Ultrafast optical spectroscopy of strongly correlated materials and high-temperature superconductors: a non-equilibrium approach

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ILAMP

Interdisciplinary laboratories for advanced materials physics

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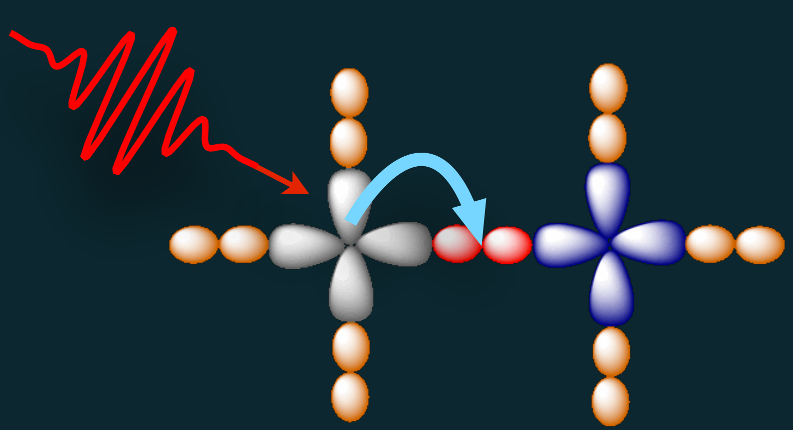


outline

- Ultrafast spectroscopies to investigate the electron dynamics in materials
  C. Giannetti et al. *Advances in Physics* **65**:2, 58-238 (2016)

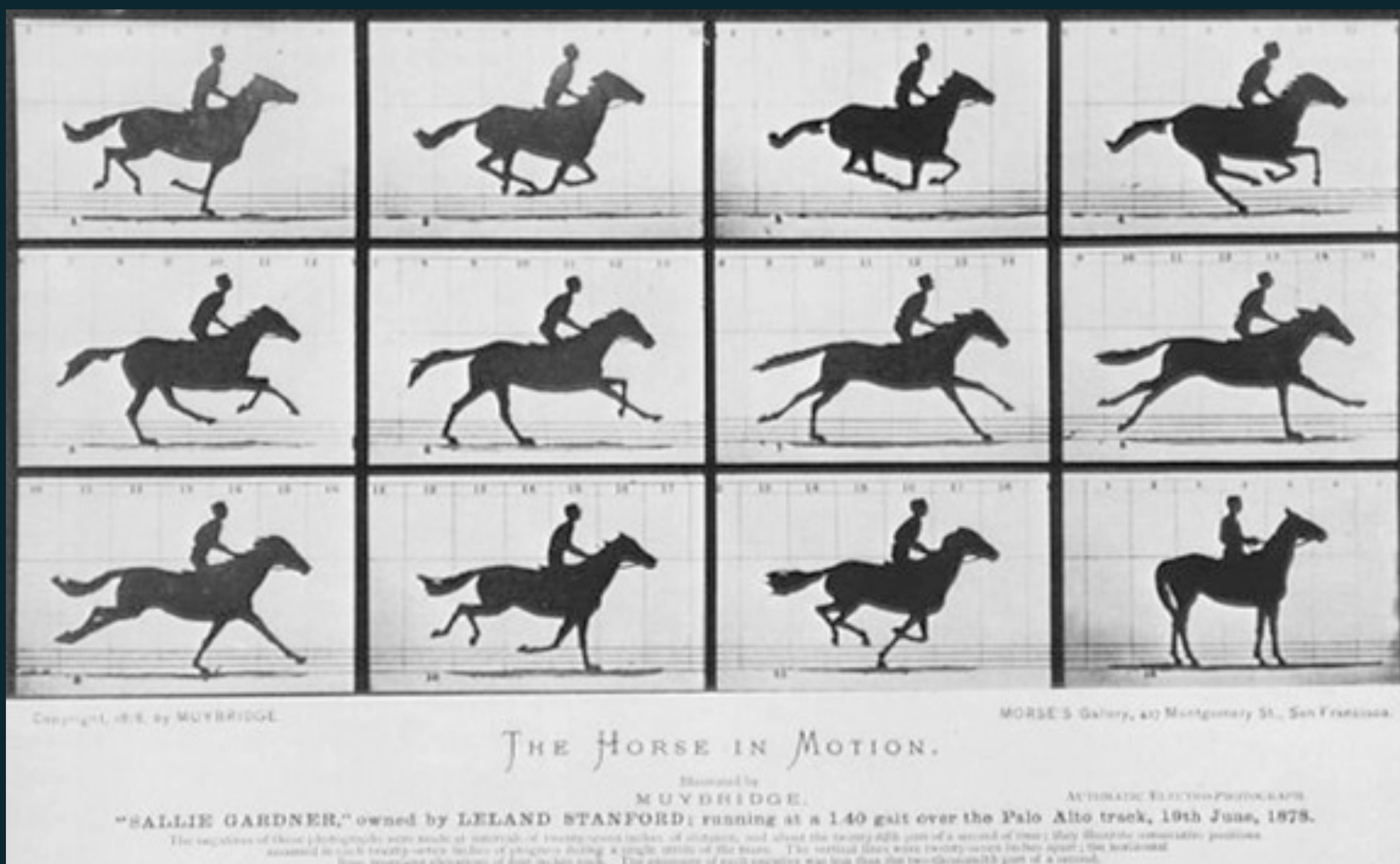
- light pulses to UNDERSTAND equilibrium properties
  ⇒ pairing glue in high-T_c superconductors

- light pulses to MANIPULATE materials properties
  ⇒ hidden states, transient photo-enhanced superconductivity

- light pulses to EXCITE specific degrees of freedom
  ⇒ coherent lattice oscillations and Higgs modes

time-resolved optics

High-speed photography by E. Muybridge (1872, San Francisco)



ultrafast shutter?

Nobel Lecture by A. Zewail (1999)
(femtochemistry)

stroboscopic pictures

stroboscopic light

⇒flashes of light shorter than the timescale of the dynamics

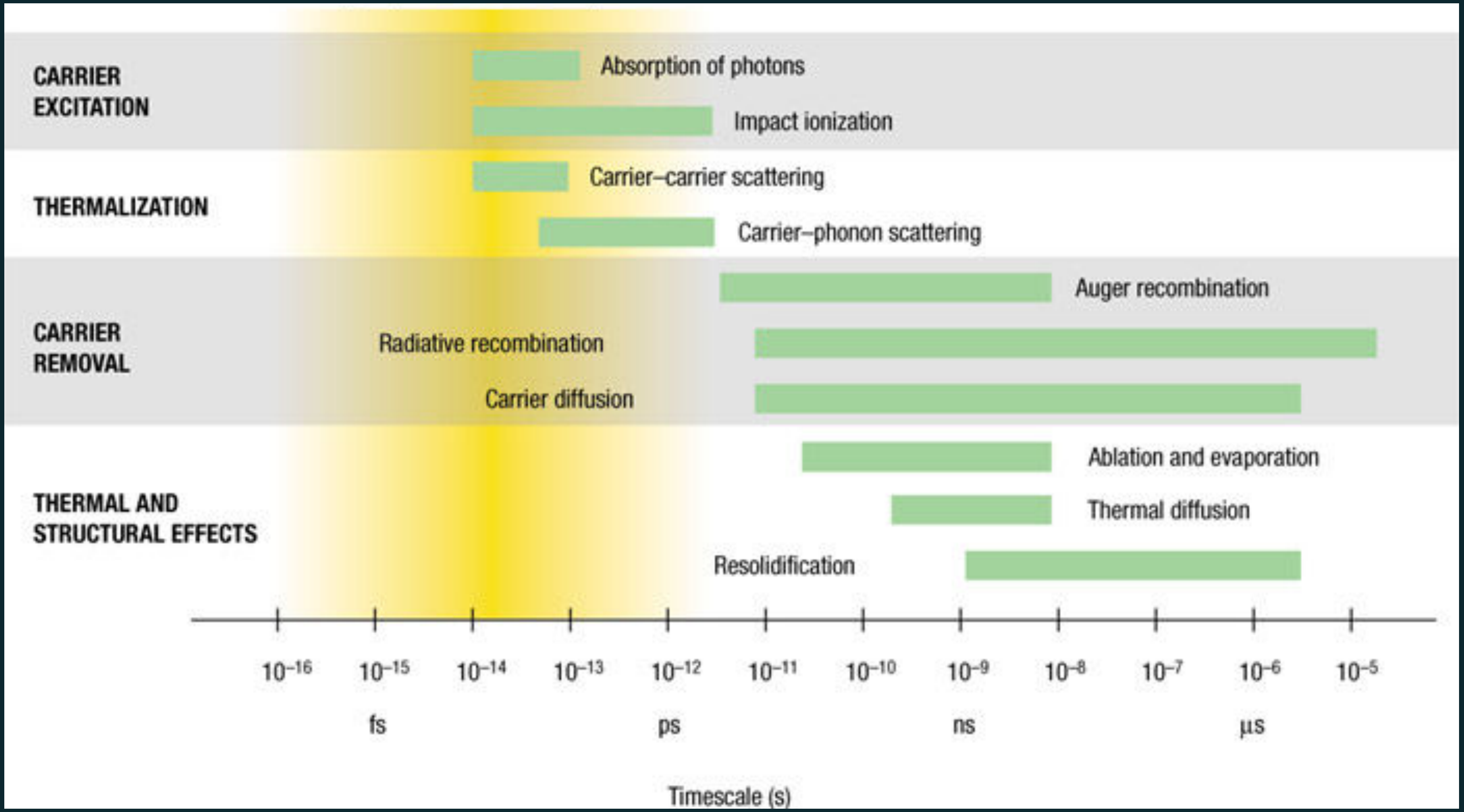
time

how fast?

1 μs shutter

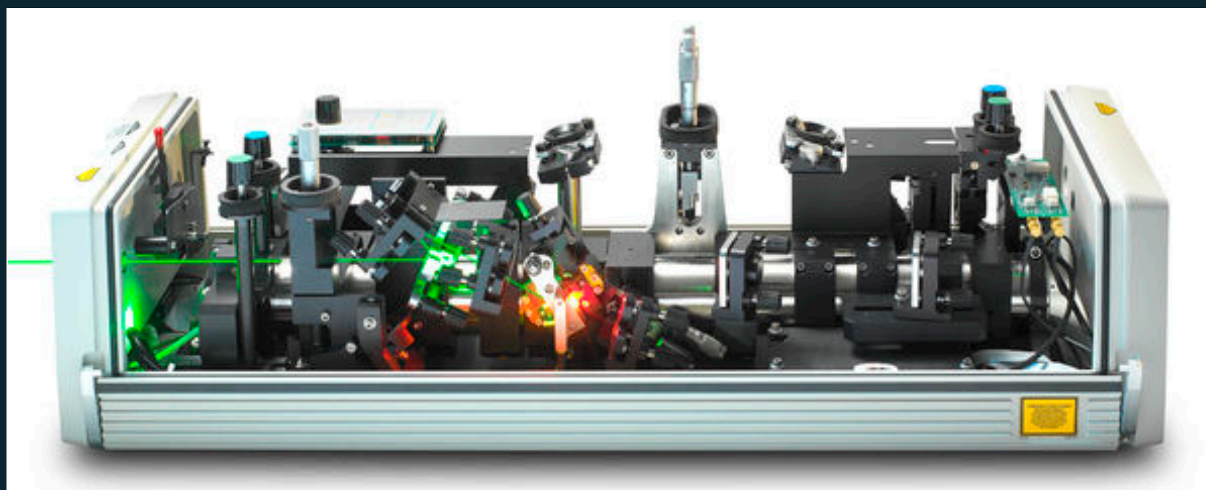
Is it possible to snap the electron dynamics in real materials?

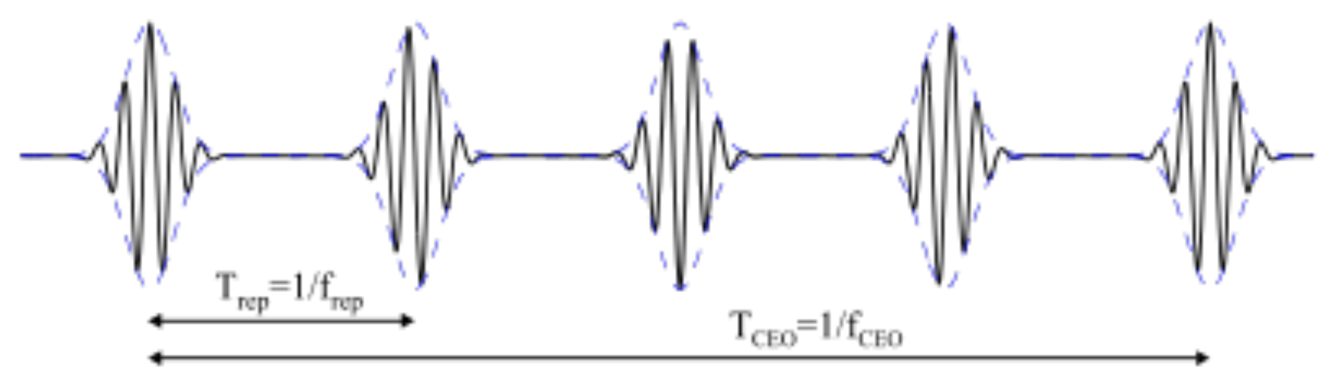
$\hbar \approx 650$ meV fs



S. K. Sundaram & E. Mazur. *Nature Materials* 1, 217-224 (2002)

⇒ femtosecond flashes of lights





Nobel prize to A. Zewail (1999)
(femtochemistry)

10 fs

electromagnetic field

1 femtosecond = 10^{-15} s = 0.000000000000001 s

optical cycle: 2 fs @ 600 nm

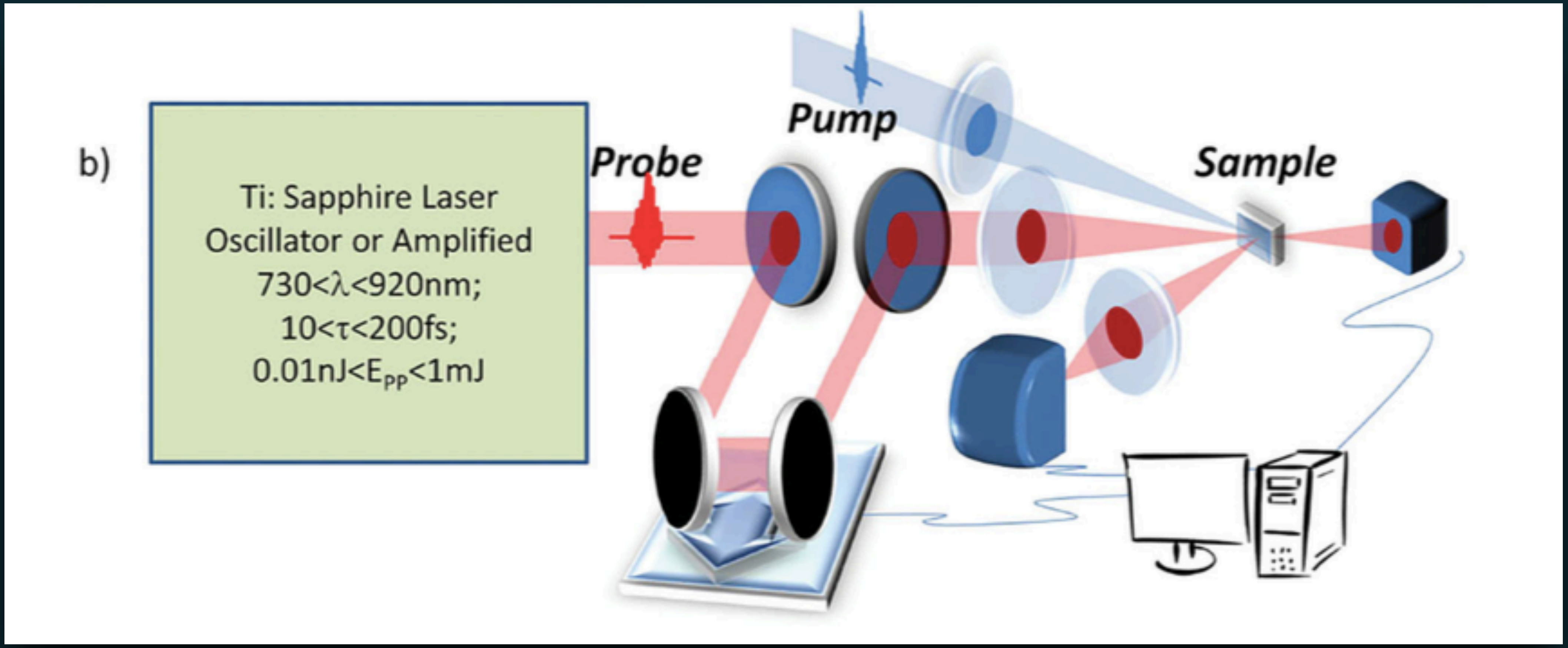
femto-photography

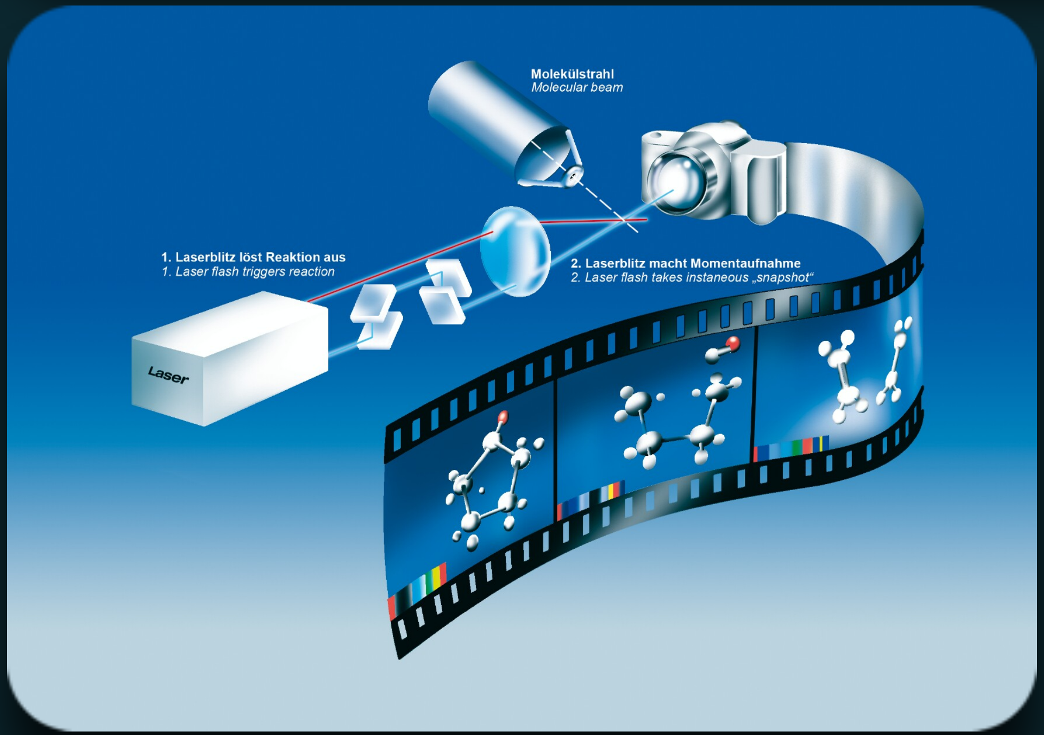
10 cm ⇒ 100 picoseconds @ speed velocity

femtocamera.info (MIT)

pump-probe spectroscopy in solids

C. Giannetti et al. *Advances in Physics* **65**:2, 58-238 (2016)





movies of chemical reactions and electronic interactions in materials electromagnetic properties

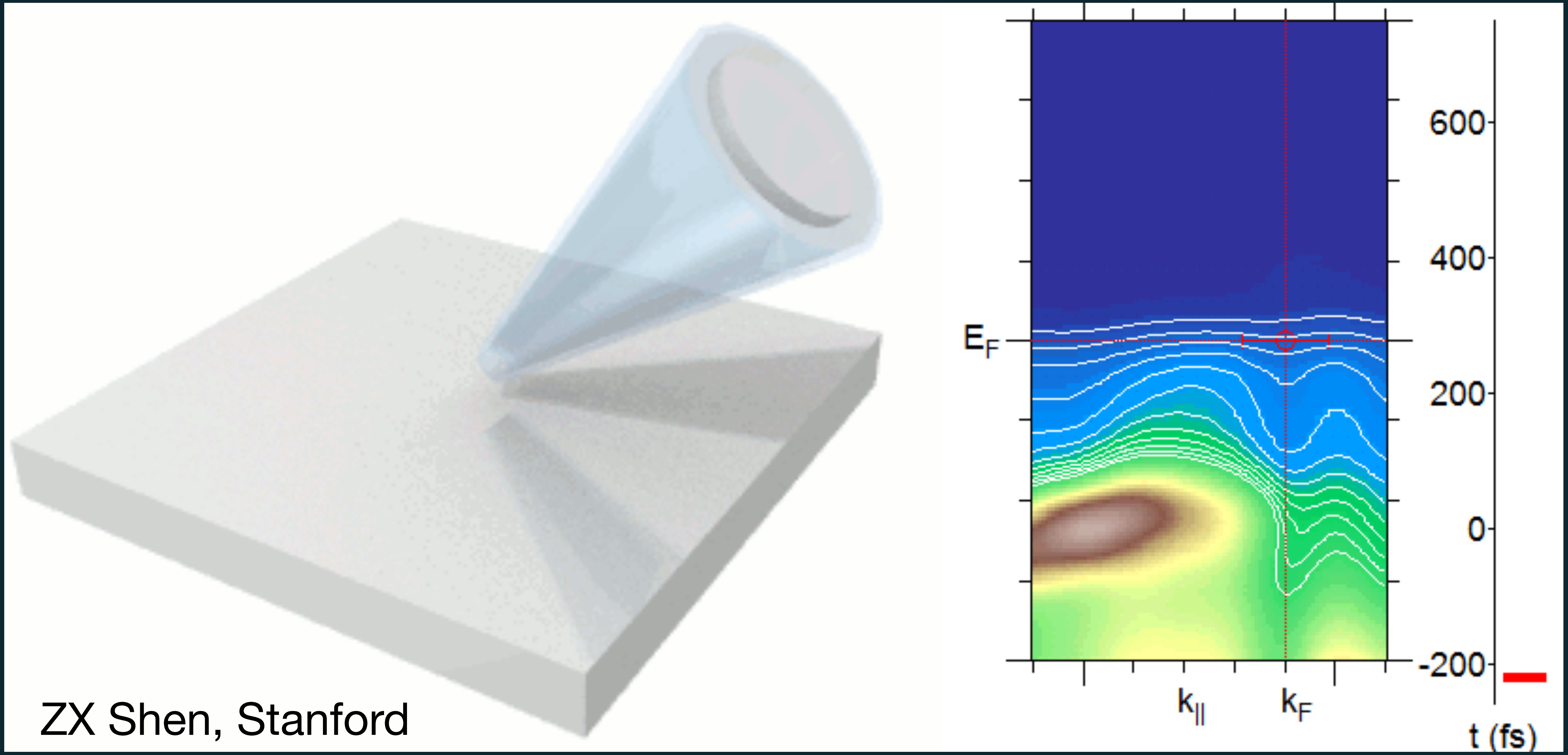
bandstructure

how many degrees of freedom it is possible to probe?

lattice

long-range orders

bandstructure



Angle-Resolved-Photoemission-Electron-Spectroscopy

energy-momentum conservation

$$E_{kin} = \hbar\omega - \Phi - |E_B|$$

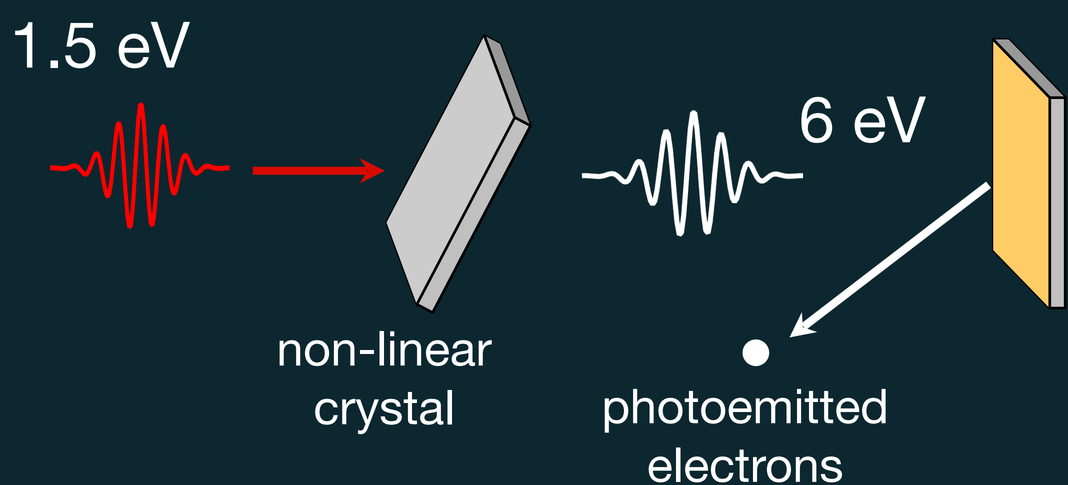
$$\hbar \mathbf{k}_{||} = \sqrt{2mE_{kin}} \cdot \sin\theta$$

⇒ mapping band dispersion:

$$E_B(\mathbf{k}_{||})$$

time-resolved ARPES

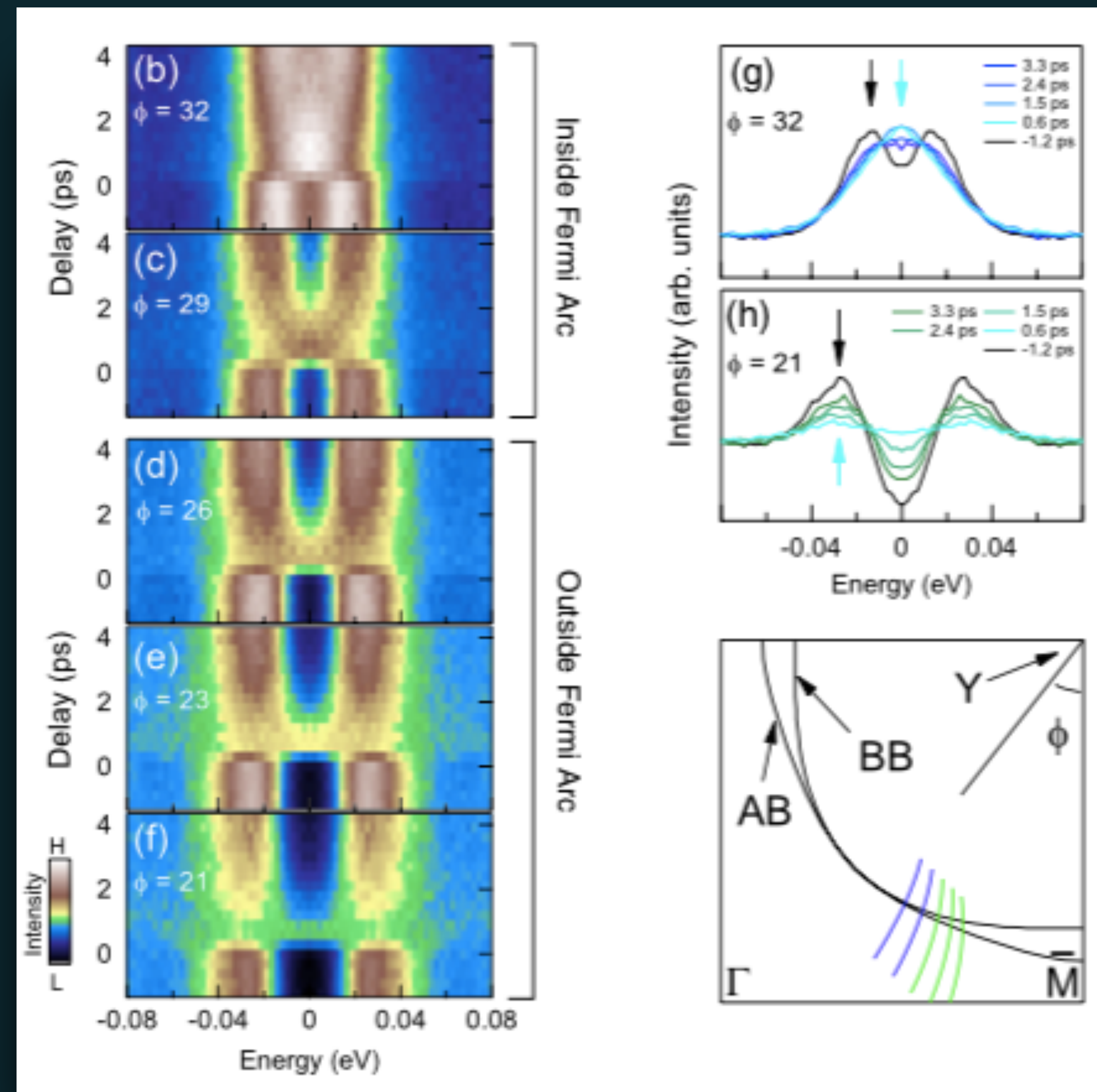
conventional scheme



LIMITS

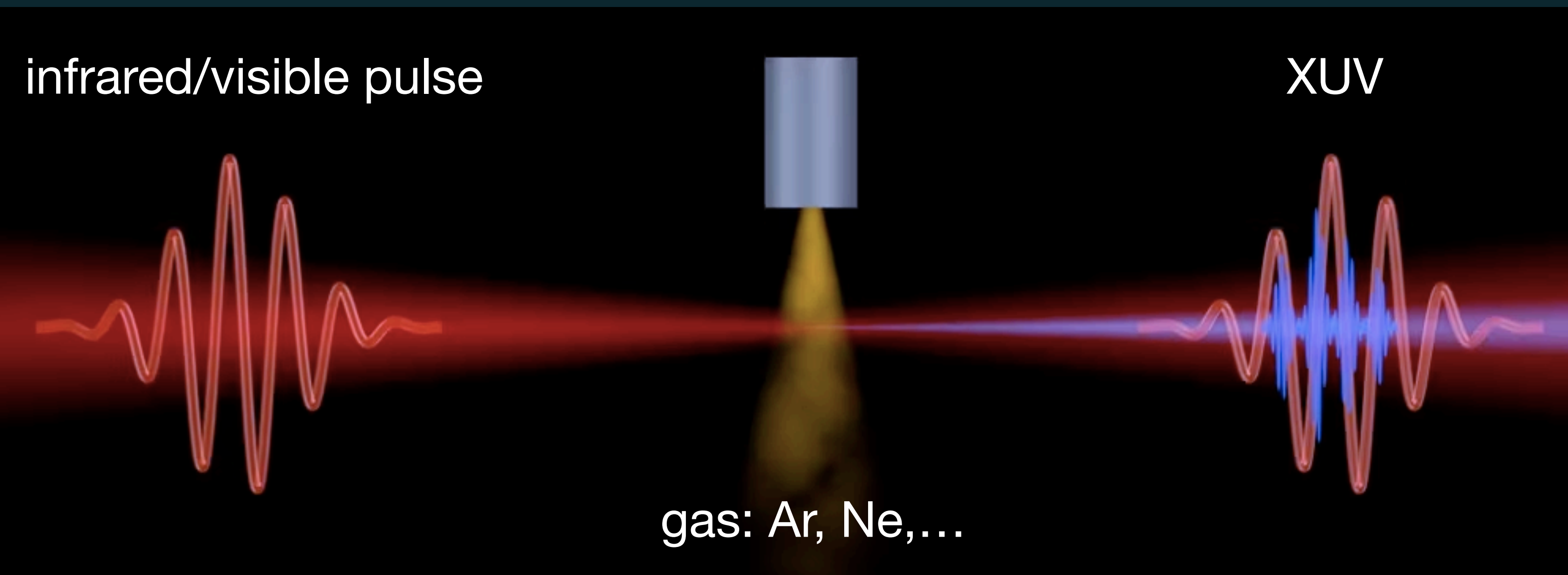
- momentum: no access to the antinodal region
- energy: no access to binding energies >1 eV

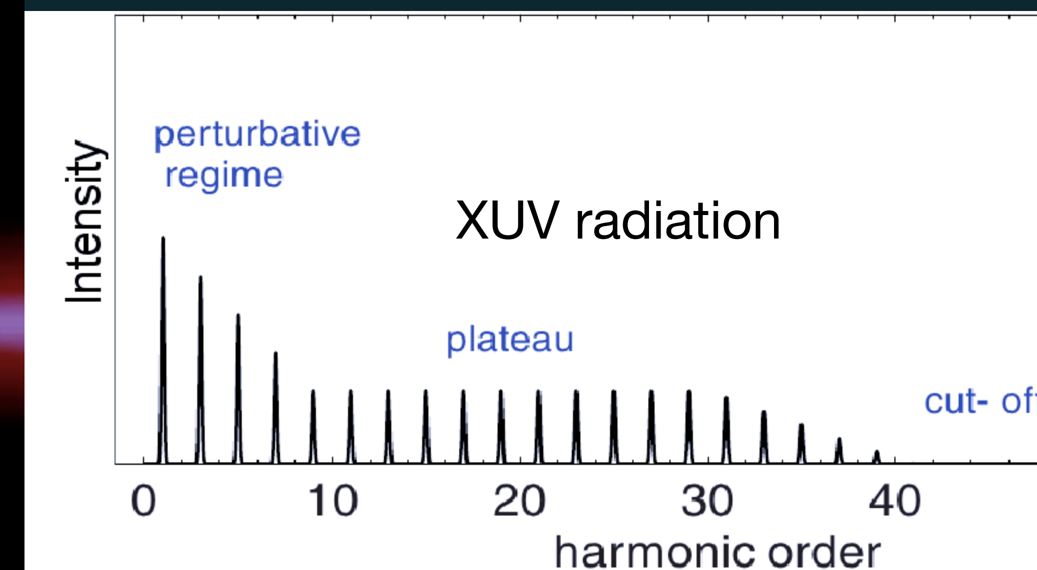
Nodal-Gap dynamics in superconducting copper oxides

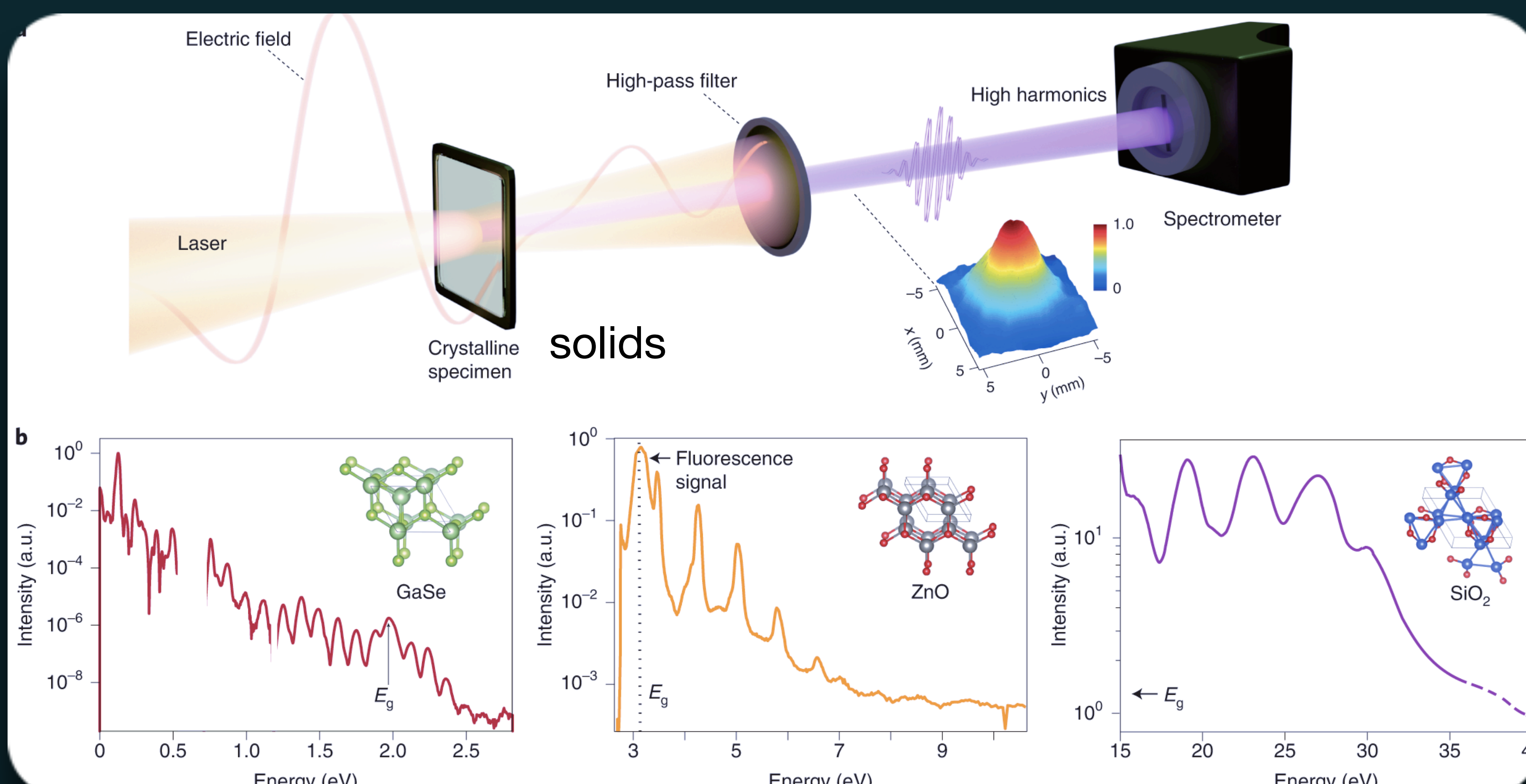


C. Smallwood et al. et al, *Phys. Rev. B* **89,** 115126 (2014)

high-harmonics generation

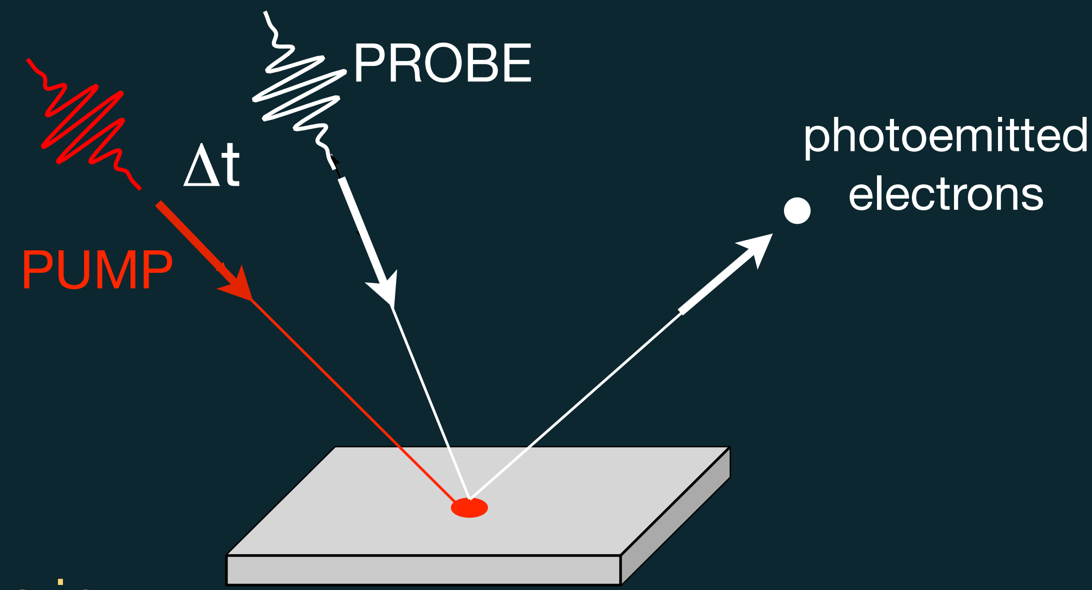




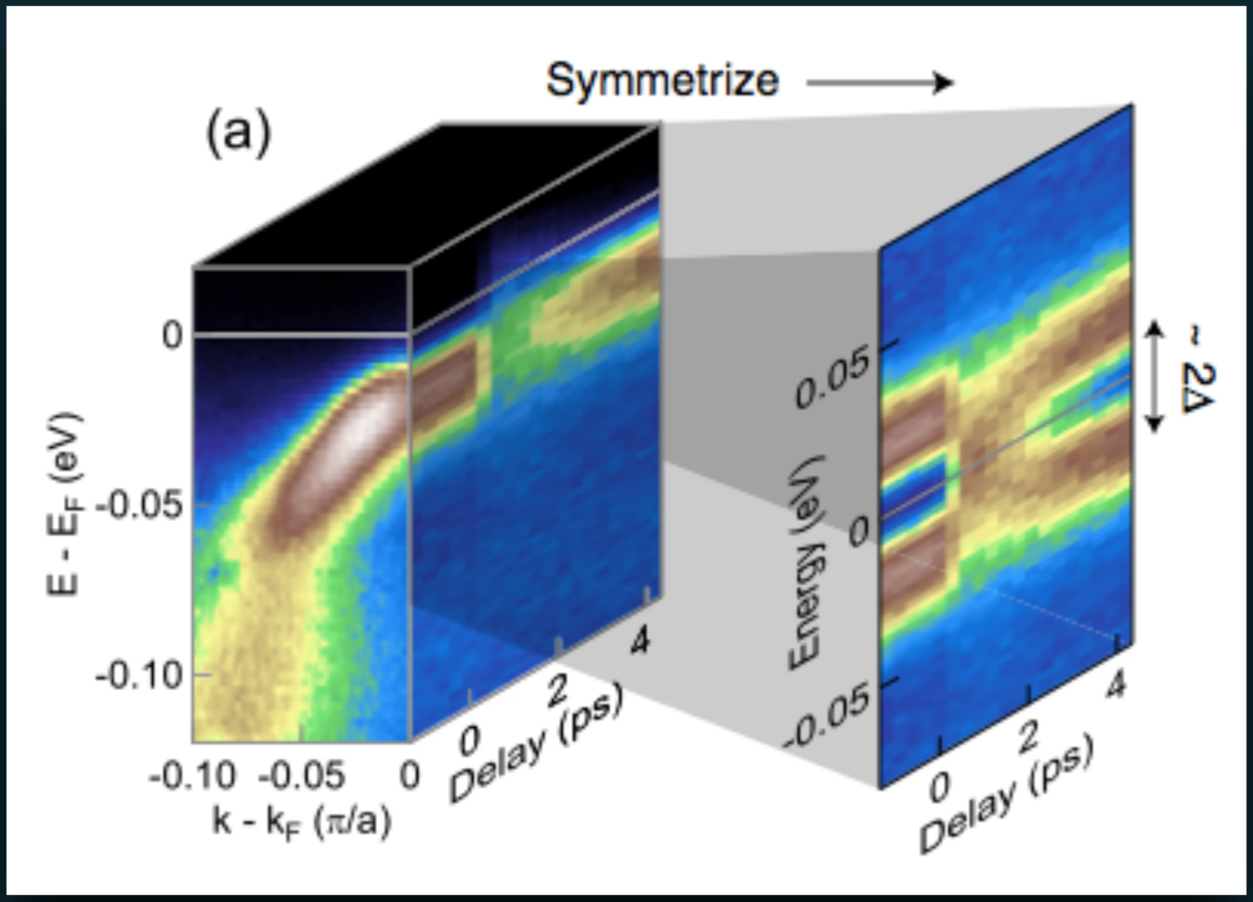


E. Goulielmakis et al., Nature Photonics **16**, 411–421 (2022)

time-resolved ARPES

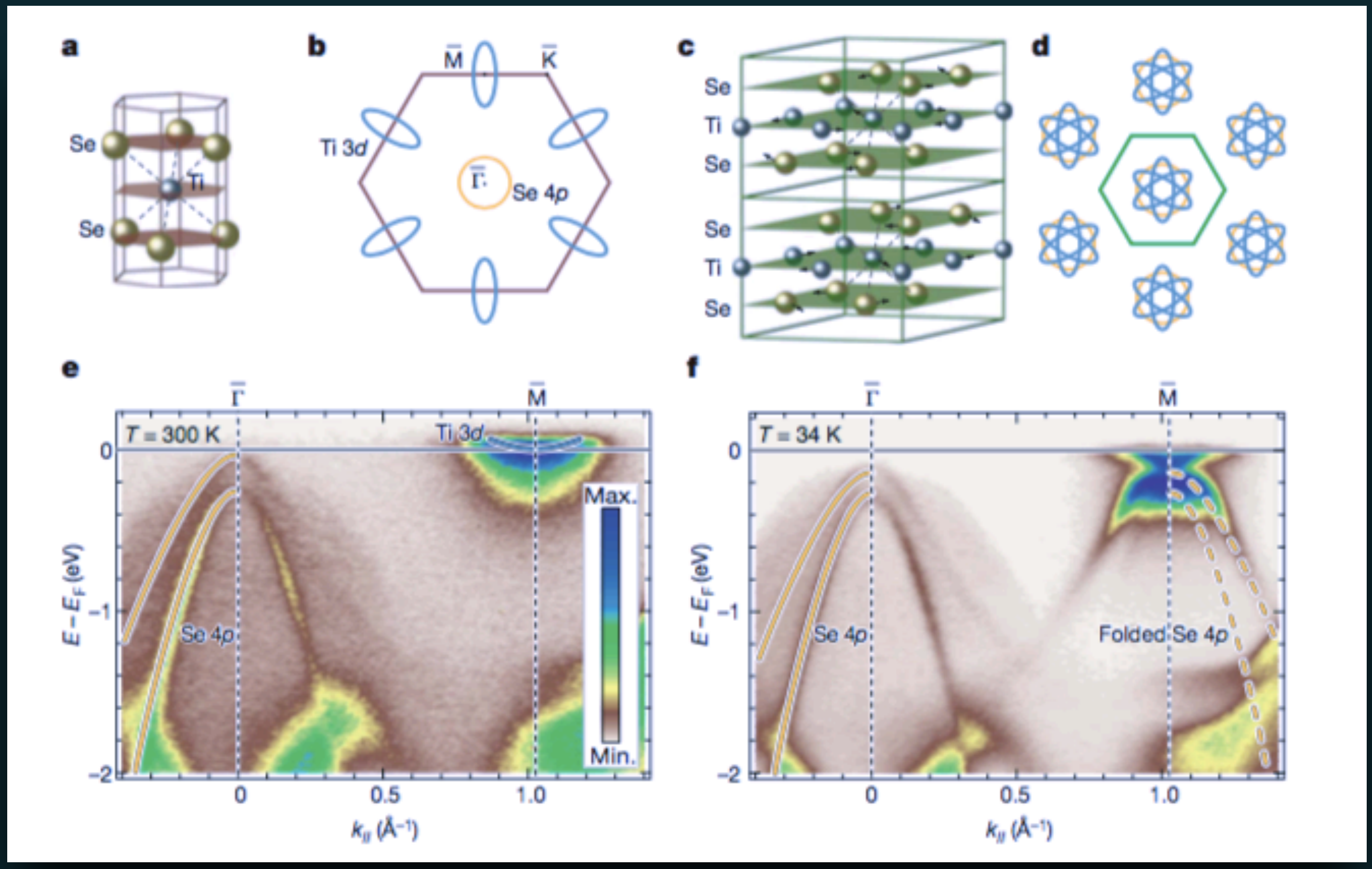


Nodal-Gap dynamics in superconducting copper oxides
UV probe



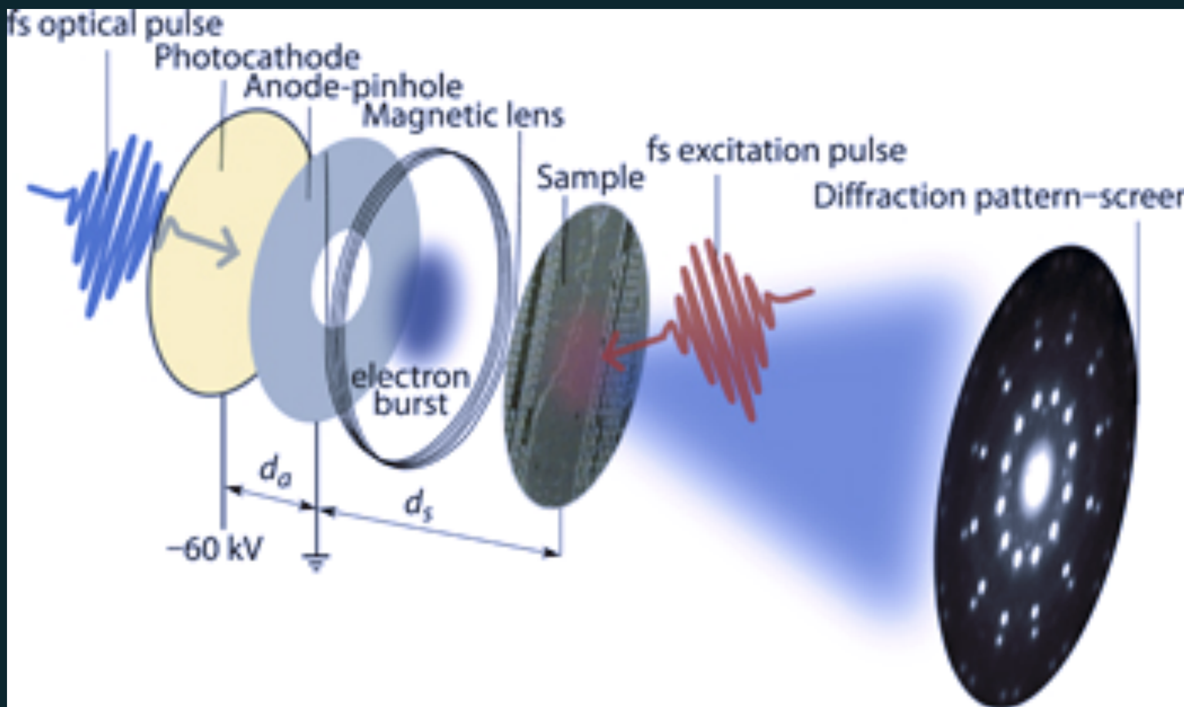
C. Smallwood et al., *Phys. Rev. B* **89,** 115126 (2014)

