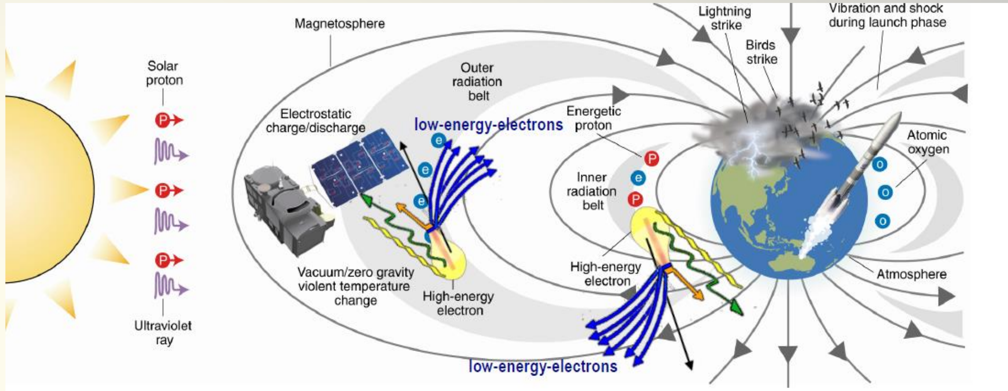
LEE2022

a brainstorming meeting on relevance of Low Energy Electrons in aerospace



Contribution of plasmon decay to secondary electron emission

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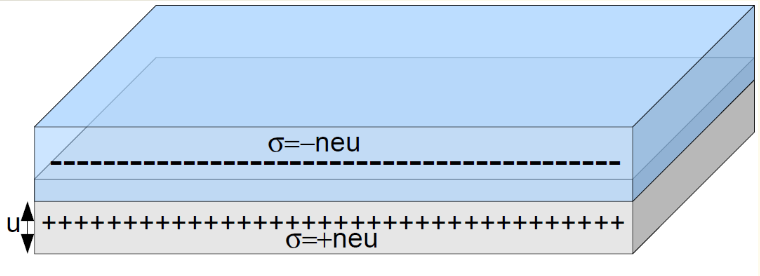
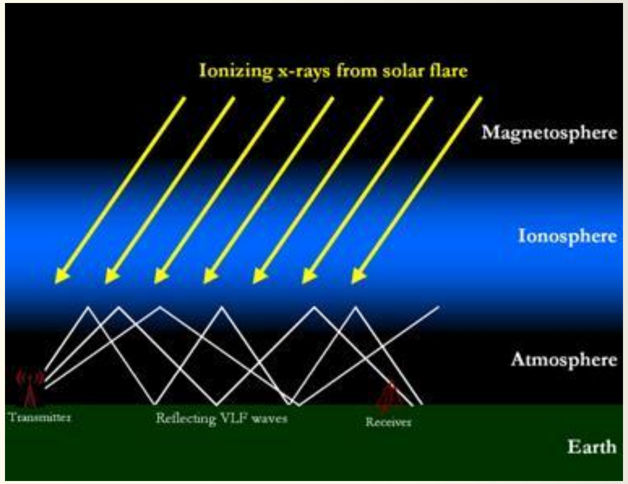
Cosa sono i plasmoni

I plasmoni sono oscillazioni di carica collettive che si possono manifestare in sistemi diversi:

Elettroni all'interno di un solido



Ionosfera



Supponiamo che gli elettroni subiscano uno spostamento longitudinale **u**:

$$u(t) = u_o e^{i\omega t}$$

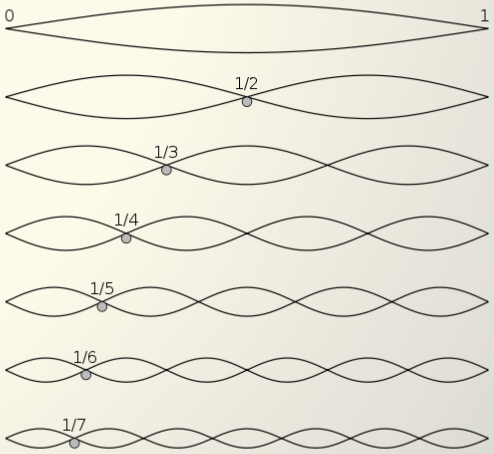
$$m\ddot{u}(t) = -eE(t) \qquad E = 4\pi\sigma \qquad \sigma = Neu$$

$$m\ddot{u}(t) + 4\pi Ne^2 u = 0$$

Equazione di un oscillatore armonico con frequenza propria:

$$\omega_p^2 = \frac{4\pi Ne^2}{m}$$

Frequenza di plasma nel limite di lunghezza d'onda infinita



Le oscillazioni di plasma esistono anche per q $\neq 0$

$$\omega(q) = \omega_p \left(1 + \frac{3v_F^2}{10\omega_p^2} q^2\right)$$

Excitation mode compatible with Maxwell equations

Plasmon is an e.m. excitation that must satisfy Maxwell equations

Maxwell equations

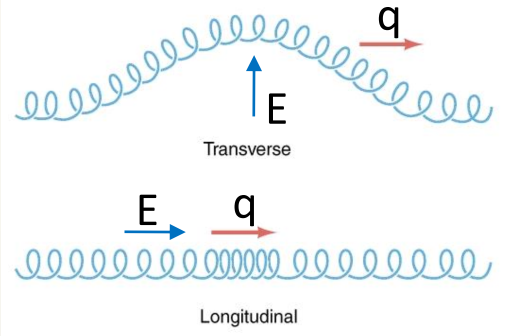
$$div(\mathbf{E}) = 4\pi(\rho_{pol} + \rho_{ext})$$
$$div(\mathbf{B}) = 0$$
$$rot(\mathbf{E}) = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}$$
$$rot(\mathbf{B}) = 4\pi(j_{ext} + j_{pol}) + \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t}$$

Maxwell equations in the Fourier space

$$\mathbf{q} \cdot \hat{\mathbf{D}} = -4\pi i \hat{\rho}_{ext}$$
$$\mathbf{q} \cdot \hat{\mathbf{B}} = 0$$
$$\mathbf{q} \wedge \hat{\mathbf{E}} = \frac{\omega}{c}\hat{\mathbf{B}}$$
$$\mathbf{q} \wedge \hat{\mathbf{H}} = \hat{j}_{ext} - \frac{\omega}{c}\hat{\mathbf{D}}.$$

In the absence of external charge and current from Maxwell equations we obtain:

$$\mathbf{q} \cdot (\mathbf{q} \cdot \mathbf{E}) - q^2\mathbf{E} = -\epsilon(\mathbf{q}, \omega)\frac{\omega^2}{c^2}\mathbf{E}$$



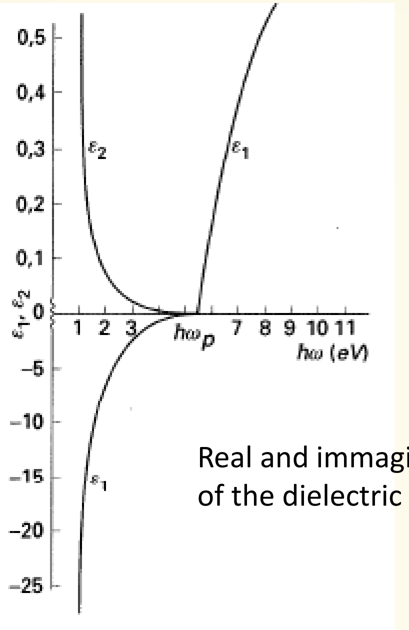
$$q^2 = \frac{\omega^2}{c^2}\varepsilon(q,\omega)$$ (transverse wave)

$$0 = \frac{\omega^2}{c^2}\varepsilon(q,\omega)E \qquad \varepsilon(q,\omega) = 0$$ (longitudinal wave)

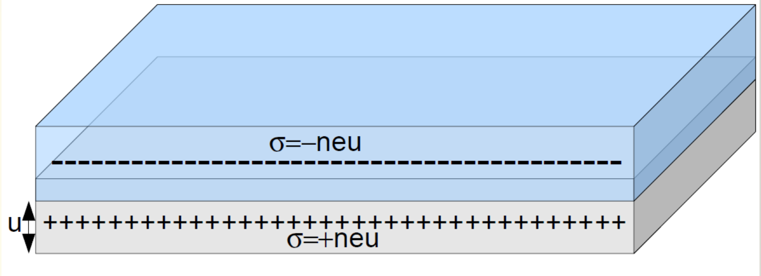
$$D = \varepsilon(q,\omega)E$$

If external field is zero, D=0
The electric field E can be different from zero only if $\varepsilon = 0$

Bulk plasmon in metal



Real and immaginary part of the dielectric function



Drude model for a simple metal:

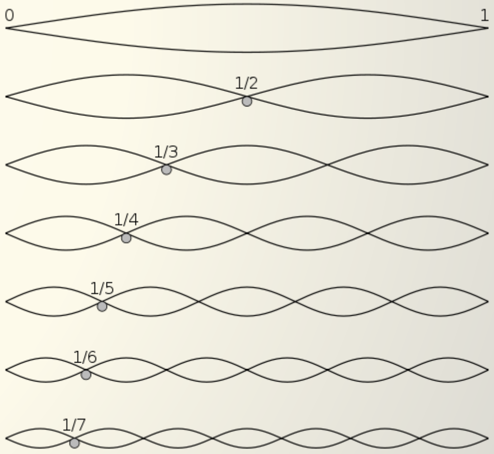
$$\varepsilon(\omega) = 1 - \frac{\omega_p^2}{\omega^2 + i\omega\Gamma}$$

$$\varepsilon(\omega) = 1 - \frac{\omega_p^2}{\omega^2}$$

$\varepsilon_1 = 0$ per $\omega = \omega_p$

$$\omega_p^2 = \frac{4\pi N e^2}{m}$$

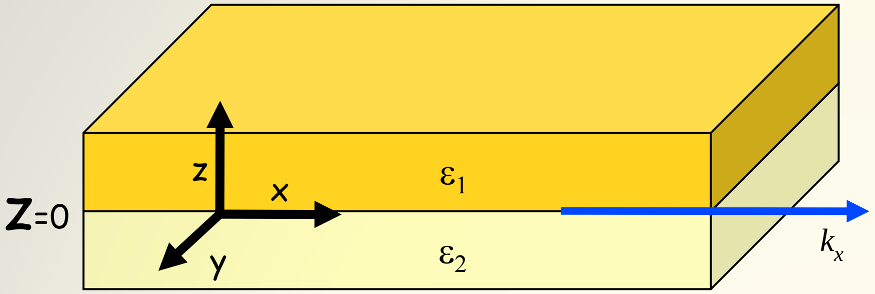
Plasma frequency in the limit of infinite wave length



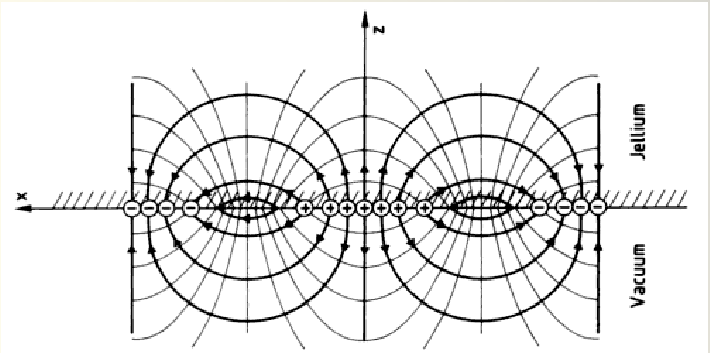
Dispersion relation for plasma excitation for q $\neq 0$

$$\omega(q) = \omega_p \left(1 + \frac{3 v_F^2}{10 \omega_p^2} q^2\right)$$

Surface plasmon



We consider an e.m. excitation propagating along x and strongly dumped in the z direction inside the two media



TMW $\boldsymbol{E}_i = (E_{i_x}, 0, E_{i_z})\, e^{-\kappa_i |z|}\, e^{i(q_i x - \omega t)}$ $\boldsymbol{H}_i = (0, H_{iy}, 0)\, e^{-\kappa_i |z|}\, e^{i(q_i x - \omega t)}$

Continuity condition across the surface separating the two media give rise to the following equation for the existence of a surface plasmon polariton

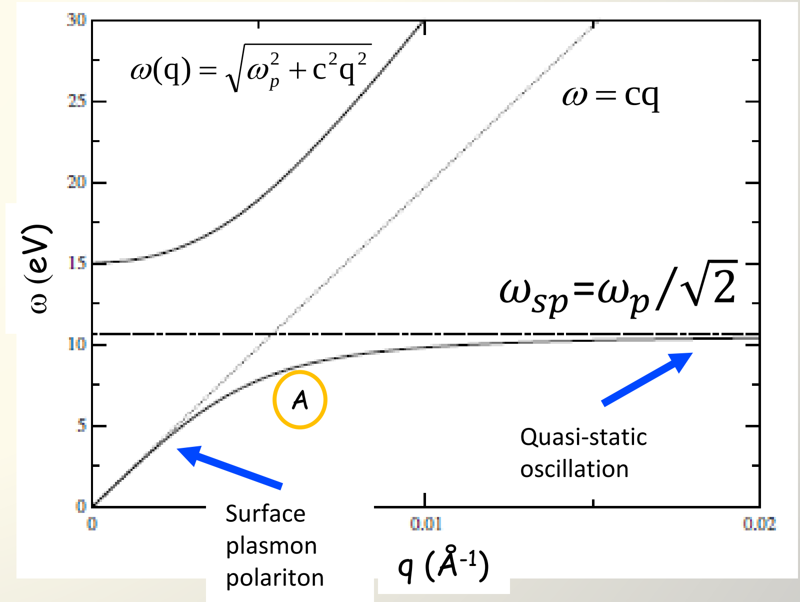
$$\frac{\varepsilon_1}{k_1} + \frac{\varepsilon_2}{k_2} = 0 \qquad q(\omega) = \frac{\omega}{c}\sqrt{\frac{\epsilon_1 \epsilon_2}{\epsilon_1 + \epsilon_2}}$$

$$\epsilon_1 + \epsilon_2 = 0$$

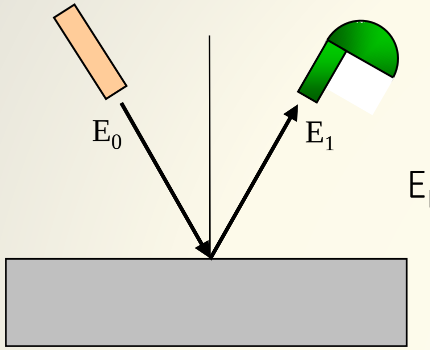
If $\varepsilon_2 = 1$ (vacuum) and ε_1 metal described by Drude model

$$\varepsilon_1 = 1 - \frac{\omega_p^2}{\omega^2}$$

$$\omega^2(q) = \omega_p^2/2 + c^2 q^2 - \sqrt{\omega_p^4/4 + c^4 q^4} \quad \text{(A)}$$



Plasmon excitation by electron scattering



$E_L=E_o-E_1$

$$\dot{W}=\frac{e^2}{4\pi^2\epsilon_0 v}\left\{\log\left[\left(\frac{\omega}{v}\right)^2+q_\perp^2\right]\right\}\Big|_0^{q_c}\int\omega d\omega Im\left\{\frac{-1}{\epsilon(\omega)}\right\}$$

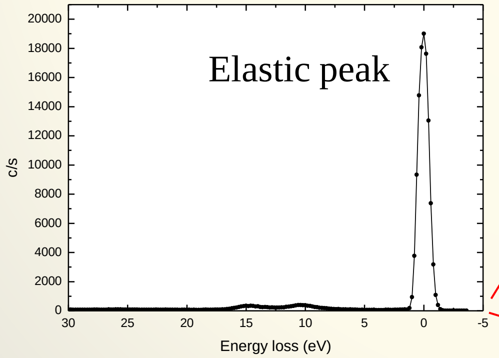
Bulk Loss function:

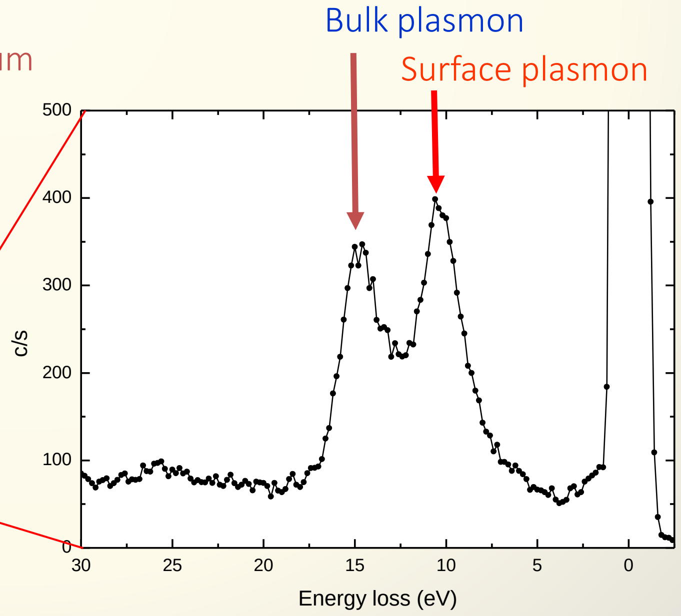
$$Im\left\{\frac{-1}{\epsilon(\omega)}\right\}=\frac{\epsilon_2(\omega)}{\epsilon_1^2(\omega)+\epsilon_2^2(\omega)}$$

Surface Loss function:

$$Im\left\{-\frac{1}{\varepsilon(\omega)+1}\right\}=\frac{\varepsilon_2(\omega)}{[\varepsilon_1(\omega)+1]^2+\varepsilon_2^2(\omega)}$$

