Light-induced superconductivity via dynamical Hubbard U

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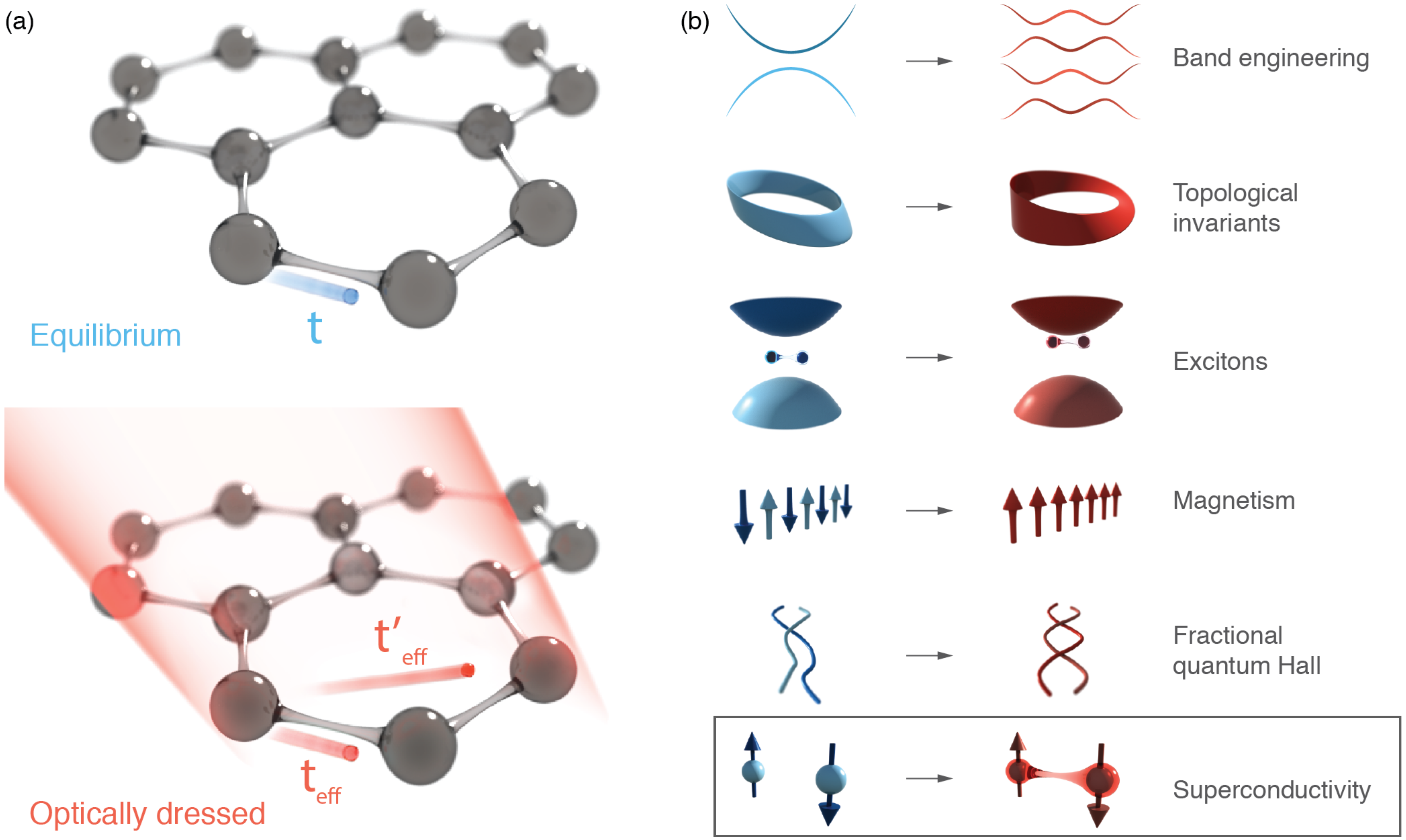
Max Planck Institute for the Structure and Dynamics of Matter

Light-matter control of quantum materials

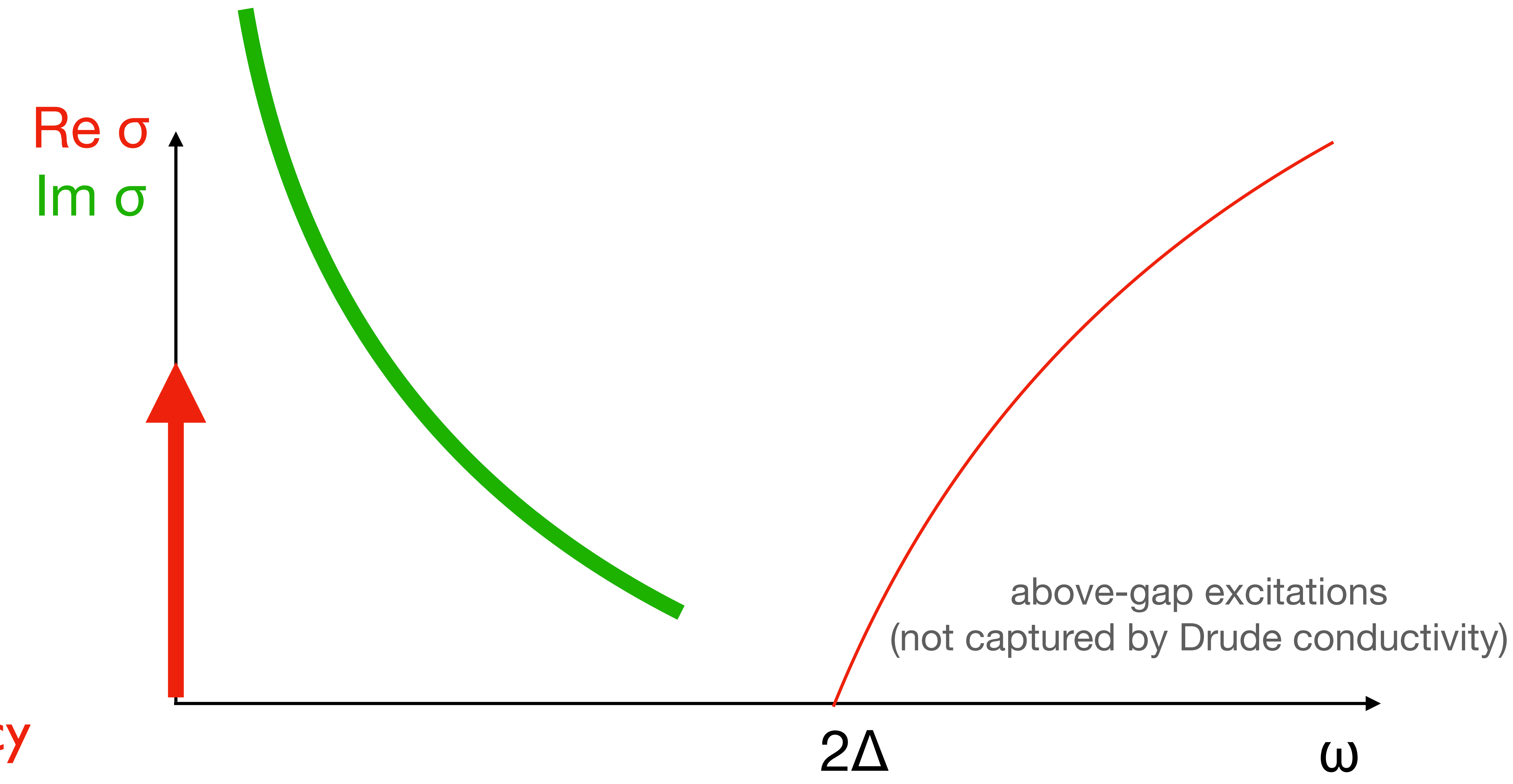
A. de la Torre, D. M. Kennes, M. Claassen, S. Gerber, J. W. McIver, and M. A. Sentef, review in prep.



Optical response of a superconductor

$$j(t) = \int_{-\infty}^{\infty} \mathrm{d}t' \sigma(t-t') E(t')$$

$$\sigma_{\mathrm{Drude}}(\omega) = \frac{\mathrm{i}e^2(n/m)_{\mathrm{eff}}}{\omega + i/\tau}$$



Dissipationless case: $1/\tau \to 0^+$
Real part: delta-function peak at zero frequency
Imaginary part: $1/\omega$ divergence
n = superfluid density

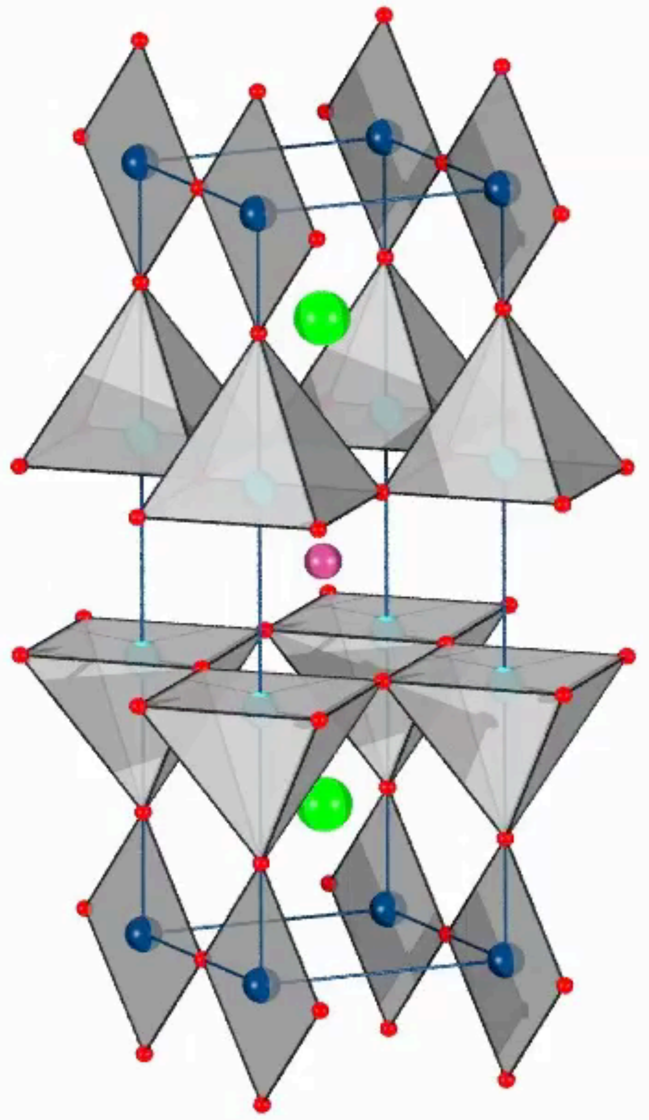
The weight of the delta-function peak / divergence in Re/Im σ measures the superfluid density

