Analysis of the Optical Response of Periodic Arrays of Nanostructures

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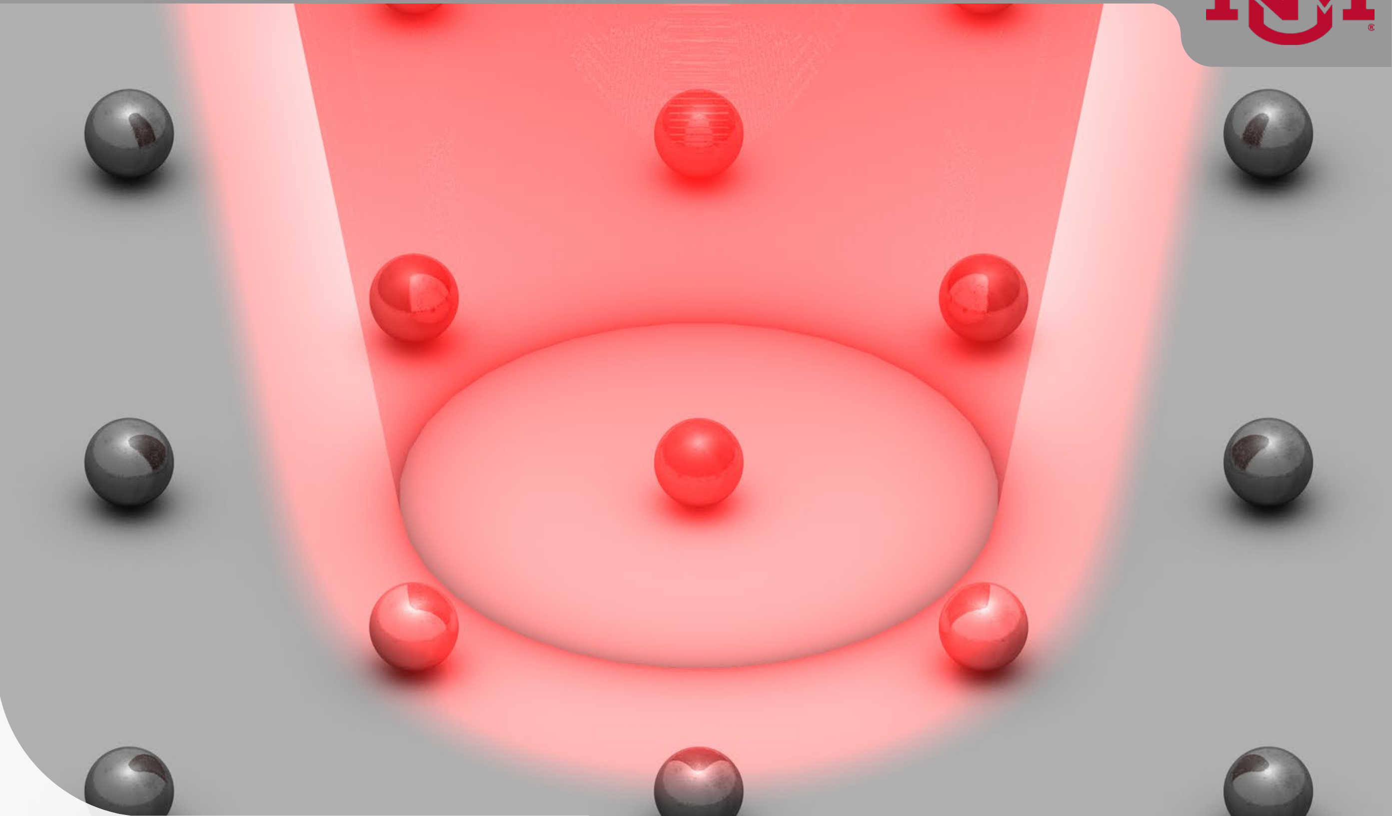
nanophotonics.unm.edu

Nanophotonics: the study of light-matter interactions at the nanoscale.

My research has mainly focused on the response of periodic arrays of nanostructures.

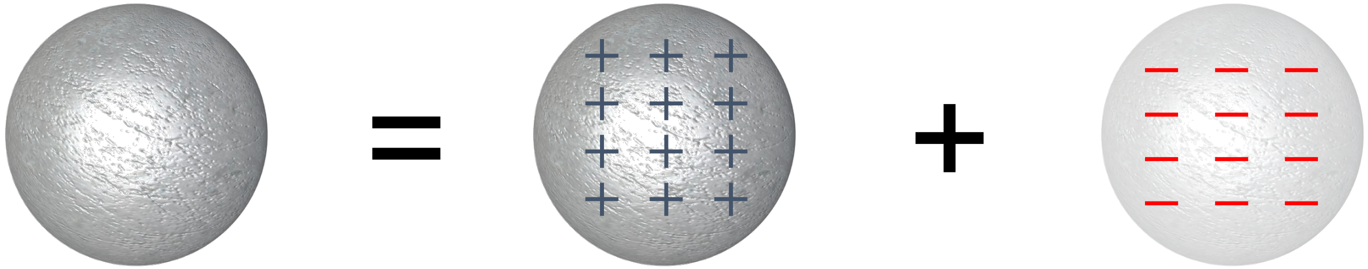
I have investigated the following problems:

- How can we manipulate the optical response of a periodic array?
- How does the nature of the excitation source affect the response of a periodic array?
- What opportunities do periodic arrays offer when excited by different sources?



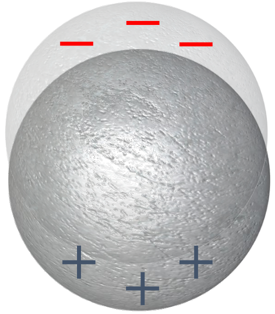
What are surface plasmons?

Surface plasmons are collective excitations of the conduction electrons of a metal coupled to an electromagnetic field



