

# Měření elektronových vlastností materiálů pomocí optické spektroskopie (elipsometrie a magneto-transmise)

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Ústav fyziky kondenzovaných látek

- Spektroskopická elipsometrie a dielektrická funkce
- Základní optické modely: Lorentzův a Drudeův model
- Studium feromagnetického stavu  $\text{La}_{0.7}\text{Sr}_3\text{CoO}_3$  pomocí elipsometrie
- Studium excitovaných stavů  $\text{LaCoO}_3$  pomocí femtosekundové elipsometrie
- Magneto-optická spektroskopie Landauových přechodů v topologických izolátorech  $\text{Bi}_2\text{Te}_3$

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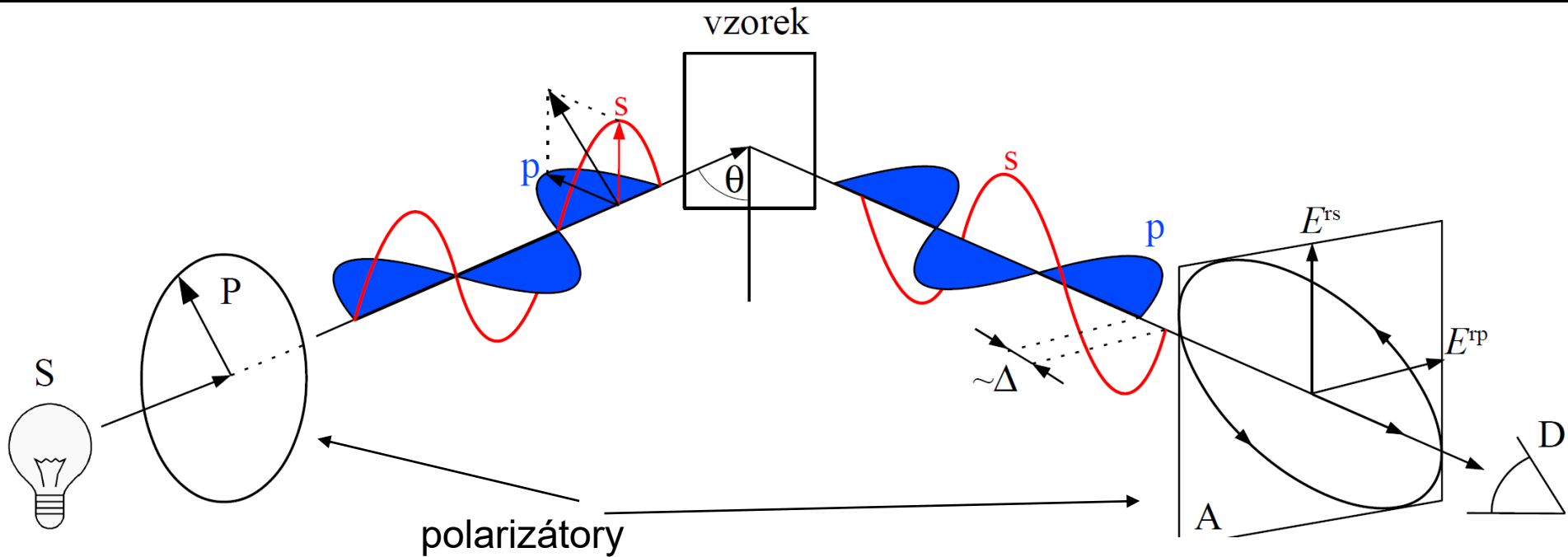
beamlines



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# Princip elipsometrie



- Elipsometrie je de facto interferenční experiment s komponentou elektrického pole rovnoběžnou (p) a kolmou (s) k rovině dopadu.

## Měřené veličiny v elipsometrii:

- úhel pootočení elipsy  $\Psi$
- elipticita  $\Delta$

$\Rightarrow$  n,k nebo  $\epsilon_1, \epsilon_2$   
bez dalších předpokladů

# základní rovnice elipsometrie

Definice elipsometrických úhlů  $\Psi$  a  $\Delta$ :  $\rho = \frac{r_p}{r_s} = \tan \Psi e^{i\Delta}$

Fresnelovy koeficienty:

$$r_p = \frac{N_2 \cos \theta_1 - N_1 \cos \theta_2}{N_1 \cos \theta_2 + N_2 \cos \theta_1} \quad r_s = \frac{N_1 \cos \theta_1 - N_2 \cos \theta_2}{N_1 \cos \theta_1 + N_2 \cos \theta_2}$$

Snellův zákon:  $N_1 \sin \theta_1 = N_2 \sin \theta_2$

Index lomu okolí:  $N_1 = \sqrt{\epsilon_a}$       Index lomu vzorku:  $N_2 = \sqrt{\epsilon_s}$

Inverzí výše uvedených rovnic obdržíme v případě polonekonečného izotropního vzorku explicitní analytický výraz pro dielektrickou funkci (jak její reálnou tak i imaginární část):

$$\epsilon_s(\Psi, \Delta) = \epsilon_a \sin^2 \theta_1 \left( 1 + \tan^2 \theta_1 \left( \frac{1 - \rho(\Psi, \Delta)}{1 + \rho(\Psi, \Delta)} \right)^2 \right)$$

shrnutí: ze dvou měřených veličin  $\Psi$  a  $\Delta$  určíme dvě veličiny  $\epsilon_1$  a  $\epsilon_2$

# Absorpce- reálná část optické vodivosti

Optická vodivost se vztahuje k dielektrické funkci jako  $\sigma(\omega) = -i\omega\varepsilon_0(\varepsilon(\omega) - 1)$

Je to komplexní funkce:  $\sigma(\omega) = \sigma_1(\omega) + i\sigma_2(\omega)$

- Reálná část vodivosti  $\sigma_1(\omega) = \omega\varepsilon_0\varepsilon_2(\omega)$ , je úměrná absorpci elektromagnetické energie
- $\sigma_1(\omega=0) = \sigma_{DC}$

•  $\sigma_1$  je vázaná sumačním pravidlem  $\int_0^{\infty} \sigma_1(\omega) d\omega = \frac{\pi n q^2}{2\varepsilon_0 m} = \text{constant}$

- Integrál z  $\sigma_1(\omega)$  přes široký frekvenční interval je proporční náboji který záření absorbuje.

# Lorentzův oscilátor

Newtonova rovnice harmonicky buzeného mechanického oscilátoru:

$$m \frac{d^2 x(t)}{dt^2} = -k x(t) - m\gamma \frac{dx(t)}{dt} + qE_0 e^{-i\omega t}$$

Řešení:

$$x_0(\omega) = \frac{F}{\omega_0^2 - \omega^2 - i\omega\gamma}$$

$$\omega_0 = \sqrt{\frac{k}{m}}, \quad F = \frac{qE_0}{m}$$

polarizace je hustota dipólového momentu

$$P(\omega) = \sum_j n q x_{0,j}(\omega) \quad n: \text{koncentrace}$$

z definice dielektrické funkce:

$$\varepsilon(\omega) = 1 + \frac{P(\omega)}{\varepsilon_0 E(\omega)} = 1 + \sum_j \frac{\omega_{pl,j}^2}{\omega_{0,j}^2 - \omega^2 - i\omega\gamma_j}$$

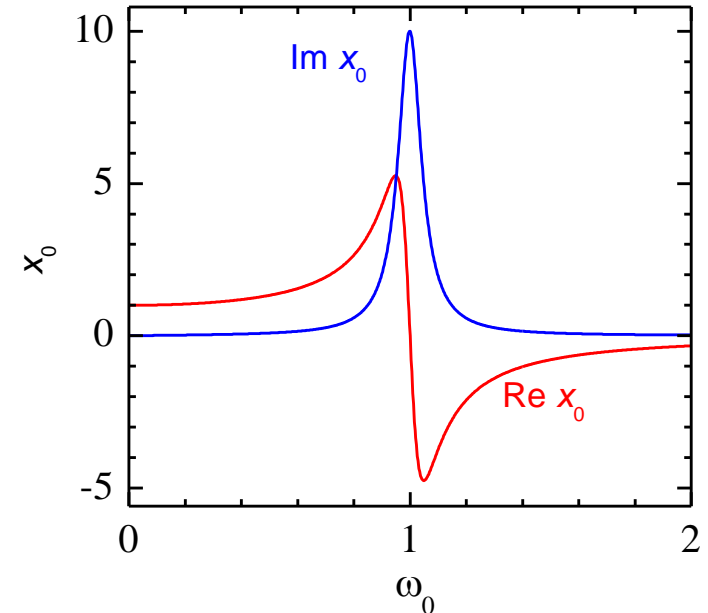
plasmová frekvence:

$$\omega_{pl,j} = \sqrt{\frac{q_j^2 n_j}{\varepsilon_0 m_j}}$$

příspěvek vysokofrekvenčních přechodů lze nejhruběji aproximovat konstantou:

$$\varepsilon(\omega) = \varepsilon_\infty + \sum_j \frac{\omega_{pl,j}^2}{\omega_{0,j}^2 - \omega^2 - i\omega\gamma_j}$$

- dielektrická funkce nezávislých Lorentzových oscilátorů. Typicky dobře funguje pro fonony. Drudeův model kovů dostaneme dosazením  $\omega_0=0$



# Drudeova formule

- odezvu volných nosičů náboje získáme pro  $\omega_0=0$

$$\varepsilon(\omega) = \varepsilon_\infty - \frac{\omega_{pl}^2}{\omega(\omega + i\gamma)}$$

plasmová frekvence  $\omega_{pl} = \sqrt{\frac{q^2 n}{\varepsilon_0 m^*}}$

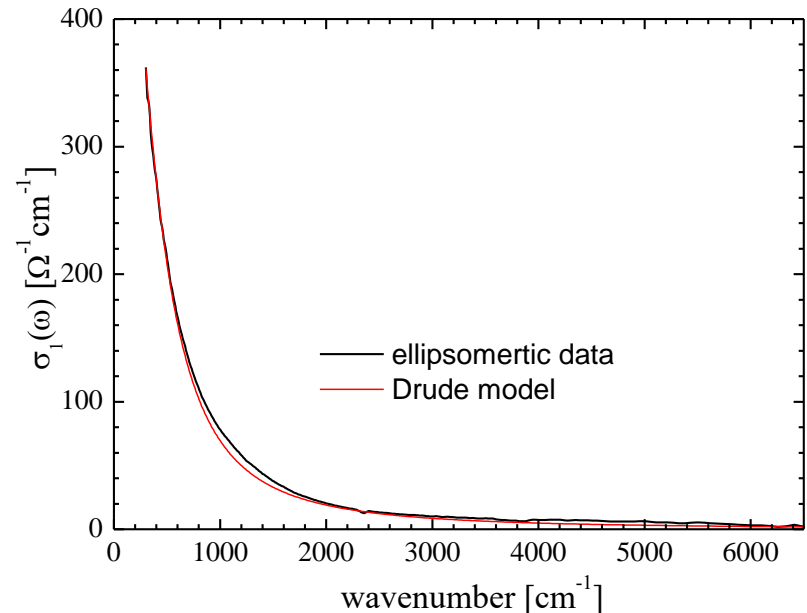
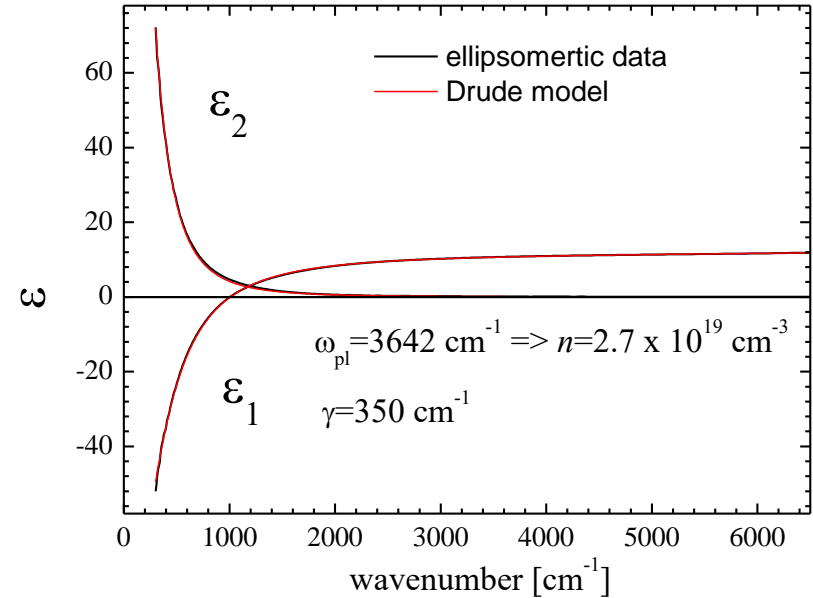
závisí na koncentraci nositelů  $n$  a na jejich efektivní hmotnosti  $m^*$

$\varepsilon_1$  prochází nulou (pro  $\gamma \sim 0$ ) pro

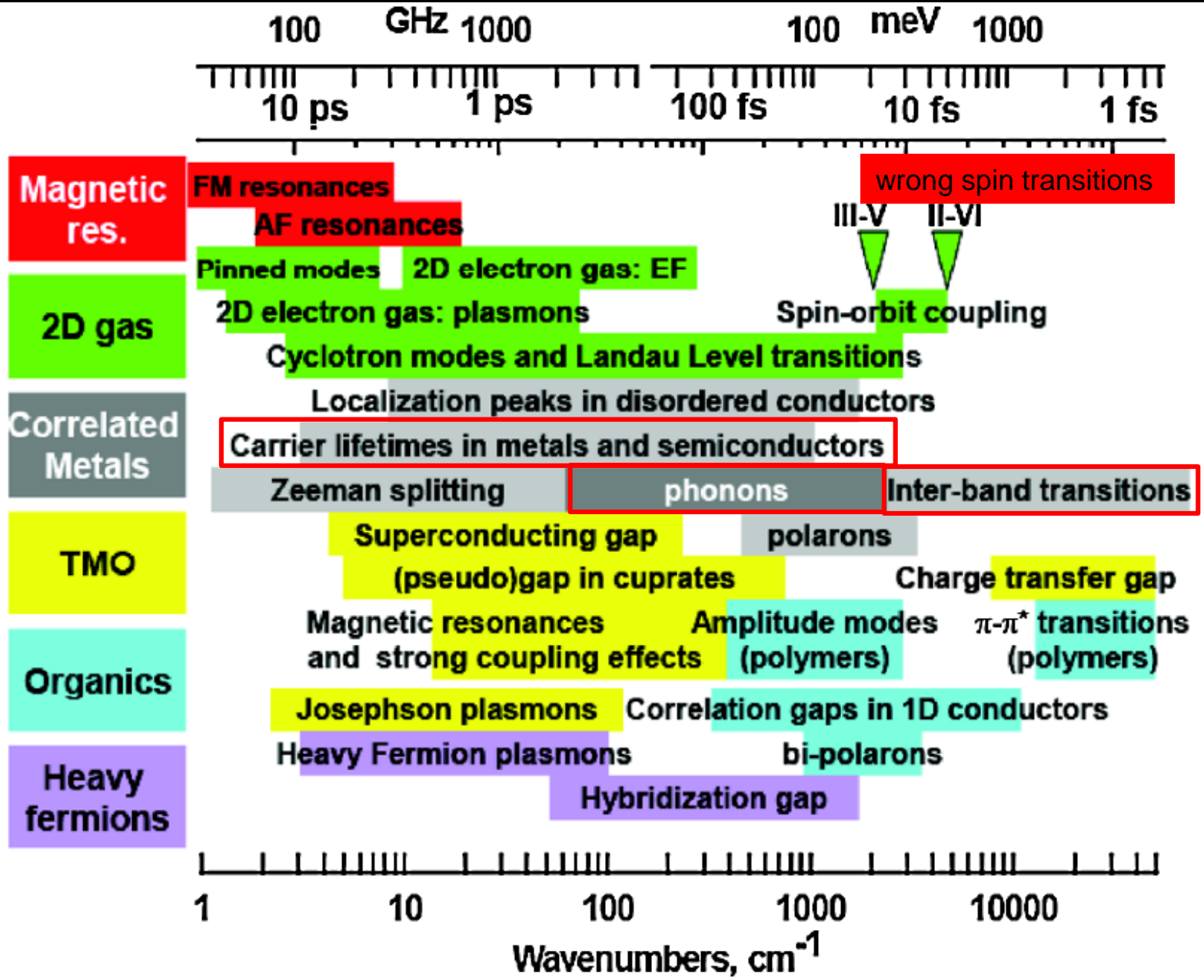
$$\omega = \frac{\omega_{pl}}{\sqrt{\varepsilon_\infty}}$$

pro  $\varepsilon_\infty = 1$  je to přímo  $\omega_{pl}$ . Na této frekvenci se v látce propaguje longitudinální plasmon, proto se této frekvenci říká plasmová.

## Ukázka dielektrické funkce n-dopovaného křemíku



# Opticky aktivní excitace mezi THz a ultrafialovým oborem





# Equilibrium ellipsometry at CEITEC Nano



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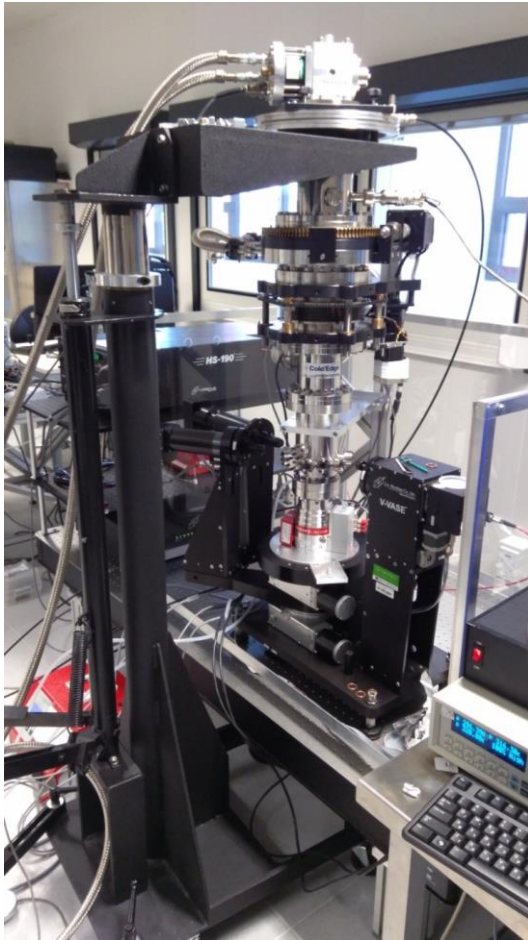
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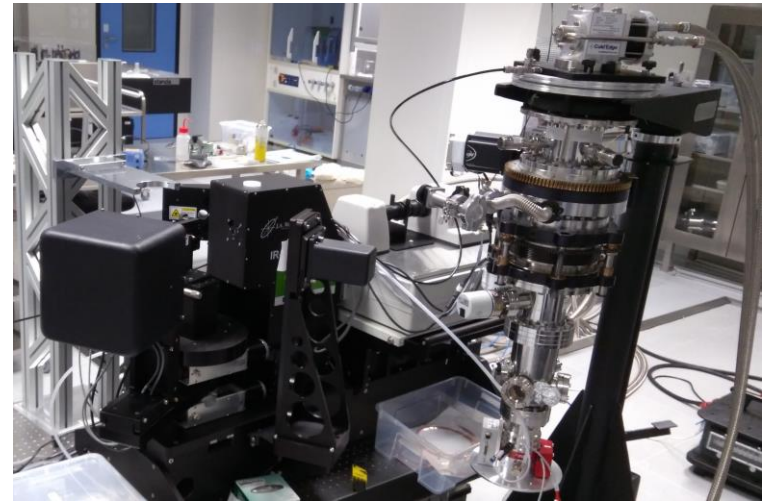
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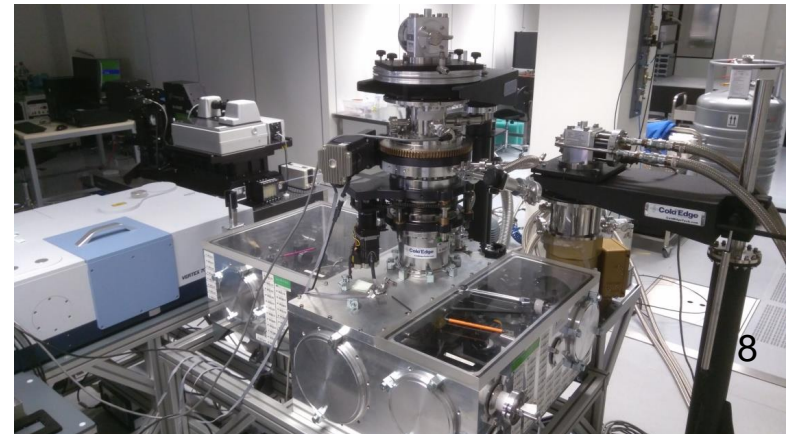
Woollam VASE, NIR-UV range  
He closed-cycle cryostat 7-400 K



Woollam IR-VASE, mid infrared range



far-infrared (50-700  $\text{cm}^{-1}$ ) ellipsometer

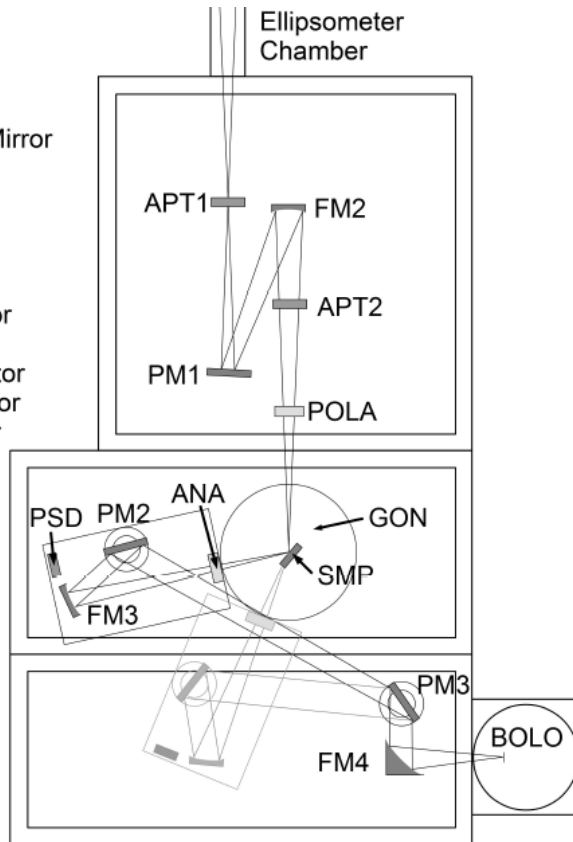




# Elipsometr pro vzdálenou infračervenou oblast v CEITECu

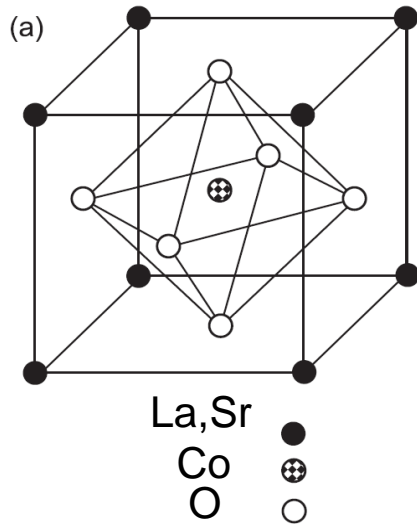
- jen asi 4 přístroje podobného typu na světě
- kryostat s uzavřeným cyklem helia 7-400 K
- rozhraní s ultra-nízkými vibracemi pro ods stranění vlivu vibrací
- motorizovaný goniometr s rozlišením  $0.01^\circ$
- automatizované měření ~15 teplot za 24 hodin
- detektor - 4.2K (a nově 1.6 K) bolometr

ANA - Analyzer  
APT1,2 - Aperture  
BMS - Beam Splitter  
BOLO - Bolometer  
FM1,3,4 - Parabolic Mirror  
FM2 - Elliptical Mirror  
GLB - Glow Bar  
GON - Goniometer  
HG - Mercury Lamp  
LAS - Alignment Laser  
PM1,2,3 - Plane Mirror  
POLA - Polarizer  
PSD - Position Detector  
RM - Removable Mirror  
SMP - Sample Holder  
W - Tungsten Lamp