Light-induced superconductivity

Optically driven superconductivity via vibrational excitation

High-T_C cuprates

~15 μm
200 fs
5 MV/cm

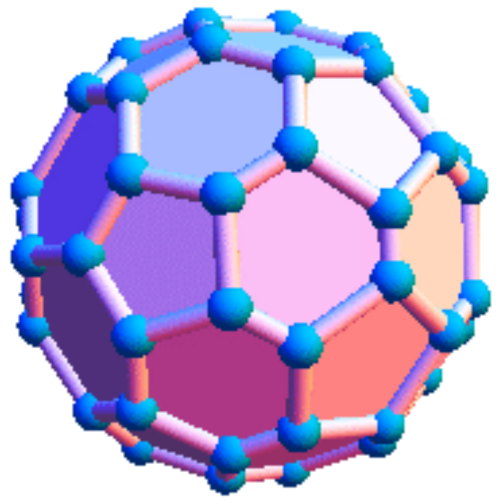


$YBa_2Cu_3O_{6+x}$

W. Hu *et al.*, Nat. Mater. **13**, 705 (2014)
R. Mankowsky *et al.*, Nature **516**, 71 (2014)

Alkali-doped Fullerides

~7-11 μm
200 fs
5 MV/cm



K_3C_{60}

M. Mitrano *et al.*, Nature **530**, 461 (2016)
A. Cantaluppi *et al.*, Nat. Phys. **14**, 837 (2018)

Light-induced superconductivity

Driving the apical oxygen phonon in YBCO

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200 fs
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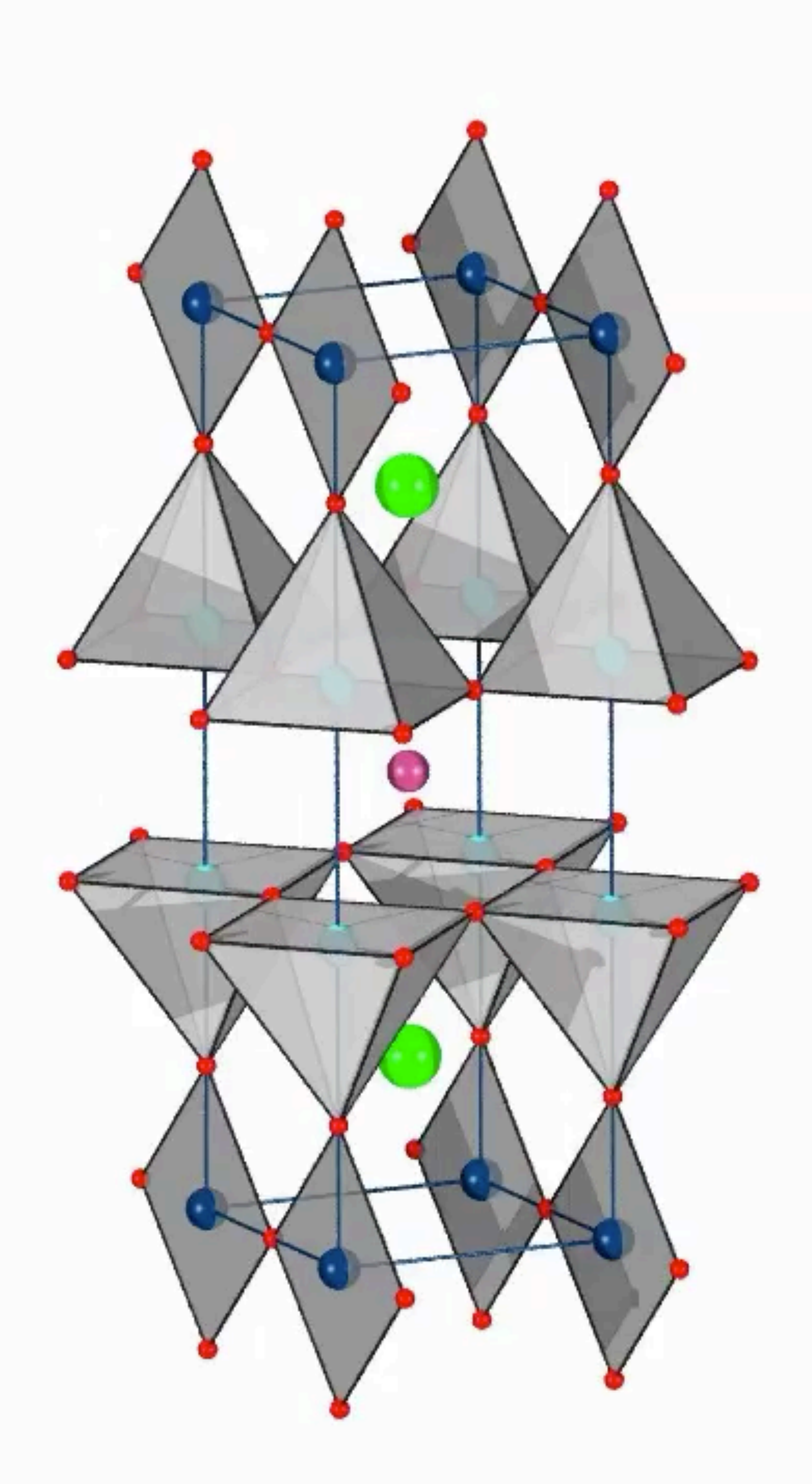
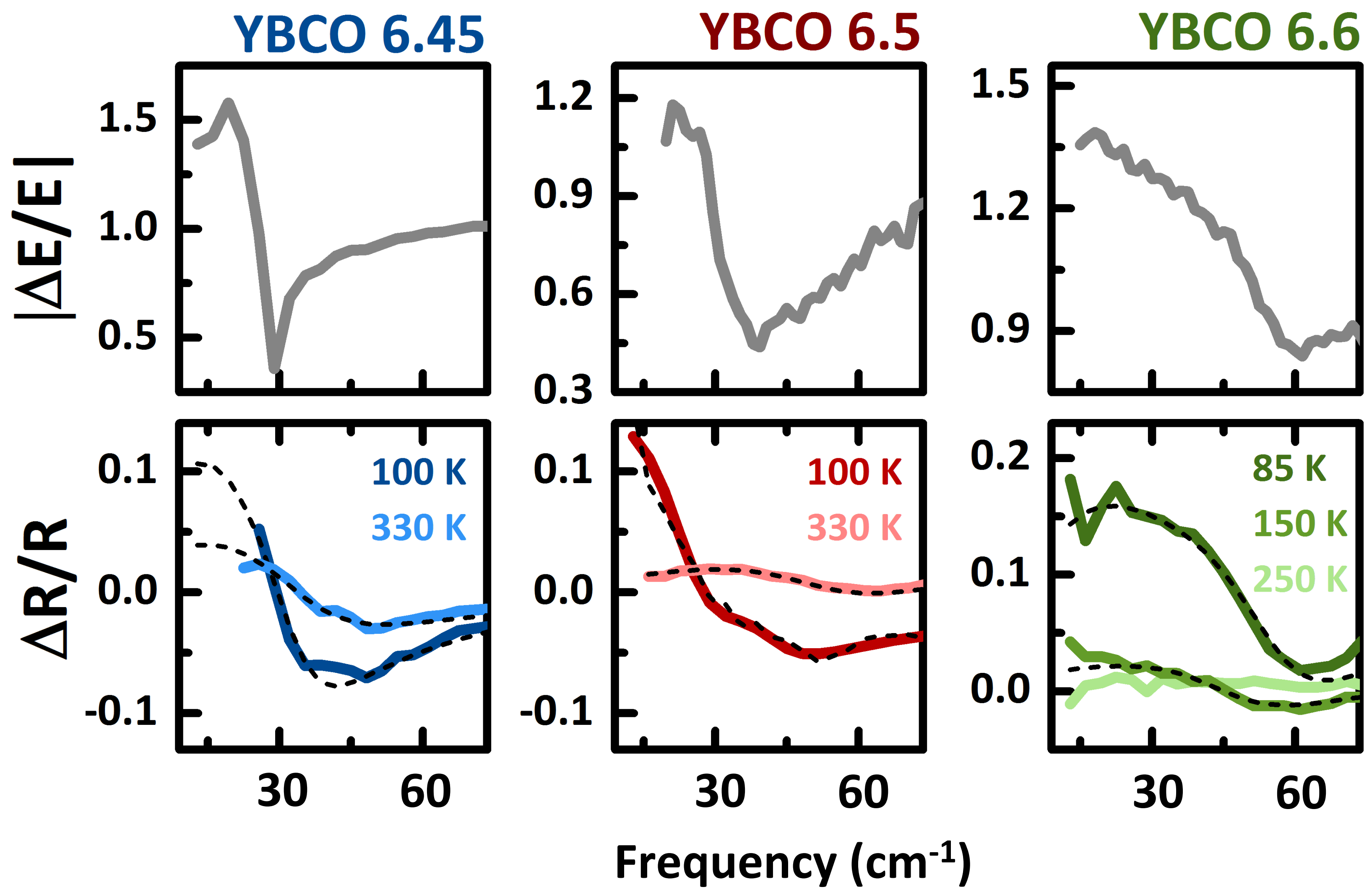
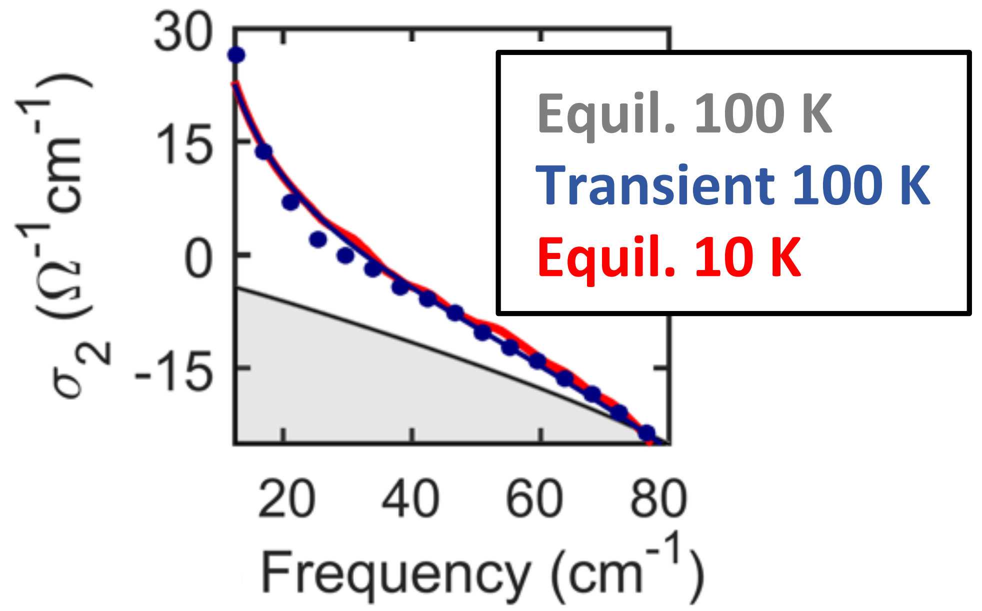