Metal sphere = Positive charge distribution + Free electron cloud

External electromagnetic field



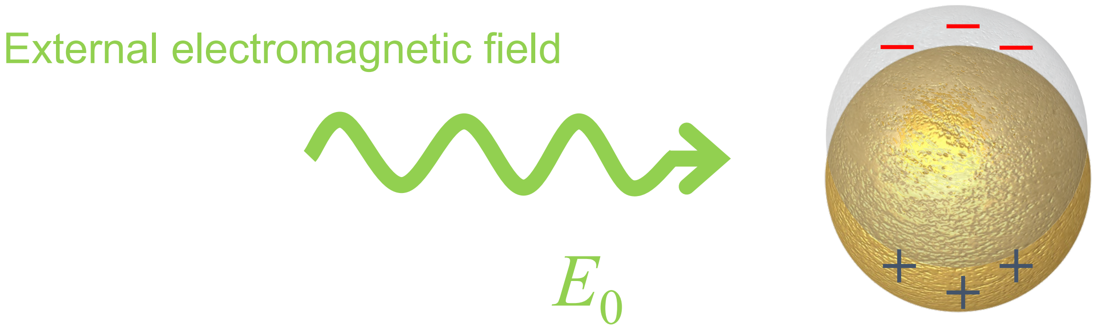
Charge displacement

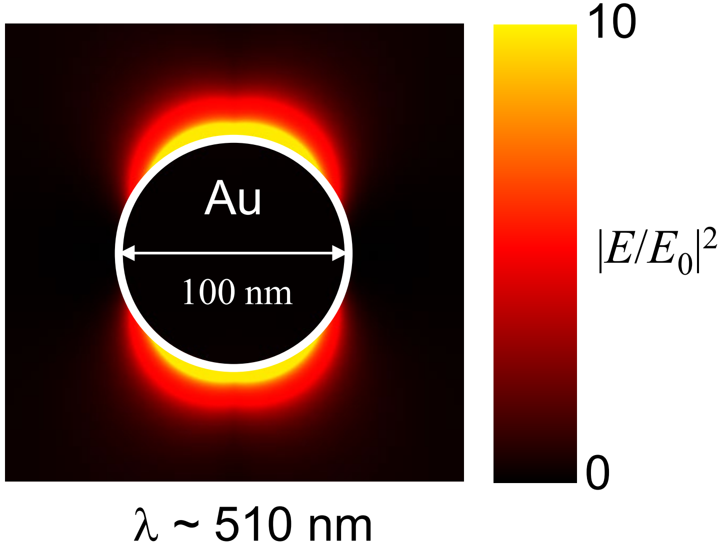
Coulomb restoring force

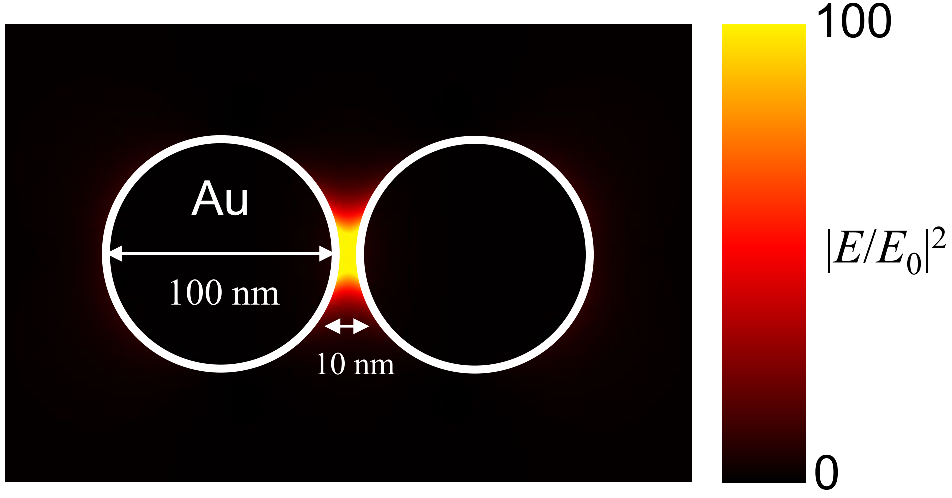
System resonance

Localized surface plasmon

Surface plasmons are collective excitations of the conduction electrons of a metal coupled to an electromagnetic field

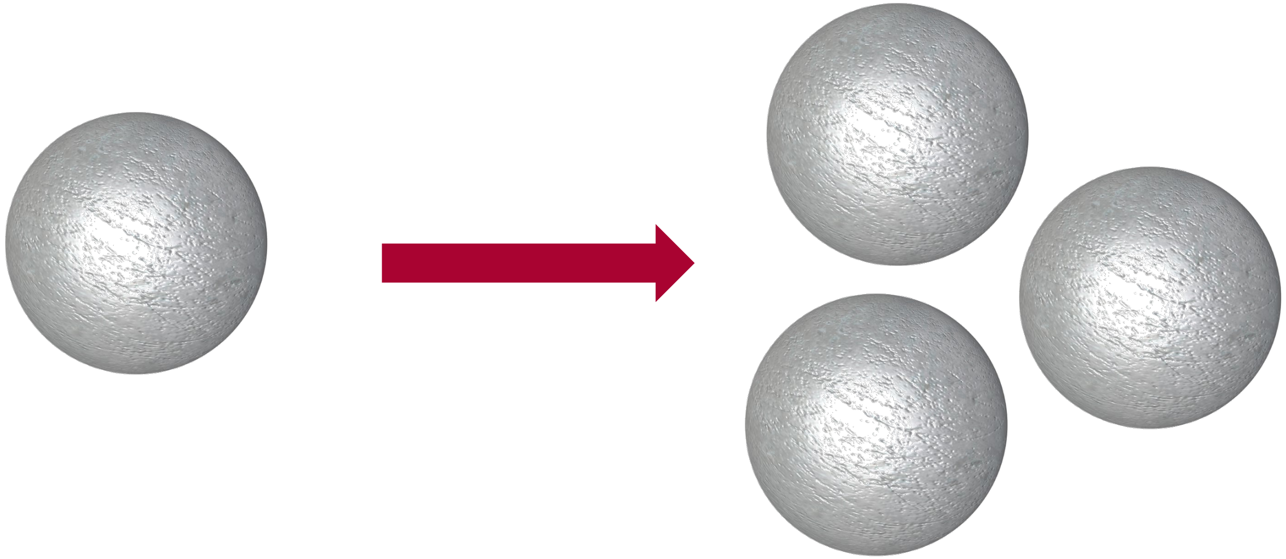


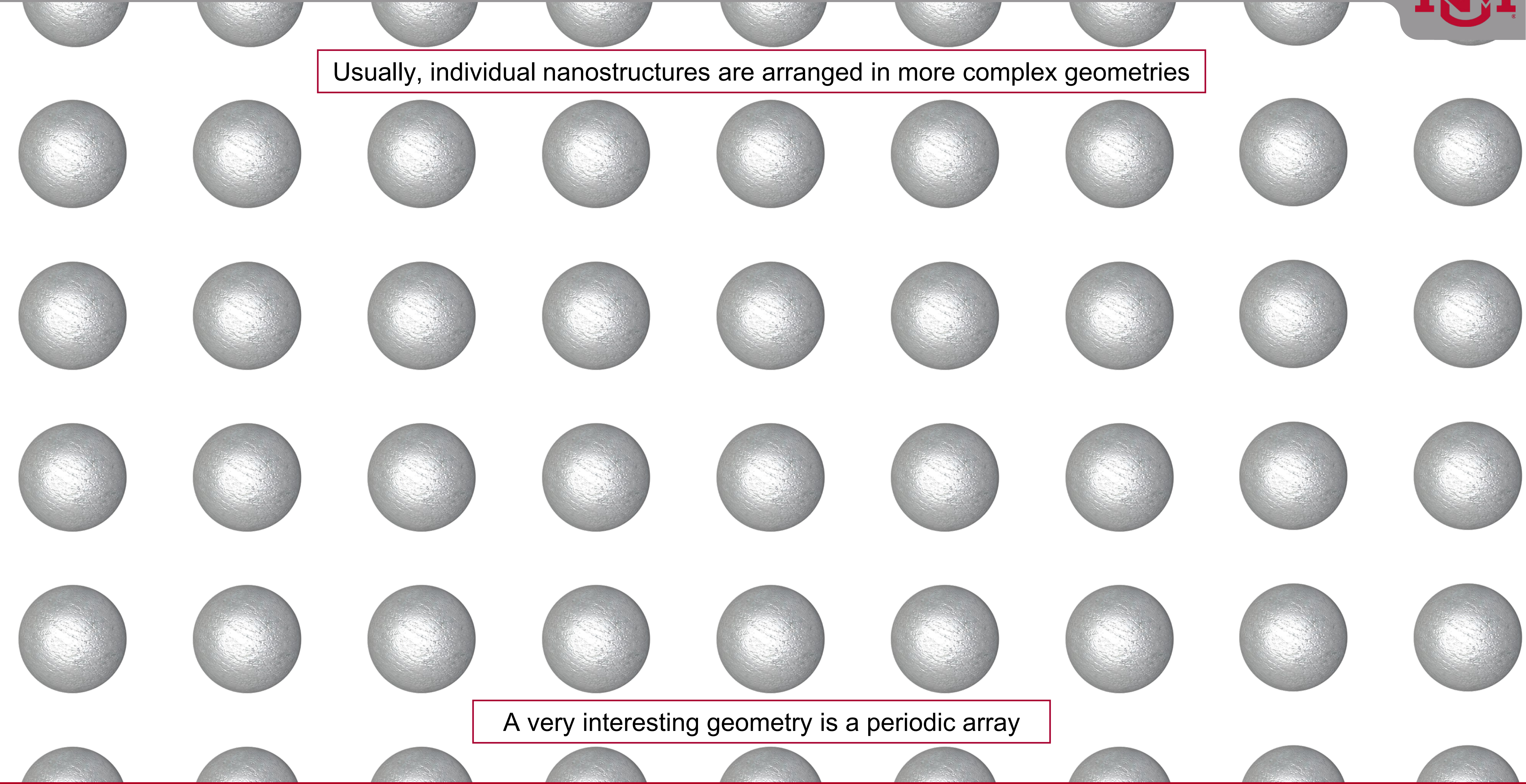




Surface plasmons interact strongly with light and confine it into subwavelength regions