Collapse of long-range charge order in 1*T*-$TiSe_2$
X-ray probe



T. Rohwer et al., *Nature 471*, 490-494 (2011)

Lattice

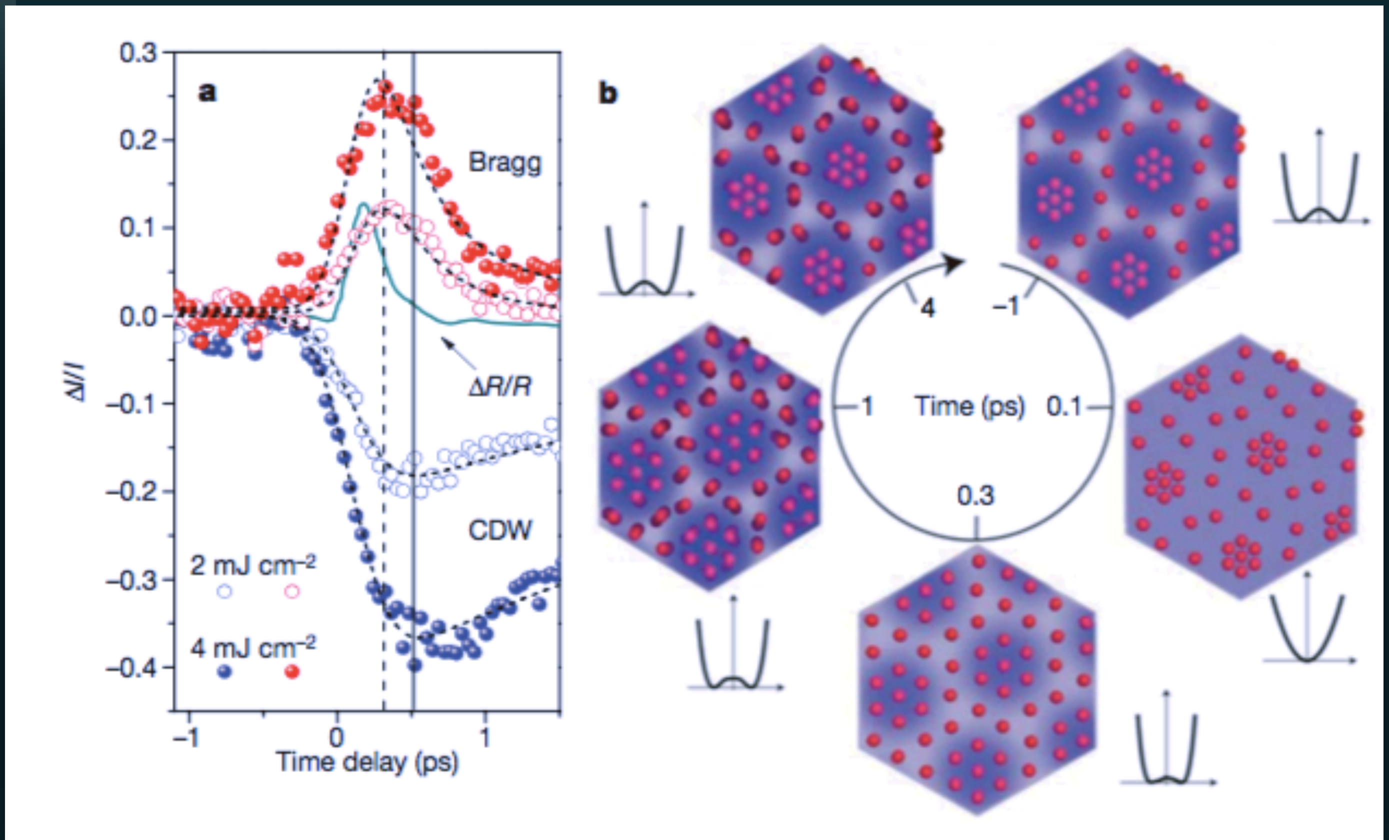


A.J. McCulloch et al., *J. Phys. B: At. Mol. Opt. Phys.* **49,** 164004 (2016)

100 fs bunch of electrons

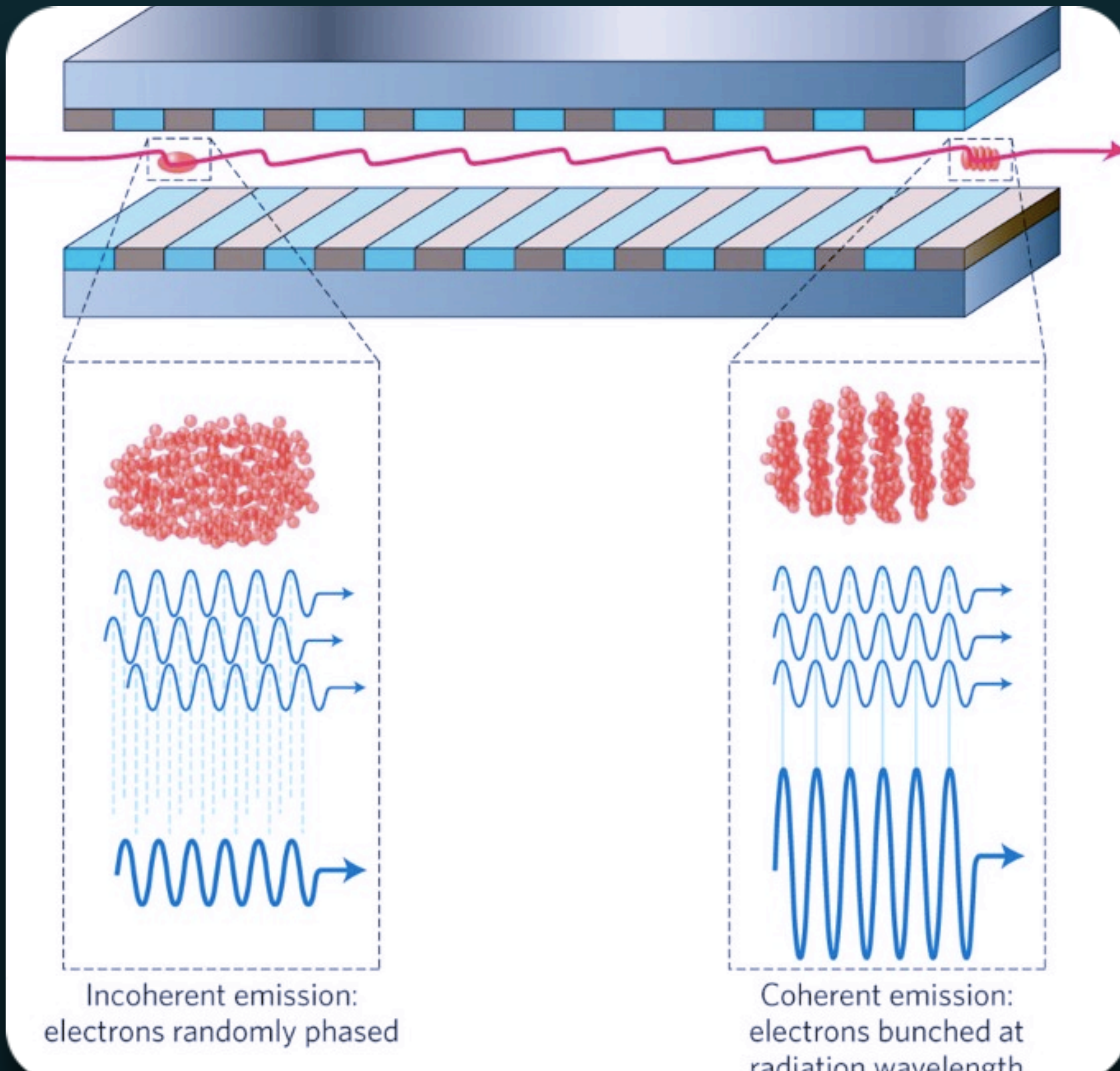
PHYSICS:
- photo-induced structural phase transitions
- dynamics of the lattice

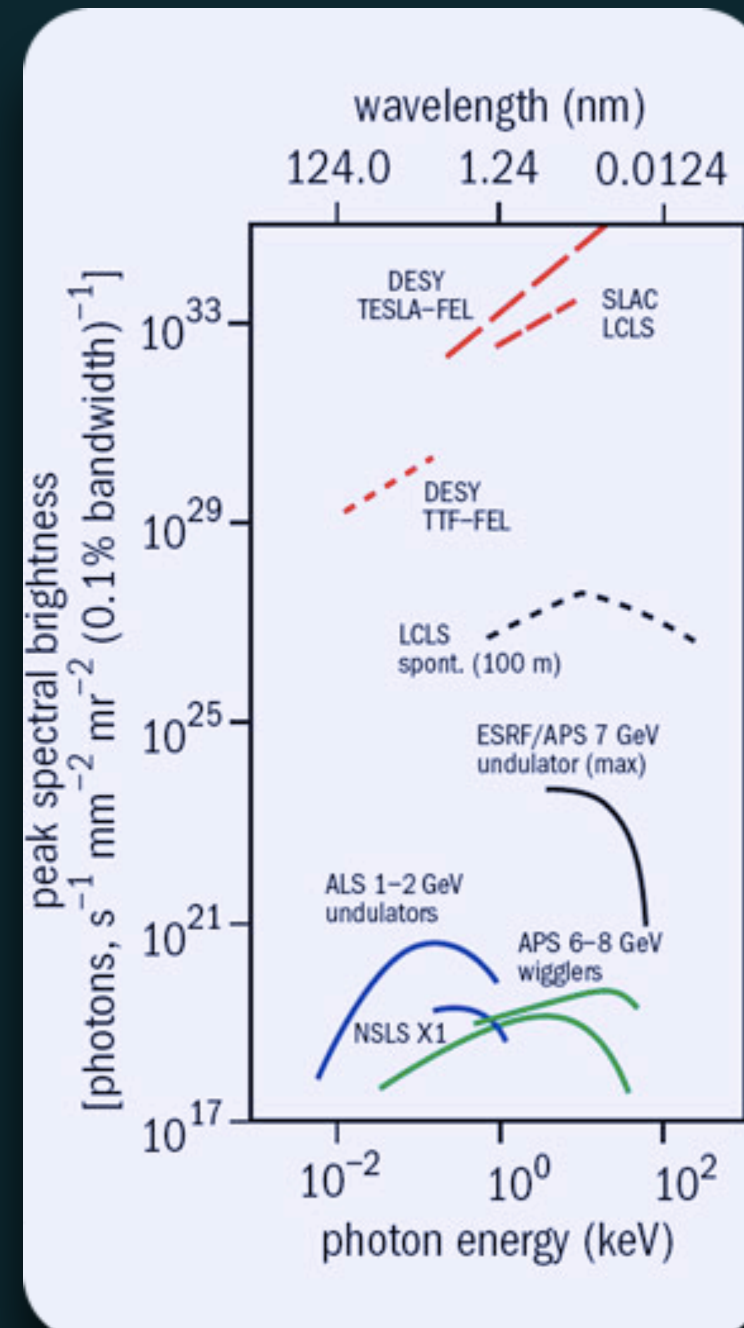
dynamics of the optical melting of a charge density wave in TaS_2



M. Eichberger et al., *Nature* **468,** 799 (2010)

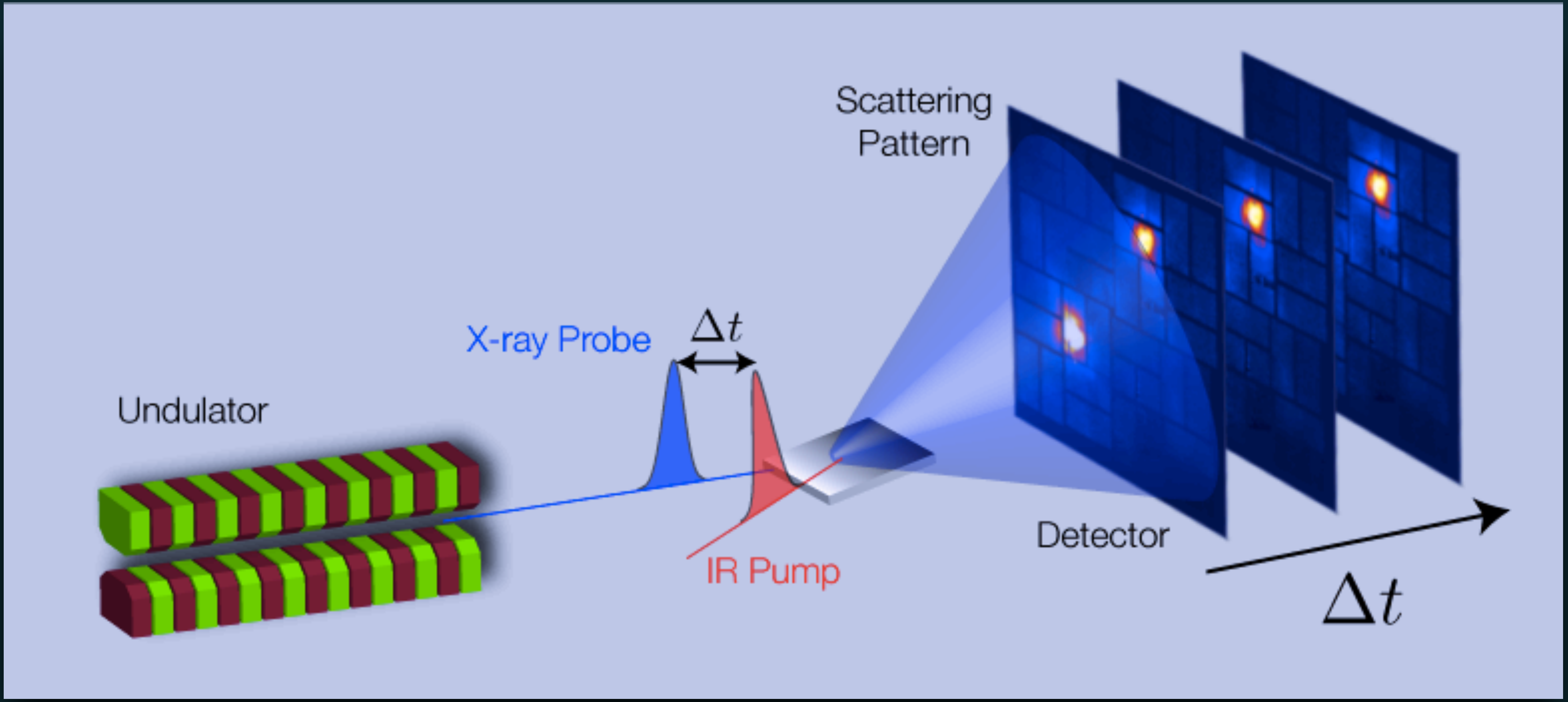
Free Electron Lasers





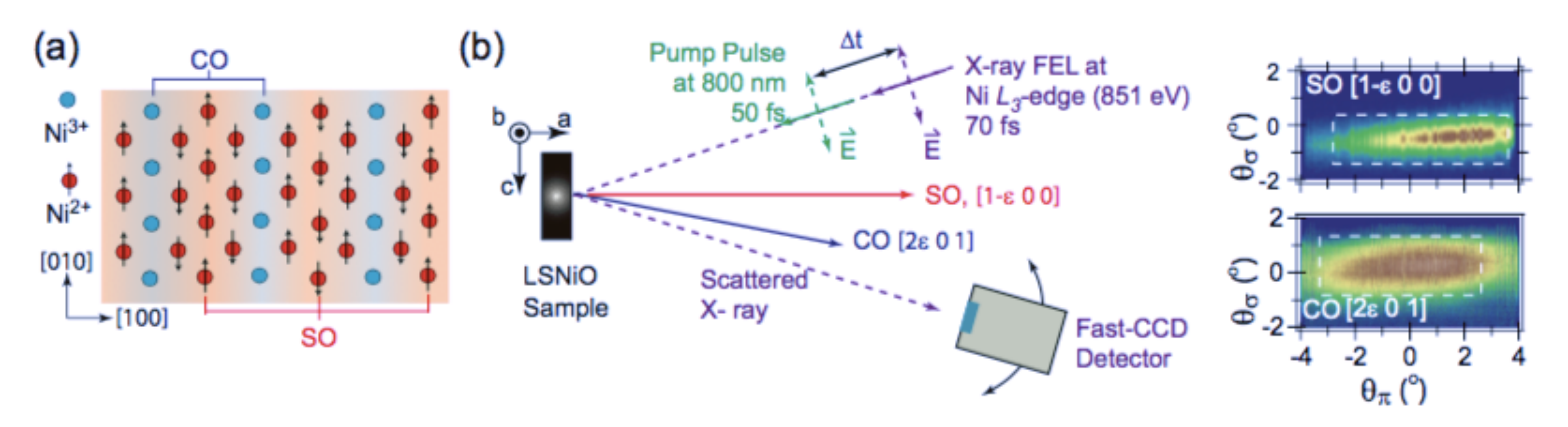
B.W.J. McNeil et al. X-ray free-electron lasers. *Nature Photonics* **4**, 814–821 (2010) time-resolved X-ray diffraction

lattice
long-range orders

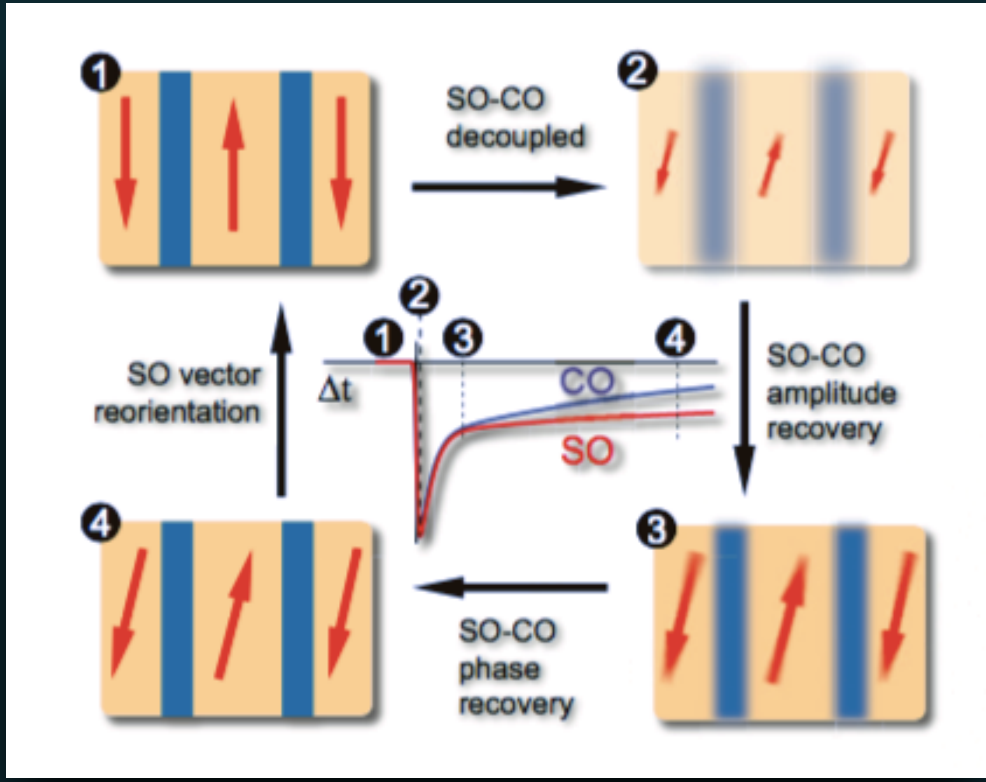


X-ray FEL pulses

long-range orders

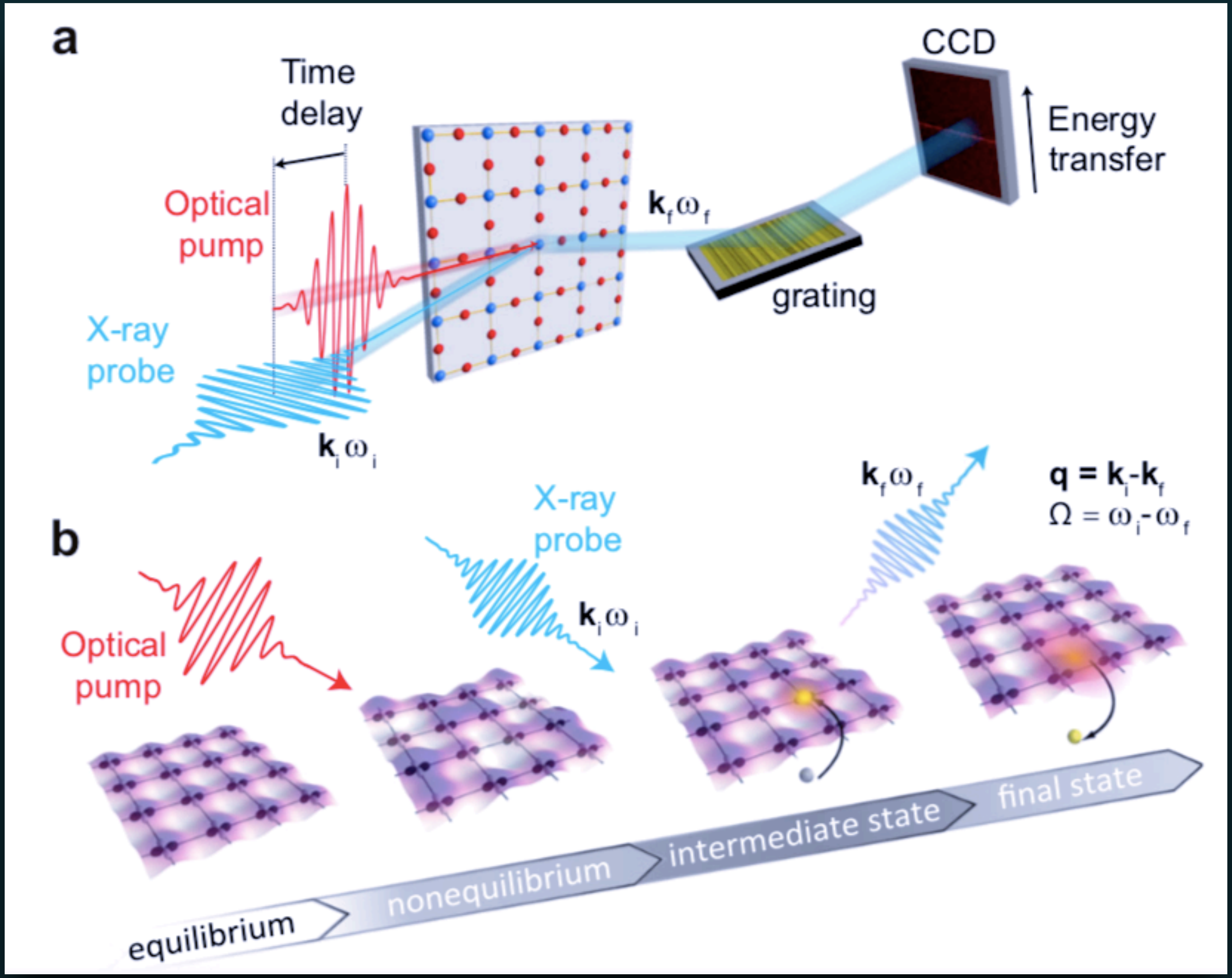


dynamics of the optical melting of intertwined charge and spin orders in a striped nickelate



Y.D. Chuang et al., *Phys. Rev. Lett.* (2012)

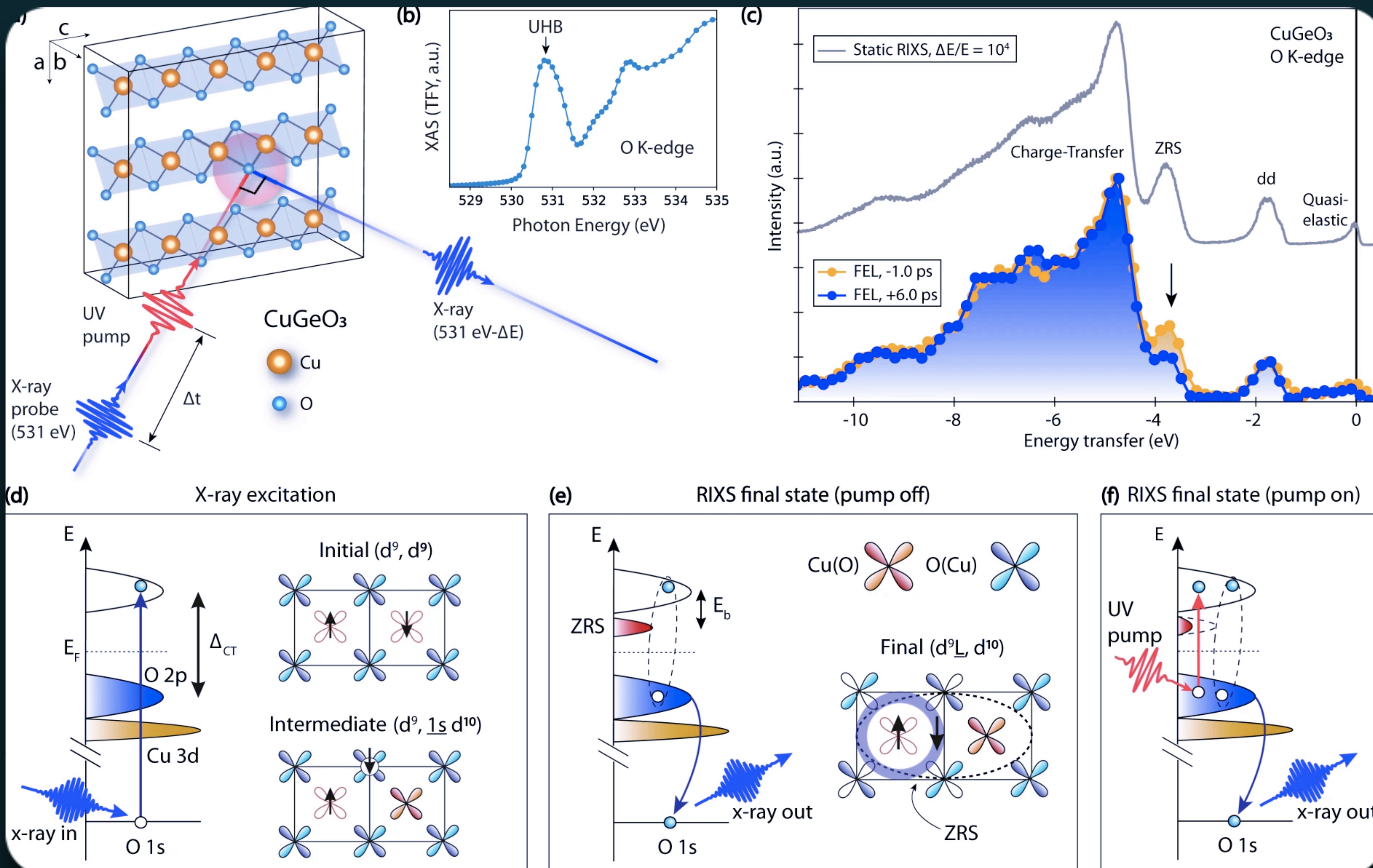
time-resolved Resonant Inelastic X-ray Scattering



M. Mitrano et al., *COMMUNICATIONS PHYSICS (2020) 3:184*

time-resolved Resonant Inelastic X-ray Scattering

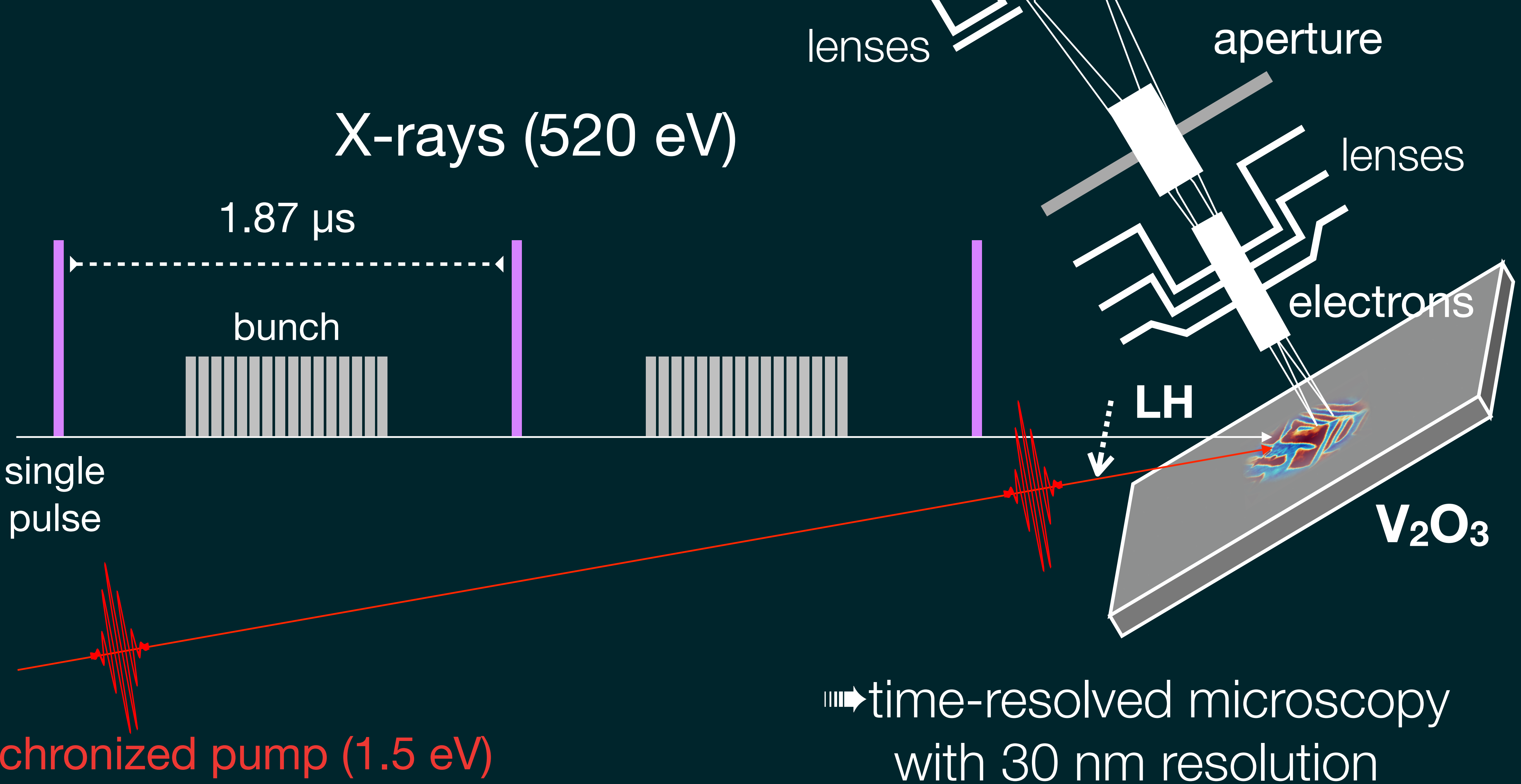
probing short-range magnetic correlations: dynamics of the Zhang-Rice singlet in $CuGeO_3$



E. Paris et al., *npj Quantum Materials* **6**, 51 (2021) towards time-resolved microscopy…

time-resolved X-ray PEEM microscopy

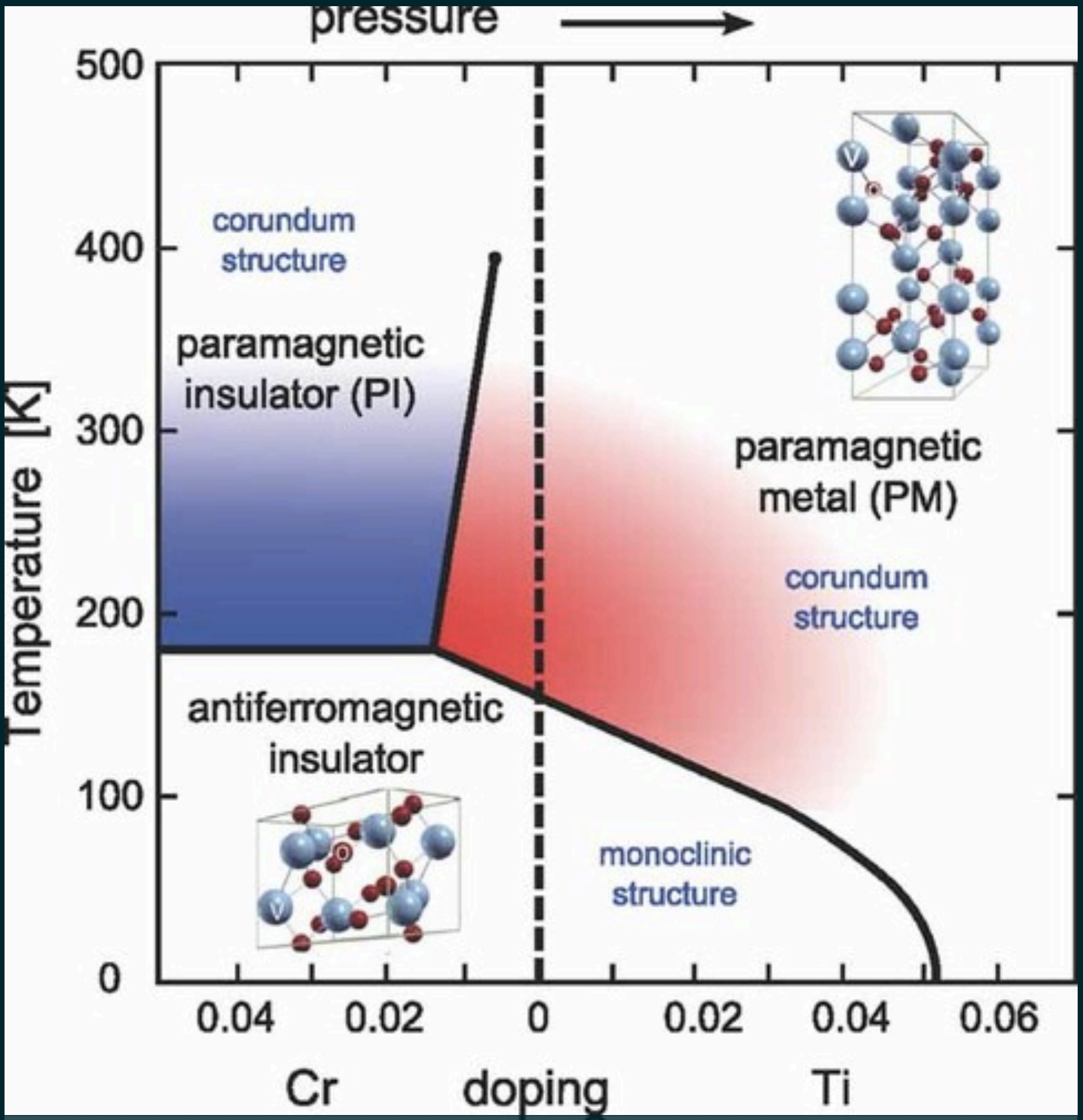
hybrid injection mode
I06 beamline @ Diamond Light Source (UK)



➠time-resolved microscopy with 30 nm resolution

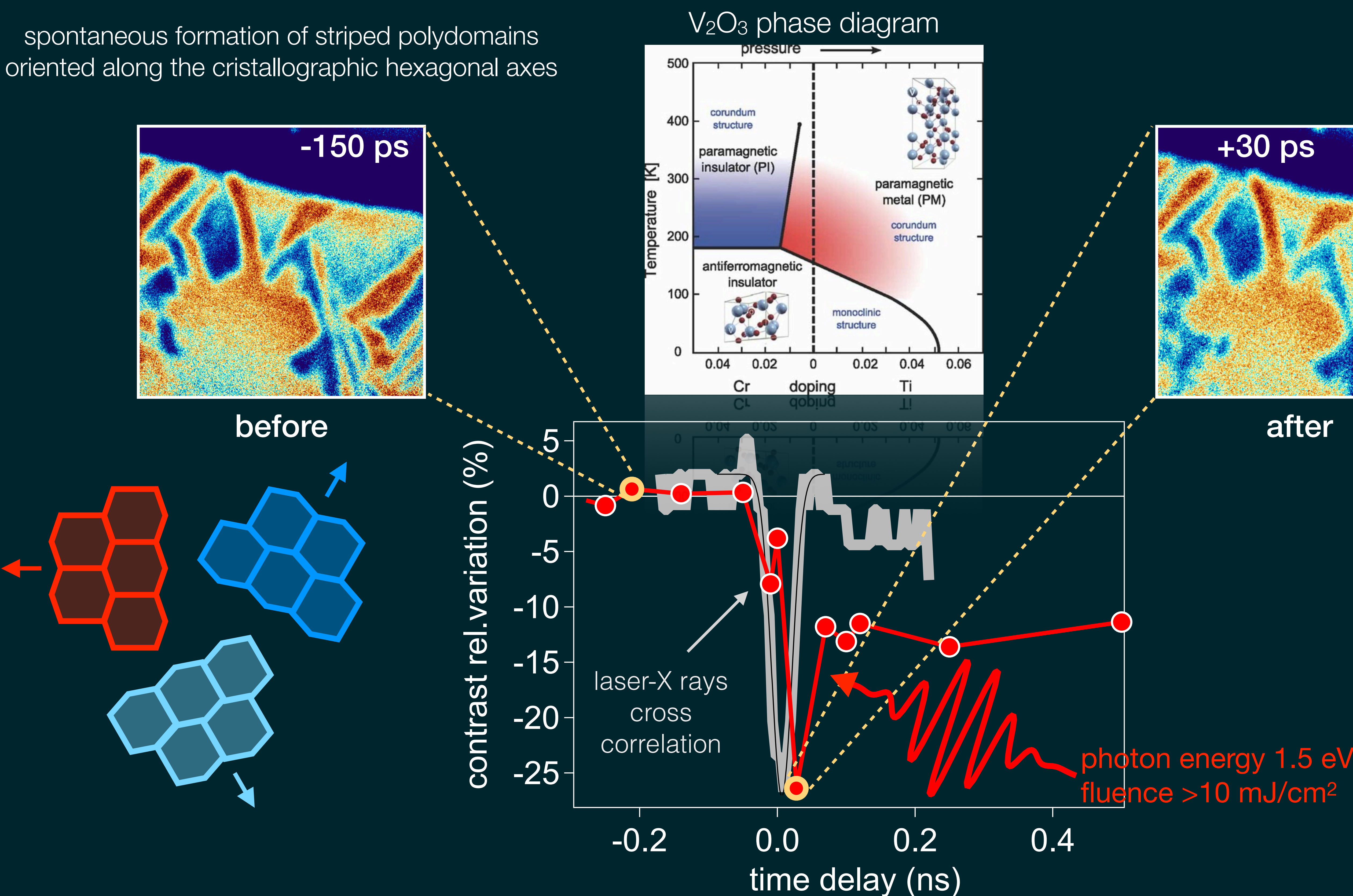
time-resolved PEEM

Mott transition in V_2O_3



time-resolved PEEM

spontaneous formation of striped polydomains oriented along the cristallographic hexagonal axes



A. Ronchi et al. in press on *Nature Communications. arXiv:2109.05116*

time-resolved PEEM

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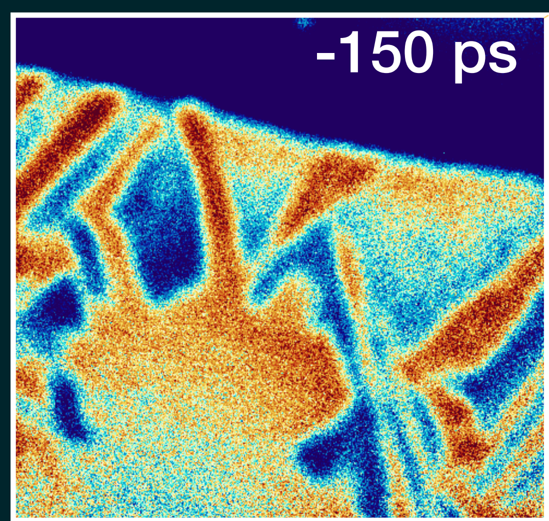
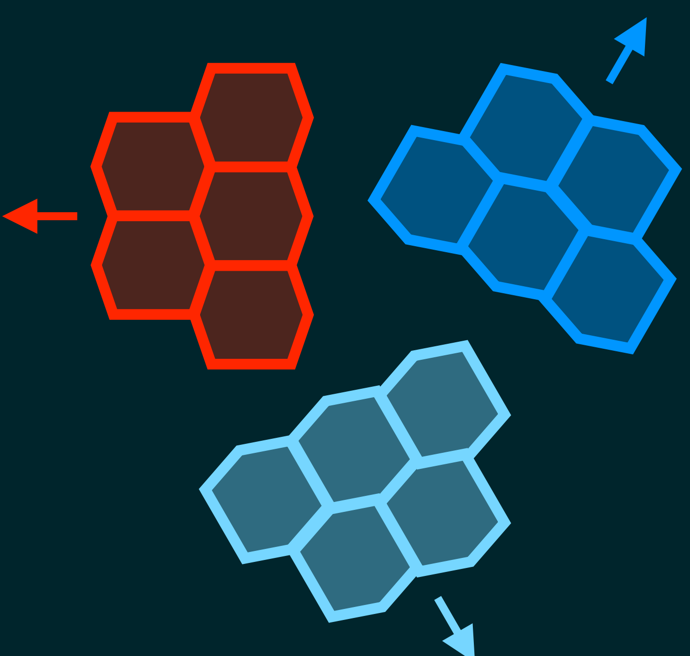
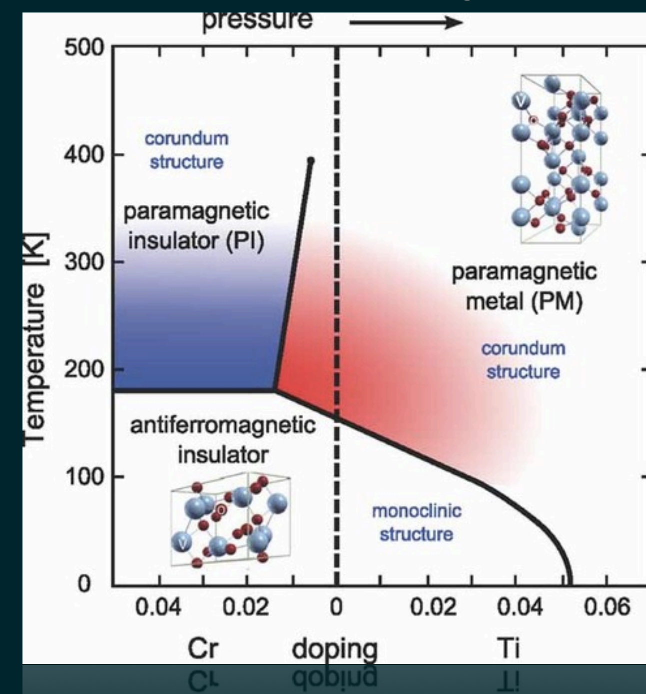
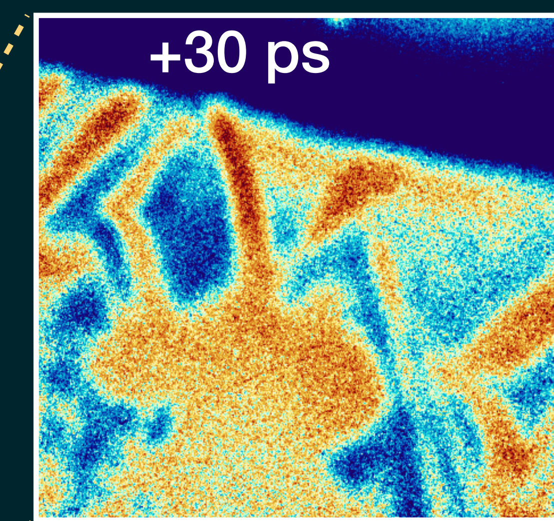


