



Selectively inducing optical modes of nanoscale structures using vector beams in FDTD simulations

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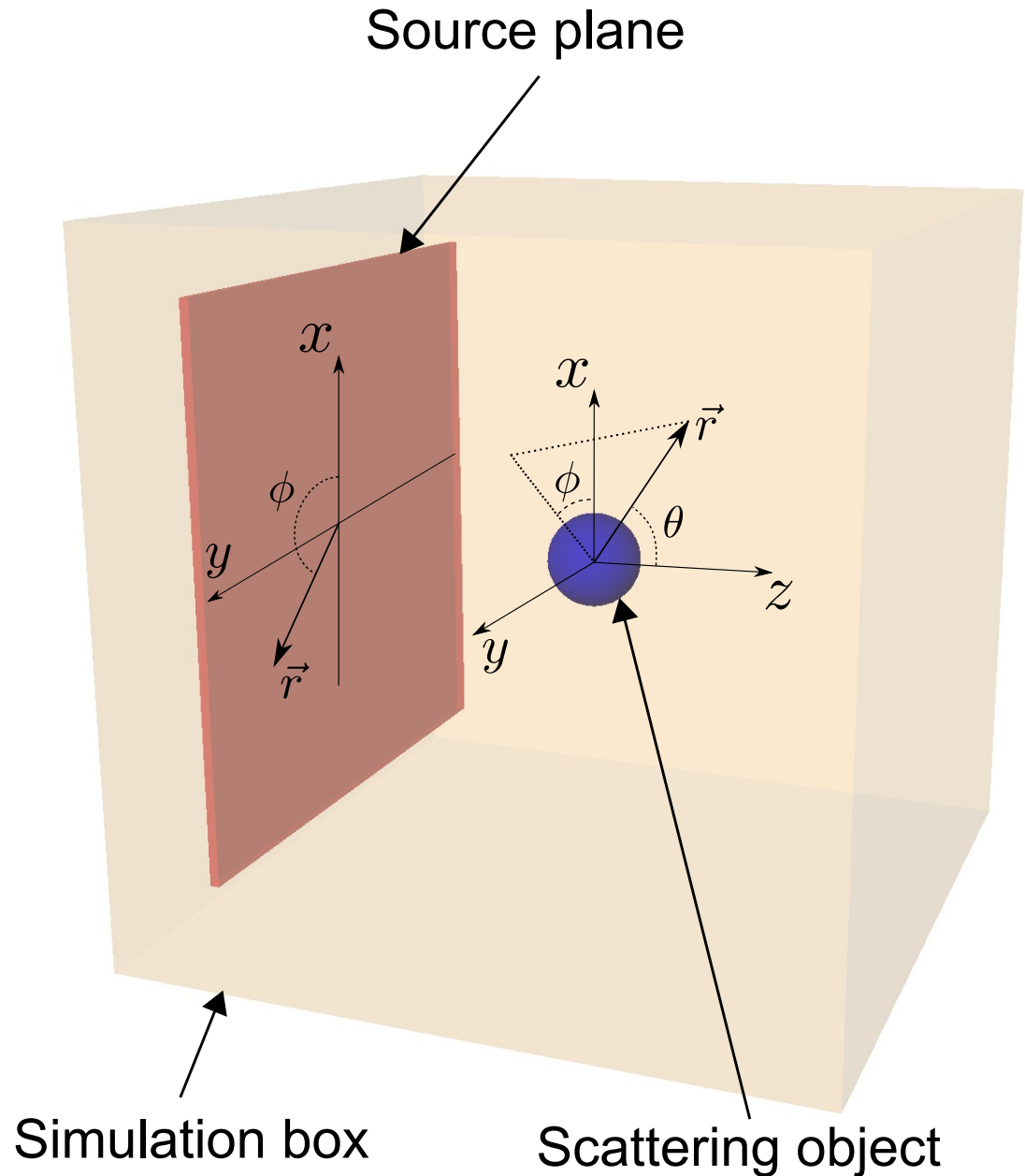
Scattering simulations in FDTD

Light source
(cylindrical coordinates)

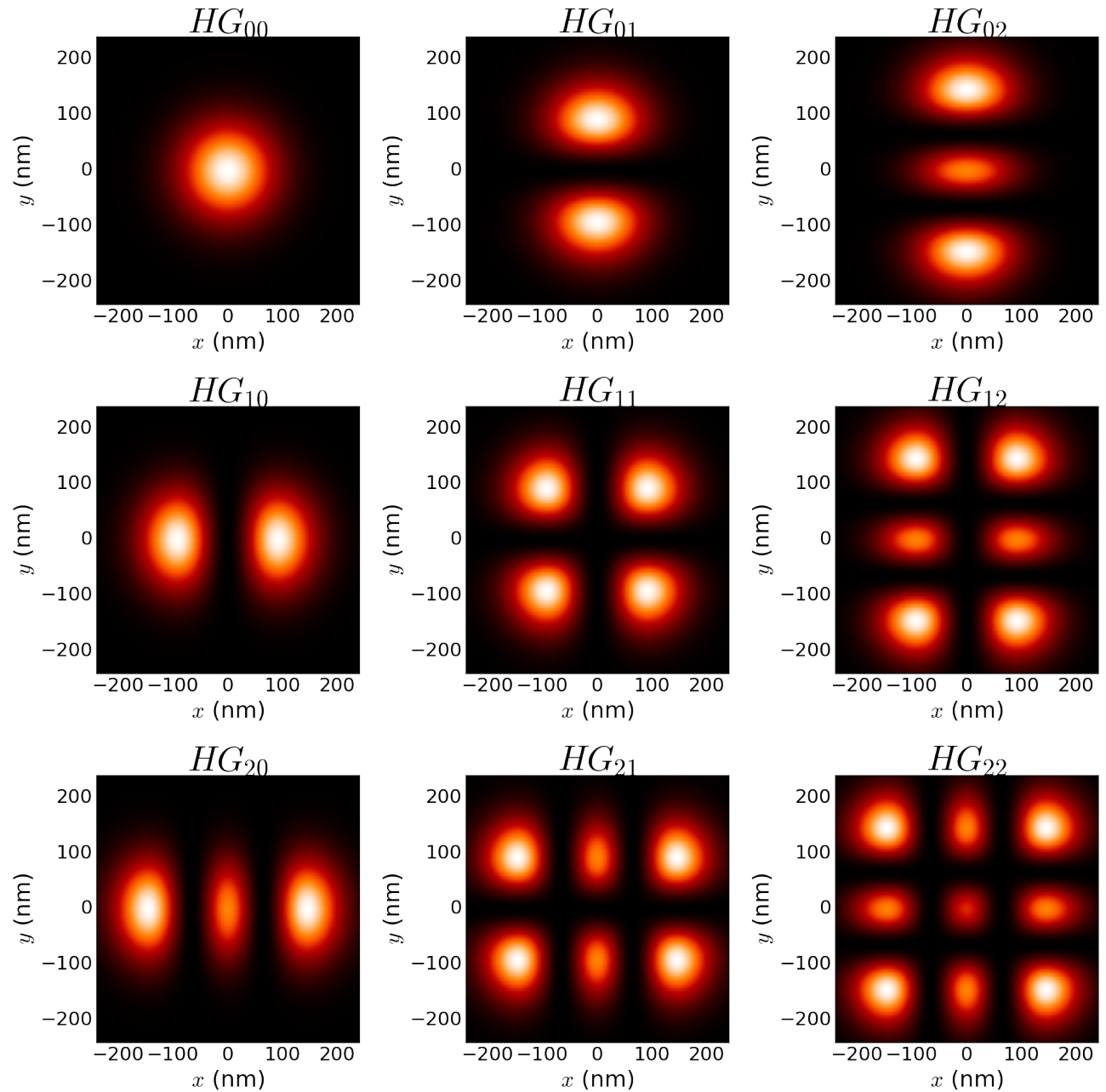
$$\mathbf{E}_{\text{inc}}(\omega, z, r, \phi)$$

Scattered light
(spherical coordinates)

