

The role of disorder in plasmonic devices for biological applications

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Outline

Introduction
Our research: light and complexity

Disordered plasmonic nanolenses for biological applications
Plasmonics for biological applications: SERS and TERS
Plasmonic nanolenses: fabrication roughness and investigation of disorder
Further developments and applications

Conclusions

Introduction



- Increasing interest in Optics and Photonics Applications for Biology
- We focus on **Surface Enhanced Raman Spectroscopy** (SERS)
- Research involves the investigation, design and realization of complex optical devices and configurations
- These devices are usually based on **regular** and **symmetric** geometries (e.g. tips, spheres)
- Fabrication disorder, however, is **unavoidable** and generally **unwanted**

Can we exploit the presence of disorder?

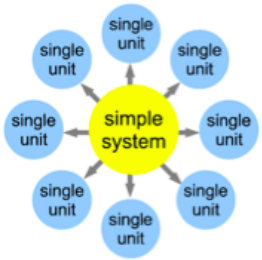
PRIMALIGHT : Our Research



We deal with **disorder and complexity** in photonic applications

Many interacting degrees of freedom, which work together to sustain emergent properties of the whole ensemble

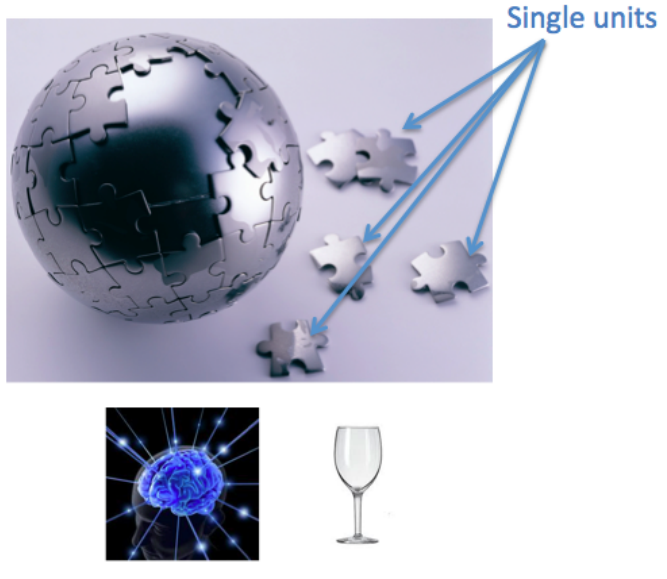
Simple system





- Distinguishable components and functions

Complex system



- Collective behaviors are the key
- Easy to find in nature

PRIMALIGHT : Our Research

Let's consider some examples:

Brain energy efficiency

Computational power vs power consumption

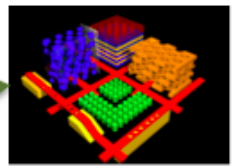


of the order of MW

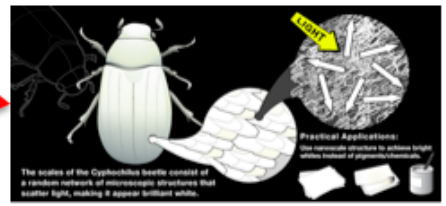


around 20W





Photonic Crystals & Metamaterials



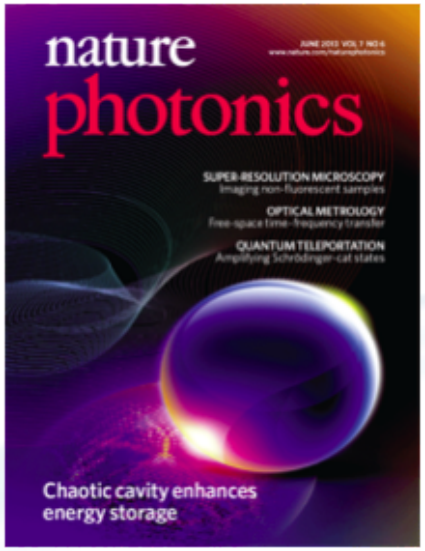
White color using disordered scatterers

Photonic crystals, and pigment-free paints derived from bug shells

Nature is full of similar examples, and this is the result of **million of years** of evolution and optimization.

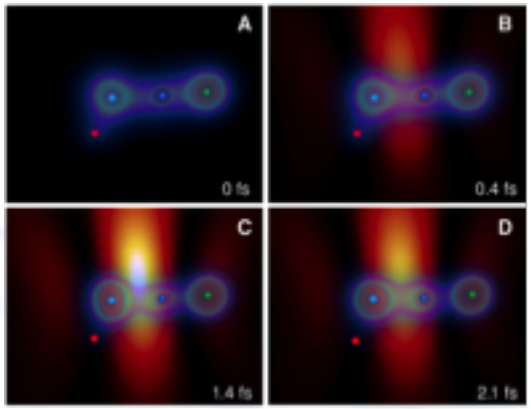
Paradigm shift: **organized complexity** can be a powerful tool

PRIMALIGHT Research: some of our applications



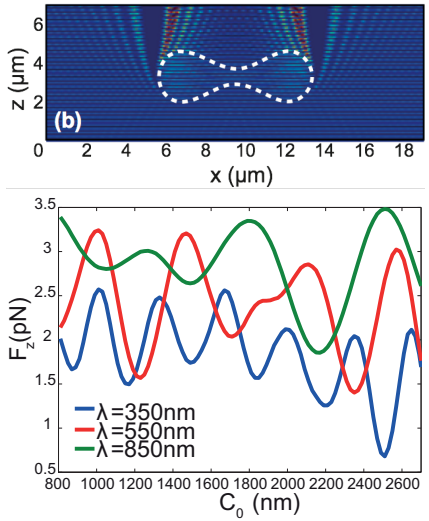
Cahotic resonators

Nature Photonics 7, 271 (2013)



XFEL Molecular imaging

PRL 106, 105504 (2011)



RBC sorting

OLE, special issue on Optical Methods in Nanobiotechnology (to appear).

