FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG
NATURWISSENSCHAFTLICHE FAKULTÄT

TRR 306 QuCoLiMa
Quantum Cooperativity of Light and Matter

Non-equilibrium steady-state description of photo-induced orders in Mott insulators

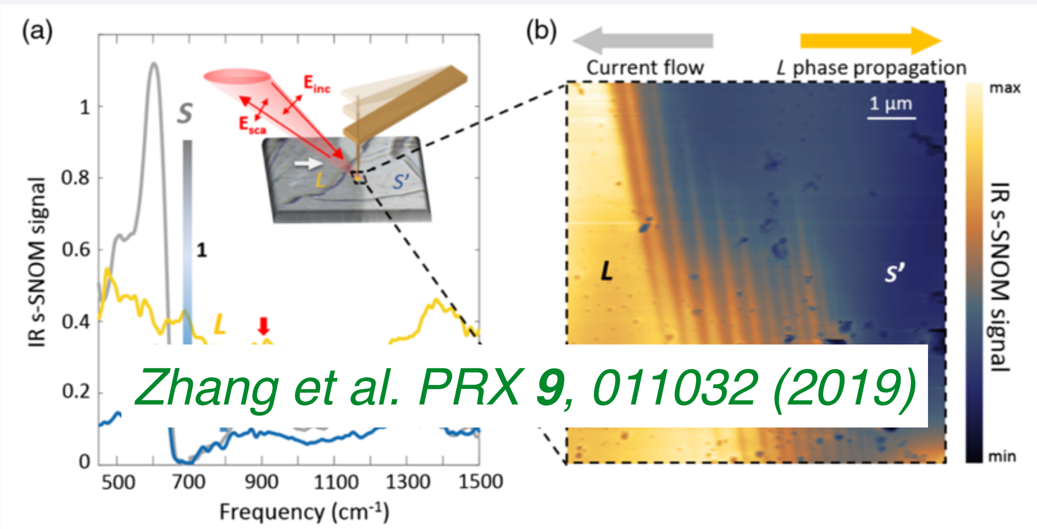
Martin Eckstein

SPICE workshop *Dissipative Phases of Entangled Quantum Matter*, May 5, 2021

Nonthermal pathways to control condensed matter

1) Nonequilibrium staedy states:

⇨ Current-induced phase transitions

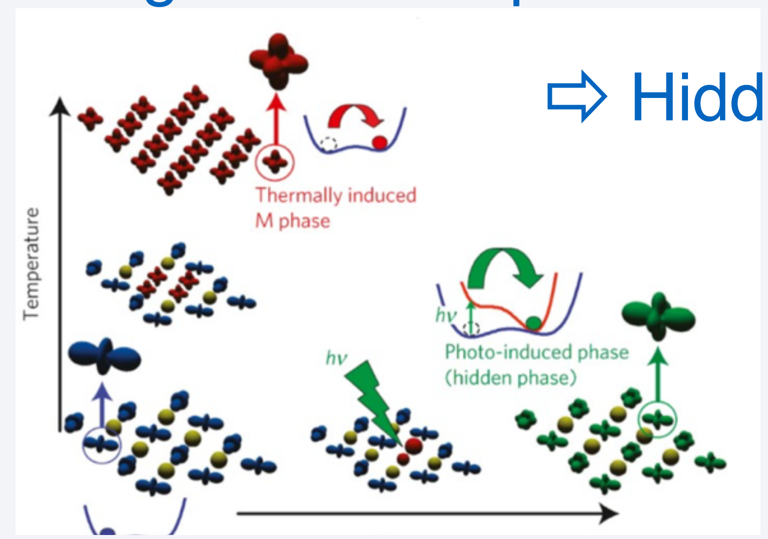


*Zhang et al. PRX **9**, 011032 (2019)*

3) Transient states

⇨ Light-induced phase transitions

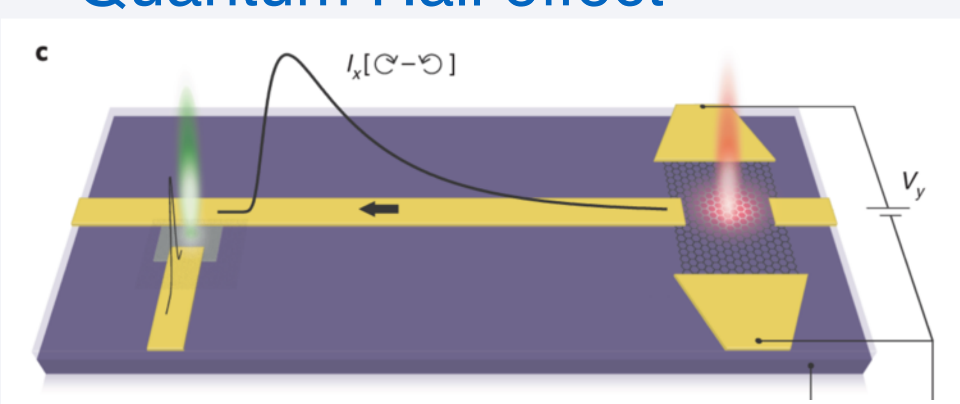
⇨ Hidden phases



*Ichikawa et al. Nature Materials **10**, 101(2011)*

2) Floquet engineering (in solids!)

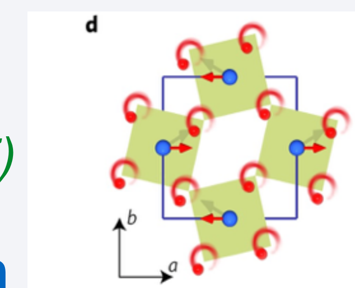
⇨ Light-induced anomalous
Quantum Hall effect



*Mc Iver et al. Nature Physics **16**, 38(2020)*

⇨ Artificial magnetic fields

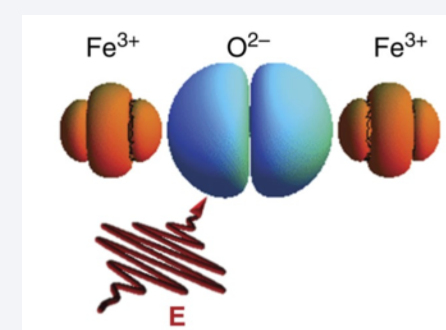
*T. Nova, Nature Physics **13,** 132 (2017)*



⇨ Light-induced modification
of magnetic exchange

⇨ …

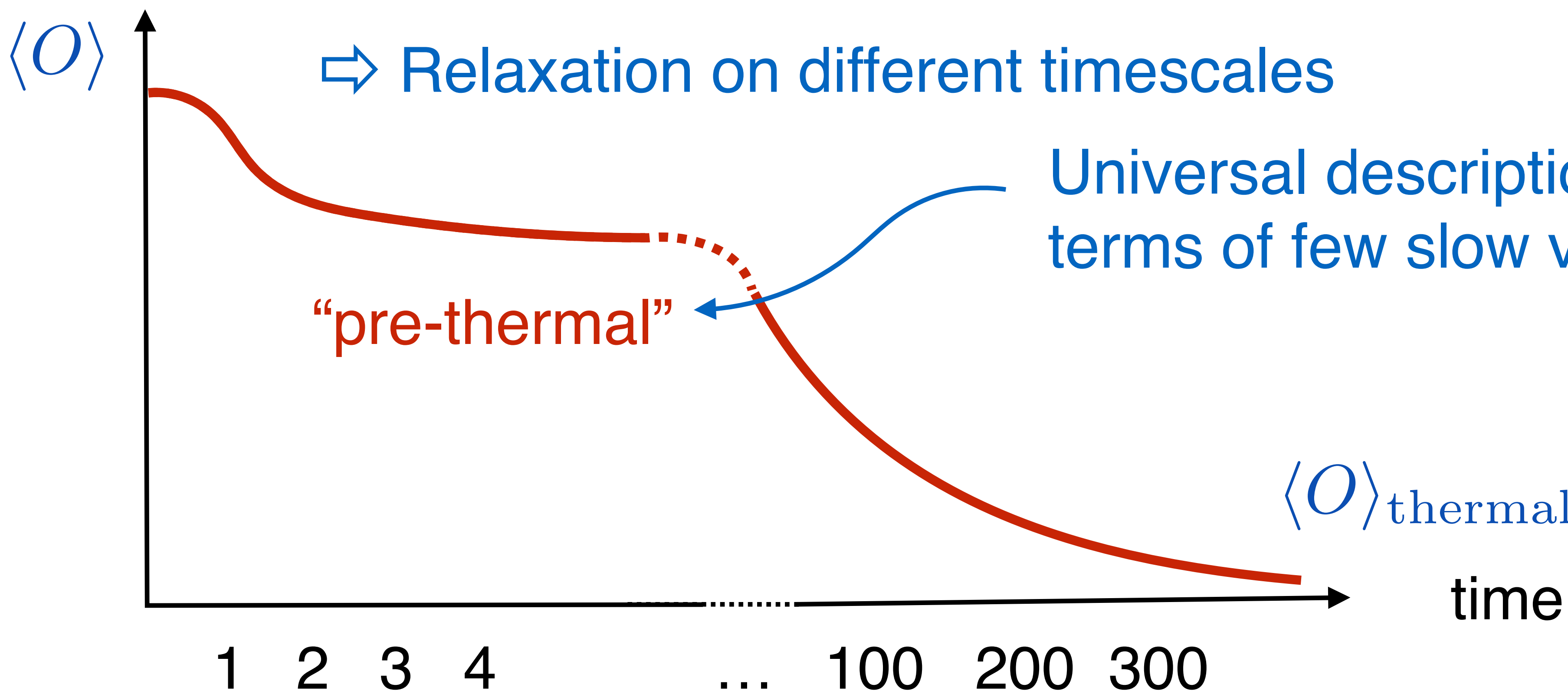
*Mikhaylovskiy et al. Nat. Comm. **6**, 8190 (2015)*



Reviews: *de la Torre et al. arXiv:2103.14888; Bavov, Hsieh, Averitt et al. Nature Mater **16**, 1077 (2017*

Relaxation of isolated quantum systems towards equilibrium

Typical relaxation of some observable after a quench:



⇨ Pre-thermalization close to integrable point: Slow variables = Integrals of motion *Berges et al 2004; Moeckel & Kehrein 2008; Kollar et al. 2011; d'Alessio 2016 Polkovnikov et al, RMP **83**, 863 (2011)*

⇨ Phenomenological description of photo-induced phase transitions: "non-equilibrium order parameters" *e.g., Beaud et al. Nature Mat. 2014*

⇨ Nonequilibrium state with slow energy/particle flow between subsystems ⇨ model as exact steady state of system driven with reservoirs

Outline

1) Examples which illustrate the evolution of long-lived intermediate states and emergence of slow variables:

⇨ Thermalization of antiferromagnetic spin density order after a quench

*Picano, Eckstein, Phys. Rev. B **103**, 165118 (2021)*

⇨ A photo-induced strange metal in a Mott insulator

Dasari, Li, Werner, Eckstein, arxiv:2010.04095

2) Quasi-steady state description of photo-doped state

*Li and Eckstein, Phys. Rev. B **103**, 045133 (2021)*
*Li, Golez, Werner, Eckstein, PRB **102**, 165136 (2020)*
Picano, Li, Eckstein, arxiv:2101.09037

Simulations based on **Non-equilibrium Dynamical mean field theory**
… for transient time-evolution and non-equilibrium steady states

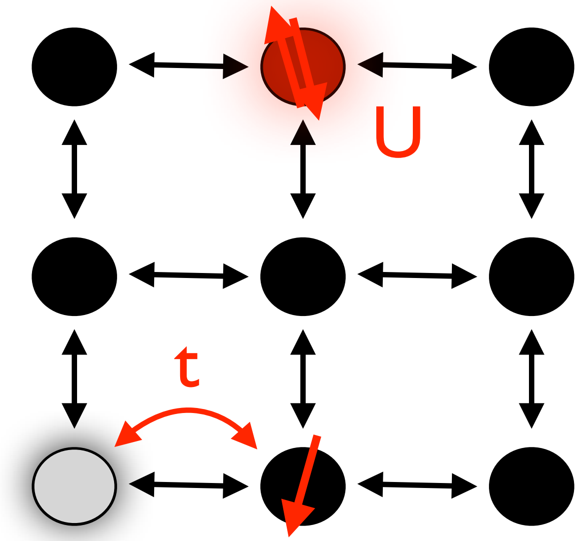
*Aoki, Tsuji, Eckstein, Kollar, Oka, Werner, RMP **86**, 779 (2014)*

