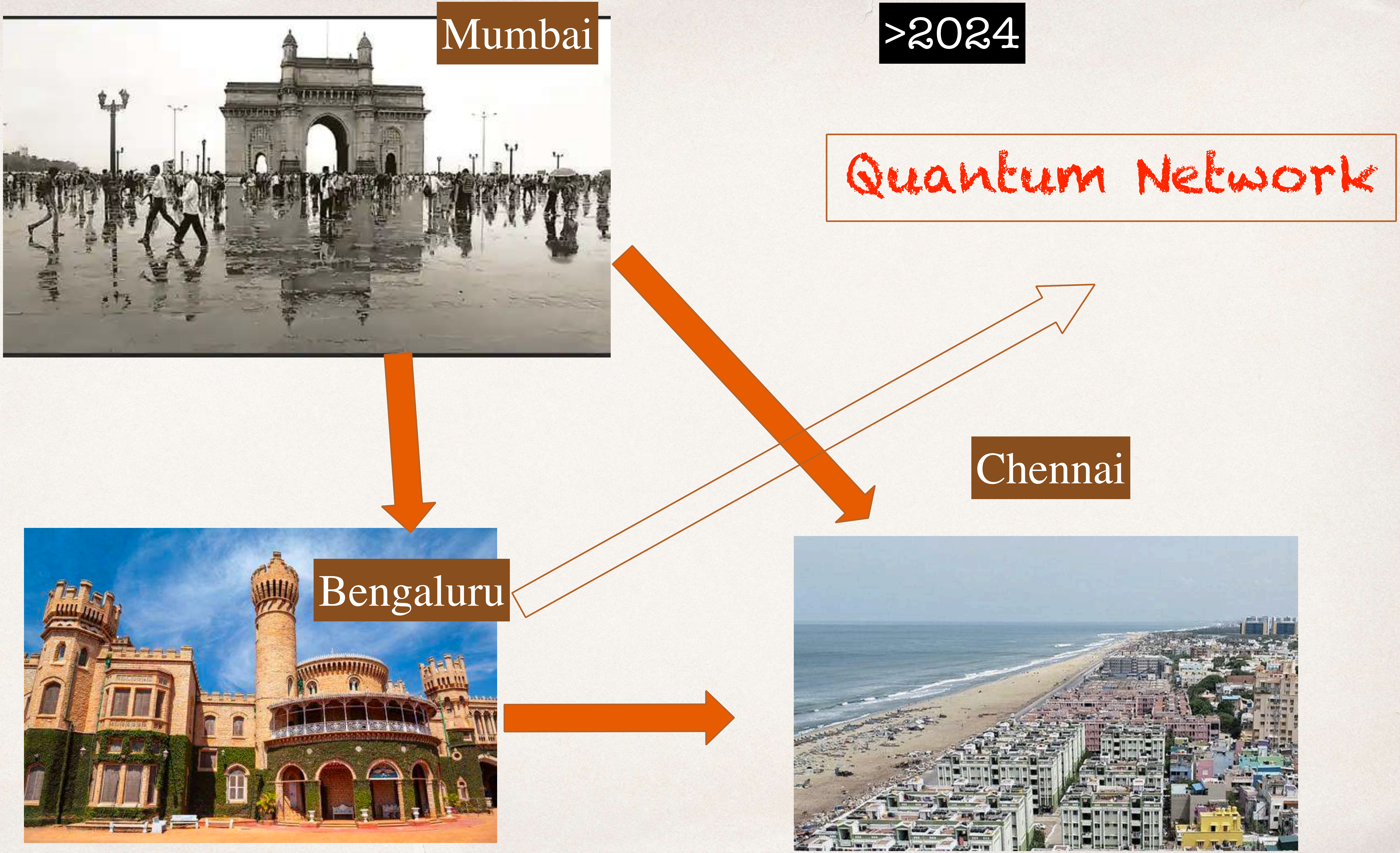
Reality

Mumbai

~1300 Km

Chennai


Mumbai
>2024
....
Chennai
Bengaluru


Mumbai
>2024
Quantum Network
Chennai
Bengaluru

>2024

Quantum internet

Chennai

Quantum Network

Phys. Rev. Research (2020), Phys. Rev. A 2022, Phys. Rev. A 2022

A network is a collection of nodes connected by edges

Sharing entanglement over large distance:
A recent challenge

Entanglement as resource for known communication protocols

Quantum Network

Phys. Rev. Research (2020), Phys. Rev. A 2022, Phys. Rev. A 2022

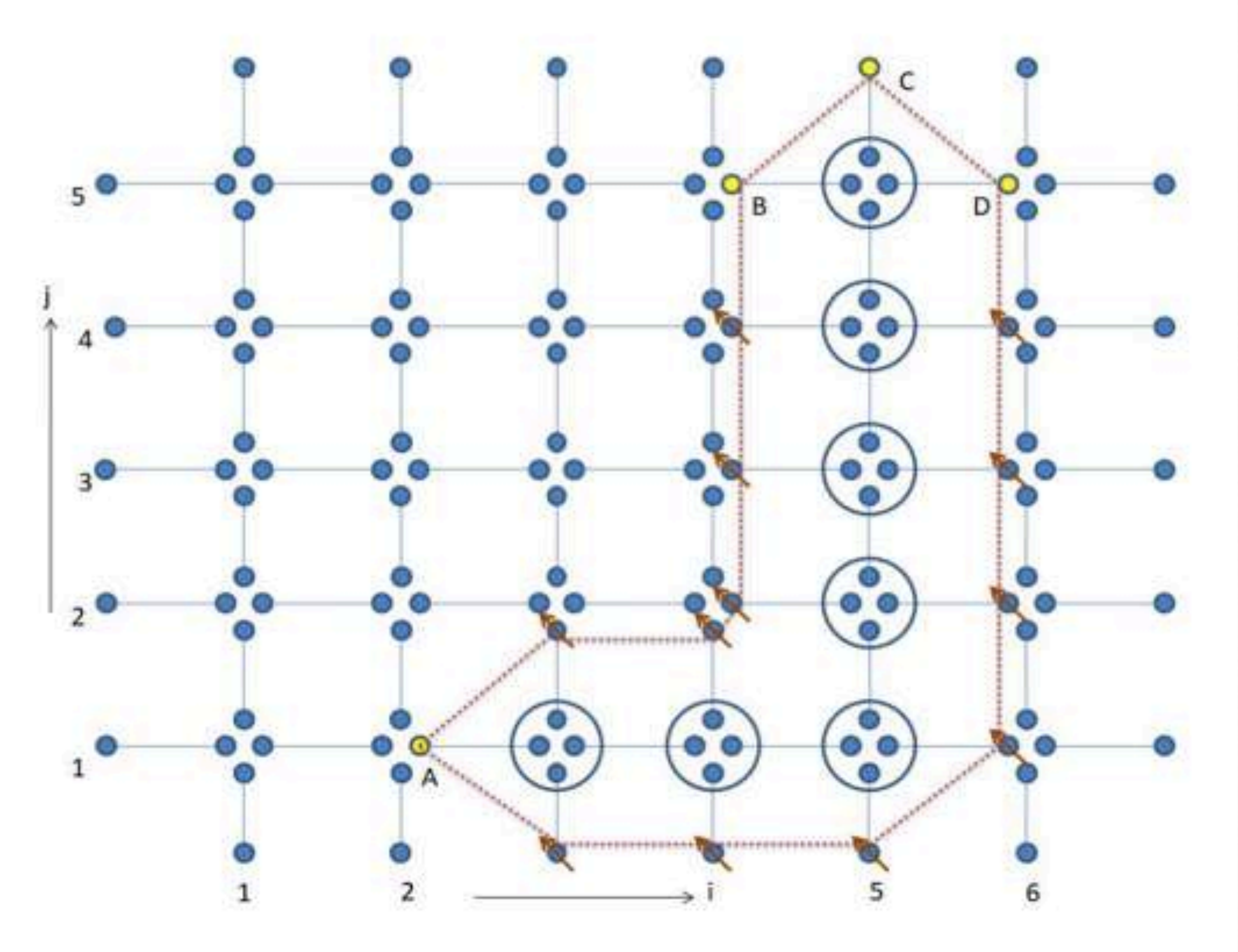
A network is a collection of nodes connected by edges

Sharing entanglement over large distance:
A recent challenge

Entanglement as resource for known communication protocols

How to share quantum resource in predecided nodes?

