

Optical magnetism in core-satellite nanostructures excited by vector beams

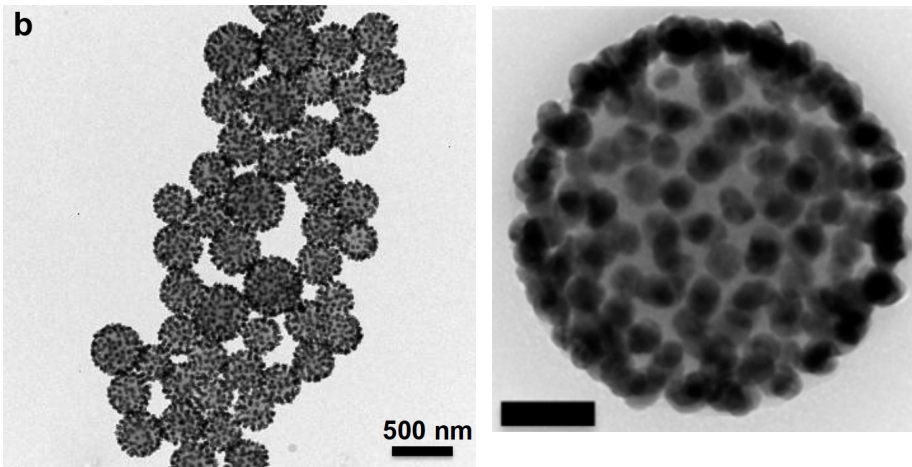
John Parker¹, Stephen Gray², Norbert Scherer¹

¹Scherer Lab, The University of Chicago, James Franck Institute & Department of Physics

²Center for Nanoscale Materials, Argonne National Laboratory



Core-satellite nanostructures



- SiO₂ dielectric core decorated with 40nm silver nanoparticles
- Isotropic, angle independent scattering properties
- Near-field coupling among nanoparticles
- Random or ordered packing

Minimize potential with gradient descent:

$$U(\theta_i, \phi_i) = \sum_{i < j} \sum_{j=1}^{N_p} \frac{1}{d_{ij}}$$

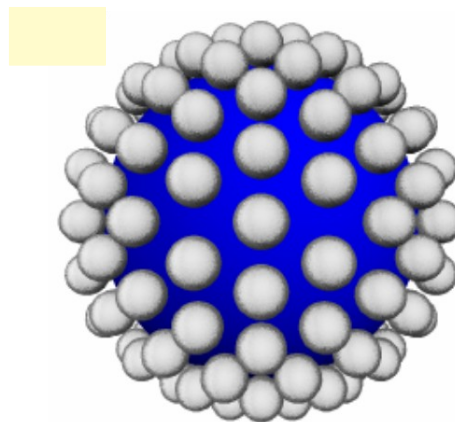
Random positions:

$$\phi = U[0, 2\pi]$$

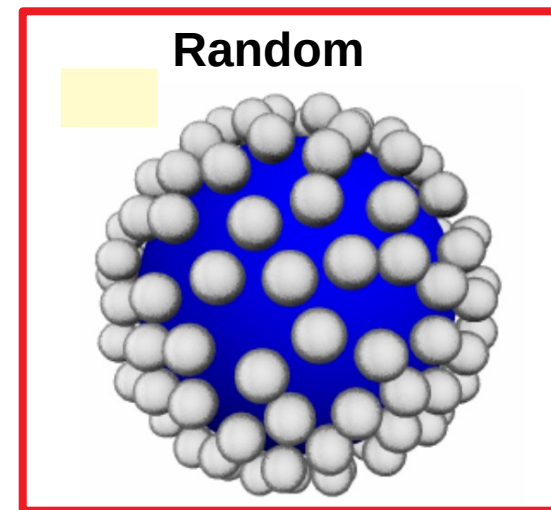
$$\theta = \cos^{-1}(U[0, 1])$$

Prevent nanoparticle overlap

Ordered



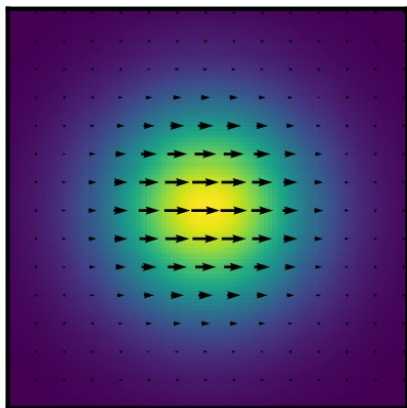
Random



Vector beam sources from the Hermite-Gaussian modes

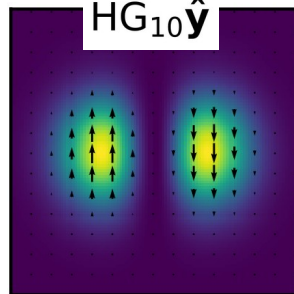
Linear
beam

$HG_{00}\hat{x}$

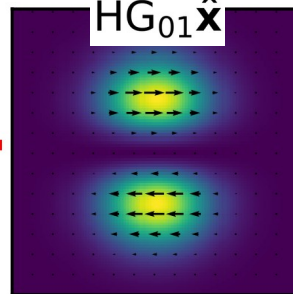


Azimuthal
beam

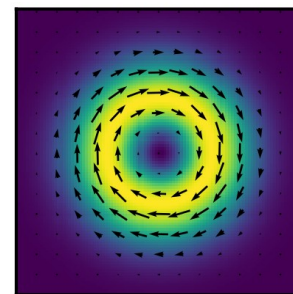
$HG_{10}\hat{y}$



$HG_{01}\hat{x}$

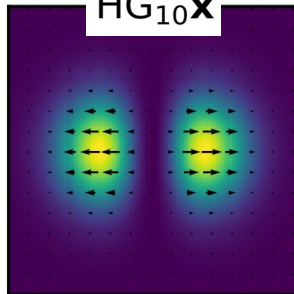


+

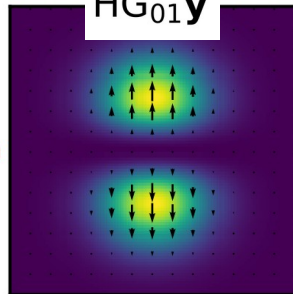


Radial
beam

$HG_{10}\hat{x}$

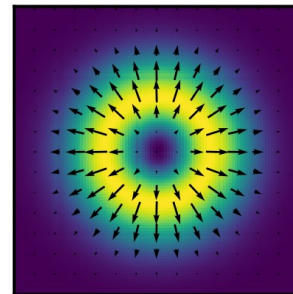


$HG_{01}\hat{y}$



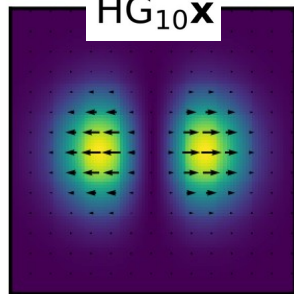
+

=

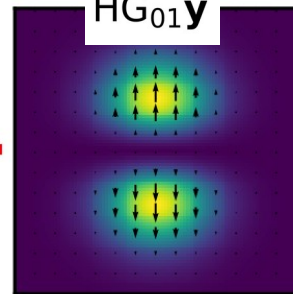


Shear
beam

$HG_{10}\hat{x}$

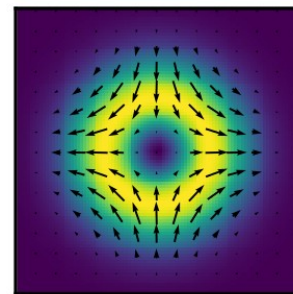


$HG_{01}\hat{y}$



-

=



Multipolar scattering theory

Expansion of the scattered field into vector spherical harmonics (VSH)

$$\mathbf{E}_{\text{scat}}(\omega, r, \theta, \phi) = \sum_{l=1}^{\infty} \sum_{m=-l}^{m=l} a_{lm}(\omega) \mathbf{N}_{lm} + b_{lm}(\omega) \mathbf{M}_{lm}$$

Multipolar decomposition using orthogonality of VSHs

$$\begin{aligned} \oint_{\Omega} \mathbf{N}_{lm} \cdot \mathbf{N}_{l'm'} d\Omega &= \delta_{ll'} \delta_{mm'} \\ \oint_{\Omega} \mathbf{M}_{lm} \cdot \mathbf{M}_{l'm'} d\Omega &= \delta_{ll'} \delta_{mm'} \\ \oint_{\Omega} \mathbf{N}_{lm} \cdot \mathbf{M}_{lm} d\Omega &= 0 \end{aligned} \quad \longrightarrow \quad \begin{aligned} a_{lm}(\omega) &= \oint_{\Omega} \mathbf{E}_{\text{scat}}(\omega, r = r_0, \theta, \phi) \cdot \mathbf{N}_{lm}(\omega, r = r_0, \theta, \phi) d\Omega \\ b_{lm}(\omega) &= \oint_{\Omega} \mathbf{E}_{\text{scat}}(\omega, r = r_0, \theta, \phi) \cdot \mathbf{M}_{lm}(\omega, r = r_0, \theta, \phi) d\Omega \end{aligned}$$

Scattering cross-section per multipolar mode

$$\sigma_{\text{scat}}(\omega) = k^2 \sum_{l=1}^{\infty} \sum_{m=-n}^n l(l+1) (|a_{lm}(\omega)|^2 + |b_{lm}(\omega)|^2)$$

