Acousto-magneto-plasmonics:
Part I: magneto-plasmonics

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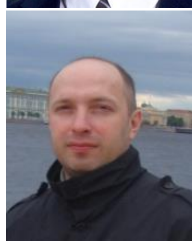
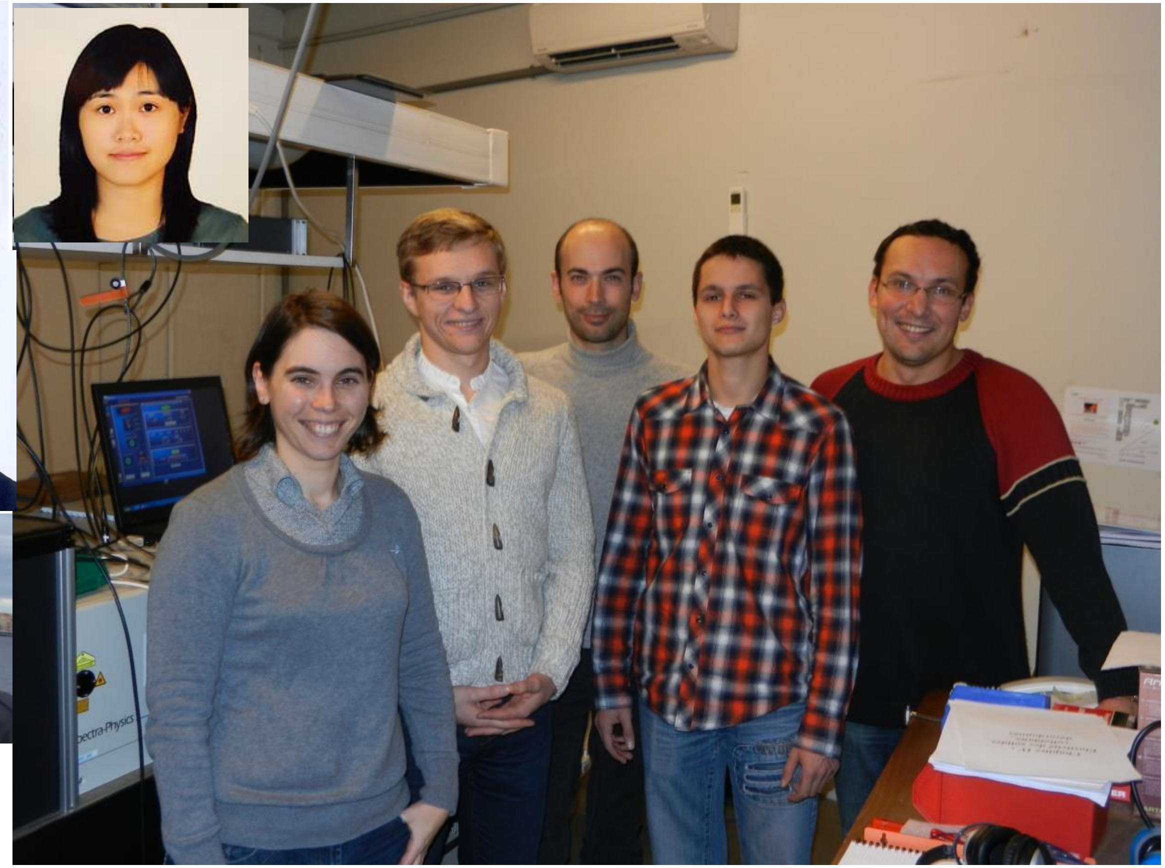
CNRS team at IMMM CNRS 6283



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- <u>Funding:</u> Nouvelle Equipe Région Pays de la Loire (2012-2015)
  Stratégie internationale NNN-Telecom (2015-2018)
  ANR(France) <-> DFG (Germany) PPMI-NANO (2015-2019)
  CNRS-RFBR French-Russian PRC "Acousto-magneto-plasmonics" (2017-2019)

Outline

Introduction:

- (Nano) plasmonics

Magneto-plasmonics the metal-ferromagnet interfaces:

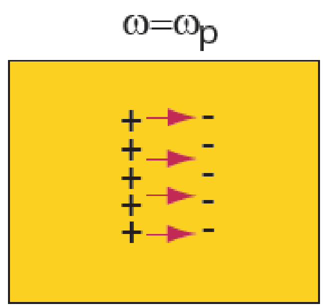
- Linear magneto-plasmonics (Kapitza resistance)
- Nonlinear magneto-plasmonics
- Dynamic modulation of magneto-plasmonic structures

Outlook:

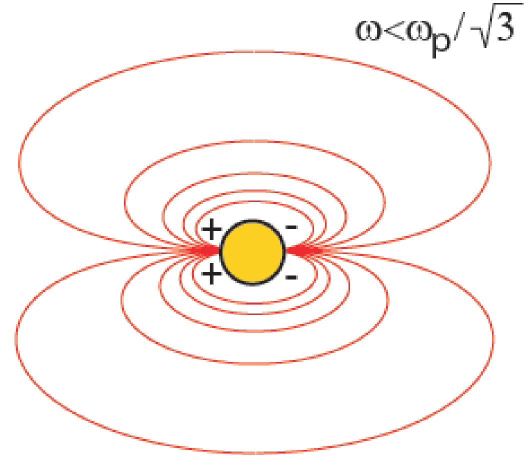
- Quantum acousto-magneto-photonics
- Acoustically driven magnetization dynamics
- “Fun” slides

Plasmonics: charge oscillations on metal surfaces

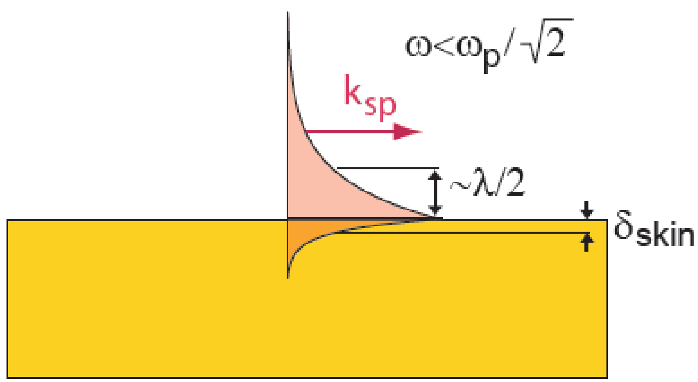
Bulk plasmon (3D)



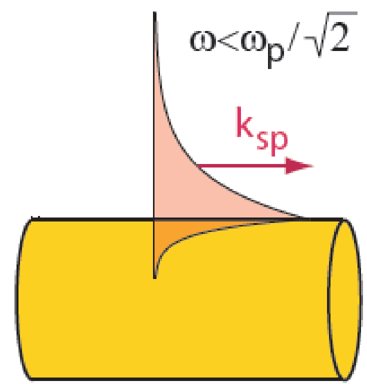
Surface (particle) plasmon (0D)

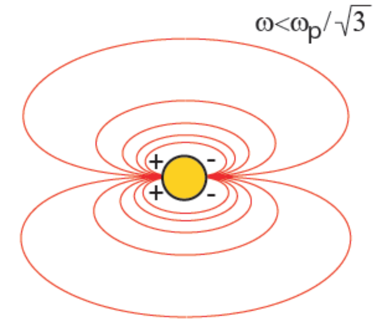


Surface plasmon (polariton in 2D)

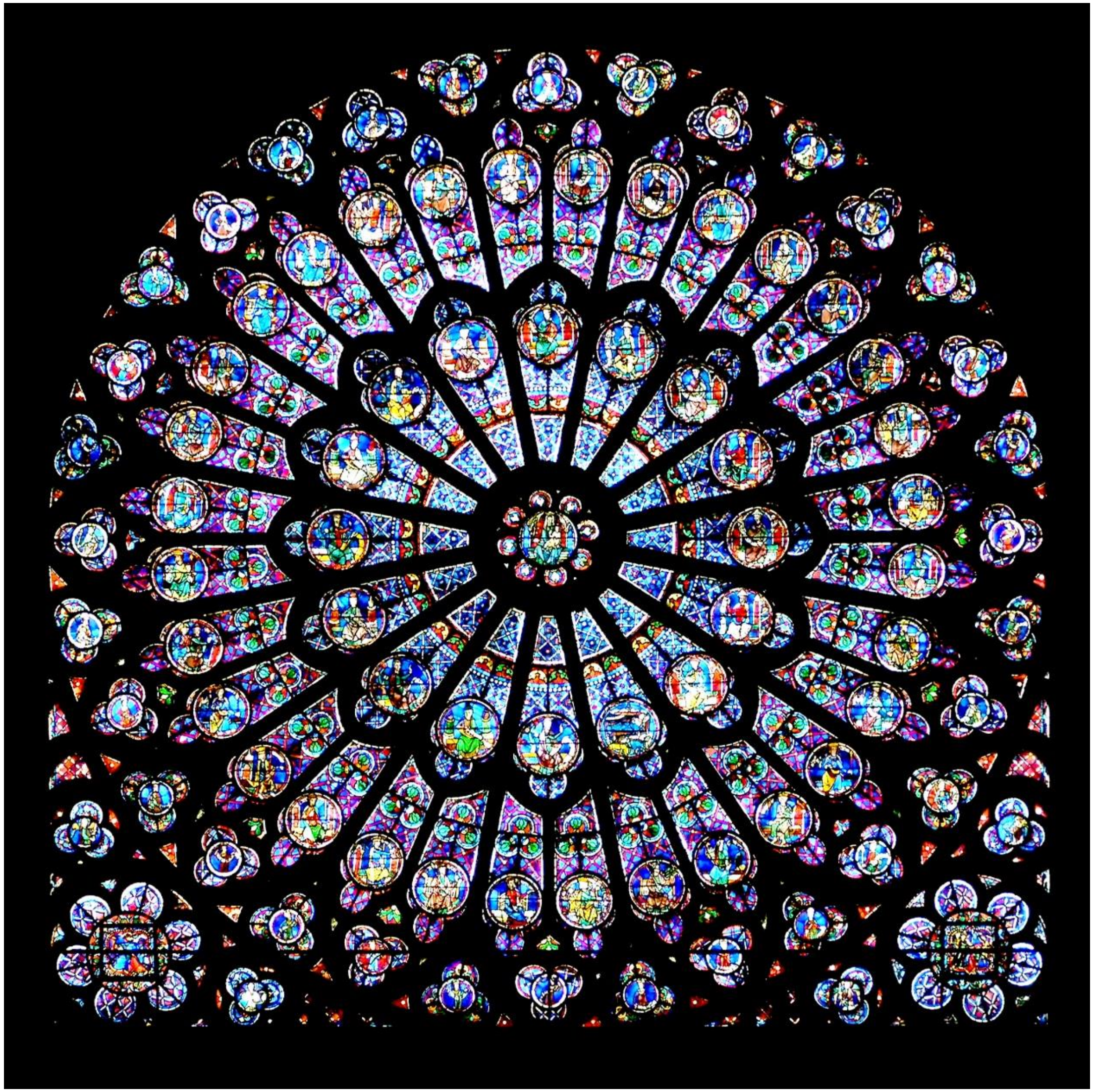


Surface plasmon (polariton in 1D)

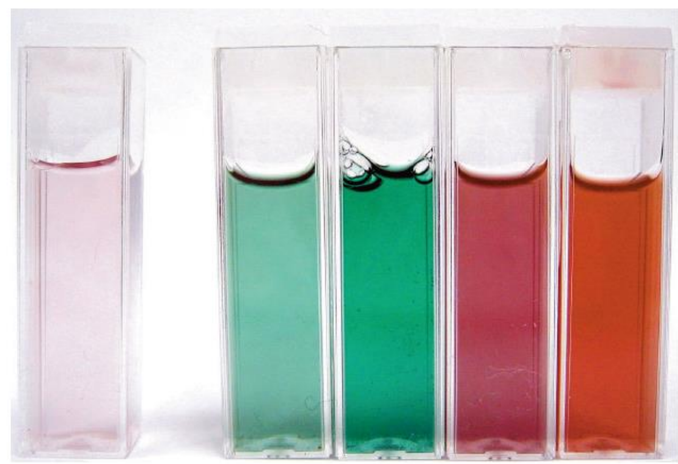




Plasmonics: since the late Middle Ages

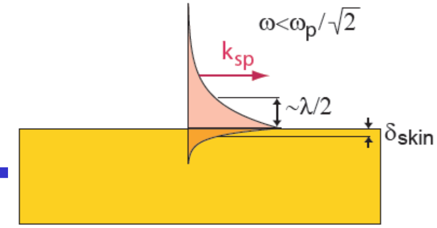


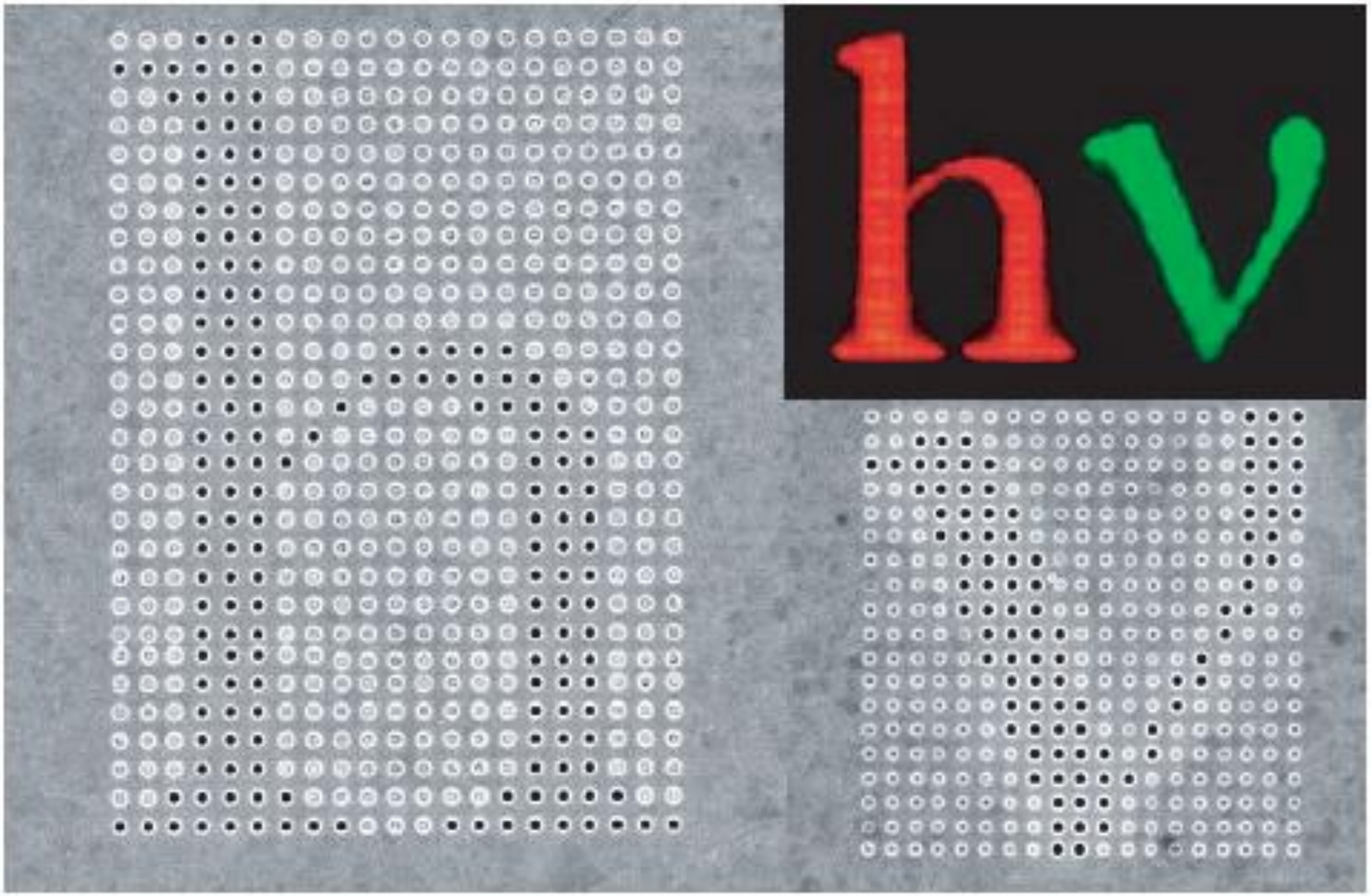
- Gothic stained glass rose window of Notre-Dame de Paris (1163-1345).
- The colors were achieved by colloids of gold nano-particles.



Pelton et al., Laser&Photon. Rev. 2 (2008)

XXI century: nanostructured metals





Lattice period d=550 nm   Lattice period d=450 nm

T.W. Ebbesen et al., Nature 391 (1998)

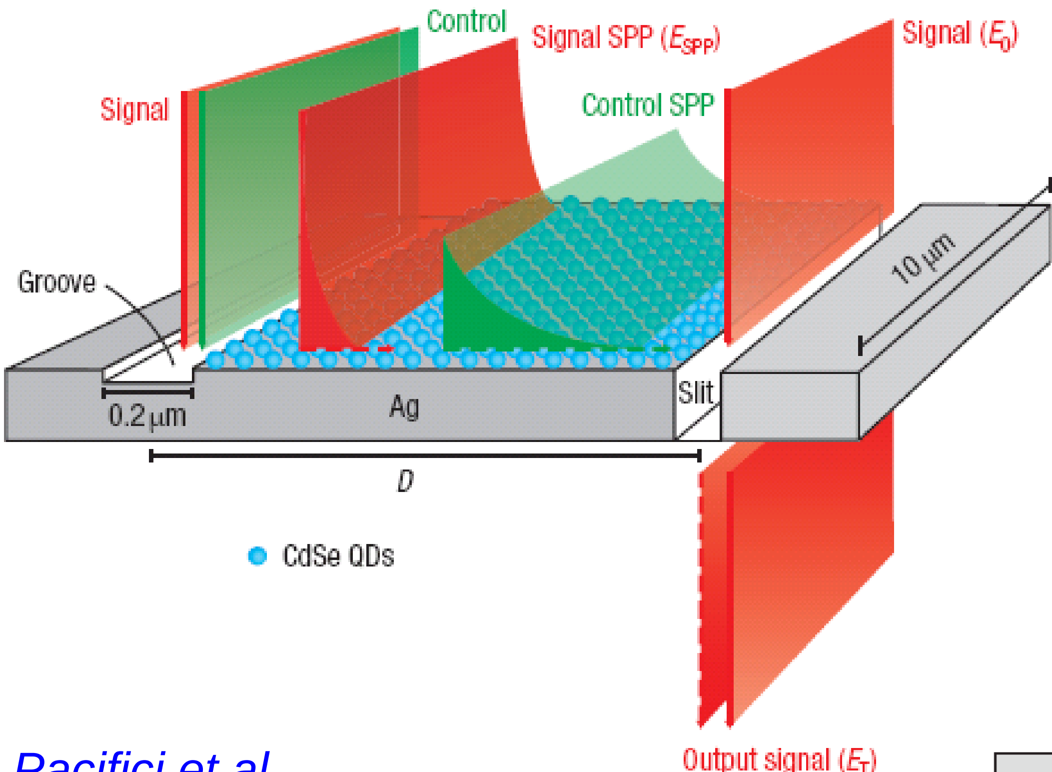
$$\lambda_{SPP} \approx d$$

SPP-surface plasmon polaritons

Recently extended to acoustics: **Lu et al., PRL 99 (2007)**
and ultracold atom optics: **Moreno et al, PRL 95 (2005)**

Nanostructured metals & semiconductors

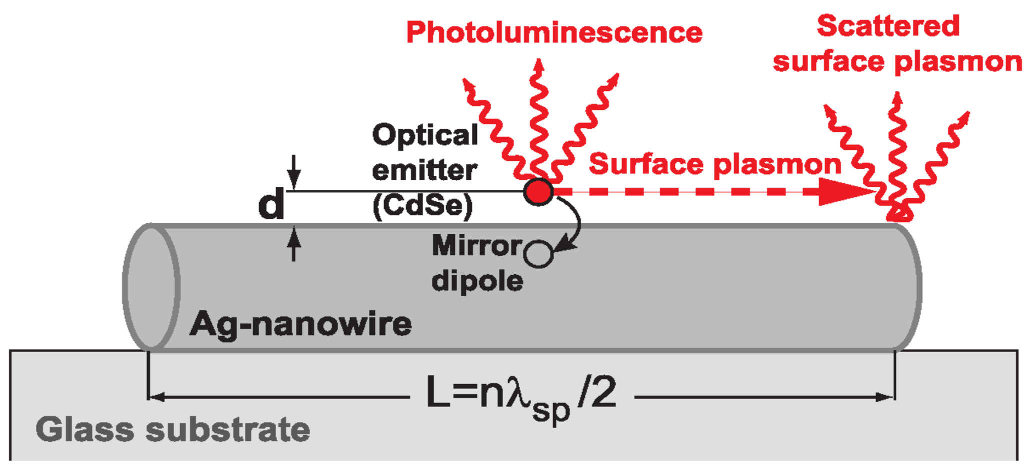
Device



Pacifici et al.,
Nature Photonics 1 (2007)

Physical mechanisms

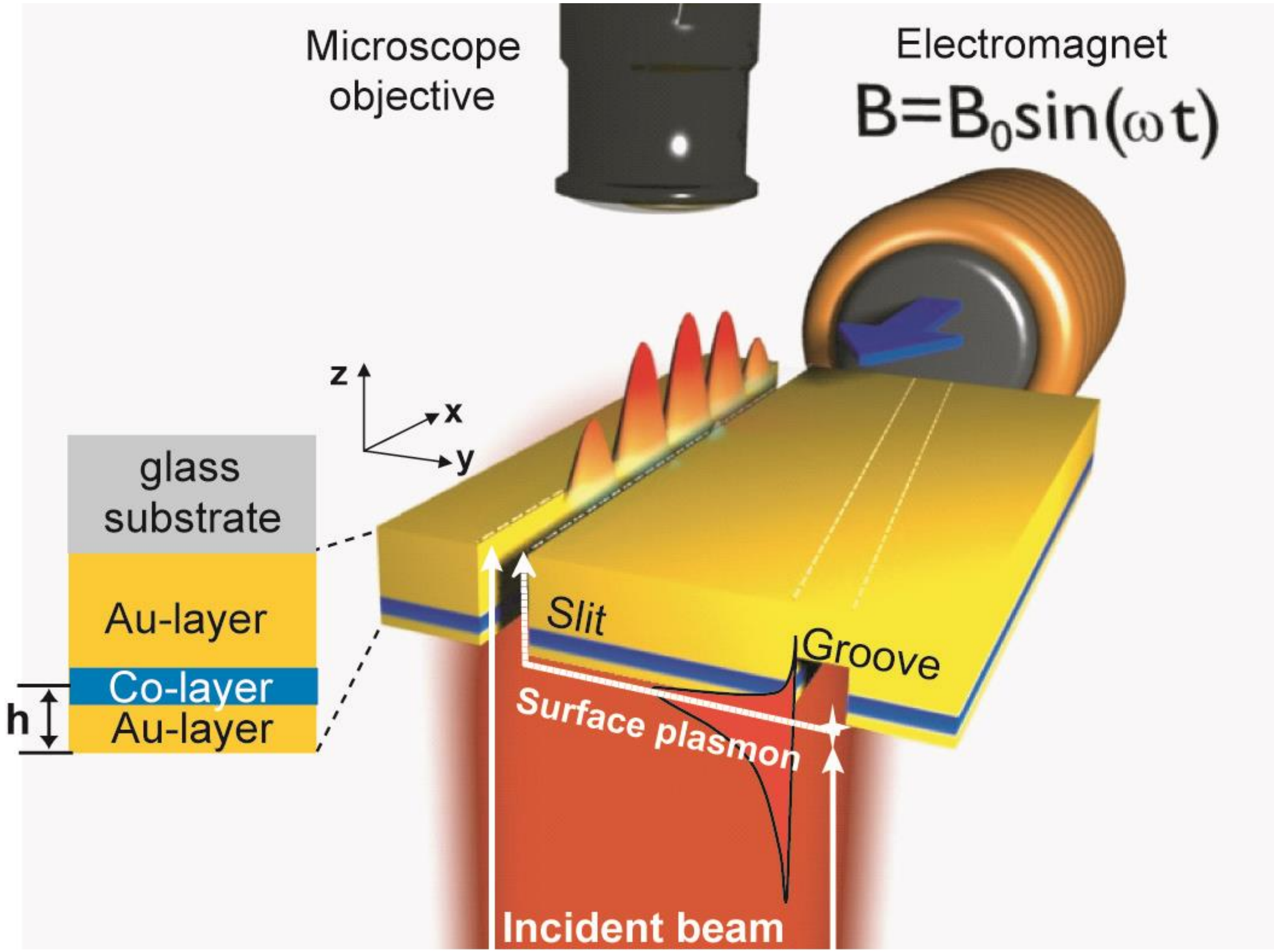
Temnov & Woggon, PRL 95 (2005)
Fedutik et al., PRL 99 (2007)



Temnov & Woggon , Chapter 11 in
"Quantum Dots: optics, electron transport and future applications", Cambridge University Press (2012)

HYBRID magneto-plasmonic switch

1) Au/Co/Au sandwich
2) SLIT-GROOVE pair
3) Electromagnet



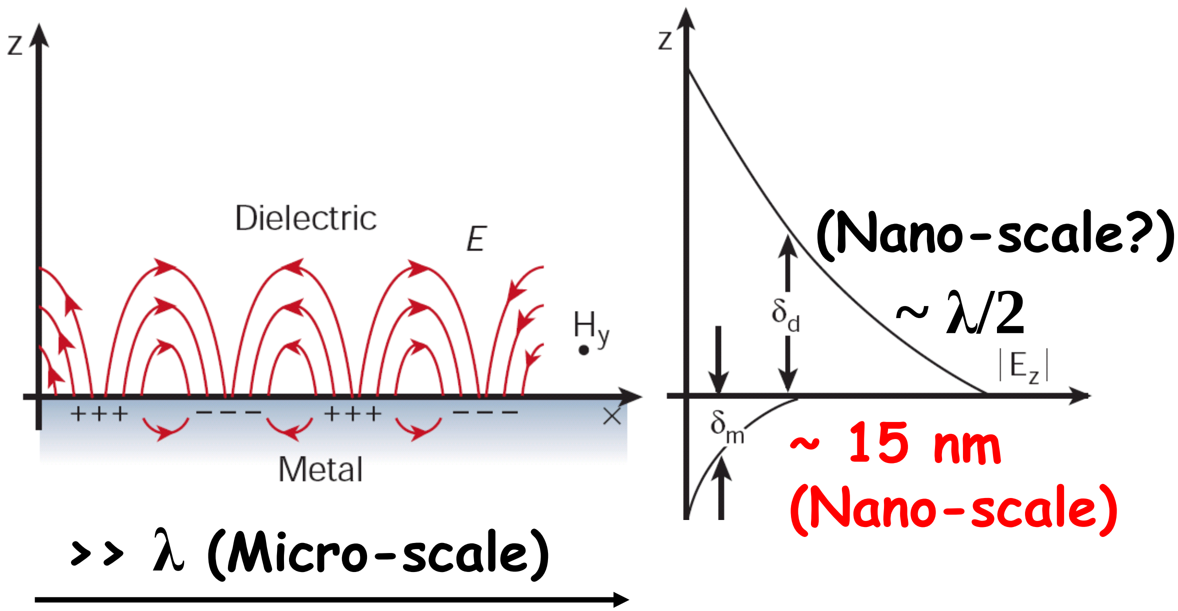
Switching speed is limited by the mechanism of magnetization reversal !

