Dirac Plasmons in Topological Insulators

M. Autore

Department of Physics and INFN, Sapienza
University of Rome, Italy

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Acknowledgements

Terahertz Experiments

Marta Autore, Fausto D'Apuzzo, Flavio Giorgianni, Paola Di Pietro, Odeta Limaj, **Stefano Lupi**

Sapienza University and INFN, Rome

SAPIENZA UNIVERSITÀ DI ROMA

INFN Istituto Nazionale di Fisica Nucleare

Bi_2Se_3 film growth

Sean Oh, Matthew Brahlek

Rutgers University, New Jersey (USA)

RUTGERS

Plasmonic array Fabrication

Alessandra Di Gaspare, Valeria Giliberti, and Michele Ortolani

INFN, CNR-IFN, Sapienza University Rome (IT)

IFN Institute for Photonics and Nanotechnologies

High Magnetic Field Experiments

Hans Engelkamp

HFML Nijmegen (NL)

Theory

Javier Garcìa de Abajo, IQFR-CSIC (EE)

Marco Polini, CNR-Pisa (IT)

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Terahertz Experiments

arta Autore, Fausto D'Apuzzo, Flavio Giorgiann

Andrea Rov

Sapienza U

Bi

Se

Rutgers

Plasm

Alessan

INFN, CNR-

High Ma

d Nanotechnologies

FR-CSIC (SPAIN)

HFML Nijmegen, (NL)

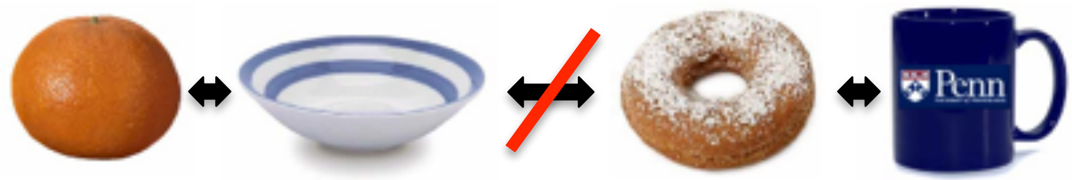
Marco Polini, CNR-Pisa (IT)

Outline

1. **Properties of 3D Topological Insulators;**
2. **Introduction to Plasmonics;**
3. **Observation of Terahertz Dirac Plasmons in TIs:**

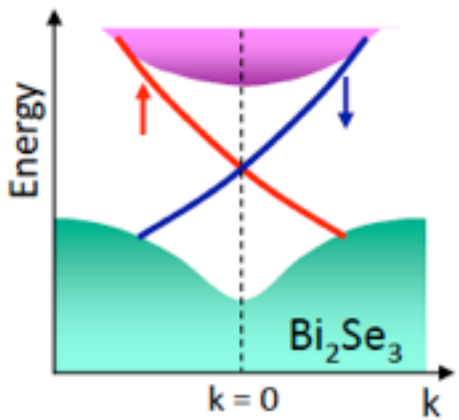
- TI Ribbon-Array Plasmons in a strong magnetic field;
- TI Ring-Array Plasmons;

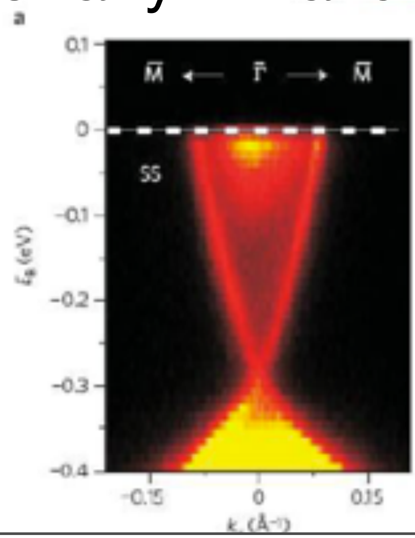
Physical properties of TIs



An insulator with non trivial topology cannot be smoothly transformed into a trivial insulator → there must be a **Quantum Phase Transition** at the boundary in which the insulating gap goes to zero

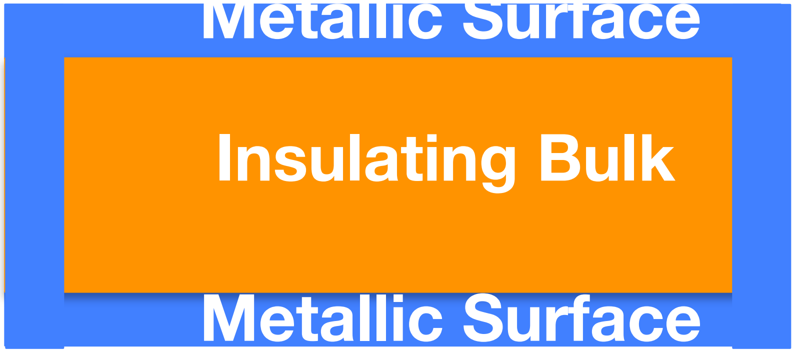
Presence of **metallic edge states** at the interface with vacuum or any trivial dielectric





Xia et al, Nature Physics 2009

Topological Insulators



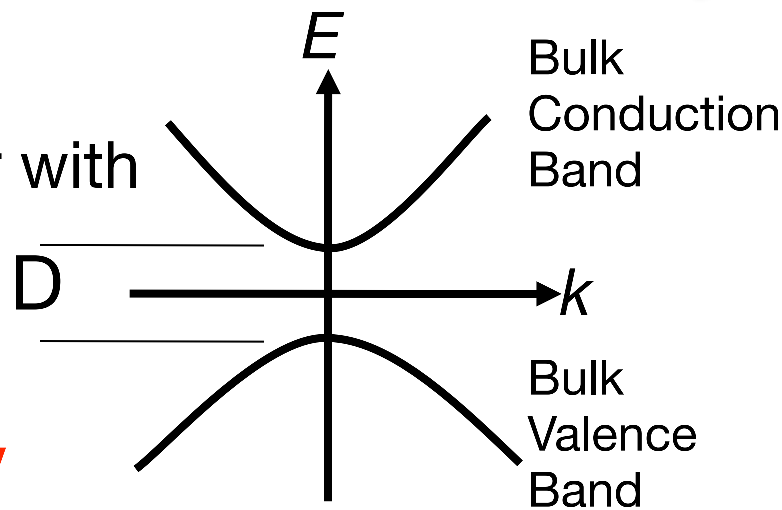
Topological Insulators

Bulk band insulator

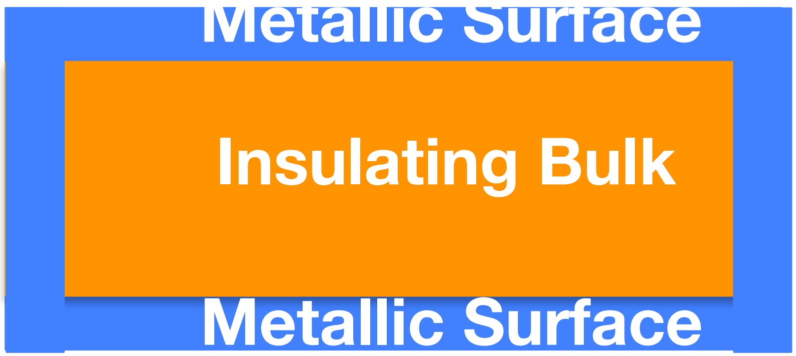
Gapped bulk insulator with massive particles

