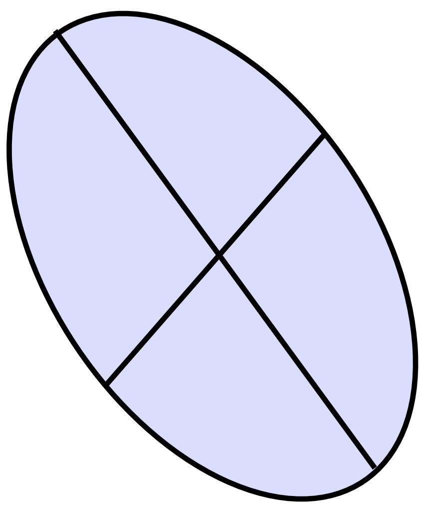
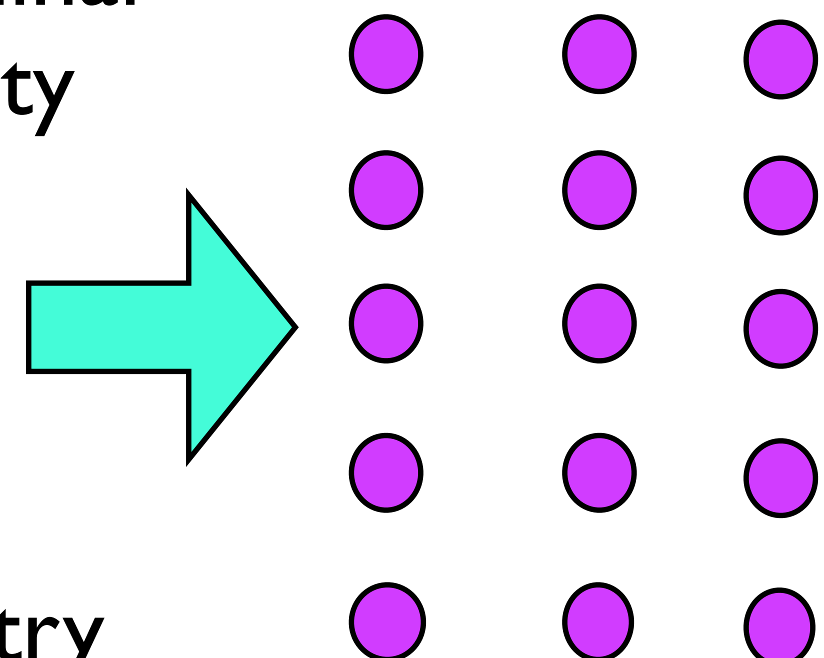
Faraday Rotation Enhancement in Magnetic Core/Gold Shell Nanoparticles



Condensed Matter Seminar
Kansas State University
October 29, 2010



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collaboration with
Viktor Chikan, chemistry

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Nanoparticle Electromagnetics

- Gold plasmonic responses in spherical NPs.
- What is and what causes Faraday Rotation?
- Dielectric response, absorption, and FR.
- Gold shell effects on magnetic core.
- Response of a collection of NPs.

ABSTRACT

We report enhanced optical Faraday rotation in gold-coated maghemite (γ-Fe_2O_3) nanoparticles. The Faraday rotation spectrum measured from 480 - 690 nm shows a peak at about 530 nm, not present in either uncoated maghemite nanoparticles or solid gold nanoparticles. This peak corresponds to an intrinsic electronic transition in the maghemite nanoparticles and is consistent with a near-field enhancement of Faraday rotation resulting from the spectral overlap of the surface plasmon resonance in the gold with the electronic transition in maghemite. This demonstration of surface plasmon resonance-enhanced magneto-optics (SuPREMO) in a composite magnetic/plasmonic nanosystem may enable design of nanostructures for remote sensing and imaging of magnetic fields and for miniaturized magneto-optical devices.

Surface Plasmon Resonance Enhanced Magneto-Optics (SuPREMO): Faraday Rotation Enhancement in Gold-Coated Iron Oxide Nanocrystals

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Received January 1, 2009; Revised Manuscript Received March 2, 2009

(Nanoletters)

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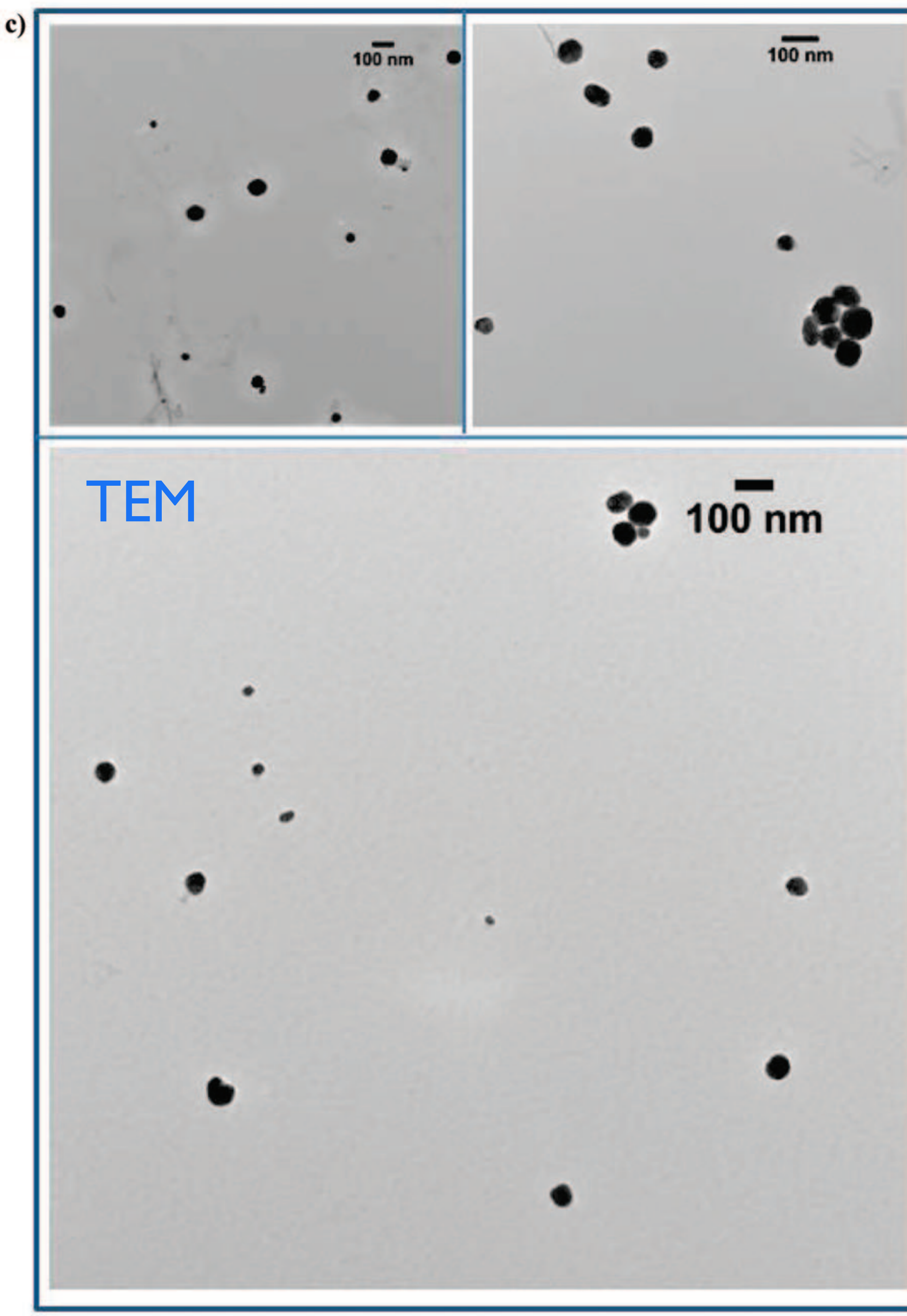
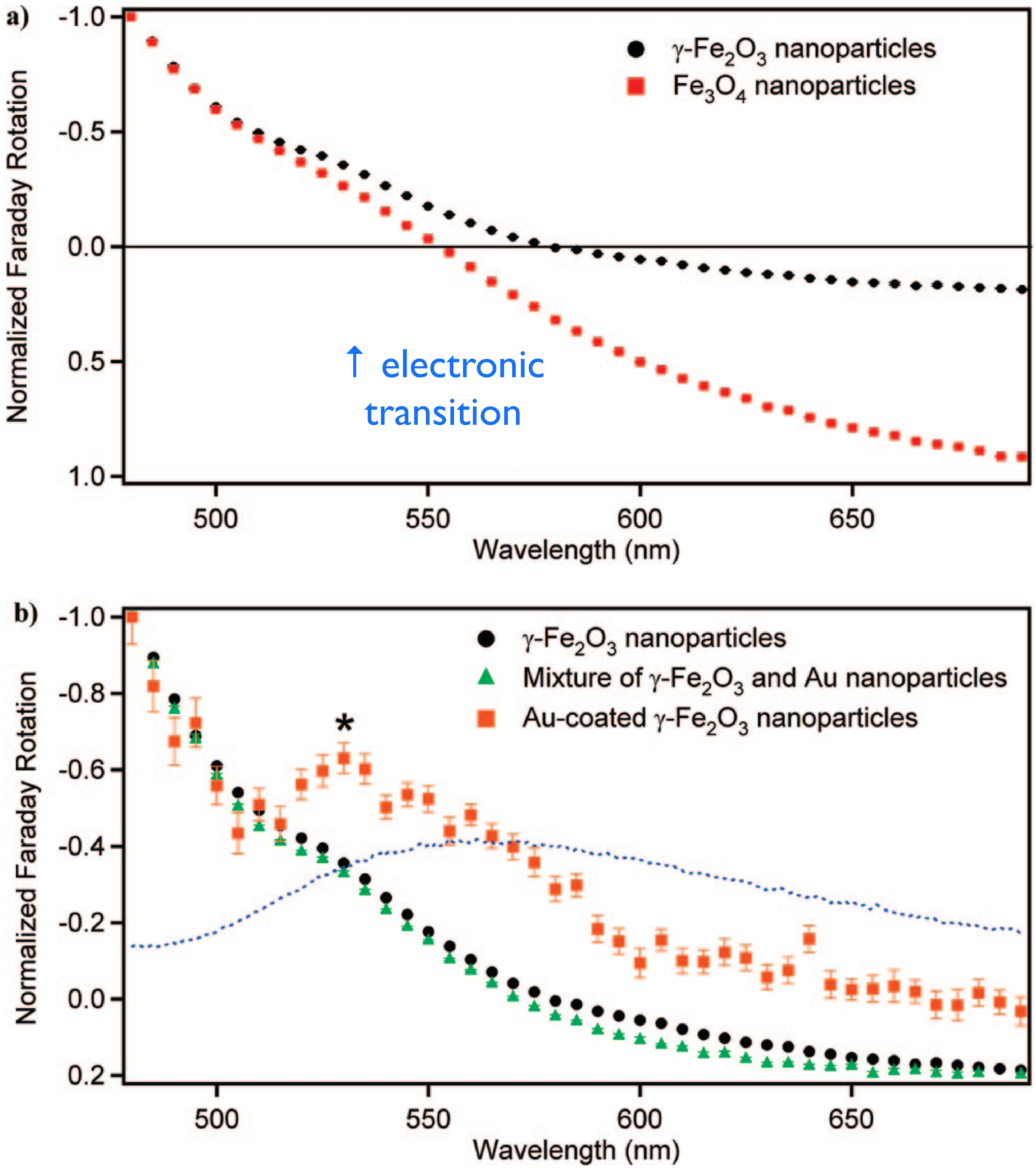


gold-coated γ-Fe_2O_3 nanoparticles



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The Faraday rotation spectra of uncoated and gold-coated γ-Fe_2O_3 nanoparticles are compared in Figure 3b. The gold-coated γ-Fe_2O_3 nanoparticles show an overall similar Faraday rotation spectrum to the uncoated particles, with the exception of a sharp peak that appears around 530 nm. The uncoated γ-Fe_2O_3 nanoparticles show only a weak shoulder in this region; no well-resolved resonant feature can be discerned. A simple "non-interacting" mixture of γ-Fe_2O_3 nanoparticles and colloidal gold nanospheres (green curve in Figure 3b) with an absorbance matched to that of the gold-coated γ-Fe_2O_3 nanoparticle sample also does not show the sharp Faraday rotation peak at 530 nm. This demonstrates that the rotation peak is not due merely to the presence of the gold component, but rather is a consequence of the close proximity of the gold and the γ-Fe_2O_3 in the composite γ-Fe_2O_3 /gold nanostructure.

The origin of the Faraday rotation peak at 530 nm can be traced to the electronic structure of the γ-Fe_2O_3, specifically the crystal field transitions of Fe^{3+} $3d^5$ electrons that dominate the visible spectrum of iron oxides.[59,60] The crystal field

gold-shell on maghemite (Fe_2O_3) cores (from Viktor Chikan's lab)

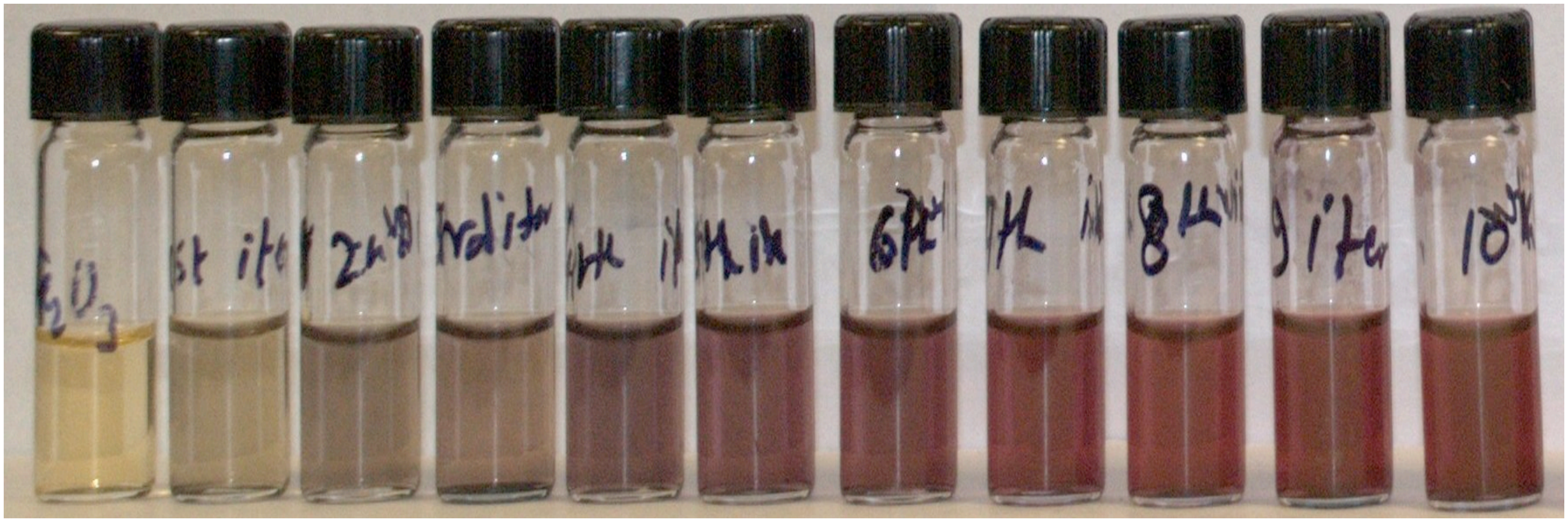


Figure 3 (b) Variation of color change when the thickness of gold onto the surface of the nanoparticles is increased.

