Creating entangled quantum systems using tweezer arrays

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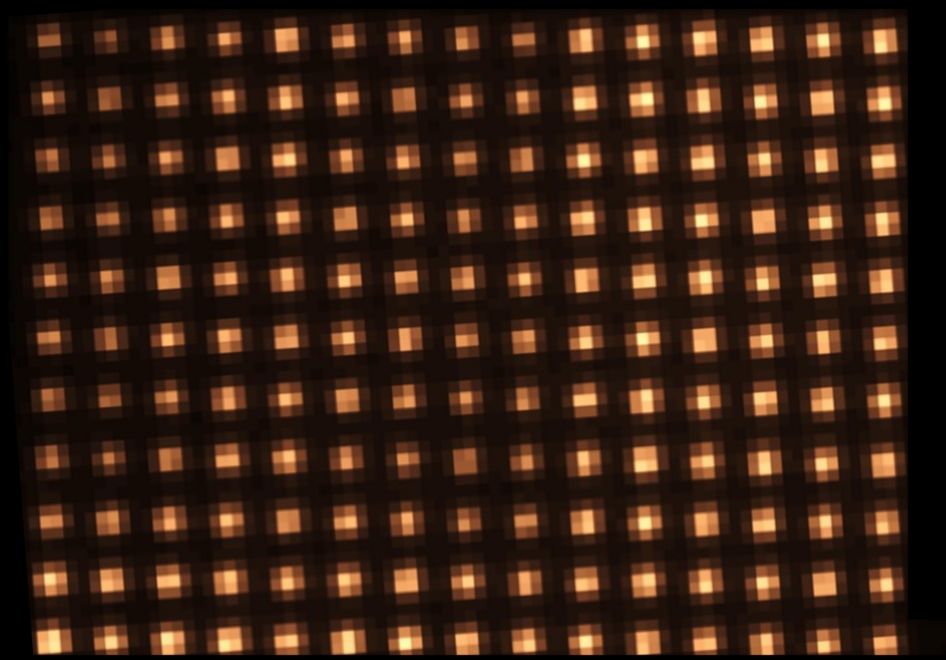
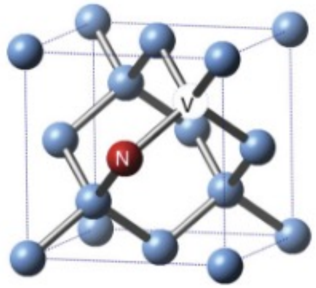
Caltech

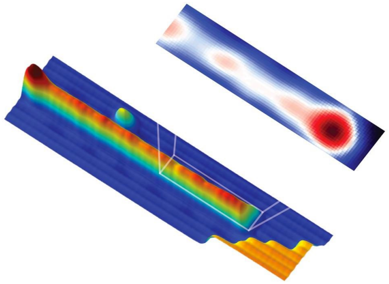
Yale Physics Club, Oct 10, 2022



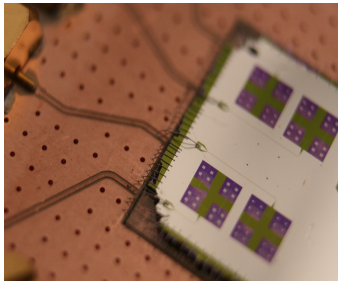
Experimental Quantum Science: Systems

Traditional solid state materials

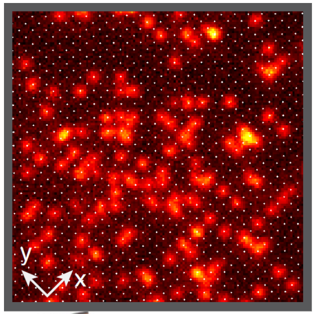




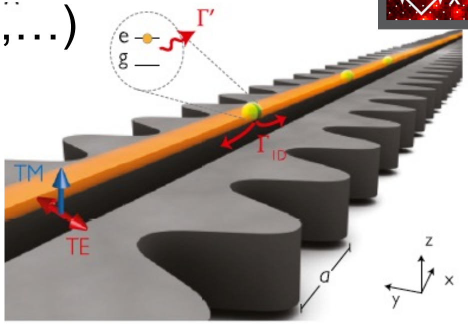
Solid state qubits (SC qubits, Majorana wires, NV centers …)



Cold atomic systems (neutral atoms, ions, molecules …)



Photonic/phononic systems (cavities, nanophotonics,…)

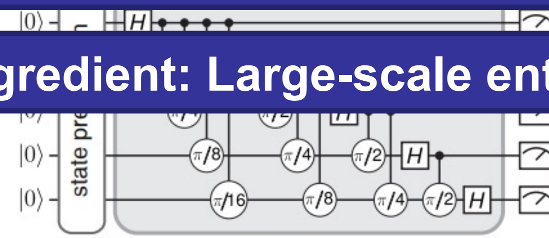


Quantum Science: Goals

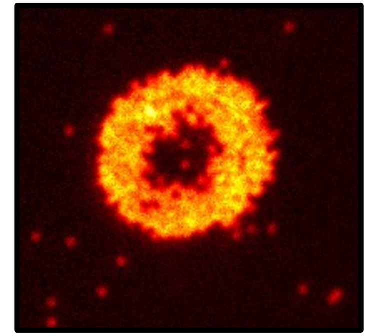
Goal: Outperform classical counterparts

Key ingredient: Large-scale entanglement

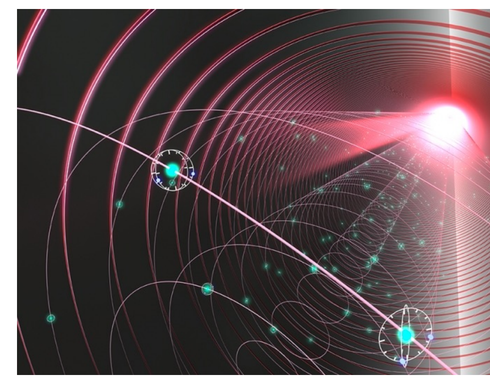
1) Quantum computing



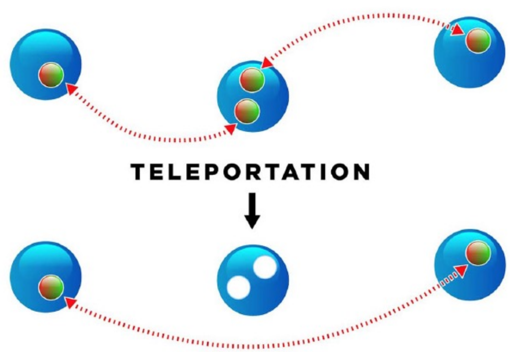
2) Quantum simulation
(quantum many-body physics)



3) Quantum metrology
(use quantum states/systems for precision measurement)



4) Quantum networks

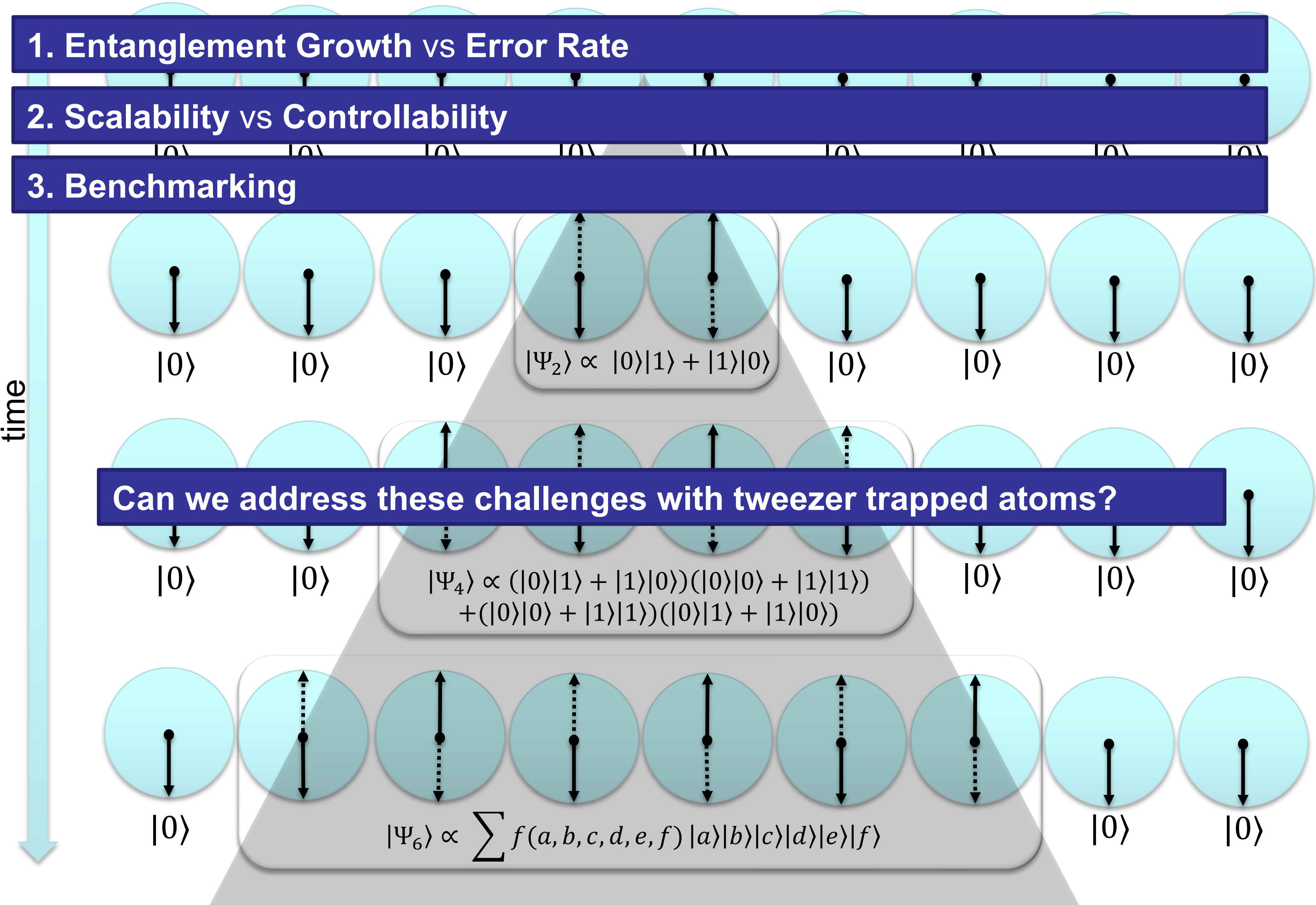


‘Entanglement challenge’

1. Entanglement Growth vs **Error Rate**

2. Scalability vs **Controllability**

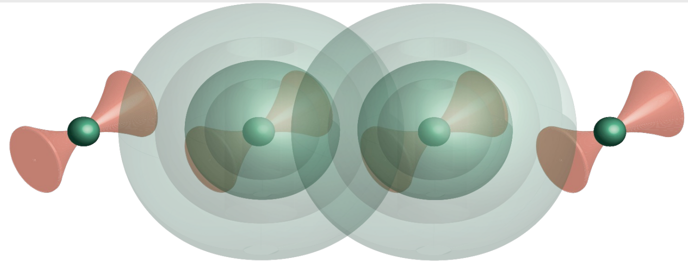
3. Benchmarking



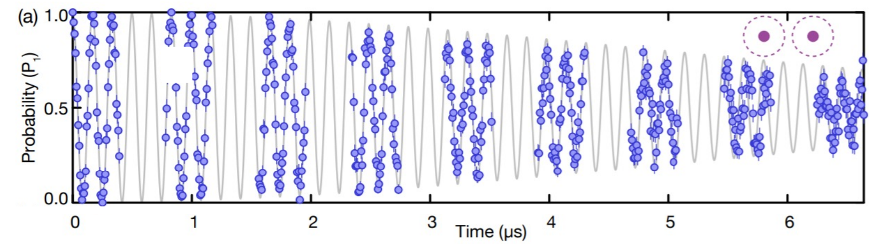
Can we address these challenges with tweezer trapped atoms?

Outline

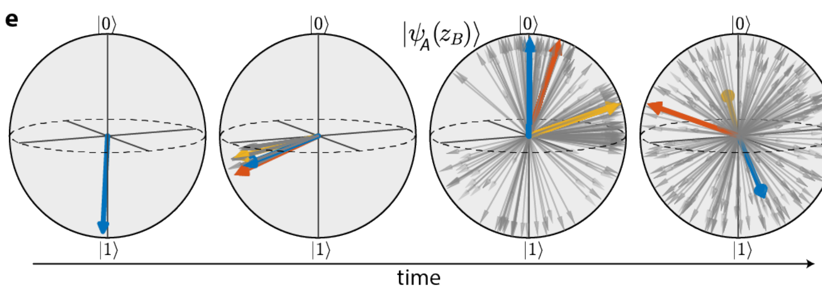
A) Intro to tweezer arrays and Rydberg interactions



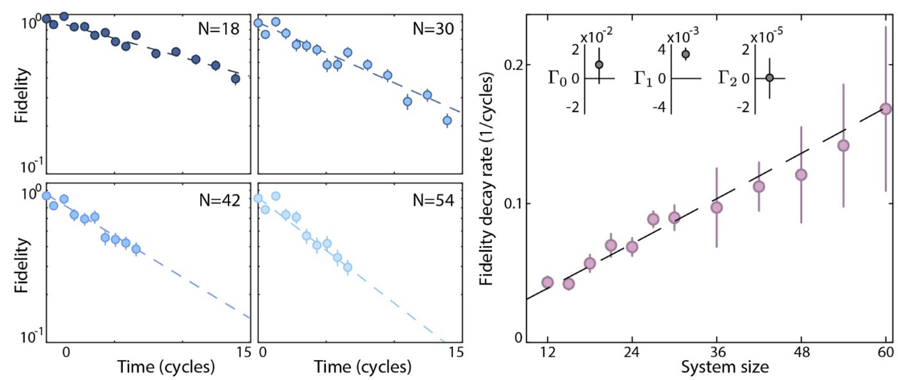
B) Single & two-qubit results, tweezer clocks



C) Benchmarking from
‘random state ensembles



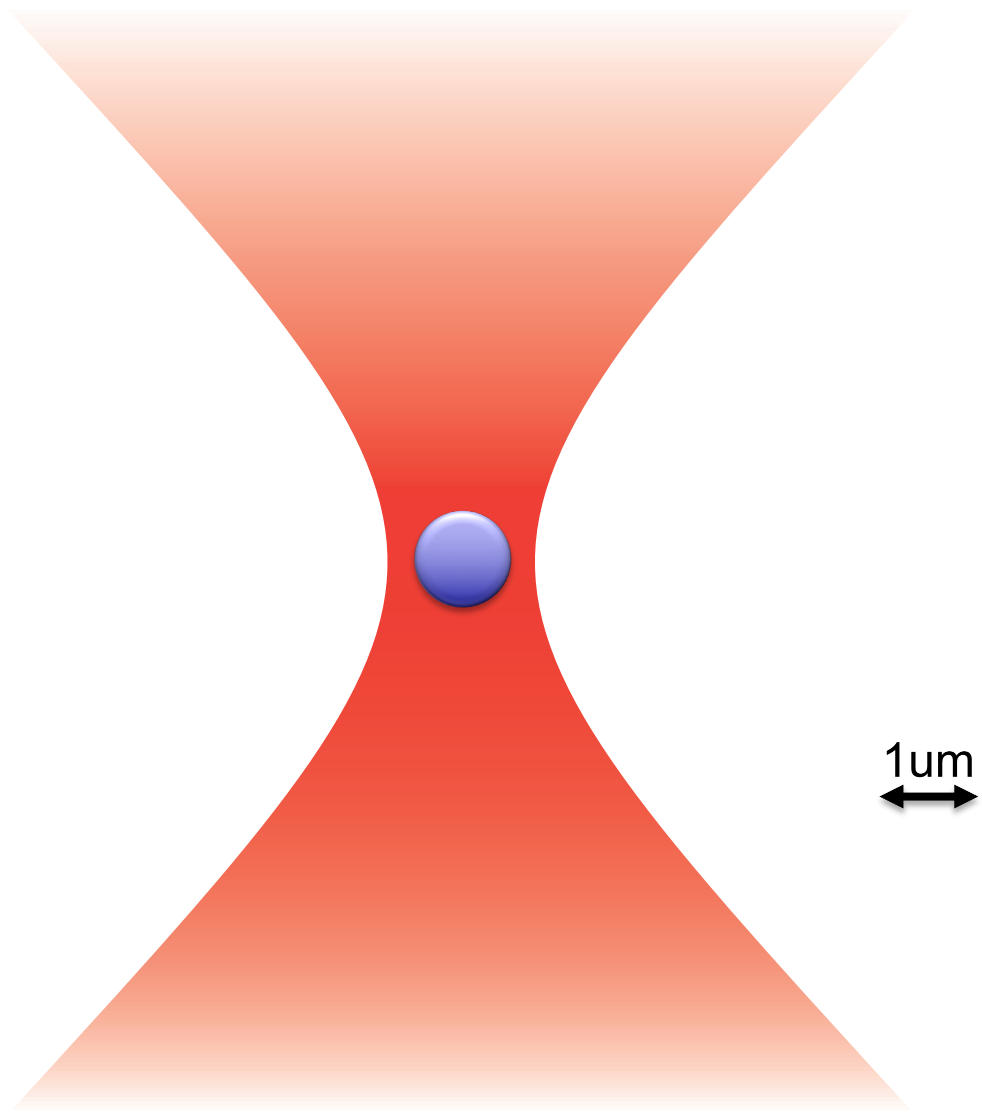
D) Quantum vs classical comparison for large-scale entangled states with N=60



Optical tweezers and atom-by-atom assembly

ME, Bernien*, Keesling*, Levine* et al. Science 354, 1024 (2016)*
See also: Browaeys Group: Science 354, 1021 (2016)