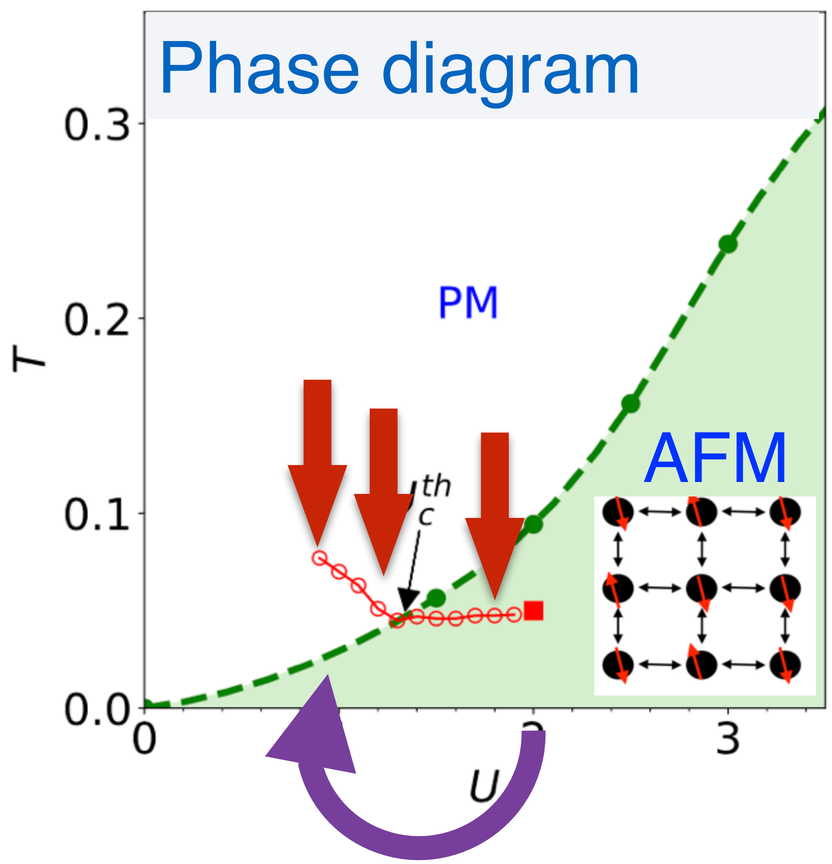
Example 1: Quench in a Slater Antiferromagnetic state (SDW)

with Antonio Picano (FAU) Phys. Rev. B **103**, 165118 (2021)

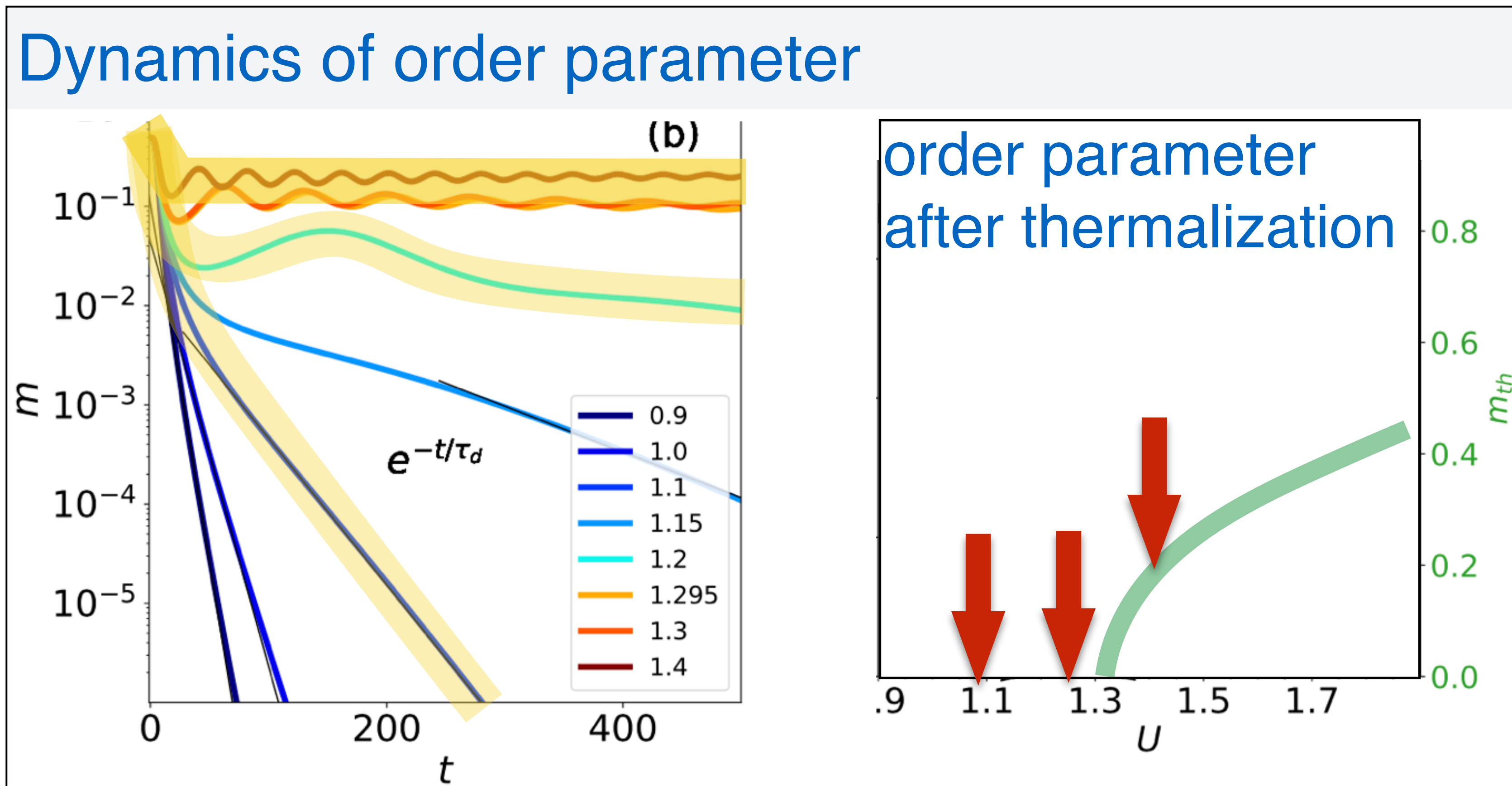
Hubbard model, Bethe lattice (bandwidth=4),
Solution: non-equilibrium DMFT

$$H = -t \sum_{\langle ij \rangle, \sigma=\uparrow,\downarrow} c^\dagger_{i\sigma} c_{j\sigma} + U \sum_i n_{i\uparrow} n_{i\downarrow}$$





Interaction quench



Prethermal non-thermal symmetry broken state

Tsuji, Eckstein Werner, PRL 2012

BCS superconductor: Barankov and Levitov 2006

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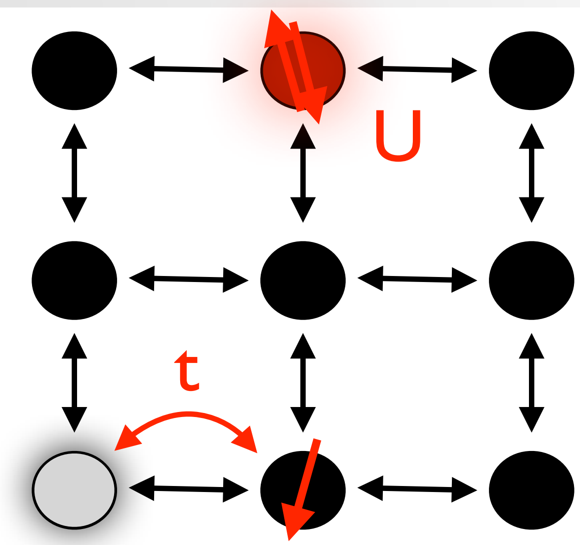
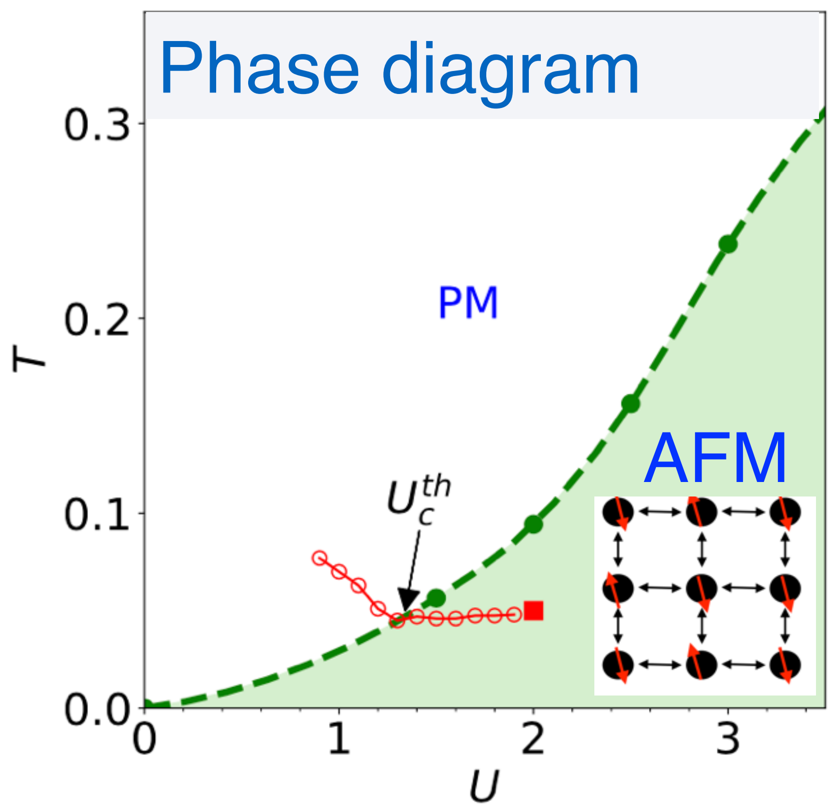
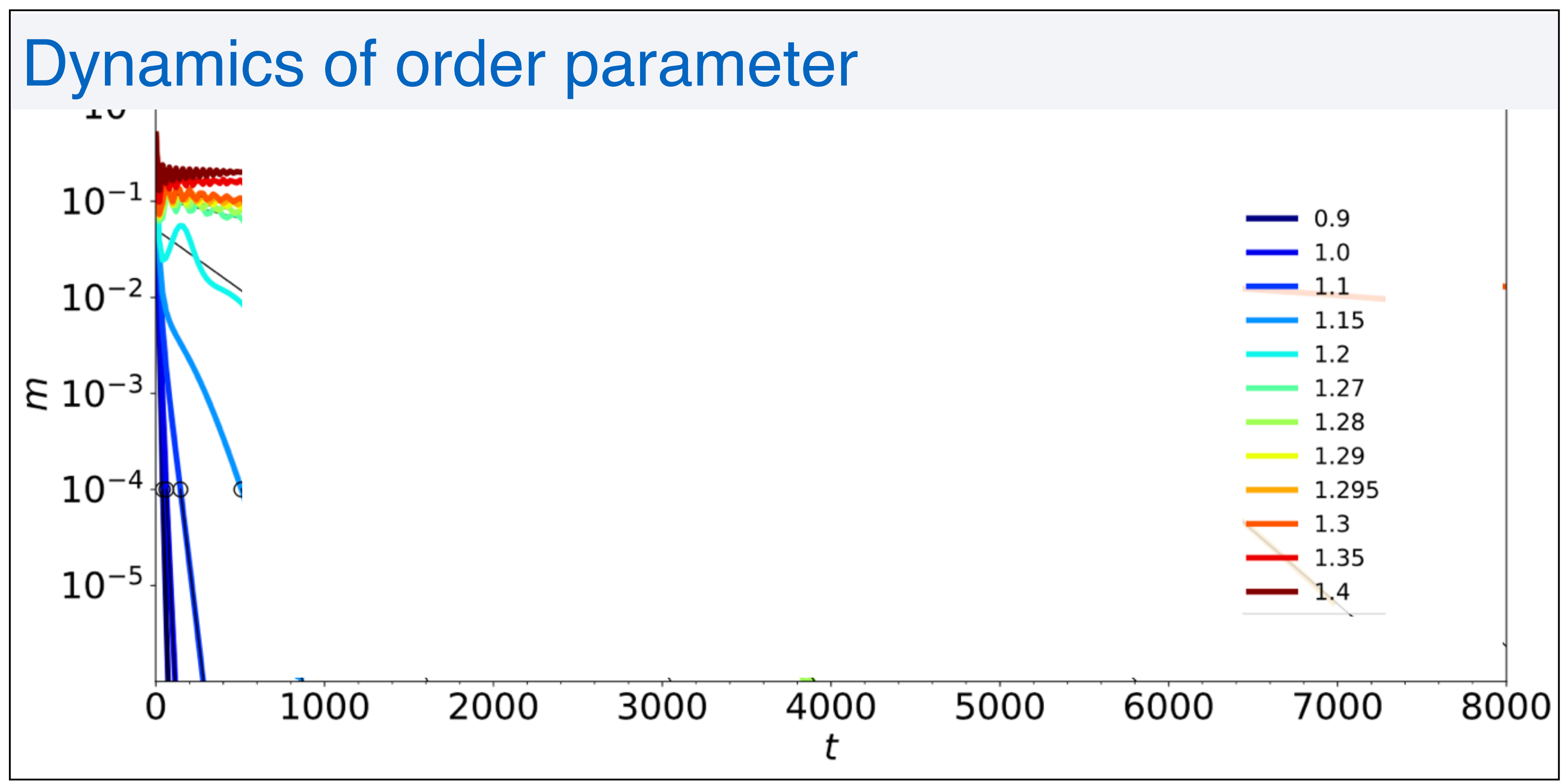