# Optická odezva feromagnetických kobaltátů

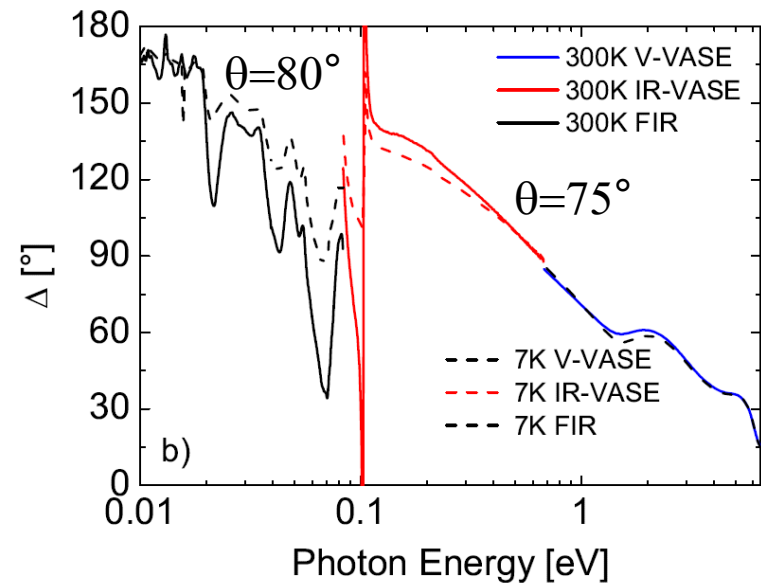
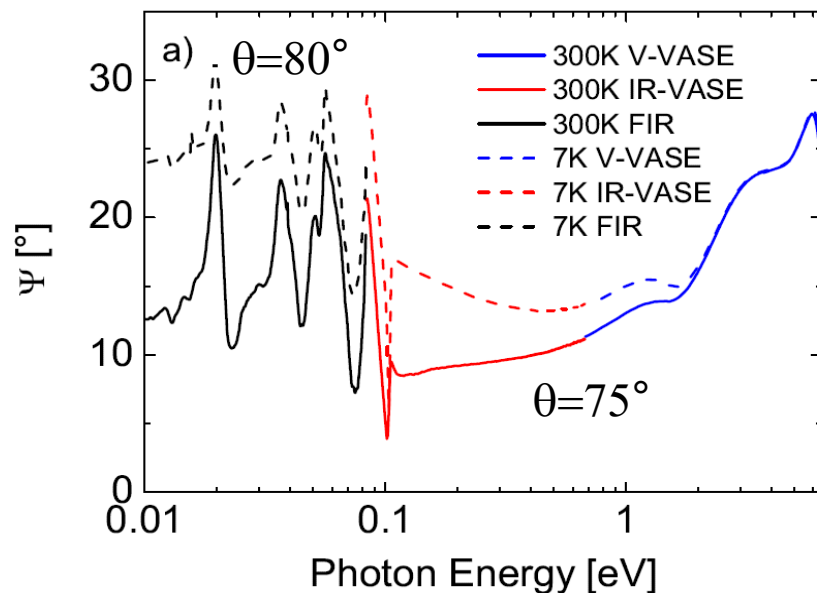
## -hrubá data na 30nm vrstvách



- tenké vrstvy (30 nm) feromagnetického  $\text{La}_{0.7}\text{Sr}_{0.3}\text{CoO}_3$  vypěstované na substrátu LSAT pomocí pulsní laserové depozice (Alineason Materials Technology)

- Curieova teplot  $T_c \sim 205$  K

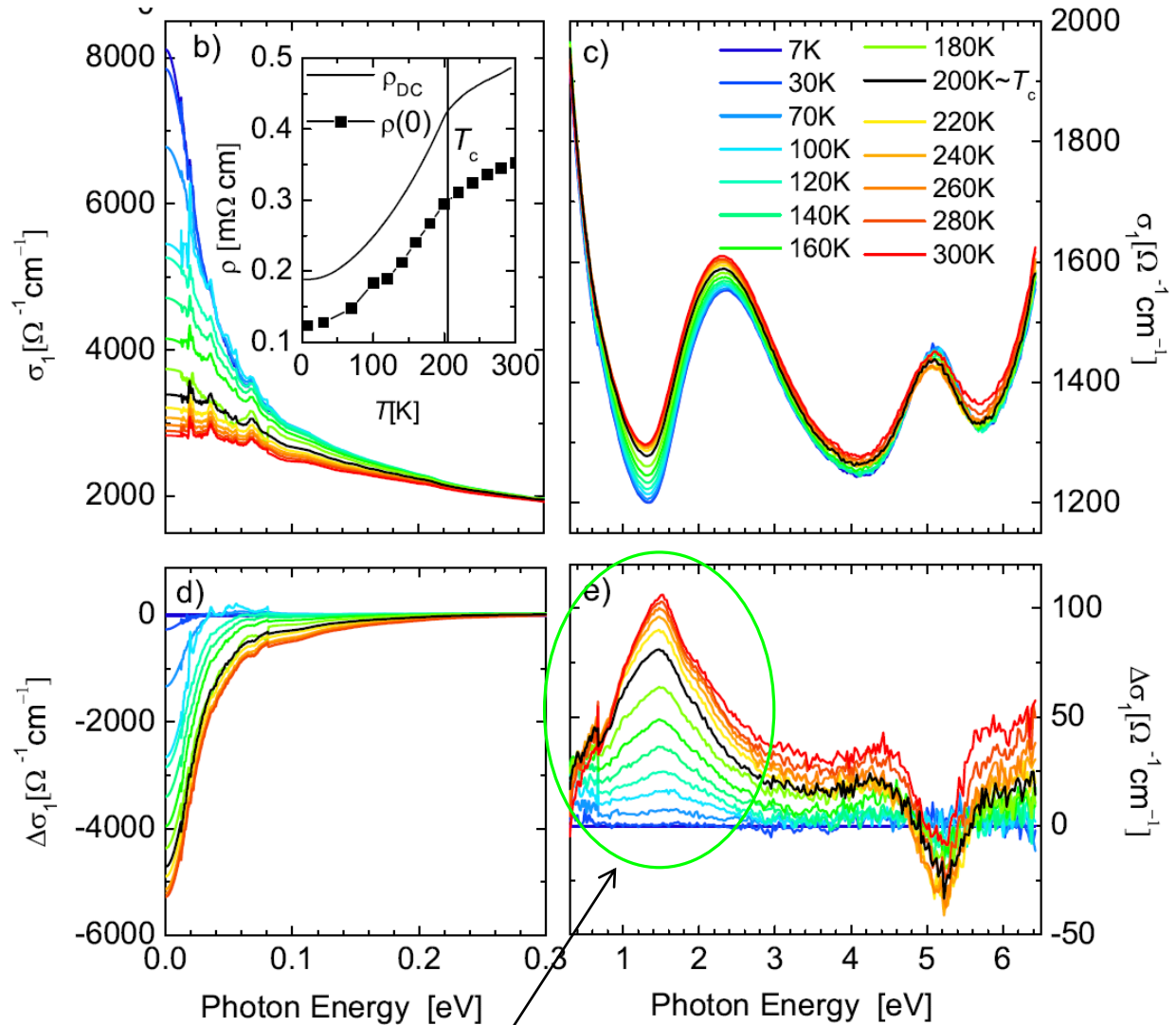
Hrubá data v podobě elipsometrických úhlů obsahují jak odezvu vrstvy tak substrátu



# Optické projevy feromagnetického stavu

$\text{La}_{0.7}\text{Sr}_{0.3}\text{CoO}_3$ ,  
 $T_c \sim 205 \text{ K}$

Absolutní optická  
vodivost (absorpce)  
 $\sigma_1(\omega) = \omega \epsilon_0 \epsilon_2(\omega)$



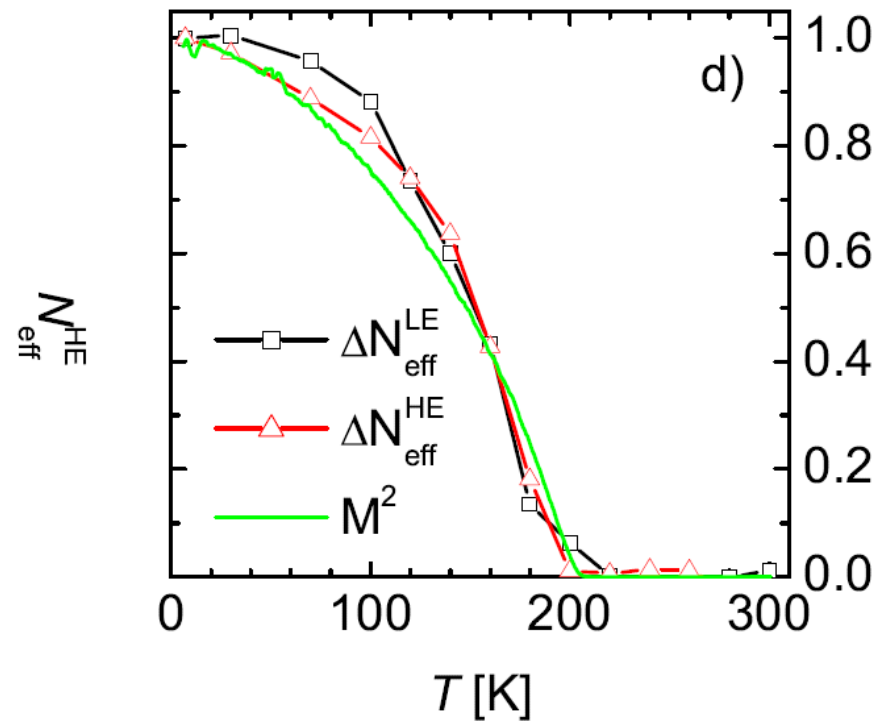
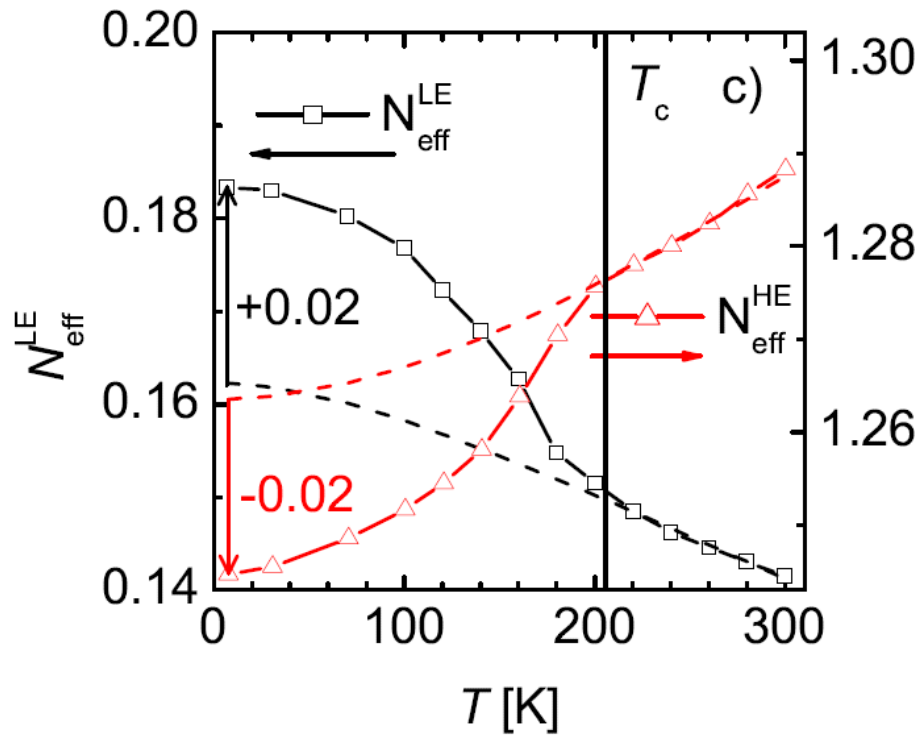
Relativní optická  
vodivost  
vzhledem k 7 K

Kandidát pro přechod „špatného spinu“ na 1.5 eV

# Optické projevy feromagnetického stavu

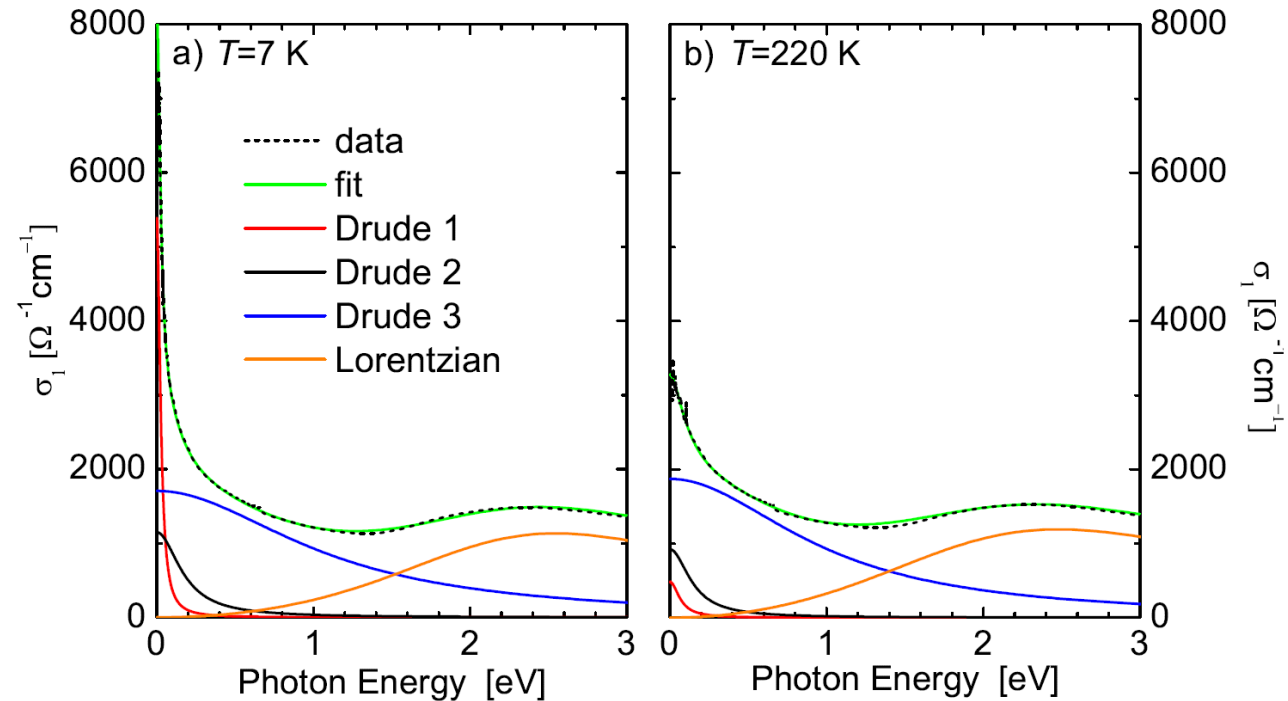
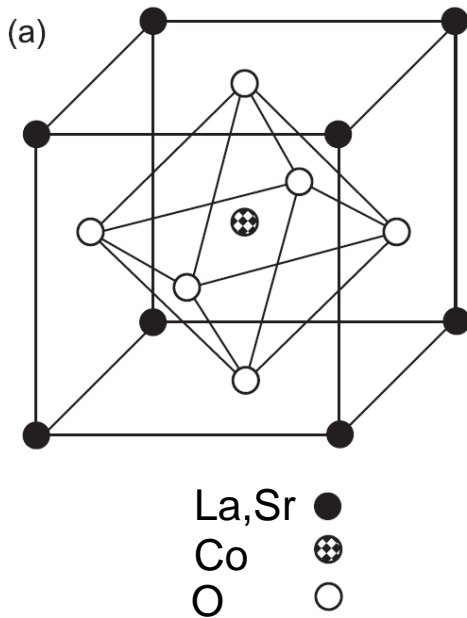
$\text{La}_{0.7}\text{Sr}_{0.3}\text{CoO}_3$ ,  $T_c \sim 205$  K

- spektrální váhy (integrál z  $\sigma_1$ ) Drudeho píku a pásu na 1.5 eV sledují vývoj magnetizace



# Modelování spekter pomocí Drudeovy-Lorentzovy formule

$\text{La}_{0.7}\text{Sr}_{0.3}\text{CoO}_3$ ,  $T_c \sim 205$  K



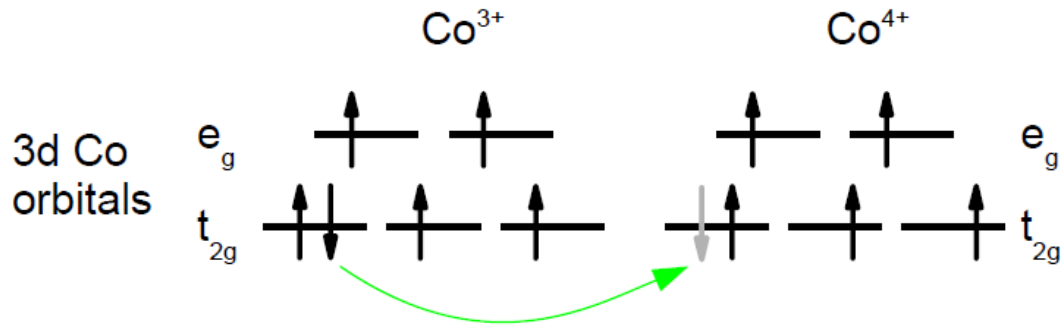
Modelování optických spekter pomocí Drudeovy-Lorentzovy formule

$$\epsilon(\omega) = 1 - \sum_j \frac{\omega_{D,j}^2}{\omega(\omega + i\gamma_{D,j})} + \sum_k \frac{\omega_{L,k}^2}{\omega_{0,k}^2 - \omega^2 - i\omega\gamma_{L,k}}$$

Vodivostní odezvu je nutné modelovat třemi Drudeho členy – typický znak interagujících vodivostních elektronů a/nebo přítomnosti několika vodivostních pásem

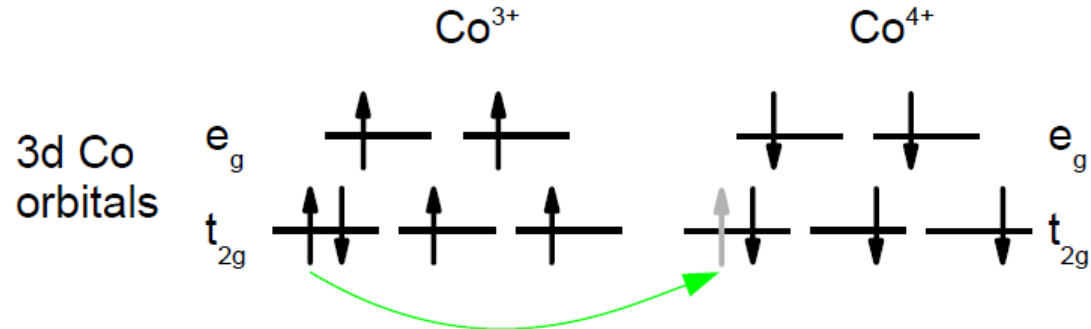
# Přechody elektronů mezi ionty kobaltu

## Feromagnetický stav



- dvojná výměnná interakce vedoucí k feromagnetismu
- delokalizace elektronů je hnací silou feromagnetického uspořádání
- vede k vodivým vlastnostem

## Paramagnetický stav



- přechod mezi kobalty s antiparalelním uspořádáním spinů se nazývá přechod se „špatným spinem“ („wrong-spin-transition“)
- tento přechod porušuje Hundova pravidla, je na něho tedy potřeba určitou energii ( $\sim 1.5$  eV).

# Photo-induced insulator-to-metal transition in $\text{LaCoO}_3$ explored by femtosecond pump-probe ellipsometry

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Institute of Condensed Matter Physics, Faculty of Science  
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The logo for beamlines, featuring a stylized red wave pattern above the text "beamlines".

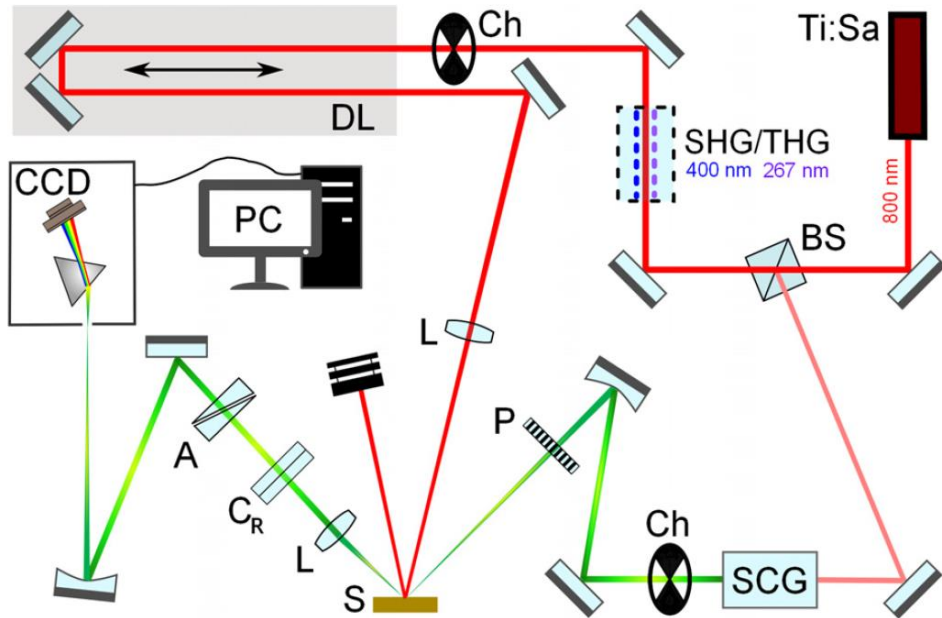
beamlines

M. Zahradník, S. Espinosa, M. Rebarz,  
J. Andreasson

ELI Beamlines, Fyzikální ústav AV ČR, v.v.i., Za Radnicí  
835, 25241 Dolní Břežany, Czech Republic



# Pump-probe femtosecond ellipsometry in ELI beamlines, Dolní Břežany



**FIG. 2.** Experimental setup of the femtosecond pump-probe spectroscopic rotating-compensator ellipsometer. Ch, chopper; A, analyzer; P, wire-grid polarizer;  $C_R$ , rotating compensator; L, lens; S, sample; DL, delay line; BS, beam splitter; SHG/THG, second/third harmonic generation (optional), SCG, super-continuum generation; and CCD, charge-coupled device detector. A photograph is shown in Fig. S1.

