

Transient cooling of low frequency excitations by impulse perturbations

Michele Fabrizio



Outline

- a simple mechanism to transiently cool down low-frequency excitations by impulse perturbations
- an exactly solvable toy-model that realises such transient cooling

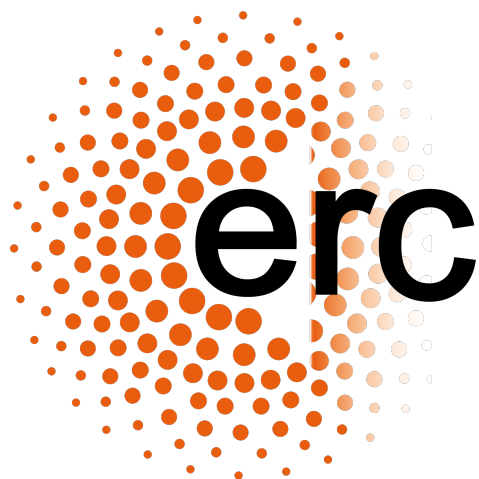
M.F., Phys. Rev. Lett. 120, 220601 (2018)
Andrea Nava and M.F., unpublished
- a possible physical realisation: light-enhanced T_c in K_3C_{60}

Andrea Nava, Claudio Giannetti, Antoine Georges, Erio Tosatti, and M.F.,
Nature Physics 14, 154 (2018)

Acknowledgments:



- [Andrea Nava](#)
- Erio Tosatti



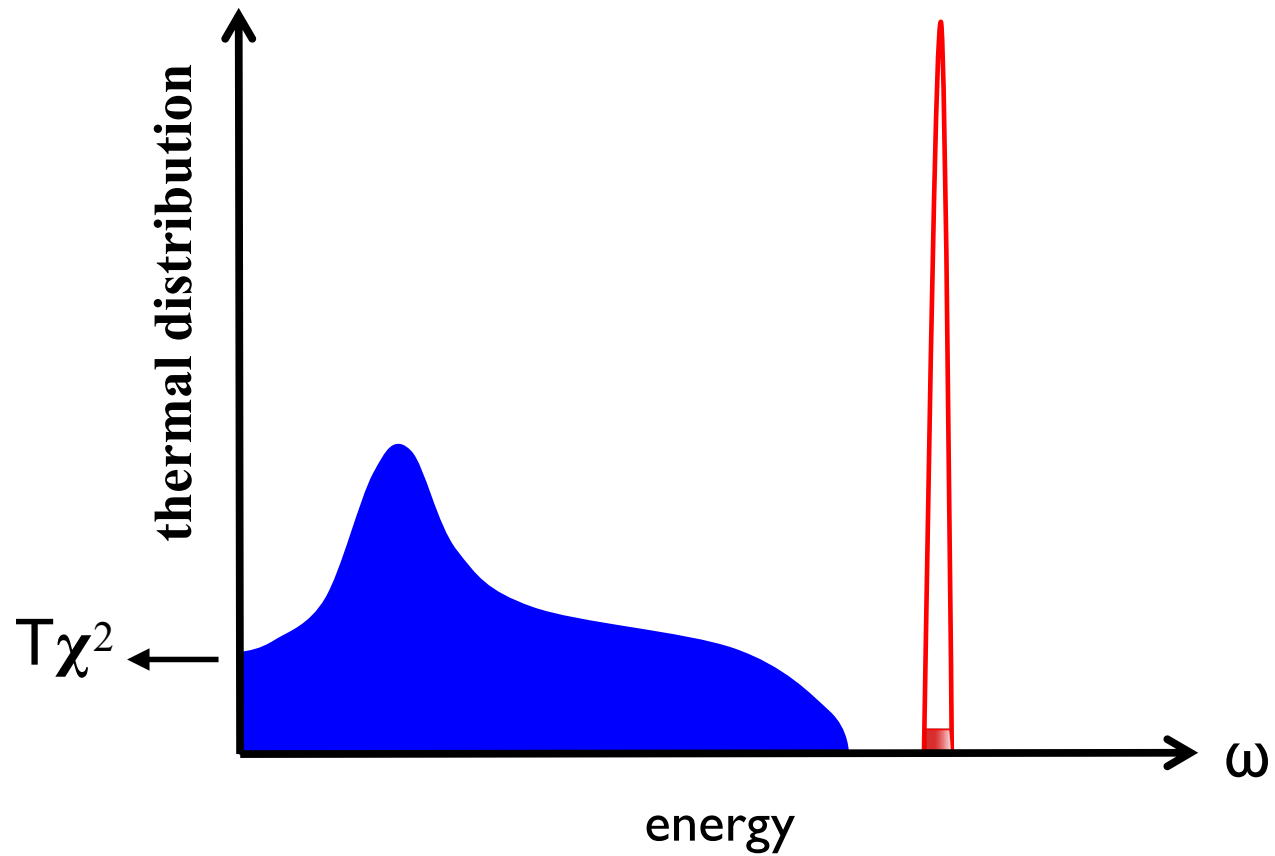
- **Claudio Giannetti**



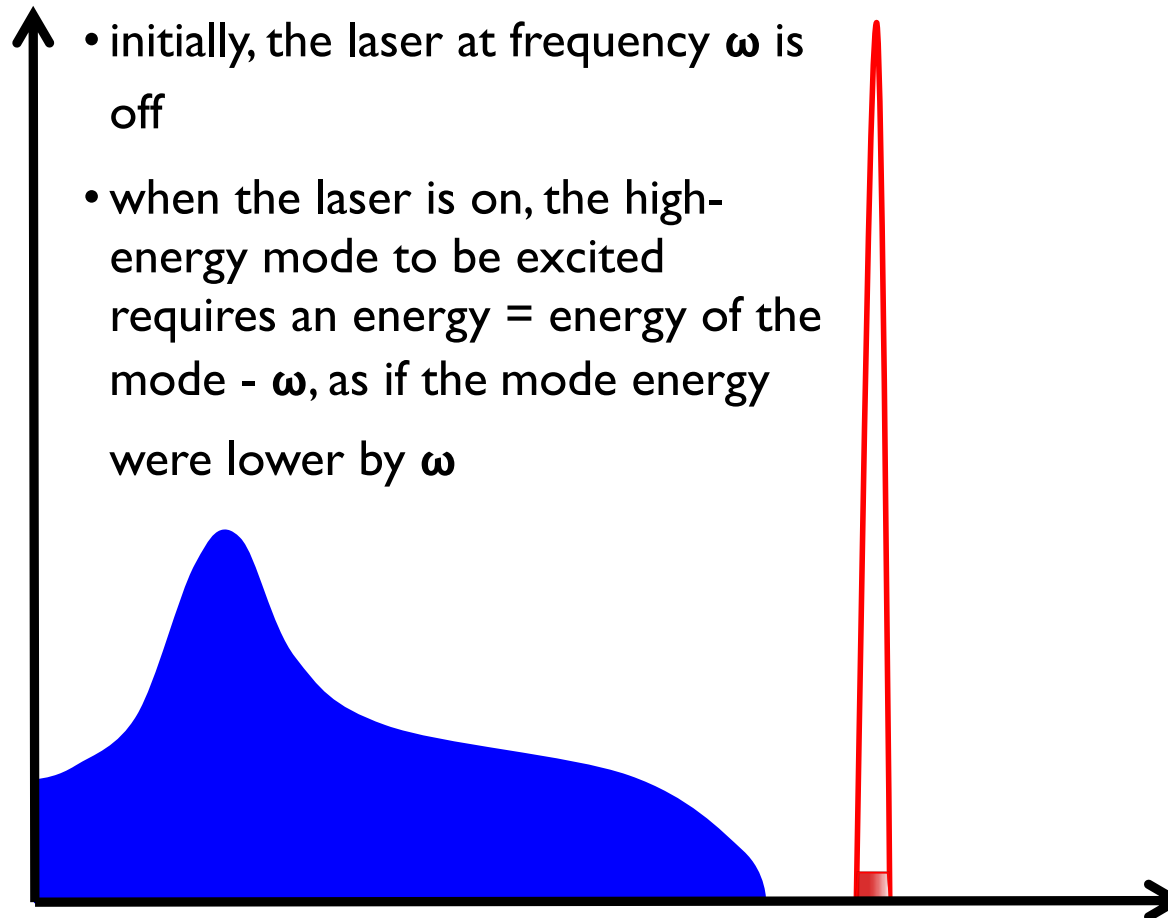
- **Antoine Georges**

● low-energy p-h continuum

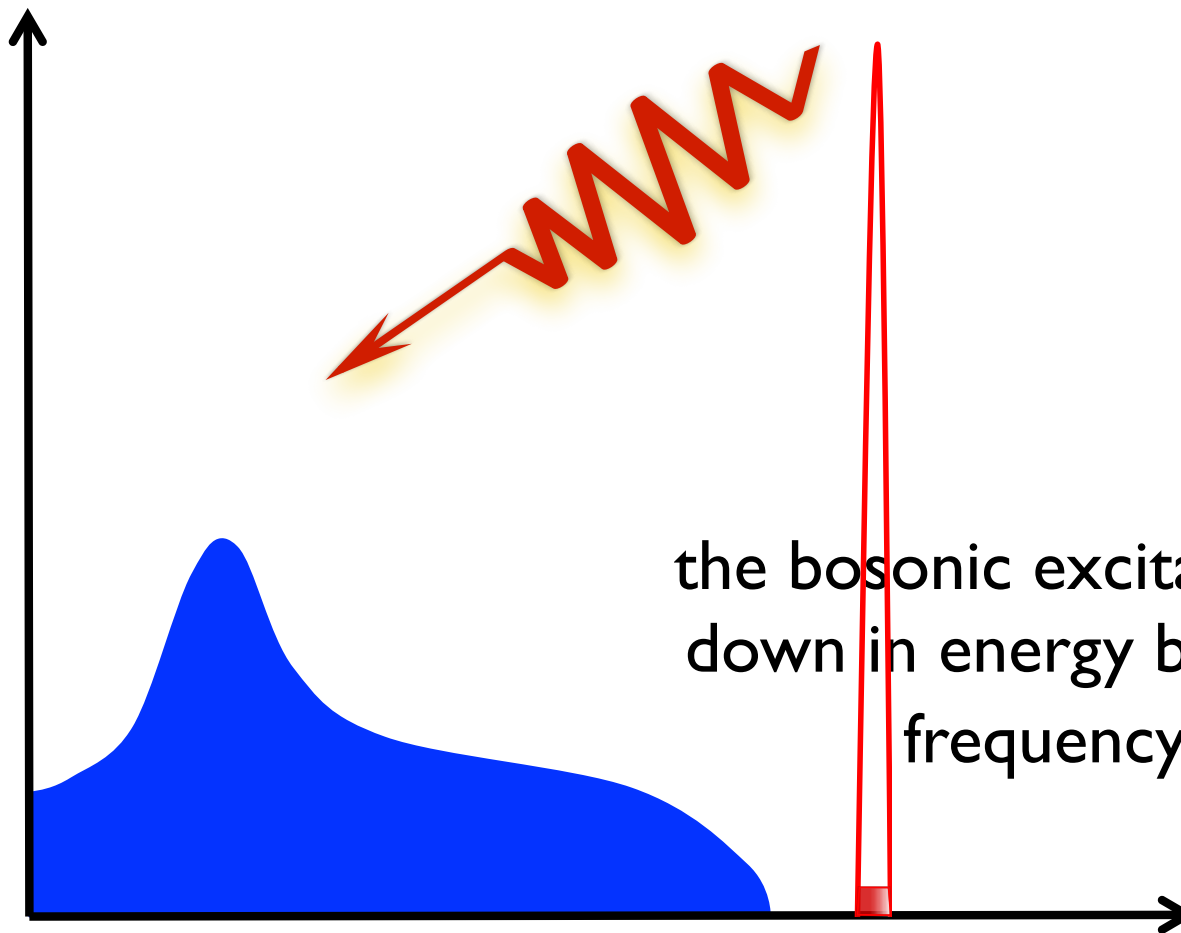
● high-energy mode



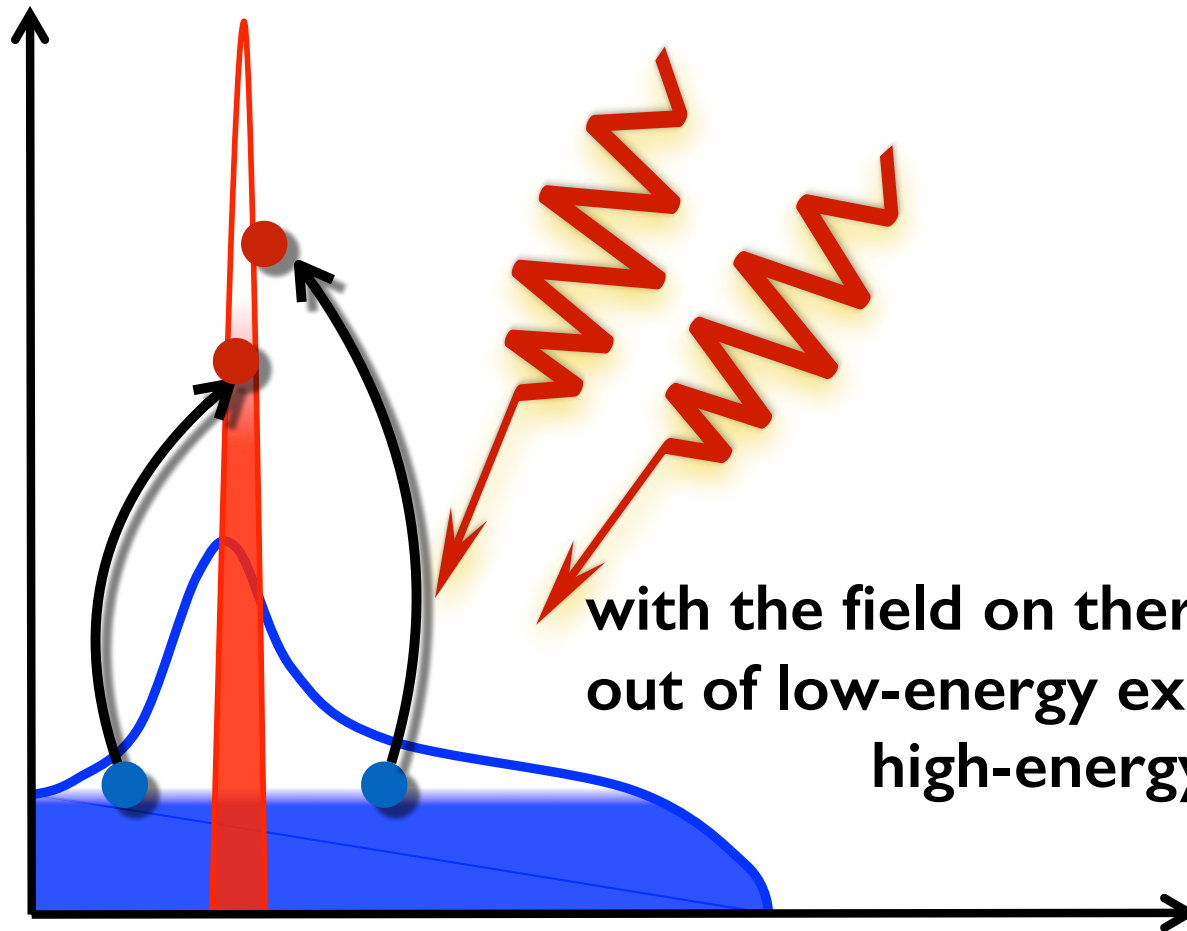
Rotating wave approximation



Rotating wave approximation



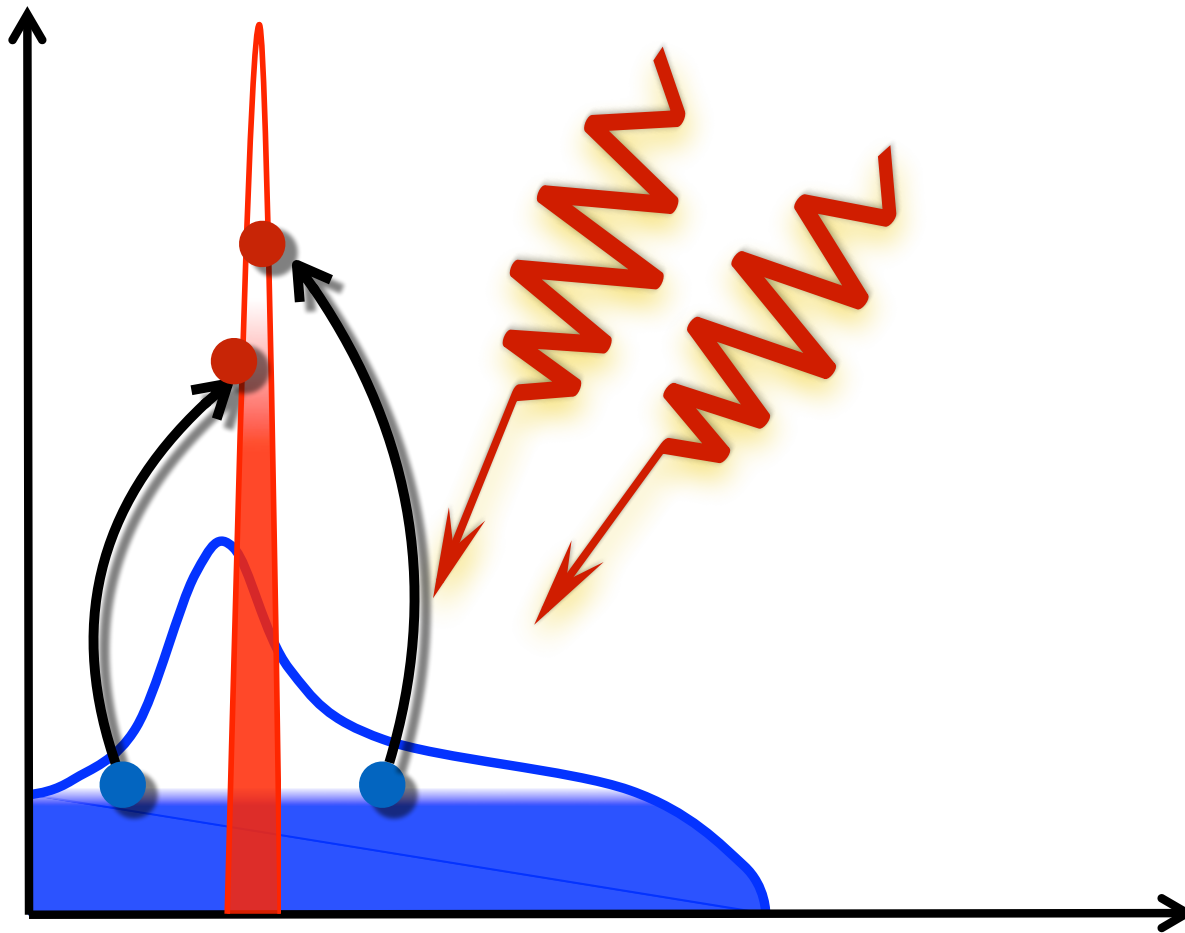
Rotating wave approximation



with the field on there will be pouring out of low-energy excitations into the high-energy mode



Rotating wave approximation

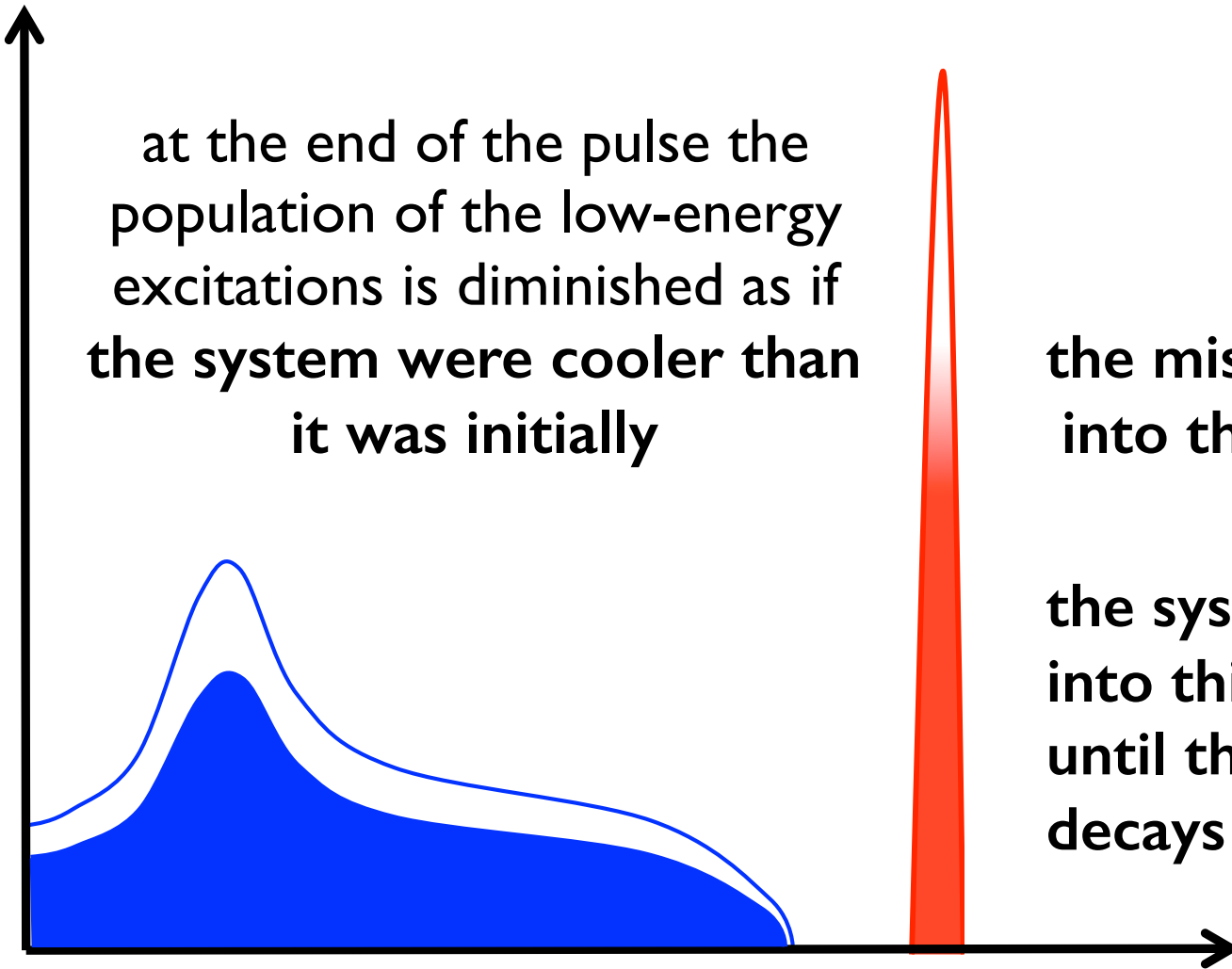


Rotating wave approximation

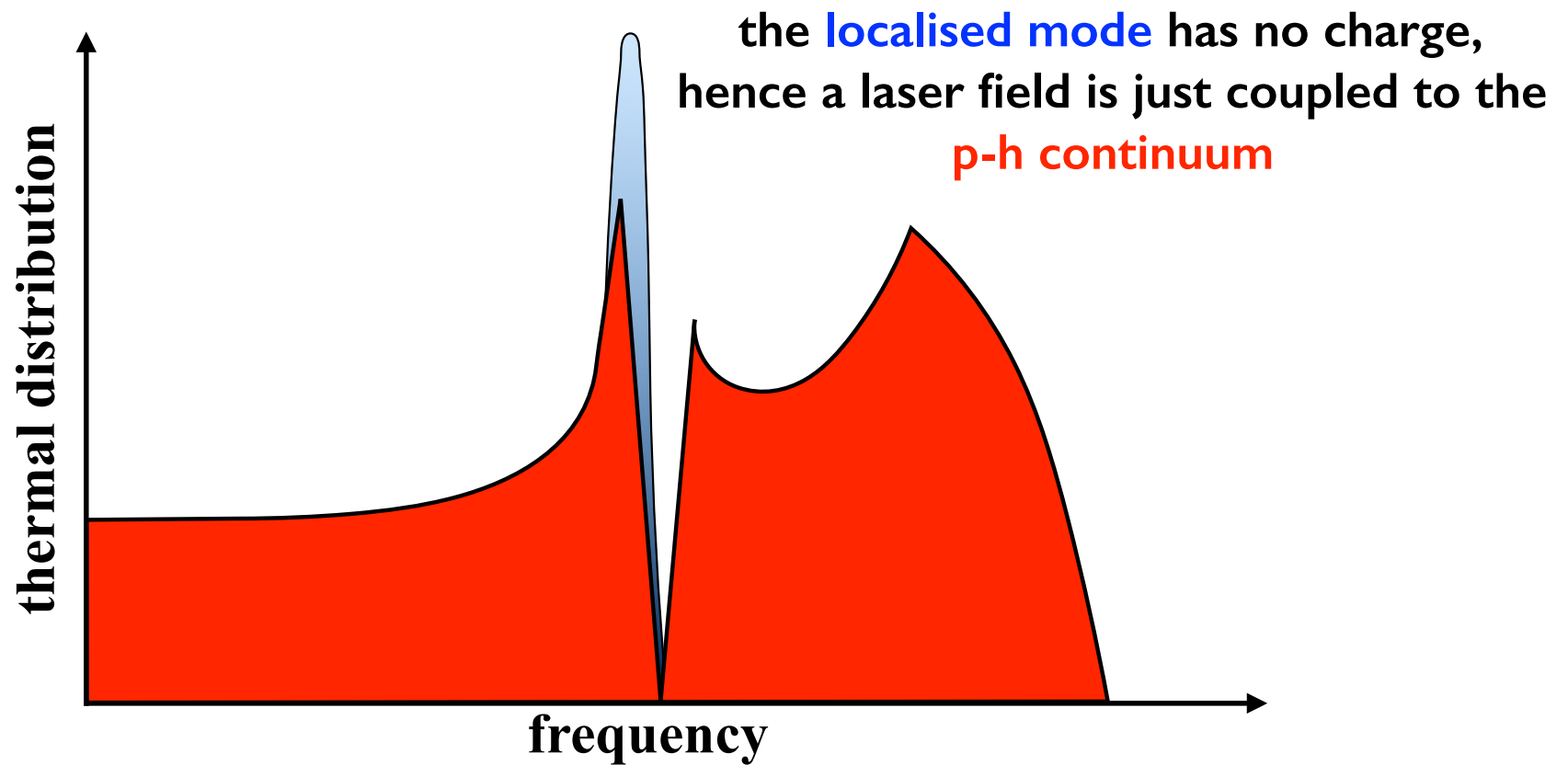
at the end of the pulse the population of the low-energy excitations is diminished as if the system were cooler than it was initially

