FRIEDRICH-ALEXANDER
UNIVERSITÄT
ERLANGEN-NÜRNBERG

NATURWISSENSCHAFTLICHE
FAKULTÄT

Non-equilibrium dynamical mean-field theory

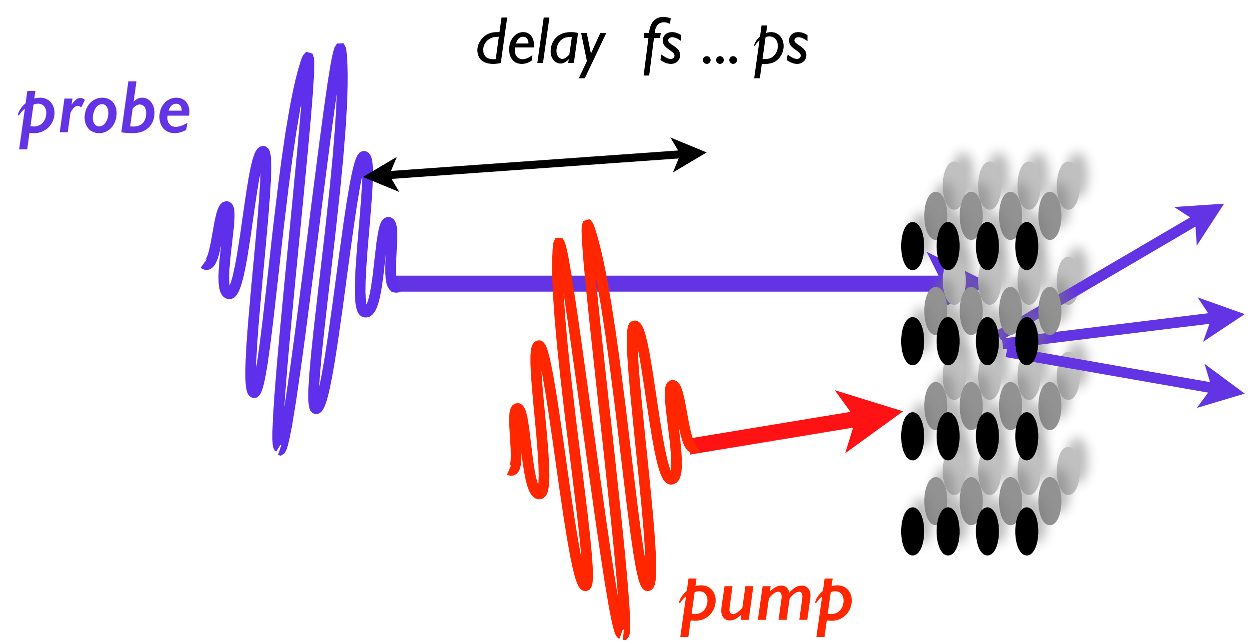
Martin Eckstein

Jülich, September 20, 2018

Pump-probe experiments on correlated solids

Pump-probe experiments

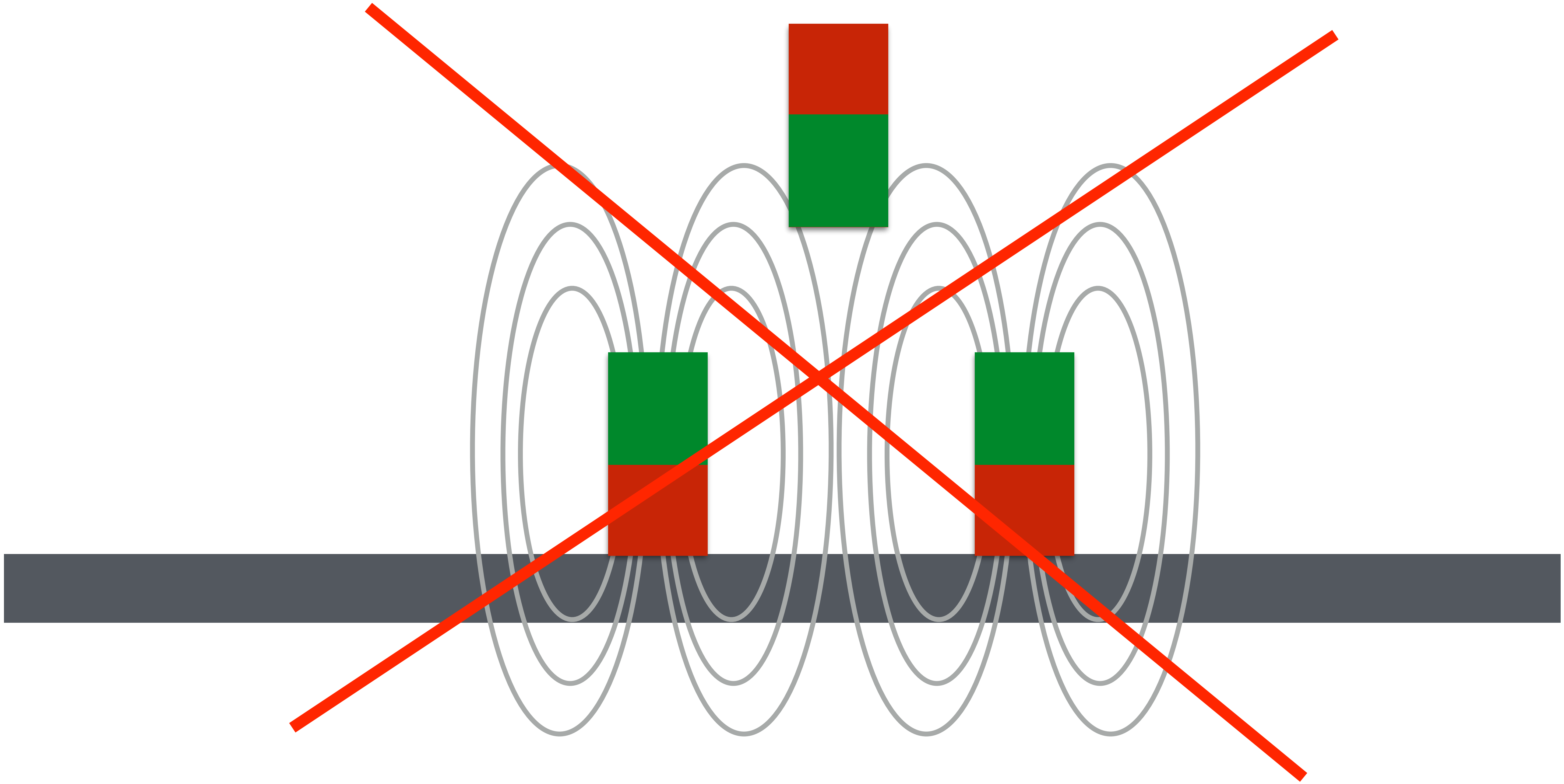
Time resolved THz, optics,
UV (photoemission), Xray, …



⇨ Real-time experiments to understand origin of complex states

⇨ Dynamical stabilization, ultra-fast switching to “novel” phases

Dynamic stabilization



Magnetic top

Example: control of the magnetic exchange interaction

one electron per site

$$H = -t \sum_{\langle ij \rangle, \sigma=\uparrow,\downarrow} c^{\dagger}_{i\sigma} c_{j\sigma} + U \sum_i n_{i\uparrow} n_{i\downarrow} \quad \xrightarrow{U \gg t} \quad H = \frac{2t^2}{U} \sum_{\langle ij \rangle} \vec{S}_i \vec{S}_j$$

+ electric field $E_0 \cos(\omega t) \longrightarrow J_{ex}(E_0, \omega)$

Ferromagnetic interaction

LETTER

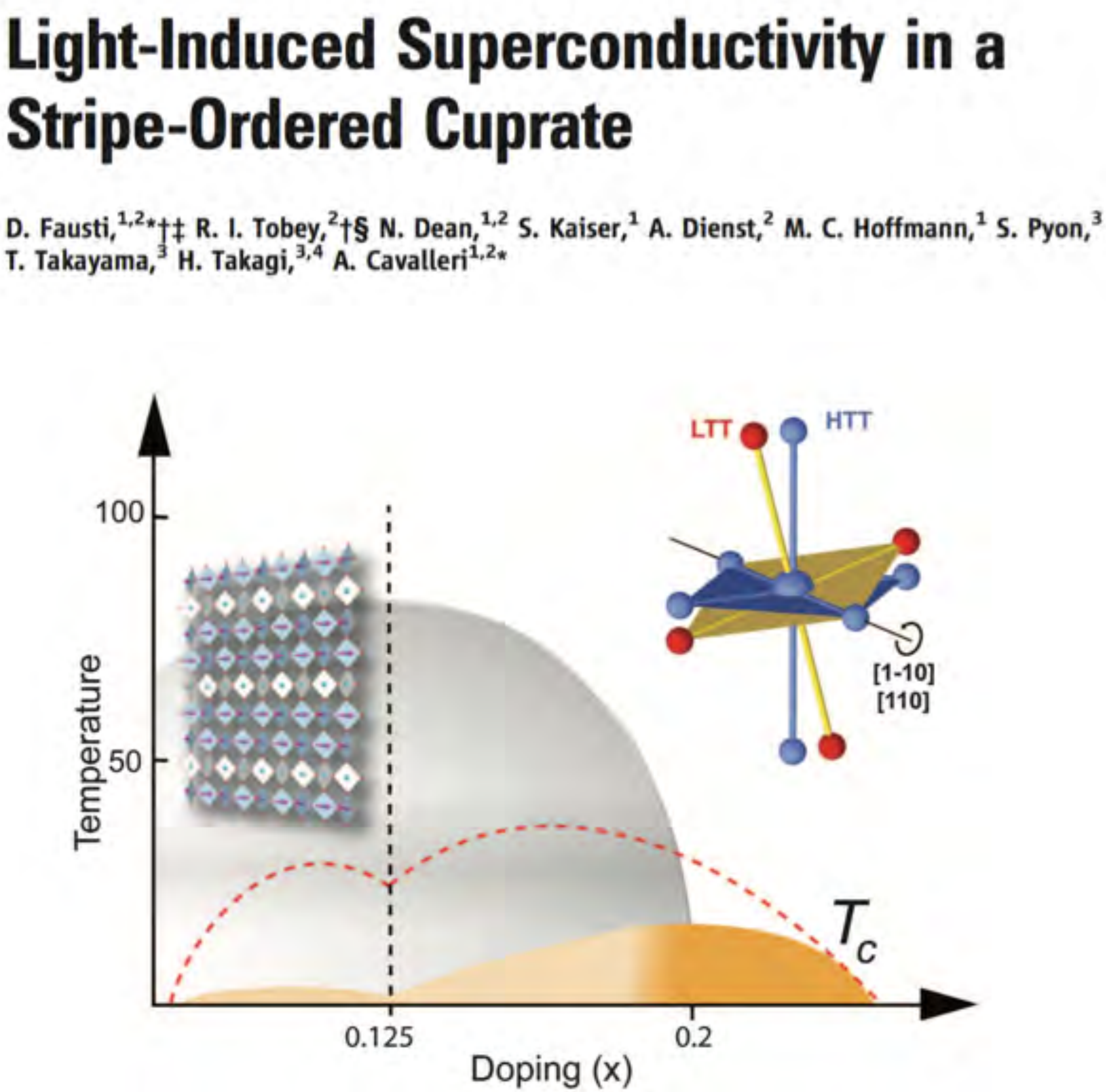
doi:10.1038/nature25135

Enhancement and sign change of magnetic correlations in a driven quantum many-body system

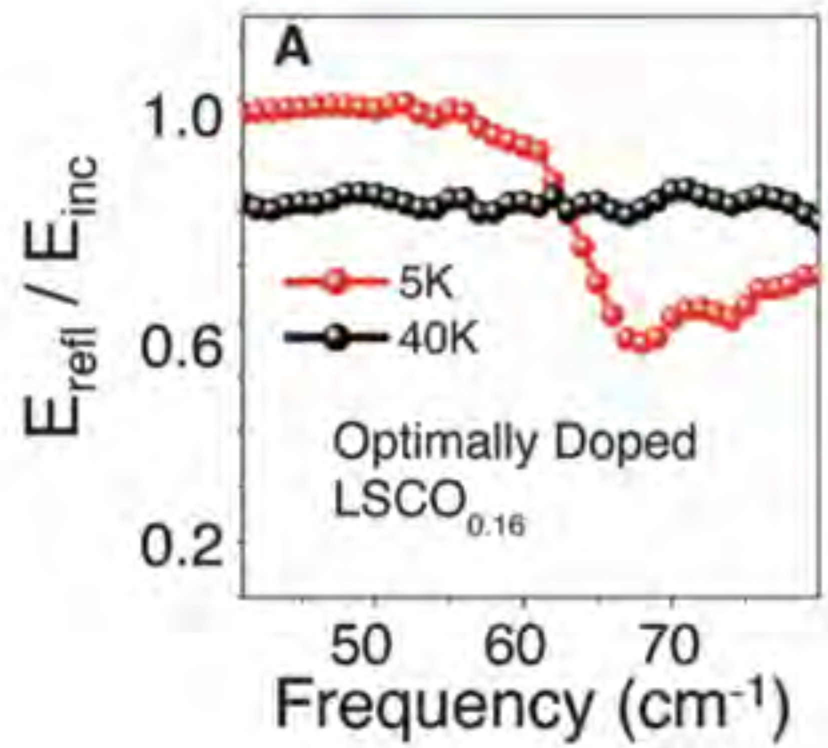
Frederik Görg[1], Michael Messer[1], Kilian Sandholzer[1], Gregor Jotzu[1,2], Rémi Desbuquois[1] & Tilman Esslinger[1]

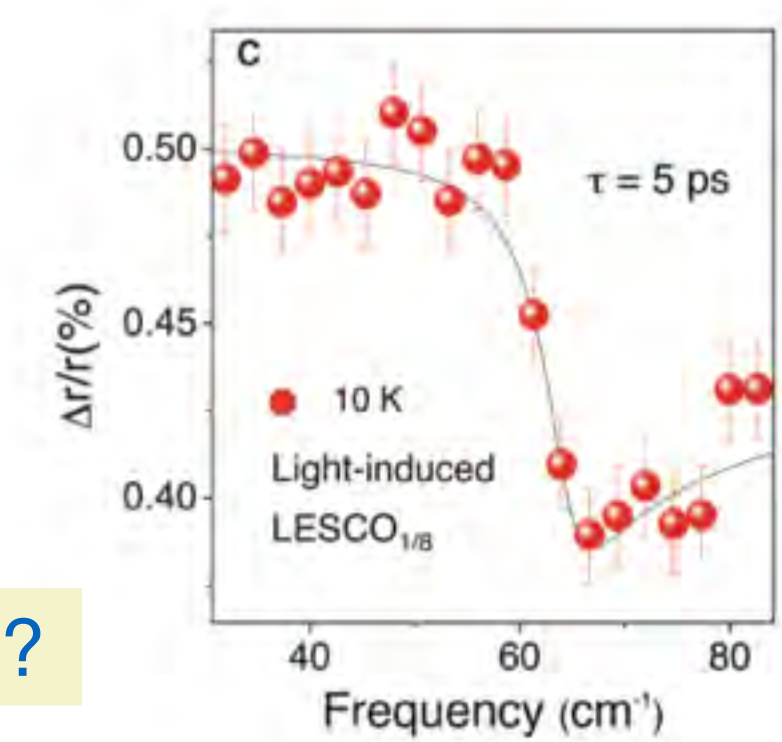
Mentink, Balzer, and Eckstein, Nature Comm **6** (2015)

Non-equilibrium phases of matter



Josephson-Plasma Resonance





Laser-induced suppression of competing phase?

Outline

⇨ Keldysh formalism & non-equilibrium Green's functions

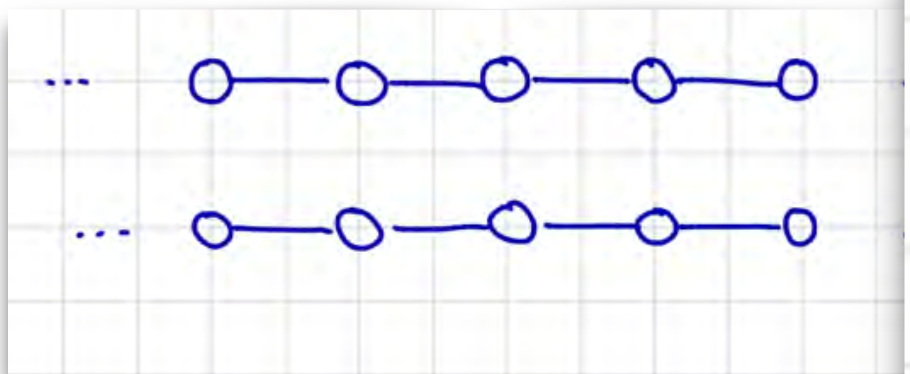
Goal: electronic structure of correlated systems out of equilibrium

⇨ Non-equilibrium DMFT

⇨ Photo-excited Mott & charge transfer insulators

Why Green's function?

