# Quantum Verification

Jara Juana Bermejo-Vega
University de Granada

**Spring School on Near-Term Quantum Computing**
April 2024

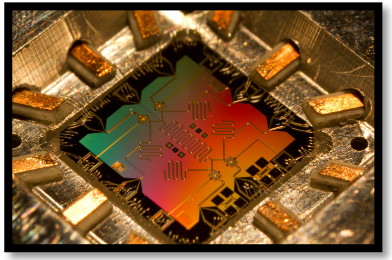
Foto: Erik Lucero/Google

# Noisy Intermediate Scale Quantum computers (NISQ)

☺️ Quantum computers offer advantages in computation

☺️ 50-1000 qubits devices are under construction

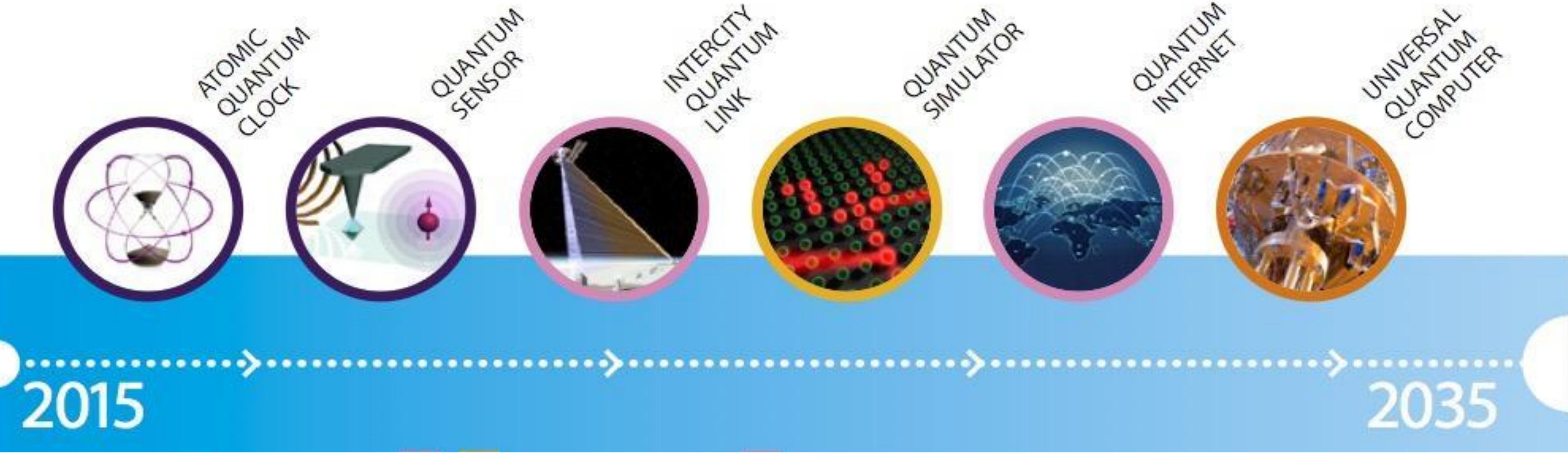
QUANTUM FLAGSHIP



IBM, D-Wave The Quantum Computing Company™, Google, Microsoft, rigetti, SILICON QUANTUM COMPUTING, IONQ, Alibaba Group, NTT, XANADU, qci, Baidu, NOKIA Bell Labs, EeroQ, QILIMANJARO, Alpine Quantum Technologies, Oxford Quantum Circuits

☹️ Quantum applications are hard to find and implement

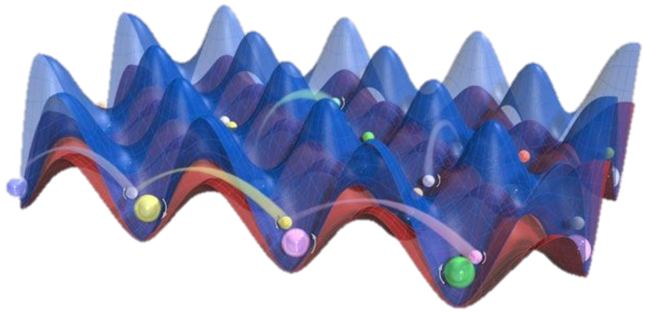
Quantum simulations can offer **practical** quantum advantages



# Quantum Simulation

Dynamical quantum simulators (e.g., using $10^4$-$10^5$ cold atoms in optical lattices) cannot be efficiently classically simulated with state-of-the-art tensor-network algorithms (a la DMRG). *But are these good enough?*

Trotzky et. al., Nature Phys. 8 (2012), Choi et al., Science 352 (2016)



$$\hat{H} = \sum_j \left[ -J\left(\hat{a}_j^\dagger \hat{a}_{j+1} + \text{h.c.}\right) + \frac{U}{2}\hat{n}_j(\hat{n}_j - 1) + \frac{K}{2}\hat{n}_j j^2 \right]$$

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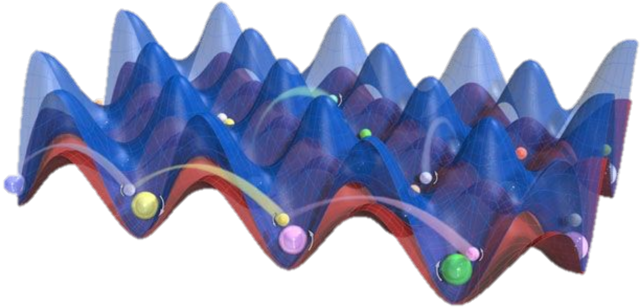
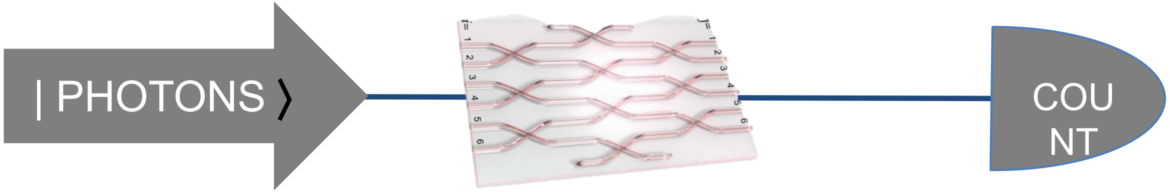


# Quantum Sampling problems offer **complexity-theoretic** advantages

## Boson sampling

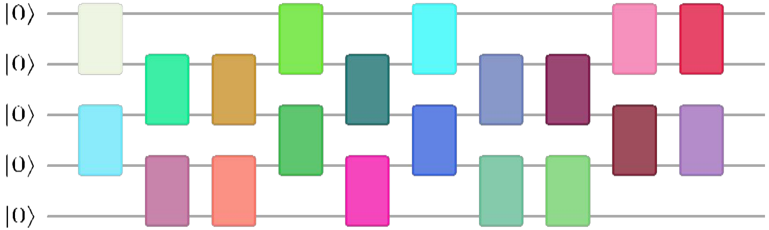
Generates random numbers using a random photonic circuit, hard to simulate based on complexity theoretic evidence.




Aaronson, Arkhipov, Th. Comp. 9 (2013)

## Random circuit sampling ("Google")

They apply a long circuit of random physical interactions on superconducting qubits.




Boixo et al., Nature Phys. 14 (2016)
Bouland, Fefferman, Nirkhe, Vazirani, Nature Phys arXiv:1803.04402
Arute, Nature, Vol 574, 505 (2019)

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# Quantum supremacy has arrived – what happens to computing now?

The claim that a quantum computer has done something a classical machine can't has generated plenty of excitement, but true quantum computing will take time to appear

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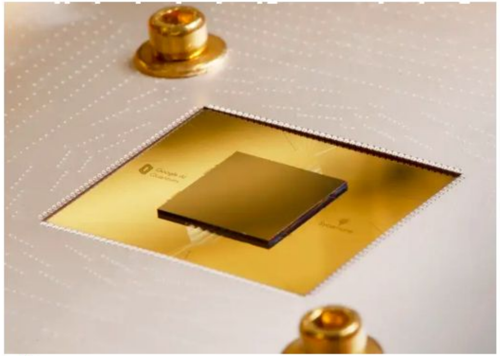

The New York Times

Opinion

# Why Google's Quantum Supremacy Milestone Matters

The company says its quantum computer can complete a calculation much faster than a supercomputer. What does that mean?

**By Scott Aaronson**

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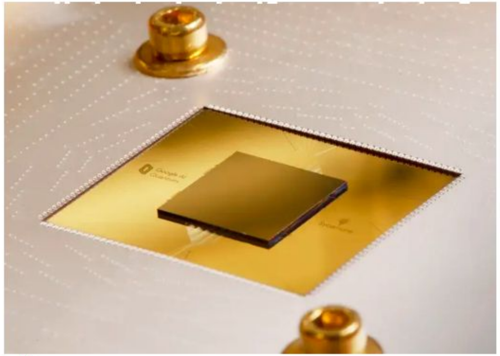

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October 21, 2019 | Written by: Edwin Pednault, John Gunnels & Dmitri Maslov, and Jay Gambetta

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Google researchers in Santa Barbara, California, say their advance may lead to near-term applications of quantum computers. ISTOCK.COM/JHVEPHOTO

## IBM casts doubt on Google's claims of quantum supremacy

By Adrian Cho | Oct. 23, 2019 , 5:40 AM

# Our work

## Two types of quantum advantages from quantum simulators

# Complexity-theoretic advantage for short-time evolutions

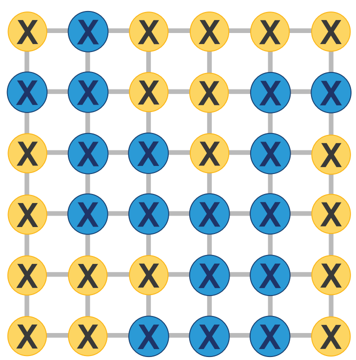
- Bermejo-Vega, Hangleiter, Schwarz, Raussendorf, Eisert, *Phys. Rev. X* 8 (2018), arxiv:1703.00466
- Hangleiter, Bermejo-Vega, Schwarz, Eisert, *Quantum* 2 (2018), arXiv:1706.03786
- Haferkamp, Hangleiter, Fefferman, Eisert, Bouland, Bermejo-Vega, Phys. Rev. Lett. 125, 250501 – Published 17 December 2020

