Ultrafast study of Dirac fermions in out of equilibrium Topological Insulators

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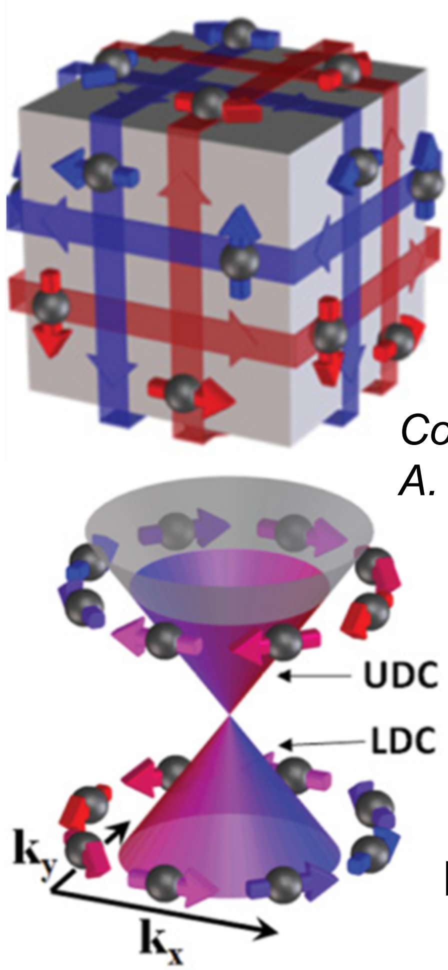
IMPACT, Cargèse, August 26th, 2016

Topological Insulators

- Novel state of quantum matter
- Insulating bulk, but gapless edge or surface states
- Combined action of spin-orbit coupling and time reversal symmetry (QSH effect)
- Unique transport properties: topologically protected states, immune to defects, perturbation
- Spin locking: the spin of the surface state lies in the surface plane and is always perpendicular to the momentum

real space

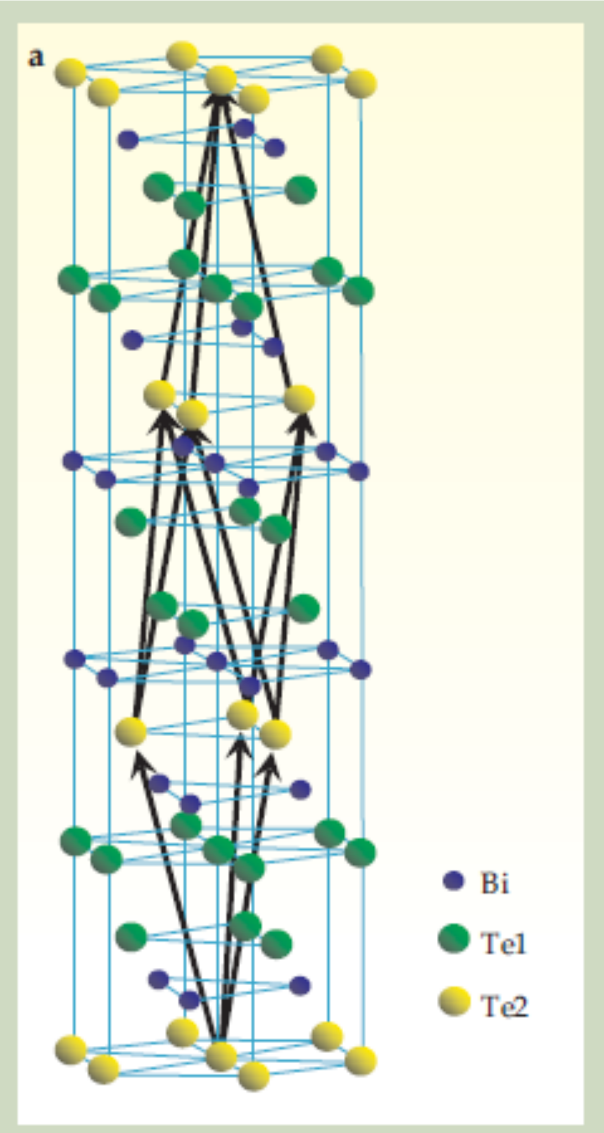


Courtesy A. Lanzara et al.

k-space

Hasan and Kane, RMP 2010
Qi and Zhang, RMP 2011
Bansil et al., RMP 2016

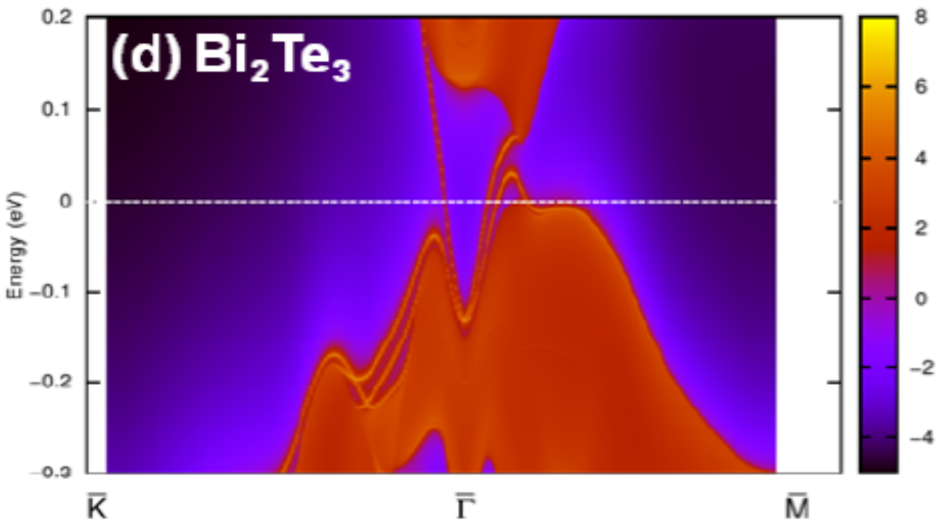
3D Topological Insulators: Bi_2Te_3



$Bi_{1-x}Sb_x$, Bi_2Te_3, Bi_2Se_3, Sb_2Te_3

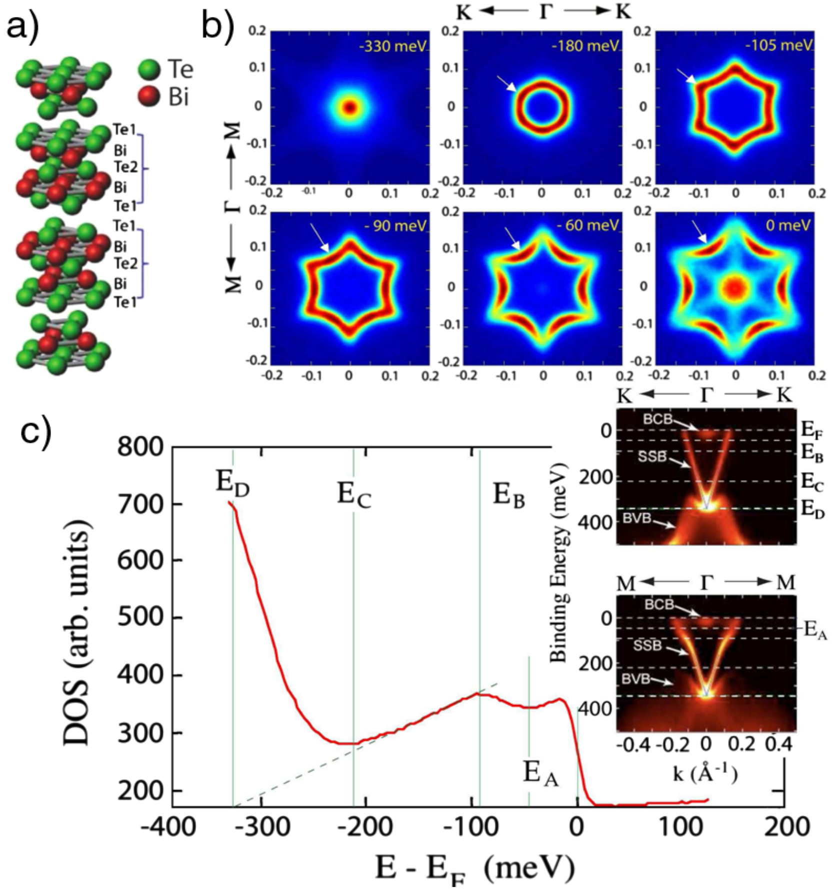
Non trivial topology ⇔ band inversion driven by strong S-O coupling

