Matrix product state formulation of frequency-space dynamics at finite temperatures

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Alexander C. Tiegel, Salvatore R. Manmana, Thomas Pruschke, and Andreas Honecker,
Phys. Rev. B (rapid comm.) **90**, 060406(R) (2014).

Numerics for Correlated Systems in Göttingen: Talk to these people

I.) Matrix Product States:

Alexander Tiegel
→ Poster P10

Thomas Köhler
→ Poster P14

II.) VCA/CPT for spin systems:

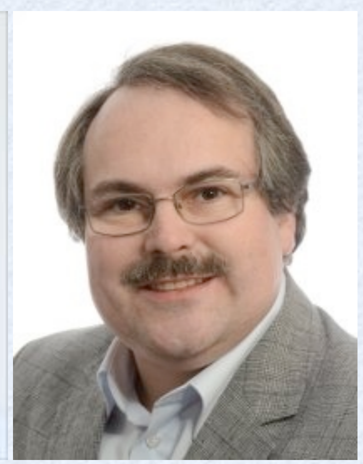
Benjamin Lenz
→ Poster P9

III.) QMC/Dual Fermions:

René Kerkdyk
→ **Talk F7**
(Tomorrow)

Patrick Haase
→ Poster P4

Thomas Pruschke



Andreas Honecker
(Göttingen
→ Cergy Pontoise, Paris)

Funding:

FOR1807 “Advanced Computational Methods for strongly correlated quantum systems”

SFB/CRC 1073 “Atomic Scale Control of Energy Conversion”

Helmholtz Virtual Institute “New states of matter and their excitations”

Dynamical correlation functions: DMRG approach for T>0?

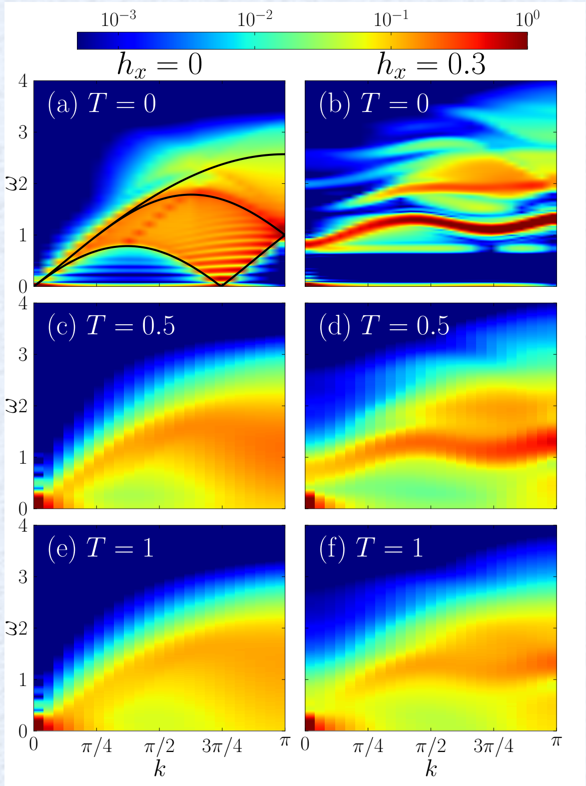
[A.C. Tiegel, S.R. Manmana, T. Pruschke, and A. Honecker, PRB **90**, 060406(R) (2014)]

Main question of this talk:
Direct computation of dynamical spectral functions via DMRG at T>0?

➠ Use Liouvillian formulation:

$$G_A(k,\omega) = -\frac{1}{\pi}\mathrm{Im}\left\langle \Psi_T \left| A^\dagger \frac{1}{z-\mathcal{L}} A \right| \Psi_T \right\rangle$$

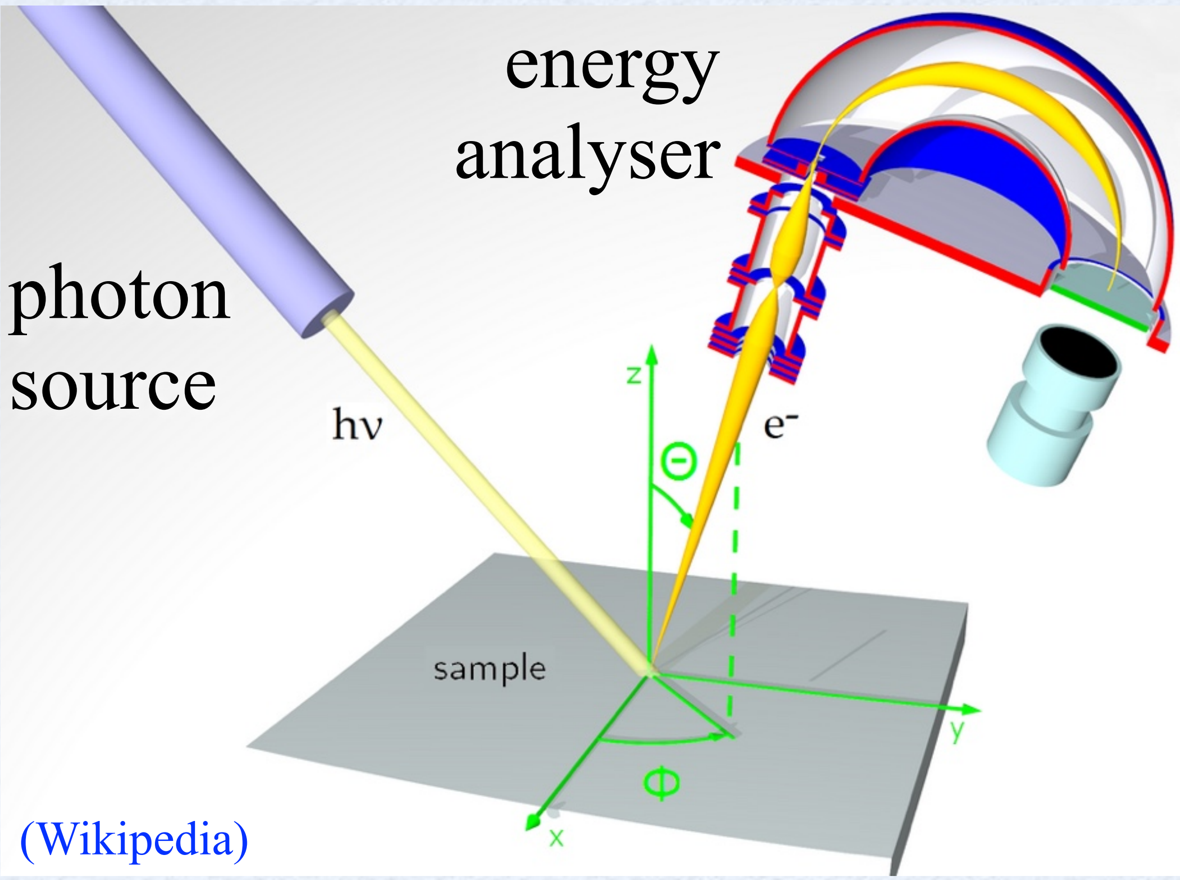
$$\mathcal{L} = \mathcal{H}_P \otimes I_Q - I_P \otimes H_Q$$



- here: proof of principle results (no optimized code)
- flexibility of approaches to resolvent
- *high* resolution, small errors
- works at all frequencies
- no further input needed (e.g. linear prediction)

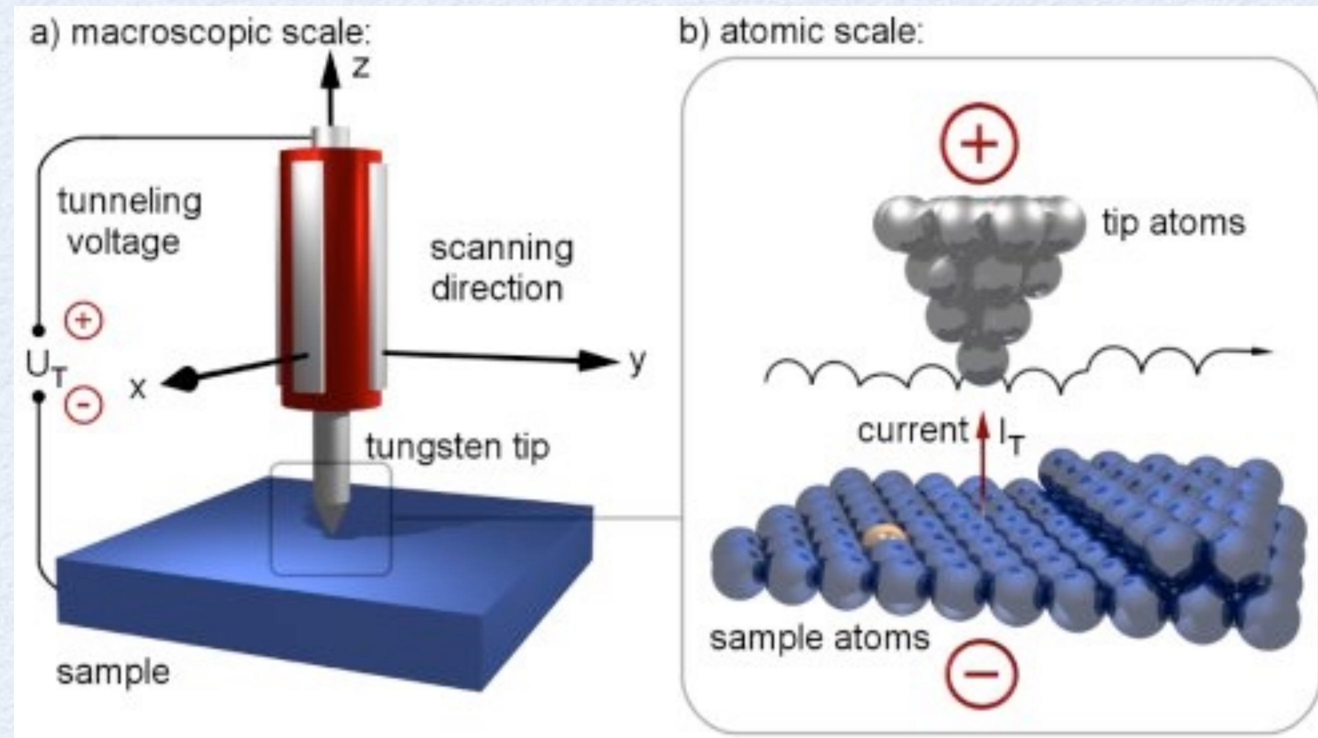
Excitations in Quantum Many-Body Systems: Dynamical Spectral Functions

angle-resolved photoemission (ARPES)



(Wikipedia)

scanning-tunneling spectroscopy



(www.physics.rutgers.edu/bartgroup/)

Linear response: measure quantities of type:

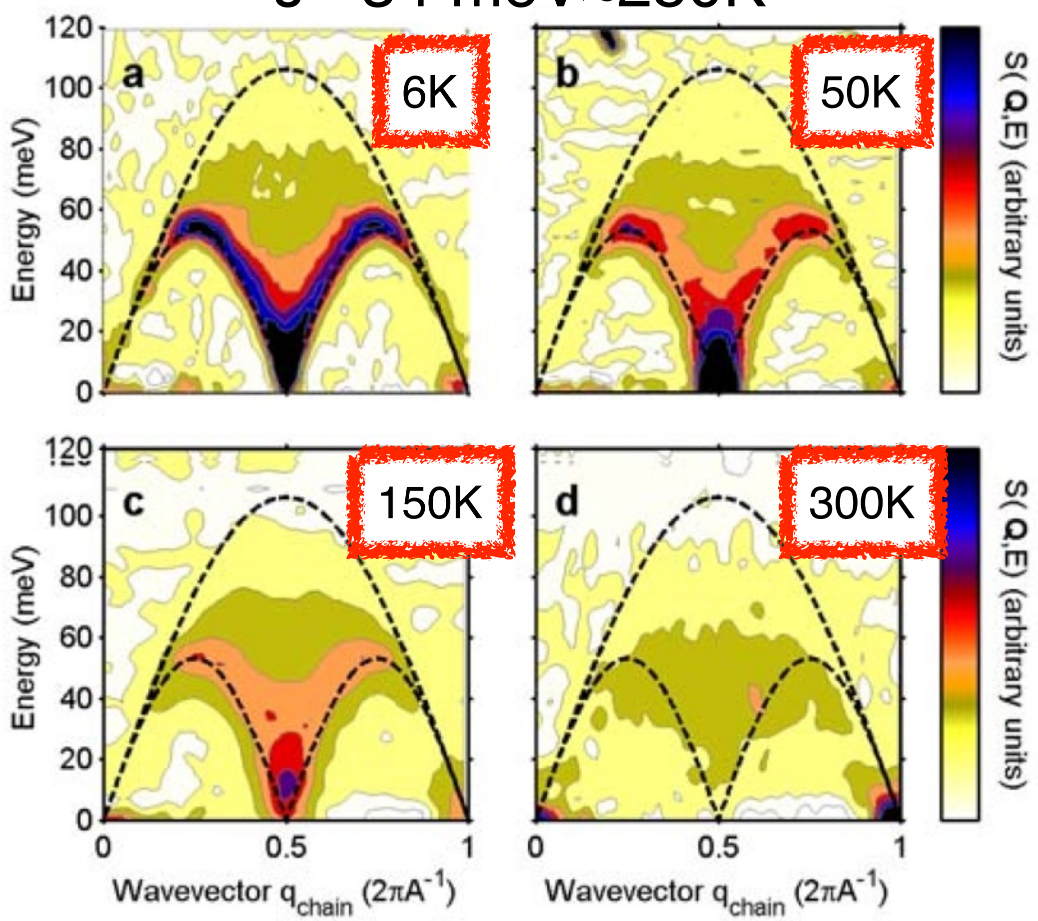
$$C_{B^\dagger,A}(\omega) \equiv \sum_n \langle \Psi_0 | B | n \rangle \langle n | A | \Psi_0 \rangle \, \delta(\omega - (E_n - E_0))$$

➠ insights into (local) density of states, excitations of the system, structure factors

Dynamical spectral functions: finite temperatures

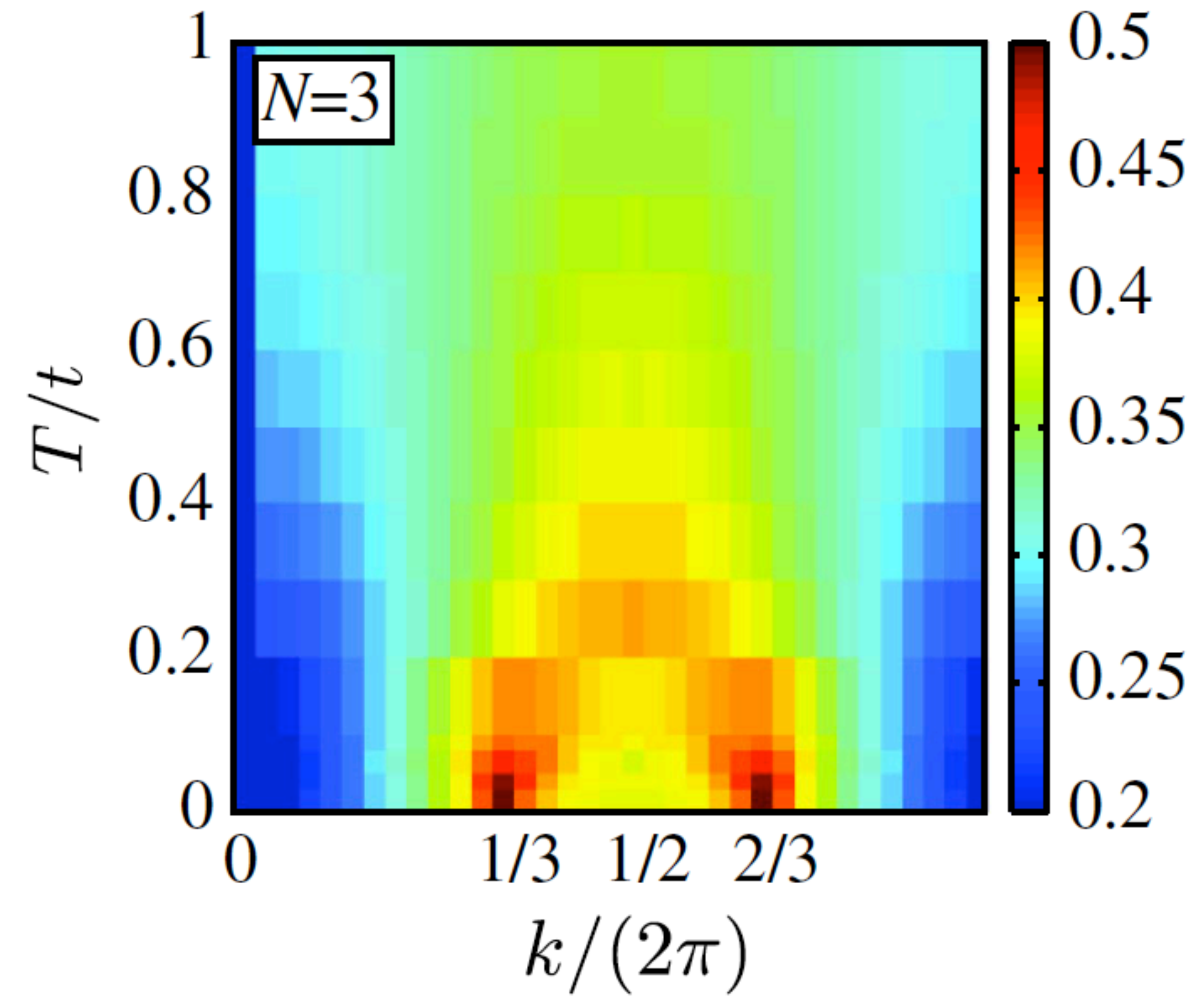
Materials (neutron scattering):

KCuF$_3$: 1D Heisenberg chain, J =34 meV≈250K



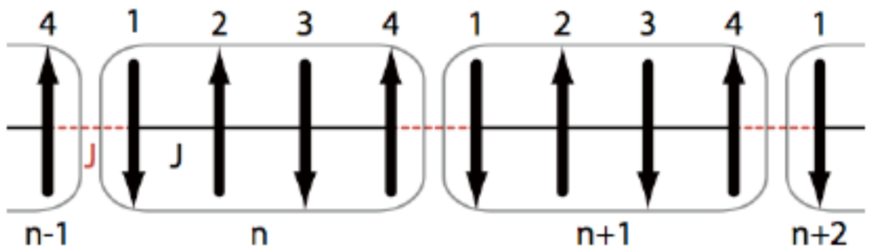
[B. Lake *et al.*, Nat. Mat. 4 (2005) 329]

Optical lattices (QMC prediction) : SU(N) Hubbard systems



[L. Bonnes *et al.*, PRL **109**, 205305 (2012)]

Dynamical spectral functions: Cluster Perturbation Theory for Spins



[A.S. Ovchinnikov, I.G. Bostrem, Vl. E. Sinitsyn, Theor. and Math. Phys. **162**, 179 (2010)]

$$G^{-1} = G_0^{-1} - V$$

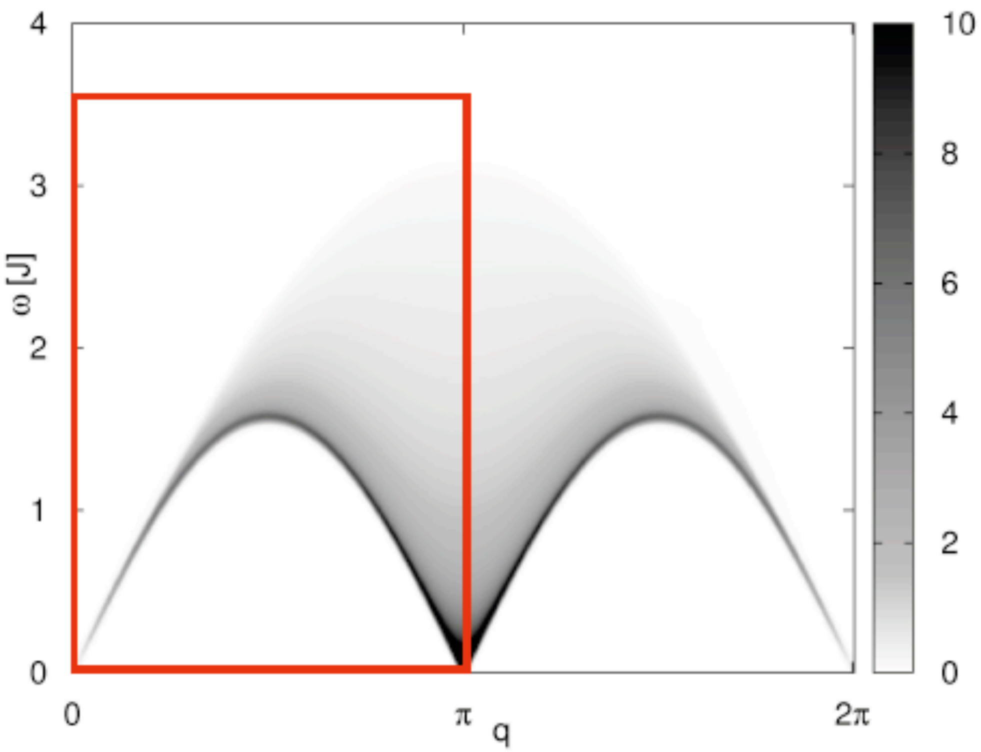
$$G_{CPT}(k,\omega) = \frac{1}{L}\sum_{i,j=1}^{L} G_{ij}(Q,\omega)e^{-ik(r_i-r_j)}$$