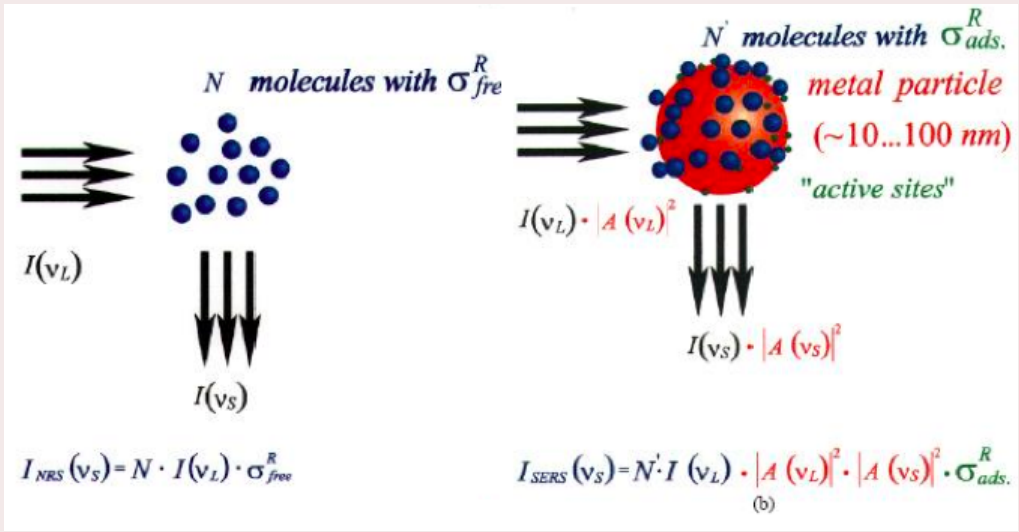
Some PRIMALIGHT Applications

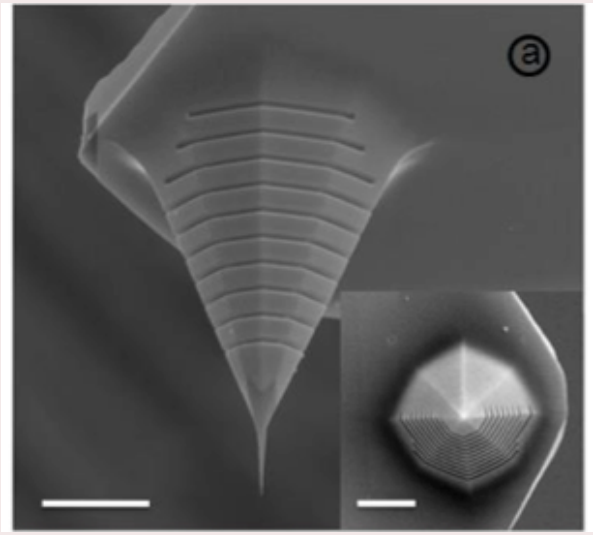
- Nonlinear dynamics
  Brain inspired optical models
- Optical Forces
  Many-body optical Tweezing
- Complex Materials
  Disordered Plasmonics
- Energy Harvesting
  Chaotic resonators

Biological applications: SERS and TERS

Light is a crucial investigation tool in Biological systems
Imaging, spectroscopy and direct manipulation of biological matter

SERS : Surface Enhanced Raman Spectroscopy





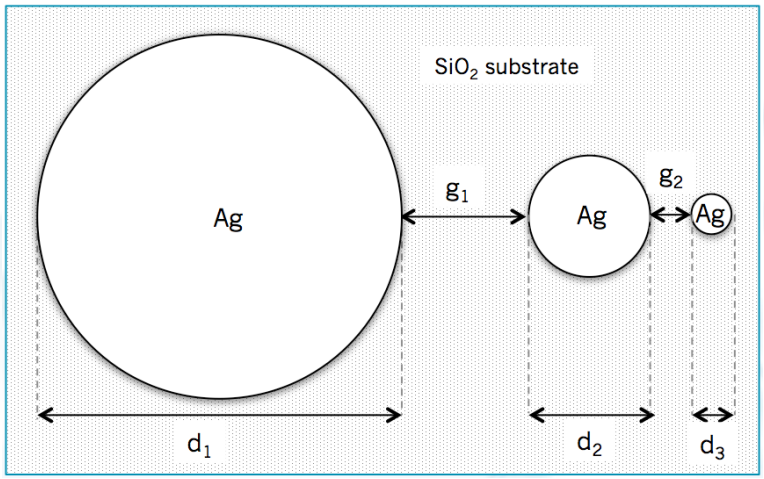
- A crucial tool is provided by **raman spectroscopy**
- Raman signal can be enhanced using external structures
- plasmonics: nanostructured metallic structures provide high enhancement

Case study: Plasmonic fractal nanolens

Exploiting self-similarity to produce highly-localized enhancement

Interesting example: **fractal plasmonic nanolens**

K. Li, M. Stockman, *Phys. Rev. Lett.* **91**, 227402 (2003)



$d_1 = 90nm\ d_2 = 30nm\ d_3 = 10nm$

$g_1 = 9nm\ \mathbf{g_2 = 3nm}$

- The fractal structure produces **highly confined enhancement**
- Fabricating fractal lenses is extremely challenging

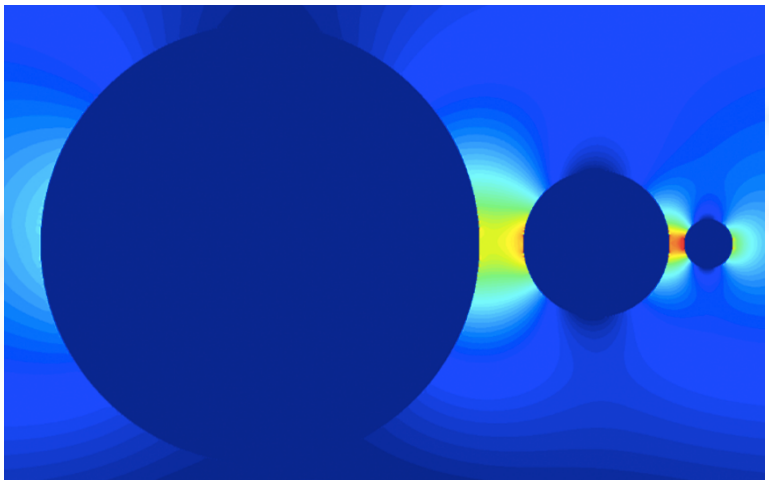
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Average **E** distribution, Wavelength=525nm