Viktor Chikan's core/shell particles

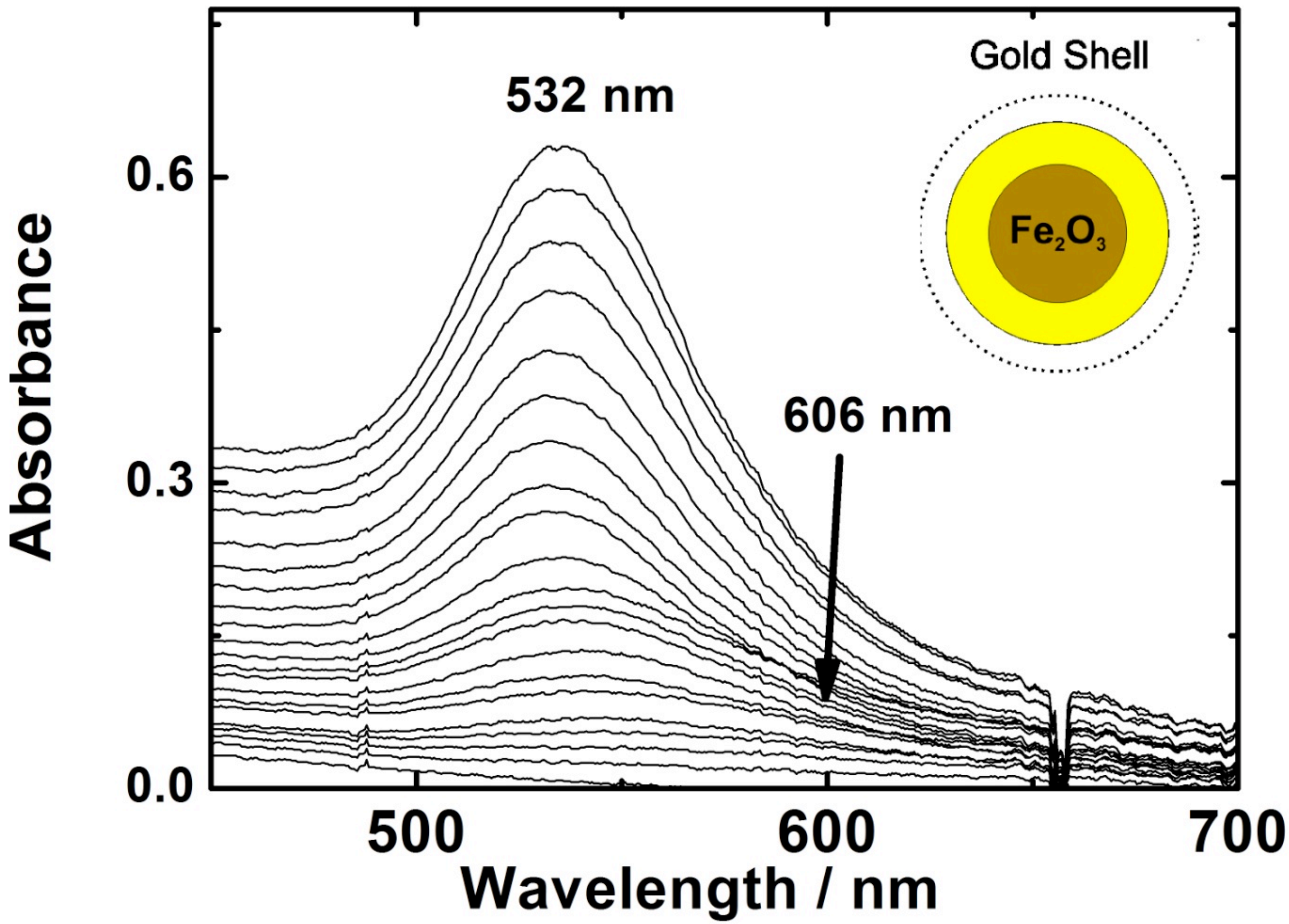


Figure 3 (a) UV-vis absorption spectrum of 3rd batch synthesis of gold coated Fe_2O_3 nanoparticles. The initial peak position is indicated by an arrow at 606 nm and shifts to 532 nm with increasing thickness of gold shell.

Viktor Chikan's core particles

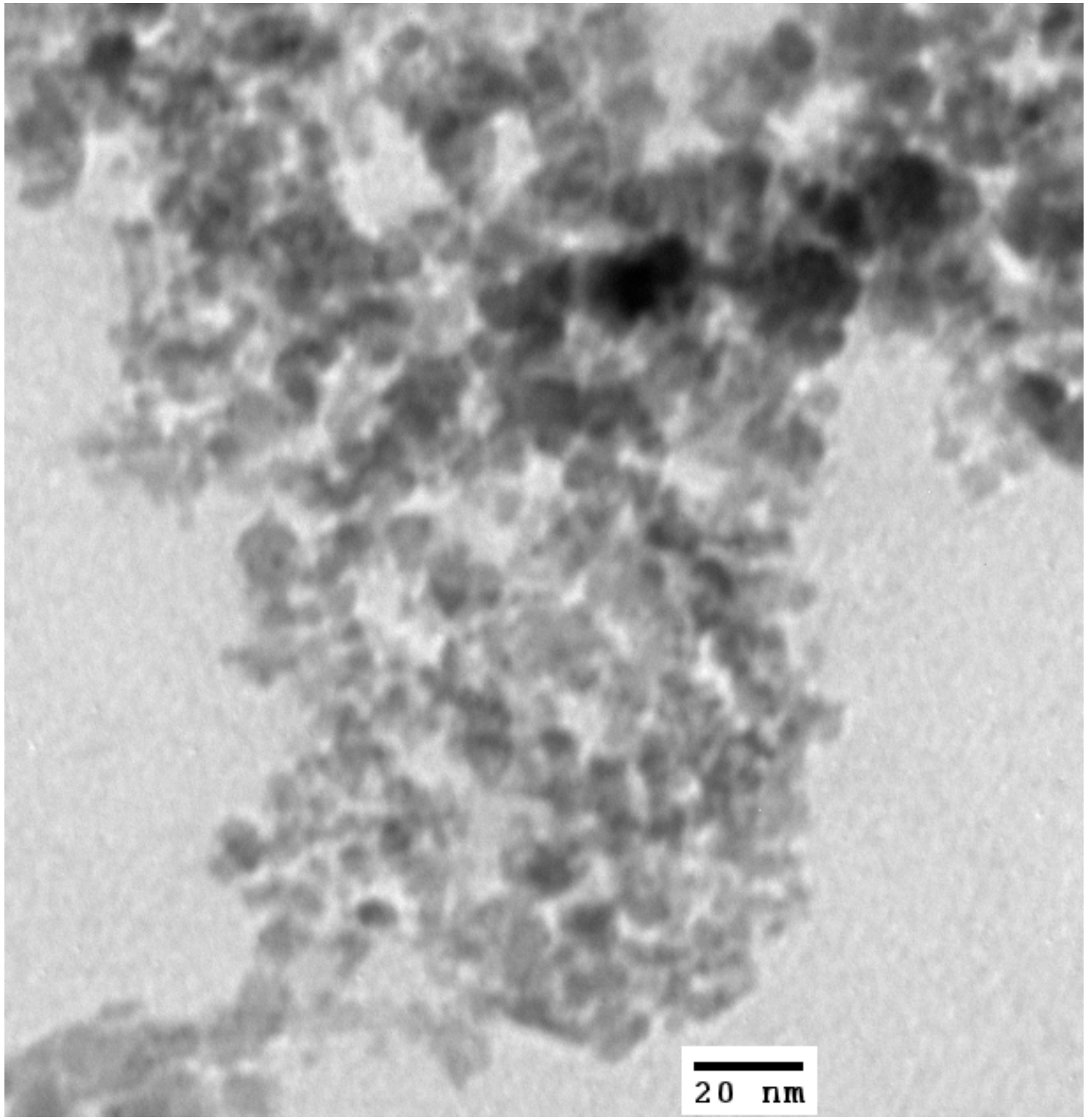


Figure 2 (a) TEM image of Fe_2O_3 nanoparticles used in the experiment.

Viktor Chikan's core/shell particles, at λ=632 nm

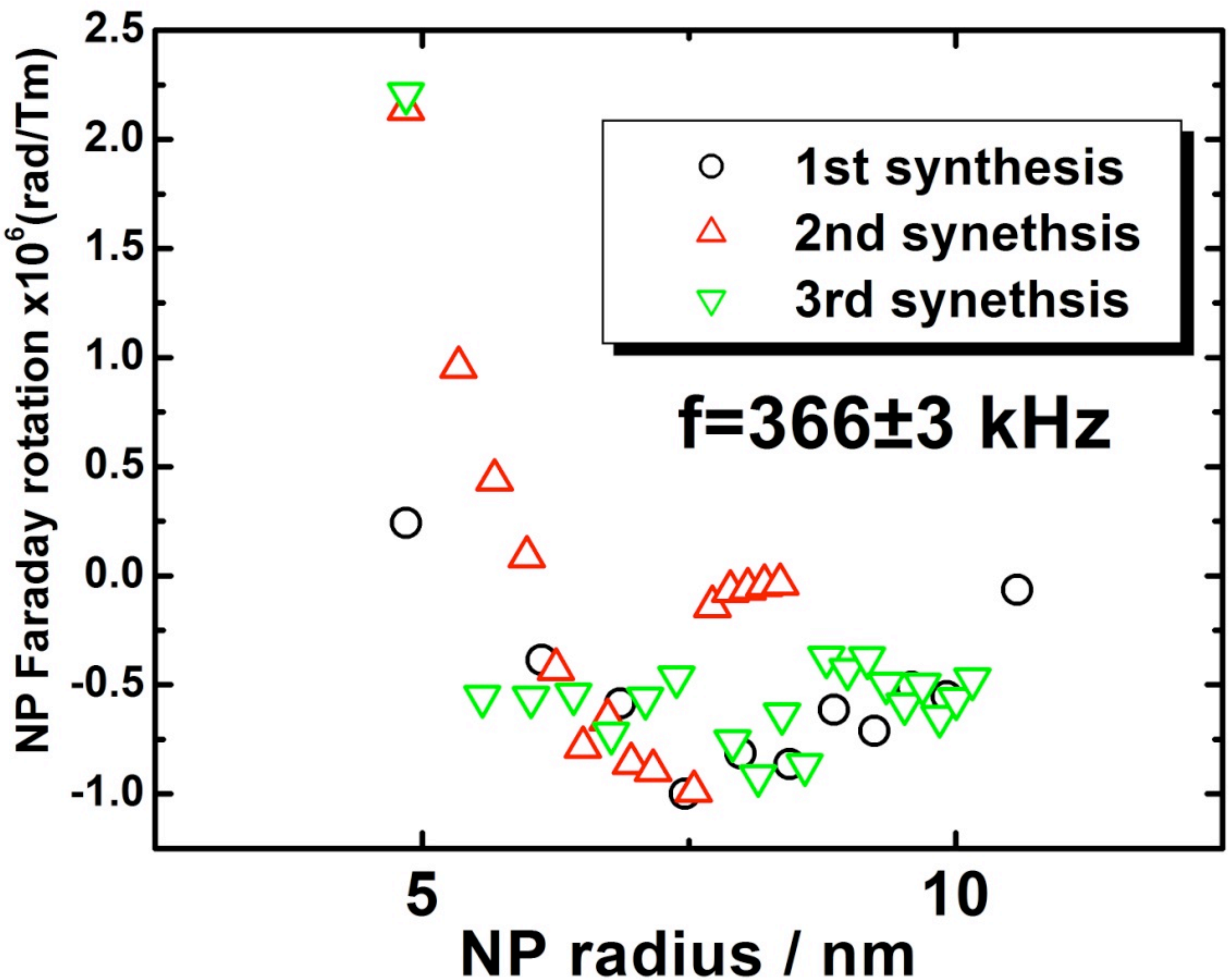
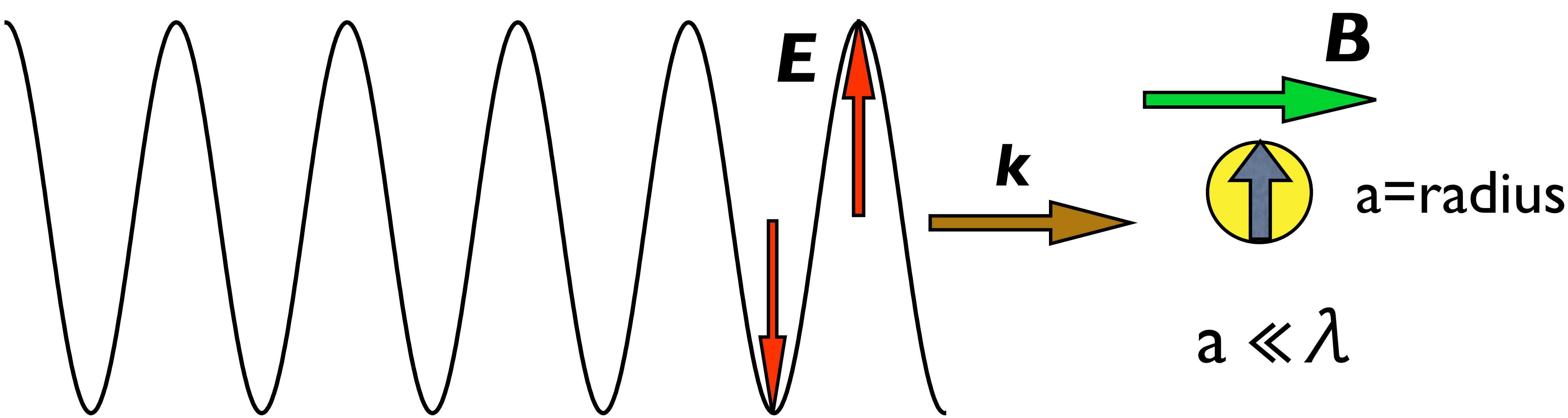


Figure 4 (b) Experimental Verdet constant of gold coated Fe_2O_3 nanoparticles only (normalized by the volume fraction of the particles) as a function of gold shell thickness

EM
scattering

spherical dielectric
or conducting
particles

incident plane waves,
frequency ω, wave vector k



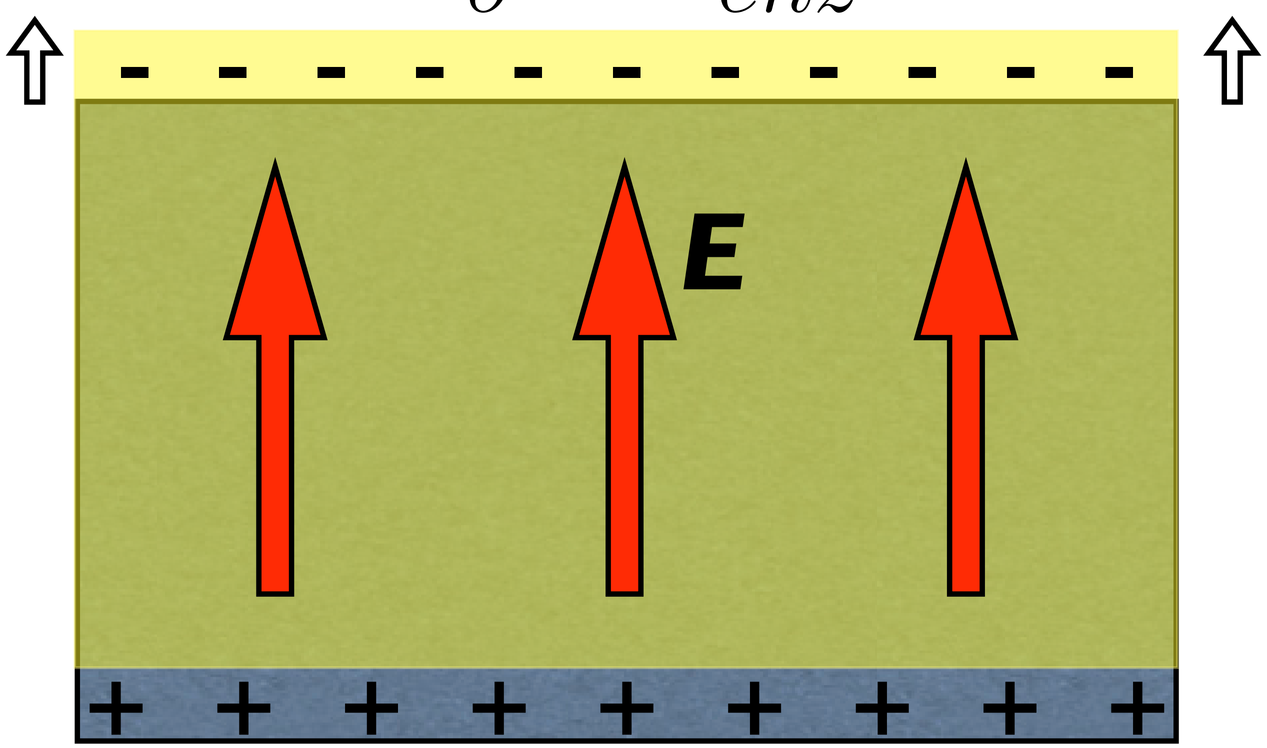
A nearly uniform polarization is induced in the NP.
Its amplitude depends on the dielectric function $\epsilon(\omega)$.
How to describe effects on the light?