the missing energy is stored into the high-energy mode

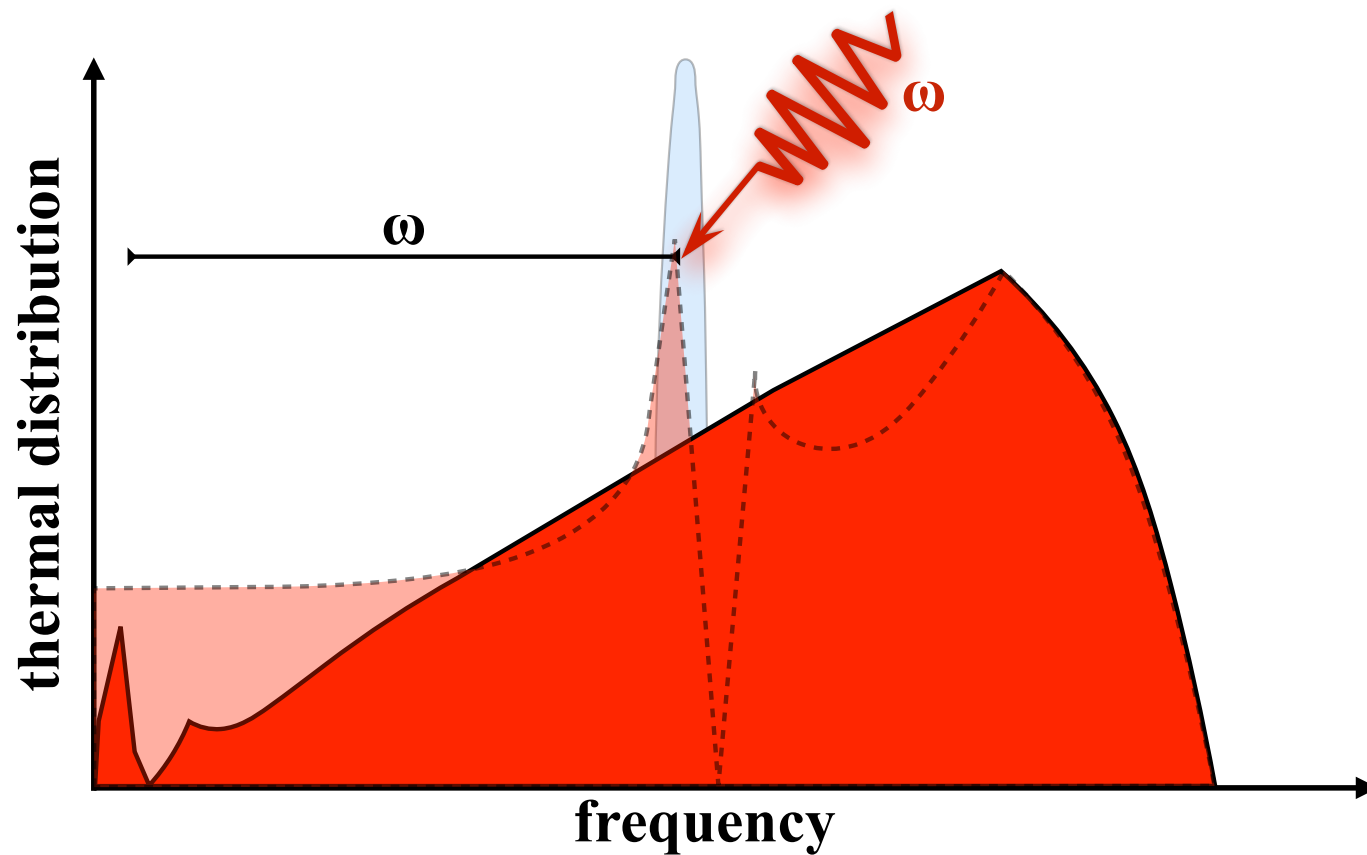
the system remains trapped into this non-equilibrium state until the high-energy mode decays back



mutatis mutandis, the same phenomenon might also occur pumping into a Fano-like resonance within a particle-hole continuum



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**an exactly solvable toy-model
where such selective transient
cooling mechanism is realised**

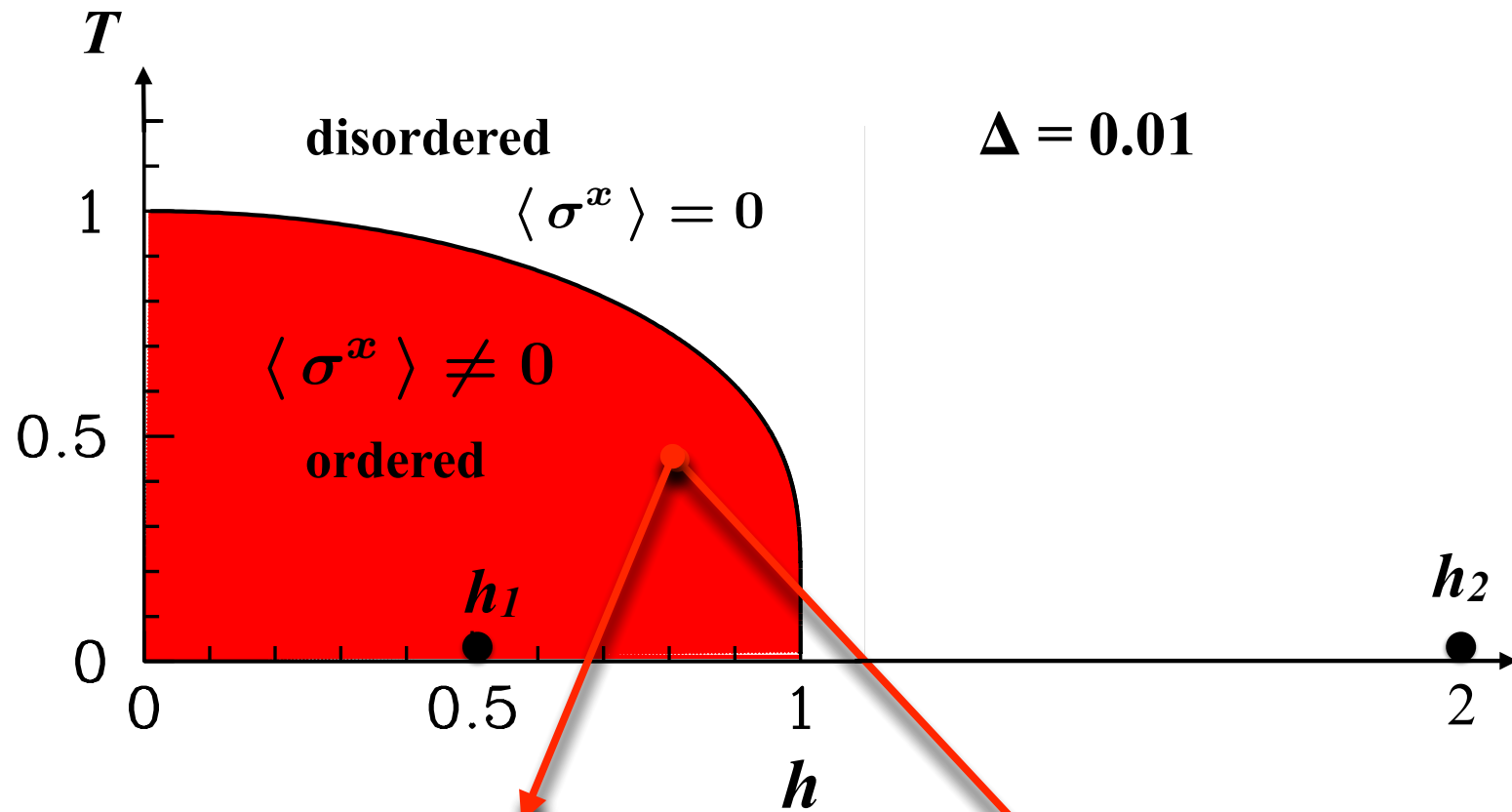
Two infinitely connected quantum Ising models coupled to each other

$$\begin{aligned} H_{2\text{QIMs}} = & -\frac{1}{4N} \sum_{i,j=1}^{2N} \sigma_{1i}^x \sigma_{1j}^x - h_1 \sum_{i=1}^{2N} \sigma_{1i}^z \\ & -\frac{1}{4N} \sum_{i,j=1}^{2N} \sigma_{2i}^x \sigma_{2j}^x - h_2 \sum_{i=1}^{2N} \sigma_{2i}^z \\ & - \Delta \sum_i \sigma_{1i}^x \sigma_{2i}^x \end{aligned}$$

for each Ising model, any spin is coupled to all others $\Rightarrow$

mean-field is exact in the thermodynamic limit $N \rightarrow \infty$

Phase diagram



disordered

$\Delta = 0.01$

$$\langle \sigma^x \rangle = 0$$

$$\langle \sigma^x \rangle \neq 0$$

ordered

h_1

h_2

0.5

h

2

0

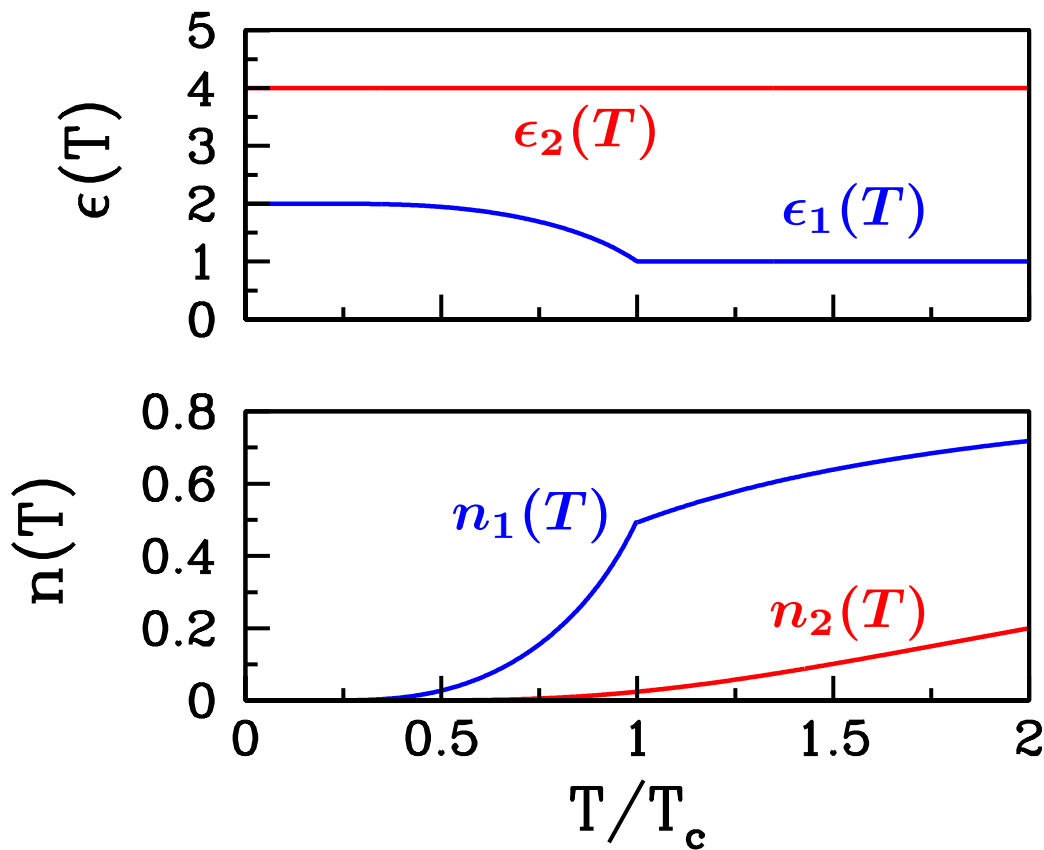
0.5

1

T

$$\langle \sigma_1^x \rangle \neq 0 \Rightarrow \langle \sigma_2^x \rangle \simeq \frac{\Delta}{h_2} \langle \sigma_1^x \rangle \neq 0$$

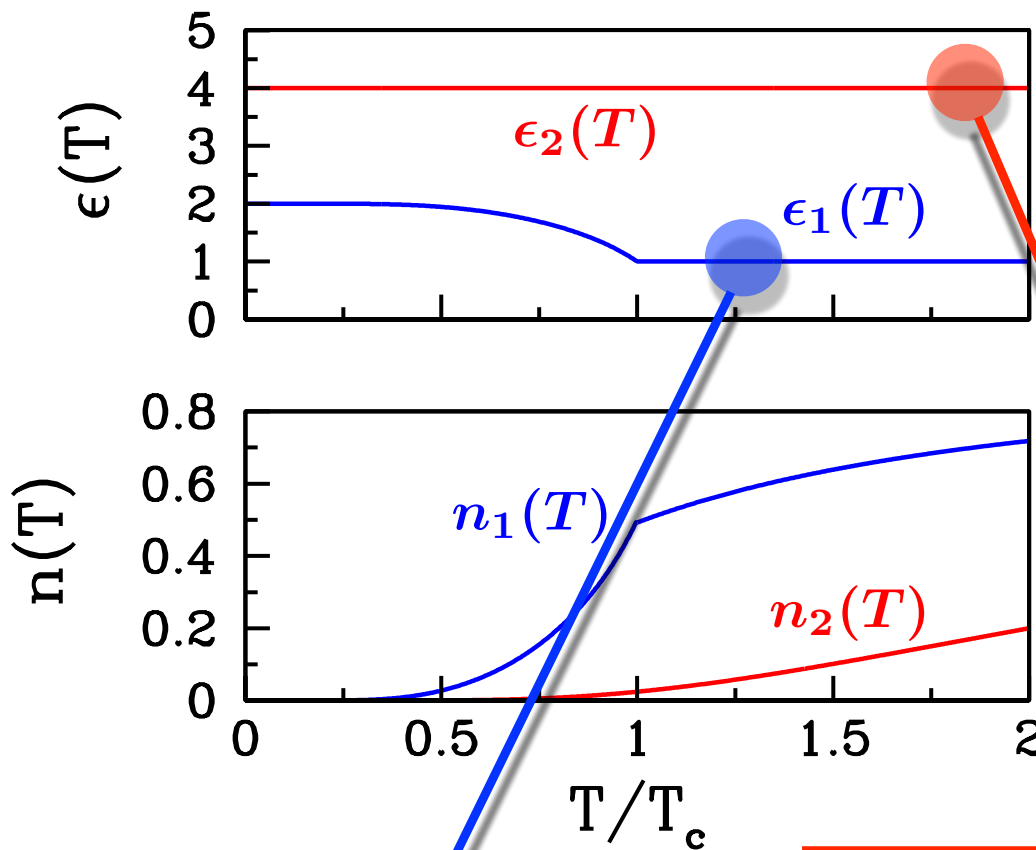
the Z_2 symmetry of the Hamiltonian
is spontaneously broken



excitation energies

n_1 and n_2 are the
corresponding
populations

for $T \gtrsim T_c$ quite many **excitations 1** are thermally populated
but very few **excitations 2**



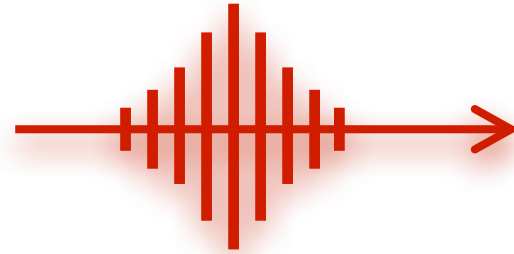
excitation energies

n_1 and n_2 are the corresponding populations

excitation 1 will play the role of low-energy modes

excitation 2 will play the role of the high-energy mode

The “laser pulse”



- in the interval $t \in [0, \tau]$ we add the time-dependent perturbation

$$\Delta H(t) = -E_0 \cos \omega t \sum_{i=1}^{2N} \sigma_{1i}^x \sigma_{2i}^x$$

- E_0 is the “electric field” amplitude

The “laser pulse”