➔ Single Dirac cone on surface



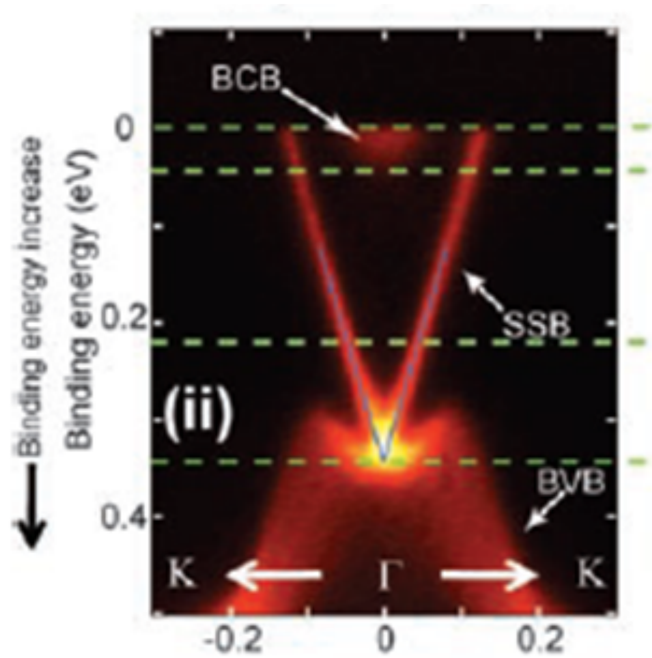
Zhang et al., Nat. Phys. 2009

3D Topological Insulators: Bi_2Te_3



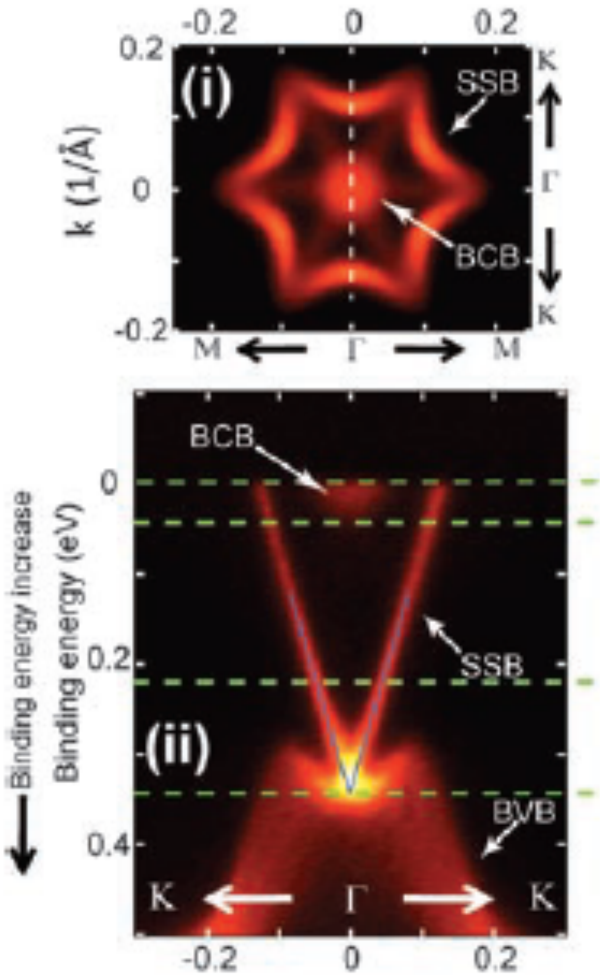
Alpichshev et al., PRL 2010

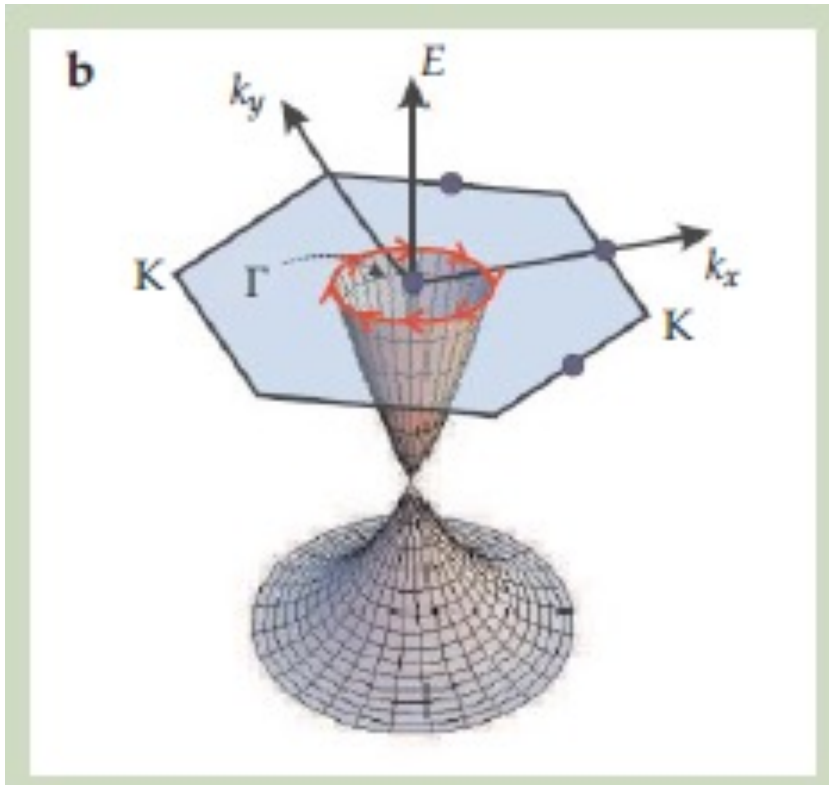
Bi_2Te_3 : Dirac cone presents hexagonal warping



3D Topological Insulators ⇔ ARPES

(Hsieh et al., Nature 2008; Chen et al., Science 2009; …)

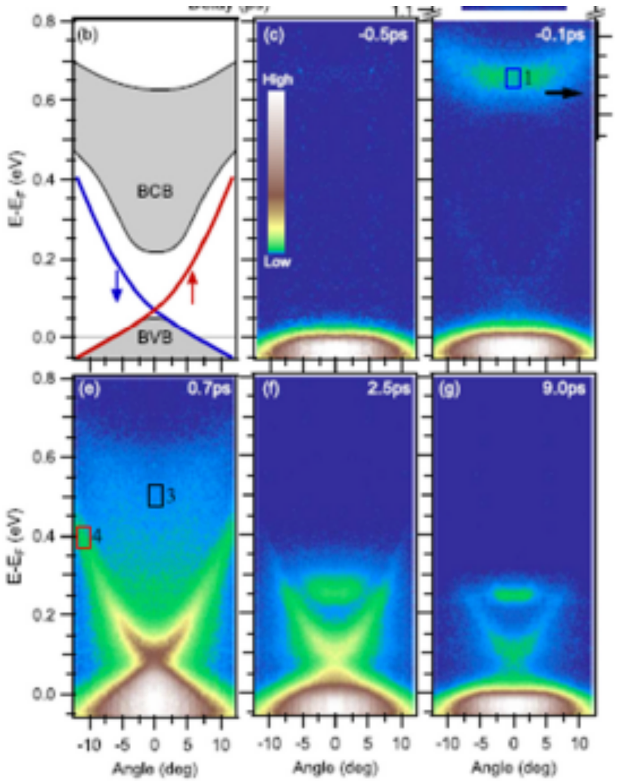




Dirac cone studied by ARPES :
Spin in surface plane, perpendicular to k

Out of equilibrium TI's⬄ ultrafast studies

J. Sobota et al., PRL 108, 117403 (2012)



➔ out of equilibrium TI's, following first studies in 2012 (Stanford, MIT, Trieste, ….)

➔ Time Resolved ARPES

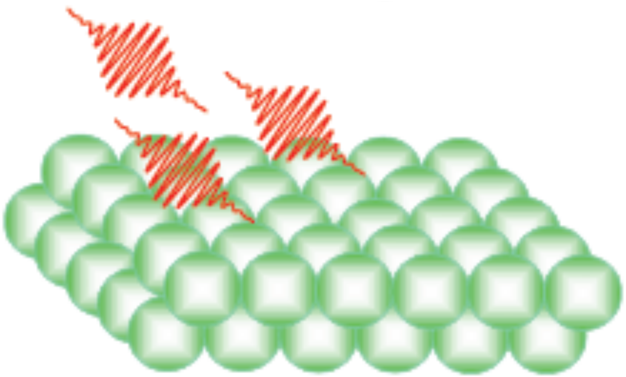
- Info on empty electronic states, interband scattering rates, hot fermion properties?

➔ Playground for a 2 dimensional Dirac system (2DDS) in interaction with bulk electronic states

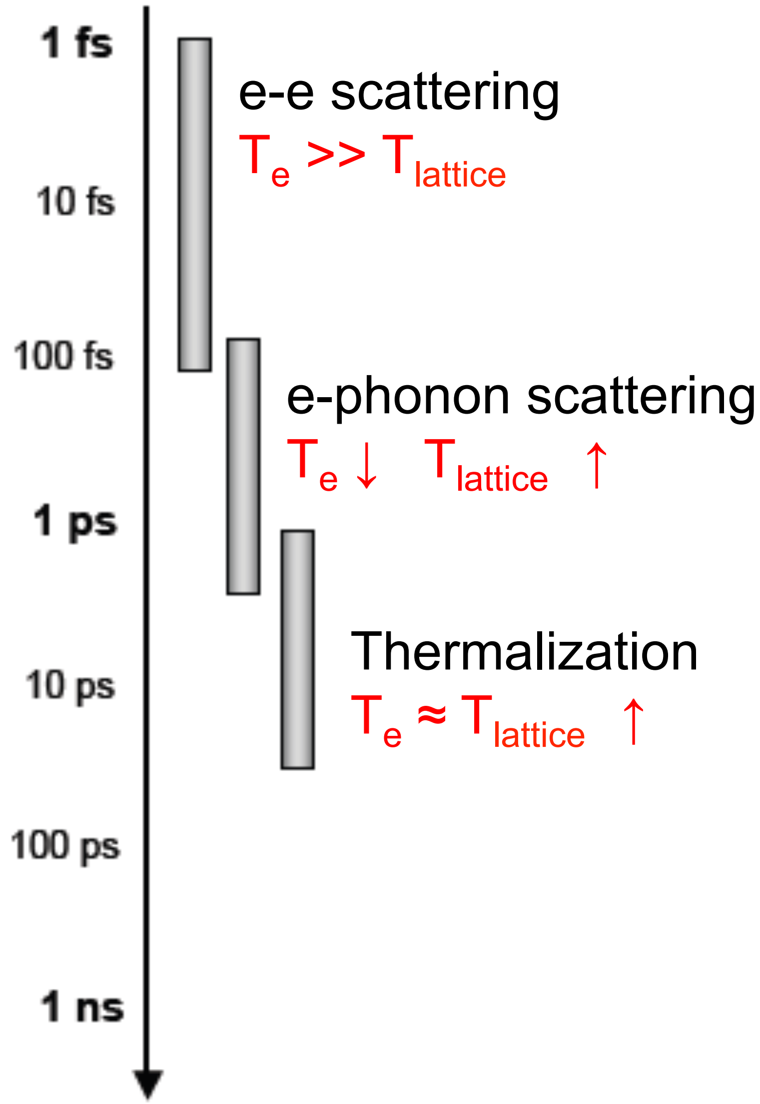
- Thermalization of an out of equilibrium conducting system

Transient phase ⇔ e-phonon coupling

Femtosecond laser excitation

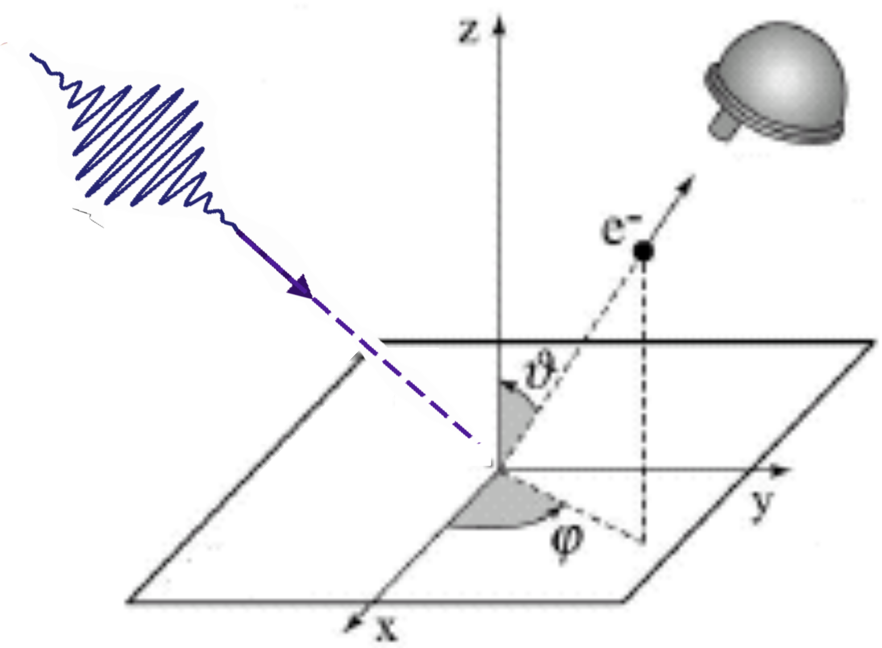


Photons interact with electrons in sample



ARPES and pump-probe ARPES

- ARPES (Angle Resolved PhotoElectron Spectroscopy)



E(**k**)

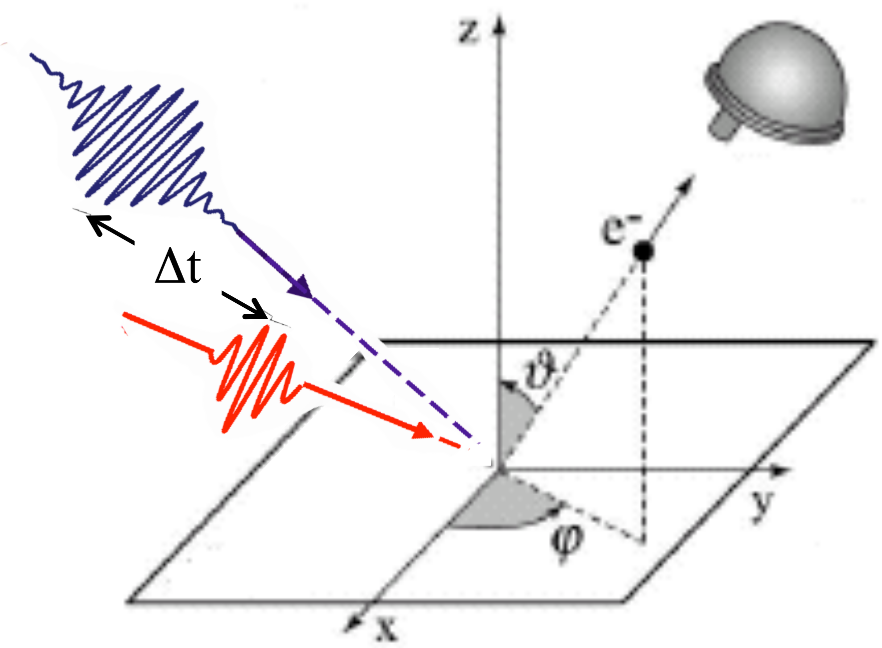
$$E_B = h\nu - E_K - W$$

$$p_{//} = \hbar k_{//} = \sqrt{2mE_K}\sin\theta\,,$$

ARPES and pump-probe ARPES

- ARPES (Angle Resolved PhotoElectron Spectroscopy)
- pump-probe ARPES ⇔ excited states