S. Kaiser *et al.*, Phys. Rev. B **89**, 184516 (2014)
C. Hunt *et al.*, Phys. Rev. B **94**, 224303 (2016)

1) Transient Plasma Resonance

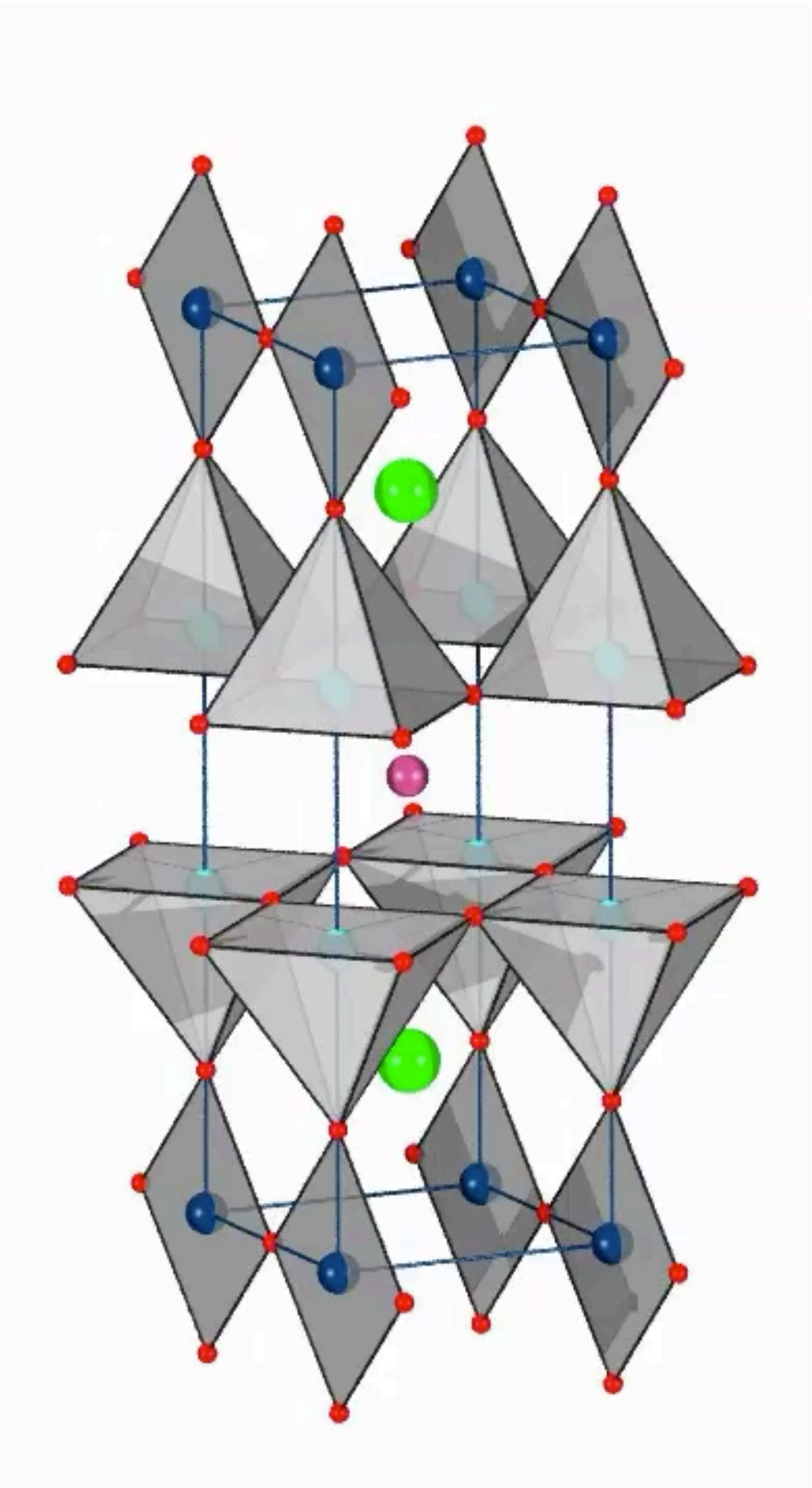


2) Divergent imaginary conductivity



Light-induced superconductivity

Driving the apical oxygen phonon in YBCO



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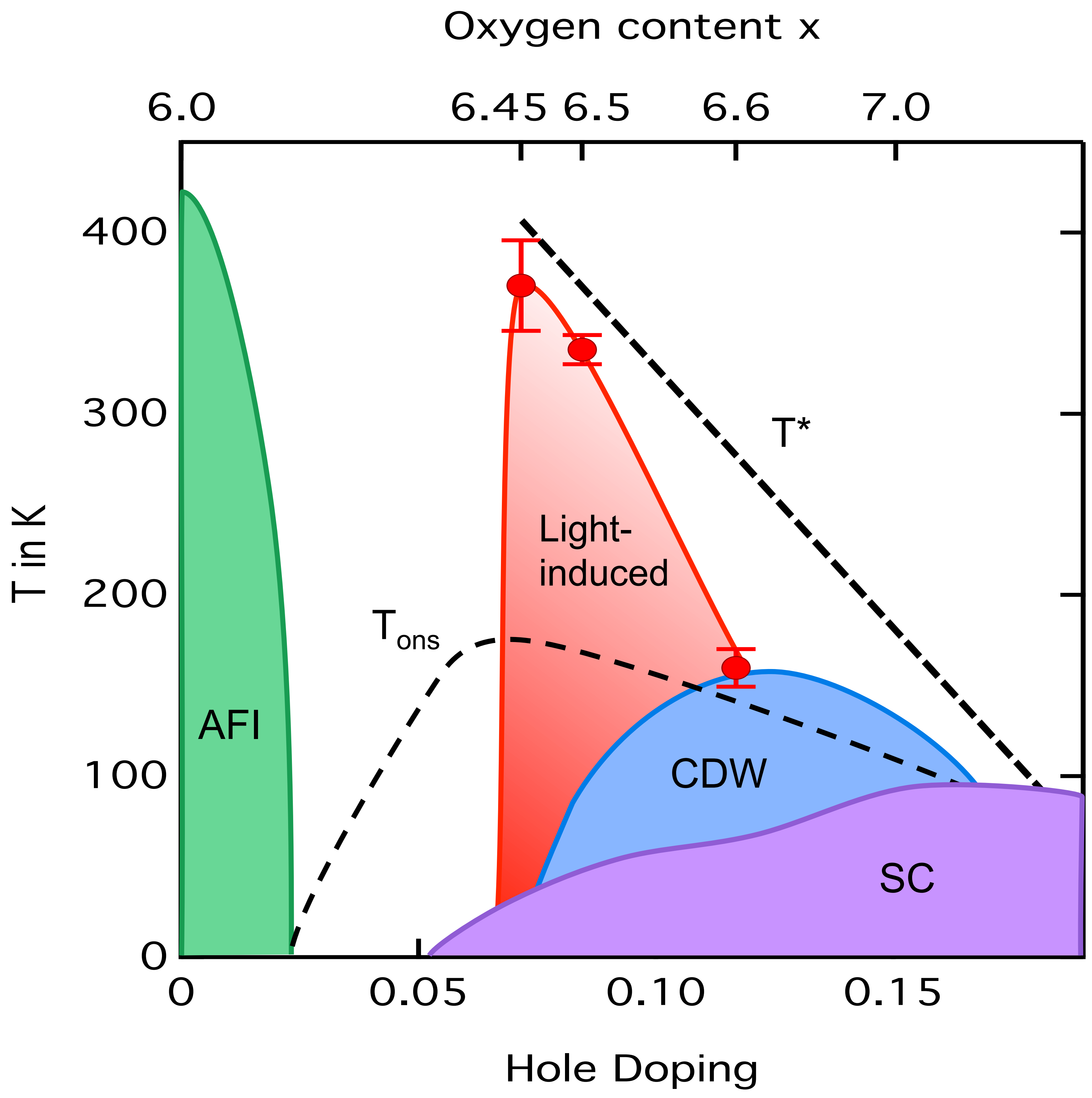
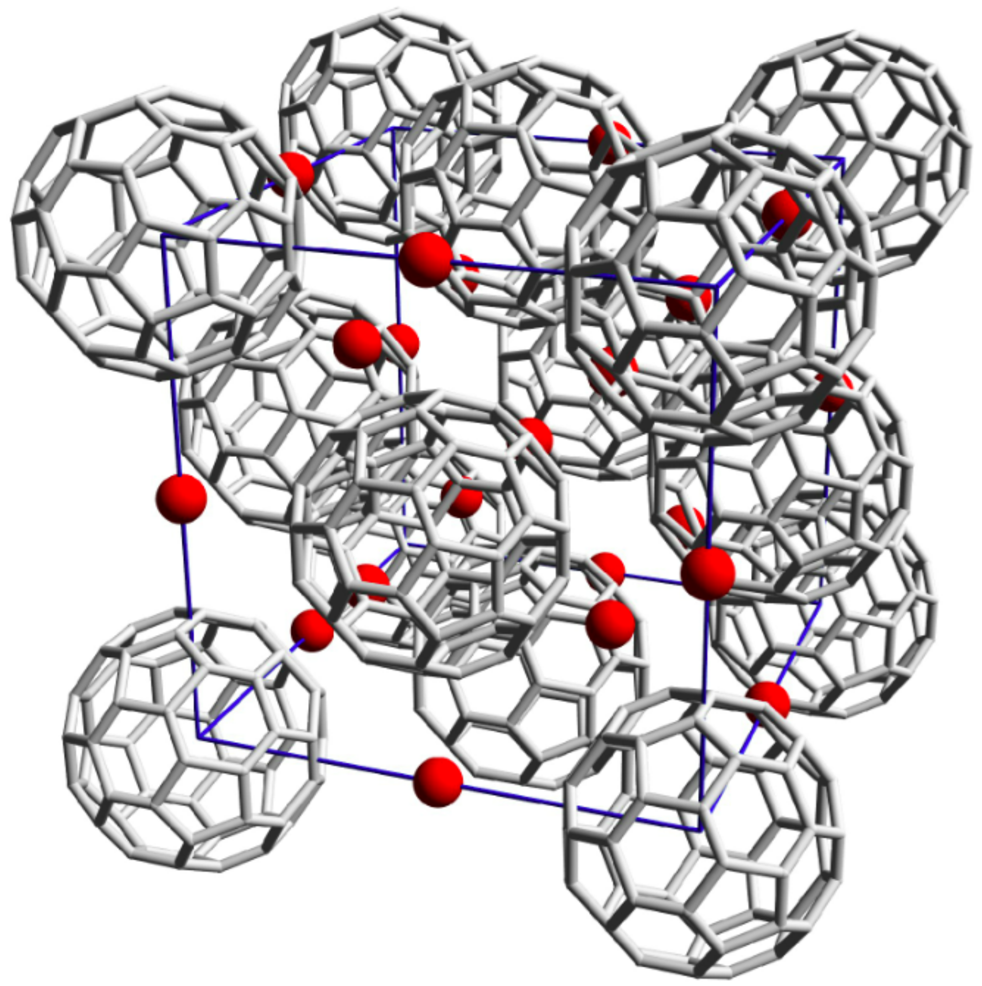
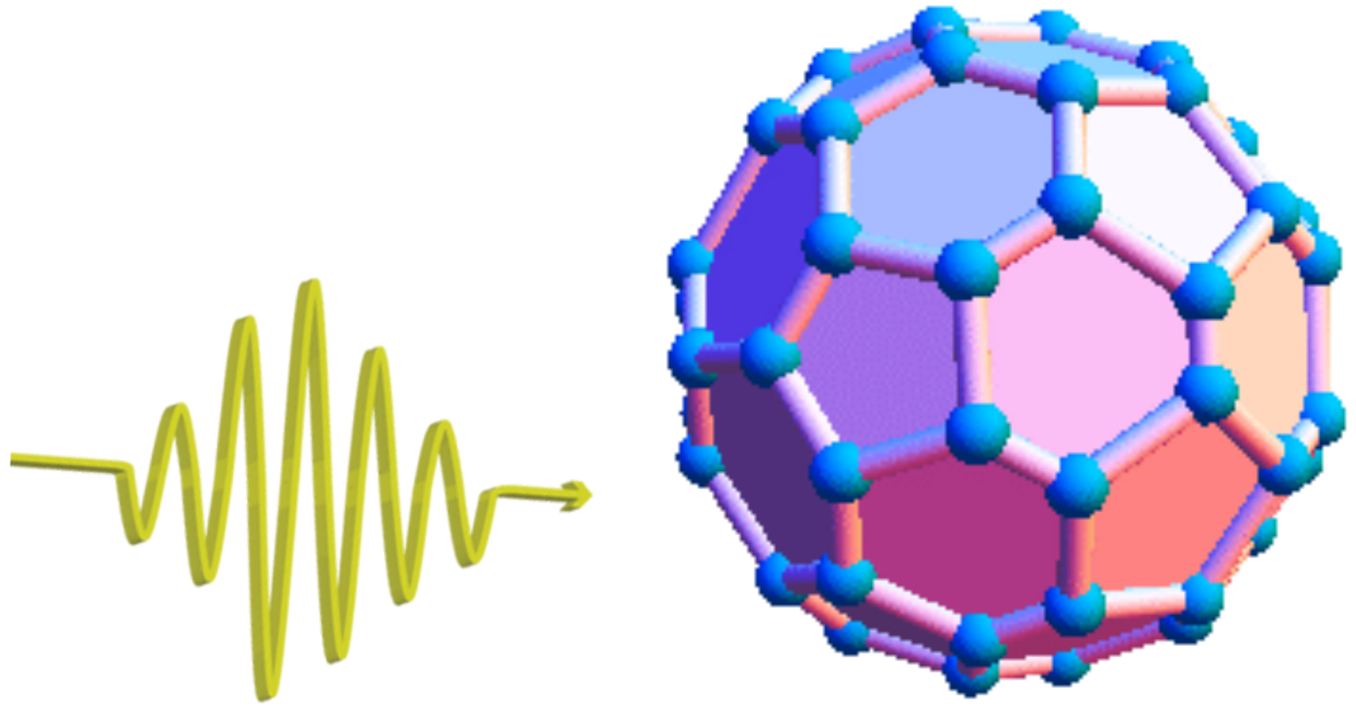


Light-induced superconductivity

Optically driven superconductivity in K_3C_{60}

K_3C_{60}
T_C = 20 K





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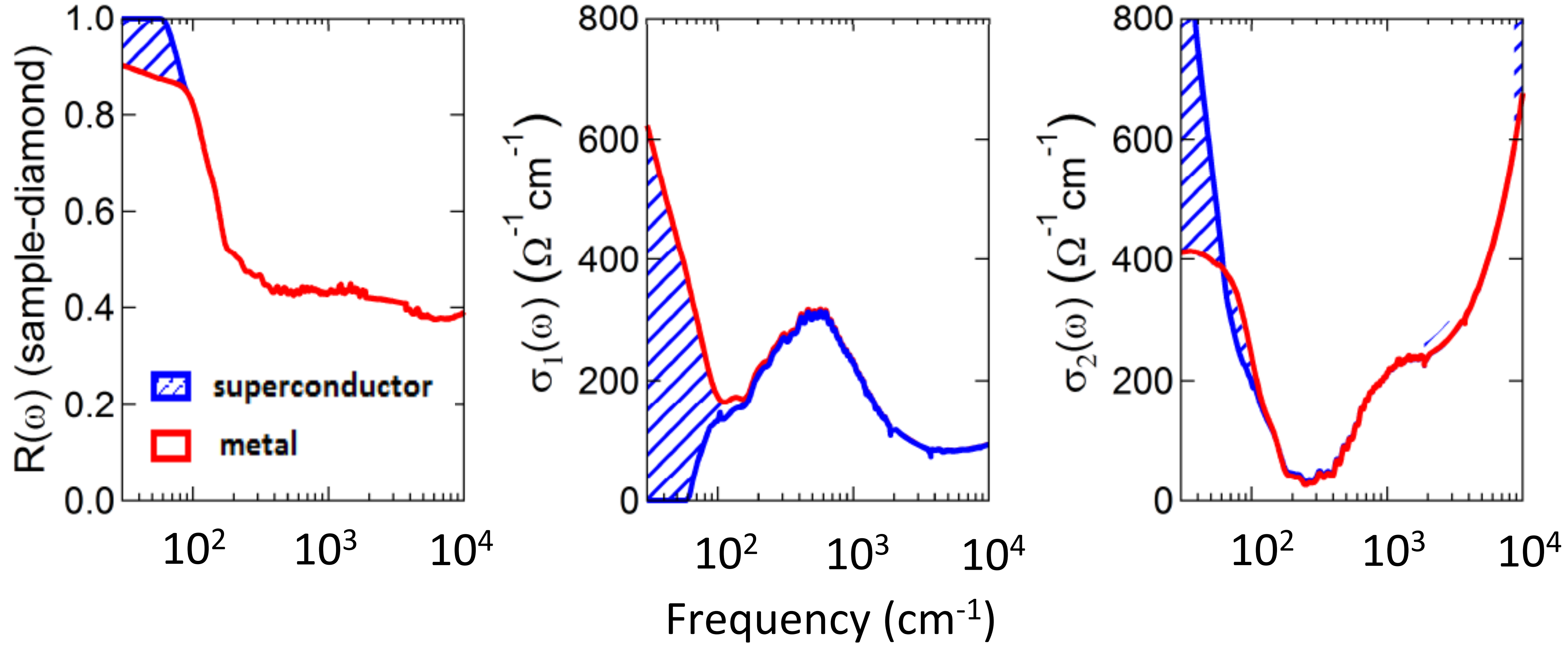
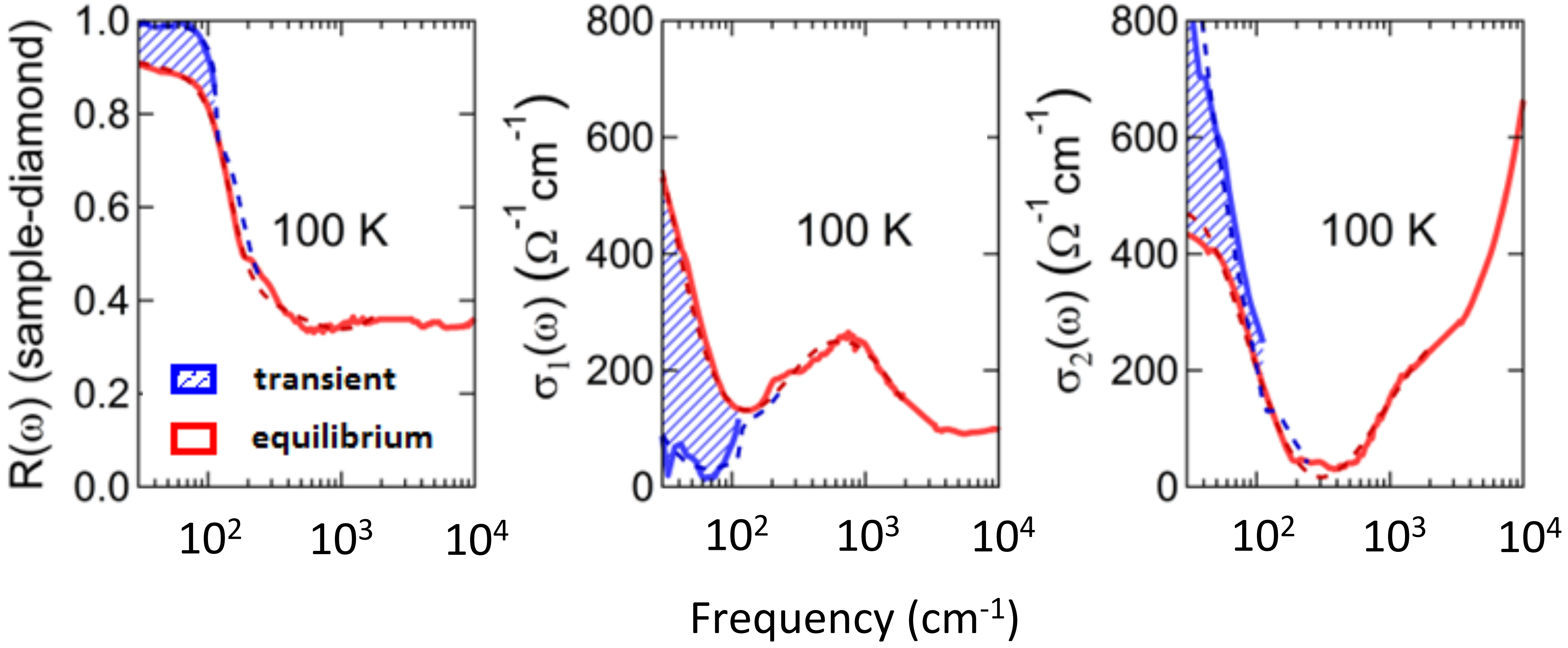
Equilibrium