Temnov et al., Nature Photonics 4 (2010)

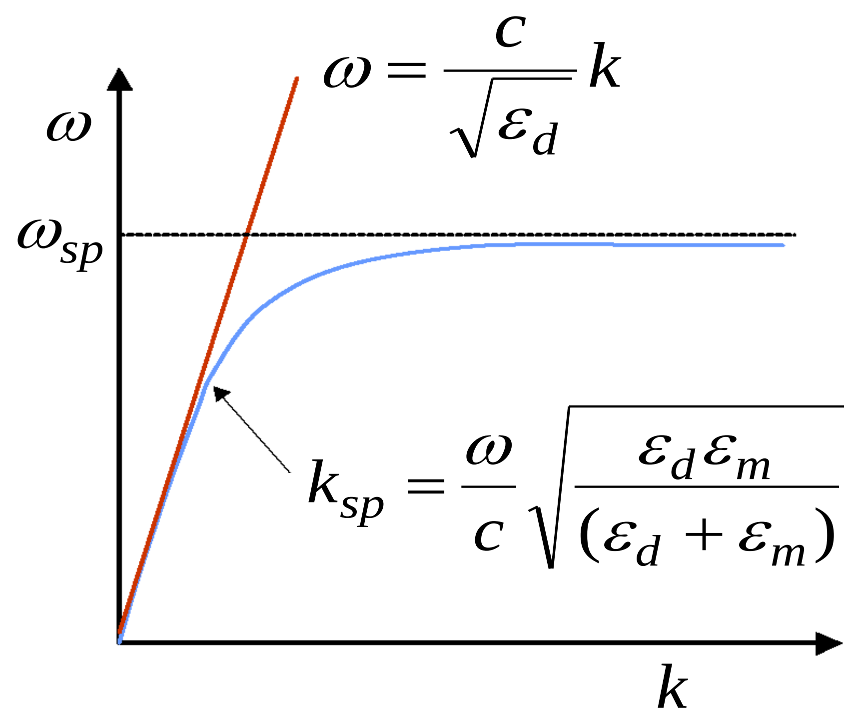
Surface plasmons: nano-scale & micro-scale

Surface plasmon polaritons (SPP or SP) are the localized evanescent electromagnetic surface waves propagating along the metal-dielectric interface

Electric field distribution of surface plasmons



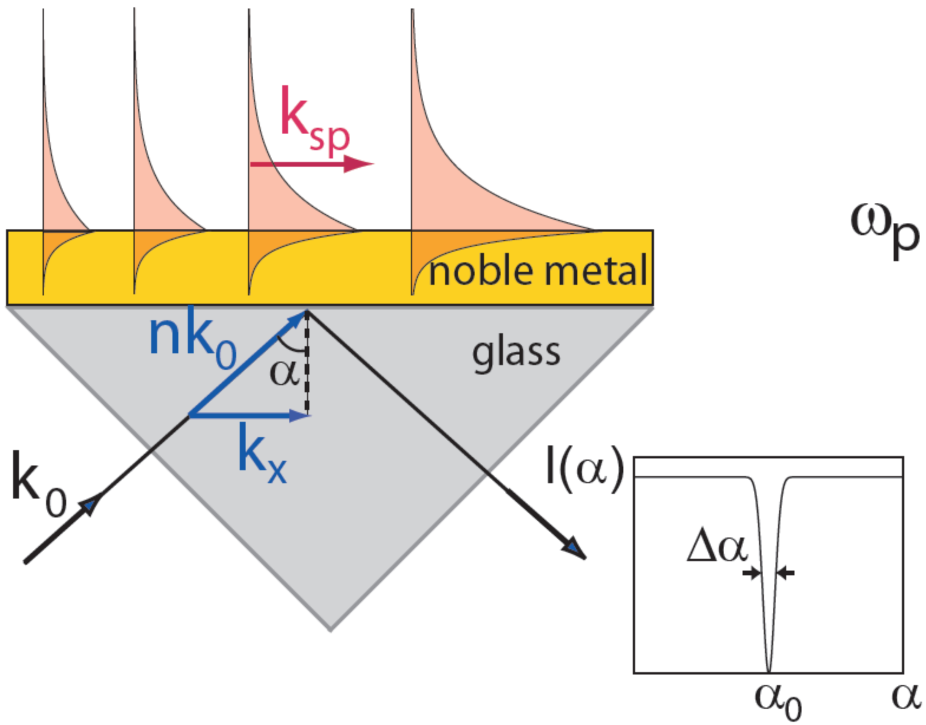
Dispersion relation

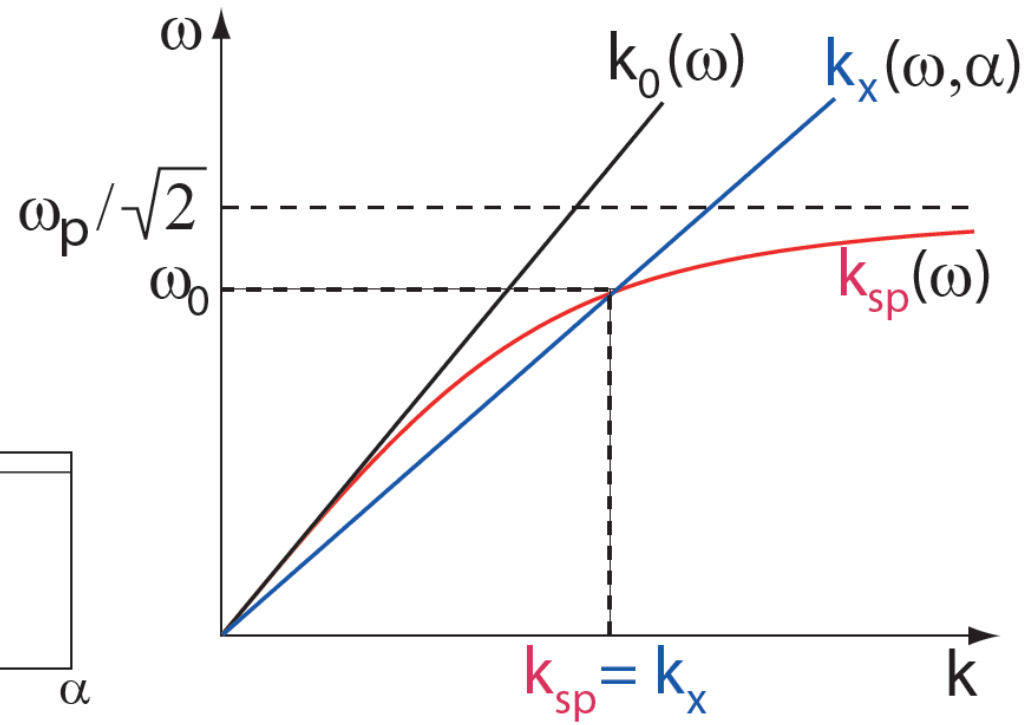


W.L. Barnes, A. Dereux & T.W. Ebbesen, Nature 424, 824 (2003)

2D-plasmon-polaritonics: Kretschmann geometry

E. Kretschmann, Z. Phys., 241, 313 (1971)





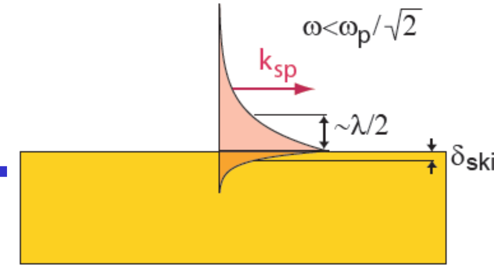
Key idea:

phase-matched excitation of SPPs

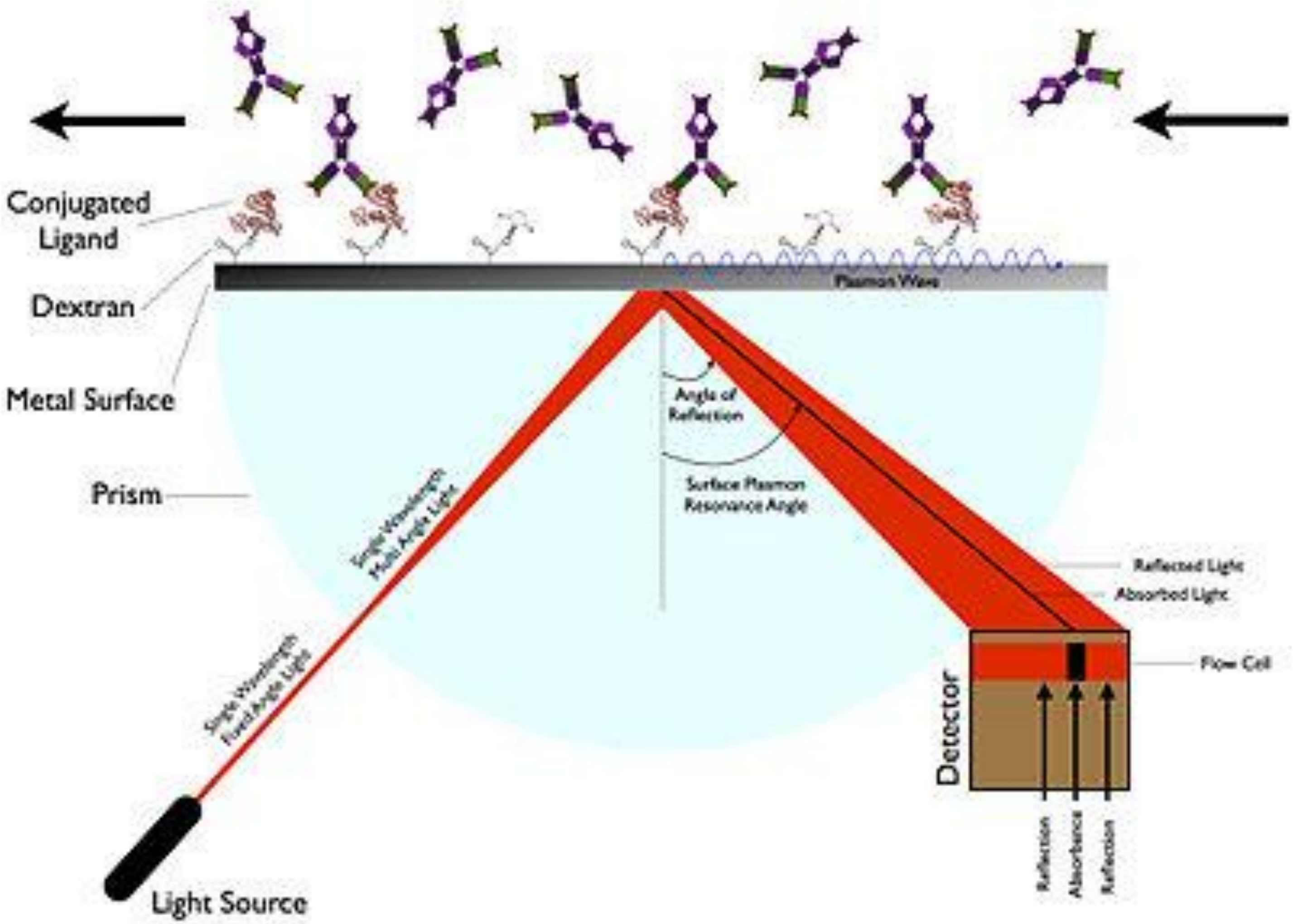
But… there exist several SPP branches !

J.J. Burke et al., Phys. Rev. B 33 (1986)
J.J. Foley et al., Sci. Reports 5 (2015)

XX century: plasmonic biosensors

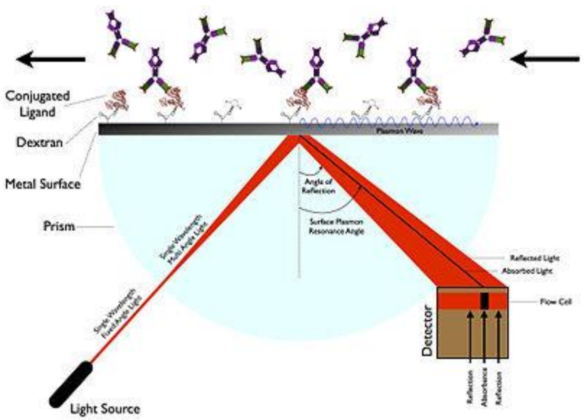


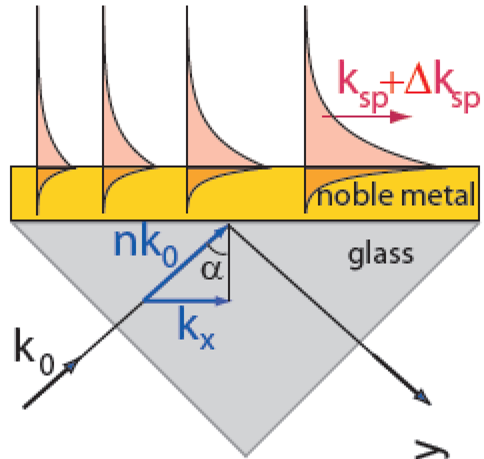
E. Kretschmann, Z. Phys., 241, 313 (1971)



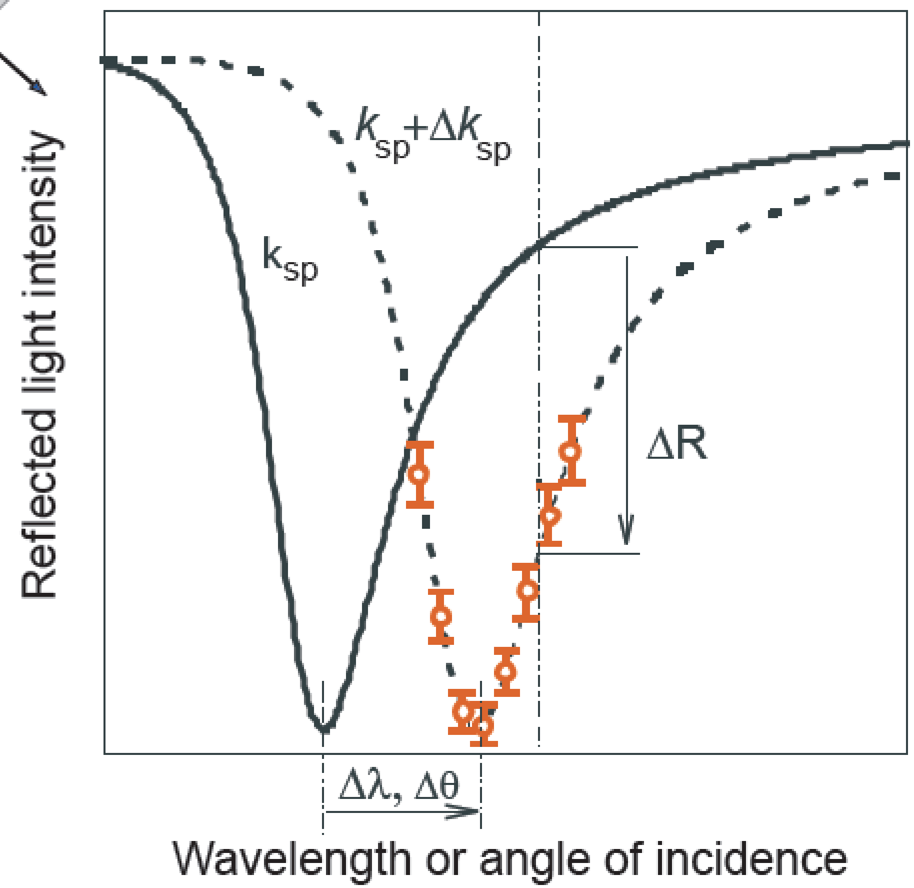
J. Homola et al., Sensors & Actuators B 54 (1999)

Application: surface plasmon resonance sensor





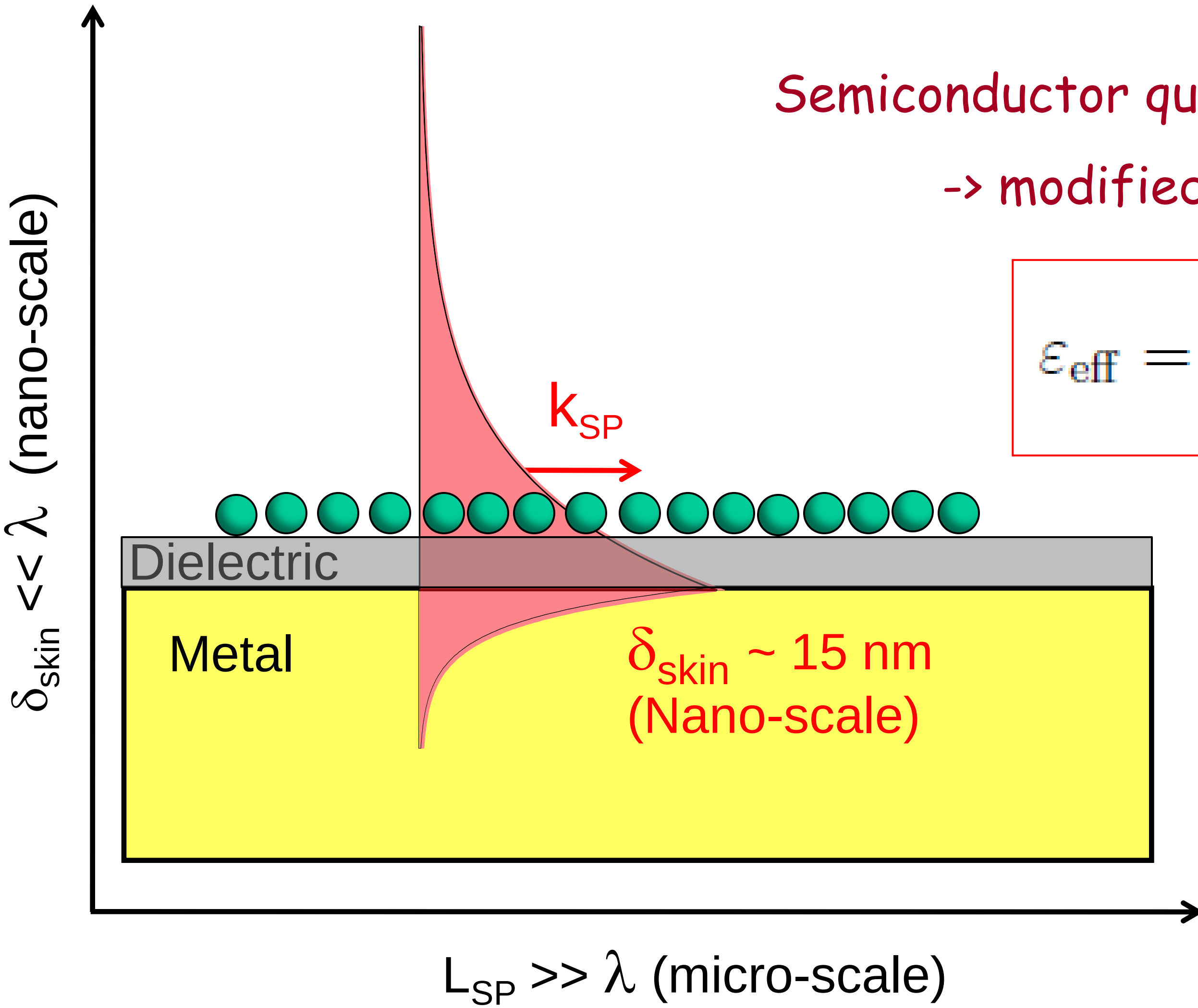
E. Kretschmann,
Z. Phys. 241, 313 (1971)



<u>Operation principle:</u>
The change of surface plasmon polariton wave vector shifts the position of the resonance angle (or wavelength)

How can we change (or control)
the wave vector
of surface plasmon polaritons?