E(**k**) vs Δt



$$E_B = h\nu - E_K - W$$

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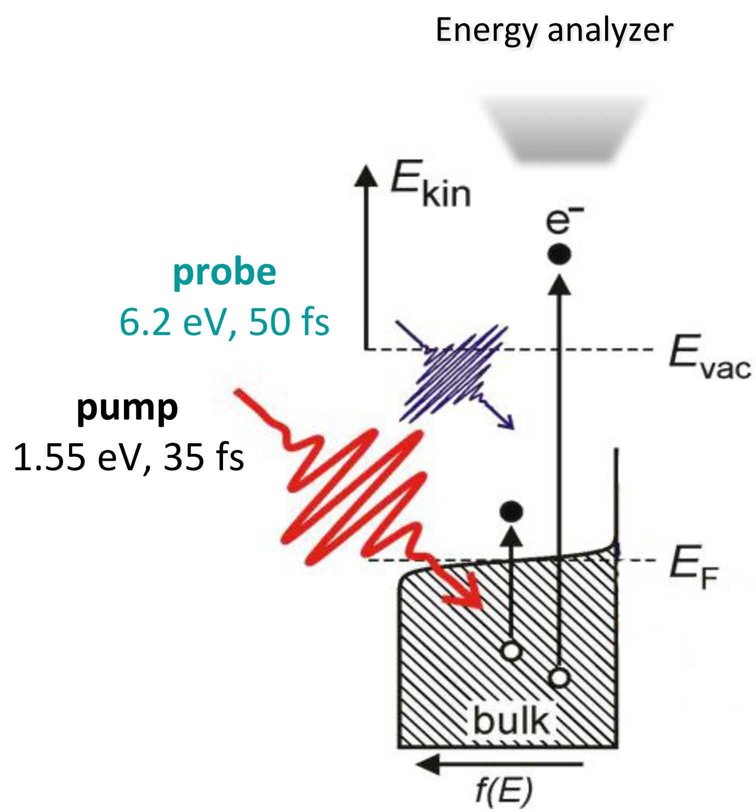
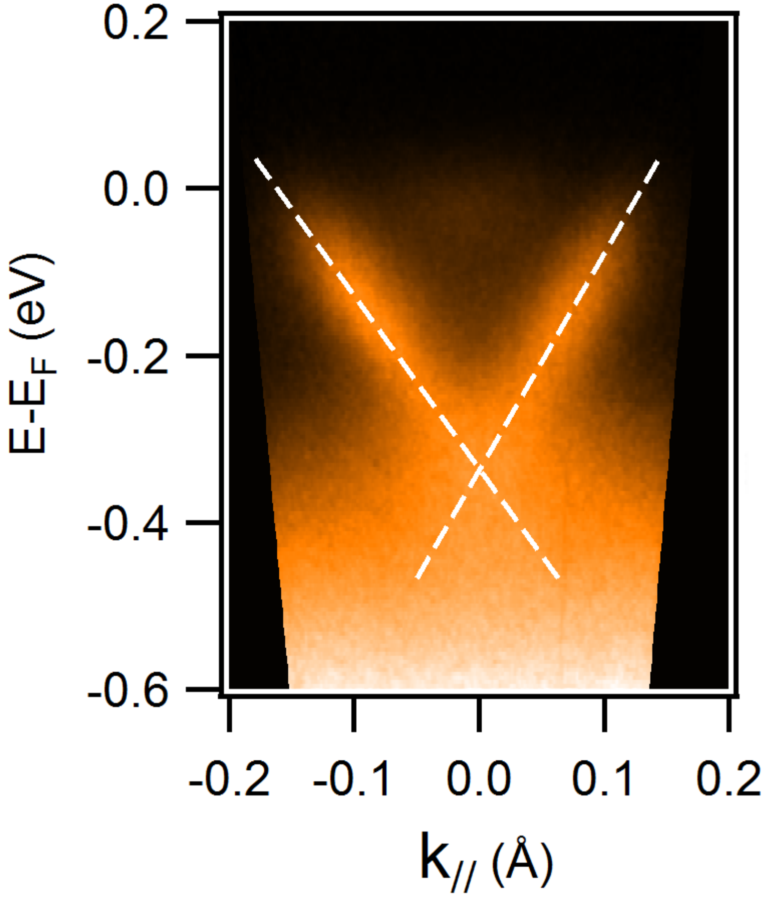
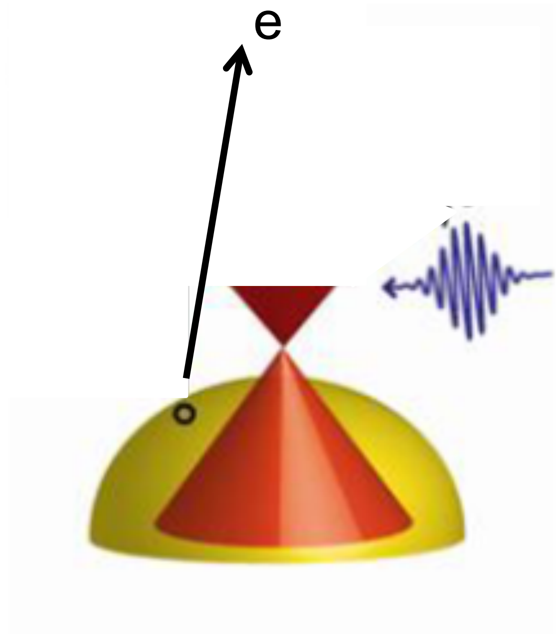


