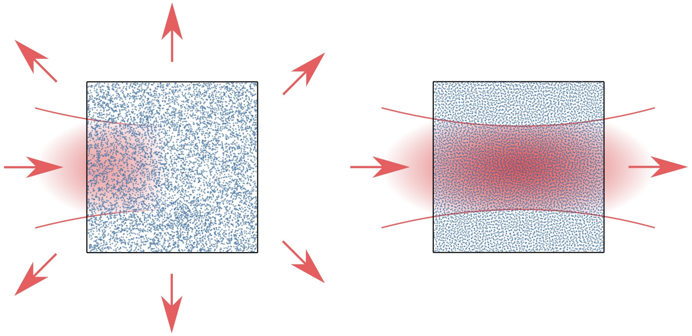
Partial order can make photonic nanomaterials different

Rémi CARMINATI

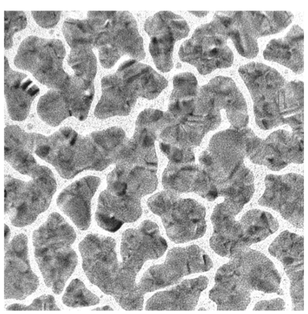
Institut Langevin
ESPCI Paris, PSL University, CNRS
Paris, France

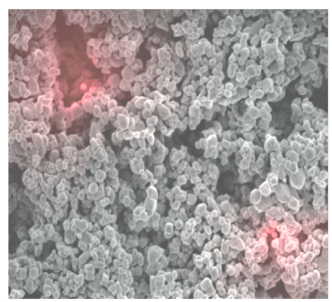


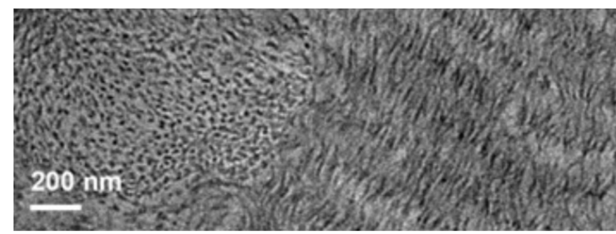
Institut **Langevin**
ONDES ET IMAGES

A long-standing collaboration on

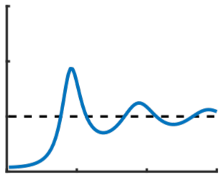
Nanophotonics + disorder



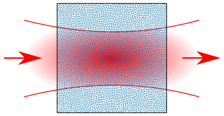




Outline



Light scattering and partial order



Hyperuniformity, transparency and absorption

A self-organized correlated material

Co-workers

Romain PIERRAT

Olivier LESEUR
(now at L'Oréal)

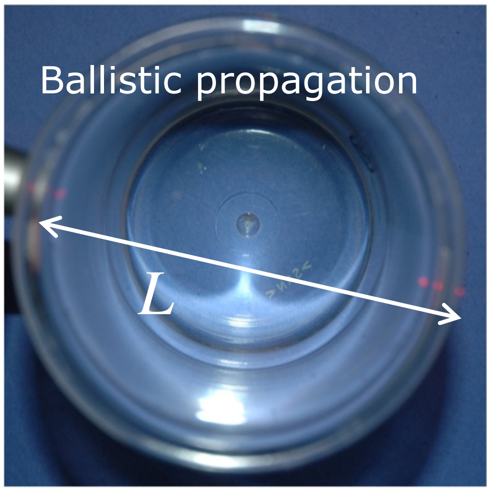
Alexandra SHEREMET
(now at Observatoire Paris)

Florian BIGOURDAN
(now at Saint-Gobain)

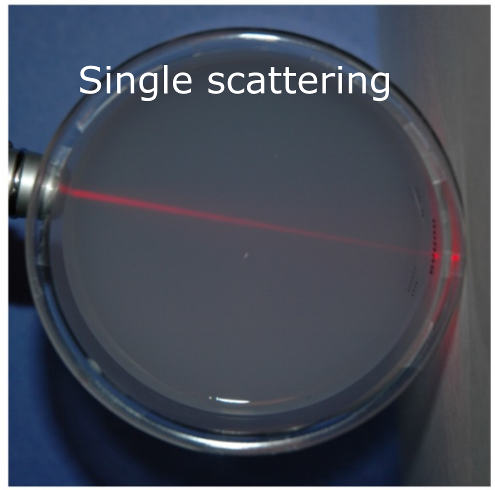
Nadine NASSIF
+ team
(LCMP, Paris, France)

Leseur *et al.*	Optica **3**, 763 (2016)
Ricouvier *et al.*	PRL **119**, 208001 (2017)
Bigourdan *et al.*	Opt. Express **27**, 8666 (2019)
Sheremet *et al.*	PRA **101**, 053829 (2020)
Salameh *et al.*	PNAS **117**, 11947 (2020)

