DYNAMICAL STRUCTURE FACTOR OF DYNAMICAL QUANTUM SIMULATORS

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OUTLINE

What?

Or… What is a dynamical structure factor? (Brief) In Benasque, we know this one

How?

Or… How can I measure it in a quantum simulator? (Somewhat brief)

PRL **111,** 147205 (2013) PHYSICAL REVIEW LETTERS week ending 4 OCTOBER 2013

Probing Real-Space and Time-Resolved Correlation Functions with Many-Body Ramsey Interferometry

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We propose to use Ramsey interferometry and single-site addressability, available in synthetic matter such as cold atoms or trapped ions, to measure real-space and time-resolved spin correlation functions. These correlation functions directly probe the excitations of the system, which makes it possible to characterize the underlying many-body states. Moreover, they contain valuable information about phase transitions where they exhibit scale invariance. We also discuss experimental imperfections and show that a spin-echo protocol can be used to cancel slow fluctuations in the magnetic field. We explicitly consider examples of the two-dimensional, antiferromagnetic Heisenberg model and the one-dimensional, long-range transverse field Ising model to illustrate the technique.

Dynamical structure factors of dynamical quantum simulators

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(Dated: January 7, 2020)

The dynamical structure factor is one of the experimental quantities crucial in scrutinizing the validity of the microscopic description of strongly correlated systems. However, despite its long-standing importance, it is exceedingly difficult in generic cases to numerically calculate it, ensuring that the necessary approximations involved yield a correct result. Acknowledging this practical difficulty, we discuss in what way results on the hardness of classically tracking time evolution under local Hamiltonians are precisely inherited by dynamical structure factors; and hence offer in the same way the potential computational capabilities that dynamical quantum simulators do: We argue that practically accessible variants of the dynamical structure factors are BQP-hard for general local Hamiltonians. Complementing these conceptual insights, we improve upon a novel, readily available, measurement setup allowing for the determination of the dynamical structure factor in different architectures, including arrays of ultra-cold atoms, trapped ions, Rydberg atoms, and superconducting qubits. Our results suggest that quantum simulations employing near-term noisy intermediate scale quantum devices should allow for the observation of features of dynamical structure factors of correlated quantum matter in the presence of experimental imperfections, for larger system sizes than what is achievable by classical simulation.

Tomographic extension to treat a wider class of problems

arXiv: 1912.0607

Why?

Or… Why should anyone care?

Computational hardness, robustness to imperfections, & PHYSICS

WHAT? DYNAMICAL STRUCTURE FACTOR FOR SPIN SYSTEMS

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

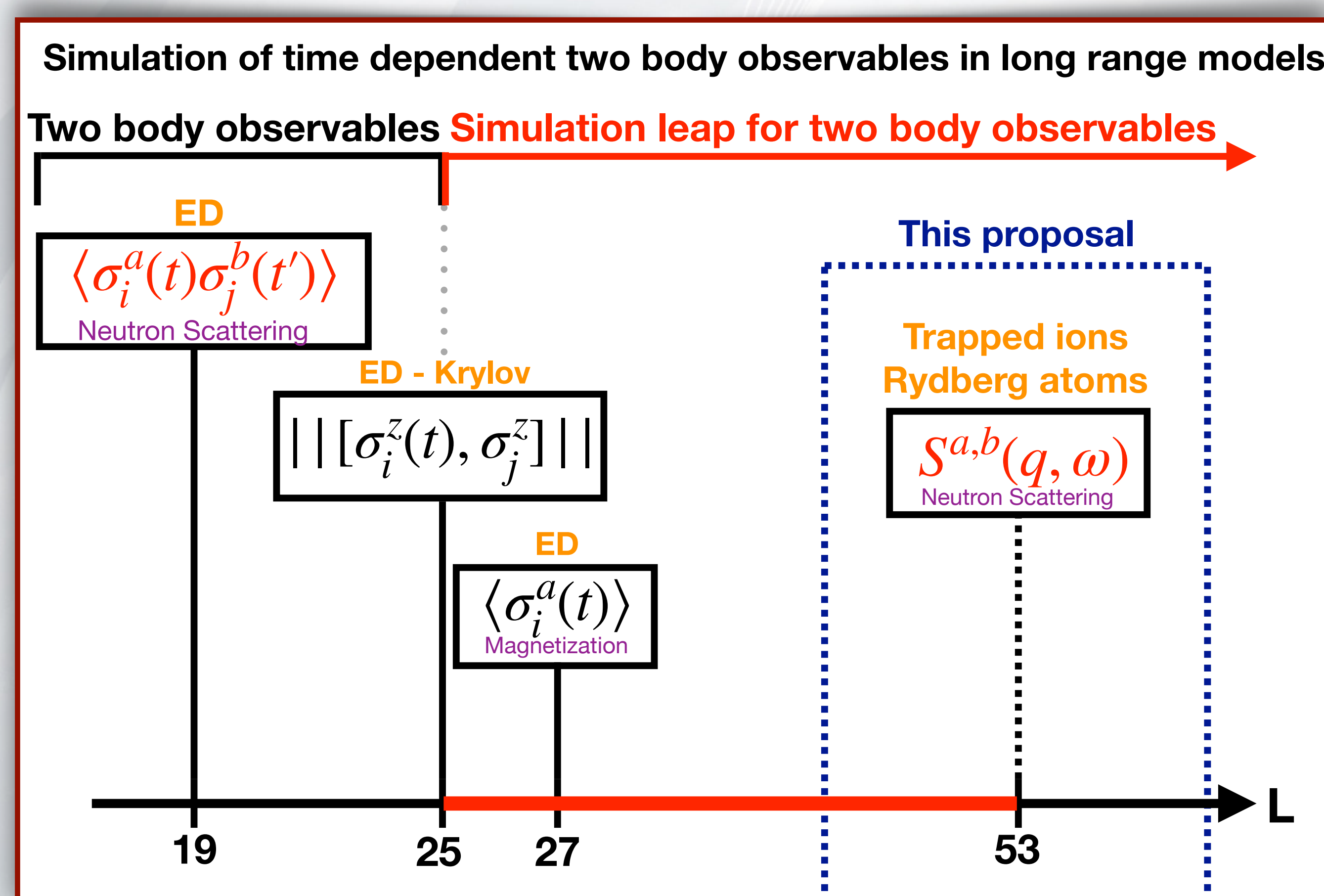
Approximating the dynamical structure factor $S^{\alpha,\beta}_{t_0,t_1}(q,\omega)$ within a constant error $\varepsilon \le 1/8$ over an interval of time $[t_0, t_1]$ is BQP-hard.