before



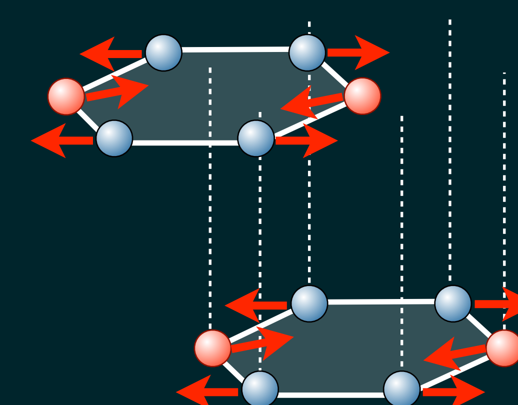
V$_2$O$_3$ phase diagram





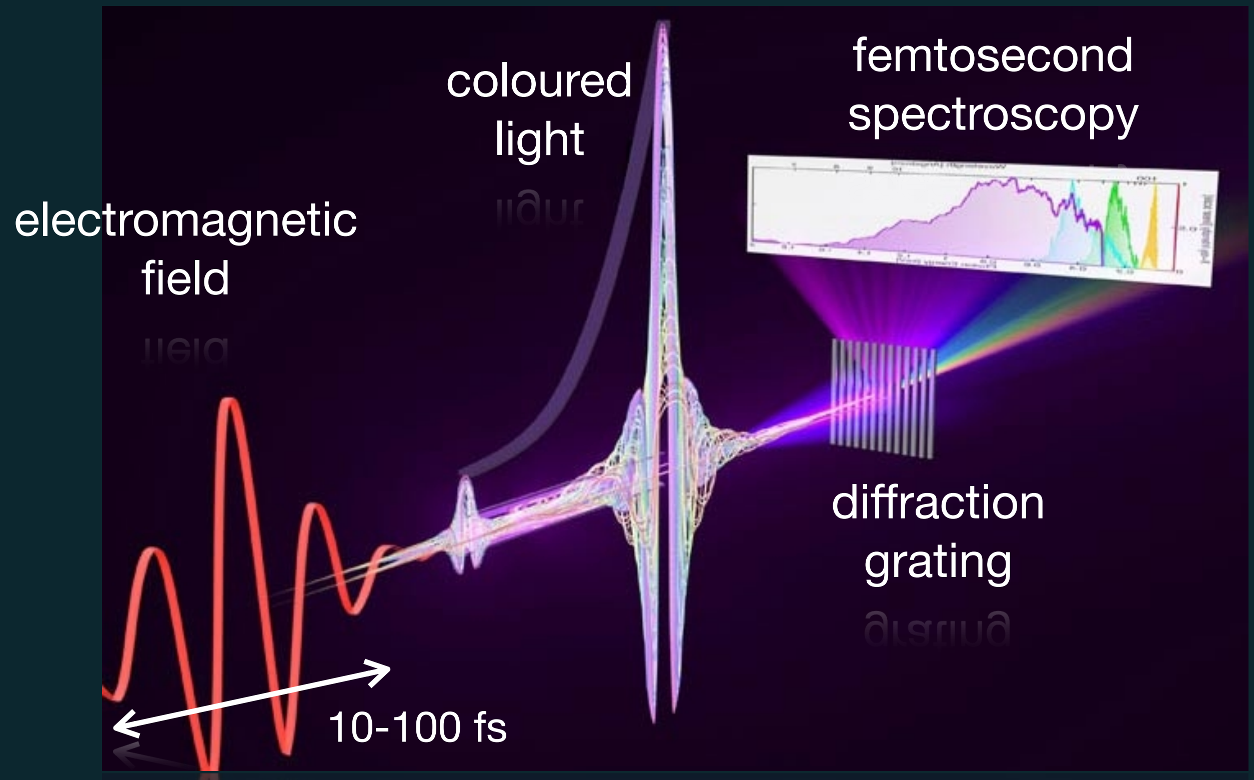
after

monoclinic metal



A. Ronchi et al. in press on *Nature Communications. arXiv:2109.05116*

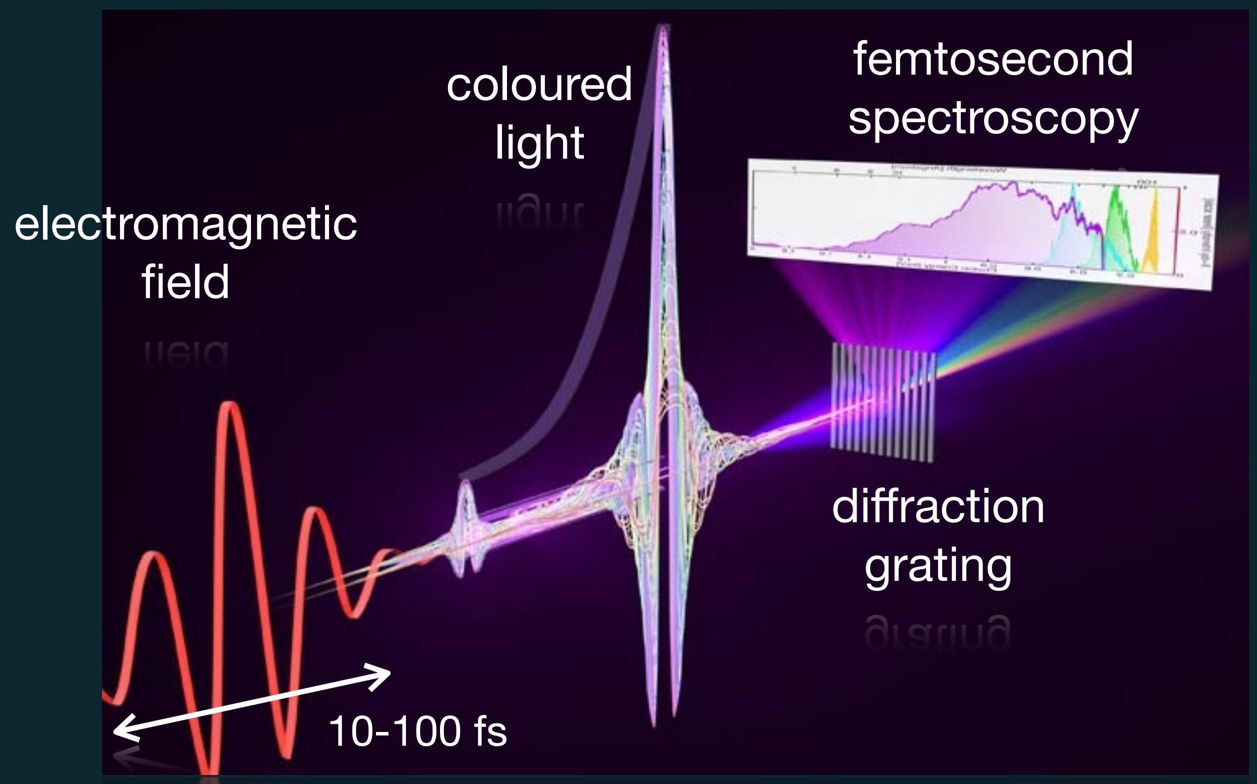
electromagnetic properties

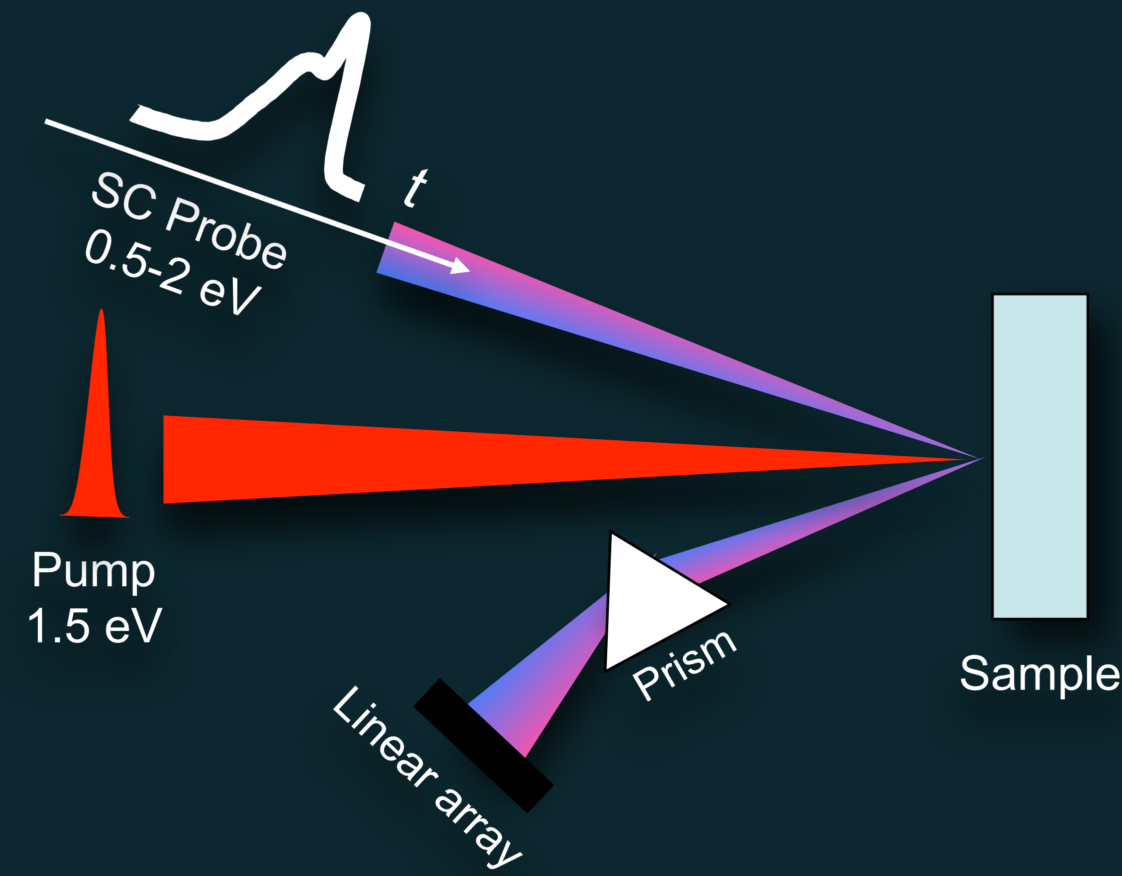


C. Giannetti et al. *Advances in Physics* **65**:2, 58-238 (2016)

non-equilibrium spectroscopy

from pump-probe to femtosecond spectroscopy





C. Giannetti et al. *Advances in Physics* **65**:2, 58-238 (2016)

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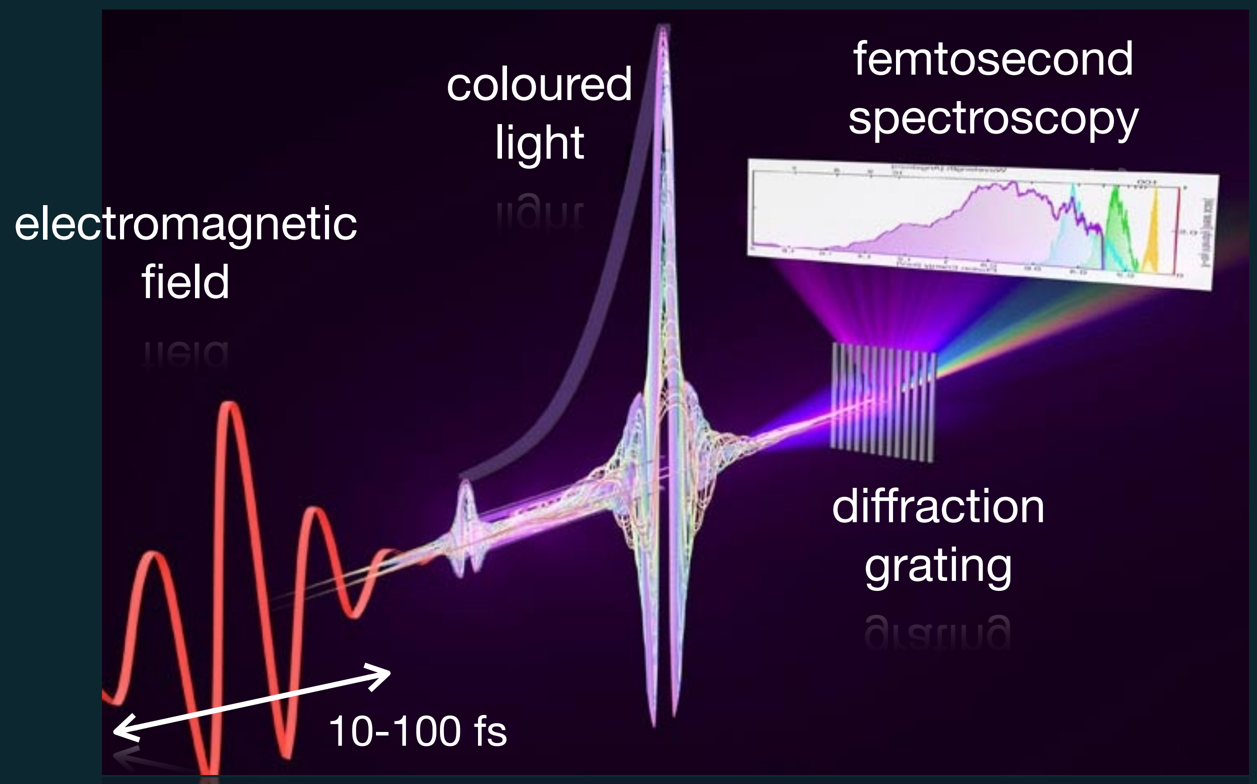
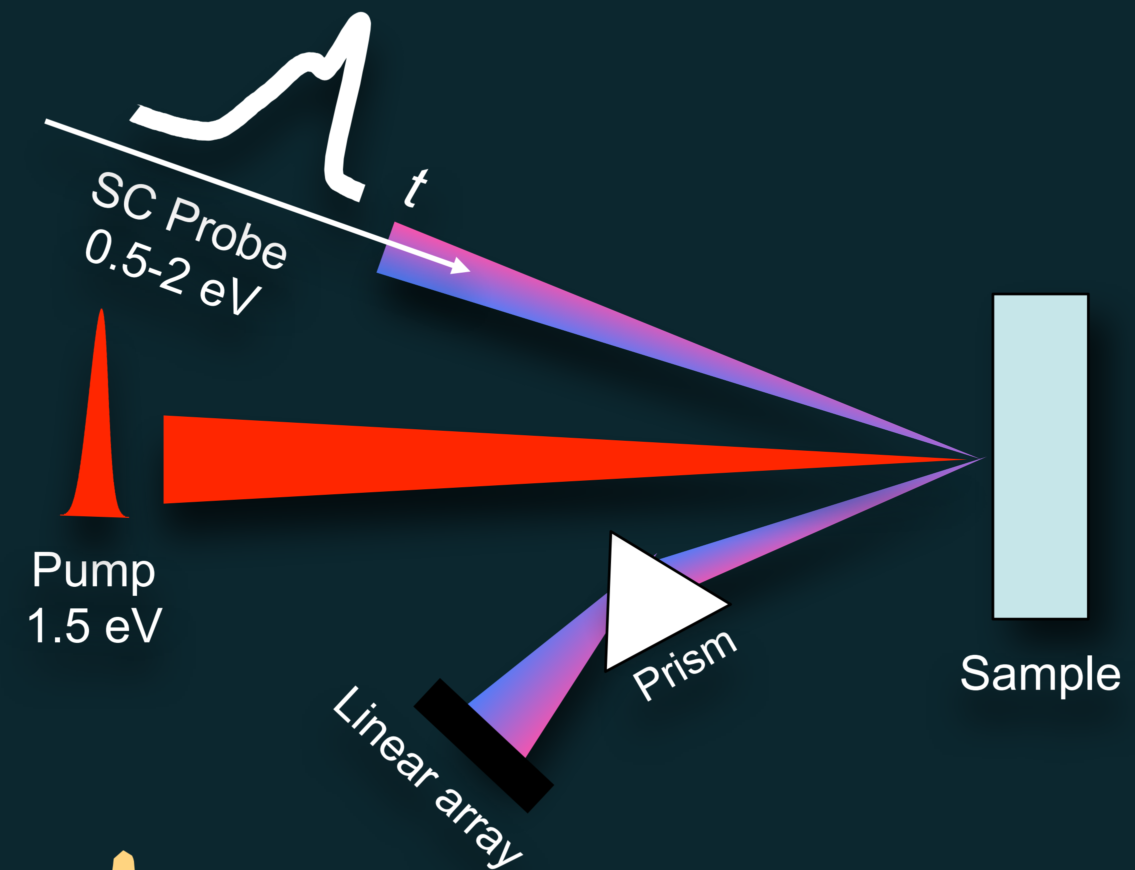
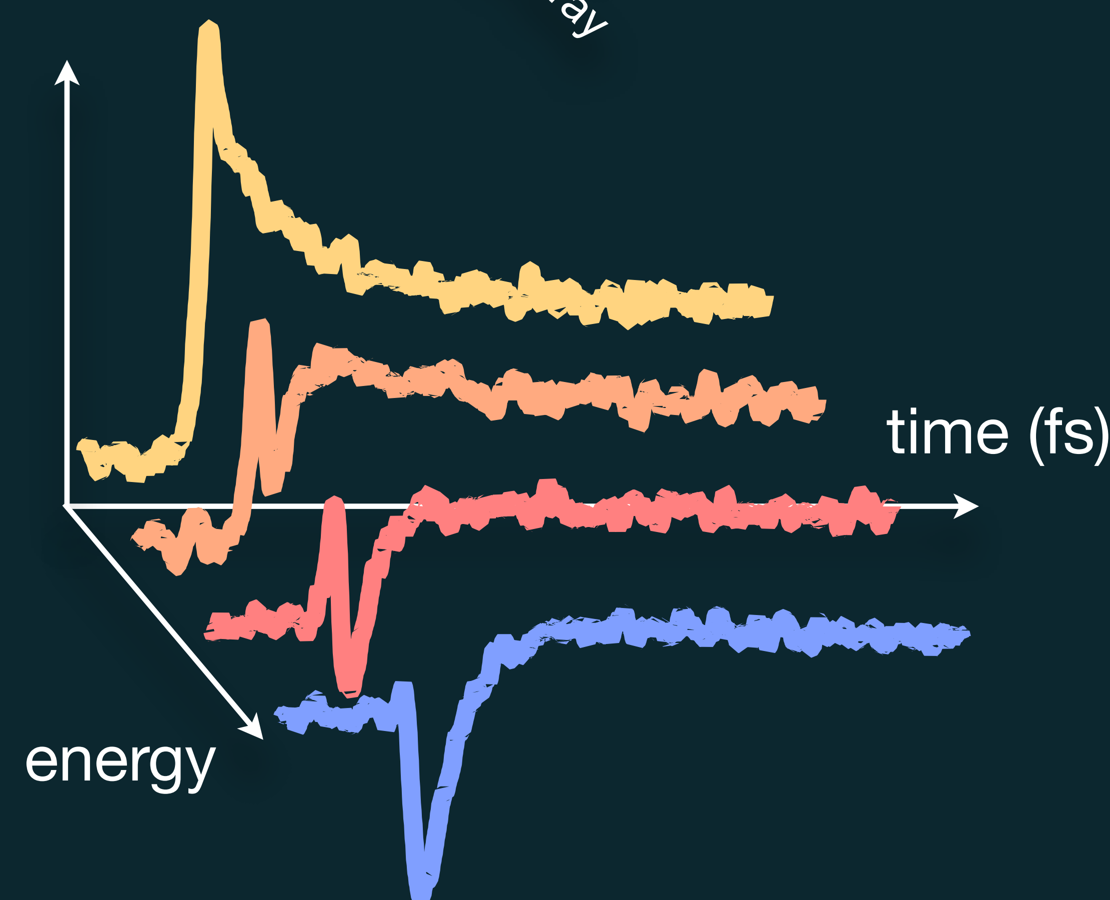




$$\frac{\delta R}{R}(\omega,t)=\frac{R_{exc}(\omega,t)-R_{eq}(\omega)}{R_{eq}(\omega)}$$

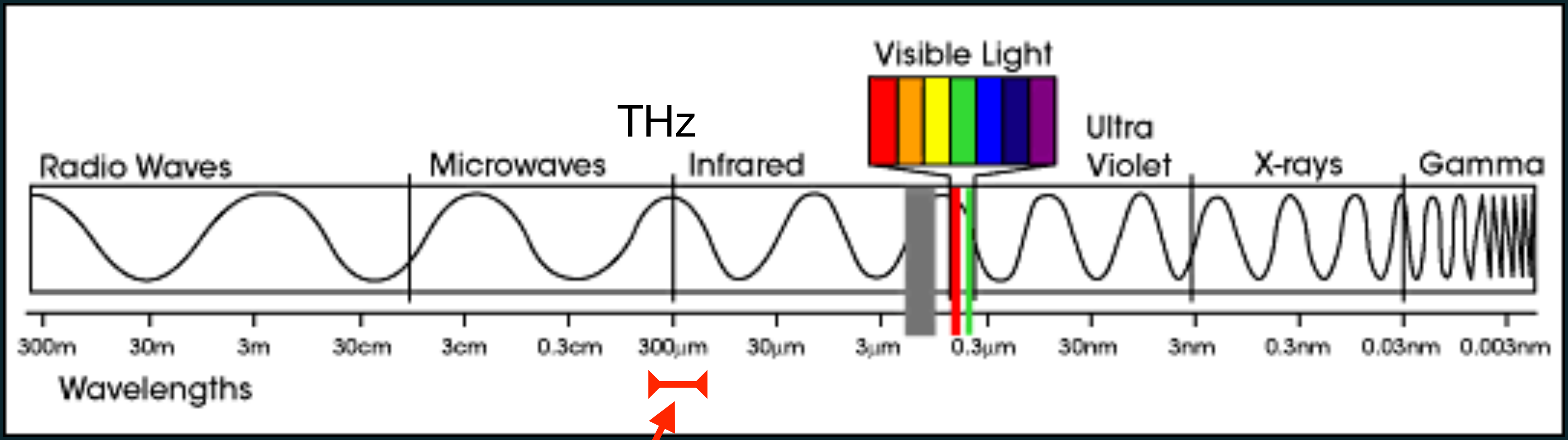
time+frequency information



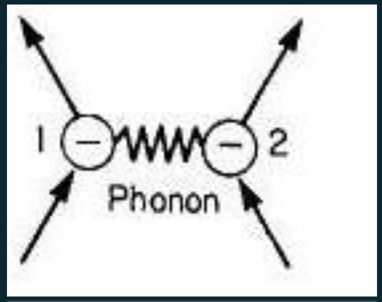
C. Giannetti et al. *Advances in Physics* **65**:2, 58-238 (2016)

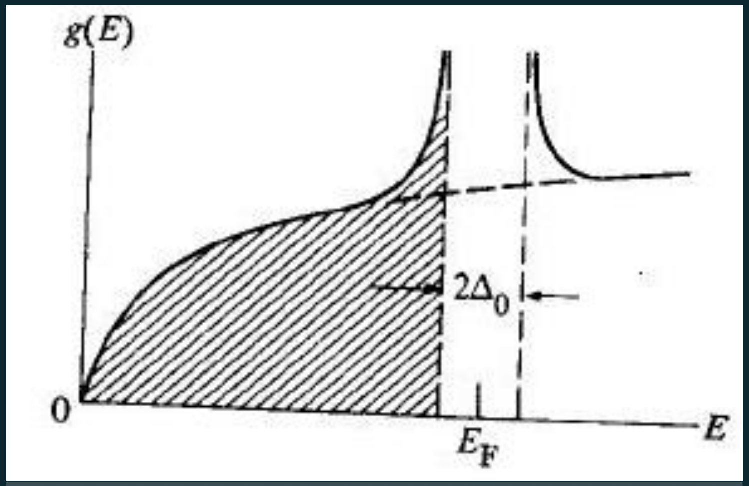
the electromagnetic spectrum

$\omega = 2\pi c/\lambda$ 1 eV=1.24 μm 4 meV=1 THz=200 μm



~1-4 meV superconducting gap in BCS





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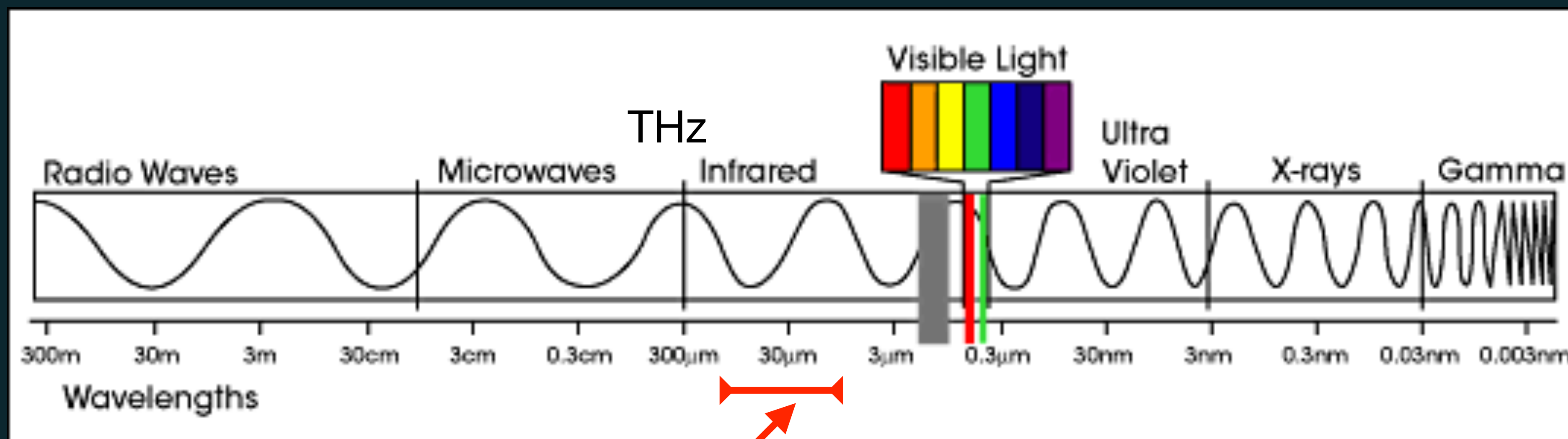
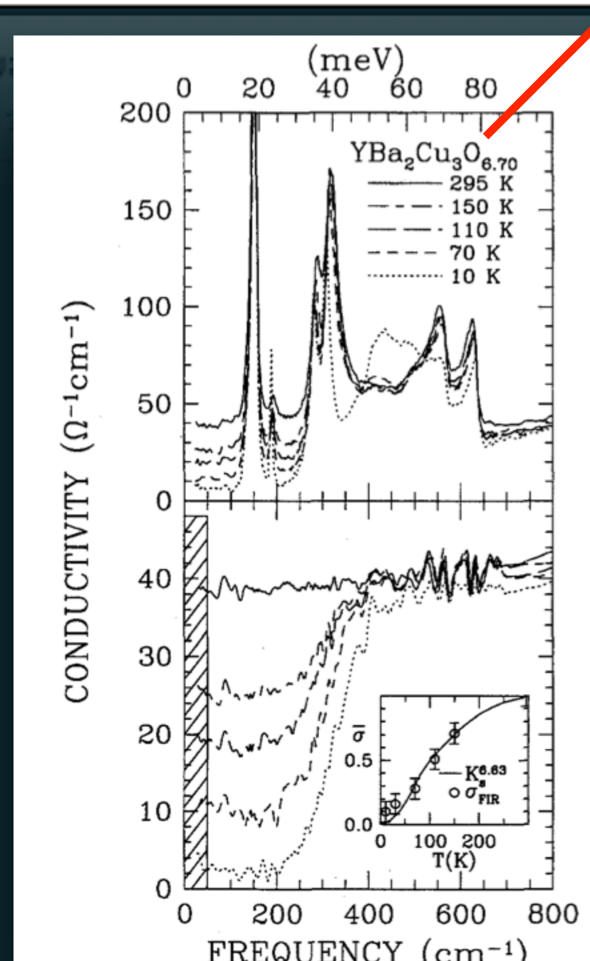




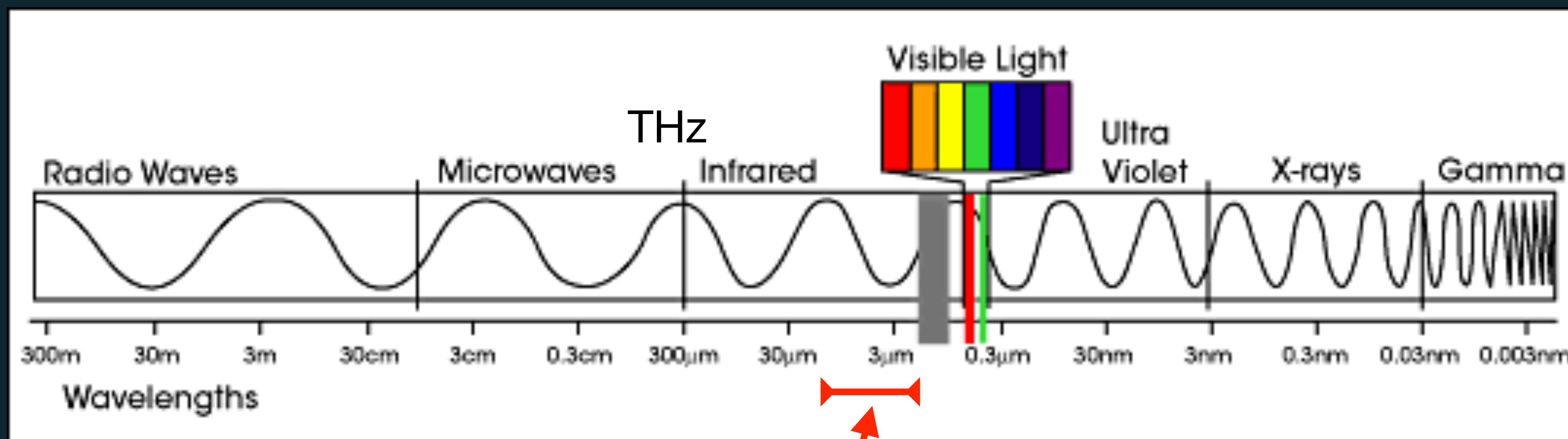
C. Homes et al, *Physica C: Superconductivity* 254, 265 (1995)

~30-90 meV infrared-active phonon modes

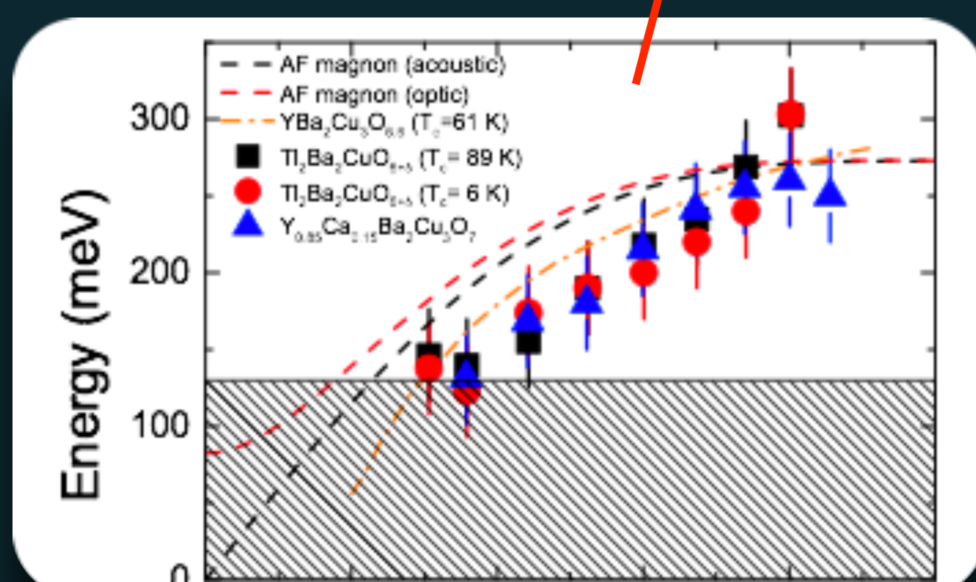
~40 meV superconducting gap and pseudogap in high-T_c

the electromagnetic spectrum

$\omega = 2\pi c/\lambda$ 1 eV=1.24 μm 4 meV=1 THz=200 μm



~300 meV spin fluctuations

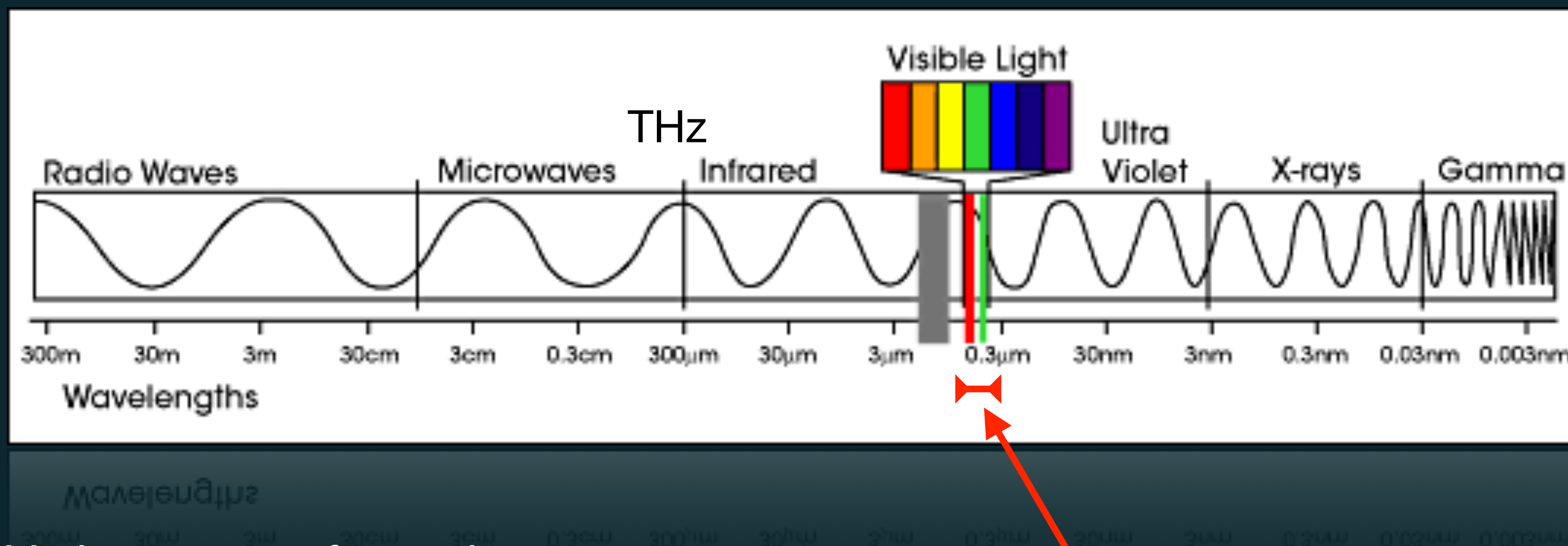


RIXS: Dispersion of paramagnons in cuprates at all dopings

M. Le Tacon et al, *Nature Physics* **7**, 725 (2011)

the electromagnetic spectrum

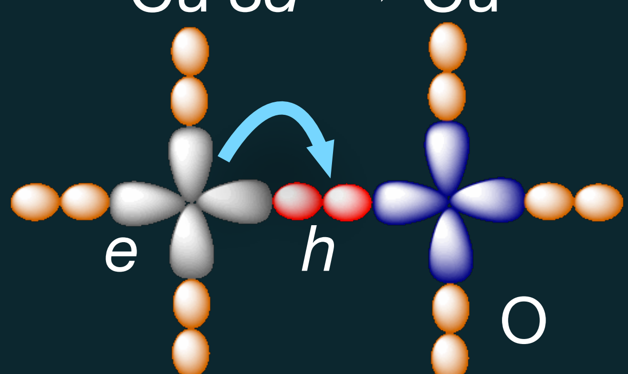
$\omega = 2\pi c/\lambda$ 1 eV=1.24 μm 4 meV=1 THz=200 μm

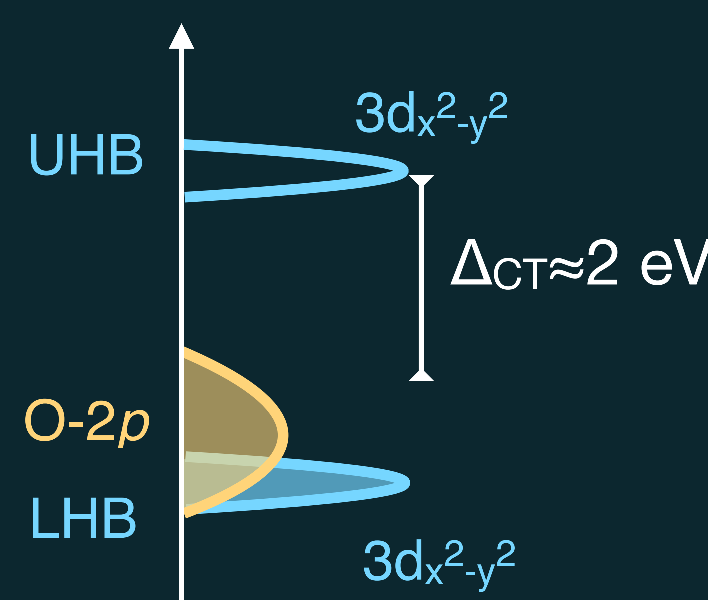


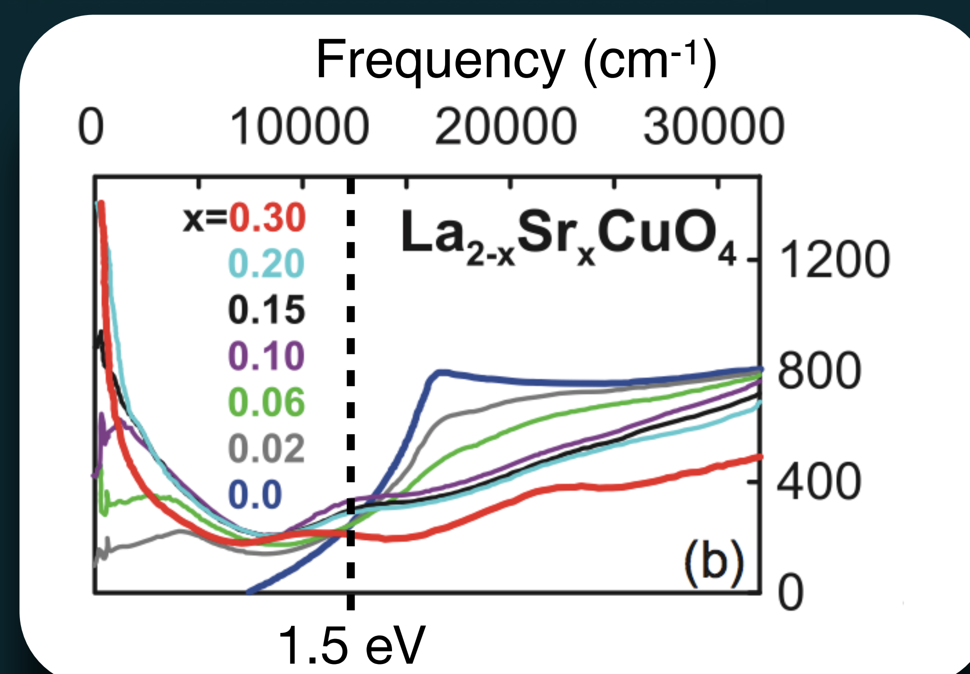
>1.5 eV charge transfer and interband transitions

8064 cm^{-1}=1 eV

Cu 3d^9 → Cu







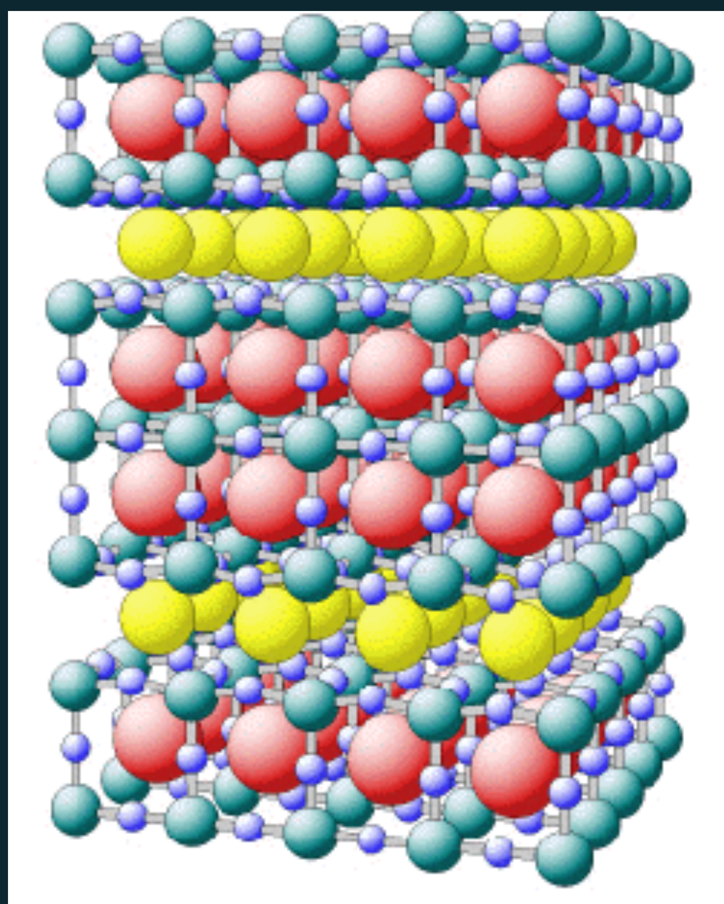
S. Uchida et al, *Phys. Rev. B* 43, 7942 (1991)

light pulses to UNDERSTAND
equilibrium properties

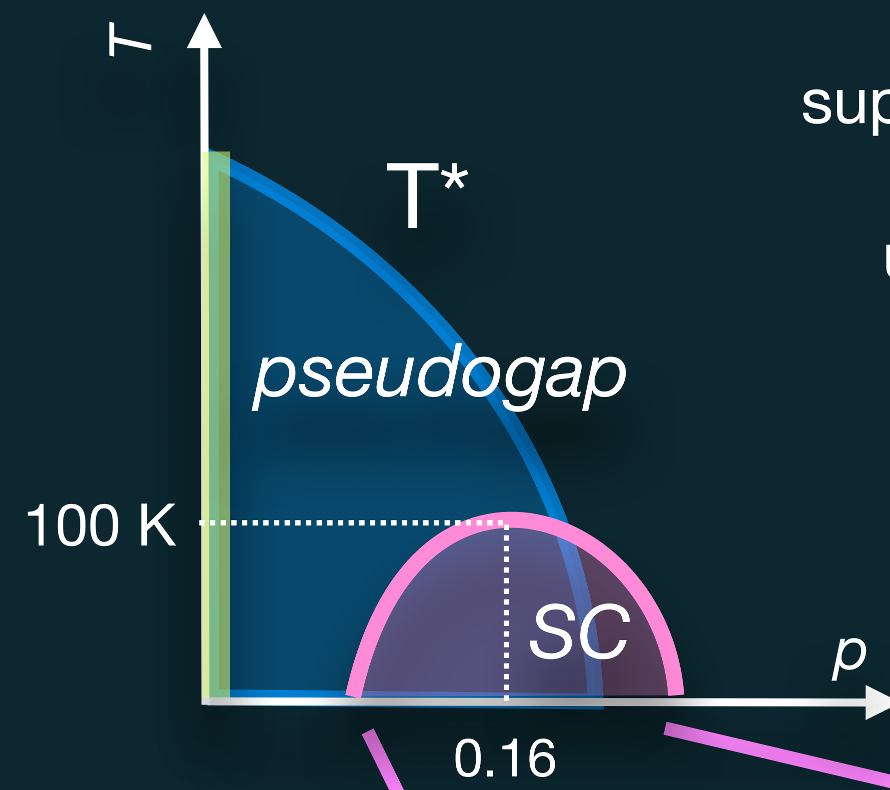
⇒ electron-boson coupling in superconductors

copper oxides

bi-dimensional copper oxides

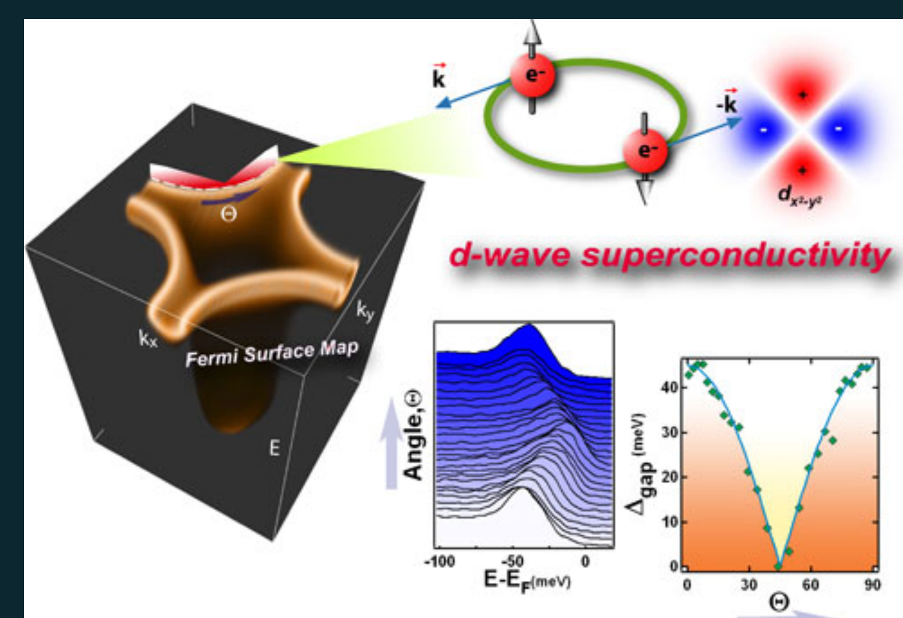


Nobel Prize 1986:
J.G. Bednorz, K.A. Müller



superconductivity on top of a very unconventional ground state!

d-wave superconducting gap



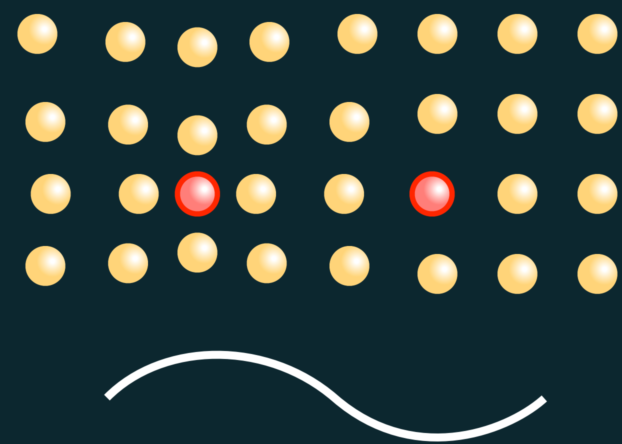
ZX Shen's group

which glue in high-T_c superconductors?

retarded interaction and the “glue” problem

BCS

glue: lattice distortion

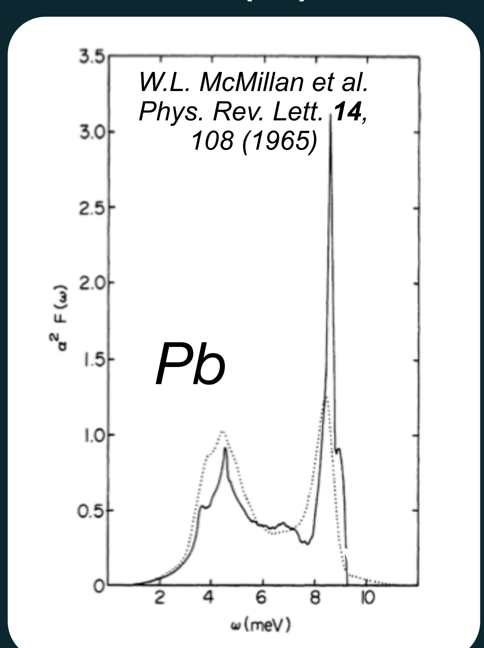


space

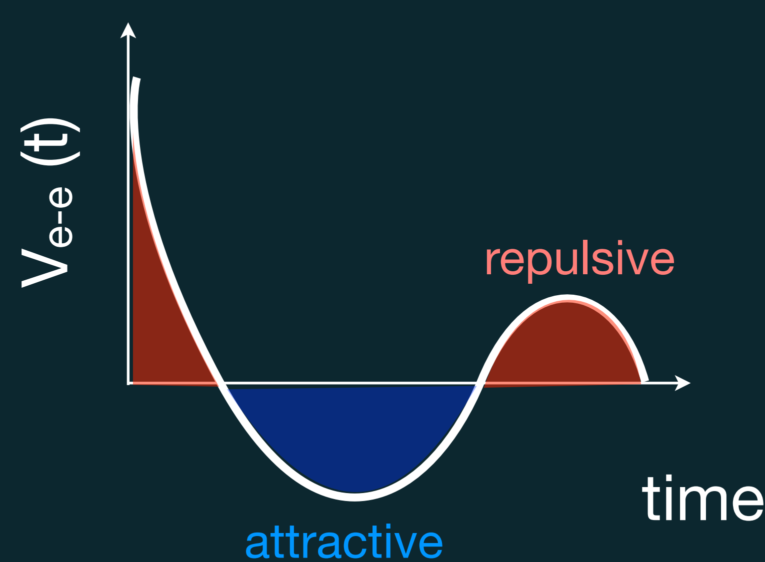
$\lambda = 2\pi/|Q|$

energy scale

$\alpha^2 F(\Omega)$



timescale

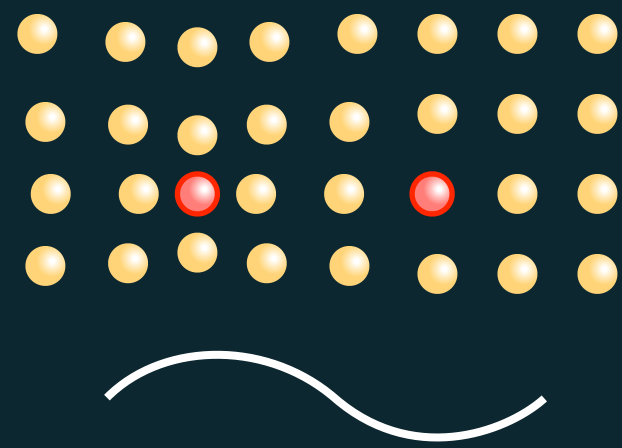


$T = 2\pi/\Omega_Q \simeq 100$ fs

retarded interaction and the "glue" problem

BCS

glue: lattice distortion



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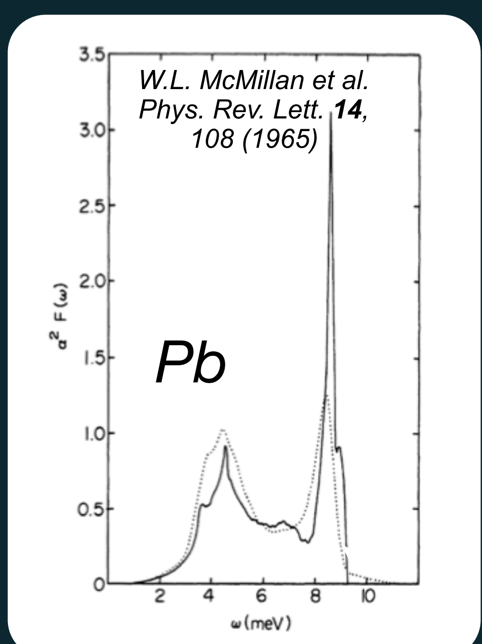
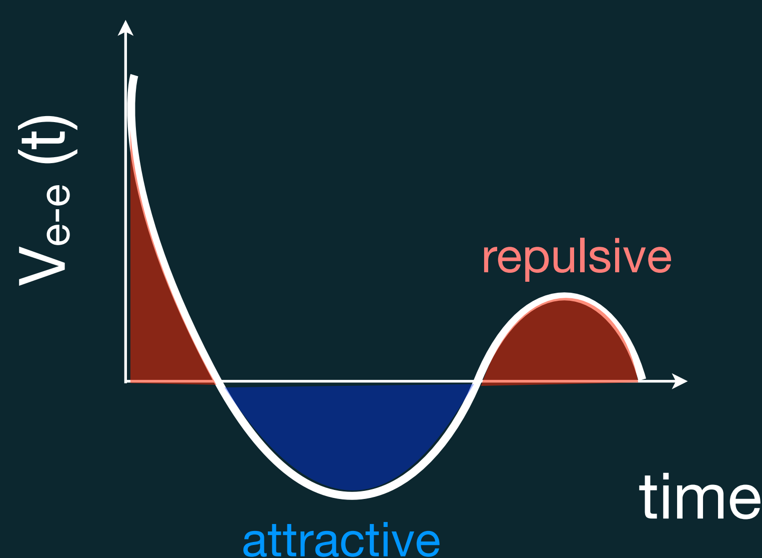


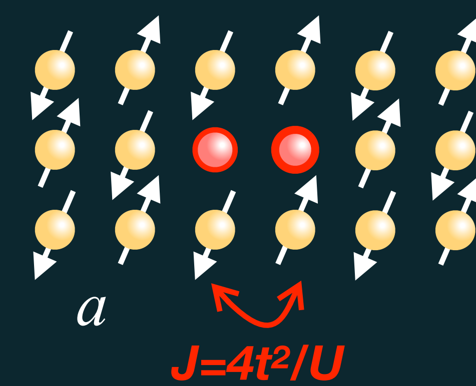
timescale



$T = 2\pi/\Omega_Q \simeq 100$ fs

unconventional

d-wave: other glue?