Bulk Plasma oscillations

$$\omega_p = \sqrt{\frac{ne^2}{m\epsilon_0}}$$

n = electron number density   z = electron gas displacement

$$\sigma = -enz$$



$$E = -\frac{\sigma}{\epsilon_0}$$

newtonian mechanics:

$$QE = M\ddot{z}$$

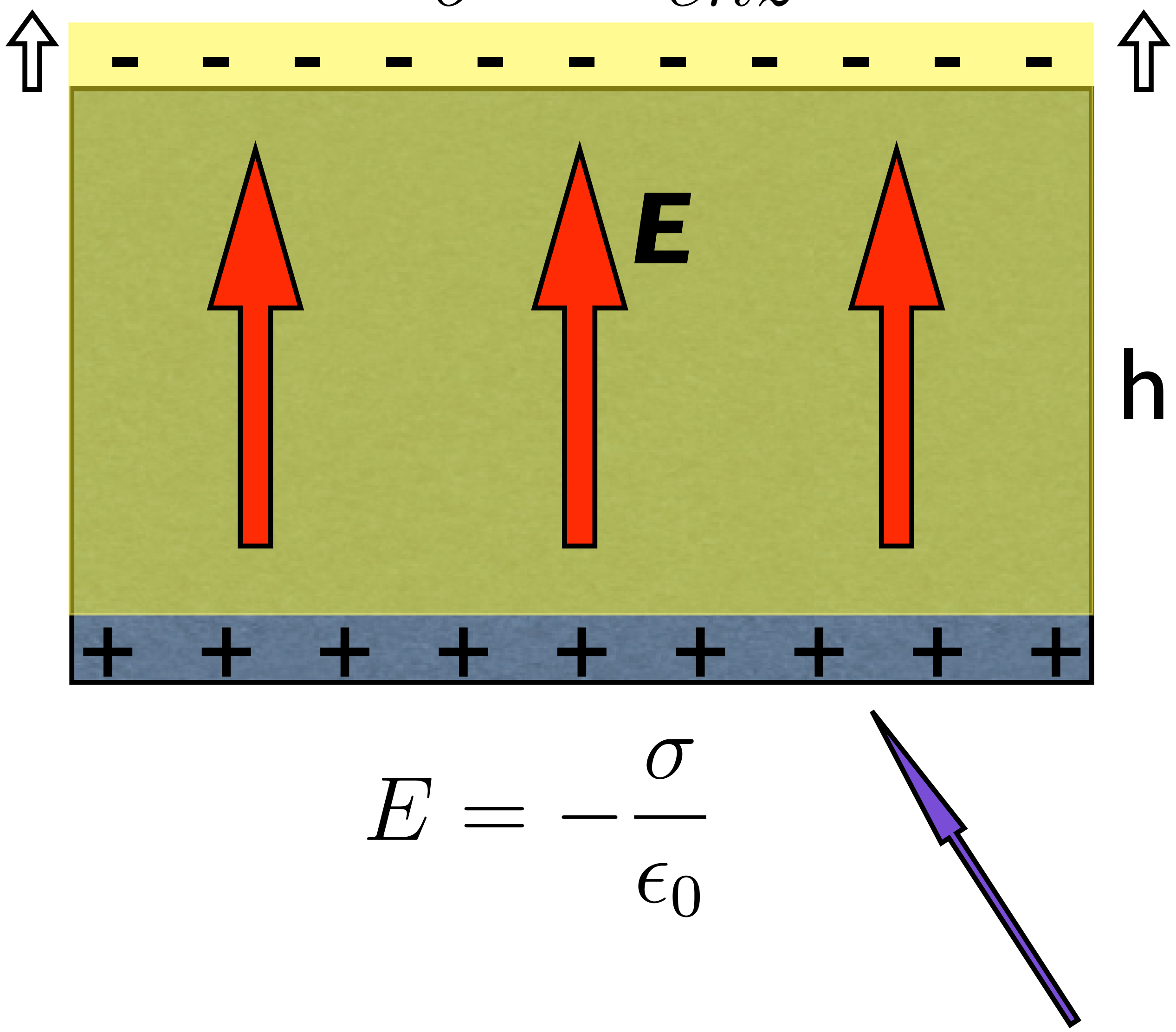
$$-(enV)\left(-\frac{\sigma}{\epsilon_0}\right) = (mnV)\,\ddot{z}$$

$$-\left(\frac{ne^2}{\epsilon_0}\right)z = m\ddot{z}$$

$$\ddot{z} = -\frac{ne^2}{m\epsilon_0}\,z = -\omega_p^2\,z$$

About electric polarization P

$\sigma = -enz$



$$E = -\frac{\sigma}{\epsilon_0}$$

dipole moment:

$p = \sigma A h$

Polarization:

$P = p/V = \sigma = -enz$

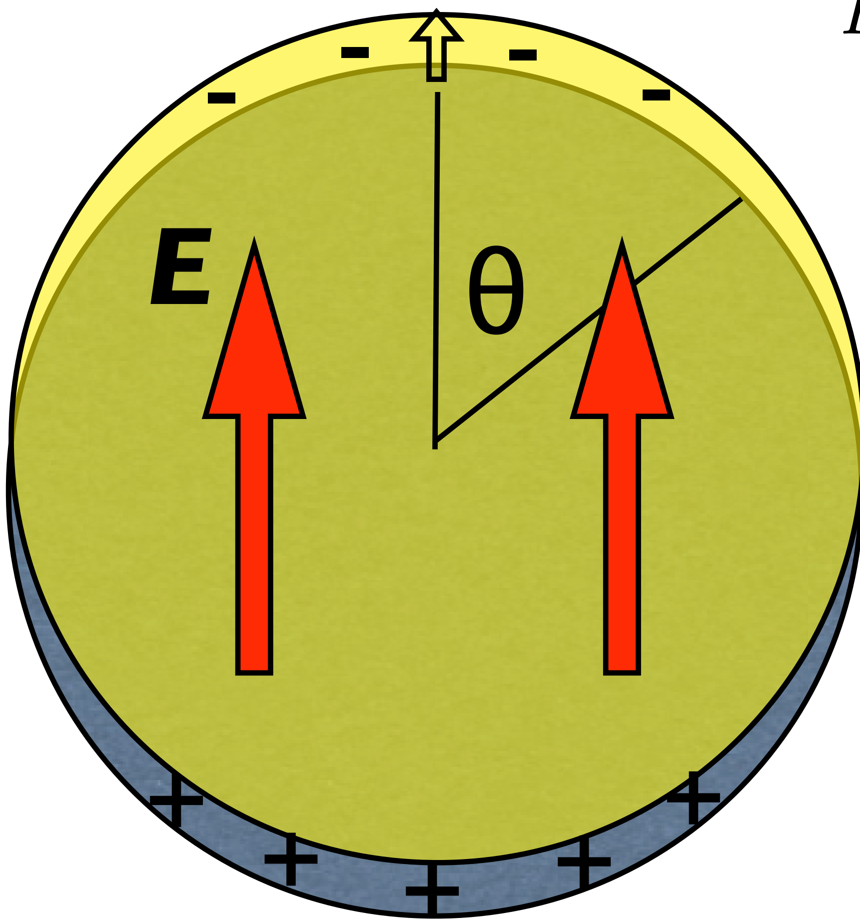
A = top/bottom surface area

Spherical conductor, plasma oscillations

$$\omega_s = \sqrt{\frac{ne^2}{3m\epsilon_0}} = \frac{\omega_p}{\sqrt{3}}$$

z = electron gas displacement

$$\sigma = -nez\cos\theta$$



$$p_z = \int \sigma(a\cos\theta)dA = -\frac{4\pi a^3}{3}(nez)$$

Polarization: $\vec{P} = -(nez)\hat{z}$

newtonian mechanics: $QE = M\ddot{z}$

$$(-enV)\frac{nez}{3\epsilon_0} = (mnV)\ddot{z}$$

$$\ddot{z} = -\frac{ne^2}{3m\epsilon_0}z = -\omega_s^2 z$$

$$\vec{E} = -\frac{\vec{P}}{3\epsilon_0} = \frac{nez}{3\epsilon_0}\hat{z}$$

Geometry affects the resonance frequency

bulk gold: $n = 5.90 \times 10^{28}/m^3$

$\omega_p = 1.36 \times 10^{16}$ rad/s

$\lambda_p = 138.5$ nm

spherical gold: $n = 5.90 \times 10^{28}/m^3$

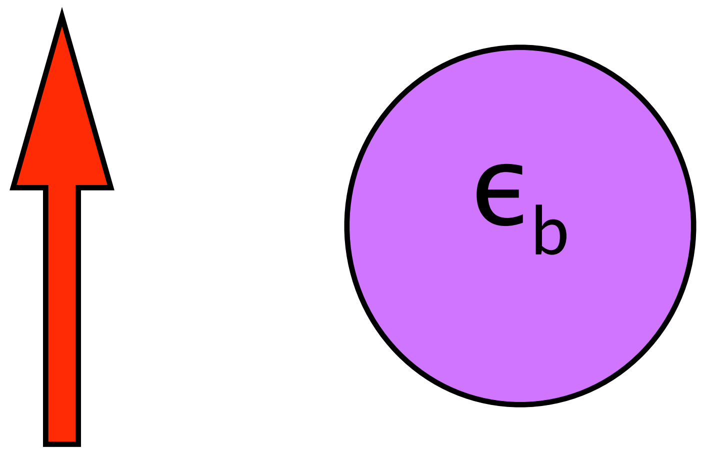
$\omega_s = 7.85 \times 10^{15}$ rad/s

$\lambda_s = 240$ nm

Sphere in a host medium, dielectric response

Laplace eqn. solution.

E₀ = field in surroundings



ϵ_a=host

$$\Phi_{\text{inside}} = -\left(\frac{3\epsilon_a}{2\epsilon_a + \epsilon_b}\right) E_0 r \cos\theta$$

$$\vec{E}_{\text{inside}} = \frac{3\epsilon_a}{2\epsilon_a + \epsilon_b}\vec{E}_0$$ = uniform

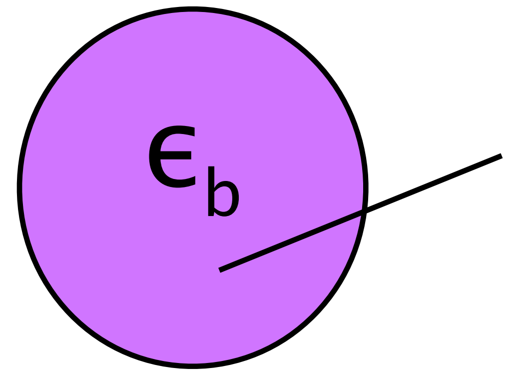
$$\Phi_{\text{outside}} = -\left[r - \left(\frac{\epsilon_b - \epsilon_a}{2\epsilon_a + \epsilon_b}\right)\frac{a^3}{r^2}\right] E_0 \cos\theta$$

$$\vec{E}_{\text{outside}} = \vec{E}_0 + \frac{\vec{p}\cdot\vec{r}}{4\pi\epsilon_a r^3}$$

induced electric dipole:

$$\vec{p} = \left(\frac{\epsilon_b - \epsilon_a}{2\epsilon_a + \epsilon_b}\right)\left(4\pi a^3 \epsilon_a \vec{E}_0\right)$$

Resonance of a conducting sphere



$$\vec{E}_{\text{inside}} = \frac{3\epsilon_a}{2\epsilon_a + \epsilon_b}\vec{E}_0$$

divergence when: $$2\epsilon_a + \epsilon_b = 0$$

Drude model, free electron gas: $$\epsilon_b(\omega) = \epsilon_0\left[1 - \frac{\omega_p^2}{\omega^2}\right]$$

resonance: $$\Longrightarrow \quad 2\frac{\epsilon_a}{\epsilon_0} + 1 - \frac{\omega_p^2}{\omega^2} = 0 \quad \Longrightarrow \quad \omega_{\text{SP}} = \frac{\omega_p}{\sqrt{2\frac{\epsilon_a}{\epsilon_0} + 1}}$$

for gold surrounded by H_20:

$n = (\epsilon_a/\epsilon_0)^{1/2} = 1.33$

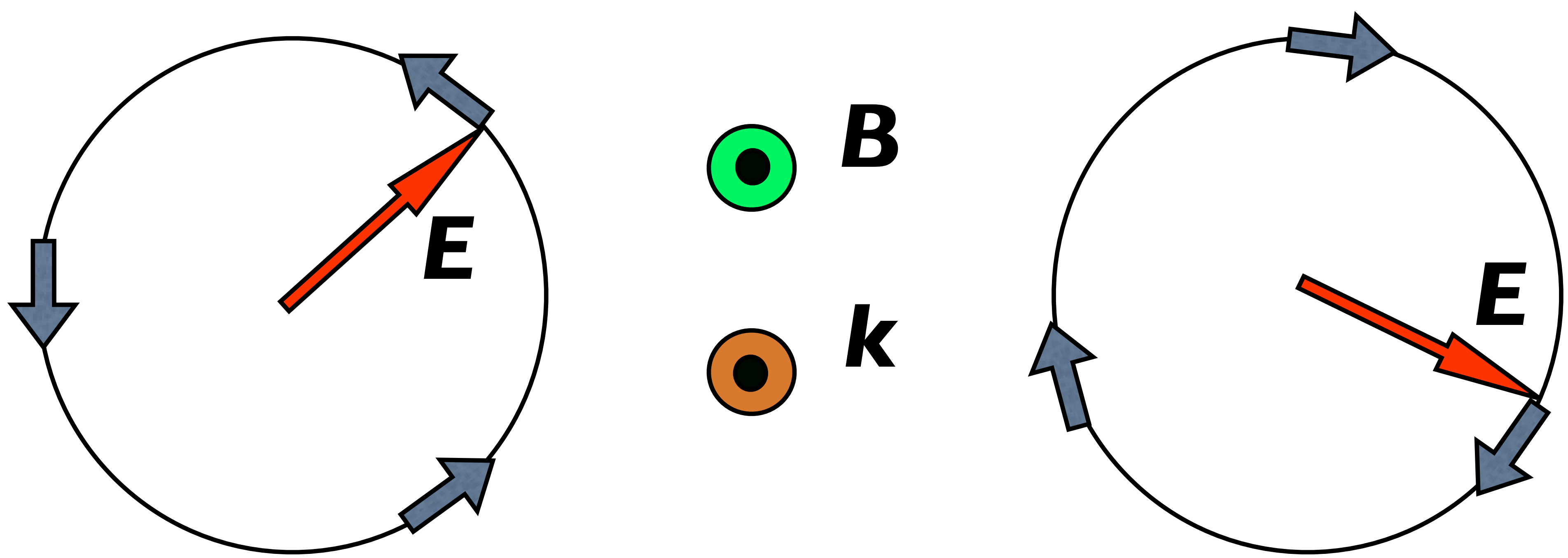
$$\omega_{\text{SP}} = \frac{\omega_p}{\sqrt{2(1.33)^2 + 1}} \approx 0.47\omega_p$$

$\Longrightarrow$ λ_{SP} = 295 nm

What about electron response and Faraday rotation?

Use circular polarization, and magnetic field ***B*** along ***k***=k***n***.