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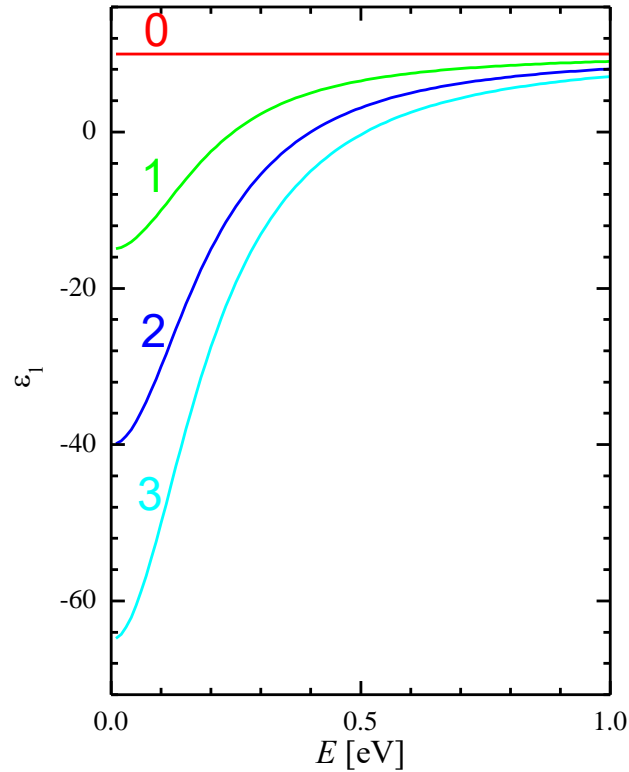
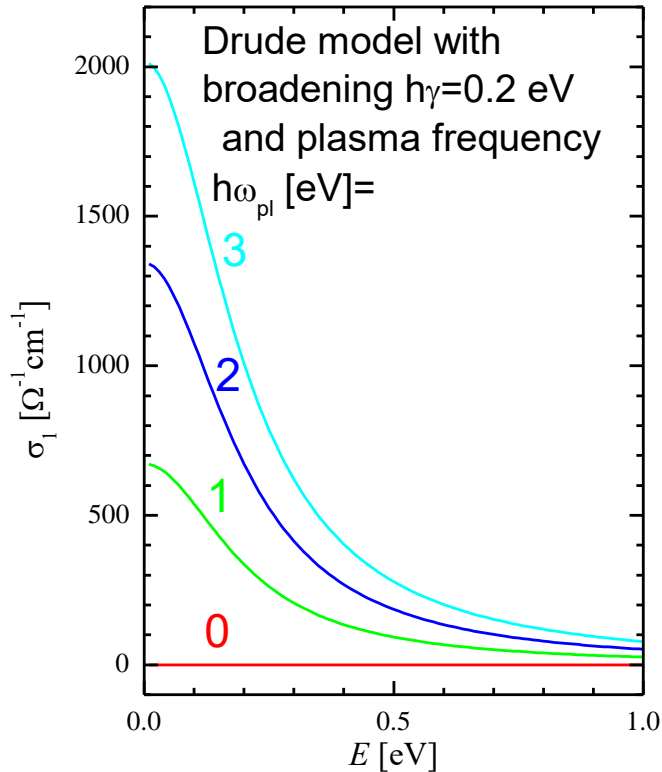
beamlines

- Ti:Sapphire laser (Coherent Astrella)
- 35 fs pulses at 800 nm
- 1 kHz rep. rate with 6 mJ pulse en.
- 10 mJ for pump mean
- fluency  $\sim 10 \text{ mJ/cm}^2$
- Angle of incidence of probe 60 deg
- Angle of incidence of pump 55 deg
- Rotating compensator design
- measurement range: 1.6-3.4 eV

S. Espinoza et al., APL **115b** 052105 (2019)

S. Richter et al., Rev. Sci. Instrum. **92**, 033104 (2021)

# Drude model



Drude model

$$\epsilon(\omega) = \epsilon_\infty - \frac{\omega_{pl}^2}{\omega(\omega + i\gamma)}$$

$$\omega_{pl} = \sqrt{\frac{q^2 n}{\epsilon_0 m^*}}$$

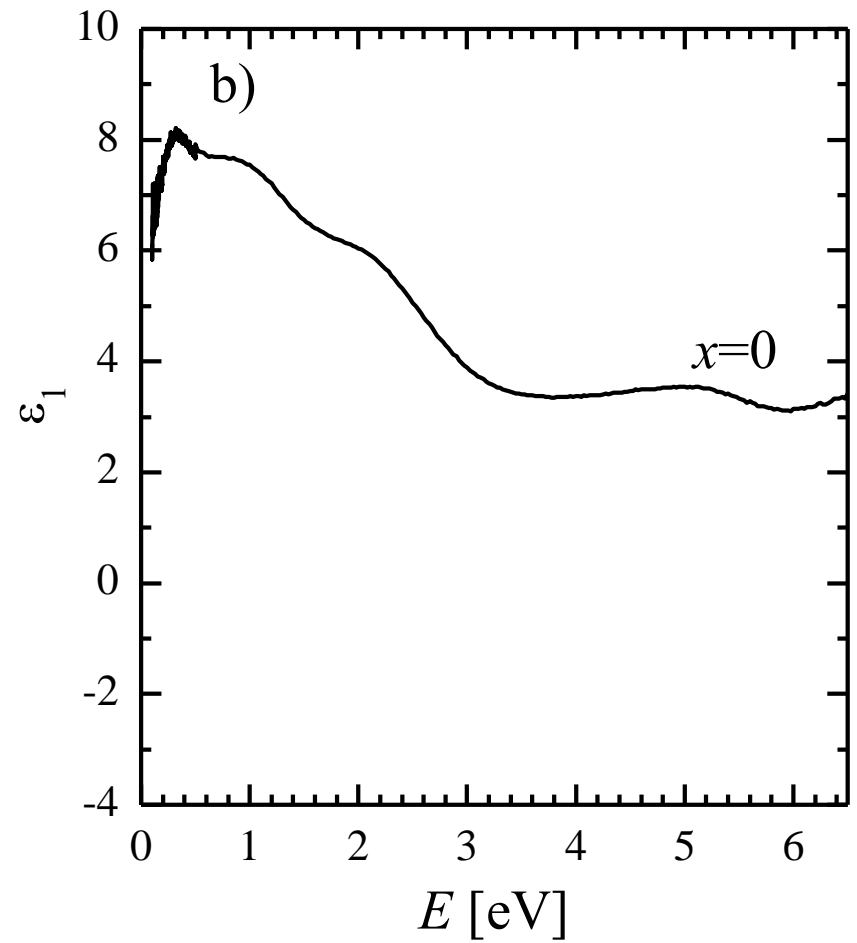
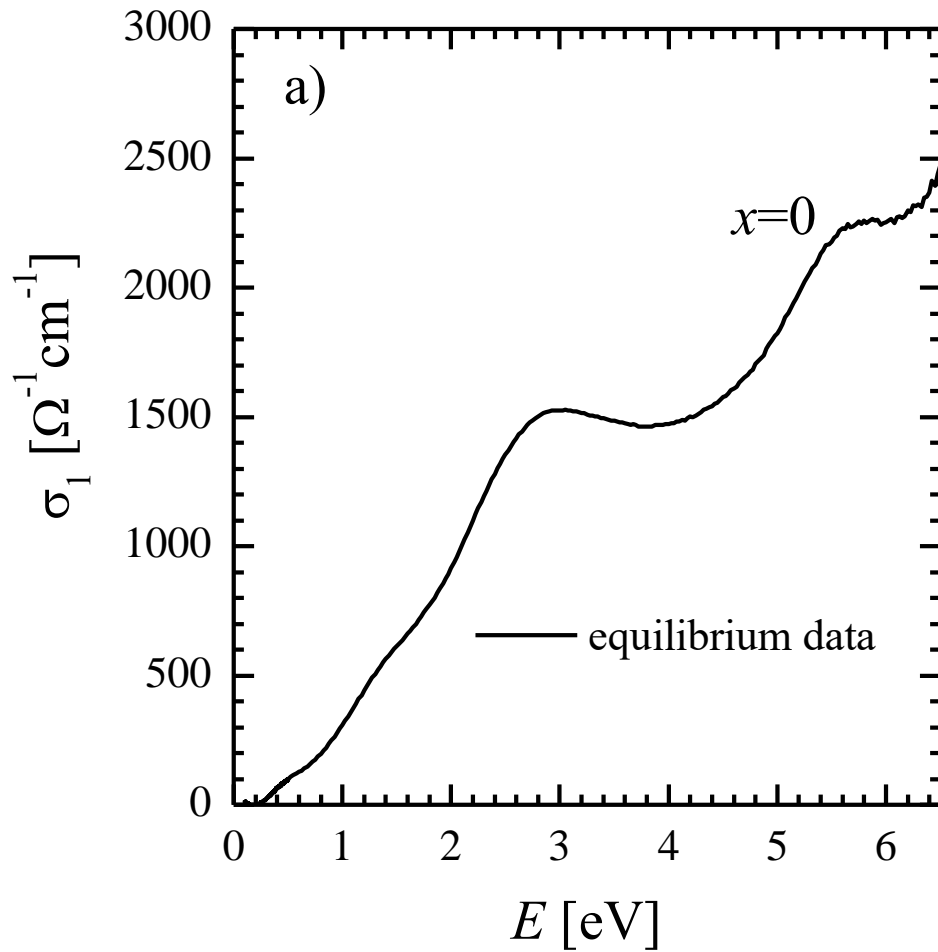
Optical conductivity  $\sigma(\omega) = -i\omega\epsilon_0(\epsilon(\omega) - 1)$

The real part of optical conductivity

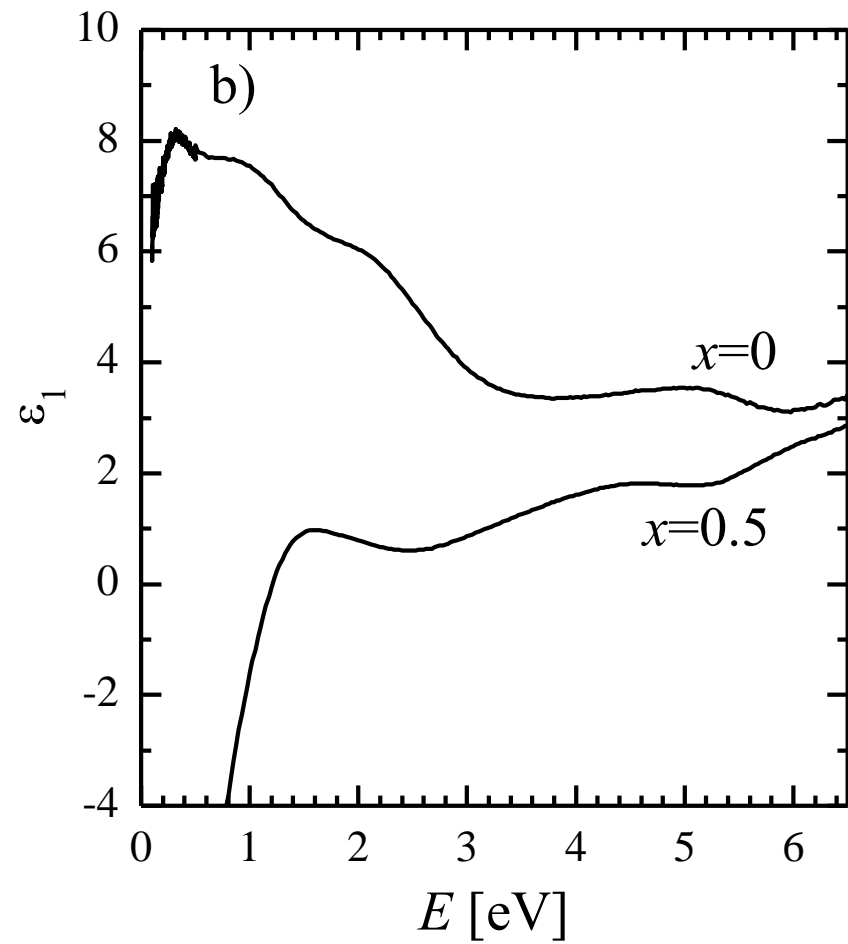
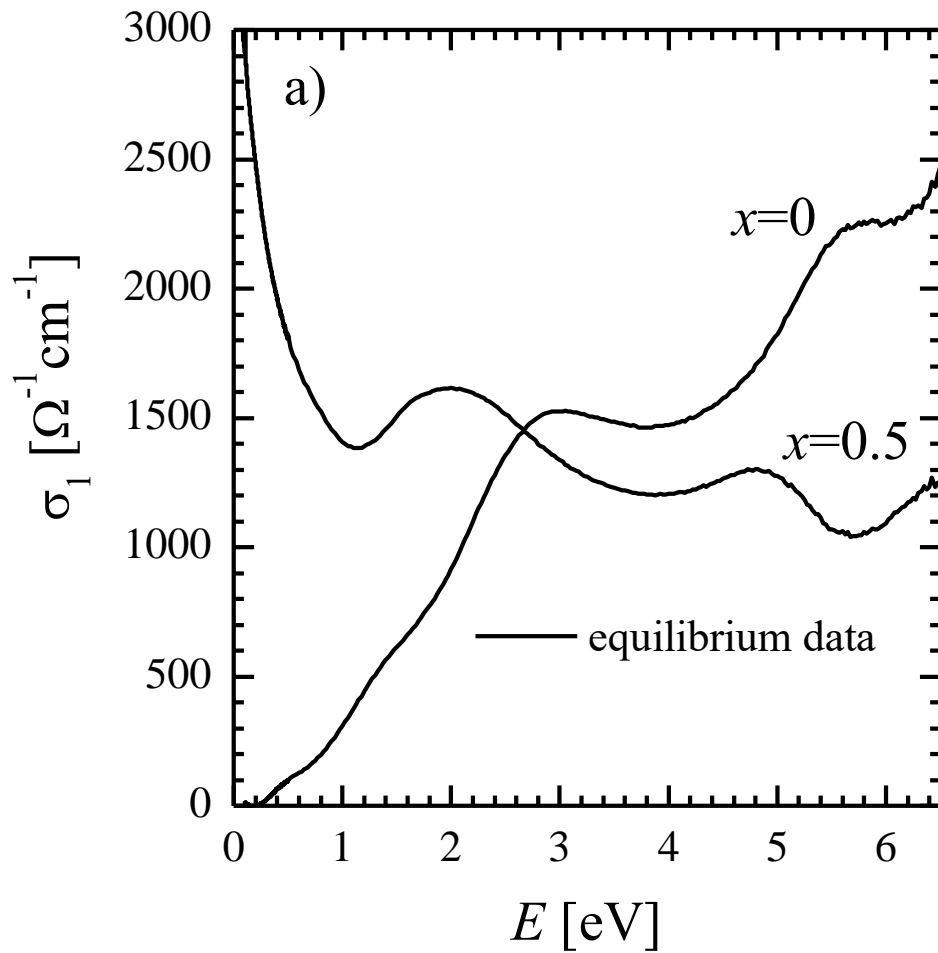
is the absorption per unit of frequency  $\sigma_1(\omega) \quad (= \omega\epsilon_0\epsilon_2(\omega))$

absorption sum rule:  $\int_0^\infty \sigma_1(\omega) d\omega = \frac{\pi n q^2}{2 \epsilon_0 m} = \text{const.}$

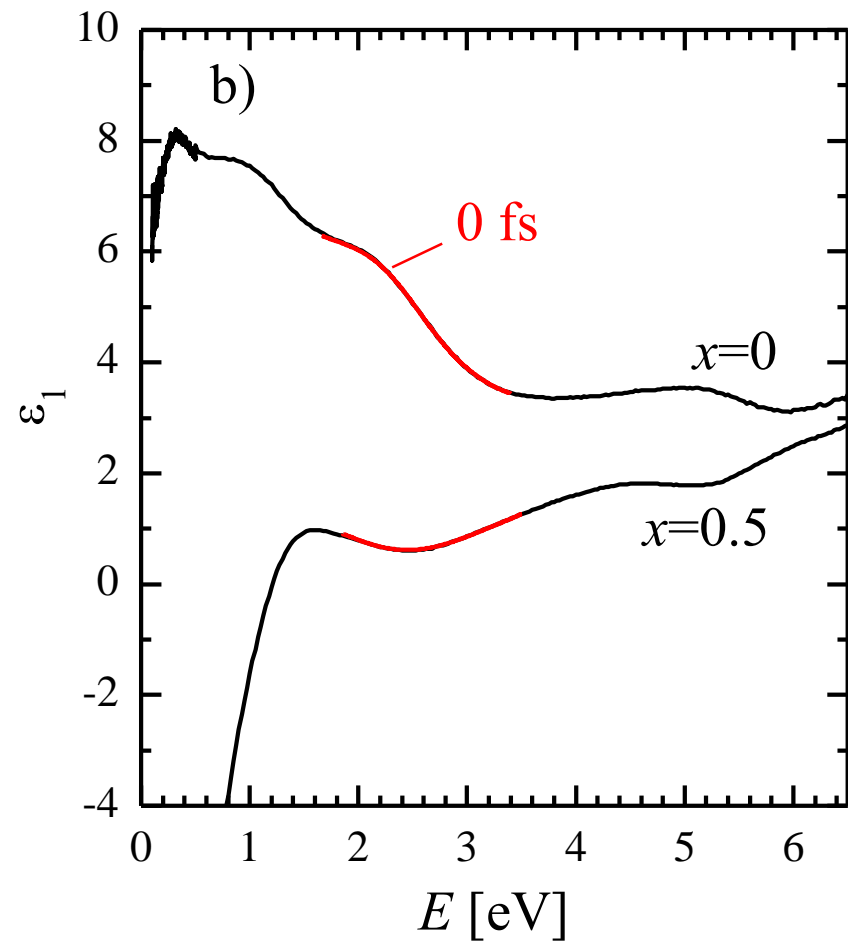
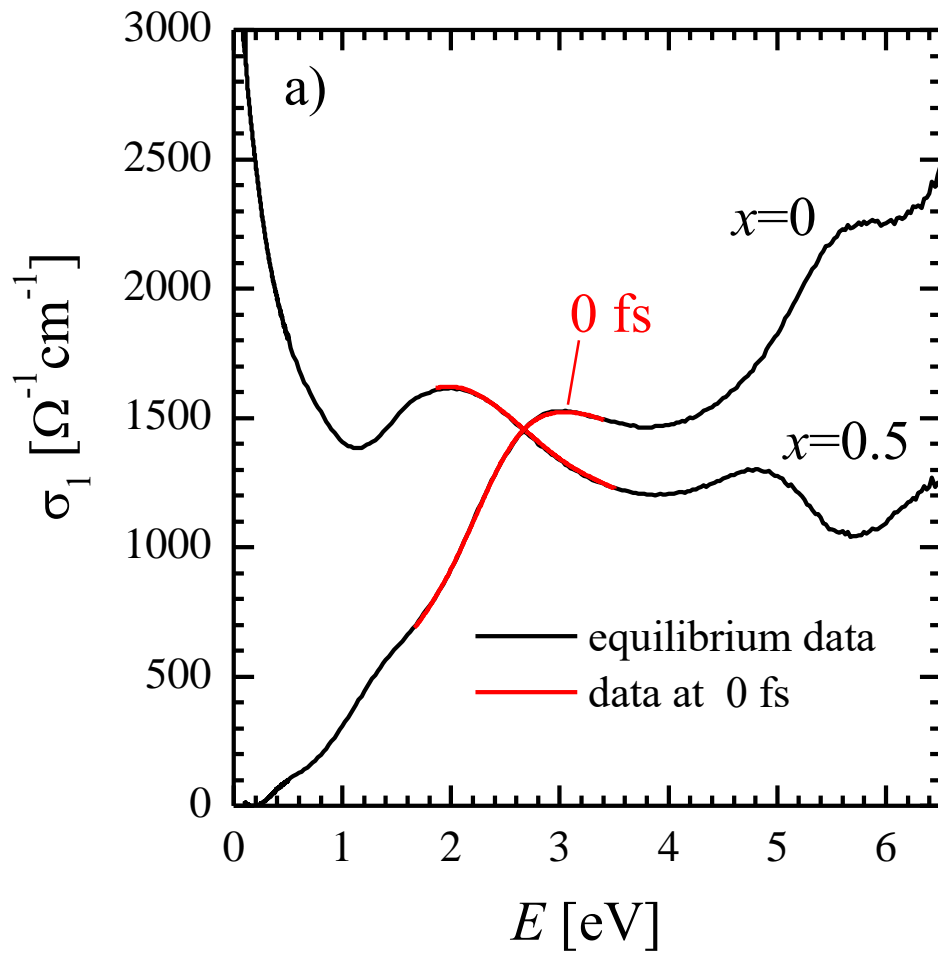
# Optical response of $\text{La}_{1-x}\text{Sr}_x\text{CoO}_3$



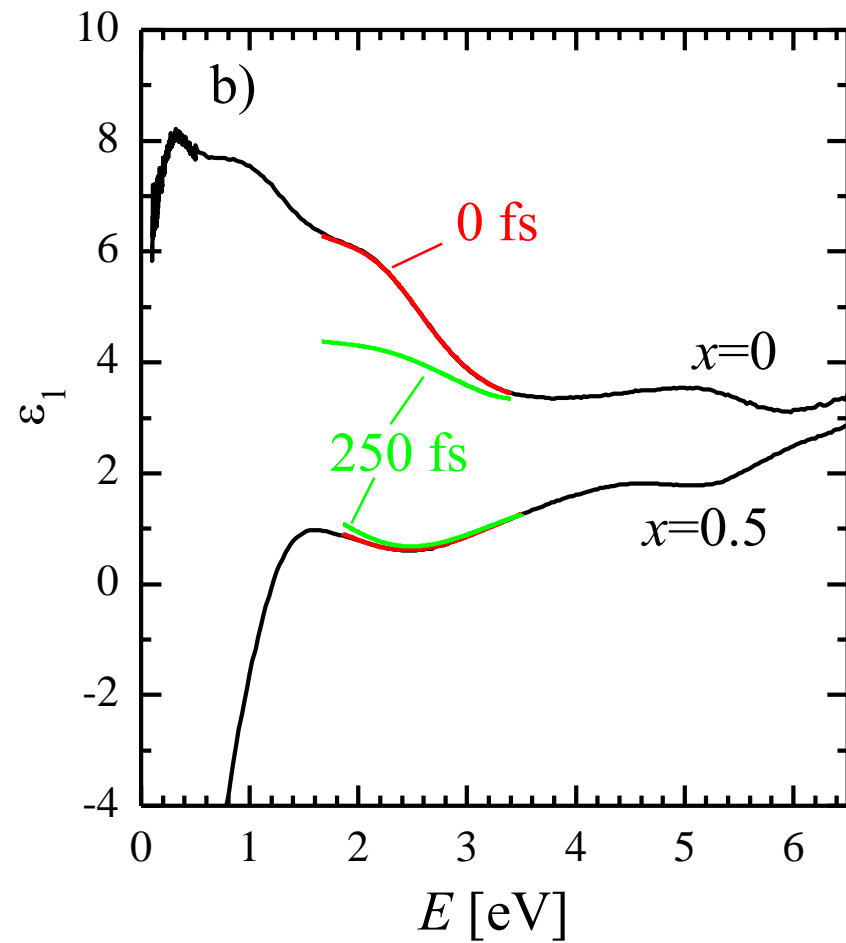
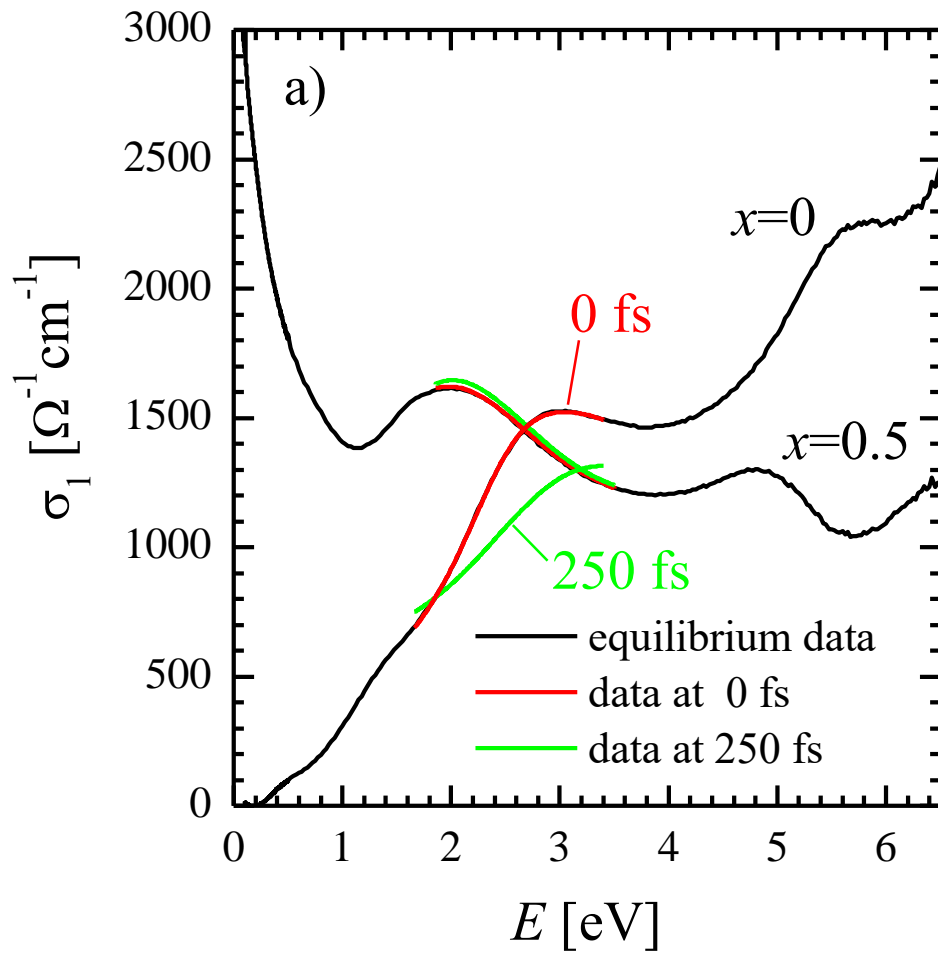
# Optical response of $\text{La}_{1-x}\text{Sr}_x\text{CoO}_3$