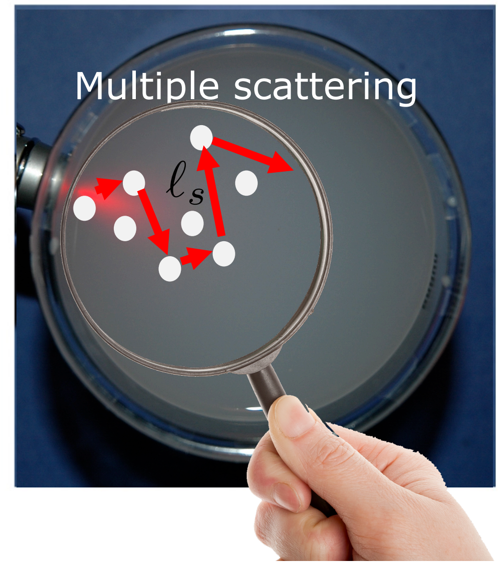
Scattering regimes



$$\ell_s \gg L$$



$$\ell_s \simeq L$$

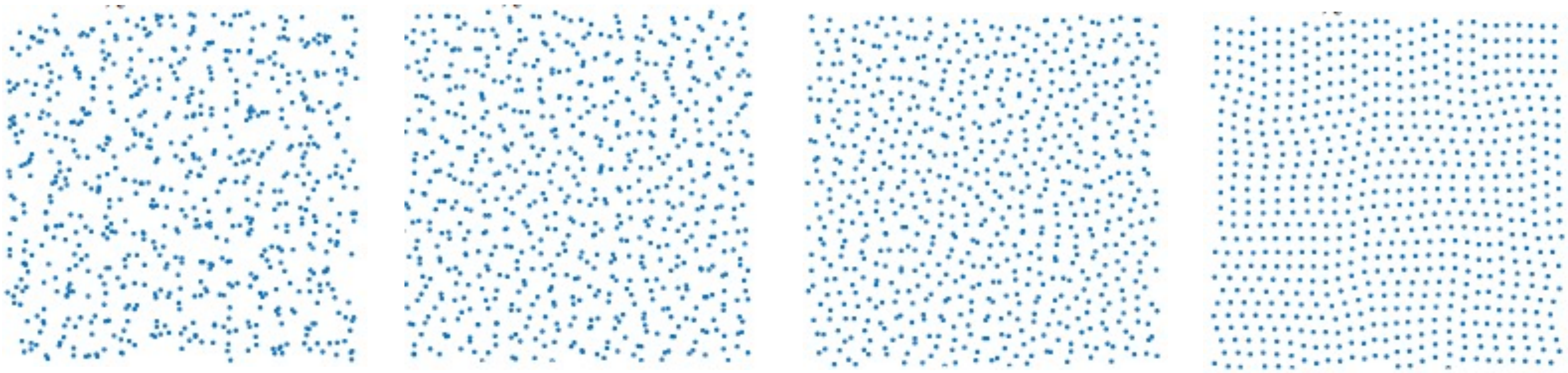


$$\ell_s \ll L$$

Courtesy of Nina Schotland

Set of scatterers/absorbers in a transparent matrix

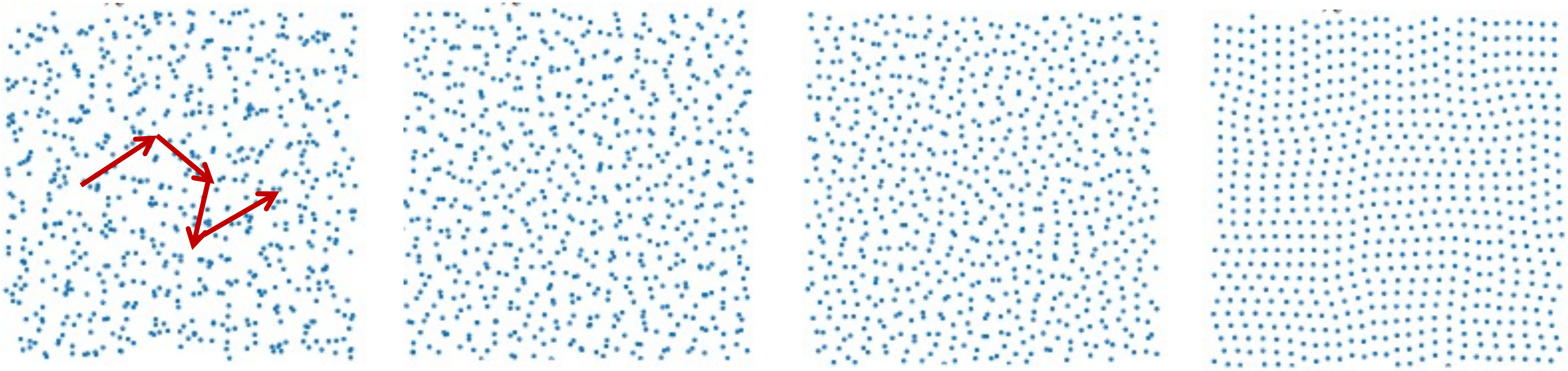
random → strongly correlated



<u>This talk</u>: Influence of partial order on scattering and absorption

Scattering mean free path

random → strongly correlated



$$\frac{1}{\ell_s} = \frac{1}{\ell_B} = \rho\sigma_s$$

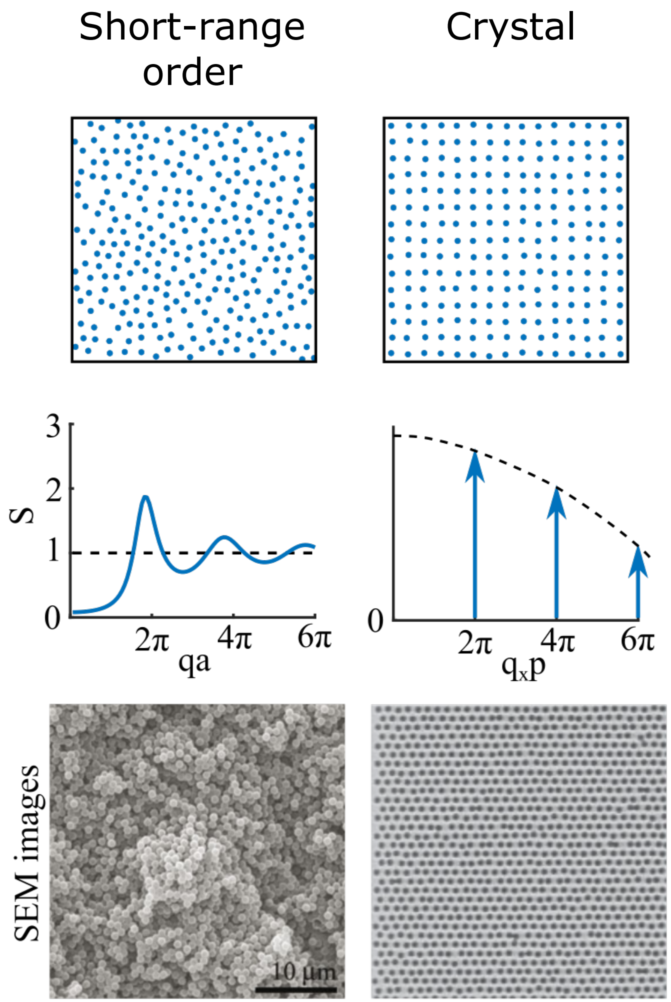
$$\frac{1}{\ell_s} = \frac{2\pi\,\rho}{k_R^4}\int_0^{2k_R} q\,F(q)\,\tilde{S}(q)\,dq$$

Individual scatterer

Structure factor

Structure factor

$$S(q) = \frac{1}{N}\left\langle \left| \sum_{j=1}^{N} e^{i\mathbf{q}\cdot\mathbf{r}_j} \right|^2 \right\rangle$$



Adapted from K. Vynk *et al.* (arXiv:2106.1389)

Experiments on correlated materials

VOLUME 65, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1990

Multiple Light Scattering from Concentrated, Interacting Suspensions

Seth Fraden[a] and Georg Maret

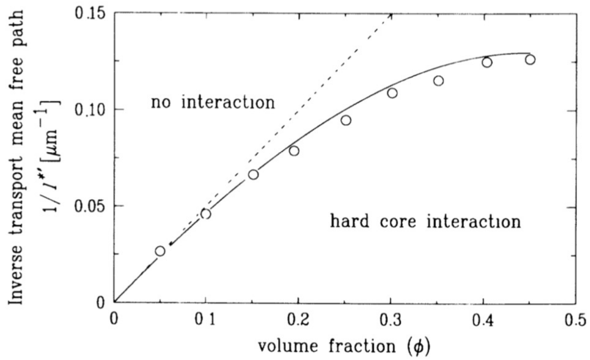
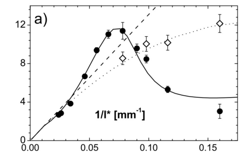


FIG. 1. The inverse of the transport mean free path of light ($1/l^{*\prime}$) for correlated 0.46-μm-diam polystyrene spheres as a function of volume fraction (ϕ). Data were obtained from the transmission of intensity through a 1-mm sample. The dashed line is calculated using Mie theory for the form factor (without interparticle correlations) and the solid line includes the calculated correction for correlations expressed by the Percus-Yevick structure factor.

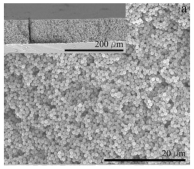
$$\frac{1}{\ell_t} = \frac{\pi\,\rho}{k_R^6} \int_0^{2k_R} q^3\,F(q)\,\tilde{S}(q)\,dq$$

S(q) modified by hard-sphere interactions

« Photonic liquids » - Scheffold *et al*. – PRL (2004)



« Photonic glasses » - Lopez, Blanco, Sapienza *et al.* - Adv. Materials (2007)

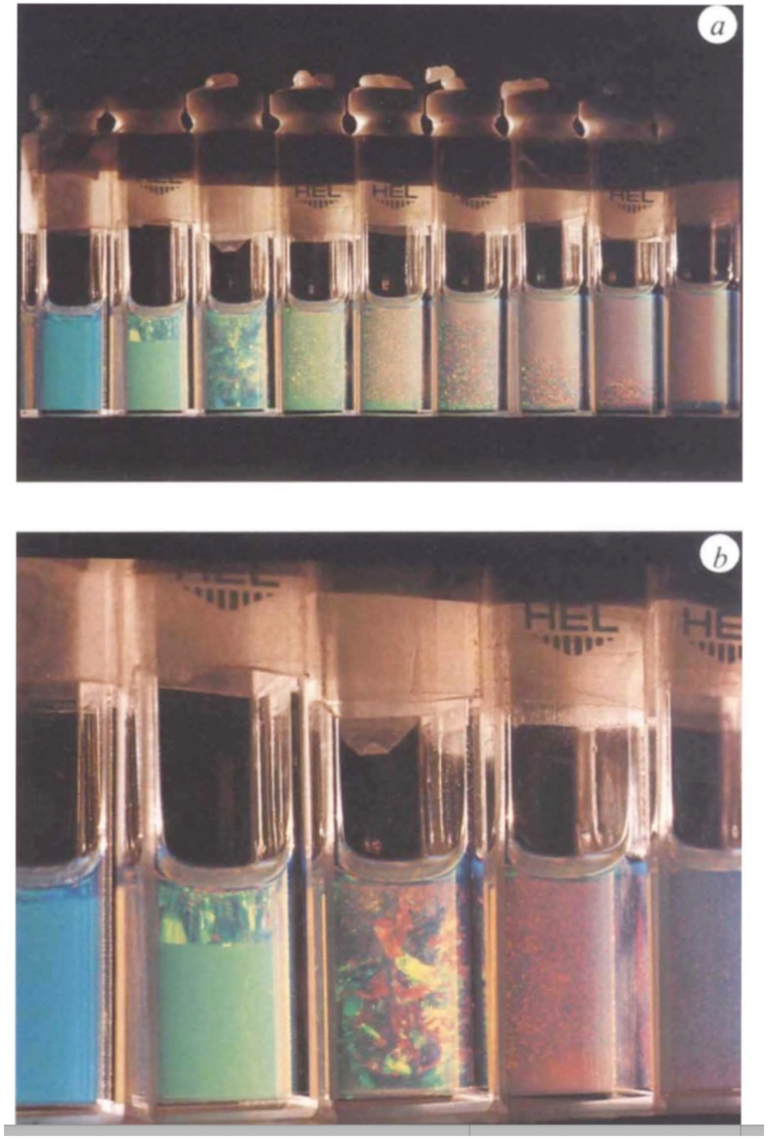


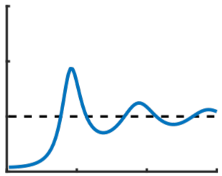
Phase behaviour of concentrated suspensions of nearly hard colloidal spheres