# Result: simple Hamiltonian evolutions are "horribly hard" to simulate classically

Approximate sampling from shallow (constant-time) evolutions of 2D translation-invariant Hamiltonians is *impossible* assuming plausible* complexity-theoretic conjectures:

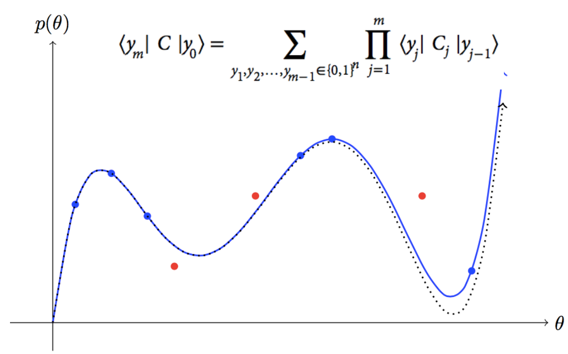
1) The Polynomial Hierarchy doesn't collapse
2) Anti-concentration ≈ "fairly flat" outputs
3) Approximate average-case hardness

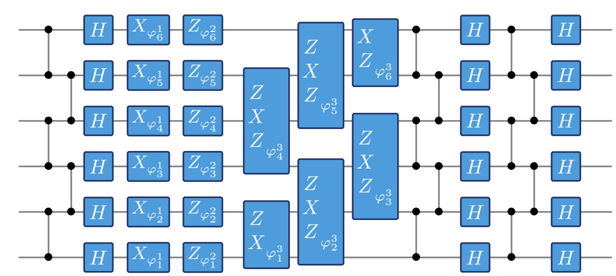
*Identical to random circuit sampling, slightly better than boson sampling



## Protocols

Bermejo-Vega, Hangleiter, Schwarz, Raussendorf, Eisert, *Phys. Rev. X* 8 (2018), arxiv:1703.00466



## Proofs: anticoncentration & *exact* average case hardness

Bouland, Fefferman, Nirkhe, Vazirani, Nature Phys arXiv:1803.04402
Hangleiter, Bermejo-Vega, Schwarz, Eisert, *Quantum* 2 (2018), arXiv:1706.03786
Haferkamp, Hangleiter, Fefferman, Eisert, Bouland, Bermejo-Vega, Upcoming!

# Protocols

arXiv:1703.00466

Prepare $N$ qubits on an $n \times m$ square lattice in a product state

$$|\psi_\beta\rangle = \bigotimes_{i=1}^{N} \left(|0\rangle + \mathrm{e}^{\mathrm{i}\beta_i}|1\rangle\right)$$

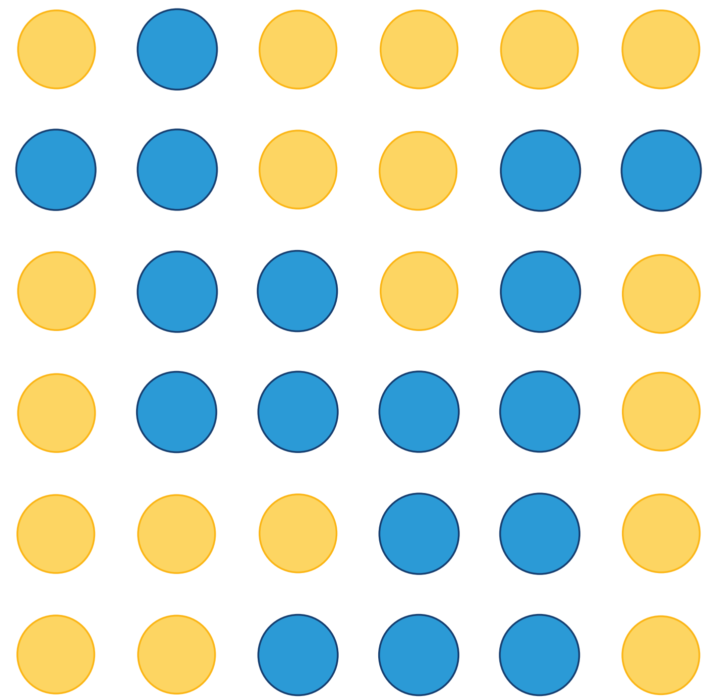
with $\beta_i \in \{0, \pi/4\}$ randomly.

Quench to

$$H = \sum_{(i,j)\in E} \frac{\pi}{4} Z_i Z_j - \sum_{i\in V} \frac{\pi}{4} Z_i .$$

and evolve under $U = e^{iH}$ .

Measure all qubits in the X basis.



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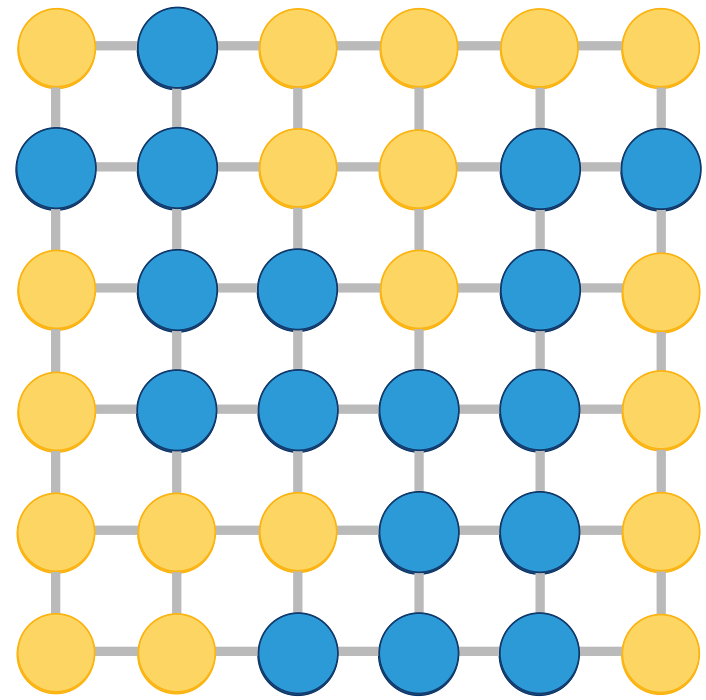

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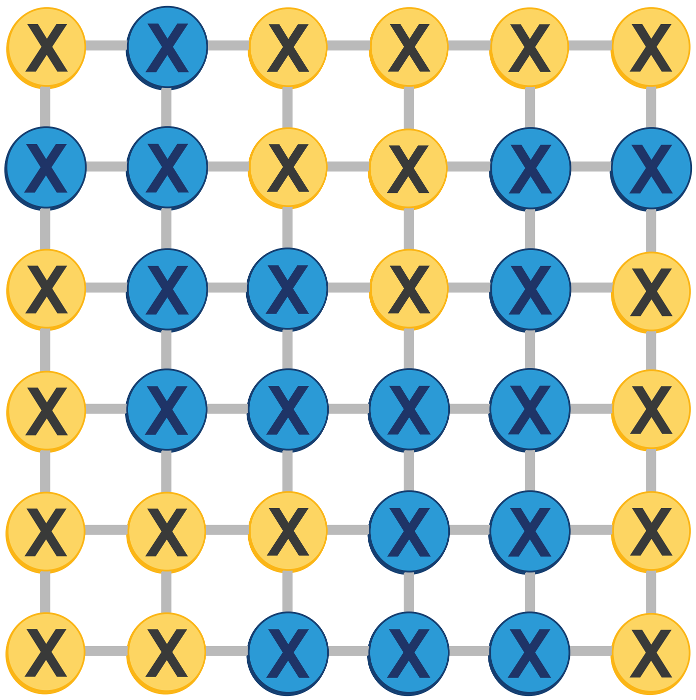

# Pr

arXiv:1

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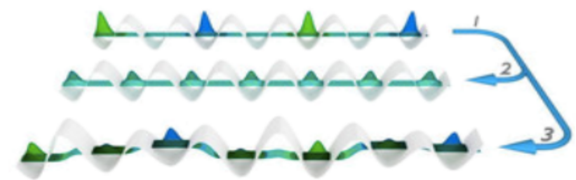
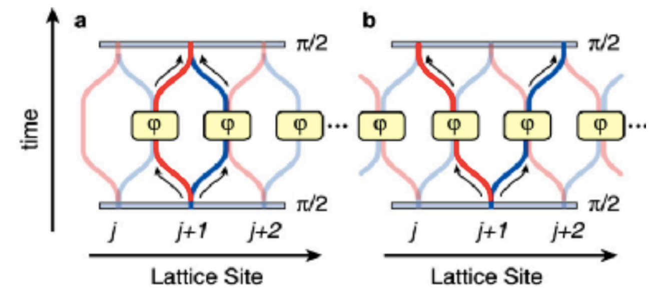
Reminiscient of disordered optical lattices



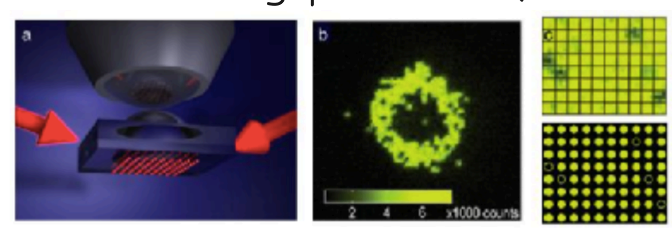

Schreiber, Hodgman, Bordia, Lüschen, Fischer, Vosk, Altman, Schneider, Bloch, Science 349 (2015)

Controlled coherent collisions long realized




Mandel, Greiner, Widera, Rom, Hänsch, Bloch, Nature, 425, (2003)

Single-site addressing possible (within limits)




Bakr, Gillen, Peng, Foelling, Greiner, Nature 462, (2009)
Weitenberg, Endres, Sherson, Cheneau, Schauß, Fukuhara, Bloch, Kuhr, Nature (2011)

# Quantum Verification/Benchmarking:

## How can we check if the quantum computation is working?

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Challenges:

1. Tomographic methods exponentially costly, no fault-tolerant solutions
2. Classical efficient verification of sampling problems is hard

   Hangleiter, Kliesch, Eisert,Gogolin, arXiv:1812.01023

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## Approach I

With additional noise/complexity assumptions, a few quantum samples + exponential classical processing is enough