EM waves approaching you, the observer:



LEFT circular polarization
CCW rotation
positive helicity **σ · *n***

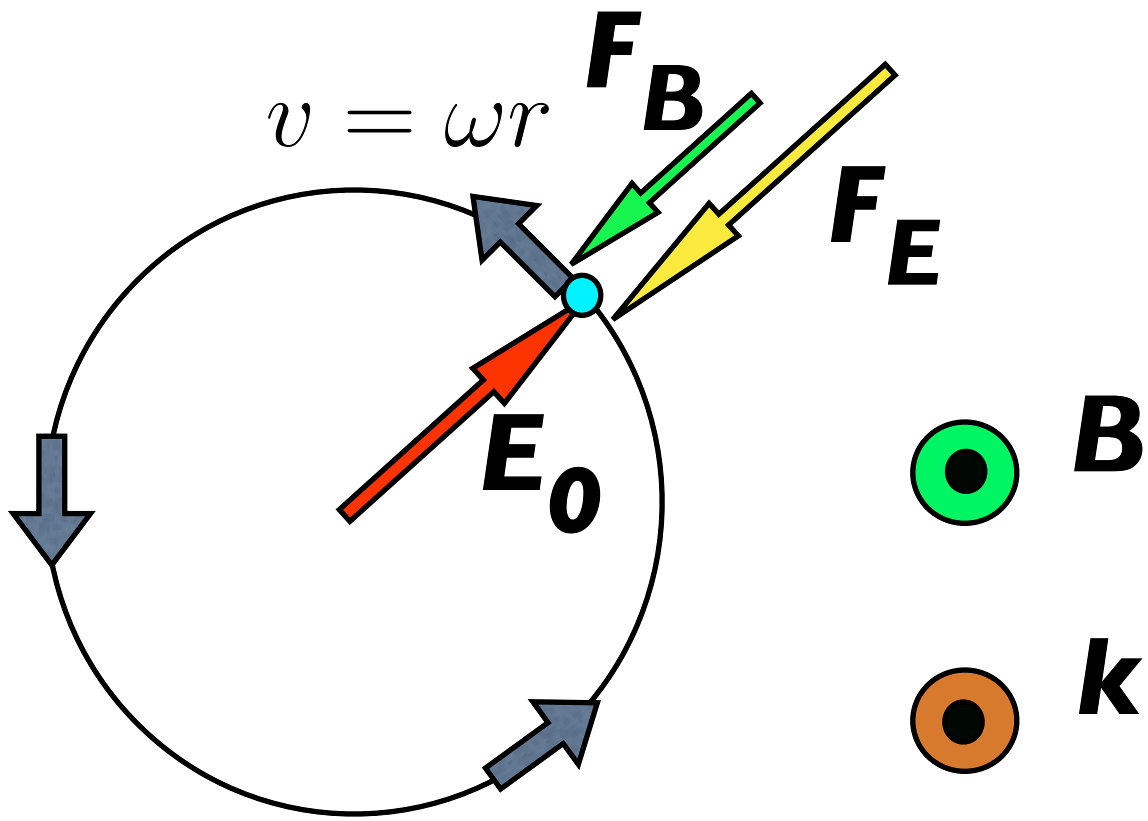
$$\hat{u}_L = \frac{1}{\sqrt{2}}(\hat{x} + i\hat{y})\ e^{-i\omega t}$$

RIGHT circular polarization
CW rotation
negative helicity **σ · *n***

$$\hat{u}_R = \frac{1}{\sqrt{2}}(\hat{x} - i\hat{y})\ e^{-i\omega t}$$

Free electron response, at frequency ω:

LEFT circular polarization



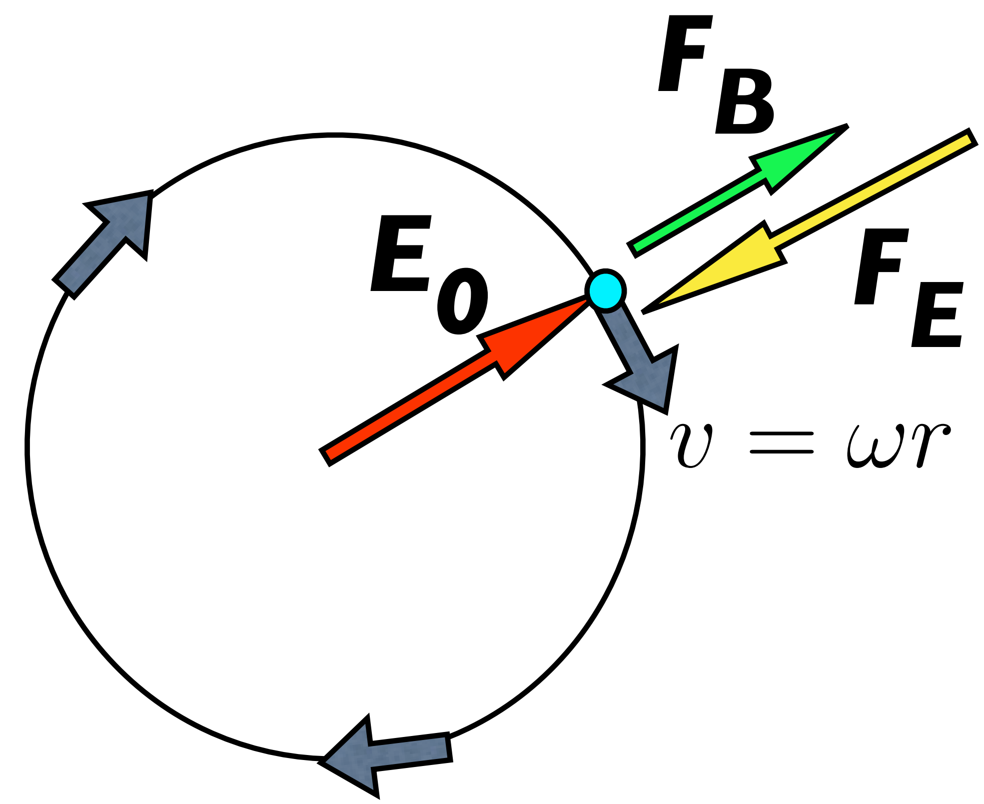
$$F_{\rm net} = eE_0 + evB_z = m\omega^2 r$$

$$r = \frac{eE_0}{m\omega^2 - e\omega B_z} = \frac{eE_0}{m\omega(\omega - \omega_B)}$$

cyclotron frequency:

$$\omega_B = \frac{eB_z}{m}$$

RIGHT circular polarization



$$F_{\rm net} = eE_0 - evB_z = m\omega^2 r$$

$$r = \frac{eE_0}{m\omega^2 + e\omega B_z} = \frac{eE_0}{m\omega(\omega + \omega_B)}$$

LEFT polarization produces larger orbit, larger induced electric dipole

Effect on electric permittivity ϵ

permittivity ϵ:

$$\epsilon \vec{E} = \vec{D} = \epsilon_0 \vec{E} + \vec{P}$$

polarization:

$$\vec{P} = n\vec{p}$$

electric dipole:

$$\vec{p} = -e\vec{r}$$

$$\epsilon = \frac{D_0}{E_0} = \frac{\epsilon_0 E_0 + P}{E_0} = \epsilon_0 + \frac{P}{E_0} \quad \Longrightarrow \quad \epsilon = \epsilon_0 - \frac{ne^2}{m\omega(\omega \pm \omega_B)}$$

$$\epsilon = \epsilon_0 \left[1 - \frac{\omega_p^2}{\omega(\omega \pm \omega_B)} \right]$$

+ for RIGHT circular
- for LEFT circular

$$\lambda_R = \frac{2\pi}{k_R}$$

$$\lambda_L = \frac{2\pi}{k_L}$$

wave vectors:

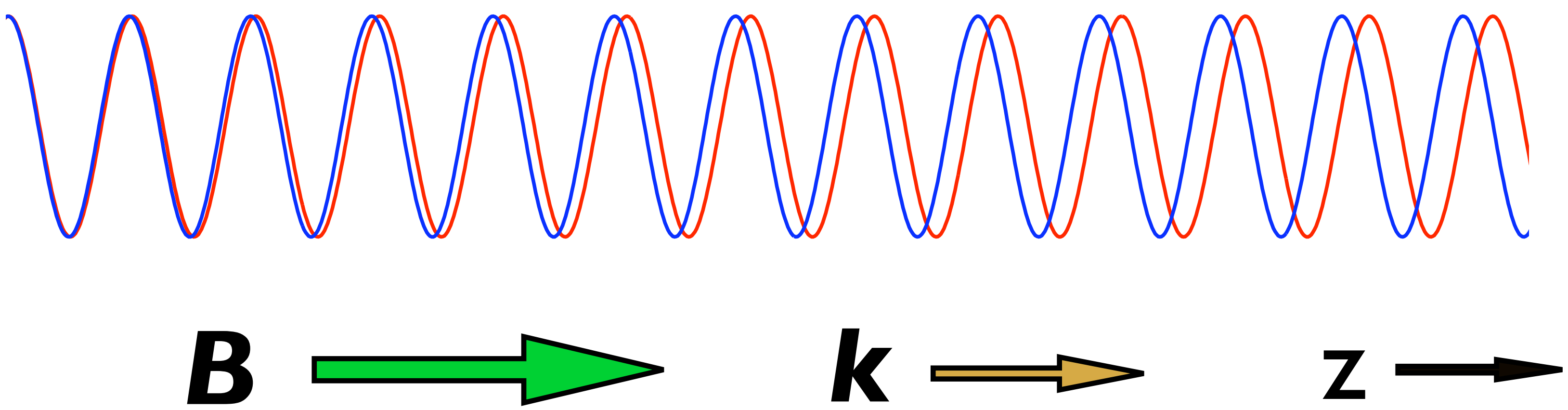
$$k = \frac{2\pi}{\lambda} = \sqrt{\epsilon\mu}\ \omega$$

$$k = \frac{\omega}{c} \sqrt{1 - \frac{\omega_p^2}{\omega(\omega \pm \omega_B)}} \quad \Longrightarrow \quad \lambda_R < \lambda_L$$

Why is there Faraday rotation, and how large is it?

Incident linear polarization, at a single frequency ω:

$$\vec{E}_{\rm inc} = E_{\rm inc}\hat{x} = E_{\rm inc}\frac{1}{\sqrt{2}}(\hat{u}_R + \hat{u}_L)$$



red = λ_L $\quad \hat{u}_L = \frac{1}{\sqrt{2}}(\hat{x} + i\hat{y})$

blue = λ_R $\quad \hat{u}_R = \frac{1}{\sqrt{2}}(\hat{x} - i\hat{y})$

After propagation through z:

$$\vec{E}(z) = \frac{E_{\rm inc}}{\sqrt{2}}\left[\hat{u}_R e^{ik_R z} + \hat{u}_L e^{ik_L z}\right]$$

$$\vec{E}(z) = E_{\rm inc}\left[\hat{x}\cos\left(\frac{\Delta k}{2}z\right) + \hat{y}\sin\left(\frac{\Delta k}{2}z\right)\right]e^{i\bar{k}z}$$

Faraday rotation:

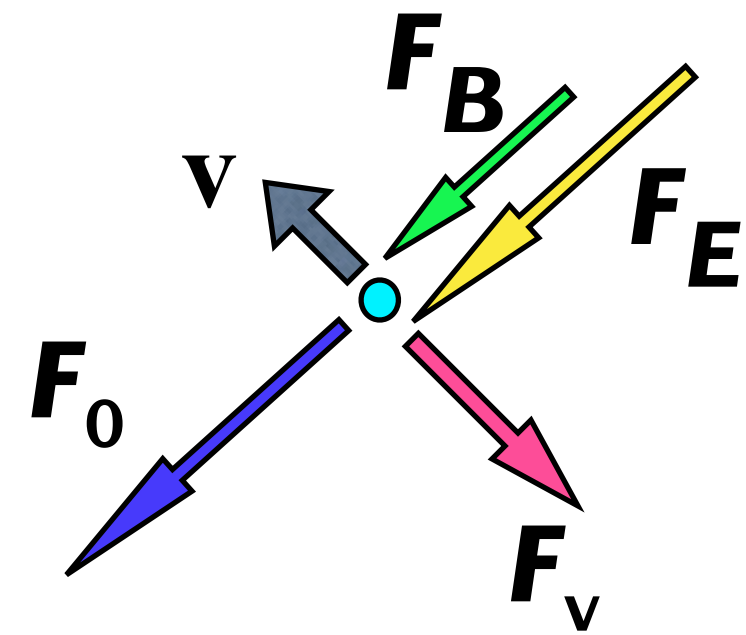
$$\Delta\phi = \frac{\Delta k}{2}z$$

$$\bar{k} \equiv \tfrac{1}{2}(k_R + k_L)$$

$$\Delta k \equiv k_R - k_L$$

Faraday rotation: Connection to dielectric matrix ϵ

An electron is affected by several forces:



$$\vec{F} = -m\omega_0^2\vec{r} - e\vec{E} - e\dot{\vec{r}} \times \vec{B} - m\gamma\dot{\vec{r}} = m\ddot{\vec{r}}$$

binding electric Lorentz damping

harmonic motion: $\vec{r}(t) = \vec{r}_0 e^{-i\omega t}$

$$m\left(\omega^2 - \omega_0^2 + i\omega\gamma\right)\vec{r} - i\omega e\vec{B} \times \vec{r} = e\vec{E}$$

incident waves

electron response

$$\begin{pmatrix} m\left(\omega^2 - \omega_0^2 + i\omega\gamma\right) & i\omega e B_z \\ -i\omega e B_z & m\left(\omega^2 - \omega_0^2 + i\omega\gamma\right) \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} eE_{0x} \\ eE_{0y} \end{pmatrix}$$

form is: $M \cdot \vec{r} = e\vec{E}$

solution is: $\vec{r} = \begin{pmatrix} x \\ y \end{pmatrix} = M^{-1} \begin{pmatrix} eE_{0x} \\ eE_{0y} \end{pmatrix}$

Result for electric permittivity ϵ

$$\epsilon\vec{E} = \epsilon_0\vec{E} + \vec{P} \qquad \vec{P} = -ne\vec{r} \qquad \vec{r} = M^{-1}\begin{pmatrix} eE_{0x} \\ eE_{0y} \end{pmatrix}$$

Then magic happens and

$$\epsilon = \begin{pmatrix} \epsilon_{xx} & i\epsilon_{xy} \\ -i\epsilon_{xy} & \epsilon_{xx} \end{pmatrix}$$

$$\epsilon_{xx} = \epsilon_0 - \frac{(ne^2/m)\left(\omega^2 - \omega_0^2 + i\omega\gamma\right)}{\left(\omega^2 - \omega_0^2 + i\omega\gamma\right)^2 - (\omega eB_z/m)^2}$$

$$\epsilon_{xy} = \frac{(ne^2/m)(\omega eB_z/m)}{\left(\omega^2 - \omega_0^2 + i\omega\gamma\right)^2 - (\omega eB_z/m)^2}$$

What's important: The eigenstates of ϵ are the RIGHT/LEFT circular polarization states!

$$\lambda_1 = \epsilon_R = \epsilon_{xx} + \epsilon_{xy} \qquad \hat{u}_1 = \hat{u}_R = \frac{1}{\sqrt{2}}(\hat{x} - i\hat{y})$$ RIGHT circular

$$\lambda_2 = \epsilon_L = \epsilon_{xx} - \epsilon_{xy} \qquad \hat{u}_2 = \hat{u}_L = \frac{1}{\sqrt{2}}(\hat{x} + i\hat{y})$$ LEFT circular

for the propagating eigenstates:

$$\epsilon_{R/L} = \epsilon_0 \left(1 - \frac{\omega_p^2}{\omega^2 - \omega_0^2 + i\omega\gamma \pm \omega\omega_B}\right) \Rightarrow \begin{array}{l} k_R = \sqrt{\epsilon_R \mu_0}\;\omega \\ k_L = \sqrt{\epsilon_L \mu_0}\;\omega \end{array}$$

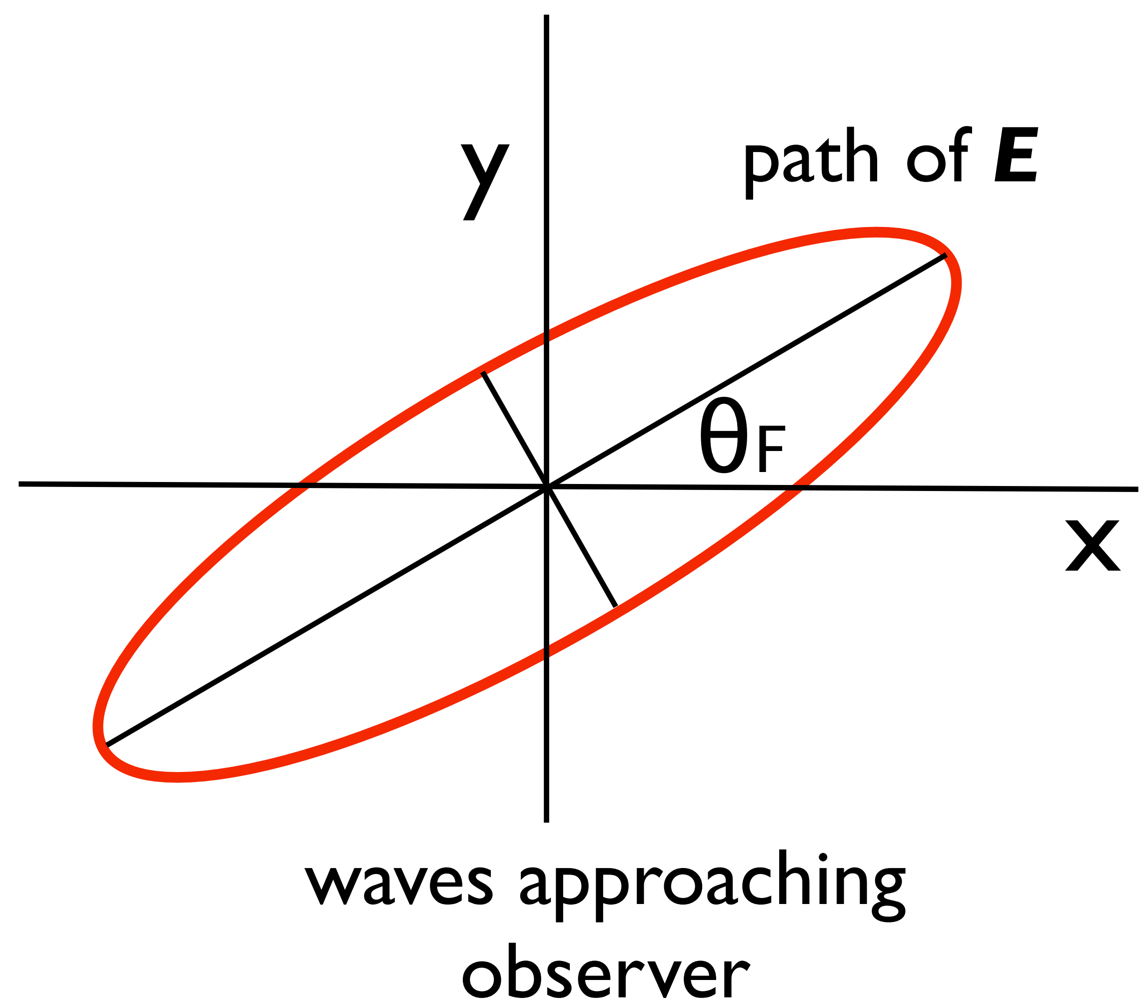
Faraday rotation:

$$\Delta\phi = \tfrac{1}{2}(k_R - k_L)z \Rightarrow \Delta\phi = \frac{\omega}{2c}\frac{\epsilon_{xy}}{\sqrt{\epsilon_{xx}}}z$$

