Time-independence does not limit information flow

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NIST and University of Maryland

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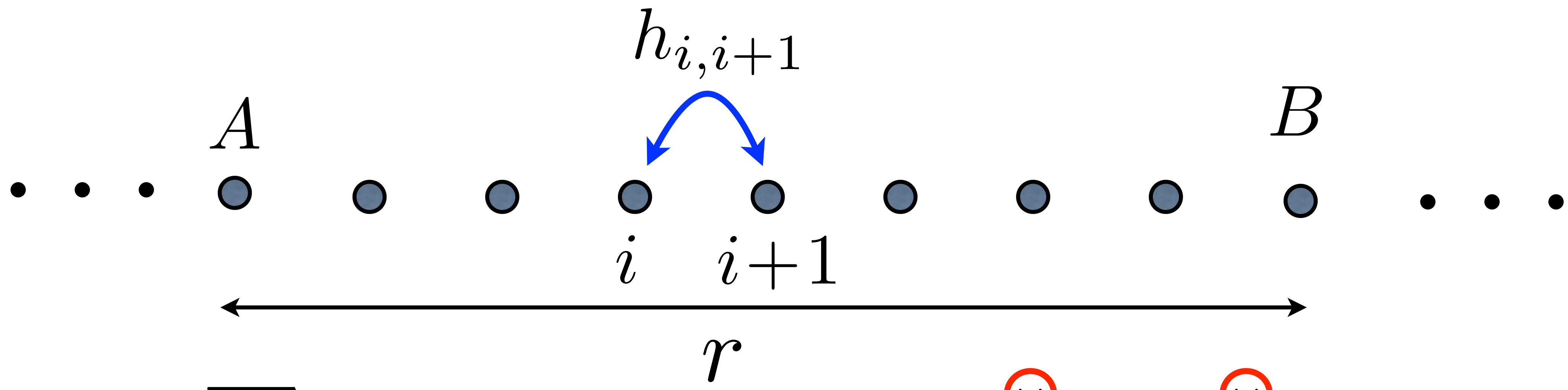
Lieb-Robinson bounds



$$H = \sum_i h_{i,i+1} \qquad ||h_{i,i+1}|| \leq 1$$

- arbitrary time dependence allowed
- arbitrary time-dependent on-site terms allowed
- $A(t) =$ Heisenberg evolution under H
- what is the shortest time t to achieve $||[A(t), B]|| \sim 1$?
- answer: $t \gtrsim r$
- bounds many things, including quantum state transfer time

E. Lieb & D. Robinson, 1972

Review: Chen, Lucas, Yin, Rep. Prog. Phys. 86, 116001 (2023)

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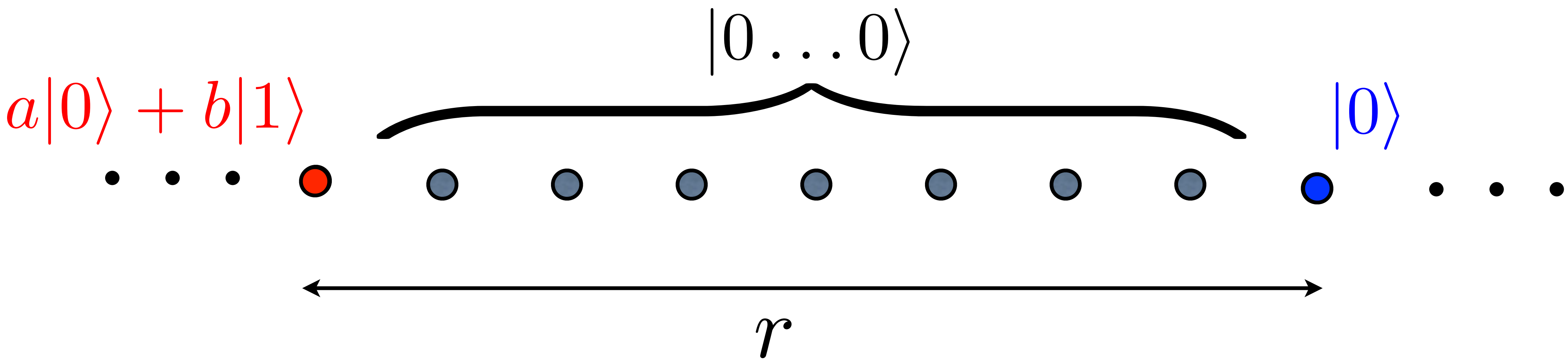

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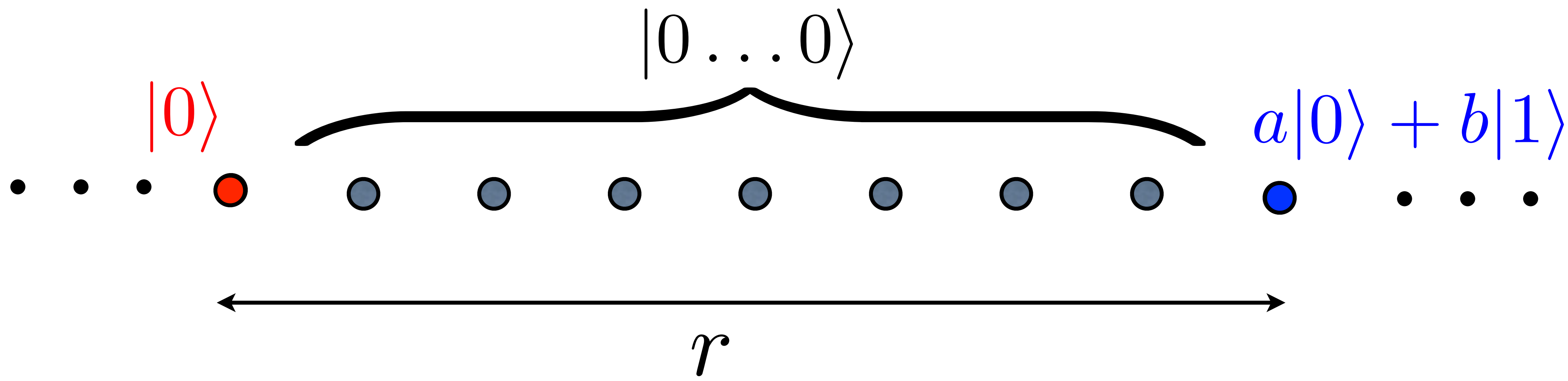

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Long-range interactions

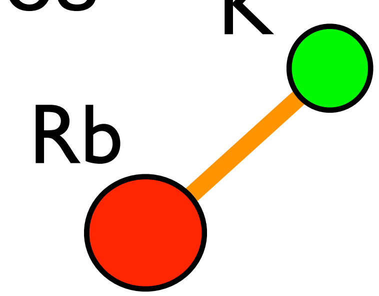
AMO and other synthetic quantum systems often exhibit

- long-range interactions = decaying with distance slower than exponential (e.g. decaying as $1/r^{\alpha}$)

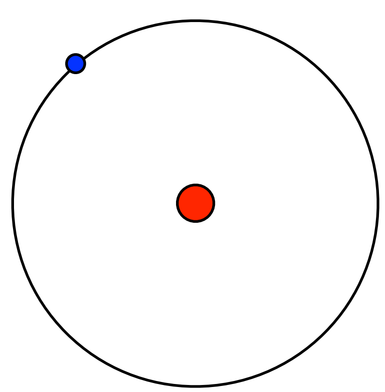
- how quickly can quantum information propagate in these systems?

Examples:

- $1/r^3$: Rydberg or magnetic atoms, excitons, NV centers, polar molecules



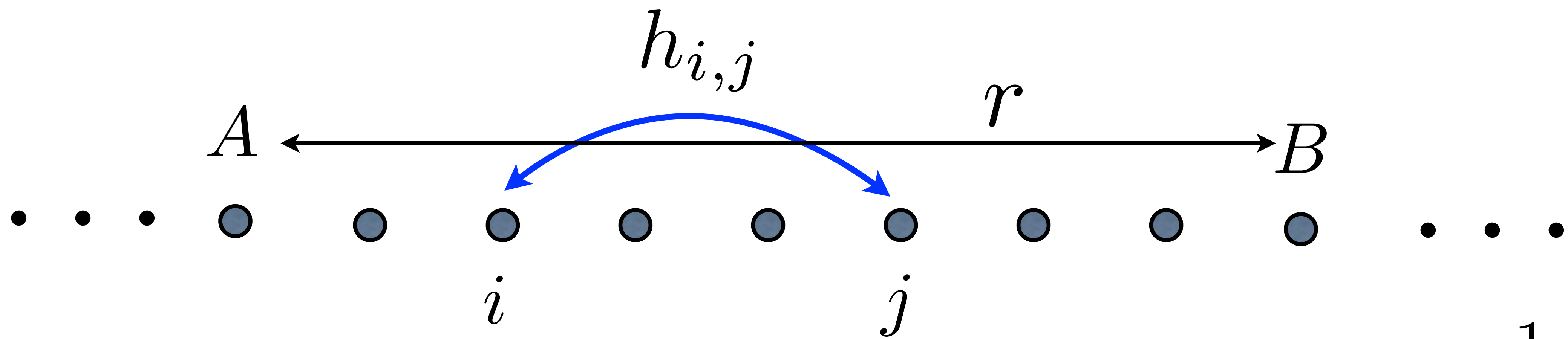
- $1/r^6$: Rydberg atoms



- $\sim 1/r^{\alpha}$ & other forms: ion crystals, atoms in multimode cavities or along waveguides

Monroe

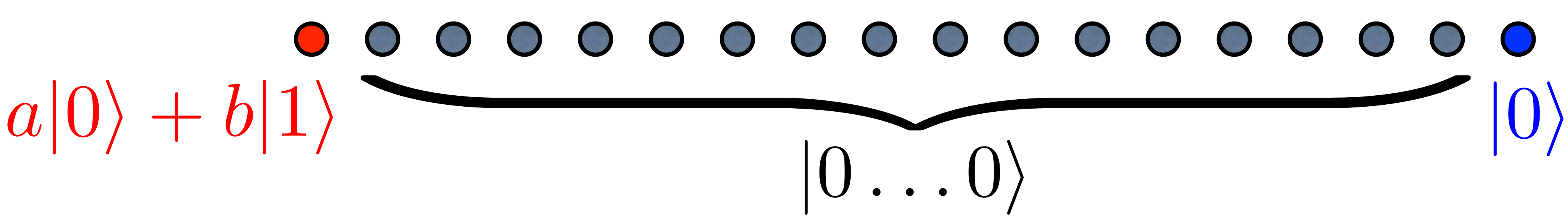
Lieb-Robinson-type bounds for $r^{-\alpha}$ interactions