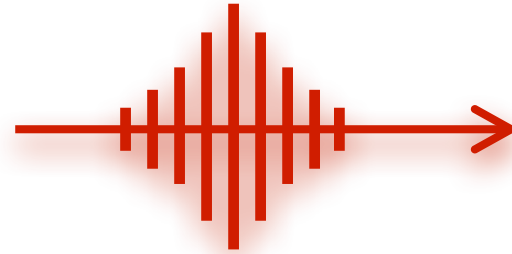
- in the interval $t \in [0, \tau]$ we add the time-dependent perturbation

$$\Delta H(t) = -E_0 \cos \omega t \sum_{i=1}^{2N} \sigma_{1i}^x \sigma_{2i}^x$$

- E_0 is the “electric field” amplitude
- τ is the pulse duration

I take τ half the Rabi period, with the Rabi frequency $\Omega = E_0/2\pi$

The “laser pulse”

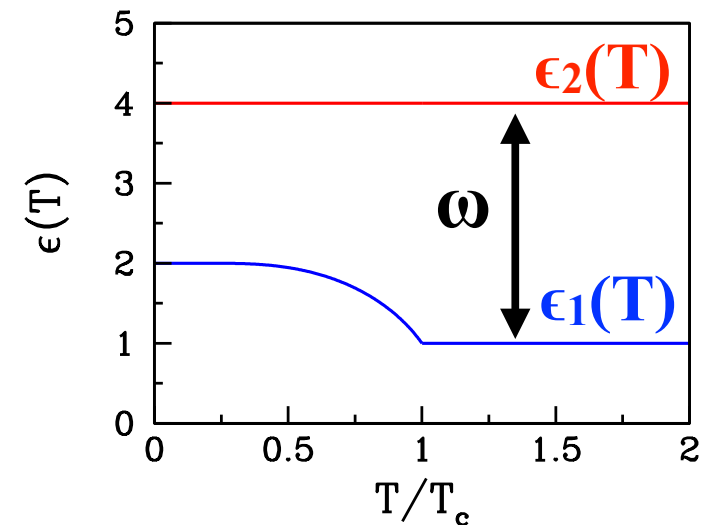


- in the interval $t \in [0, \tau]$ we add the time-dependent perturbation

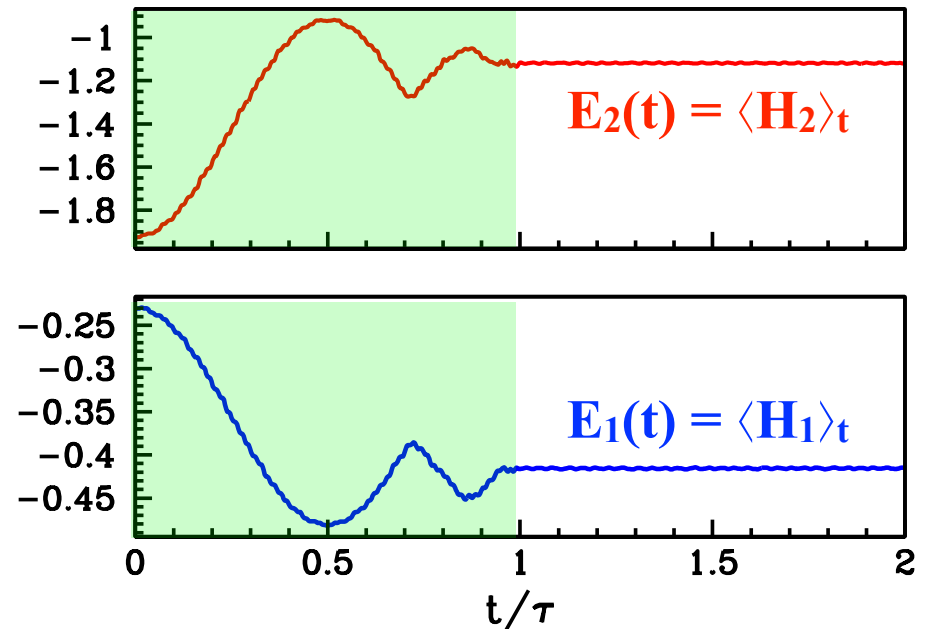
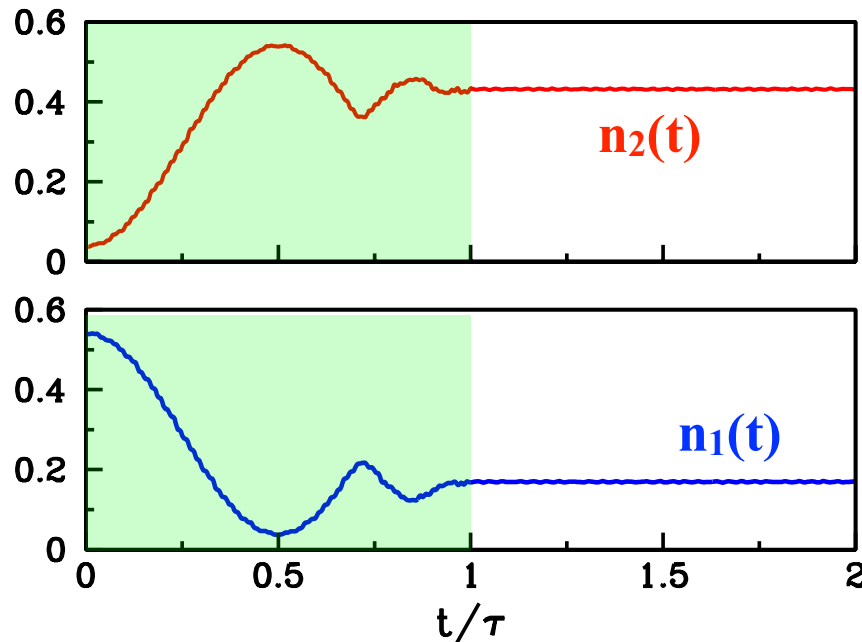
$$\Delta H(t) = -E_0 \cos \omega t \sum_{i=1}^{2N} \sigma_{1i}^x \sigma_{2i}^x$$

- E_0 is the “electric field” amplitude
- τ is the pulse duration
- ω the “laser” frequency

I stick to resonance $\omega = \epsilon_2(T) - \epsilon_1(T)$

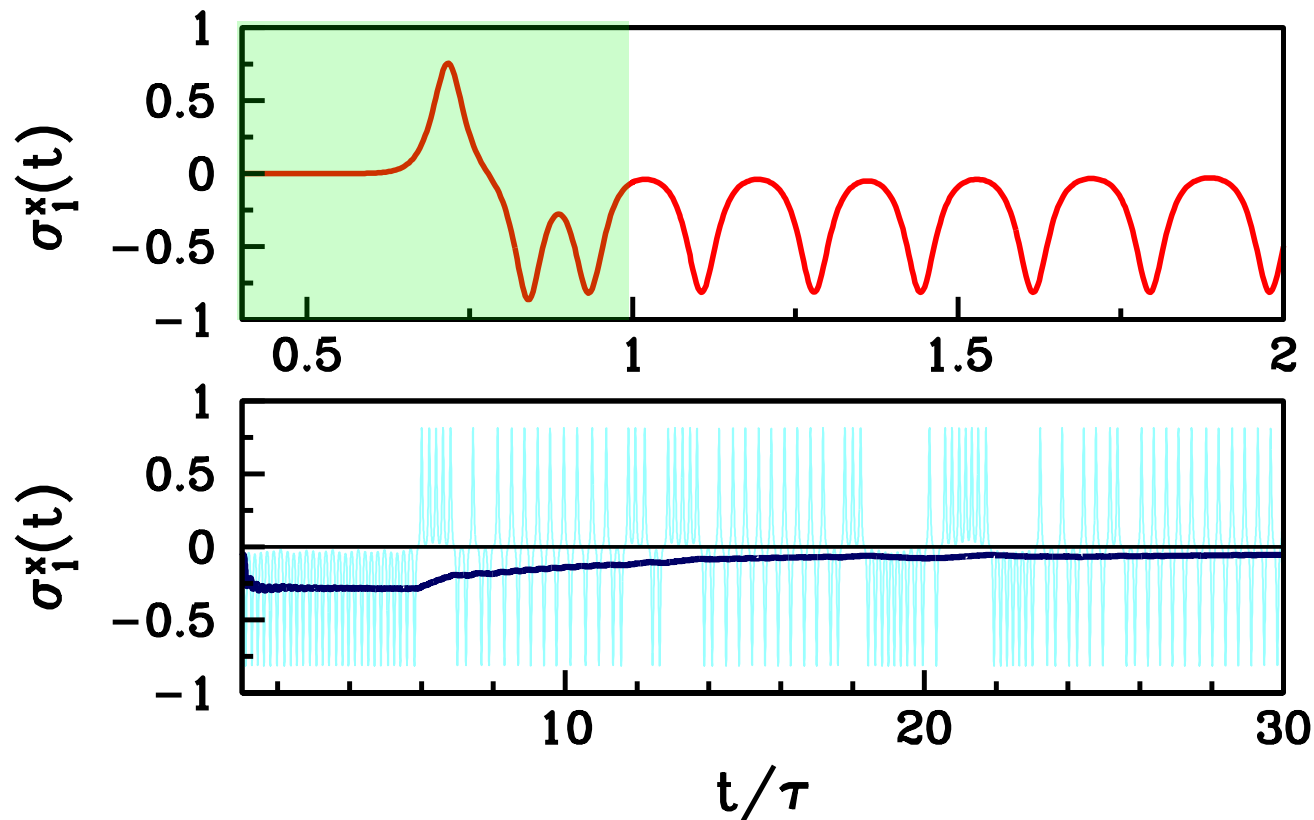


Results at $T = 1.1T_c > T_c$



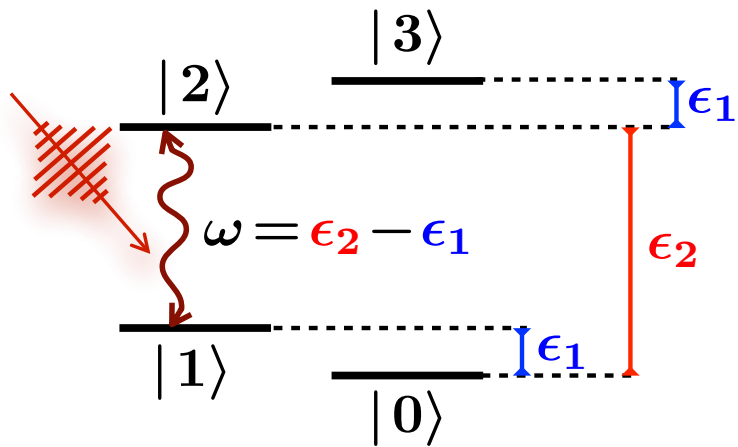
- during the pulse duration $0 < t < \tau$ the population of mode **2** grows whereas that of **mode 1** diminishes
- concurrently the energy of the Ising copy **1** decreases, which is overcompensated by the energy increase of **2**

Results at $T = 1.1T_c > T_c$



remarkably, a finite symmetry-breaking order parameter transiently develops despite initially $T > T_c$

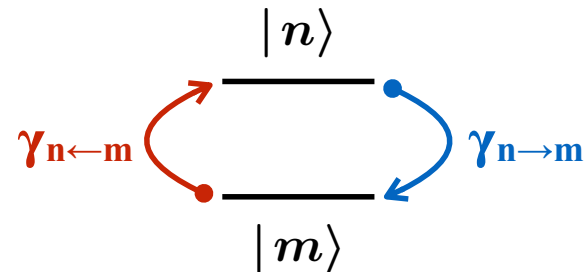
Include dissipation via Lindblad's equations



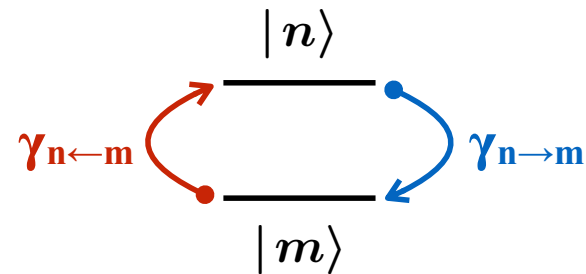
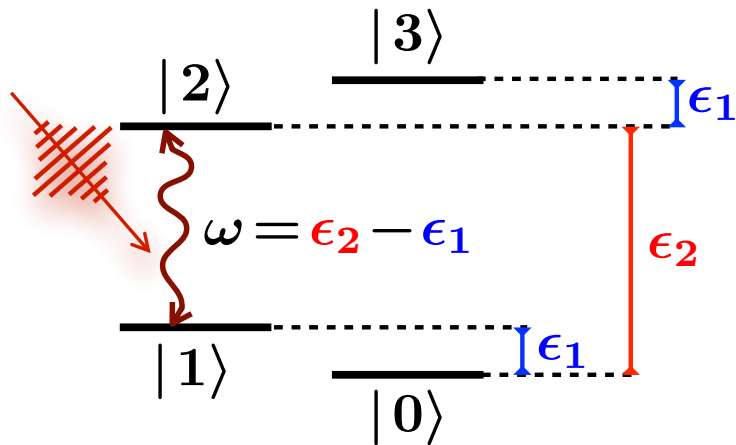
- I add a dissipative bath at each site, so that mean field remains exact