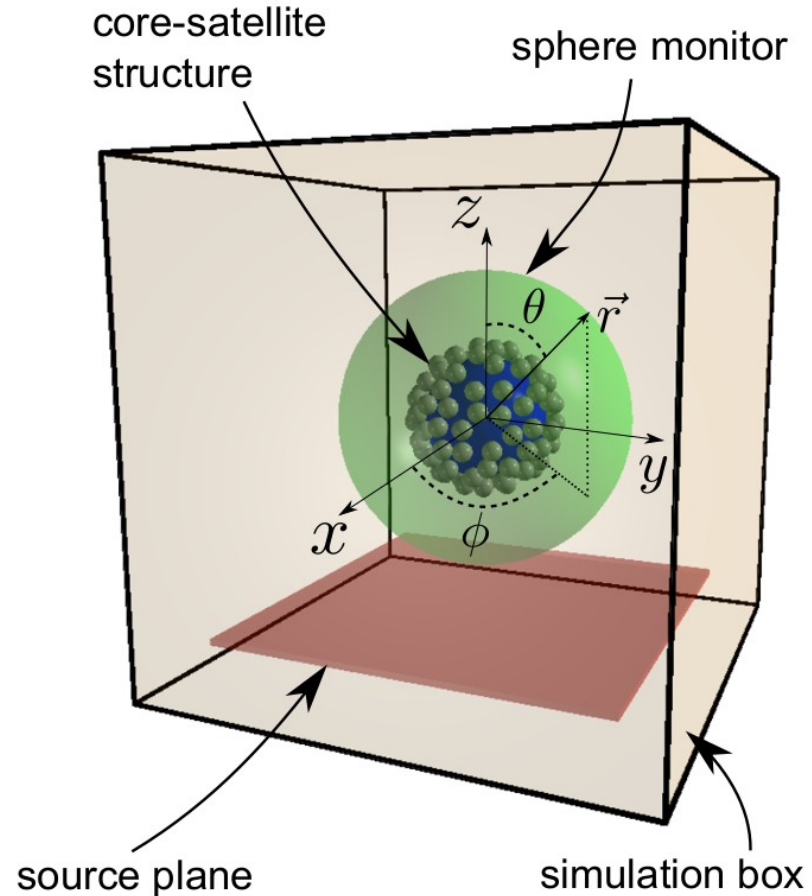
Simulation Setup

Finite-Difference Time-Domain method (FDTD) used to compute:

- Scattering cross-section
- Field enhancement
- Displacement currents

Sphere monitor collects scattered fields to measure:

- Angular scattering cross-section
- Multipolar scattering
- Multipolar interference effects



Field enhancement and displacement currents



Field enhancement and displacement currents

An electromotive force (EMF) drives the displacement currents

$$\text{EMF} = \oint_{\Omega} \mathbf{E}_{\text{inc}} \cdot d\mathbf{l}$$

Linear beam

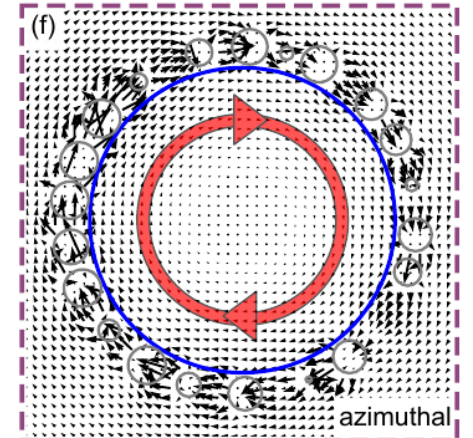
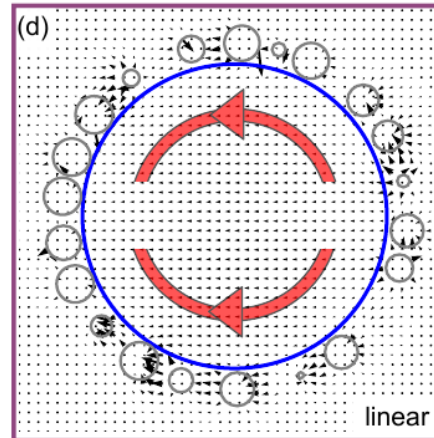
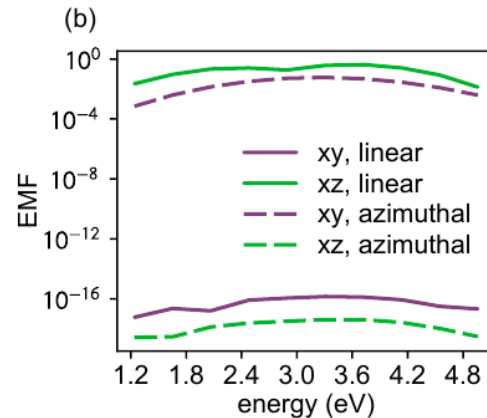
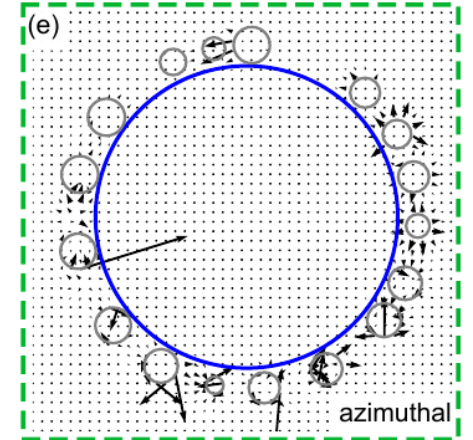
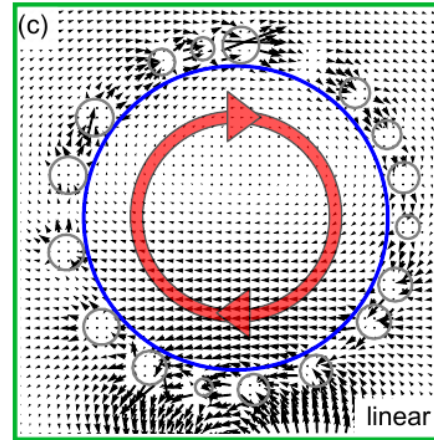
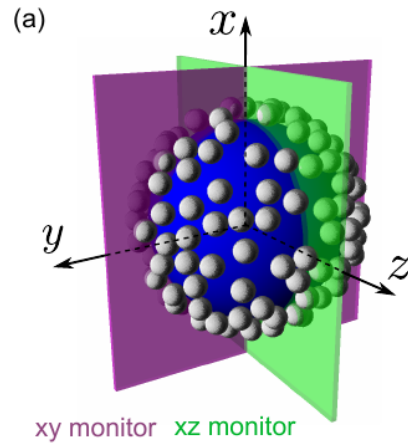
EMF in xz plane