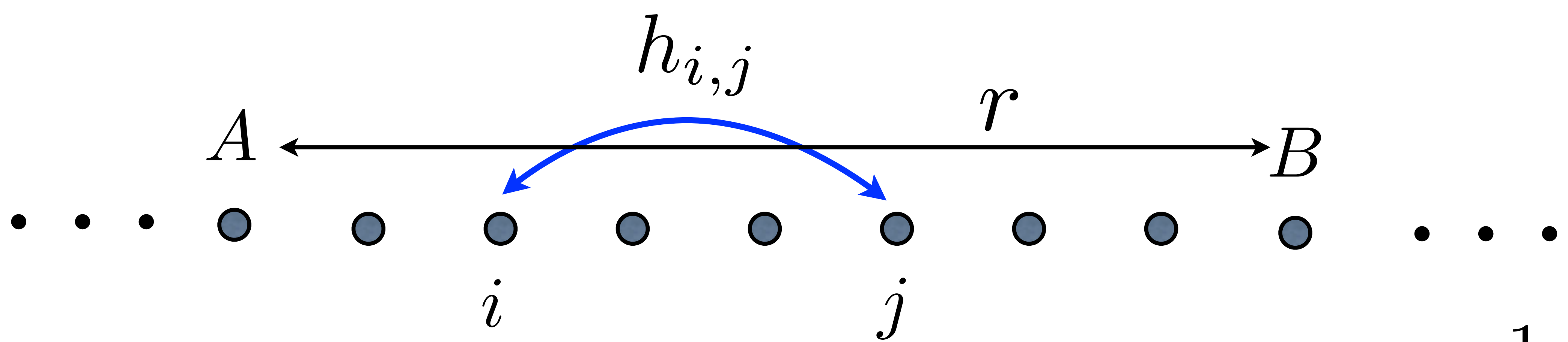
$$H = \sum_{i<j} h_{i,j} \qquad ||h_{i,j}|| \leq \frac{1}{|i-j|^\alpha}$$

- arbitrary time dependence allowed
- arbitrary time-dependent on-site terms allowed
- consider all $\alpha \geq 0$
- what is the shortest time t to achieve $||[A(t), B]|| \sim 1$?

= shortest time to send quantum information over distance r in the sense of quantum state transfer?



Lieb-Robinson-type bounds for $r^{-\alpha}$ interactions



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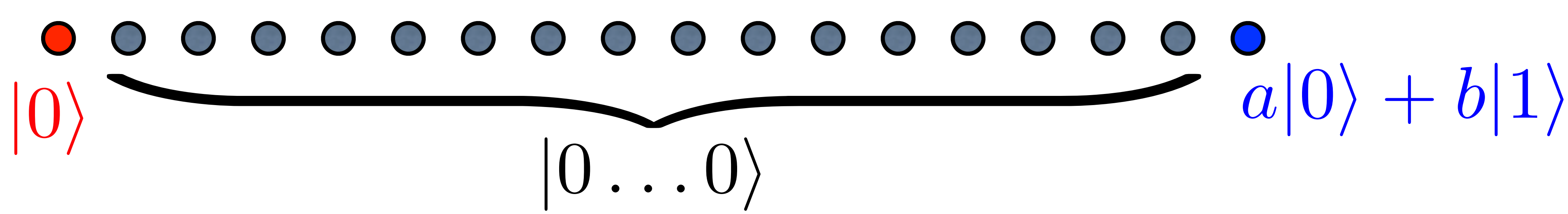


Lieb-Robinson-type bounds for $r^{-\alpha}$ interactions

~ "shortest time t to send quantum info over distance r"

d = dimension

Lieb-Robinson-type bounds for $r^{-\alpha}$ interactions

~ "shortest time t to send quantum info over distance r"

d = dimension

N = total number of sites
(formulas shown for $N \sim r^d$)

$\alpha = 0$ $\qquad$ $\alpha = \infty$

$t \gtrsim \frac{\log N}{N^{1-\alpha/d}}$

Guo, Tran, Childs, AVG, Gong, PRA (2020)

d

$t \gtrsim \log r$

Hastings, Koma, CMP '06

$2d$

$t \gtrsim r^{\alpha - 2d}$

$d = 1$: Chen, Lucas, PRL '19

$d > 1$: Tran et al (AVG, Lucas), PRL '21

$2d + 1$

$t \gtrsim r$

Chen, Lucas, PRL '19

Kuwahara, Saito, PRX '20

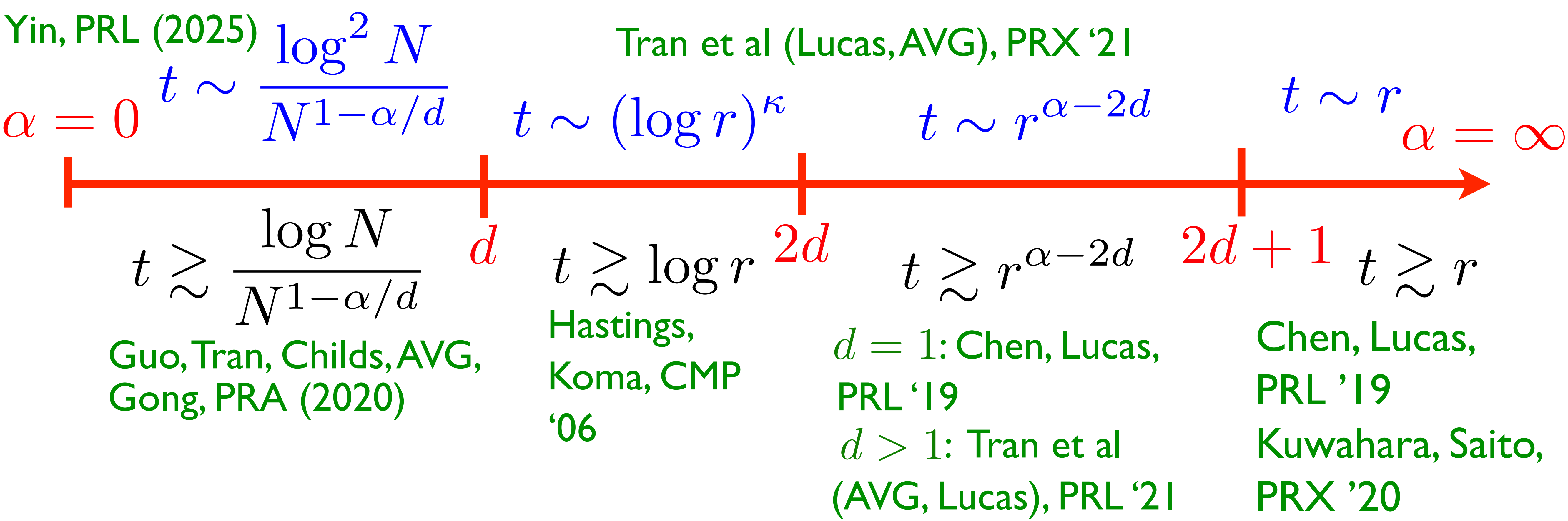
Fastest known protocols

Shortest time t to send quantum info over distance r
$1/r^\alpha$ interactions in d dimensions

- fastest protocols use time-dependent Hamiltonians
- can we achieve the same with a time-independent Hamiltonian?
- yes*, i.e. time-independence does not limit information flow

*need number of local ancilla qubits for each data qubit polylogarithmic in the number of data qubits

Mooney, Yuan, Ehrenberg, Baldwin, AVG, Childs, arXiv:2505.18254



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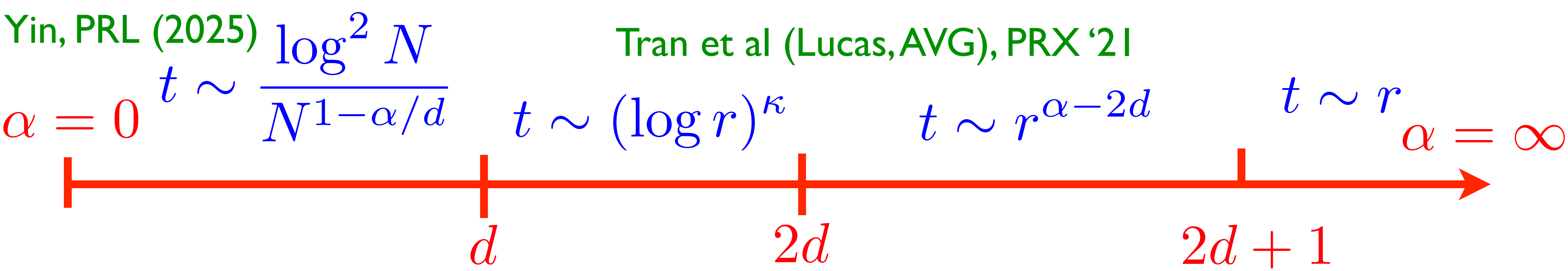


- approach: “staticize” time-dependent protocols using a clock construction

Staticizing time-independent Hamiltonians

- Watkins, Wiebe, Roggero, Lee, arXiv:2203.11353: given a time-dependent Hamiltonian, output an equivalent (up to small controllable error) time-independent Hamiltonian driven by a global clock

- to preserve locality, we replace one global clock with many local clocks (one per site)

