Sensing, Entanglement, and Scrambling

Alexey V. Gorshkov

Joint Quantum Institute (JQI)
Joint Center for Quantum Information and Computer Science (QuICS)
NIST and University of Maryland

Quantum Information Science for Fundamental Physics
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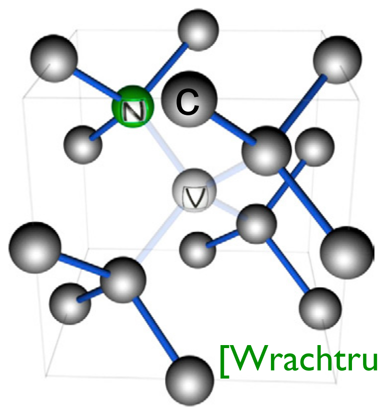
Quantum sensors

• combine high spatial resolution and high precision

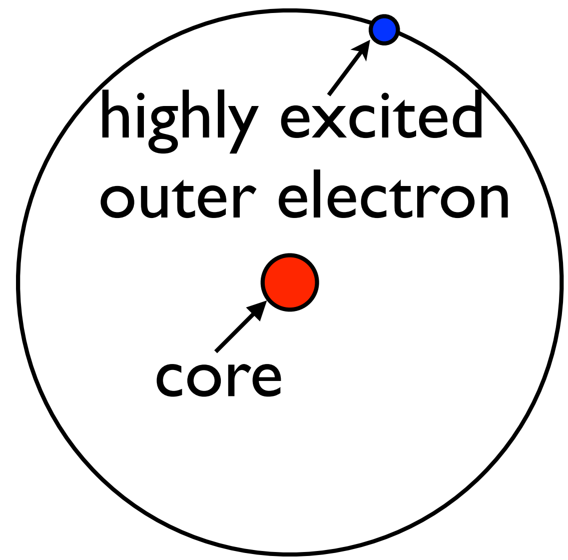
NV-center magnetometer & thermometer



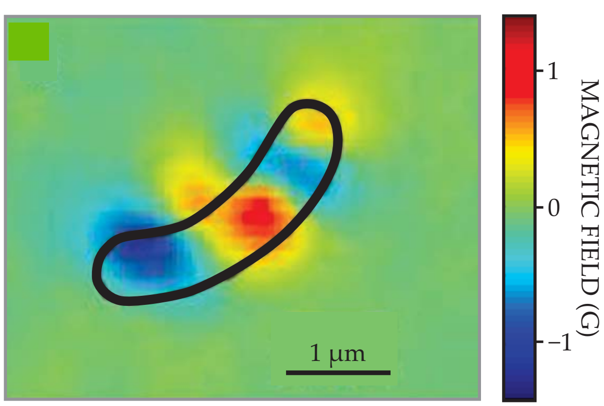
[Wrachtrup et al.]

Rydberg-atom electrometer

[Holloway et al, 2014 (NIST); Facon, Haroche et al, 2016]

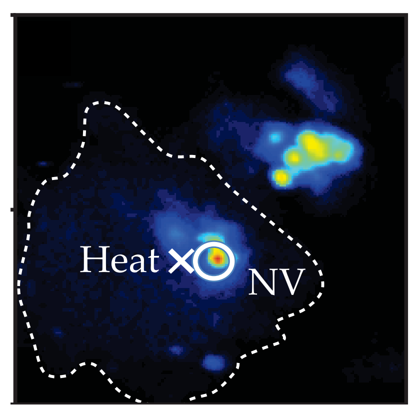


magnetic imaging of live bacteria



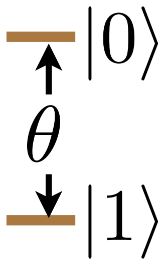
[Le Sage, Walsworth et al, 2013]

nanoscale thermometry of live human cells



[Kucsko, Lukin et al, 2013]

Quantum sensors



$$\hat{H} = \frac{1}{2}\theta\hat{Z}$$

parameter of interest

$$\hat{Z} = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$|0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \qquad |1\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

$$|\psi(t=0)\rangle = (|0\rangle + |1\rangle)/\sqrt{2}$$

$$|\psi(t)\rangle = e^{-i\hat{H}t}|\psi(0)\rangle = (e^{-i\theta t/2}|0\rangle + e^{i\theta t/2}|1\rangle)/\sqrt{2}$$

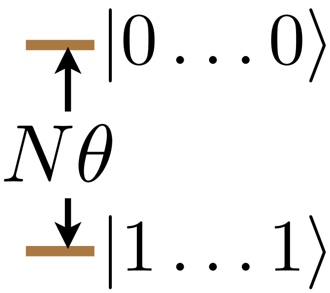
- measure $\hat{X}$

$$\hat{X} = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

- measurement uncertainty $\Delta\theta = \frac{1}{t}$

N sensors

$$\hat{H} = \frac{1}{2}\theta \sum_{i=1}^{N} \hat{Z}_i$$



Used independently: $|\psi(0)\rangle \propto (|0\rangle + |1\rangle) \otimes \cdots \otimes (|0\rangle + |1\rangle)$

$$\Delta\theta = \frac{1}{t\sqrt{N}}$$ standard quantum limit

Using entanglement: $|\psi(0)\rangle \propto |0\ldots0\rangle + |1\ldots1\rangle$ GHZ state