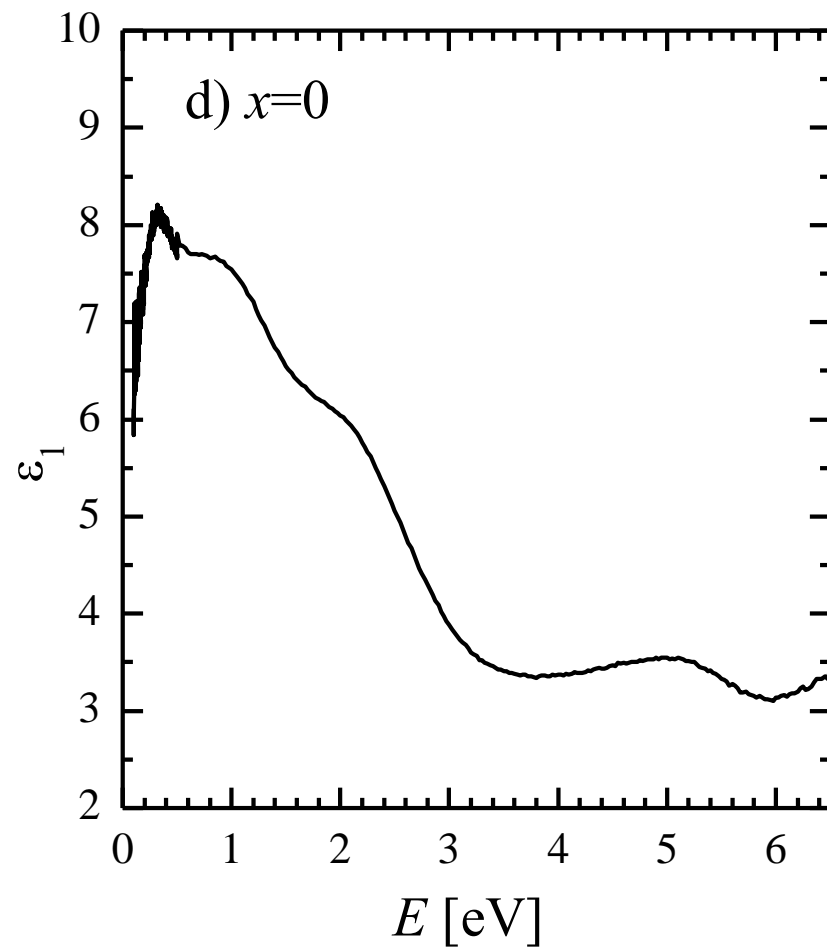
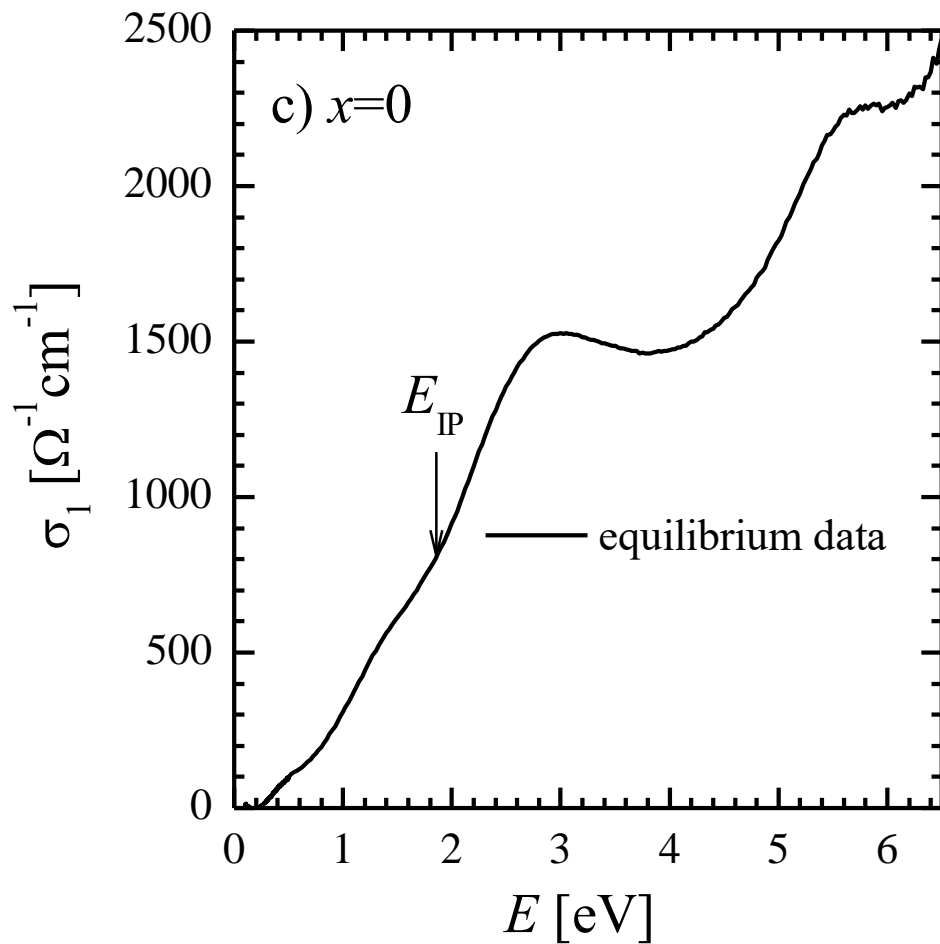
# Optical response of $\text{La}_{1-x}\text{Sr}_x\text{CoO}_3$



# Optical response of $\text{La}_{1-x}\text{Sr}_x\text{CoO}_3$

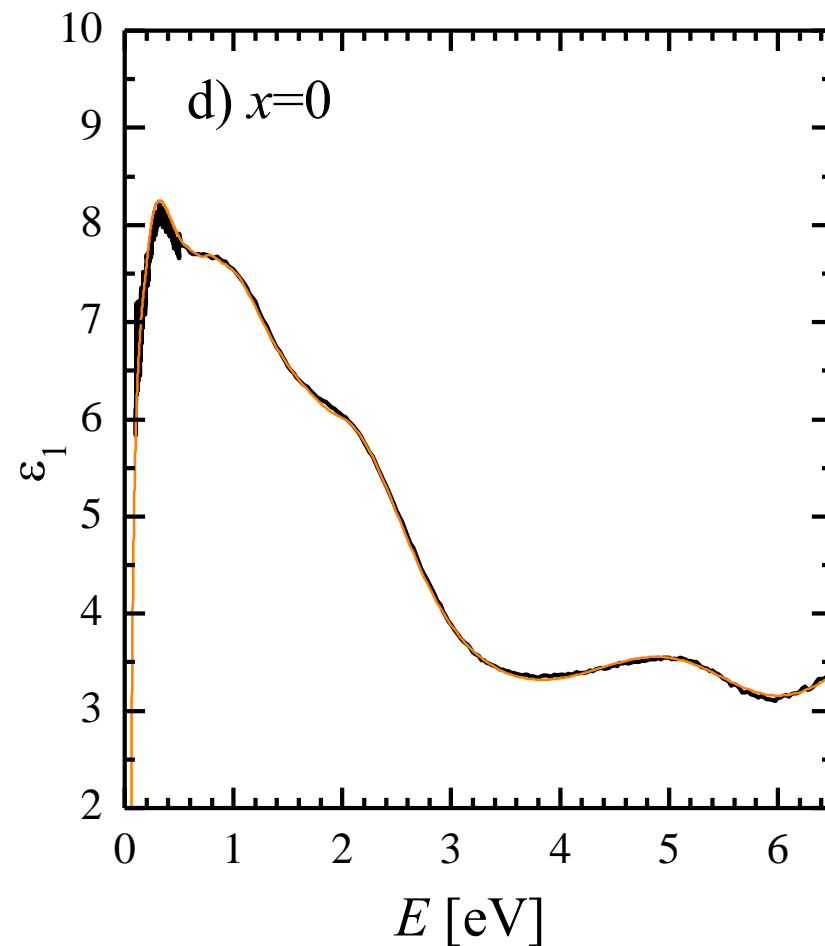
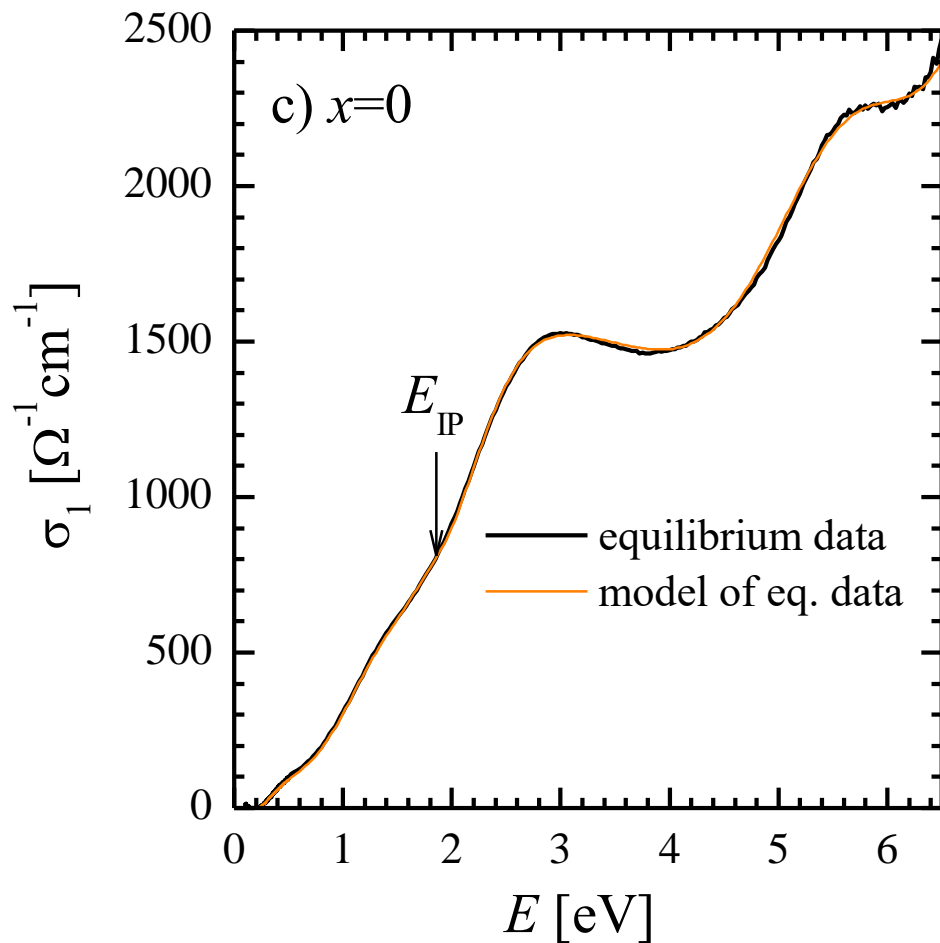


# Kramers-Kronig modeling of $\text{LaCoO}_3$ at 250 fs



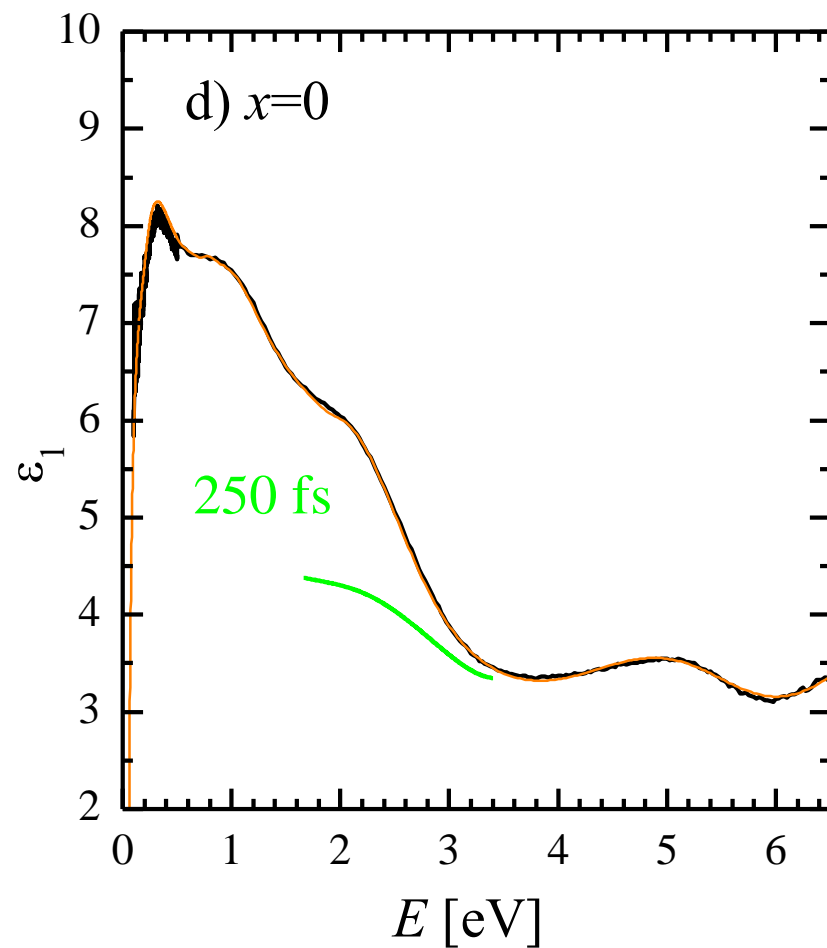
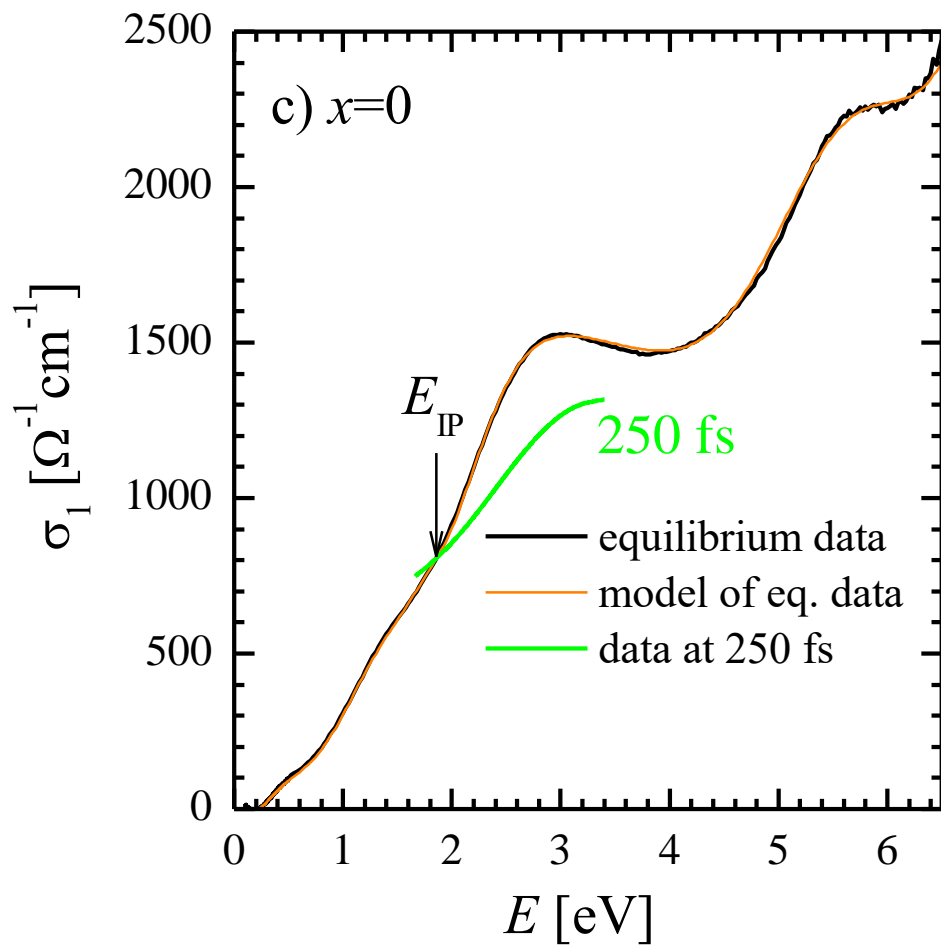


# Kramers-Kronig modeling of $\text{LaCoO}_3$ at 250 fs

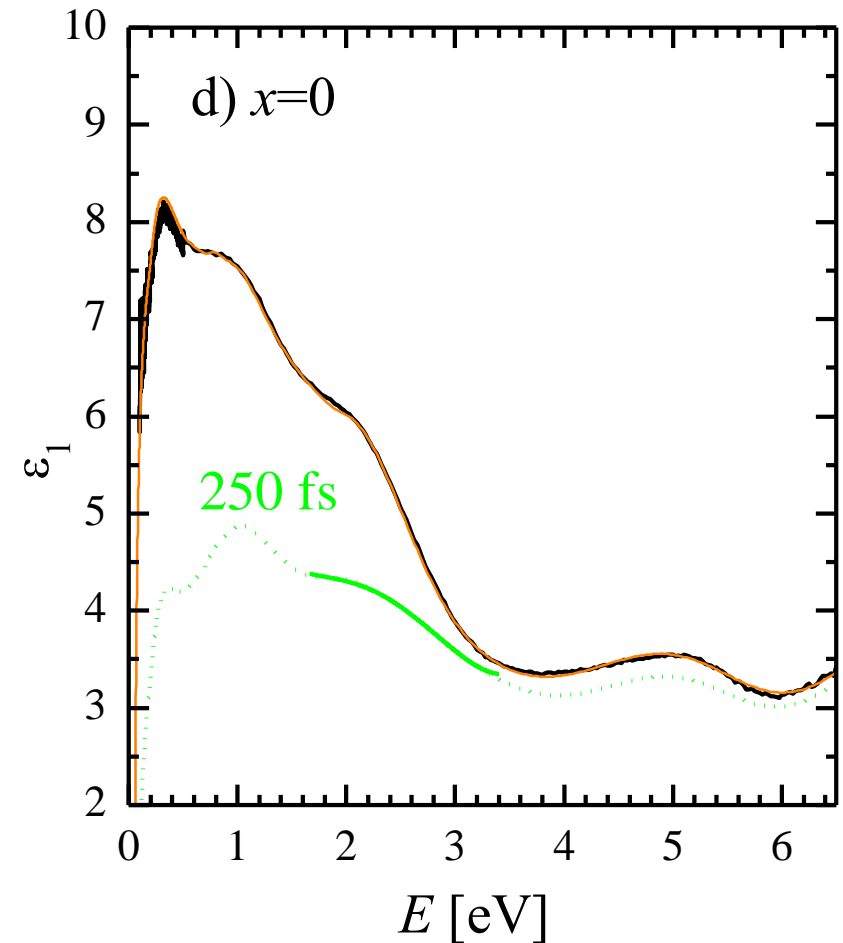
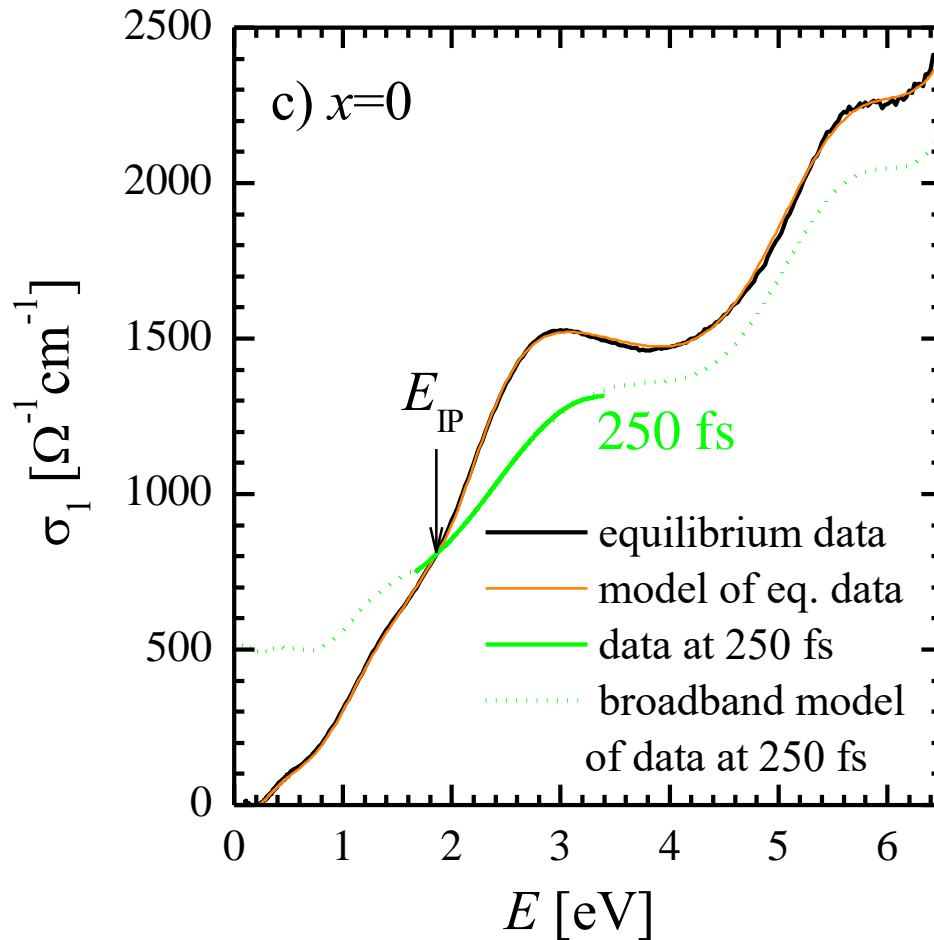


- Modeling the equilibrium data with a set of Kramers-Kronig consistent functions (Tauc-Lorentz+ Gaussian)

# Kramers-Kronig modeling of $\text{LaCoO}_3$ at 250 fs



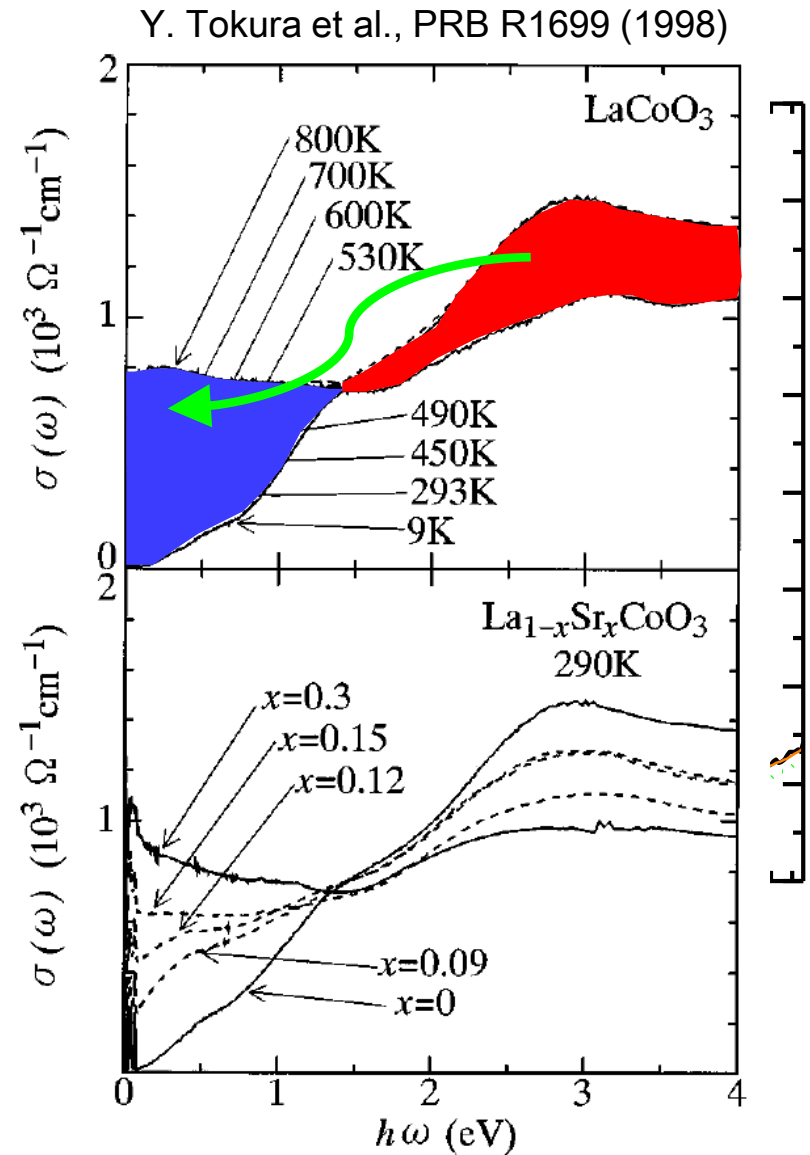
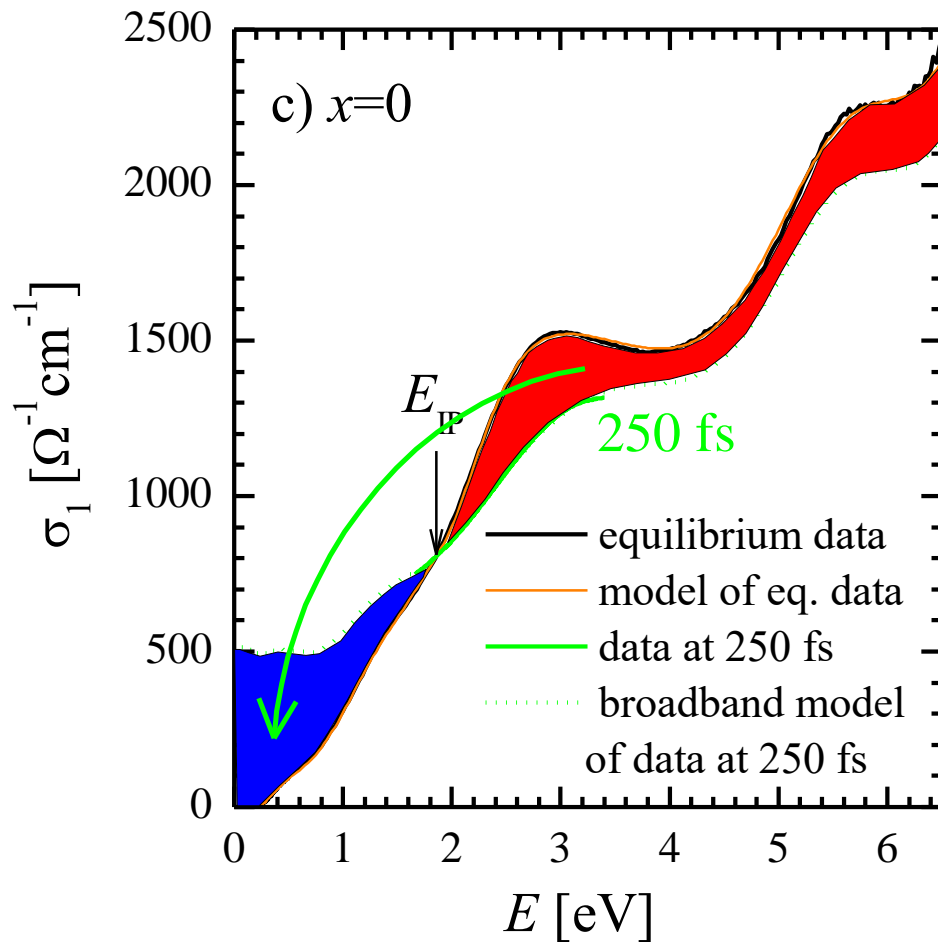
# Kramers-Kronig modeling of LaCoO<sub>3</sub> at 250 fs