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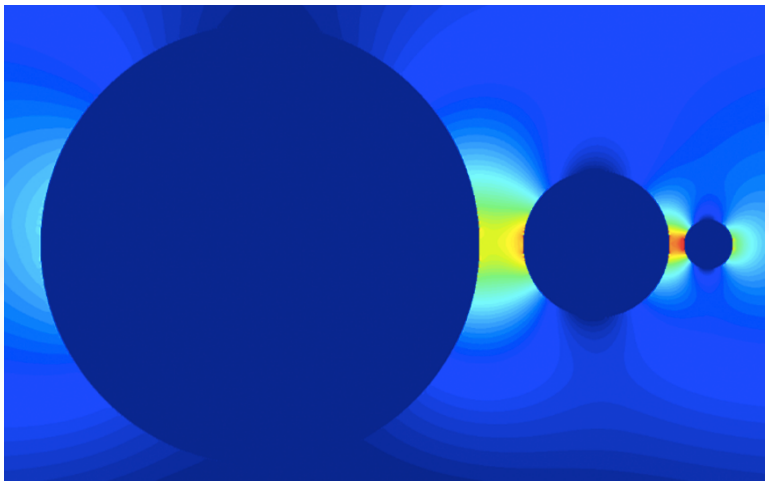
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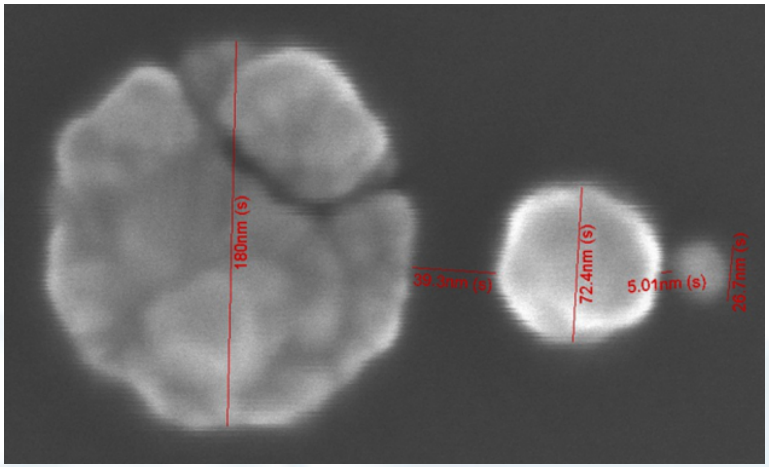
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SEM image of state-of-the-art fabricated sample

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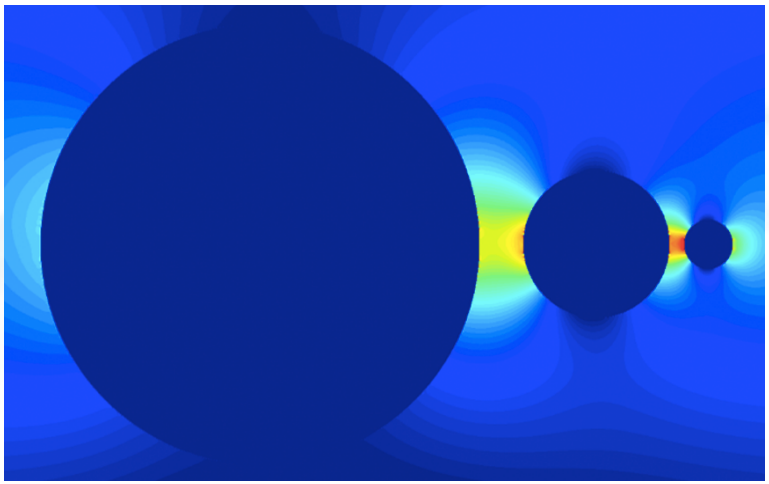
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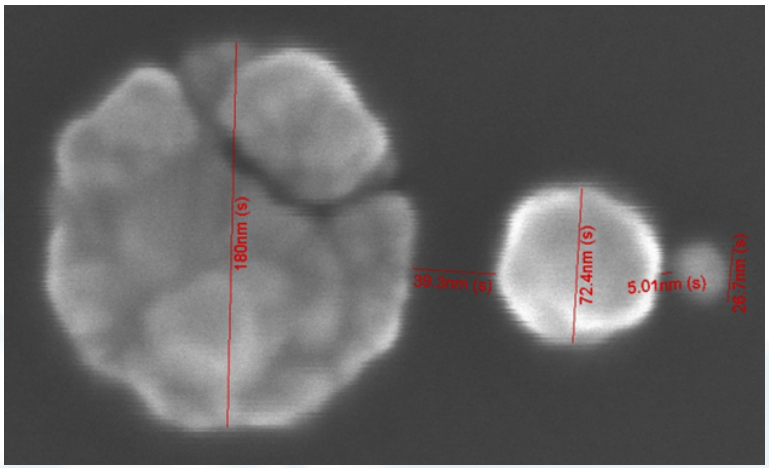
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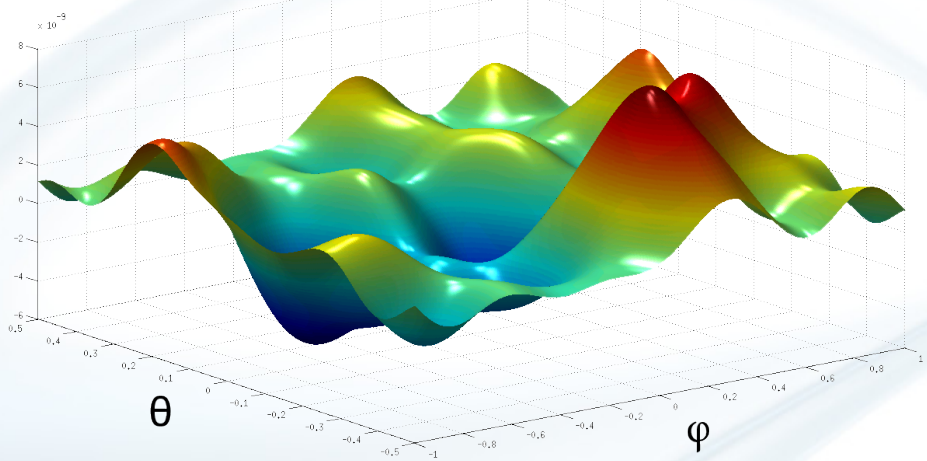
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Realistic surface roughness

Modeling fabrication disorder

Realistic corelated disorder model

$$\delta r(\theta,\varphi) = \int d\xi d\eta R_{\Delta}(\xi-\theta,\eta-\varphi)\exp\left(-\frac{\theta^2+\varphi^2}{2c_l^2}\right)$$