Cross-entropy, HOG, BOG

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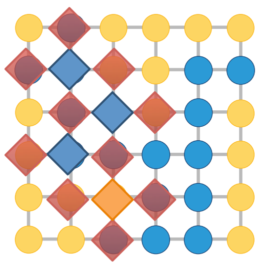
Bouland, Fefferman, Nirkhe, Vazirani, Nature Phys arXiv:1803.04402
Aaronson, Chen, CCC 17

## Approach II

With reliable single-qubit measurements, the fidelity of the prepared final state an be efficiently estimated



$$F(\rho_0, \rho) \geq 1 - \frac{\langle H \rangle_\rho}{\Delta}$$

Hangleiter, Kliesch, Schwarz, Eisert, Quant. Sc. Tech. 2, (2017)
Bermejo-Vega, Hangleiter, Schwarz, Raussendorf, Eisert, *Phys. Rev. X* 8 (2018), arxiv:1703.00466

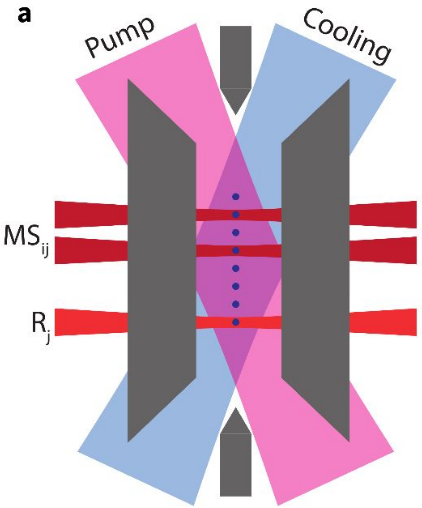
# Experimental demonstration
## (arXiv:2307.14424v1)

**Verifiable measurement-based quantum random sampling with trapped ions**

Martin Ringbauer,[1] Marcel Hinsche,[2] Thomas Feldker,[1,3] Paul K. Faehrmann,[2] Juani Bermejo-Vega,[2,4,5] Claire Edmunds,[1] Lukas Postler,[1] Roman Stricker,[1] Christian D. Marciniak,[1] Michael Meth,[1] Ivan Pogorelov,[1] Rainer Blatt,[1,3,6] Philipp Schindler,[1] Jens Eisert,[2,7,8] Thomas Monz,[1,3] and Dominik Hangleiter[9,10]

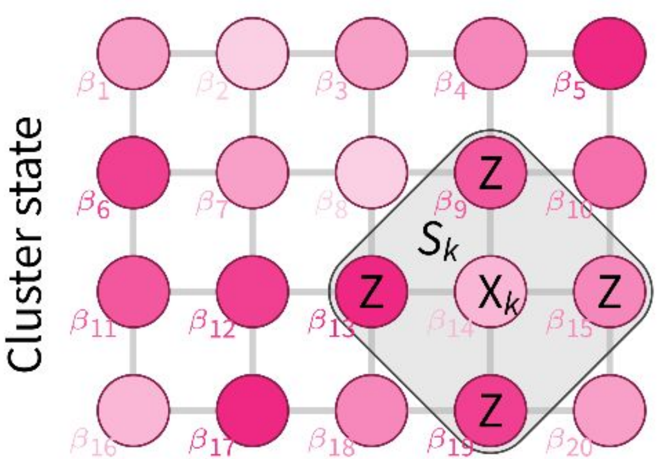
[1] *Universität Innsbruck, Institut für Experimentalphysik, Technikerstrasse 25, 6020 Innsbruck, Austria*
[2] *Dahlem Center for Complex Quantum Systems, Freie Universität Berlin, 14195 Berlin, Germany*
[3] *Alpine Quantum Technologies GmbH, 6020 Innsbruck, Austria*
[4] *Departamento de Electromagnetismo y Física de la Materia, Avenida de la Fuente Nueva, 18071 Granada, Universidad de Granada, Granada, Spain*
[5] *Institute Carlos I for Theoretical and Computational Physics, Campus Universitario Fuentenueva, Calle Dr. Severo Ochoa, 18071, Granada, Spain.*
[6] *Institut für Quantenoptik und Quanteninformation, Österreichische Akademie der Wissenschaften, Otto-Hittmair-Platz 1, 6020 Innsbruck, Austria*
[7] *Helmholtz-Zentrum Berlin für Materialien und Energie, 14109 Berlin, Germany*
[8] *Fraunhofer Heinrich Hertz Institute, 10587 Berlin, Germany*
[9] *Joint Center for Quantum Information and Computer Science (QuICS), University of Maryland & NIST, College Park, MD 20742, USA*
[10] *Joint Quantum Institute (JQI), University of Maryland & NIST, College Park, MD 20742, USA*

(Dated: July 28, 2023)



# Direct fidelity estimation

$$F = \frac{1}{2^N}\sum_{s\in\mathcal{S}}\langle s\rangle_\rho = \frac{1}{2^N}\sum_{s\in\mathcal{S}}\sum_{\sigma=\pm 1}\langle \pi_s^\sigma\rangle_\rho\cdot\sigma,$$




**Requirements:**

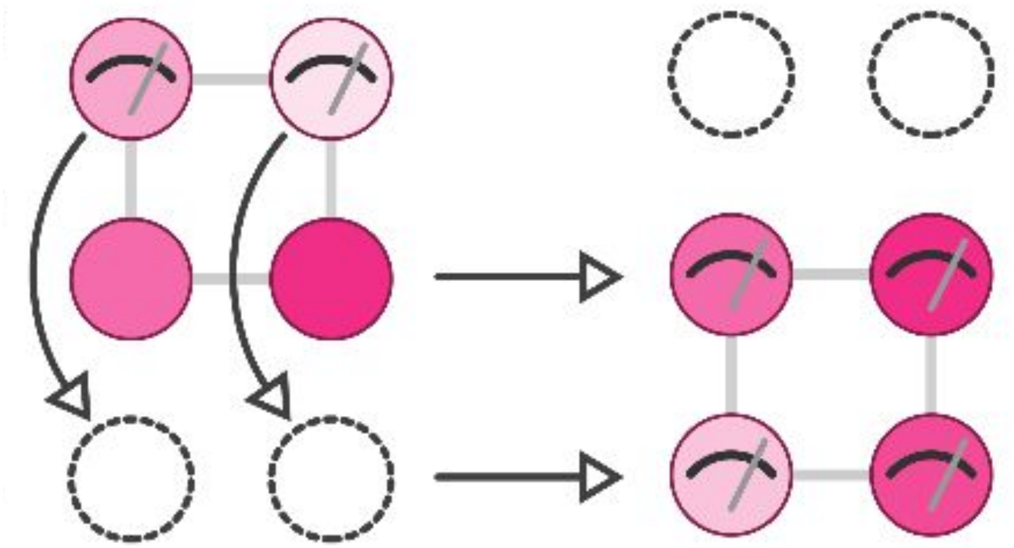
- single qubit measurements

**Advantages (over XEB approaches):**

- efficient in terms of both sample and computational complexity
- knowledge only of the measurement noise
- bounds the quality of the samples from a fixed quantum state
- system size efficient: estimates F with error $\epsilon$ using $1/\epsilon^2$ measurements

S. T. Flammia and Y.-K. Liu, Phys. Rev. Lett. 106, 230501 (2011).

# Qubit recycling (non-adaptive MBQC with ions)



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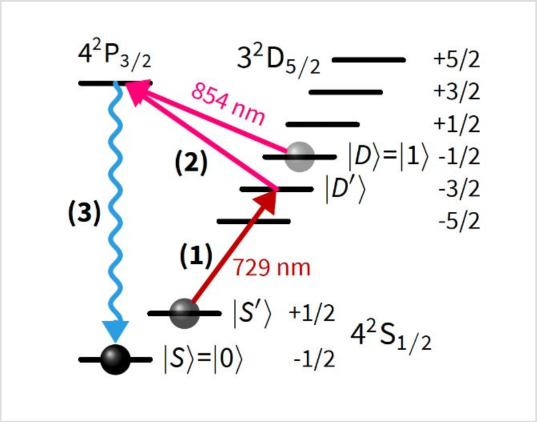
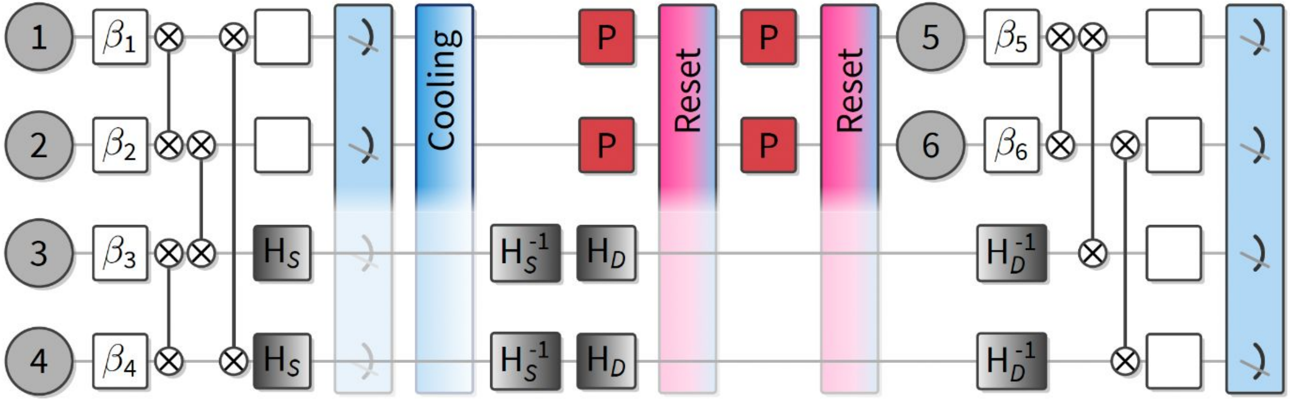
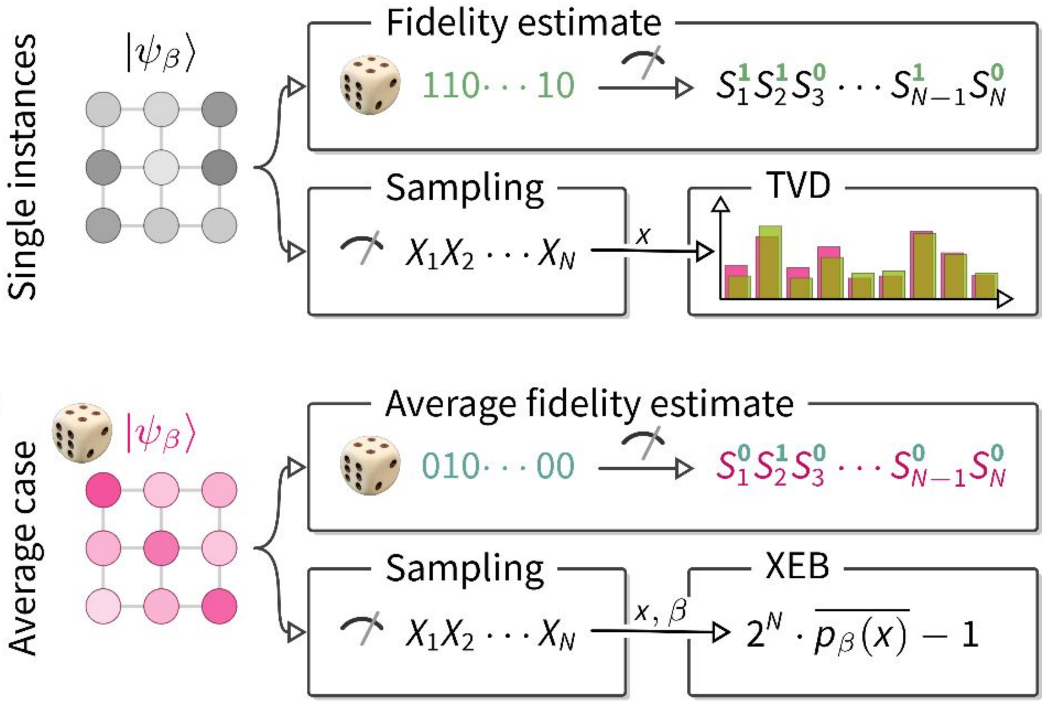



