Higher-order resonances in single-arm nanoantennas: Evidence of Fano-like interference

FANO PLASMONICS MADE SIMPLE

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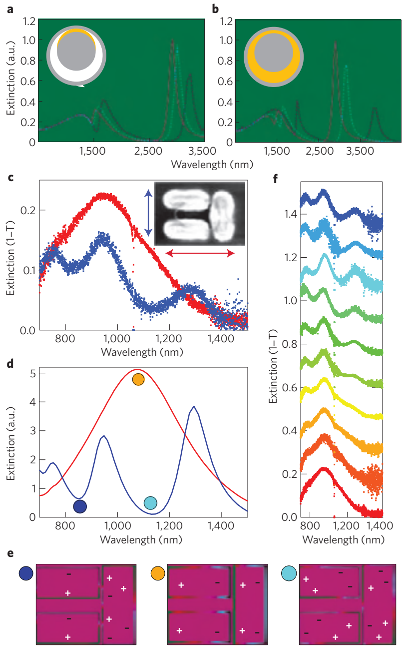
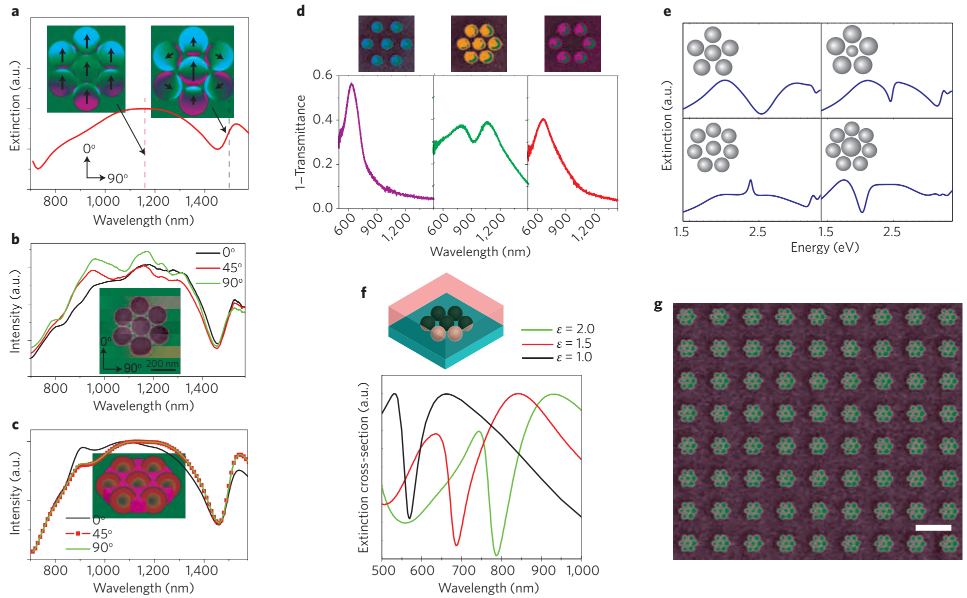
Motivation: Fano in Plasmonics

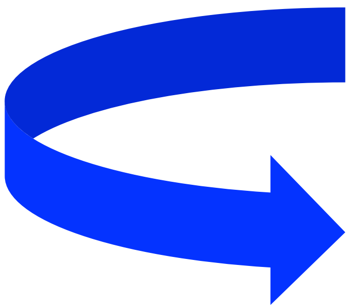
Fano-like plasmon resonances on a variety of complex nanostructures

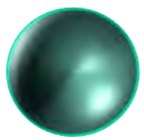


Nano-disk-rings,
nanodolmens,
nanoclusters,...



Luk'yanchuk, Zheludev, Maier, Halas, Nordlander, Giessen, Chong, Nat. Mater. 2010



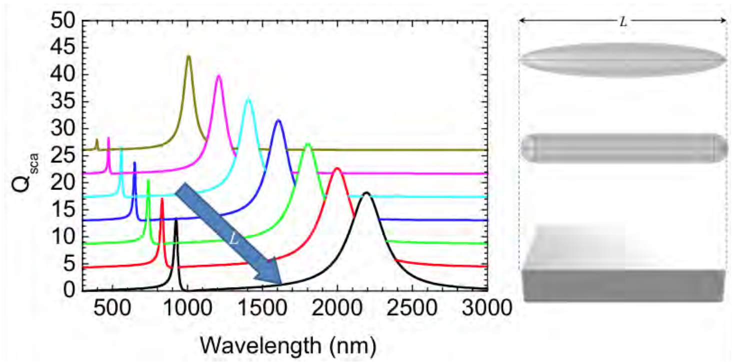


??