$$\mathbf{E}_{\text{scat}}(\omega, r, \theta, \phi)$$



Hermite-Gaussian beams

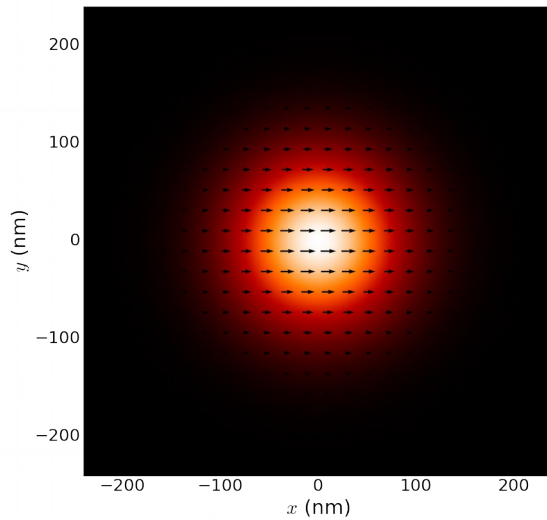


Hermite-Gaussian modes

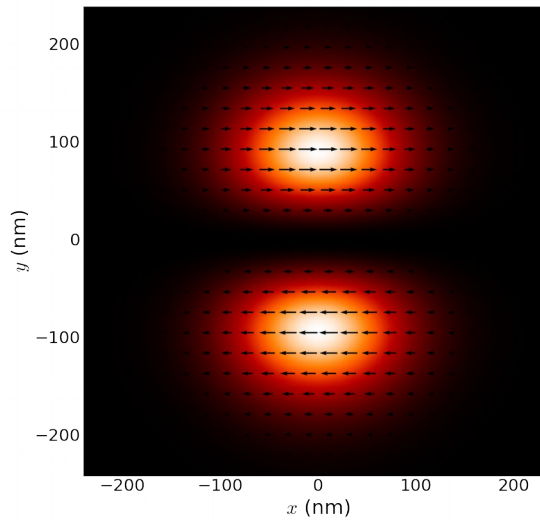
$$HG_{lm}(x, y, z = 0)$$

Hermite-Gaussian beams: polarized

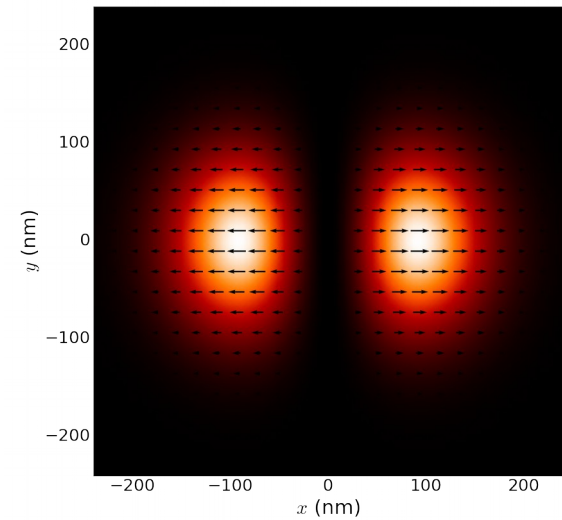
$\text{HG}_{00} \hat{x}$



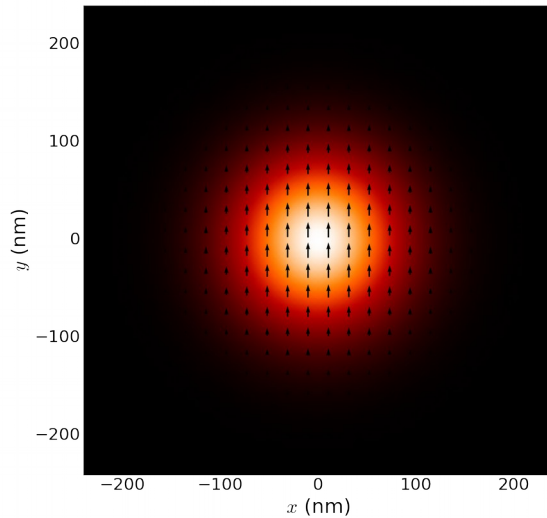
$\text{HG}_{01} \hat{x}$



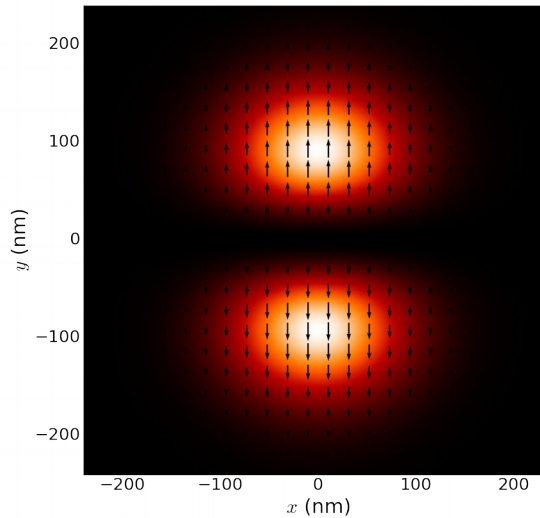
$\text{HG}_{10} \hat{x}$



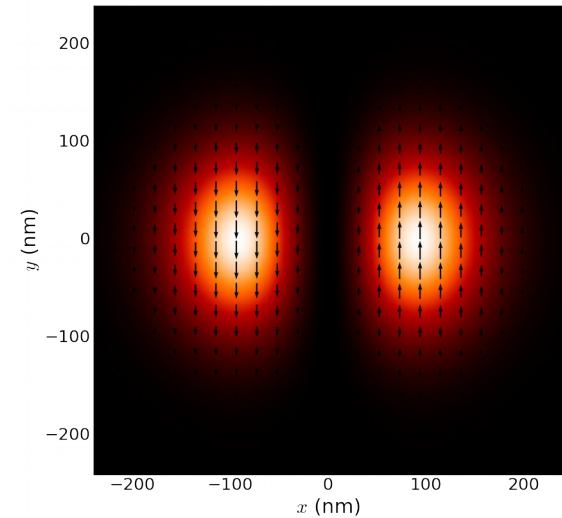
$\text{HG}_{00} \hat{y}$



$\text{HG}_{01} \hat{y}$

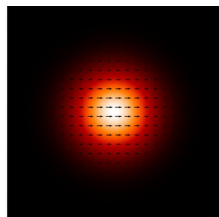


$\text{HG}_{10} \hat{y}$

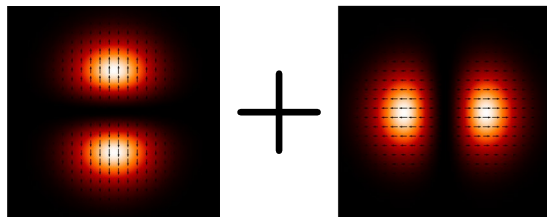


Vector beams

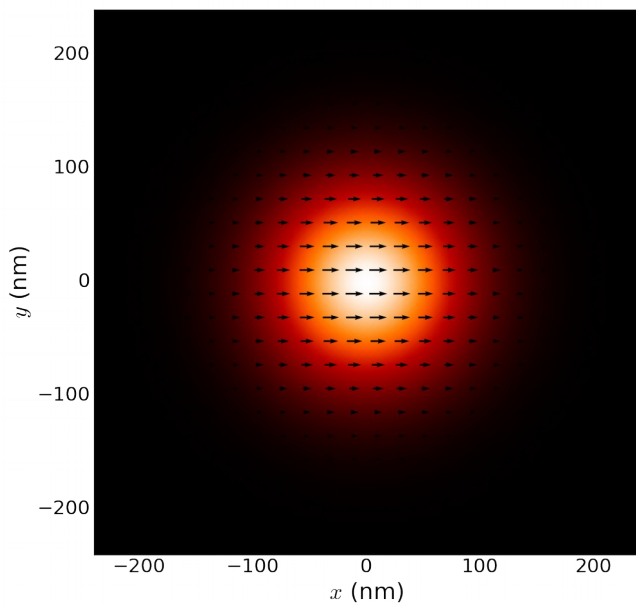
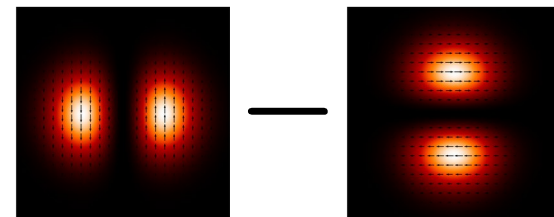
$\text{HG}_{00} \hat{x}$



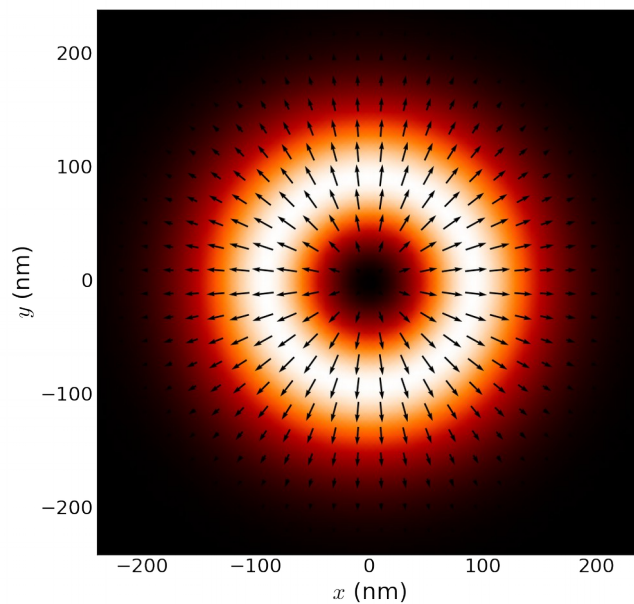
$\text{HG}_{01} \hat{y} + \text{HG}_{10} \hat{x}$



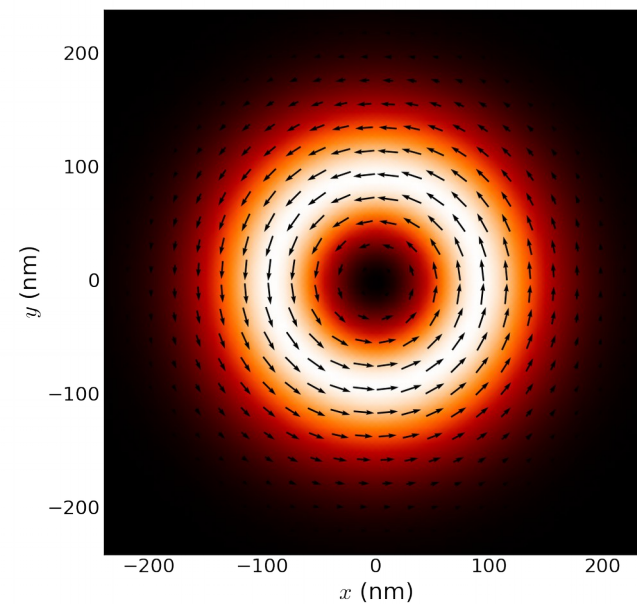
$\text{HG}_{10} \hat{y} - \text{HG}_{01} \hat{x}$