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

arXiv: 1912.0607

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

$$\hat{H}(J,B) = \sum_i B_z\sigma^z_i - \sum_{i<j}\frac{J}{|r_i - r_j|^\alpha}\sigma^x_i\sigma^x_j$$



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.

HOW? DSFS IN QUANTUM SIMULATORS

Analogue quantum simulator: Non universal, designed to tackle a specific class of problems

Optical lattices → Fermi and Bose Hubbard models, Lattice gauge theories, spin systems

Fukuhara, et. al. Nature 2013, Nature 2013, PRL 2015. Mazurenko, et. al, Nature 2017. etc…

Ready to perform the experiment

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. etc…

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. etc…

Superconducting qubits → Designed for universal computations. Used for Hubbard and XY models

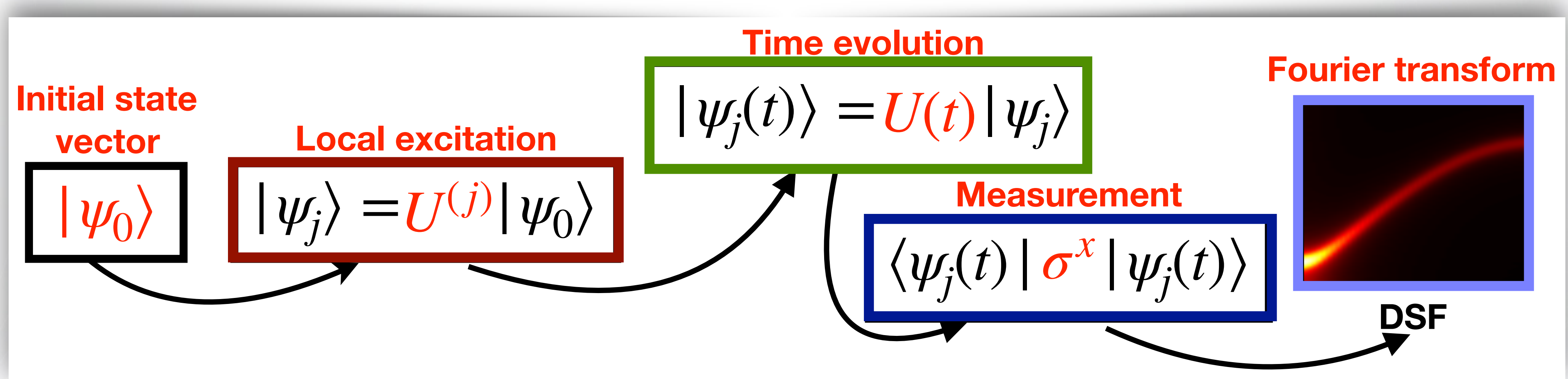
Hacohen-Gourgy, et. al. PRL 2015. Roushan, et. al. Science 2017. etc…?

Measurement is usually done by a single shot. Based on the fluorescence of the ions or atoms

↓

We need to get an unequal time correlation from one single measurement

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 $U^{(j)} = \frac{1}{\sqrt{2}}(1 - i\sigma_j^x)$