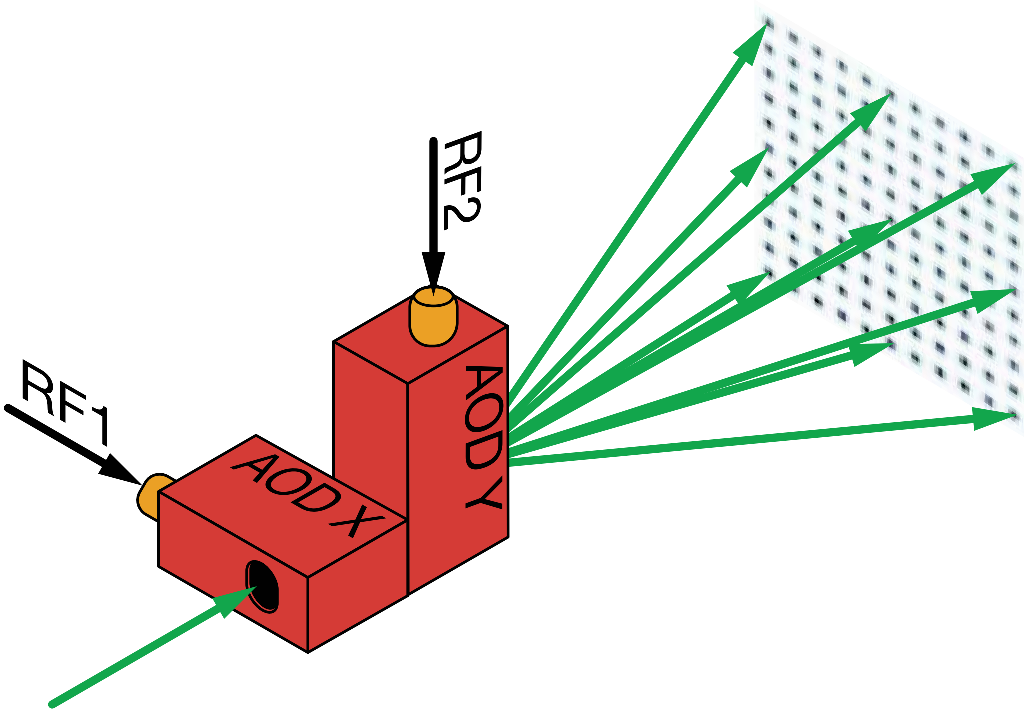
Optical tweezer



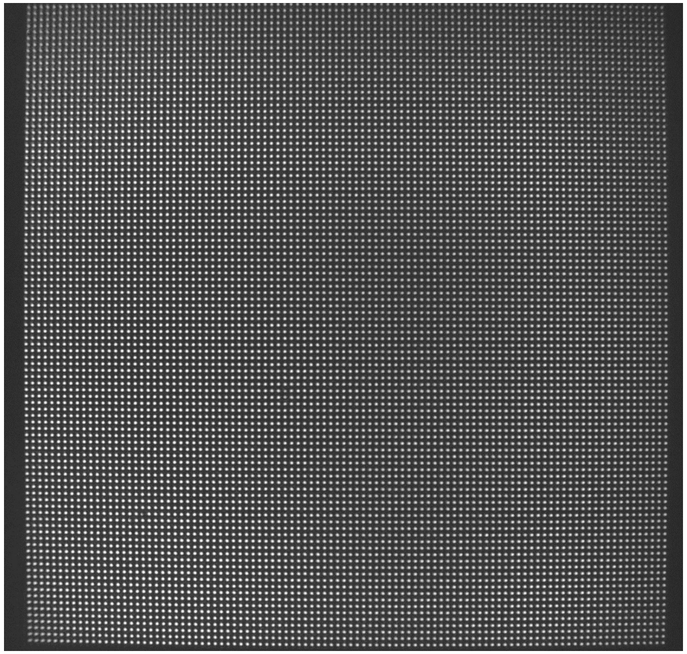
N. Schlosser, G. Reymond, I. Protsenko and P. Grangier, “Sub-poissonian loading of single atoms in a microscopic dipole trap”, *Nature* **411**, 1024 (2001)

Tweezer Arrays

1d or 2d array generation with crossed AODs



100x100 of **EMPTY** tweezers



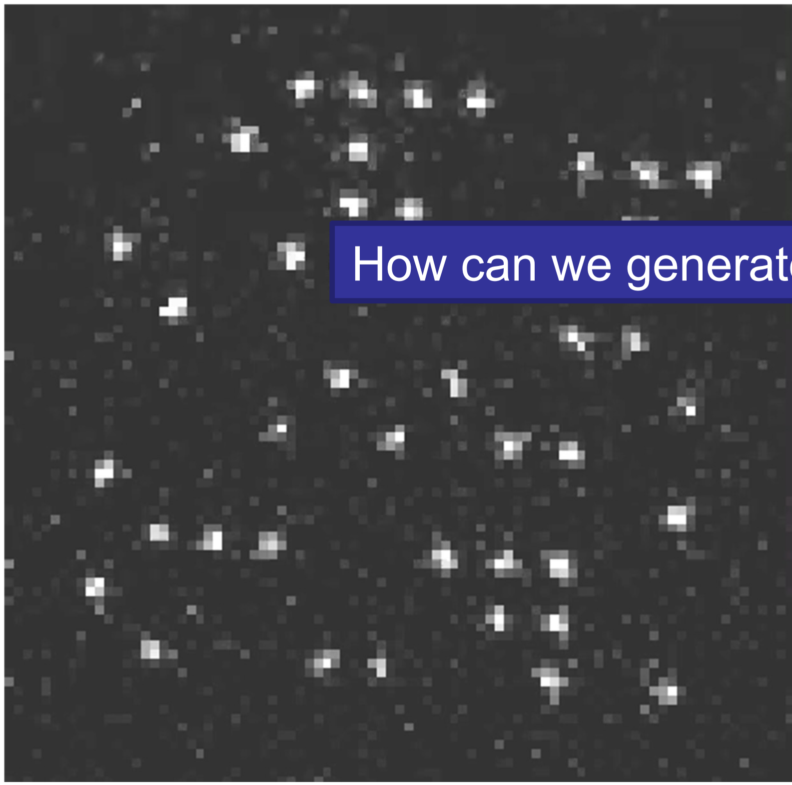
(Caltech data)

First large arrays: Single-Atom Trapping in Holographic 2D Arrays of Microtraps with Arbitrary Geometries
F. Nogrette, H. Labuhn, S. Ravets, D. Barredo, L. Béguin, A. Vernier, T. Lahaye, and A. Browaeys
Phys. Rev. X **4**, 021034

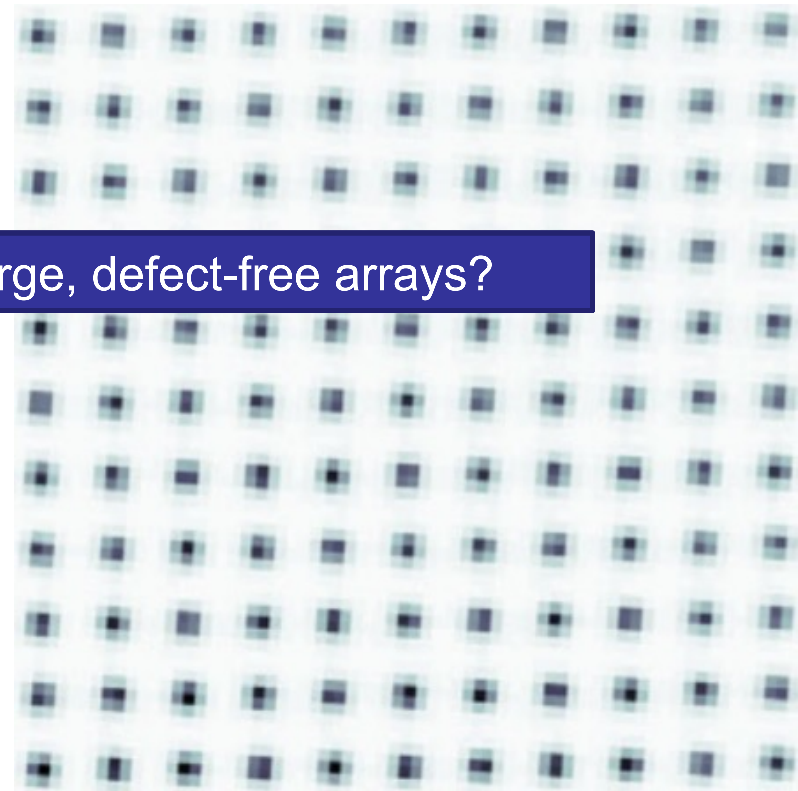
Stochastic loading

Challenge: **stochastic loading** (either 0 or 1 atom per tweezer)

Single shots



Average image

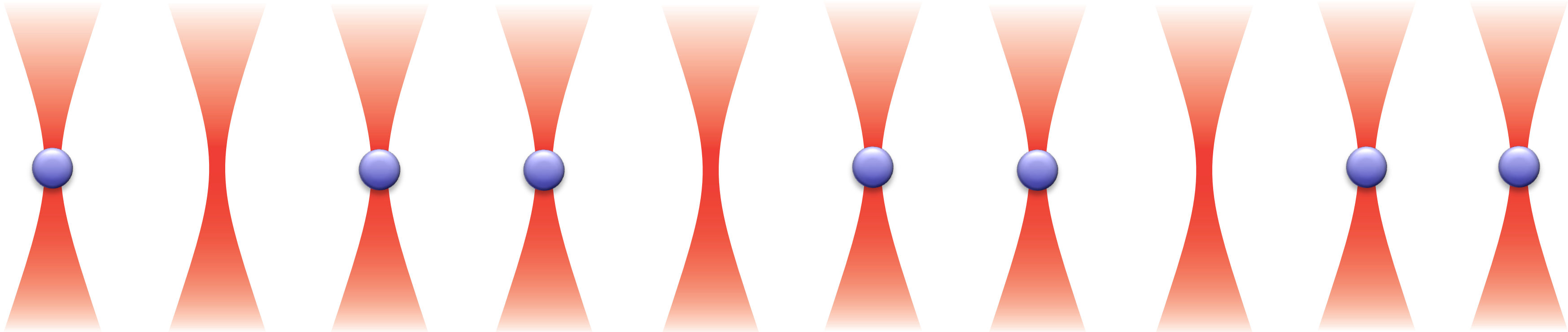


How can we generate large, defect-free arrays?

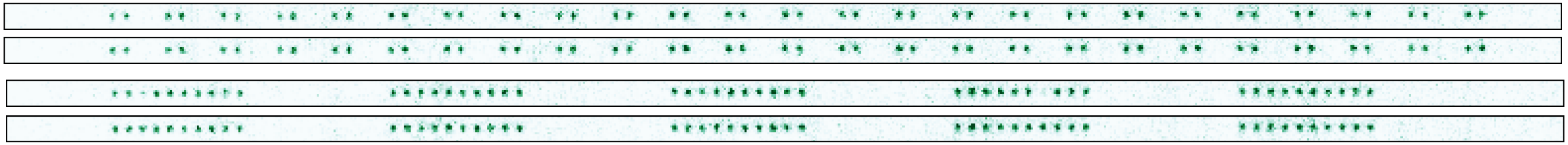
Caltech data : Cooper, Covey, Madjarov, Porsev, Safronova, ME, PRX 8, 041055 (2018)

Atom-by-atom scheme

1. Tweezers loaded from a cold cloud of atoms
2. Image and remove empty traps
3. Rearrange remaining traps to form a defect-free array



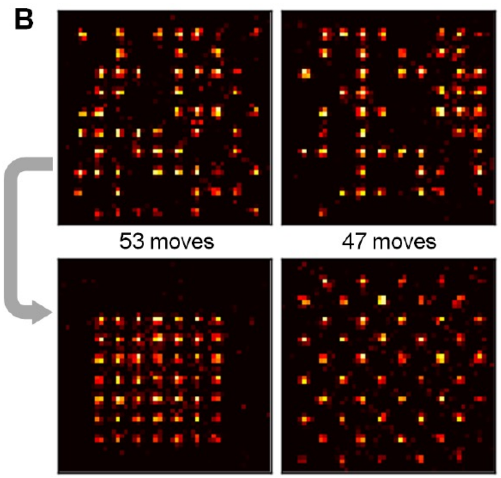
Varying geometries:



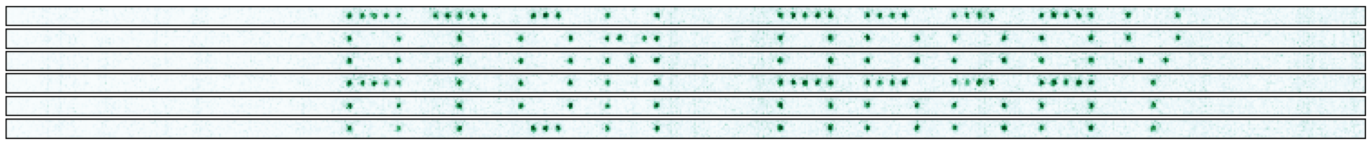
ME*, Bernien*, Keesling*, Levine* et al. Science 354, 1024 (2016)
See also: Browaeys Group, Science 354, 1021 (2016) & KAIST group
Original proposals: Weiss et al., Phys. Rev. A **70**, 040302 (2004), Vala et al., Phys. Rev. A **71**, 032324 (2005)

Atom-by-atom assembly

Browaeys, Paris



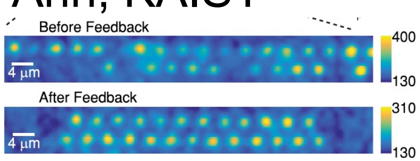
Harvard



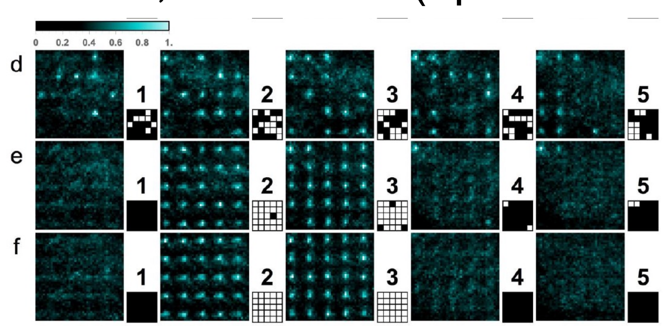
- defect-free arrays of **hundreds of atoms in 1d, 2d, and quasi-3d**
- atomic distances adjustable ~1um - 100um
- flexible geometries
- much faster rep. rate compared to traditional cold atom exp.

Limits:
- Number of traps
- Total success prob. ~ p^N, p =single-atom rearrangement prob.

Ahn, KAIST



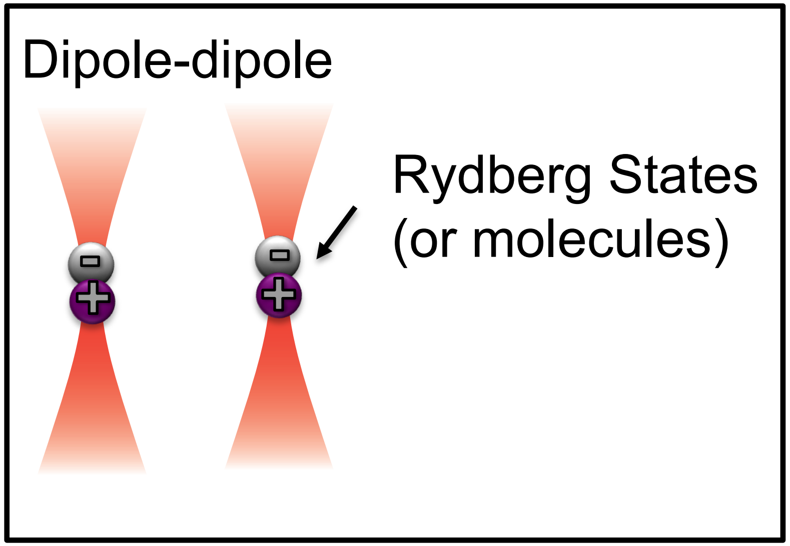
Weiss, Pennstate (optical lattice)

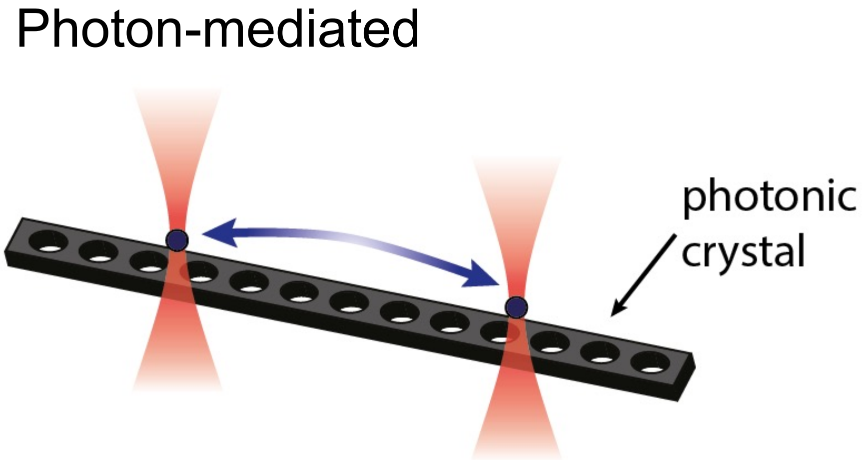


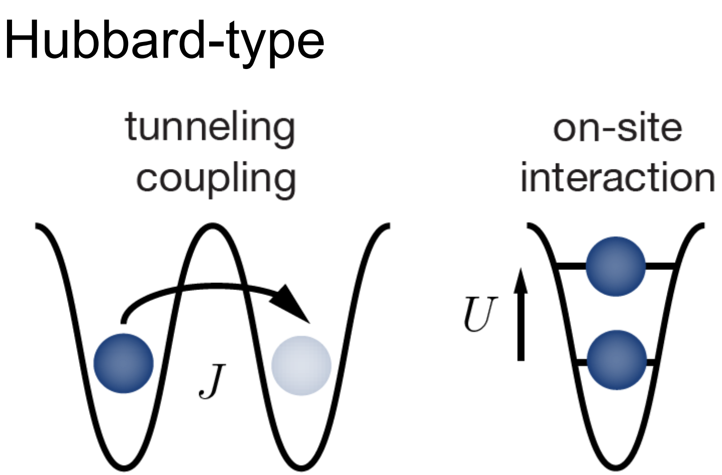
+ few others including Chicago Caltech, …

Original Proposal: *Weiss et al., Phys. Rev. A* ***70****, 040302 (2004), Vala et al., Phys. Rev. A* ***71****, 032324 (2005)*

Interaction mechanisms







Rydberg interactions and limits

Bernien, Schwartz, Keesling, Levine, Omran, Pichler, Choi, Zibrov, ME, Greiner, Vuletić, Lukin, Nature 551, 579, (2017). And others …

Rydberg atoms

electronic
ground state
size ≈ 0.2 nm

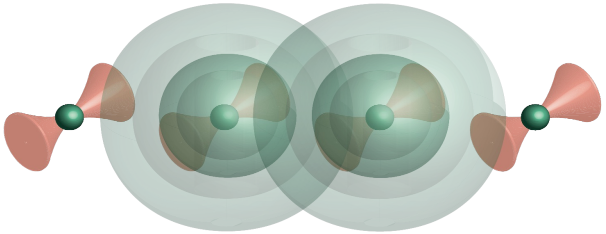
Go to high principal
quantum number
$N \gg 1$

N=70
size > 200 nm

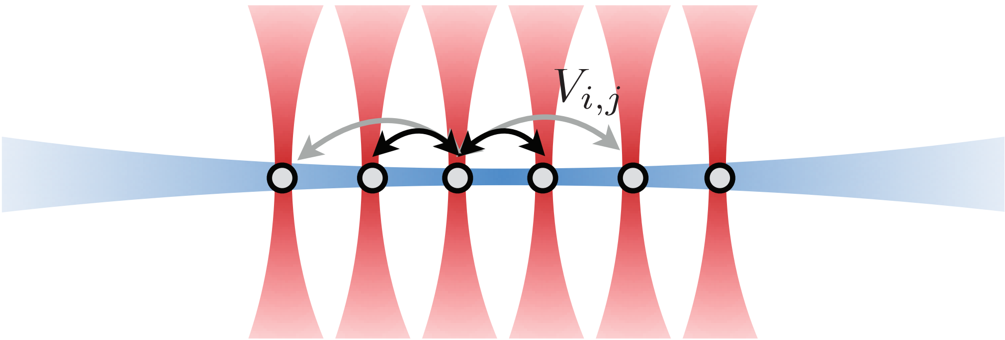
Strong van der Waals interactions:

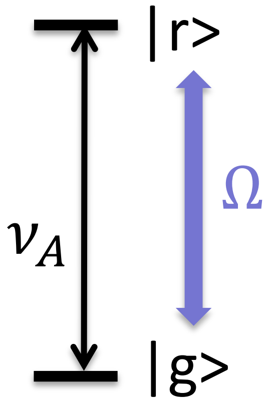
- scale as $N^{11}/\boldsymbol{R}^{\mathbf{6}}$
- for N=70: ~10GHz @ 2μm
  ~1MHz @ 10μm

Interaction suited for typical atomic distances!