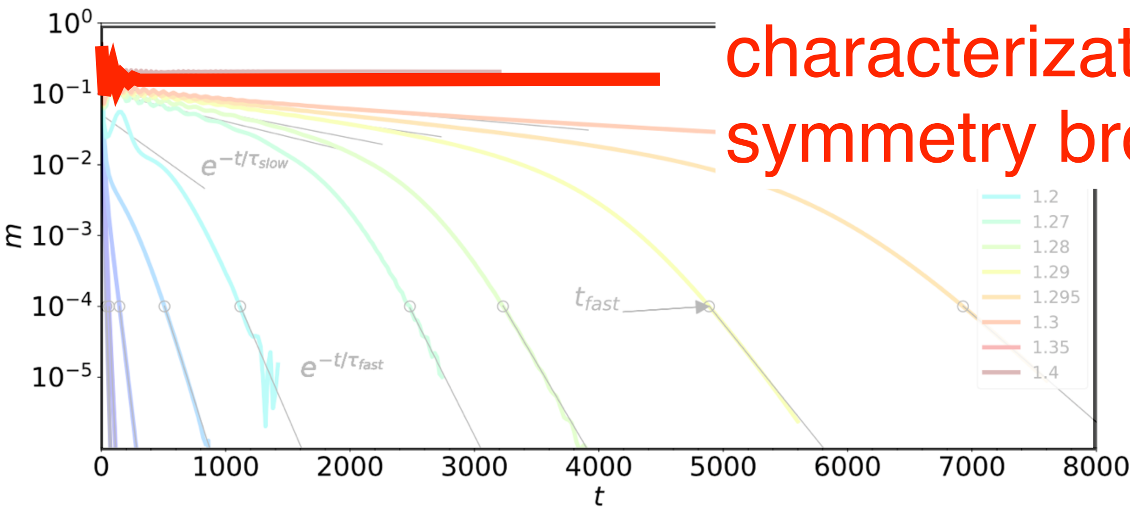


⇨ Evolution/properties of pre-thermal state at long times?

Long-time nonequilibrium DMFT simulations *Stahl et al., to appear*

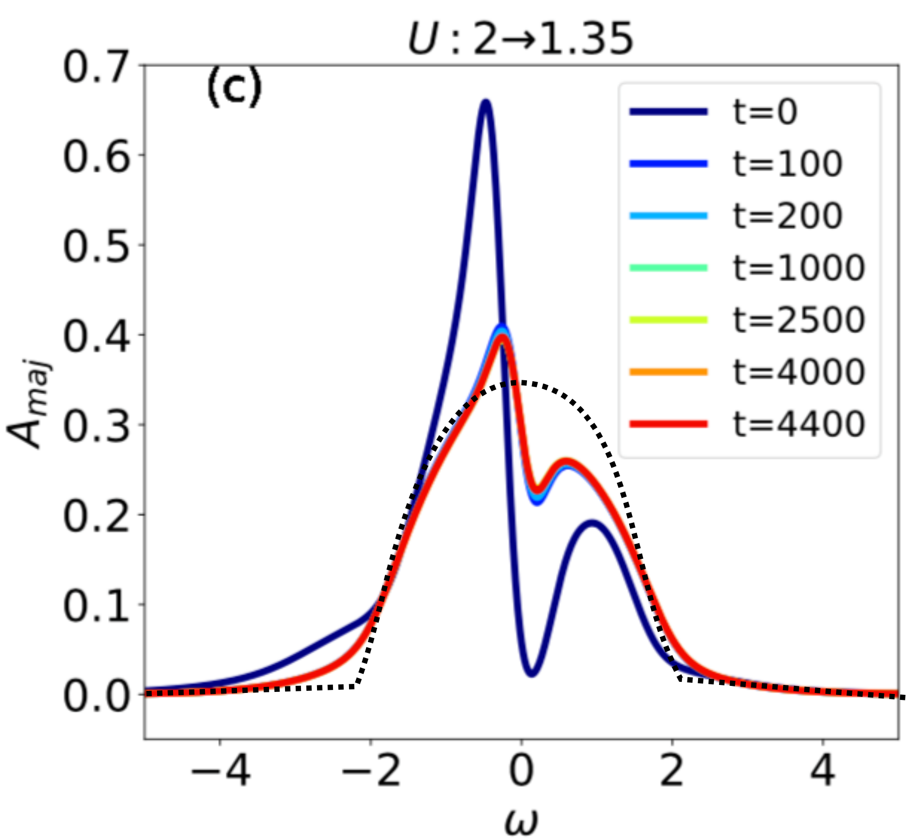
Example 1: Quench in a Slater Antiferromagnetic state (SDW)

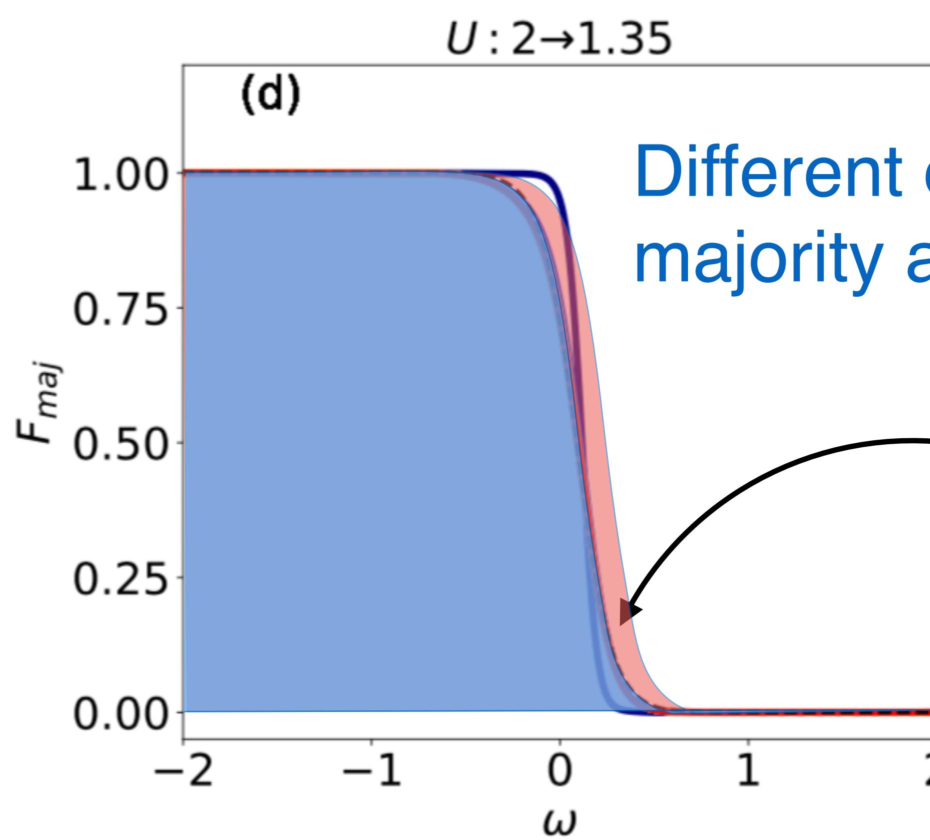
with Antonio Picano (FAU) Phys. Rev. B **103**, 165118 (2021)



characterization of nonthermal symmetry broken state

Spectral function, occupied density of states: $G^<_\sigma(\omega,t) = A_\sigma(\omega,t)F_\sigma(\omega,t)$





Different chemical potentials for majority and minority spins

$$F(\omega) = \frac{1}{e^{\beta(\omega-\lambda)}+1}$$

Slow variables ⇨ occupations in subbands

Example 1: Quench in a Slater Antiferromagnetic state (SDW)

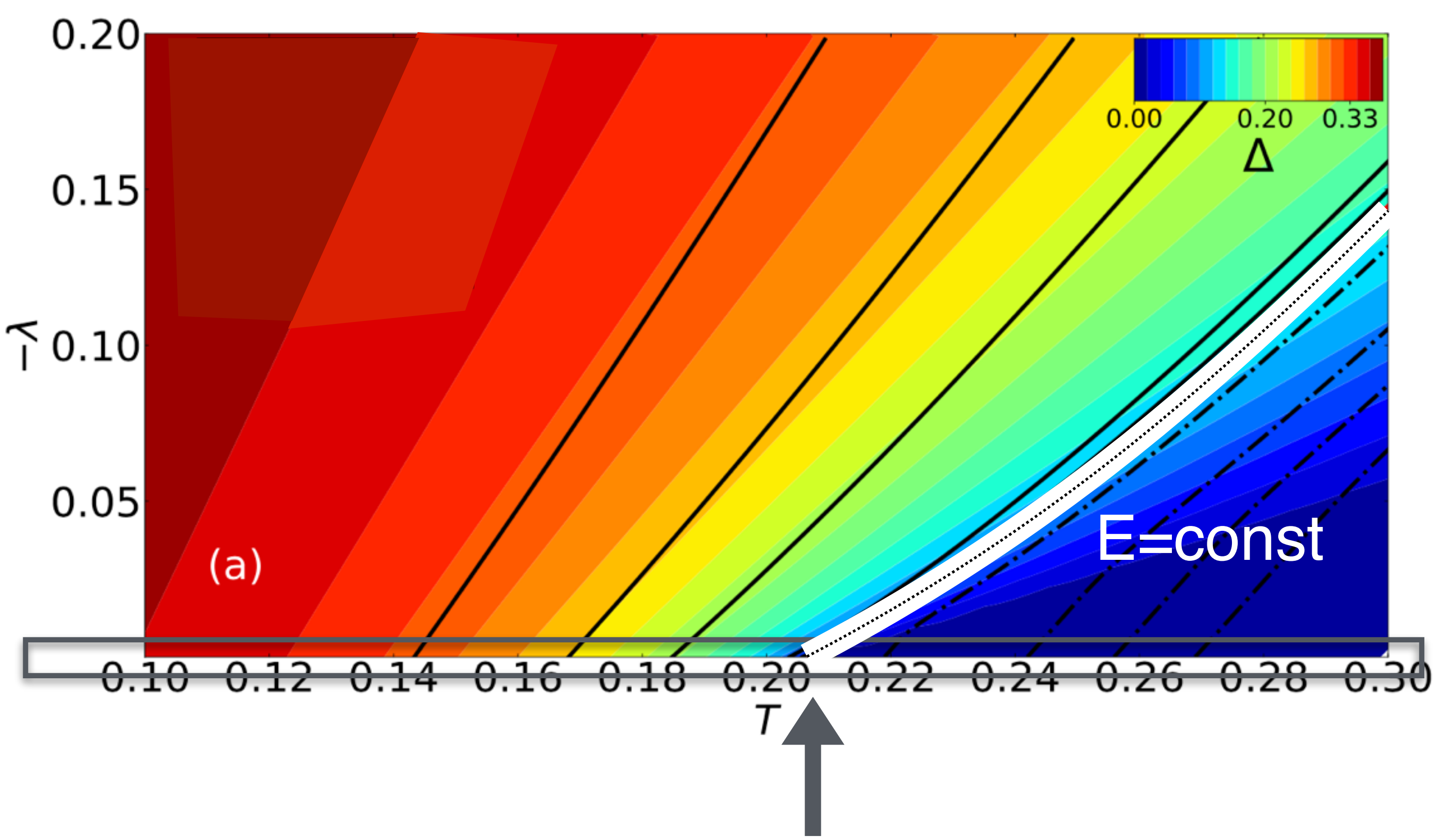
with Antonio Picano (FAU) Phys. Rev. B **103**, 165118 (2021)

Mean-field description of non-thermal state?