$T < T_c$



Light-Induced

$T = 5 \cdot T_c$

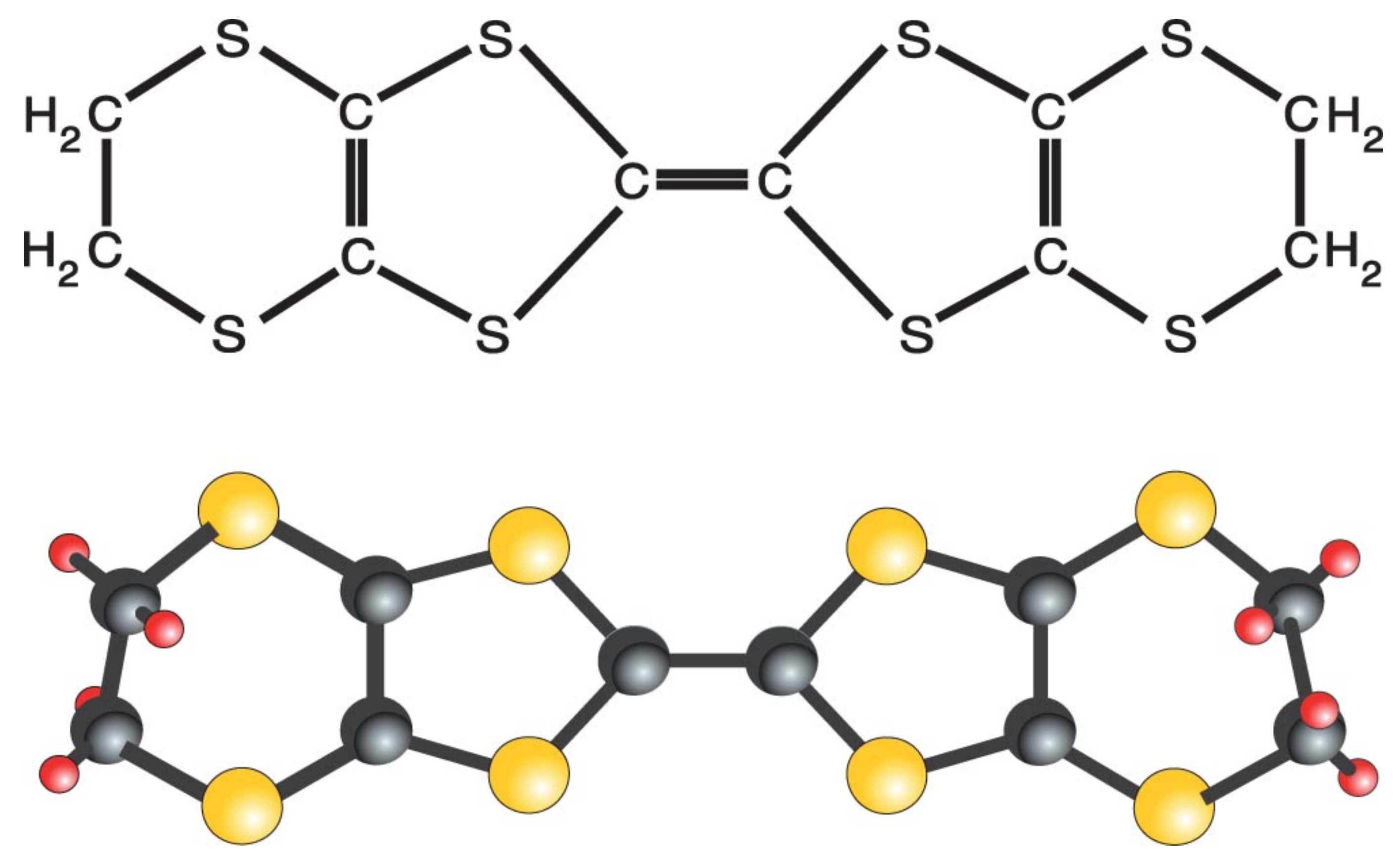


Light-induced superconductivity

M. Buzzi et al., PRX 10, 031028 (2020)

What about other materials? Can we get a handle on the microscopic mechanism?

BEDT-TTF a.k.a. ET



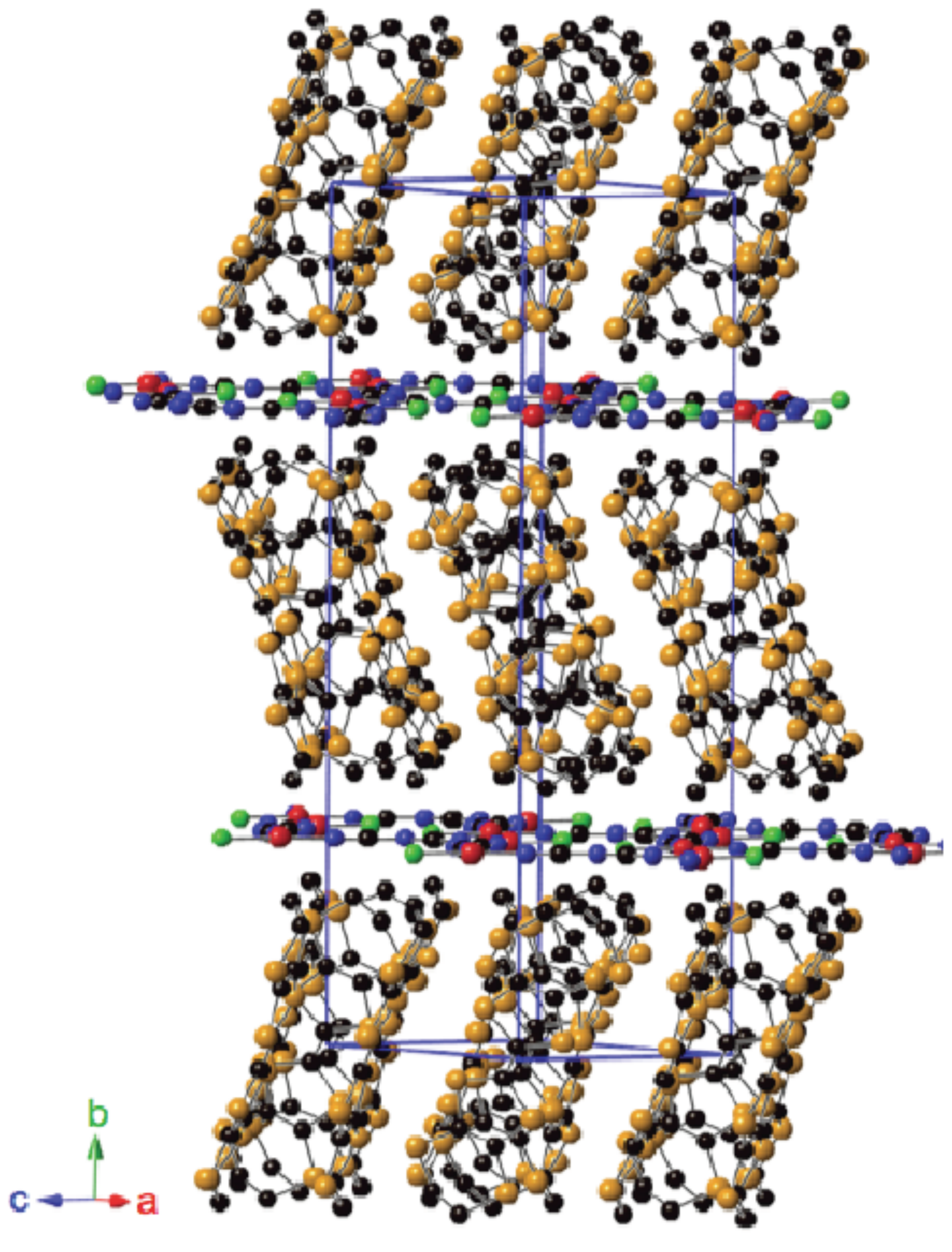
Building block of many organic charge transfer salts

Typically electron donor

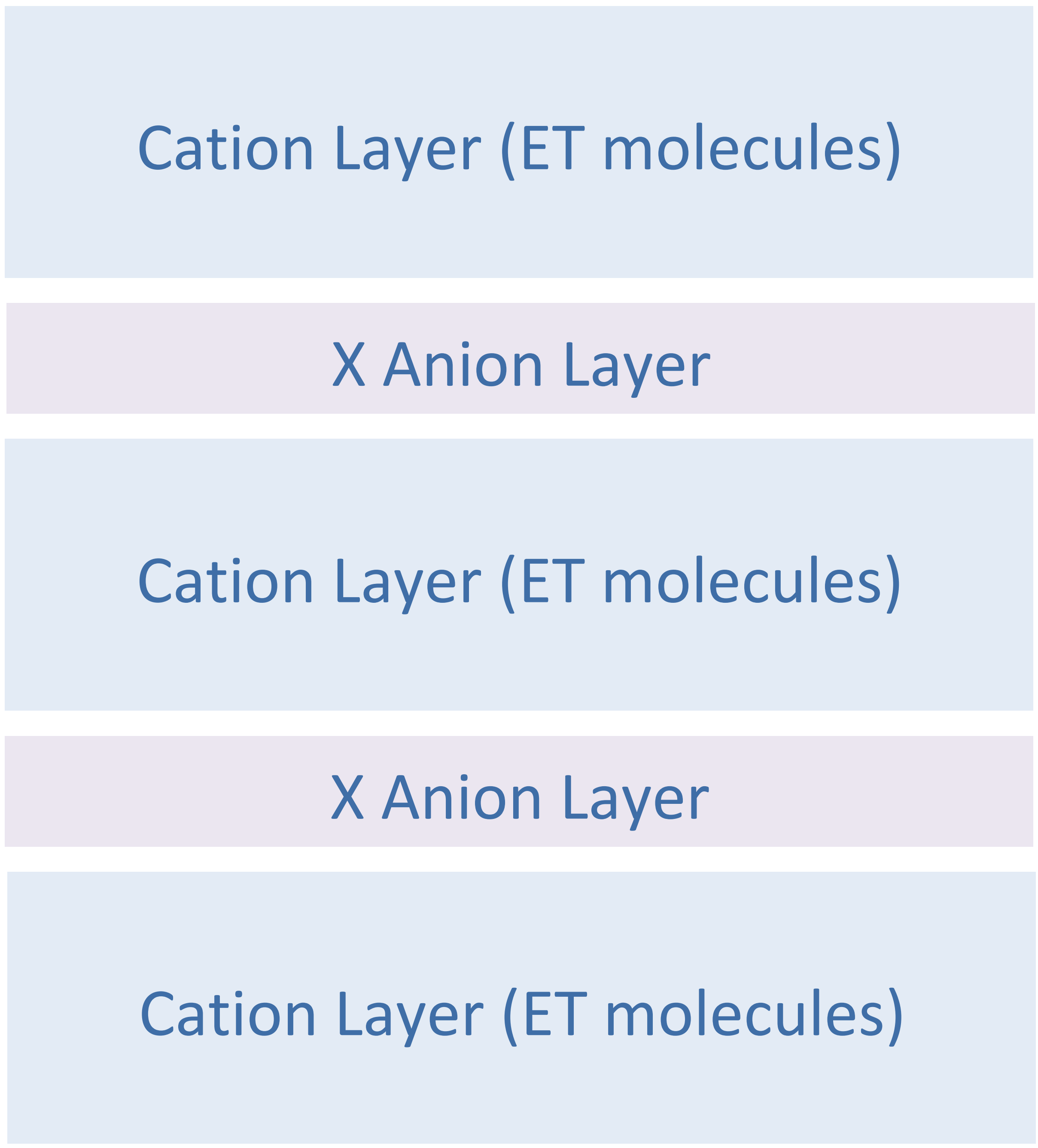
Light-induced superconductivity

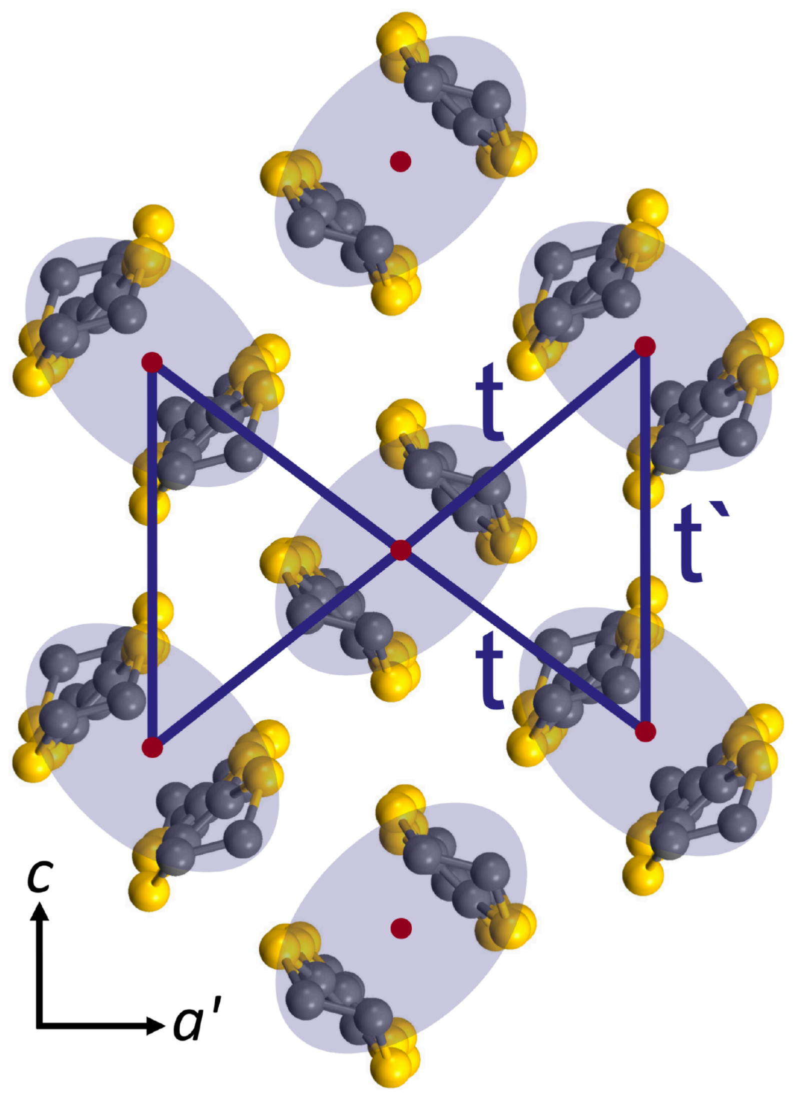
M. Buzzi et al., PRX 10, 031028 (2020)

Photo-molecular high-temperature superconductivity in an organic kappa salt



Müller et al., Crystals (2018)