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

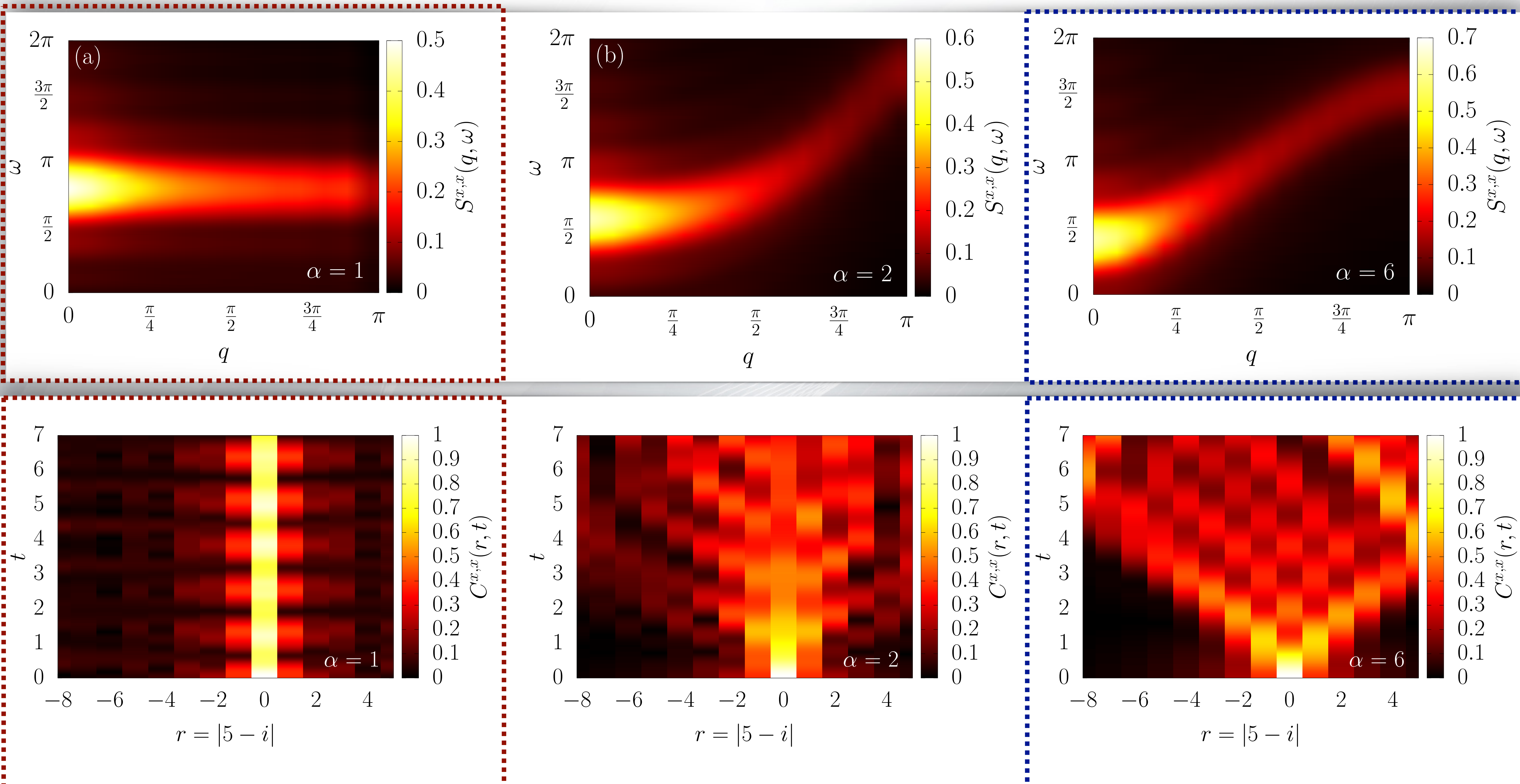
Full ED: 16-18 sites

Lanczos: 28 sites, 250 states

TVDP: 128 sites, equal time correlators