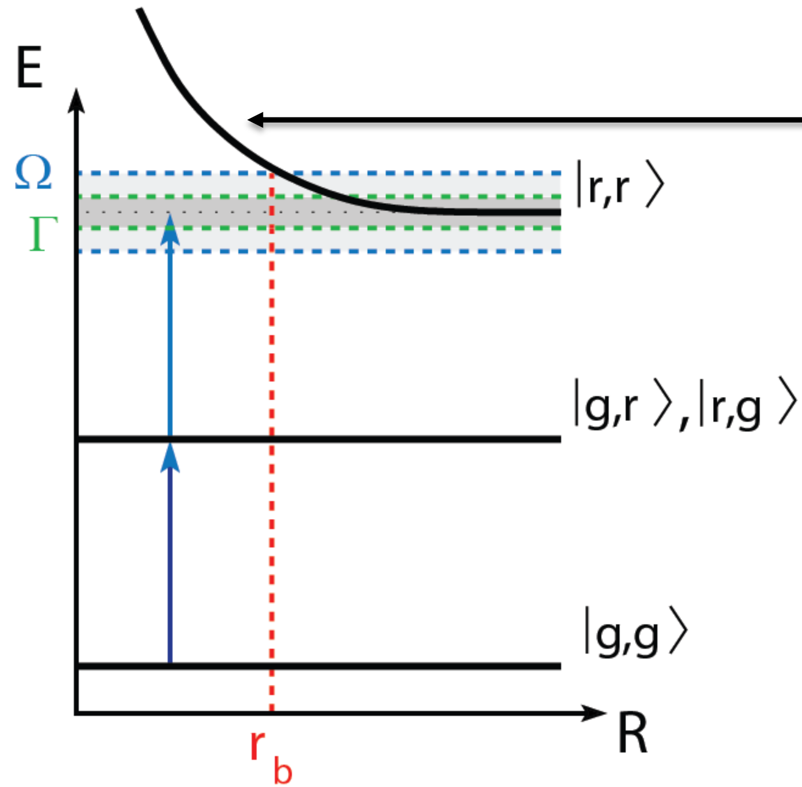


Rydberg array Hamiltonian



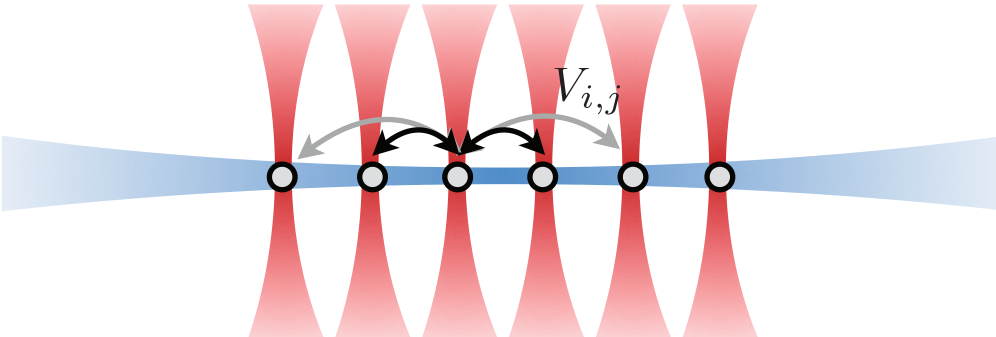


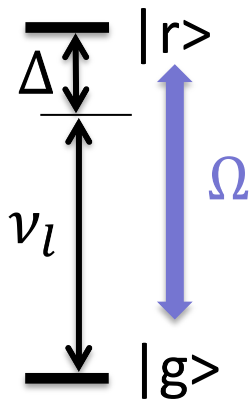
Rabi frequency
(coupling strength)
controlled by laser intensity



Interaction strength
controlled by distance

Rydberg array Hamiltonian





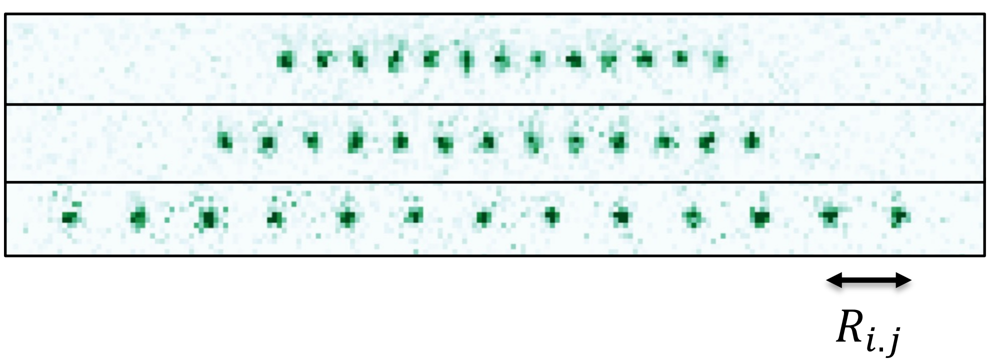
$n = |r\rangle\langle r|$

$\sigma_z = |r\rangle\langle r| - |g\rangle\langle g|$

$\sigma_x = |r\rangle\langle g| + |g\rangle\langle r|$

$$H = \underbrace{\frac{\Omega}{2}\sum_i \sigma_x^{(i)} - \frac{\Delta}{2}\sum_i \sigma_z^{(i)}}_{\text{Single-atom}}$$

Tune V_{ij} by atom spacing:

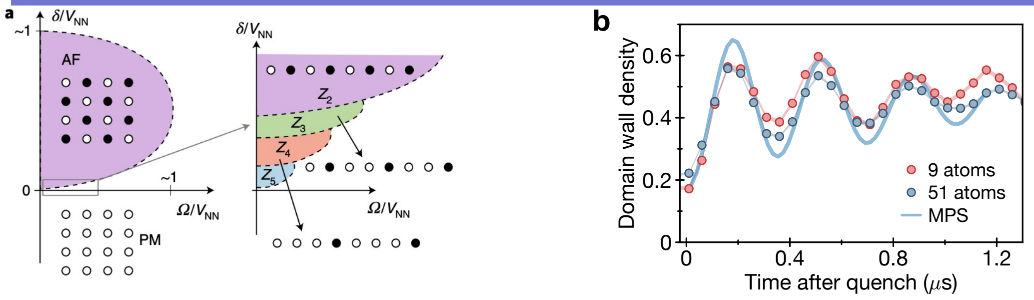


$$V_{ij} = \frac{C_6}{R_{i,j}^6}$$

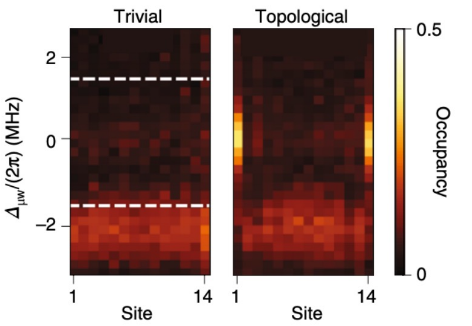
Quantum Science Applications

Quantum simulation/ Many-body physics

Remarkable experimental progress
but we have only seen the tip of the iceberg.



Topological physics



Open:

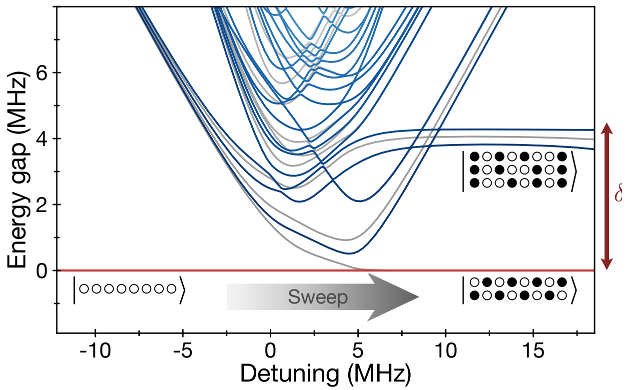
- CFTs
- Lattice gauge theories
- Confinement
- Quantum chaos
- …

Review: Browaeys, Lahaye, Nature Physics **16**, 132 (2020)
Nature 551, 579 (2017), Nature 568, 207 (2019) [ME]

Quantum computing/ Entangled state generation

Ground/Rydberg: F~0.97
Hyperfine: F~0.97

GHZ states ~ 20 qubits



PRL 121, **123603** (2019), Science **365**, 570 (2020) [ME]

Experimental challenges and limitations

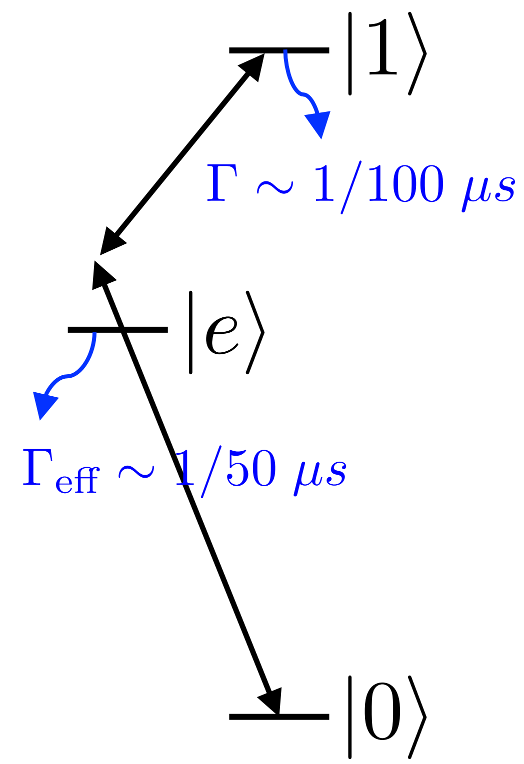
Readout error

e.g. $0.98^{100} = 0.13$

Preparation error

e.g. $|\psi_0\rangle \neq |0\rangle^{\otimes N}$

Spontaneous decay



$$|\psi(t)\rangle = e^{-iHt}|\psi_0\rangle$$

$$H = \Omega \sum_i S_i^x - \Delta \sum_i n_i + C_6 \sum_{i>j} \frac{n_i n_j}{R_{ij}^6}$$

Rabi frequency noise $\Omega \to \Omega(t)$

Detuning noise $\Delta \to \Delta(t)$

Positional disorder $R \to R + \delta R(t)$

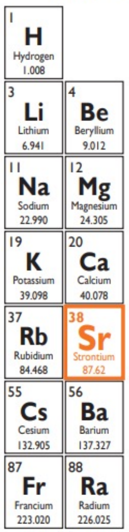
Can we potentially improve on this by using alkaline earth atoms?

Are there qualitatively different applications?

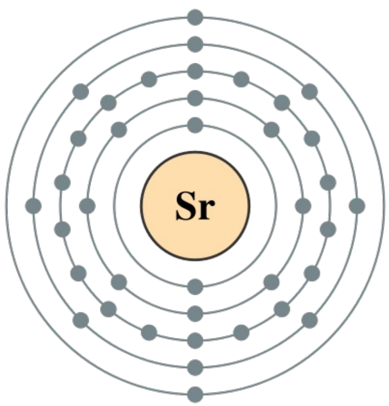
Alkaline Earth Atoms

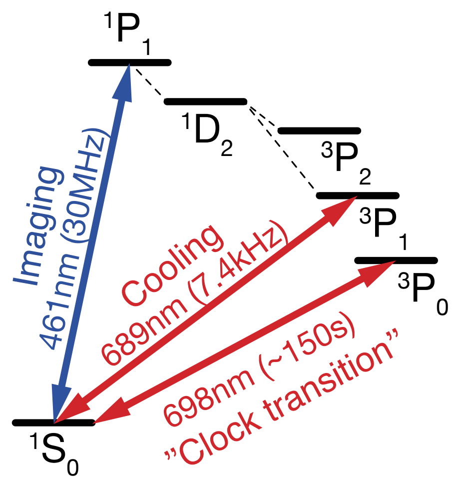
Alkaline-earth-(like) atoms: Two valence electrons

-> Narrow optical transitions & Meta-stable states (typically used in optical clocks)

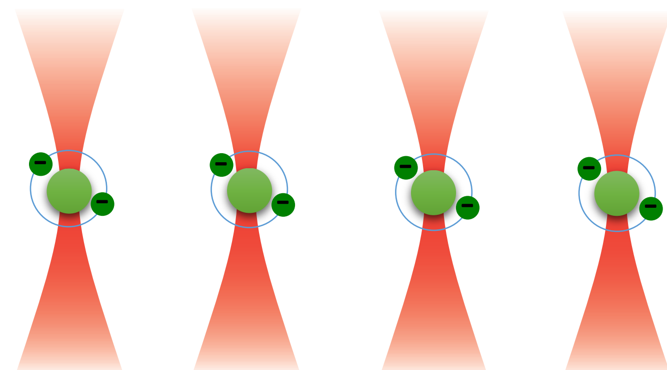


^{88}Sr



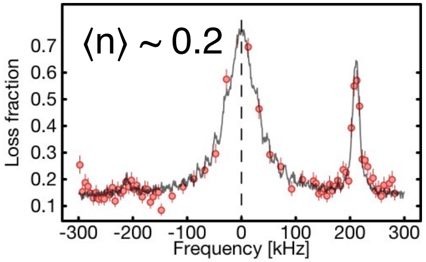


^{88}Sr atom array



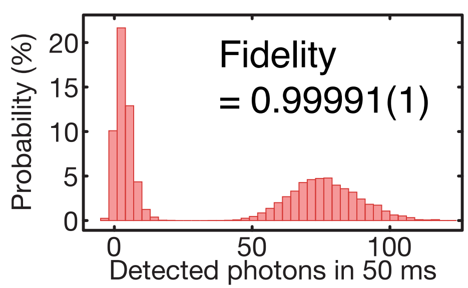
First imaging + Narrow-line cooling

Cooper *et al*, PRX (2018)



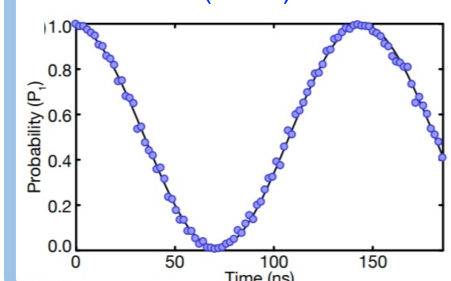
High-fidelity imaging

Covey *et al*, PRL (2019)



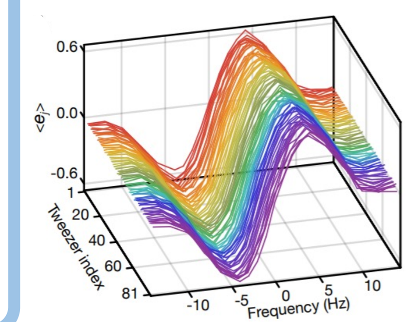
High-fidelity Rydberg

Madjarov, *et al*, Nat. Phys. (2020)



Tweezer clock

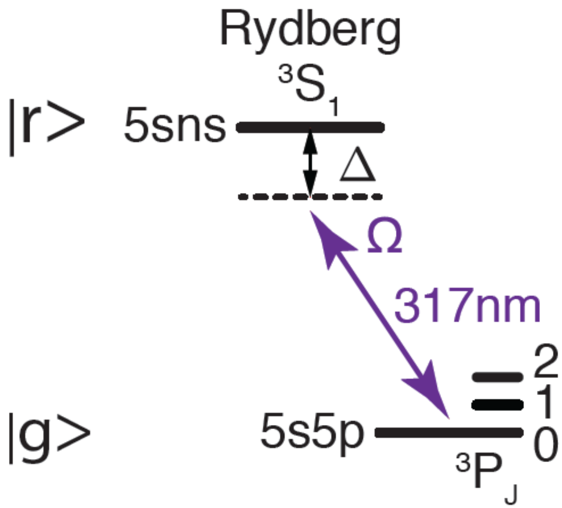
Madjarov *et al*, PRX (2019)