Azimuthal beam

EMF in xy plane

Radial beam

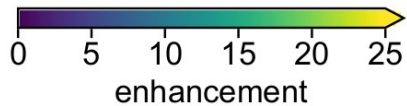
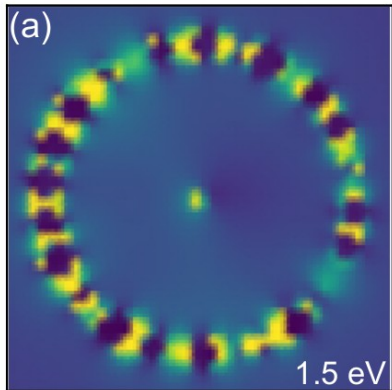
No EMF



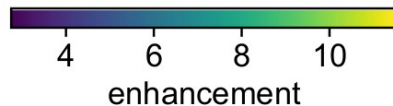
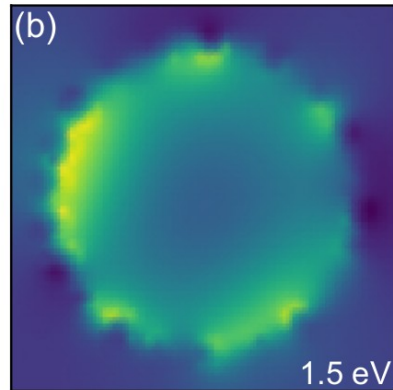
Field enhancement and displacement currents

On magnetic resonance

$$|\mathbf{E}_{\text{enh}}|^2$$

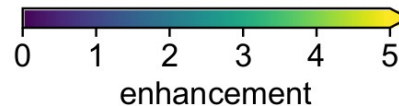
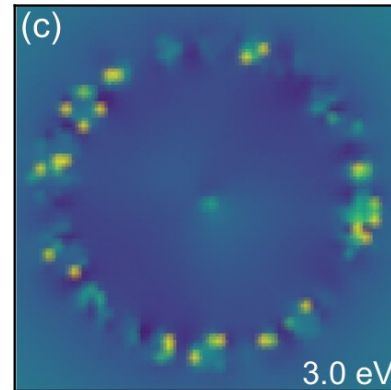


$$|\mathbf{H}_{\text{enh}}|^2$$

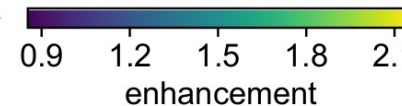
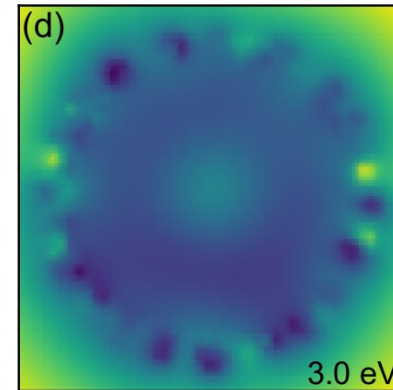