Active SP control: quantum dots

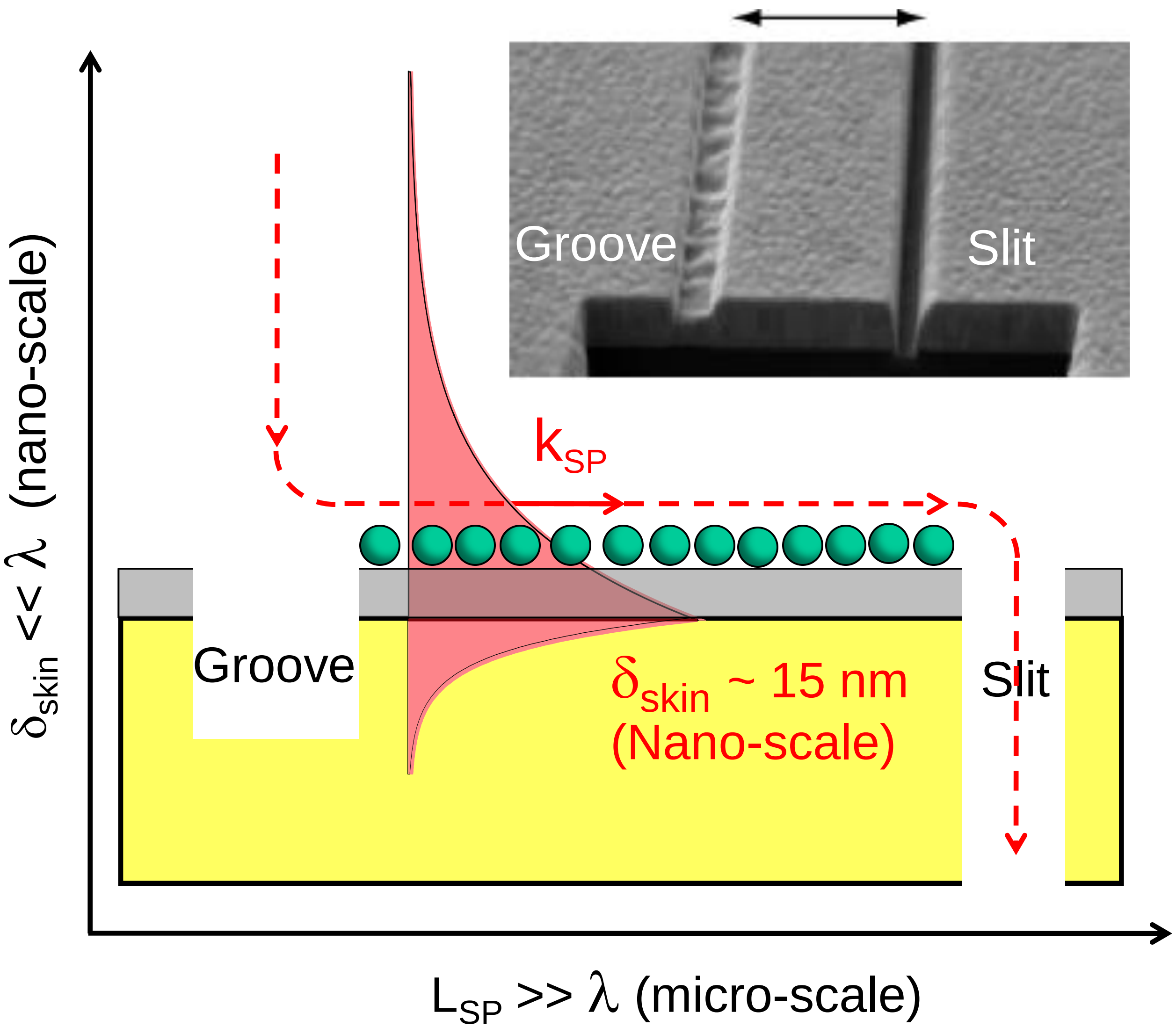


Semiconductor quantum dot (QD) layer

-> modified SP Propagation length L_{SP}

$$\varepsilon_{\text{eff}} = \frac{1}{\delta_{\text{skin}}} \int_0^{\infty} \varepsilon(z) e^{-z/\delta_{\text{skin}}} dz \,,$$

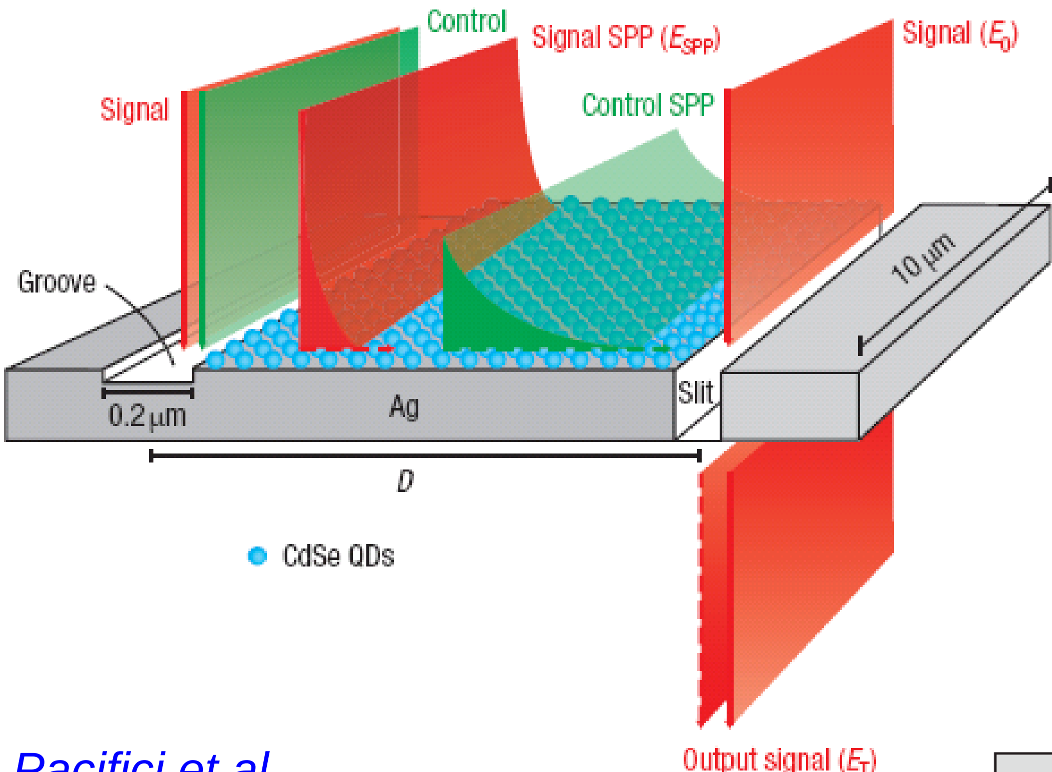
Active SP control: quantum dots



Sub-wavelength slit-groove pairs produced by the focused ion beam
-> efficient in- and out-coupling of SP

Nanostructured metals & semiconductors

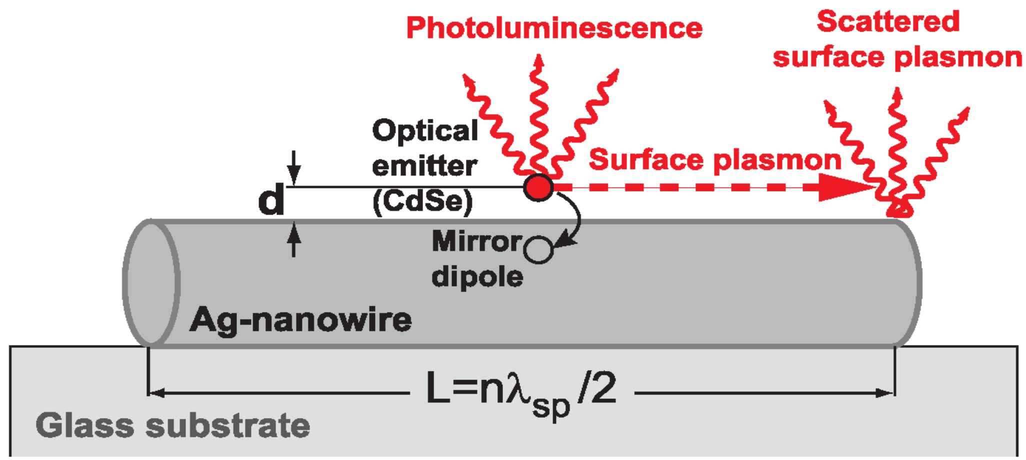
Device



Pacifici et al., Nature Photonics 1 (2007)

Physical mechanisms

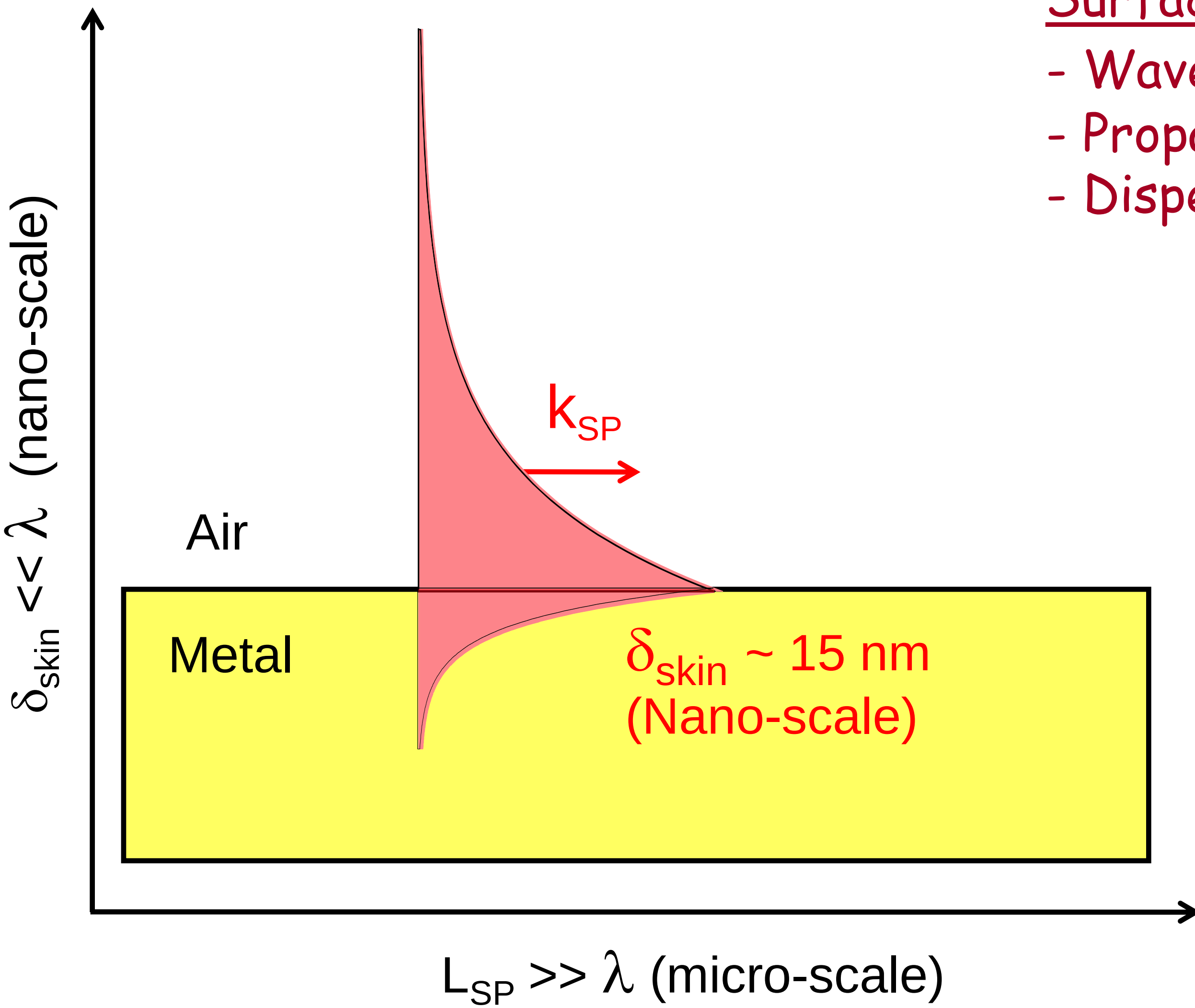
Temnov & Woggon, PRL 95 (2005)
Fedutik et al., PRL 99 (2007)



Temnov & Woggon , Chapter 11 in *"Quantum Dots: optics, electron transport and future applications"*, Cambridge University Press (2012)

How ELSE can we change (or control)
the wave vector
of surface plasmon polaritons?

Surface plasmons: nano-scale and micro-scale



Surface plasmon (polaritons)

- Wavelength λ (=800nm)
- Propagation length L_{SP} (~40μm)
- Dispersion relation

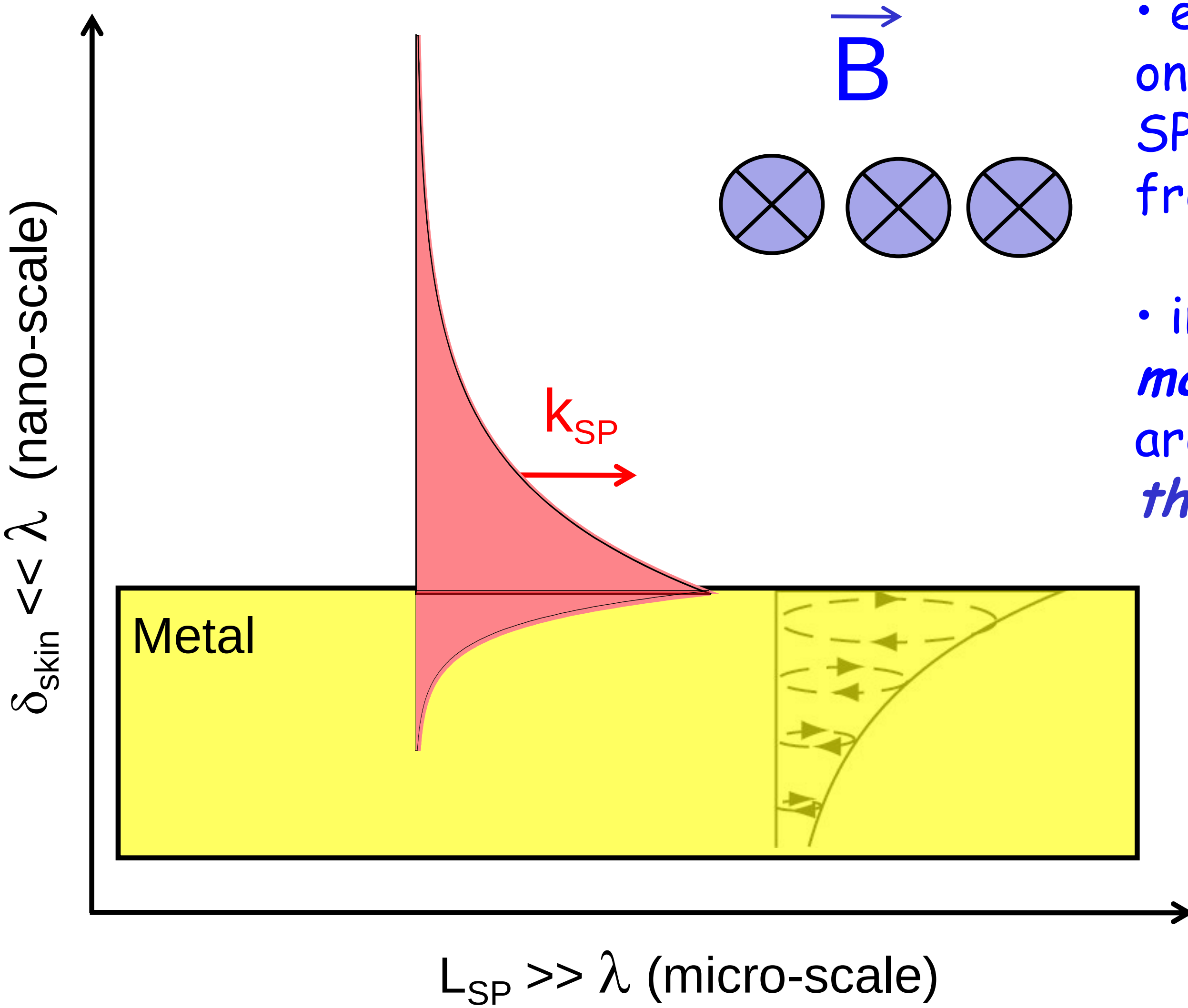
$$k_{sp} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_d \varepsilon_m}{(\varepsilon_d + \varepsilon_m)}}$$

$$\varepsilon_m = 1 - const(T_e) \times n_e$$

n_e - electron density
T_e - electron temperature

Barnes et al., Nature 424, 824 (2003)

Active SP control: external magnetic field



- electrons in the metal move on ***closed elliptical orbits*** in SPP electric field at optical frequency

- in a presence of the ***static magnetic field*** these orbits are slightly distorted by ***the Lorentz force***

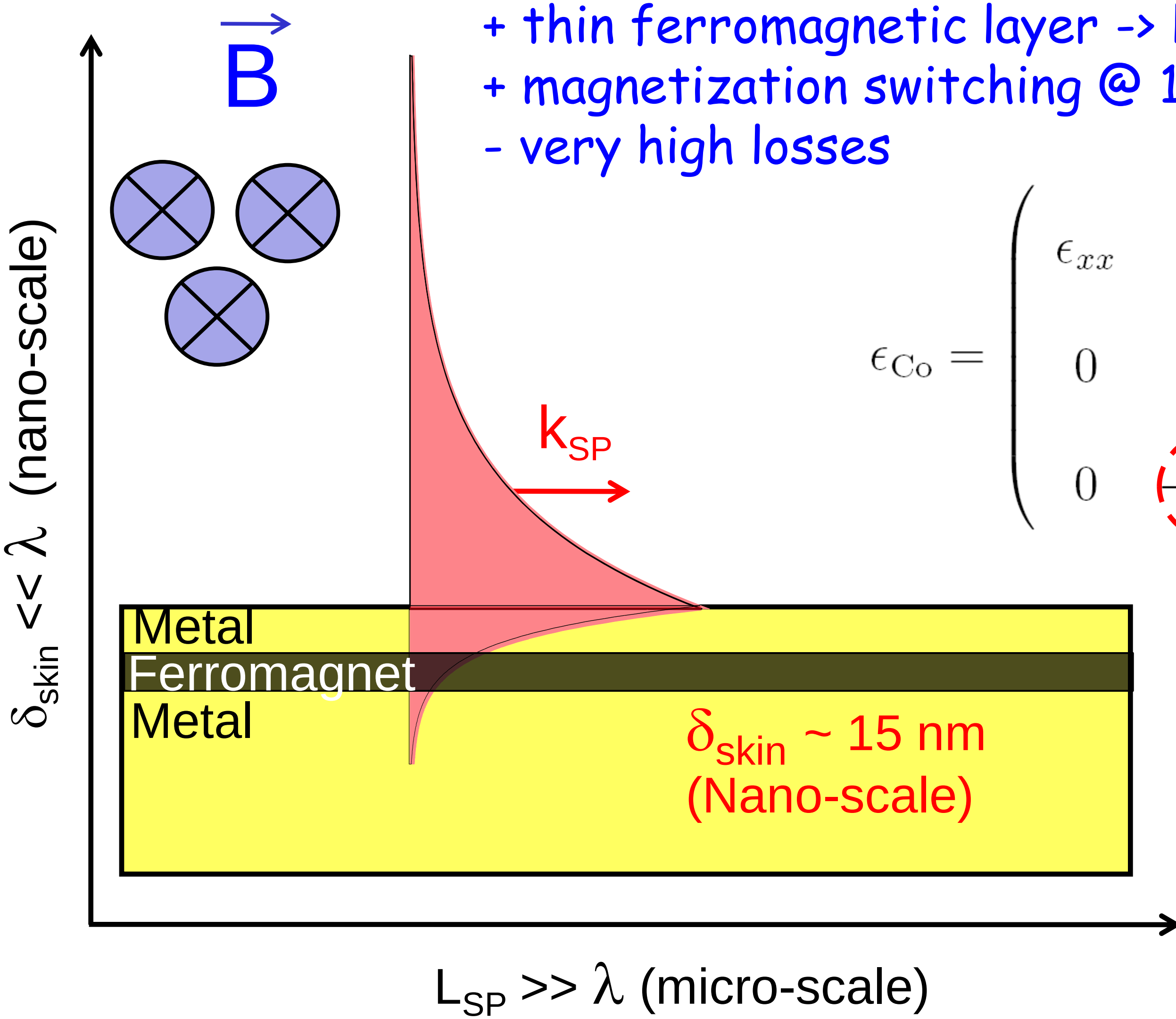
$$\vec{F} = q\vec{E} + q\vec{v} \times \vec{B}$$

Electric force — Magnetic force

- **SPP wavelength changes !**
- **But: very small effect!!!**

Temnov, Nature Photonics 6 (2012)

Magnetic control in metal-ferromagnetic multilayers



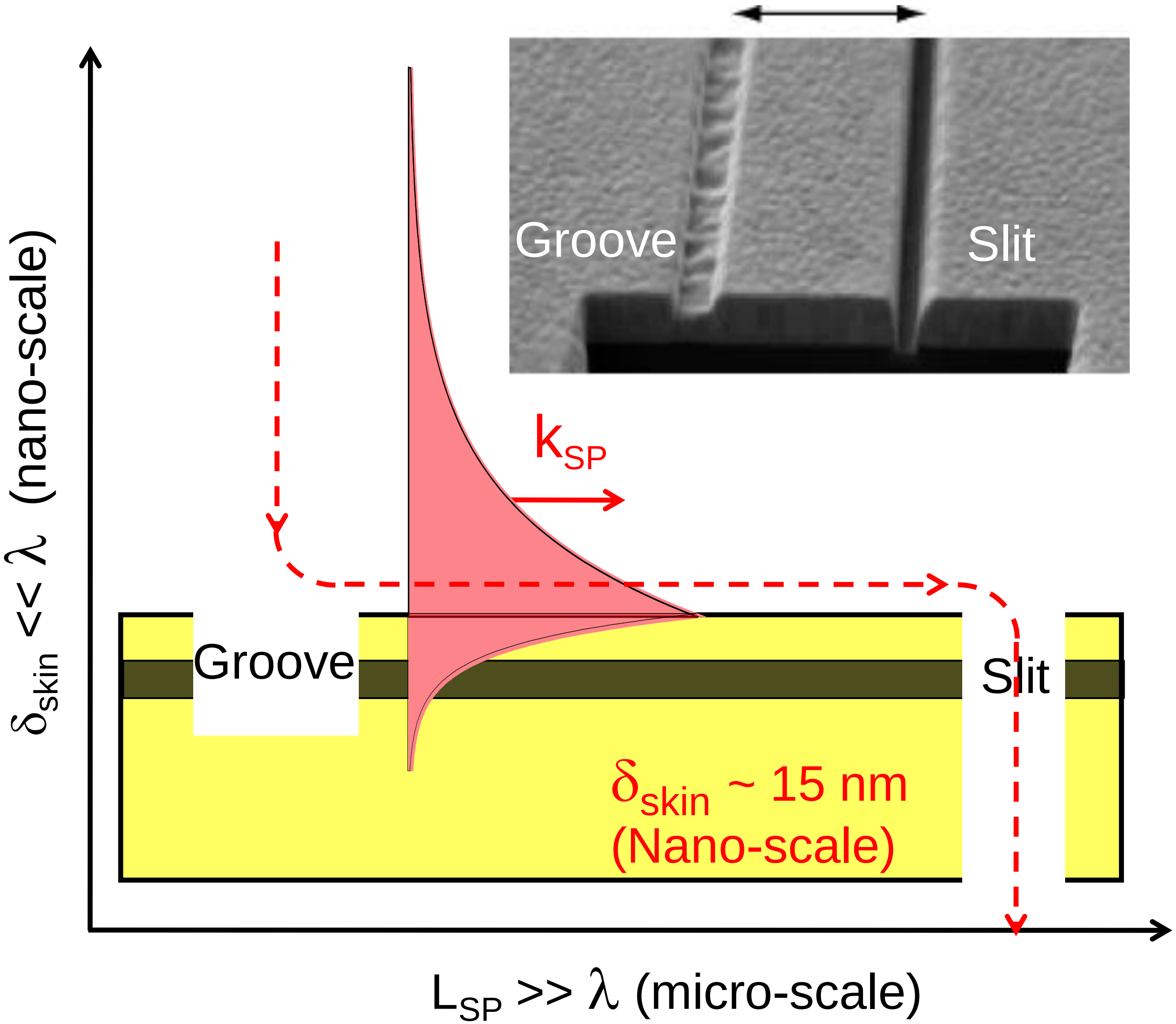
+ thin ferromagnetic layer -> large magneto-optical effect
+ magnetization switching @ 15 mT
- very high losses

$$\epsilon_{\mathrm{Co}} = \begin{pmatrix} \epsilon_{xx} & 0 & 0 \\ 0 & \epsilon_{xx} & \epsilon_{yz} M_x \\ 0 & -\epsilon_{yz} M_x & \epsilon_{xx} \end{pmatrix}$$

- Magnetic modulation of SPP wave vector (SPP phase)
- Measurements within the skin depth

Gonzalez-Diaz et al., Phys. Rev. B 76 (2007)

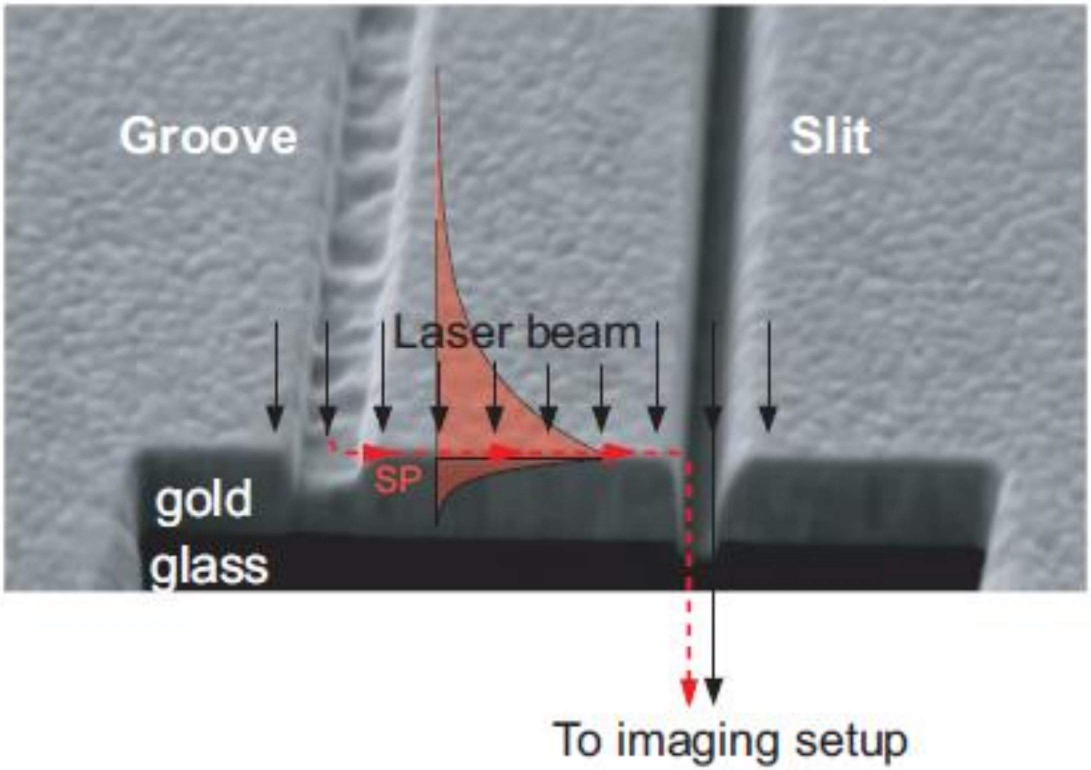
SP-excitatation on slit-groove nanostructures