Bi_2Te_3 ⇔ low energy ARPES

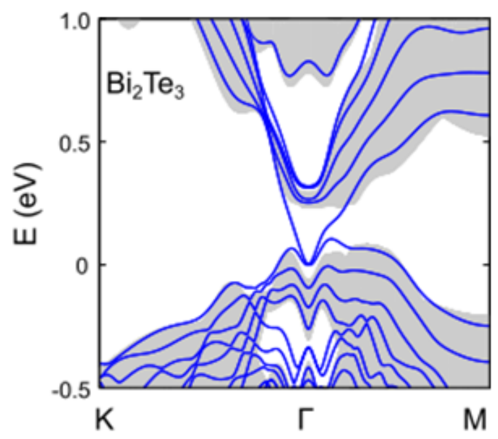
n-type Bi_2Te_3

gap = 0.3 eV





probe: hν = 6.28 eV

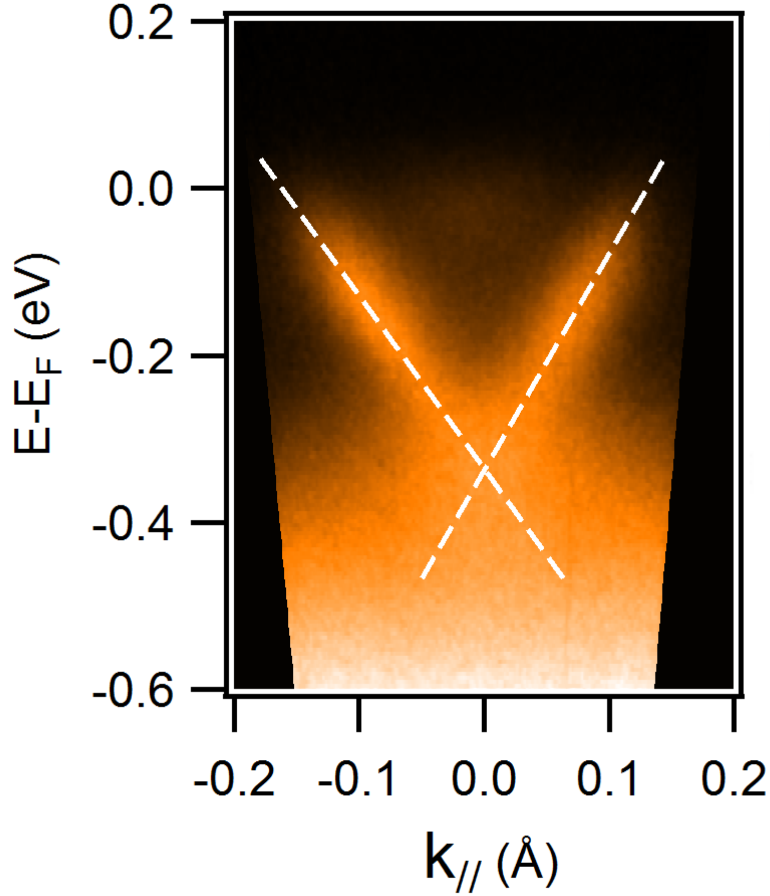


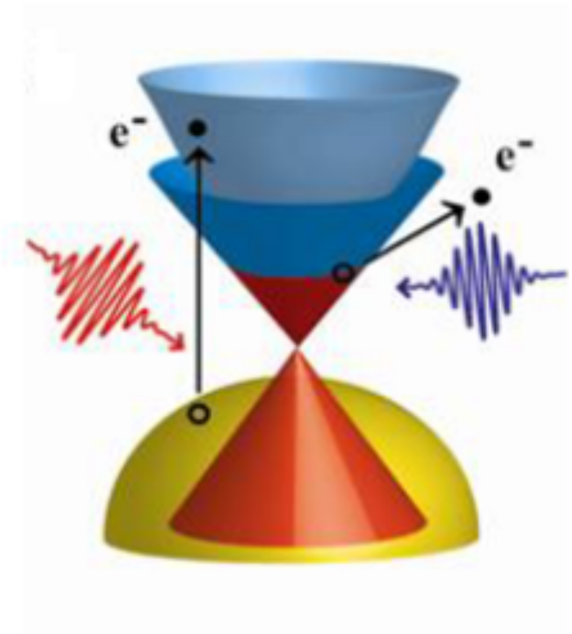
Yazyev and al ,
PRL 105, 266806

Bi_2Te_3 ⇔ pump-probe ARPES

n-type Bi_2Te_3

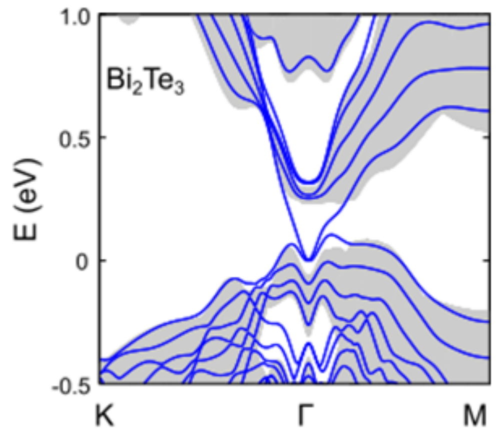
gap = 0.3 eV





probe: hν = 6.28 eV

pump: hν = 1.5 eV



Yazyev and al ,
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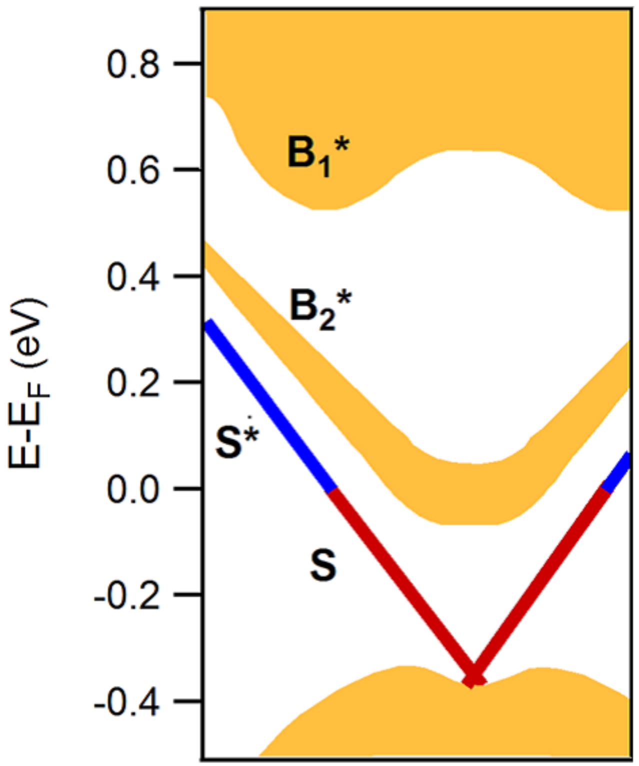
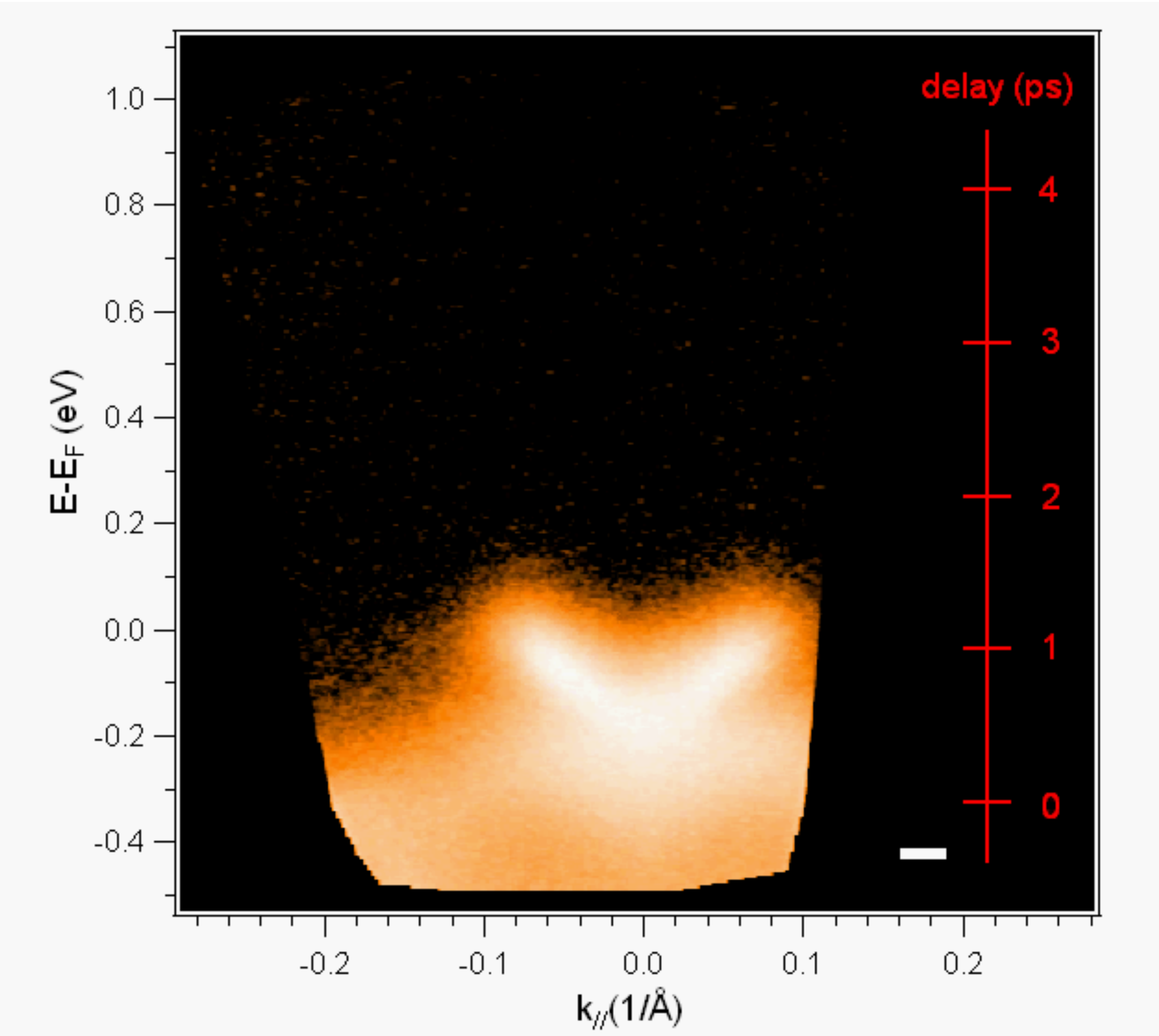
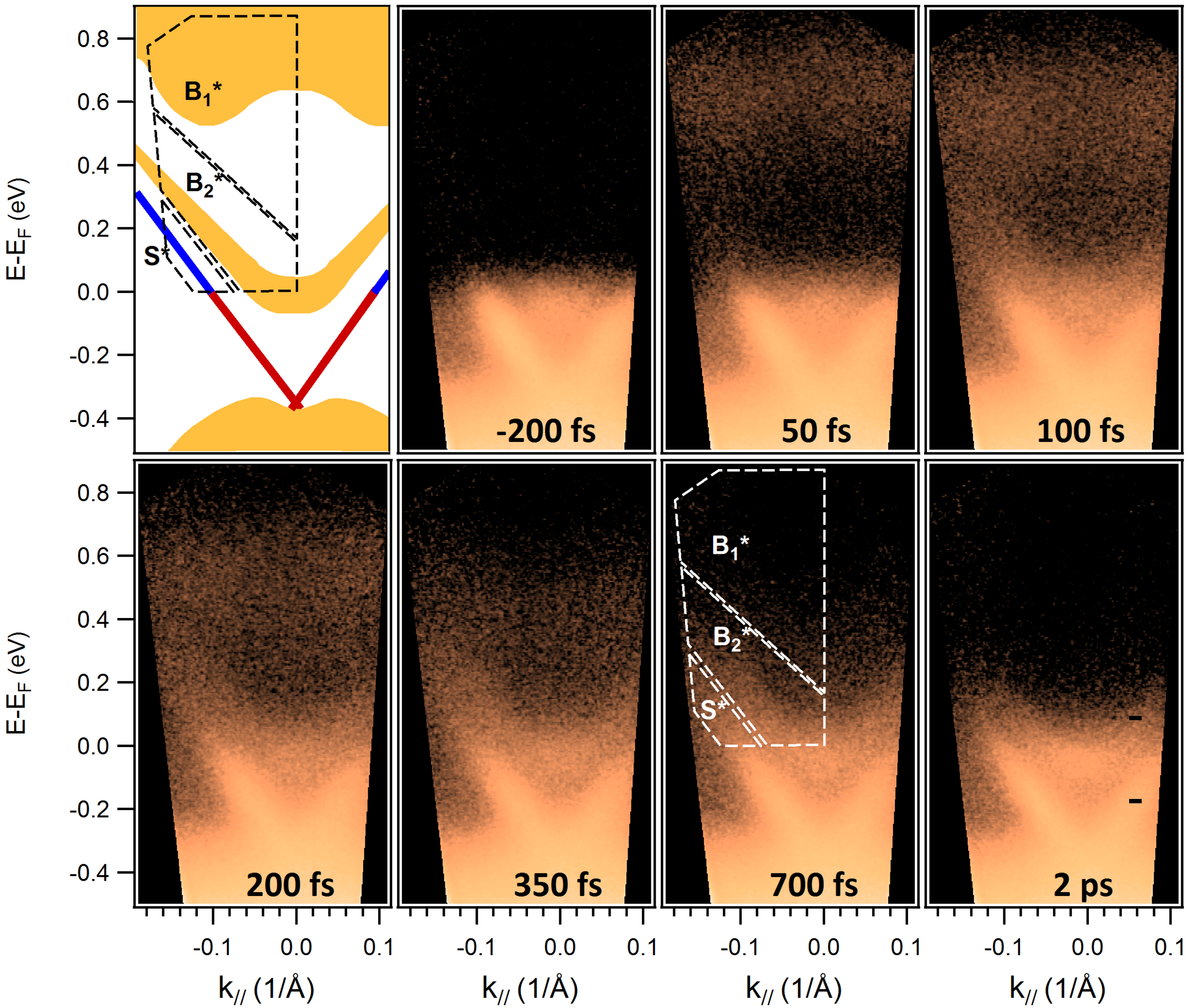
Time resolved ARPES on n-Bi_2Te_3

Band structure and
Dirac cone dynamics





Time resolved ARPES on n-Bi_2Te_3



Ultrafast time scale for:

Optical excitation

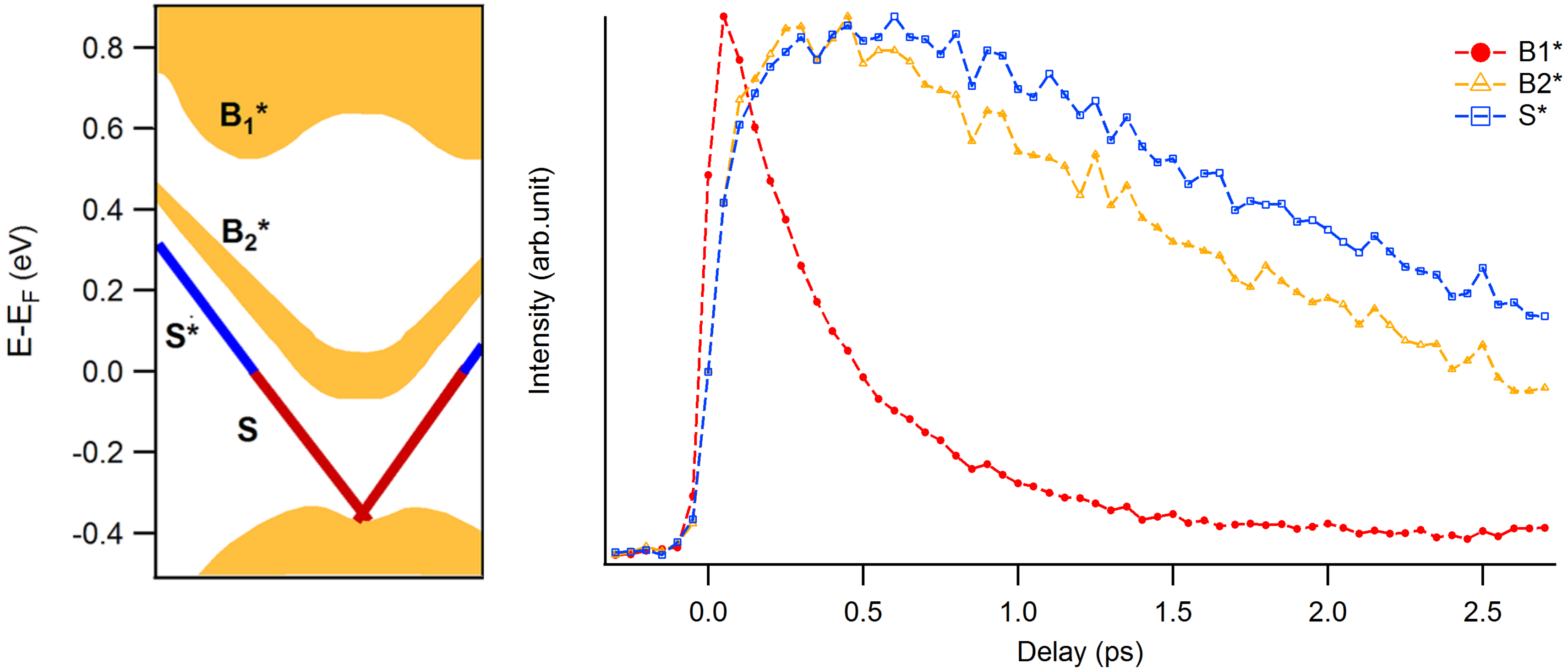
Interband scattering

Intraband scattering

Hot electron relaxation

E-phonon coupling

Transient band populations in n-Bi_2Te_3



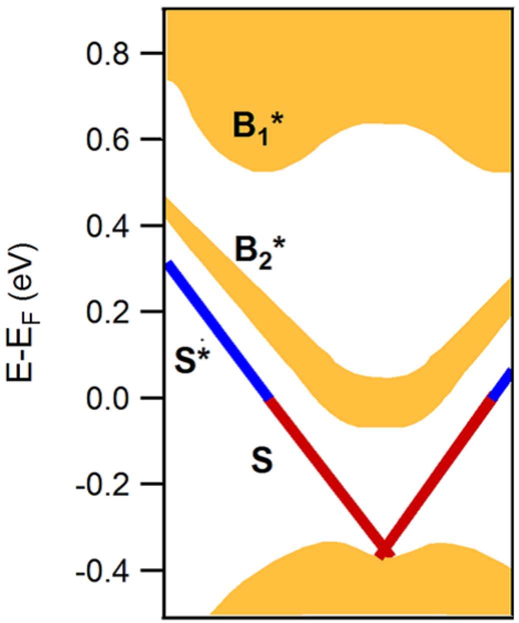
➔ Excitation VB to B_1^*

➔ scattering B_1^* → S^* and B_2^*

➔ Relaxation of S^* slow ⬄ weak e-phonon coupling

Hajlaoui et al., Nano Lett. 12, 3532 (2012)