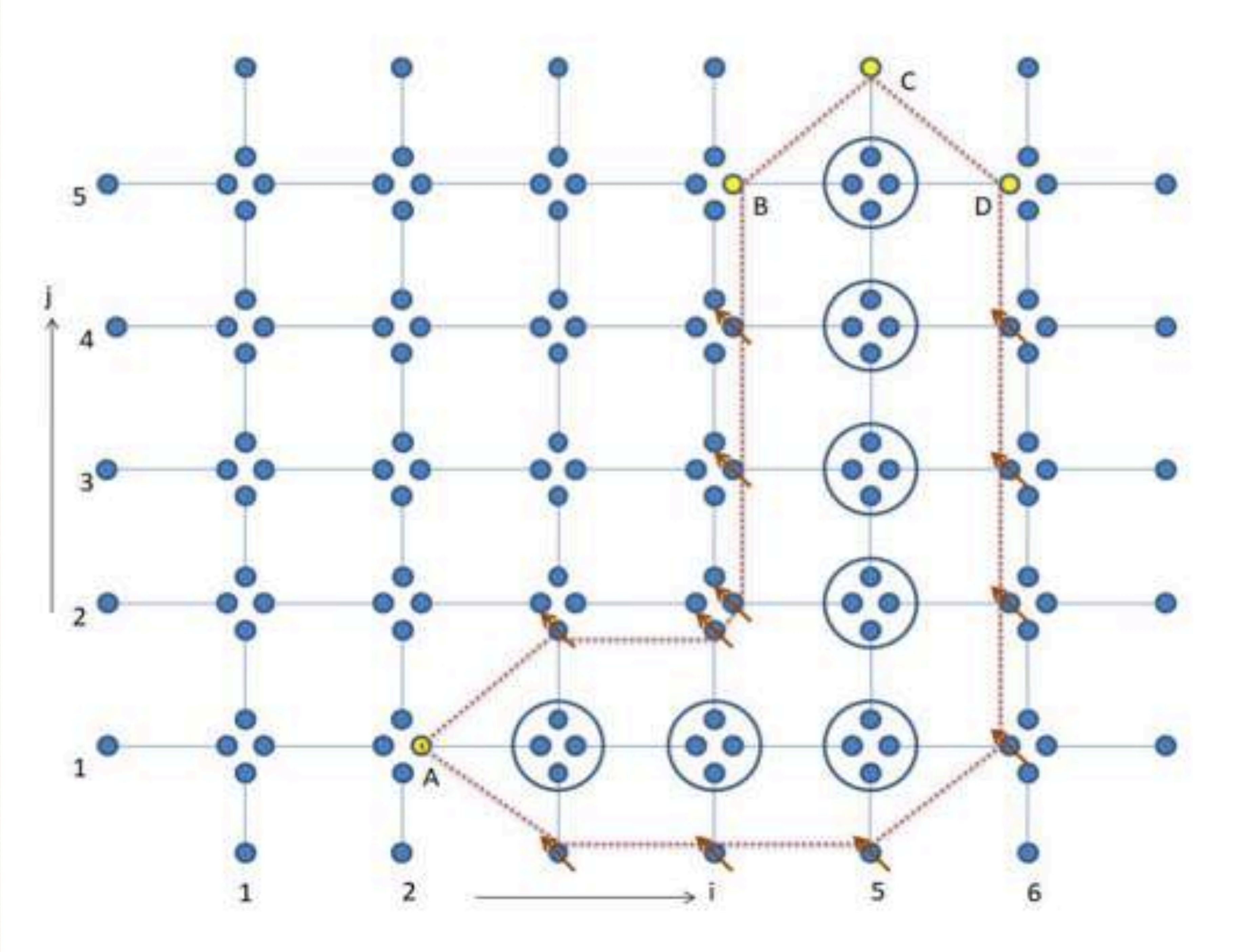
Q Networks: Measurement vs Gates

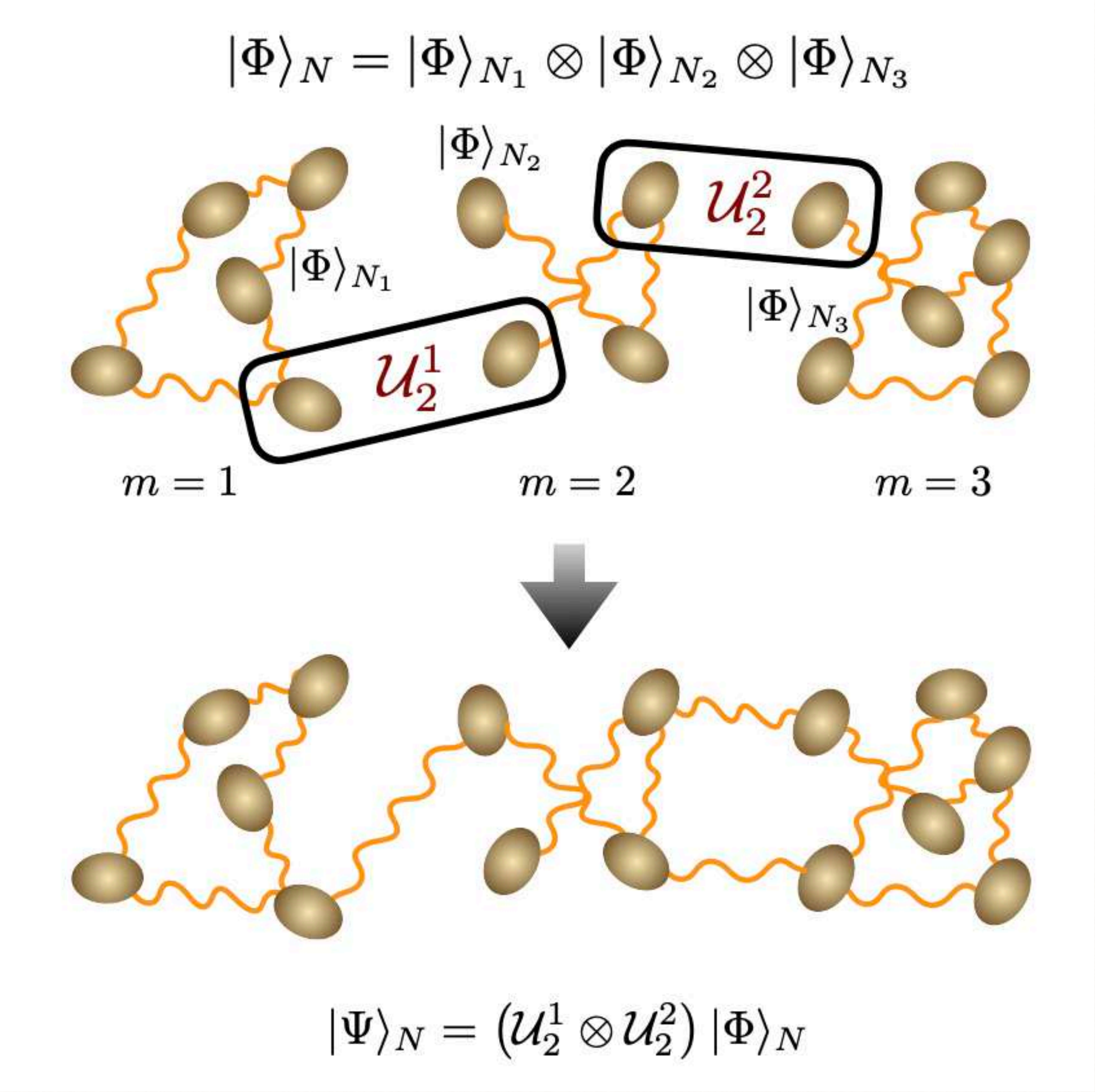


Measurement-based

Probabilistic

Q Networks: Measurement vs Gates





Measurement-based

Probabilistic

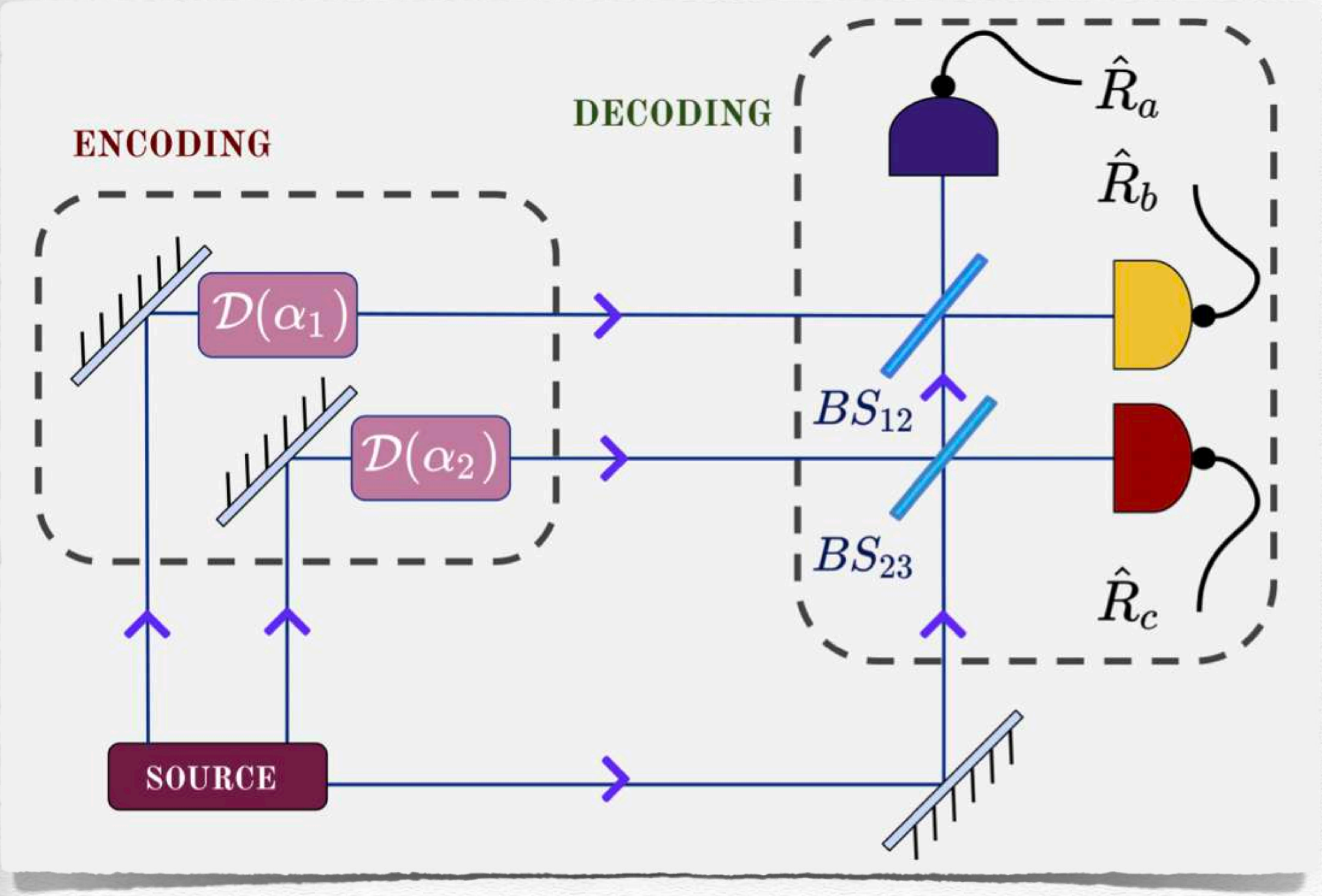
Gate-based quantum circuit

Deterministic

Quantum Repeater — NQM

Quantum Network w photons

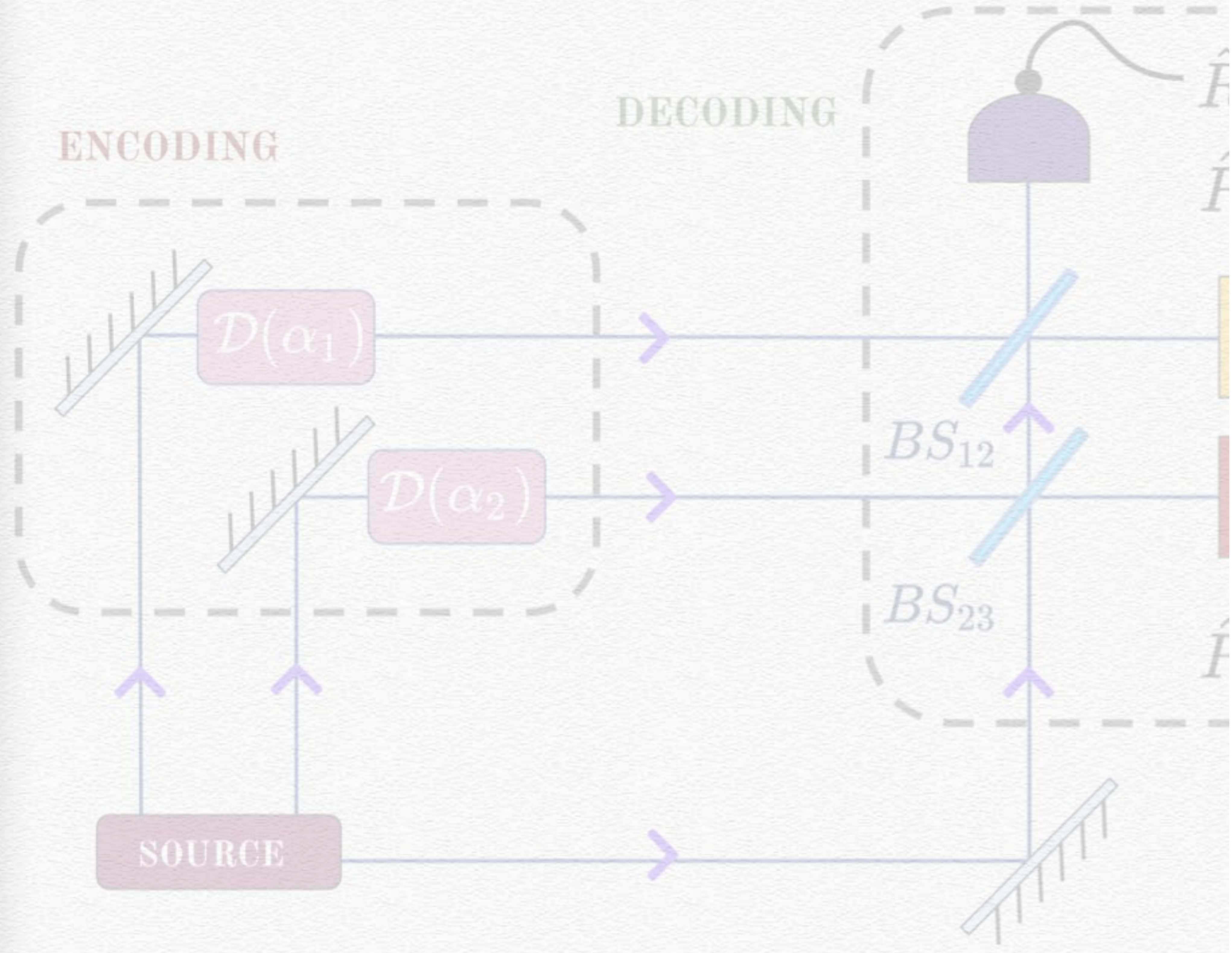
Samanta, Patra, Gupta, Ghosh, Roy, ASD, Phys. Rev. Research (2020), Phys. Rev. A 2022, Phys Rev A 2023, arXiv: 2407:

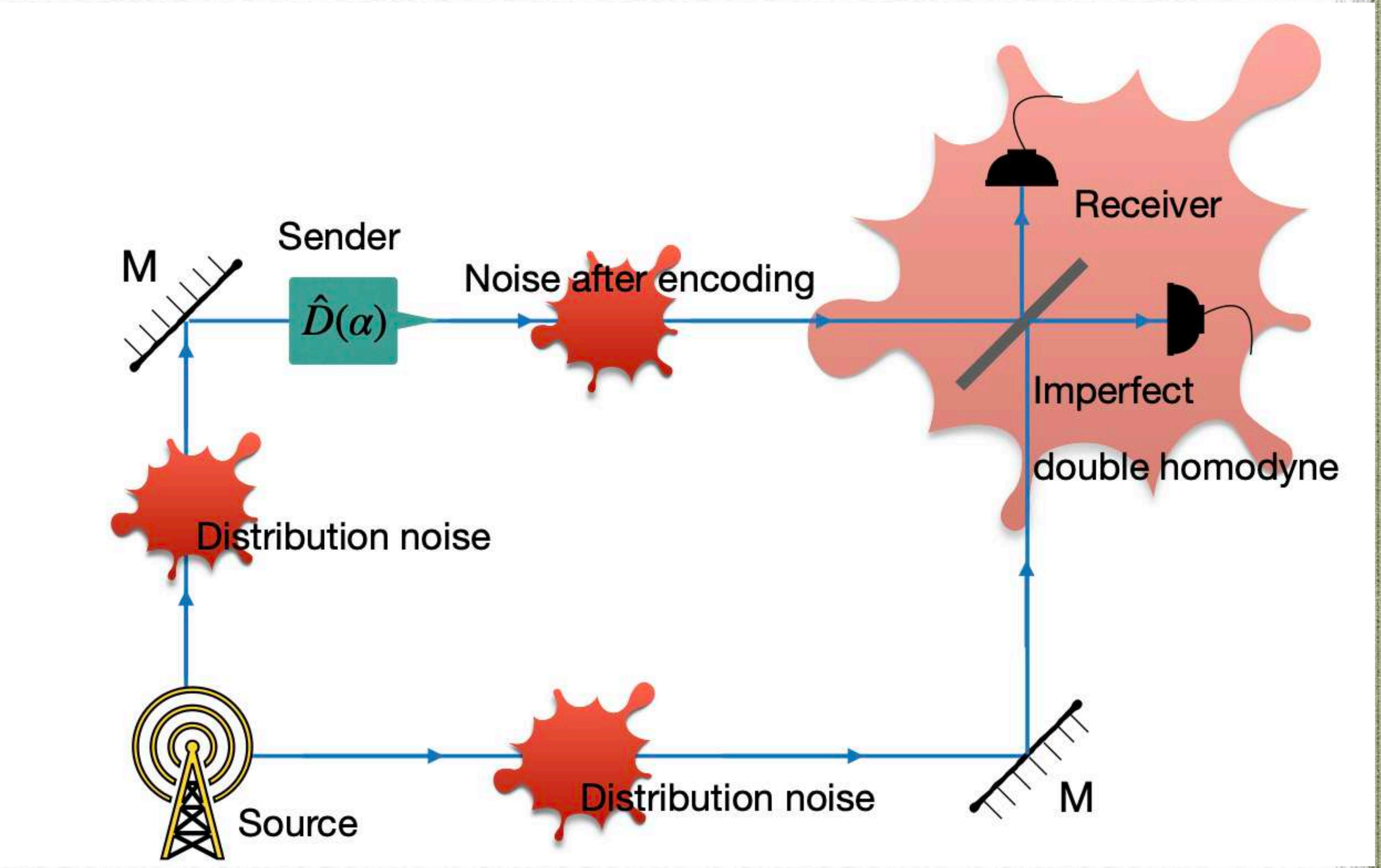


Proposed an experimental set-up to implement

Quantum Network w photons

Samanta, Patra, Gupta, Ghosh, Roy, ASD, Phys. Rev. Research (2020), Phys. Rev. A 2022, Phys Rev A 2023, arXiv: 2407: 07609





Proposed an experimental set-up to implement

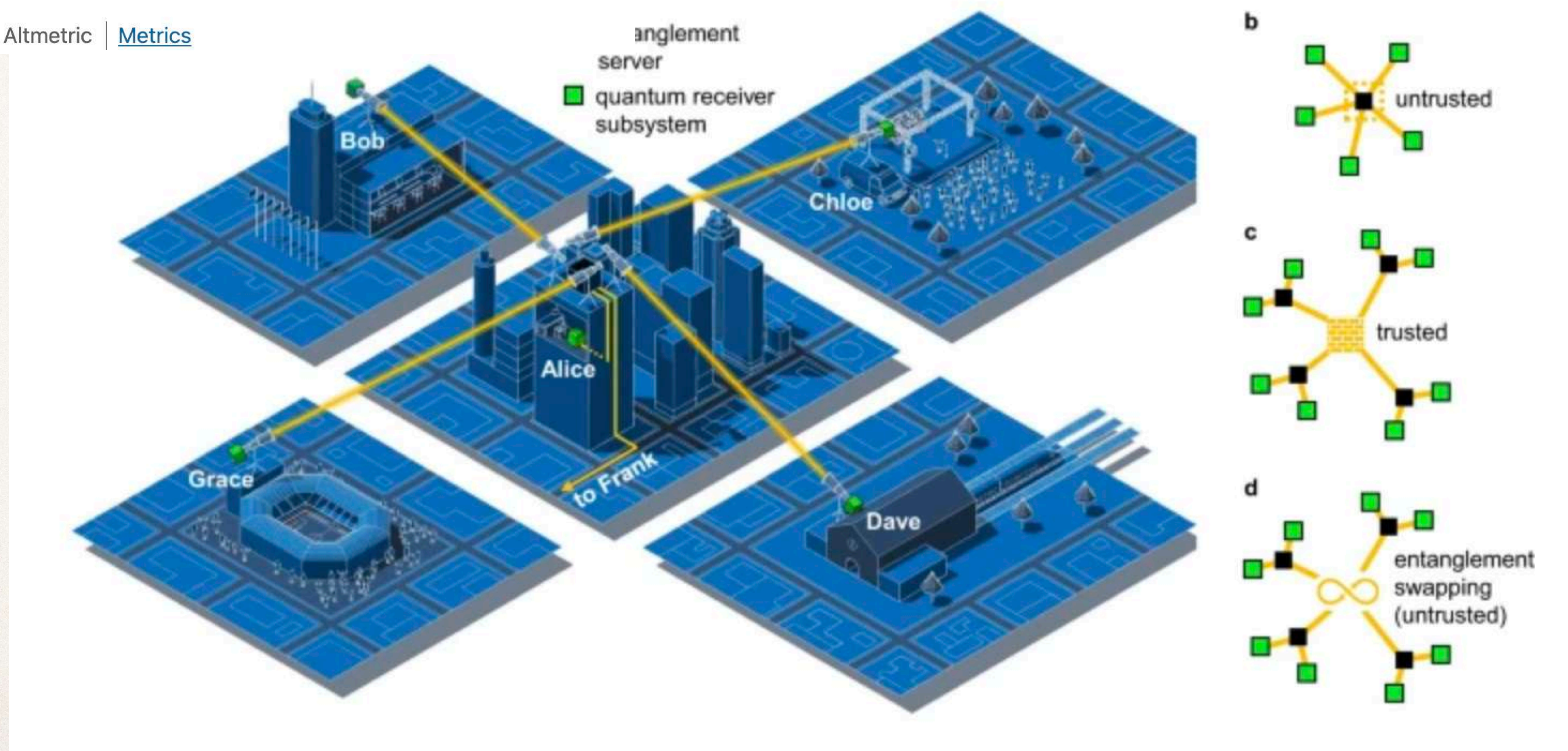
Realistic noisy capacity set-up

Towards metropolitan free-space quantum networks

Andrej Kržič, Sakshi Sharma, Christopher Spiess, Uday Chandrashekara, Sebastian Töpfer, Gregor Sauer, Luis Javier González-Martín del Campo, Teresa Kopf, Stefan Petscharnig, Thomas Grafenauer, Roland Lieger, Bernhard Ömer, Christoph Pacher, René Berlich, Thomas Peschel, Christoph Damm, Stefan Risse, Matthias Goy, Daniel Rieländer, Andreas Tünnermann & Fabian Steinlechner

npj Quantum Information **9**, Article number: 95 (2023) | Cite this article

t-based free-space network.