Usually, individual nanostructures are arranged in more complex geometries

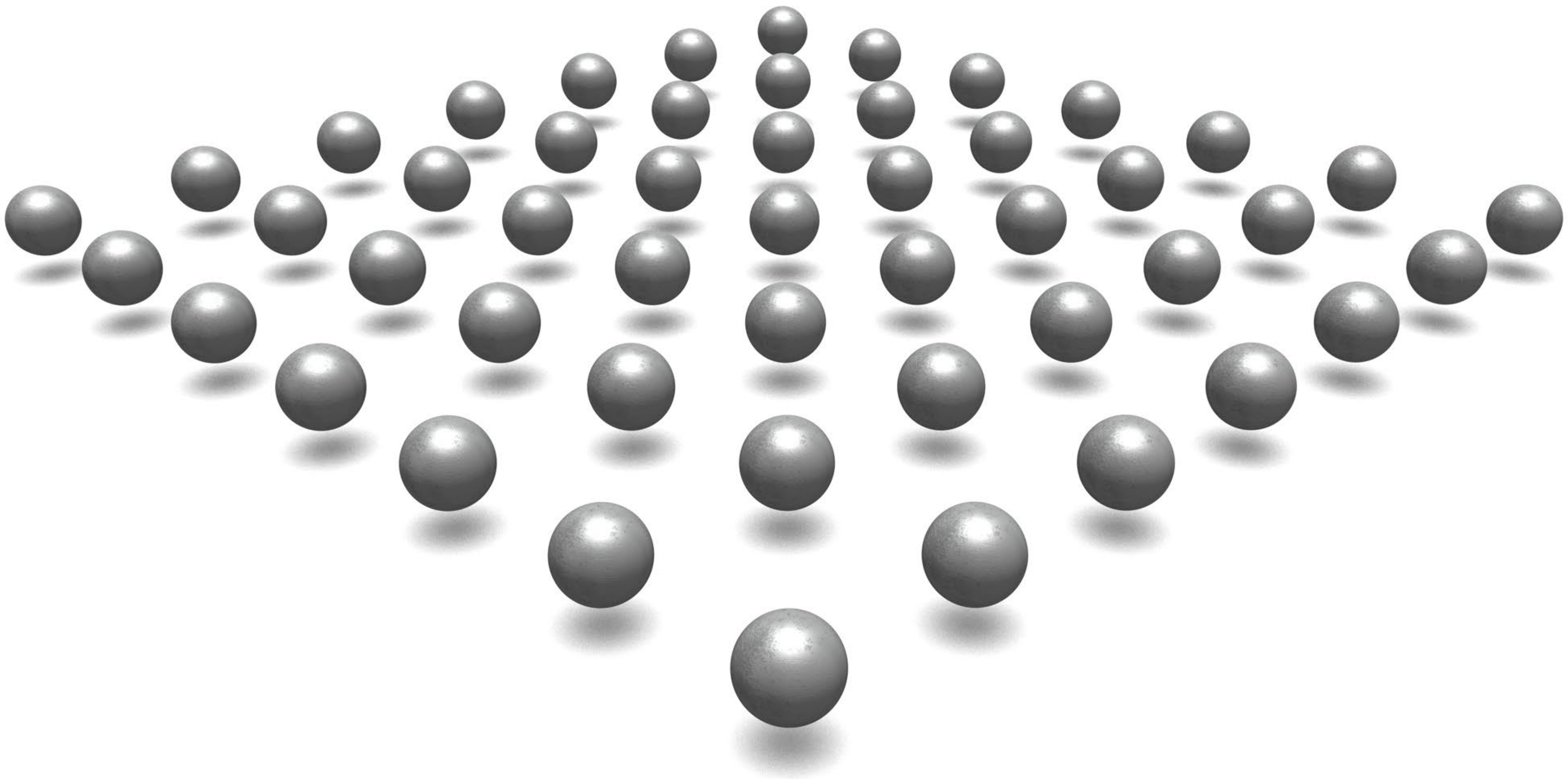




Usually, individual nanostructures are arranged in more complex geometries

A very interesting geometry is a periodic array

These systems support collective resonances known as Lattice Resonances (LR)



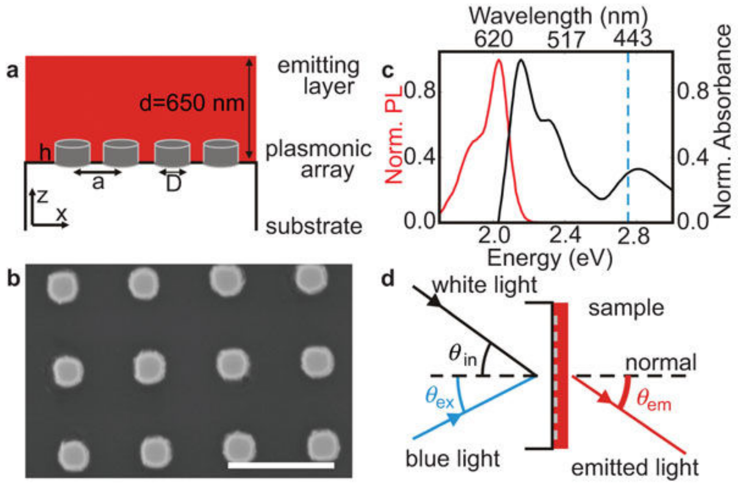
Lattice resonances give rise to strong and spectrally narrow optical responses

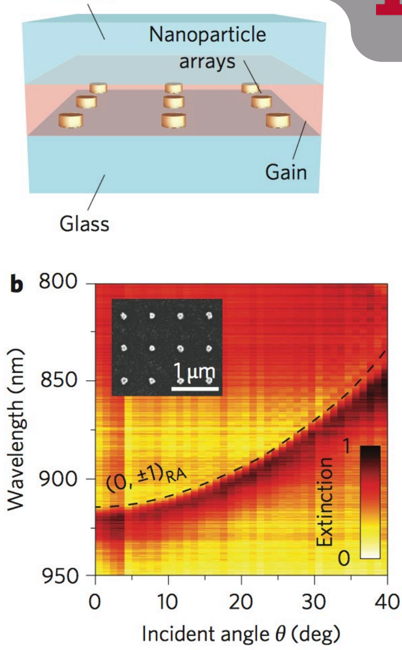
Periodic arrays of plasmonic nanoparticles have been studied extensively

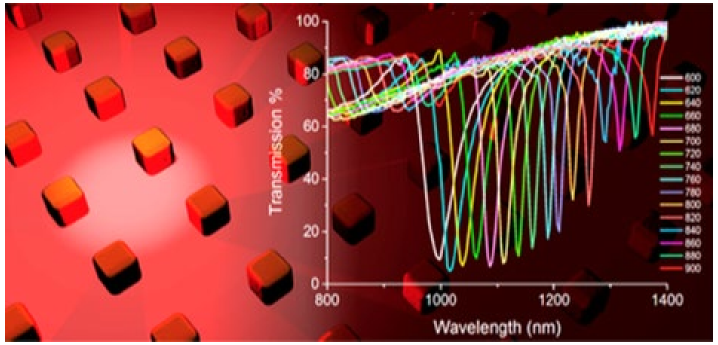
- Nanoscale light sources
  - G. Lozano, D. J. Louwers, S. R. K. Rodriguez, et al., **Light Sci. Appl.** (2013)
  - W. Zhou, M. Dridi, J. Y. Suh, et al., **Nat. Nanotech.** (2013)
  - A. H. Schokker, A. F. Koenderink, **Phys. Rev. B** (2014)
  - T. K. Hakala, H. T. Rekola, A. I. Väkeväinen, et al., **Nat. Commun.** (2017)
- Biosensing
  - B. D. Thackray, V. G. Kravets, F. Schedin, et al., **ACS Photonics** (2014)
  - A. Danilov, G. Tselikov, F. Wu, et al., **Biosens. Bioelectron.** (2018)
- Color printing
  - J. Olson, A. Manjavacas, T. Basu, et al., **ACS Nano** (2015)
  - A. Kristensen, J. K. W. Yang, S. I. Bozhevolnyi, et al., **Nat. Rev. Mat.** (2016)
- Bose-Einstein condensates
  - T. K. Hakala, A. J. Moilanen, A. I. Väkeväinen, et al., **Nat. Phys.** (2018)