Transient band populations



$$\frac{dB_1^*}{dt} = G_1(t) - \frac{B_1^*(t)}{\tau_1}$$

$$\frac{dB_2^*}{dt} = G_2(t) + \alpha\frac{B_1^*(t)}{\tau_1} - \frac{B_2^*(t)}{\tau_2}$$

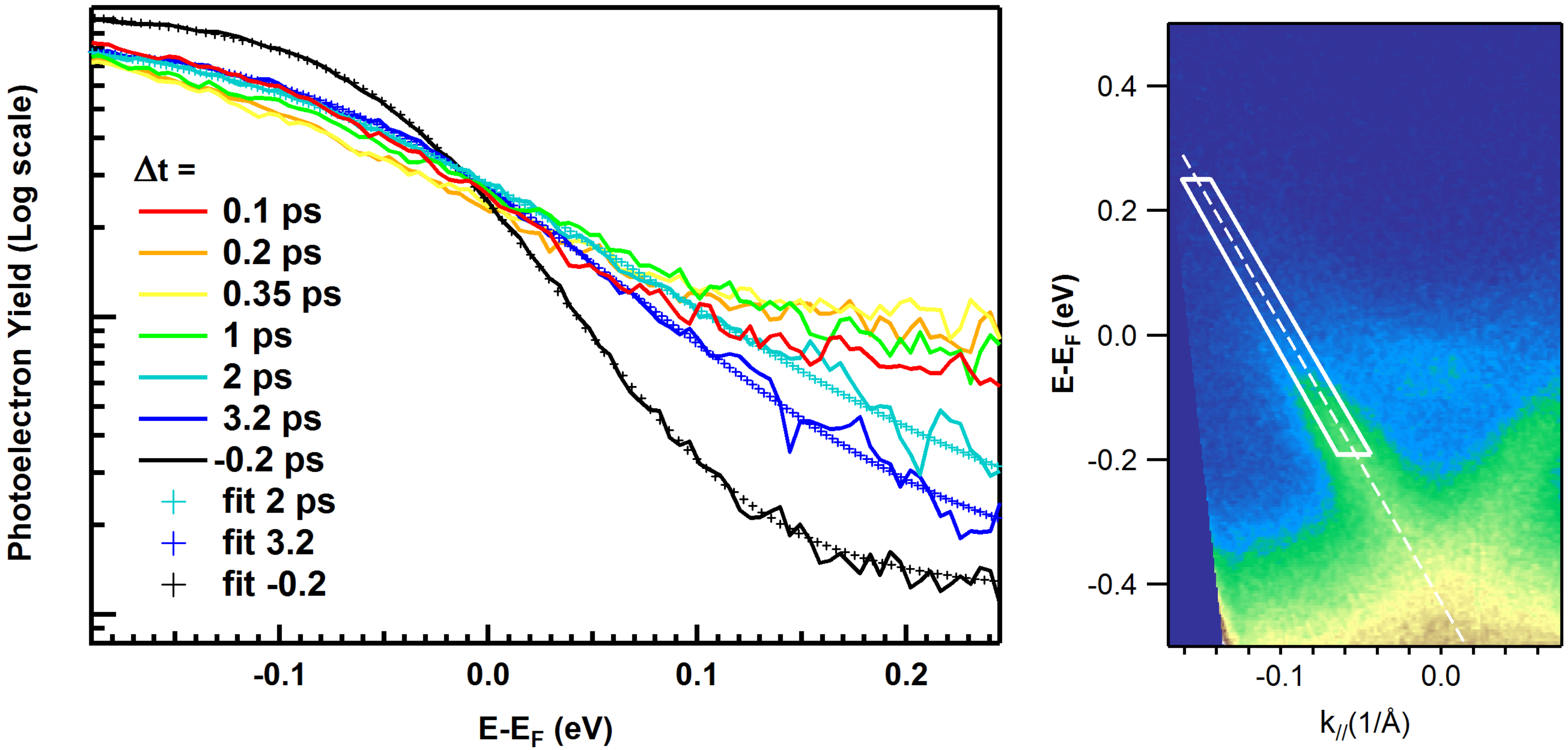
$$\frac{dS^*}{dt} = G_{S*}(t) + \beta\frac{B_1^*(t)}{\tau_1} - \frac{S^*(t)}{\tau_{D1}}$$

$$\frac{dS}{dt} = -G_S(t) - \frac{B_{tot} - B(t)}{\tau_h} + \frac{S_{tot} - S(t)}{\tau_{D2}}$$

- ➔ Excitation VB to B_1*
- ➔ scattering B_1* → S* and B_2*
- ➔ Relaxation of S* slow ⇔ weak e-phonon coupling

Hajlaoui et al., Nano Lett. 12, 3532 (2012)

EDC’s from transient Dirac cone states

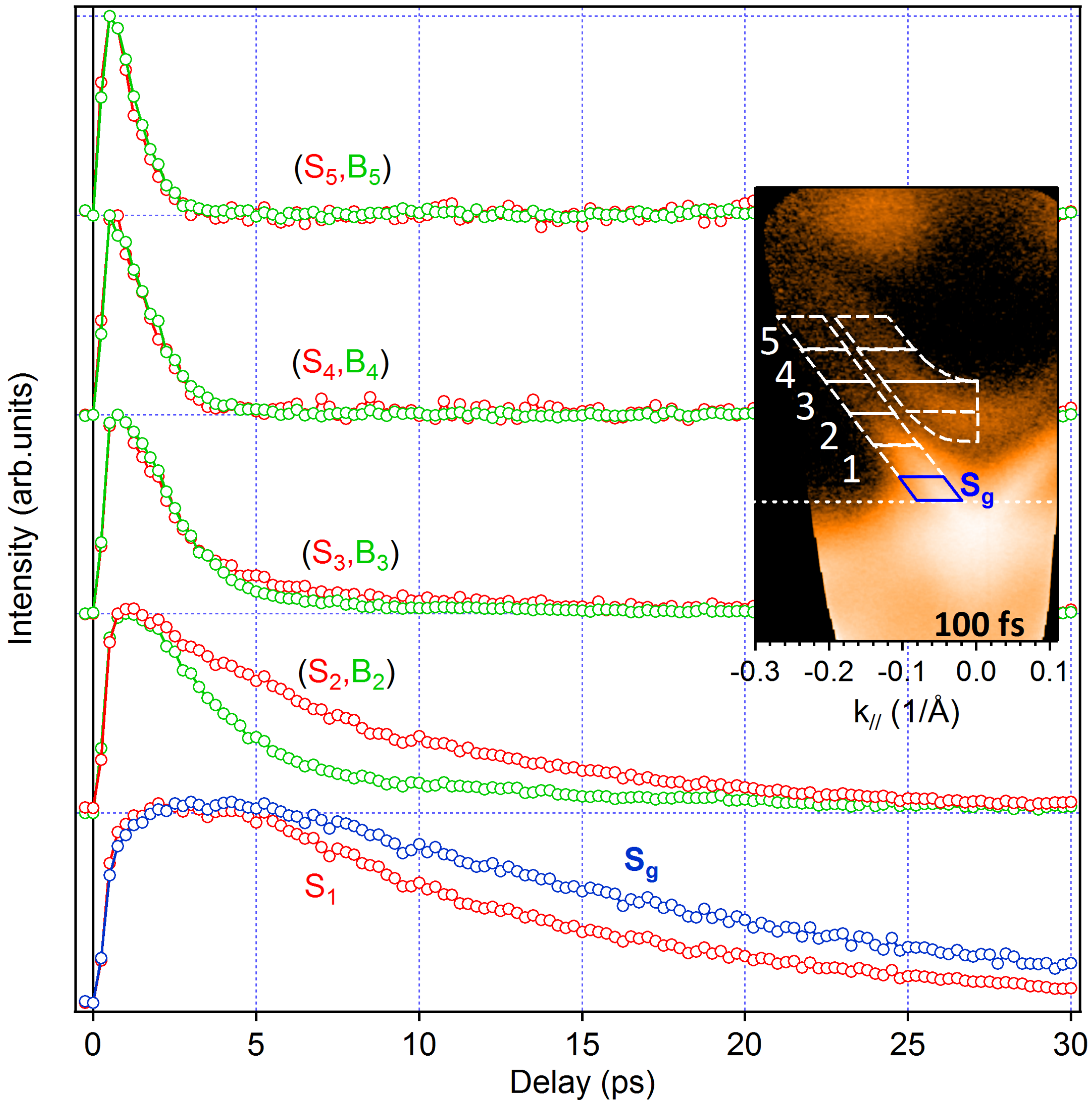


➔ Energy Distribution Curves of hot electrons in the Dirac cone

➔ electron thermalization: ps scale ⇔ influenced by interband scattering

Hajlaoui et al., Nano Lett. 12, 3532 (2012)

Dirac cone relaxation in p-Bi_2Te_3



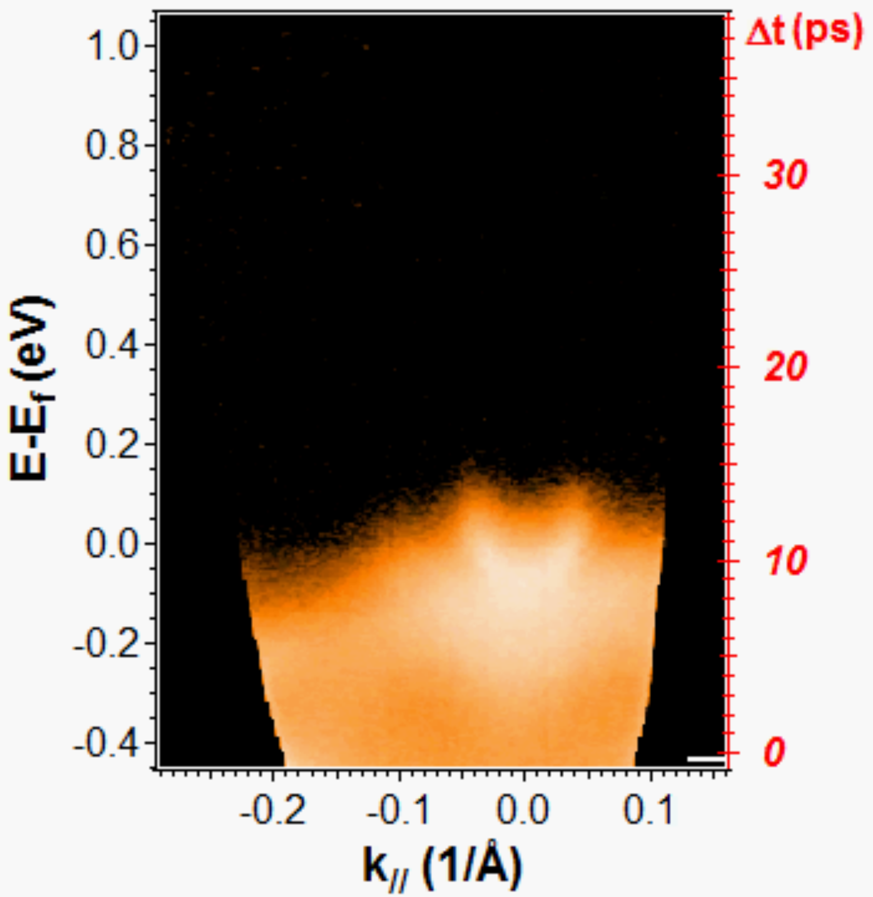
Intrinsic Dirac cone relaxation much slower than bulk recombination