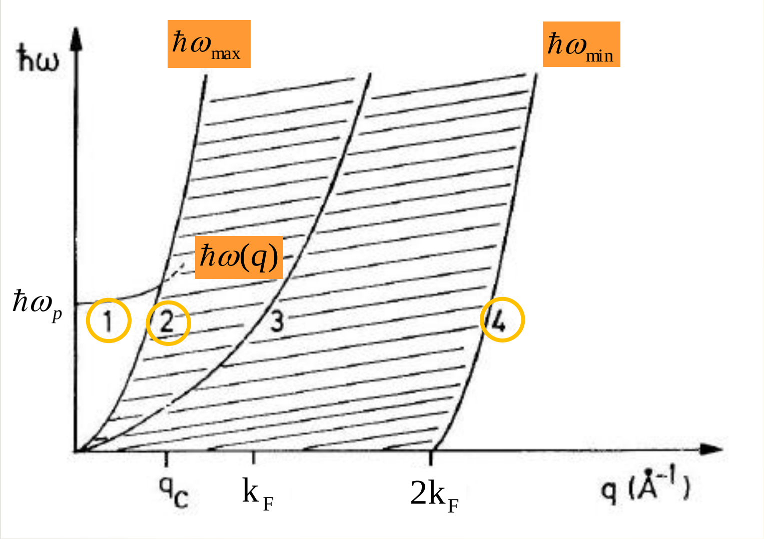
Al(100) Reflection Energy Loss Spectrum





Plasmon excitation by electron scattering

Il processo di eccitazione di un plasmone da parte di un fascio incidente di elettroni è in competizione con l’eccitazione di un un singolo elettrone all’interno di un solido



$$\mathbf{k}_f = \mathbf{q} + \mathbf{k}$$

$\hbar\omega, \hbar\mathbf{q}$ impulso ed energia persi dall’elettrone esterno

$\mathbf{k}, \mathbf{k}_f$ impulso iniziale e finale dell’elettrone nel solido

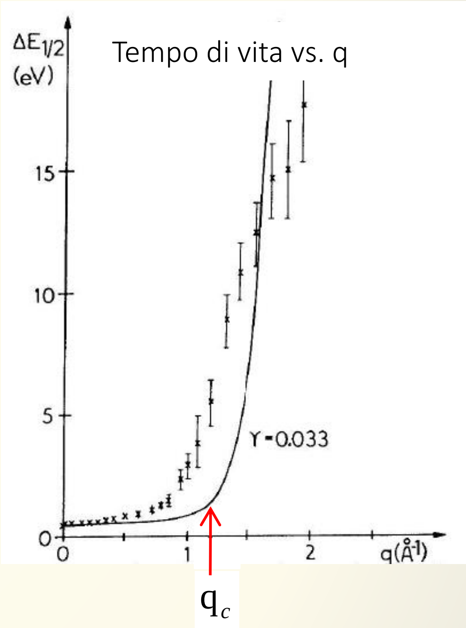
$$\hbar\omega = \underbrace{\frac{\hbar^2}{2m}(\mathbf{q}+\mathbf{k})^2}_{\text{E finale}} - \underbrace{\frac{\hbar^2}{2m}k^2}_{\text{E iniziale}} = \frac{\hbar^2}{2m}(q^2 + 2\mathbf{q}\cdot\mathbf{k})$$

4 $\hbar\omega_{min} = \frac{\hbar^2}{2m}(q^2 - 2qk_F)$

2 $\hbar\omega_{max} = \frac{\hbar^2}{2m}(q^2 + 2qk_F)$

Relazione di dispersione per il plasmone

$$\hbar\omega(q) = \hbar\omega_p\left(1 + \frac{3v_F^2}{10\omega_p^2}q^2\right) \quad (1)$$



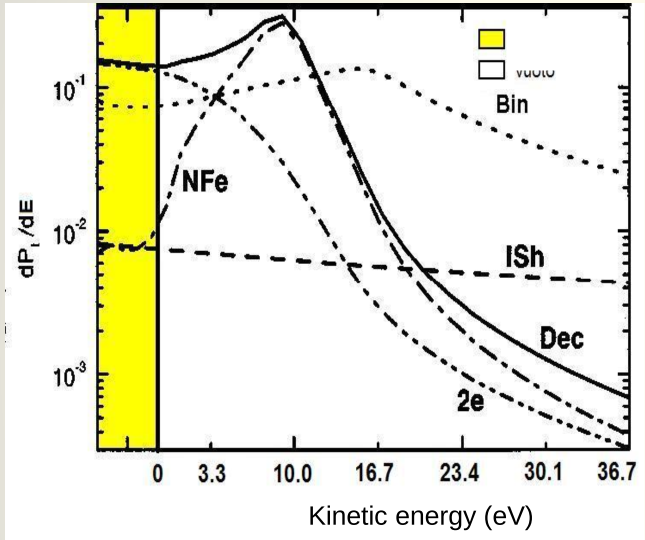
Stima di q_c ovvero quando la curva di dispersione del plasmone è degenere con l’eccitazione di singolo elettrone

$$\frac{\hbar^2}{2m}(q^2 + 2qk_F) = \hbar\omega_p\left(1 + \frac{3v_F^2}{10\omega_p}q^2\right)$$

trascurando i termini in q^2 ⟹ $q_c = \frac{\omega_p}{v_F} \approx 1\,\text{Å}^{-1}$

Decay channels of plasma oscillations

Calculation of secondary emission after the decay of volume plasmon in Aluminum



Bocan et al. Phys. Rev. A **69** (2004) 012901

- Two interacting electrons (2e) is important only at low energy

-The dominant process is the interband transition (NFe)

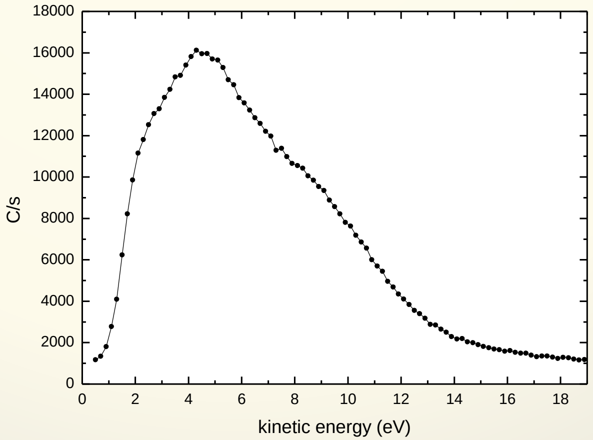
$$\hbar\omega_p \approx 5 \div 20\,\mathrm{eV}$$

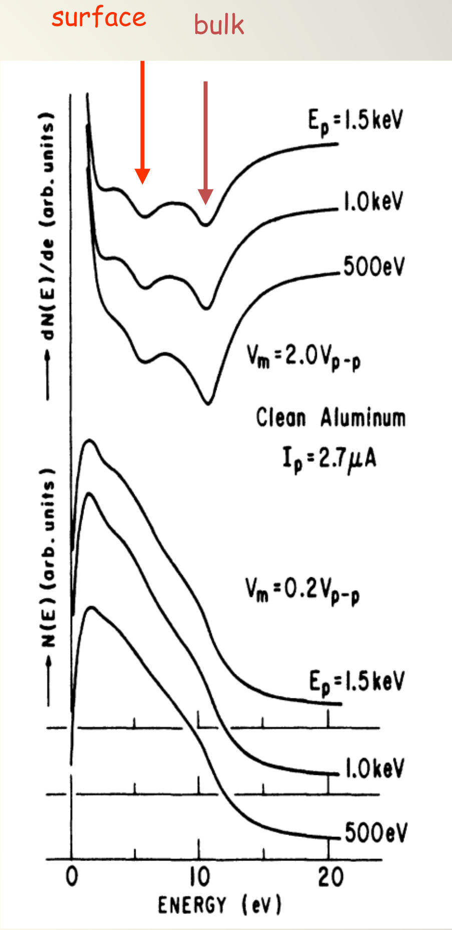
- understand how plasmons decay

- literature: plasmon transfer its energy and momentum to an electron of the solid

- emission of an electron in the secondary region (plasmon energy: few eV up to 20 eV)

