Nematic Colloidal Crystals, Microresonators and 3D Microlasers for Soft Matter Photonics

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Motivation for this work: photonic crystals

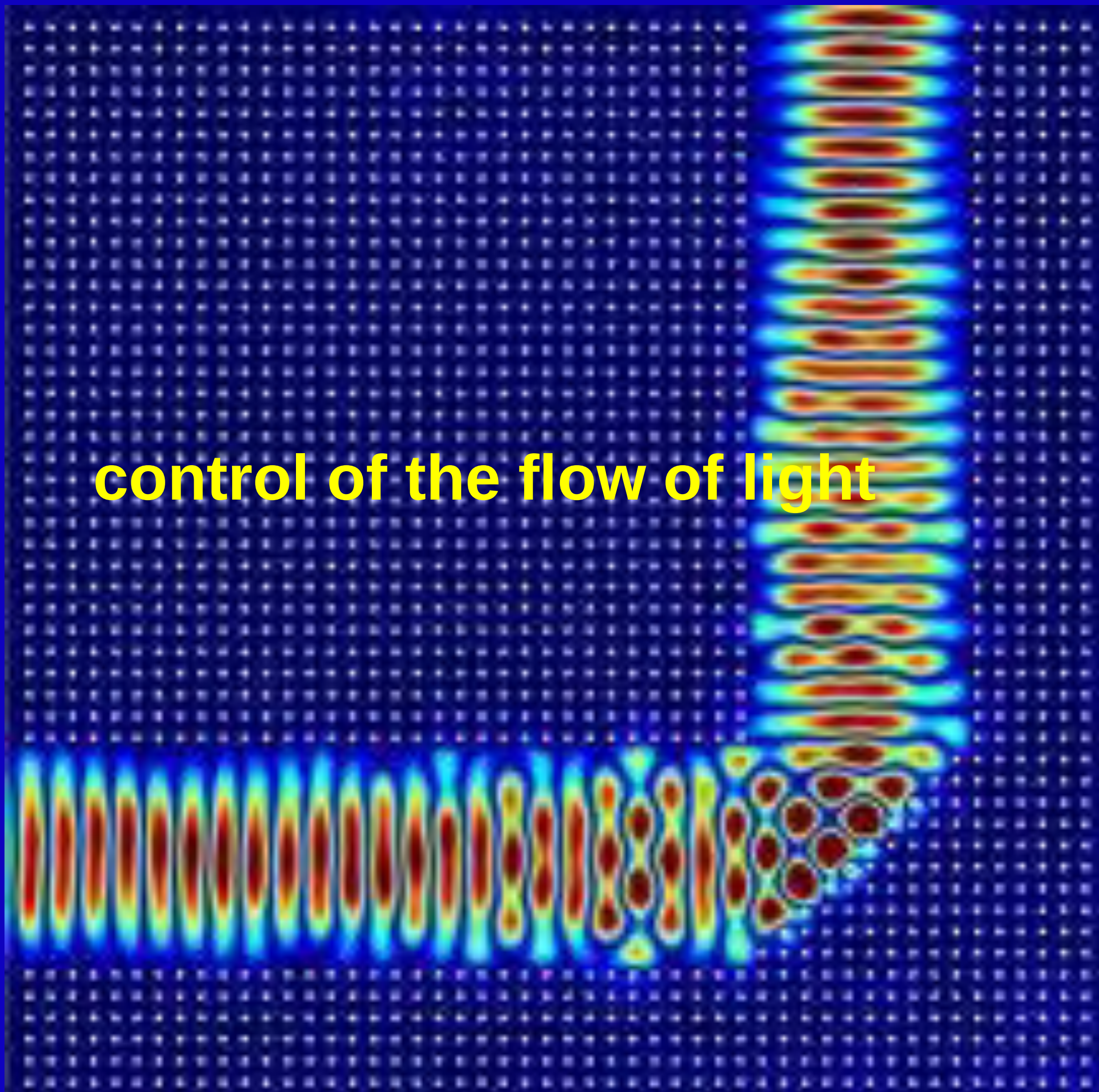
Photonics and the concept of a „photonic crystal“ by Eli Yablonovitch

VOLUME 63, NUMBER 18 PHYSICAL REVIEW LETTERS 30 OCTOBER 1989

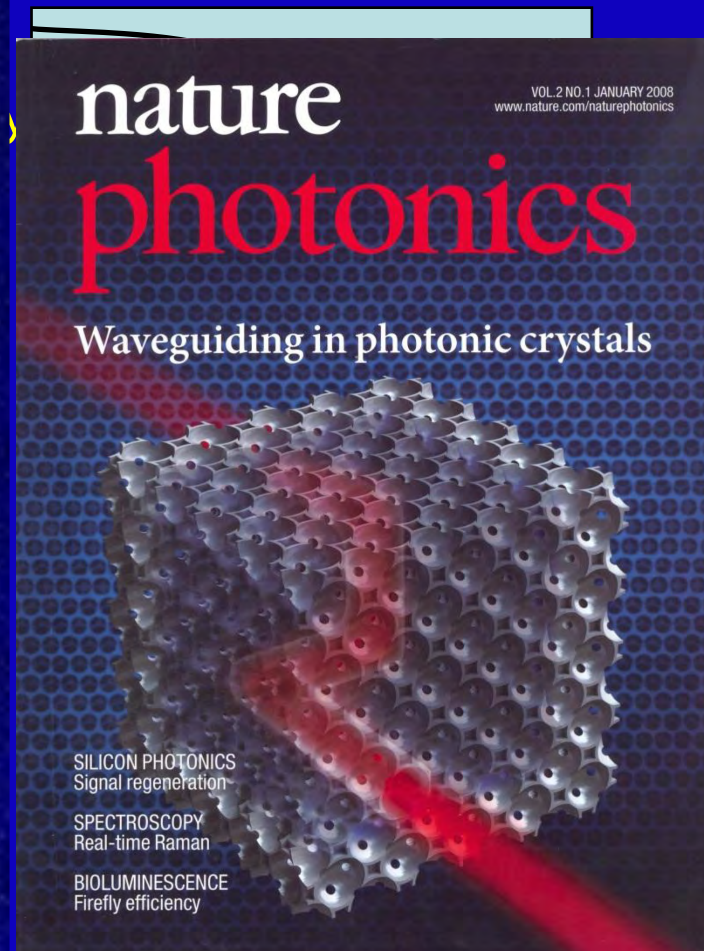
Photonic Band Structure: The Face-Centered-Cubic Case

E. Yablonovitch and T. J. Gmitter
Bell Communications Research, Navesink Research Center, Red Bank, New Jersey 07701-7040
(Received 25 July 1989)

We employ the concepts of band theory to describe the behavior of electromagnetic waves in three dimensionally periodic face-centered-cubic (fcc) dielectric structures. This can produce a "photonic band gap" in which optical modes, spontaneous emission, and zero-point fluctuations are all absent. In the course of a broad experimental survey, we have found that most fcc dielectric structures have "semimetallic" band structure. Nevertheless, we have identified one particular dielectric "crystal" which actually has a "photonic band gap." This dielectric structure requires a refractive-index contrast greater than 3 to 1, which happens to be readily obtainable in semiconductor materials.

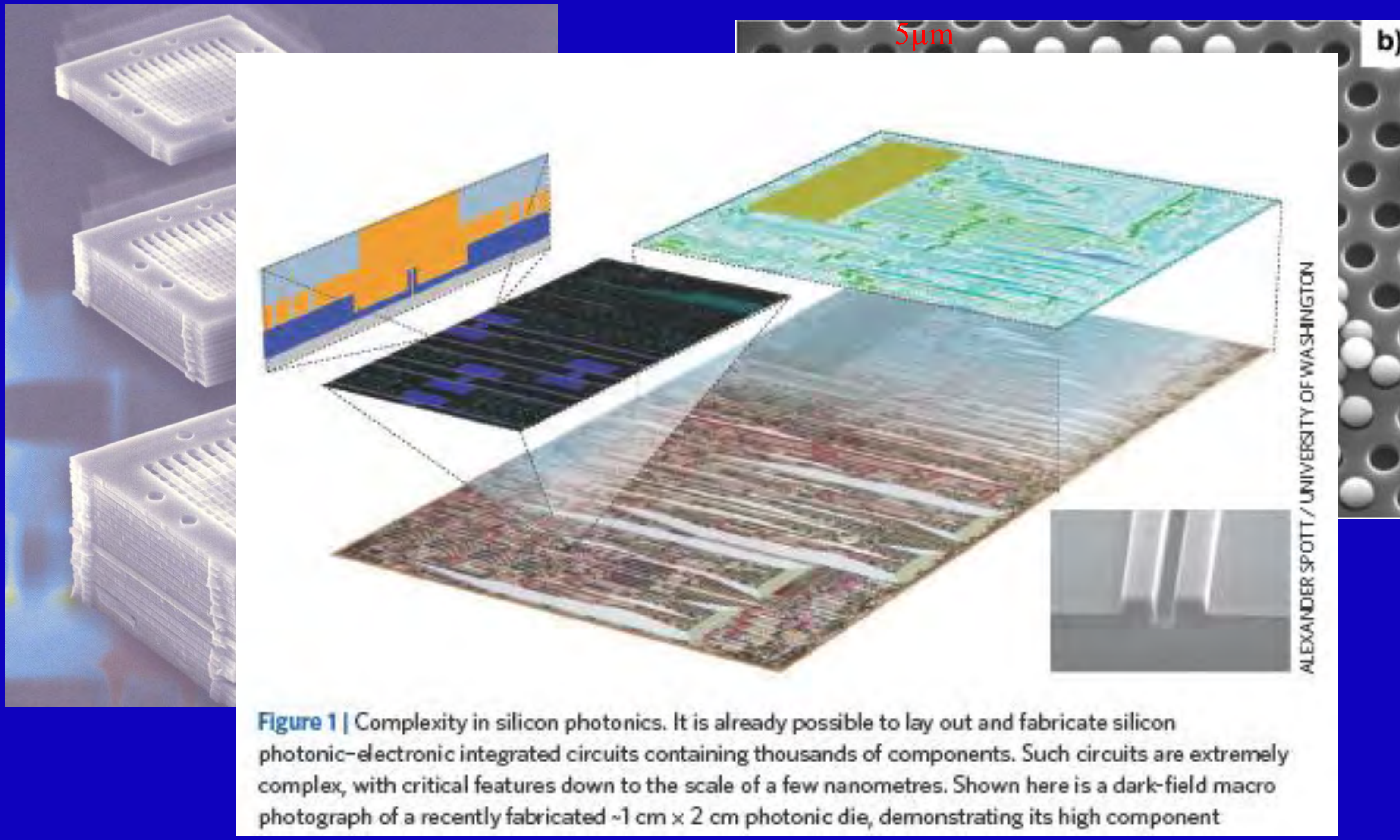


control of the flow of light



micromanipulation

(A.Aoki et al., *Nature Materials* 2003)

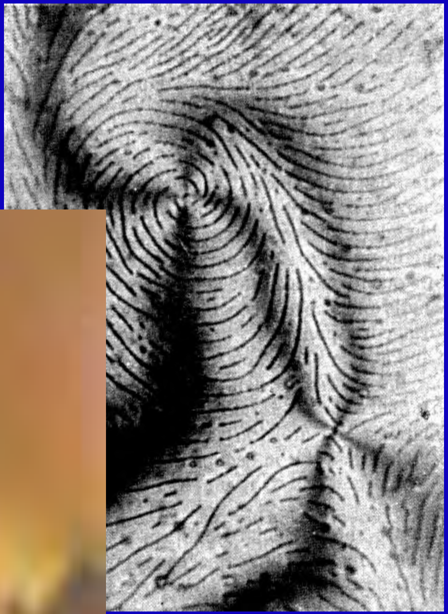


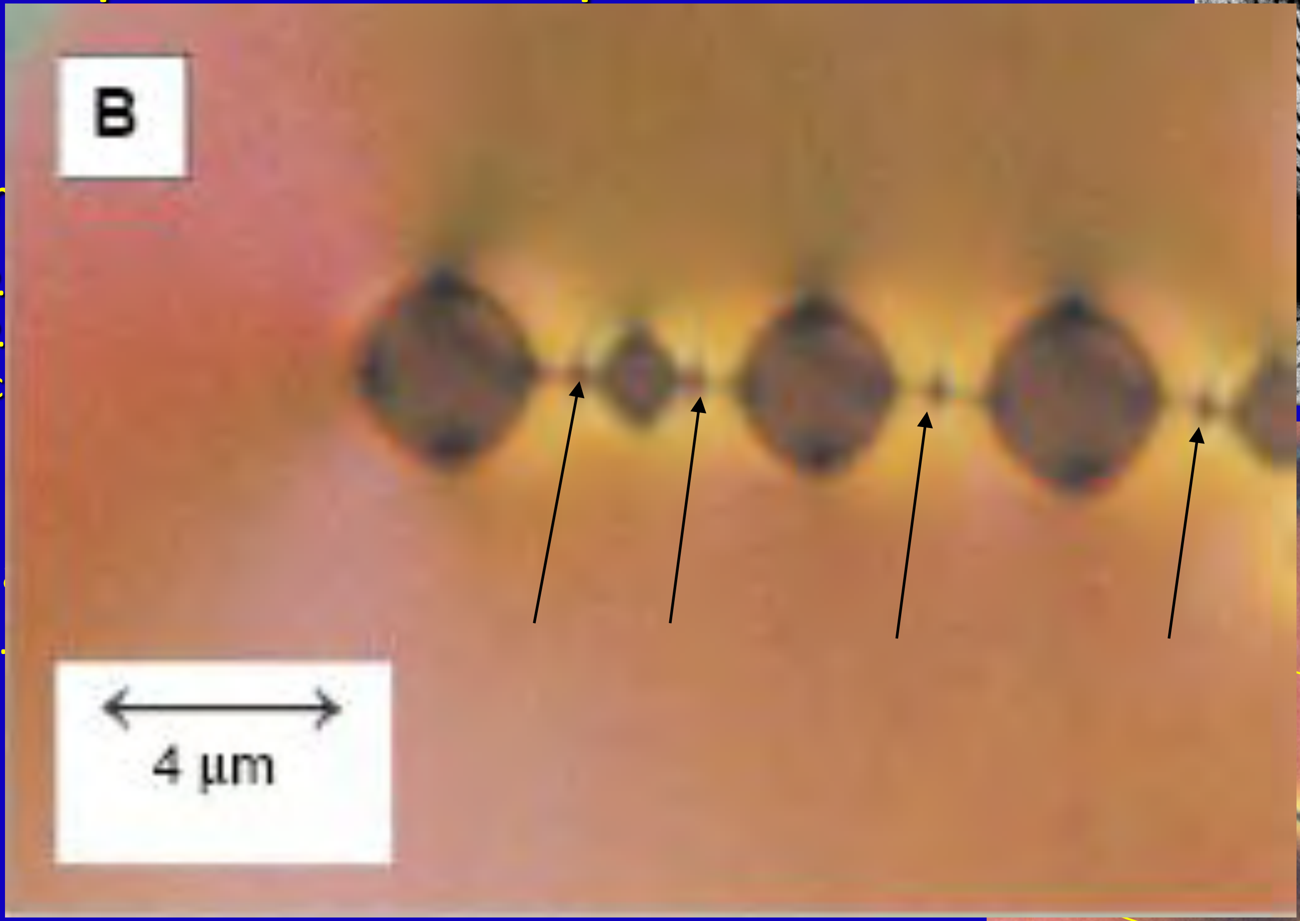
colloidal sedimentation, growth on structured interfaces, dielectrophoresys, 2-photon polymerization, holographic polimerization-HPDLC optical and optoelectronic tweezers, etc…

Can we use nematic liquid crystals
to assemble photonic structures?

nematic colloids:

dispersion of solid particles





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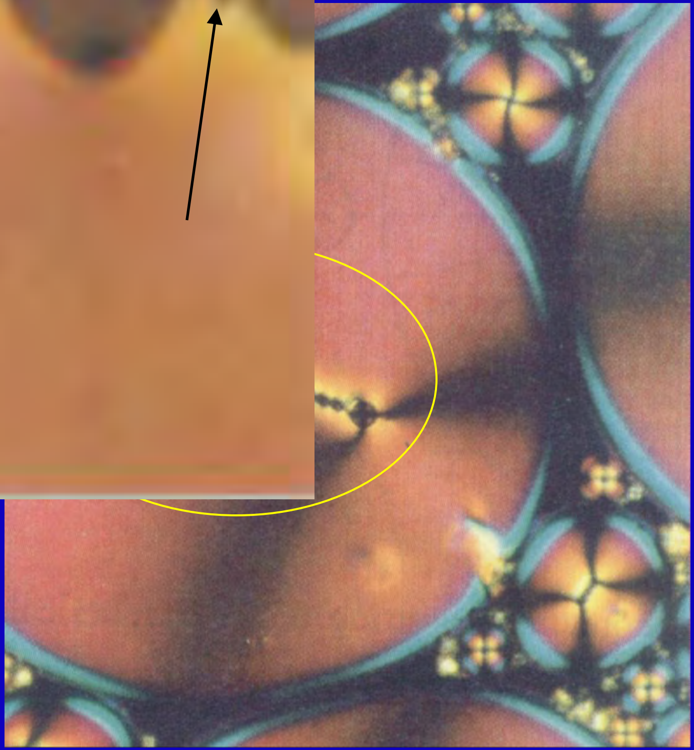
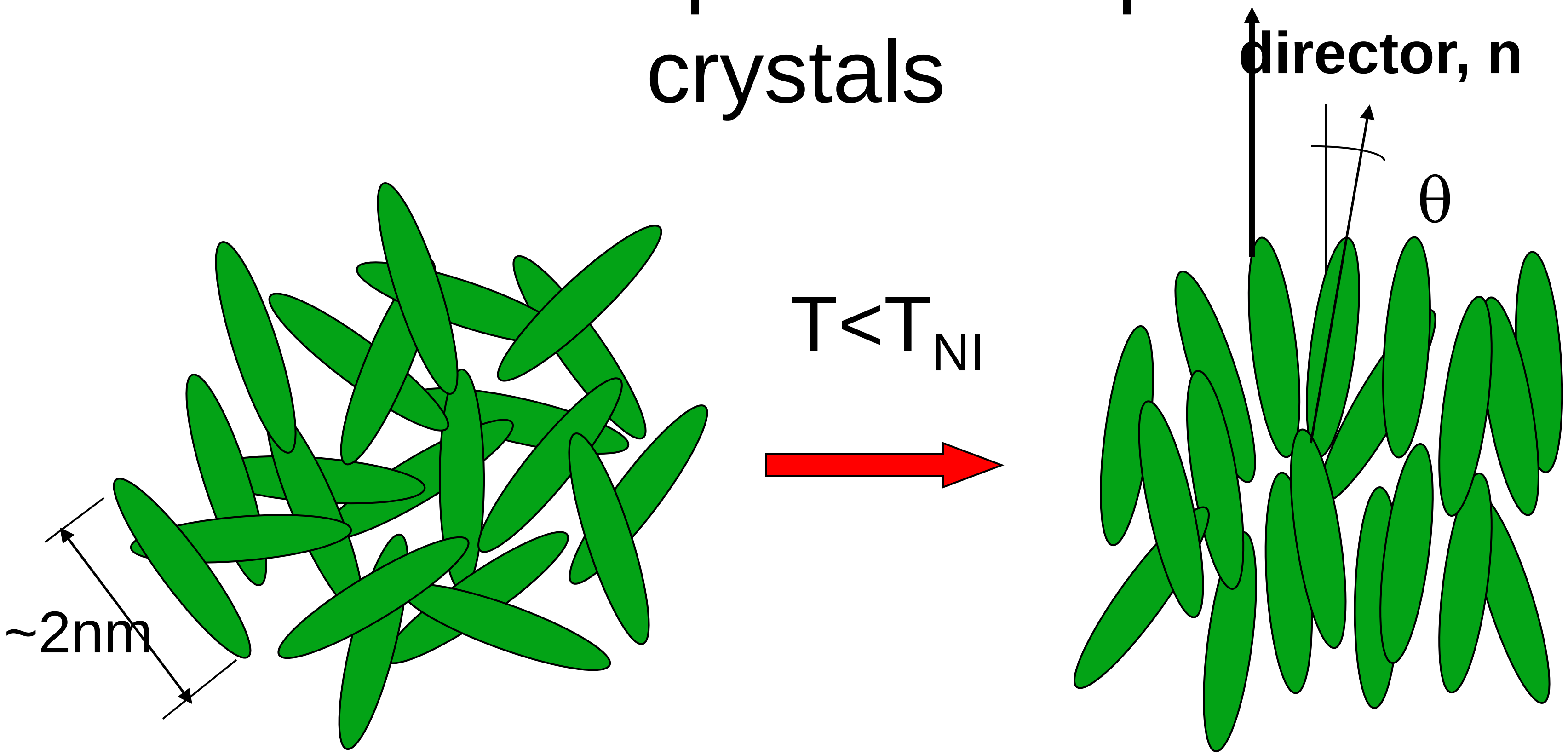


- why water droplets do not coalesce?
- what stabilizes them?
- what is the role of topology?