$E \approx k^2$

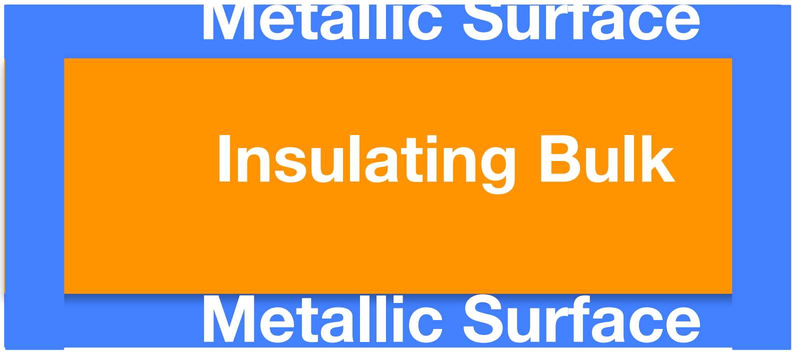
$\Delta \approx 300$ meV



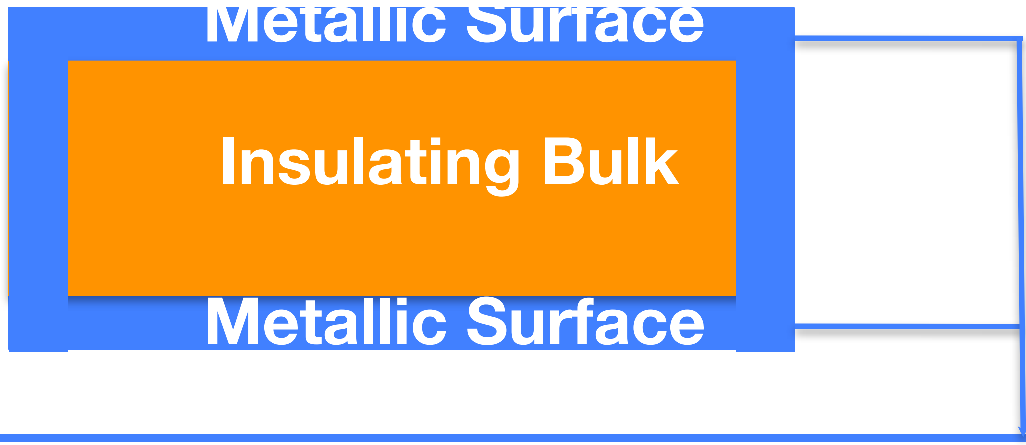
Topological Insulators



Topological Insulators



Topological Insulators

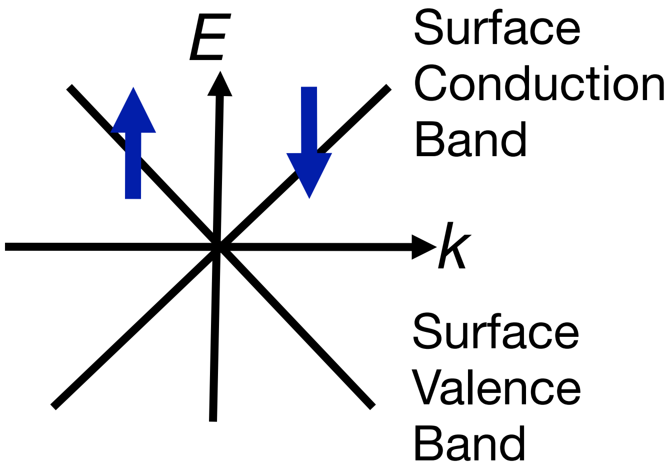


Gapless Dirac surface states

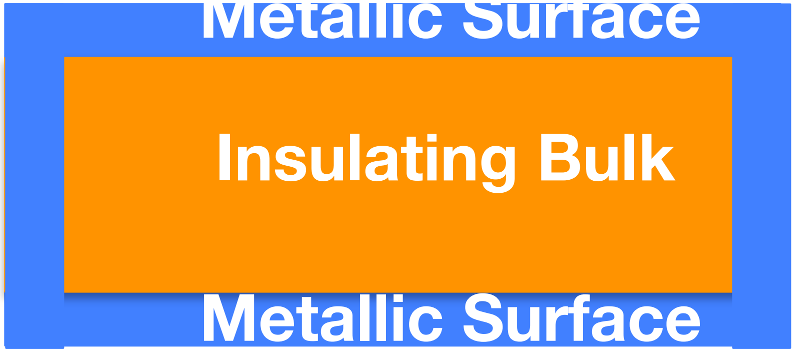
$E \approx k$

Properties:

Spin locked to Momentum;
Backscattering protection;
Superconductivity



Topological Insulators



TIs for novel applications

Topological Insulators
(Bi_2Se_3, Bi_2Te_3, ..)

- 2D intrinsic transport
- Spin-momentum locking
- $n_{2D} \geq 10^{13}$ cm^{-2}, $v_F \geq 10^7$ cm/s
- Dirac fermions: high tunability

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(Bi_2Se_3, Bi_2Te_3, ..)

2D intrinsic transport

Spin-momentum locking

$n_{2D} \geq 10^{13}$ cm^{-2}
$v_F \geq 10^7$ cm/s

Dirac fermions: high tunability

NOVEL APPLICATIONS

Spintronics

GMR valves, magnetic QU-bits

Plasmonics

Biosensing, light subwavelength confinement, THz sensors

Outline

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- TI Ribbon-Array Plasmons in a strong magnetic field;
- TI Ring-Array Plasmons;

Plasmons

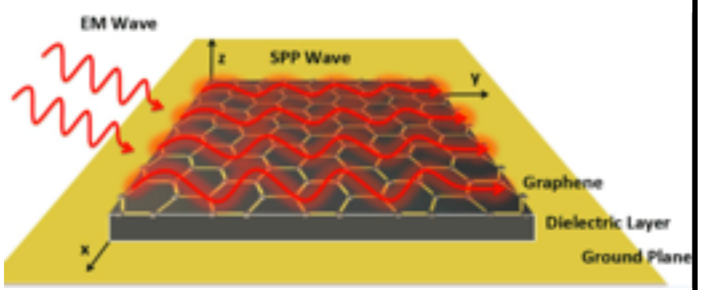
Plasma oscillations = density fluctuations of free-electrons

$\omega_p \propto k$

Plasmons on 2D electron systems

on 2DEG or graphene

$\omega_p \propto \sqrt{k}$



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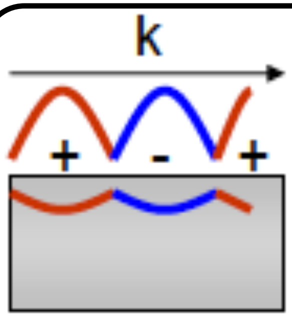

Plasmons at the interface between a metal and a dielectric can strongly interact with light forming propagating hybrid mode: Surface-Plasmon-Polariton

$$\omega_p \propto k$$

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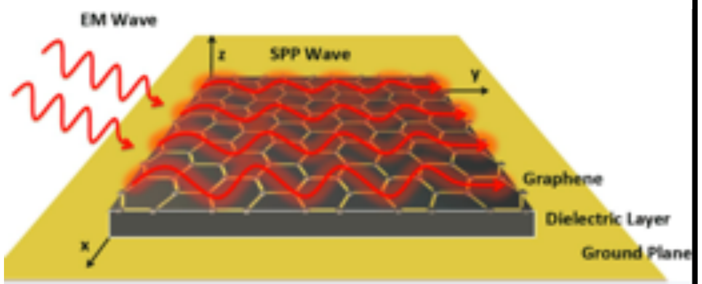
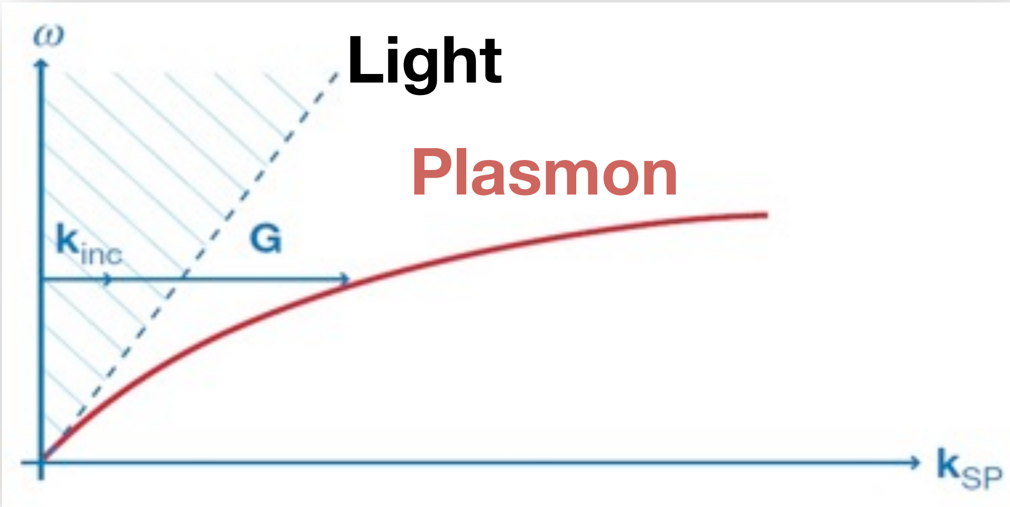


Light Excitation of Plasmons

Additional Wave-vector →micro/nano-structures



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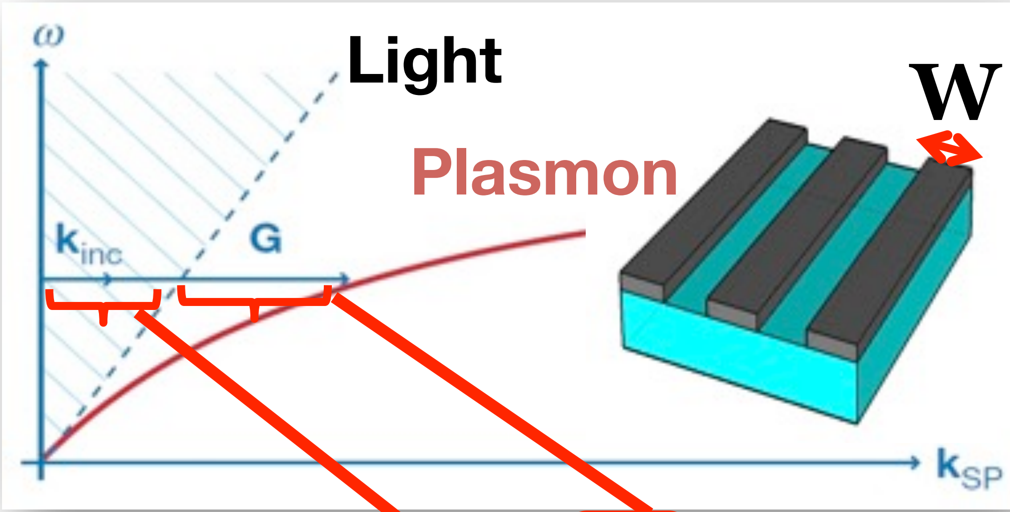

$$k_P = k_{light} + \frac{\pi}{W}$$

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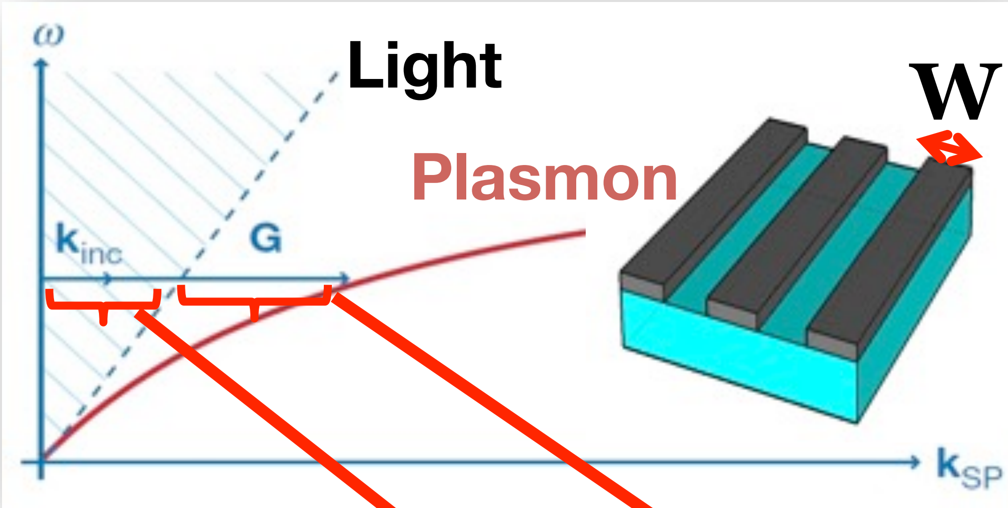
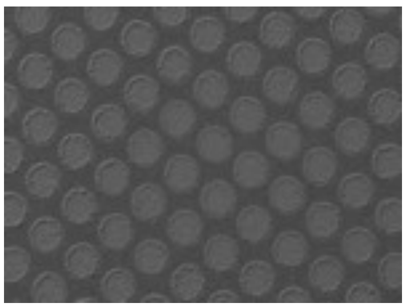