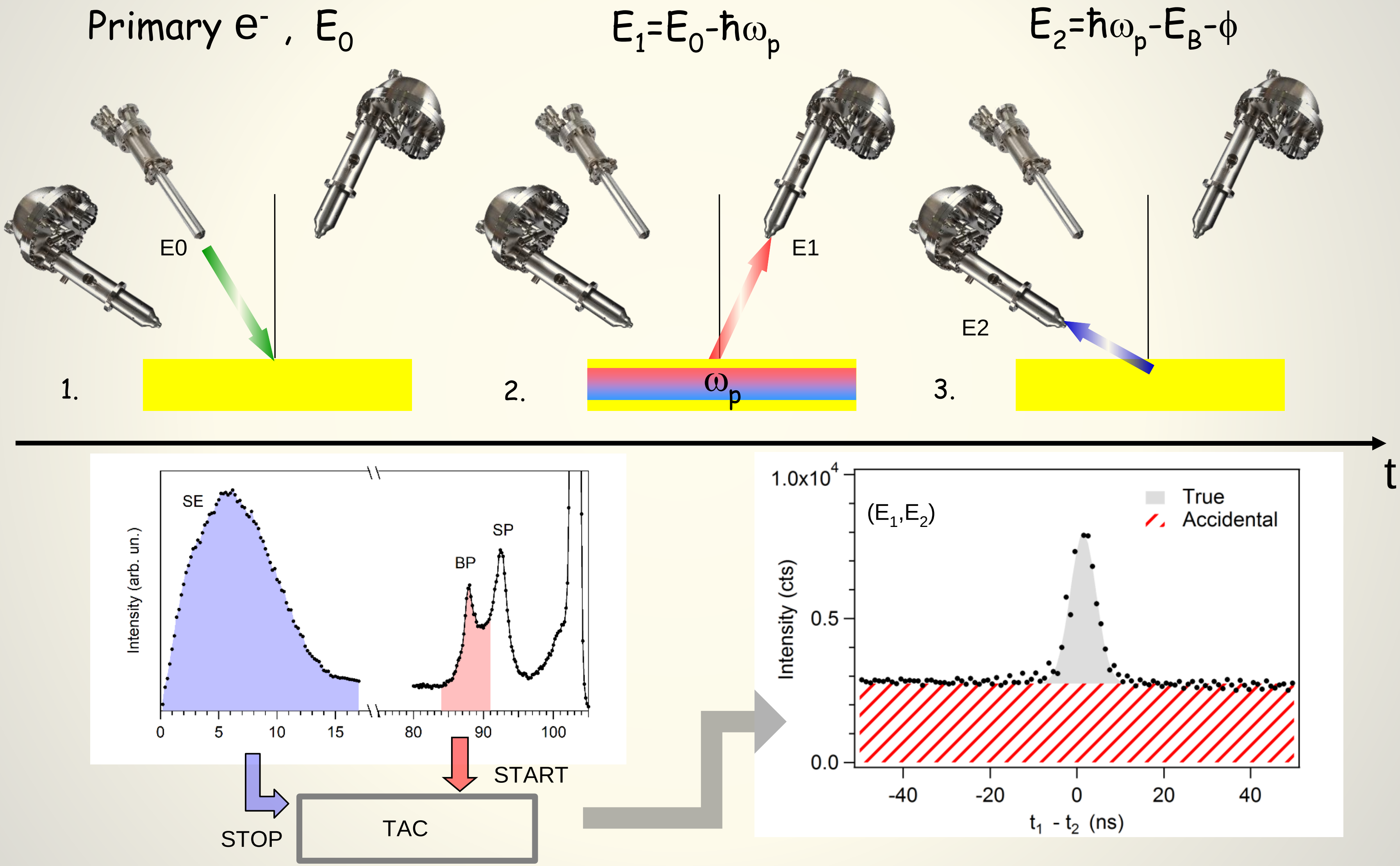
Al(100) Secondary electron energy region





Chung and Everhart
Phys. Rev. B **15** (1977) 4699

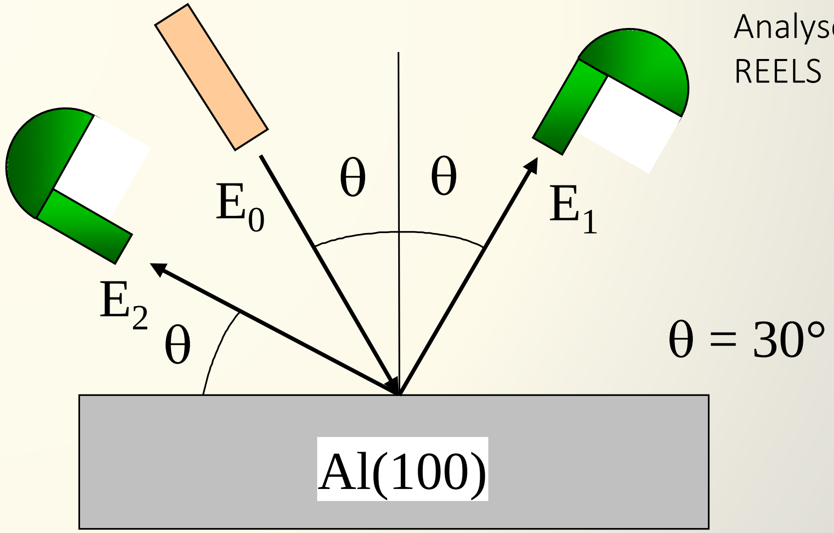
Electron-electron coincidence spectroscopy



Experimental apparatus

LASEC laboratory
Department of Physics
University of Roma Tre

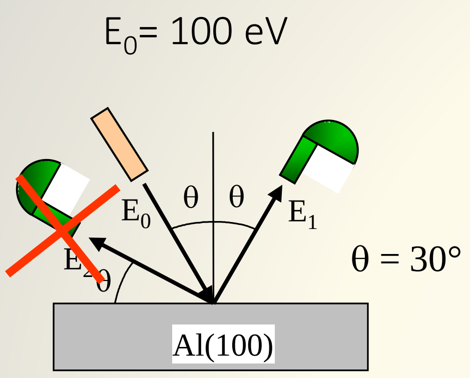
Geometry



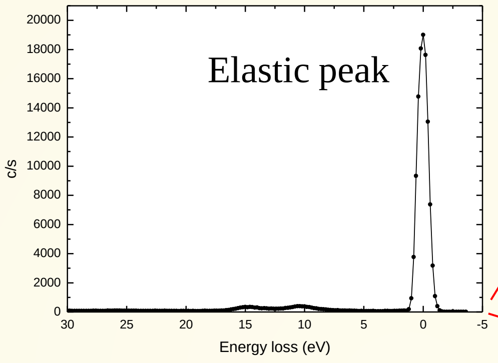
- -UHV apparatus (base pressure $2 \cdot 10^{-10}$ mbar)
- -Al(100) prepared each day by sputtering and annealing
- Magnetic field compensated by Helmotz coil

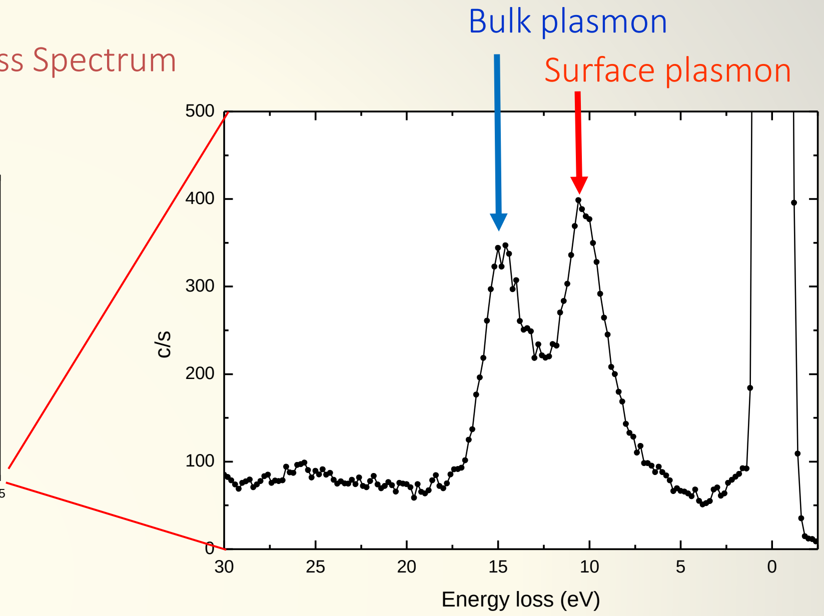
In this geometry plasmon is created with a well defined **q** not far from zero