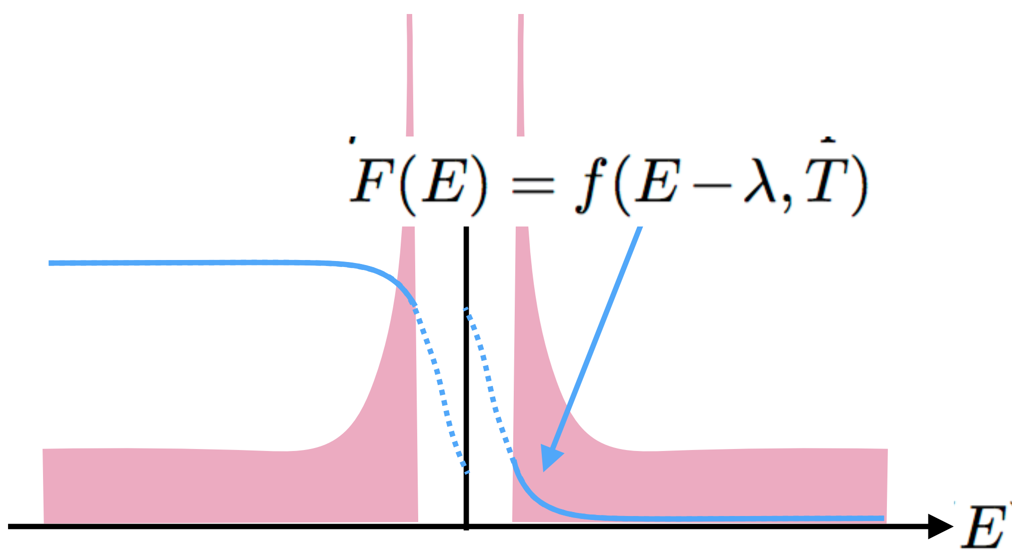
⇨ gap equation

$$\frac{1}{U} = \int_0^\infty d\epsilon D_0(\epsilon) \frac{F(-E) - F(E)}{E} \quad E = \sqrt{\epsilon^2 + \Delta^2}$$

Non-thermal mean-field phase diagram



Equilibrium Tc



Energy ⇦ ⇨ λ, β

upper band occupation

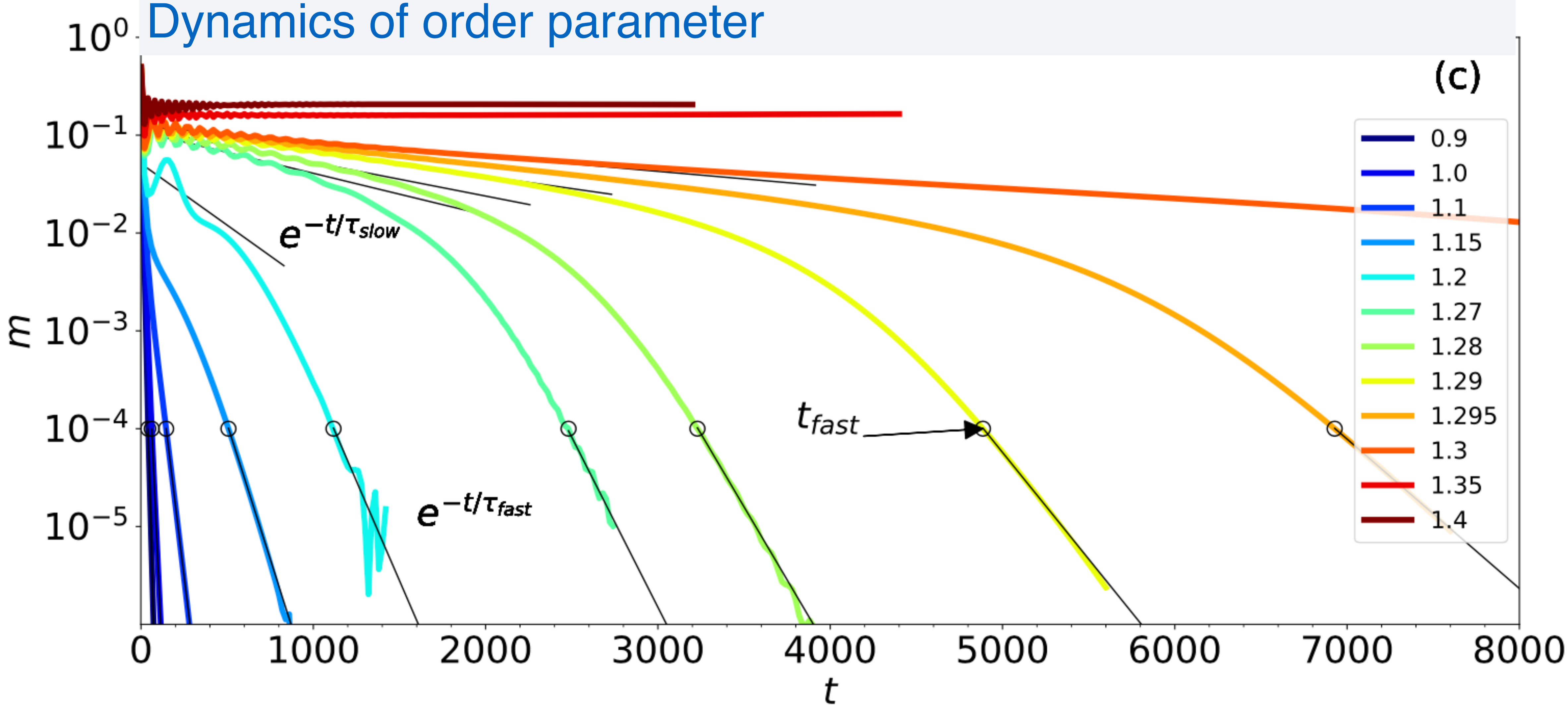
⇨ Non-thermal distribution consistent with enhancement of order

Example 1: Quench in a Slater Antiferromagnetic state (SDW)

with Antonio Picano (FAU) Phys. Rev. B **103**, 165118 (2021)

Thermalization of prethermal state?

Dynamics of order parameter



Accelerated collapse of the gap

⇨ Contrast to two stage relaxation

⇨ Precursor of metastability?

⇨ Origin? Not within mean-field + kinetic equations (some correlation effect)

Outline

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⇨ Thermalization of antiferromagnetic spin density order after a quench

Picano, Eckstein, Phys. Rev. B 103, 165118 (2021)

⇨ A photo-induced strange metal in a Mott insulator

Dasari, Li, Werner, Eckstein, arxiv:2010.04095

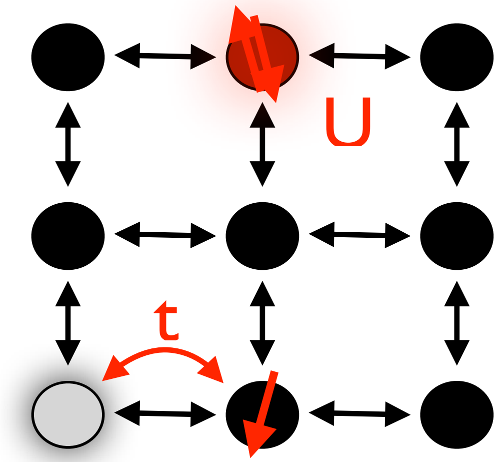
2) Quasi-steady state description of photo-doped state

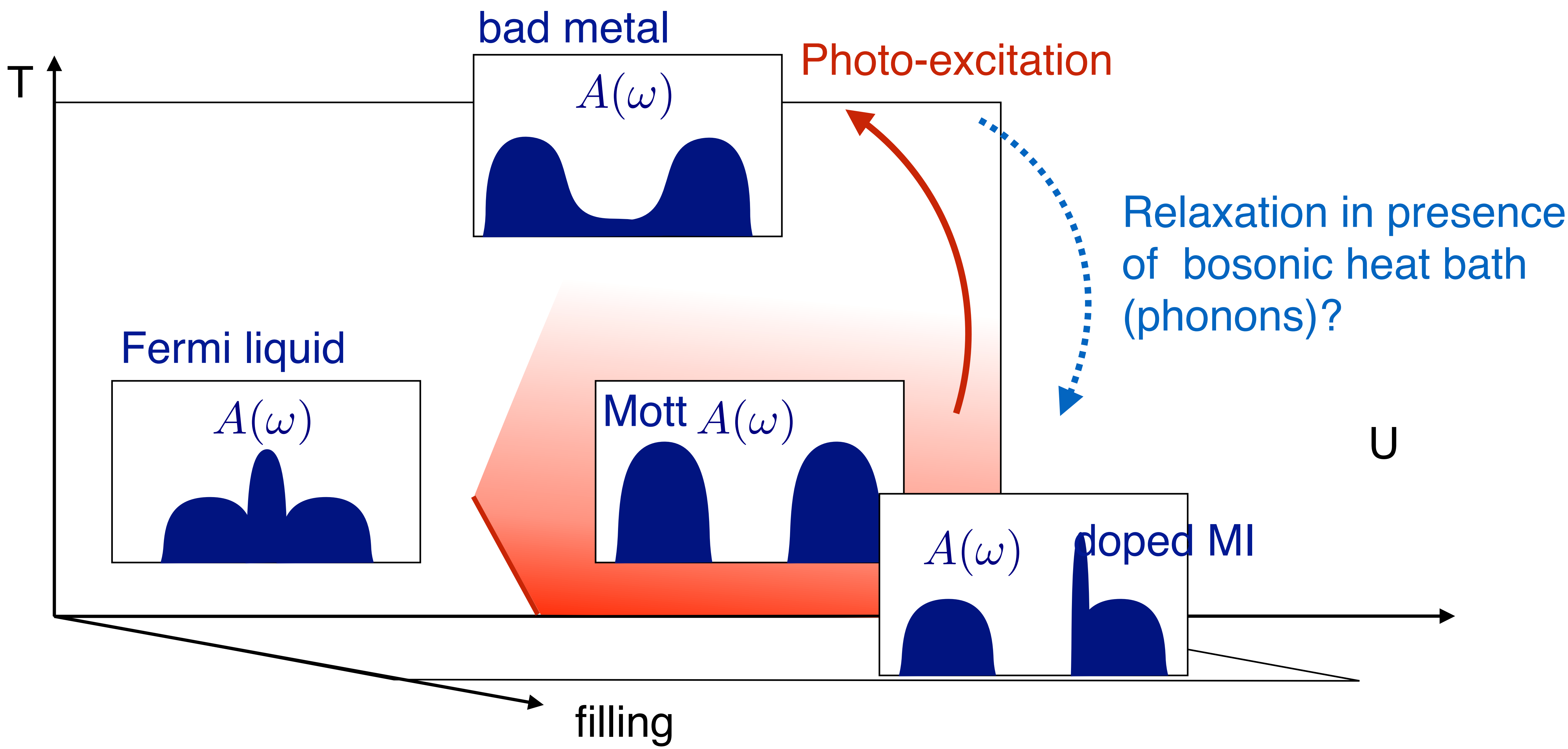
*Li and Eckstein, Phys. Rev. B **103**, 045133 (2021)*
*Li, Golez, Werner, Eckstein, PRB **102**, 165136 (2020)*
Picano, Li, Eckstein, arxiv:2101.09037