See previous work: Yb quantum gas microscopes (Takahashi, Kozuma)

See related AEA tweezer array work at JILA (A. Kaufman) and Princeton (J. Thompson)

AEA Rydberg scheme



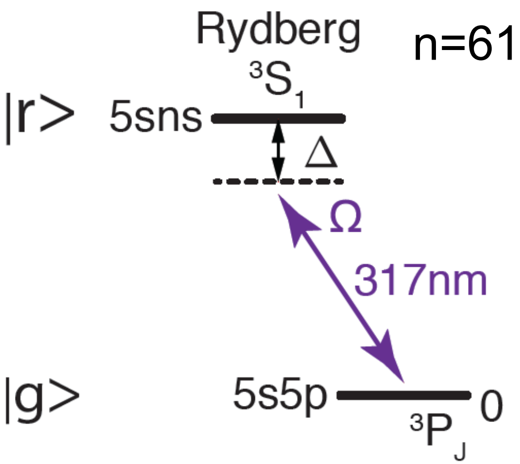
Main features:

- Large Rabi frequencies possible
- No extra decoherence from intermediate state
- Atoms are very cold ($\langle n \rangle \sim 0.2$)
- New detection schemes (auto-ionization, F>0.996)
- Rydberg states are trappable

meta-stable state ($\tau > 100s$)
= new ground state

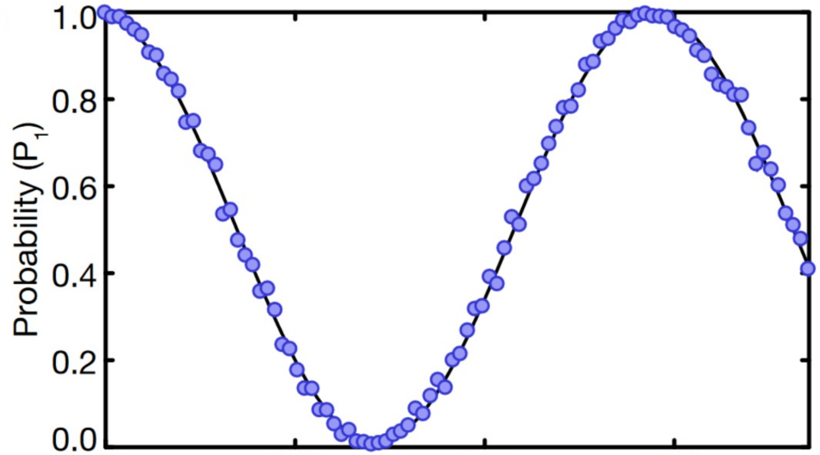
Gil et al., PRL 112, 103601 (2014), Lochead et al., PRA 87, 053409 (2013)
See Princeton (J. Thompson) for first trapping results: Wilson, Saskin, Meng, Ma, Burgers, Thompson, PRL 128 (3), 033201(2019)

AEA Rabi Oscillations

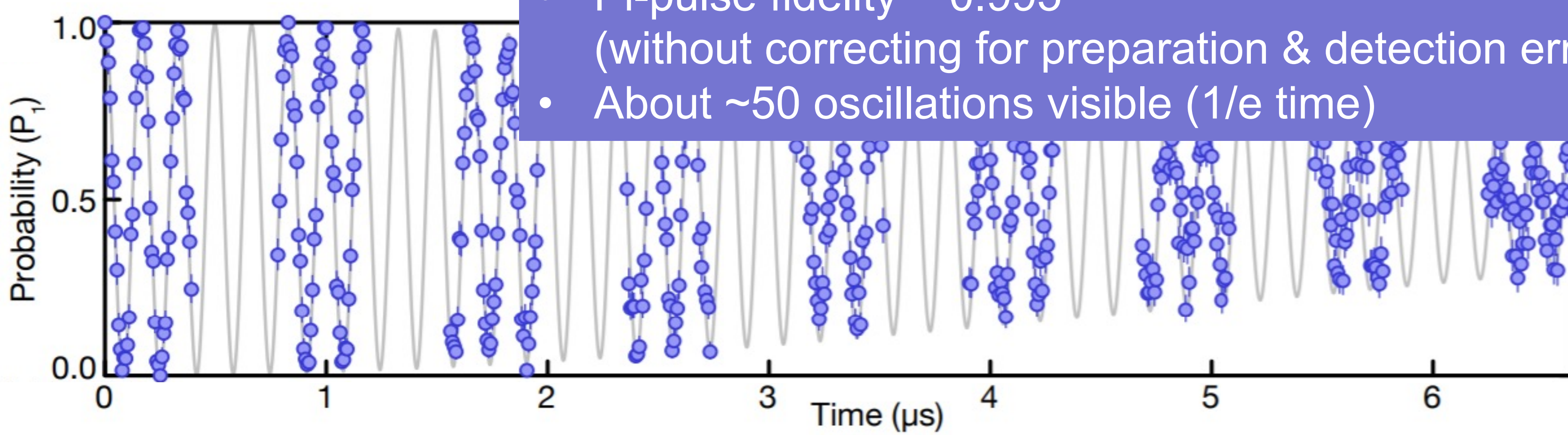


n=61

Rabi oscillations (non-interacting, large distance, $\Delta = 0$)



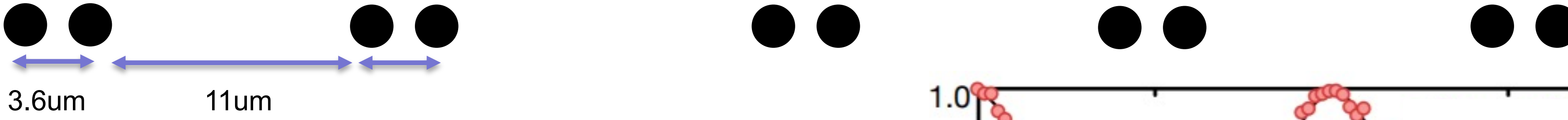
- First Rydberg Rabi oscillation with single AEAs
- Ω ~ 6 - 15 MHZ
- Pi-pulse fidelity ~ 0.995
  (without correcting for preparation & detection errors)
- About ~50 oscillations visible (1/e time)

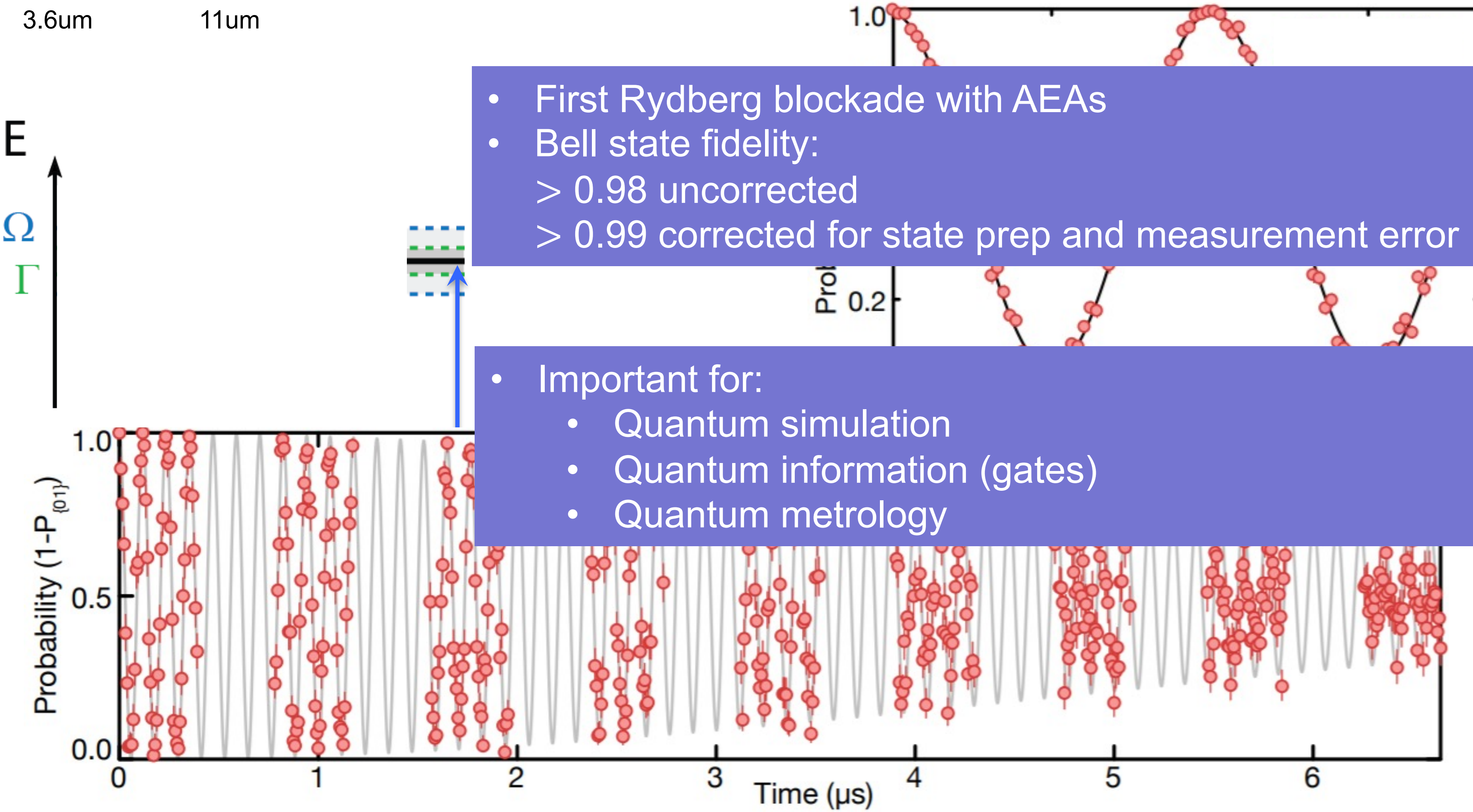


Madjarov*, Covey*, Shaw, Choi, Kale, Cooper, Pichler, Schkolnik, Williams, ME, Nature Physics **16**, 857 (2020)

AEA Blockade

Use assembly to generate pairs





- First Rydberg blockade with AEAs
- Bell state fidelity:
  > 0.98 uncorrected
  > 0.99 corrected for state prep and measurement error

- Important for:
  - Quantum simulation
  - Quantum information (gates)
  - Quantum metrology

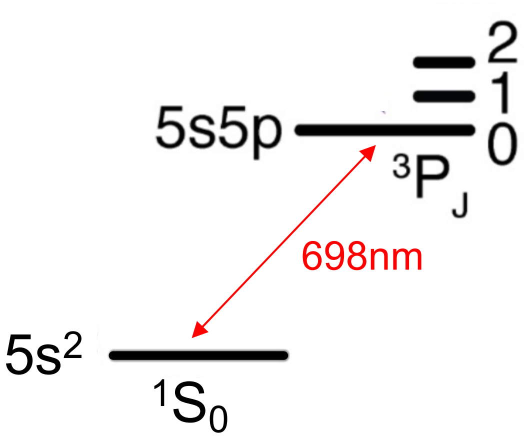
Madjarov*, Covey*, Shaw, Choi, Kale, Cooper, Pichler, Schkolnik, Williams, ME, Nature Physics **16**, 857 (2020)

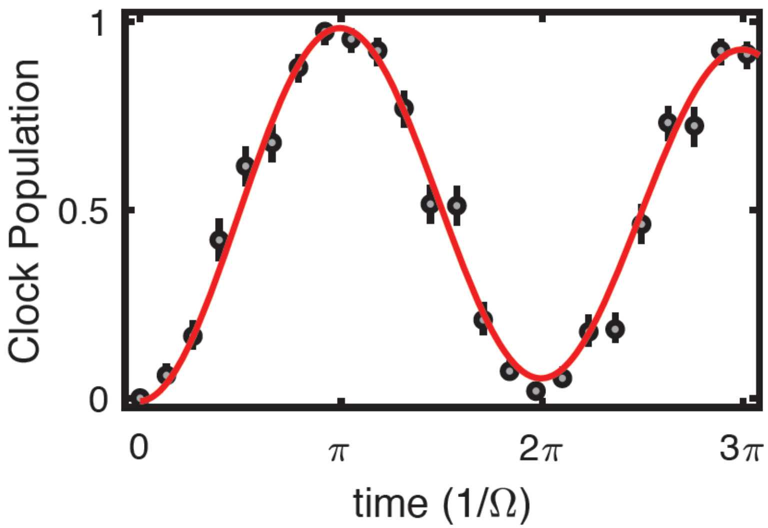
Clock transition control

Clock state control

Control of optical transition to metastable clock state

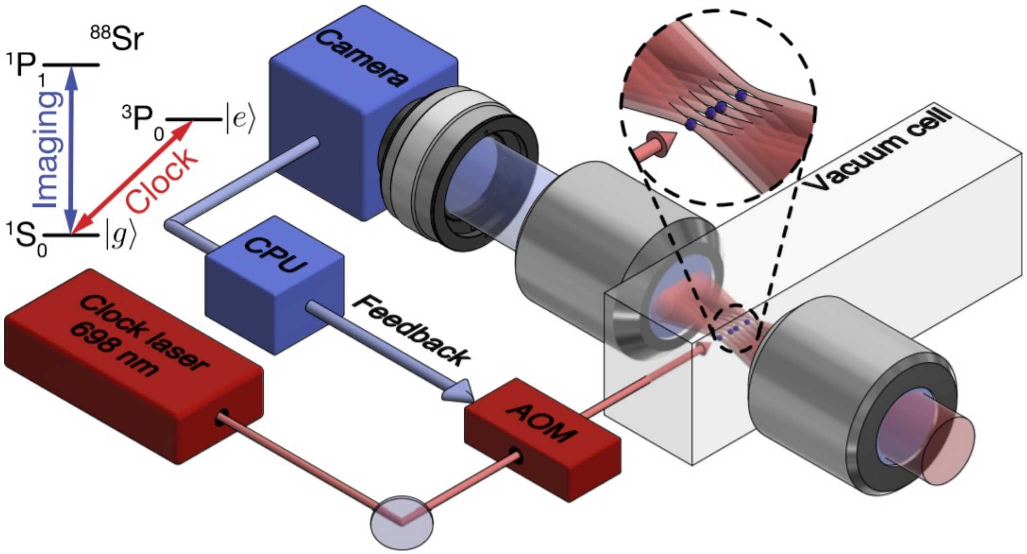
- What's the minimal linewidth we can achieve?
- Can we build an optical clock out of this?



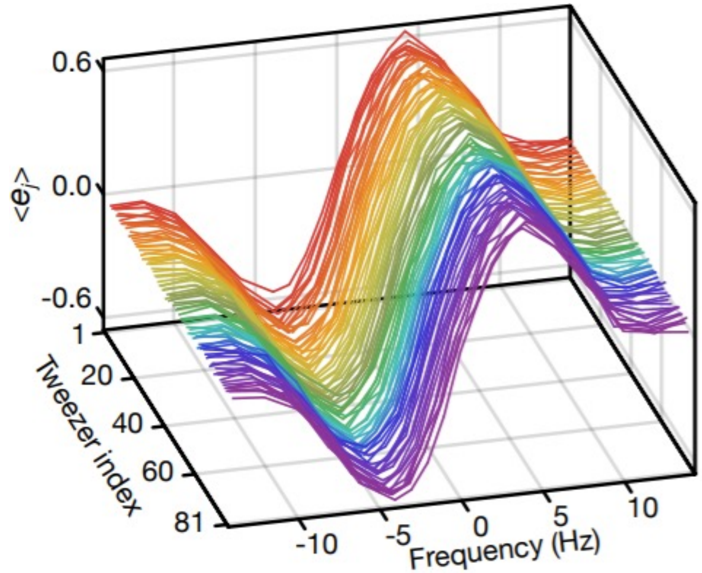


Currently achieve ~0.99 pi-fidelity

"Tweezer clock"



Site-resolved error signal:



Precision measurements

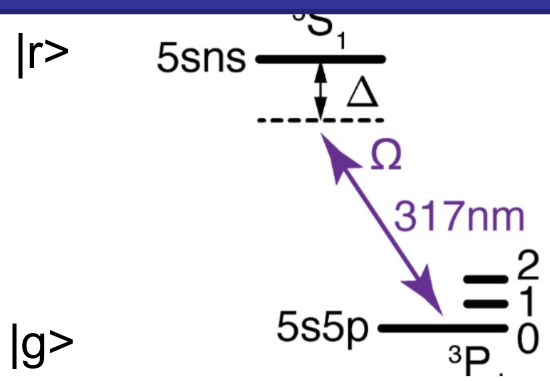
Programmable control

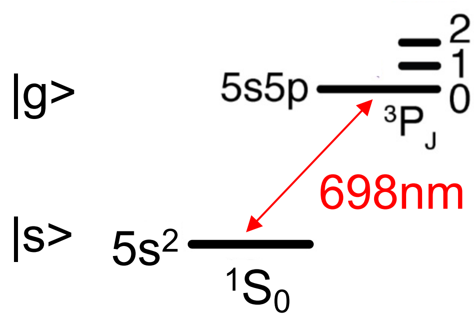
Madjarov, Cooper, Shaw, Covey, Schkolnik, Yoon, Williams, ME, PRX **9**, 041052 (2019)
See also JILA (A. Kaufman): Norcia, Young, Eckner, Oelker, Ye, Kaufman, Science **366**, 6461 (2019)
Young, Eckner, Milner, Kedar, Norcia, Oelker, Schine, Ye, Kaufman, arXiv:2004.06095 (2020)

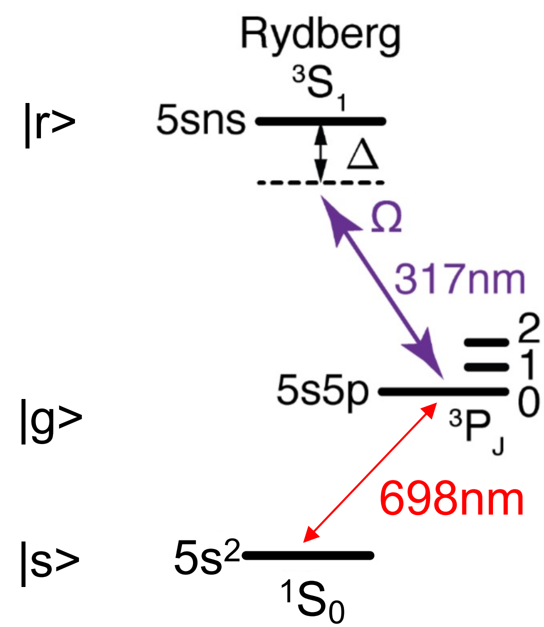
Rydberg and Clock

Some work in progress:
- Single-site rotations
- Two-qubit gates for |s> ↔ |g>
- Can we have a fully ‘programmable quantum clock’?