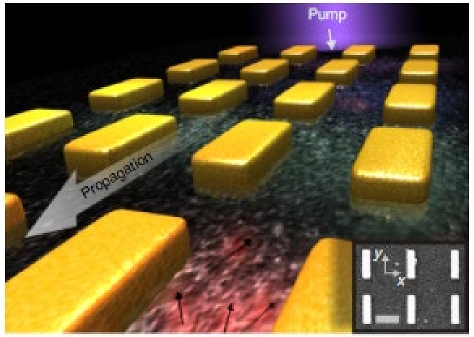
See the reviews:

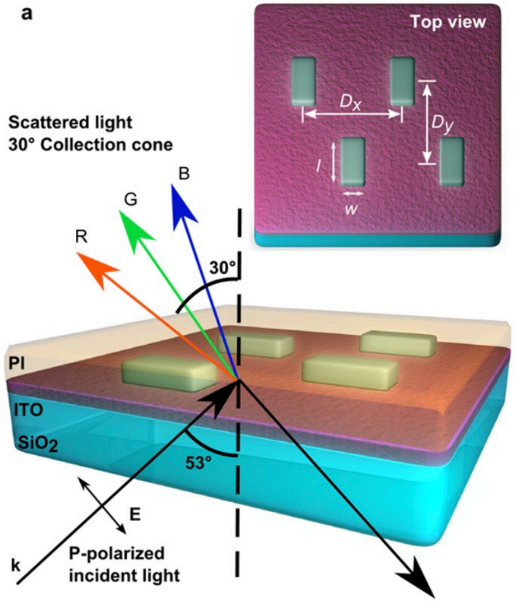
F. J. García de Abajo, **Rev. Mod. Phys.** (2007)
W. Wang, M. Ramezani, A. Väkeväinen, et al., **Mater. Today** (2018)
V. Kravets, A. Kabashin, W. Barnes, et al., **Chem. Rev.** (2018)
A. Utyushev, V. Zakomirnyi, and I. Rasskazov, **Reviews in Physics** (2021)



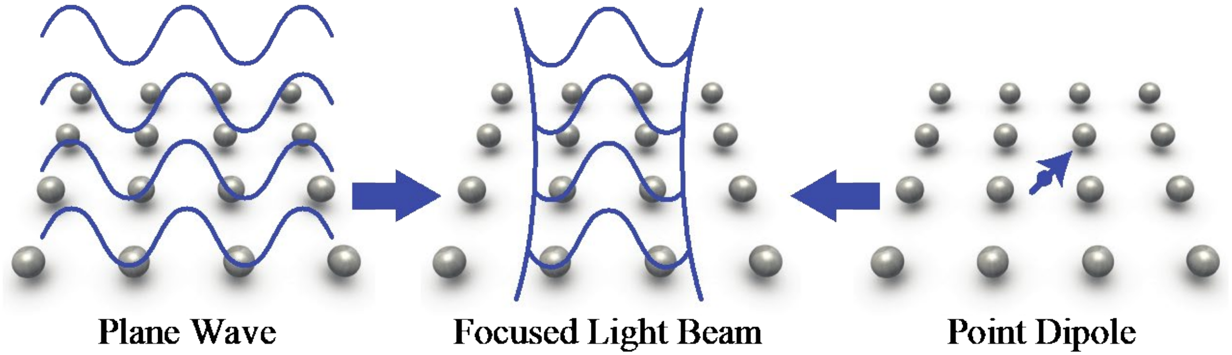






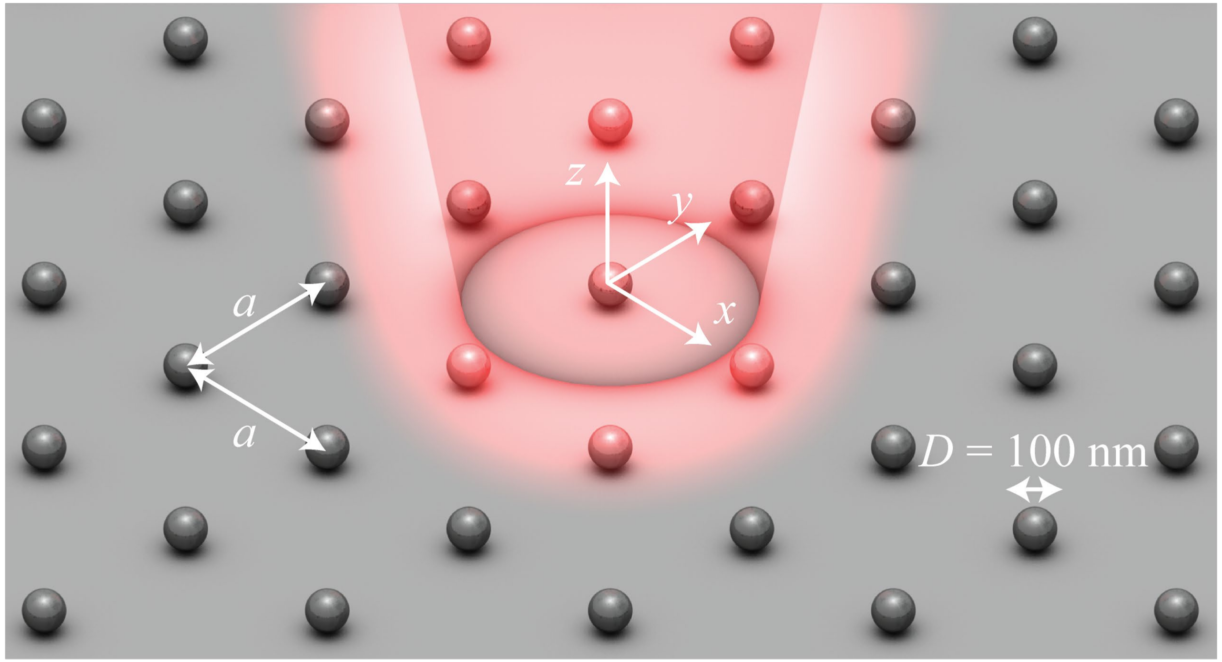


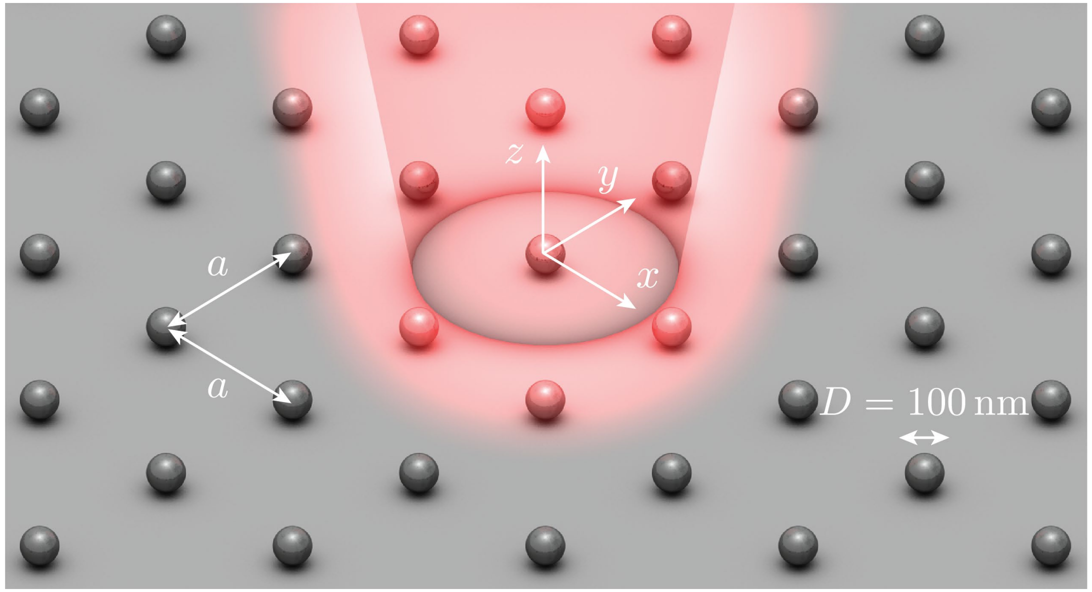
The response of arrays to plane waves has been studied extensively.