Effective single-particle descriptions



$$H = \sum_{\substack{k \\ \alpha=1,2}} \varepsilon_{k\alpha}\, c^{+}_{k\alpha} c_{k\alpha} + U \sum_{j} \underbrace{c^{+}_{j1} c_{j1}\, c^{+}_{j2} c_{j2}}_{\circledast}$$

mean-field decoupling:

$$\circledast \Rightarrow - c^{+}_{j1} c_{j2} \langle c^{+}_{j2} c_{j1} \rangle - \langle c^{+}_{j1} c_{j2} \rangle c^{+}_{j2} c_{j1}$$

Fock exchange self energy ($U\Phi$)

$$H = \sum_{k} \left(c^{+}_{k1} \;\; c^{+}_{k2} \right) \underbrace{\begin{pmatrix} \varepsilon_{k1} & U\Phi \\ U\Phi^{*} & \varepsilon_{k2} \end{pmatrix}}_{h_k} \underbrace{\begin{pmatrix} c_{k1} \\ c_{k2} \end{pmatrix}}_{\psi_k} \qquad \Phi = -\frac{1}{N} \sum_{k} \langle c^{+}_{k1} c_{k2} \rangle$$

Effective single-particle descriptions

Fock exchange self energy

$$H = \sum_{k} \underbrace{(c_{k1}^{+} \; c_{k2}^{+})}\underbrace{\begin{pmatrix} \varepsilon_{k1} & U\Phi \\ U\Phi^{*} & \varepsilon_{k2} \end{pmatrix}}_{h_k} \underbrace{\begin{pmatrix} c_{k1} \\ c_{k2} \end{pmatrix}}_{\psi_k} \qquad \Phi = -\frac{1}{N}\sum_{k} \langle c_{k1}^{+} c_{k2} \rangle$$

Coherent evolution of single-particle states:

$$H = \sum_{\boldsymbol{k}} c_{\boldsymbol{k},n}^{\dagger} h_{\boldsymbol{k}}[\rho]_{nm} c_{\boldsymbol{k},m}$$

$$(\rho_{\boldsymbol{k}})_{mn} = \langle c_{\boldsymbol{k},n}^{\dagger} c_{\boldsymbol{k},m} \rangle$$

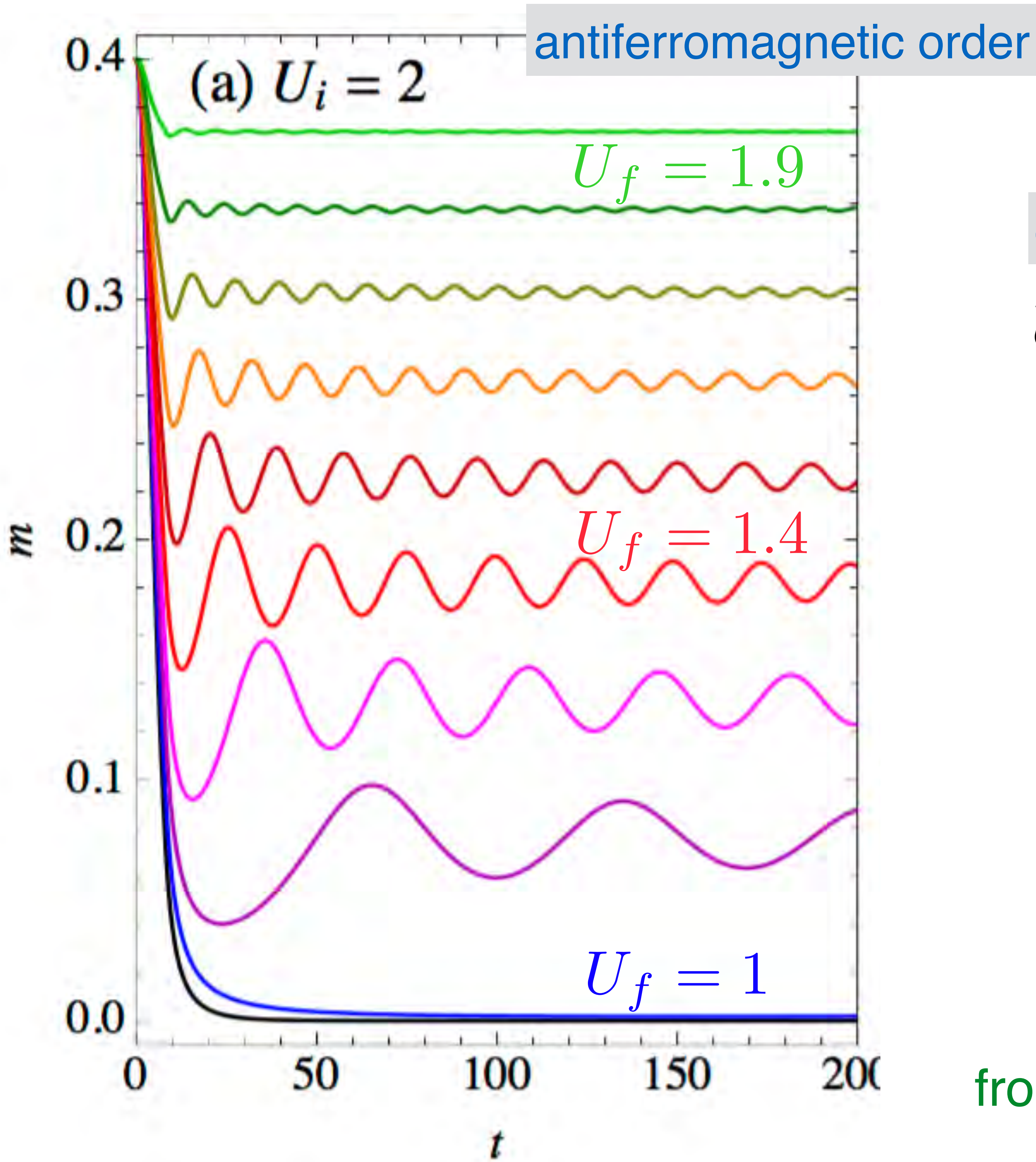
$$\frac{d}{dt}\rho_{\boldsymbol{k}} = i[h_{\boldsymbol{k}}, \rho_{\boldsymbol{k}}]$$

Single-particle Hamiltonian:
Instantaneous function of
one-particle density matrix

⇨ Time-dependent BCS theory, …

⇨ Time-dependent density-functional theory (adiabatic approximation)

Effective single-particle descriptions



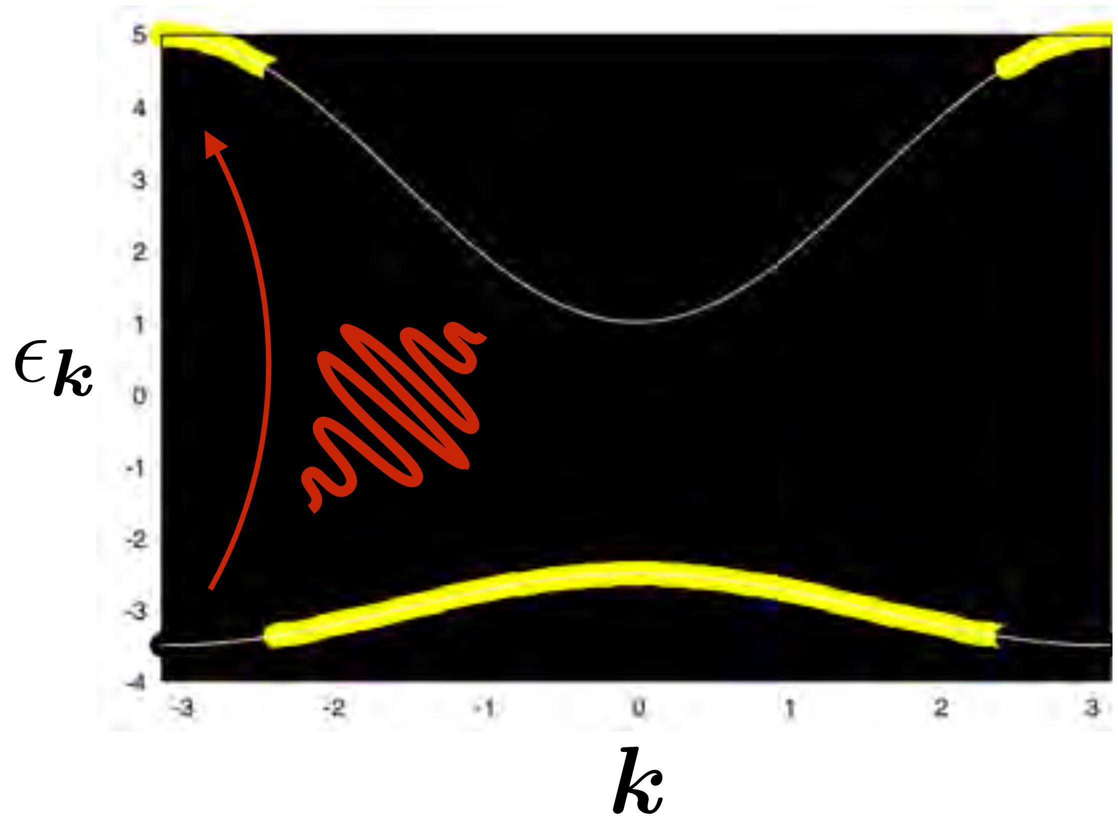
quench in the Hubbard model

$$U(t) = U_i = 2 \text{ for } t < 0$$

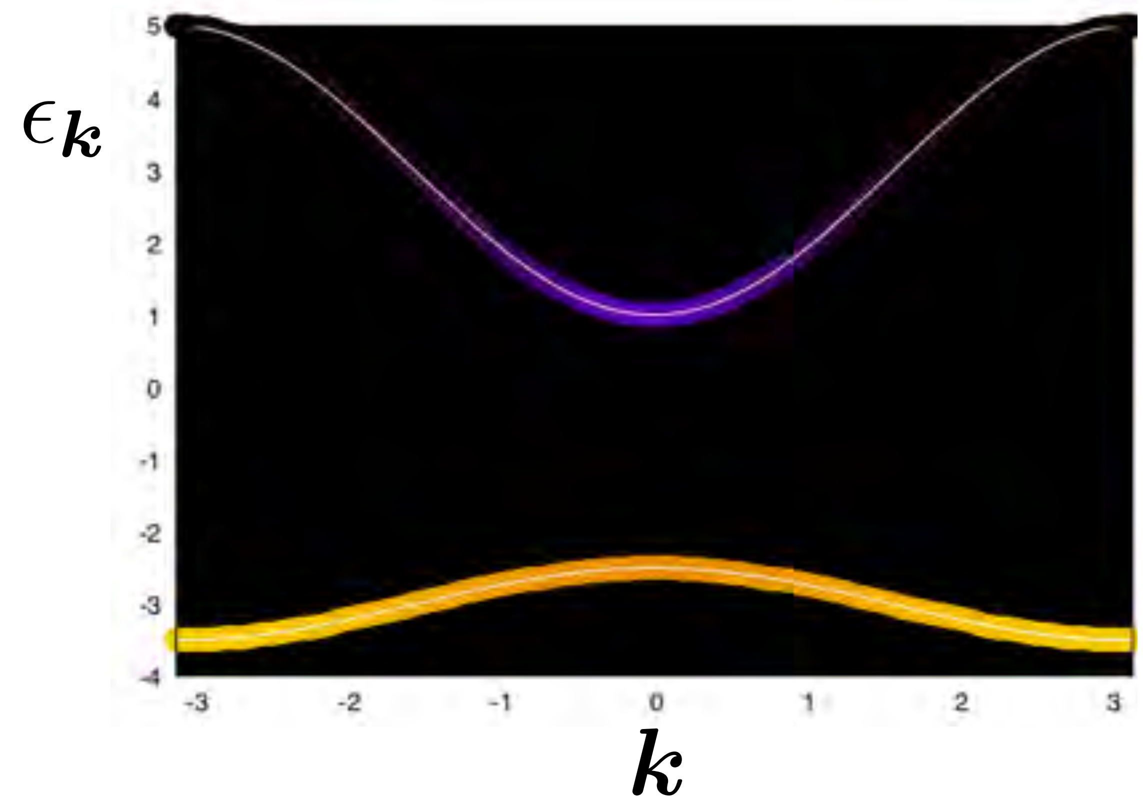
$$U(t) = U_f \text{ for } t > 0$$

from Tsuji, ME, Werner, (2012)

Effective single-particle descriptions: Thermalization?



⇨ ?



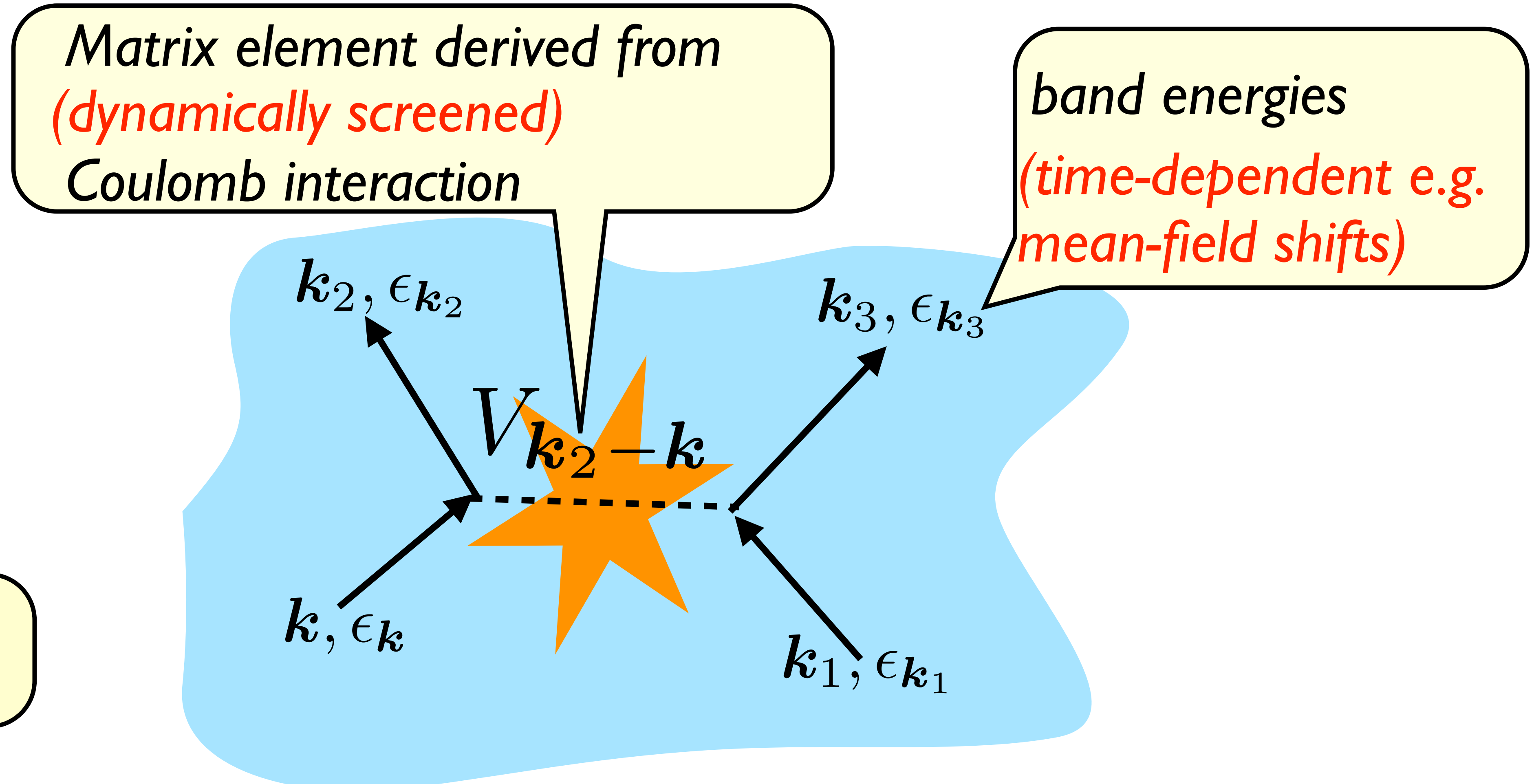
Thermal state: $\mathrm{tr}\rho_{\boldsymbol{k}} = \sum_n \langle c^\dagger_{\boldsymbol{k},n} c_{\boldsymbol{k},n} \rangle$ at small k increased for higher temperature

Coherent evolution of single-particle states:

$$\frac{d}{dt}\rho_{\boldsymbol{k}} = i[h_{\boldsymbol{k}}, \rho_{\boldsymbol{k}}] \Rightarrow \mathrm{tr}\rho_{\boldsymbol{k}}$$ conserved if H is translationally invariant

Cannot describe electron thermalization (lack of incoherent scattering)

Kinetic equations



occupation of states

$$\partial_t n_{\boldsymbol{k}}(t) = \sum_{\boldsymbol{k}_1, \boldsymbol{k}_2, \boldsymbol{k}_3} V_{\boldsymbol{k}_2 - \boldsymbol{k}} \delta(\epsilon_{\boldsymbol{k}} + \epsilon_{\boldsymbol{k}_1} - \epsilon_{\boldsymbol{k}_2} - \epsilon_{\boldsymbol{k}_3}) \times$$

$$\times \left[n_{\boldsymbol{k}} n_{\boldsymbol{k}_1} (1 - n_{\boldsymbol{k}_2})(1 - n_{\boldsymbol{k}_3}) - (1 - n_{\boldsymbol{k}})(1 - n_{\boldsymbol{k}_1}) n_{\boldsymbol{k}_2} n_{\boldsymbol{k}_3} \right]$$

Occupation of states, spectrum, quasiparticle lifetime, screening of Coulomb interaction, etc. evolve on comparable timescales

Non-equilibrium Green’s functions

Non-equilibrium Green's functions

$$H = H_0 + \phi_q(t)\,\rho_{-q}(t)$$

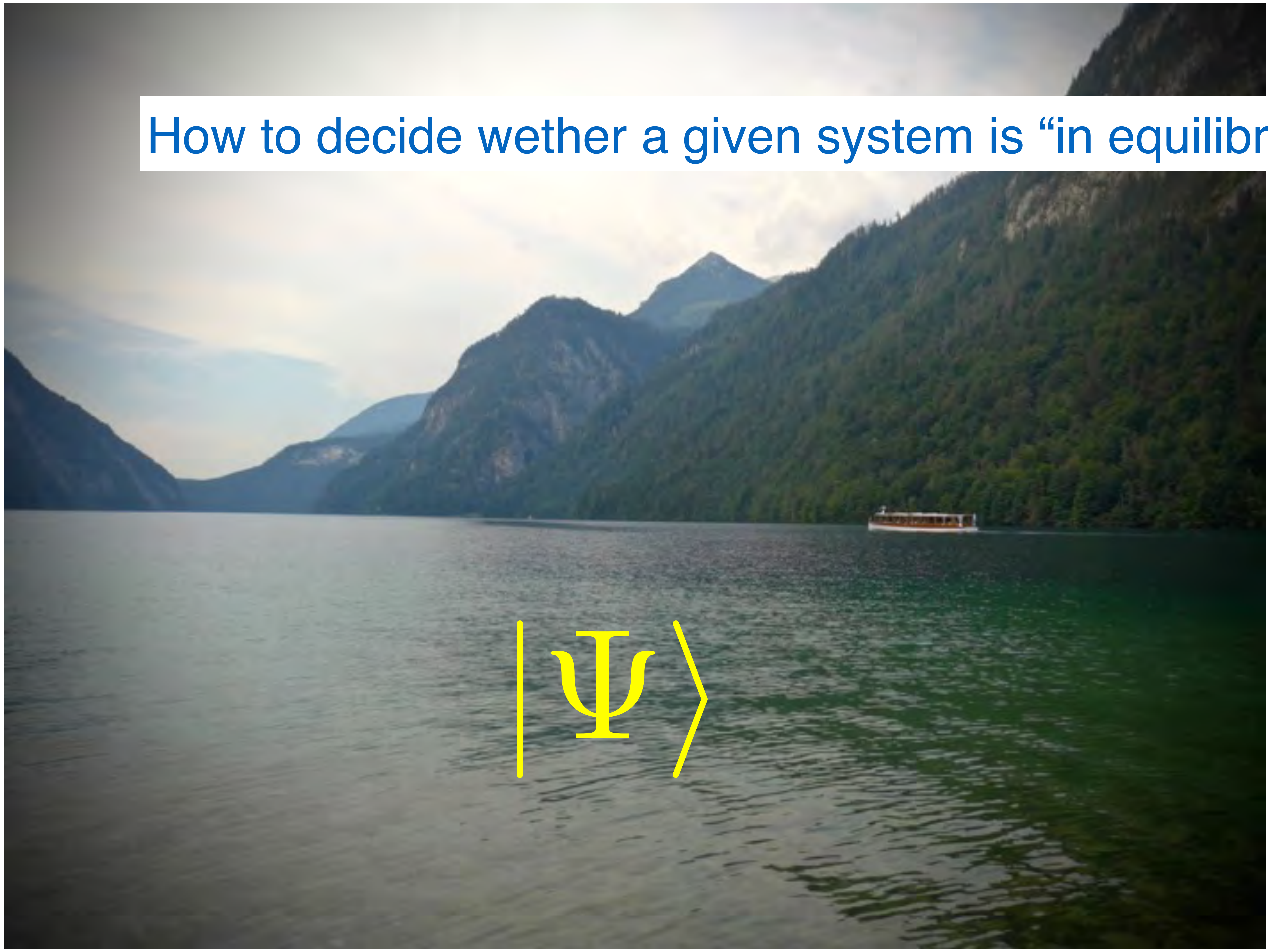
$$\delta\rho_q = \int_{-\infty}^{t} \chi_q(t,t')\,\phi(t')\,dt' \qquad \chi_q = -i\,\Theta(t,t')\,\langle[\rho_q(t),\rho_{-q}(t')]\rangle$$