(Q_{sca}) SINGLE NANOPARTICLES

Outline

- Introduction: Plasmon Fano reso/single-NP
- Nano-Spheroid
  - Quasi-analytical approach: Mode interference
- Nano-rods & nano-wires
  - Numerical calcs
  - 1st-3rd mode: Spatial interference
- Conclusions:
  Spectral & spatial overlap



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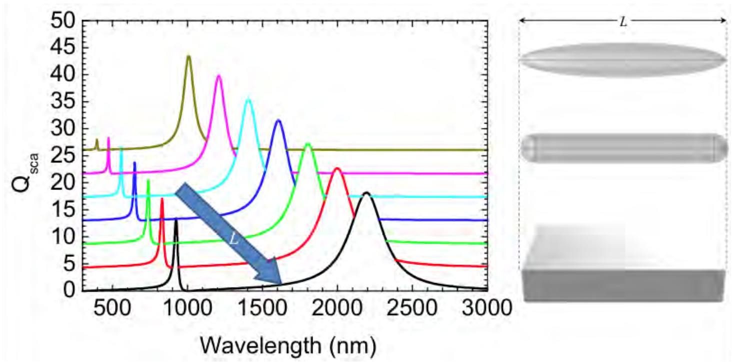


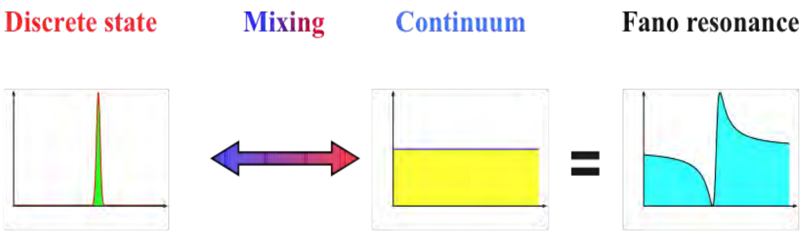
Introduction: Fano resonances

*A **Fano resonance** exhibits a distinctly asymmetric shape with the following functional form:*

$$\frac{(F\gamma + \omega - \omega_0)^2}{(\omega - \omega_0)^2 + \gamma^2}$$

where ω_0 and γ are standard parameters that denote the position and width of the resonance, respectively; F is the so-called Fano parameter, which describes the degree of asymmetry. The microscopic origin of the Fano resonance arises from the constructive and destructive interference of a narrow discrete resonance with a broad spectral line or continuum.

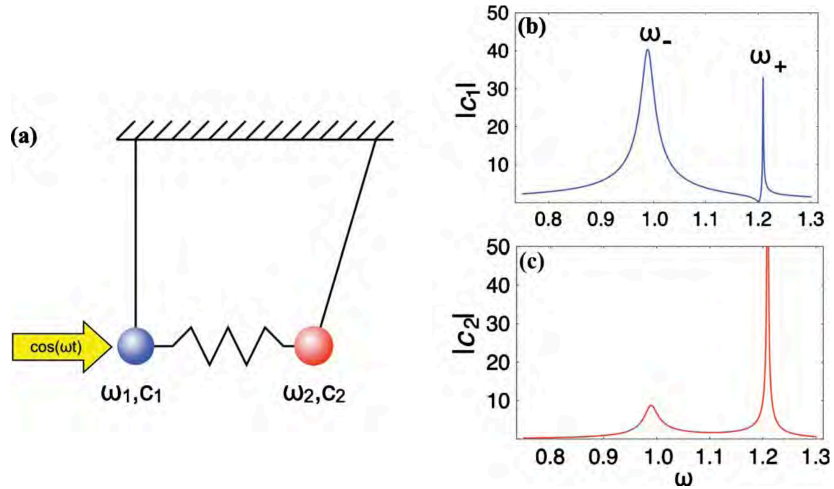
QUANTUM



$$\frac{q^2-1}{\epsilon^2+1} + \frac{2q\epsilon}{\epsilon^2+1} + 1 = \frac{(\epsilon+q)^2}{\epsilon^2+1}$$

Fano, "Effects of configuration interaction on intensities and phase shifts", Phys. Rev. 1961.