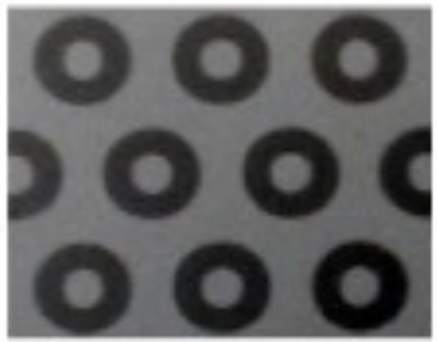
Ribbons

$$k_P = k_{light} + \frac{\pi}{W}$$

Disks



Rings



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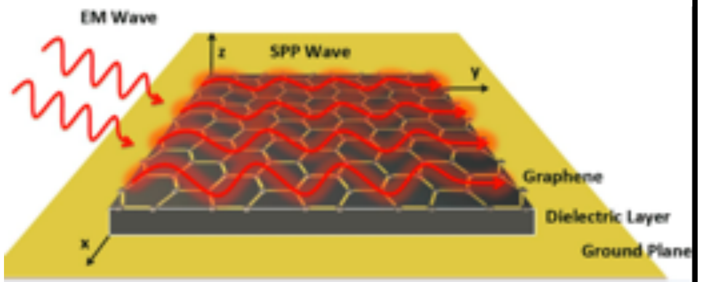
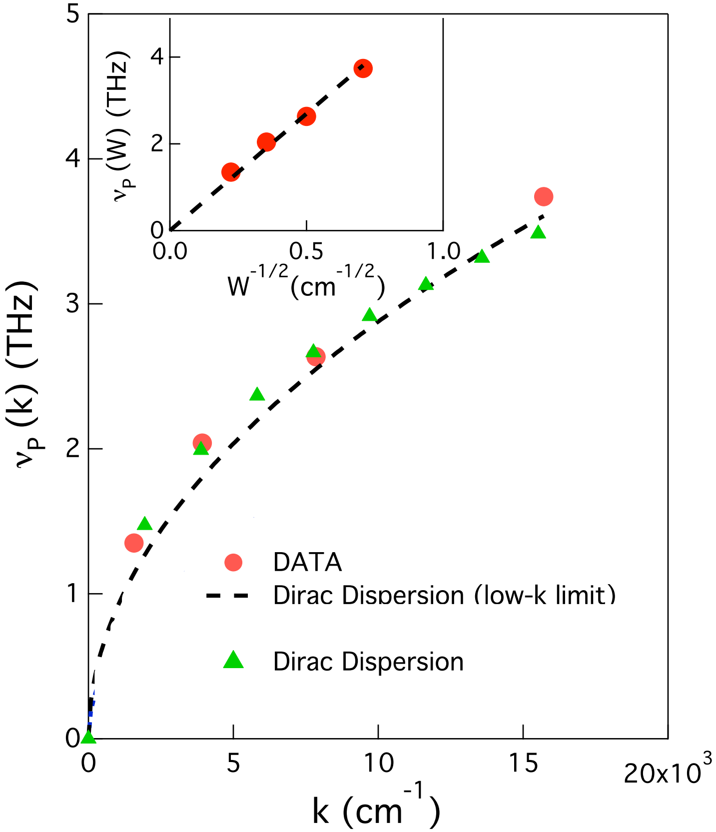


Bi_2Se_3 microribbon arrays



P. Di. Pietro *et al.*, Nature Nanotech. 8, 556 (2013)

Plasmons

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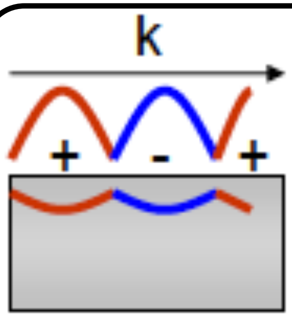

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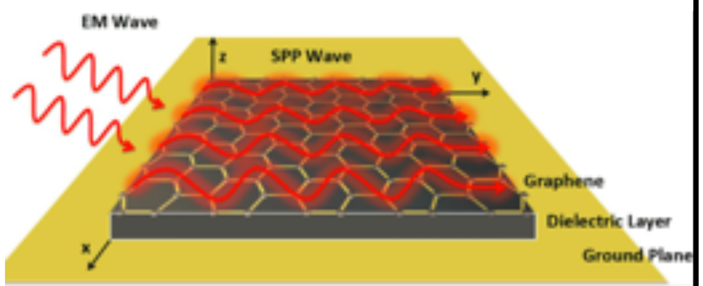
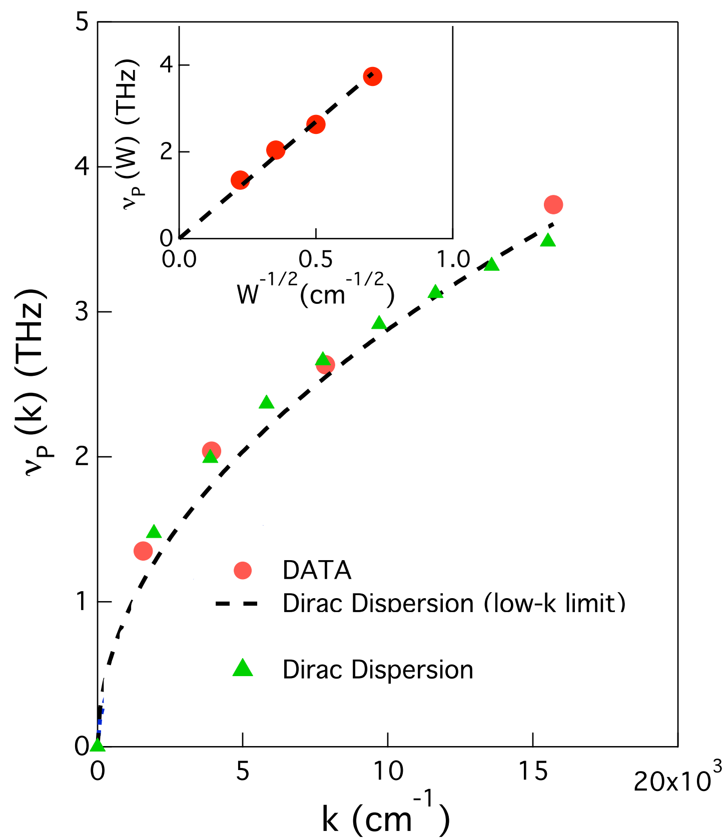


Bi_2Se_3 microribbon arrays



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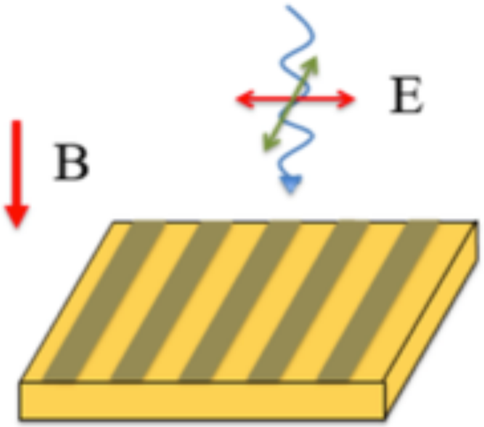
- TI Ring-Array Plasmons;

TI Ribbon-Plasmons in a strong magnetic field (I)

In Topological Insulators the cyclotron frequency is comparable
to the Plasmon frequency (for micrometric patterning)