1D Heisenberg model

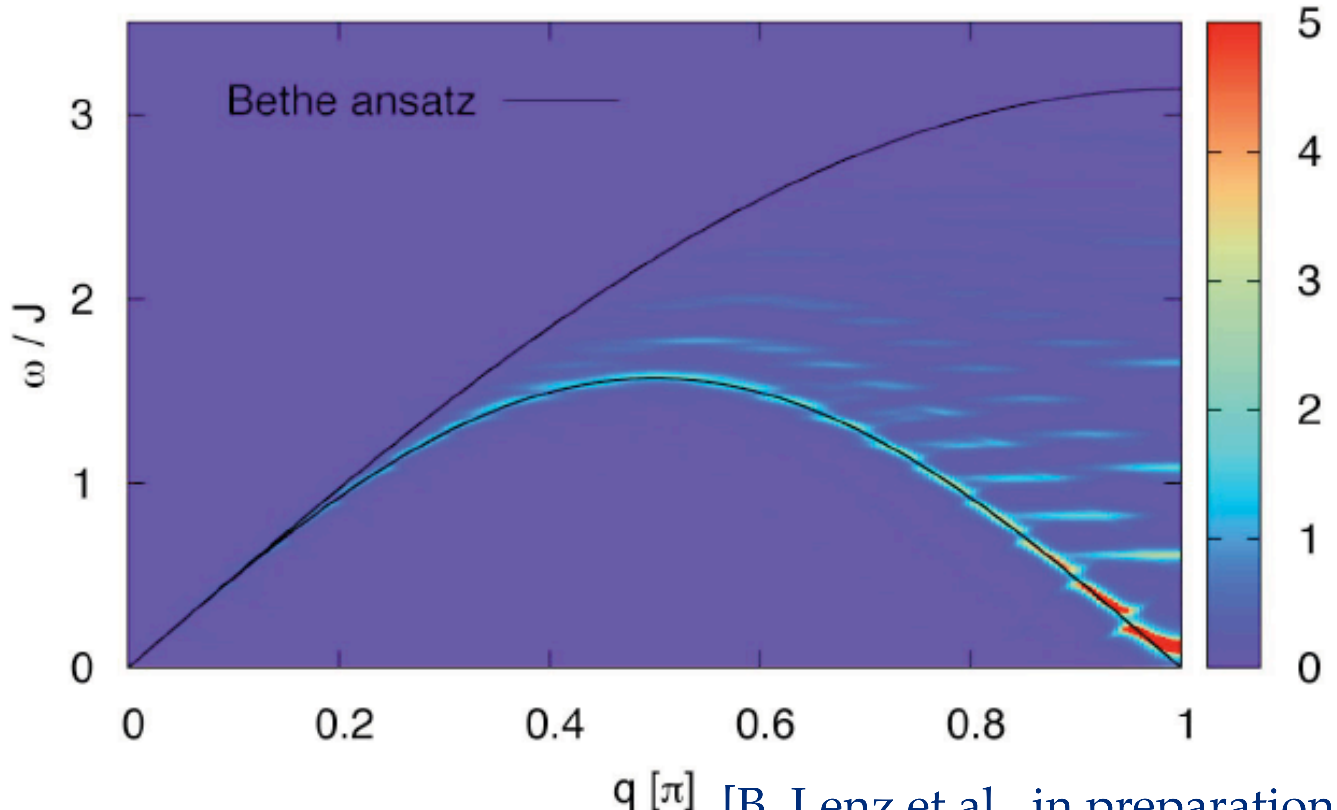
$$\mathcal{H} = -J\sum_i \left(\frac{1}{2}(S_i^+ S_{i+1}^- + S_i^- S_{i+1}^+) + S_i^z S_{i+1}^z\right)$$

Bethe ansatz (L=400)

CPT (L=20)



Klauser et al. (2011)



[B. Lenz et al., in preparation]

Dynamical correlation functions: $T = 0$ vs. $T > 0$

Dynamical correlation functions at T = 0:

$$G_A(\omega) = -\frac{1}{\pi}\mathrm{Im}\left\langle \psi_0 \left| A^\dagger \frac{1}{\omega + E_0 + i\varepsilon - H} A \right| \psi_0 \right\rangle = \sum_n \left|\langle n \left| A \right| \psi_0\rangle\right|^2 \delta\left(\omega - (E_n - E_0)\right)$$

$$\mathcal{H}_0 \left|n\right\rangle = E_n \left|n\right\rangle$$

Dynamical correlation functions at T > 0:

$$G_A(\omega, T) = \frac{1}{Z}\sum_{n,m} e^{-\beta E_m} \langle m|A|n\rangle\langle n|A|m\rangle\delta(\omega - (E_n - E_m))$$

➠ Need the full spectrum...difficult ☹

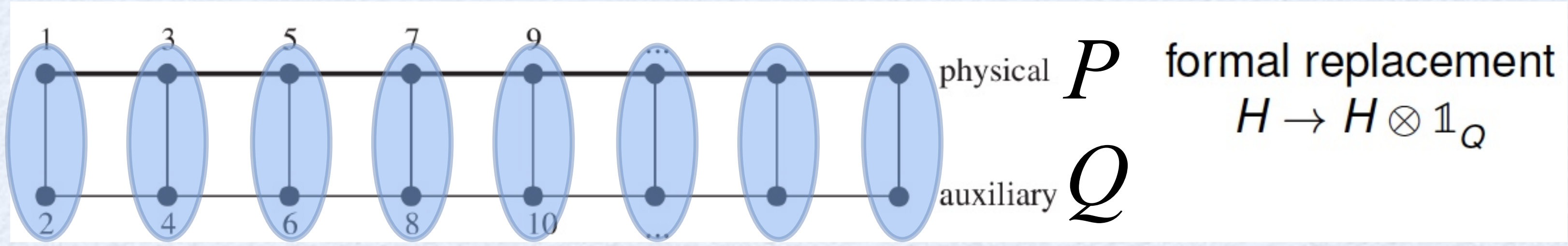
Ways out: continued fraction expansion, (D)DMRG, QMC,...

Here: DMRG+continued fraction/Chebyshev expansions

Finite temperature methods: purification with matrix product states

☞ Compute thermal density matrix via a pure state in an extended system:

[U. Schollwöck, Annals of Physics (2011)]



$$|\Psi_T\rangle \sim e^{-(H_P \otimes I_Q)/(2T)} \left[\otimes_{j=1}^{L} |\mathrm{rung} - \mathrm{singlet}\rangle_j \right]$$

$$\Rightarrow \varrho_T = e^{-H/T} = \mathrm{Tr_Q} |\Psi_T\rangle \langle \Psi_T|$$

☞ Real time evolution at finite temperature:

$$|\Psi_T\rangle (t) = e^{-i(H_P \otimes U_Q)t} |\Psi_T\rangle \Rightarrow G_A(T,t) \overset{\text{Fourier}}{\Rightarrow} G_A(T,\omega)$$

- Problem: reach long times for large systems
- Ways out: linear prediction, backward time evolution in Q

[T. Barthel, U. Schollwöck & S.R. White, PRB (2009); C. Karrasch, J.H. Bardarson & J.E. Moore, PRL (2012)]

Dynamical correlation functions at finite T: Liouvillian formulation

$$G_A(\omega, T) = \frac{1}{Z} \sum_{n,m} e^{-\beta E_m} \langle m|A|n\rangle\langle n|A|m\rangle \delta(\omega - (E_n - E_m))$$

Note: 1) *Difference* of *all* energies

2) MPS approach: $|\Psi_T\rangle$ vector in the Liouville space spanned by $\mathcal{H}_P \otimes \mathcal{H}_Q$

➠ Dynamics is actually governed by Liouville equation [Barnett, Dalton (1987)]

$$\frac{\partial}{\partial t}|\Psi_T\rangle = -i\mathcal{L}|\Psi_T\rangle, \qquad \mathcal{L} = \mathcal{H}_P \otimes I_Q - I_P \otimes H_Q$$

(backward evolution in Q by Karrasch et al.)

$$G_A(k, \omega) = -\tfrac{1}{\pi}\mathrm{Im}\left\langle \Psi_T \left| A^\dagger \tfrac{1}{z-\mathcal{L}} A \right| \Psi_T \right\rangle$$

[A.C. Tiegel et al., arXiv:1312.6044 : proof of principle calculations]
Earlier: Superoperator approach to mixed-state dynamics [Zwolak & Vidal (2004)]

Liouville space formalism: "Thermofields"

J. Phys. A: Math. Gen. 20 (1987) 411–418. Printed in the UK

Liouville space description of thermofields and their generalisations

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Received 14 January 1986, in final form 13 May 1986

Abstract. The thermofield representation of a thermal state by a pure-state wavefunction in a doubled Hilbert space is generalised to arbitrary mixed and pure states. We employ a Liouville space formalism to investigate the connection between these generalised thermofield wavefunctions and a generalised thermofield state vector in Liouville space which is valid for all cases of the quantum density operator. The system dynamics in the Schrödinger and Heisenberg pictures are discussed.

+ references therein

$$i\frac{d\varrho}{dt} = \left[\hat{H}, \varrho\right] \Rightarrow i\frac{d}{dt}|\varrho\rangle\rangle = \mathcal{L}|\varrho\rangle\rangle$$

von Neumann equation

Liouville equation

Dynamical correlation functions: Lanczos recursion

[E. Dagotto, RMP (1994)]

☞ use continued fraction expansion (CFE)

$$G_A(z) = -\frac{1}{\pi}\mathrm{Im}\left\langle \psi_0 \left| A^\dagger \frac{1}{z-\mathcal{L}} A \right| \psi_0 \right\rangle = -\frac{1}{\pi}\mathrm{Im}\frac{\langle \Psi_0 |\, A^\dagger\; A \,| \Psi_0 \rangle}{z - a_0 - \frac{b_1^2}{z - a_1 - \frac{b_2^2}{z - ..}}}$$

via Lanczos recursion

$$|f_0\rangle \;=\; A\,|\Psi_0\rangle\,, \qquad |f_{n+1}\rangle = \mathcal{L}\,|f_n\rangle - a_n\,|f_n\rangle - b_n^2\,|f_{n-1}\rangle$$

$$a_n \;=\; \frac{\langle f_n |\,\mathcal{L}\,| f_n \rangle}{\langle f_n | f_n \rangle}\,, \qquad b_{n+1}^2 = \frac{\langle f_{n+1} | f_{n+1} \rangle}{\langle f_n | f_n \rangle}\,, \qquad b_0 = 0$$

Dynamical correlation functions: Chebyshev recursion

[MPS: A. Holzner *et al.*, PRB **83**, 195115 (2011); A. Weiße *et al.*, RMP **78**, 275 (2006)]

☞ Representation via Chebyshev polynomials:

$$G_A(\omega) = \frac{2}{\pi W \sqrt{1-\omega'^2}} \left[g_0\, \mu_0 + 2 \sum_{n=1}^{N-1} g_n\, \mu_n T_n(\omega') \right]$$

with

$$\mu_n = \langle t_0 | t_n \rangle = \left\langle \Psi_T \left| A^\dagger T_n(\mathcal{L}') A \right| \Psi_T \right\rangle$$

$$|t_0\rangle = A|\Psi_T\rangle, \quad |t_1\rangle = \mathcal{L}'|t_0\rangle, \quad |t_n\rangle = 2\mathcal{L}'|t_{n-1}\rangle - |t_{n-2}\rangle$$