Example 2: Photo-doped strange metal in a Mott insulator

Hubbard model at large U

$$H = -t \sum_{\langle ij\rangle,\sigma=\uparrow,\downarrow} c^\dagger_{i\sigma} c_{j\sigma} + U \sum_i n_{i\uparrow} n_{i\downarrow}$$



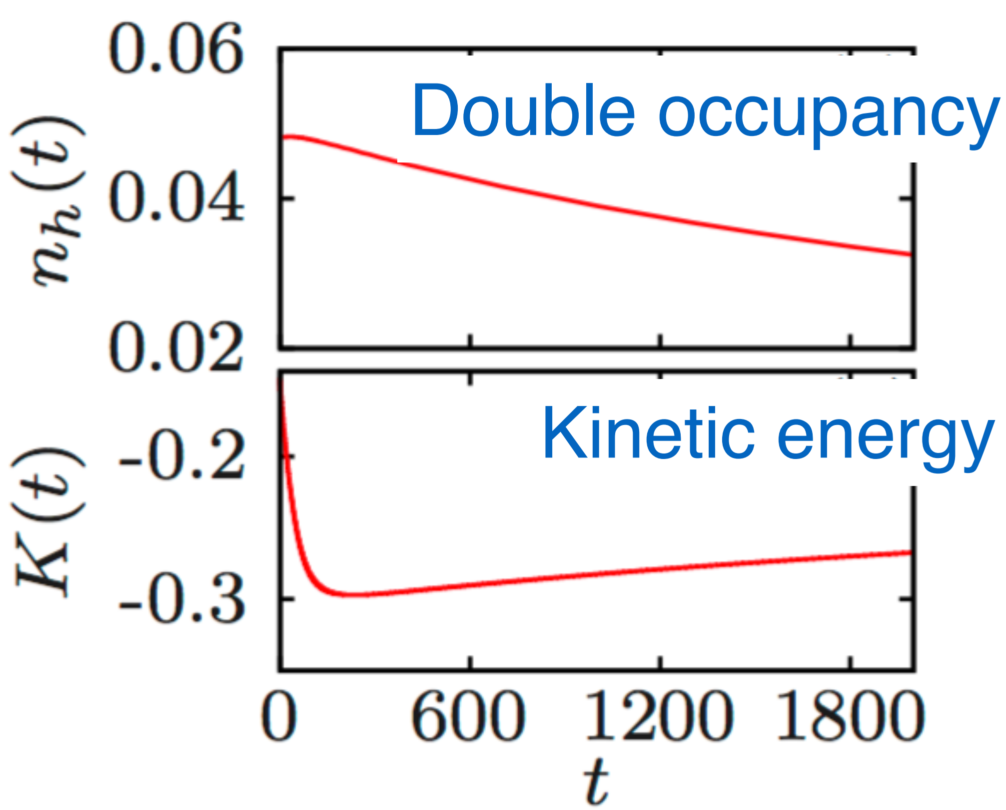


Example 2: Photo-doped strange metal in a Mott insulator

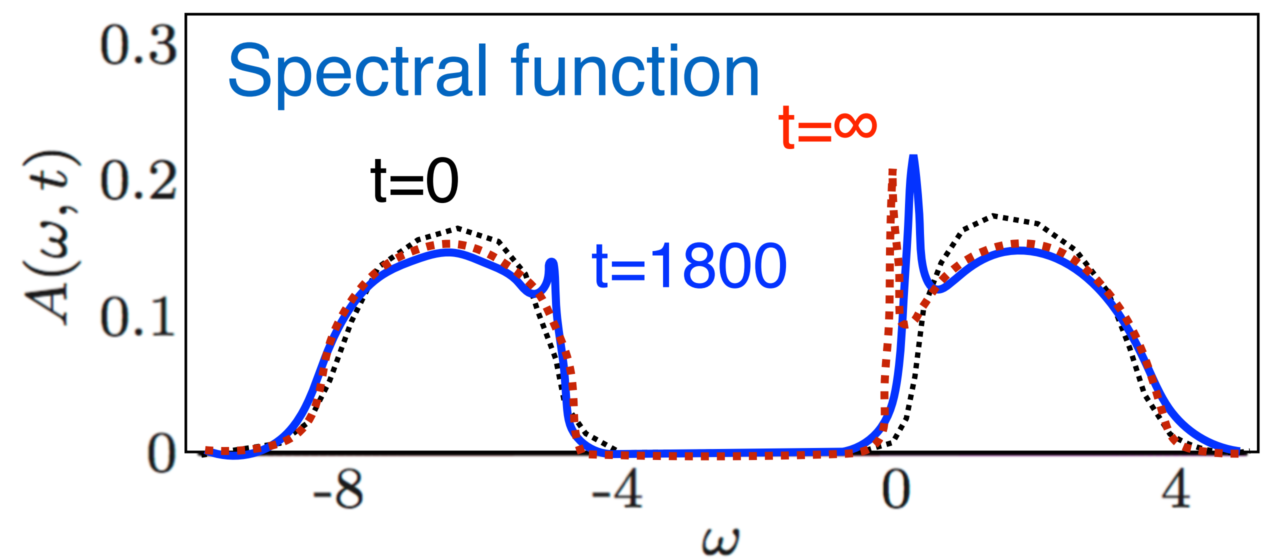
with N. Dasari (FAU -> HH), J. Li (FAU), Ph. Werner (Fribourg) arxiv:2010.04095

Initial state (bad metal at T ~ bandwidth), U=2×bandwidth, bandwidth=4

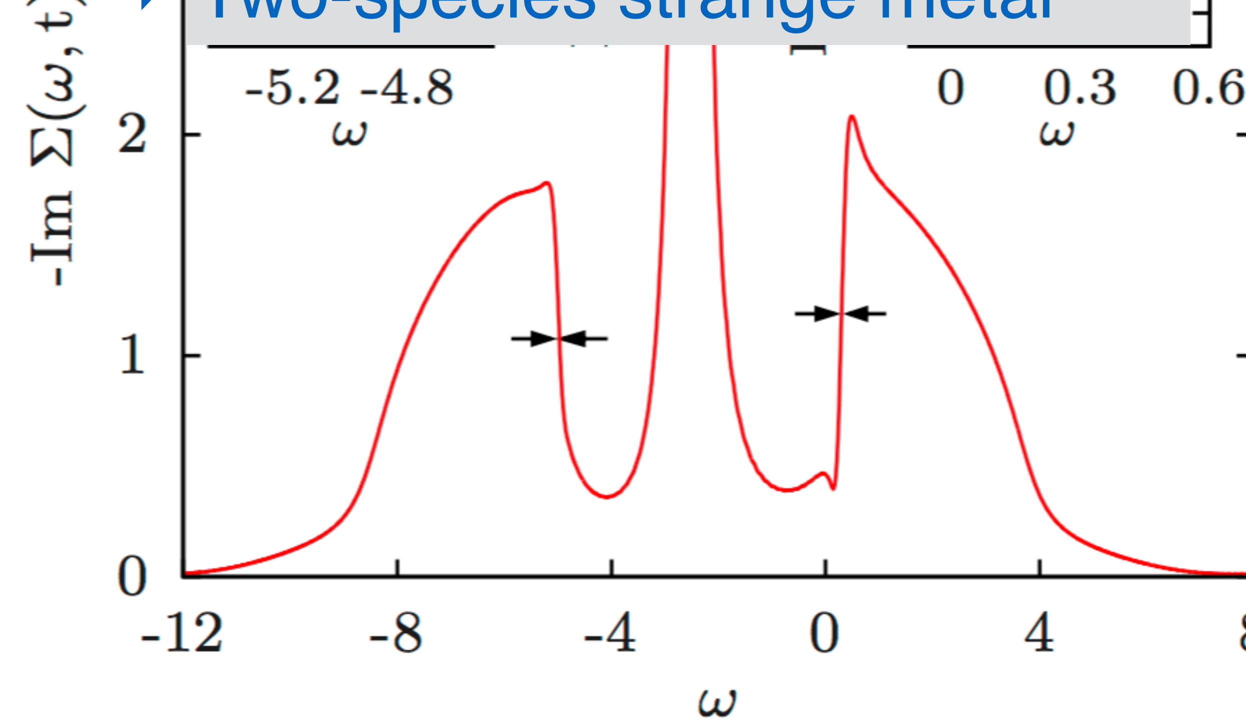
⇨ relaxation with ohmic bath at T~0.01 bandwidth



⇨ Double occupancy and hole density are slow variables (expected for U>>t: t-J model)



⇨ Two-species strange metal



Similar data for short time evolution (t<50): Eckstein end Werner PRB 2011, PRL 2013