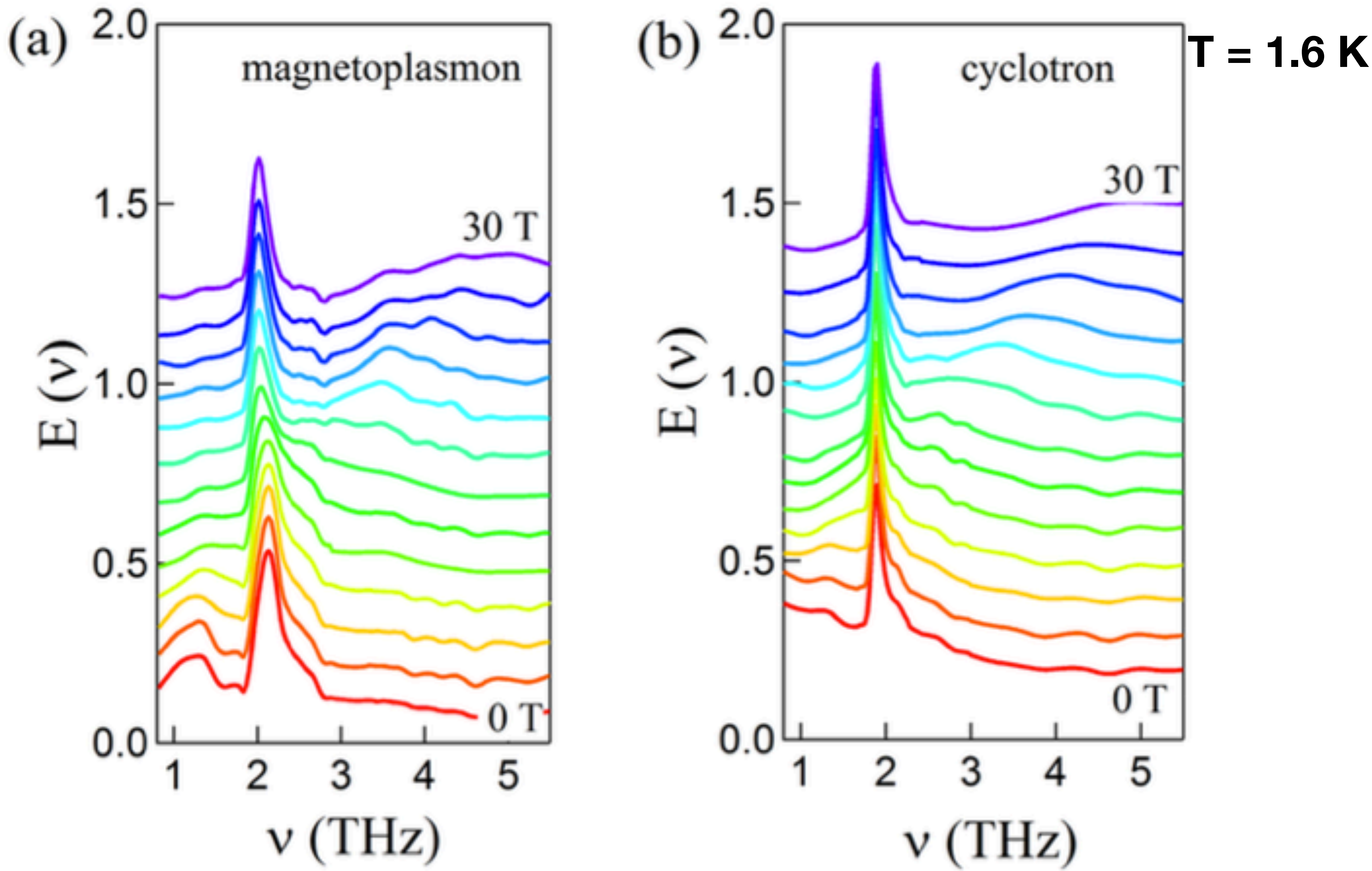
First observation of magnetoplasmons on TIs

Measure of the cyclotron mass



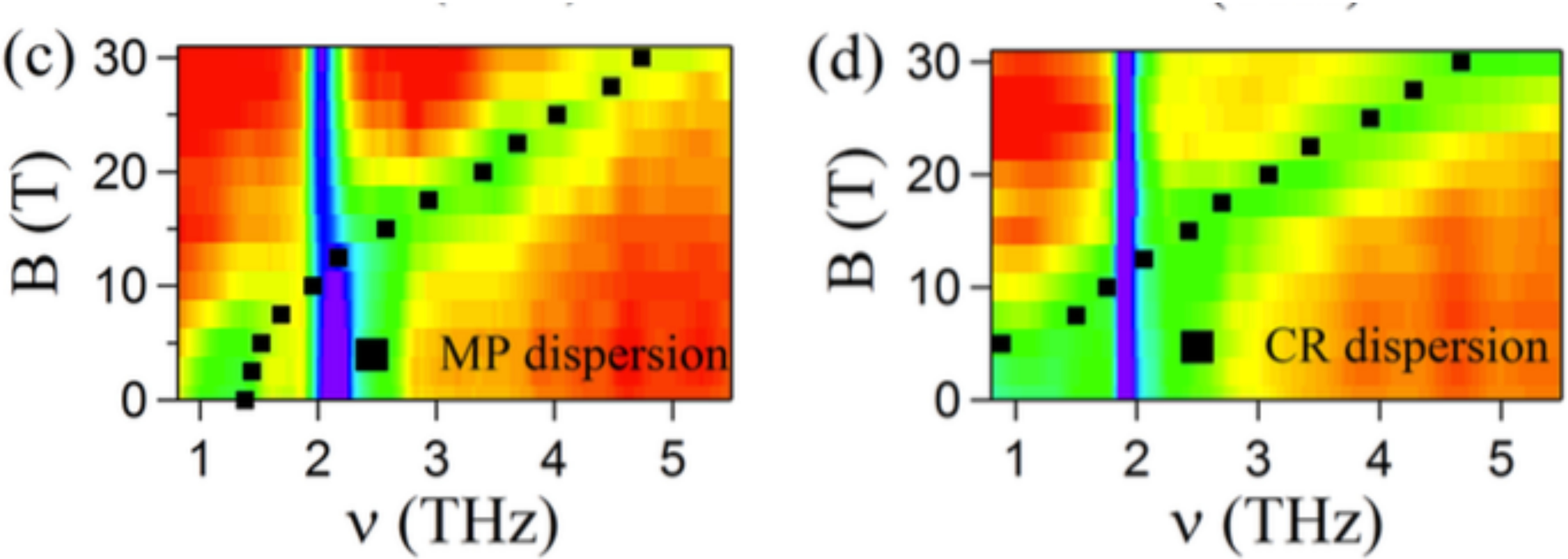
Terahertz Spectroscopy in Faraday configuration from
700 GHz to 7 THz at 1.2 K and from 0 to 30 T at HMFL-Nijmegen (NL) on Bi_2Se_3 ribbon arrays

TI Ribbon-Plasmons in a strong magnetic field (II)



M. Autore at al., *ACS Photonics* **2,** 1231–1235 (2015)

TI Ribbon-Plasmons in a strong magnetic field (III)



data fitted by Fano model

data fitted by Drude model in magnetic field

Magnetoplasmon frequency

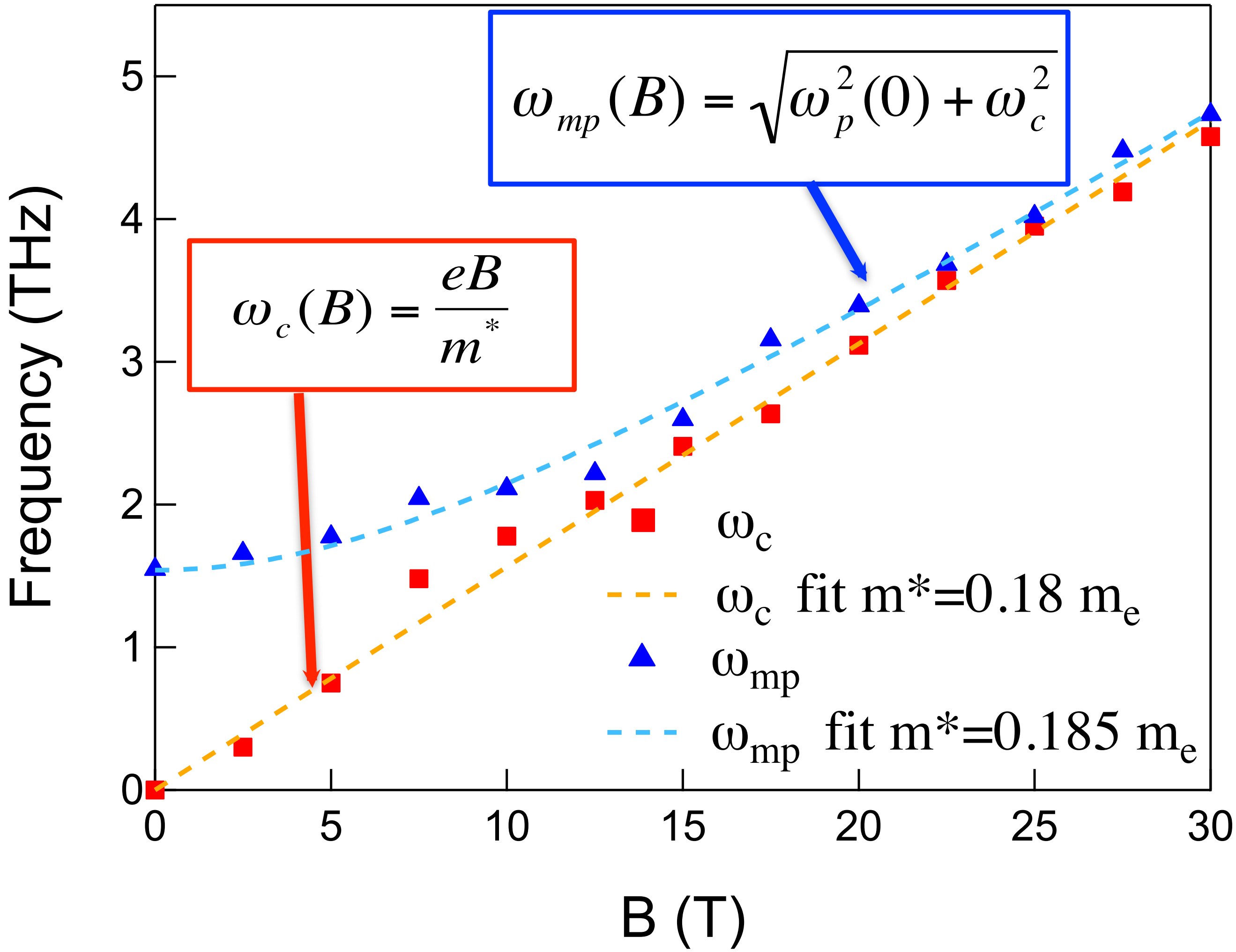
$$\omega_{mp}(B) = \sqrt{\omega_p^2 + \omega_c^2}$$

Cyclotron frequency

$$\omega_c = \frac{eB}{m^*}$$

M. Autore at al., *ACS Photonics* **2,** 1231–1235 (2015)

TI Ribbon-Plasmons in a strong magnetic field (IV)