P. N. Pusey & W. van Megen*

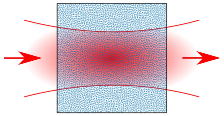
Royal Signals and Radar Establishment, St Andrews Road, Malvern WR14 3PS, UK

Nature (1986)





Light scattering and partial order



Hyperuniformity, transparency and absorption

A self-organized correlated material

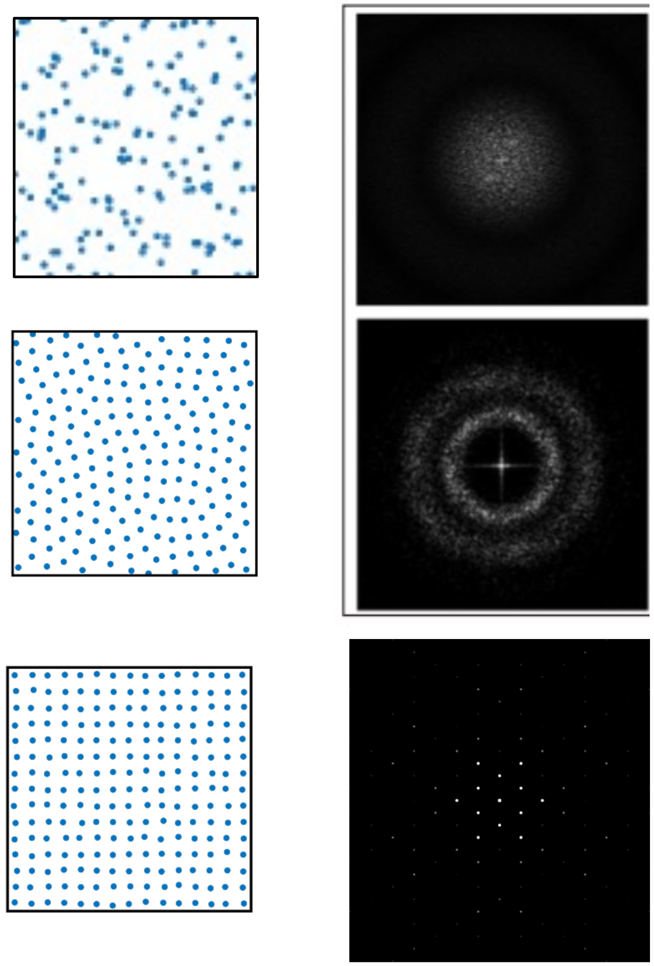
Hyperuniform point patterns

$S(\mathbf{q})$

Uncorrelated

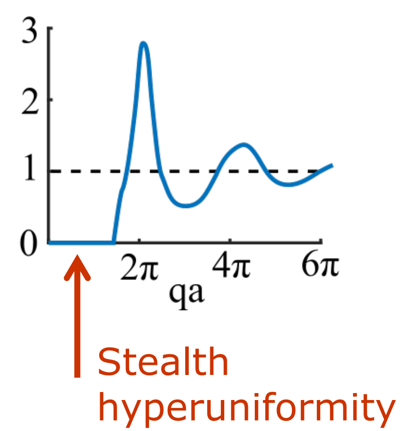
Hyperuniform

Periodic



Hyperuniform point patterns

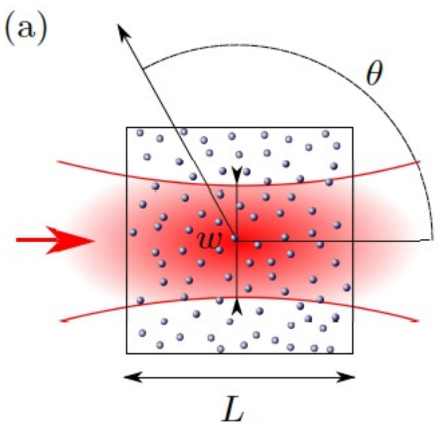
$$S(\mathbf{q}) \to 0 \quad \text{when} \quad q \to 0$$

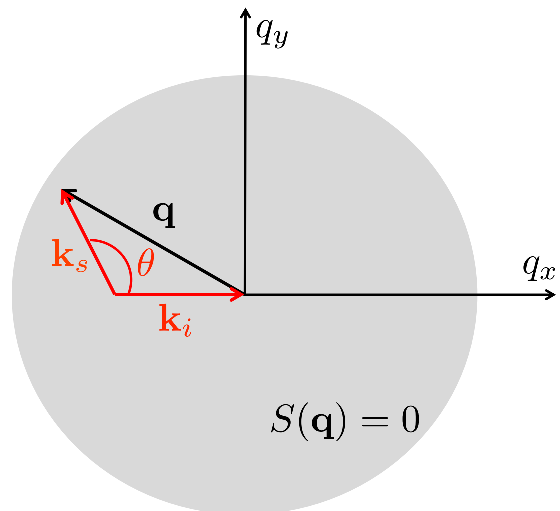


Torquato and Stillinger, Phys. Rev. E (2003)
S. Torquato, « Hyperuniform states of matter », Phys. Rep. (2018)

Single scattering

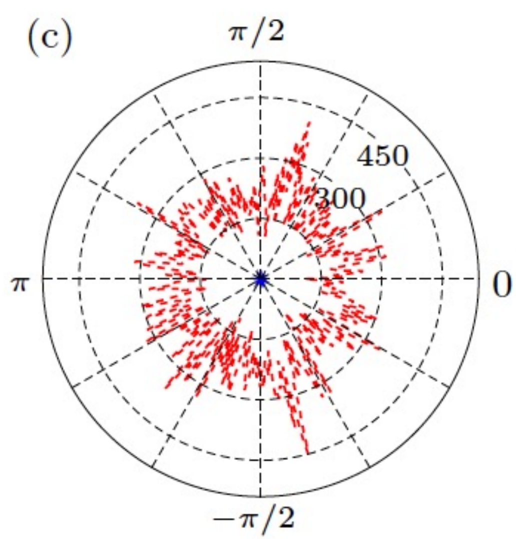
Single scattering $L < \ell_B$





Scattered intensity

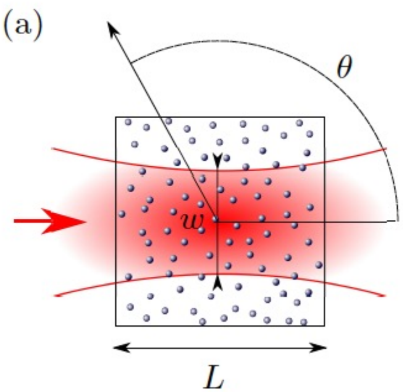
$$I_{\text{diff}}(\theta) \sim N\, S(\mathbf{q})$$

