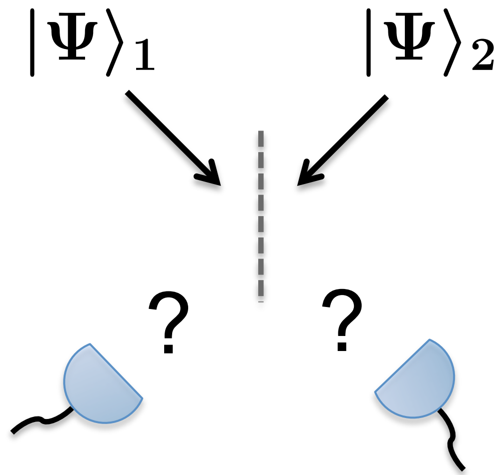


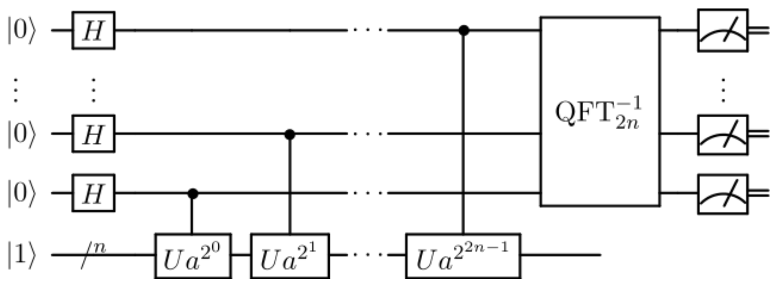
Studies in entanglement with utracold neutral atoms

Adam M. Kaufman
JILA, Unversity of Colorado Boulder
Harvard University

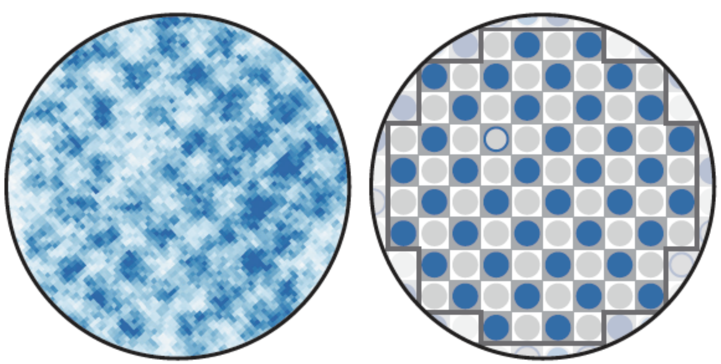
KITP, 2017

Studying and exploiting entanglement

Quantum information

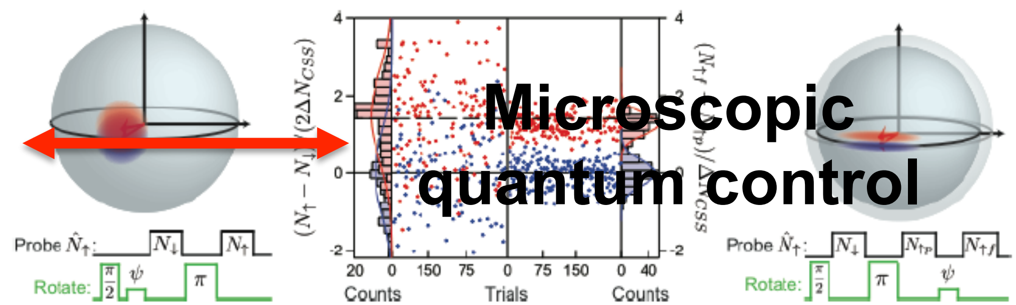


Quantum simulation



2D Fermi-hubbard: Greiner group, Harvard

Squeezing

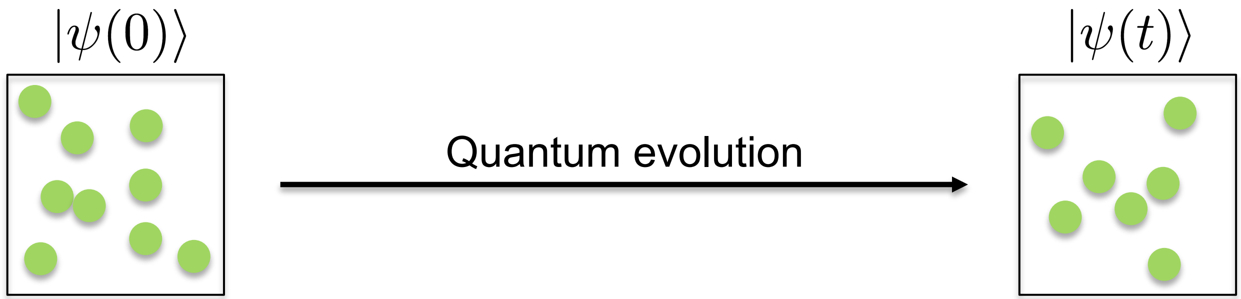


Microscopic quantum control

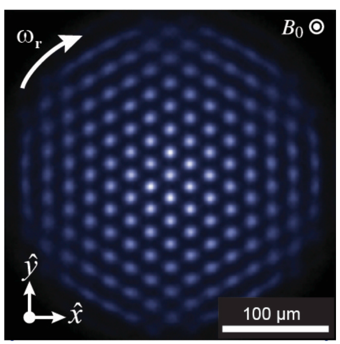
10-fold enhancement: Thompson group, JILA

….not to mention cryptography, communication, etc.

“Microscopically control a quantum state”?



Trapped ions

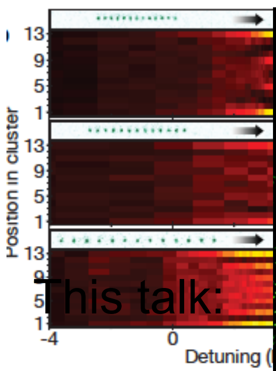


Bollinger group:
1204.5789

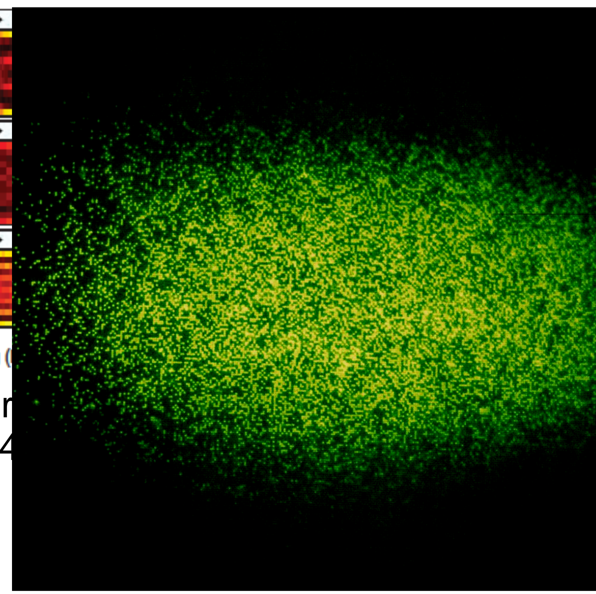
Rydberg atoms

Ultracold neutral atoms

Photons

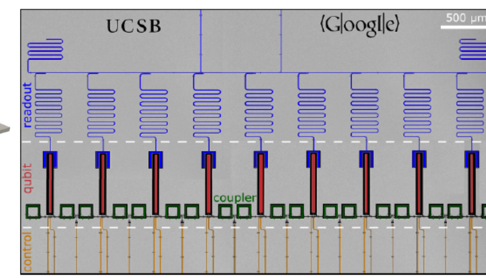


This talk:



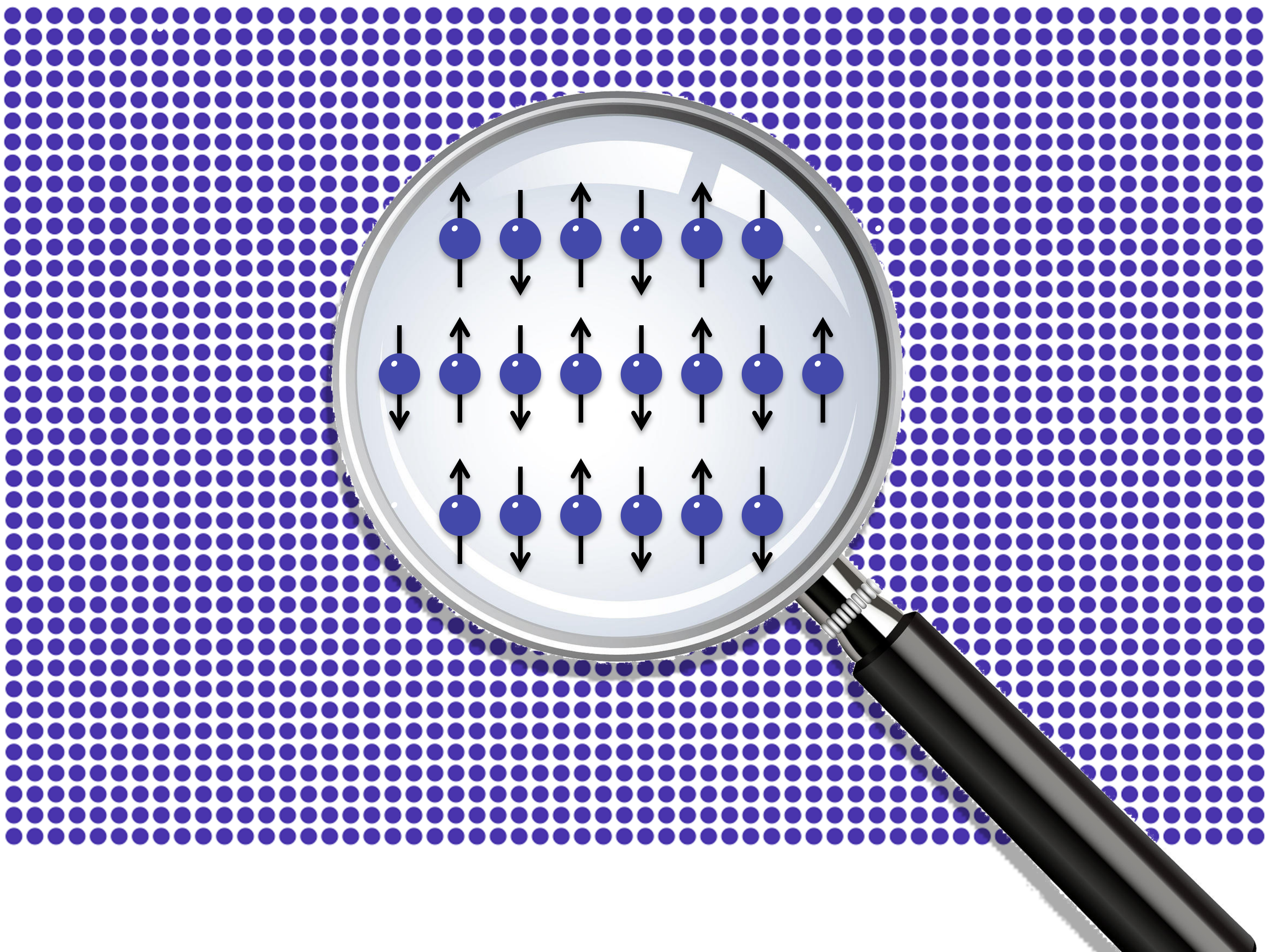
Lukin gr
1707.04

SC-qubits

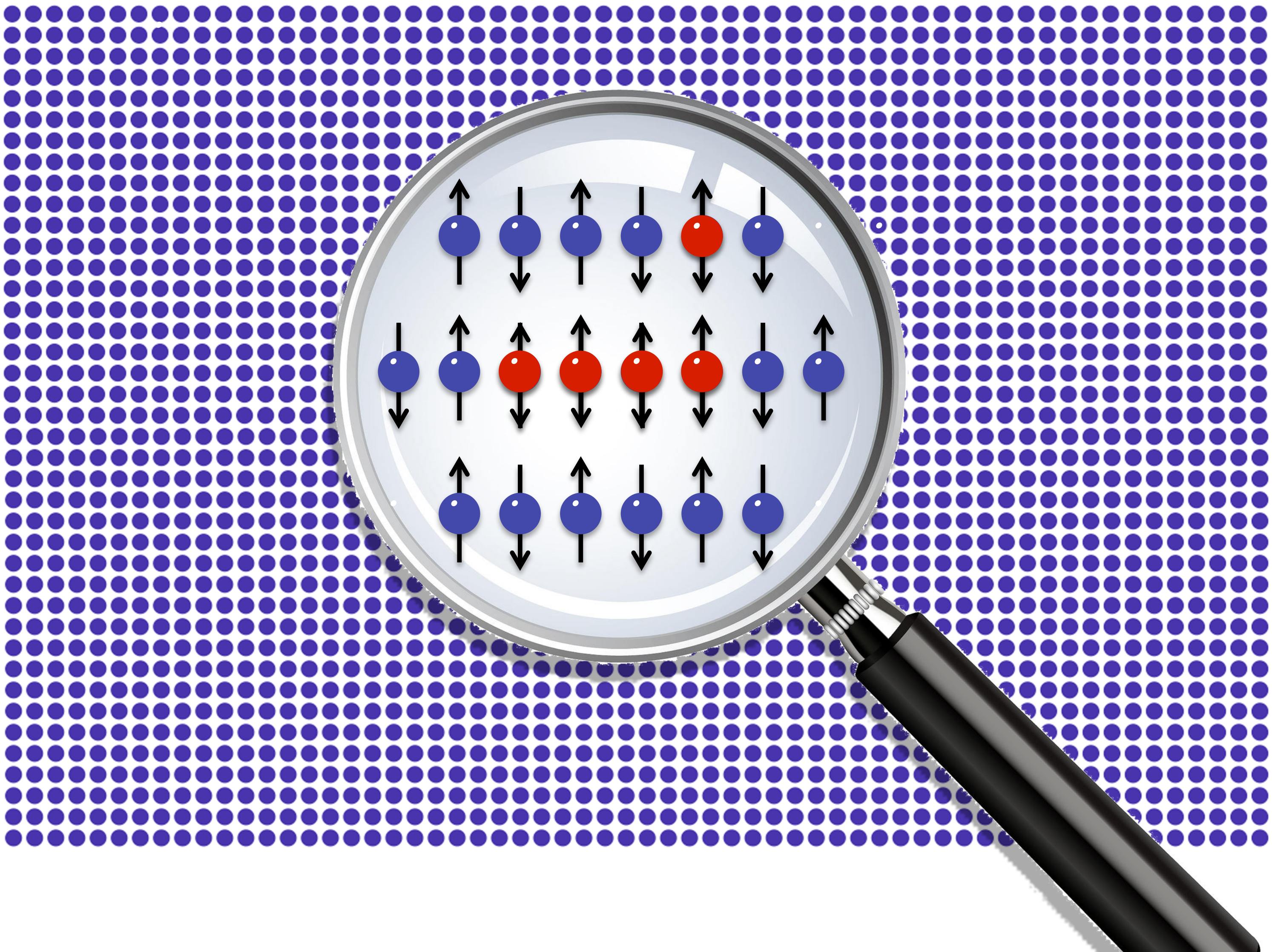


Google:
1709.06678

“Microscopically control a quantum state”?

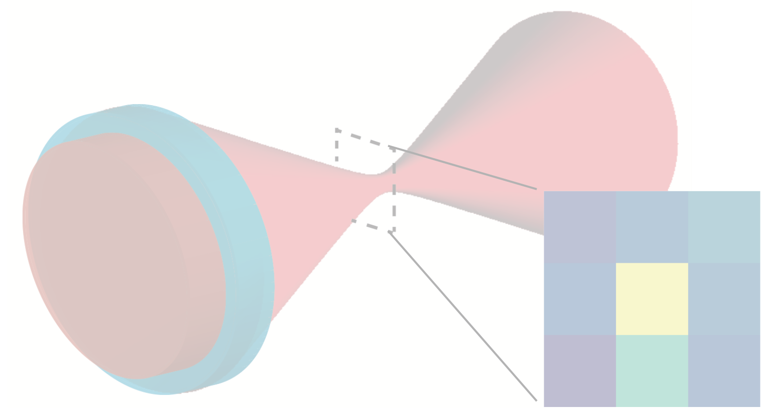


"Microscopically control a quantum state"?

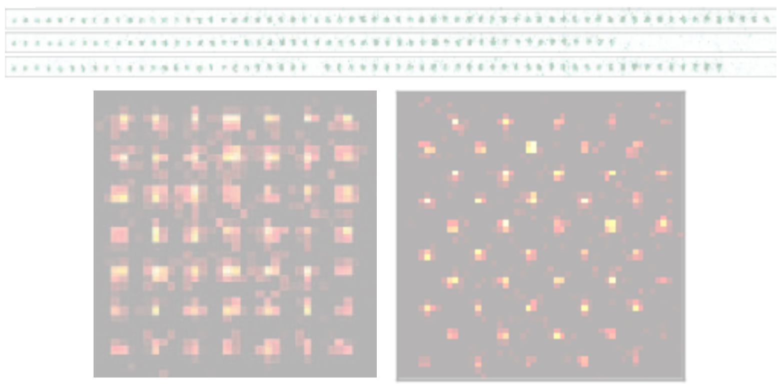


Microscopically controlled ultracold neutral atoms

Optical tweezers: Scalable, ground-state "coolable" → assembly



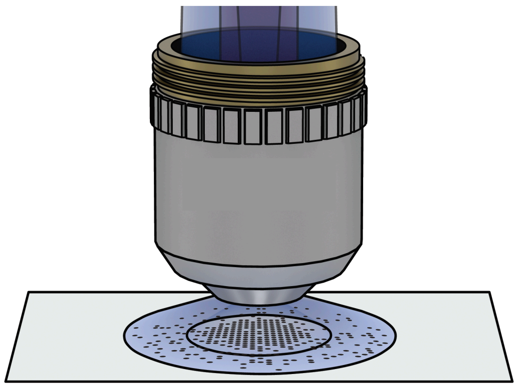
Regal group



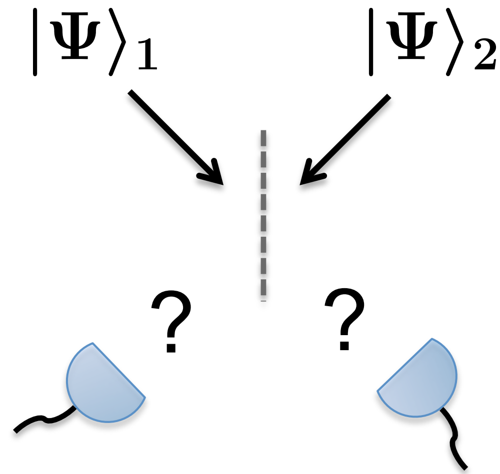
Lukin, Browaeys group

This talk

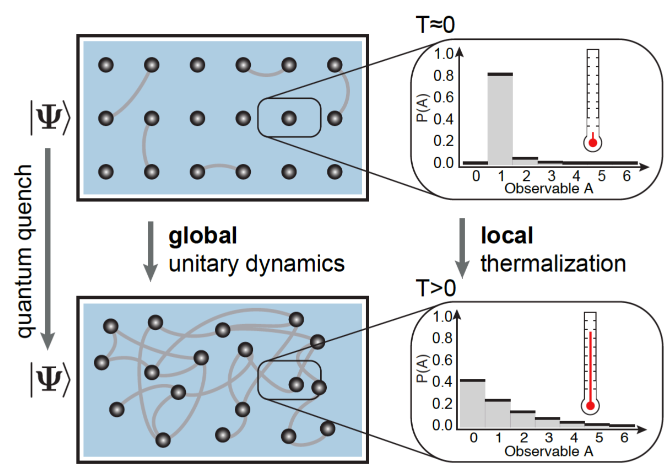
Experimental setup: bosonic quantum gas microscope



Measuring entanglement entropy



Quantum thermalization

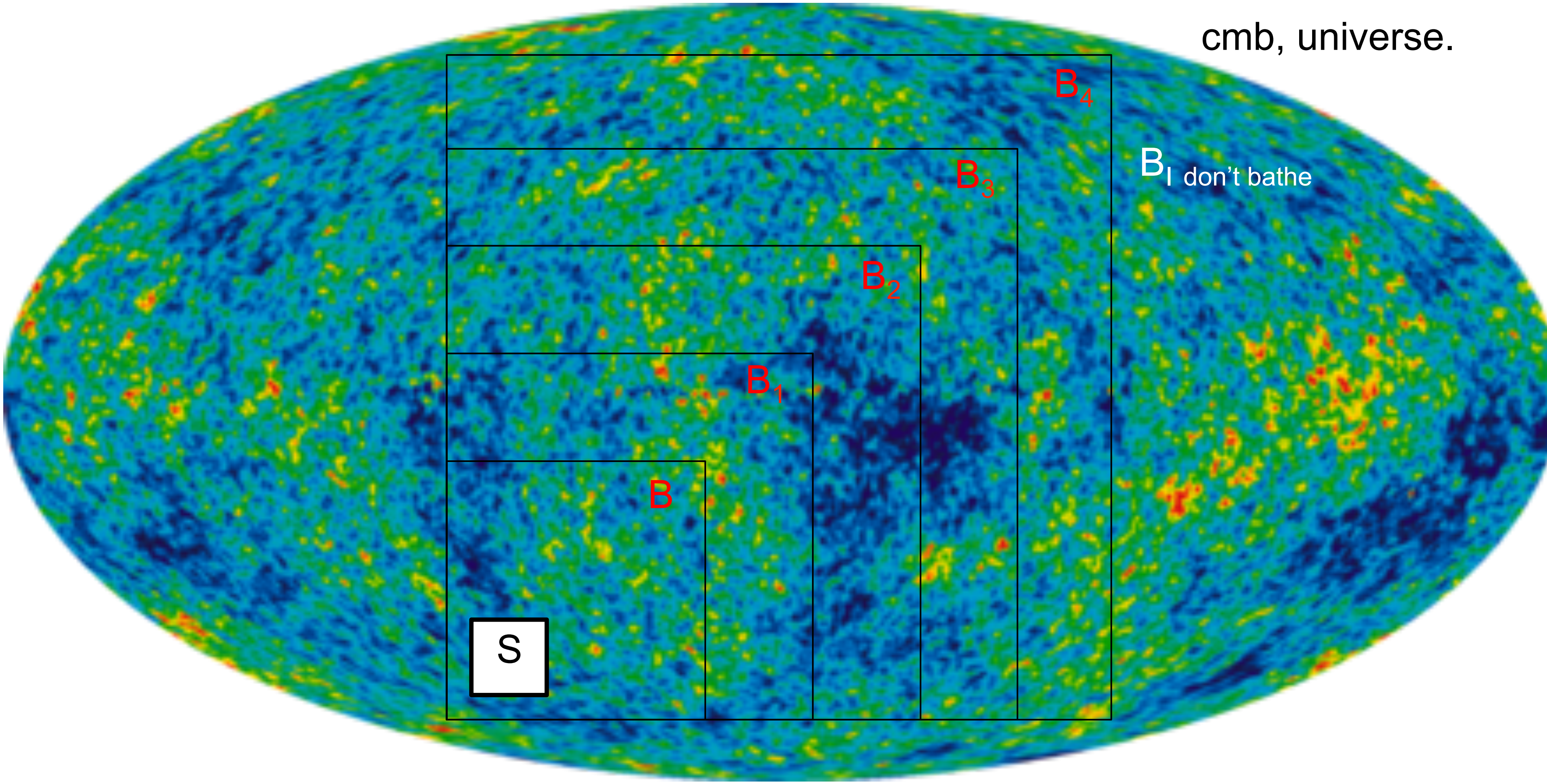


Discussed at this conference:

- ground-state area laws
- MBL phase transitions
- Thermal eigenstates…

Why do systems look thermal?

cmb, universe.