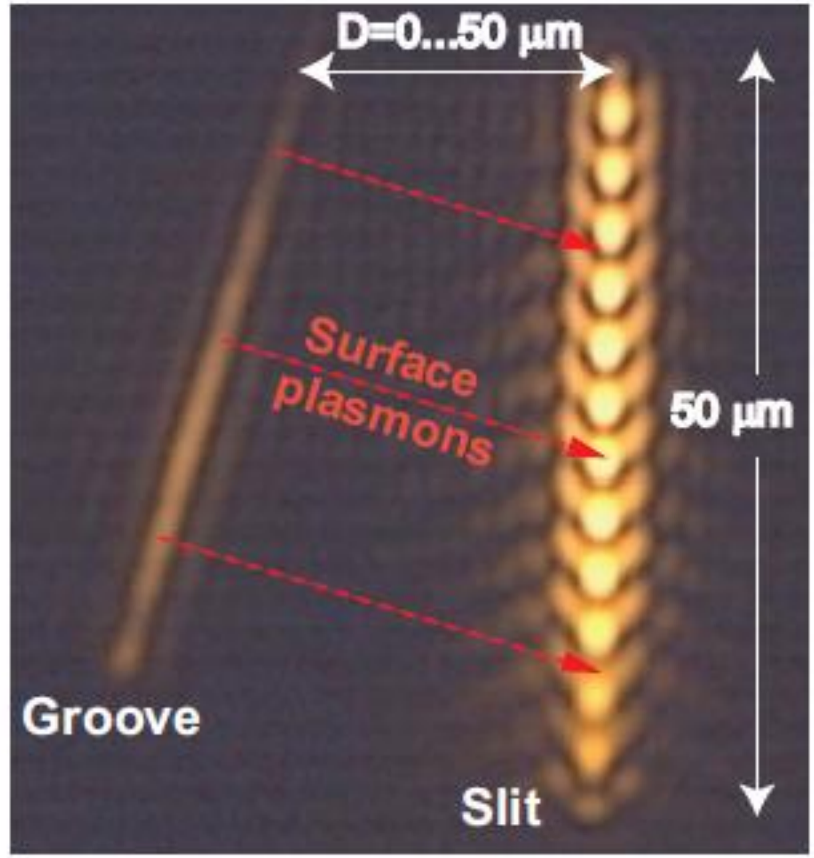


Sub-wavelength slit-groove pairs produced by the focused ion beam

-> efficient in- and out-coupling of SP

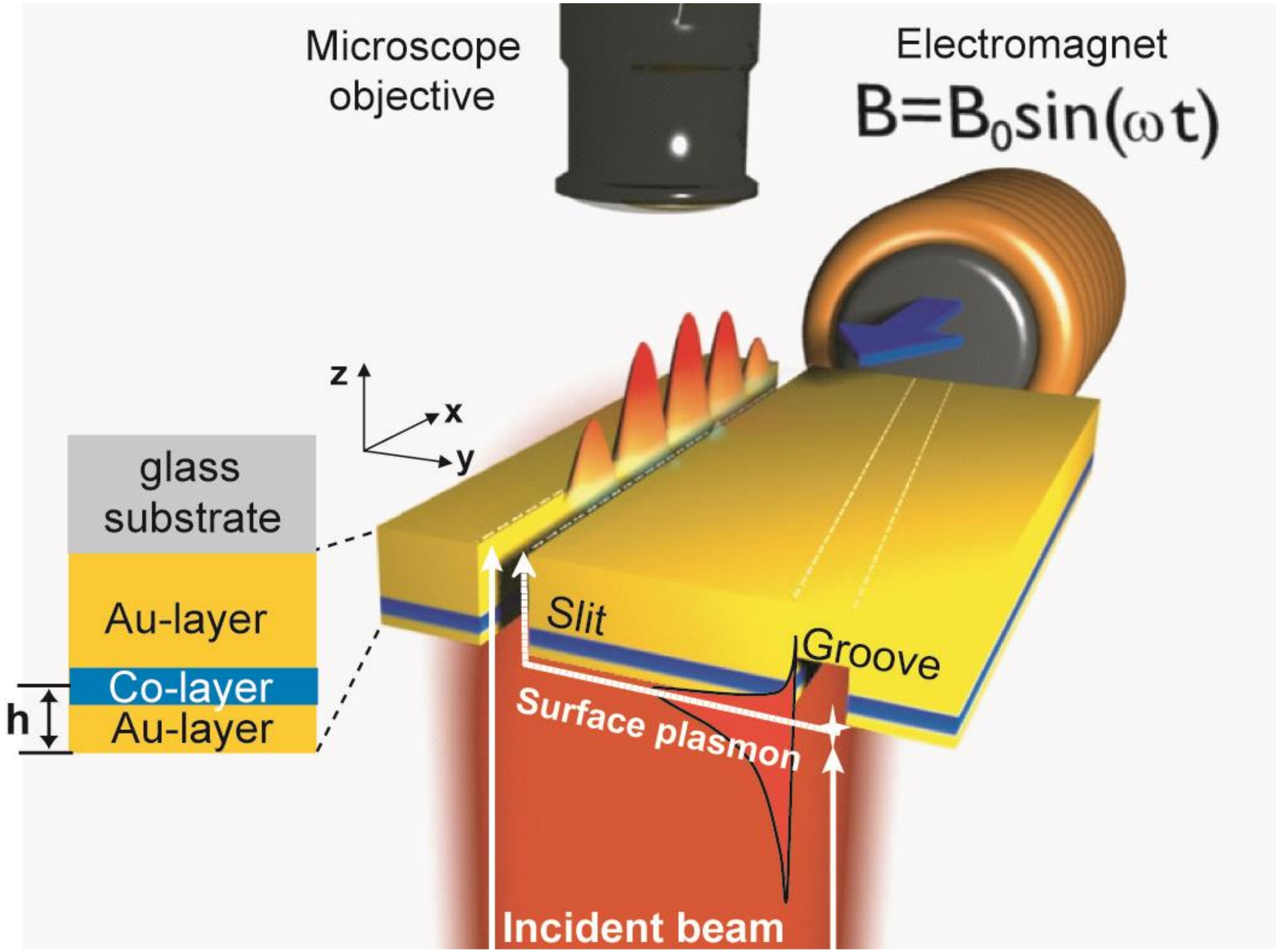
Magneto-plasmonic interferometry





HYBRID magneto-plasmonic switch

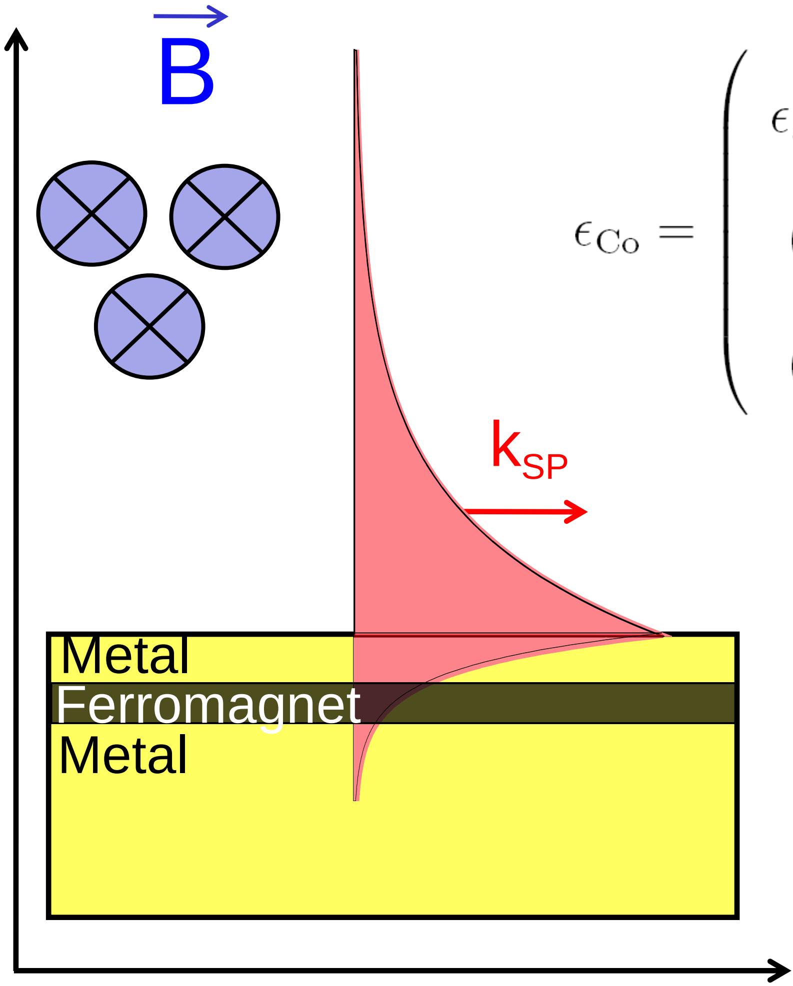
1) Au/Co/Au sandwich
2) SLIT-GROOVE pair
3) Electromagnet



Switching speed is limited by the mechanism of magnetization reversal !

Temnov et al., Nature Photonics 4 (2010)

Magneto-plasmonics: effective medium approximation



$$\epsilon_{\mathrm{Co}} = \begin{pmatrix} \epsilon_{xx} & 0 & 0 \\ 0 & \epsilon_{xx} & \epsilon_{yz} M_x \\ 0 & -\epsilon_{yz} M_x & \epsilon_{xx} \end{pmatrix}$$

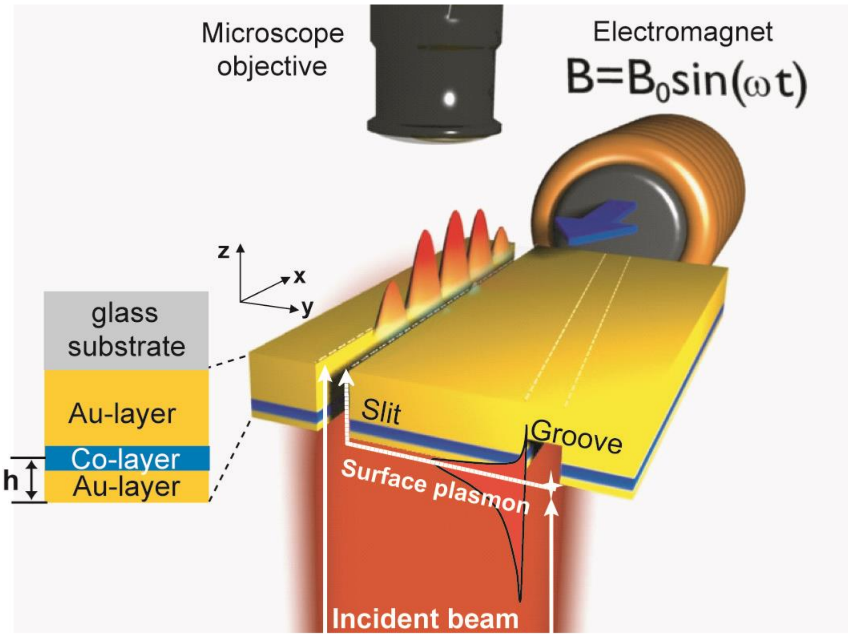
$$\varepsilon_{\mathrm{eff}} = \frac{1}{\delta_{\mathrm{skin}}} \int_0^\infty \varepsilon(z) \mathrm{e}^{-z/\delta_{\mathrm{skin}}} dz \, ,$$

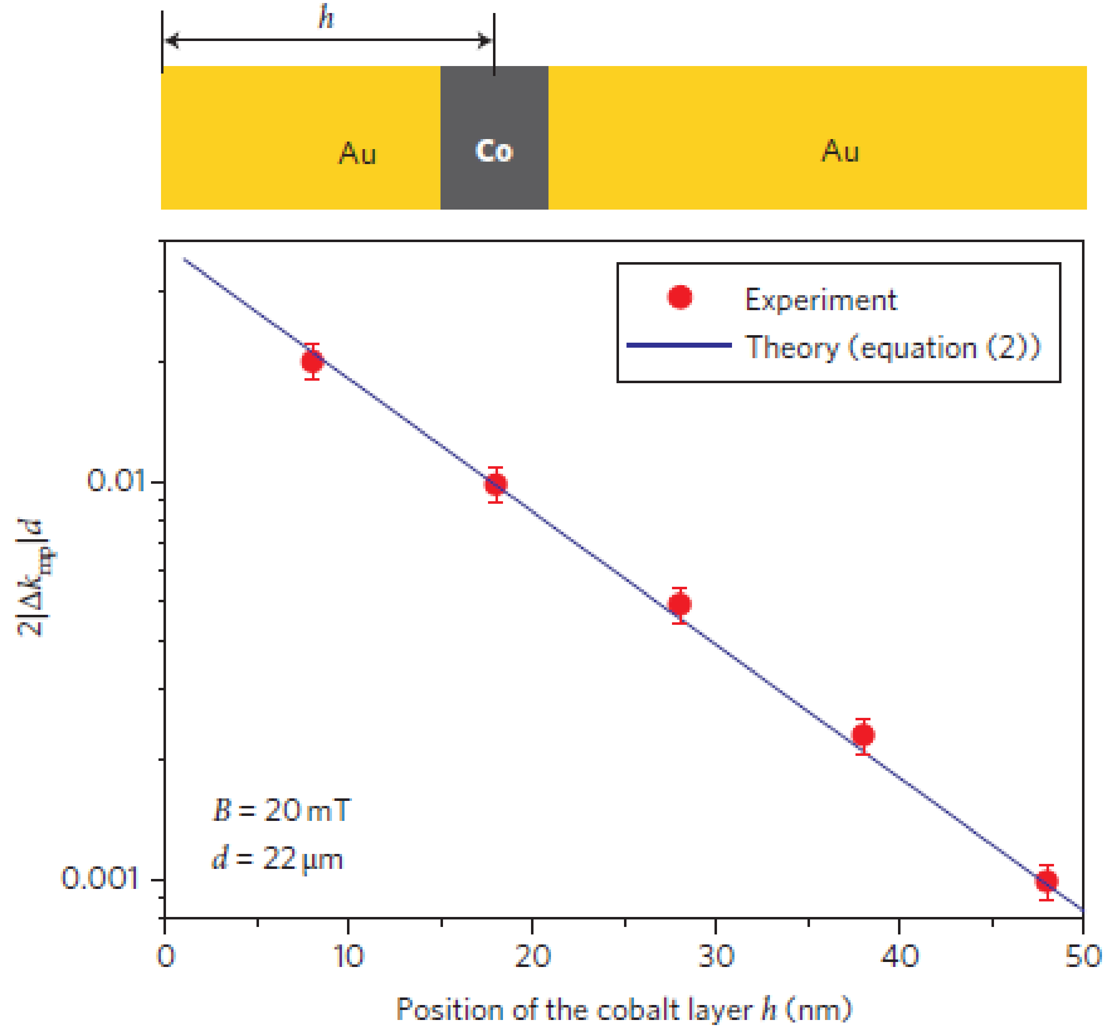
$$\varepsilon_{\mathrm{eff}}^{xz} = \frac{1}{\delta_{\mathrm{skin}}} \int_0^\infty \varepsilon^{xz}(z) \mathrm{e}^{-z/\delta_{\mathrm{skin}}} dz$$

$$k_{\mathrm{spp}}(\pm M) = k_0 \sqrt{\frac{\varepsilon_{\mathrm{eff}}}{1+\varepsilon_{\mathrm{eff}}}} \left(1 \pm \frac{i \varepsilon_{\mathrm{eff}}^{xz} M}{(1-\varepsilon_{\mathrm{eff}}^2)\sqrt{\varepsilon_{\mathrm{eff}}}}\right)$$

Temnov et al.,
J. of Optics 18 (2016)

Application: magnetic sensing at the nano-scale





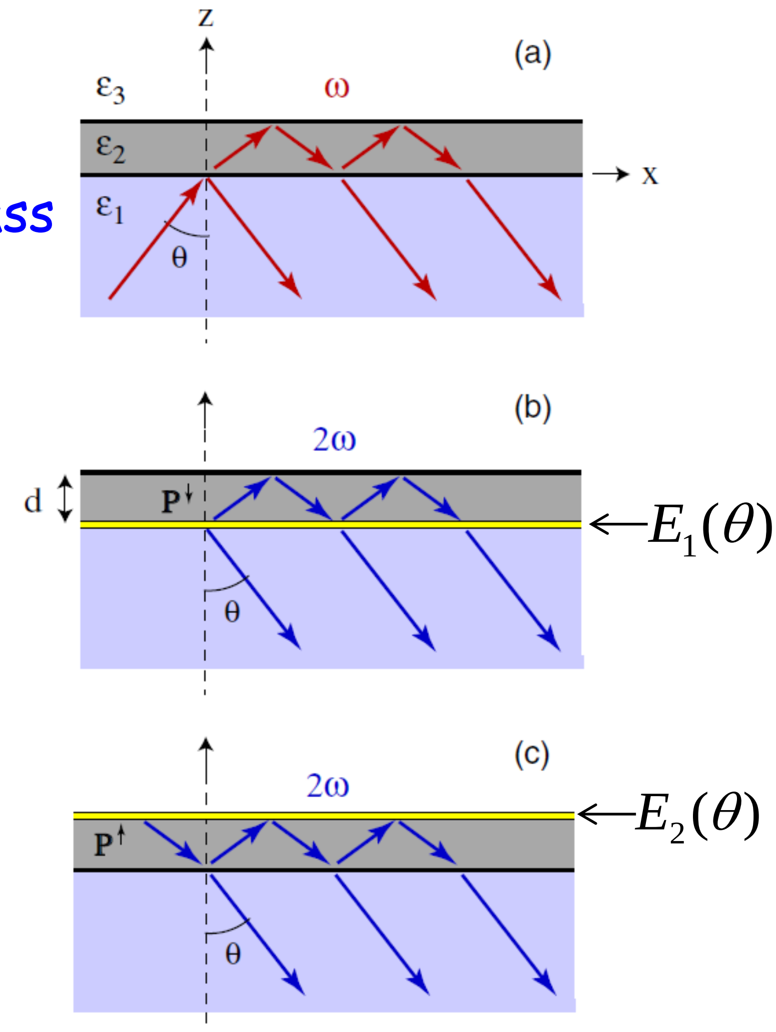
Temnov et al.,
Nature Phot. 4 (2010)
J. of Optics 18 (2016)

$$k_{\text{spp}}(\pm M) = k_0 \sqrt{\frac{\varepsilon_{\text{eff}}}{1+\varepsilon_{\text{eff}}}} \left(1 \pm \frac{i\varepsilon_{\text{eff}}^{xz} M}{(1-\varepsilon_{\text{eff}}^2)\sqrt{\varepsilon_{\text{eff}}}}\right)$$

Nonlinear (magneto)-optics with surface plasmon polaritons?

Caution: nonlinear optics is quite complex!

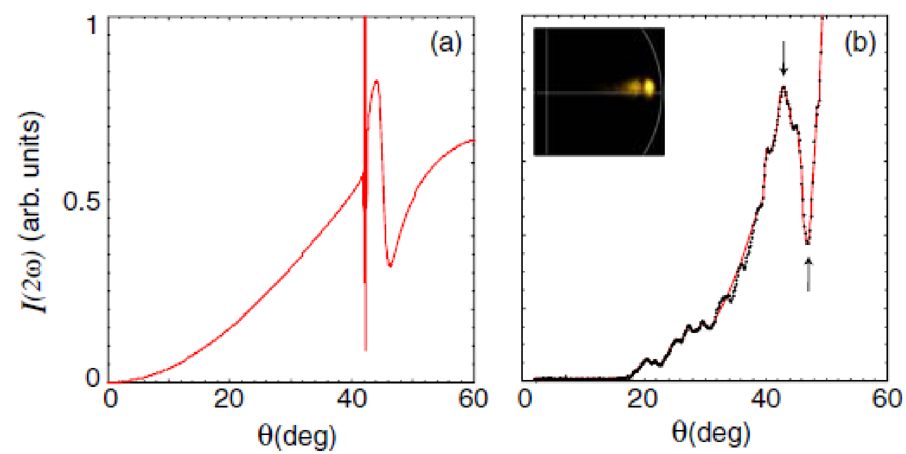
air
Au
glass



$$\omega + \omega = 2\omega$$

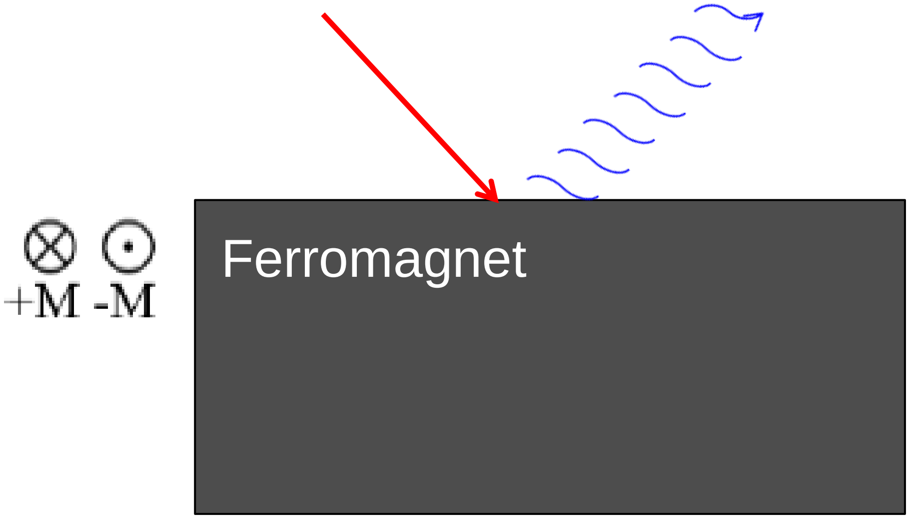
Second harmonic generation (SHG) from two INTERFACES:

$$I_{2\omega}(\theta) = | E_1(\theta) + E_2(\theta) |^2$$



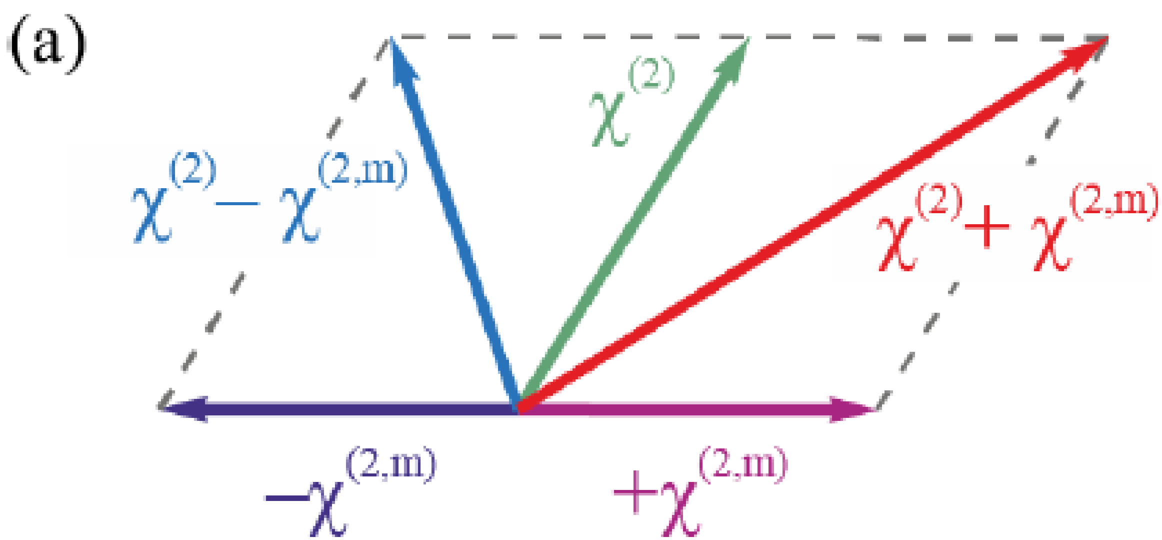
Palomba & Novotny, PRL 101 (2008)

