Quasi-steady state descriptions for photo-doped Mott insulators

Yuta Murakami (RIKEN CEMS)

Ref

YM, S. Takayoshi, T. Kaneko, Z. Sun, D. Golež , A. J. Millis and P. Werner, Comm. Phys. **5**, 23 (2022).

YM, S. Takayoshi, T. Kaneko, A. Läuchli and P. Werner, Phys. Rev. Lett. **130**, 106501 (2023).

Review: YM, D Golež, M Eckstein, P Werner, arXiv:2310.05201.

RIKEN

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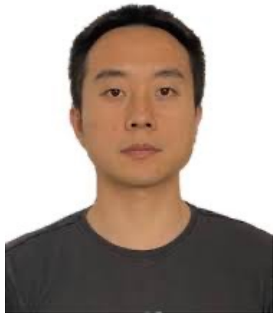

Z. Suni

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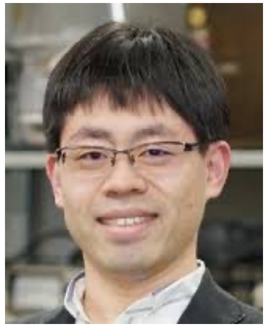

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科研費 KAKENHI

Background: Physics out of strong light-matter coupling

Weak light excitation (Linear regime)

- ▷ Same frequencies of input and output
- ▷ Matter stays in equilibrium

Strong light excitation (Nonlinear regime)

- ▷ Change in properties of output light
  ex) High-harmonic generation
- ▷ Change in properties of matter
  ex) Insulator-metal transition,
  light-induced superconductor

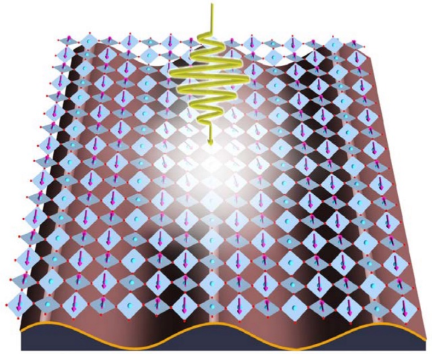
Strong light + Matter = Control of properties of light and matter

Strong light-matter coupling and emergent phenomena

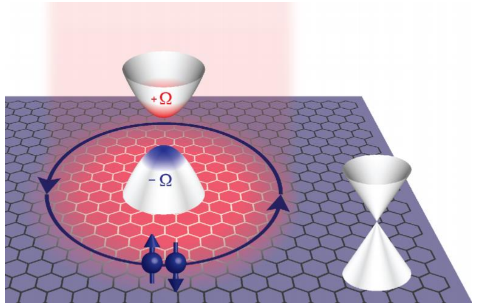
Rapid development on strong laser techniques in THz and mid-infrared regime

Control of physical properties

Photo-indued phase transition, Photo-doping,
Floquet engineering, nonlinear phononics, etc..



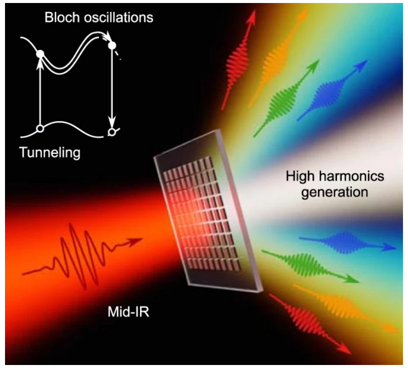
From S. Keiser



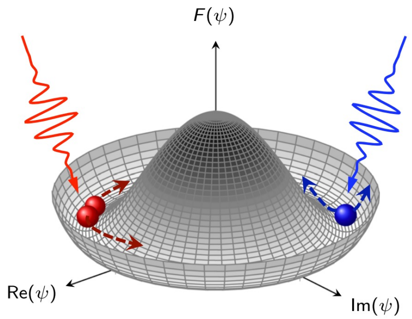
From J. McIver

Intriguing optical responses

High-harmonic generation, Shift current,
Higgs modes in superconductors, etc…



From D. Shilkin



From F. Gabliele

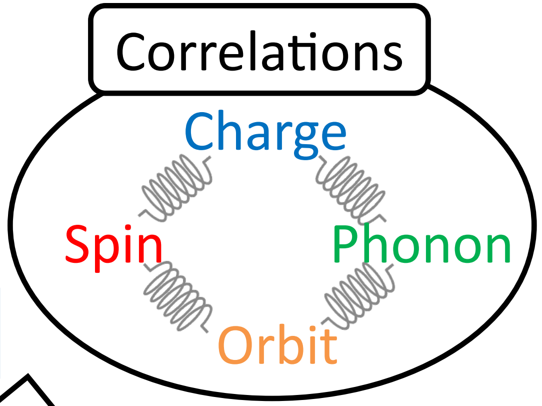
Potential impact on next generation photo-electronics technology & new spectroscopy techniques

ex) Fast memory, Spintronics, 6G telecommunication , Attosecond spectroscopy, etc..

Appeal of strongly correlated systems

Strongly correlated systems: Crucial role of interactions between electrons

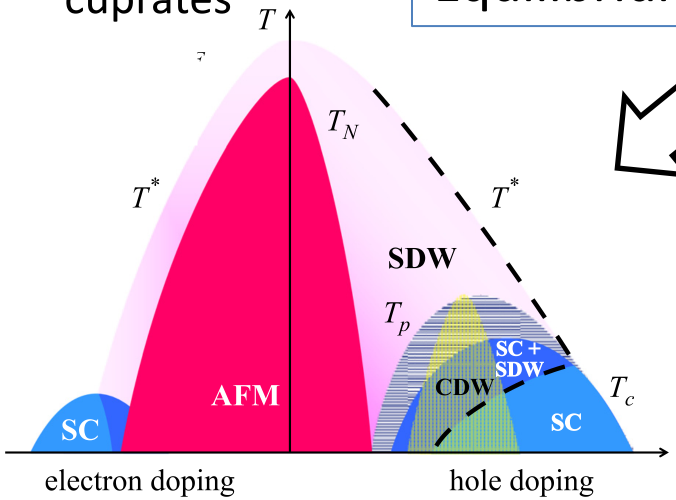
⇨ Various emergent collective phenomena in and out of equilibrium



Equilibrium

Noneq.･Nonlinear

ex)Phase diagram of cuprates



Rich physics & order

A. Kordyuk, Low. Temp. Phys. **41**, 319 (2015)

▷ Exotic excitation structure

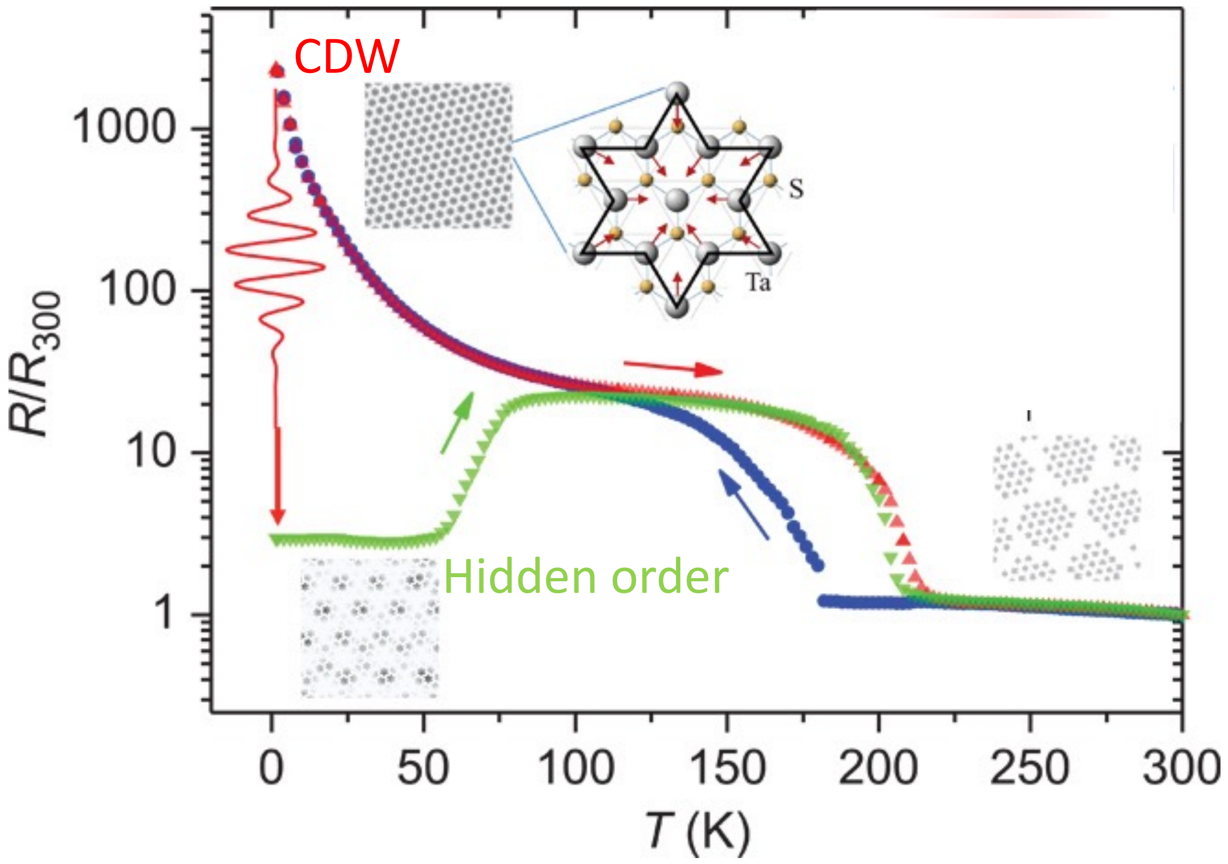
→ Intriguing optical response

▷ Balance between different degrees of freedom

→ Rich photo-induced phase transitions

Examples of Photo-induced phase transitions

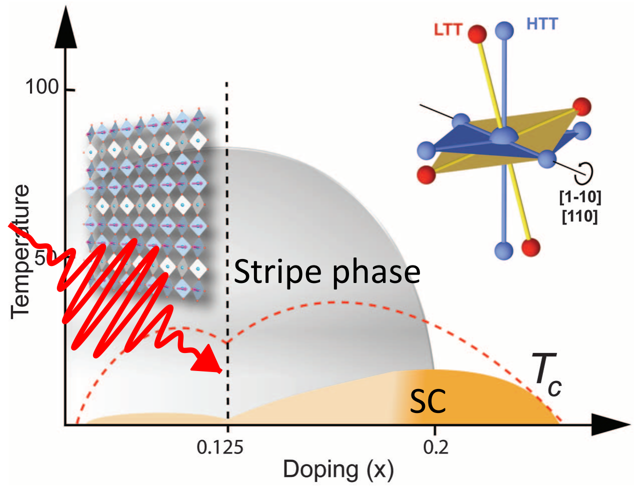
Hidden CDW phase @ 1T-TaS_2



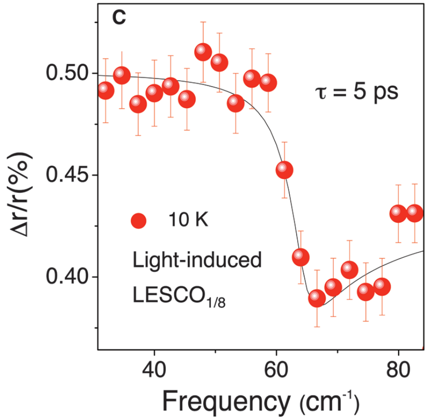
Stojchevska et al., Science **344**, 6180 (2014);
Vaskivskyi et al., Sci. Adv. **1**:e150016 (2015).