- Modeling 250 fs data with the same model function + Drude term
- Modeling yields  $\omega_{pl}^2 = 3.8 \pm 0.1 \text{ eV}^2$  with  $\gamma$  fixed to 1 eV
- For charge per Co ion  $N = n^* a^3$ , we obtain  $N = 0.15$  with  $m^* = m_e$
- The modelling strongly suggest that pump-induced insulator-to-metal transition takes place

$$-\frac{\omega_{pl}^2}{\omega(\omega + i\gamma)} \quad \omega_{pl} = \sqrt{\frac{q^2 n}{\epsilon_0 m^*}}$$

# Kramers-Kronig modeling of $\text{LaCoO}_3$ at 250 fs



- pump induces shift of spectral weight to low frequencies just like the with temperature
- Observation of pump-induced insulator-to-metal transition

# Magneto-spectroscopy on topological insulator $\text{Bi}_2\text{Te}_3$

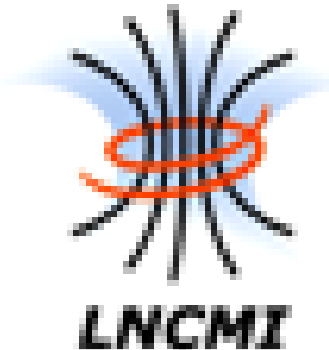
optical spectroscopy: A. Dubroka (MU Brno)  
M. Orlita (LNCMI Grenoble),  
I. Mohelský (LNCMI Grenoble, BUT Brno)

sample growth: G. Springholz (Uni Linz)

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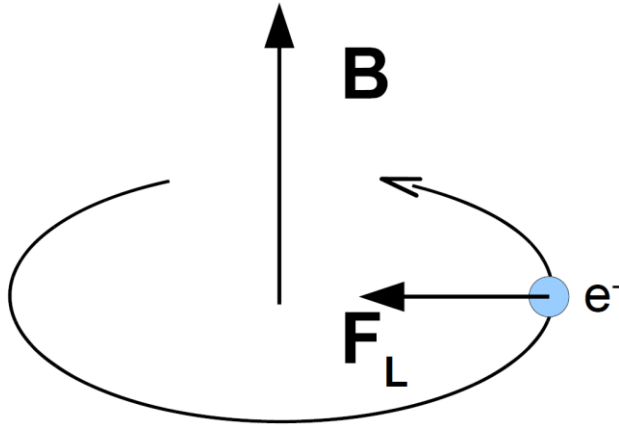
central european institute of technology  
BRNO | CZECH REPUBLIC



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# Cyclotron frequency

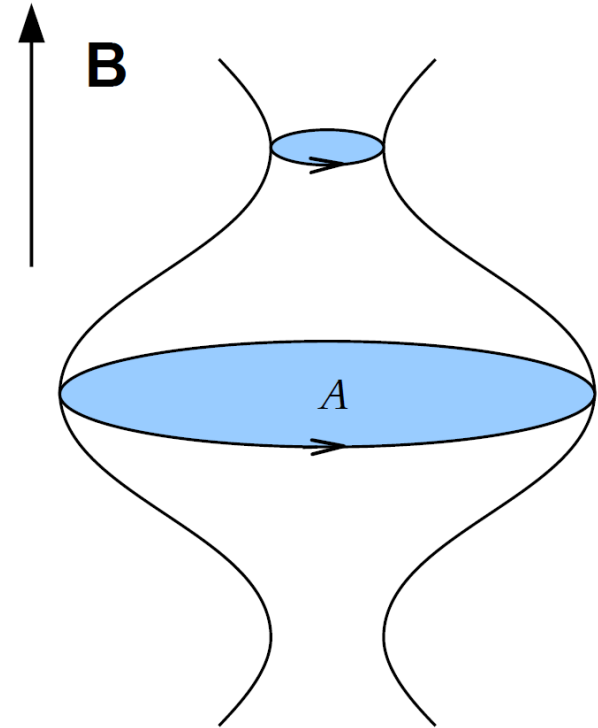
Classical free electron in magnetic field



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

Cyclotron frequency

Electrons in a solid



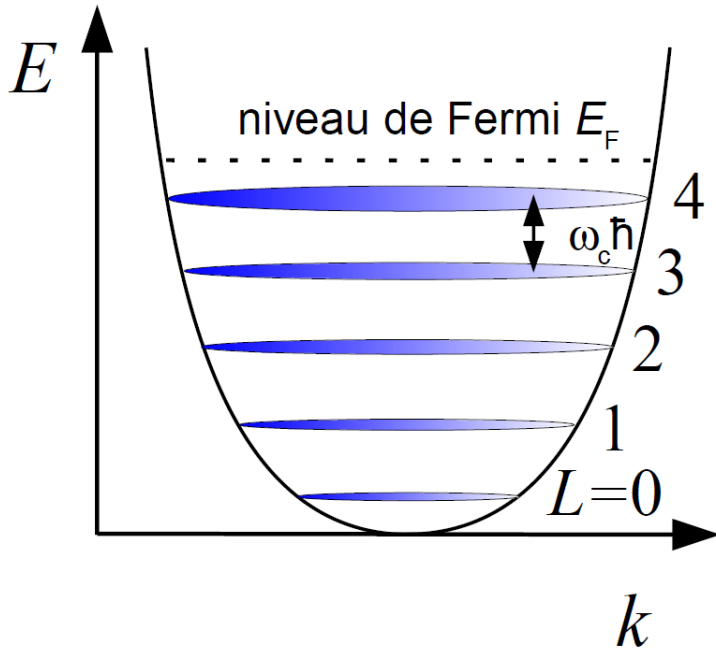
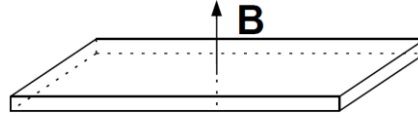
$$\omega_c = \frac{eB}{m_c}, \quad m_c = \frac{\hbar^2}{2\pi} \frac{\partial A(E)}{\partial E}$$

$A$  = surface of the orbit

$m_c$  = cyclotron mass

# Landau levels in two dimensions

Electron gas in 2D:  
with parabolic dispersion



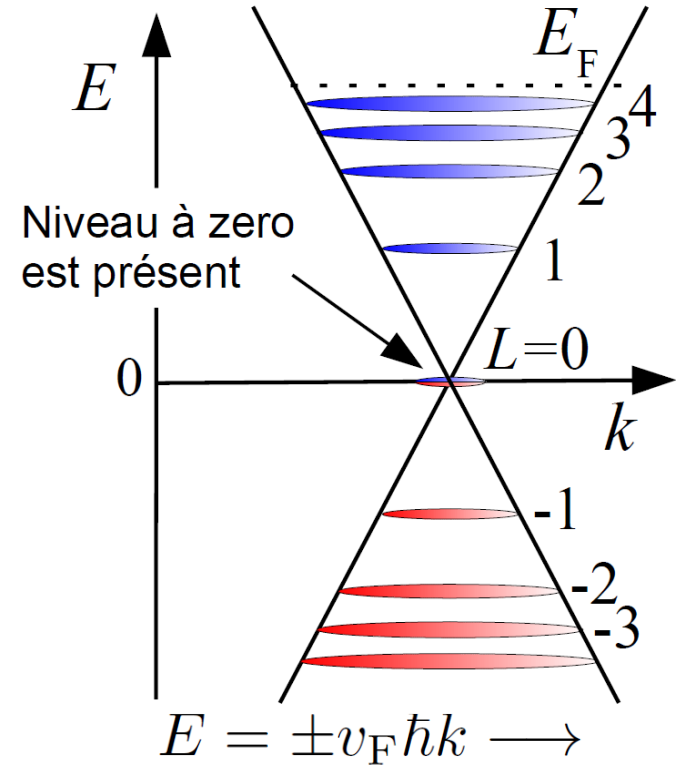
$$E(k) = \frac{\hbar^2 k^2}{2m} \longrightarrow$$

$$E_L = \hbar\omega_c \left(L + \frac{1}{2}\right)$$

$$L = 0, 1, 2, \dots, \quad \omega_c = \frac{eB}{m_c}$$

L.D. Landau, Z. Phys. 64, 629 (1930)

relativistic particles with zero mass:  
linear dispersion



$$E = \pm v_F \hbar k \longrightarrow$$

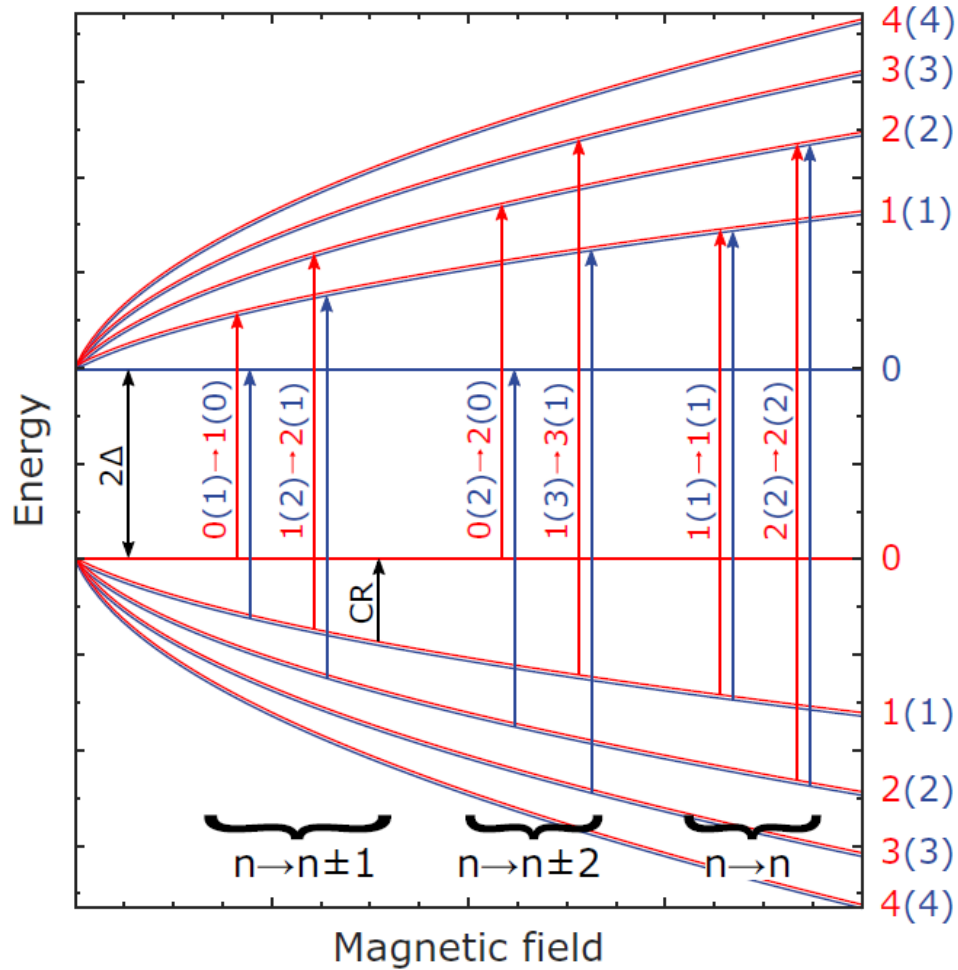
$$E_L = \text{sgn}(L) \sqrt{2e\hbar v_F^2 |LB|}$$

$$L = 0, \pm 1, \pm 2, \dots$$

I.I. Rabi, Z. Phys. 49, 507 (1928)



# Landau levels of two band model of Dirac Fermions



Two band model:

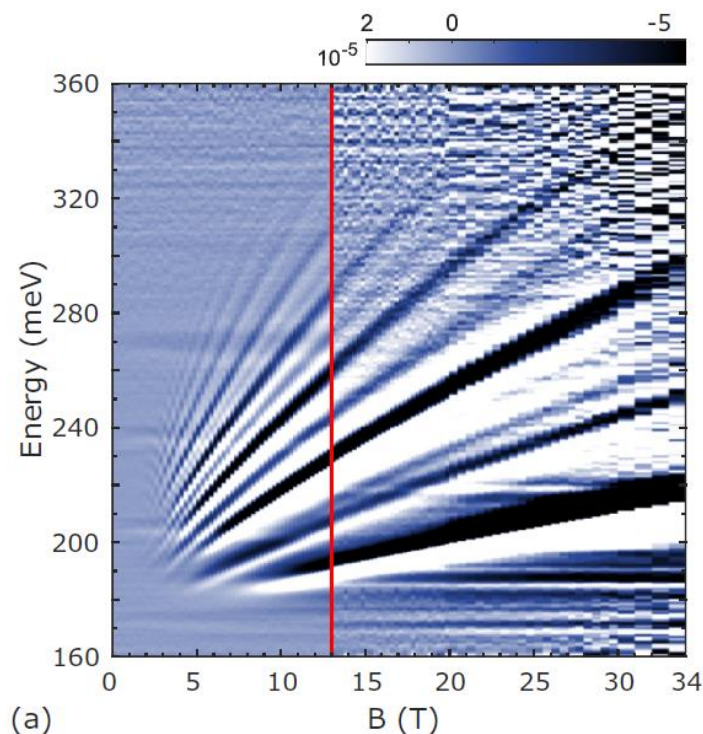
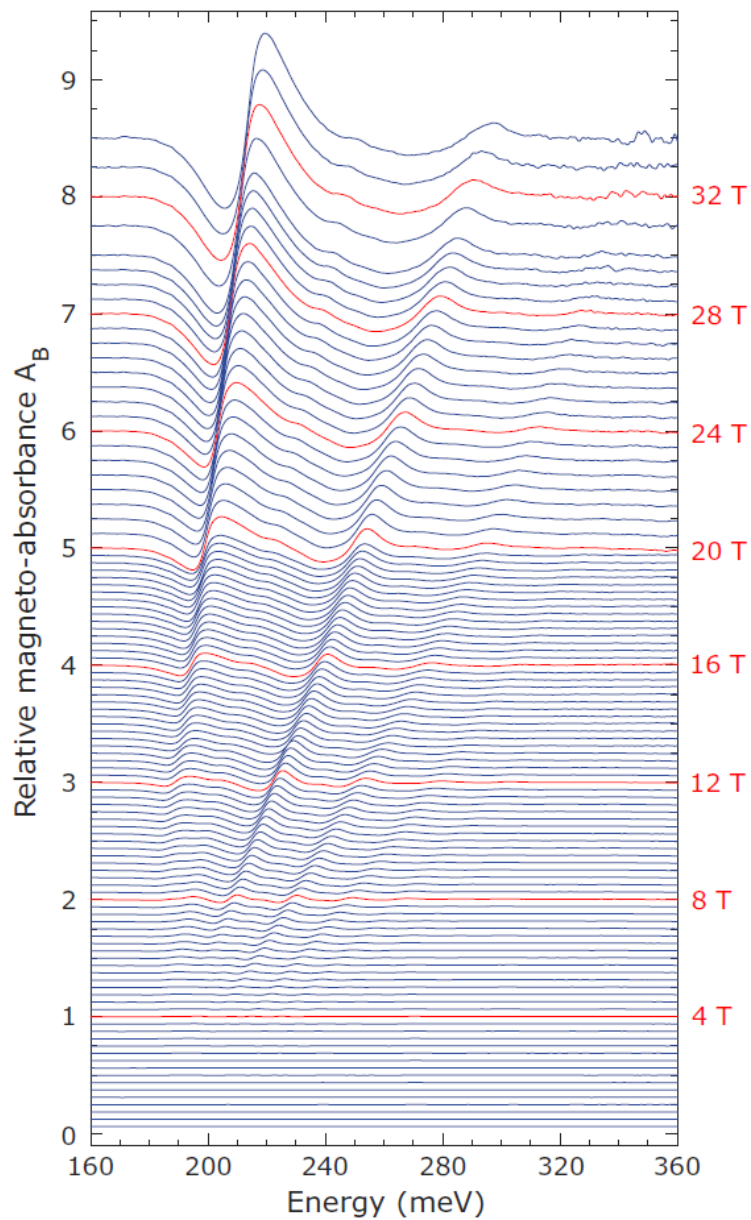
$$E(k) = \pm \sqrt{\Delta^2 + \hbar^2 v_D^2 k^2}$$

Landau level spectrum

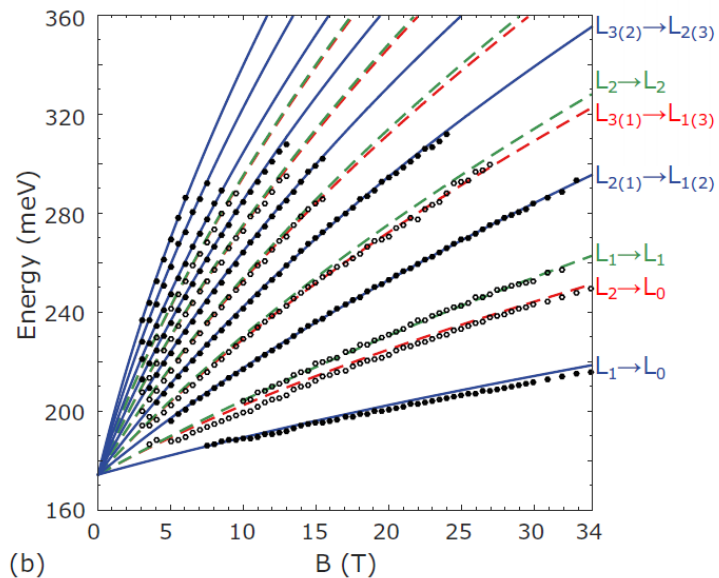
$$E_n = \pm \sqrt{v_D^2 2e\hbar B n + \Delta^2}, \text{ where } n > 0$$

Selection rule  $n \rightarrow n \pm 1$

# Magneto-transmission in high magnetic fields (Grenoble)

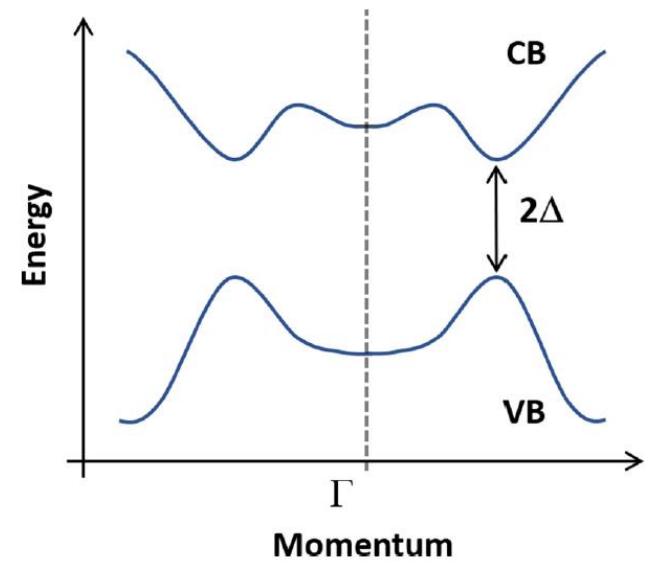
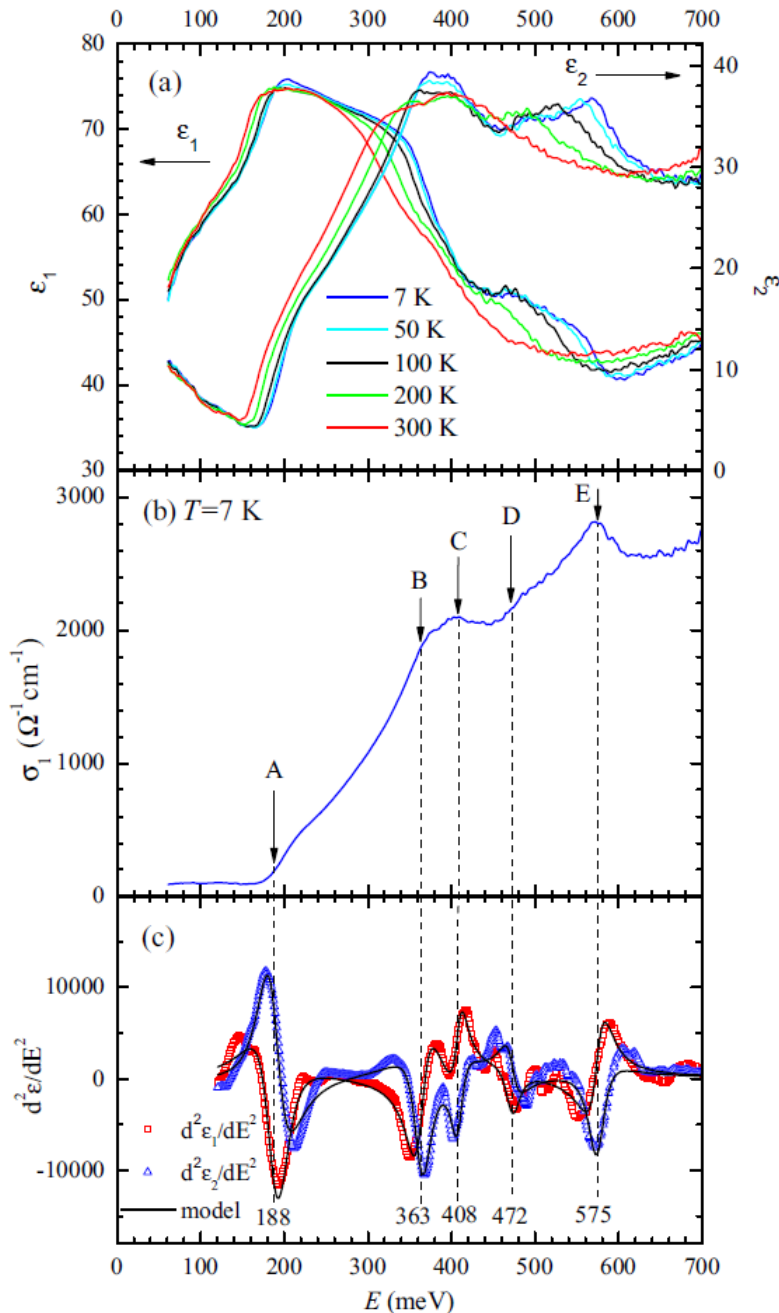


(a)



(b)

# Analysis of critical points of bandstructure of $\text{Bi}_2\text{Te}_3$



$$\frac{d^2 \epsilon}{dE^2} = A e^{i\phi} (E - E_{\text{CP}} + i\zeta)^{n-2}$$

TABLE I. The values of the amplitude  $A$ , energy  $E_{\text{CP}}$ , broadening  $\zeta$ , and phase  $\phi$  obtained from the fit of the CP model to the data shown in Fig. 10(c).

Label	$A$	$E_{\text{CP}}$ (meV)	$\zeta$ (meV)	$\phi$ (deg)	Line shape
A	7.8	188	24	-29	2D
B	$21 \text{ eV}^{-1/2}$	363	16	23	3D
C	$8 \text{ eV}^{-1/2}$	408	11	76	3D
D	$6 \text{ eV}^{-1/2}$	472	13	300	3D
E	$16 \text{ eV}^{-1/2}$	575	15	60	3D

**Děkuji za pozornost**

# Historie elipsometrie



Paul Karl Ludwig Drude  
1863-1906

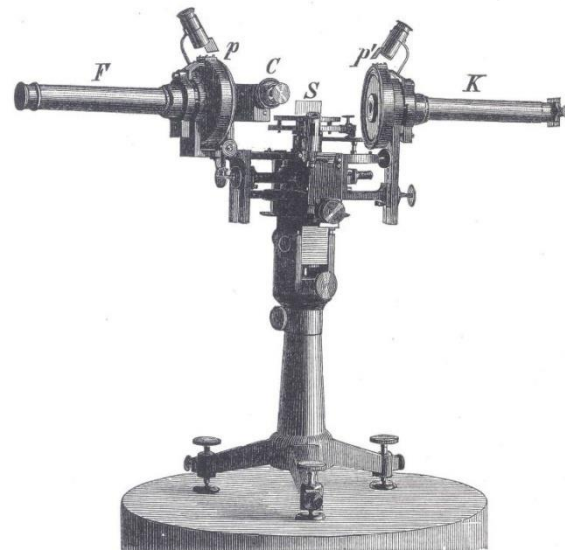


Fig. 81.