Linear



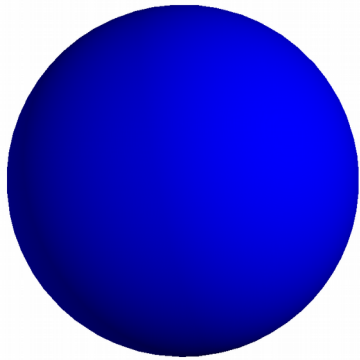
Radial



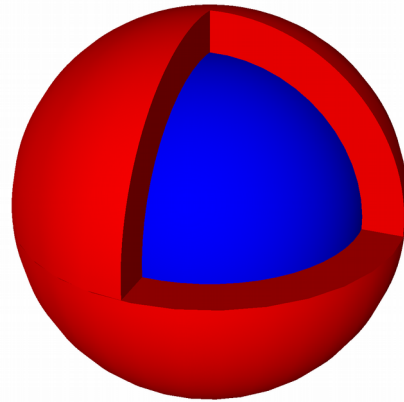
Azimuthal

Nanoscale structures

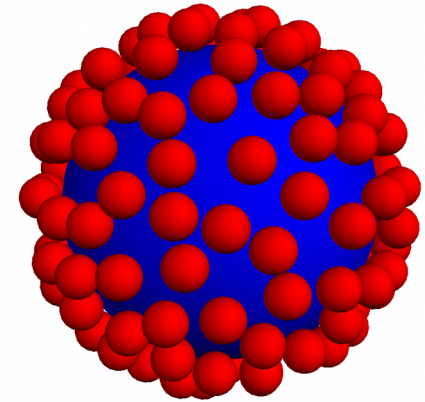
Sphere



Core-shell



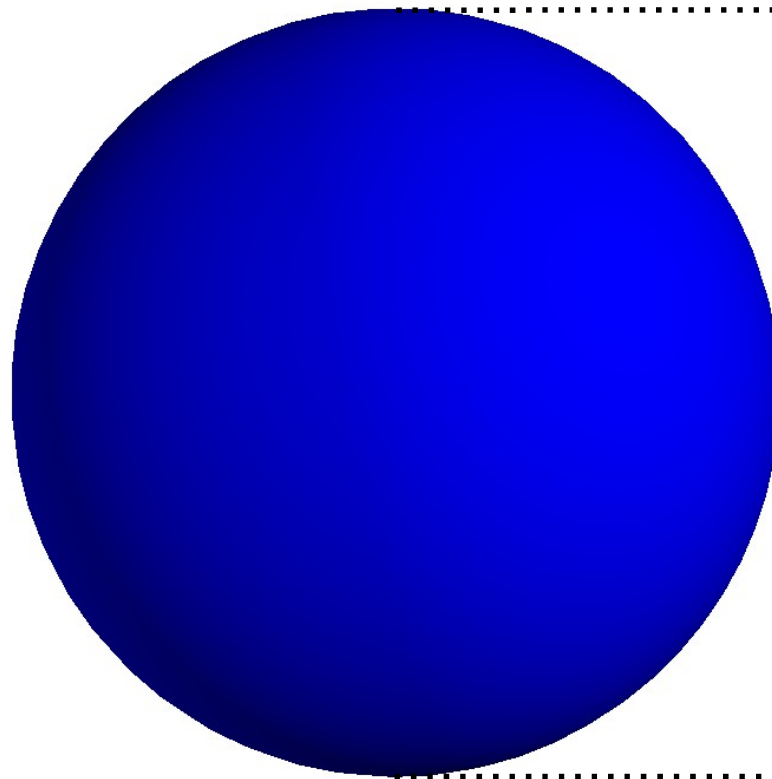
Core-satellite



Sphere

Dielectric sphere

$$n = 3.7$$



200 nm

Scattering simulations in FDTD

Incident flux from source

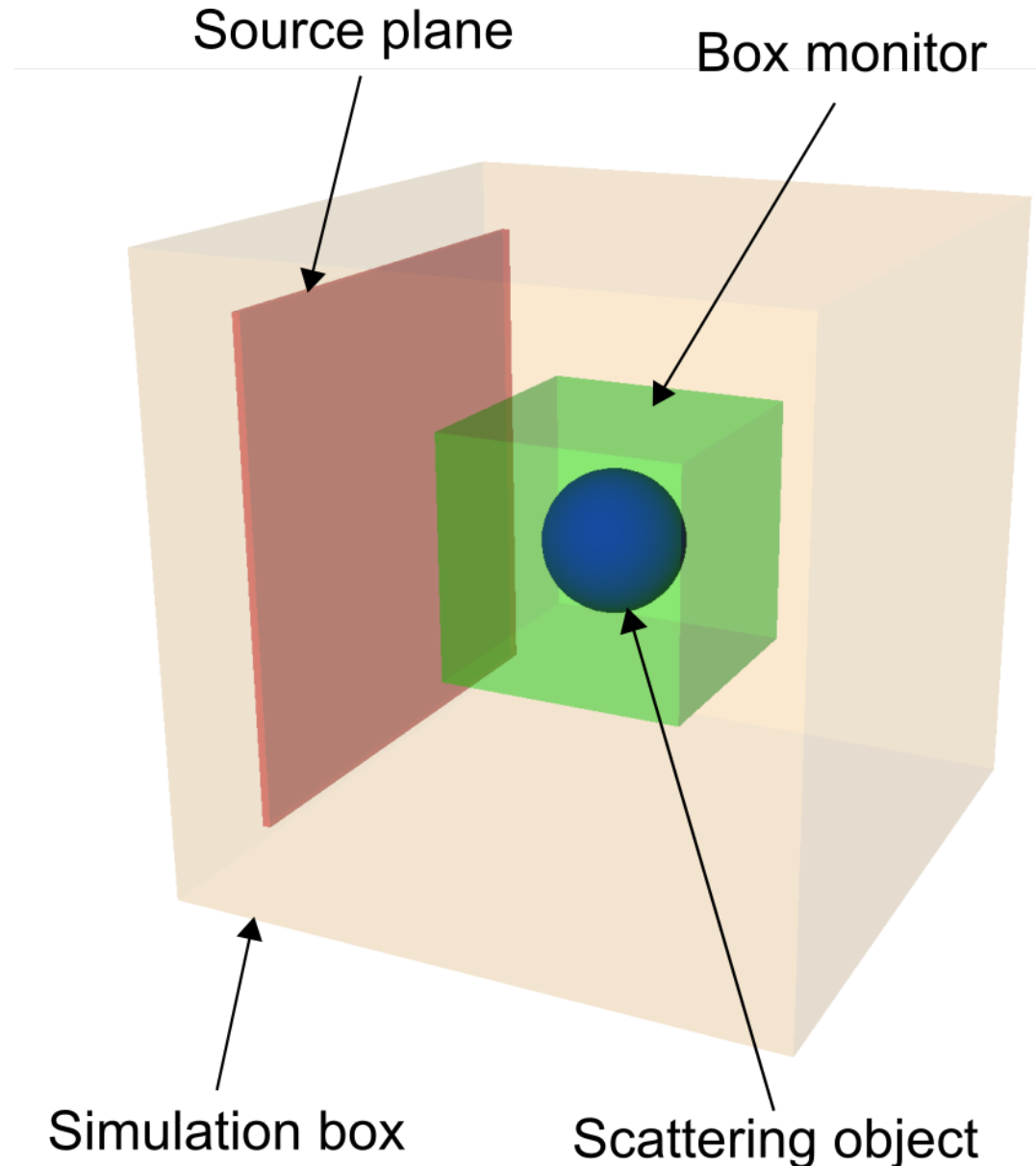
$$\sigma_{\text{inc}}(\omega)$$

Scattered flux from object

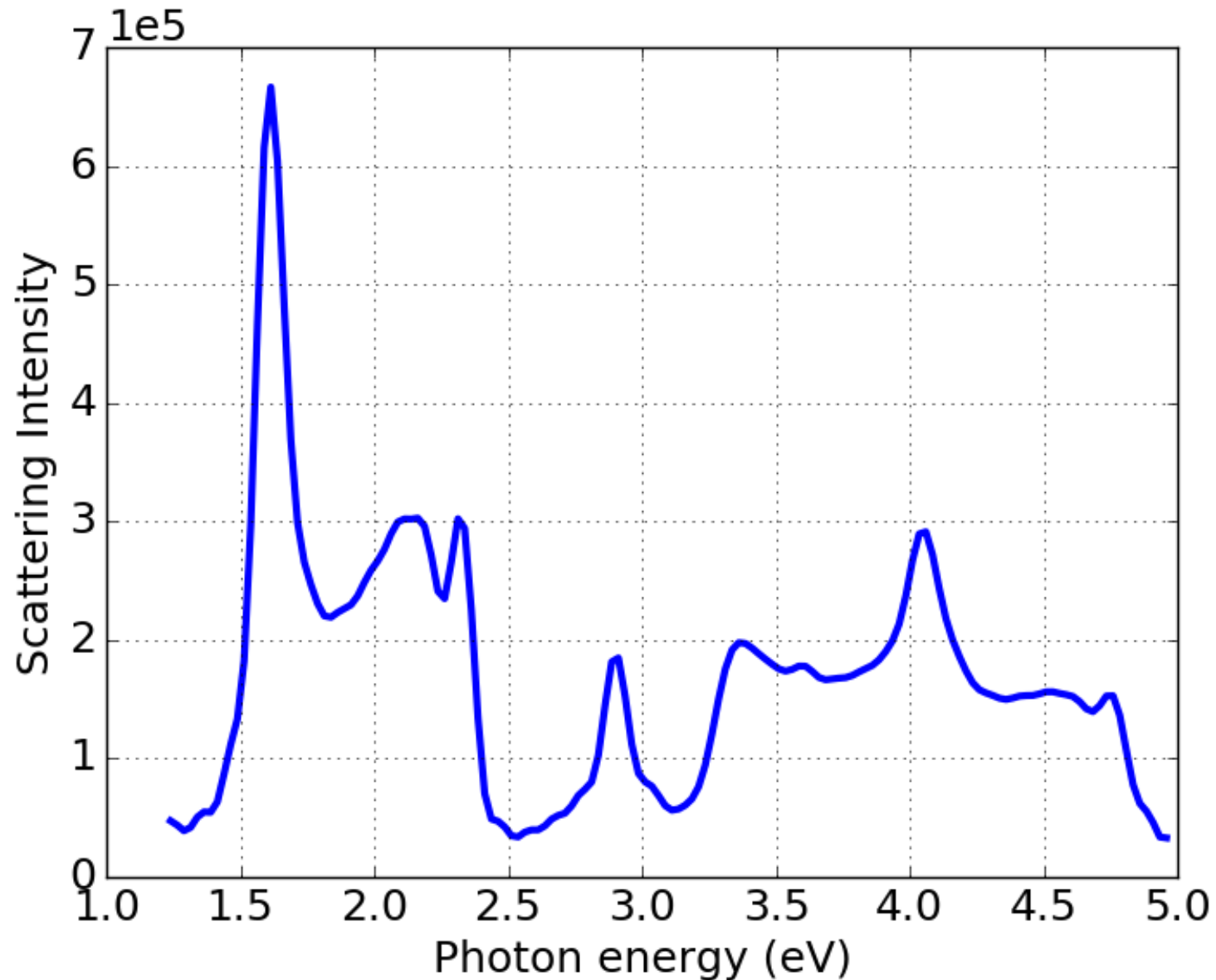
$$\sigma_{\text{scat}}(\omega) = \sum_{\text{faces}} \sigma_{\text{face}}(\omega)$$

Scattering intensity

$$I_{\text{scat}}(\omega) = \frac{\sigma_{\text{scat}}(\omega)}{\sigma_{\text{inc}}(\omega)}$$



Sphere: scattering intensity by linear beam



Multipole modes

Helmholtz equation for scattered field

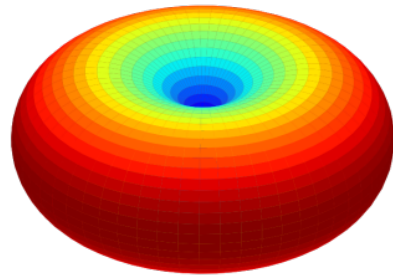
$$\nabla^2 \mathbf{E}_{\text{scat}}^\omega = -k^2 \mathbf{E}_{\text{scat}}^\omega$$

The eigenmodes are labeled as

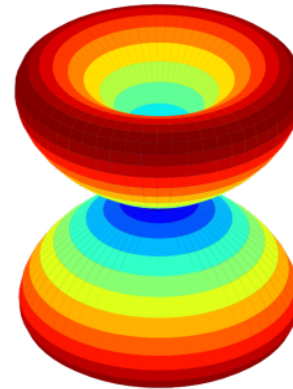
	(order)	(configuration)
Electric Modes	<u>l</u>	<u>m</u>
$\mathbf{N}_{lm}(\omega, r, \theta, \phi)$	1 (dipole)	$-l$
	2 (quadrupole)	$-l + 1$
Magnetic Modes		\vdots
$\mathbf{M}_{lm}(\omega, r, \theta, \phi)$	3 (octupole)	$l + 1$
	\vdots	l