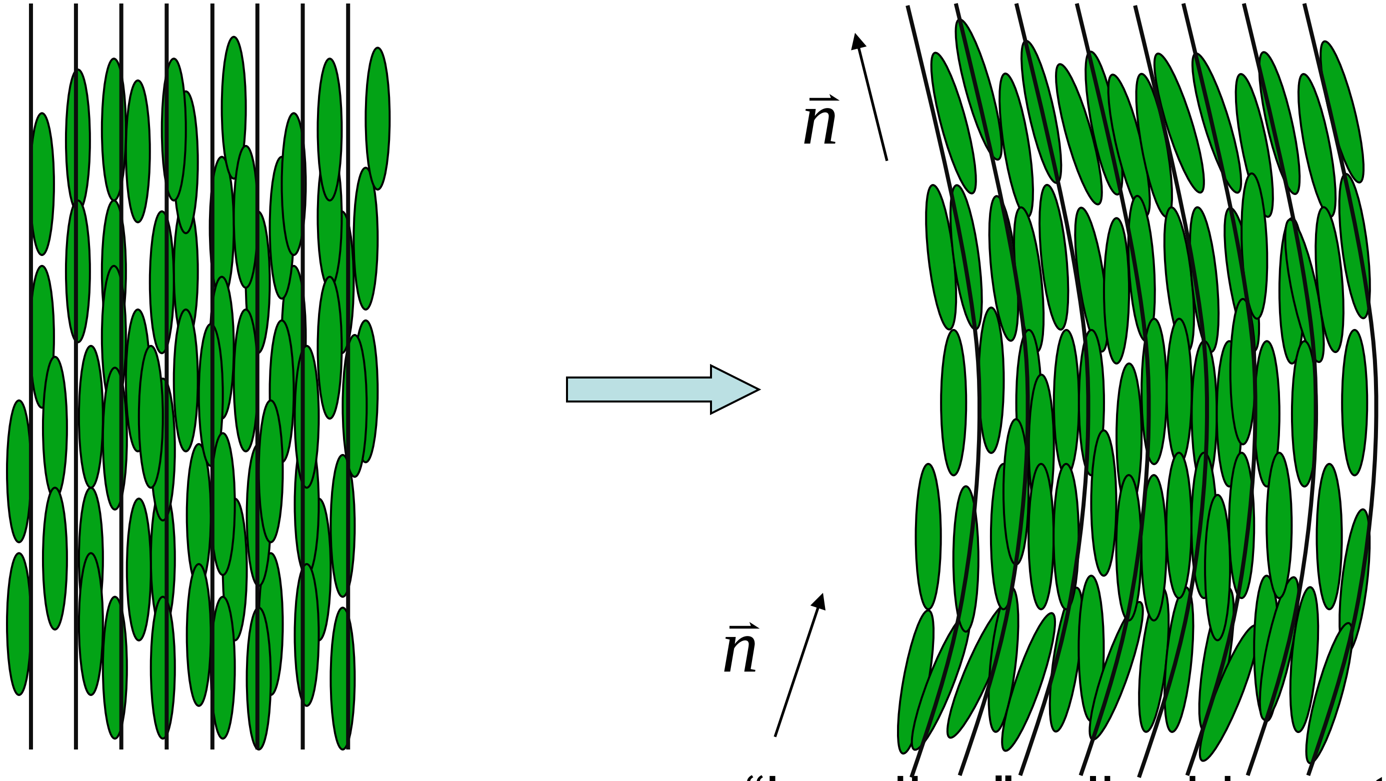
Nematic phase of liquid crystals



Orientational and positional disorder.
System is isotropic.

Orientational order, positional disorder.
System is anisotropic, usually uniaxial

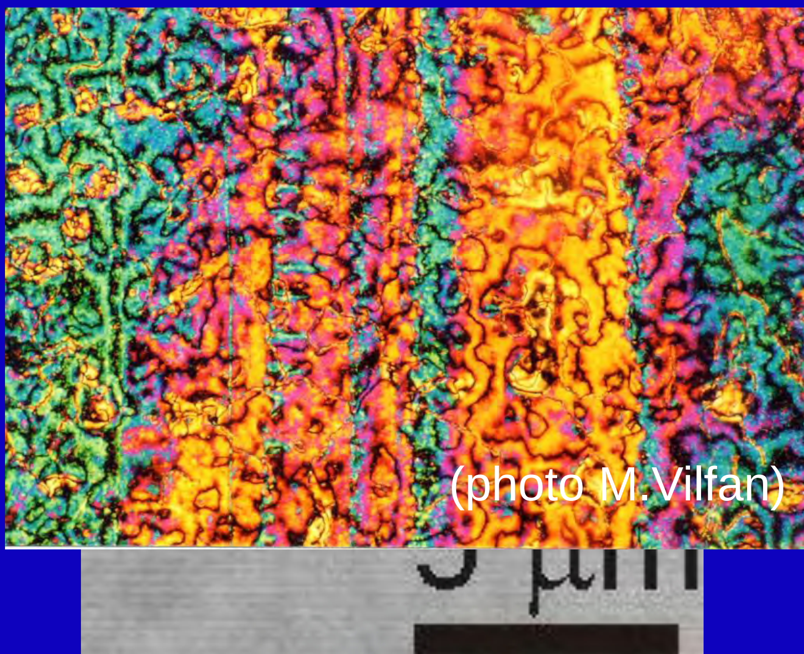
orientational order gives rise to "elasticity"



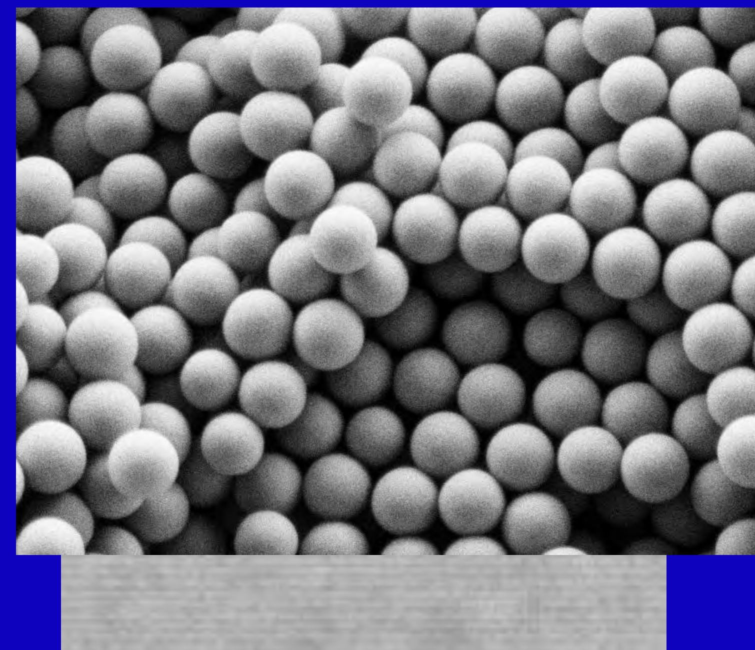
"bending" a liquid crystal

bending (and other deformation) reduce the degree of local order
(Landau-de Gennes theory, tensorial order parameter)

What happens when we mix solid microspheres and nematic?

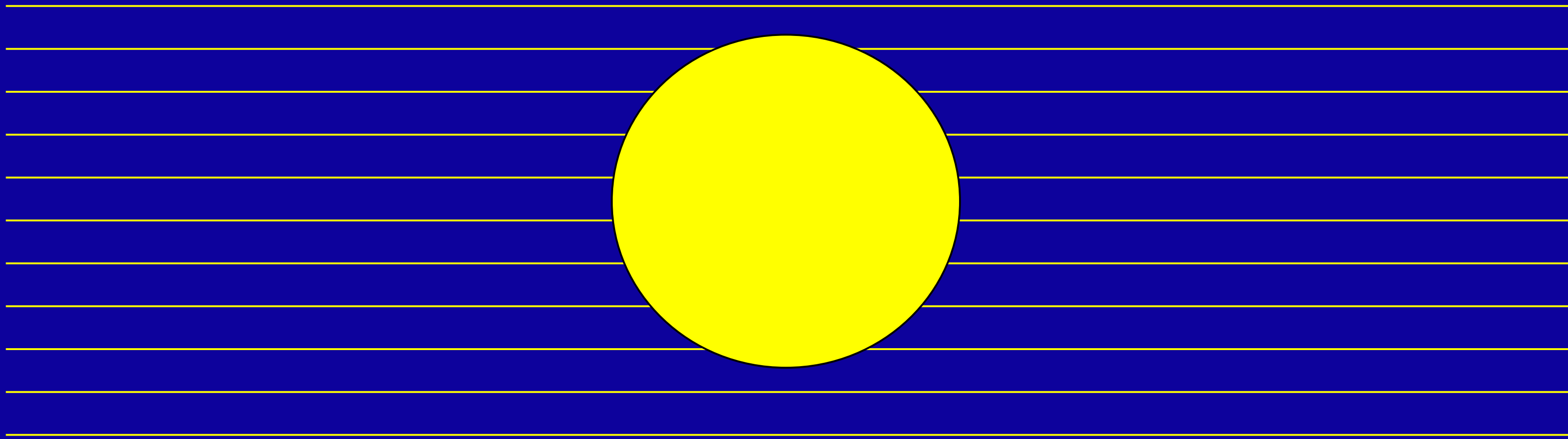


\+

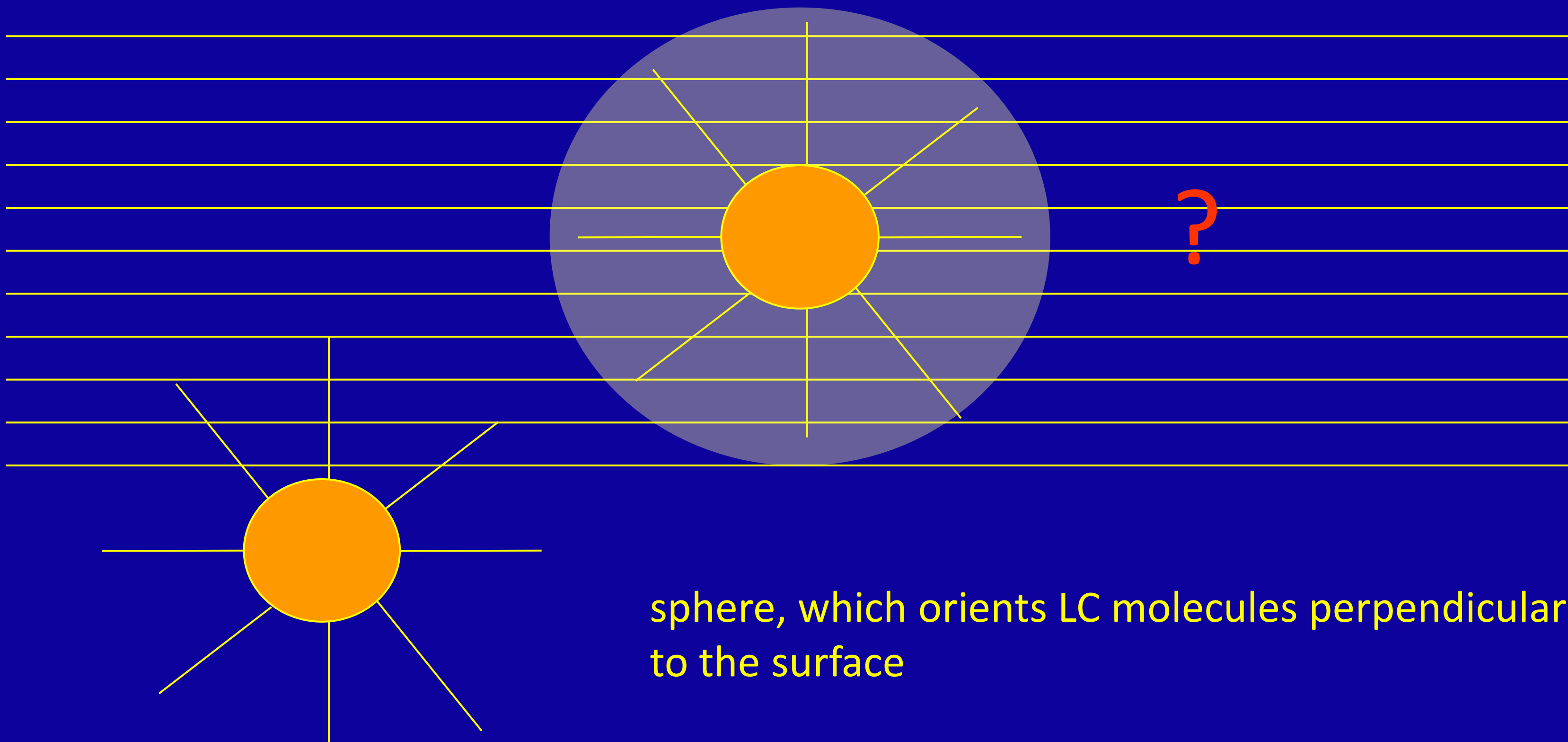


or

why?



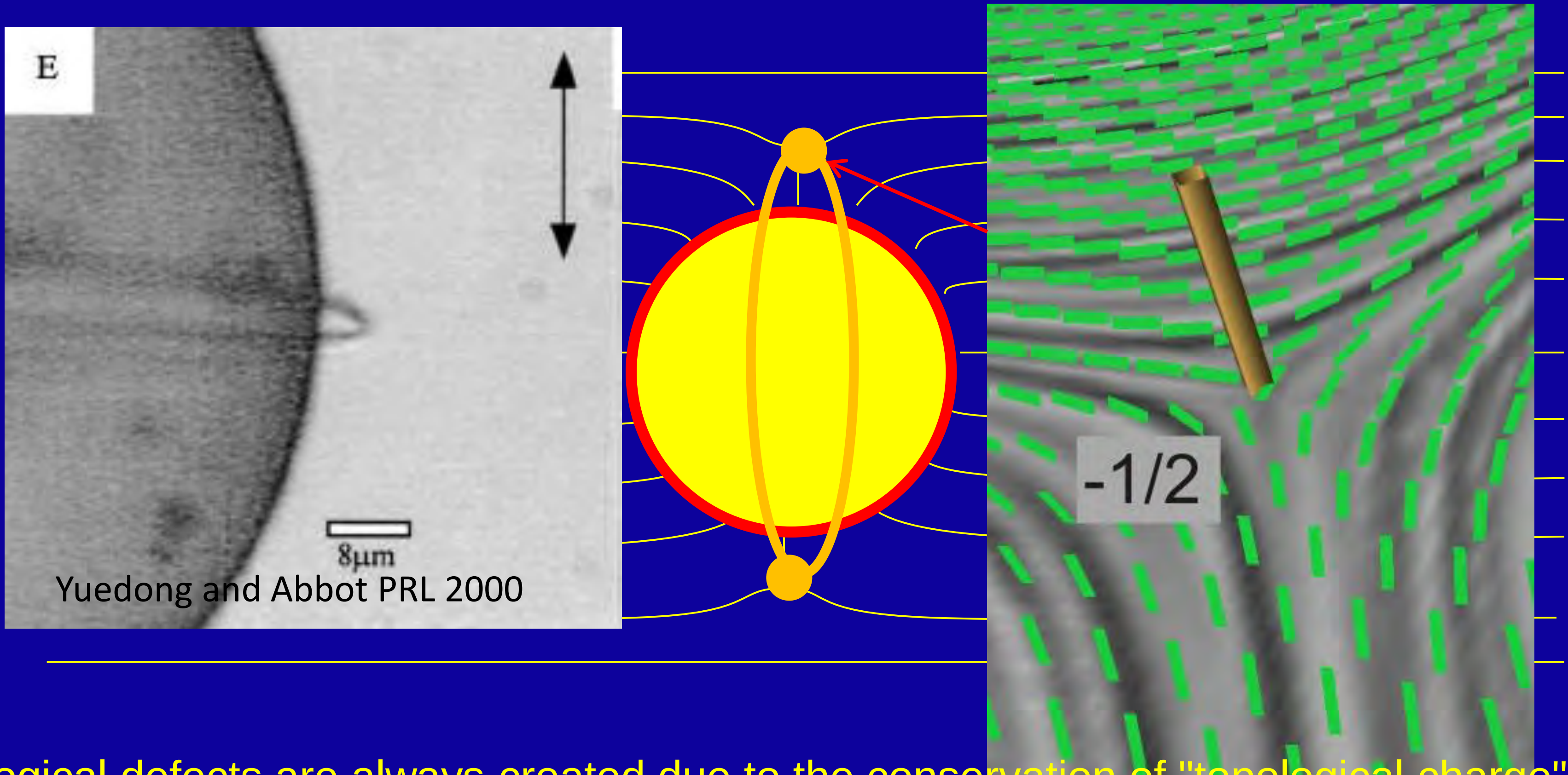
sphere with no surface coupling to LC molecules is "invisible" to the LC



sphere, which orients LC molecules perpendicular to the surface

The inability to fill the space uniformly generates <u>topological defects in a form of points and loops</u>

(E.M.Terentjev, PRE 51, 1330(1995), S.Ramaswamy et al. MCLC 288, 175(1996), O.V.Kuksenok et al., PRE 54, 5198(1996), T.C.Lubensky et al., PRE 57, 610(1998), O.D.Lavrentovich, Liq.Cryst. 24, 117(1998), B.Lev and P.M.Tomchuk, PRE 59, 591(1999) H.Stark, Phys.Rep.351, 389(2001), D. Andrienko et al., PRE 63, 041701(2001); J.C.Loudet et al. Nature 407, 611(2000), O.Mondain-Monval et al. Eur.Phys. J. B12, 167(1999))

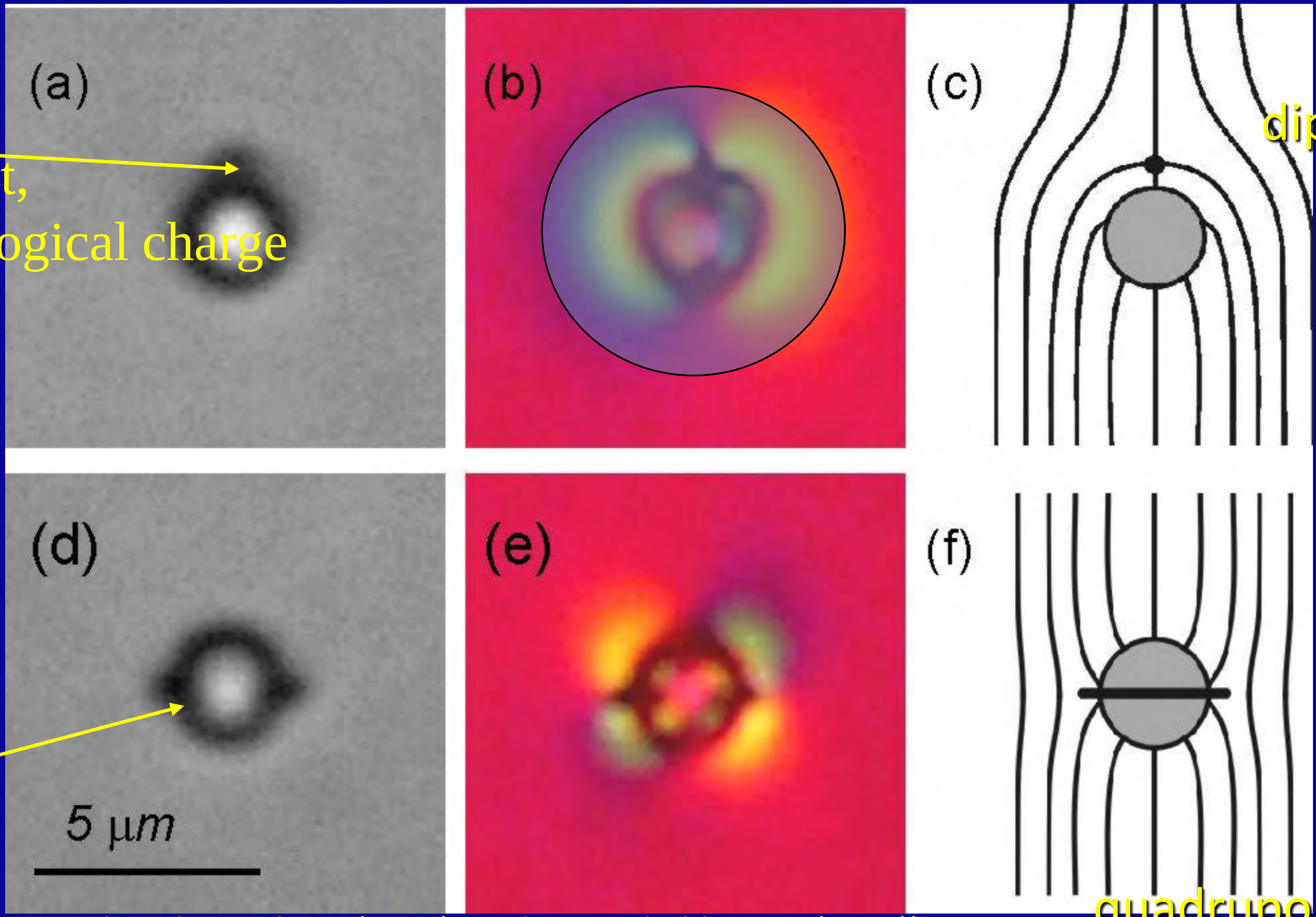


topological defects are always created due to the conservation of "topological charge"

result: dipolar and quadrupolar colloids

(homeotropic-perpendicular surface anchoring)

point defect, topological charge



dipole

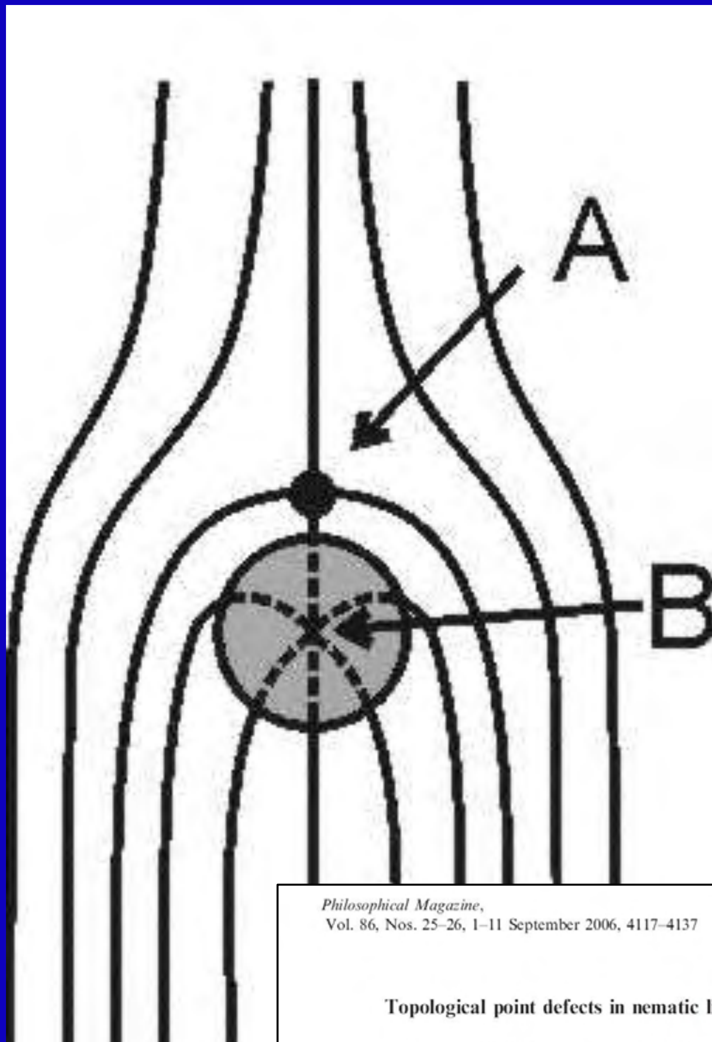
Saturn ring

quadrupole

(Mondain-Monval et al. Eur.Phys.J.(1999),Yuedong and Abbot PRL(2000))