- six downward jump operators $L_{n \rightarrow m} = |m\rangle\langle n|$ with $n > m = 0, \dots, 3$, and coupling strengths $\gamma_{n \rightarrow m} > 0$
- six upward jump operators $L_{n \leftarrow m} = |n\rangle\langle m|$ with $n > m = 0, \dots, 3$, and coupling strengths $\gamma_{n \leftarrow m}$

$$\gamma_{n \leftarrow m} = \gamma_{n \rightarrow m} e^{-\beta(E_n - E_m)}$$



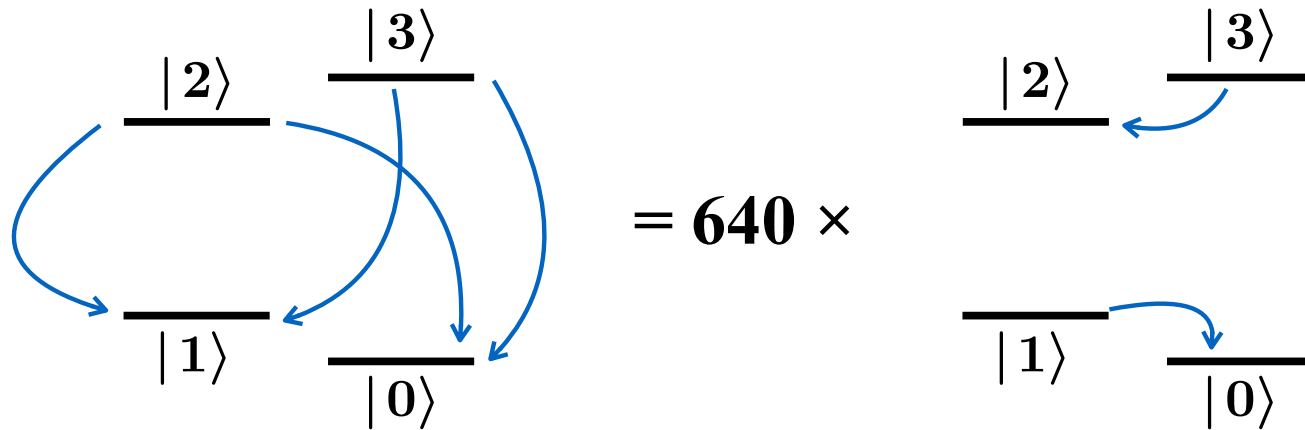
Include dissipation via Lindblad's equations



$$\gamma_{n \leftarrow m} = \gamma_{n \rightarrow m} e^{-\beta(E_n - E_m)}$$

- the dissipative dynamics is controlled by the six parameters $\gamma_{n \rightarrow m}$
- if all $\gamma_{n \rightarrow m}$ are of the same order, the system reaches fast thermal equilibrium, without showing any transient cooling
- if $\gamma_{n \rightarrow m}$ grow with $E_n - E_m$, i.e., the high energy excitations decay sufficiently faster than the low energy ones, we do find cooling

Show results for



- $\gamma_{2 \rightarrow 0} = \gamma_{3 \rightarrow 0} = \gamma_{3 \rightarrow 1} = \gamma_{2 \rightarrow 1} = 640 \gamma_{1 \rightarrow 0} = 640 \gamma_{3 \rightarrow 2}$

- a pulse profile

$$E(t) \cos \omega t = \left(\frac{t}{\tau} \right)^2 \exp \left[1 - \frac{1}{E_0} \left(\frac{t}{\tau} \right)^2 \right] \cos \omega t$$

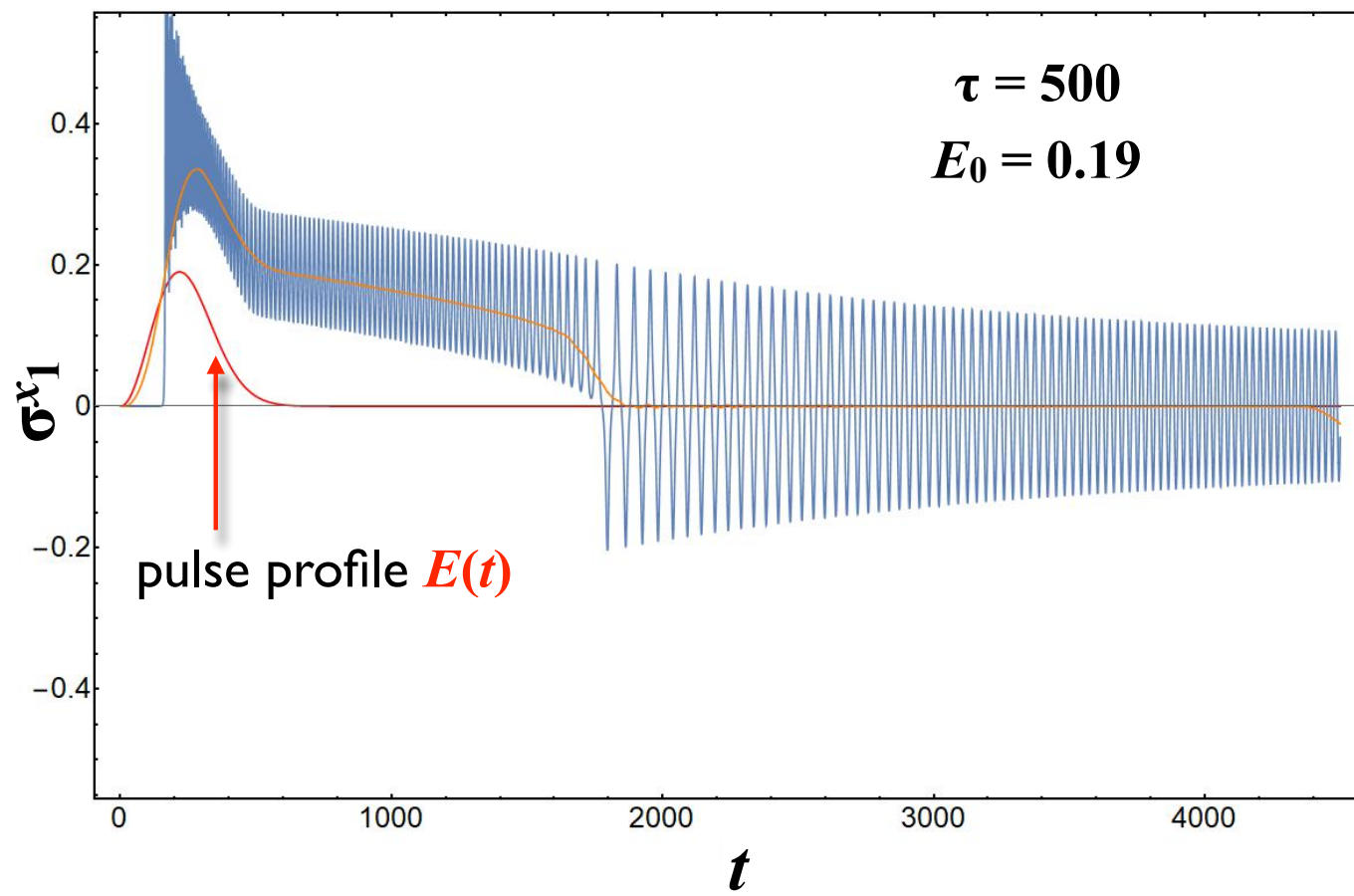
- E_0 = peak amplitude of the pulse

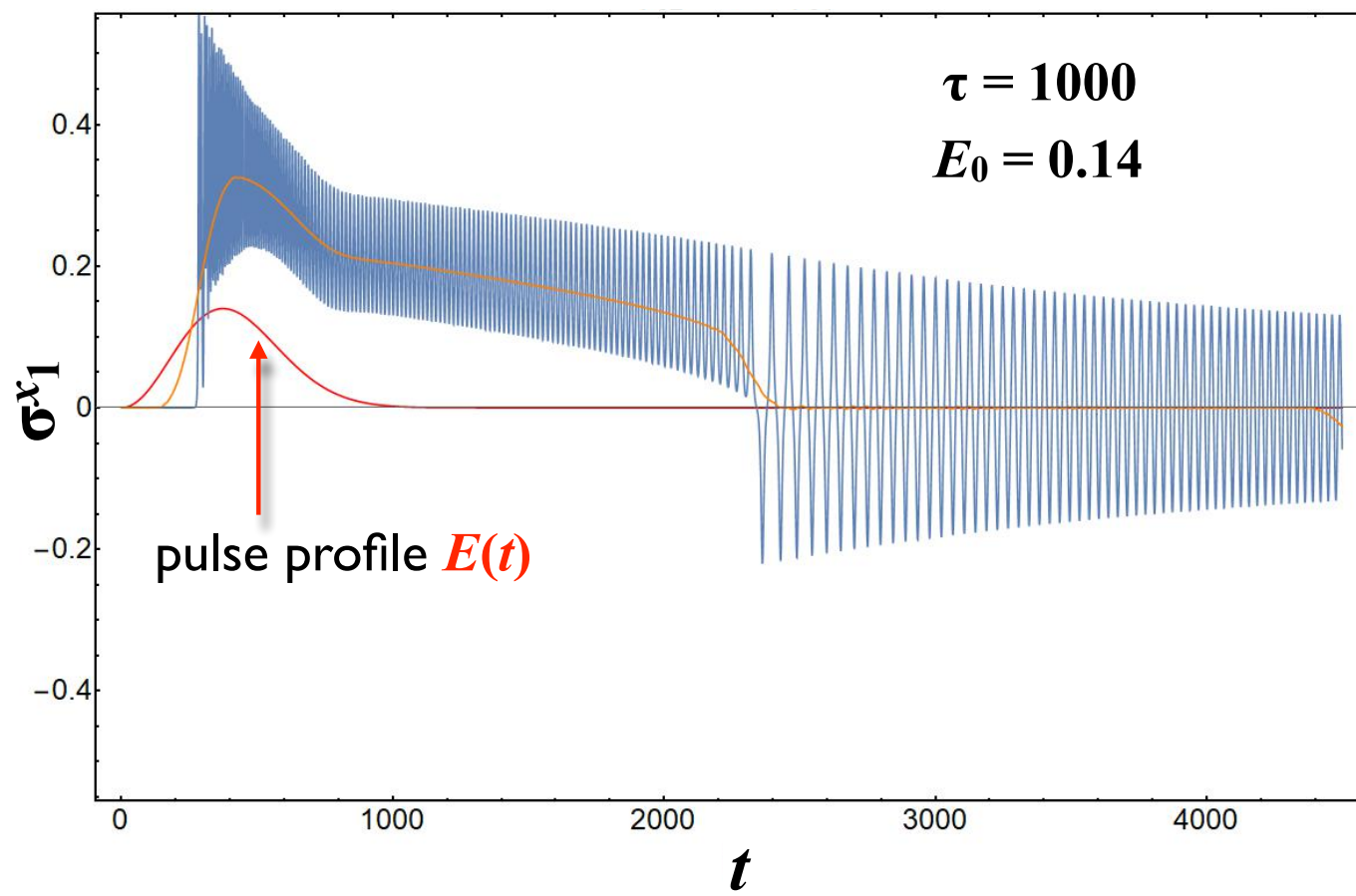
- τ = pulse duration

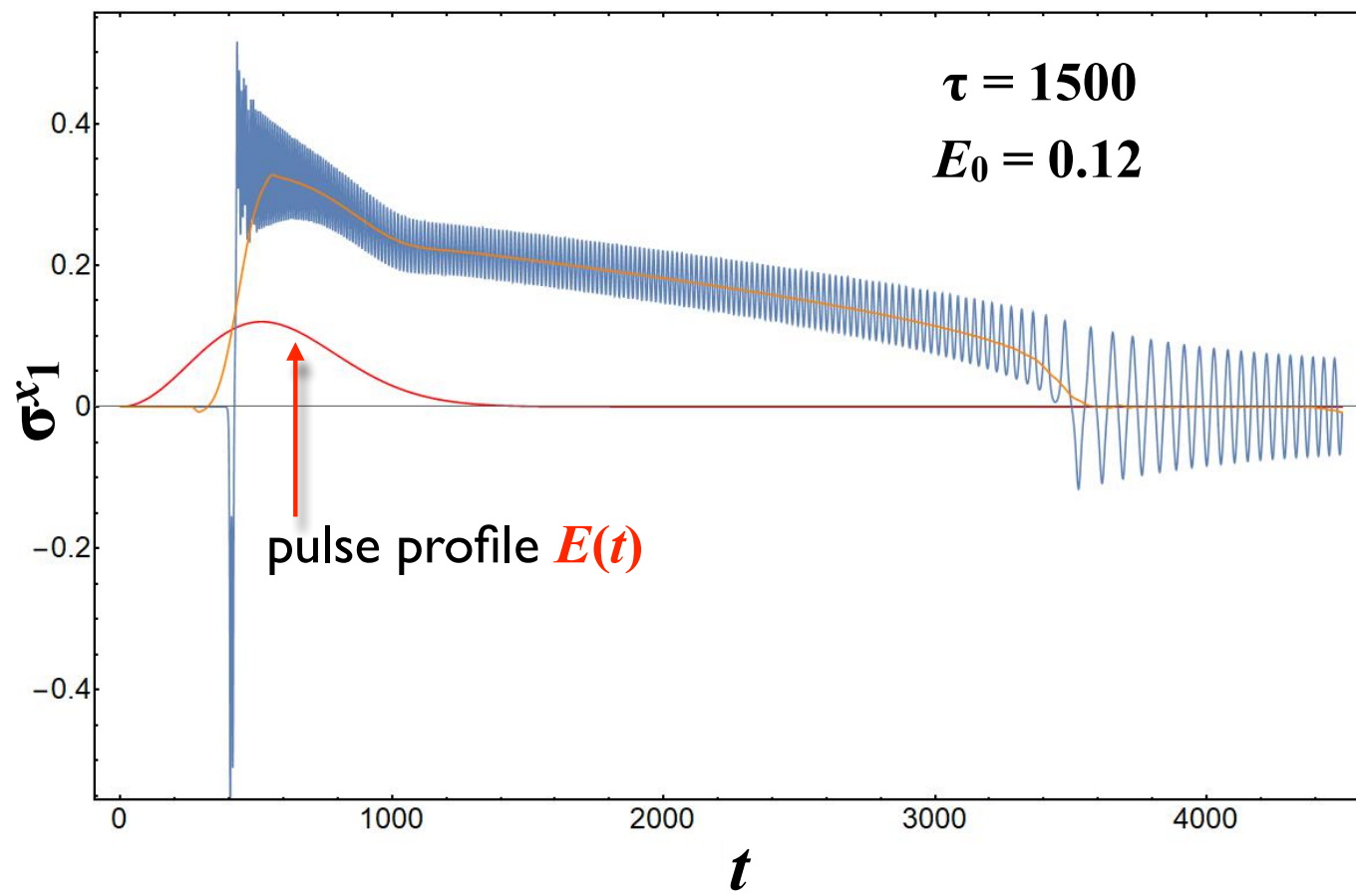
$$E(t) \cos \omega t = \left(\frac{t}{\tau} \right)^2 \exp \left[1 - \frac{1}{E_0} \left(\frac{t}{\tau} \right)^2 \right] \cos \omega t$$