$$|\psi(t)\rangle \propto |0\ldots0\rangle + e^{iN\theta t}|1\ldots1\rangle$$

- measure $\hat{X}_1 \otimes \cdots \otimes \hat{X}_N$

$$\Delta\theta = \frac{1}{tN}$$

Heisenberg limit - best possible measurement

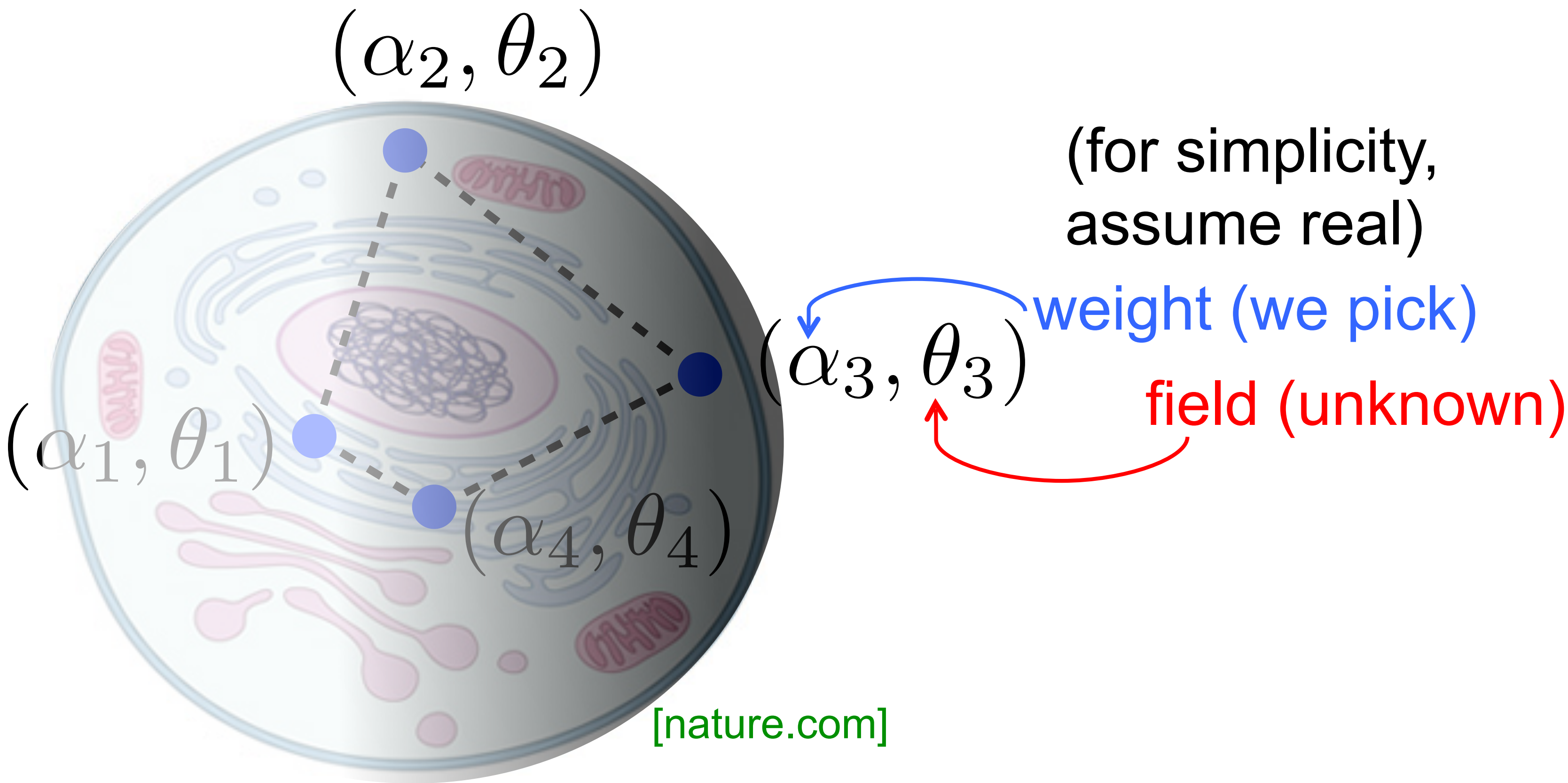
[Caves, Wineland, Holland, etc… '90s]

- contributions to quantum noise from each sensor conspire to cancel

Quantum sensor network

$$\hat{H} = \frac{1}{2}\sum_{i=1}^{N} \theta_i \hat{Z}_i \qquad\qquad Q = \sum_{i=1}^{N} \alpha_i \theta_i$$

- measure a desired linear combination of fields at the sensors



- target spatial profile of desired signal (e.g. Fourier mode or spherical harmonic)

Eldredge, Foss-Feig, Gross, Rolston, AVG, Phys. Rev. A 97, 042337 (2018)

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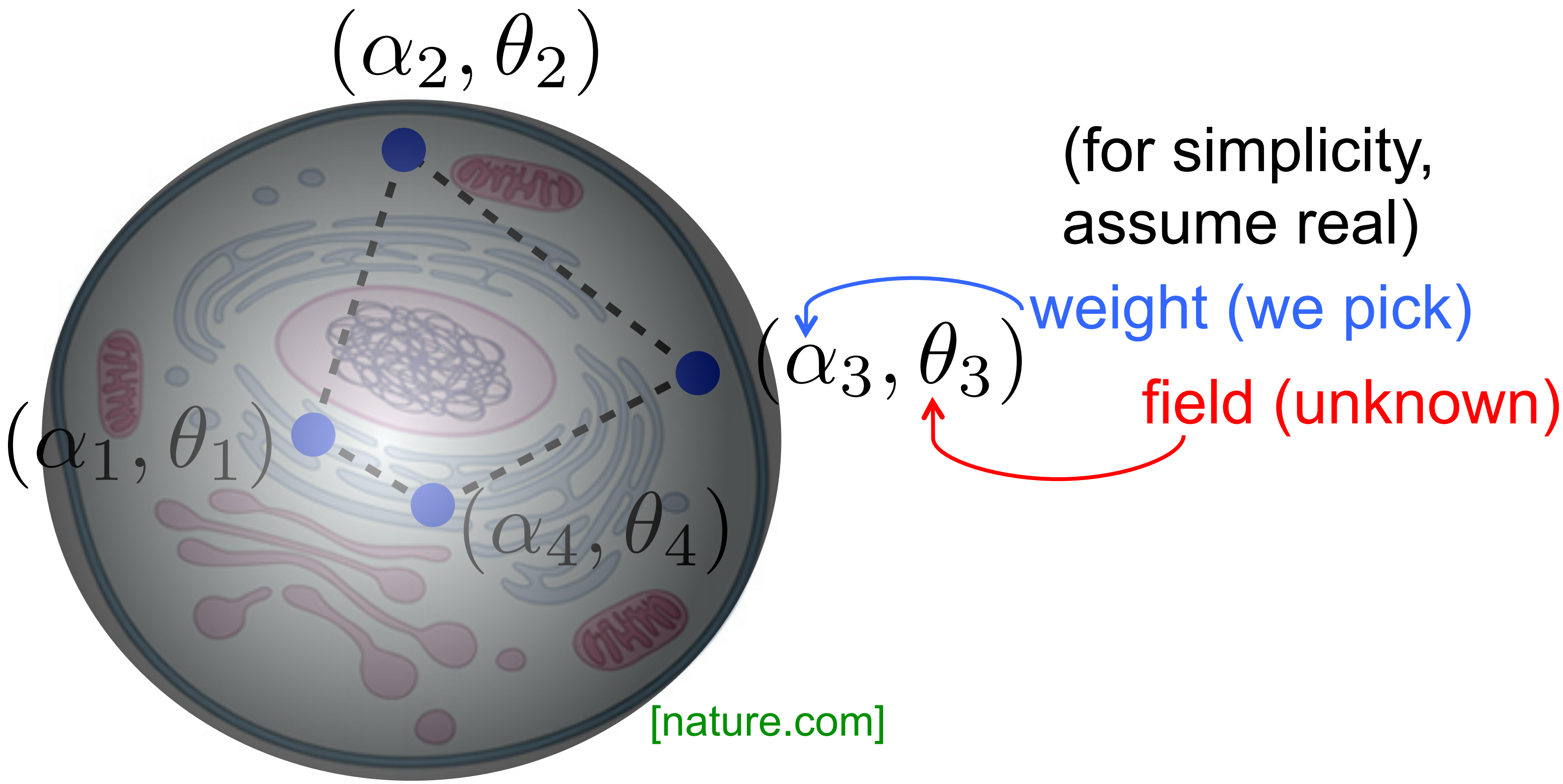