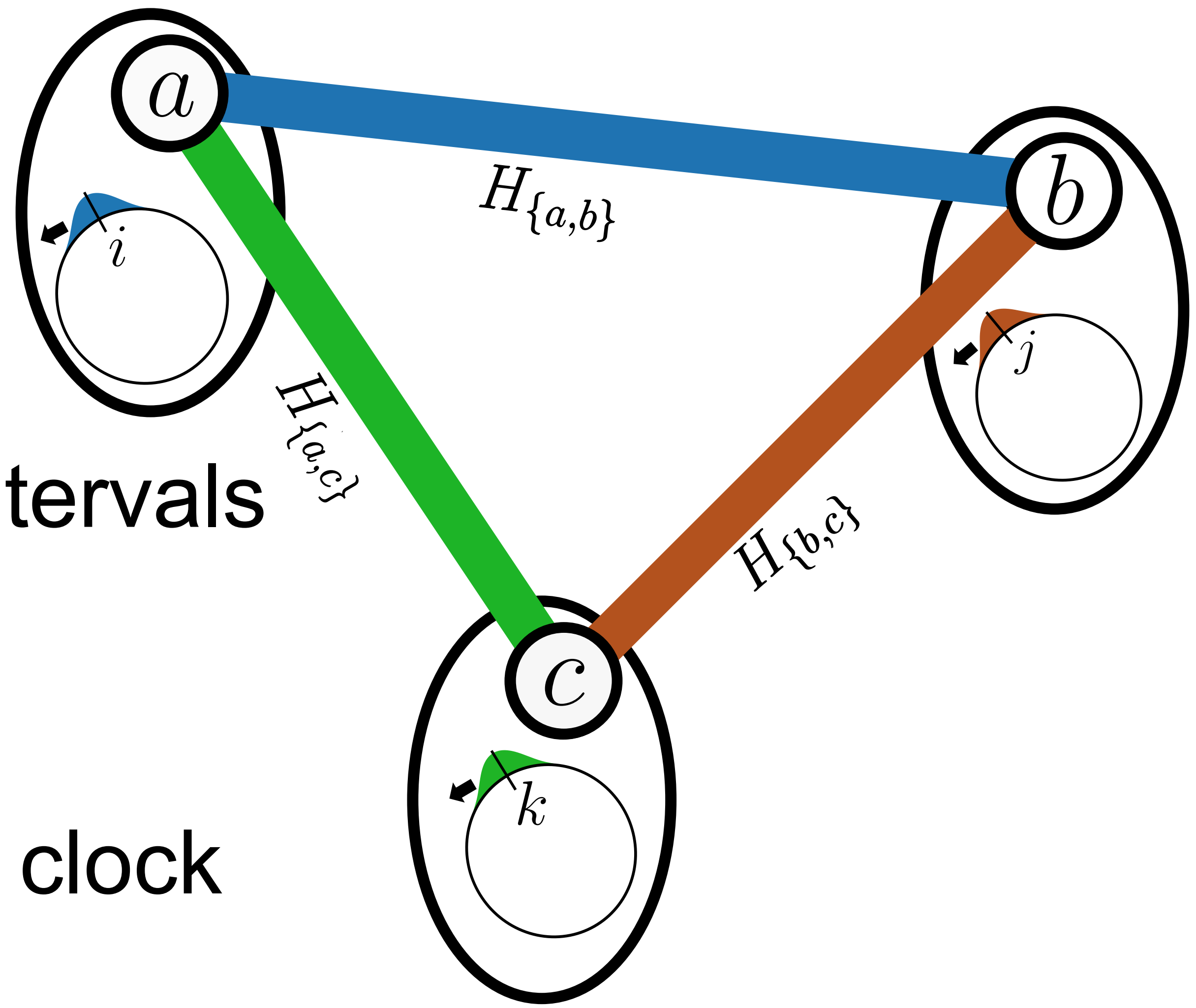
Mooney, Yuan, Ehrenberg, Baldwin, AVG, Childs, arXiv:2505.18254

Staticizing time-independent Hamiltonians

3-qubit example of our construction:

$$H(t) = H_{\{a,b\}}(t) + H_{\{b,c\}}(t) + H_{\{a,c\}}(t)$$

- for each edge e, we arbitrarily choose one of the vertices in e (call it $\rho(e)$) to control the interaction $H_e(t)$
- divide total time T into N_c small intervals of duration $\delta = T/N_c$
- each clock has N_c states $|k\rangle$
- clock Hamiltonian $\mathbf{\Delta}$ advances the clock on each site: $e^{-i\mathbf{\Delta}\delta}|k\rangle = |k+1\rangle$



$$\overline{H} = \mathbf{\Delta} + \sum_k \sum_e H_e(k\delta) \otimes (|k\rangle\langle k|)_{\rho(e)}$$

Mooney, Yuan, Ehrenberg, Baldwin, AVG, Childs, arXiv:2505.18254

Summary

• time-independence does not limit information flow, provided we allow for a polylogarithmic number of ancilla qubits per data qubit

Outlook

• our staticization construction applies to any piecewise-continuous Hamiltonian, including circuit-based quantum algorithms, quantum annealing protocols, entangled-state preparation (e.g. for sensing)

- would be interesting to investigate the specifics

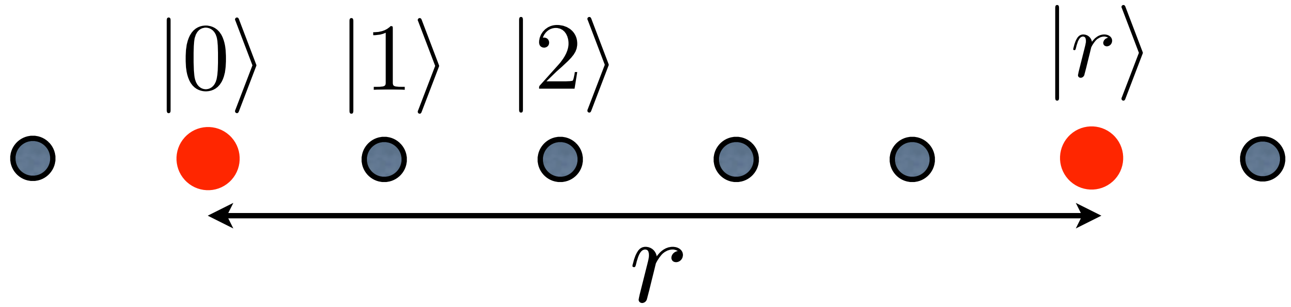
• in some scenarios (architecture + application), it can be easier to implement Hamiltonian dynamics without time-dependent control

• our protocols incur error (which can be made arbitrarily small), but can we find a protocol that achieves perfect state transfer?

• can we reduce the local ancilla account to a constant or even to zero?

• can get rid of ancillas in the restricted setting of free-particle Hamiltonians!

Free-particle bounds and protocols



$$H = \sum_{i<j} h_{ij}(t)|i\rangle\langle j| + h.c. + \sum_i \mu_i(t)|i\rangle\langle i| \qquad |h_{ij}| \leq \frac{1}{|i-j|^\alpha}$$

- how long does it take to evolve from $|0\rangle$ to $|r\rangle$?

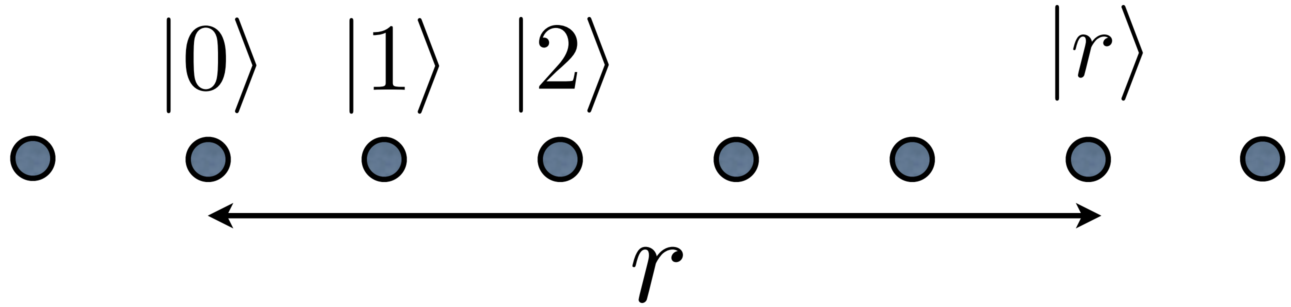
Equivalent to

$$H = \sum_{i<j} h_{ij}(t)c_i^\dagger c_j + h.c. + \sum_i \mu_i(t)c_i^\dagger c_i$$

$c_i^\dagger$ = bosonic or fermionic creation operators

- what is the shortest time t to achieve $c_0^\dagger(t) = c_r^\dagger(0)$?

Free-particle bounds and protocols



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Slower than with interactions.

- how long does it take to evolve from $|0\rangle$ to $|r\rangle$?
- can we achieve the same with a time-independent Hamiltonian?

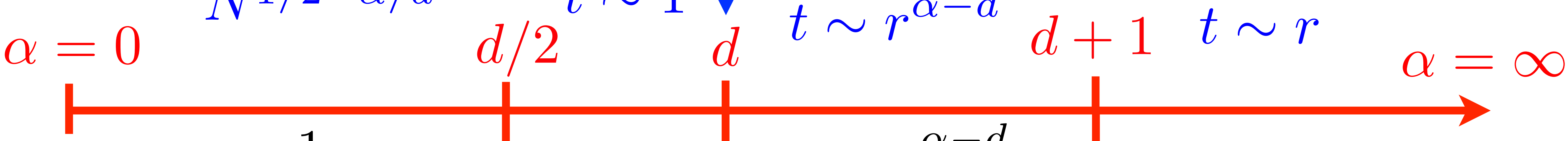
Yes!

Guo, Tran, Childs, AVG, Gong, PRA (2020)

Tran et al (Gong, AVG, Lucas), PRX (2020)

N = total number of sites

$t \sim \frac{1}{N^{1/2-\alpha/d}}$ $\quad$ $t \sim 1$ $\quad$ $t \sim \log r$ $\quad$ $t \sim r^{\alpha-d}$ $\quad$ $t \sim r$



$t \gtrsim \frac{1}{N^{1/2-\alpha/d}}$ $\quad$ $t \gtrsim 1$ $\quad$ $t \gtrsim \frac{r^{\alpha-d}}{\log r}$ $\quad$ $t \gtrsim r$

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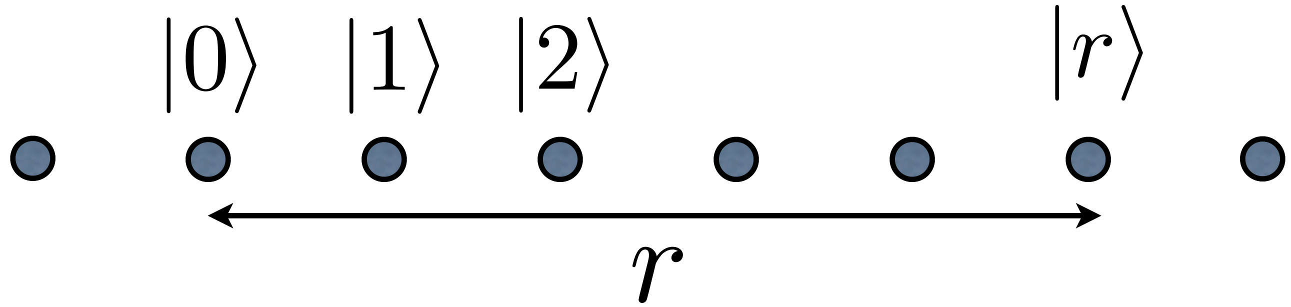