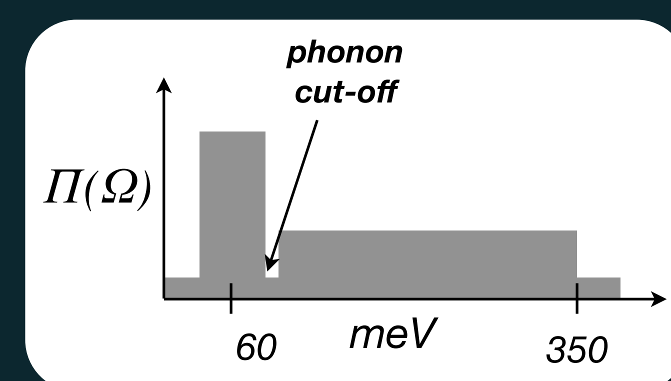


space

$\lambda = a$ ($\cong$ 4 Å)

energy scale

$\Pi(\Omega) = \alpha^2 F(\Omega) + I^2 \chi(\Omega)$



J. Carbotte et al. *Rep. Prog. Phys.* **74**, 066501 (2011)

timescale

$\hbar/J$ ($\cong$ 6 fs)

$T = 2\pi/J < 10$ fs

electron-boson coupling

electron-boson coupling affects the electron dynamics ⇒

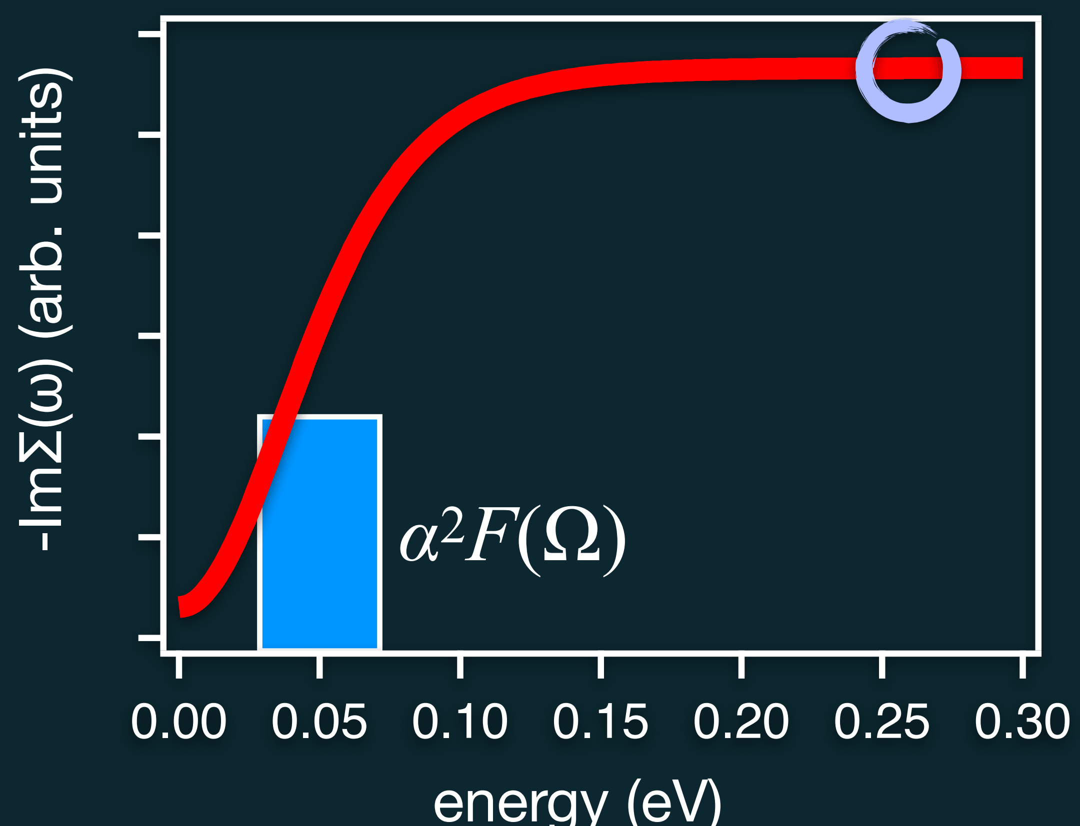
frequency-dependent electron self-energy: $\Sigma(\omega)$

for Fermi liquids: $$\Sigma(\mathbf{k},\omega,T) = \int_0^\infty \alpha^2 F(\mathbf{k},\Omega) L(\omega,\Omega,T) d\Omega$$

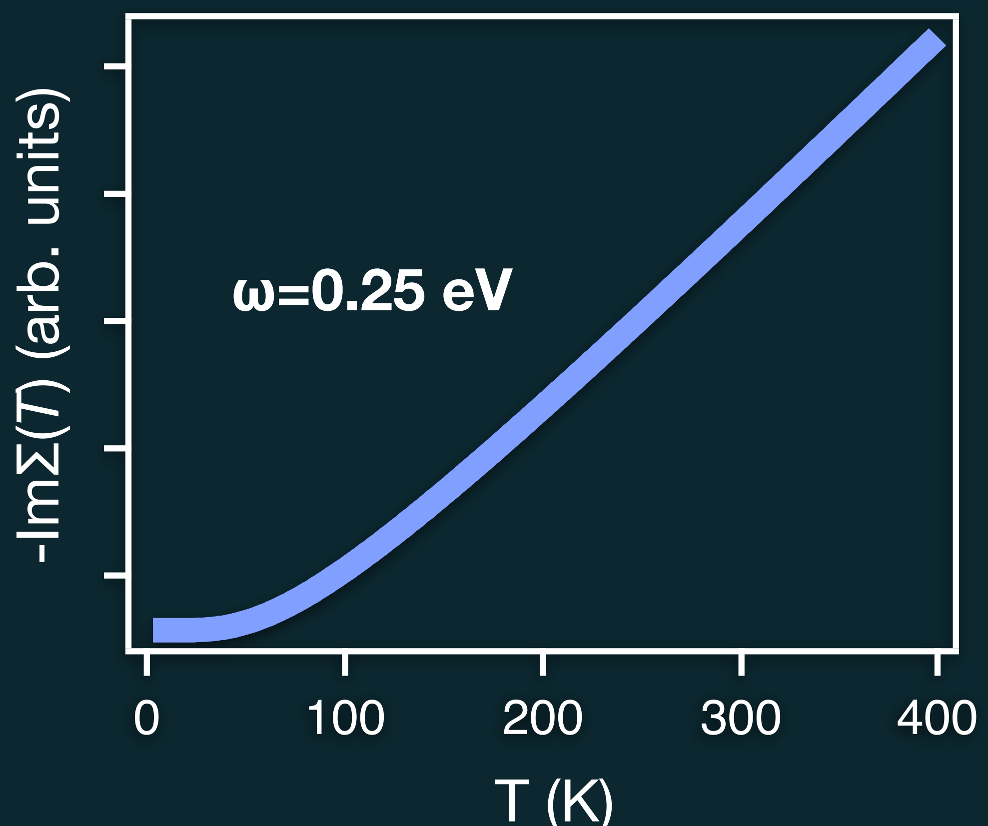
bosonic function: the coupling

kernel function: the population

frequency dependence

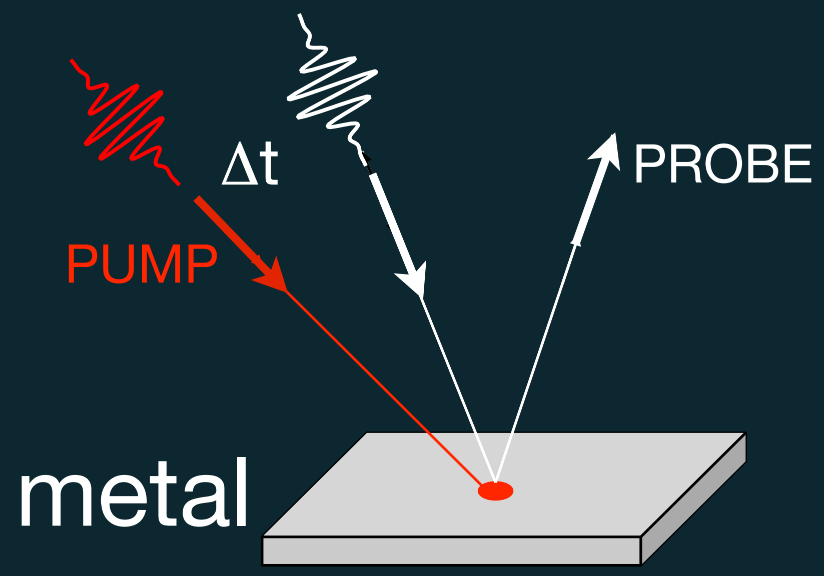


temperature dependence



energy relaxation pathways

pump probe on metals



effective-temperature model

PUMP

$$\frac{\partial T_e}{\partial t} = \frac{G(\Pi_{lat}, T_{lat}, T_e)}{\gamma_e T_e} + \frac{p}{\gamma_e T_e}$$

$$\frac{\partial T_{lat}}{\partial t} = -\frac{G(\Pi_{lat}, T_{lat}, T_e)}{C_{lat}} \longrightarrow$$

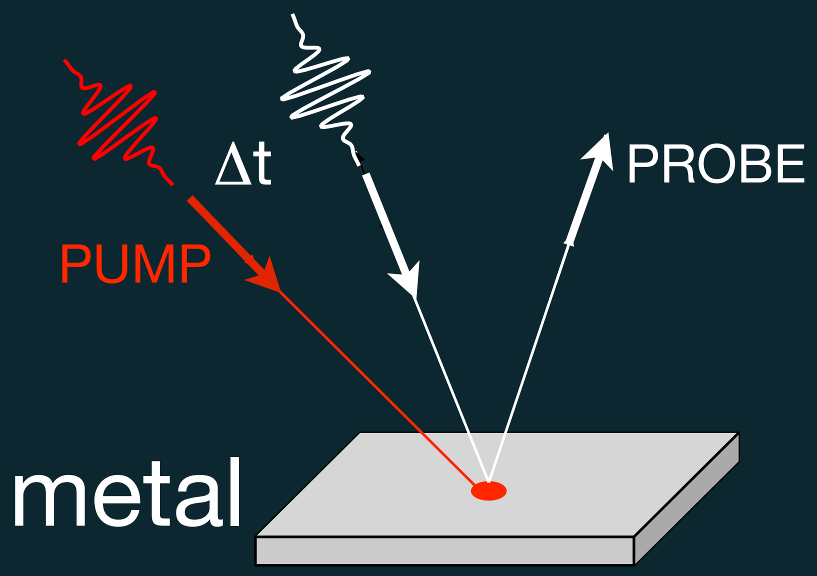
G/C

determines the dynamics in the time domain

P.B. Allen, *Phys. Rev Lett.* **59** 1460 (1987)

energy relaxation pathways

pump probe on metals



effective-temperature model

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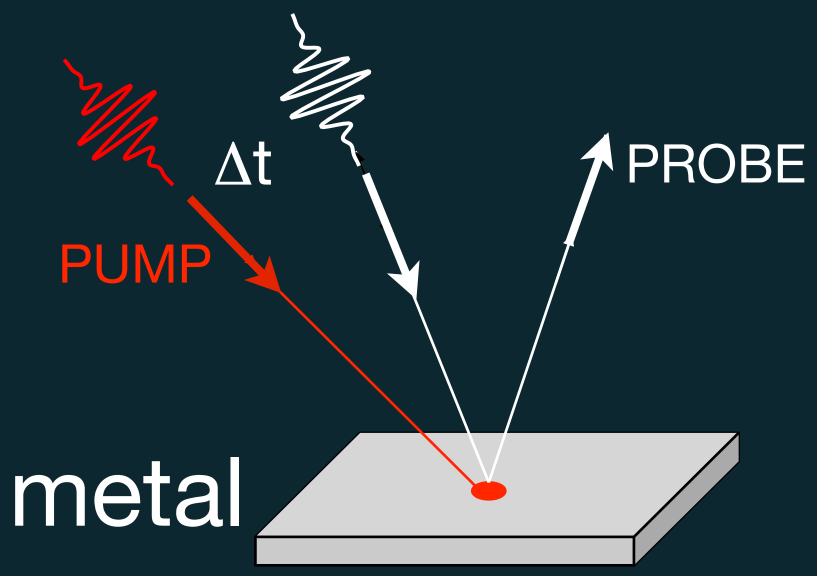
$$\frac{\partial T_{lat}}{\partial t} = -\frac{G(\Pi_{lat}, T_{lat}, T_e)}{C_{lat}}$$

→ G/C determines the dynamics in the time domain

$$G = \frac{3\gamma_e}{\pi \hbar k_B^2} \int_0^\infty d\Omega \Pi_{lat}(\Omega)[N(\Omega, T_{lat}) - N(\Omega, T_e)]$$

energy relaxation pathways

pump probe on metals



effective-temperature model

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$$\frac{\partial T_{lat}}{\partial t} = -\frac{G(\Pi_{lat}, T_{lat}, T_e)}{C_{lat}}$$

→ G/C determines the dynamics in the time domain

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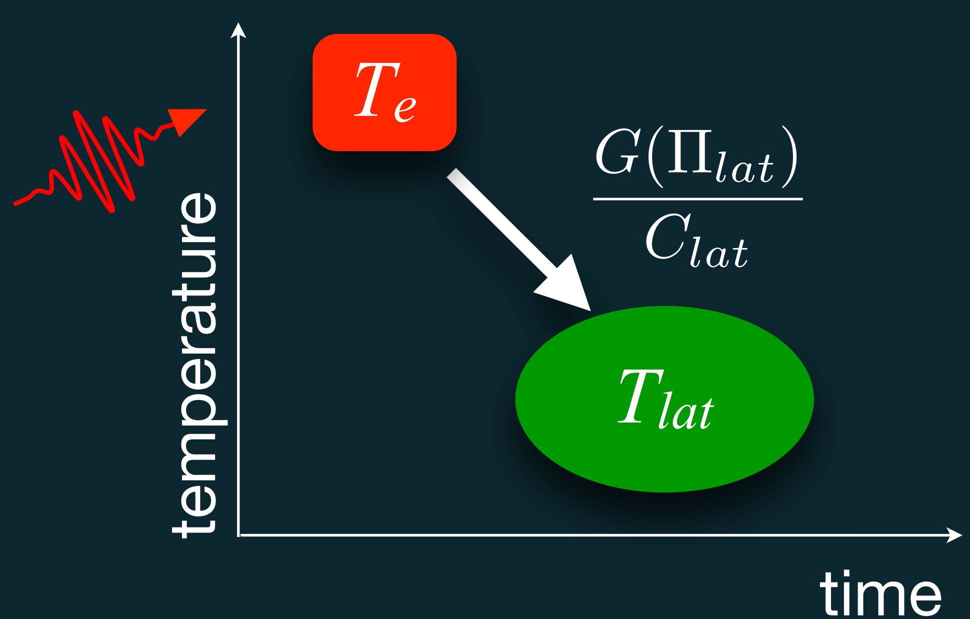
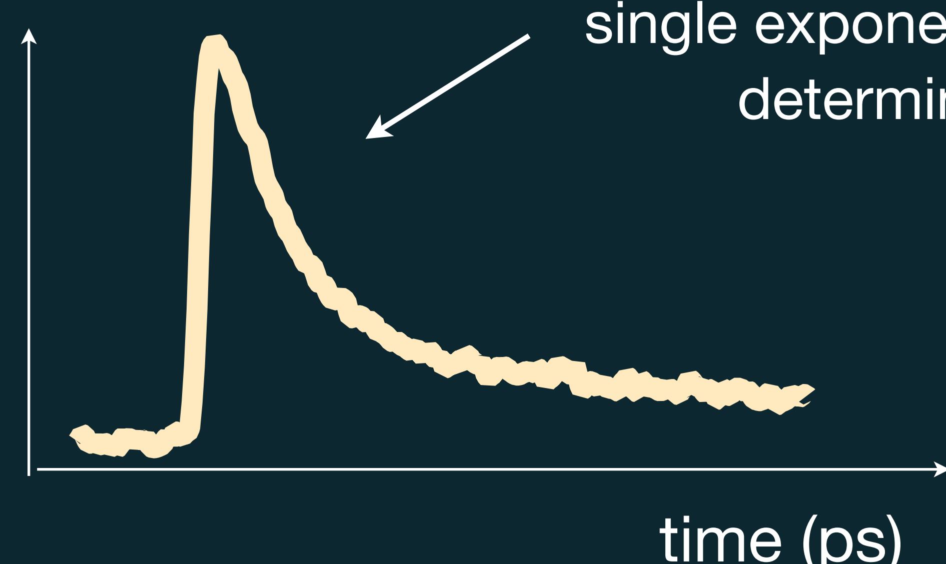
hierarchy in the dynamics

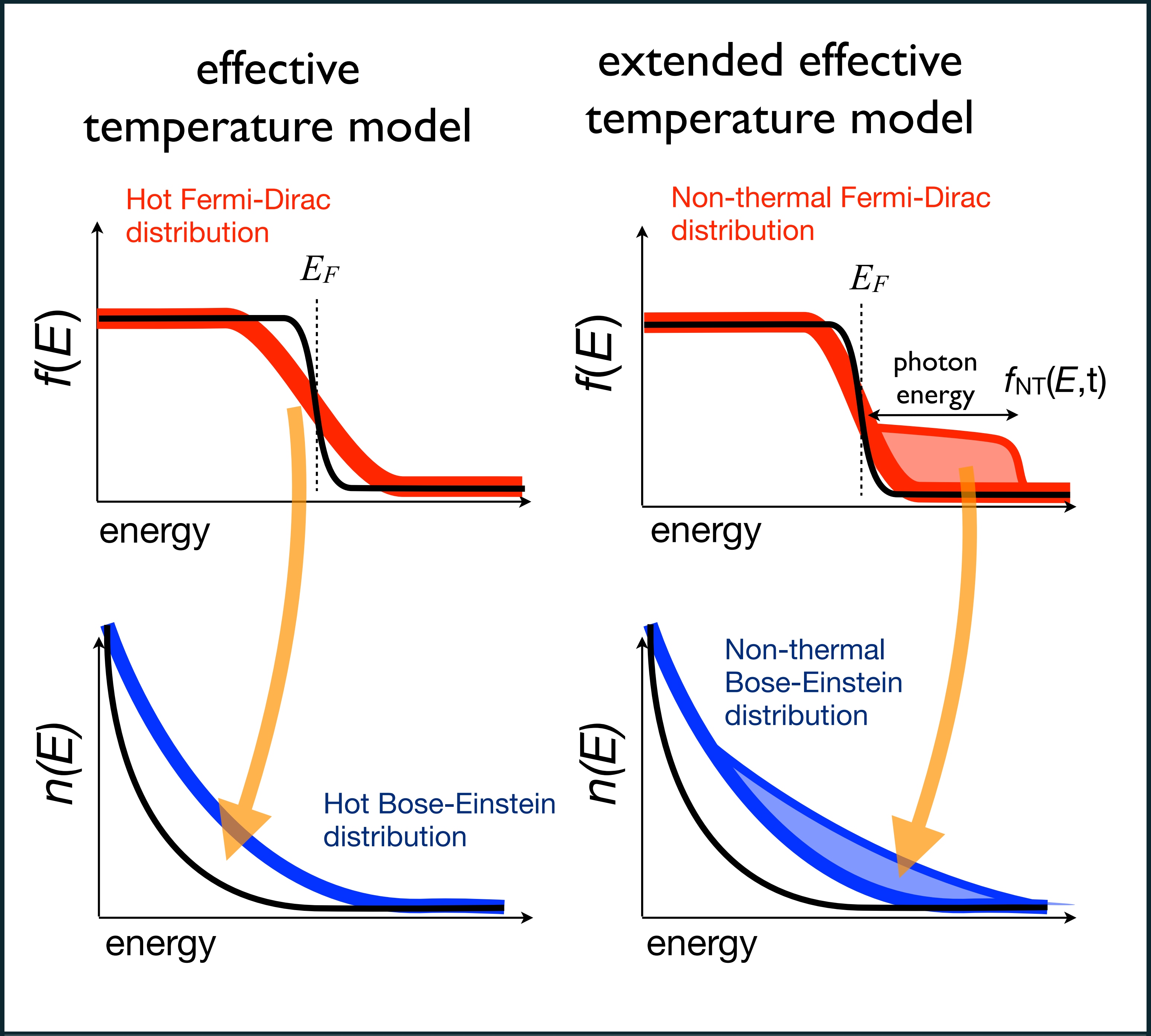


$\delta R/R \propto \delta T_e/T_e$

in conventional metals: single exponential decay determines λ



be careful with the 2TM!

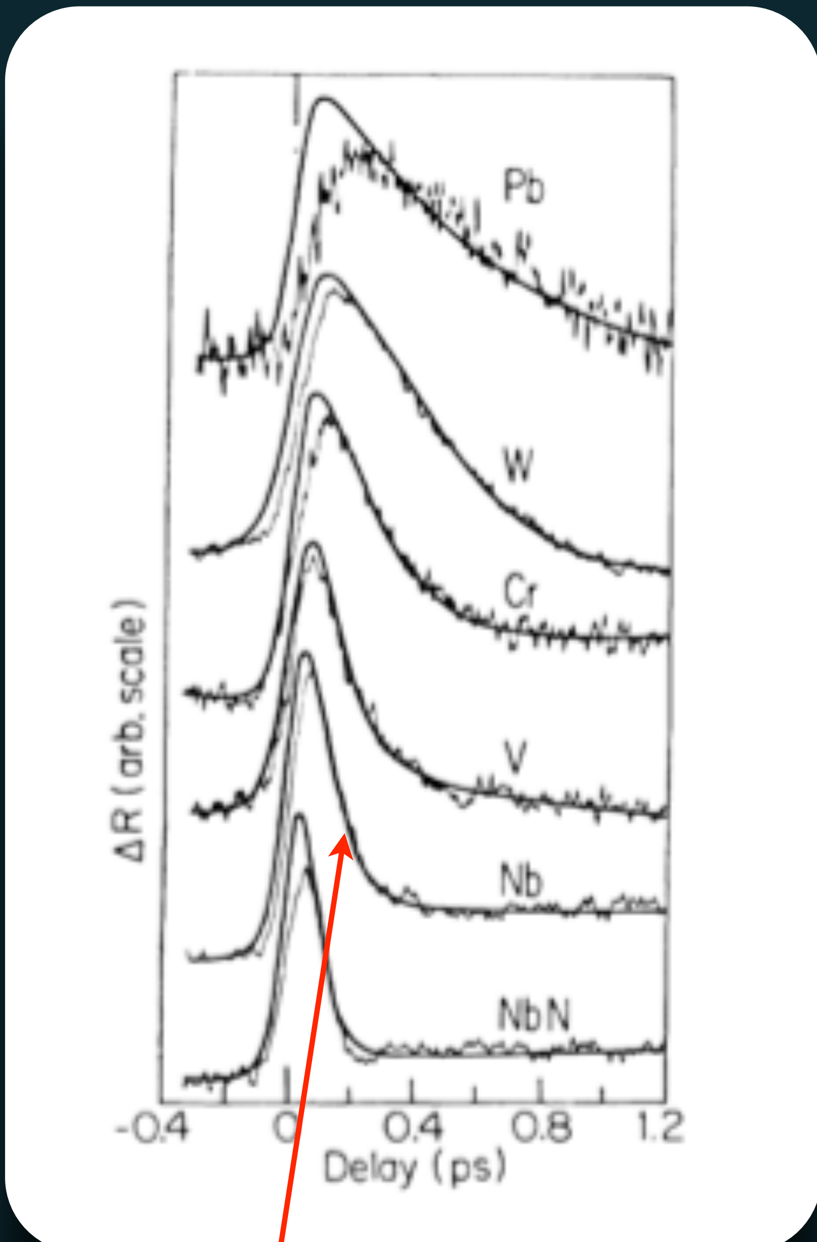


Fermi-liquid theory: the QP lifetime diverges at E_F!!

$1/\tau_e \propto (E-E_F)^2$

Boltzmann equations to account for $f_{NT}(E,t)$

non-equilibrium spectroscopy on metals



single exponential decay

	$T_c(0)$ (K)[a]	$\lambda_{exp}\langle\omega^2\rangle$ (meV^2)	$\langle\omega^2\rangle$ (meV^2)	λ_{exp}	λ_{th}
Cu	590	29 ± 4	377[b]	0.08 ± 0.01	0.10[b]
Au	650	23 ± 4	178[c]	0.13 ± 0.02	0.15[c]
Cr	716	128 ± 15	987[d]	0.13 ± 0.02	···
W	1200	112 ± 15	425[e]	0.26 ± 0.04	0.26[e]
V	700	280 ± 20	352[f]	0.80 ± 0.06	0.82[f]
Nb	790	320 ± 30	275[g]	1.16 ± 0.11	1.04[g]
Ti	820	350 ± 30	601[g]	0.58 ± 0.05	0.54[g]
Pb	570	45 ± 5	31[i]	1.45 ± 0.16	1.55[i]
NbN	1070	640 ± 40	673[j]	0.95 ± 0.06	1.46[j]
V_3Ga	1110	370 ± 60	448[k]	0.83 ± 0.13	1.12[k]

S.D. Brorson et al. *Phys. Rev. Lett.* **64,** 2172 (1990)

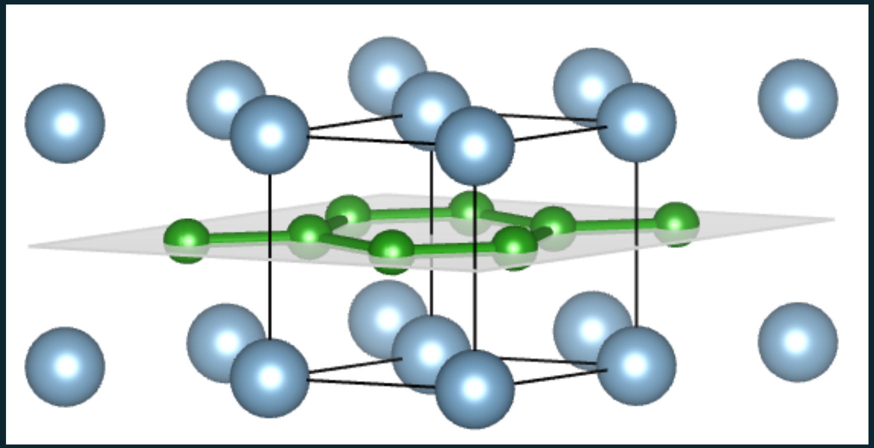
$$\tau_{e-lat} = \frac{\pi k_B^2 T_e}{3\hbar\lambda\langle\Omega^2\rangle}$$

Eliashberg coupling $\lambda = 2\int_0^\infty \alpha^2 F(\Omega)/\Omega d\Omega$

electron-phonon coupling in superconductors

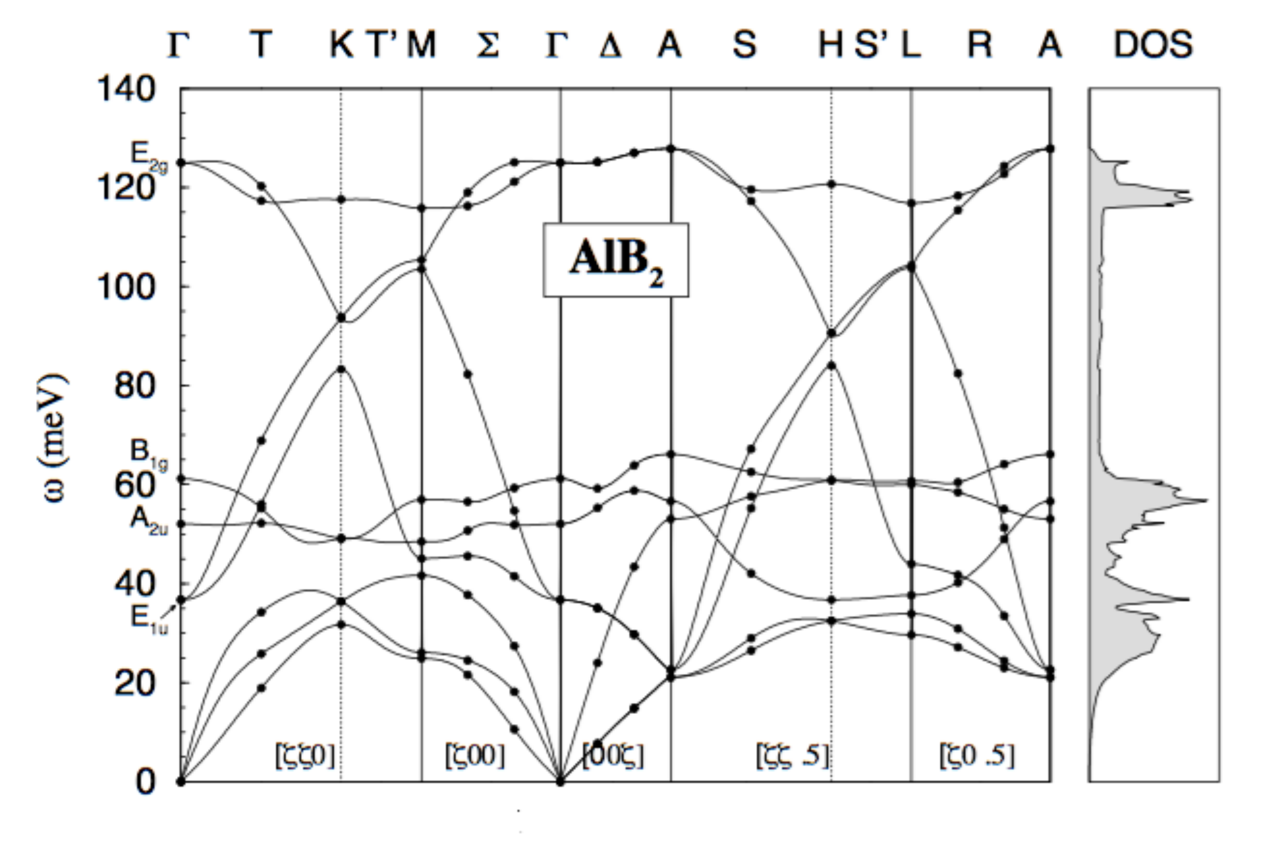
the paradigmatic example of the isostructural MgB_2 and AlB_2

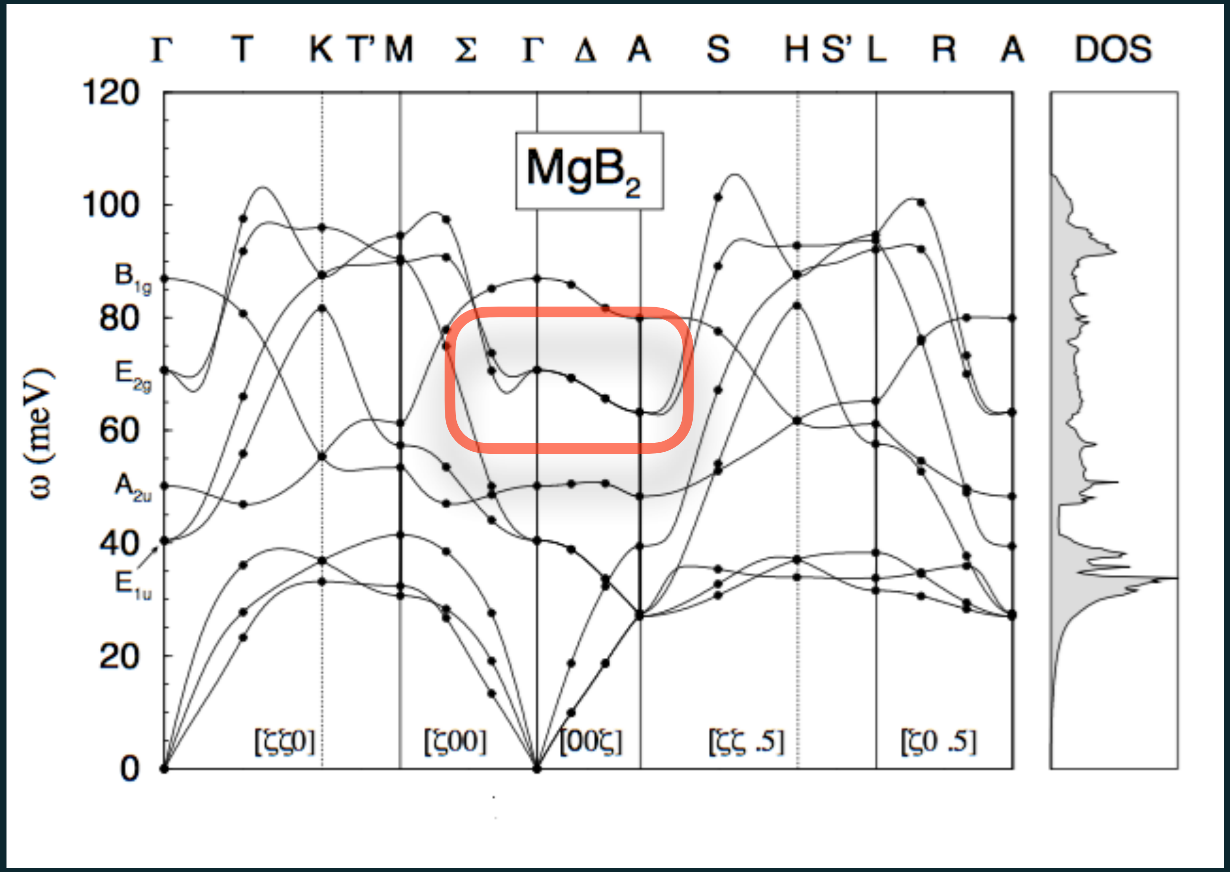
Mg/Al



boron planes

very similar phonon dispersion



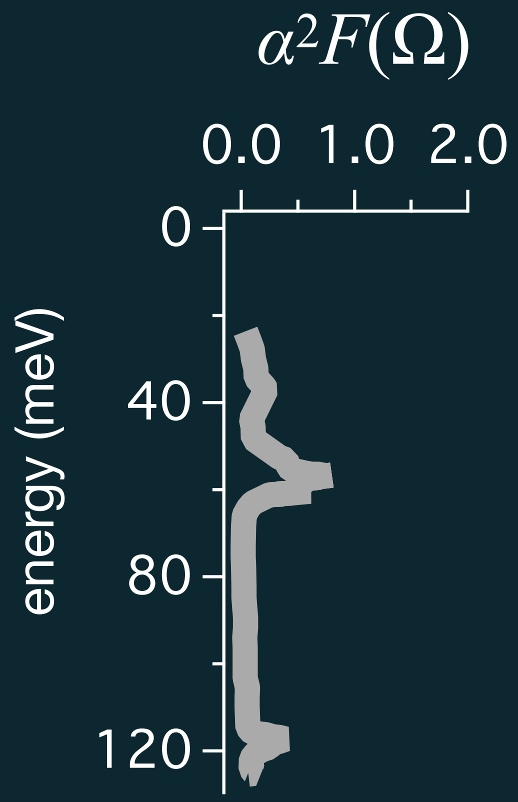


K.-P. Bohnen et al. Phys. Rev. Lett. **86**, 5771 (2001)

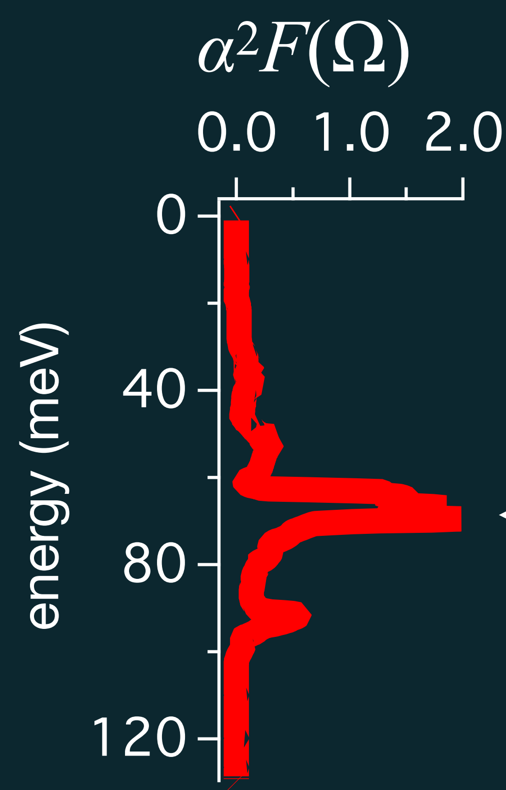
Y. Kong et al. Phys. Rev. B **64**, 020501R (2001)

electron-phonon coupling in superconductors

AlB_2 (non superconducting)



MgB_2 (T_c=39 K)



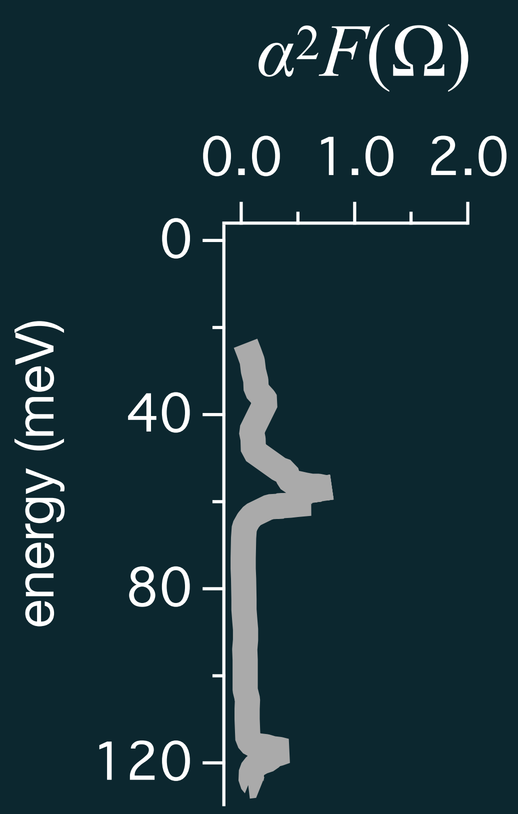
E_{ph}=73 meV $\Longrightarrow$ $\Delta t \simeq$10 fs

strong coupling with the optical bond-stretching E_{2g} mode

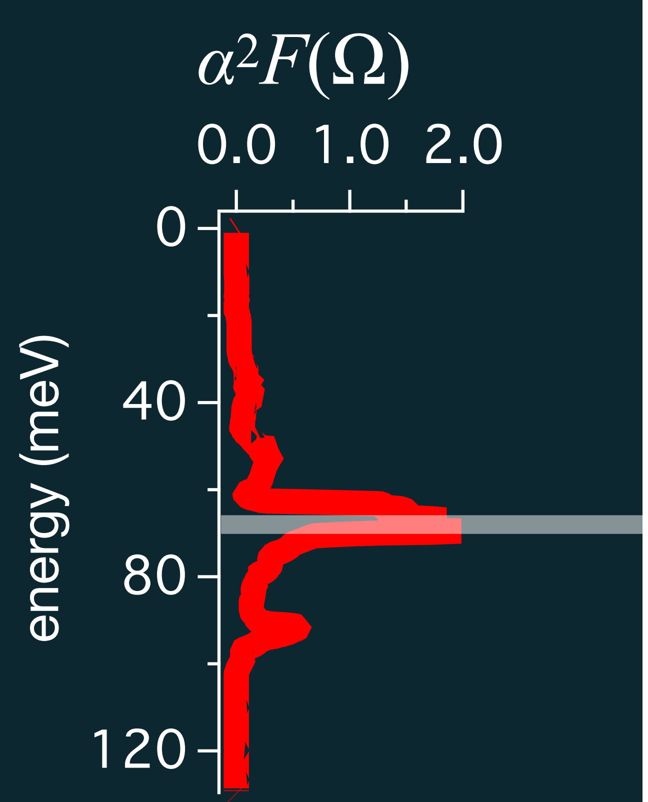
K.-P. Bohnen et al. Phys. Rev. Lett. **86**, 5771 (2001)

electron-phonon coupling in superconductors

AlB_2 (non superconducting)

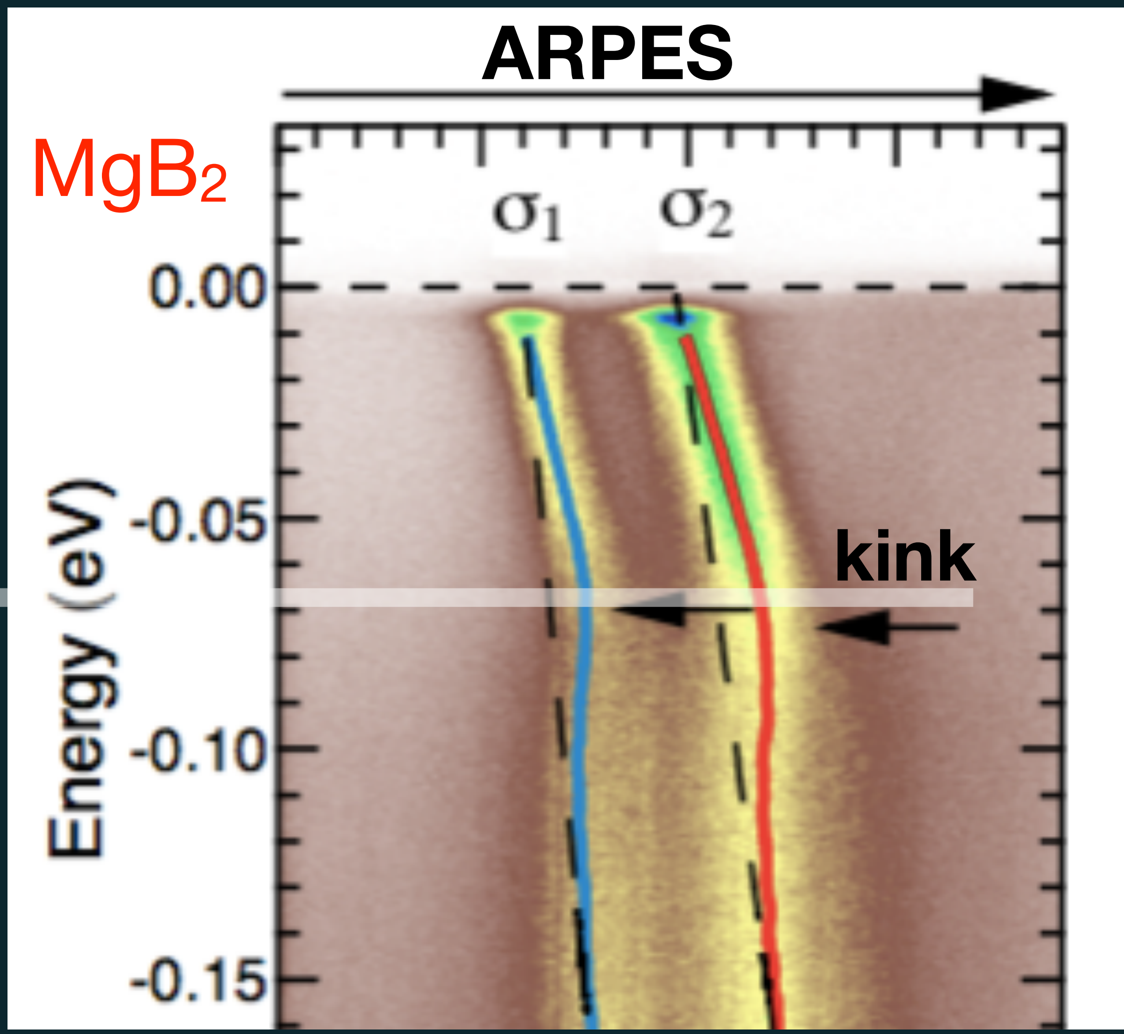


MgB_2 (T_c=39 K)



λ~0.62⇒T_c~40 K

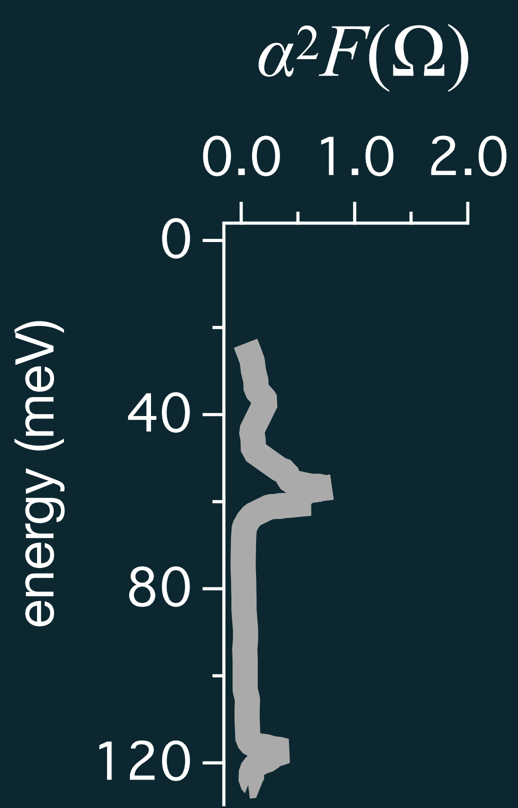
D. Mou et al. Phys. Rev. Lett. (2015)



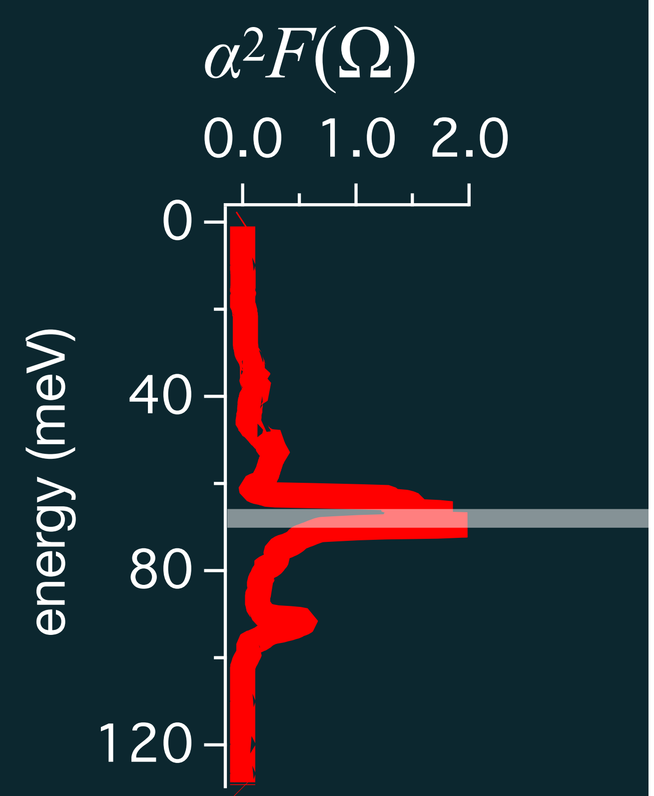
momentum

electron-phonon coupling in superconductors

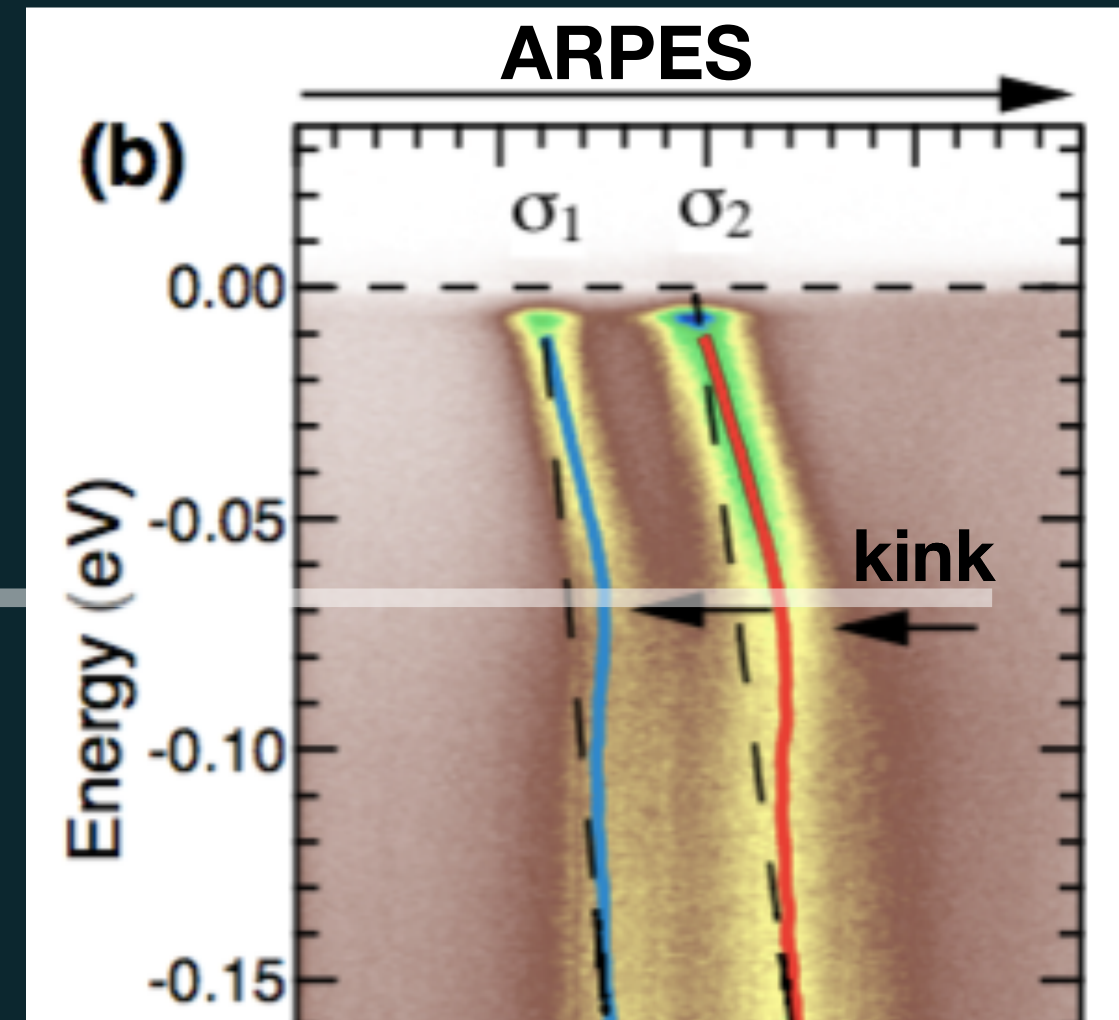
AlB_2 (non superconducting)



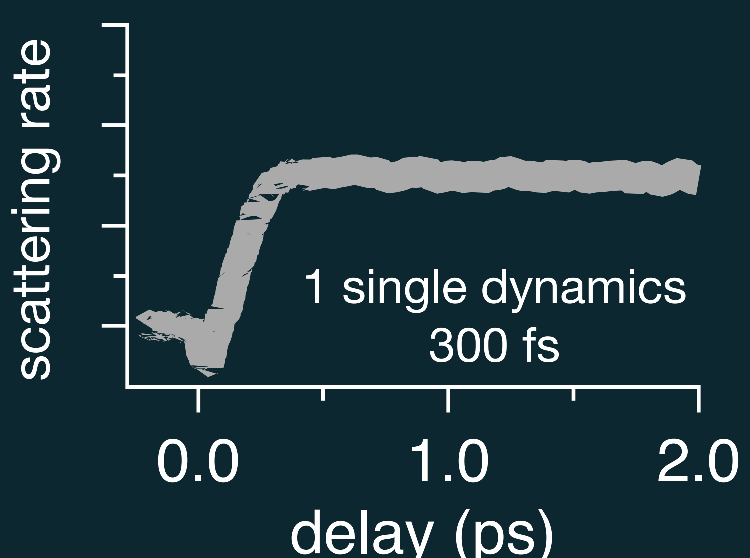
MgB_2 (T_c=39 K)

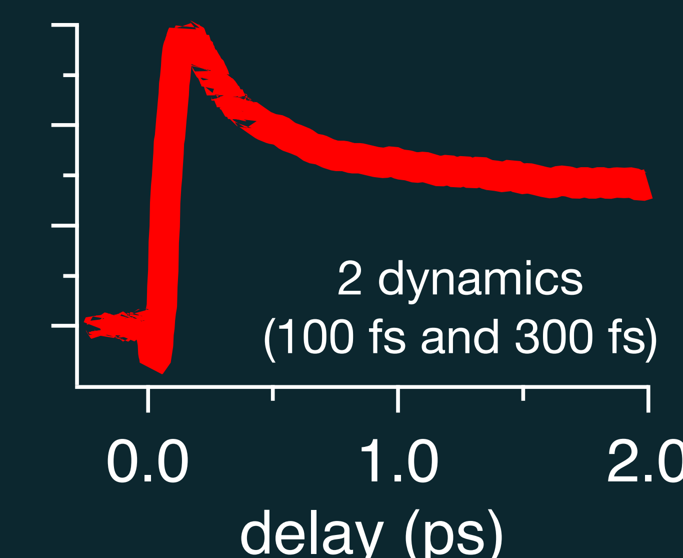


D. Mou et al. Phys. Rev. Lett. (2015)



in the time domain:





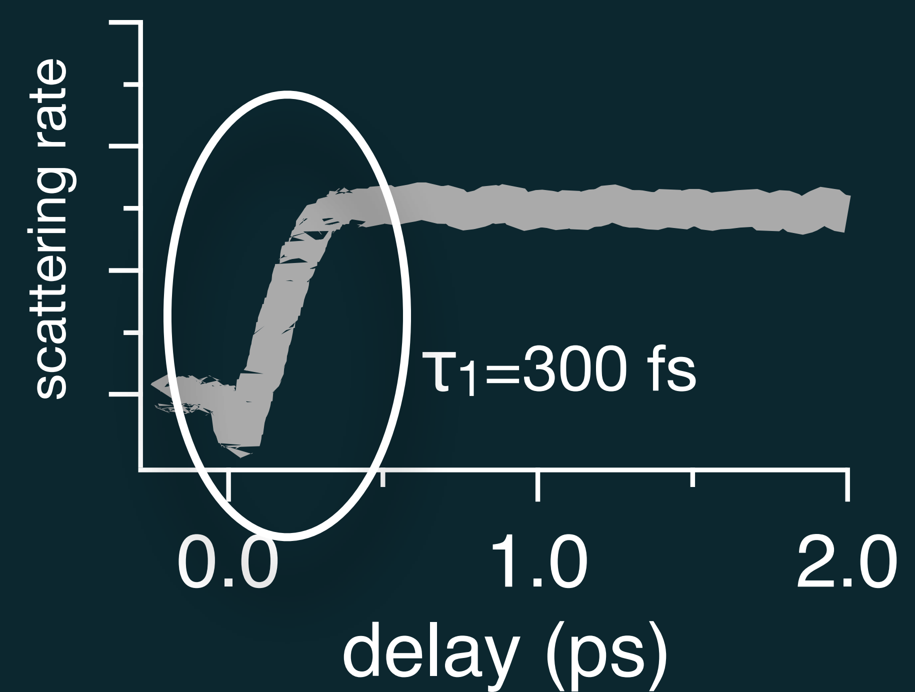
the measured dynamics tracks the change of the boson temperature (density):

$$\delta R/R \propto \delta T_{bos}/T_{bos}$$

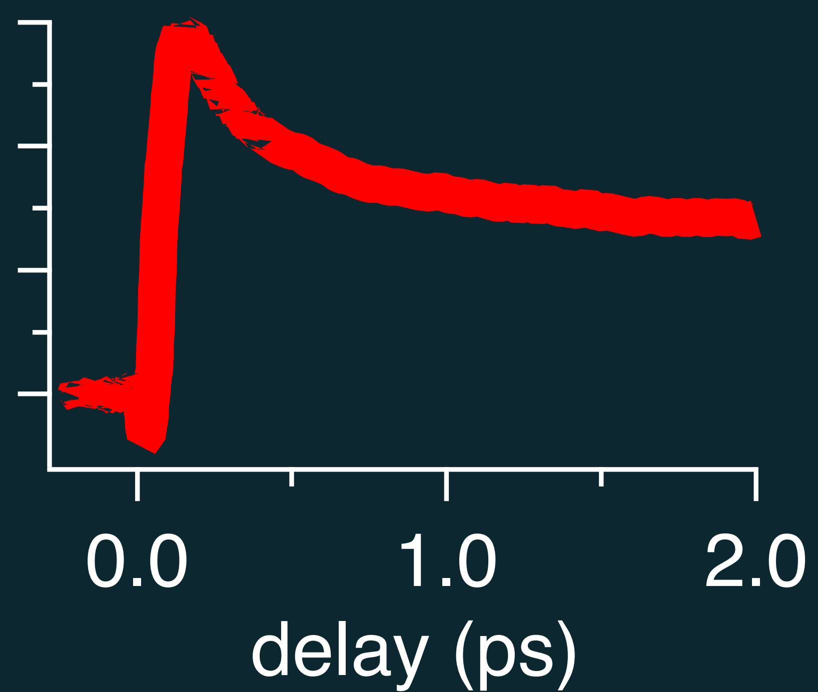
S. Dal Conte et al. *in preparation*

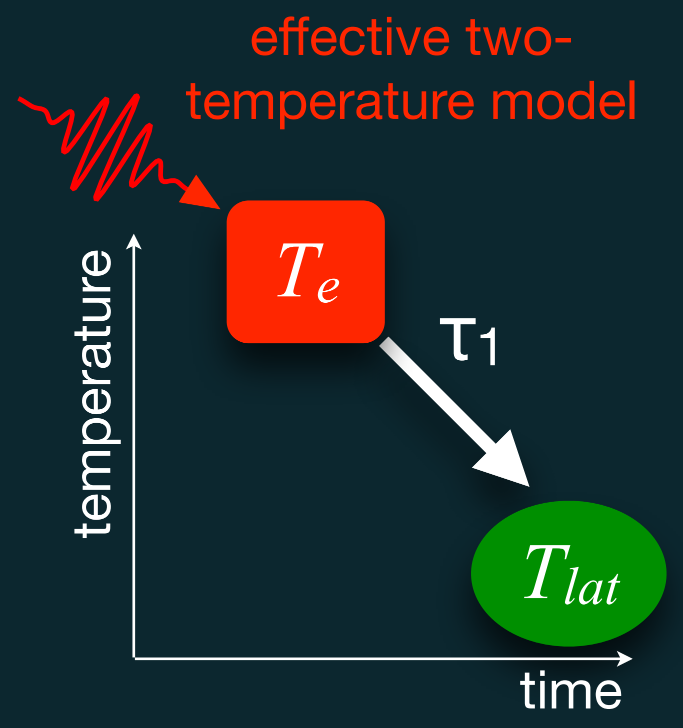
electron-phonon coupling in superconductors