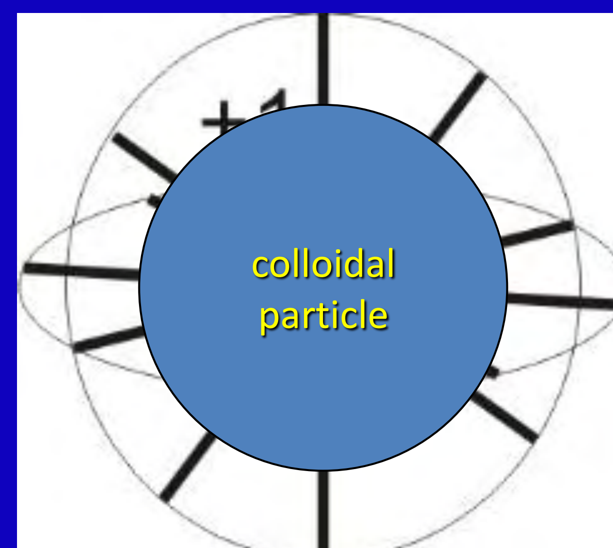
note: colloidal particles appear much larger than their size

Topological dipoles and charges



A ... hyperbolic hedgehog

B.... radial hedgehog



Philosophical Magazine,
Vol. 86, Nos. 25–26, 1–11 September 2006, 4117–4137
Taylor & Francis

Topological point defects in nematic liquid crystals

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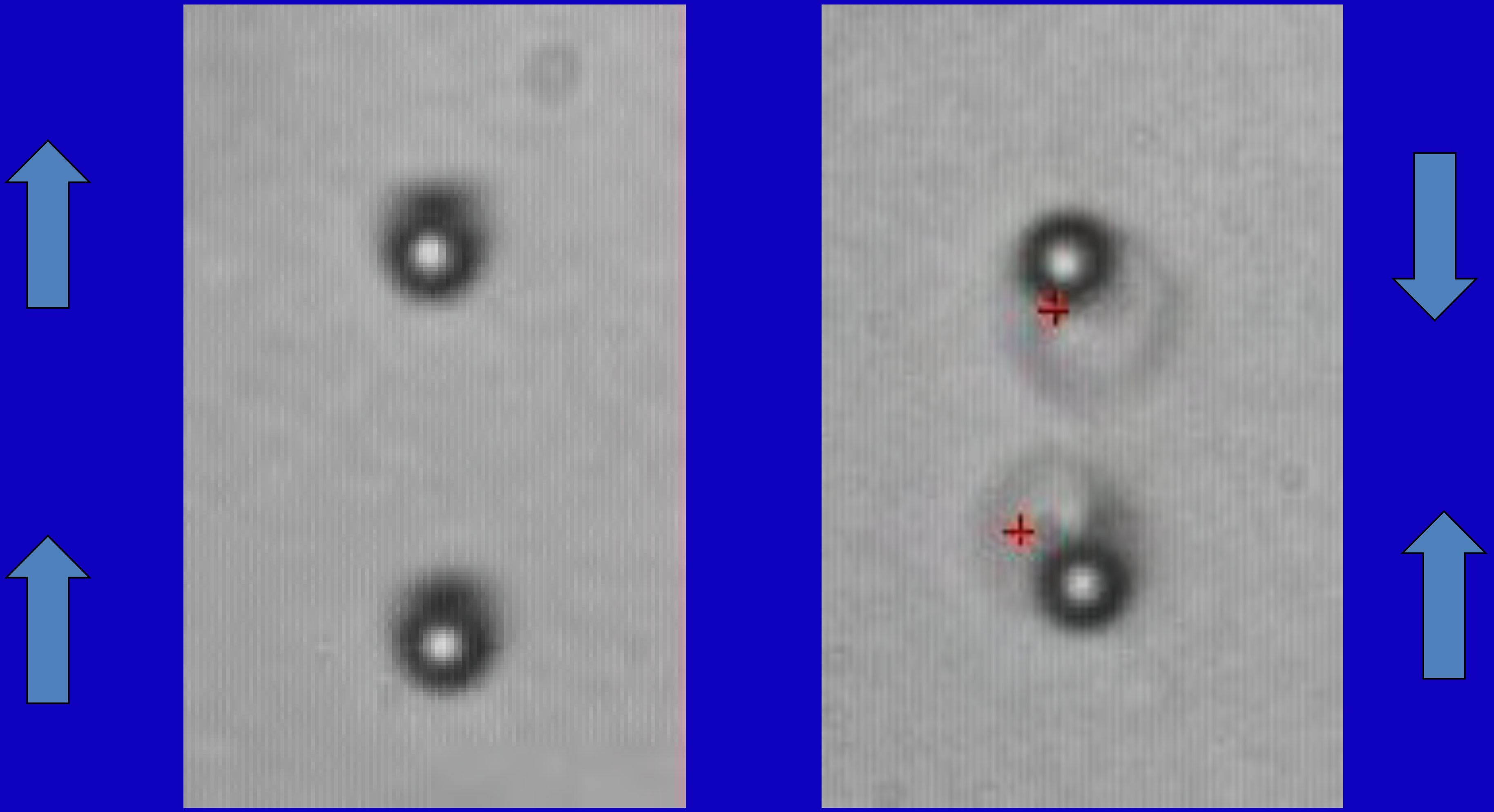
(*Received 10 October 2005; in final form 17 January 2006*)

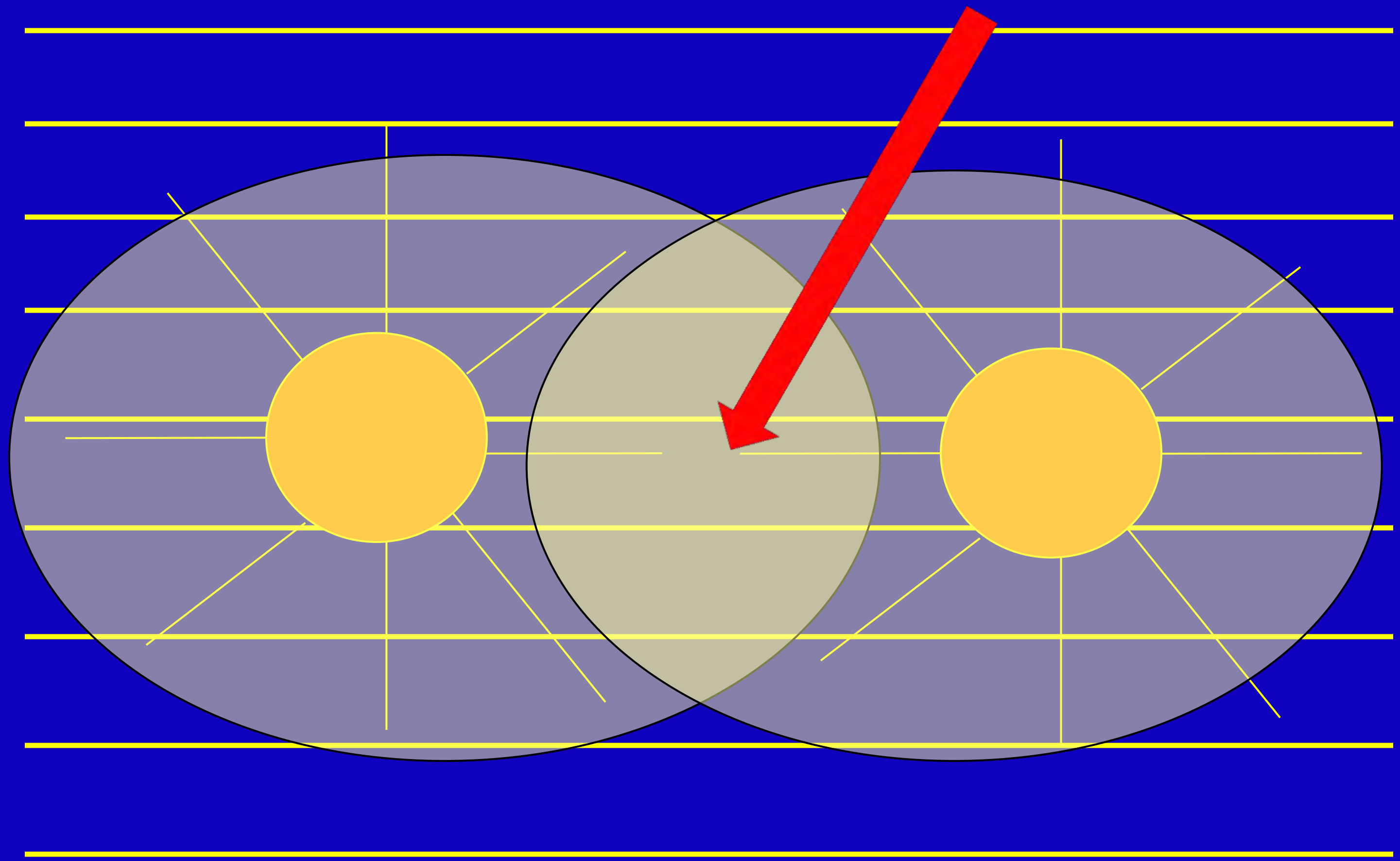
topological dipoles and quadrupoles interact



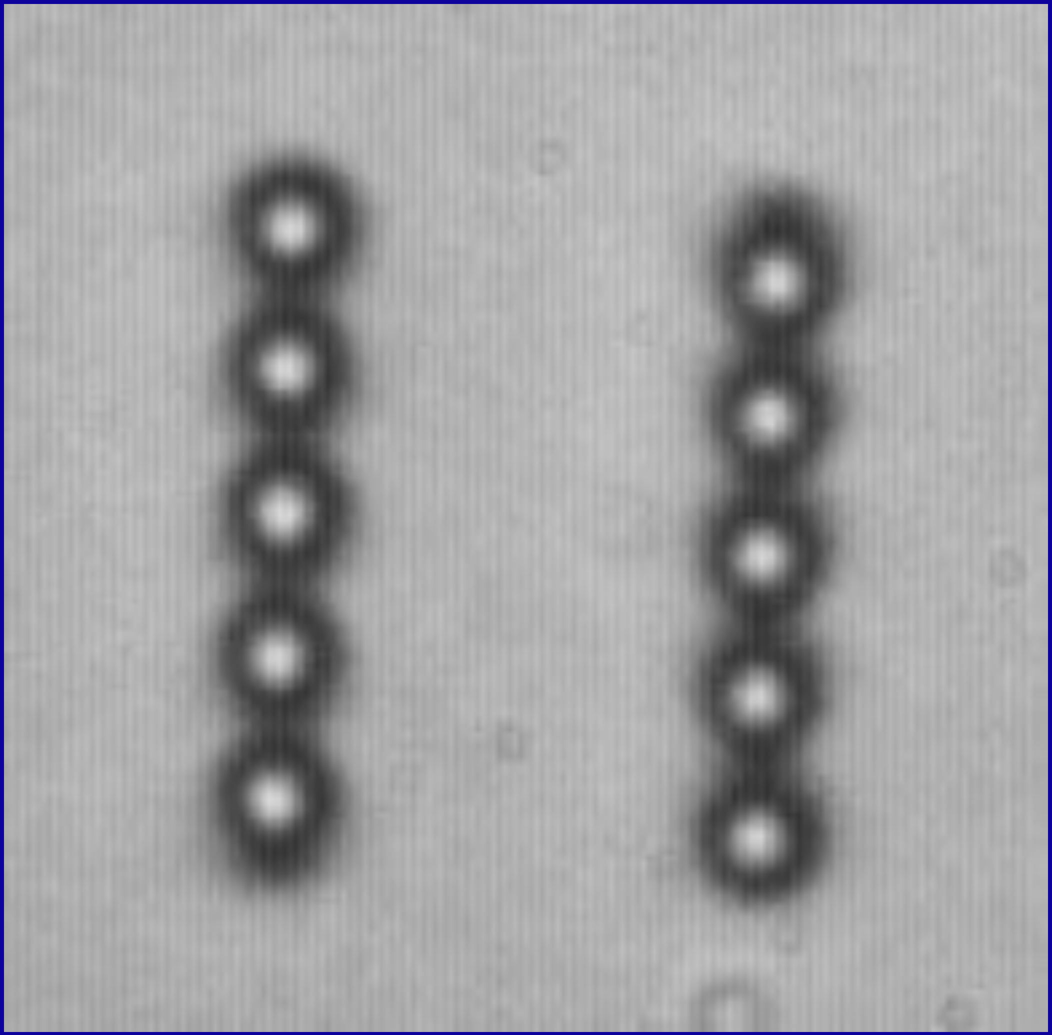
topological multipoles interact like electric multipoles

Lubensky et al., PRE 1998, Pergamenshchik and Uzunova, PRE **79**, 021704(2009)

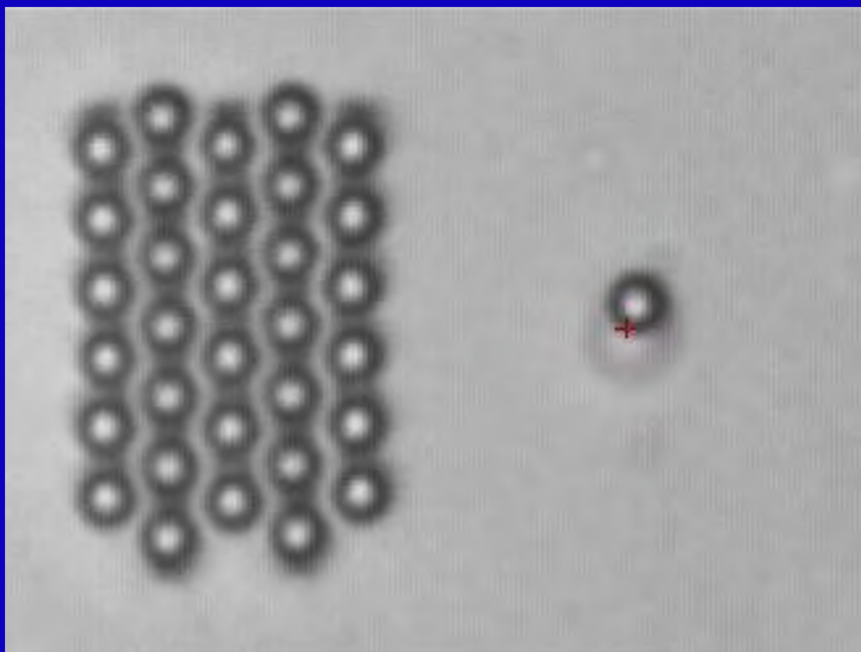
Why?

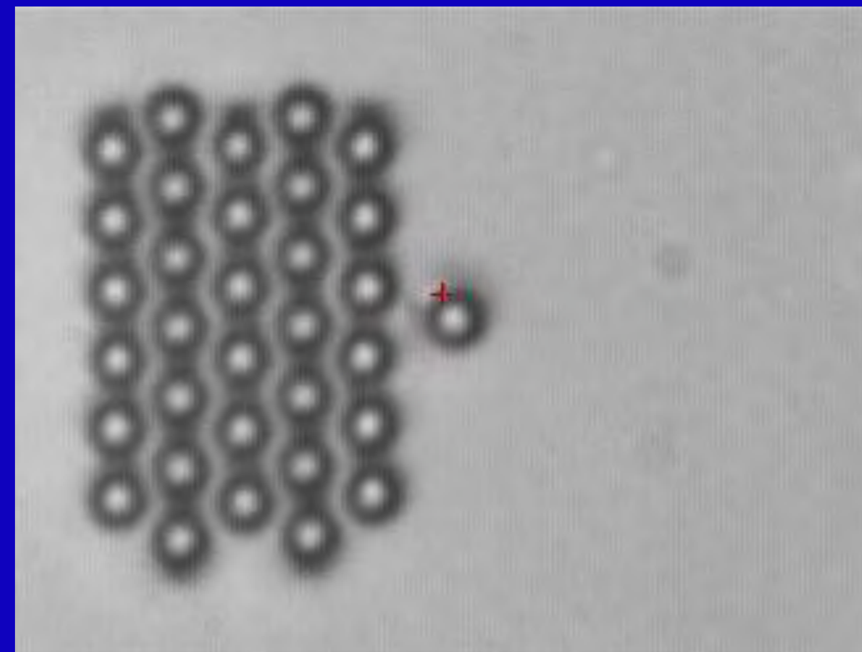


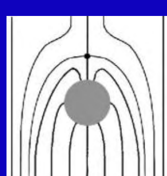
"sharing" of elastically distorted regions of LC generates forces



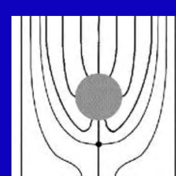
Dipoles form 2D crystals some dipoles are repelled from, others attracted to!!

