# Magnetic transport in 1D materials

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CCQCN

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*NOVMAG + LOTHERM*

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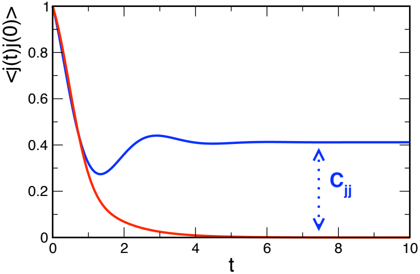
# *2 ideas*

*integrable quantum correlated systems can show unconventional - ballistic- charge, spin, thermal transport at all temperatures*

*novel - magnetic - mode of heat transport*

# background[1]




$$D \sim \beta C_{jj}$$

$$\sigma'' = \frac{D}{\omega}\Big|_{\omega\to 0}$$

$$\sigma'_{dc} \sim \beta \int_0^\infty dt \langle j(t) j \rangle$$

[1] W. Kohn 1964

# Mazur inequality[2]

$$[Q_n, H] = 0, \quad \langle Q_m Q_n \rangle = \delta_{mn}$$

$$\langle j(t) j \rangle_{t \to \infty} \sim C_{jj} \geq \sum_n \frac{\langle j Q_n \rangle^2}{\langle Q_n^2 \rangle}$$

[2] P. Mazur 1969

# $S = 1/2$ Heisenberg model

$$H = J \sum_{l=1}^{L} S_l^x S_{l+1}^x + S_l^y S_{l+1}^y + \Delta S_l^z S_{l+1}^z$$

- $J > 0$ antiferromagnet
- $\Delta < 1$ *easy-plane*
- $\Delta > 1$ *easy-axis*
- $\Delta = cos(\pi/\nu)$

- $[S^z, H] = 0$
- $j^z = J \sum_l (S_l^x S_{l+1}^y - S_l^y S_{l+1}^x)$

Bethe ansatz integrable model

# conservation laws [3]

$Q_3 = j^E$

[a] diverging $\kappa$

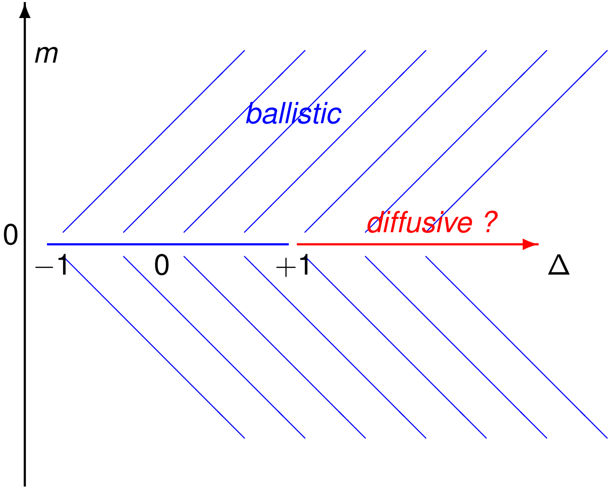
[a] D. Huber, J.S. Semura 1969,
T. Niemeijer, H.A.W. van Vianen 1971,
A. Klümper, K. Sakai 2002

*spin conductivity*

- $D(T) \geq \frac{\beta}{2L}\frac{\langle j^z Q_3\rangle^2}{\langle Q_3^2\rangle}$
- $\beta \to 0$
- $D(T) \geq \frac{\beta}{2}\frac{8\Delta^2 m^2(1/4-m^2)}{1+8\Delta^2(1/4+m^2)}$
- $m = \langle S^z \rangle$

[3] X.Z., F. Naef, P. Prelovšek 1997

# $S = 1/2$ scenario



# expertise

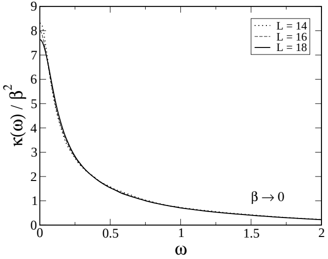
**exact analytical methods**

Bethe ansatz

**numerical simulations**

exact diagonalization (microcanonical)
Lanczos
QMC

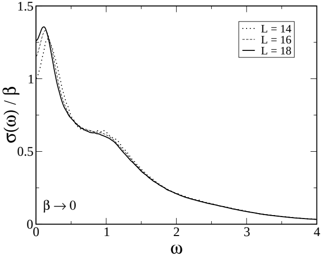
# $S = 1$ Heisenberg model[4]




