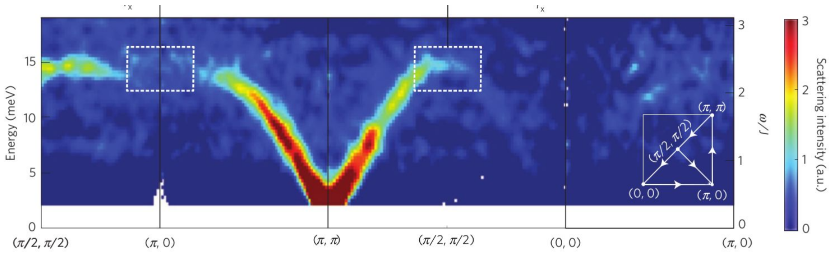
Quench Spectroscopy: Low-energy excitations from real-time dynamics

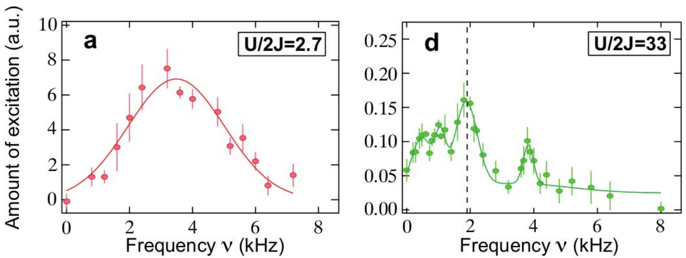
[T. Comparin, F. Mezzacapo, T. Roscilde - ENS de Lyon]

How to probe elementary excitations in quantum matter?

Traditional spectroscopy: Excite the system at a specific (**k**,**ω**), probe energy absorption, extract Dynamical Structure Factor (examples: neutron scattering, Bragg spectroscopy).



2D Heisenberg antiferromagnet [Della Piazza et al., Nat. Phys. 2015]



1D Bose-Hubbard chain [Clement et al., JLTP 2010]

Quench spectroscopy: Prepare an initial state which contains excitations at many (**k**,**ω**), let it evolve in time, examine the contribution of each excitation to the dynamics of correlations.

Dynamical Structure Factor vs Quench Spectroscopy

Menu&Roscilde PRB 2018
Frérot et al., PRL 2018
Schemmer et al., PRA 2018
Villa et al., PRA 2019&2020

Traditional spectroscopy gives access to single quasiparticle excitations:

$$\mathrm{DSF}(\mathbf{k},\omega)=\sum_{i,j}\int dt\,\frac{e^{i\omega t-i\mathbf{k}(\mathbf{r}_i-\mathbf{r}_j)}}{N}\langle S_i^z(t)S_j^z(0)\rangle=\sum_{n,m}\frac{e^{-\beta E_n}}{Z}\left|\langle m|S_{\mathbf{k}}^z|n\rangle\right|^2\delta(\omega-\omega_{nm})$$

It peaks at the quasiparticle dispersion $\omega=E_{\mathbf{k}}$ [for other models, replace $S_{\mathbf{k}}^z$ with the operator that creates a quasiparticle with momentum **k** - see for instance Villa et al., PRA 2019].

Quench spectroscopy gives access to two-quasiparticles excitations:

$$\mathrm{QS}(\mathbf{k},\omega)=\sum_{i,j}\int dt\,\frac{e^{i\omega t-i\mathbf{k}(\mathbf{r}_i-\mathbf{r}_j)}}{N}\langle\Psi(t)|S_i^zS_j^z|\Psi(t)\rangle=\sum_{n,m}\langle\Psi_0|n\rangle\langle m|\Psi_0\rangle\langle n|S_{\mathbf{k}}^zS_{-\mathbf{k}}^z|m\rangle\delta(\omega-\omega_{nm})$$

It has a peak at $\omega=2E_{\mathbf{k}}$ (for independent quasiparticles), or it may have richer structure (quasiparticle interactions - including bound states?).
It lets us explore the connection between elementary excitations and correlation spreading.