Confinement

"Nearest neighbour"



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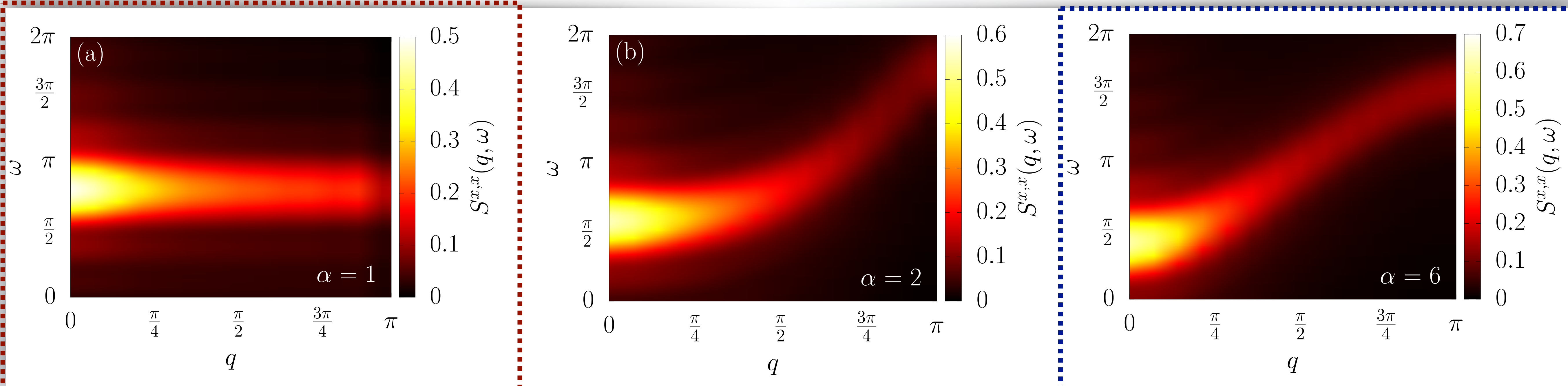
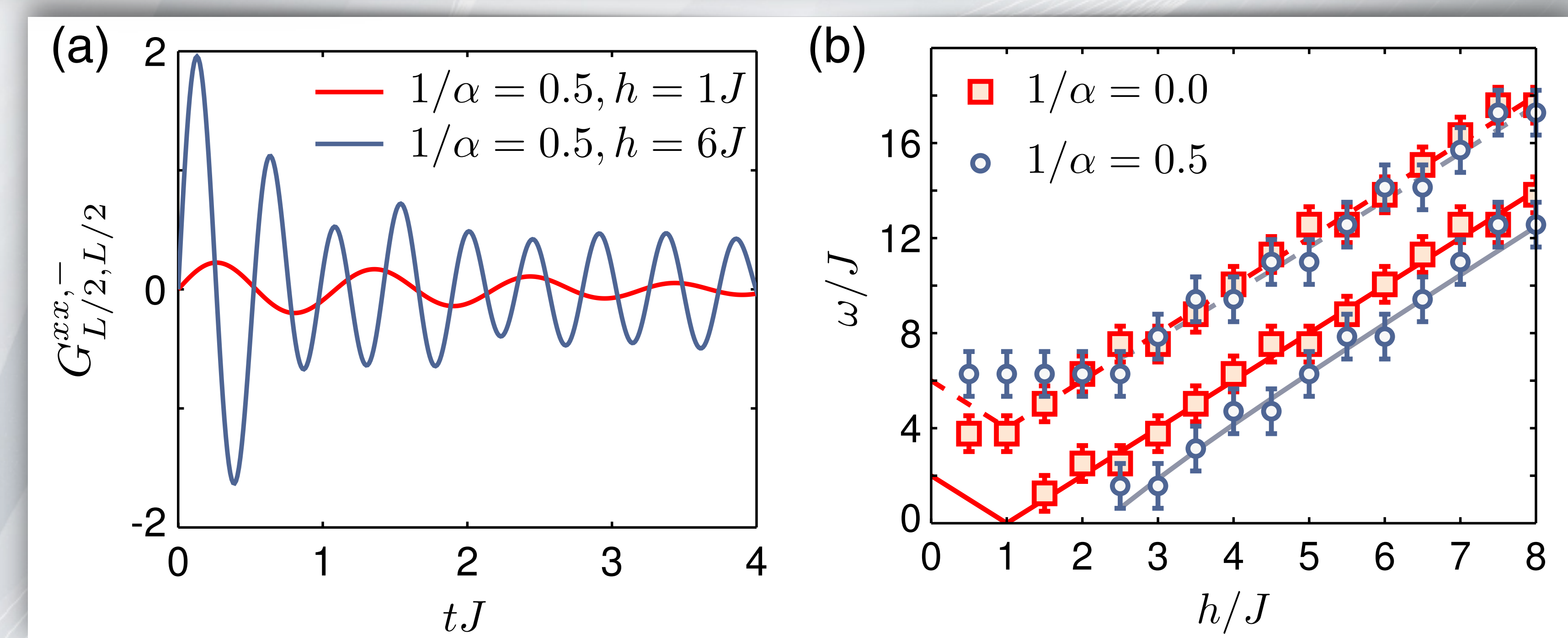