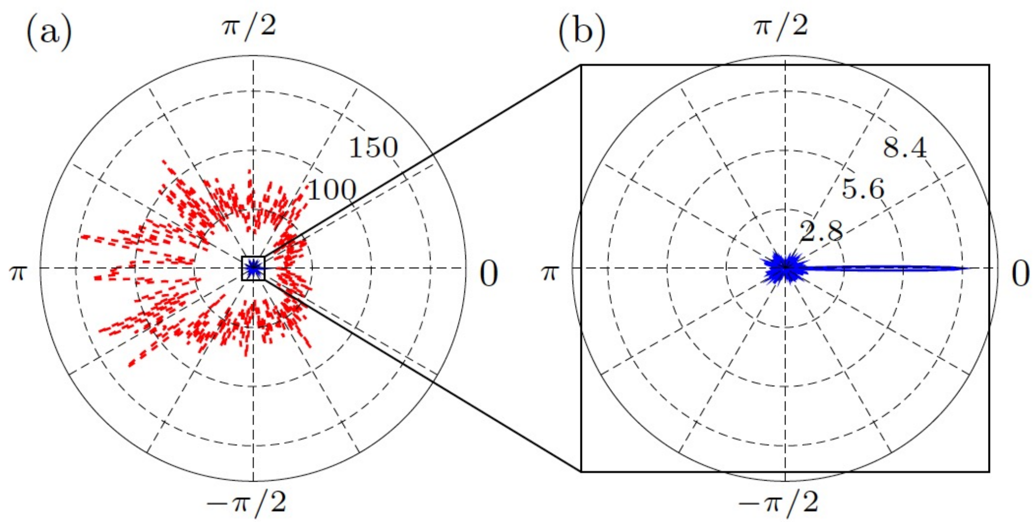


Uncorrelated
Hyperuniform

Multiple scattering : Transparency at high density

Multiple scattering $L \gg \ell_B \ (L/\ell_B = 5)$





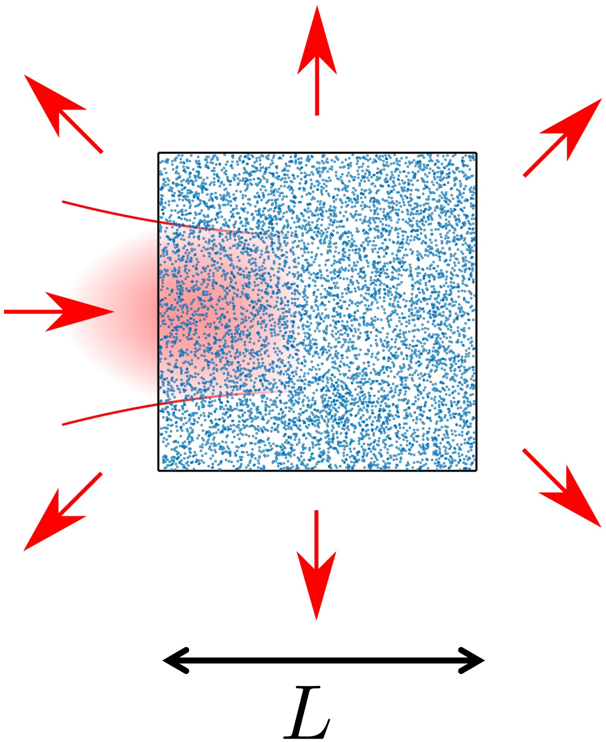
$k_0 = K/8$

Uncorrelated
Hyperuniform

Leseur, Pierrat, Carminati, Optica (2016)

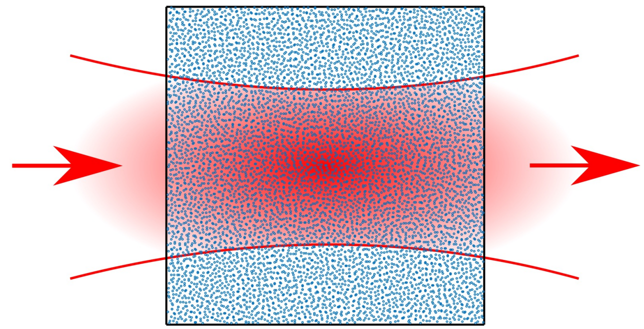
Dense hyperuniform materials can be transparent

Fully disordered



$$\ell_B \ll L$$

Hyperuniform
(same density)

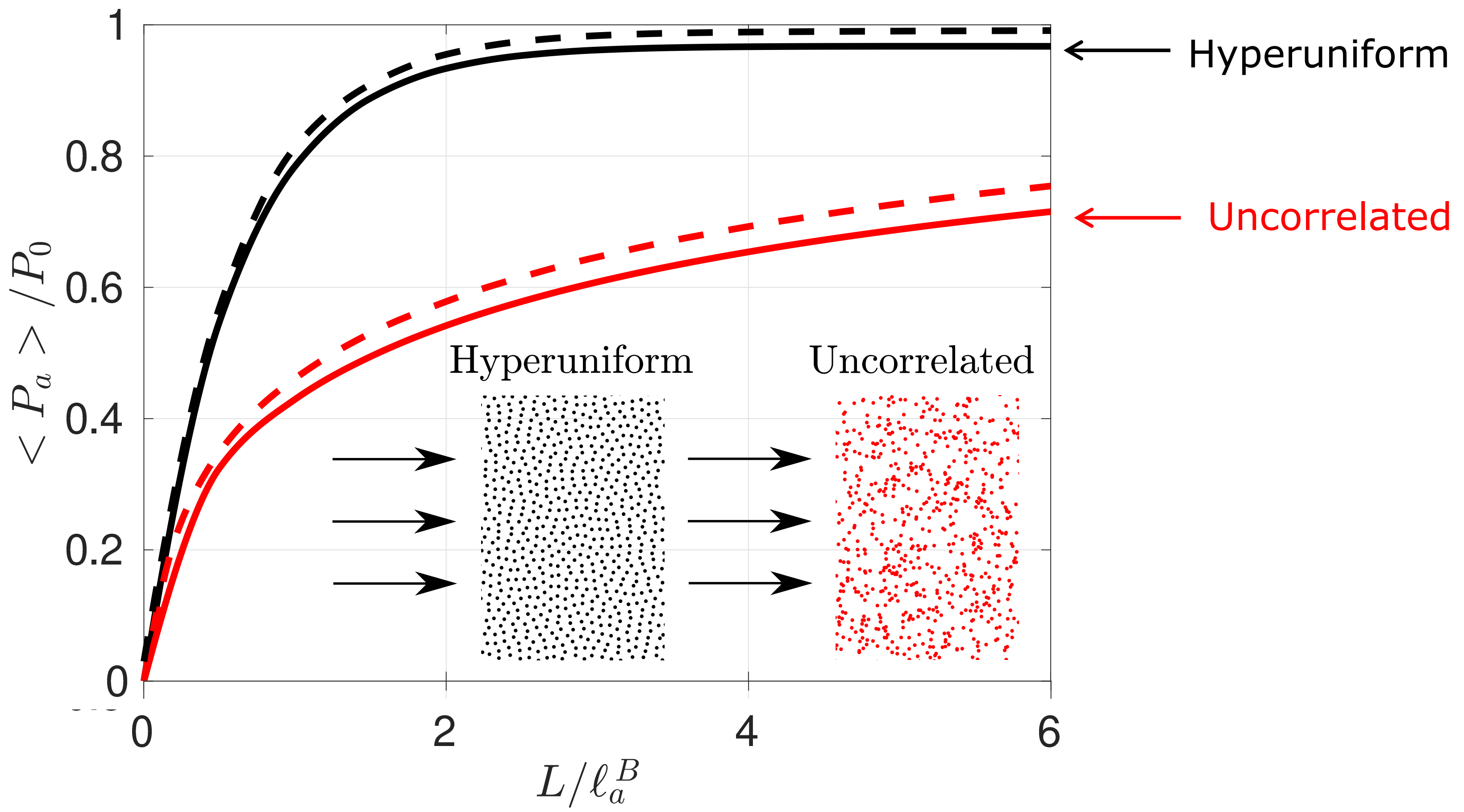


$$S(q) = 0$$

$$\ell_s \gg L$$

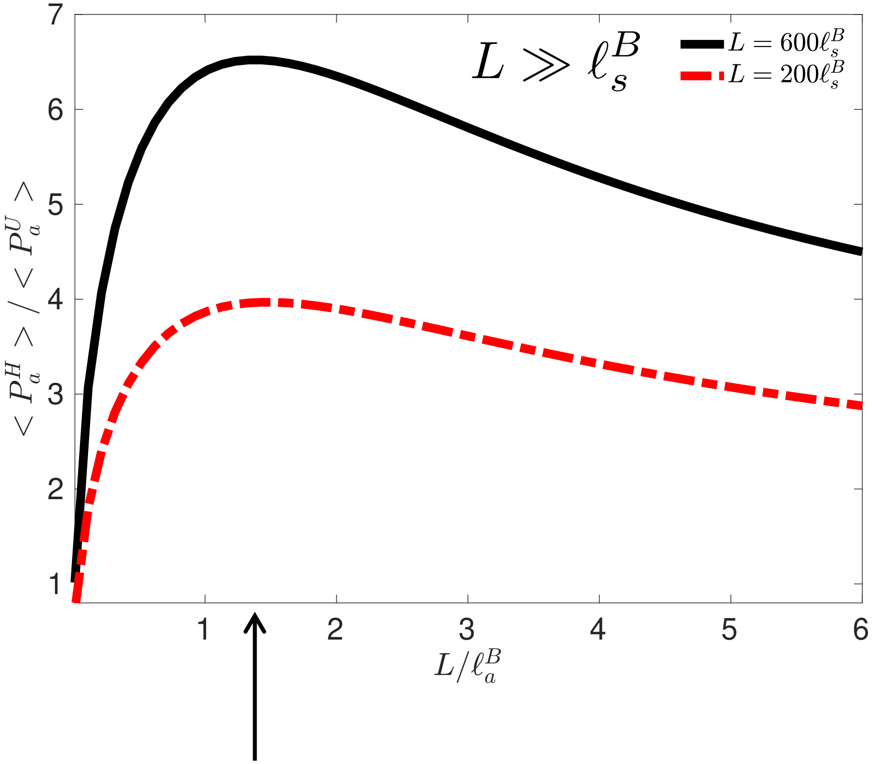
Leseur, Pierrat, Carminati, Optica (2016)