- Measurement (P ↔ S)
- P = Cooling Reset (S' → D')
- $H_S$ = Recycling (S → D' transition)
- $H_D$(D → S')

# Measuring the fidelity and XEB for our setup

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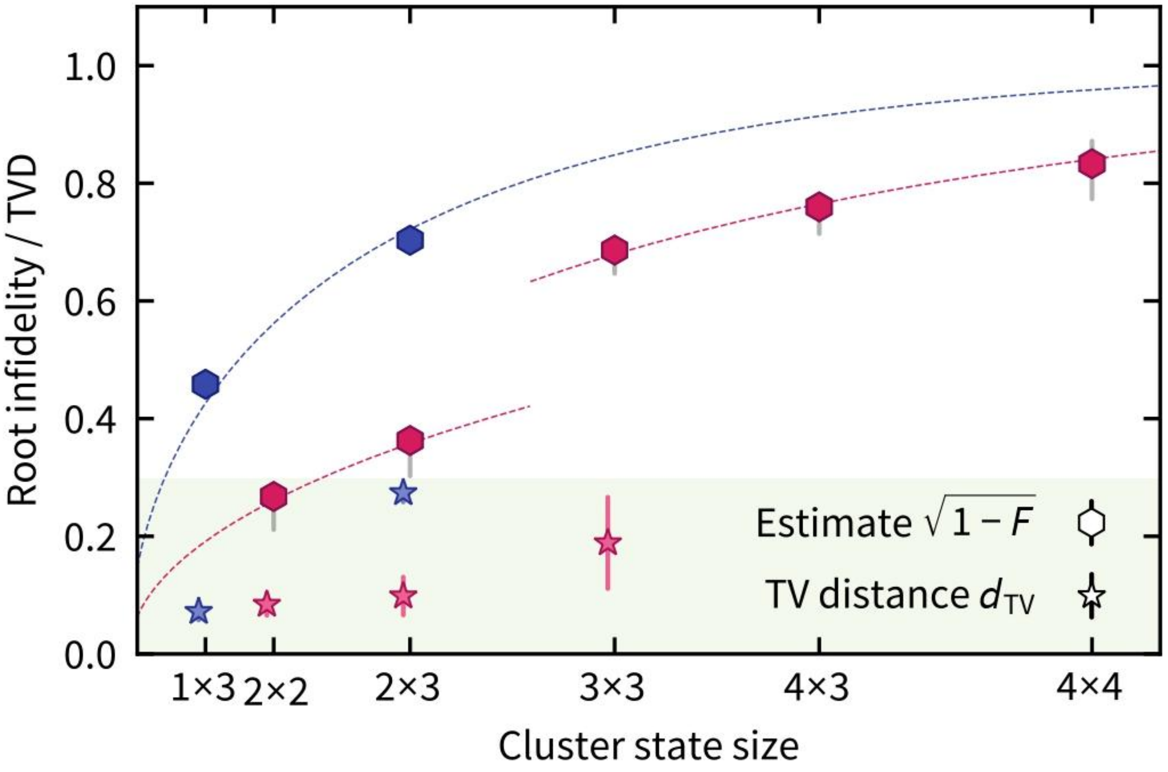
S. T. Flammia and Y.-K. Liu, Phys. Rev. Lett. 106, 230501 (2011).

# Experimental results for single-instance verification of random cluster states



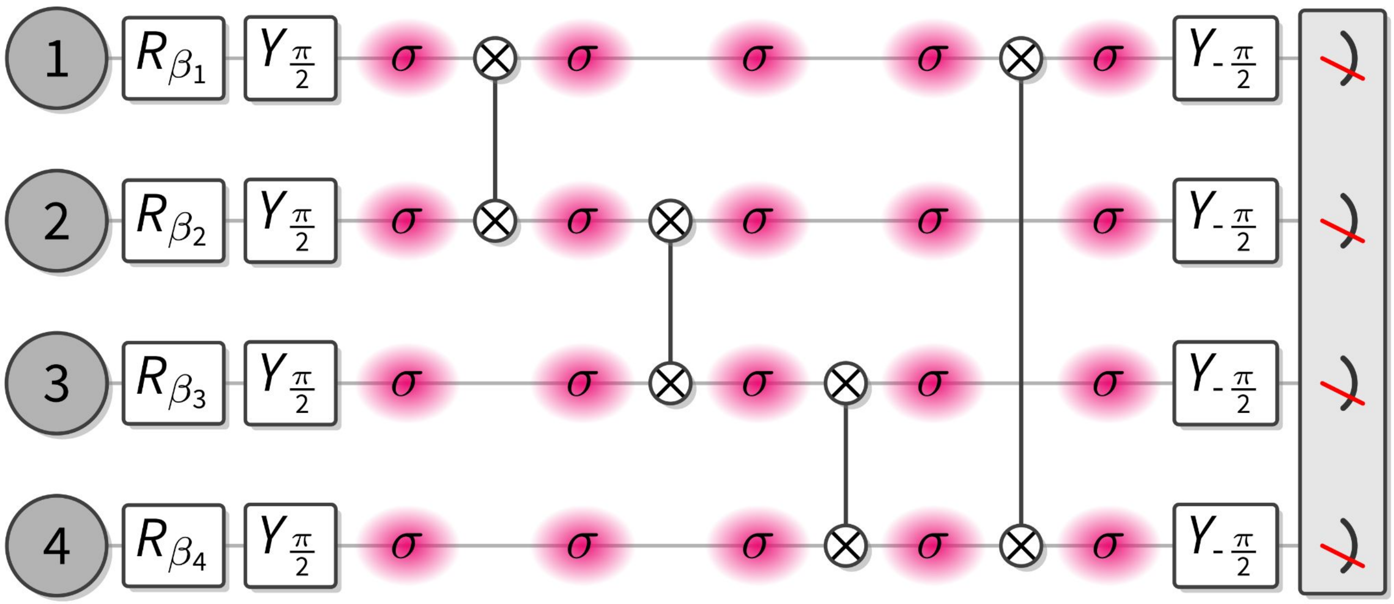

- Blue = with recycling (blue)
- Pink = without recycling
- Gray error bars = measurement noise (from benchmarking)
- Colored error bars = 3σ statistical error
- Shaded green area = acceptance region


M. Ringbauer, M. Meth, L. Postler, R. Stricker, R. Blatt, P. Schindler, and T. Monz,Nat. Phys. 18, 1053 (2022)

I. Pogorelov, T. Feldker, C. D. Marciniak, L. Postler, G. Jacob,
O. Krieglsteiner, V. Podlesnic, M. Meth, V. Negnevitsky, M. Stadler, B. Höfer, C. Wächter, K. Lakhmanskiy, R. Blatt, P. Schindler, and T. Monz,, PRX Quantum 2, 020343 (2021))