Photoinduced SC@$La_{1.8-x}Eu_{0.2}Sr_xCuO_4$

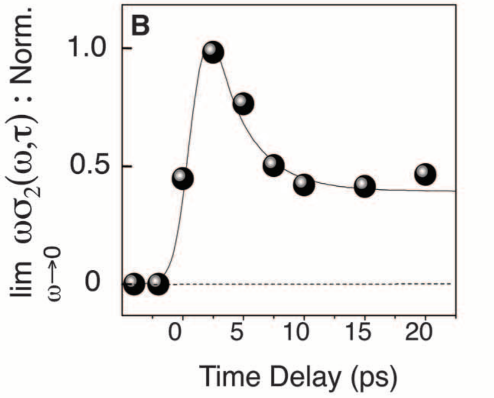
D. Fausti et al., Science **331**, 189 (2011) .



Josephson plasma



1/w @ optical conductivity

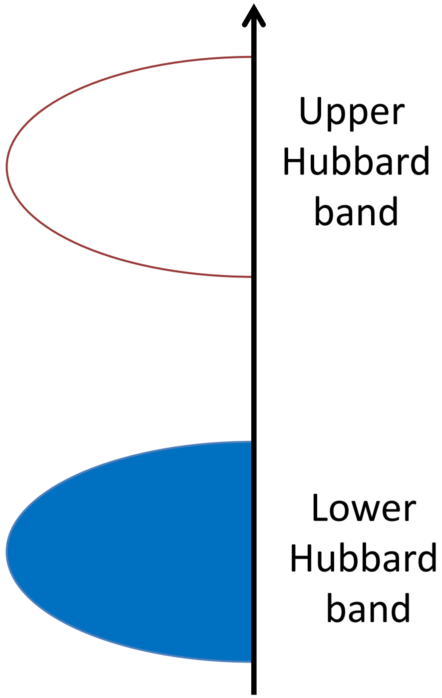


General question: Origin of nonequilibrium phases?

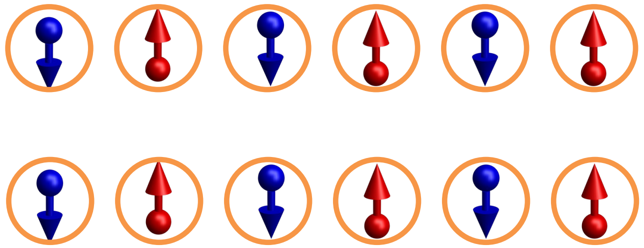
Doping charge carriers into Mott insulators: Equilibrium

Ex) Hubbard model

$$\hat{H} = -v \sum_{\langle i,j \rangle,\sigma} \hat{c}_i^\dagger \hat{c}_j + U \sum_i n_{i\uparrow} n_{i\downarrow}$$

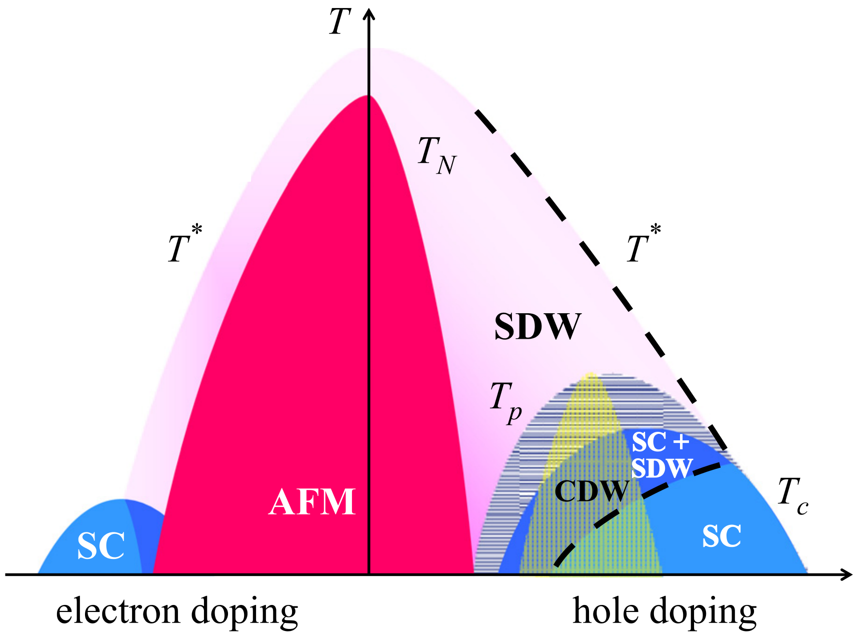


Mott Insulator@$U>>v$



Half filling: # electrons= # sites

Phase diagram of cuprate



A. Kordyuk, Low. Temp. Phys. **41**, 319 (2015)

Doping activates correlations between spin, orbital and charge

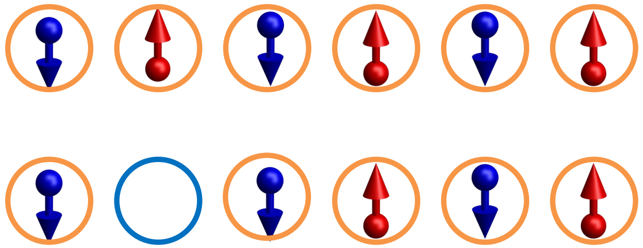
⇨ Emergence of rich phases

Doping charge carriers into Mott insulators: Equilibrium

Ex) Hubbard model

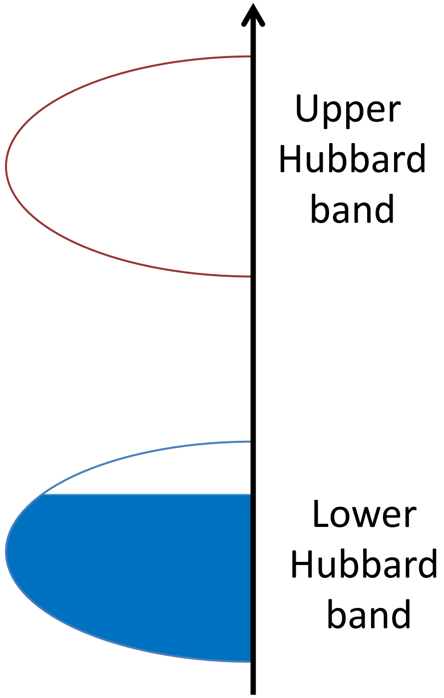
$$\hat{H} = -v \sum_{\langle i,j\rangle,\sigma} \hat{c}_i^\dagger \hat{c}_j + U \sum_i n_{i\uparrow} n_{i\downarrow}$$

Mott Insulator@*U*>>*v*

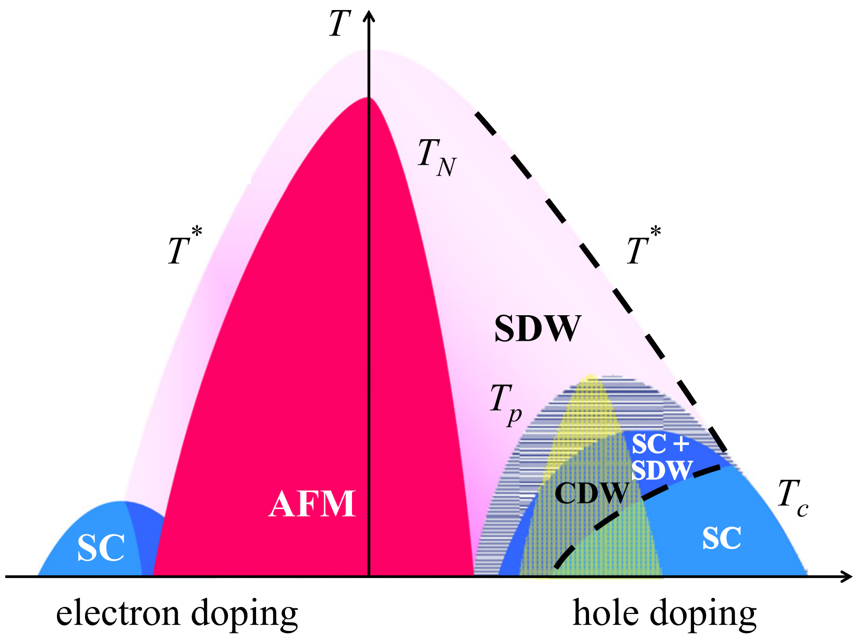


holon

ex) chemical doping



Phase diagram of cuprate

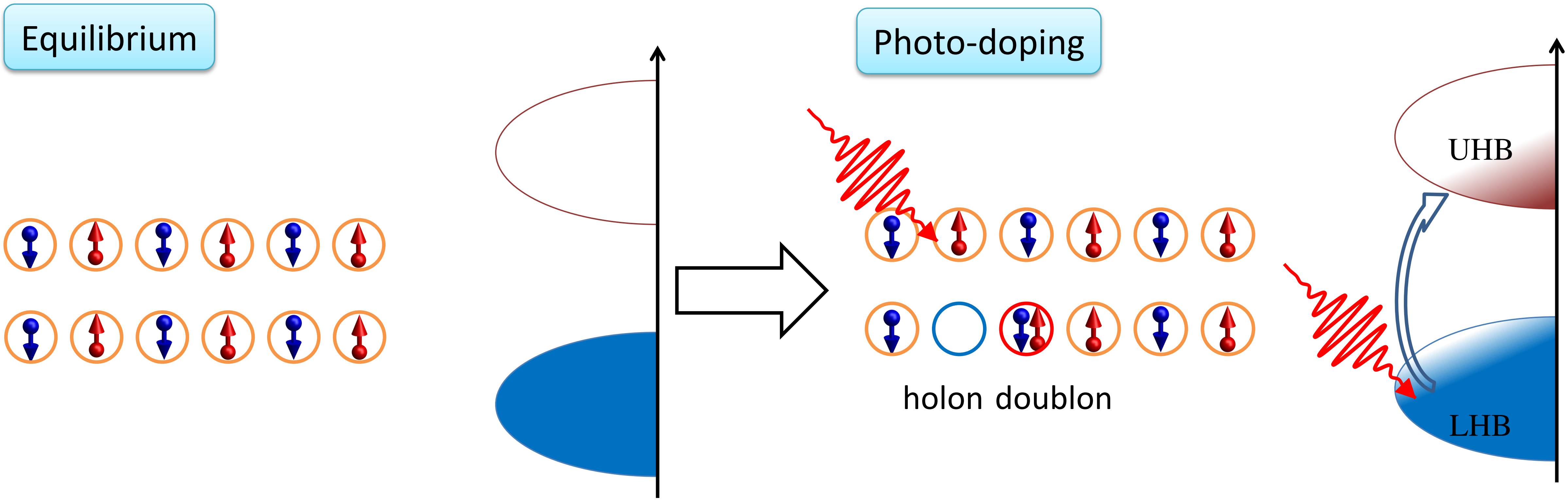


A. Kordyuk, Low. Temp. Phys. **41**, 319 (2015)

Doping activates correlations between spin, orbital and charge

Emergence of rich phases

Doping charge carriers into Mott insulators



Various types of charge carriers are activated at the same time

cf. Equilibrium doping → holon **or** doublon

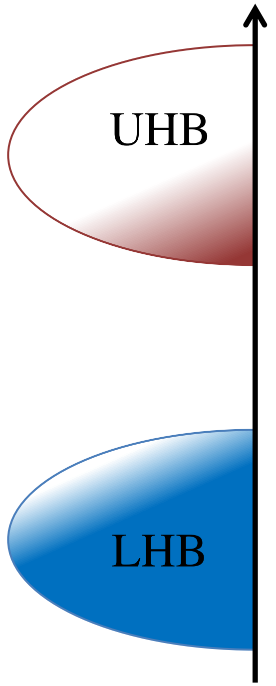
Long-life time of photo-carriers and metastable states

Life-time of doublon・holon

$U \gg v \quad \Rightarrow \quad \tau_{\mathrm{rec}} \gg 1/v$ (Exponential with U/v)

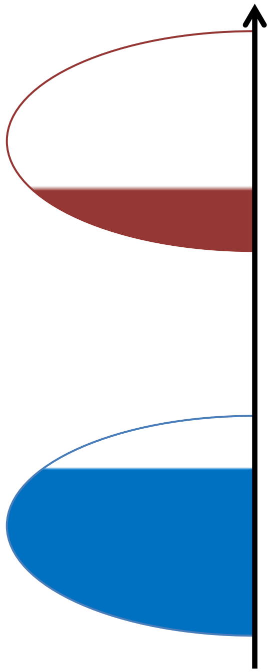
N. Strohmaiser, et. al., PRL **104**, 080401 (2010).
R. Sensarma, et. al., PRB **82**, 224302 (2010).
A. Rosch, et. al., PRL **101**, 265301 (2008).