CLASSICAL

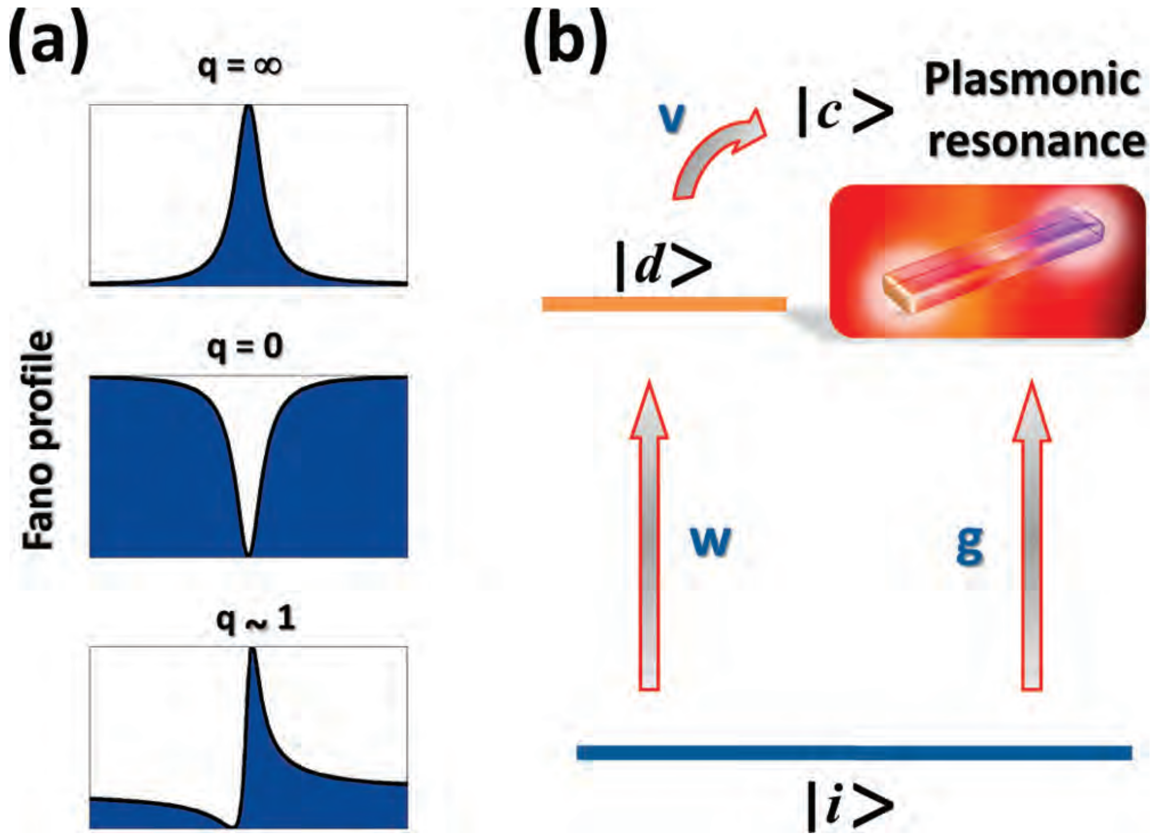


Joe, Satanin, and Kim, "Classical analogy of Fano resonances," Phys. Scr. 2006.

Miroshnichenko, Flach, Kivshar, Rev. Mod. Phys. 2010

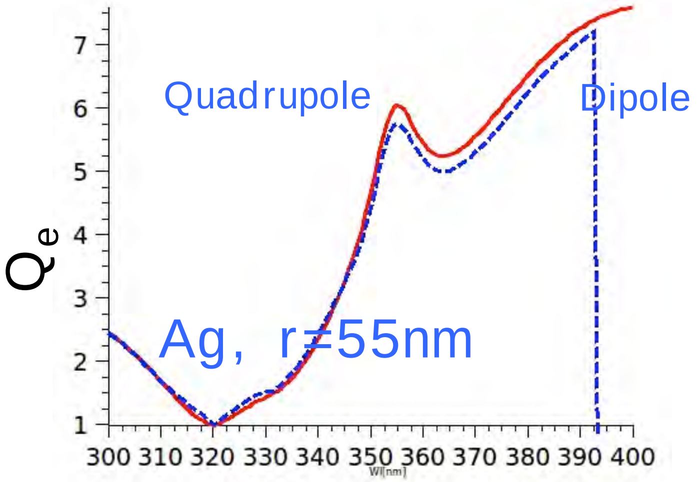
Plasmon-Fano model

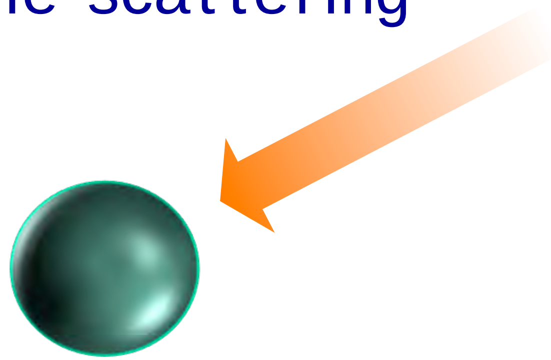
Giannini, Francescato, Amrania, Phillips, Maier, Nano Lett. 2011



Introduction: Fano resonances

PLASMONICS: SPHERE ➔Mie scattering

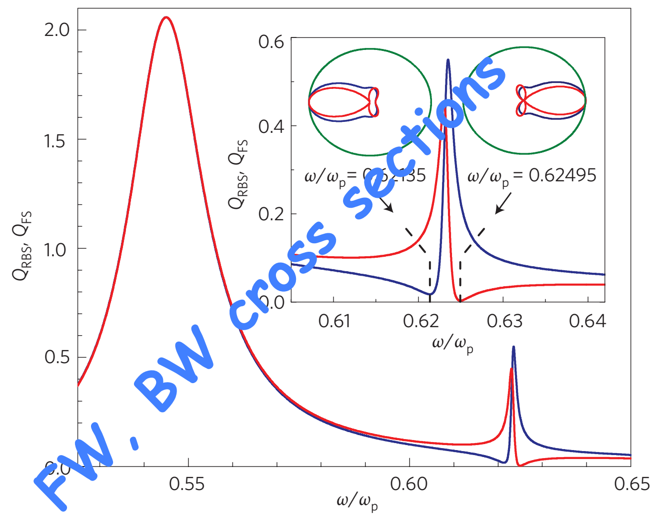




BROAD mode (Lowest-order, E-Dipole)
DARK mode (Higher-order, EM Multipole)

$$Q_{sca} = \frac{2}{q^2} \sum_n (2n+1) \boxed{|a_n|^2} + \boxed{|b_n|^2}$$

Q_{sca} Mie ➔NO INTERFERENCE!!