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Quantum sensor network

$$\hat{H} = \frac{1}{2}\sum_{i=1}^{N} \theta_i \hat{Z}_i \qquad\qquad Q = \sum_{i=1}^{N} \alpha_i \theta_i$$

- measure a desired linear combination of fields at the sensors

- found optimal protocol that also starts with the GHZ state

$$|\psi(0)\rangle \propto |0\ldots 0\rangle + |1\ldots 1\rangle$$

  - weights are α_i are dialed in using single-qubit pulses

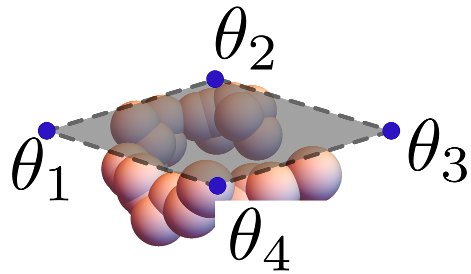
- measure any desired analytic function $f(\theta_1, \ldots, \theta_N)$

- found optimal protocol [Qian et al (AVG), PRA 100, 042304 (2019)]:
  - measure individual θ_i for negligible fraction of time
  - linearize f around the measurement result
  - use the optimal linear combination protocol

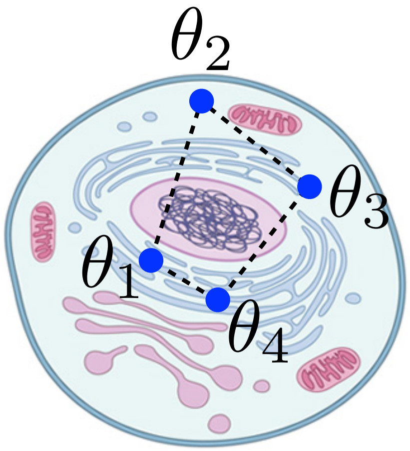
Eldredge, Foss-Feig, Gross, Rolston, AVG, Phys. Rev. A 97, 042337 (2018)

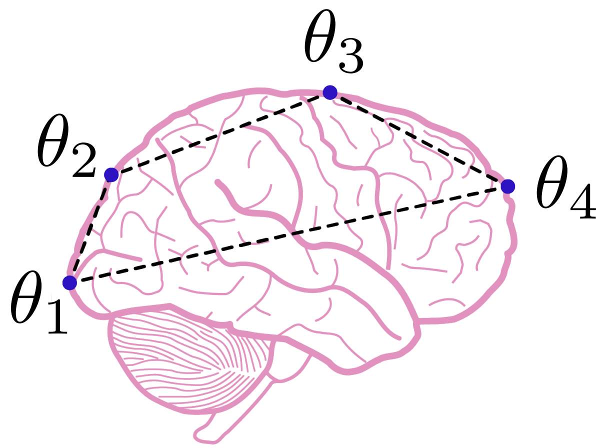
Applications

Small & intermediate scale

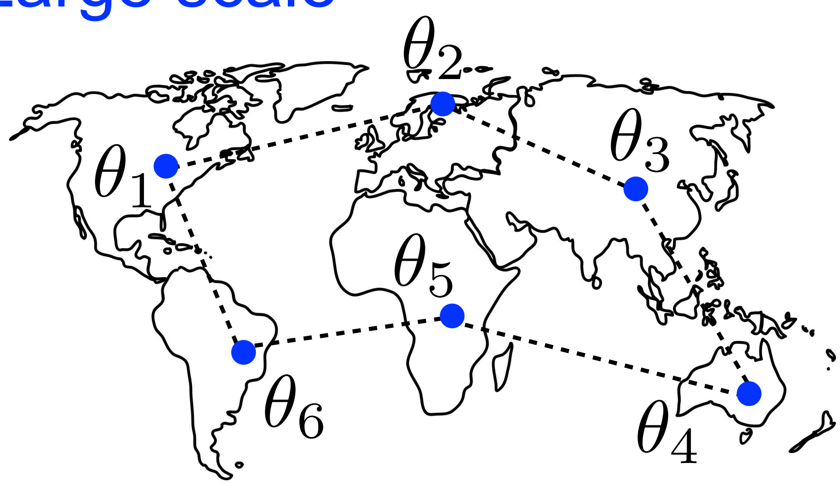


- chemistry, biology, medicine (magnetic fields, electric fields, temperature)





Large scale



- geodesy & geophysics (earthquake/volcano prediction)
- e.g. magnetometry, electrometry, thermometry, gravimetry, etc…