This could be complex.

$$\theta_F = \mathrm{Real}\left\{\frac{\omega}{2c}\frac{\epsilon_{xy}}{\sqrt{\epsilon_{xx}}}z\right\} \text{ = rotation}$$

$$\chi_F = \mathrm{Imag}\left\{\frac{\omega}{2c}\frac{\epsilon_{xy}}{\sqrt{\epsilon_{xx}}}z\right\} \text{ = ellipticity}$$



Faraday rotation at $\omega_B \ll \omega$

cyclotron frequency at B=1.0 T

ω_B = eB/m = 1.8×10^{11} rad/s

$\ll$

optical frequency at λ=600 nm

$\omega = 2\pi c/\lambda = 3.1 \times 10^{15}$ rad/s

Then the Faraday rotation is proportional to B:

$$\theta_F = \upsilon B z$$

υ = Verdet constant

Viktor Chikan's core/shell particles, at λ=632 nm

υ = Verdet constant

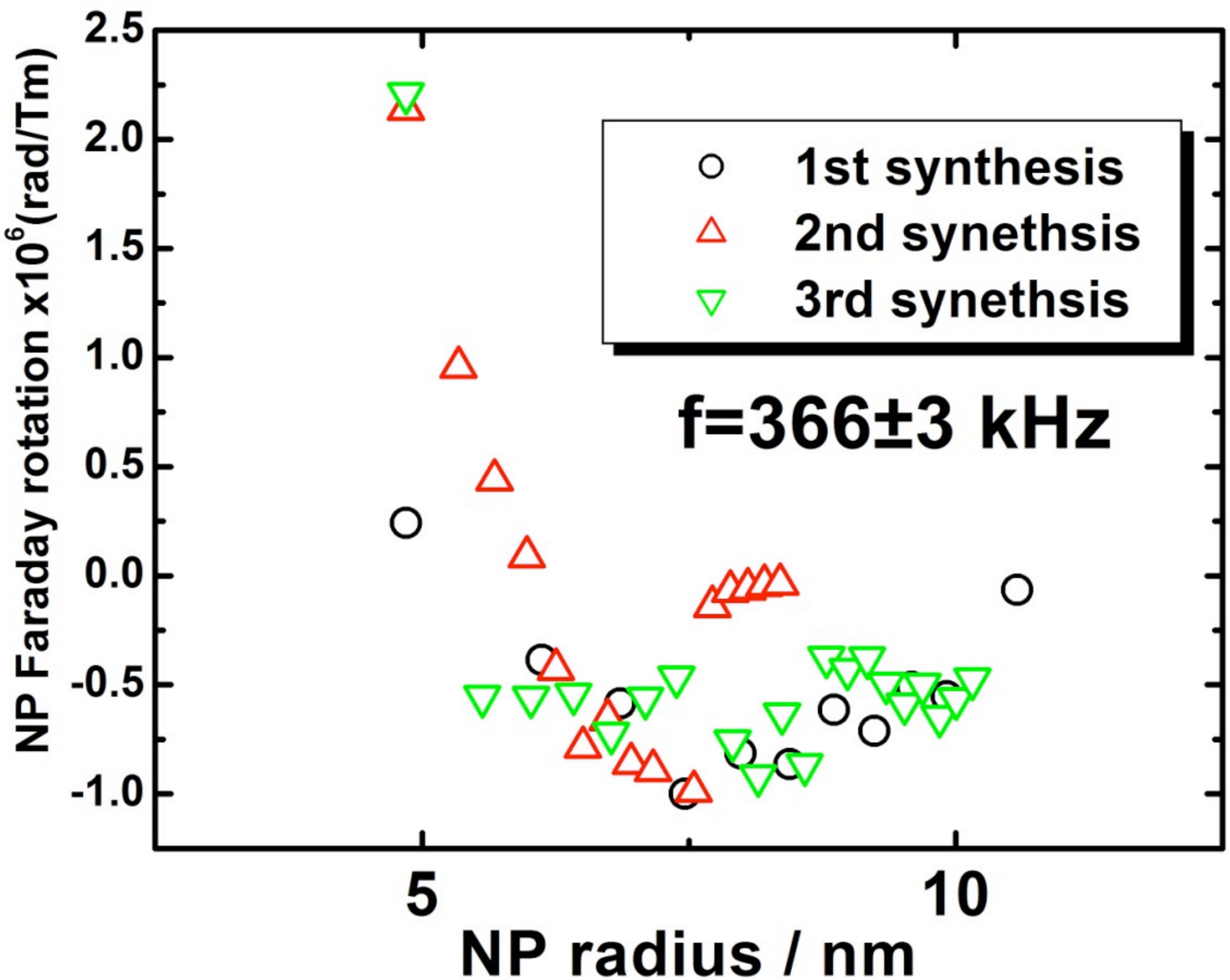
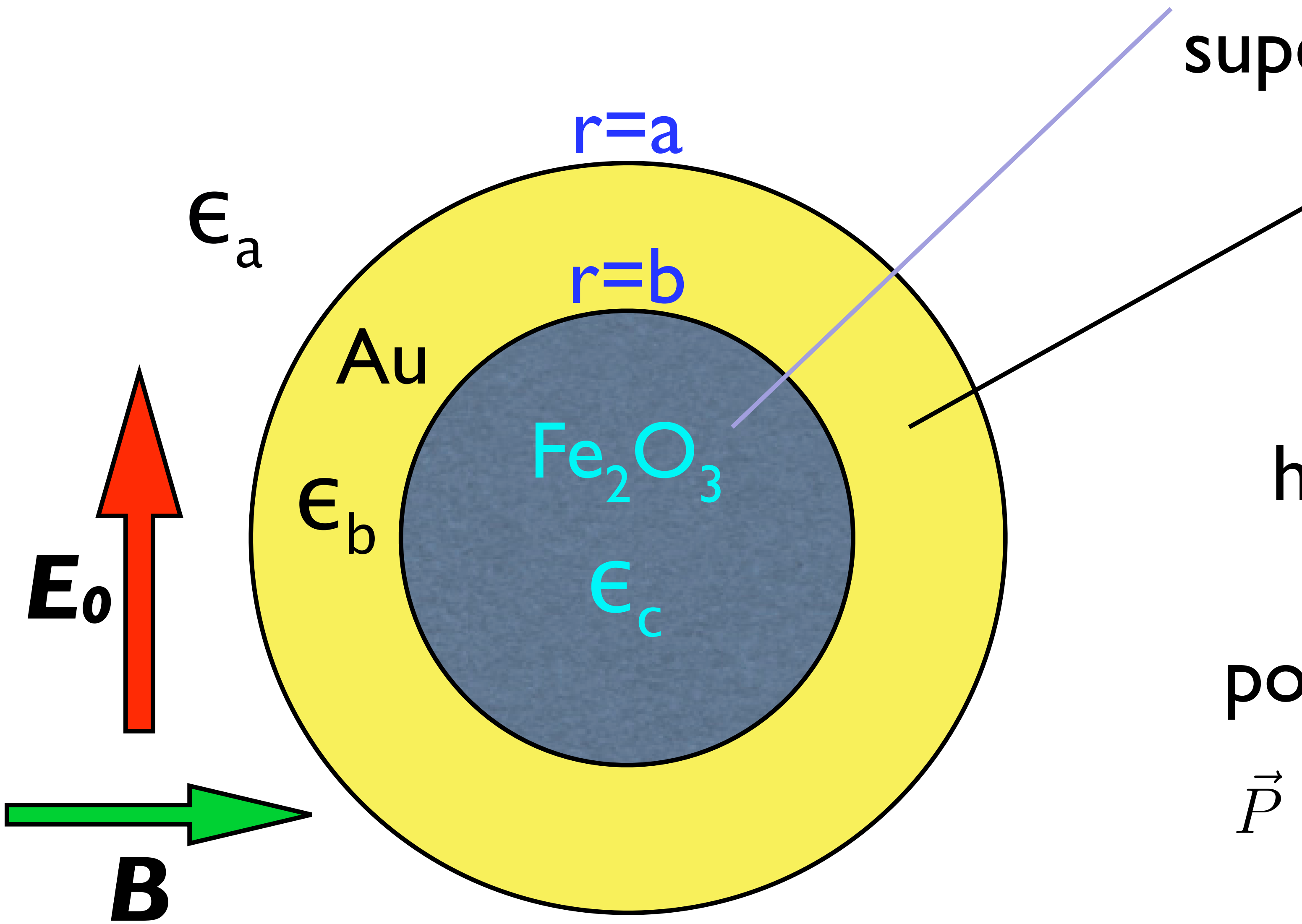


Figure 4 (b) Experimental Verdet constant of gold coated Fe_2O_3 nanoparticles only (normalized by the volume fraction of the particles) as a function of gold shell thickness

core/shell NP electrostatics:

maghemite core, superparamagnetic

gold shell



surrounded by host medium, ϵ_a

polarization:

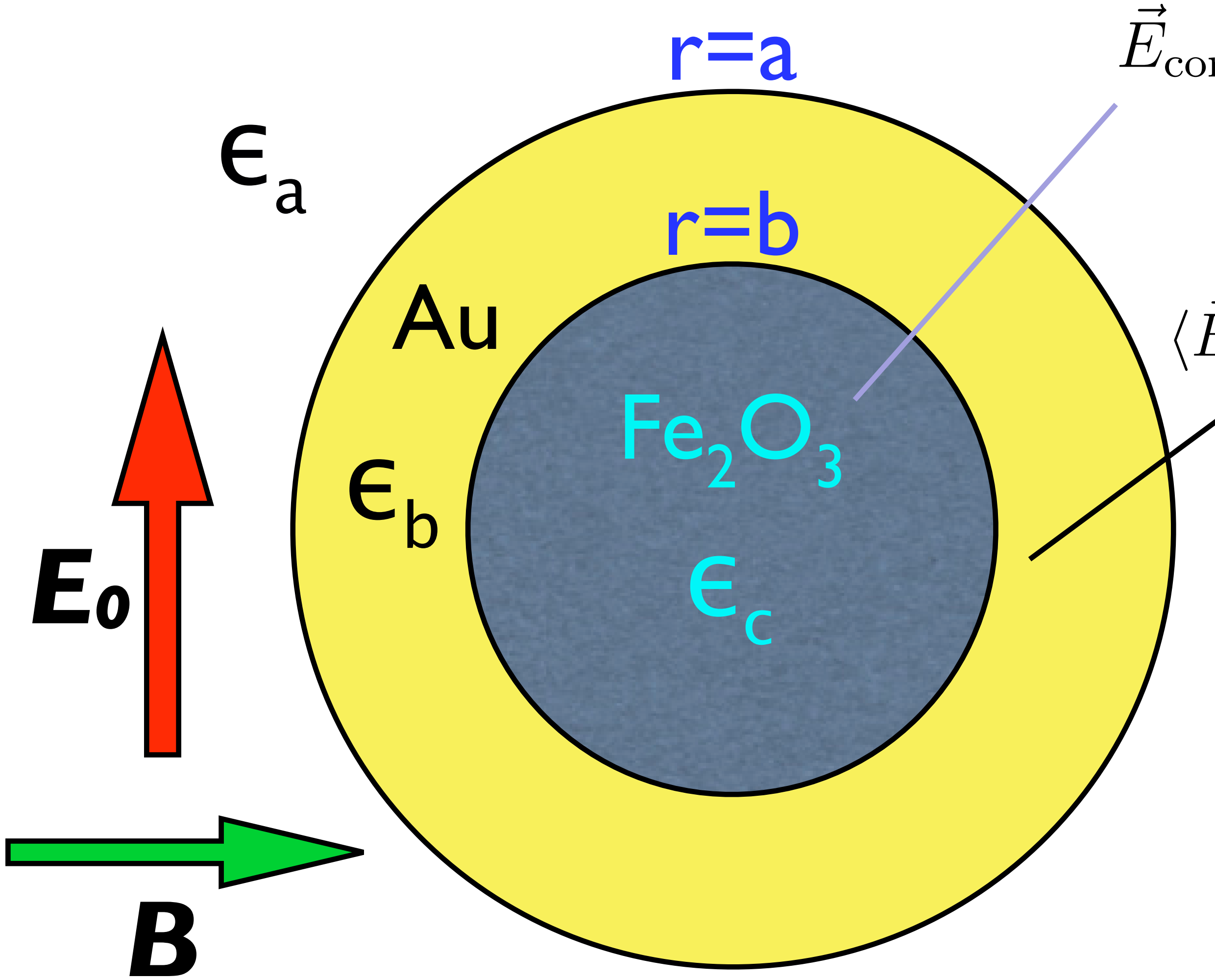
$$\vec{P} = \frac{\vec{p}}{4\pi a^3/3} = \alpha_s \vec{E}_0$$

induced electric dipole (from Laplace eqn. solution):

$$\vec{p} = 3\epsilon_a \frac{\left(\frac{\epsilon_b-\epsilon_a}{2\epsilon_a+\epsilon_b}\right) + \left(\frac{b}{a}\right)^3 \left(\frac{2\epsilon_b+\epsilon_a}{2\epsilon_a+\epsilon_b}\right)\left(\frac{\epsilon_c-\epsilon_b}{2\epsilon_b+\epsilon_c}\right)}{1+2\left(\frac{b}{a}\right)^3 \left(\frac{\epsilon_b-\epsilon_a}{2\epsilon_a+\epsilon_b}\right)\left(\frac{\epsilon_c-\epsilon_b}{2\epsilon_b+\epsilon_c}\right)} \left(\frac{4\pi a^3}{3}\right) \vec{E}_0$$

NP polarizability α_s

core/shell NP electrostatics:



$$\vec{E}_{\text{core}} = \left(\frac{3\epsilon_a}{2\epsilon_a + \epsilon_b}\right) \frac{\left(\frac{3\epsilon_b}{2\epsilon_b+\epsilon_c}\right)}{1 + 2\left(\frac{b}{a}\right)^3 \left(\frac{\epsilon_b-\epsilon_a}{2\epsilon_a+\epsilon_b}\right)\left(\frac{\epsilon_c-\epsilon_b}{2\epsilon_b+\epsilon_c}\right)} \vec{E}_0$$

$$\langle \vec{E}_{\text{shell}} \rangle = \left(\frac{3\epsilon_a}{2\epsilon_a + \epsilon_b}\right) \frac{1}{1 + 2\left(\frac{b}{a}\right)^3 \left(\frac{\epsilon_b-\epsilon_a}{2\epsilon_a+\epsilon_b}\right)\left(\frac{\epsilon_c-\epsilon_b}{2\epsilon_b+\epsilon_c}\right)} \vec{E}_0$$

averaged internal field:

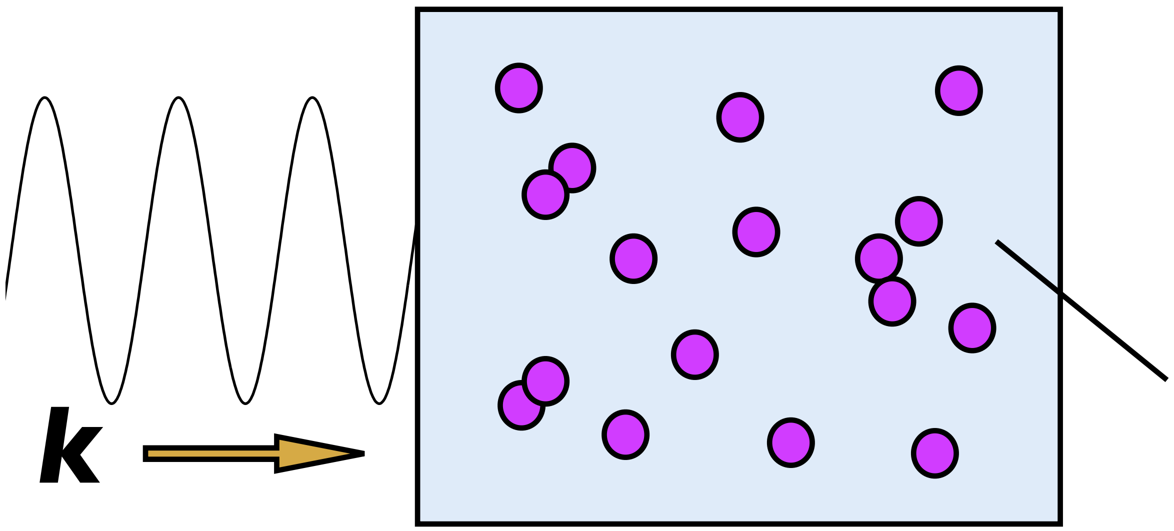
$$\langle \vec{E}_{\text{in}} \rangle = \frac{V_{\text{core}} \langle \vec{E}_{\text{core}} \rangle + V_{\text{shell}} \langle \vec{E}_{\text{shell}} \rangle}{V_{\text{particle}}}$$

$$\langle \vec{E}_{\text{in}} \rangle = \left(\frac{3\epsilon_a}{2\epsilon_a + \epsilon_b}\right) \frac{1 + \left(\frac{b}{a}\right)^3 \left(\frac{\epsilon_b-\epsilon_c}{2\epsilon_b+\epsilon_c}\right)}{1 + 2\left(\frac{b}{a}\right)^3 \left(\frac{\epsilon_b-\epsilon_a}{2\epsilon_a+\epsilon_b}\right)\left(\frac{\epsilon_c-\epsilon_b}{2\epsilon_b+\epsilon_c}\right)} \vec{E}_0 \quad \Rightarrow \quad \langle \vec{E}_{\text{in}} \rangle = F_s \vec{E}_0$$

F_s

But scattering is from a collection of NPs.
Use some kind of *effective medium theory*.