Just after excitation



- (Approximate) conservation of doublons and holons
- Intraband relaxation + Cooling via environment

Metastable steady state



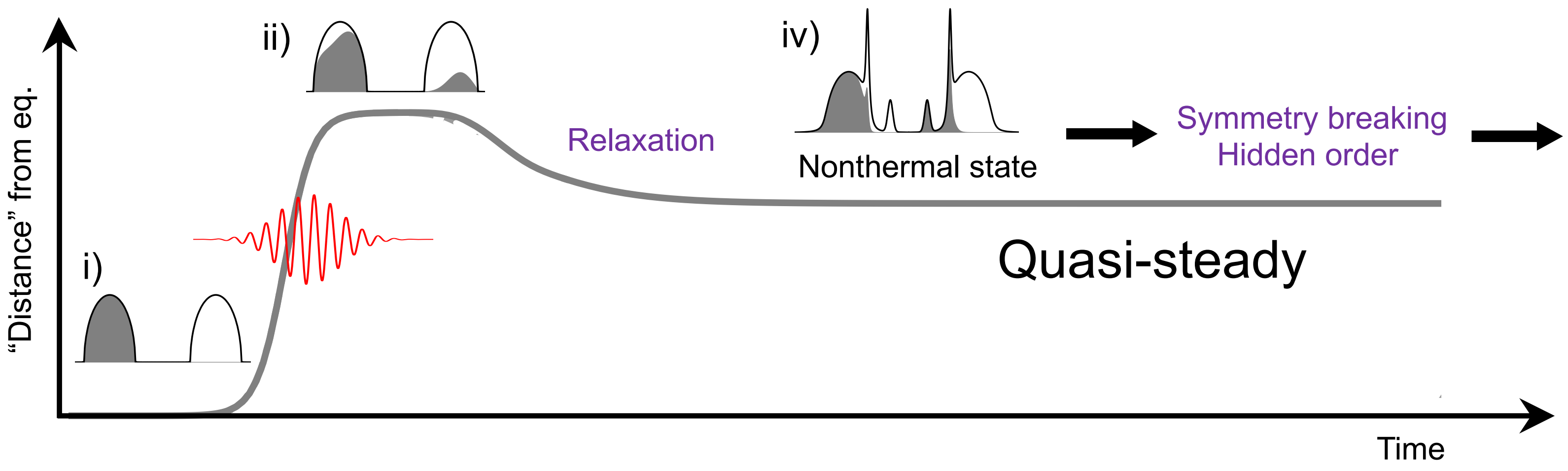
General question & three complementary approaches

What kinds of metastable states emerge in photo-doped Mott insulators?

Review: YM, D Golež, M Eckstein, P Werner, arXiv:2310.05201

1) Direct time-evolution

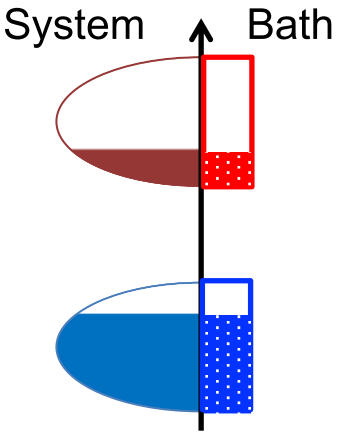
Methods:
Exact Diagonalization,
Tensor network,
Dynamical mean-field theory,
etc…



2) Quasi-NESS approach

Approximate quasi-steady state with a true steady state supported by external bath

J. Li, et. al., PRB **102**, 165136 (2020).
J. Li and M. Eckstein, PRB **103** 045133 (2021).



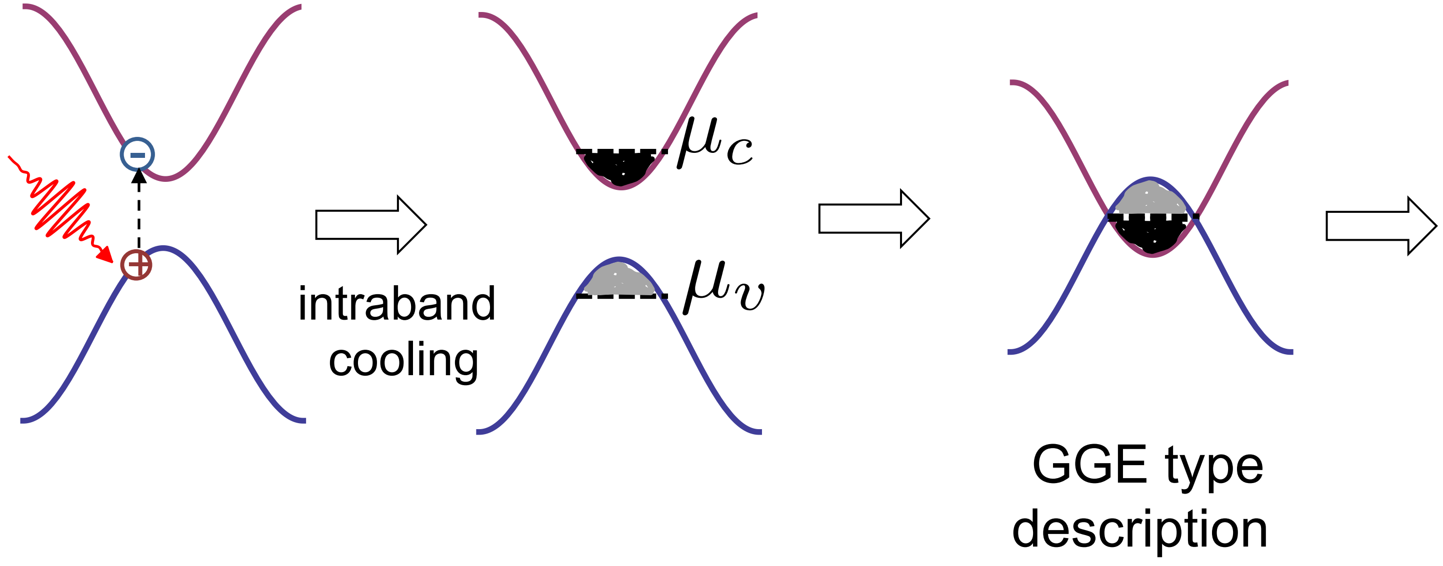
3) Quasi-equilibrium approach

- Analogous to photo-doped semiconductor
- Mainly used in this talk

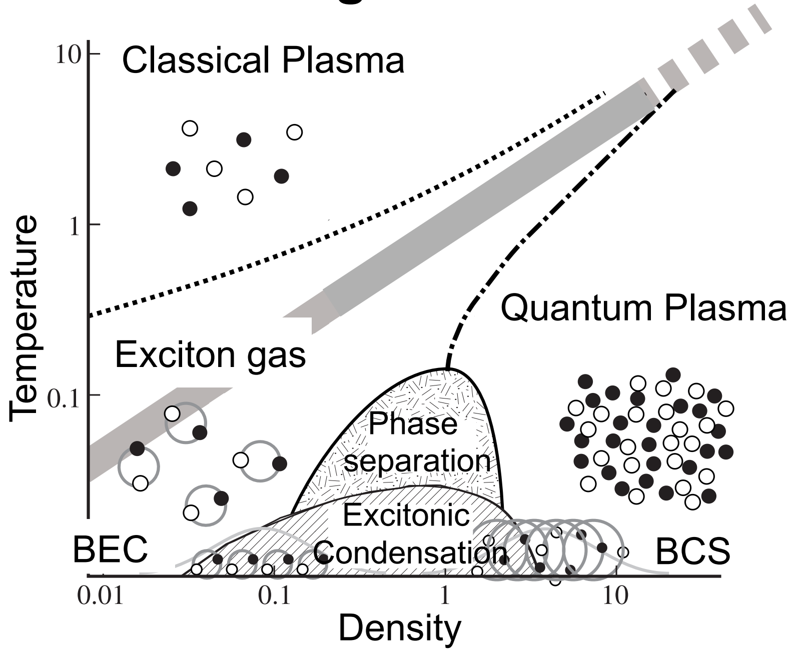
A. Rosch, et. al., PRL **101**, 265301 (2008).
Y. Kanamori, et al., PRL 107, 167403 (2011).
YM, et. al., Comm. Phys. 5, 23 (2022).

Quasi-equilibrium approach for photo-doped semiconductors

K. Asano, Bussei Kenkyu (2013).
L. V. Keldysh, *Contemporary Phys.* **27**, 395 (1986).



Phase diagram



Conservation of electrons and holes ⇨ Effective equilibrium problem

Effective chemical potential & temperature
"μ_c, μ_v, T_{eff}"

Strongly correlated systems?

YM, et. al., Comm. Phys. **5**, 23 (2022).

Step1

Apply the Schrieffer-Wolff transformation (1/U expansion)

Original Hamiltonian: $\hat{H}$

↓

Effective model with conserved local multiplets dressed with virtual fluctuation

Effective Hamiltonian: $\hat{H}_{\mathrm{eff}}$

ex) doublons, holons

Step2

Introducing **chemical potential** for local multiplets and effective temperature

$$\hat{K}_{\mathrm{eff}} = \hat{H}_{\mathrm{eff}} - \sum_{g \in \mathrm{ps}} \mu_g \hat{n}_g \qquad \hat{\rho}_{\mathrm{eff}} = \exp(-\beta_{\mathrm{eff}} \hat{K}_{\mathrm{eff}})$$

GGE type description

Step3

Solve the effective problem with existing **equilibrium** methods

Example : Extended Hubbard model

$$\hat{H} = -v \sum_{\langle i,j \rangle, \sigma} \hat{c}_i^\dagger \hat{c}_j + \hat{H}_U + \hat{H}_V$$

with

$$\hat{H}_U = U \sum_i \hat{n}_{i\uparrow} \hat{n}_{i\downarrow}$$

$$\hat{H}_V = V \sum_{\langle ij \rangle} \hat{n}_i \hat{n}_j$$

$$U \gg v, V$$

Effective model with conserved local multiplets and effects of virtual fluctuation

$$\hat{H}_{\text{eff}} = \hat{H}_U \quad \leftarrow \mathcal{O}(U)$$

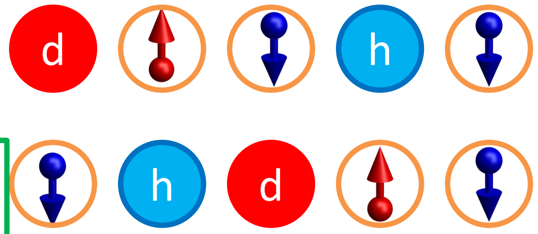
$$+ \hat{H}_{\text{kin,LHB}} + \hat{H}_{\text{kin,UHB}} \quad \leftarrow \mathcal{O}(v)$$

$$+ \hat{H}^{(2)}_{U,\text{shift}} + \hat{H}_{\text{spin,ex}} + \hat{H}_{\text{dh,ex}} + \hat{H}^{(2)}_{\text{kin,LHB}} + \hat{H}^{(2)}_{\text{kin,UHB}} + \hat{H}^{(2)}_{\text{dh,slide}} + \hat{H}_V$$

$\mathcal{O}(J_{\text{ex}})$ $\quad J_{\text{ex}} = \dfrac{4v^2}{U}$

3 site terms

4 types of pseudo-particles



Exchange coupling for spins

$$\hat{H}_{\text{spin,ex}} = J_{\text{ex}} \sum_{\langle i,j \rangle} \hat{\mathbf{s}}_i \cdot \hat{\mathbf{s}}_j$$