Summary

- found optimal entanglement-based protocol for measuring analytic functions of fields at the sensors

Outlook

- simultaneous measurement of several functions

- non-commuting generators

- measuring properties of stochastic processes

- same ideas apply to photons or phonons as sensors:

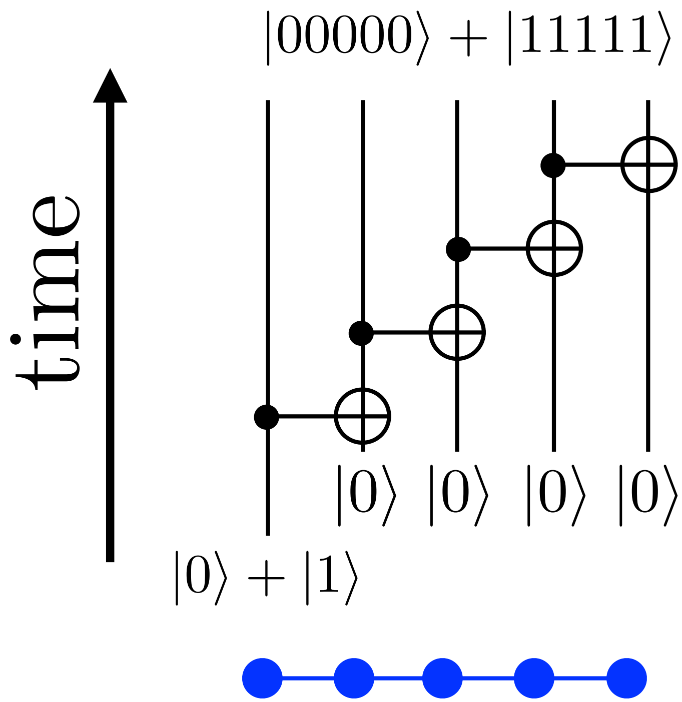
$$\hat{H} = \sum_i \theta_i \hat{a}_i^\dagger \hat{a}_i \qquad \hat{H} = \sum_i \theta_i (\hat{a}_i + \hat{a}_i^\dagger)$$

[Proctor et al, arXiv:1702.04271; Ge, Jacobs, Eldredge, AVG, Foss-Feig, PRL 121, 043604 (2018); Zhuang, Zhang, Shapiro, PRA 97, 032329 (2018); Qian et al (AVG), PRA 100, 042304 (2019)]

- practical applications to fundamental physics?

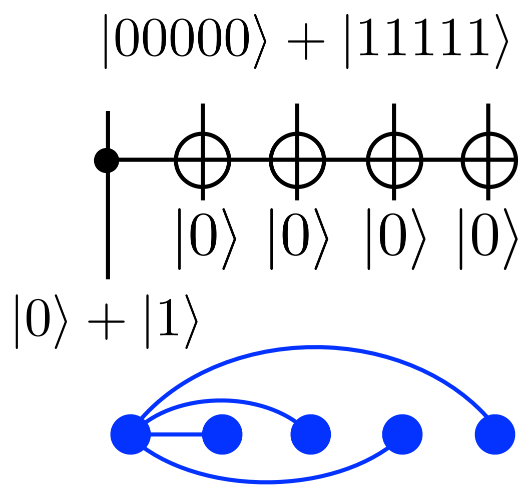
How to create the state $|0\ldots0\rangle + |1\ldots1\rangle$

nearest-neighbor interactions



- time $\sim N$

infinite-range interactions

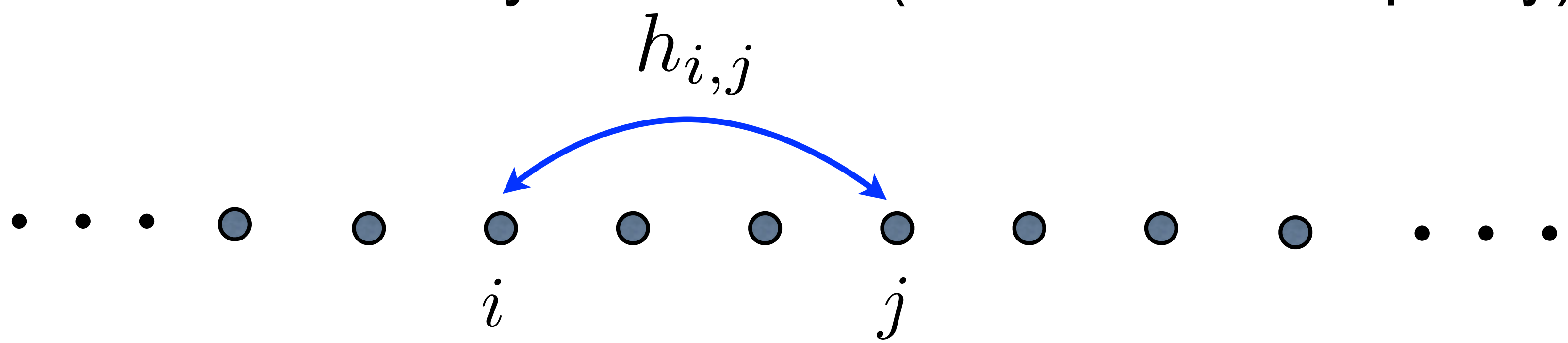


- time ~ 1

- modern quantum hardware often features long-range interactions decaying with distance r as $1/r^{\alpha}$ (e.g. Rydberg atoms, trapped ions)

Setup

- lattice in arbitrary dimension (draw 1D for simplicity)



- initial state: $|00\ldots00\rangle$
- desired final state: $(|00\ldots00\rangle + |11\ldots11\rangle)/\sqrt{2}$