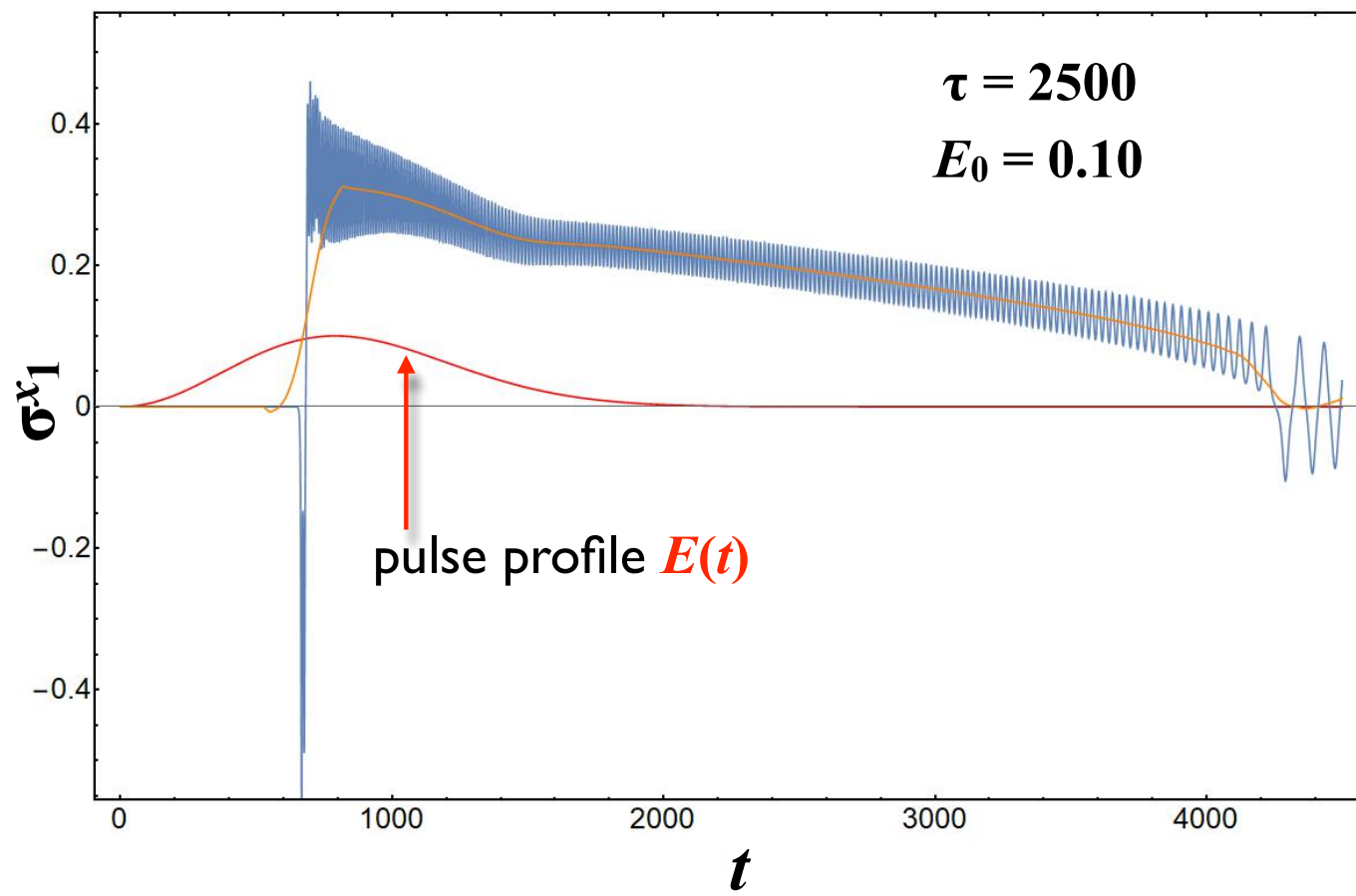
I will show results at $T = 1.5 T_c$ varying E_0 and τ so as to maintain the fluence constant

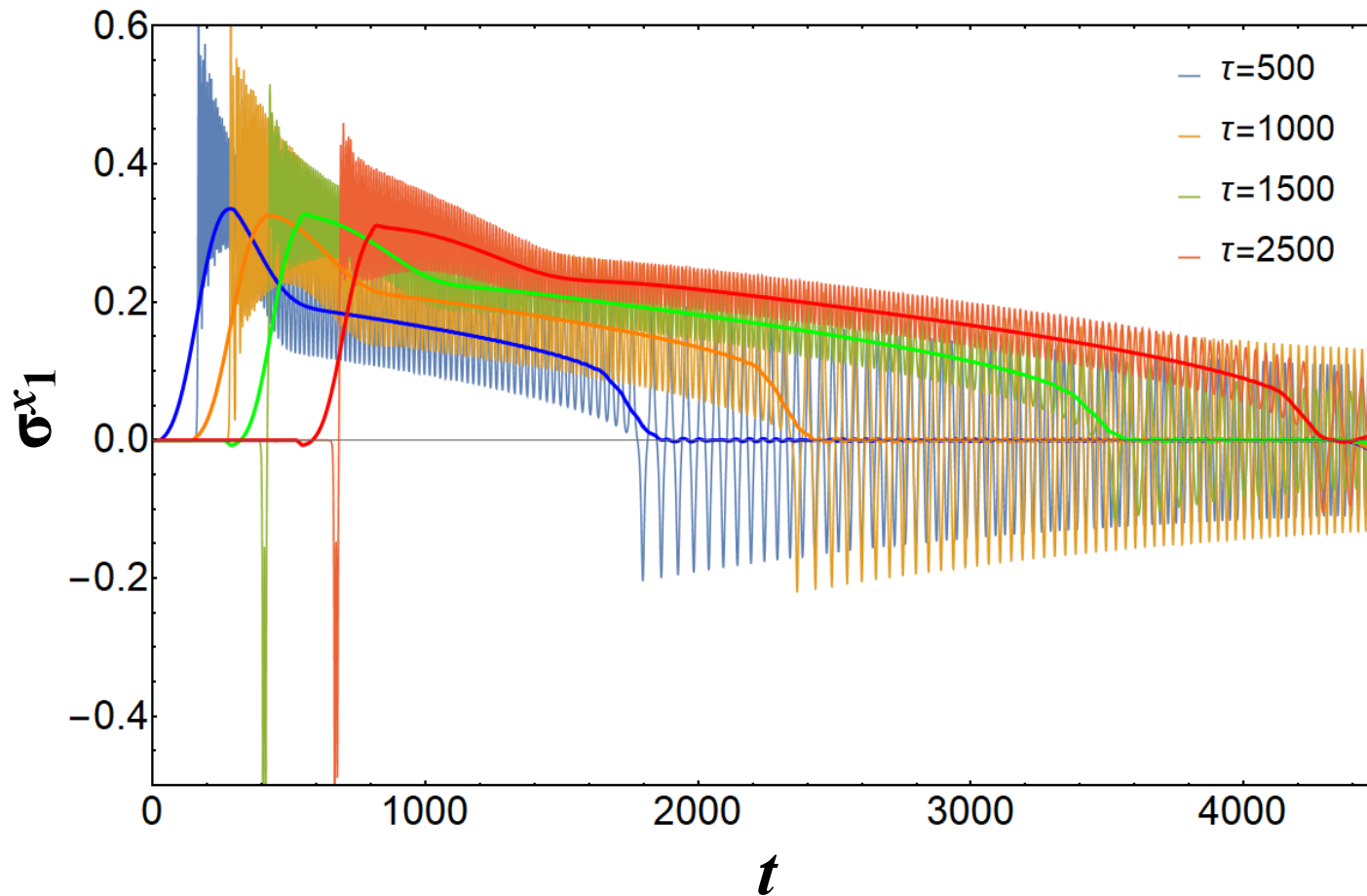
$$\text{fluence} \propto \int dt E(t)^2 = \text{constant}$$











despite $T = 1.5 T_c > T_c$ the order parameter becomes finite, and remains so for longer times the bigger τ is at constant fluence

possibly, a physical realisation of that same cooling mechanism

LETTER

doi:10.1038/nature16522

Possible light-induced superconductivity in K_3C_{60} at high temperature

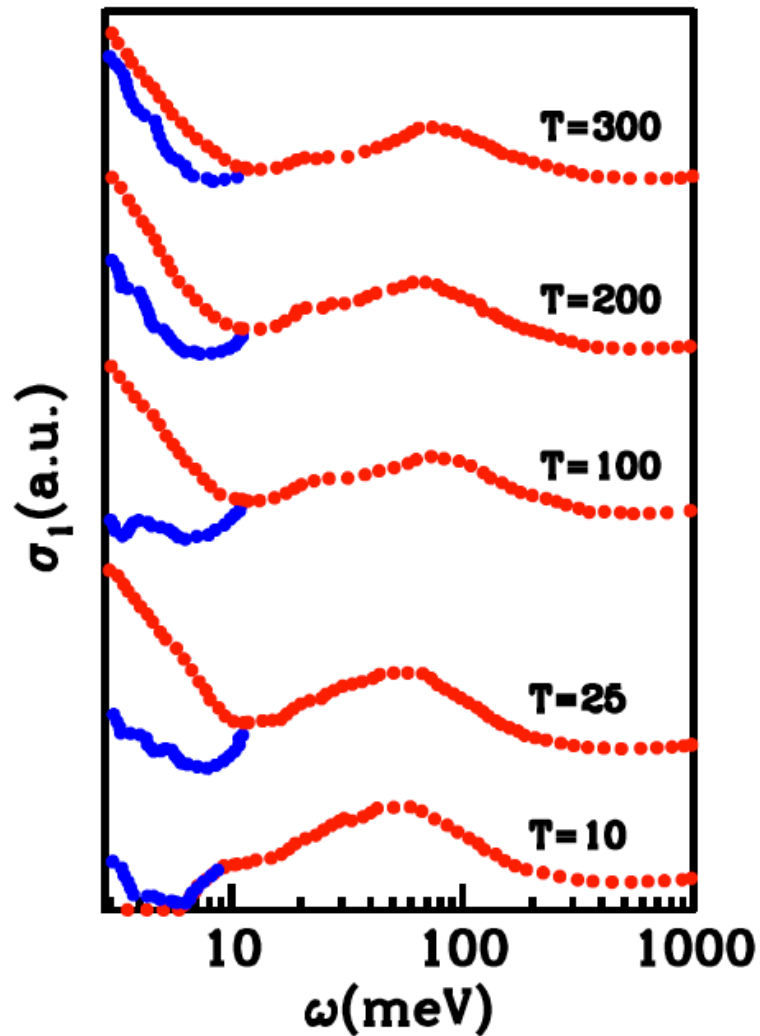
M. Mitrano¹, A. Cantaluppi^{1,2}, D. Nicoletti^{1,2}, S. Kaiser¹, A. Perucchi³, S. Lupi⁴, P. Di Pietro³, D. Pontiroli⁵, M. Riccò⁵, S. R. Clark^{1,6,7}, D. Jaksch^{7,8} & A. Cavalleri^{1,2,7}

25 FEBRUARY 2016 | VOL 530 | NATURE | 461

pump-probe experiment on K_3C_{60} molecular superconductor:

- pump pulse of 300 fs with MIR frequency**
- optical probe**

Results of the pump-probe experiment

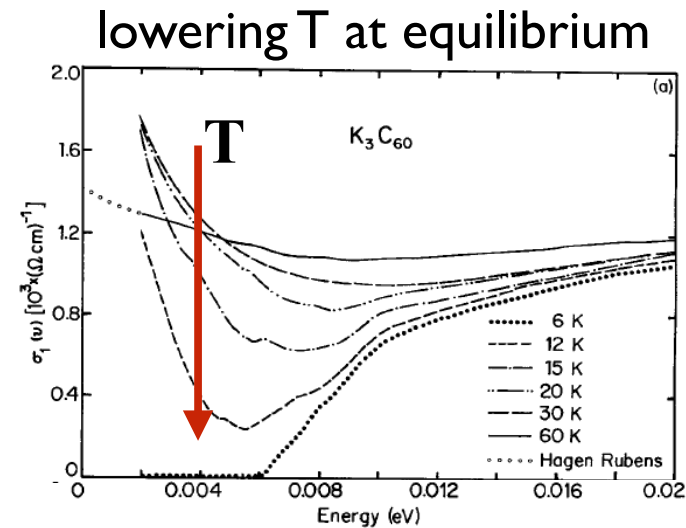
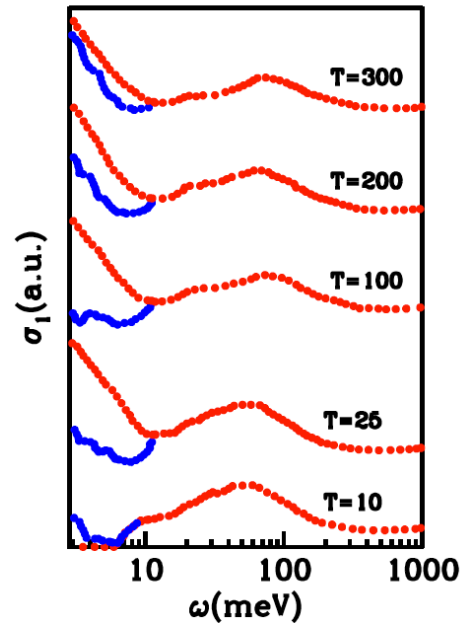