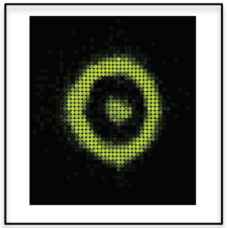


Closed systems should thermalize on their own.

J. M. Deutsch, PRA (1991)

How does a **quantum** state thermalize?

$|\psi(0)\rangle$



Quantum evolution →

$|\psi(t)\rangle$

Thermal?!

Key player: entanglement (entropy)

See also:

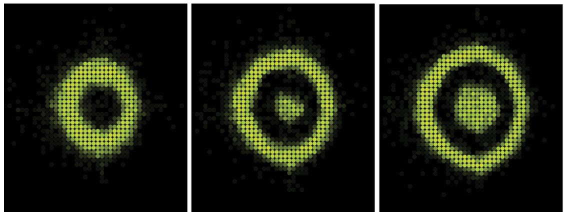
BECs: Langen…Schmiedmayer, Science (2014)

Sc-Qubits: Neill…Martinis, Nature Physics (2016)

Ions: Clos...Schaetz, PRL (2016)

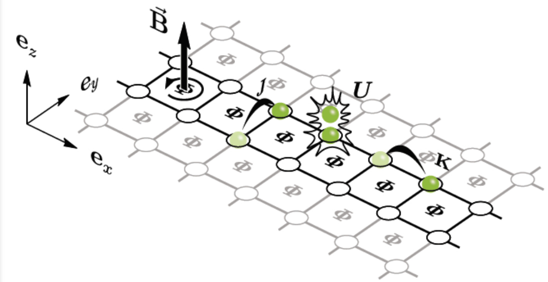
Quantum gas microscopes

Bose-Hubbard model

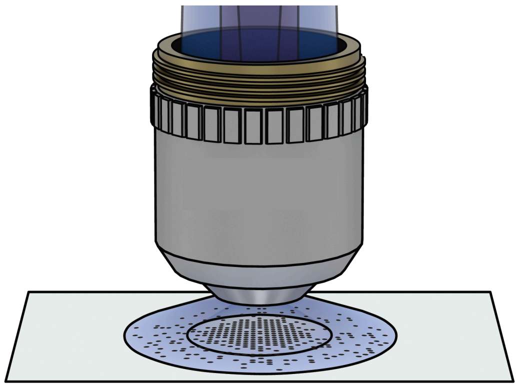


Bakr…Greiner, Science (2010),
+ Bloch group

Artificial gauge fields

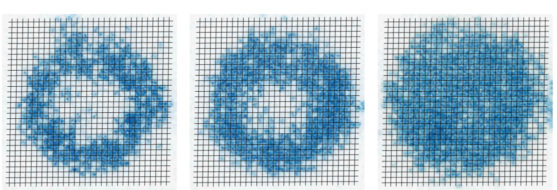


Tai…AMK, Greiner, arXiv:1612.05631



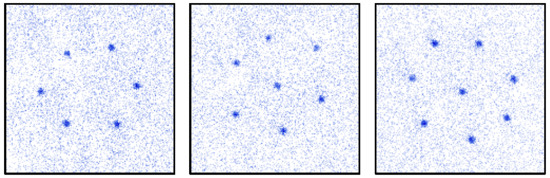
Lattice-bound 2D quantum gas

Fermi-Hubbard model



Greif…Griener, Science (2016),
+ Bloch group, Zwierlien group

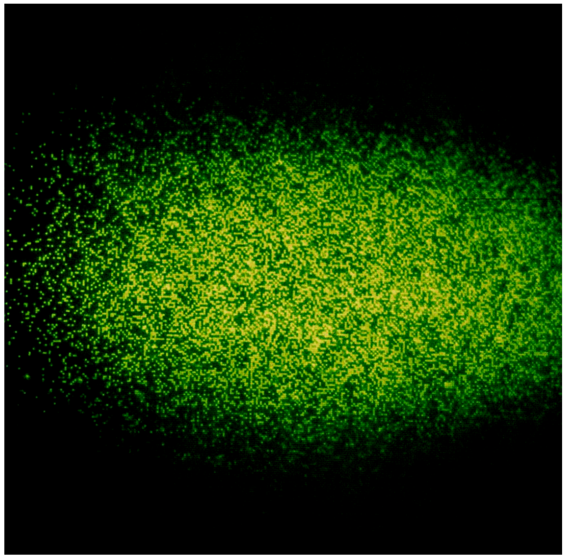
2D Rydberg crystals

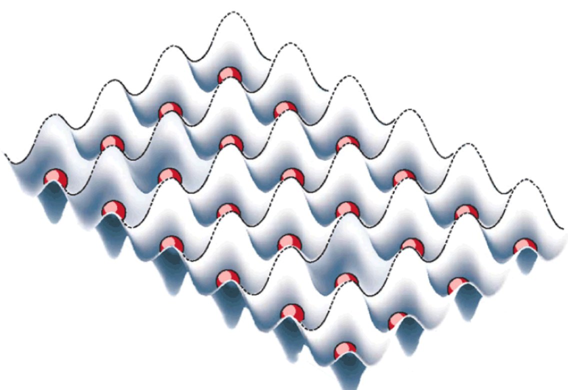


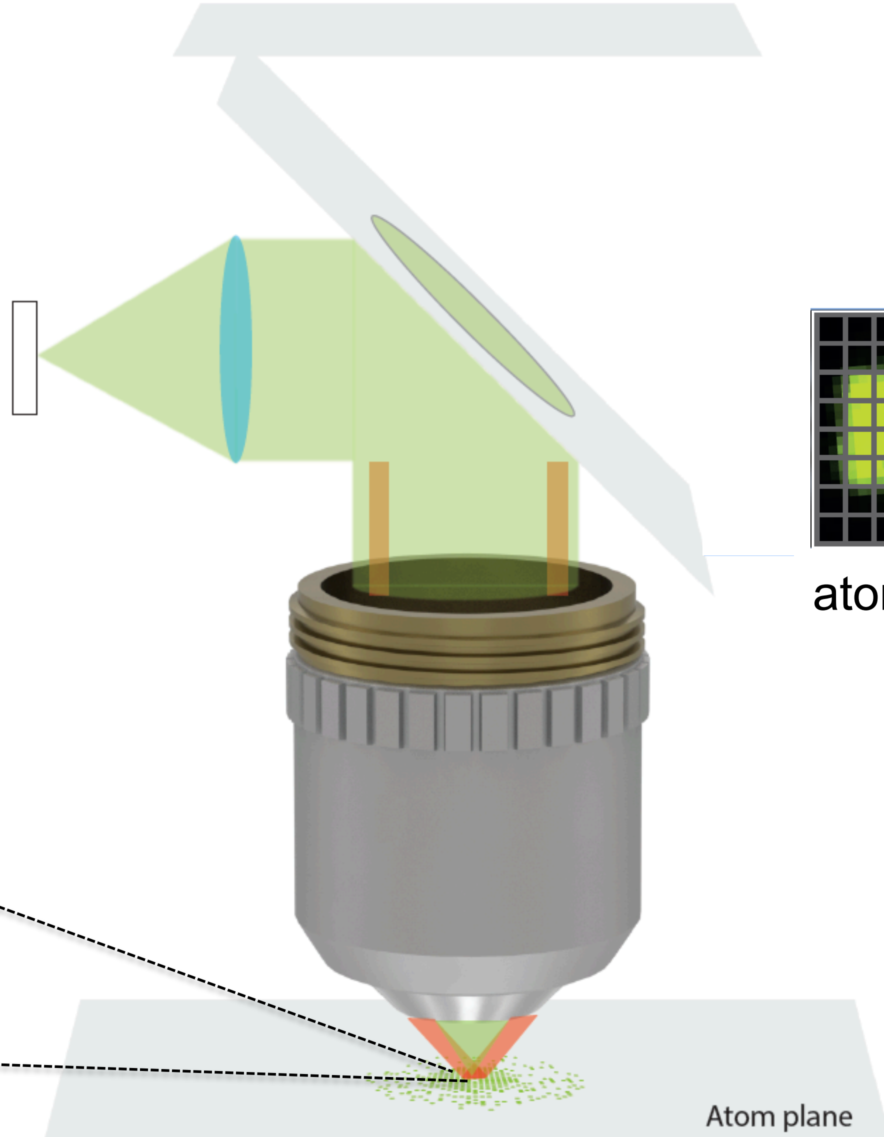
Schauss…Bloch, Gross, Science (2015)

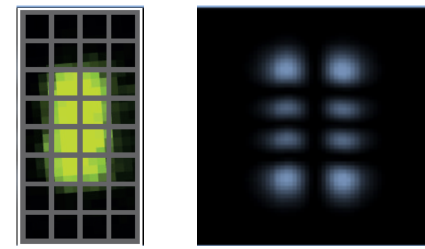
Quantum gas microscope

High resolution imaging





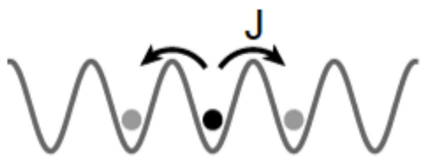




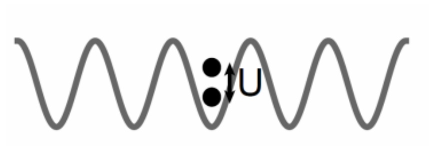
atoms light

Bose-Hubbard model

$$H = -J \sum_{\langle i,j \rangle} (a_i^\dagger a_j + \mathrm{h.c.}) + \frac{U}{2} \sum_i n_i(n_i - 1)$$



tunneling J

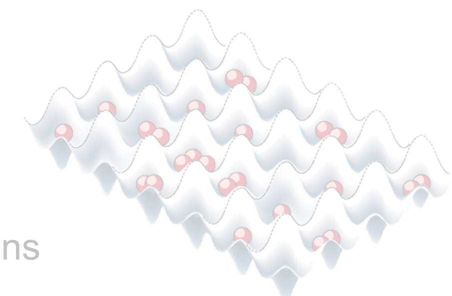


interaction U

$U \ll J$

Superfluid

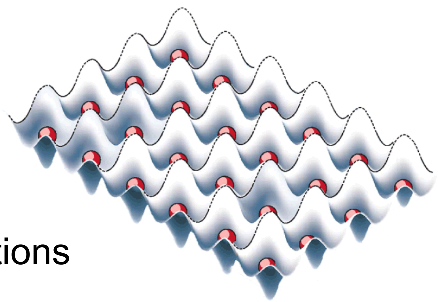
- Large number fluctuations
- Coherent state on-site