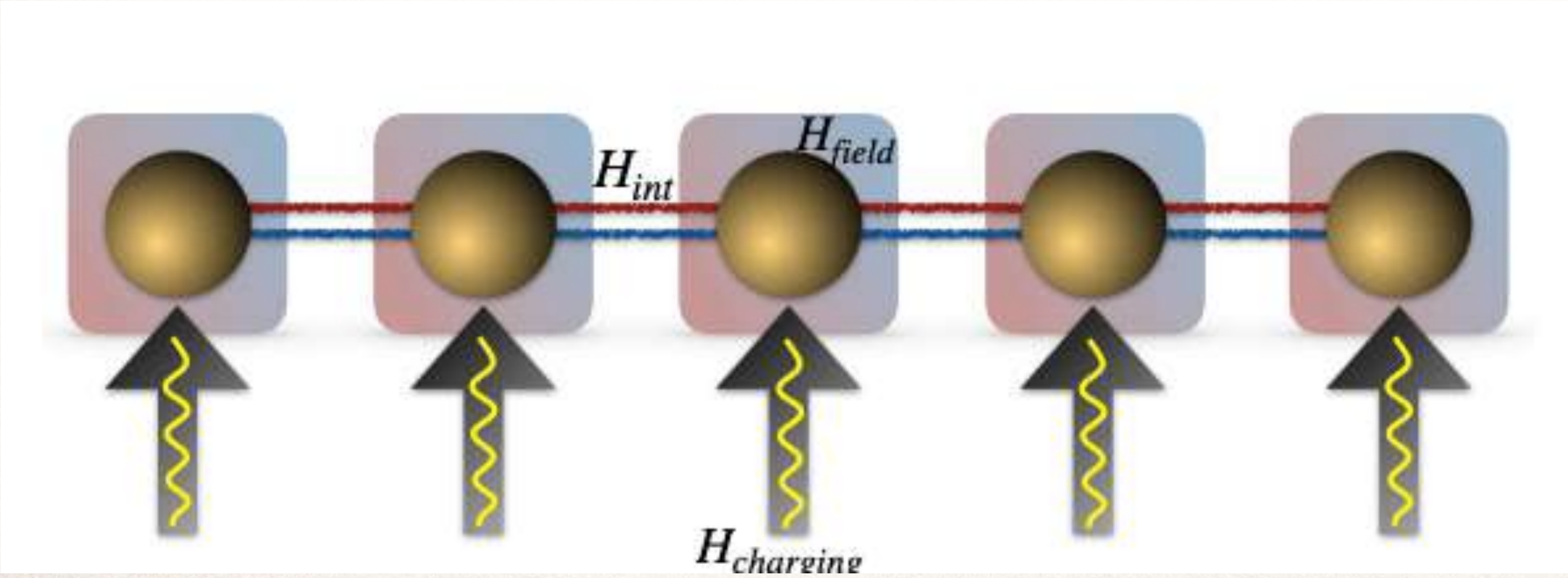
Pathways

- Quantum computer
- Quantum communication
- Quantum cryptography
- Other quantum devices
- Fundamental queries

Quantum thermal machines

Quantum battery

Goal: to store energy



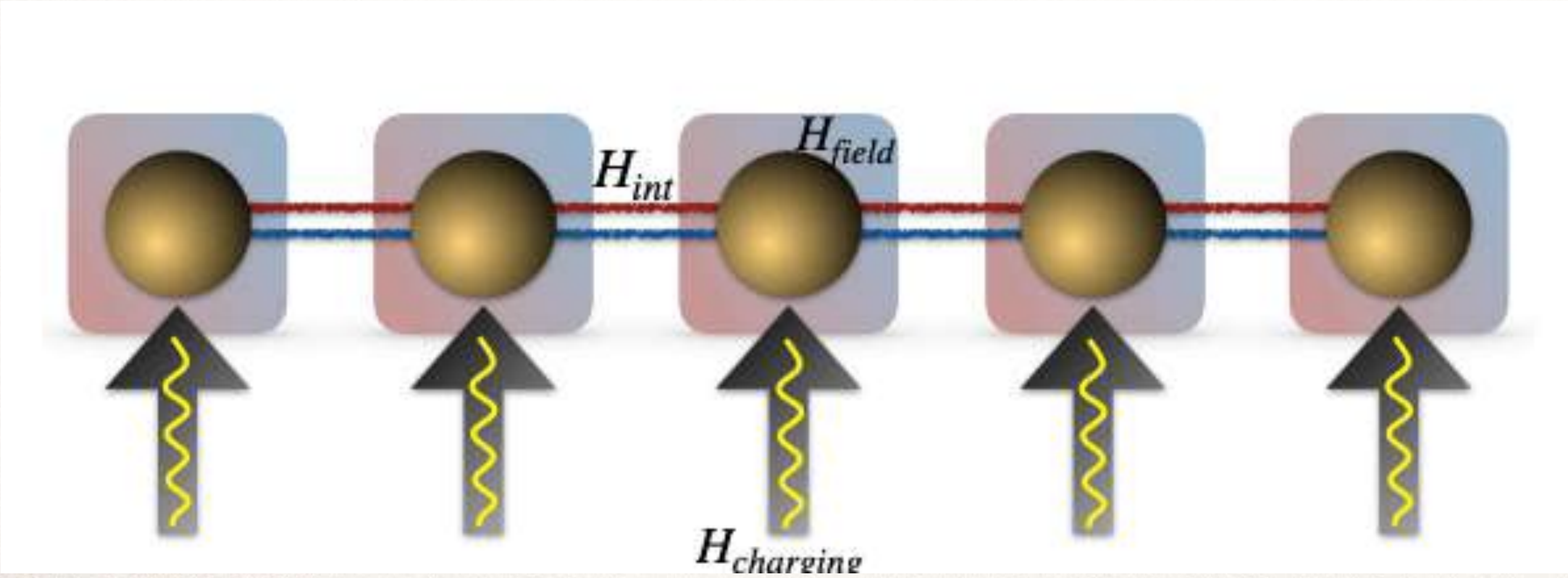
PRA'20-24

Quantum thermal machines

Quantum battery

Goal: to store energy

PRA'20-24



Design an interacting spin-1/2 model as a quantum battery

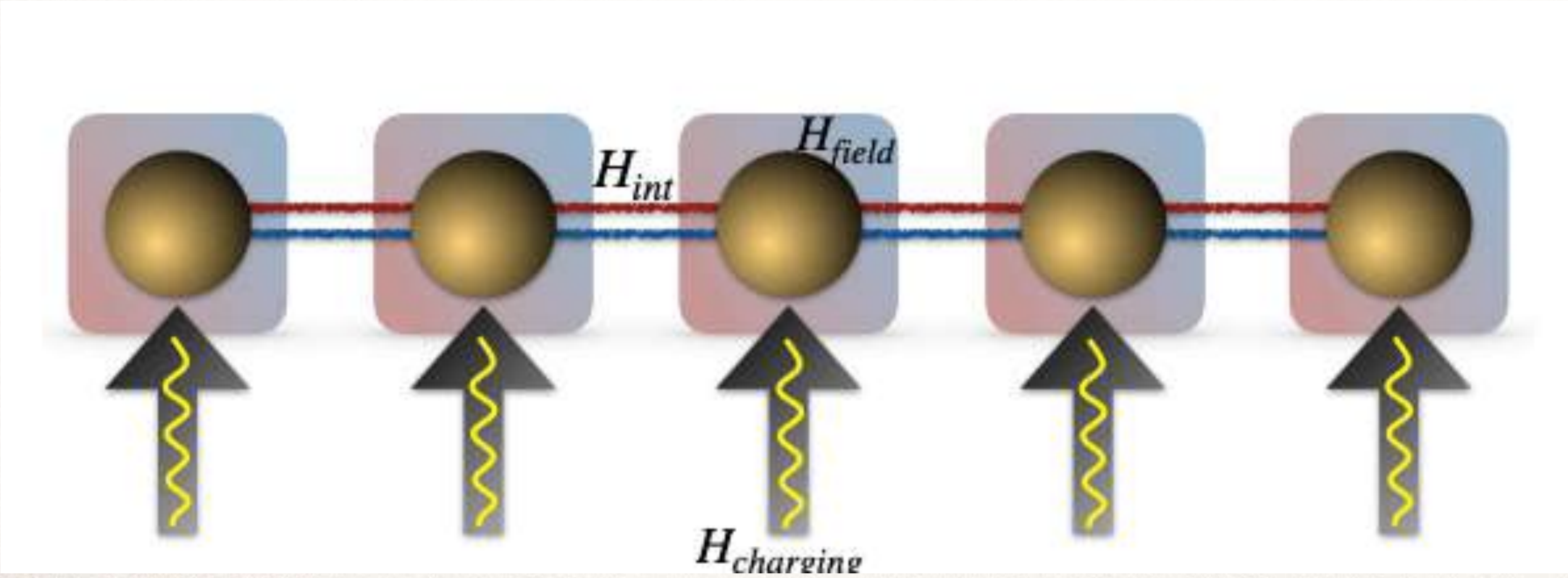
$$H_0 = \underbrace{\frac{1}{2}h\sum_{j=1}^{N}\sigma_j^z}_{H_{field}} + \underbrace{\frac{1}{4}\sum_{j=1}^{N-1} J_j[(1+\gamma)\sigma_j^x \otimes \sigma_{j+1}^x + (1-\gamma)\sigma_j^y \otimes \sigma_{j+1}^y]}_{H_{int}}$$

Quantum thermal machines

Quantum battery

Goal: to store energy

PRA'20-24



Design an interacting spin-1/2 model as a quantum battery

Local magnetic field as charger

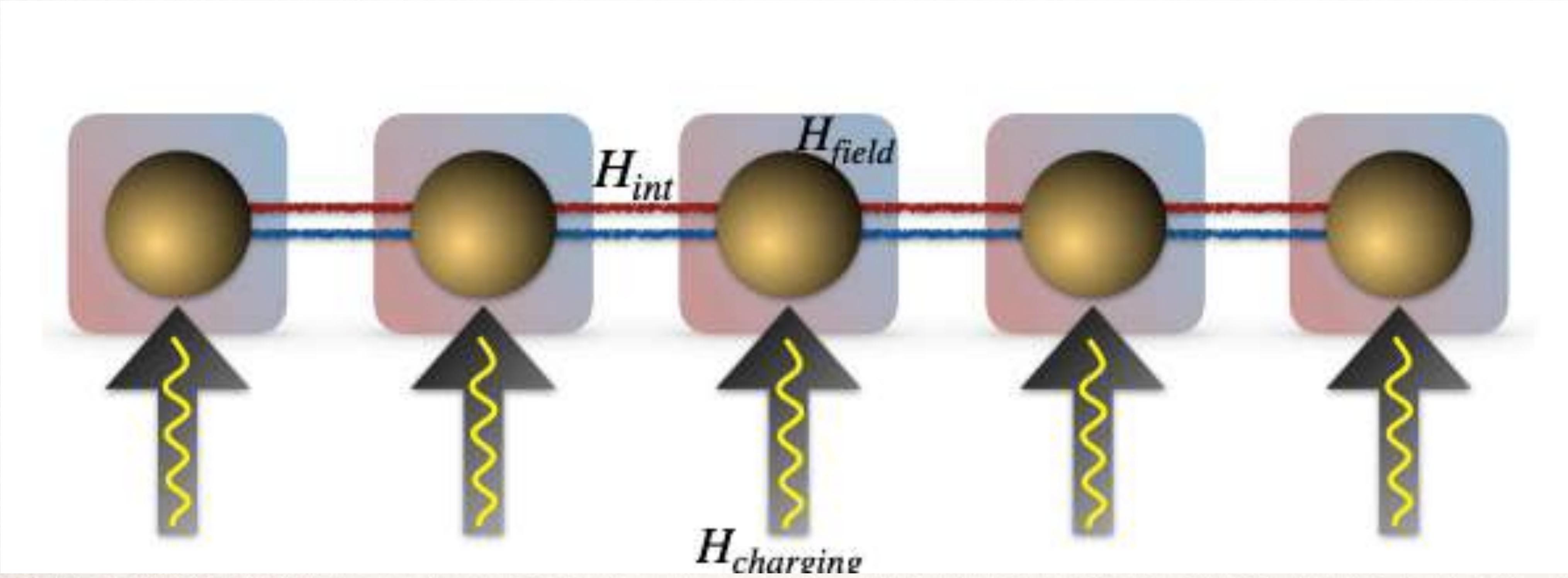
$$H_{charging} = \frac{\omega}{2} \sum_{j=1}^{N} \sigma_j^x .$$