"resilient quasiparticles" *Deng et al, PRL 2013*

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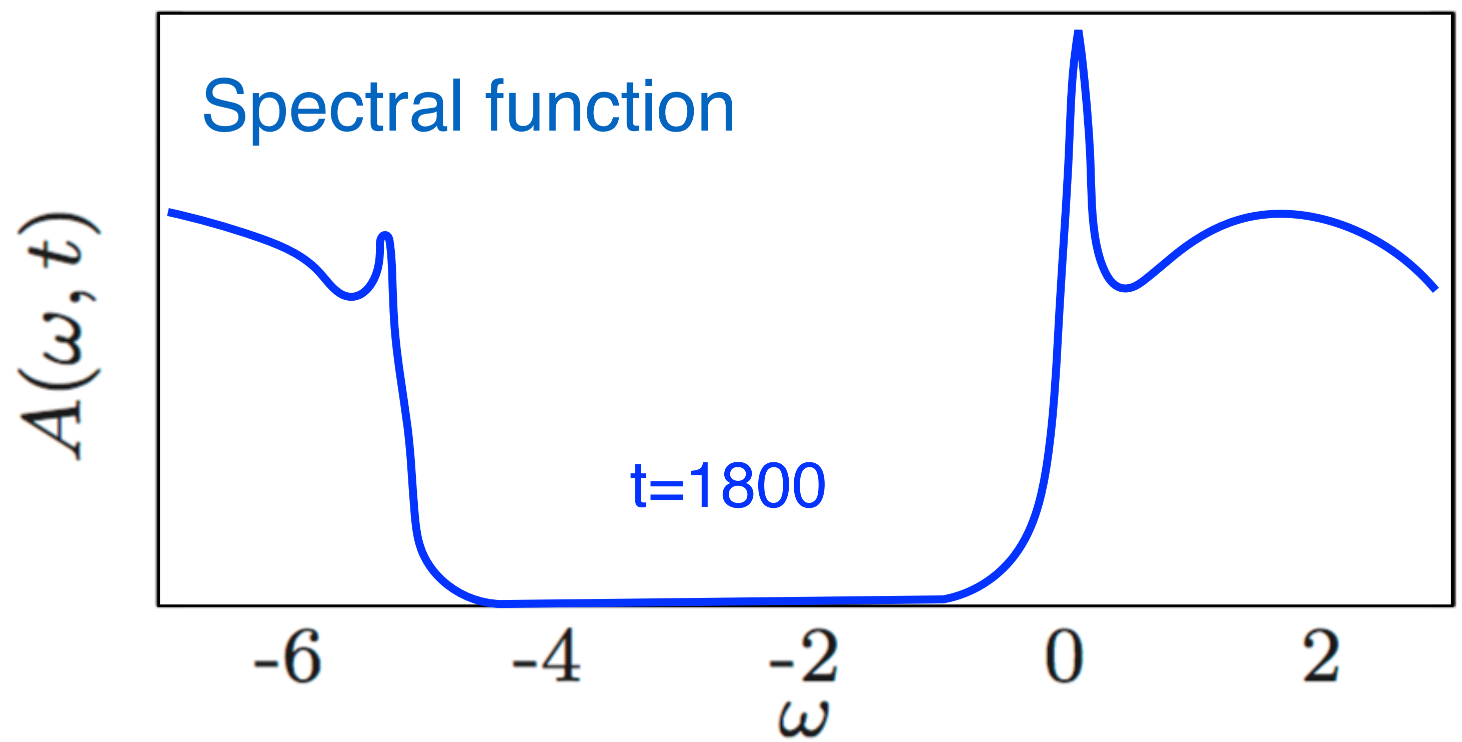
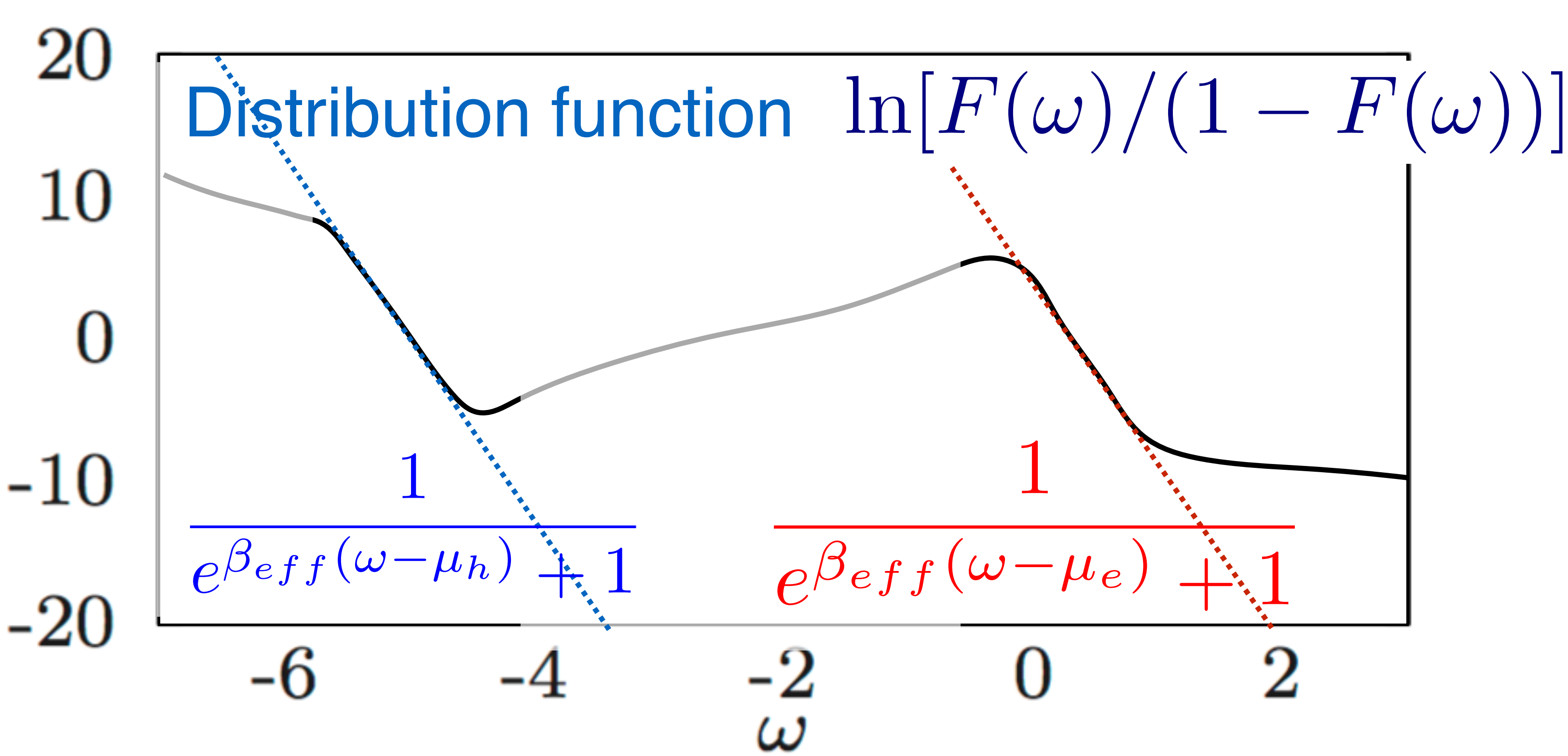
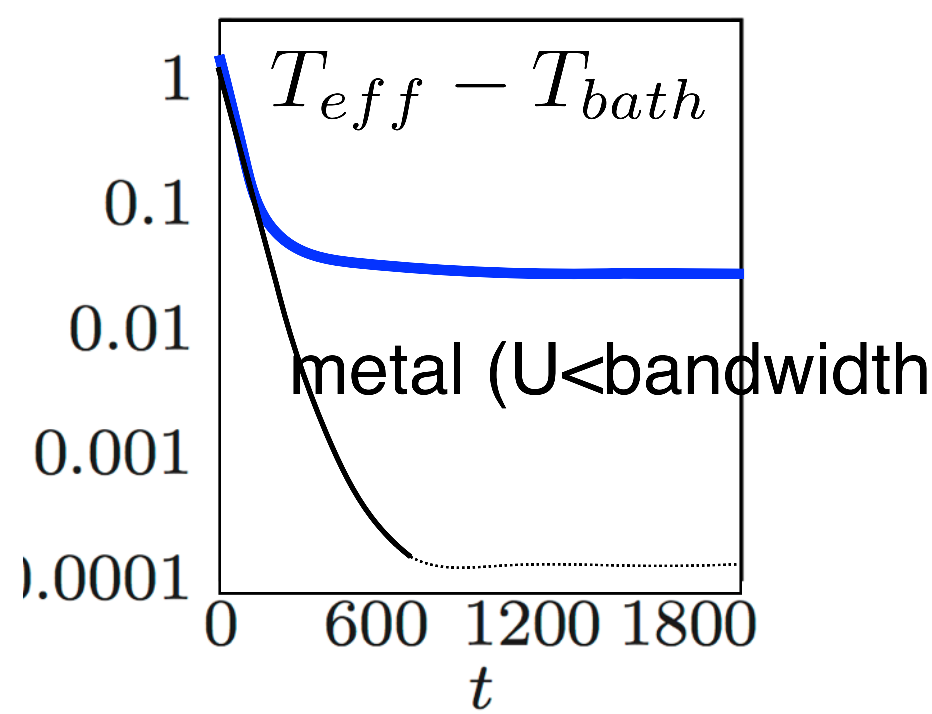




Relaxation to bath T ??

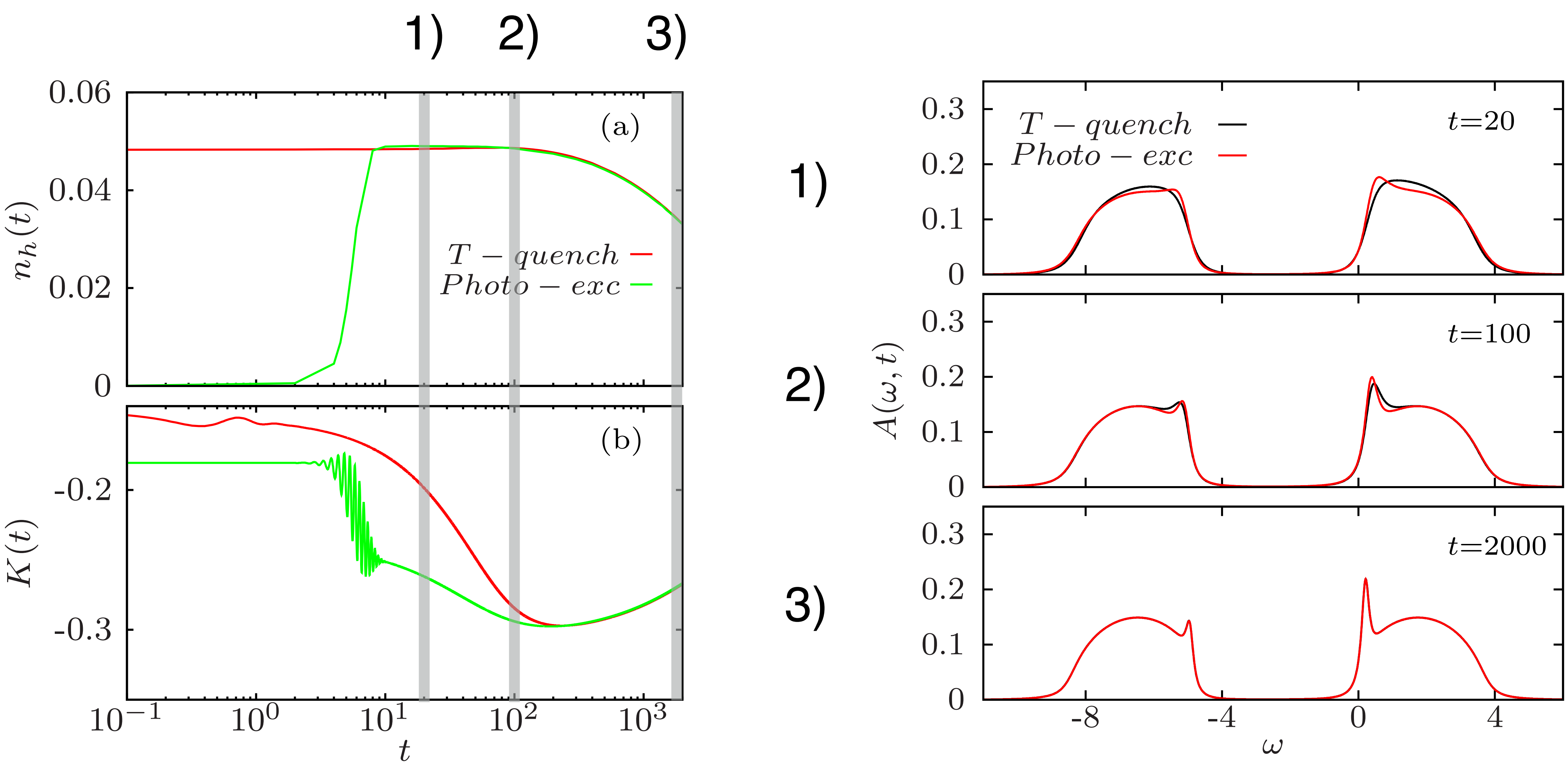


⇨ Universal distribution,different chemical potentials for “holes” and “”doublons

Example 2: Photo-doped strange metal in a Mott insulator

with N. Dasari (FAU -> HH), J. Li (FAU), Ph. Werner (Fribourg) arxiv:2010.04095

“Universality”: Temperature quench vs field-induced photo-excitation:



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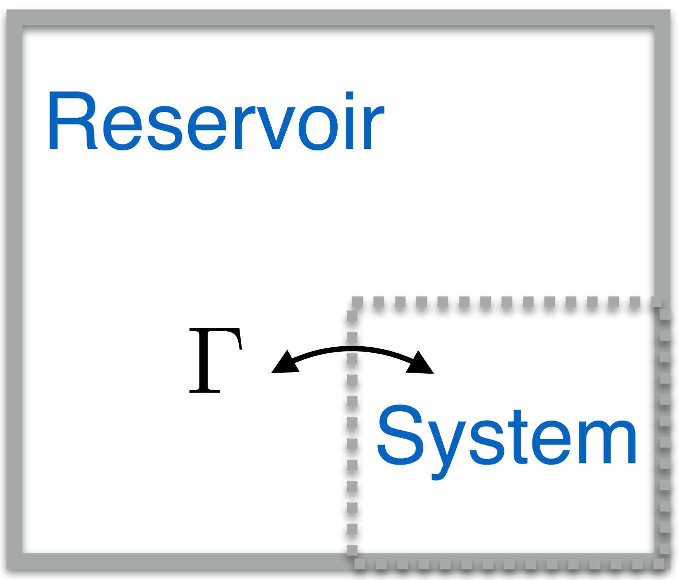
Picano, Li, Eckstein, arxiv:2101.09037

NESS representation of photo-doped states

transient non-equilibrium states with universal distributions characterized by few generalized chemical potentials ⇨ infinitely long lived states by coupling suitable reservoirs.