$D_{th} = \kappa_{dc}/C \sim 5.6$

$$D_{th}^{moment} = \frac{\sqrt{\pi S(S+1)/3}}{(1 - 3/4S(S+1))}$$

$\sim 2.3$



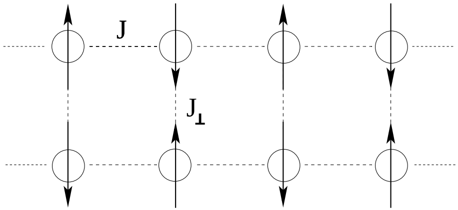

$D_s = \sigma_{dc}/\chi \sim 2.1$

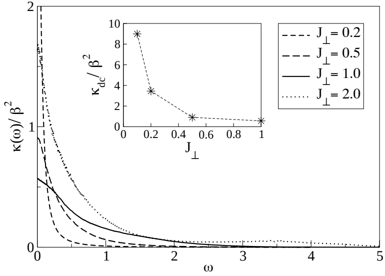
$$D_s^{moment} = \sqrt{2\pi S(S+1)/3}$$

$\sim 2.1$

[4] J. Karadamoglou, X.Z. 2004

# 2-leg $S = 1/2$ ladder[5]

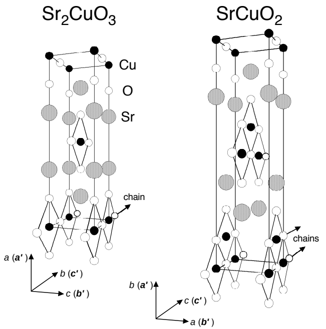


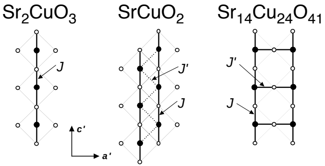




$$\kappa \sim (J/J_\perp)^2$$

[5] X.Z. 2004

# A novel mode of thermal transport [6]




$$J'/J \sim 10^{-4}$$
$$J \sim 2'400K$$

$BaCu_2Si_2O_7$

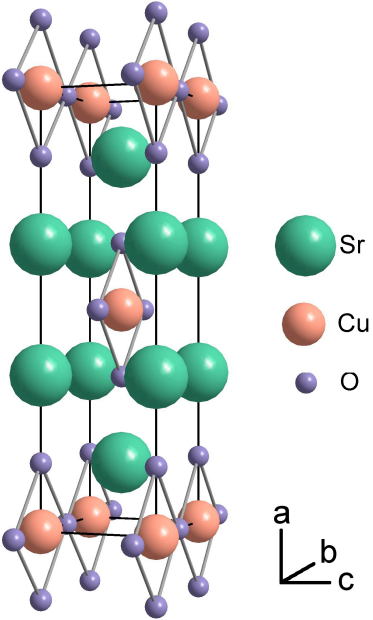
$J \sim 280K$

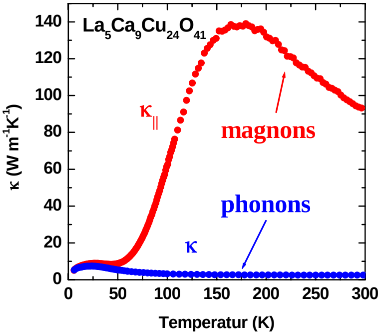
$AgVP_2S_6$

$S = 1, \quad J \sim 780K$

[6] A. Revcolevschi, C. Hess, B. Büchner, A. Sologubenko, H.R. Ott, Y. Koike

# $Sr_2CuO_3$






magnetic thermal transport

- highly directional
- electrically insulating
- ”metallic” $J \sim \epsilon_F$
- ”mechanical” - switching

**Figure 5:** Single crystalline samples. a) pure $Ca_9La_5Cu_{24}O_{41}$, b) Zn (2%) doped $Ca_9La_5Cu_{24}O_{41}$, c) cleaved 1% Mg-doped $Sr_2CuO_3$ , d) (1%) Mg-doped $SrCuO_2$.

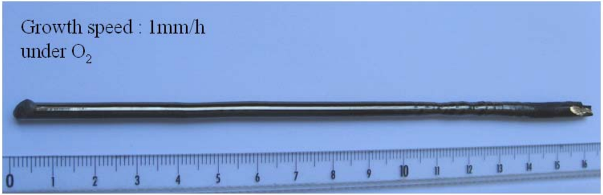



**Figure 7:** High-quality $SrCuO_2$ single crystal grown by the travelling solvent zone method (TSZM).

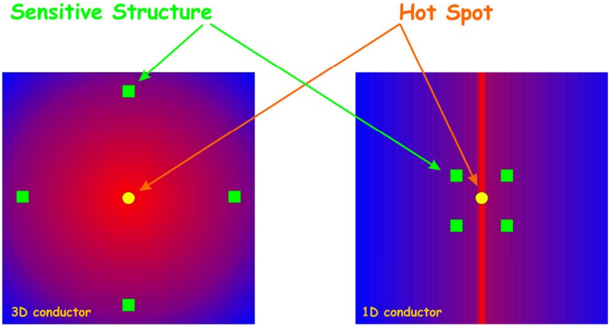



**Figure 1:** Schematic illustration of a thermal management problem. A hot spot in a microelectronic structure is generating unwanted heat. This heat could on one hand hamper the performance of the heat releasing structure. On the other hand, heat sensitive structures in its proximity could be damaged. A possible strategy for dissipating the heat is to use a layer with high thermal conduction to guide the heat to a heat sink. **Left**: A conventional heat conductor is normally roughly isotropic (3D heat conductor). The lateral temperature gradient is therefore small and sensitive structures have to be placed far away. **Right**: In the case of a quasi one-dimensional heat conductor heat is channeled away and sensitive structures can be placed much closer.