Frequency of oscillations is related to the gap

Quantum phase transition at $h/J = 1$

Knap, et. al. PRL 2013

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
$J \propto \Omega$	$J \propto \Omega$
$\alpha \propto 6$	$B_z \propto \Omega$
Ω is the Rabi frequency	$\alpha \in [0,3]$

Ω 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

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

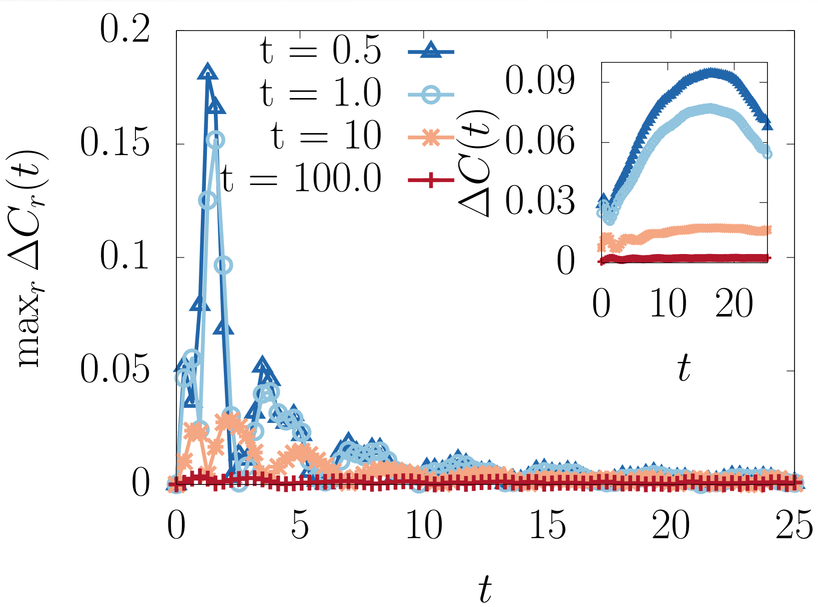
Random transverse field

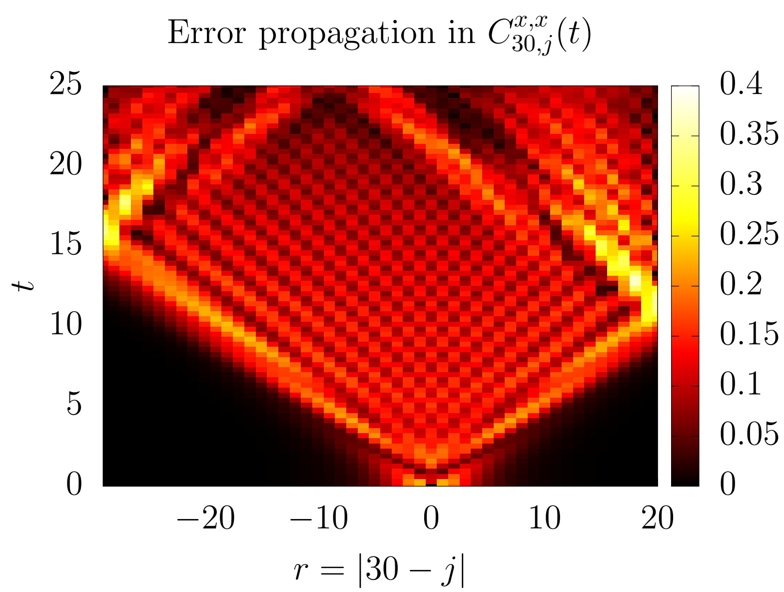
$$B_z = B + A\xi$$

Experiments have control up to $A \propto 0.01$

DSF: FOURIER TRANSFORM AS A NOISE FILTER

MLB, et al. arXiv: 1912.0607



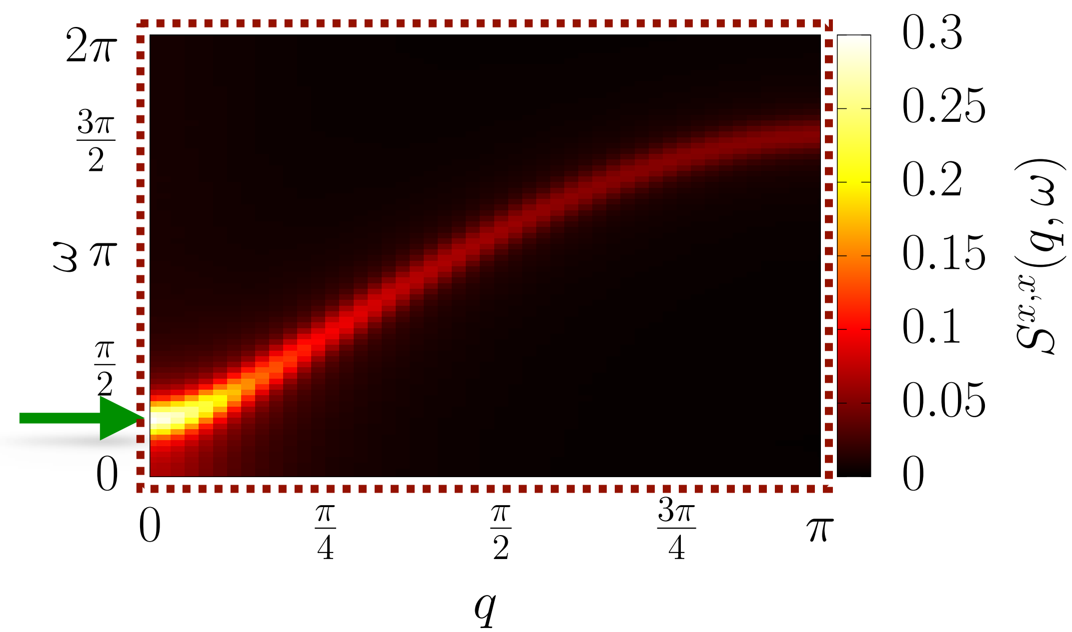


Initial state fidelity - Short range model

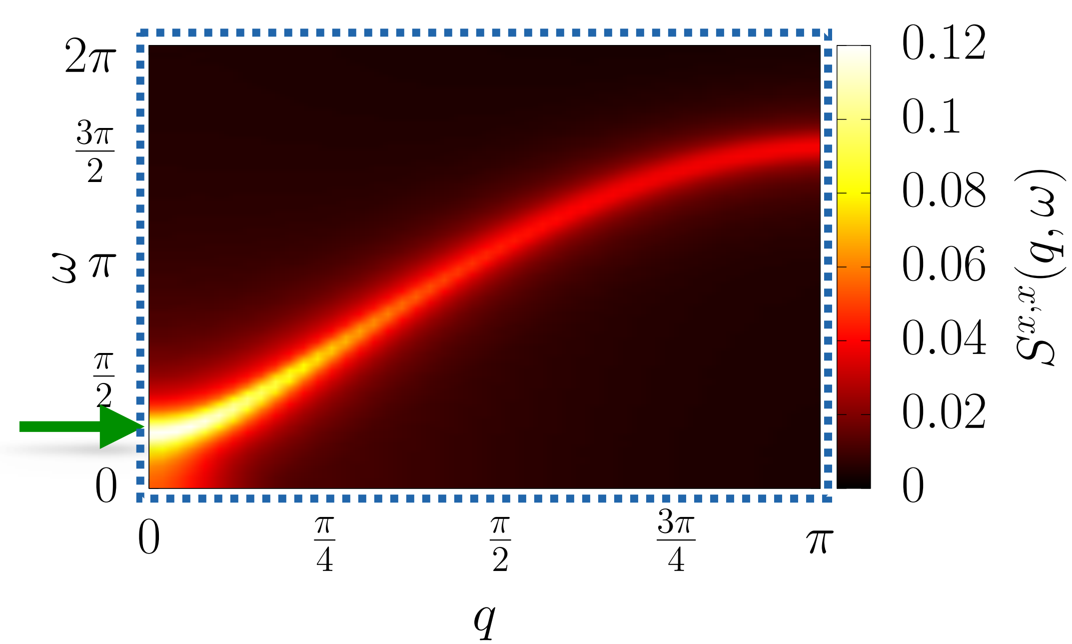
Correlators $\Delta C_r(t) = |\,\tilde{C}_r(t) - C_r(t)\,|$