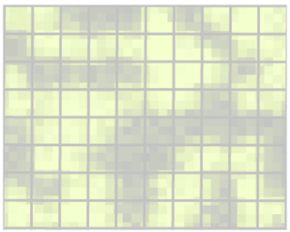


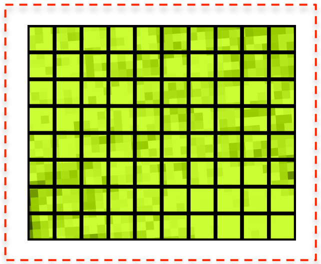
$J \ll U$

Mott insulator

- No number fluctuations
- Fock state on-site



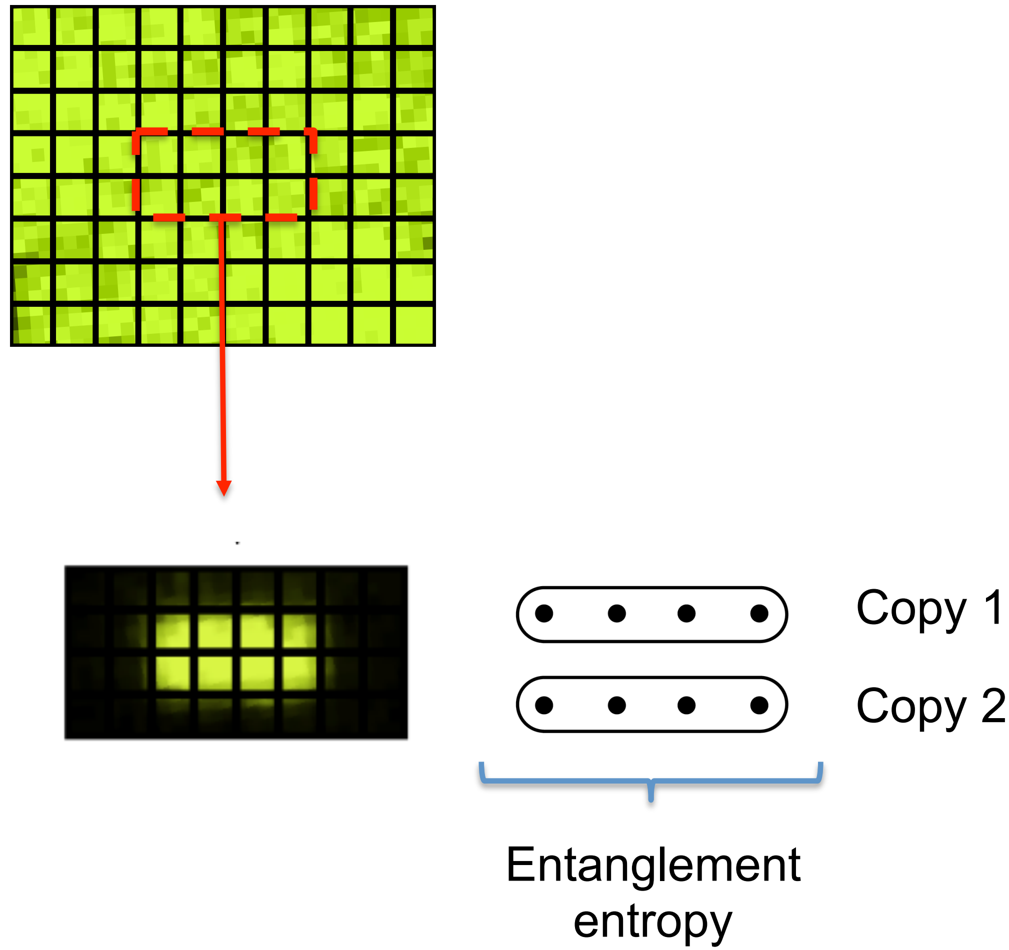




Good for cookie cutting. “Cookie cutting”?

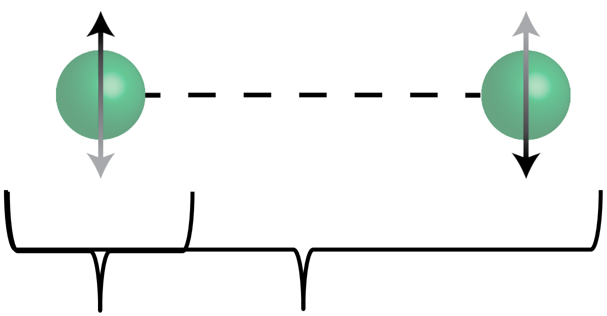
Cookie cutting

Prepare two copies of a quantum state:



Entanglement entropy

- Globally pure, but locally mixed:



$$\frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle\right)$$

$$\frac{1}{2}\left(|\uparrow\rangle\langle\uparrow| + |\downarrow\rangle\langle\downarrow|\right)$$

Classical mixed state → local entropy.

Pure two-particle state.

This local entropy is called "entanglement entropy"

Local reduction in purity encodes entanglement

So, how do we measure purity?

Connecting purity to "state sameness"

Density matrix: $\rho = \sum_n P_n |\psi_n\rangle\langle\psi_n|$ ⟷ Statistical mixture of states

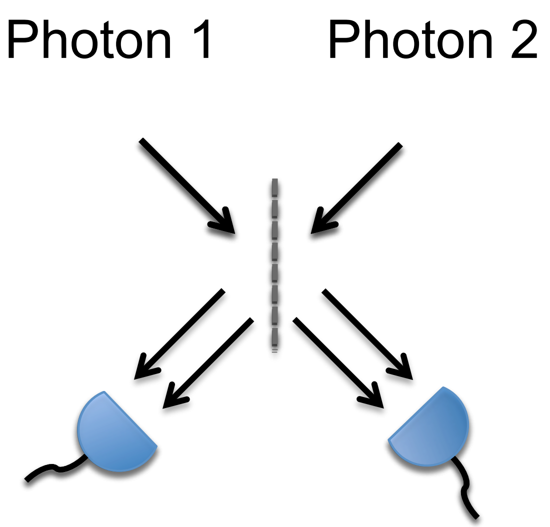
Purity: $\mathrm{Tr}(\rho^2) = \sum_n P_n^2$ ⟷ Probability to choose the same state twice from mixture*

Measure purity: two copies of a density matrix, how often you observe the same state in each copy!

*Insight from Hannes Pichler

Probing purity with Hong-Ou-Mandel interference

Photons on a 50/50 beam splitter

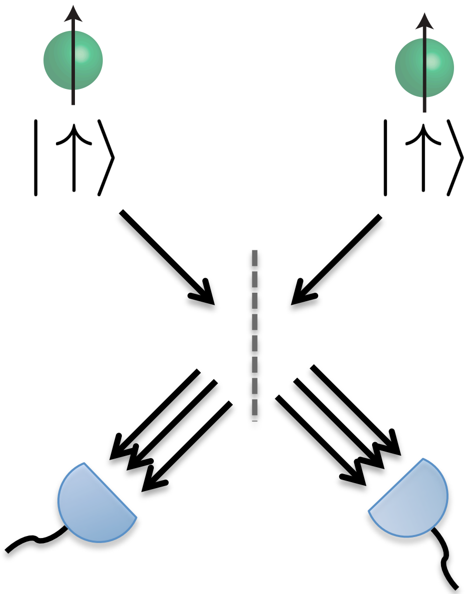


Dip in coincidence detection
for identical photons

Hong C K, Ou Z Y and Mandel L, Phys. Rev. Lett. 59 2044 (1987)

Probing purity with Hong-Ou-Mandel interference

Pure, **indistinguishable** states:

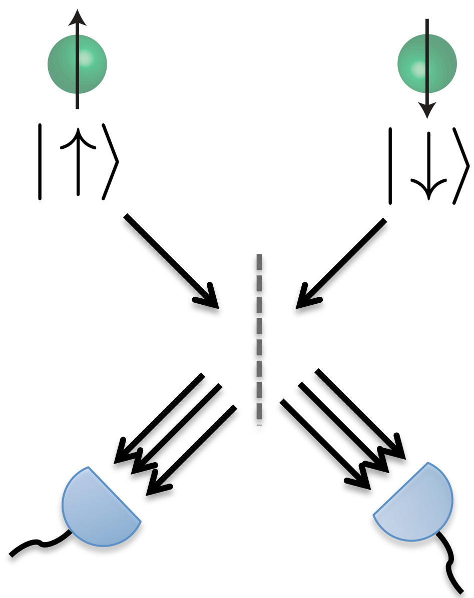


P_{odd}: 0

P_{even}: 1.0

Measuring purity with HOM

Pure, **distinguishable** states:

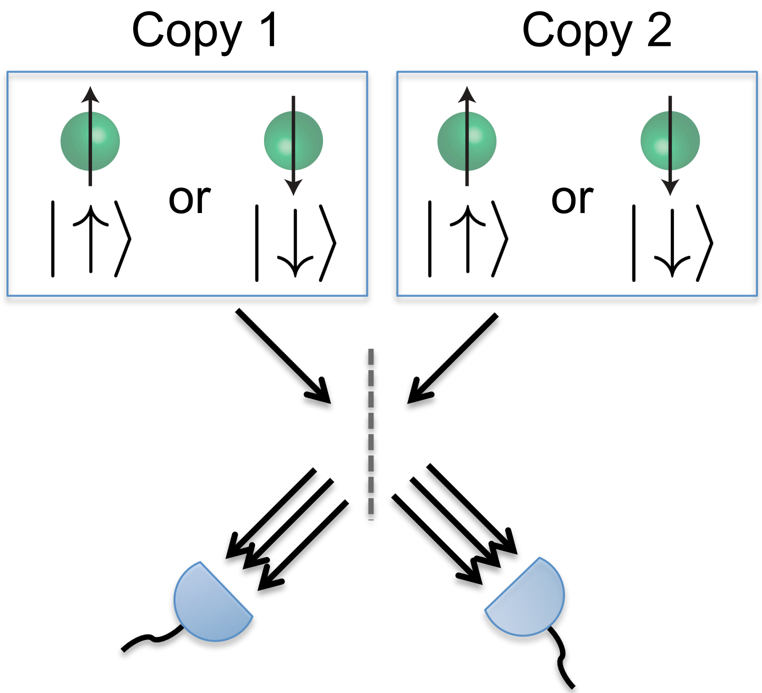


P_{odd}: 0.5

P_{even}: 0.5

Measuring purity with HOM

Two copies of **mixed** states:

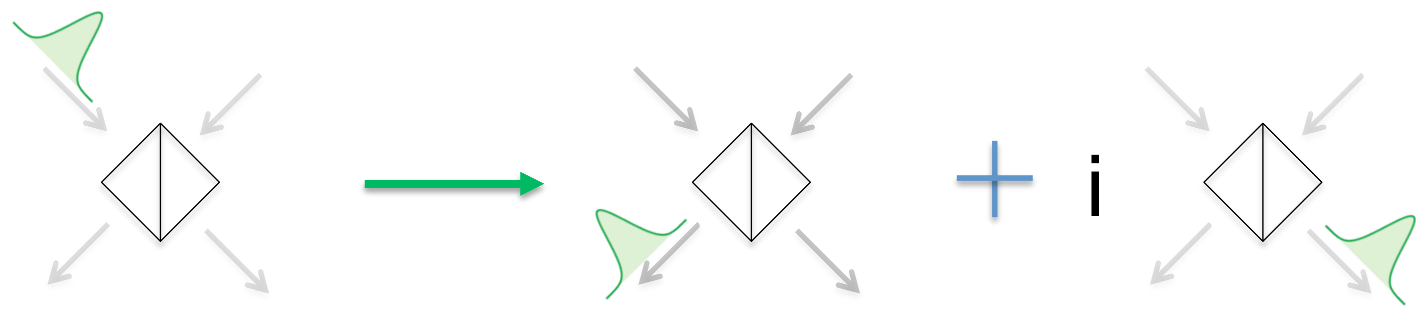


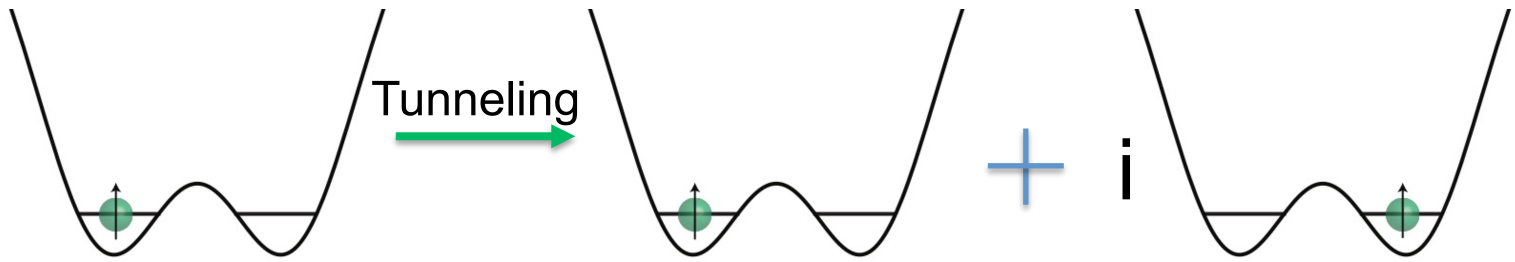
P_{odd}: 0.25

P_{even}: 0.75

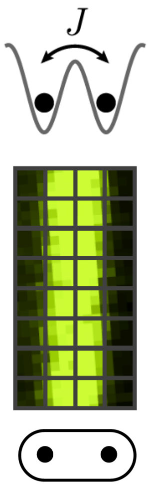
Even odd, probability
quantifies purity

Single atom beamsplitter





Atomic Hong-Ou-Mandel interference

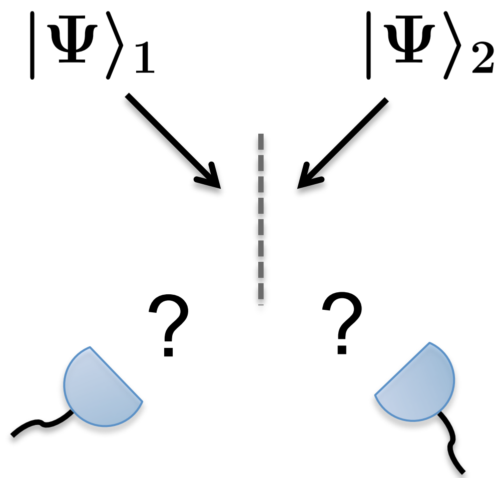


+

See also: Kaufman, Lester…Regal, Science 345, 306 (2014)