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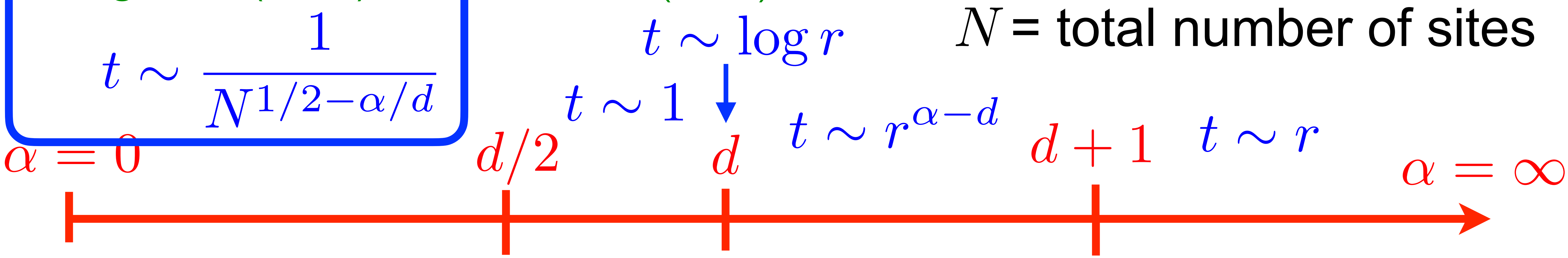
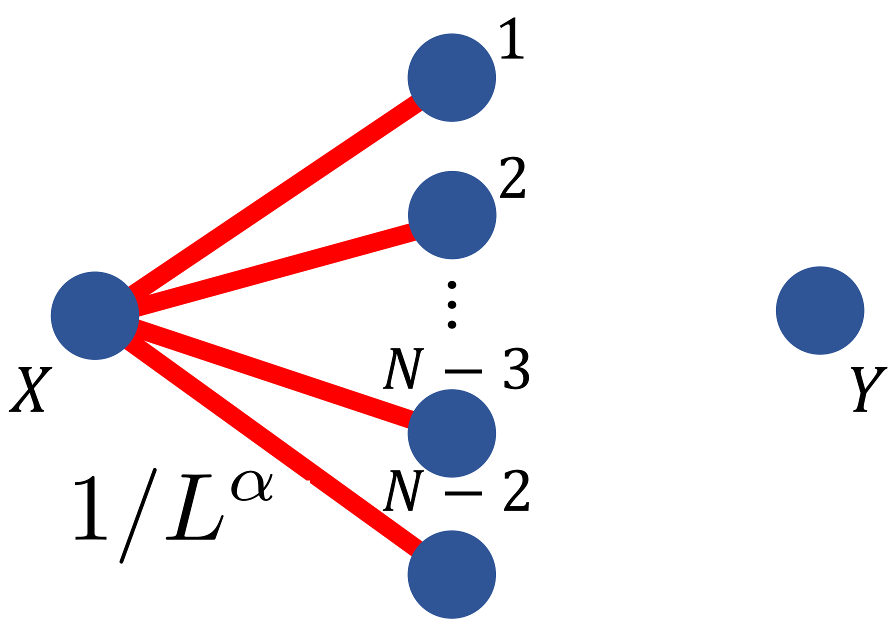


Related prior work: Avellino, Fisher, Bose, PRA (2006); Gualdi, Kostak, Marzoli, Tombesi, PRA (2008); Hermes, Apollaro, Paganelli, Macri, PRA (2020); Lewis, Banchi, Teoh, Islam, Bose, Quantum Sci. Technol. (2023).

Time-dependent protocol for $\alpha < d/2$

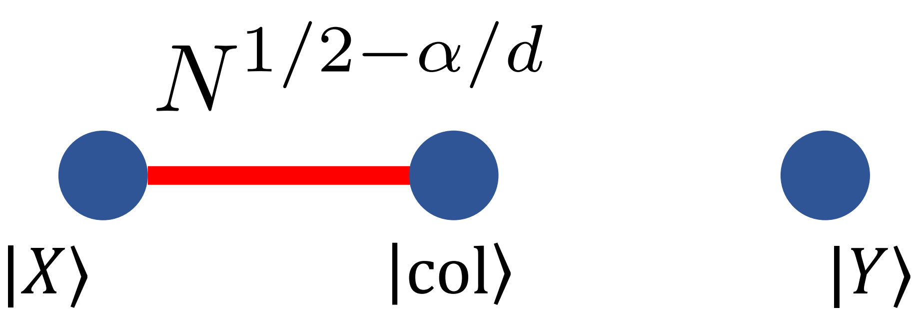
- $N \sim L^d$ sites on a d-dimensional cubic lattice of linear size L
- interaction strength upper bounded by $1/r^\alpha$
- want to evolve from $|X\rangle$ to $|Y\rangle$



$$H = \frac{1}{L^\alpha} |X\rangle \sum_{i=1}^{N-2} \langle i| + h.c.$$

$$\sim \frac{\sqrt{N}}{L^\alpha} |X\rangle\langle \mathrm{col}| + h.c.$$

$$|\mathrm{col}\rangle = \frac{1}{\sqrt{N-2}} \sum_{i=1}^{N-2} |i\rangle$$



- takes time $\sim 1/N^{1/2-\alpha/d}$ to hop from $|X\rangle$ to $|\mathrm{col}\rangle$
- then hop from $|\mathrm{col}\rangle$ to $|Y\rangle$

Guo, Tran, Childs, AVG, Gong, PRA (2020)

Staticize the protocol for $\alpha < d/2$

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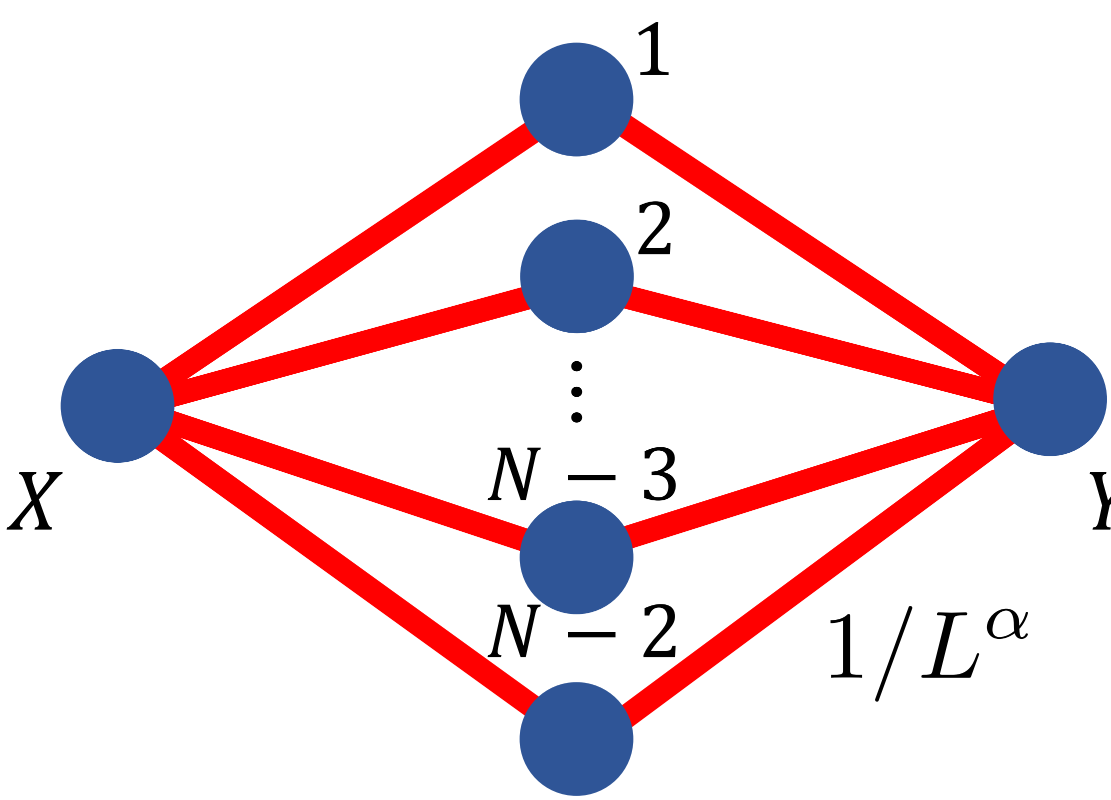


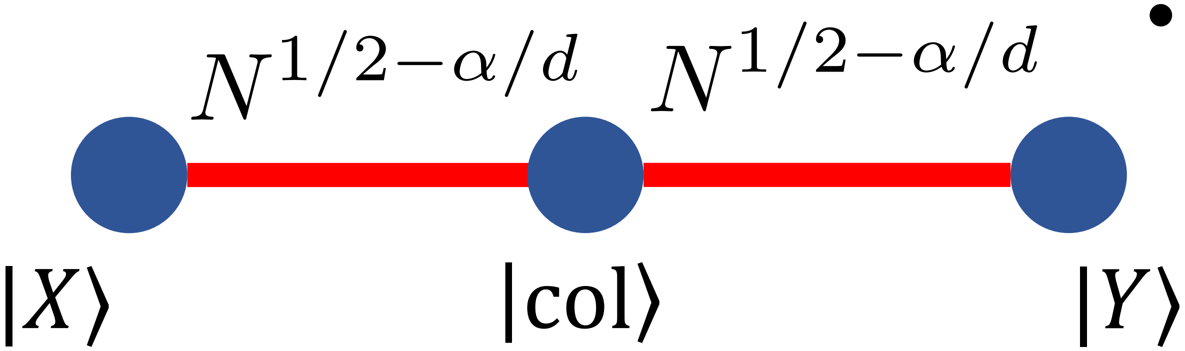
$$H = \frac{1}{L^\alpha}(|X\rangle + |Y\rangle)\sum_{i=1}^{N-2}\langle i| + h.c.$$

$$\sim \frac{\sqrt{N}}{L^\alpha}(|X\rangle + |Y\rangle)\langle \mathrm{col}| + h.c.$$

- takes time $\sim 1/N^{1/2-\alpha/d}$ to do a 2π pulse from $|X\rangle + |Y\rangle$ via $|\mathrm{col}\rangle$
- $|X\rangle \propto (|X\rangle + |Y\rangle) + (|X\rangle - |Y\rangle)$

$$\to -(|X\rangle + |Y\rangle) + (|X\rangle - |Y\rangle)$$

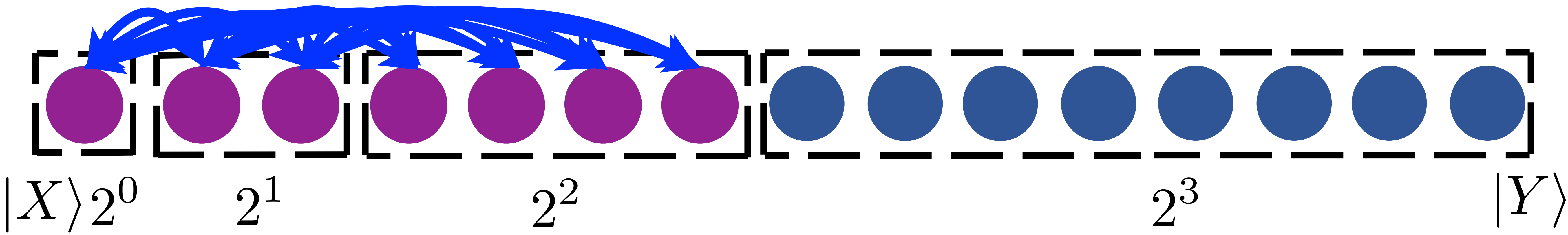
$$\propto |Y\rangle$$



Yuan, Yin, Mooney, Baldwin, Childs, AVG, arXiv:2505.18249

Time-dependent protocol for $d/2 < \alpha < d+1$

- $N \sim L^d$ sites on a d-dimensional cubic lattice of linear size L
- interaction strength upper bounded by $1/r^\alpha$
- want to evolve from $|X\rangle$ to $|Y\rangle$
- show for d=1