equilibrium

1ps after the pulse

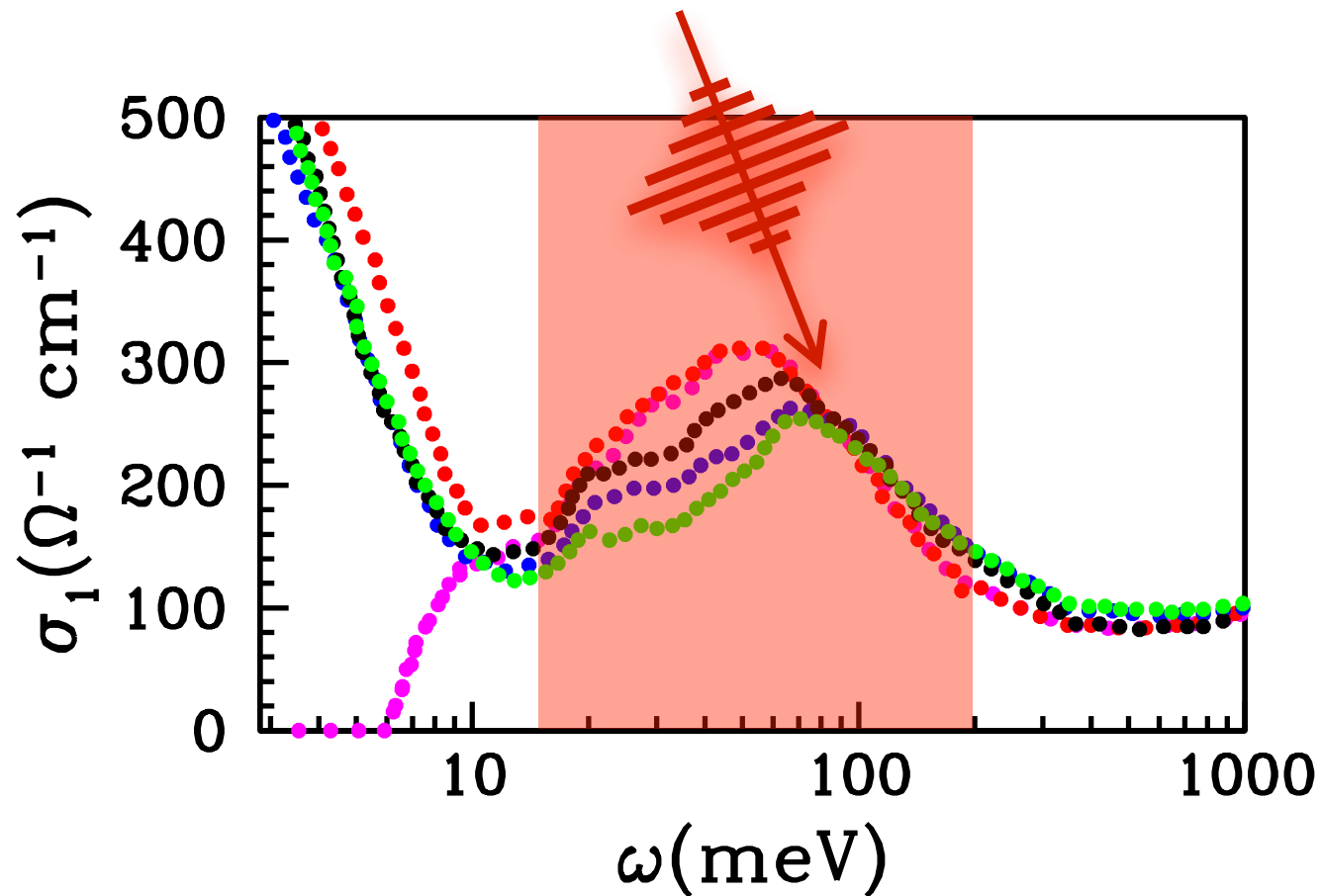
**How can we
interpret those
data?**

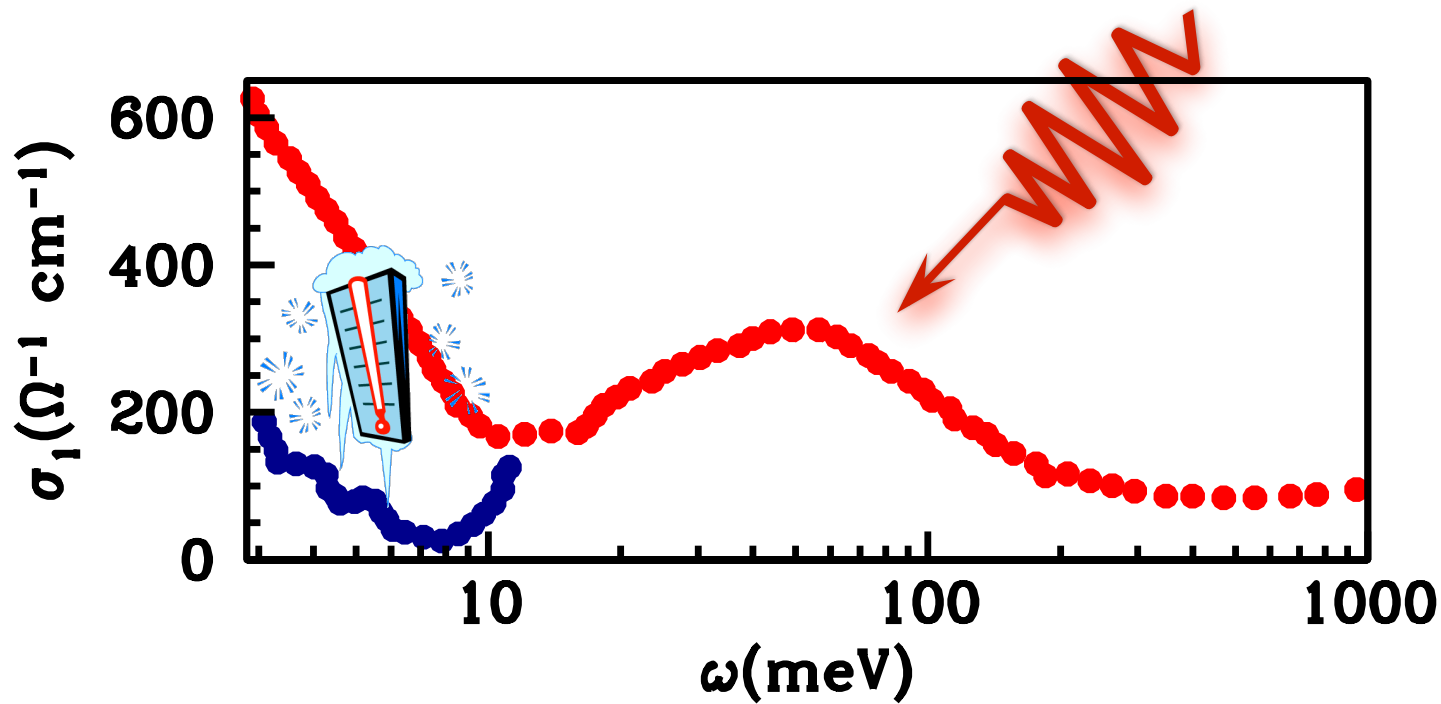




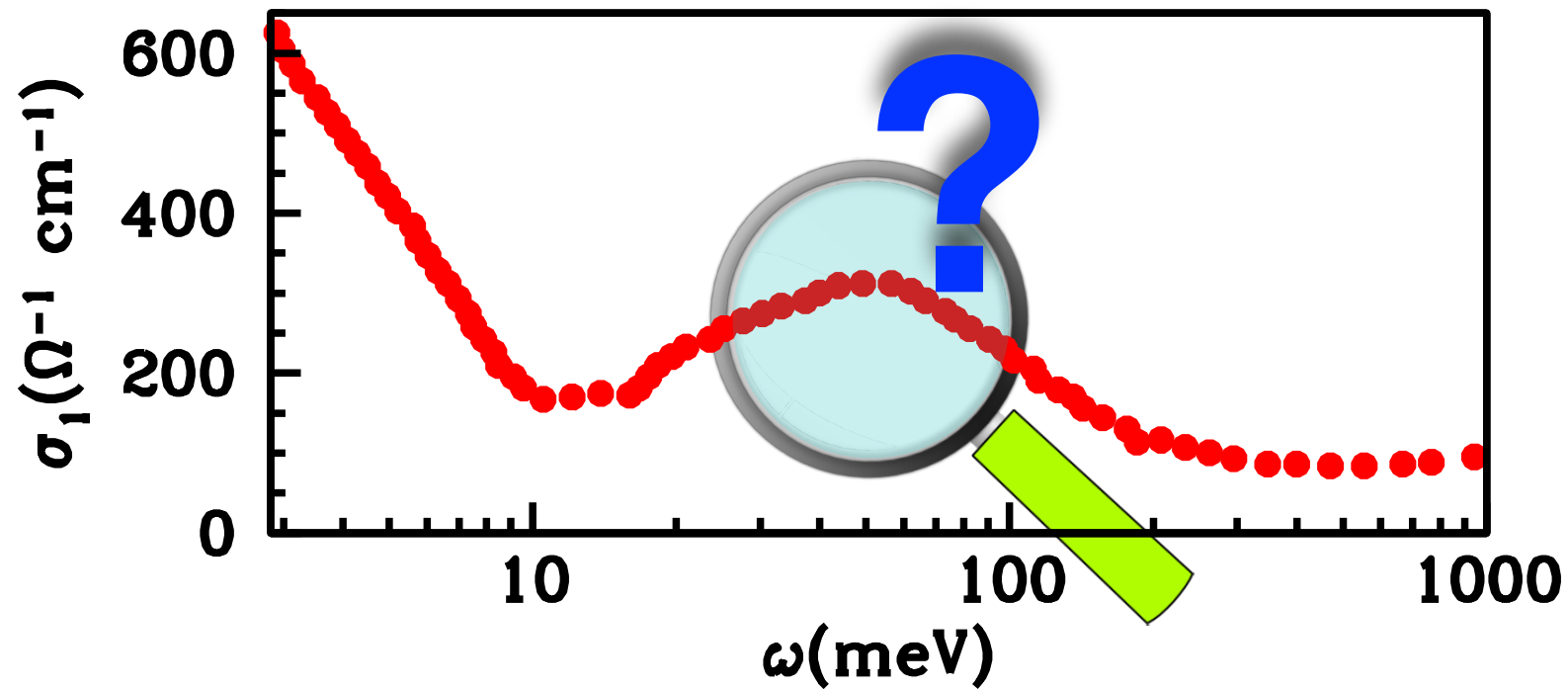
- the laser pump cleans out thermal excitations from the gap, as if it effectively cooled down the system at low frequency

the transient superconducting-like optical response is observed only when the laser frequency hits a mid-infrared absorption peak

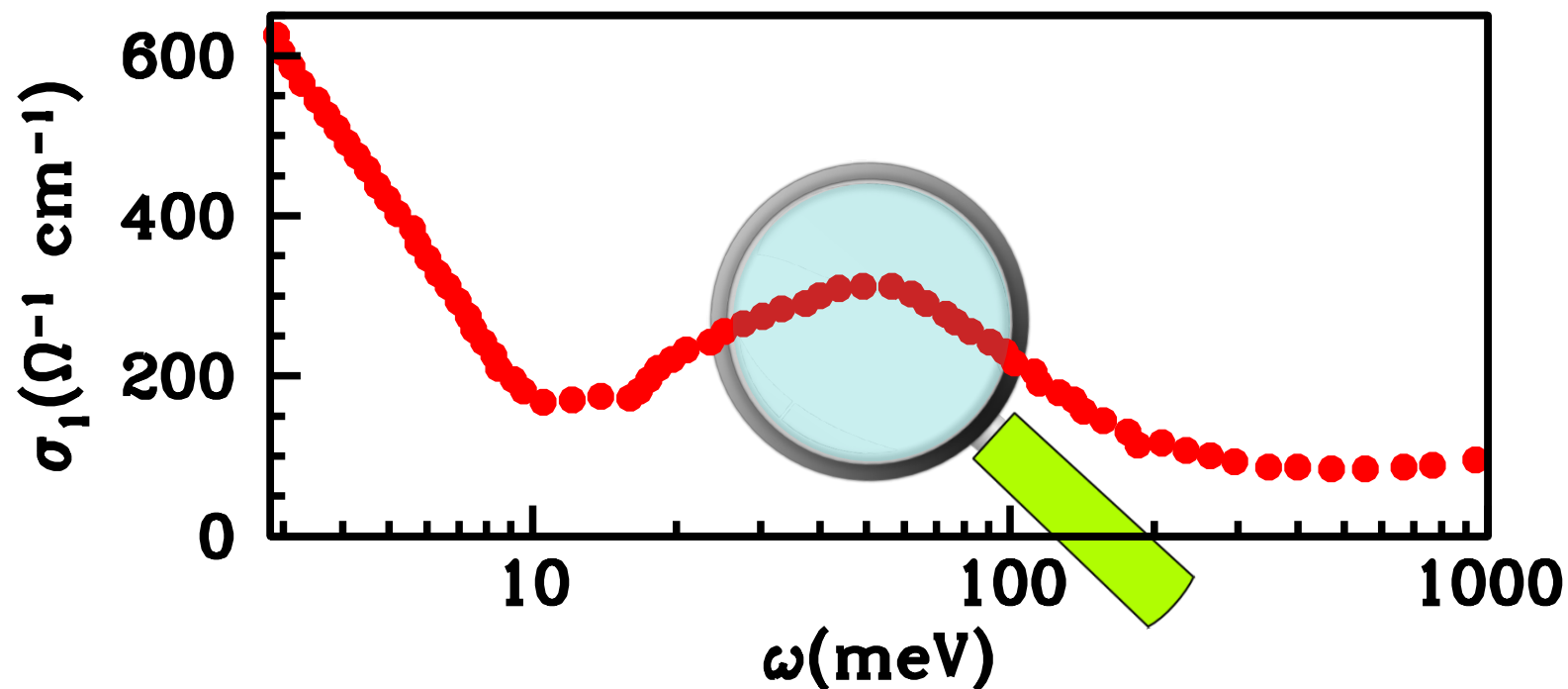




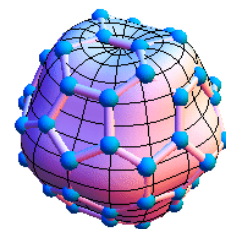
- it looks like our cooling mechanism: one pumps into a high-energy mode, and finds that the low-energy excitations are cooled down