Stealth hyperuniformity maximizes absorption



Bigourdan, Pierrat, Carminati, Opt. Express (2019)

Enhancement at large optical thickness

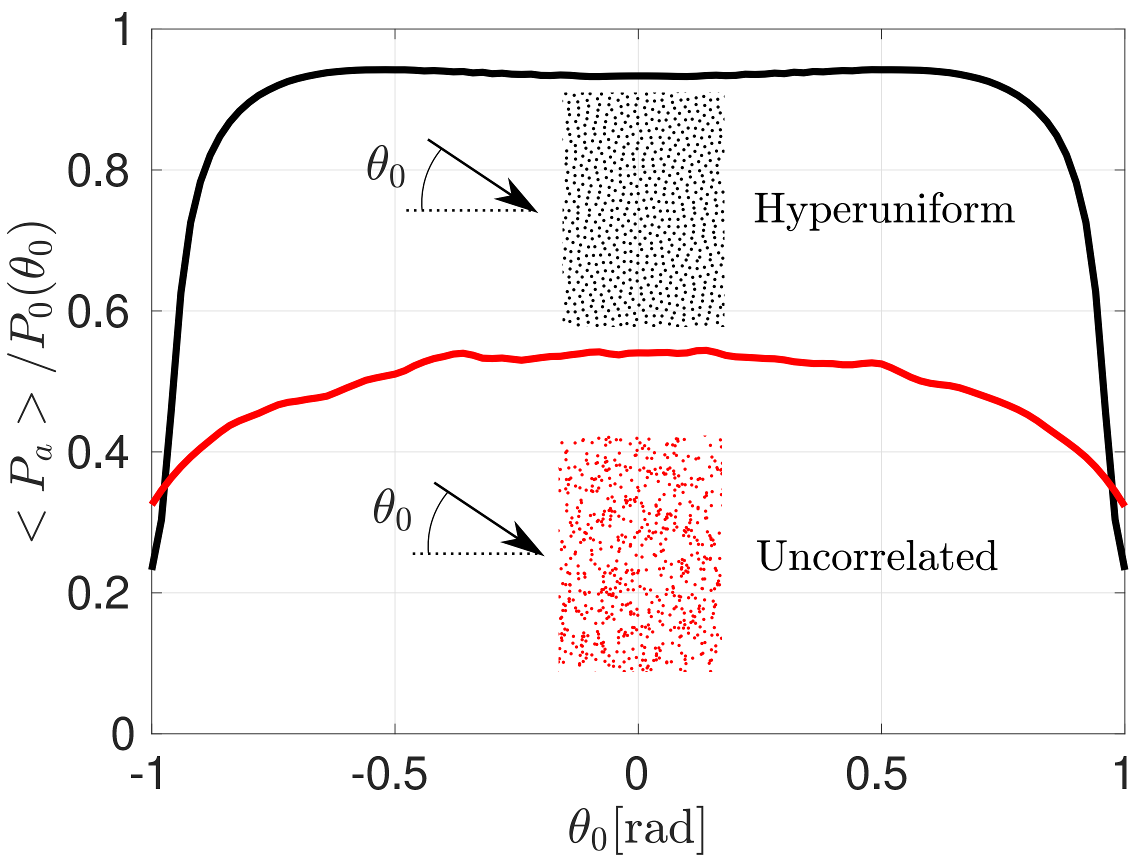


$L/\ell_a^B \simeq 1.26$

Absorption enhancement $\simeq 0.24\sqrt{\dfrac{L}{\ell_s^B}}$

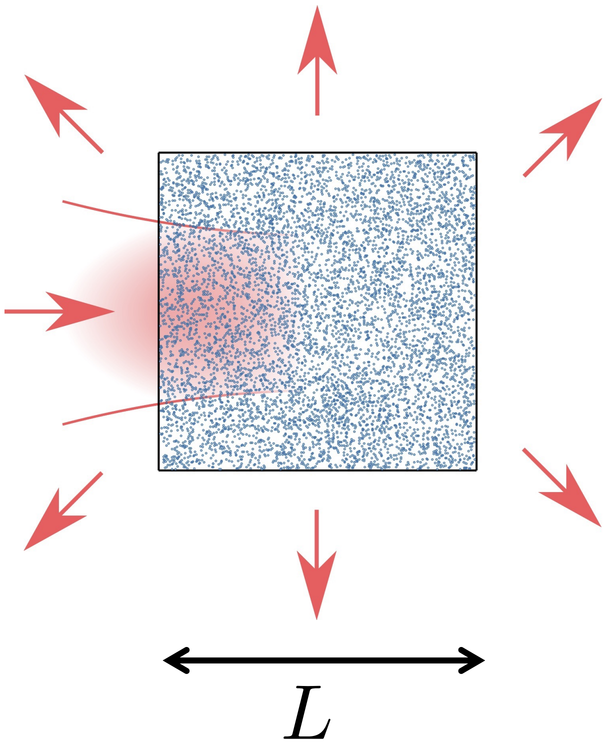
Bigourdan, Pierrat, Carminati, Opt. Express **27**, 8666 (2019)
Sheremet, Pierrat, Carminati, Phys. Rev. A **101**, 053829 (2020)

High absorption is angularly robust



Stealth hyperuniformity maximizes absorption

Fully disordered



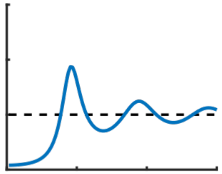
Hyperuniform
(same density)

Blackbody-like

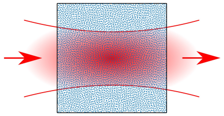
$$\ell_s \gg L$$

$$\ell_a \simeq \ell_a^B \simeq L$$

Bigourdan, Pierrat, Carminati, Opt. Express (2019)
Sheremet, Pierrat, Carminati, Phys. Rev. A (2020)