W : bandwidth of $\mathcal{L}$

$\mathcal{L}'$: rescaled Liouvillian, so that $W \to [-1, 1]$

$\omega' \in [-1, 1]$, $T_n(\omega') = \cos\left[n\,(\arccos \omega')\right]$

g_n : damping factors $\to$ Gaussian broadening $\eta \sim 1/N$

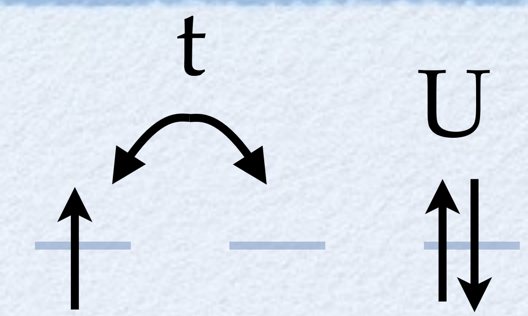
$$g_n^J = \frac{(N-n+1)\cos\frac{\pi n}{N+1} + \sin\frac{\pi n}{N+1}\cot\frac{\pi}{N+1}}{N+1}$$

"Jackson damping"

Effective Models for Quantum Magnets

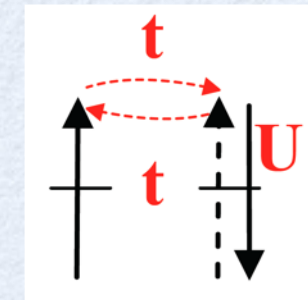
Starting point : Hubbard model

$$\mathcal{H} = -t \sum_{\langle ij \rangle, \sigma} \left[c^\dagger_{i+1,\sigma} c_{i,\sigma} + h.c. \right] + U \sum_i n_{i,\uparrow} n_{i,\downarrow}$$



Heisenberg exchange: 2nd order perturbation theory for U >> t

$$J \, \vec{S}_1 \cdot \vec{S}_2 \qquad J = \frac{4t^2}{U}$$



Real materials: additional spin-orbit coupling

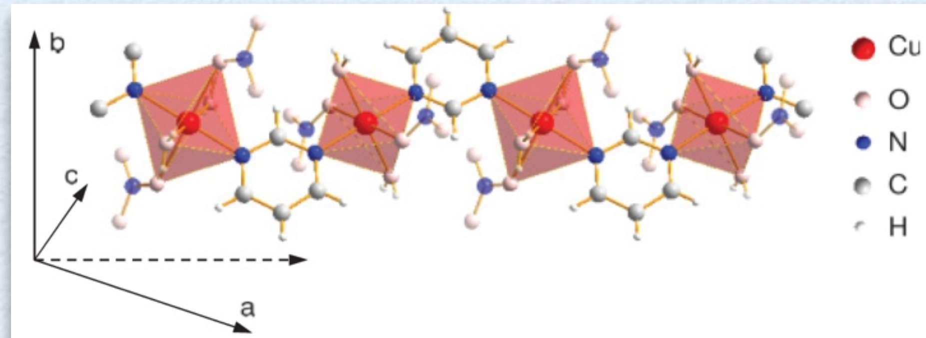
$$\sim \lambda \vec{L} \cdot \vec{S} \quad \lambda \ll 1 \qquad \vec{D} \cdot \left(\vec{S}_1 \times \vec{S}_2 \right) \qquad |\vec{D}| \sim \lambda$$

- Heisenbergterm symmetric under permutations, SU(2) invariant
- Dzialoshinskii-Moriya-Term antisymmetric, breaks SU(2) invariance
- Typically D ~ 1 - 10% J

Here: interplay of D, J and T in dynamical quantities

Dynamical properties of quantum magnets: ESR on Cu-PM in magnetic fields

Copper pyrimidine dinatrate:



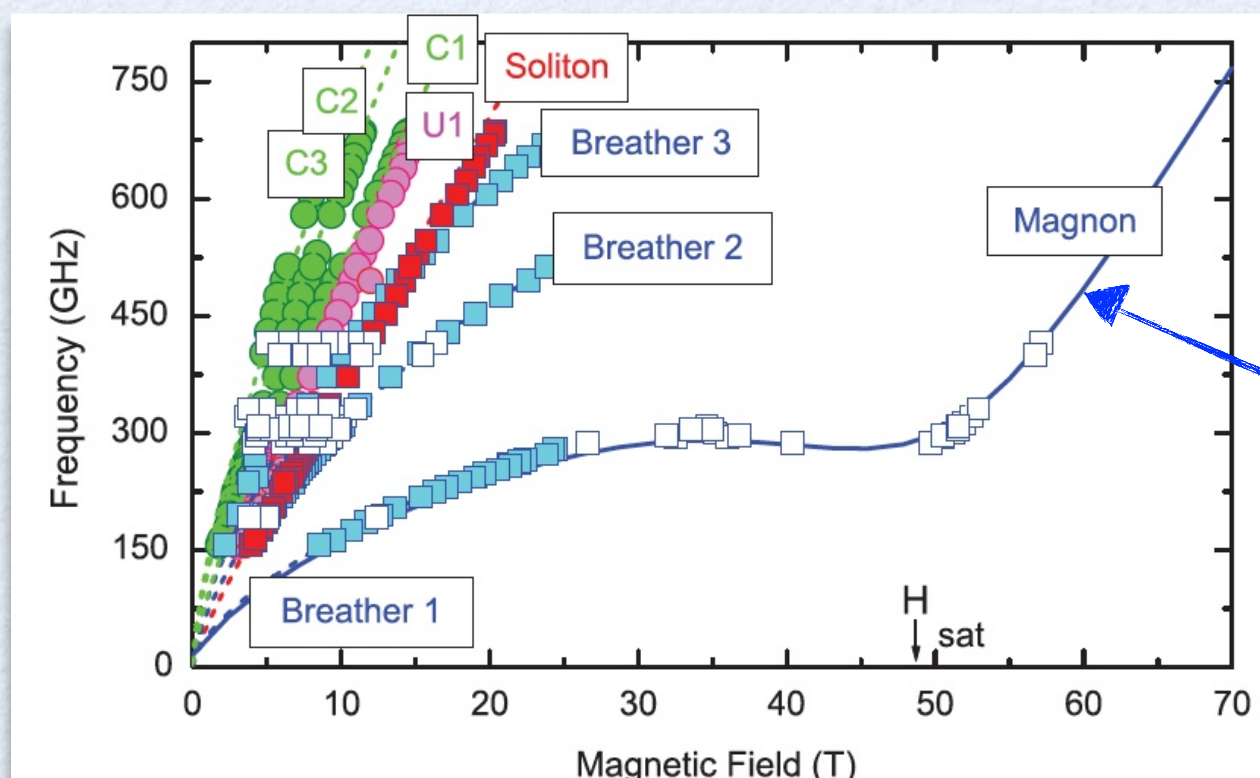
[S. Zvyagin et al., PRB(R) (2011)]

(Quasi-)1D Heisenberg AFM, described by

$$\mathcal{H} = \sum_j \left[J \mathbf{S}_j \cdot \mathbf{S}_{j+1} - H S_j^z - h (-1)^j S_j^x \right]$$

effect of staggered g-tensor + DM interaction

ESR spectrum in magnetic field:

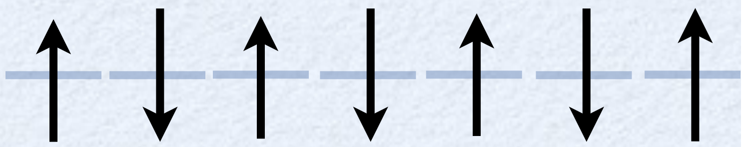


DMRG results

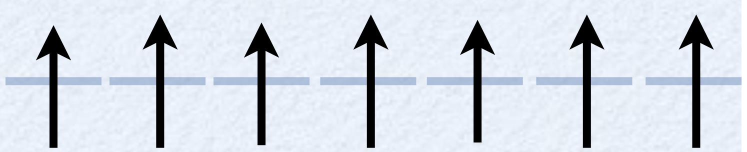
Spectral functions at finite field

Finite-T dynamics
in strong magnetic fields:

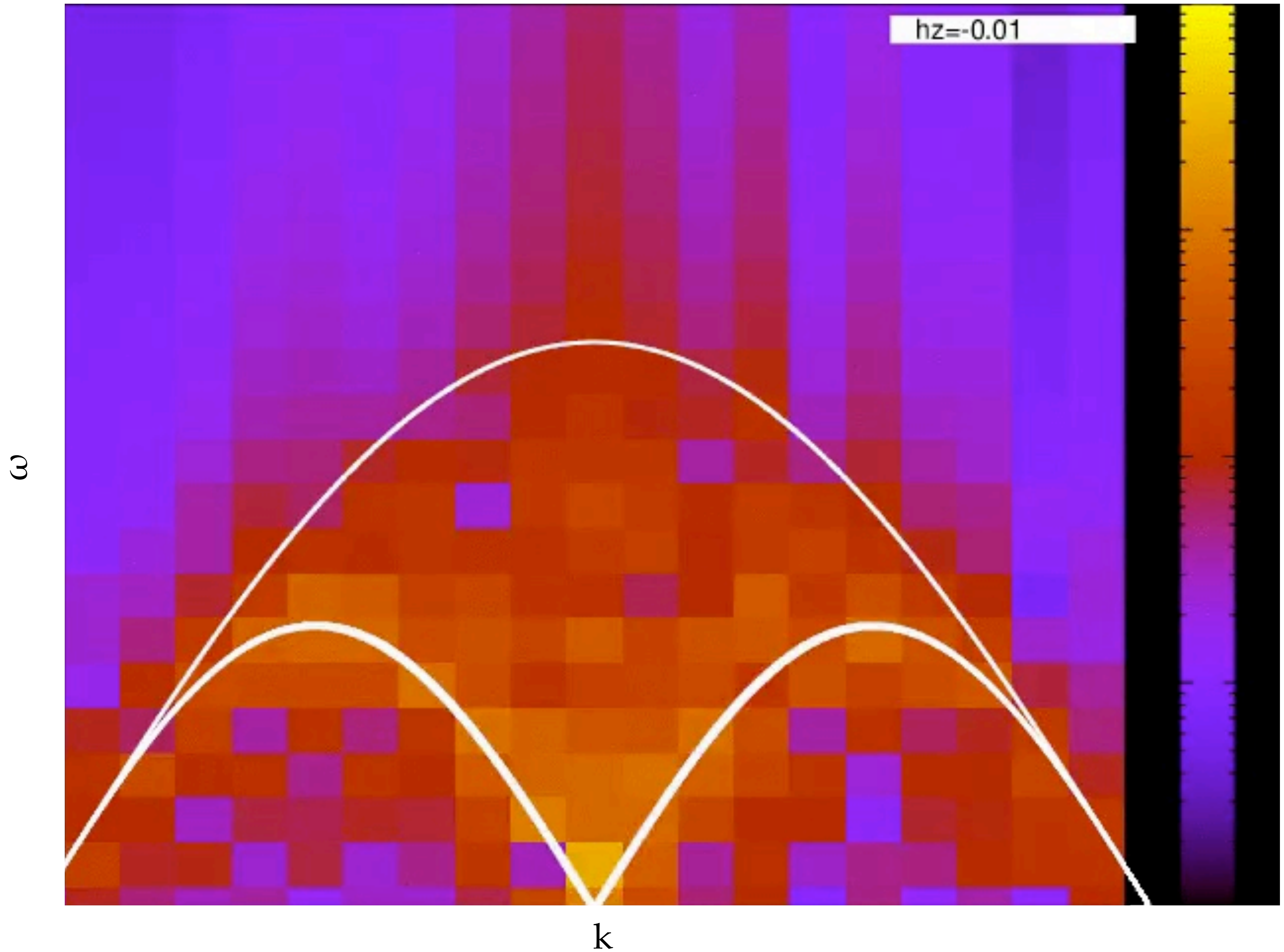
small H: spinons



large H: magnons



Time evolution at T=0.2 + Fourier transform
(non-optimized code, no linear prediction)