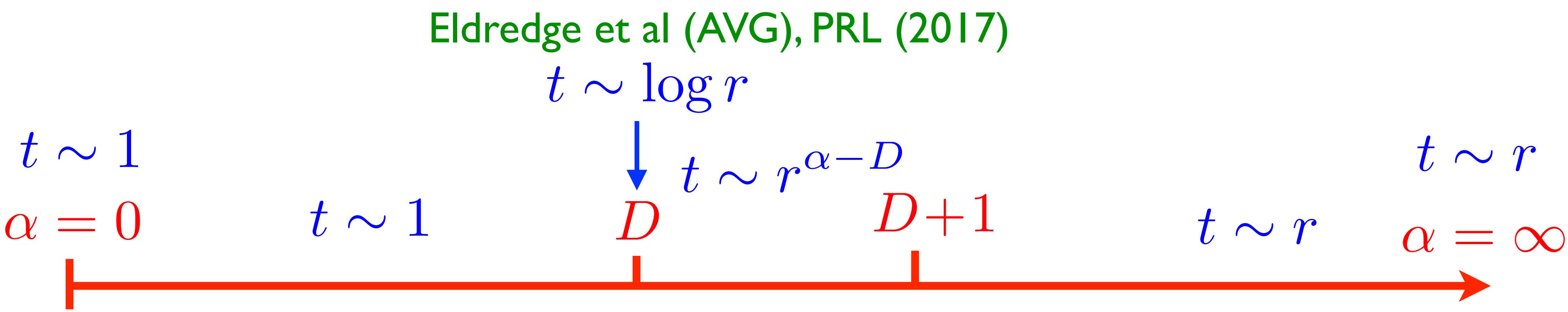
$$H = \sum_{i<j} h_{i,j} \qquad\qquad ||h_{i,j}|| \leq \frac{1}{|i-j|^\alpha}$$

- arbitrary time dependence allowed
- arbitrary time-dependent on-site terms allowed
- consider all $\alpha \geq 0$

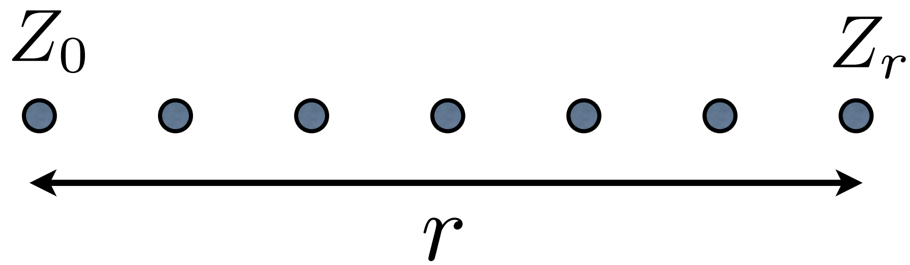
(can include normalization at the end if desired)

Preparing the GHZ state

Time t to prepare GHZ state on $N \sim r^D$ sites
using $1/r^\alpha$ interactions in D dimensions



Lower bounds on GHZ preparation time



- initial state: $|00\ldots00\rangle$

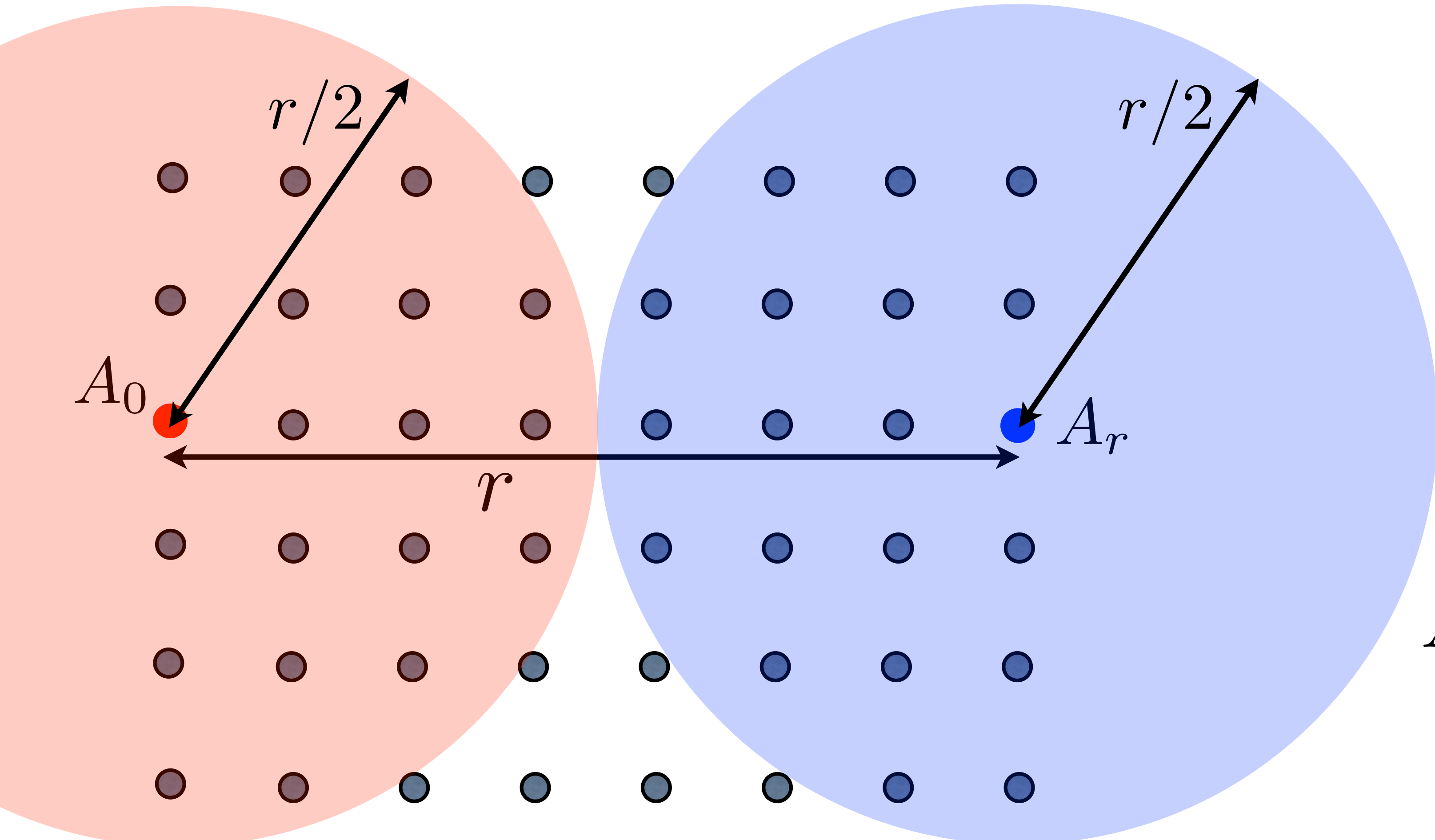
$$\langle Z_0(0)Z_r(0)\rangle - \langle Z_0(0)\rangle\langle Z_r(0)\rangle = 0$$