- spread to larger uniform superpositions, then reverse to $|Y\rangle$

Tran et al (Gong, AVG, Lucas), PRX (2020)

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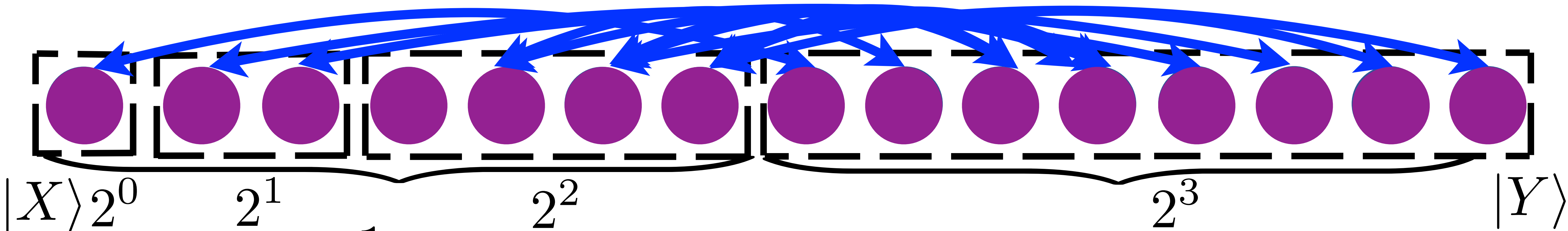

$$|A\rangle \sim \frac{1}{\sqrt{2^j}} \sum_{i \in A} |i\rangle \qquad |B\rangle \sim \frac{1}{\sqrt{2^j}} \sum_{i \in B} |i\rangle$$

- spread to larger uniform superpositions, then reverse to $|Y\rangle$
- time to spread to additional 2^j sites ~ $2^{j(\alpha-1)}$

$$H \sim \frac{1}{(2^j)^\alpha} \sum_{i \in A, k \in B} |i\rangle\langle k| + h.c. \sim \frac{2^j}{(2^j)^\alpha} |A\rangle\langle B| + h.c.$$

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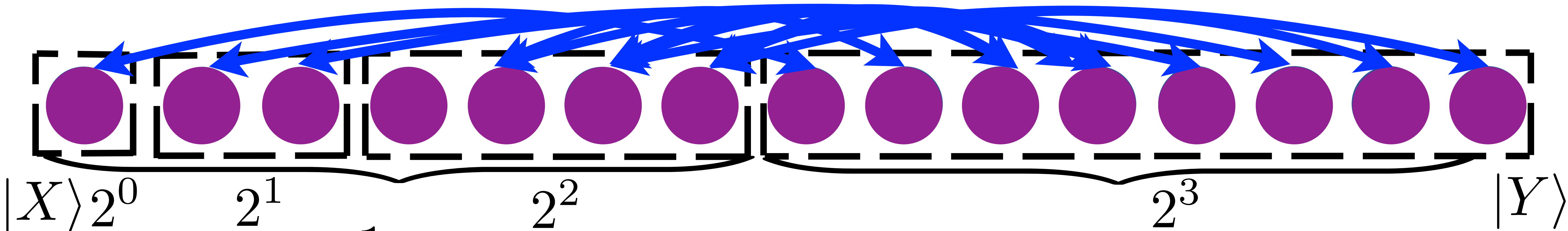

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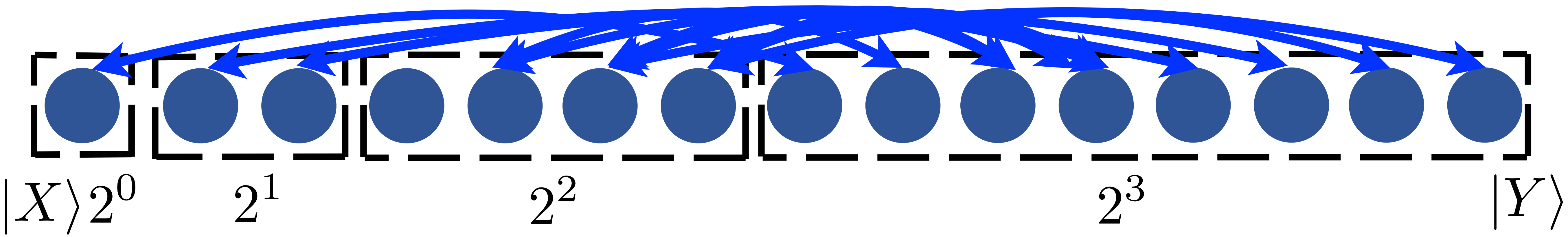
- spread to larger uniform superpositions, then reverse to $|Y\rangle$
- time to spread to additional 2^j sites ~ $2^{j(\alpha-1)}$
- time to spread to full lattice $\sim \sum_{j=1}^{\log L} (2^{\alpha-1})^j$

$$\sim 1 \qquad \alpha < 1$$
$$\sim \log L \qquad \alpha = 1$$
$$\sim L^{\alpha-1} \qquad \alpha > 1$$

Tran et al (Gong, AVG, Lucas), PRX (2020)

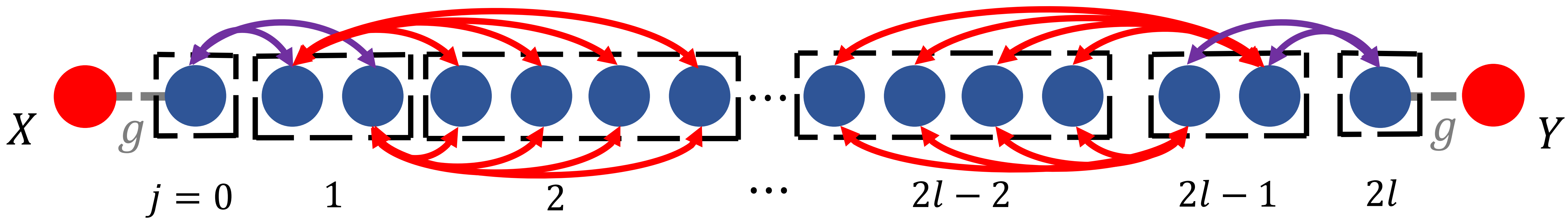
Staticize the protocol for $d/2 < \alpha < d+1$



- turning simultaneously all the interactions needed to spread from $|X\rangle$ and to concentrate onto $|Y\rangle$ doesn't work

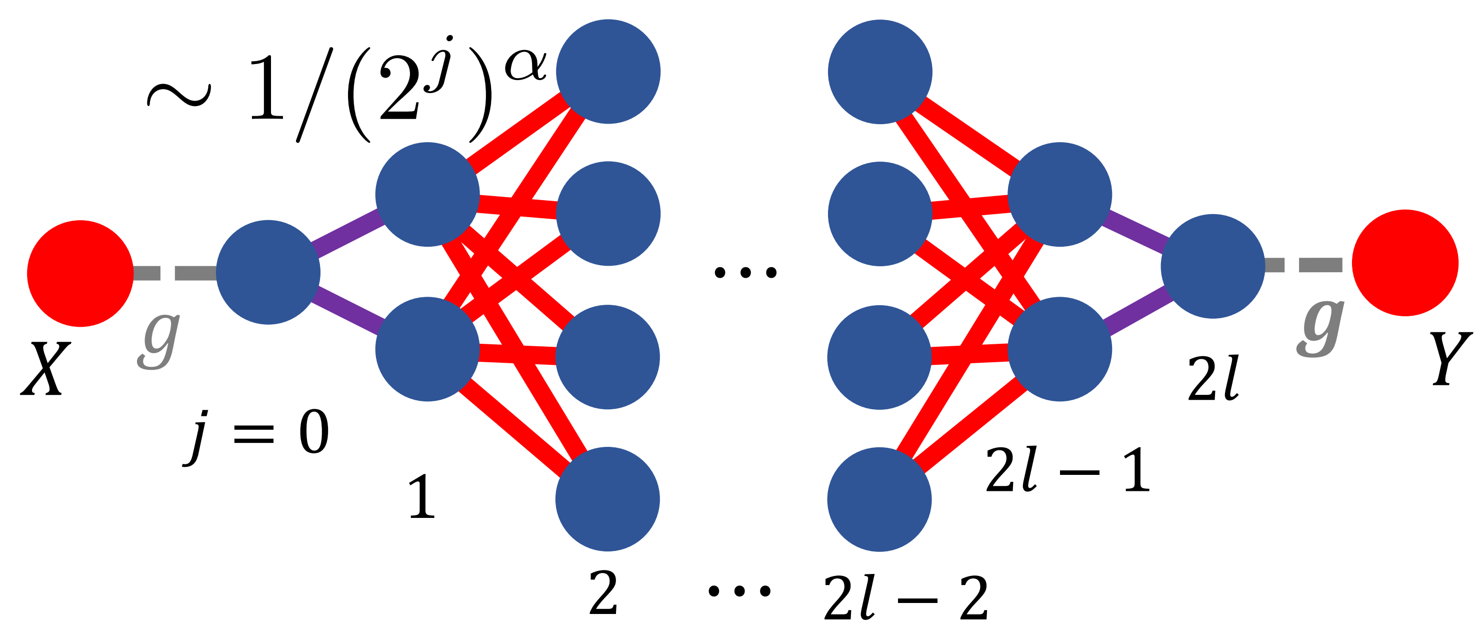
Yuan, Yin, Mooney, Baldwin, Childs, AVG, arXiv:2505.18249

Staticize the protocol for $d/2 < \alpha < d+1$



$l \sim \log L$

- couple X and Y weakly to the rest of the chain
- as before, 2^j sites in block j, but halfway through the chain start reducing the block size
- turn on all interactions (left half of chain: at same strength $\sim 1/(2^j)^\alpha$) between neighboring blocks j and j+1