Kubo

$$-\frac{1}{\pi}\,\mathrm{Im}\,\chi_q(\omega) \equiv A_q(\omega)$$ → phonon spectrum

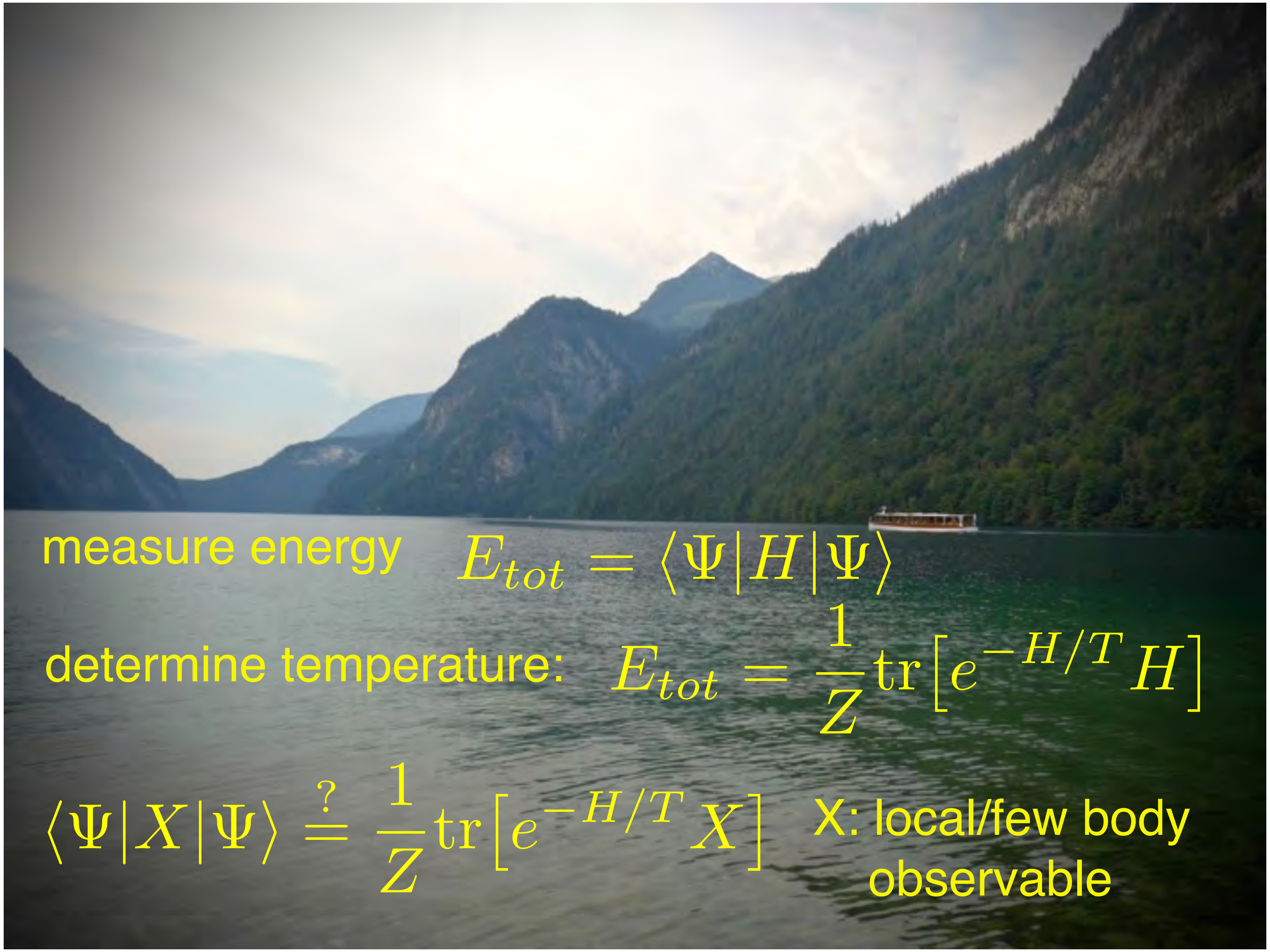
Non-equilibrium Green's functions

How to decide wether a given system is "in equilibrium"?



Non-equilibrium Green's functions

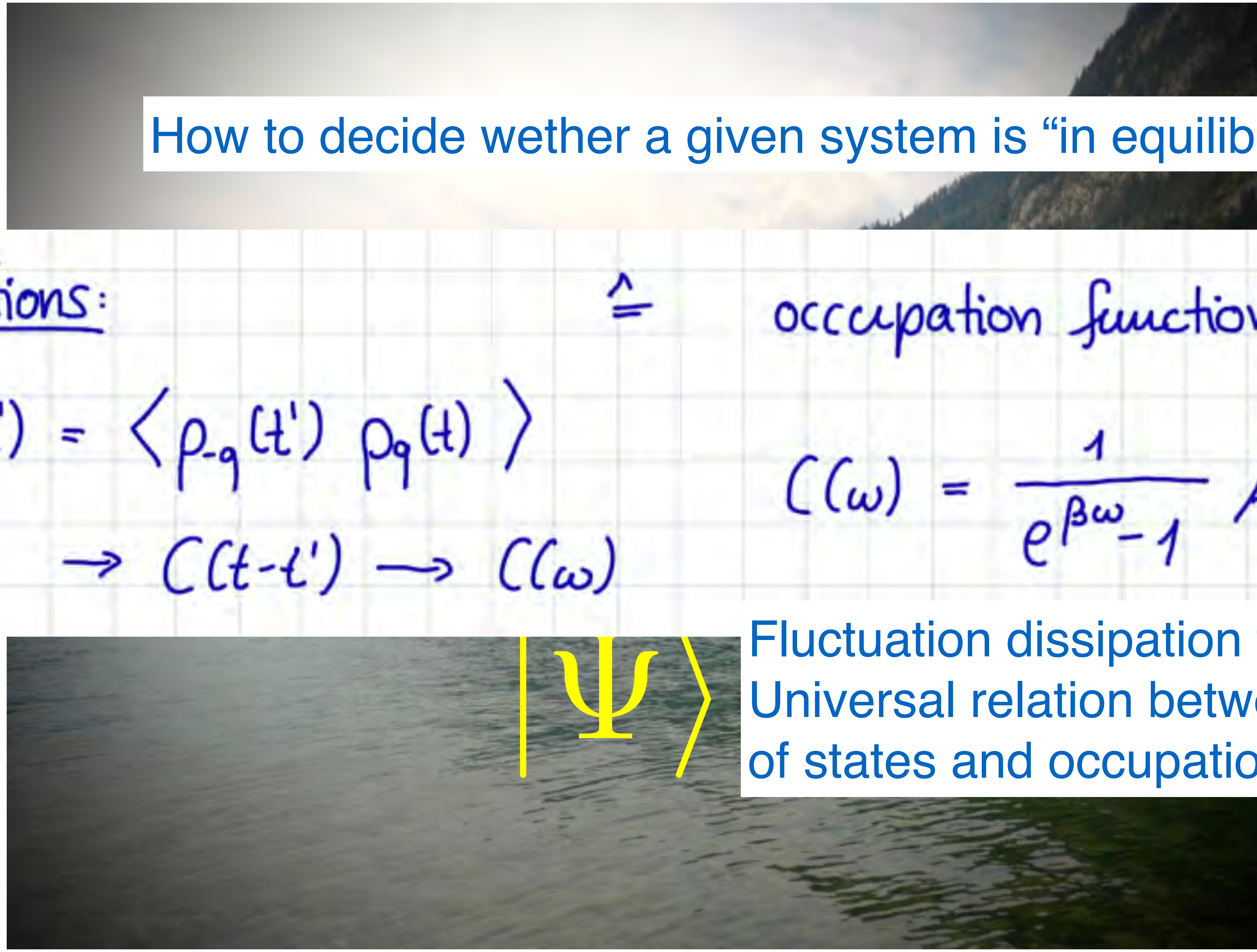
How to decide wether a given system is "in equilibrium"?



Requires knowledge of the Hamiltonian.

Non-equilibrium Green's functions

How to decide wether a given system is "in equilibrium"?



fluctuations: ≙ occupation function

$$C_q(t,t') = \langle \rho_{-q}(t')\, \rho_q(t) \rangle$$

$$\to C(t-t') \to C(\omega)$$

$$C(\omega) = \frac{1}{e^{\beta\omega}-1} A_q(\omega)$$

Fluctuation dissipation theorem:
Universal relation between density of states and occupation

Non-equilibrium Green's functions

Equilibrium:

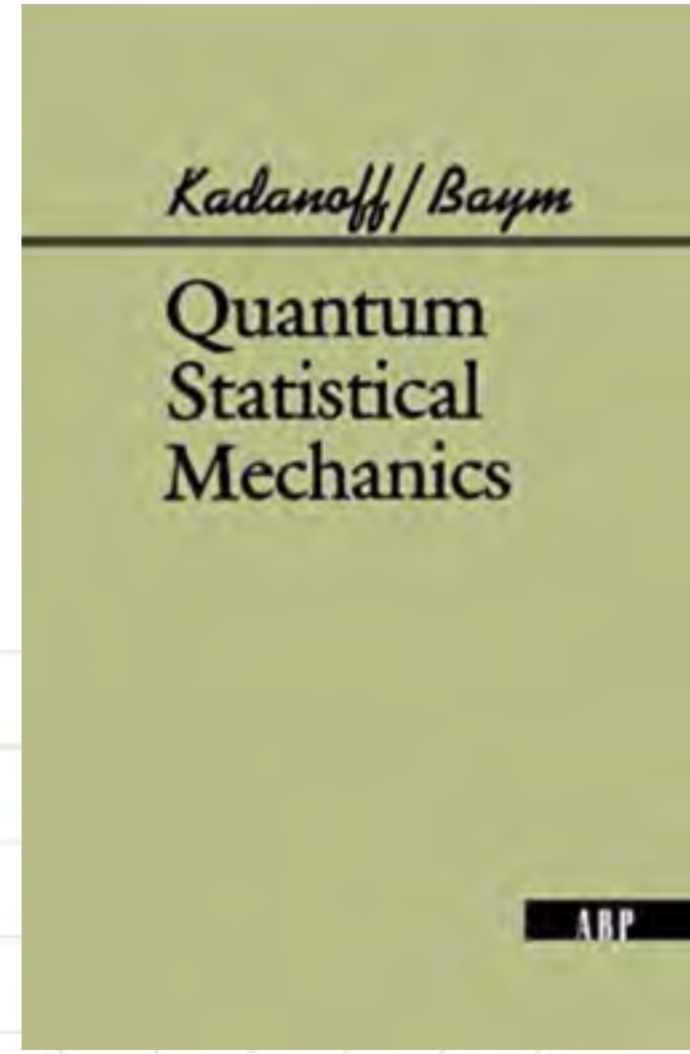
Formulate many body theory in terms of propagators which describe spectrum of collective and quasiparticle excitations; time-translational invariance

(mathematically, this is formulated in imaginary time)

Non-equilibrium:

Response and correlation function (spectrum and occupation function) are independent dynamic variables in many-body theory; time-translational invariance can be lost

Non-equilibrium Green's functions



hole propagator $G^{>}_{jj'}(t,t') = -i\langle c_j(t)c^{\dagger}_{j'}(t')\rangle$

electron propagator $G^{<}_{jj'}(t,t') = i\langle c^{\dagger}_{j'}(t')c_j(t)\rangle$

$$G^r_k(t,t') = -i\,\Theta(t,t')\,\langle [c_k(t), c_k(t')^+]_+ \rangle$$

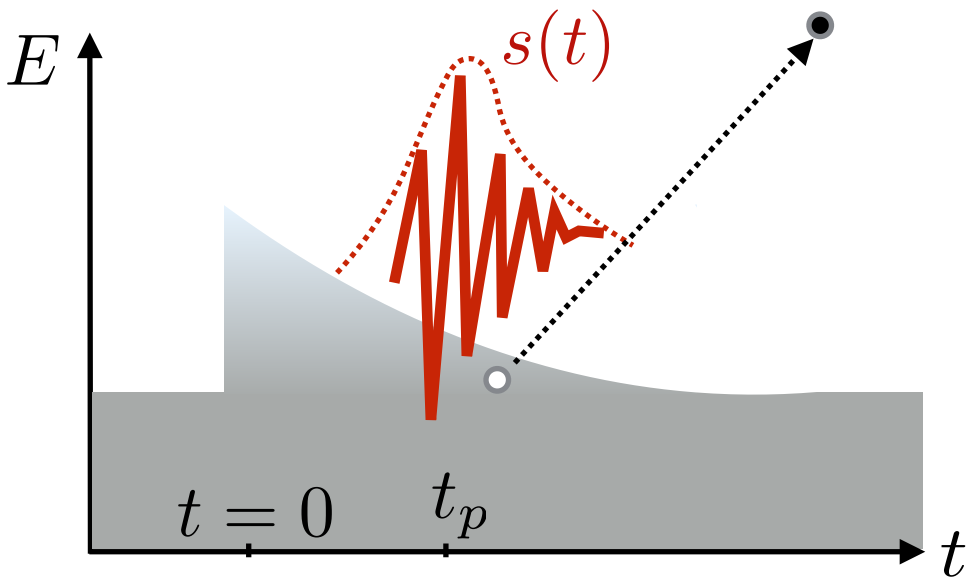
$$A_k(\omega) = -\frac{1}{\pi}\,\mathrm{Im}\,G^r(\omega+i0)$$ Spectrum

$$G^<_k(t,t') = \langle c_k^+(t')\,c_k(t)\rangle$$

$$G^<_k(\omega) = f(\omega)\,A_k(\omega)\,(2\pi i)$$ occupied density of states

Photoemission spectroscopy:

electron with asymptotic momentum k, energy E,



classical field $A^+(t) = e^{i\Omega t} s(t)$

$$H_{int} = \sum_{k,\alpha} M_{k,\alpha} c_k^\dagger A^+(t) c_\alpha + h.c.$$

orbital in the solid

Outgoing electron with asymptotic momentum k

Sudden approximation: No interaction between outgoing electron states and electrons in solid

$$I_k(E, t_p) = -i \int dt dt' e^{iE(t-t')} \sum_{\alpha,\alpha'} M_{k,\alpha} M_{k,\alpha'} G^<_{\alpha,\alpha'}(t_p + t, t_p + t') S(t) S(t')$$

Green-function of solid only

Pulse Autocorrelation function

Freericks, Krishnamurthy & Pruschke, Phys. Rev. Lett. **102**, 136401 (2009).
Eckstein & Kollar, Phys. Rev. B, **78**, 245113 (2008).

Mixed time-frequency representation

Mixed time-frequency representation:

Gaussian pulse envelope

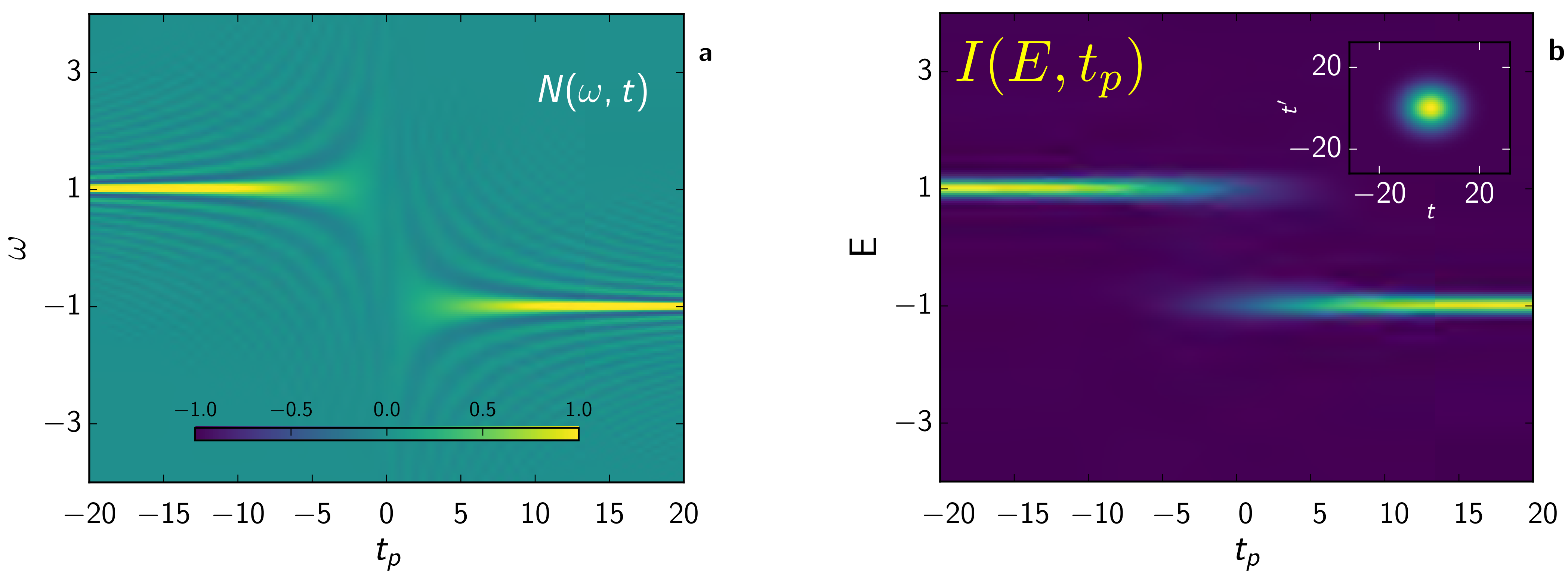
$$s(t) \propto e^{-(t/\delta t)^2}$$

$$I(E,t_p) \propto \int d\omega dt \; e^{-\frac{t^2}{\Delta t^2}} e^{-\omega^2 \Delta t^2} N(E+\omega, t_p+t)$$

Wigner transform (time-dependent band structure)

filter constrained by energy-time uncertainty

$$H(t) = \begin{cases} \epsilon\, c^\dagger c & t<0 \\ -\epsilon\, c^\dagger c & t>0 \end{cases}$$



with Francesco Randi, Daniele Fausti (Trieste)

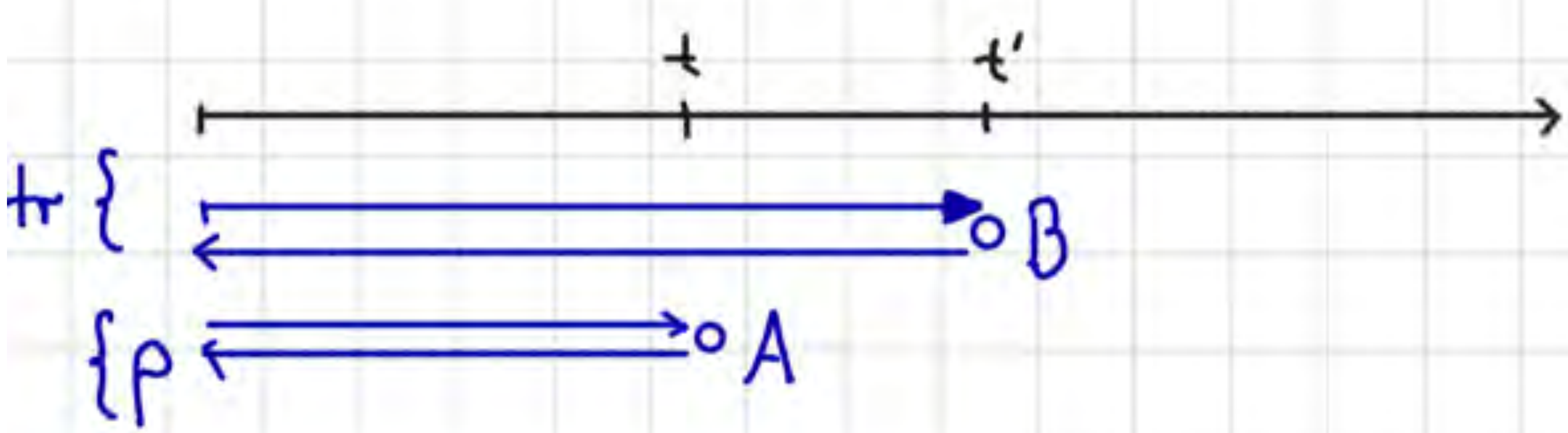
Many body theory with non-equilibrium Green's functions