Light scattering and partial order

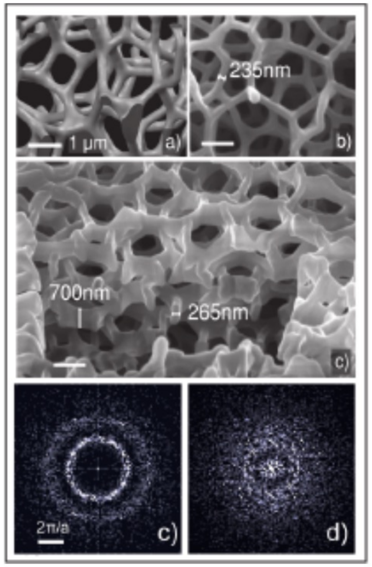


Hyperuniformity, transparency and absorption

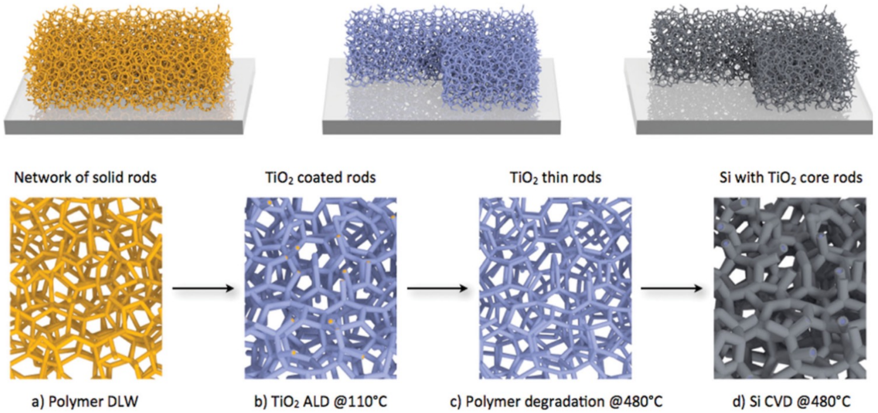
A self-organized correlated material

Routes towards engineering of disorder

Top-down lithography

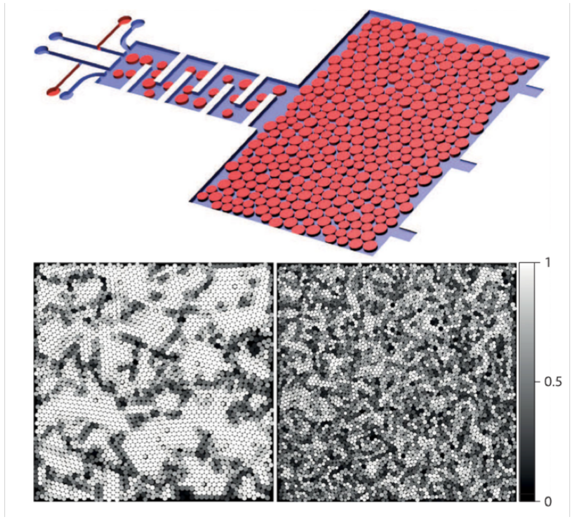


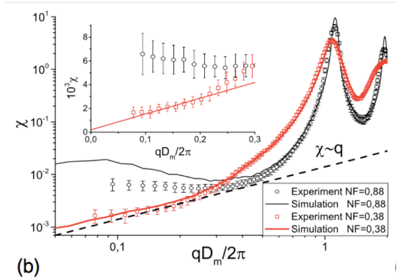
Muller, Haberko, Marichy, Scheffold,
Adv. Opt. Mater. **2**, 115 (2014)



Bottom-up self-assembly

Bidisperse emulsion produced by microfluidics

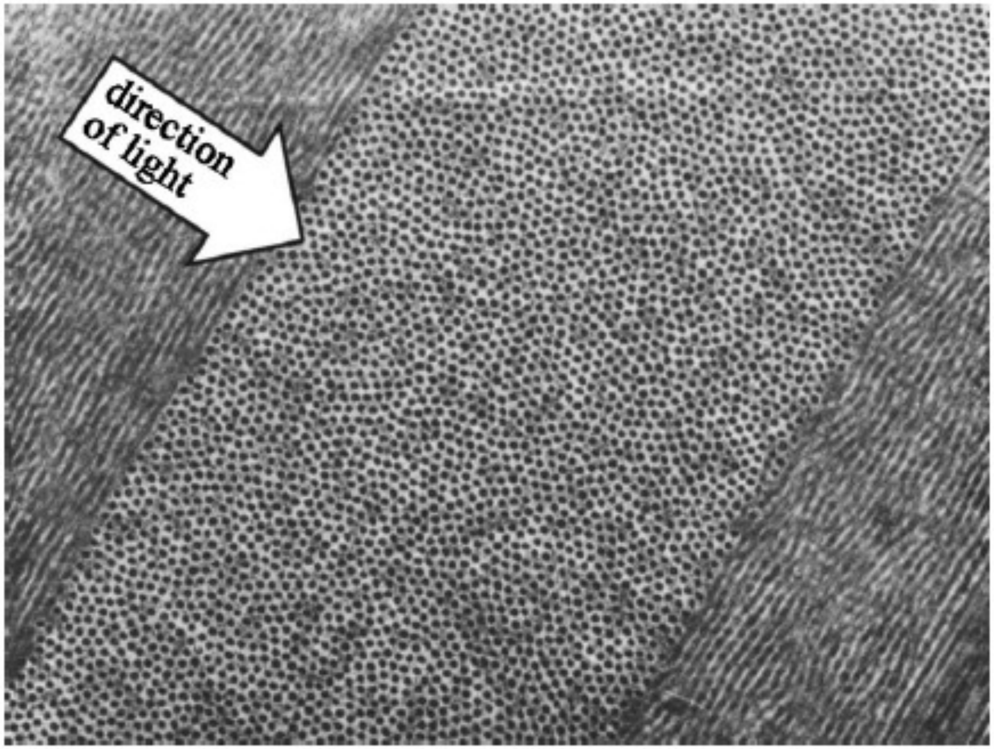




Ricouvier, Pierrat, Carminati, Tabeling, Yazhgur
PRL **119**, 208001 (2017)

Microstructure of the cornea

The cornea contains stacks of layers made of partially ordered arrays of collagen fibrils

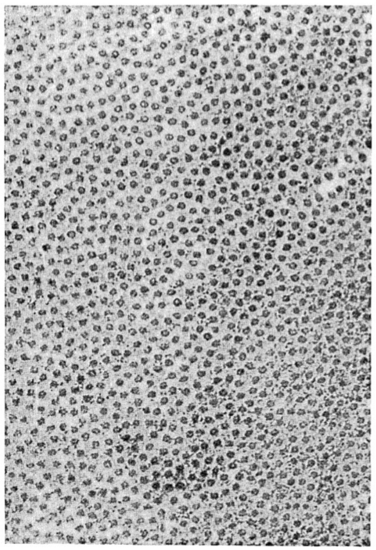


Cornea as a correlated photonic material

JOURNAL OF THE OPTICAL SOCIETY OF AMERICA VOLUME 59, NUMBER 6 JUNE 1969

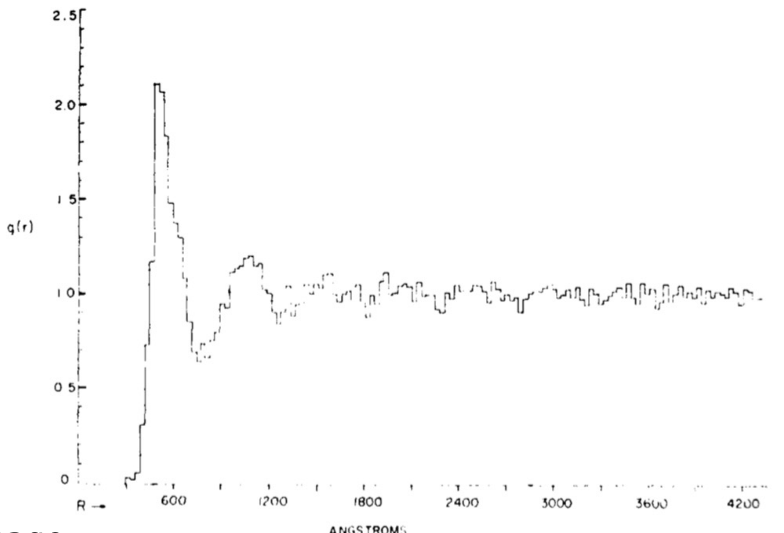
Light Scattering in the Cornea*

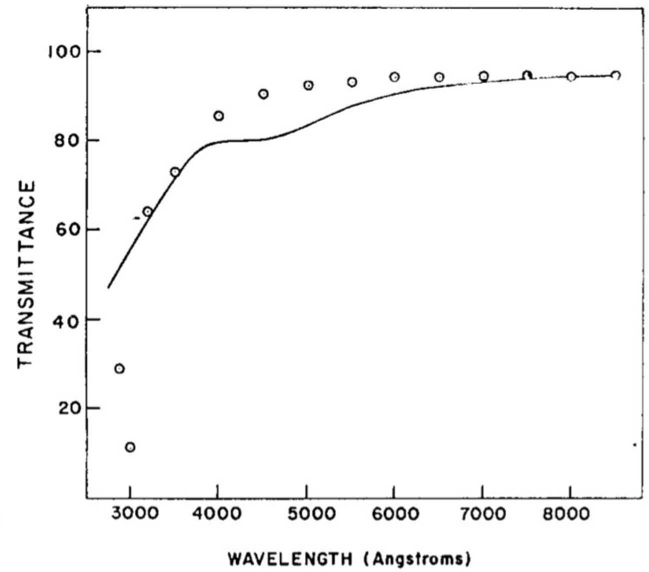
ROBERT W. HART AND RICHARD A. FARRELL
Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland 20910