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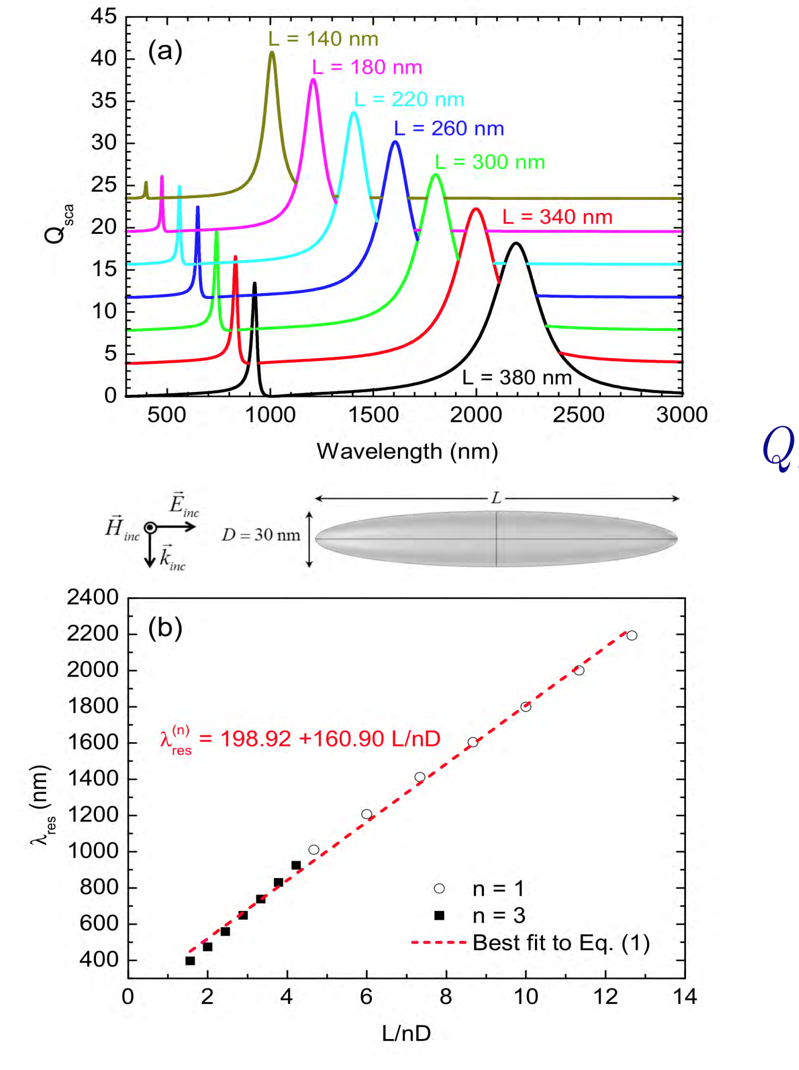
Fano LSPR/Nanospheroid

Longitudinal plasmon resonances

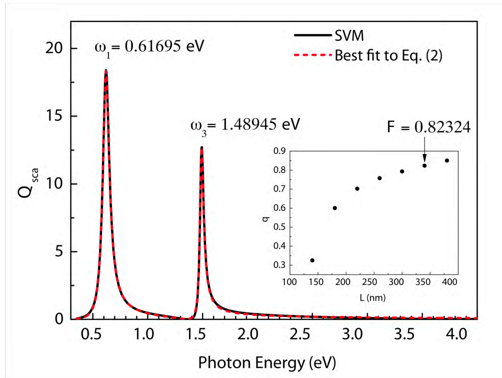
Normal incidence: odd-symmetry modes

Separation of variables (SVM)



Modified Fano line shape

$$Q_{sca}(\omega) \propto \left| A(\omega) + B\left[\frac{b_1}{(\omega-\omega_1)+ib_1} + \frac{Fb_3}{(\omega-\omega_3)+ib_3}\right]\right|^2$$