Green's functions: Book-keeping trick (Keldysh)

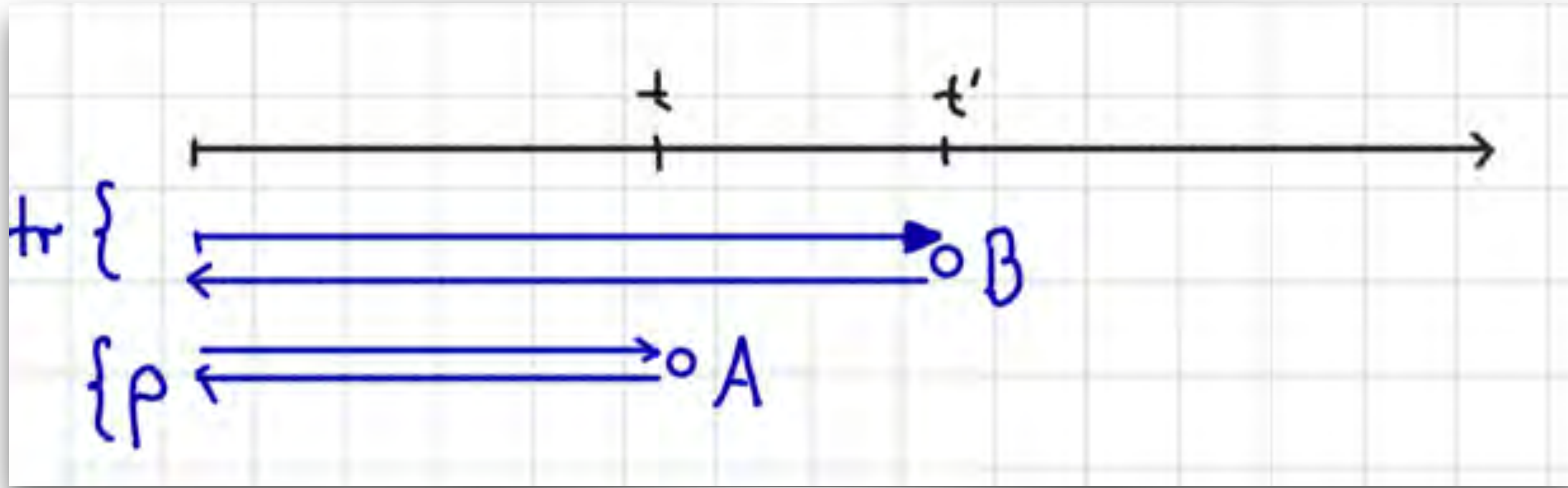
$$\langle A_H(t)\, B_H(t')\rangle \qquad A_H(t) = e^{+iHt} A e^{iHt} \qquad \langle \dots \rangle = \mathrm{tr}(\rho_0 \dots)$$

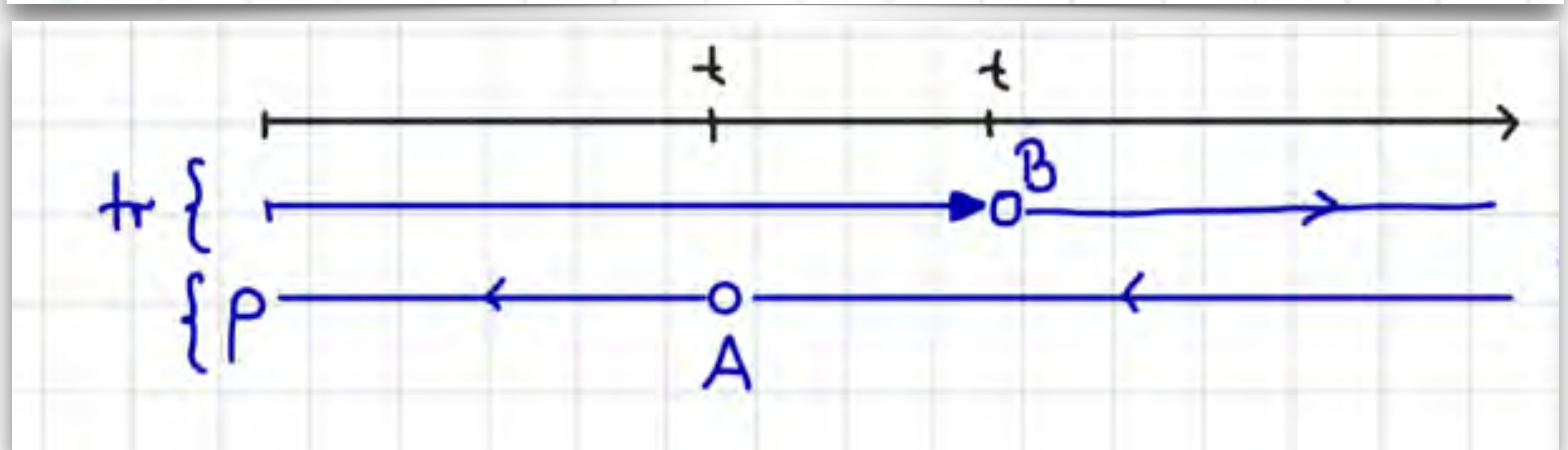
$$t_1 \longmapsto t_2 = e^{-iH(t_2-t_1)} \equiv T_t\, e^{-i\int_{t_1}^{t_2} d\bar{t}\, H(\bar{t})}$$

$$t_1 \longleftarrow\!\!\shortmid\ t_2 = e^{iH(t_2-t_1)} \equiv T_{\bar{t}}\, e^{-i\int_{t_2}^{t_1} d\bar{t}\, H(\bar{t})}$$

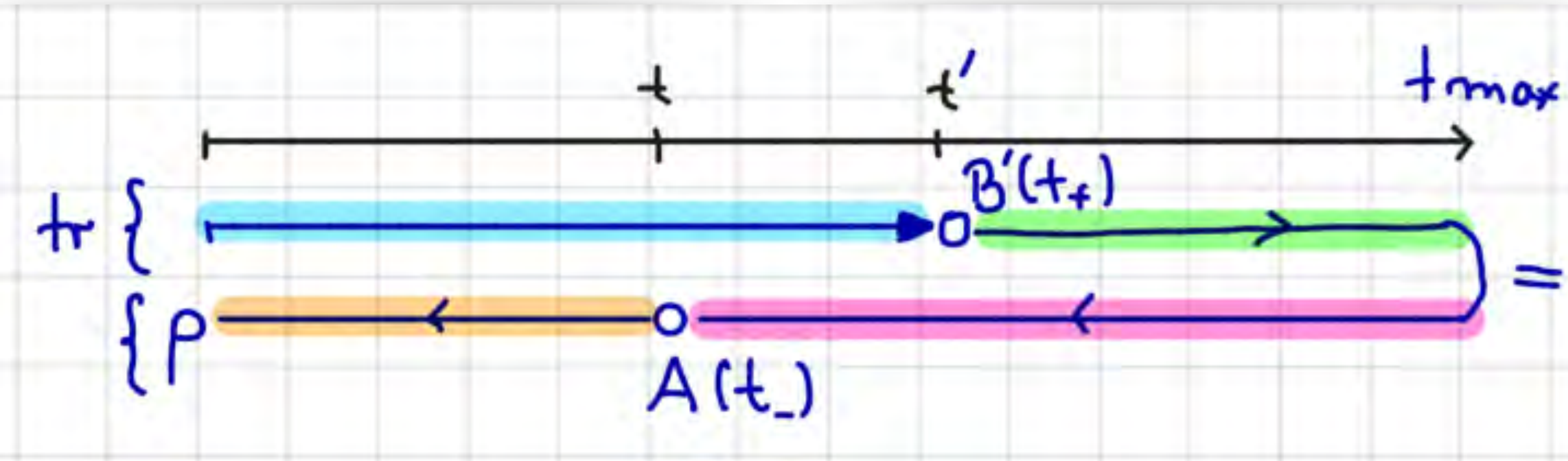


Green‘s functions: Book-keeping trick (Keldysh)





Green's functions: Book-keeping trick (Keldysh)



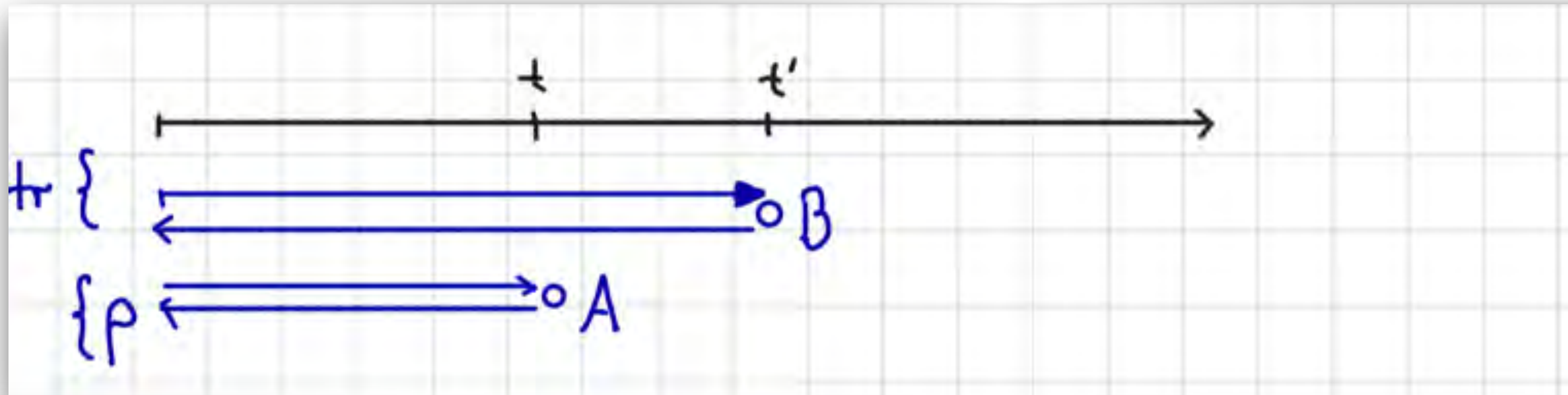
$$\mathrm{tr}\{\rho\, A_H(t)\, B_H(t')\} =$$

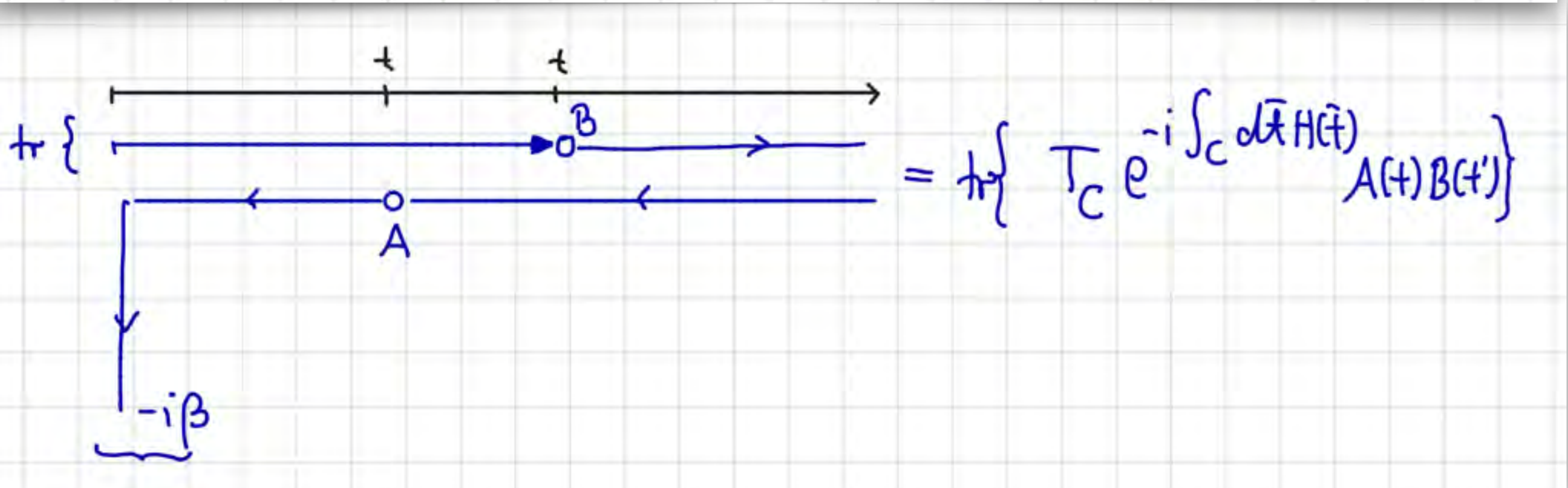
$$= \mathrm{tr}\Big\{ \rho \;\; T_{\tilde t}\, e^{-i\int_t^0 d\bar t\, H(\bar t)} \;\; A \;\; T_{\tilde t}\, e^{-i\int_{t_{max}}^{t} d\bar t\, H(\bar t)} \;\times$$

$$\times\;\; T_t\, e^{-i\int_{t'}^{t_{max}} d\bar t\, H(\bar t)} \;\; B\; T_t e^{-i\int_0^{t'} d\bar t\, H(\bar t)} \Big\}$$

$$= \mathrm{tr}\Big\{\rho \;\; T_{C_K}\, e^{-i\int_{C_K} d\bar t\, H(\bar t)} \;\; A(t_-)\; B(t'_+) \Big\}$$

Green‘s functions: Book-keeping trick (Keldysh)

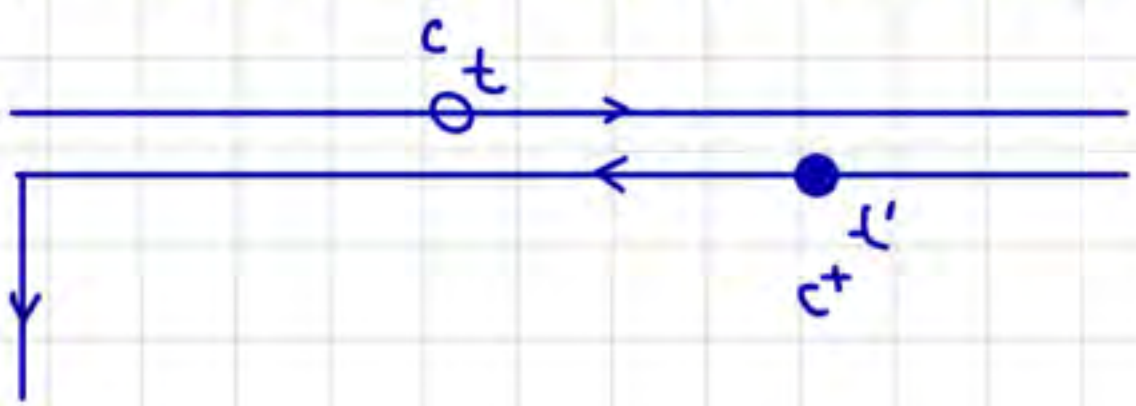




Green's functions: Book-keeping trick (Keldysh)

$$G(t,t') = -i \langle T_c\, c(t)\, c^+(t') \rangle$$

$$\Rightarrow \quad G^<(t,t') = i \langle c^+(t')\, c(t) \rangle \equiv G(t_+, t'_-)$$



Contour-ordered correlation functions

$\Rightarrow$ path integrals: $$\langle T_c\, A(t)\, B(t') \rangle_S = \int_{c(0^+) = -c(-i\beta)} \mathcal{D}(c^*, c)\; e^{iS} A(t)\, B(t')$$

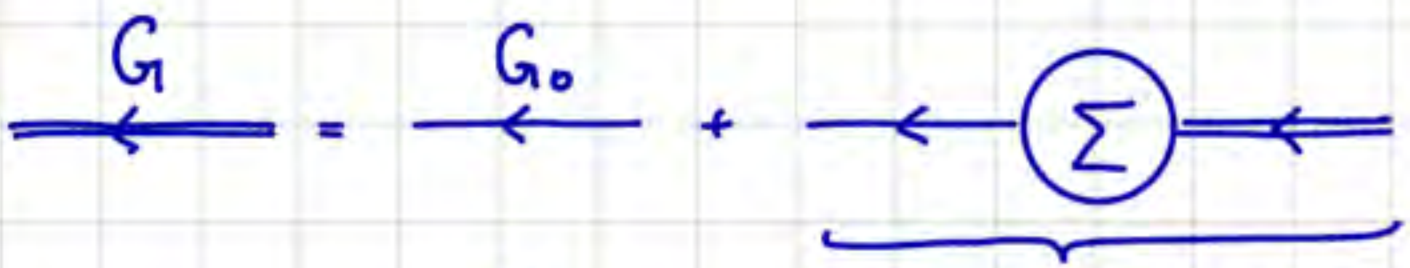
$$S = \int_c dt \left\{ c^*(t)\, i\partial_t\, c(t) - H[c^*, c] \right\}$$

Green's functions: Book-keeping trick (Keldysh)

Feynman diagrams:

Obtained from S like in equilibrium!