Magnetic SHG generation: phenomenology



$$P_i(2\omega) = \chi^{(2)}_{ijk}(-2\omega;\omega,\omega) : E_j(\omega)E_k(\omega)$$

magnetic SHG "ugly" photons



Magnetic and nonmagnetic contributions

Recent development in plasmonic mSHG generation

Pavlov et al., APL 75 (1999)

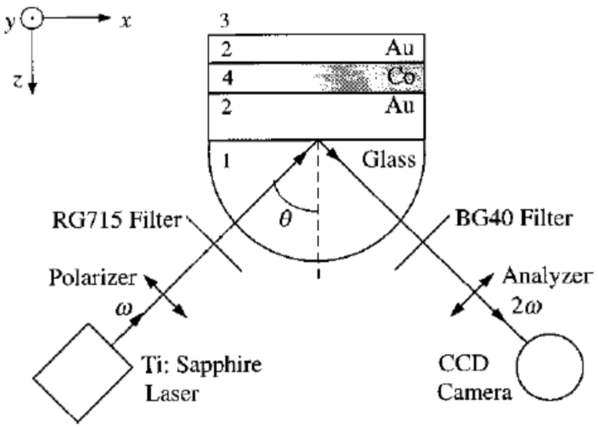
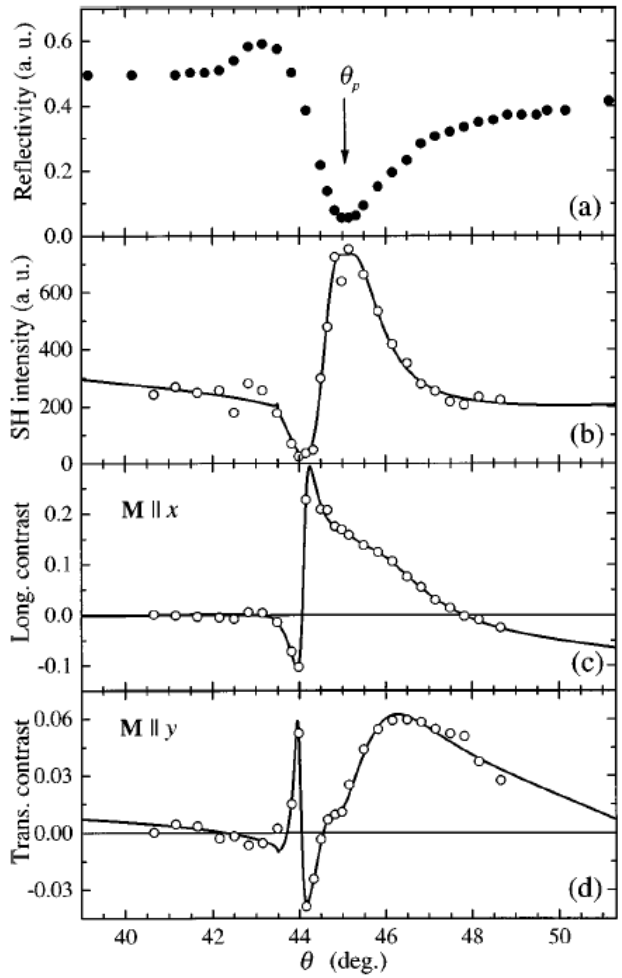


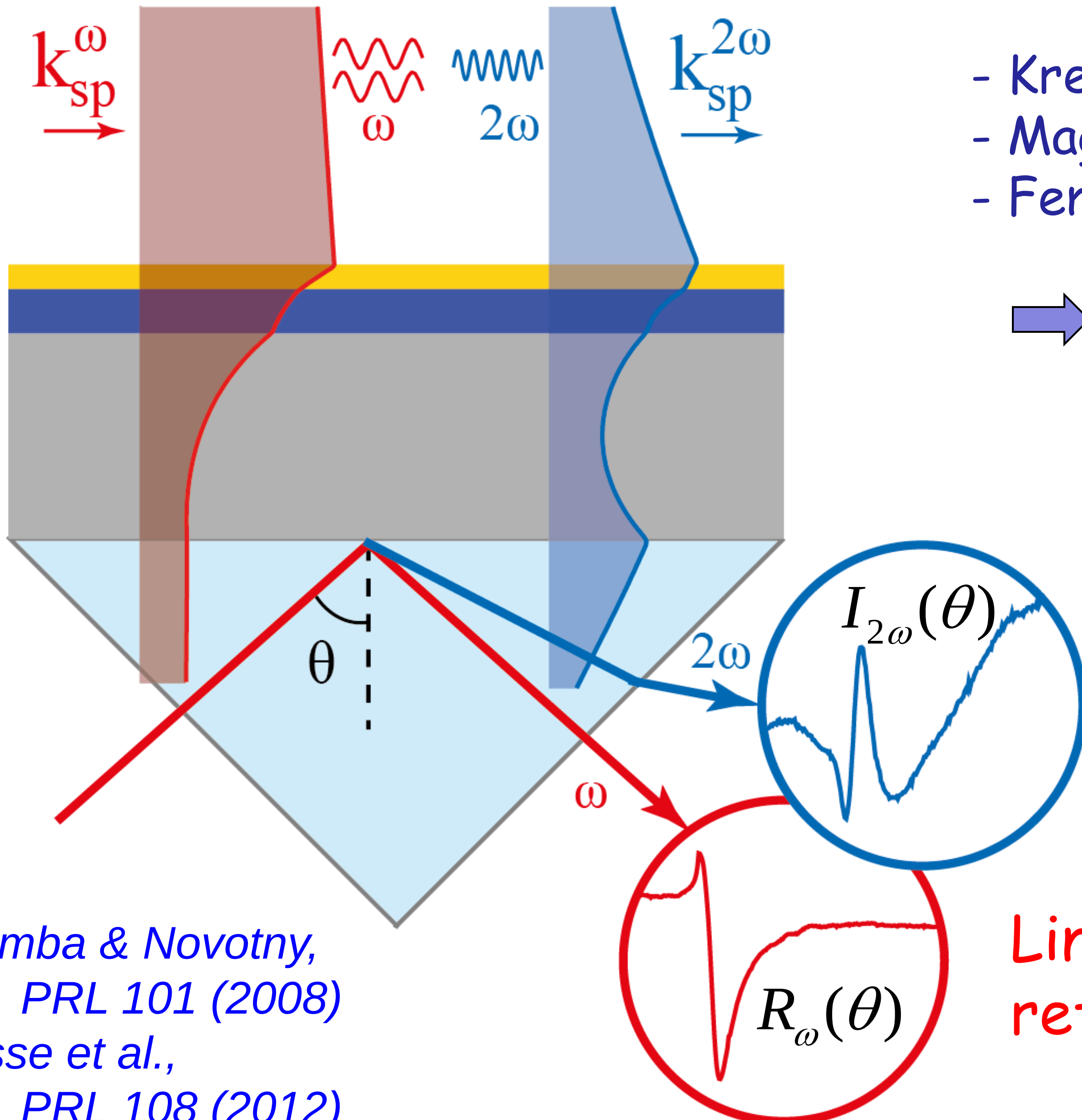
FIG. 1. Schematics of the experimental setup.



$$E_i^{2\omega} \propto T^{24}T^{42}T^{21}\chi^{32}_{ijk}F^{32}_j F^{32}_k e^{2i(K_2 d_2' + K_4 d_4 + K_2 d_2)} + T^{42}T^{21}\chi^{24}_{ijk}F^{24}_j F^{24}_k e^{2i(K_4 d_4 + K_2 d_2)} - T^{21}\chi^{24}_{ijk}F^{42}_j F^{42}_k e^{2iK_2 d_2} + \chi^{21}_{ijk}F^{21}_j F^{21}_k ,$$

Do we still have a chance to understand something?

Nonlinear plasmonics in Au/Co/Ag trilayers



- Kretschmann configuration
- Magneto-plasmonic multilayer
- Femtosecond laser excitation

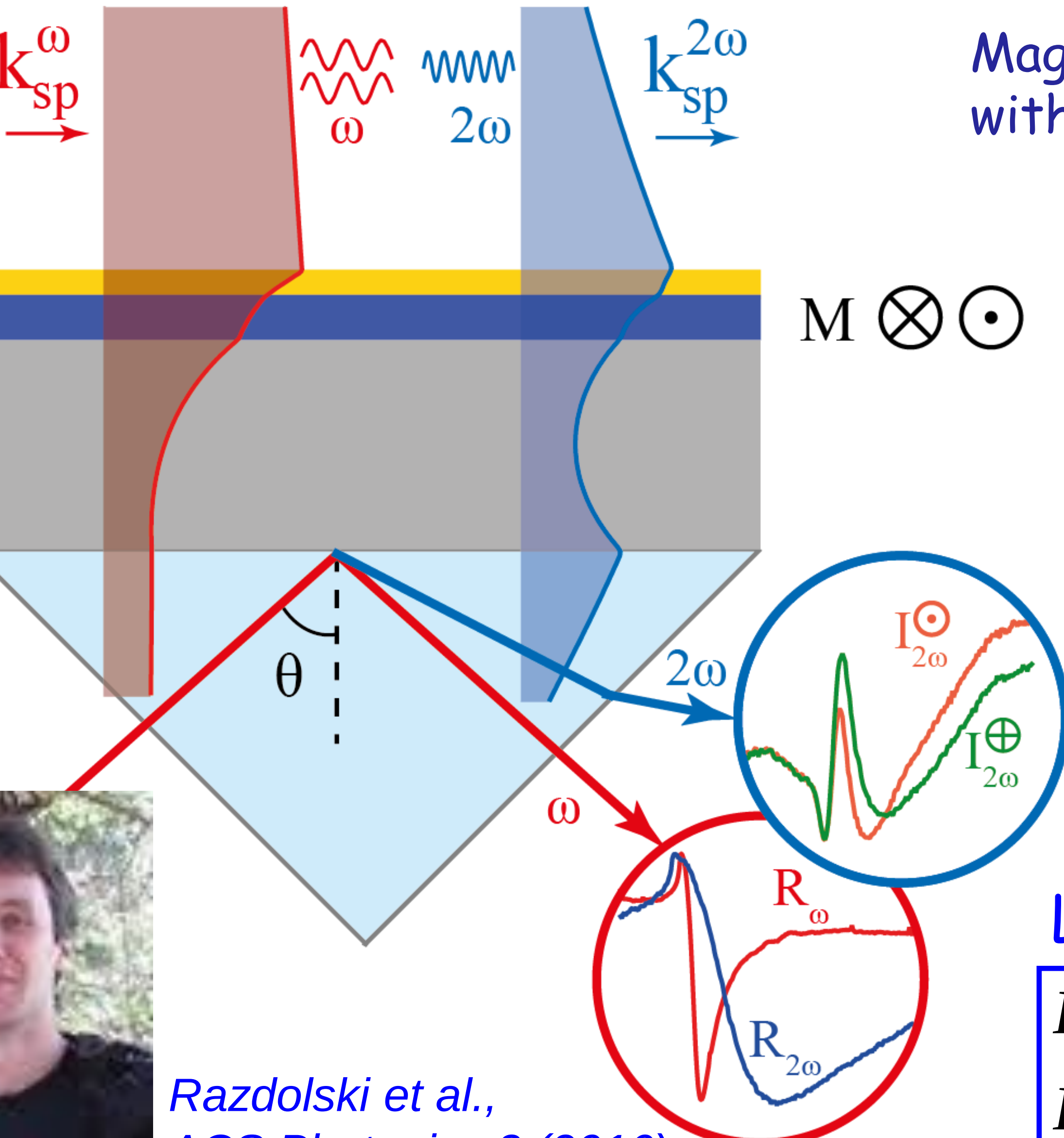
➡ Nonlinear (magneto)-optics

Second harmonic generation (SHG)

Linear reflectivity

Palomba & Novotny, PRL 101 (2008)
Grosse et al., PRL 108 (2012)

Nonlinear magneto-plasmonics in Au/Co/Ag trilayers



Magnetization reversal in cobalt with ~ 10 mT magnetic field

Magnetic second harmonic generation (mSHG):

$$I_{2\omega}(+M) \neq I_{2\omega}(-M)$$

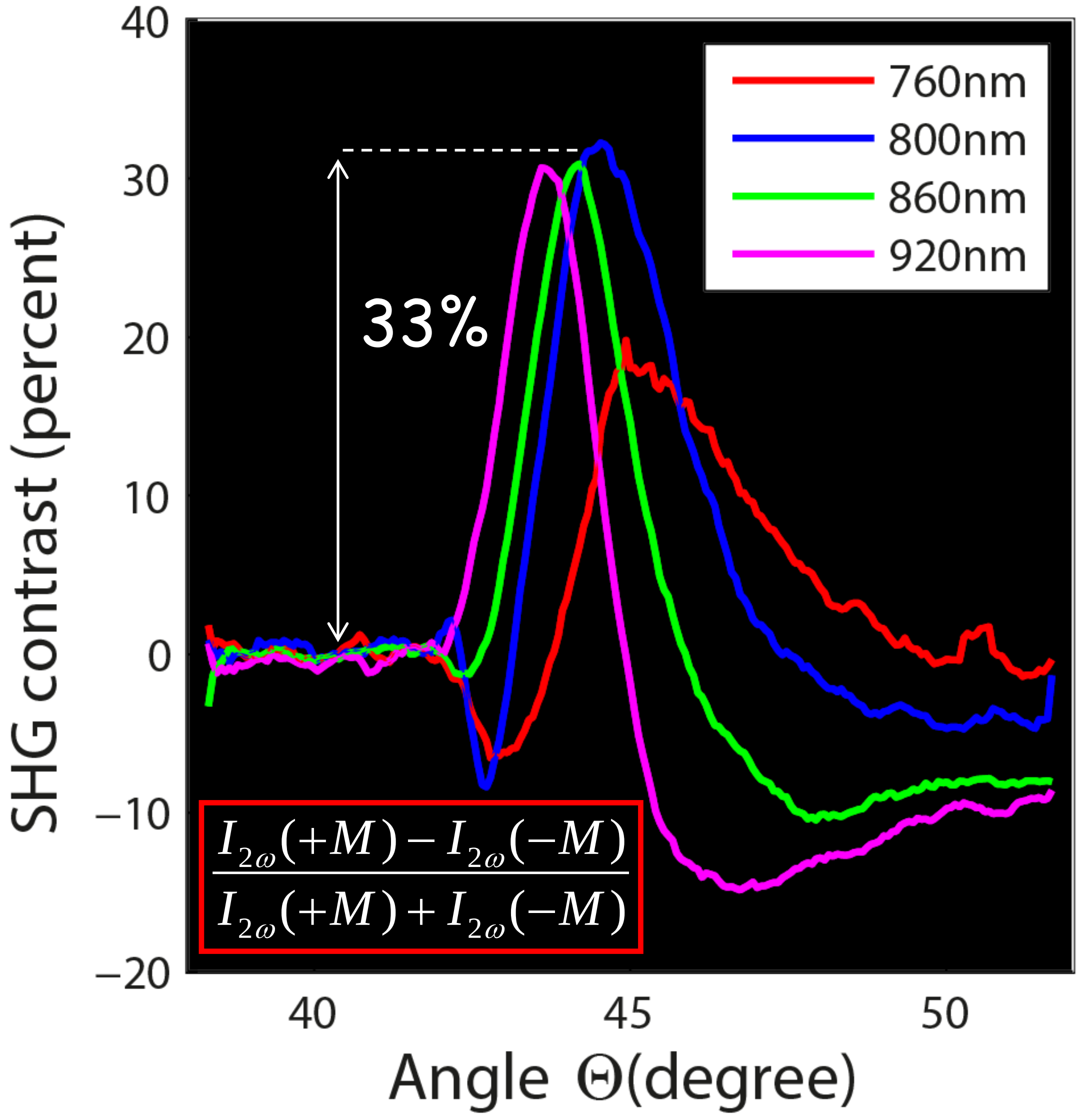
Linear contrast:

$$R_{\omega}(+M) \approx R_{\omega}(-M)$$

$$R_{2\omega}(+M) \approx R_{2\omega}(-M)$$

Razdolski et al., ACS Photonics 3 (2016)

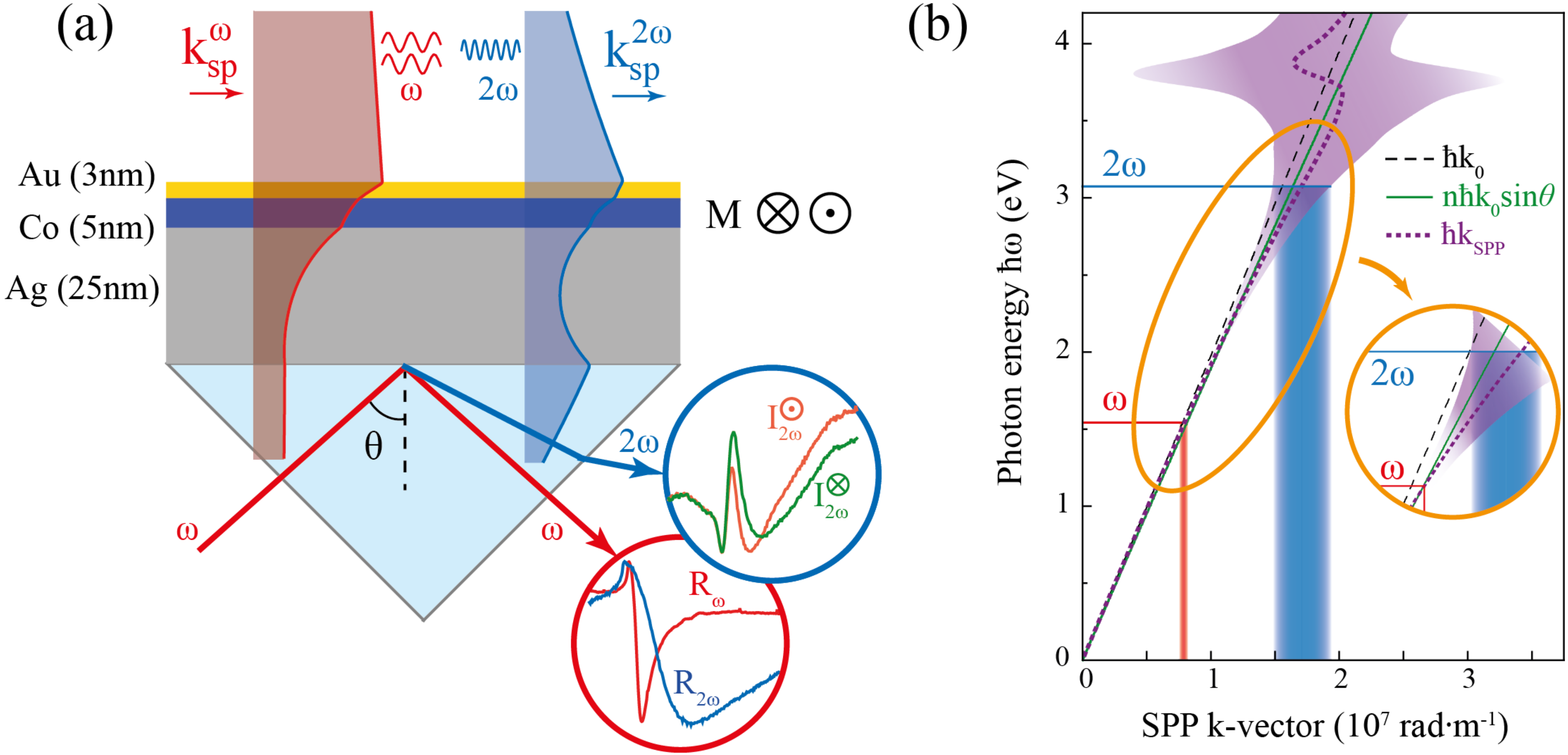
Giant nonlinear magnetic contrast-> Optical Switch



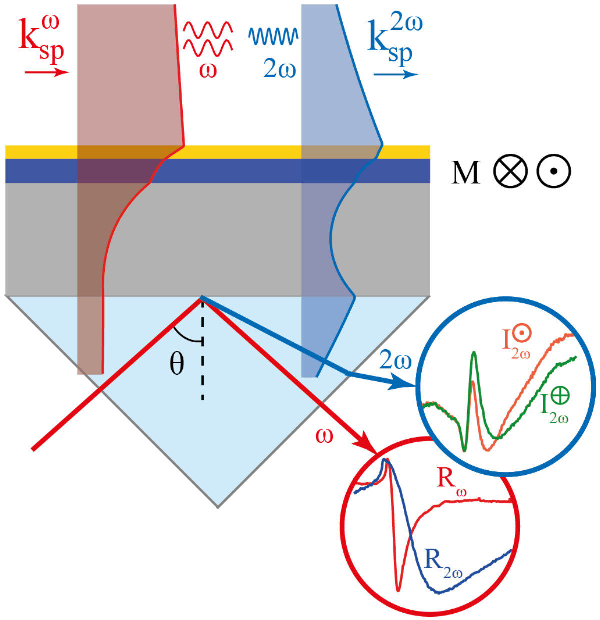
33% = magnetic SHG intensity change by factor 2x

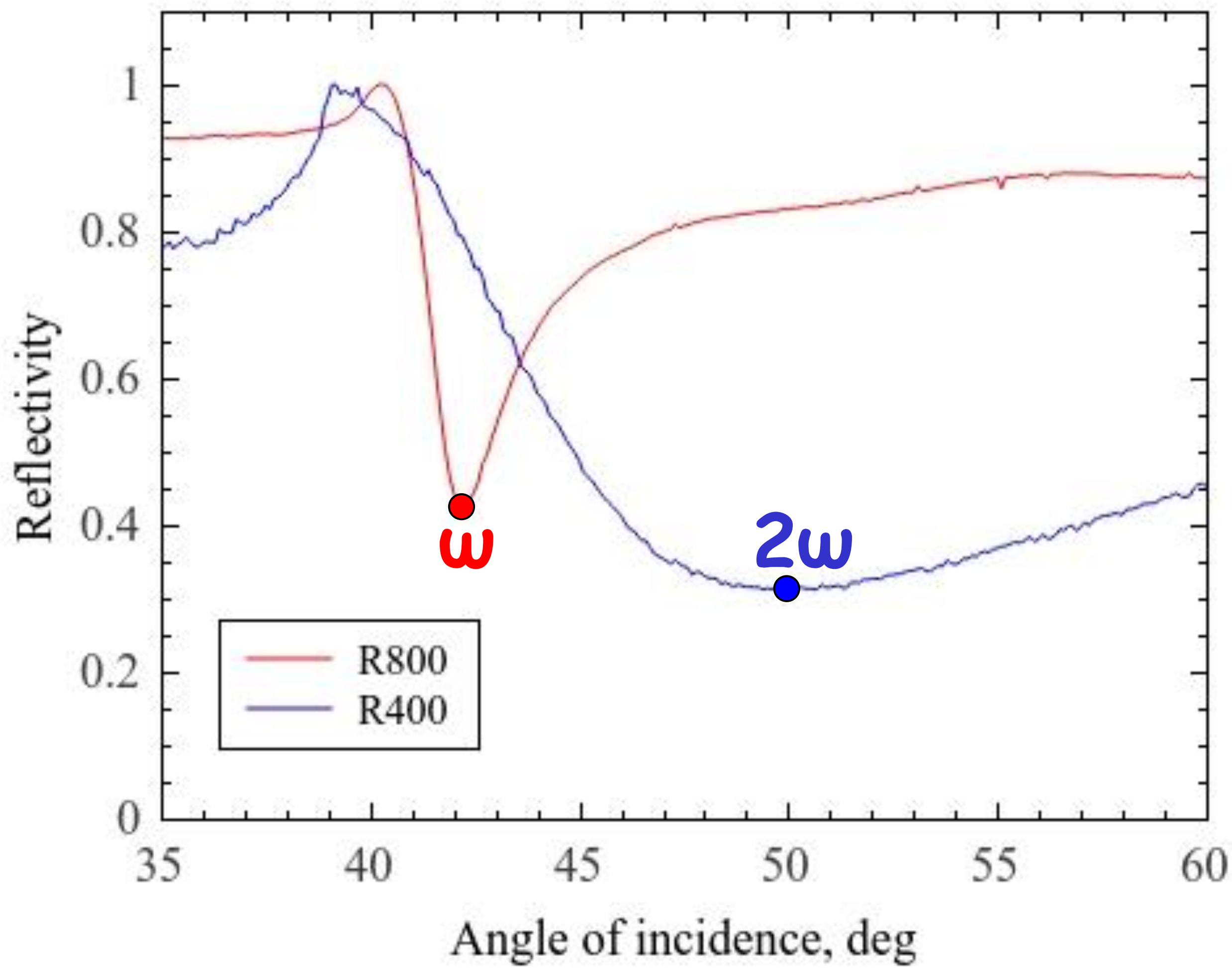
Razdolski et al., ACS Photonics (2016)
Temnov et al, J. Optics (2016)