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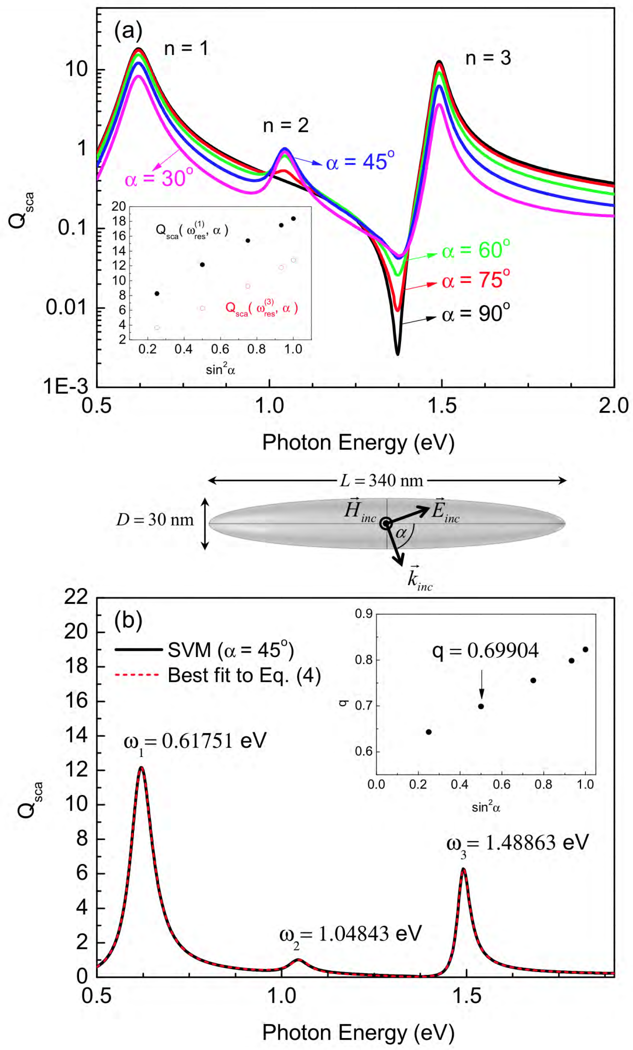
Longitudinal plasmon resonances

Oblique incidence: all modes n=1,2,3,...

SVM



Fano line-shape + Lorentzian

N=1,3 + N=2

$$Q_{sca}(\omega,\alpha \neq 90^{o}) \approx |f(\omega)|^2 + \frac{|B_2|^2 b_2^2}{b_2^2 + (\omega - \omega_2)^2}$$

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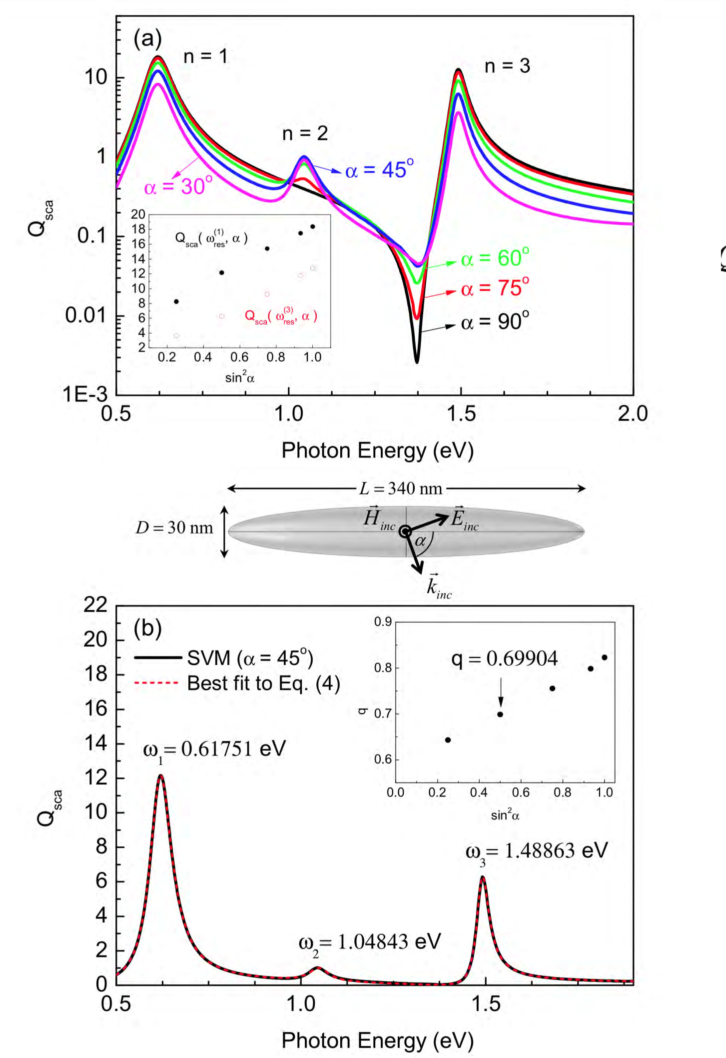
Longitudinal plasmon resonances

Oblique incidence: all modes n=1,2,3,...