Example:



$$\int dt_1 dt_2 \; G_0(t,t_1)\,\Sigma(t_1,t_2)\,G(t_2,t')$$

$$\Sigma(t,t') = U^2\, G(t,t')\,G(t,t')\,G(t',t)$$

$\Longrightarrow$ integral equation on C

Kadanoff-Baym equations

Dyson equation

→ equation of motion for Green's functions

with nonlinear Memory kernel Σ[G]

time-dependent mean-field

$$\left(i\partial_t - H_{MF}(t)\right)G(t,t') - \int_{\text{previous time}} ds \;\; \Sigma[G](t,s)G(s,t') = \delta(t,t')$$

„Kadanoff-Baym equations"

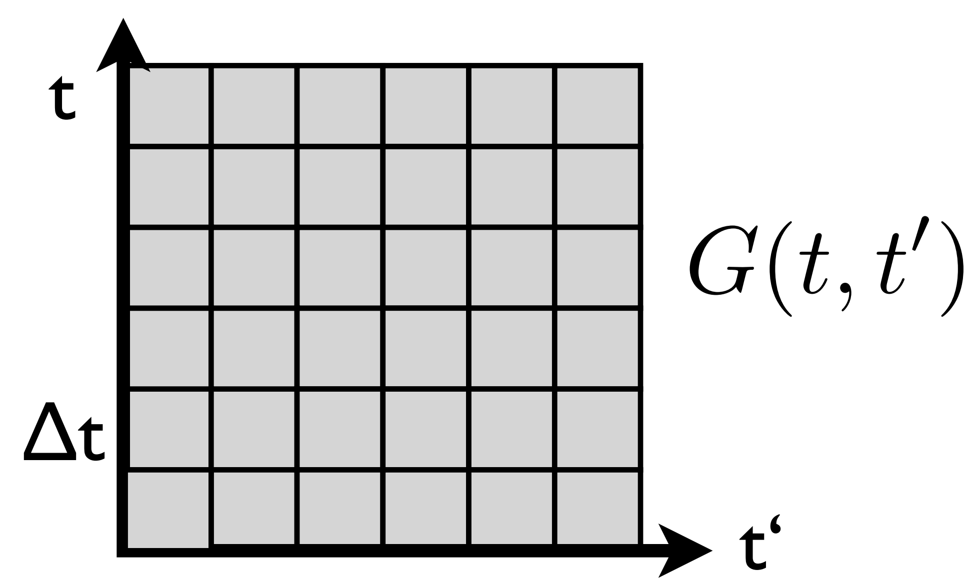
Kadanoff & Baym; Bonitz 2000; Bonitz and Semkat 2003, Balzer & Bonitz 2012

„causal" time-propagation:

Memory: $\sim N^2 L^2$

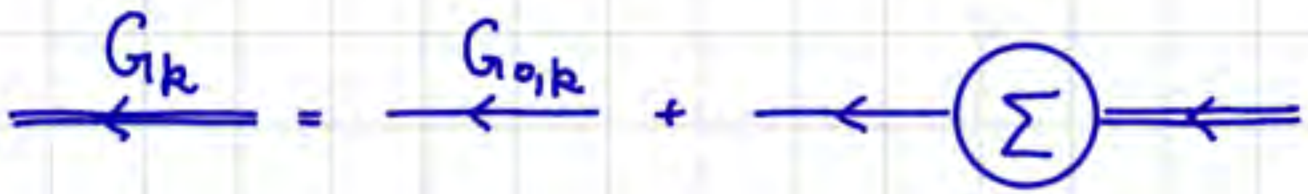
Compute time: $\sim N^3 L^3$

(N: #timesteps, L#orbitals)



Dynamical mean-field theory

Georges, Rozenberg, Krauth & Kotliar, RMP 1996
Aoki, Tsuji, ME, Kollar, Oka, Werner, RMP 2014



$$G_{0,k} = -i \langle T_c \, c_k(t) \, c_k^\dagger(t') \rangle_{H_0}$$

no interaction ⇒ solve $c_k(t)$ by equations of motion (with external fields!)

$$\Sigma[G] = \Sigma_{loc}[G_{loc}] \quad \text{all local diagrams}$$

$$S = S_{loc} + \int dt\, dt' \, c^*(t) \, \Delta(t,t') \, c(t')$$

$$G_{imp} = \mathcal{G}_\Delta + \mathcal{G}_\Delta \, \Sigma \, G_{imp}$$

$$= \frac{1}{Z} \int \mathcal{D}(c^* c) \, e^{iS} \, c(t) \, c^*(t')$$

Impurity problem:
Many-body problem:
QMC, IPT, NCA, ED, DMRG, ...

Formulation in Keldysh framework: Schmid & Monien (2002) Freericks, Turkowski, Zlatic 2006

The quantum impurity problem

Solution of effective impurity problem:

CT-QMC: numerically exaxt, phase problem
bold-line version work by E. Gull et al.

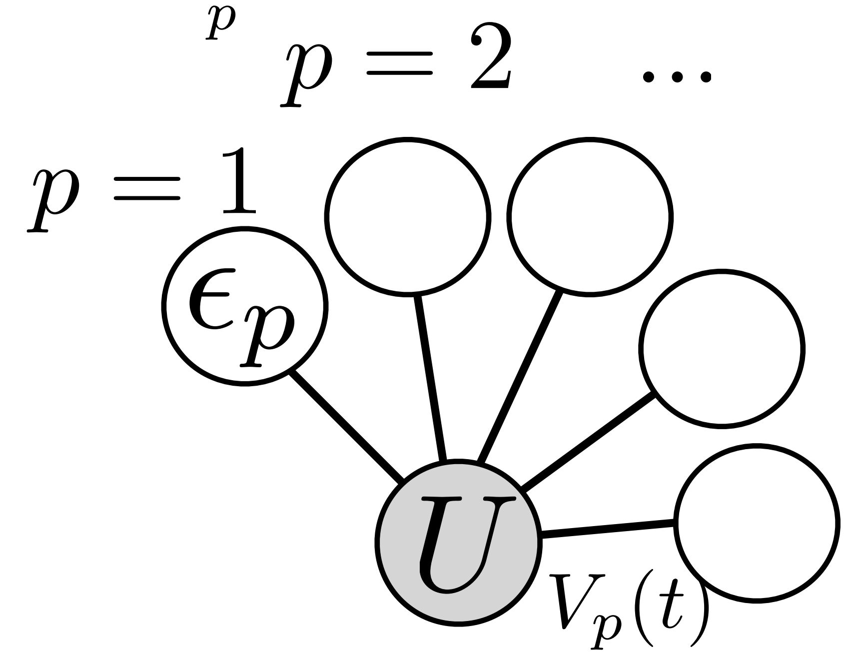
Strong-coupling expansion: NCA, OCA
ok for Mott phase;
✓ *multi-orbital extension,*
✓ *bosonic systems,*
✓ *phonons (Hubbard Holstein)*

Weak-coupling perturbation theory

Finite representation of the bath

Gramsch, Balzer, ME, Kollar PRB 2013,

$$\Delta(t,t') \leftrightarrow \sum_p V_p(t)(i\partial_t - \epsilon_p)^{-1} V_p(t')^*$$



$$H_{imp} = U n_\uparrow n_\downarrow + \sum_{p\sigma} \epsilon_p a^\dagger_{p\sigma} a_{p\sigma} + \sum_{p\sigma} (V_p(t) c^\dagger_\sigma a_{p\sigma} + h.c.)$$

→ Krylov
→ *Matrix-product states (td-DMRG)*

A. Wolf et al., 2014, Balzer et al. arXiv 1504.02461

Strong-coupling expansion

Strong-coupling expansion

Expansion in the coupling to the bath?

$$\langle \mathcal{O}(t) \rangle = \frac{1}{Z} \mathrm{tr}\left[T_{\mathcal{C}} e^{-i\int_{\mathcal{C}} dt' H_{loc}(t')} e^{-i\int_{\mathcal{C}} dt_1 dt_2 c^\dagger(t_1)\Delta(t_1,t_2)c(t_2)} \mathcal{O}(t) \right]$$

0th order is interacting Hamiltonian H_{loc} $\Rightarrow$ very general starting point

But: no Wick's theorem → Resolvent expansions:

- Perturbative: "non-crossing approximation", first developed for the Kondo model

  Keiter & Kimball '71; Kuramoto '83; Grewe '83; Pruschke & Grewe 89
  Bickers, Cox & Wilkins '87; Coleman '83; Haule, Kirchner, Kroha & Wölfle '01

- Hybridization Quantum Monte Carlo: Werner *et al.,* 2006
  Stochastic resummation of perturbation series

Strong-coupling expansion

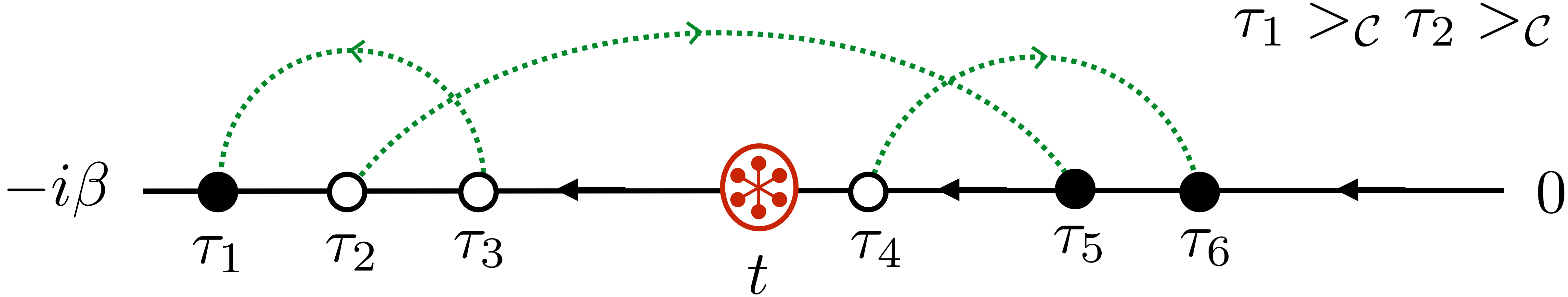
$$\langle \mathcal{O}(t) \rangle = \frac{1}{Z} \mathrm{tr}\left[T_{\mathcal{C}} e^{-i\int_{\mathcal{C}} dt' H_{loc}(t')} e^{-i\int_{\mathcal{C}} dt_1 dt_2 c^\dagger(t_1) \Delta(t_1,t_2) c(t_2)} \mathcal{O}(t) \right]$$

$$= \frac{1}{Z} \sum_{n=0}^{\infty} \frac{(-i)^n}{n!} \int_{\mathcal{C}} dt_1 dt_1' \cdots dt_n dt_n' \; \Delta(t_1, t_1') \cdots \Delta(t_n, t_n') \times$$

$$\times \; \mathrm{tr}\left[T_{\mathcal{C}} e^{-i\int_{\mathcal{C}} dt' H_{loc}(t')} c^\dagger(t_1) c(t_1') \cdots c^\dagger(t_n) c(t_n') \mathcal{O}(t) \right]$$

Sum of all possible contributions like this:

contour ordered $\tau_1 >_{\mathcal{C}} \tau_2 >_{\mathcal{C}} \ldots$



 $= \mathcal{O}$ ● $= c^\dagger$ ○ $= c$ $t' \cdots\cdots\blacktriangleright t = \Delta(t, t')$

$t' \longrightarrow t \; = g(t, t') = T_{\mathcal{C}} e^{-i\int_{t'}^{t} ds H_{loc}(s)}$

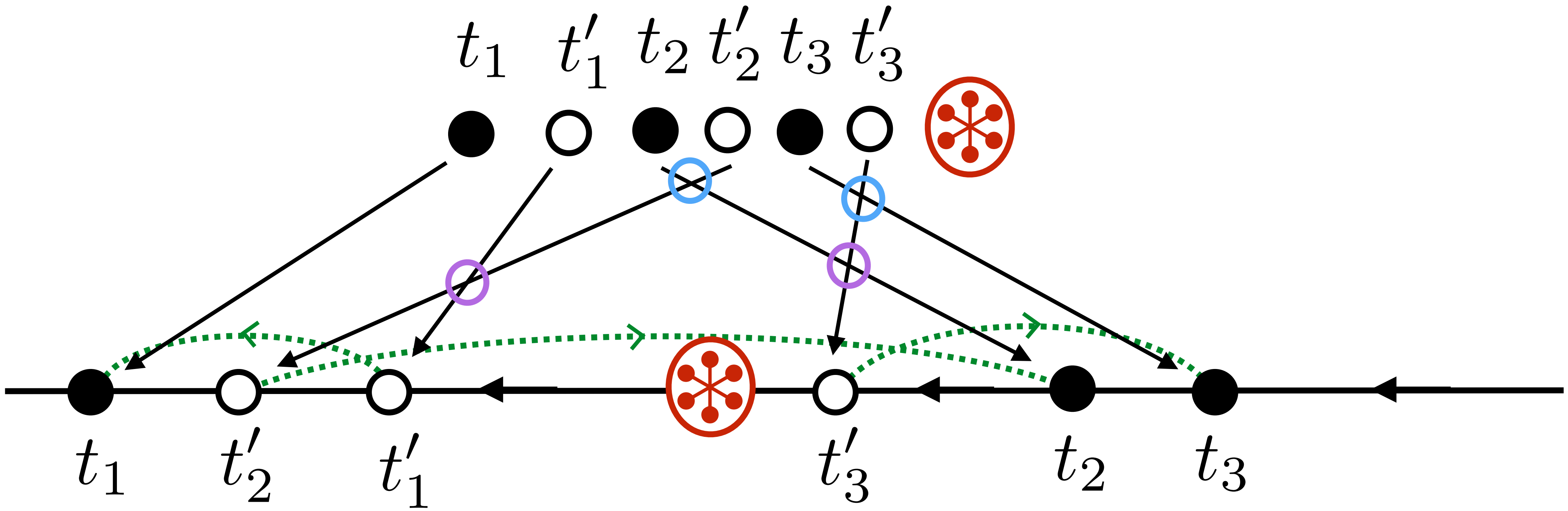
matrices in local many-body basis

$\mathcal{O}_{nm} \equiv \langle n | \mathcal{O} | m \rangle$

etc.

Strong-coupling expansion

sign of the diagram (from reordering operators under contour ordering)



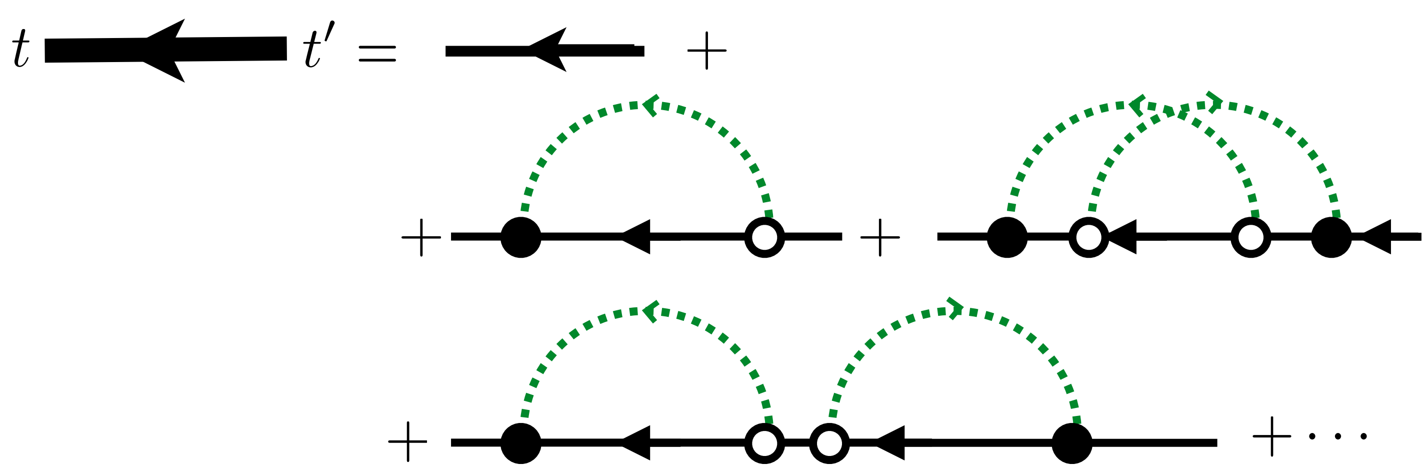
$(-1)^{\text{crossing of } \Delta \text{ lines}} \times (-1)^{\# \text{ of } \Delta \text{ lines with reversed direction}}$

count every topology once removes n! factor

Strong-coupling expansion

No symmetry factors for diagrams
(count every topology once removes n! factor)

$\Rightarrow$ Define re-summed propagators



(t later on C than t')

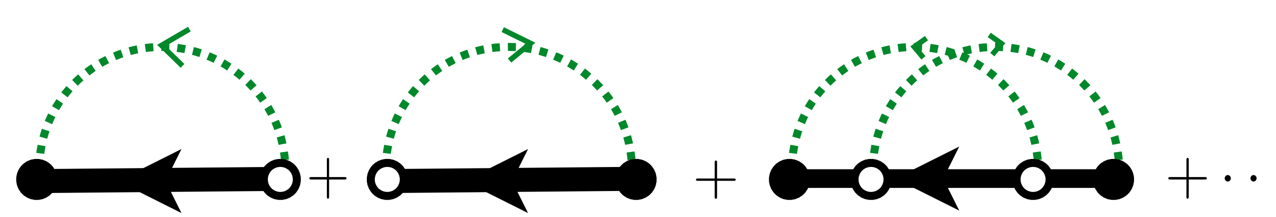
Dyson equation:

$$\mathcal{G}(t,t') = g(t,t') + \int_{\mathcal{C}}^{t'} dt_1 dt_2 g(t,t_1)\Xi(t_1,t_2)\mathcal{G}(t_2,t')$$

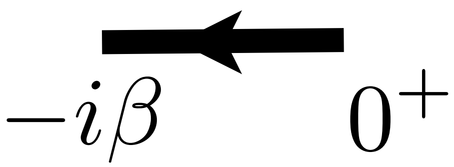
$$t >_{\mathcal{C}} t_1 >_{\mathcal{C}} t_2 >_{\mathcal{C}} >_{\mathcal{C}} t'$$

Skeleton expansion

$\Xi(t,t') =$

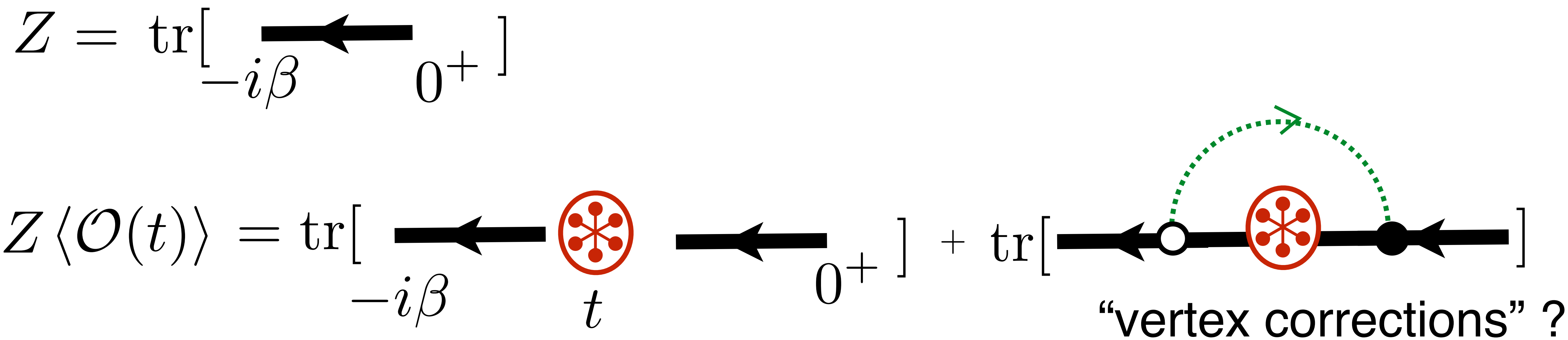


Strong-coupling expansion

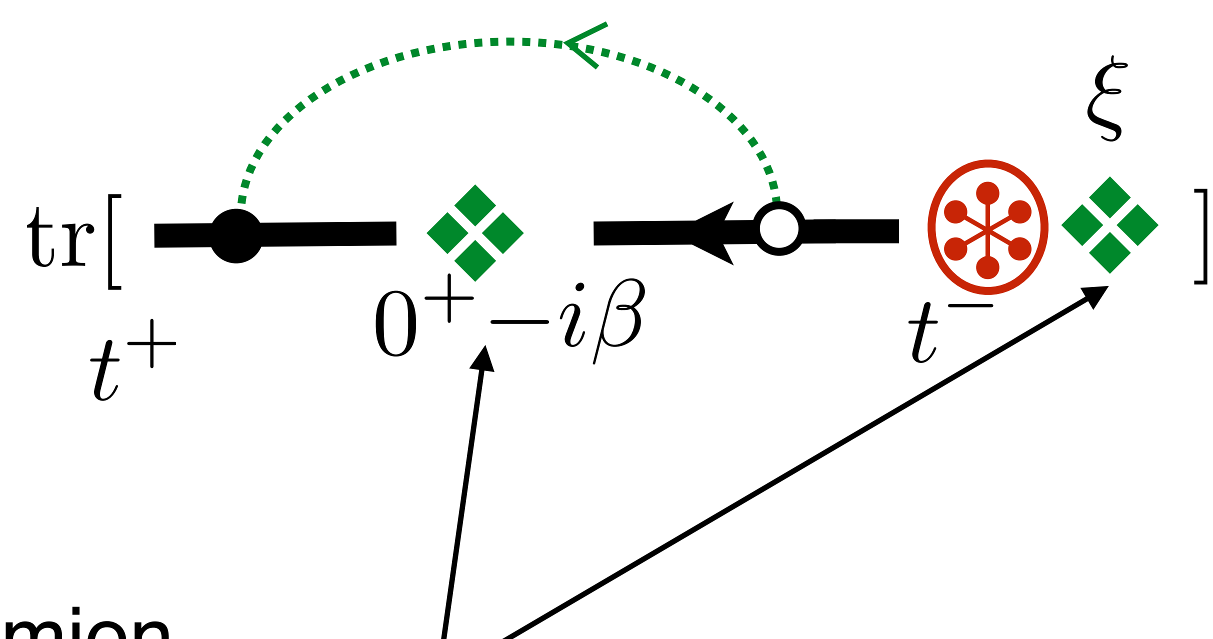


= ?