3) Rydberg + clock
(+ nuclear spins):







- |g> ↔ |r> qubit
- Quantum Simulation
- Quantum Optimization

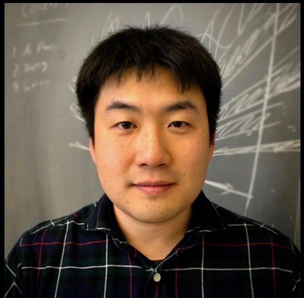
- |s> ↔ |g> transition
- Tweezer Clock

- |s> ↔ |g> qubit
- Quantum Metrology
- Quantum Computing

Gil et al., PRL 112, 103601 (2014)

How to benchmark many-body systems?

Soonwon Choi (MIT)

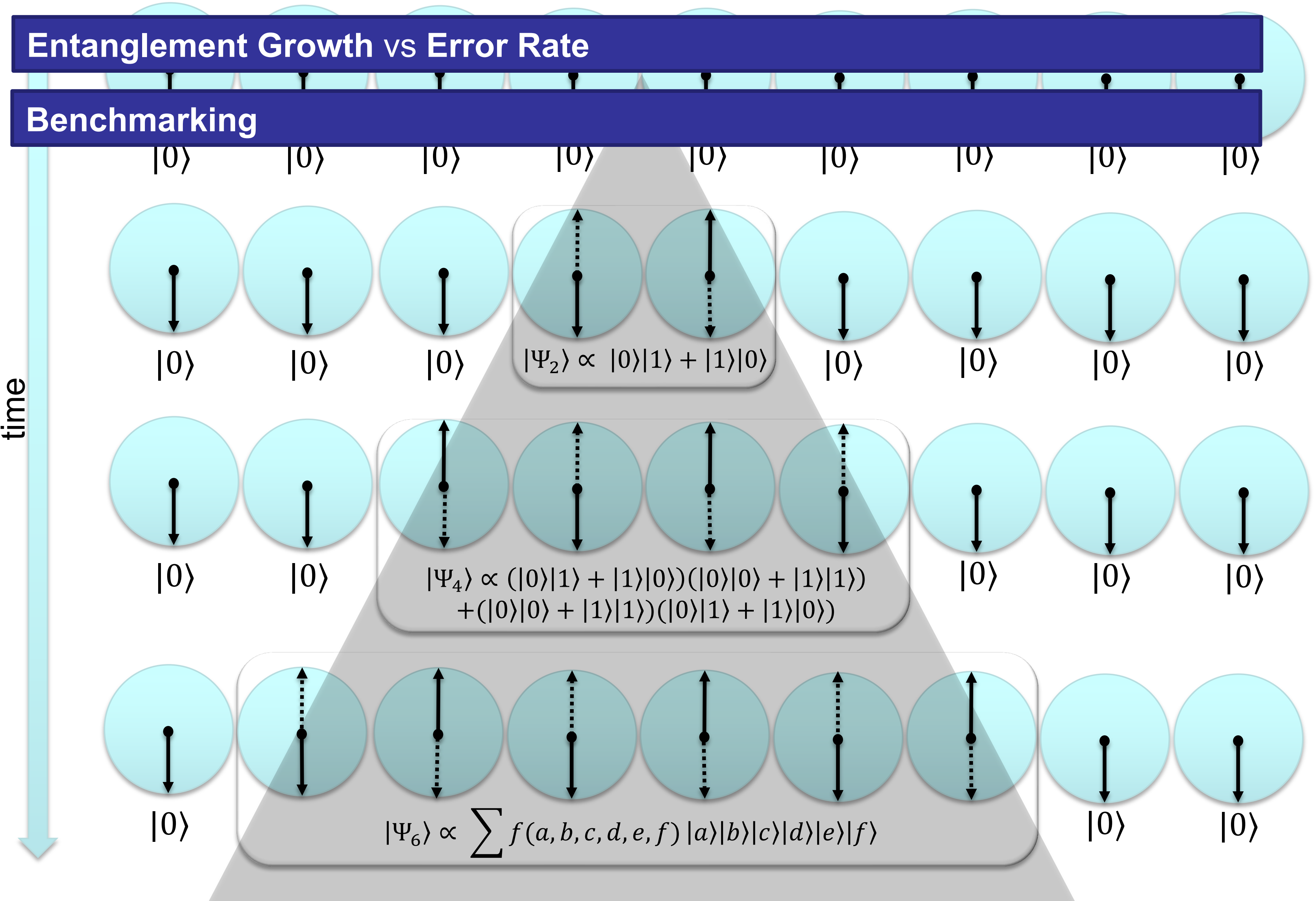


J. Choi*, A. L. Shaw*, et al. arXiv:2103.03535 (2021)
Cotler*, Mark*, Huang*, et al. arXiv:2103.03536 (2021)
Mark, et al., arXiv:2205.12211 (2022)

‘Entanglement challenge’

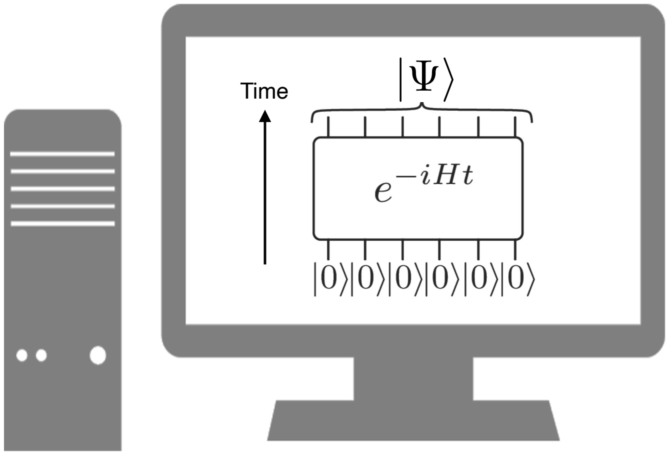
Entanglement Growth vs **Error Rate**

Benchmarking



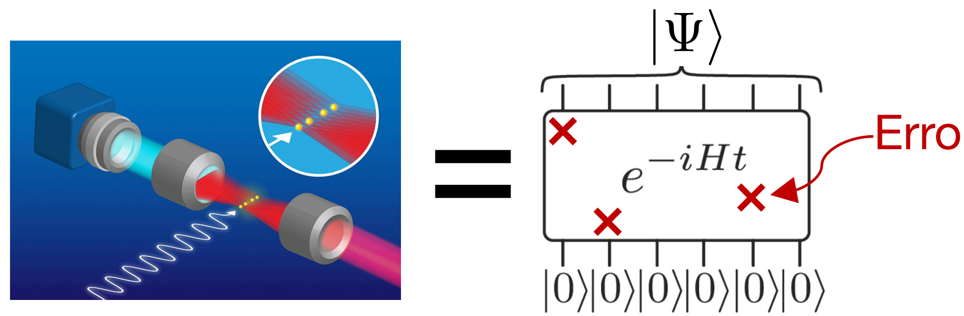
Quantum simulator benchmarking

Pure state from theory



Mixed state from experiment

$$\rho_{\text{exp}} \approx F|\Psi\rangle\langle\Psi| + (1-F)\xi_{\text{error}}$$



$$\boxed{\text{Fidelity:} \quad F = \langle\Psi|\rho_{\text{exp}}|\Psi\rangle}$$

Challenge: reconstructing ρ_{exp} is not possible for large systems

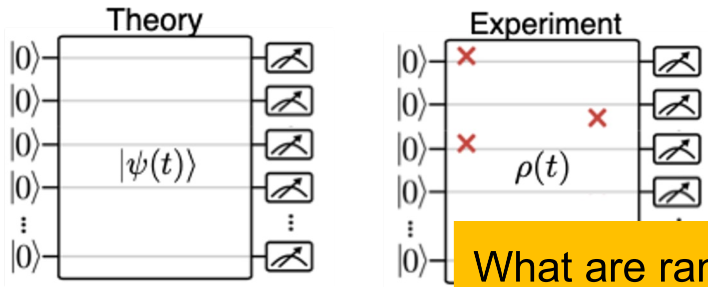
F ~ Probability of having made no error in experiment

… **utilize new insights into quantum chaos to estimate F**

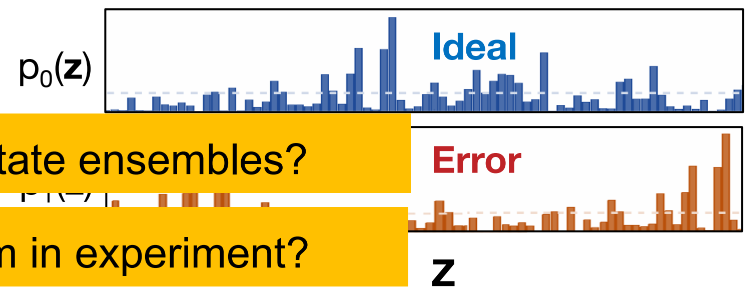
See also work by P. Zoller & R. Blatt as well as J. Eisert

J. Choi*, A. L. Shaw*, I. S. Madjarov, X. Xie, J. P. Covey, J.S. Cotler, D. K. Mark, HY Huang, A. Kale, H, Pichler, F. G.S.L. Brandão, S. Choi, ME arXiv:2103.03535 (2021)

Many-body benchmarking from randomness



Fidelity ~ Theory-Experiment bitstring correlations



What are random state ensembles?

How do we get them in experiment?

Fidelity: $F = \langle \Psi | \rho_{\mathrm{exp}} | \Psi \rangle$

Example: linear cross-entropy

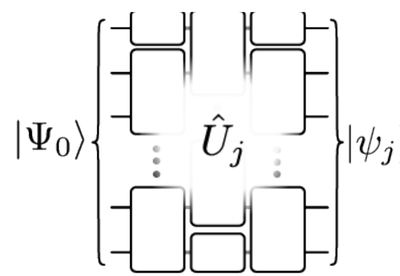
$$F_{XEB} = (D+1)\sum_z p_0(z)p_1(z) - 1$$
$$\approx F$$

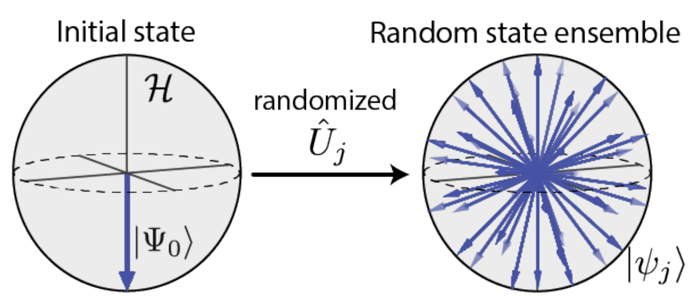
Features:

- Single basis readout
- Required samples independent of system size (in principle)

However: Requires random state ensembles

Random circuit





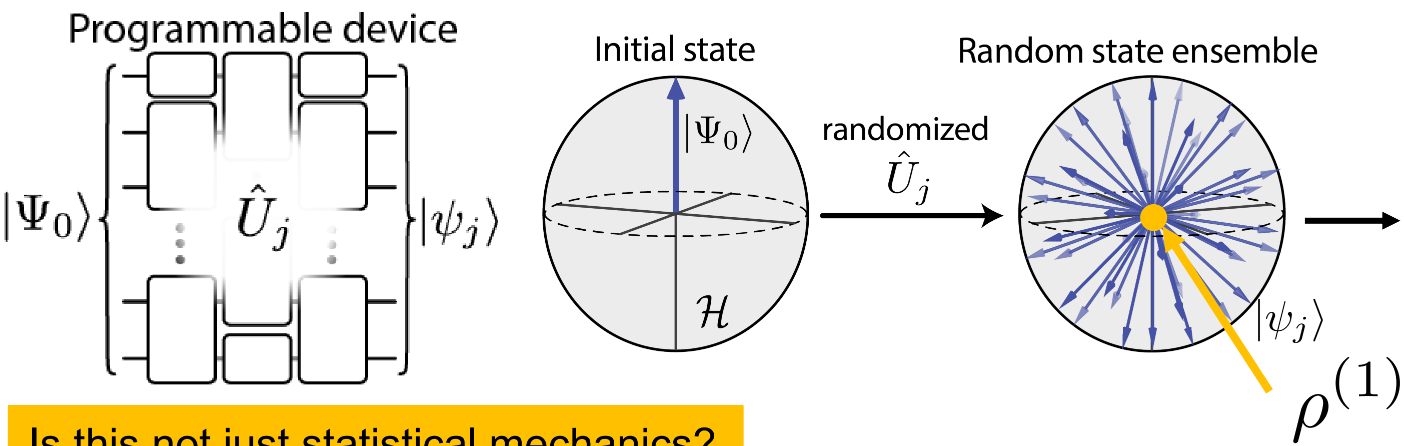
See Arute et al., Nature 574, 505–510(2019)

What are random state ensembles?

Random state ensembles

Set of states that uniformly covers the Hilbert space

$$\{|\psi_j\rangle, j = 1, ..., M\}$$



$$p_j(z) = |\langle\psi_j|z\rangle|^2$$

Is this not just statistical mechanics?

Statistical operator = 1st moment of a state ensemble

$$\rho^{(1)} = \frac{1}{M}\sum_j |\psi_j\rangle\langle\psi_j| \xrightarrow{\text{mean}} \frac{1}{M}\sum_j p_j(z) = \mathrm{Tr}[|z\rangle\langle z|\rho^{(1)}]$$

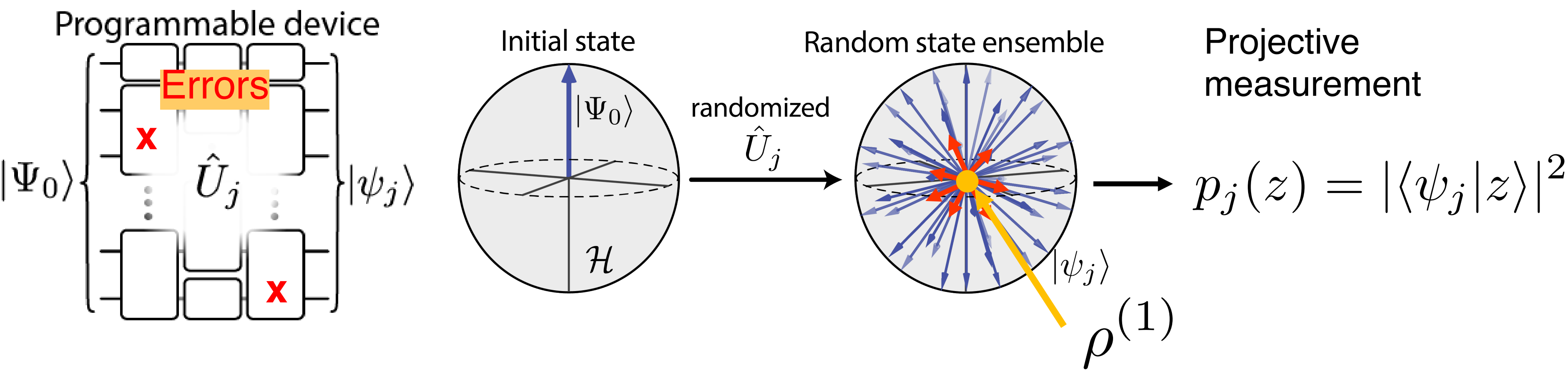
$$\rho^{(2)} = \frac{1}{M}\sum_j |\psi_j\rangle\langle\psi_j|^{\otimes 2} \xrightarrow{\text{fluctuations?}} \frac{1}{M}\sum_j p_j^2(z)$$

$$\propto (\hat{1} + \hat{S}) \longrightarrow \text{Fidelity estimation (state-overlap)}$$

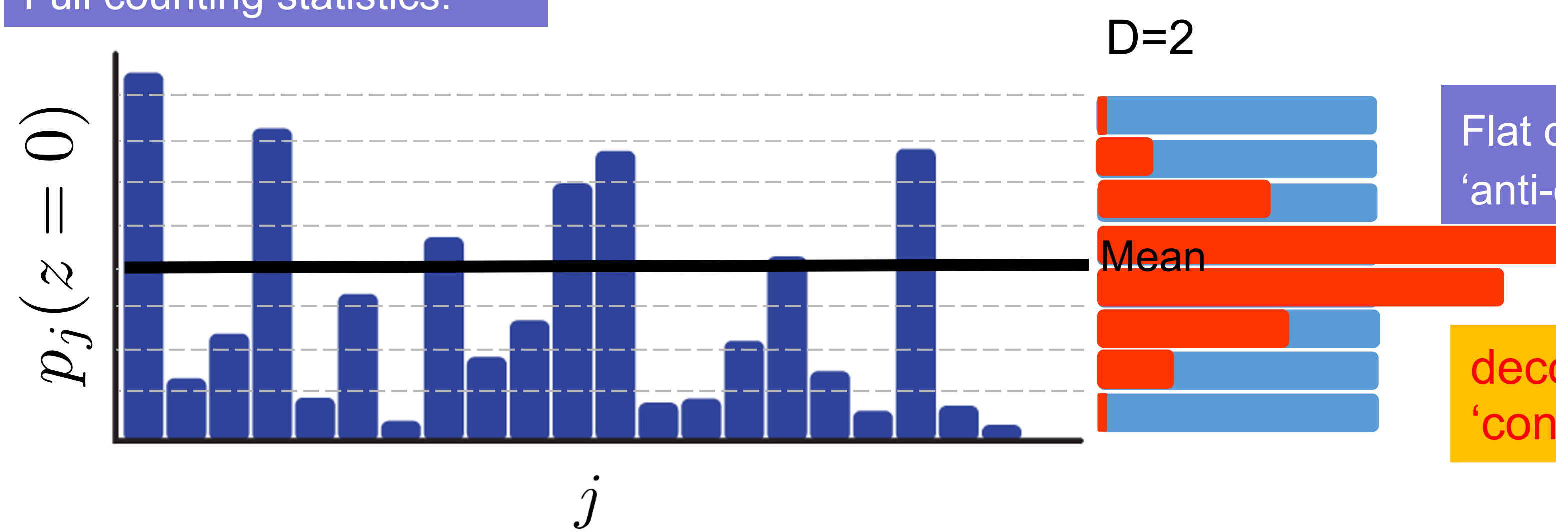
Random state ensembles

Set of states uniformly covering the Hilbert space

$$\{|\psi_j\rangle, j = 1, ..., M\}$$



Full counting statistics:



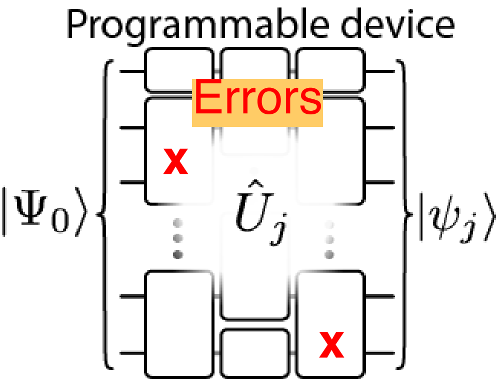
Flat distribution
'anti-concentration'

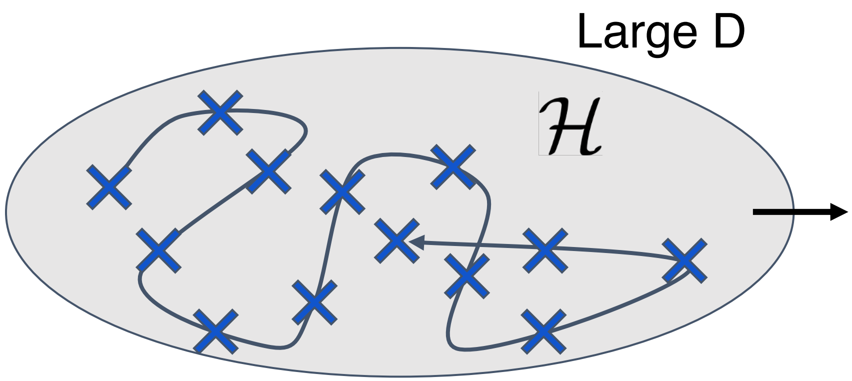
decoherence:
'concentration'

Random state ensembles

Set of states uniformly covering the Hilbert space

$$\{|\psi_j\rangle, j = 1, ..., M\}$$

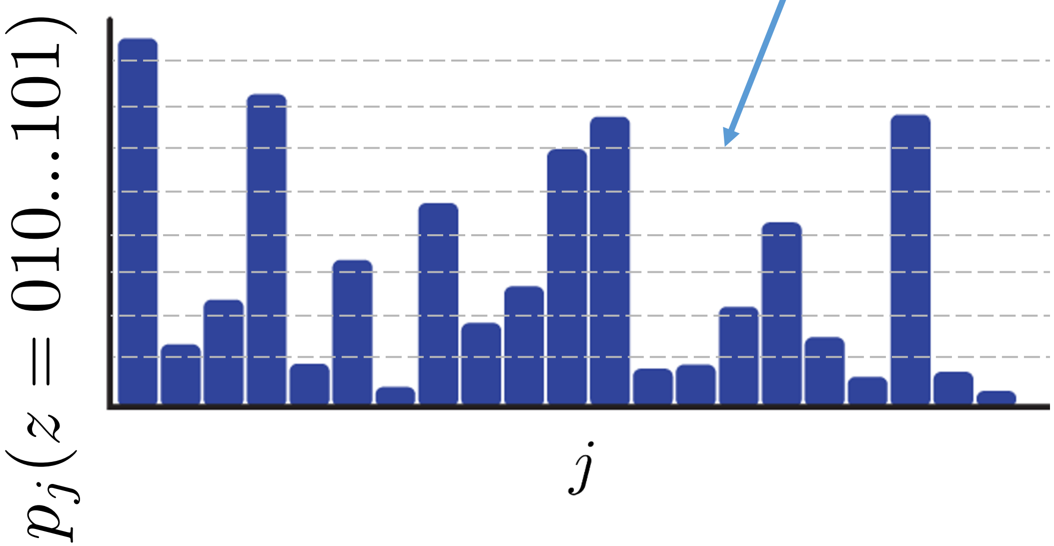




$$p_j(z) = |\langle\psi_j|z\rangle|^2$$

Full counting statistics:

"Speckle pattern"

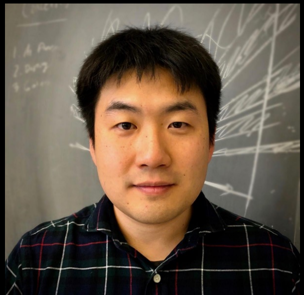


Does many-body dynamics naturally produce random state ensembles?

Option 1: temporal sampling

Option 2: ‘measurement-induced’

Soonwon Choi (MIT)

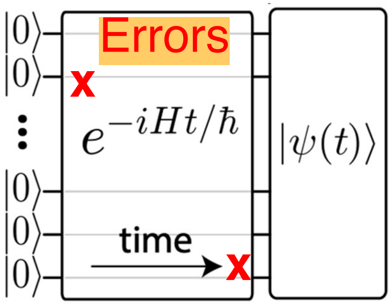


J. Choi*, A. L. Shaw*, et al. arXiv:2103.03535 (2021)
Cotler*, Mark*, Huang*, et al. arXiv:2103.03536 (2021)
Mark, et al., arXiv:2205.12211 (2022)

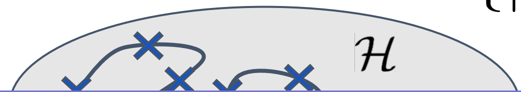
Random state ensembles from temporal sampling

What about sampling from different evolution times?

Preliminary!



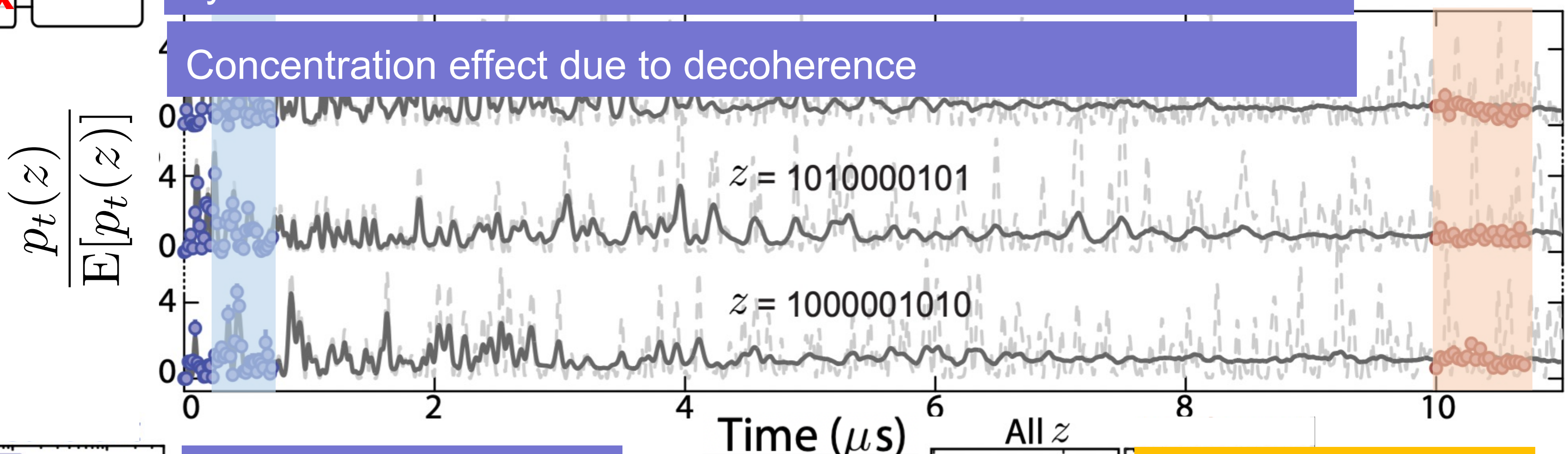
'temporal ensemble' $\{|\psi(t_j)\rangle\}$

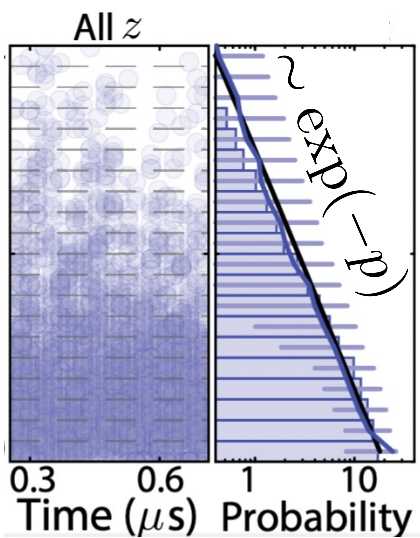


Measurement in Z-basis

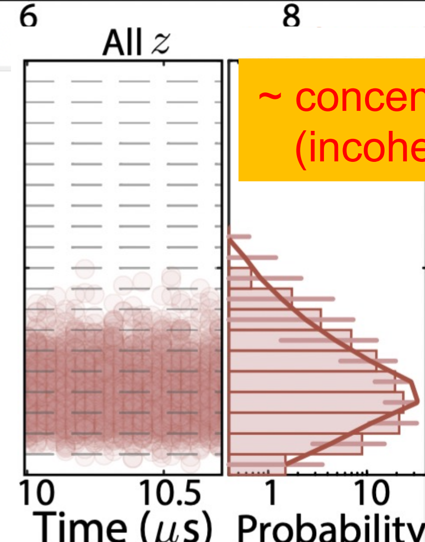
Porter-Thomas (anti-concentration) observed globally in quench dynamics

Concentration effect due to decoherence





~ Porter-Thomas anti-concentration (coherent effect)

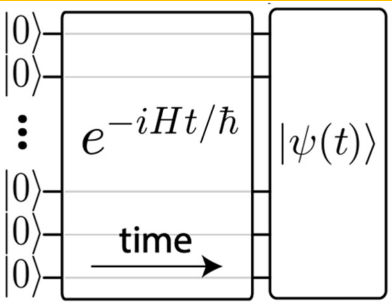


~ concentration (incoherent effect)

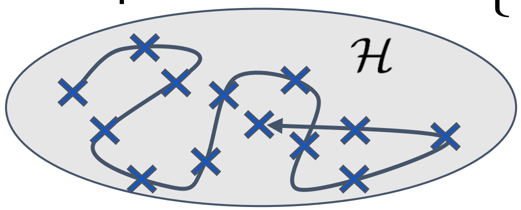
Random state ensembles from temporal sampling

What about sampling from different evolution times?

Preliminary!



'temporal ensemble' $\{|\psi(t_j)\rangle\}$



~ some signatures of random ensembles

Are these states actually randomly distributed?

$$|\psi(t)\rangle = \sum_n \sqrt{p_n} e^{-i\omega_n t} |n\rangle$$

Energy eigenstates

No! At best, phases are random

$$|\psi_{\{\phi_n\}}\rangle = \sum_n \sqrt{p_n} e^{-i\phi_n} |n\rangle$$

"Fully ergodic": Phases are random

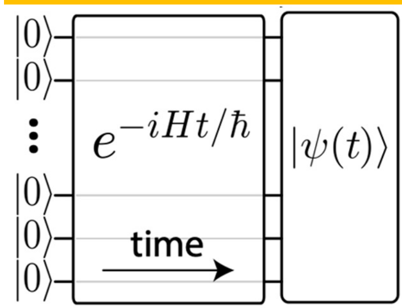
But: probabilities are fixed

Temporal sampling -> random phase ensemble

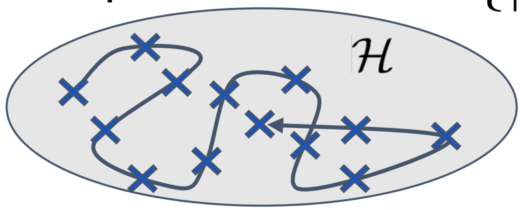
Random state ensembles from temporal sampling

What about sampling from different evolution times?

Preliminary!



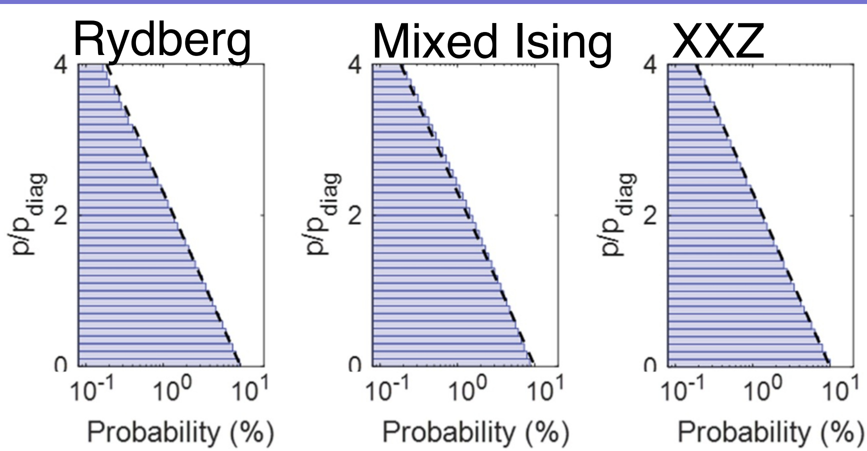
'temporal ensemble' $\{|\psi(t_j)\rangle\}$



Ergodic many-body dynamics forms
a "random phase ensemble"

$$|\psi_{\{\phi_n\}}\rangle = \sum_n \sqrt{p_n} e^{-i\phi_n} |n\rangle$$

1) Full counting statistics is Porter-Thomas/anti-concentrated (for generic measurement)



Hubbard …

→ Universal

2) 2nd moment -> Swap operator -> Benchmarking possible

$$\rho^{(2)} = \rho^{(1)} \otimes \rho^{(1)} (\hat{1} + \hat{S}) - \hat{\delta}^{(2)}$$

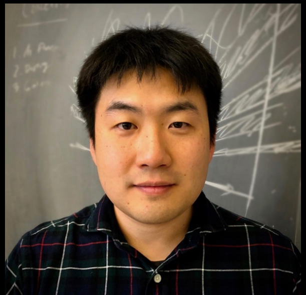
Mark, et al., arXiv:2205.12211 (2022)

Does many-body dynamics naturally produce random state ensembles?

Option 1: temporal sampling

$\boxed{\text{Option 2: ‘measurement-induced’}}$

Soonwon Choi (MIT)



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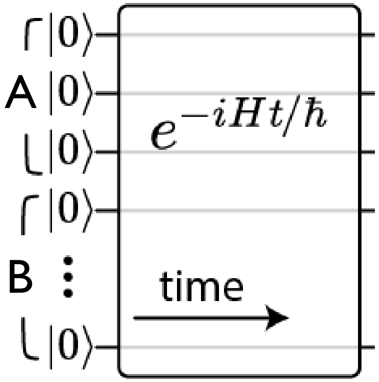
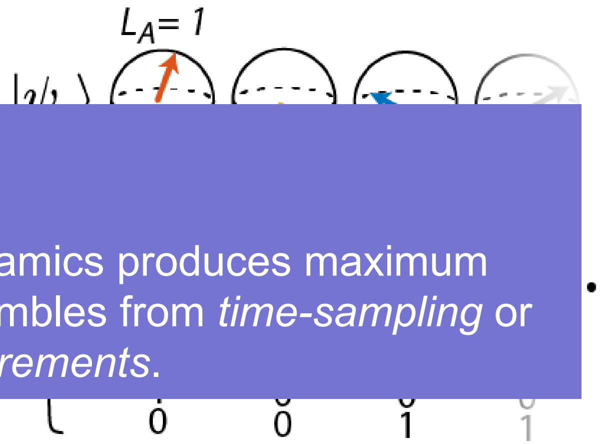
Cotler*, Mark*, Huang*, et al. arXiv:2103.03536 (2021)
Mark, et al., arXiv:2205.12211 (2022)

Measurement-induced generation

Hamiltonian dynamics at a fixed time t





Governing principle:

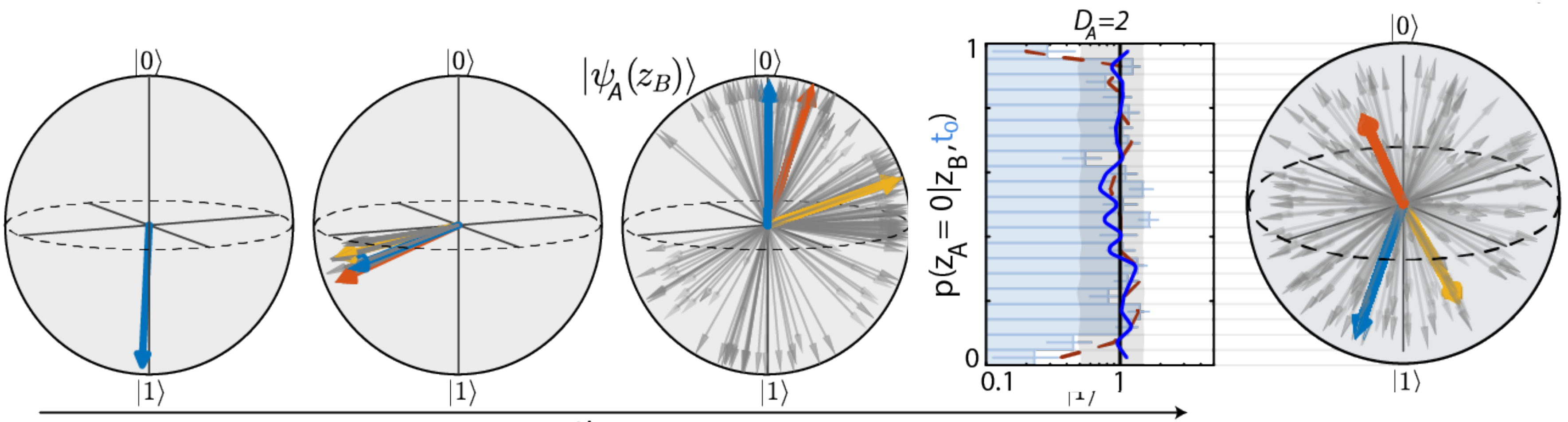
Ergodic many-body dynamics produces maximum entropy pure state ensembles from *time-sampling* or *partial projective measurements*.