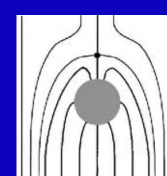




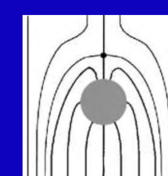


attraction

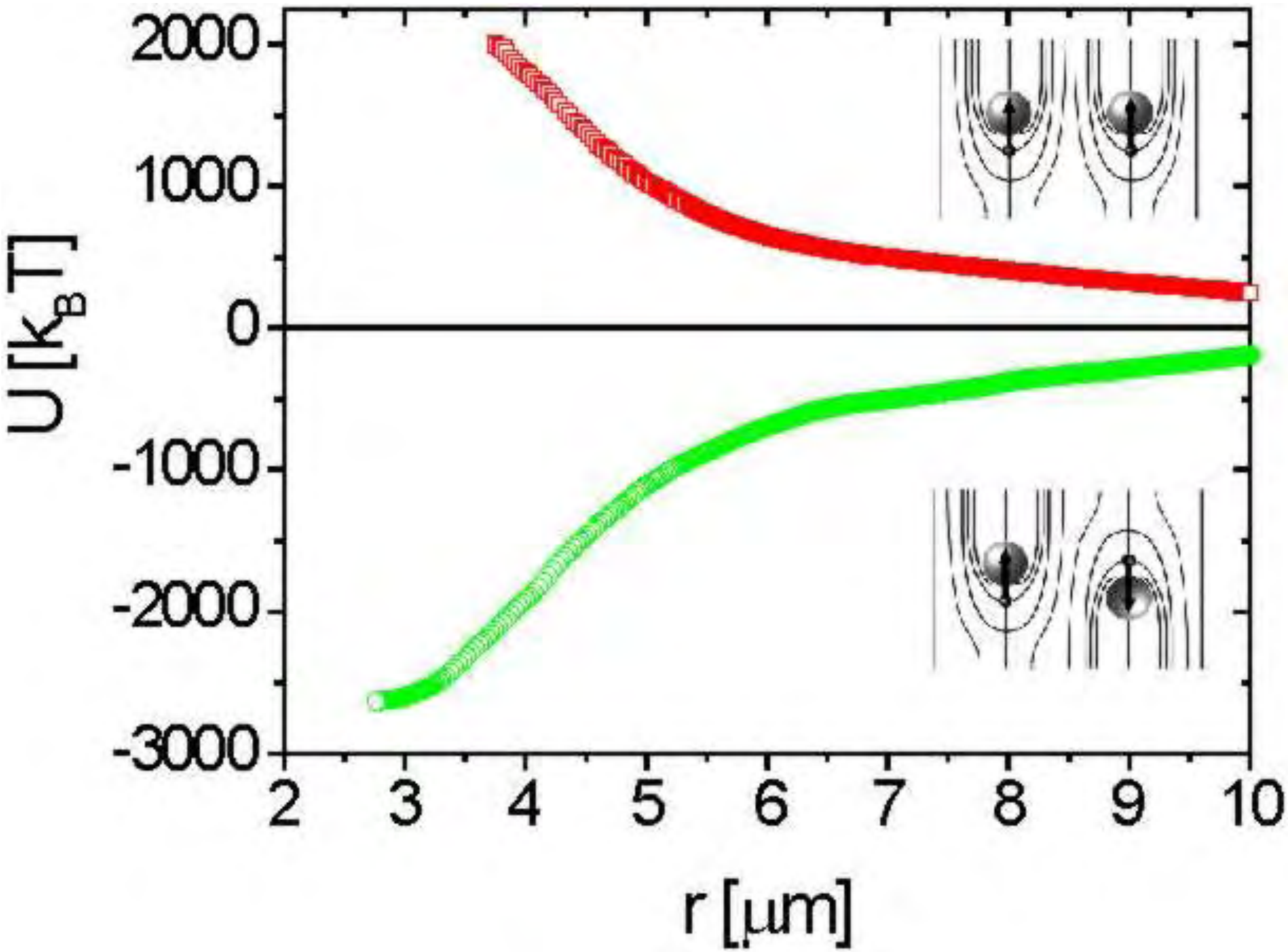




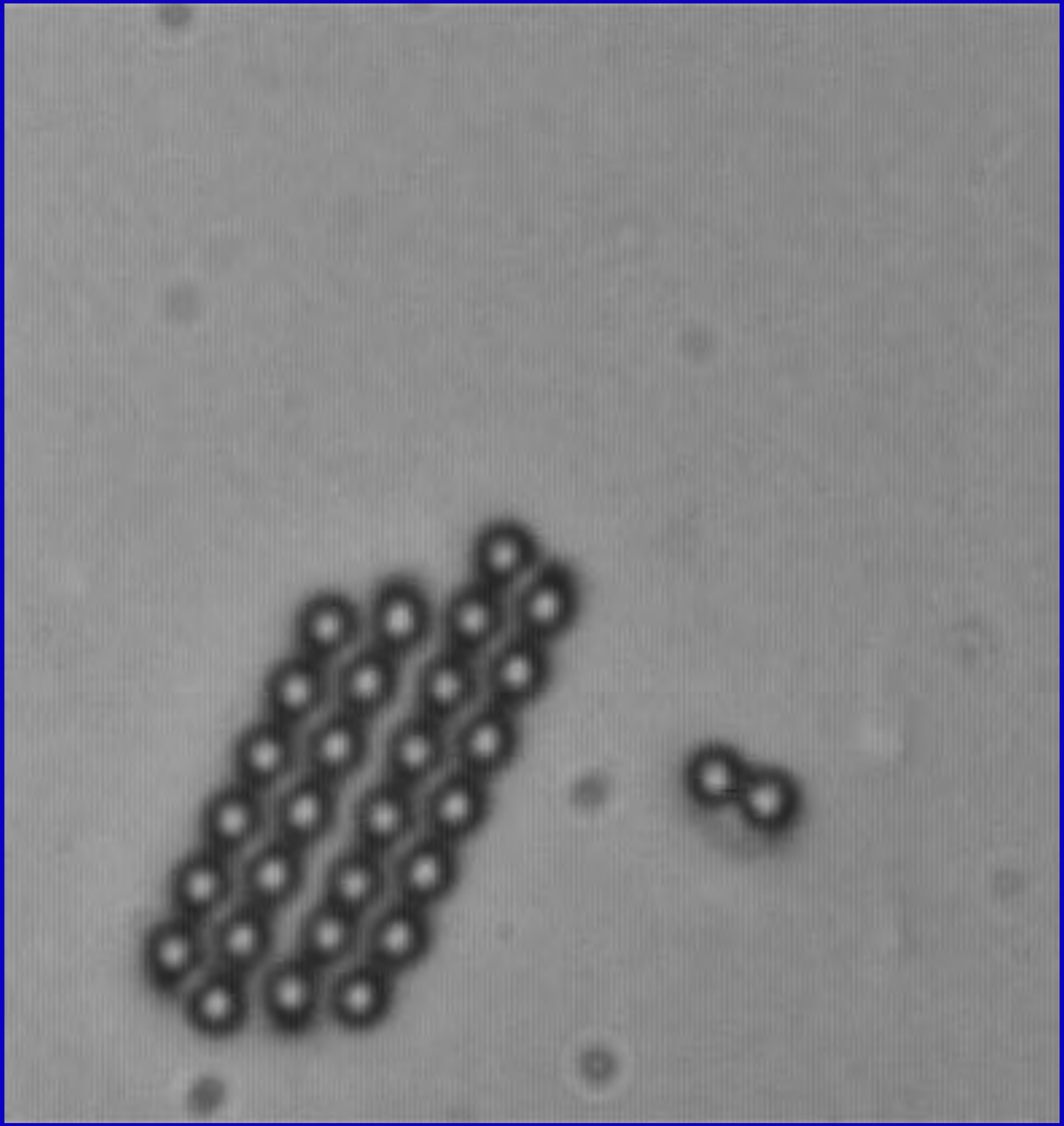
repulsion

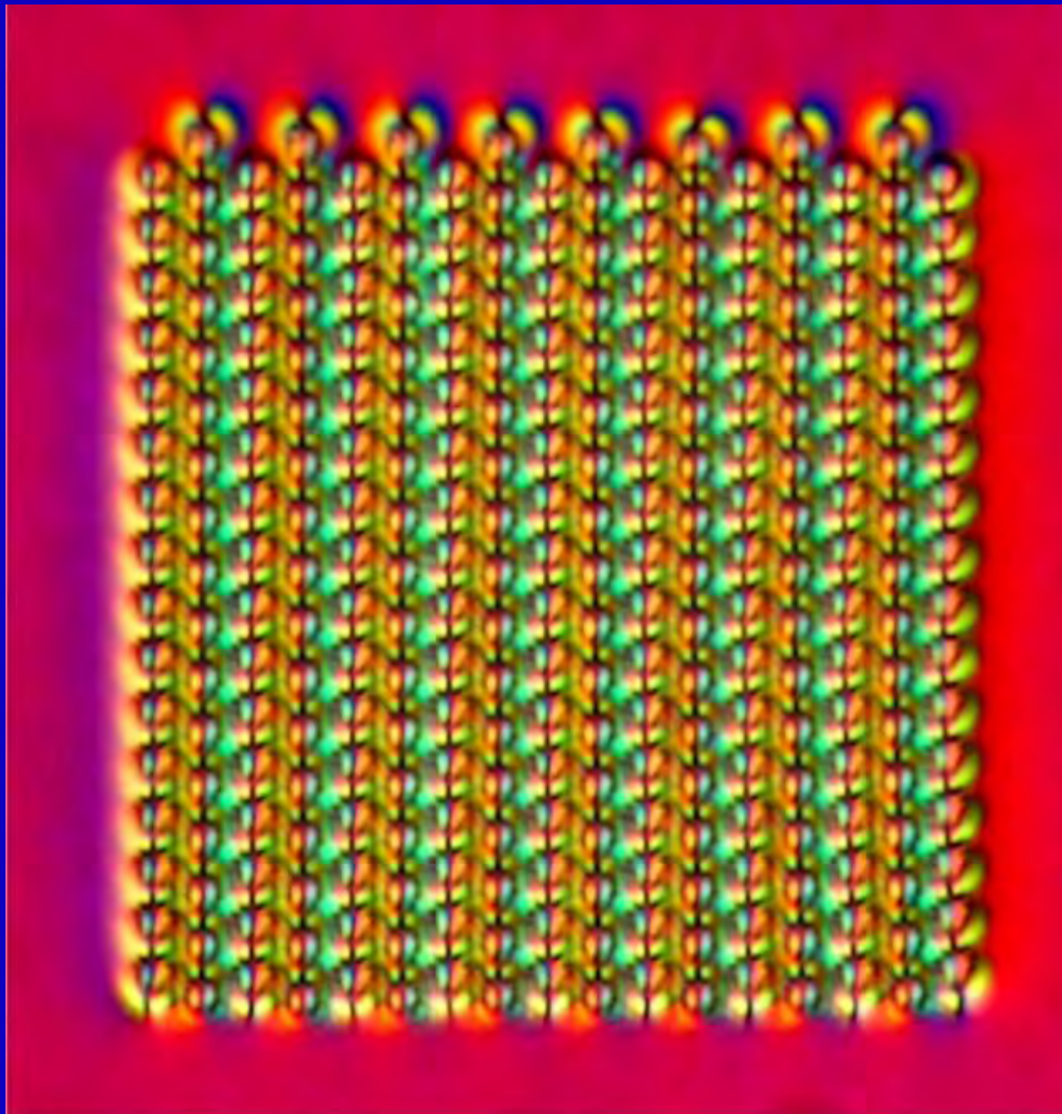


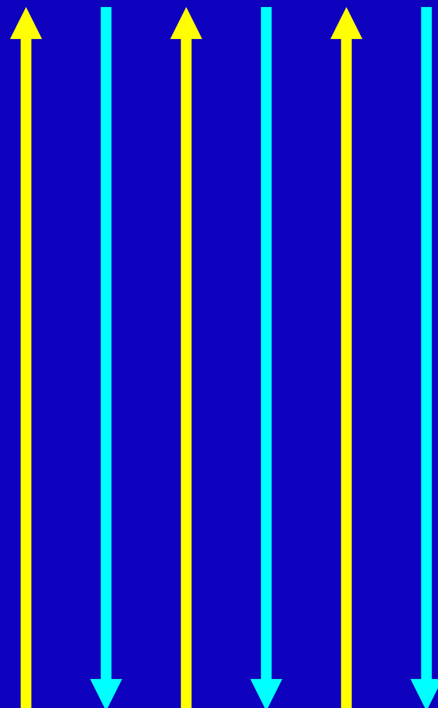
Note the strength of interaction: 2000 $k_B T$ for 2 μm particle!



assembling a 2D dipolar nematic colloidal crystal:

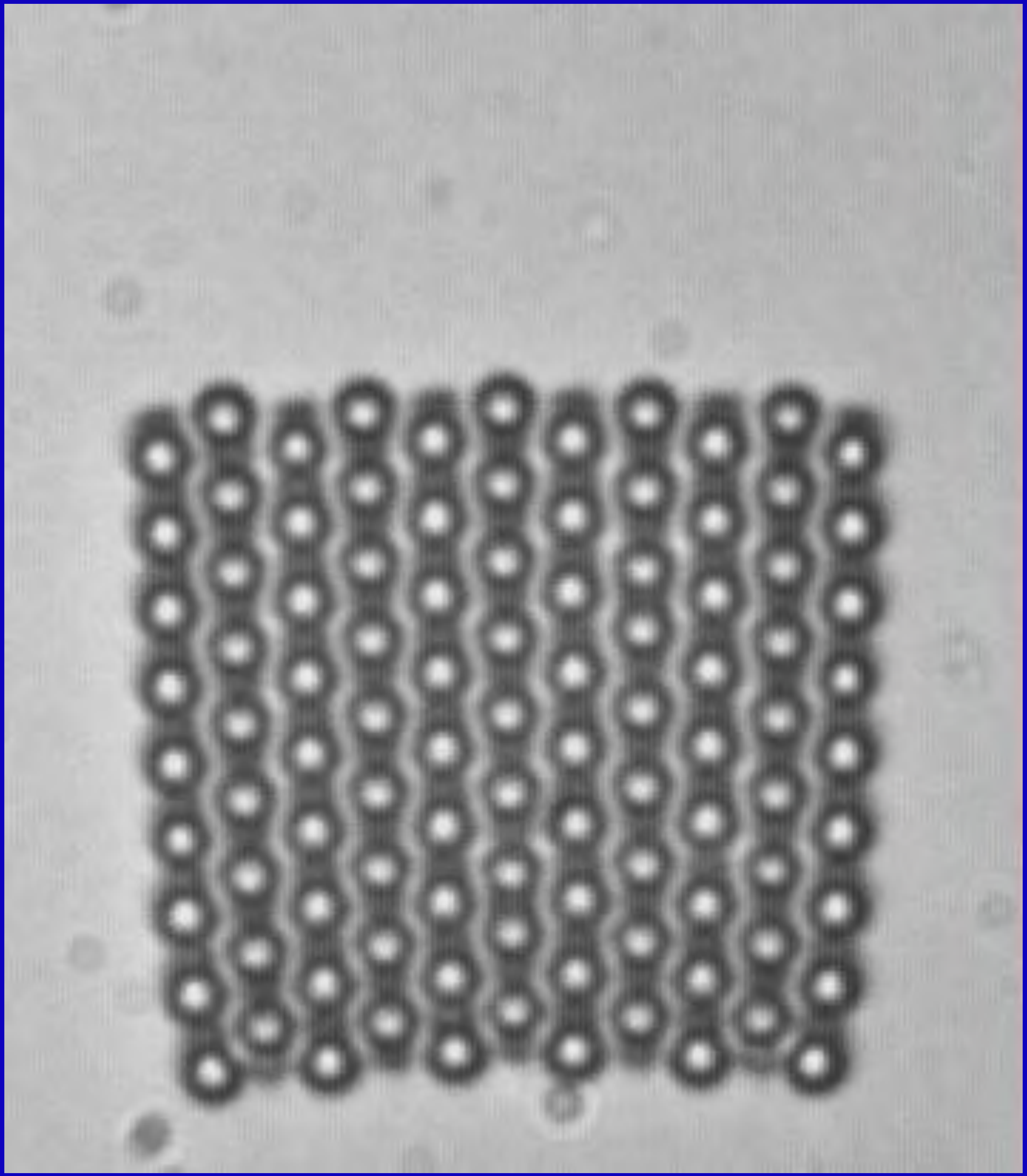




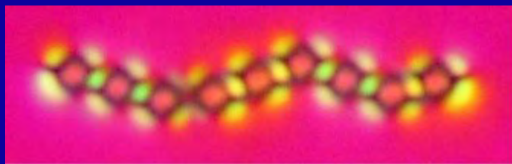


"anti-ferroelectric" lattice of "ferroelectric chains"

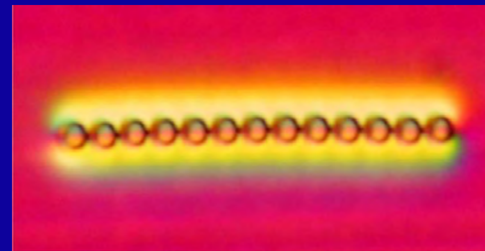
Muševič, Škarabot, Tkalec, Ravnik, Žumer, Science **313**, 954(2006) moving a 2Dcolloidal microcrystal with a laser tweezers



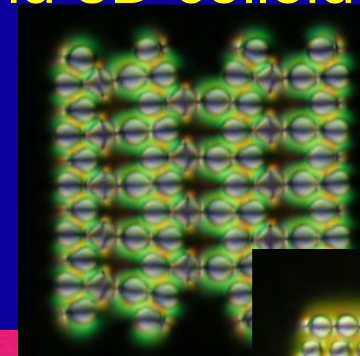
point/loop defects are binding chains, 2D and 3D colloidal crystals

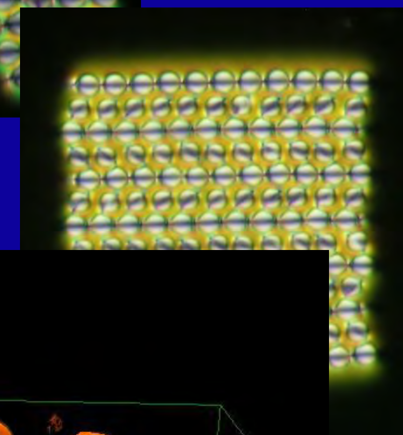


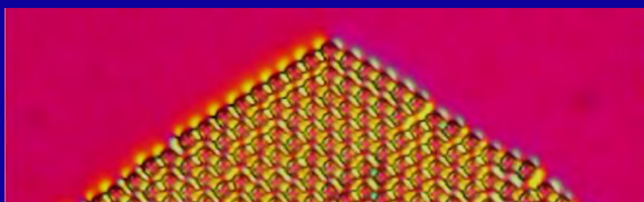
kinked quadrupolar chains

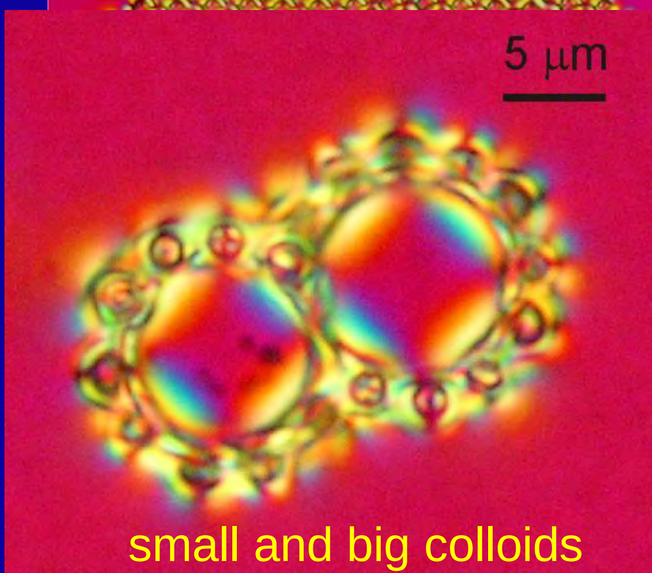


straight dipolar chains

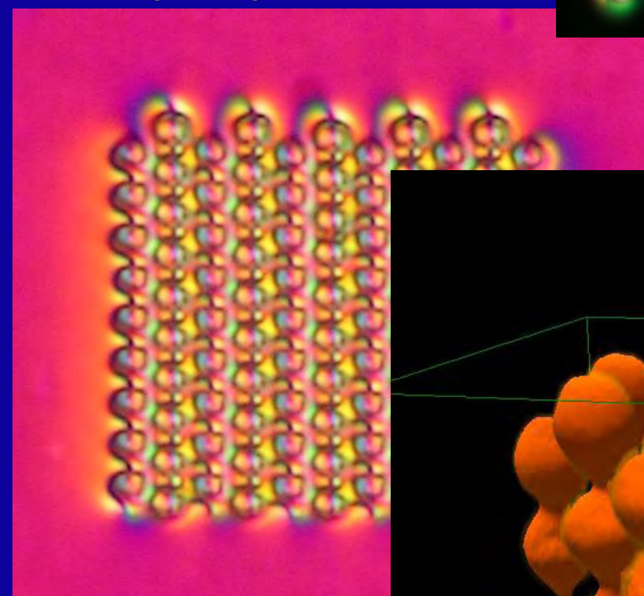




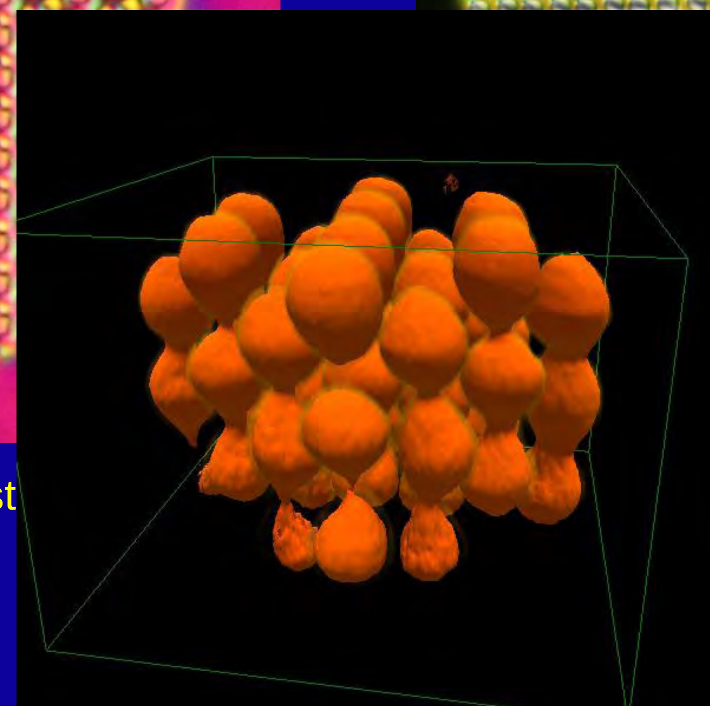




small and big colloids



2D <u>dipolar</u> cryst



I.Muševič et al., *Science* 2006; M.Škarabot et al., PRE 2007; PRE2008;
Ognysta et al. PRL 2008; Ognysta et al. Langmuir 2009.