Strong-coupling expansion



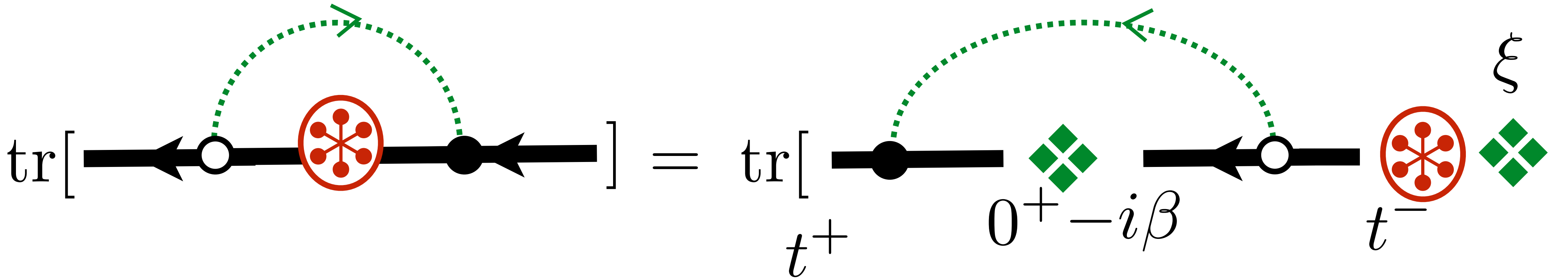
Cyclic permutation under the trace:



How many fermion permutations? measure $\xi = (-1)^{\text{particle number}}$

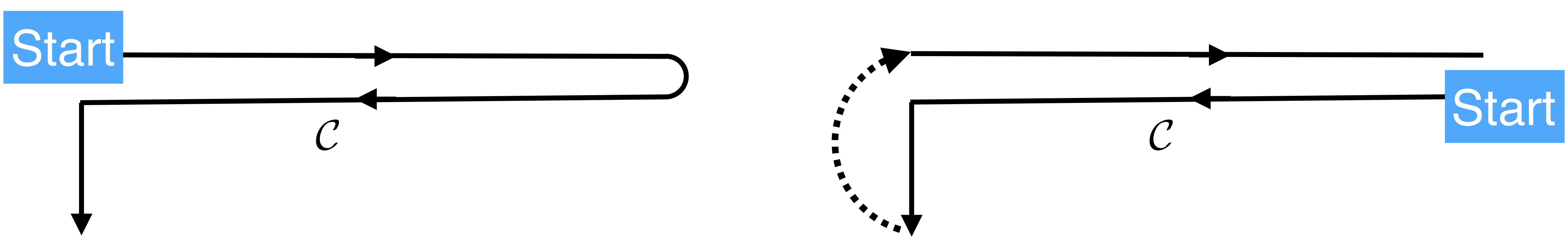
Strong-coupling expansion

Cyclic permutation under the trace:



Just redefine starting point on the contour

…. and an operator ξ whenever the propagator winds around 0

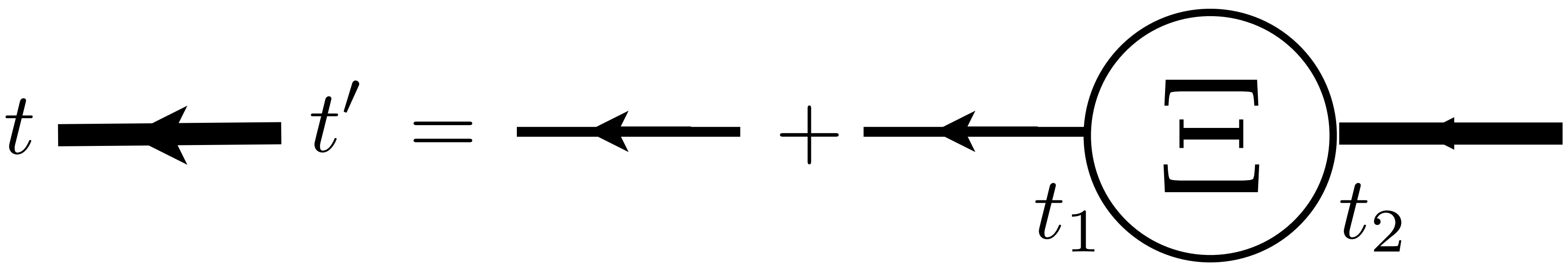


contour-ordered integrals → cyclically ordered integrals, e.g. in Dyson

Strong-coupling expansion

Summary:

$$\langle \mathcal{O}(t) \rangle = \frac{1}{Z} \mathrm{tr}\big[\mathcal{G}(t^+, t-)\mathcal{O}\xi\big] \qquad Z = \mathrm{tr}\big[\mathcal{G}(t^+, t-)\xi\big]$$

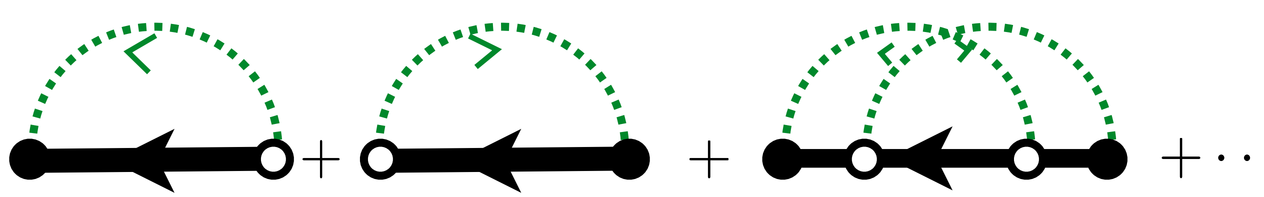


t, t_1, t_2, t' cyclic

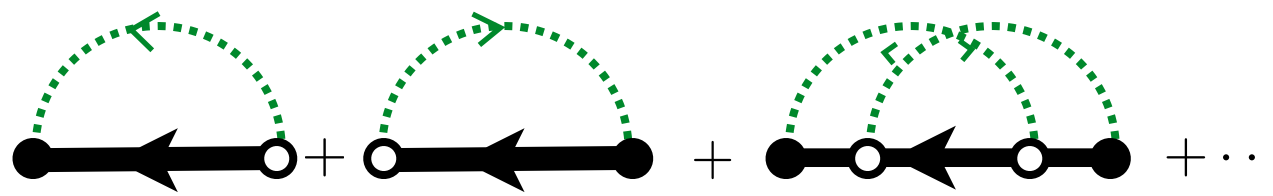
$$g(t,t') = T_{\mathcal{C}} e^{-i\int_{t'}^{t} ds H_{loc}(s)}$$

$$g(t,t') = g(t_+, 0^-)\xi g(-i\beta, t') \text{ (for } t <_{\mathcal{C}} t'\text{)}$$

$\Xi(t,t') =$



Strong-coupling expansion

$\Xi(t,t') =$ 

Conserving approximation (Skeleton)

First order: “non-crossing approximation”:
recovers Kondo physics (but with underestimation of T_K)

In DMFT: artefacts in the metallic phase at low temperatures, second order can already be almost quantitatively correct, in particular towards the Mott phase

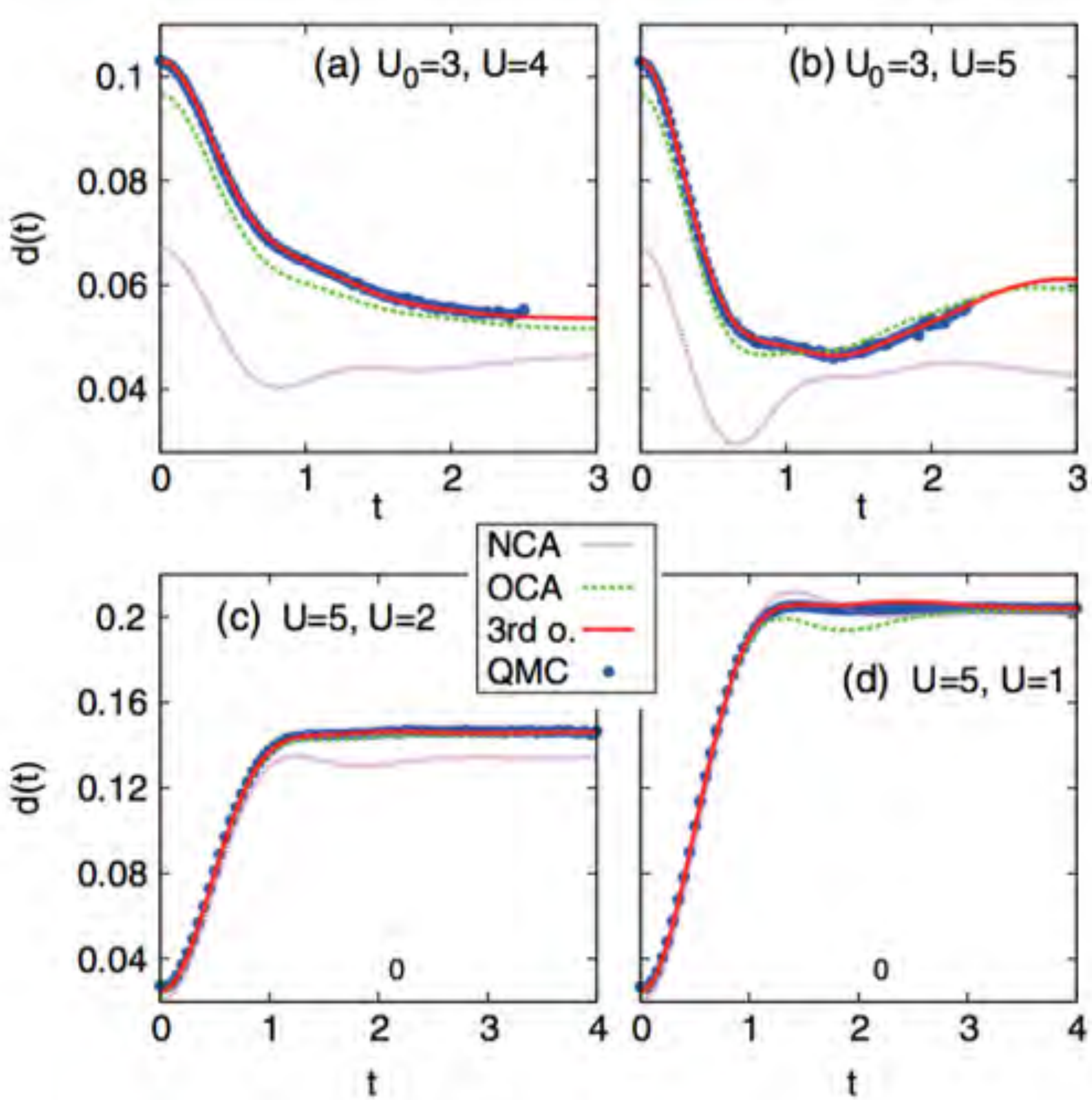
Very general staring point:

In real time, NCA for
Bosons (Bose Hubbard model)
Hubbard-Holstein model
Cluster impurity model (larger local Hilbert space)

Strong-coupling expansion

Example: Hubbard model, quench U_0 to U

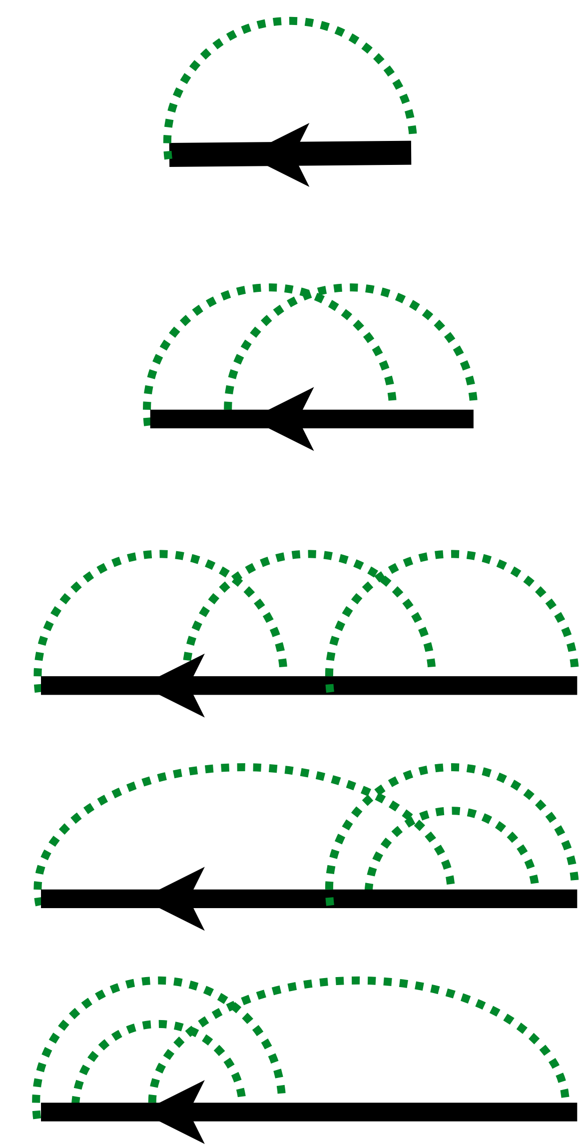
double occupancy $\langle n_{\uparrow} n_{i\downarrow} \rangle$:



NCA

OCA

3rd order

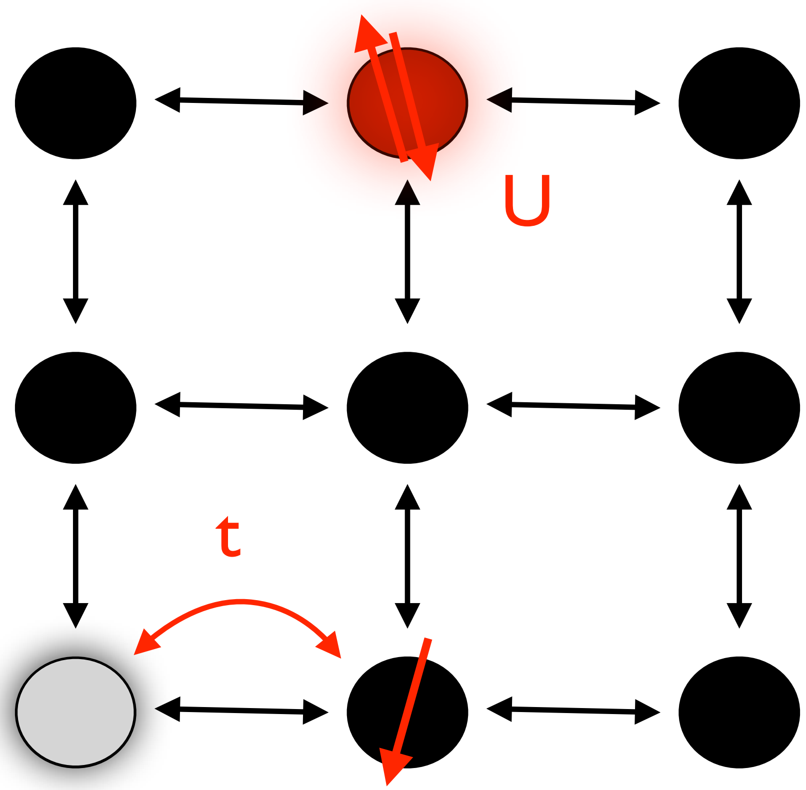


Eckstein & Werner, PRB 2010

Photo-doped states in the single-band Mott insulator

Hubbard model and Peierls substitution

Hubbard model



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

+ electric fields (Peierls substitution)

$$t_{ij} \to t_{ij} e^{i\phi_{ij}} \quad \phi_{ij} = e\vec{A}(t)(\vec{r}_j - \vec{r}_i)$$

$$\epsilon(\boldsymbol{k}) \to \epsilon(\boldsymbol{k} - \boldsymbol{A})$$

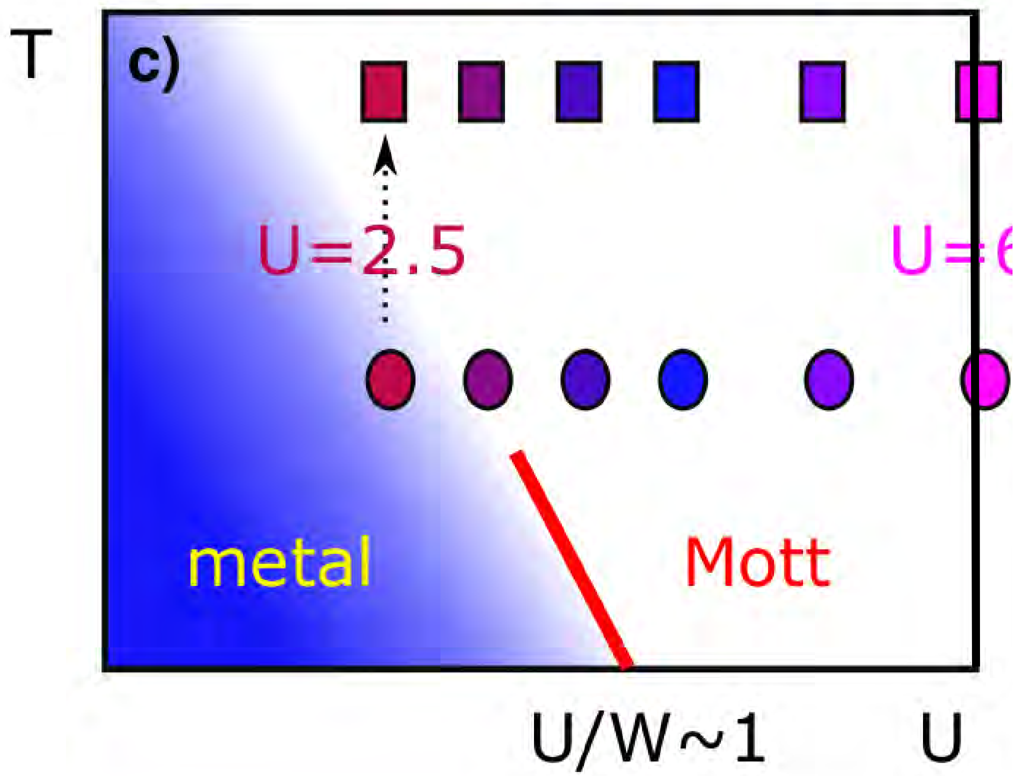
Units:

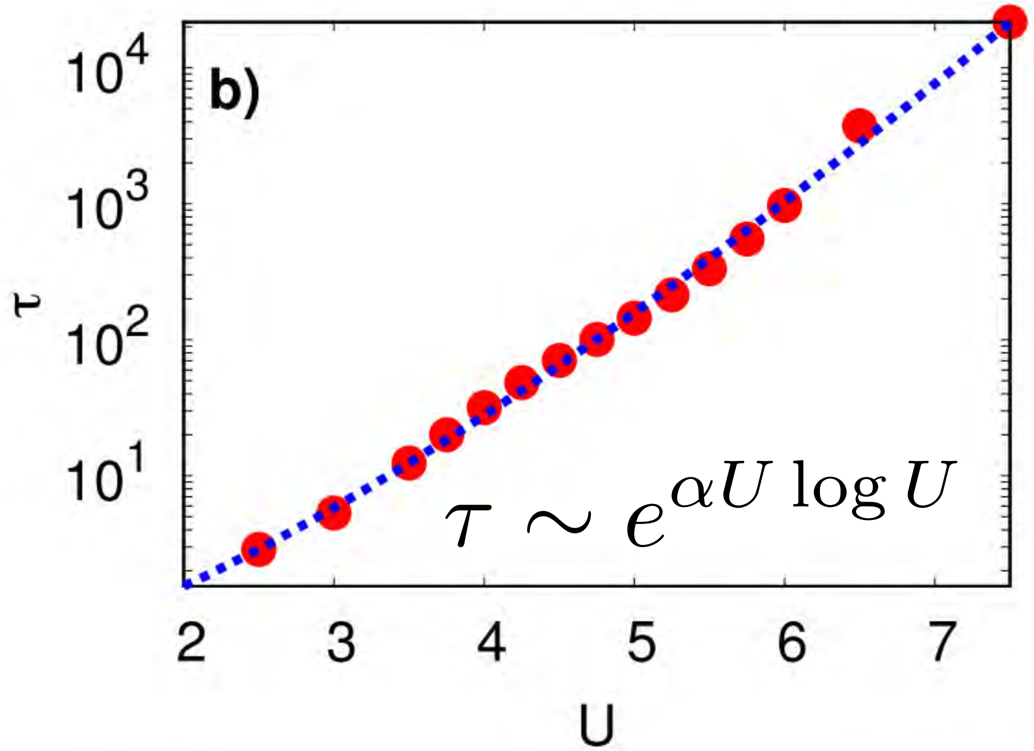
Energy: hopping ~ 1eV
Time ($\hbar = 1$): $\hbar / 1\mathrm{eV} = 1\mathrm{fs}$
Field: hopping / lattice constant

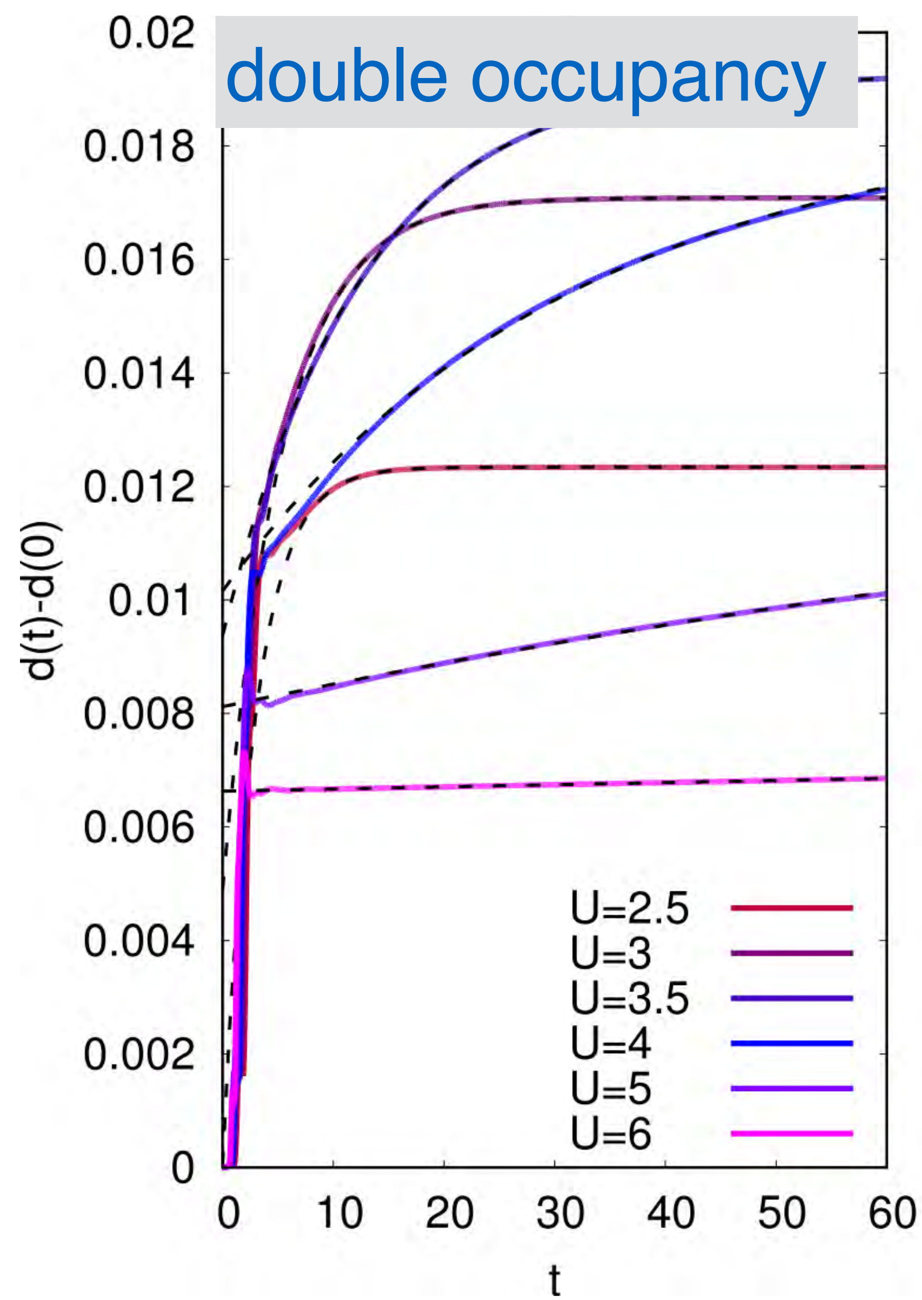
Photo-doping: correlated metal

Eckstein & Werner, PRB (2012)

bandwidth=4 (Bethe lattice) (in NCA: $U_c \sim 3.4$)







fit: $d(t) = d(T_{\text{eff}}) + Ae^{-t/\tau}$

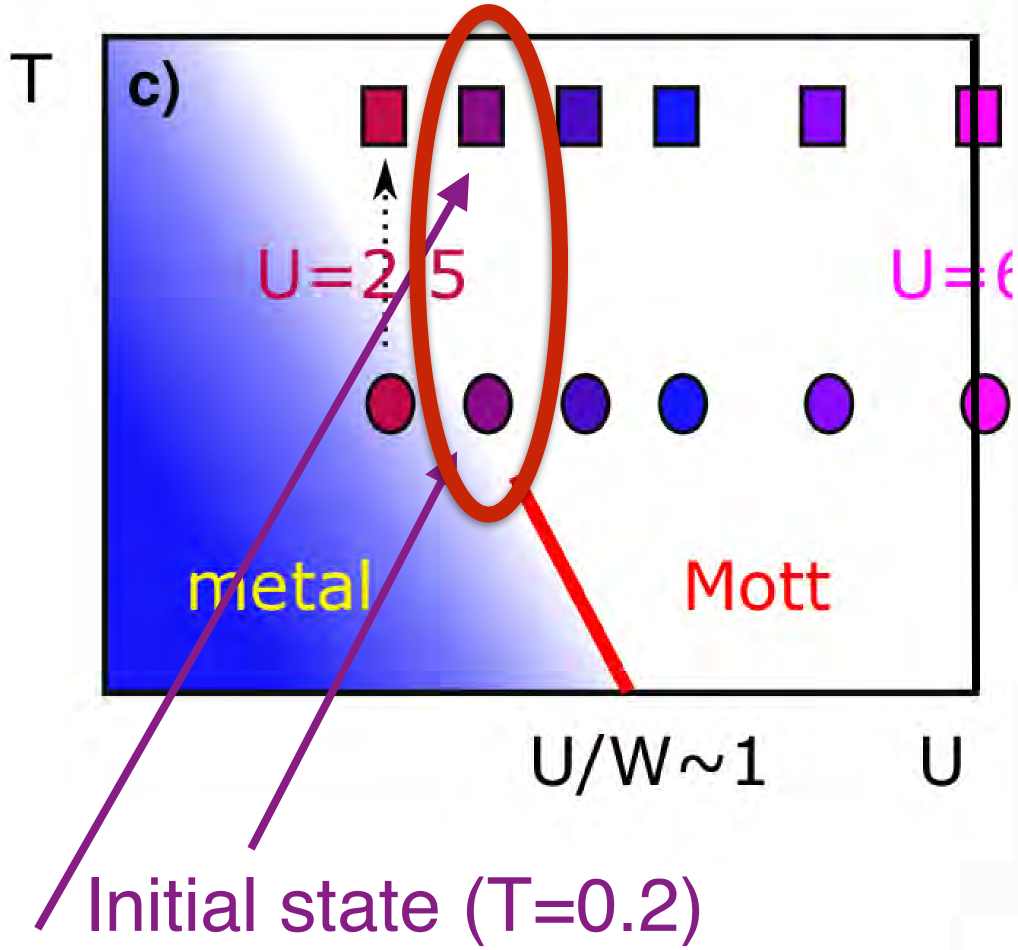
U > bandwidth: slow thermalization

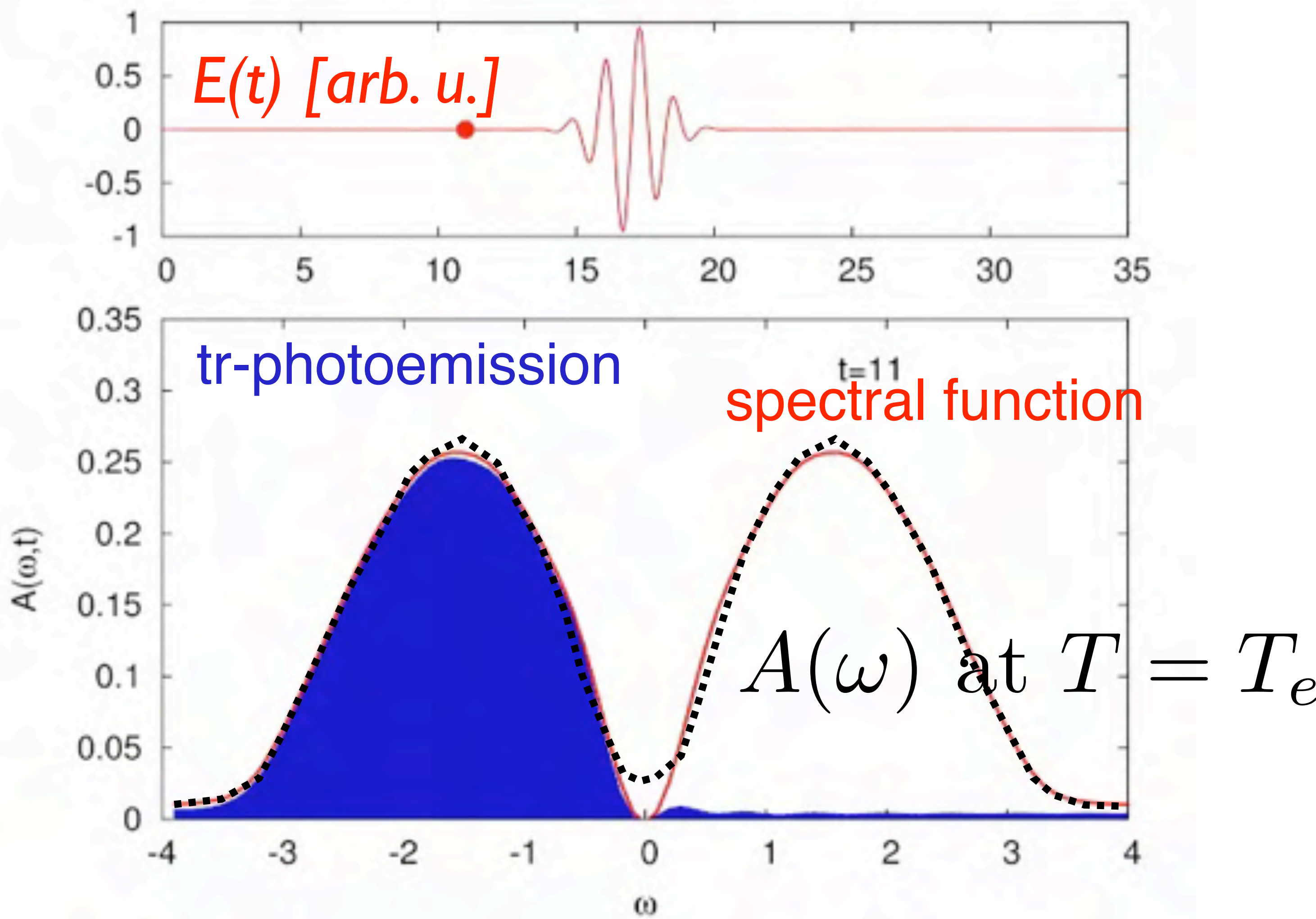
Rosch et al. PRL 2008; Strohmaier et al. PRL 2010

Photo-doping: correlated metal

Eckstein & Werner, PRB (2012)

bandwidth=4 (Bethe lattice) (in NCA: $U_c \sim 3.4$)





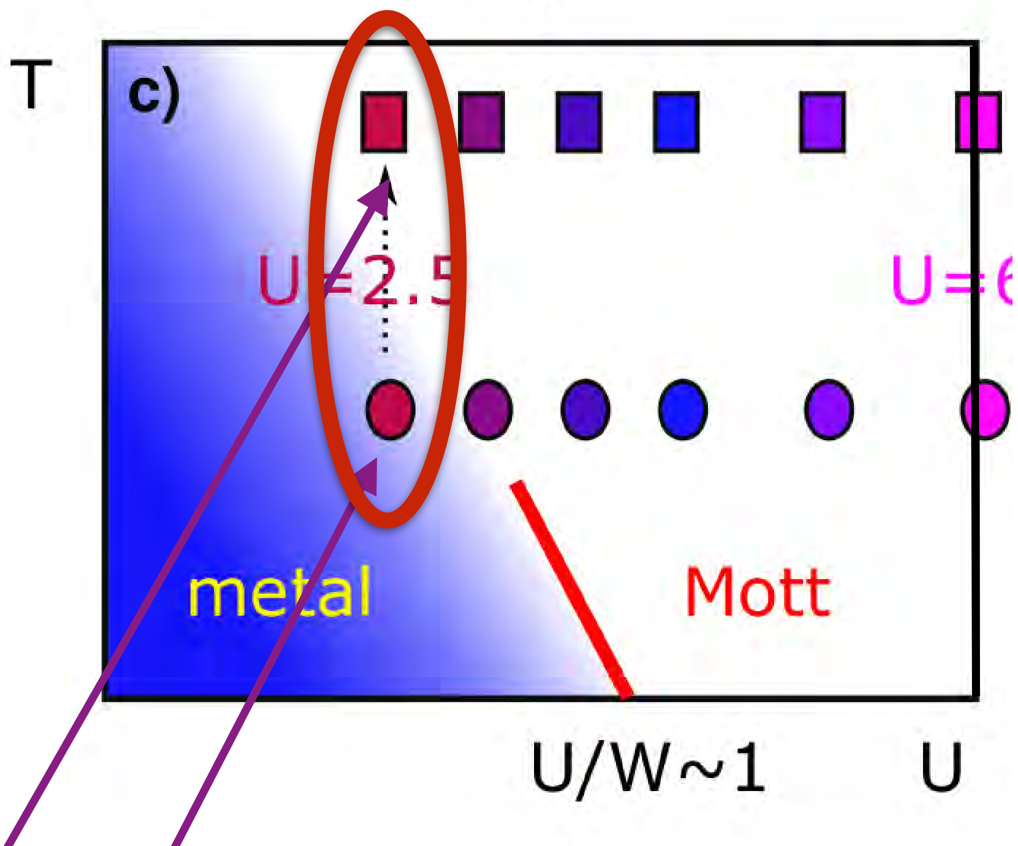
after (possible) thermalization

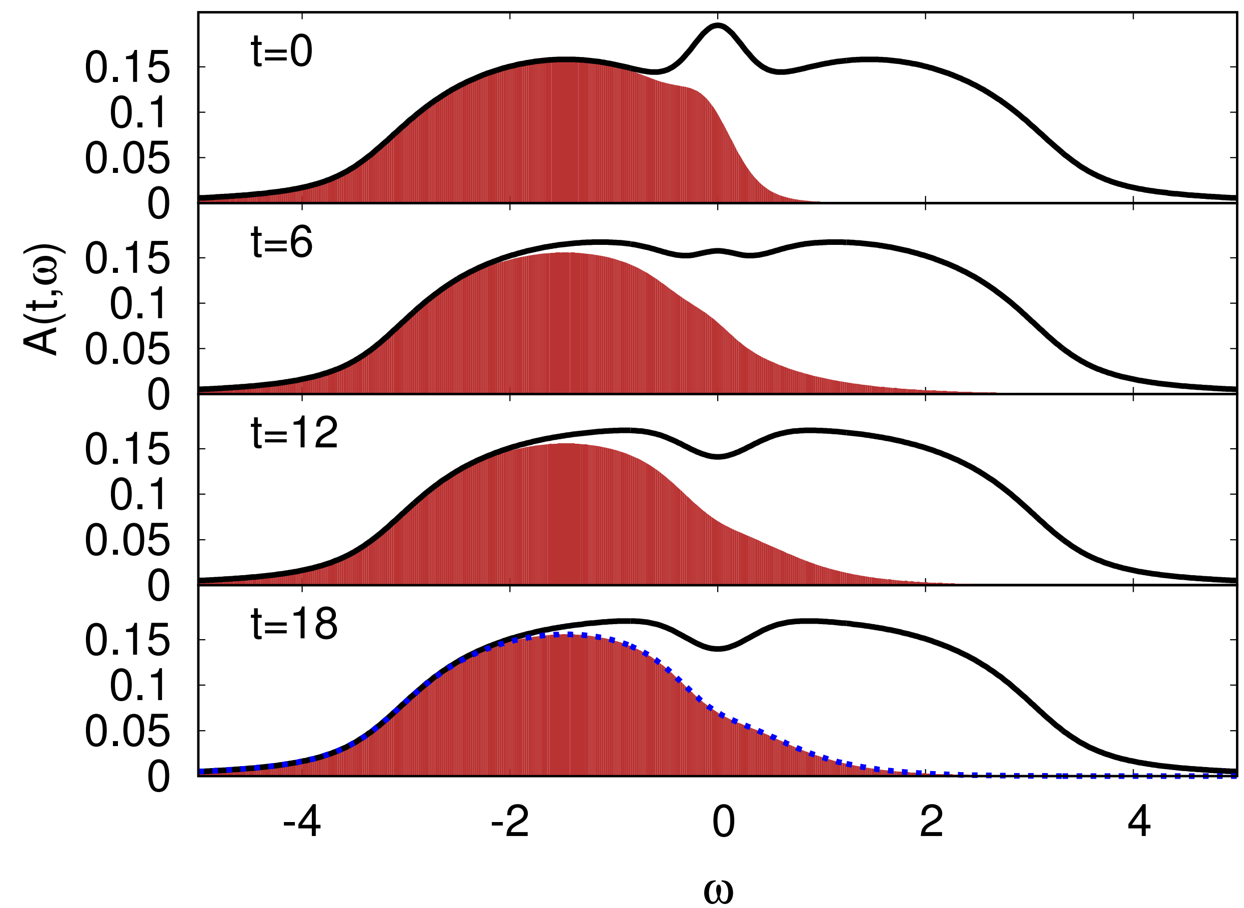
Ultra-fast electron thermalization (without well-defined quasi-particles!)