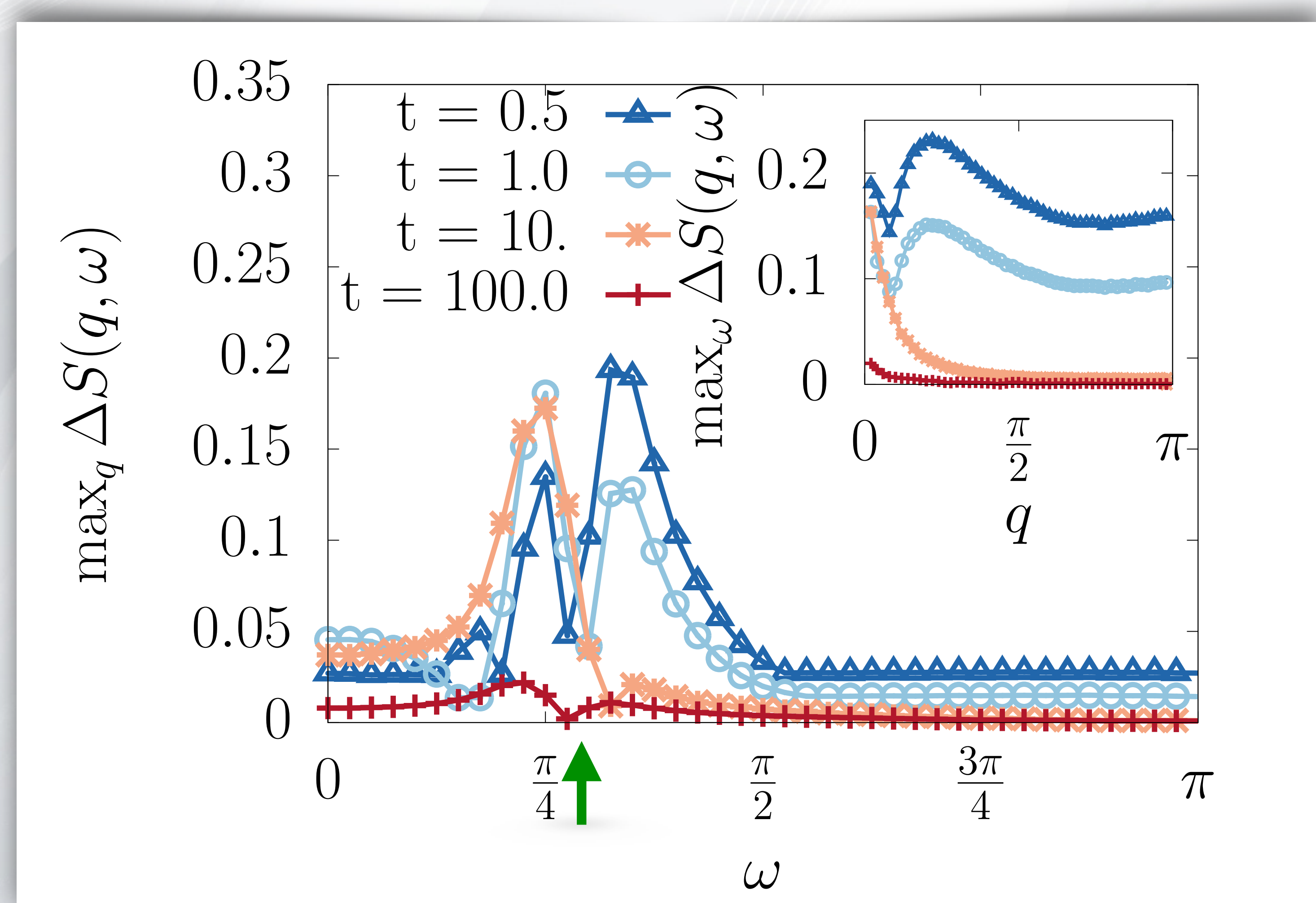
DSF $\Delta S(q,\omega) = |\,\tilde{S}(q,\omega) - S(q,\omega)\,|$

(a) Exact solution



(e) Adiabatic evolution





DSF: FOURIER TRANSFORM AS A NOISE FILTER

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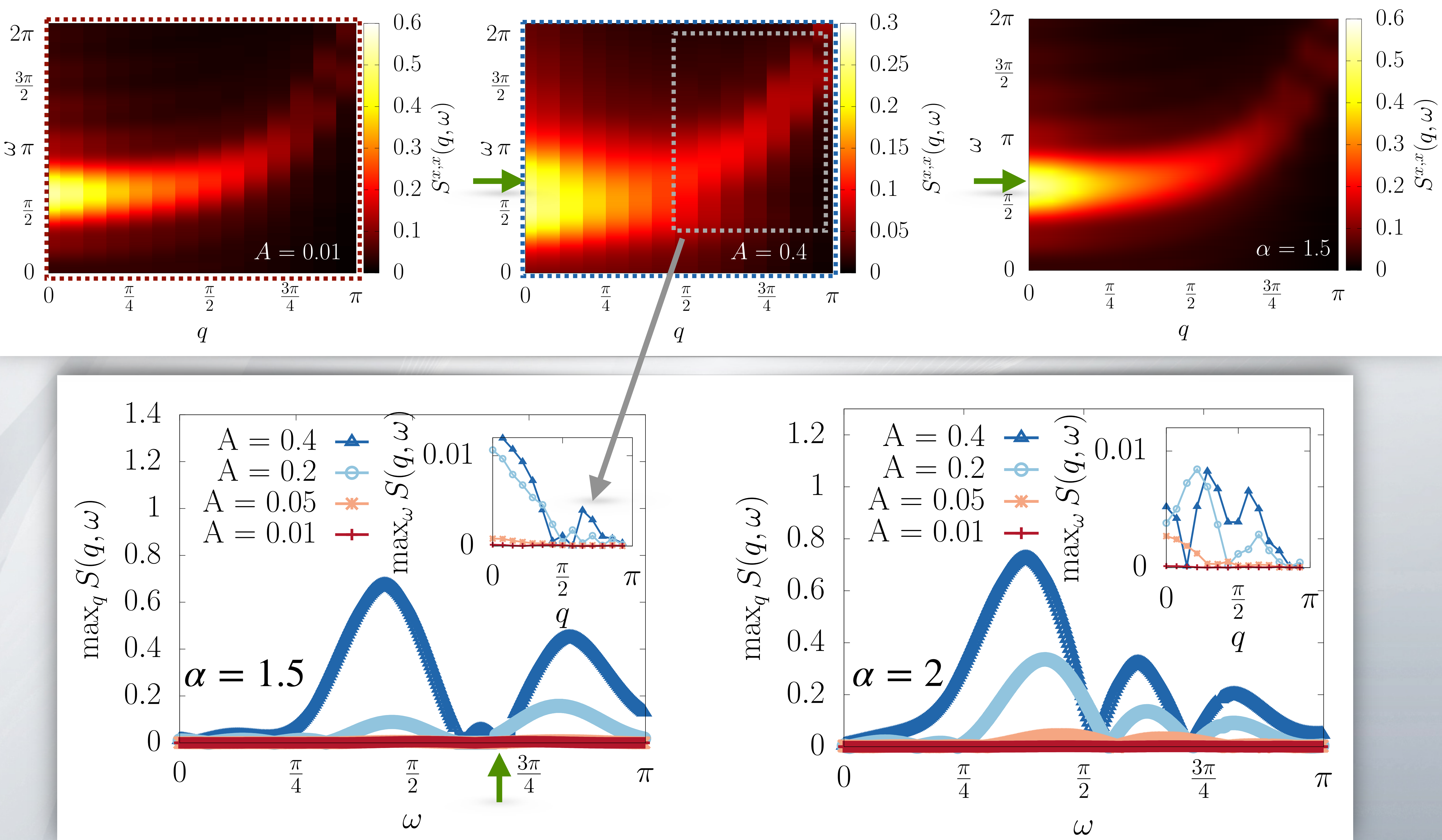
Random fields - Long range model