Single channel: REELS and secondary electron region

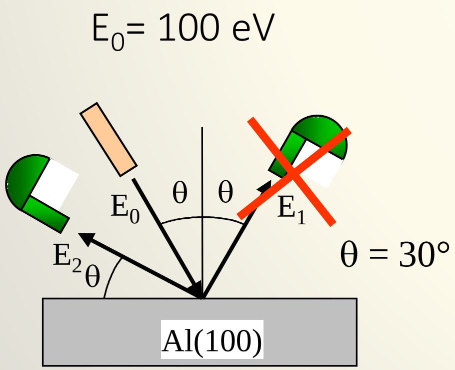


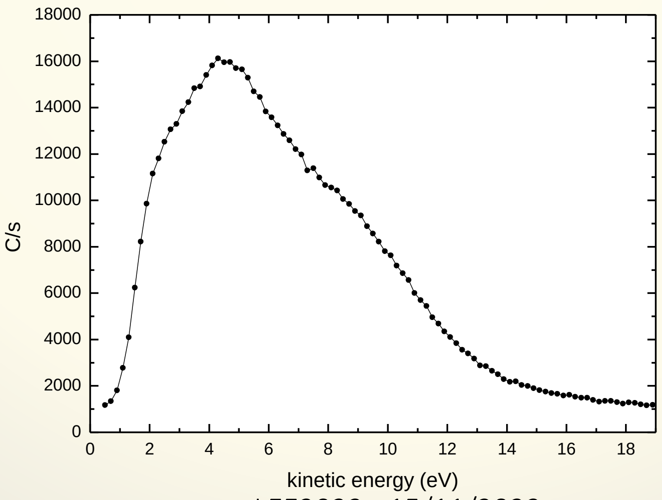
Al(100) Reflection Energy Loss Spectrum



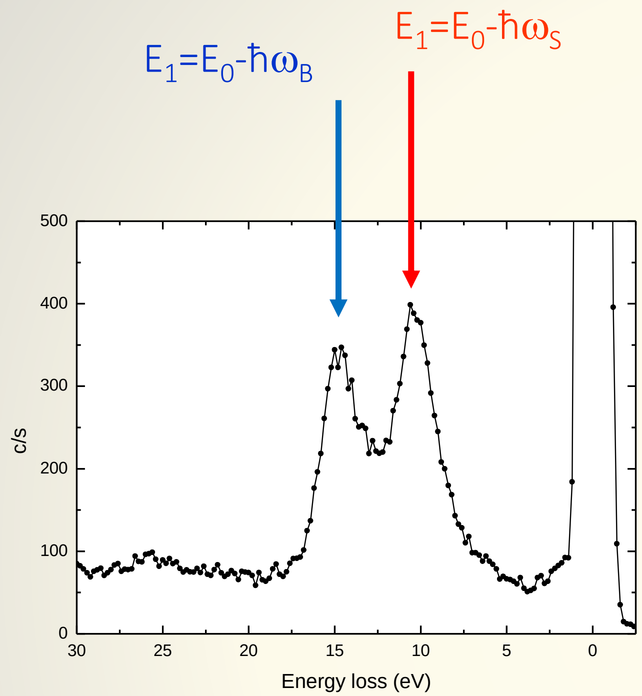


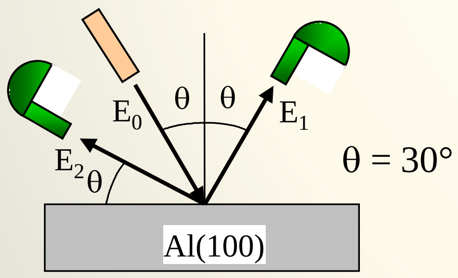
Al(100) Secondary electron energy region



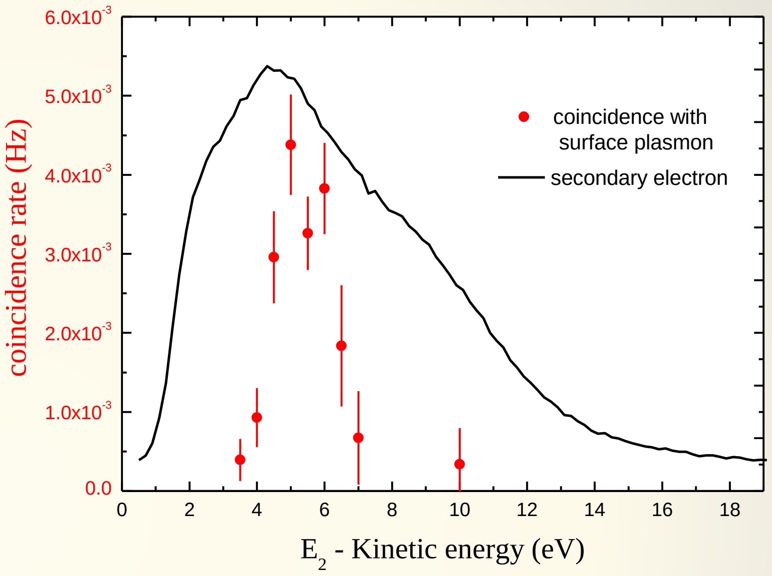


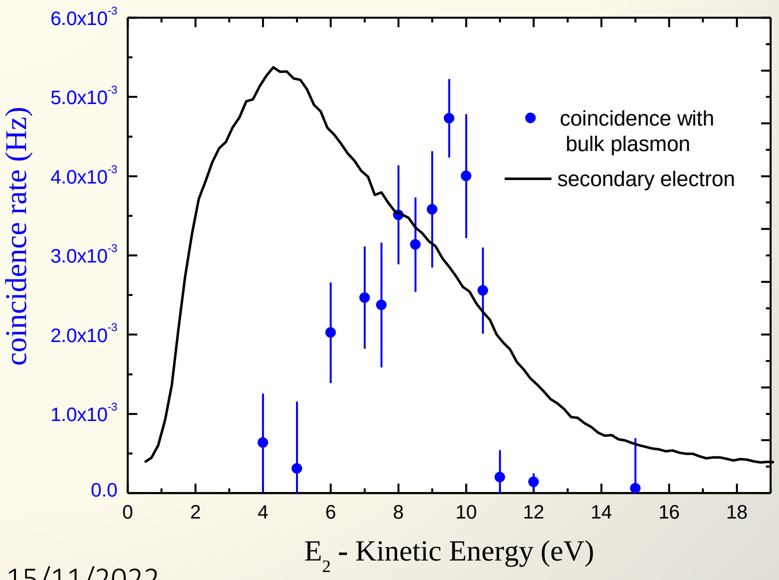
Coincidence: decay of the bulk and surface plasmon in Al(100)





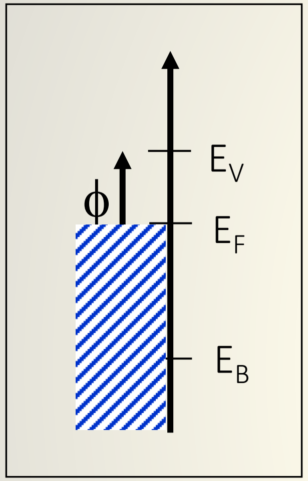
E_O = 100 eV



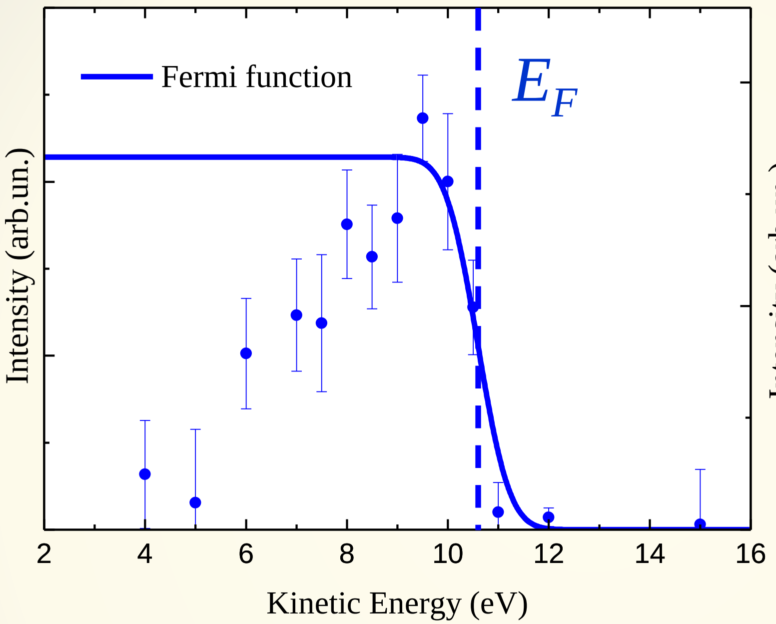


W. Werner et al., *Phys. Rev. B* **78** (2008) 233403

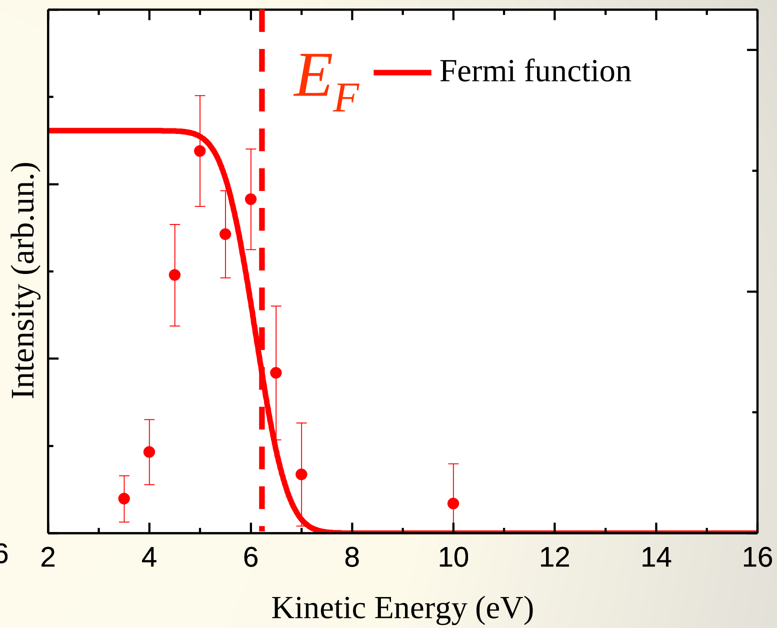
Plasmon-emission



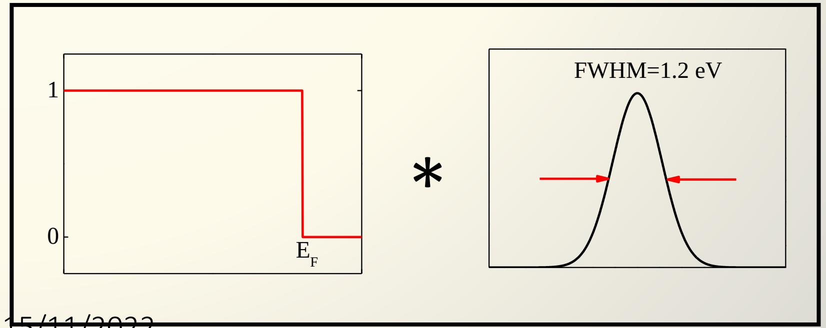
$$E_F = \hbar\omega_{BP} - \Phi = 10.6\, eV$$