In Bi_2Se_3, exceptionally weak e-ph coupling (see for instance
Z.-H. Pan et al., PRL 2012
Sobota et al. PRL 2012
Wang et al., PRL 2012)

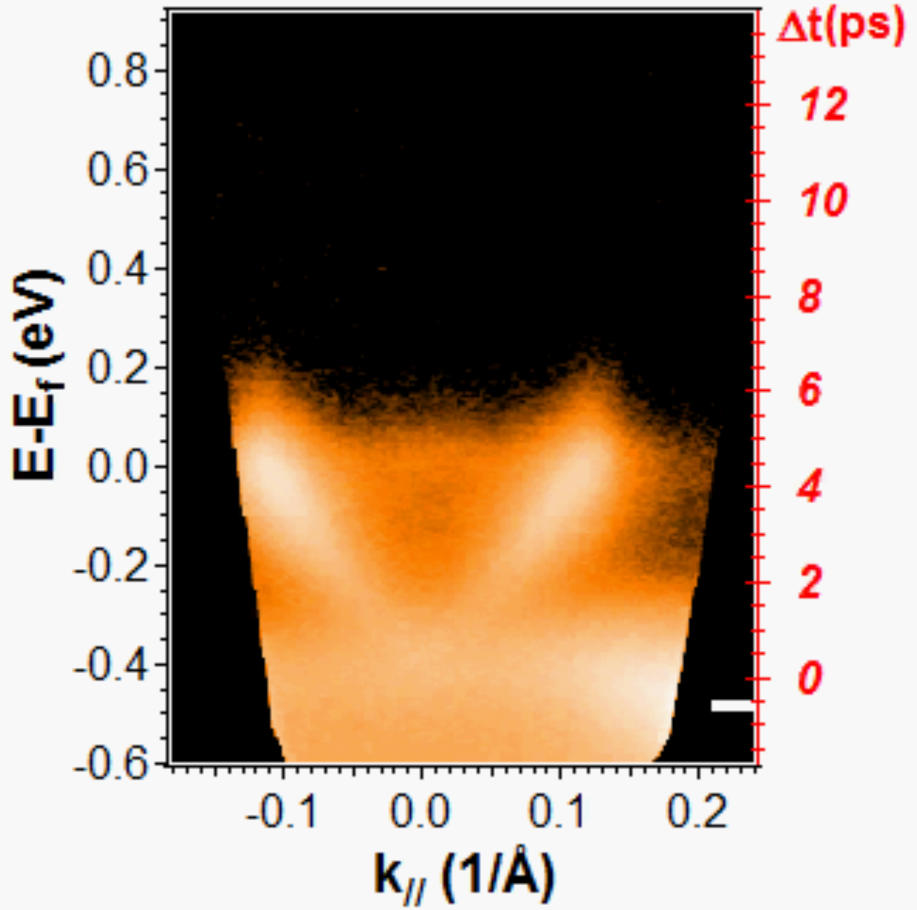
Hajlaoui et al.,
Nature Comm. 5, 3003 (2014)