Exchange coupling for doublon-holon

$$\hat{H}_{\text{dh,ex}} = -J_{\text{ex}} \sum_{\langle i,j \rangle} \hat{\boldsymbol{\eta}}_i \cdot \hat{\boldsymbol{\eta}}_j$$

$$\hat{\eta}_i^+ = (-)^i \hat{c}_{i\downarrow}^\dagger \hat{c}_{i\uparrow}^\dagger$$

$$\hat{\eta}_i^z = \frac{1}{2}(\hat{n}_i - 1)$$

Previous analysis : metastable η pairing phase

Cold atom with extreme doping

A. Rosch, et. al., PRL **101**, 265301 (2008).

Metastable state with doublon or holon

$$\hat{H}_{\mathrm{dh,ex}} = -J_{\mathrm{ex}} \sum_{\langle i,j \rangle} \hat{\boldsymbol{\eta}}_i \cdot \hat{\boldsymbol{\eta}}_j \qquad \hat{\eta}_i^+ = (-)^i \hat{c}_{i\downarrow}^\dagger \hat{c}_{i\uparrow}^\dagger, \quad \hat{\eta}_i^z = \frac{1}{2}(\hat{n}_i - 1)$$

$SU_c(2)$ Symmetry

$$\Rightarrow \quad |\Psi\rangle = e^{-i\theta \sum_i S_i^x} |\Uparrow\Uparrow\Uparrow \ldots\rangle = e^{-i\frac{\theta}{2}\sum_i (-1)^i (c_{i\uparrow}^\dagger c_{i\downarrow}^\dagger + \mathrm{H.c.})} |0\rangle,$$

$$\cos\theta = 1 - 2n_d \qquad \langle c_{i\uparrow}^\dagger c_{i\downarrow}^\dagger \rangle = \frac{(-1)^i}{2} \sin\theta$$

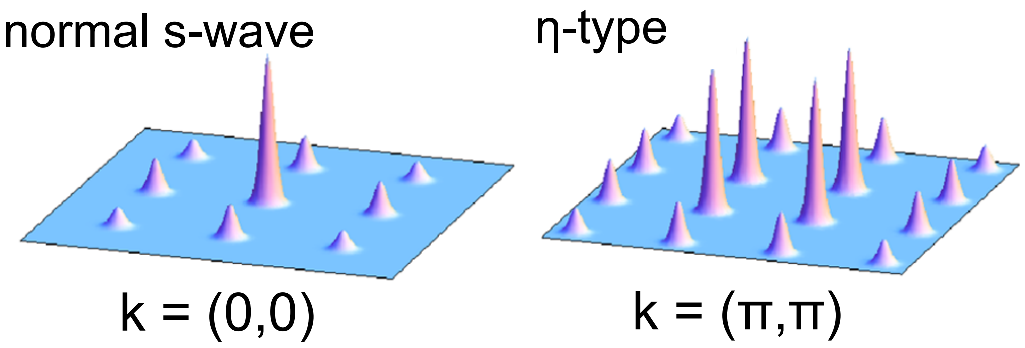
η paring state

Yang's η-pairing state

$$|\phi_{N_\eta}\rangle = \frac{1}{\sqrt{\mathcal{C}_{N_\eta}}} (\hat{\eta}^+)^{N_\eta} |0\rangle$$

$$\hat{\eta}^+ = \sum_j (-1)^j \hat{c}_{j,\downarrow}^\dagger \hat{c}_{j,\uparrow}^\dagger = \sum_k \hat{c}_{\pi-k,\downarrow}^\dagger \hat{c}_{k,\uparrow}^\dagger$$

C. N. Yang, Phys. Rev. Lett. 63, 2144 (1989)



Momentum distribution of fermion pair

Photo-doped metastable states in 1D ?

Quasi-equilibrium approach for 1D extended Hubbard model

- ▷ Numerical analysis (A tensor network: iTEBD) — YM, et al., Comm. Phys. **5**, 23 (2022).
- ▷ Analytical discussion — YM, et al., Phys. Rev. Lett. **130**, 106501 (2023).

⇩

Main points

- ▷ Exact from of wave function of photo-doped states: $|\Psi\rangle = |\Psi^{\mathrm{GS}}_{\mathrm{SF}}\rangle|\Psi^{\mathrm{GS}}_{\mathrm{spin}}\rangle|\Psi^{\mathrm{GS}}_{\eta-\mathrm{spin}}\rangle$
- ▷ Spin, charge and η-spin separation
- ▷ Intuitive insight into physics of metastable states

Emergent degrees of freedoms by photo-doping lead to intriguing nonequilibrium phases!

Exact wave function of photo-doped metastable states

YM, et al., PRL. **130**, 106501 (2023).

Wave function @ $U \to \infty$, V/J_{ex} = const, $T_{eff} = 0$

$$|\Psi\rangle = |\Psi^{\mathrm{GS}}_{\mathrm{SF}}\rangle |\Psi^{\mathrm{GS}}_{\mathrm{spin}}\rangle |\Psi^{\mathrm{GS}}_{\eta-\mathrm{spin}}\rangle$$

Spinless fermion (Position of Singlons)	Squeezed spin space	Squeezed η -spin space
$H_{\mathrm{SF,free}}$	$H^{(\mathrm{SQ})}_{\mathrm{spin}}$	$H^{(\mathrm{SQ})}_{\eta-\mathrm{spin}}$

- ▹ Extension of Ogata-Shiba state in equilibrium $|\Psi\rangle = |\Psi^{\mathrm{GS}}_{\mathrm{SF}}\rangle |\Psi^{\mathrm{GS}}_{\mathrm{spin}}\rangle$

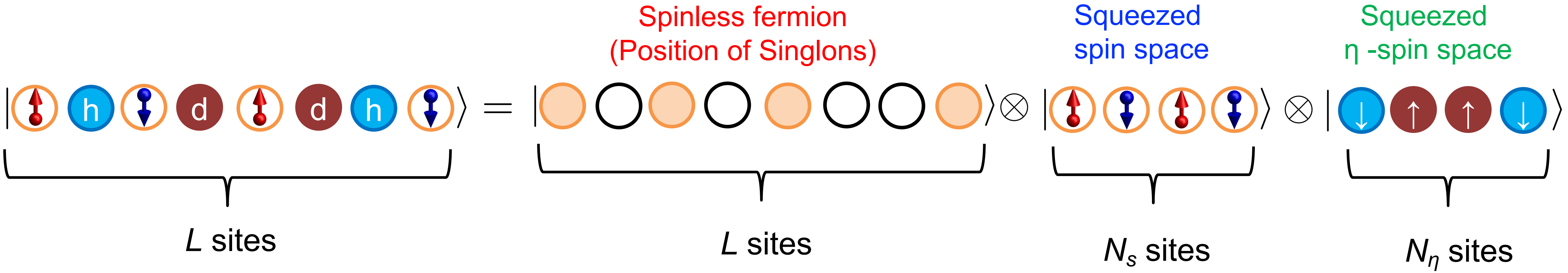
  M. Ogata & H. Shiba, PRB 41 2326 (1990).
- ▹ Spin, charge and η-spin separation
- ▹ Useful insight into physics

Explanation of $|\Psi\rangle = |\Psi_{\mathrm{SF}}^{\mathrm{GS}}\rangle|\Psi_{\sigma}^{\mathrm{GS}}\rangle|\Psi_{\eta}^{\mathrm{GS}}\rangle$

YM, et al., PRL. **130**, 106501 (2023).

New expression of states: $\hat{U}$

L: System size
N_s: Number of singly occupied sites
N_η: Number of doublons and holons



Hamiltonian for J_{ex} = 0 in the new expression

0 th order wave function

$$\hat{U}\hat{H}_{\mathrm{kin}}\hat{U}^{\dagger} = -t_{\mathrm{hop}}\sum_{\langle i,j\rangle}(\hat{c}_i^{\dagger}\hat{c}_j + \mathrm{h.c.})(\equiv \hat{H}_{\mathrm{SF,free}}) \Rightarrow |\Psi_{\mathrm{SF}}^{\mathrm{GS}}\rangle|\Psi_{\sigma,\eta}\rangle$$

i.e. Degeneracy of $2^{N_s}\cdot 2^{N_\eta}$

$|\Psi_{\sigma,\eta}\rangle$ is determined by degenerate perturbation theory

Explanation of $|\Psi\rangle = |\Psi_{\mathrm{SF}}^{\mathrm{GS}}\rangle|\Psi_{\sigma}^{\mathrm{GS}}\rangle|\Psi_{\eta}^{\mathrm{GS}}\rangle$

$\mathcal{O}(J_{\mathrm{ex}})$ terms projected to $|\Psi_{\mathrm{SF}}^{\mathrm{GS}}\rangle|\boldsymbol{\sigma}\rangle|\boldsymbol{\eta}\rangle$

YM, et al., PRL. **130**, 106501 (2023).

$$\hat{H}_{\mathrm{spin}}^{(\mathrm{SQ})} = J_{\mathrm{ex}}^{s} \sum_{i} \hat{\mathbf{s}}_{i+1} \cdot \hat{\mathbf{s}}_{i},$$

$$\hat{H}_{\eta-\mathrm{spin}}^{(\mathrm{SQ})} = -J_{X}^{\eta} \sum_{j} (\hat{\eta}_{j+1}^{x}\hat{\eta}_{j}^{x} + \hat{\eta}_{j+1}^{y}\hat{\eta}_{j}^{y}) + J_{Z}^{\eta} \sum_{j} \hat{\eta}_{j+1}^{z}\hat{\eta}_{j}^{z},$$

with

$$J_{\mathrm{ex}}^{\mathrm{s}} = (\tilde{x} - \tilde{x}')J_{\mathrm{ex}}$$

$$J_{X}^{\eta} = (\tilde{y} - \tilde{y}')J_{\mathrm{ex}}$$

$$J_{Z}^{\eta} = -(\tilde{y} - \tilde{y}')J_{\mathrm{ex}} + 4\tilde{y}V$$

2-site terms

$$\tilde{x} = n_s - \frac{\sin^2(\pi n_s)}{\pi^2 n_s},$$

$$\tilde{y} = n_\eta - \frac{\sin^2(\pi n_\eta)}{\pi^2 n_\eta};$$

3-site terms

$$\tilde{x}' = \frac{\sin(2\pi n_s)}{2\pi} - \frac{\sin^2(\pi n_s)}{\pi^2 n_s},$$

$$\tilde{y}' = \frac{\sin(2\pi n_\eta)}{2\pi} - \frac{\sin^2(\pi n_\eta)}{\pi^2 n_\eta}.$$

n_s: Density of singly occupied sites
n_η: Density of doublons and holons

▷ spin and η-spin are separated
▷ Exchange couplings are renormalized

Summary

$$|\Psi\rangle = \underbrace{|\Psi_{\mathrm{SF}}^{\mathrm{GS}}\rangle}_{H_{\mathrm{SF,free}}} \underbrace{|\Psi_{\mathrm{spin}}^{\mathrm{GS}}\rangle}_{H_{\mathrm{spin}}^{(\mathrm{SQ})}} \underbrace{|\Psi_{\eta-\mathrm{spin}}^{\mathrm{GS}}\rangle}_{H_{\eta-\mathrm{spin}}^{(\mathrm{SQ})}}$$

Indication to nonequilibrium phases

YM, et al., PRL. **130**, 106501 (2023).

η-spin sectors — Described by the XXZ model ⇨ Two types of phases

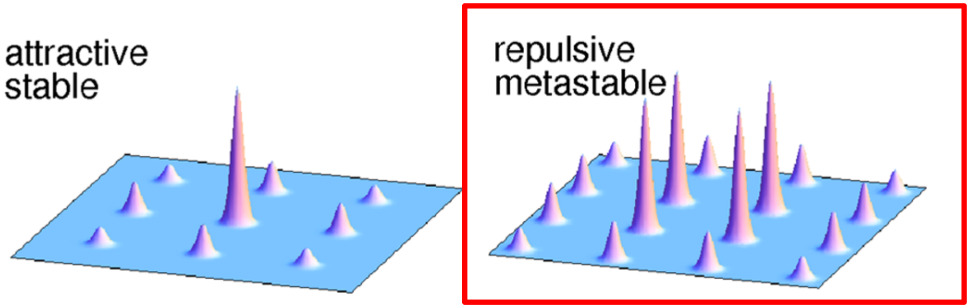
$J_Z < J_X$: **Gapless** phase of the XXZ model	$J_Z > J_X$: **Gapful** phase of the XXZ model

η-pairing state with slowly decaying

$$\chi_{\mathrm{pair}}(r) \equiv \langle \hat{\eta}^x(r)\hat{\eta}^x(0)\rangle$$

※ Alternating sign in definition of $\hat{\eta}_i^+ = (-)^i \hat{c}_{i\downarrow}^\dagger \hat{c}_{i\uparrow}^\dagger$

⇨ **usual pair correlations are staggered**



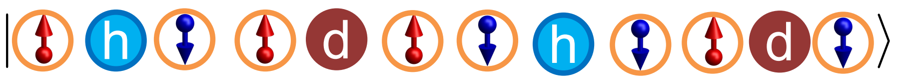
A. Rosch, et. al., PRL **101**, 265301 (2008).