AlB_2 (non superconducting)

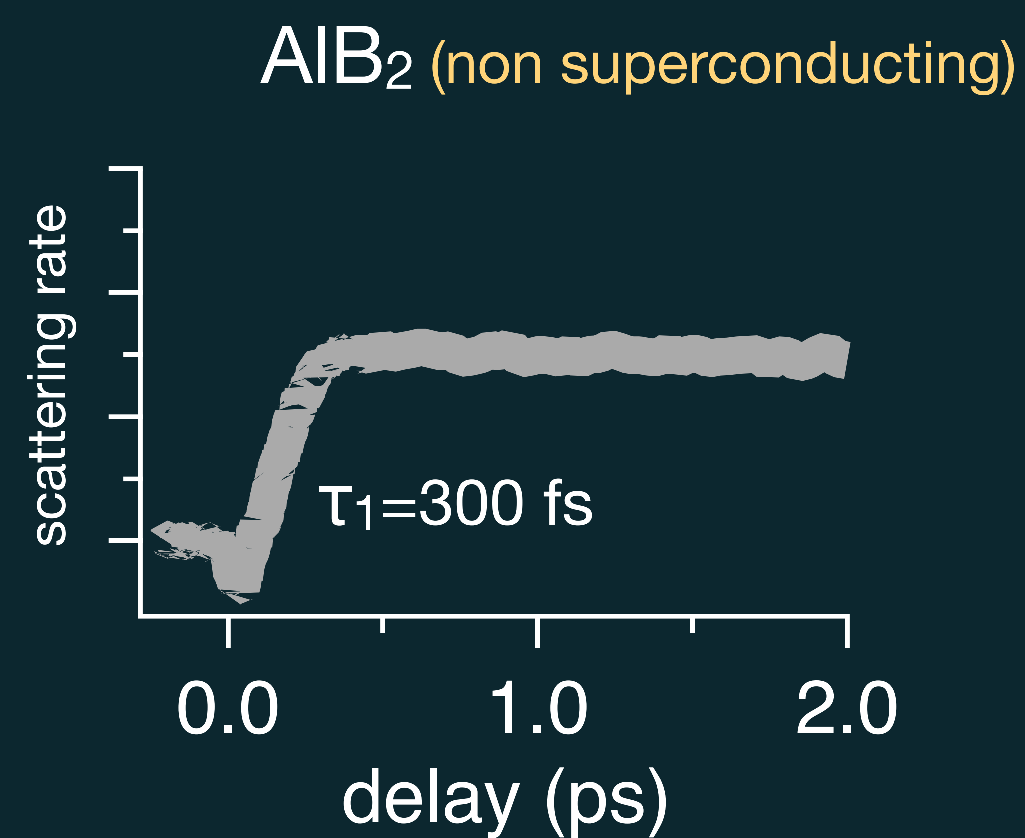


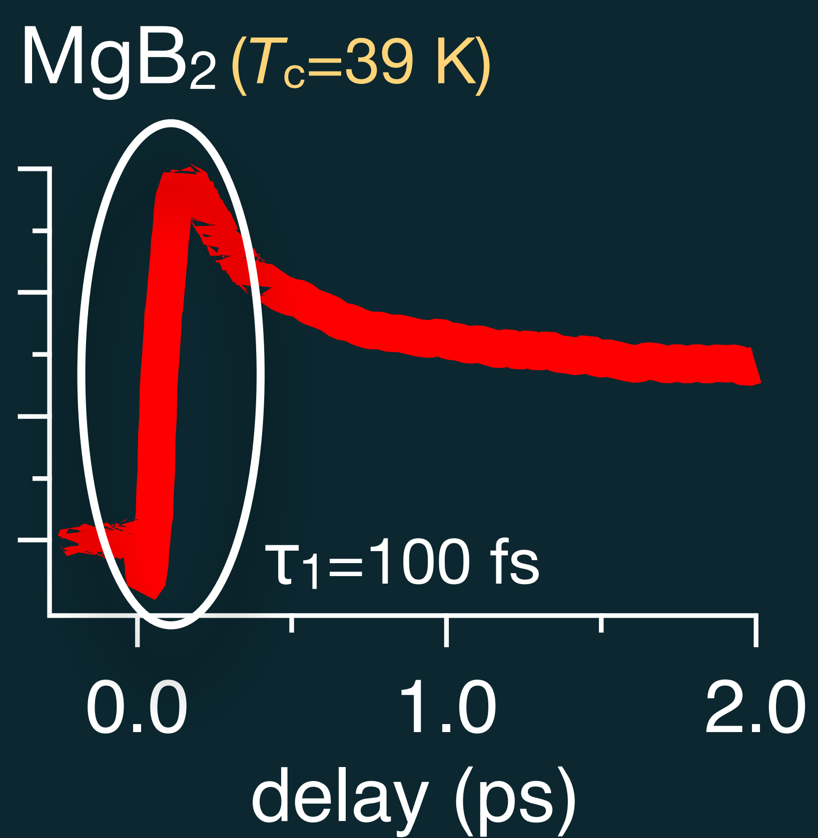
MgB_2 (T_c=39 K)

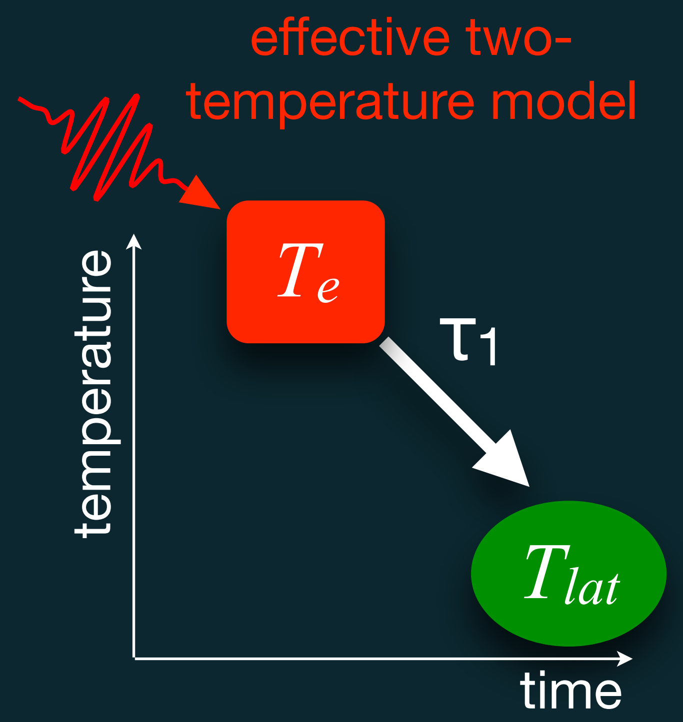




electron-phonon coupling in superconductors

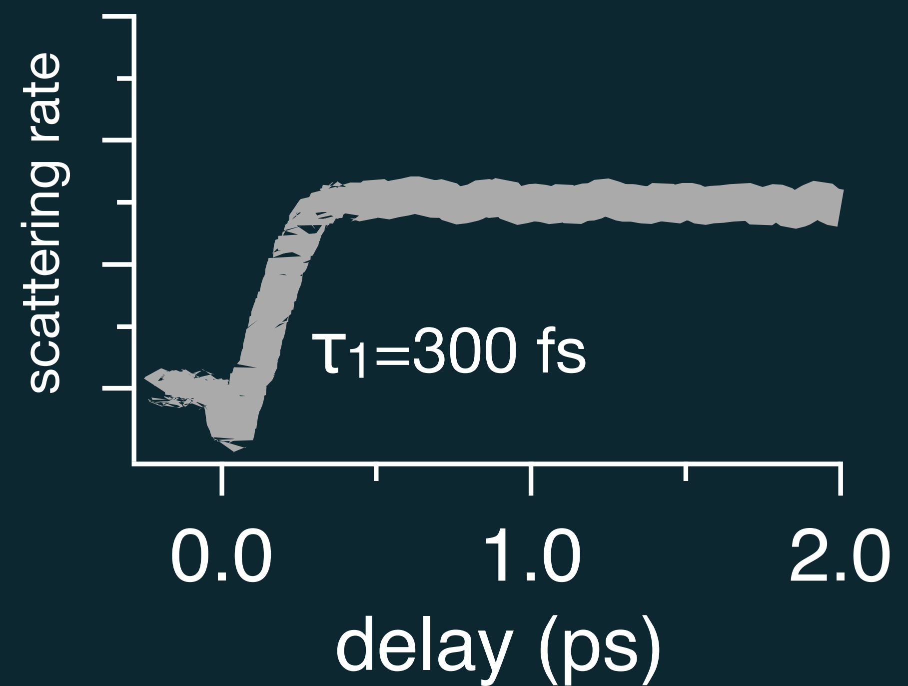




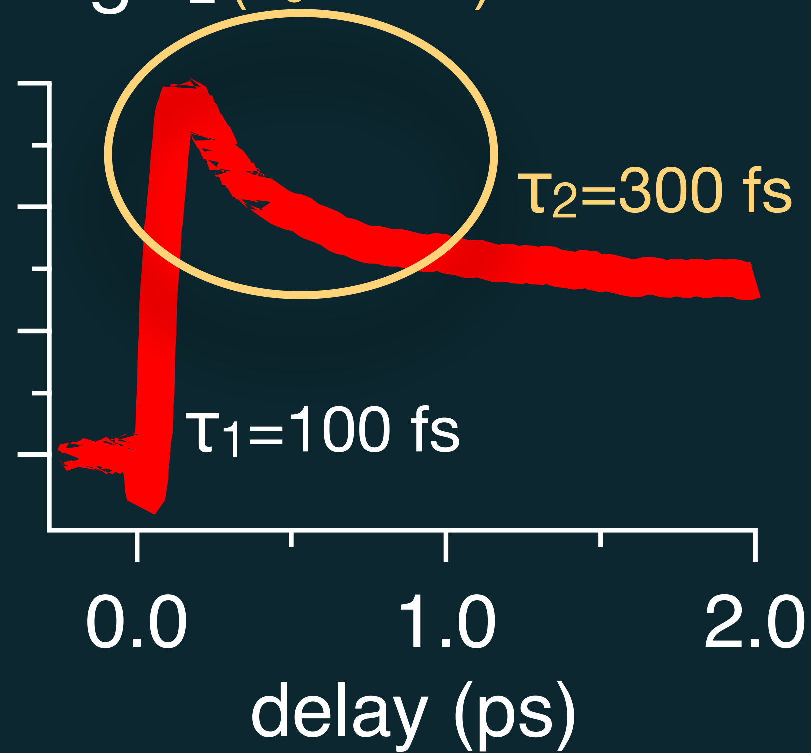


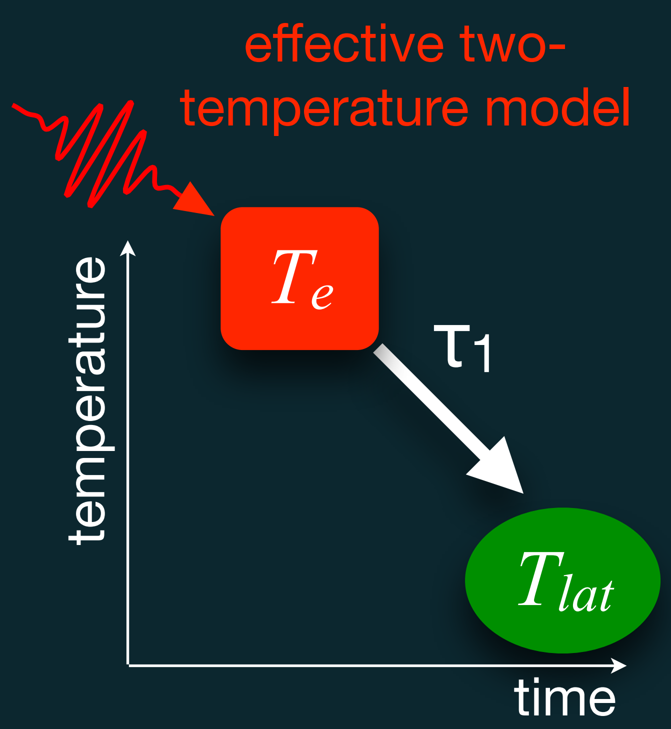
electron-phonon coupling in superconductors

AlB_2 (non superconducting)

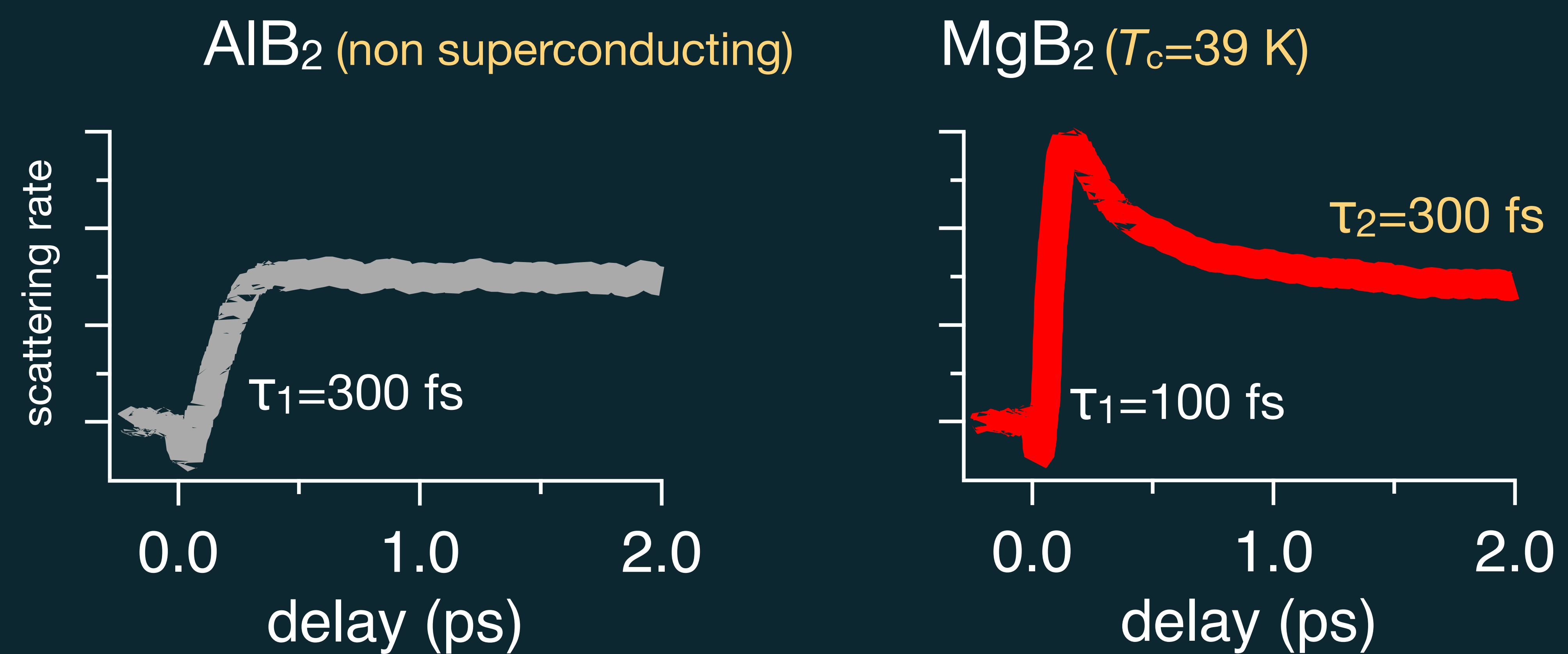


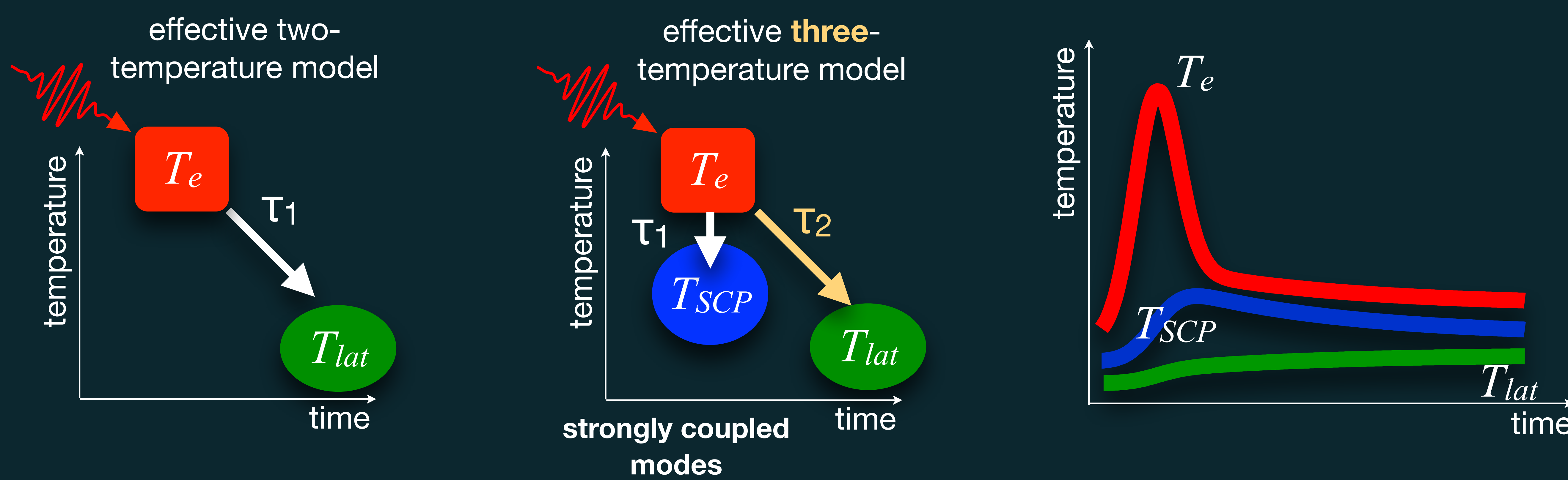
MgB_2 (T_c=39 K)





electron-phonon coupling in superconductors

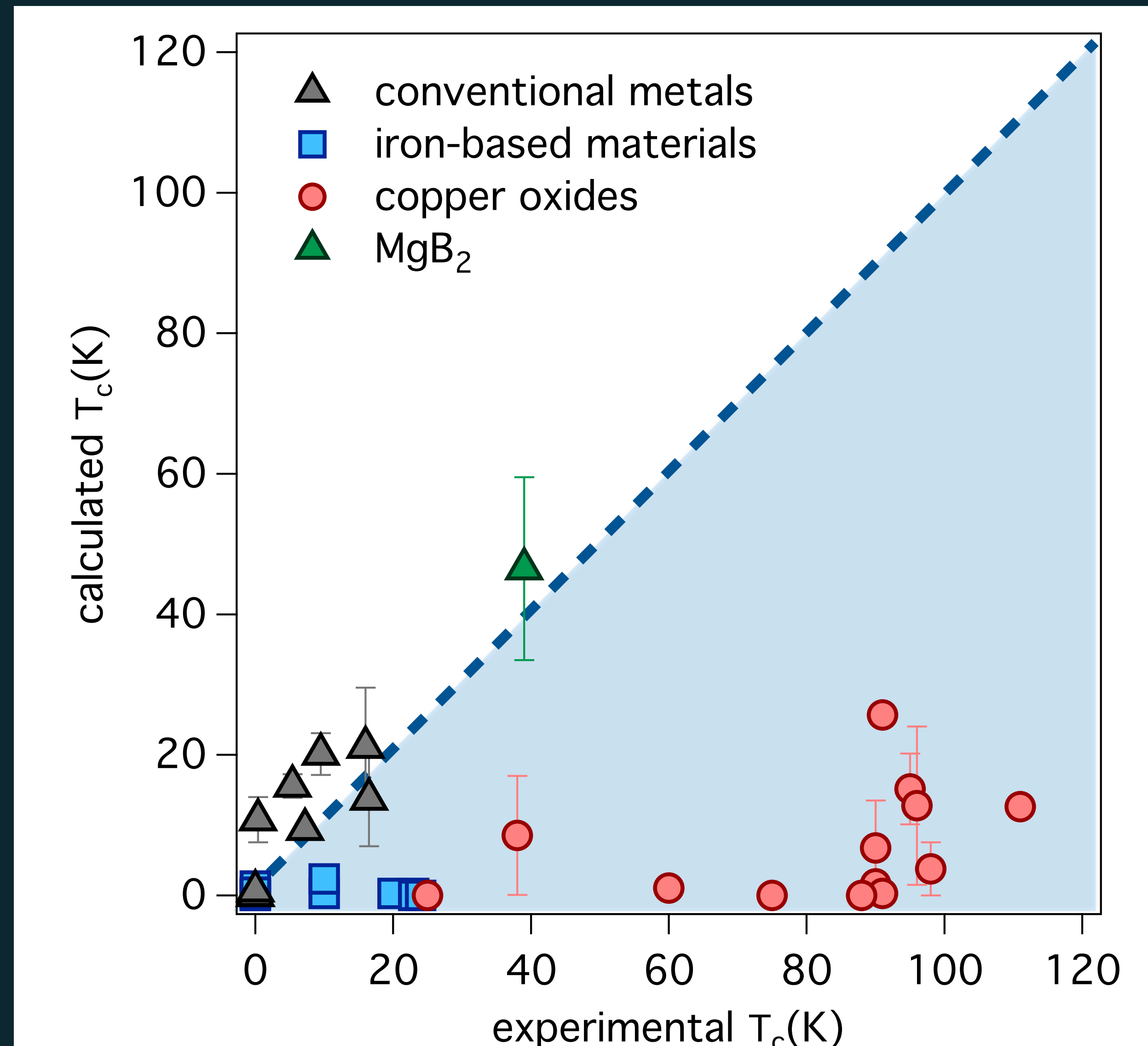




electron-phonon coupling in unconventional superconductors

electron-phonon coupling λ obtained from time-resolved techniques

C. Giannetti et al. Advances in Physics **65**:2, 58-238 (2016)



CUPRATES: some glue is missing!!!

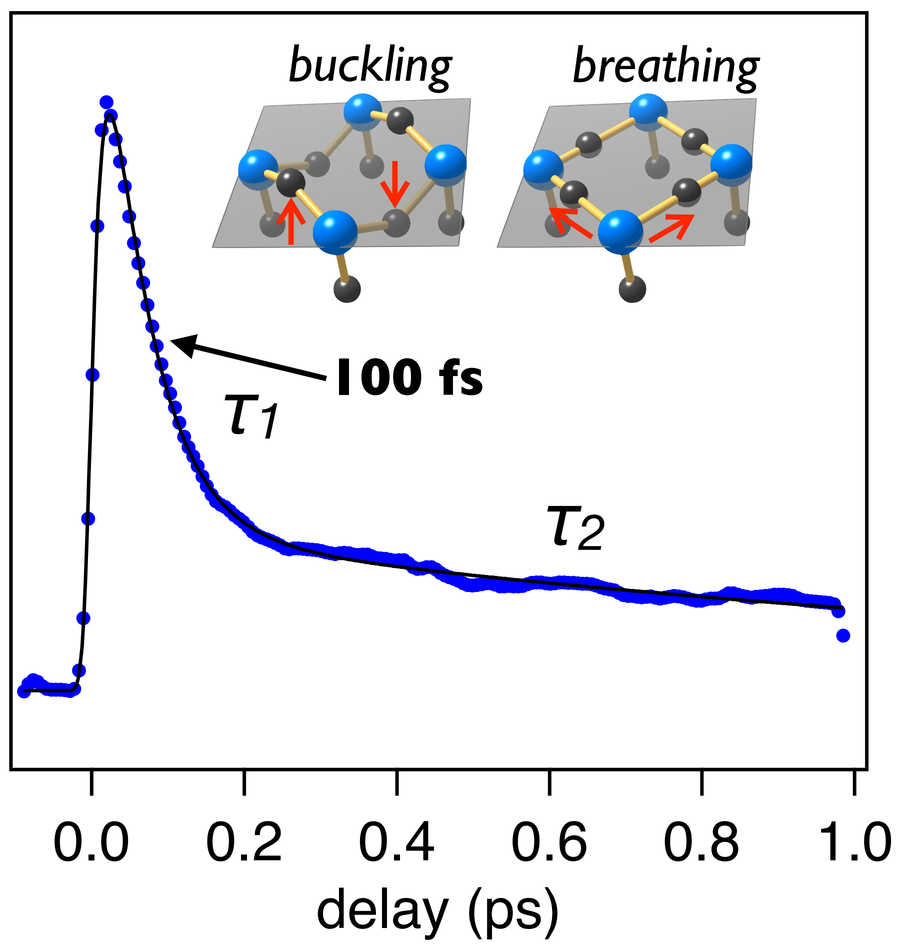
$\tilde{\Omega}$: frequency log-average

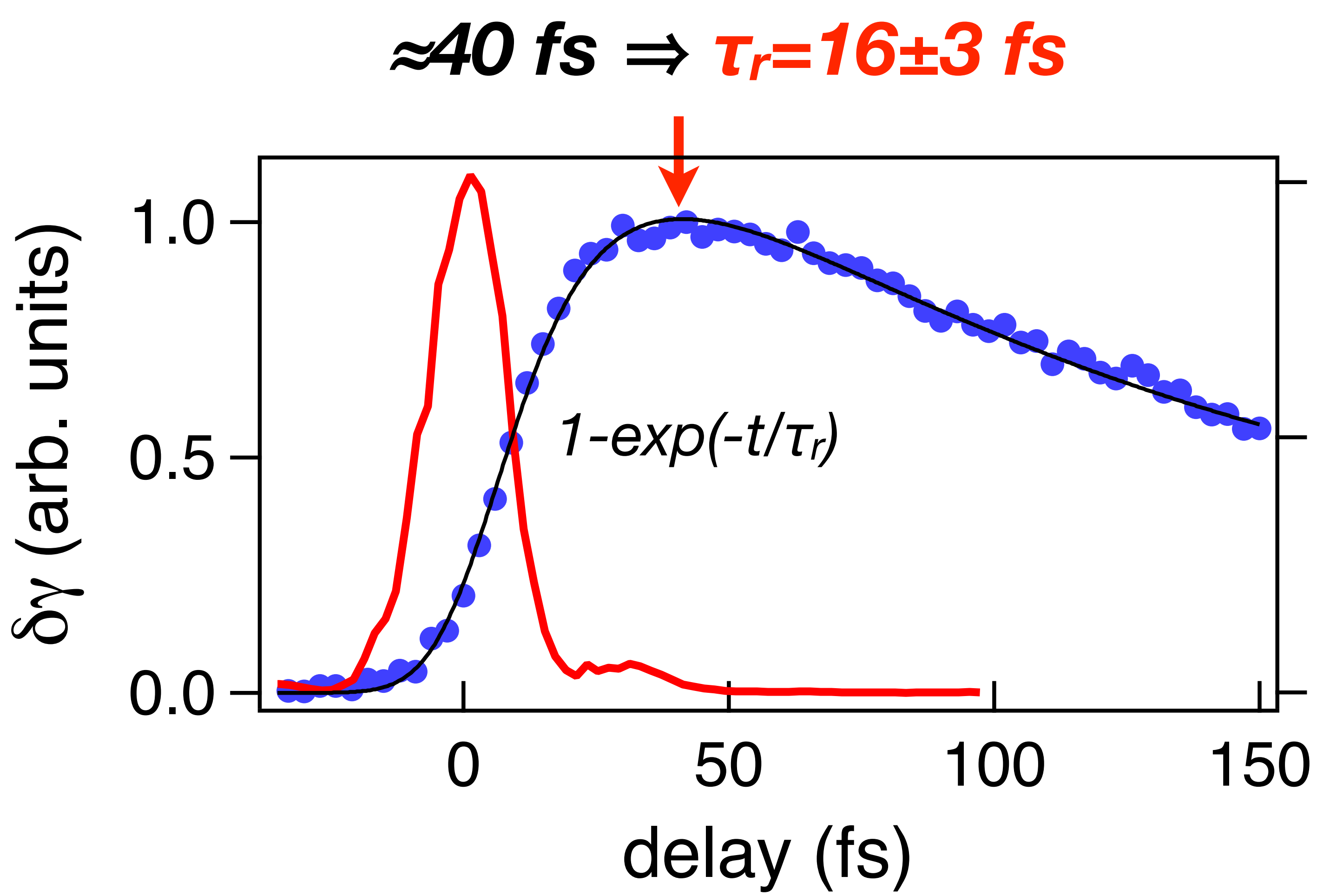
μ*: effective Coulomb repulsion
g<1 for d-wave superconductors

$$T_c = 0.83\tilde{\Omega} e^{-\frac{1.04(1+\lambda)}{g(\lambda-\mu^*(1+0.62\lambda))}}$$

P.B. Allen and R.C. Dynes, Phys. Rev B 12 905 (1975)
A. J. Millis, S. Sachdev, C. M. Varma, Phys. Rev. B **37**, 4975 (1988)

superconducting copper oxides

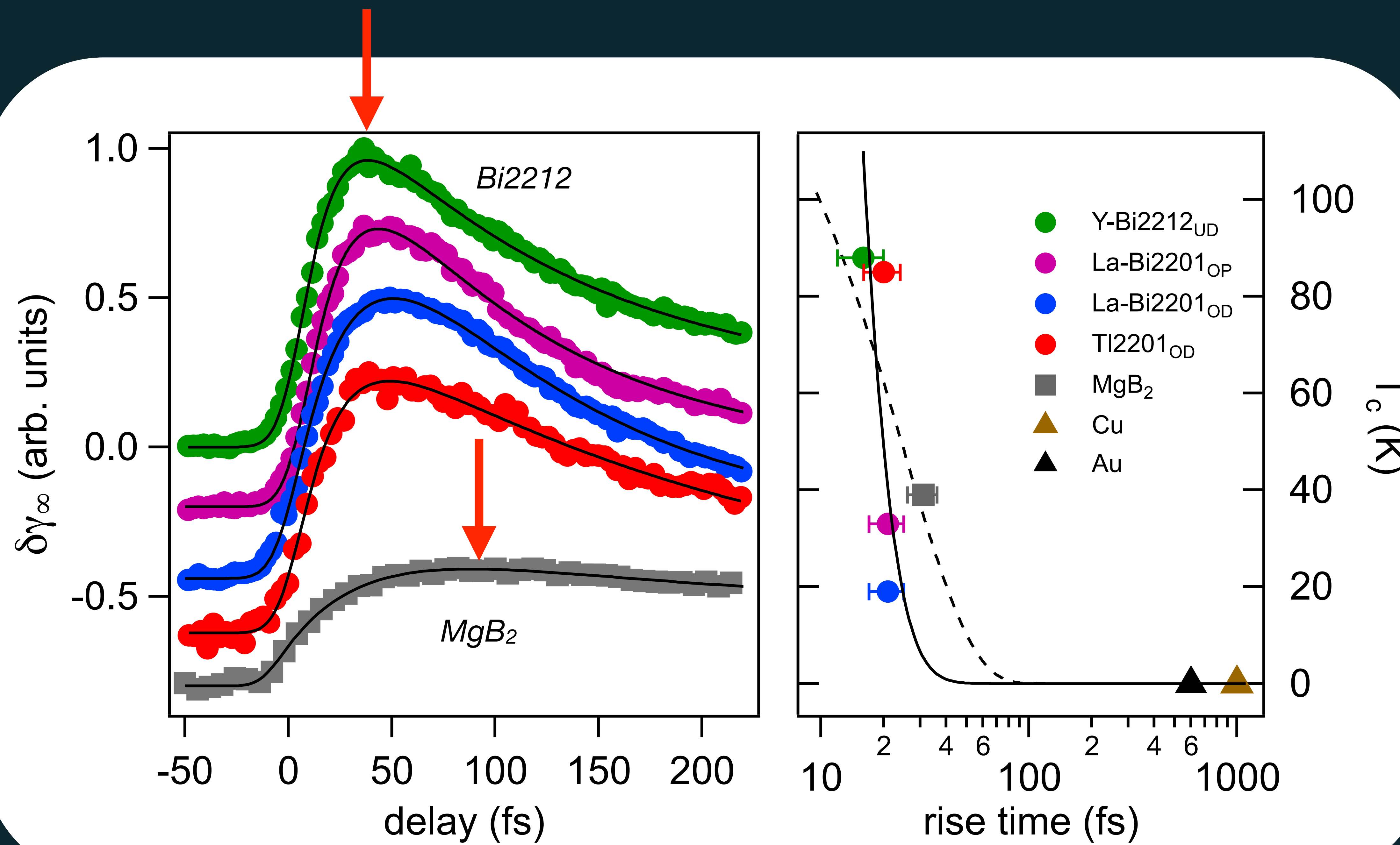




$\delta R(\omega) \propto \delta T_b$

3 different electronic timescales!

comparing to conventional superconductors (MgB_2)



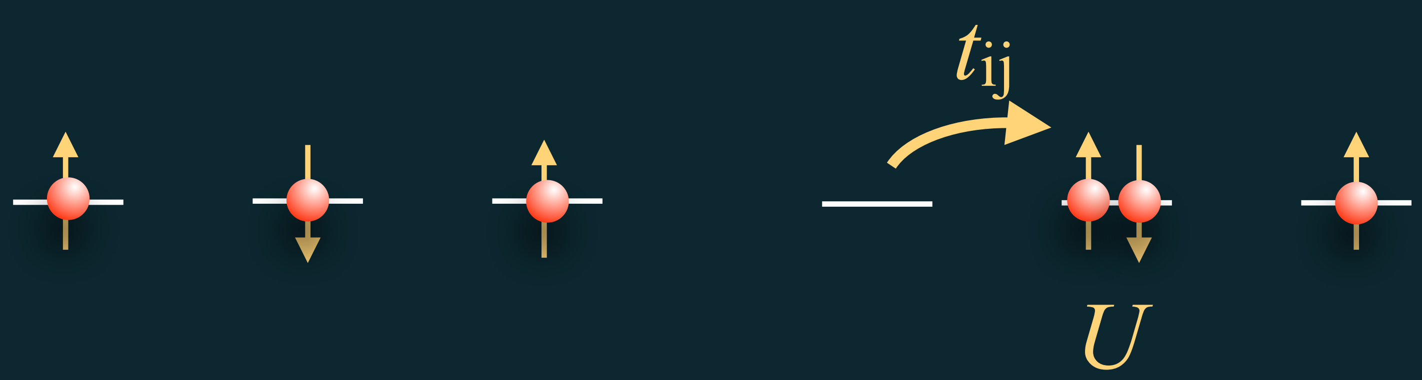
$$T_c = 0.83\tilde{\Omega}e^{-\frac{1.04(1+\lambda)}{g(\lambda-\mu^*(1+0.62\lambda))}}$$

S. Dal Conte et al. *Nature Physics* **11**, 421 (2015)

Hubbard model

single-band Hubbard model

$$\hat{H} = -\sum_{i,j,\sigma} (t_{ij}\hat{c}^{\dagger}_{i\sigma}\hat{c}_{j\sigma} + c.c.) + U\sum_{i}\hat{n}_{i,\uparrow}\hat{n}_{i,\downarrow} - \mu\sum_{i}\hat{n}_{i}$$



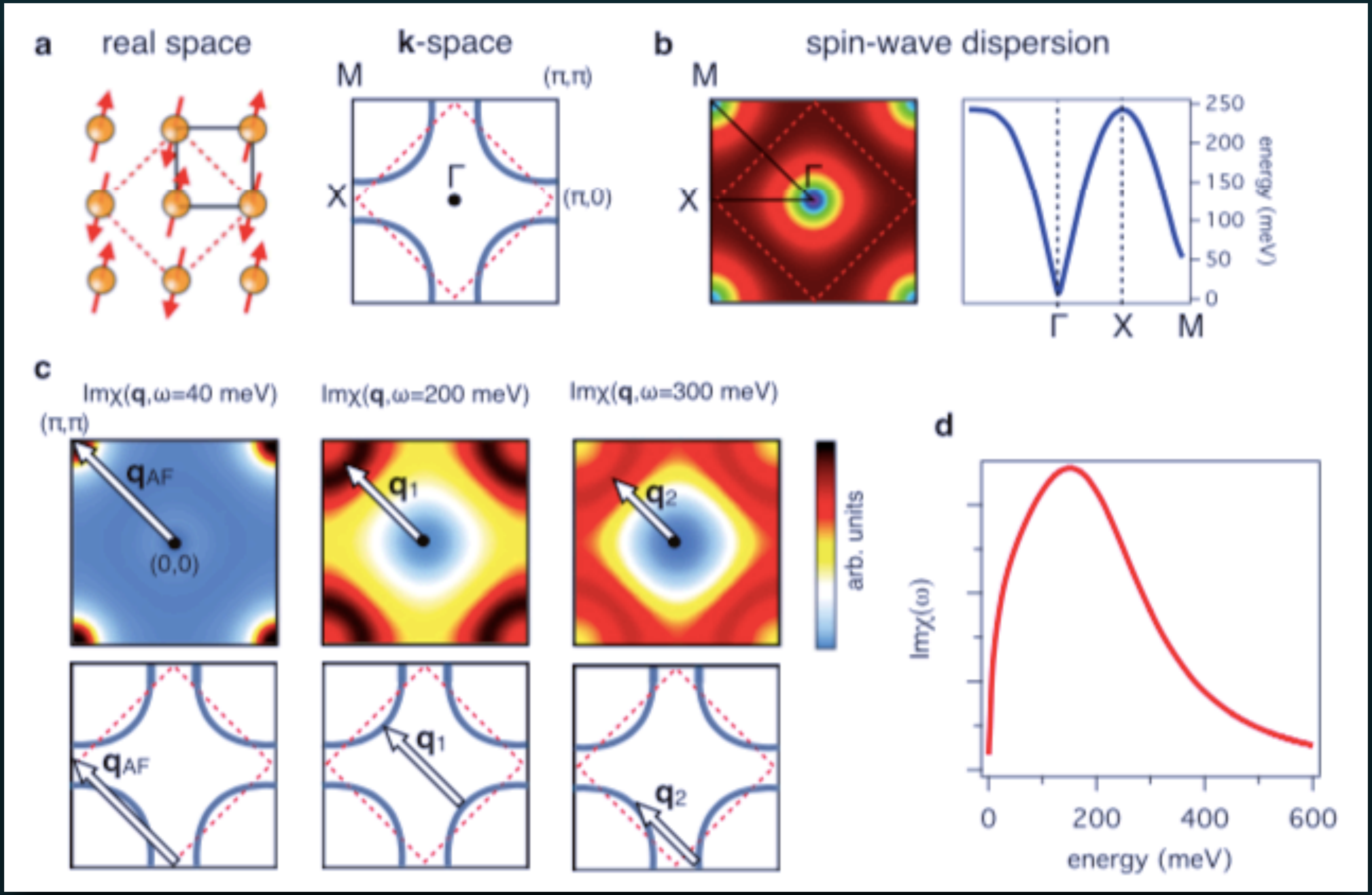
2nd order $J=4t^2/U$ energy gain for antiferromagnetic ground state

t-J model in the $U\rightarrow\infty$ limit

$$H = -t_h \sum_{\langle \mathbf{lj}\rangle,\sigma} (c^{\dagger}_{\mathbf{l},\sigma}\tilde{c}_{\mathbf{j},\sigma} + \mathrm{h.c.}) + J\sum_{\langle \mathbf{lj}\rangle} \mathbf{S_l}\cdot\mathbf{S_j}$$

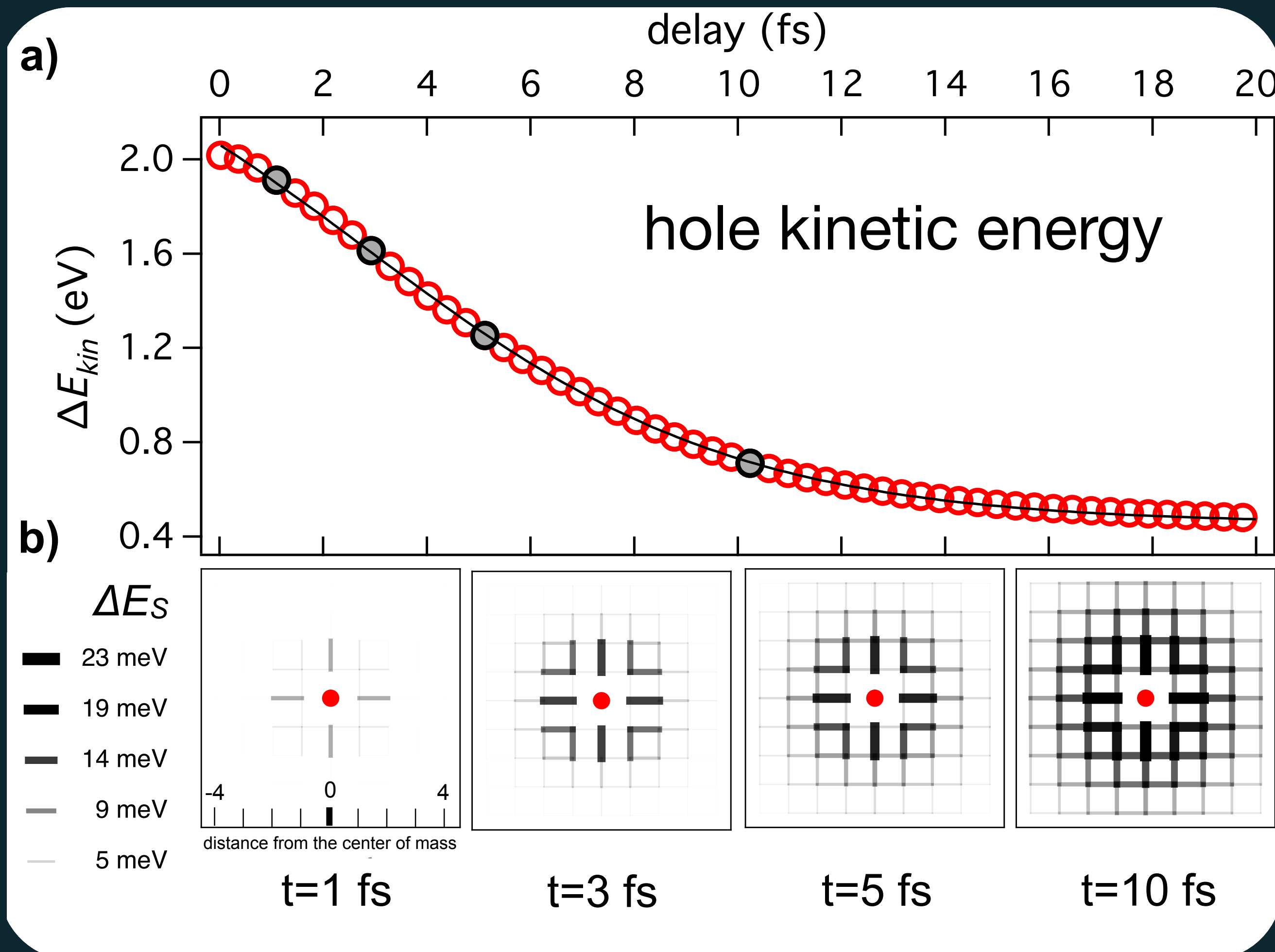
t=360 meV J=120 meV

Magnetic excitations in the copper sublattice



C. Giannetti et al. Advances in Physics **65**:2, 58-238 (2016)

non-equilibrium t-J model

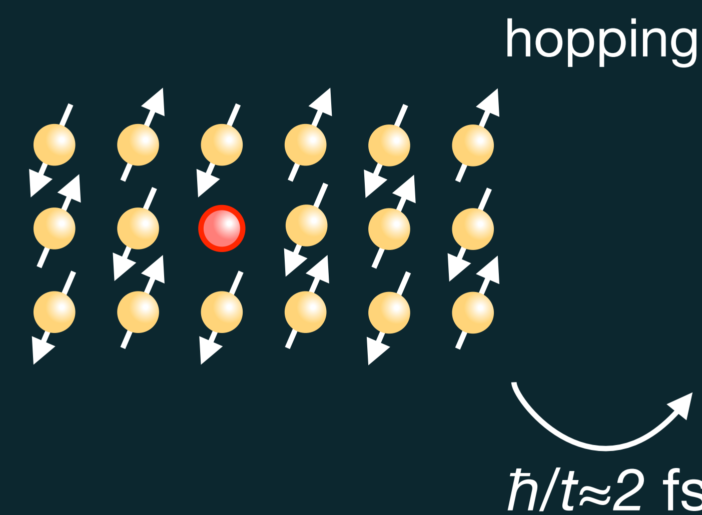


energy transfer to AF background

→time-dep. Schr. equation

Ultrafast coupling to high-energy short-range AF spin fluctuations:

- 10 fs coupling to short-range AF spin background



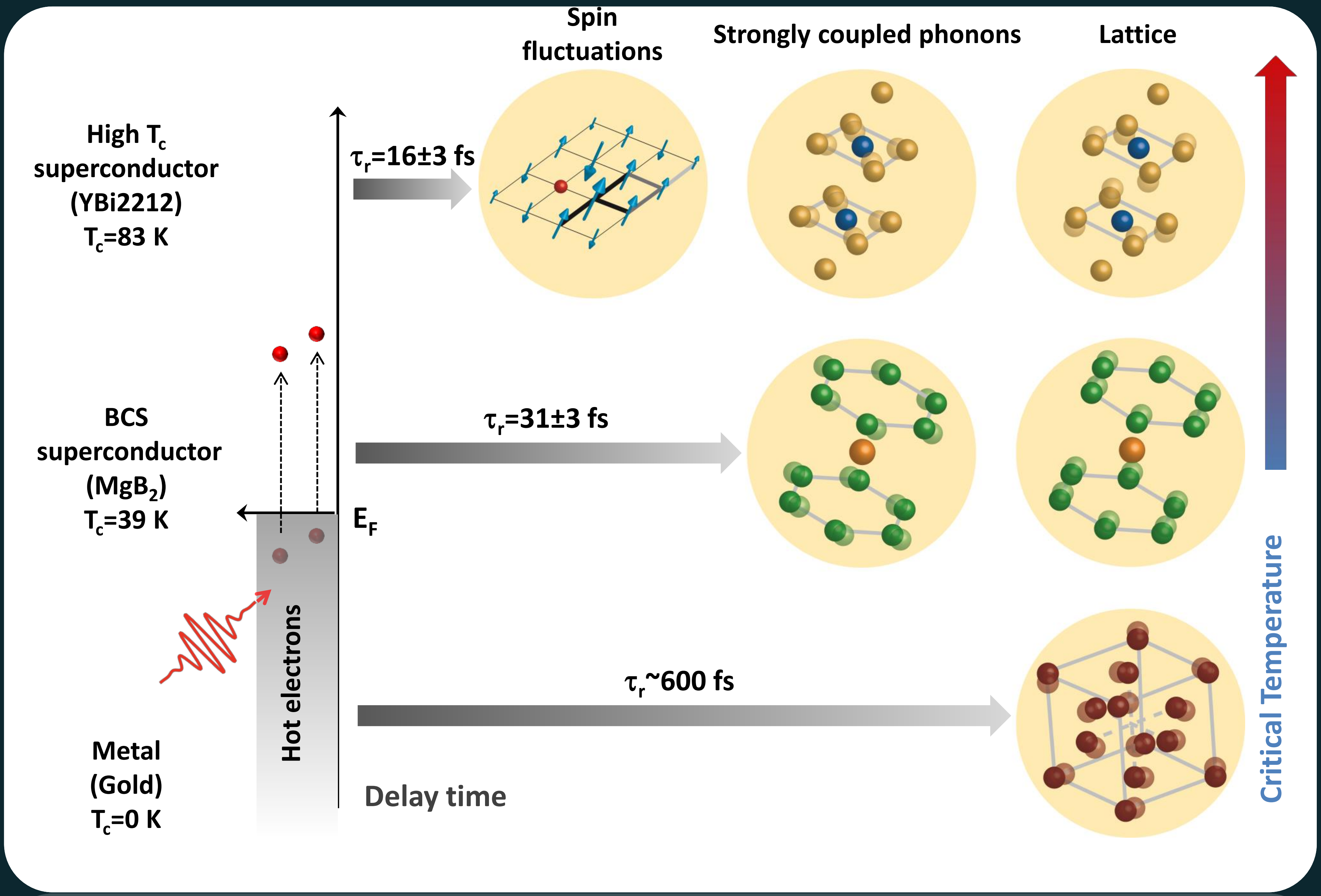
$$H = -t_h \sum_{\langle \mathbf{lj} \rangle, \sigma} (c^{\dagger}_{\mathbf{l},\sigma} \tilde{c}_{\mathbf{j},\sigma} + \mathrm{h.c.}) + J \sum_{\langle \mathbf{lj} \rangle} \mathbf{S_l} \cdot \mathbf{S_j}$$

t=360 meV   J=120 meV

In 16 fs photoexcited carriers can exchange energy with bosons ✔

S. Dal Conte et al. *Nature Physics* **11**, 421 (2015)

retarded e-boson interaction

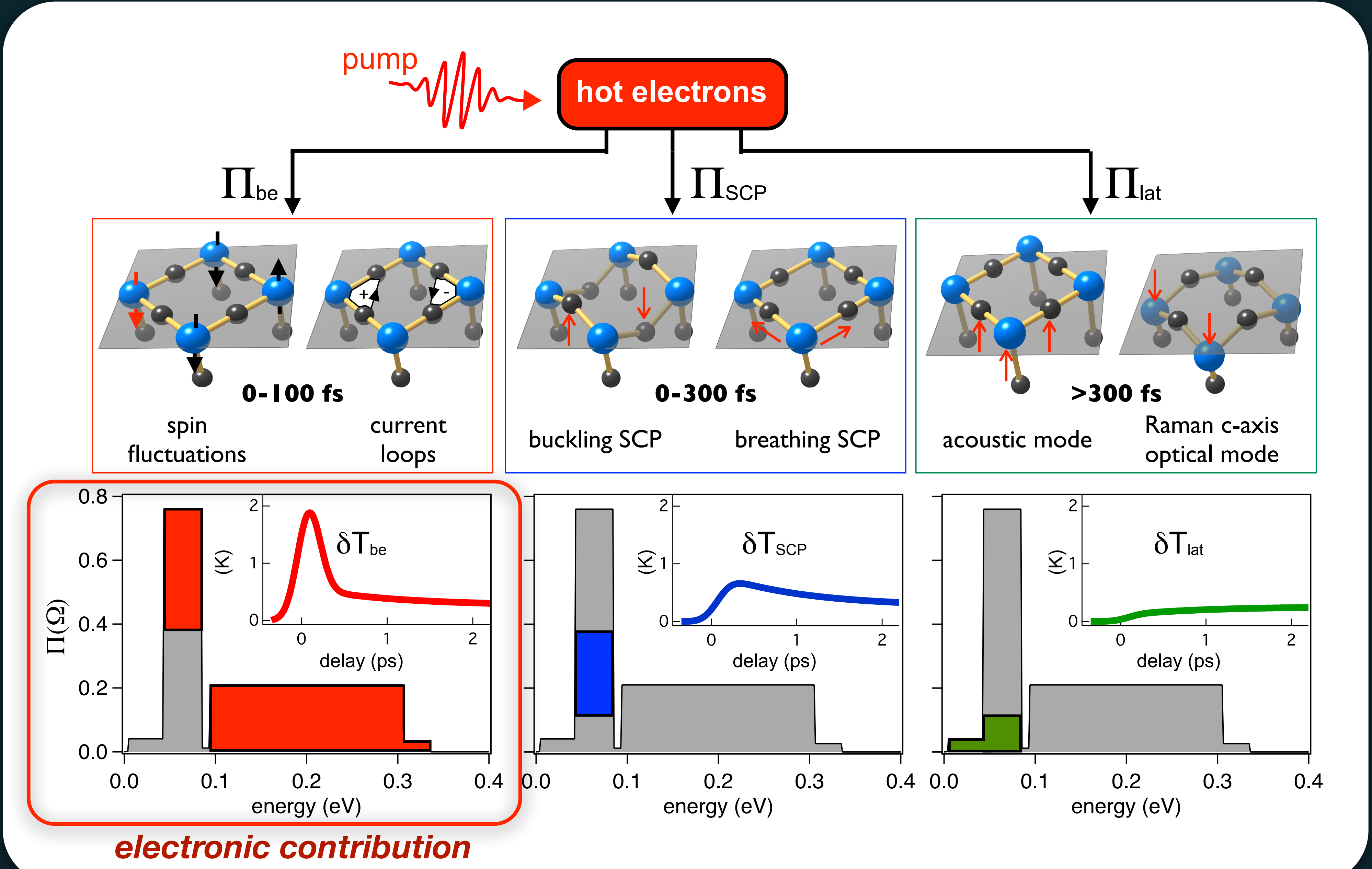


Direct observation of coupling with spin fluctuations (<20 fs) in copper oxides

S. Dal Conte et al. *Nature Physics* **11**, 421 (2015)

retarded e-boson interaction

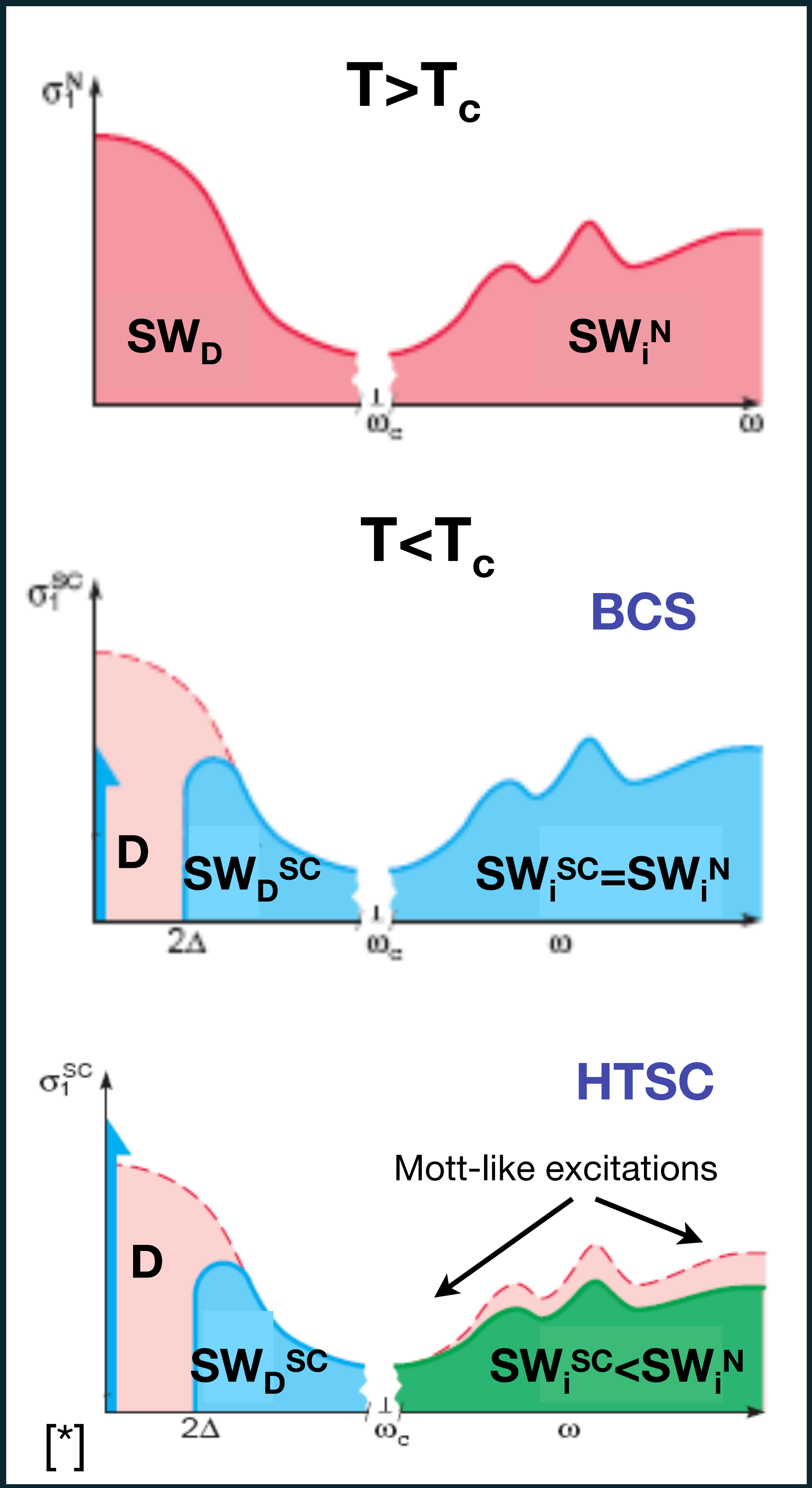
S. Dal Conte et al., *Science* **335**, 1600 (2012)



retarded interaction (glue) of charge carriers with ultrafast fluctuations in cuprates light pulses to UNDERSTAND equilibrium properties

⇒ optical spectral-weight transfer in superconductors

Interplay between the low- and high-energy scale in HTSC?



Adapted from M. R. Noman and C. Pepin, Rep. Prog. Phys. 2003

spectral weight $SW = \int_0^\infty \sigma_1(\omega)d\omega = \frac{\pi n e^2}{m}$

optical conductivity superconductor

$$\sigma(\omega) = \frac{ne^2}{m}\frac{1}{\tau^{-1} - i\omega} \xrightarrow{\tau\to\infty} \frac{ne^2}{m}\left[\pi\delta(\omega) - \frac{1}{i\omega}\right]$$

Ferrel-Glover-Tinkham sum rule

$$SW_i^N - SW_i^{SC} = D - SW_D^N + SW_D^{SC}$$

Kinetic energy in a single conduction band within the nearest-neighbour tight-binding model

$$\langle K \rangle = \frac{4\hbar^2 V_{Cu}}{\pi^2 a_\delta^2 e^2}[SW_i^N - SW_i^{SC}]$$

Interplay between the low- and high-energy scale in HTSC?

Fundamental questions:

-Is high-T_c a kinetic-energy driven phenomenon?

$$\langle E \rangle_{SC} - \langle E \rangle_N = \underbrace{\left[\frac{\Delta^2}{V} - \frac{1}{2}N(0)\Delta^2\right]}_{\text{KE}} - \underbrace{\frac{\Delta^2}{V}}_{\text{PE}}$$

M. Tinkham, *Introduction to Superconductivity*

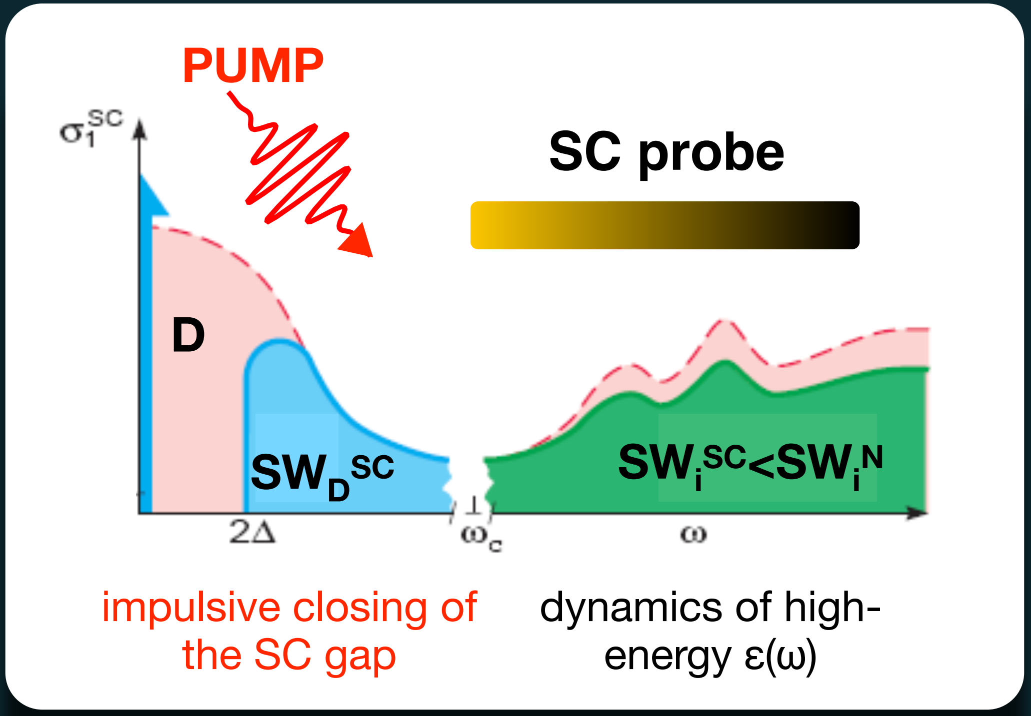
-Is the electronic structure modified at high-energy scales by the condensate?

time+spectral resolution

Problems of equilibrium optical spectroscopies:

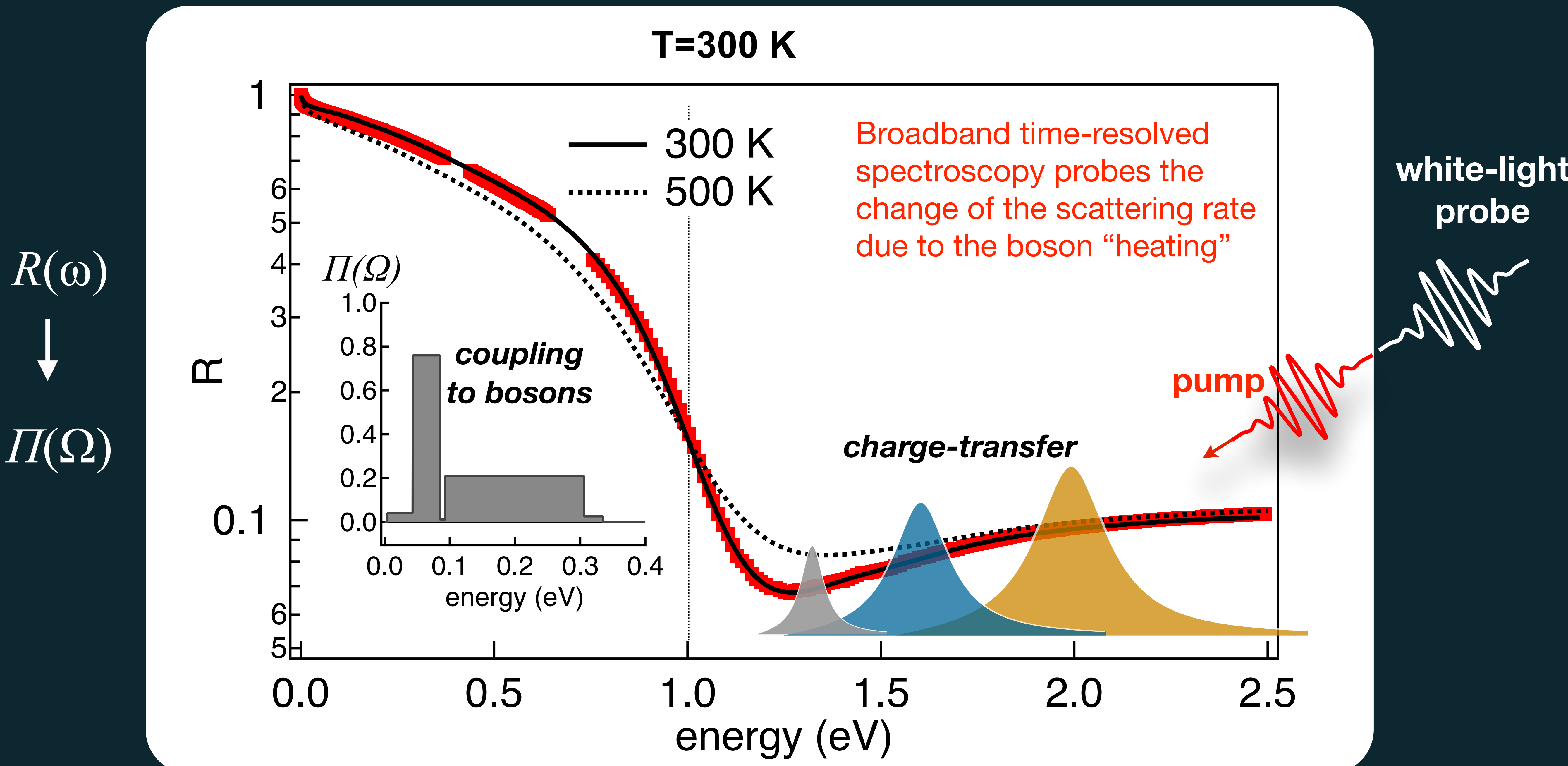
-Finite cut-off for calculating SW
-Temperature dependent Drude broadening

Holcomb, PRL (1994)
Rübhausen, PRL (2001)
Molegraaf, Science (2002)
Boris, Science (2004)
Santander-Syro, PRB (2004)



reflectivity of cuprates

optimally doped $Bi_2Sr_2Y_{0.08}Ca_{0.92}Cu_2O_{8+\delta}$ (YBi2212)
T_c=96 K



E. van Heumen et al., *Phys. Rev. B* **79**, 184512 (2009)

Time-resolved optical spectroscopy on Y-Bi2212

$$\frac{\delta R}{R}(\omega, t)$$

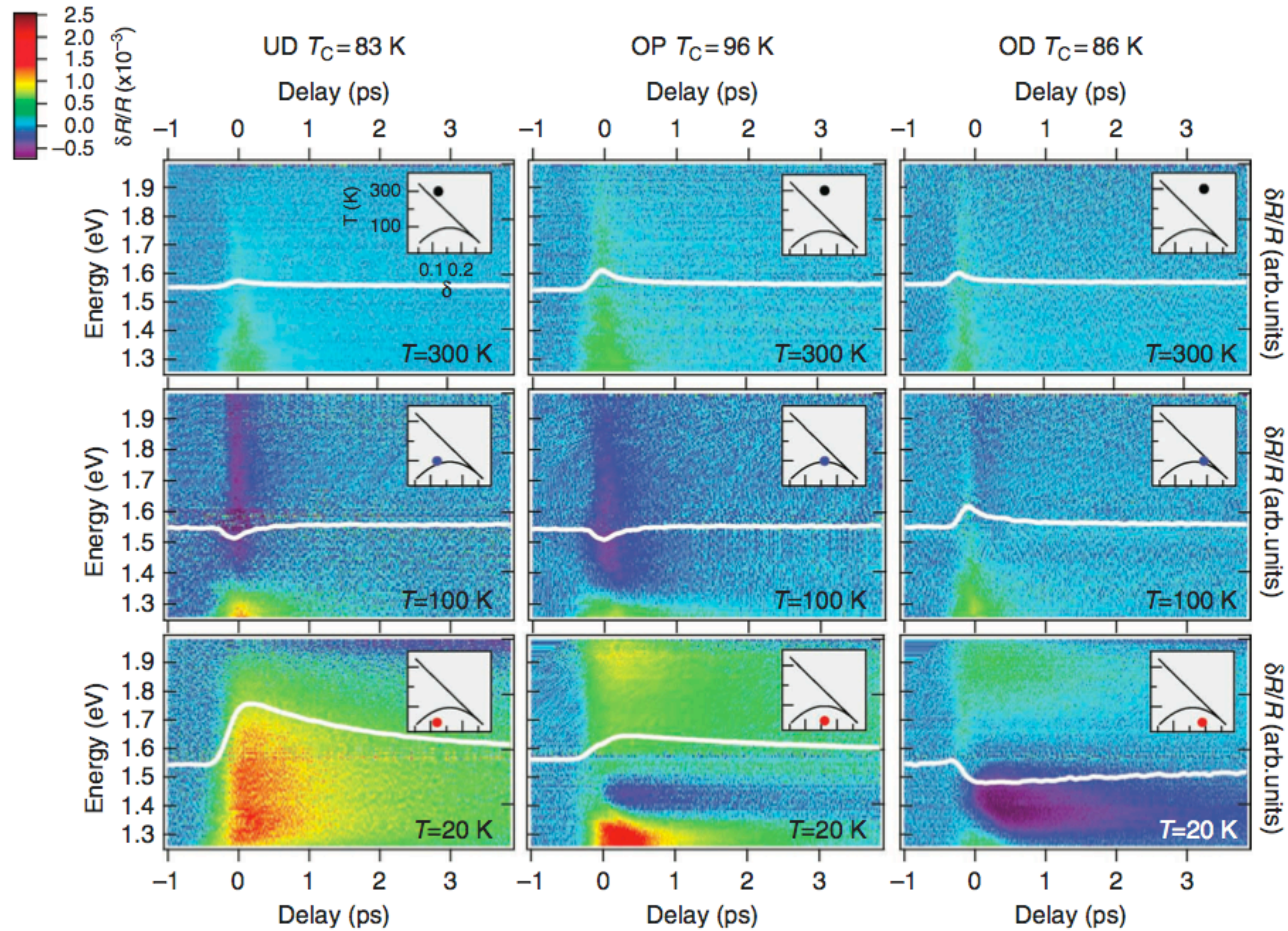
< 10 μJ/cm²

Normal state

Pseudogap state

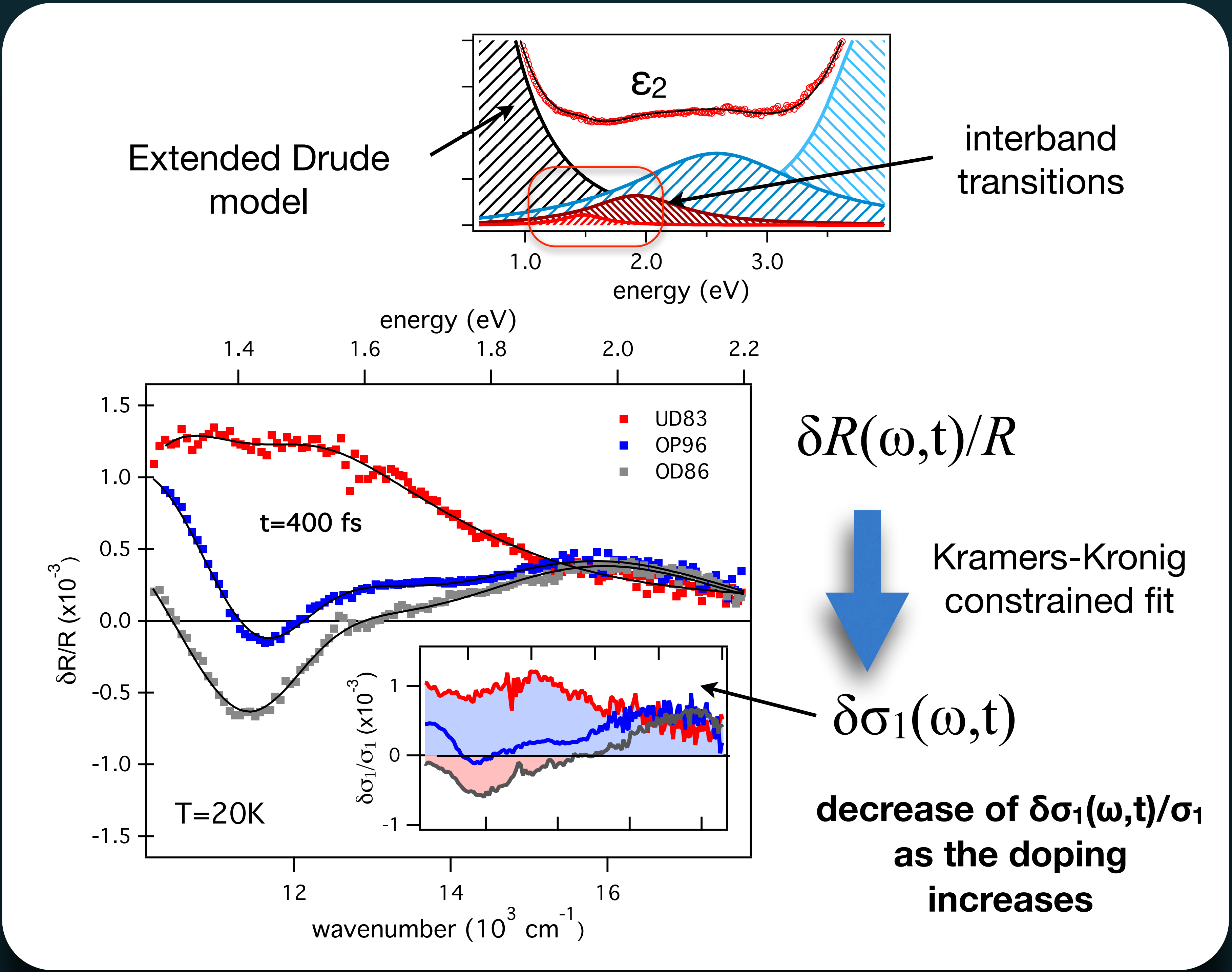
Superconducting state

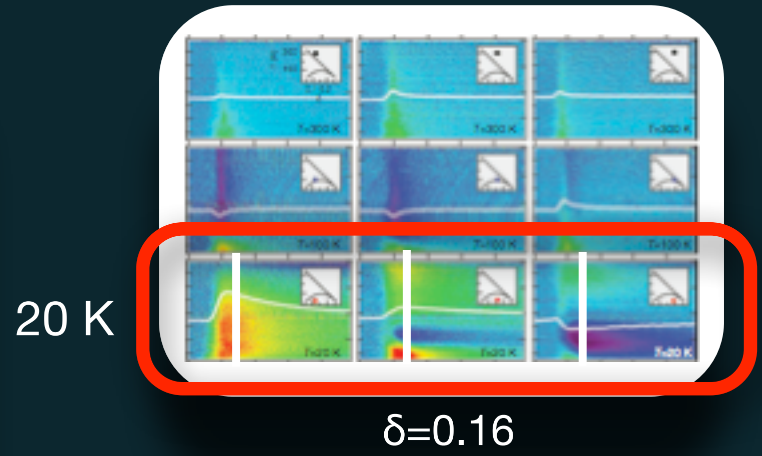
$Bi_2Sr_2Ca_{0.92}Y_{0.08}Cu_2O_{8+\delta}$

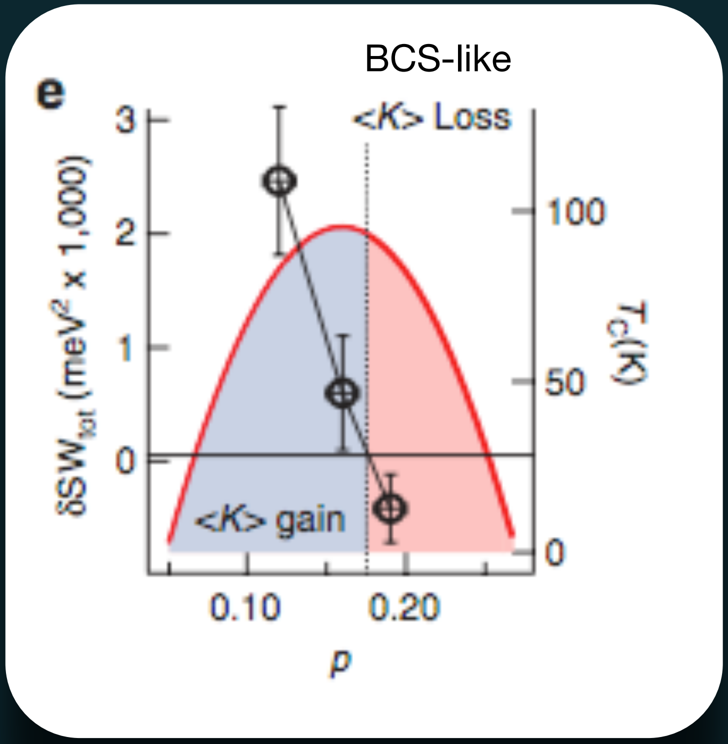


C. Giannetti et al., *Nature Commun*. 2:353 (2011)

High-energy excitations and superconductivity





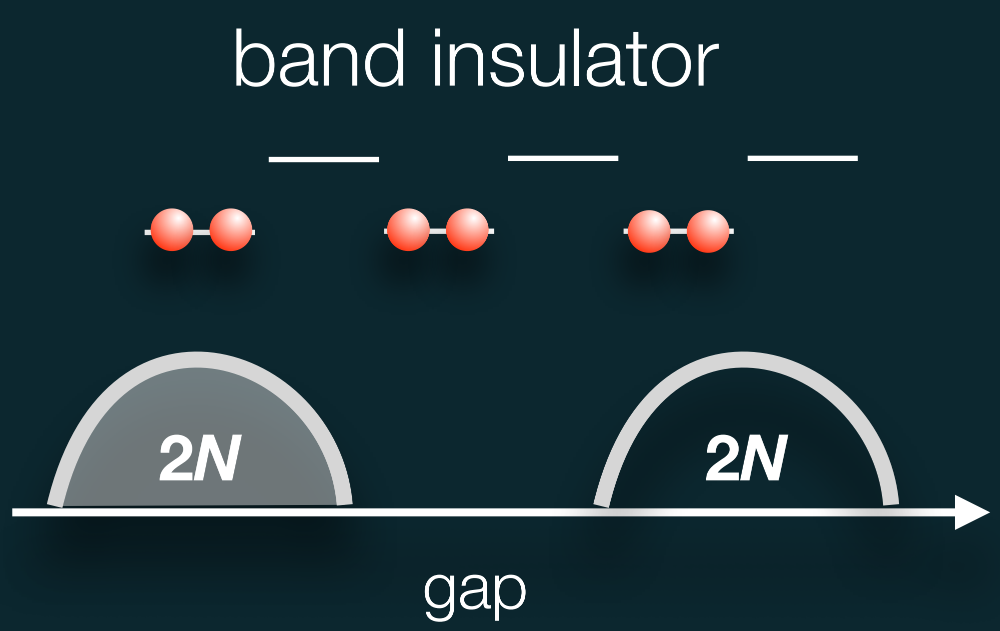


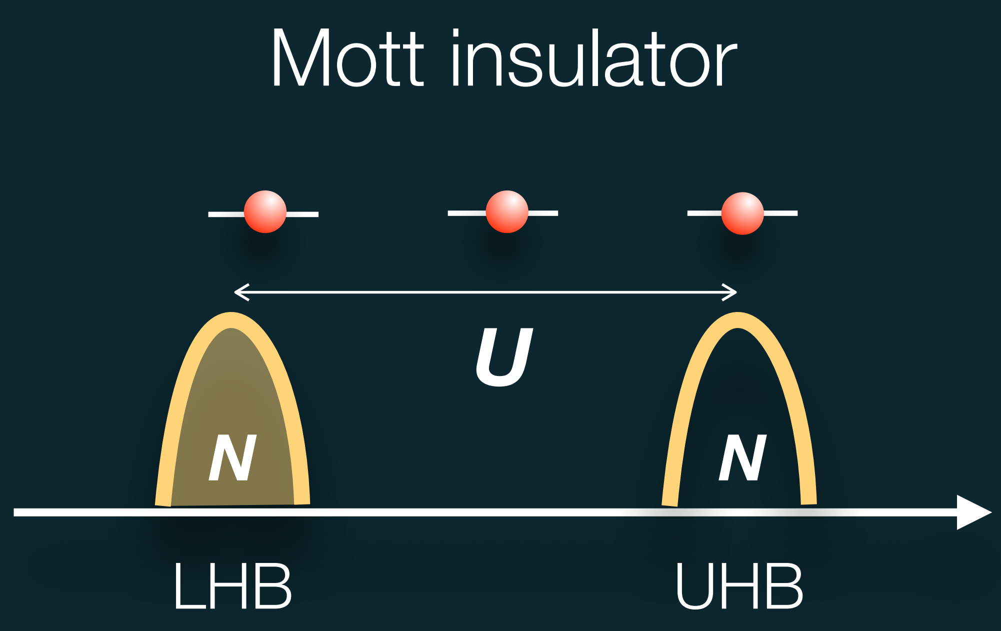
C. Giannetti et al., *Nature Commun*. 2:353 (2011)

light pulses to UNDERSTAND
equilibrium properties

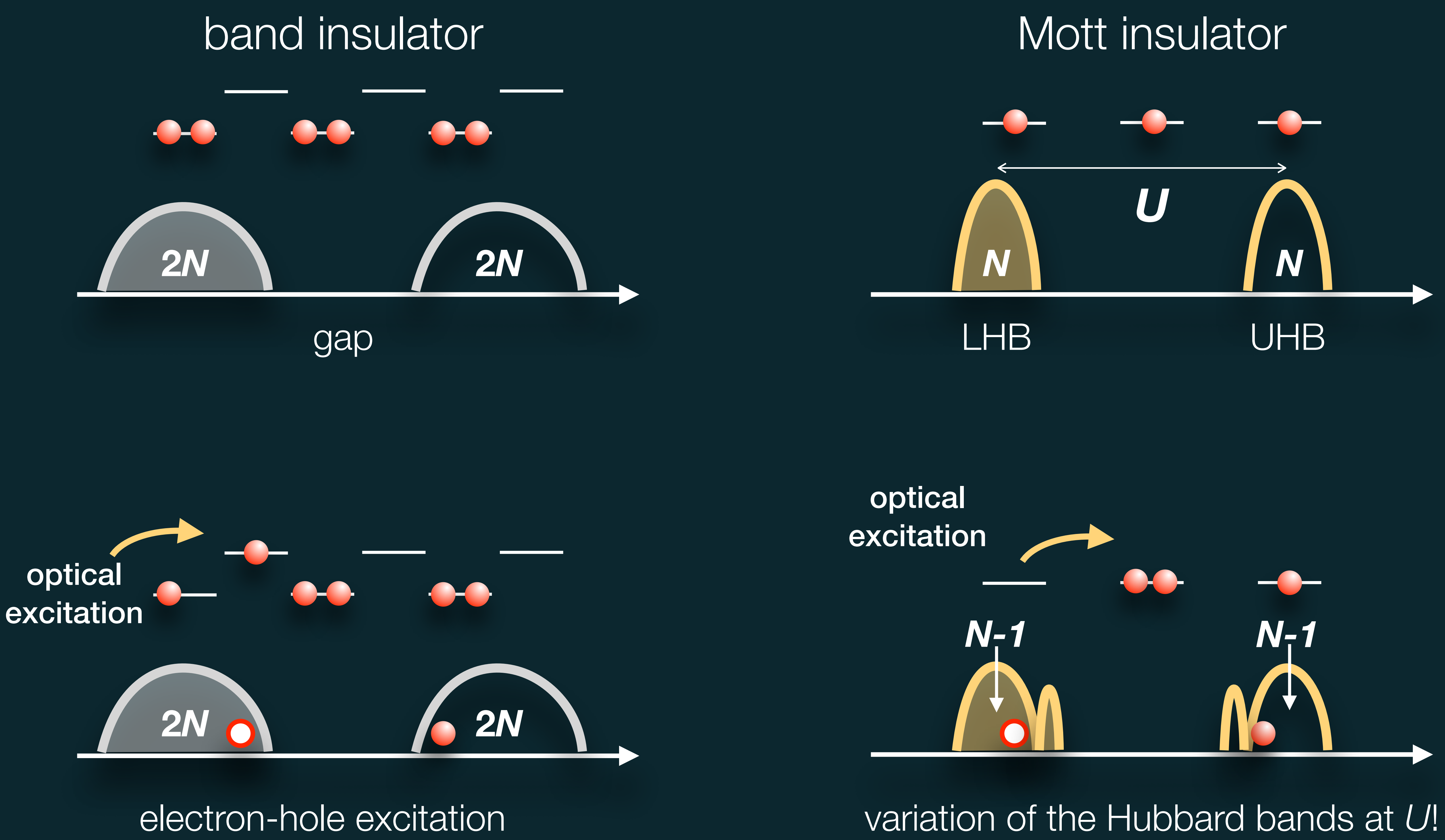
$\Rightarrow$ anti-nodal Mottness

Mottness





Mottness

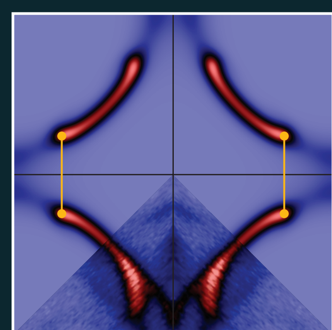


M.B.J. Meinders, H. Eskes, G.A. Sawatzky, *Phys. Rev. B* **48**, 3916 (1993)

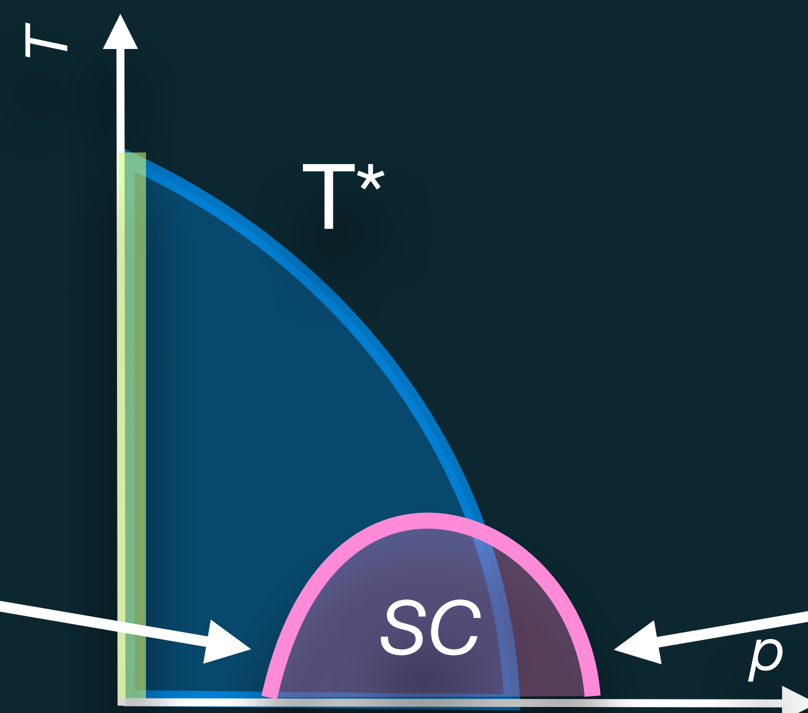
the puzzle of antinodal gap in cuprates

Fermi arcs

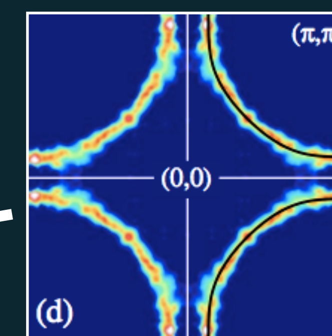
antinodal suppression of states



R. Comin et al. *Science* **343**, 390 (2014)



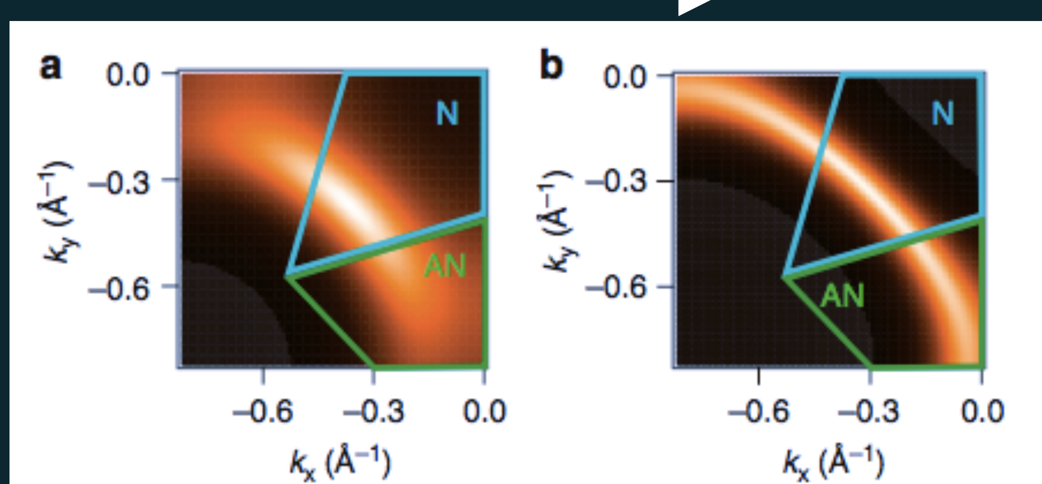
complete Fermi surface



M. Platè et al. *Phys. Rev. Lett.* **95**, 077001 (2005)

Is the universal antinodal suppression of states a consequence of the correlations?

doping



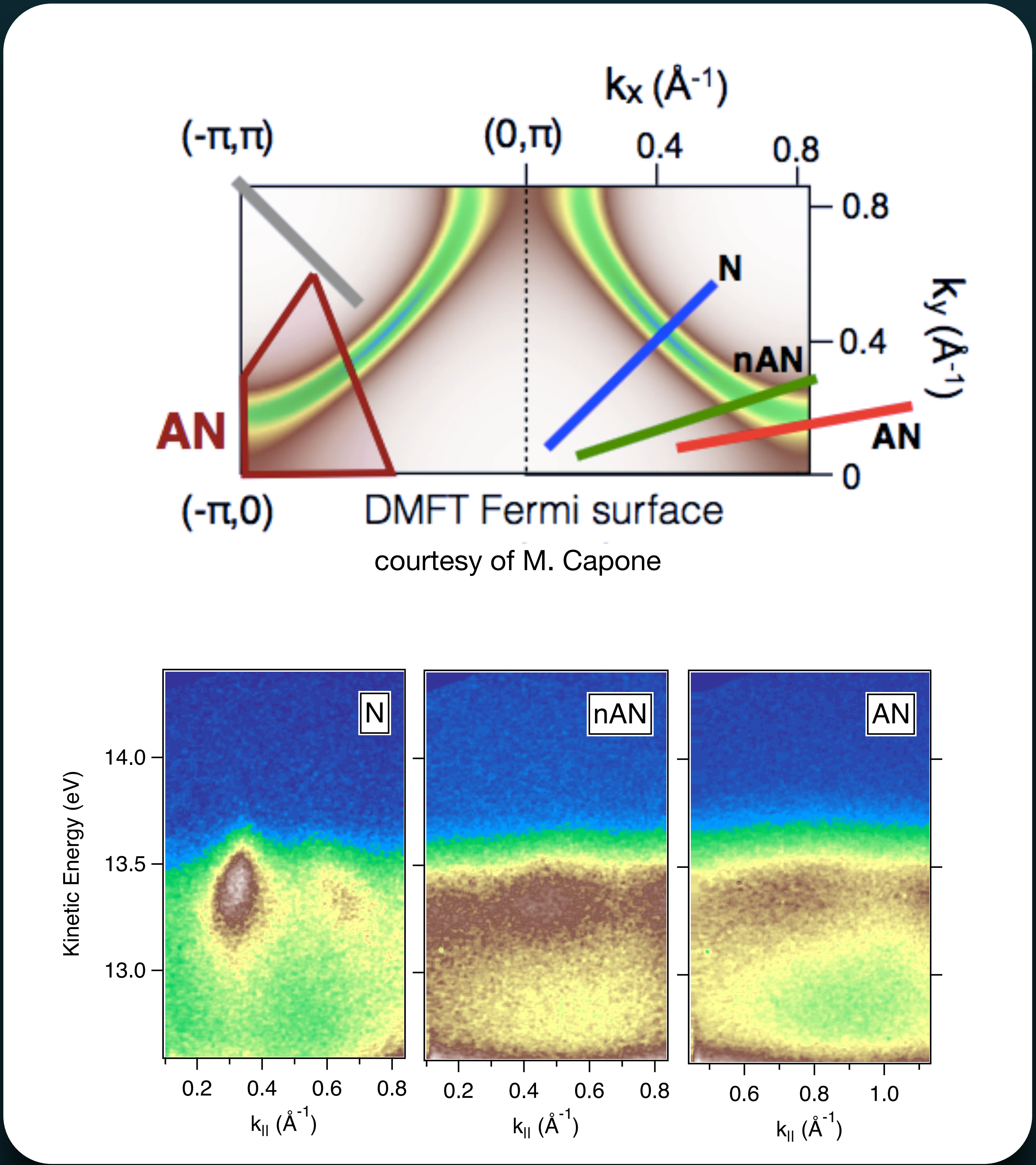
F. Cilento et al. *Nat. Commun.* **5**:4353 (2014)

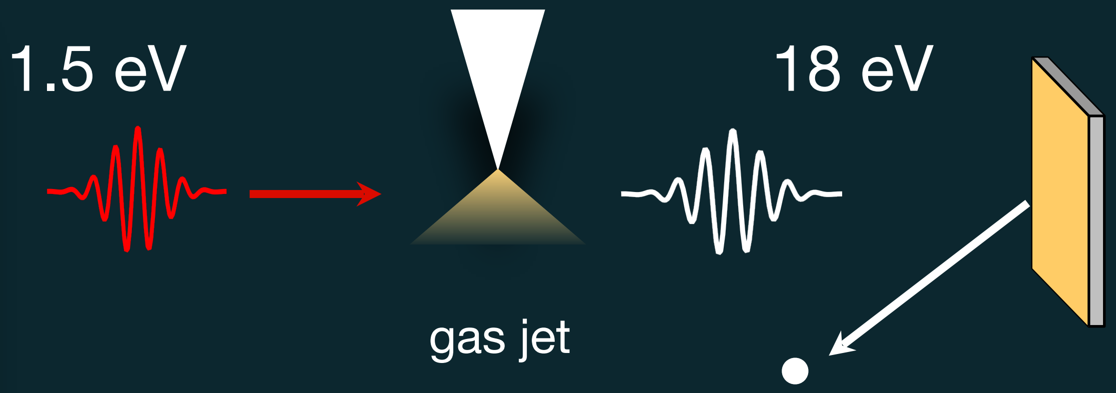
It is already within the Hubbard model!

k-selective Mottness

E. Gull et al. *Phys. Rev. B* **82,** 155101 (2010)

antinodal dynamics



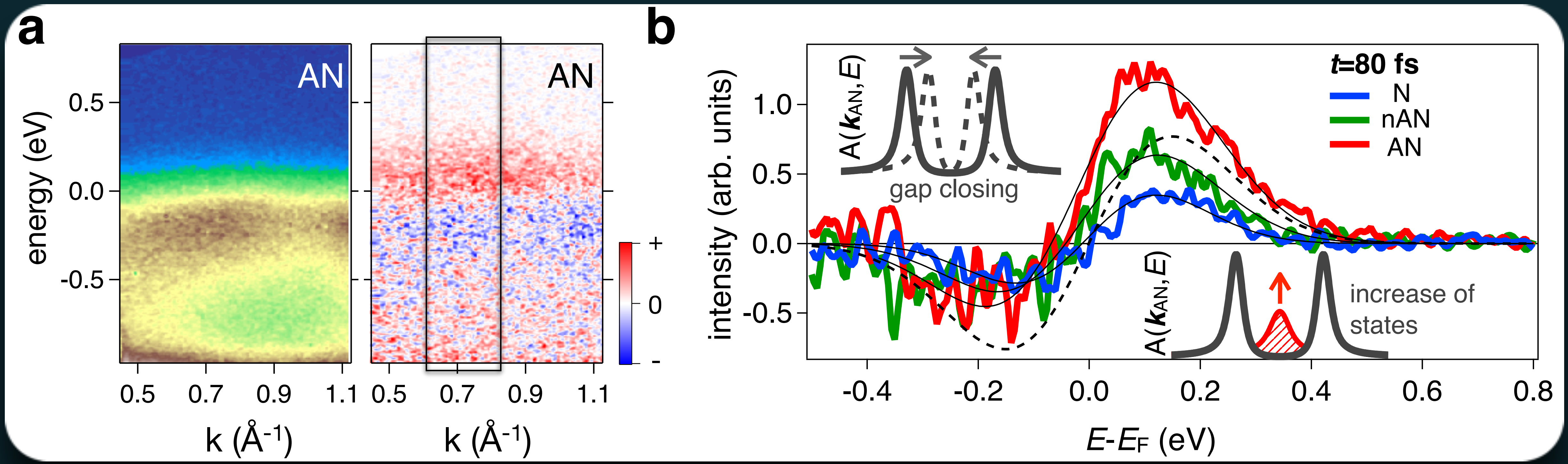


complete mapping of the dynamics in the full Brillouin zone in optimally-doped (T_c=96K) $Bi_2Sr_2Ca_{0.92}Y_{0.08}Cu_2O_{8+\delta}$

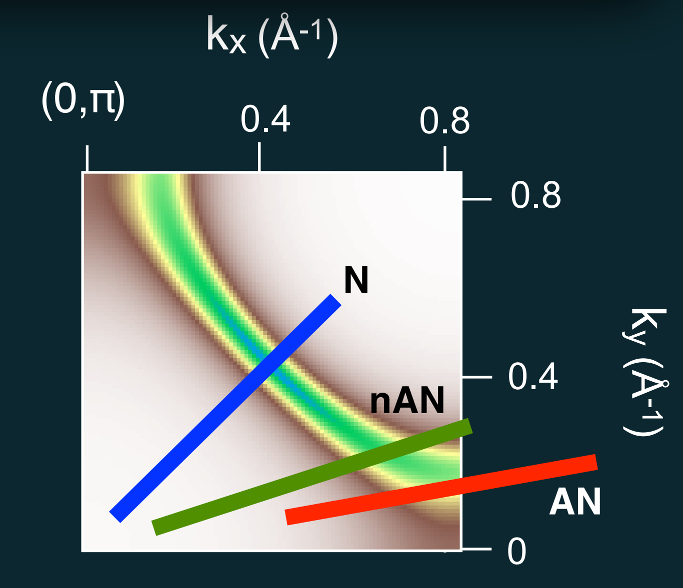
F. Cilento et al. *Science Advances* **4**, eaar1998 (2018)

AN dynamics

t=80 fs



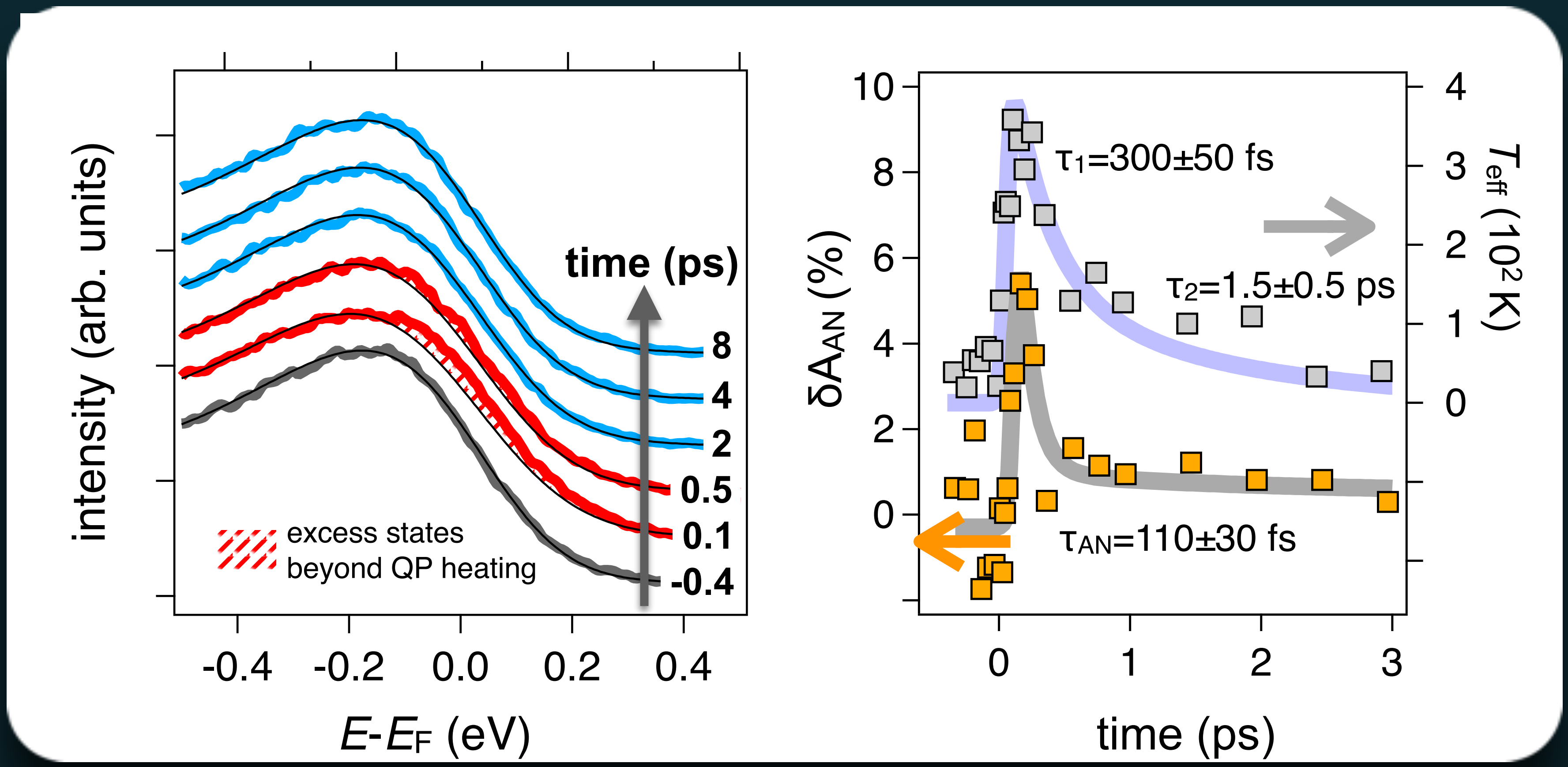
- the antinodal asymmetric signal can be reproduced by assuming a transient increase of states at the Fermi level