"kappa" arrangement

ET molecules paired in dimers

Half filled conduction band

Effectively a 2D U-t-t' Hubbard model on an anisotropic triangular lattice

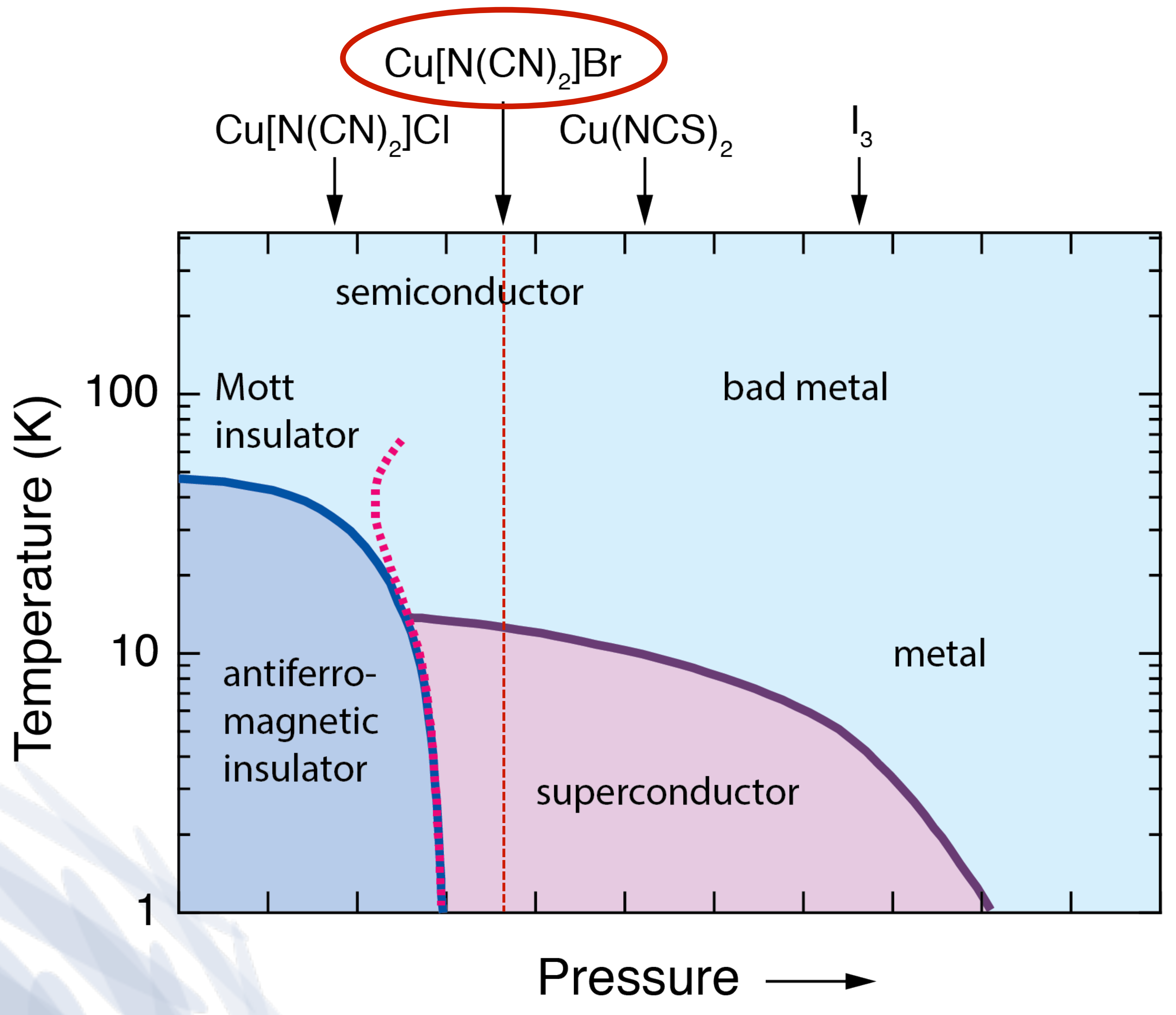
e.g., H. C. Kandpal et al., PRL 103, 067004 (2009)

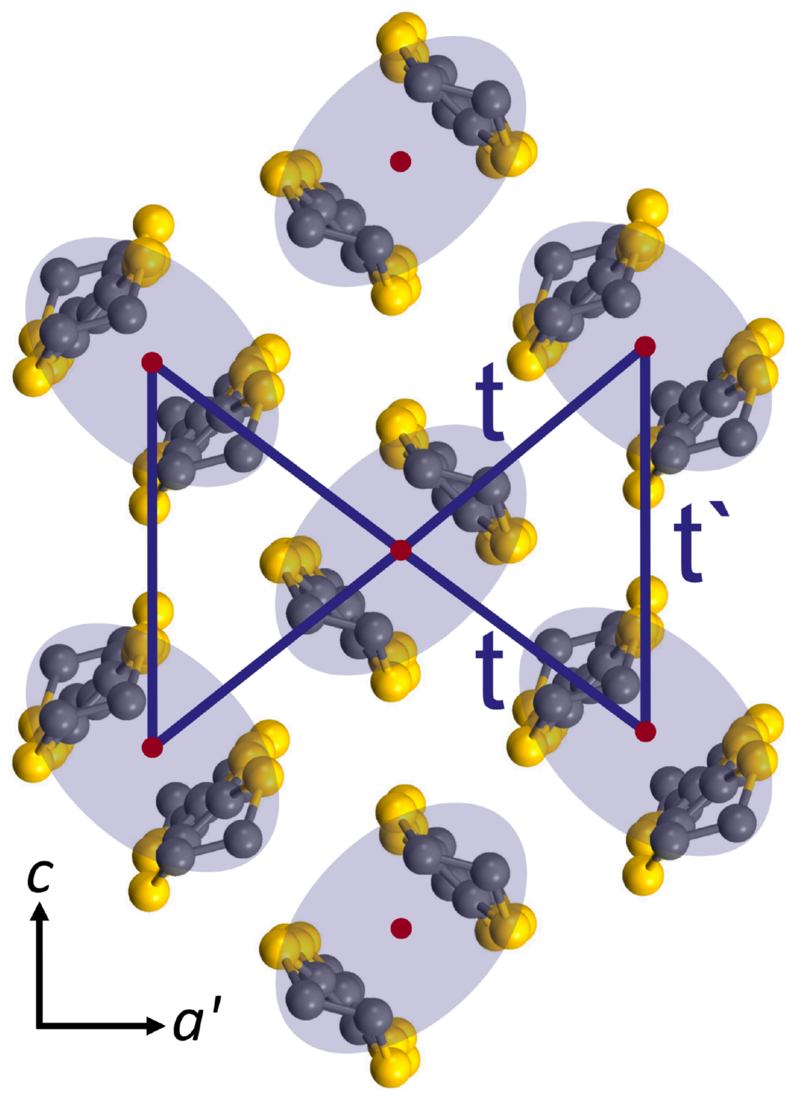
Light-induced superconductivity

M. Buzzi et al., PRX 10, 031028 (2020)

Photo-molecular high-temperature superconductivity in an organic kappa salt

kappa-(ET)$_2$X phase diagram





"kappa" arrangement

ET molecules paired in dimers

Half filled conduction band

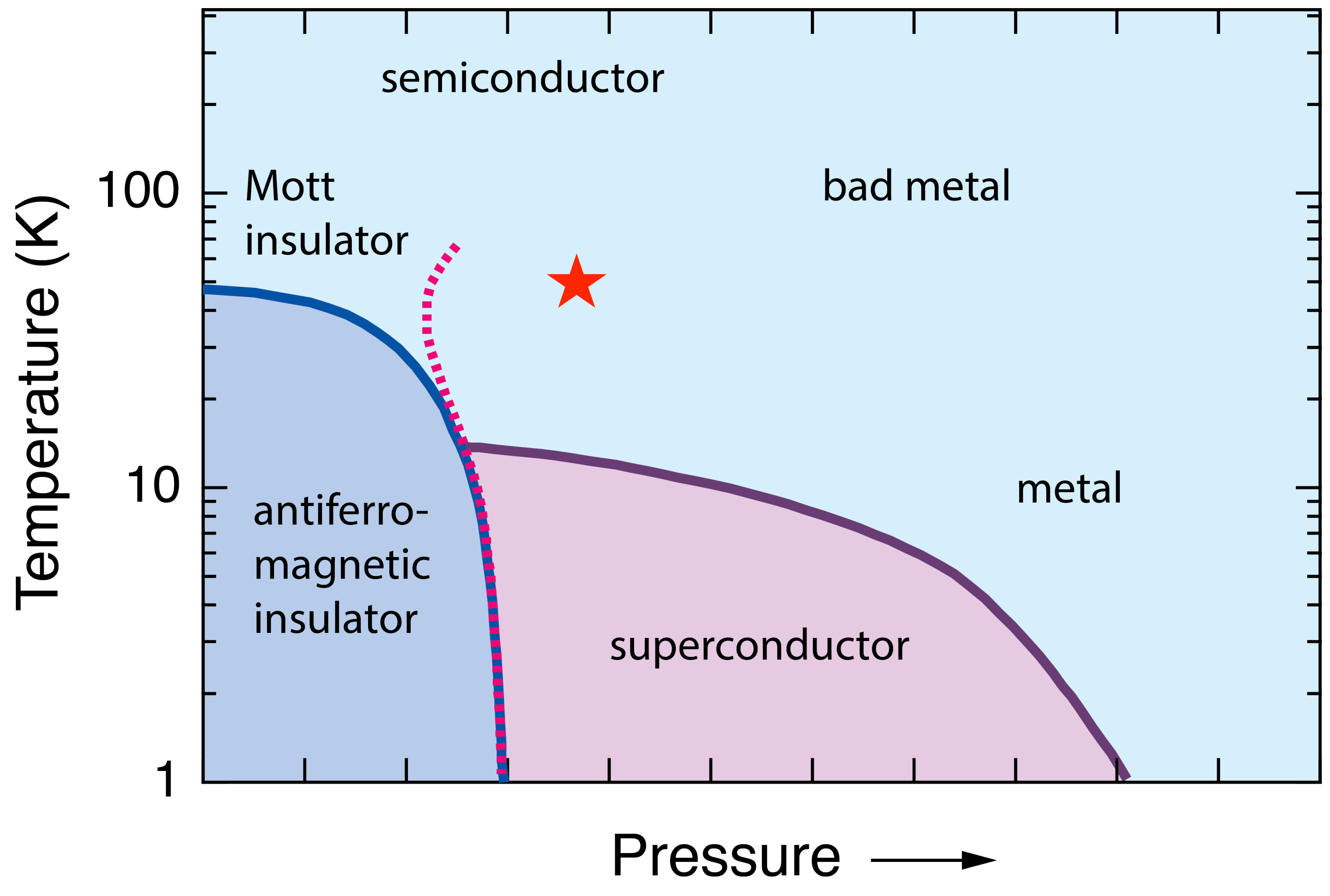
D. Faltermeier *et al.*, Phys. Rev. B **76**, 165113 (2007)

Nernst effect indicating superconducting fluctuations above Tc:
M.-S. Nam et al., Nature **449**, 584 (2007)