Multipole modes: orders

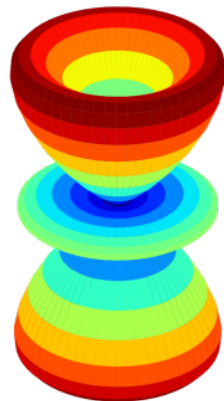
Dipole



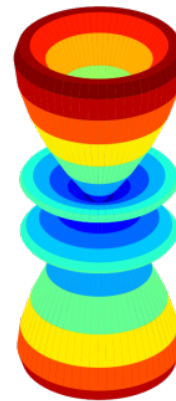
Quadrupole



Octupole

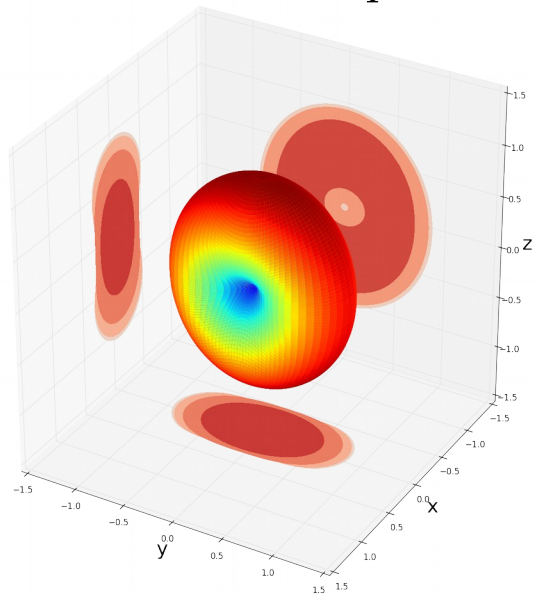


16-pole



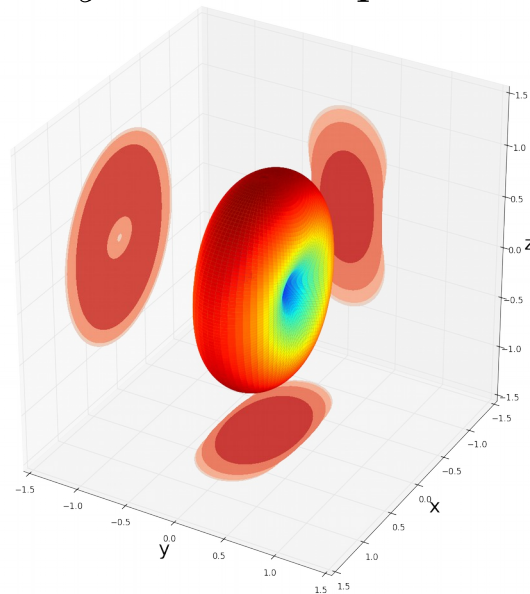
Multipole modes: configurations

x -oriented dipole



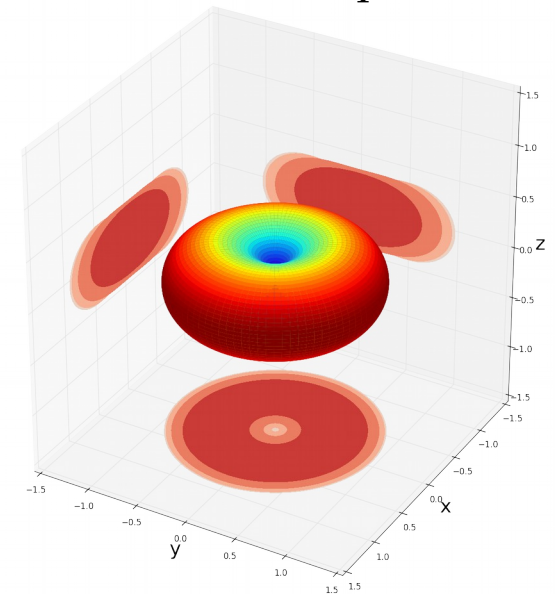
$$N_{1,1} - N_{1,-1}$$

y -oriented dipole



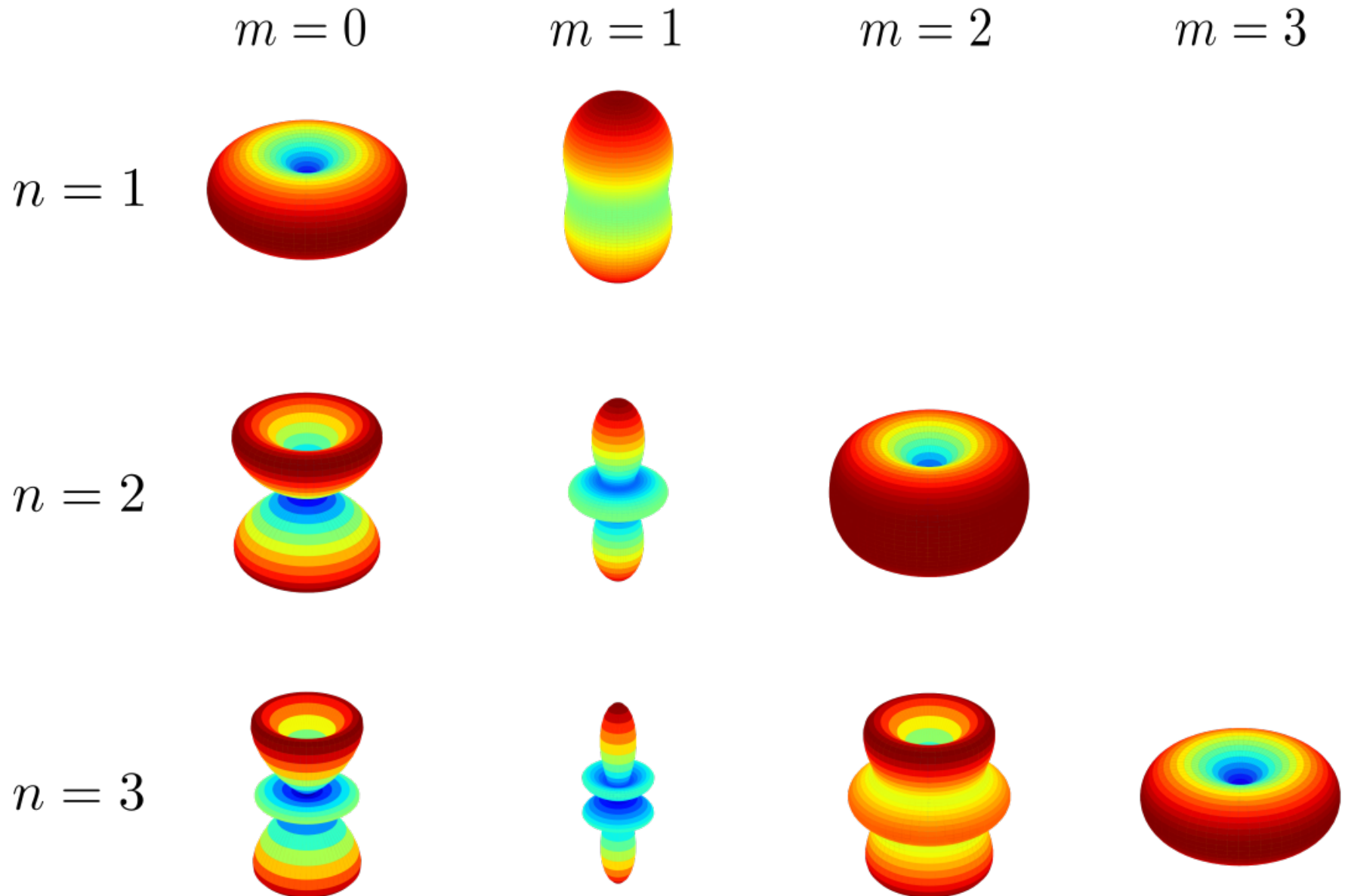
$$N_{1,1} + N_{1,-1}$$

z -oriented dipole



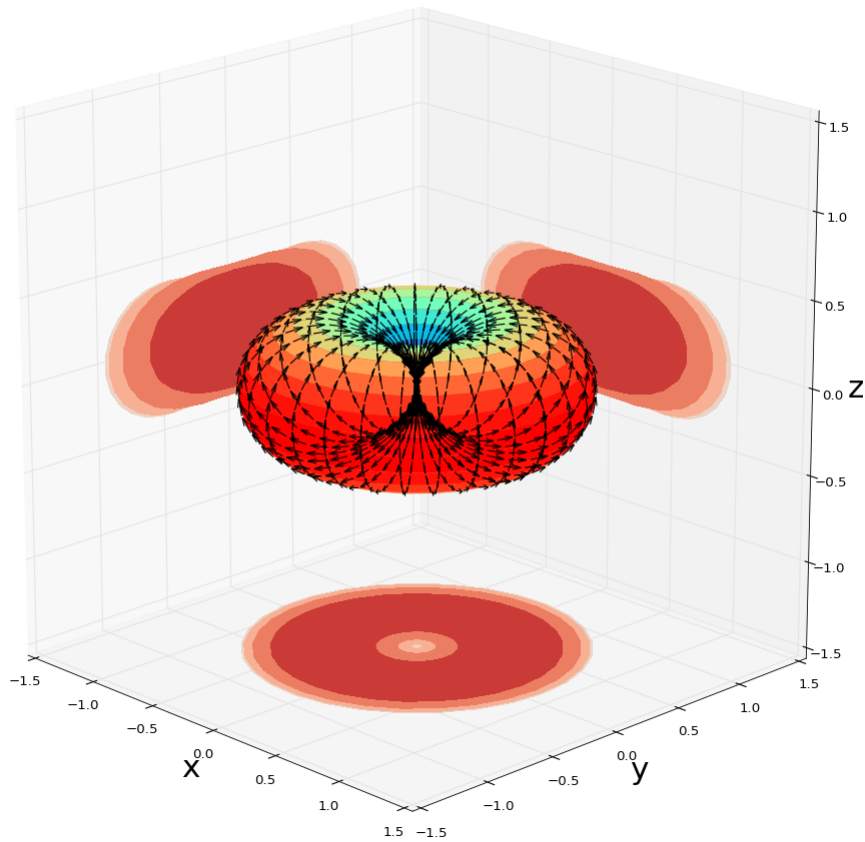
$$N_{1,0}$$

Multipole modes: configurations

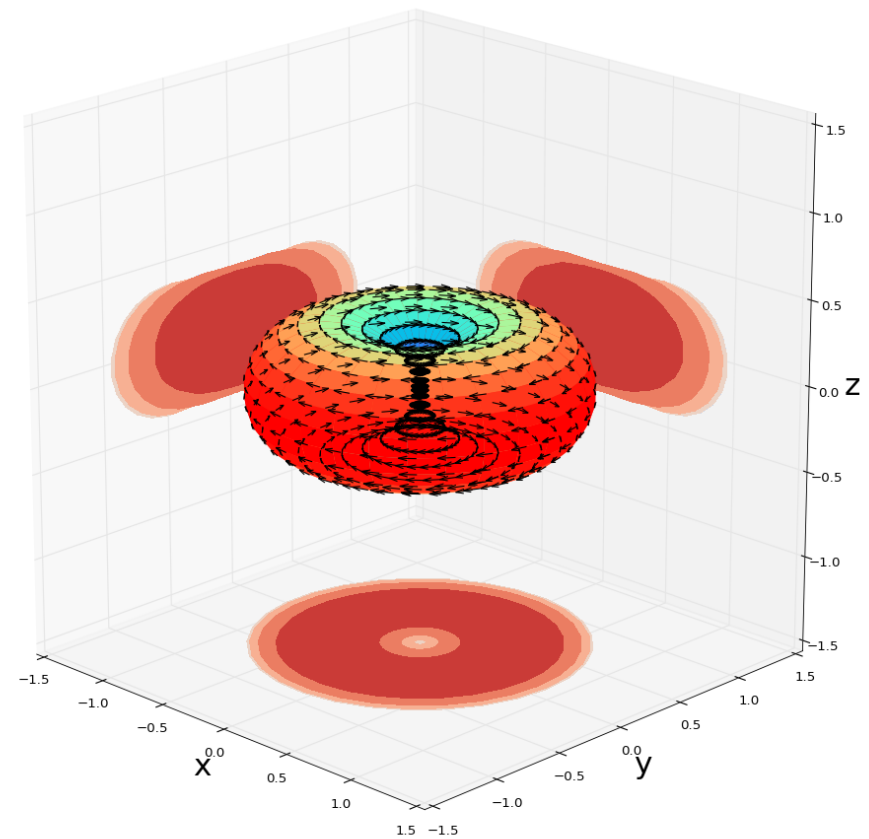


Electric vs Magnetic

Electric Dipole

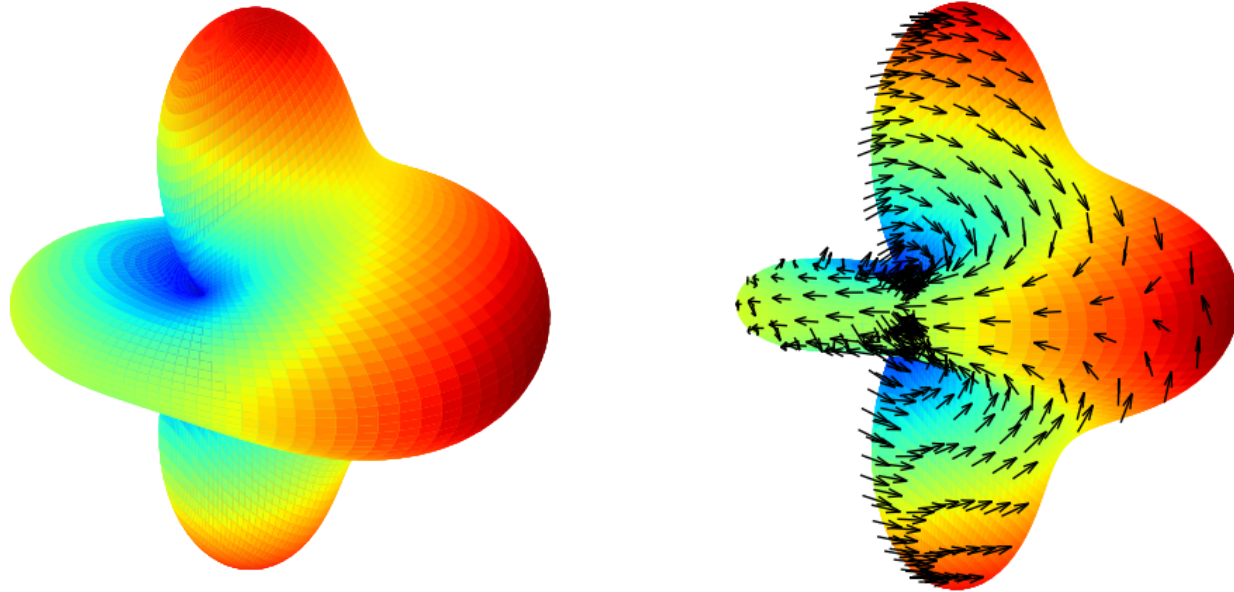


Magnetic Dipole



→ Electric field polarization
Intensity

Mixed multipole mode



$$(1 + 1i)\mathbf{N}_{1,-1} - (0.3 - 0.6i)\mathbf{N}_{1,1} + i\mathbf{M}_{1,0} \\ + (1 - 1i)\mathbf{N}_{2,0} + 2\mathbf{M}_{2,1} - \mathbf{N}_{2,-1}$$

Scattering simulations: spherical monitor

Incident flux from source

$$\sigma_{\text{inc}}(\omega)$$

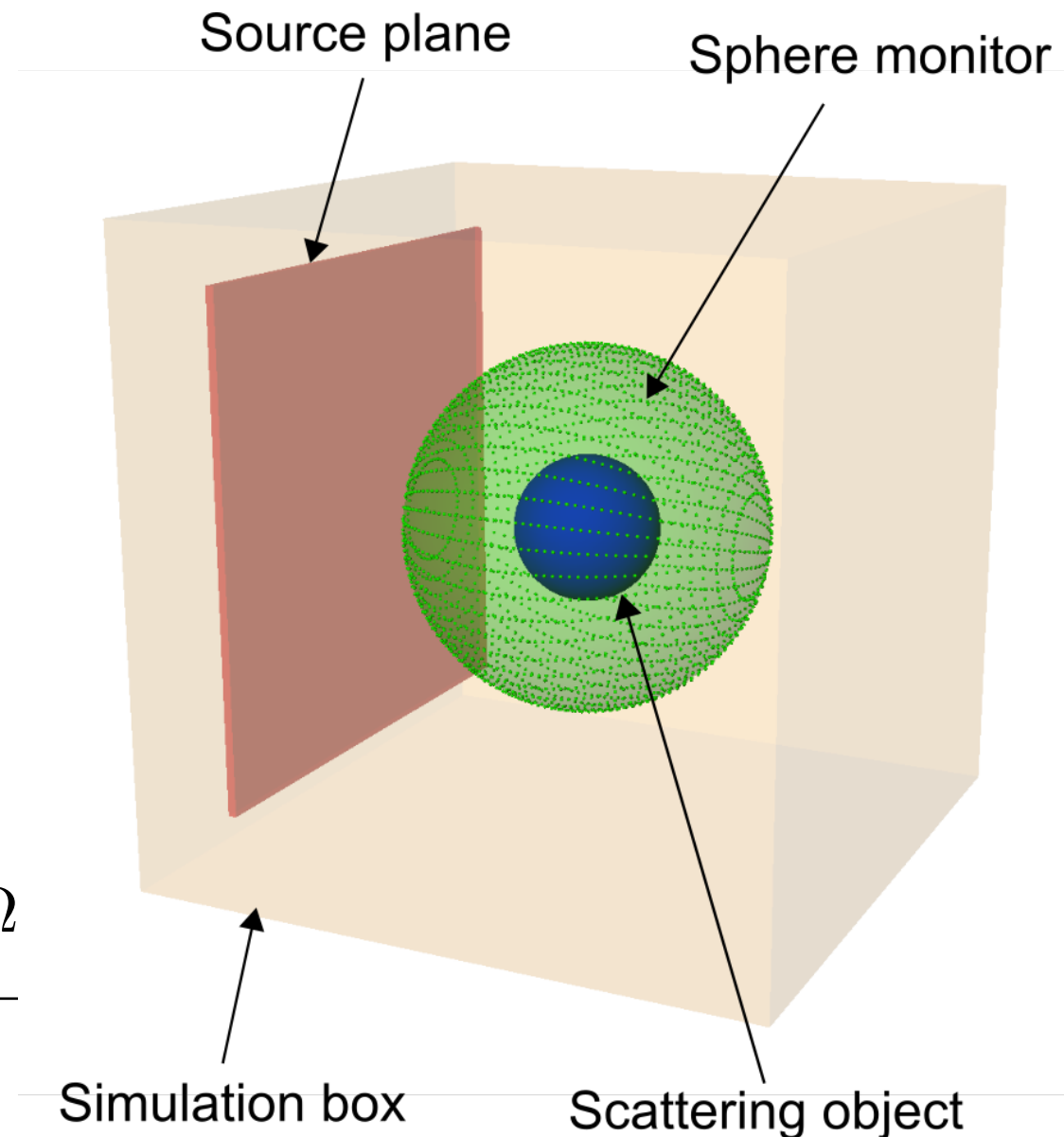
Scattered fields from object

$$\mathbf{E}_{\text{scat}}(\omega, r = a, \theta, \phi)$$

$$\mathbf{H}_{\text{scat}}(\omega, r = a, \theta, \phi)$$

Scattering intensity

$$I_{\text{scat}}(\omega) = \frac{\int_{\Omega} (\mathbf{E}^{\omega} \times \mathbf{H}^{\omega}) \cdot \hat{\mathbf{r}} d\Omega}{\sigma_{\text{inc}}(\omega)}$$



Multipole decomposition

Multipole expansion:

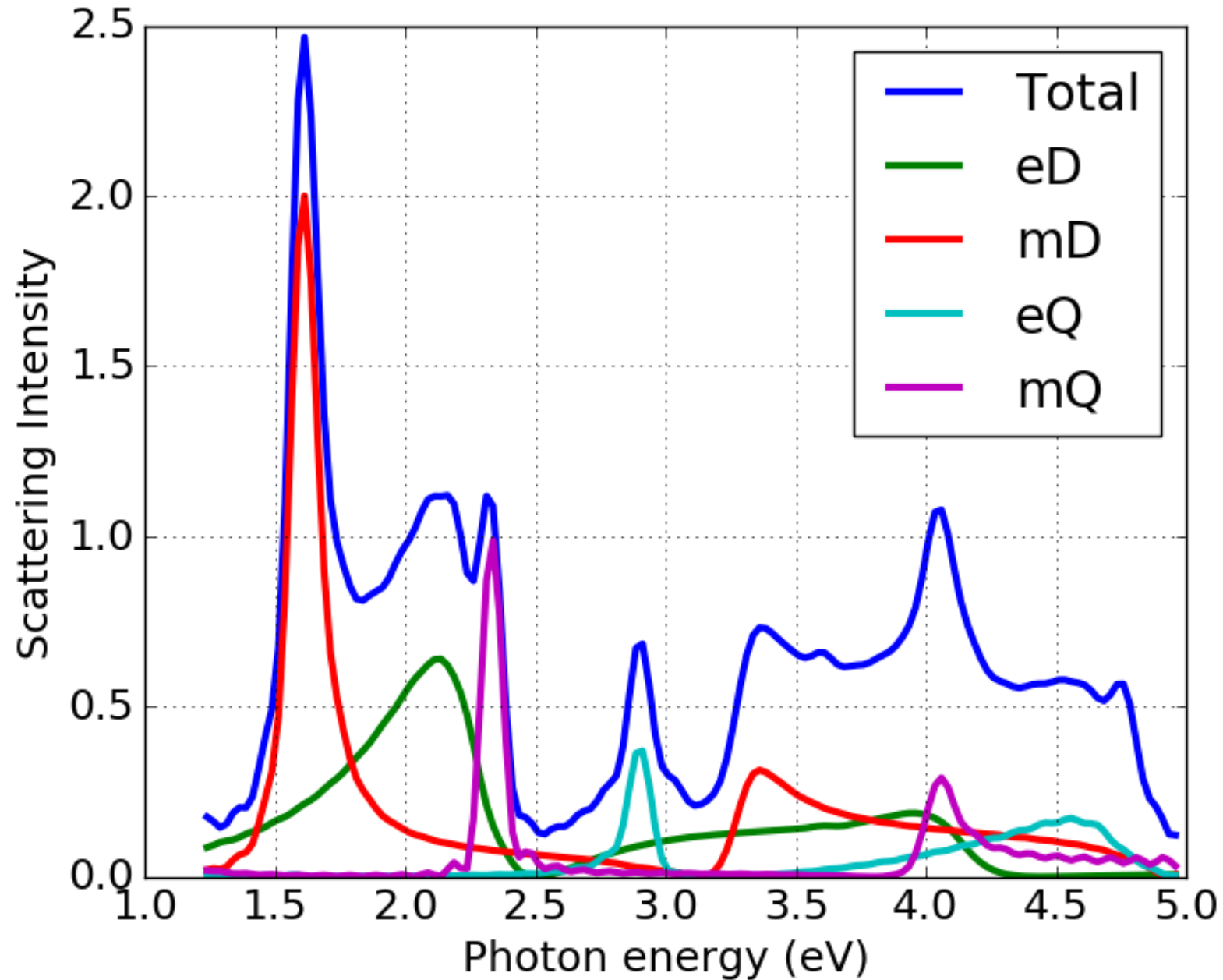
$$\mathbf{E}_{\text{scat}}^{\omega} = \sum_{l=1}^{\infty} \sum_{m=-l}^{m=l} a_{lm}^{\omega} \mathbf{N}_{lm}^{\omega} + b_{lm}^{\omega} \mathbf{M}_{lm}^{\omega}$$

Multipole decomposition:

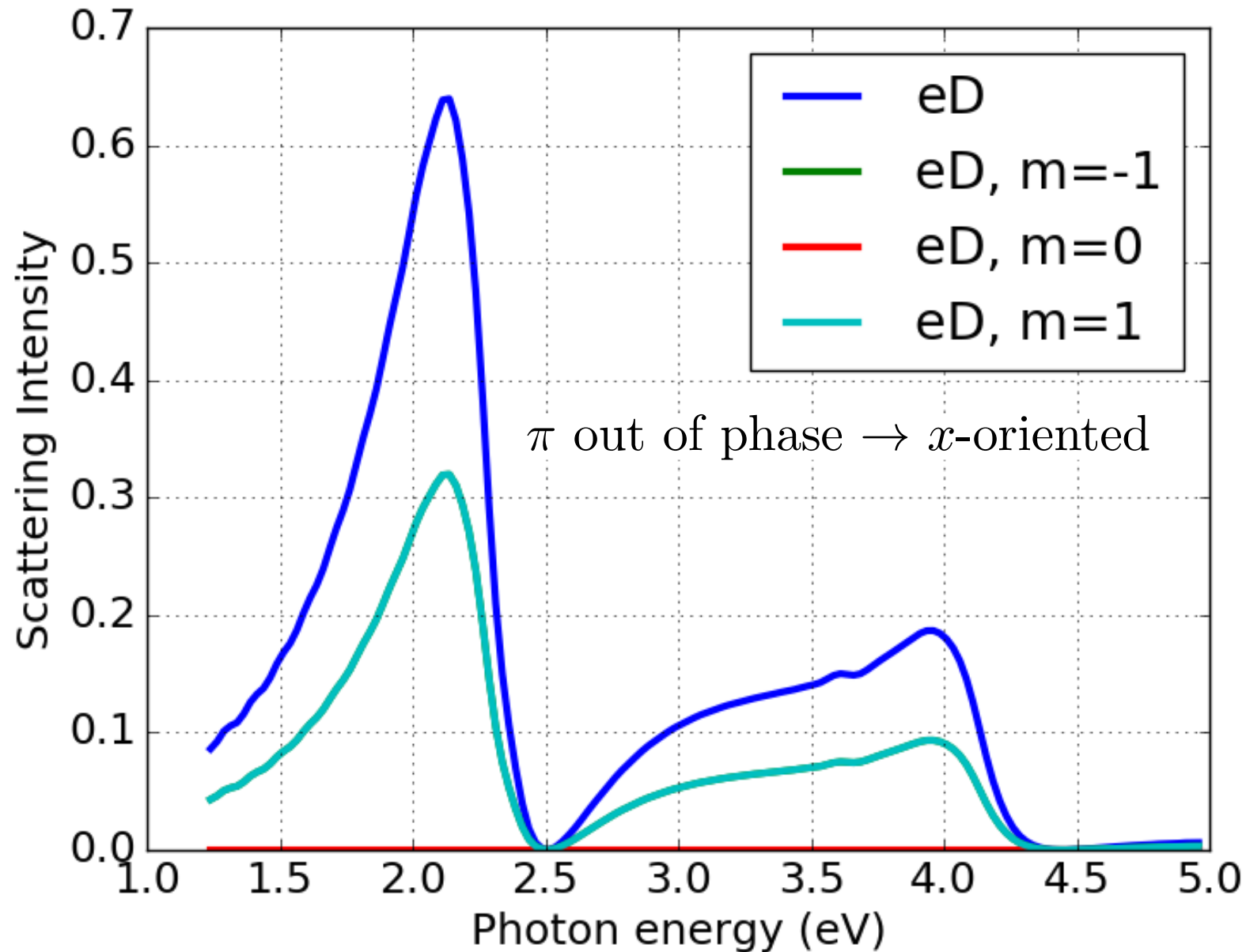
$$a_{lm}^{\omega} = \int_0^{2\pi} \int_0^{\pi} \mathbf{E}_{\text{scat}}^{\omega}(r = a, \theta, \phi) \cdot \mathbf{N}_{lm}^{\omega}(r = a, \theta, \phi) \sin \theta \, d\theta \, d\phi$$

$$b_{lm}^{\omega} = \int_0^{2\pi} \int_0^{\pi} \mathbf{E}_{\text{scat}}^{\omega}(r = a, \theta, \phi) \cdot \mathbf{M}_{lm}^{\omega}(r = a, \theta, \phi) \sin \theta \, d\theta \, d\phi$$

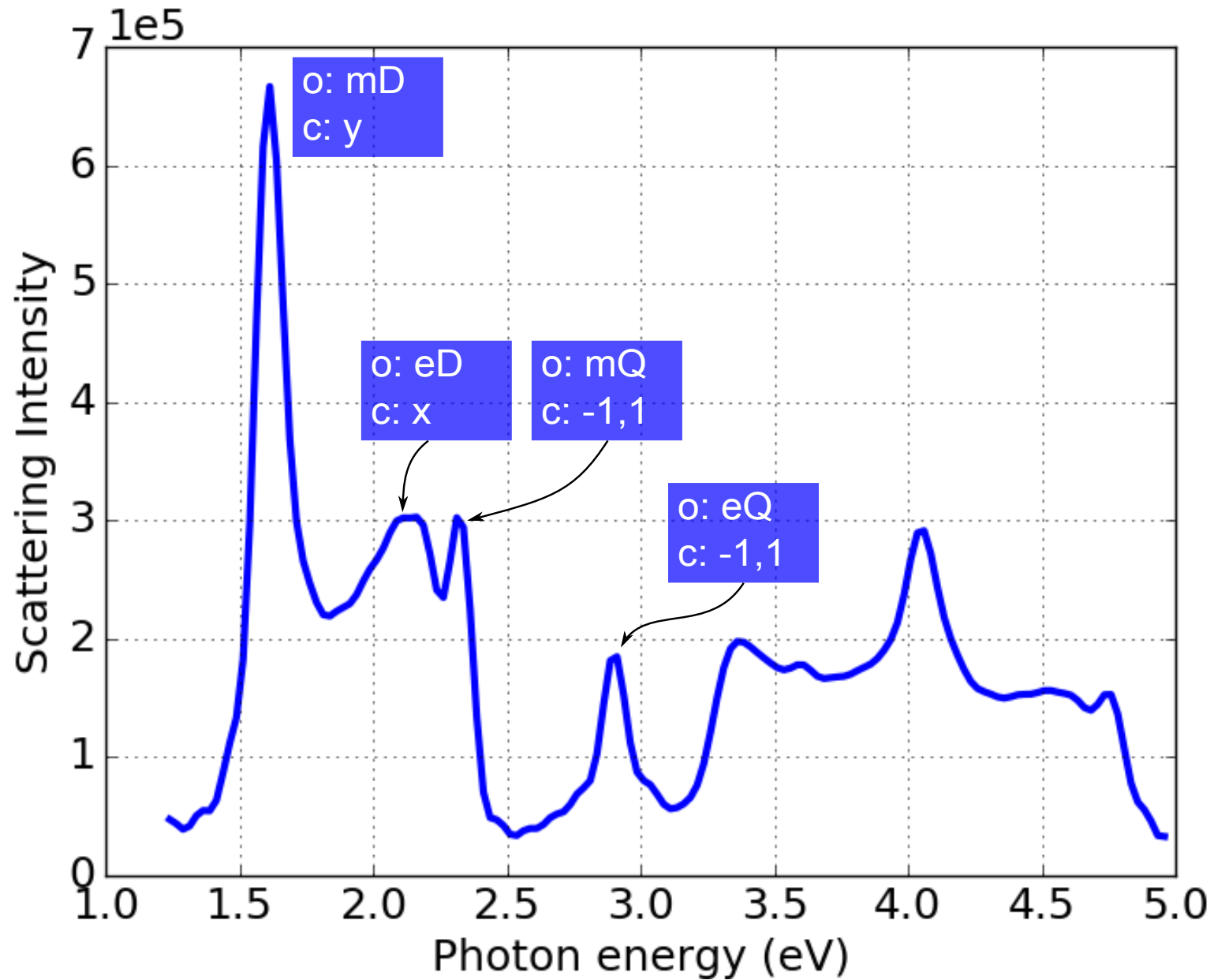
Sphere: scattering intensity per multipole by linear beam