Off magnetic resonance

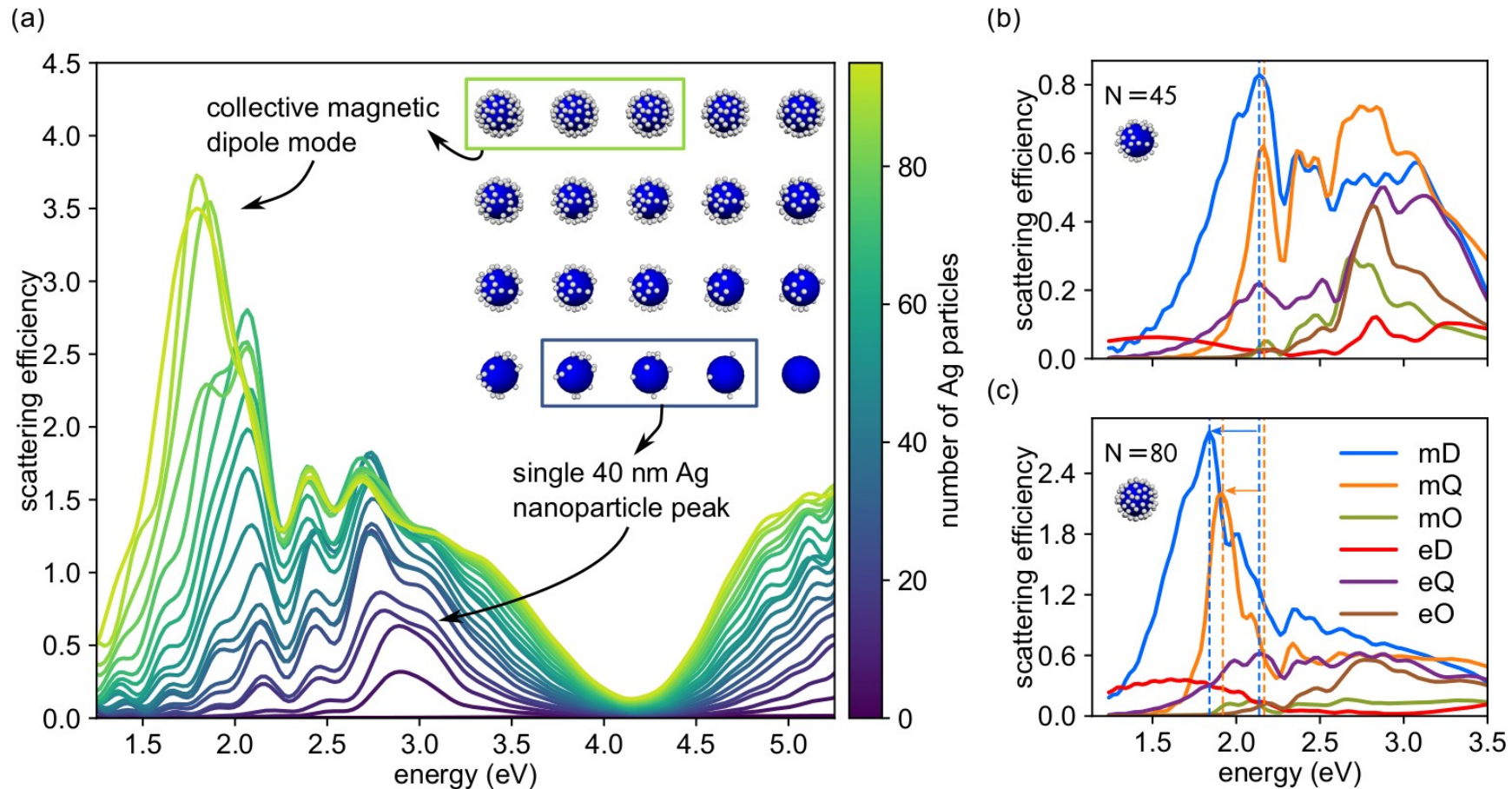
$$|\mathbf{E}_{\text{enh}}|^2$$



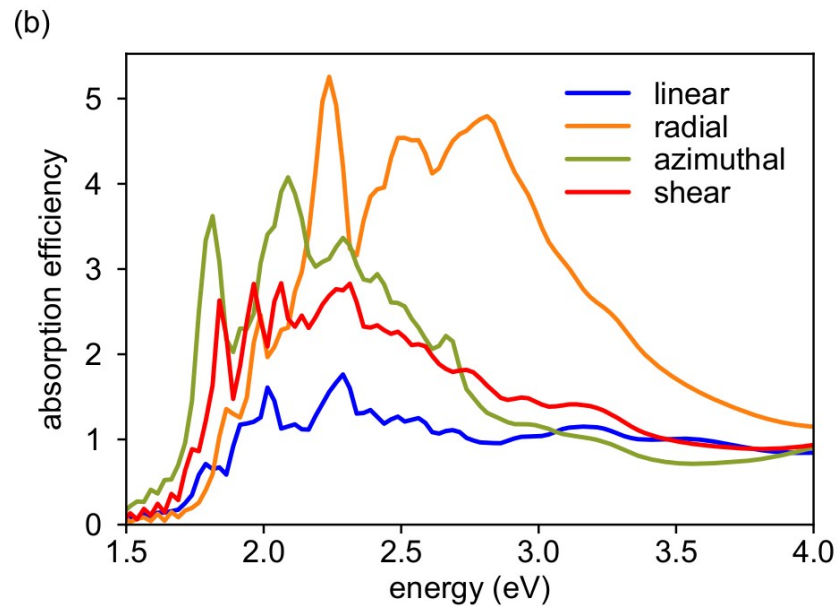
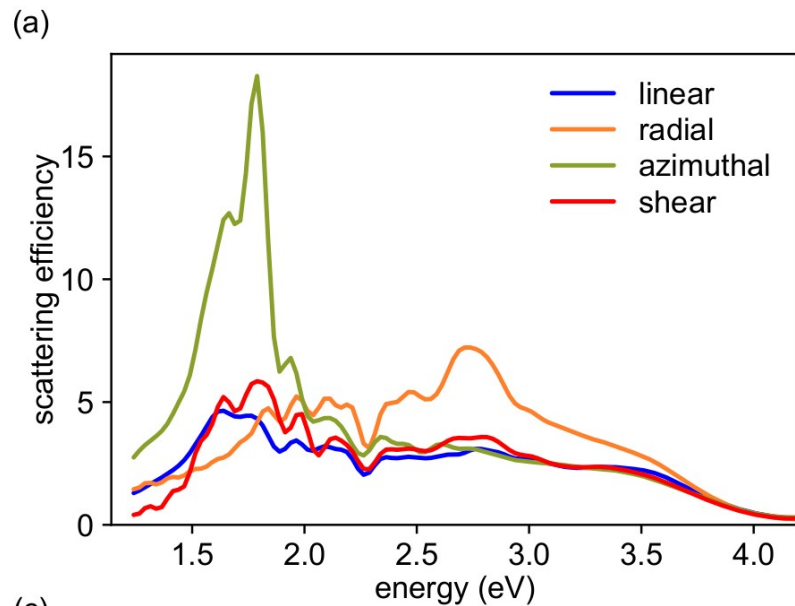
$$|\mathbf{H}_{\text{enh}}|^2$$