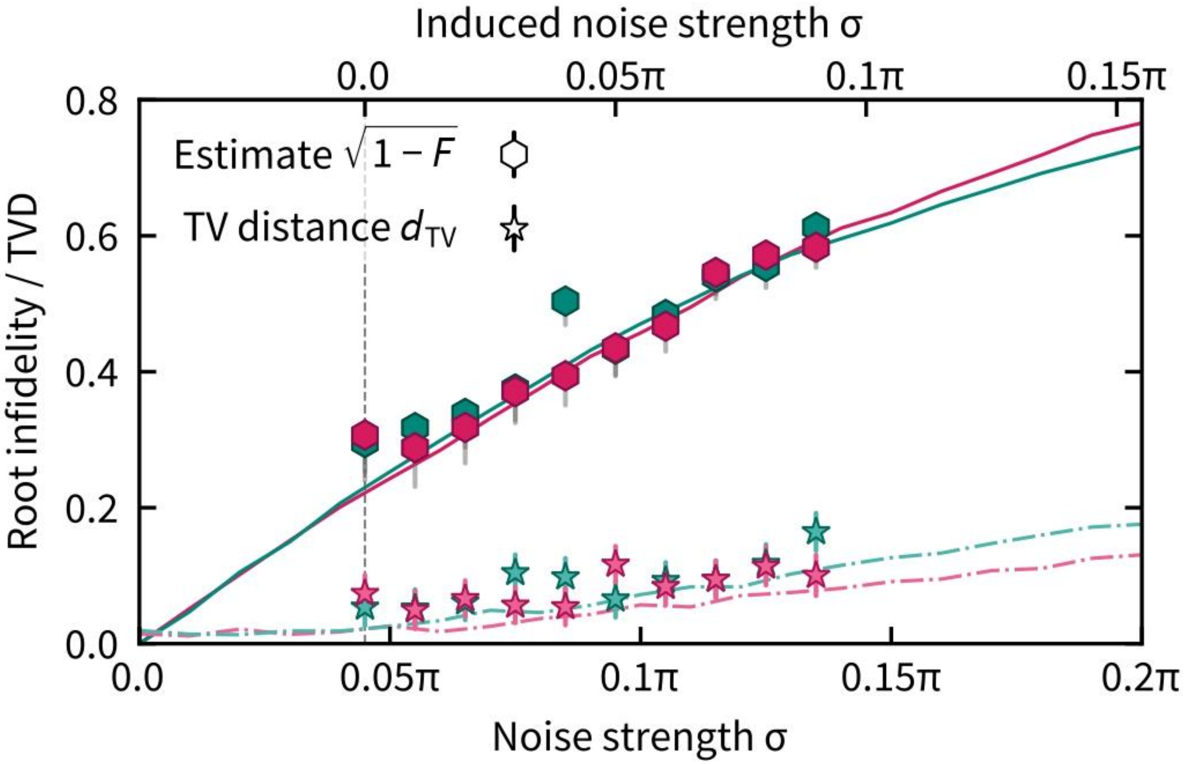
P. Schindler, D. Nigg, T. Monz, J. T. Barreiro, E. Martinez, S. X. Wang, Stephan Quint, M. F. Brandl, V. Nebendahl, C. F. Roos, M. Chwalla, M. Hennrich, and Rainer Blatt,, New J. Phys. 15, 123012 (2013).

# Estimating the noise strength: verification with artificially induced phase noise




We add dephasing noise on all qubits after initial state preparation and each MS gate.
Rotation angles of Z rotations are drawn from normal distribution with zero mean and standard deviation σ ∈ [0, 0.2π] every 50 shots. For correlated noise, the parameters in each time step are chosen equally and for uncorrelated noise, they are chosen independently.

# Estimating the noise strength: verification with artificially induced phase noise




- Green = induced global noise
- Pink = induced local noise
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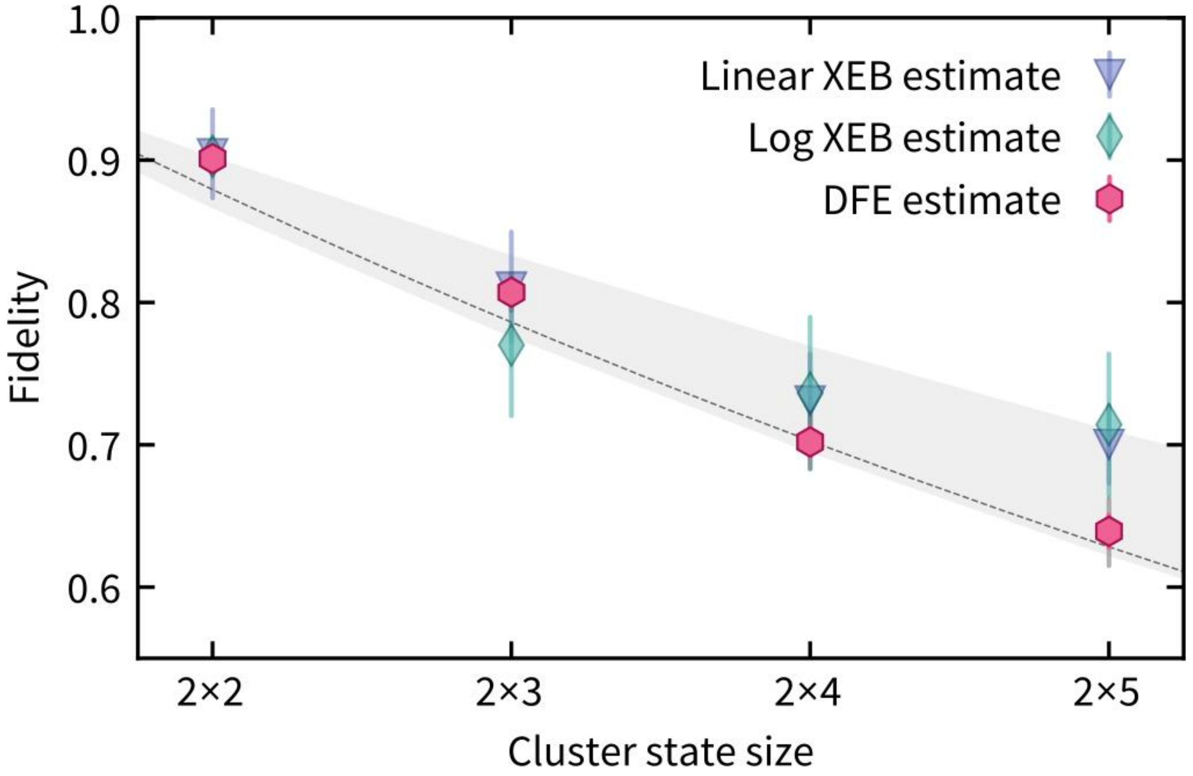
# Experimental results for average performance verification




- Gray error bars = measurement noise (from benchmarking)
- Colored error bars = 3σ statistical error
- Gray shaded area = Fidelity prediction from calibration data gate fidelities of single-qubit gates f1Q = 99.8%, twoqubit gates f2Q = 97.5 ± 0.5%, and measurements fM = 99.85%,
- Dotted line: effective local Pauli error probability of 1.7%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Direct fidelity estimation provides an efficient and scalable means of certifying both single instances and the average quality of MBQCS

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Sample efficient: Larger systems can be verified with the same number of experiments as we have performed (30k -100 k shots)

Applications: tool for verifying NISQ devices and quantum advantages based on sampling problems in MBQC

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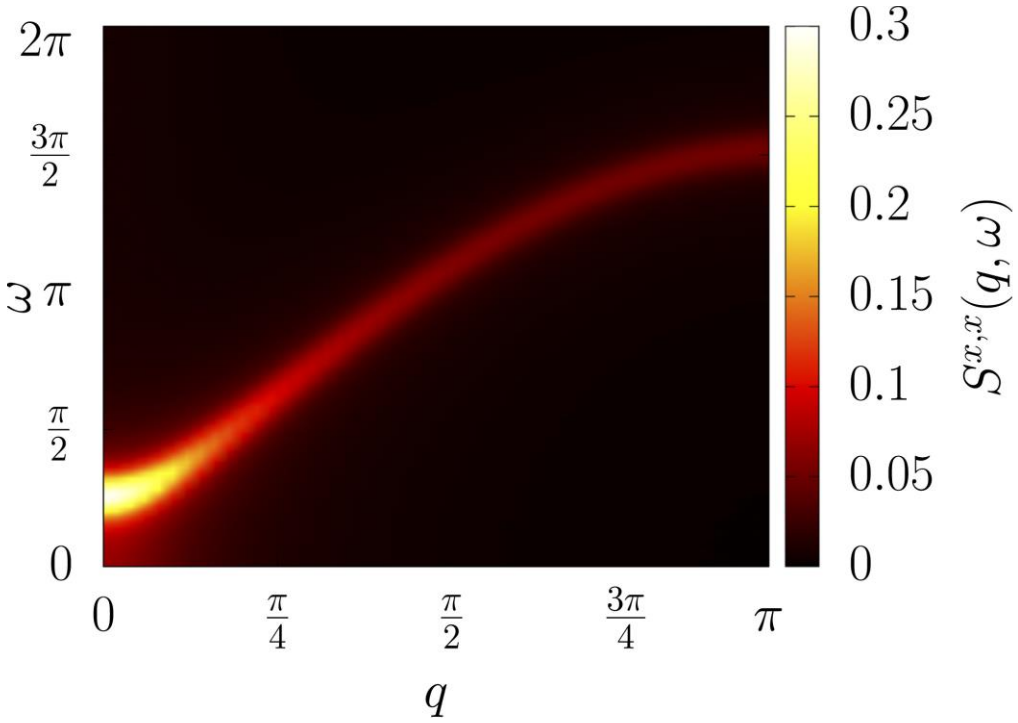
# Practical quantum advantage for measuring dynamical structure factors




ML Baez, M Goihl, J Haferkamp, J Bermejo-Vega, M Gluza, J Eisert

Proceedings of the National Academy of Sciences 117 (42), 26123-26134

# WHAT? DYNAMICAL STRUCTURE FACTOR FOR SPIN SYSTEMS

$$S^{a,b}(\mathbf{q},\omega) = \frac{1}{N}\sum_{ij}\int_{-\infty}^{\infty} dt e^{-i\mathbf{q}.(\mathbf{r}_i-\mathbf{r}_j)} e^{i\omega t} C_{i,j}^{a,b}(t)\,, \quad C_{i,j}^{a,b}(t) = \langle \sigma_i^a(0)\sigma_j^b(t)\rangle$$