M. Autore at al., *ACS Photonics* **2,** 1231–1235 (2015)

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ii) TI Ribbon-Array Plasmons in a strong magnetic field;
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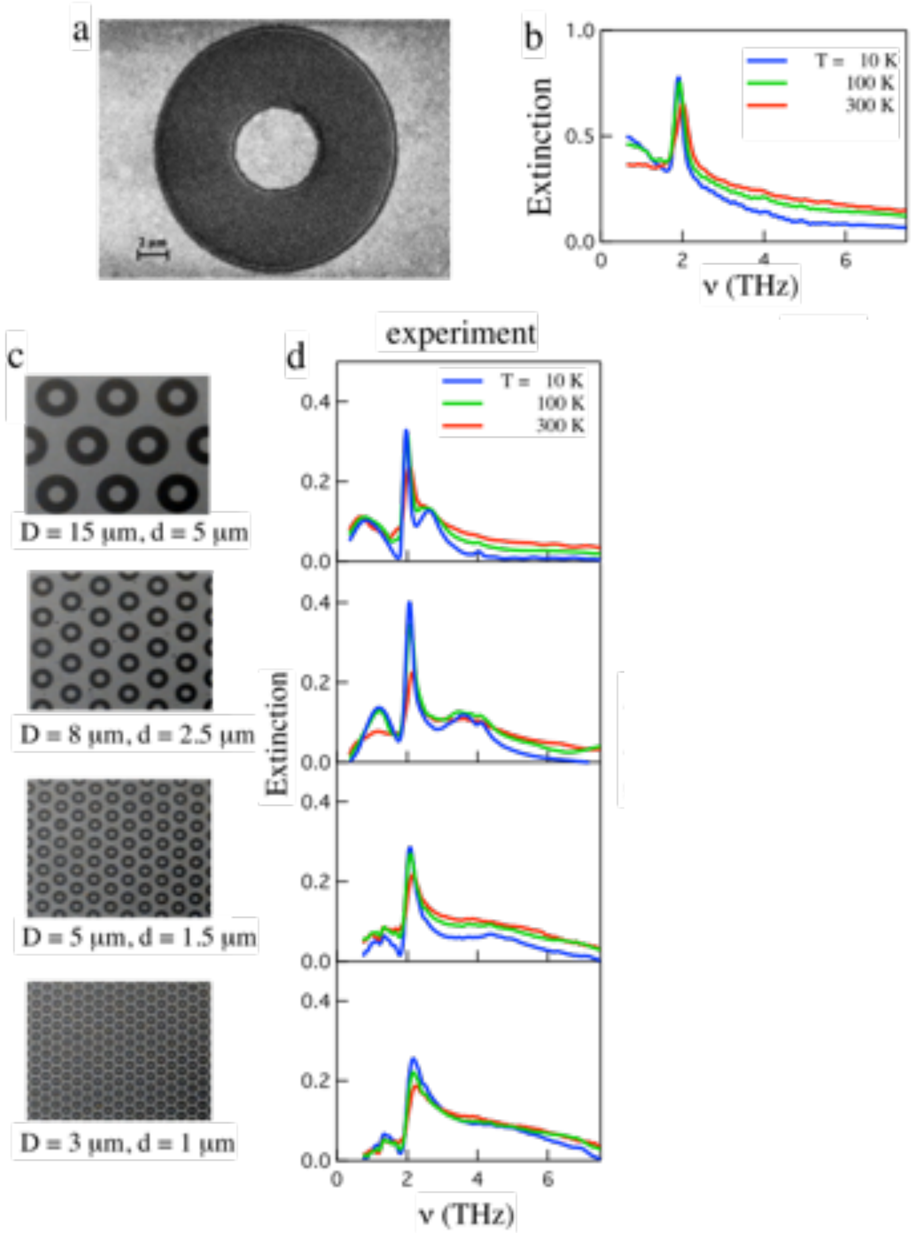
Plasmons in Bi_2Se_3 Ring-Arrays: data



Drude-Lorentz response for unpatterned samples

M. Autore et al., Adv. Opt. Mat. **3**, 9 (2015)

Plasmons in Bi_2Se_3 Ring-Arrays

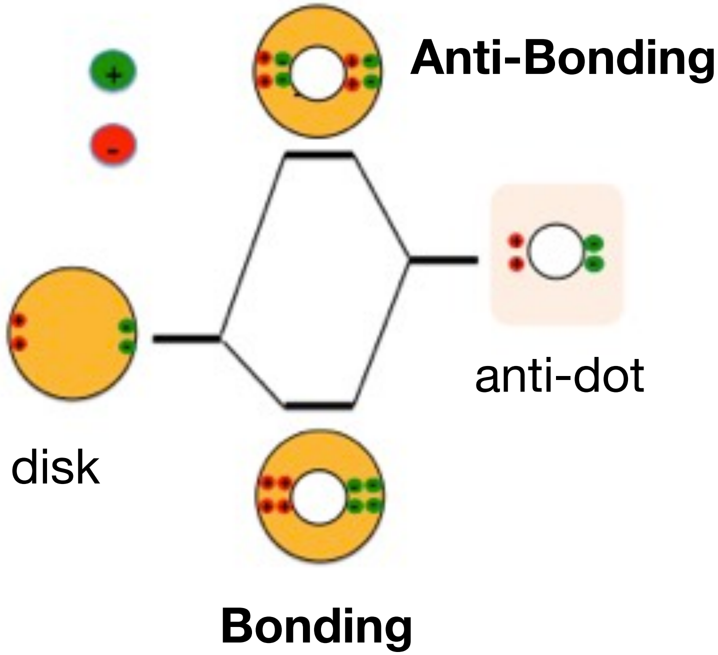

D = 15 μm, d = 5 μm


D = 8 μm, d = 2.5 μm


D = 5 μm, d = 1.5 μm


D = 3 μm, d = 1 μm

Plasmon-Plasmon hybridization



Plasmons in Bi_2Se_3 Ring-Arrays

Plasmon-Plasmon hybridization
+
Plasmon-Phonon hybridization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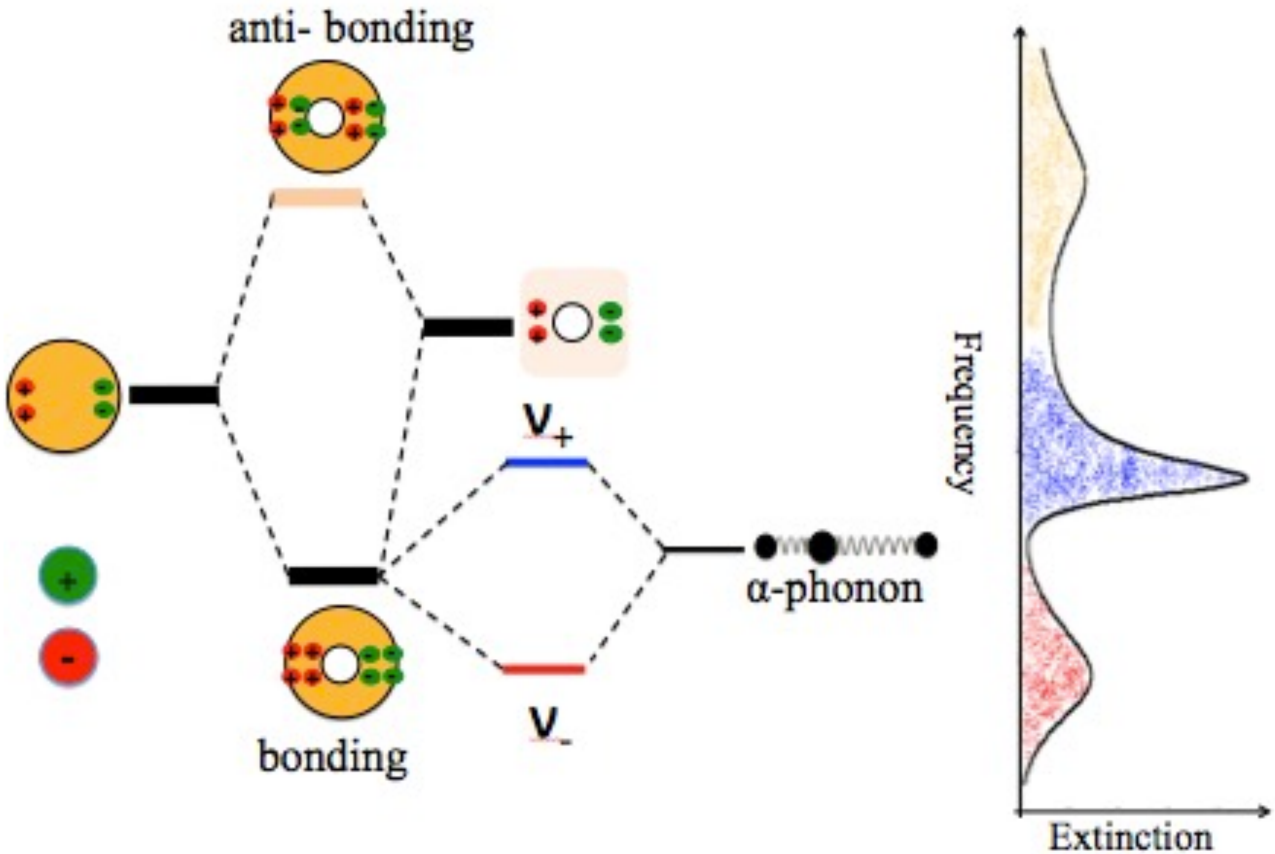
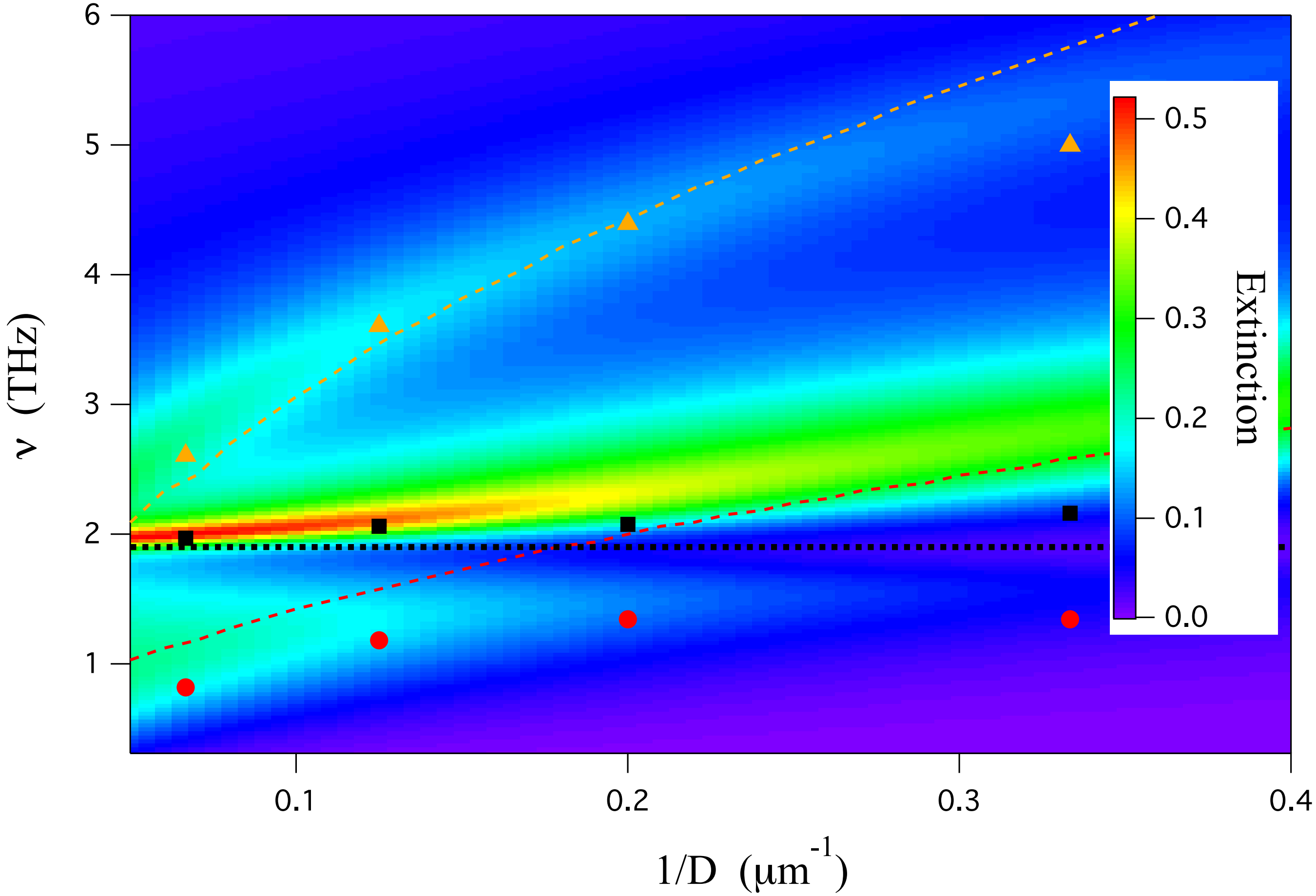