Identifying a collective magnetic mode: increasing the density of nanoparticles

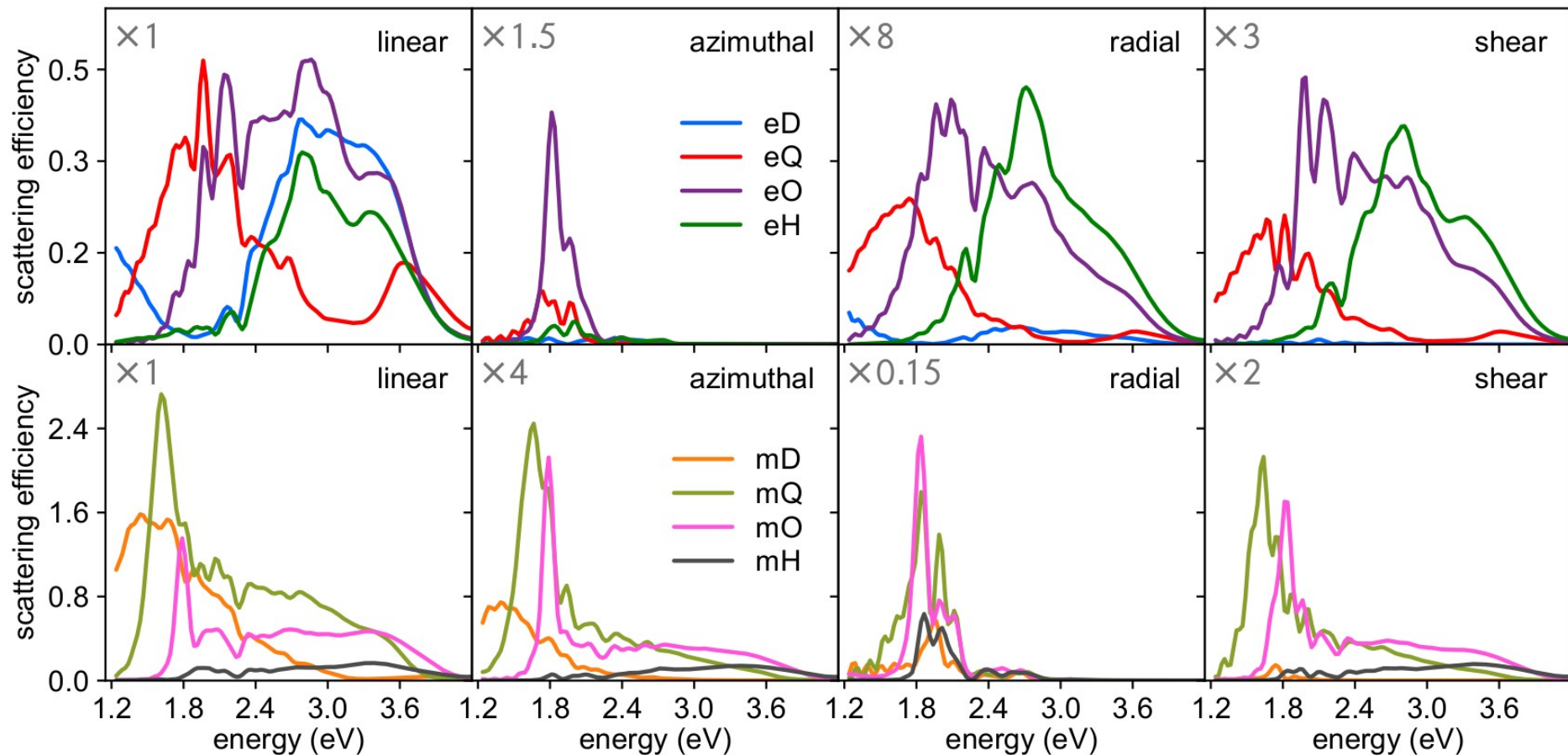


Total scattering and absorption properties



(c)

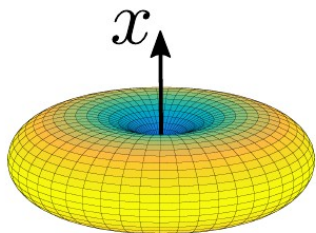
Vector beams selectively excite and enhance different multipolar modes



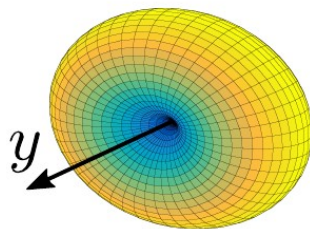
Angular scattering of multipolar modes excited by different vector beams

(b)