Electron microscope image of fibrils organization

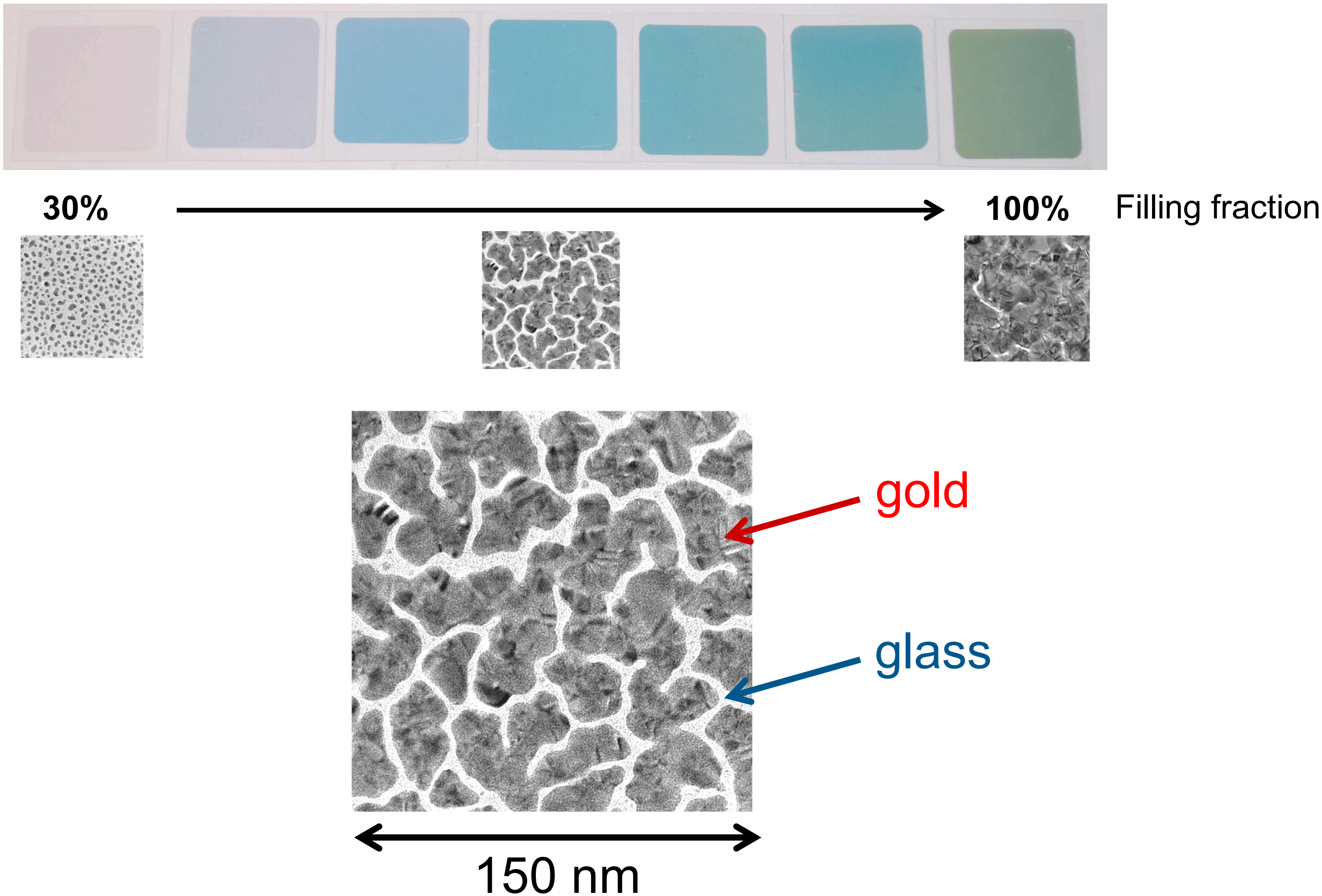
Pair correlation function





$$\frac{1}{\ell_s} = \frac{2\pi\,\rho}{k_R^4}\int_0^{2k_R} q\,F(q)\,\tilde{S}(q)\,dq$$

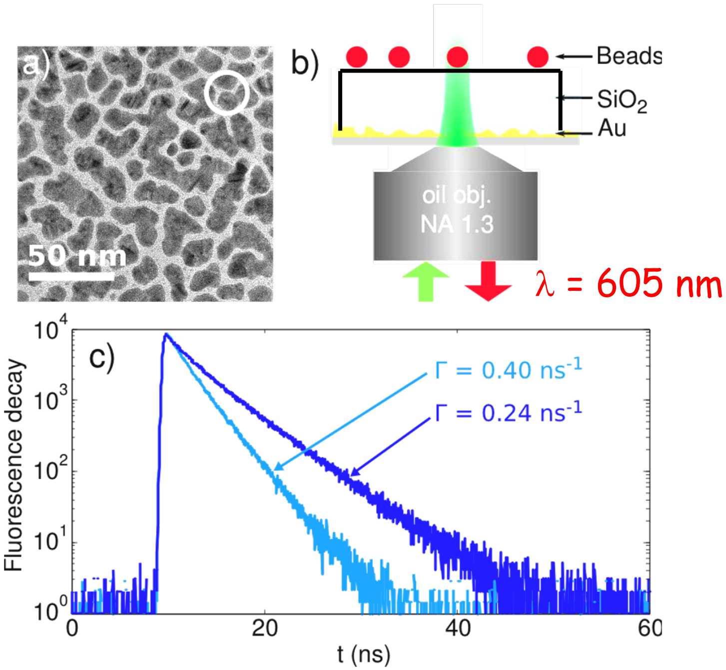
Structural colors in gold



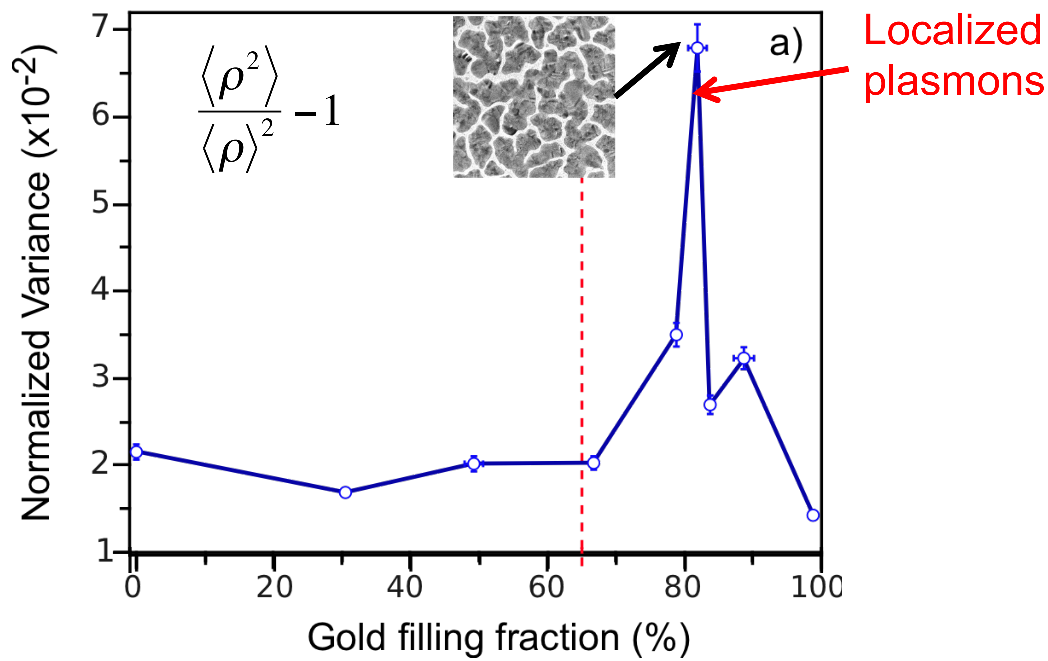
LDOS fluctuations reveal localized plasmons