CDW state with slowly decaying

$$\chi_{\mathrm{charge}}(r) \equiv \langle \hat{\eta}^z(r)\hat{\eta}^z(0)\rangle$$

※ Long range order in the squeezed η spin space

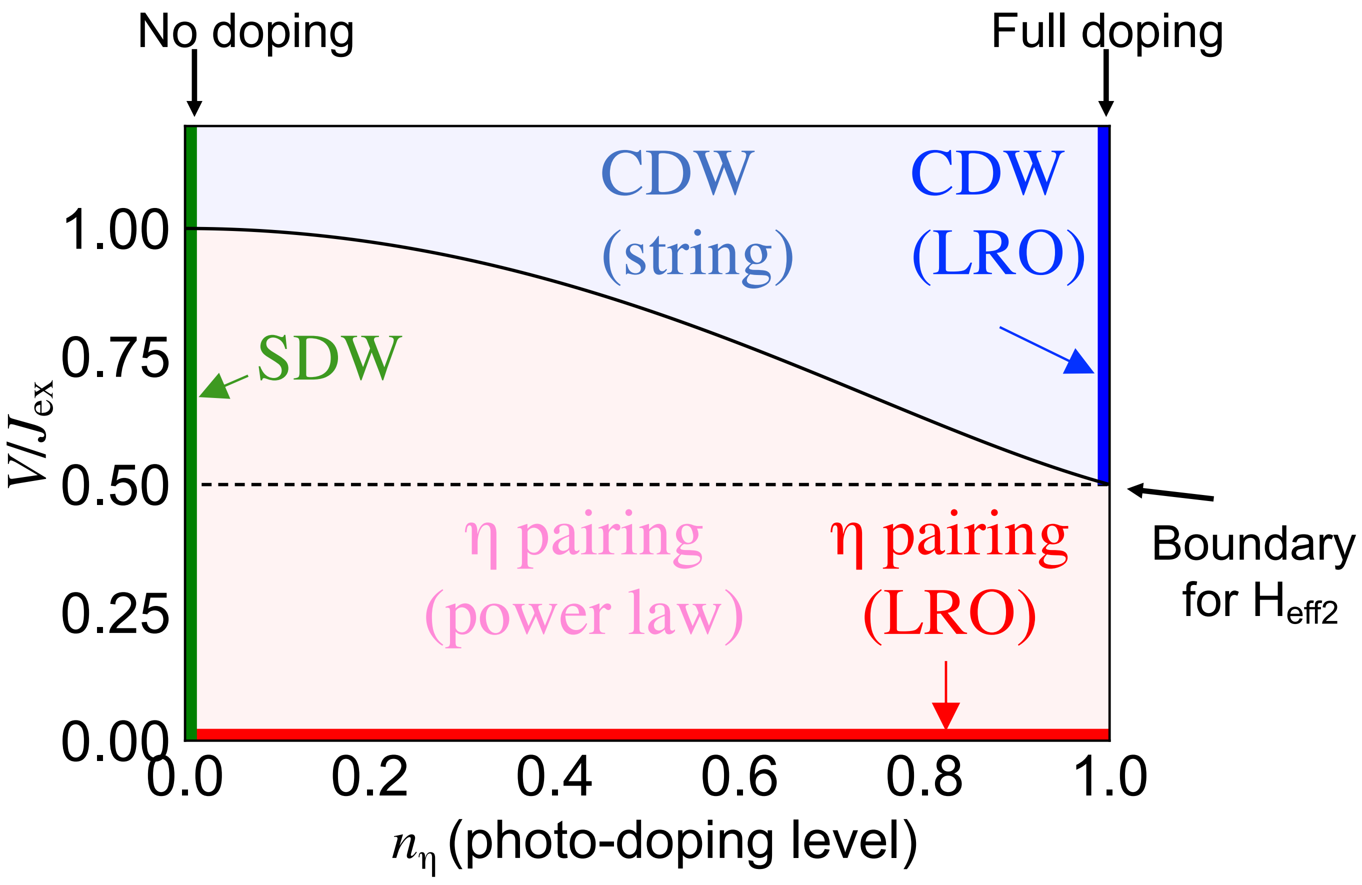
⇨ **String type order** cf. Haldane phase



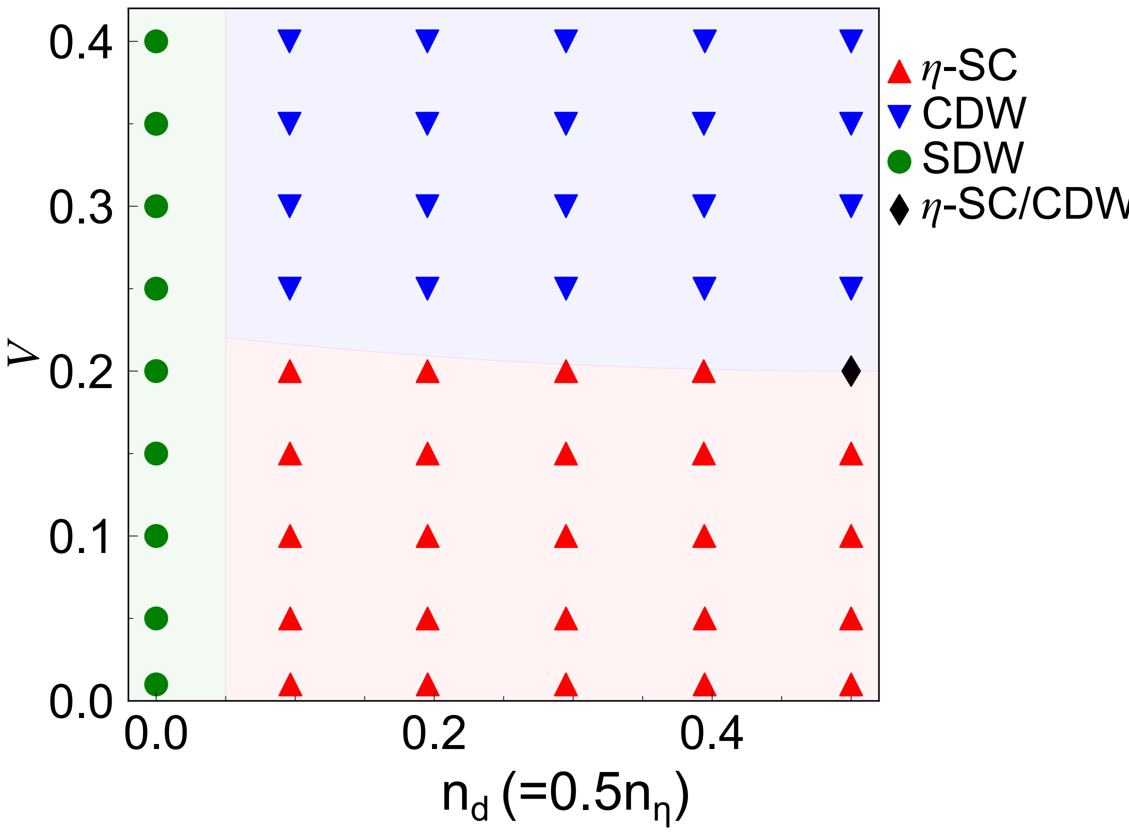
squeezed
space

Phase diagram of the photo-doped states at T_{eff} =0

U→∞ phase diagram @ half-filling



iTEBD results for H_{eff2} with J_{ex} =0.4



- 3 site terms favor η pairing phase
- Analytic argument well explains numerically obtained phase diagram for H_{eff2} (no 3 site terms)
- Picture at U→∞ works well even for finite U

Insight into total central charge

Total central charge (**c**) ~ Number of massless modes

$$|\Psi\rangle = \underbrace{|\Psi^{\mathrm{GS}}_{\mathrm{SF}}\rangle}_{H_{\mathrm{SF,free}}} \underbrace{|\Psi^{\mathrm{GS}}_{\mathrm{spin}}\rangle}_{H^{(\mathrm{SQ})}_{\mathrm{spin}}} \underbrace{|\Psi^{\mathrm{GS}}_{\eta-\mathrm{spin}}\rangle}_{H^{(\mathrm{SQ})}_{\eta-\mathrm{spin}}}$$

▹ **Charge (SF) sector**: gapless

▹ **Spin sector**: gapless

▹ **η-spin sector:** { η pairing → gapless; CDW → gapful }

⇨ **η pairing: c=3 ? & CDW: c=2 ?**

Total central charge: iTEBD analysis for H_{eff2}

Scaling analysis

J. A. Kjäll, et al., PRB **87**, 235106 (2013).

$$S_E = \frac{c}{6}\ln(\xi_D) + s_0$$

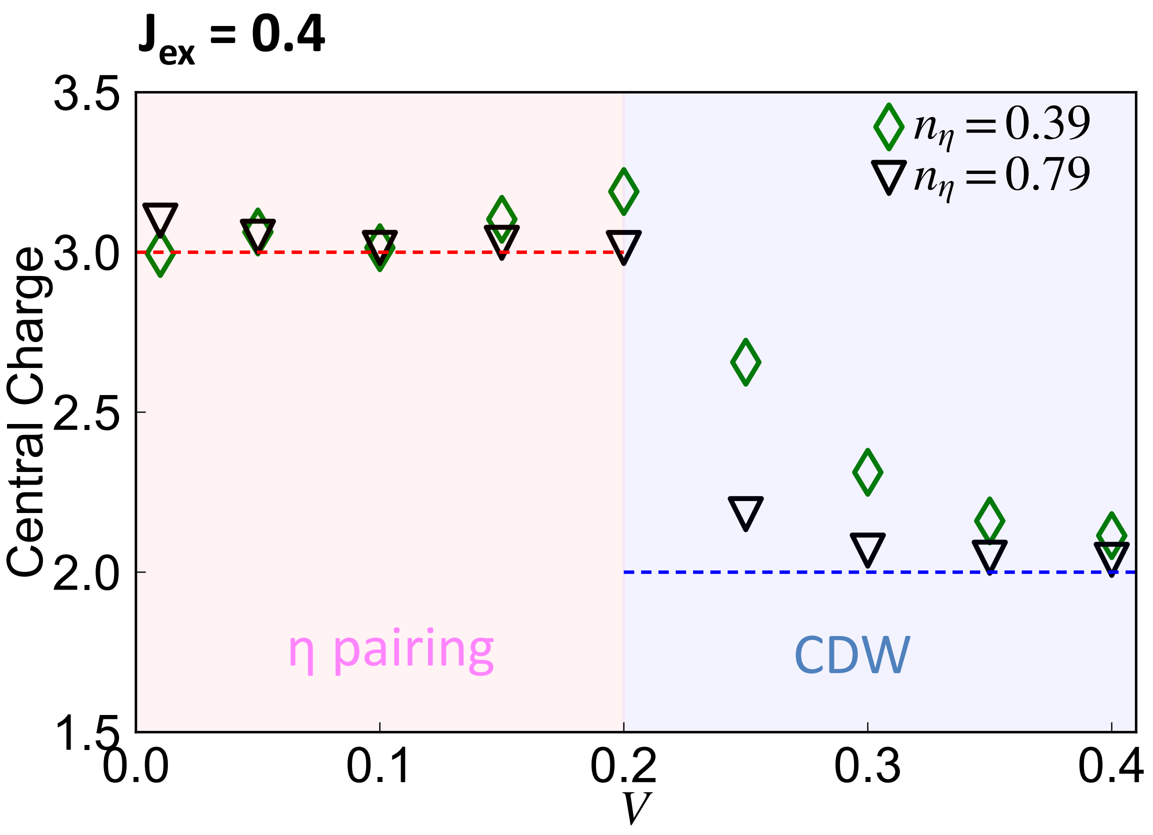
c: central charge

D: cut-off dimension

ξ_D: correlation length at D

S_E: entanglement entropy at D

η pairing: c=3 & CDW: c=2



c=3 in single-band Hubbard model is not expected in equilibrium

⇩

Emergence of extra degrees of freedom by photo-doping!