"Exotic" mechanism of colloidal assembly:

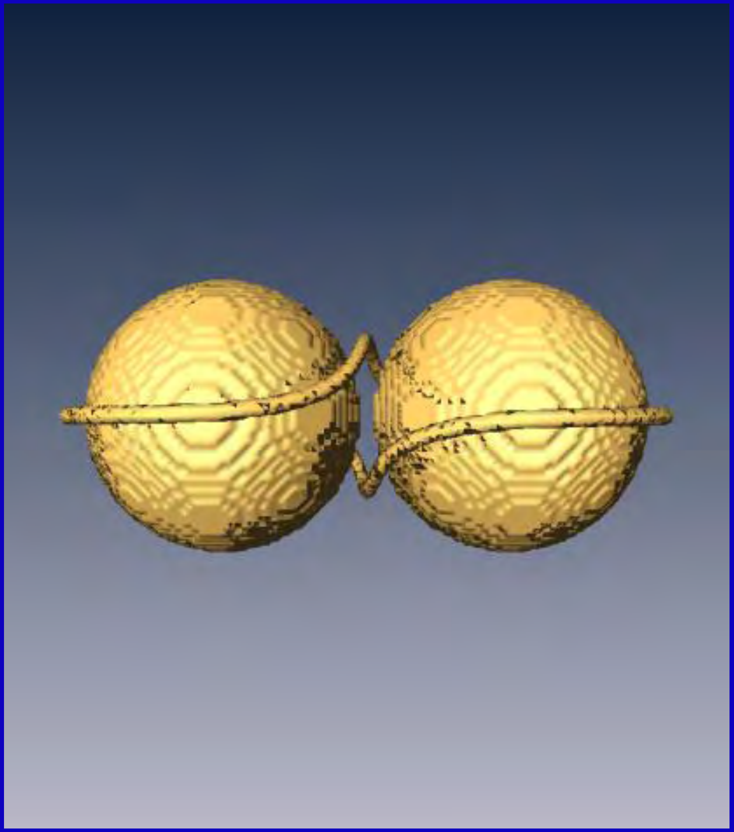
entangled topology in a thin nematic layer

Theory: quenching a colloidal pair in Landau-de Gennes simulation

LdG simulation M.Ravnik, S.Žumer

heating and quenching with laser tweezers

figure of 8



theory (LdG)

predicted by Araki and Tanaka, PRL 2006; S. Zumer ILCC 2006
observed by M.Ravnik et al., PRL 99, 247801(2007)

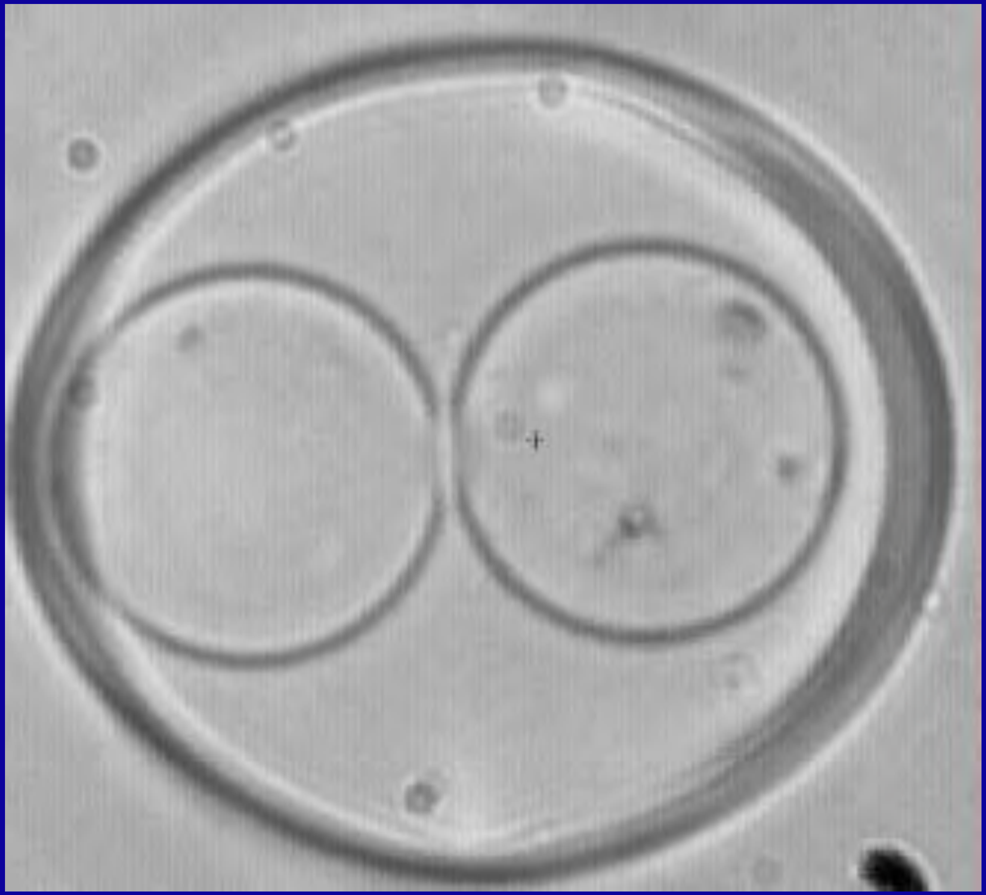
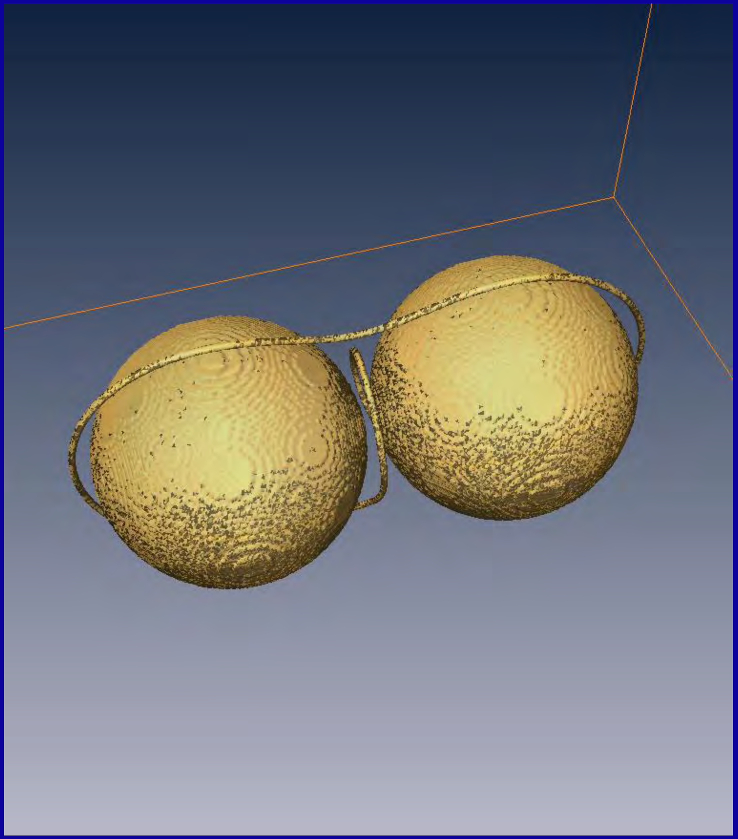


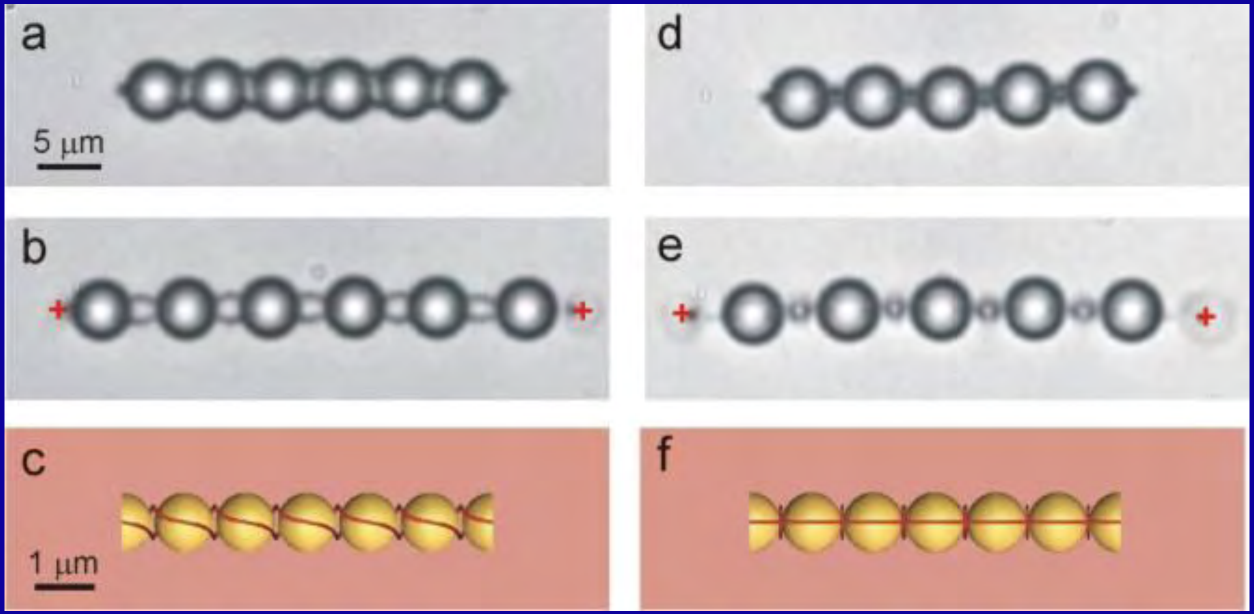
figure of Ω

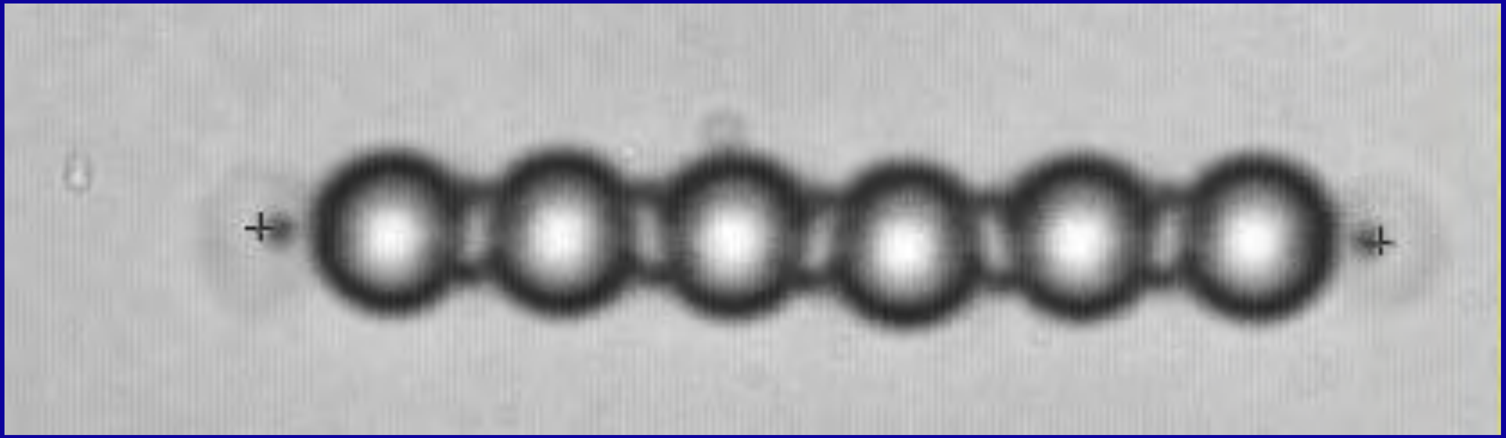


theory

entangled colloidal wires

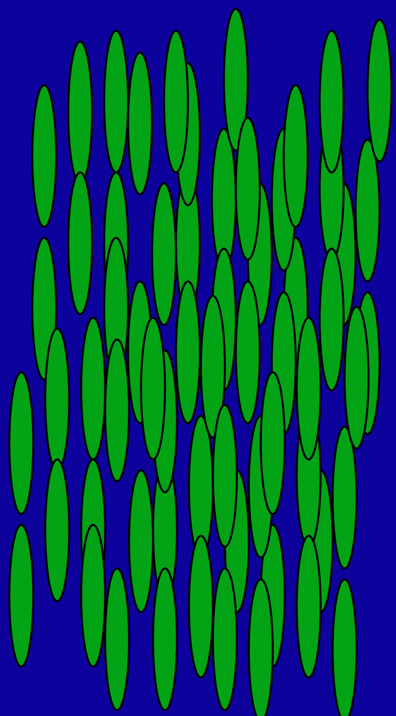
figure of 8 colloidal wire



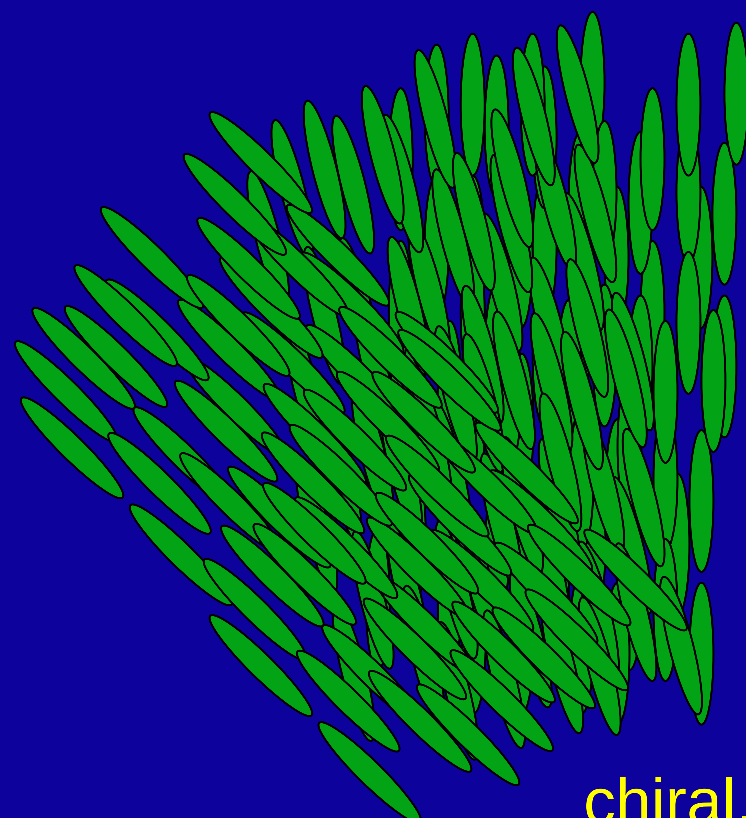


string-like force, M.Ravnik et al. PRL (2007).

Even more exotic 2D entanglement <u>in chiral nematics</u>

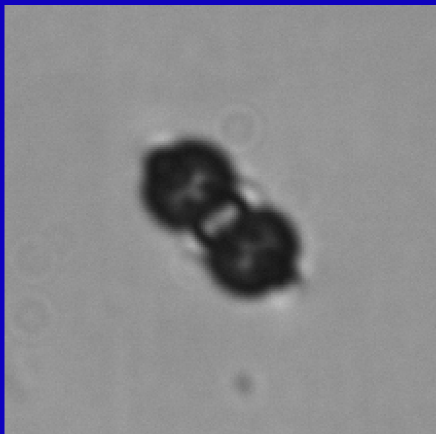


achiral nematic

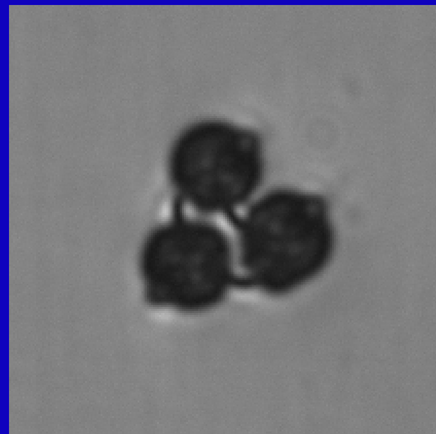


chiral, twisted

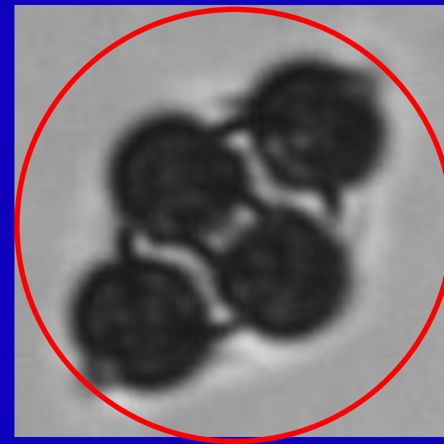
colloids in „low chirality“-$\pi/2$ twisted nematic cell



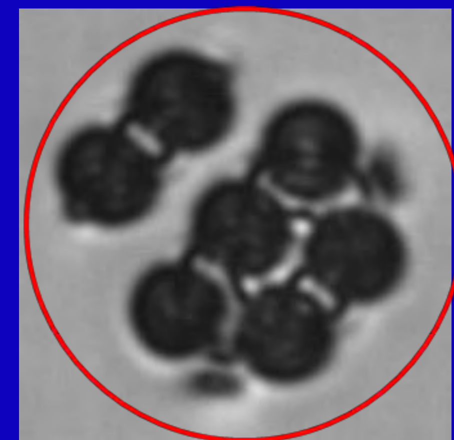
N=2



N=3

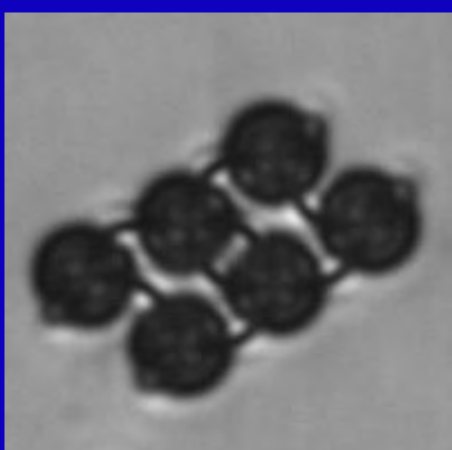


N=4

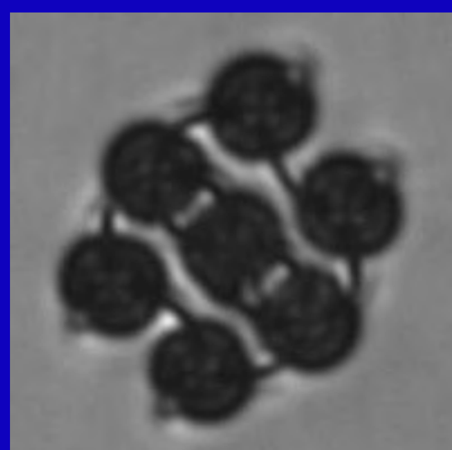


N=5

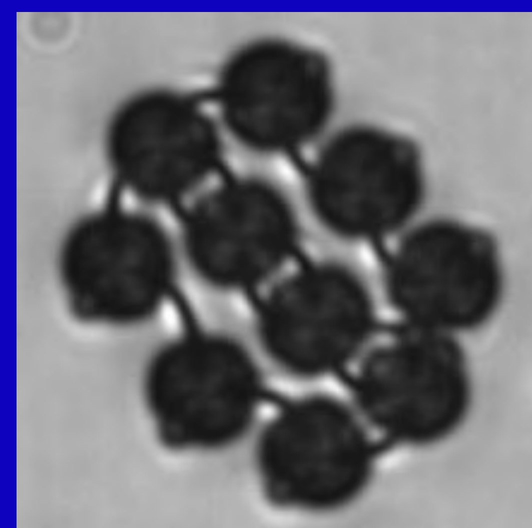
Links and knots?