What are this sample's averaged ϵ_R, ϵ_L? N=# of NPs



$$f = \frac{N V_{\rm NP}}{V_{\rm sys}}$$ = volume fraction of NPs

ϵ_a=host medium permittivity

$\boldsymbol{E}_0$=field in the host

simple averaging (Maxwell Garnet theory):

$$\langle \vec{E} \rangle = (1-f)\vec{E}_0 + f\langle \vec{E}_{\rm in}\rangle = [(1-f) + fF_s]\,\vec{E}_0 \Rightarrow \Rightarrow \vec{E}_0 = \frac{\langle \vec{E}\rangle}{[(1-f)+fF_s]}$$

$$\langle \vec{D} \rangle = \langle \epsilon_{\rm eff}\rangle\langle \vec{E}\rangle = \epsilon_a\langle \vec{E}\rangle + f\vec{P} = \epsilon_a\langle \vec{E}\rangle + f\alpha_s\vec{E}_0 \Leftarrow \Leftarrow$$

$$\langle \vec{D} \rangle = \langle \epsilon_{\rm eff}\rangle\langle \vec{E}\rangle = \left[\epsilon_a + \frac{f\alpha_s}{1-f+fF_s}\right]\langle \vec{E}\rangle \quad \Rightarrow \quad \boxed{\langle \epsilon_{\rm eff}\rangle = \epsilon_a + \frac{f\alpha_s}{1-f+fF_s}}$$

Find this for RIGHT/LEFT polarizations

gold parameters

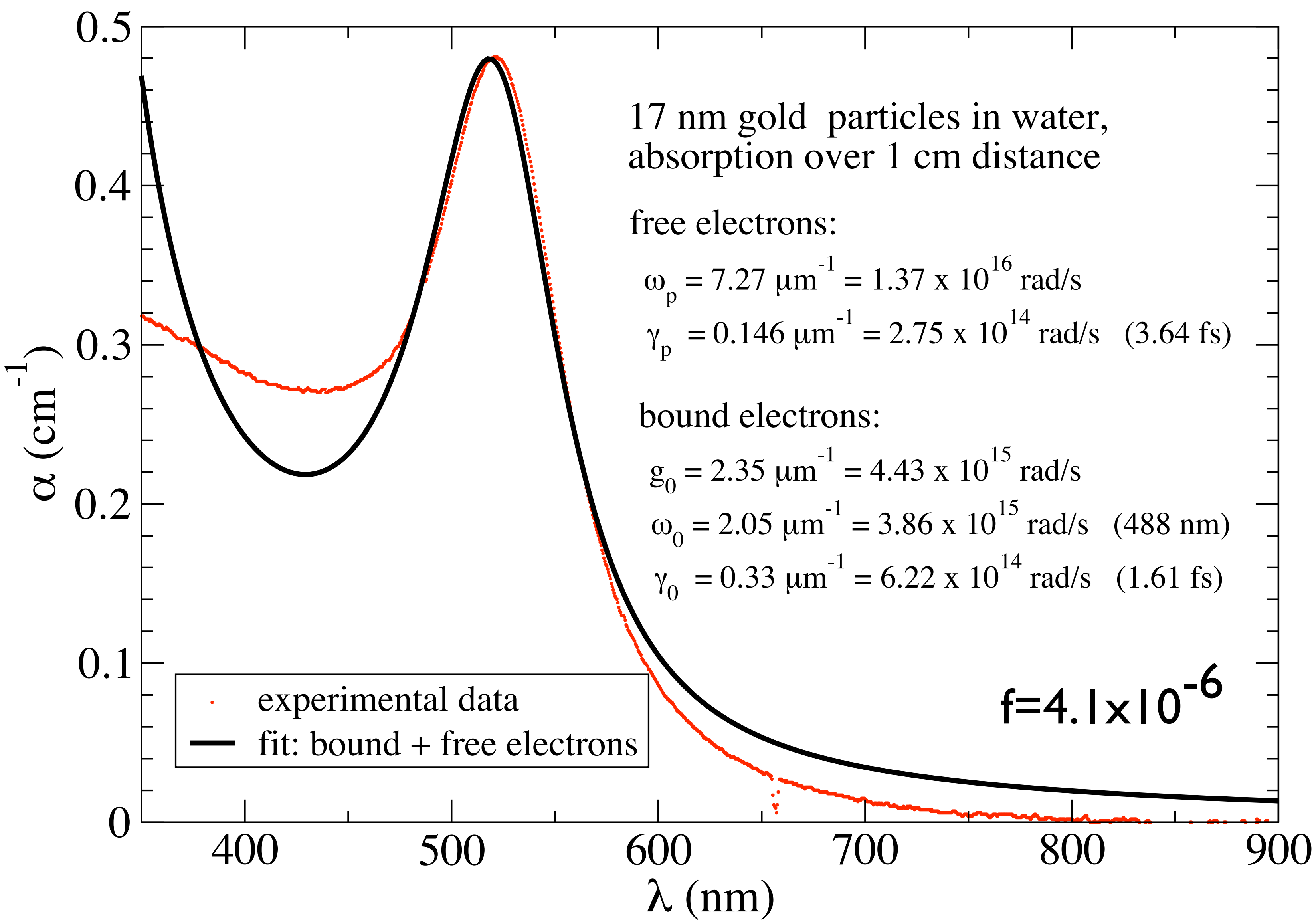
fit ϵ_{eff} via absorption:

$$\alpha = \frac{\omega}{c}\,\mathrm{Im}\left\{\sqrt{\varepsilon_{\text{eff}}}\right\}$$

assumption for the gold: ($\nu = \pm 1$ for R/L)

$$\varepsilon = 1 - \frac{g_0^2}{\omega^2 - \omega_0^2 + i\gamma_0\omega - \nu\omega\omega_B} - \frac{\omega_p^2}{\omega^2 + i\gamma_p\omega - \nu\omega\omega_B}$$

(bound e^-) (free e^-)



Fits the plasmon resonance peak near 530 nm

Gold *shell* has extra scattering. This increases the effective damping of free electrons.

$$\gamma_p = \frac{1}{\tau} + \frac{v_F}{d}$$

intrinsic scattering

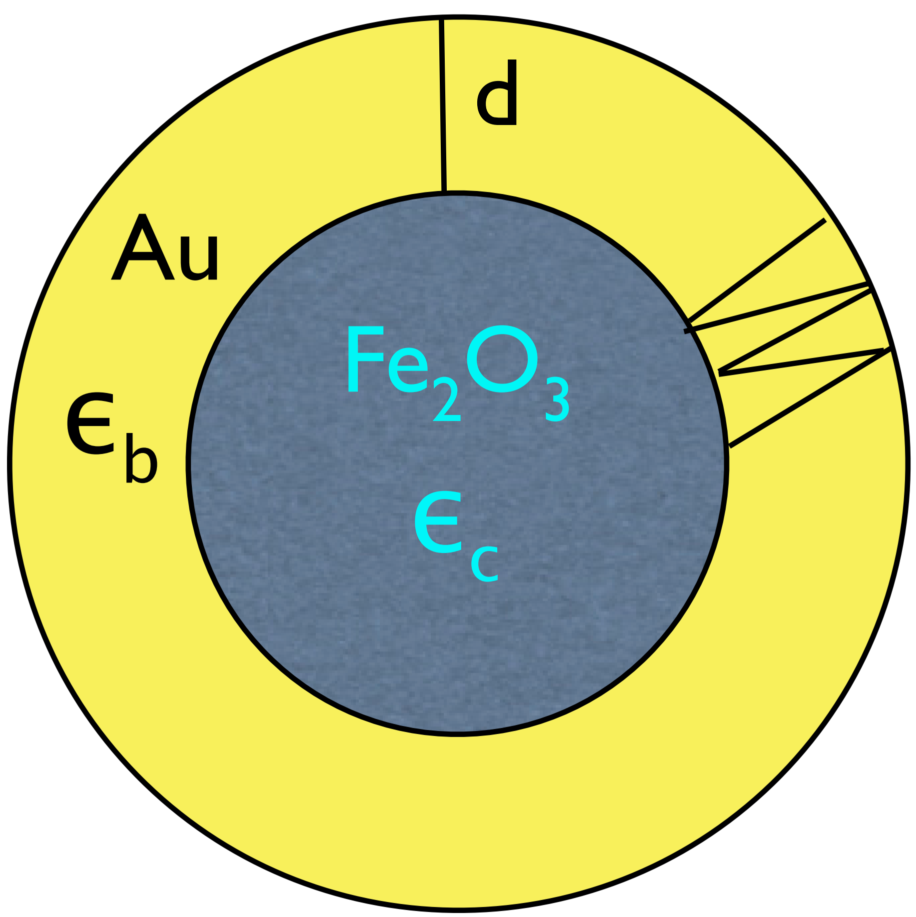
surface scattering

scattering time

$\tau = 9.1$ fs,

Fermi velocity

$v_F = 1.40 \times 10^6$ m/s



The superparamagnetic Fe_2O_3 core:

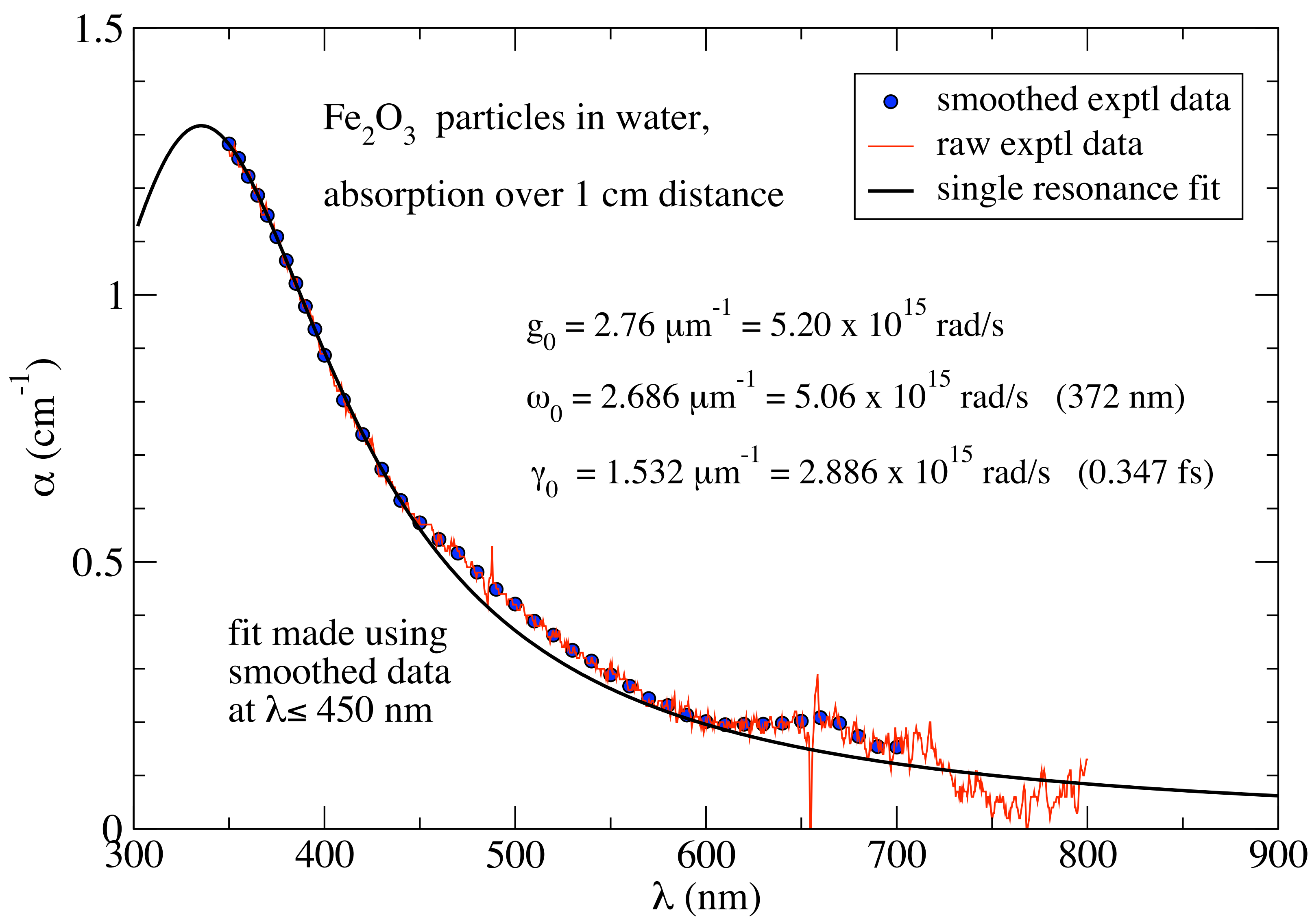
fit ϵ_{eff} via absorption:

$$\alpha = \frac{\omega}{c}\,\mathrm{Im}\left\{\sqrt{\varepsilon_{\mathrm{eff}}}\right\}$$

assumption: ($\nu = \pm 1$ for R/L)

$$\varepsilon = 1 - \frac{g_0^2}{\omega^2 - \omega_0^2 + i\gamma_0\omega - \nu\omega\omega_B}$$

(single resonance, bound e⁻)



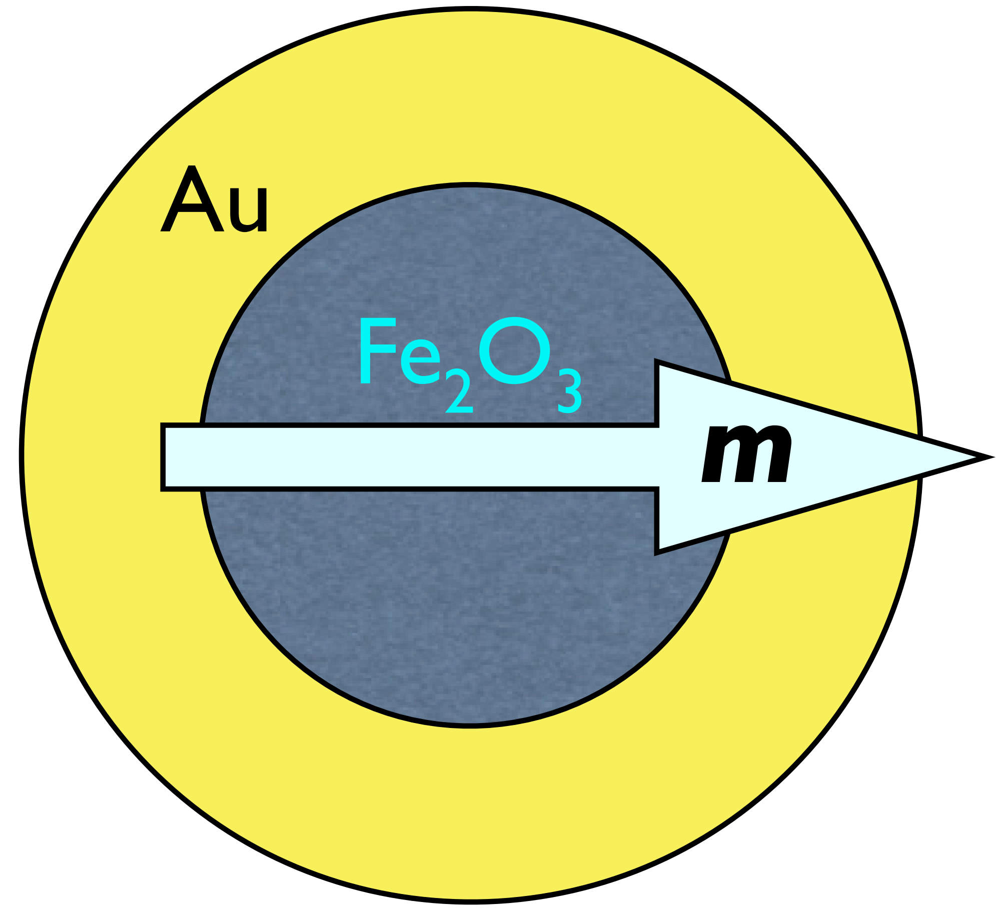
radius b=4.85 nm

Fits the primary resonance near 350 nm, that is responsible for faraday rotation.