- final state: $(|00\ldots00\rangle + |11\ldots11\rangle)/\sqrt{2}$

$$\langle Z_0(t)Z_r(t)\rangle - \langle Z_0(t)\rangle\langle Z_r(t)\rangle = 1$$

approach: derive bound on the growth of connected correlations

Time to build connected correlations



$A_0(t) \to \tilde{A}_0$

trace over complement of red ball

$$C(t,r) = \langle A_0(t) A_r(t)\rangle - \langle A_0(t)\rangle\langle A_r(t)\rangle$$
$$\leq ||A_0(t) - \tilde{A}_0|| + ||A_r(t) - \tilde{A}_r||$$
$$\leq 2||[A_0(t), B]||$$

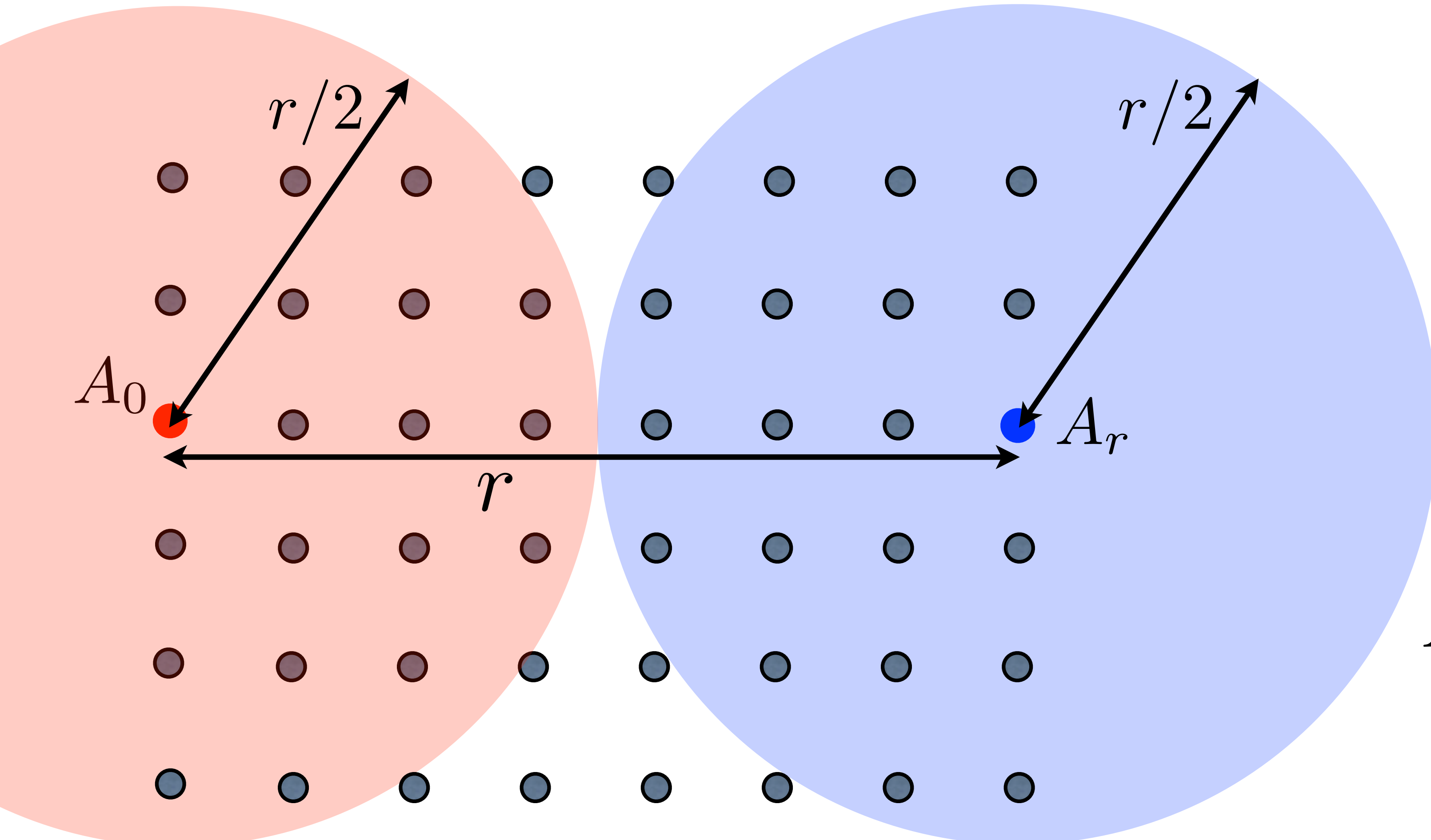
$||B|| = 1$

B supported on complement of red ball

max over B

Bravyi, Hastings, Verstraete, PRL 97, 050401 (2006)

Time to build connected correlations



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$$\leq ||A_0(t) - \tilde{A}_0|| + ||A_r(t) - \tilde{A}_r||$$