Quantum thermal machines

Quantum battery

Goal: to store energy

PRA'20-24



Design an interacting spin-1/2 model as a quantum battery

Local magnetic field as charger

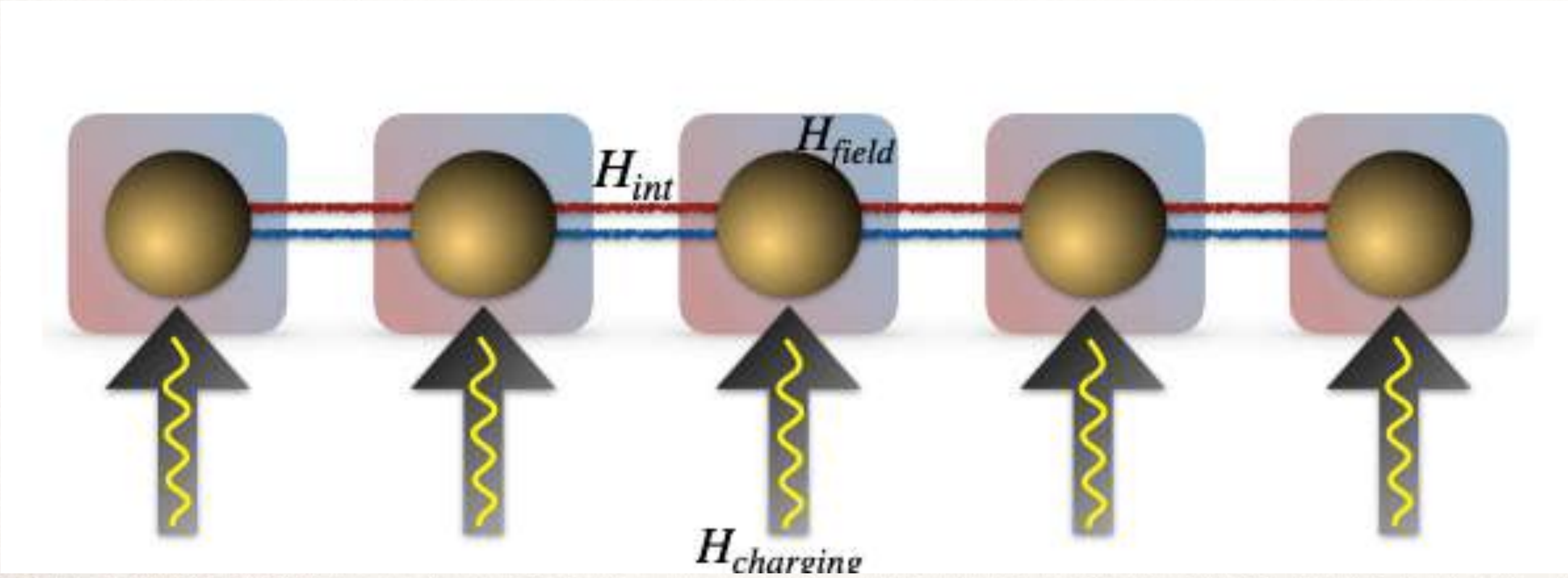
Performance quantifier

- Total work-output of the QB $W(t) = \mathrm{Tr}(H_0\rho(t)) - \mathrm{Tr}(H_0\rho(t=0)),$
- Average Power at time t: $P_{max} = \max_t \frac{W(t)}{t}$

Quantum thermal machines

Quantum battery

Goal: to store energy



Design an interacting spin-1/2 model as a quantum battery

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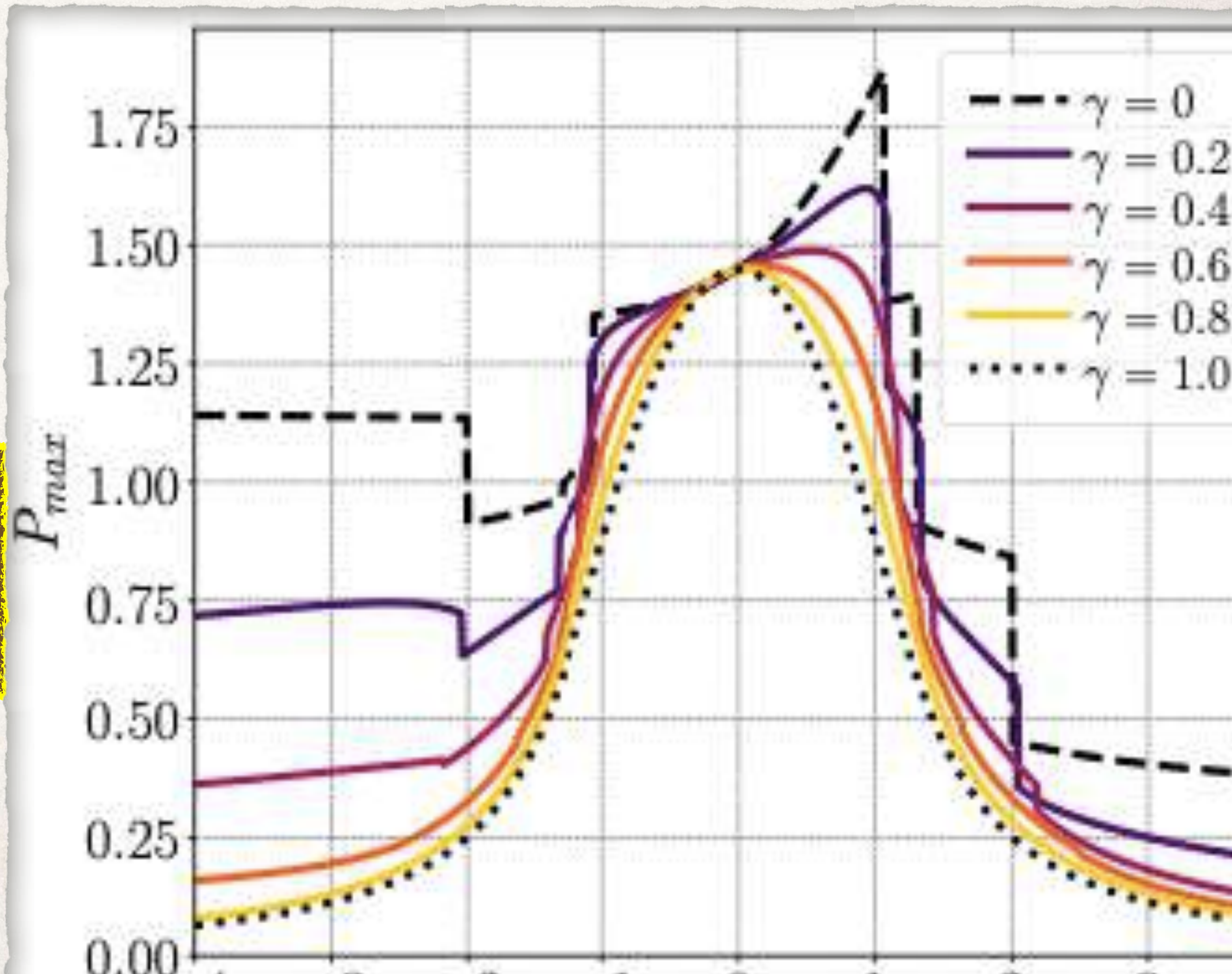
PRA'20-24



Interaction strengths play a crucial role to increase the extraction of power from it.