N=6

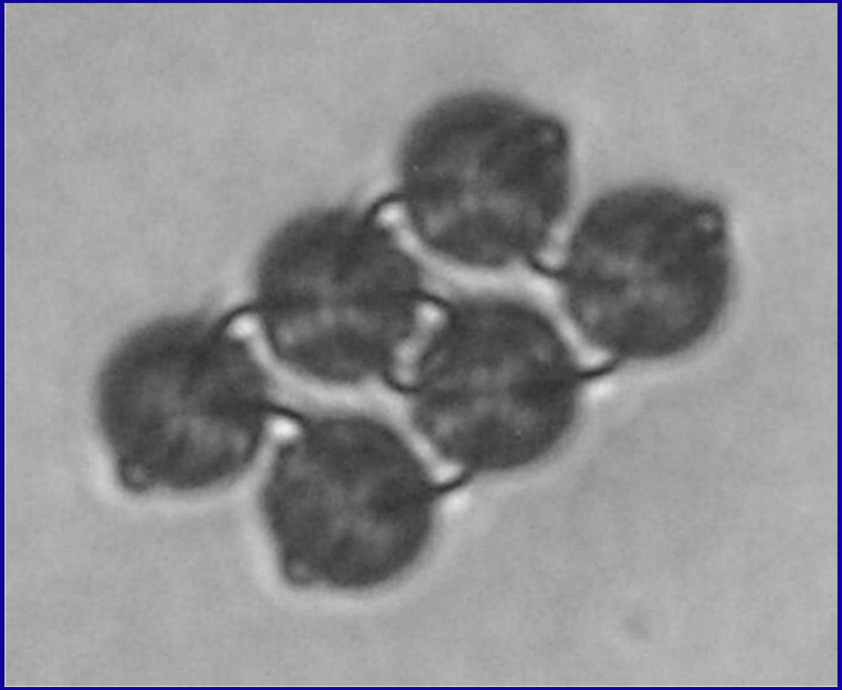


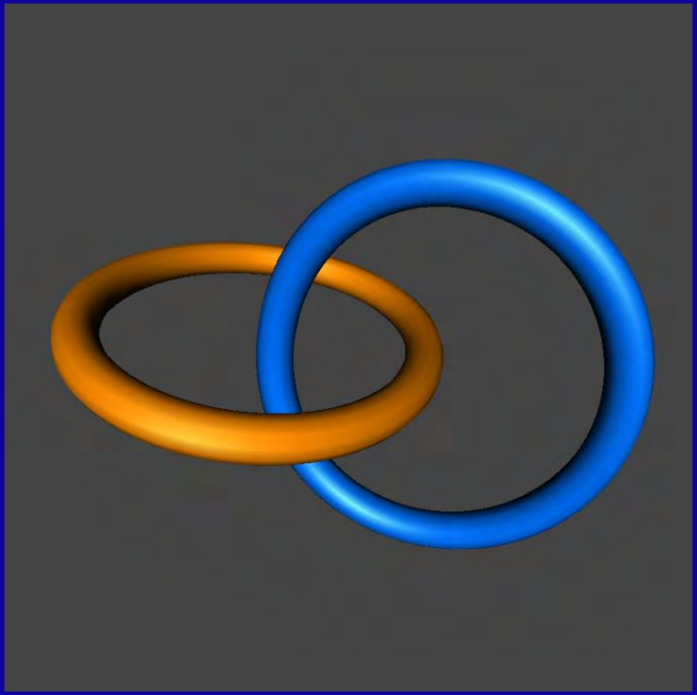
N=7



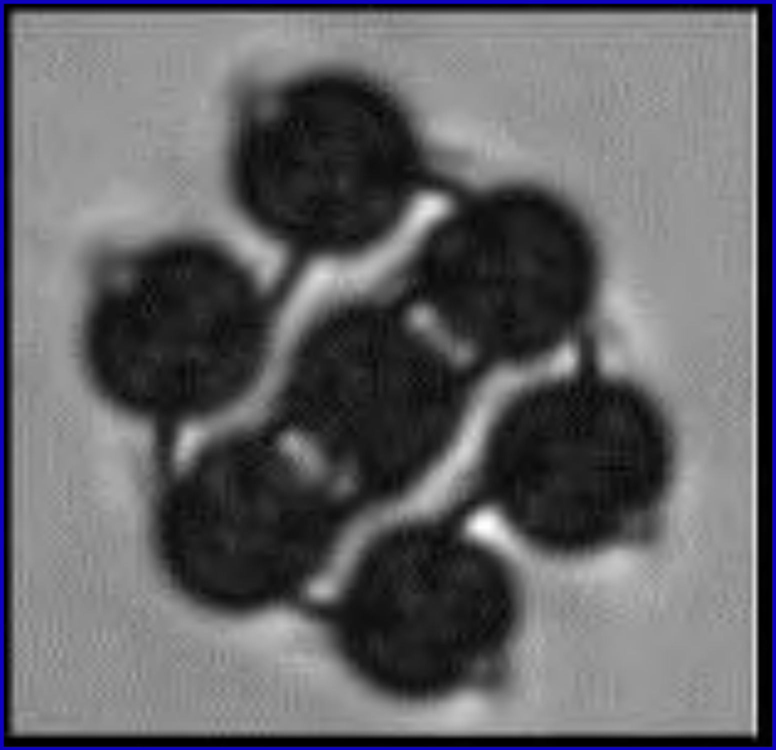
N=8

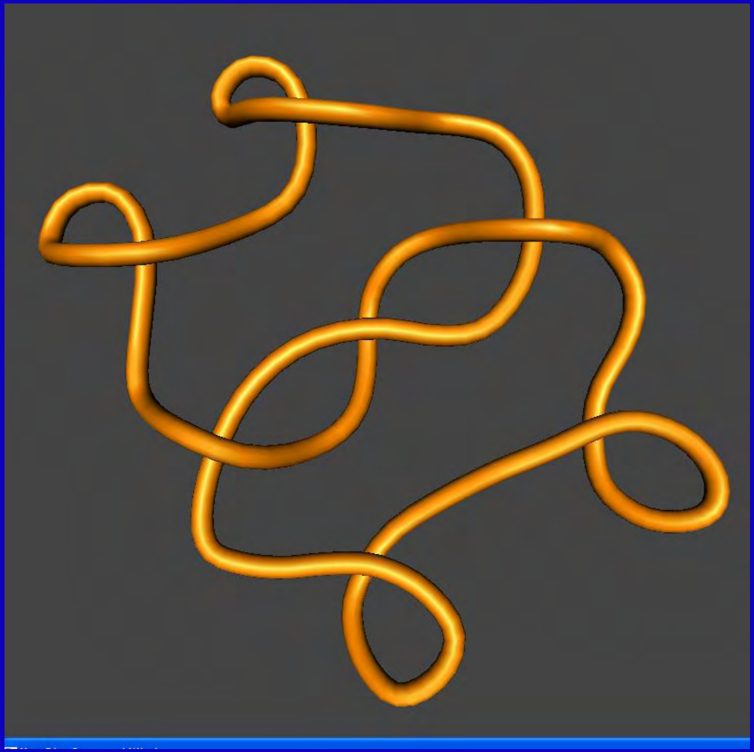
Example of a link: "Hopf" link





Example of a knot: "trefoil" knot

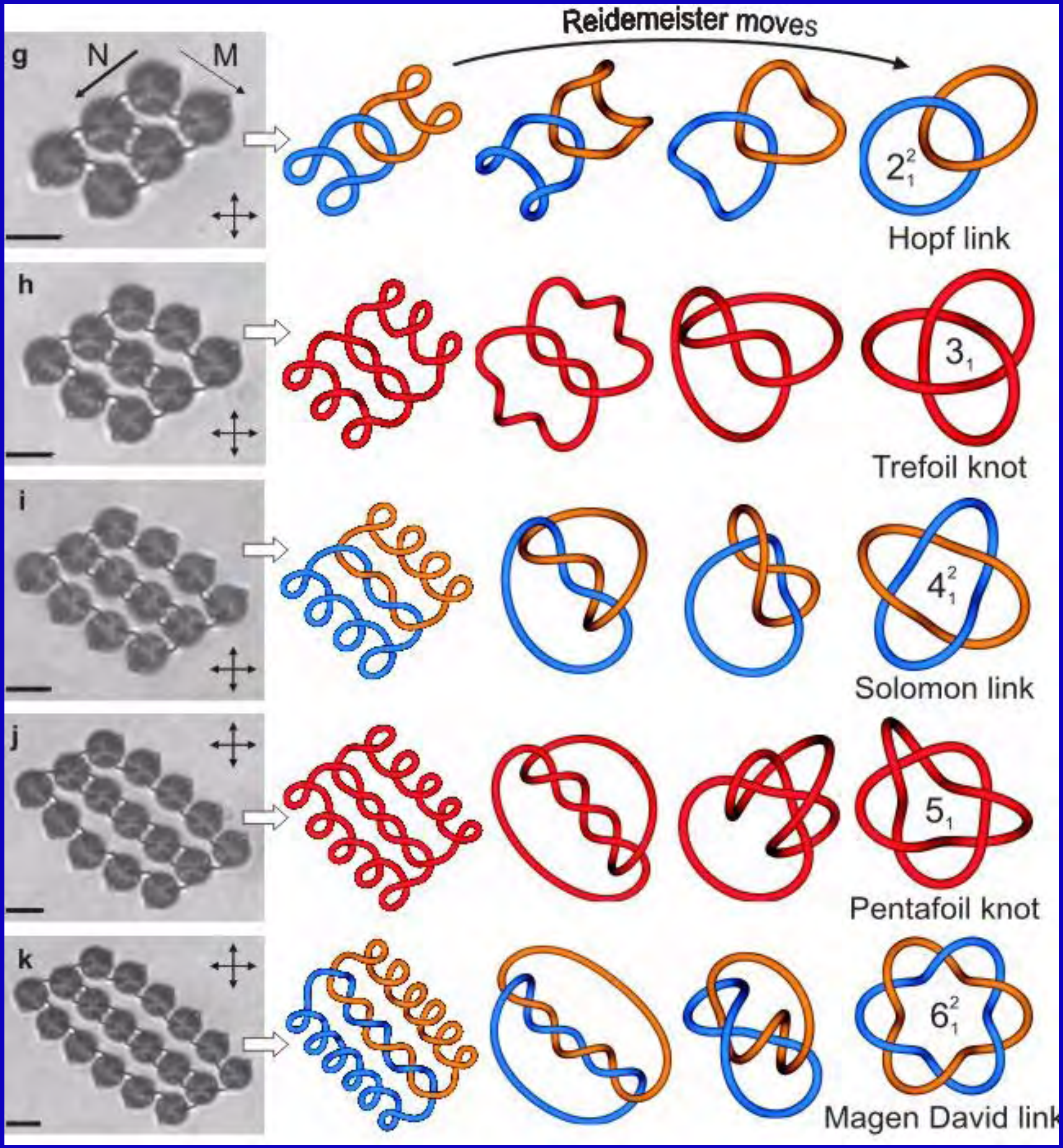




Is it?

Reidemeister moves and evolution towards the trefoil knot

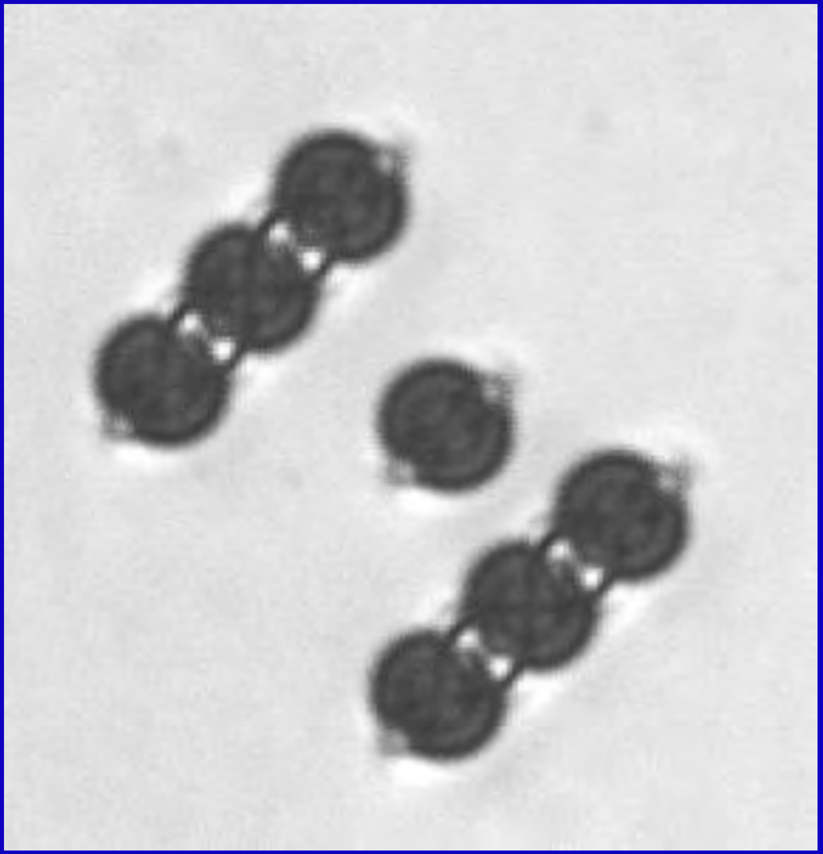
C.C.Adams, *The Knot Book*, American Mathematical Society, Providence 2004.



first reported in bulk chiral nematic by Y. Bouligand *J. Physique (France)*(1974).
Knotted optical fields: Irvine and Bouwmeester, *Nat.Phys.*2008; Dennis et al. *Nat.Phys.* 2010

Knots and links can be re-knitted by laser tweezers

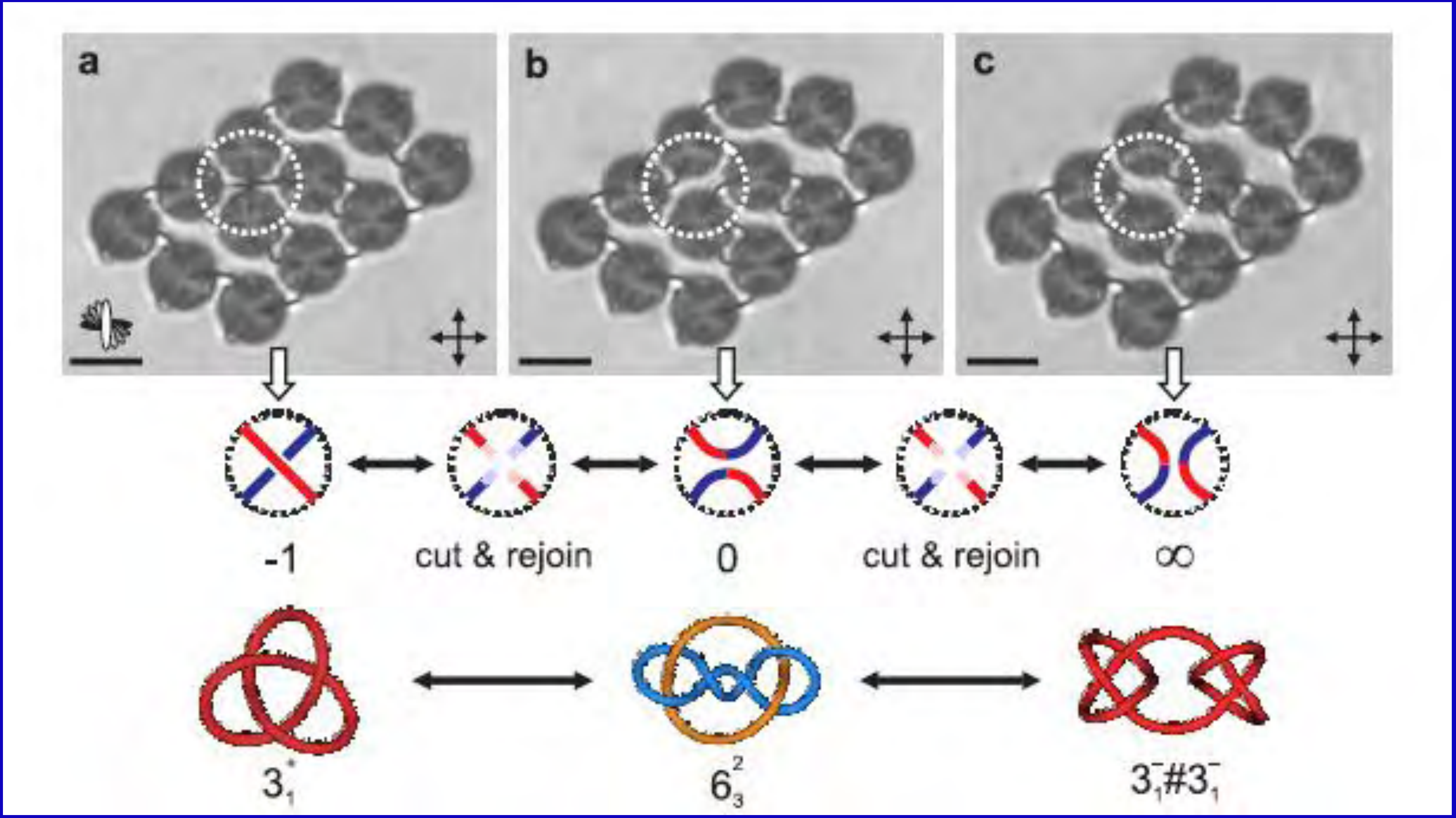
linking a Hopf link



knitting a trefoil knot

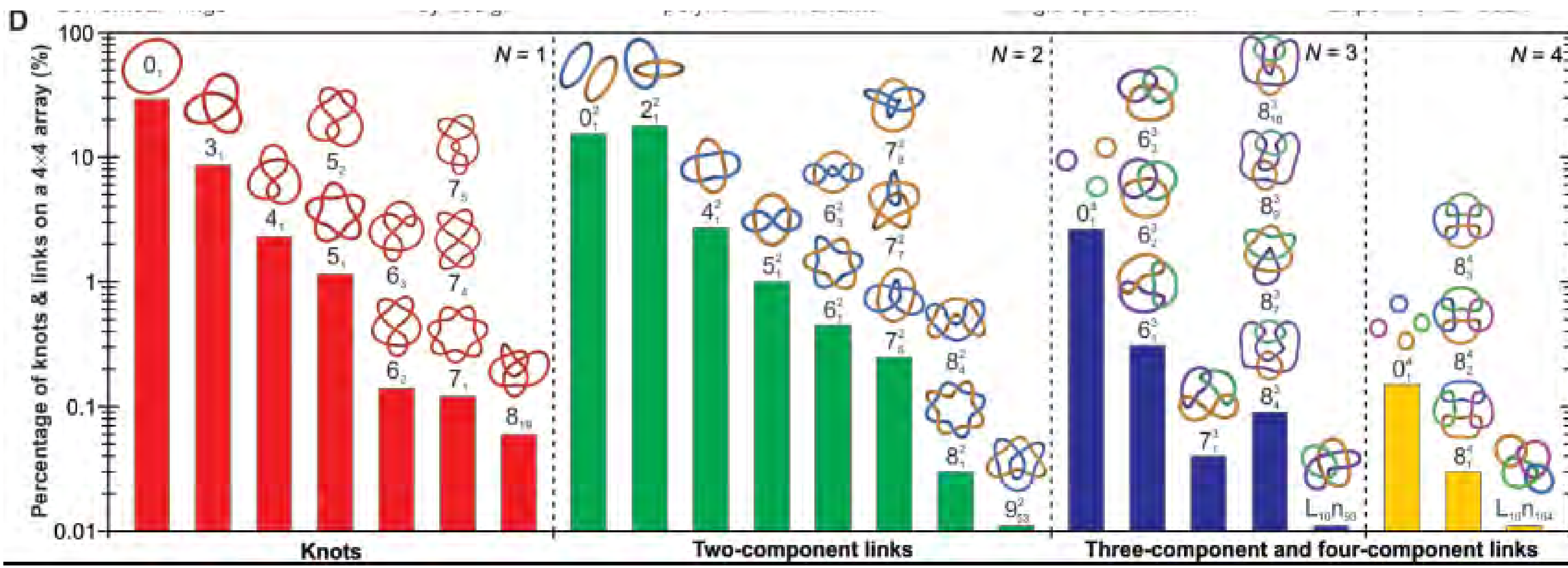
What do we do with the laser tweezers?