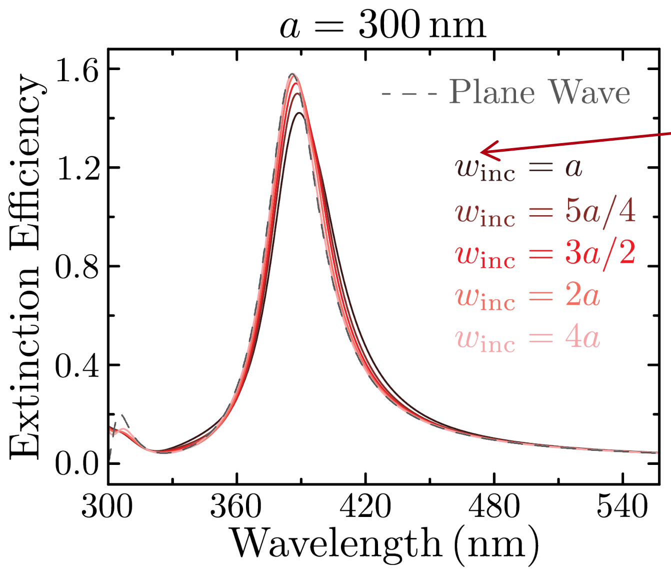


We have recently studied the excitation of arrays by localized sources.

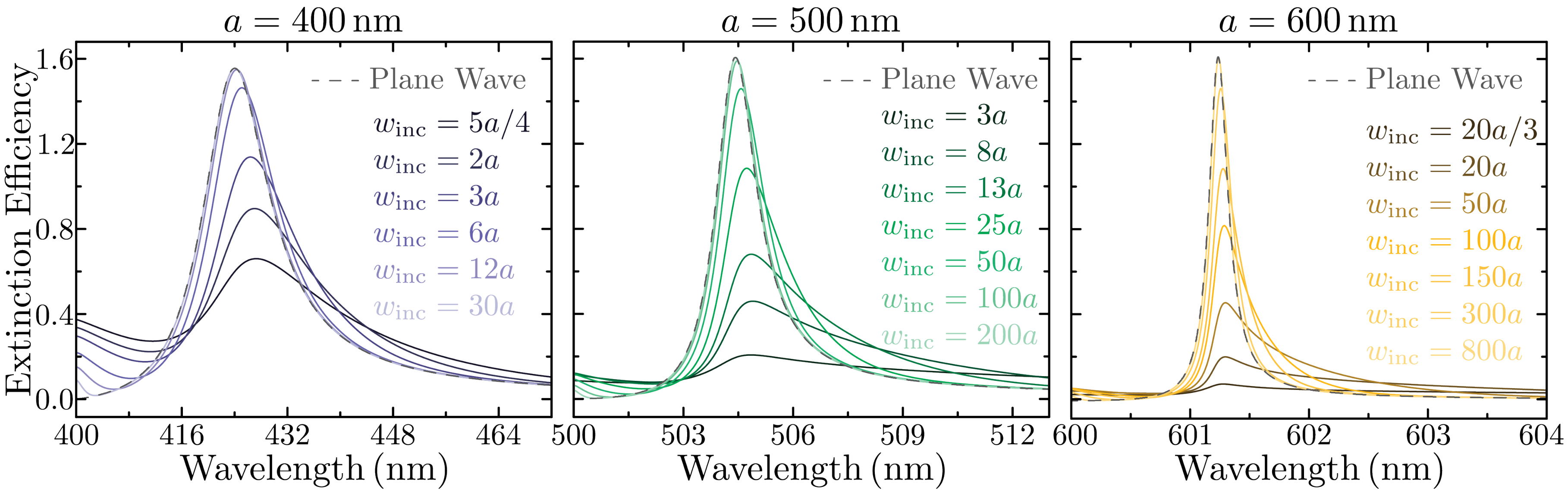
These represent two extremes… but what happens in the middle?



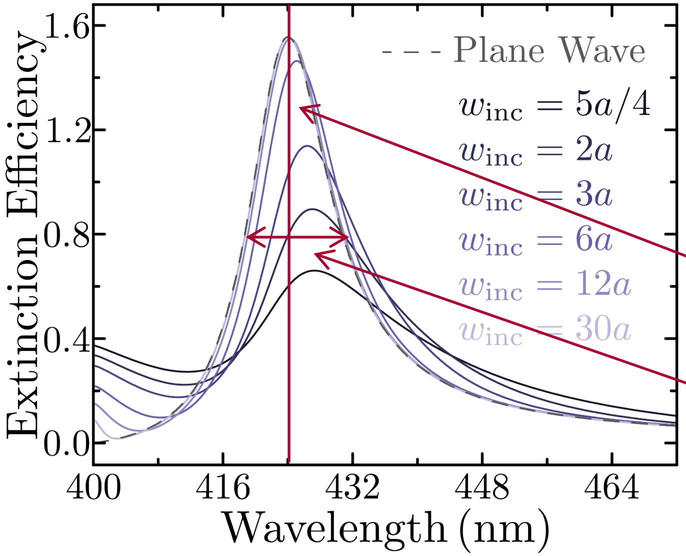




Controls width of light beam



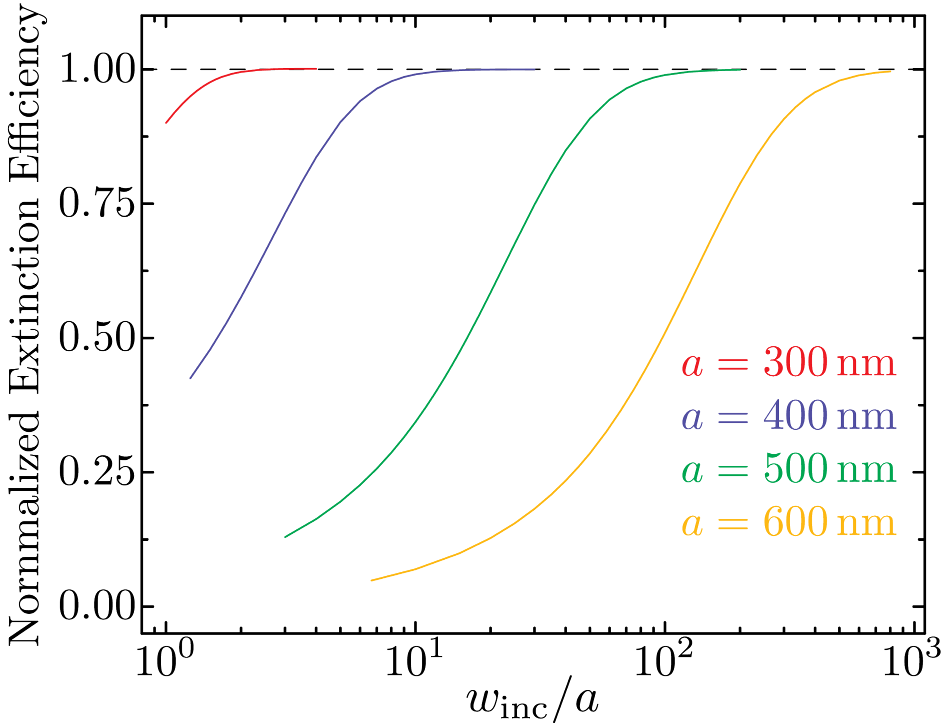
Wider beams are needed to excite the lattice resonances of arrays with larger periods