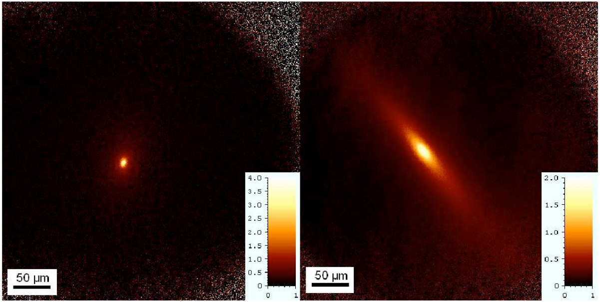
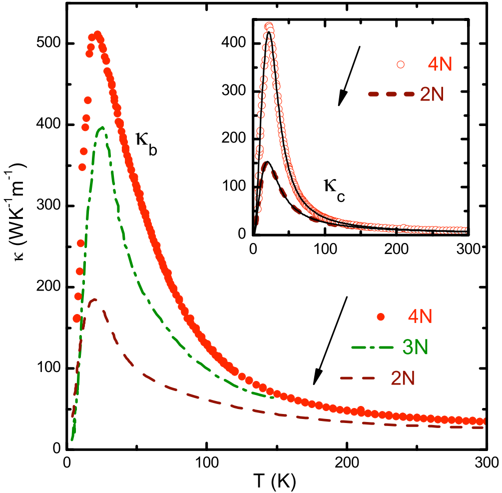
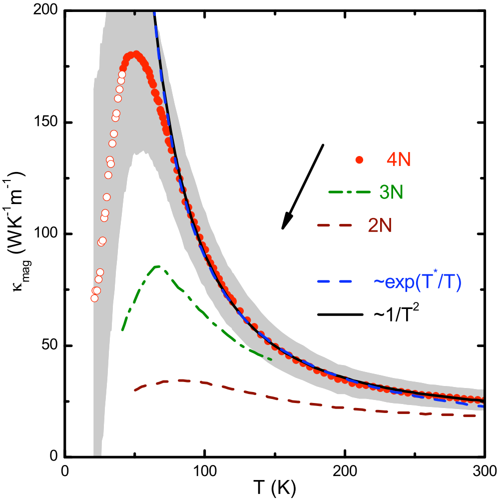



**Figure 2:** Left panel: Thermal image on the ab plane of $La_5Ca_9Cu_{24}O_{41}$ showing very localized symmetric heating after a 40 ms heat pulse. Right panel: similar image on the ac plane showing a highly asymmetric streaked heating pattern due to the large magnon heat conductivity in the (diagonal) c-direction.

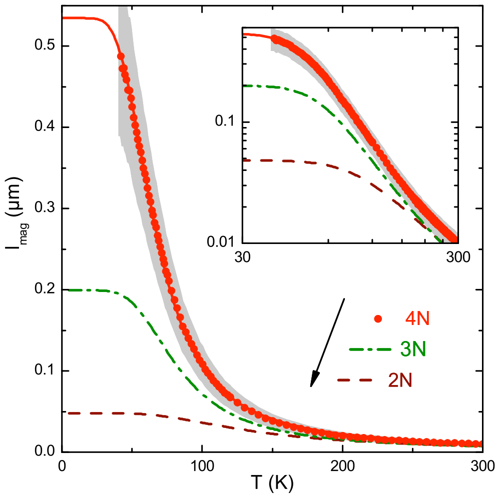
# $Sr_2CuO_3$ from 2N to 4N



# magnetic contribution

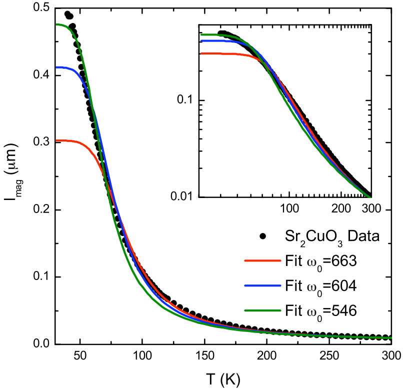


# mean free path



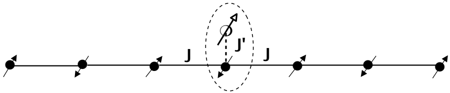
# memory function approach

- XY model, $J_{eff} = \frac{\pi}{2} J$
- spin-phonon decoupling
- optical phonon $\omega_0$