Plasmonic second harmonic generation



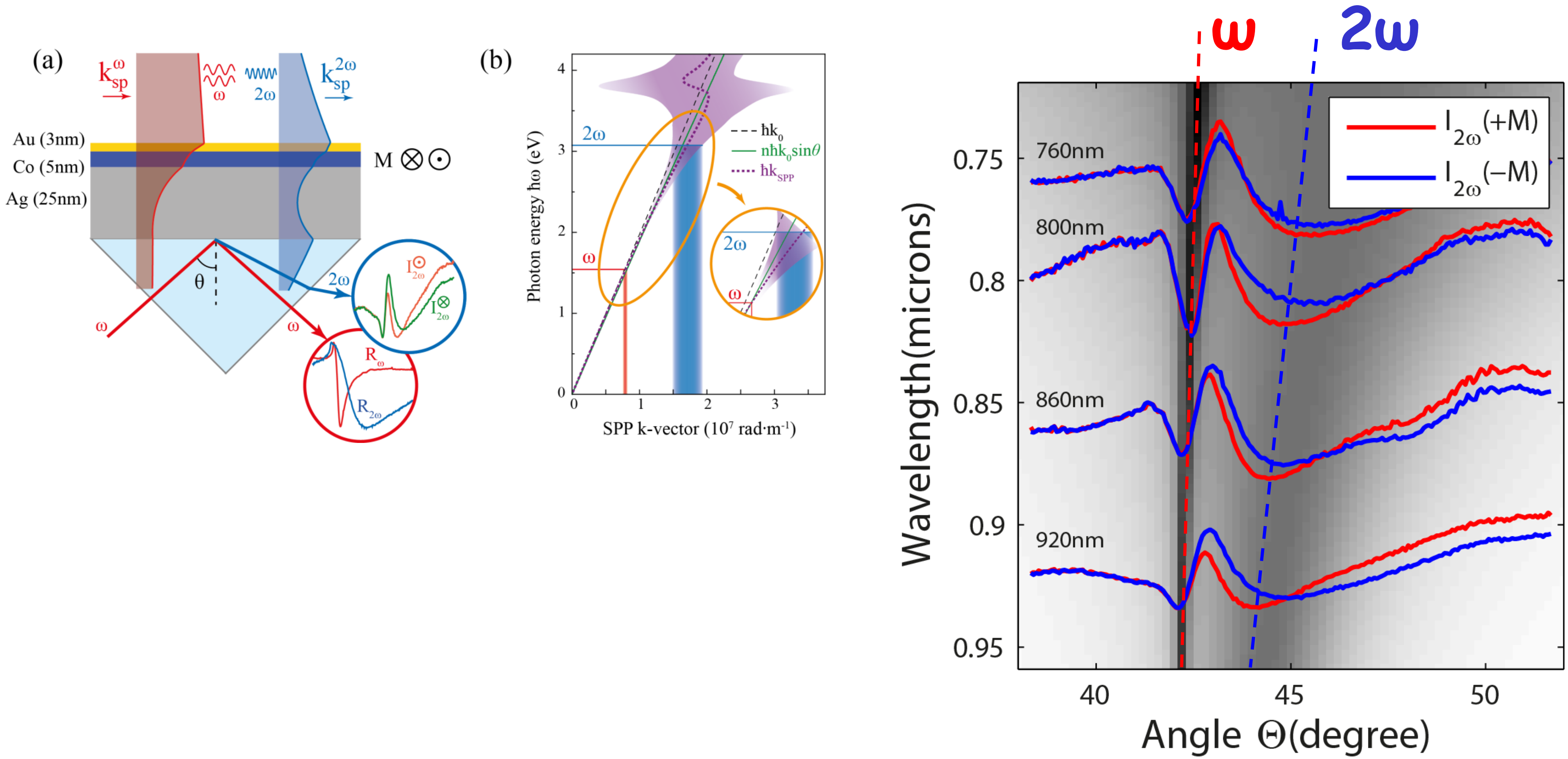
Linear plasmonics: two SPP resonances for ω and 2ω





SPP excitation at both frequences ω and 2ω ?

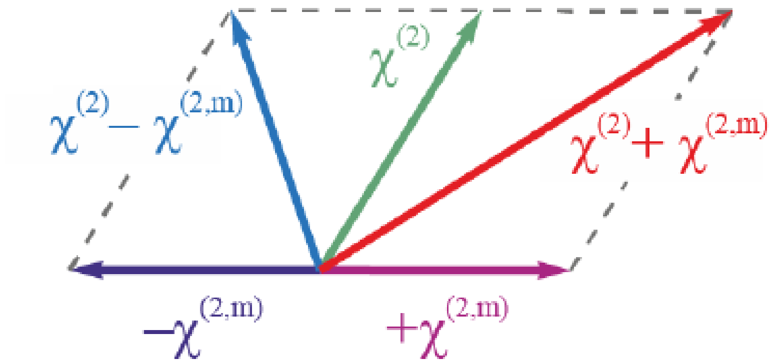
Wavelength dependence of mSHG contrast

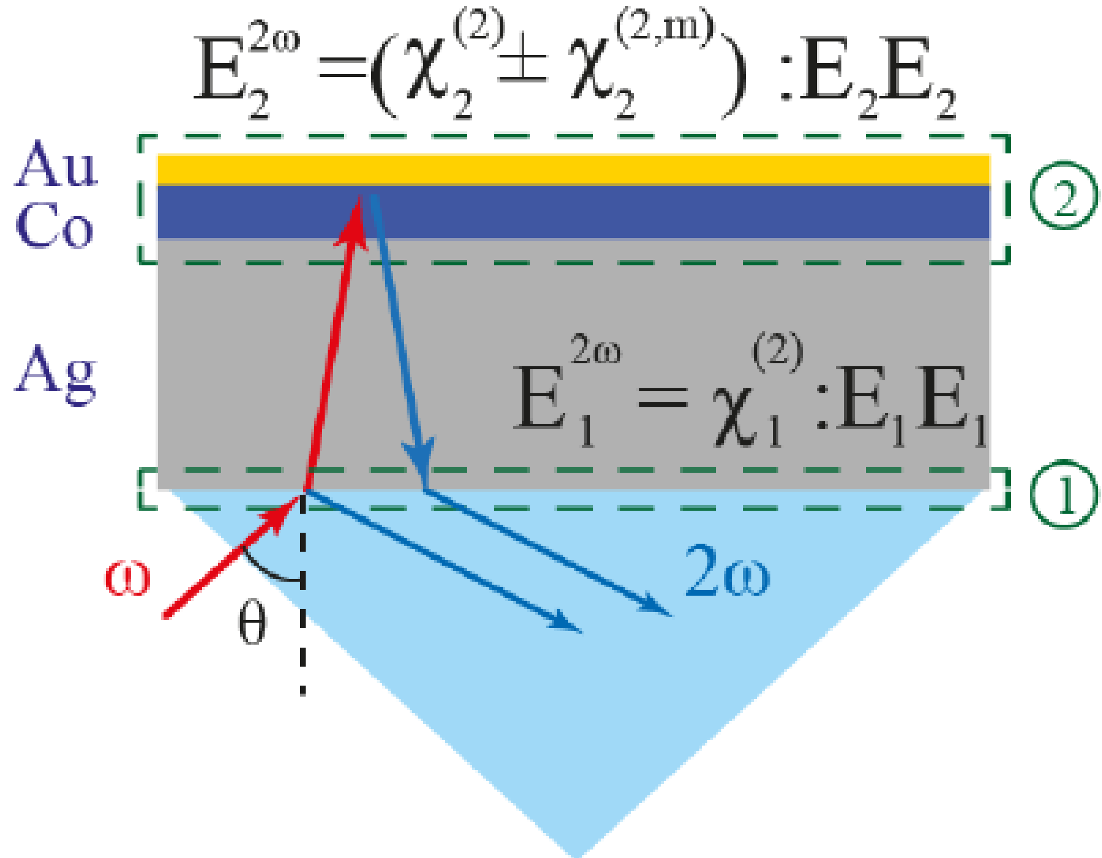


The nonlinear mSHG peak is squeezed between two SPR resonances

Magnetic SHG generation: phenomenology

$$P_i(2\omega) = \chi^{(2)}_{ijk}(-2\omega;\omega,\omega) : E_j(\omega)E_k(\omega)$$

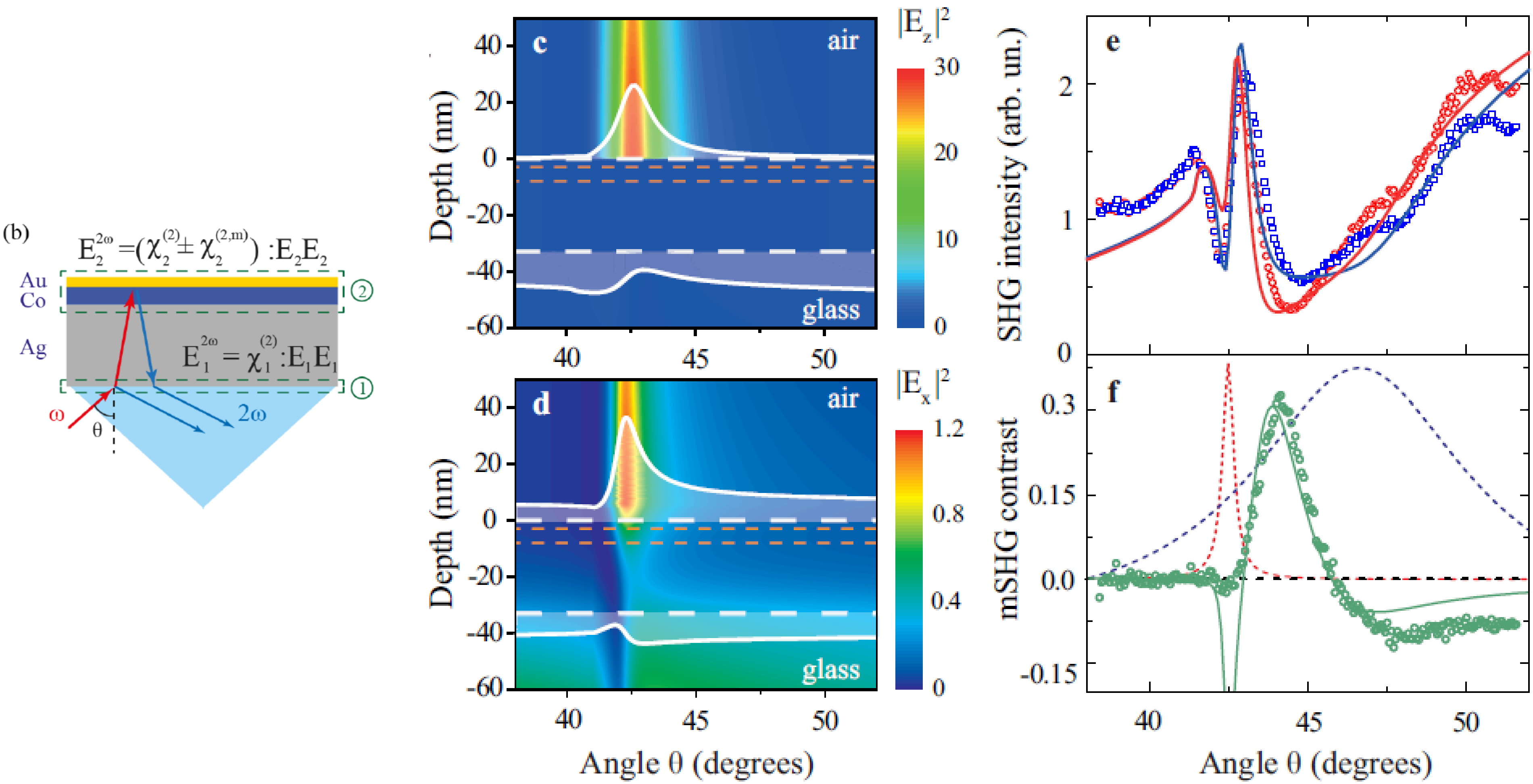




- Broken inversion symmetry at interfaces
- SHG from ALL interfaces
- Magnetic and nonmagnetic SHG from ALL interfaces !

<u>Solution:</u> replace 3 upper interfaces with a single EFFECTIVE INTERFACE !

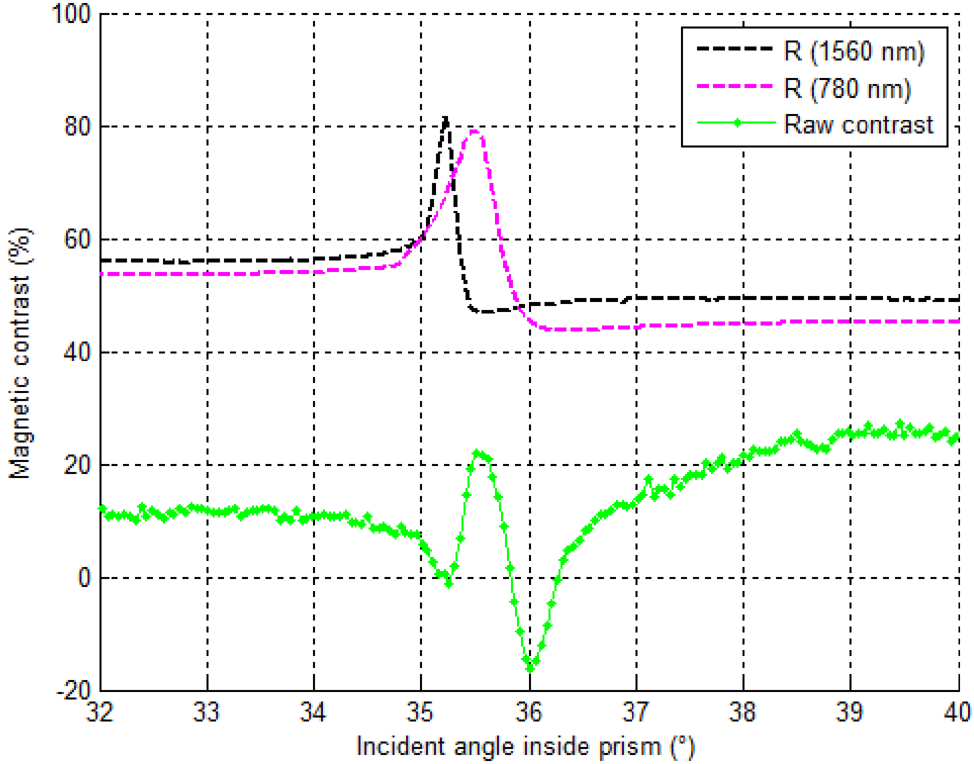
Magnetic SHG generation: phenomenology

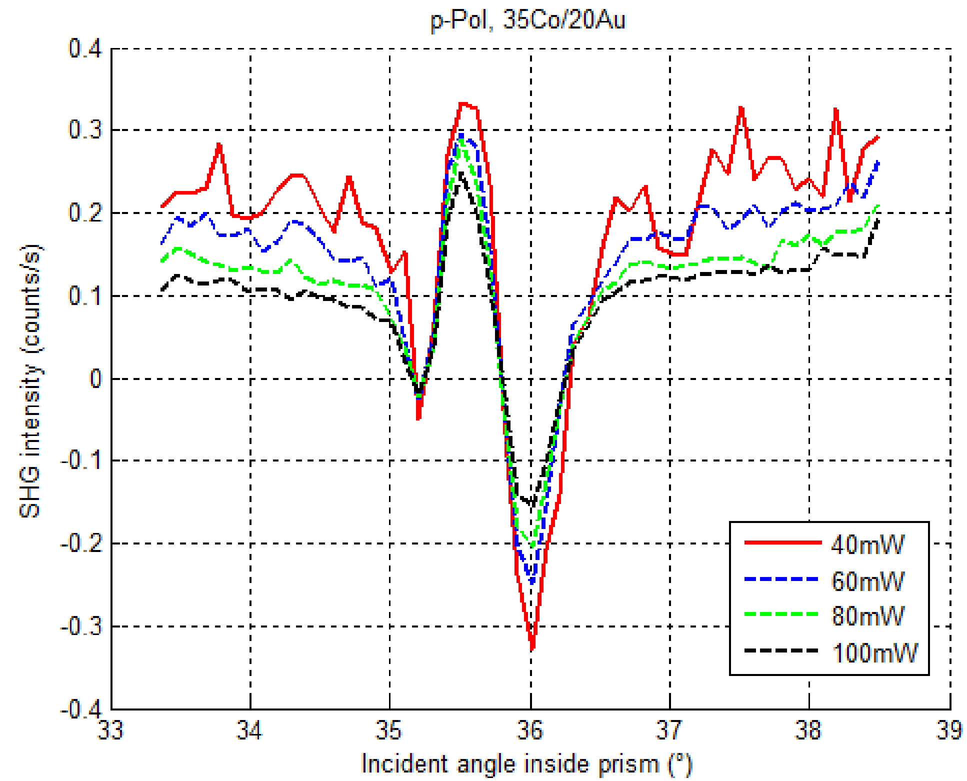


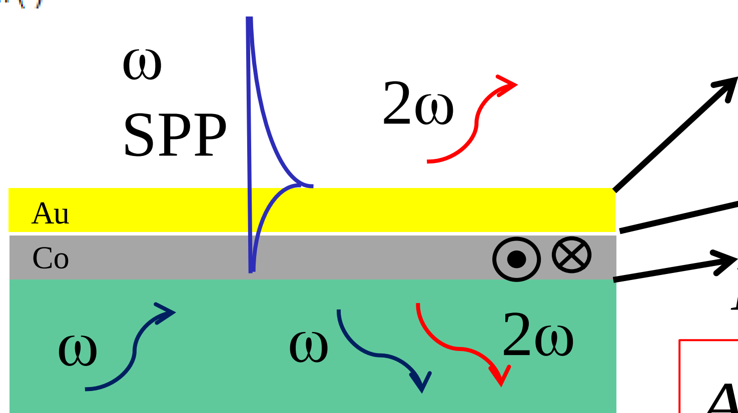
Phenomenological eff. interface approximation
-> results “explained”

$$\chi^{(2)}_{\mathrm{res}}(\theta) \propto \frac{1}{\theta - \theta_{\mathrm{nl}} + i\Gamma}$$

Magneto-plasmonics in bilayer structures







$$P^i_{NL,z} = \chi^i_{zzz} E^{\omega,i}_z E^{\omega,i}_z$$

$$P^i_{NL,x} = \chi^i_{xxx} E^{\omega,i}_x E^{\omega,i}_x$$

$$A^{2\omega} \sim \iint \left(\vec{E}^{2\omega}, \vec{P}^{2\omega}_{NL} \right) dxdz$$

Dynamic multilayer structures ?

Picosecond ultrasonics

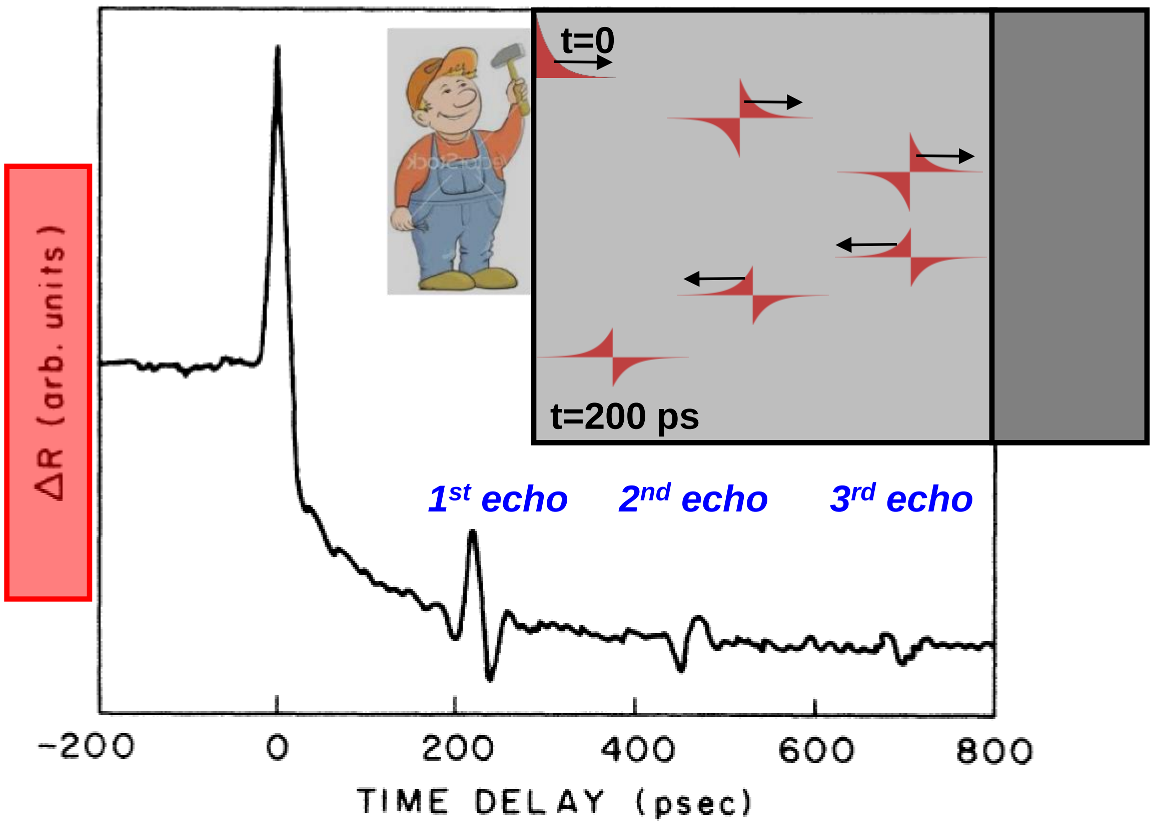
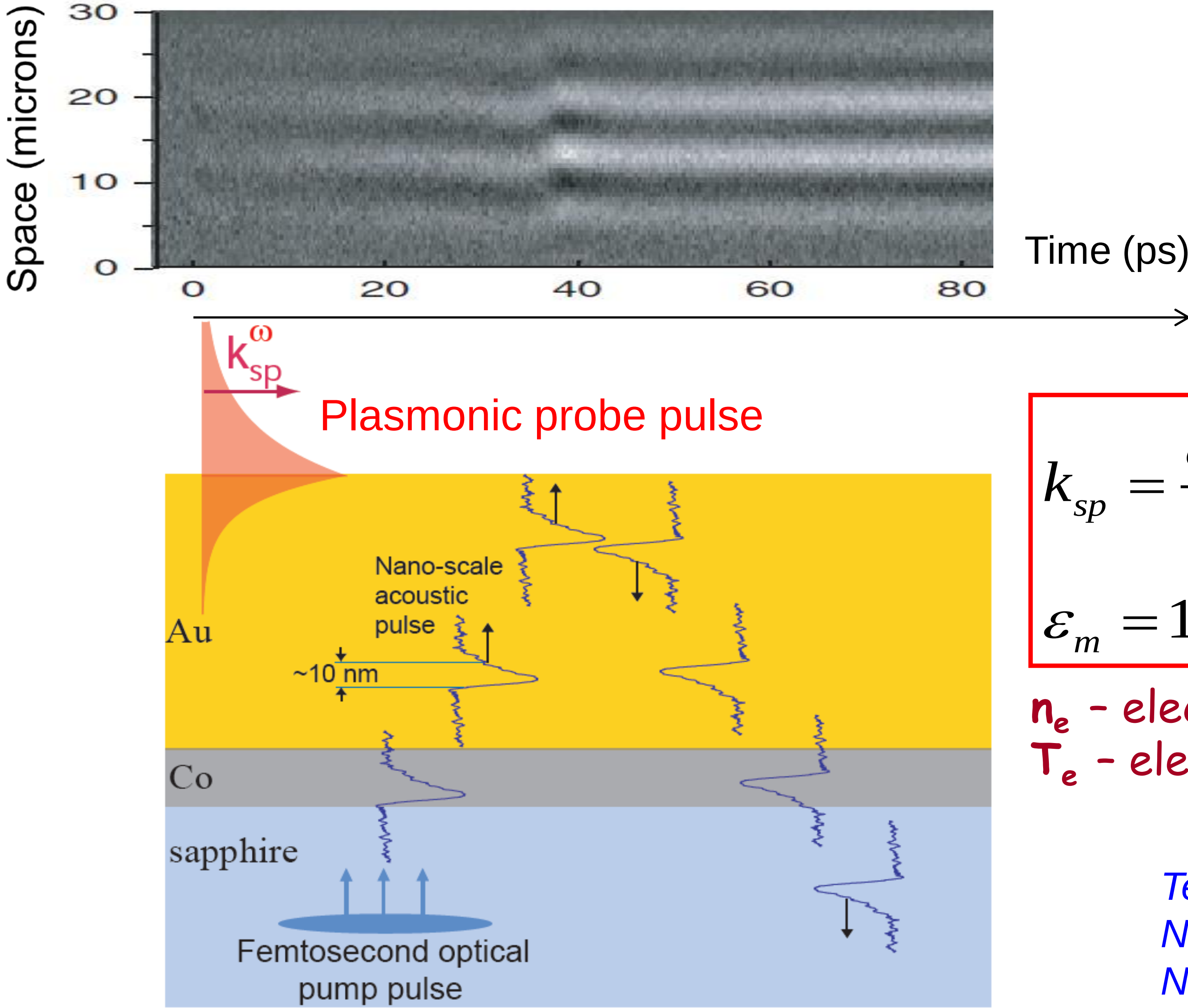


FIG. 4. Photoinduced changes in reflectivity of a 2200-Å film of As_2Te_3 sputtered onto a sapphire substrate.