N conserved

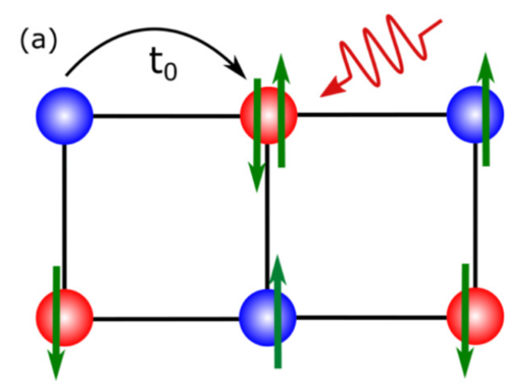
⇨ Nonanalytic response to bath: arbitrary small bath coupling determines N

⇨ Universality: properties of system given by N only (not on details of bath)

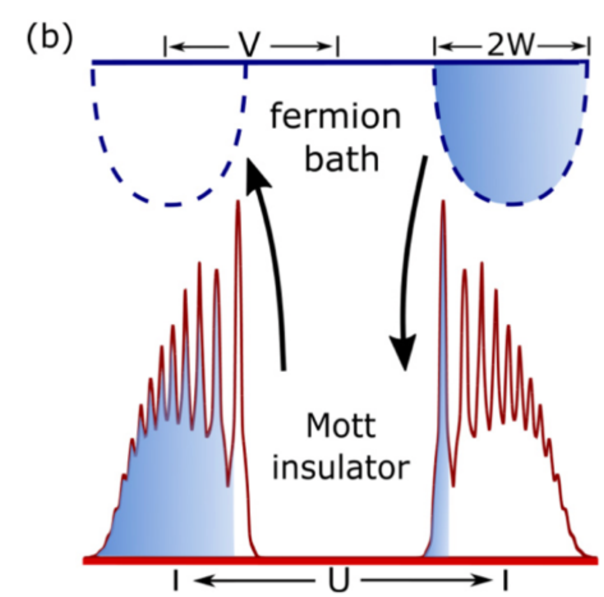
Generalization to almost conserved quantities:

Lange, Lenarčič, Rosch, Nature Comm 2019

Here: Use bath to activate photo-doped carrier density



⇨



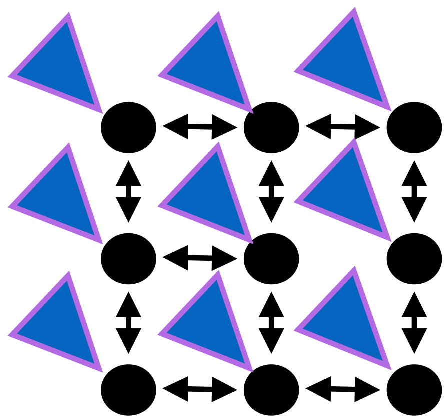
NESS representation of photo-doped states

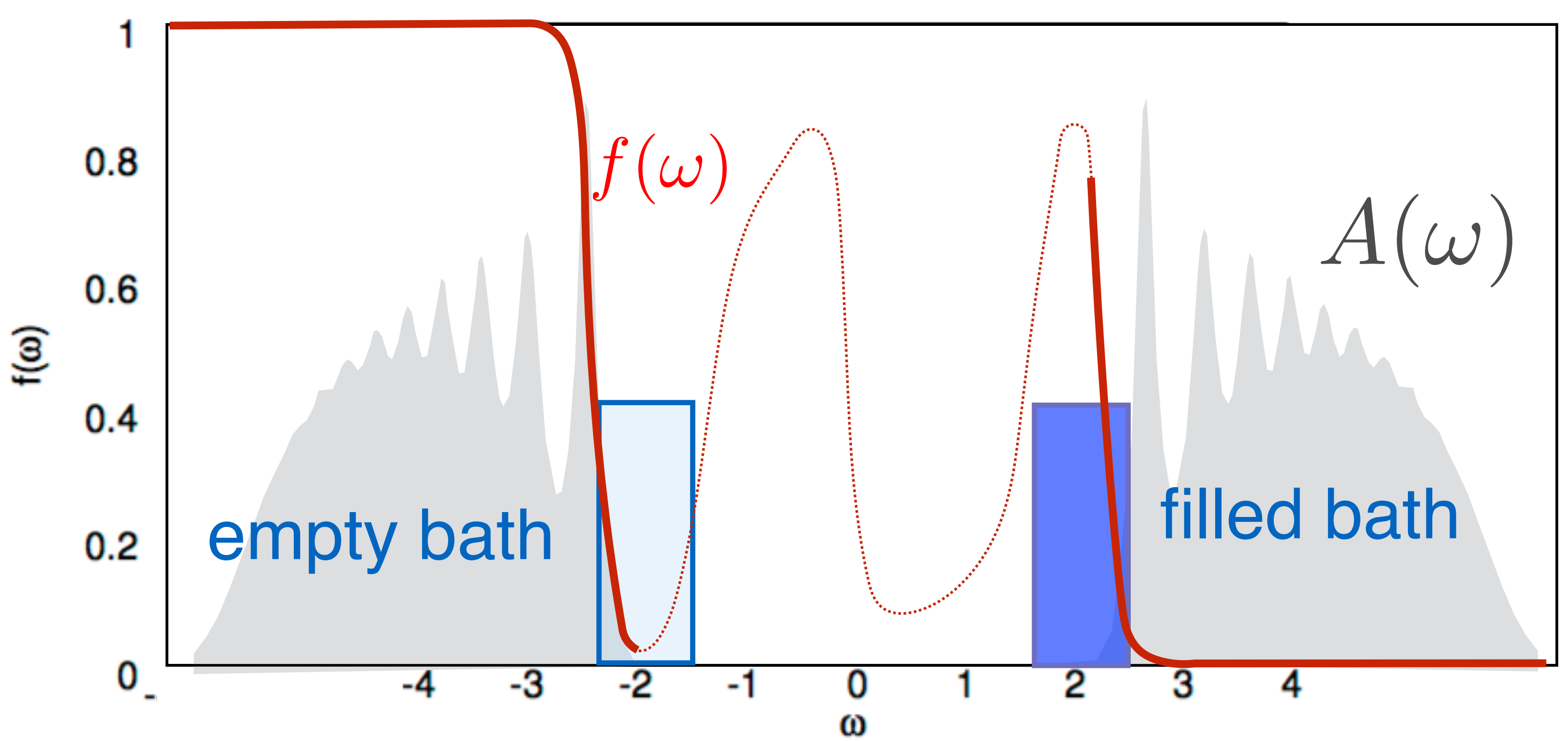
with J. Li (FAU) Phys. Rev. B 103, 045133 (2021)

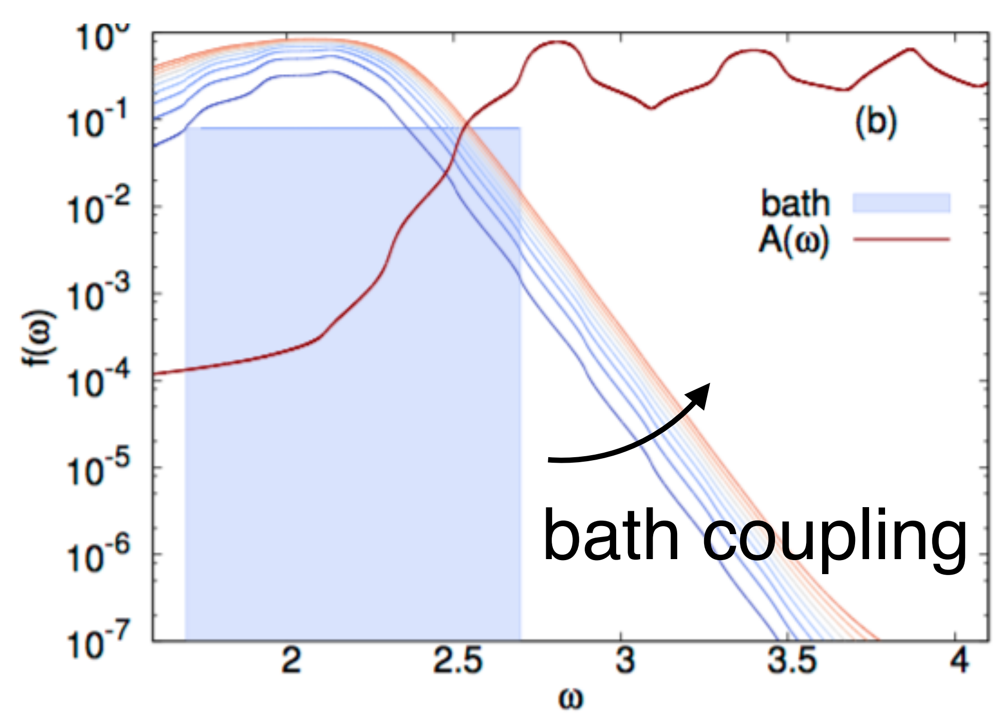
Use bath to activate photo-doped carrier density?

Hubbard model, U=8, bandwidth=4, antiferromagnetic Mott phase

bath coupled to each site $\sum_j \sum_p \left[c_j V_{p,j} a_{p,j} + H.c. + \epsilon_p a^\dagger_{p,j} a_{p,j} \right]$







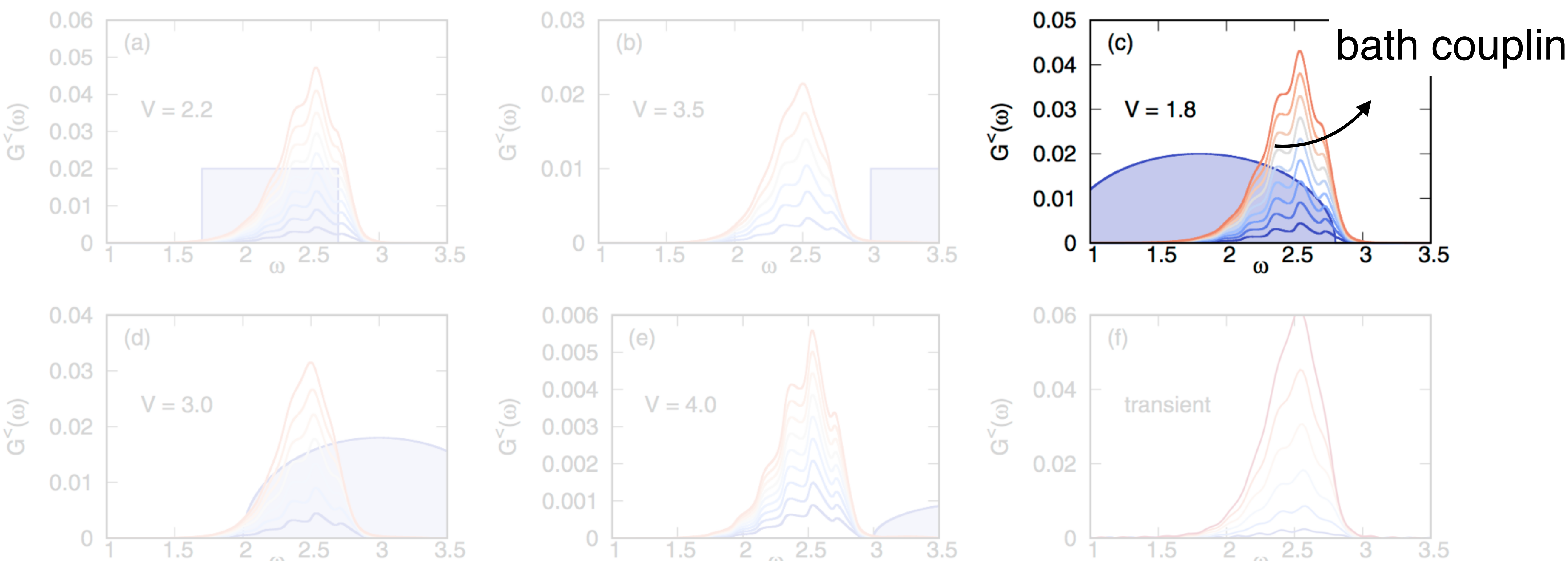
NESS representation of photo-doped states

with J. Li (FAU) Phys. Rev. B 103, 045133 (2021)

Use bath to activate photo-doped carrier density?