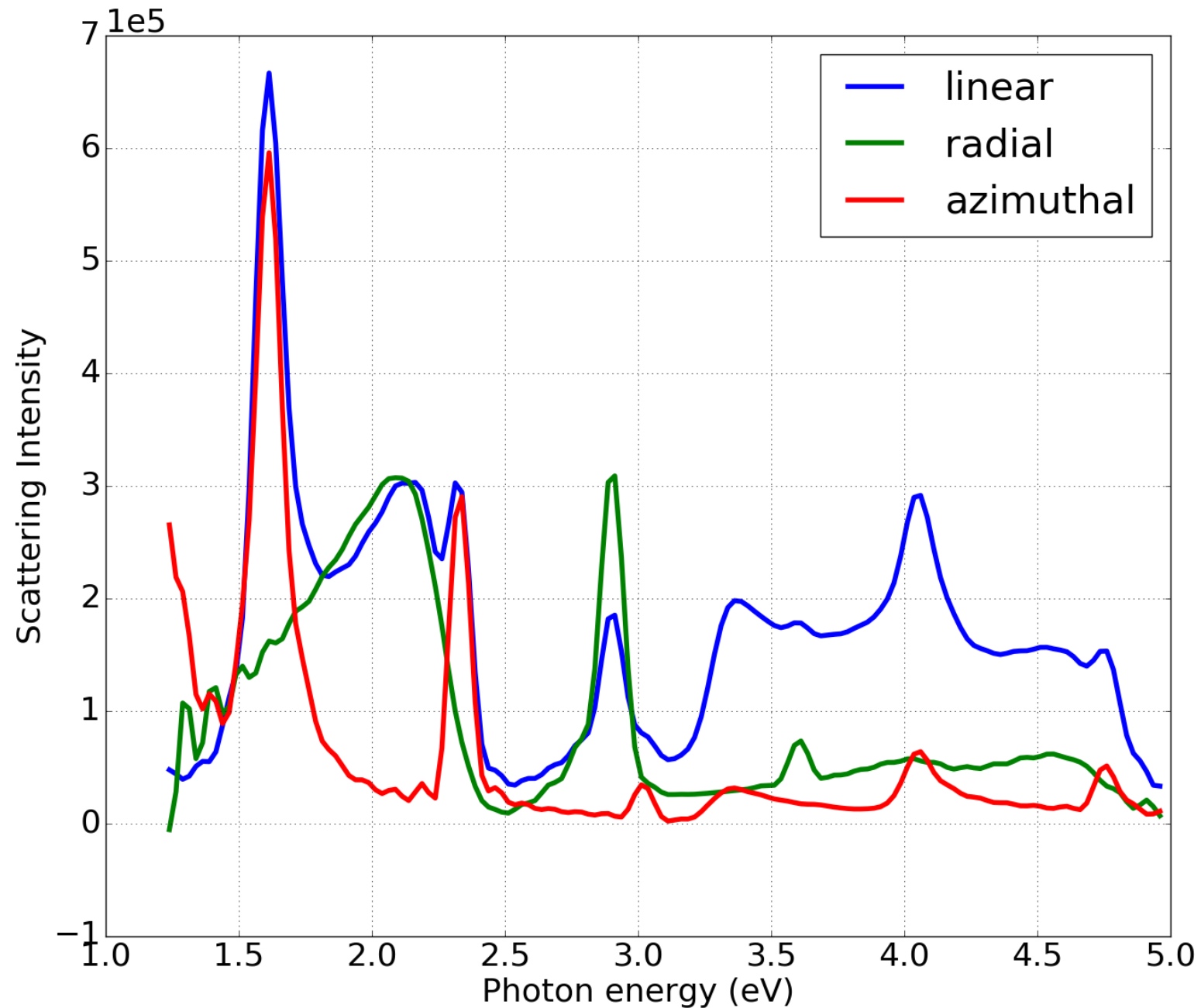
Sphere: electric dipole scattering intensity per configuration by linear beam



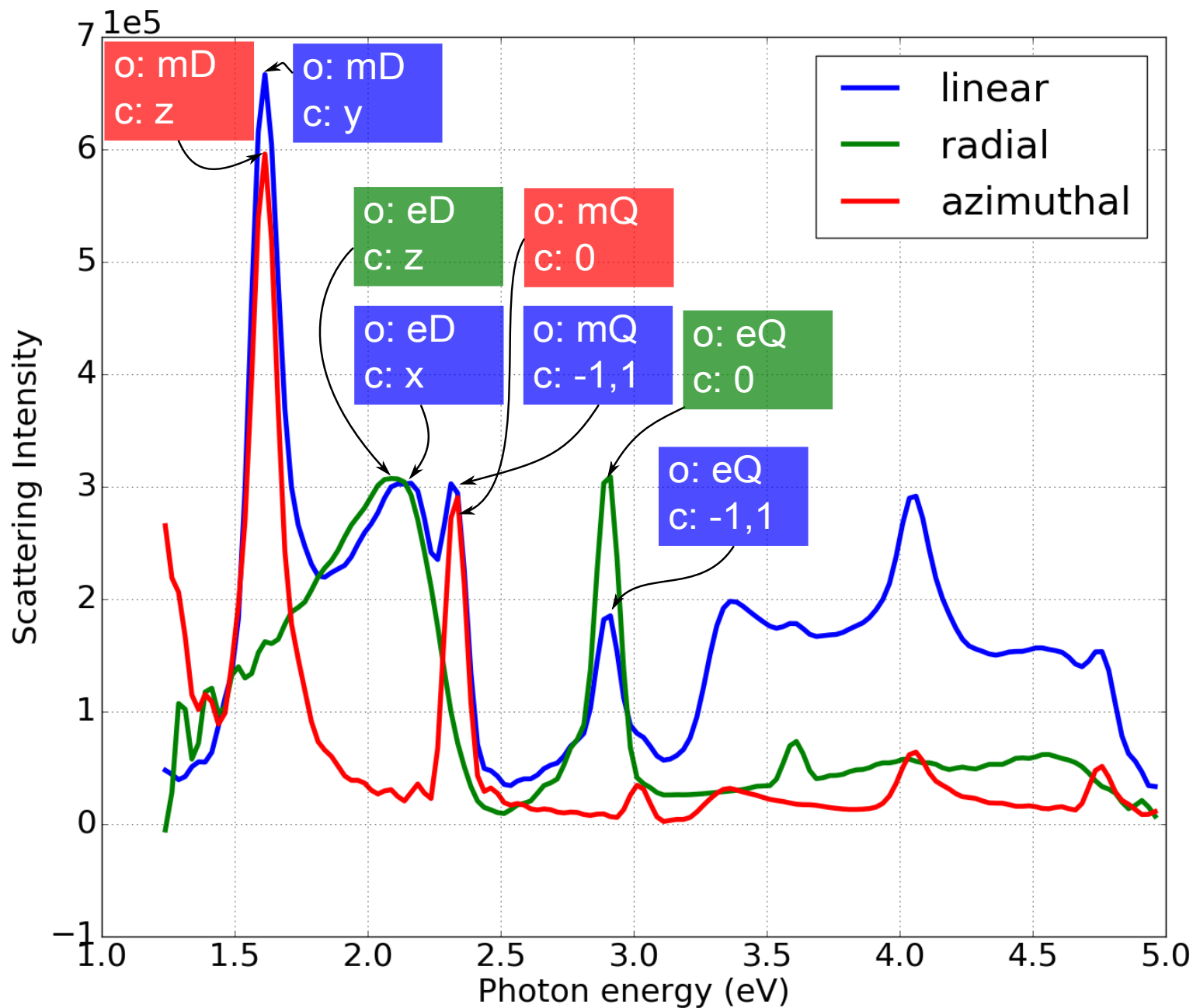
Sphere: scattering spectrum by linear beam



Sphere: scattering spectrum per beam type



Sphere: scattering spectrum per beam type



Conjecture

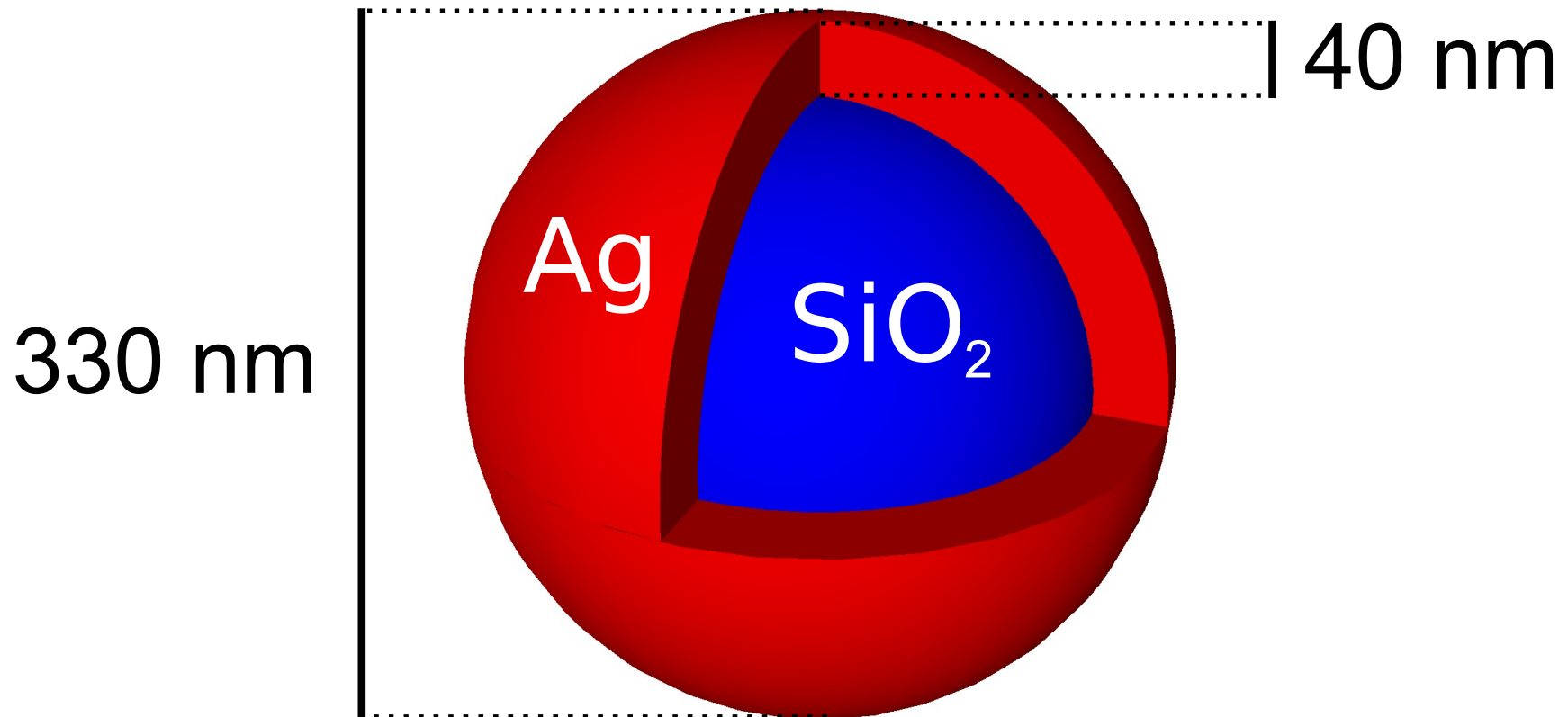
The linear beam excites **electric** and **magnetic** modes of **all orders**

The radial beam selectively excites **electric** modes of **all orders**, but of a different configuration

The azimuthal beam selectively excites **magnetic** modes of **all orders**, but of a different configuration