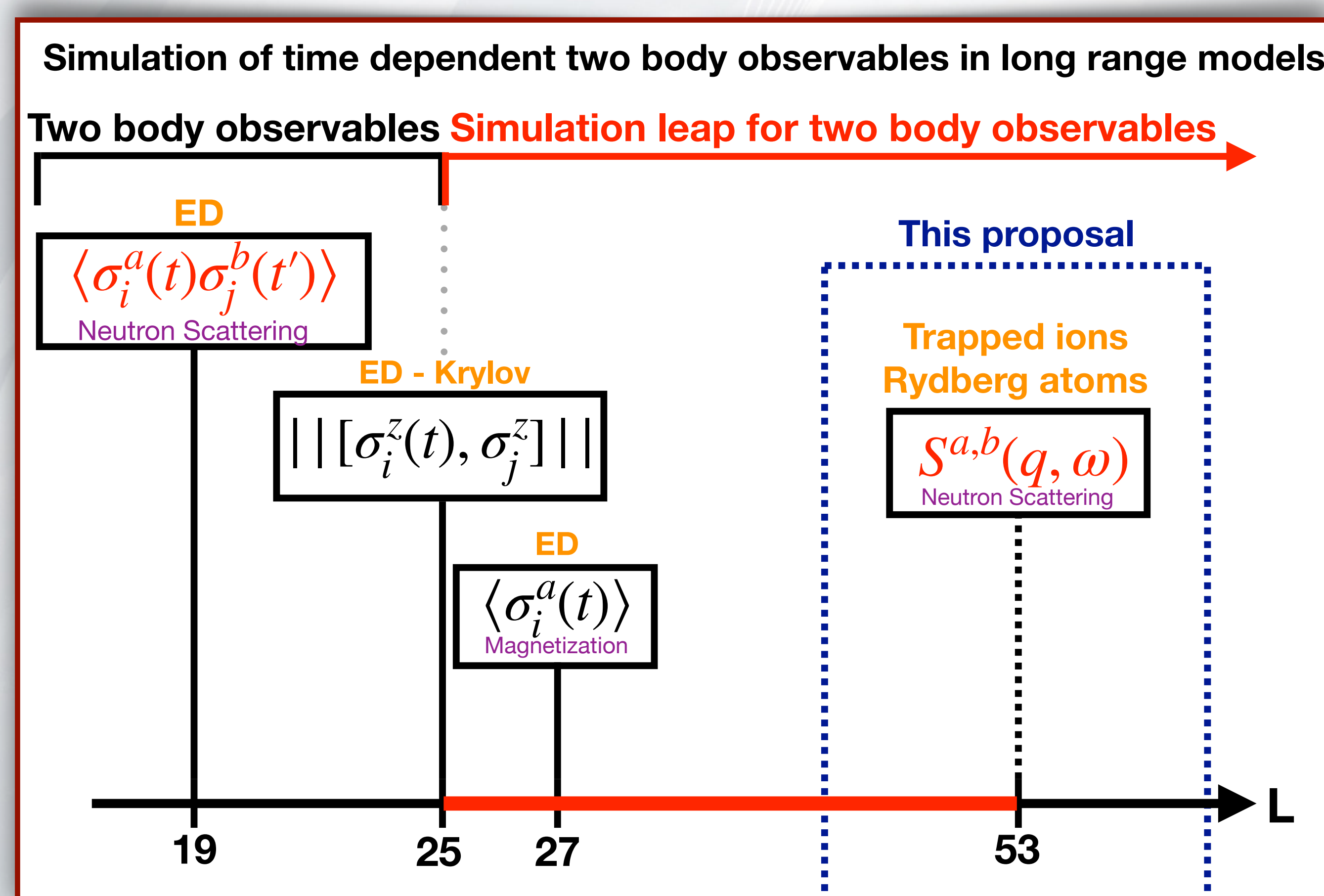
**Approximating the dynamical structure factor $S_{t_0,t_1}^{\alpha,\beta}(q,\omega)$ within a constant error $\varepsilon \leq 1/8$ over an interval of time $[t_0, t_1]$ is BQP-hard.**

**For polynomially large ($t_1 - t_0 = \mathrm{poly}(n)$) then it is BQP-hard to approximate $S_{t_0,t_1}^{\alpha,\beta}(q,\omega)$ within an error $\varepsilon = \mathrm{poly}^{-1}(n)$.**

arXiv: 1912.0607

J. Haferkamp, J. Bermejo-Vega, J. Eisert

$$\hat{H}(J,B) = \sum_i B_z \sigma_i^z - \sum_{i<j} \frac{J}{|r_i - r_j|^\alpha}\sigma_i^x \sigma_j^x$$




PHYSICAL REVIEW LETTERS **122,** 150601 (2019)

**Confined Quasiparticle Dynamics in Long-Range Interacting Quantum Spin Chains**

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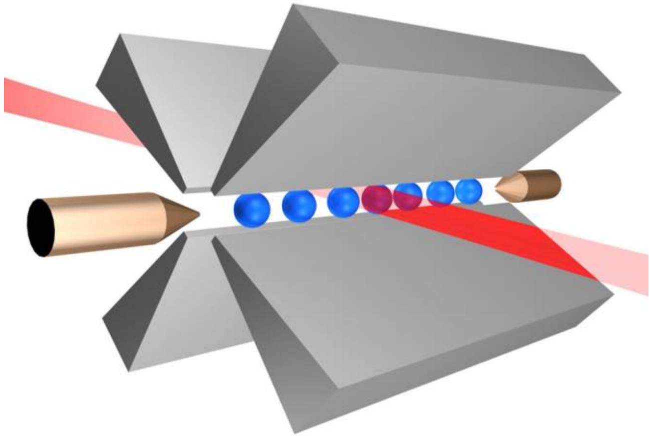
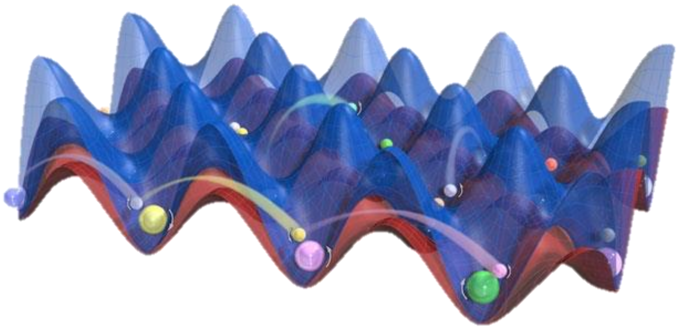
We study the quasiparticle excitation and quench dynamics of the one-dimensional transverse-field Ising model with power-law ($1/r^\alpha$) interactions. We find that long-range interactions give rise to a confining potential, which couples pairs of domain walls (kinks) into bound quasiparticles, analogous to mesonic states in high-energy physics. We show that these quasiparticles have signatures in the dynamics of order parameters following a global quench, and the Fourier spectrum of these order parameters can be exploited as a direct probe of the masses of the confined quasiparticles. We introduce a two-kink model to qualitatively explain the phenomenon of long-range-interaction-induced confinement and to quantitatively predict the masses of the bound quasiparticles. Furthermore, we illustrate that these quasiparticle states can lead to slow thermalization of one-point observables for certain initial states. Our work is readily applicable to current trapped-ion experiments.

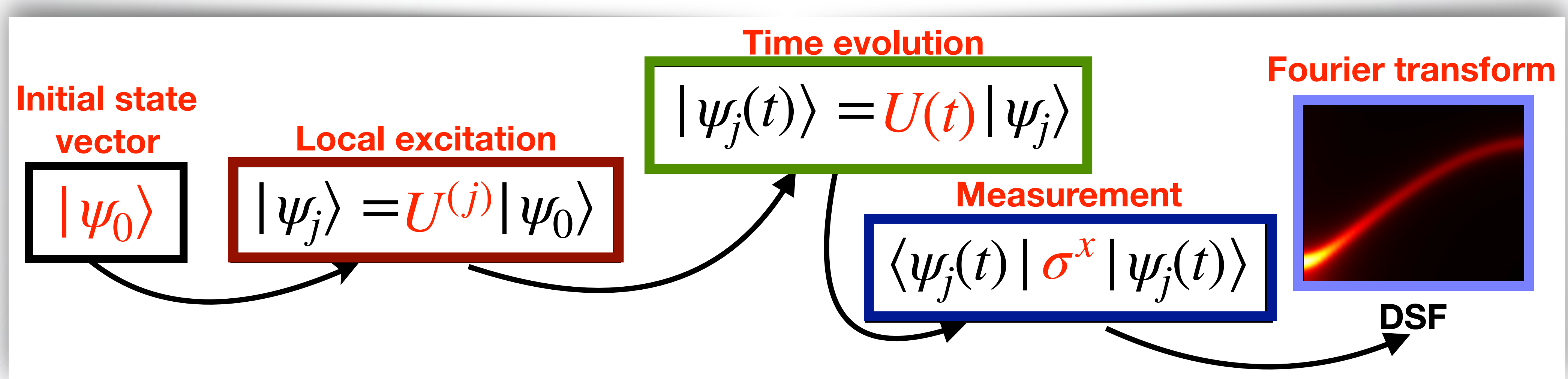




- **Trapped ions** Long range transverse field Ising model with variable interaction range
  Islam, et. al. Science 2013. Bohnet, et. al. Science 2016. Zhang, et. al. Nature 2017.

- **Rydberg atoms** Long range transverse field Ising and XXZ models
  Bernien, et. al. Nature 2017. Levine, et. al. PRL 2018. Labuhn, et. al. Nature 2016. et

## HOW? DSFS IN QUANTUM SIMULATORS




Transverse field Ising model:

$$H(J,B) = \sum_i B_z \sigma_i^z - \sum_{i<j} J_{i,j}\sigma_i^x\sigma_j^x .$$

Spin-reflection parity

$$\sigma^x \to -\sigma^x \qquad \sigma^y \to \sigma^y \qquad \sigma^z \to -\sigma^z$$

Expectation value of an odd number of Paulis vanishes

Without symmetries -> Tomographic recovery of the dynamical structure factor

MLB, et al. arXiv: 1912.0607

Controlled local initial operation $U^{(j)} = \dfrac{1}{\sqrt{2}}(1 - i\sigma_j^x)$

Free time evolution $|\psi\rangle = U(t)U^{(j)}|\psi_0\rangle$

Local measurement

$$\langle\psi|\sigma_i^x|\psi\rangle = \langle\psi_0|U^{(j)\dagger}\sigma_i^x(t)U^{(j)}|\psi_0\rangle = G_{x,x}^{\mathrm{ret}(i,j,t)}$$

$$G_{x,x}^{\mathrm{ret}}(t) = -\frac{i}{2}\langle\sigma_i^x(t)\sigma_j^x(0) - \sigma_j^x(0)\sigma_i^x(t)\rangle_0$$

Fluctuation-Dissipation within linear response theory

$$S^{xx}(\mathbf{q},\omega) = -\frac{1}{\pi}[1 + n_B(\omega)]\mathrm{Im}[G_{x,x}^{\mathrm{ret}}(\mathbf{q},\omega)]$$

## WHY? TEST CASES

MLB, et al. arXiv: 1912.0607

Transverse field Ising model:

$$\hat{H}(J,B) = \sum_i B_z \sigma_i^z - \sum_{i<j} J_{ij} \sigma_i^x \sigma_j^x$$