In practice: Quench Spectroscopy with quantum simulators

Current quantum simulators have access to quench dynamics starting from a “simple” initial state.
What would one observe through Quench Spectroscopy?

Models we are looking at

- 2D Heisenberg antiferromagnet (ultracold fermions with quantum gas microscope, e.g. in Greiner’s lab).
- Ferromagnetic dipolar XX model (Rydberg atoms, cf. D. Barredo’s talk this morning):

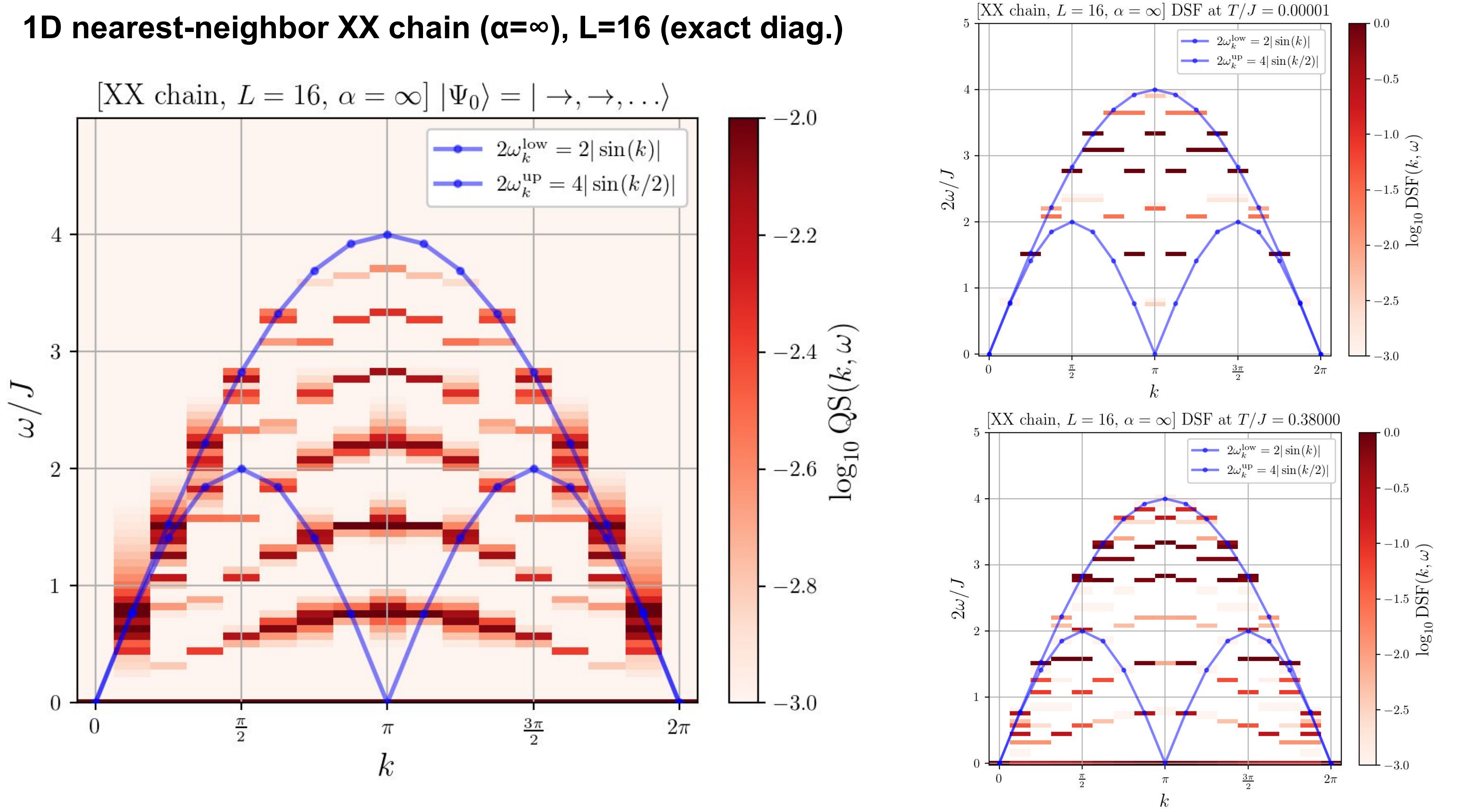
$$H = \sum_{i,j} \frac{J}{r_{ij}^{\alpha}} \left(S_i^x S_j^x + S_i^y S_j^y \right)$$

with the initial state being a low-energy product state (mean-field), e.g.:

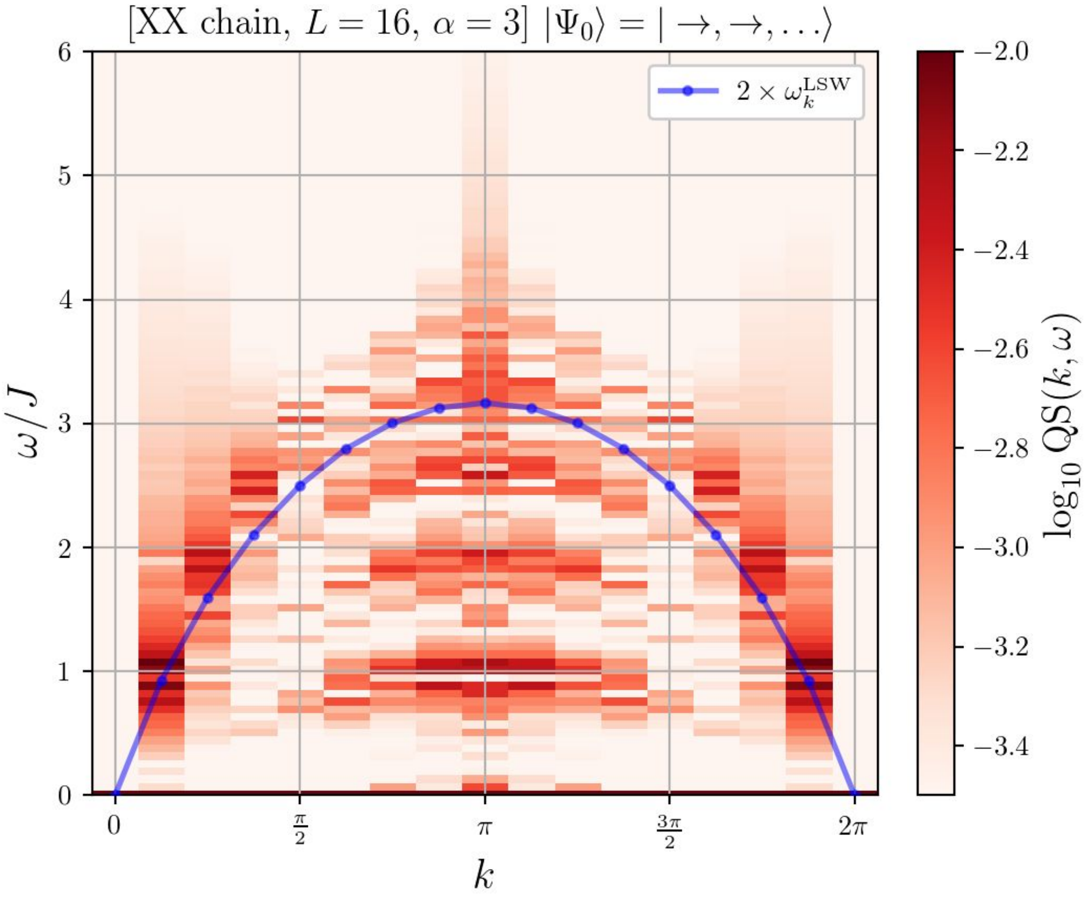
$$|\Psi_0\rangle = |\rightarrow, \rightarrow, \ldots\rangle$$