Consequence 1): Universal fluctuations (beyond standard stat. mech.)

Consequence 2): Enables fidelity estimation

Thought experiment:

1) Projective measurements in B
2) For each outcome,
3) Defines an ensembl

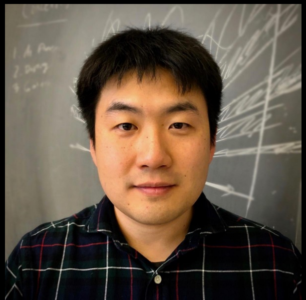


J. Choi*, A. L. Shaw*, et al. arXiv:2103.03535 (2021)
Cotler*, Mark*, Huang*, et al. arXiv:2103.03536 (2021)

→ Haar-random moments!

Random state ensembles
→ Many-body fidelity estimation

Soonwon Choi (MIT)



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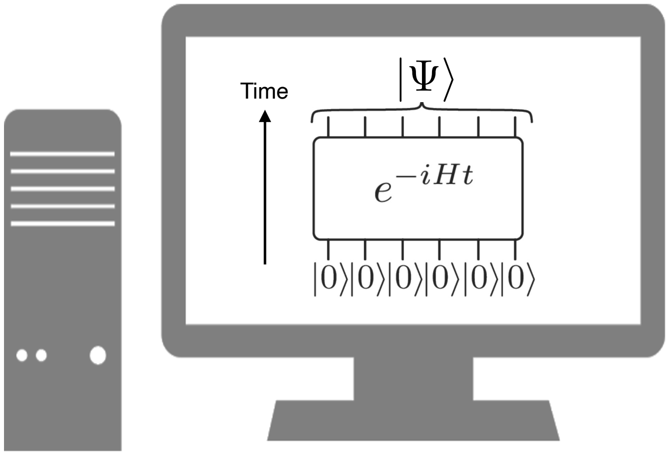
Mark, et al., arXiv:2205.12211 (2022)

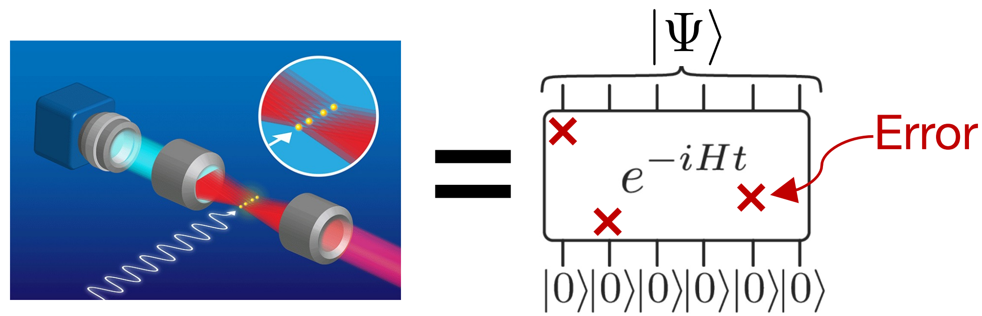
Quantum simulator benchmarking

Pure state from theory



Mixed state from experiment

$$\rho_{\text{exp}} \approx F|\Psi\rangle\langle\Psi| + (1-F)\xi_{\text{error}}$$



$$\text{Fidelity:} \quad F = \langle\Psi|\rho_{\text{exp}}|\Psi\rangle$$

Challenge: reconstructing ρ_{exp} is not possible for large systems

Solution: Estimate F utilizing properties of random state ensembles

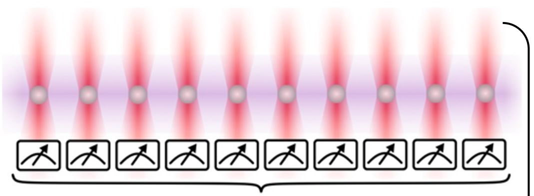
See also work by P. Zoller & R. Blatt as well as J. Eisert
J. Choi*, A. L. Shaw*, I. S. Madjarov, X. Xie, J. P. Covey, J.S. Cotler, D. K. Mark, HY Huang, A. Kale, H, Pichler, F. G.S.L. Brandão, S. Choi, ME arXiv:2103.03535 (2021)

Fidelity estimation for analog quantum simulators

Analog quantum simulator in 1d

Start with all atoms in |g> 'quench' $H = \frac{\Omega}{2}\sum_i \sigma_x^{(i)} - \frac{\Delta}{2}\sum_i \sigma_z^{(i)} + \sum_{i<j} V_{ij}\, n_i n_j$

Experiment



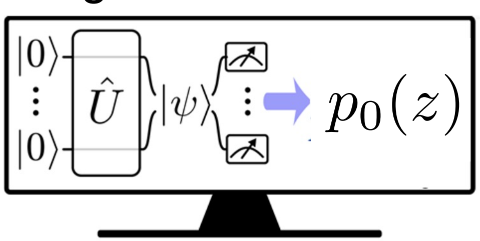
$p_1(z)$

$$F_{\text{est}} = \frac{2\sum_z w(z)p_1(z)p_0(z)}{\sum_z w(z)p_0(z)^2} - 1$$

$$\approx F = \langle\psi|\hat{\rho}_{\text{exp}}|\psi\rangle$$

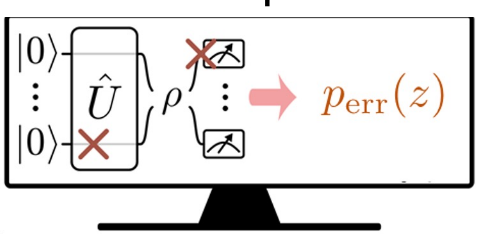
for quench dynamics with 'ergodic' Hamiltonians

Target state



F_{est}
F
Noisy model serves as a cross check

Model of experiment



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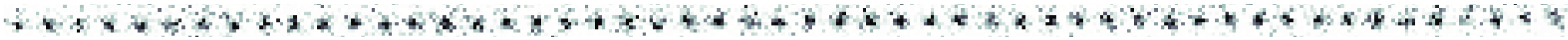
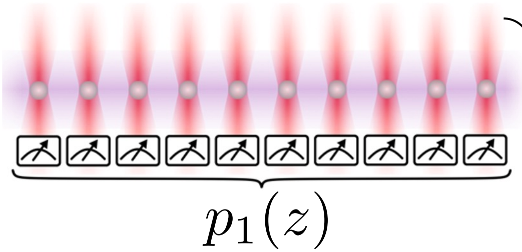
Fidelity estimation for analog quantum simulators

Analog quantum simulator in 1d



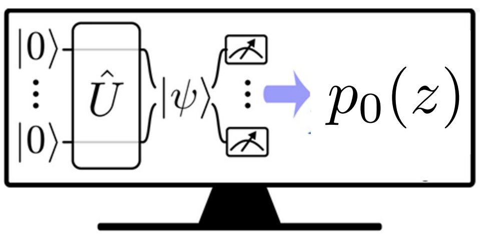
Start with all atoms in |g> —'quench'→ $H = \frac{\Omega}{2}\sum_i \sigma_x^{(i)} - \frac{\Delta}{2}\sum_i \sigma_z^{(i)} + \sum_{i<j} V_{ij}\, n_i n_j$

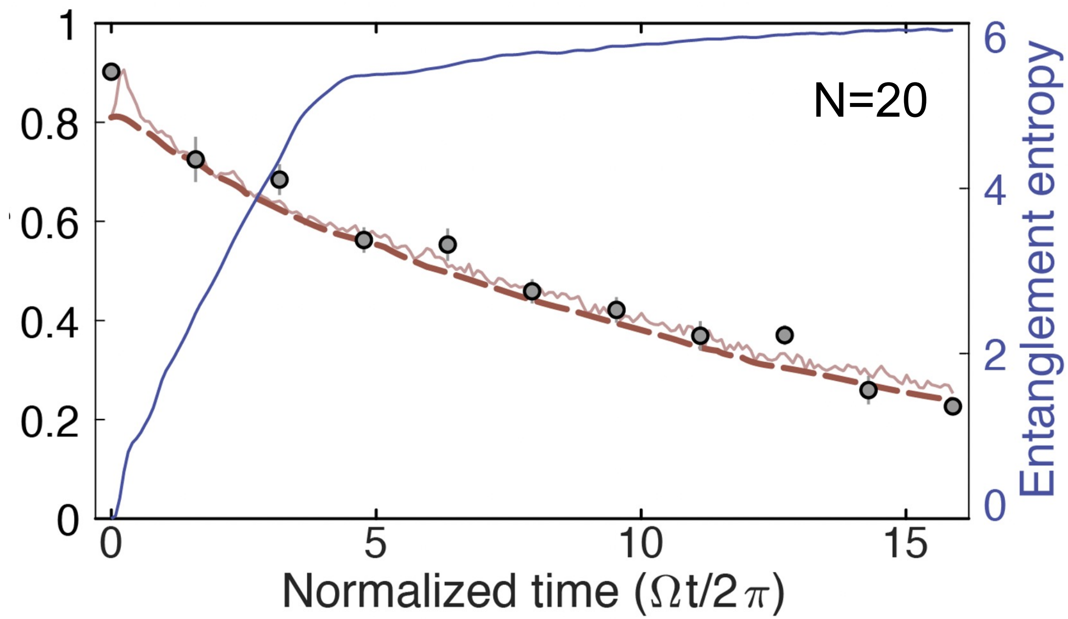
Experiment



F_{est}

Target state



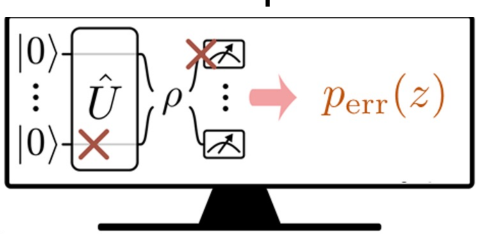


F_{est}

F

Estimator works for realistic errors

Model of experiment

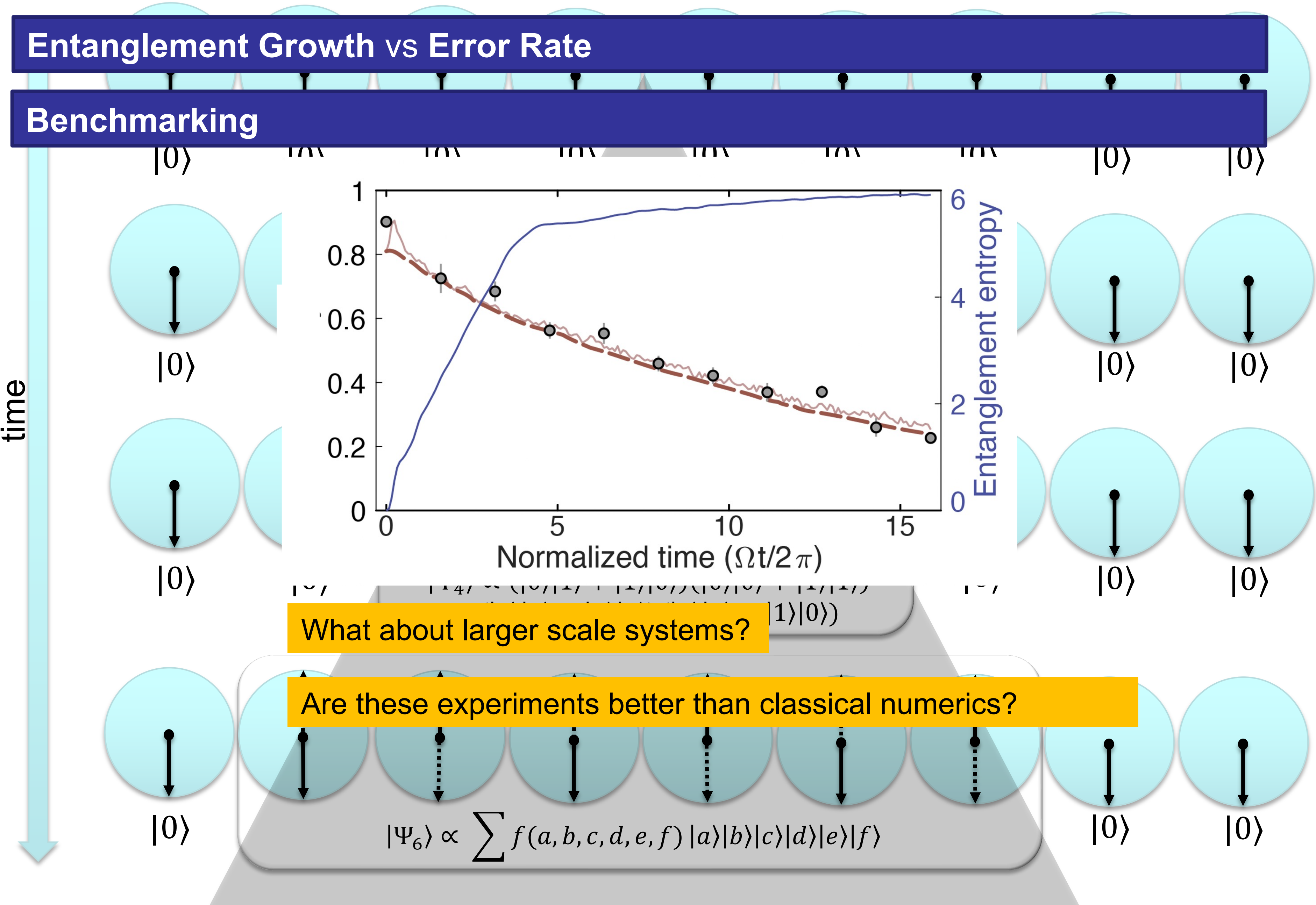


J. Choi*, A. L. Shaw*, et al. arXiv:2103.03535 (2021)
Mark, et al., arXiv:2205.12211 (2022)

‘Entanglement challenge’

Entanglement Growth vs Error Rate

Benchmarking

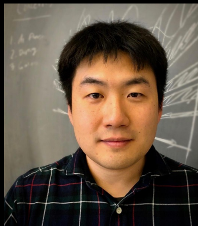


What about larger scale systems?

Are these experiments better than classical numerics?

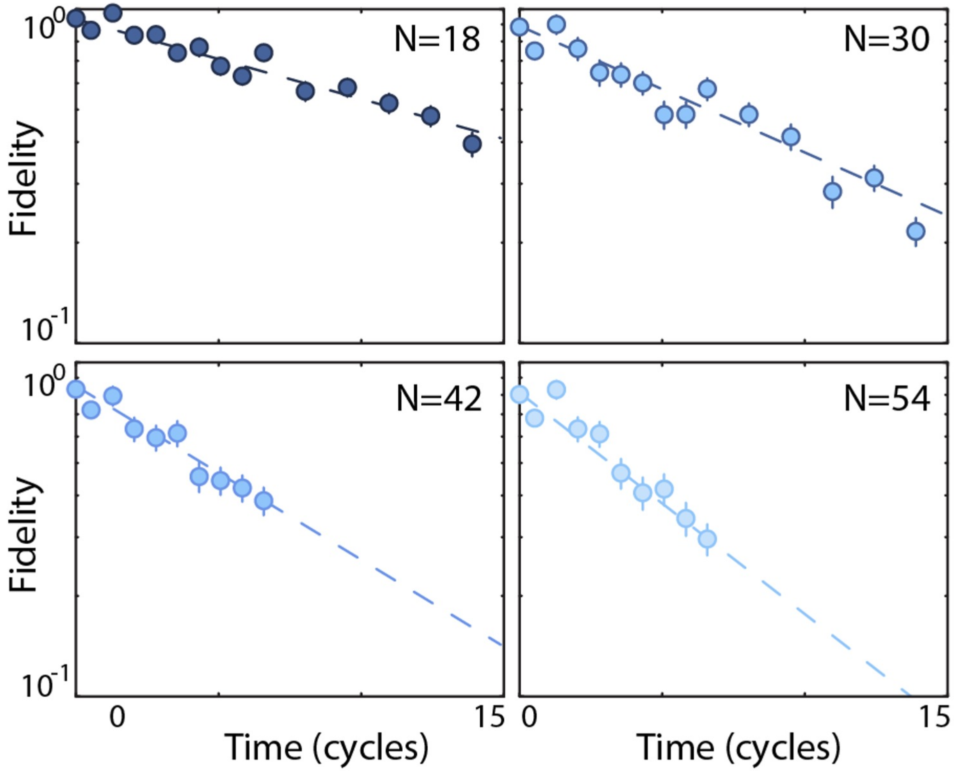
Large-scale benchmarking in 1d

Preliminary!
Numbers not final



Large-scale benchmarking

Preliminary!



$$F \approx p_0^N \exp(-\gamma(N)t)$$

SPAM errors ($p_0 \sim 0.996$)