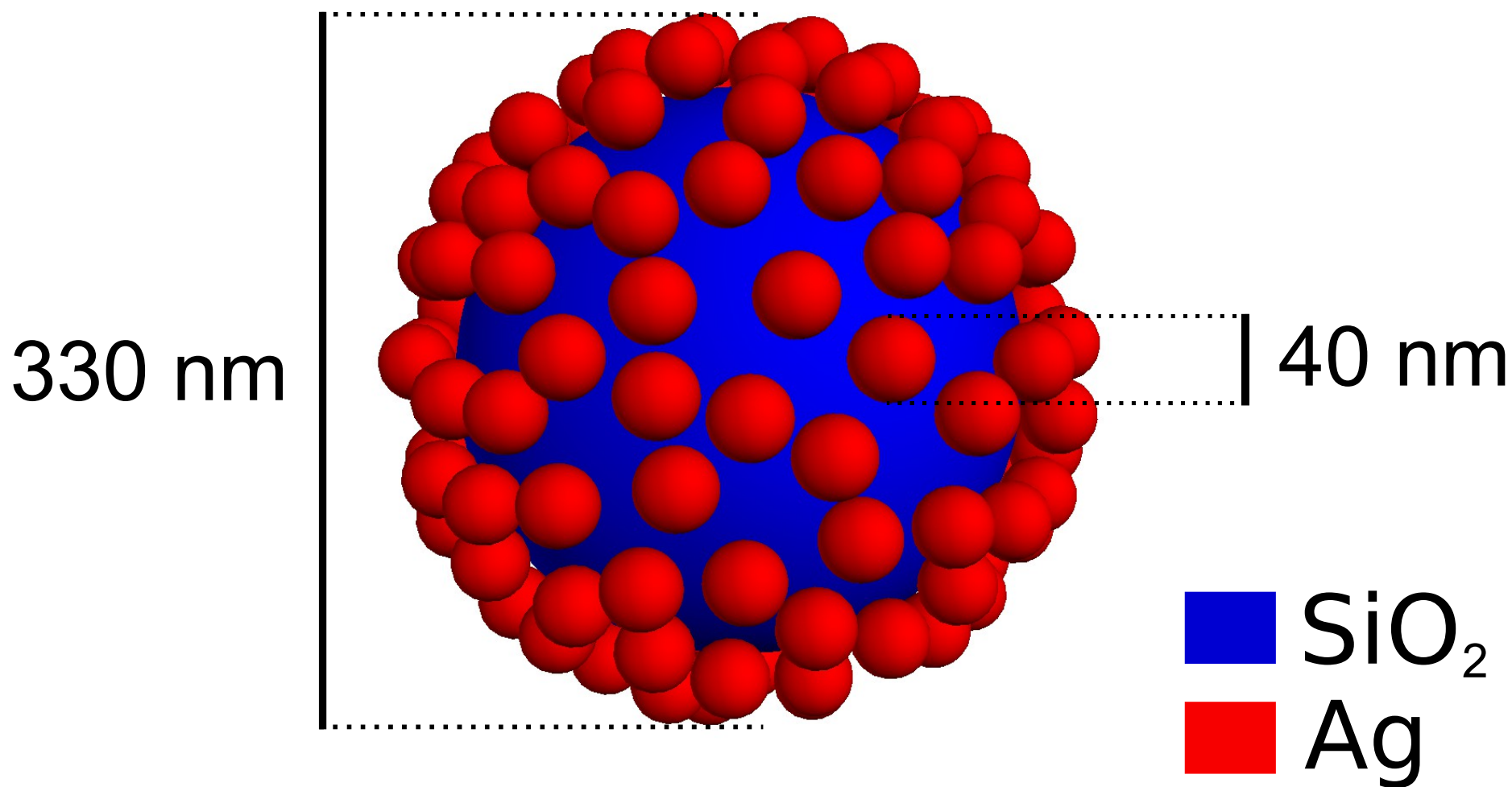
Core-shell

Core-shell

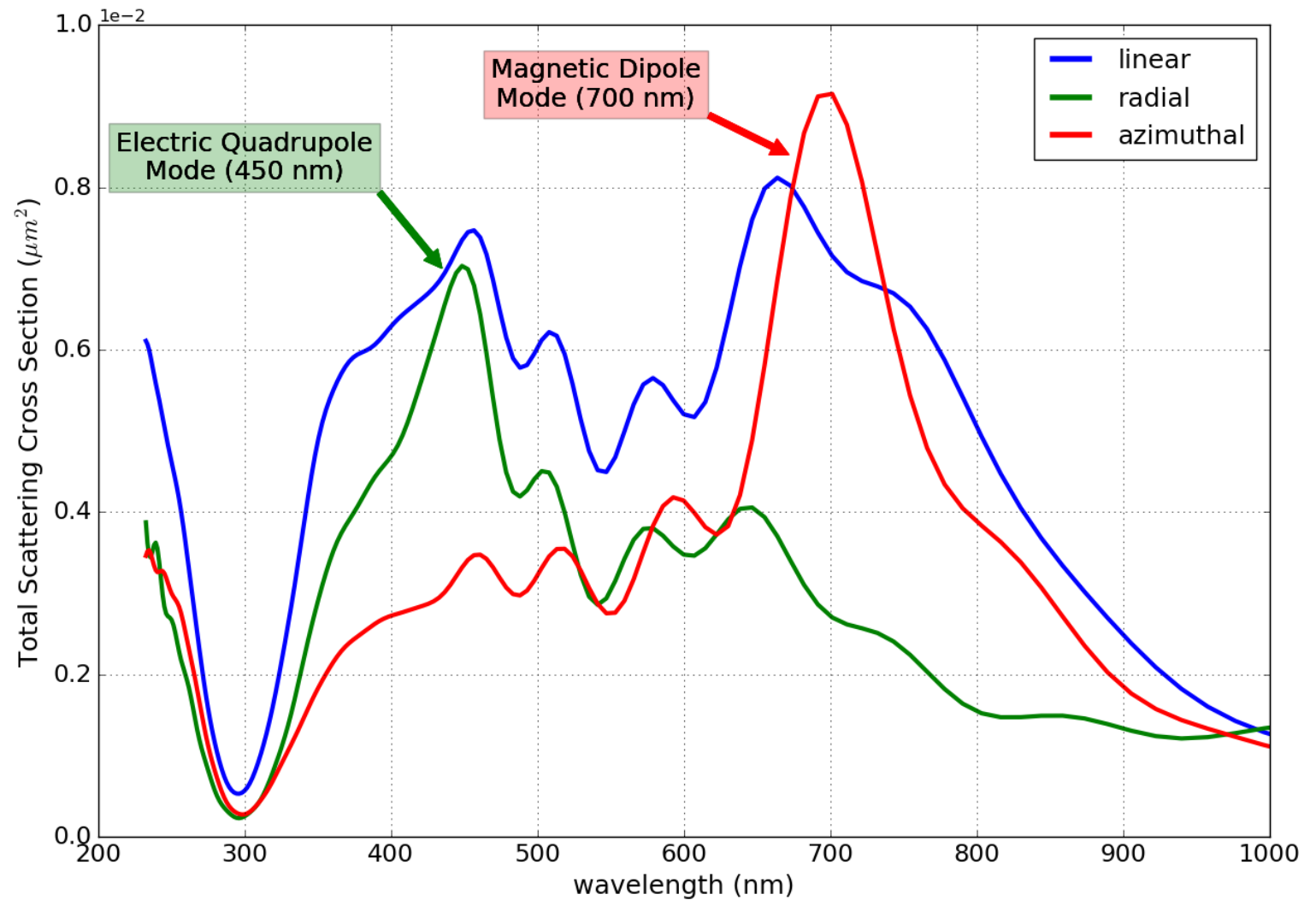
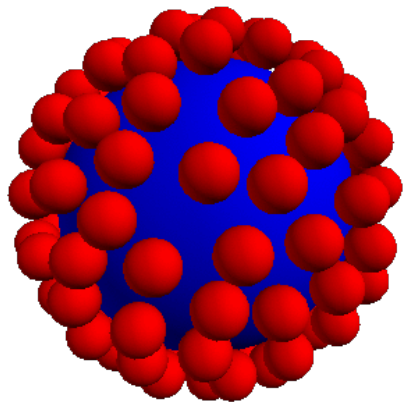


Core-satellite

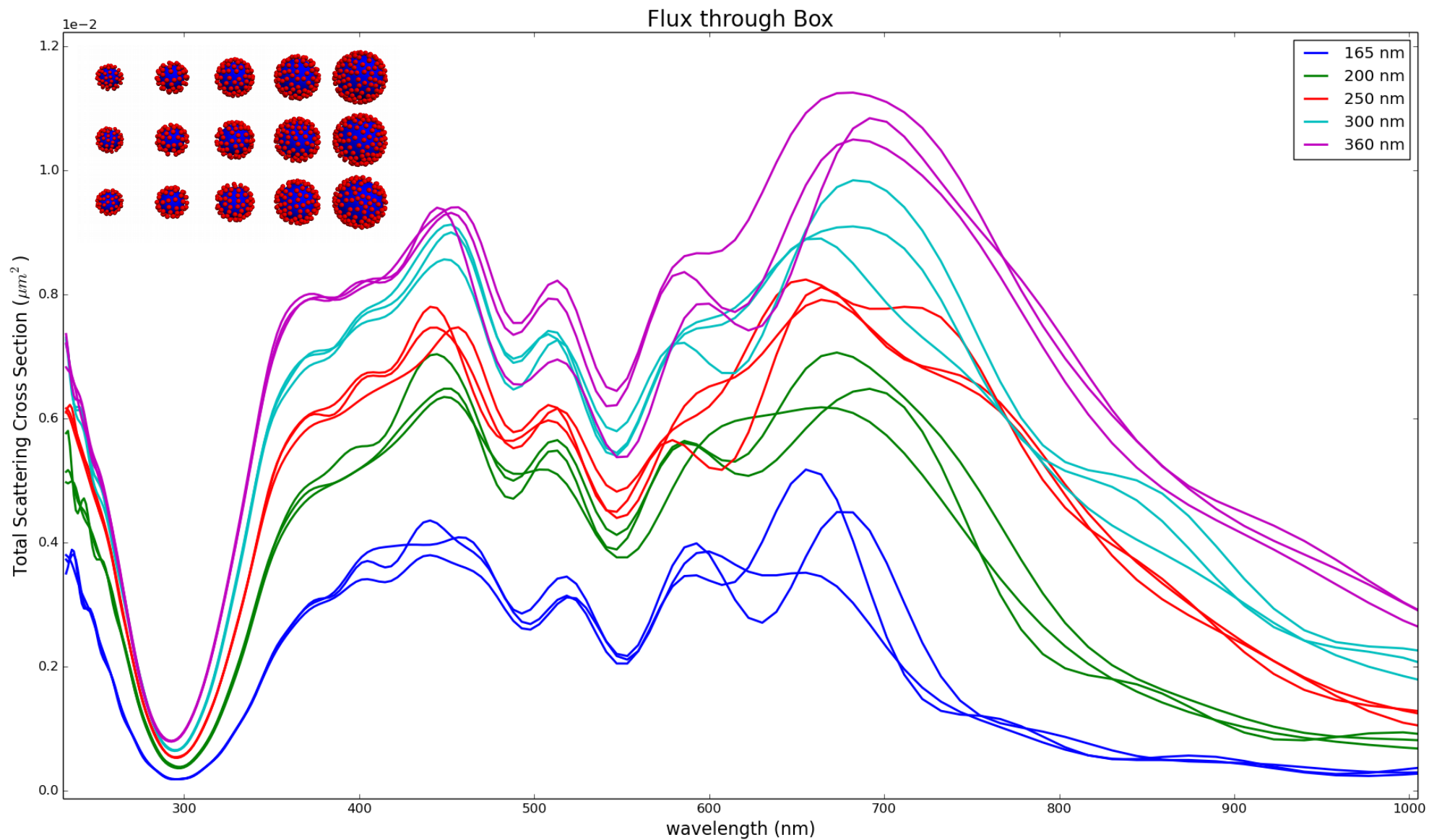
Core-satellite



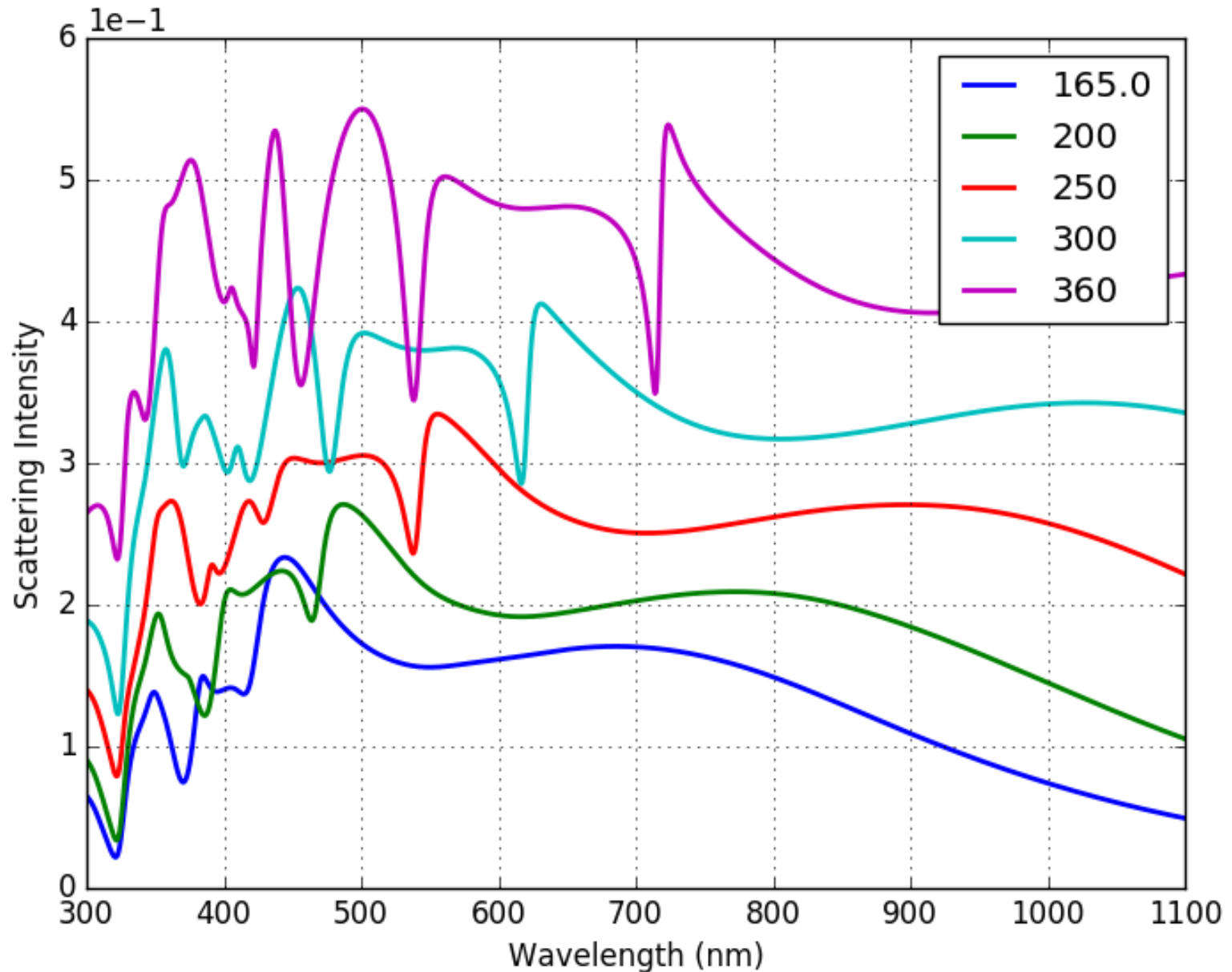
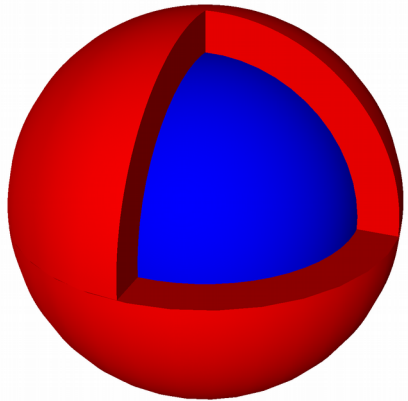
Core-satellite: spectra