“cut and rejoin tangles”



trefoil two-component link Granny knot

Knots and links on a 4 x 4 colloidal array



REPORTS

Reconfigurable Knots and Links in Chiral Nematic Colloids

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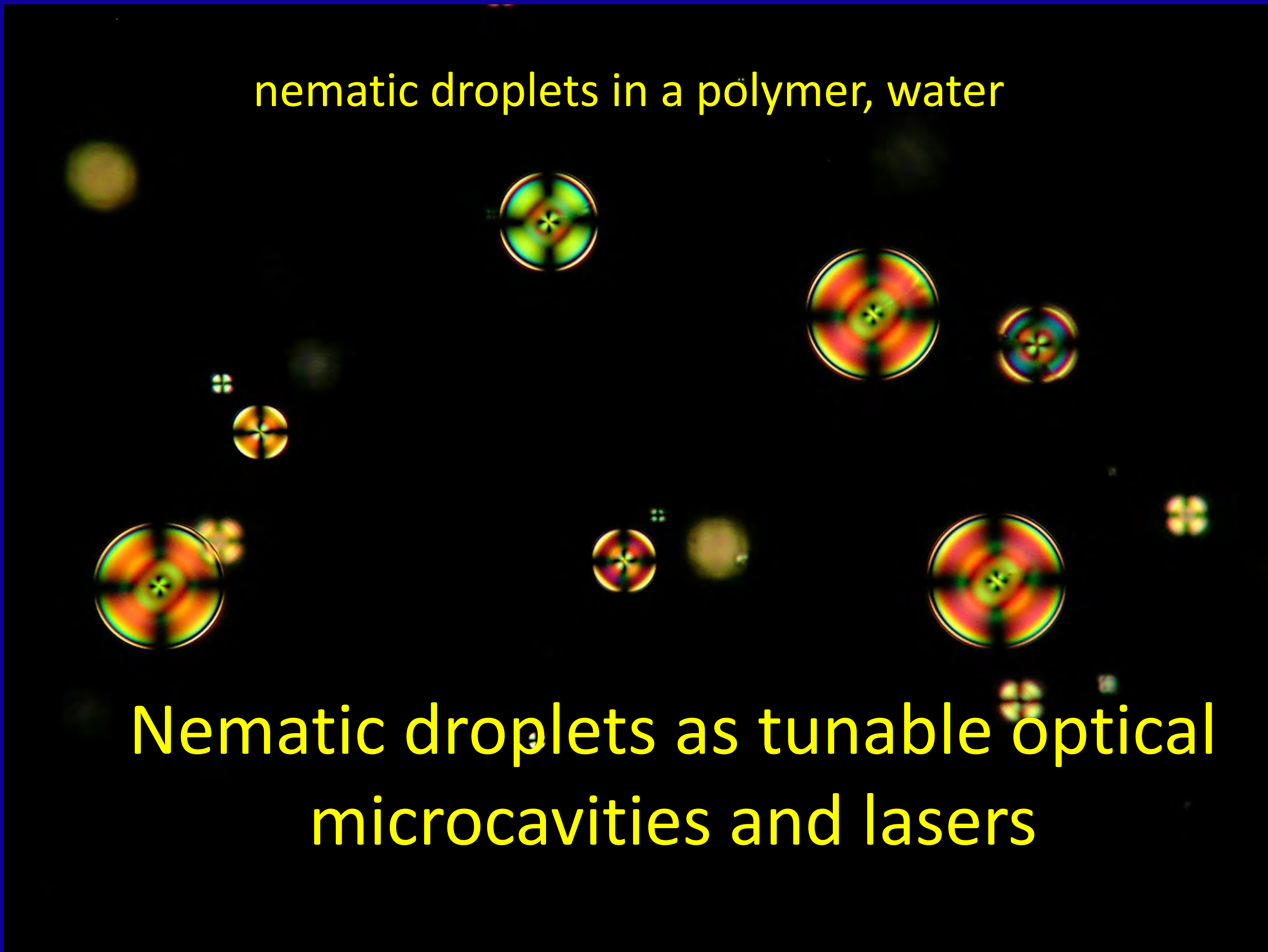
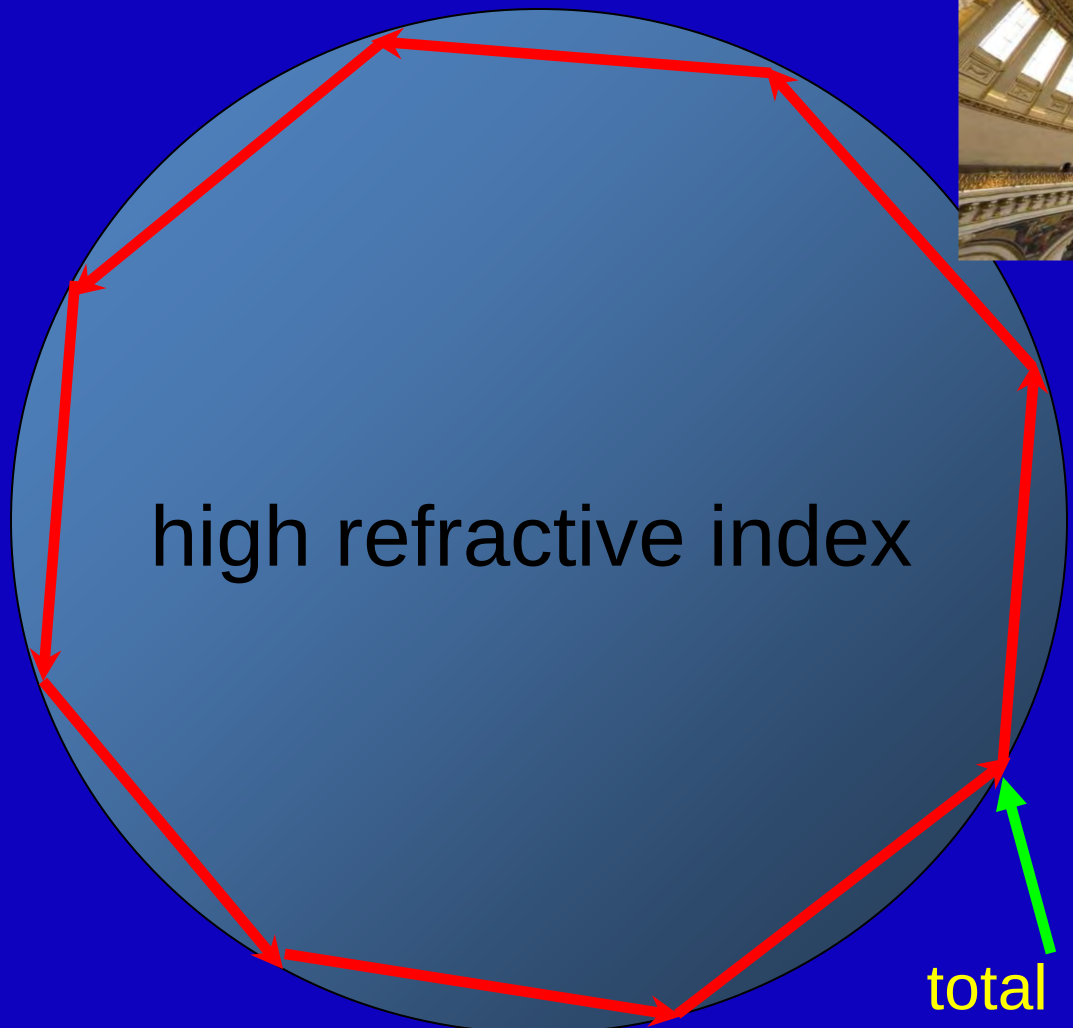
Tying knots and linking microscopic loops of polymers, macromolecules, or defect lines in complex materials is a challenging task for material scientists. We demonstrate the knotting of microscopic topological defect lines in chiral nematic liquid-crystal colloids into knots and links of arbitrary

are created. Each particle is encircled by its own micro-loop, also called a Saturn's ring, in which the degree of molecular order is reduced in the ~10-nm-thick core, and the director exhibits fast spatial variations, making the rings visible under an optical microscope (16). The Saturn's ring behaves as an elastic strip that can be stretched and deformed with laser tweezers (17–20). More importantly, several Saturn's rings can be fused together by using the laser tweezers to entangle a pair or multiple colloidal particles (21, 22). Here,

Optical properties of LC emulsions



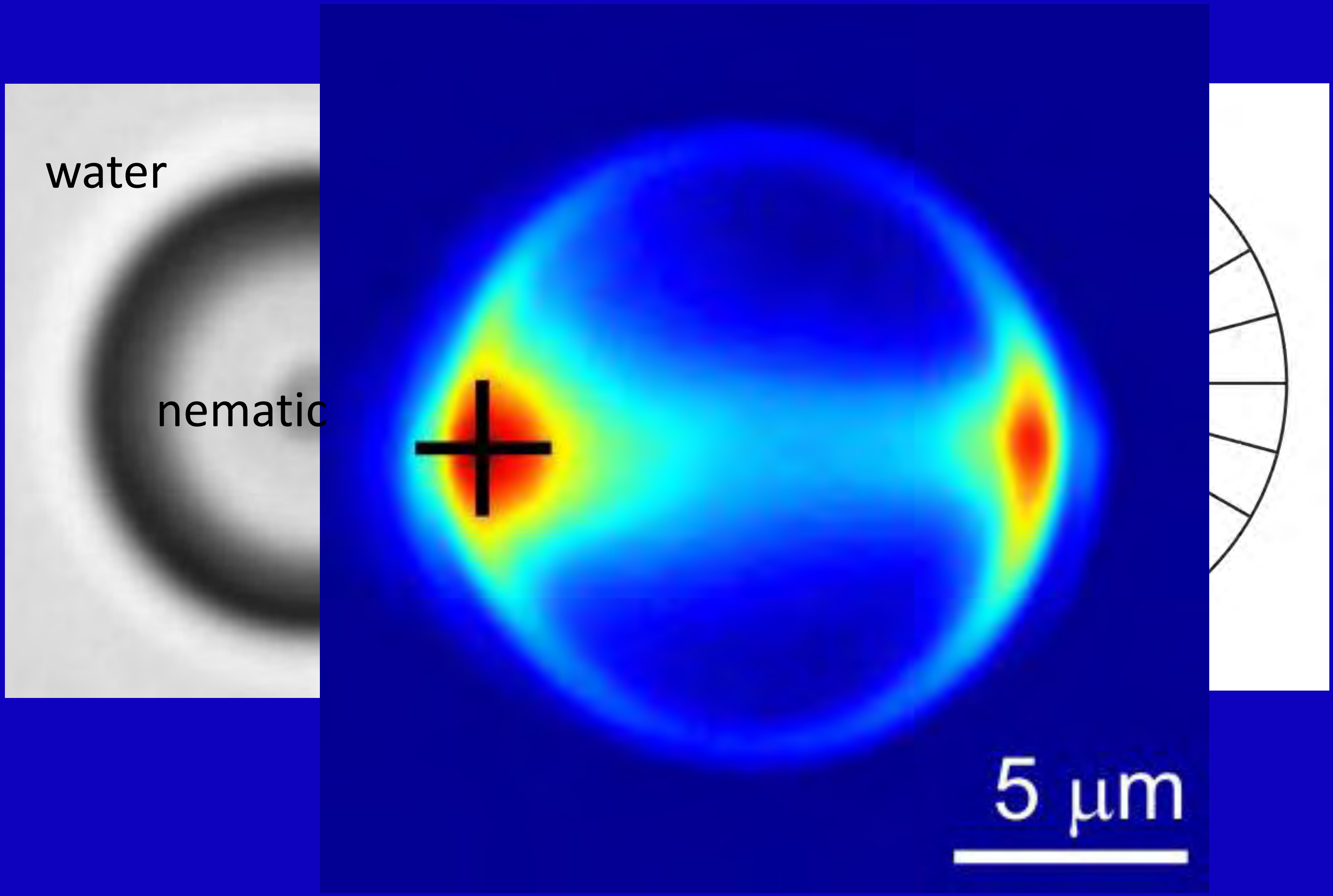
Confinement of light by total internal reflection



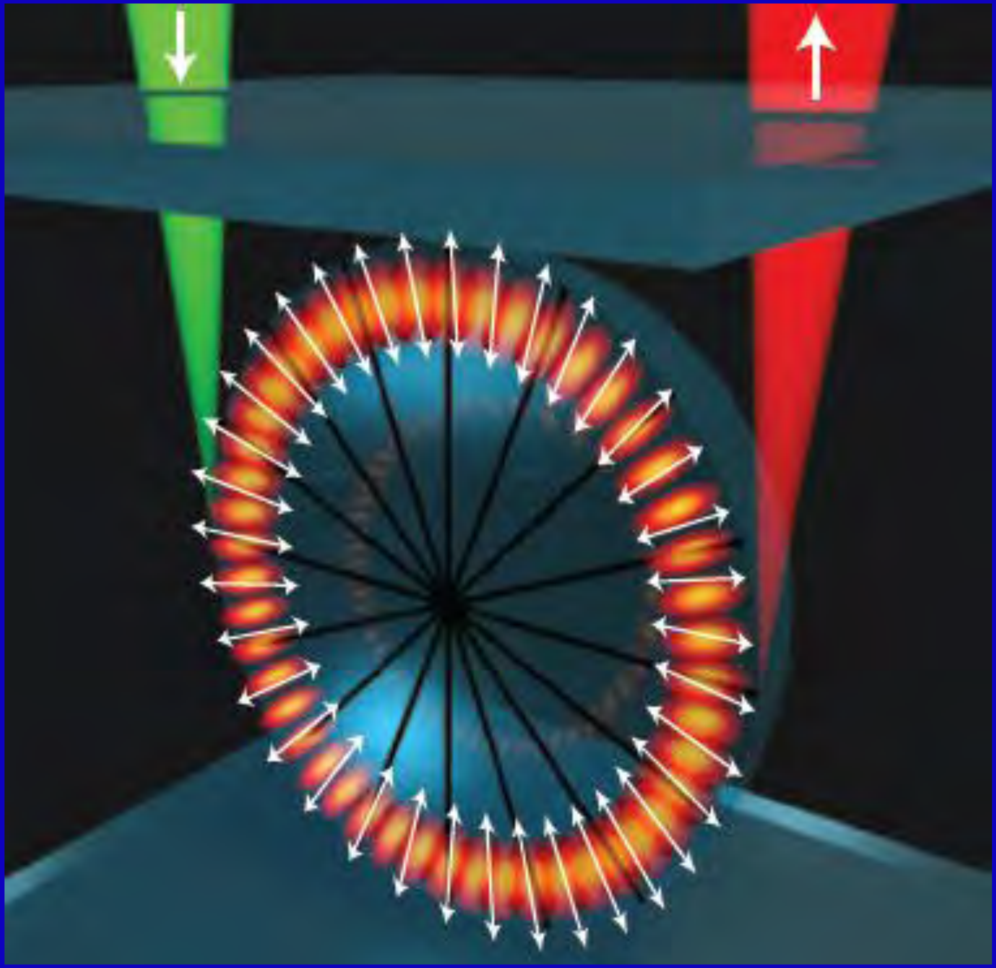
low refractive index

"whispering gallery modes", WGMs

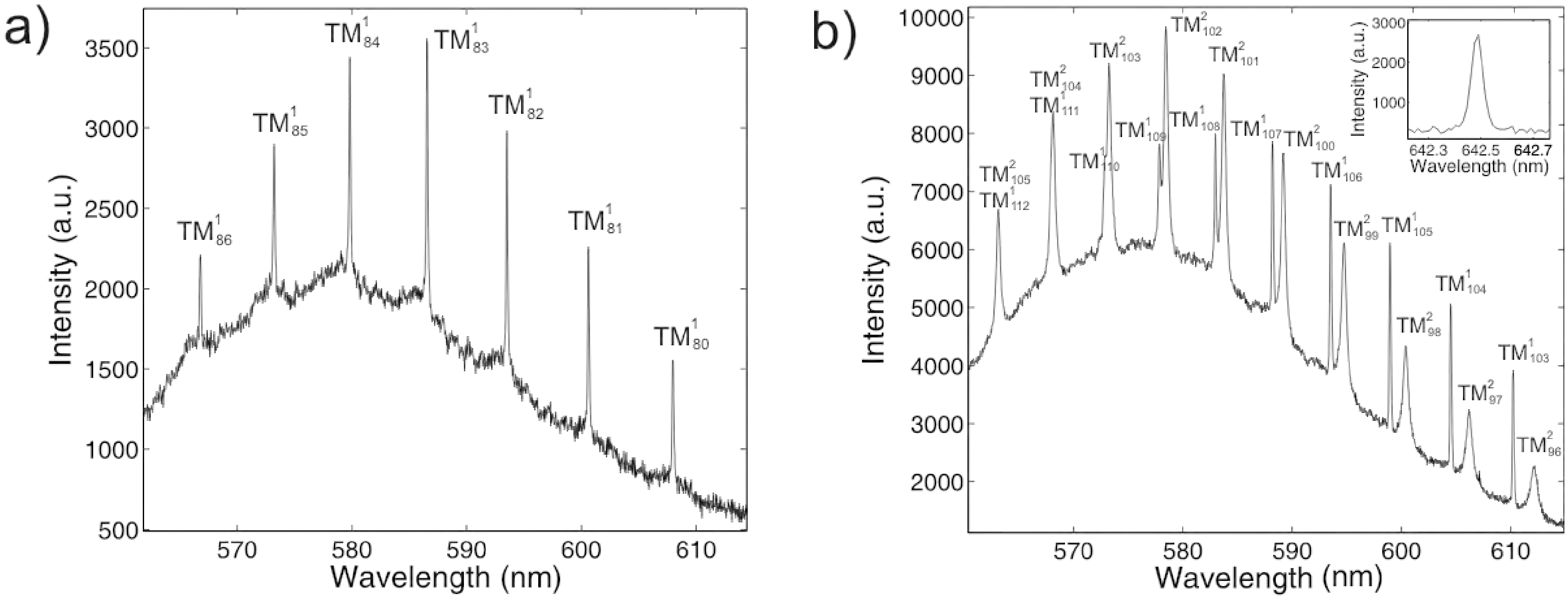
small LC droplets are WGM microresonators:



fluorescent dye is added to the nematic 5CB

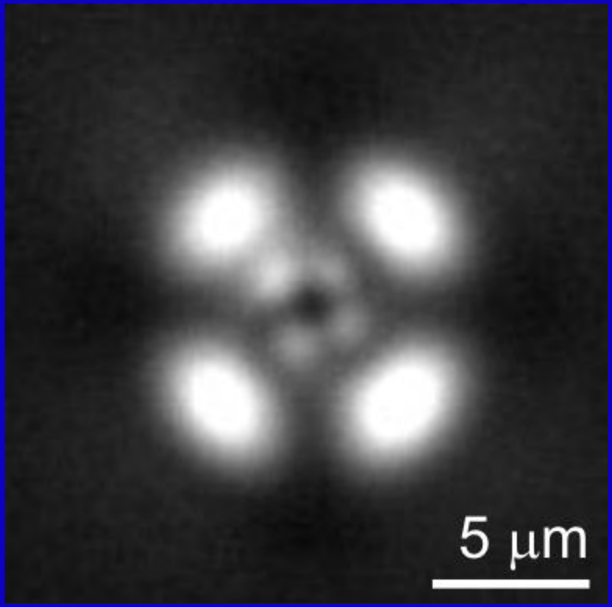


spectrum of light emitted from the droplet: WGM resonances

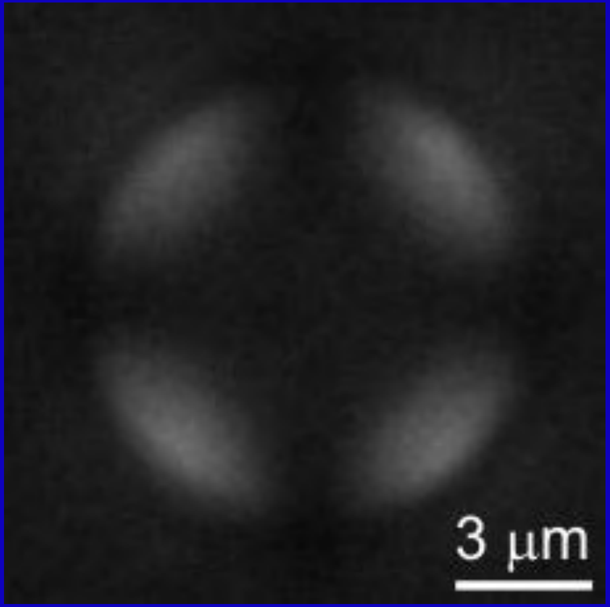


- resonances are narrow, ~ 0.05nm, ~15 GHz
- Q-factors are high, Q~12.000

can we tune the WGM resonances using the electric field?