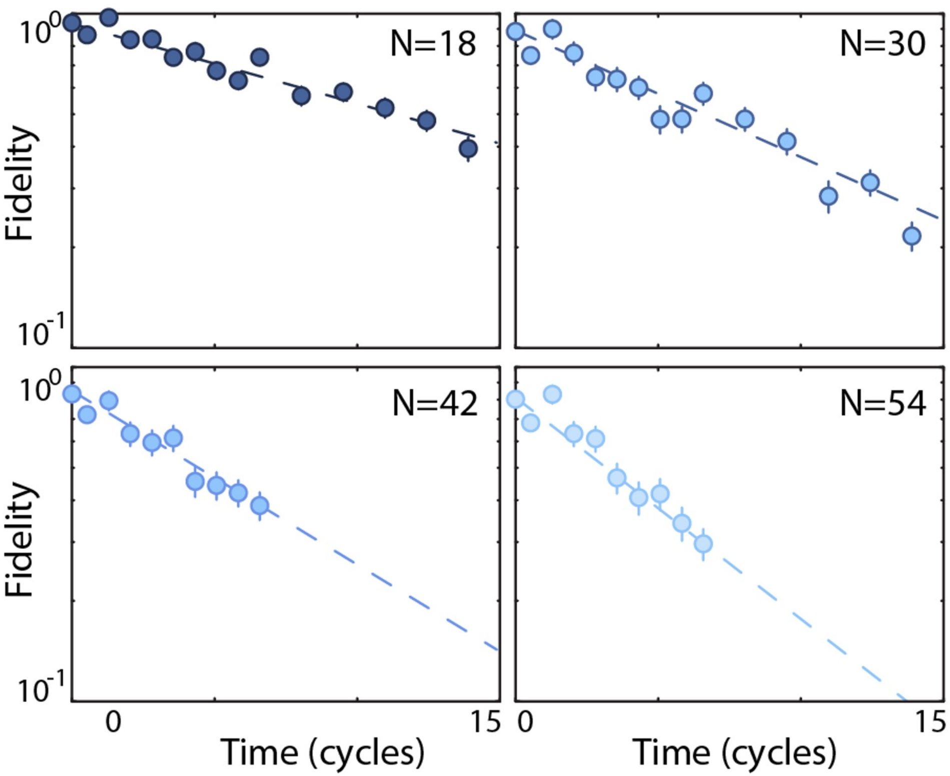
Many-body error-rate

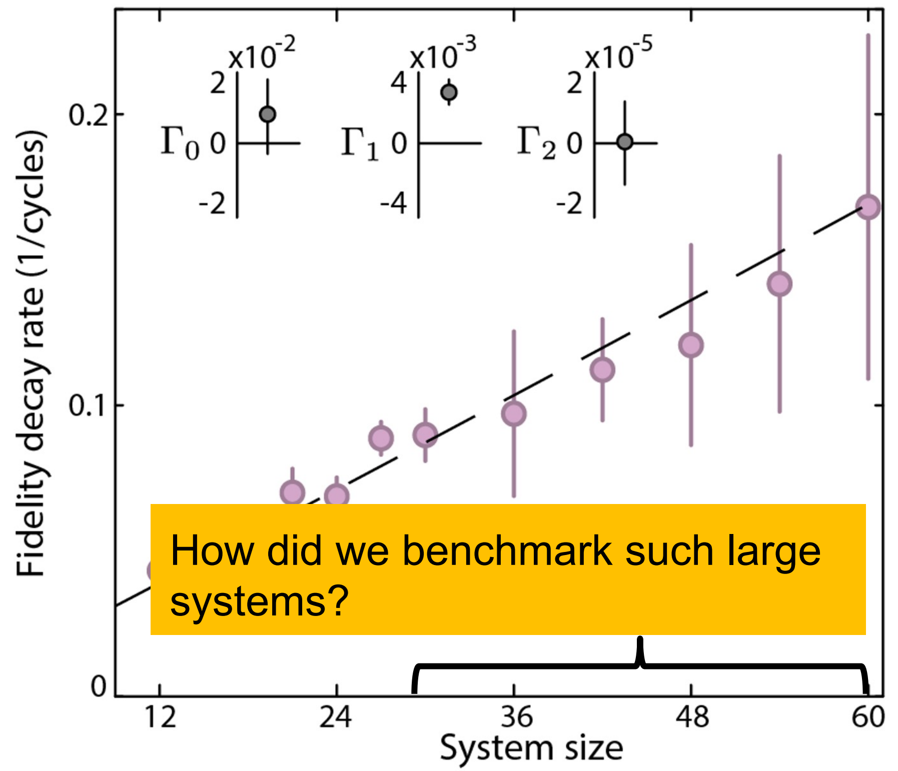
$$\gamma(N) \approx \gamma_0 + \gamma_1 N + \cancel{\gamma_2 N^2}$$

–> linear, so far

Large-scale benchmarking

Preliminary!





How did we benchmark such large systems?

$$F \approx p_0^N \exp(-\gamma(N)t)$$

SPAM errors ($p_0 \sim 0.996$)

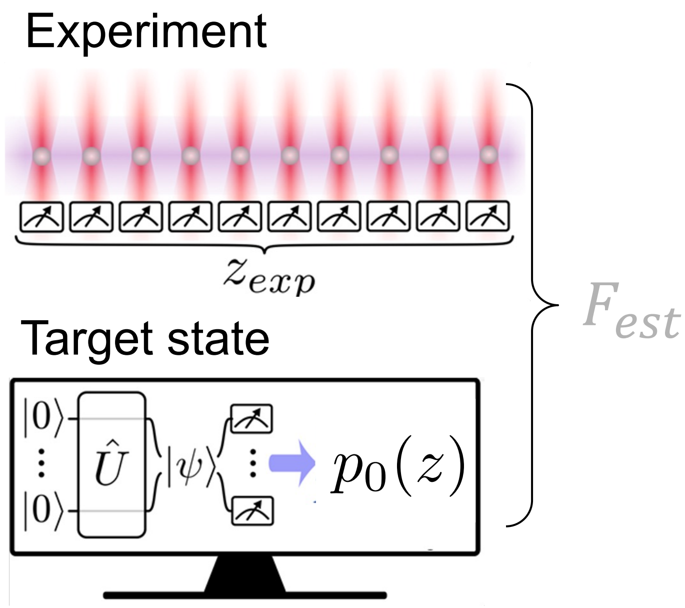
Many-body error-rate

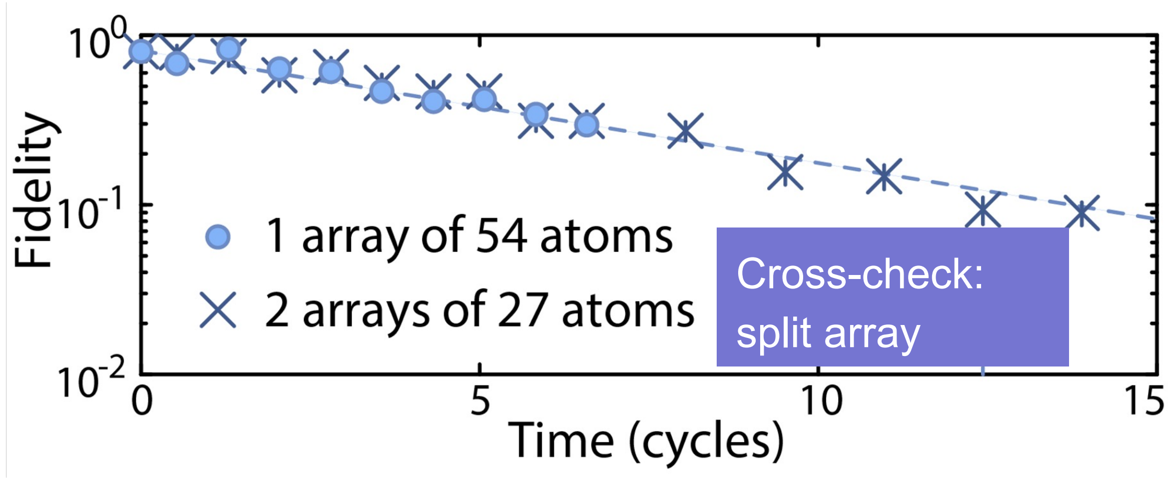
$$\gamma(N) \approx \gamma_0 + \gamma_1 N + \cancel{\gamma_2 N^2}$$

–> linear, so far

MPS-based benchmarking

Preliminary!



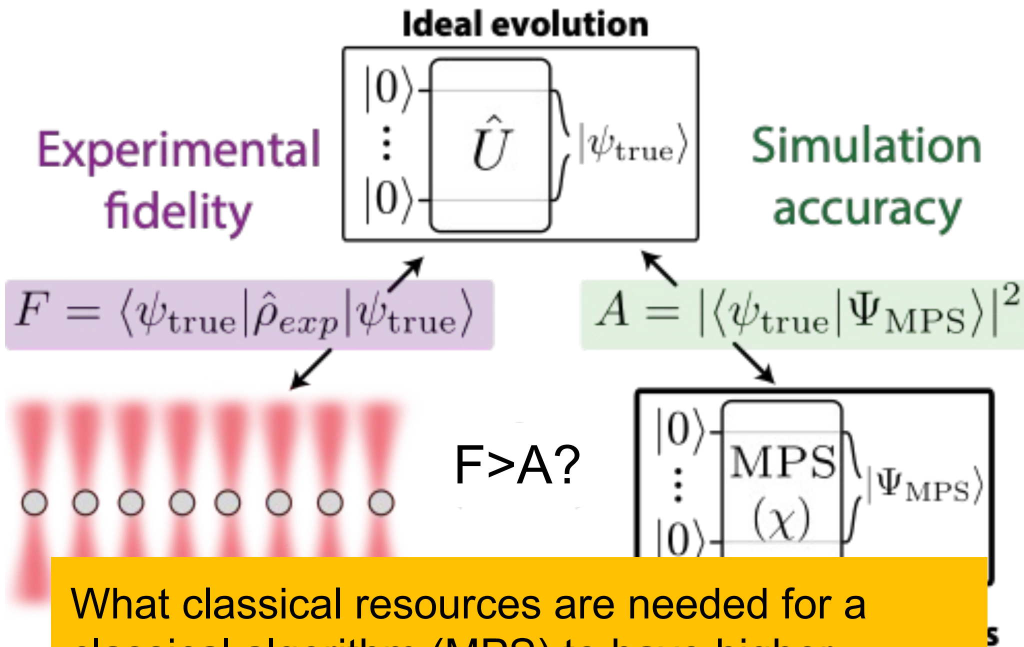


For $N > 35$ at late time
→ no exact algorithm

Use matrix product states (MPS, TEBD):
Exact up to some max time (even for large N)

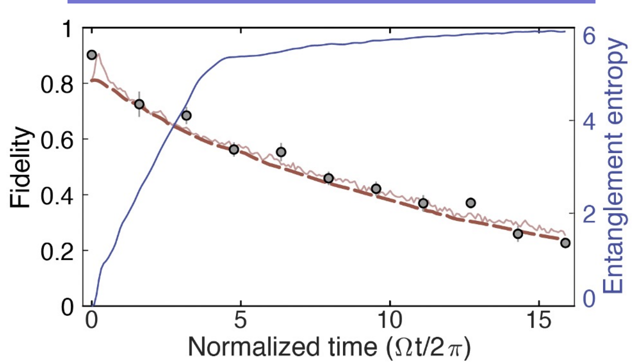
Quantum vs Classical

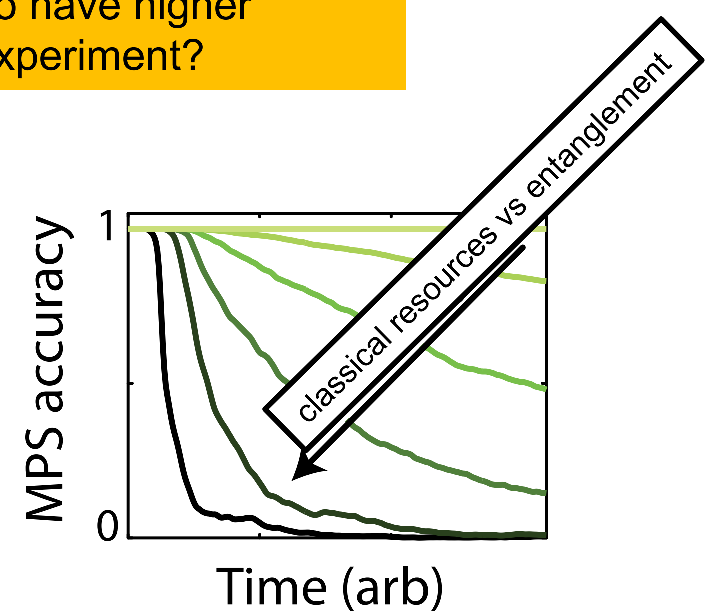
Preliminary!



What classical resources are needed for a classical algorithm (MPS) to have higher fidelity/accuracy than the experiment?

Example: F~5% for N=60 for max entanglement entropy state

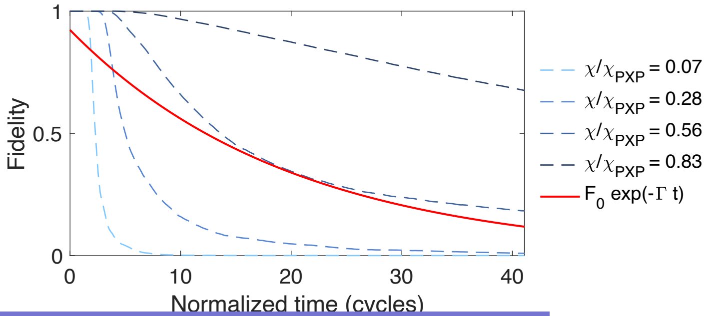




Classical resource analysis

Preliminary!

Classical resources needed for
$|\langle\psi_{true}|\psi_{MPS}(\chi)\rangle|^2 > |\langle\psi_{true}|\,\hat{\rho}_{exp}\,|\psi_{true}\rangle|^2$



- Significant classical resources needed
- Classical resources keep growing with system size

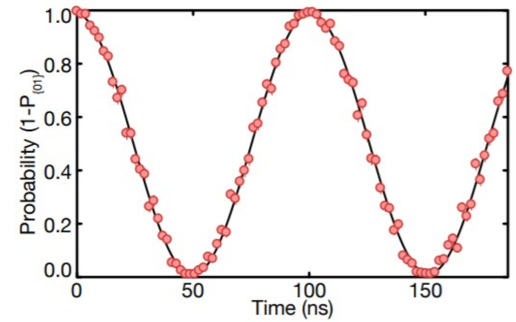
Outlook: 2d

Time ~ 3 weeks

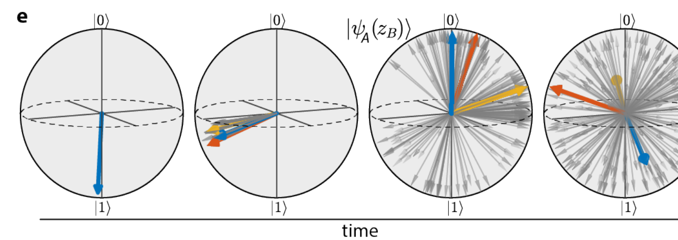
Summary

Summary

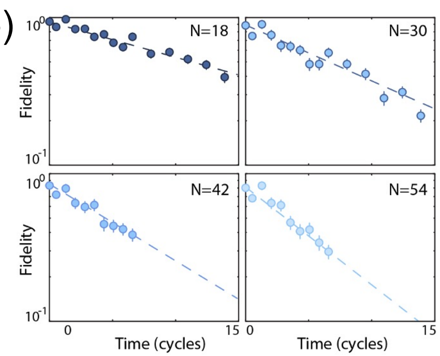
- Atom-by-atom assembly + Rydberg with alkali atoms
    - ME*, Bernien*, Keesling*, Levine* et al. Science 354, 1024 (2016)
    - …

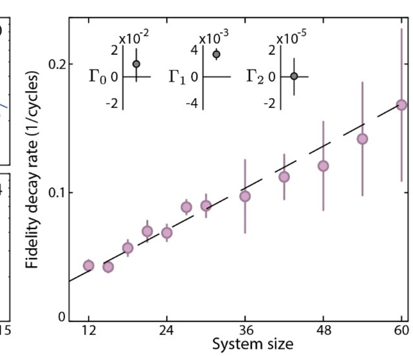


- Alkaline-earth tweezer arrays:
    - Arrays of AEAs and narrow line cooling
        - Cooper *et al.* PRX **8**, 041055 (2018)
    - High-fidelity imaging (and long lifetime)
        - Covey *et al.* PRL **122**, 173201 (2019)
    - High-fidelity Rydberg control, detection and entanglement
        - Madjarov*, Covey* *et al. Nature Physics 16, 857 (2020)*
    - 'Tweezer clock'
        - Madjarov *et al.* PRX **9**, 041052 (2019)



- Random states and benchmarking
    - Projected ensembles and benchmarking (up to N=25)
        - Choi*, Shaw*, et al., [arXiv:2103.03535 (2021)]()
    - Projected ensembles theory
        - Cotler*, Mark*, Huang*, et al. [arXiv:2103.03536 (2021)]()
    - Benchmarking theory
        - Mark, et al., [arXiv:2205.12211 (2022)]()
    - Temporal sampling (unpublished)
    - Large-scale benchmarking (N=60, unpublished)



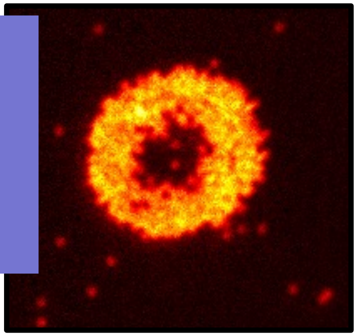


Outlook tweezer arrays

1) Quantum computing

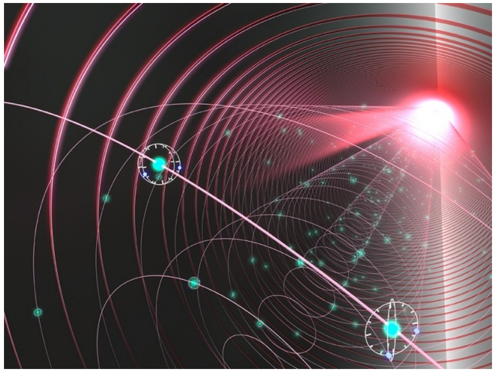
Tweezer arrays are a forefront platform for
- Quantum Simulation (→ quantum advantage)
- Metrology (→ competetive atomic clocks & quantum metrology)

What about quantum computing?
- Mid-circuit readout & feedback
- Higher-fidelity two-qubit gates
- Scaling up



2) Quantum simulation
(quantum many-body

3) Quantum metrology
(use quantum states/systems for precision measurement)

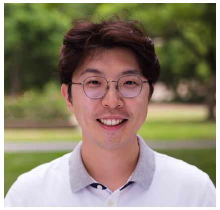


Acknowledgments

Endres group: https://www.endreslab.com/

Sr:


Adam


Joonhee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Alex Cooper Roy
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Cs:


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Thank you for your attention!

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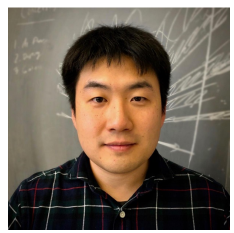
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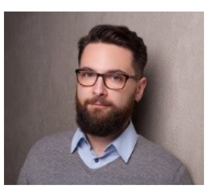
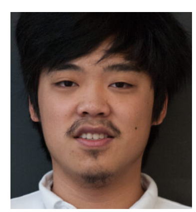
Andrew Ivanov (Caltech)


Vladimir Schkolnik (Berlin)


Hannes Pichler (Innsbruck)


Jordan Cotler (Harvard)


Daniel Mark (MIT)


Zhou Chen (MIT)

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