TR-ARPES on p-Bi_2Te_3 n-Bi_2Te_2Se

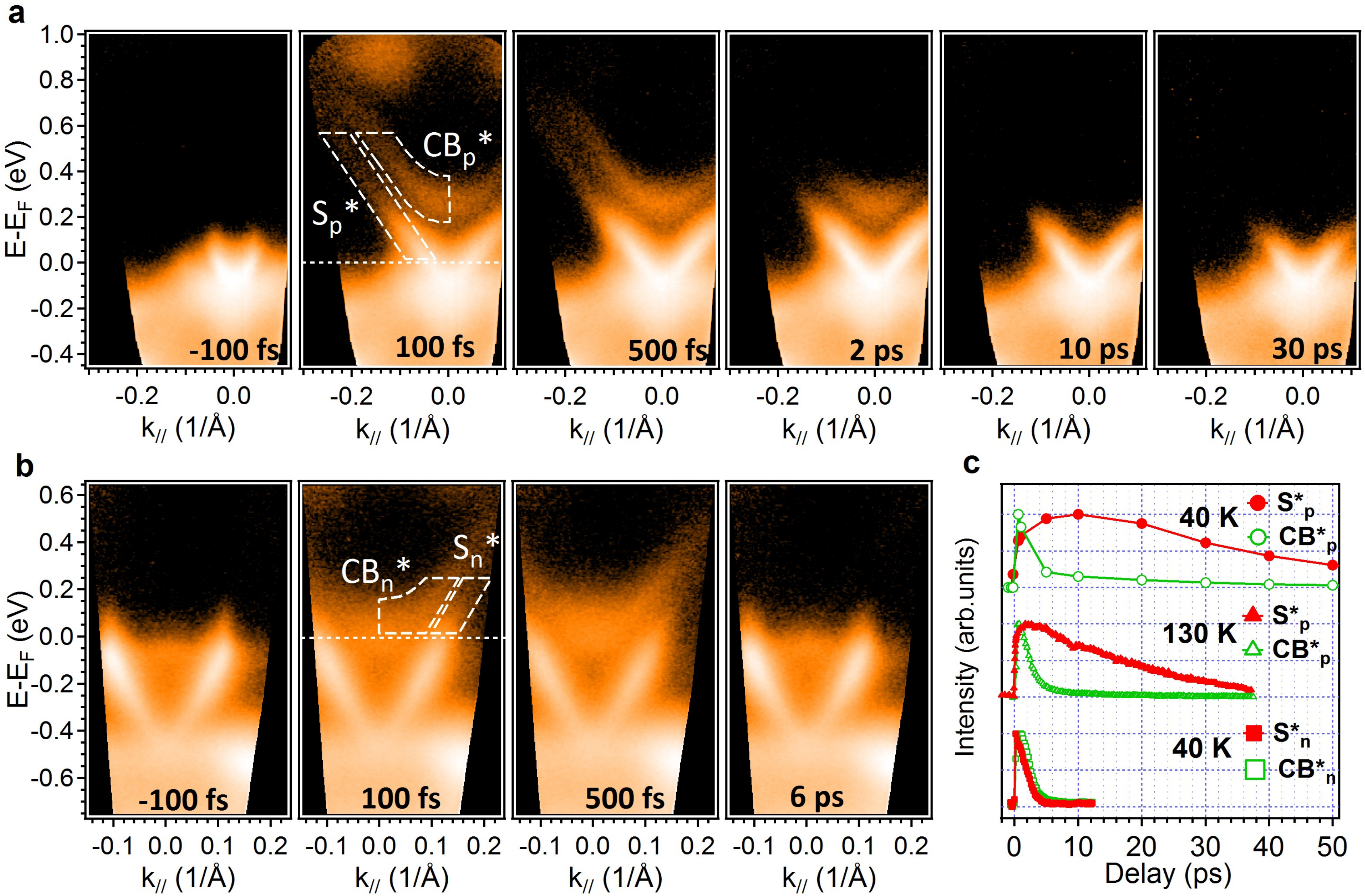
p-Bi_2Te_3



n-Bi_2Te_2Se

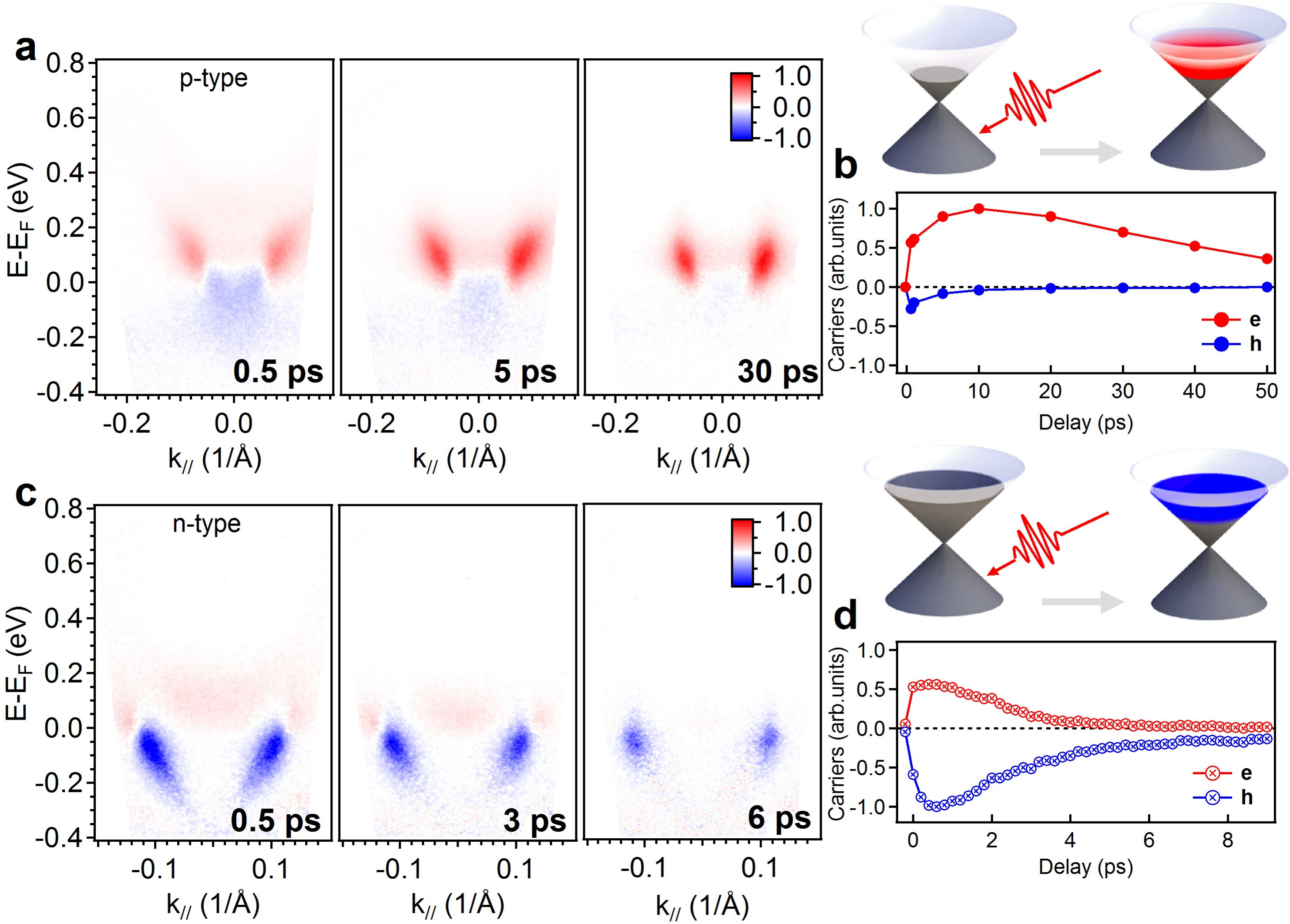


TR-ARPES on p-Bi_2Te_3 n-Bi_2Te_2Se

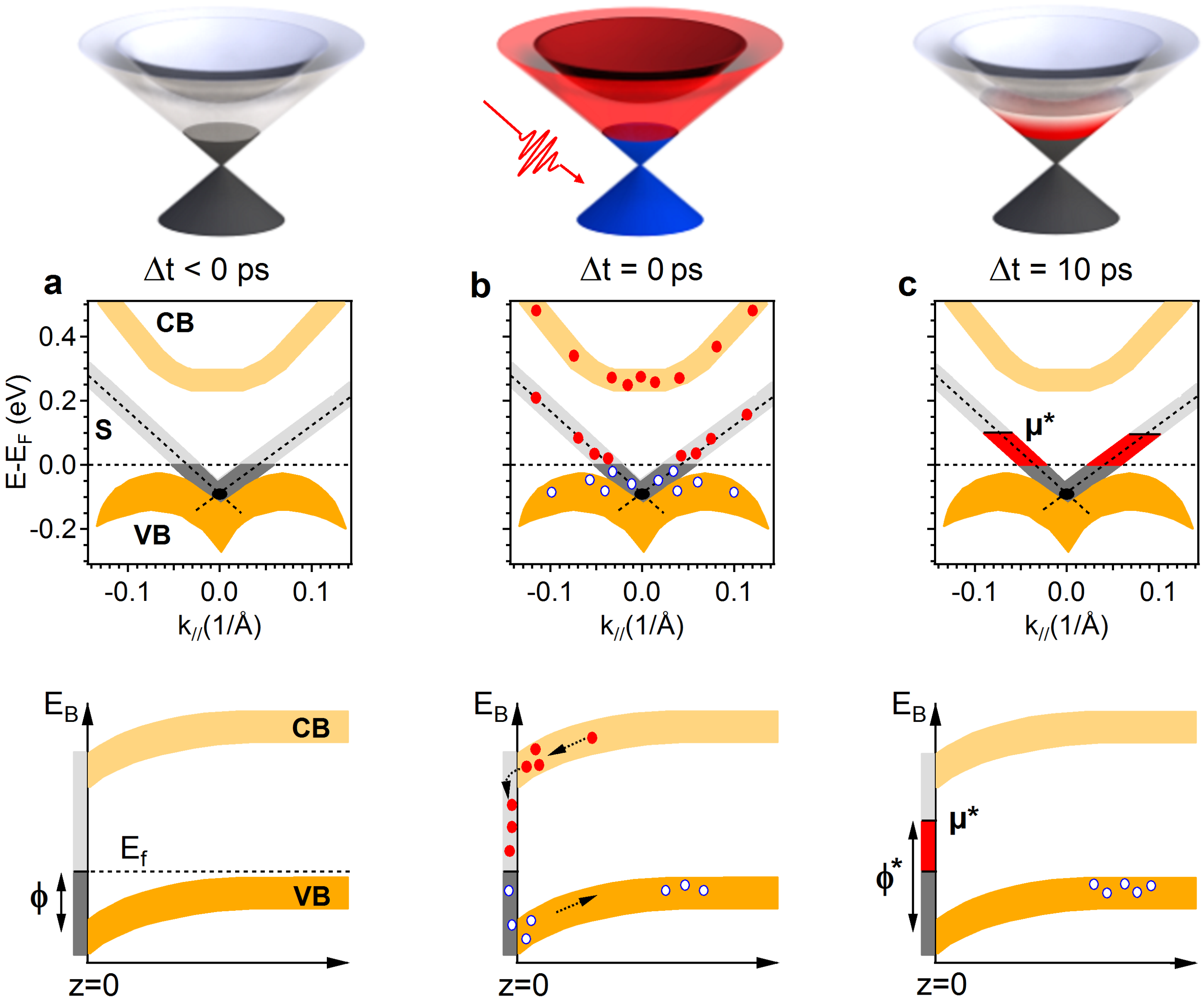


Hajlaoui et al., Nature Commun. 5, 3003 (2014)

Transient e-h asymmetry in Dirac cone

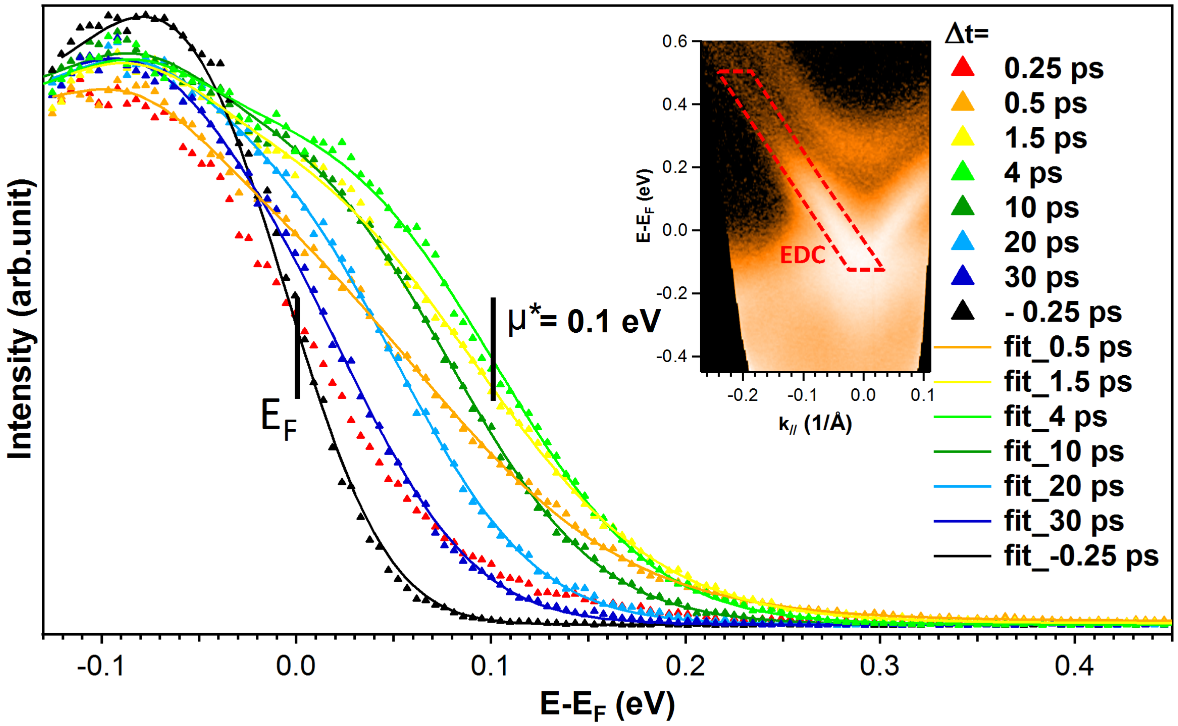


Non equilibrium p-Bi_2Te_3



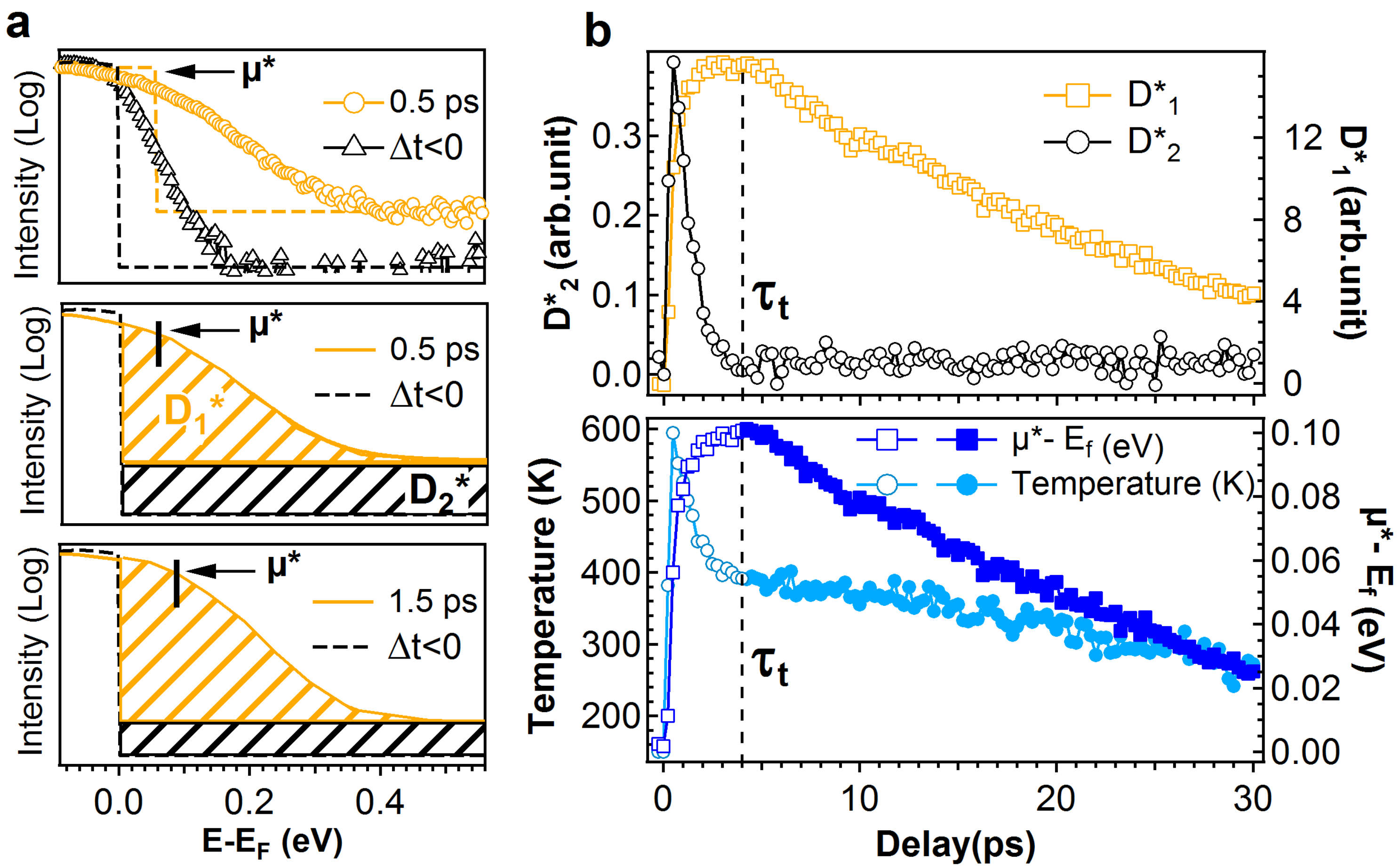
Pre-existing surface band bending helps create a strong e-h transient asymmetry in Dirac cone