Using our model we can control the roughness and the spatial correlation

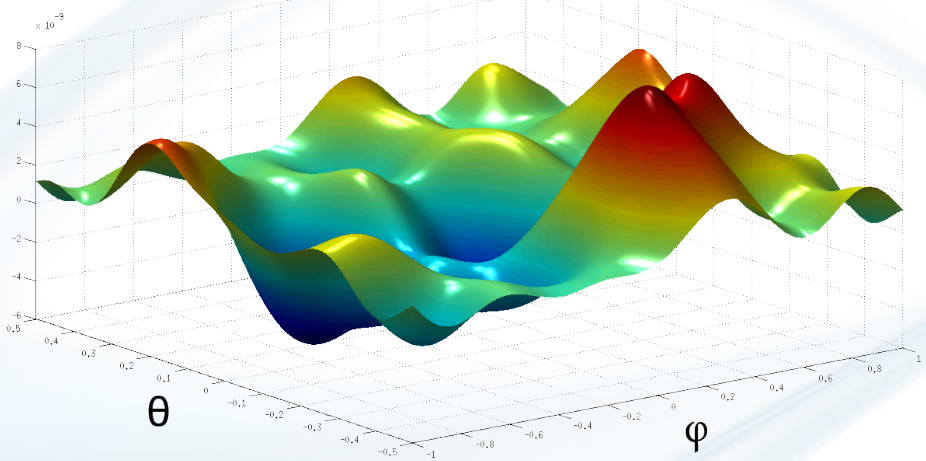
Full control of disorder $\Longrightarrow$ Matching of experimental samples

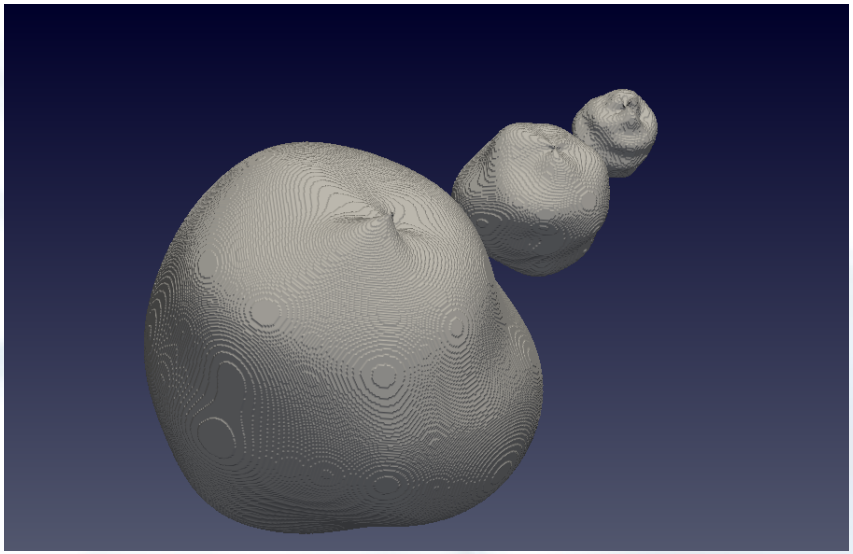
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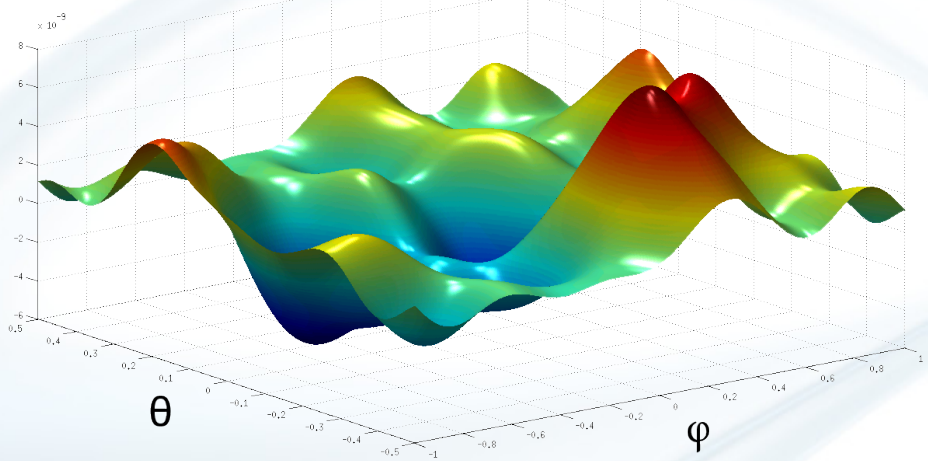
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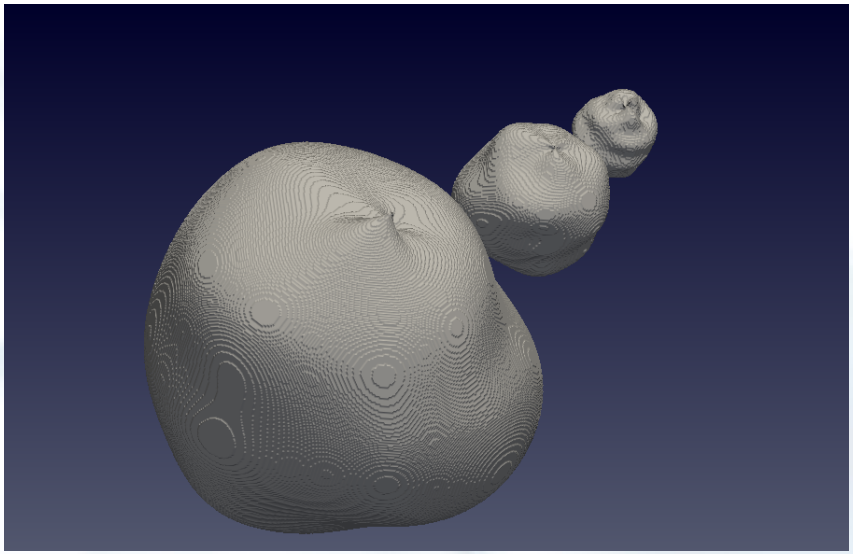
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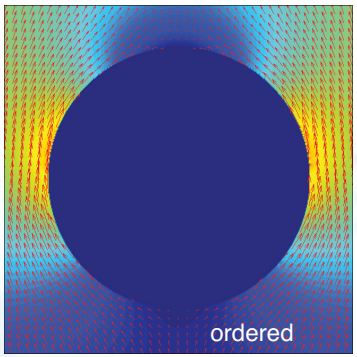


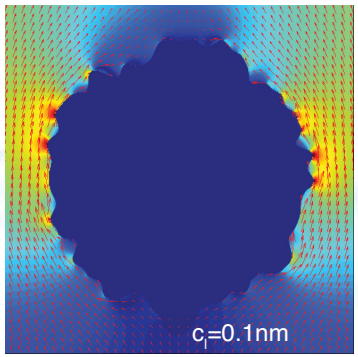
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Theoretical analysis: scattering of a disordered sphere