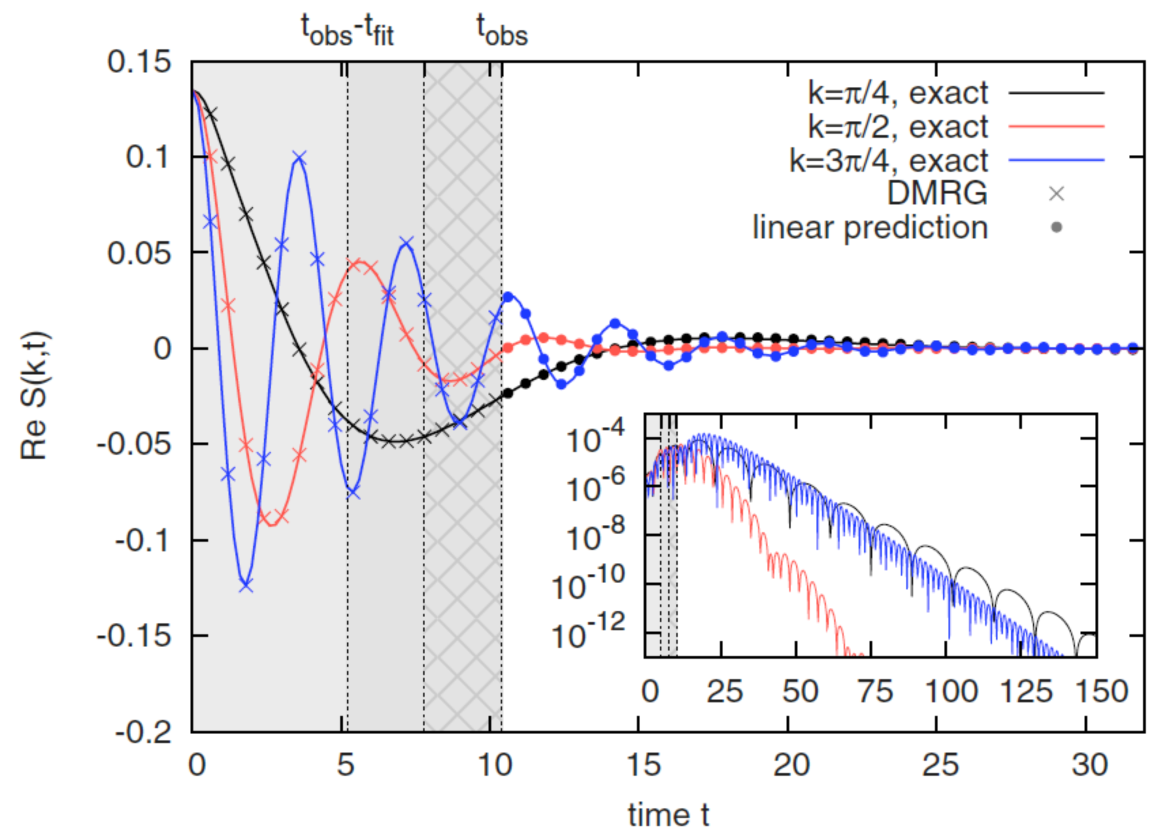


[T. Köhler, Master thesis, Univ. Göttingen 2013]

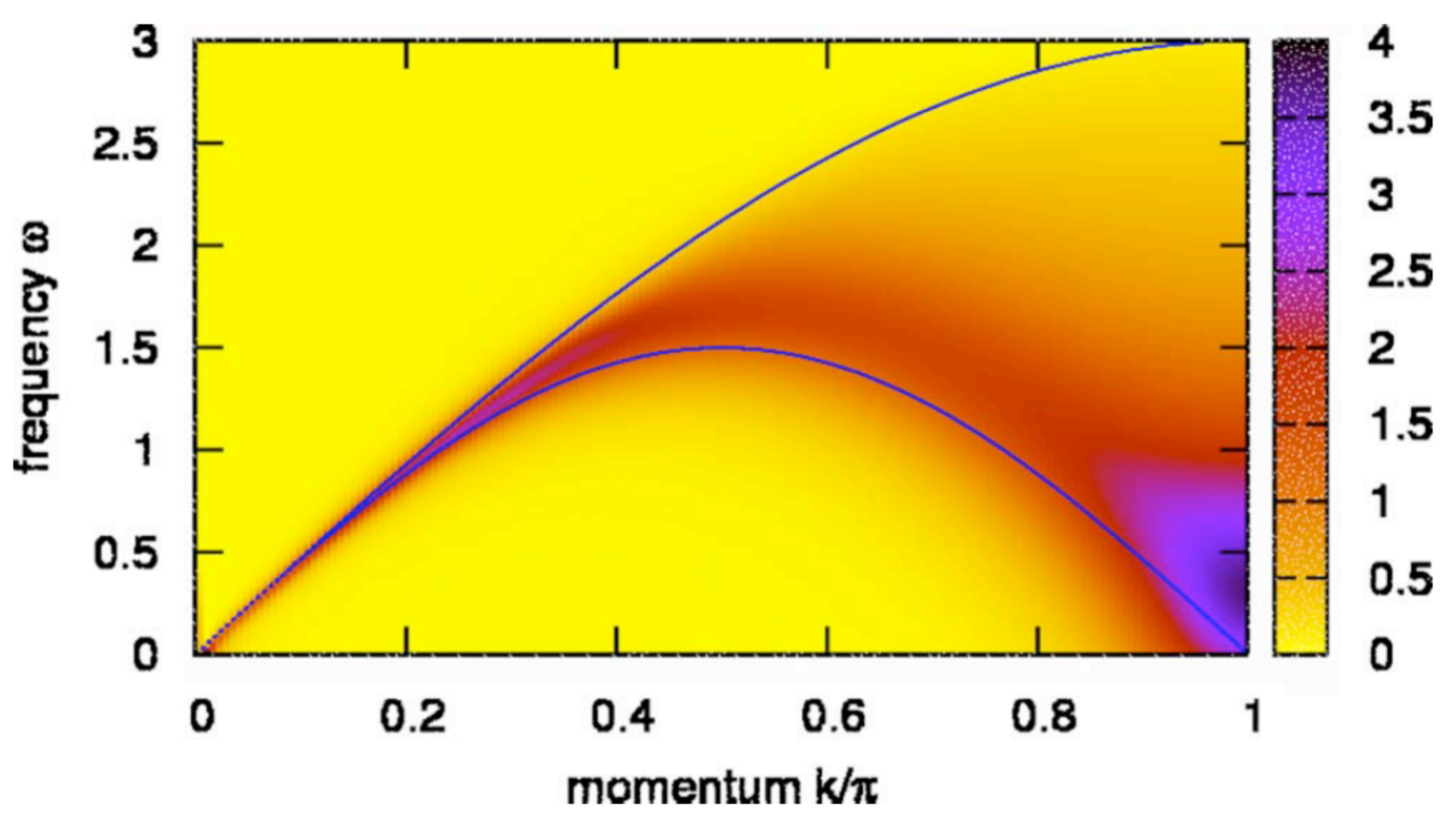
Time evolution approaches: linear prediction

[T. Barthel, U. Schollwöck & S.R. White, PRB (2009)]

real time behavior: linear prediction



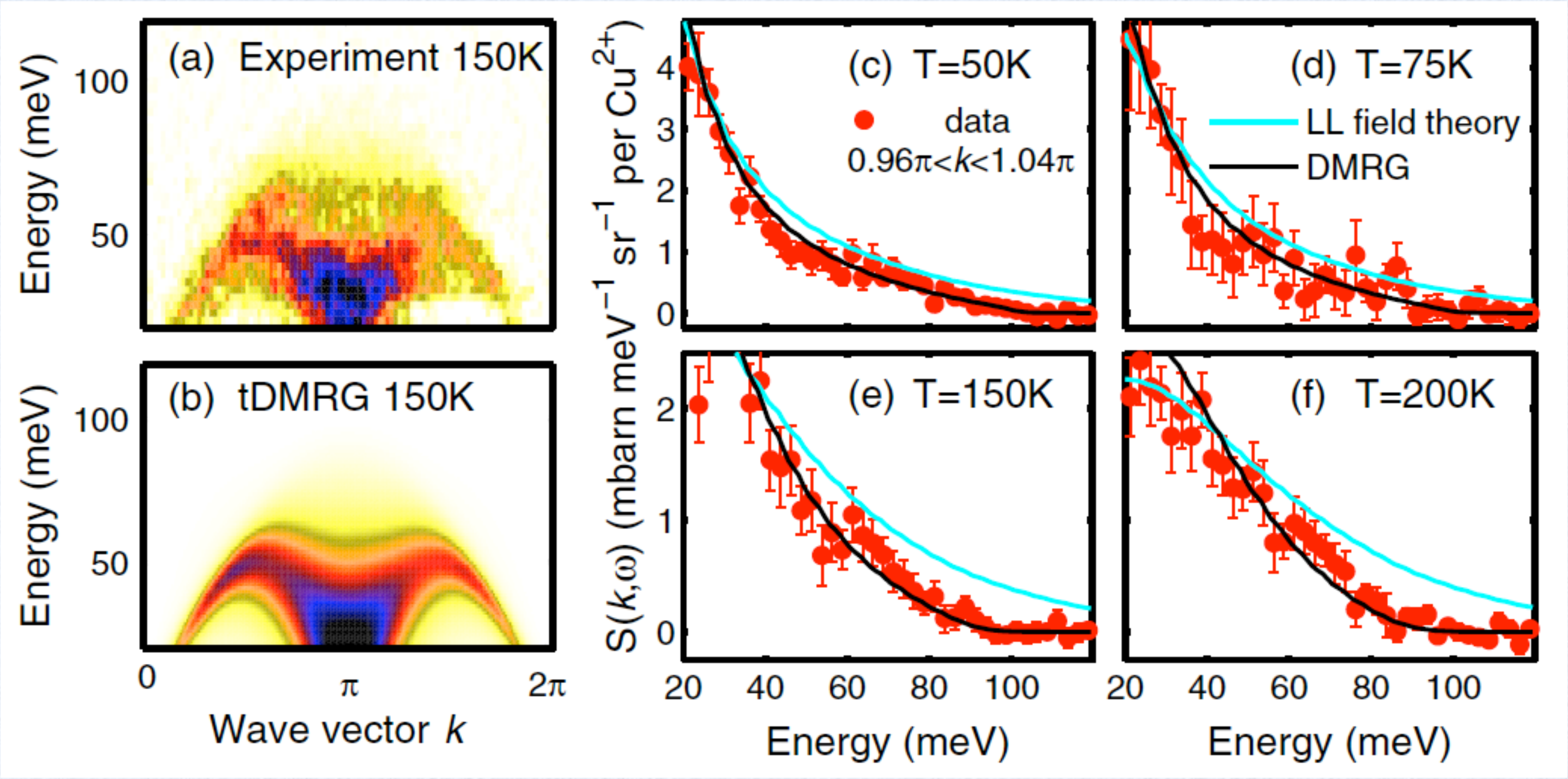
Fourier space:



Time evolution approaches: linear prediction

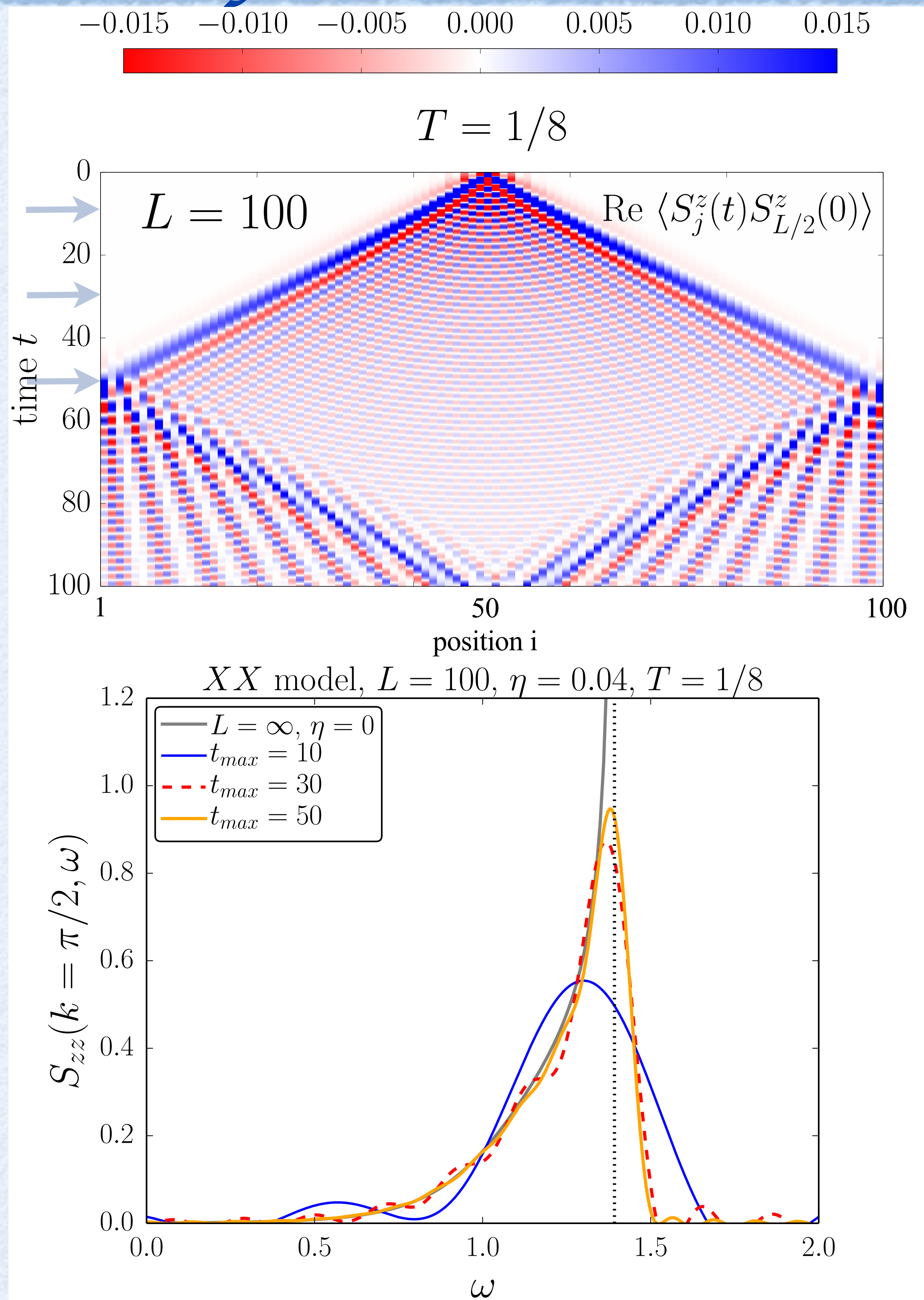
[B. Lake et al., PRL (2013)]

Comparison to experiments: $KCuF_3$



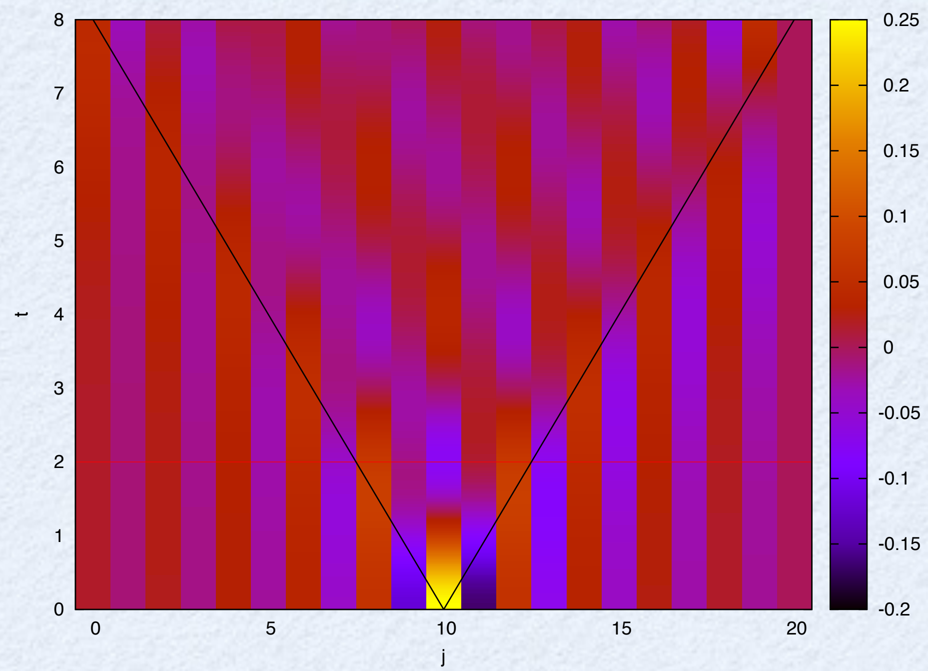
Time evolution approaches: linear prediction

Exact results
for analytically solvable
XX-model:

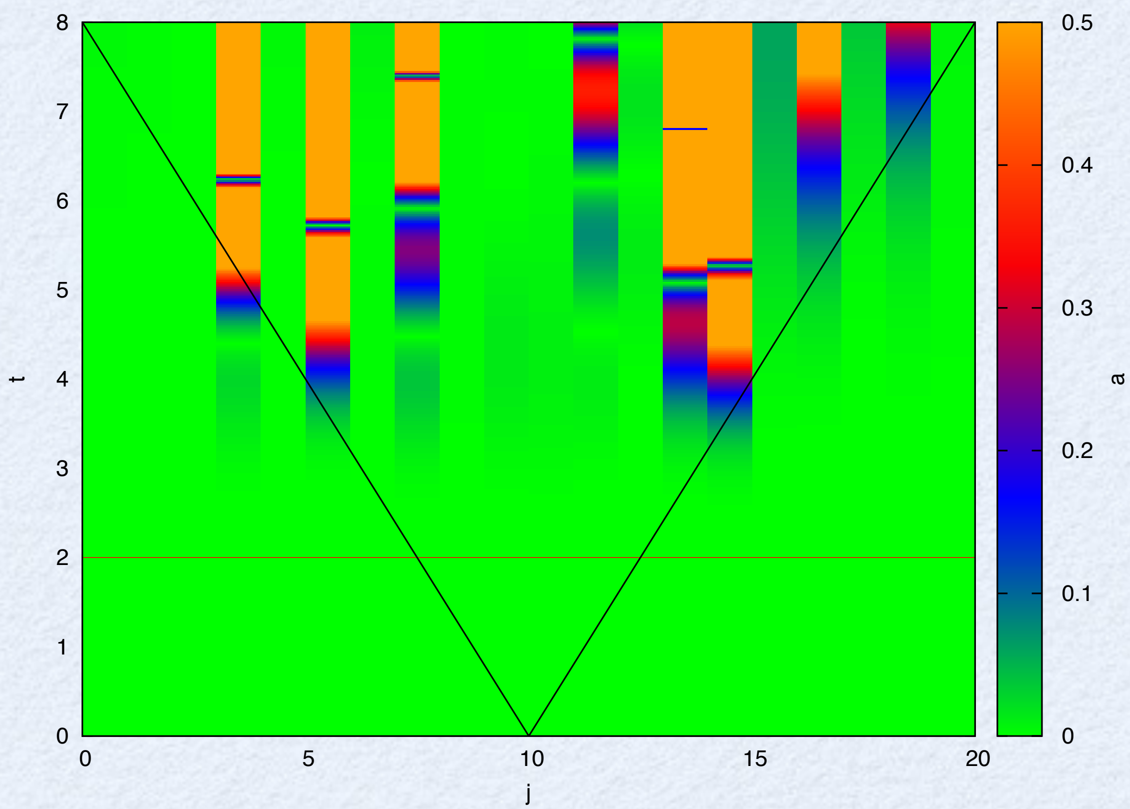


Time evolution approaches: linear prediction

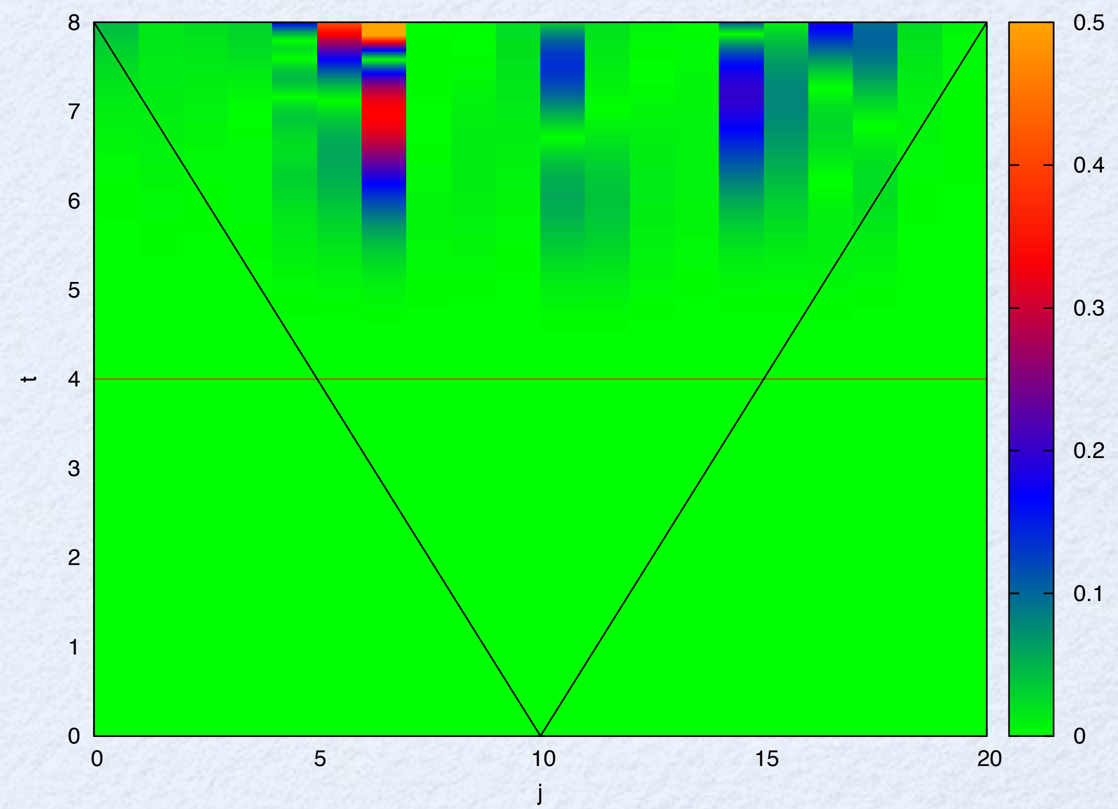
Time evolution with MPS:



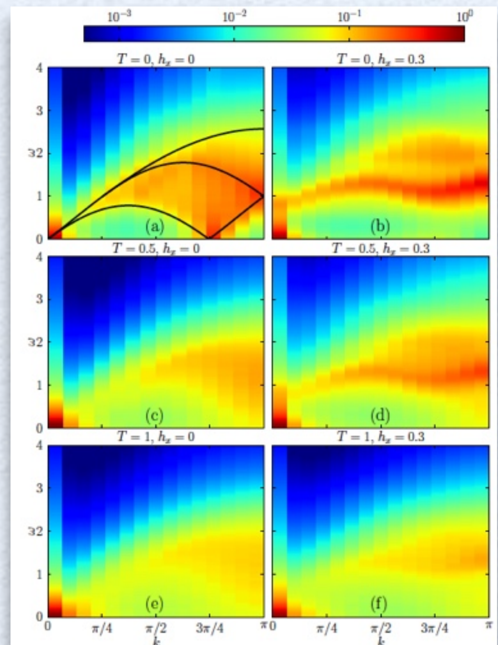
Difference to linear prediction from t=2

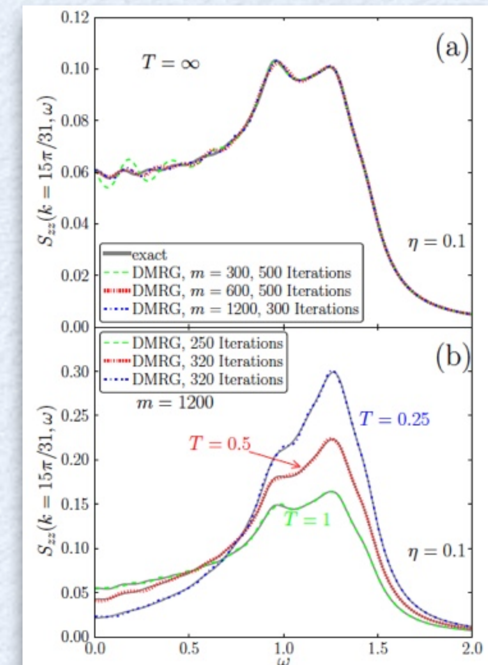


Difference to linear prediction from t=4

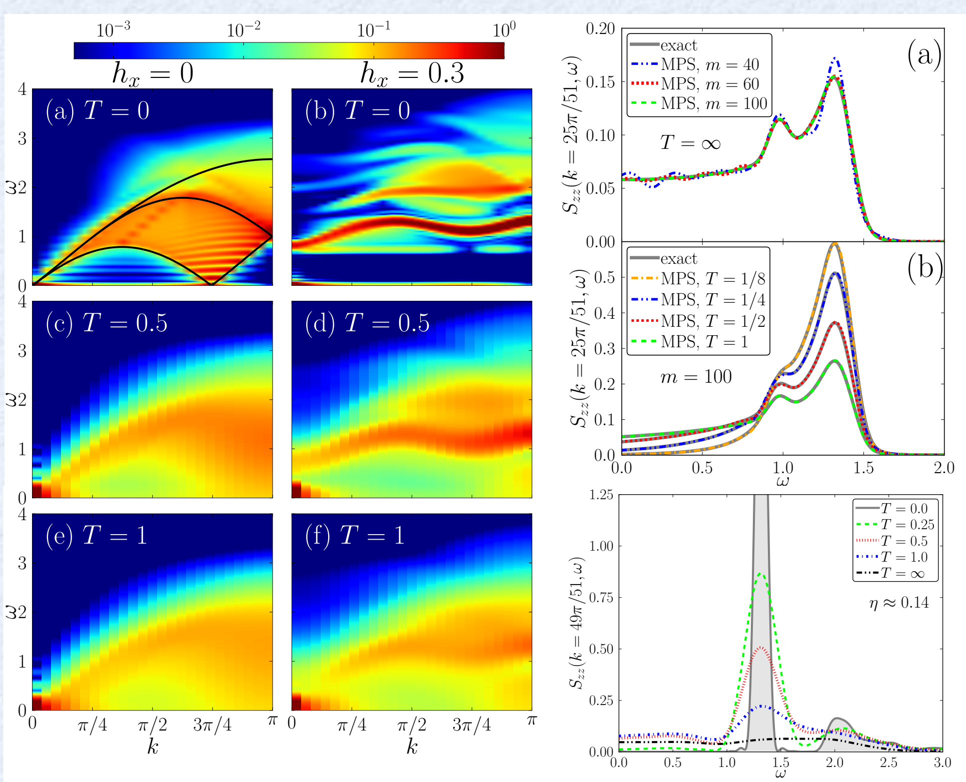


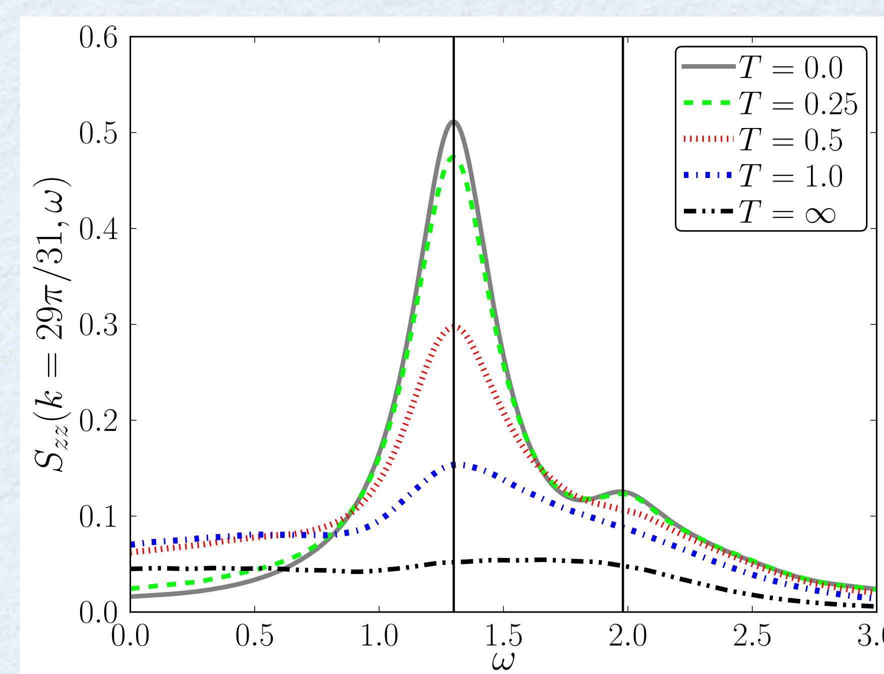
Work directly in frequency space: Liouvillian finite-T approach





Proof of Principle Calculations!





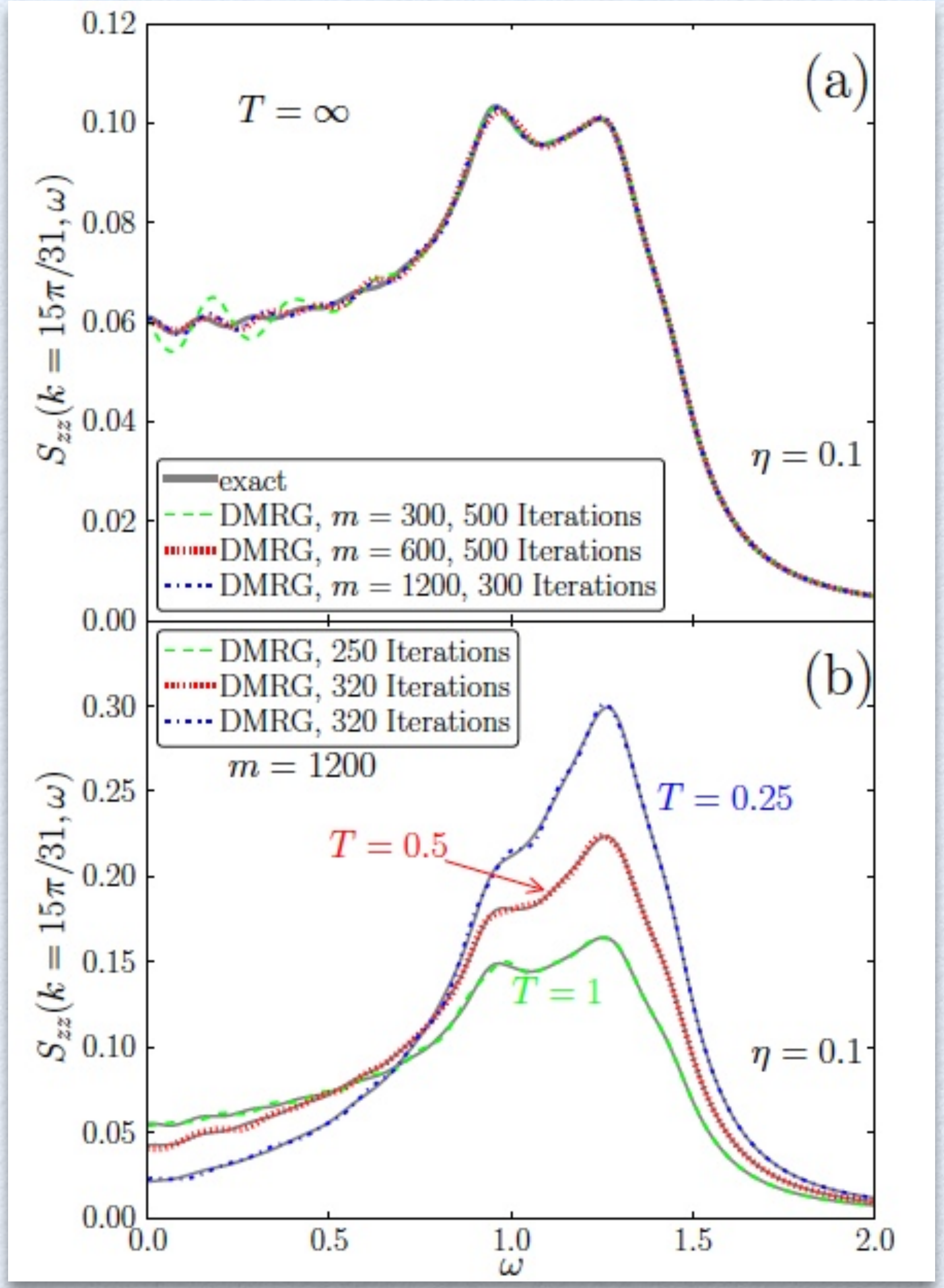
Liouvillian finite-T approach: comparison to exact results