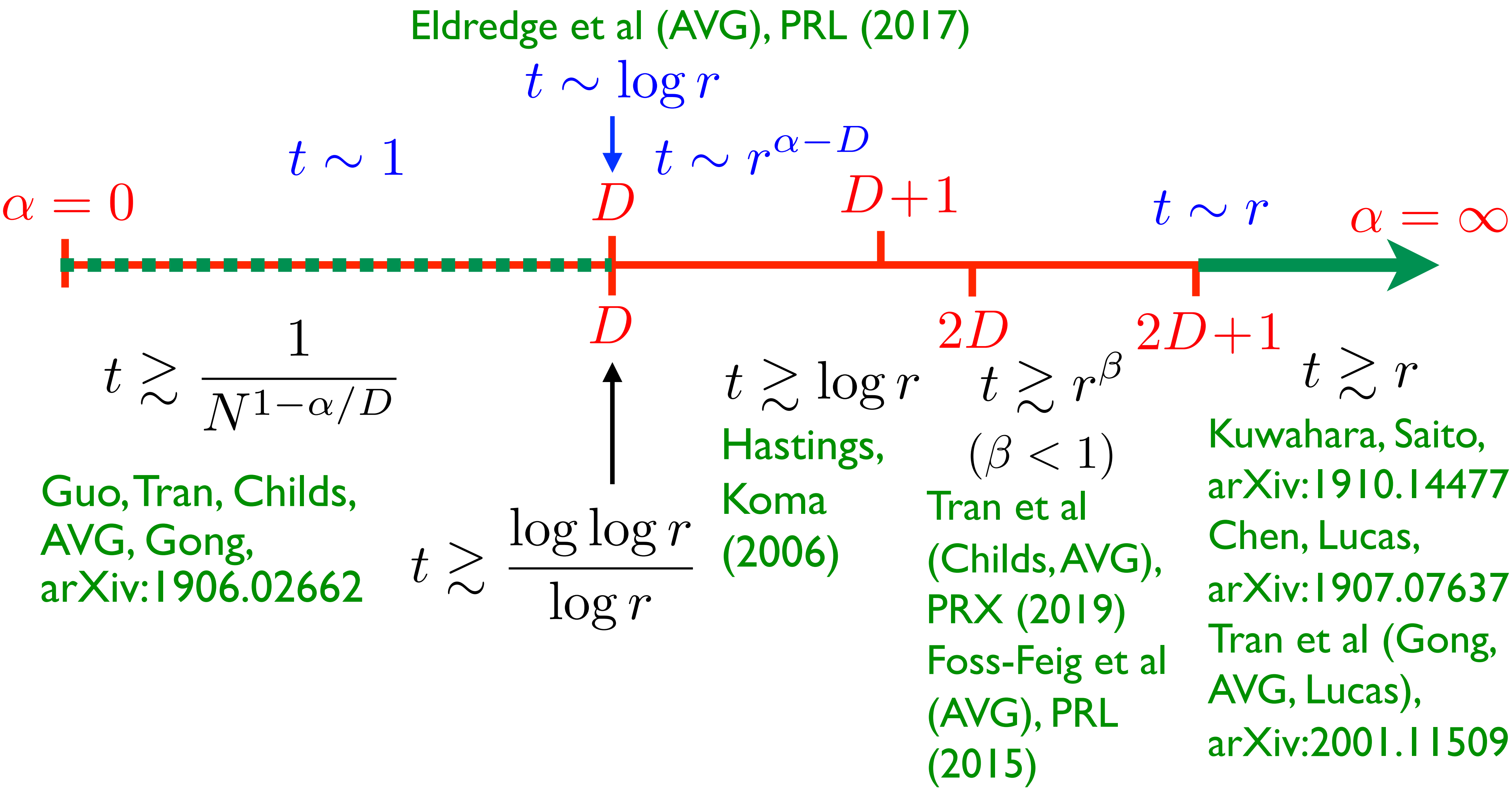
$||B|| = 1$

$$\leq 2||[A_0(t), B]||$$ B supported on complement of red ball

derive and use Lieb-Robinson bound on multisite signaling

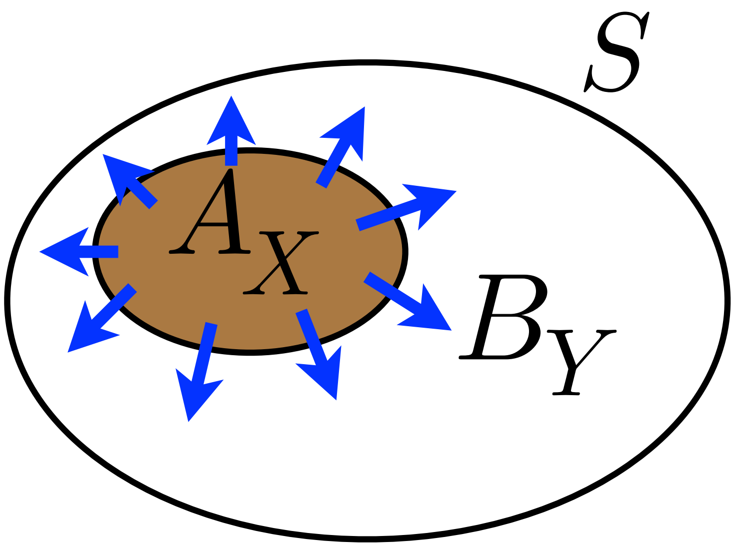
Preparing the GHZ state

Time t to prepare GHZ state on $N \sim r^D$ sites
using $1/r^\alpha$ interactions in D dimensions



another application of multisite signaling bound:
lower bound on scrambling time

Lower bound on scrambling time



- lattice system S is said to scramble in time $t_{\rm sc}$ if info initially stored in subsystem X of size ~ 1 is no longer recoverable from measurements on X alone

- instead, info can be recovered from Y, the complement of X

$\Rightarrow$ scrambling implies signaling from X to Y (of size $\boxed{\sim N}$)

$\Rightarrow t_{\rm sc} \geq t_{\rm si}$ = signaling time from X to Y ($\|[A_X(t_{\rm si}), B_Y]\| \sim 1$)

$$\frac{\log N}{N} \gtrsim t_{\rm sc} \geq t_{\rm si} \gtrsim \frac{1}{N^{1-\alpha/D}} \qquad 0 \leq \alpha < D$$

$\alpha = 0$

Lashakari et al, JHEP (2013)

tight!

- nearly tight lower bound on scrambling time!