**Long range interactions**

$$J_{i,j} = \frac{J}{|i-j|^\alpha}$$

Dynamics

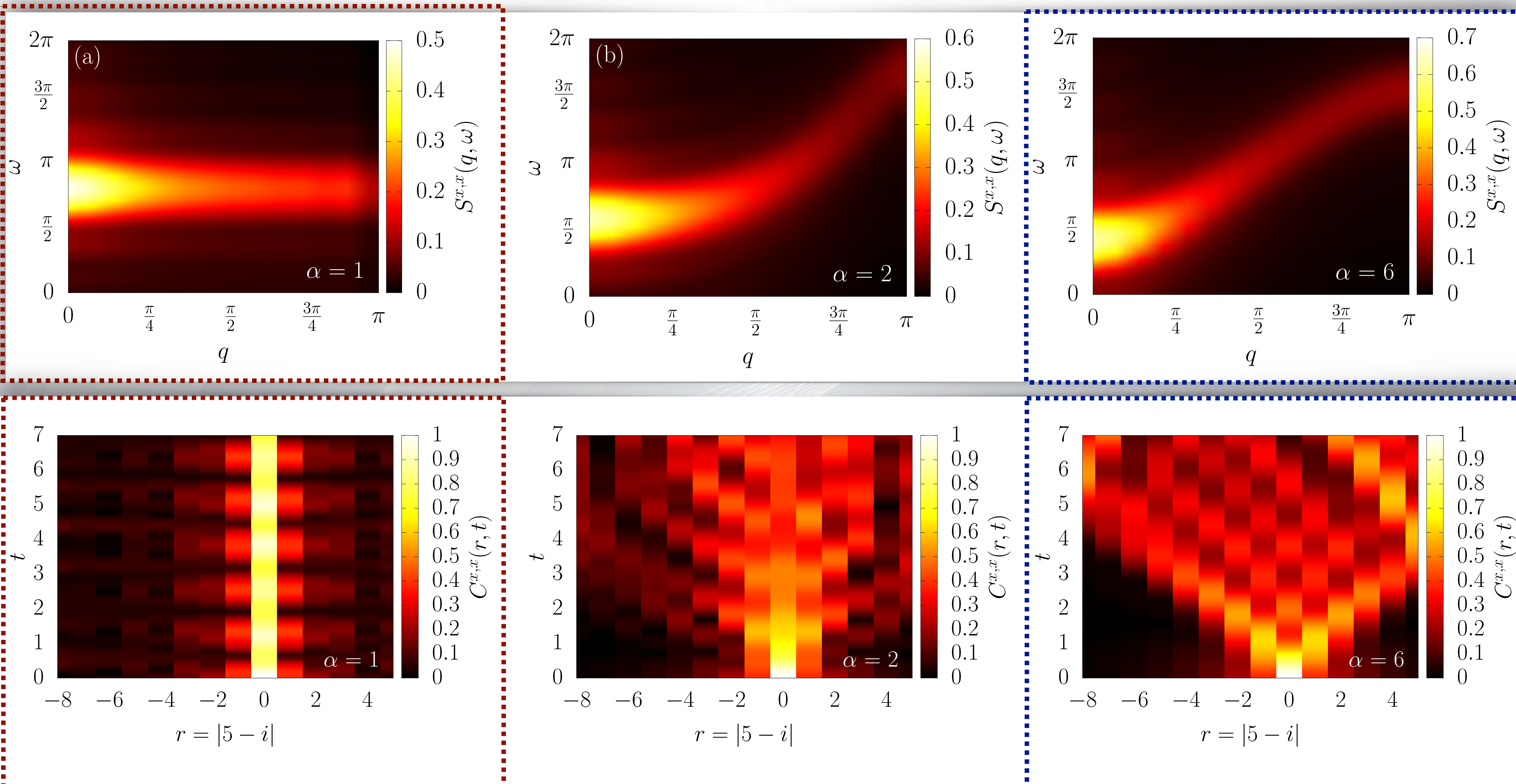
Full ED: 16-18 sites

Lanczos: 28 sites, 250 states

TVDP: 128 sites, equal time correlators

Confinement

"Nearest neighbour"



## WHY? TEST CASES AND NOISE MODELS

MLB, et al. arXiv: 1912.0607

**Initial state fidelity**

Bad ground state preparation → Adiabatically or QAOA preparation

| Rydberg atoms | Trapped ions |
|---|---|
| $J \propto \Omega$ | $J \propto \Omega$ |
| $\alpha \propto 6$ | $B_z \propto \Omega$ |
| $\Omega$ is the Rabi frequency | $\alpha \in [0,3]$ |

$\Omega$ depends on atom-atom distance and on coupling to the ions

Trapped ions: Spin-spin interactions generated by coupling hyperfine states to normal mode of motion of the ions → Periodic oscillations of the Rabi frequency induced by non-uniform laser frequency

**Globally fluctuating Ising couplings**

$$J = \frac{J(0)}{r^\alpha}(1 + A\sin(wt))$$

Finite temperatures, and imperfect control over ions/atoms leads to changes on the distance between components → Random interactions in both architectures

&

Rabi frequency is not uniform in the chain nor from shot to shot → Random fields in Rydberg atom setups