Plasmons in Bi_2Se_3 Ring Arrays: data vs model

(in collaboration with F. J. Garcìa de Abajo, ICFO Barcelona)



Bonding and antibonding plasmons if we artificially switch off the phonon

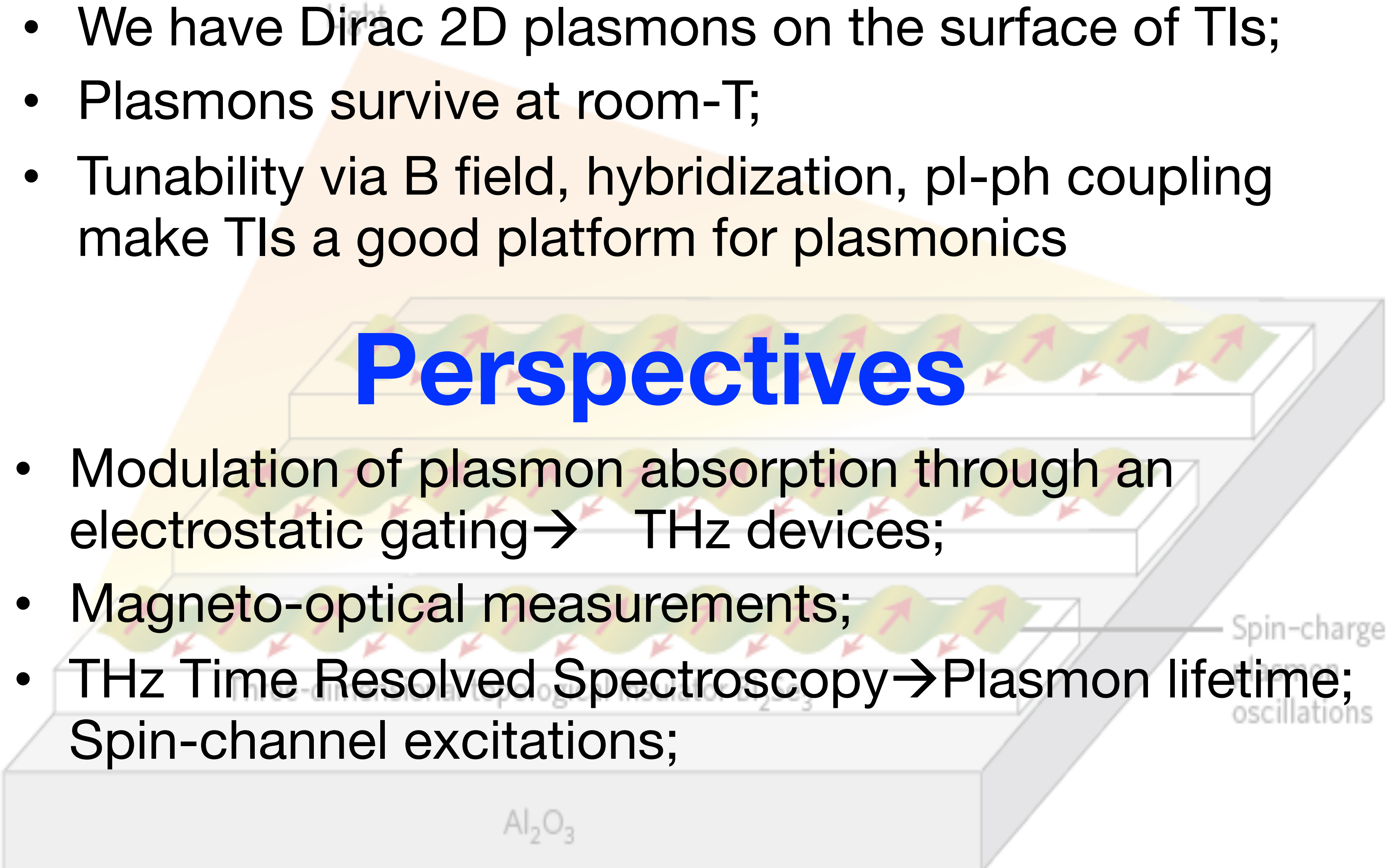
M. Autore et al., Adv. Opt. Mat. **3**, 9 (2015)

Conclusion

- We have Dirac 2D plasmons on the surface of TIs;
- Plasmons survive at room-T;
- Tunability via B field, hybridization, pl-ph coupling make TIs a good platform for plasmonics

Perspectives

- Modulation of plasmon absorption through an electrostatic gating→ THz devices;
- Magneto-optical measurements;
- THz Time Resolved Spectroscopy→Plasmon lifetime; Spin-channel excitations;



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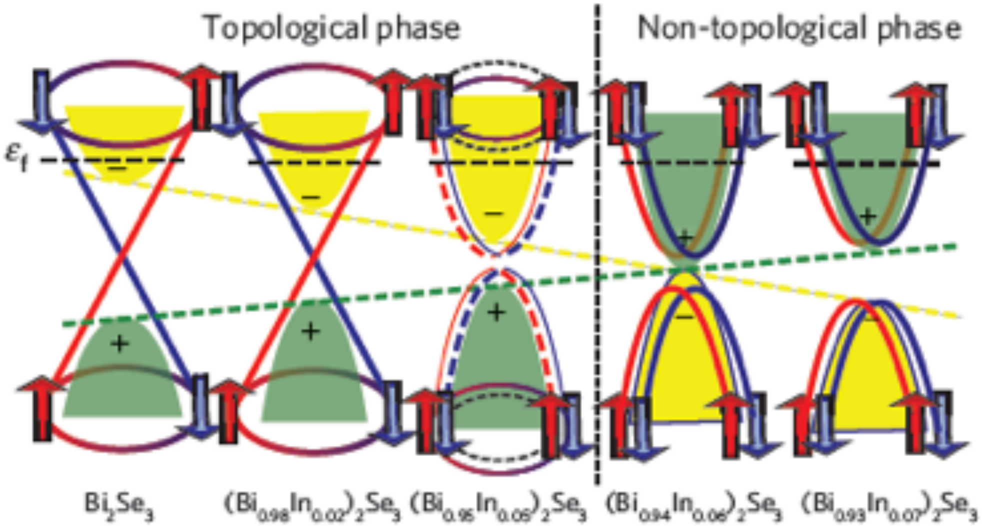
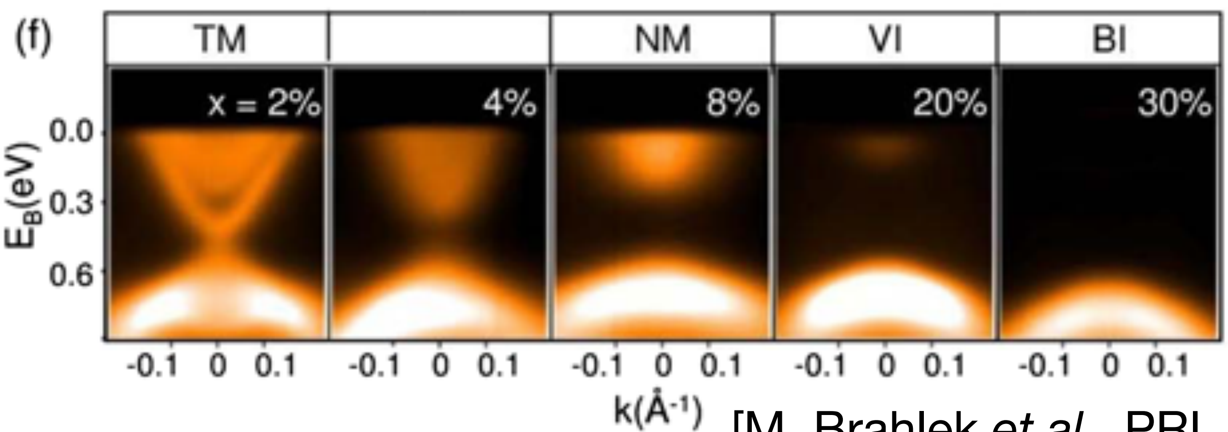
Thank you for your attention!