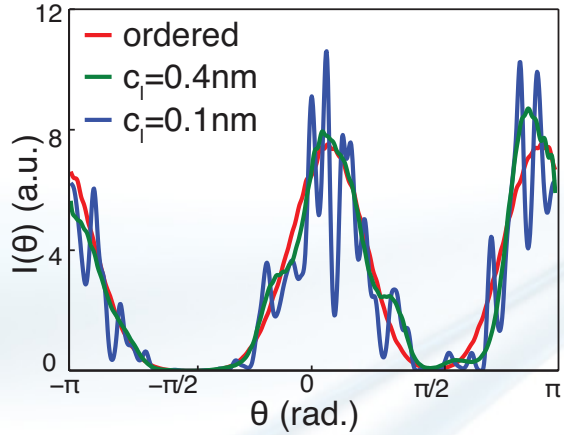
Near-field properties of a single disordered nanosphere

Let's first examine the scattering of single **disordered sphere**





Field and poyinting vector distribution



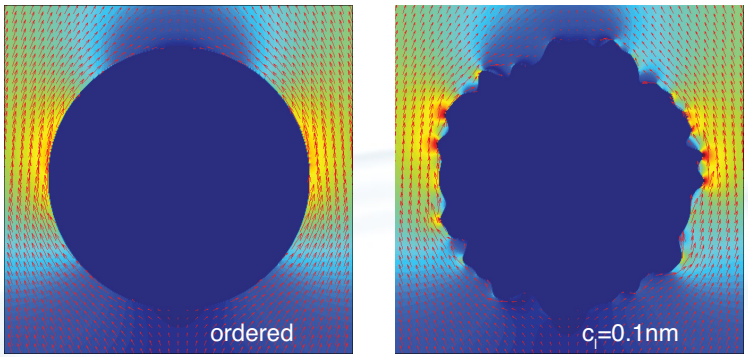
Near-field angular intensity

- FDTD simulations for different disorder realizations
- Disorder enhancement is confined to the near-field

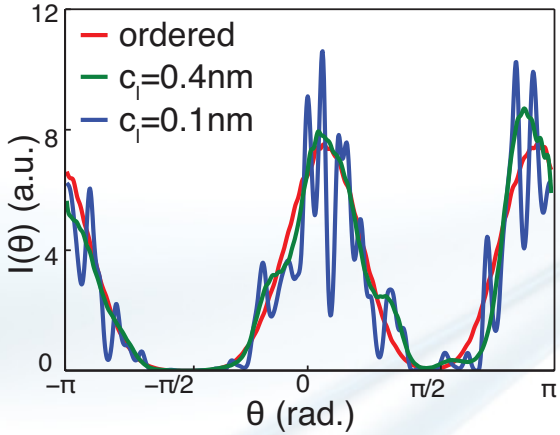
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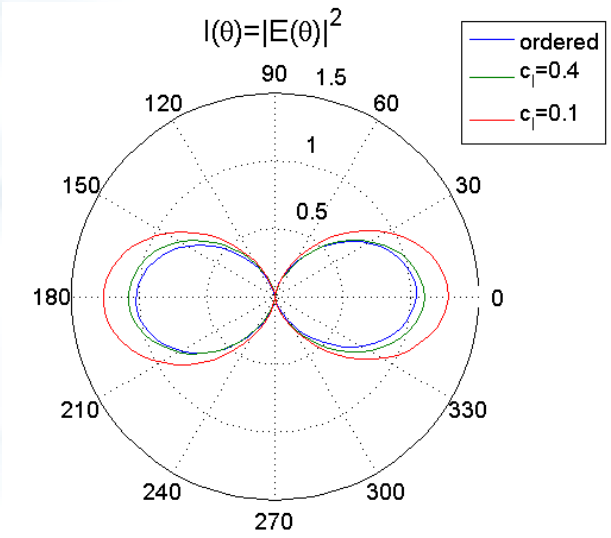


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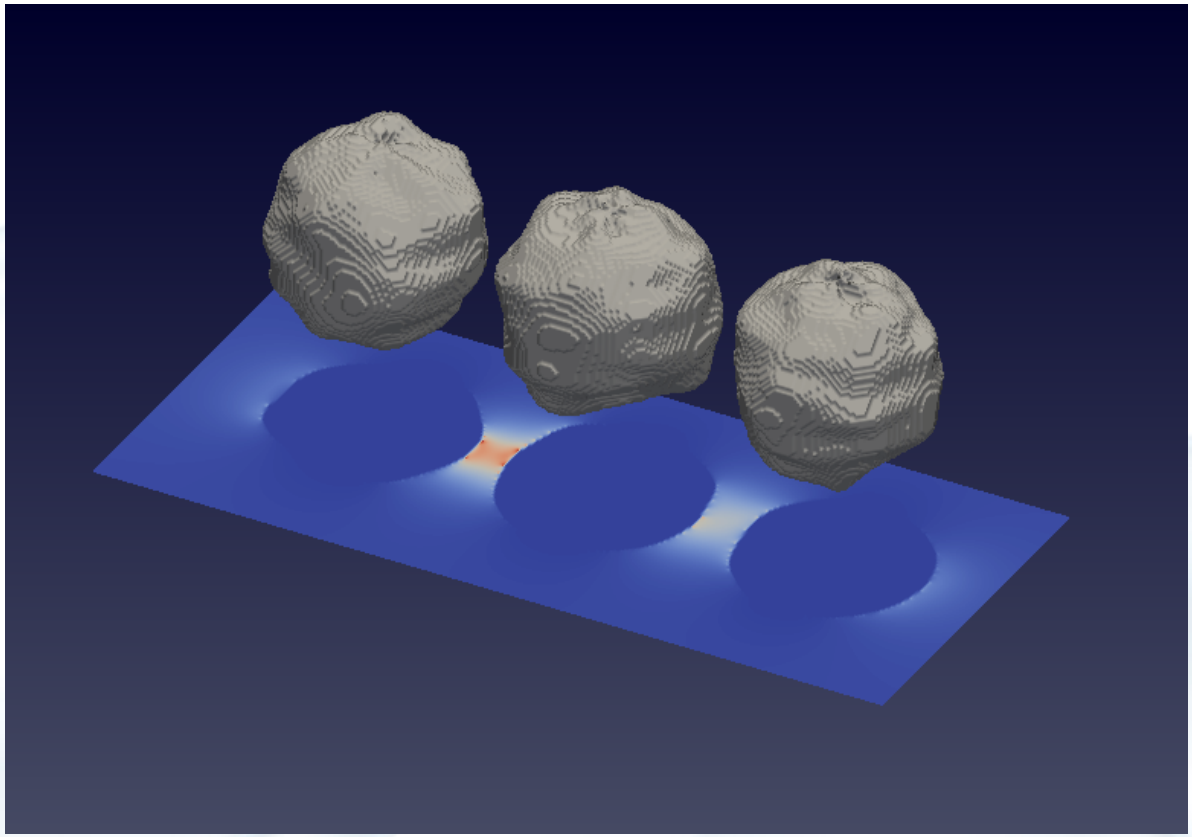