Separation of variables (SVM)~Extended Mie

$$
\mathcal{Q}_{sca} = \frac{4}{LDk_d^2}\Bigg\{ 2\sum_{l=1}^{\infty} \boxed{|b_l^{(1)}|^2} N_{1l}^2(c_d) + \mathrm{Re}\sum_{l=1}^{\infty}\sum_{m=l}^{\infty}\sum_{n=m}^{\infty} i^{\,n-l}\Big[k_d^2 \boxed{a_{ml}^{(d)}\left(a_{mn}^{(d)}\right)^*} \omega_{ln}^{(m)}(c_d,c_d) + ik_d\left(\boxed{b_{ml}^{(d)}\left(a_{mn}^{(d)}\right)^*}\kappa_{ln}^{(m)}(c_d,c_d) - \boxed{a_{ml}^{(d)}\left(b_{mn}^{(d)}\right)^*}\kappa_{nl}^{(m)}(c_d,c_d)\right) + \boxed{b_{ml}^{(d)}\left(b_{mn}^{(d)}\right)^*}\tau_{ln}^{(m)}(c_d,c_d)\Big] N_{ml}(c_d)N_{mn}(c_d)\Bigg\}
$$

Mie-like: NO INTERFERENCE

Ext-Mie: INTERFERENCE

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Fano resonances/Nanospheroid

- Plasmon Fano reso/single-Nano-Spheroids
- Quasi-analytical approach: Mode interference
- Odd modes: 1st-3rd interference
- Even-odd modes: 1st-2nd NO interference
- Explore other single NP geometries

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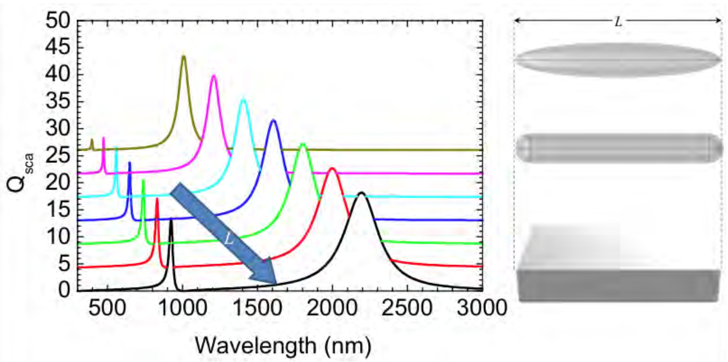
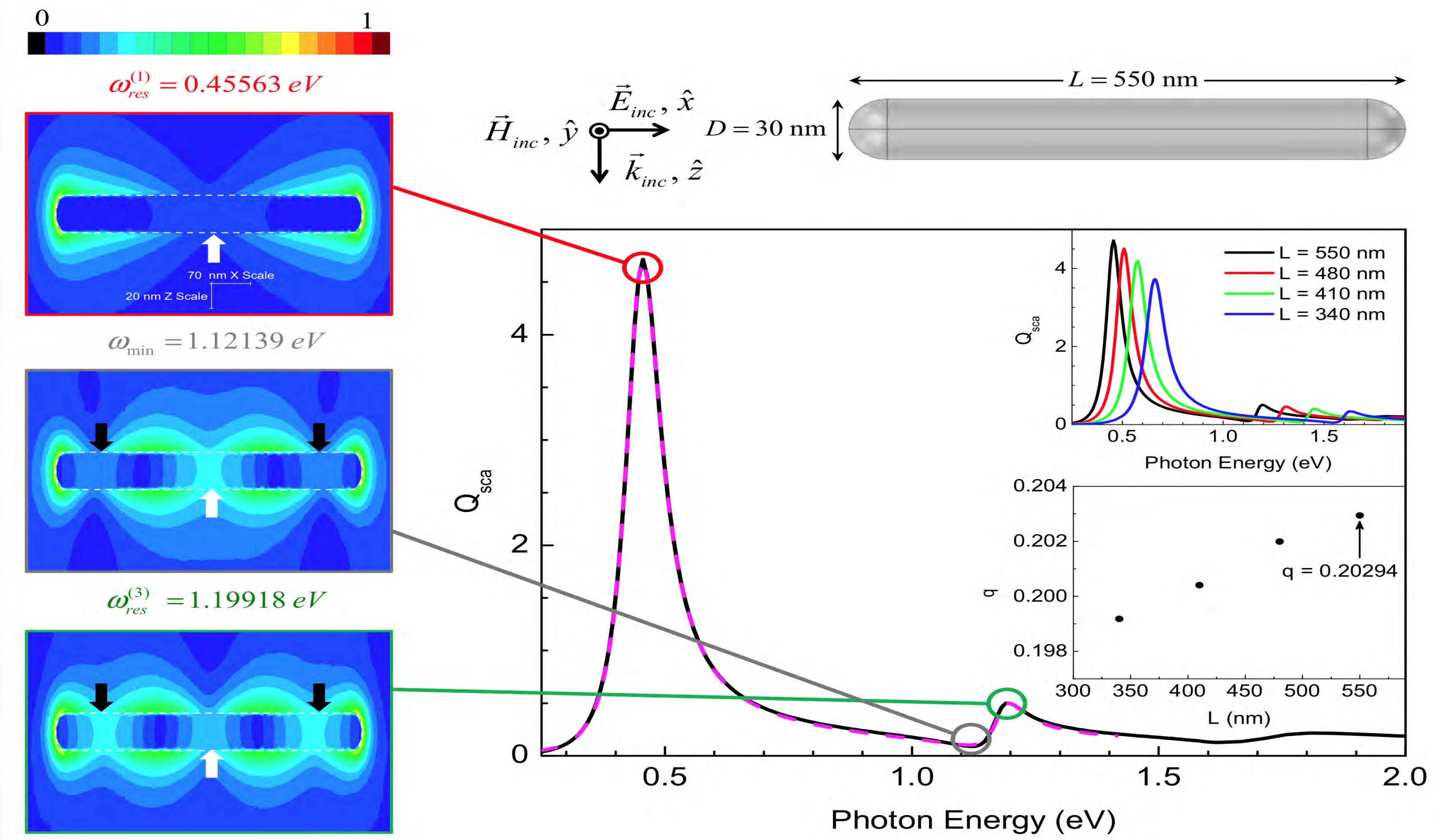