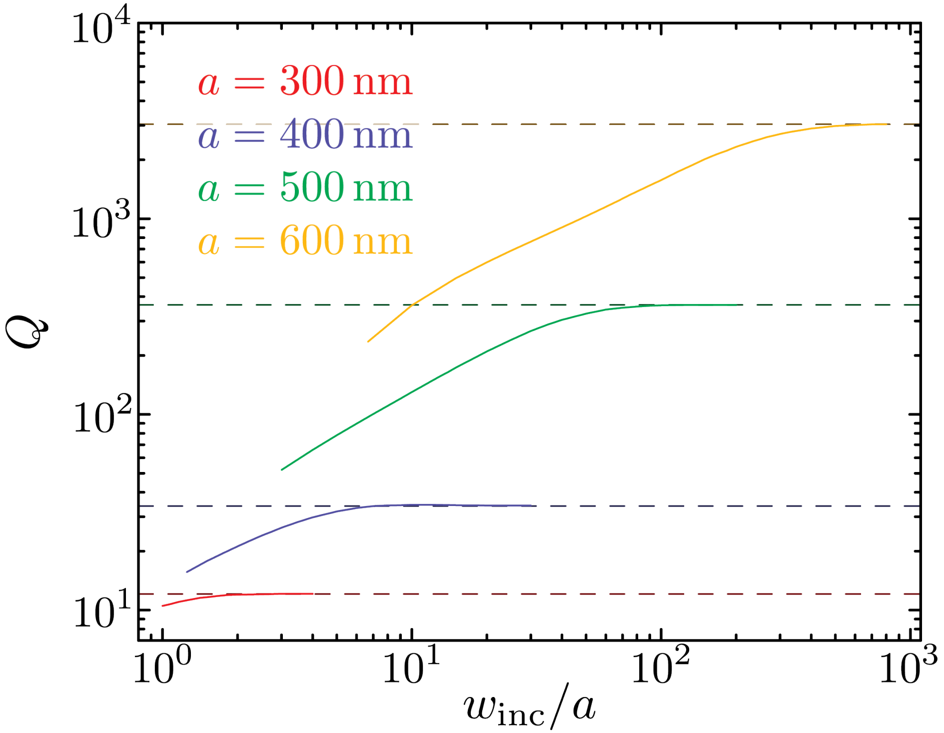


Changing w_{inc} affects two primary aspects of the optical response of the array:

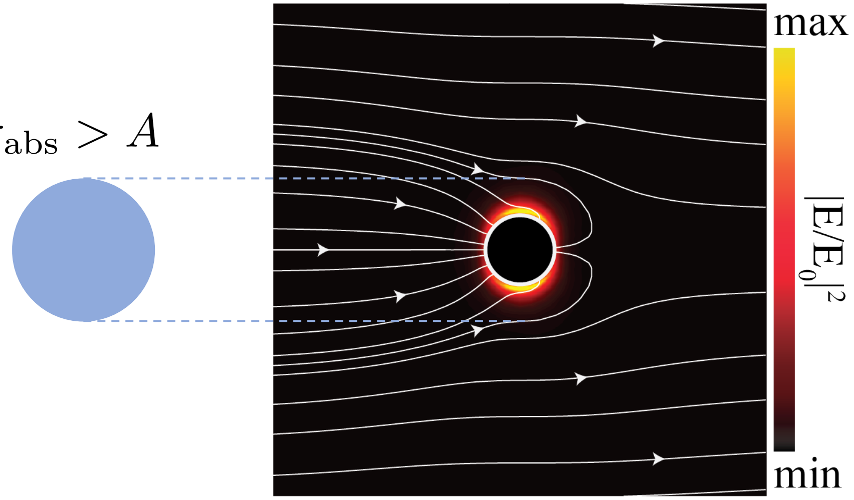
- Maximum extinction efficiency, which grows with w_{inc}
- Width of the resonance, which shrinks with w_{inc}

$$Q = \frac{\lambda_{LR}}{\text{FWHM}}$$





$\sigma_{\text{abs}} > A$



Nanoparticles supporting plasmons have very large absorption cross-sections

This makes them excellent at transducing light into heat → Thermoplasmonics

Thermo-plasmonics: using metallic nanostructures as nano-sources of heat

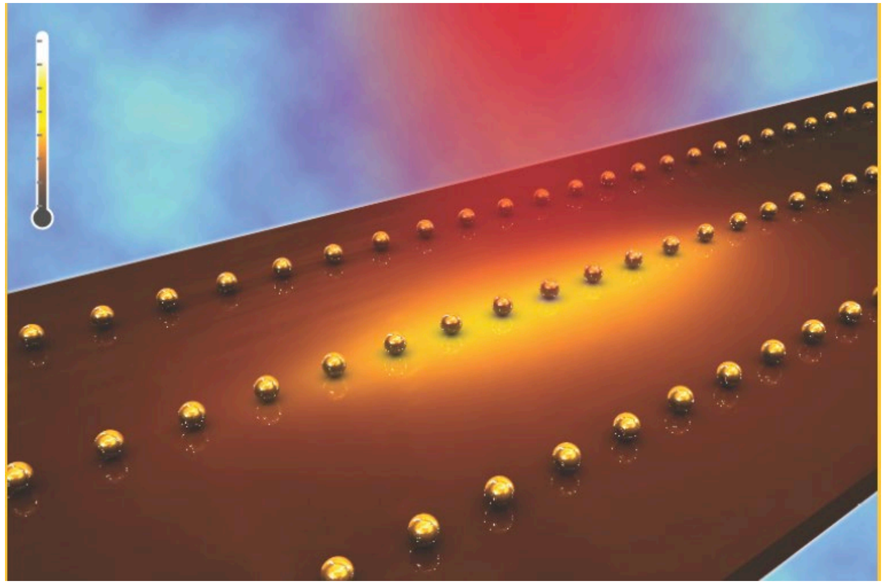
Guillaume Baffou[1,*] and Romain Quidant[2,3,*]

LASER & PHOTONICS REVIEWS

Applications and challenges of thermoplasmonics

Guillaume Baffou[1], Frank Cichos[2] and Romain Quidant[3,4,5]

nature materials



- Cancer therapy

PNAS

Gold nanoshell-localized photothermal ablation of prostate tumors in a clinical pilot device study

Ardeshir R. Rastinehad[a,b,1], Harry Anastos[a], Ethan Wajswol[a], Jared S. Winoker[a], John P. Sfakianos[a], Sai K. Doppalapudi[a], Michael R. Carrick[b], Cynthia J. Knauer[a], Bachir Taouli[b], Sara C. Lewis[b], Ashutosh K. Tewari[a], Jon A. Schwartz[c], Steven E. Canfield[d], Arvin K. George[e], Jennifer L. West[f], and Naomi J. Halas[g,1]

- Drug and gene delivery

Nanobiotechnol (2007) 3:40–45
DOI 10.1007/s12030-007-0005-3

Drug and Gene Delivery using Gold Nanoparticles

Gang Han · Partha Ghosh · Mrinmoy De · Vincent M. Rotello

- Nanoscale welding

iScience

Review

Nanoscale thermoplasmonic welding

Lin Wang,[1] Yijun Feng,[1] Ze Li,[1] and Guohua Liu[1,*]

- Water Desalination

nature photonics LETTERS
PUBLISHED ONLINE: 25 APRIL 2016 | DOI: 10.1038/NPHOTON.2016.75

3D self-assembly of aluminium nanoparticles for plasmon-enhanced solar desalination

Lin Zhou[1,2†], Yingling Tan[1†], Jingyang Wang[1], Weichao Xu[1], Ye Yuan[1], Wenshan Cai[3], Shining Zhu[1] and Jia Zhu[1*]

- Thermophotovoltaics

DE GRUYTER OPEN Nanophotonics 2016; 5 (1):1–21

Review Article Open Access

Zhiguang Zhou*, Enas Sakr, Yubo Sun, and Peter Bermel

Solar thermophotovoltaics: reshaping the solar spectrum

- Epoxy photocuring

ELSEVIER

Plasmonic nanoparticle-based epoxy photocuring: A deeper look

Adam T. Roberts[1,†,‡], Jian Yang[2,‡], Matthew E. Reish[3], Alessandro Alabastri[4], Naomi J. Halas[2,4,5], Peter Nordlander[2,4], Henry O. Everitt[1,4,*]

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Drug and G

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- Thermophotovoltaics

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Open Access

Solar thermophotovoltaics: reshaping the solar spectrum

Can we exploit lattice resonances to advance thermoplasmonics?