~ 1900

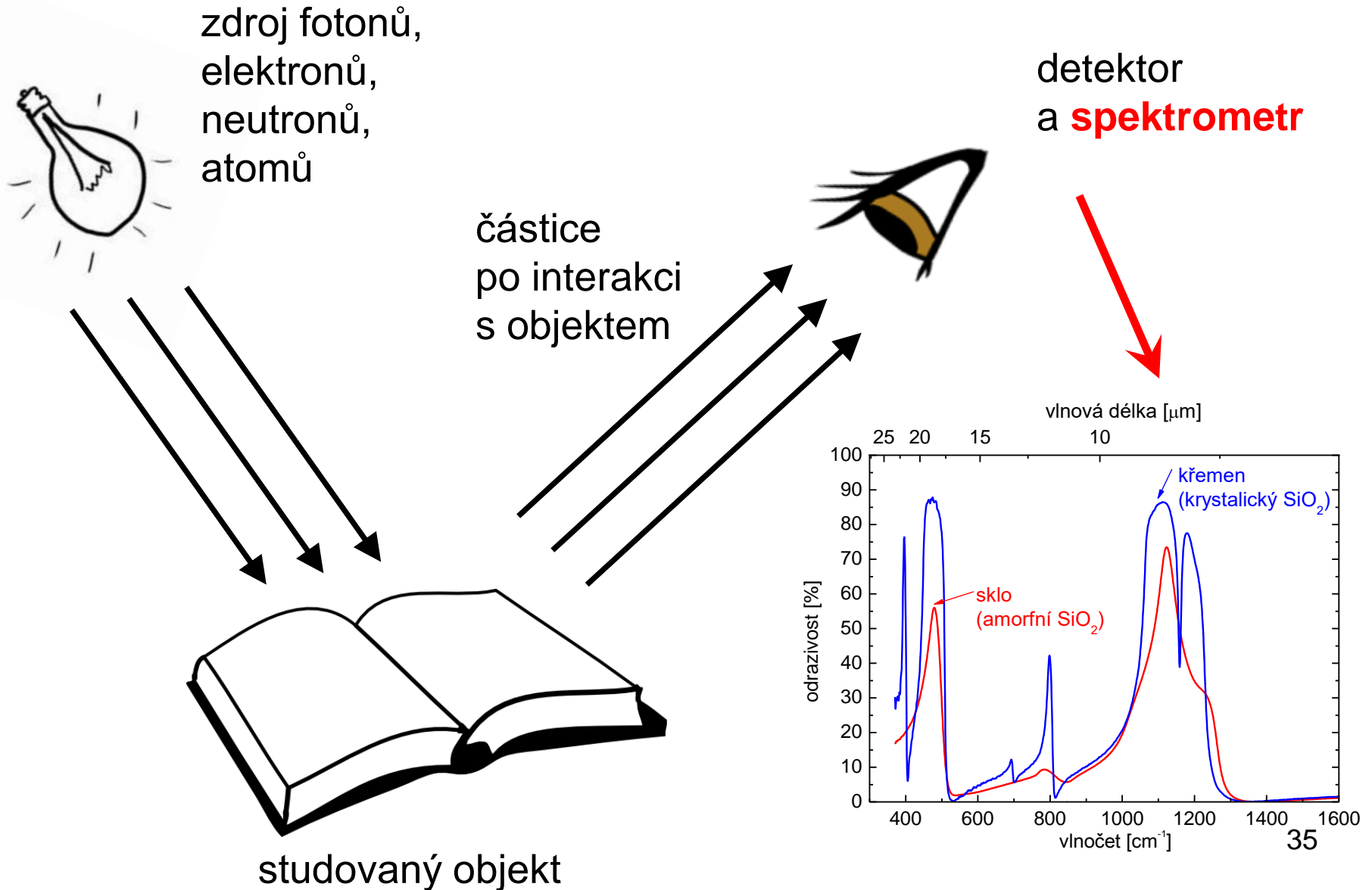


Prof. Antonín Vašíček  
1903-1966



~ 1938

# Spektroskopie: Studium interakce mezi látkou a sondou s určitou energií



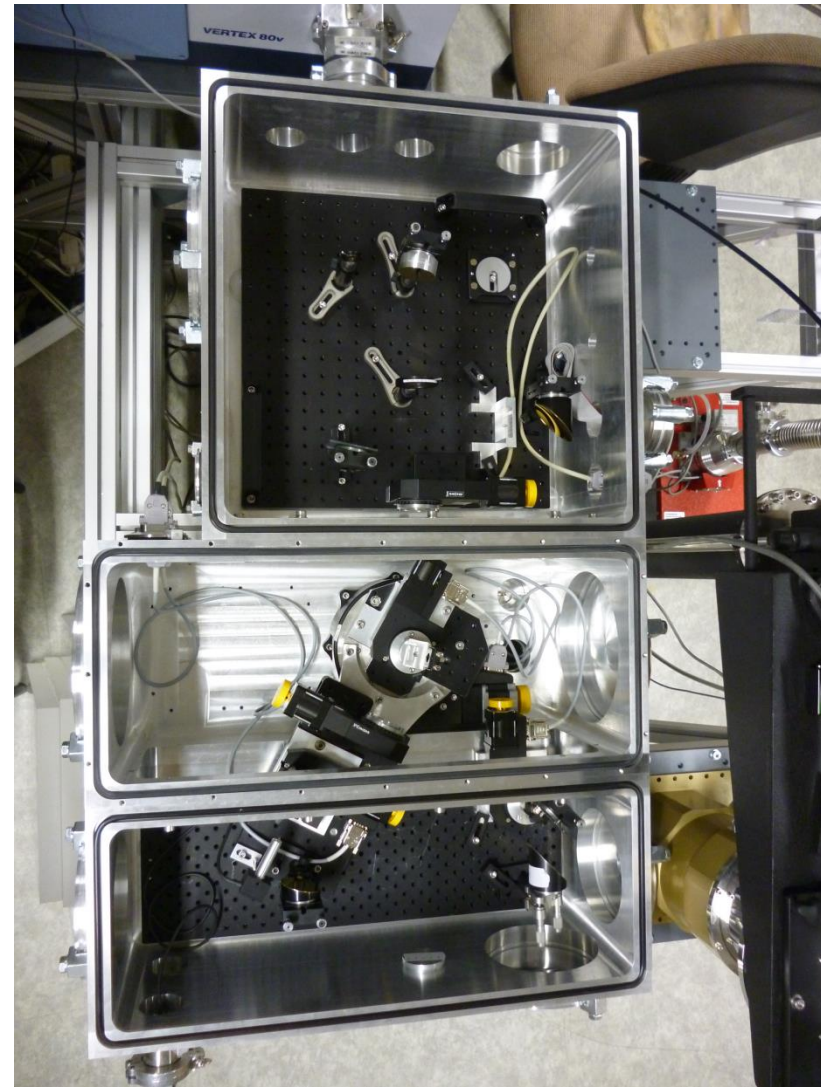
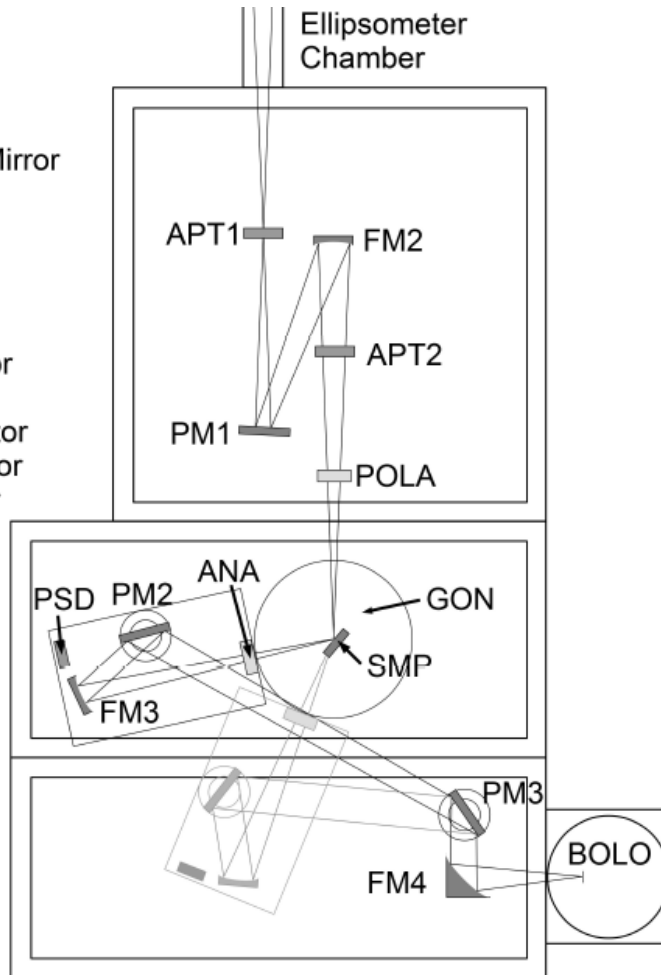


# design of far-infrared ellipsometer at CEITEC

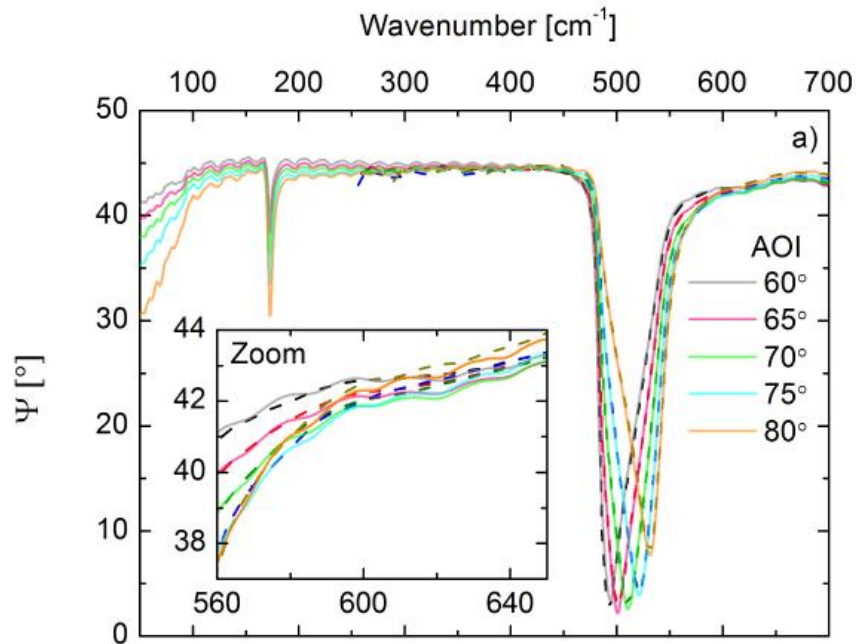
alternated Max-Planck design

- three chambers to support top loaded cryostat
- detection arm on a goniometer for reproducible exchange of angle of incidence

ANA - Analyzer  
APT1,2 - Aperture  
BMS - Beam Splitter  
BOLO - Bolometer  
FM1,3,4 - Parabolic Mirror  
FM2 - Elliptical Mirror  
GLB - Glow Bar  
GON - Goniometer  
HG - Mercury Lamp  
LAS - Alignment Laser  
PM1,2,3 - Plane Mirror  
POLA - Polarizer  
PSD - Position Detector  
RM - Removable Mirror  
SMP - Sample Holder  
W - Tungsten Lamp

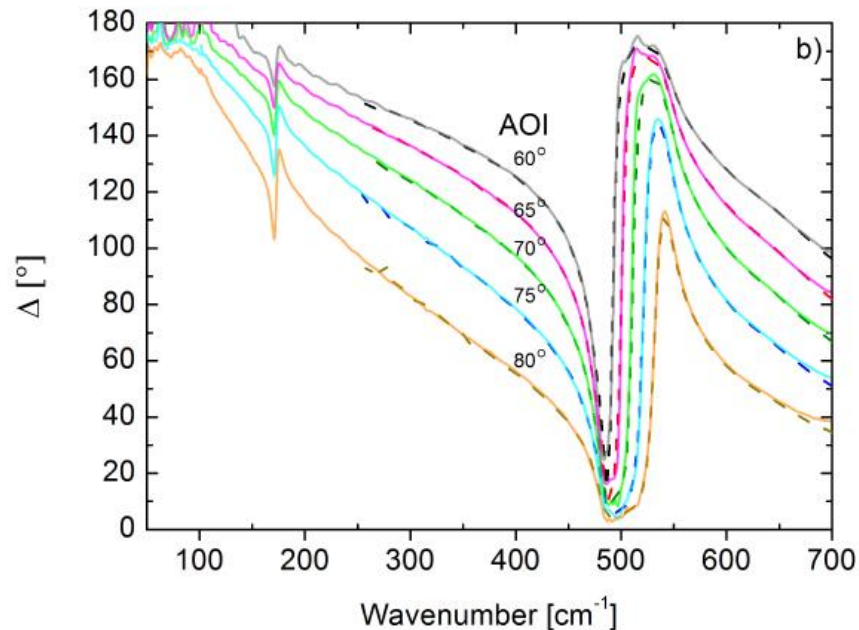


# Testing performance on SrTiO<sub>3</sub> single crystal



- Measured  $\Psi$  and  $\Delta$  in comparison with those measured with Woollam IR-VASE.

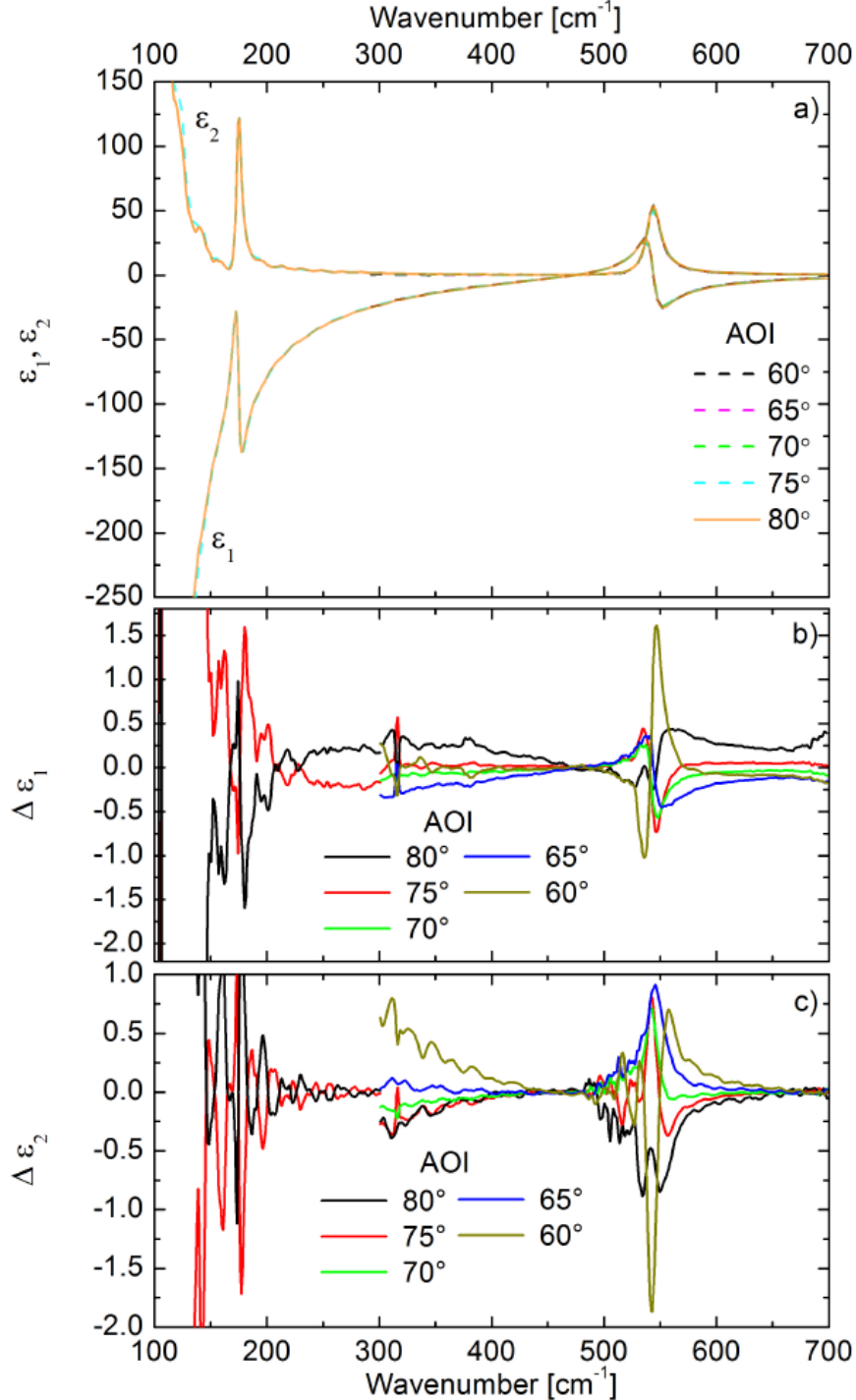
- The difference is less than  $0.2^\circ$  in  $\Psi$  and less than  $1^\circ$  in  $\Delta$ .



- Reproducibility in  $\Psi$  is better than  $0.1^\circ$  and better than  $0.3^\circ$  in  $\Delta$ .



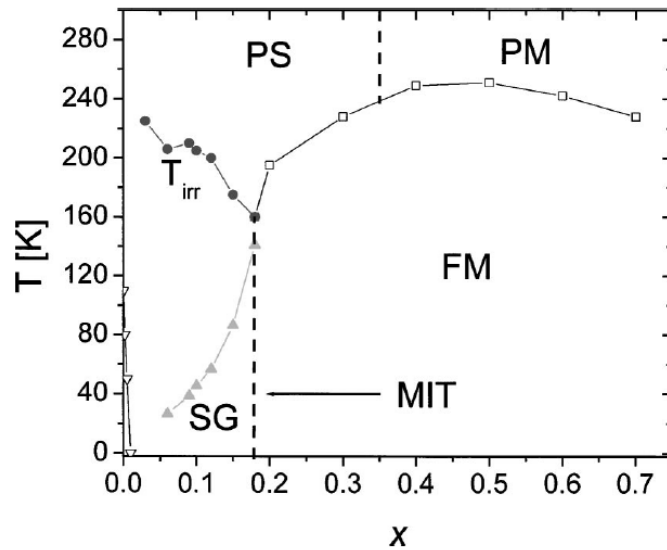
# dielectric function of SrTiO<sub>3</sub>



- obtained dielectric function of SrTiO<sub>3</sub> from different angles of incidence
- agreement down to factor about 1:100

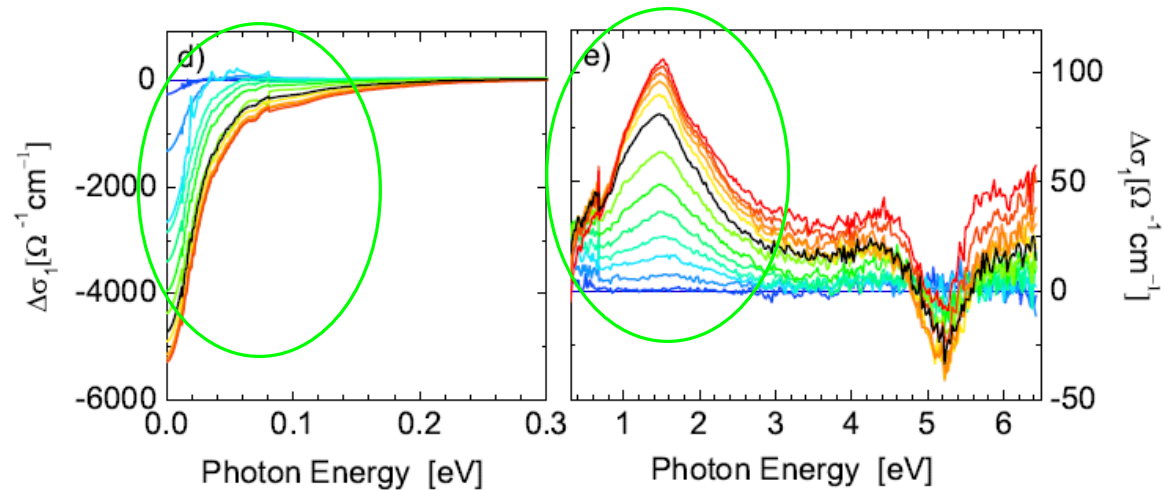
# Jak vypadá přechod se „špatným spinem“ v $\text{La}_{1-x}\text{Sr}_x\text{CoO}_3$ pro další úrovně koncentrací stroncia?

- elektronová struktura (Drude a “wrong spin transition”) feromagnetického stavu v  $\text{La}_{1-x}\text{Sr}_x\text{CoO}_3$  v závislosti na koncentraci děr  $x$ . Evoluce z izolujícího stavu ( $x=0$ ) do feromagnetu ( $x>0$ )



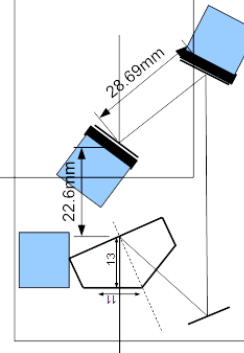
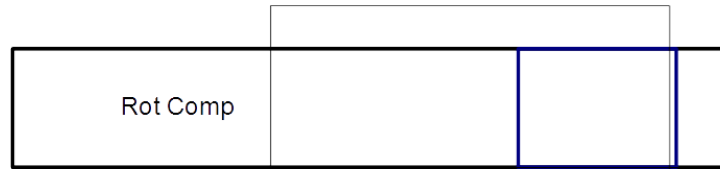
- dopování  $x=0.5, 0.7$ , a  $0.2$

- dopování  $x=0.3$

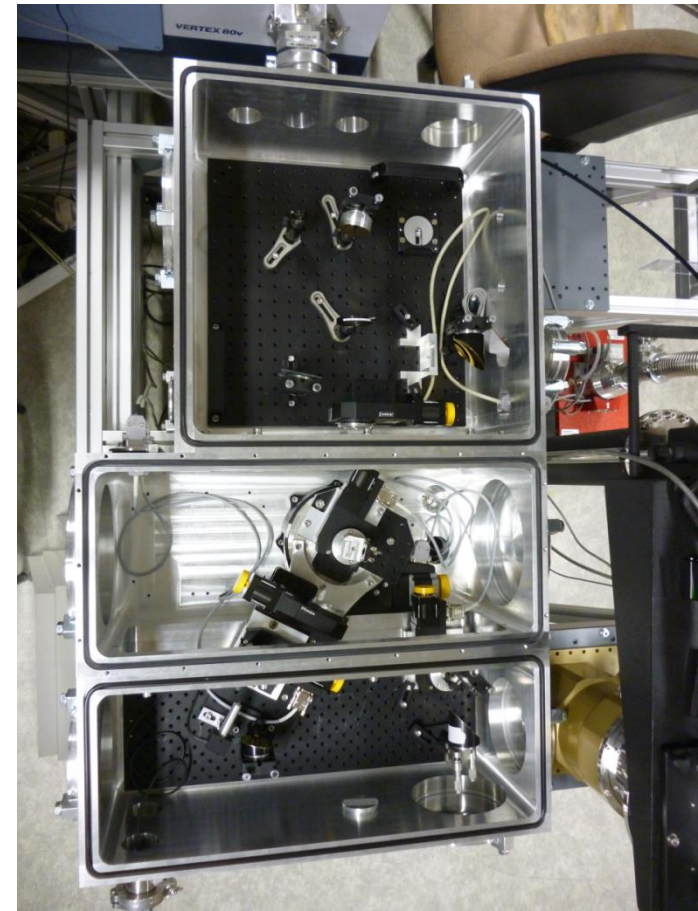
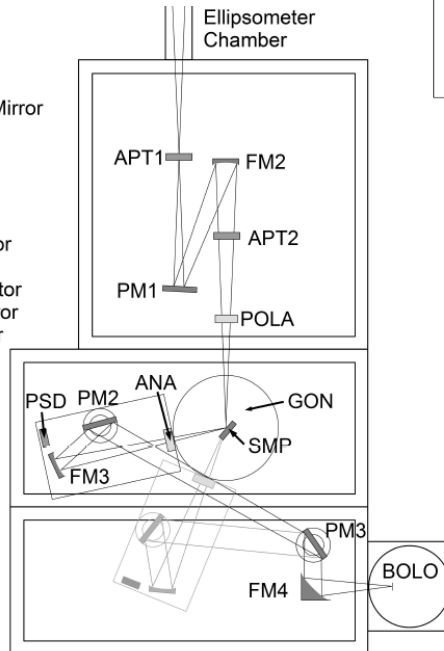


# Rotační kompenzátor (čtvrtvlnová destička) pro FIRový elipsometr

- kompenzátor (čtvrtvlnová „destička“) pro FIRový elipsometr
- umožňuje provádět elipsometrii s „rotačním kompenzátořem“, která umožňuje měřit depolarizaci a lépe měřit  $\Delta$  v celém oboru
- pouze jediný další takový elipsometr na světě (Brookhaven, USA)