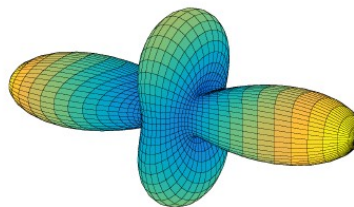
linear, eD



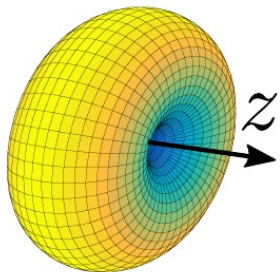
linear, mD



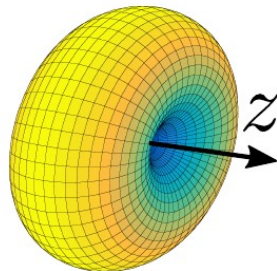
linear, mQ



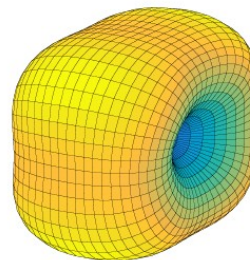
radial, eD



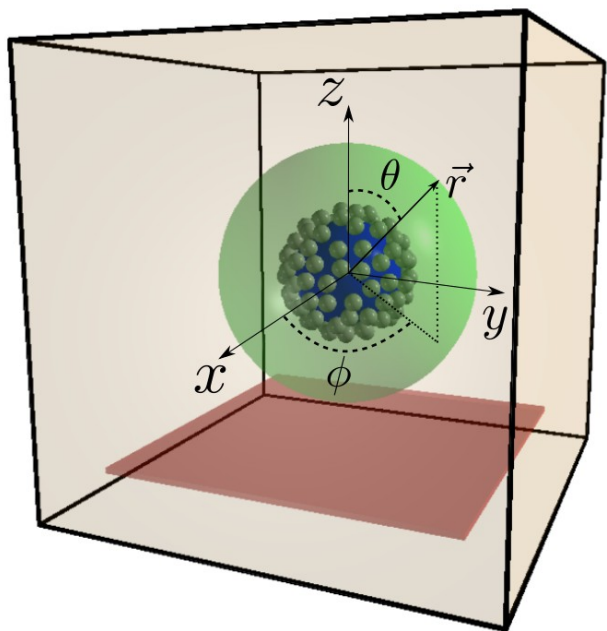
azimuthal, mD



shear, mQ

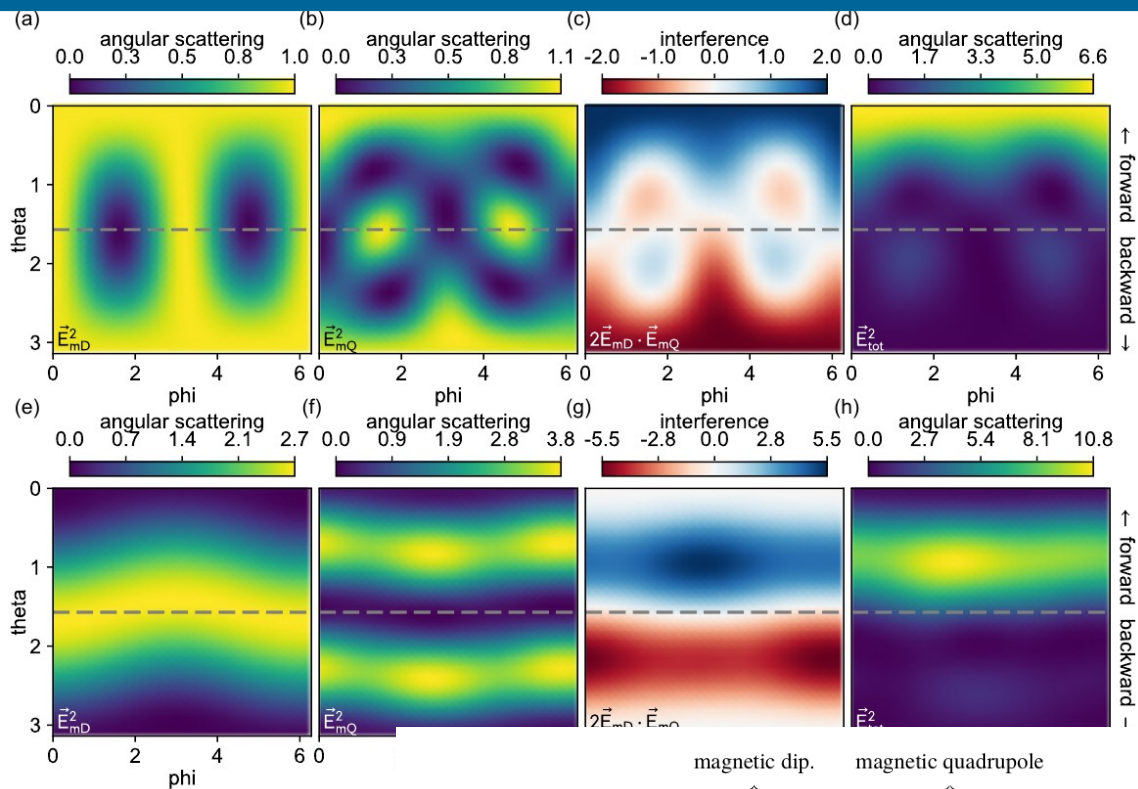


Magnetic-dipole and magnetic-quadrupole interference in the far-field



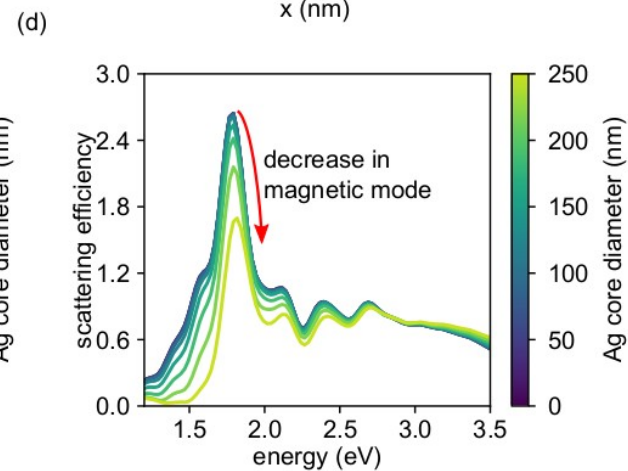
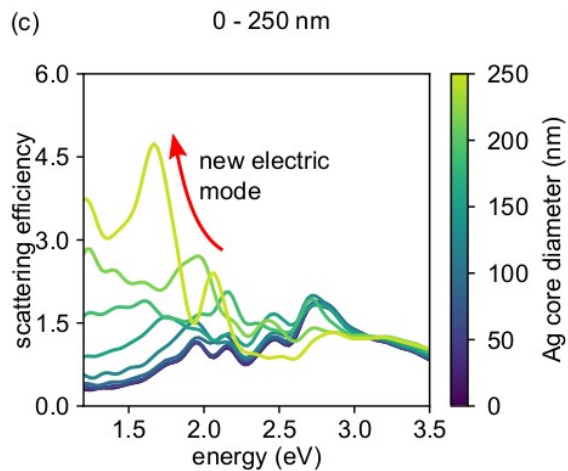
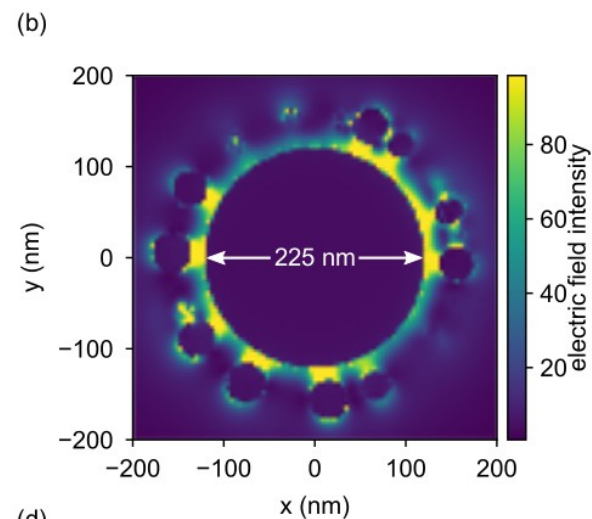
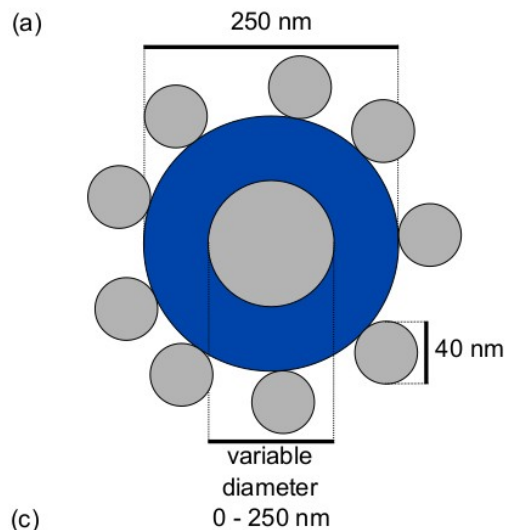