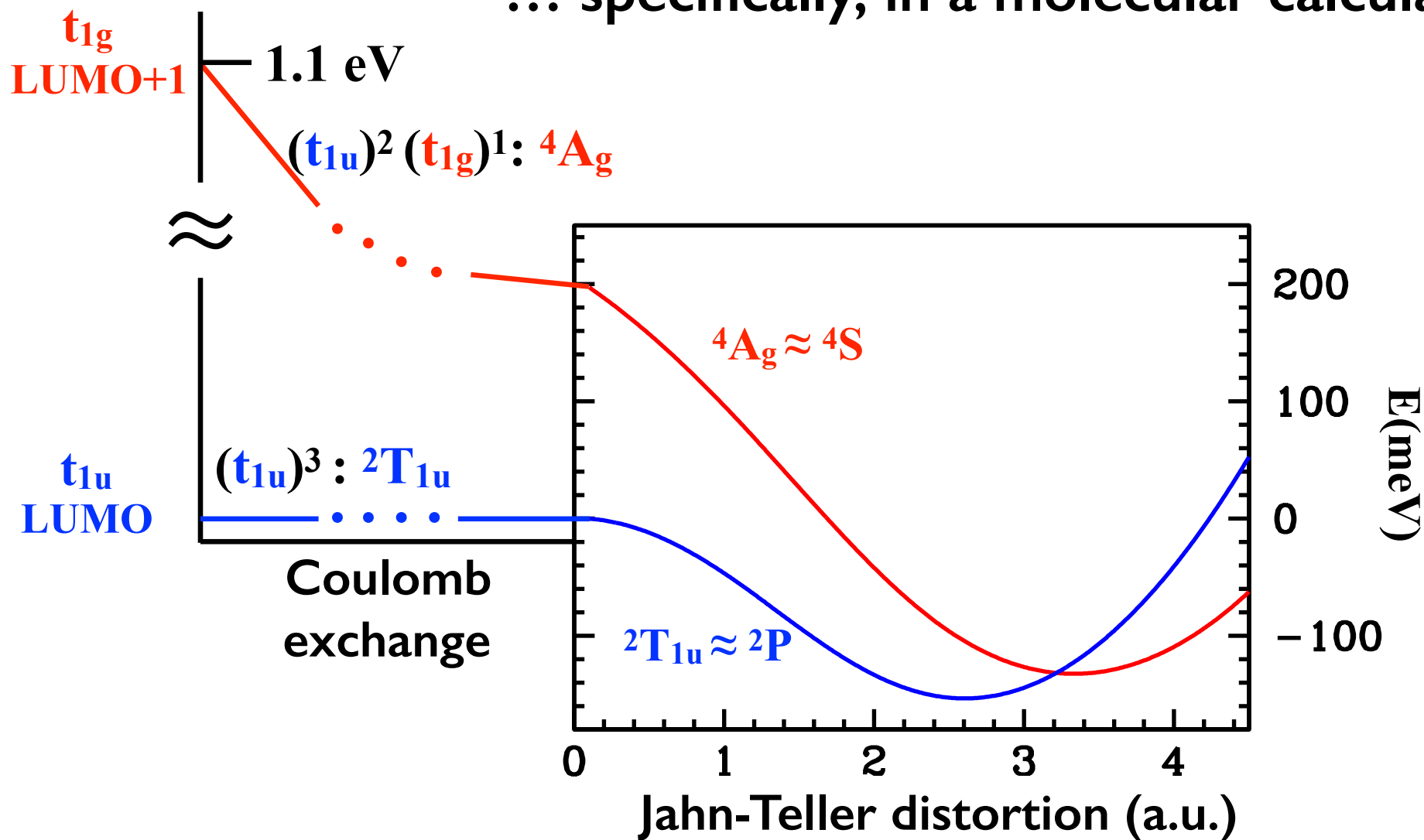
- we need to find the main actor, i.e., the excitation responsible of the MIR absorption peak



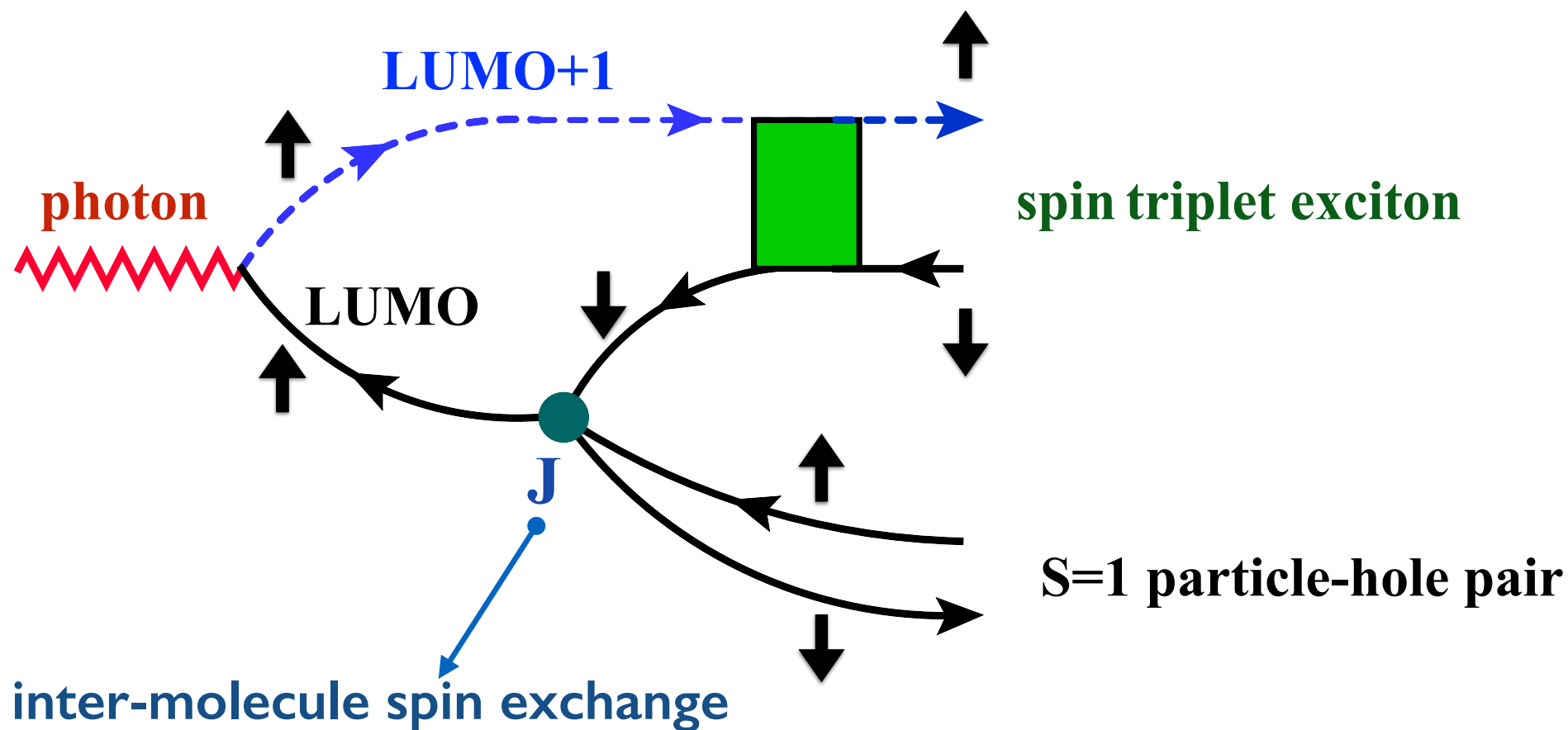
✓ a spin-triplet molecular exciton deriving from the t_{1u} LUMO $\rightarrow$ t_{1g} LUMO+1 transition strongly pushed down in energy by the positive interplay of Coulomb exchange and Jahn-Teller effect



... specifically, in a molecular calculation



The absorption process in diagrams



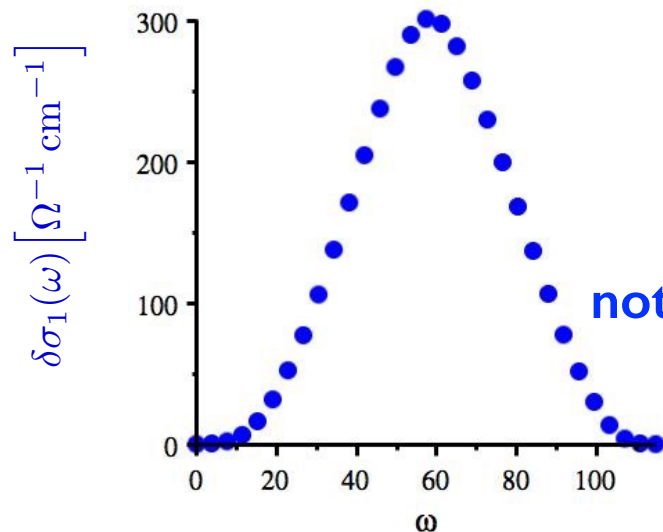
The absorption process in formulas

exciton DOS

Bose distribution at temperature T

$$\delta\sigma_1(\omega, T) = \gamma \int_0^\infty d\epsilon \mathcal{A}_{\text{exc}}(\epsilon, T) \left[b(\epsilon - \omega, T) \left(\theta(\epsilon - \omega) \chi''(\epsilon - \omega, T) - \theta(\omega - \epsilon) \chi''(\omega - \epsilon, T) \right) - b(\epsilon + \omega, T) \chi''(\epsilon + \omega, T) \right]$$

imaginary part of the dynamical magnetic susceptibility, large since K_3C_{60} is not far from becoming an AF Mott insulator



not much different from experiment!

note that the width is controlled by $\chi''(\omega)$ rather than by the exciton lifetime

**Assuming Fermi-liquid theory and local equilibrium,
the dynamics during the laser pulse is described
by the equation of motion**

$$\begin{aligned}\dot{E}_{\text{qp}}(T(t)) &= \frac{\partial E_{\text{qp}}(T(t))}{\partial T(t)} \dot{T}(t) = c_V(T(t)) \dot{T}(t) \\ &= \alpha (\omega - E_{\text{exc}}) \delta\sigma_1(\omega, T(t))\end{aligned}$$

•where

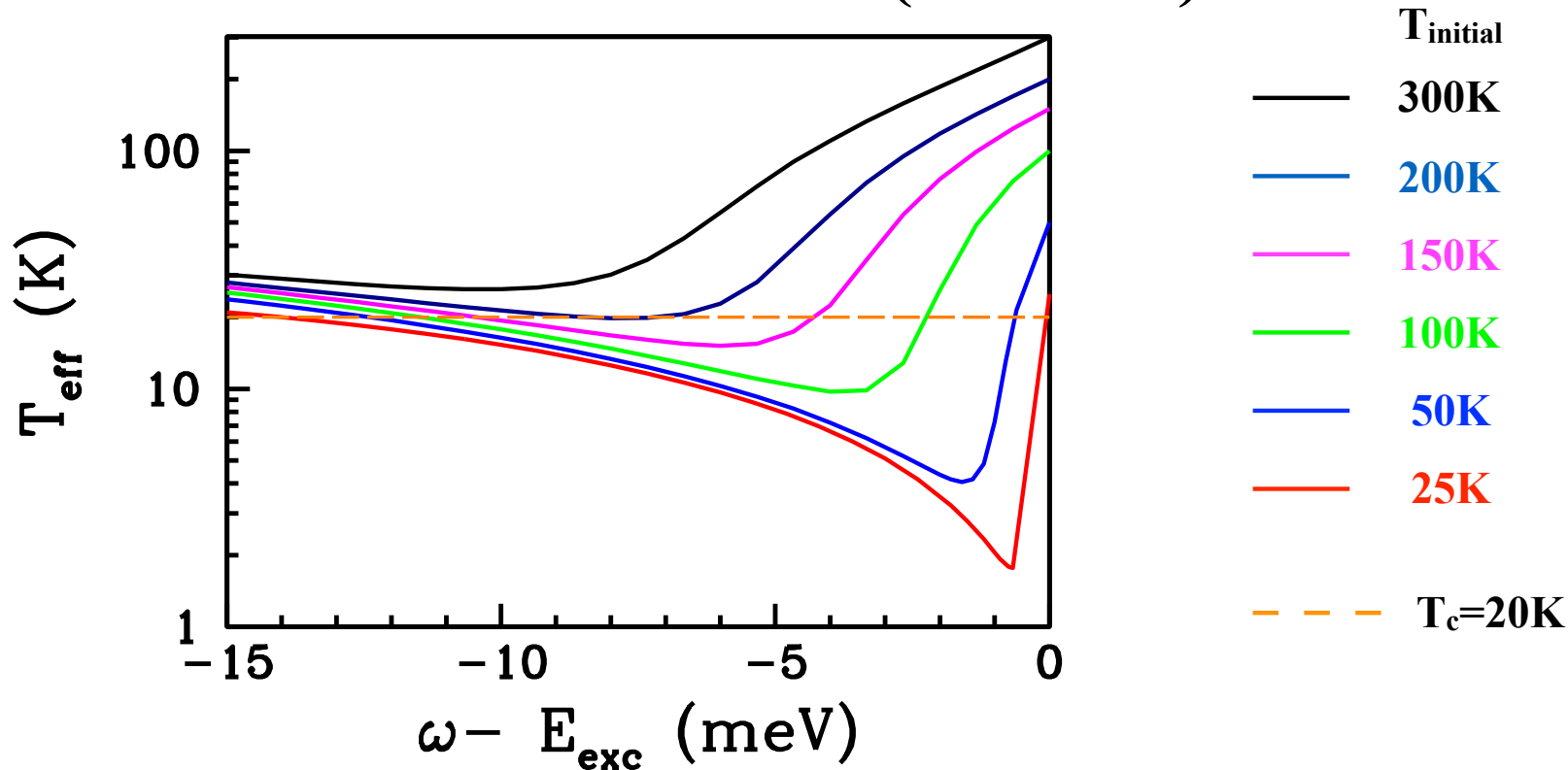
$$\alpha = \frac{\text{fluence}}{\omega \times \text{penetration depth}} \times V_{C_{60}}$$

- **time-dependent temperature $T(t)$**

$$\dot{T}(t) = \alpha \frac{\omega - E_{\text{exc}}}{c_V(T(t))} \delta\sigma_1(\omega, T(t))$$

in such simple modelling the quasiparticle temperature decreases below resonance, $\omega < E_{\text{exc}}$, and increases above

Effective temperature at the end of the pulse: $T_{\text{eff}} = T(t = 300\text{fs})$



- T_{eff} after the laser shot can be substantially lower than the external value, even lower than T_c

Conclusions

- a simple and general mechanism to transiently cool down low-frequency excitations might explain the light-enhanced T_c observed in K_3C_{60}
- it requires just a high-energy excitation that acts as entropy sink for low-energy ones when the laser is on, and gradually release back that entropy when the laser is turned off

Thank you!