Quantitative

Qualitative

Clean limit $L = 14$



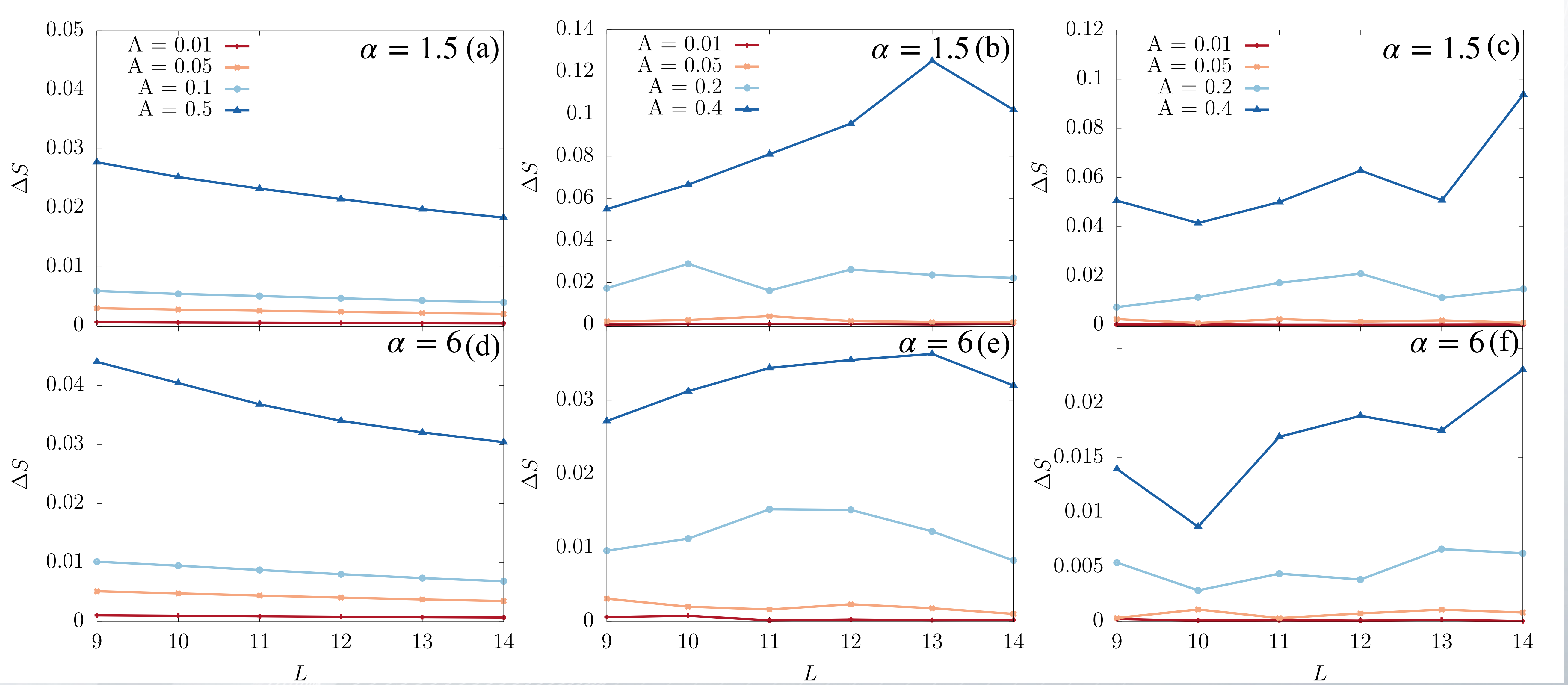
TEST CASES AND NOISE MODELS

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

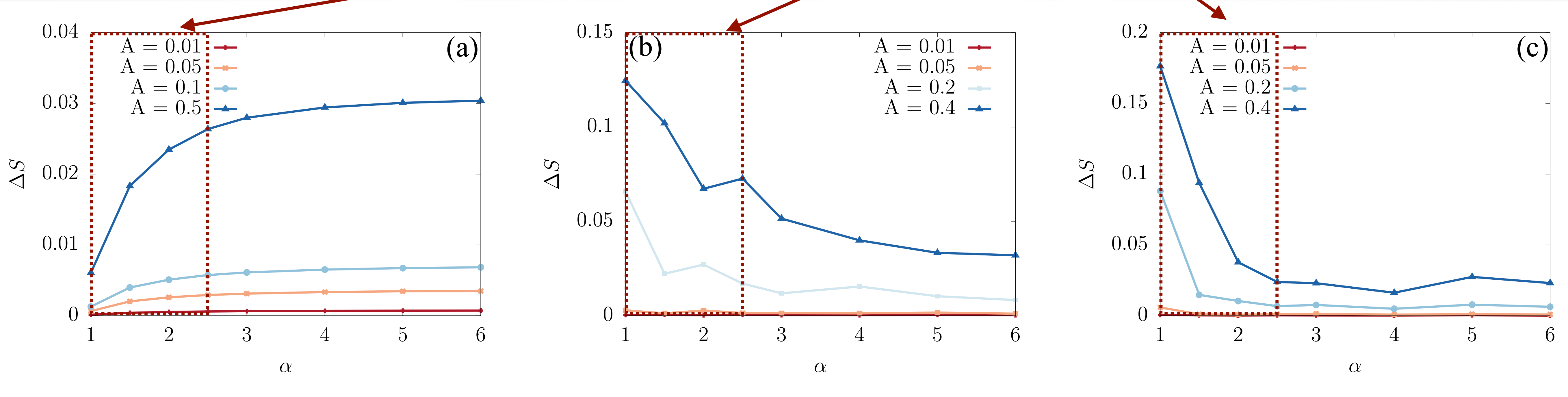
Imperfection effects are negligible and scale in a controlled way up to $A \propto 0.05$

TEST CASES AND NOISE MODELS

MLB, et al. arXiv: 1912.0607

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

Confinement of excitations



Globally fluctuating Ising couplings

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

Small noise: equilibrium dynamics.

Strong noise: Floquet physics (?)

Random Ising interactions

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

Random transverse field

$$B_z = B + A\xi$$

Small noise: equilibrium dynamics.

Strong noise: Many body localisation (?)