Photo-doping: correlated metal

Eckstein & Werner, PRB (2012)

bandwidth=4 (Bethe lattice)   (in NCA: $U_c \sim 3.4$)





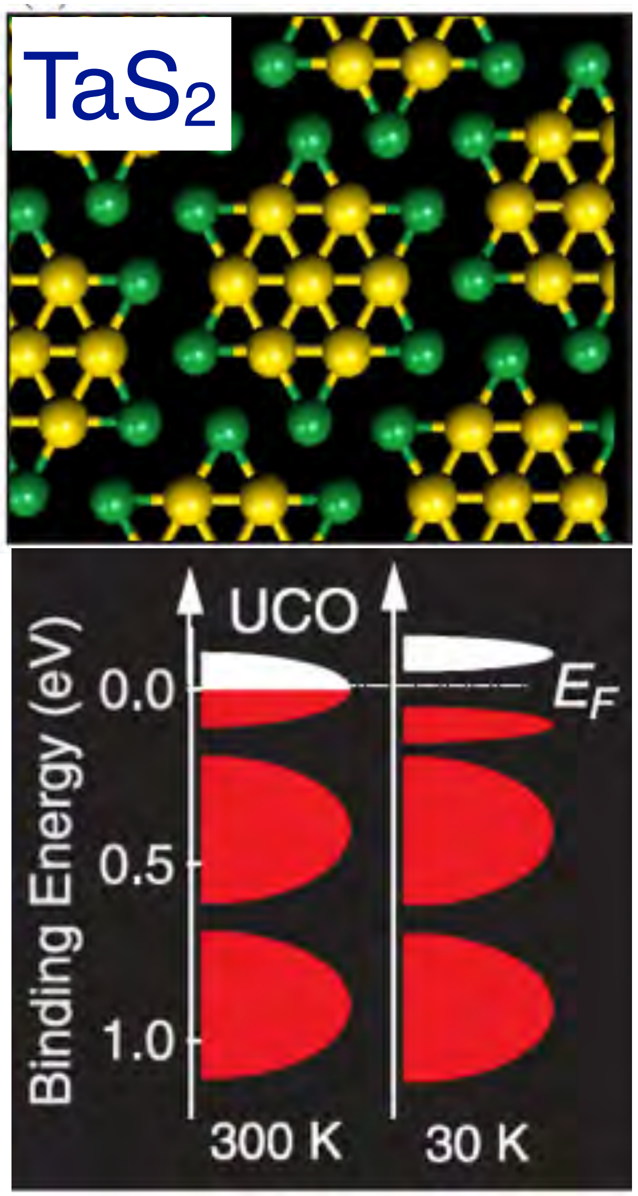
Initial state (T=0.2)

after (possible) thermalization

Ultra-fast electron thermalization   (without well-defined quasi-particles!)

Experiment: Manuel Ligges et al. arXiv:1702.05300 (PRL)

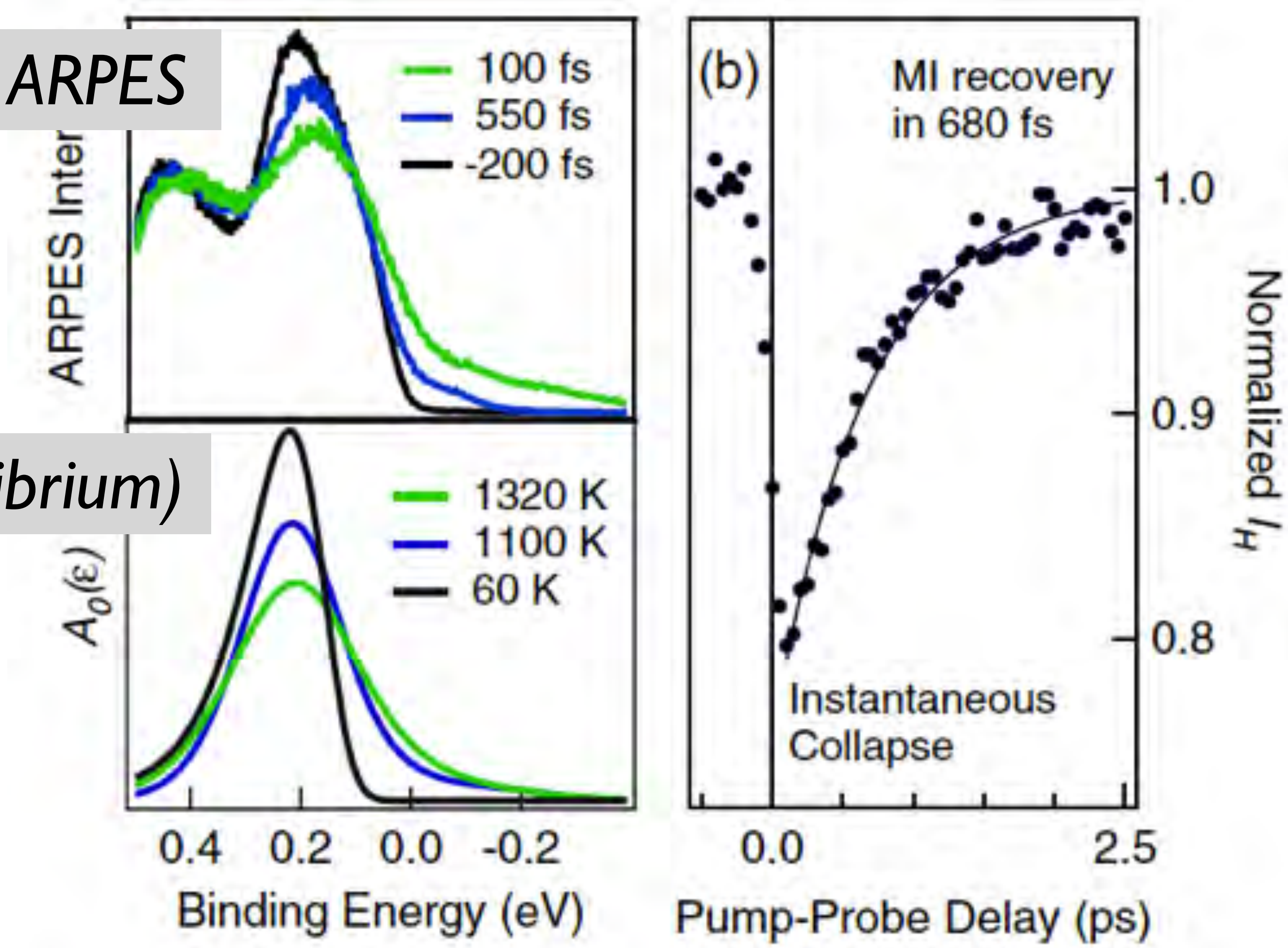
Ultra-fast electron thermalization:



Perfetti et al., Phys. Rev. Lett. **97**, 067402 (2007)

time-resolved ARPES

DMFT (equilibrium)



⇨ consistent with photo-induced transition to bad metallic state at high electronic temperature

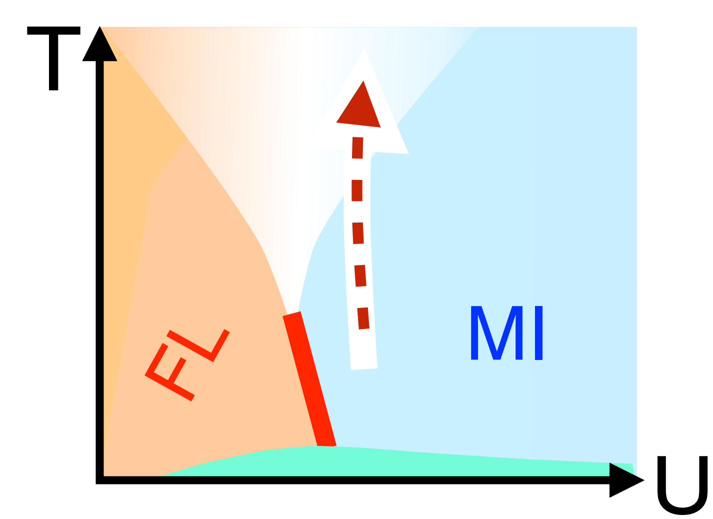
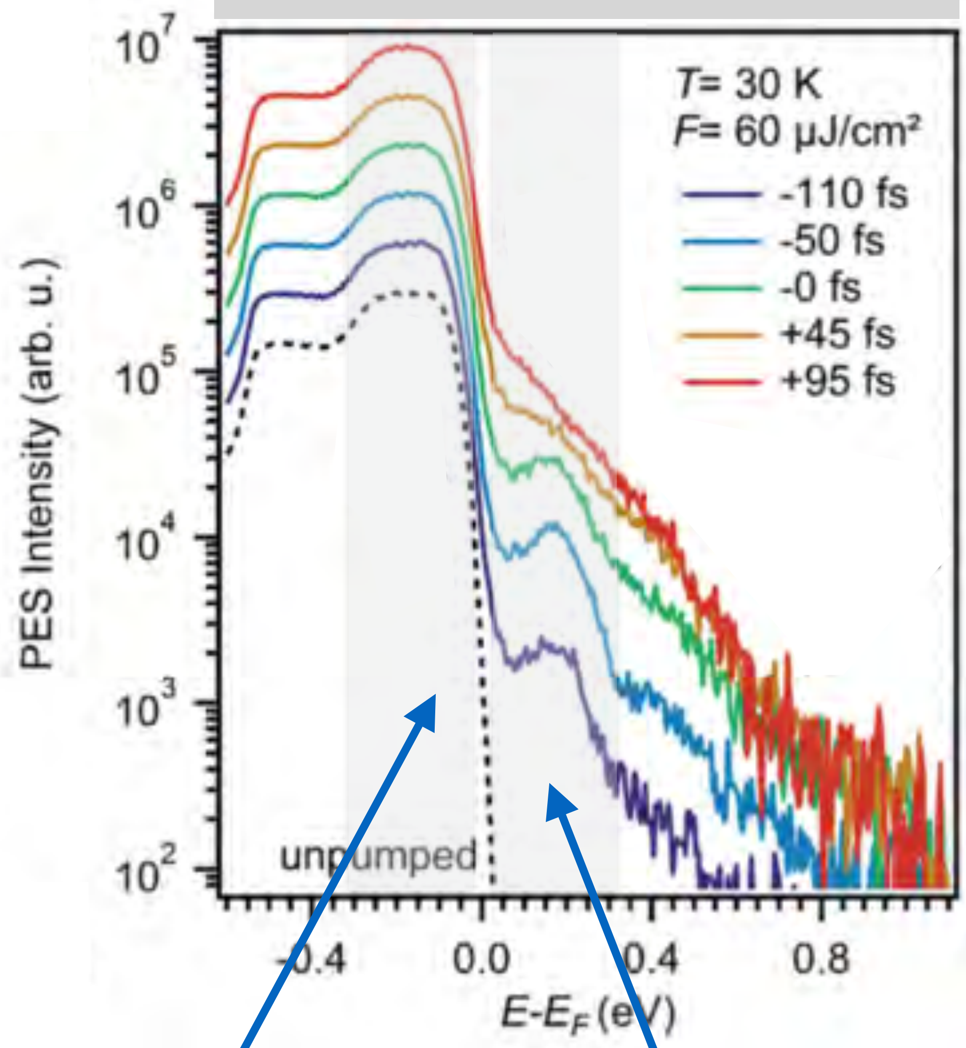


Photo-doping: correlated metal

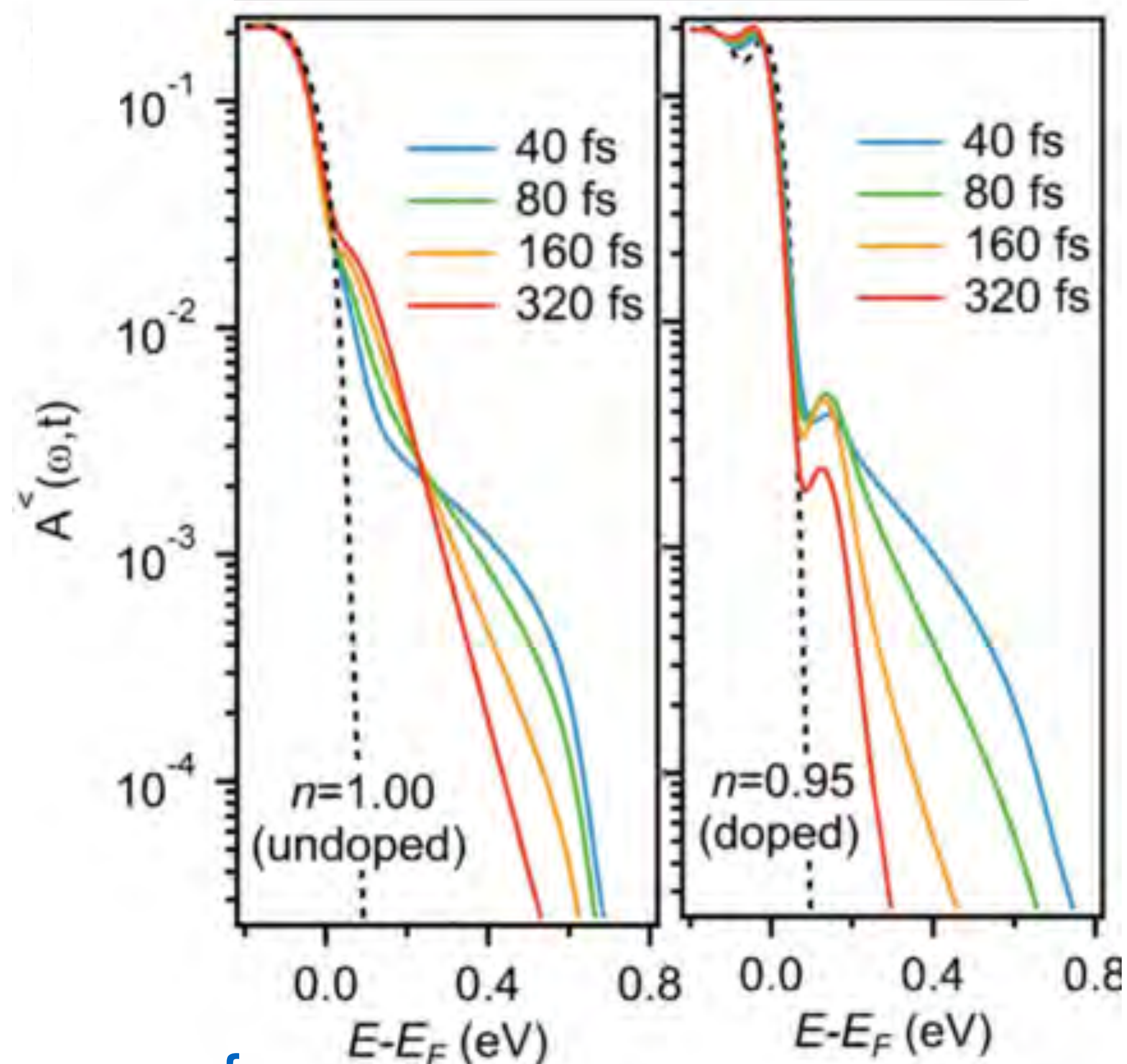
New measurement on TaS_2

Ligges et al., arXiv 2017 (to appear in PRL)

time-resolved ARPES



DMFT (non-equilibrium)



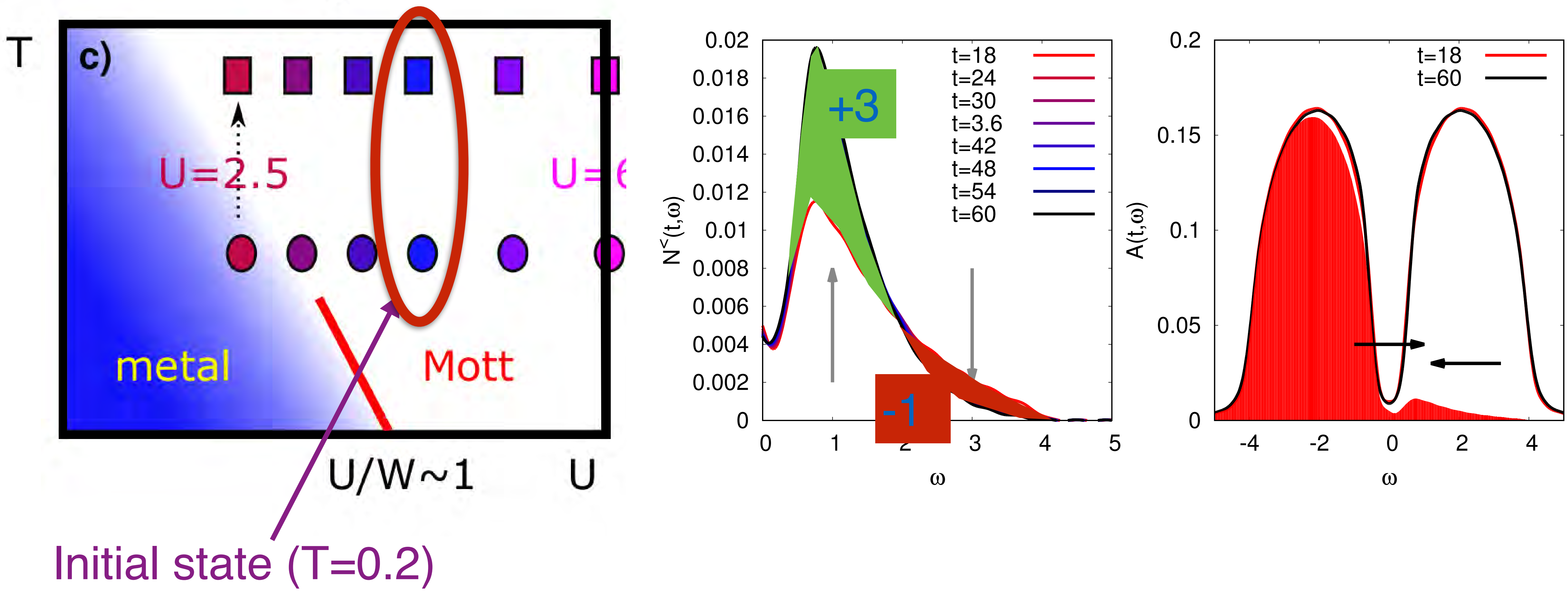
lower Hubbard band

transient appearance of occupied upper HB decay less than 50fs

⇨ consistent with electronic thermalization in slighty doped regime

Photo-doping: correlated metal

bandwidth=4 (Bethe lattice)   (in NCA: $U_c \sim 3.4$)



Thermalization involves “impact ionization”

Werner, Eckstein, Held, PRB (2014)