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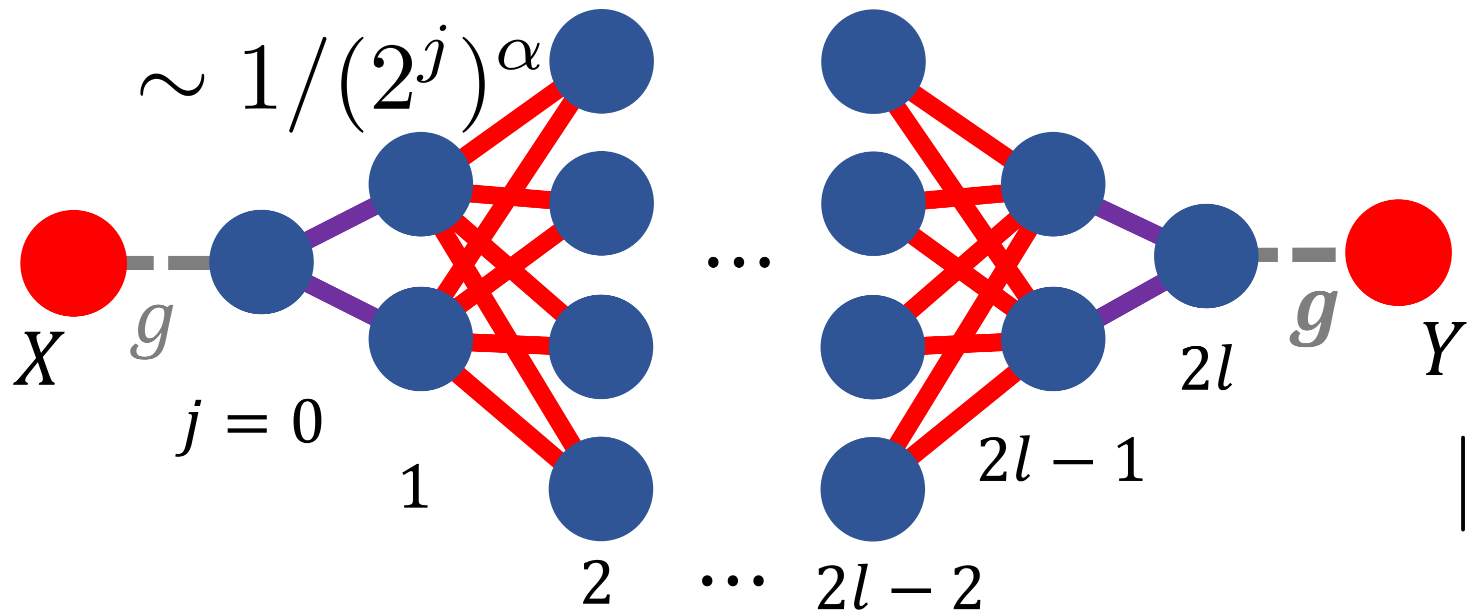
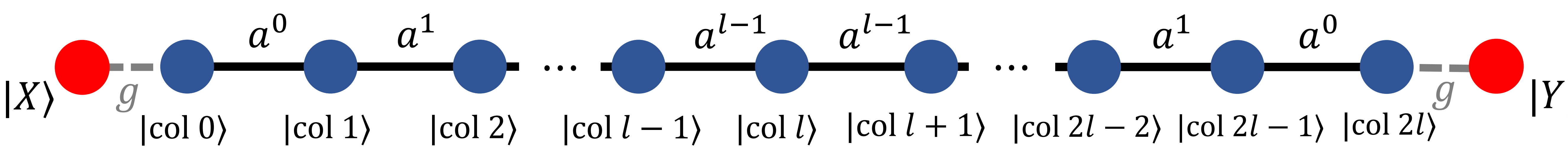


$$|\text{col } j\rangle \sim \frac{1}{\sqrt{2^j}} \sum_{i \in \text{col } j} |i\rangle$$

$$|\text{col } j+1\rangle \sim \frac{1}{\sqrt{2^j}} \sum_{i \in \text{col } j+1} |i\rangle$$

$$a = 2^{1-\alpha}$$



- left half: hopping amplitude between $|\text{col } j\rangle$ and $|\text{col } j+1\rangle$:

$$\sim \frac{(2^j)^2}{\left(\sqrt{2^j}\right)^2} \frac{1}{(2^j)^\alpha} \sim \frac{2^j}{(2^j)^\alpha} = (2^{1-\alpha})^j$$

Yuan, Yin, Mooney, Baldwin, Childs, AVG, arXiv:2505.18249

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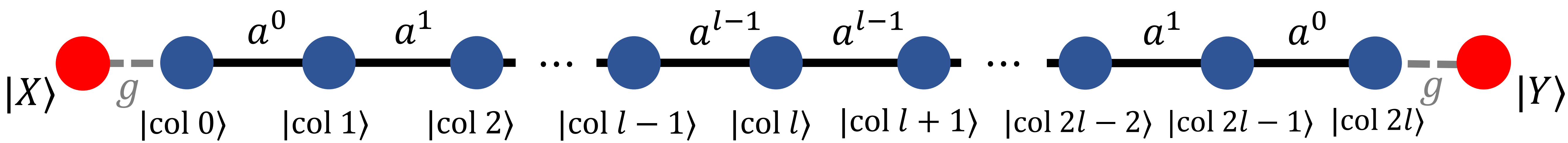

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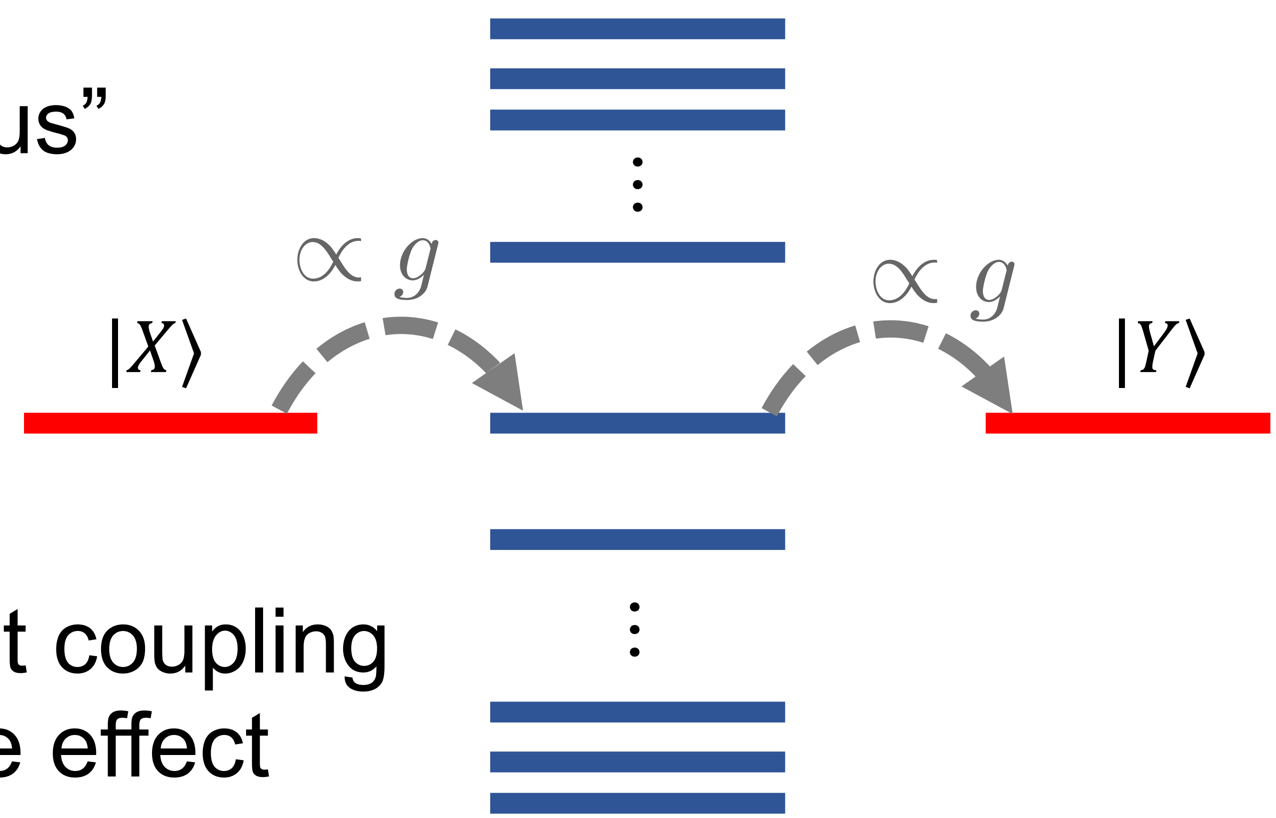

- X and Y coupled weakly to the “bus”
- spectrum of bus is symmetric
- tune X and Y to resonance with the zero-energy eigenstate
- need to make g small enough that coupling to off-resonant levels has negligible effect
- $\alpha = 1$ particularly easy: uniform hopping
- protocol time agrees with optimal one for all $d/2 < \alpha < d+1$

“Tunneling trick”: Li, Shi, Chen, Song, Sun, PRA (2005); Plenio, Semiao, NJP (2005); Wojcik, Łuczak, Kurzynski, Grudka, Gdala, Bednarska, PRA 72, 034303 (2005), etc…