Quantum thermal machines

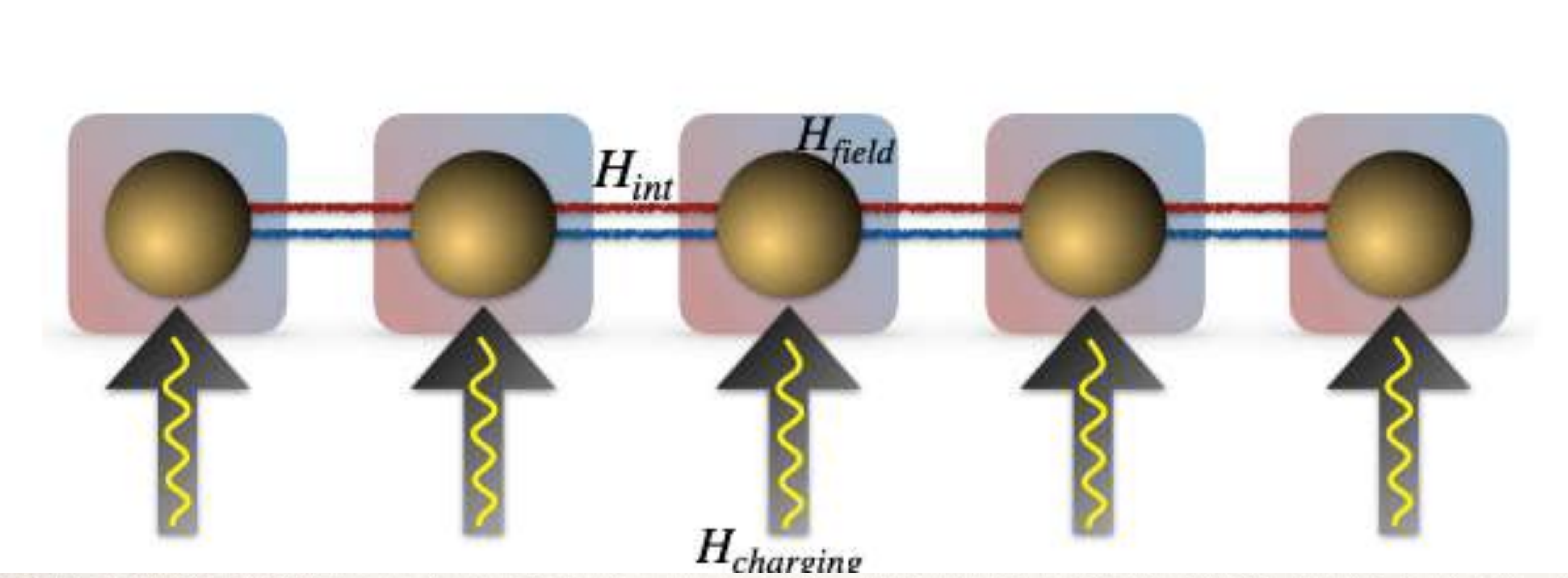
Quantum battery

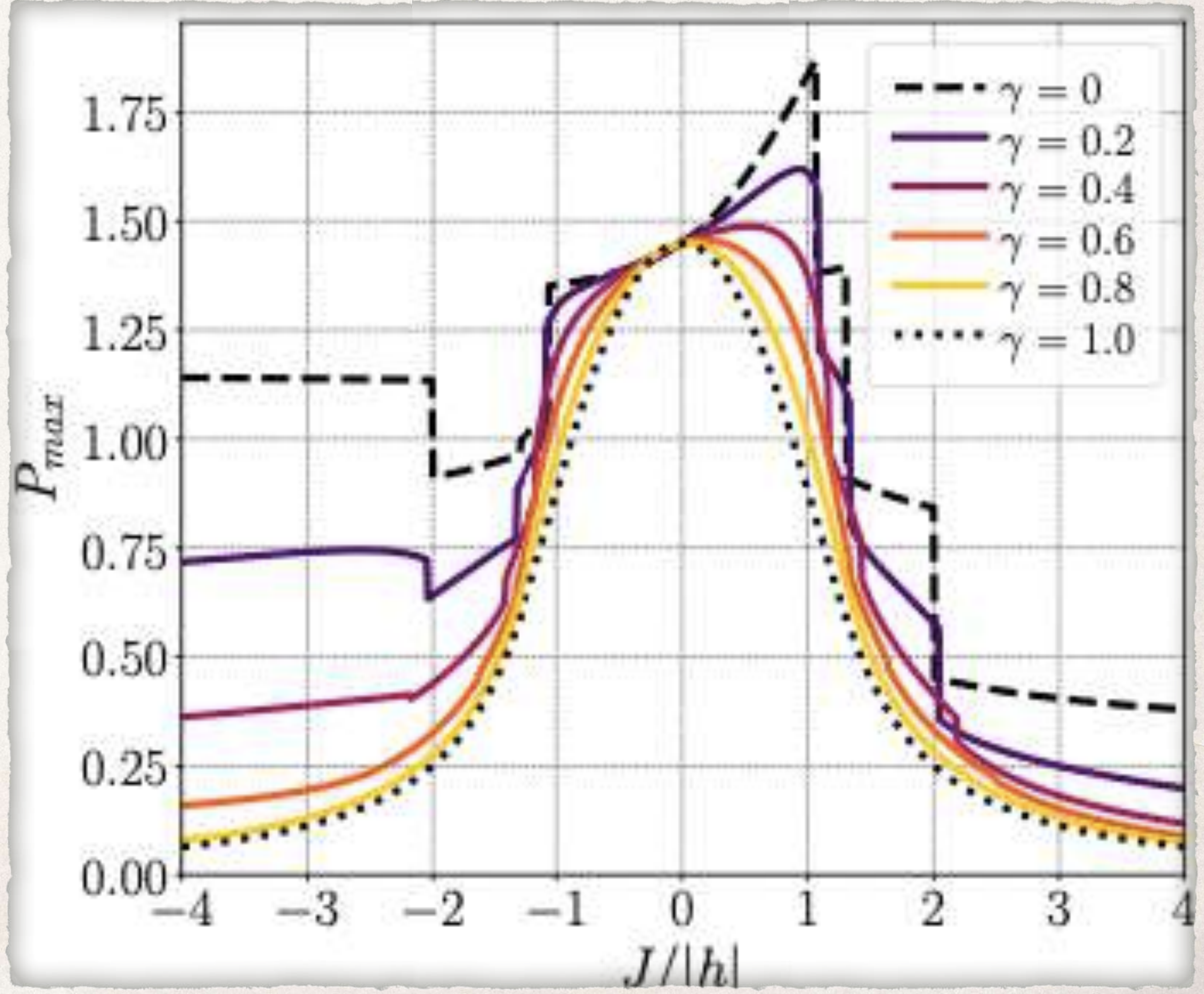
Goal: to store energy

PRA'20-24

Design an interacting spin-1/2 model as a quantum battery

Local magnetic field as charger



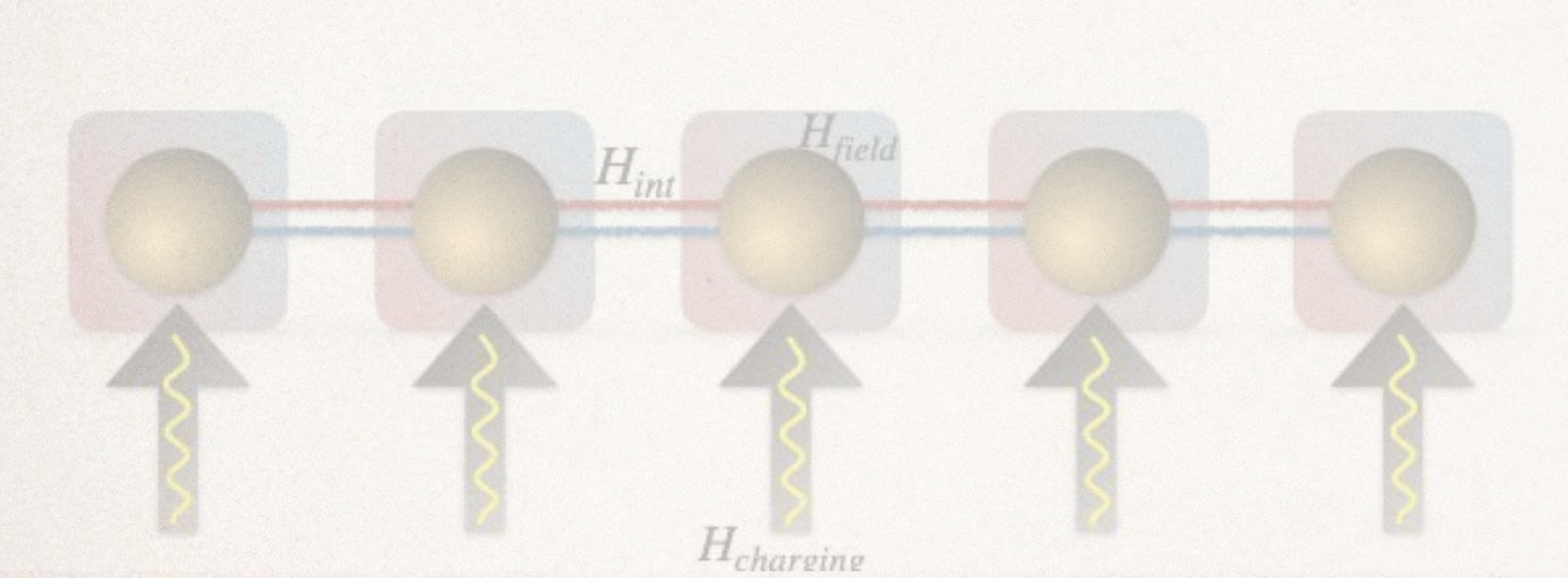


Robust against impurities, decoherence

Quantum thermal machines

Quantum battery