Light-induced superconductivity

M. Buzzi et al., PRX 10, 031028 (2020)

Photo-molecular high-temperature superconductivity in an organic kappa salt



Driving with a specific molecular vibration

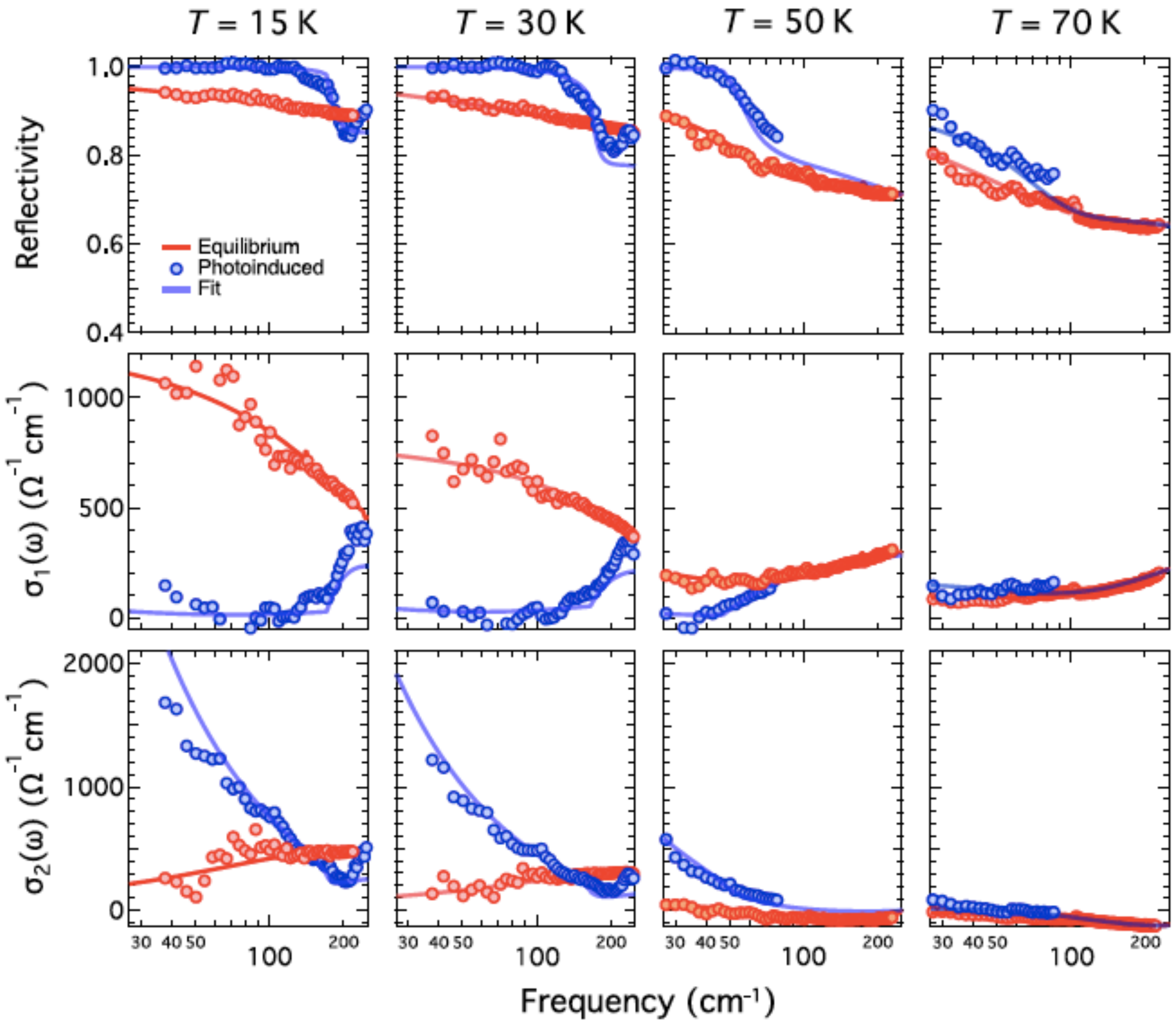


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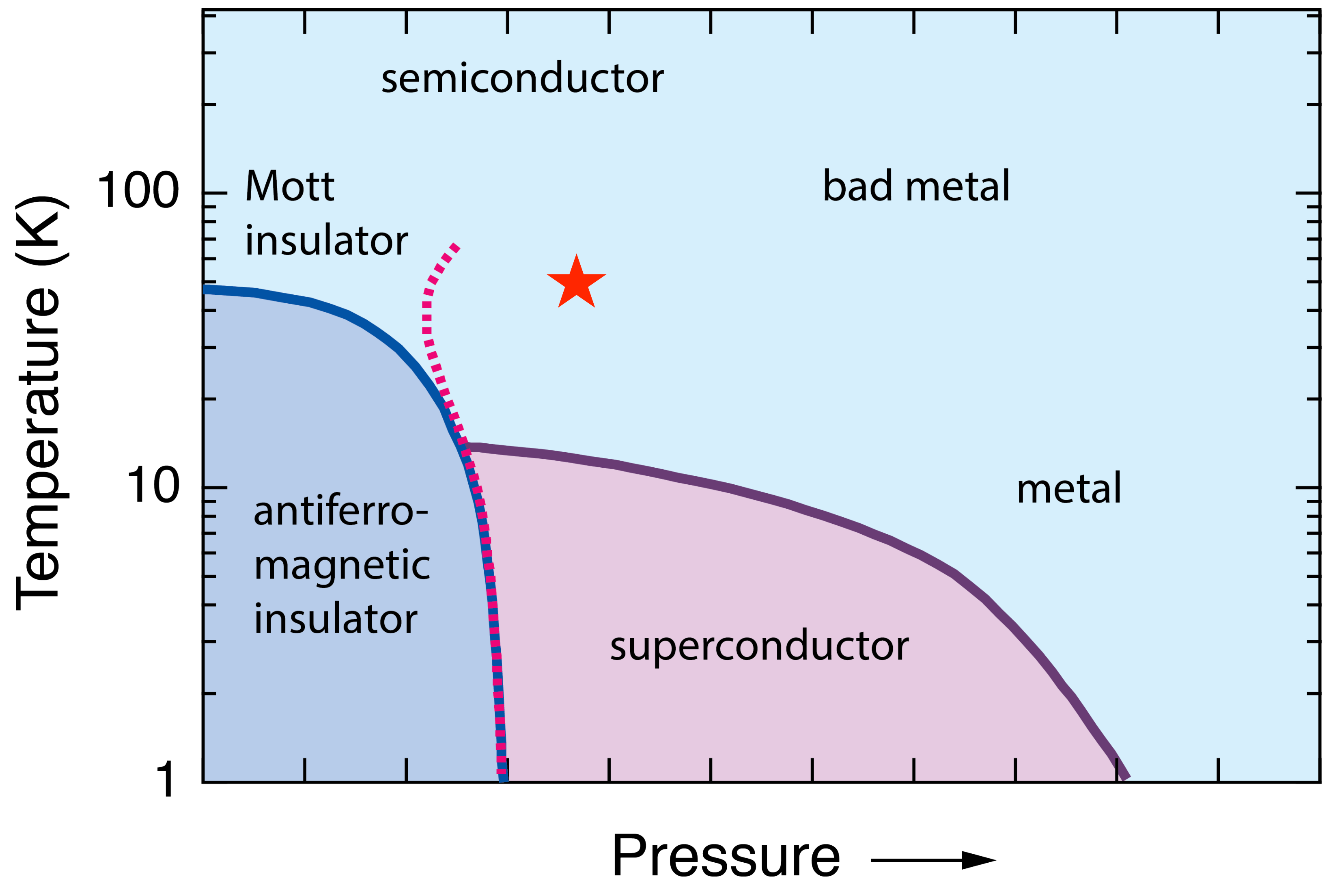
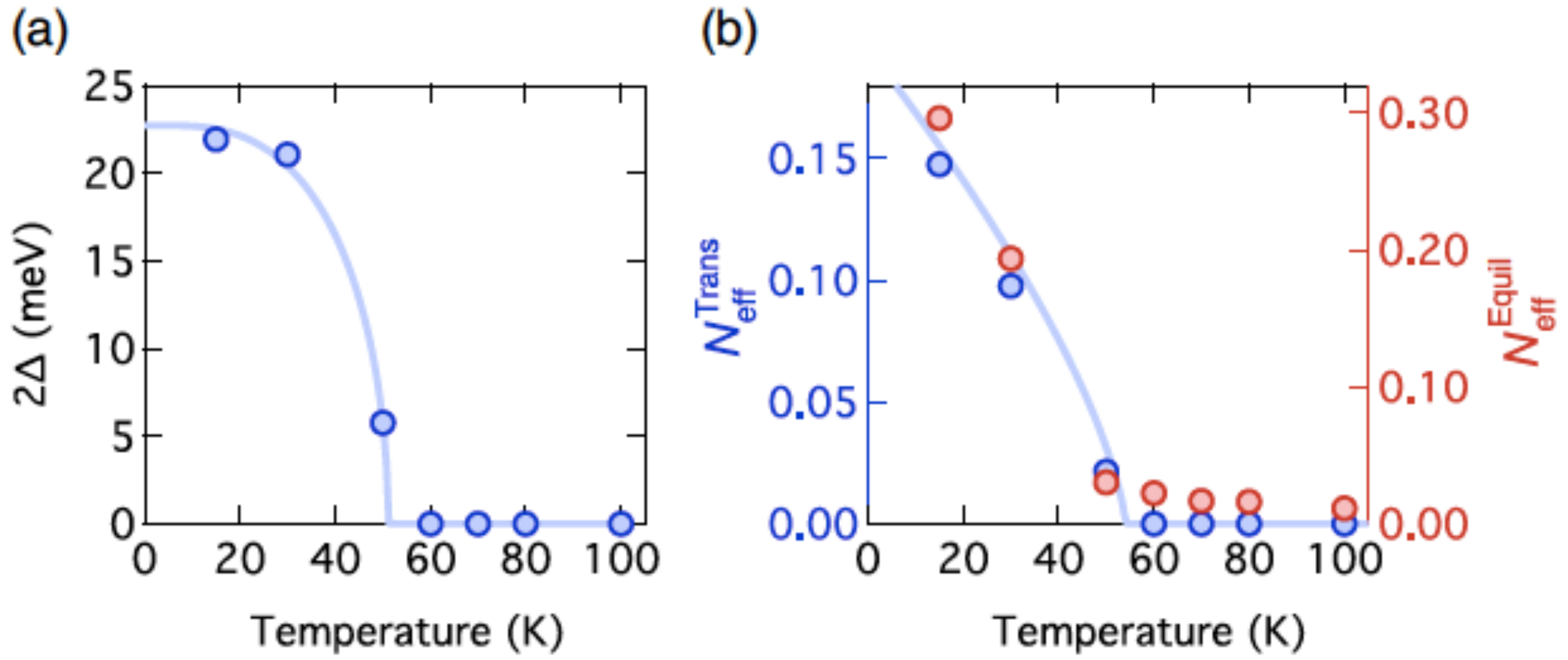
Photo-molecular high-temperature superconductivity in an organic kappa salt



The effect persists up to 50 Kelvin!
(equilibrium Tc = 12.5 K)