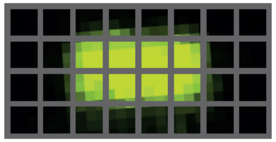
Measuring state purity with HOM

How pure are the many-body states



Measuring state purity with HOM

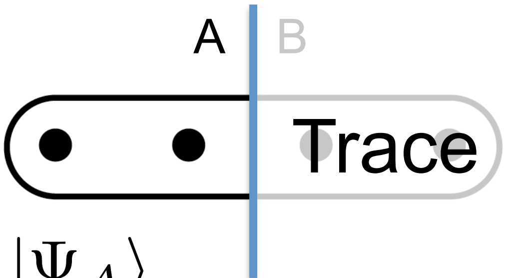
Interfere copies of
many-body states



Entanglement Entropy in itinerant atomic systems

Product state

$$|\Psi\rangle = |\Psi_A\rangle \otimes |\Psi_B\rangle$$

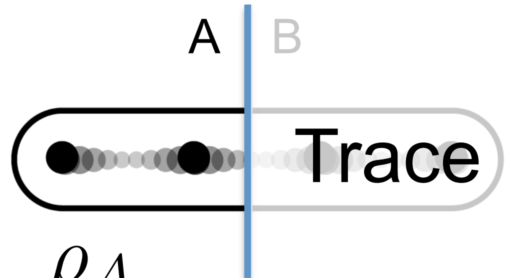


$|\Psi_A\rangle$

pure state

Entangled state

$$|\Psi\rangle \neq |\Psi_A\rangle \otimes |\Psi_B\rangle$$



ρ_A

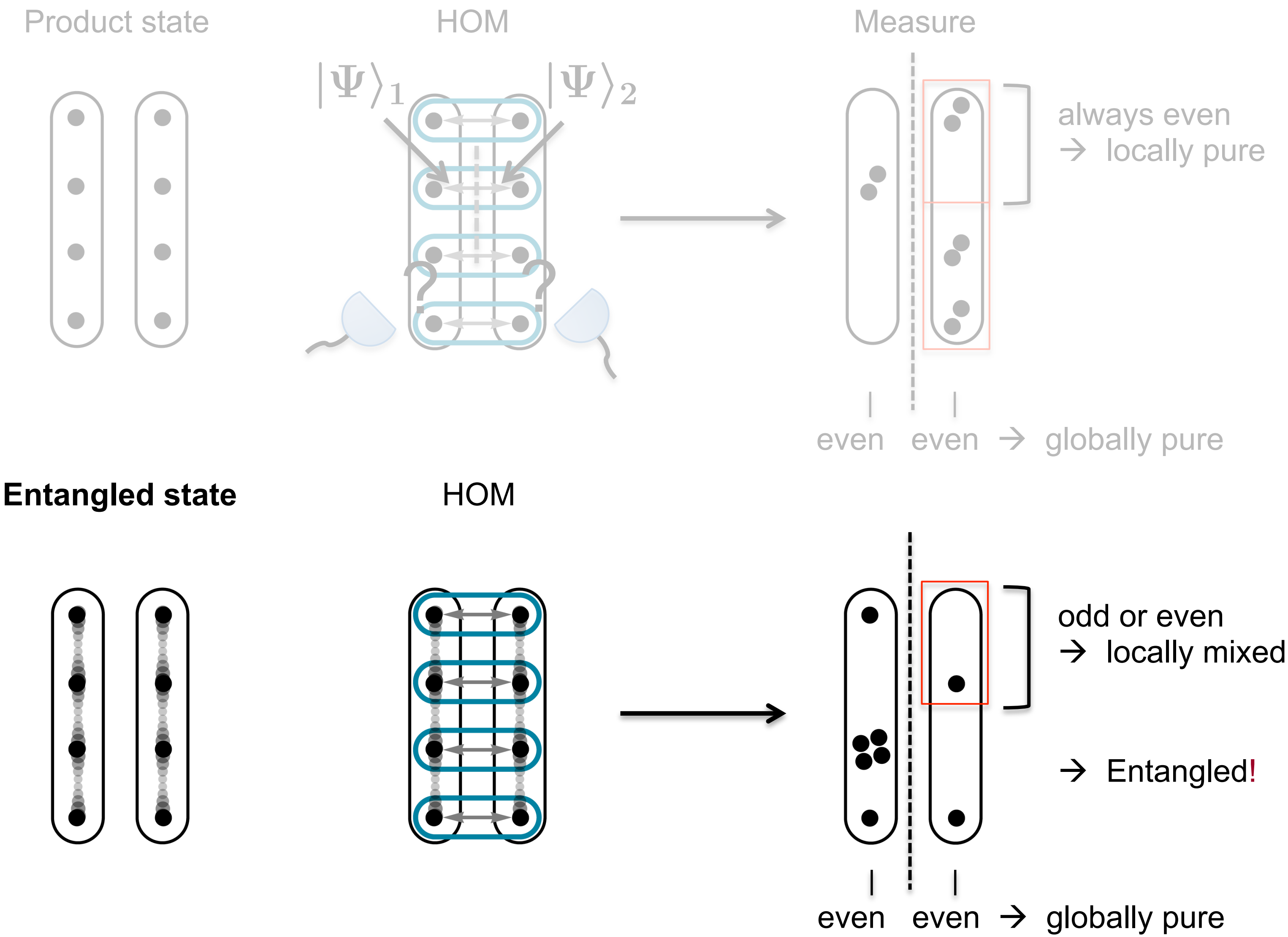
mixed state

Entanglement reduces the local purity after tracing

Quantified by the 2nd order **Rényi entanglement entropy**

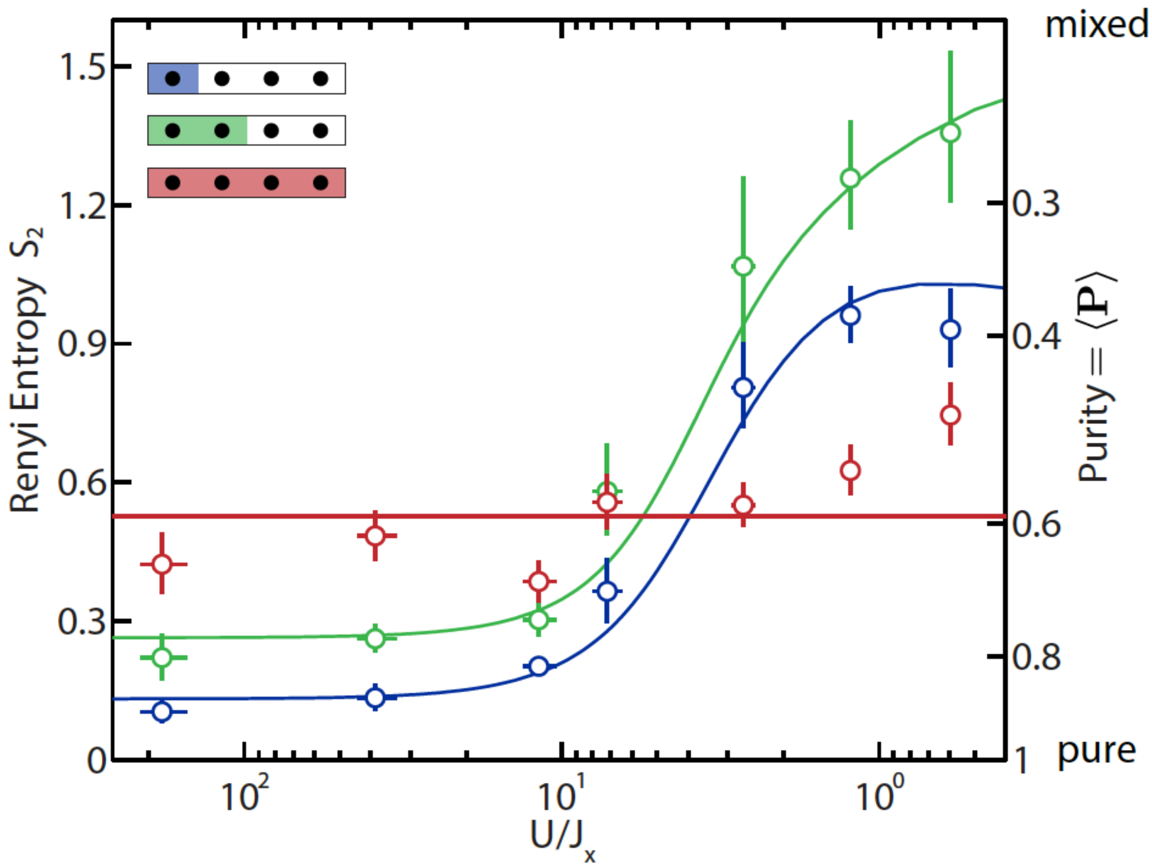
$$S_A = -\log(\mathrm{Tr}(\rho_A^2))$$

Measuring entanglement entropy: 4 particles



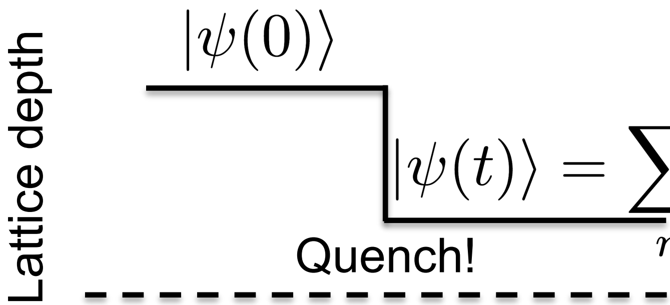
Alves…Jaksch, PRL (2004); Daley…Zoller, PRL (2012); Islam…Greiner, Nature (2015)

Measuring entanglement entropy: 4 particles



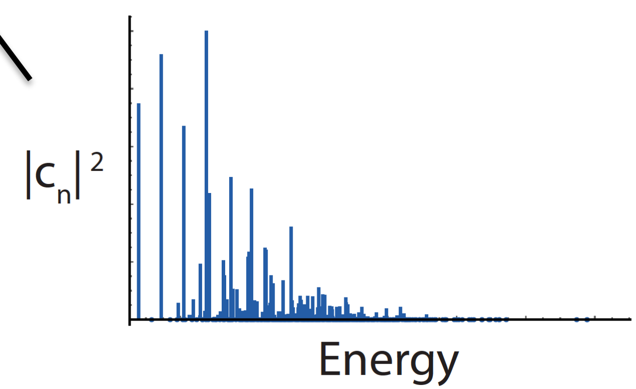
Alves…Jaksch, PRL (2004); Daley…Zoller, PRL (2012); Islam…Greiner, Nature (2015)

How do we apply to thermalization?