Valentina KRACHMALNICOFF

Yannick DE WILDE



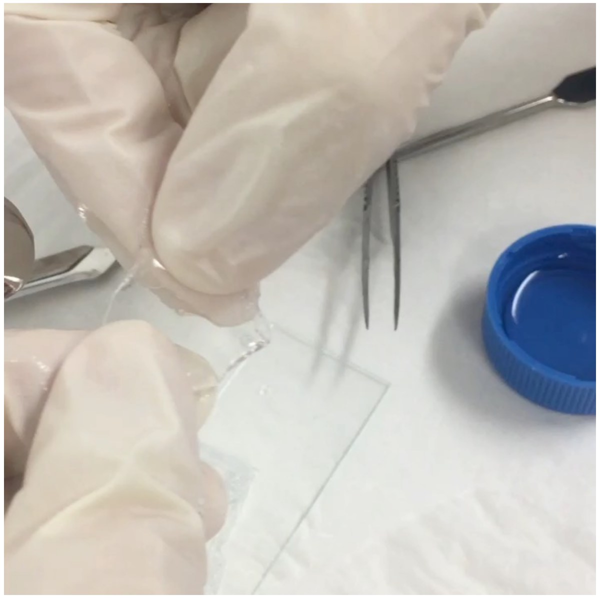
Measured LDOS fluctuations



Krachmalnicoff, Castanié, De Wilde, Carminati, Phys. Rev. Lett. (2010)

Cazé, Pierrat, Carminati, Phys. Rev. Lett. (2013)

Artificial collagen hydrogels



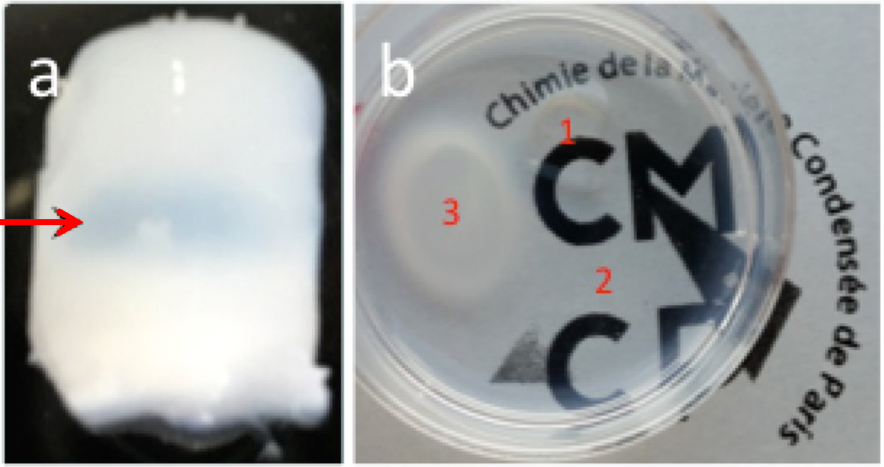
A material made of 95% water

Nadine NASSIF *et al.*
LCMCP, Sorbonne Université, CNRS, Paris

Transparency at a critical collagen concentration

Transparency gap

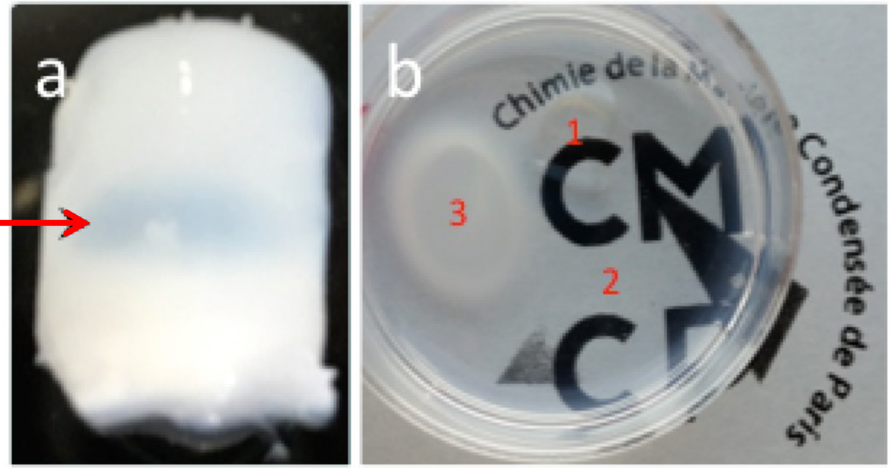
$\sim 45\,\mathrm{mg/mL}$



collagen concentration

C. Salameh, (…), Marco Faustini, R. Carminati and N. Nassif, PNAS **117**, 11947 (2020)

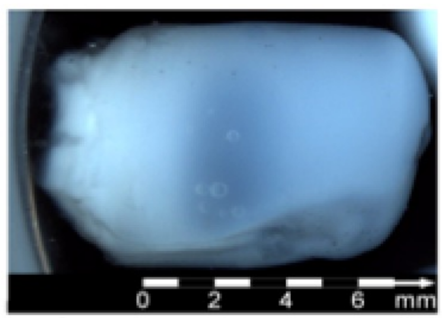
Scattering mean free path



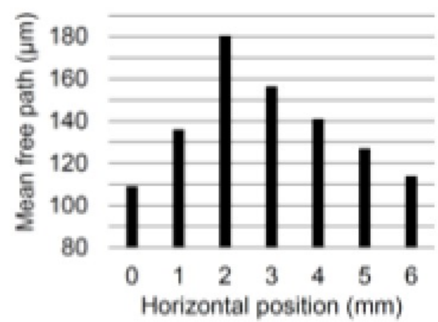
Transparency gap

$\sim 45\,\mathrm{mg/mL}$

collagen concentration

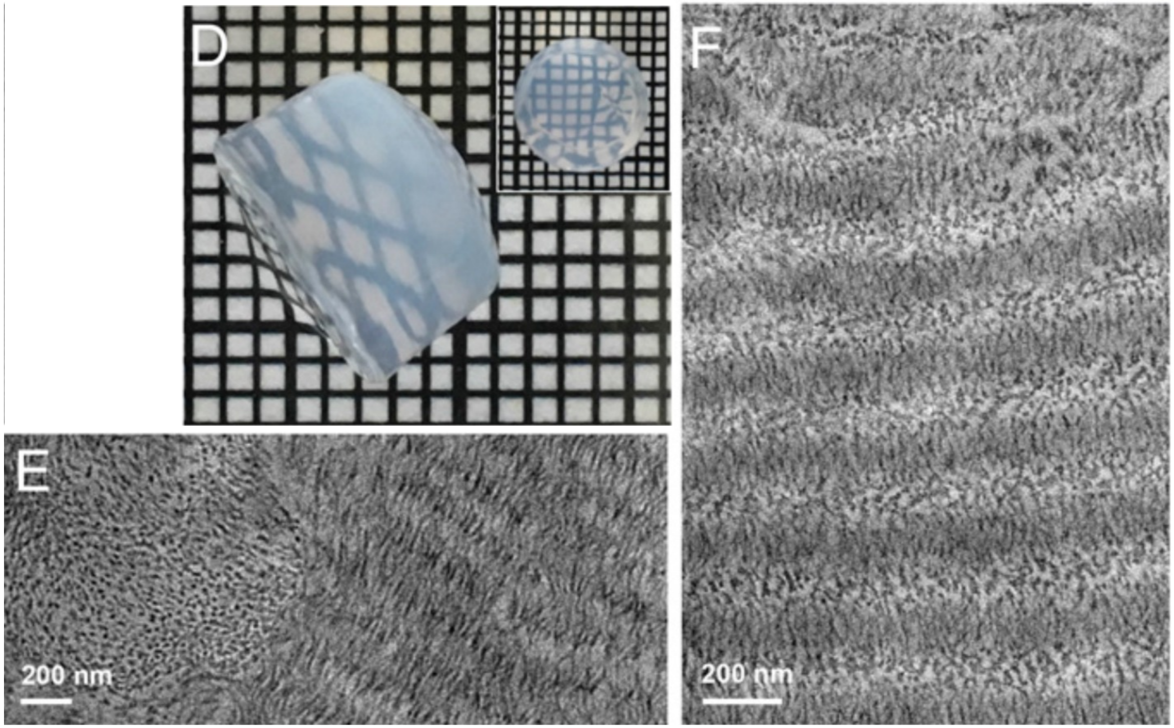


Scattering mean free path



C. Salameh, (…), Marco Faustini, R. Carminati and N. Nassif, PNAS **117**, 11947 (2020)

Ultrastructure shows a complex correlated pattern



At critical concentration

- Partial order
- Enhanced optical and biomimetic mechanical properties

C. Salameh, (…), Marco Faustini, R. Carminati and N. Nassif, PNAS **117**, 11947 (2020)

Juan José Sáenz
(1960 – 2020)

Light in correlated disorder

K. Vynck, R. Pierrat, R. Carminati
L.S. Froufe-Pérez, F. Scheffold
R. Sapienza, S. Vignolini, J.J Sáenz

arXiv: 2106.1389
Rev. Mod. Phys. (in revision, 2022)