- Pump-probe reflectivity measurements
- Acoustic echoes
- But… quite complex quantitative analysis
  Unknown photoelastic coefficients

Thomsen et al., Phys . Rev. B 34, 4129 (1986)

Dynamic multilayer structures: acousto-plasmonics



$$k_{sp} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_d \varepsilon_m}{(\varepsilon_d + \varepsilon_m)}}$$

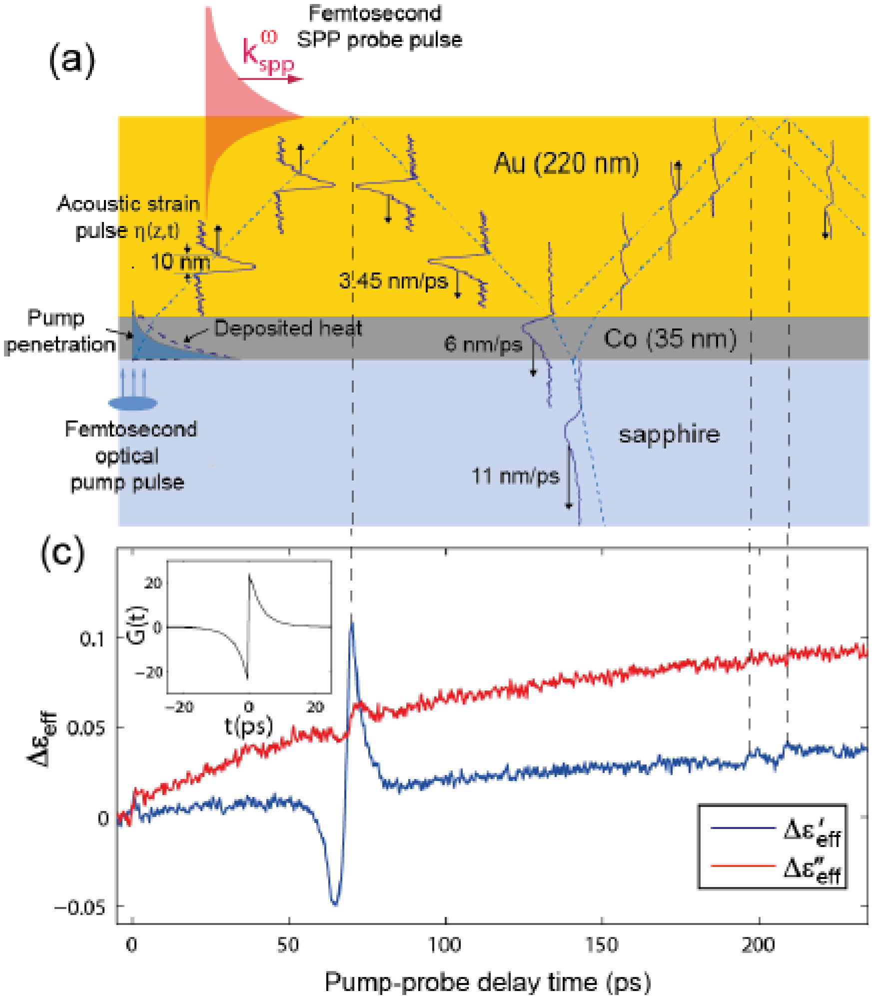
$$\varepsilon_m = 1 - const(T_e) \times n_e$$

n_e - electron density

T_e - electron temperature

Temnov et al.,
Nature Phot. 6 (2012)
Nature Comm. 4 (2013)

Eff. medium approximation: linear effect in the bulk



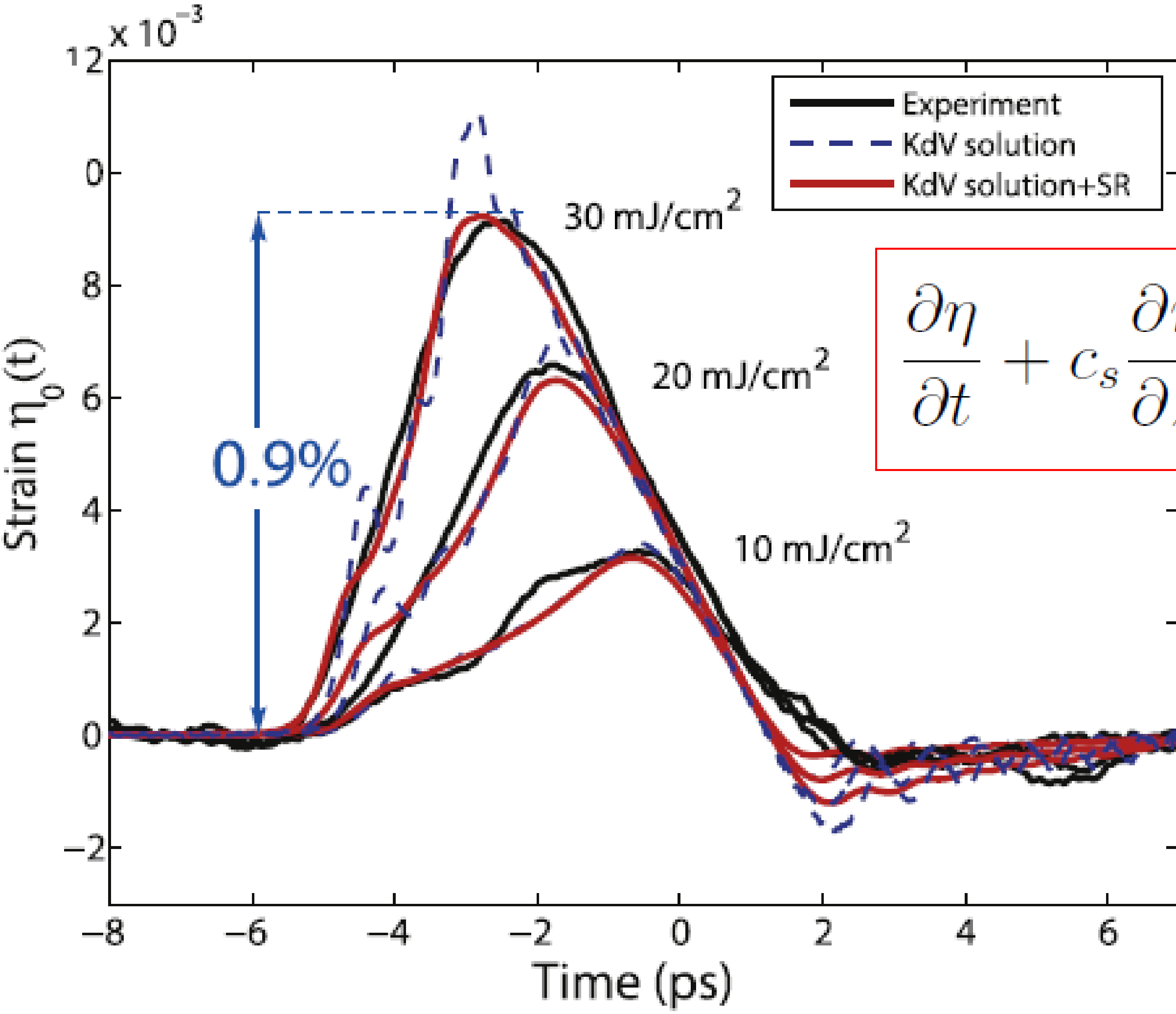
$$k_{\rm spp} = k_0\sqrt{\frac{\varepsilon_{\rm eff}}{1+\varepsilon_{\rm eff}}}$$

$$\varepsilon_{\rm eff}(t) = \frac{\varepsilon_{\rm Au}}{\delta_{\rm skin}}\int_0^{\infty}[1+\eta(z,t)]\exp(-z/\delta_{\rm skin})dz$$

Acoustic pulse

Temnov et al.,
J. of Optics 18 (2016)

Application: giant GPa acoustic pulses



$$\frac{\partial \eta}{\partial t} + c_s \frac{\partial \eta}{\partial z} + \gamma \frac{\partial^3 \eta}{\partial z^3} + \frac{C_3}{2\rho c_s} \eta \frac{\partial \eta}{\partial z} = 0$$

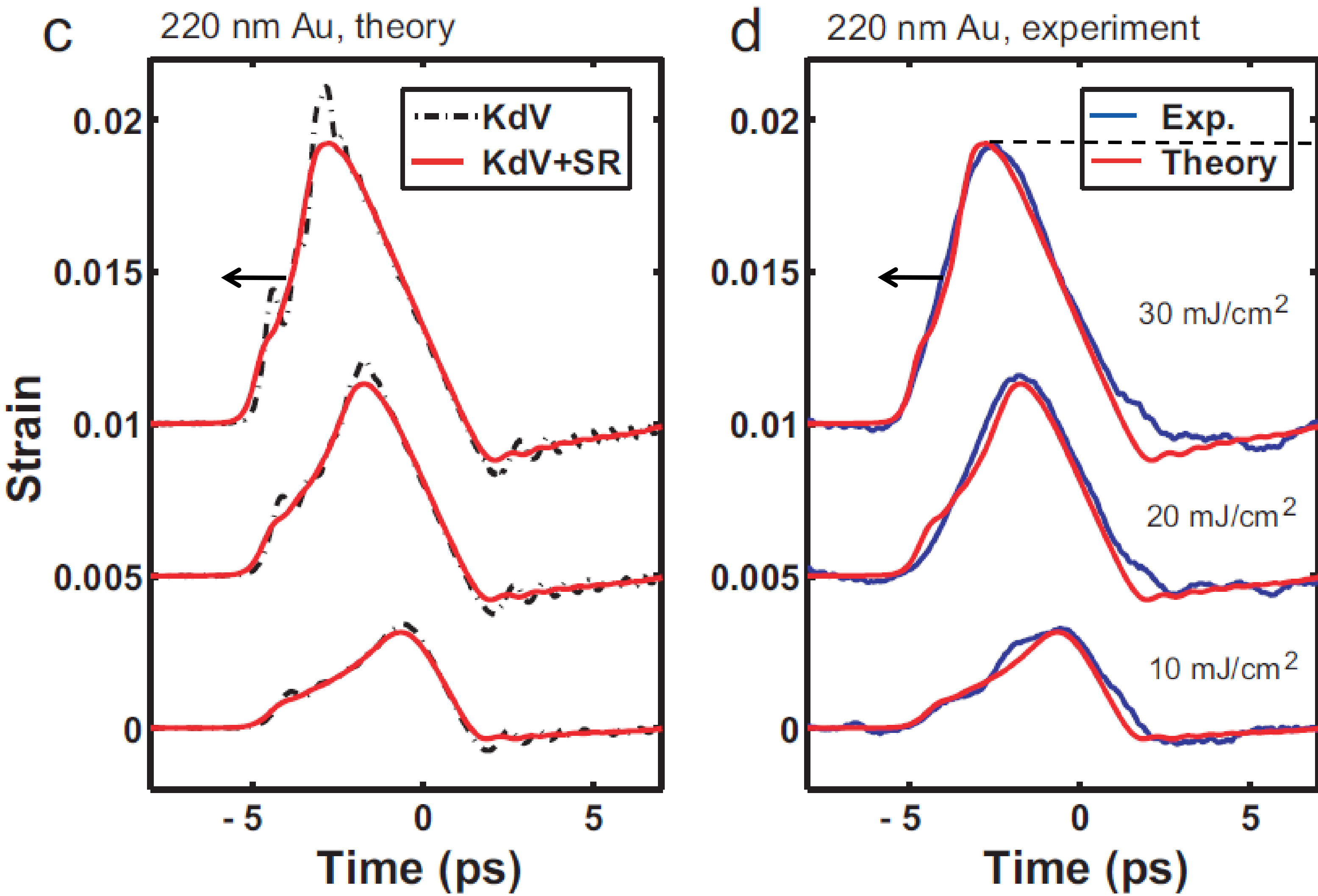
Nonlinear acoustics
in GOLD
at the nano-scale
at room temperature

- Generated in a 30nm Co layer
- Measured after propagation through a 220nm thin gold layer

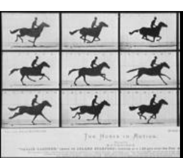
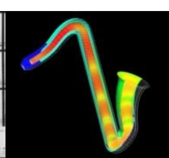
Temnov et al., Nature Comm. 4 (2013)
J. of Optics 18 (2016)

NO fit parameters !

Theory versus experiment



Apply 2.3 GPa stress during 3 ps

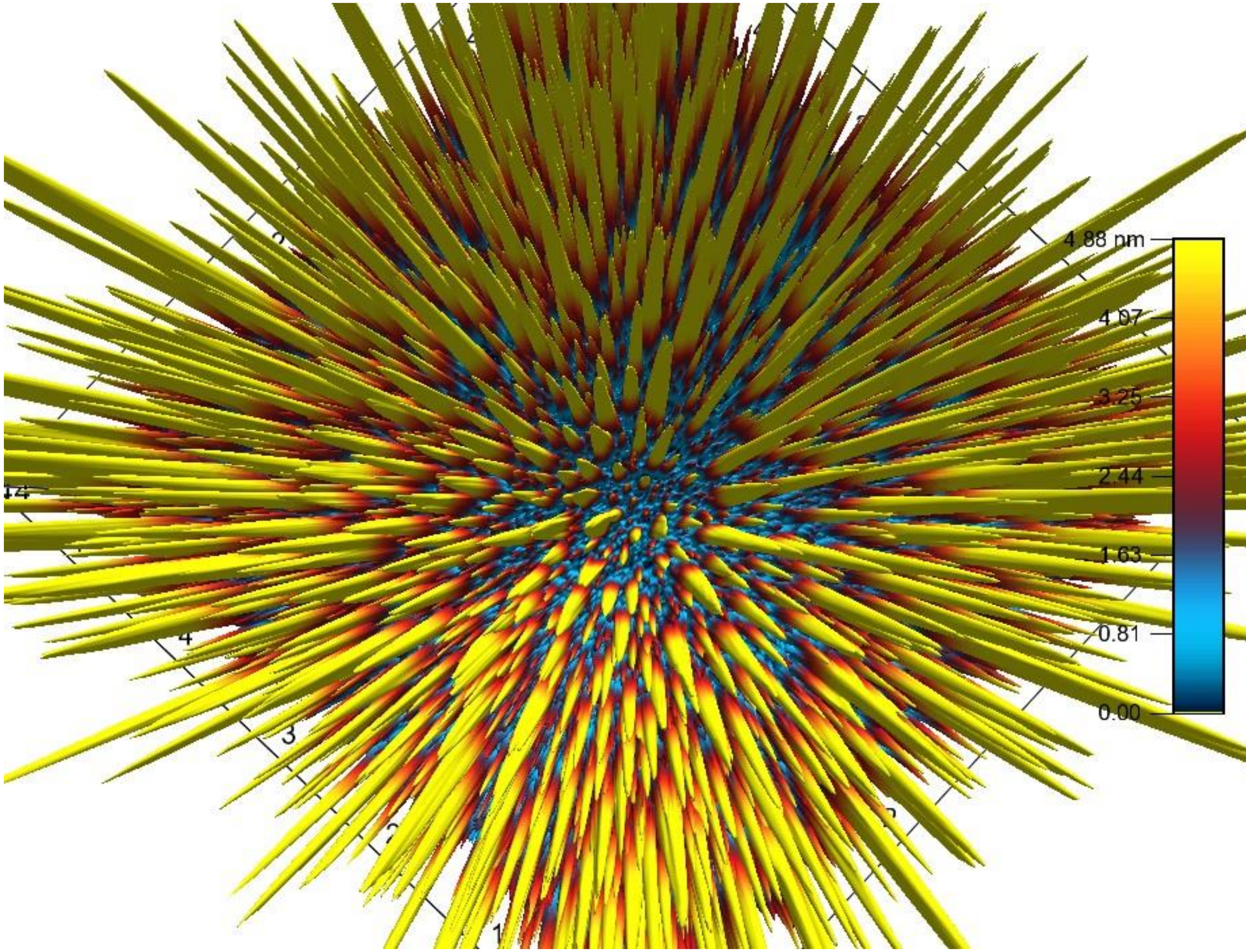




Giant 1% and ultrashort (4ps) acoustic pulses

$$\lambda_{ac}^{1THz} = 3.5nm$$

Surface roughness & THz acoustics

d=220nm



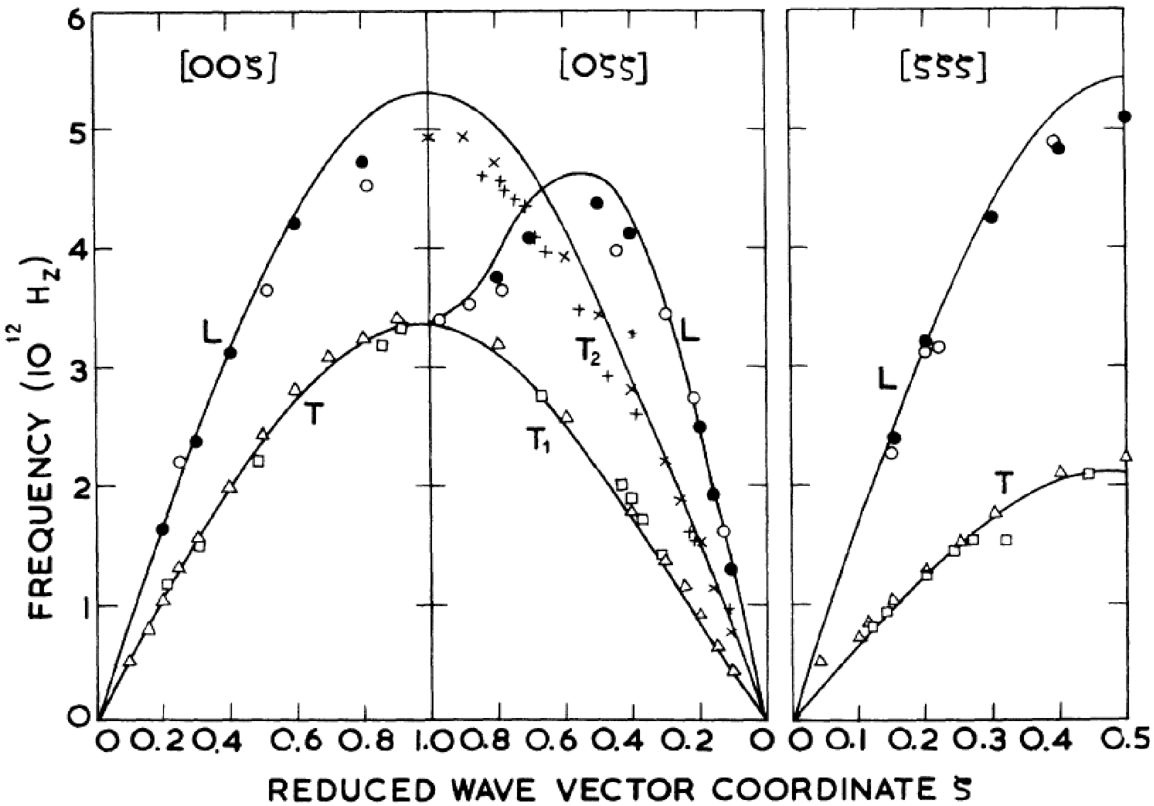
← 4.88nm

← 0 nm

- RMS = 1.5 nm -> acoustic delay ~ 500 fs, frequency cut off 1THz
- Surface roughness prevents exper. observation of ACOUSTIC SOLITONS

Why is THz ultrasonics important?