- Nanoscale welding

iScience

Review

Nanoscale thermoplasmonic welding

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Absorbance ≈ 0.5 for all a

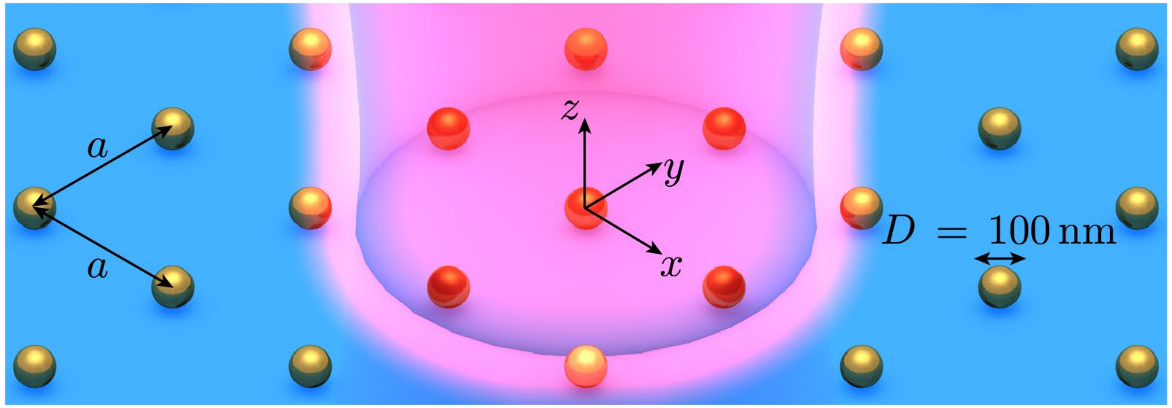
+

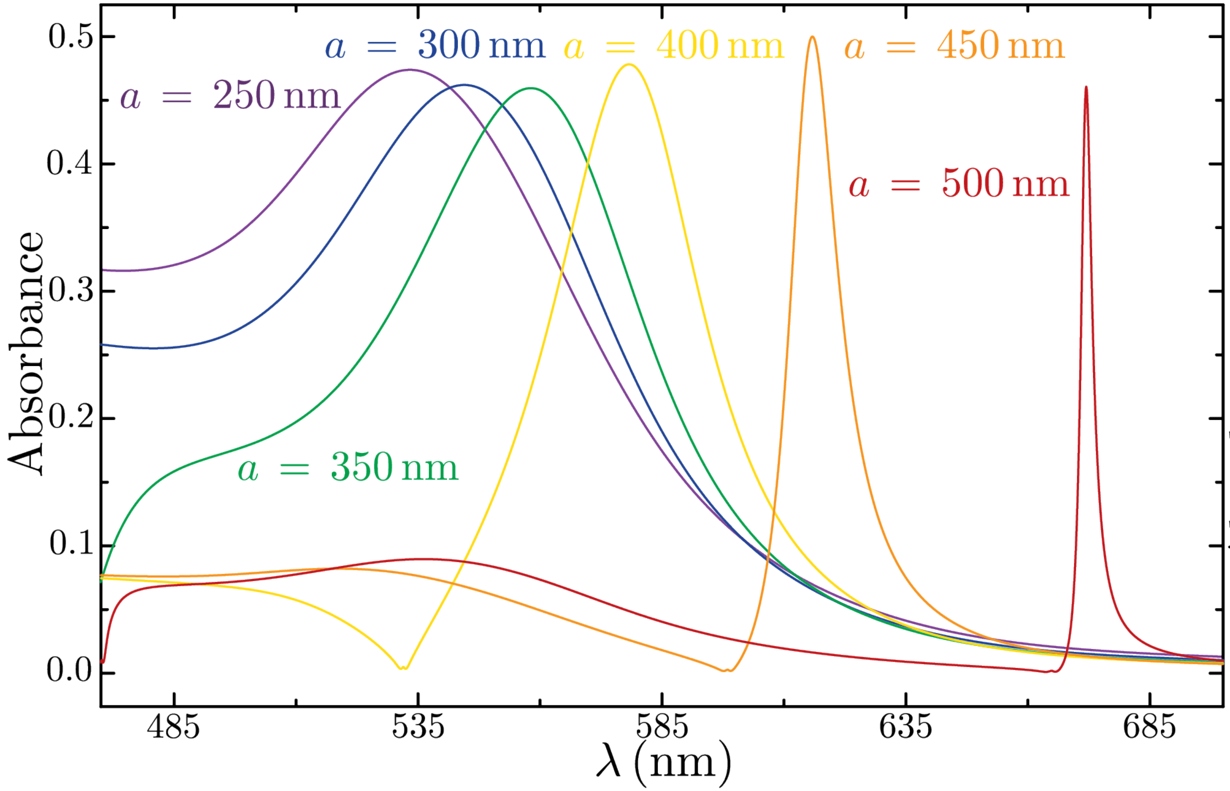
Density of nanoparticles ∝ a^{-2}

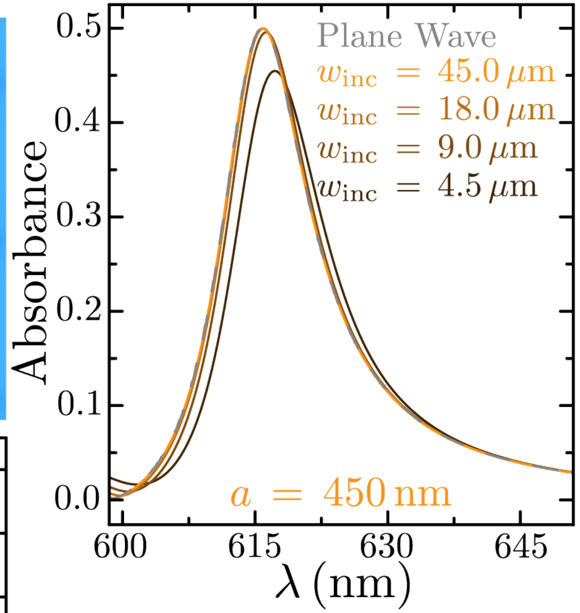
⬇

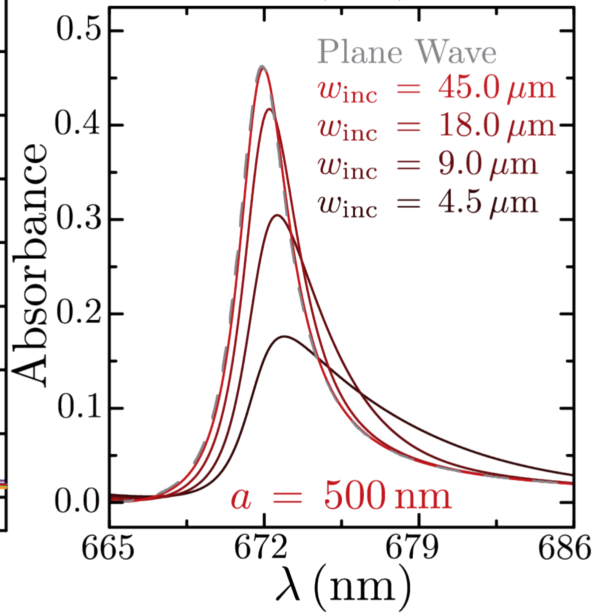
Absorbance / nanoparticle ∝ a^2

Gold nanoparticles in water



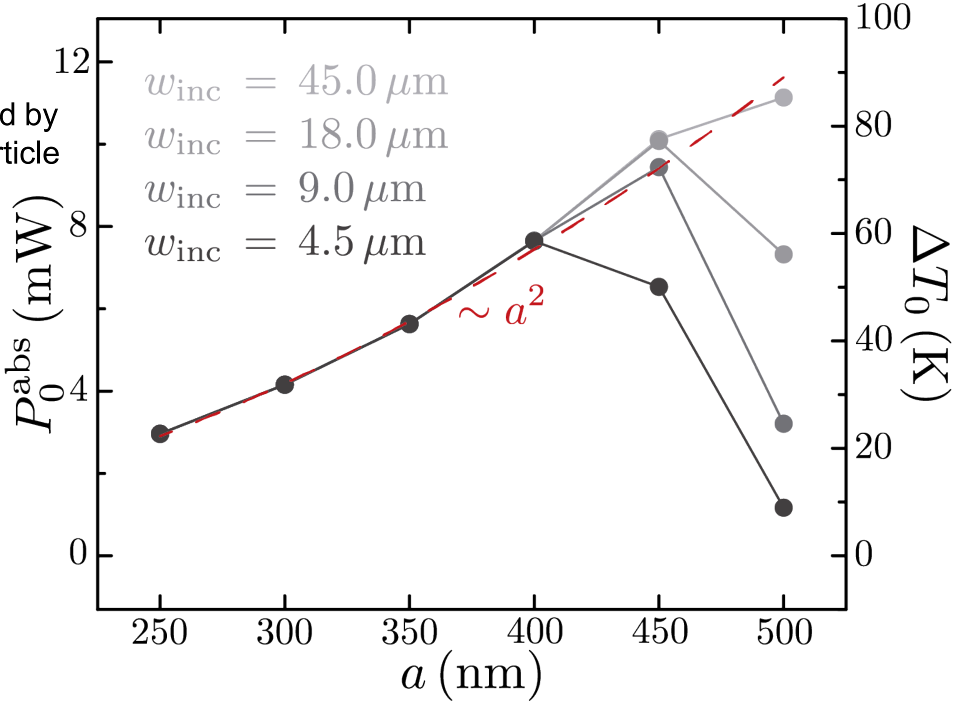




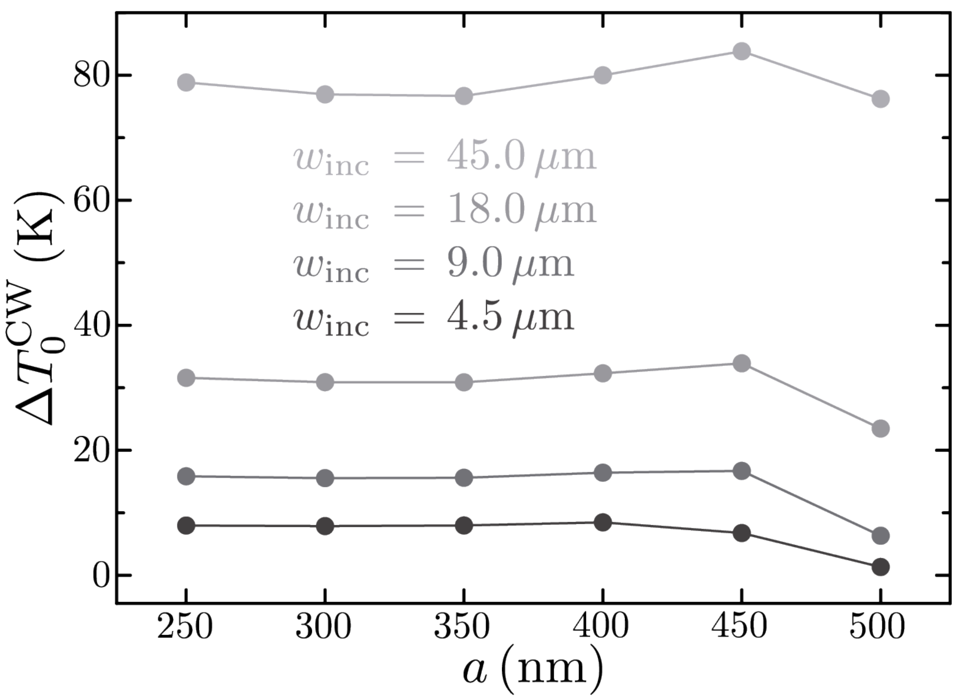


Temperature increase grows as a^2

Power absorbed by central nanoparticle



Temperature increase independent of a



Under pulsed illumination:

$$\Delta T_0 = \frac{P_0^{\rm abs}\tau}{V\rho_{\rm Au}c_{\rm Au}}$$

- τ: Pulse duration (here 10 ps)
- V: Volume of the nanoparticle
- $\rho_{\rm Au}$: Density of gold
- $c_{\rm Au}$: Specific heat capacity of gold

Under continuous wave (CW) illumination:

$$\Delta T_0^{\rm CW} = \frac{P_0^{\rm abs}}{2\pi\kappa D} + \sum_{i\neq 0}\frac{P_i^{\rm abs}}{4\pi\kappa|\mathbf{R}_i|}$$

- κ: Thermal conductivity of water (0.6 W m^{-1} K^{-1})
- $\sum_{i\neq 0}\frac{P_i^{\rm abs}}{4\pi\kappa|\mathbf{R}_i|}$: Interaction with other nanoparticles

Most of my work is embarrassingly parallel…

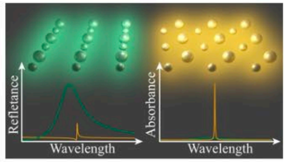
But that doesn’t mean it doesn’t benefit from HPC!

Computing the response of arrays of nanostructures requires:

- The inversion of large matrices
- Performing multidimensional integrals over very sharp, complex-valued, features
- Computing special functions (Bessel, Hankel, error function, etc.) with complex arguments

And you have to do these things for each wavelength.

As you can imagine, this demands a lot of computational resources.



New advancement in nanophotonics has the potential to improve light-based biosensors

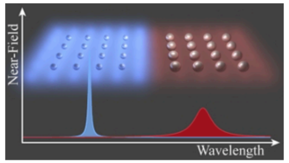
As COVID-19 swept across the world this year, claiming hundreds of thousands of lives, it quickly became clear that one essential factor for controlling its spread is the ability to rapidly and accurately test for the virus causing it, SARS-CoV-2, as...