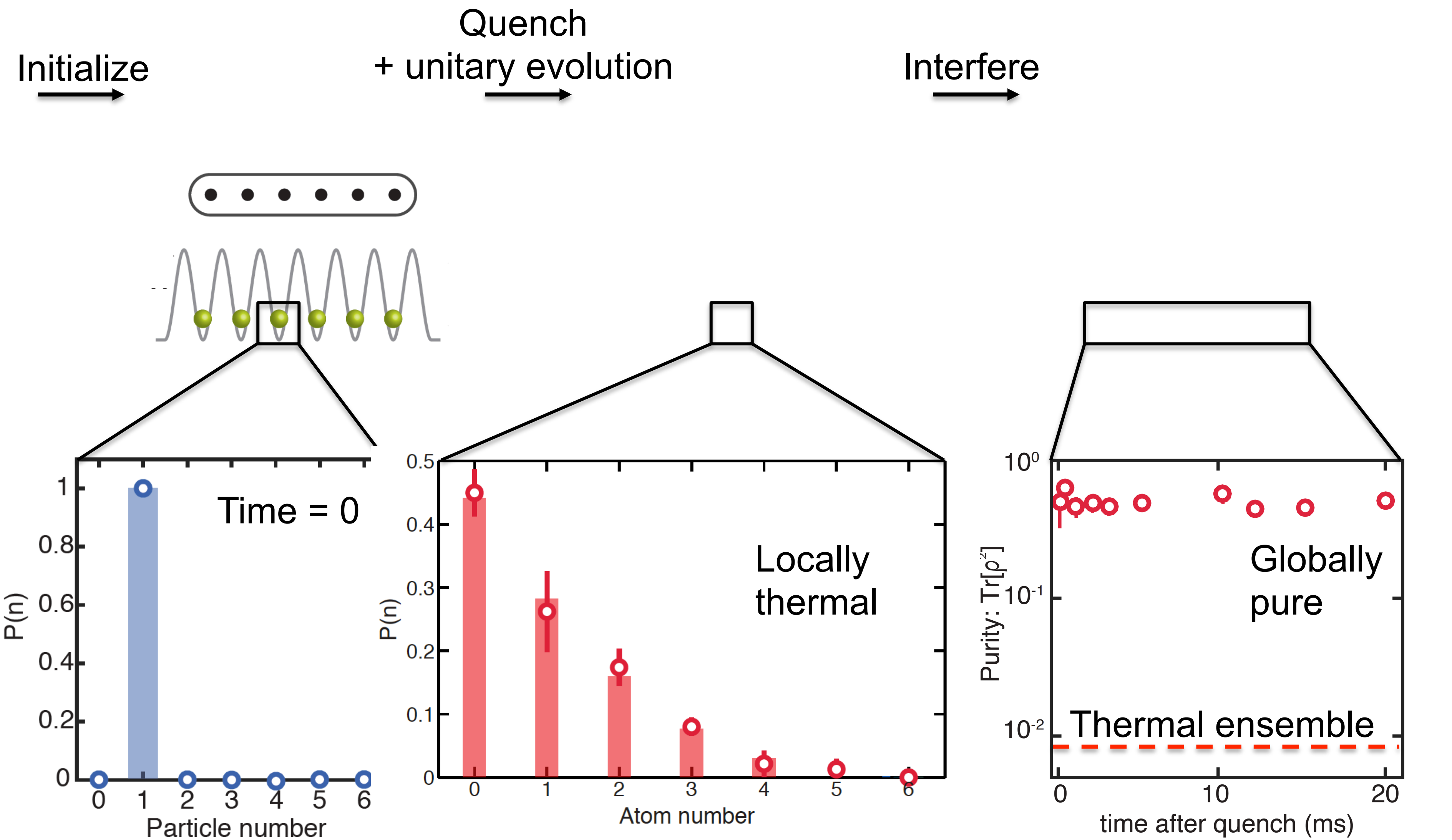


$$|\psi(t)\rangle = \sum_n c_n e^{-iE_n t}|n\rangle$$

"Equilibrate" → Thermal?

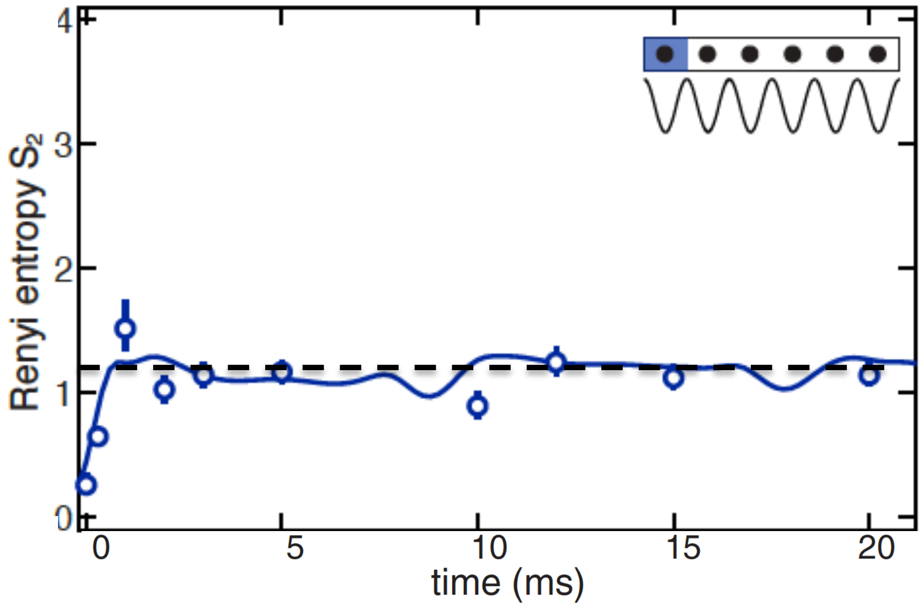


Thermalization measurement

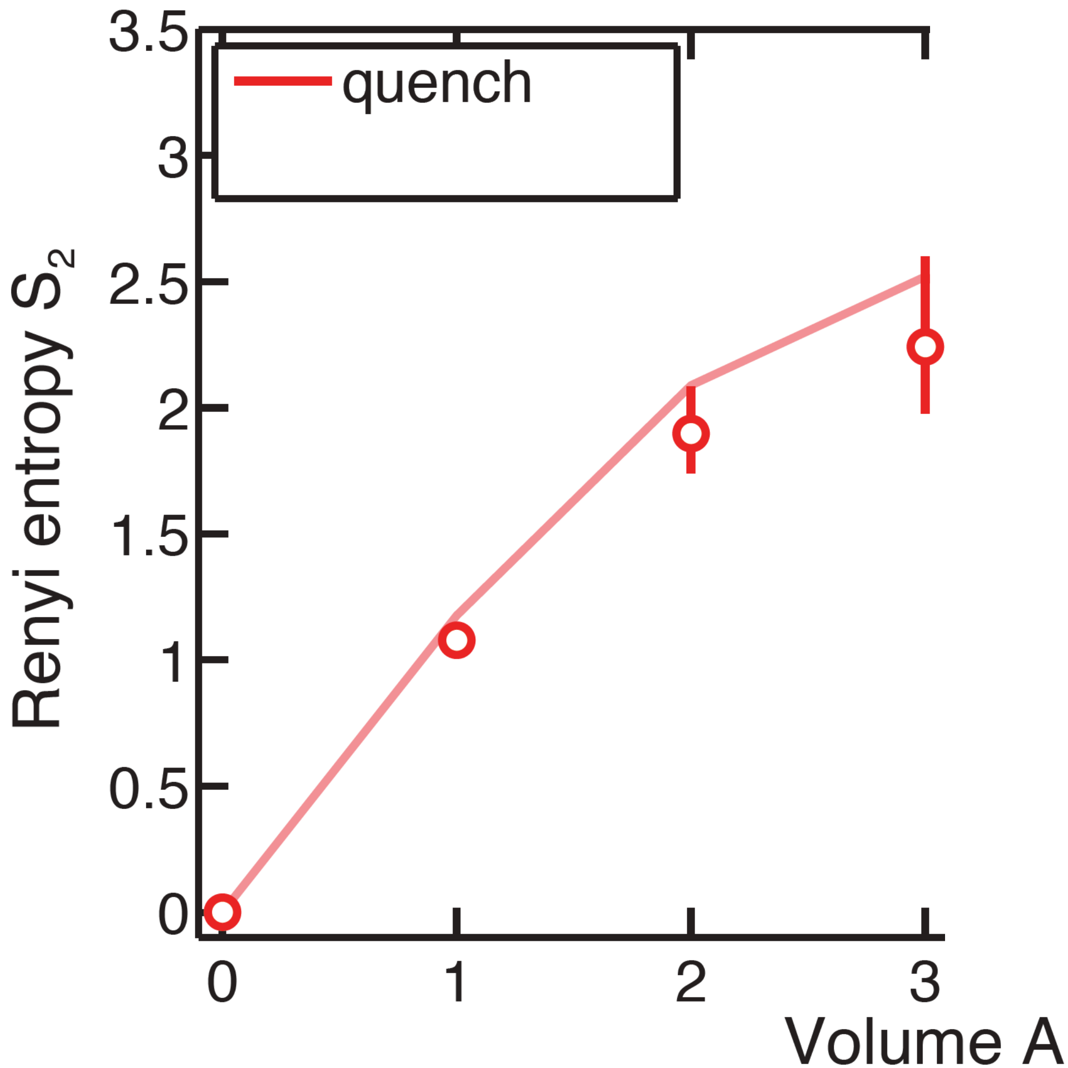


AMK…Preiss, Greiner, Science (2016)