Far-field distribution

Theoretical analysis: chain of equal spheres

Interaction between SPPs distributions

A single sphere is not so interesting... Let's consider a composite system

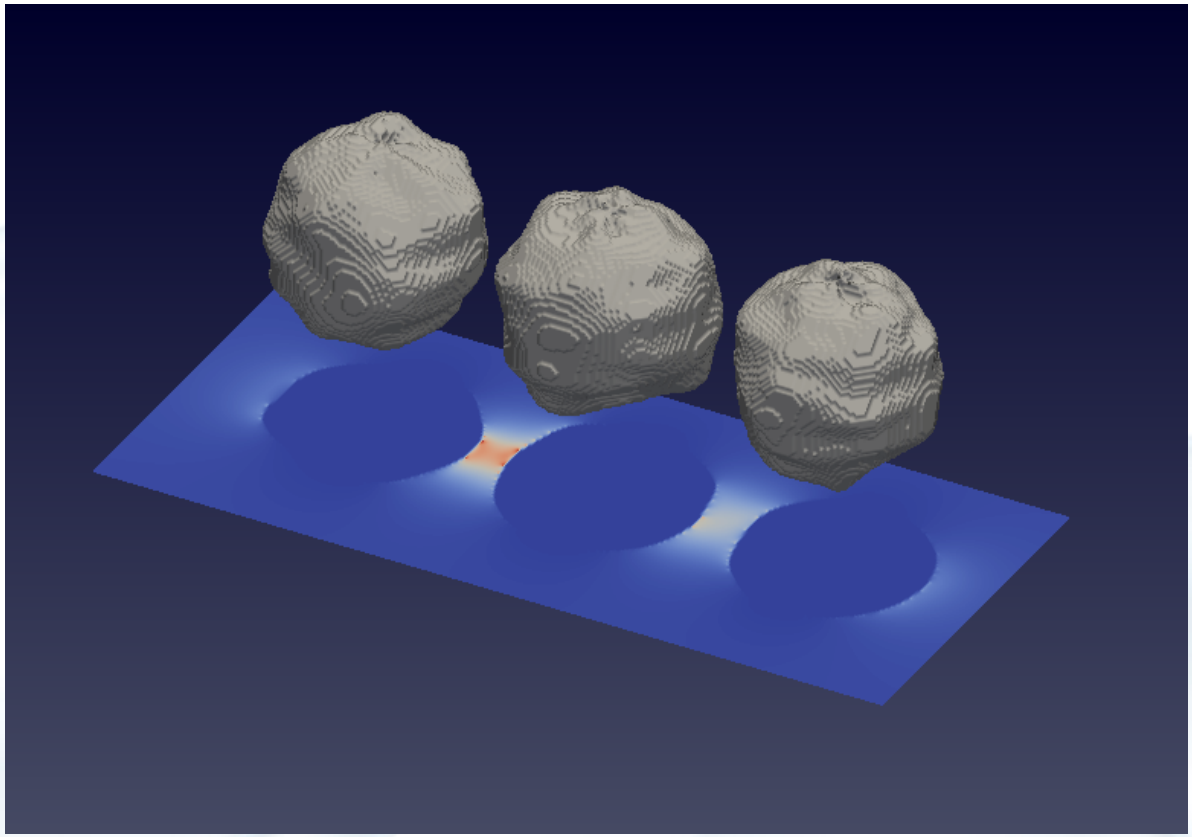


- Identical spheres with different disorder realizations
- The SPPs distributions interact and produce **enhancement**

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Results from FDTD simulations

Disorder-enhanced plasmonic nanolenses

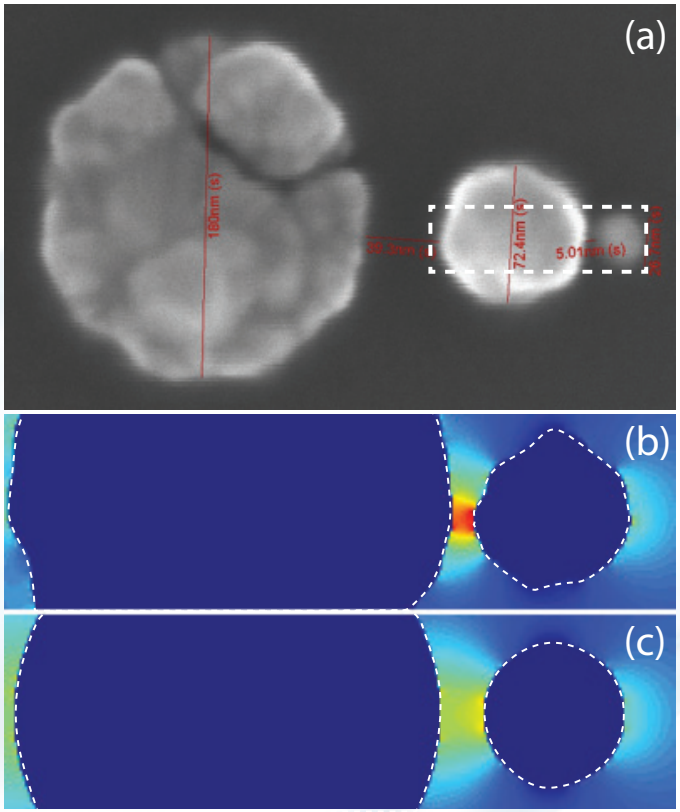
Plasmonic nanolens : geometrical parameters from **SEM images**