Non-equilibrium metallic layer: p-Bi_2Te_3



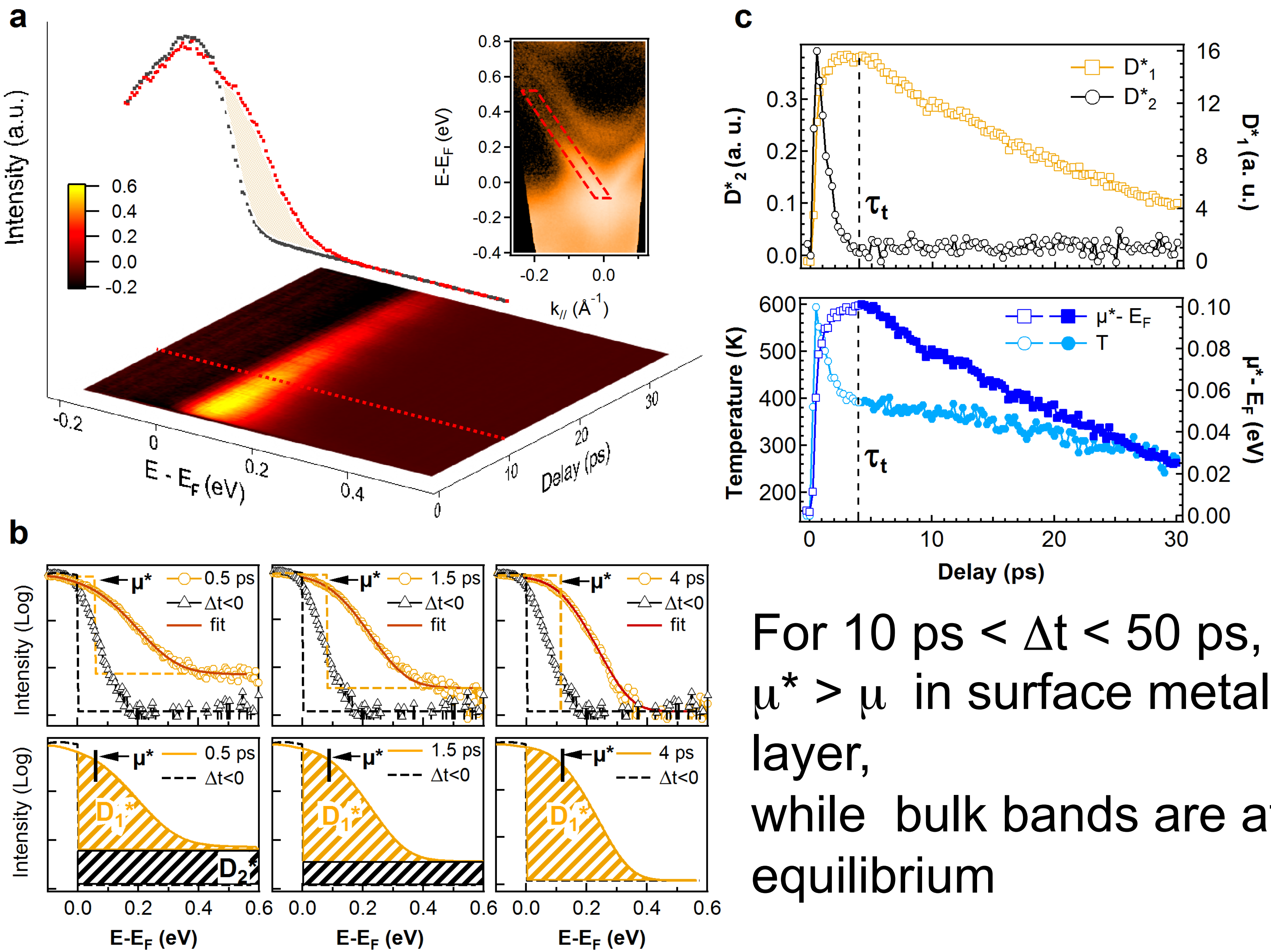
➔ Fermi Dirac distribution with $\mu^* > \mu$

Transient temperature, chemical potential in Bi_2Te_3



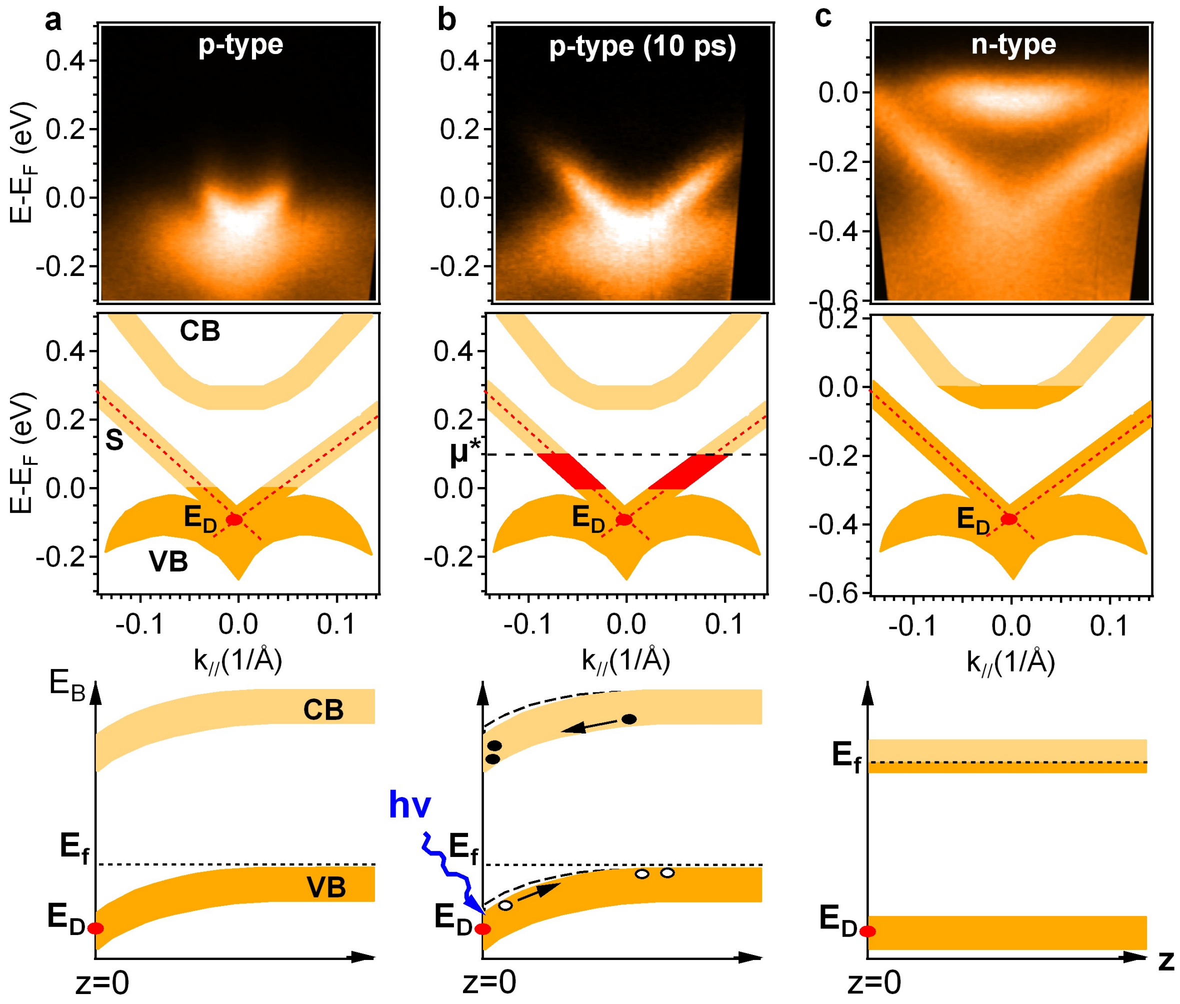
After 4 ps, real Fermi-Dirac distribution

« Hot » Dirac fermions : T* and μ*



For 10 ps < Δt < 50 ps,
μ* > μ in surface metallic layer,
while bulk bands are at equilibrium

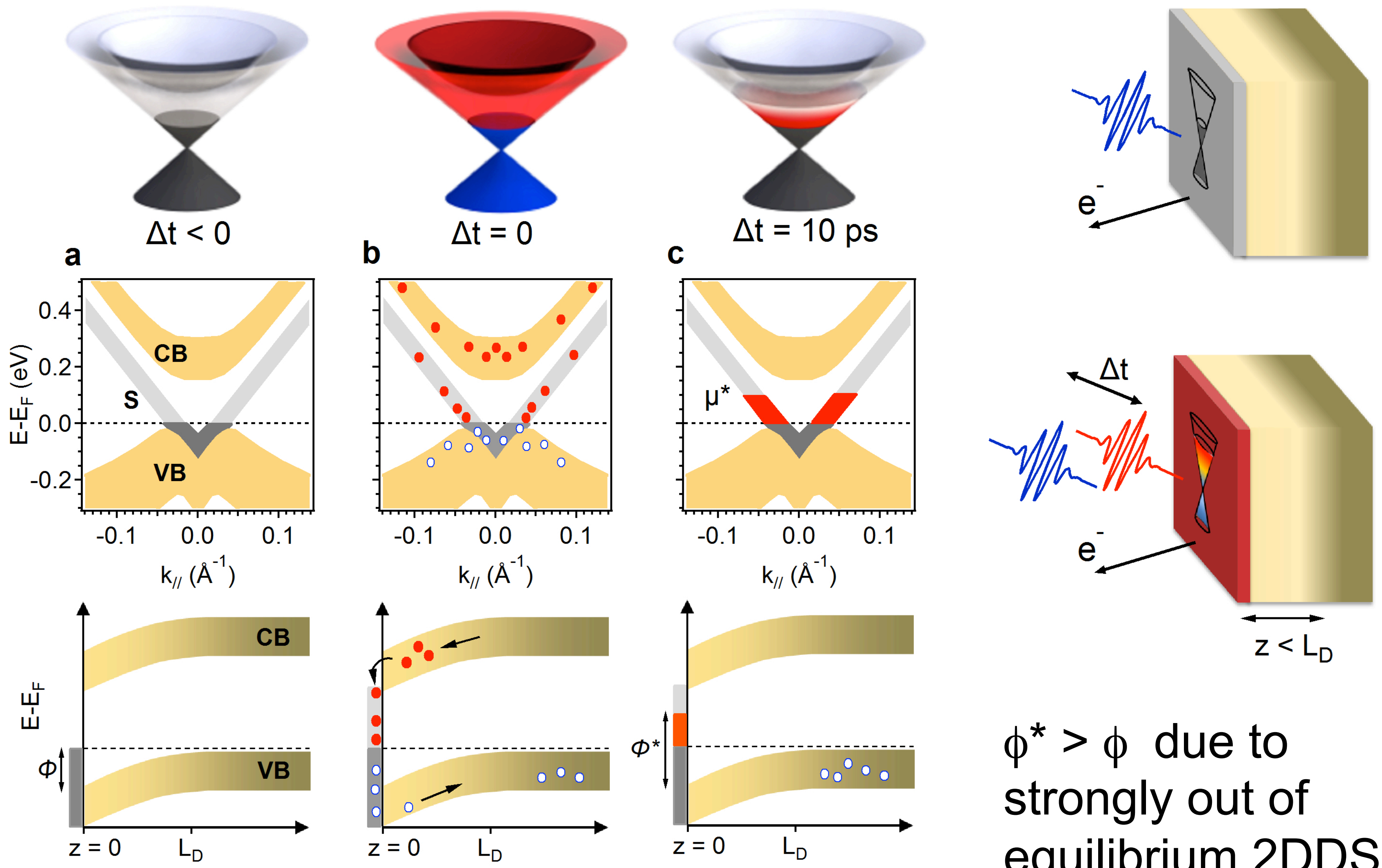
« Transient Topological Insulator »



For Δt > 10 ps photoexcited p-type looks like an n-type with no electrons in bulk conduction band

➔ « real TI* », Insulating bulk vs conducting surface in photoexcited state

Transient tuning of a nm-scale Schottky barrier



$\phi^* > \phi$ due to strongly out of equilibrium 2DDS

Conclusion and perspectives

➔ Dirac cone dynamics in Bi_2Te_3 : direct observation of inter- and intra-band scattering, electron-phonon coupling, hot electron relaxation

➔ Long time for Dirac cone relaxation, weak electron-phonon coupling

➔ Possibilty of creating a strong e-h asymmetry in Dirac cone

➔ Strongly out of equilibrium (μ^*=0.1 eV), long lived (50 ps) excited conducting system, impossible to obtain in a conventional metal

➔ Photoinduced tuning of a nanoscale Schottky barrier

➔ SEE POSTER Lama Khalil (Monday afternoon): continuing these studies on materials with reduced bulk conductivity

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