Naïve expectation of single-particle spectrum

$$A_k(\omega) = -\frac{1}{\pi}\mathrm{Im}G_k^R(\omega) \quad \text{with} \quad G_k(t,t') = -i\langle \mathcal{T} c_k(t) c_k^\dagger(t')\rangle$$

Equilibrium doped system

Electron = charge (SF) degree + spin degree

gapless gapless

⇨ **Gapless** around Fermi level

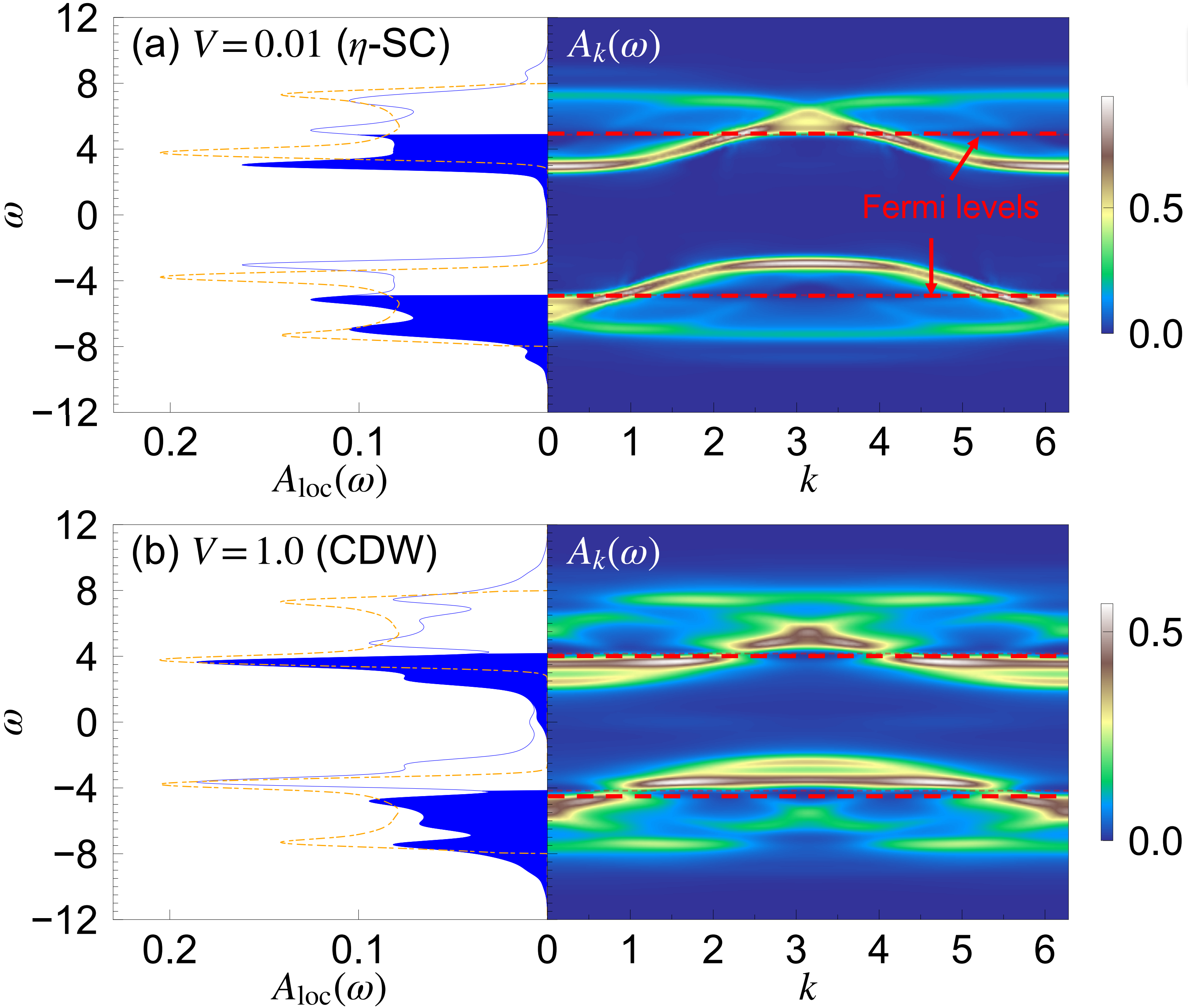
Photo-doped system

Electron = charge (SF) degree + spin degree + η spin degree

gapless gapless η pairing: gapless
CDW: gapful

⇨ η pairing phase : **Gapless** around Fermi level ?
CDW phase : **Gapful** around Fermi level ?

Single particle spectra for η pairing state and CDW state



η pairing state

No gap close to the Fermi level

⇨ Gapless SC

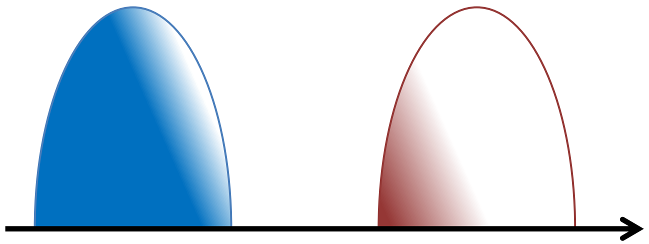
cf. DMFT J. Li et al, Mod. Phys. Lett B (2022)

CDW

Finite Gap at the Fermi level

Summary

Large gap Mott system ⇨ Approximate conservation of charge carriers ⇨ Quasi steady states



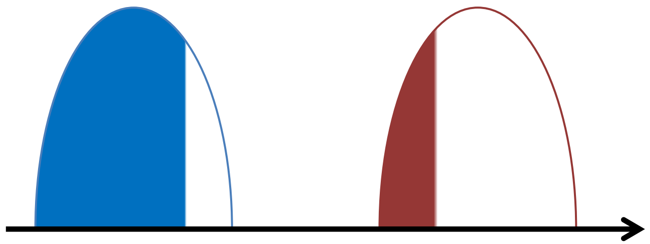


Photo-doped states in 1D extended Hubbard model

▷ Extension of Ogata-Shiba state in equilibrium : $|\Psi\rangle = |\Psi^{\mathrm{GS}}_{\mathrm{SF}}\rangle|\Psi^{\mathrm{GS}}_{\mathrm{spin}}\rangle|\Psi^{\mathrm{GS}}_{\eta-\mathrm{spin}}\rangle$

▷ Spin, charge and η-spin separation

YM, et al., Comm. Phys. **5**, 23 (2022):

YM, et al., PRL. **130**, 106501 (2023).

▷ Intuitive insight into physics of metastable states

Emergent degrees of freedoms by photo-doping lead to intriguing nonequilibrium phases!

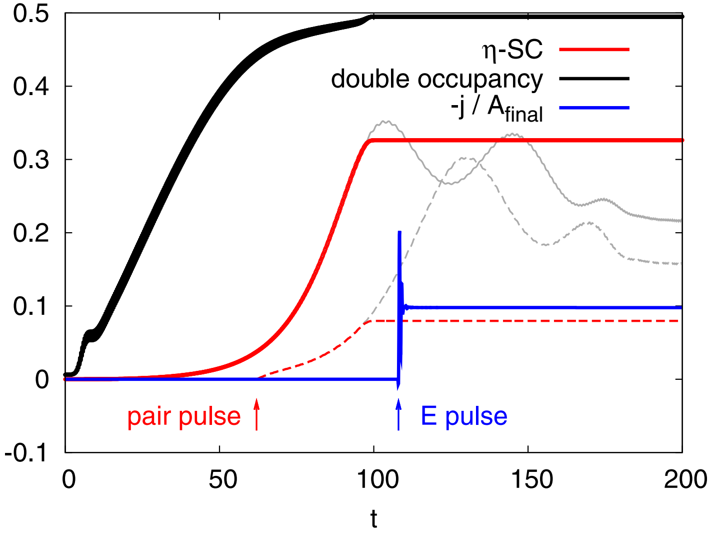
Review on nonequilibrium Mott insulators: YM, D Golež, M Eckstein, P Werner, arXiv:2310.05201