C-DMFT Fermi surface

F. Cilento et al. *Science Advances* **4**, eaar1998 (2018)

AN dynamics



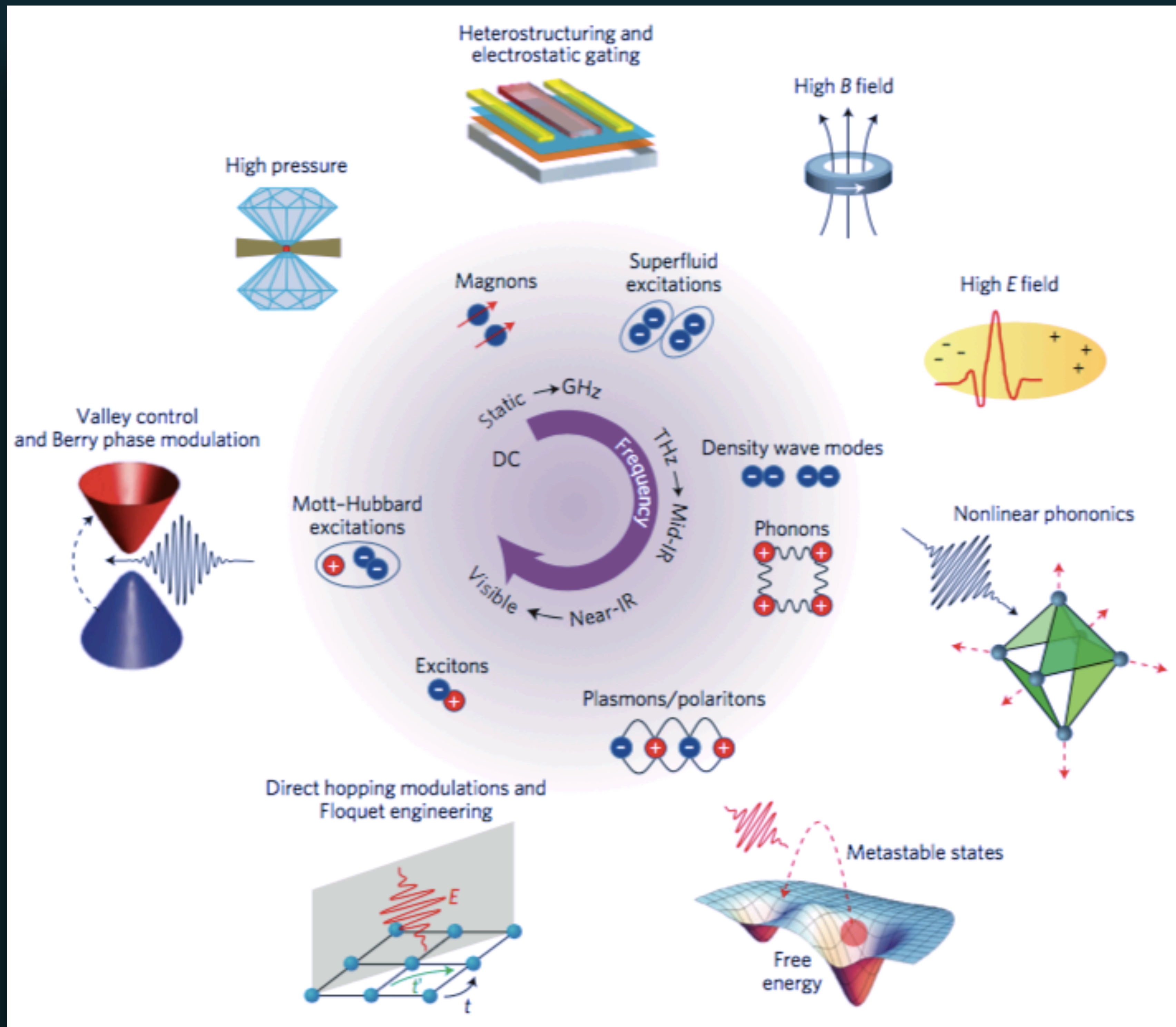
- the AN increase of states (≈100 fs) is decoupled from the effective temperature
- the excitation at 1.5 eV drives the transient increase of antinodal states, which become more metallic

F. Cilento et al. *Science Advances* **4**, eaar1998 (2018)

light pulses to MANIPULATE materials properties

⇒ hidden states, transient photo-enhanced superconductivity, competition of different orders

properties on demand in quantum materials



new functionalities: methods for controlling quantum phases on demand

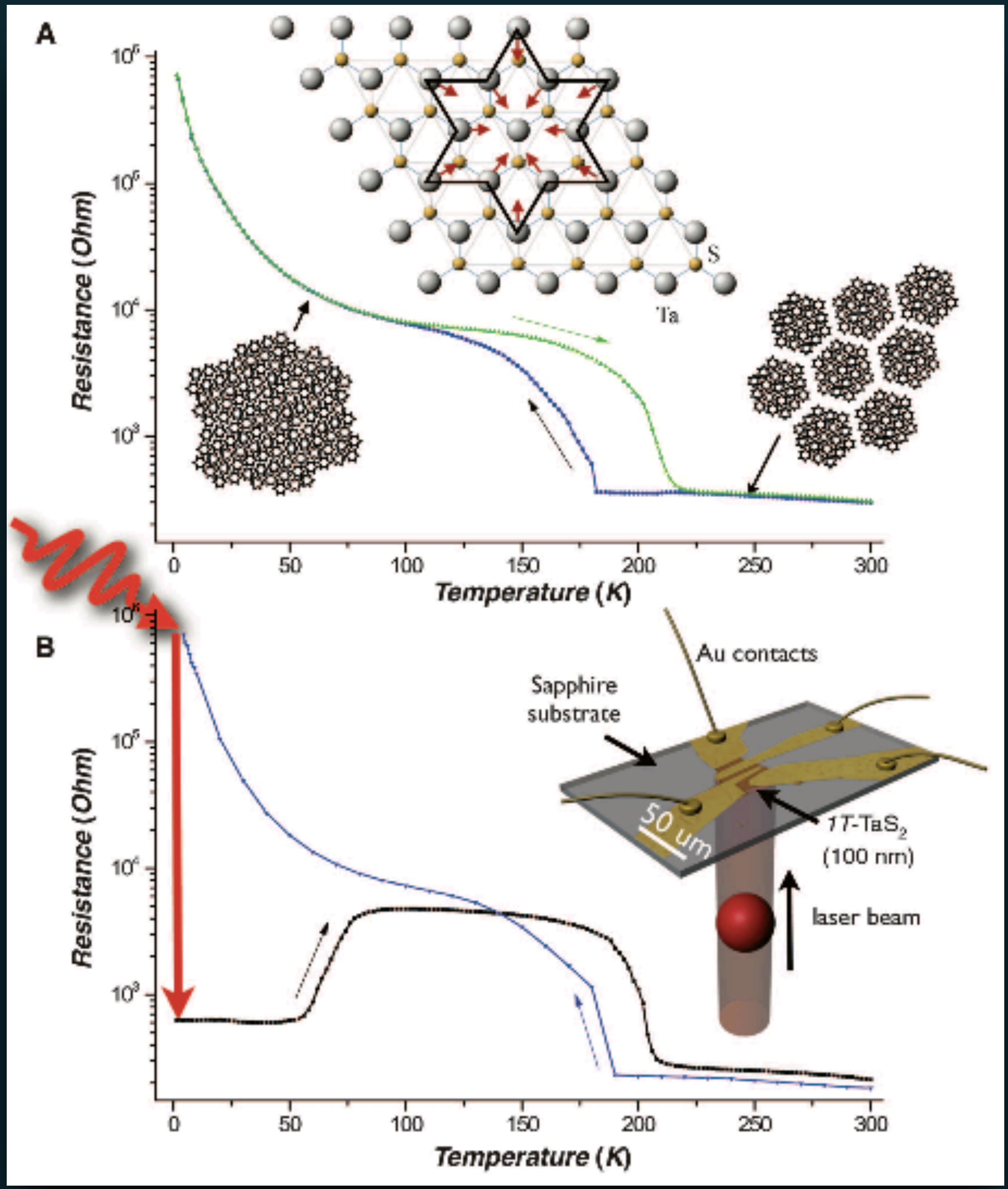
D.N. Basov, R.D. Averitt, D. Hsieh, *Nat. Materials* **16**, 1077 (2017)

light pulses to MANIPULATE
materials properties

$\Rightarrow$ hidden states

photo-induced hidden states

Ultrafast switching to a stable hidden state in *1T*-TaS_2



L. Stojchevska et al.,
Science **344**, 177 (2014)

light pulses to MANIPULATE materials properties

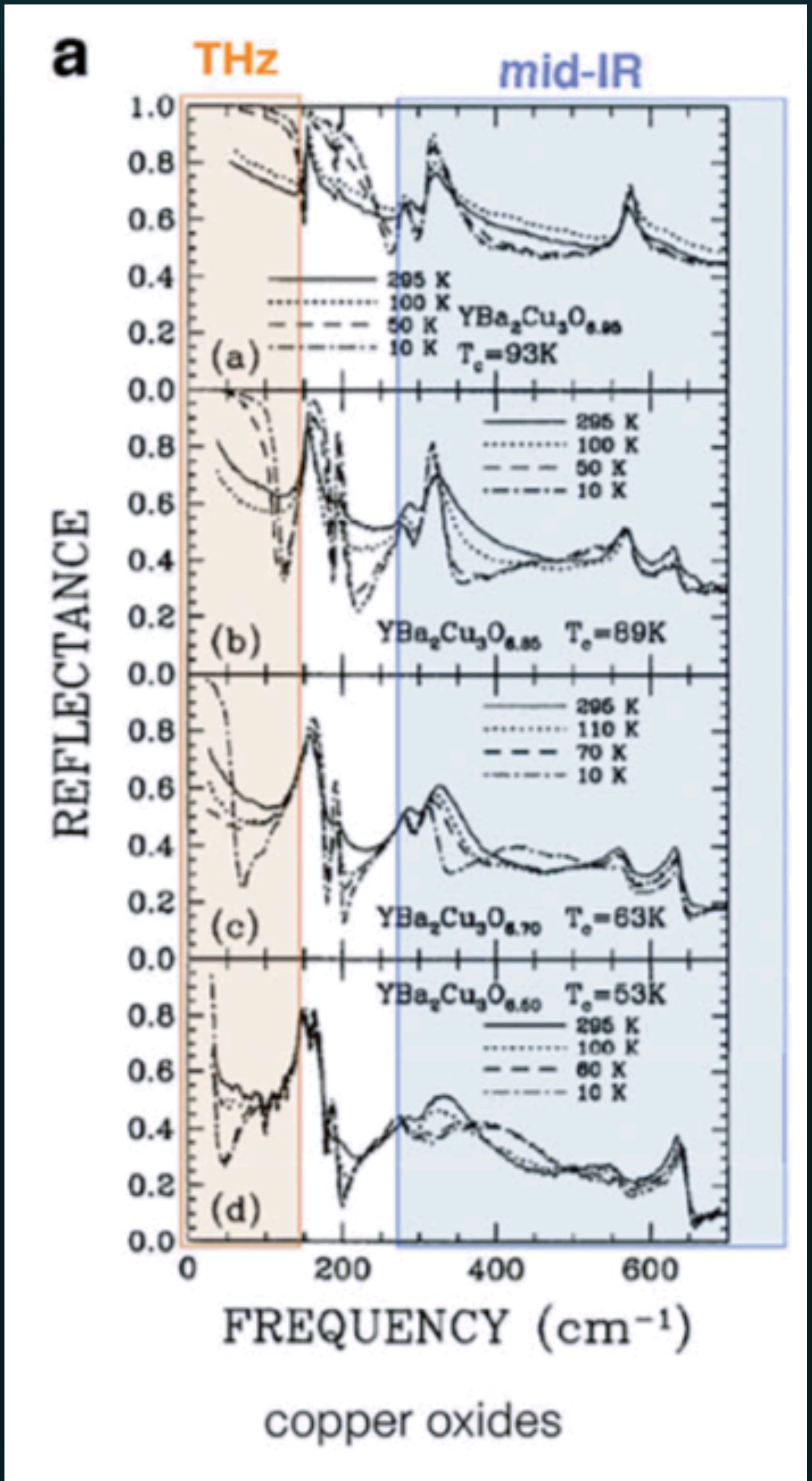
⇒ transient photo-enhanced superconductivity

phonon pumping

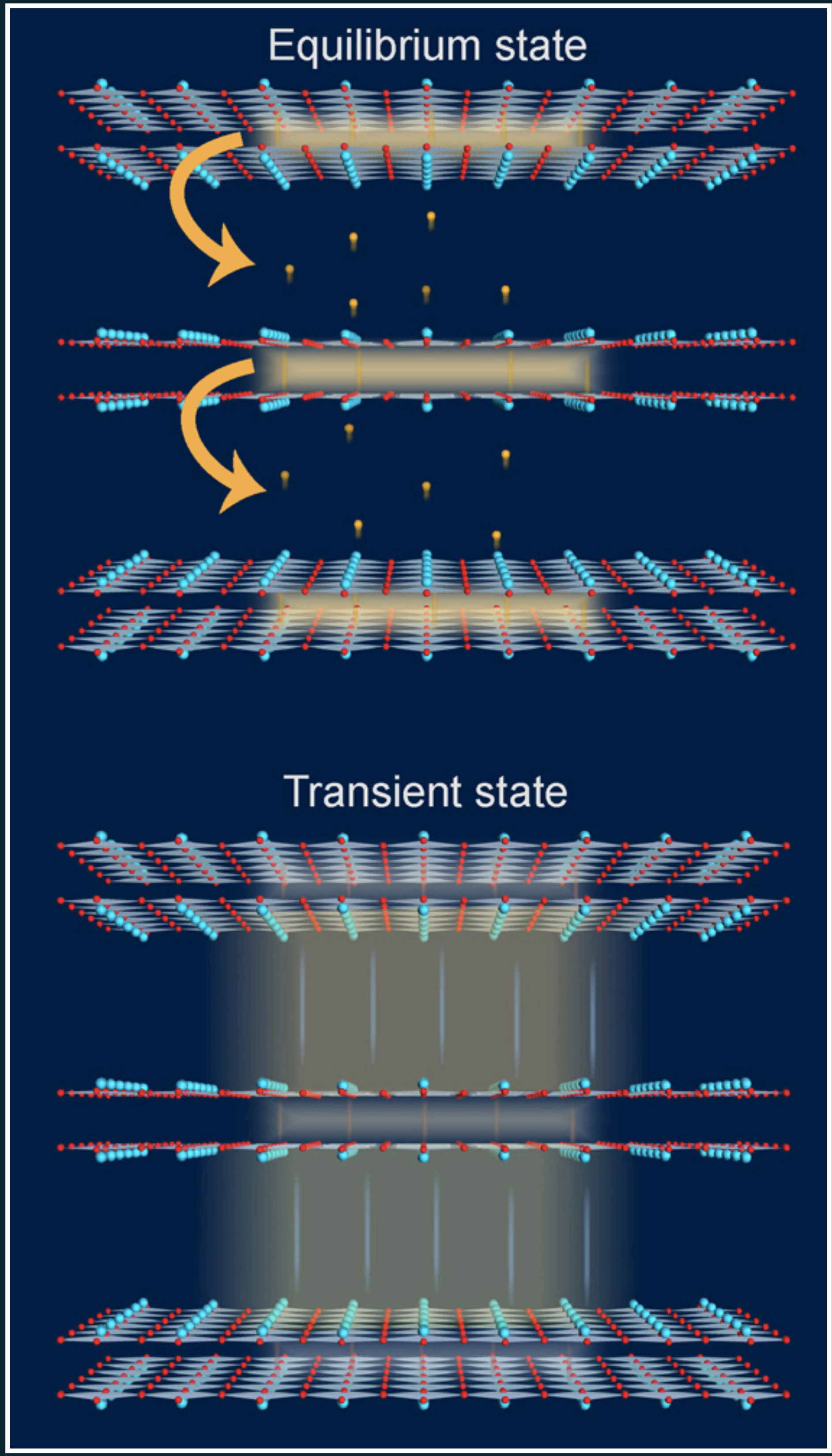
➠mid-IR enhancement of superconductivity in high-T_c?

role of the lattice?

C.C. Homes et al., *Phys. C: Supercond.* **254**, 265 (1995)

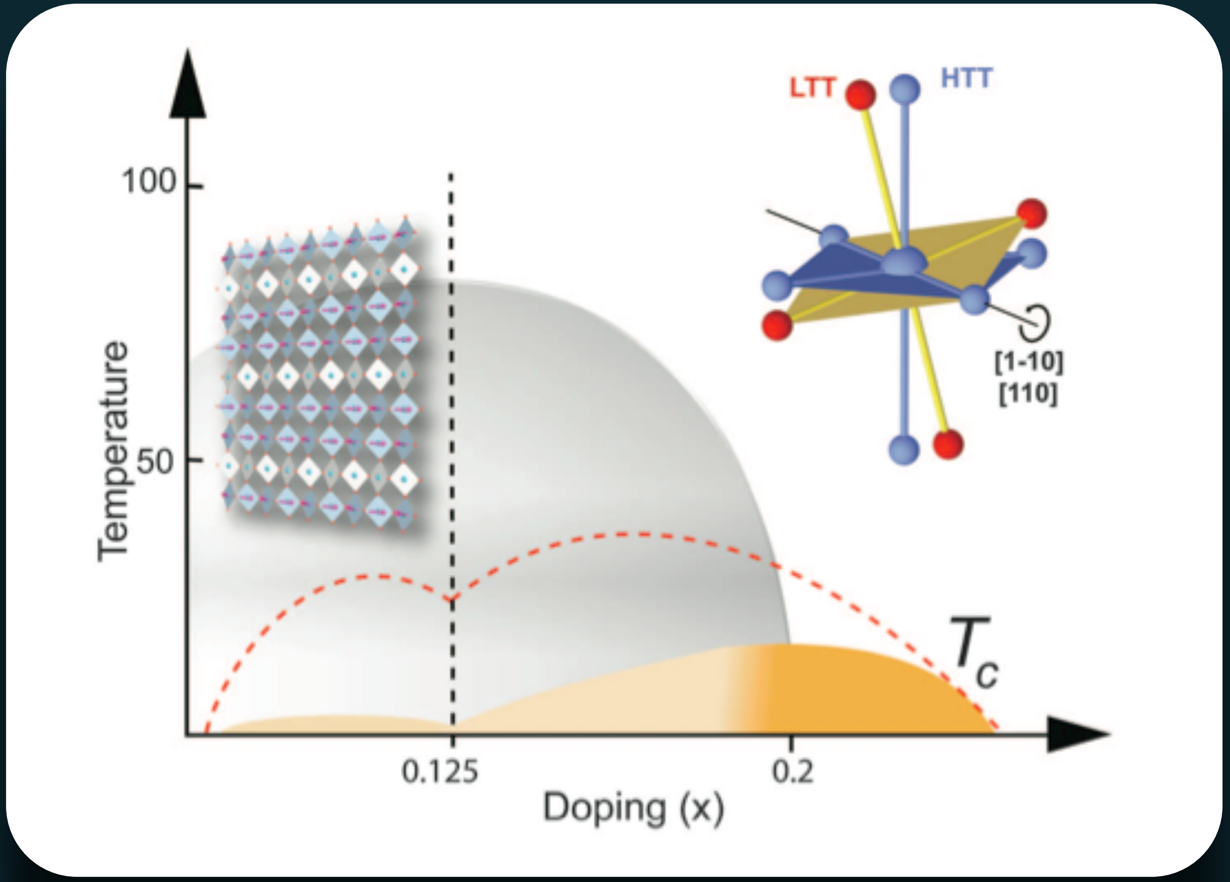


possible light-induced transient superconductivity



courtesy of A. Cavalleri

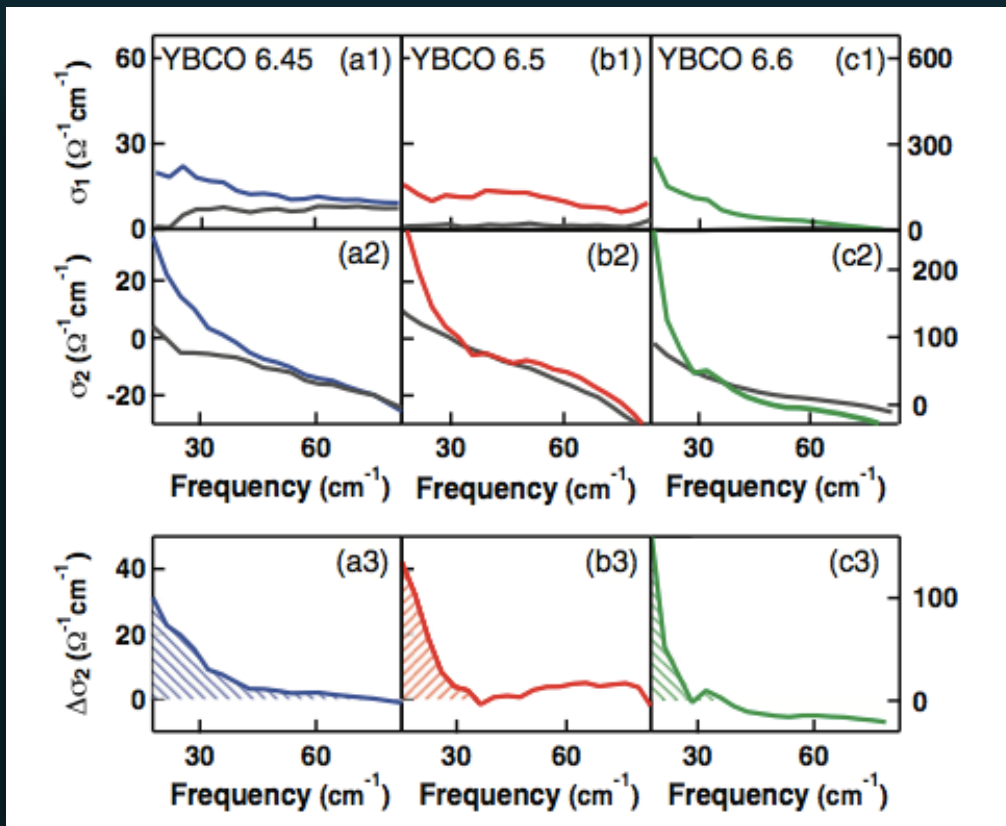
Transient superconductivity by removing a competing order

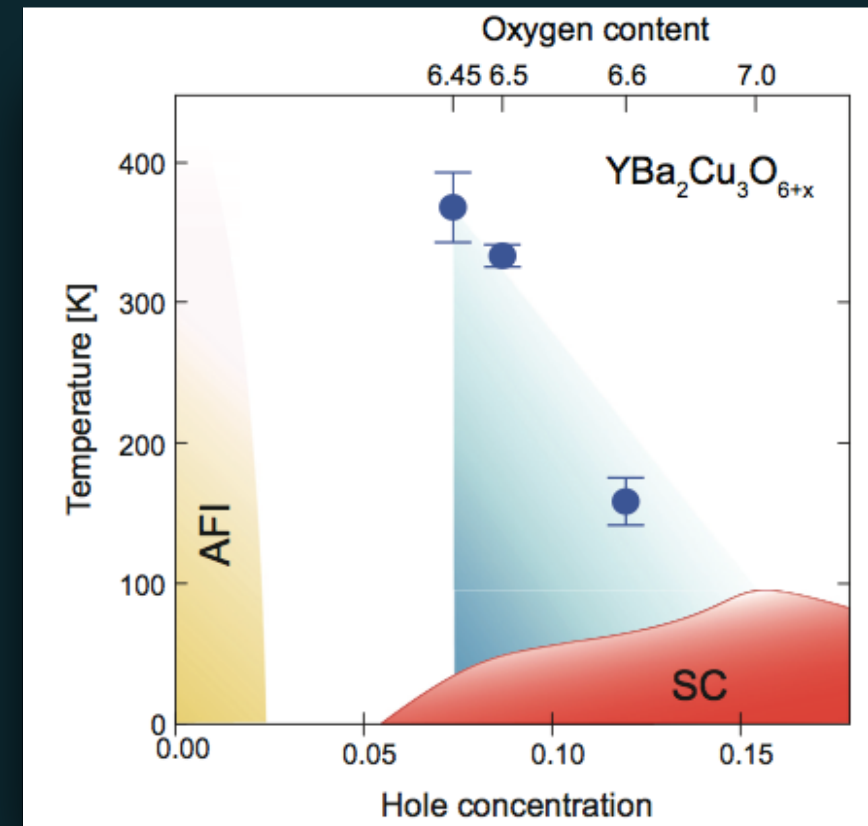


D. Fausti et al., *Science* **331**, 189 (2011)

optical-control of phase transitions

transient enhancement of superconductivity in copper oxides





S. Kaiser et al., *Physical Review B* **89**, 184516 (2014)
W. Hu et al, *Nature Materials* **13**, 705 (2014)

mid-IR pump
THz probe (c-axis)

Drude opt. cond.

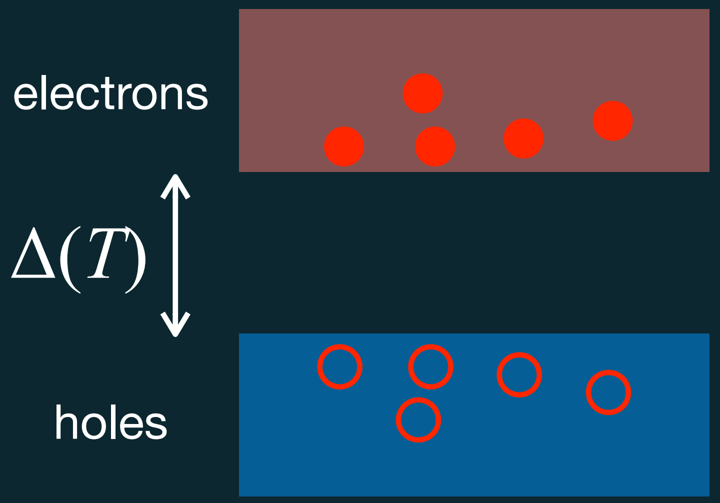
$$\sigma(\omega) = \frac{ne^2}{m}\frac{1}{\tau^{-1} - i\omega} \xrightarrow{\tau\to\infty} \frac{ne^2}{m}\left[\pi\delta(\omega) - \frac{1}{i\omega}\right]$$

gap enhancement via sub-gap excitation

BCS gap equation at finite temperature

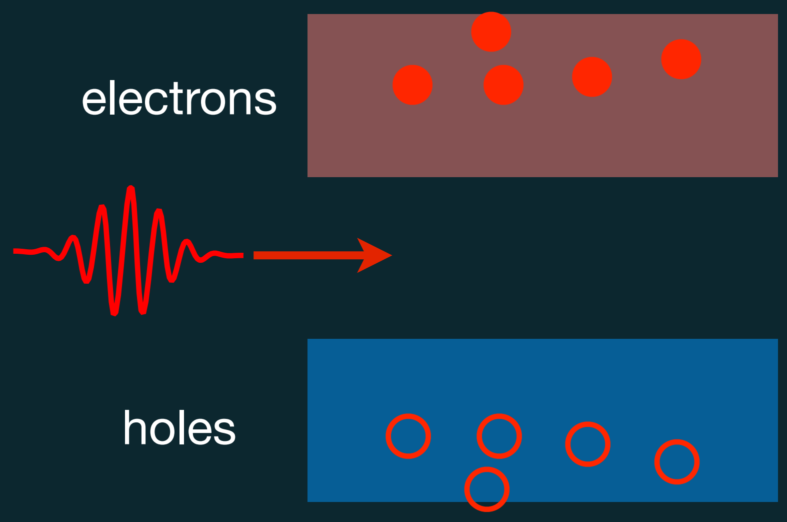
thermal distribution of excitations

$$1 = VN(0)\int_{-\infty}^{\infty} \frac{f(T)}{\sqrt{\epsilon^2 + \Delta^2(T)}} d\epsilon$$



changing the distribution without injecting new excitations

$$\frac{\delta T_{eff}}{T} = \int_{-\infty}^{\infty} \frac{\delta f}{\sqrt{\epsilon^2 + \Delta^2(T)}} d\epsilon$$



gap enhancement via sub-gap excitation

➠microwave gap enhancement in Al

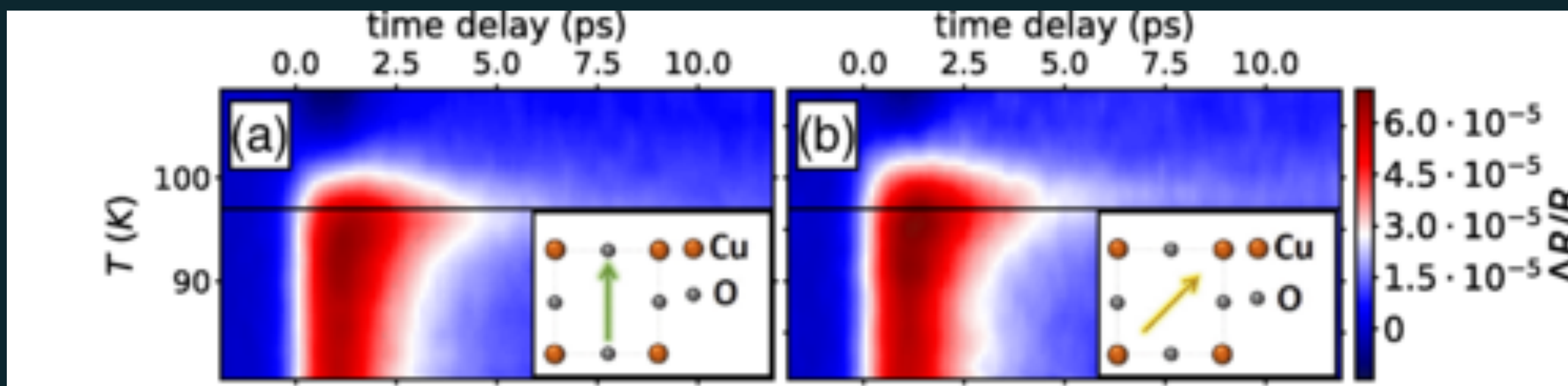
T. Kommers et al., *Phys. Rev. Lett.* **38**, 1091 (1977)

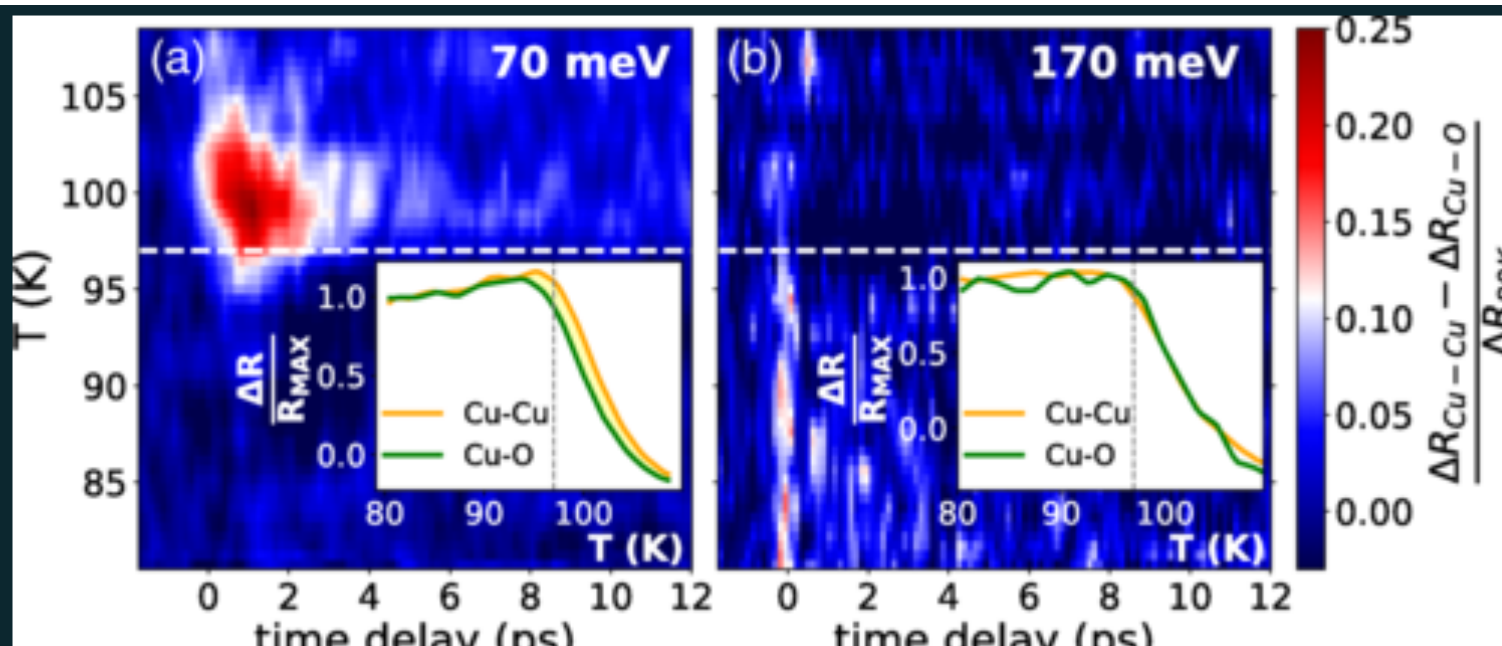
➠THz gap enhancement in NbN

M. Beck et al., *Phys. Rev. Lett.* **110**, 267003 (2013)

➠mid-IR gap enhancement in $Bi_2Sr_2Y_{0.08}Ca_{0.92}Cu_2O_{8+\delta}$

F. Giusti et al., *Phys. Rev. Lett.* **122**, 067002 (2019)

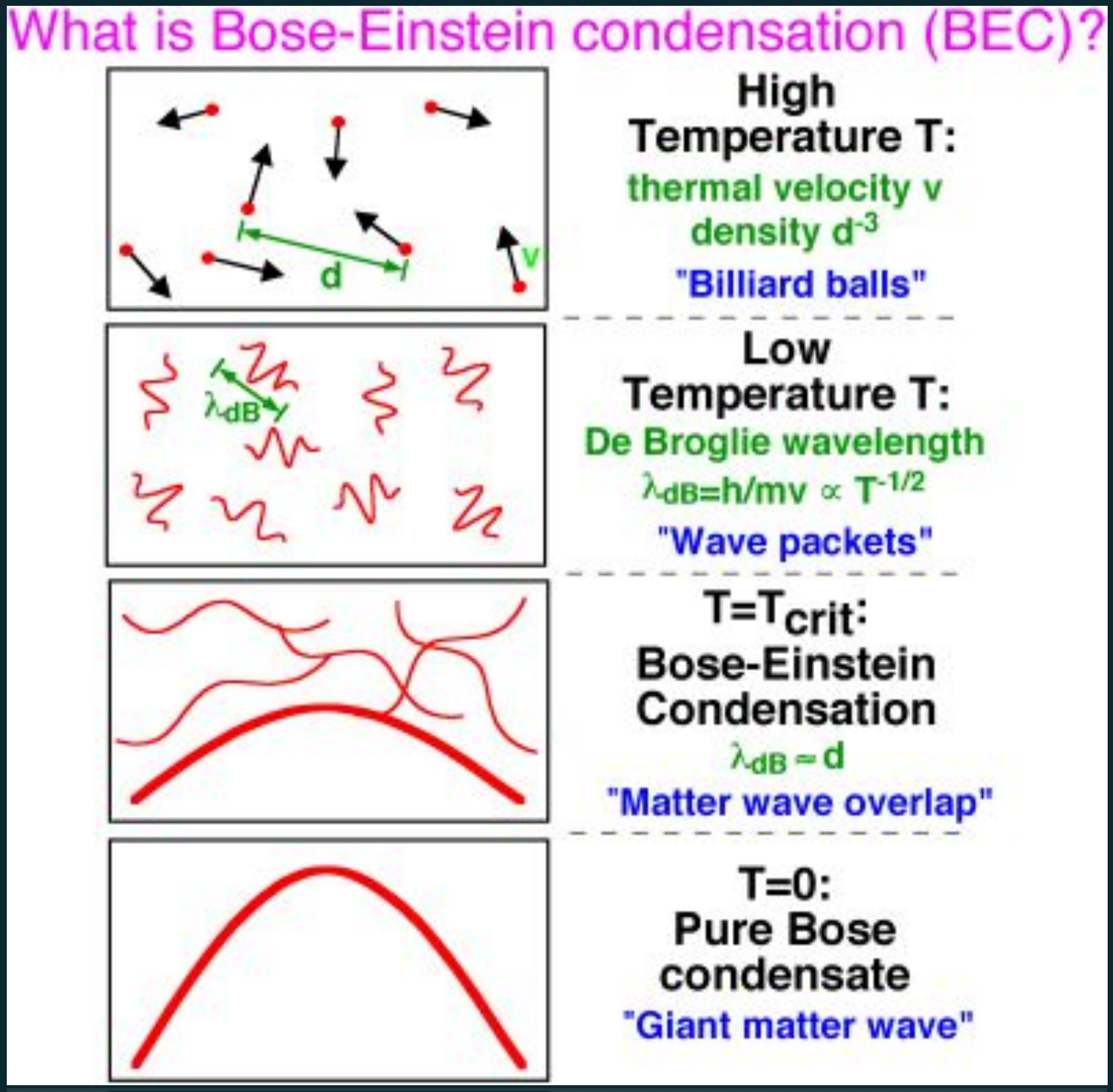




light pulses to MANIPULATE materials properties

⇒ quenching the phase coherence

destroying phase coherence with light



kinetic energy $$\frac{1}{2}mv^2 = \frac{3}{2}K_BT$$ thermal energy

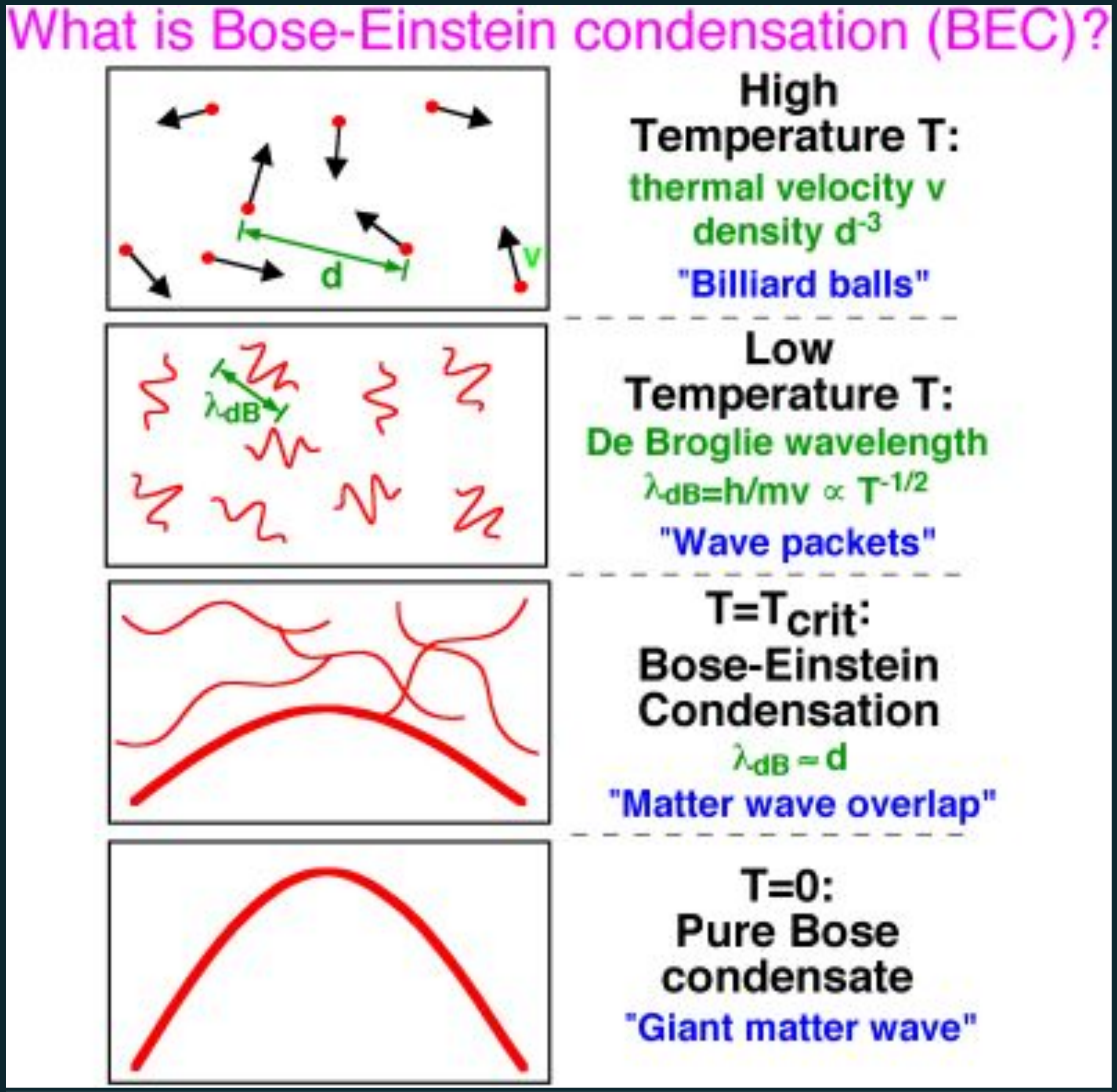
De Broglie wavelength

Planck const.

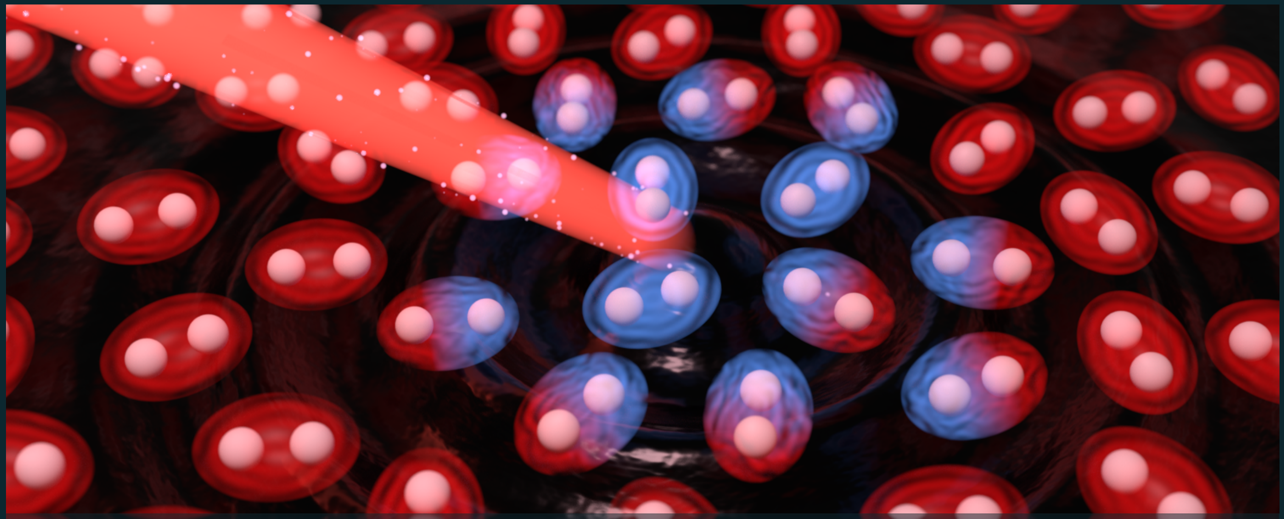
$$\lambda_{DB} = \frac{h}{mv} \propto \frac{1}{\sqrt{T}}$$

light can be used to destroy the phase coherence of the condensate without heating it up

destroying phase coherence with light



cartoon: light excitation of the Cooper pair condensate



courtesy of F. Boschini (UBC, Vancouver)

light can be used to destroy the phase coherence of the condensate without heating it up

superconducting to normal state transition

Open problems:

- what drives the ultrafats dynamics of the superconducting condensate?

gap closing (BCS)
vs
loss of phase coherence

fragility of low-density (n_S) superconductors
to phase fluctuations:

$$\hbar\Omega_{\Theta} = \frac{\hbar^2 n_S(0) a}{2m^*} \simeq k_B T_C$$

V.J. Emery and S.A. Kivelson. *Nature* **374,** 434 (1995)

superconducting to normal state transition

GAP closing or filling?

what drives the non-thermal melting?