ANA - Analyzer  
APT1,2 - Aperture  
BMS - Beam Splitter  
BOLO - Bolometer  
FM1,3,4 - Parabolic Mirror  
FM2 - Elliptical Mirror  
GLB - Glow Bar  
GON - Goniometer  
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LAS - Alignment Laser  
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RM - Removable Mirror  
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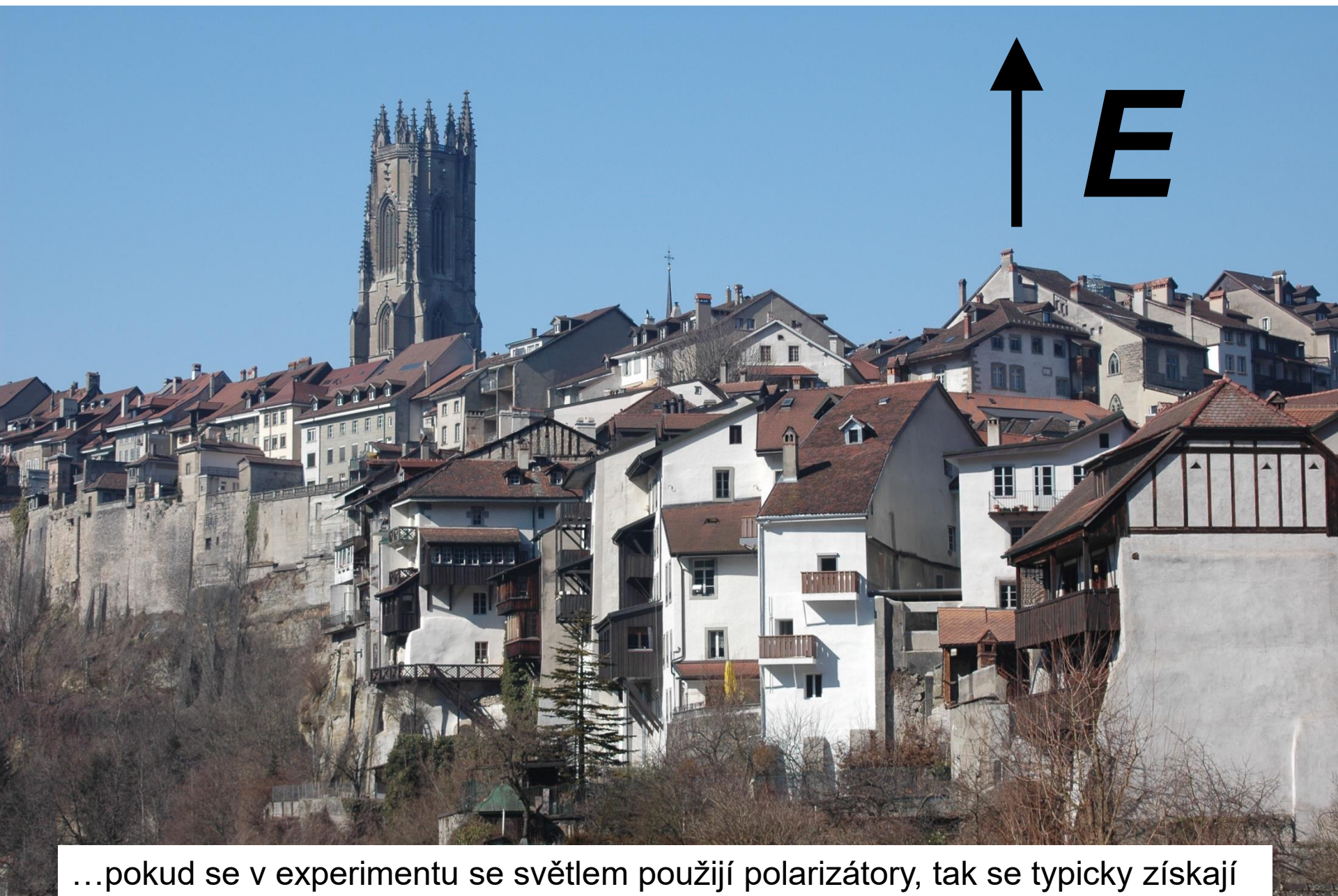


**dodatky**



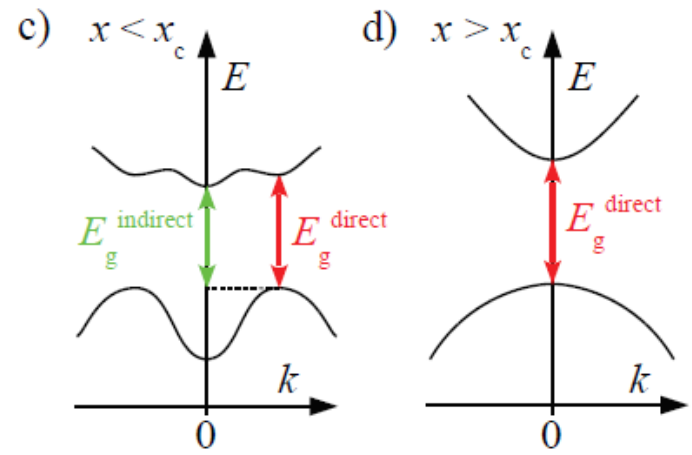
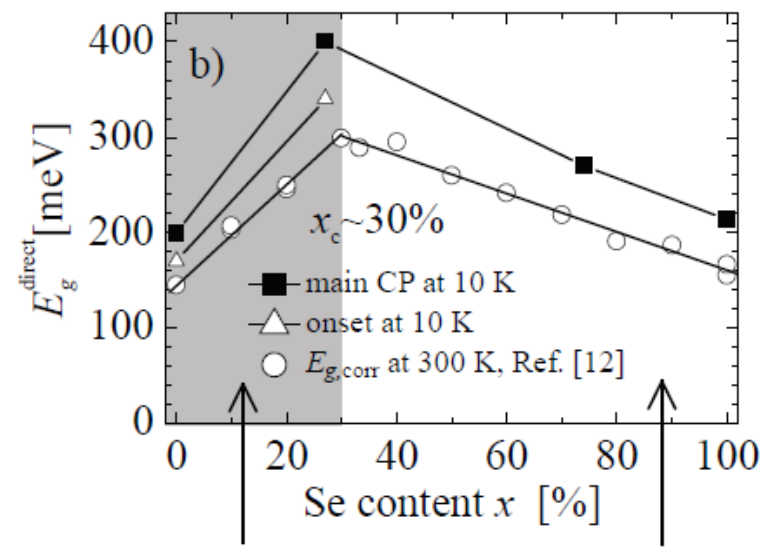
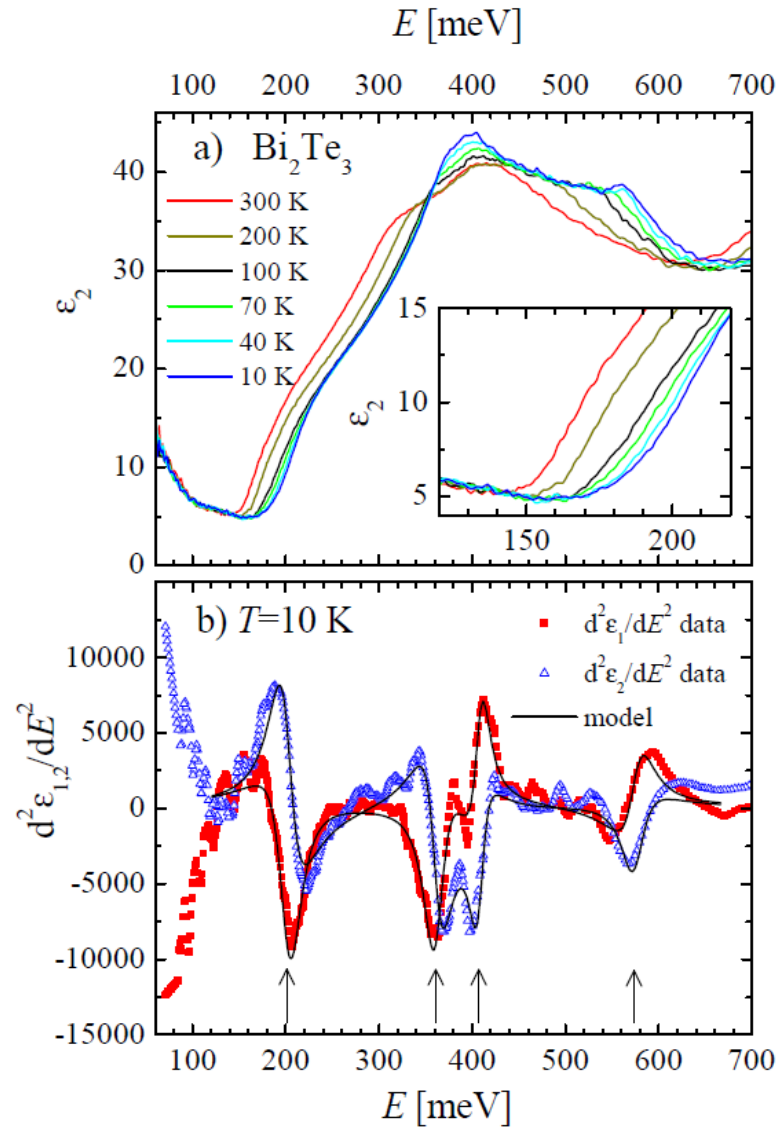






...pokud se v experimentu se světlem použijí polarizátory, tak se typicky získají nové informace

# Absorpční hrana v topologických izolátorech $\text{Bi}_2\text{Se}_x\text{Te}_{1-x}$



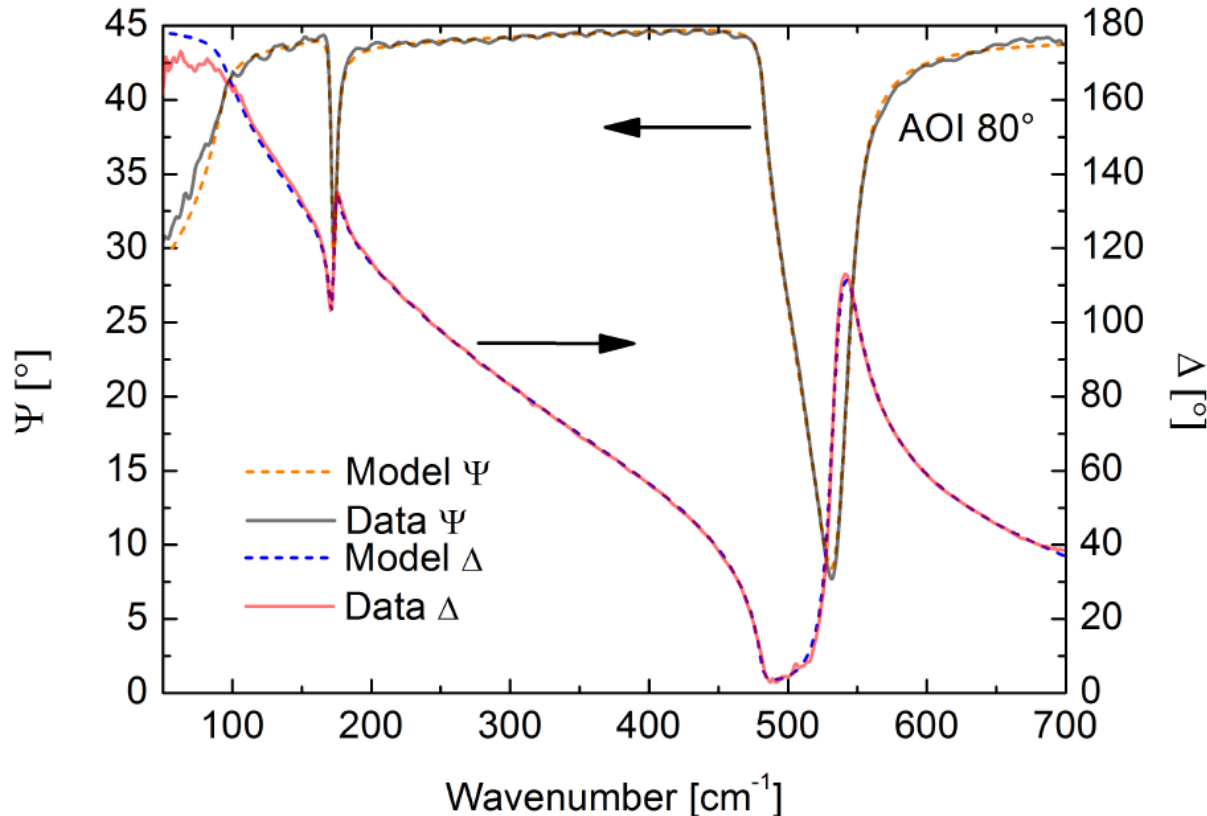
Druhé derivace kritických bodů modelovány funkcí

$$\frac{d^j \hat{\epsilon}(E)}{dE^j} = A e^{i\phi} (E - E_{\text{CP}} + i\Gamma)^{-n-j},$$

# automated variable angle far-infrared ellipsometer

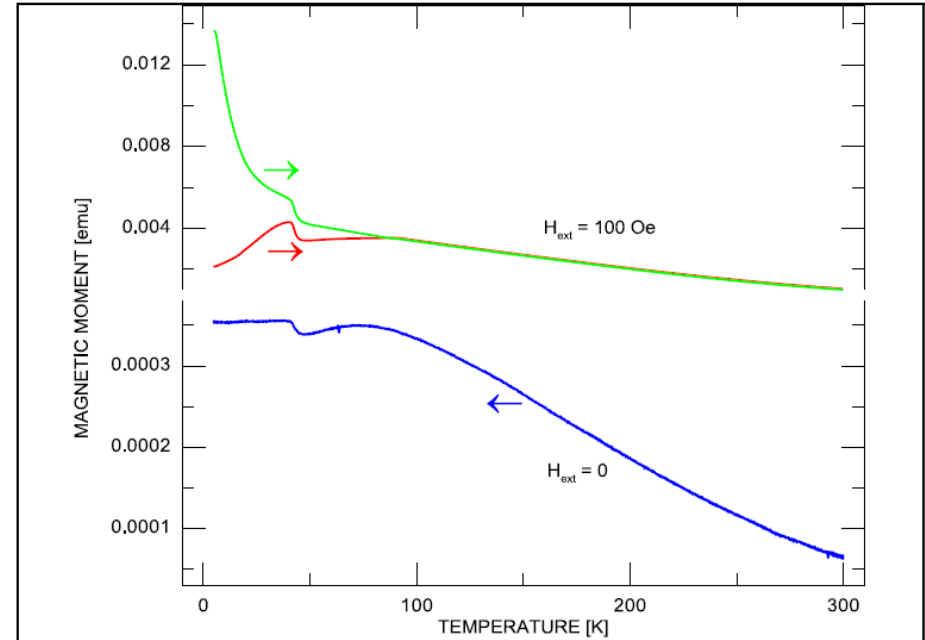
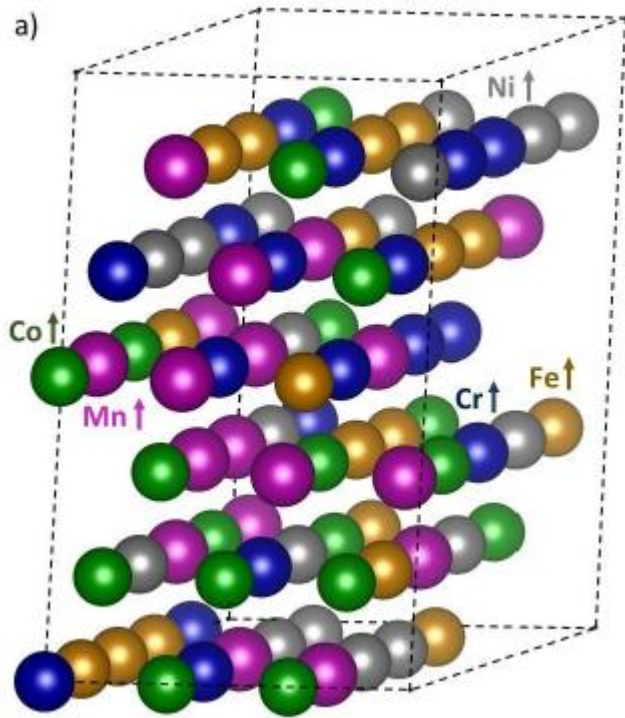
- Fitting of data at AOI = 80° with complex lorentzians demonstrates Kramers-Kronig consistency of our data.
- Effect in  $\Delta$  below 100 cm<sup>-1</sup> is likely an onset of diffraction effects

$$\varepsilon(\omega) = \varepsilon_{\infty} + \sum \frac{\omega_{pl}^2 + i\omega_c\omega}{\omega_0^2 - \omega^2 - i\omega\gamma}$$





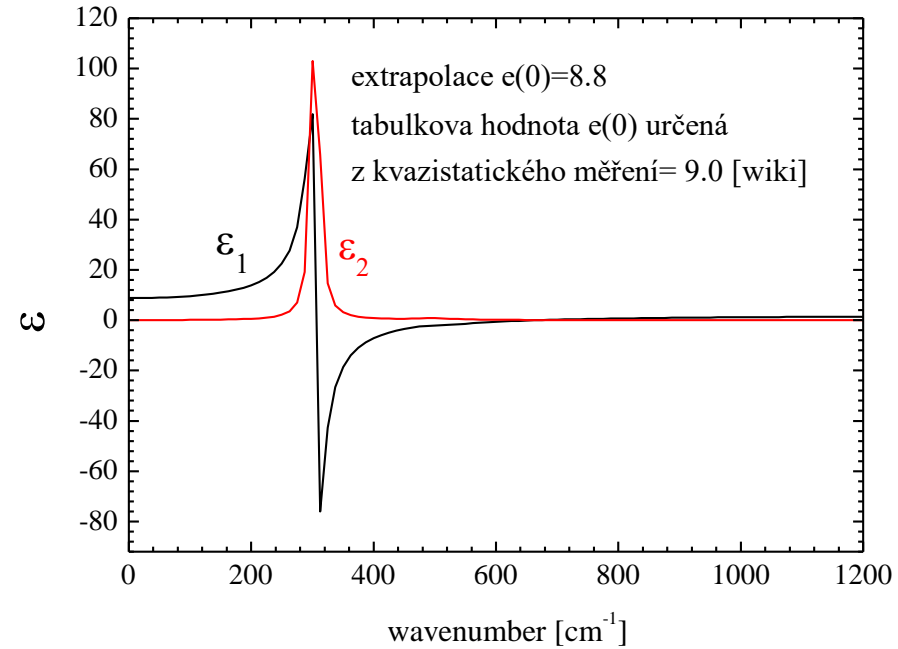
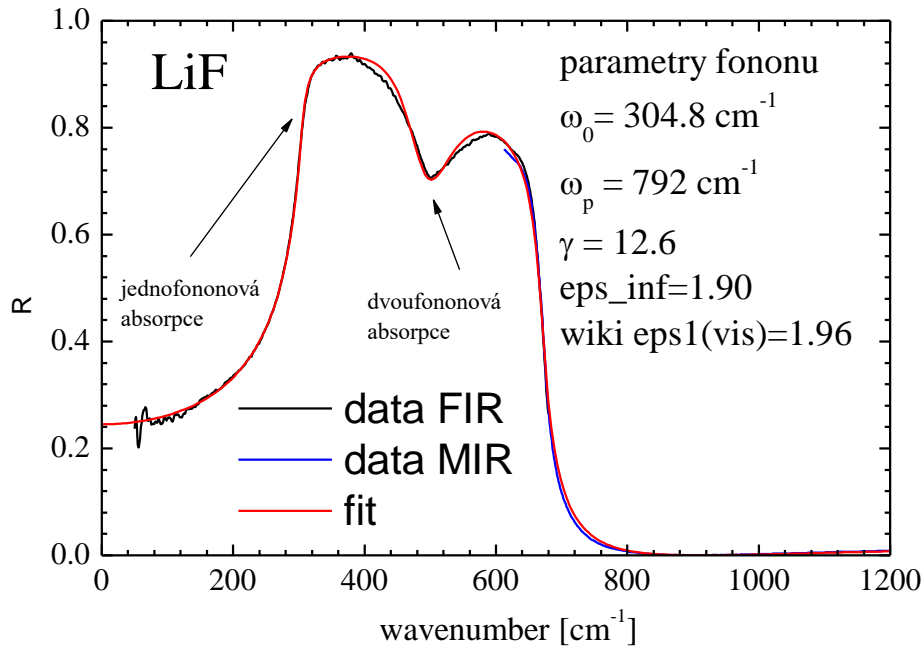
# CrMnFeCoNi high-entropy alloy



*Fig. 4 Temperature dependence of magnetic moment measured with decreasing temperature in zero field (-), with increasing temperature after zero field cooling in 100 Oe, and with increasing temperature after 5 T (-) field cooling in 100 Oe.*

- Paramagnetic to spin glass transition at 93K
- ferromagnetic transition at 38 K

# ukázka: IČ Reflektivita LiF



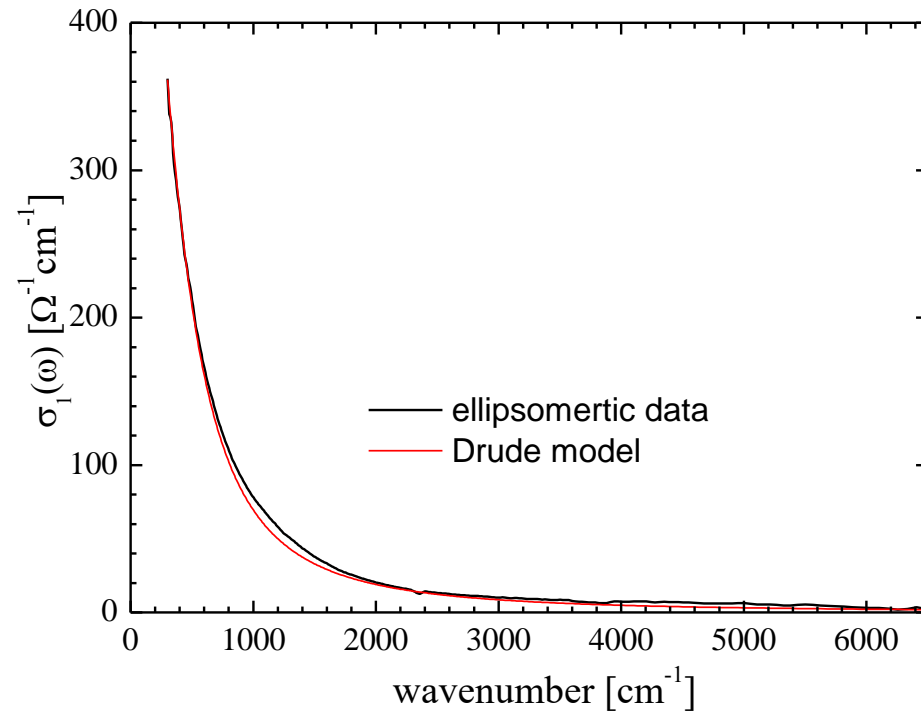
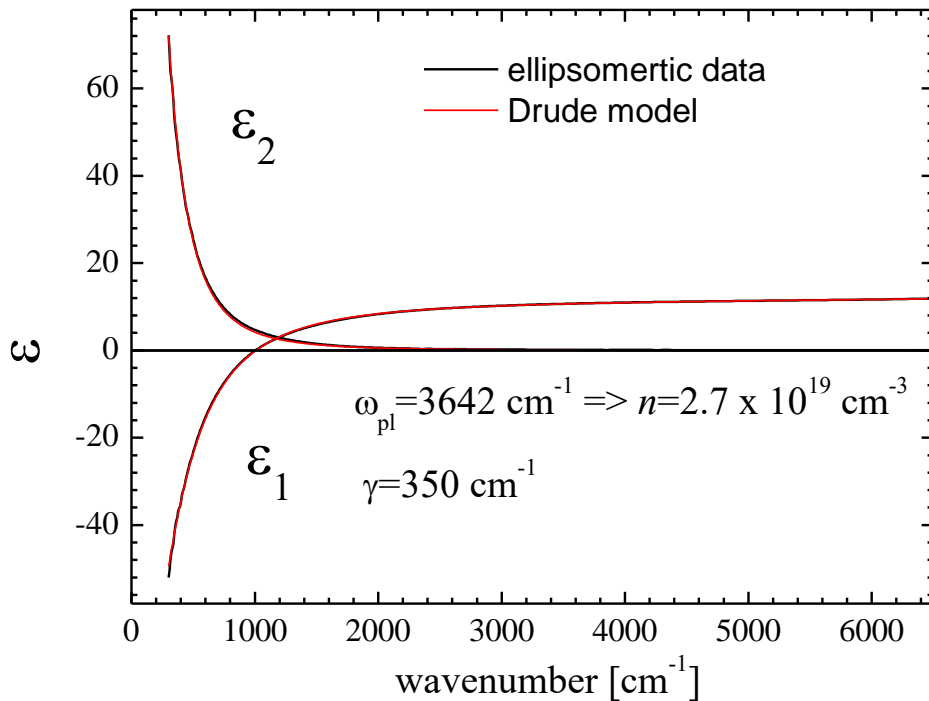
# Drude model