Approach to equilibrium: quench dynamics

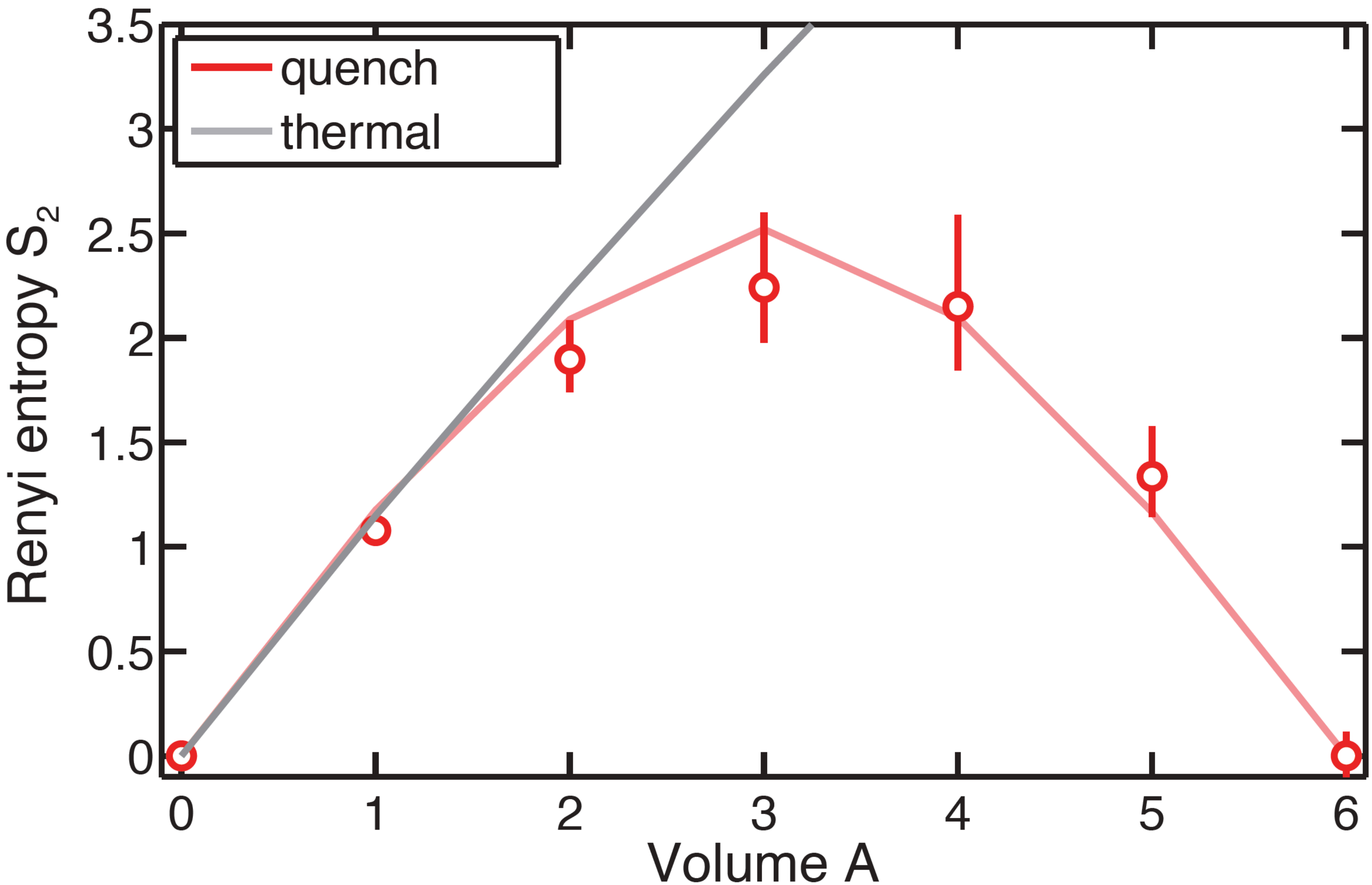


Entanglement entropy scaling



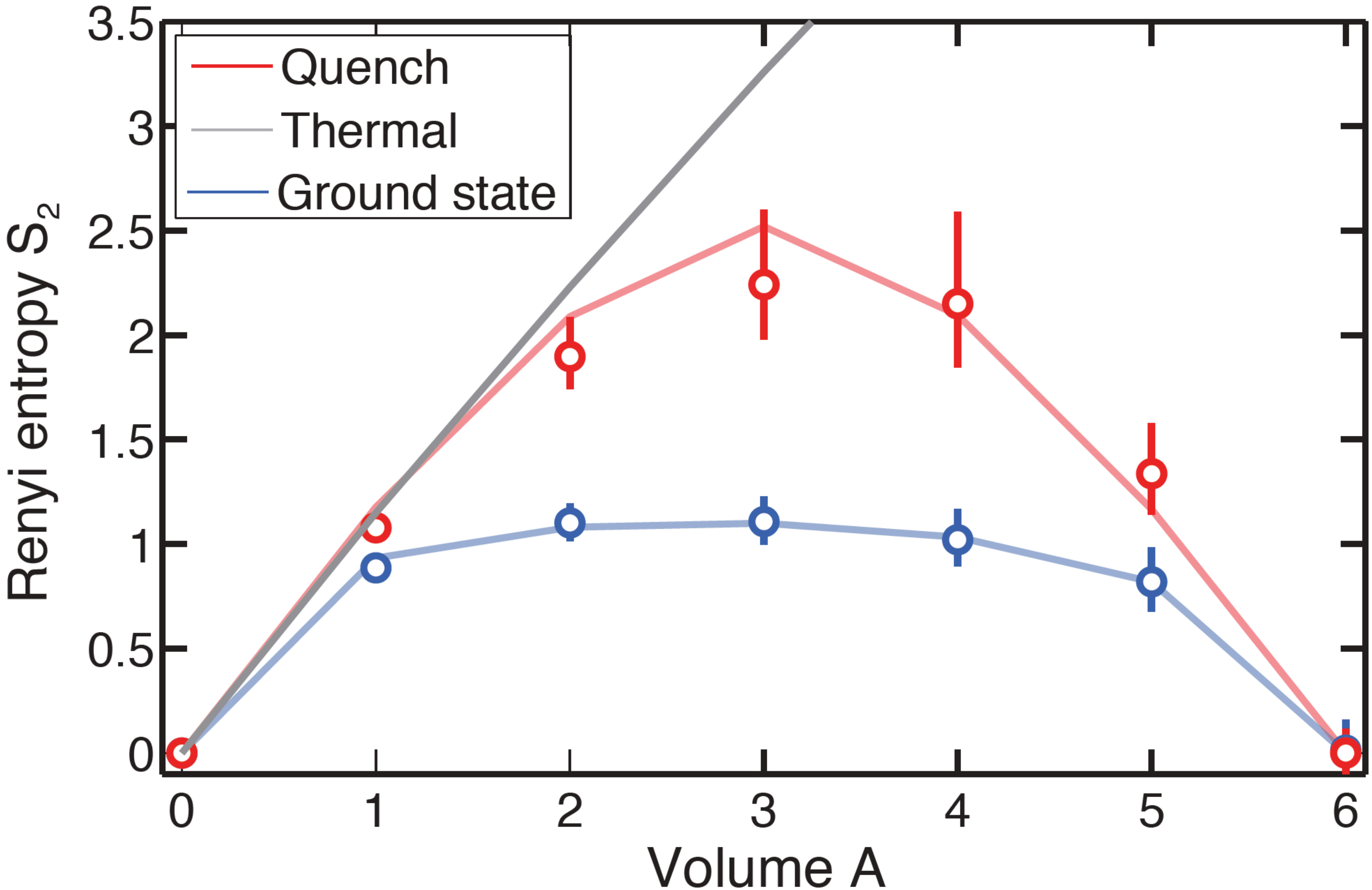
Calabrese…Cardy, J.Stat.Mech (2005); Deutsch…Sharma, PRE (2013); Santos...Rigol, PRE, (2013); Eisert… Plenio, RMP (2010)

Entanglement entropy ~ thermal entropy



Calabrese…Cardy, J.Stat.Mech (2005); Deutsch…Sharma, PRE (2013); Santos...Rigol, PRE, (2013); Eisert… Plenio, RMP (2010)

Ground state comparison

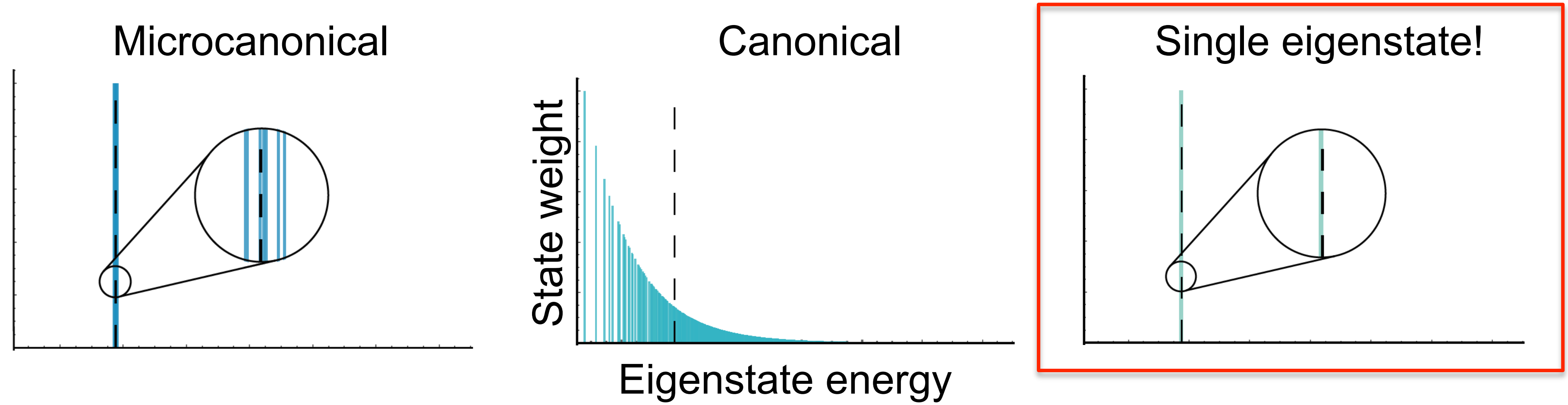


Calabrese…Cardy, J.Stat.Mech (2005), Deutsch…Sharma, PRL (2013), Santos…Rigol, PRL, (2013), Eisert… Plenio, RMP (2010)

Comparison to ensembles: number distribution

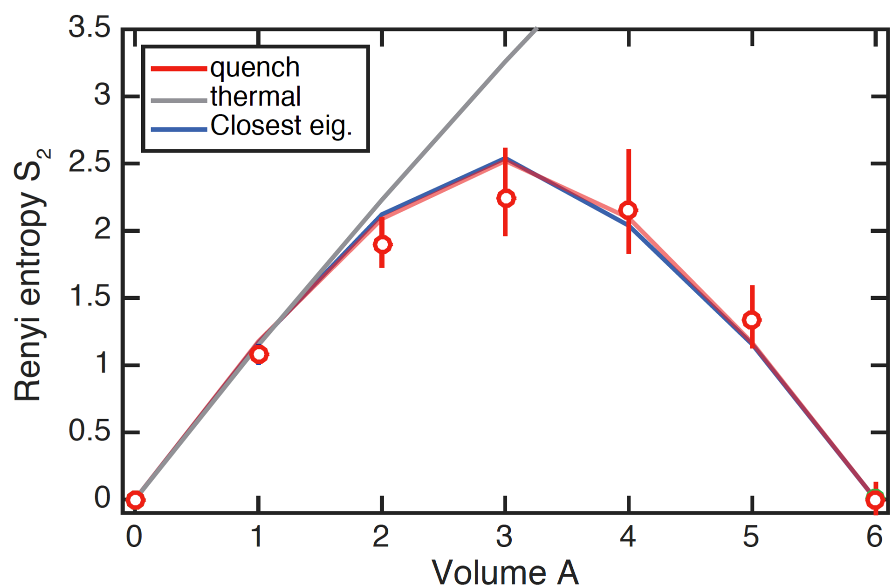
Global eigenstates

Eigenstate thermalization



Local observables

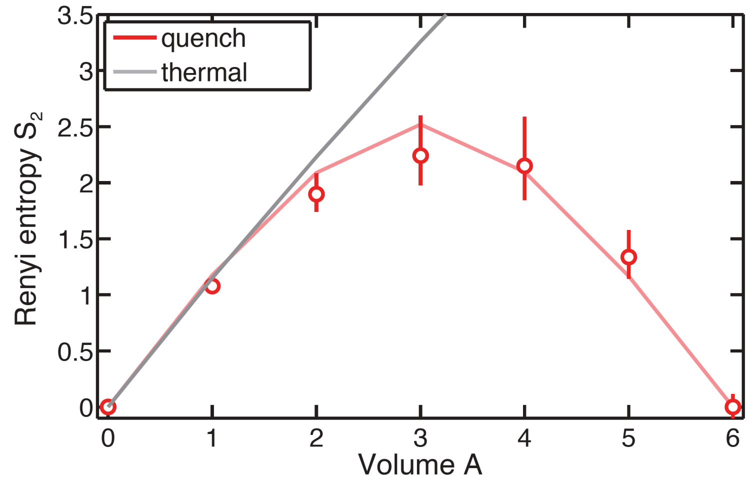
Entropy



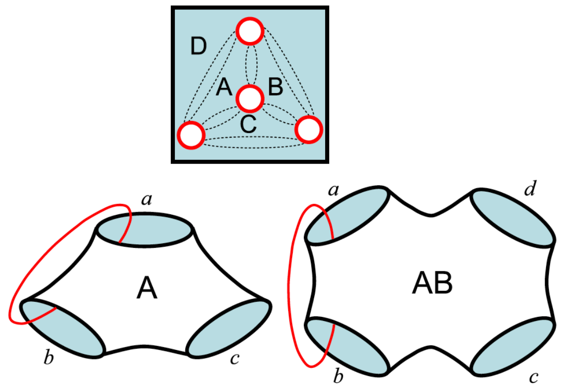
Jensen…Shankar, PRL(1984); Deutsch, PRA (1991); Srednicki, PRE (1994); Rigol...Olshanii., Nature (2008)

Going forward

"Entanglement microscopy"

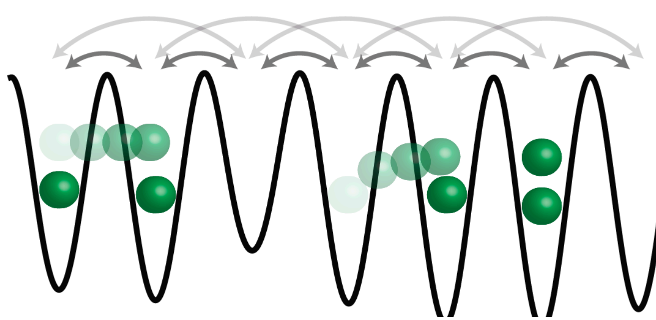


Topological entanglement entropy



Kitaev and Preskill, PRL (2006)