**Random Ising interactions**

$$J = \frac{J(0)}{r^\alpha}(1 + A\xi)$$

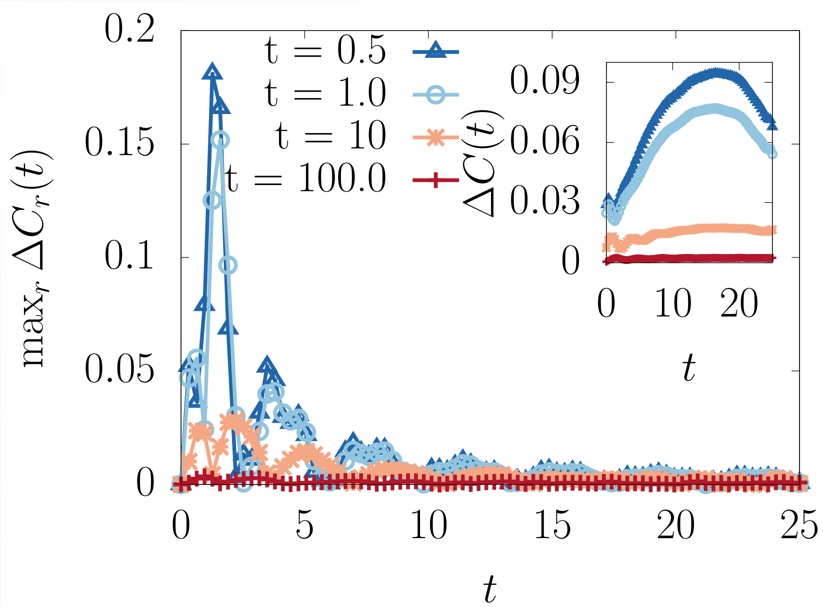
**Random transverse field**

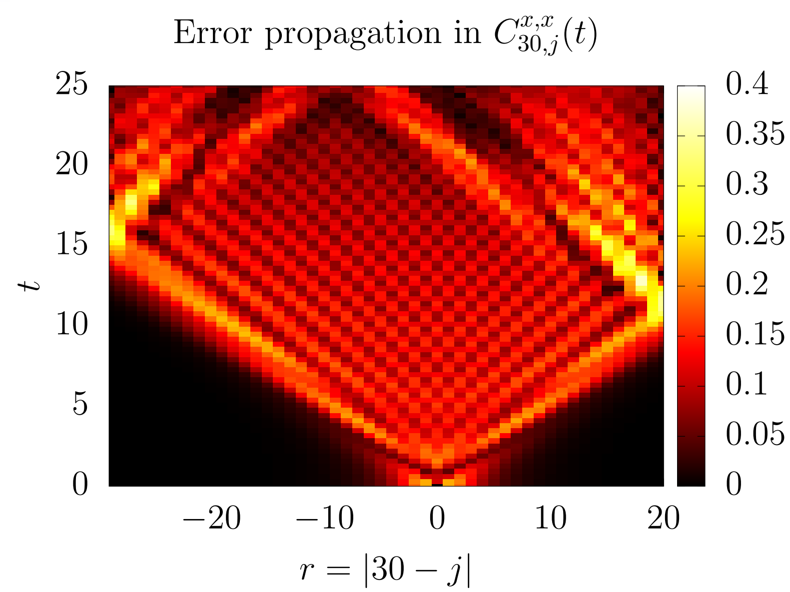
$$B_z = B + A\xi$$

Experiments have control up to $A \propto 0.01$

# DSF: FOURIER TRANSFORM AS A NOISE FILTER

MLB, et al. arXiv: 1912.0607

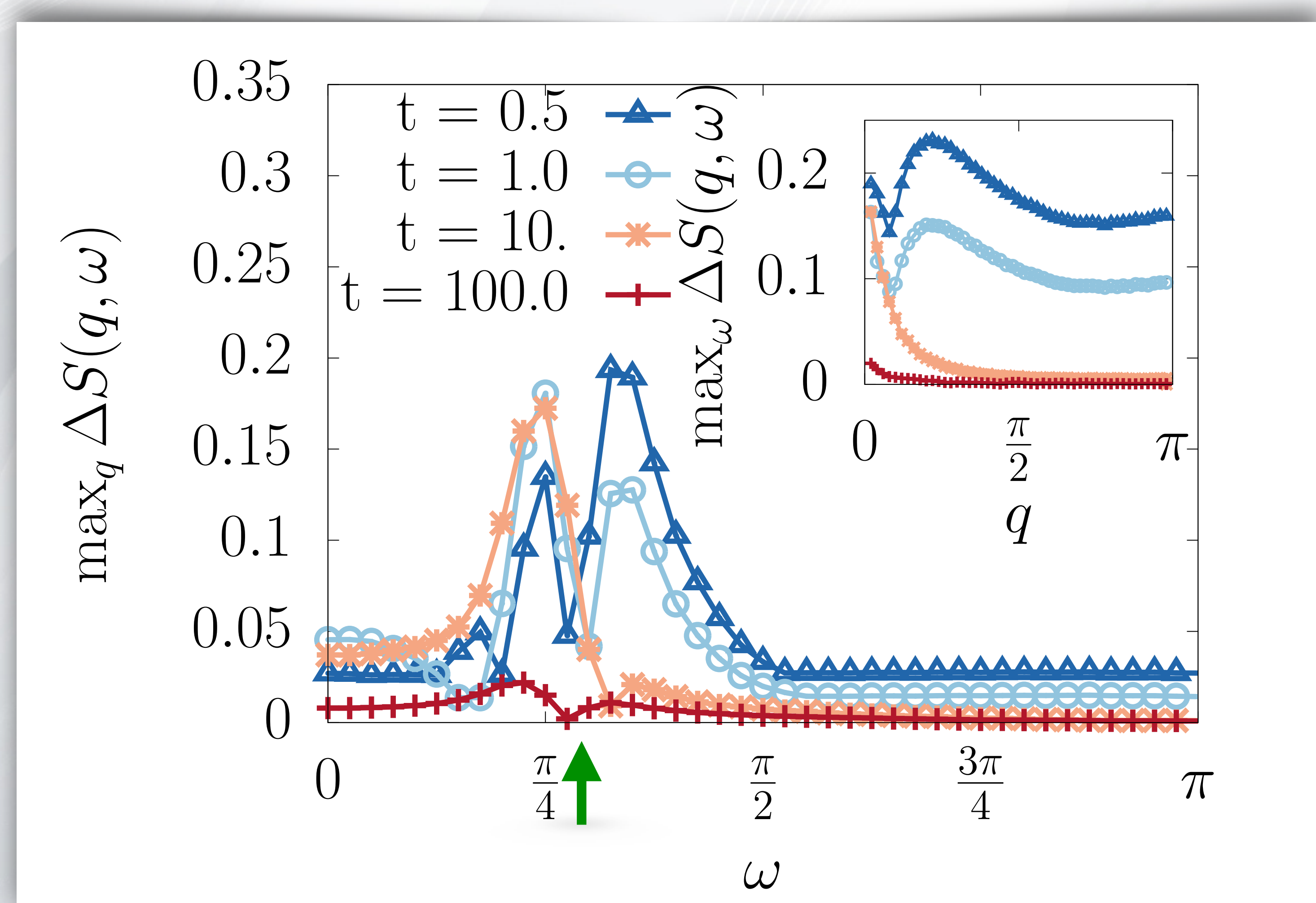


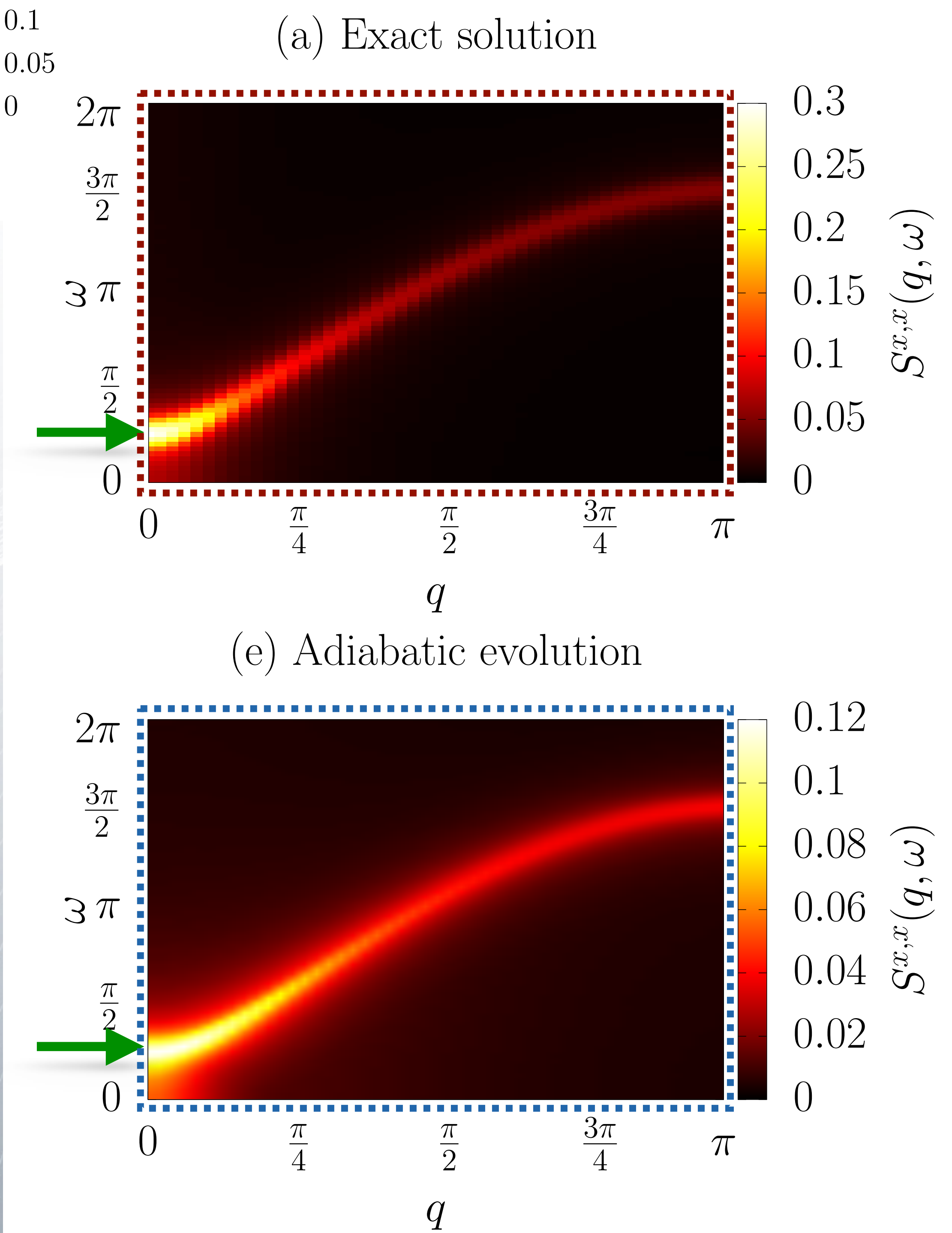




**Initial state fidelity - Short range model**

Correlators $\Delta C_r(t) = |\tilde{C}_r(t) - C_r(t)|$

DSF $\Delta S(q, \omega) = |\tilde{S}(q, \omega) - S(q, \omega)|$



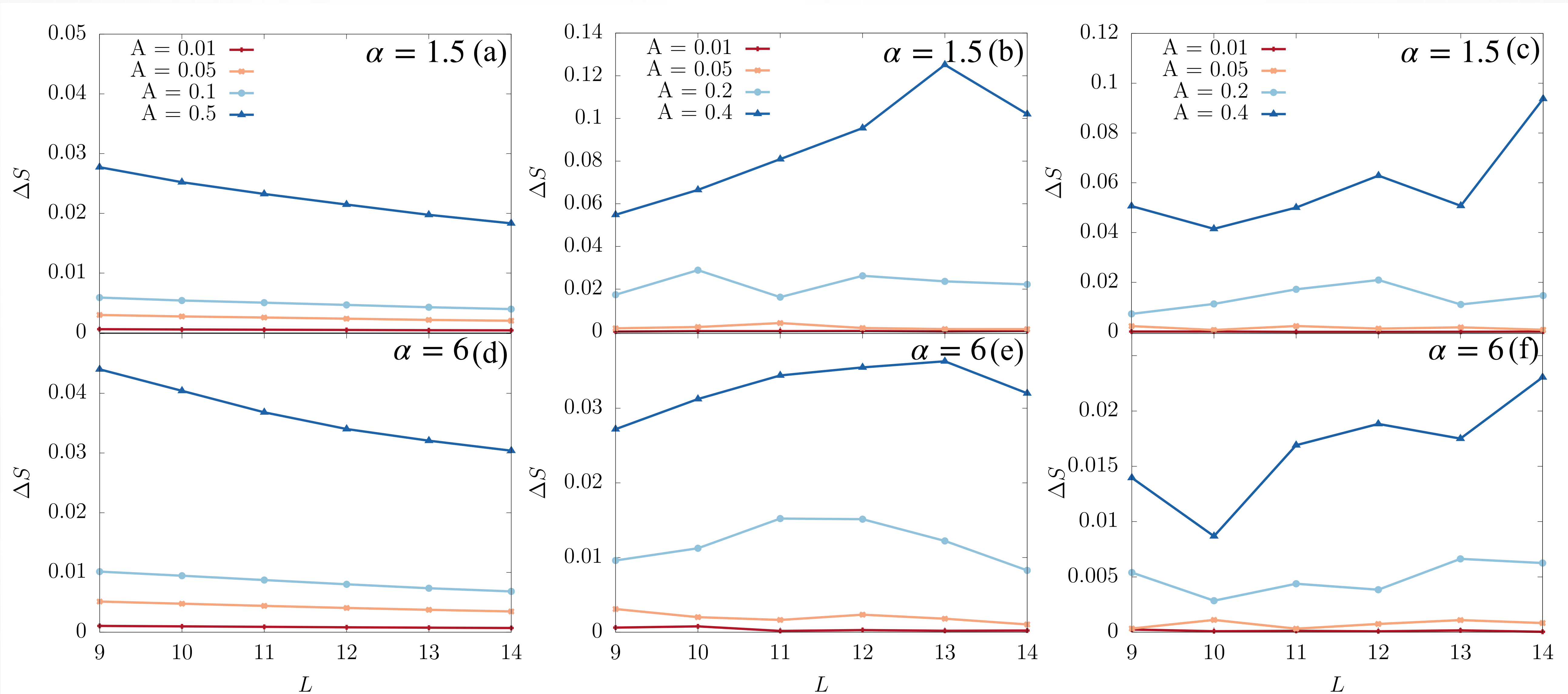
# TEST CASES AND NOISE MODELS

MLB, et al. arXiv: 1912.0607

Long range scaling up to $L = 14$

$$\Delta S = \frac{1}{L^2 N_\omega} \sum_q \sum_\omega S(q, \omega)$$

Experiments have control up to $A \propto 0.01$




Globally fluctuating Ising couplings

Random Ising interactions

Random transverse field

Imperfection effects are negligible and scale in a controlled way up to $A \propto 0.05$

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