Open problems:

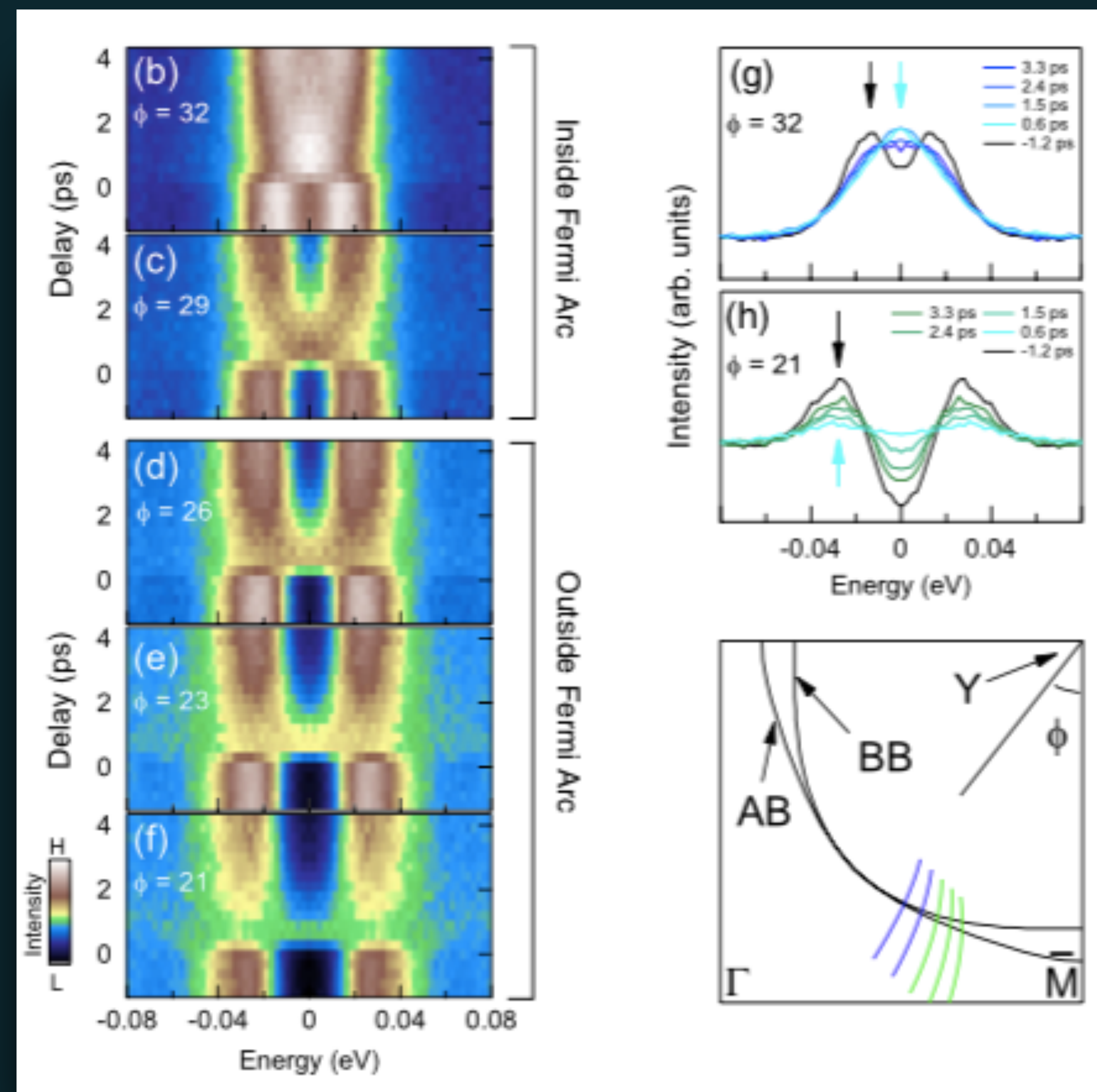
- what drives the ultrafats dynamics of the superconducting condensate?

gap closing (BCS)
vs
loss of phase coherence

fragility of low-density (n_S) superconductors to phase fluctuations:

$$\hbar\Omega_{\Theta} = \frac{\hbar^2 n_S(0)a}{2m^*} \simeq k_B T_C$$

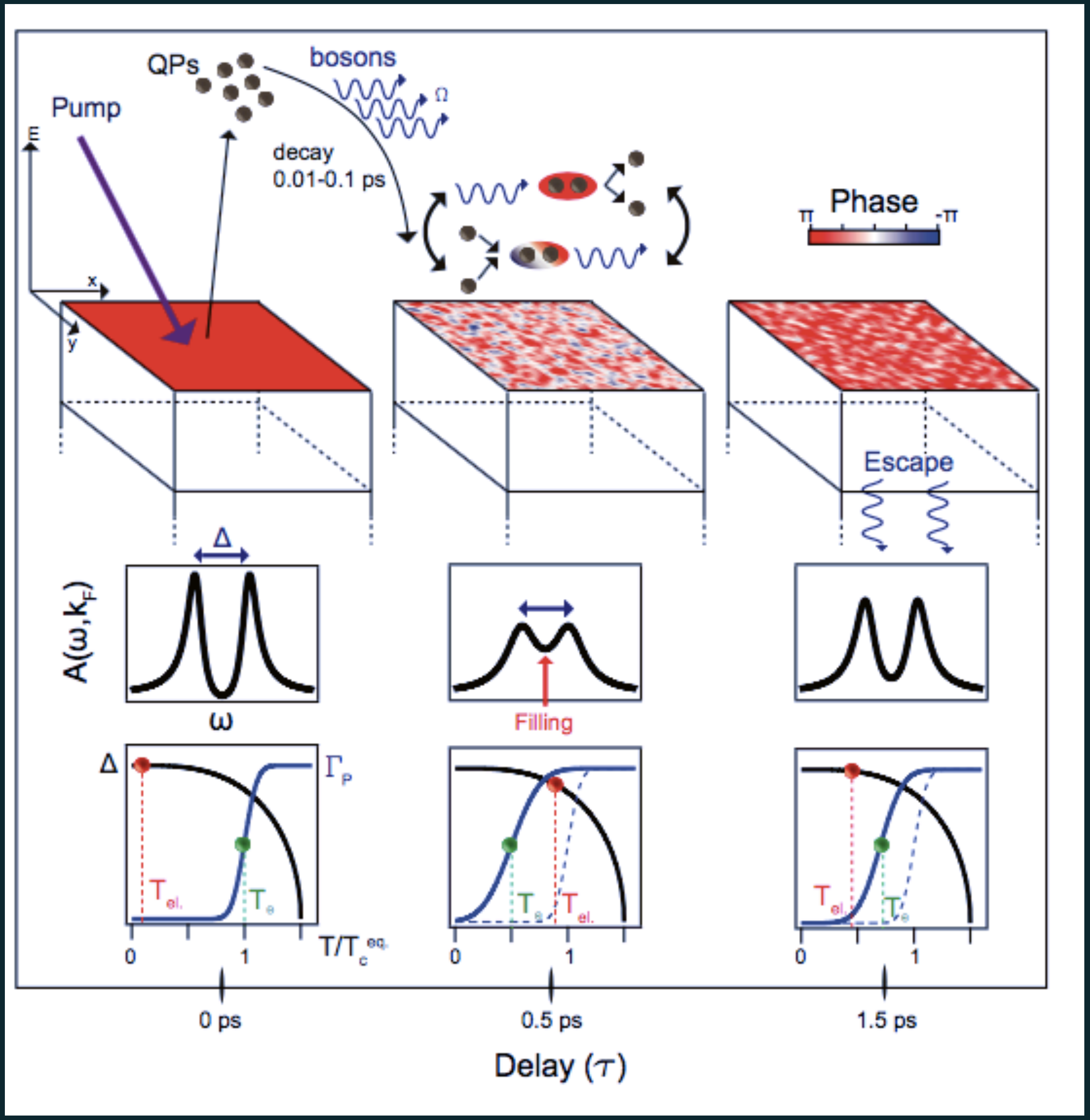
V.J. Emery and S.A. Kivelson. *Nature* **374,** 434 (1995)



C. Smallwood et al. et al, *Phys. Rev. B* **89,** 115126 (2014)

destroying phase coherence with light

Collapse of high-T_C superconductivity via ultrafast quenching of the phase coherence in $Bi_2Sr_2CaCu_2O_{8+\delta}$



F. Boschini et al., *Nature Materials* **17**, 416–420 (2018)

➡fragility of low-density (n_S) superconductors to phase fluctuations:

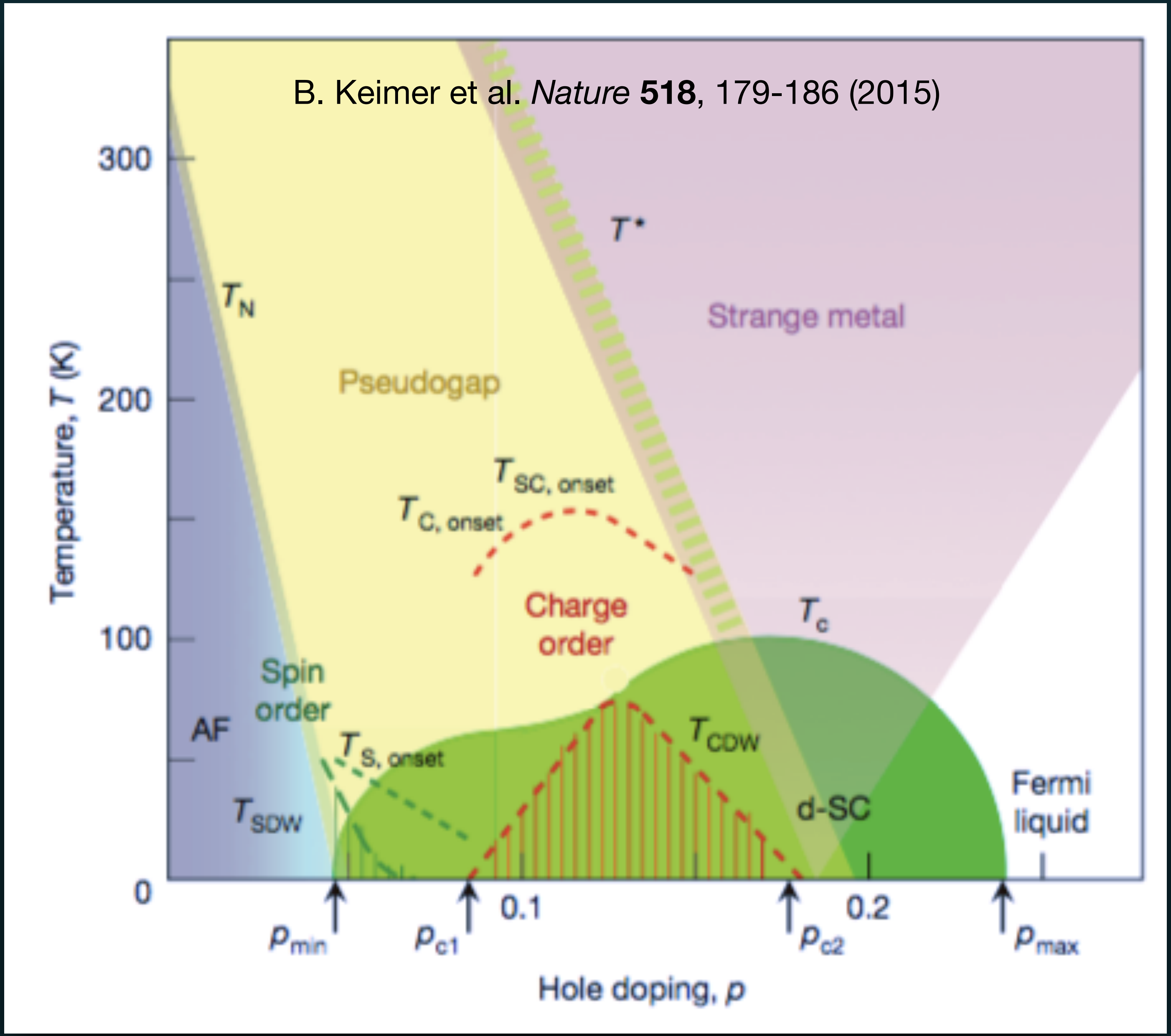
$$\hbar\Omega_\Theta = \frac{\hbar^2 n_S(0)a}{2m^*} \simeq k_B T_C$$

V.J. Emery and S.A. Kivelson. *Nature* **374,** 434 (1995)

On the ultrafast timescale it is possible to quench the macroscopic phase coherence without changing the gap and the pairing strength!

⇒new time-window for exploring quantum phase transitions

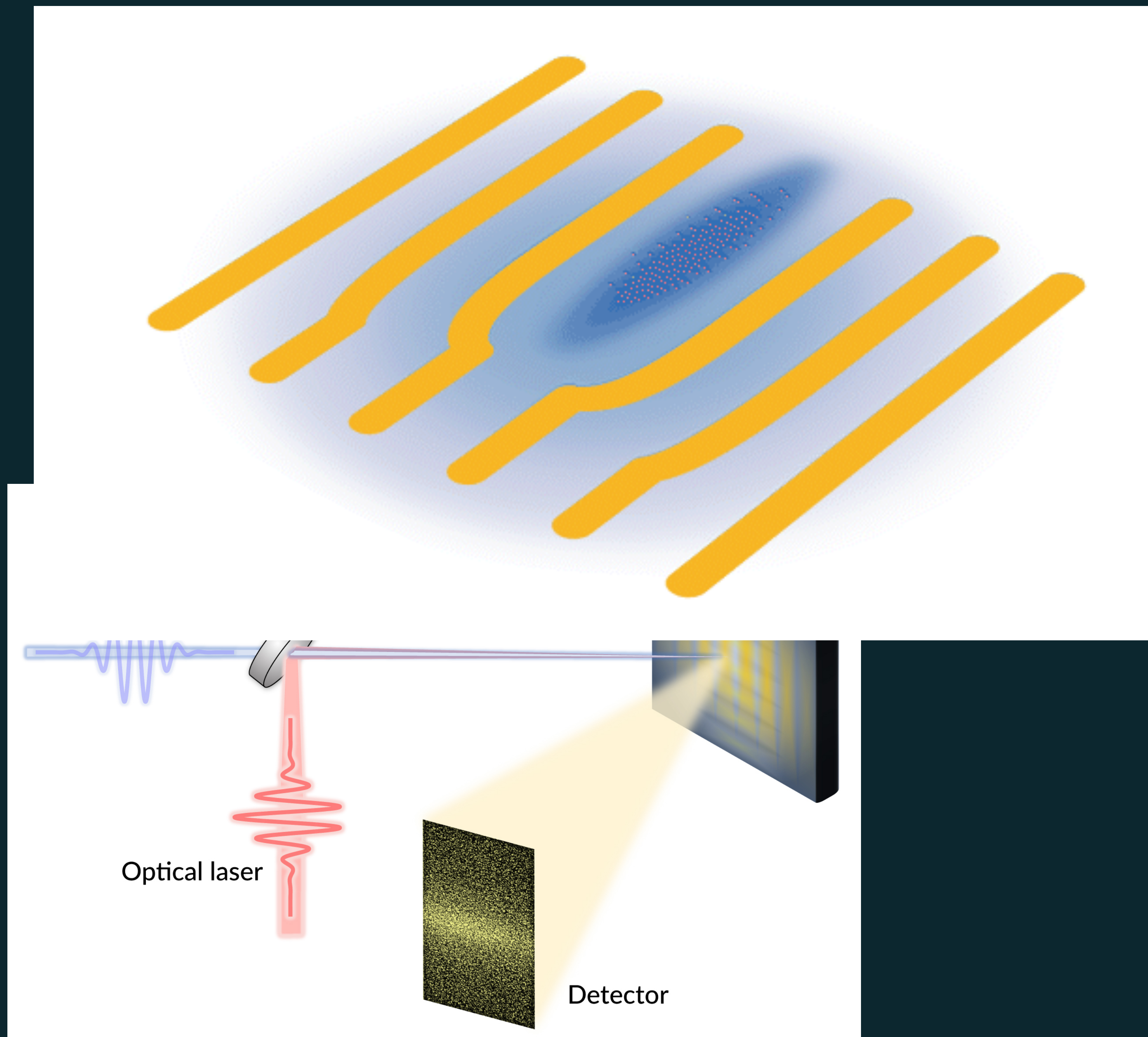
the phase diagram of copper oxides



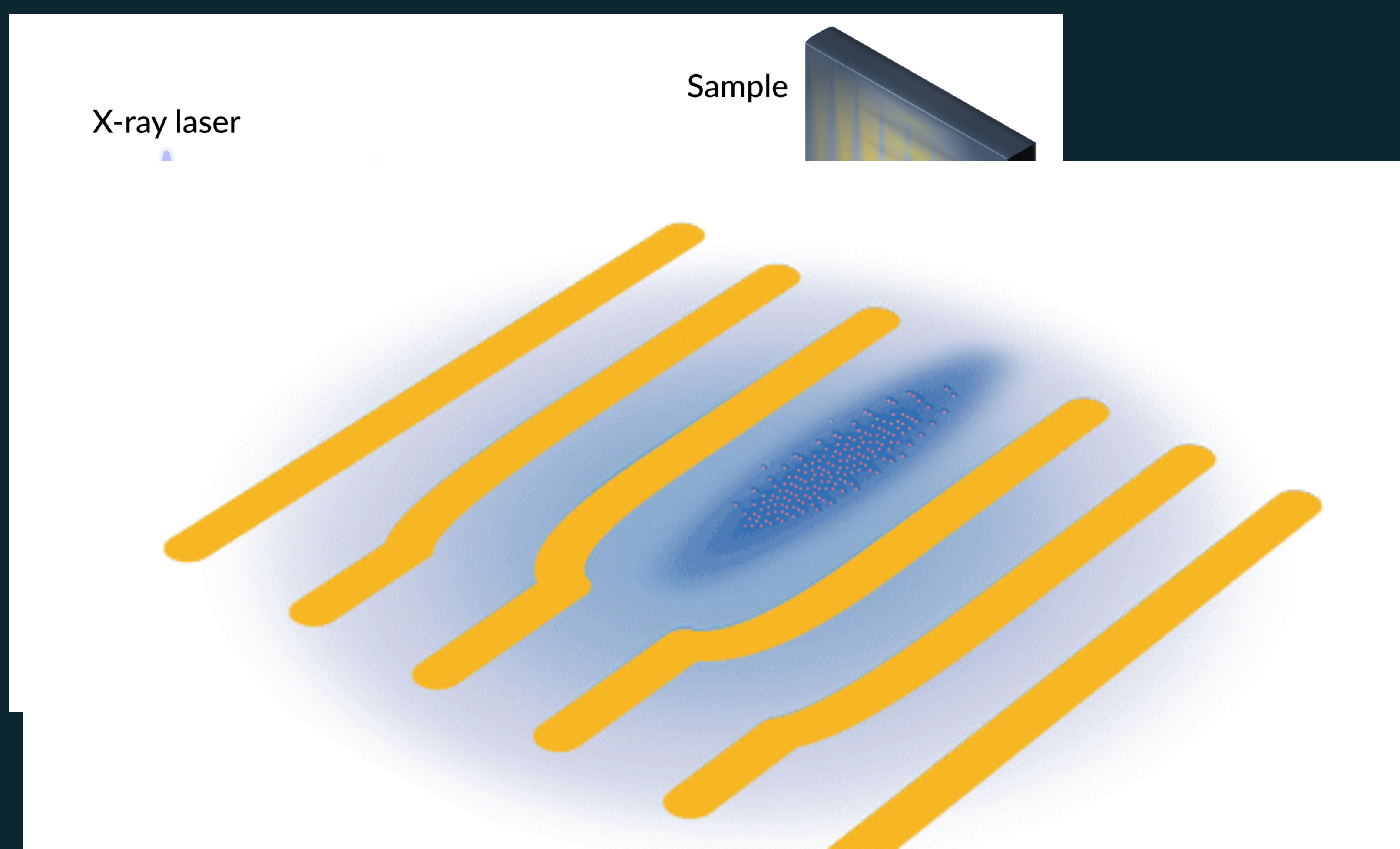
what is the interplay between Charge Density Waves and superconductivity?

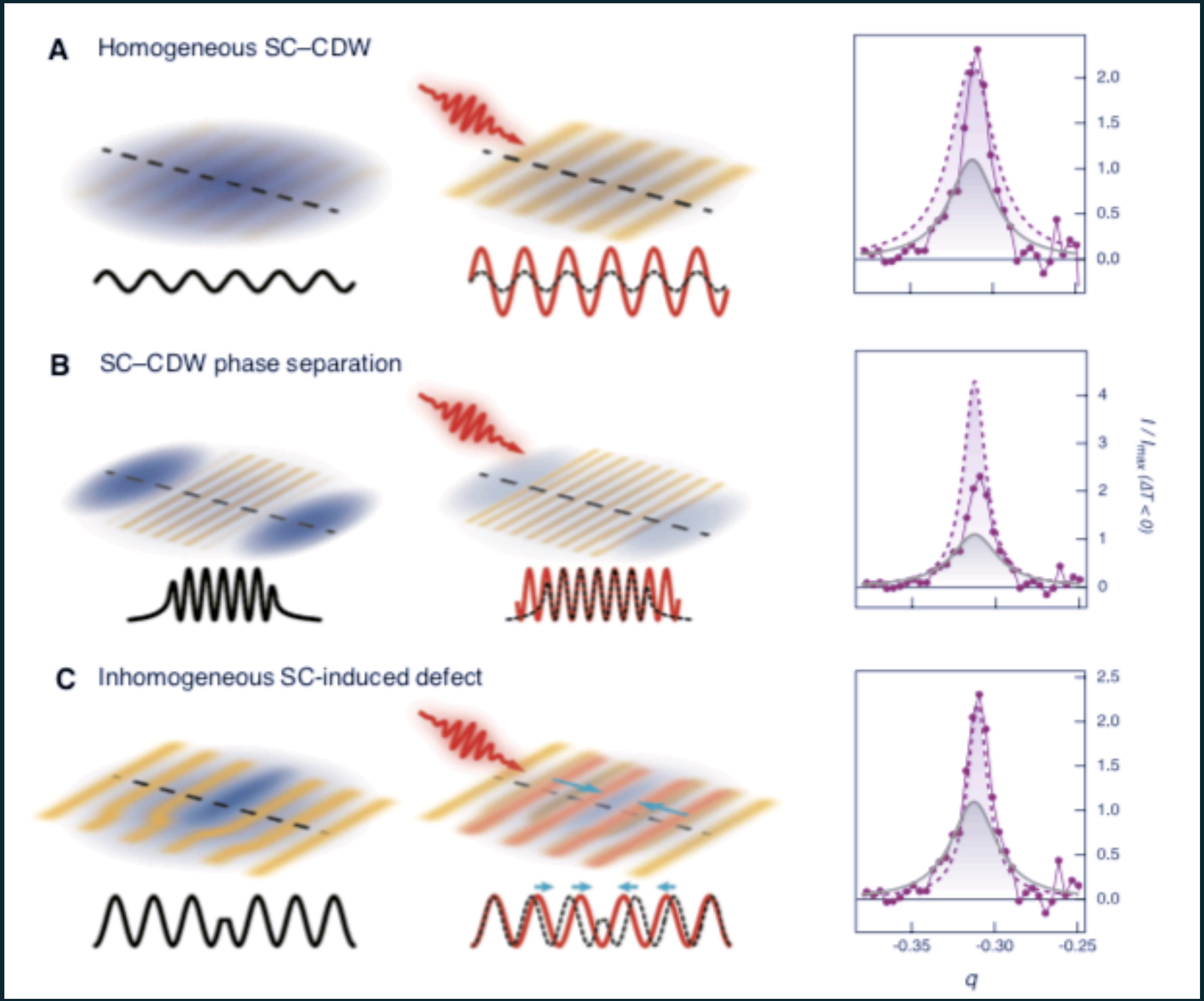
light pulses to MANIPULATE materials properties

⇒ competition between charge-order and superconductivity



Optical laser
Detector


Sample
X-ray laser



A Homogeneous SC–CDW
B SC–CDW phase separation
C Inhomogeneous SC-induced defect
2.0
1.5
1.0
0.5
0.0
4
3
2
1
0
2.5
I / I_{max} (ΔT < 0)
-0.35
-0.30
-0.25
q

light pulses to EXCITE
specific degrees of freedom

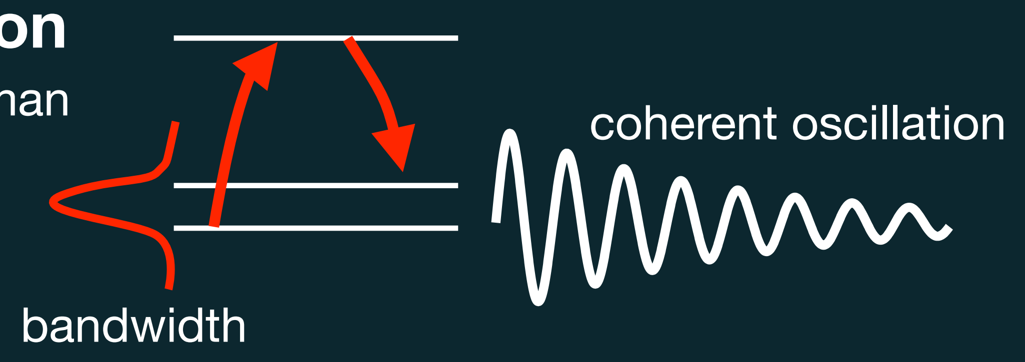
⇒ coherent lattice oscillations

and Higgs modes

coherent lattice driving

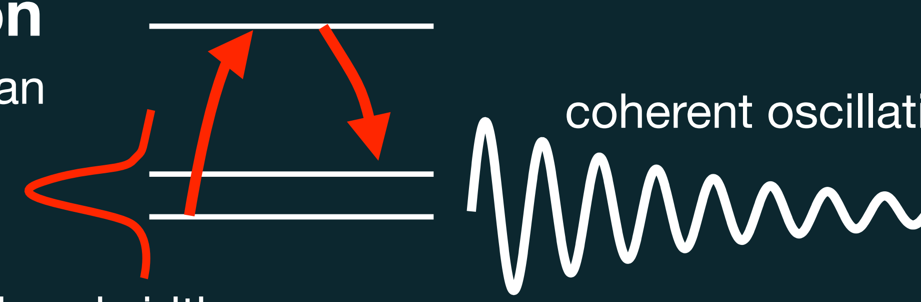
coherent excitation

impulsive Raman



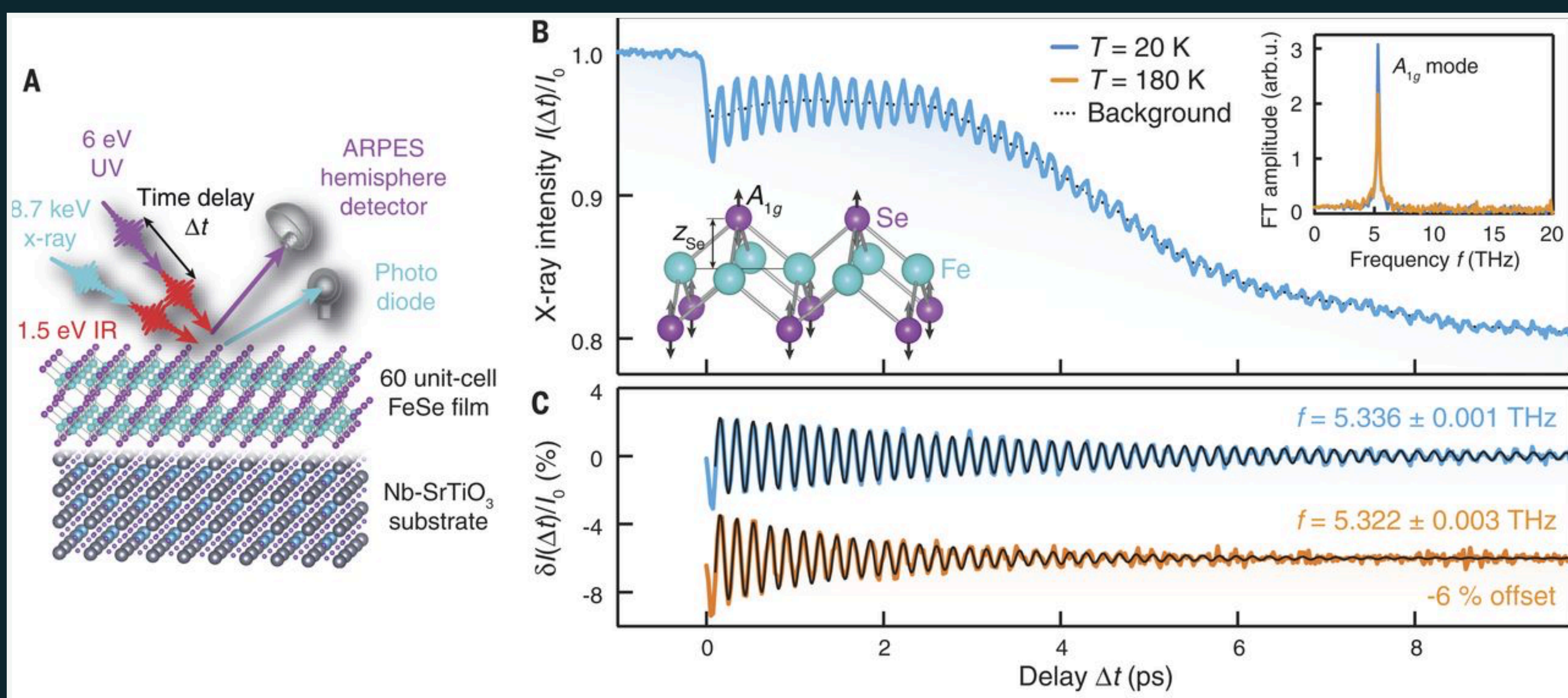
coherent lattice driving

coherent excitation
impulsive Raman

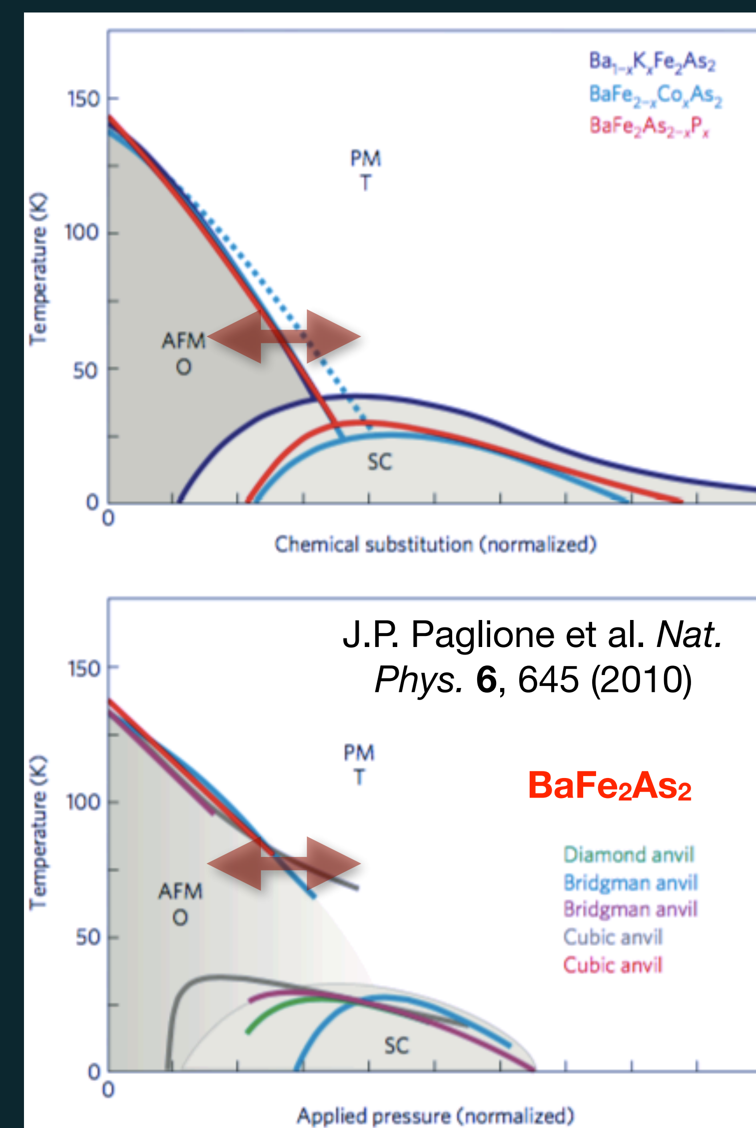


inducing macroscopic magnetic orded via coherent phonons in $BaFe_2As_2$

Coherent phonon oscillation in FeSe



S. Gerber et al. *Science* **357**, 71-75 (2017)



K.W. Kim et al. *Nature Mater.* **11**, 497-501 (2012)

X-rays: lattice oscillation
ARPES: band distortion
→ deformation potential & e-ph coupling

order parameter in a symmetry-broken phase

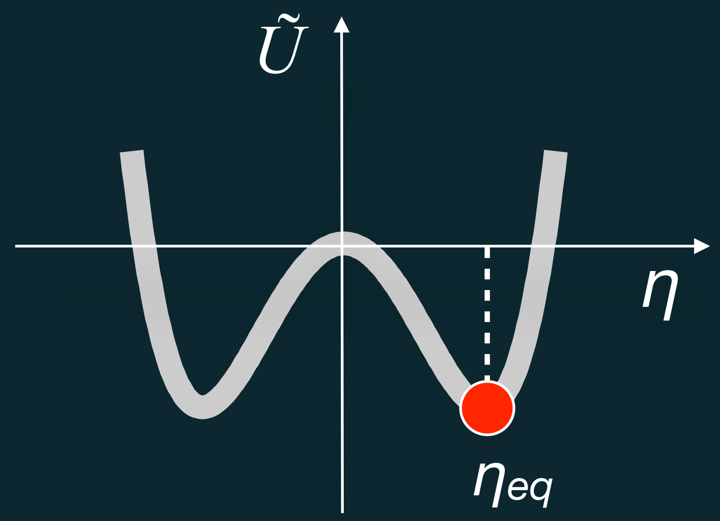
potential landscape based on Ginzburg-Landau functionals

free energy of a symmetry-broken phase

η: order parameter

$$\tilde{U} = \int (\tilde{u}_0 + \frac{A_0(P,T)}{2}|\eta|^2 + \frac{B(P)}{4}|\eta|^4)dv$$

$A_0 = a(P) \cdot (T - T_c)$



C. Giannetti et al. *Advances in Physics* **65**:2, 58-238 (2016)

order parameter in a symmetry-broken phase

potential landscape based on Ginzburg-Landau functionals

free energy of a symmetry-broken phase

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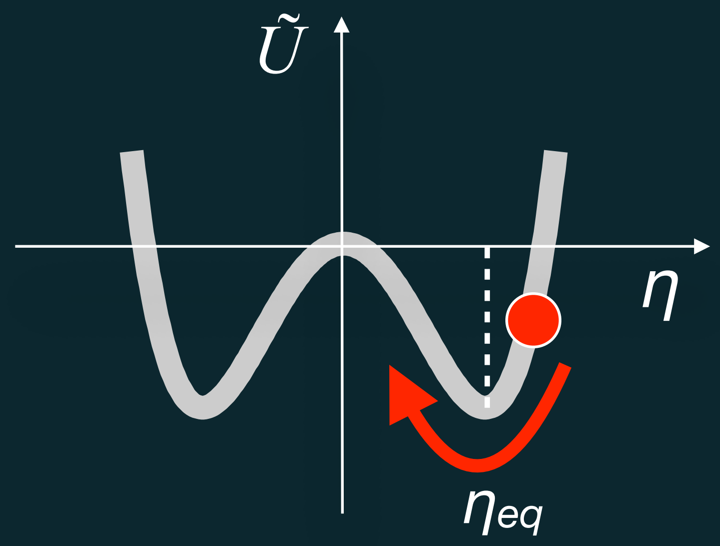
$$\tilde{U} = \int \left(\tilde{u}_0 + \frac{A_0(P,T)}{2}|\eta|^2 + \frac{B(P)}{4}|\eta|^4\right) dv$$

$A_0 = a(P) \cdot (T - T_c)$



motion equation for time-dependent perturbation

$$\frac{d^2\eta}{dt^2} + \alpha\omega_0 \frac{d\eta}{dt} = -\omega_0^2 \frac{\partial \tilde{U}}{\partial \eta}$$

damping (decoherence)

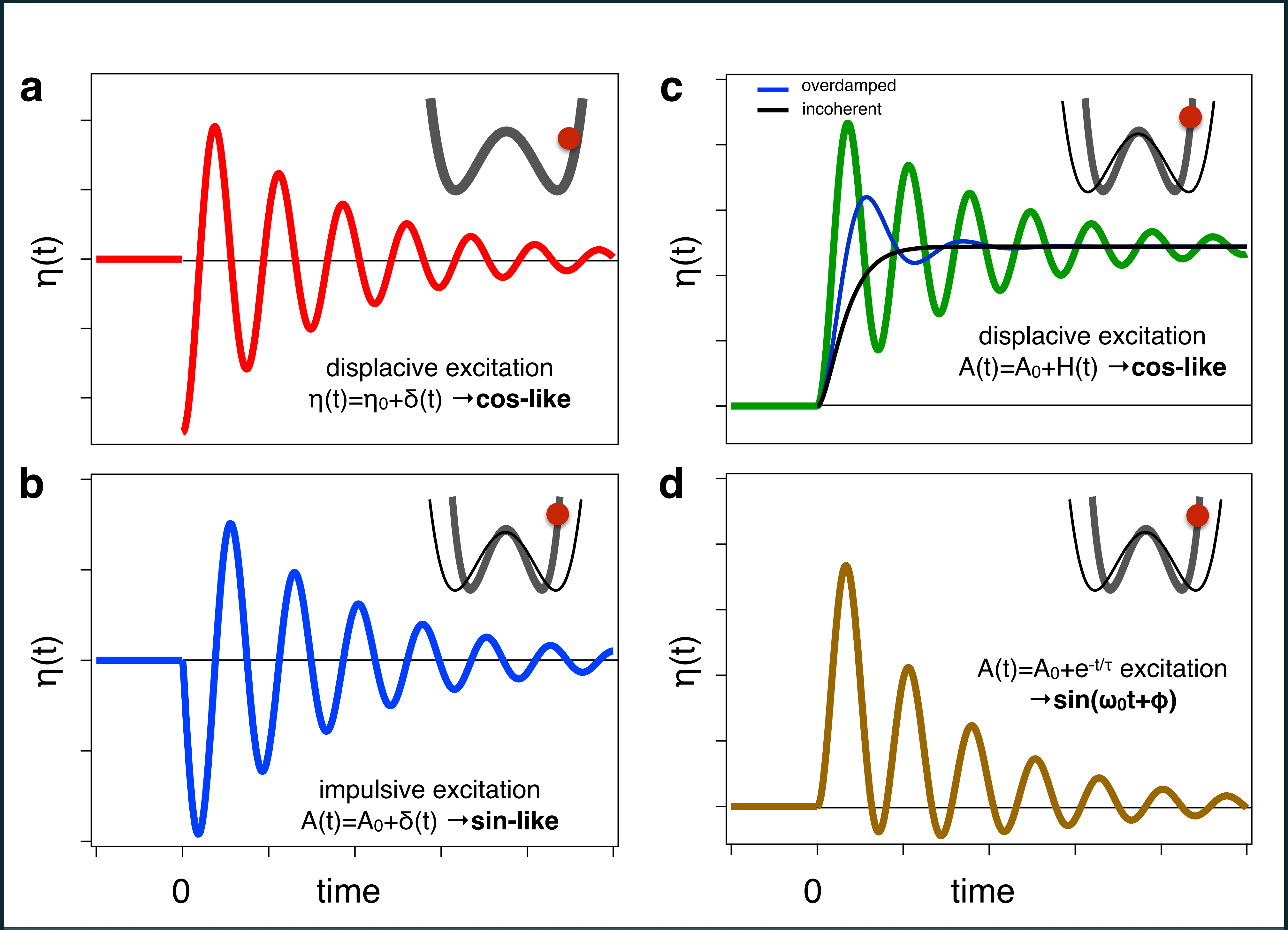
intrinsic frequency of the mode

perturbation of the potential

C. Giannetti et al. *Advances in Physics* **65**:2, 58-238 (2016)

order parameter in a symmetry-broken phase

different excitation schemes

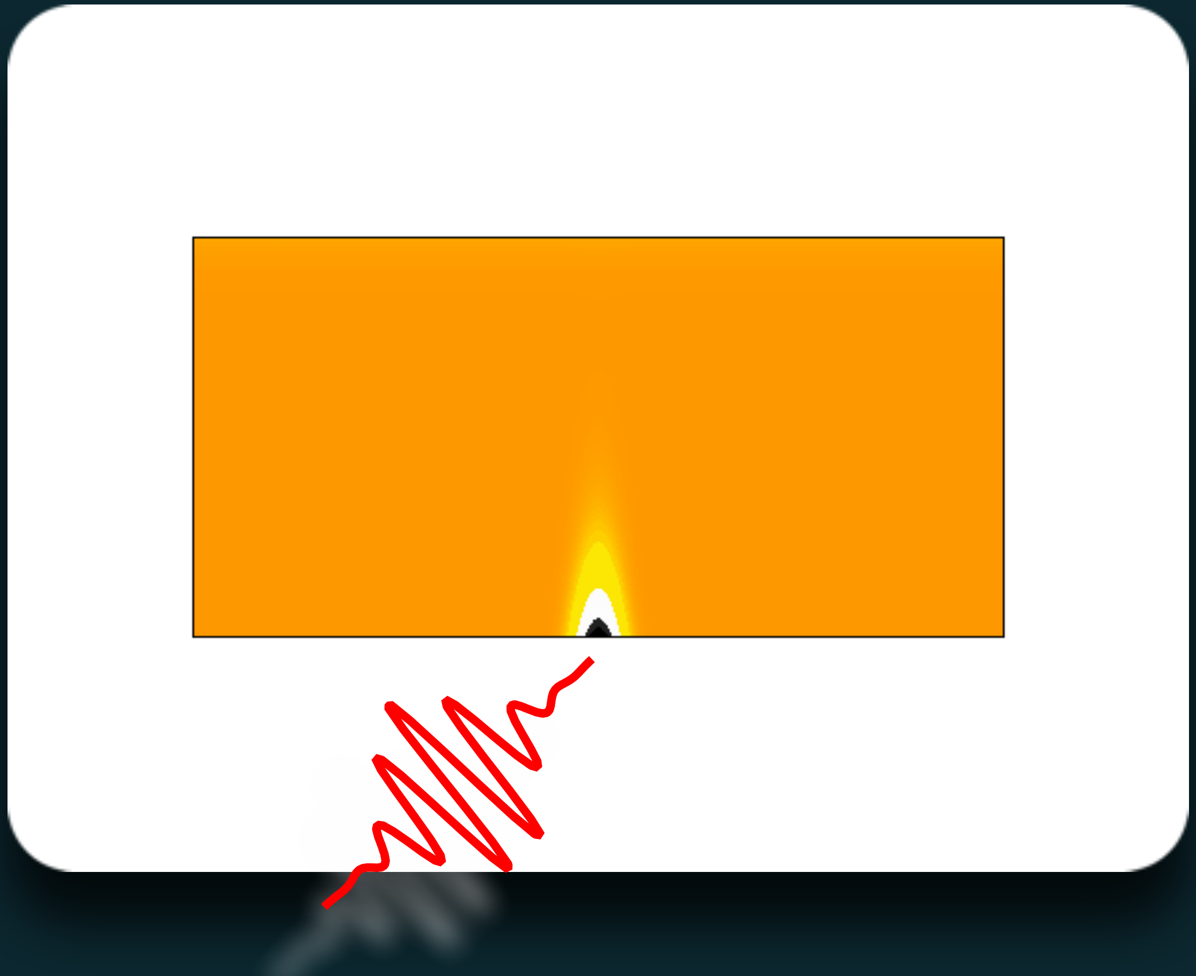


C. Giannetti et al. *Advances in Physics* **65**:2, 58-238 (2016)

coherent excitation of amplitude modes with THz

looking for Higgs modes (amplitude modes) in symmetry-broken phases

wave-behaviour of the amplitude mode

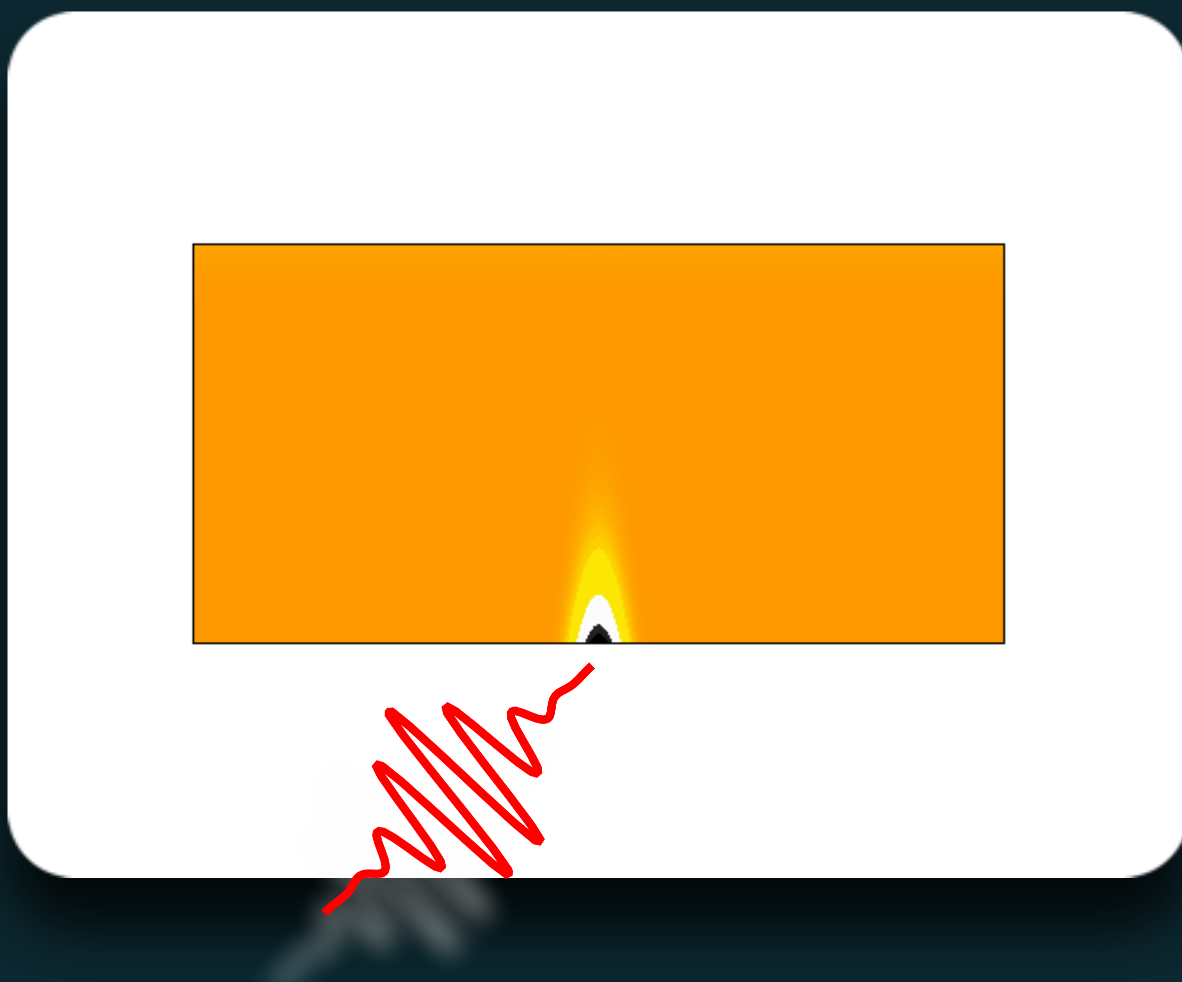


THz excitation of the amplitude mode

coherent excitation of amplitude modes with THz

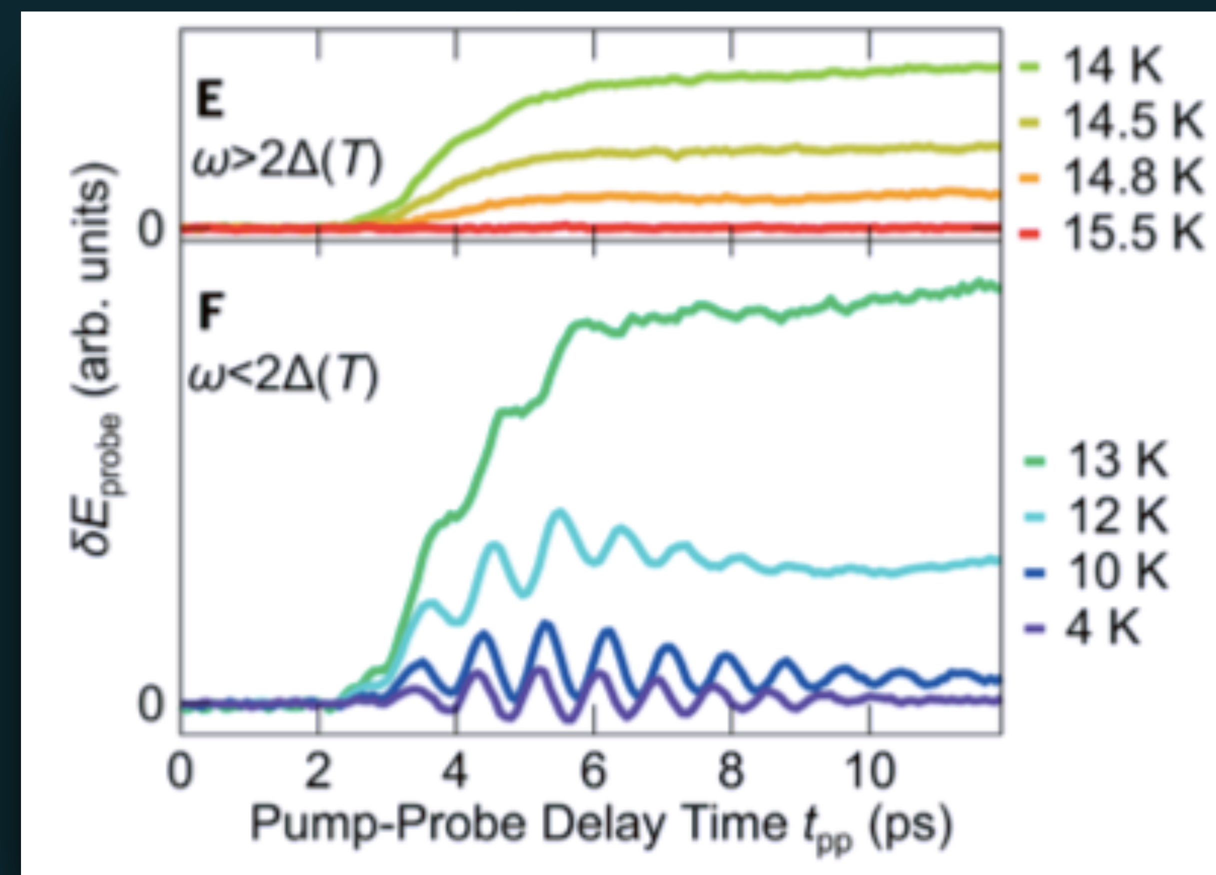
looking for Higgs modes (amplitude modes) in symmetry-broken phases

wave-behaviour of the amplitude mode



THz excitation of the amplitude mode

Higgs mode (amplitude mode of the superconducting order parameter) in $Nb_{1-x}Ti_xN$



R. Matsunaga et al, *Phys. Rev. Lett.* **111**, 057002 (2013)
R. Matsunaga et al, *Science* **345**, 1145-1149 (2014)
T. Cea et al, *Phys. Rev. Lett.* **115**, 157002 (2015)

THz pump-THz probe (below-gap excitation)

outline

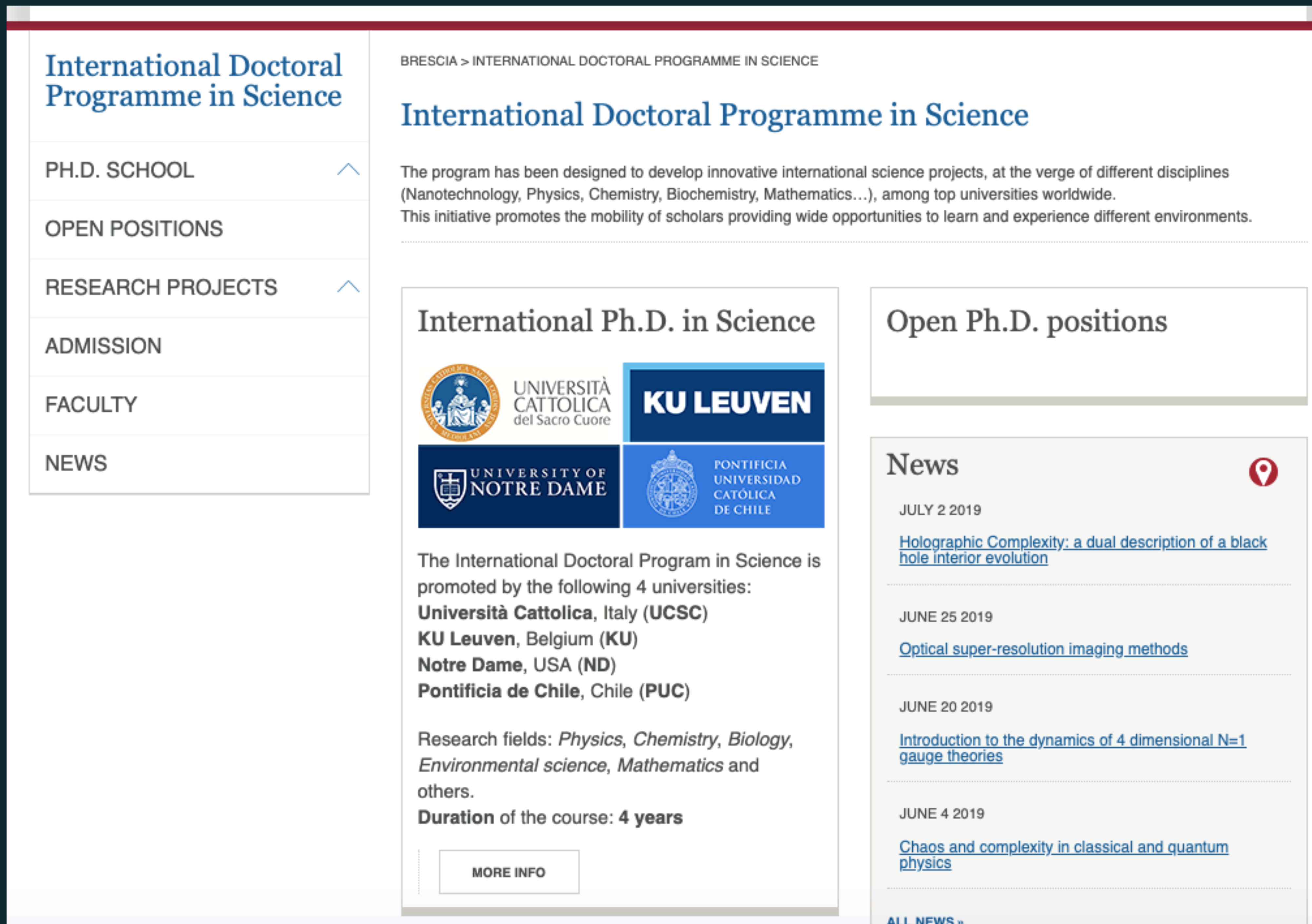
- Ultrafast spectroscopies to investigate the electron dynamics in materials
  C. Giannetti et al. *Advances in Physics* **65**:2, 58-238 (2016)

- light pulses to UNDERSTAND equilibrium properties
  ⇒ pairing glue in high-T_c superconductors

- light pulses to EXCITE specific degrees of freedom
  ⇒ coherent lattice oscillations and Higgs modes

- light pulses to MANIPULATE materials properties
  ⇒ hidden states, transient photo-enhanced superconductivity

Looking for a PhD position?



BRESCIA > INTERNATIONAL DOCTORAL PROGRAMME IN SCIENCE

International Doctoral Programme in Science

International Doctoral Programme in Science

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