Phonon dispersion in silver



Sharma & Singh, PRB 4, 4636 (1971)

- <u>Exotic:</u> Only a few monolayers of metal are moving coherently => phonon spectrum extends over the entire Brillouin zone

- <u>Applied:</u> determine mean free path of acoustic phonons => thermal properties of the materials

M. Siemens et al.,
Nature Materials 9, 26 (2010)

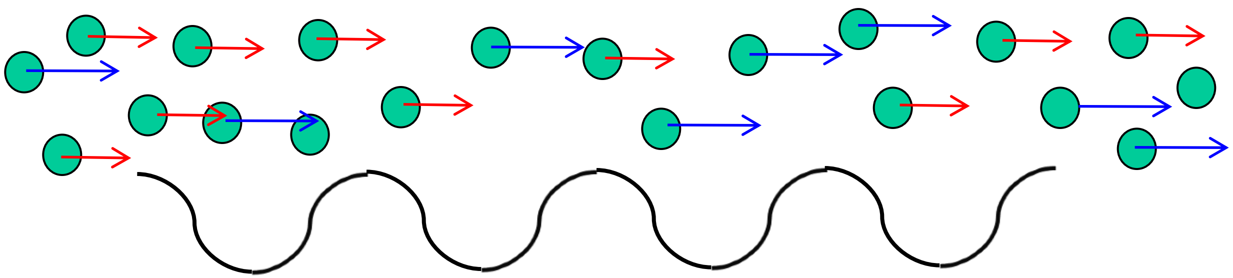
- <u>Fundamental:</u> poorly understood mechanims of damping for THz phonons in metals

$$\lambda_{phonon} \ll l_{electron}$$

Beyer & Letcher, "Physical Ultrasonics" (1969)

Nonlinear sound absorption via Landau damping

Collisionless electronic absorption of sound (Landau damping):
-resonant (phase matching) condition



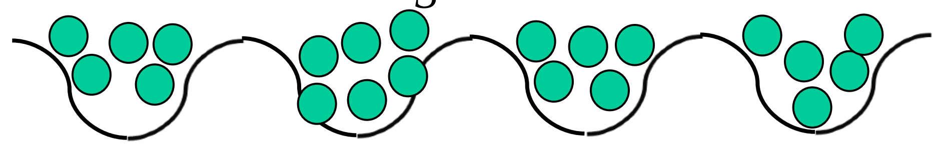
$$\cos\Theta_{1,2} \approx \frac{c_S}{v_F} = 2.5\times10^{-3}$$

$$c_S \approx v^{(x)}_{electron}$$

Non-linear saturation of electronic absorption of sound:
a small resonant group of electrons is **trapped** by phonon potential

Trapping condition:

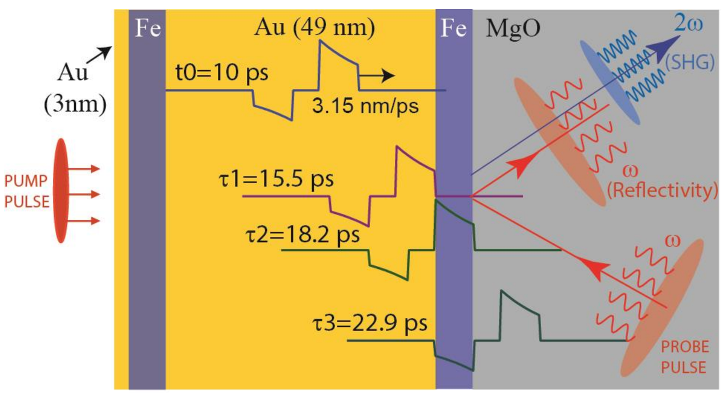
$$\sqrt{\sigma}\,\frac{2\pi}{\lambda_{phonon}}\,l_{electron} \geq 1$$

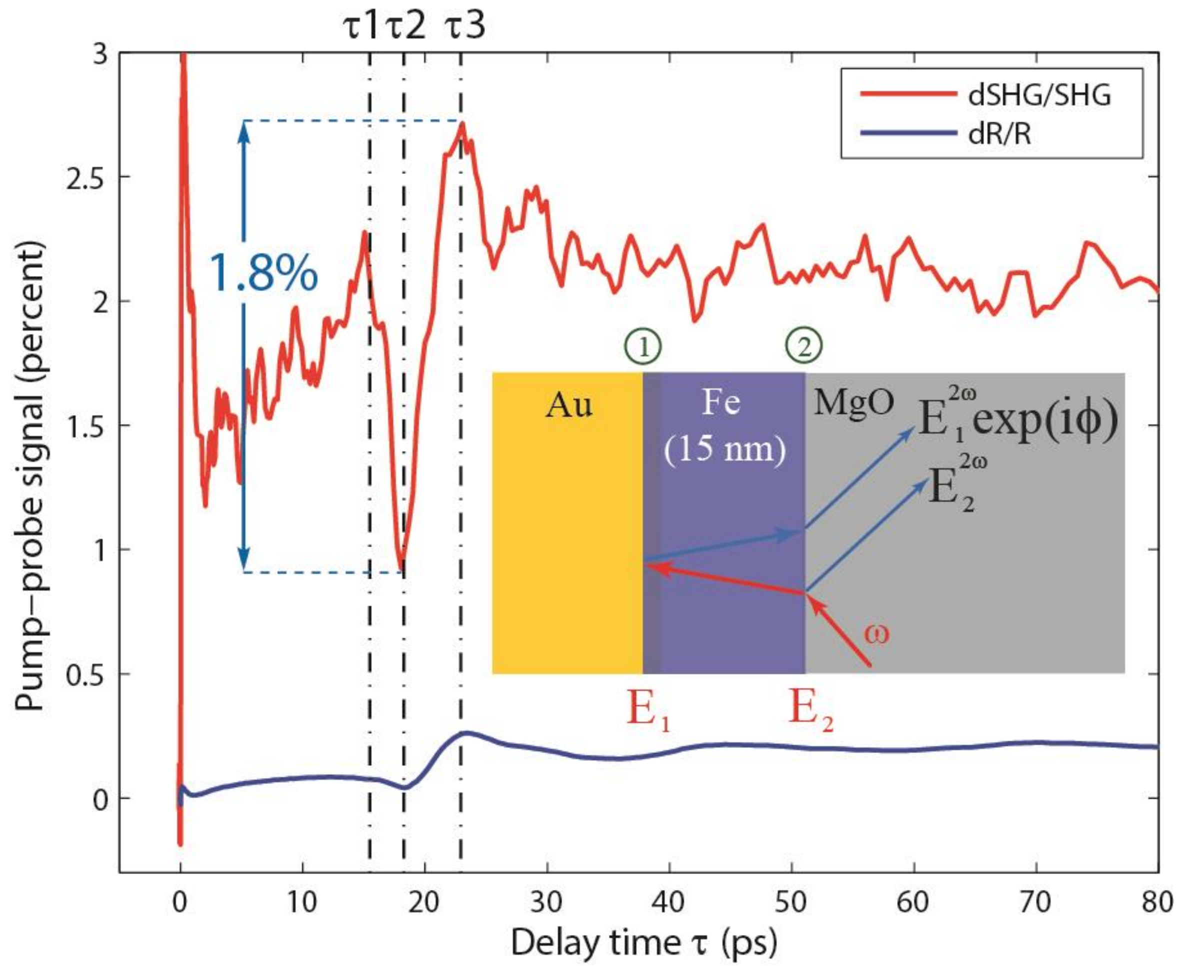


is fulfilled for strain $\sigma > 10^{-5}$ @ 1THz in gold!

A.A. Abrikosov, "Fundamentals of the theory of metals" (1987)

Application: acoustic modulation of nonlinear SHG

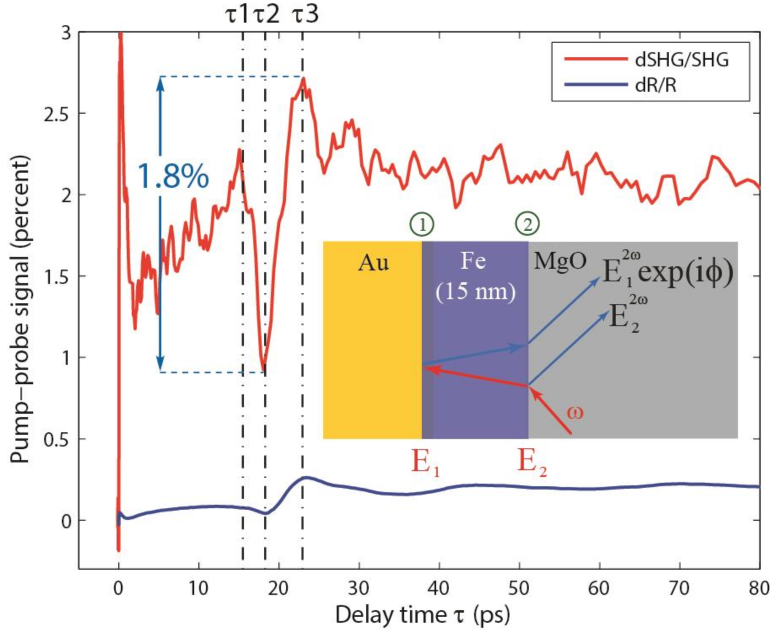


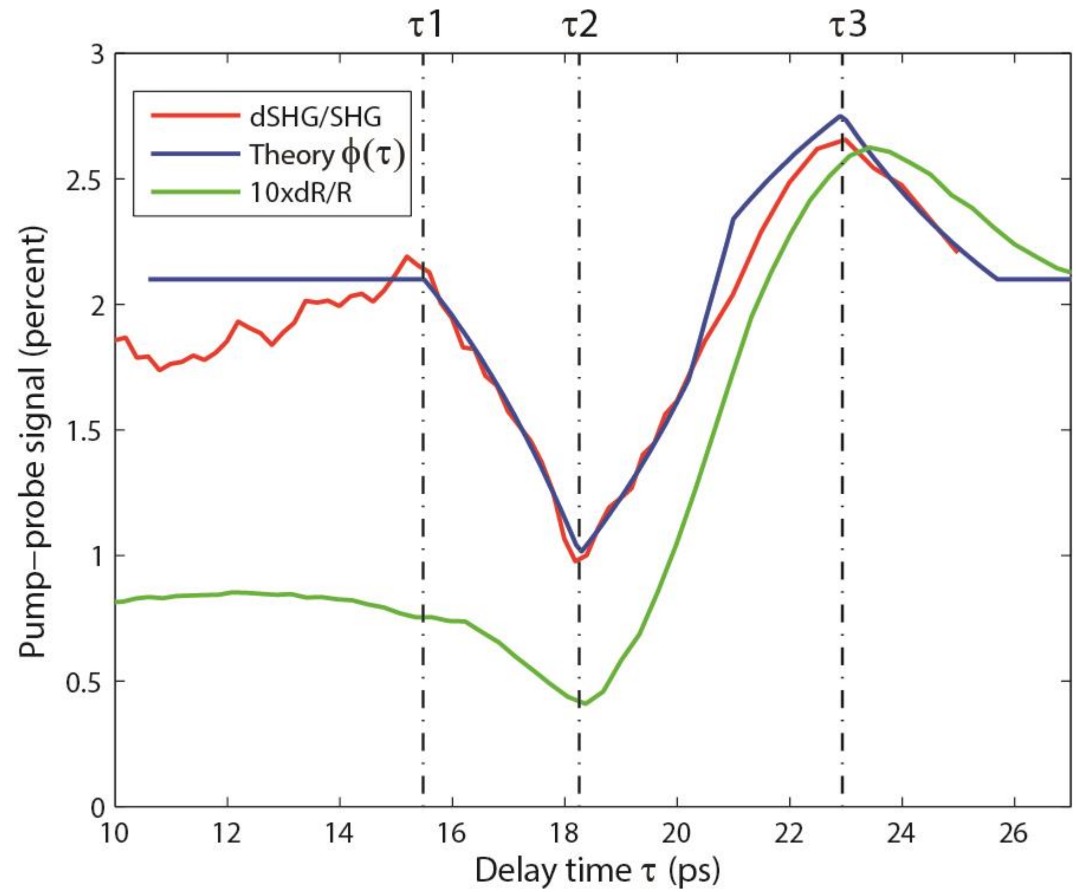


SHG is 10x larger than linear reflectivity
1.8% SHG modulation depth

Temnov et al.,
J. of Optics 18 (2016)

Acoustic modulation of effective SHG interfaces



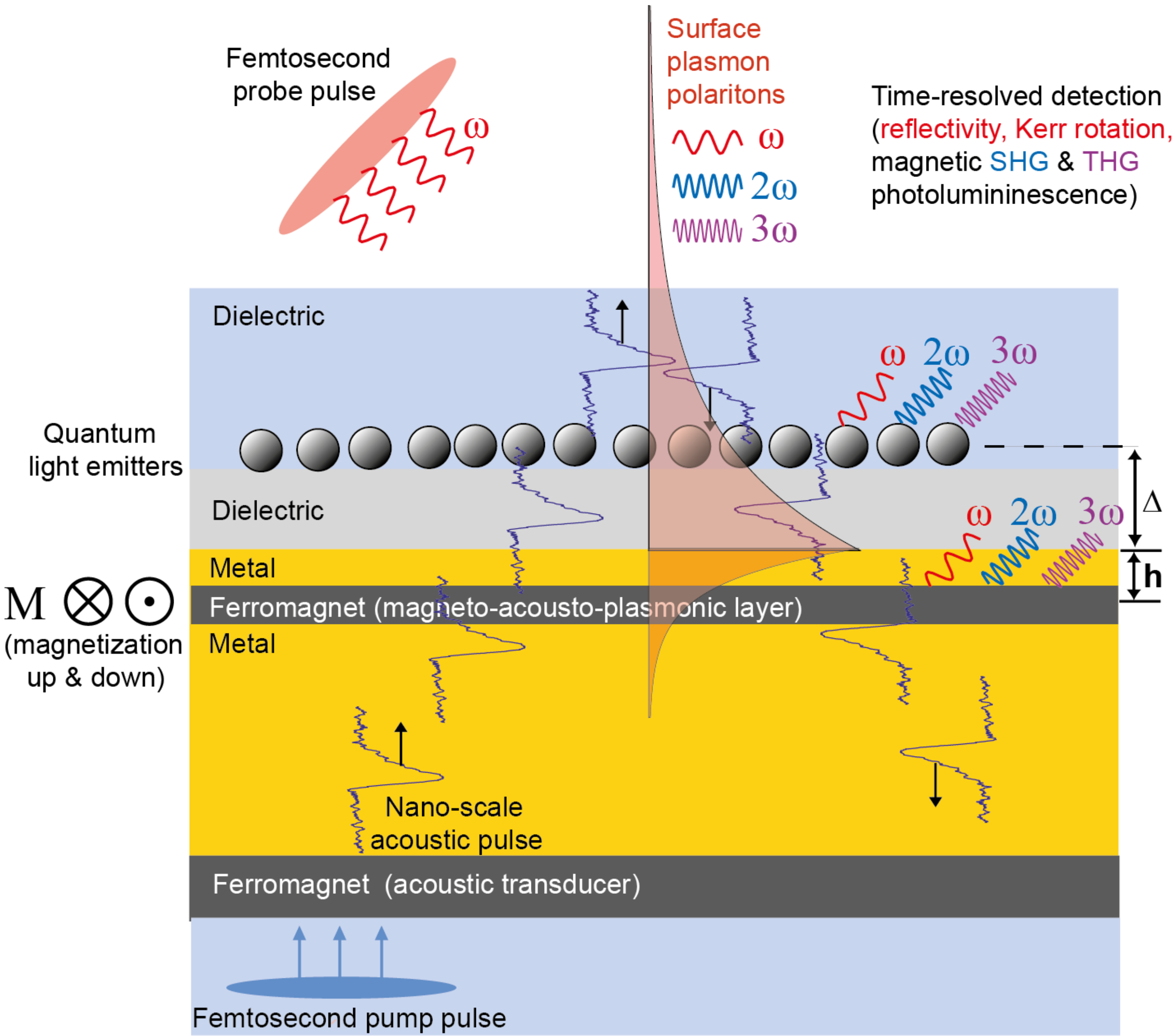


$$\Delta\phi(\tau) \propto \frac{2\pi}{\lambda}\int_0^{d_{\mathrm{Fe}}} \eta(z,\tau)dz$$

d_{Fe}= 15 nm

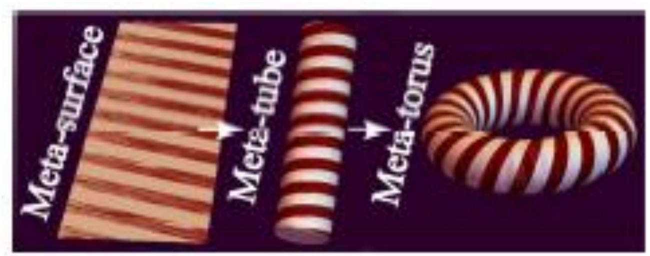
Two interfering surface SHG sources + acoustic PHASE modulation

Outlook: quantum acousto-magneto-photonics



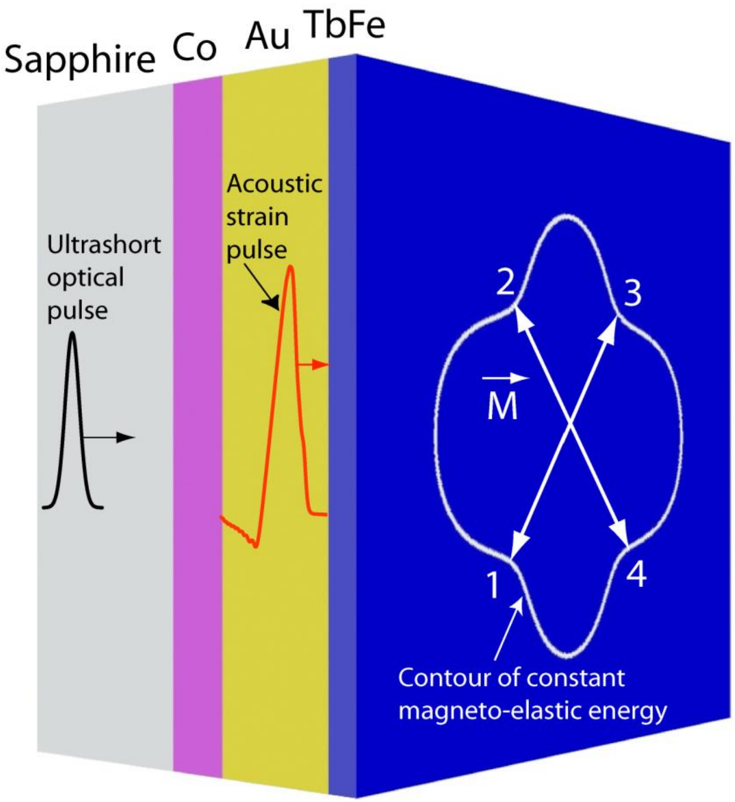
Ultrafast optics
Complex multilayers
Magnetic fields
PLASMONICS

Temnov, Razdolski, Pezeril, Melnikov, Makarov, Seletskiy & Nelson, review article in Journal of Optics (2016)



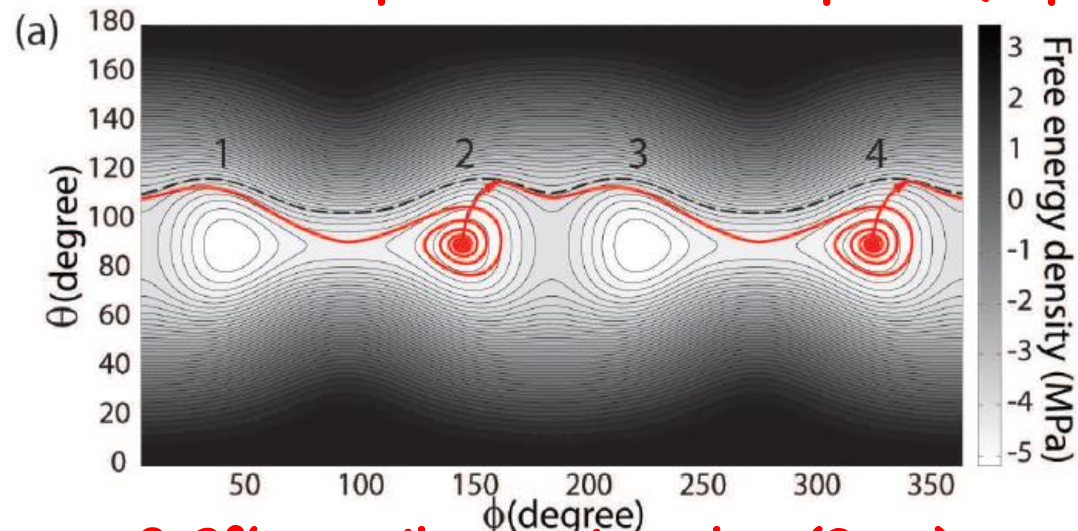
"Topological plasmonics" Kuzmin, Bychkov, Shavrov, Temnov, ACS Photonics (2017) Nanophotonics (2018)

Application: ultrafast magneto-acoustic switch !

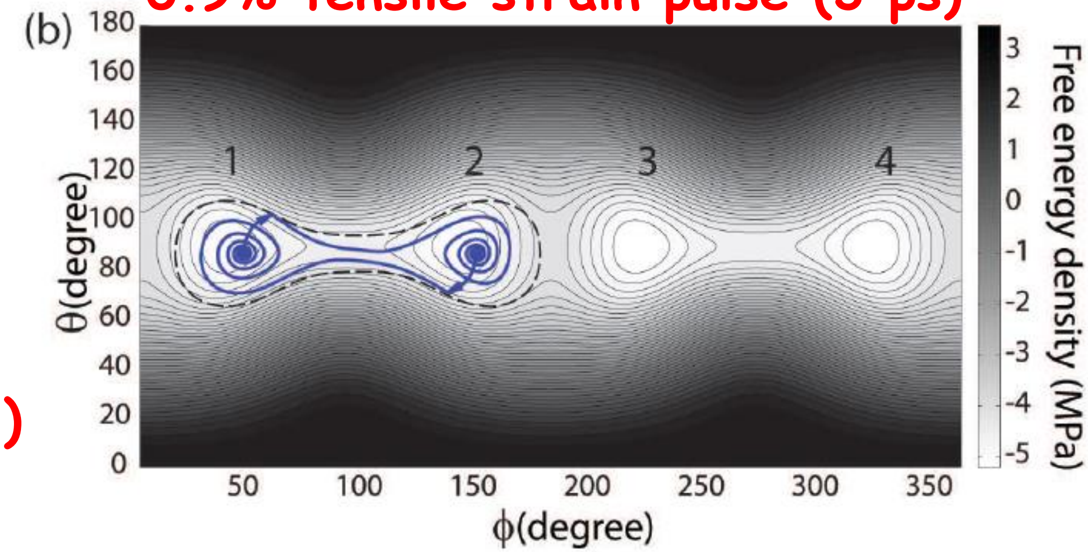


Magneto-acoustic switching for compressional (2->4, 4->2) and tensile strain pulses (1->2, 2->1)

1.6% compressional strain pulse (3 ps)



0.9% tensile strain pulse (3 ps)



Kovalenko et al., Phys. Rev. Lett. 110 (2013)

Next lecture

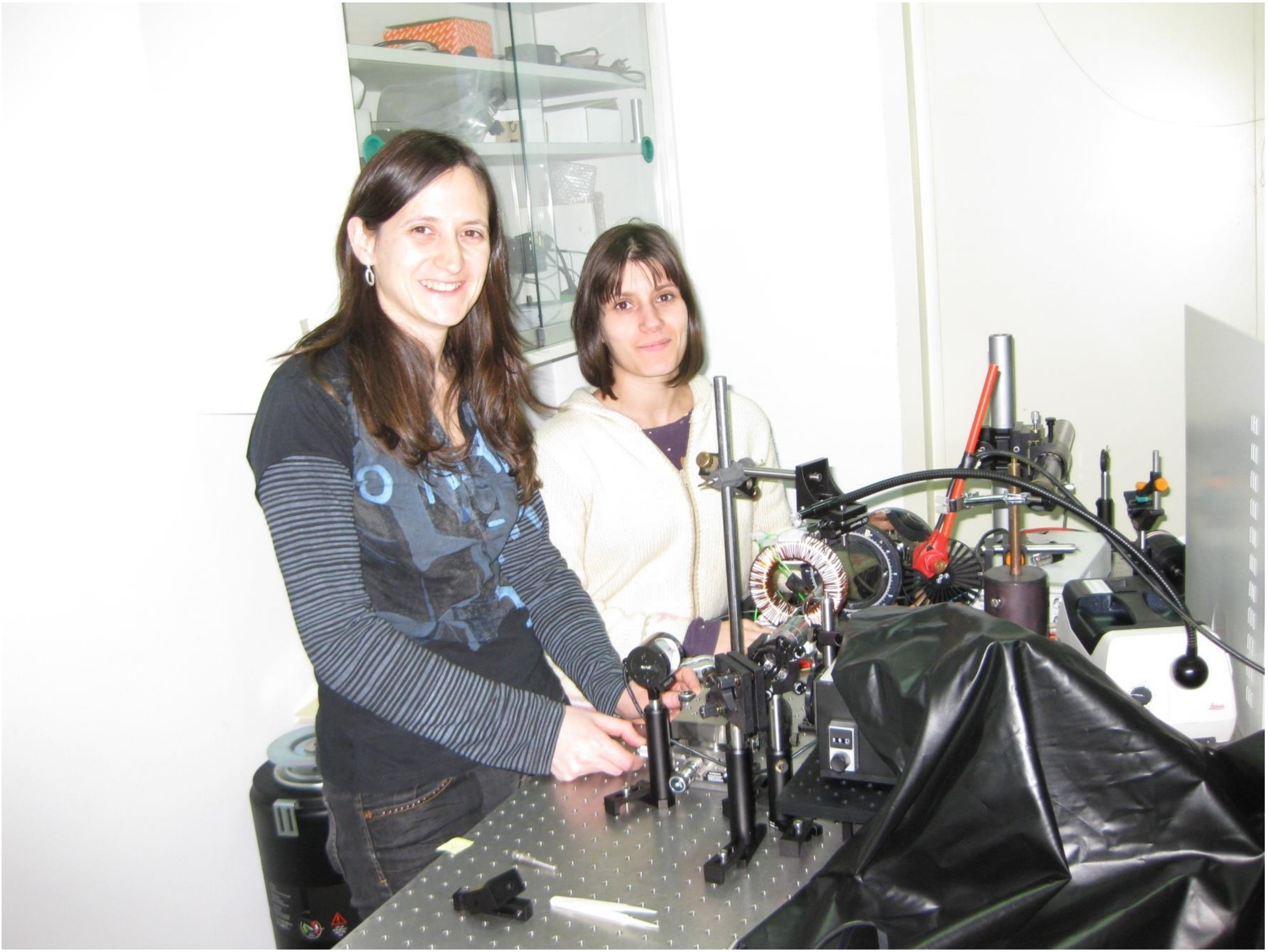
- Speed limits of magnetization switching?
- Pathways of magnetization switching?
- Ultrafast coupled THERMAL, ACOUSTIC and MAGNETIC dynamics
- in ferromagnets

Ultrafast * : 100 fs - 100 ps

1 femtosecond = 10^{-15} s
1 picosecond = 10^{-12} s

Having fun in Madrid (IMM-CSIC Madrid)

Strong men in an optical lab (IMM-CSIC)



Funding:

Ultrafast acoustics in hybrid magnetic nanostructures **186 k€**

NNN-TELECOM **290 k€**

ANR "ULTRAMOX" **186 k€**

ANR-DFG "PPMI-NANO" **185 k€**

ANR international "MagPlas" **480 k€** (under review)

PRC with "Siberia" (**46 k€**)

NNN-Telecom postdocs working in Le Mans:

V. Besse (Univ. Angers)

A. Alekhin (FHI Berlin-> DFG research fellow @ IMMM)

V. Juvé (Max Born Institute Berlin) -> CNRS CR2 in 2016!

I. Razdolski (FHI Berlin -> guest professor @ IMMM)

AMP 2017 in Versailles (June 2017):

"Acousto-magneto-plasmonics"

(Campus France, Humboldt, DAAD, GEMaC, IMMM, TU Hamburg, Uni Konstanz, FHI Berlin …)