Collective excitations through Topological Phase Transition in $(Bi_{1-x}In_x)_2Se_3$ (I)

A Topological Phase Transition occurs between x=0.03 and x=0.07
[L. Wu *et al.*, Nature Phys. 9, 410 (2013)]



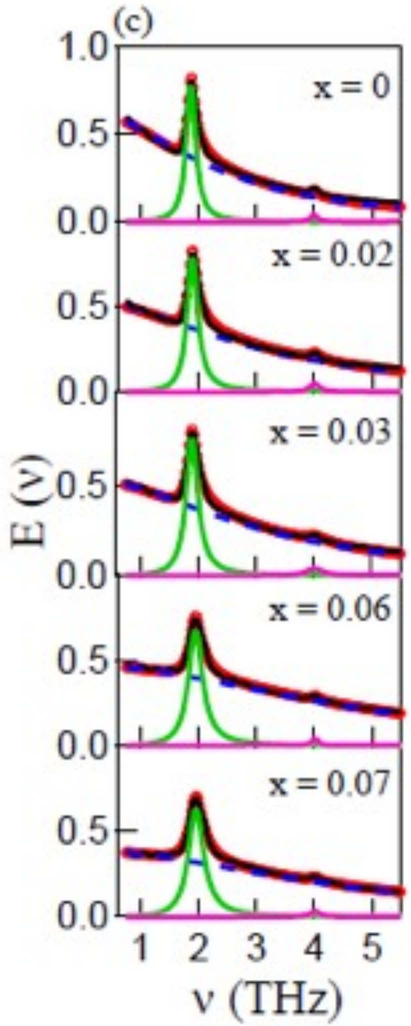
What happens to collective excitations through the transition?



[M. Brahlek *et al.*, PRL. 109, 186403 (2012)]

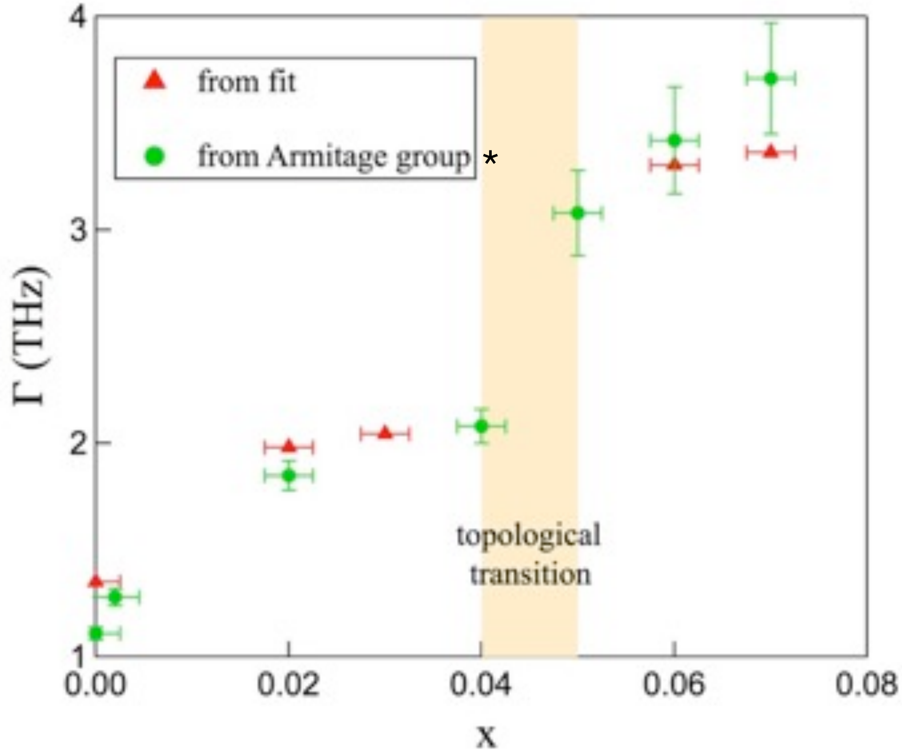
Collective excitations through Topological Phase Transition in $(Bi_{1-x}In_x)_2Se_3$ (II)

Firstly we studied single particle excitations in $(Bi_{1-x}In_x)_2Se_3$ thin films with several x values



Drude-Lorentz fits allowed us to extract the single particle scattering rate

*[L. Wu *et al.*, Nature Phys. 9, 410 (2013)]

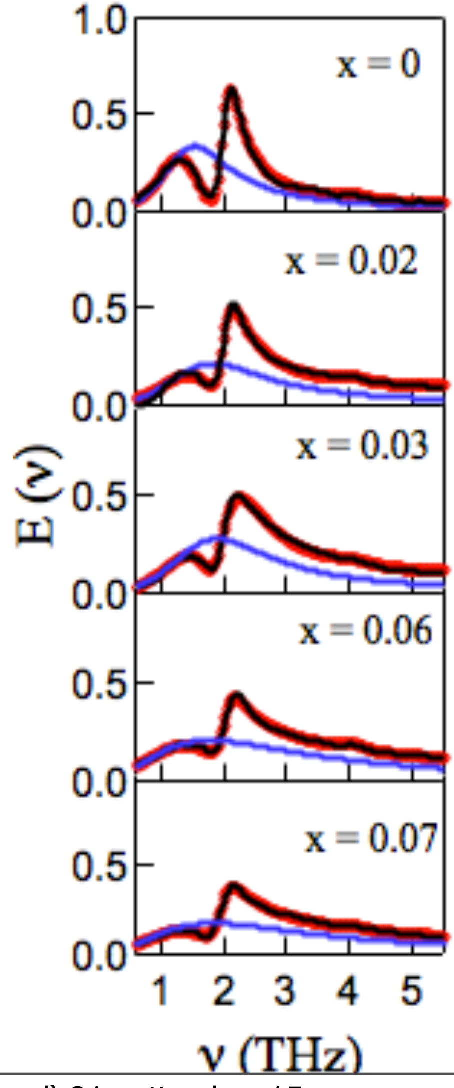


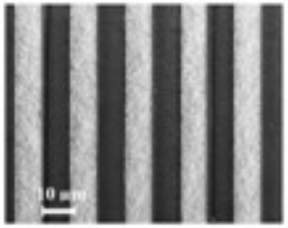
A sudden collapse in the single particle lifetime appears across the topological transition as a loss of topological protection

M. Autore *et al.*, submitted to NanoScale (2015)

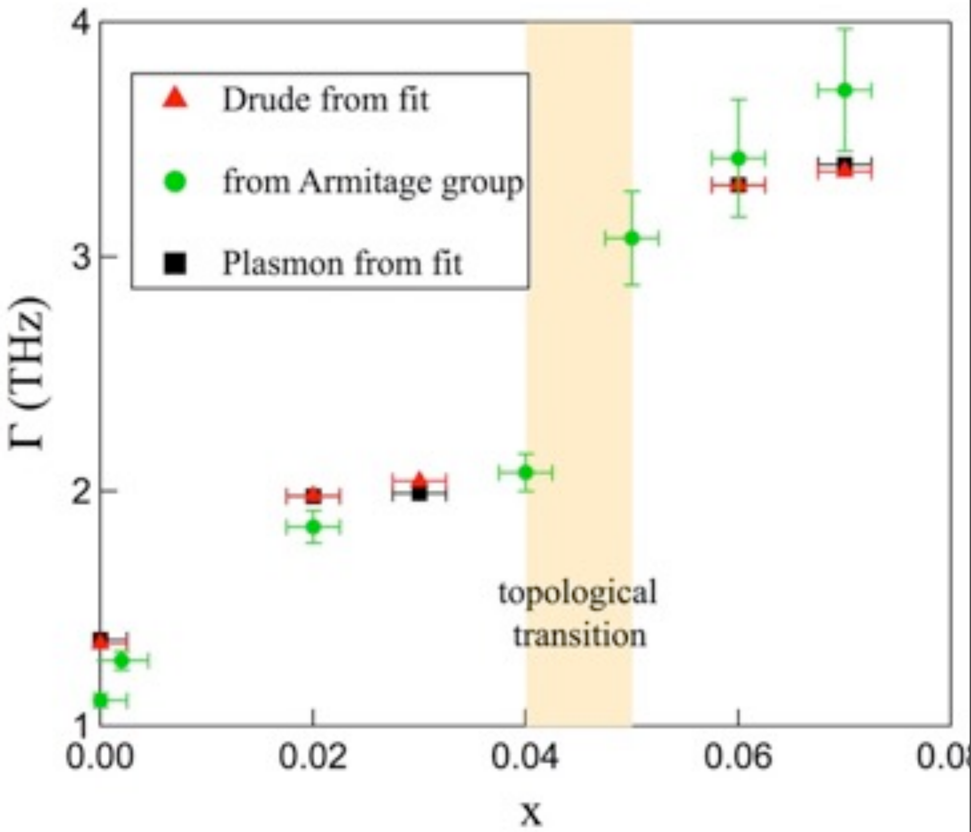
Collective excitations through Topological Phase Transition in $(Bi_{1-x}In_x)_2Se_3$ (II)

We studied plasmon excitations in ribbon arrays of $(Bi_{1-x}In_x)_2Se_3$ with W=8μm and several x values