Many-body localization



Bardardson…Moore, PRL, (2012)

Related schemes emerging

Measuring out-of-time-order correlations and multiple quantum spectra in a trapped ion quantum magnet

Martin Gärttner,[1,*] Justin G. Bohnet,[2,*] Arghavan Safavi-Naini,[1]
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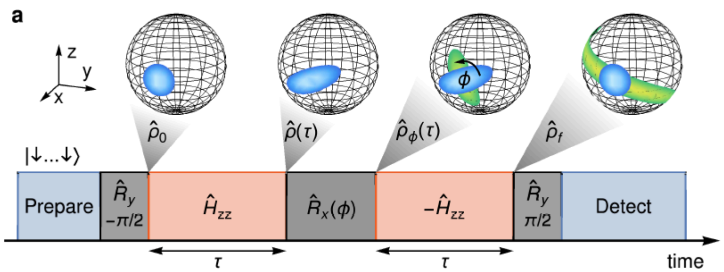
(Dated: June 13, 2017)



Quantum Simulation and Spectroscopy of Entanglement Hamiltonians

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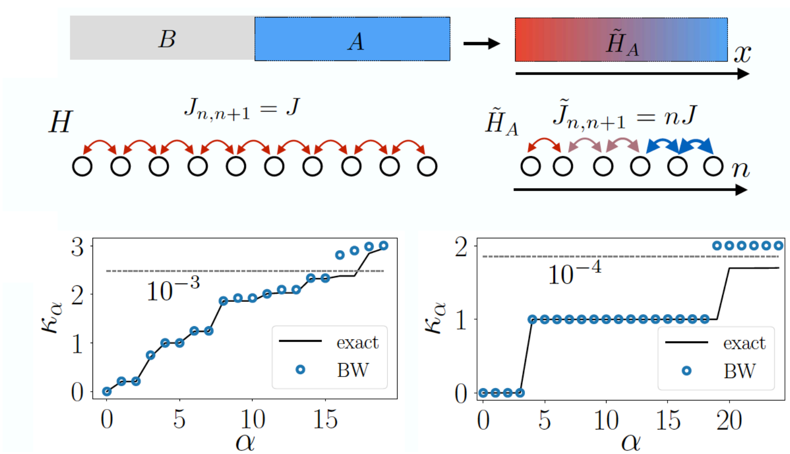

Rényi Entropies from Random Quenches in Atomic Hubbard and Spin Models

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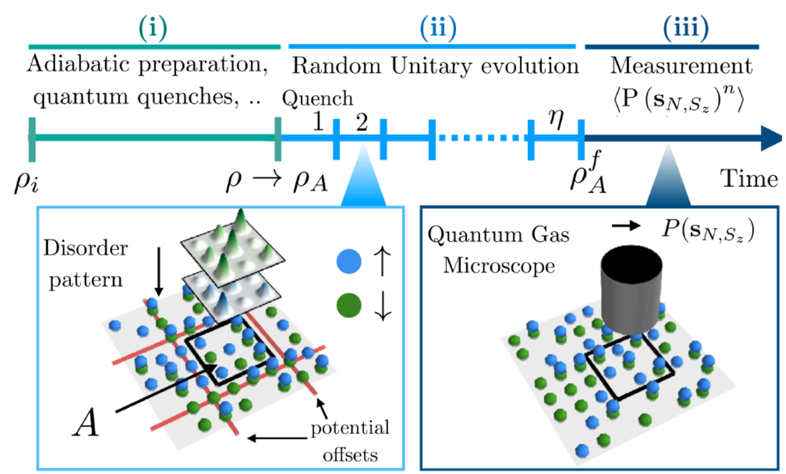
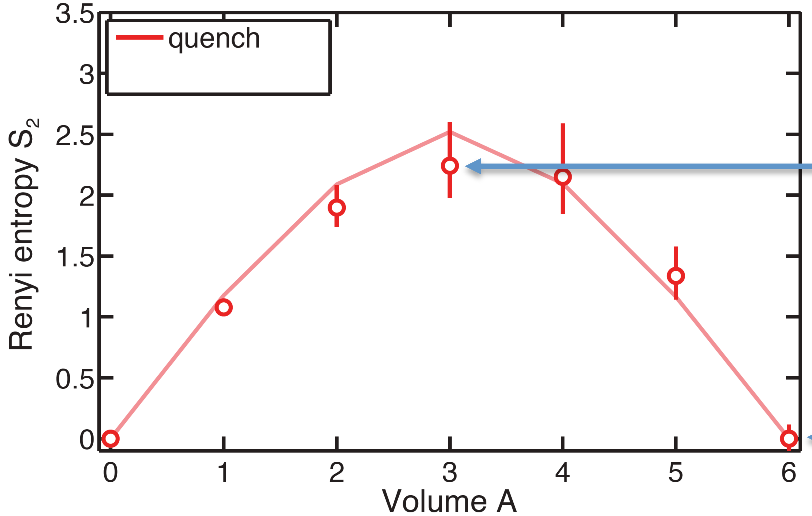
(Dated: September 18, 2017)



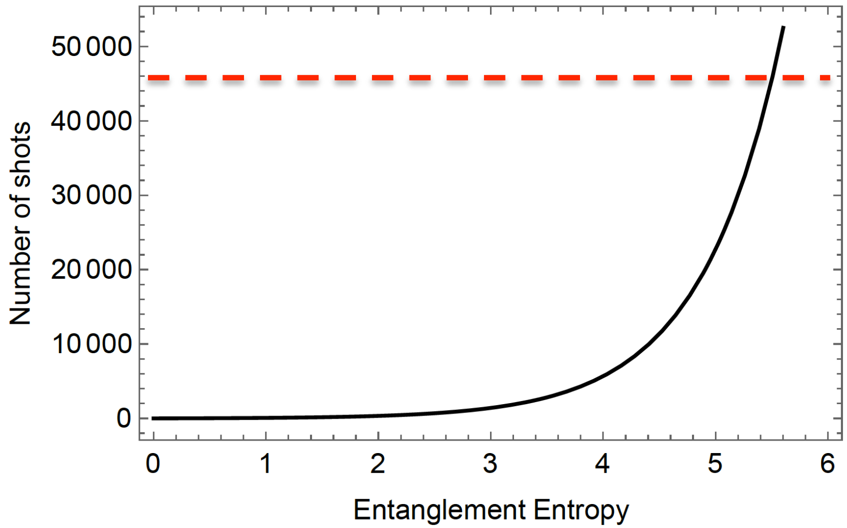
Utility?



1000s of runs

<100 runs

Proves closed system, purity!



1 year, quantum gas microscope

How do we scale, apply to larger systems?

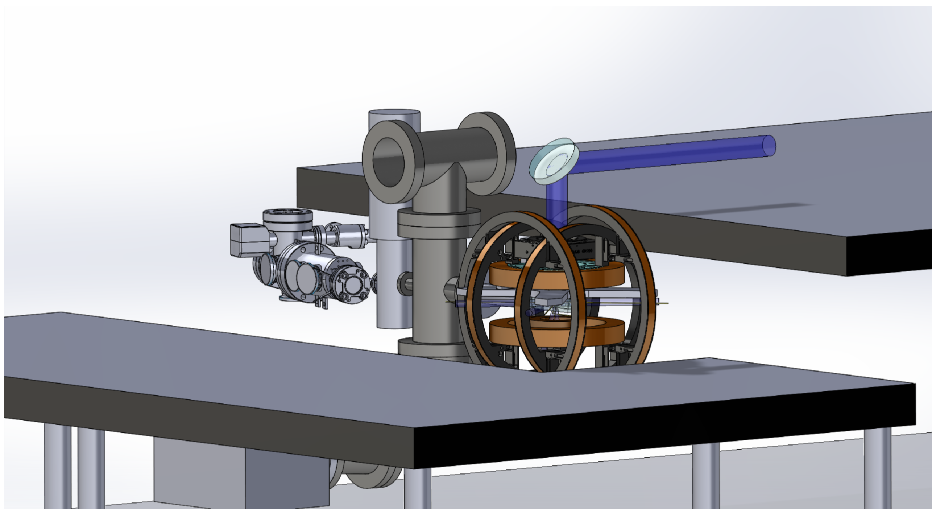
The issues:

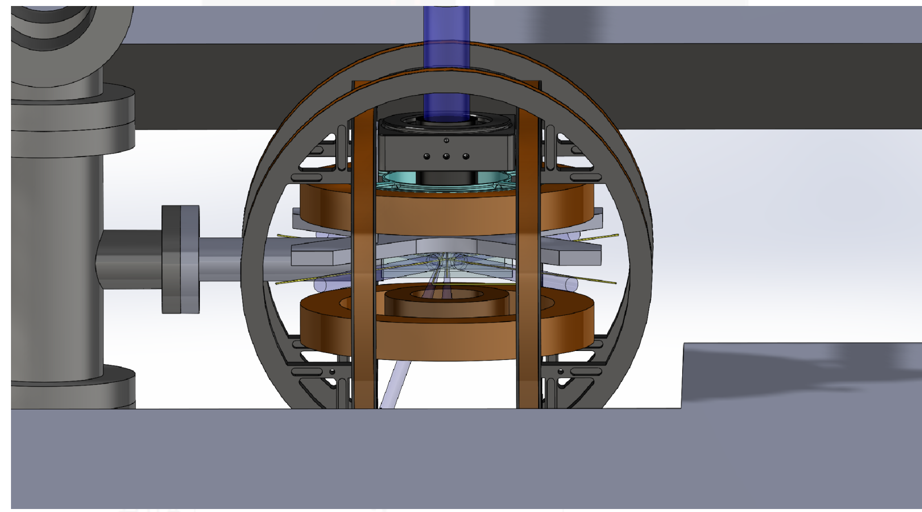
- Time: (previous slide)

New experiment at JILA

Objective: use optical tweezers to rapidly define low-entropy atomic states in optical lattices.

In progress…





Endres...Lukin, Science (2016); Barredos…Browaeys, Science (2016); Martin...Ye, Science (2013)

Acknowledgements

Harvard group

Rb lab:

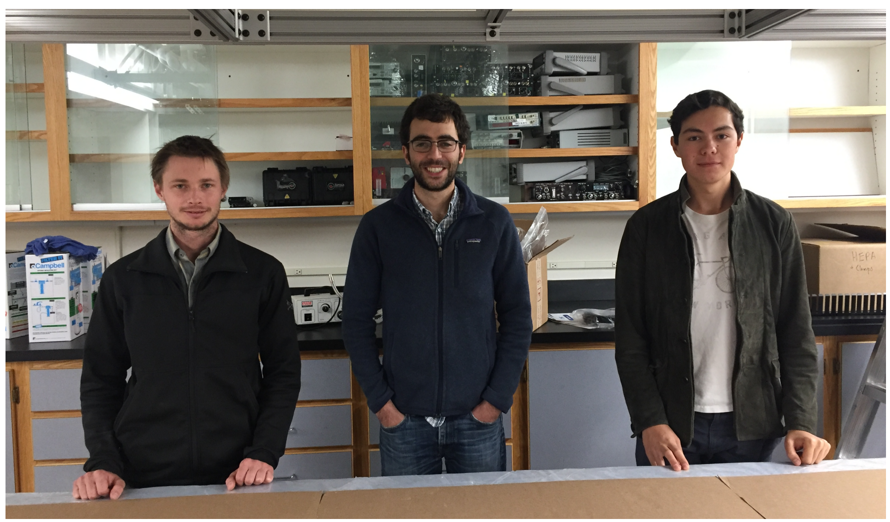
Philipp Preiss
Eric Tai

Alex Lukin
Matthew Rispoli
Robert Schittko

Tim Menke

Markus Greiner

JILA group



Sr lab:

Matt Norcia (PD)

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