Supplement

Previous analysis : metastable η pairing phase

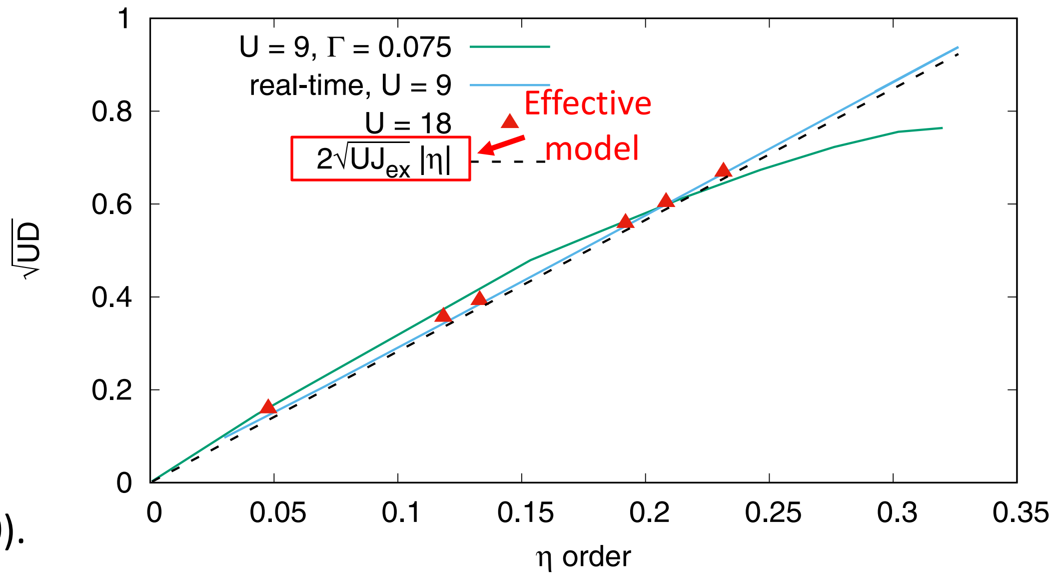
DMFT time evolution

P. Werner, et al., PRB 100, 155130 (2019).



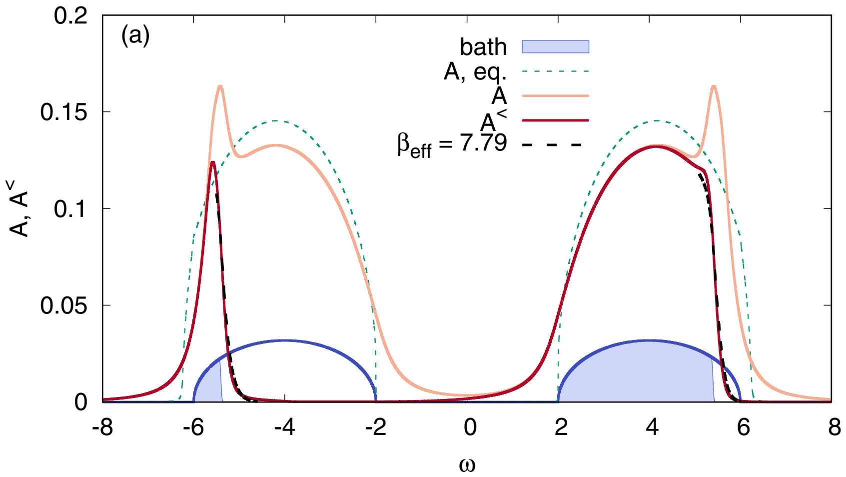
Comparison of three approaches

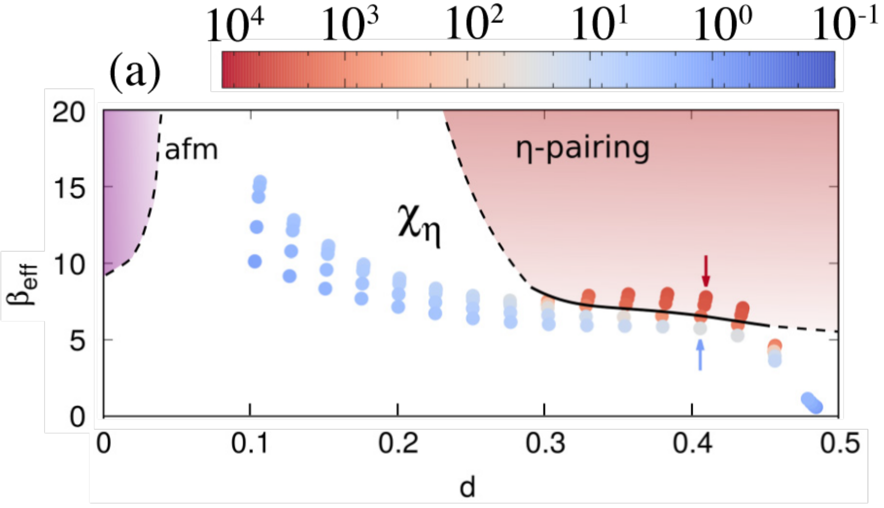
D: superfluid density



Ness approach with DMFT

J. Li, et. al., PRB **102**, 165136 (2020).





▷ Three approaches are consistent

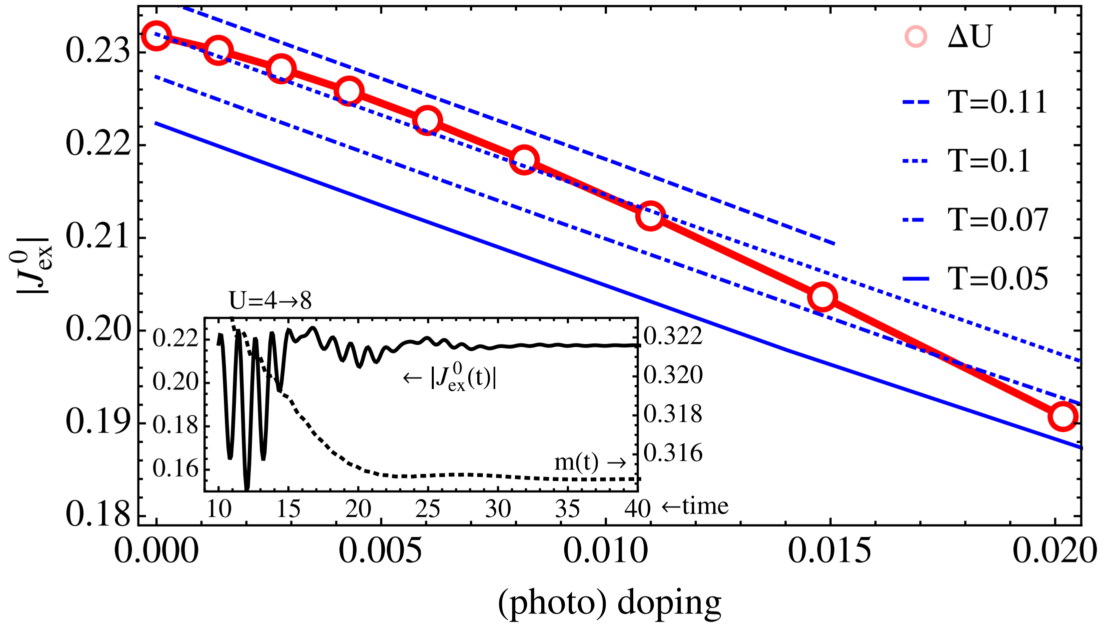
Indication to spin properties

$$|\Psi\rangle = \underbrace{|\Psi^{GS}_{SF}\rangle}_{H_{SF,free}} \underbrace{|\Psi^{GS}_{spin}\rangle}_{H^{(SQ)}_{spin}} \underbrace{|\Psi^{GS}_{\eta-spin}\rangle}_{H^{(SQ)}_{\eta-spin}}$$

SF and spin part is independent of the ratio between N_h and N_d.

⇨ Chemical doping and photo-doping have the same effect on spin correlations

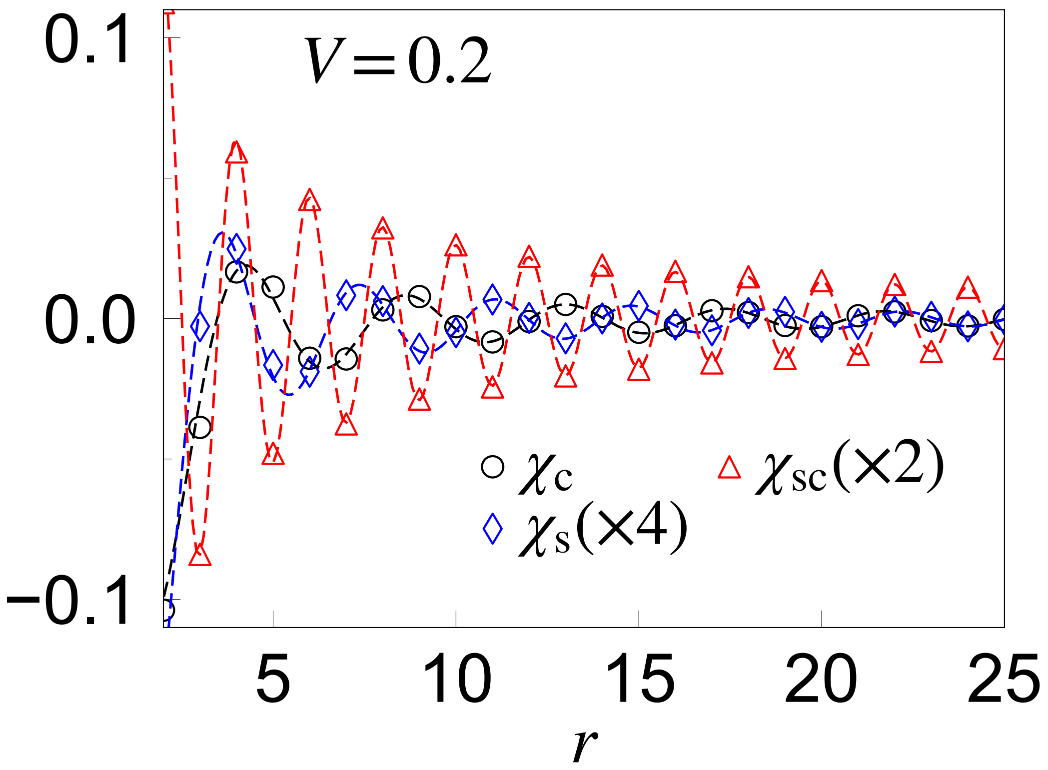
cf. DMFT results



J. Mentink & M. Eckstein PRL 113 057301 (2014).

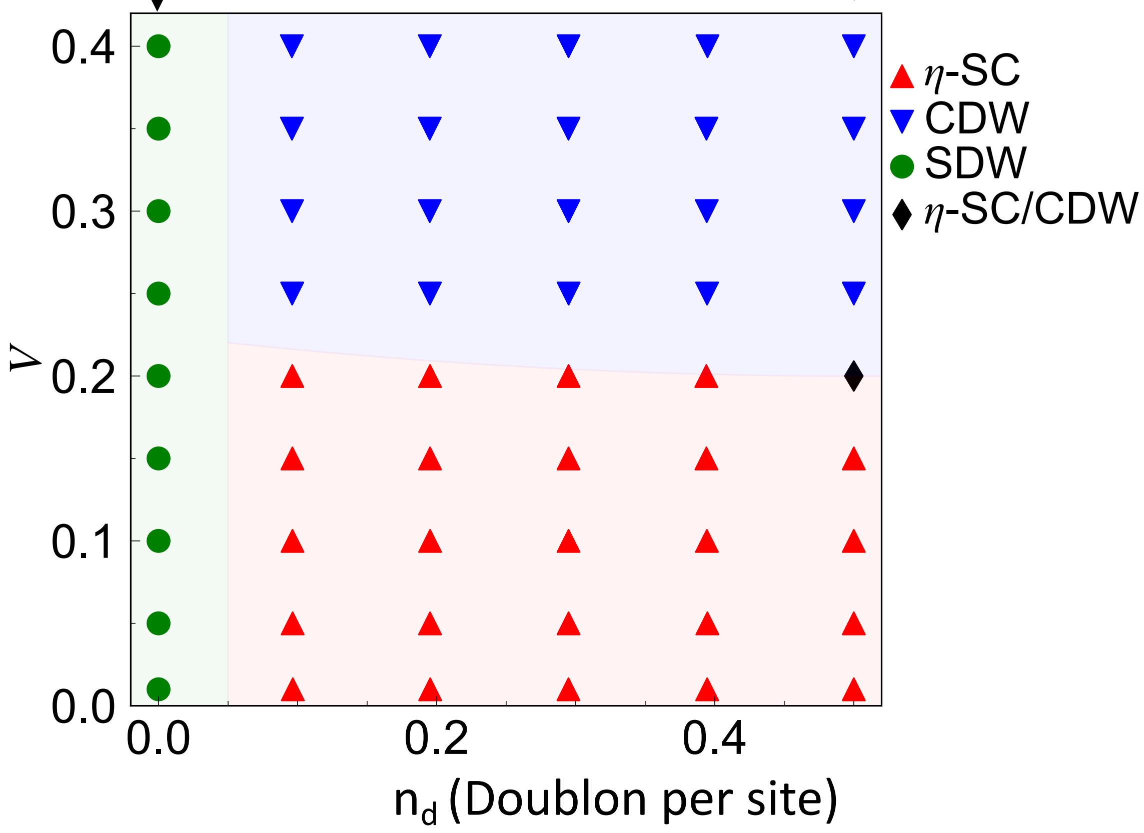
Nonequilibrium phase diagram @ $U=10, J_{ex}=0.4$

Correlation functions at $n_d = 0.23$



No doping

Full doping (cf Rosch , et. al., PRL **101**, 2008)



▷ Quasi-long range order

$\chi(r) \propto \cos(qr)/r^a$ with $q=\pi$ (η-SC) $q=2n_d\pi$ (CDW) $q=(1-2n_d)\pi$ (SDW)

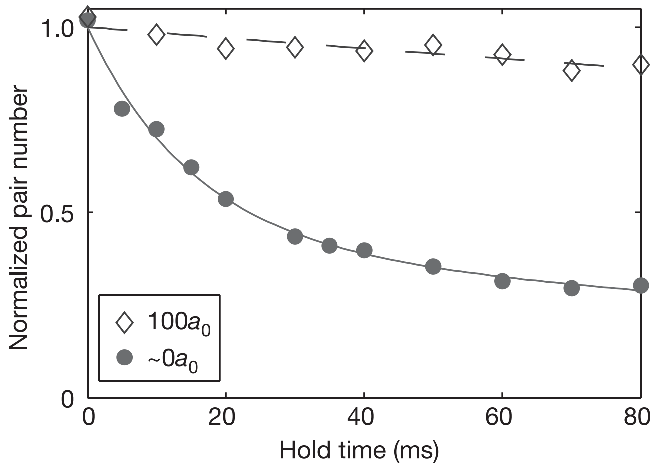
▷ Boundary of ηSC and CDW ≒ $V=J_{ex}/2$