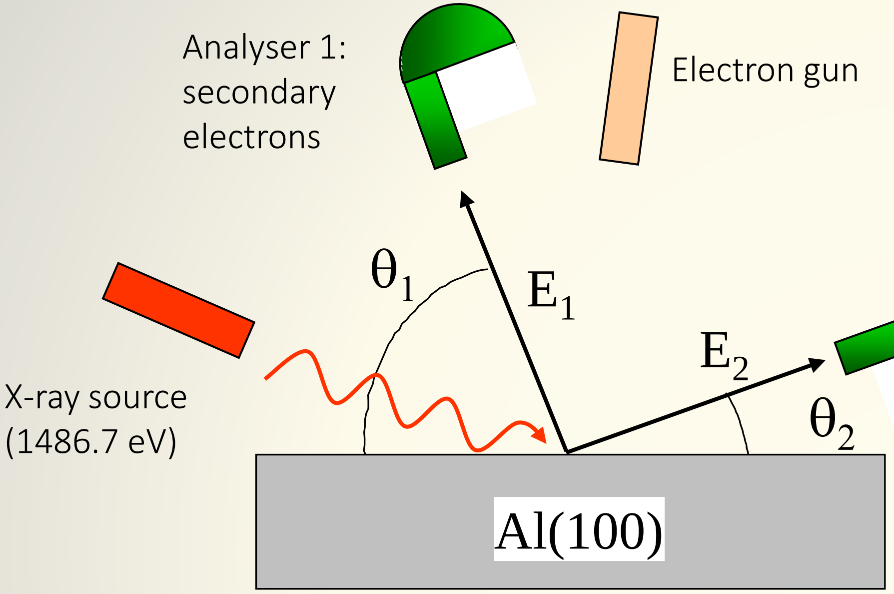
$$E_F = \hbar\omega_{SP} - \Phi = 6.1\, eV$$



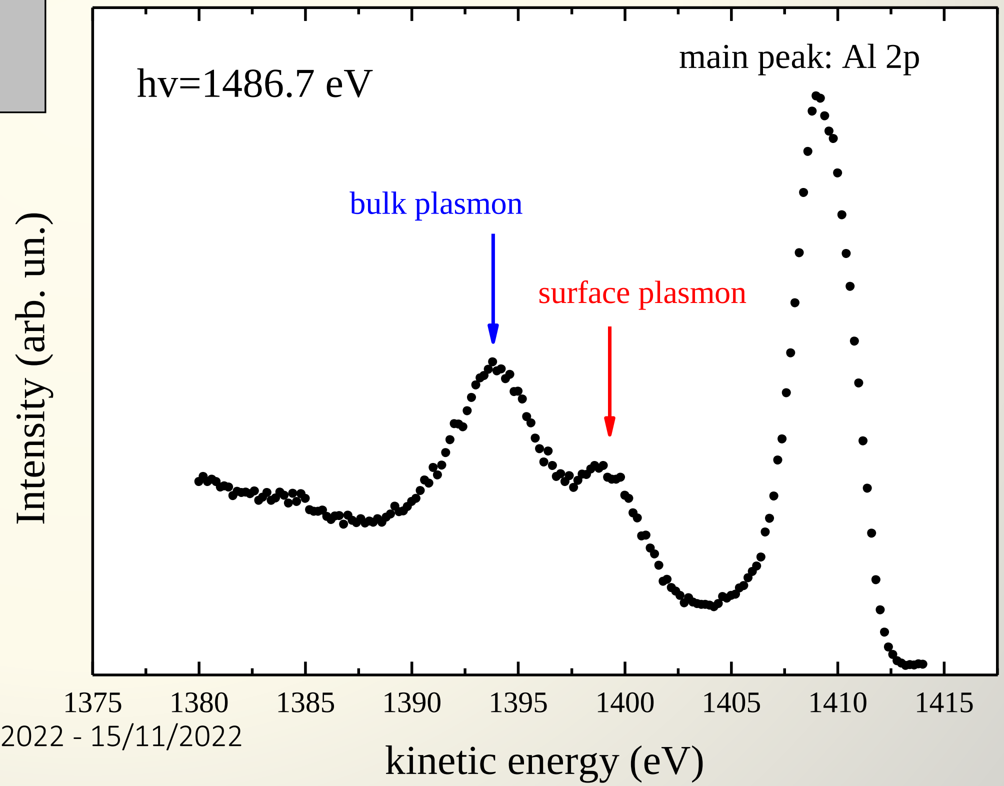
The Fermi energy is derived from the experiment:
the plasmon energy from EELS and the analyser work function from independent measurements (photoemission)



Plasmons decay in (γ,2e) experiment: the role of the band structure



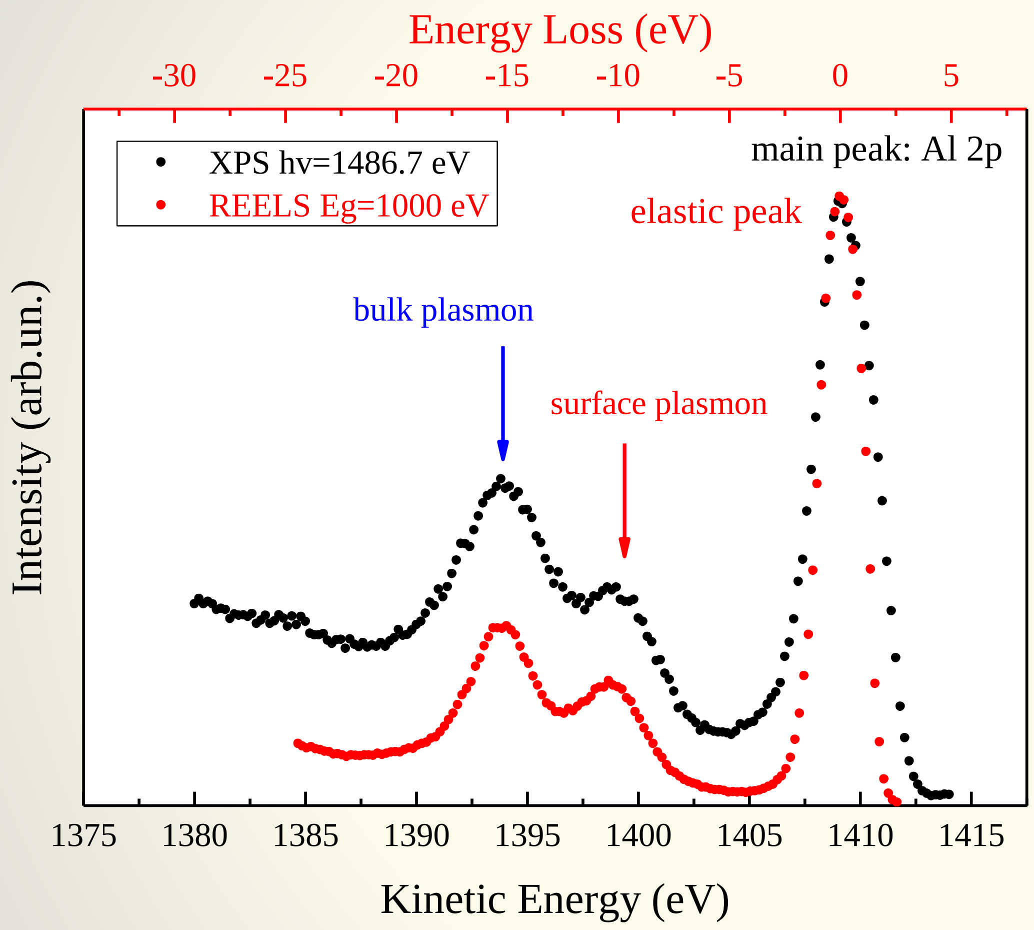
$\theta_1 = 70°$
$\theta_2 = 20°$

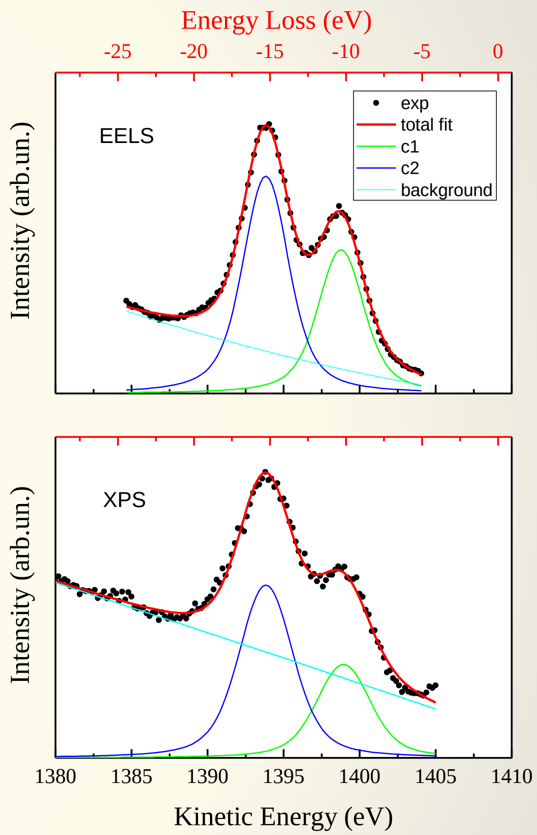


X-ray photoemission and plasmon creation, two possible channels:

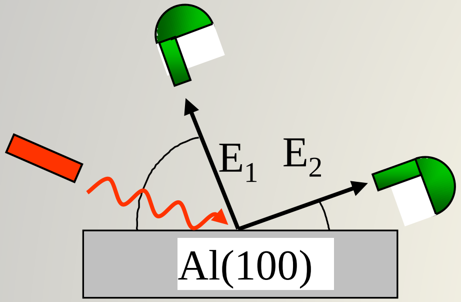
1) intrinsic plasmon
2) extrinsic plasmon

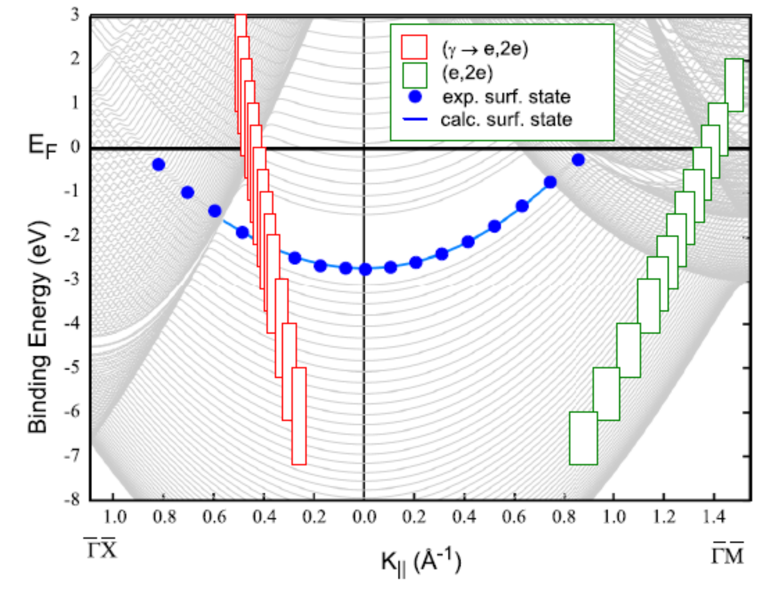
Very similar EELS and XPS spectra

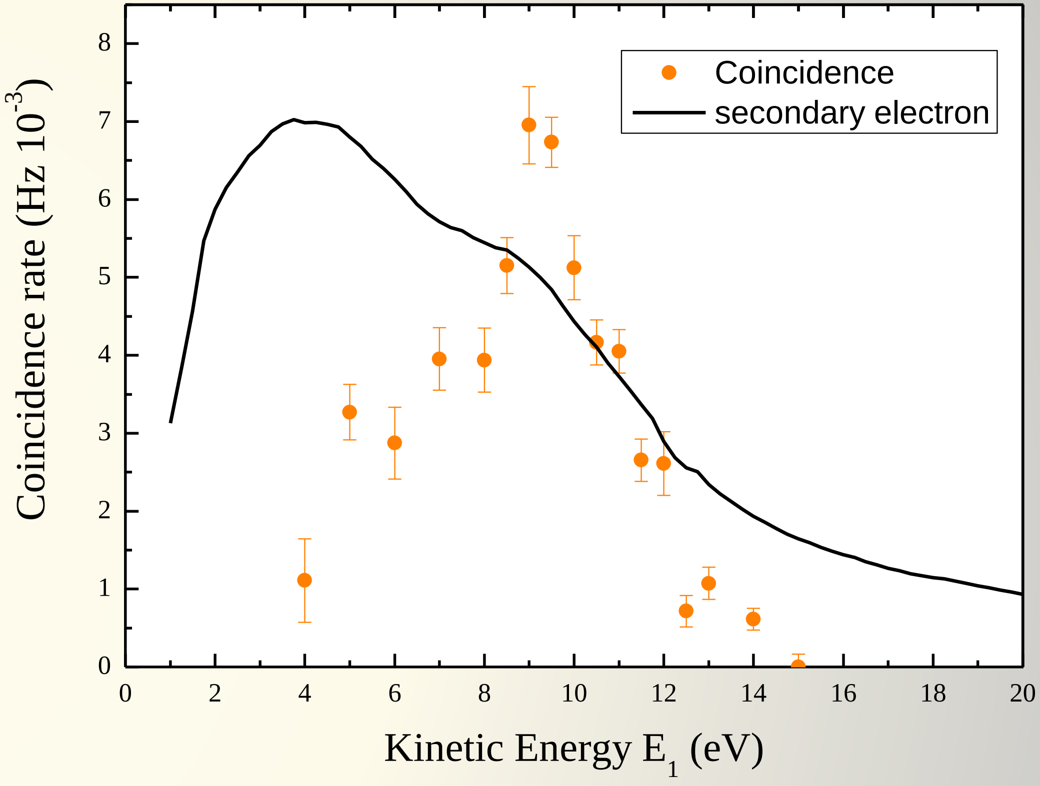




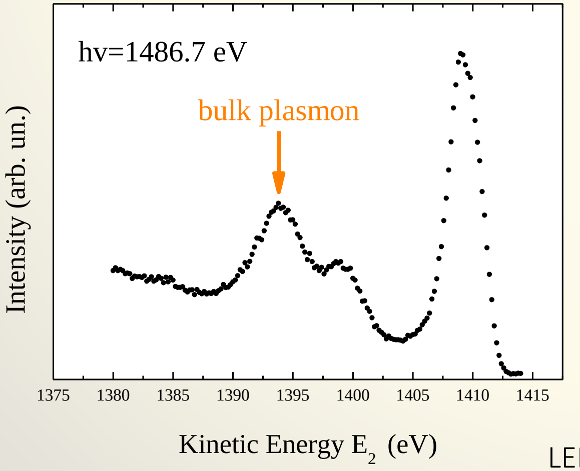
(γ,2e) coincidence: decay of the bulk plasmon