# 1 magnetic impurity [7]

$$
\begin{aligned}
H &= \sum_{l=0}^{L-1} h_{l,l+1} + J' \mathbf{s}_0 \cdot \mathbf{S} \\
h_{l,l+1} &= J \sum_{l=0}^{L-1} (s_l^x s_{l+1}^x + s_l^y s_{l+1}^y + \Delta s_l^z s_{l+1}^z)
\end{aligned}
$$




unique system - $\kappa$ ballistic

[7] A. Metavitsiadis et al. Phys. Rev. B81, 205101 (2010)

# *Kondo physics*

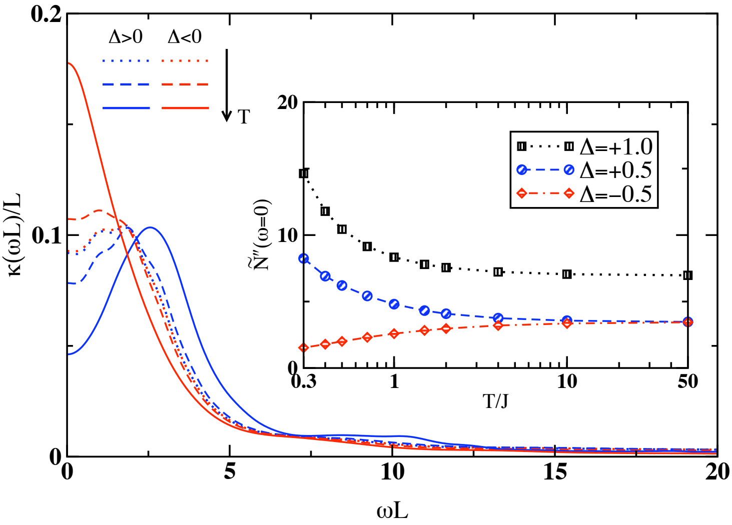
*Kane - Fisher (1992)*

- 1 weak link + Luttinger liquid
- repulsive interaction $\rightarrow$ *cutting* of chain at $T = 0$
- attractive interaction $\rightarrow$ *healing* of chain at $T = 0$

*Eggert - Affleck - Römmer, Furusaki - Hikihara*

- antiferromagnetic spin-1/2 Heisenberg chain at $T = 0$
  1 magnetic impurity $\mathbf{S} \rightarrow$ *cutting*
- $\Delta < 0$ (attractive) $\rightarrow$ *healing*

# cutting vs. healing



# puzzle: SSM vs. FFM method [8]

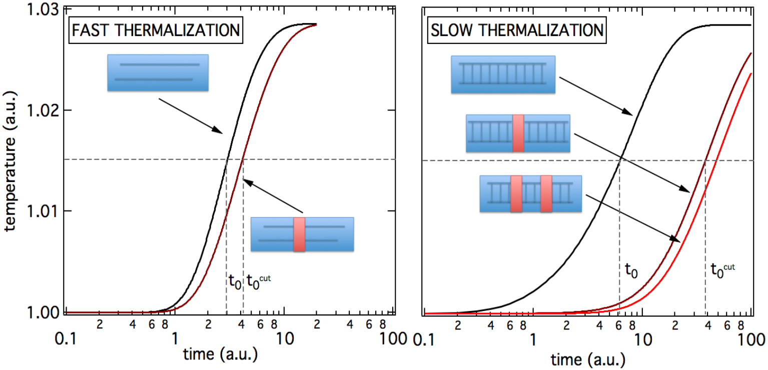
3- layer toy model $(m+p)-p-(m+p)$
interface - "cut" chain $L = L/2 + cut + L/2$

$$\frac{\partial T^p}{\partial t} = \frac{1}{\tau_p}\frac{\partial^2 T^p}{\partial \xi^2} - \frac{c_m}{c_p + c_m}\frac{1}{\tau}(T^p - T^m)$$

$$\frac{\partial T^m}{\partial t} = \frac{1}{\tau_m}\frac{\partial^2 T^m}{\partial \xi^2} - \frac{c_p}{c_p + c_m}\frac{1}{\tau}(T^m - T^p)$$

phenomenology

[8] PRL **110**, 147206 (2013)



FAST THERMALIZATION
SLOW THERMALIZATION
temperature (a.u.)
time (a.u.)
$t_0$
$t_0^{cut}$
1.00
1.01
1.02
1.03
0.1
1
10
100

# perspectives

- ballistic vs. diffusive
- BA matrix elements
- coupling to phonons
- switsching
- thermal rectification
- ...