⇨ Special kinematics of doublons and holons in one dimensional system

Long-life time of photo-carriers and their relaxation

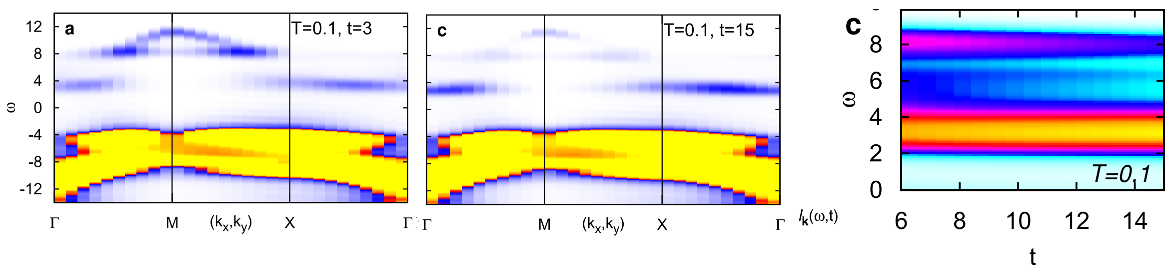
Cold Atoms

K. Winkler et al., Nature **441**, 853 (2006).



Cooling of carriers in Photo-doped Mott

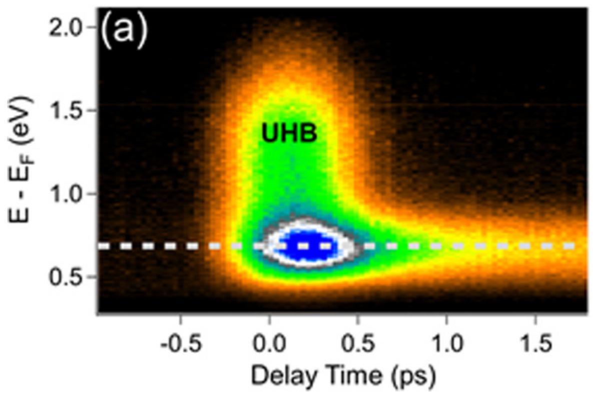
Cluster DMFT study

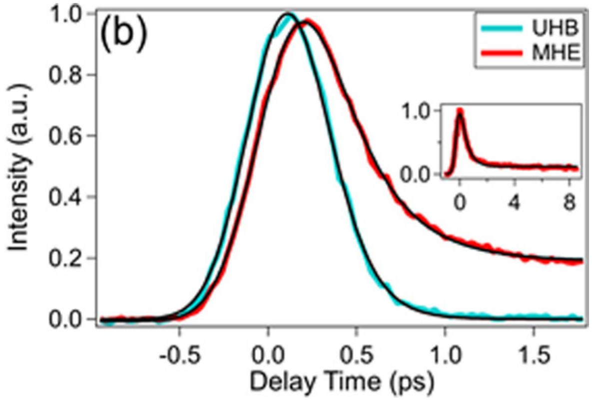


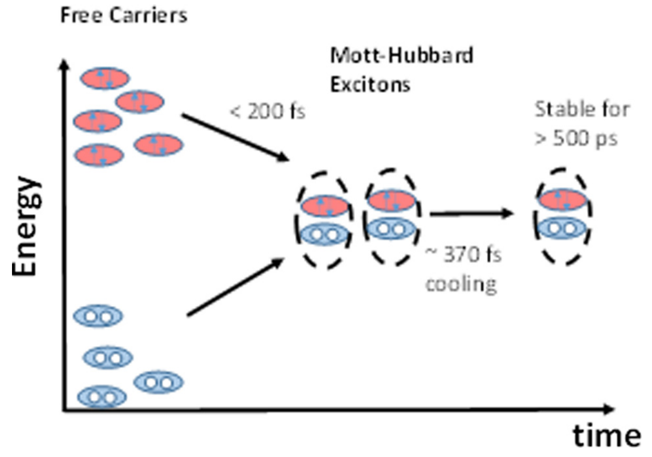
M. Eckstein & P. Werner Sci. Rep. **6** 21235 (2015)

α-$RuCl_3$

D. Nevola, et al., PRB **103**, 245105 (2021)



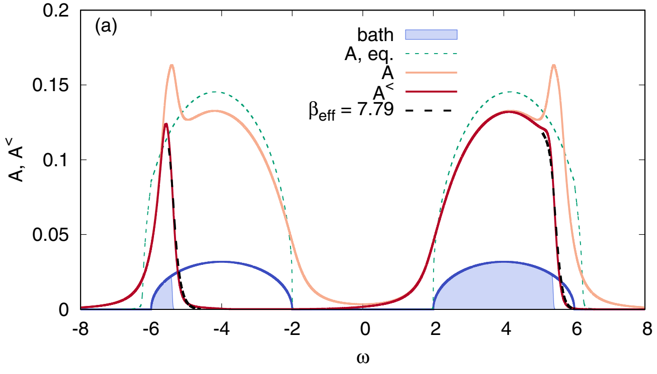


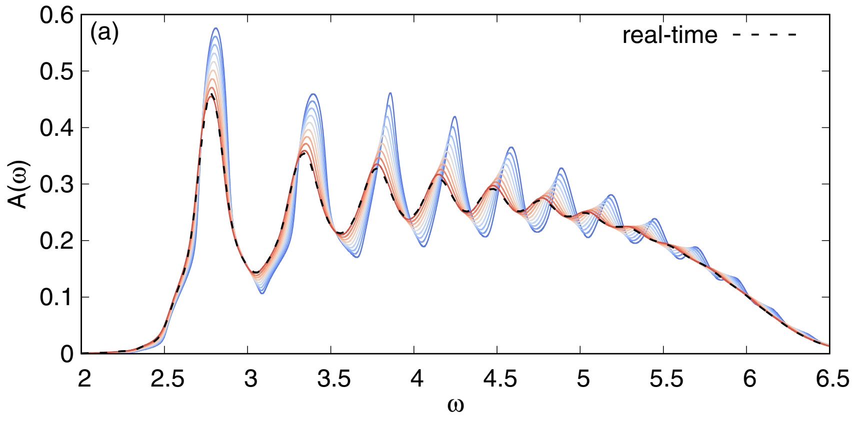


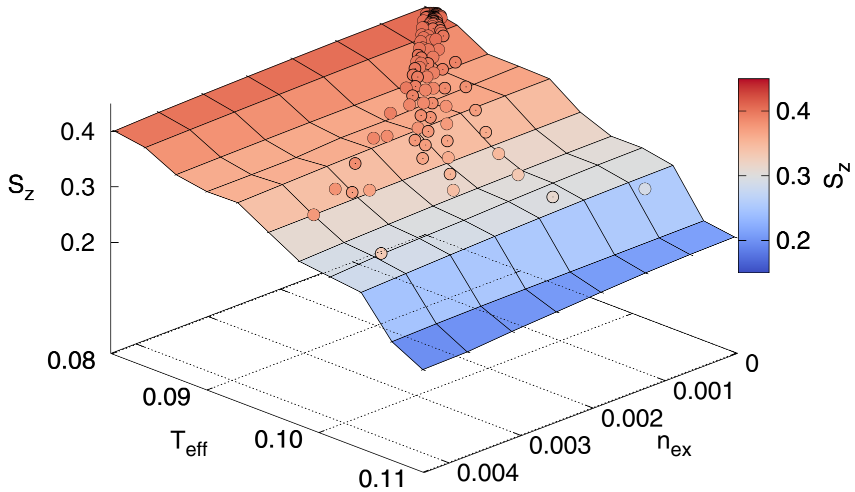
光誘起されたMott絶縁体の理論研究

NESS @ coupling with heat and particle bath

J. Li, et. al., PRB **102**, 165136 (2020).
J. Li and M. Eckstein, PRB **103** 045133 (2021).







▷ Transient state ≒ NESS

▷ NESS ← Effective temp + doping level description looks good

Analysis with infinite boundary condition

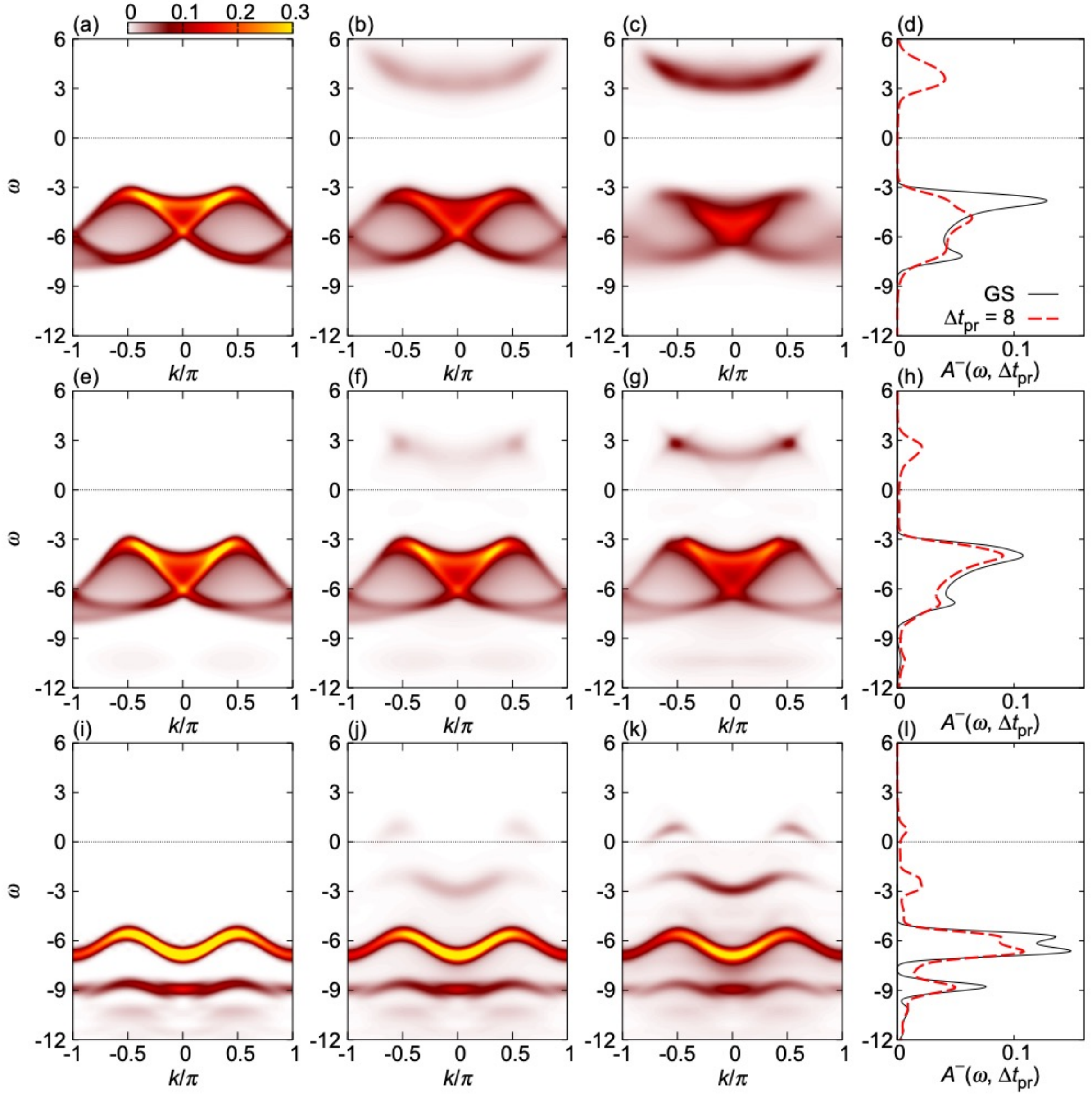


FIG. 5. Calculated single-particle excitation spectra of the 1DEHM at (a), (e), (i) $\Delta t_{\rm pr} = -\infty$ (GS); (b), (f), (j) $\Delta t_{\rm pr} = 0$; and (c), (g), (k) $\Delta t_{\rm pr} = 8$. (d), (h), (l) TDOSs at $\Delta t_{\rm pr} = -\infty$ (black solid line) and $\Delta t_{\rm pr} = 8$ (red dashed line). The on-site interaction is set to $U = 10$, and the intersite interaction, the pump-light frequency, and its intensity are set to (a)-(d) $V = 0$, $\omega_0 = 8.0$, and $A_0 = 0.6$; (e)-(h) $V = 3$, $\omega_0 = 6.04$, and $A_0 = 0.3$; and (i)-(l) $V = 6$, $\omega_0 = 6.34$, and $A_0 = 0.3$.