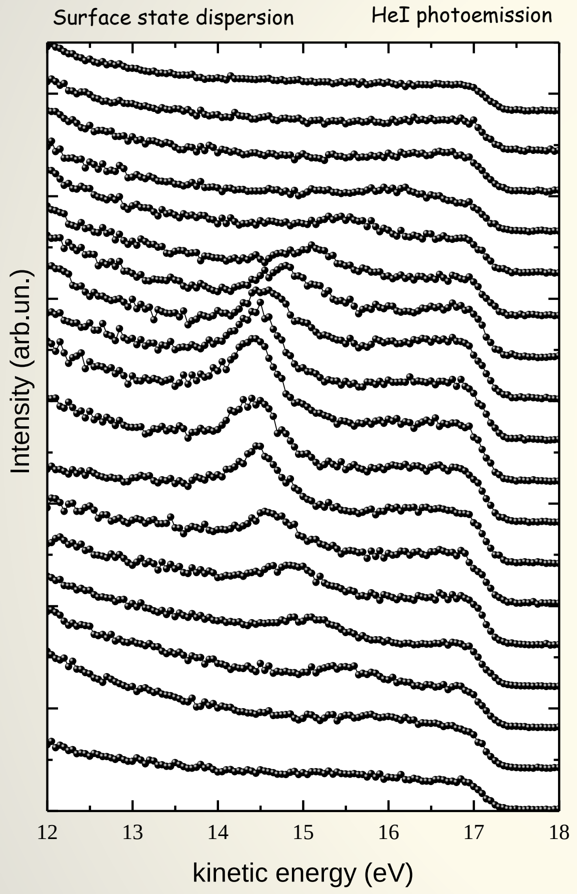




E_2 fixed at bulk plasmon excitation energy

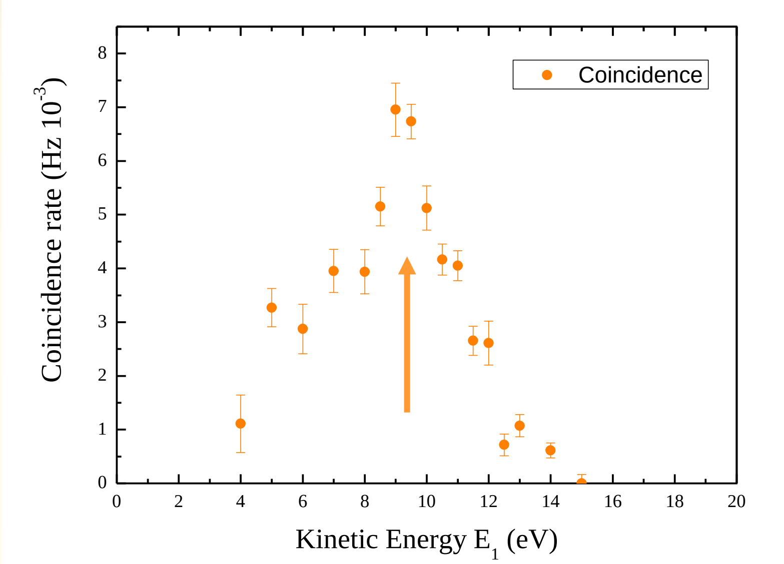


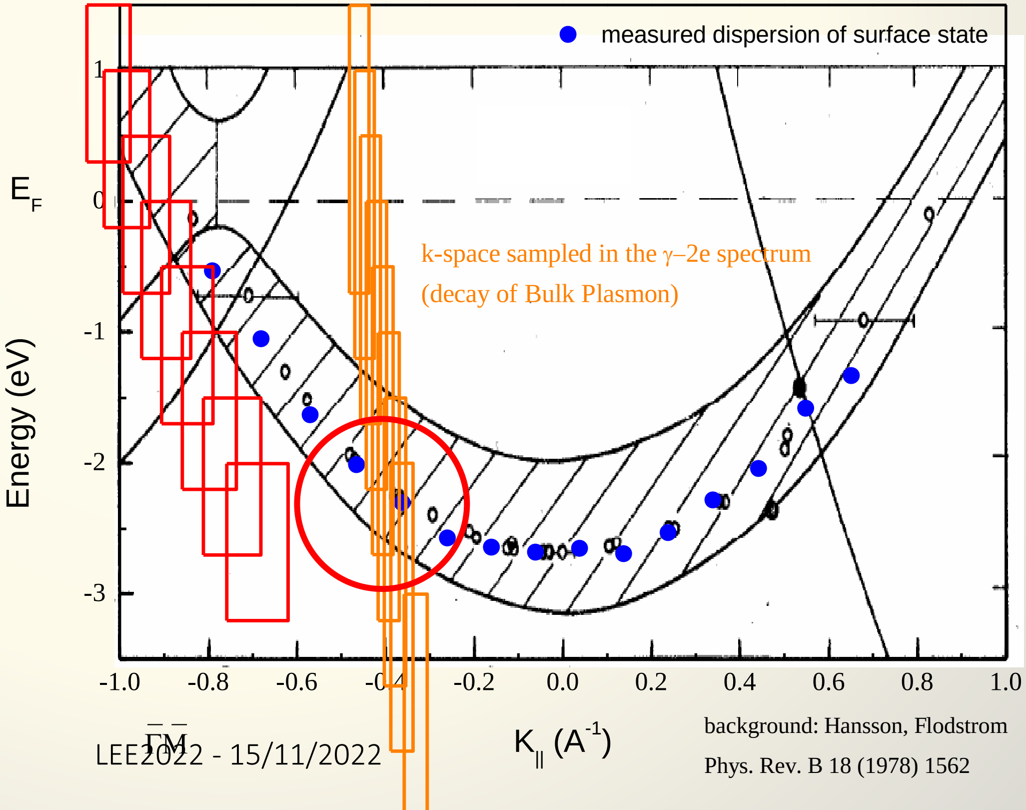
Sampled K-space in coincidence spectrum



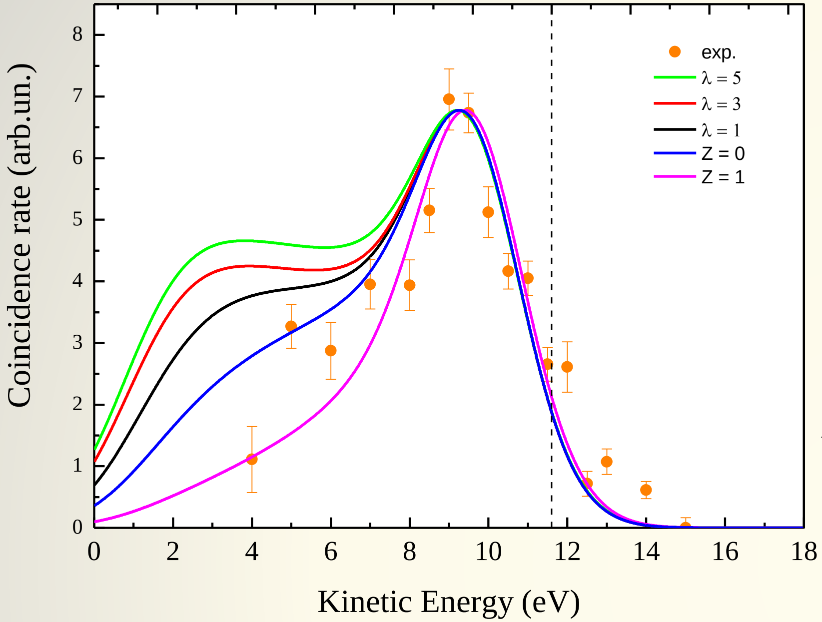
$$E_k = \hbar\omega_p - E_B - \Phi$$

$$\mathbf{k}_{\parallel}^{f} = \mathbf{k}_{\parallel}^{i} + \mathbf{k}_{\parallel}^{p}$$



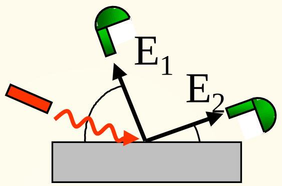


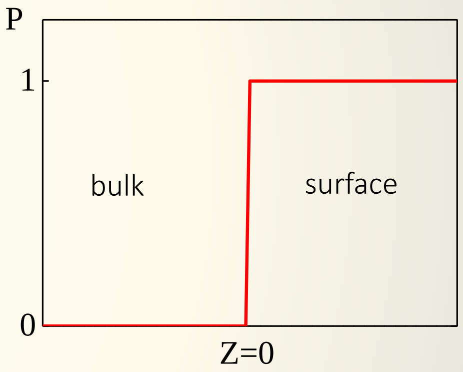
Comparison with calculated density of state

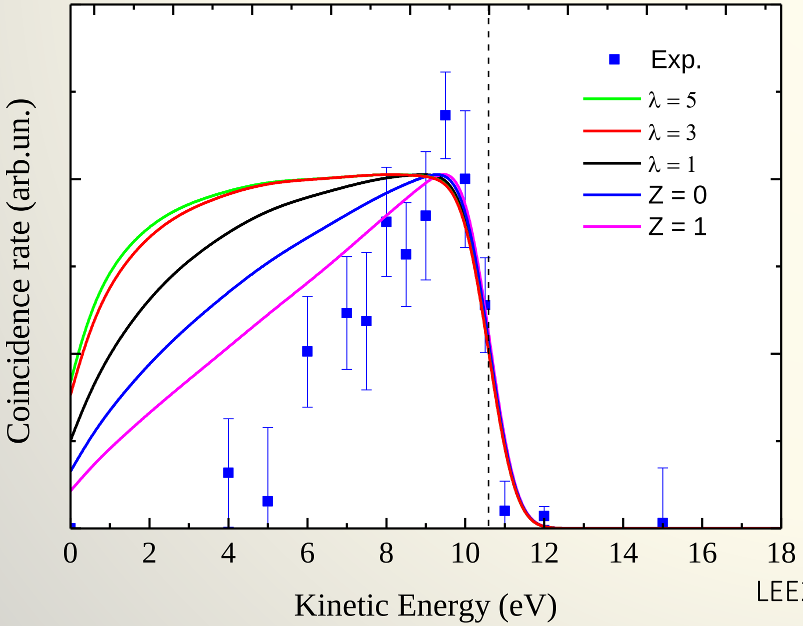


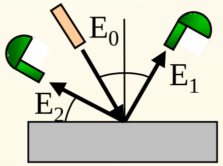
Calculation:

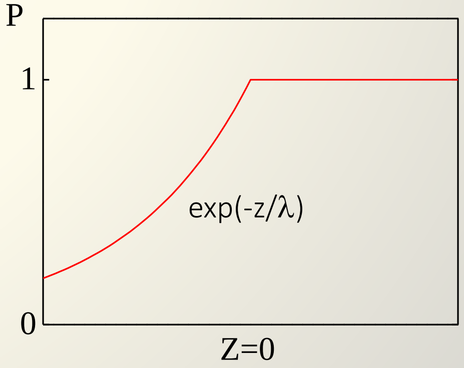
- bulk DOS (jellium) + surface state @ selected K
- refraction of outgoing electron
- experimental broadening
- probing depth











Conclusions

-Experimental evidence of the decay of bulk and surface plasmons in the region of secondary electron

- large contribution of surface plasmon decay to secondary region

- Agreement with theory seems good but better refinement and check are needed

- Interband transition not assisted by other particle is the dominant decay channel (Plasmo-emission)

  plasmon with fixed momentum
  lineshape of the emitted electrons

In collaboration with:

G. Stefani	RomaTre
F. Offi	RomaTre
D. Sbaraglia	RomaTre
G. DiFilippo	Roma Tre
S. Iacobucci	ISM-CNR
W. Werner	TU Wien
W. Smekal	TU Wien