The superparamagnetic Fe_2O_3 core:

radius $b = 4.85$ nm

volume $V = 4\pi b^3/3 = 478\ \text{nm}^3$



saturation magnetization M=414 kA/m

uniaxial anisotropy $K_A = 4700\ \text{J/m}^3$

anisotropy energy $K_A V = 14$ meV

(thermal energy $k_B T = 26$ meV)

magnetic moment

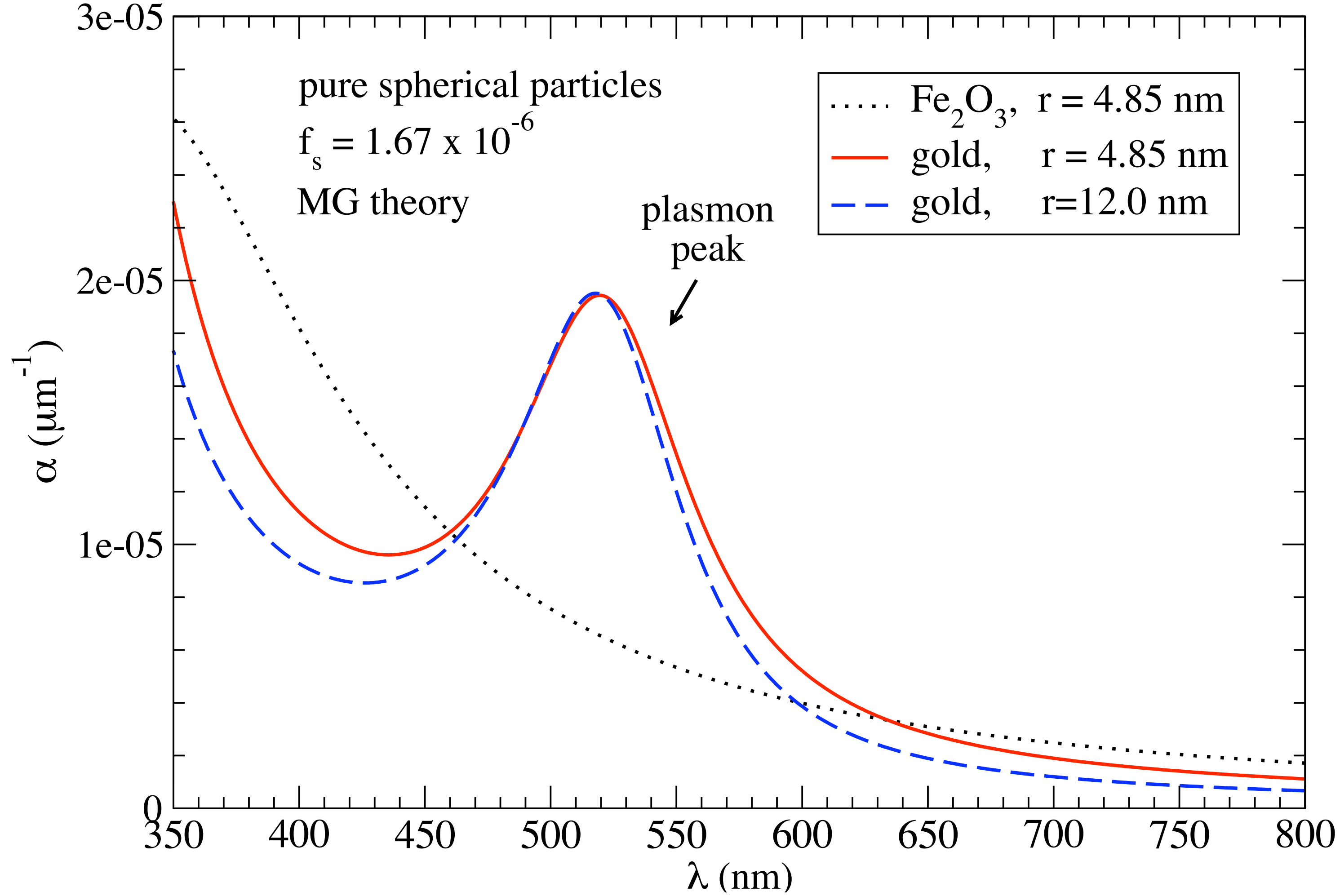
$m = MV \approx 21000\mu_B$

internal field $B_{in} \approx 5.5 B_{external}$

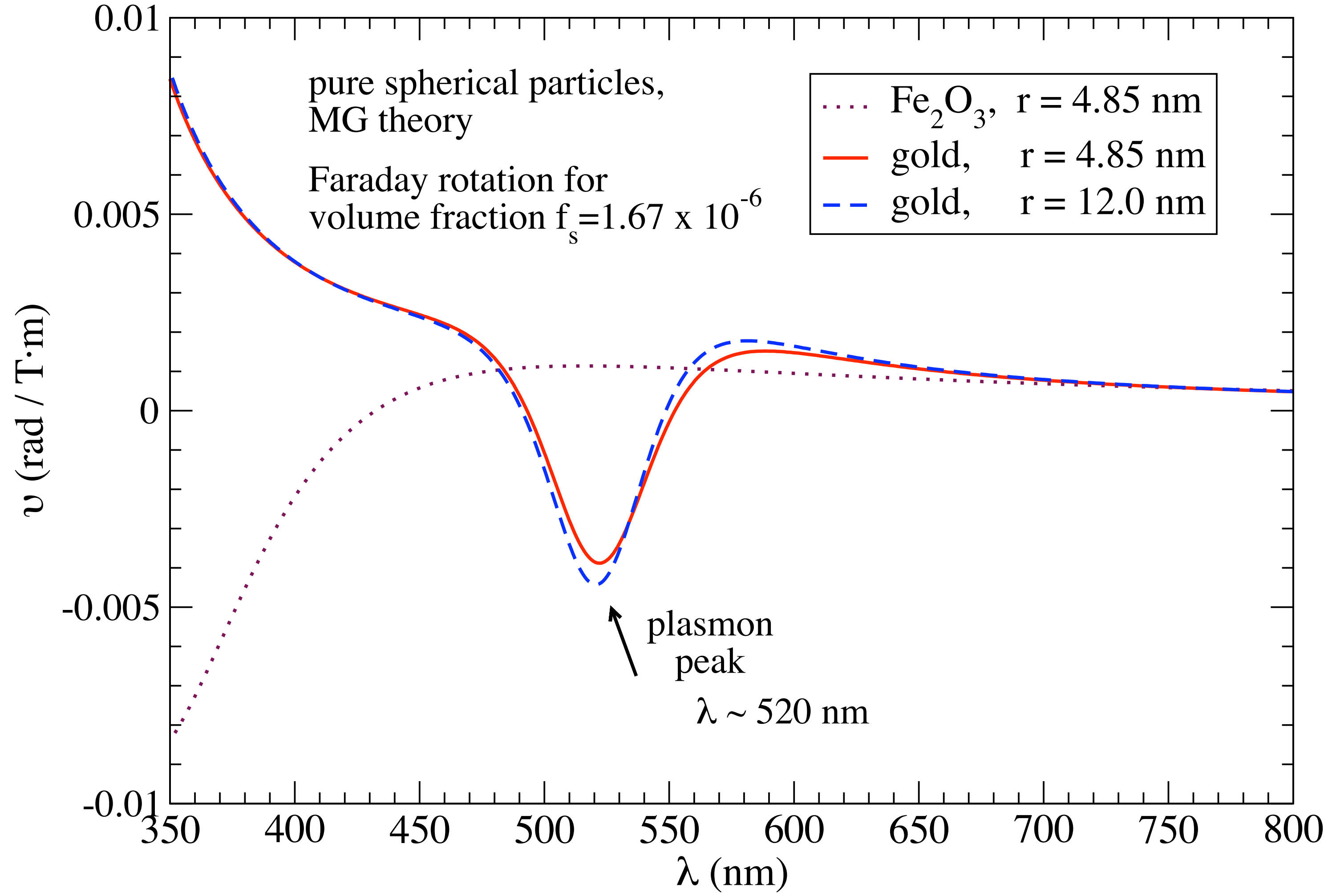
(cyclotron freq. $\omega_B = eB_{in}/m_e$) ☜ enhanced compared to the gold

simple nanoparticles
(core only)

absorption



Faraday rotation
(Verdet constant)

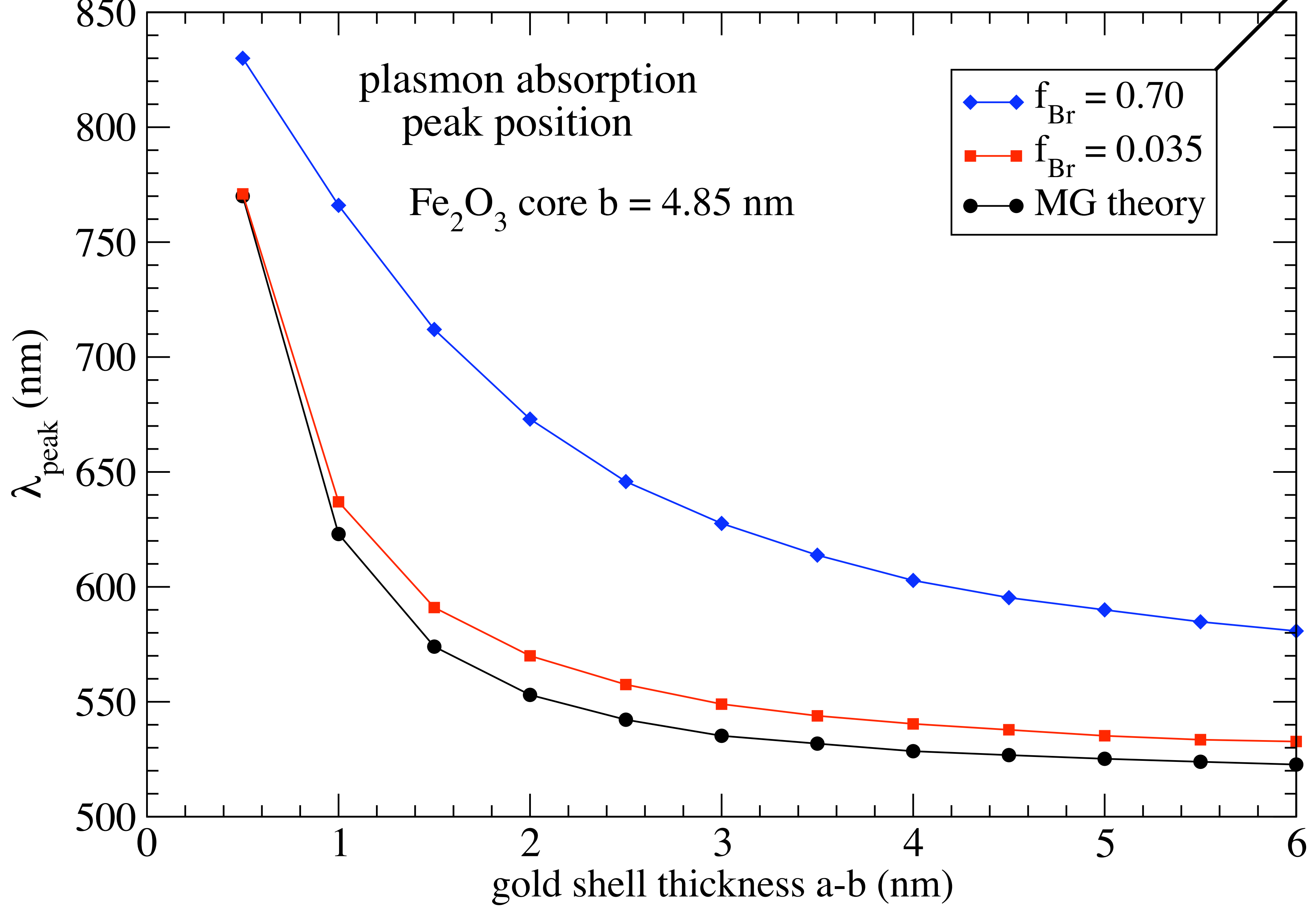


core/shell nanoparticles

core radius b=4.85 nm fixed.

different shell thicknesses d=a-b.

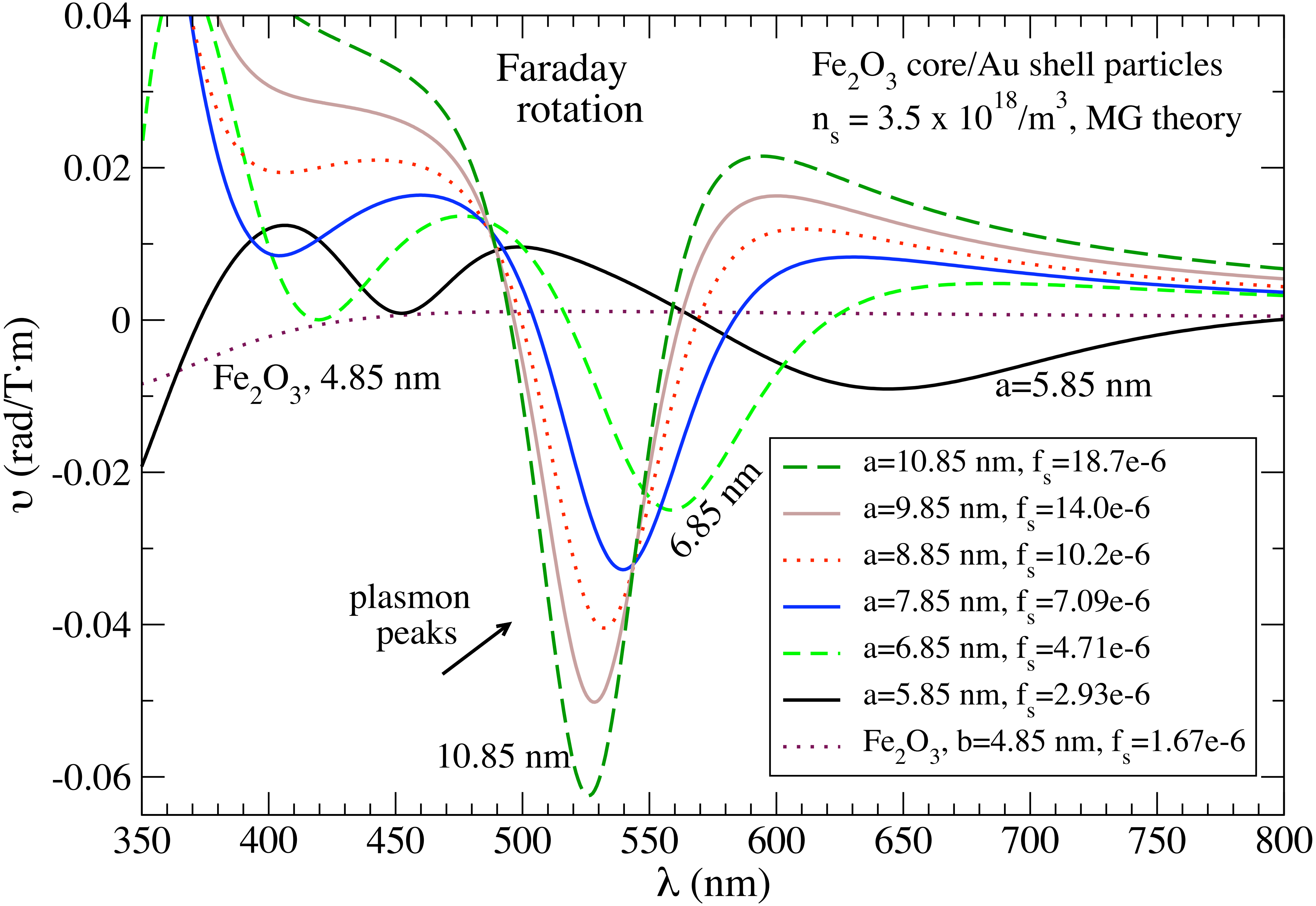
different effective medium or clustering theories



core/shell nanoparticles

core radius b=4.85 nm fixed.