Guo, Tran, Childs, AVG, Gong, arXiv:1906.02662

Summary

• fast protocols for preparing the GHZ state required for optimal sensing and (not tight) lower bounds on preparation time

• same multi-site signaling bound gives a nearly-tight lower bound on the scrambling time

Outlook

• improve protocols and bounds until saturation

• for specific tasks, can get tighter bounds

infinite temperature OTOC $= \sqrt{\dfrac{\mathrm{tr}([A_0(t), B_r]^\dagger [A_0(t), B_r])}{\mathrm{tr}(\mathbb{1})}}$

$= ||[A_0(t), B_r]||_F \leq ||[A_0(t), B_r]||$

- can get tighter light cone for OTOC
- can get even tighter light cone for free particles

Tran et al (Gong, AVG, Lucas), arXiv:2001.11509

Summary

• fast protocols for preparing the GHZ state required for optimal sensing and (not tight) lower bounds on preparation time

• same multi-site signaling bound gives a nearly-tight lower bound on the scrambling time

Outlook

• improve protocols and bounds until saturation

• for specific tasks, can get tighter bounds

• improve understanding of equilibrium and non-equilibrium properties of long-range-interacting many-body systems

• speed up & bound quantum computing, quantum simulation, classical simulation, preparation of entangled states for metrology & sensing, etc…

Thank you

Graduate Students

Zachary Eldredge
Jeremy Young
Abhinav Deshpande
Yidan Wang
Fangli Liu
Su-Kuan Chu
Minh Tran
Andrew Guo
Ani Bapat
Jon Curtis
Ron Belyansky
Adam Ehrenberg
Jake Bringewatt
Pradeep Niroula
Dhruv Devulapalli

Undergraduate & High-School Students

Pradeep Niroula (Harvard), Joseph Iosue (MIT), Kevin Wang (Stanford), Nishad Maskara (Caltech), Kevin Qian

Postdocs

Mohammad Maghrebi → Asst. Prof. @ Michigan State
Zhe-Xuan Gong → Asst. Prof. @ Colorado School of Mines
Sergey Syzranov → Asst. Prof. @ UC Santa Cruz
Paraj Titum → Applied Physics Lab at Johns Hopkins

James Garrison
Rex Lundgren
Przemek Bienias
Seth Whitsitt
Lucas Brady
Igor Boettcher
Chris Baldwin
Oles Shtanko
Zhicheng Yang
Simon Lieu
Yaroslav Kharkov
Luis Pedro García-Pintos

$$$: DoE ASCR Quantum Testbed Pathfinder, NSF PFCQC, NSF PFC, AFOSR, ARO MURI, ARL CDQI, DoE BES QIS, DoE ASCR FARQC

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James Ca... ...lwin
Rex Lundgren ...nko
Przemek Bien... ...Yang
Seth Whitsitt ...u
Lucas Brady ...Kharkov
Igor Boettcher ...o García-Pintos

Poster: perfect quantum mirroring on a spin chain

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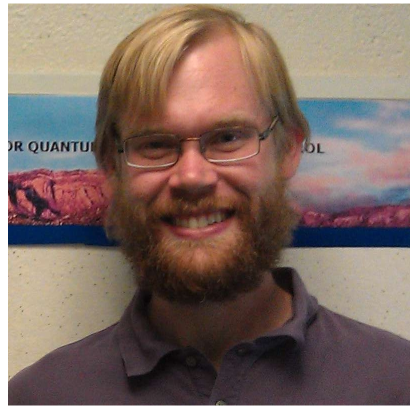
Thank you: sensor networks

Zachary Eldredge (→ DoE)

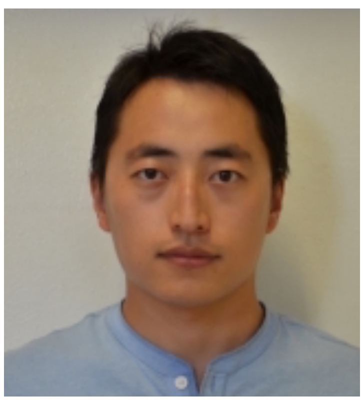
Michael Foss-Feig (→ Honeywell)



Jonathan Gross (UNM)

Steve Rolston

Kevin Qian (Montgomery Blair High/MIT)



Wenchao Ge (→Texas A&M)

Guido Pagano (→Rice)

Chris Monroe

Trey Porto

Kurt Jacobs (ARL)

PRA 97, 042337 (2018); PRA 100, 042304 (2019); PRL 121, 043604 (2018)

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Thank you: bounds and protocols


Minh Tran


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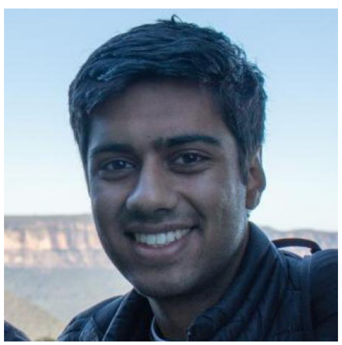
Zhe-Xuan Gong (→ Mines)


Zachary Eldredge (→ DoE)


Andrew Guo


Abhinav Deshpande


Nishad Maskara (Caltech/UMD/ Harvard)


Adam Ehrenberg


Andy Lucas (Boulder)


Chi-Fang Chen (Caltech)

PRL 114, 157201 (2015)
PRL 119, 170503 (2017)
PRX 9, 031006 (2019)
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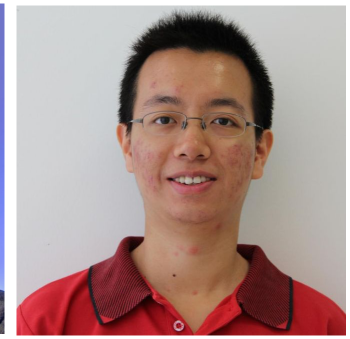
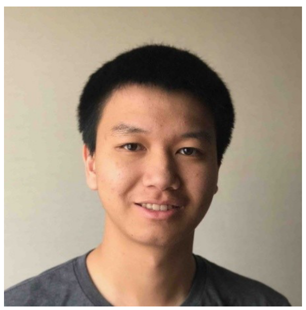
Ali Hamed Moosavian

Andrew Childs



Yuan Su

Charles Clark



Yifan Hong
(Boulder)

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Conclusions

Thank You

$$\hat{H} = \frac{1}{2}\sum_{i=1}^{N} \theta_i \hat{Z}_i \qquad f(\theta_1, \ldots, \theta_N)$$

$(|00\ldots00\rangle + |11\ldots11\rangle)/\sqrt{2}$ preparation time