Continued fraction expansion:

$$H_{XX} = J \sum_{i}^{L-1} \left(S_i^x S_{i+1}^x + S_i^y S_{i+1}^y \right)$$

$$S_k^\alpha = \sqrt{\frac{2}{L+1}} \sum_{i=1}^{L} \sin(ki)\, S_i^\alpha$$

Excellent agreement with exact results!



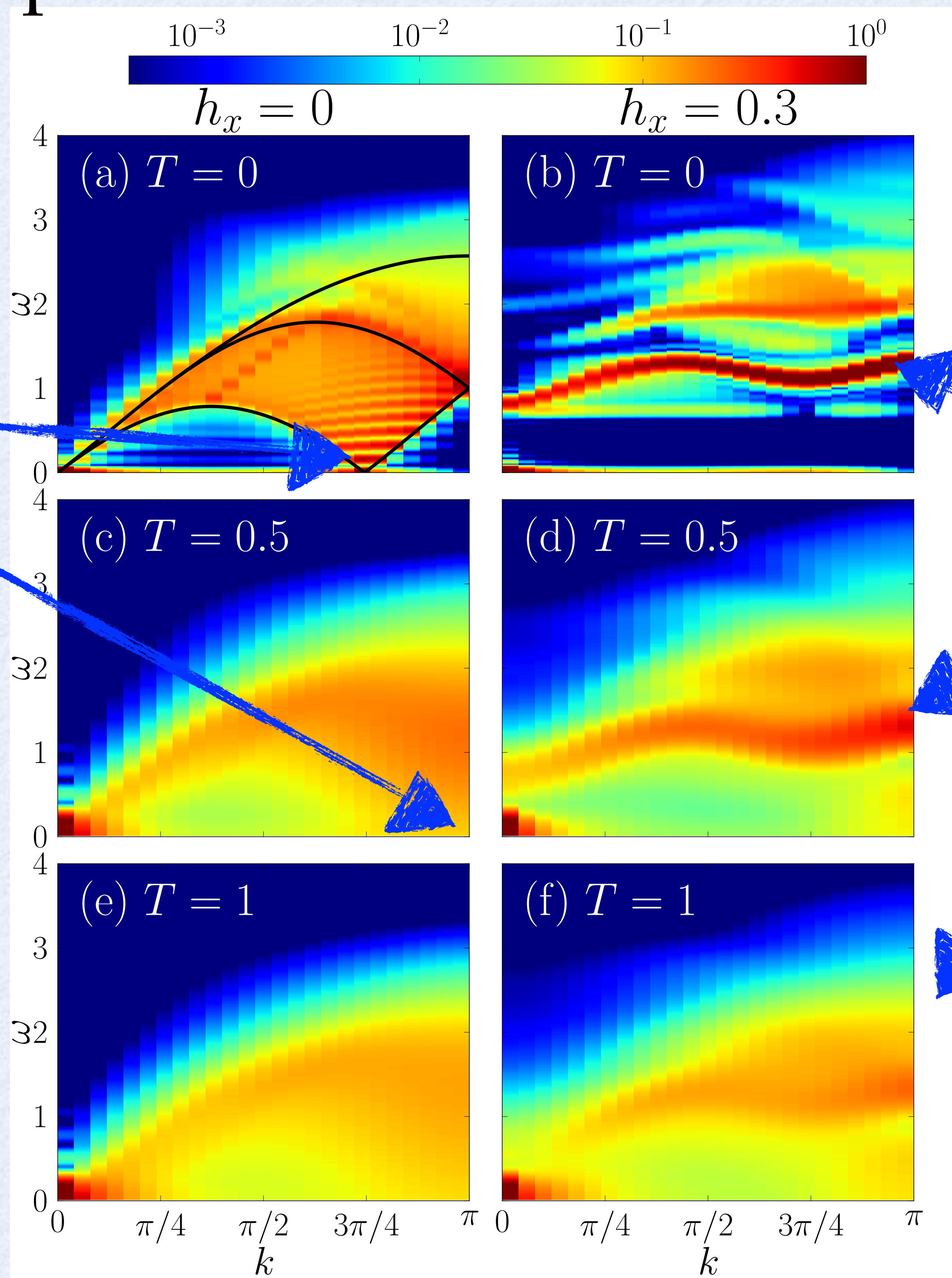
Liouvillian finite-T approach: Heisenberg antiferromagnet in magnetic field

Chebyshev approach:

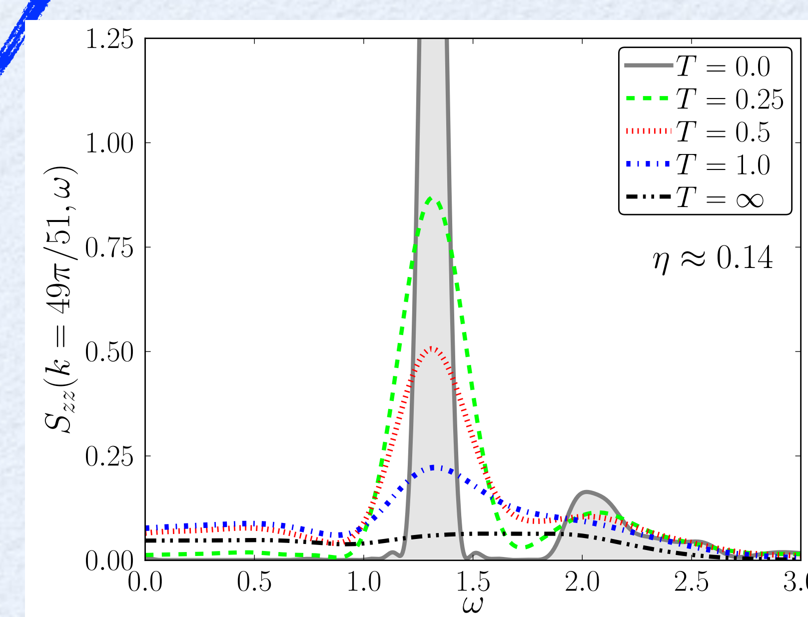
no DM

with DM

'Melting' of a Luttinger liquid



Formation of bands, thermal broadening



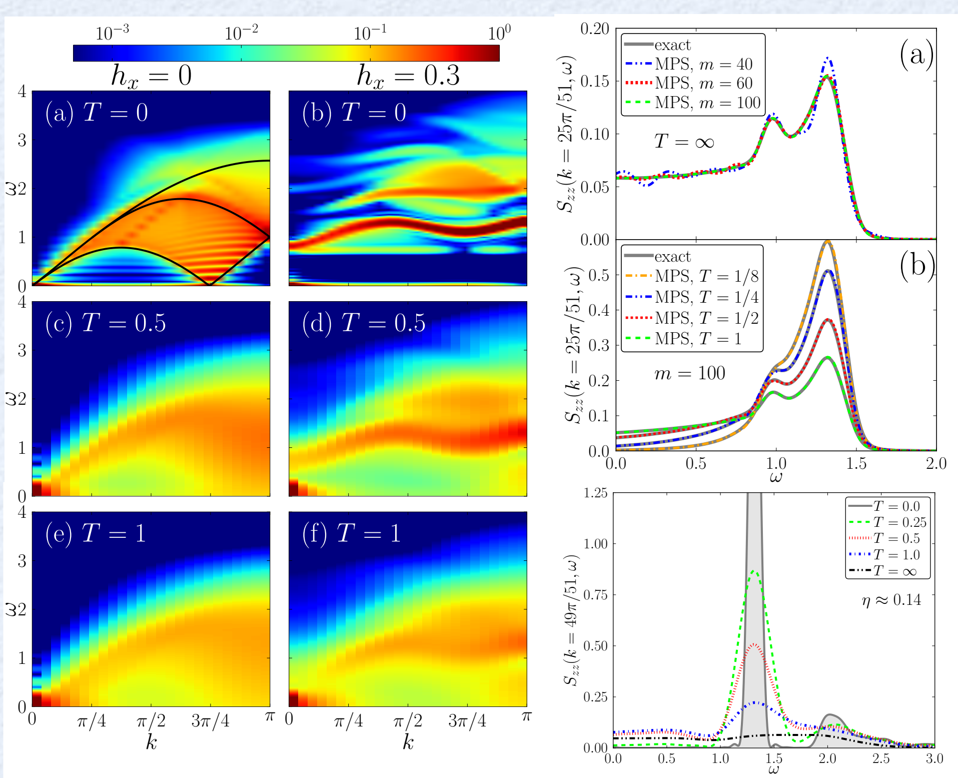
Conclusions

Go to Liouville space and work directly in frequency space:

$$G_A(k,\omega) = -\frac{1}{\pi}\mathrm{Im}\left\langle \Psi_T \left| A^\dagger \frac{1}{z-\mathcal{L}} A \right| \Psi_T \right\rangle \qquad \mathcal{L} = H_P \otimes I_Q - I_P \otimes H_Q$$

Independent of method: also possible to use PEPS, further tensor networks, other numerical approaches (ED, DMFT impurity solver, ...?)

Heisenberg chain with Dzyaloshinskii-Moriya interaction:



very accurate
observe "melting" of LL,
formation of bands via DM interaction

Next steps: optimize code,
ESR lines,
other systems (S>1/2, fermions, bosons)