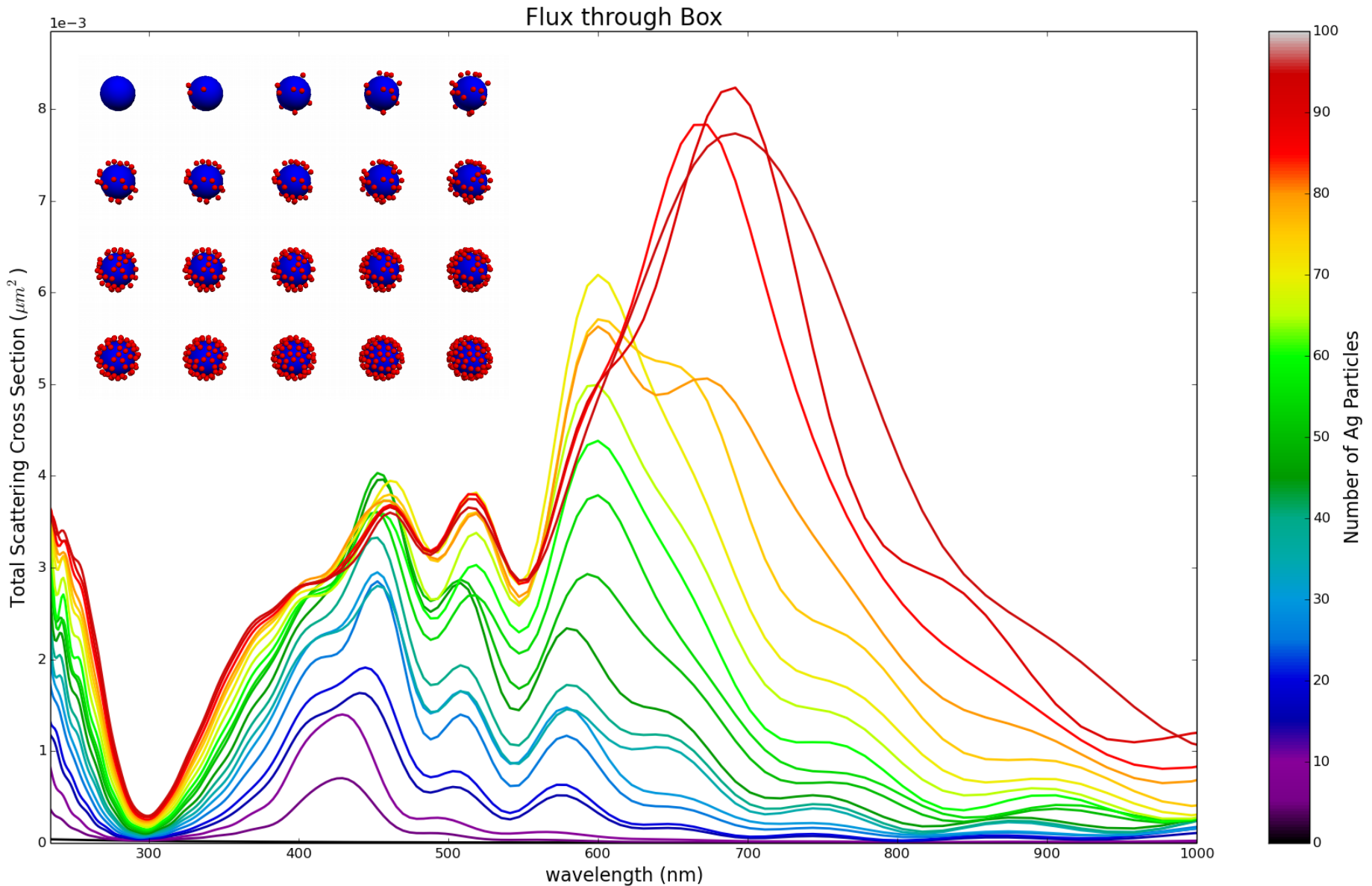
Core-satellite: increasing the core size, linear beam



Core-shell: increasing the core size, linear beam



Core-satellite: increasing the nanoparticle density, azimuthal beam



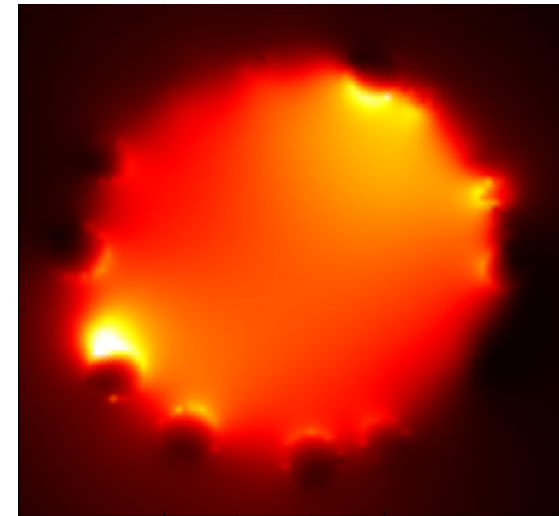
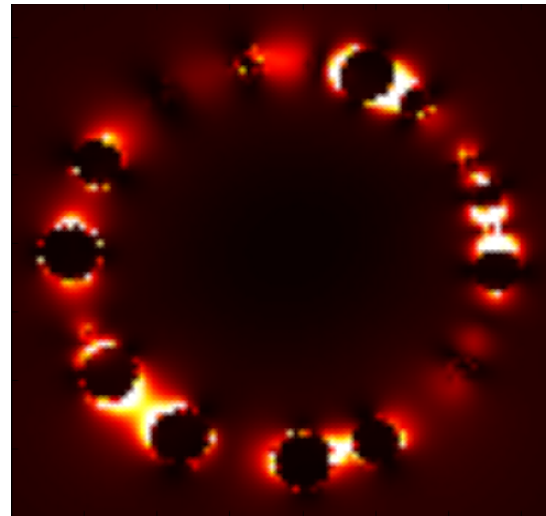
Magnetic resonance with azimuthal beam

Electric Field

Magnetic Field

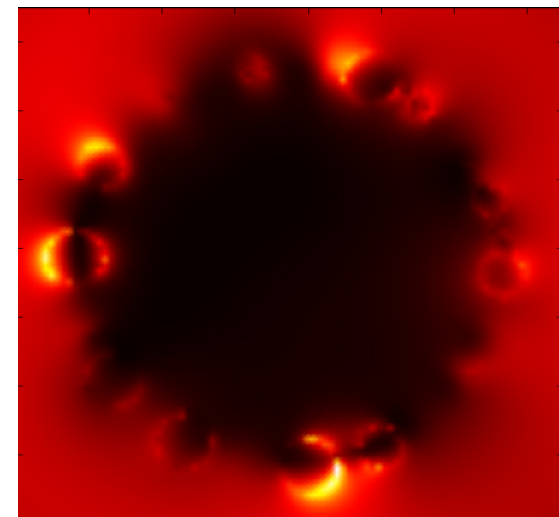
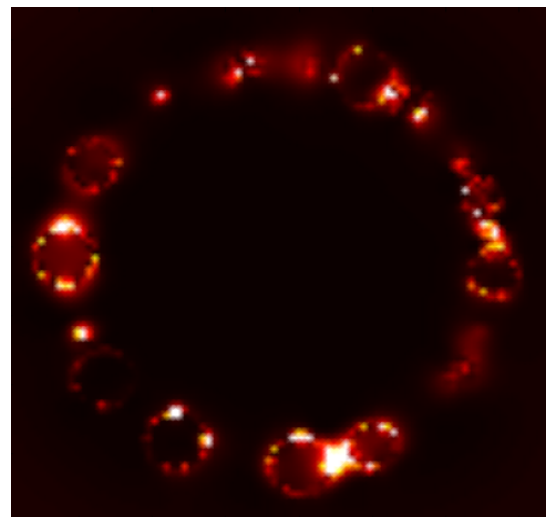
On Magnetic Resonance

700 nm

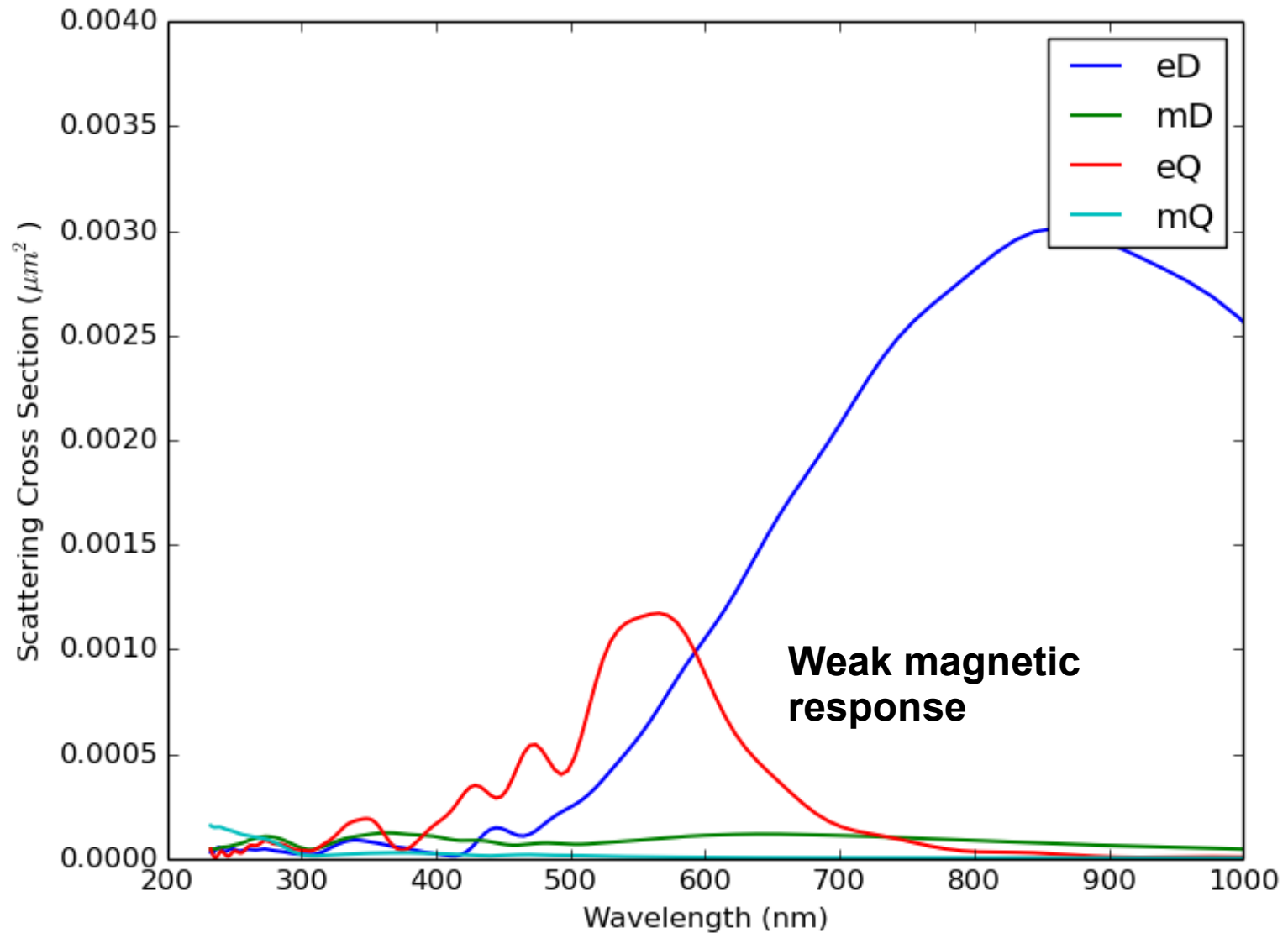
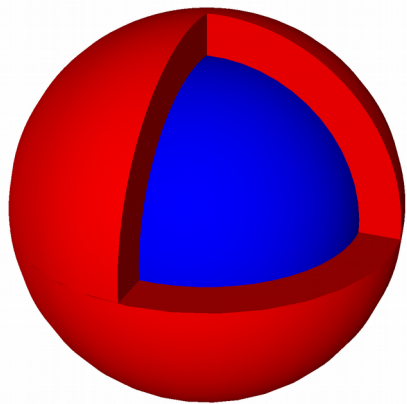


Off Magnetic Resonance

450 nm



Core-shell: linear beam spectrum



Core-satellite: current density