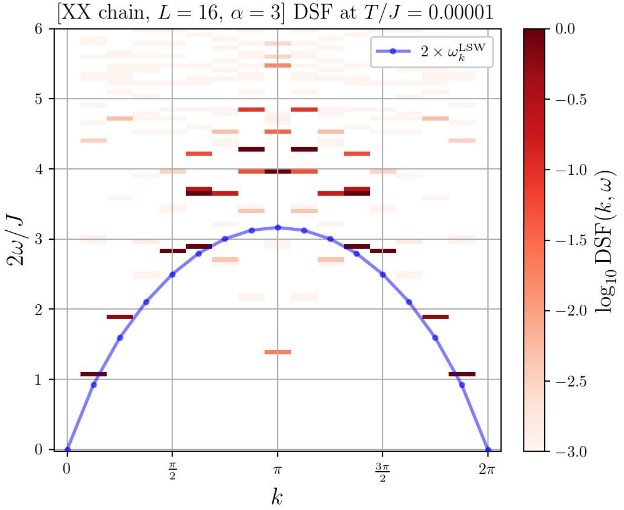
We simulate quantum dynamics with different numerical schemes: Exact diagonalization on small systems, time-dependent Variational Monte Carlo, Discrete Truncated Wigner Approximation.

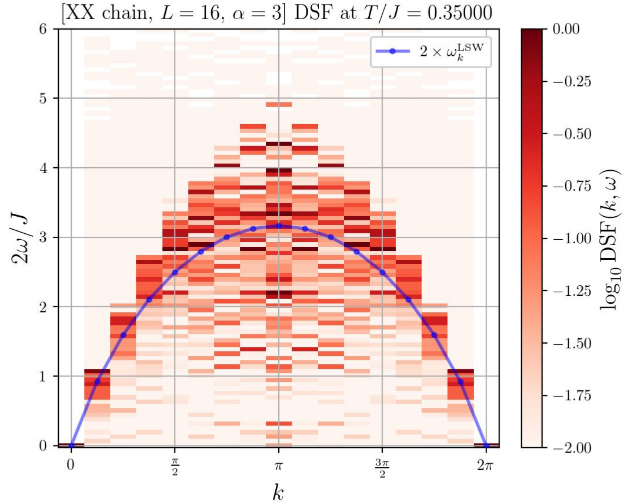
1D nearest-neighbor XX chain (α=∞), L=16 (exact diag.)



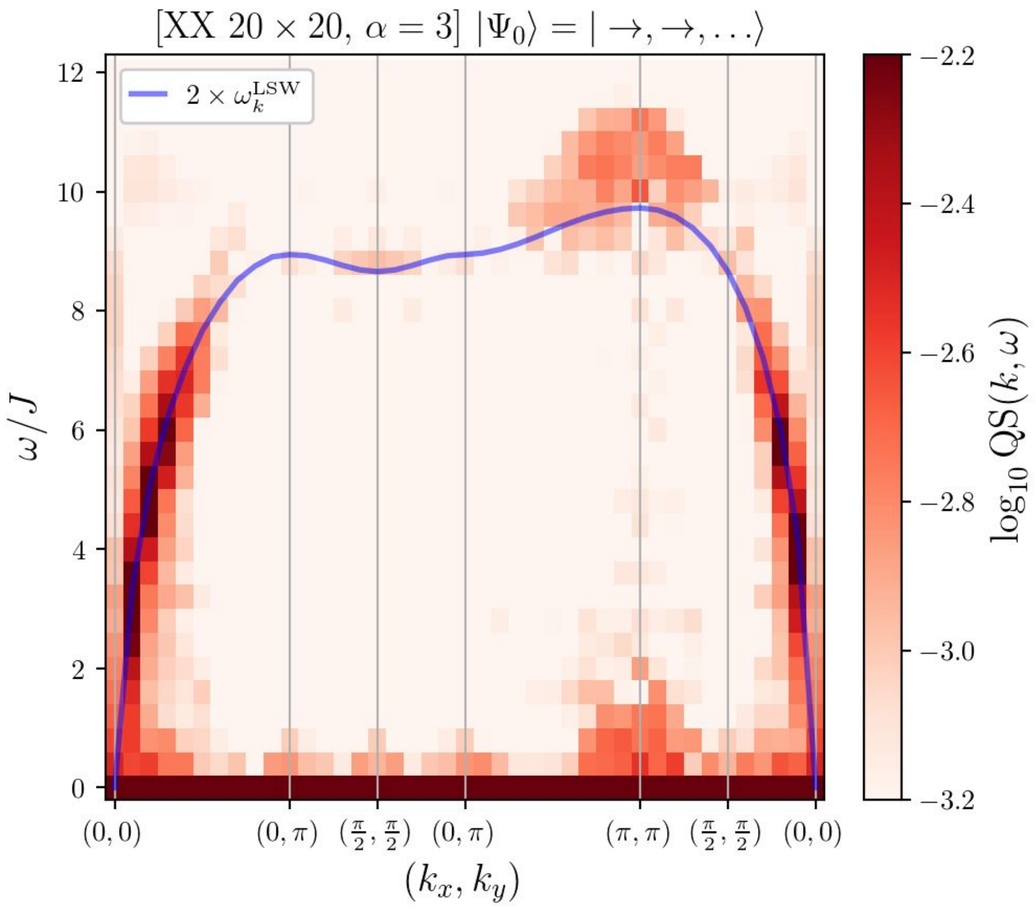
1D dipolar XX chain (α=3), L=16 (exact diag.)