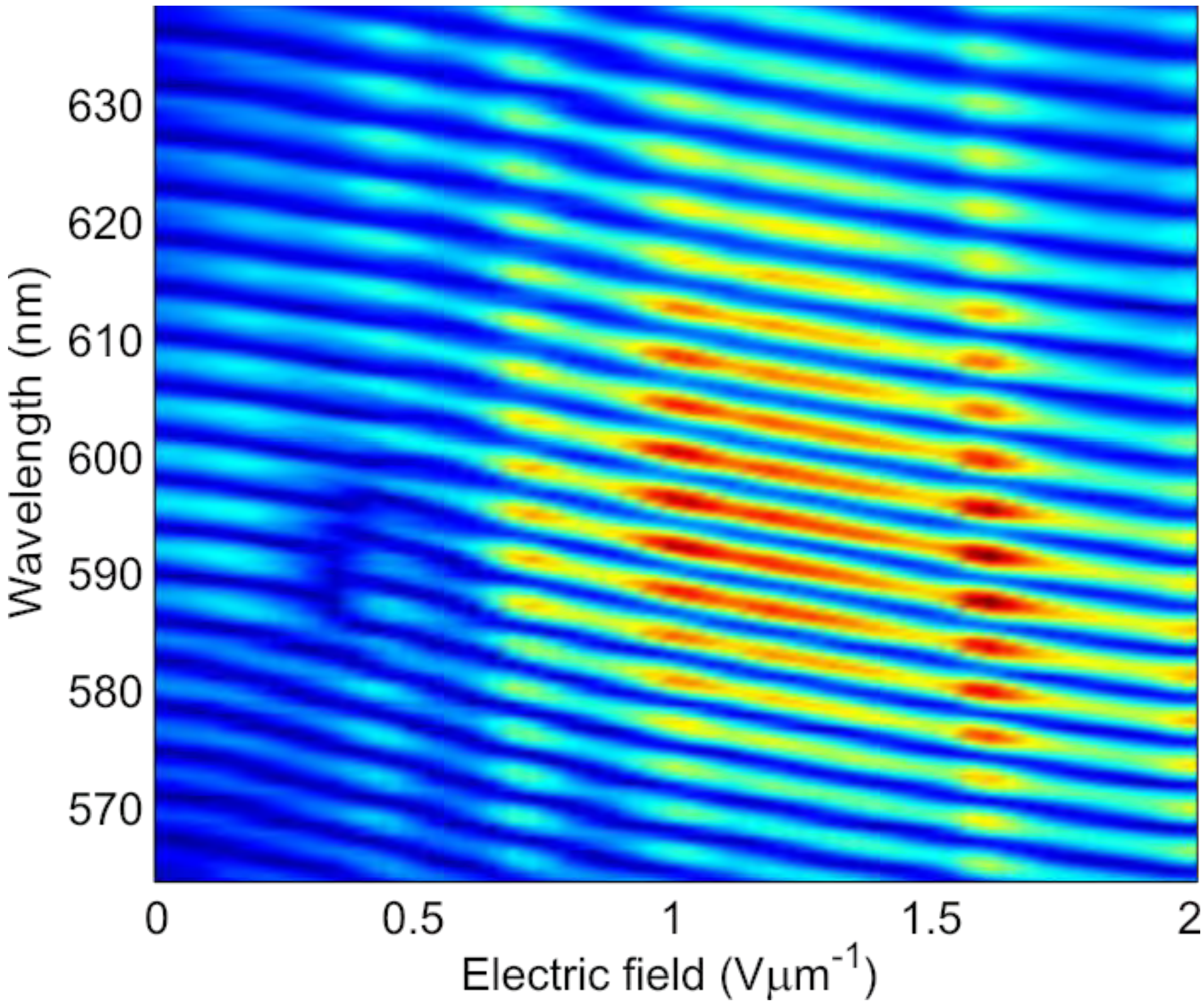


no field



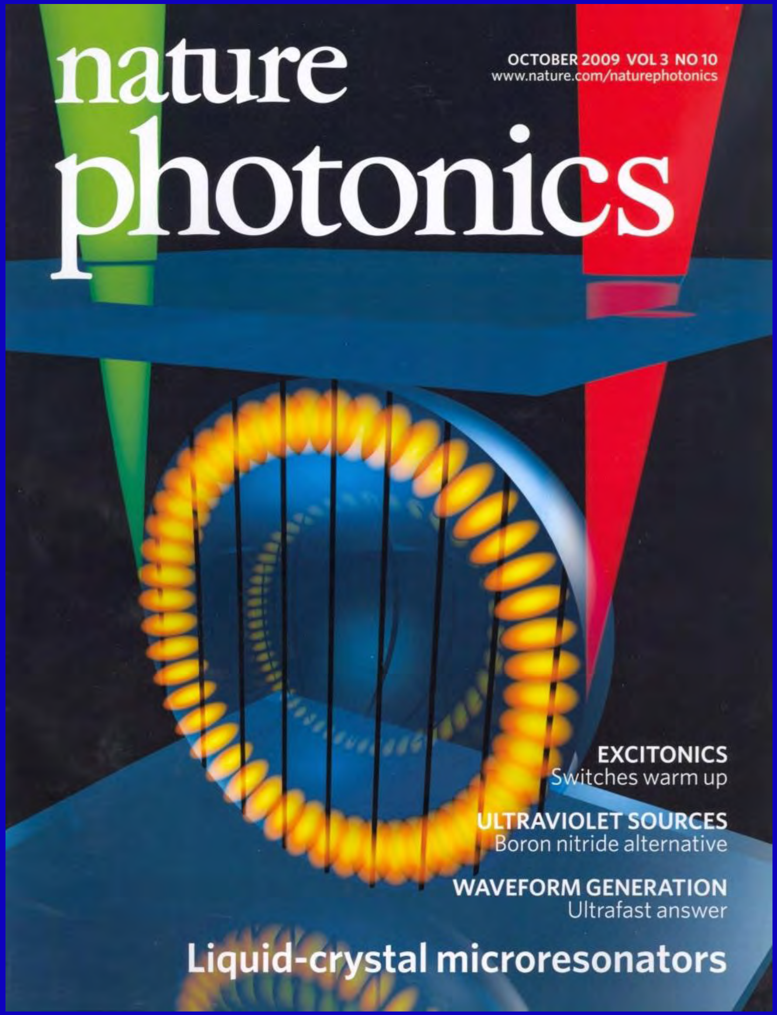
field

Small electric field shifts the resonances



~100 times larger range of tuning compared to a solid!

Humar, Ravnik, Pajk, Musevic, *Nature Photonics* **3**, 595(2009)

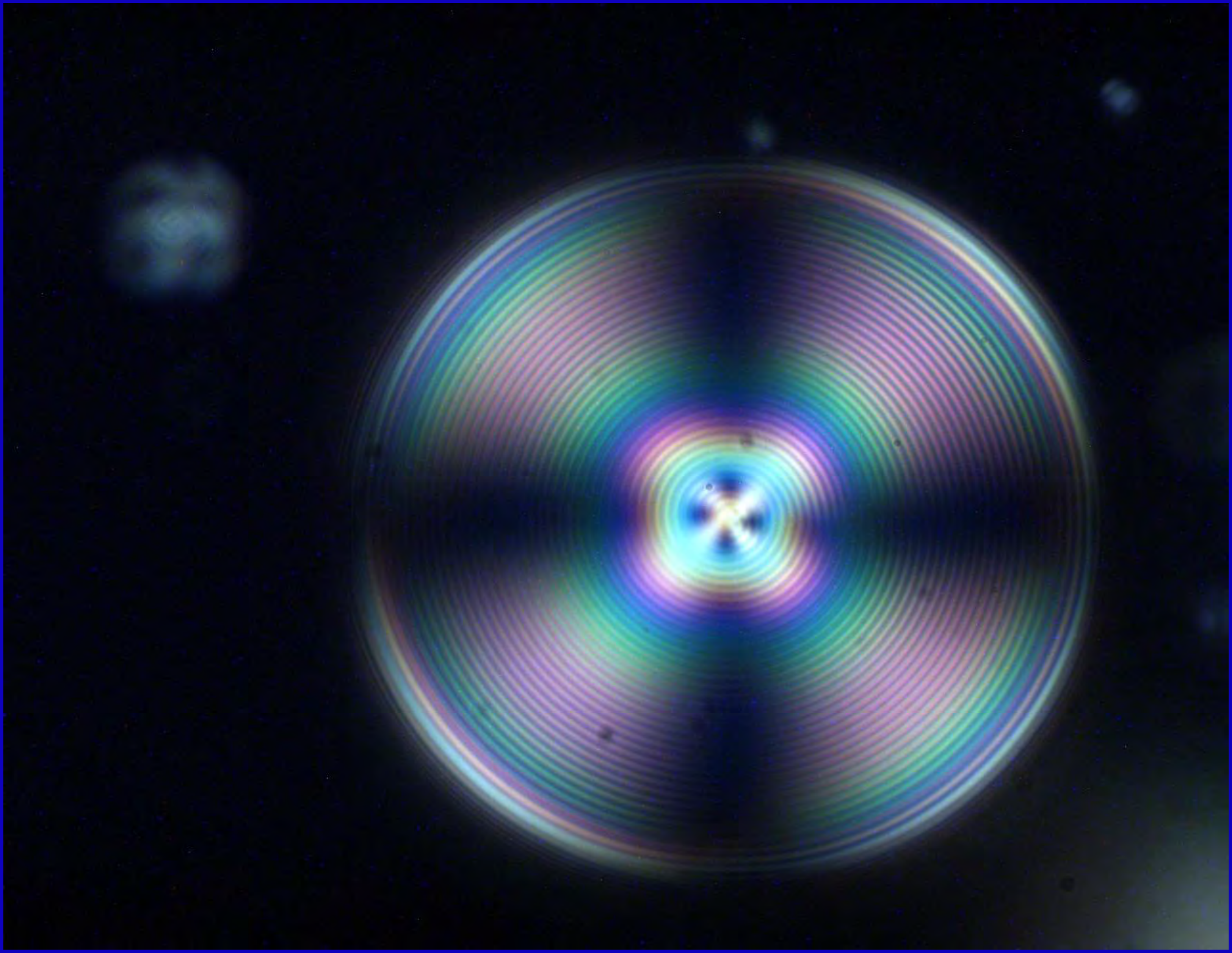


Applications:

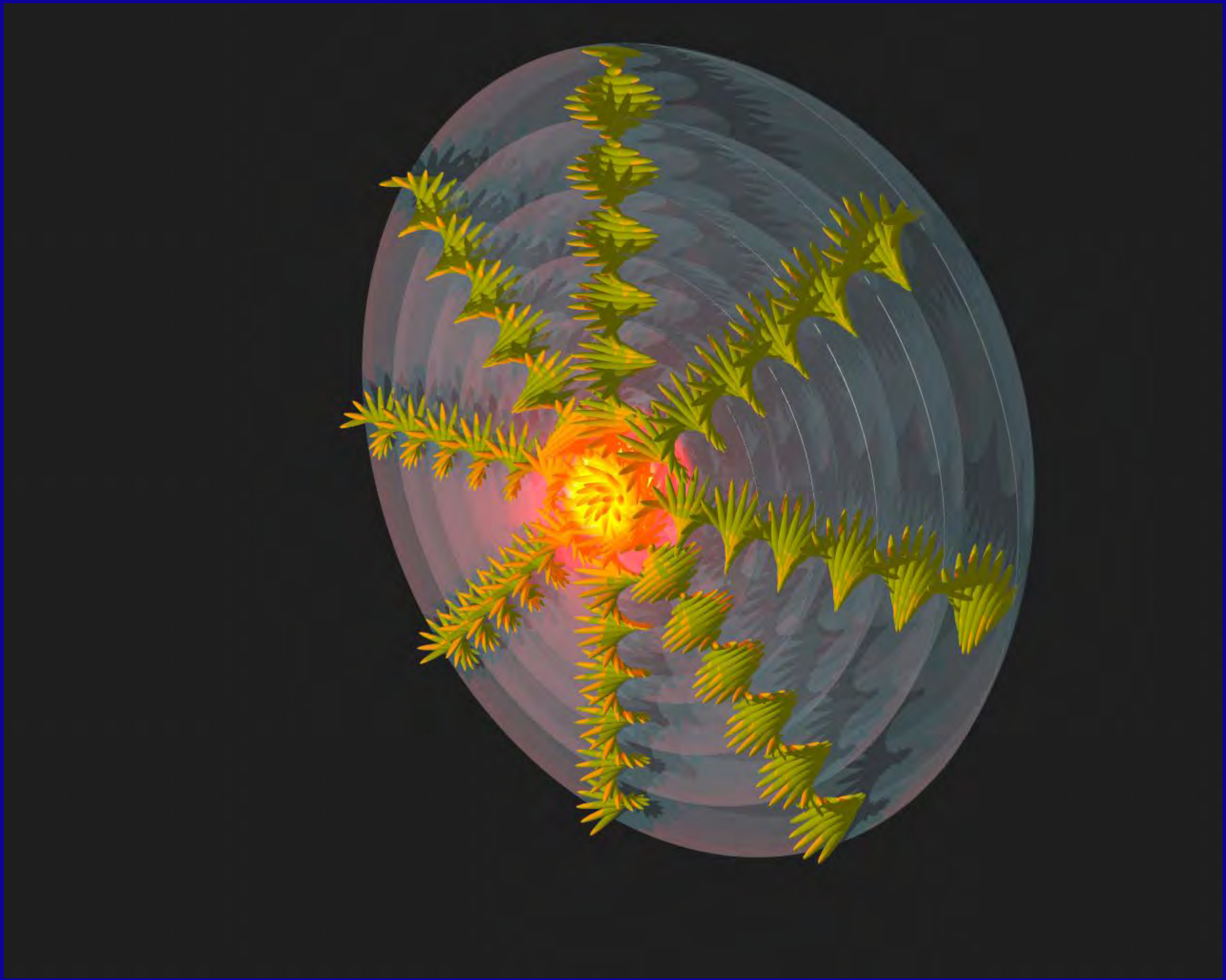
- tunable liquid filters
- liquid switches
- "photonic molecules"
  -coupled resonators
- tunable liquid microlasers
- liquid sensors: surface adsorption

Example : lasing from onion-Bragg LC resonator

small droplets of a cholesteric (chiral nematic) LC in water



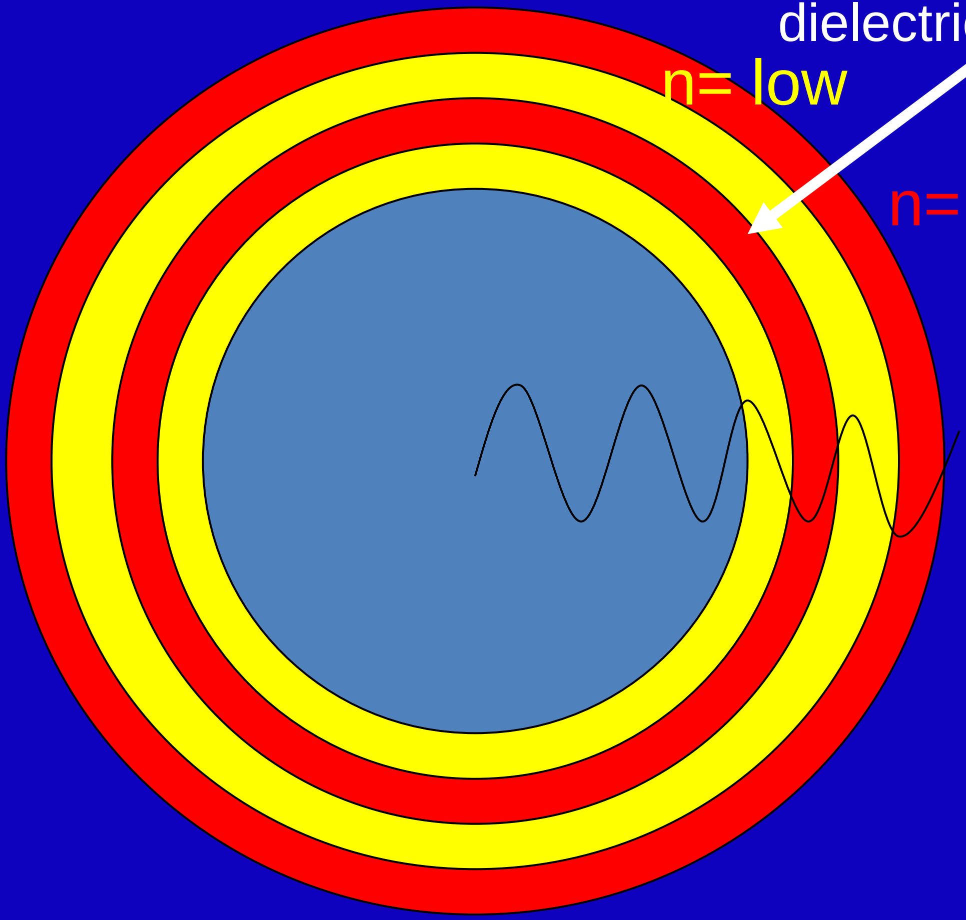
Helix going out from the center in all directions

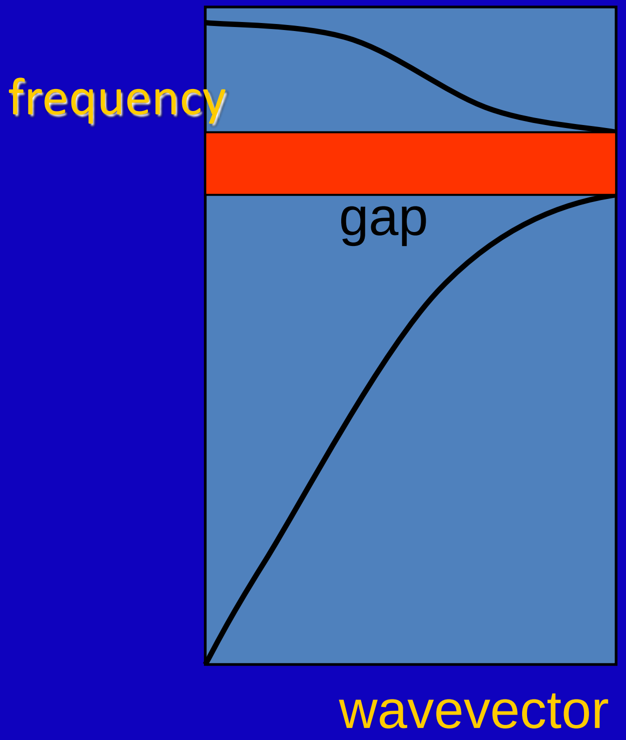


a small amount of the laser dye Nile red is mixed into CLC

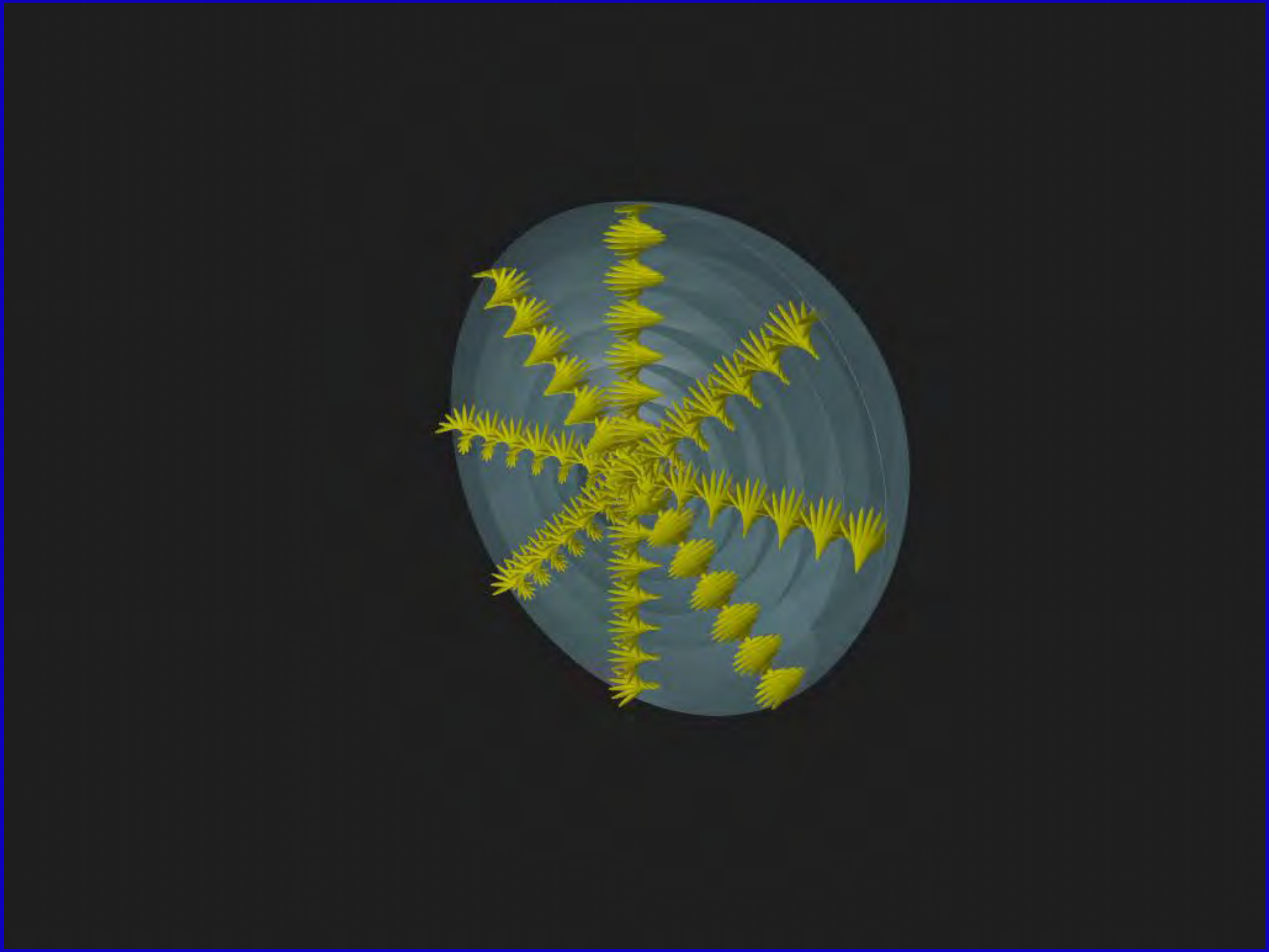
Bragg-reflector: “onion resonator”

waves are Bragg-reflected from periodic dielectric structure





Sulivan and Hall, PR A50,2701(1994)



Lasing of the world‘s first 3D microlaser

Humar and Musevic, *Optics Express* **18**, 26996(2010)
Optical Society of America: Press Release, December 8, 2010

Conclusions

"classical" colloids: EM field (isotropic solvent)

"nematic" colloids: orientational field (anisotropic solvent)

- topology and colloidal interactions:
  - localized singularities
  - entangled singularities
  - links and knots
- playground for topology: knitting and linking a chiral tensorial field.
- a large variety of 2D crystals, 3D also assembled
- very robust: 500-20.000 k_BT binding energy for a 2μm particle!

- interesting microstructures for optical applications

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