Hubbard model, U=8, bandwidth=4, antiferromagnetic Mott phase

Universal distribution function: $A(\omega)f(\omega)$



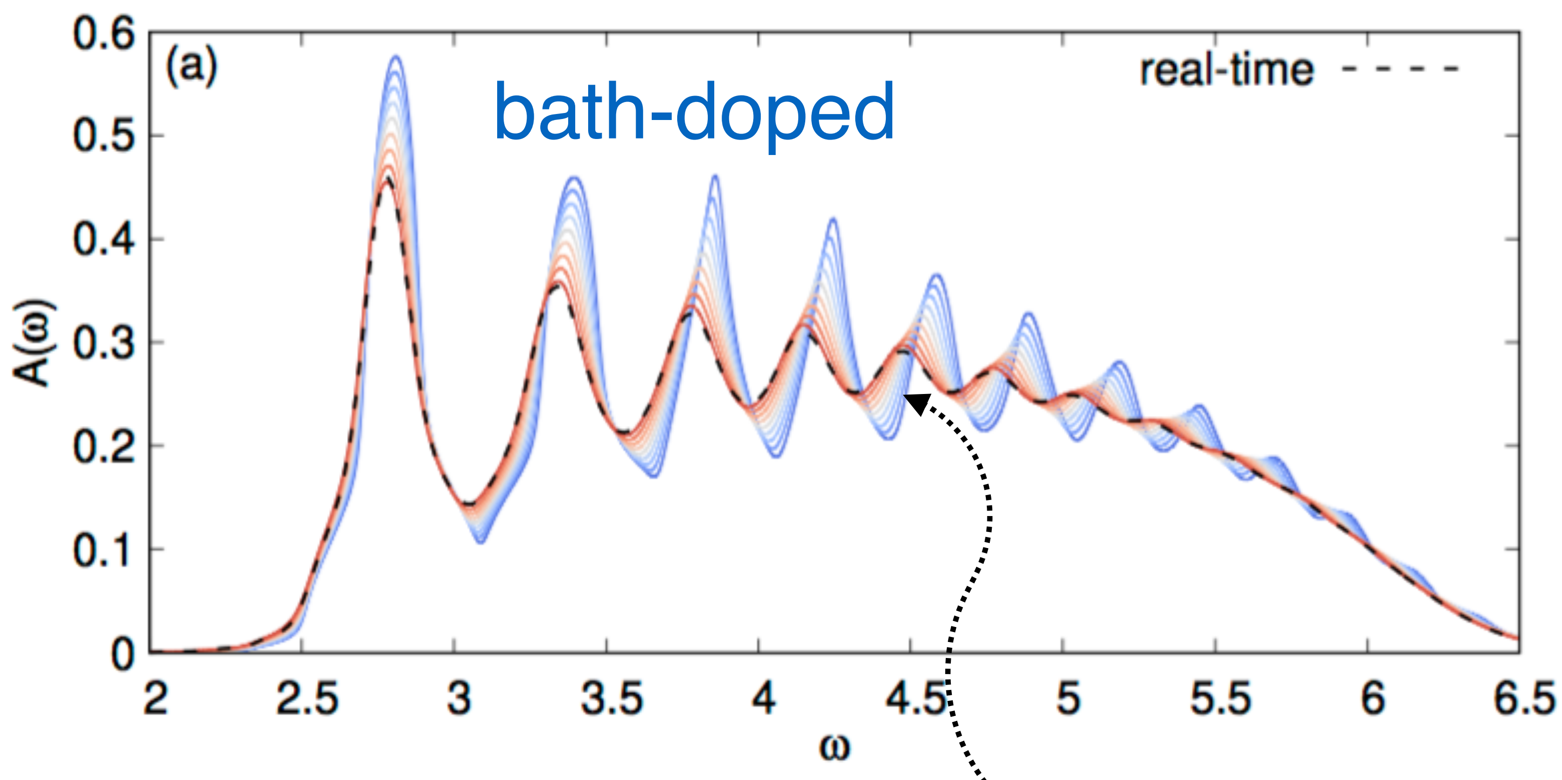
NESS representation of photo-doped states

with J. Li (FAU) Phys. Rev. B 103, 045133 (2021)

Use bath to activate photo-doped carrier density?

Hubbard model, U=8, bandwidth=4, antiferromagnetic Mott phase

Spectral function: $A(\omega)$



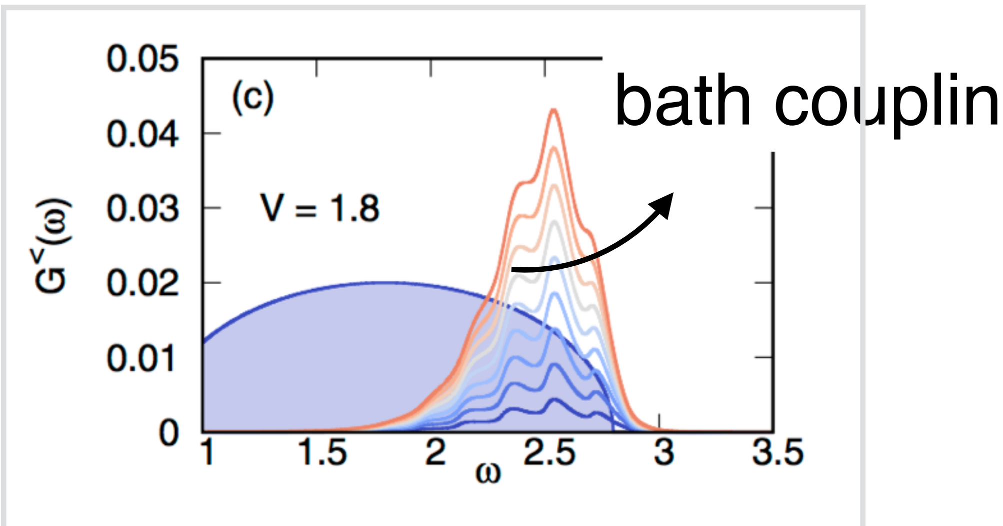


photo-doped state with same (1) order parameter and (2) upper band occupation

Also similar to doped equilibrium state Werner, Tsuji, Eckstein 2012

Phase diagram of eta-paired superconducting state

with Jiajun Li, Denis Golez, Philipp Werner Phys. Rev. B 102, 165136 (2020)

$$H = \sum_{\langle i,j \rangle, \sigma} c^\dagger_{i\sigma} c_{j\sigma} + U \sum_i n_{i\uparrow} n_{i\downarrow}$$

$$\eta_j^+ = (-1)^j c^\dagger_{j\uparrow} c^\dagger_{j\downarrow} \qquad \eta_j^- = (-1)^j c_{j\downarrow} c_{j\uparrow} \qquad \begin{pmatrix} |\uparrow\downarrow\rangle \\ |0\rangle \end{pmatrix}$$

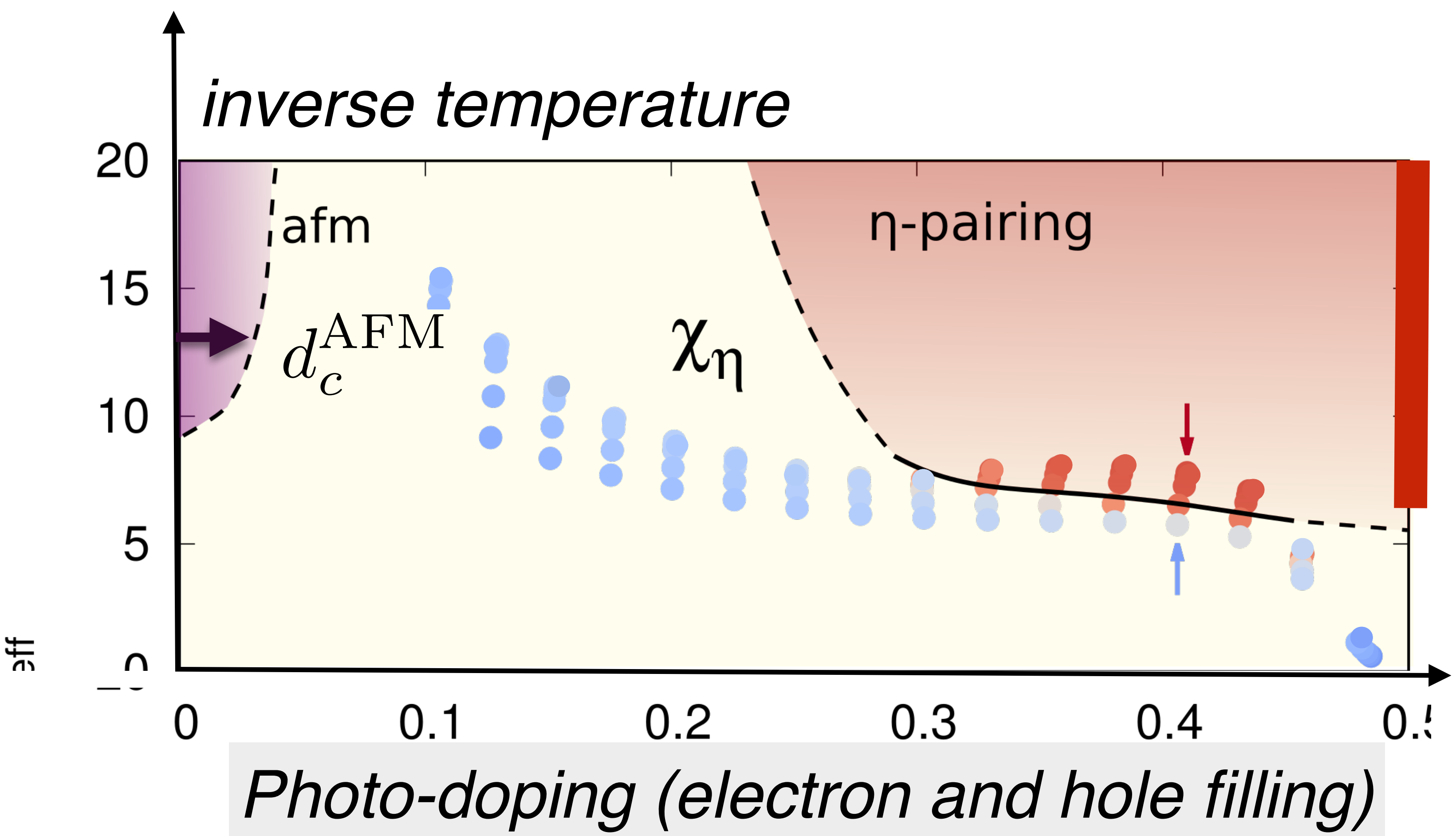
Large U limit, with only $|\uparrow\downarrow\rangle$ and $|0\rangle$:

$$H^{\mathrm{eff}} = -\sum_{\langle ij \rangle} J_{\mathrm{ex}} \boldsymbol{\eta}_i \cdot \boldsymbol{\eta}_j$$

Long-range η-pairing: $\langle \eta_j^+ \rangle \equiv \Delta$

Kaneko et al, 2018
Peronacci et al. 2020

Phase-diagram of photo-doped Hubbard model



one fluid limit

Rosch et al, PRL (2008)

Summary

Examples for universal non-thermal distribution functions with slow variables and conjugate generalized chemical potentials

⇨ SDW after quench, Mott insulator after photo-doping

Picano, Eckstein, Phys. Rev. B 103, 165118 (2021)   Dasari, Li, Werner, Eckstein, arxiv:2010.04095

Some mysteries in the evolution to be understood conceptually

⇨ accelerated gap melting (precursor of metastability)

Dissipative preparation of slowly evolving “prethermal states”

⇨ phase-diagram of photo-doped state   *Li and Eckstein, Phys. Rev. B **103**, 045133 (2021)*
*Li, Golez, Werner, Eckstein, PRB **102**, 165136 (2020)*

⇨ QBE for slow evolution of such states: *Picano, Li, Eckstein, arxiv:2101.09037*

Thanks to:
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N. Dasari (FAU moved to Univ. HH)
Jiajun Li (FAU)
Denis Golez (Flatiron NY, moved to JSI Ljubljana)
Philipp Werner (Fribourg)

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