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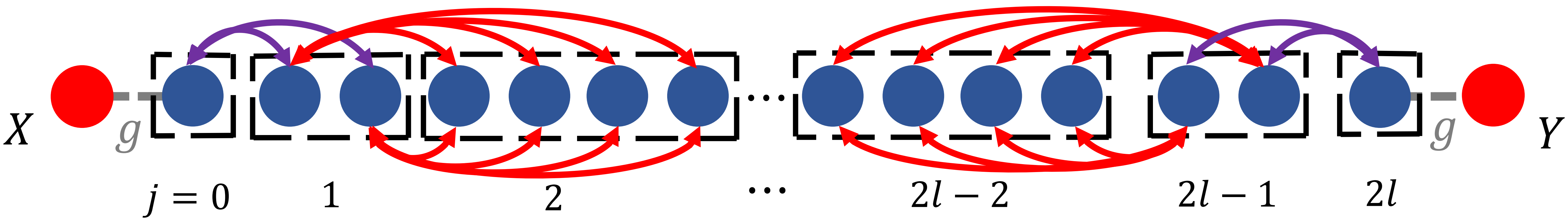
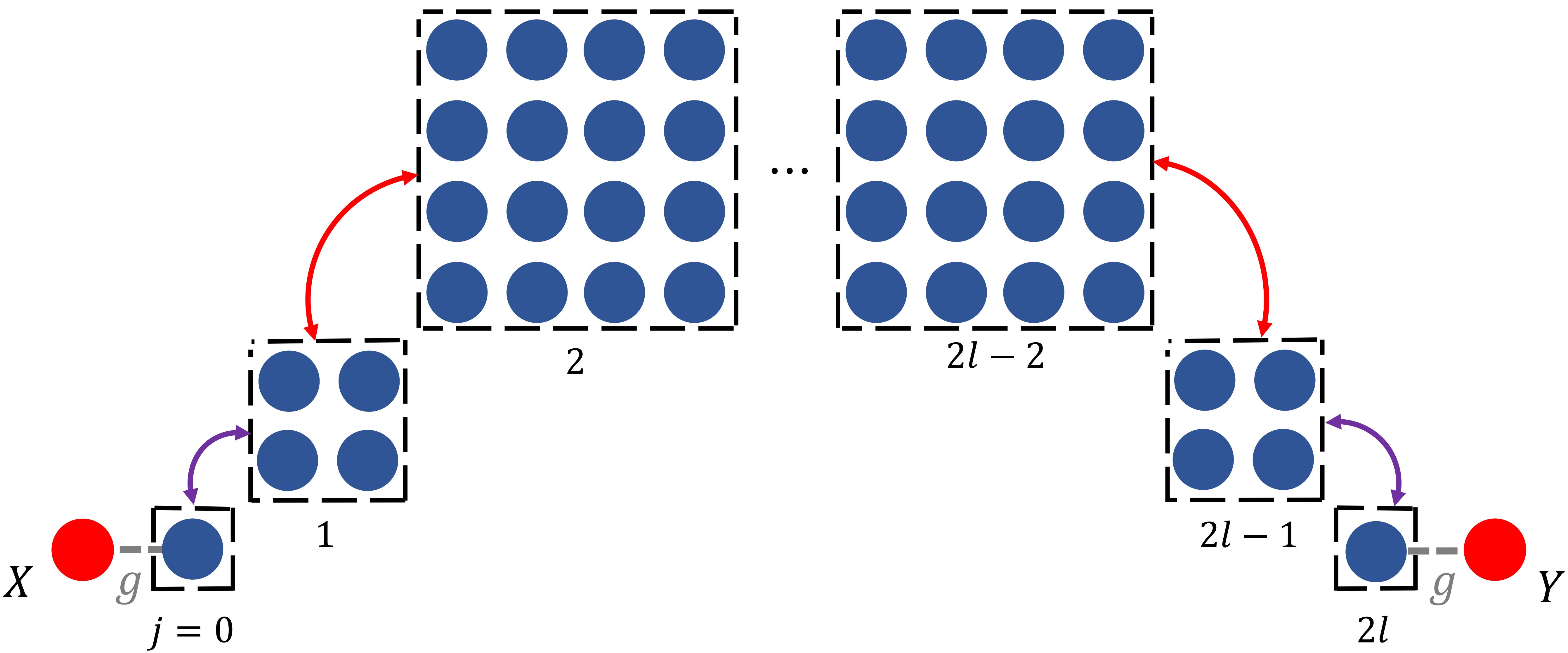
Staticize the protocol for $d/2 < \alpha < d+1$





Yuan, Yin, Mooney, Baldwin, Childs, AVG, arXiv:2505.18249

Summary

• time-independence does not limit information flow for free-particle Hamiltonians

Outlook

• in some scenarios (architecture + application), it can be easier to implement Hamiltonians dynamics without time-dependent control

• slower than interacting protocols but

- do not depend on whether intermediate sites are occupied
- utilize W ($|10\ldots0\rangle + |01\ldots0\rangle + \cdots + |00\ldots1\rangle$) states instead of GHZ ($|00\ldots0\rangle + |11\ldots1\rangle$) states
- W states more robust against errors in Hamiltonian
  Tran et al (Gong, AVG, Lucas), PRX (2020); Hong, Lucas, PRA (2021)

• we propose another time-independent protocol where hopping strength exactly follows $J_{ij} = J_0/r_{ij}^{\alpha}$:

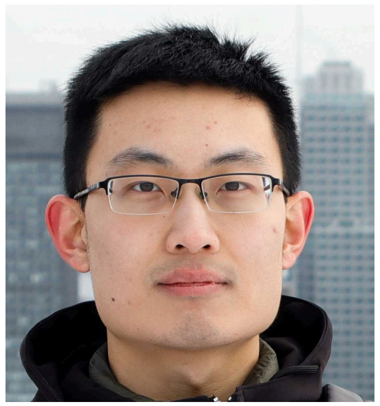
- can be naturally realized with synthetic quantum matter
- suboptimal, but provides speedup over short-range protocols

Yuan, Yin, Mooney, Baldwin, Childs, AVG, arXiv:2505.18249

Thank You

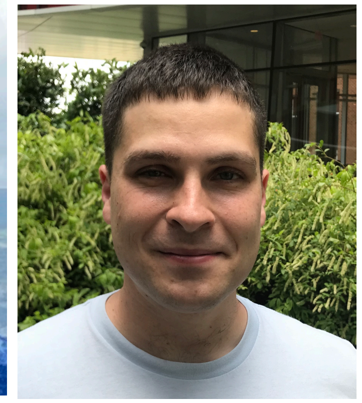
Time independence does not limit information flow. I. The free-particle case

Dong Yuan (Tsinghua)



Chao Yin (Boulder)

Connor Mooney



Chris Baldwin

Andrew Childs

(→Michigan State)

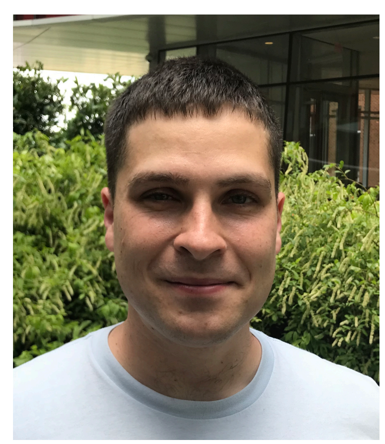
arXiv:2505.18249

Time independence does not limit information flow. II. The case with ancillas

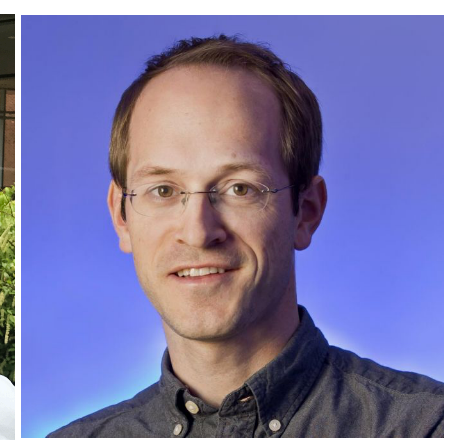
Connor Mooney

Dong Yuan (Tsinghua)

Adam Ehrenberg



Chris Baldwin



Andrew Childs

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arXiv:2505.18254

Thank You

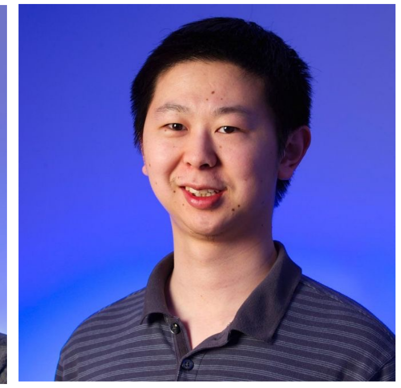
Optimal time-dependent protocols:

Free-particle, $\alpha < d/2$


Andrew Guo (→ Quantinuum)


Minh Tran (→ IBM)


Andrew Childs


Zhe-Xuan Gong (→ Mines)

PRA 102, 010401 (2020)

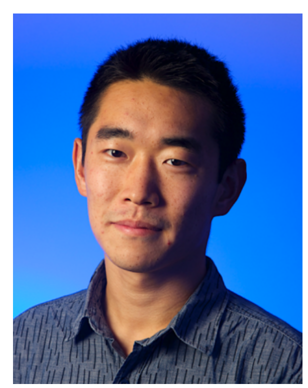
Free-particle, $d/2 < \alpha < d+1$

PRX 10, 031009 (2020)

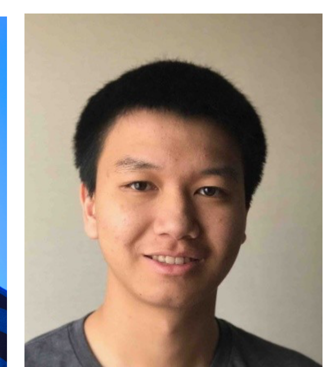

Minh Tran (→ IBM)

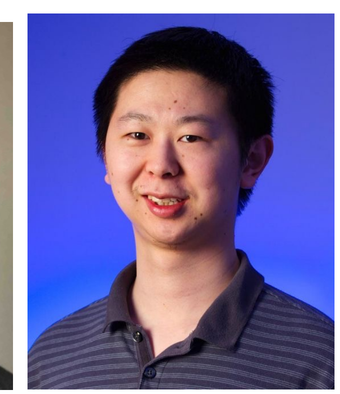

Chi-Fang Chen (Caltech)


Adam Ehrenberg


Andrew Guo (→ Quantinuum)


Abhinav Deshpande (→ IBM)


Yifan Hong (Boulder →Maryland)


Zhe-Xuan Gong (→ Mines)


Andy Lucas (Boulder)

Thank You

Optimal time-dependent protocols:

Interacting, $\alpha > d$


Minh Tran (→ IBM)


Abhinav Deshpande (→ IBM)


Andrew Guo (→ Quantinuum)


Andy Lucas (Boulder)

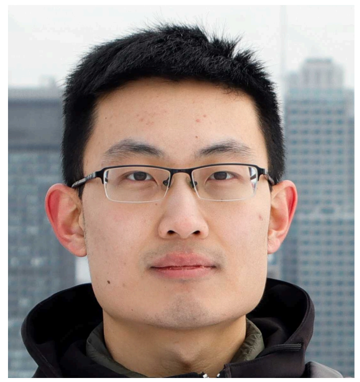
PRX 11, 031016 (2021)

Interacting, $\alpha < d$ Yin, PRL 134, 130604 (2025).