A classical model of dielectric response of free and *mutually non-interacting* charge carriers

$$\varepsilon(\omega) = \varepsilon_\infty - \frac{\omega_{\text{pl}}^2}{\omega(\omega + i\gamma)}$$

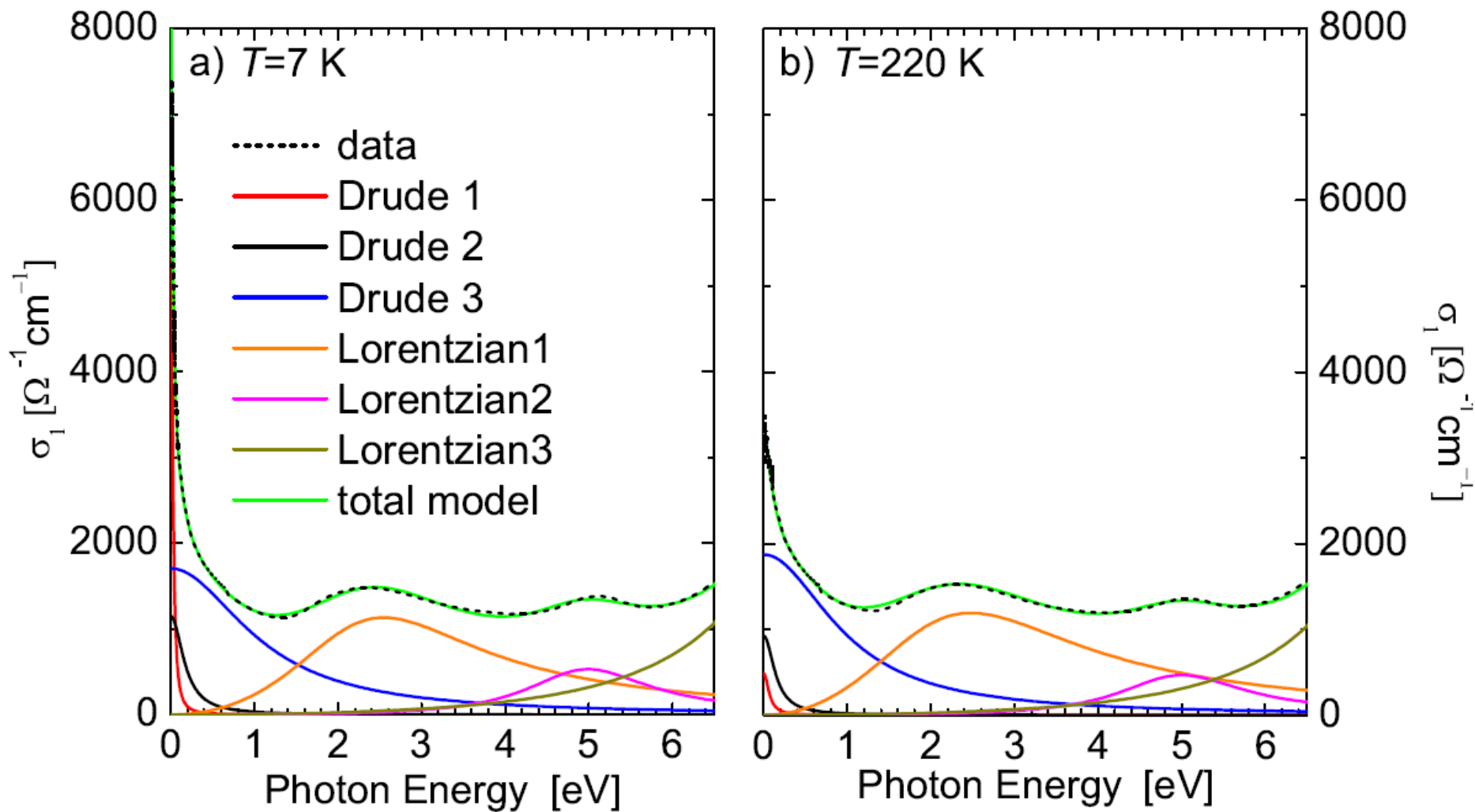
where  $\omega_{\text{pl}}$  is the plasma frequency  $\omega_{\text{pl}} = \sqrt{\frac{q^2 n}{\varepsilon_0 m^*}}$

Example on n-doped silicon:



# Optical signatures of ferromagnetic state

$\text{La}_{0.7}\text{Sr}_{0.3}\text{CoO}_3$ ,  
 $T_c \sim 205 \text{ K}$



# supravodivá mezera v $\text{YBa}_2\text{Cu}_3\text{O}_7$ , $T_c=92\text{K}$

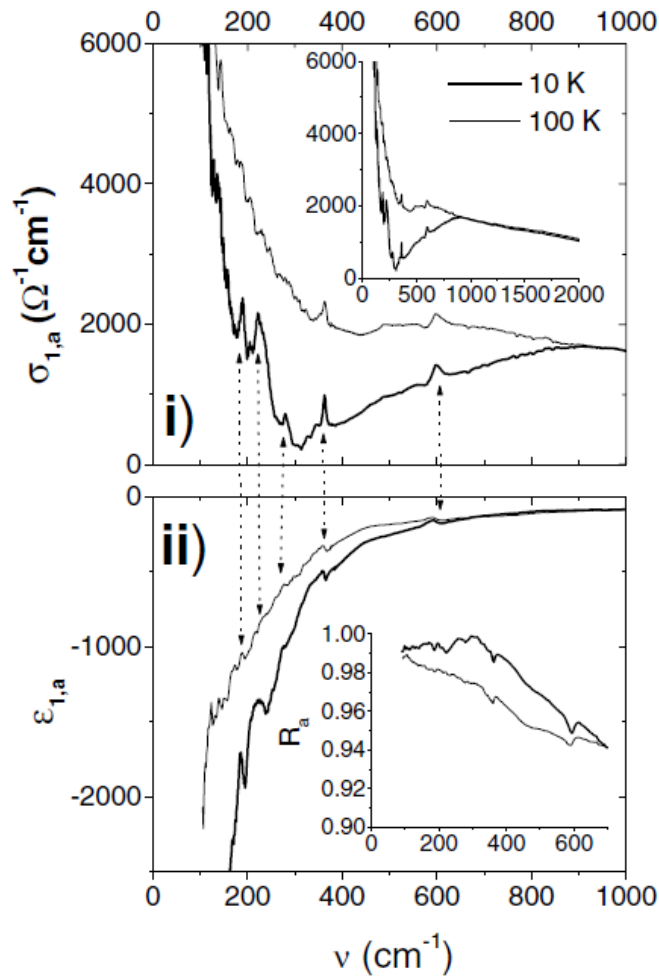
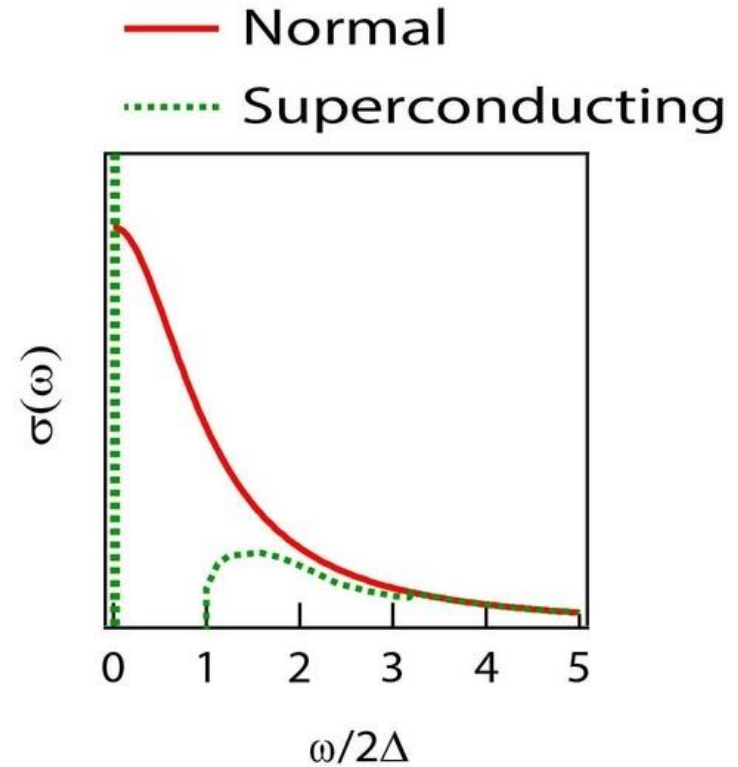


Fig. 1. *a*-Axis component of the real part of the: (i) conductivity and (ii) dielectric function of  $\text{YBa}_2\text{Cu}_3\text{O}_{6.95}$  ( $T_c = 91.5\text{ K}$ ) at 100 K (thin solid line) and 10 K (thick solid line). Dotted arrows mark the collective modes. Inset: (i)  $\sigma_{1,a}(\nu)$  over an extended spectral range and (ii) normal incidence reflectivity,  $R_n$ , as deduced from the ellipsometric data.

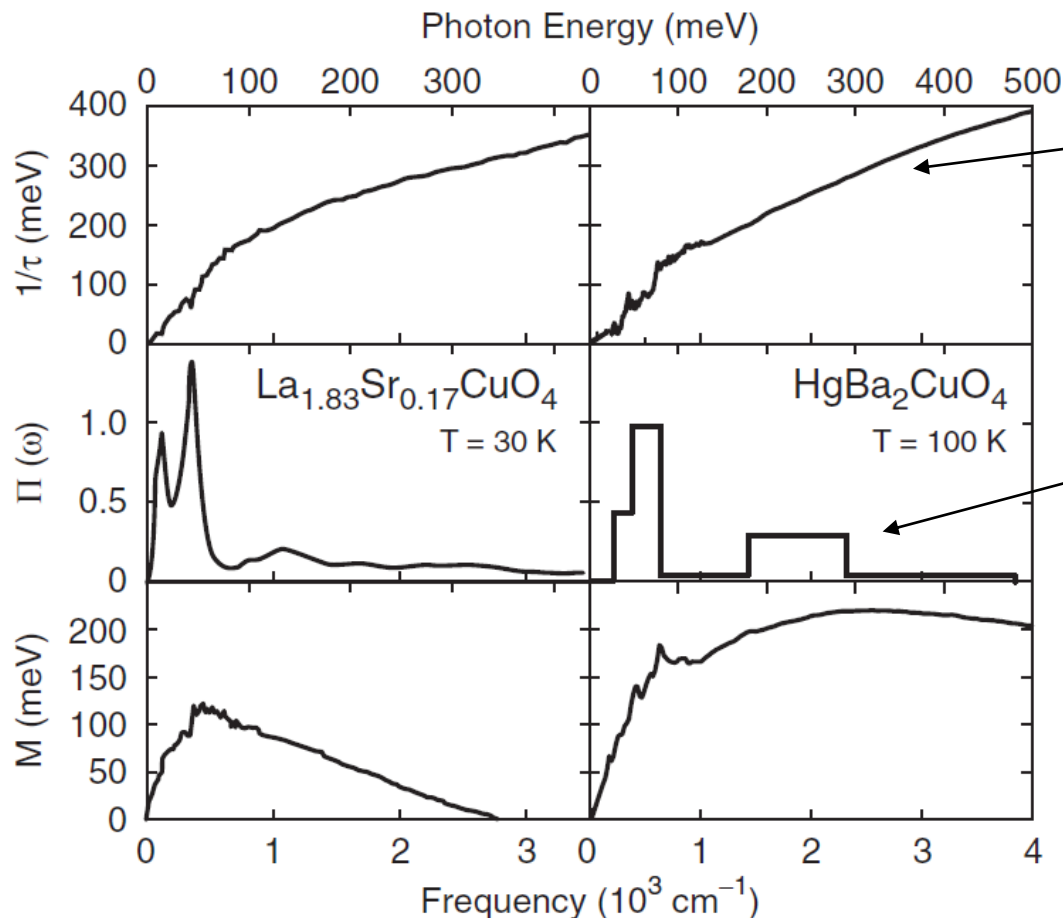
C. Bernhard, Sol. Stat. Comm (2001)



V supravodivém stavu je v absorpci očekávaná mezera pod dvojnásobkem supravodivé mezery  $2\Delta$ . Integrál spektrem se však zachovává- přesunuje se do delta funkce na  $\omega=0$ .

sumační pravidlo: 
$$\int_0^{\infty} \sigma_1(\omega) d\omega = \frac{\pi}{2} \frac{nq^2}{\epsilon_0 m} = \text{const.}$$

# určení interakce mezi elektrony ve vysokoteplotních supravodičích



frekvenčně závislé  $\tau(\omega)$  značí interakci mezi elektrony

• frekvenčně závislé interakční funkce (glue-lepidlo) odvozená z dat.

• Její složka na vysokých energiích 250 meV značí, že glue nemůže být pouze díky fononům.

• na základě tohoto glue byla vypočtena kritická supravodivost  $\sim 200$  K

FIG. 13. Comparison at  $T \approx T_c$  of the imaginary part [ $1/\tau(\omega)$ ] and the real part [ $M(\omega)$ ] of the optical self-energy, and the electron-boson coupling functions of  $\text{La}_{1.83}\text{Sr}_{0.17}\text{CuO}_4$  ( $T_c = 31$  K) (Hwang *et al.*, 2008) and  $\text{HgBa}_2\text{CuO}_4$  ( $T_c = 97$  K). From van Heumen, Muhlethaler *et al.*, 2009.

# supravodivá mezera v $\text{YBa}_2\text{Cu}_3\text{O}_7$ , $T_c=92\text{K}$

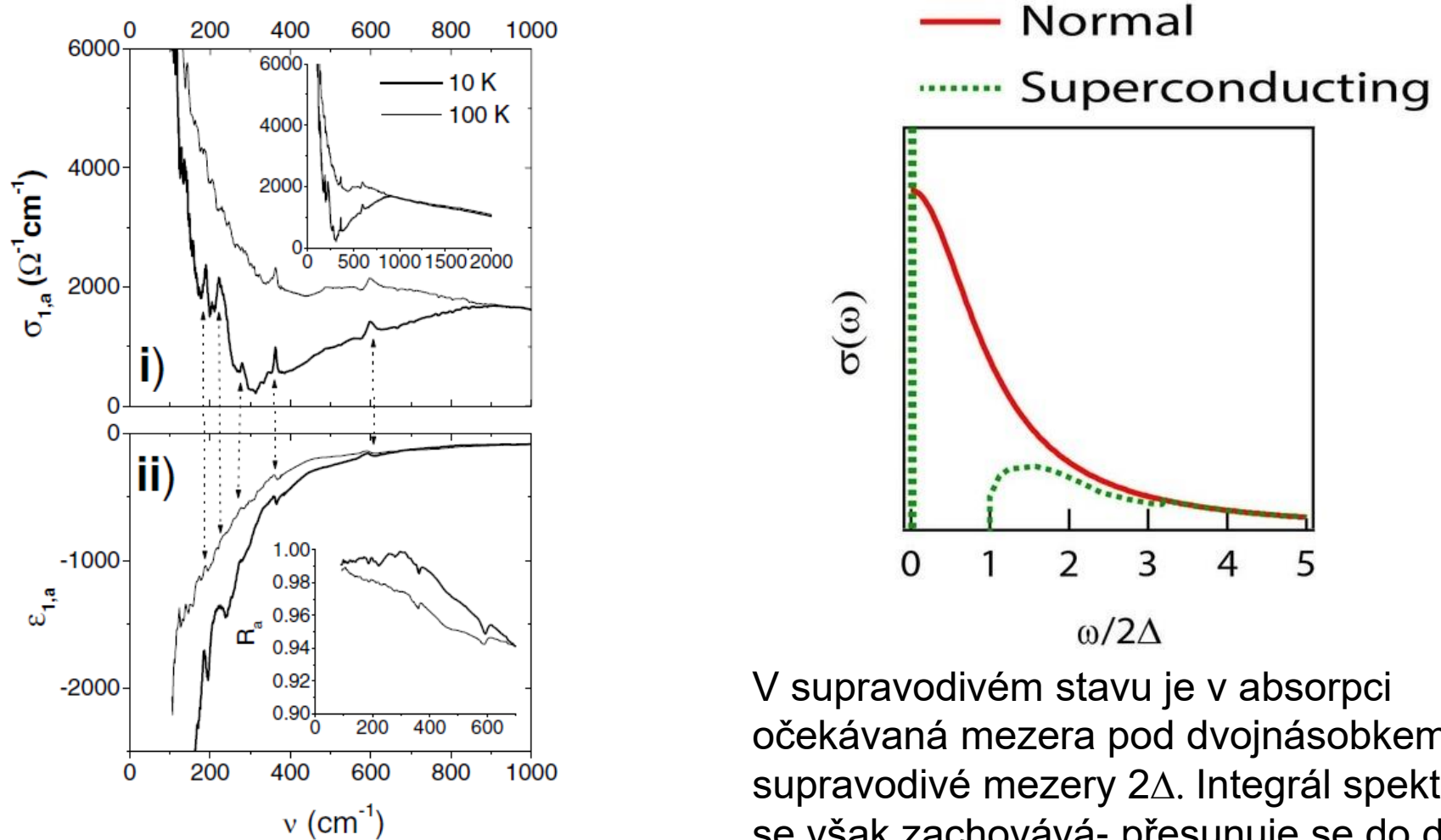


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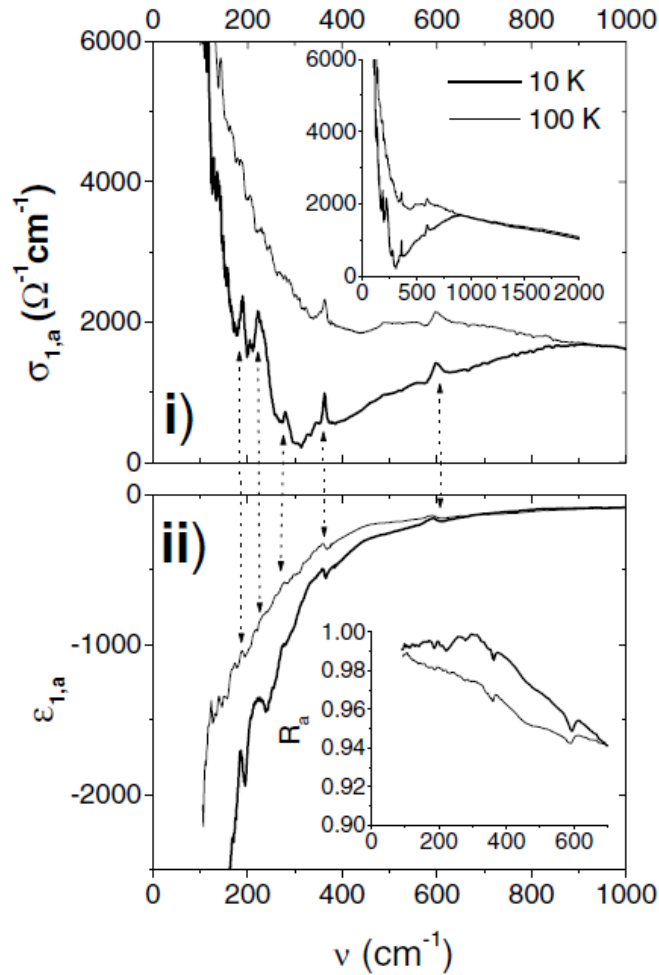
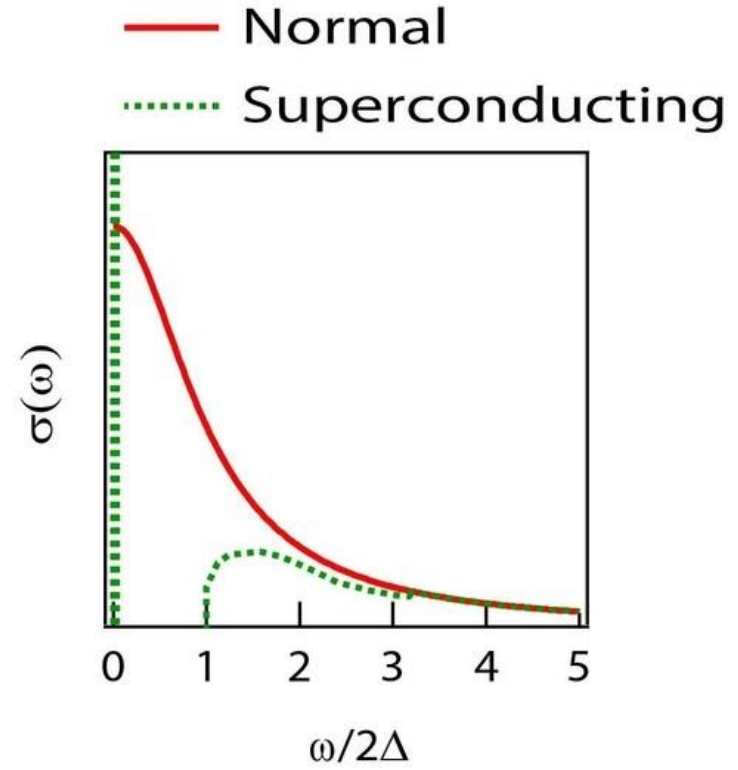


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C. Bernhard, Sol. Stat. Comm (2001)



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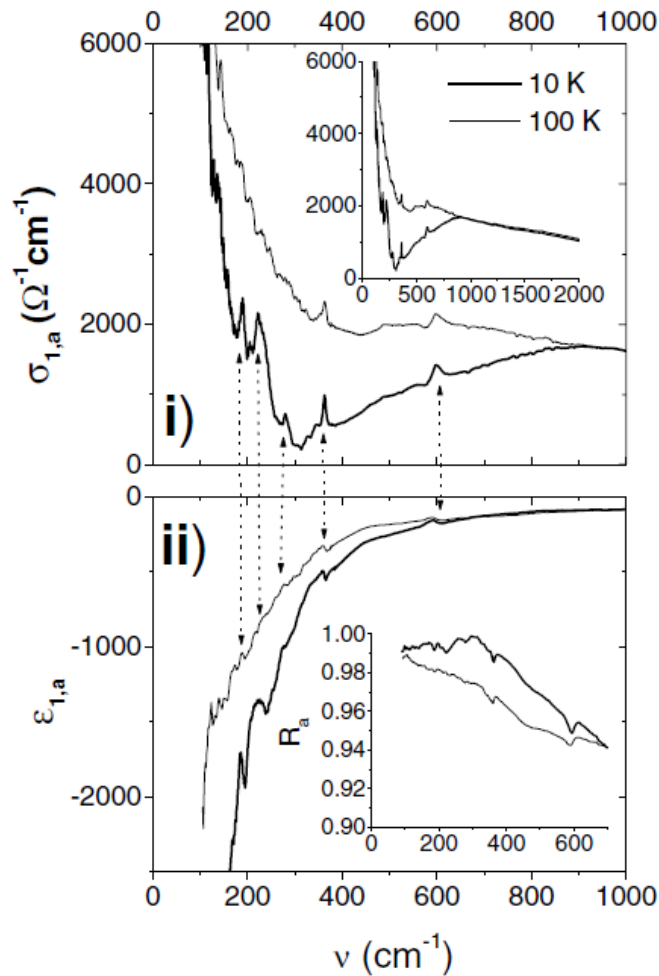
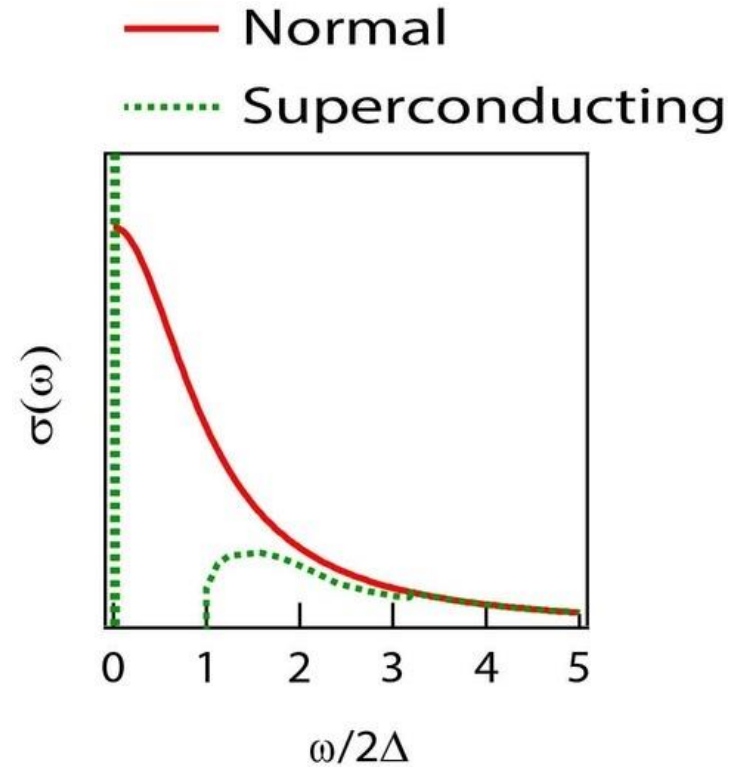


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C. Bernhard, Sol. Stat. Comm (2001)



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