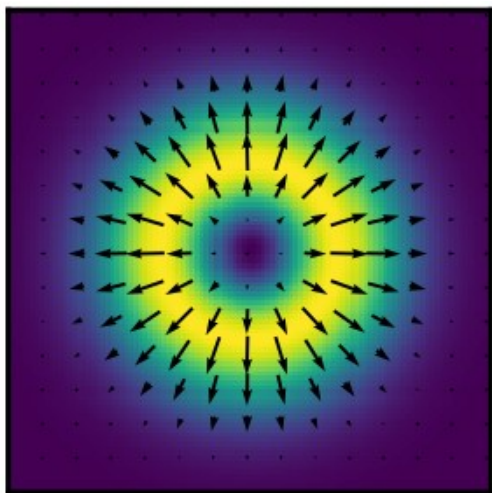
Linear beam

Azimuthal beam



$$|a\mathbf{M}_{\text{dip.}} + b\mathbf{M}_{\text{quad.}}|^2 = \underbrace{|a|^2 |\mathbf{M}_{\text{dip.}}|^2}_{\text{magnetic dip.}} + \underbrace{|b|^2 |\mathbf{M}_{\text{quad.}}|^2}_{\text{magnetic quadrupole}} + \underbrace{ab^* \mathbf{M}_{\text{dip.}} \cdot \mathbf{M}_{\text{quad.}}^* + a^* b \mathbf{M}_{\text{dip.}}^* \cdot \mathbf{M}_{\text{quad.}}}_{\text{magnetic dipole - quadrupole interference terms}}$$

Core-shell-satellite nanostucture



Core-shell-satellite nanostucture