Longitudinal L~nλ/2 resonances

Oblique incidence: all modes n=1,2,3,...

FEM-COMSOL



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Nanowire (~2D Nanorods)

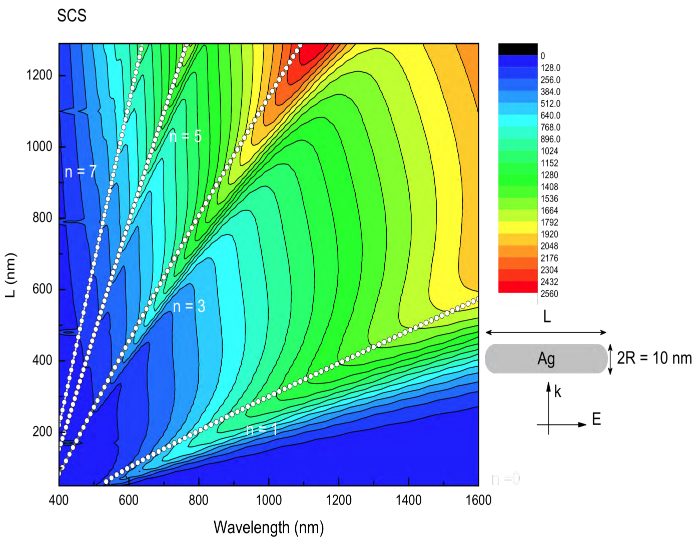
2DSIE

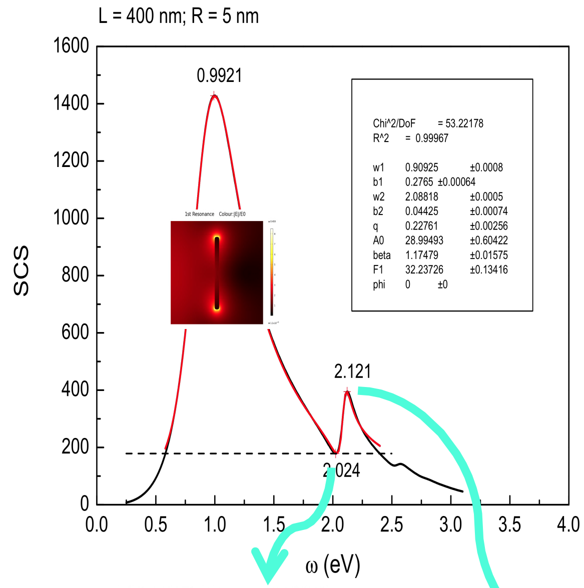
Longitudinal $L = n\lambda_{eff}/2[1-R]$ resonances