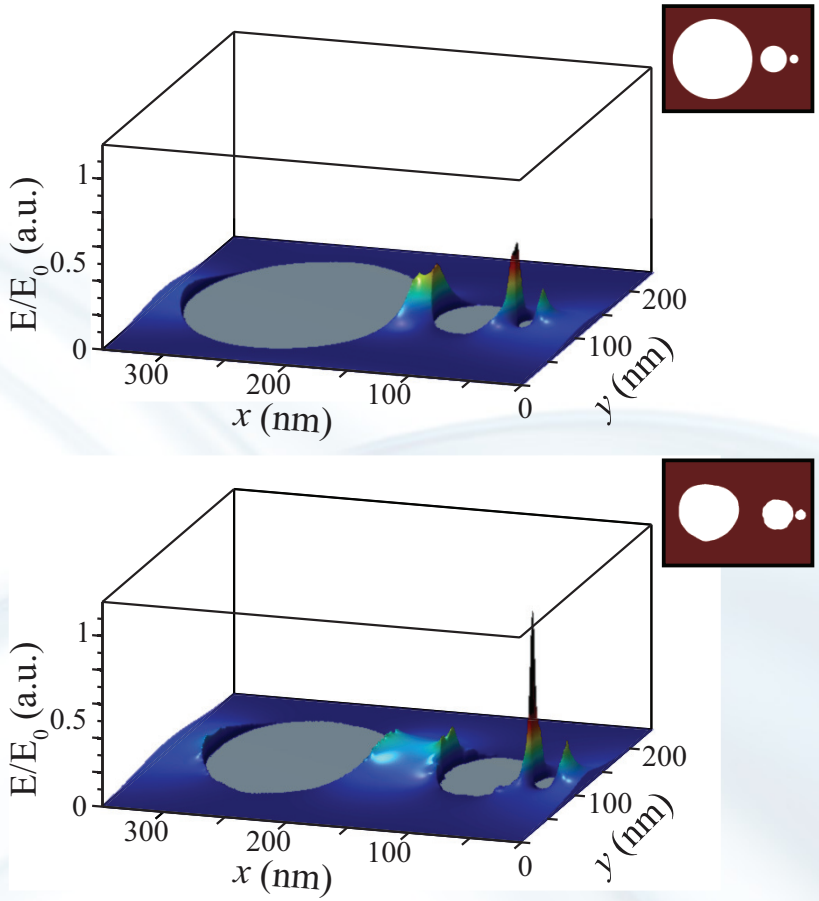
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Plasmonic nanolens : geometrical parameters from **SEM images**

Disorder **enhances** nanofocusing

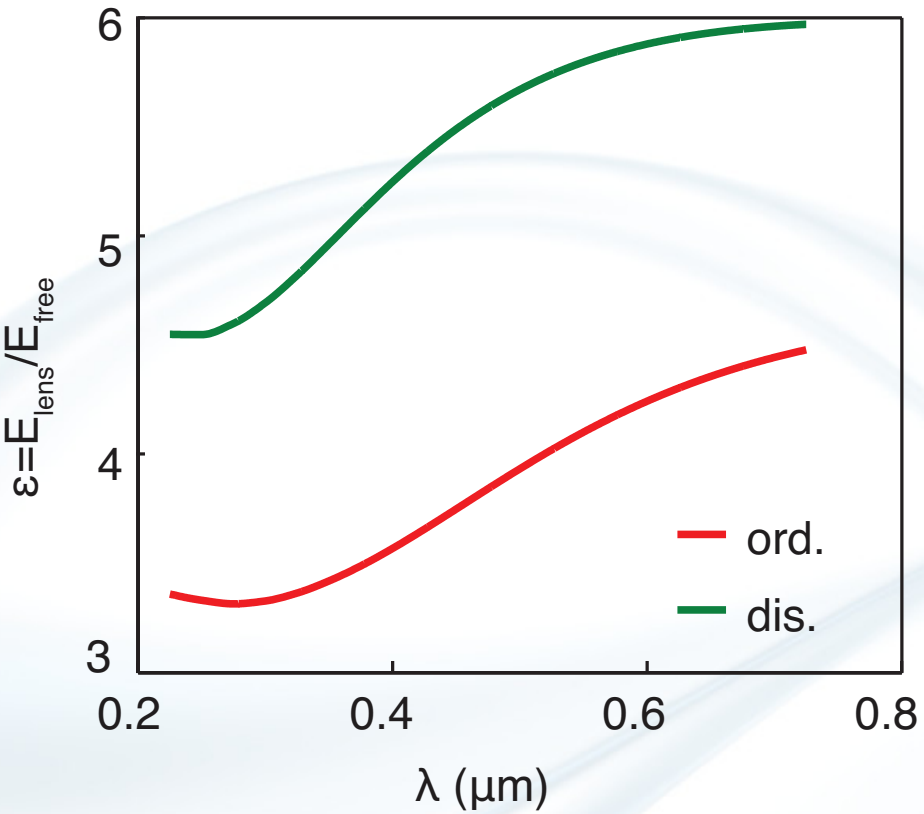




BUT, How can we be sure this is not due to some lucky configuration?

Results from FDTD simulations

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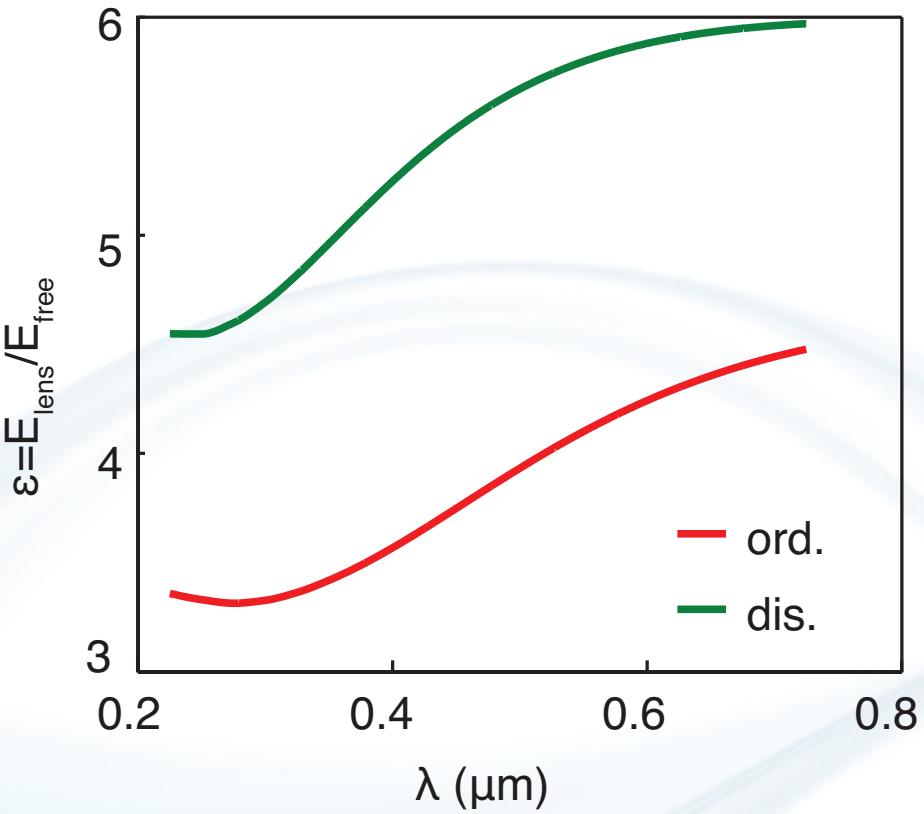