different shell thicknesses d=a-b.



fixed NP number density n_s

varying volume fraction f_s

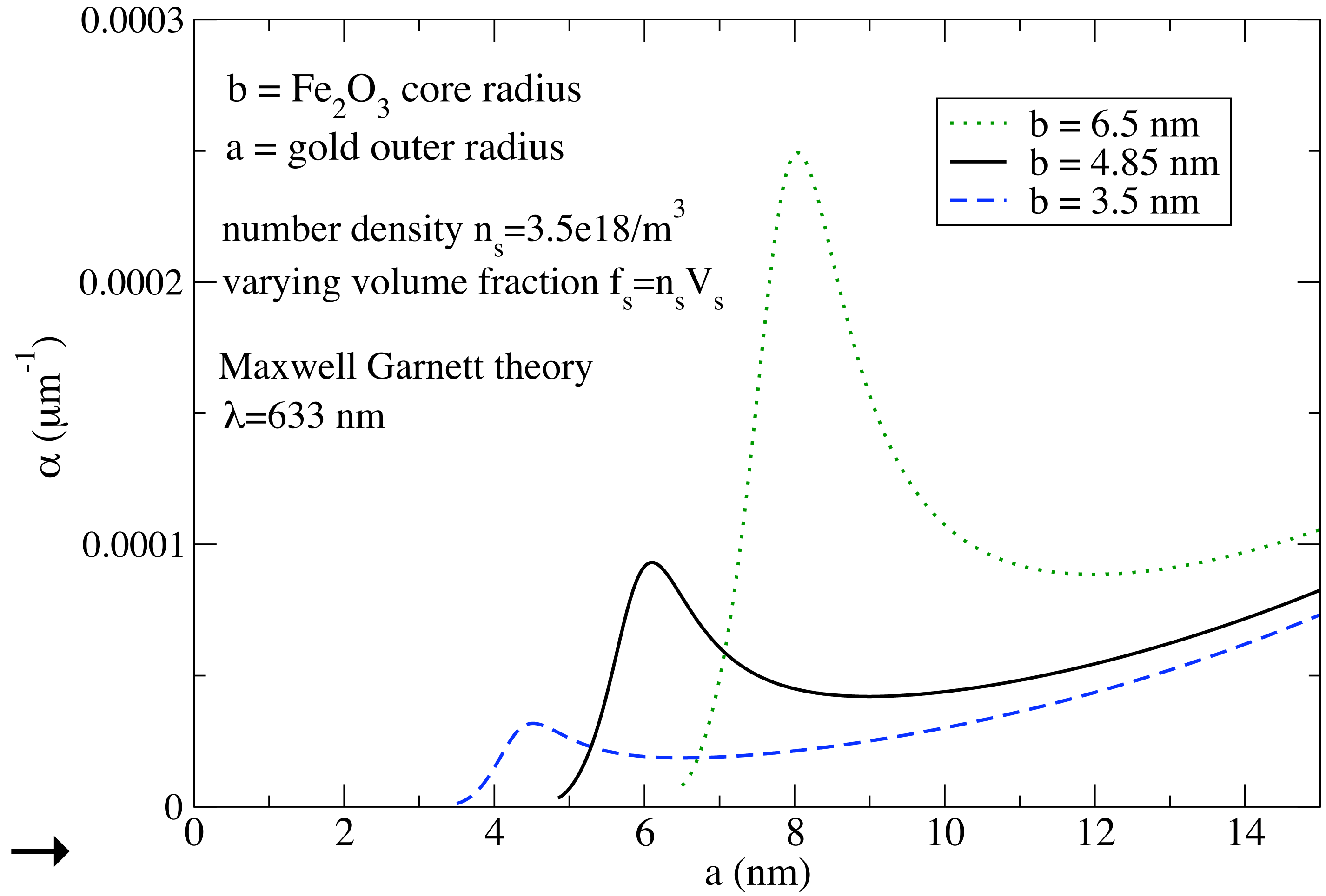
$$f_s = n_s V_s$$

$$V_s = 4\pi a^3/3$$

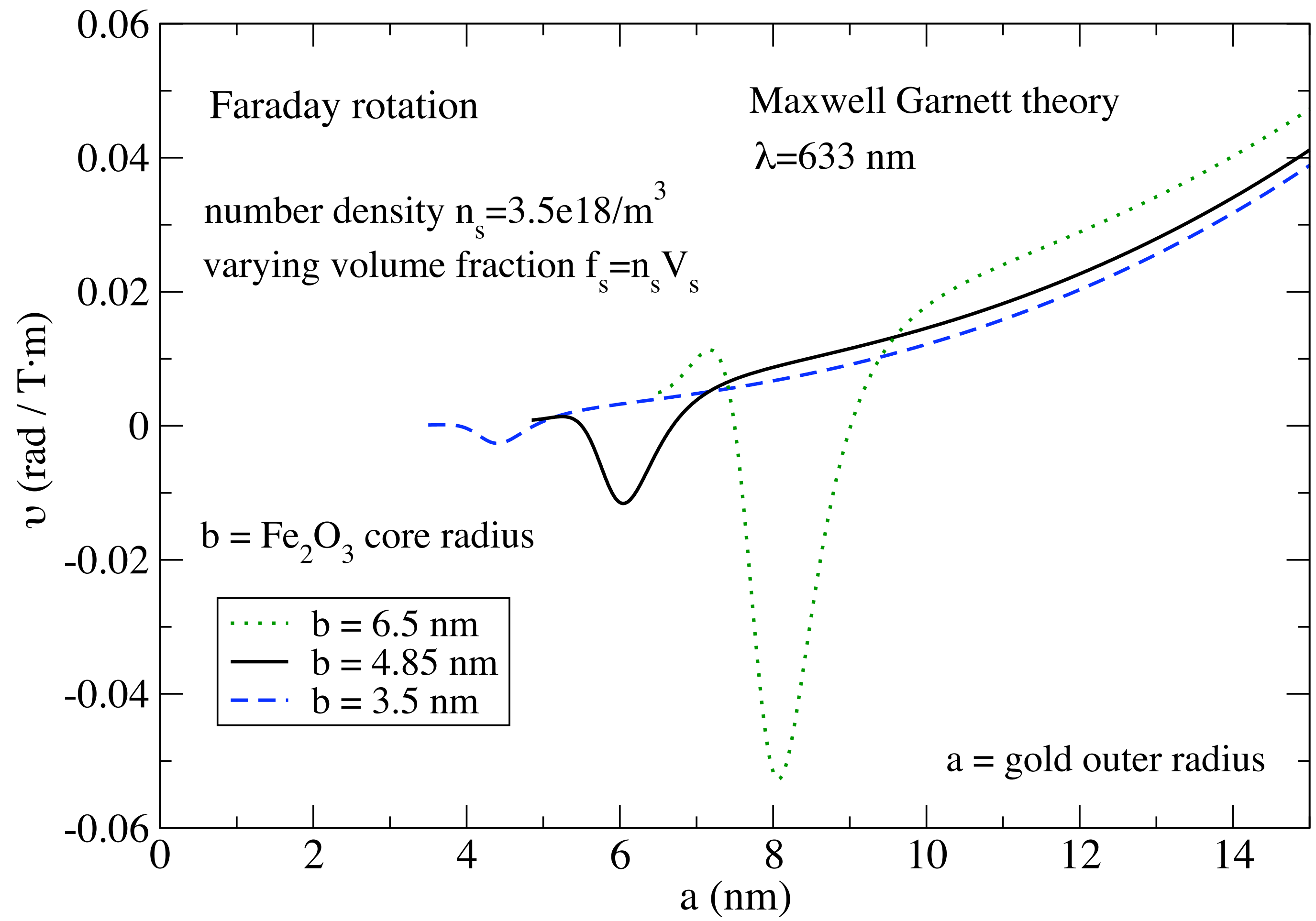
core/shell nanoparticles

absorption

vs. shell outer radius →

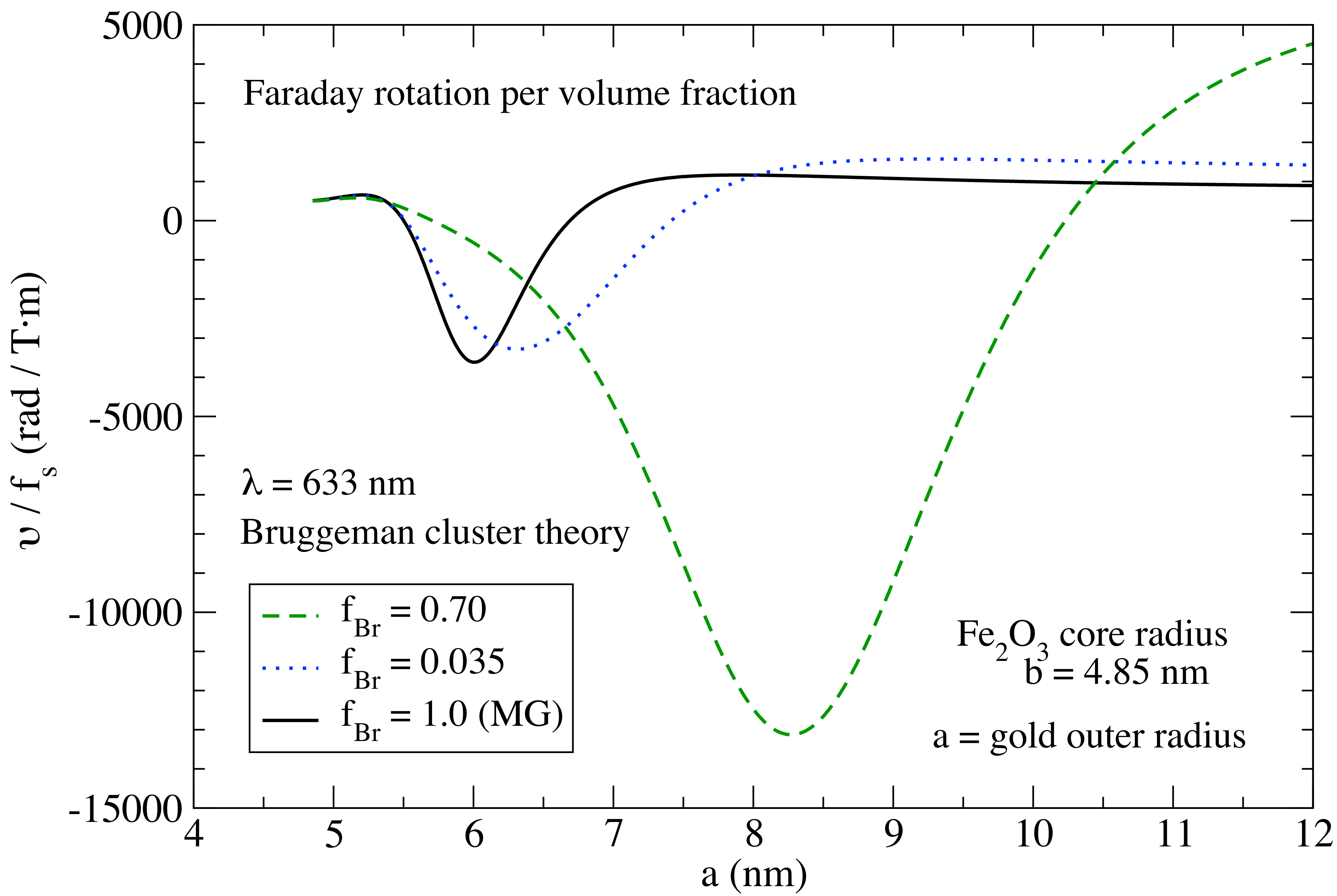


Faraday rotation
(Verdet constant)



core/shell nanoparticles

Faraday rotation divided by volume fraction of NPs



shell outer radius

Viktor's core/shell particles, at λ=632 nm

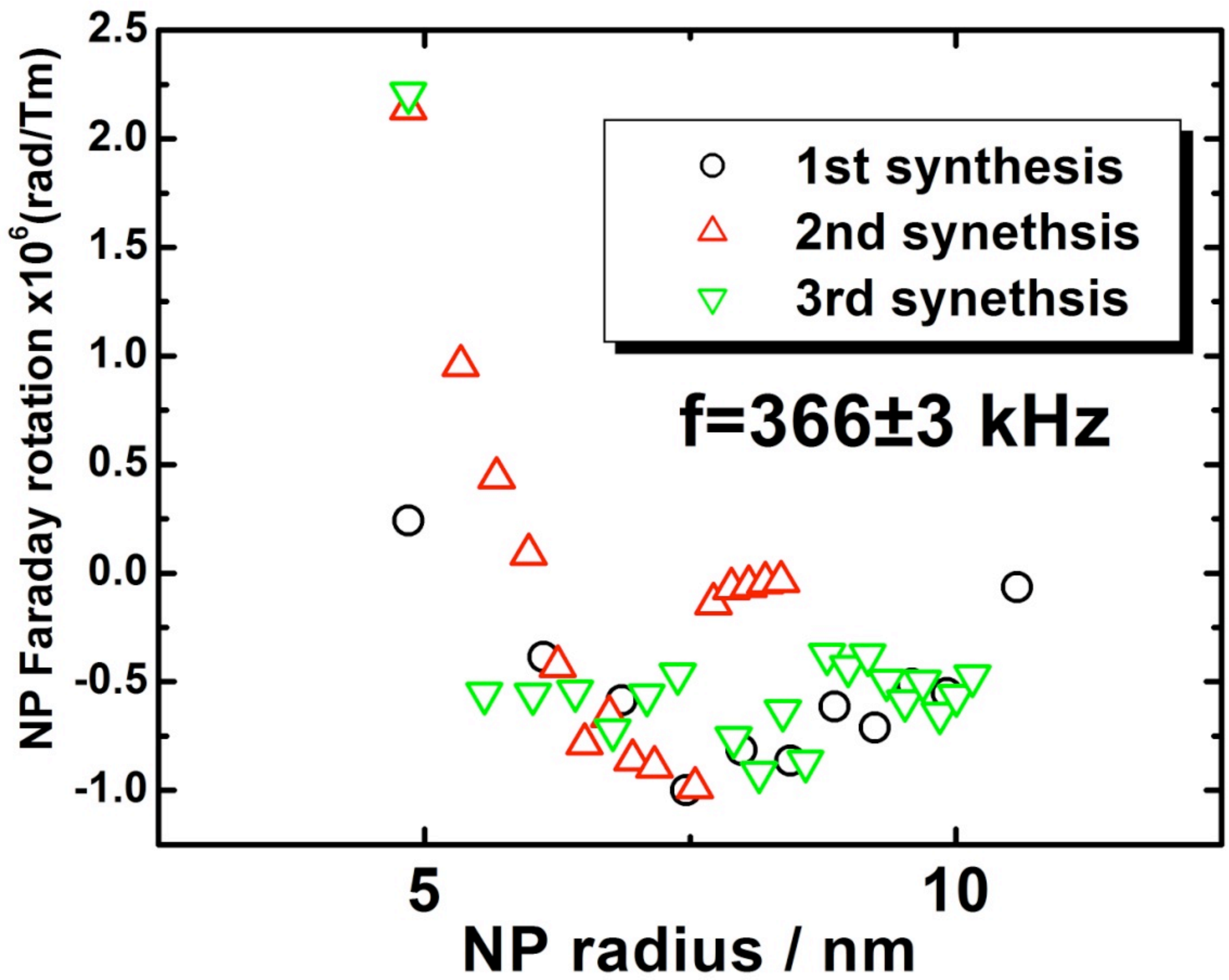


Figure 4 (b) Experimental Verdet constant of gold coated Fe_2O_3 nanoparticles only (normalized by the volume fraction of the particles) as a function of gold shell thickness

Summary

- A model for $\epsilon(\omega)$ was developed to calculate Faraday rotation in core/shell NPs.
- The gold shell has a plasmonic resonance that depends on thickness.
- Absorption and Faraday rotation are driven by this resonance.
- Clustering of particles needs to be accounted for.