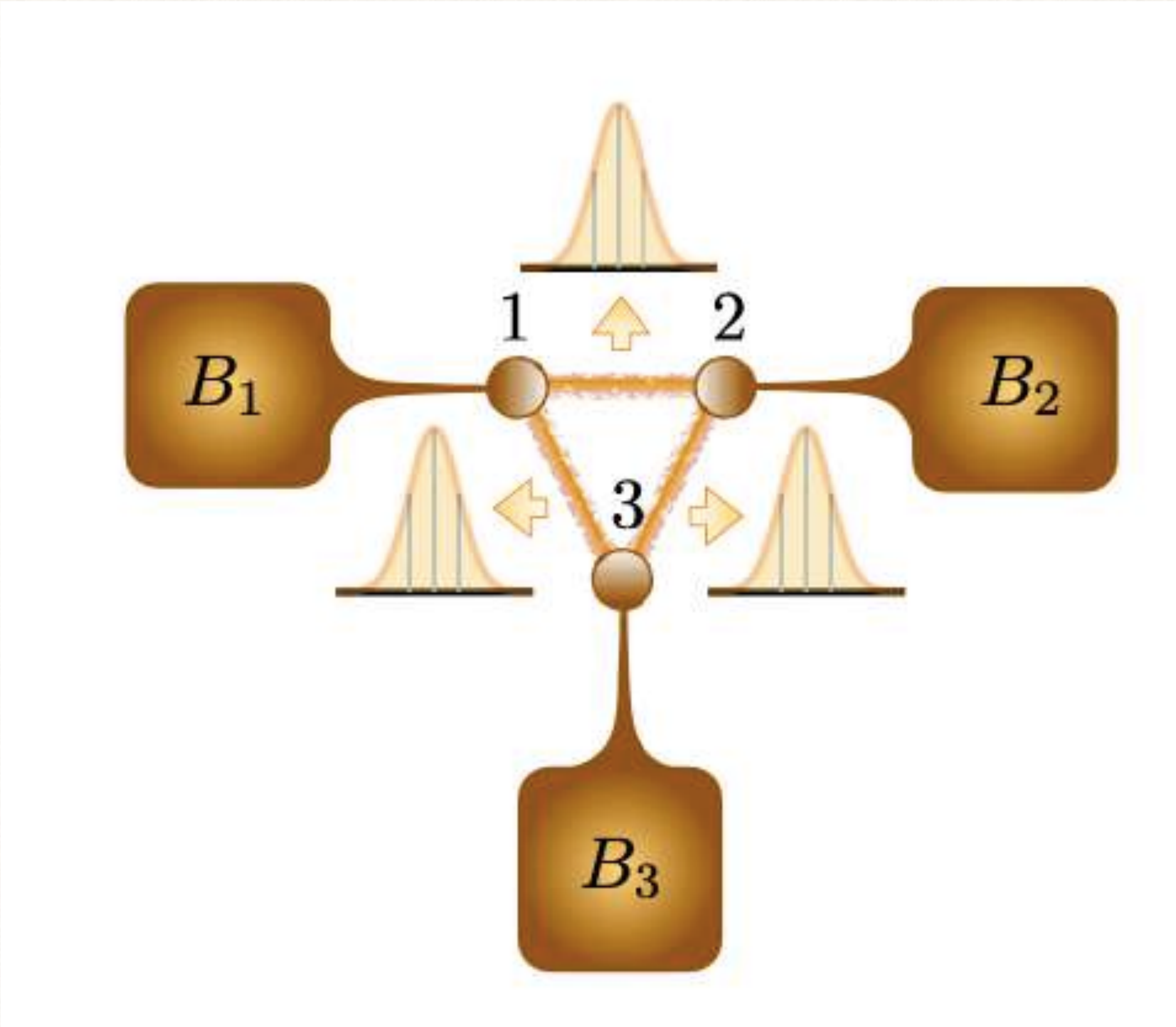
Goal: to store energy



Quantum Refrigerator

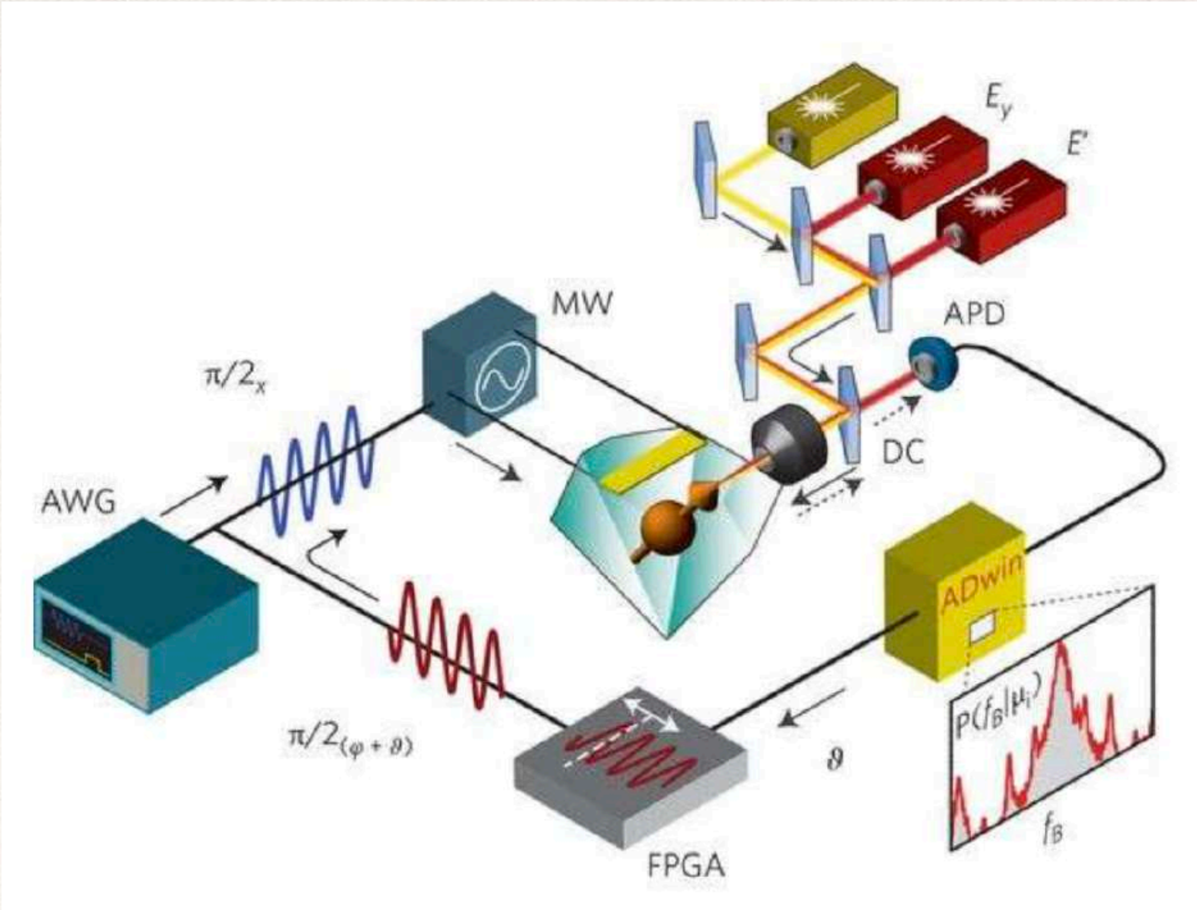
Goal: to decrease temperature

Interacting spin-1/2 model attached to bath



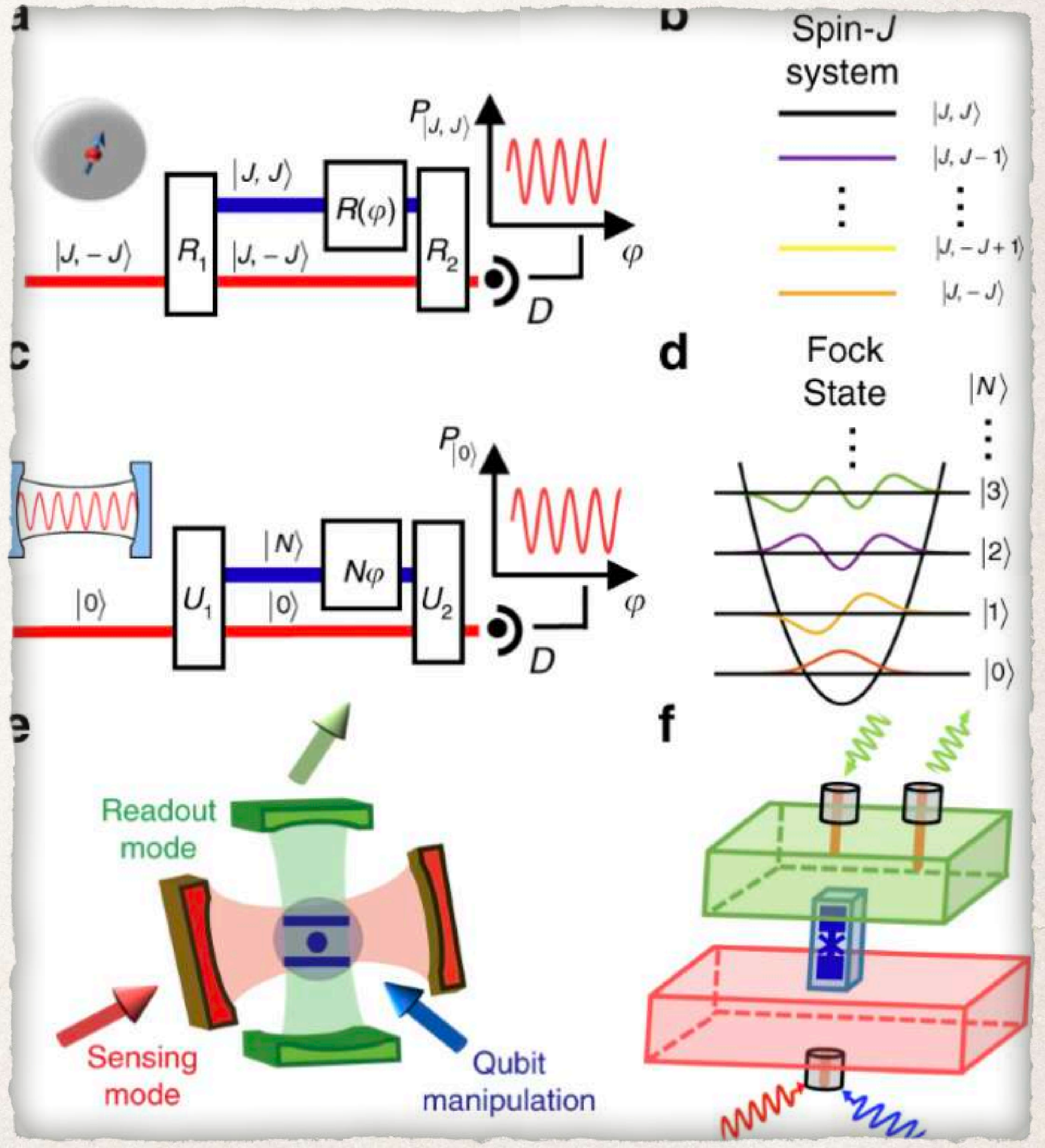
PRA22-23

Quantum Sensors



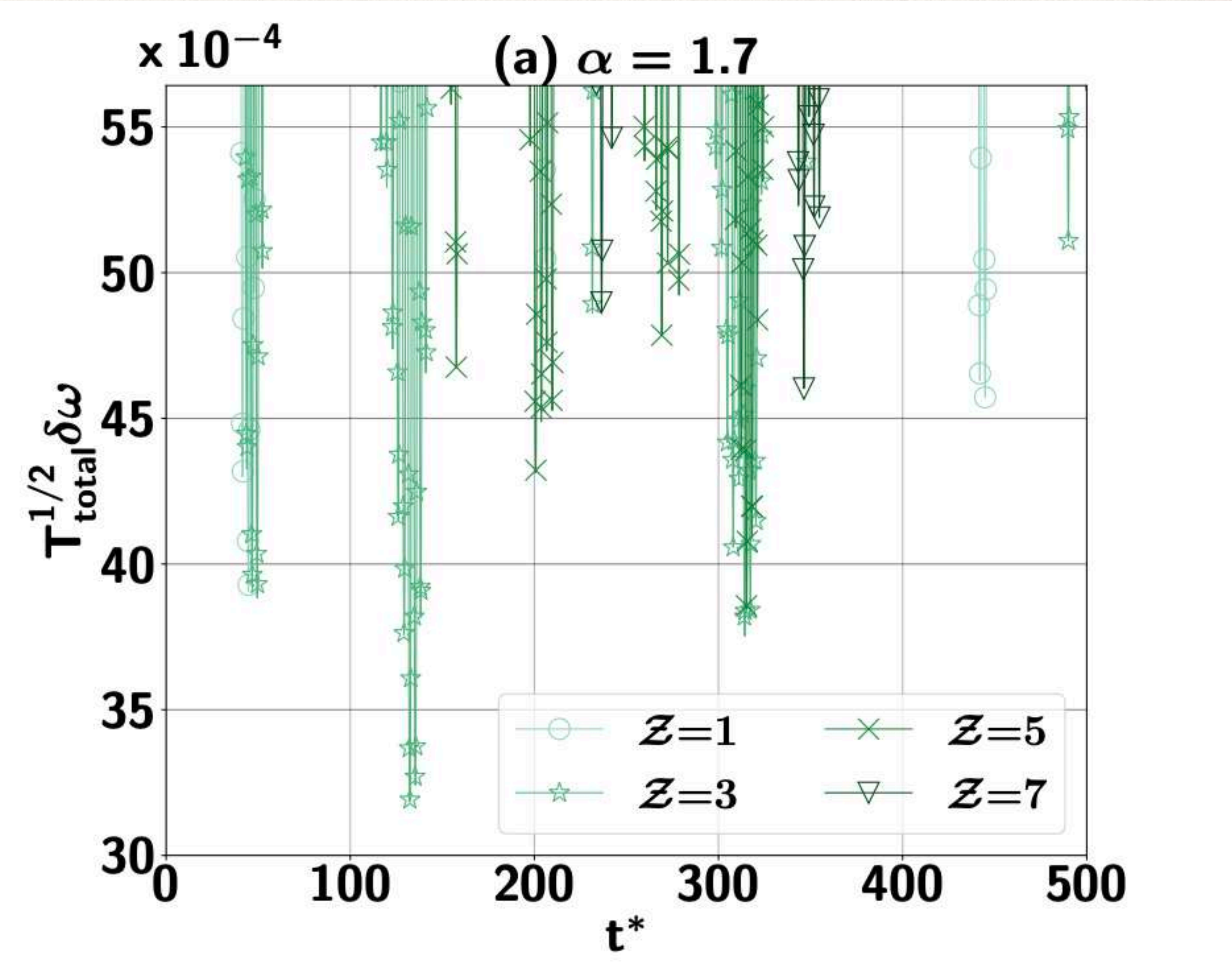
Quantum sensors:
Design to improve precision,
robustness against noise, imperfections