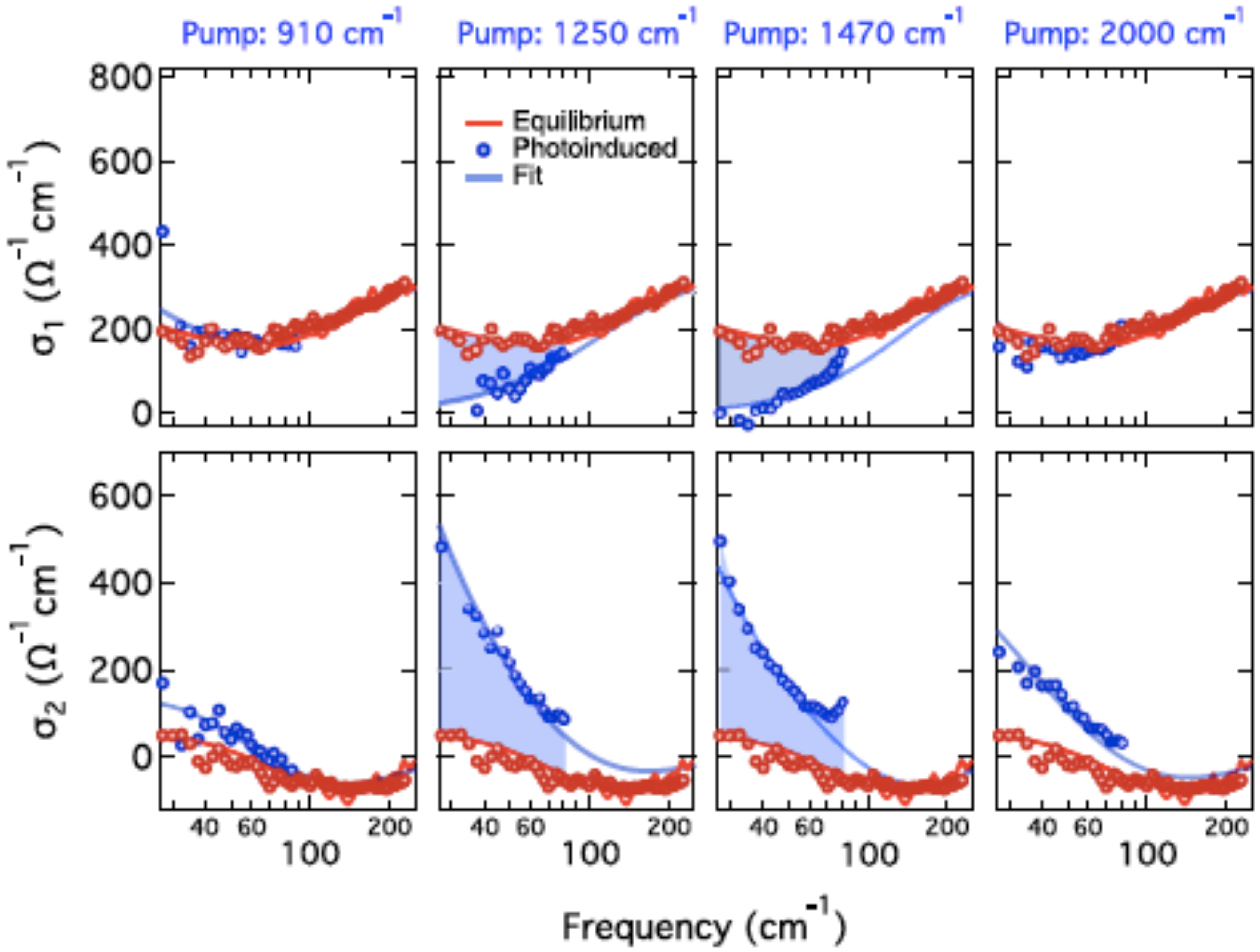


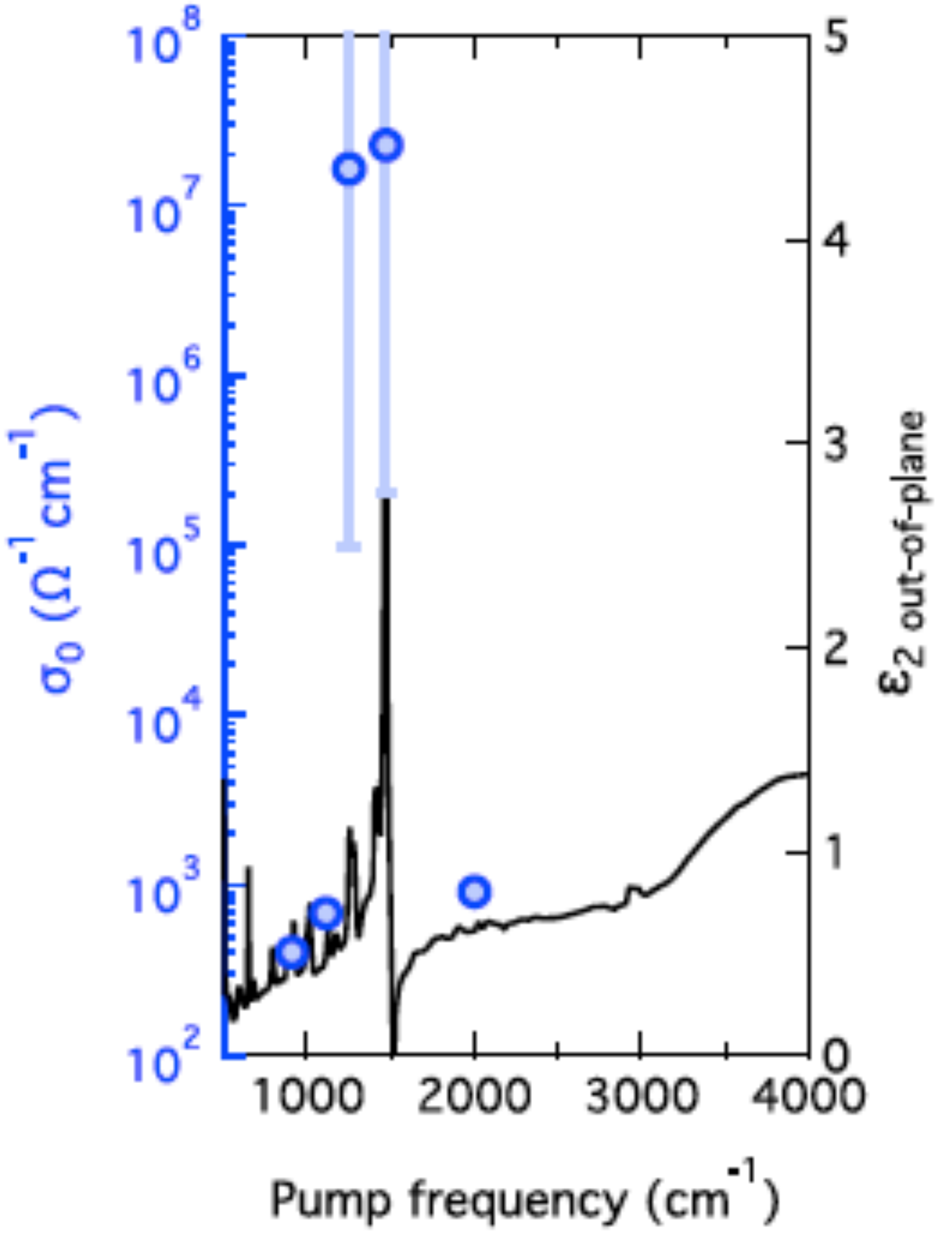
Light-induced superconductivity

M. Buzzi et al., PRX 10, 031028 (2020)

Photo-molecular high-temperature superconductivity in an organic kappa salt

It only works for specific molecular vibrations



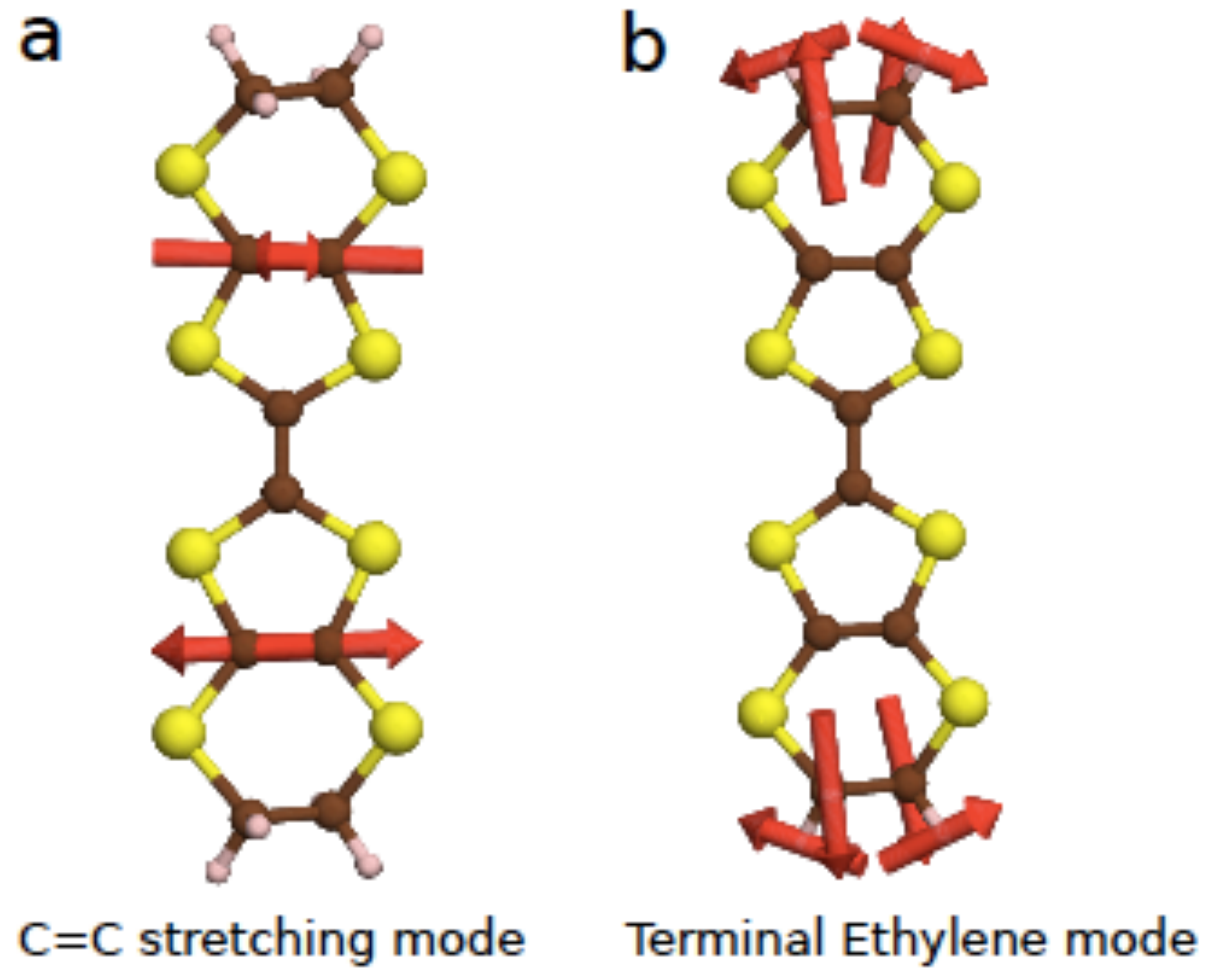


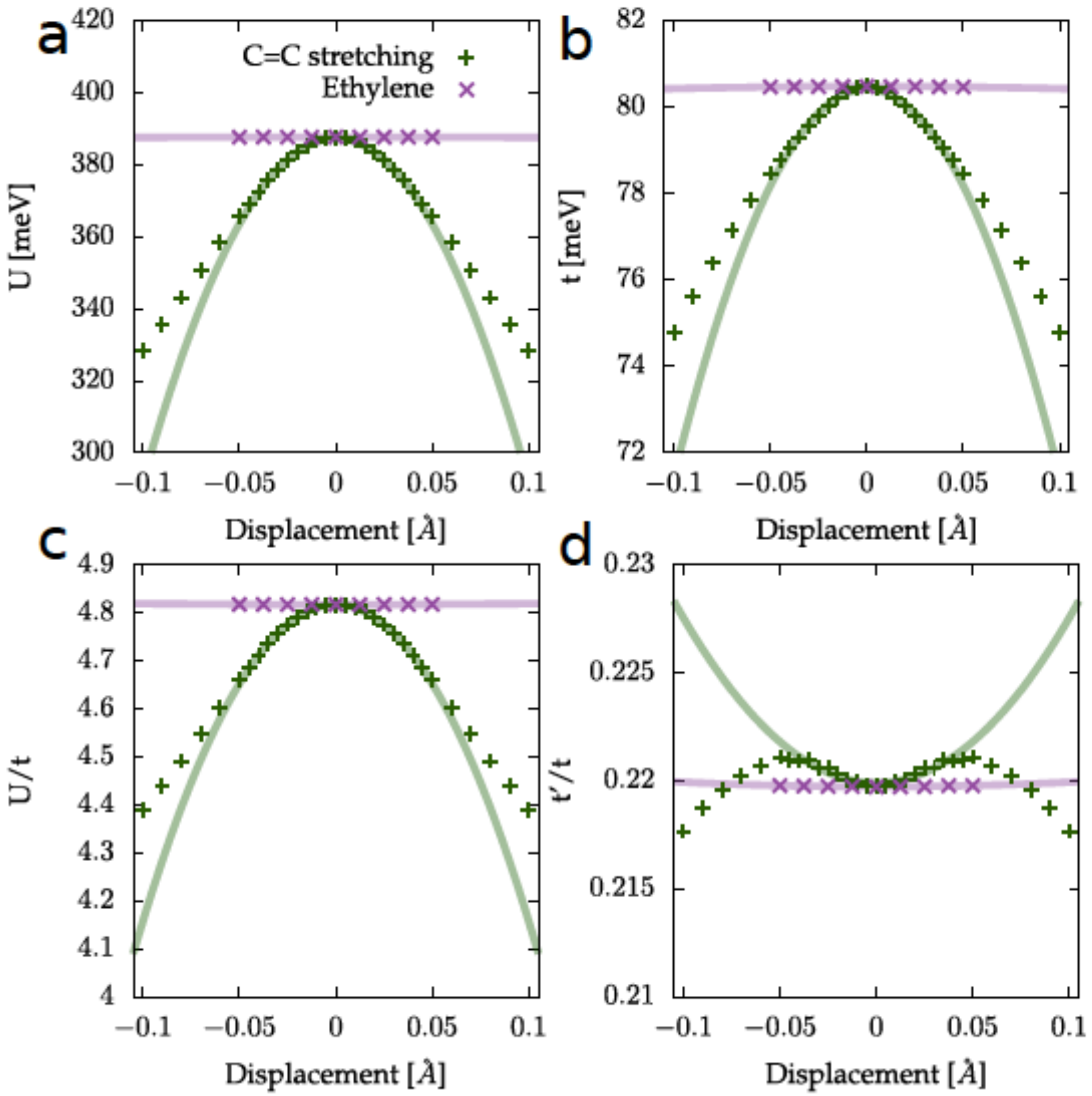
Light-induced superconductivity

M. Buzzi et al., PRX 10, 031028 (2020)

Photo-molecular high-temperature superconductivity in an organic kappa salt

What is special about these vibrations?





The C=C bond stretching modes change Hubbard U!

$$H = \sum_{<ij>,\sigma} t(c^{\dagger}_{i\sigma} c_{j\sigma} + H.c.) + \sum_{[ij],\sigma} t'(c^{\dagger}_{i\sigma} c_{j\sigma} + H.c.) + U \sum_{i} (n_{i\uparrow} - \frac{1}{2})(n_{i\downarrow} - \frac{1}{2})$$

H. C. Kandpal et al., PRL 103, 067004 (2009)

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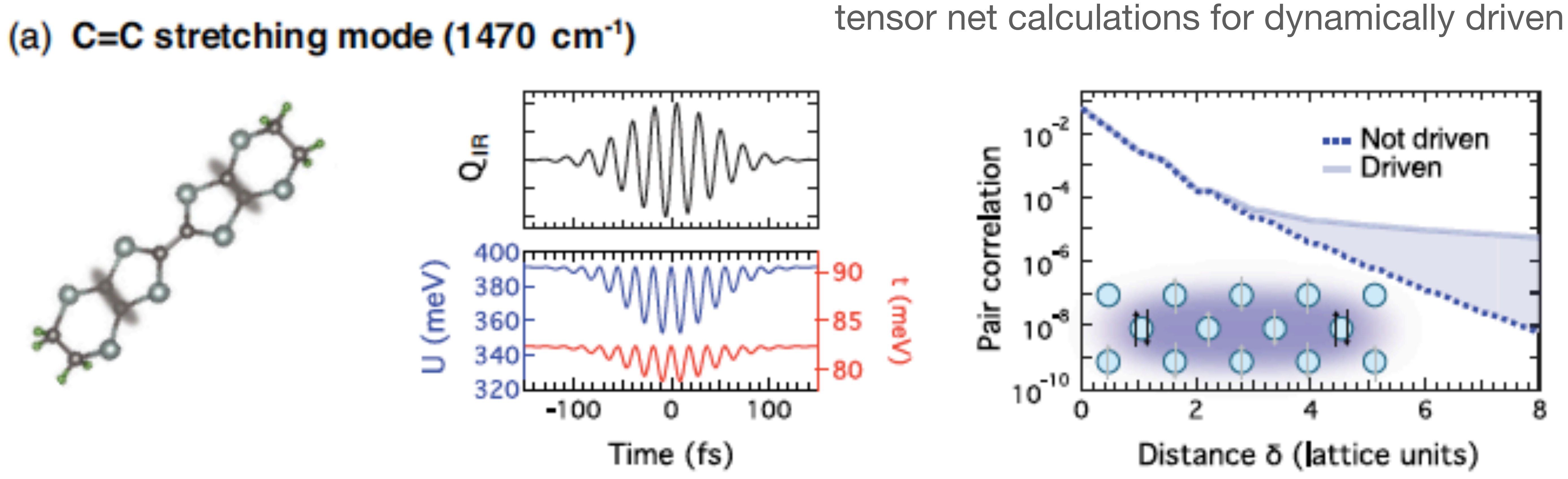
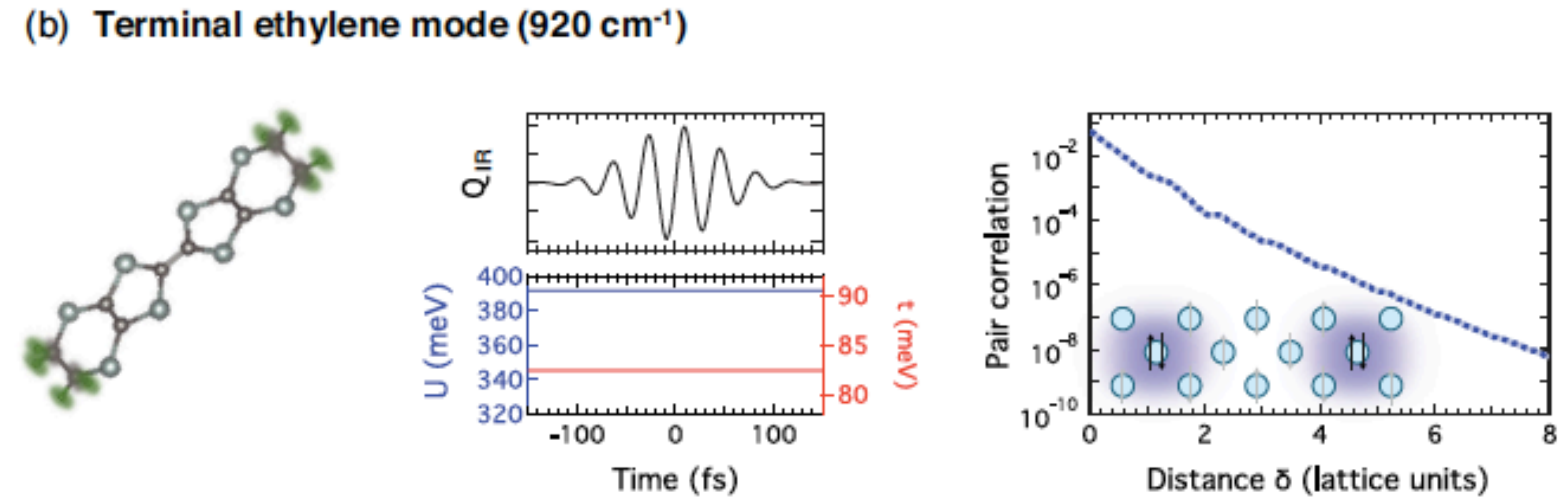
What is special about these vibrations?

tensor net calculations for dynamically driven U-t-t' Hubbard diamond chain



We find an enhancement of long-range pair correlations in a Hubbard system driven via U(t)



Theory follow-up: J. Tindall et al., PRL 125, 137001 (2020)