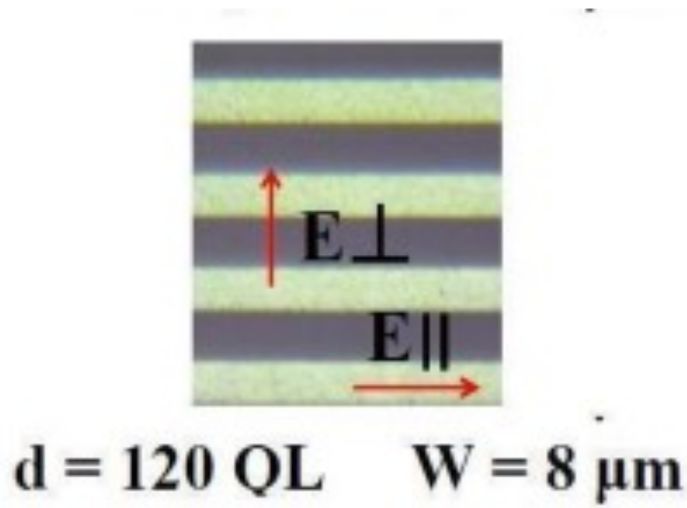
Fano fits allowed us to extract the plasmon scattering rate



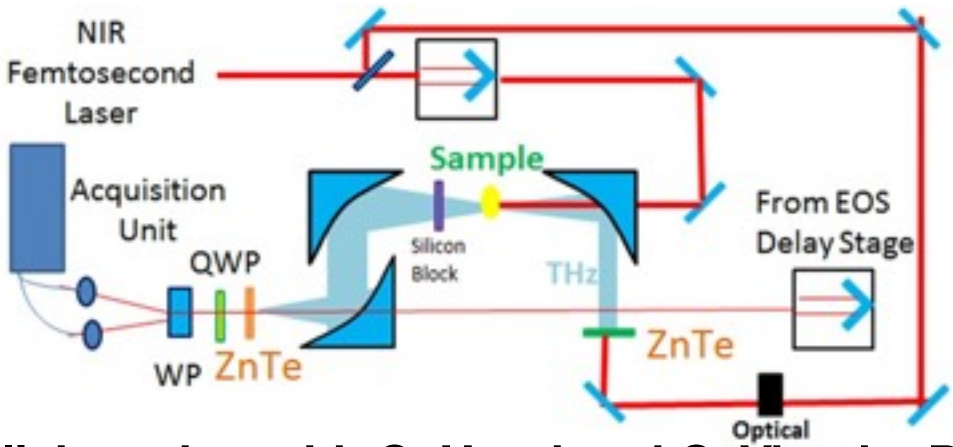
Same behavior as single particles
→ strong indication of topological protection of collective modes

M. Autore *et al.*, submitted to NanoScale (2015)

Time-Resolved THz dynamics of Dirac Plasmon in Bi2Se3 Topological Insulator



Optical-Pump THz-Probe

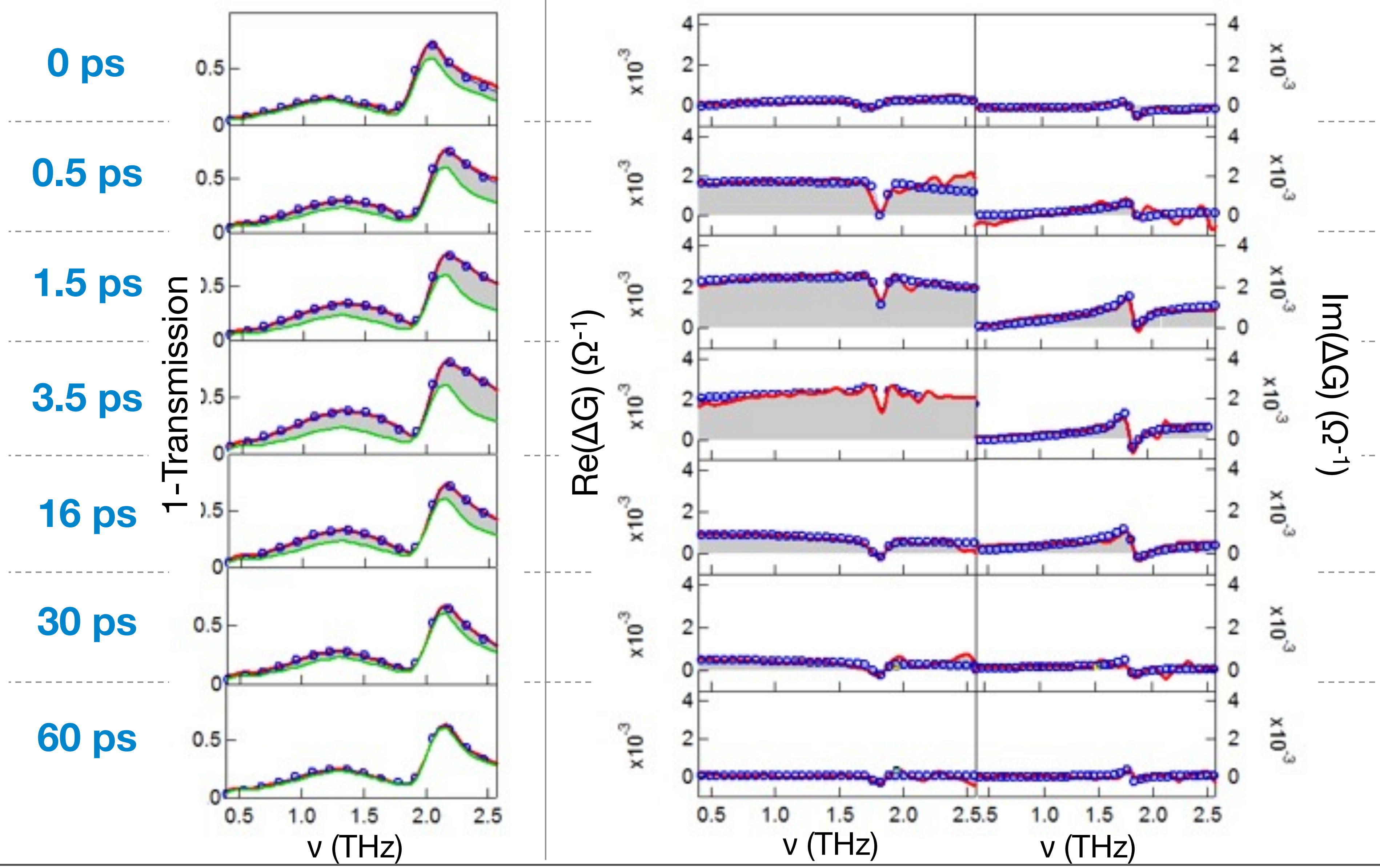


In collaboration with C. Hauri and C. Vicario, PSI (SW)

800 nm 650 uJ/cm^2 35 fs Pump – (0.4-2.5) THz Probe

Plasmon Dynamics

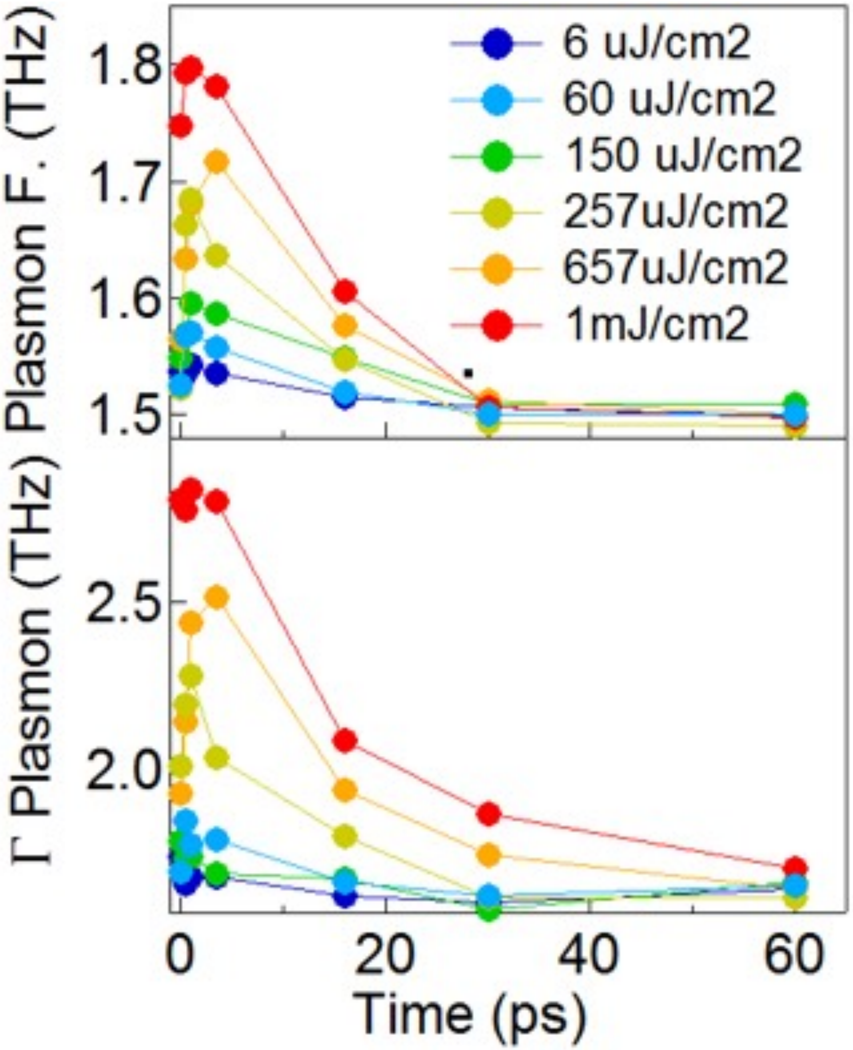
Single Particle Dynamics



Temporal Dynamics Vs Pump

Plasmon Dynamics

Evolution of Dirac Plasmon Parameters



Single Particle Dynamics

Evolution of Drude Parameters