My group makes extensive use of the HPC resources at the UNM Center for Advanced Research Computing (CARC).

Some of my work that has been highlighted by CARC:

UNM physicist's team investigates cause of haziness in 19th century daguerreotypes

In 2019, a team of scientists, led by University of New Mexico Associate Professor Alejandro Manjavacas, used UNM Center for Advanced Research Computing resources to make a discovery explaining some of the mysterious characteristics of daguerreotypes....



Nanoscale manipulation of light leads to exciting new advancement

Controlling the interactions between light and matter has been a long-standing ambition for scientists seeking to develop and advance numerous technologies that are fundamental to society. With the boom of nanotechnology in recent years, the nanoscale...

- We studied the lattice resonances supported by complex arrays of nanoparticles
- We analyzed the excitation of lattice resonances by light beams of finite width
- We studied the application of lattice resonances to thermoplasmonics

Publications Supported by the CSGF

1. L. Cerdán, L. Zundel, and A. Manjavacas, **ACS Photonics** (2023)
2. L. Zundel, K. Malone, L. Cerdán, R. Martínez-Herrero, and A. Manjavacas, **ACS Photonics** (2023)
3. L. Zundel, J. R. Deop-Ruano, R. Martínez-Herrero, and A. Manjavacas, **ACS Omega** (2022)
4. L. Zundel, P. Gieri, S. Sanders, and A. Manjavacas, **Adv. Opt. Mat.** (2022)
5. L. Zundel, A. Cuartero-González, S. Sanders, A. I. Fernández-Domínguez, and A. Manjavacas, **ACS Photonics** (2022)
6. S. Sanders, L. Zundel, W. J. M Kort-Kamp, D. A. R. Dalvit, and A. Manjavacas, **Phys. Rev. Lett.** (2021)
7. L. Zundel, A. May, and A. Manjavacas, **ACS Photonics** (2021)
8. A. Cuartero-González, S. Sanders, L. Zundel, A. I. Fernández-Domínguez, and A. Manjavacas, **ACS Nano** (2020)
9. L. Zundel and A. Manjavacas, **Phys. Rev. Applied** (2020)
10. A. Manjavacas, L. Zundel, and S. Sanders, **ACS Nano** (2019)

DOE CSGF

Thank you to my group and the CSGF!

Alejandro Manjavacas
Advisor

Luis Cerdán

Juanra Deop-Ruano

Keith Sanders

Paul Gieri

Álvaro Cuartero-González

Dora