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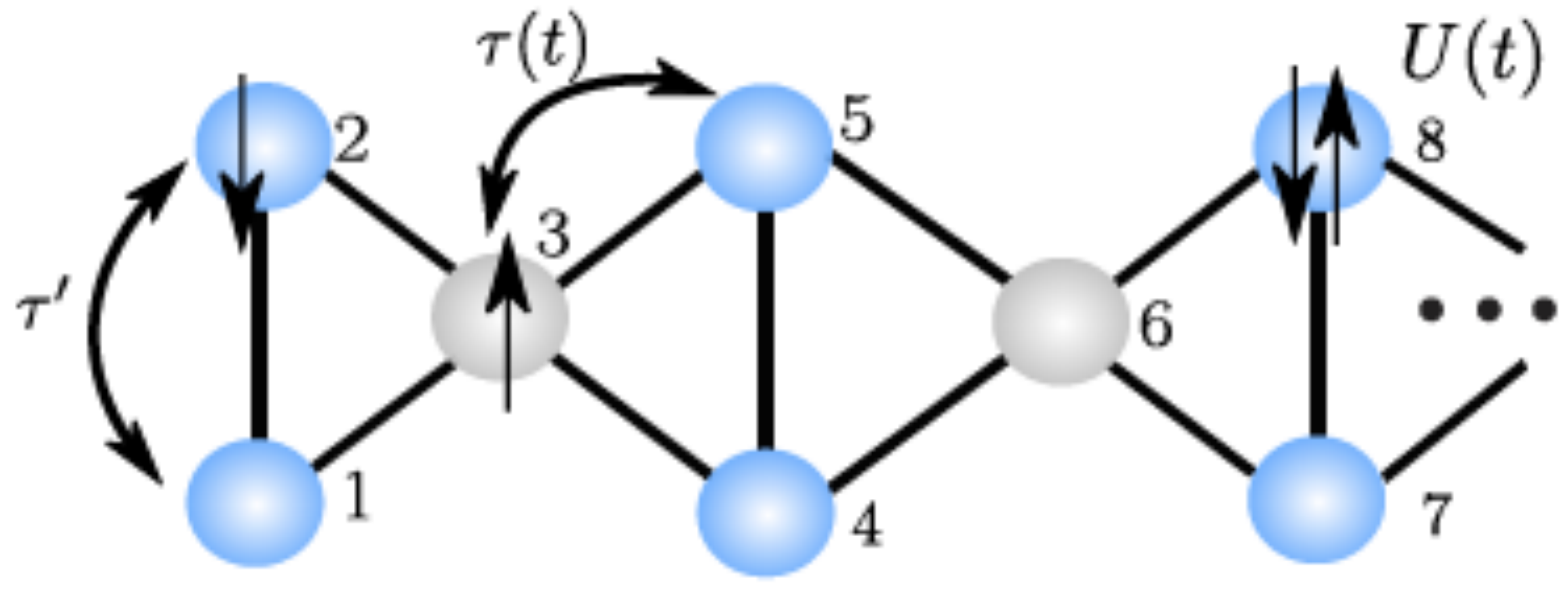
J. Tindall et al.,
PRL 125, 137001 (2020);
PRB 103, 035146 (2021)



$$H(t) = -\tau(t) \sum_{ij\in\langle \mathrm{n.n}\rangle,\sigma} (c^\dagger_{\sigma,i} c_{\sigma,j} + \mathrm{h.c}) - \tau' \sum_{ij\in\langle \mathrm{vert}\rangle,\sigma} (c^\dagger_{\sigma,i} c_{\sigma,j} + \mathrm{h.c}) + U(t) \sum_i n_{i,\uparrow} n_{i,\downarrow},$$

Approximate eta SU(2) symmetry (exact for τ'=0, bipartite lattice):

$$[H(t), \eta^z] \equiv 0, \qquad [H(t), \eta^+\eta^-] \propto \tau', \qquad (3)$$

where

$$\eta^+ = \sum_{i=1}^{L} f(i) c^\dagger_{i,\uparrow} c^\dagger_{i,\downarrow}, \qquad \eta^z = \sum_i (n_{\uparrow,i} + n_{\downarrow,i} - 1), \quad (4)$$

put reference to Yang & Zhang, SO4 paper

Light-induced superconductivity

M. Buzzi et al., PRX 10, 031028 (2020)

Photo-molecular high-temperature superconductivity in an organic kappa salt

Theory follow-up:
J. Tindall et al.,
PRL 125, 137001 (2020);
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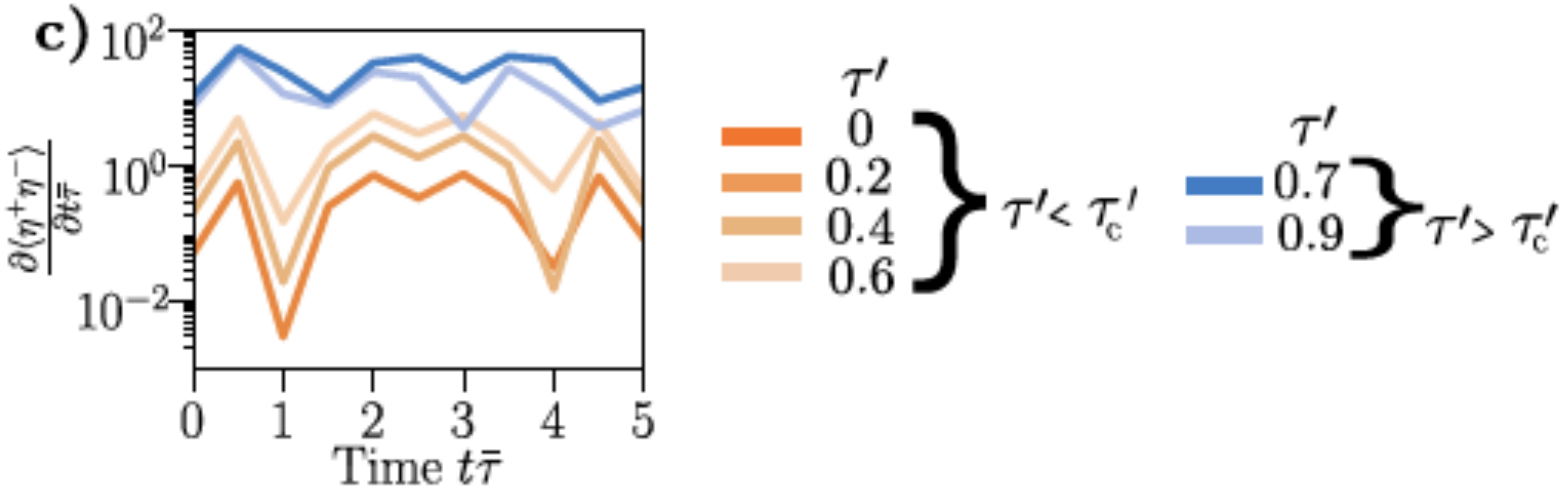
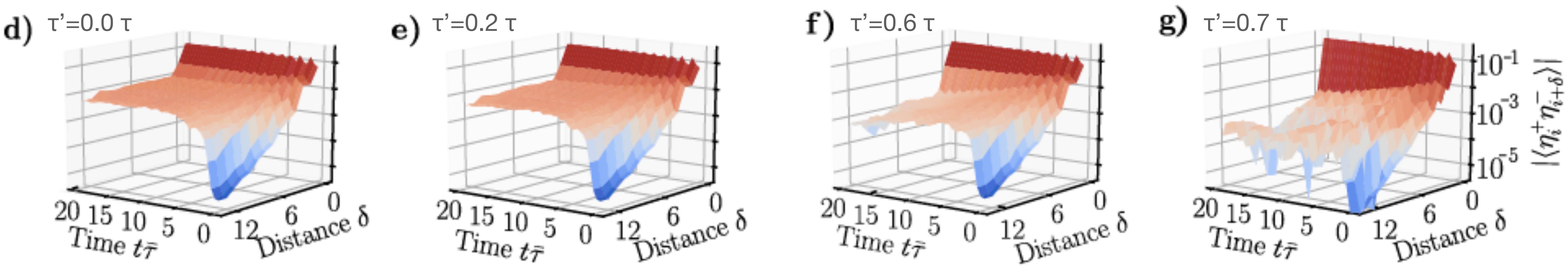


Rate of change of total $\langle\eta^+\eta^-\rangle$ tends to zero for τ’ to zero

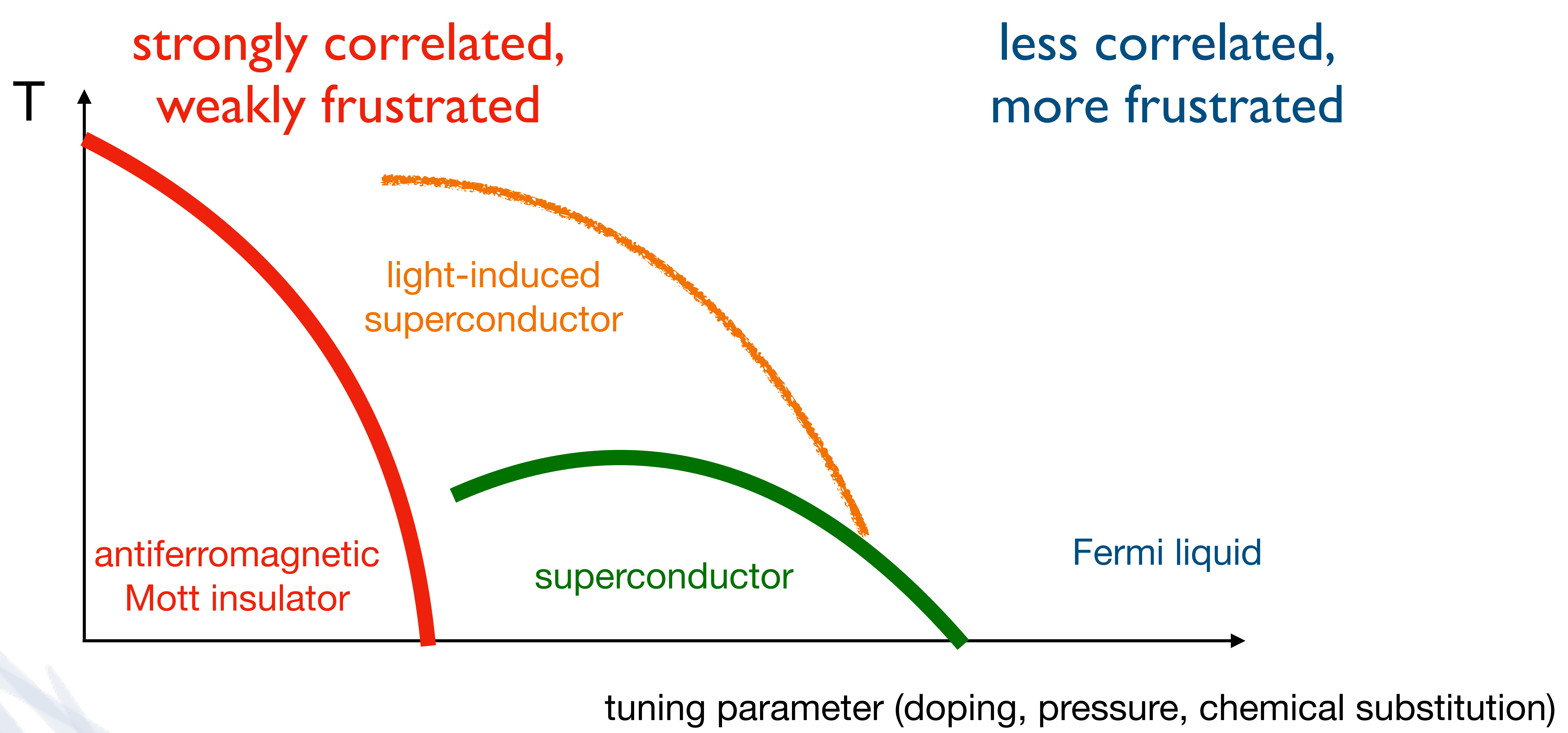


Enhancement of long-range pairing persists up to a critical value of τ’=0.7τ

„heating-induced order“: driving heats the system maximizing its entropy subject to symmetry constraints

Light-induced superconductivity

What is the big picture?



what does light-induced SC tell us about a material?
predictions? (e.g., MATBG?)

is there a generic mechanism?

what are ideal conditions for light-induced SC?

- superconducting instability at low T
- temperature typically 3-5 times equilibrium Tc
- intermediate to strong correlations - fluctuation regime above Tc

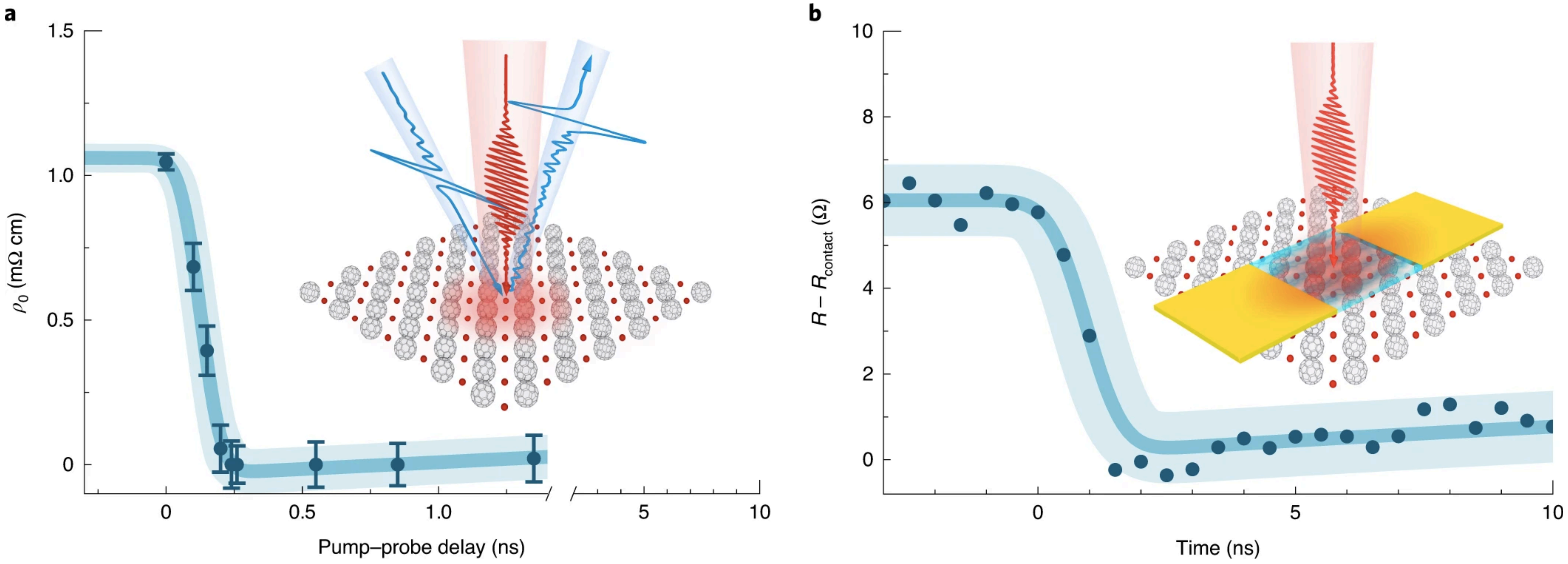
Long-lived light-induced SC?

LIGHT-INDUCED SUPERCONDUCTIVITY

Stay just a little bit longer

The short lifetime of light-induced superconductivity prevents the measurement of its transport properties. Encouraging this state to stay a little longer in K_3C_{60} allows the observation of vanishing electrical resistance.

Anshul Kogar



Budden, M. et al. *Nat. Phys.* https://doi.org/10.1038/s41567-020-01148-1 (2021).

Acknowledgments

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Emmy Noether-Programm

Deutsche Forschungsgemeinschaft DFG

Thank you for your attention!