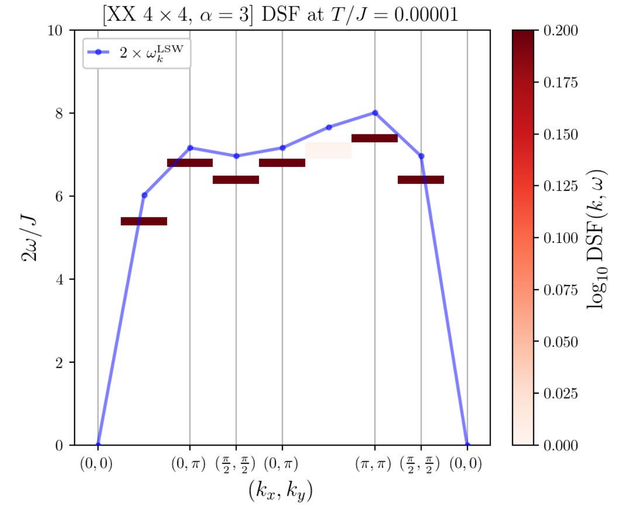


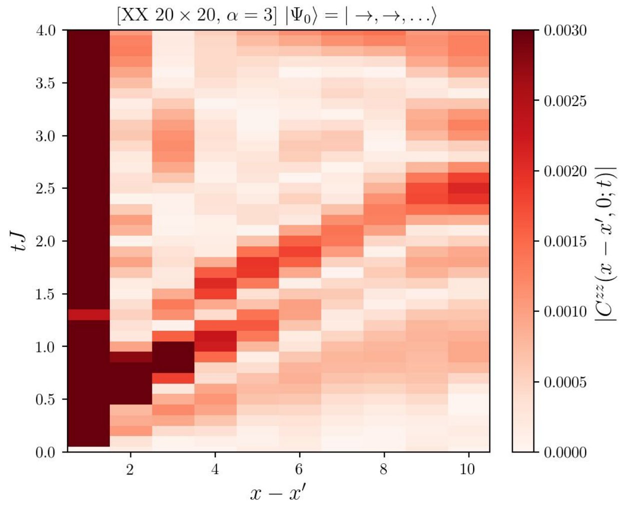




2D dipolar XX model (α=3), 4x4 (ED) and 20x20 (DTWA)







Quench spectroscopy of 2D Heisenberg antiferromagnet, from Néel state [preliminary]
(TVMC on 6x6 square, through mapping to XXZ model)