We have access to a **full population** of realistic samples

- Quantity of interest:
  ratio between gaps
- **Statistical campaign**
  200 realizations per wavelength
- The enhancement is statistically significant
  Standard deviation between 0.3 and 0.5

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The presence of disorder strongly enhances the focusing properties of the fractal nanolens

Analytic Device Including Nanostructures - Patent App. No. 61/920,725

Further developments and applications

Single molecule spectroscopy applications

- We exploited the high enhancement to perform advanced **single molecule** spectroscopy
- In particular, we have observed that we can distinguish single molecules in low concentration peptides mixtures from breast cancer
- The strong performance of our device is directly related to the interplay between metallic geometry and fabrication roughness
- Our work is currently under review, and will be published in the following months

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Single molecule spectroscopy applications

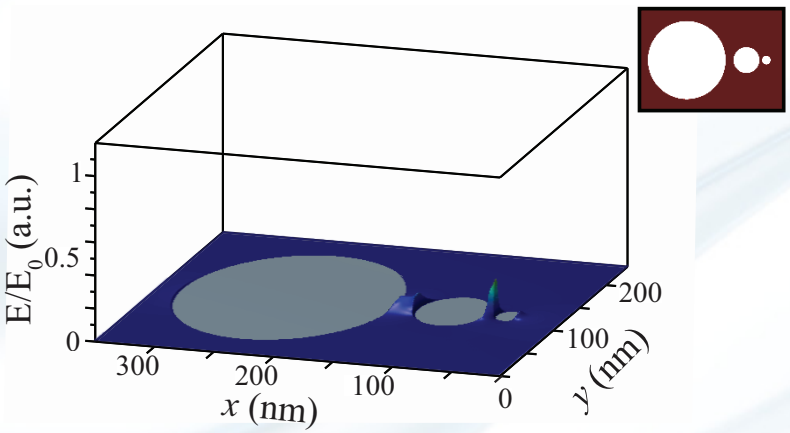
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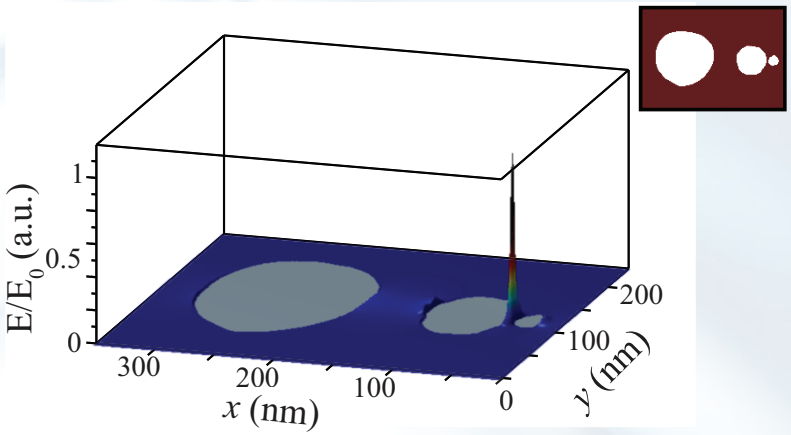
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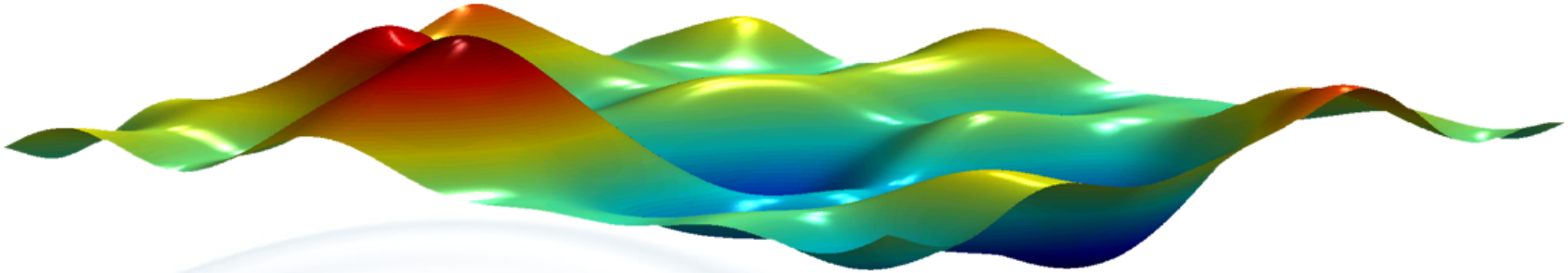
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Raman intensity $\longrightarrow I_{Raman} \propto |E|^4$



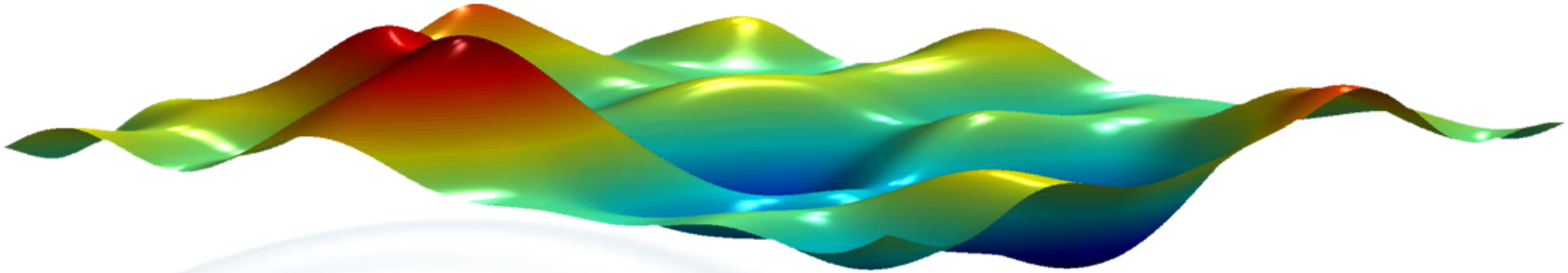


Conclusions



- Plasmonic devices enable advanced spectroscopy techniques as in the case of SERS spectroscopy
- We focused on the role of fabrication disorder in a state-of-the-art plasmonic nanolens
- Interestingly, we showed how the natural roughness arising from fabrication can enhance the performance of **state-of-the-art plasmonic nanolenses**
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Thanks for your attention!