Implementation in NMR, NV centres, trapped ions,
superconducting qubits



Quantum Sensors

Higher sensitivity of magnetic field with long-range interactions



Better sensing with variable-range interactions

Monika, Leela Ganesh Chandra Lakkaraju, Srijon Ghosh, Aditi Sen De

arXiv:2401.14853 [pdf, other] quant-ph cond-mat.str-el

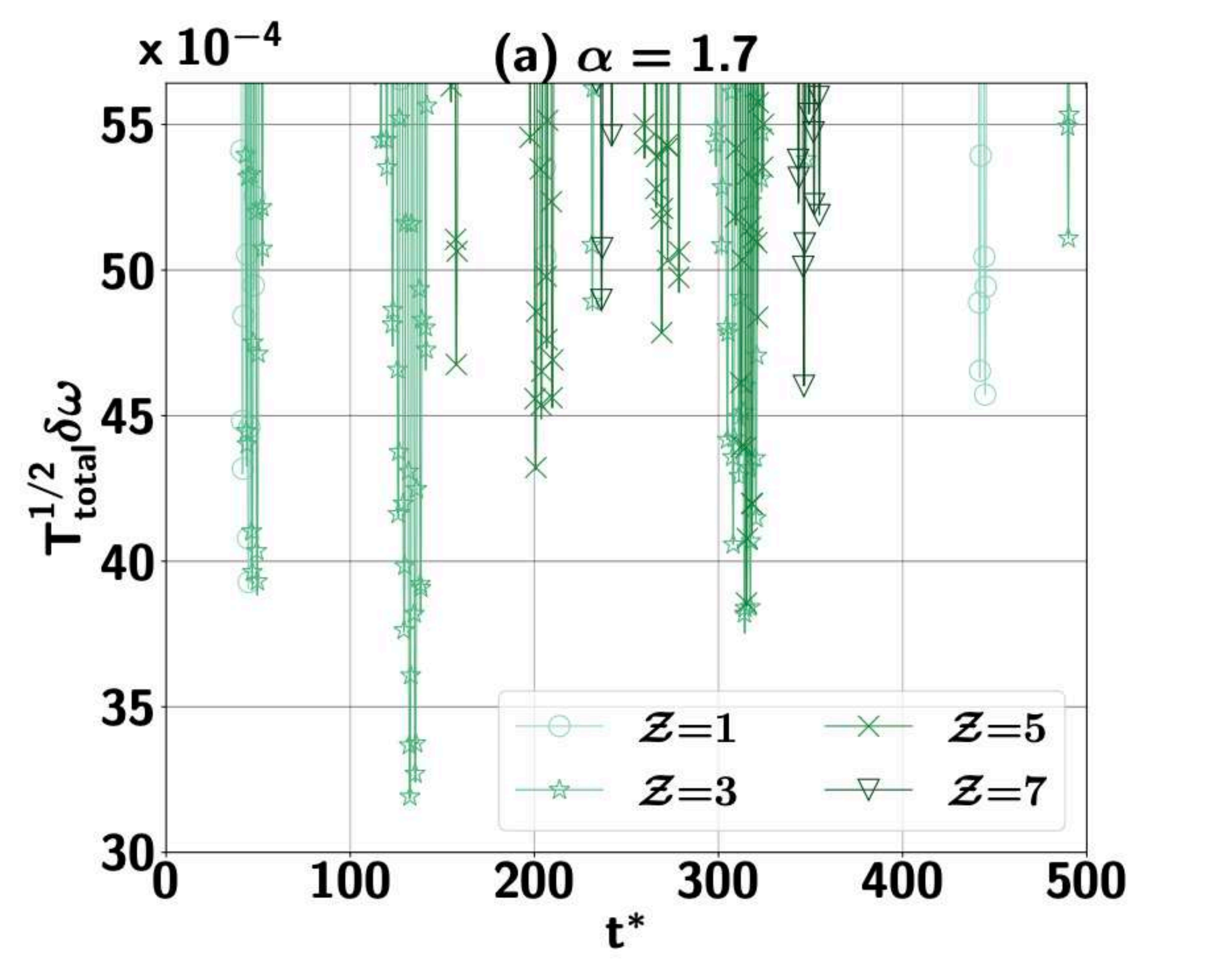
Dimensional gain in sensing through higher-dimensional quantum spin chain

Authors: Shivansh Singh, Leela Ganesh Chandra Lakkaraju, Srijon Ghosh, Aditi Sen De

Quantum Sensors

Higher sensitivity of magnetic field with long-range interactions

Enhancement in sensitivity with spin-s systems than spin-1/2



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Good vs Bad

Resource Theory

higher

Why speed up in quantum algorithms?

Why more efficiency in quantum communication devices?

REPORT ON PROGRESS

Quantum discord and its allies: a review of recent progress

Anindita Bera[1,2], Tamoghna Das[2], Debasis Sadhukhan[2], Sudipto Singha Roy[2], Aditi Sen(De)[2] and Ujjwal Sen[3,2]

Published 21 December 2017 • © 2017 IOP Publishing Ltd

Reports on Progress in Physics, Volume 81, Number 2

Resource theory of nonabsolute separability

Ayan Patra, Arghya Maity, and Aditi Sen(De)

Phys. Rev. A **108**, 042402 – Published 2 October 2023

Possible queries @HRI

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higher

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Possible queries @HRI

Quantum Technology ~2035

?

Quantum computer

?

Quantum internet

~2018—

Quantum cryptography

Quantum Technology ~2035

?

Quantum computer

?

Quantum internet

Quantum sensors

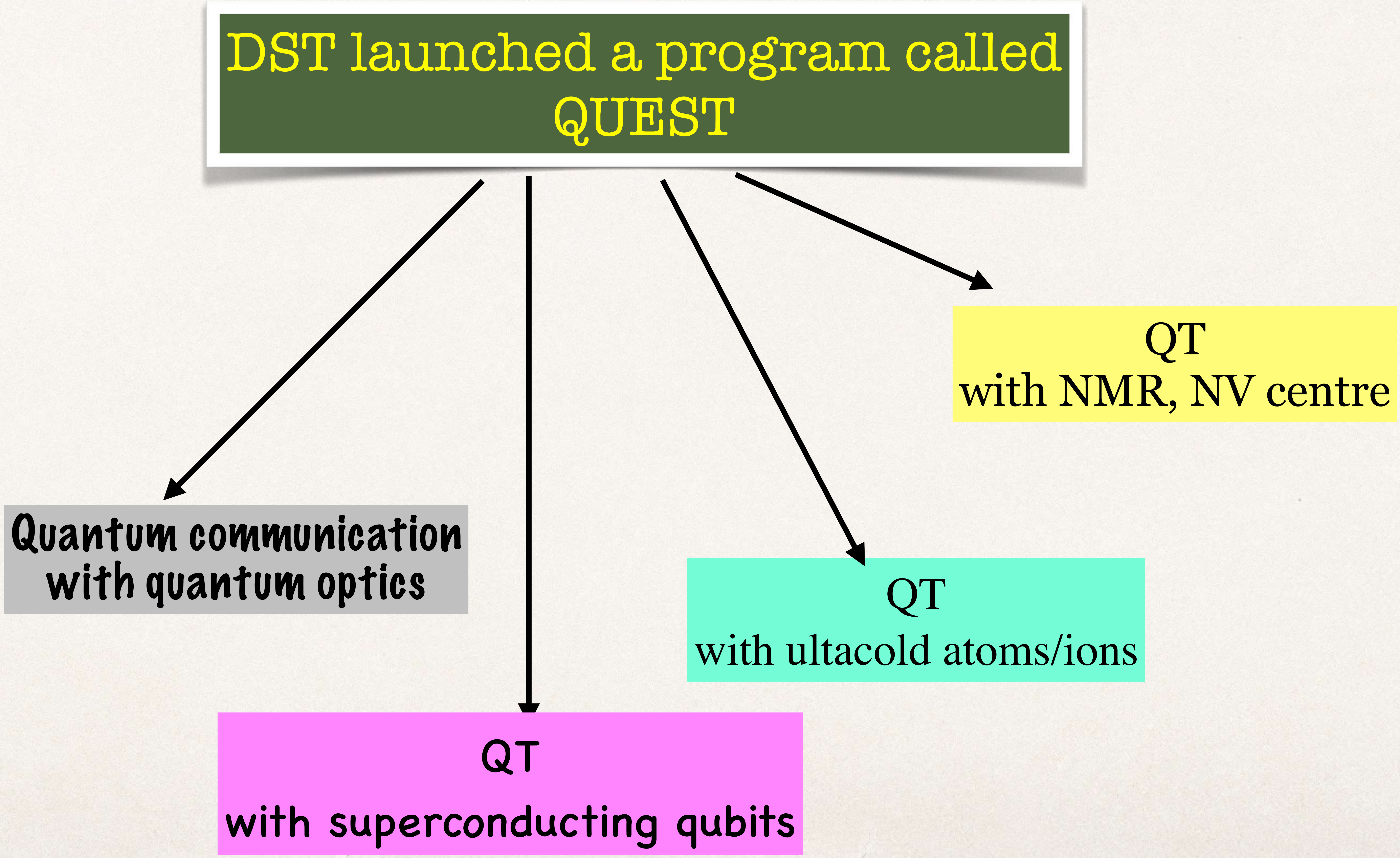
Quantum thermal machines

~2018—

Quantum cryptography

Quantum simulators

India's efforts on Quantum Technology

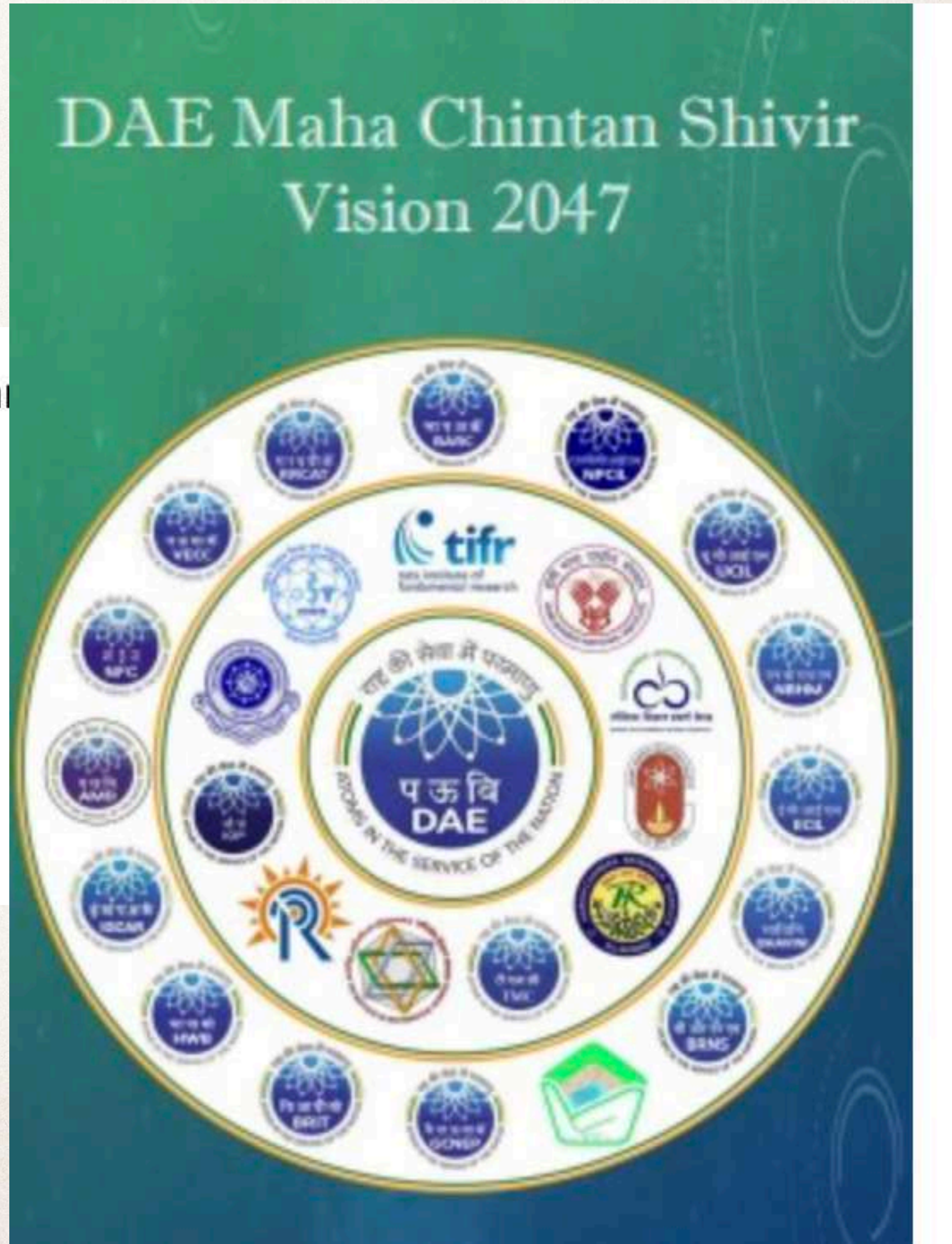


India's efforts on Quantum Technology

National Quantum mission

Mission Implementation includes setting up of four Thematic Hubs (T-Hubs) in top academic a

1. **Quantum Computing**
2. **Quantum Communication**
3. **Quantum Sensing & Metrology**
4. **Quantum Materials & Devices**



Current group

QIC@HRI

3 Faculty, 1 visiting Faculty
26 PhD students,
3PDFs+1
Several master students