Normal incidence: odd modes

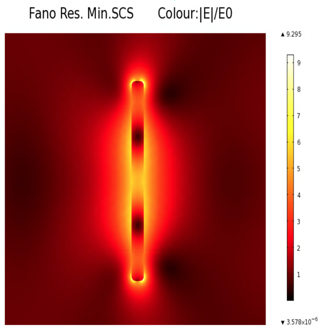
n=1 (HW) ► Broad, Bright

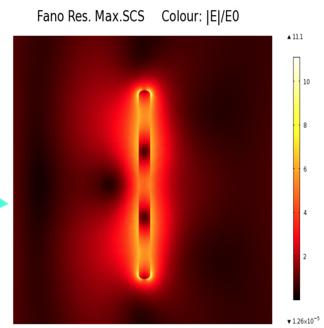
n=3,5,... (HW) ► Narrow, Dark





Modified Fano line-shape fit





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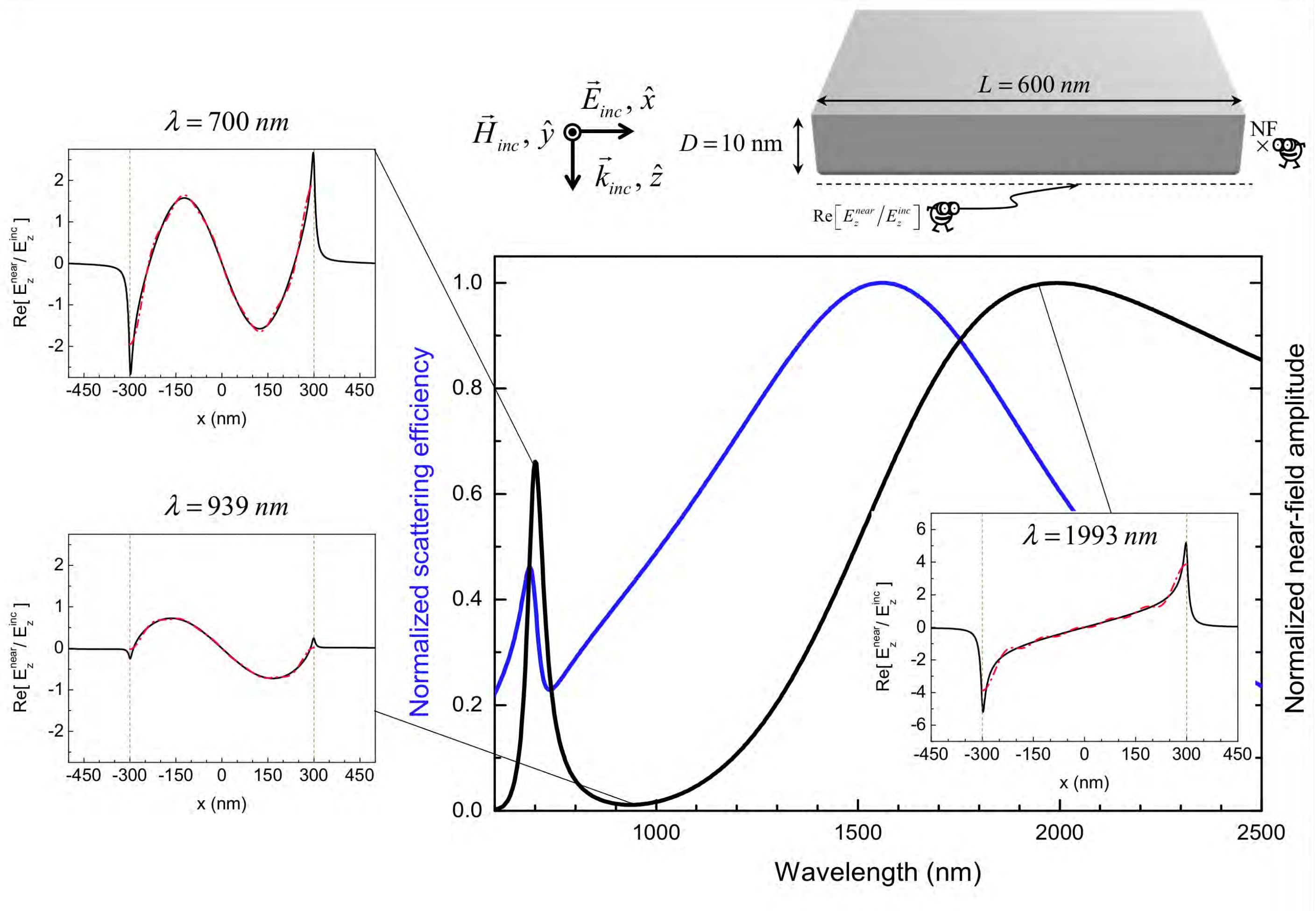
Spatial Mode Interference



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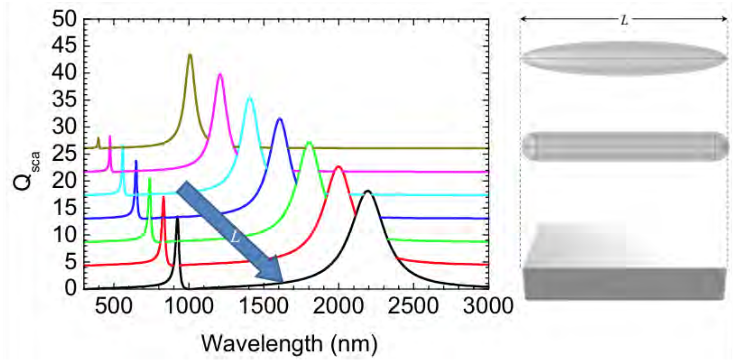
Conclusions

► Fano-like LSPR on a single nanorod

►Spectral & Spatial overlap



Explore new physics & configurations

► Applications: Fano made simple!!

Plasmonics,

Nanophotonics,
Metamaterials,

...EM

Sensing, lasing, switching, NL optics,…

Acknowledgements

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…Thank you