Thank You

Quantum routing through bottlenecks

Dhruv Devulapalli



Chao Yin (Boulder)

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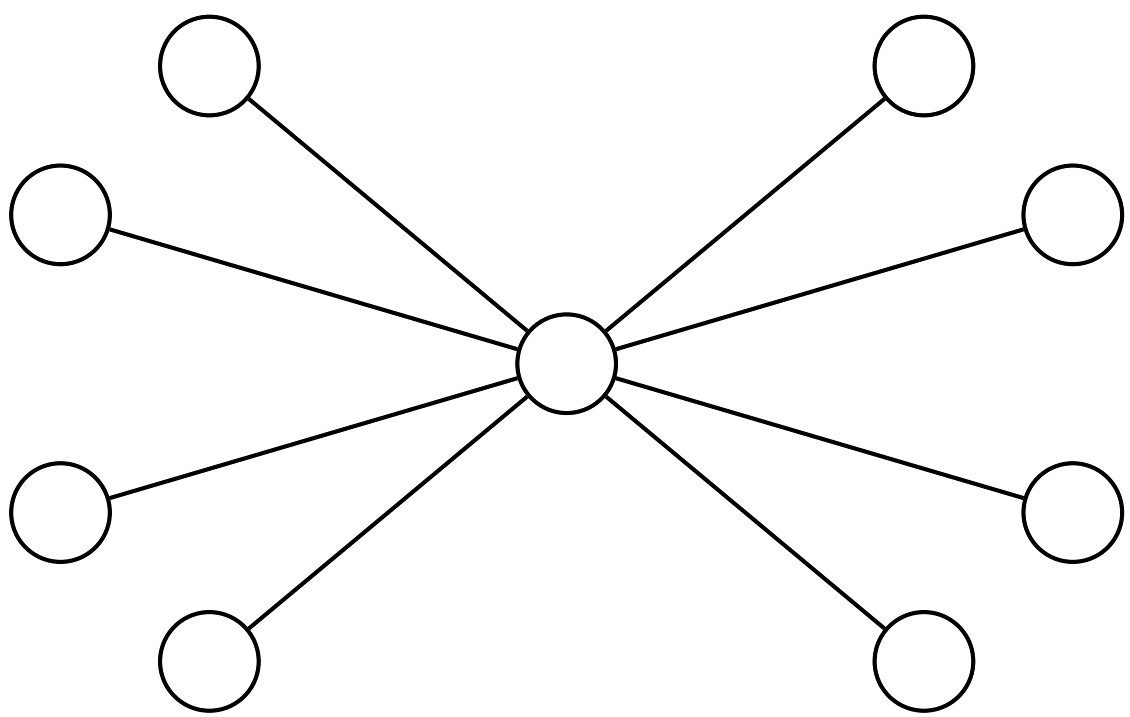
Eddie Schoute (→ IBM)

Andrew Childs

Andy Lucas (Boulder)



arXiv:2505.16948

Thank you

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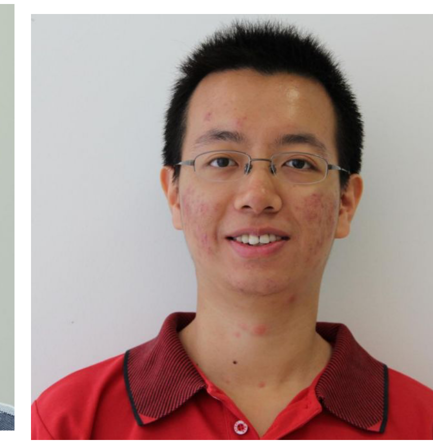
Jeremy Young (→ JILA)

Jim Garrison (→ IBM)

Ali Hamed Moosavian



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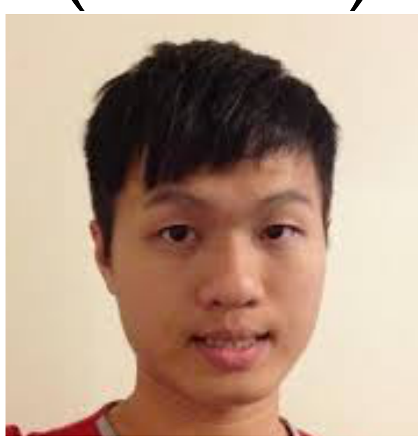
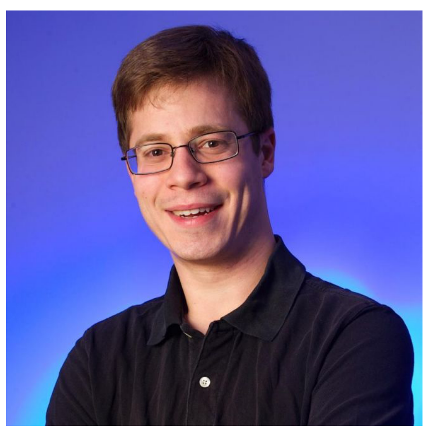


Su-Kuan Chu



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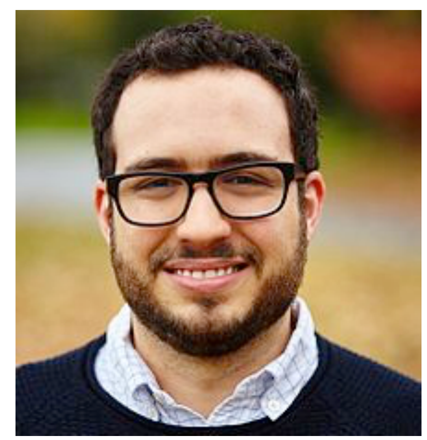
Paraj Titum (→ APL)



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Dima Abanin (Geneva)

Spiros Michalakis (Caltech)

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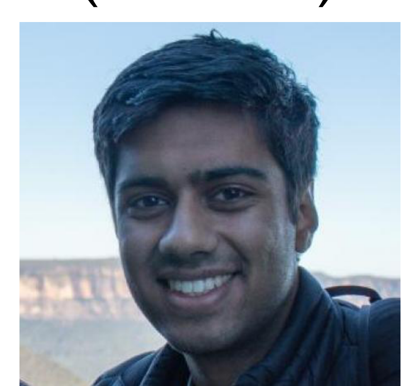
Simon Lieu (→ AWS)



Nishad Maskara (Caltech/UMD/Harvard)

$$$: DoE, AFOSR, ARO, NSF, DARPA

Thank you

Our other Lieb-Robinson papers:
PRL 113, 030602 (2014)
PRL 114, 157201 (2015)
PRL 119, 050501 (2017)
PRL 119, 170503 (2017)
PRX 9, 031006 (2019)
PRA 100, 052103 (2019)
PRL 129, 150604 (2022)
PRL 127, 160401(2021)
PRX Quantum 4, 020349 (2023)
arXiv:2110.15368

$$$: DoE, AFOSR, ARO, NSF, DARPA

Thank You

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Yidan Wang → Harvard
Minh Tran → MIT
Ani Bapat → LBNL
Fangli Liu → QuEra
Andrew Guo → Sandia
Ron Belyansky → Chicago
Pradeep Niroula → J.P. Morgan
Su-Kuan Chu → JILA
Jake Bringewatt → Harvard
Adam Ehrenberg → IDA
Dhruv Devulapalli
Sharoon Austin
Chris Fechisin
Daniel Spencer
Connor Mooney
Zhenning Liu
Alexandra Behne
Twesh Upadhyaya
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Jeet Shah
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Zhe-Xuan Gong → Asst. Prof. @ Colorado School of Mines
Sergey Syzranov → Asst. Prof. @ UC Santa Cruz
Paraj Titum → Applied Physics Lab at Johns Hopkins
Igor Boettcher → Asst. Prof. @ U Alberta
Rex Lundgren → NSA Laboratory for Physical Sciences
Zhicheng Yang → Asst. Prof. @ Peking U
Chris Baldwin → Asst. Prof. @ Michigan State
Oles Shtanko → IBM
James Garrison → IBM
Przemek Bienias → AWS
Lucas Brady → NASA QuAIL
Yaroslav Kharkov → AWS
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Kishor Bharti → IHPC, Singapore
Luispe García-Pintos → Los Alamos
Ella Crane → MIT
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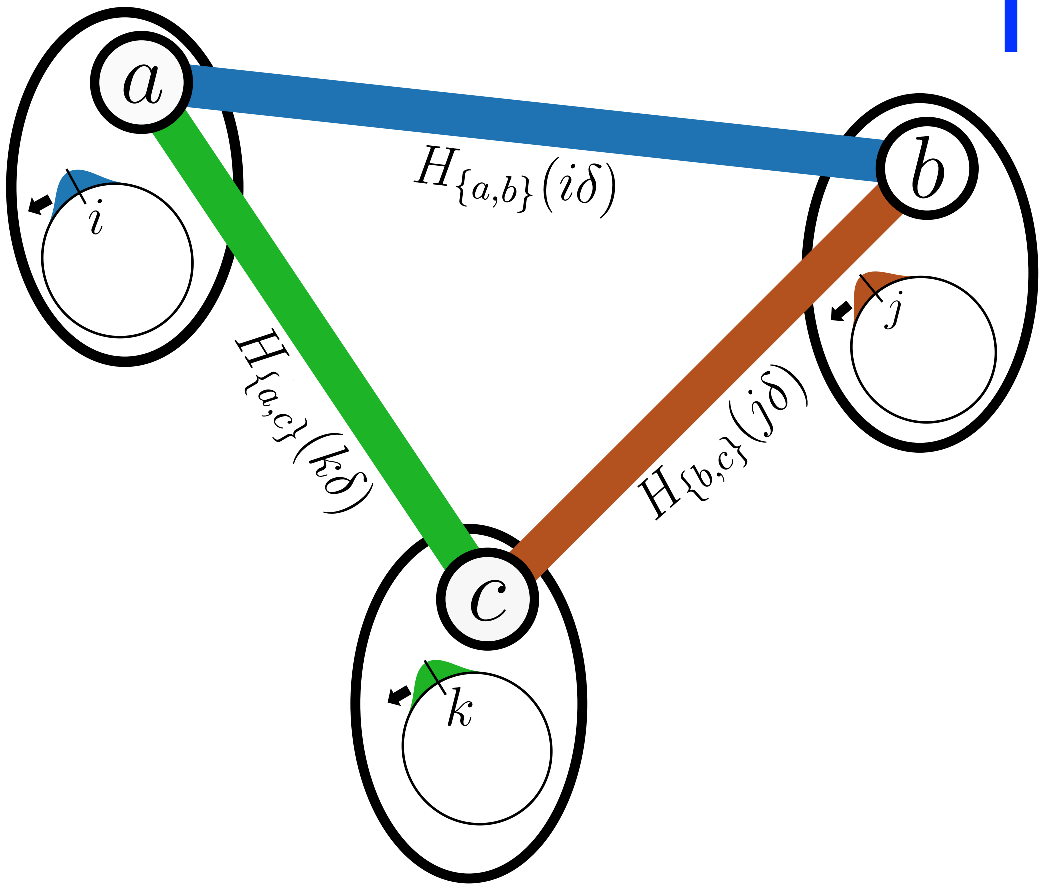
Emil Khabiboulline
Ali Fahimniya
Alex Schuckert
Jacob Lin
Sean Muleady
Yuxin Wang
Yan-Qi Wang
Yifan Hong
Anthony Brady
Lorcan Conlon

$$$: DoE, AFOSR, ARO, NSF, DARPA

Thank You



Mooney, Yuan, Ehrenberg, Baldwin, AVG, Childs, arXiv:2505.18254

Yuan, Yin, Mooney, Baldwin, Childs, AVG, arXiv:2505.18249