Access to confined regime up to $A \propto 0.05$

CONCLUSIONS

We have shown that DSFs can be accessed with analog quantum simulators

For the case of short and long range TFIM, the DSF is robust to experimental imperfections

We can access exotic confined states of the long range TFIM

Strong levels of imperfections can lead to interesting many body phenomena on exotic states

PROMISING DIRECTIONS

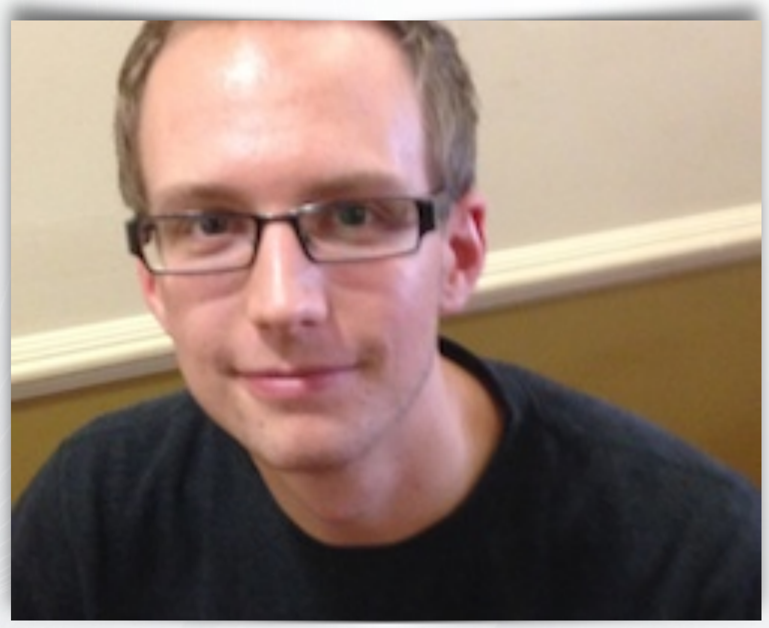
Which other initial excitations can we use?

Do we recover useful Green functions? ARPES, Raman?

Transport properties of Hubbard models out of equilibrium?

Can we study many body effects from strong imperfection levels?

THANK YOU!



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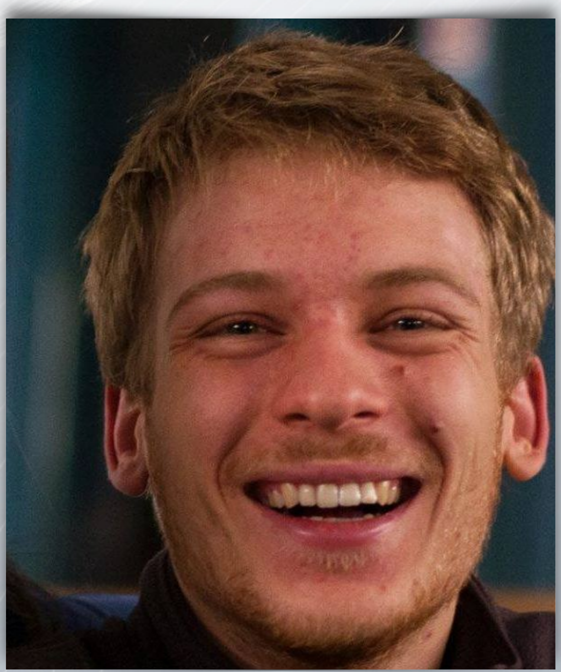

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